Neutrino Astrophysics
The High Energy Frontier

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Introduction

- Fermion
- Weak Interactions : exchange of Boson W, Z

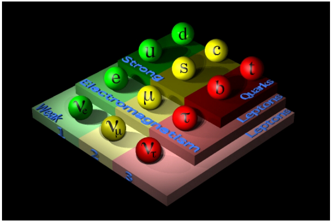
⇒ escapes dense regions

- Elementary particle : no compositeness, no decay
- Mass close to zero

⇒ velocity c

- Neutral particle

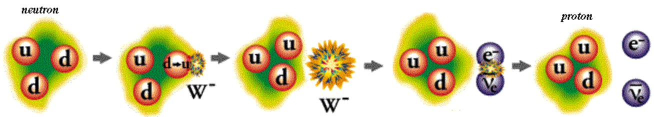
⇒ no effect of magnetic fields



Introduction

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.*

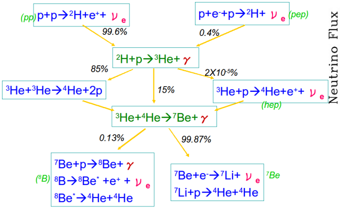


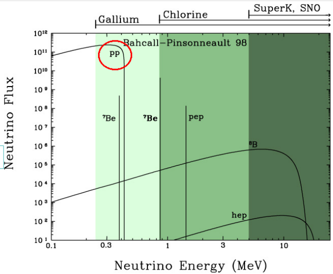
- 1933 : Fermi develops the theory of the little neutron (neutrino), discovered in 1932 by Chadwick
- 1953 : Experimental observation at Savannah River (Reines & Cowan) through $\bar{\nu} + p \rightarrow e^{+} + n$

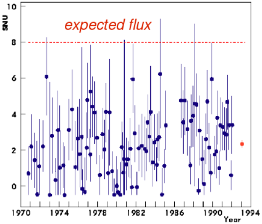
Introduction

A brief history of neutrinos...

- 1968 : Solar Neutrinos observed at Homestake (Davis) - only the third of expectations...(see A. Meregaglia's lecture yesterday)
- 1987 : SN1987A in Large Magellanic Could







HomeStake Data (from 1968)

Introduction

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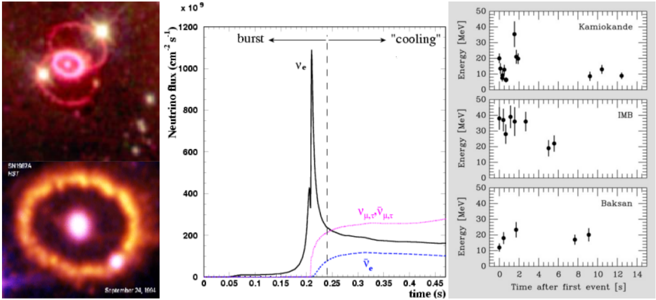
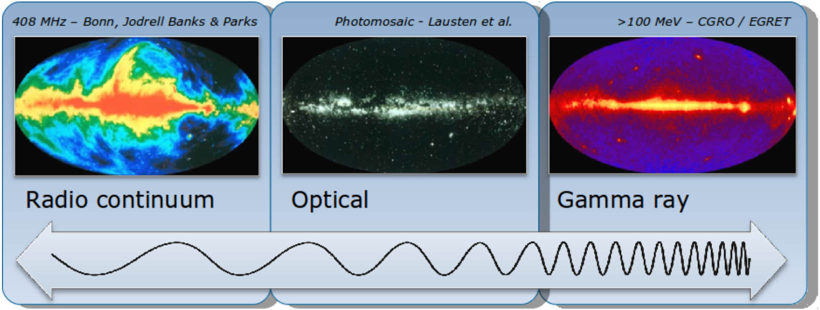
Introduction



Birth of Neutrino Astronomy !

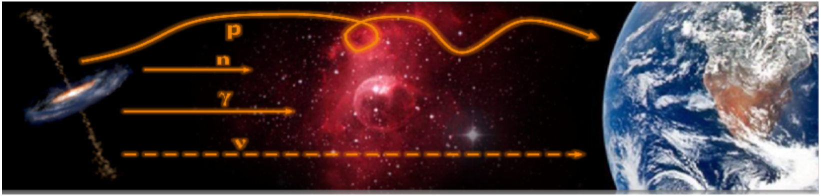
Neutrinos as Cosmic Messengers...



What about neutrinos... ?

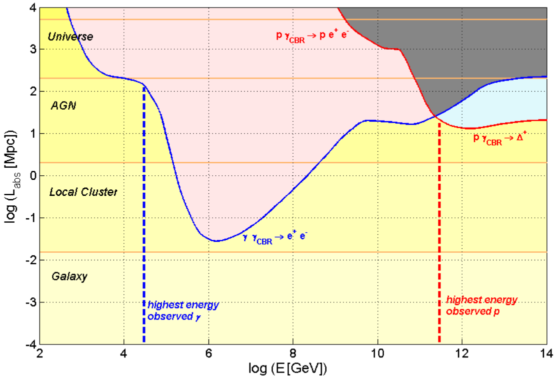
- If $E_\nu \approx 10 GeV - 10^2 EeV$, same span as Radio-X-rays in EM radiation !

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...

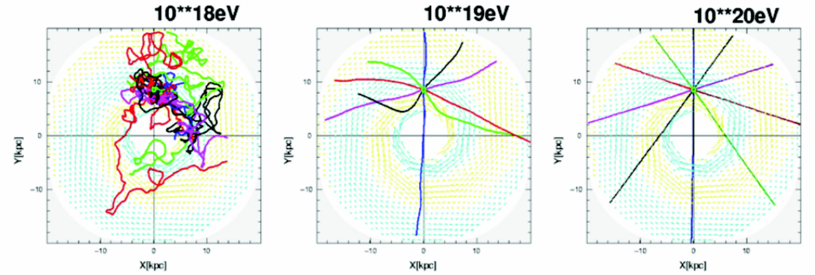
Neutrinos as Cosmic Messengers...



Compute a mean free path ?

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

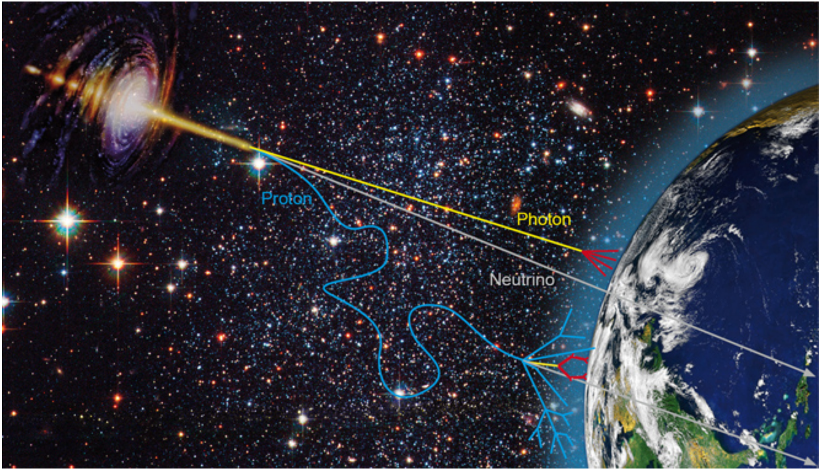
Neutrinos as Cosmic Messengers...



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...

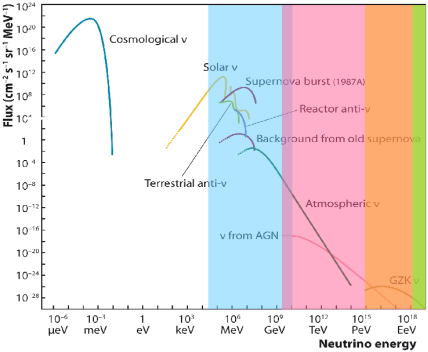


How are they detectable ?

- Requires large volume of detection...

Sources of neutrinos...

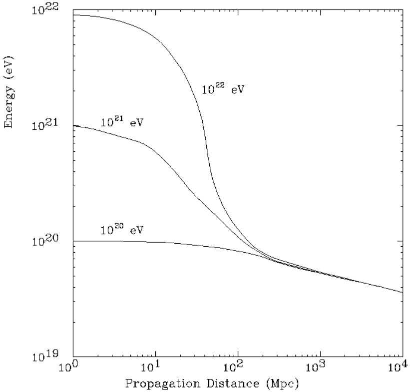
- Under rock
- Under water/ice
- Acoustics/Radio
- Giant Air Shower

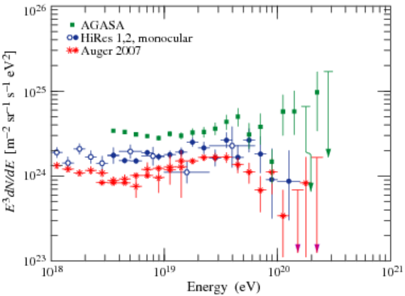


How many ?

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

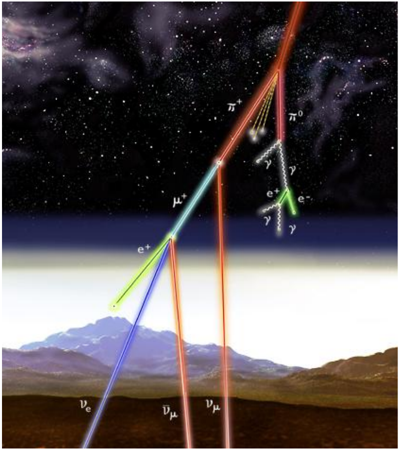
The far end of the spectrum...

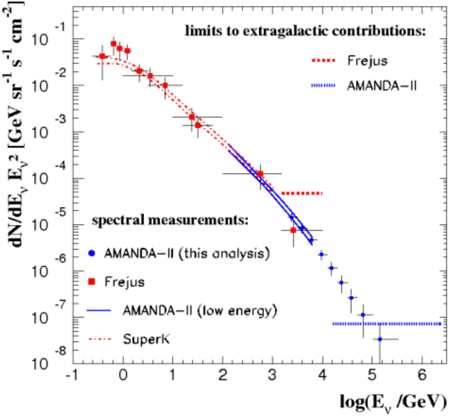




- Guaranteed source of UHE neutrinos...
- [Exercise] Threshold $\gamma_{\text{CMB}} + p \to \Delta \to \pi + N \approx 10^{20} eV$
- Flux : less than $100/km^2/yr$!

