High-energy Neutrino Astronomy

An overview oriented towards:
- Cherenkov Technique
- ANTARES

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A few references

Books

- Grotz & Klapdor, *The Weak Interaction in Nuclear, Particle and Astrophysics,* Adam Hilger 1990
- Halzen & Marteen, *Quarks and Leptons*, John Wiley 2004
- Winter, *Neutrino Physics,* Cambridge University Press 1991
- Zuber, *Neutrino Physics*, IoP 2004
- Mohaparta & Pal, *Massive Neutrinos in Physics and Astrophysics*, World Scientific, 2004
- Bahcall, *Neutrino Astrophysics*, Cambridge University Press 1989

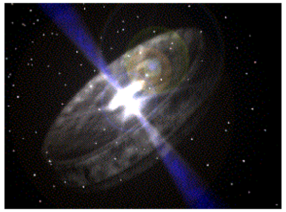
Reviews

✓Baret and Van Elewyck, *High energy neutrino astronomy*, Reports on Progress in Physics, Volume 74, Issue 4, pp. 046902 (2011).

✓Anchordoqui & Montaruli*, In Search for Extraterrestrial High Energy Neutrinos*, Ann. Rev. Nucl. Part. Sci. 60 (2010) 129-162

✓T. Chiarusi, M. Spurio*, High-Energy Astrophysics with Neutrino Telescopes*,, arXiv:0906.2634, 2010

Outline

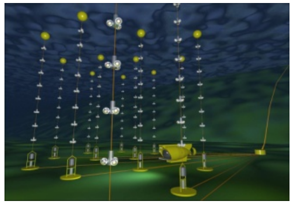


Neutrino astronomy

Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

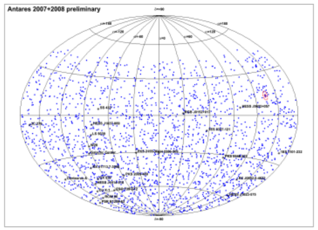


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

Diffuse Flux

Search for point sources

Multi-messenger search

KM3NeT

KM3NeT project

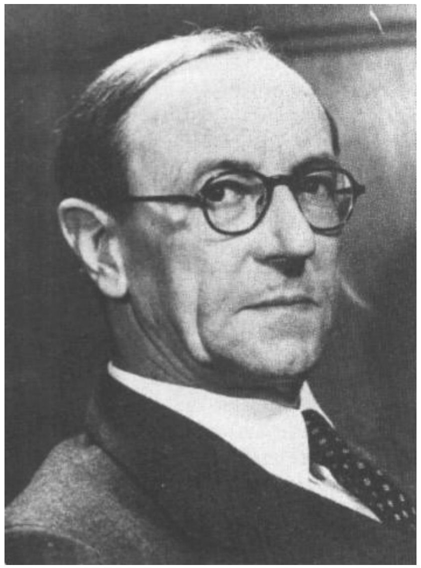
β Radioactivity

1911-1912 : Van Bayer, O. Hahn, L. Meitner
measure the energy of β electrons → discrete spectrum !
📖 Z Physik 12 (1911) 273

1878 - 1968

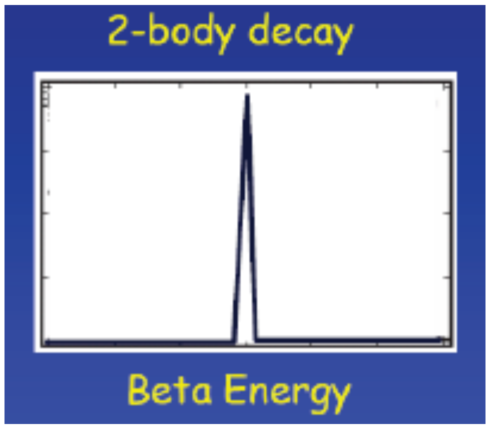
Compatible with interpretations of that time:
nucleus = A protons + (A- Z) electrons
β Disintegration : (A, Z) —> (A, Z-1) + e^-

