High Energy Neutrino Astronomy
An introduction to Methods & Recent Results

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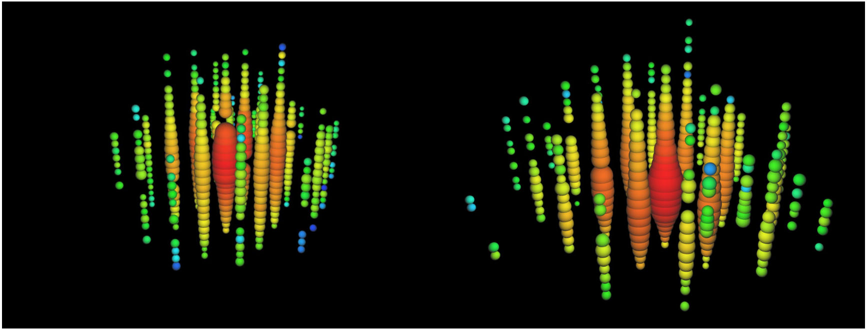
IceCube and PeV Neutrinos



May 2013

IceCube reports first evidence for extraterrestrial high-energy neutrinos

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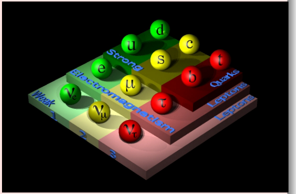
Introduction : properties and history of neutrinos

Neutrino Properties

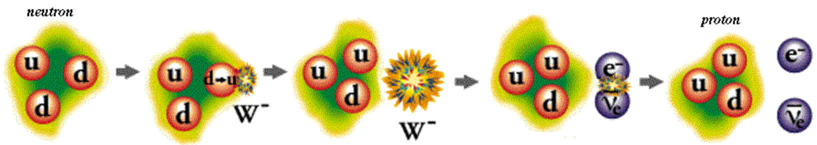
- Fermion
- Weak Interactions : exchange of W, Z
  - $\Rightarrow$ **escapes dense regions**
- Elementary particle : no decay
- Mass close to zero
  - $\Rightarrow$ **velocity** c
- Neutral particle
  - $\Rightarrow$ **no effect of magnetic fields**



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.*

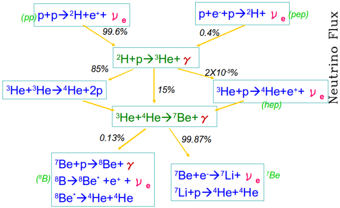


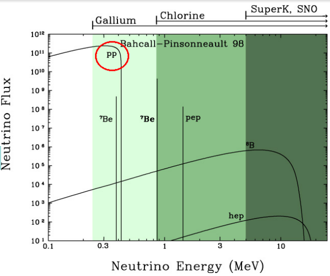
- 1933 : Fermi develops the theory of the little neutron (neutrino), discovered in 1932 by Chadwick
- 1953 : **Experimental observation** at Savannah River (Reines & Cowan) through $\bar{\nu} + p \rightarrow e^+ + n$

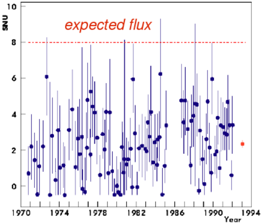
An introduction to Neutrino Astronomy

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

A brief history of neutrinos...

- 1968 : Solar Neutrinos observed at Homestake (Davis) - only the third of expectations...
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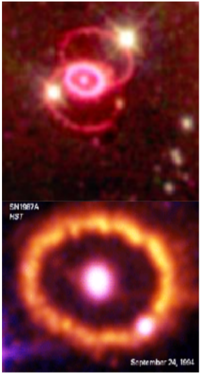
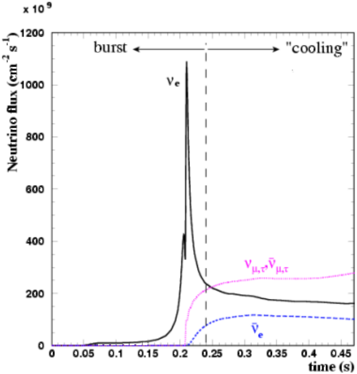
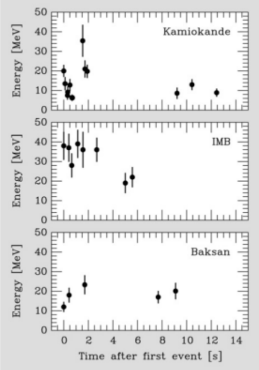
An introduction to Neutrino Astronomy





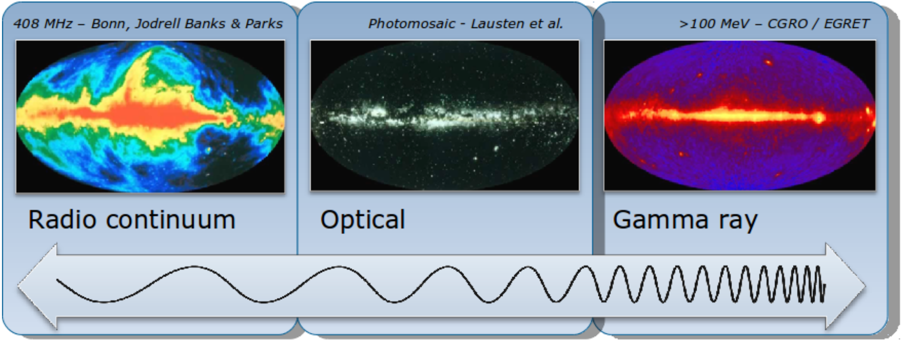


⇒ Birth of Neutrino Astronomy (1987) !

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

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

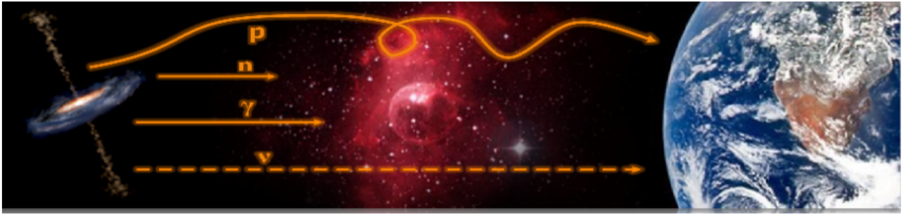
Neutrinos as Cosmic Messengers...



What about neutrinos...?

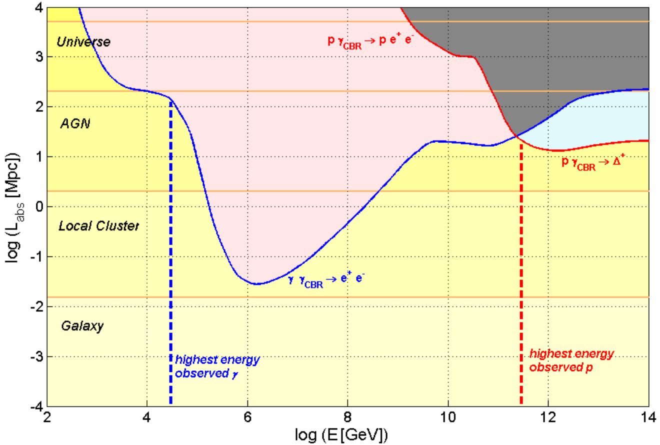
- If $E_\nu \approx 10 GeV - 10^2 EeV$, same span as Radio to X-rays !

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**...

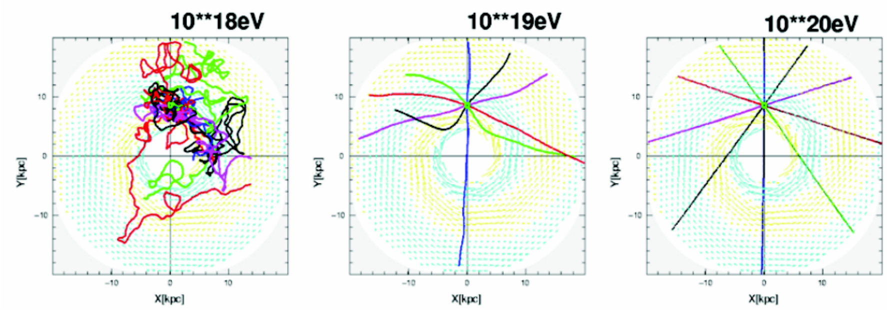
Neutrinos as Cosmic Messengers...



Compute a mean free path ?

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

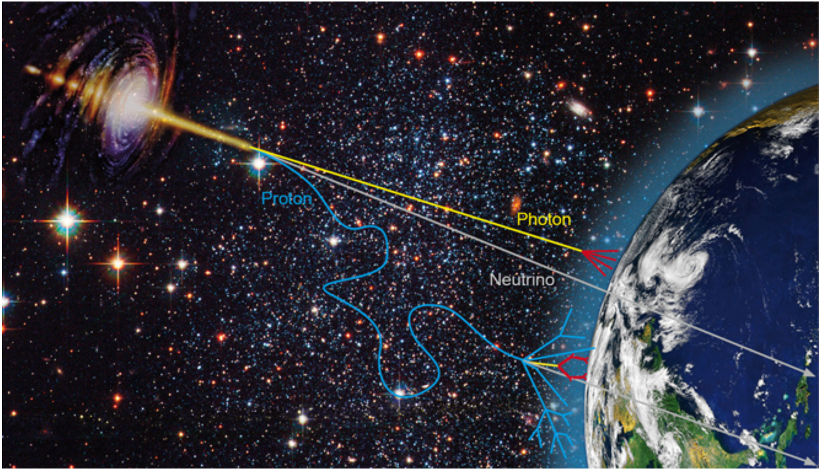
Neutrinos as Cosmic Messengers...



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 ?

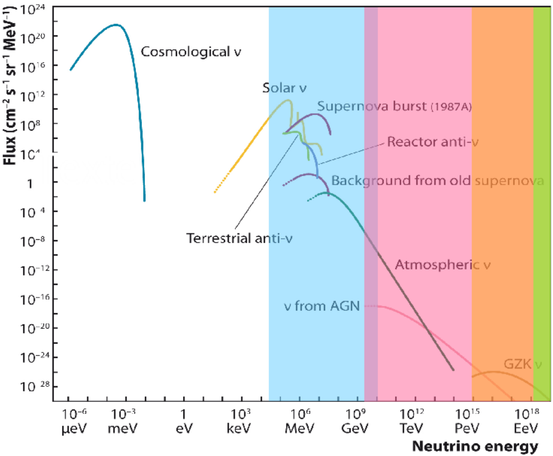
- **Requires large volume of detection...**

Sources of neutrinos...

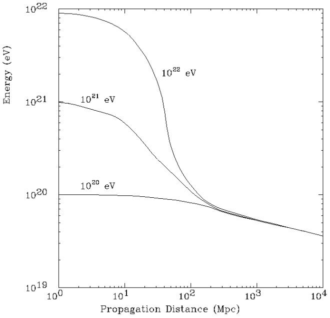
- Under rock
- Under water/ice
- Acoustics/Radio
- Giant Air Shower

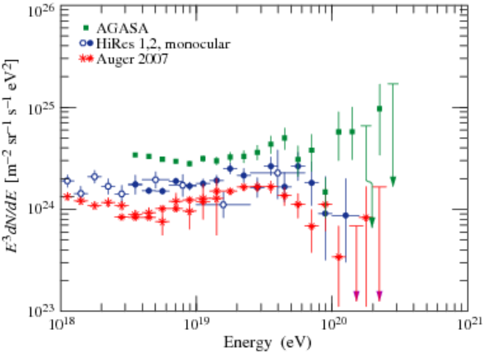
How many ?

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



The far end of the spectrum...