Atmospheric neutrinos

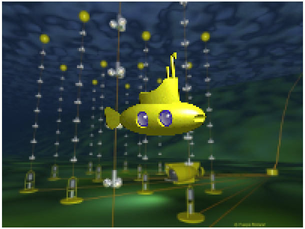




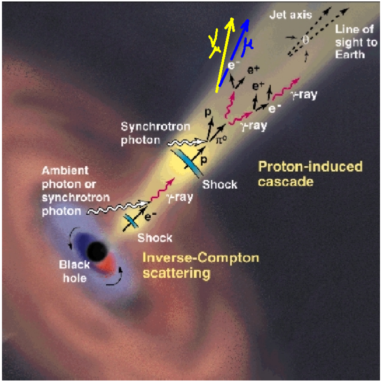
Background for detection of astrophysical neutrinos !

High-Energy Neutrinos :

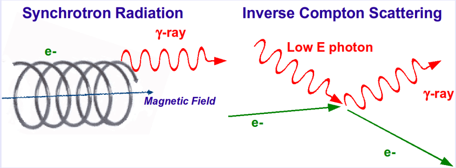
The Cosmic-Ray Connection



The Cosmic-Ray Connection



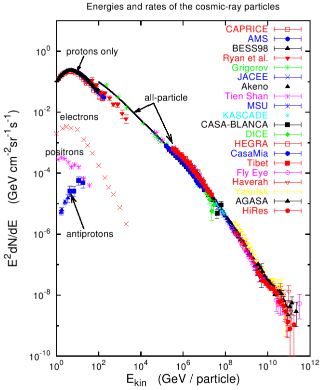
Leptonic Production of HE γ :



Hadronic Production of HE γ/CRs :

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

The Cosmic-Ray Connection



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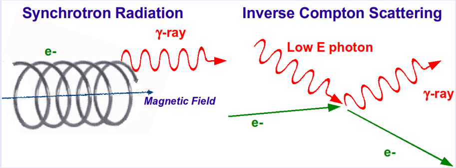

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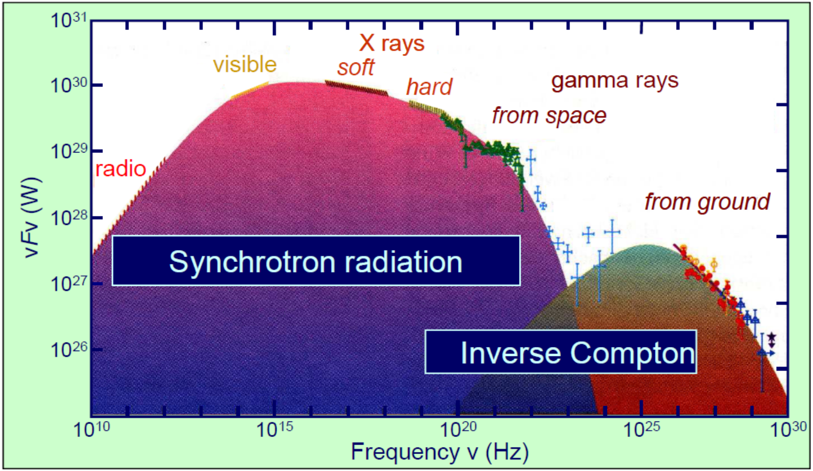
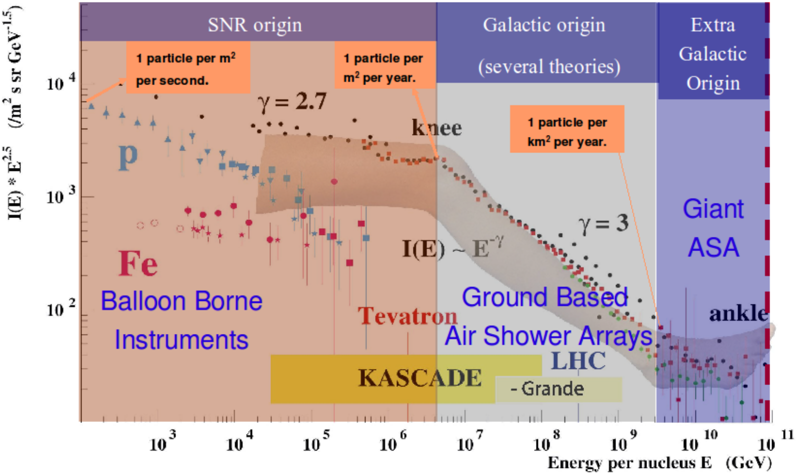
Neutrinos are the **smoking gun** of hadronic processes

The Cosmic-Ray Connection



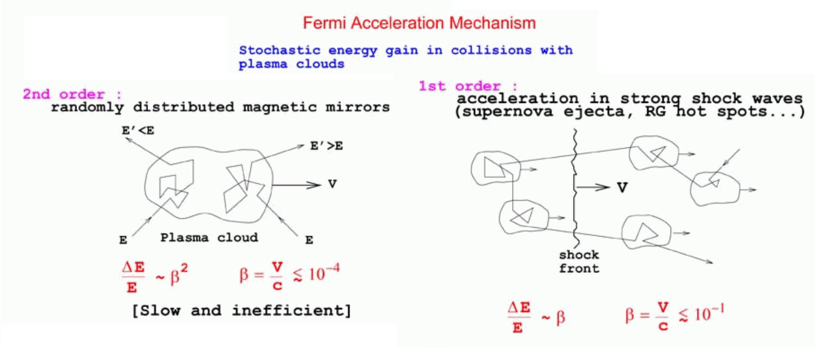
Multi-wavelength/messenger analysis ⇒ Modelling of the source

The Cosmic-Ray Connection



See lecture on Cosmic-Ray Physics by R. Engel on Monday

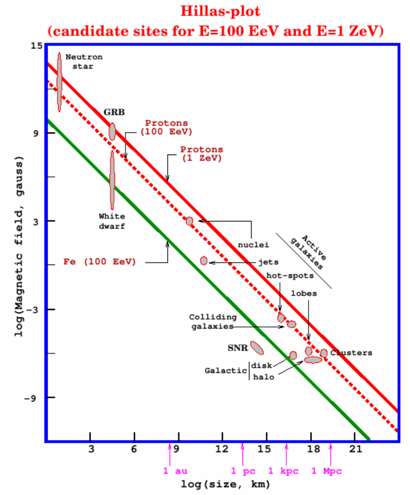
Fermi processes for Acceleration



Spectrum

- $\frac{dN}{dE} \propto E^{-\gamma}$, with $1.5 < \gamma < 2.5$
- [Exercise] Demonstrate Gain of Energy and Power-Law...

Fermi processes for Acceleration



Maximum Energy

- From Maxwell $\vec{\nabla} \times \vec{E} = -\frac{\partial B}{\partial t} \Rightarrow E = Bc$
- $E_{\text{max}} = \gamma mc^2 = \int ZeEdx = ZeBcL$
- Impose $L < R_L \Rightarrow E_{\text{max}} \sim ZBL$ with L size of accelerating region

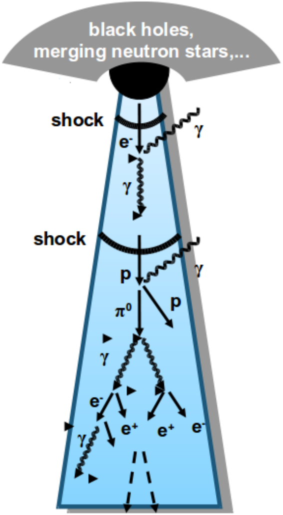
$\Rightarrow$ Compact sources...

- Ultra-Relativistic shocks : $E_{\text{max}} \sim \Gamma ZBL$

Leptonic/Hadronic ?

Leptonic scenario

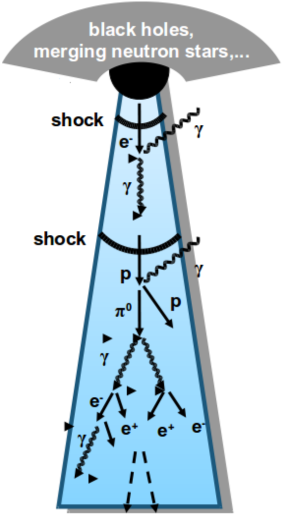
- $e-$ accelerated via Fermi mechanism
- X-Rays, observed, produced via synchrotron : $e^{\pm}\vec{B} \rightarrow e^{\pm}\gamma_X$
- HE γ-rays by Inverse Compton : $e^{\pm}\gamma_{\text{low E}} \rightarrow e^{\pm}\gamma_{\text{high E}}$
- No neutrinos !



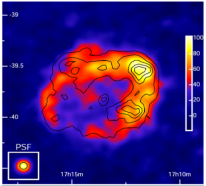
Leptonic/Hadronic ?

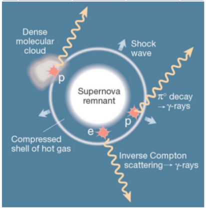
Hadronic scenario

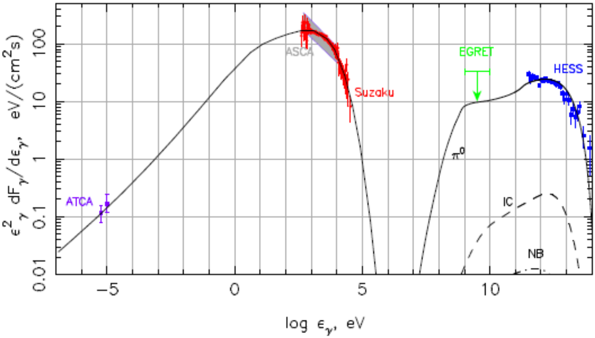
- Protons and Heavy nuclei (observed !) accelerated via Fermi mechanism
- Interaction with ambient photons :
  - $p + \gamma/A \rightarrow \Delta^+ \rightarrow \pi^0 + p$
  - $p + \gamma/A \rightarrow \Delta^+ \rightarrow \pi^+ + n$
- γ-rays via $\pi^0 \rightarrow \gamma\gamma$
- Neutrinos via $\pi^+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



A Hadronic origin for γ emission ?





