Astrophysics with Neutrinos
The High Energy Frontier

Thierry Pradier

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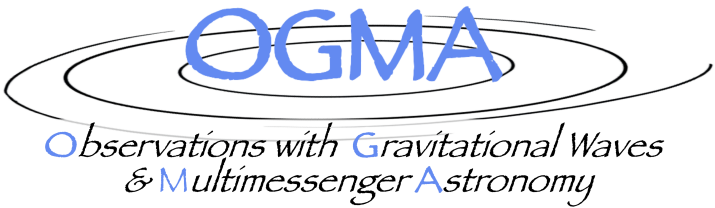

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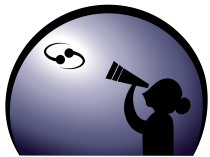






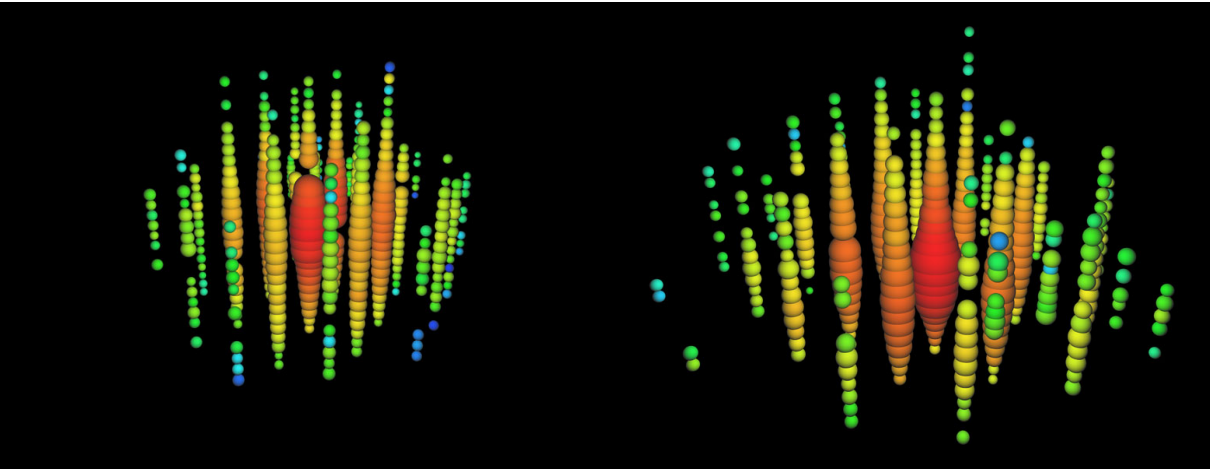


Neutrino Astrophysics - High Energies



1. Introduction : *Neutrinos and other messengers, Sources and Detection*
2. Neutrinos & Cosmic-Rays : *From γ to ν astrophysical fluxes*
3. Neutrino Telescopes : *from Neutrino Interactions to Detection*
4. IceCube and Antares : *Description and Selected Results*
5. MultiMessenger Astronomy : *combining all cosmic signals*
6. GRB GW170817
7. Blazar TXS0506+056
8. KM3-230213A
9. Perspectives : from KM3NeT to the unknown ?

ICECUBE and PeV Neutrinos



May 2013

IceCube reports first evidence for extraterrestrial high-energy neutrinos

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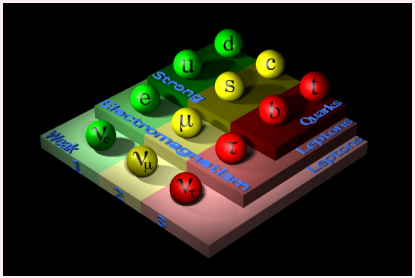
Introduction : properties and history of neutrinos

Neutrino Properties

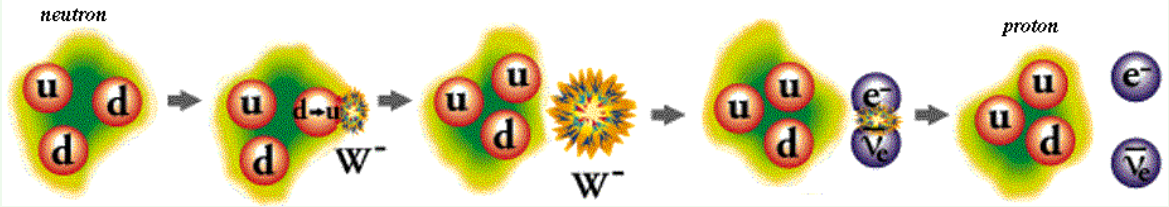
- Fermion
- Weak Interactions : exchange of W, Z
  - ⇒ **escapes dense regions**
- Elementary particle : no decay
- Mass close to zero
  - ⇒ **velocity** c
- Neutral particle
  - ⇒ **no effect of magnetic fields**



An introduction to Neutrino Astronomy

A brief history of neutrinos...

- 1930 : Pauli invents the neutrino to **explain** β **decay**...*I have done something very bad today by proposing a particle that cannot be detected ; it is something no theorist should ever do.*

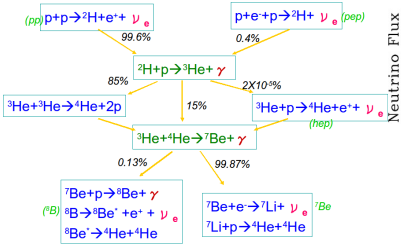


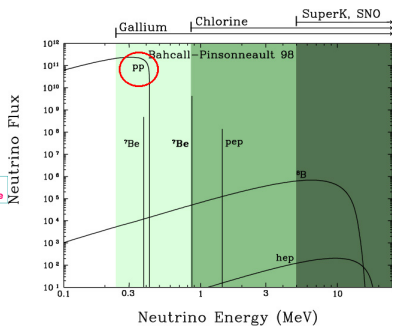
- 1933 : Fermi develops the theory of the little neutron (neutrino), discovered in 1932 by Chadwick
- 1953 : **Experimental observation** at Savannah River (Reines & Cowan) through $\bar{\nu} + p \rightarrow e^+ + n$

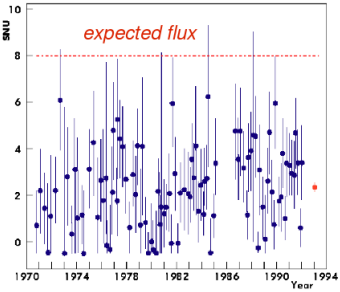
An introduction to Neutrino Astronomy

A brief history of neutrinos...

- 1968 : Solar Neutrinos observed at Homestake (Davis) - only the third of expectations...
- 1987 : SN1987A in Large Magellanic Could







HomeStake Data (from 1968)

An introduction to Neutrino Astronomy

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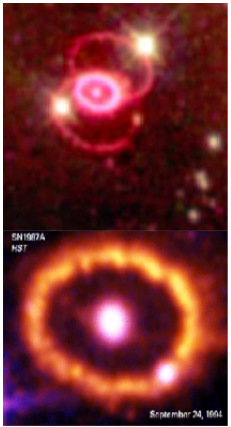
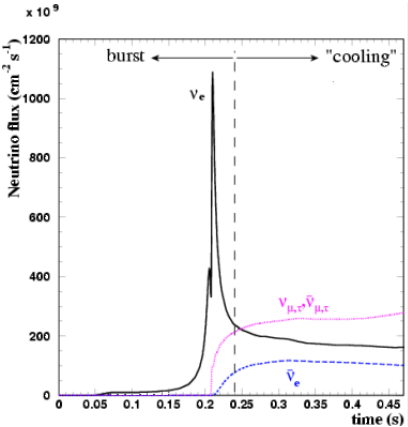
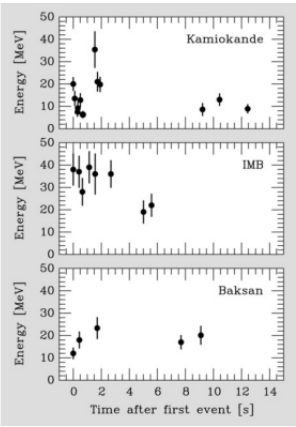
An introduction to Neutrino Astronomy





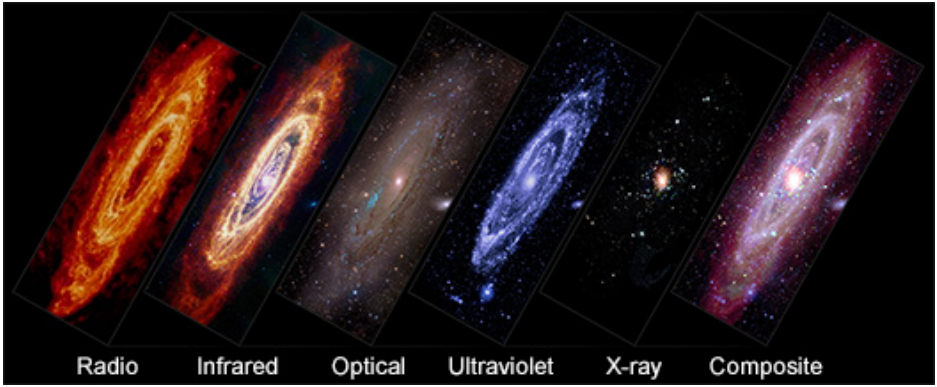


$\Rightarrow$ Birth of Neutrino Astronomy (1987) !

R. M. Bionta et al. , Phys. Rev. Lett. 58, 1494–1496 (1987)

K. Hirate et al.,Phys. Rev. Lett. 58, 1490–1493 (1987)

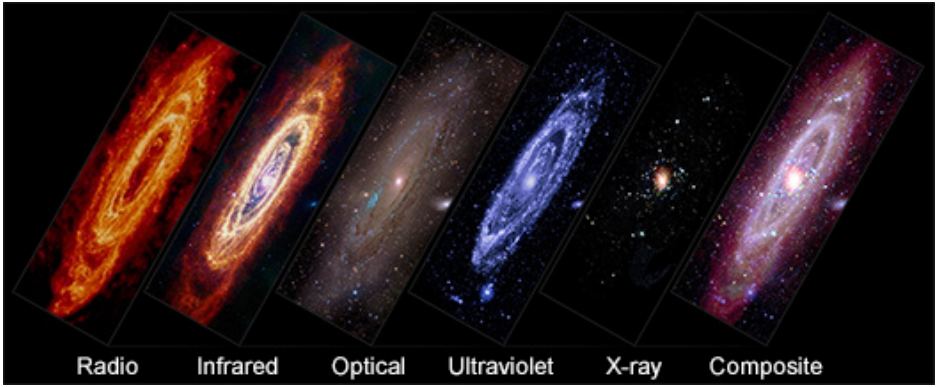
From multi-wavelength to multimessenger astronomy



Submm/Radio band

- Synchrotron (non-thermal) (e in B-field) + bremmsstrahlung (in star forming regions)
- Gas in Molecular Clouds - dense gas concentrations hosting star formation sites

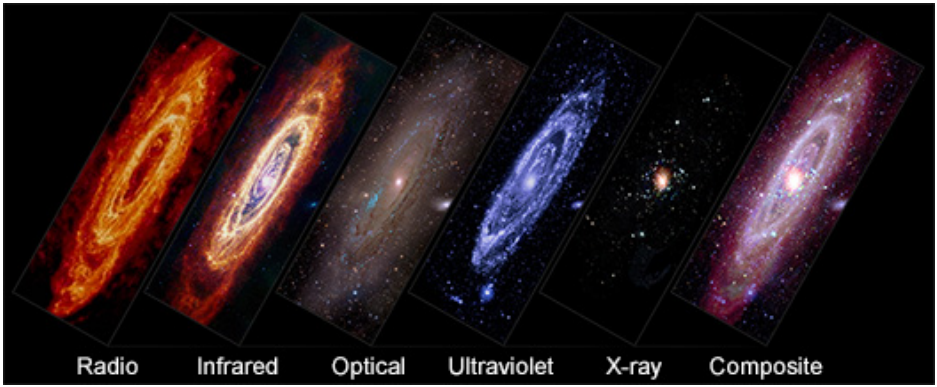
From multi-wavelength to multimessenger astronomy



Infrared band

- Dust in Molecular Clouds
- Small grains (< 0.01 μm) 3-30μm, larger grains at between 10-100 μm (or above if > 0.1 μm)

From multi-wavelength to multimessenger astronomy



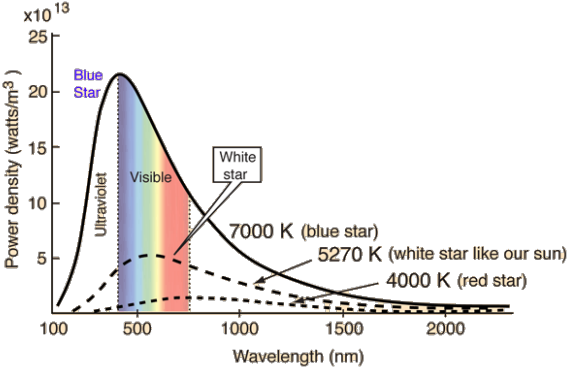
Optical band

- $\lambda.T =$ constant
- Thermal emissions of stars

From multi-wavelength to multimessenger astronomy

Ultraviolet band

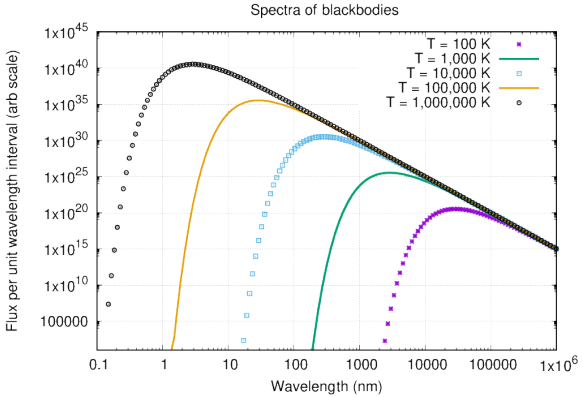
- $\lambda.T =$ constant
- Thermal emissions of massive stars



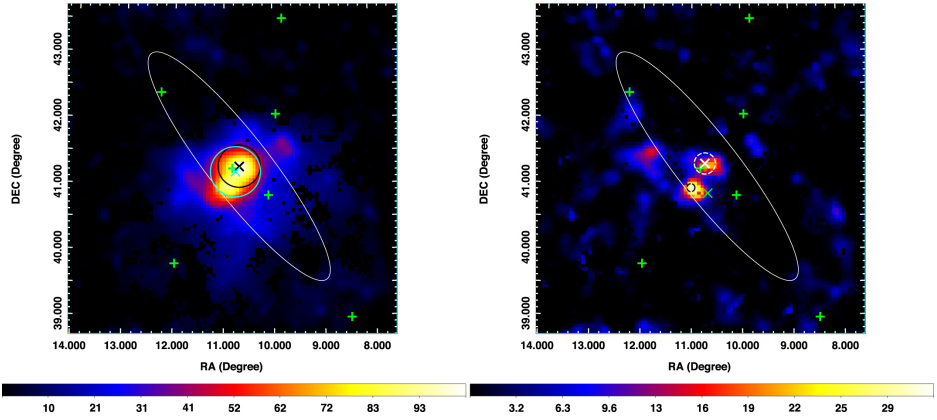
From multi-wavelength to multimessenger astronomy

X-Ray band

- Thermal emission (BB + Brem) : gas in galaxy clusters, accretion onto compact objects
- Non-thermal emission : synchrotron + inverse-compton (scattering of LE photons by electron)



From multi-wavelength to multimessenger astronomy



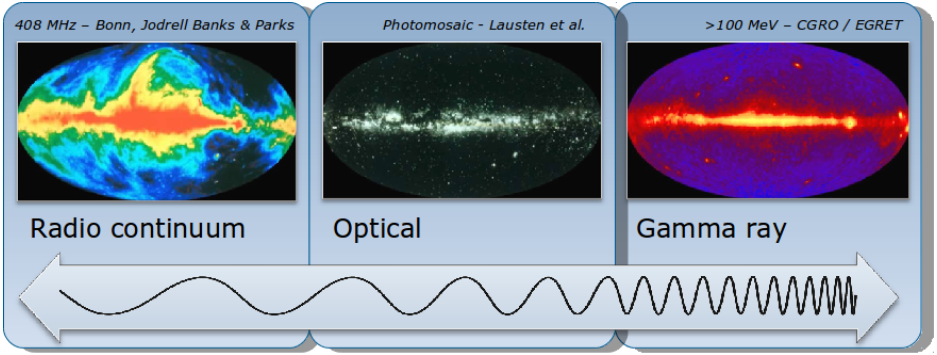
Gamma-rays

- Non-thermal processes : inverse compton (leptons), pp or pγ interactions
- Angular resolution $\approx 1^\circ$

From multi-wavelength to multimessenger astronomy



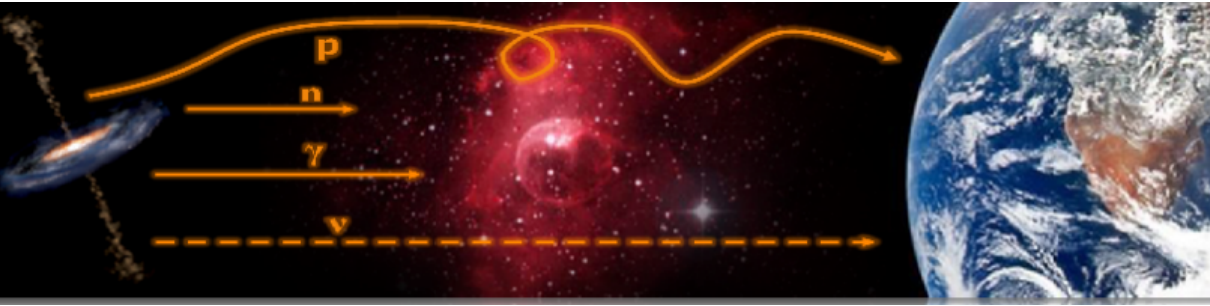
Neutrinos as Cosmic Messengers...



What about neutrinos... ?

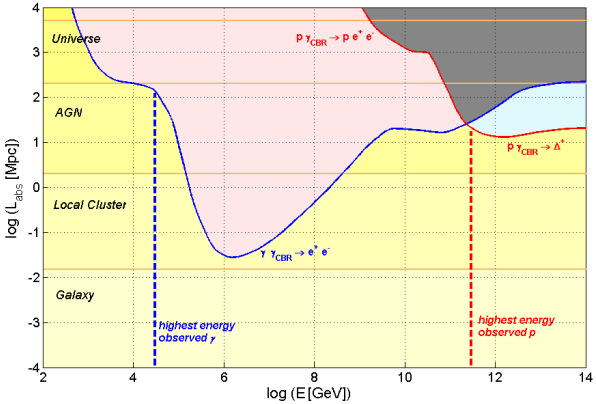
- If $E_\nu \approx 10GeV - 10^2 EeV$, same span as Radio to X-rays !

Neutrinos as Cosmic Messengers...



- Protons : **deflected by magnetic fields** ($E_p < 10^{19} GeV$) ; UHE interact with CMB photons ($\mathcal{L} \sim 30 Mpc$)
- Neutrons : decay ($\mathcal{L} \sim 10 kpc$ at $E \sim EeV$)
- Photons : **interact with ExtraGalactic Background Light** ($\mathcal{L} \sim 100 Mpc$) and CMB ($\mathcal{L} \sim 10 kpc$)
- Neutrinos : **neutral, weakly interacting**...

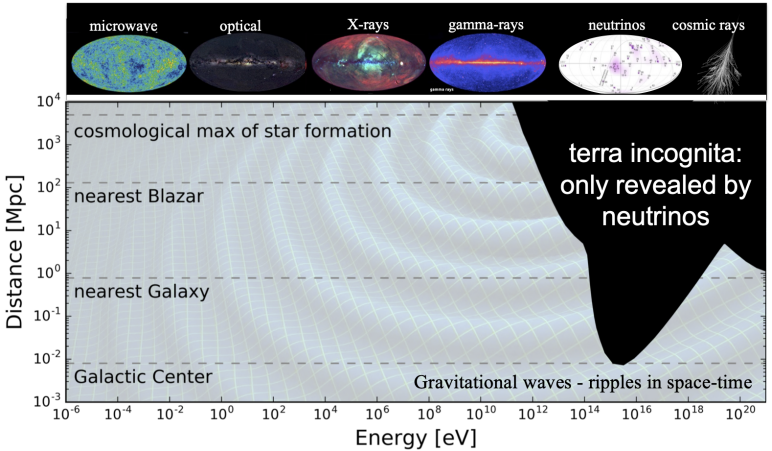
Neutrinos as Cosmic Messengers...



Compute a mean free path ?

- $\mathcal{L} \approx \frac{1}{n_{\text{target}} \times \sigma_{\text{process}}}$

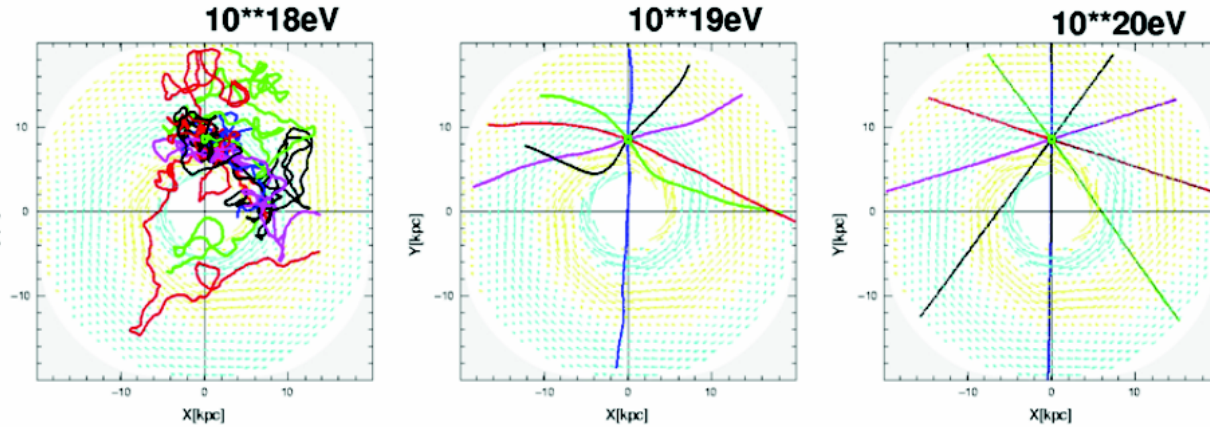
Neutrinos as Cosmic Messengers...



Observing violent sources

- Universe beyond our Galaxy is opaque to gamma rays

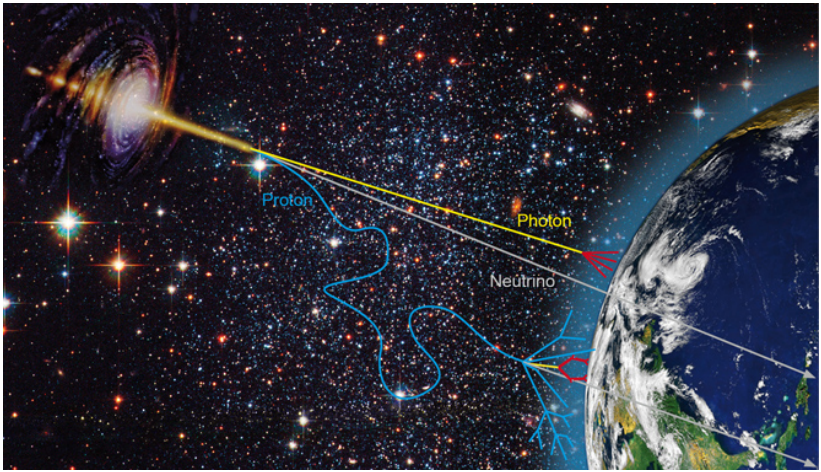
Neutrinos as Cosmic Messengers...



Compute a radius of curvature ?

- $\vec{F} = q(\vec{v} \times \vec{B}) \Rightarrow \frac{mv_\perp^2}{R_L} = qv_\perp B \Rightarrow R_L(m) \sim 3.3 \frac{p(GeV/c)}{ZeB} \propto \frac{E}{ZeBc}$

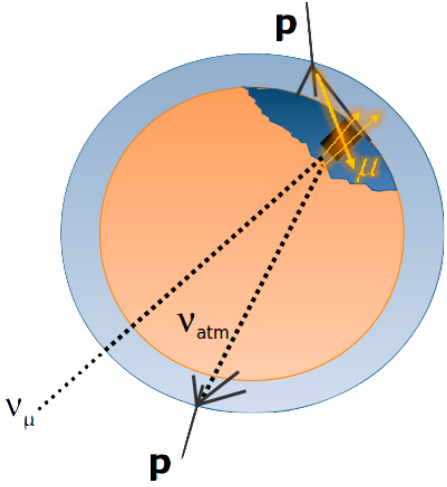
Neutrinos as Cosmic Messengers...

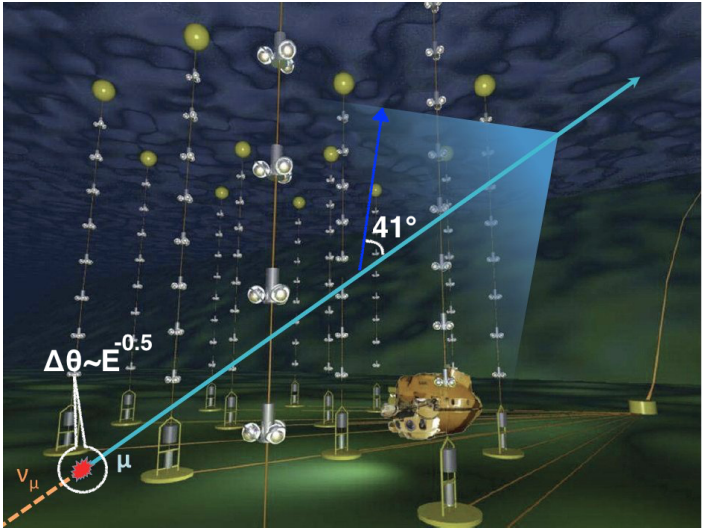


How are they detectable ?

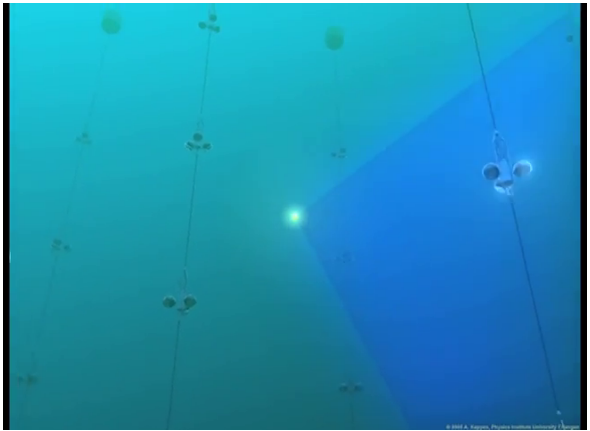
- **Requires large volume of detection**...

Neutrinos as Cosmic Messengers...





Neutrinos as Cosmic Messengers...

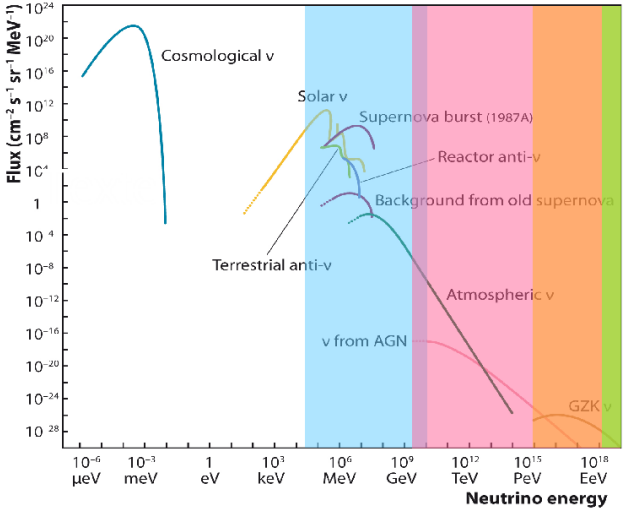


Sources of neutrinos...

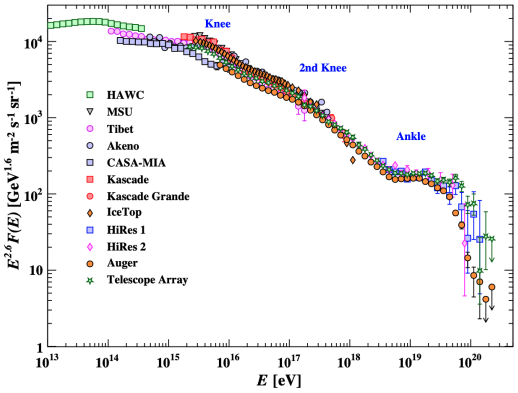
- Under rock
- Under water/ice
- Acoustics/Radio
- Giant Air Shower

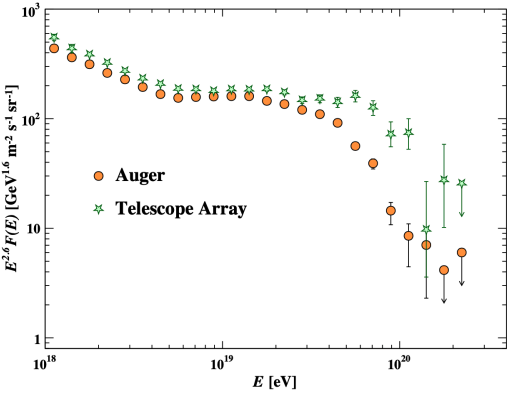
How many ?

- CνB : $N \approx 4\pi \times \frac{dN}{dE} \times E \sim 10 \times 10^{22} cm^{-2}.s^{-1}.sr^{-1}.MeV^{-1} \times 10^{-9} MeV \approx 10^{14} cm^{-2}.s^{-1}$
- Sun : $N \approx 10^{12} cm^{-2}.s^{-1}$
- Cosmic : $N < 10^{-10} cm^{-2}.s^{-1}$
- GZK : $N \approx 10^{-15} cm^{-2}.s^{-1}$



GZK Neutrinos : The far end of the spectrum...

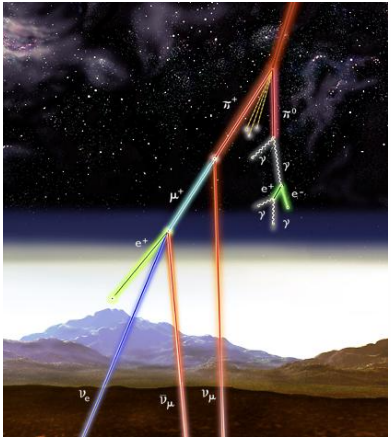


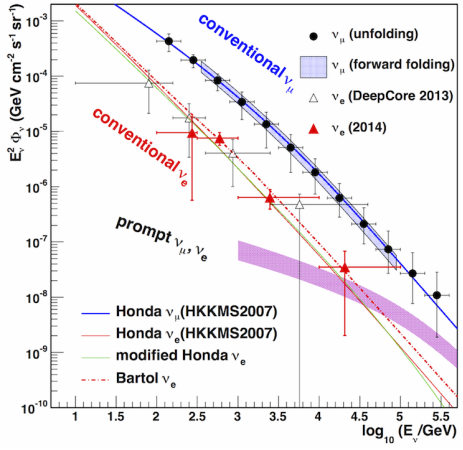


Guaranteed source of UHE neutrinos

- Threshold $\gamma_{\mathrm{CMB}} + p \rightarrow \pi + N \approx 10^{20} eV$
- Flux : less than $100/km^2/yr$!
- Detected with Giant Air Shower Arrays

Atmospheric neutrinos





Background for detection of astrophysical neutrinos !

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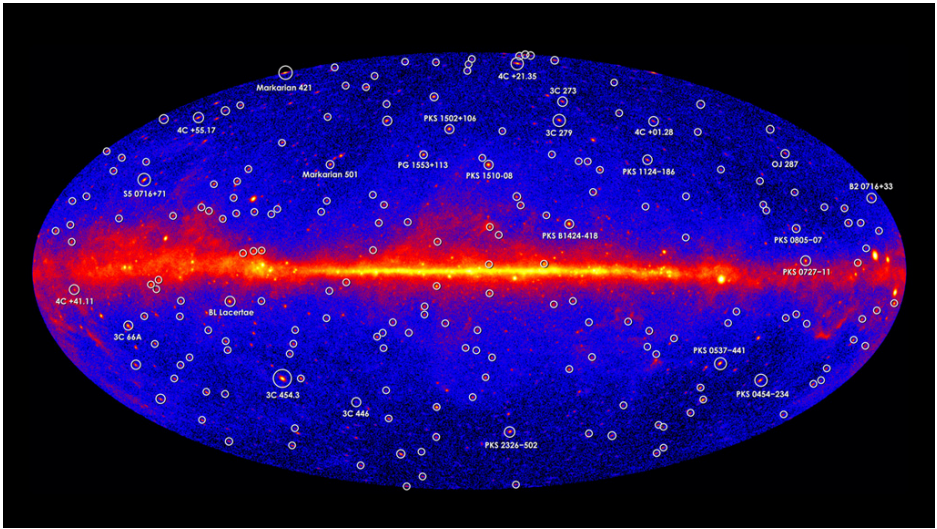
High-Energy Neutrinos :

The Cosmic-Ray Connection

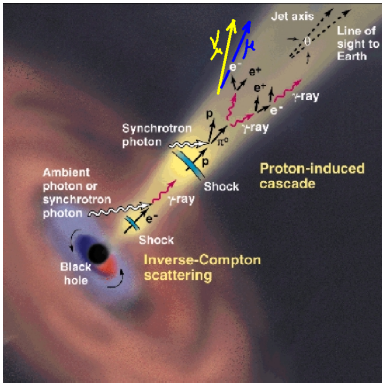


The TeV Gamma-Ray Sky

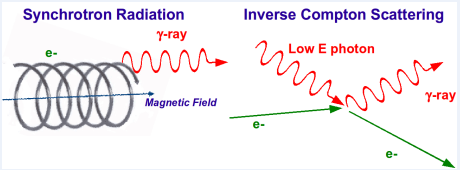


from TeV Gamma-Ray Catalog

The Cosmic-Ray Connection

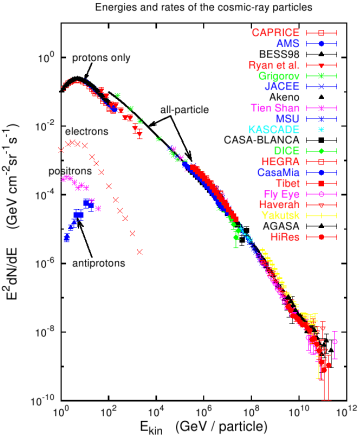


Leptonic Production of HE γ :



Hadronic Production of HE γ/CRs :

$$p/A + p/\gamma \longrightarrow \begin{array}{cc} \pi^0 & \pi^{\pm} \\ \downarrow & \downarrow \\ \gamma\gamma & \mu\,\nu_\mu \\ & \downarrow \\ & \nu_\mu\,\nu_e\,e \end{array}$$



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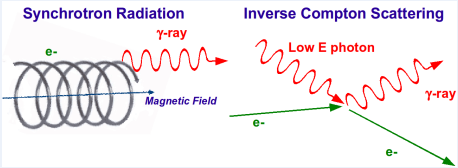
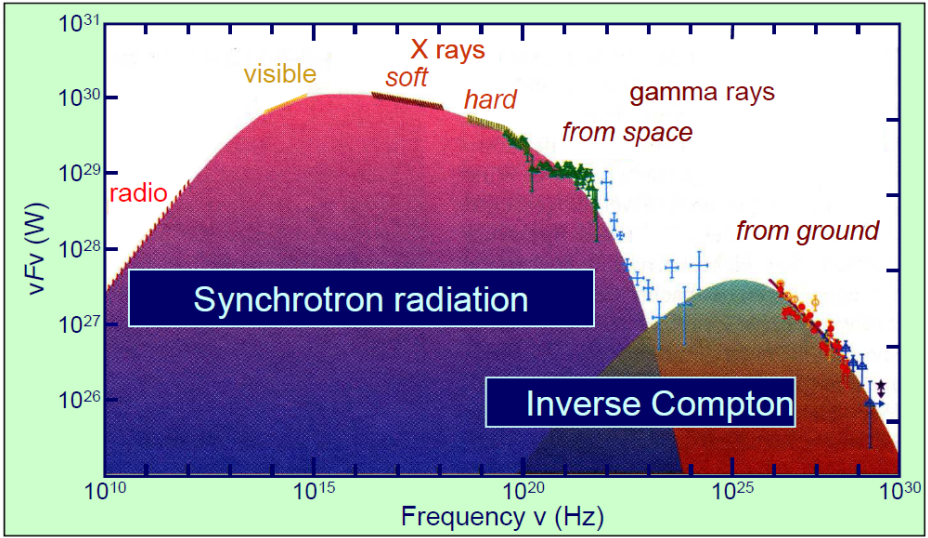


Hadronic Production of HE γ/CRs :

$$p/A + p/\gamma \longrightarrow \begin{array}{cc} \pi^0 & \pi^\pm \\ \downarrow & \downarrow \\ \gamma\gamma & \mu\ \nu_\mu \\ & \downarrow \\ & \nu_\mu \nu_e e \end{array}$$

Neutrinos are the **smoking gun** of hadronic processes

The Cosmic-Ray Connection



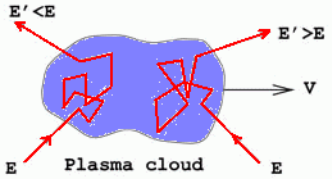
Fermi Acceleration

Fermi again !