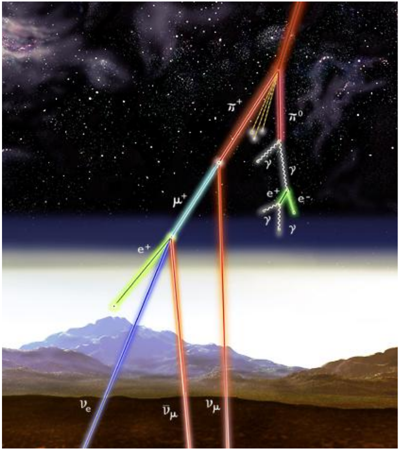


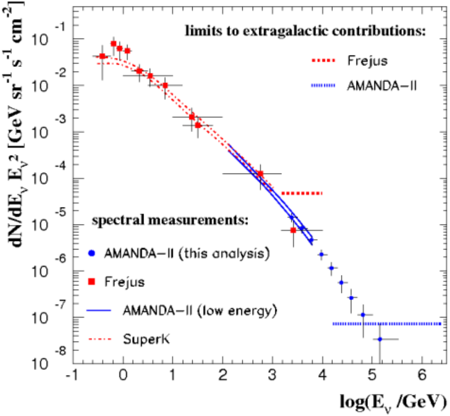


Guaranteed source of UHE neutrinos

- Threshold $\gamma_{\rm CMB} + p \to \Delta \to \pi + N \approx 10^{20} eV$
- Flux : less than $100/km^2/yr$!
- See Lectures on Charged CR on Ground by T. Suomijärvi

Atmospheric neutrinos

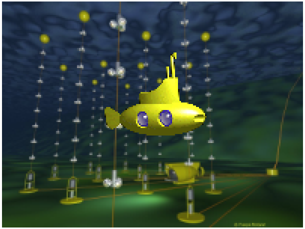




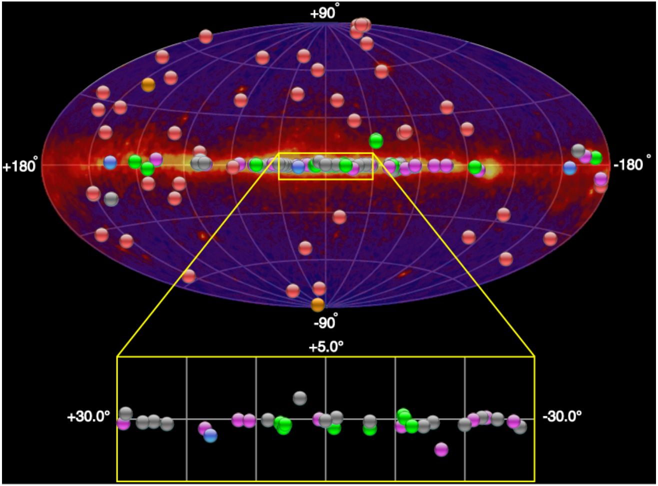
Background for detection of astrophysical neutrinos !

High-Energy Neutrinos :

The Cosmic-Ray Connection

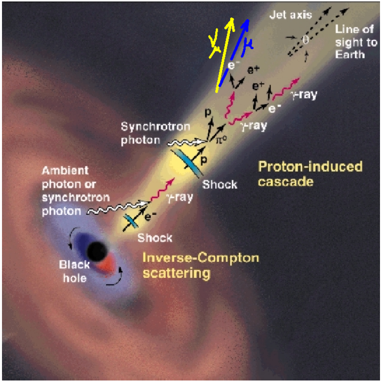


The TeV Gamma-Ray Sky

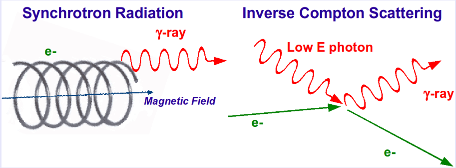


from TeV Gamma-Ray Catalog

The Cosmic-Ray Connection

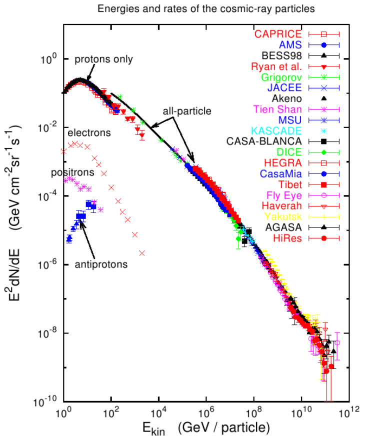


Leptonic Production of HE γ :



Hadronic Production of HE γ/CRs :

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



Hillas 2006, arXiv :astro-ph/0607109

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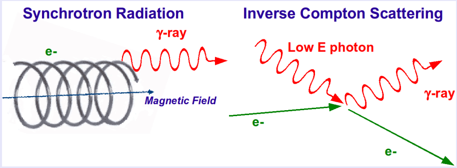
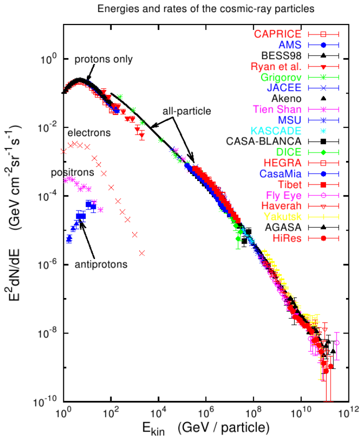


Hadronic Production of HE γ/CRs :

$$p/A + p/\gamma \longrightarrow \pi^0 \quad \pi^\pm$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^\pm \rightarrow \mu \; \nu_\mu, \quad \mu \rightarrow \nu_\mu \nu_e e$$

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



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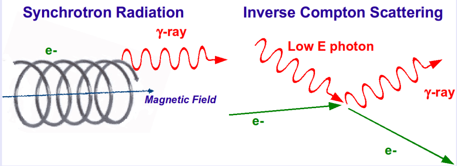

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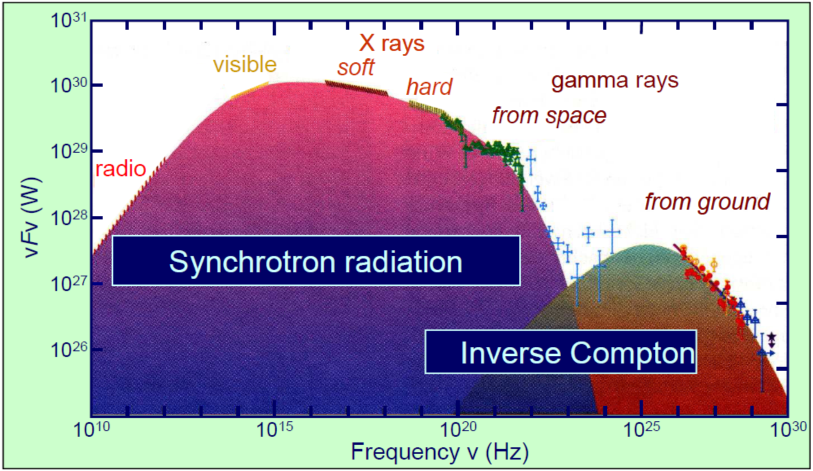
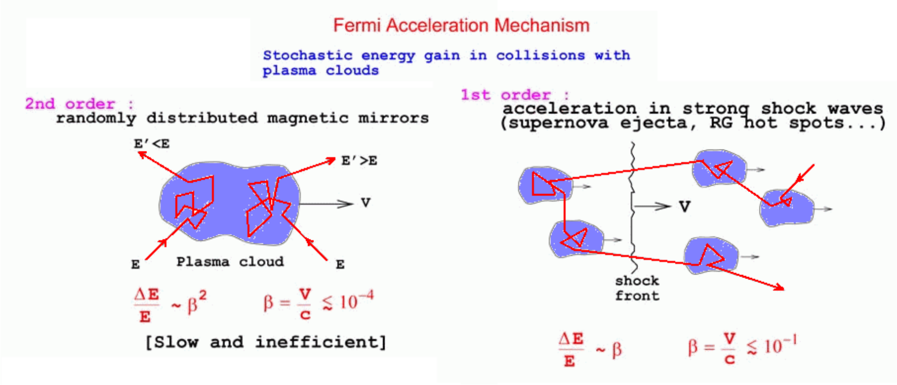
See Lectures on γ **and charged cosmic-rays**

The Cosmic-Ray Connection



Multi-wavelength/messenger analysis $\Rightarrow$ Modelling of the source

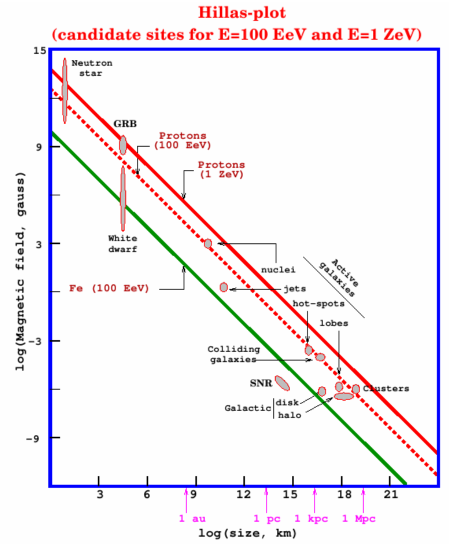
Fermi processes for Acceleration



Spectrum

- $\frac{dN}{dE} \propto E^{-\gamma}$, with $1.5 < \gamma < 2.5$
- See Lectures by **A. Marcowith**

Fermi processes for Acceleration



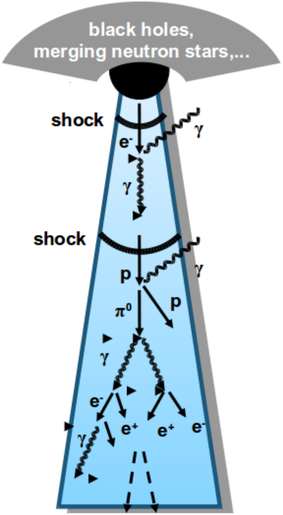
Maximum Energy

- Impose $L < R_L$
- $\Rightarrow E_{\max} \sim ZBL$ with L size of accelerating region
  - $\Rightarrow$ **Compact sources**
- Ultra-Relativistic shocks : $E_{\max} \sim \Gamma ZBL$

Leptonic/Hadronic ?

Leptonic scenario

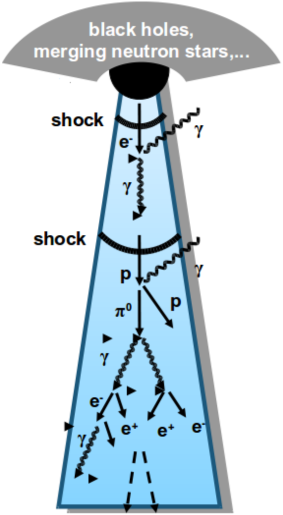
- $e-$ accelerated via Fermi mechanism
- X-Rays, observed, produced via synchrotron : $e^{\pm}\vec{B} \to e^{\pm}\gamma_X$
- HE γ-rays by Inverse Compton : $e^{\pm}\gamma_{\text{low E}} \to e^{\pm}\gamma_{\text{high E}}$
- **No neutrinos !**



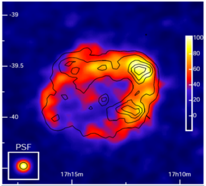
Leptonic/Hadronic ?

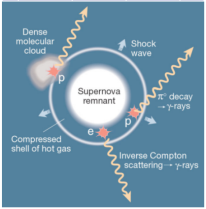
Hadronic scenario

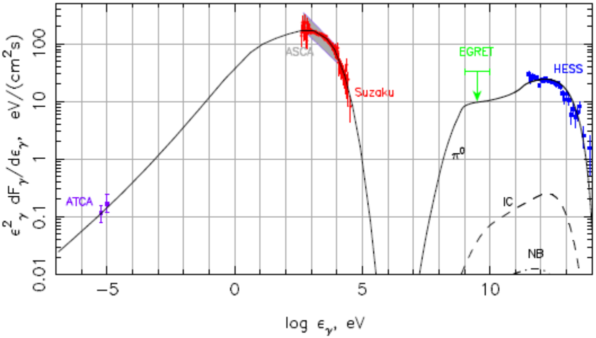
- Protons and Heavy nuclei (observed !) accelerated via Fermi mechanism
- Interaction with ambient photons :
  - $p + \gamma/A \to \Delta^+ \to \pi^0 + p$
  - $p + \gamma/A \to \Delta^+ \to \pi^+ + n$
- γ-rays via $\pi^0 \to \gamma\gamma$
- **Neutrinos via** $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$



A Hadronic origin for γ emission ?