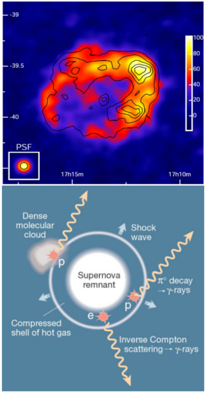


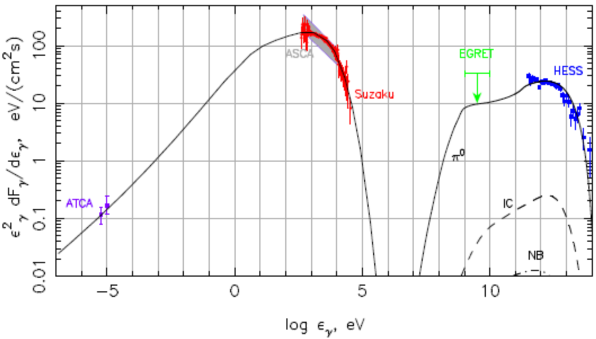
The case of RXJ 1713-3946

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

Berezhko & Völk, `arXiv-08100988v2`

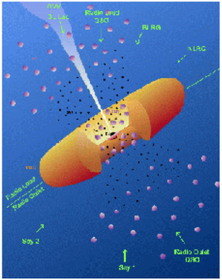
A Hadronic origin for γ emission ?

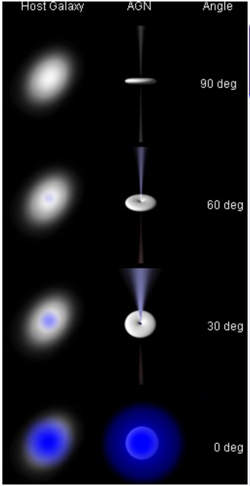




See Lecture on γ-Ray Astronomy by M. Lemoine-Goumard on Tuesday

Active Galactic Nuclei...

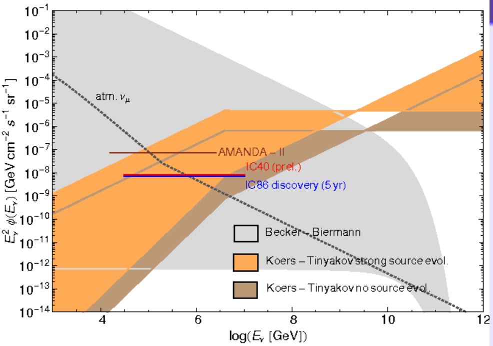




AGNs - Studied at Observatoire de Strasbourg

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

Active Galactic Nuclei...



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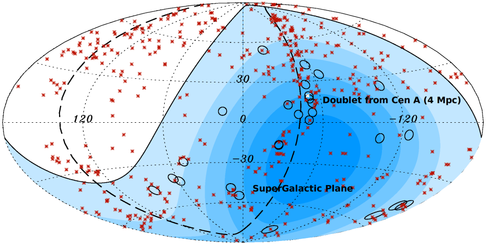
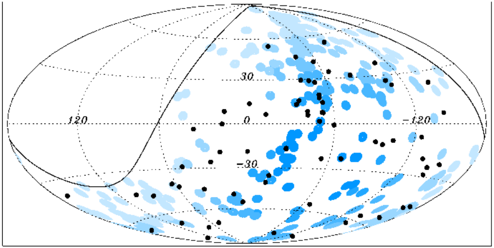


UHECRs and AGNs - 2007 Results

- 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%)
- ...VCV Catalogue incomplete
- Correlation is not a proof of causality !

Active Galactic Nuclei...



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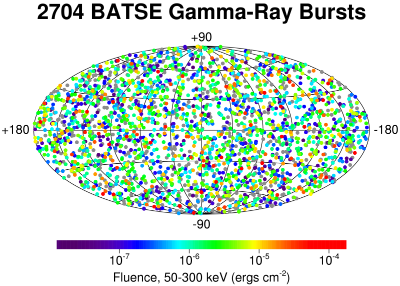
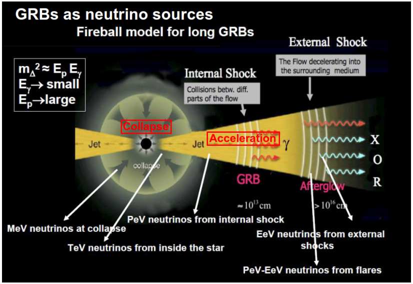
Gamma-Ray Bursters...

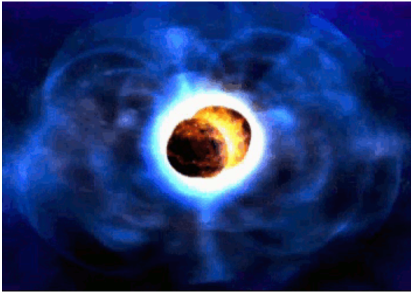


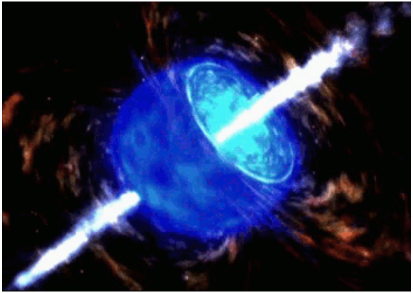


Gamma-Ray Bursts

- 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...





Short GRBs

Binary Mergers : BH or NS

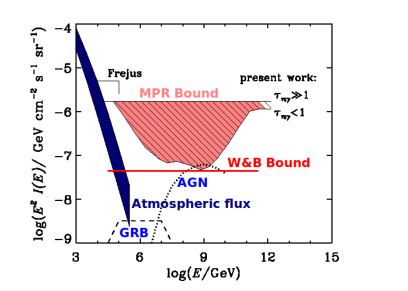
Long GRBs

Collapsars - massive star collapse

Upper Bounds

Bounds for extra-galactic sources

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



Upper Bounds

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

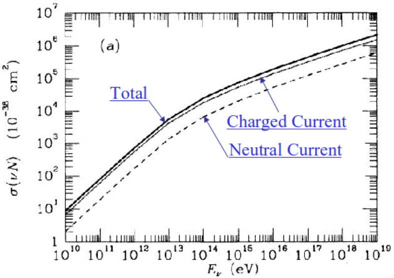
  $\Rightarrow$ No radiation, except outer layers and blackbody

Upper Bounds

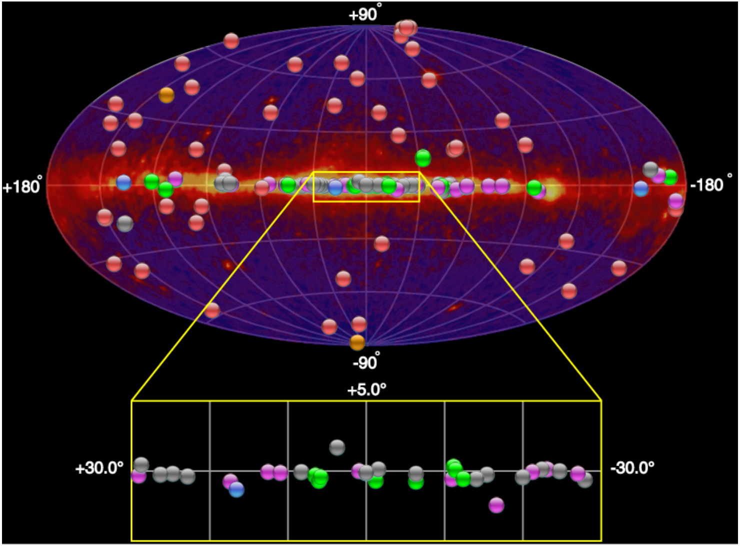
Bounds for extra-galactic sources

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

$\Rightarrow$ Needs large detection volumes !



The TeV Gamma-Ray Sky



The TeV Gamma-Ray Sky

How to compute a ν Flux from γ-Ray Observations

- Hypothesis : TeV emission dominated by π^0 decay...
- Parametrisation of π production in hadronic interactions
- Proton Injection Spectra $\frac{N_p}{E_p} = k_p \left(\frac{E_p}{1\,TeV}\right)^{-\alpha} e^{-\frac{E_p}{\epsilon_p}}$ (cut-off)
- Results in :

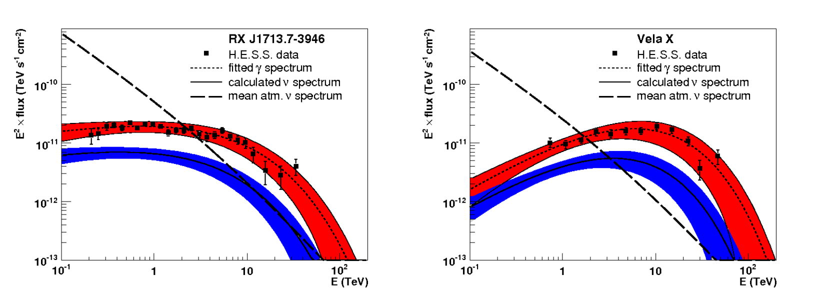
$$\frac{N_{\gamma/\nu}}{E_{\gamma/\nu}} = k_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1\,TeV}\right)^{-\Gamma_{\gamma/\nu}} e^{-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}}$$

- $k_\nu \approx (0.71 - 0.16\alpha)k_\gamma$, $\Gamma_\nu \approx \Gamma_\gamma \approx \alpha - 0.1$, $\epsilon_\nu = 0.59\epsilon_\gamma \approx \epsilon_p/40$
- Assumptions : no γ absorption, low radiation and matter density, weak $\vec{B}$...

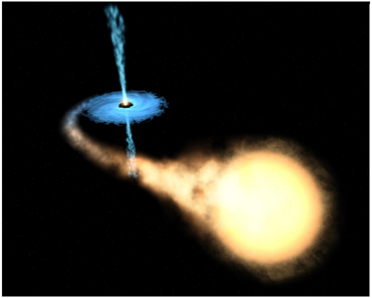
The TeV Gamma-Ray Sky

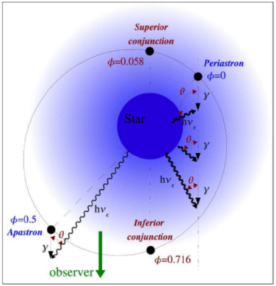
How to compute a ν Flux from γ-Ray Observations

$$\frac{N_{\gamma/\nu}}{E_{\gamma/\nu}} = k_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1\,TeV} \right)^{-\Gamma_{\gamma/\nu}} e^{-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}}$$



In the Galaxy...