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

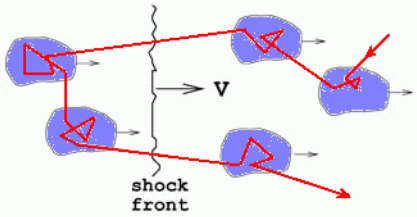
2nd order :
randomly distributed magnetic mirrors



$$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$$

[Slow and inefficient]

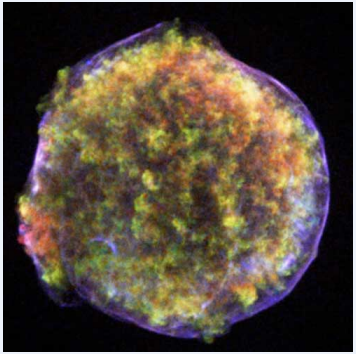
1st order :
acceleration in strong shock waves (supernova ejecta, RG hot spots...)



$$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$$

Fermi Acceleration

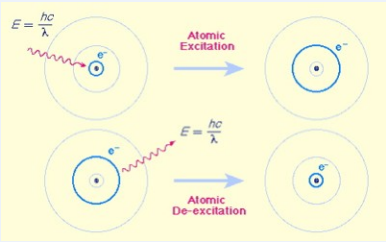
Acceleration at shocks : X-rays to probe the shock

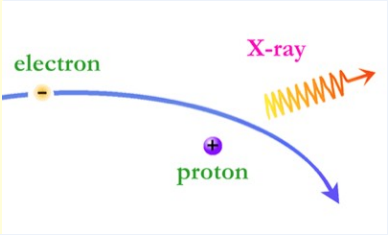


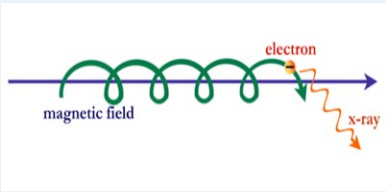
- Predicts power-law, with $\alpha \sim 2.1$
- Differences observed explained by energy-dependent escape probability
- Works well until 10^{14} eV

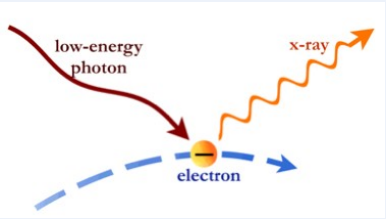
Fermi Acceleration

Acceleration at shocks : X-rays to probe the shock







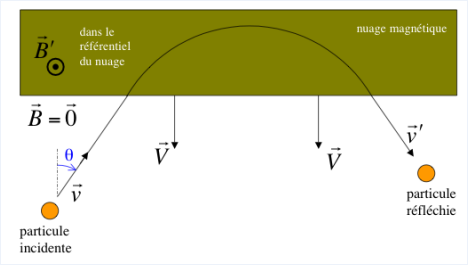


Magnetic field and acceleration

- Interstellar plasma conductive, no stable $E\ \vec{E} = 0$
- Induced electric field : $\vec{\nabla} \times \vec{E} = \frac{d\vec{B}}{dt}$
  - $\Rightarrow$ Field B in rotation - pulsars
  - $\Rightarrow$ Reconnection of magnetic field lines
- Movement in magnetized space : $\vec{E} = \vec{v} \times \vec{B}$ pour $\beta \ll 1$
  - $\Rightarrow$ on magnetized clouds : Fermi 2nd order
  - $\Rightarrow$ on shock wave : Fermi 1st order

Fermi Acceleration - 2nd Order

Magnetic Clouds



- Deflection of charged particles
- Random movement
- Particles gain energy in head-on collision
- Loss of energy in "back" collision
- On average, head-on collisions more probable : energy gain

Fermi Acceleration - 2nd Order

Moving magnetic mirror

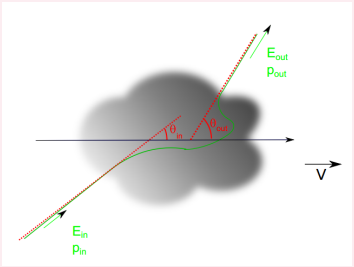
- In cloud ref. K' : $E'_i = \gamma(E_i - p_{i\parallel}V)$
- Momentum reversed in K' : $p'_{f\parallel} = -p'_{i\parallel}$
- In K : $E_f = \gamma(E'_f + p'_{f\parallel}V)$
- But $p_\parallel = -E/c^2 v\cos\theta$:

$$E_f = \gamma^2\left(E_i(1+\frac{V^2}{c^2}) - 2p_{i\parallel}V\right) \sim \gamma^2 E_i\left(1+\frac{2Vv\cos\theta}{c^2}+\frac{V^2}{c^2}\right)$$

- At 1st order in V/c : $\frac{\Delta E}{E} = \frac{2Vv\cos\theta}{c^2} = -2\frac{\vec{v}.\vec{V}}{c^2}$
- Energy variation proportionnal to initial energy
- Gain or loss depending on relative direction of $\vec{v}$ et $\vec{V}$
- ΔE is independant of charge and $\vec{B}$

Fermi Acceleration - 2nd Order

Isotropization of movement



- All possible movements have to be taken into account
- Ref. Cloud : $E'_{\text{in}} = \gamma(E_{\text{in}} - \beta p_{\text{in}} c \cos\theta_{\text{in}}) \sim \gamma E_{\text{in}}(1 - \beta\cos\theta_{\text{in}})$
- In lab frame : $E_{\text{out}} = \gamma E'_{\text{out}}(1 + \beta\cos\theta'_{\text{out}})$
- Elastic scattering : $E'_{\text{in}} = E'_{\text{out}}$

$$\frac{\Delta E}{E} = \frac{\beta(\cos\theta'_{\text{out}} - \cos\theta_{\text{in}}) + \beta^2(1 - \cos\theta_{\text{in}}\cos\theta'_{\text{out}})}{1 - \beta^2}$$

Fermi Acceleration - 2nd Order

Average energy gain

- Particles are isotropic in cloud frame : $< \cos\theta'_{\text{out}} >= 0$
- Cloud velocity V, number of incident particles at θ_{in} : $dN = 2\pi \sin\theta_{\text{in}} d\theta_{\text{in}}$
- During δt, $dN \propto (c - V\cos\theta_{\text{in}})\delta t$

$$< \cos\theta_{\text{in}} >= \frac{\int_{-1}^{1} \cos\theta_{\text{in}}(c - V\cos\theta_{\text{in}}) d\cos\theta_{\text{in}}}{\int_{-1}^{1} (c - V\cos\theta_{\text{in}}) d\cos\theta_{\text{in}}}$$

$$< \cos\theta_{\text{in}} >= \frac{-2V/3}{2c} = -\frac{\beta}{3}$$

- Energy gain $< \frac{\Delta E}{E} >= \frac{\beta(<\cos\theta'_{\text{out}}> - <\cos\theta_{\text{in}}>)}{1-\beta^2} + \beta^2 \frac{1 - <\cos\theta_{\text{in}}><\cos\theta'_{\text{out}}>}{1-\beta^2} = \frac{4\beta^2}{3(1-\beta^2)} \sim \frac{4}{3}\beta^2$
- Positive gain $\propto E$, stochastic (gain on average), 2nd order in β

Fermi Acceleration - 2nd Order

Acceleration rate

- Between 2 collisions $\tau_{\rm coll}$, between 2 clouds L
- For particle at angle α, $v_{\parallel} \sim c \cos\alpha$, $t_{\rm coll} = \frac{L}{c\cos\alpha}$
- Average on α : $< v_{\parallel} >= c/2$ et $< t_{\rm coll} > \sim \frac{2L}{c}$
- Acceleration rate independent of energy : $\frac{1}{E}\frac{dE}{dt} = \frac{4}{3}\frac{c}{2L}\beta^2 \propto \frac{1}{\tau \rm acc}$
- Diffusion equation with $\tau_{\rm esc}$ independent of E :
  - $\Rightarrow \frac{\partial N}{\partial t} = -\frac{N}{\tau_{\rm esc}} - \frac{\partial}{\partial E}(\frac{dE}{dt}N(E))$
  - $\Rightarrow 0 = -\frac{N}{\tau_{\rm esc}} - \frac{\partial}{\partial E}(\frac{E}{\tau_{\rm acc}}N(E))$
  - $\Rightarrow \frac{dN}{dE} = -\frac{N}{E}\left(1 + \frac{\tau_{\rm acc}}{\tau_{\rm esc}}\right)$
  - $\Rightarrow N \propto E^{-\alpha}$, avec $\alpha = 1 + \frac{\tau_{\rm acc}}{\tau_{\rm esc}}$

Fermi Acceleration - 2nd Order

Limitations of Fermi 2nd order

- Acceleration too long !
  - $\Rightarrow$ $V \sim 10km/s$, $\beta \sim 10^{-4}$ et $< \Delta E/E > \sim 10^{-8}$
  - $\Rightarrow$ $L \sim pc$, donc $t_{\rm coll} \sim$ yrs
  - $\Rightarrow$ $\tau_{\rm acc} > 10^8$yrs $\gg t_{CR}$
- Injection
  - $\Rightarrow$ Coulomb losses independent of E : dominate at low E
  - $\Rightarrow$ Particles must be injected at few 100 MeV
  - $\Rightarrow$ Other mechanism at low E ?
- Non-universal Power-law :
  - $\Rightarrow$ Index depends on β et $\tau_{\rm acc}$
  - $\Rightarrow$ Density of scattering clouds (via $\tau_{\rm esc}$)

Fermi Acceleration - 1st order

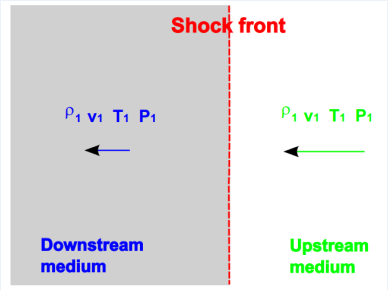
Shocks !



- Conservation of mass : $\frac{\partial \rho}{\partial t} = -\nabla \rho V$
- Conservation of momentum : $\rho \left(\frac{\partial \vec{V}}{\partial t} + (\vec{V}.\nabla)\vec{V} \right) = -\nabla P$
- Conservation of energy : $-\frac{\partial}{\partial t}\left[\frac{1}{2}\rho V^2 + U_{int}\right] = \nabla\left[\left(\frac{1}{2}\rho V^2 + U_{int} + P\right)\vec{V}\right]$

Fermi Acceleration - 1st order

Plane shock wave



- In shock frame (Conditions of Rankine–Hugoniot) :

$$\Rightarrow \rho_1 v_1 = \rho_2 v_2$$
$$\Rightarrow p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2$$
$$\Rightarrow \rho_1 v_1 \left(\frac{v_1^2}{2} + \frac{P_1}{\rho_1} + u_1 \right) = \rho_2 v_2 \left(\frac{v_2^2}{2} + \frac{P_2}{\rho_2} + u_2 \right)$$

Fermi Acceleration - 1st order

Plane shock wave

- Sound velocity $c_s = \sqrt{\frac{\gamma P}{\rho}}$, avec $\gamma = C_p/C_v$
- $P + \rho v^2 = P(1 + \gamma M^2)$, $M = v/c_s$ Mach number, and $u = P/\rho(\gamma - 1)$
- Discontinuity of velocity and density :

  $\Rightarrow r = \frac{v_1}{v_2} = \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}$
- Pressure :

  $\Rightarrow \frac{P_2}{P_1} = \frac{2\gamma M_1^2-(\gamma-1)}{\gamma+1}$
- Temperature :

  $\Rightarrow \frac{T_2}{T_1} = \frac{(2\gamma M_1^2-(\gamma-1))((\gamma-1)\gamma M_1^2+2)}{(\gamma+1)^2 M_1^2}$

Fermi Acceleration - 1st order

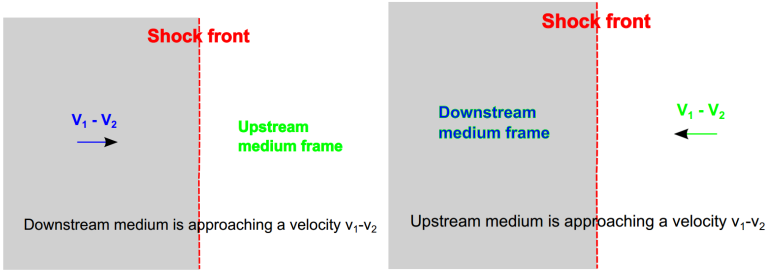
Compression ratio r

- Characterizes density jump
- Strong shock : $M \gg 1$, $r = \frac{\gamma+1}{\gamma-1}$
- Monoatomic gas, $\gamma = 5/3$ et $r = 4$
- Density increases $\rho_2 = r\rho_1$
- Velocity decreases $v_2 = v_1/r$
- Shock converts energy from kinetics upstream to thermal energy downstream

Fermi Acceleration - 1st order

Diffusive acceleration at the shock

- Particles are "isotropized" by MHD waves
- Particle sees a magnetic wall $\delta v = v_1 - v_2 = v_1(1 - 1/r)$
- Always head-on collisions
- Can escape downstream



Fermi Acceleration - 1st order

Energy gain

- $\frac{\Delta E}{E} = \beta(< \cos\theta'_{\rm out} > - < \cos\theta_{\rm in} >)$
- Upstream : isotropic distribution, $dN(\theta_{\rm in})/d\Omega = \frac{1}{2}\sin\theta_{\rm in} d\theta_{\rm in}$
- On average :

$$\frac{dN}{dSdt} = n_0 c \cos\theta_{\rm in} d\Omega = \frac{1}{2} n_0 c \cos\theta_{\rm in} \sin\theta_{\rm in} d\theta_{\rm in}$$

$$< \cos\theta_{\rm in} >= \frac{\cos 2\theta_{\rm in} \sin\theta_{\rm in} d\theta_{\rm in}}{\int_{\pi/2}^{\pi} \cos\theta_{\rm in} \sin\theta_{\rm in} d\theta_{\rm in}} = -\frac{2}{3}$$

- Similarly, $< \cos\theta_{\rm out} >= \frac{2}{3}$, et donc $< \Delta E >= \frac{4}{3}\beta E = \frac{4}{3}\frac{v_1}{c}\left(1 - \frac{1}{r}\right) E$

$\Rightarrow$ $\Delta E > 0$: acceleration

$\Rightarrow$ $\Delta E = kE$ at each crossing, and $E_n = (k+1)^n E_0$

$\Rightarrow$ $\Delta E/E = v_1/c$ si $r = 4$: 1st order

Fermi Acceleration - 1st order

Escape probability

- Seen from shock frame : upstream medium closes in, a particle upstream has a probability 1 to cross the shock, indep. of E
- Upstream medium away from shock, a particle downstream can be carried far from the shock, with a velocity v_2
- $P_{\rm esc}$: independent of energy
- Flux crossing the shock : $\frac{dN1\to2}{dSdt} = \int_{\pi/2}^{\pi} \frac{1}{2} n_0 c \cos\theta \sin\theta d\theta = \frac{n_0 c}{4}$
- Escaping flux : $\frac{dNesc}{dSdt} = n_0 v_2 = n_0 v_1/r \Rightarrow P_{esc} = \frac{Nesc}{N1\to2} = \frac{4v_1}{rc}$
- If N_0 particles are injected at $t = 0$, $N_0(1 - P_{esc})^n$ at cycle n
- To produce particle at energy E, needs $n = \frac{\log(E/E_0)}{\log(k+1)}$ $(k = \Delta E/E)$
- Hence $N(> E) = N_0(1 - P_{esc})^{\frac{\log(E/E_0)}{\log(k+1)}} = N_0 \left(\frac{E}{E_0}\right)^{\frac{\log(1-Pesc)}{\log(k+1)}}$
- If $V_c \ll c$, $\frac{\log(1-Pesc)}{\log(k+1)} \sim -\frac{P_{esc}}{k} = \frac{3}{1-r}$

Fermi Acceleration - 1st order

Acceleration rate

- $N(E) \propto \left(\frac{E}{E_0}\right)^{-\alpha}$, $\alpha = \frac{r+2}{r-1}$
- Does not depend on V_c, only on r : $\alpha = 2$ si $r = 4$ (strong shock) $\Rightarrow$ Universal law !
- Diffusion coefficient D in m^2/s : during t, diffusion on $l_d \sim \sqrt{Dt}$, while shock has moved $l_s = vt$

$\Rightarrow$ Residence time : $\frac{D}{v^2}$

- Upstream D/v_1, with (...) $\tau_{\rm acc} = \frac{4}{c}\left(\frac{D_1}{v_1} + \frac{D_2}{v_2}\right)$
- With $D = pc/ZeB$ (Bohm), and $D_1 = D_2$ $\tau_{\rm acc} = 4(r+1)/3ZeBv_1c \propto E$

Fermi Acceleration - 1st order

Efficiency

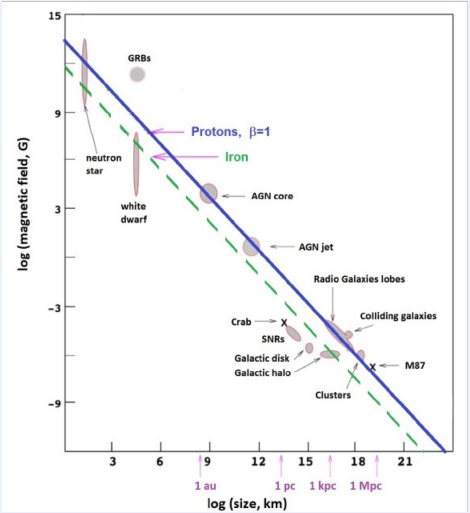
- Young Supernova remnant shock : $v_1 \sim 10^4$ km/s, with $B \sim 2nT$

$$\frac{dE}{dt} \sim 30keV/s \left(\frac{v}{10^4 km/s}\right)^2 \left(\frac{B}{2nT}\right)$$

- To reach 100 TeV, only 100 years needed : efficient mechanism
- $E_{\max}$ limited by :
  - $\Rightarrow$ energy losses
  - $\Rightarrow$ time : age of the system
  - $\Rightarrow$ geometry : escape

Hillas Graph and GZK cut-off

Maximum energy



- $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \Rightarrow \frac{E}{L} = \frac{B}{L/c}$, ou $E = Bc$
- $E_{\max} = \gamma mc^2 = \int ZeEdx = ZeBcL$
- Larmor Radius $R_L = \frac{c}{\omega_c} = \frac{p}{ZeB} = \frac{E}{ZeBc}$, avec $\omega_c = \frac{ZeB}{m}$

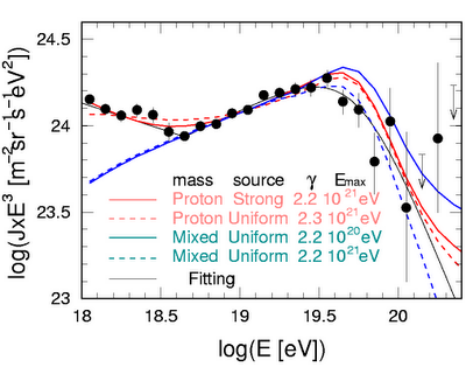
$\Rightarrow$ $R_L < L$ for efficient acceleration

$\Rightarrow$ $E_{\max} \sim ZeBL$

- Left plot - for 10^{20} eV

Hillas Graph and GZK cut-off

GZK threshold



- CMB Photons energy $\sim 10^{-3}$ eV
- $p_\mu = (\epsilon, \vec{p})$ for photon, $P_\mu = (E, \vec{P})$ for a proton
- $\epsilon_{\text{CM}}^2 = (E + \epsilon)^2$
- Resonance Δ : $\gamma + p \to \Delta \to \pi + N$
  - $\Rightarrow$ $\epsilon_{\text{CM}}^2 = M_N^2 + 2\left(E\epsilon - \vec{P}.\vec{p}\right)$
  - $\Rightarrow$ chooses $\cos\theta \sim -1$
- Incident nucleon ultra-relativistic : $E \sim P$, $\left(\epsilon_{\text{CM}}^{\max}\right)^2 \sim M_N^2 + 4E.\epsilon \gtrsim (m_\pi + M_N)^2$
  - $\Rightarrow$ $E_{\text{seuil}} \gtrsim \frac{m_\pi^2 + 2M_N m_\pi}{4\epsilon} \sim 7 \times 10^{19}$ eV

Confinement and origin of CRs

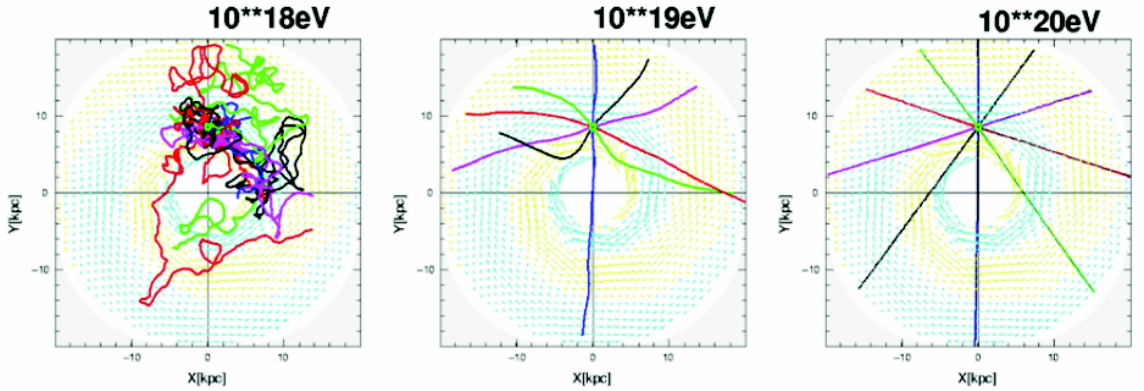
Confinement

- Curvature radius $r \approx \frac{E(EeV)}{ZB(\mu G)}$ in kpc ($B \sim 3\mu G$) - 1 EeV = 10^9 GeV = 10^{18} eV
- Proton of $10^{14} eV \sim 1pc$, Crab Nebula distance
- Directionnality of CRs is blurred by magnetic field
- For p à 10^{19} eV, $r \sim 3.3$ kpc ($10\times$ disk thickness)
- For Iron 10^{19} eV, $r \sim 100pc$

  $\Rightarrow$ **Confinement**

Confinement and origin of CRs

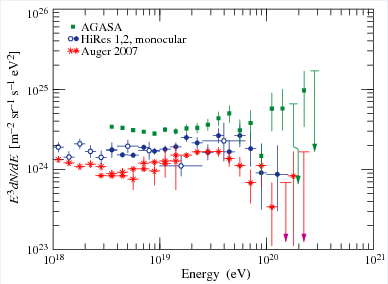
Confinement



- $\sim 10^{18} eV$ **Cosmic-rays confined**
- $> 10^{19} eV$ **extragalactic sources**
- $\sim 10^{20} eV$, deflection $\sim 1^{\circ}$

Confinement and origin of CRs

Ultra-High Energies - 1



- Curvature Radius at 10^{20}eV $\sim$ 1Mpc

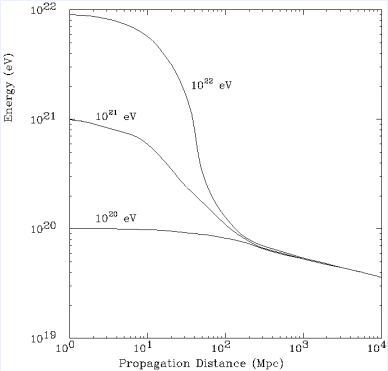
$\Rightarrow$ **Directionnality conserved**

$\Rightarrow$ **UHE CRs not confined**

$\Rightarrow$ **Extragalactic origin**

Confinement and origin of CRs

Ultra-High Energies - 2



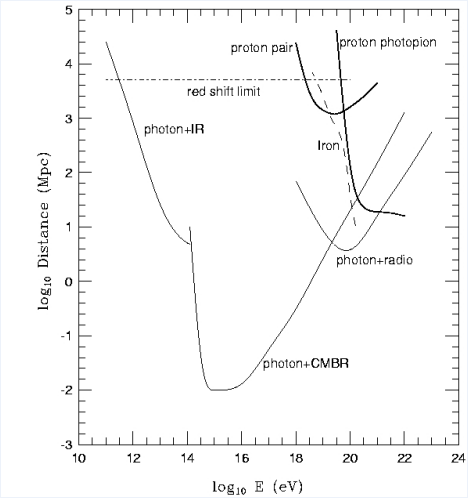
Confinement and origin of CRs

Ultra-High Energies - 2

- $\gamma_{CMB} + p \to \Delta^+ \to p + \pi^0/n + \pi^+$
- Energy $\epsilon \sim 10^{-3}$eV for CMB
- Threshold for pion photoproduction $E_p \approx \frac{E_\gamma m_p}{E\epsilon} = \frac{7\times10^{16}}{\epsilon}$ eV
- $\sigma \sim 130\mu$b $\sim 0.13 \times 10^{-27}$ cm^2, $\rho_{CMB} \sim 400$/cm^{-3}
- **Mean free path** $= 1/\sigma\rho \sim 6$ **Mpc (Local Cluster)**

Confinement and origin of CRs

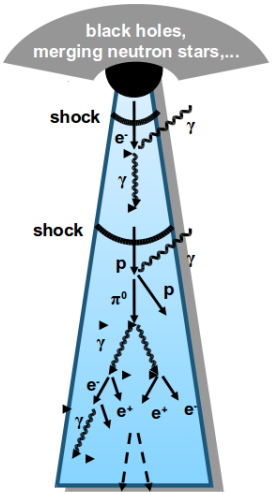
Ultra-High Energies - 2



Leptonic/Hadronic ?

Leptonic scenario

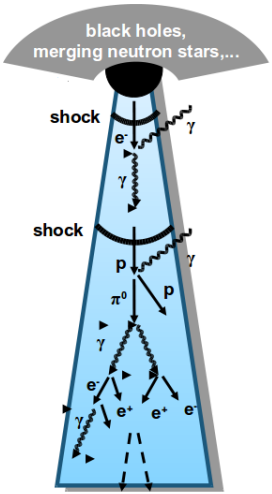
- $e-$ accelerated via Fermi mechanism
- X-Rays, observed, produced via synchrotron : $e^{\pm}\vec{B} \rightarrow e^{\pm}\gamma_X$
- HE γ-rays by Inverse Compton : $e^{\pm}\gamma_{\text{low E}} \rightarrow e^{\pm}\gamma_{\text{high E}}$
- **No neutrinos !**



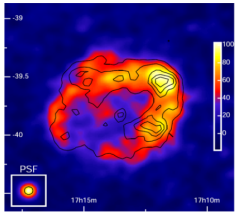
Leptonic/Hadronic ?

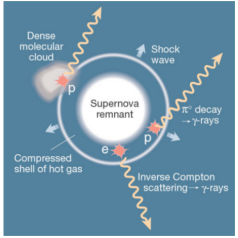
Hadronic scenario

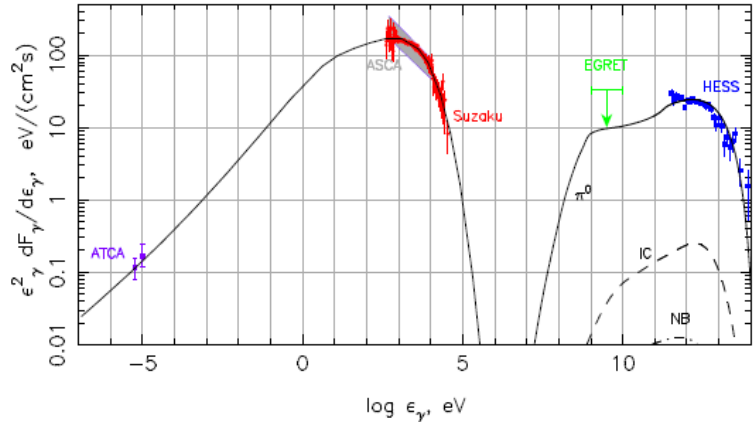
- Protons and Heavy nuclei (observed !) accelerated via Fermi mechanism
- Interaction with ambient photons :
  - $p + \gamma/A \rightarrow \Delta^+ \rightarrow \pi^0 + p$
  - $p + \gamma/A \rightarrow \Delta^+ \rightarrow \pi^+ + n$
- γ-rays via $\pi^0 \rightarrow \gamma\gamma$
- **Neutrinos via** $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu\nu_\mu$



A Hadronic origin for γ emission ?



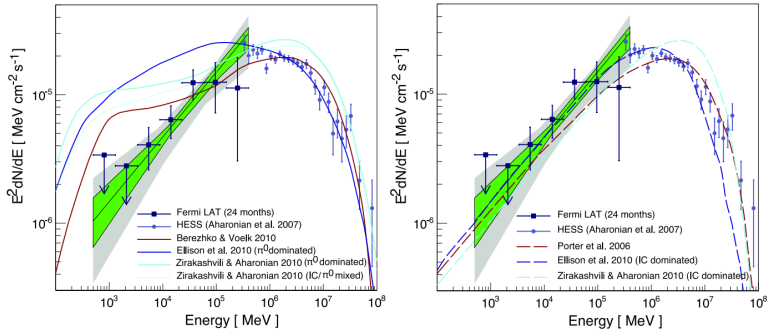




The case of RXJ 1713-3946

- Purely leptonic models not satisfactory
- Proton acceleration + beam dump on nearby molecular clouds ? - **Berezhko & Völk, arXiv-08100988v2**

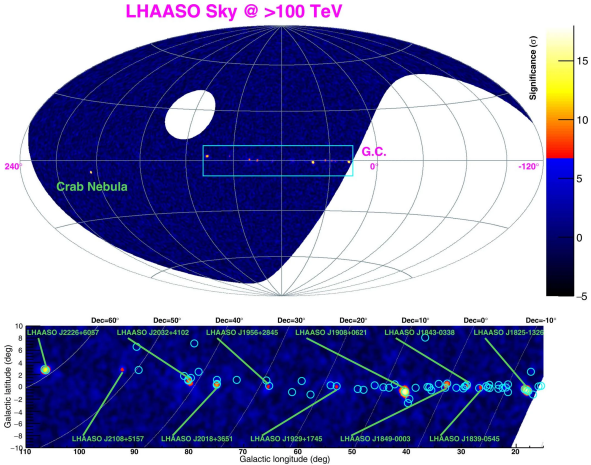
A Hadronic origin for γ emission ?



The case of RXJ 1713-3946 - Fermi observations

- According to Fermi, hadronic models not satisfactory
- Different conclusions for Yuan et al.

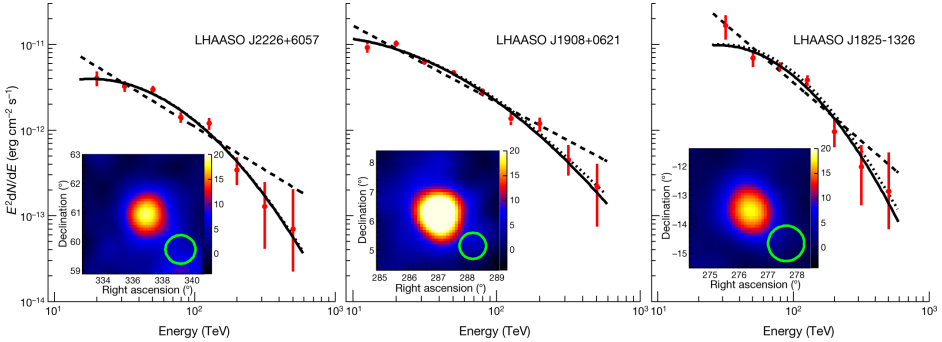
A Hadronic origin for γ emission ?



Galactic Pevatrons with LHAASO (2021)

- Are they associated to hadronic sources ?

A Hadronic origin for γ emission ?



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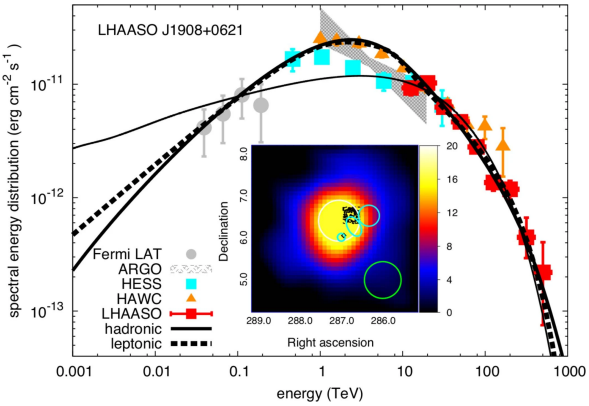
- Are they associated to hadronic sources ?