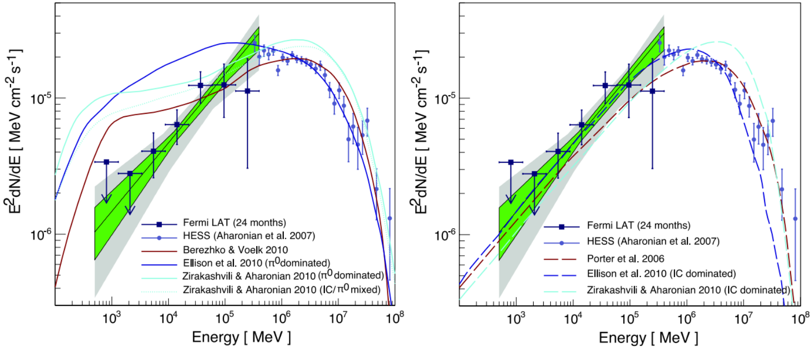


The case of RXJ 1713-3946

- Purely leptonic models not satisfactory
- Proton acceleration + beam dump on nearby molecular clouds ?

Berezhko & Völk, arXiv-08100988v2

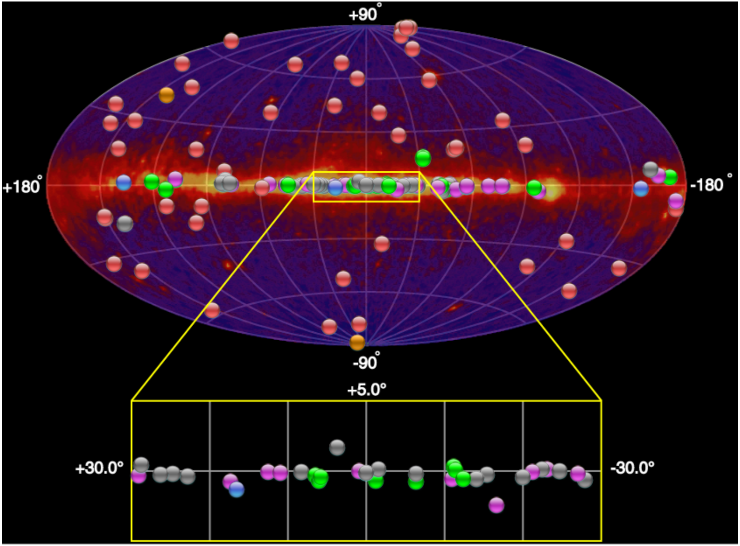
A Hadronic origin for γ emission ?



The case of RXJ 1713-3946 - Fermi observations

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

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 :

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

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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 $K_{p\gamma} = 4$
- $p\gamma \to \Delta \to \pi N : 2/3 p\pi^0, 1/3 n\pi^+$
- 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 $< x_{p\to\gamma} > \approx 0.2$

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

The TeV Gamma-Ray Sky

ν production at the source

- For *pp* collisions :

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

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

- For $p\gamma$ collisions :

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

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

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 :

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

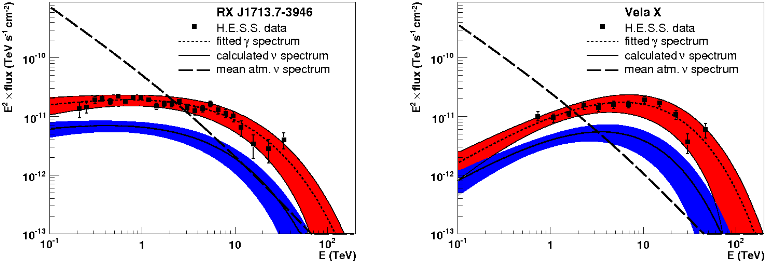
- After oscillations :

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

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

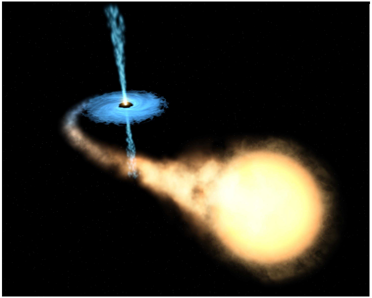
The TeV Gamma-Ray Sky

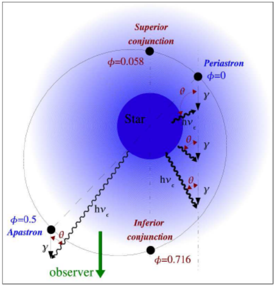
How to compute a ν Flux from γ-Ray Observations



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

In the Galaxy...

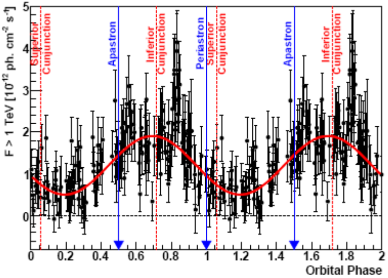


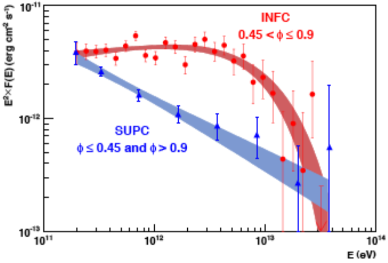


MicroQuasars

- 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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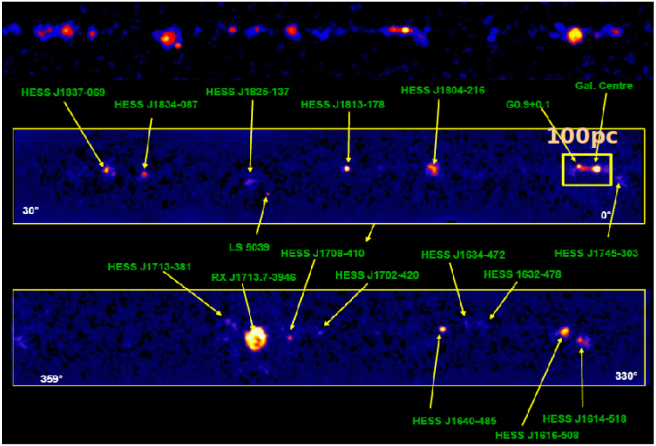
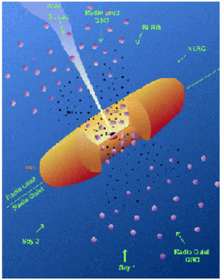
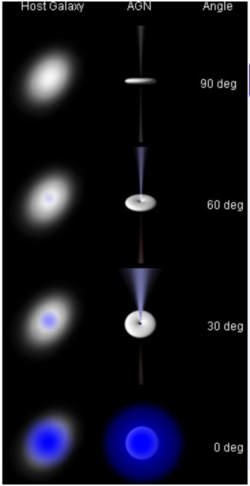


The Galactic Plane - visible with Antares !

- Lots of New Sources discovered by HESS

Active Galactic Nuclei...

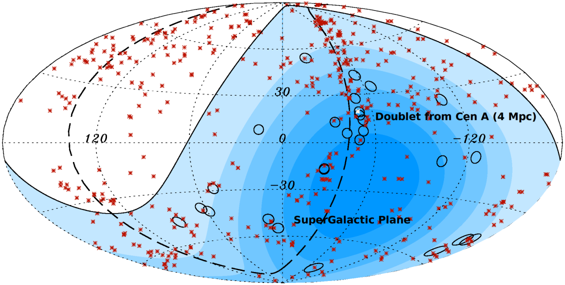




AGNs

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

Active Galactic Nuclei...



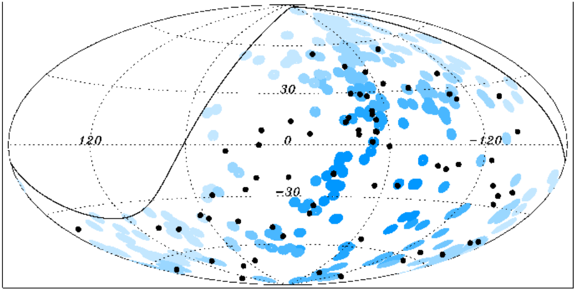
UHECRs and AGNs - 2007 Results

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

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

Auger Collab, Astroparticle Physics, Volume 34, Issue 5, p. 314-326 (2010)

Active Galactic Nuclei...



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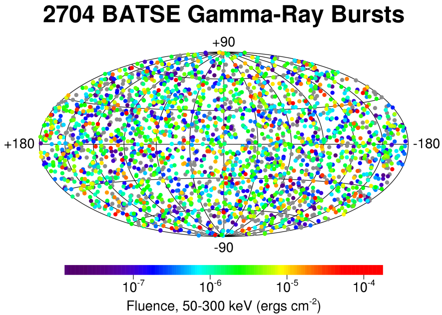
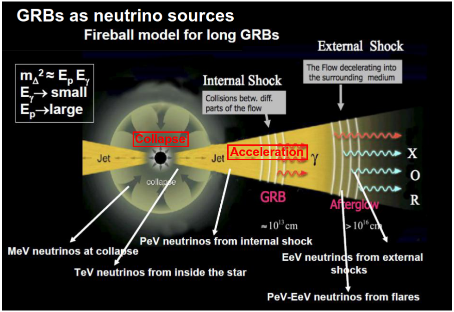
Gamma-Ray Bursters and Dark Bursters

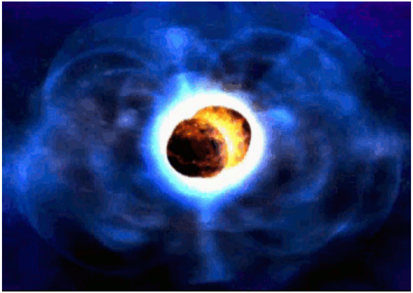


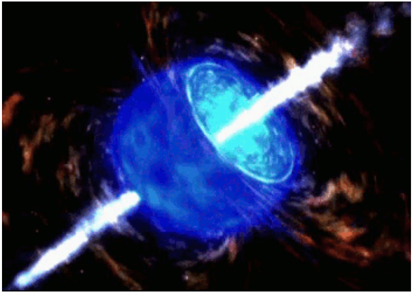


Gamma-Ray Bursts

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

Gamma-Ray Bursters and Dark Bursters





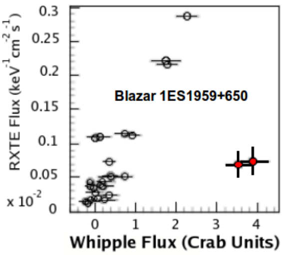
Short GRBs

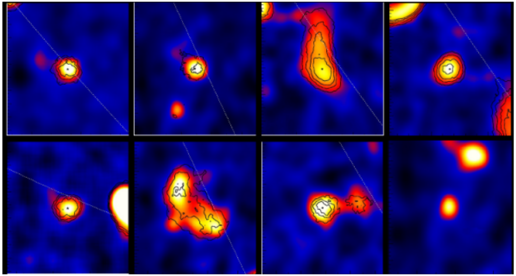
Binary Mergers : BH or NS

Long GRBs

Collapsars - massive star collapse

Gamma-Ray Bursters and Dark Bursters





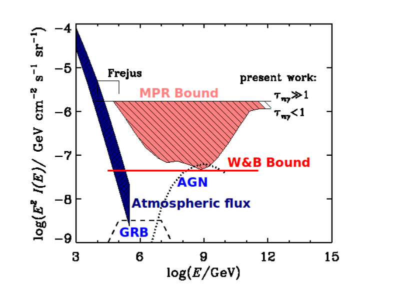
Dark Sources ?

- 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} :

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

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

- Neutrino luminosities : $E^2_\nu \Phi_\nu = \frac{c}{4\pi} E^2_\nu \frac{dN_\nu}{dE_\nu} = \frac{1}{2}\epsilon I_{max}$
- 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 $(1+z)E$

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

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

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

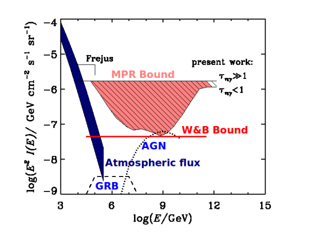
Upper Bounds on High Energy Neutrino Fluxes ?