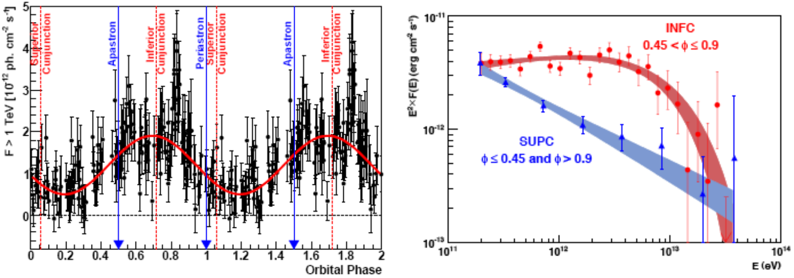




MicroQuasars - Studied at Observatoire de Strasbourg

- 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
- LS5039 : Phasogramm shows orbital motion in flux and spectrum

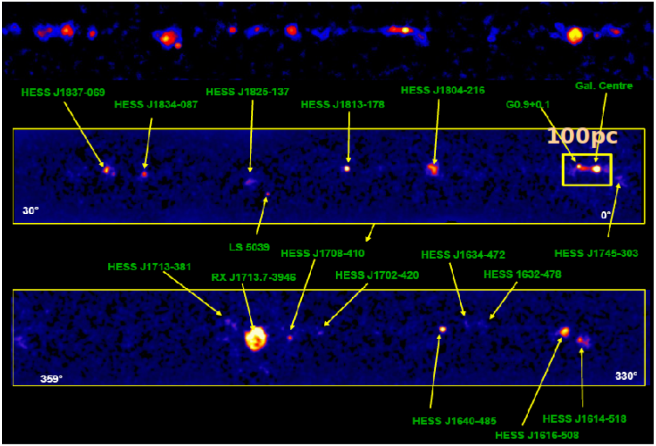
In the Galaxy...



MicroQuasars - Studied at Observatoire de Strasbourg

- 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
- LS5039 : Phasogramm shows orbital motion in flux and spectrum

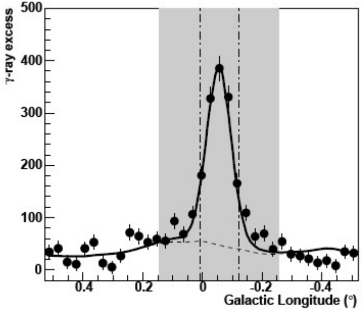
In the Galaxy...

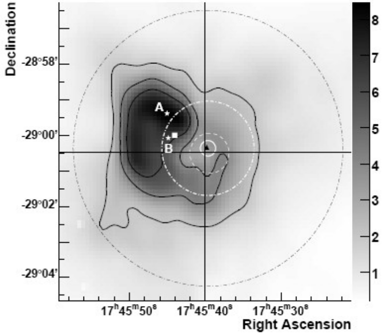


The Galactic Plane - visible with Antares !

- Lots of New Sources discovered by HESS

In the Galaxy...

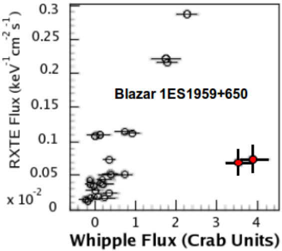


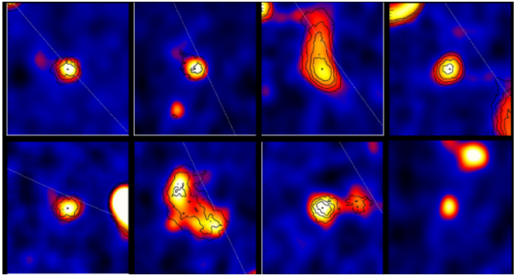


The Galactic Centre - only visible with Antares

- 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

In the Galaxy...



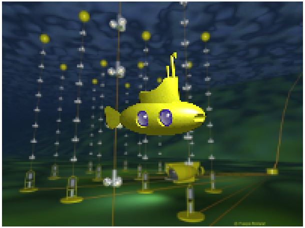


Dark Sources ?

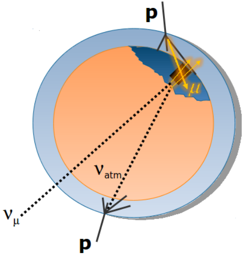
- Several sources observed only in γ, no radio, no X-Rays
- Orphan Flares

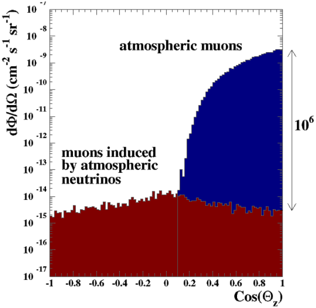
High-Energy Neutrinos :

Neutrino Telescopes, How they work...



Detection of Cosmic Neutrinos





Idea of Markov (1960)

- *We propose getting up an 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

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

Lectures on CRs

E~ 1 - 10 EeV

Radio

Earth based

RICE
GLUE
SalSA
CODALEMA
ARIANNA

In space

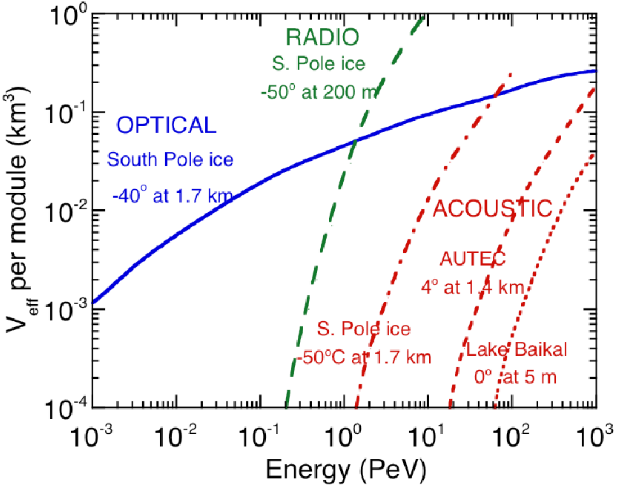
ANITA
FORTE

Acoustic

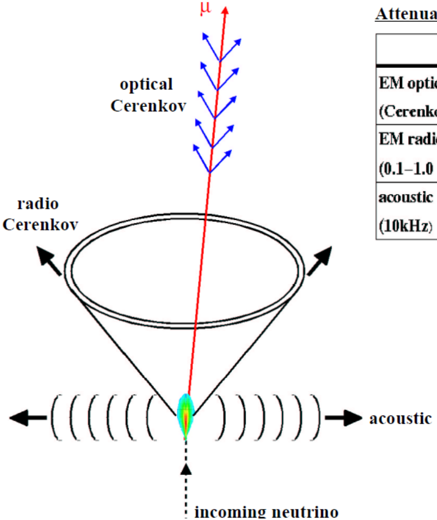
SAUND
SADCO (Greece)
ANTARES R&D
IceCube
AUTEC
AGAM

E~EeV - ZeV

Detection of Cosmic Neutrinos

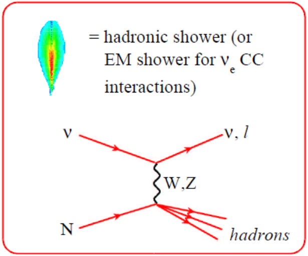


Acoustics and Radio

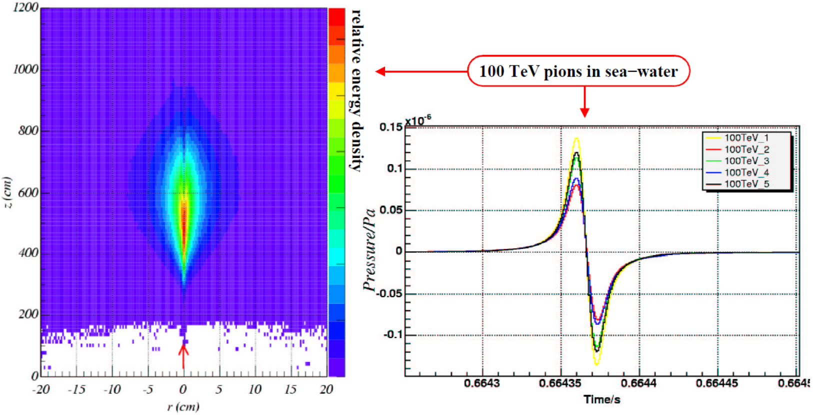


Attenuation Lengths :

	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)



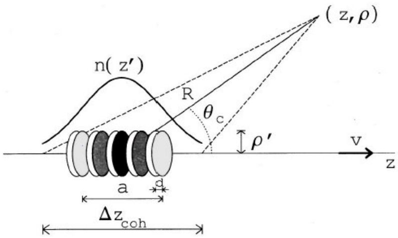
Acoustics and Radio

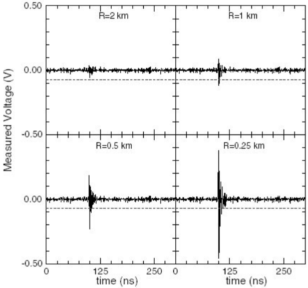


An Acoustic pulse

- R&D in Antares (Germany, Marseilles)

Acoustics and Radio





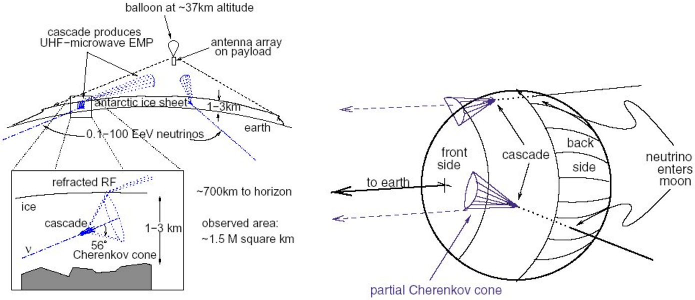
Askaryan Effect - used in Codalema, LOPES...

- 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



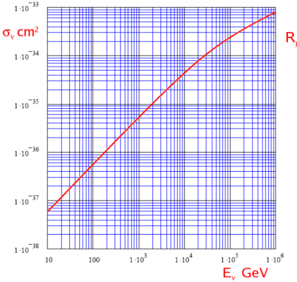
Askaryan Effect - used in Codalema, LOPES...