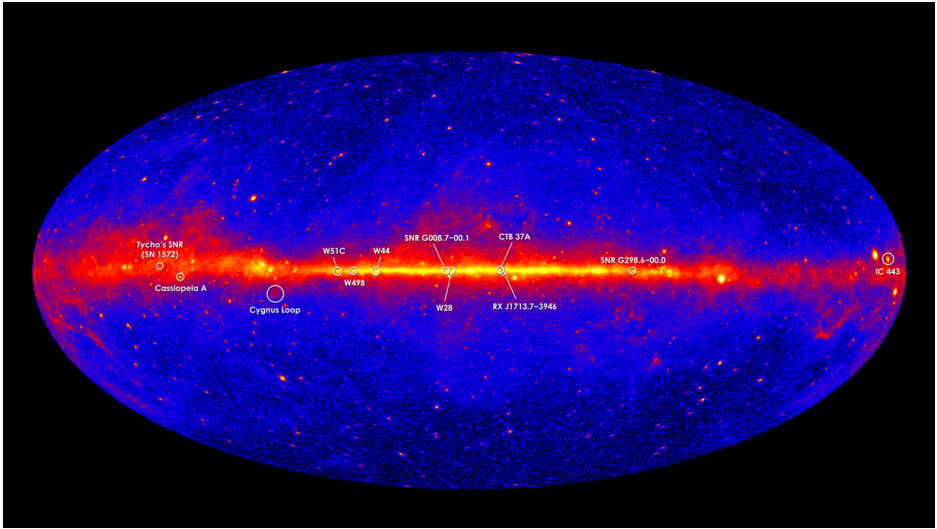
A Hadronic origin for γ emission ?



Galactic Pevatrons with LHAASO (2021)

- Are they associated to hadronic sources/neutrinos ?

The TeV Gamma-Ray Sky



The TeV Gamma-Ray Sky

How to compute a ν Flux from γ-Ray Observations

- Assume a **primary spectrum at the source**
- Describe the **interaction mechanism**
- **Renormalize expected flux to the observed HE γ flux**

A. Kappes et al., ApJ, 656, 870 (2007)

Hadronic Production of HE γ/CRs :

$$
\begin{array}{lcccc}
p/A + p/\gamma & \longrightarrow & \pi^0 & & \pi^{\pm} \\
 & & \downarrow & & \downarrow \\
 & & \gamma\gamma & & \mu\ \nu_\mu \\
 & & & & \downarrow \\
 & & & & \nu_\mu \nu_e e
\end{array}
$$

The TeV Gamma-Ray Sky

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A. Kappes et al., ApJ, 656, 870 (2007)

Neutrino oscillations

- **Expect flavor ratios (1,2,0)** $(\nu + \bar{\nu}) \rightarrow (1, 1, 1)$
  - $\Rightarrow$ But depends on source properties
- If $\vec{B}$ high, pions+muons at HE have energy losses before decaying
- Smaller life time of muons/pions, suppression of contribution to ν flux from μ decay :
  - $\Rightarrow$ flavor ratio can be $(\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau) = (0, 1, 0)$
- At Earth, becomes $(\nu_e + \bar{\nu}_e, \nu_\mu + \bar{\nu}_\mu, \nu_\tau + \bar{\nu}_\tau) = (1, 1.8, 1.9)$

The TeV Gamma-Ray Sky

How to compute a ν Flux from γ-Ray Observations

- Spectral index of γ-rays could be different to that of primaries and neutrinos, due to interactions in the sources
- Can reprocess photons giving rise to "softer" spectra, i.e. more low energy events
- Total energy can still be related through :

$$\int_{E_\gamma^{min}}^{E_\gamma^{max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} = K \int_{E_\nu^{min}}^{E_\nu^{max}} E_\nu \frac{dN_\nu}{dE_\nu}$$

- If $E_\gamma^{max} \gg E_\gamma^{min}$, with $\frac{dN_\gamma}{dE_\gamma} = A_\gamma E_\gamma^{-\alpha}$:

$$\frac{dN_\nu}{dE_\nu} \approx A_\nu E_\nu^{-2} \approx \frac{A_\gamma E_{\gamma,min}^{-\alpha+2}}{(\alpha-2)K \ln(E_{\nu,max}/E_{\nu,min})} E_\nu^{-2}$$

The TeV Gamma-Ray Sky

pp interactions

- $\int_{E_\gamma^{min}}^{E_\gamma^{max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} = K \int_{E_\nu^{min}}^{E_\nu^{max}} E_\nu \frac{dN_\nu}{dE_\nu}$, with $K_{pp} = 1$
- $pp \rightarrow pp/np/nn + \pi^0(1/3E_p) + \pi^+(1/3E_p) + \pi^-(1/3E_p)$
  - $\Rightarrow$ $\pi^0 \rightarrow \gamma\gamma : 1/2E_\pi$
  - $\Rightarrow$ $\pi^+ \rightarrow \nu_\mu(1/4E_\pi)\ \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu(1/4E_\pi)$
  - $\Rightarrow$ $\pi^- \rightarrow \bar{\nu}_\mu(1/4E_\pi)\ \mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu(1/4E_\pi)$
- 3 pions produced at each interactions : **each carry** $E_p/3$
- Each neutral pion gives 2 γ : **each** γ **carries** $E_p/6$
- Each charged pion gives 4 particles : **each particle carries** $E_p/12$**, hence** $E_p/6$ **under the form of** ν_μ

$$\int E_\nu = \int E_\gamma,\ E_\gamma^{max} = \frac{E_p^{max}}{6},\ E_\nu^{max} = \frac{E_p^{max}}{12}$$

The TeV Gamma-Ray Sky

pp interactions

- $\int_{E_\gamma^{min}}^{E_\gamma^{max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} = K \int_{E_\nu^{min}}^{E_\nu^{max}} E_\nu \frac{dN_\nu}{dE_\nu}$, $K_{pp} = 1$
- **Maximum E_p^{max} of protons** depends on kinematics of acceleration mechanism (jets...)
- **Minimum E_p^{min} given by threshold energy for pion production** :

$$E_p^{min} = \Gamma \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p} \approx \Gamma \times 1.23 GeV$$

- Γ **Lorentz Factor of accelerator relative to the observer**, related to Doppler Boosting of radiation in jet δ_j, to angle between jet's axis and line of sight θ, β bulk velocity of plasma in units of c

$$\delta_j = \frac{1}{\Gamma(1 - \beta \cos\theta)}$$

The TeV Gamma-Ray Sky

pγ interactions

- $\int_{E_\gamma^{min}}^{E_\gamma^{max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} = K \int_{E_\nu^{min}}^{E_\nu^{max}} E_\nu \frac{dN_\nu}{dE_\nu}$, with $K_{p\gamma} = 4$
- $p\gamma \rightarrow \Delta \rightarrow \pi N : 2/3 p\pi^0, 1/3 n\pi^+$
- One pion produced at each interaction : **each photon carries** $E_\pi/2$
- Each charged pion gives 4 particles : **each neutrino carries** $E_\pi/4$

  $\Rightarrow$ $1/3E_p$ **for photons,** $1/12E_p$ **for** ν_μ**, or** $\int E_\nu = \frac{1}{4} \int E_\gamma$
- Average fraction of proton energy transferred to π $< x_{p\rightarrow\gamma} > \approx 0.2$

$$E_\gamma^{max} = \frac{E_p^{max} < x_{p\rightarrow\gamma} >}{2}, E_\nu^{max} = \frac{E_p^{max} < x_{p\rightarrow\gamma} >}{4}$$

The TeV Gamma-Ray Sky

ν production at the source

- For pp collisions :

$$\frac{dN_\nu}{dE_\nu} E_\nu^2 \approx 2 \times 10^{-12} TeV/cm^2/s \times ...$$

$$... \left(\frac{A_\gamma}{3.2 \times 10^{-11} TeV/cm^2/s} \right) \left(\frac{10}{\Gamma} \right)^{\alpha-2} \left(\frac{2.8-2}{\alpha-2} \right)$$

- For $p\gamma$ collisions :

$$\frac{dN_\nu}{dE_\nu} E_\nu^2 \approx 4 \times 10^{-13} TeV/cm^2/s \times ...$$

$$... \left(\frac{A_\gamma}{3.2 \times 10^{-11} TeV/cm^2/s} \right) \left(\frac{10}{\Gamma} \right)^{2\alpha-4} \left(\frac{2.8-2}{\alpha-2} \right) \left(\frac{E_{\gamma,target}}{1 MeV} \right)^{\alpha-2}$$

Alvarez-Muniz & Halzen, The Astrophysical Journal, 576 (2002) L33–L36

The TeV Gamma-Ray Sky

Taking oscillations into account

- If only part of the total flux is considered (if only interested in μ neutrinos for instance), effects of propagation need to be taken into account :

$$\Phi_{total}^{source} = \Phi_{e}^{source} + \Phi_{\mu}^{source} + \Phi_{\tau}^{source} = (0.5 + 1)\Phi_{\mu}^{source}$$

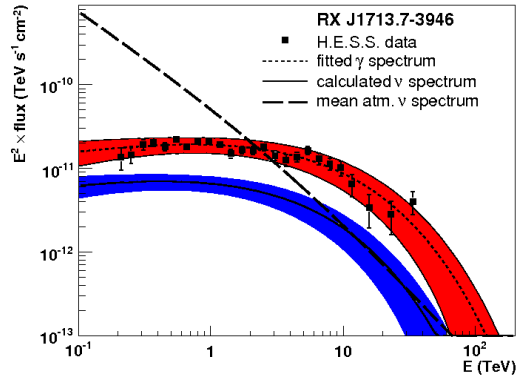
- After oscillations :

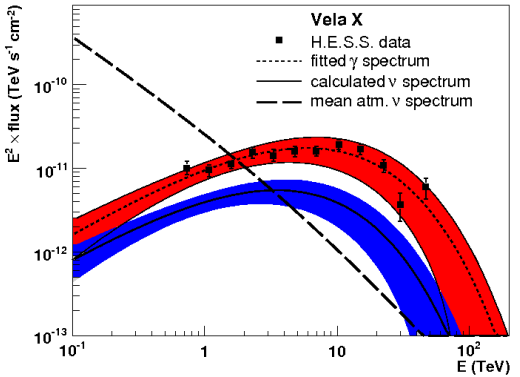
$$\Phi_{total}^{Earth} = 3\Phi_{\mu}^{Earth}$$

$$\text{Measured } \Phi_{\mu}^{Earth} = 0.5\Phi_{\mu}^{source} \text{ Calculated}$$

The TeV Gamma-Ray Sky

How to compute a ν Flux from γ-Ray Observations





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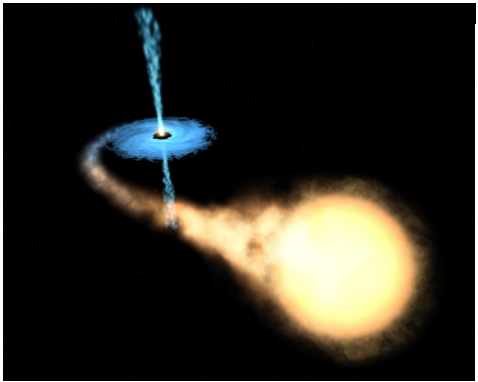
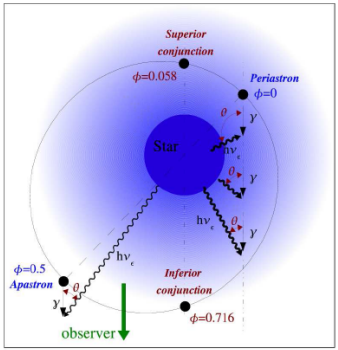
In the Galaxy...

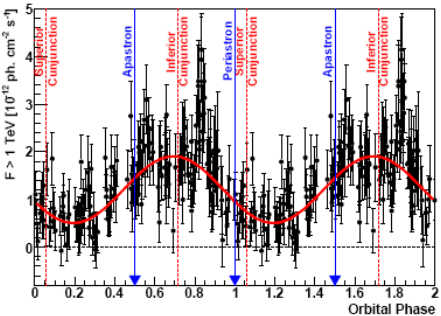


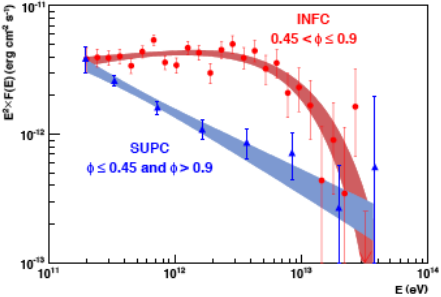


MicroQuasars

- Compact Object (BH or NS) fed by a massive star
- Particles accelerated in jets or in accretion disk
- Nature or primary particles unknown !
- A few of them observed in γ : HESS, MAGIC, VERITAS

In the Galaxy...





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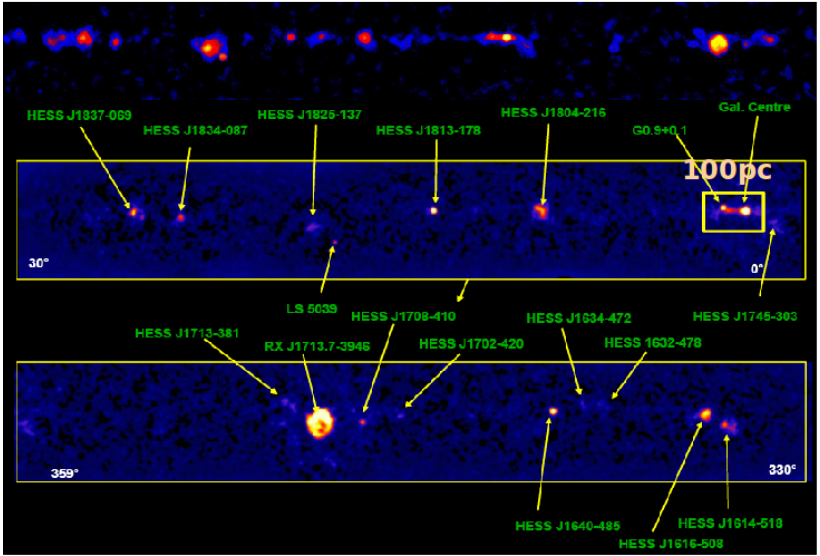
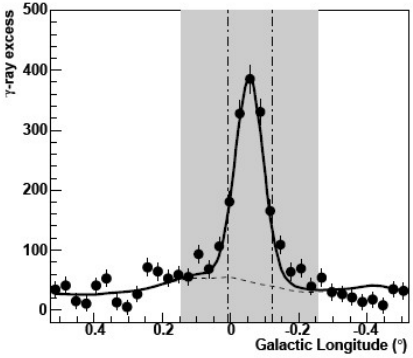
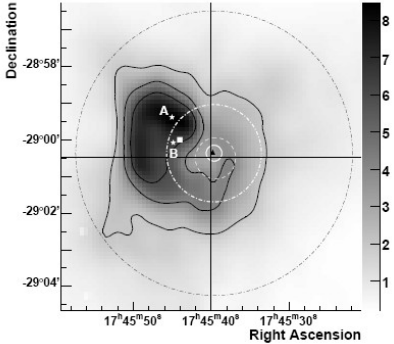


In the Galaxy...

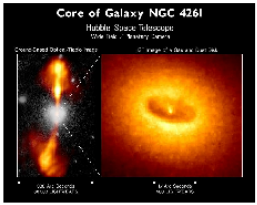


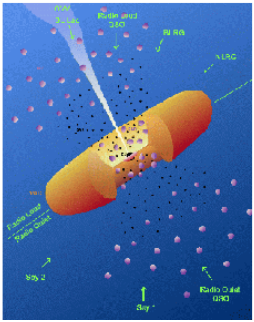


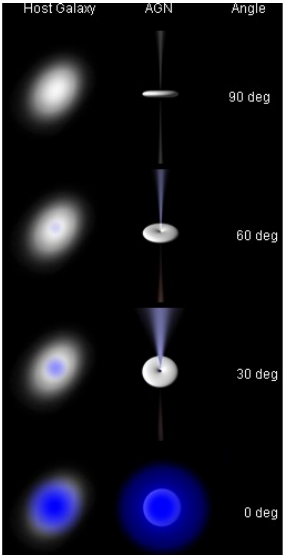
The Galactic Centre - only visible with Antares

- Sgr A* (radio source) on the position of a SuperMassive Black Home ($M \sim 3 \times 10^6 M_\odot$)
- Sgr A* emits X-rays - HESS J1745-290 very close !
- **No coincidence of X-Ray flares and γ-rays observed**

Active Galactic Nuclei...



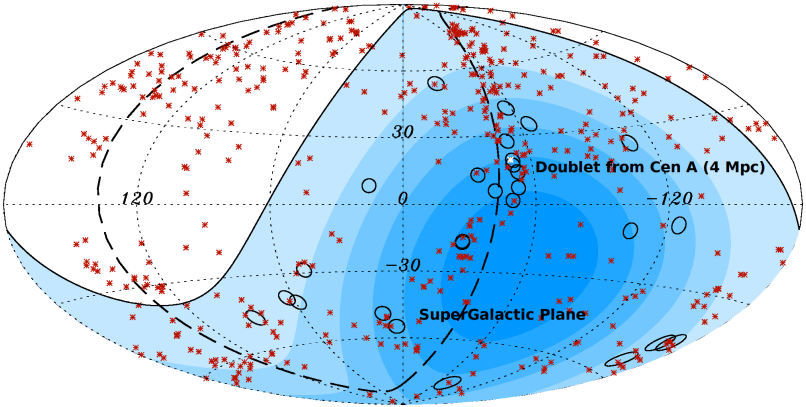




AGNs

- High Luminosity compact region at the centre of some galaxies...
- Supermassive Black Holes accreting matter
- Different features depending of angle of jet :
  - ⇒ Blazars (BL Lac, FSRQs,...) have jet towards earth
- Results of the Pierre Auger Observatory ?

Active Galactic Nuclei...

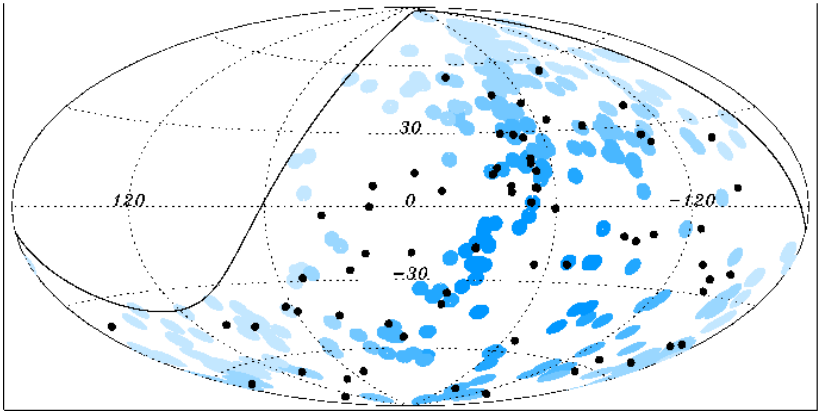


UHECRs and AGNs - 2007 Results

- 20 out of 27 CRs with $E > 57EeV$ correlate within 3.2° with nearby AGNs from Véron-Cetty&Véron Catalogue (292 AGNs with $D < 75Mpc$)
- Significance of effect has decreased with time...(68% to 38%)

Auger Collab., Science, 318, Issue 5852, pp. 938- (2007)

Active Galactic Nuclei...



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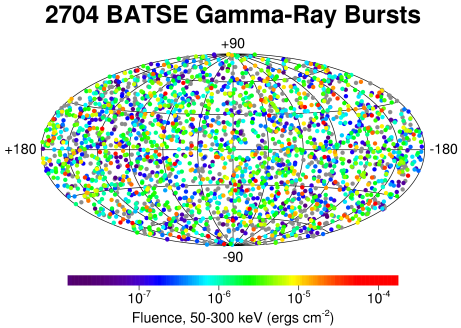
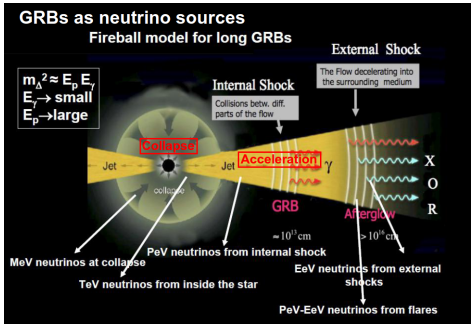
Gamma-Ray Bursters and Dark Bursters

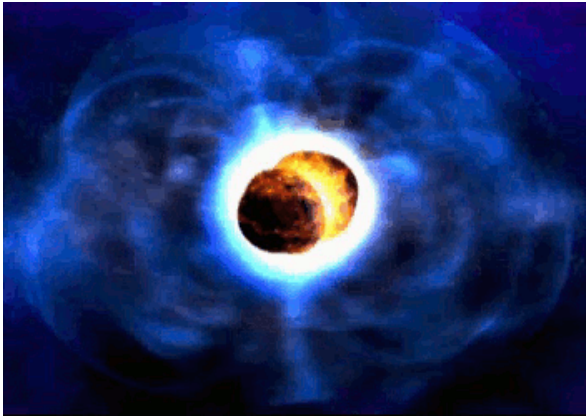


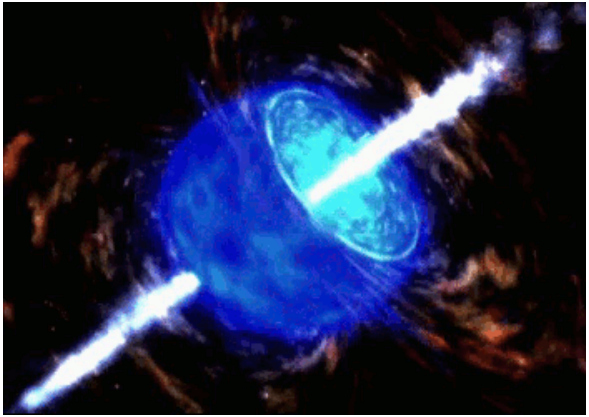


Gamma-Ray Bursts

- Isotropic in Distribution
- Cosmological : most distant $z \sim 9$, $D \sim 13Gpc$
- Energy released up to $10^{55} erg \approx 10^{22} L_\odot$

Gamma-Ray Bursters and Dark Bursters





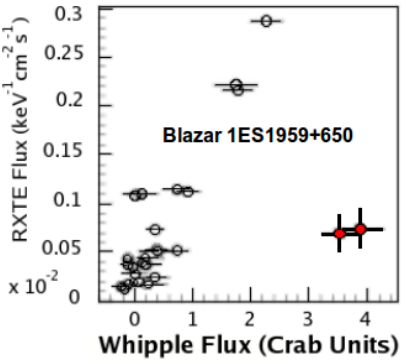
Short GRBs

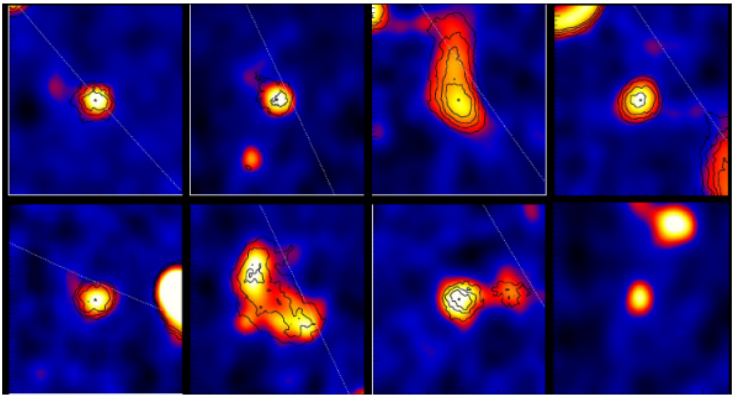
Binary Mergers : BH or NS

Long GRBs

Collapsars - massive star collapse

Gamma-Ray Bursters and Dark Bursters





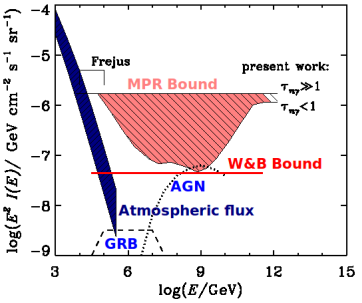
Dark Sources ?

- Several sources observed only in γ, no radio, no X-Rays
- **Orphan Flares**

Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

- Waxman-Bahcall upper bound : W & B, Phys.Rev.D59 :023002 (1999)
  - $E^2 \frac{dN}{dE} \approx 10^{44} erg/Mpc^3/yr$ from observed CR fluxes
  - Assume optically thin sources and evolution with z
- Mannheim, Protheroe, Rachen (MPR) Bound : Phys.Rev.D63 :023003 (2001)
  - Different injection spectra, optically thin/hidden sources



Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

- $\frac{dN_{CR}}{dE_{CR}} \propto E_{CR}^{-2}$ (Fermi)
- In range $10^{19} - 10^{21} eV$ $\dot{\epsilon}_{CR} \sim 5 \times 10^{44}\ erg.Mpc^{-3}.yr^{-1}$

  $\Rightarrow\ E_{CR}^2 d\dot{N}_{CR}/dE_{CR} = \frac{\dot{\epsilon}_{CR}}{\ln(10^{21}/10^{19})} \approx 10^{44}\ erg.Mpc^{-3}.yr^{-1}$ [Waxman]
- Energy loss fraction of HE protons $\epsilon < 1$ through photo-meson production of pions before escaping the sources
- Present day energy density of ν_μ :

$$E_\nu^2 dN_\nu/dE_\nu \approx 0.25 \epsilon t_H E_{CR}^2 d\dot{N}_{CR}/dE_{CR}$$

  where $t_H \approx 10^{10} yrs$ Hubble time
- ϵ follows proton generation spectrum : fraction of proton energy carried by ν produced through photo-meson production $E_\nu \approx 0.05 E_p$ is independent of proton energy
- Factor 0.25 **:** $1/2$ **from** π^0 **+** ν_μ **carry** $1/2$ **of** π^+ **energy in decay**

Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

- For $\epsilon = 1$, obtain maximal ν_μ intensity I_{max} :

$$I_{max} \approx 0.25 \epsilon \xi_z t_H \frac{c}{4\pi} E_{CR}^2 d\dot{N}_{CR}/dE_{CR}$$

$$\approx 1.5 \times 10^{-8} \xi_z GeV.cm^{-2}.s^{-1}.sr^{-1}$$

- Neutrino luminosities : $E_\nu^2 \Phi_\nu = \frac{c}{4\pi} E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{2} \epsilon I_{max}$
- With $\Phi_{\nu_e} \approx \Phi_{\bar{\nu}_\mu} \approx \Phi_{\nu_\mu}$
- $\xi_z \approx 1$: evolution with redshift
- Sources of size not larger than proton photo-meson mean free path
  - $\Rightarrow$ Otherwise, proton fluxes higher than observed
- But **higher ν luminosities possible if "optical depth" $\gg 1$** : only ν can escape the source (MPR Models)

Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

- ν with observed E produced at z with energy $(1+z)E$

$$n_\nu(>E) = \int_0^{z_{max}} dz \frac{dt}{dz} \dot{n}_\nu(>(1+z)E_z)$$

$$= \dot{n}_0(>E) \int_0^{z_{max}} dz \frac{dt}{dz} (1+z)^{-1} f(z)$$

- $\dot{n}_\nu(>E) \propto E^{-1}$
- $f(z) = \frac{\dot{n}_\nu(z)}{\dot{n}_0}$
- $t_H = \int_0^\infty dz \frac{dt}{dz}$

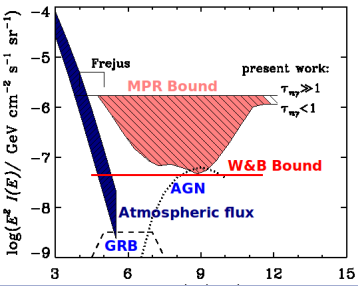
Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

- Finally, with $g(z) = -H_0(1+z)^{5/2}dt/dz$, where $g(z) = 1$ for a flat universe with zero cosmological constant :

$$\xi_z = \frac{\int_0^{z_{max}} dz g(z)(1+z)^{-7/2} f(z)}{\int_0^{\infty} dz g(z)(1+z)^{-5/2}}$$

- Luminosity density of AGNs : $f(z) = (1+z)^{\alpha} \Rightarrow \xi_z \approx 3$
- No evolution $f(z) =$ constant, $\xi_z \approx 0.6$



Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

- **Optical depth** $\frac{I}{I_0} = e^{-\tau}$, measures how opaque is a medium to a radiation
- $dI = -\kappa\rho I dl$, with κ opacity in cm^2/g, ρ density of medium
- Finally $\mathcal{L} = \frac{1}{\kappa\rho}$ and $\tau = \int \kappa\rho dl = \int n\sigma dl$, with n number density, σ cross-section

$\Rightarrow$ τ **= number of mean free paths through medium**

- Optically thin $\tau \ll 1$
  - 1 km of Earth atmosphere : $\kappa \sim 10^{-4} cm^2/g$, $\rho \sim 10^{-3} g/cm^3$, $\tau \sim 10^{-2}$

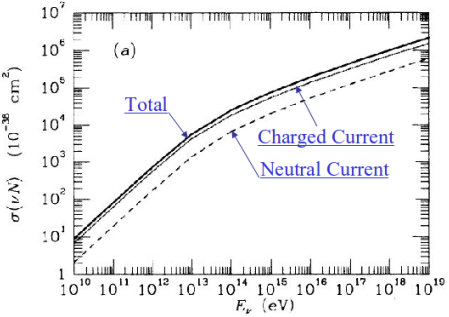
  $\Rightarrow$ Double the material, double the extinction
- Optically thick $\tau \gg 1$
  - 1 km of polluted city atmosphere : $\kappa \sim 0.1 cm^2/g$, $\rho \sim 10^{-3} g/cm^3$, $\tau \sim 10$

  $\Rightarrow$ No radiation, except outer layers and blackbody

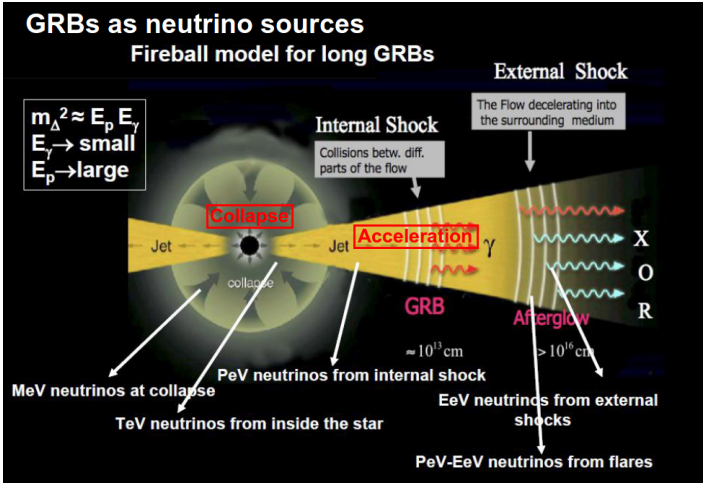
Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

- Result : $E_\nu^2 \Phi_\nu \lesssim 10^{-8} GeV.cm^{-2}.s^{-1}.sr^{-1}$
- $\Phi_\gamma^{\text{Crab}}(E > 1TeV) \approx 10^{-11} cm^{-2}.s^{-1}$...
- With a ν cross-section $\in 10^{-35} - 10^{-33} cm^2$ for $TeV - PeV$...
  $\Rightarrow$ **Needs large detection volumes !**



GRBs and neutrinos



Interaction of protons with photons $\longrightarrow$ neutrinos

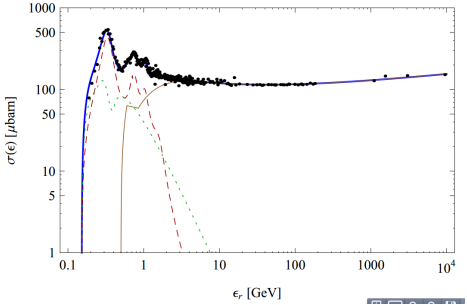
GRBs and neutrinos

Basic approach by Waxmam/Bahcall (1998)

- Approximation of $p\gamma$ interaction cross-section using Δ-resonance :

$$p + \gamma \rightarrow \Delta^{+} \rightarrow n\pi^{+}(1/3), p\pi^{0}(2/3)$$

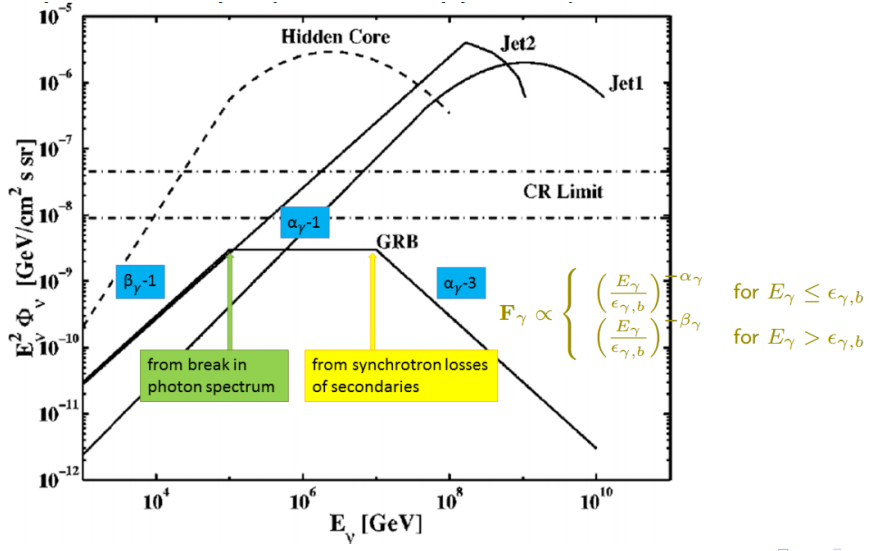
- π^{+} decay producing $\nu_{\mu}, \bar{\nu}_{\mu}, \nu_{e}$: $pi^{+} \rightarrow \mu^{+}\nu_{\mu}$, with $\mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu}$
- ν result from interaction of $p\gamma$ in GRBs, with a ratio $(\nu_e, \nu_\mu, \nu_\tau) = (1, 2, 0)$ or $(1, 1, 1)$ after flavor mixing



GRBs and neutrinos

- Normalization : $\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) = \overbrace{\frac{1}{8}}^{x_{\pi\to\nu}=1/2\times1/4} \underbrace{\left(1-(1-\langle x_{p\to\pi}\rangle)^{\Delta R/\lambda_{p\gamma}}\right)}_{f_\pi\approx\Delta R/\lambda_{p\gamma}\langle x_{p\to\pi}\rangle} \underbrace{\frac{1}{f_e}\int_{1keV}^{10MeV} dE_\gamma E_\gamma F_\gamma(E_\gamma)}_{\text{energy in protons}}$
- Number of interaction $\Delta R/\lambda_{p\gamma} = \left(\frac{L_\gamma^{iso}}{10^{52}erg/s}\right)\left(\frac{0.01s}{t_{\rm var}}\right)\left(\frac{10^{2.5}}{\Gamma_{\rm jet}}\right)^4\left(\frac{1MeV}{\epsilon_\gamma}\right)$
- Average energy lost to pions (/interaction) : $\langle x_{p\to\pi}\rangle \approx 0.2$

GRBs and neutrinos



$$F_\gamma \propto \begin{cases} \left(\frac{E_\gamma}{\epsilon_{\gamma,b}}\right)^{-\alpha_\gamma} & \text{for } E_\gamma \leq \epsilon_{\gamma,b} \\ \left(\frac{E_\gamma}{\epsilon_{\gamma,b}}\right)^{-\beta_\gamma} & \text{for } E_\gamma > \epsilon_{\gamma,b} \end{cases}$$

GRBs and neutrinos

LETTER

doi:10.1038/nature11068

An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

IceCube Collaboration*

Very energetic astrophysical events are required to accelerate cosmic rays to above 10^{18} electronvolts. GRBs (γ-ray bursts) have been proposed as possible candidate sources[1–3]. In the GRB 'fireball' model, cosmic-ray acceleration should be accompanied by neutrinos produced in the decay of charged pions created in interactions between the high-energy cosmic-ray protons and γ-rays[4]. Previous searches for such neutrinos found none, but the constraints were weak because the sensitivity was at best approximately equal to the predicted flux[5–7]. Here we report an upper limit on the flux of energetic neutrinos associated with GRBs that is at least a factor of 3.7 below the predictions[4,8–10]. This implies either that GRBs are not the only sources of cosmic rays with energies exceeding 10^{18} electronvolts or that the efficiency of neutrino production is much lower than has been predicted.