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 : $\kappa \sim 0.1 cm^2/g$, $\rho \sim 10^{-3} g/cm^3$, $\tau \sim 10$

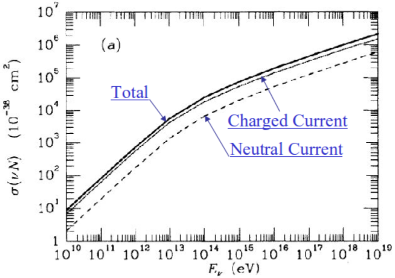
  $\Rightarrow$ No radiation, except outer layers and blackbody

Upper Bounds on High Energy Neutrino Fluxes ?

Bounds for extra-galactic sources

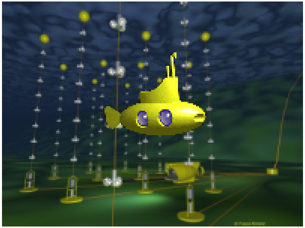
- Result : $E_\nu^2 \Phi_\nu \lesssim 10^{-8} GeV.cm^{-2}.s^{-1}.sr^{-1}$
- $\Phi_\gamma^{\mathrm{Crab}}(E > 1\,TeV) \approx 10^{-11} cm^{-2}.s^{-1}$...
- With a ν cross-section $\in 10^{-35} - 10^{-33} cm^2$ for $TeV - PeV$...

  $\Rightarrow$ **Needs large detection volumes !**

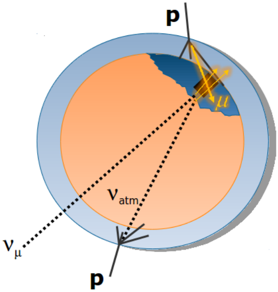


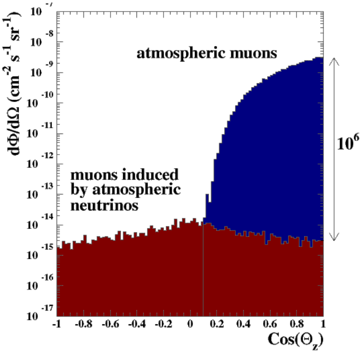
High-Energy Neutrinos :

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 $\nu_\mu + N \rightarrow \mu + X$ 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**

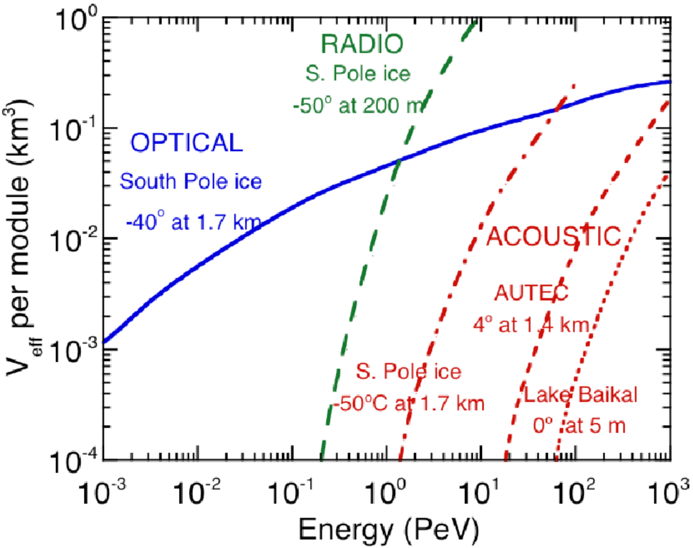
Detection of Cosmic Neutrinos

Optical Cherenkov		Atmospheric showers		Radio		Acoustic
In Ice	In water	Earth based	In space	Earth based	In space	
AMANDA B-10 AMANDA II IceCube	Baikal ANTARES NEMO NESTOR → KM3NeT	Auger	EUSO OWL	RICE GLUE SalSA CODALEMA ARIANNA	ANITA FORTE	SAUND SADCO (Greece) ANTARES R&D IceCube AUTEC AGAM

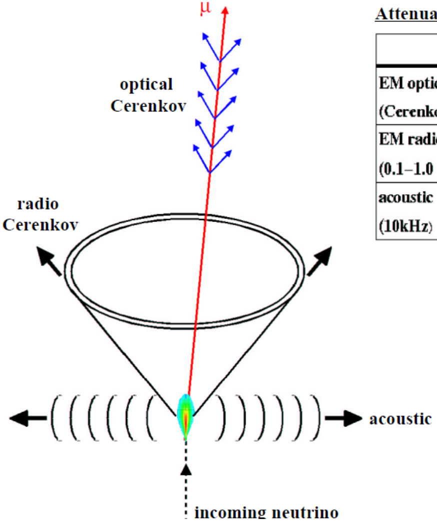
Lectures on CRs

E~TeV - PeV | ***E~ 1 - 10 EeV*** | ***E~EeV - ZeV***

Detection of Cosmic Neutrinos

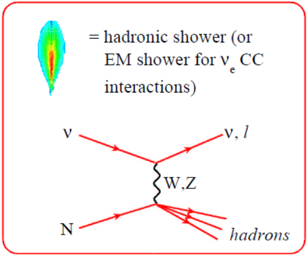


Acoustics and Radio



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)



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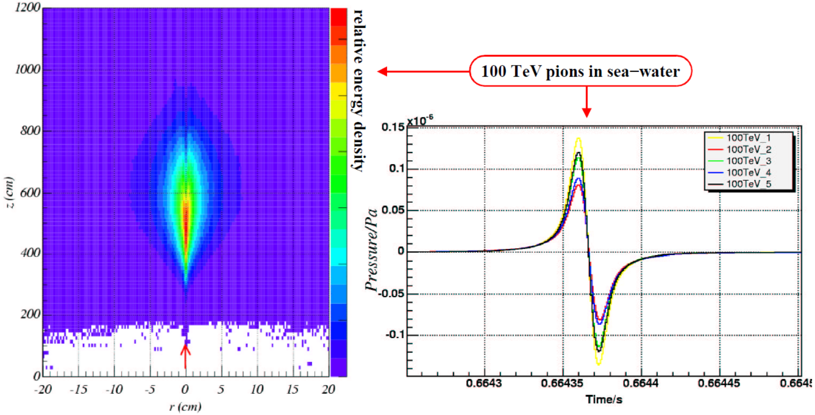
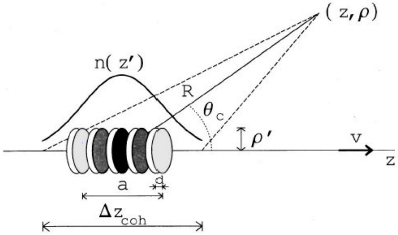
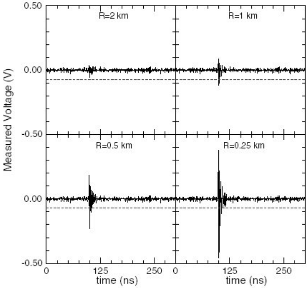


An Acoustic pulse

- R&D in Antares (Germany, Marseilles)

Acoustics and Radio





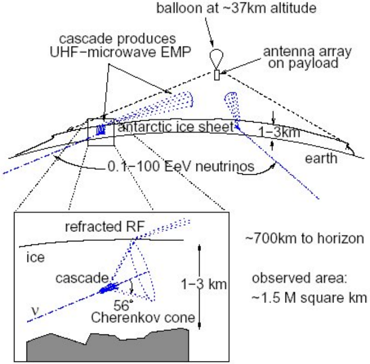
Askaryan Effect - used in Codalema, LOPES...

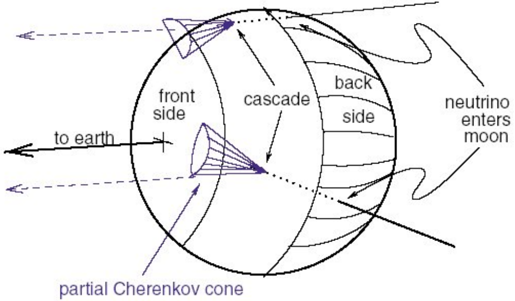
- Coherence length Δz along Oz axis of shower : fields arrive simultaneously at distance R if $\frac{dR}{dt} = v \cos\theta = \frac{c}{n}$
- But $\frac{dR}{dt}$ varies : $\frac{dR^2}{dt^2} = v^2 \frac{\sin^2\theta}{R^2}$
- Coherence implies $\Delta R = \frac{1}{2} \frac{v^2 \sin^2\theta}{R^2} \Delta t^2 < \lambda$
- $\Delta z_{\mathrm{coh}} = v \Delta t_{\mathrm{coh}} \approx \frac{\sqrt{\lambda R}}{\sin\theta}$

$\Rightarrow$ Optical domain : $\Delta z \ll a$, emitting zone around maximum

$\Rightarrow$ Radio domain : $\Delta z \gg a$

Acoustics and Radio





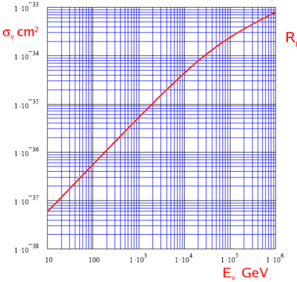
Askaryan Effect - used in Codalema, LOPES...

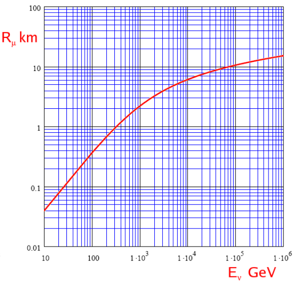
ANITA - GLUE

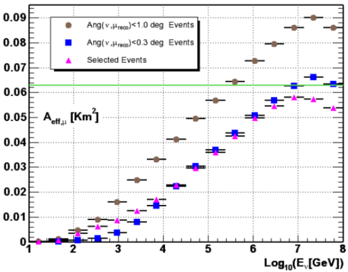
Optical Cherenokov : Event Rate & Detector Size

Luminosity needed for Event Rate N_ν

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







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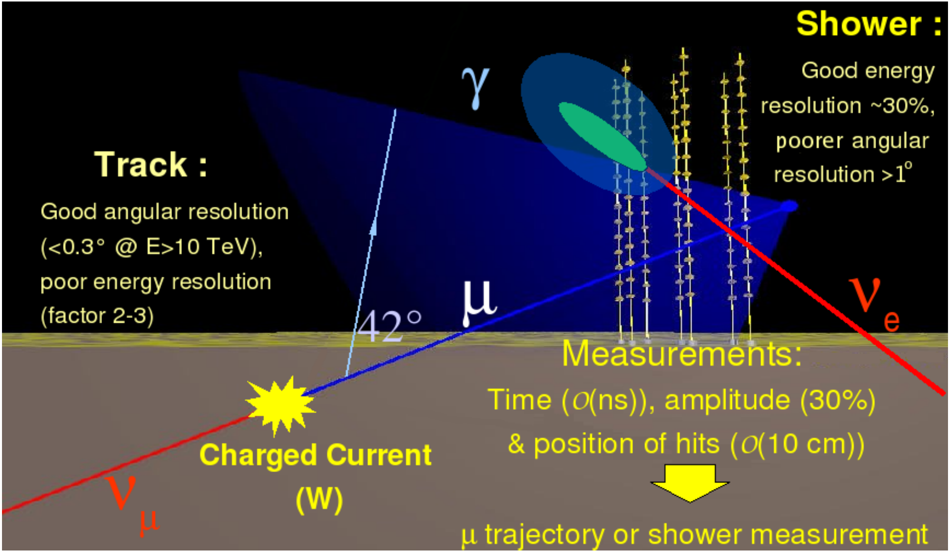
$$L_\nu = 4\pi d^2 \Phi_\nu \approx 10^{46} N_\nu \left(\frac{d}{4\,Gpc}\right)^2 \left(\frac{E_\nu}{100\,TeV}\right)^{1-\alpha} \left(\frac{A_\mu T}{km^2 yr}\right)^{-1} \text{erg/s}$$

- $\alpha \sim 1$ for $E_\nu < 100\,TeV$, $\alpha \sim 0.5$ 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 detection of cosmic neutrinos



Number of detected muons...