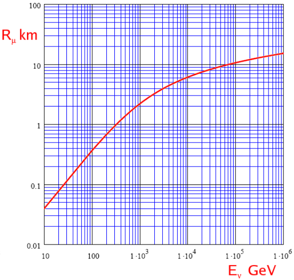
ANITA - GLUE

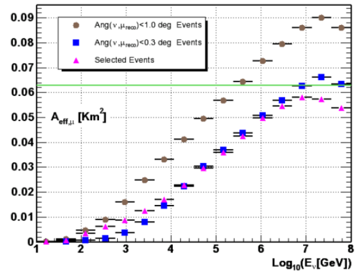
Event Rate & Detector Size

Event Rate N_ν & Luminosity needed

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







Event Rate & Detector Size

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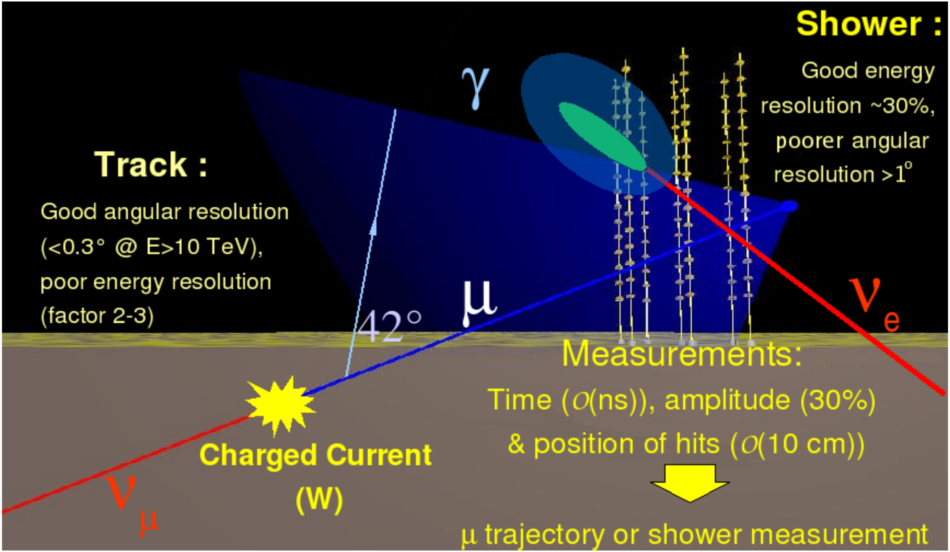
$$L_\nu = 4\pi d^2 \Phi_\nu \approx 10^{46} N_\nu \left(\frac{d}{4\,Gpc}\right)^2 \left(\frac{E_\nu}{100\,TeV}\right)^{1-\alpha} \left(\frac{A_\mu T}{km^2 yr}\right)^{-1} \mathrm{erg/s}$$

- $\alpha \sim 1$ 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...

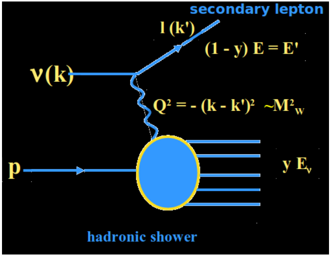
For area A and observation time T

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

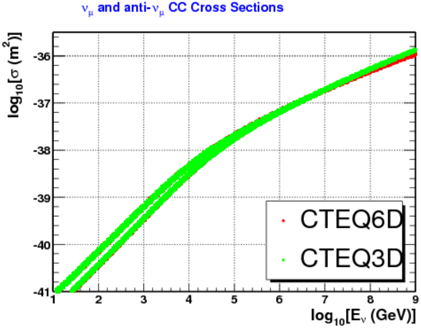
Interaction in Rock/Water/Ice



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



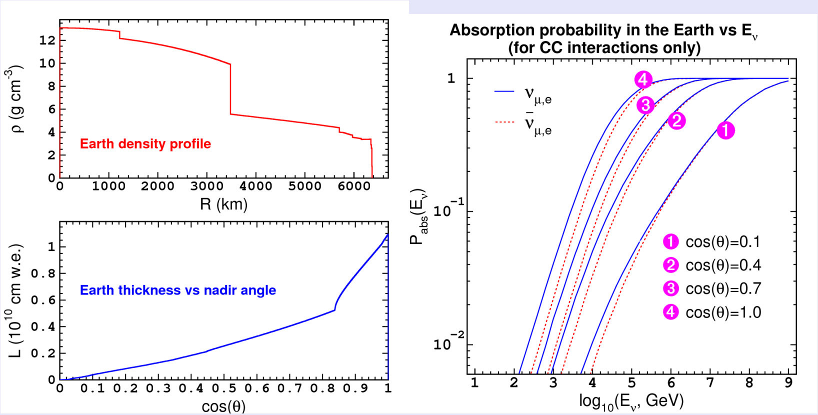
Deep-Inelastic Scattering

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

Interaction in Rock/Water/Ice

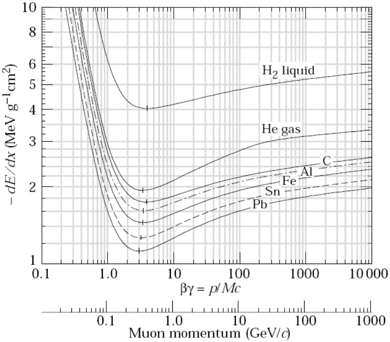
Transmission through Earth

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

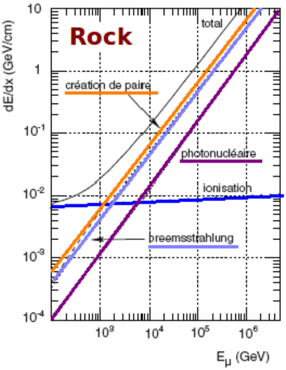


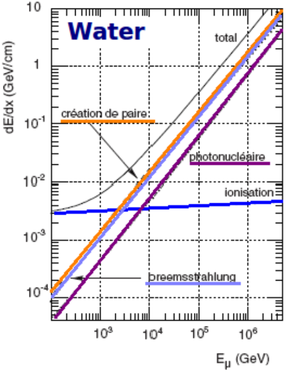
Energy Losses

- 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

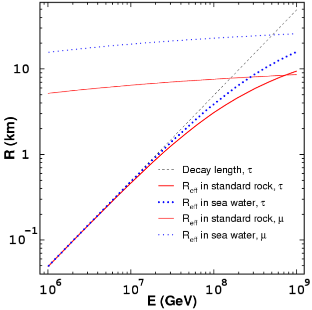




Energy Losses and muon range

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

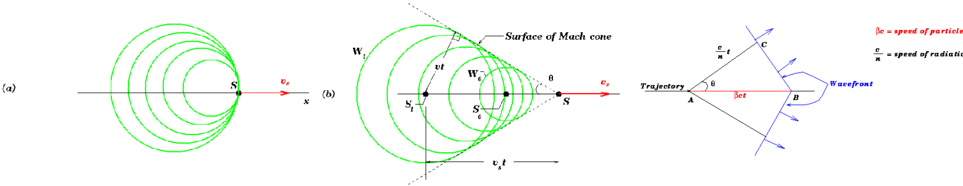
Energy Losses



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 !

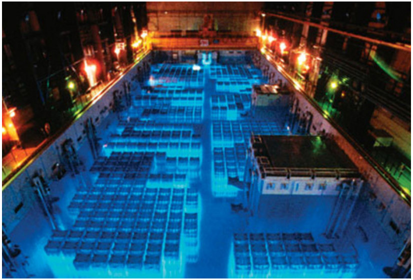
Cherenkov Effect



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

Cherenkov Effect



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Cherenkov Effect

Number of Photons

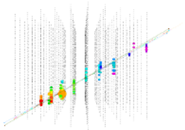
$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) \approx \frac{2\pi\alpha}{\lambda^2}\sin\theta_C^2$$

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

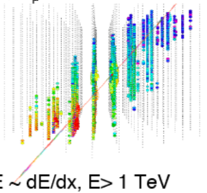
Event Topologies

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



b) E_μ=6 PeV ~1000 hits



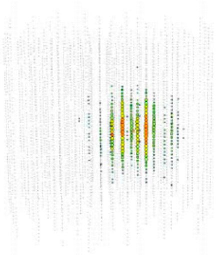
E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3

Angular Res.: 0.8 -2 deg

Electron neutrino

E = 375 TeV

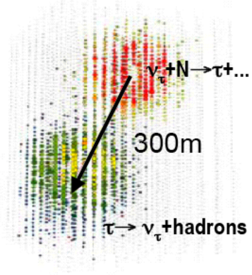


Energy Res. log(E)~0.1-0.2

Poor Angular Resolution

Tau neutrino

E = 10 PeV



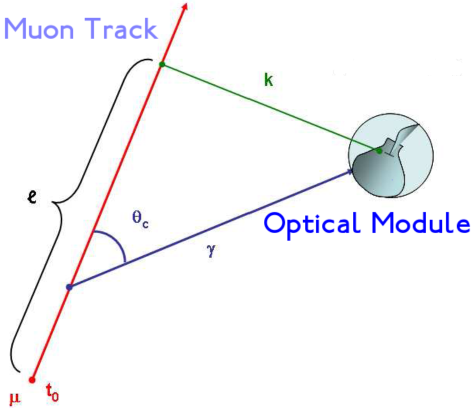
Double-bang signature above ~ 1 PeV

Very low background

Pointing capability

Best energy measurement

Reconstruction of the track...

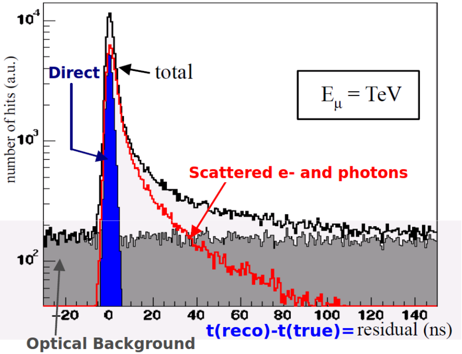


A χ^2 minimisation

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

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

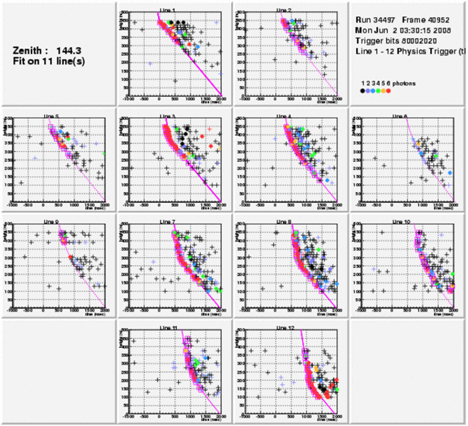
Reconstruction of the track...