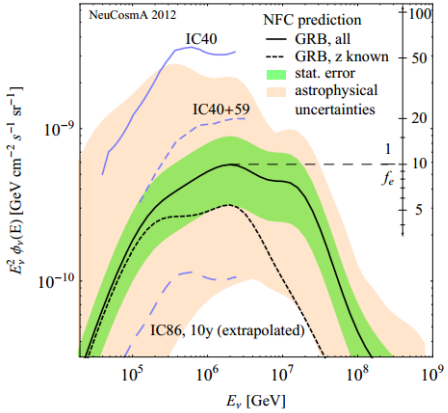
Neutrinos from GRBs are produced in the decay of charged pions produced in interactions between high-energy protons and the intense γ-ray background within the GRB fireball, for example in the Δ-resonance process $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$ (p, proton; γ, photon (here γ-ray); Δ^+, delta baryon; n, neutron; π^+, pion). When these pions decay via $\pi^+ \rightarrow \mu^+ \nu_\mu$ and $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$, they produce a flux of high-

As in our previous study[7], we conducted two analyses of the IceCube data. In a model-dependent search, we examine data during the period of γ-ray emission reported by any satellite for neutrinos with the energy spectrum predicted from the γ-ray spectra of individual GRBs[6,9]. The model-independent analysis searches more generically for neutrinos on wider timescales, up to the limit of sensitivity to small numbers of events at ±1 day, or with different spectra. Both analyses follow the methods used in our previous work[7], with the exception of slightly changed event selection and the addition of the Southern Hemisphere to the model-independent search. Owing to the large background of downgoing muons from the southern sky, the Southern Hemisphere analysis is sensitive mainly to higher-energy events (Supplementary Fig. 3). Systematic uncertainties from detector effects have been included in the reported limits from both analyses, and were estimated by varying the simulated detector response and recomputing the limit, with the dominant factor being the efficiency of the detector's optical sensors.

In the 59-string portion of the model-dependent analysis, no events were found to be both on-source and on time (within 10^5 of a GRB and between T_{start} and T_{stop}). From the individual burst spectra[6,9] with an

IceCube (2012)

GRBs and neutrinos

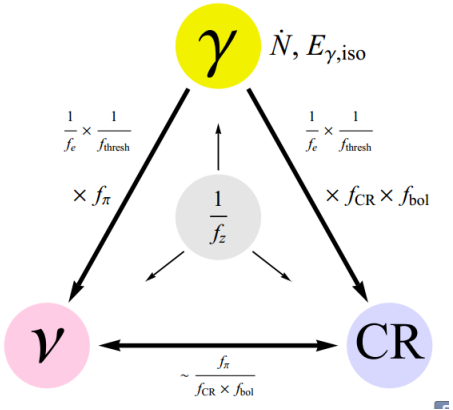


- Significantly reduced prediction
- Uncertainties of astrophysical parameters; tested ranges: $t_v = 0.001 - 0.1\,\mathrm{s}$, $\Gamma = 200 - 500$, $\alpha_p = 1.8 - 2.2$, and $\epsilon_B/\epsilon_e = 0.1 - 10$
- Conservative bounds only with known parameters, here: known redshifts
- Additional uncertainty from statistics in stacking analysis

from [Hümmer, PB, and Winter, arXiv:1112.1076, accepted for publication in Phys. Rev. Lett.]

Fireball model not ruled out yet!

GRBs and neutrinos



- f_z cosmic evolution factor, how representative the local GRB rate is representative
- f_e baryonic loading $f_e^{-1} > 10$; total energy in protons to the kinetic energy in electrons
- $f_{\mathrm{thresh}} \approx 0.2 - 0.5$ Instrument threshold correction
- f_{CR} Fraction of baryonic energy into CR production
- f_π fraction of baryonic energy into pion production
- $f_{\mathrm{bol}} \ll 1$ bolometric correction factor ; ratio of energy in protons in $10^{10} - 10^{12}$ GeV

Neutrino Astrophysics - High Energies



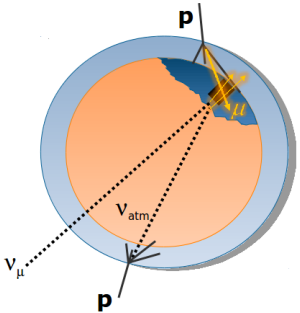
1. Introduction : *Neutrinos and other messengers, Sources and Detection*
2. Neutrinos & Cosmic-Rays : *From γ to ν astrophysical fluxes*
3. Neutrino Telescopes : *from Neutrino Interactions to Detection*
4. IceCube and Antares : *Description and Selected Results*
5. MultiMessenger Astronomy : *combining all cosmic signals*
6. GRB GW170817
7. Blazar TXS0506+056
8. KM3-230213A
9. Perspectives : from KM3NeT to the unknown ?

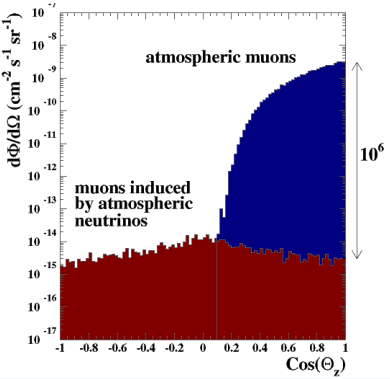
High-Energy Neutrinos :

Neutrino Telescopes, How they work...



Detection of Cosmic Neutrinos





Idea of Markov (1960)

- *...apparatus in an underground lake or deep in the ocean in order to separate charged particle direction by Cherenkov radiations*
- Interaction $\nu_\mu + N \to \mu + X$ with $R_\mu \sim 1 - 10km$ in 1 TeV-1 PeV
- **Effective volume of detection increases with energy**
- **Colinearity of μ with ν increases with energy $\Rightarrow$ astronomy**

Detection of Cosmic Neutrinos



Optical Cherenkov



In Ice

AMANDA B-10
AMANDA II

IceCube

In water

Baikal

ANTARES
NEMO
NESTOR

KM3NeT

E~TeV - PeV

Atmospheric showers



Earth based

Auger

In space

EUSO
OWL

Radio



Earth based

RICE
GLUE
SalSA
CODALEMA
ARIANNA

In space

ANITA
FORTE

E~ 1 - 10 EeV

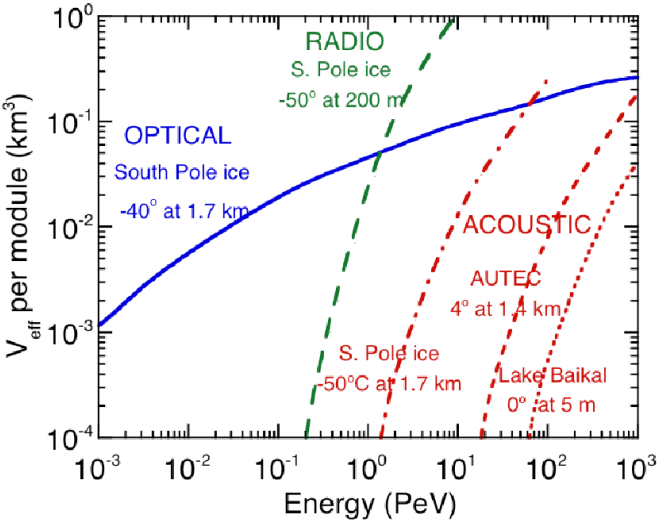
Acoustic



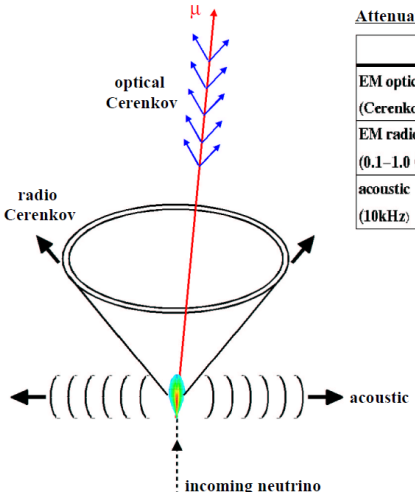
SAUND
SADCO (Greece)
ANTARES R&D
IceCube
AUTEC
AGAM

E~EeV - ZeV

Detection of Cosmic Neutrinos

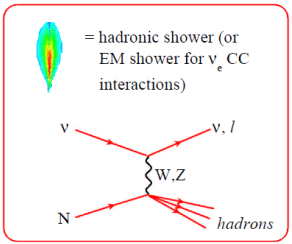


Acoustics and Radio

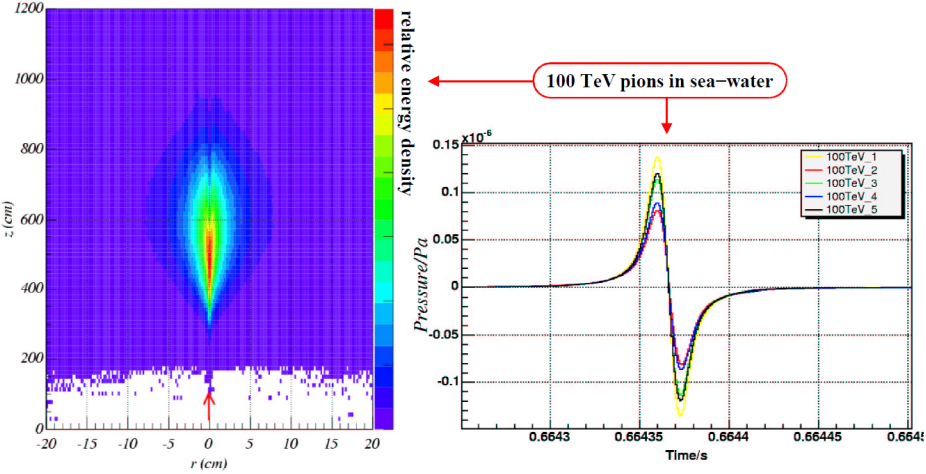


Attenuation Lengths :

	water	ice	salt
EM optical (Cerenkov)	~ 50 m	~ 100 m	~ 0
EM radio (0.1–1.0 GHz)	~ 0	~few km	~1 km (?)
acoustic (10kHz)	~10 km	? (large)	? (large)



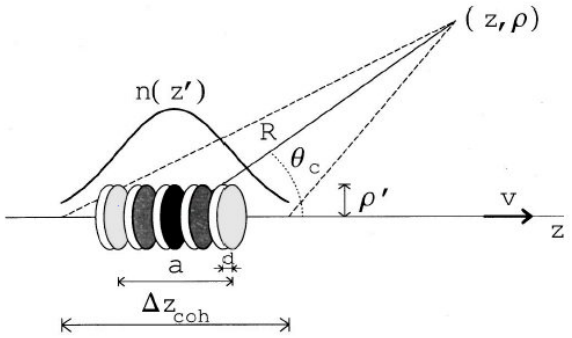
Acoustics and Radio

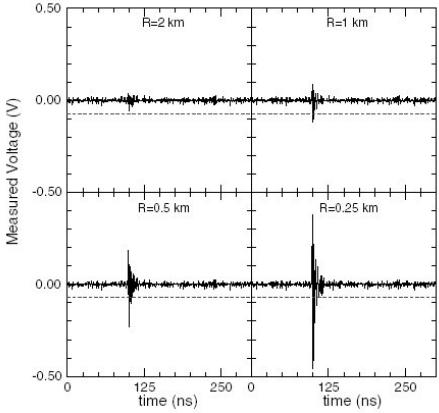


An Acoustic pulse

- R&D in several experiments

Acoustics and Radio

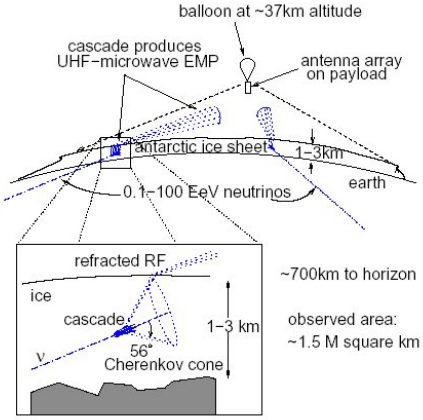


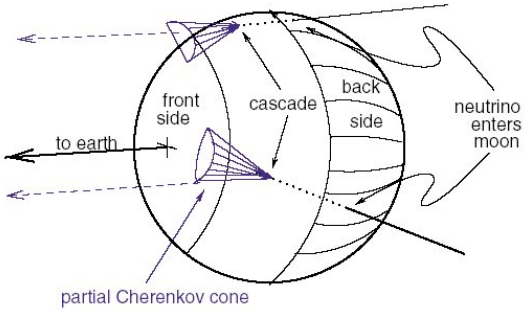


Askaryan Effect - used in Codalema, LOPES...

- Coherence length Δz along Oz axis of shower : fields arrive simultaneously at distance R if $\frac{dR}{dt} = v \cos\theta = \frac{c}{n}$
- But $\frac{dR}{dt}$ varies : $\frac{dR^2}{dt^2} = v^2 \frac{\sin^2\theta}{R^2}$

Acoustics and Radio



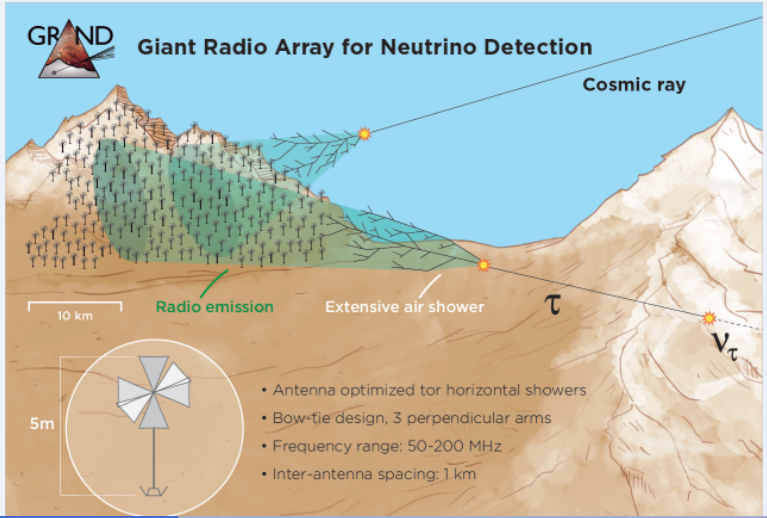


Askaryan Effect - used in Codalema, LOPES...

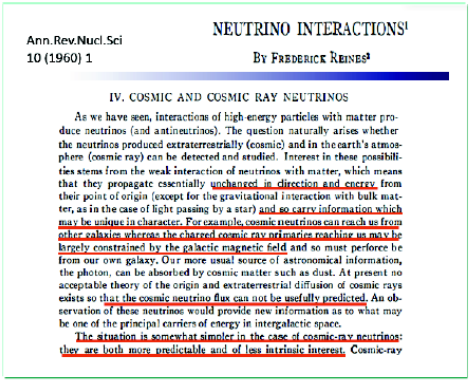
ANITA - GLUE

Acoustics and Radio

Askaryan Effect - used in Codalema, LOPES...



Optical Cherenokov : the idea behind Neutrino astronomy



Ann.Rev.Nucl.Sci
10 (1960) 1

NEUTRINO INTERACTIONS[1]

By Frederick Reines[2]

IV. COSMIC AND COSMIC RAY NEUTRINOS

As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies whereas the charged cosmic ray primaries reaching us may be largely constrained by the galactic magnetic field and so must perforce be from our own galaxy. Our more usual source of astronomical information, the photon, can be absorbed by cosmic matter such as dust. At present no acceptable theory of the origin and extraterrestrial diffusion of cosmic rays exists so that the cosmic neutrino flux can not be usefully predicted. An observation of these neutrinos would provide new information as to what may be one of the principal carriers of energy in intergalactic space.

The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

Greisen, 1960, Proc. Int. Conf on Instrum for HE physics

One may even anticipate eventual high-energy neutrino astronomy, since neutrino travel in straight lines, unlike the usual primary cosmic rays, and the neutrinos will convey a new type of astronomical information quite different from that carried by visible light and radio waves

Optical Cherenokov : the idea behind Neutrino astronomy

Ann.Rev.Nucl.Sci
10 (1960) 63

COSMIC RAY SHOWERS[1]

By Kenneth Greisen

Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward

For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $5 \cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with the lower of the theoretical cross sections—rather marginal, though the background from other particles than neutrinos can be made just as small. The detector has the virtue of good angular resolution to assist in distinguishing rare events having unique directions.

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

Optical Cherenokov : the idea behind Neutrino astronomy

8.B:9.A

Nuclear Physics **27** (1961) 385—394; © *North-Holland Publishing Co., Amsterdam*

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ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH

P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

Received 3 January 1961

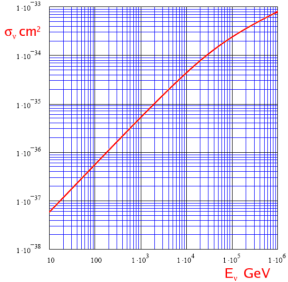
Abstract: The paper is concerned with the problems of detecting high-energy cosmic neutrinos in underground experiments. Various kindred problems of high-energy neutrino physics are discussed, viz. (1) the magnitude of weak-interaction cut-off momentum, (2) muon and electron neutrinos and (3) intermediate boson. It is shown that a reasonable counting rate could be obtained with available equipment.

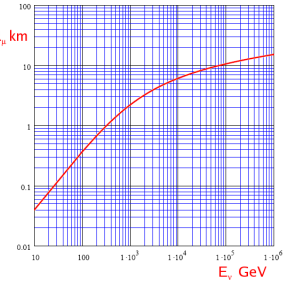
1961 - μ well suited for detection at high energy !

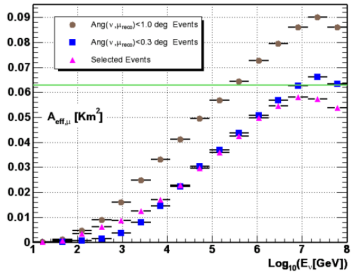
Optical Cherenokov : Event Rate & Detector Size

Luminosity needed for Event Rate N_ν

$$N_\nu \propto \Phi_\nu \times P_{\text{absorption}}(\theta, E) \times \underbrace{\sigma_\nu}_{\text{cross-section}} \times \underbrace{R_\mu}_{\mu \text{ range}} \times \underbrace{A_\mu}_{\text{Effective Area for } \mu}$$







Optical Cherenokov : Event Rate & Detector Size

Luminosity needed for Event Rate N_ν

$$N_\nu \propto \Phi_\nu \times P_{\text{absorption}}(\theta, E) \times \underbrace{\sigma_\nu}_{\text{cross-section}} \times \underbrace{R_\mu}_{\mu \text{ range}} \times \underbrace{A_\mu}_{\text{Effective Area for } \mu}$$

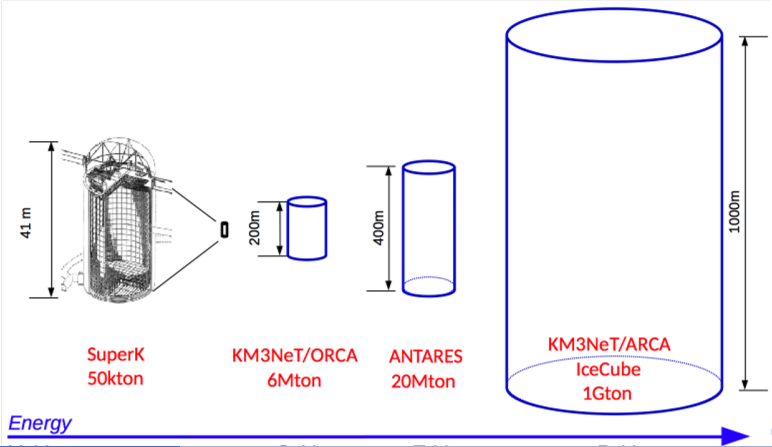
$$L_\nu = 4\pi d^2 \Phi_\nu \approx 10^{46} N_\nu \left(\frac{d}{4Gpc}\right)^2 \left(\frac{E_\nu}{100TeV}\right)^{1-\alpha} \left(\frac{A_\mu T}{km^2 yr}\right)^{-1} \text{ erg/s}$$

- $\alpha \sim 1$ for $E_\nu < 100TeV$, $\alpha \sim 0.5$ above 100 TeV
- Blazars $\sim Gpc$, $L \sim 10^{47}$ erg/s $\Rightarrow A_\mu \sim 1\ km^2$
- Galactic Sources $L_\nu \simeq 10^{35}$ erg/s for $A_\mu \sim 0.1\ km^2$

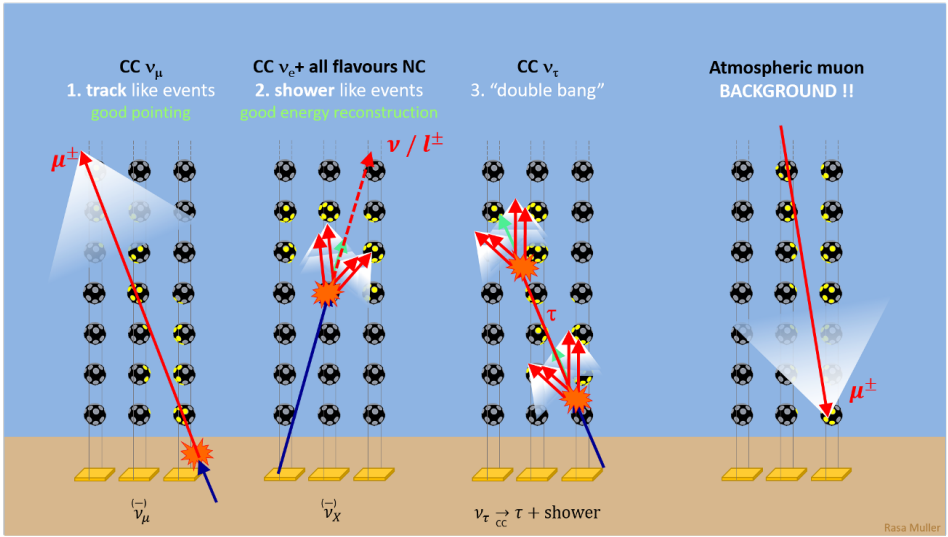
Optical Cherenokov : Event Rate & Detector Size

Luminosity needed for Event Rate N_ν

$$N_\nu \propto \Phi_\nu \times P_{\text{absorption}}(\theta, E) \times \underbrace{\sigma_\nu}_{\text{cross-section}} \times \underbrace{R_\mu}_{\mu \text{ range}} \times \underbrace{A_\mu}_{\text{Effective Area for } \mu}$$



Optical detection of cosmic neutrinos



Number of detected muons...

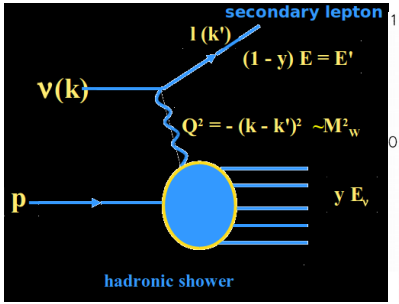
For area A and observation time T

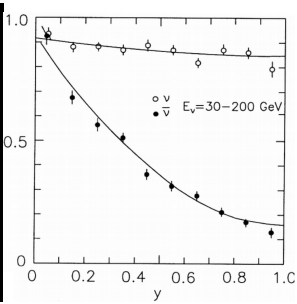
- $N_\mu(\theta) = A.T. \int_{E_{\min}}^{E_\nu} \Phi_\nu(E_\nu, \theta) dE_\nu P_{\nu\to\mu} P_\oplus$
  - $\Rightarrow$ $\Phi_\nu(E_\nu, \theta)$ neutrino spectrum
  - $\Rightarrow$ $P_{\nu\to\mu}$ Probability to produce a detectable muon with $E_\mu > E_{\min}$
  - $\Rightarrow$ $P_\oplus$ Earth transparency to HE neutrinos

Producing a detectable muon

- $P_{\nu\to\mu} \propto \int \frac{d\sigma}{dE_l} R_l(E_l, E_{\min}) dE_l$
- R_l **range of muon of energy** E_l **before it reaches** $E_{\min}$
- $\frac{d\sigma}{dE_l}$ differential interaction cross-section...

Interaction in Rock/Water/Ice

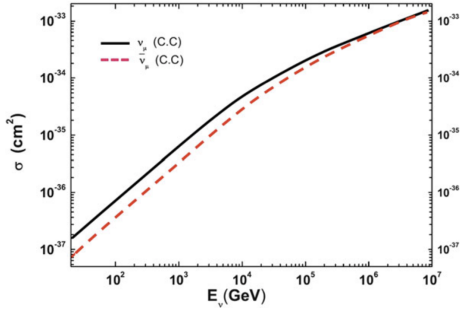




Deep-Inelastic Scattering

- $\frac{d\sigma}{dE_l} = \frac{2G_F^2 m_N E_\nu}{\pi} \left(\frac{M_W^2}{Q^2+M_W^2} \right)^2 \left[xq(x,Q^2) + x\bar{q}(x,Q^2)(1-y)^2 \right]$ [m_N, M_W, nucleon and boson mass]
- Q transfer momentum, $\nu = E_\nu - E_l$ hadronic energy in lab-frame
- $x = \frac{Q^2}{2m_N \nu}$ momentum fraction carried by parton, $y = \frac{\nu}{E_\nu}$

Interaction in Rock/Water/Ice



Deep-Inelastic Scattering

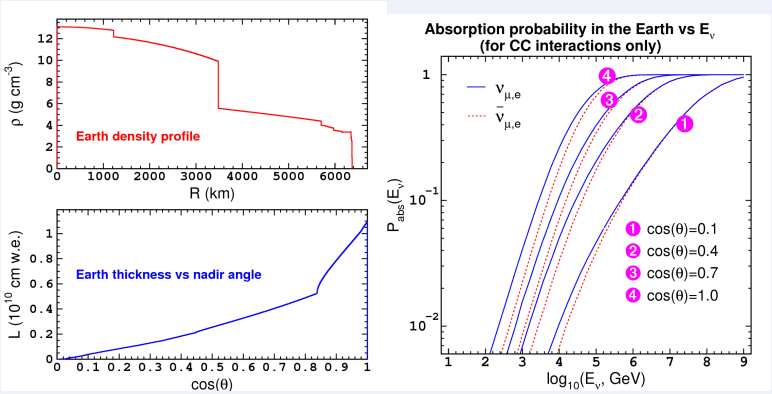
- $\sigma_{\nu N} \propto E_\nu$ below 5 TeV
- $\sigma_{\nu N} \propto E_\nu^{0.4}$ above 5 TeV
- **Pointing :** $\sqrt{< \theta^2_{\mu\nu} >} \approx \sqrt{\frac{m_N}{E_\nu}} \Rightarrow < \theta > \approx \frac{1.5^\circ}{\sqrt{E_\nu (TeV)}}$

  $\Rightarrow$ Colinear at high energy !

Interaction in Rock/Water/Ice

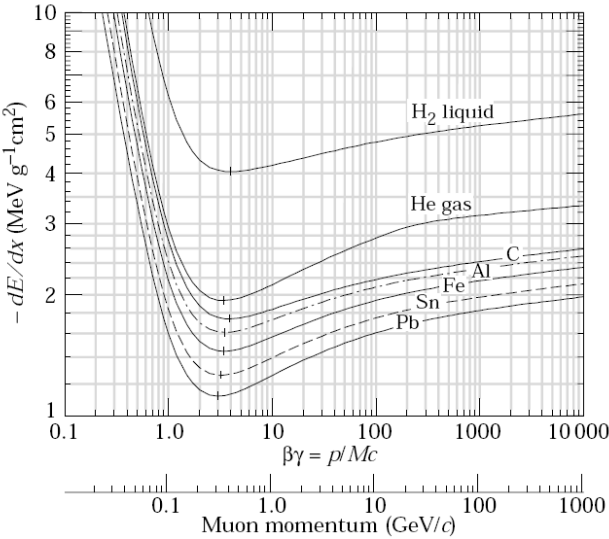
Transmission through Earth

- $P_{\oplus} = e^{-l/\lambda}$, where $\lambda^{-1} = \rho \mathcal{N}_A \sigma_\nu(E_\nu)$

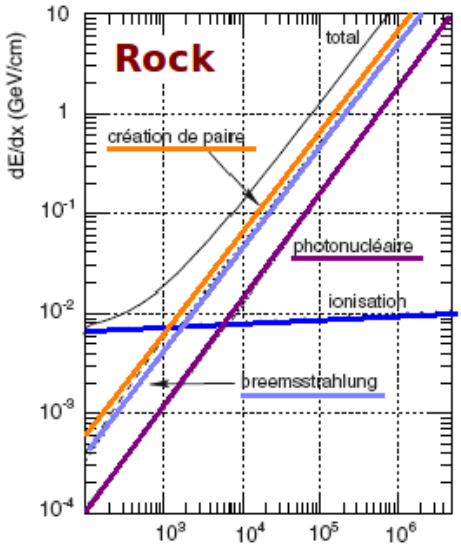


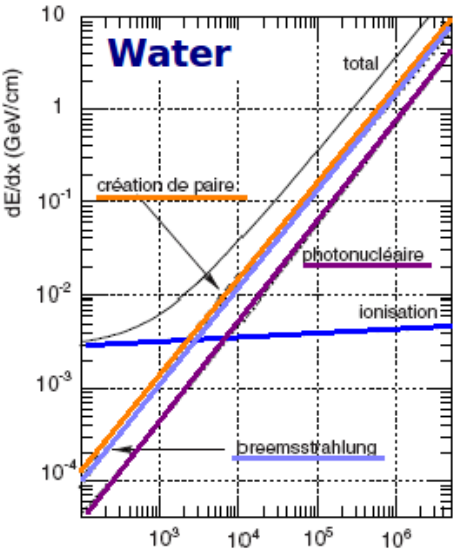
Energy Losses

- Ionization and atomic excitation : interactions with electrons in the media (continuous) - minimum at $2MeV/g/cm^2$
- Radiative - discrete and stochastic
  - ⇒ Bremmsstrahlung : accelerated particle through field of atomic nuclei $\propto 1/m^2$
  - ⇒ Pair production : $\mu + N \rightarrow e^+e^-$
  - ⇒ Photonuclear : inelastic interaction of muon with nuclei, produces hadronic shower

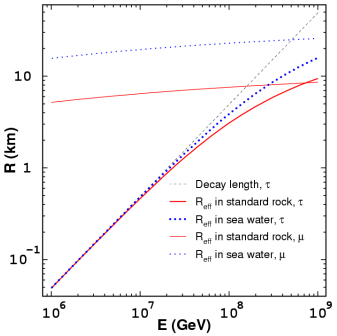


Energy Losses





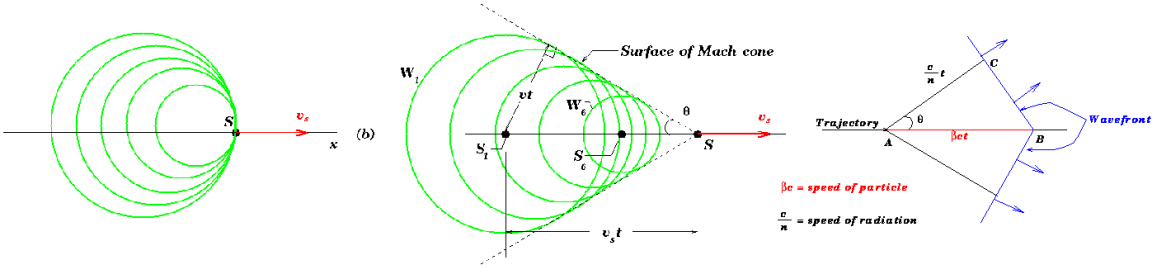
Energy Losses



Energy Losses and muon range

- Muon Range $R_\mu = \int_0^E \frac{dx}{dE} dE \approx \int_0^E \frac{dE}{a+bE} = \frac{1}{b} \log\left(1 + \frac{E}{E_c}\right)$ with $E_c = a/b$ critical energy
- For upgoing muons, the interaction volume is much larger than instrumented volume !

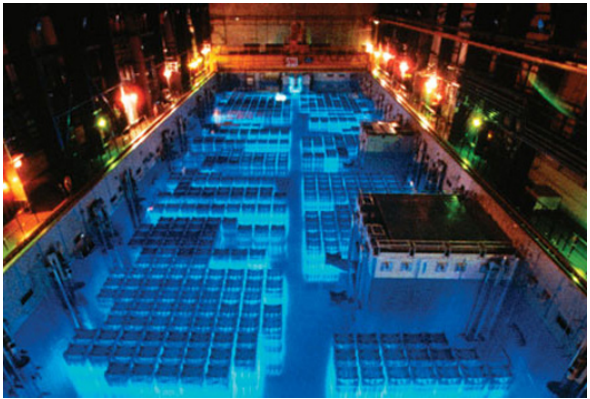
Cherenkov Effect



Charged Particle with velocity > phase velocity of light

- $v > \frac{c}{n}$ or $\beta > \frac{1}{n}$ refraction index
- Coherent emission along a cone of $\theta_C \sim$ constant
- $\theta_C \sim 1°$ in air, $\theta_C \sim 43°$ in water, $\theta_C \sim 41°$ in ice

Cherenkov Effect



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Cherenkov Effect

Number of Photons

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) \approx \frac{2\pi\alpha}{\lambda^2}\sin\theta_C^2$$

- Between 300-600 nm, $\frac{dN}{dx} \approx 350$ photons/cm
- $\frac{d^2N}{dEdx} \approx 370\sin^2\theta_C(E)eV^{-1}cm^{-1} \approx 10^{-4} \times 2MeV/cm$
  $\Rightarrow$ **But directional effect !**

Different radiators...