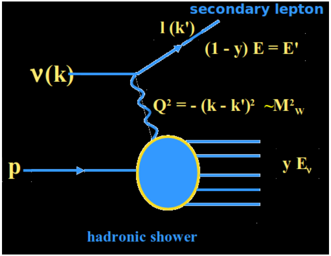
For area A and observation time T

- $N_\mu(\theta) = A.T.\int_{E_{\min}}^{E_\nu} \Phi_\nu(E_\nu,\theta) dE_\nu P_{\nu\to\mu} P_\oplus$
  - $\Rightarrow$ $\Phi_\nu(E_\nu,\theta)$ 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...

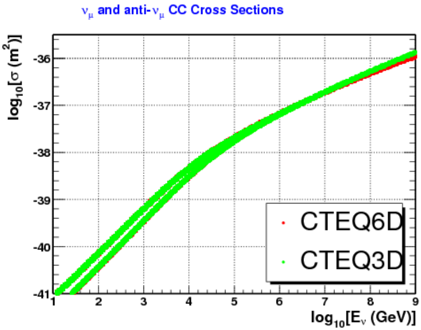
Interaction in Rock/Water/Ice



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

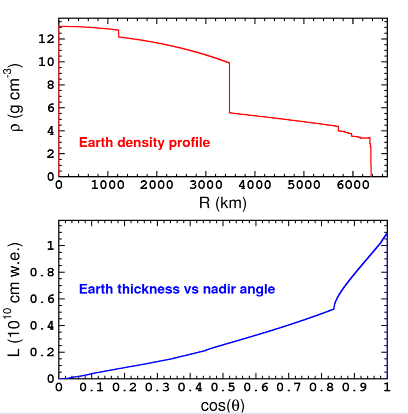
- $\sigma_{\nu N} \propto E_\nu$ below 5 TeV
- $\sigma_{\nu N} \propto E_\nu^{0.4}$ above 5 TeV
- **Pointing :** $\sqrt{<\theta^2_{\mu\nu}>} \approx \sqrt{\frac{m_N}{E_\nu}} \Rightarrow <\theta> \approx \frac{1.5^\circ}{\sqrt{E_\nu(TeV)}}$

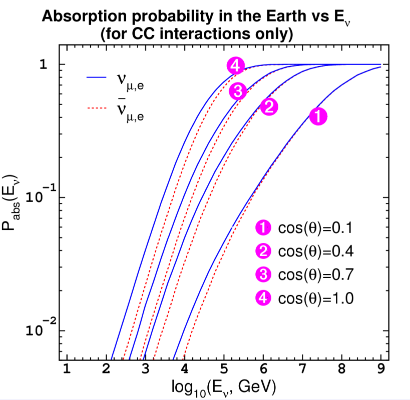
  $\Rightarrow$ Colinear at high energy !

Interaction in Rock/Water/Ice

Transmission through Earth

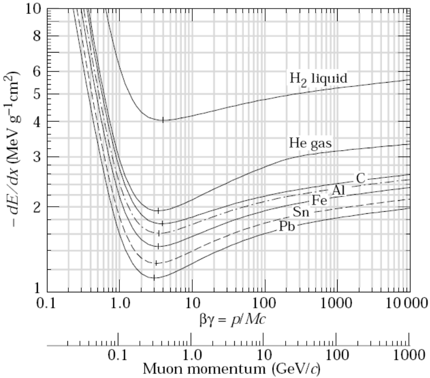
- $P_\oplus = e^{-l/\lambda}$, where $\lambda^{-1} = \rho \mathcal{N}_A \sigma_\nu(E_\nu)$



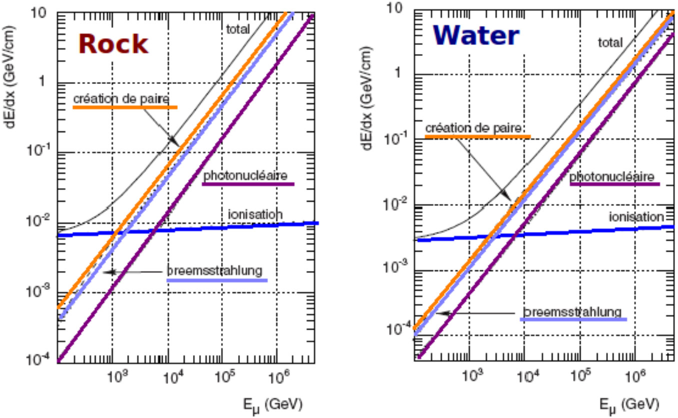


Energy Losses

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



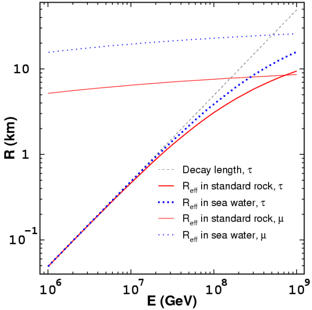
Energy Losses



Energy Losses and muon range

- $-\frac{dE}{dx} = a(E) + b(E)E$

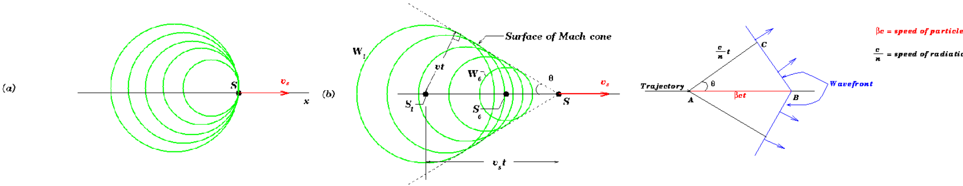
Energy Losses



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 !

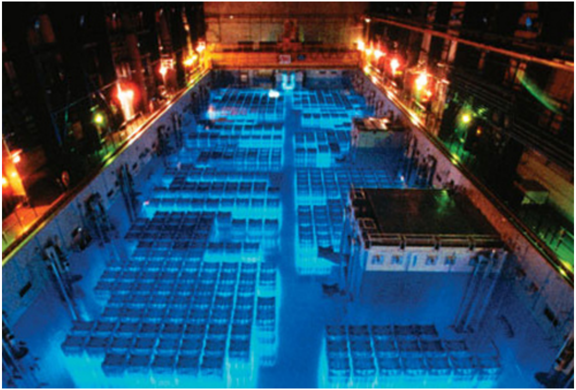
Cherenkov Effect



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



Charged Particle with velocity > phase velocity of light

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- $\theta_C \sim 1°$ in air, $\theta_C \sim 43°$ in water, $\theta_C \sim 41°$ in ice

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

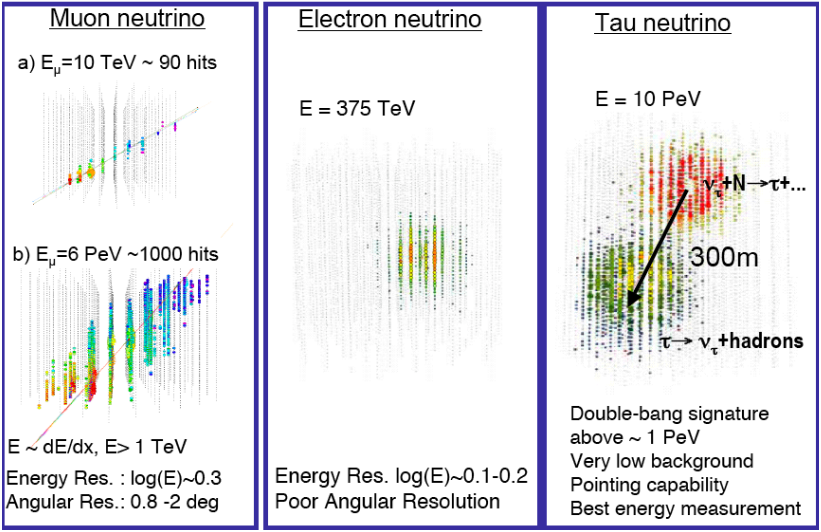
$$I(r) \propto \frac{1}{R} e^{-R/\lambda_{\rm att}}$$

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

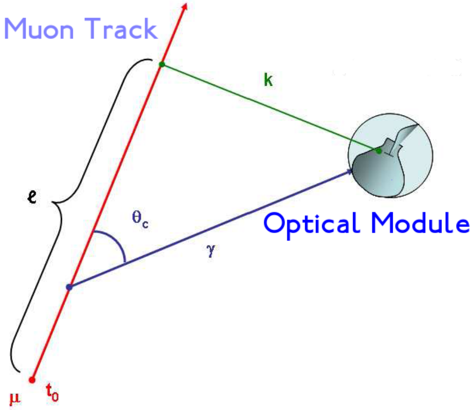
Medium	Attenuation	Absorption	Scattering	$\Delta\theta$ 10 TeV
Sea water	40-50m	50-60m	>200m	0.2°
Lake Baikal	20m	15-30m	>100m	1.5°
Polar Ice		100m	25m	3°

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

Event Topologies



Reconstruction of the track...

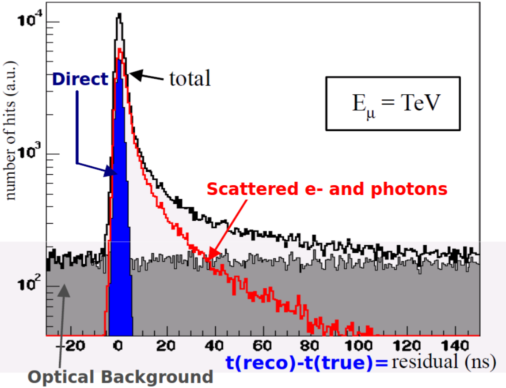


A χ^2 minimisation

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

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

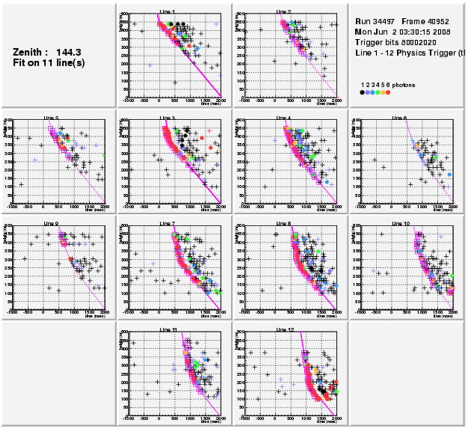
Reconstruction of the track...

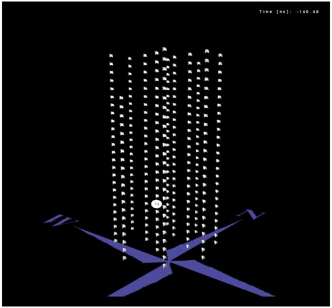


Importance of scattering

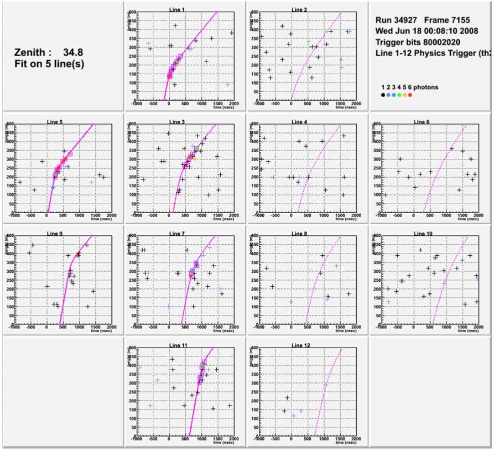
- **Few of photons are direct !**
- Impact on angular resolution

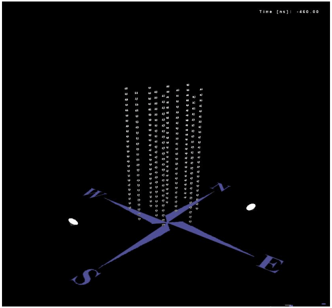
Atmospheric μ (downward) event





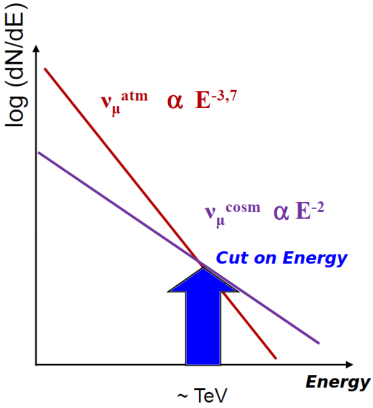
Atmospheric ν (upward) event

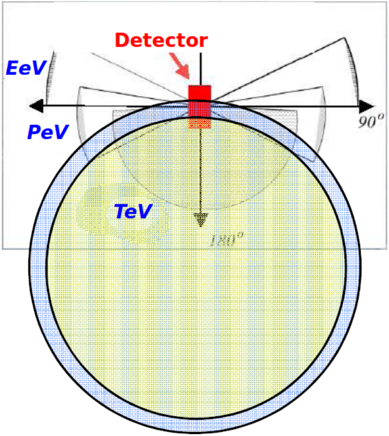




Atmospheric or Cosmic ?