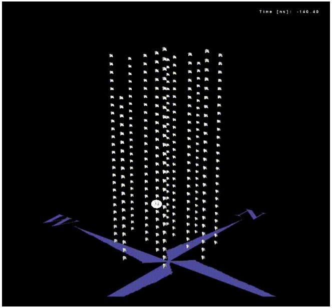


Importance of scattering

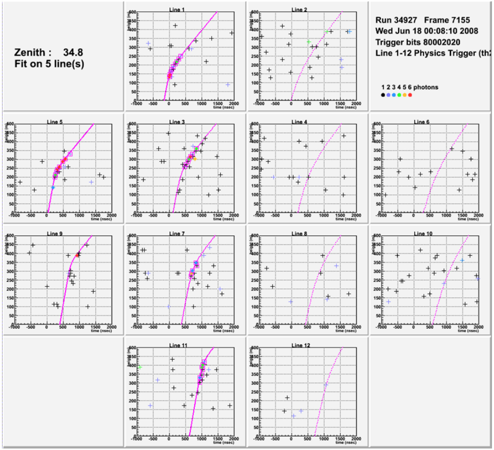
- Few of photons are direct !
- Impact on angular resolution

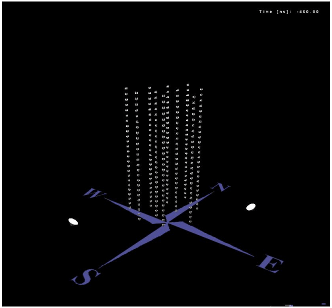
Atmospheric μ (downward) event





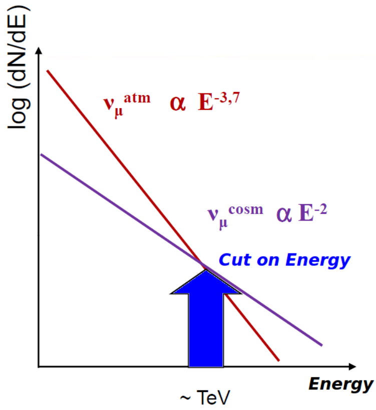
Atmospheric ν (upward) event

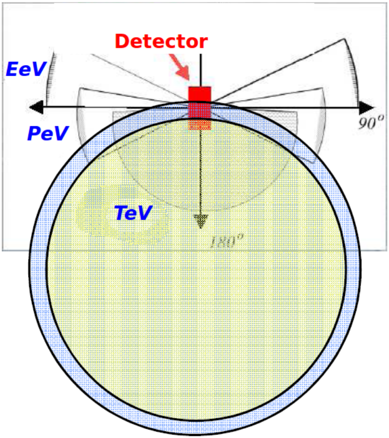




Atmospheric or Cosmic ?

Methods to distinguish between Atmospheric and Cosmic Neutrinos...

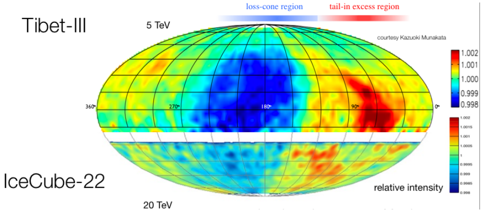


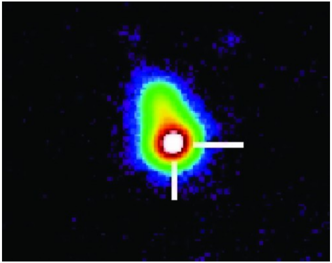


Look for an excess at high energies...⇒ need good energy resolution

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...

Different radiators...

Photons are absorbed and scattered

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

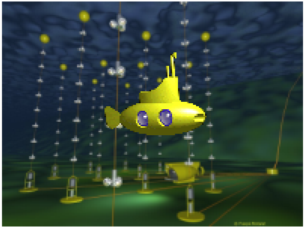
- Note the $1/R$ because light on a cone, not on a sphere ! (`not so easy to demonstrate!`)
- Here Attenuation length : $\frac{1}{\lambda_{\rm att}} = \frac{1}{\lambda_{\rm abs}} + \frac{1}{\lambda_{\rm scatt}}$

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°

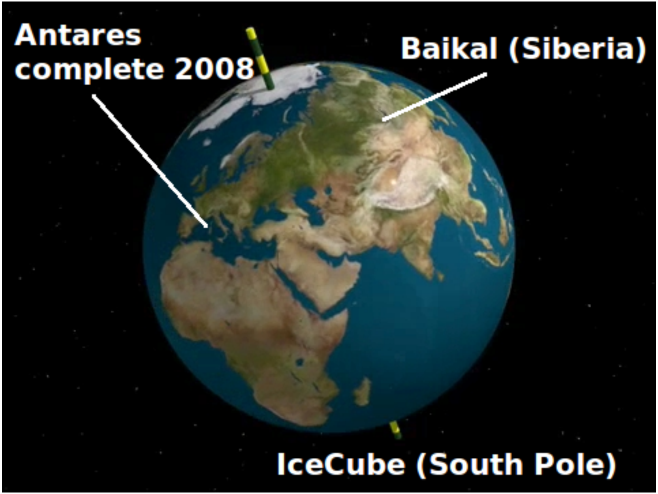
- Ice : no current, no bioluminescence, no β decay from salt
- Water : less scattering, better angular resolution

High-Energy Neutrinos :

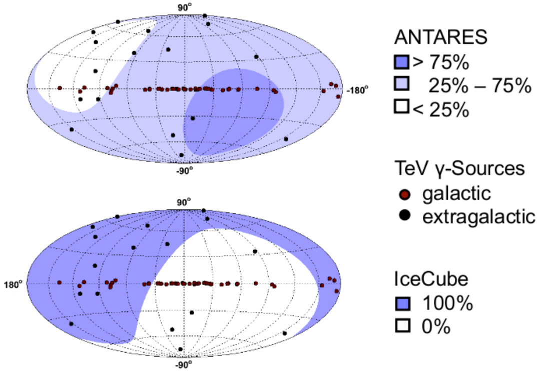
Neutrino Telescopes - IceCube and Antares



Neutrino Telescopes in the World...



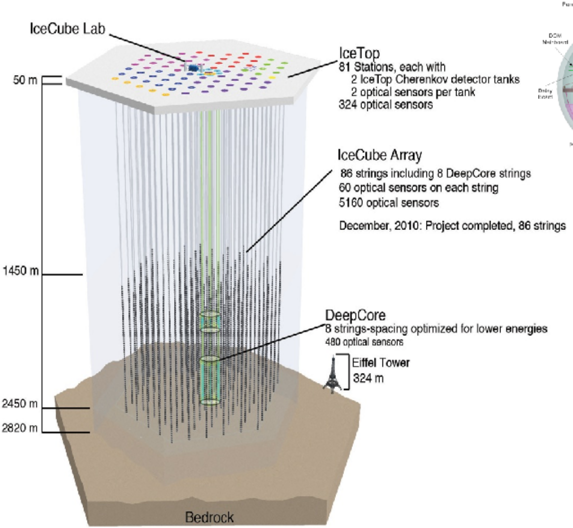
Neutrino Telescopes in the World...

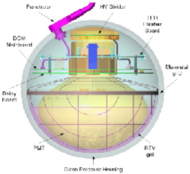


Different Telescopes are complementary

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

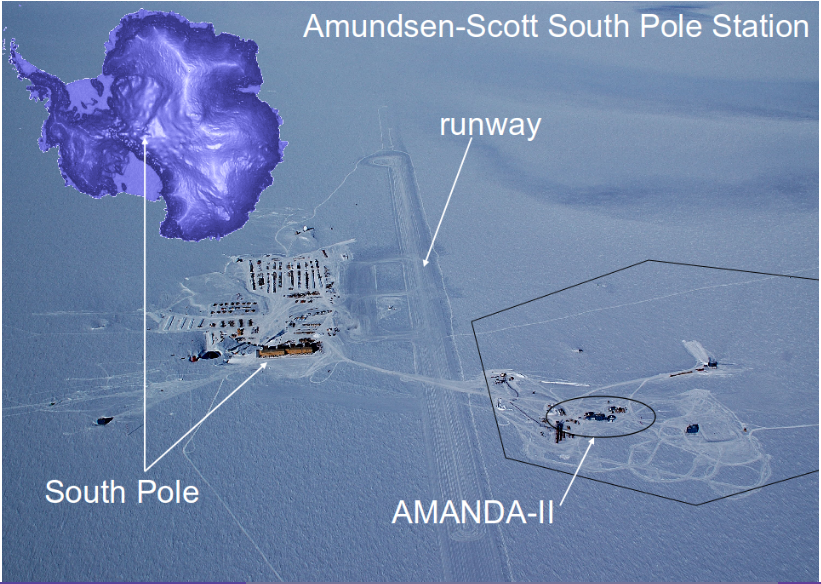
IceCube



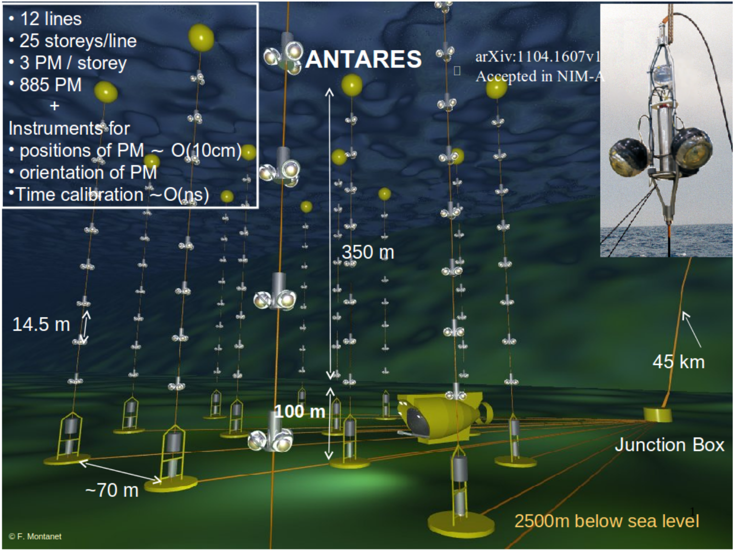


IC1 : 2004-5
IC9 : 2005-6
IC22 :2006-7
IC40:2007-8
IC59:2008-9
IC79:2009-10
IC86:2010-11

IceCube


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

Antares

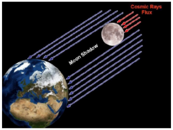

• 12 lines
• 25 storeys/line
• 3 PM / storey
• 885 PM
+
Instruments for
• positions of PM ~ O(10cm)
• orientation of PM
•Time calibration ~O(ns)
ANTARES
arXiv:1104.1607v1
Accepted in NIM-A
350 m
14.5 m
100 m
~70 m
45 km
Junction Box
2500m below sea level
© F. Montanet