Photons are absorbed and scattered

$$I(r) \propto \frac{1}{R} e^{-R/\lambda_{\text{att}}}$$

- Note the $1/R$ because light on a cone, not on a sphere ! (`not so easy to demonstrate!`)
- Here Attenuation length : $\frac{1}{\lambda_{\text{att}}} = \frac{1}{\lambda_{\text{abs}}} + \frac{1}{\lambda_{\text{scatt}}}$

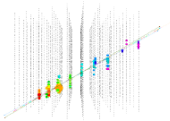
Medium	Attenuation	Absorption	Scattering	$\Delta\theta$ 10 TeV
Sea water	40-50m	50-60m	>200m	0.2°
Lake Baikal	20m	15-30m	>100m	1.5°
Polar Ice		100m	25m	3°

- Ice : no current, no bioluminescence, no β decay from salt
- Water : less scattering, better angular resolution

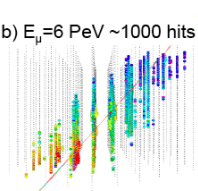
Event Topologies

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



b) E_μ=6 PeV ~1000 hits

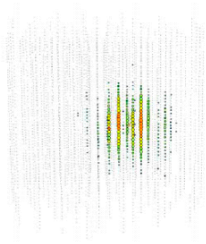


E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3
Angular Res.: 0.8 -2 deg

Electron neutrino

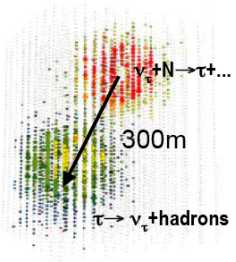
E = 375 TeV



Energy Res. log(E)~0.1-0.2
Poor Angular Resolution

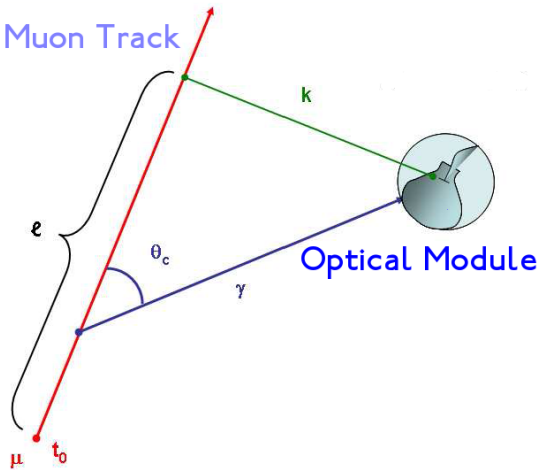
Tau neutrino

E = 10 PeV



Double-bang signature
above ~ 1 PeV
Very low background
Pointing capability
Best energy measurement

Reconstruction of the track...

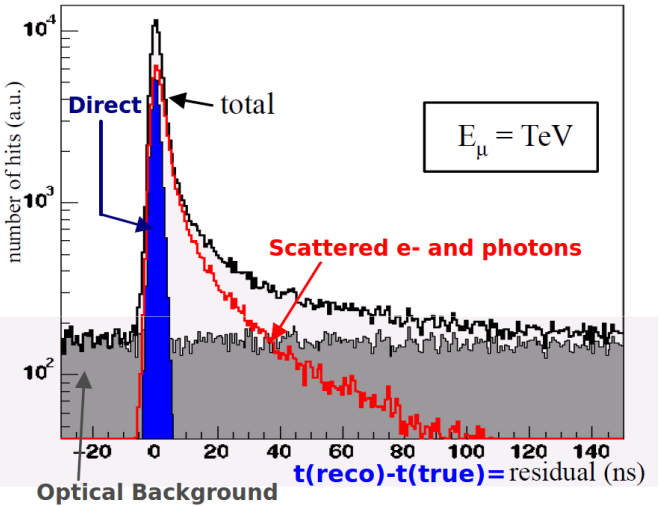


A χ^2 minimisation

$$t_{\text{theory}} = t_0 + \frac{1}{c}\left(l - \frac{k}{\tan\theta_C}\right) + \frac{1}{v_g}\left(\frac{k}{\sin\theta_C}\right)$$

- 5 parameters : $t_0, \theta, \phi, x_0, y_0$

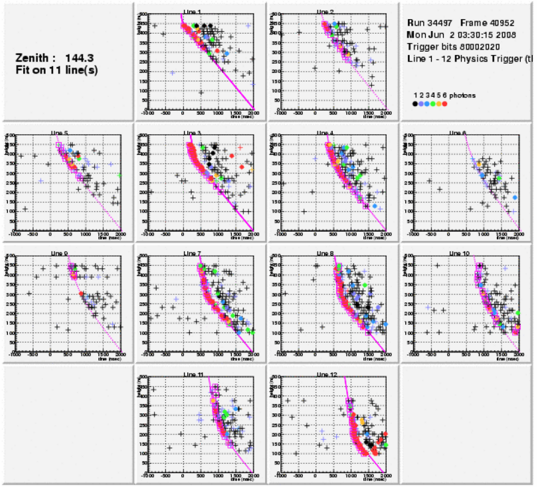
Reconstruction of the track...

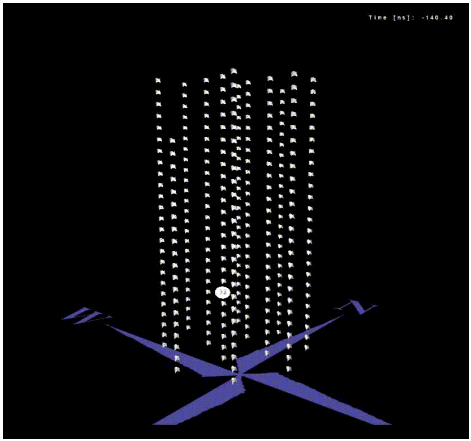


Importance of scattering

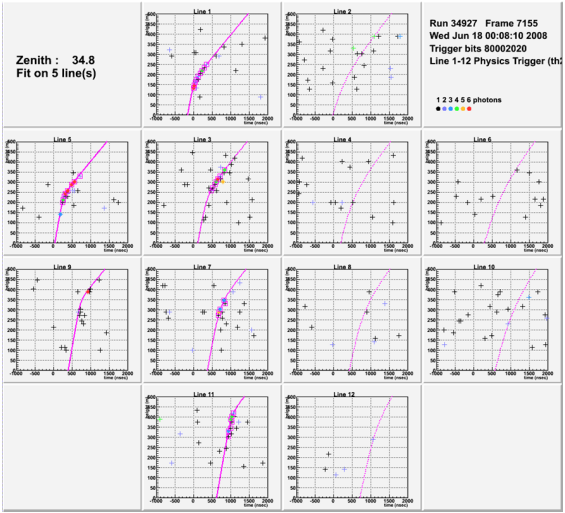
- **Few of photons are direct !**
- Impact on angular resolution

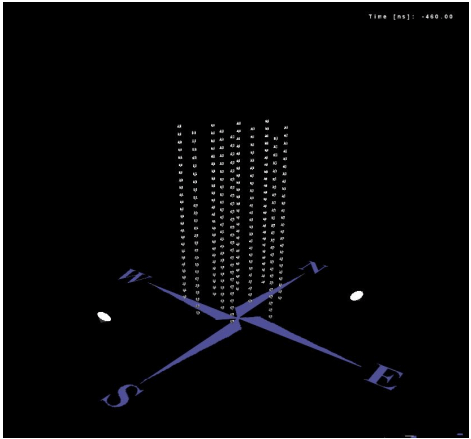
Atmospheric μ (downward) event





Atmospheric ν (upward) event





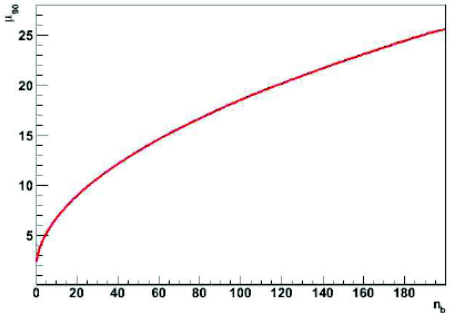
Two words on setting limits...

Model Rejection Factor MRF

- Given $\Phi_s = kE^{-\alpha}$ predicting $< n_s >$ signal events :

$$90\%\text{ CL average flux limit}\Phi_{90} = k \times \text{MRF} = k\frac{\bar{\mu_{90}}}{< n_s >}$$

- where $\bar{\mu_{90}}(< n_b >) = \sum_{n_{\text{obs}}=0}^{\infty} \mu 90(n_{\text{obs}}, < n_b >)P(n_{\text{obs}}, < n_b >)$
- Average upper limit of Background fluctuation at 90% CL observed with expected background $< n_b >$ and no signal



Two words on setting limits...

Model Discovery Potential MDP

- Probability for observing $\geq n_{n\sigma}$ with only background :

$$P(\geq n_{n\sigma}|n_b) = \sum_{n=n_{\rm obs}}^{\infty} P(n|n_b) = 1 - \sum_{0}^{n_{\rm obs}-1} P(n|n_b)$$

- Discovery = excess of 5σ over background
- $P(\geq n_{n\sigma}|n_b) \leq 2.85 \times 10^{-7}$ [**the $p-$value**]
- If signal n_s present, probability to observe $n_{n\sigma}$:

$$P(\geq n_{n\sigma}|n_b + n_s) = \sum_{n=n_{\rm obs}}^{\infty} P(n|n_b + n_s) = 1 - \sum_{0}^{n_{\rm obs}-1} P(n|n_b + n_s) = \beta$$

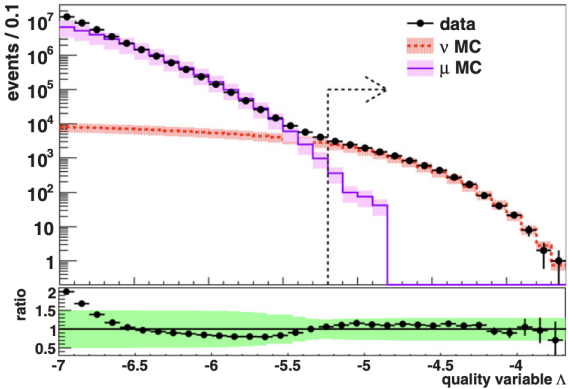
- Fixing β (with $n_{n\sigma}$) $\Rightarrow n_s$
- Model Discovery Potential = $\frac{n_{n\sigma}}{n_s} = \frac{\Phi_{n\sigma}}{\Phi_s}$

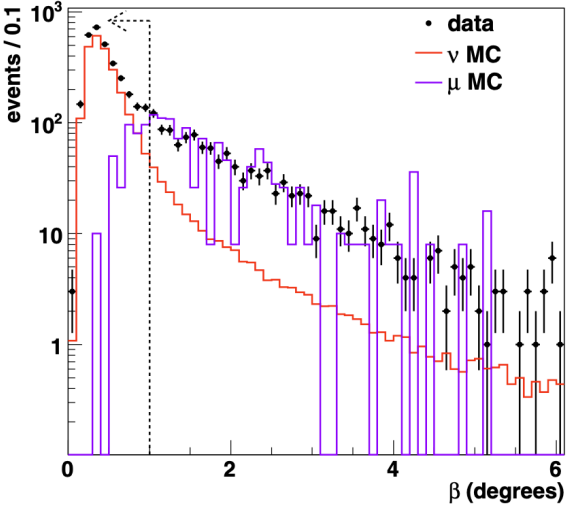
An example : a search for Point-Like Sources

First, select the events !

- We want to get rid of misreconstructed downgoing muons !
  - $\Rightarrow$ Cut on quality of the reconstruction Λ
  - $\Rightarrow$ Cut on estimate of angular error β
- The set of cuts depends on the Energy Spectrum considered
- Minimize MRF or MDP

An example : a search for Point-Like Sources

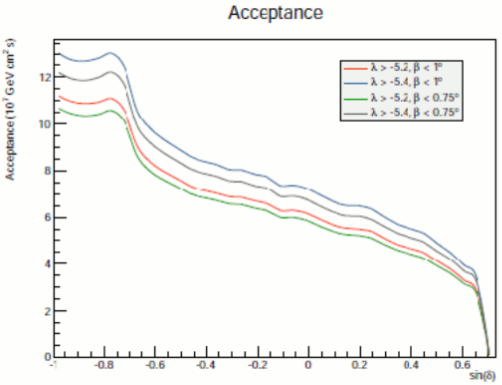


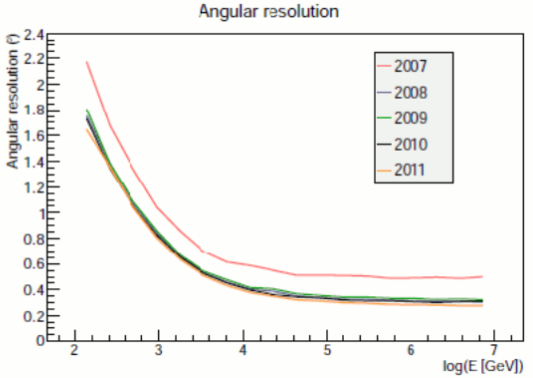


ANTARES 2021

An example : a search for Point-Like Sources

Estimate the Performances





An example : a search for Point-Like Sources

Compute a LogLikelihood and Test Statistics

$$\log \mathcal{L}_{\mathrm{s+b}} = \sum_i \log[\mu_{\mathrm{sig}} \times \mathcal{F}(\beta_i(\delta_s, \alpha_s)) \times \mathcal{N}(N_{hits}^{i,sig}) + \mathcal{B}_i \times \mathcal{N}(N_{hits}^{i,bkg})] + \mu_{\mathrm{tot}}$$

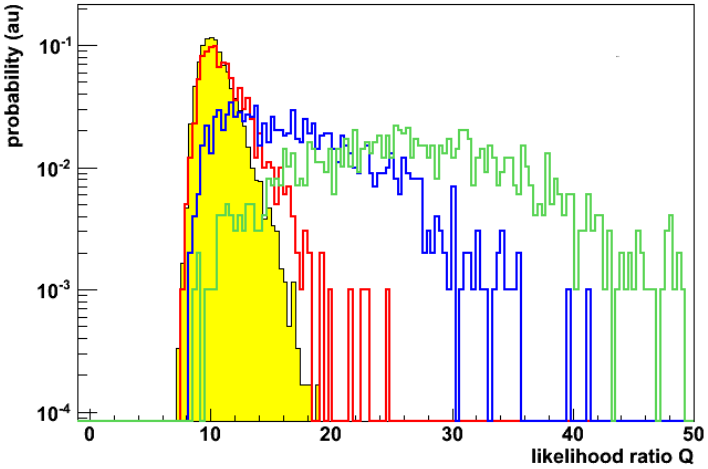
- Source with position (α_s, δ_s)
- $\mathcal{F}$ point spread function, for event at angular distance β_i from source
- $\mathcal{B}$ rate of background events as a function of δ
- μ_{tot} total number of expected events
- $\mathcal{N}(N^i_{\mathrm{hits}}$ probability for event i to be reconstructed with N^i_{hits} hits

$$\mathcal{Q} = \log \mathcal{L}_{\mathrm{s+b}} - \log \mathcal{L}_{\mathrm{b}}$$

Test Statistics, MRF and MDP

- $\mathcal{Q}$ with $0, +3, +6, +9$ signal events at $\delta = -70°$
- Allows to compute the sensivity to number of signal events for a discovery and median limit on signal events

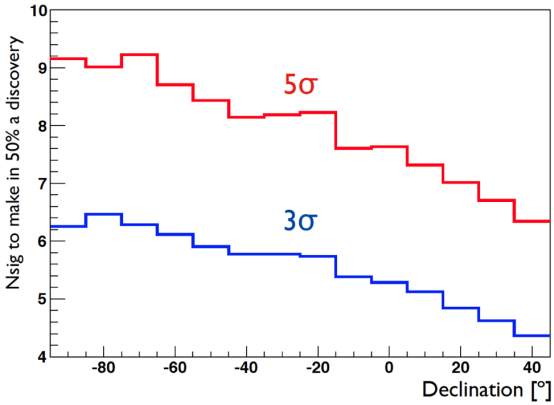
An example : a search for Point-Like Sources

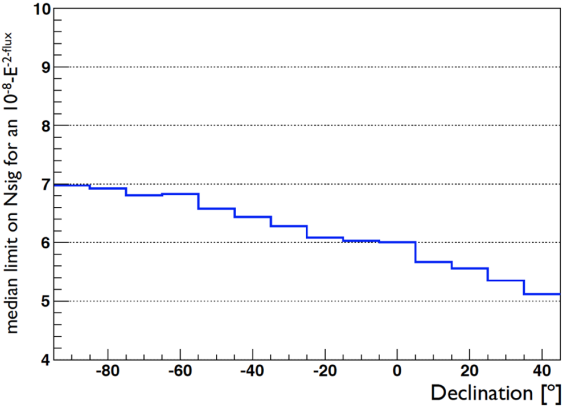


An example : a search for Point-Like Sources

Test Statistics, MRF and MDP

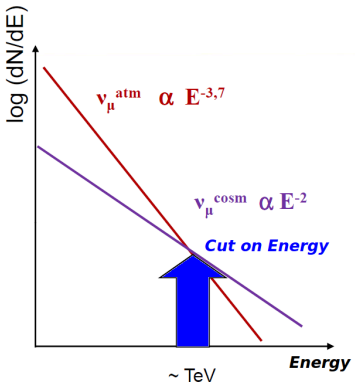
- Allows to compute the sensivity to number of signal events for a discovery and median limit on signal events

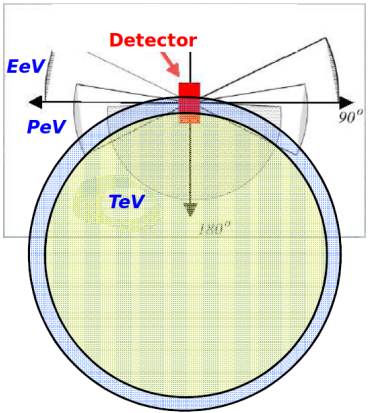




Atmospheric or Cosmic ?

Methods to distinguish between Atmospheric and Cosmic Neutrinos...

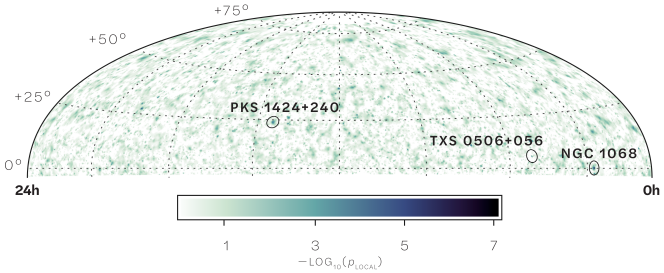


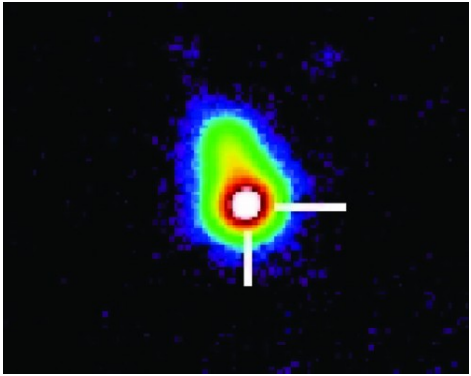


Look for an excess at high energies...⇒ **need good energy resolution**

Atmospheric or Cosmic ?

Methods to distinguish between Atmospheric and Cosmic Neutrinos...





Look for anisotropies/excess around chosen sources ⇒ **need good angular resolution**

Confirmation with other messengers : GRBs, optical follow-up, gravitational waves...

Neutrino Astrophysics - High Energies



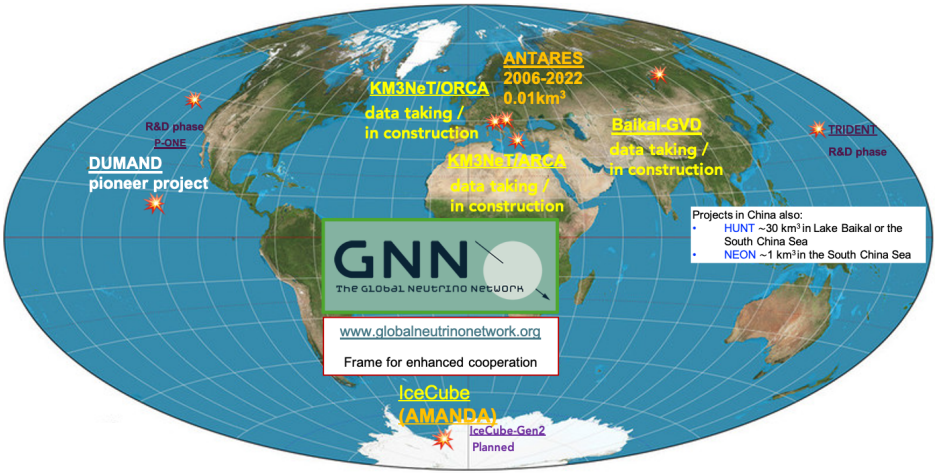
1. Introduction : *Neutrinos and other messengers, Sources and Detection*
2. Neutrinos & Cosmic-Rays : *From γ to ν astrophysical fluxes*
3. Neutrino Telescopes : *from Neutrino Interactions to Detection*
4. IceCube and Antares : *Description and Selected Results*
5. MultiMessenger Astronomy : *combining all cosmic signals*
6. GRB GW170817
7. Blazar TXS0506+056
8. KM3-230213A
9. Perspectives : from KM3NeT to the unknown ?

High-Energy Neutrinos :

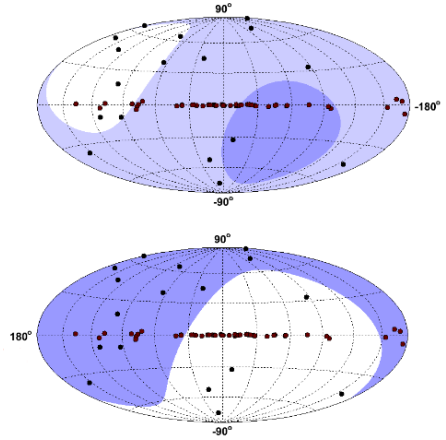
Neutrino Telescopes - ANTARES, KM3NeT, IceCube



Neutrino Telescopes in the World...



Neutrino Telescopes in the World...



ANTARES
- > 75%
- 25% – 75%
- < 25%

TeV γ-Sources
- galactic
- extragalactic

IceCube
- 100%
- 0%

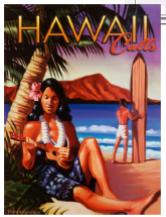
Different Telescopes are complementary

- 0.5π sr instantaneous overlap
- 1.5π sr integrated overlap

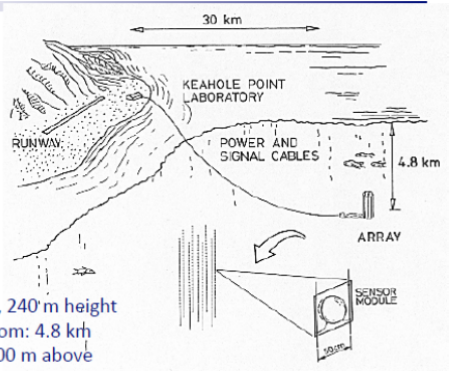
First there was DUMAND !

See also: A.Roberts: The birth of high-energy neutrino astronomy: a personal history of the DUMAND project, Rev. Mod. Phys. 64 (1992) 259.



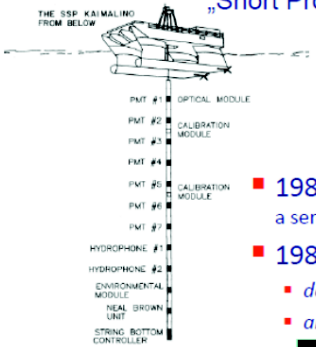


DUMAND-II (The Octagon)



- 9 strings
- 216 OMs
- 100 diameter, 240 m height
- Depth of bottom: 4.8 km
- Lowest OM 100 m above bottom

First there was DUMAND !





- 1982-87:
  a series of 14 cruises, with two lost strings
- 1987: success !
  - *depth-intensity curve*
  - *angular distributions*
- December 1993: deployment of first string and connection to junction box. Failure after several hours
  1995: DUMAND project is terminated



“At first, when we talked about DUMAND our accelerator friends laughed and said we were crazy. Now they ask why have you not got it operating yet !”
J G Learned (1992)

First there was DUMAND !

Observation of muons using the polar ice cap as a Cerenkov detector

Nature Sept 91

D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

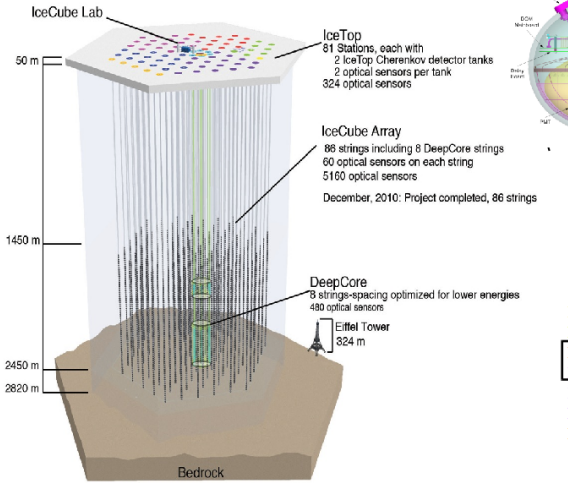
* Department of Physics, University of California, Berkeley, California 94720, USA
† Department of Physics, University of California, Irvine, California 92717, USA
‡ Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA

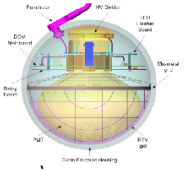
ACKNOWLEDGEMENTS. We thank B. Koci and the entire PICO organization for the use of the borehole and for on-site assistance, E. K. Solarz and W. Williams for their help with the mechanical construction of the PMT string, J. Lynch and H. Zimmerman of the NSF, J. Learned for his sharing of DUMAND expertise, and E. Zeller of the University of Kansas for suggesting the idea of using South Pole ice in a neutrino telescope. This work was supported in part by the Division of Polar Programs of the US NSF and by the California Space Institute.

F. Halzen



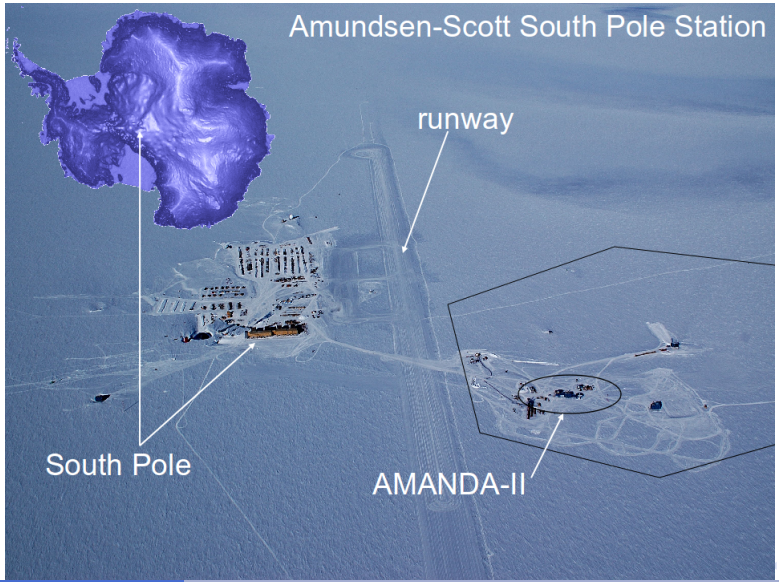
IceCube



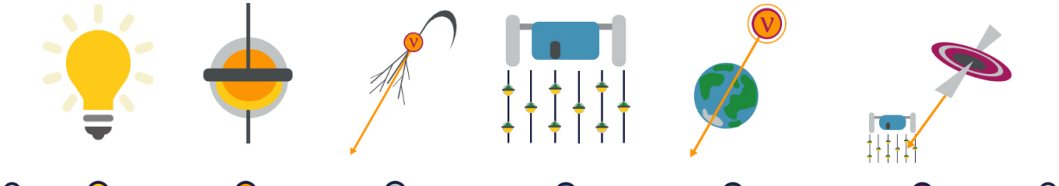


IC1 : 2004-5
IC9 : 2005-6
IC22 :2006-7
IC40:2007-8
IC59:2008-9
IC79:2009-10
IC86:2010-11

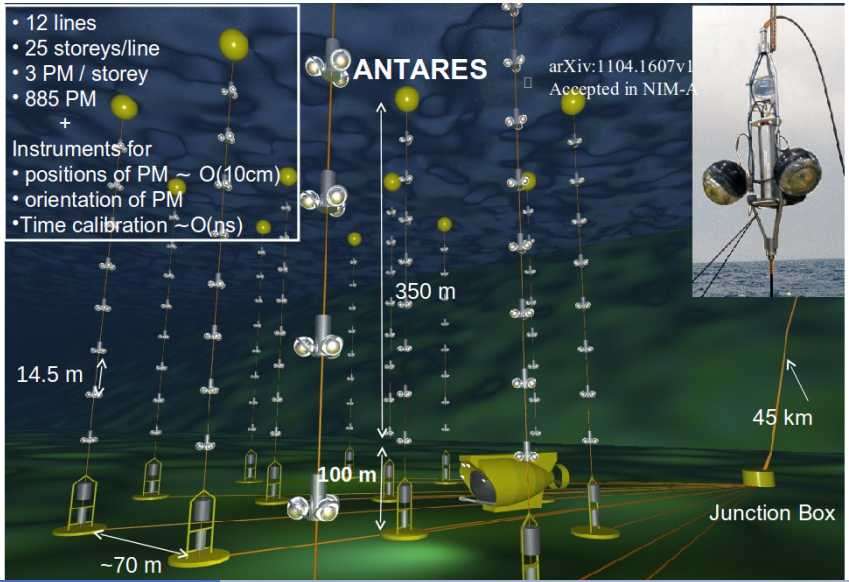
IceCube


Amundsen-Scott South Pole Station
runway
South Pole
AMANDA-II

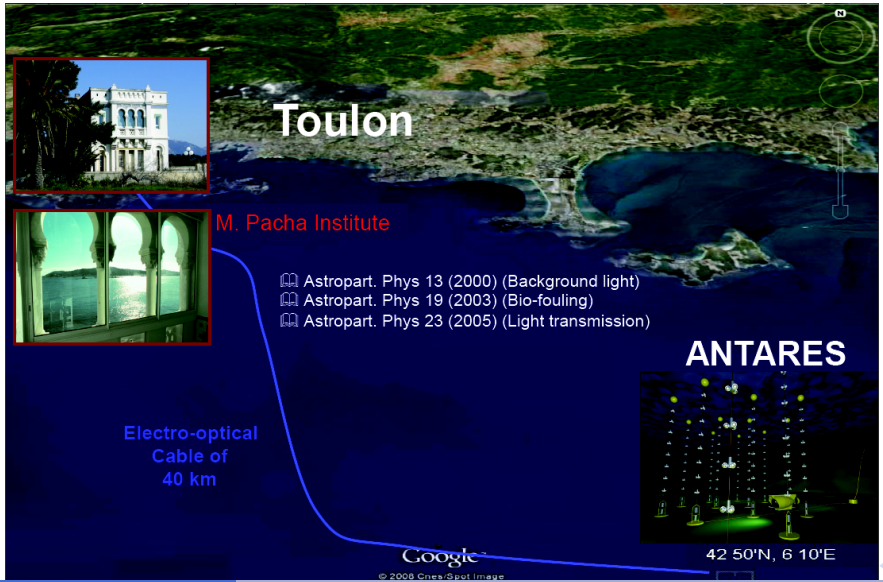
IceCube


1988
Telescope in the Ice Envisioned
2000
AMANDA Completed
2001
Atmospheric Neutrinos Detected
2011
IceCube Completed
2013
Astrophysical Neutrinos Discovered
2018
First Source Identified

Antares and its successor KM3NeT



Antares and its successor KM3NeT



Antares and its successor KM3NeT



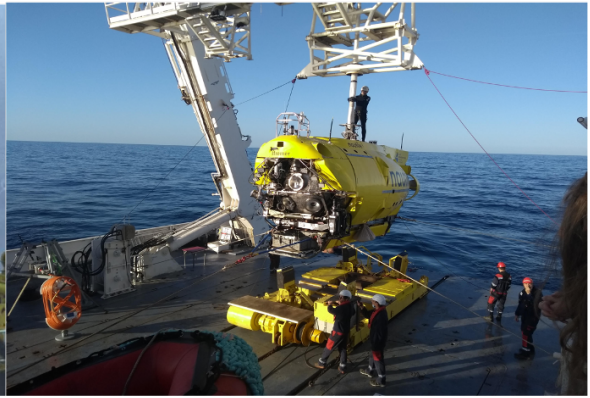


Detector 2006-2022

12 Lines in operation

Antares and its successor KM3NeT



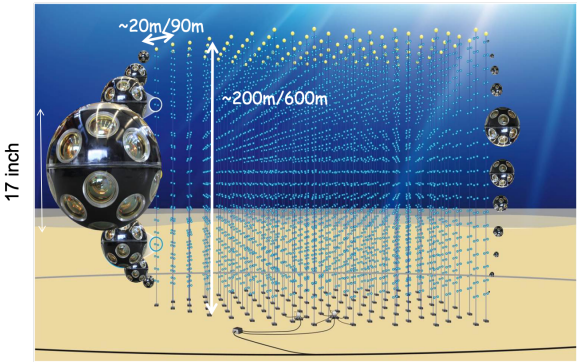


Detector 2006-2022

12 Lines in operation $\sim 0.1\mathrm{km}^2$

Antares and its successor KM3NeT

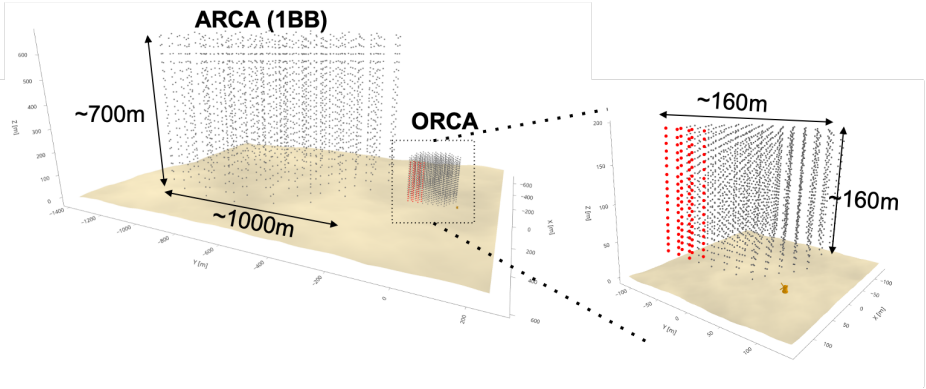




The next Mediterranean HEN Telescope : KM3NeT

Volume $\approx 1 - 2\times$ IceCube, construction started

Antares and its successor KM3NeT



The future Mediterranean HEN Telescope : KM3NeT

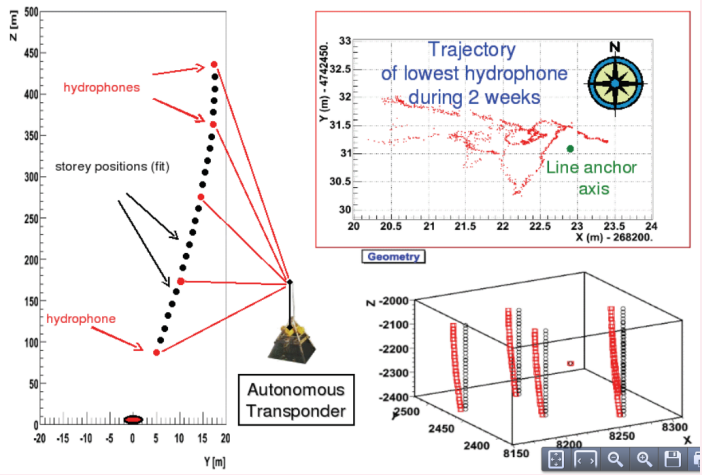
ARCA $\sim$ 0.15 km^3, ORCA $\sim 25\%$

→ Links to Deployment movies

Calibration and Performances - Antares

Positioning and Timing

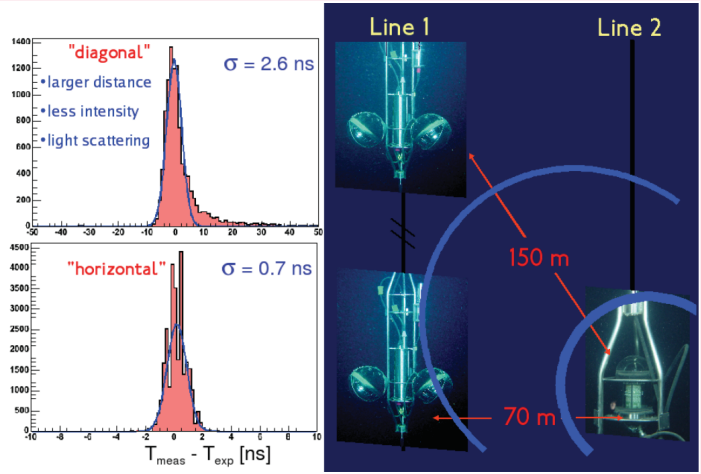
- Positioning with Hydrophones



Calibration and Performances - Antares

Positioning and Timing

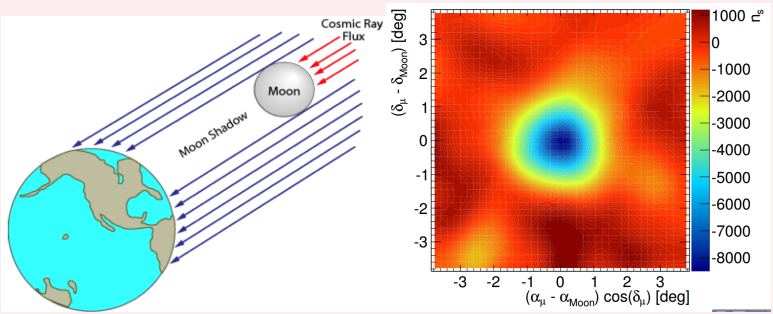
- Timing with LEDs and Laser



Calibration and Performances - IceCube

Positioning and Timing

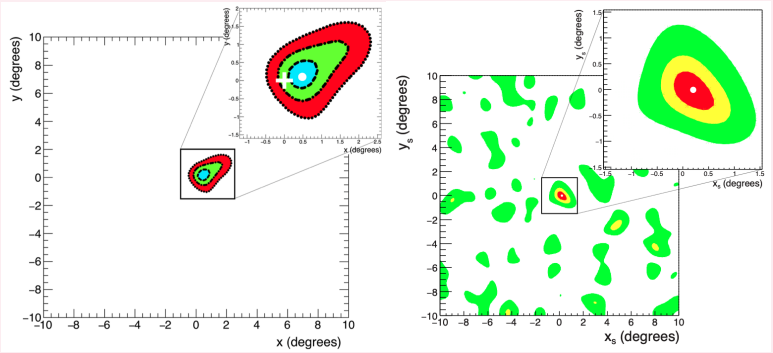
- Check pointing with *Moon Shadow*
  - ⇒ blocks cosmic-ray muons !