Methods to distinguish between Atmospheric and Cosmic Neutrinos...

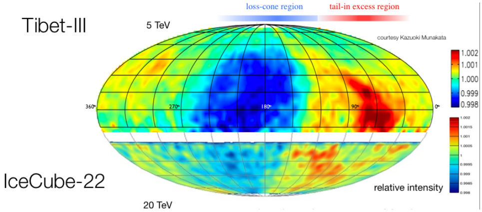


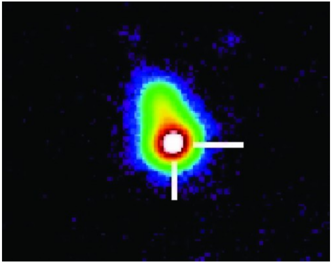


Look for an excess at high energies... ⇒ **need good energy resolution**

Atmospheric or Cosmic ?

Methods to distinguish between Atmospheric and Cosmic Neutrinos...



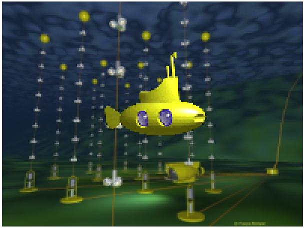


Look for anisotropies/excess around chosen sources ⇒ **need good angular resolution**

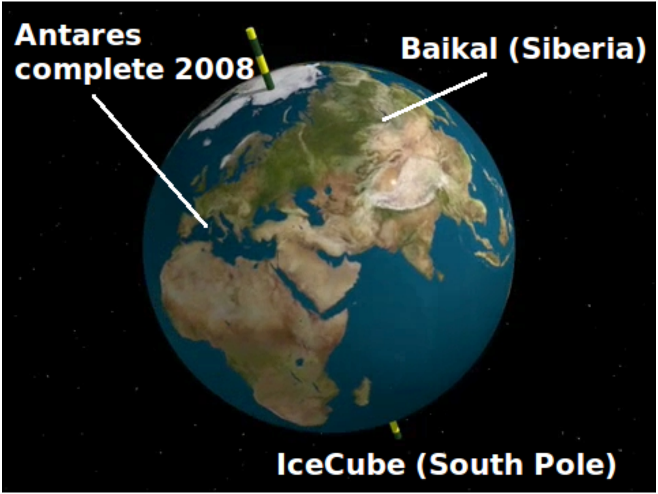
Confirmation with other messengers : GRBs, optical follow-up, gravitational waves...

High-Energy Neutrinos :

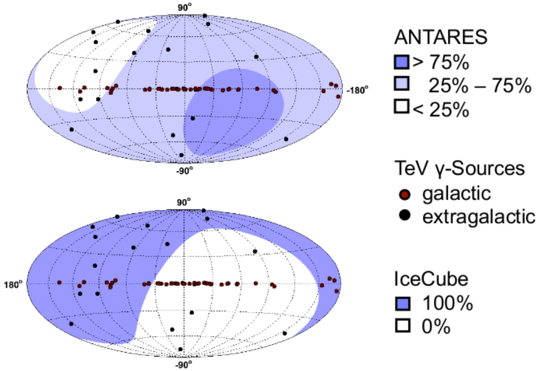
Neutrino Telescopes - IceCube and Antares



Neutrino Telescopes in the World...



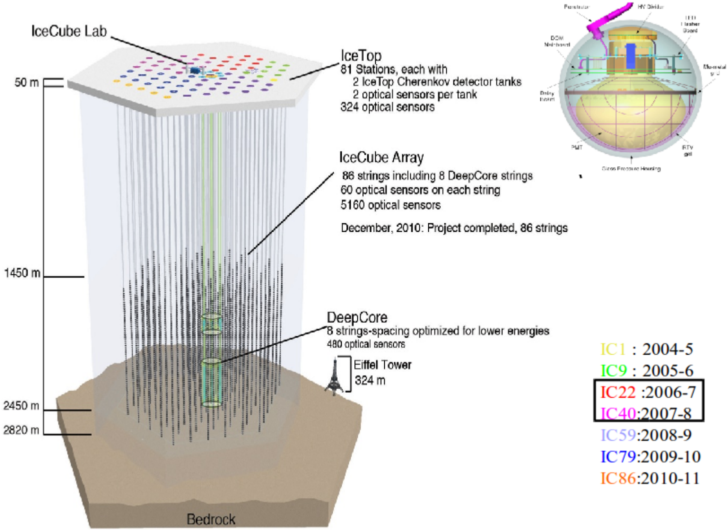
Neutrino Telescopes in the World...



Different Telescopes are complementary

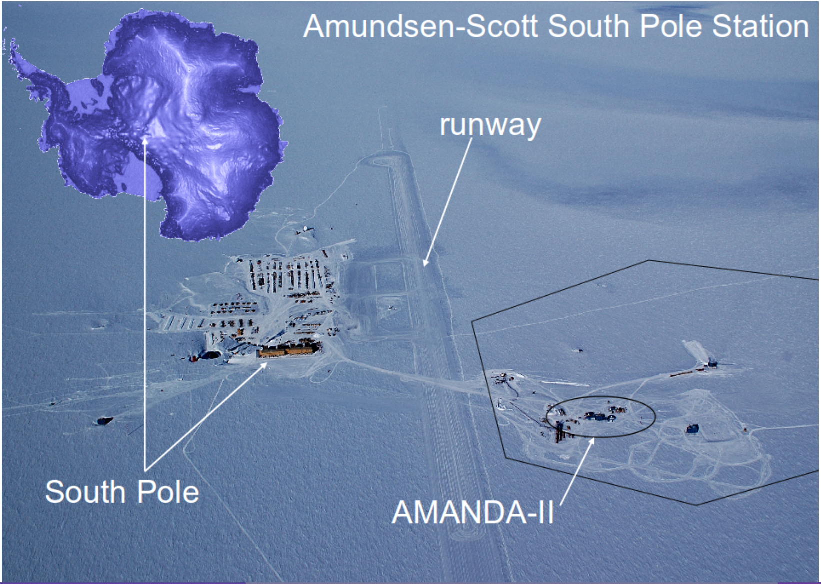
- 0.5π sr instantaneous overlap
- 1.5π sr integrated overlap

IceCube

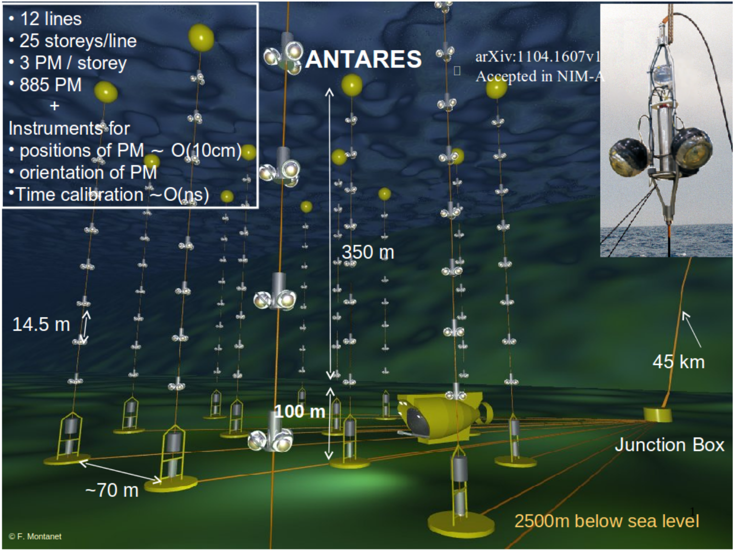


IC1 : 2004-5
IC9 : 2005-6
IC22 :2006-7
IC40:2007-8
IC59:2008-9
IC79:2009-10
IC86:2010-11

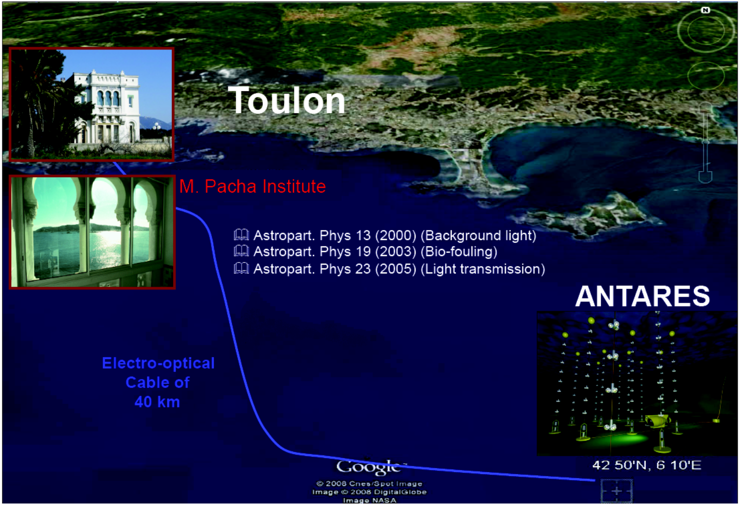
IceCube


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

Antares and its successor KM3NeT

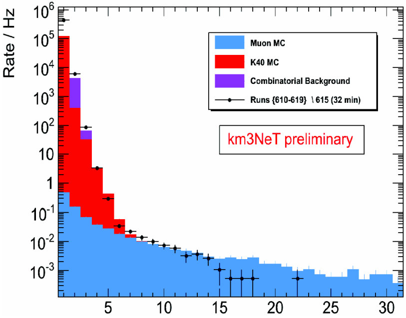


Antares and its successor KM3NeT



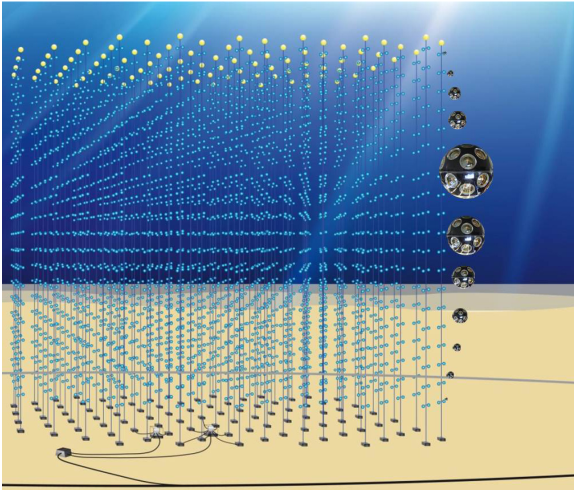
Antares and its successor KM3NeT

Antares and its successor KM3NeT



A future Km3NeT Digital Optical Module is already taking data

Antares and its successor KM3NeT



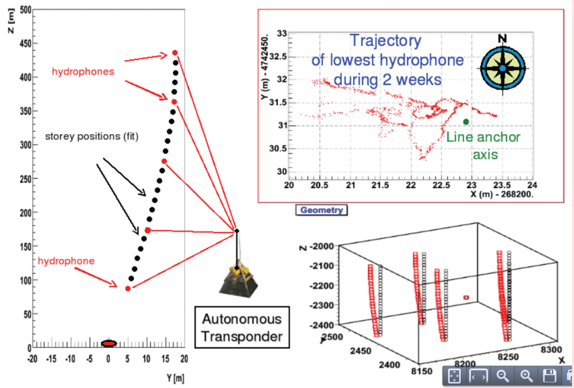
The future Mediterranean HEN Telescope : KM3NeT

Volume $\geq 5\times$ IceCube, construction to begin in 2015-2016 ?