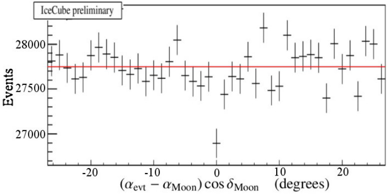
Antares

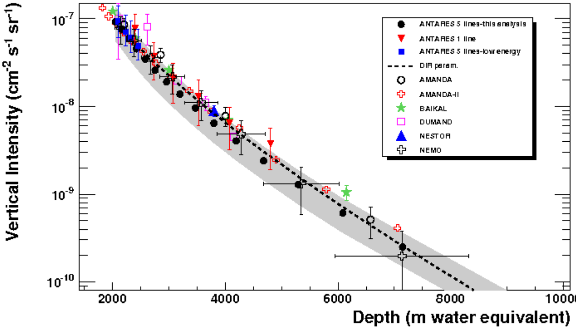
Antares

Antares

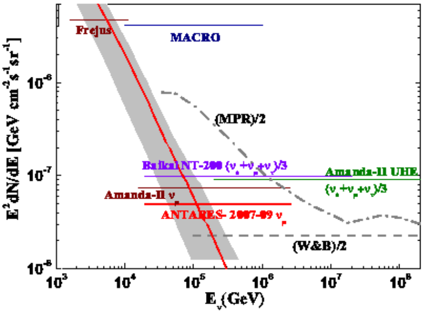
Some “Calibration” Results...

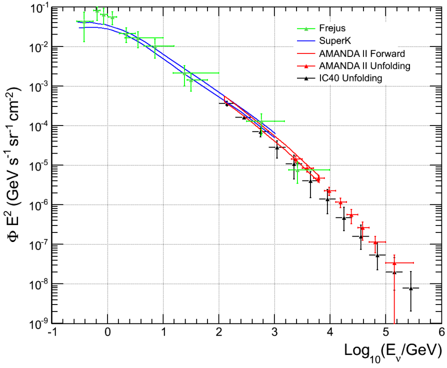




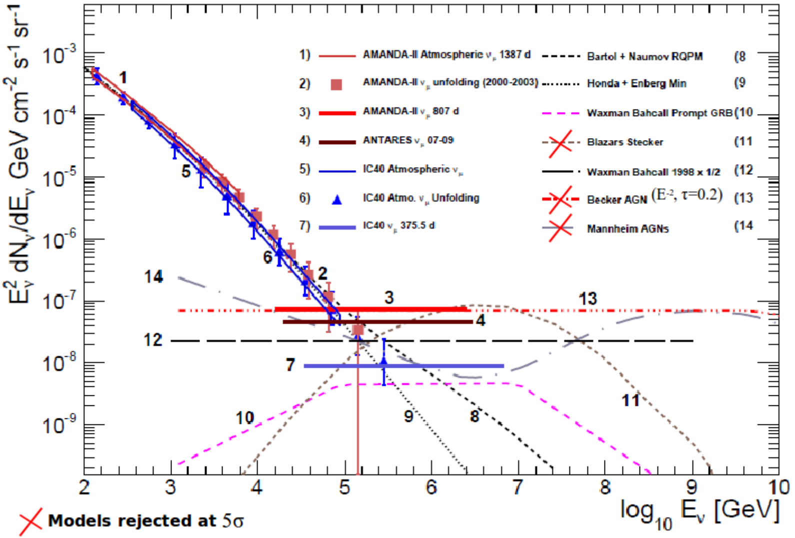


Some “Calibration” Results...

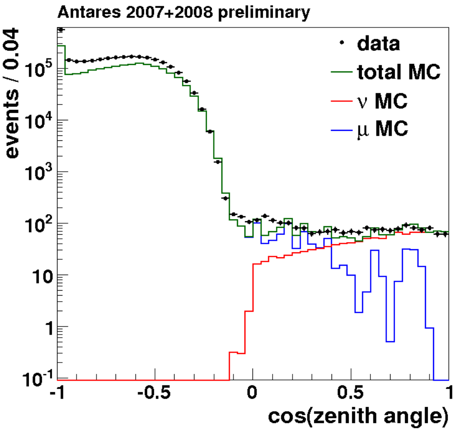


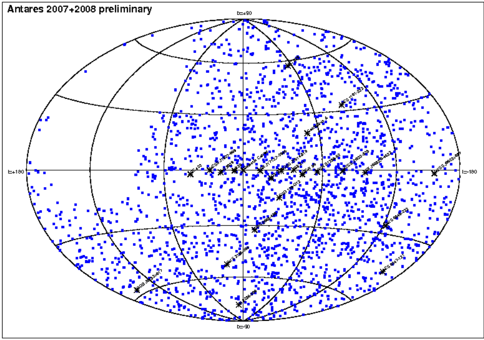


Diffuse Fluxes

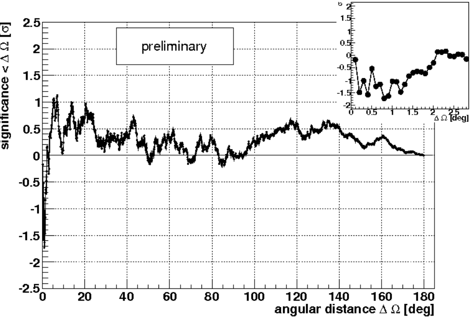


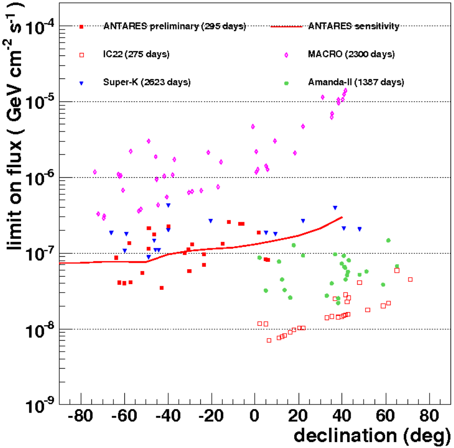
Diffuse Fluxes



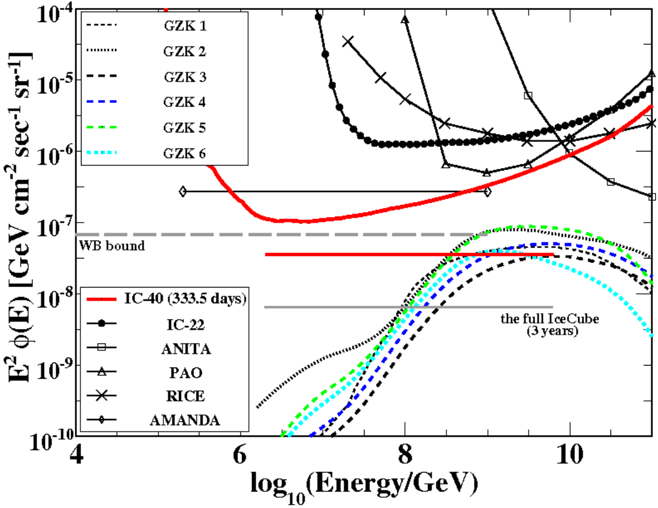


Diffuse Fluxes

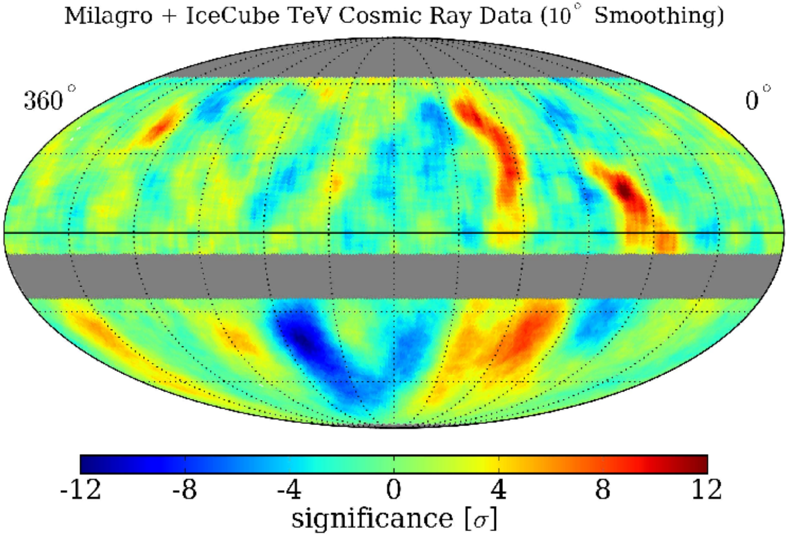




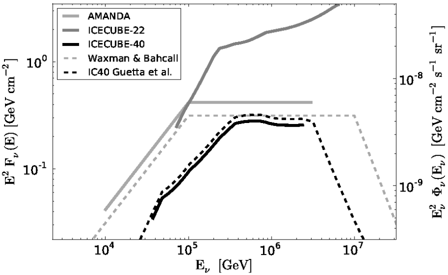
Extremely-High Energies

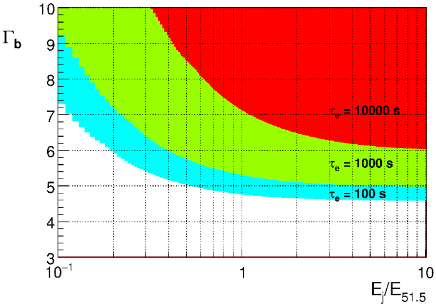


Anisotropies ?