Calibration and Performances

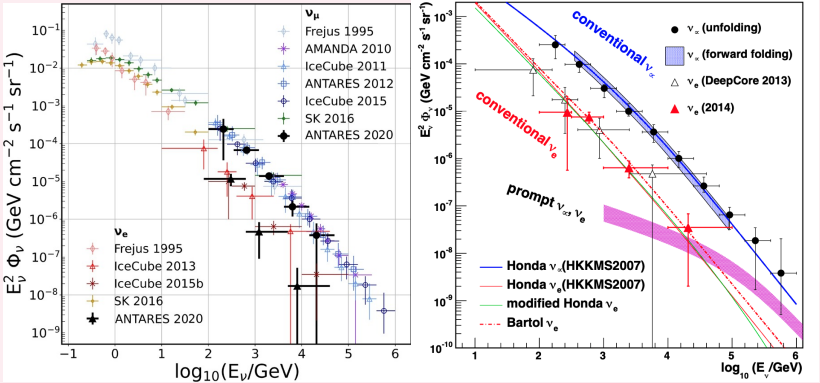
Positioning and Timing

- Positioning with Hydrophones
- Timing with LEDs and Laser
- Check pointing with *Moon Shadow* + Sun Shadow (down<ard atm. muons)
  - ⇒ Angular resolution $= 0.59^\circ \pm 0.1^\circ$



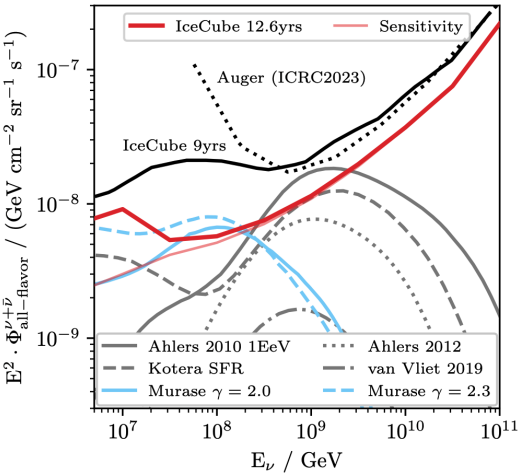
Calibration and Performances

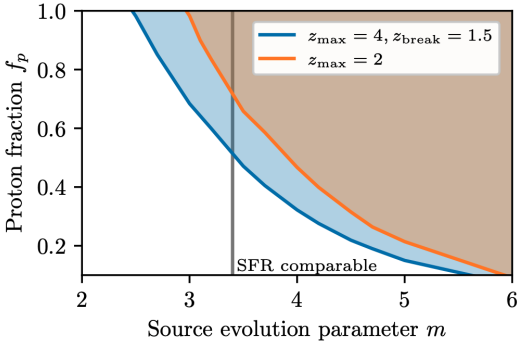
Measurement of Atmospheric Neutrino Spectrum



Antares 2020 **IceCube 2015**

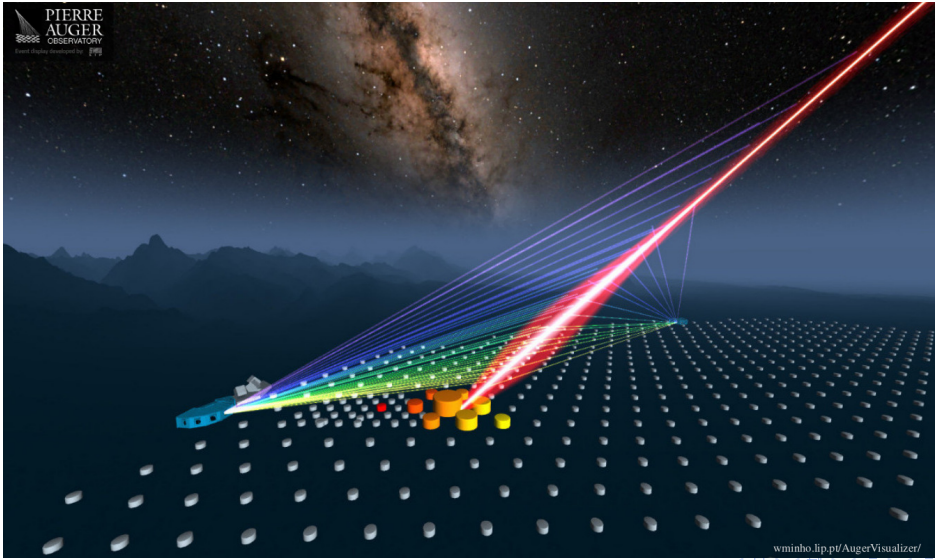
Neutrinos at Extremely-High Energies - IceCube



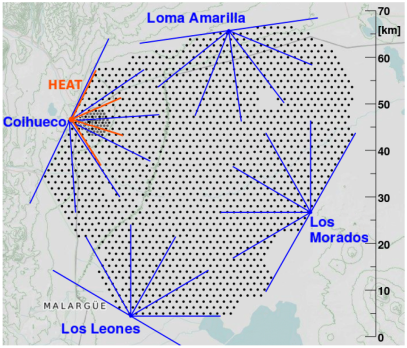


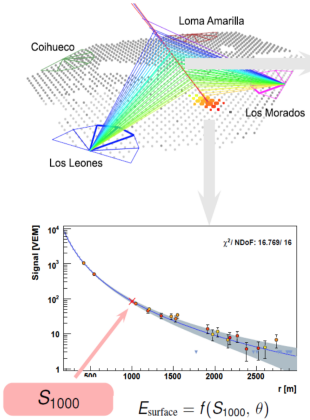
Exclusion of all top-down scenarios, constraints on source population (IceCube 2025)

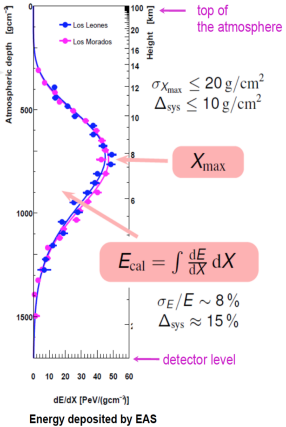
Ultra-High Energies with the Pierre Auger Observatory



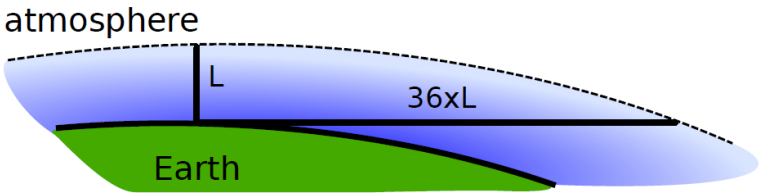
Ultra-High Energies with the Pierre Auger Observatory



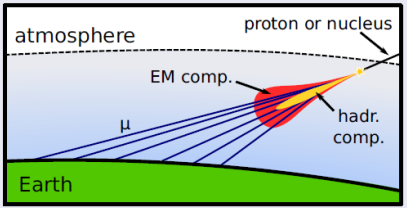


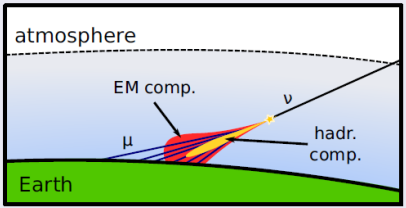


Ultra-High Energies with the Pierre Auger Observatory

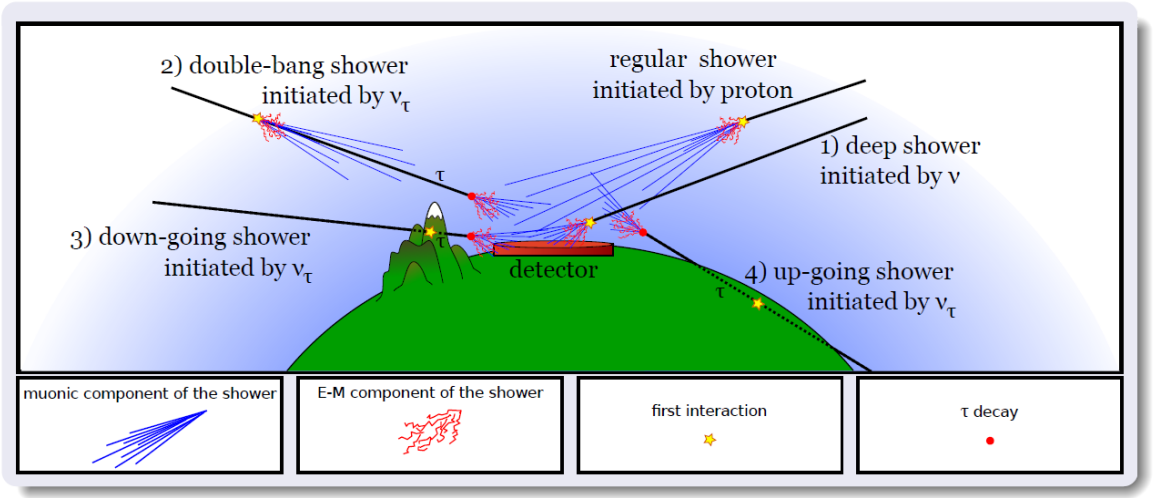


High zenith angle showers

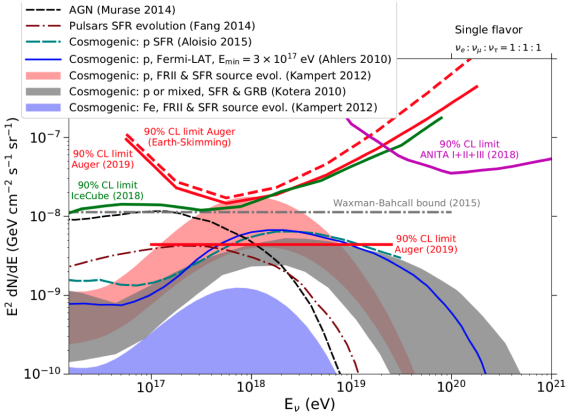


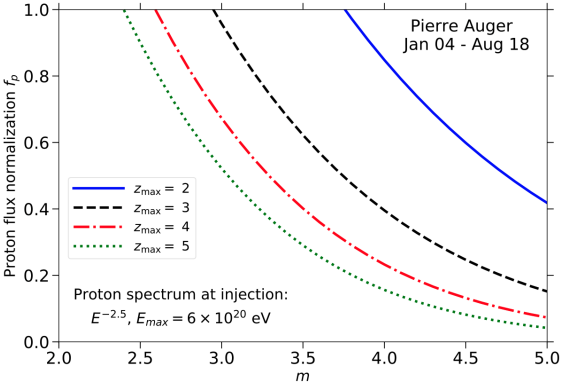


Ultra-High Energies with the Pierre Auger Observatory



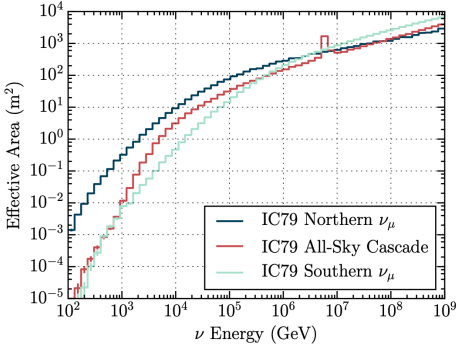
Ultra-High Energies with the Pierre Auger Observatory

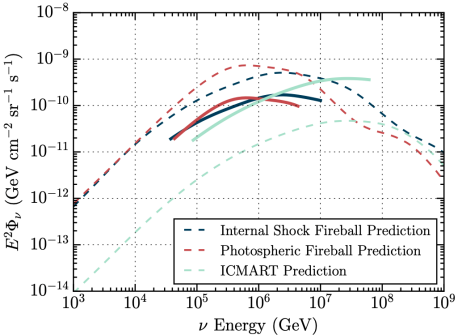




Pierre Auger 2019

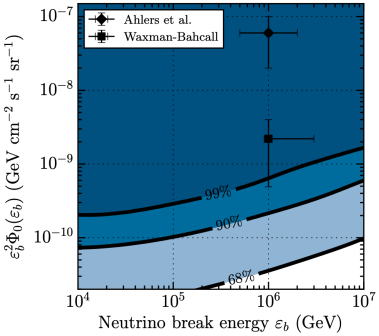
Neutrinos and Cosmic-Rays from Gamma-Ray Bursts (GRBs)

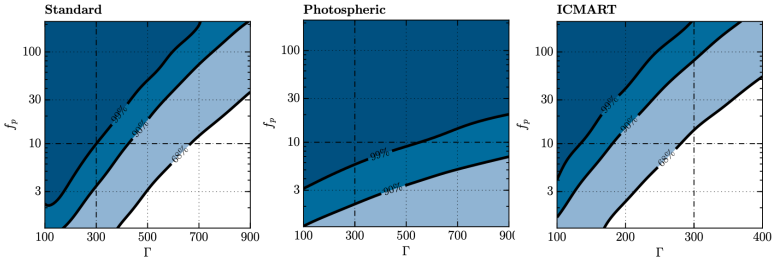




IceCube 2017

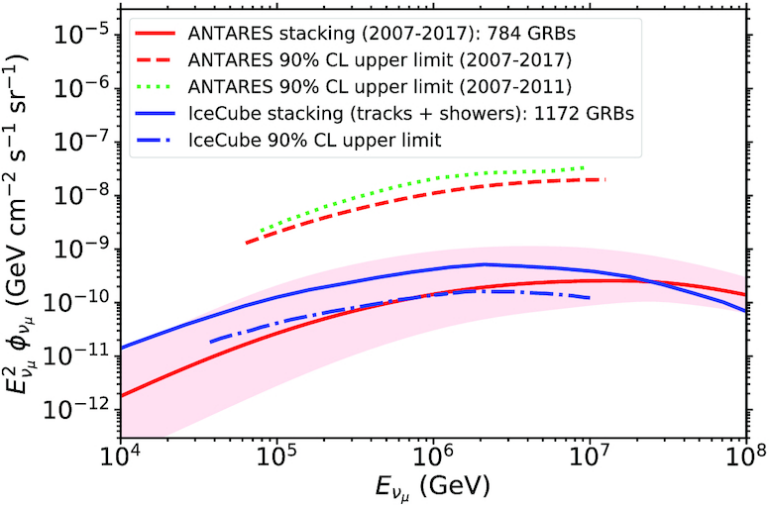
Neutrinos and Cosmic-Rays from Gamma-Ray Bursts (GRBs)





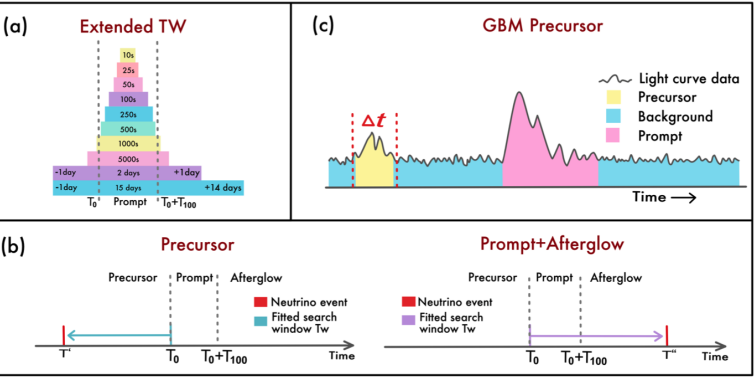
IceCube 2024

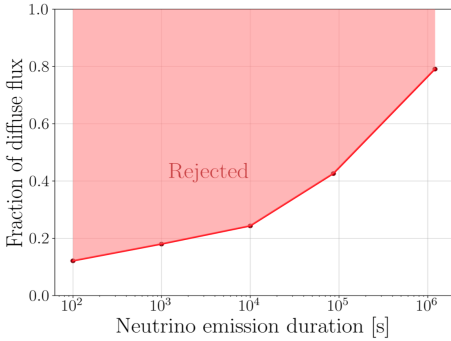
Neutrinos and Cosmic-Rays from Gamma-Ray Bursts (GRBs)



ANTARES 2020

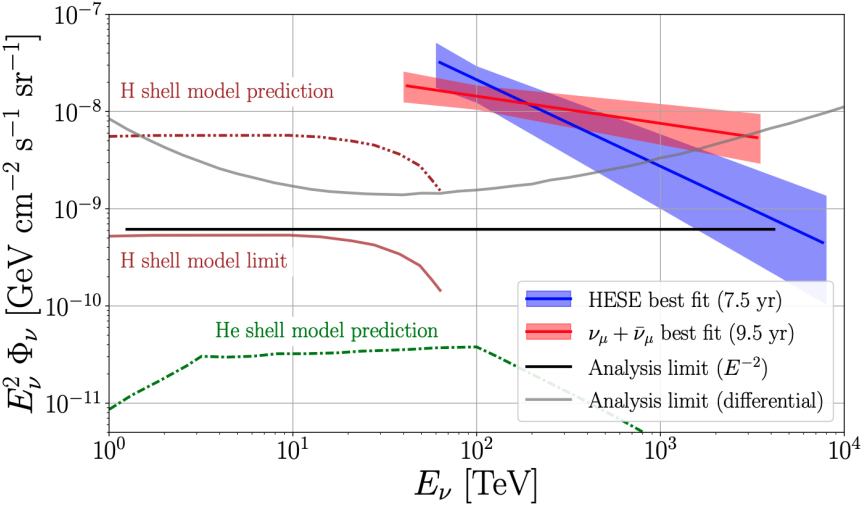
Neutrinos and Cosmic-Rays from Gamma-Ray Bursts (GRBs)





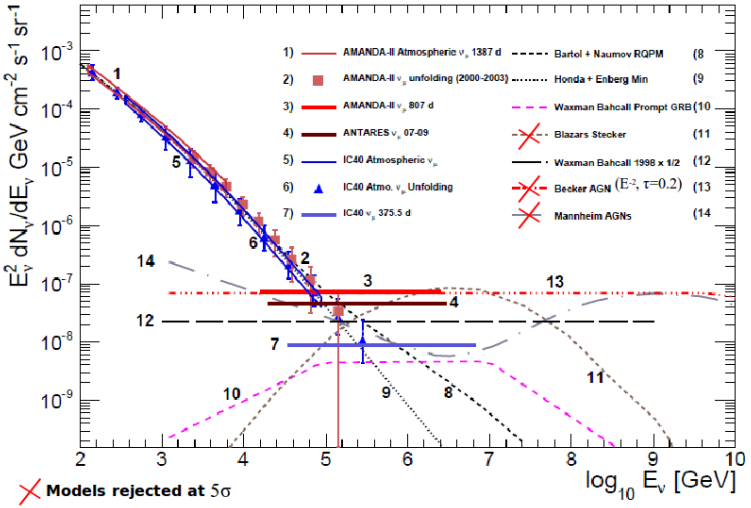
IceCube 2022

Neutrinos and Cosmic-Rays from Gamma-Ray Bursts (GRBs)



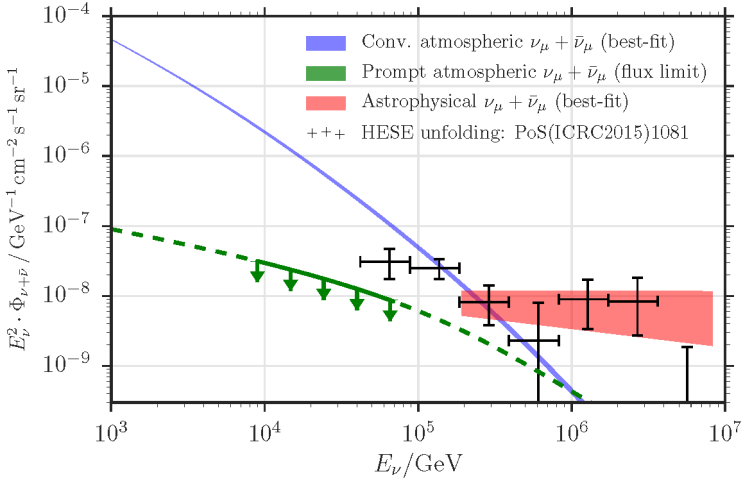
IceCube 2022

The search for a High Energy Neutrino (Cosmic) Diffuse Fluxes



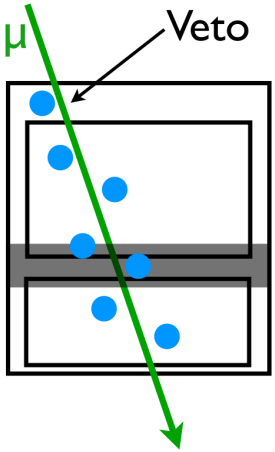
From 2012 (no signal)...

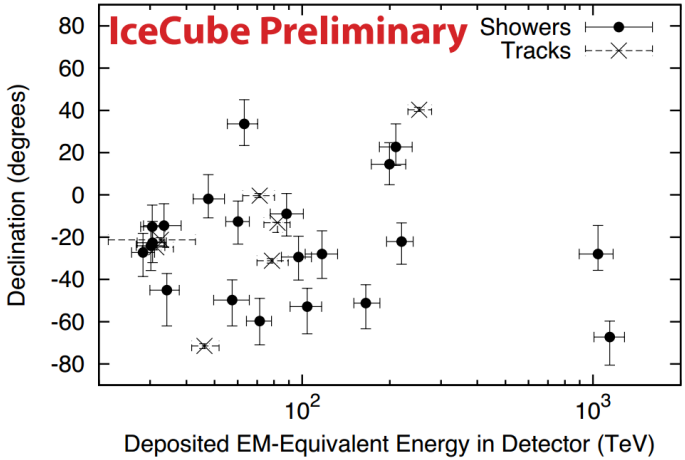
The search for a High Energy Neutrino (Cosmic) Diffuse Fluxes



...to 2016 (signal !)

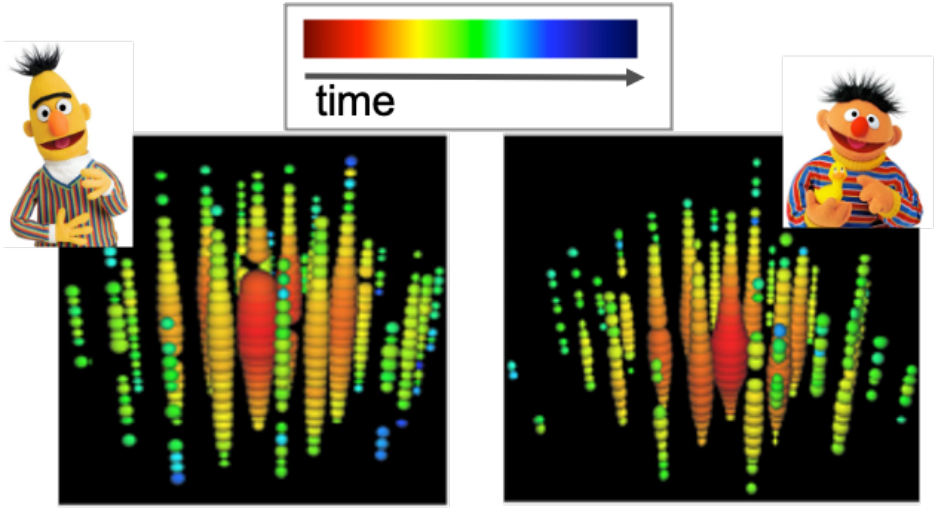
TeV-PeV events in IceCube : a clever veto



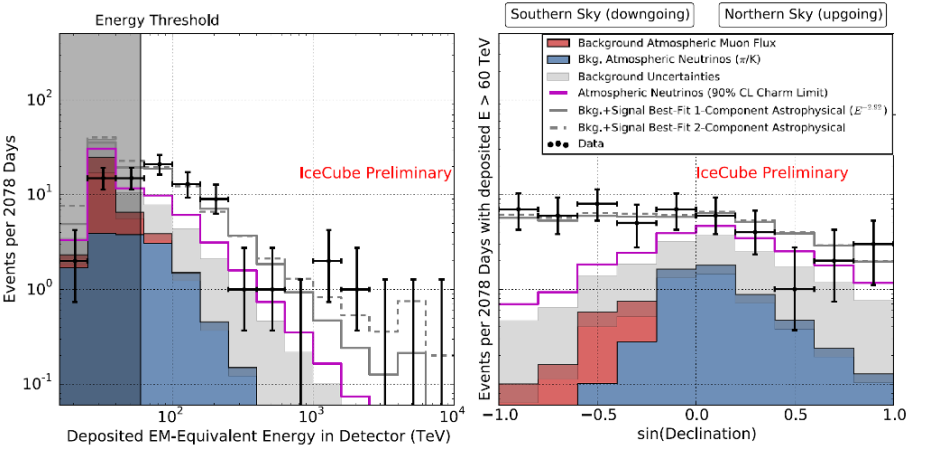


28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

TeV-PeV events in IceCube : a clever veto

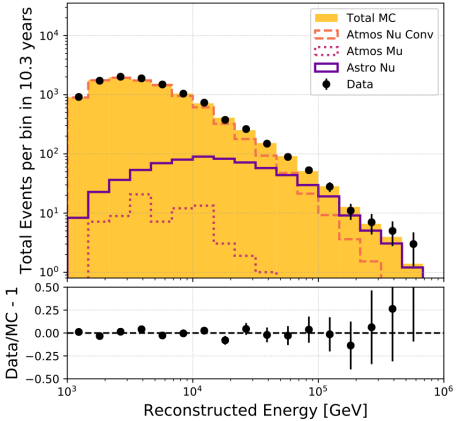


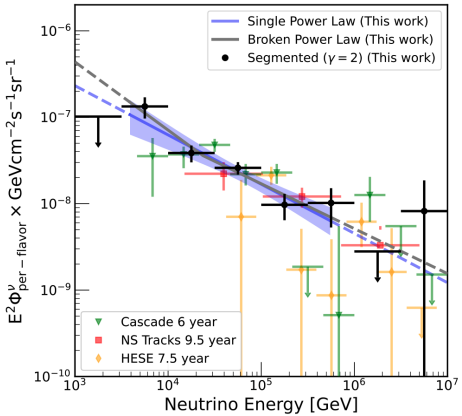
TeV-PeV events in ICECUBE : a clever veto



- Corresponds to $\Phi_{nu} = 3 \times 10^{-18} \times 1.68^{+0.19}_{-0.22} \times \left(\frac{E_\nu}{100\text{TeV}}\right)^{-\gamma} GeV^{-1}.cm^{-2}.s^{-1}.sr^{-1}$
- with $\gamma = 2.58^{+0.1}_{-0.09}$ for single power-law (IceCube 2024)

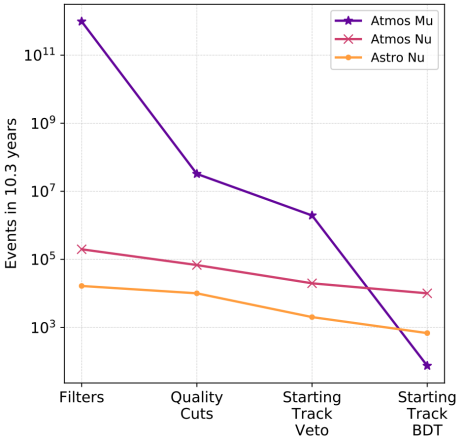
TeV-PeV events in IceCube

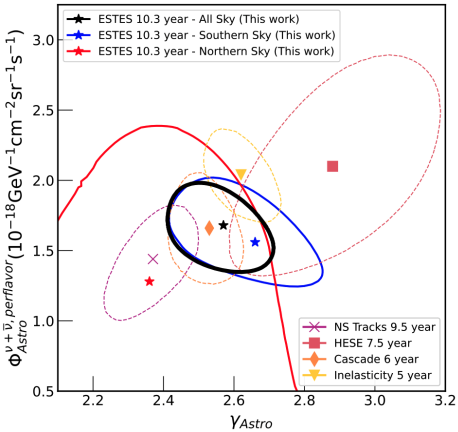




IceCube (2024)

TeV-PeV events in IceCube

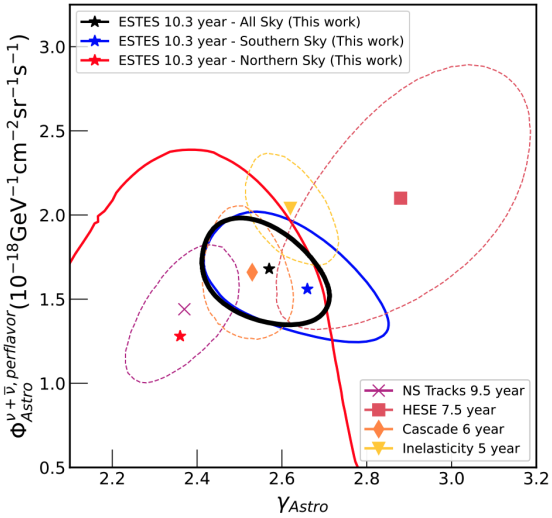




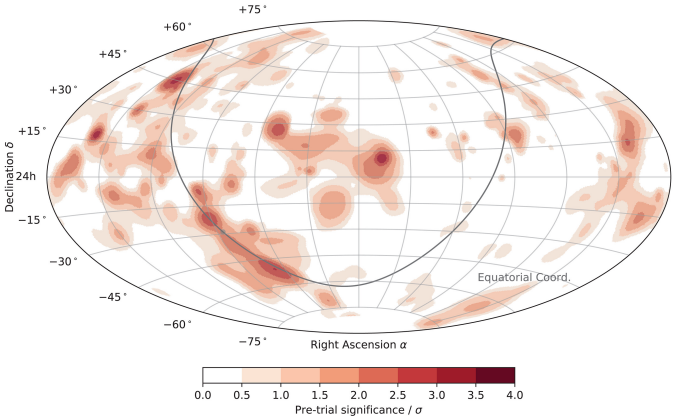
IceCube (2024)

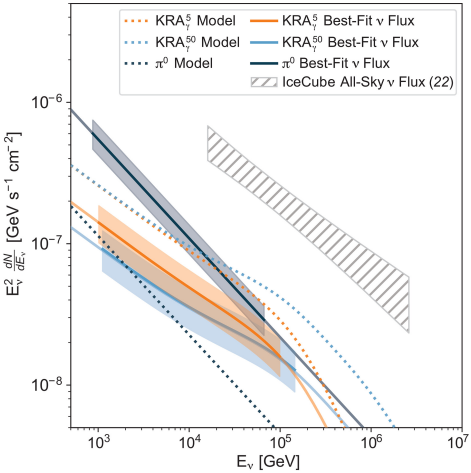
TeV-PeV events in IceCube

- HESE 7.5yr : cascade-like events with non-negligible contribution from starting track-like events (17%) - minimum energy cut at 60 TeV limiting measurement
- Cascade 6yr : cascade events, down to 16 TeV
- Northern Sky Tracks 9.5yr : through going and starting muon tracks in the northern equatorial sky -measurement limited by energy resolution of through-going events - no self-veto
- ESTES 10.3yr : starting track-like events over the entire sky for energies above 1 TeV
- Consistent picture - no departure from single power law at lower energies
- From 3 TeV up to 550 TeV