Calibration and Performances - Antares

Positioning and Timing

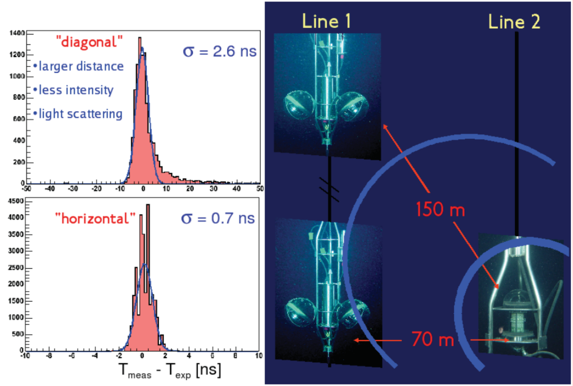
- Positioning with Hydrophones



Calibration and Performances - Antares

Positioning and Timing

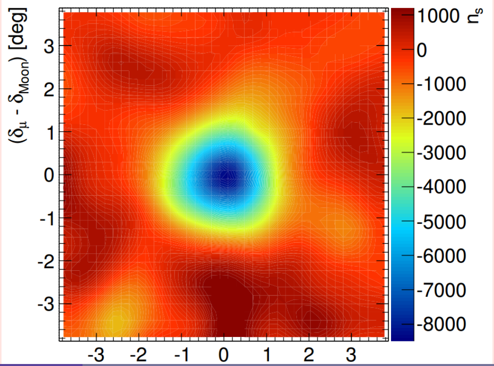
- Positioning with Hydrophones
- Timing with LEDs and Laser



Calibration and Performances - IceCube

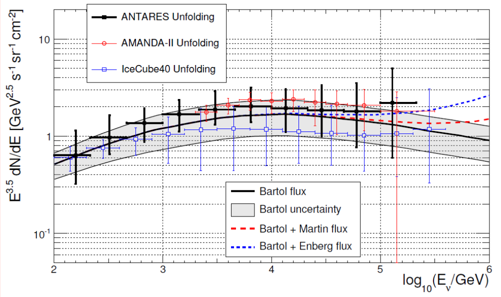
Positioning and Timing

- Positioning with Hydrophones
- Timing with LEDs and Laser
- Check pointing with *Moon Shadow*
  - $\Rightarrow$ blocks cosmic-ray muons !

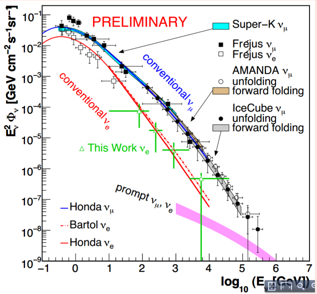


Calibration and Performances

Measurement of Atmospheric Neutrino Spectrum

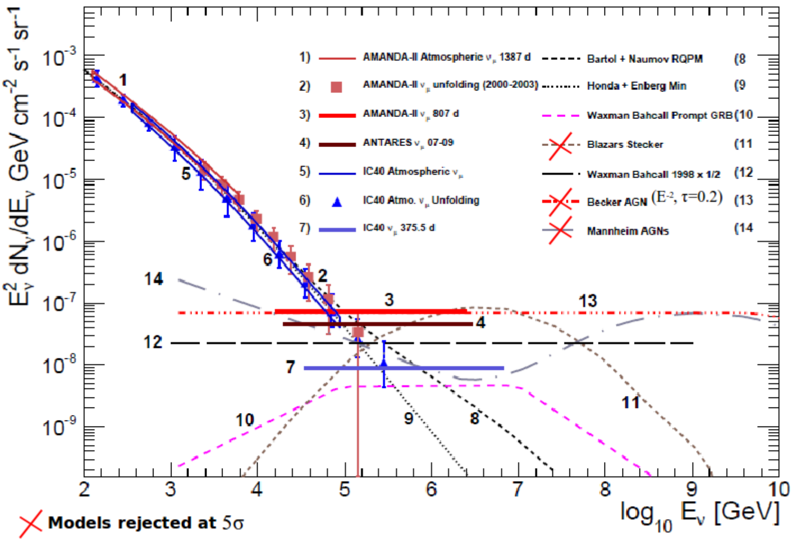


Antares 2008-2011

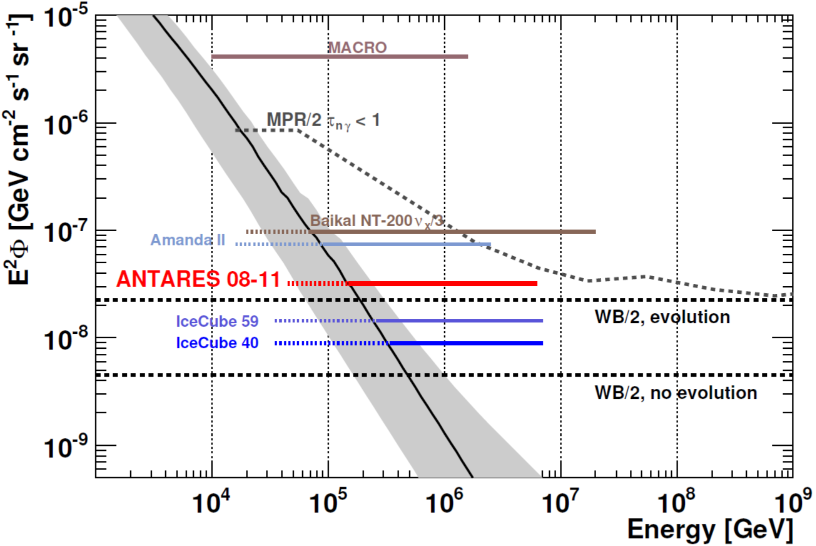


IceCube

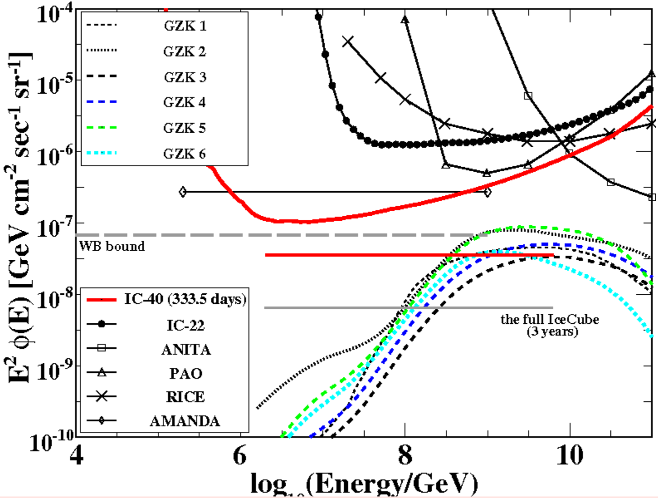
The search for a Diffuse Fluxes : IceCube



The search for a Diffuse Fluxes : Antares

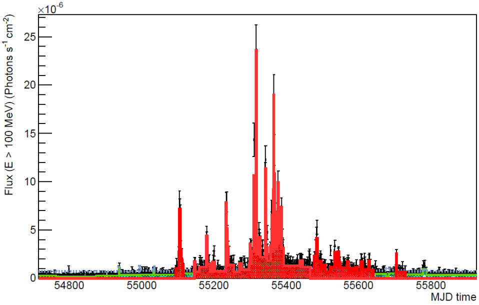


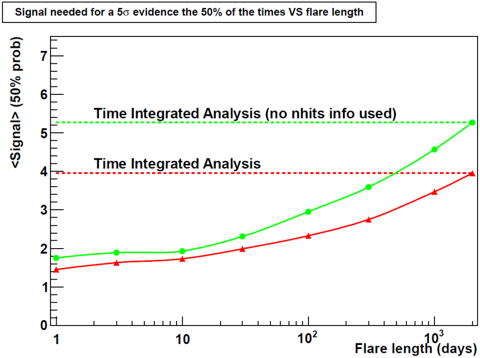
Neutrinos at Extremely-High Energies - IceCube



Exclusion of (most) top-down scenarios [LINK]

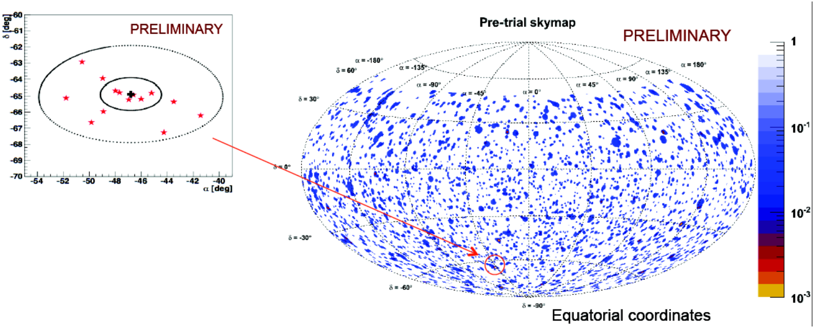
Time-Dependent Point Source Searches





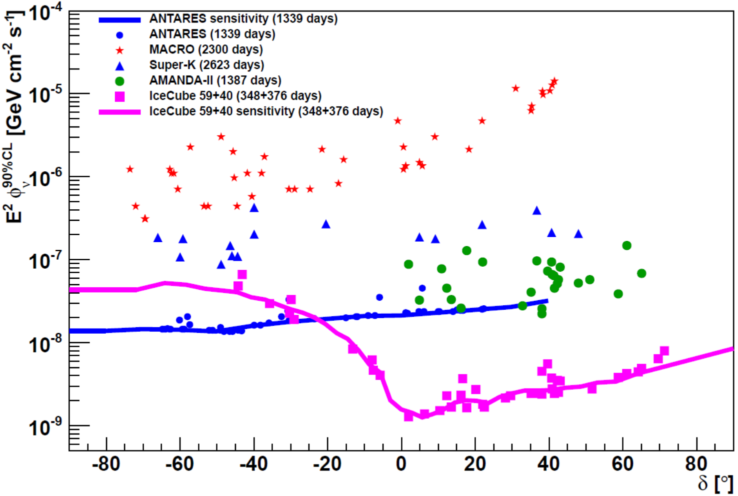
- **Selection of sources and time-periods** [Antares]

Time independent Point Source Searches



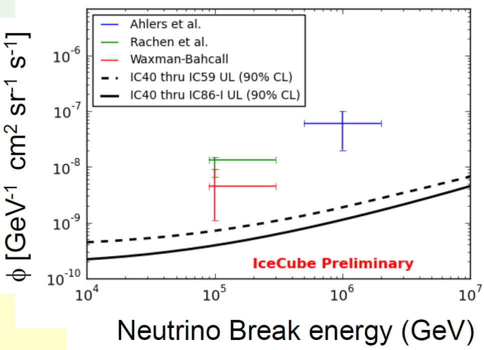
- **Time integrated search** [Antares] - 2.3σ

Time independent Point Source Searches

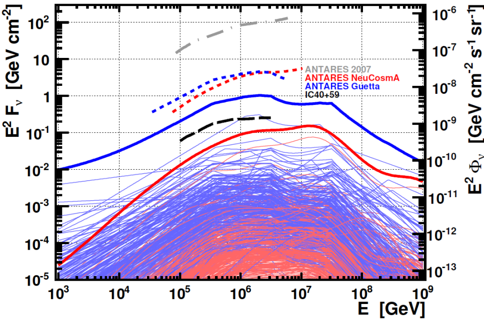


- **Time integrated search** [Antares]