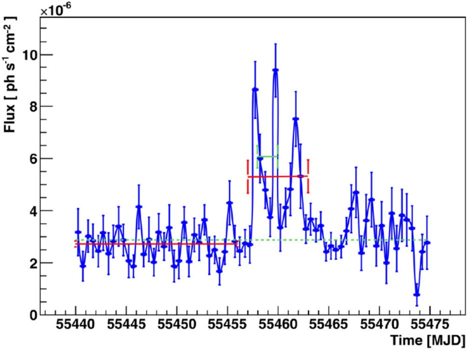


Gamma-Ray Bursts and Supernova SN2008D

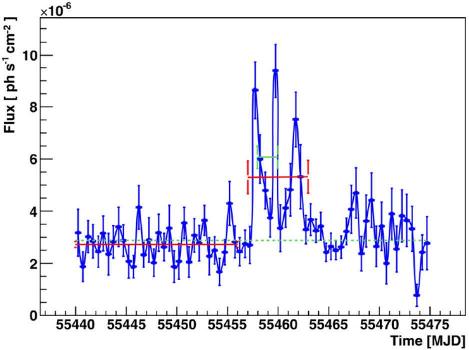


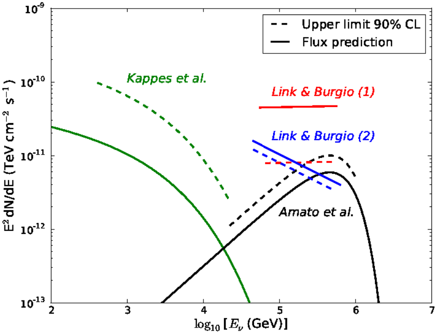


Flare of the Crab Nebula in September 2010

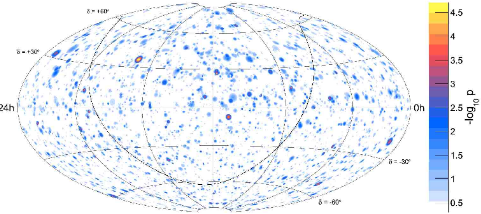


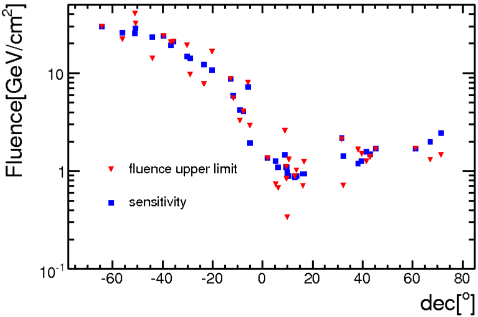
Flare of the Crab Nebula in September 2010





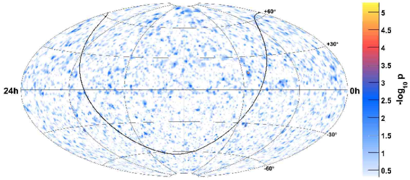
Time-(In)Dependent Point Source Searches

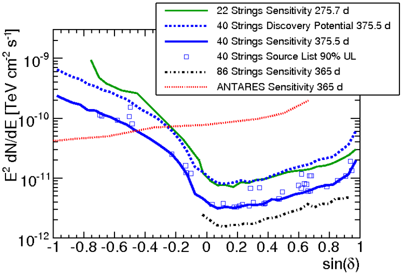




- Selection of sources and time-periods

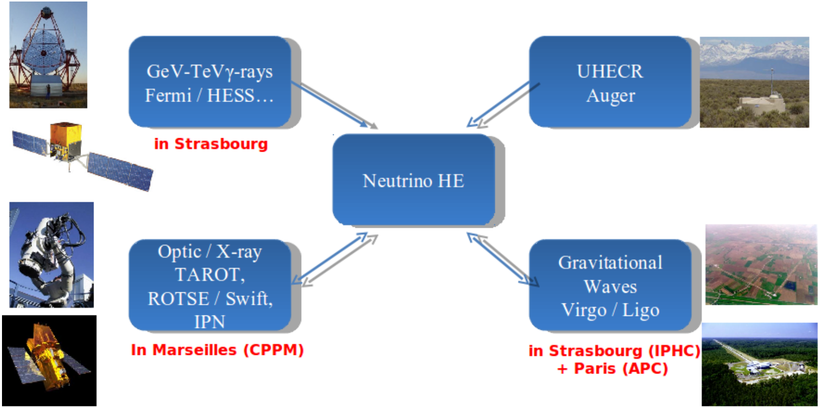
Time-(In)Dependent Point Source Searches





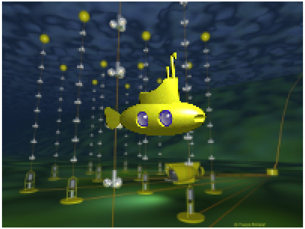
- Time integrated search

Correlations with other messengers...

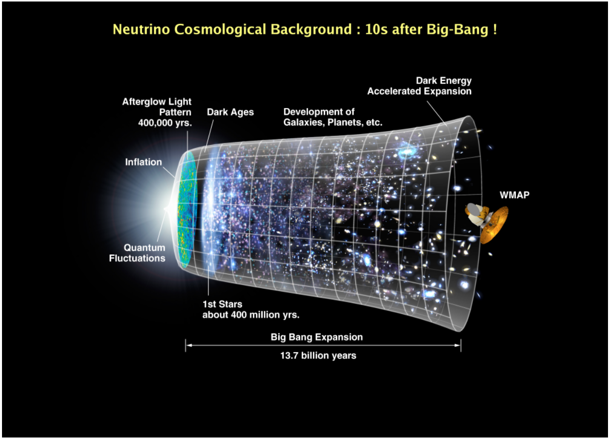


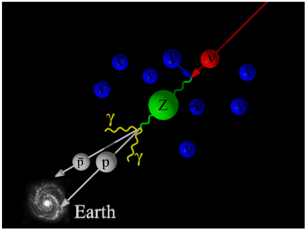
High-Energy Neutrinos :

Perspectives...



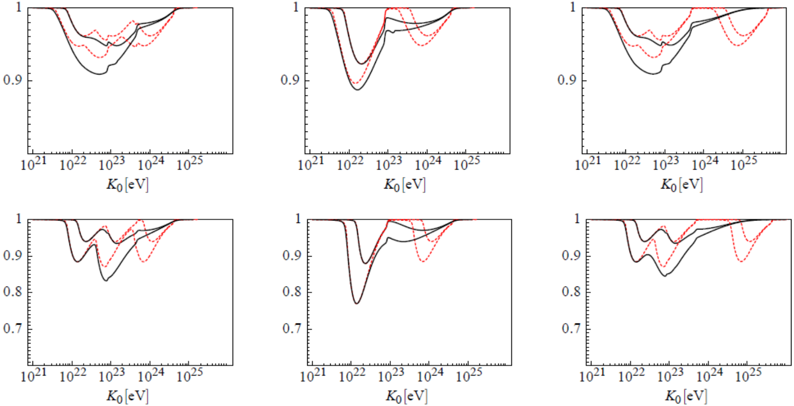
Relic ν and UHE ν





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

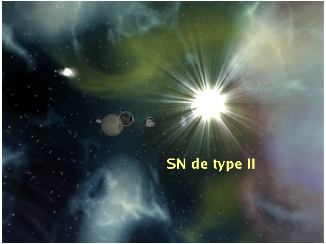
Relic ν and UHE ν

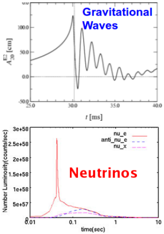


Interaction of ν UHE with Relic ν from Big-Bang

Dip in Neutrino Spectrum...

An example of GW-ν Coincidences : Type II SN





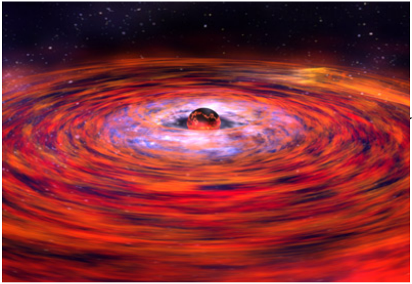
Type II SN

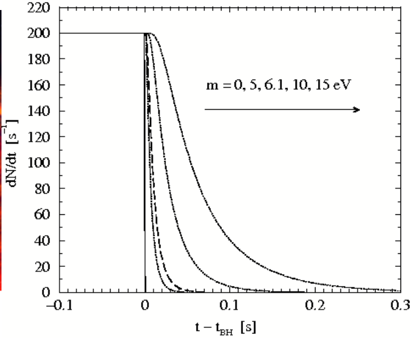
- $m_\nu \neq 0 : \delta t_{\rm propagation} \simeq 5.15 ms \left(\frac{L}{10 kpc}\right)\left(\frac{m_\nu c^2}{1 eV}\right)^2\left(\frac{10 MeV}{E_\nu}\right)^2$
- $E_\nu^{SN} \sim MeV$, $\delta t_{{\rm GW}-\nu_e^{\rm flash}} \lesssim 0.5\ ms$

  $\Rightarrow$ 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

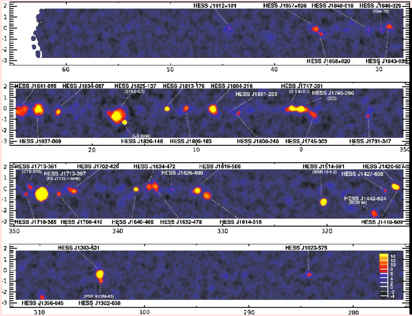
- Quantum Gravity : $c^2p^2 = E^2\left[1 + \xi\left(\frac{E}{E_{QG}}\right) + \mathcal{O}\left(\frac{E^2}{E_{QG}^2}\right) + \ldots\right]$

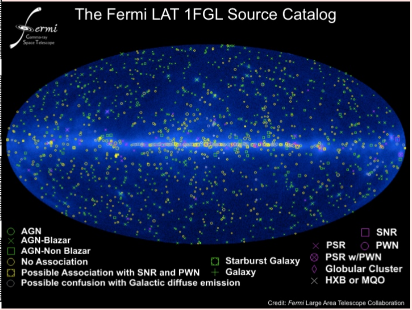
$\Rightarrow$ $|\Delta t_{QG}| \simeq 0.15ms\left(\frac{d}{10\ kpc}\right)\left(\frac{E_\nu^{HE}}{1\ TeV}\right)\left(\frac{10^{19}\ GeV}{E_{QG}}\right)$ for $z \ll 1$

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