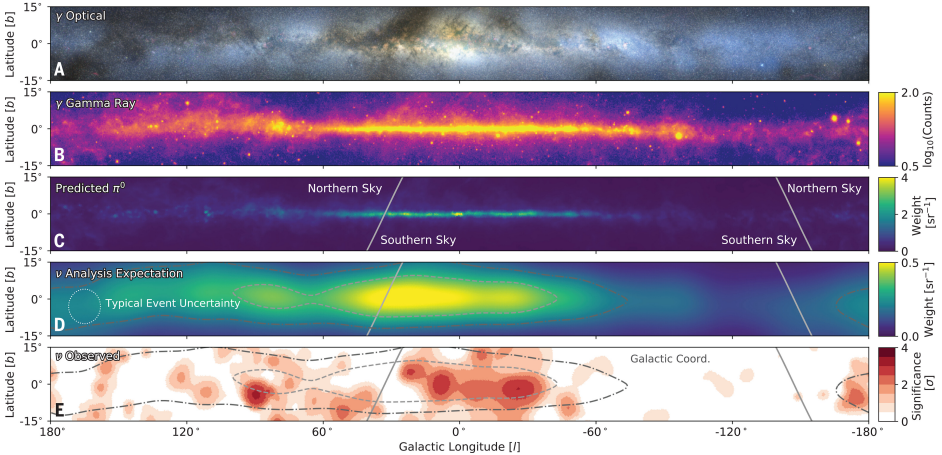
TeV-PeV events in IceCube : the Galactic Plane





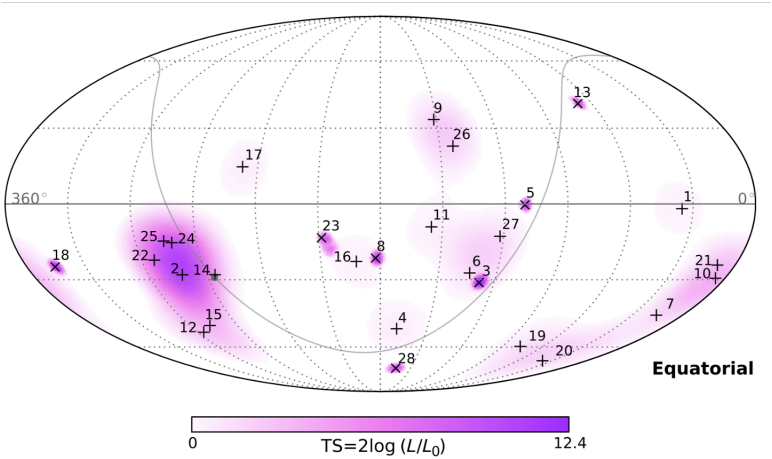
IceCube (2023)

TeV-PeV events in IceCube : the Galactic Plane



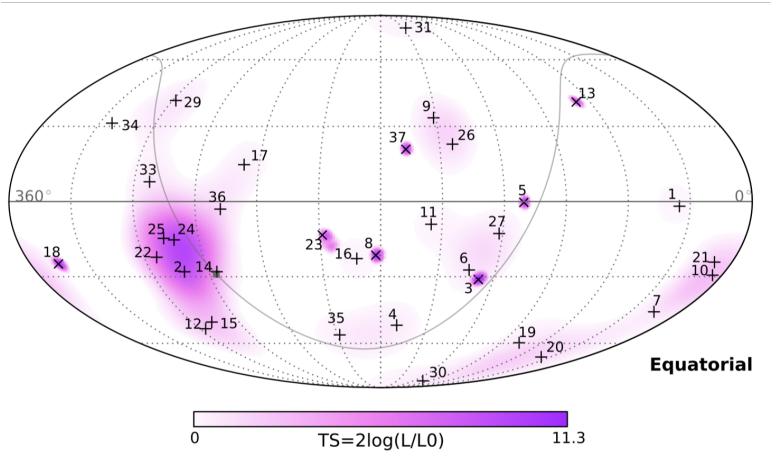
IceCube (2023)

Searching for High Energy Neutrino point-like sources - the quest



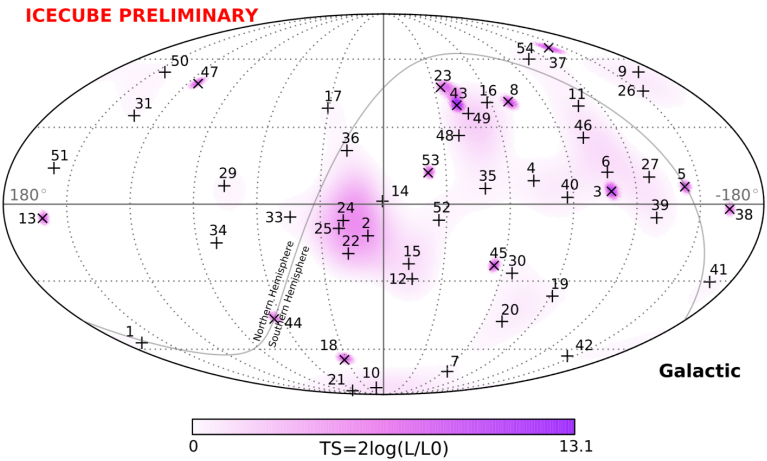
IceCube 2 yrs - 4.1σ

Searching for High Energy Neutrino point-like sources - the quest



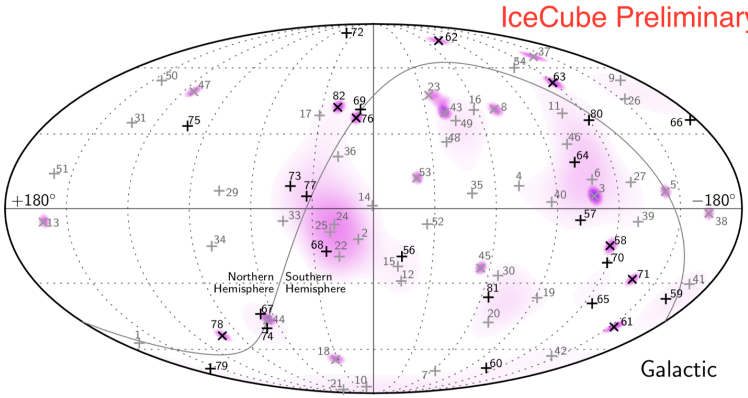
IceCube 3 yrs - 5.7σ

Searching for High Energy Neutrino point-like sources - the quest



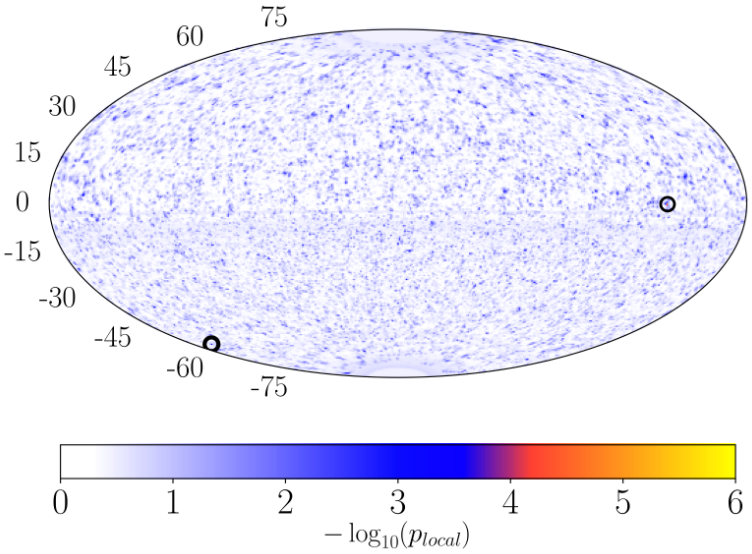
IceCube 4 yrs > 7σ

Searching for High Energy Neutrino point-like sources - the quest

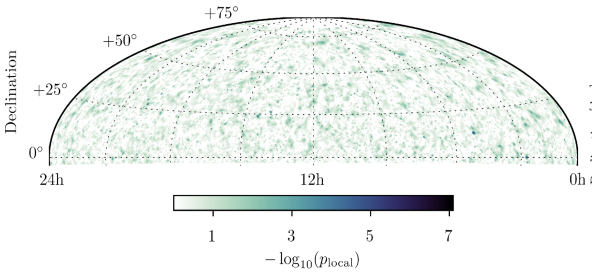


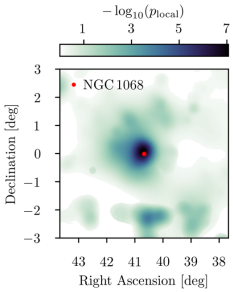
IceCube 6 yrs > 7σ

Searching for High Energy Neutrino point-like sources - the quest



Searching for High Energy Neutrino point-like sources - the quest

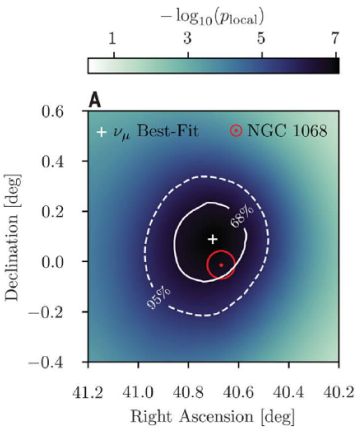


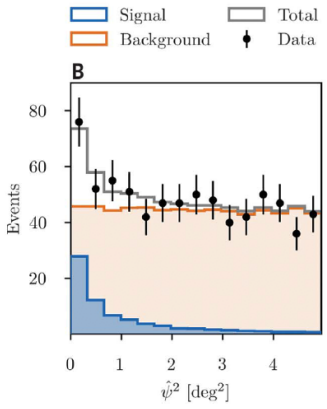


Hottest spot is NGC1068

Searching for High Energy Neutrino point-like sources - the quest







NGC1068 - a Seyfert Galaxy

Searching for High Energy Neutrino point-like sources - the quest



NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

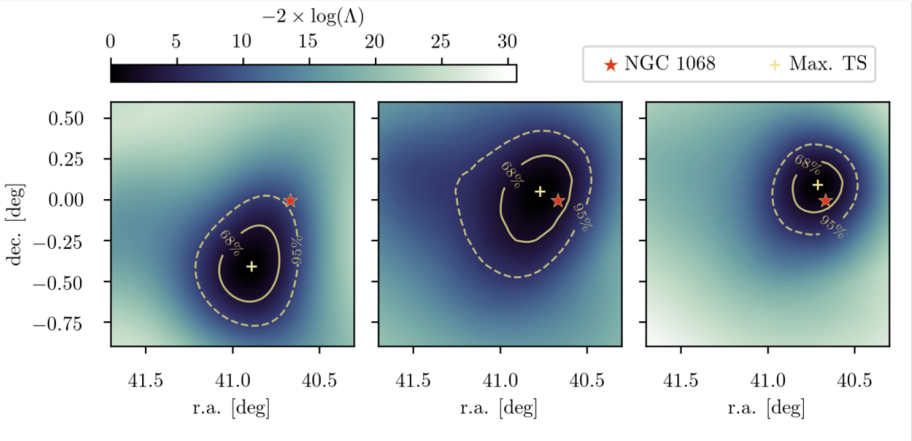
1943

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

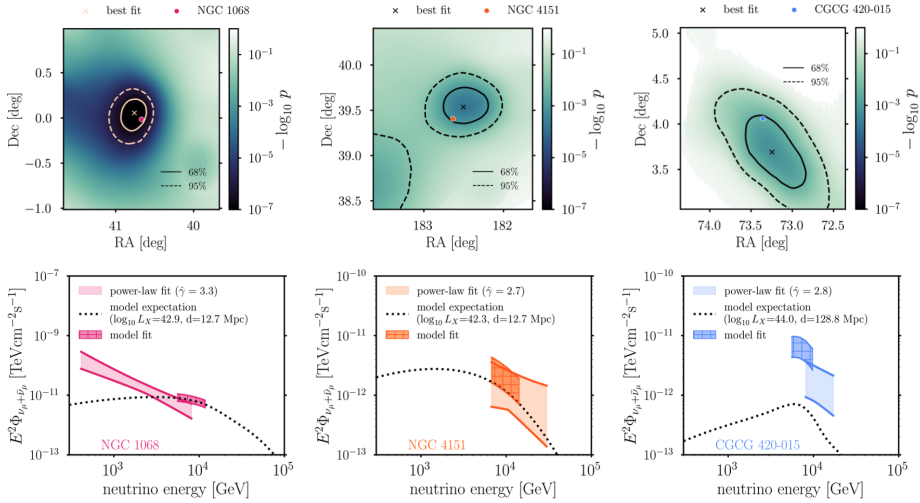
NGC1068 - a Seyfert Galaxy

Searching for High Energy Neutrino point-like sources - the quest



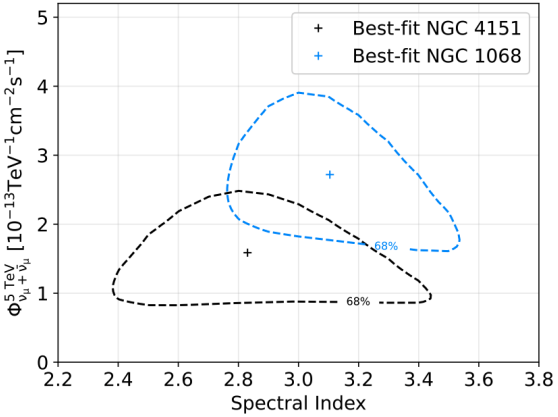
NGC1068 : from 2.9σ to 3.3σ and 4.2σ

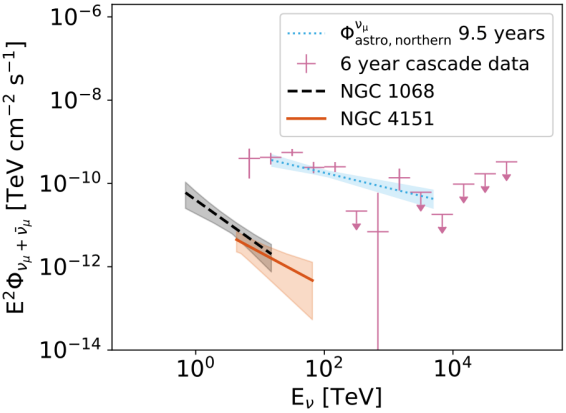
Searching for High Energy Neutrino point-like sources - the quest



NGC1068 and other X-Ray Bright Seyfert Galaxies - IceCube 2024

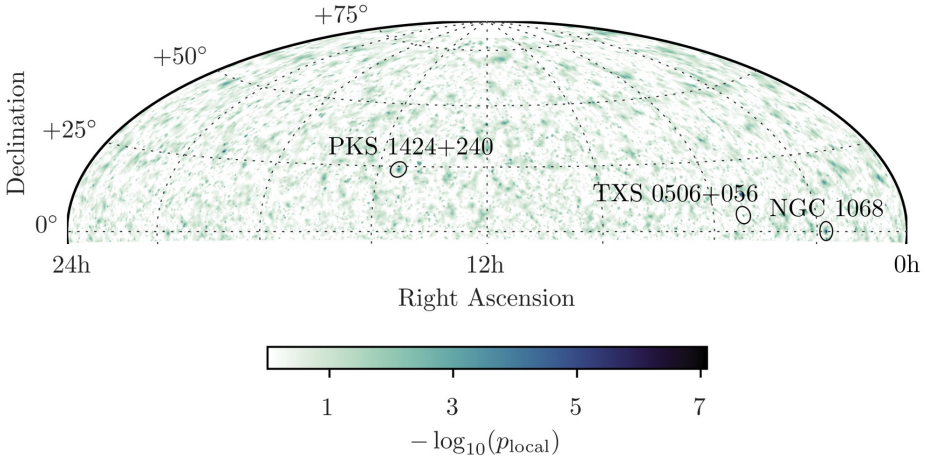
Searching for High Energy Neutrino point-like sources - the quest





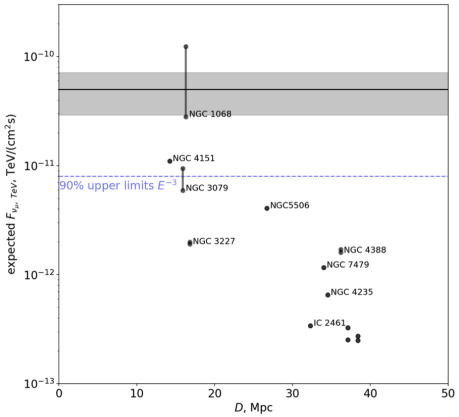
NGC1068 and other Hard X-Ray AGN - Confirmed in IceCube 2024

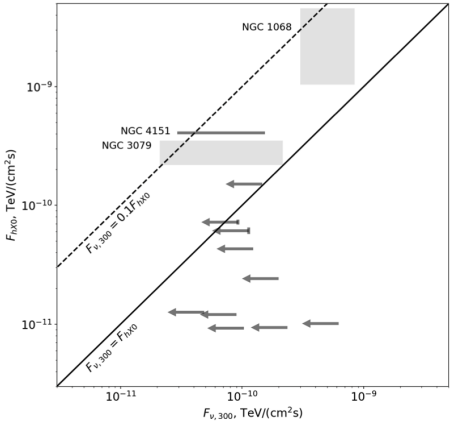
Searching for High Energy Neutrino point-like sources - the quest



PKS1424+20 close to 3σ - IceCube 2022

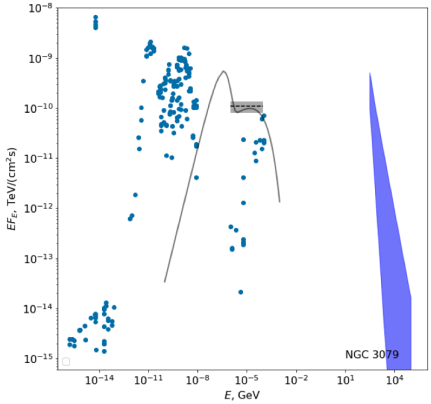
Searching for High Energy Neutrino point-like sources - the quest

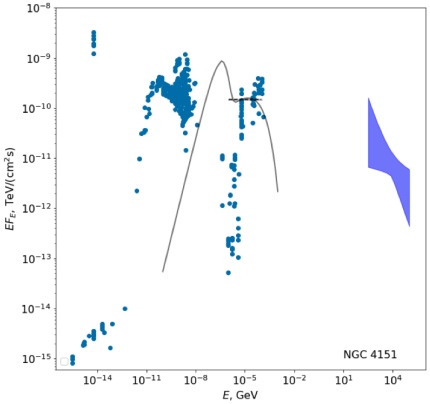




Using Public data (Neronov 2024) - NGC 4151 + NGC 3079

Searching for High Energy Neutrino point-like sources - the quest





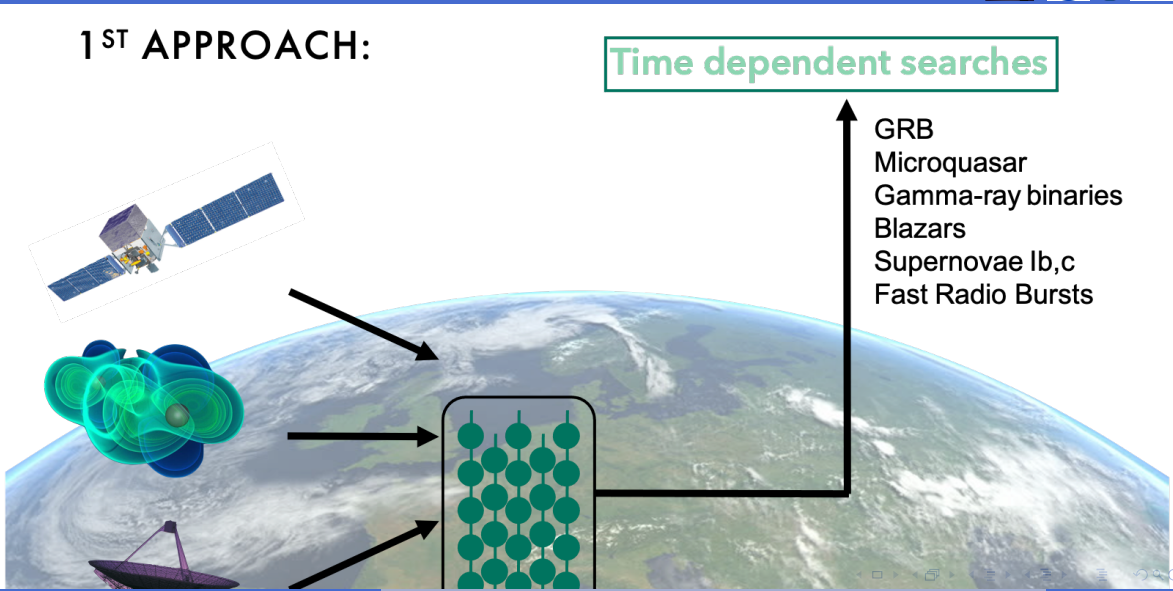
Using Public data (Neronov 2024) - NGC 4151 + NGC 3079

Correlations with other messengers...

1ST APPROACH:

Time dependent searches

GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts



Correlations with other messengers...

2ND APPROACH:

Alert triggering

Real-time analysis





- Time to send an alert: ~5 s
- First optical image <20 s
- Median angular resolution: ~0.3°
- Triggers: single HE, preferred direction, multiplets

Neutrino Astrophysics - High Energies



1. Introduction : *Neutrinos and other messengers, Sources and Detection*
2. Neutrinos & Cosmic-Rays : *From γ to ν astrophysical fluxes*
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5. MultiMessenger Astronomy : *combining all cosmic signals*
6. GRB GW170817
7. Blazar TXS0506+056
8. KM3-230213A
9. Perspectives : from KM3NeT to the unknown ?

Antares :

MultiMessenger Astronomy



MultiMessenger Astronomy

1ST APPROACH:

Time dependent searches

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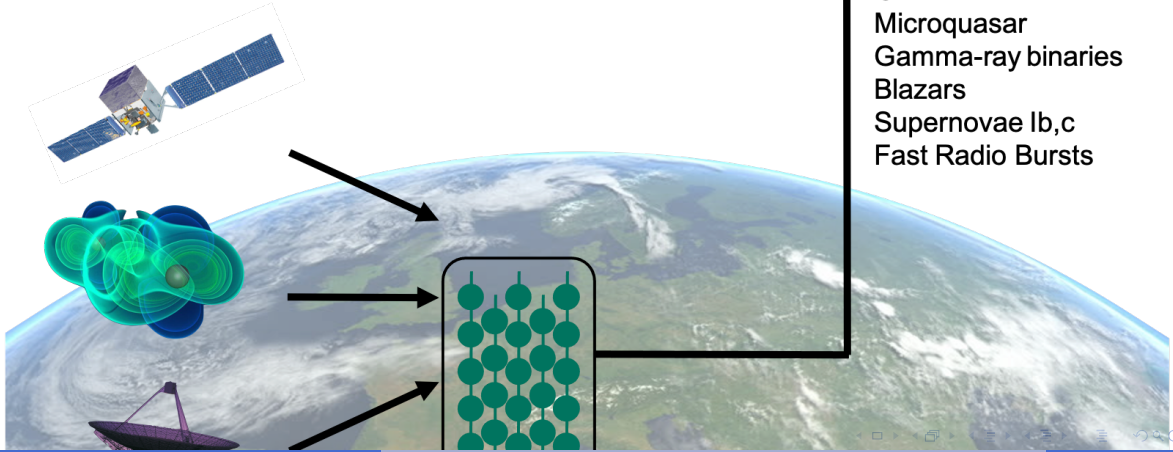
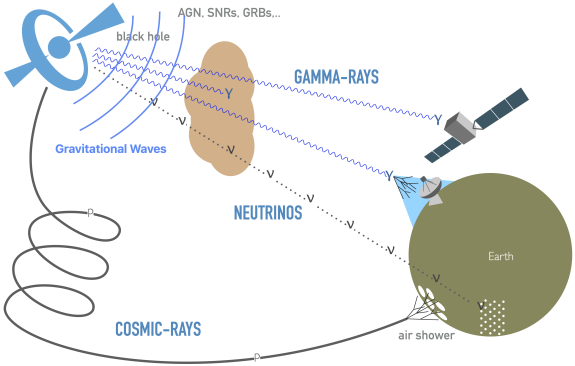
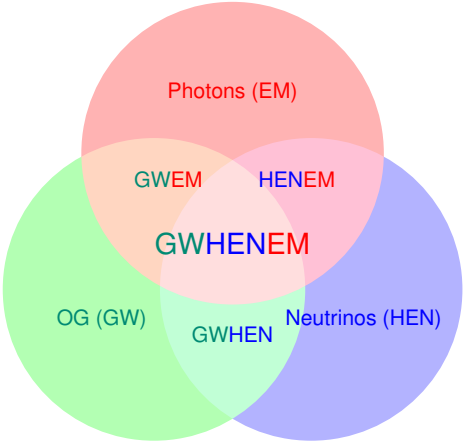


Quick re-introduction

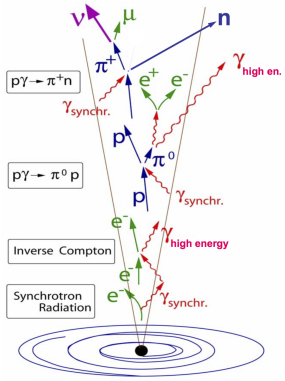


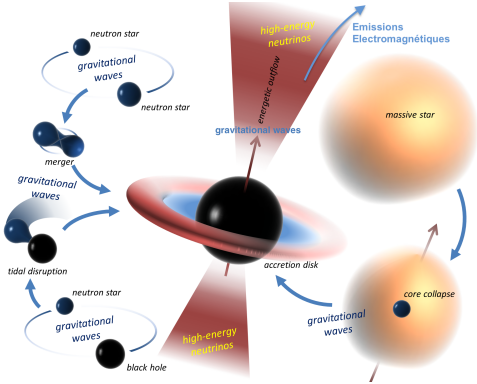


MultiMessenger Astronomy

Using multiples *messengers* : photons, neutrinos, GW

Quick re-introduction





HE Neutrino Astronomy

- ν smoking gun of processes with Cosmic Rays
- Flux ν depends on content in protons, electrons...

Gravitational Astronomy

- $P \propto \text{asymetry}^2 \times \text{compacity}^2 \times \text{speed}^6$

$\Rightarrow$ Sources of HEN !

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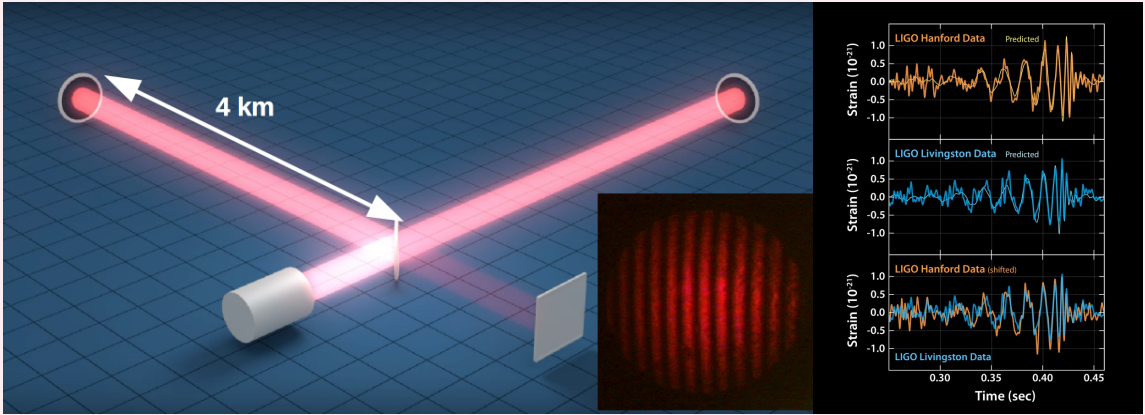
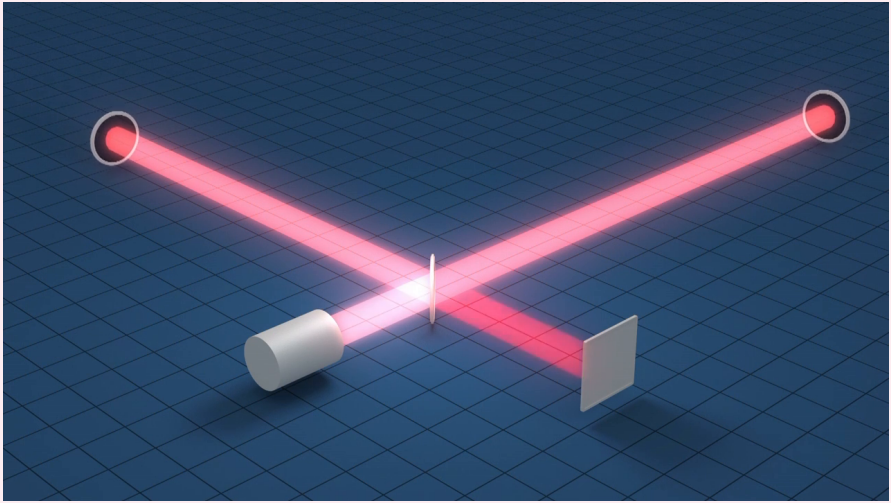
From an external trigger to neutrinos : Gravitational Waves

The LIGO/Virgo signals



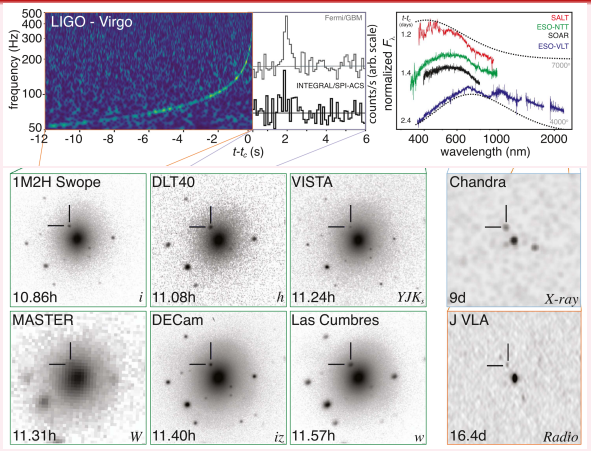
From an external trigger to neutrinos : Gravitational Waves

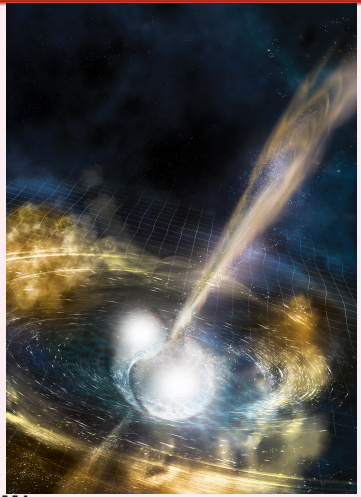
The LIGO/Virgo signals



From an external trigger to neutrinos : Gravitational Waves

The LIGO/Virgo signals

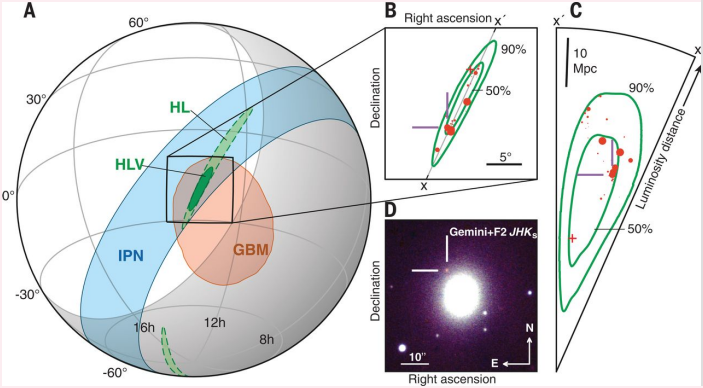


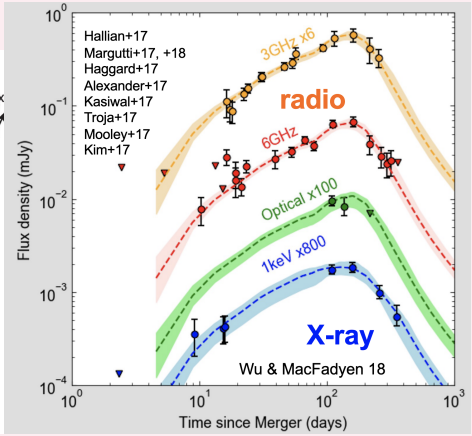


Multi-Messenger Astronomy GWEM !