Neutrinos and Cosmic-Rays from GRBs

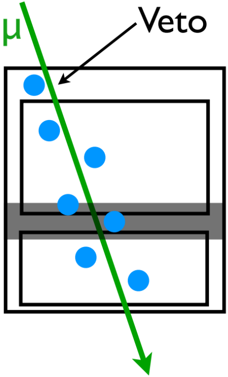


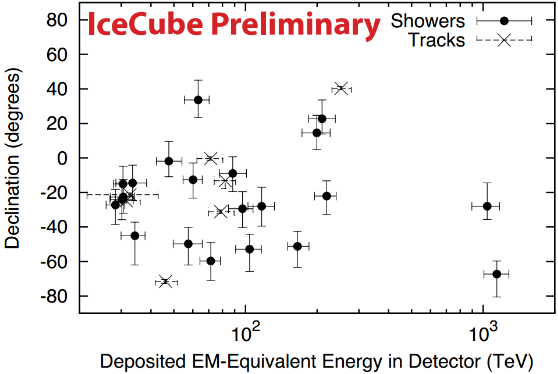
IceCube



Antares

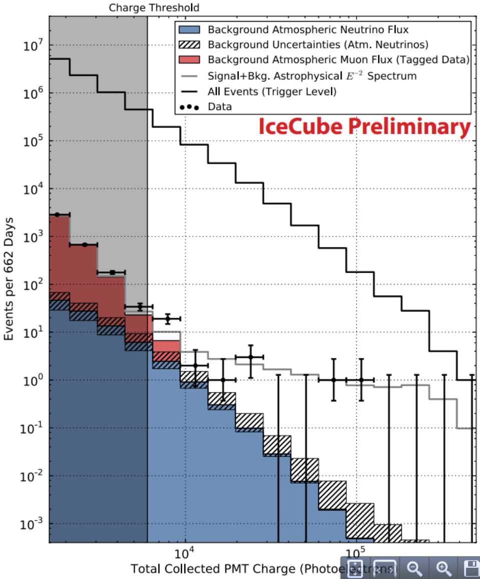
PeV events in IceCube : a clever veto



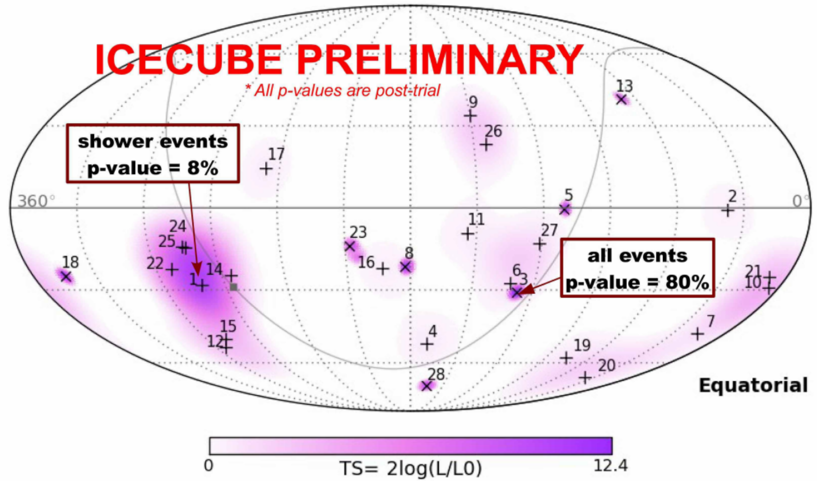


28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

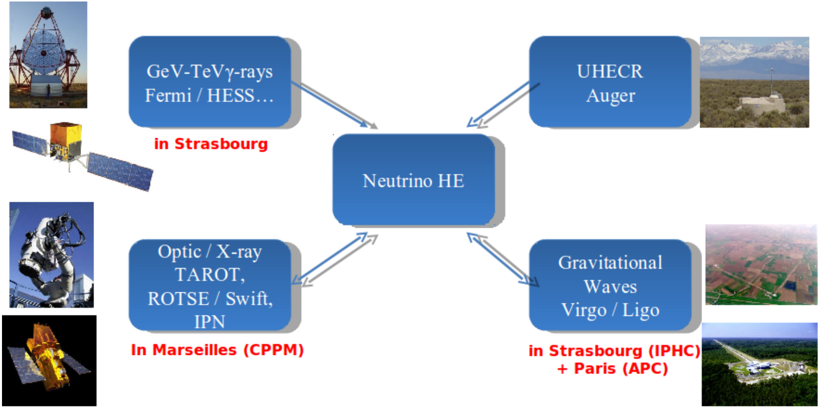
PeV events in IceCube : a clever veto



PeV events in IceCube : Skymap ⇒ no point source yet



Correlations with other messengers...



See the complete list of Antares publications

Selected References

Fluxes, bounds, event rates

- R. Gandhi et al., Ultrahigh-Energy Neutrino Interactions, APh. 5 (1996) 81-110
- J. K. Becker, HEN in the context of multimessenger physics, Phys.Rept.458 (2008) 173-246

Diffuse Fluxes

- Antares : Fermi Bubbles, recently submitted
- IceCube : Recent PeV events - Physical Review Letters 111 (2013) 021103

Point Sources

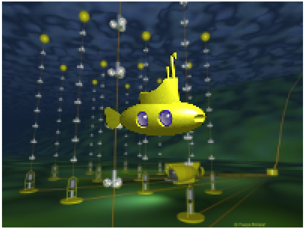
- Antares : latest 4-yr analysis - The Astrophysical Journal 760 :53(2012)
- IceCube : IC40-79 - Astrophysical Journal (2013)

Multi-Messenger Analyses

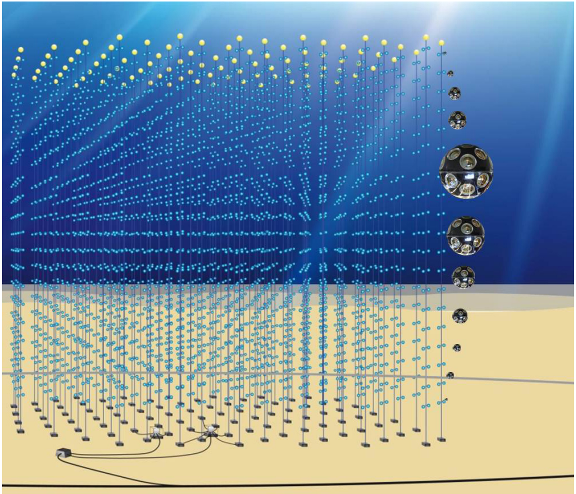
- Antares : GW+HEN coincidences with Virgo/LIGO - JCAP 06 (2013) 008
- IceCube : Crab Flare 2010 - Astrophysical Journal 745, 45 (2012)

High-Energy Neutrinos :

Perspectives...

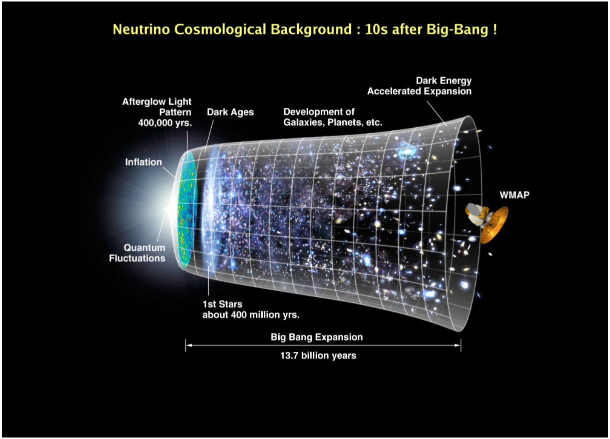


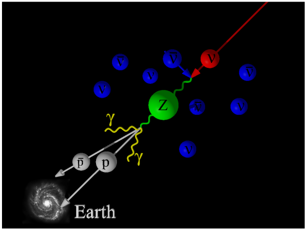
The future Mediterranean HEN Telescope : KM3NeT



Construction to begin in 2015-2016 ?

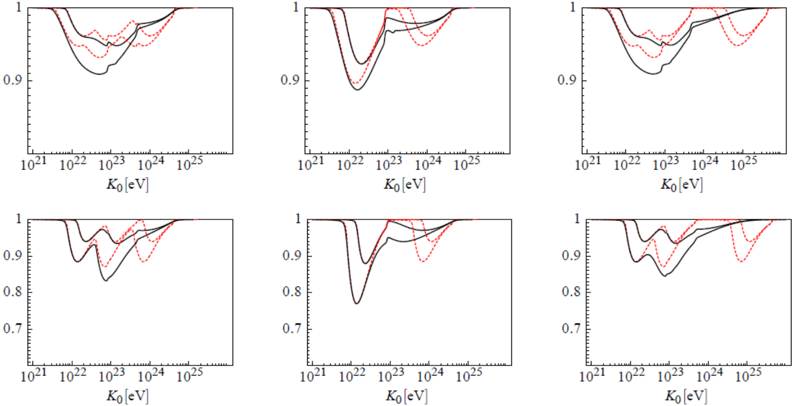
Relic ν and UHE ν





- $E_{\nu_i}^{\text{résonance}} = \dfrac{m_Z^2}{2m_{\nu_i}} \simeq 4 \times 10^{21} \left(\dfrac{1 \text{ eV}}{m_{\nu_i}}\right) \text{ eV}$

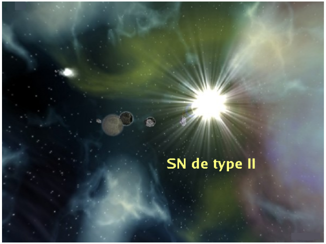
Relic ν and UHE ν

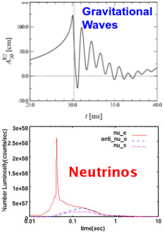


Interaction of ν UHE with Relic ν from Big-Bang

Dip in Neutrino Spectrum...

An example of GW-ν Coincidences : Type II SN





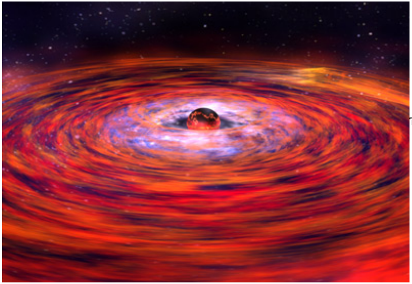
Type II SN

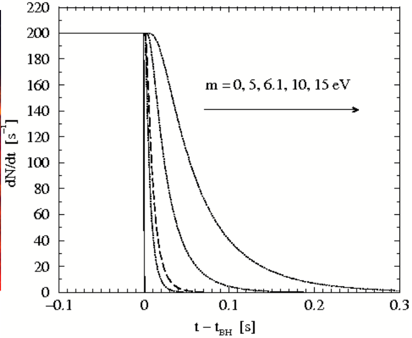
- $m_\nu \neq 0 : \delta t_{\text{propagation}} \simeq 5.15 ms \left(\frac{L}{10kpc}\right)\left(\frac{m_\nu c^2}{1eV}\right)^2\left(\frac{10MeV}{E_\nu}\right)^2$
- $E_\nu^{SN} \sim MeV$, $\delta t_{\text{GW}-\nu_e^{\text{flash}}} \lesssim 0.5\ ms$

  $\Rightarrow$ Limits on ν absolute mass scale from $\Delta t_{GW-\nu}$

N. Arnaud,...,Th. P. - Phys.Rev. D65 (2002) 033010

An example of GW-ν Coincidences : Type II SN





Collapse of NS into BH induced by accretion

$\Rightarrow$ Sudden stop of neutrino signal

$\Rightarrow$ Strong GW Signal

$\Rightarrow$ Limits on ν absolute mass scale from $\Delta t_{GW-\nu}$

J. F. Beacom et al. - Phys.Rev. D63 (2001) 073011

Fundamental Physics at High Energy

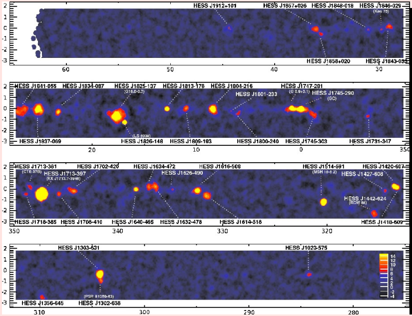
- Quantum Gravity : $c^2p^2 = E^2\left[1+\xi\left(\frac{E}{E_{QG}}\right)+\mathcal{O}\left(\frac{E^2}{E_{QG}^2}\right)+\ldots\right]$

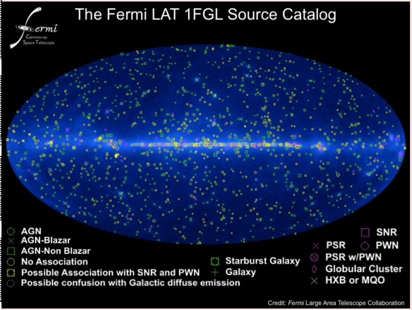
$\Rightarrow$ $|\Delta t_{QG}| \simeq 0.15ms\left(\frac{d}{10\ kpc}\right)\left(\frac{E_\nu^{HE}}{1\ TeV}\right)\left(\frac{10^{19}\ GeV}{E_{QG}}\right)$ for $z \ll 1$

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

Expect the Unexpected...

Some surprises perhaps... ?





- New instruments bring new sources !
- 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