From an external trigger to neutrinos : Gravitational Waves

The LIGO/Virgo signals

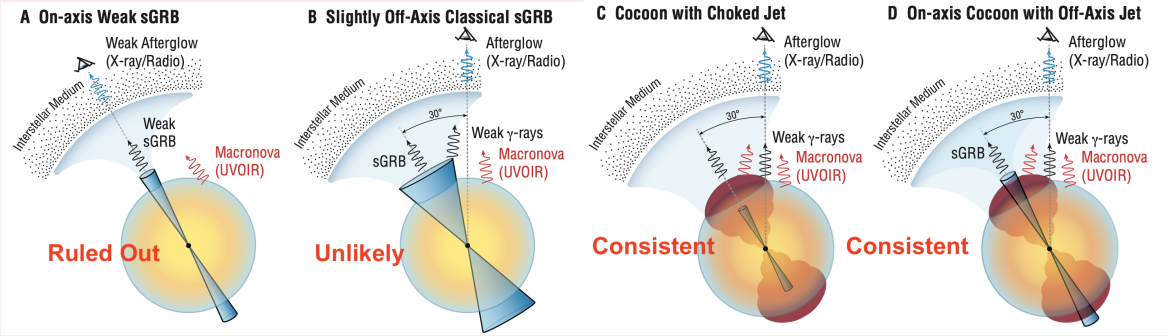




- $T_0 \xrightarrow{+2s}$ Short GRB 170817A $\xrightarrow{+5h}$ Localization at $(30°)^2$ at 42 Mpc $\xrightarrow{+6h}$ Optical counterpart AT2017gfo in NGC4993
- $T_0 \xrightarrow{+1.2d}$ Kilonova spectrum $\xrightarrow{+9d}$ X-ray $\xrightarrow{+16d}$ Radio

From an external trigger to neutrinos : Gravitational Waves

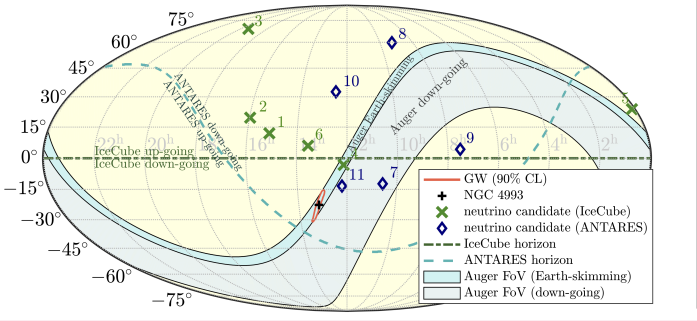
The LIGO/Virgo signals

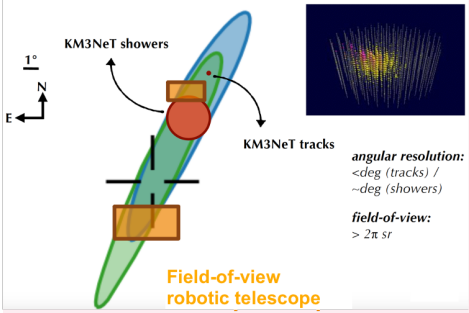


- Consistent picture emerges - off-axis jet

From an external trigger to neutrinos : Gravitational Waves

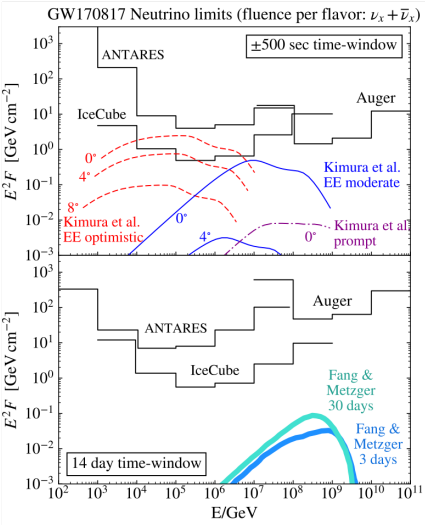
The LIGO/Virgo signals





- No HEN in coincidence with GW170817 ⇒ limits on emission/models

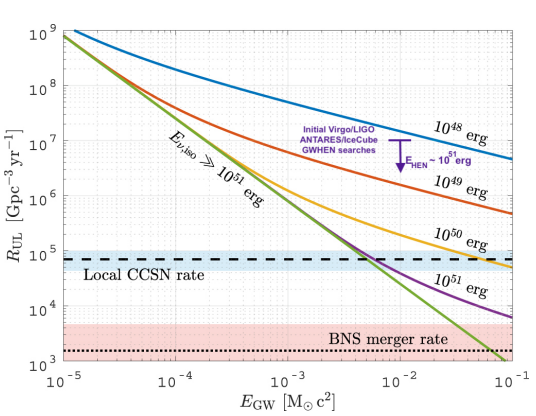
From an external trigger to neutrinos : Gravitational Waves

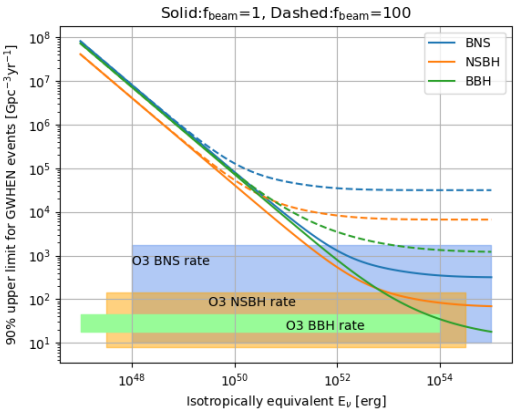


GWHEN analyses

- No prompt detection - consistent with off-axis
- Even in 14-day window

From an external trigger to neutrinos : Gravitational Waves



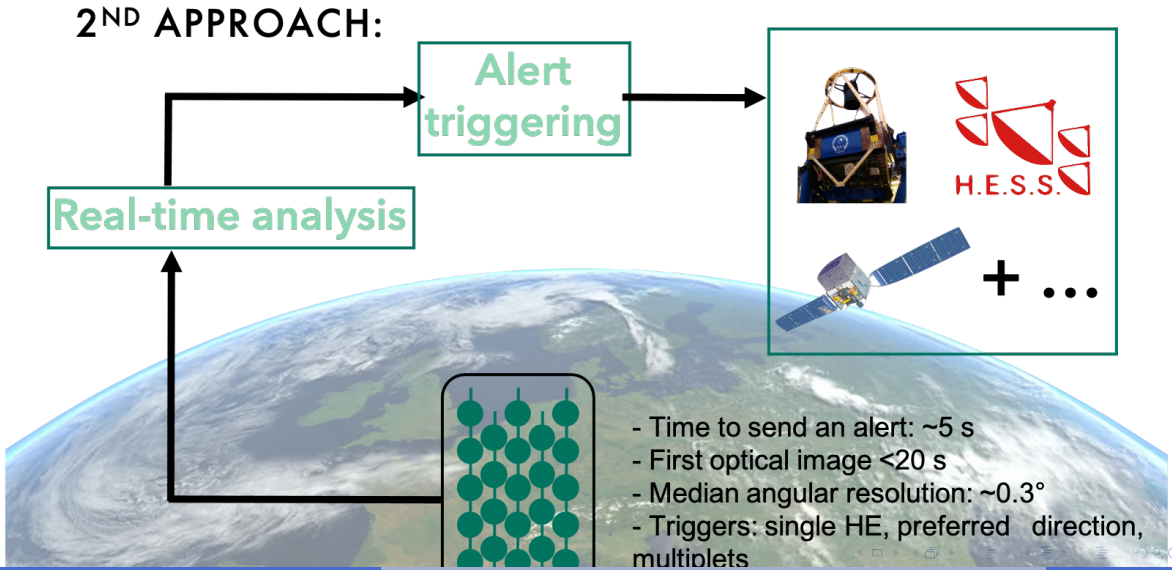


GWHEN analyses

- Combining all GW events detected
- Constrain population vs energy emitted in neutrinos

MultiMessenger Studies

2ND APPROACH:



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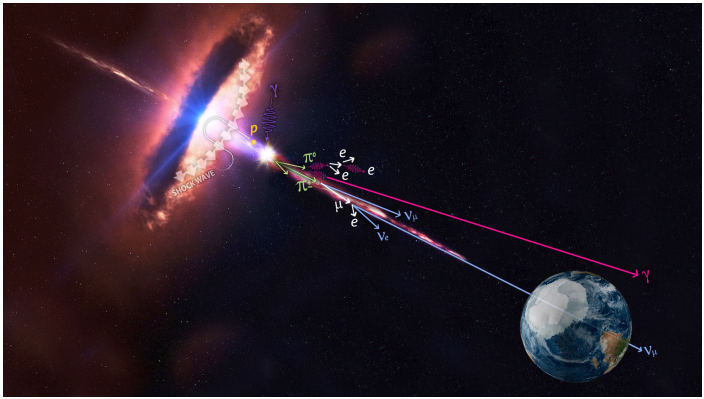
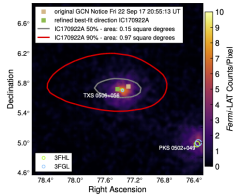
IceCube and Blazars







2017 - Connection established between Photons & Neutrinos (HENEM)...

...thanks to Blazar TXS0506+056 (Fermi-LAT, MAGIC)

IceCube and Blazars

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

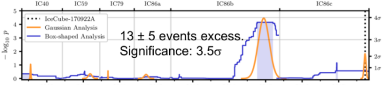
NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

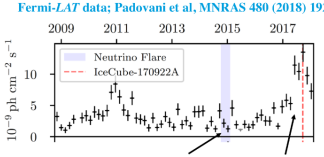
IceCube Collaboration*†

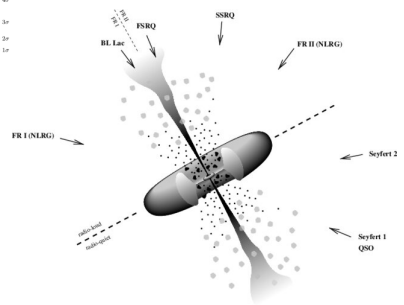
IceCube and Blazars

2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

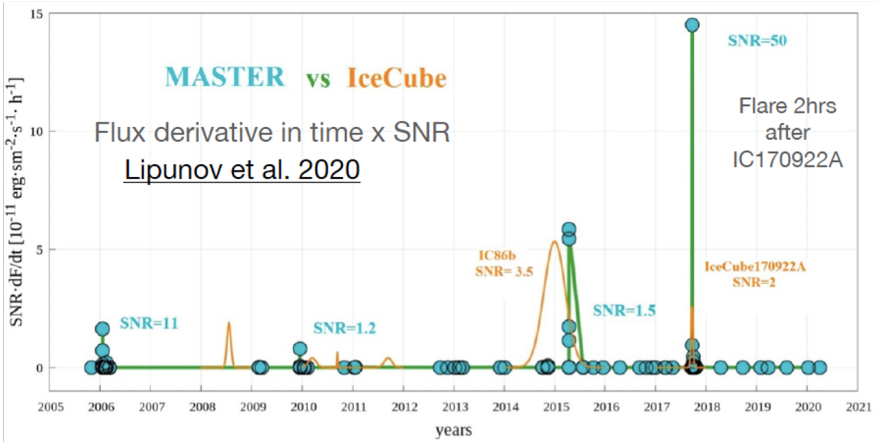




Previous flare detected

- Flat-spectrum-radio quasars - Optical/UV spectrum with broad emission lines
- BL Lacertae - featureless optical/UV spectrum

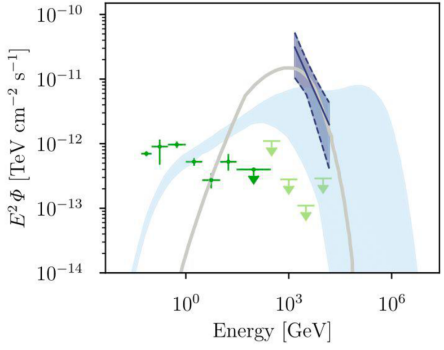
IceCube and Blazars



Optical flare detected from TXS0506+056

- Blazar in off-state 1 minute after the HEN
- Switched to on-state 2 hours after the event

IceCube and Blazars



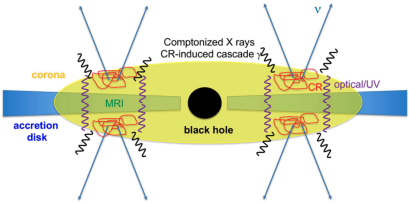


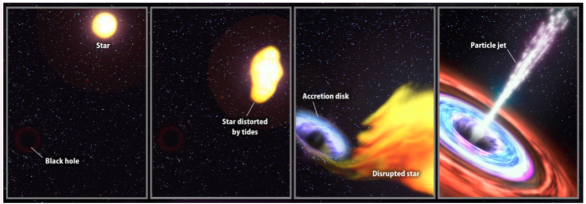
FIG. 1: Schematic picture of the AGN disk-corona scenario. Protons are accelerated by plasma turbulence generated in the coronae, and produce high-energy neutrinos and cascaded gamma rays via interactions with matter and radiation.

Coming back to NGC 1068

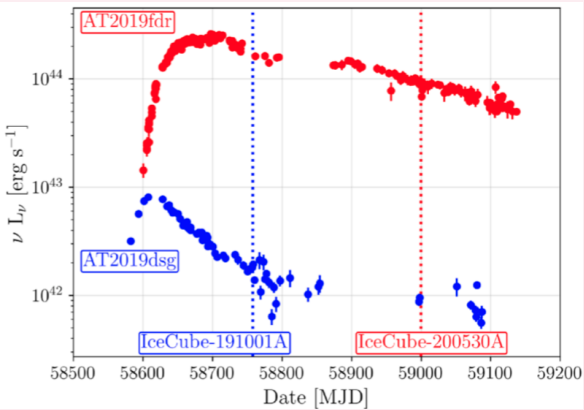
- No gamma-rays from π^0 - suppressed by high matter density
- Requires production within 100 Schwartzschild radii of the central black hole (Murase 2020, Yinoue 2020)

Electromagnetic followup of HEN alerts

Tidal Disruption Events (TDE) & possible neutrinos



Credit: NASA

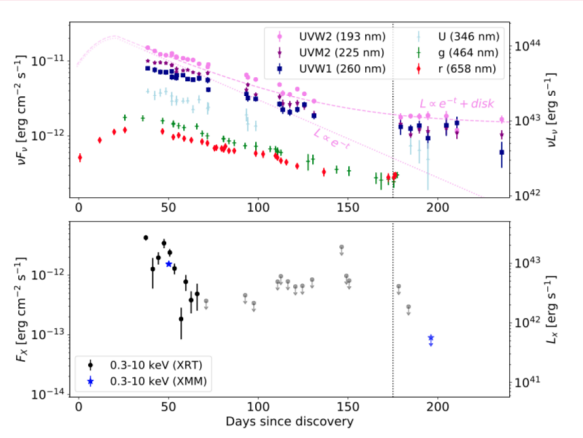


A tidal disruption event coincident with a high-energy neutrino (R. Stein et al, Nature 2021)

Neutrinos from tidal disruption events (R. Stein, 12/2020)

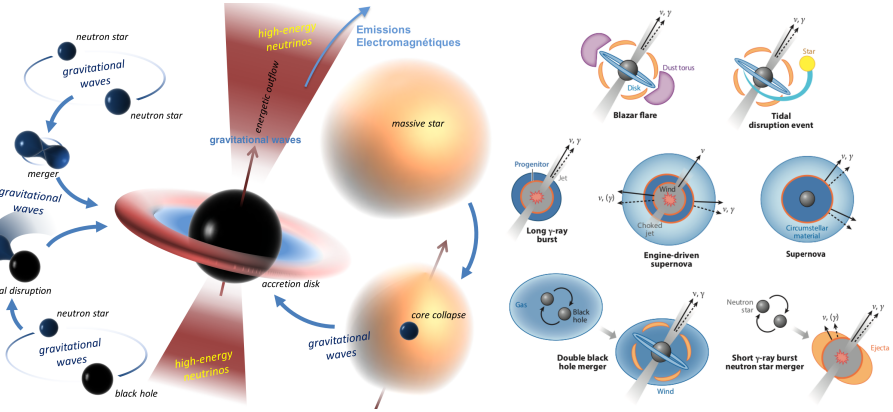
Electromagnetic followup of HEN alerts

Tidal Disruption Events (TDE) & possible neutrinos



A tidal disruption event coincident with a high-energy neutrino (R. Stein et al, 2021)

Electromagnetic followup of HEN alerts



Lexicon

- GRB = Gamma-Ray Burst
- AGN = Active Galactic Nucleus (Blazar)
- TDE = Tidal Disruption Event

Understanding Cosmic Radiations at IPHC

- Connect Collapse/Merger to Jet production : **GWHEN** [GW - Gravitational Waves / HEN - High Energy Neutrinos]
- Connect Jet dynamics to HEN production : **HENEM** - [HEN / EM - ElectroMagnetic (Radio → γ)]

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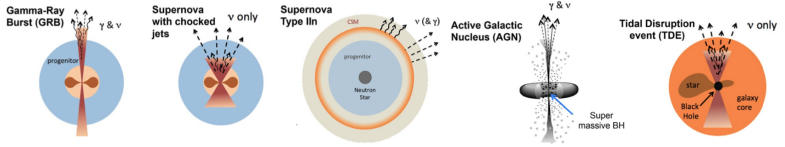
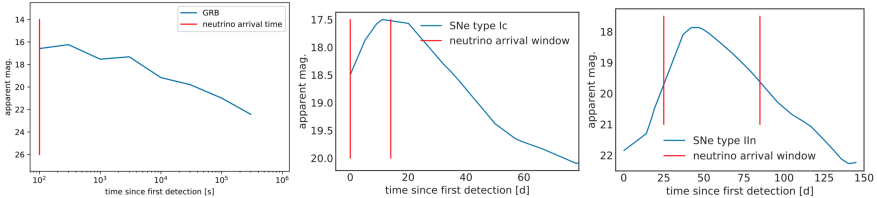


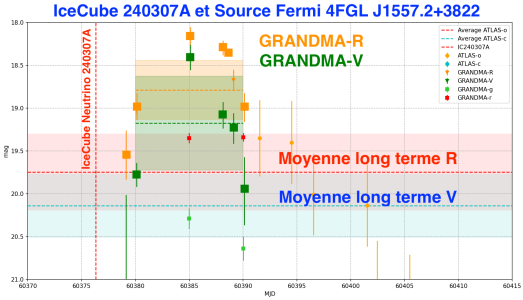
...and of the signals

- Short duration - **GRB-like** - falling lightcurve, few hours - **GWHENEM** - GW burst or merger signal
- Medium duration - **SNIc, Kilonova** - few weeks - **GWHENEM** - GW burst or merger signal
- Long duration - **SNIIn**, **TDE, AGN** - few months - **HENEM** - GW burst signal



Electromagnetic followup of HEN alerts



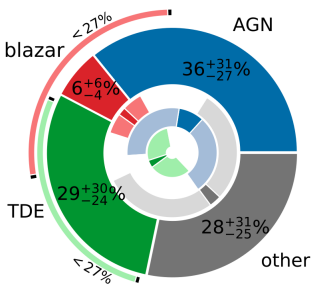


Disentangle Signal from Background

- Rapid followup to identify possible transient counterparts
- Tricky to establish whether or not a flaring blazar is the actual source !
- GRANDMA = network of robotic/human-operated telescopes around the world for the followup of GW / HEN alerts

Electromagnetic followup of HEN alerts

source class	local density [$\mathrm{Mpc^{-3}\,(yr^{-1})}$]	min. dist. [Mpc]	limit	source energy [erg]	max. fluence [$\mathrm{GeV^{-1}\,cm^{-2}}$]
long GRBs	4×10^{-10}	470	< 1% (stacked)	$< 6 \times 10^{51}$	$< 4 \times 10^{-3}$
short GRBs	3×10^{-9}	220	< 32% (OFU)	$< 3 \times 10^{52}$	$< 9 \times 10^{-2}$
llGRBs	1.6×10^{-7}	64	< 100% (flux)	$< 1.5 \times 10^{51}$	$< 6 \times 10^{-2}$
SNe Ic broad.	1.4×10^{-6}	30	< 100% (flux)	$< 2 \times 10^{50}$	$< 4 \times 10^{-2}$
SNe IIn	4×10^{-6}	20	< 66% (stacked)	$< 4 \times 10^{49}$	$< 1.4 \times 10^{-2}$
SNe Ib/c	1.7×10^{-5}	12	< 32% (stacked)	$< 5 \times 10^{48}$	$< 5 \times 10^{-3}$
CCSNe	7×10^{-5}	8	< 100% (flux)	$< 4 \times 10^{48}$	$< 8 \times 10^{-3}$
FSRQs	6×10^{-10}	1 000	< 17% (EHE)	$< 1.6 \times 10^{53}$	$< 3 \times 10^{-2}$
BL Lac objects	2×10^{-7}	120	< 25% (EHE)	$< 3 \times 10^{51}$	$< 2.5 \times 10^{-2}$
all AGN	10^{-3}	7	< 100% (flux)	$< 3 \times 10^{46}$	$< 8 \times 10^{-5}$
jetted TDEs	3×10^{-11}	1 000	< 100% (flux)	$< 10^{54}$	$< 1.4 \times 10^{-1}$
galaxy cluster	5×10^{-6}	40	< 100% (flux)	$< 3 \times 10^{50}$	$< 3 \times 10^{-2}$
starburst gal.	3×10^{-5}	22	< 100% (flux)	$< 2 \times 10^{49}$	$< 2 \times 10^{-3}$

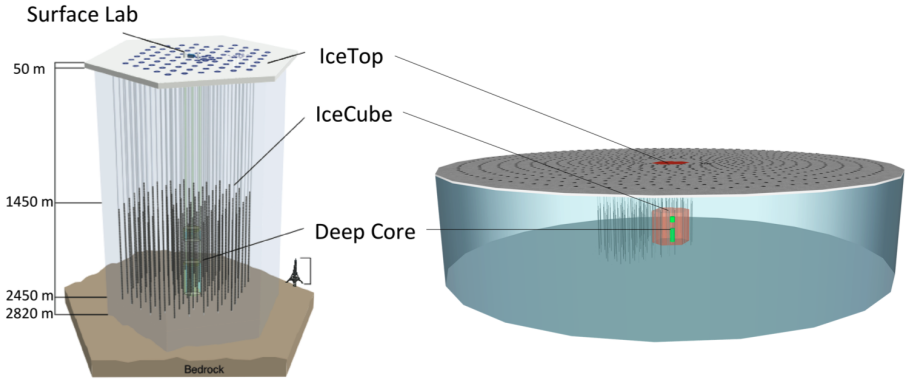


N. L. Strotjohann, PhD, https ://edoc.hu-berlin.de/handle/18452/21791

What are the sources of high energy neutrinos

- Short duration - GRB-like - **GRBs disfavored as HEN sources** precursor/prompt/afterglow
- Medium duration - SNIc, Kilonova - **mostly unconstrained**
- Long duration - SNIIn, TDE, AGN - **constrained**
- A good fraction of the diffuse flux is unknown ?

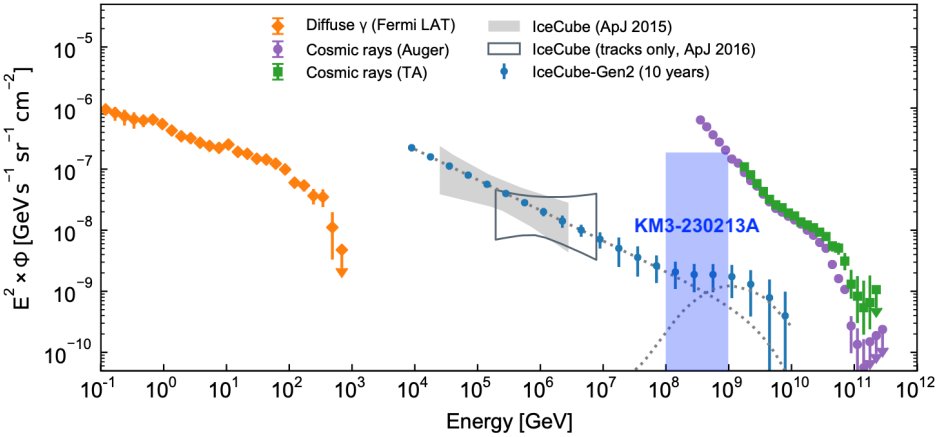
Future with IceCube...and KM3NeT



IceCube-Gen2

- DeepCore + High-Energy extension
- From neutrino physics to high energy source characterization

Future with IceCube...and KM3NeT



IceCube-Gen2

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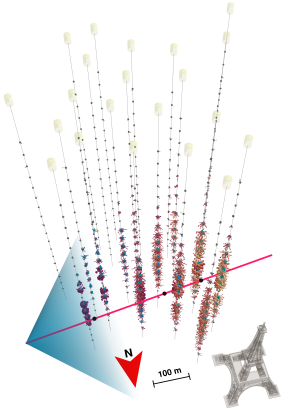
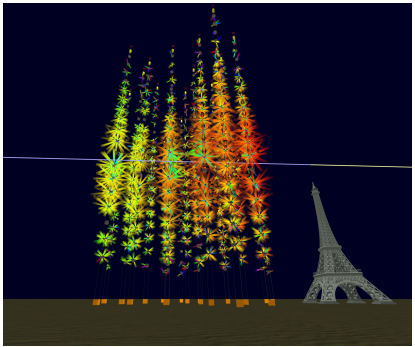
Neutrino Astrophysics - High Energies



1. Introduction : *Neutrinos and other messengers, Sources and Detection*
2. Neutrinos & Cosmic-Rays : *From γ to ν astrophysical fluxes*
3. Neutrino Telescopes : *from Neutrino Interactions to Detection*
4. IceCube and Antares : *Description and Selected Results*
5. MultiMessenger Astronomy : *combining all cosmic signals*
6. GRB GW170817
7. Blazar TXS0506+056
8. KM3-230213A
9. Perspectives : from KM3NeT to the unknown ?

KM3-230213A - the highest energy neutrino so far

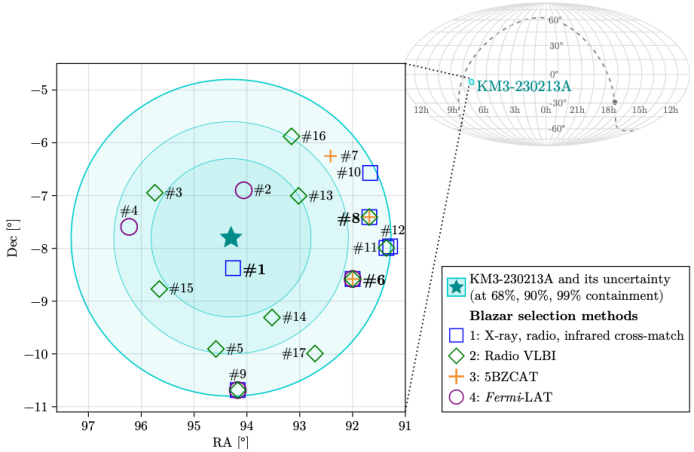




KM3-230213A

- Almost horizontal muon track $\sim 0.6^\circ$ above the horizon
- Unlikely for atmospheric muons to travel through that much water/ground (∼140 km)
- 35% of all detector was illuminated $\Rightarrow E_\mu = 120^{1+10}_{-60}$ PeV $\Rightarrow E_\nu = 220^{+570}_{-100}$ PeV

KM3-230213A - the highest energy neutrino so far

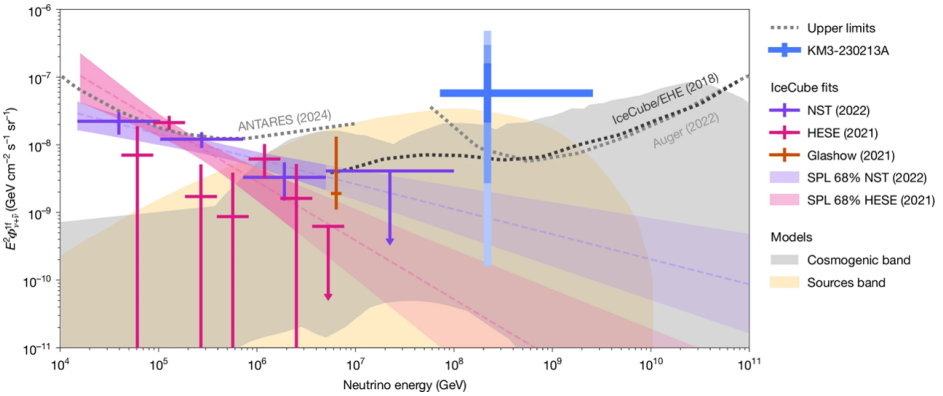


KM3-230213A

- No obvious association with an astrophysical source (yet)

→ More information on this exceptional event

KM3-230213A - the highest energy neutrino so far



KM3-230213A

- Possibly cosmogenic origin - to be investigated further

→ More information on this exceptional event

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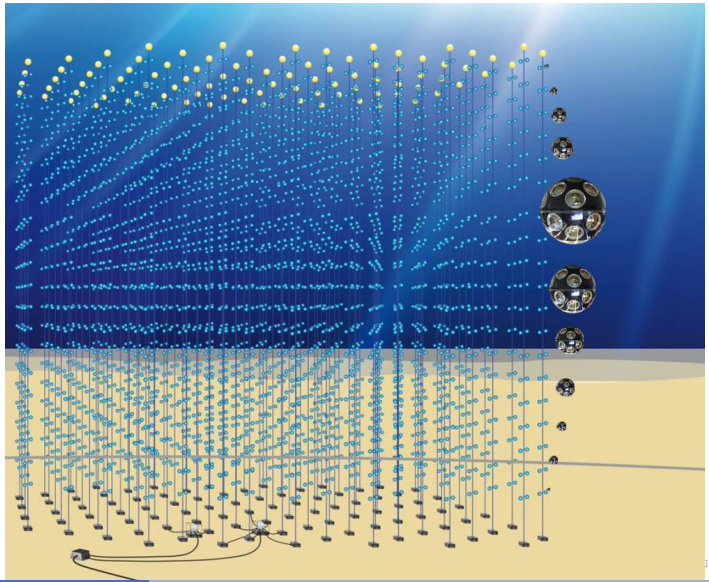
High-Energy Neutrinos :

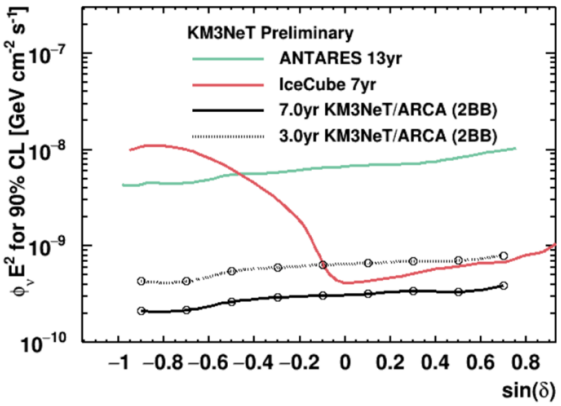
Perspectives...

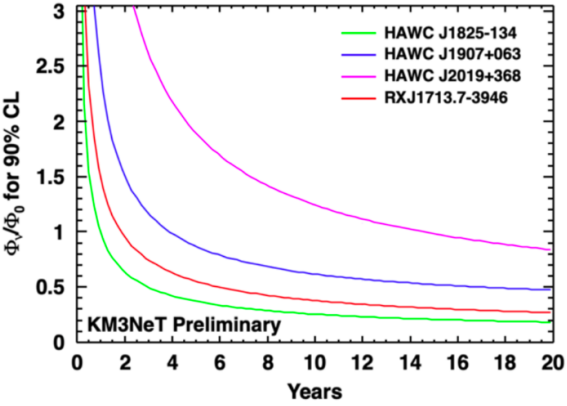


The new Mediterranean HEN Telescope : KM3NeT



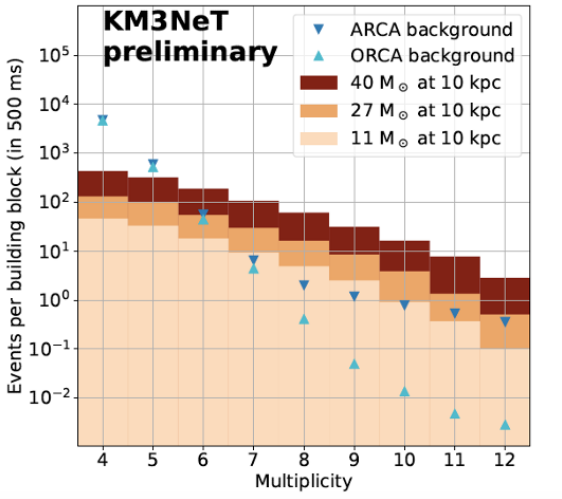
The new Mediterranean HEN Telescope : KM3NeT

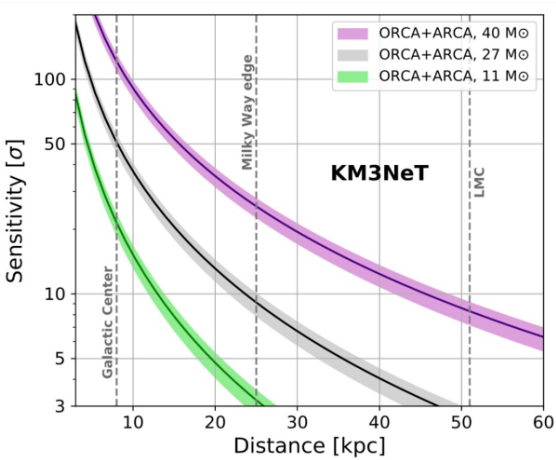




Ability to study extragalactic/galactic sources with ARCA

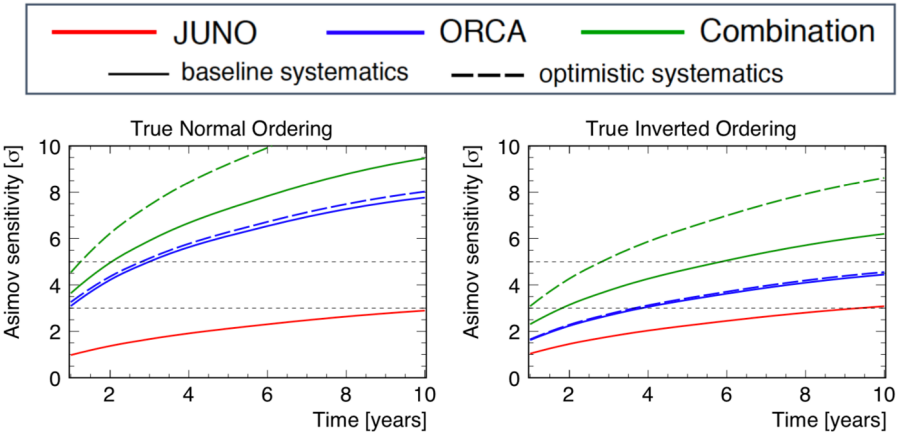
The new Mediterranean HEN Telescope : KM3NeT





Supernova Monitoring with low energy neutrinos in ORCA/ARCA

The new Mediterranean HEN Telescope : KM3NeT



Determination of Neutrino Mass Ordering with ORCA (+ JUNO JHEP 2022)

Fundamental Physics at High Energy



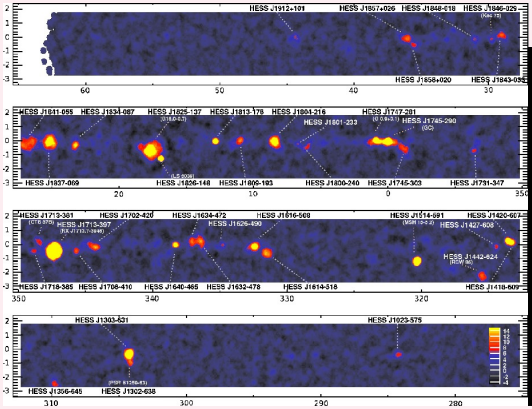
- Quantum Gravity : $c^2 p^2 = E^2 \left[1 + \xi \left(\frac{E}{E_{QG}} \right) + \mathcal{O} \left(\frac{E^2}{E_{QG}^2} \right) + \dots \right]$

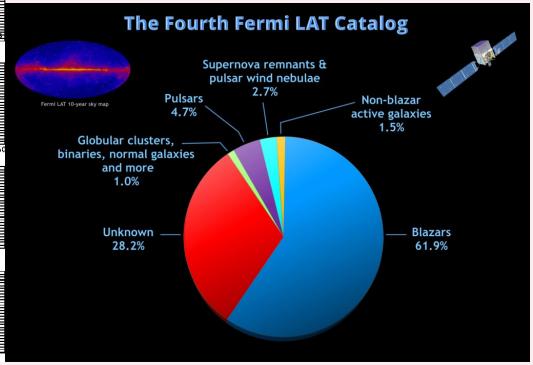
  $\Rightarrow \; |\Delta t_{QG}| \simeq 0.15 ms \left(\frac{d}{10\ kpc} \right) \left(\frac{E_\nu^{HE}}{1\ TeV} \right) \left(\frac{10^{19}\ GeV}{E_{QG}} \right)$ for $z \ll 1$

  *S. Choubey & S. F. King - Phys. Rev. D **67**, 073005 (2003)*

Expect the Unexpected...

Some surprises perhaps... ?





- New instruments bring new sources - new sources discovered daily
- Neutrino Astronomy $\approx \gamma$-ray astronomy 20...or 30 ? years ago !

Expect the Unexpected...

Some surprises perhaps... ?

Instrument	User	Date	Intended Use	Actual Use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio Galaxies
MW	Penzias, Wilson	1965	Radio-Galaxies	3K CMB
X-Ray	Giacconi	1965	Sun, Moon	Neutron Stars Binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	Military	1960	Nuclear Tests	GRBs
ν	Davis, Koshiba...	'50-'00	Sun	ν Oscillations SN1987A

Neutrino Telescopes

- detect atmospheric/cosmic neutrinos from GeV to PeV-EeV
- study the origin of cosmic-rays and their sources
- combine low energies and high energies, from fundamental physics to astrophysics !

Expect the Unexpected...