1914: James Chadwick: The electron energy spectrum is continuous (ionization chamber)

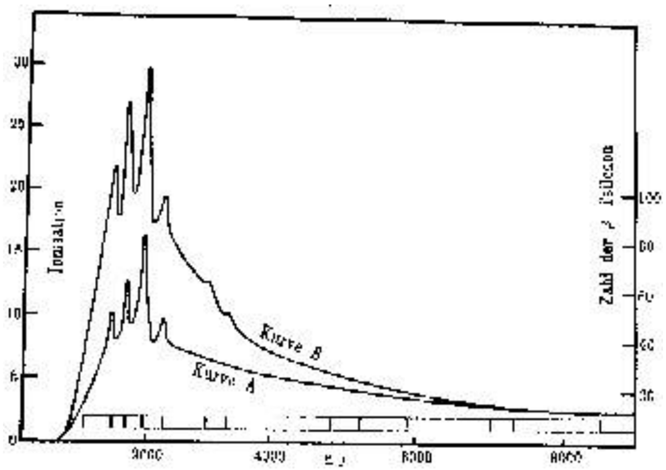


1891 - 1974

Expected



Measured



"there is probably some silly mistake somewhere"

Some interpretations

Several e^- emitted? In 1924 K. G. Emeleus measures that 1.43 e^- is emitted per β decay per nucleon (Geiger counter)

L. Meitner 1924 : β radiation is initially discrete but is transformed into continuous spectrum through secondary processes.
Inhomogeneous slowdown of emitted electrons inside the source.
But the initial electron has never been observed.

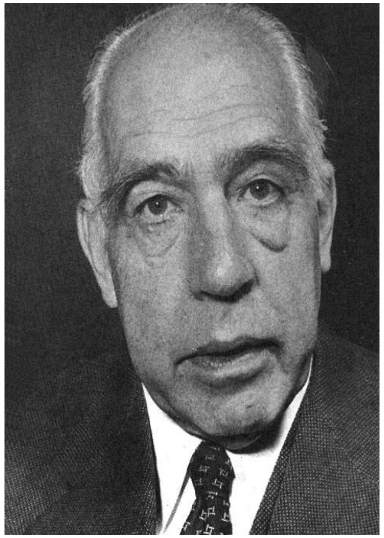
Or the total energy is shared in between the electron and γ rays:
$E_\gamma = E_{max} - E_{e.}$
But where are the γ's?

C. D. Ellis 1924 : The observed lines in Chadwick spectrum are due to γ emitted by the nucleus by internal conversion and which provide energy to the atomic electrons (not related to the intrinsic β process).

The debate is closes in 1927 with calorimetric measurements by Ellis & Wooster

Possible theoritical solutions

Niels Bohr (1885-1962)



« Energy is conserved only statistically » (on average)

📖 Bohr, Kramers, Slater, Phil Mag. 47 (1924) 785

Wolfgang Pauli (1900-1958)

« 1930: another neutral and light particle is emitted »

Letter to « radioactive» physicists meeting in Tübingen.

This is the neutrino birth, first called "neutron".

Dec 4th 1930: Pauli's letter

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the **"wrong" statistics of the N** and Li6 nuclei and the **continuous beta spectrum**, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei **electrically neutral particles**, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. **The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...**

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Brussels: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
W. Pauli

About the “N anomaly”

After Rutherford's experiments had showed that atomic nuclei are made of constituent particles, the world view was that these consisted of protons and electrons. Rutherford himself thought so. The proton was the massive core at the heart of the simplest atom of hydrogen, but he realised that the masses of the nuclei of heavier elements could only be explained if there was also some neutral particle of similar mass to the proton. Rutherford named it the 'neutron'. His picture was that a neutron was some tightly bound combination of a single proton and an electron.

This idea fell apart in 1927. The electron and proton had each been found to spin, and always with the same rate. This was soon explained theoretically by the mathematician Paul Dirac as a consequence of quantum mechanics and relativity.[3] What also became obvious was that a neutron could not be a combination of these two. The reason had to do with what was known as the 'nitrogen anomaly'.

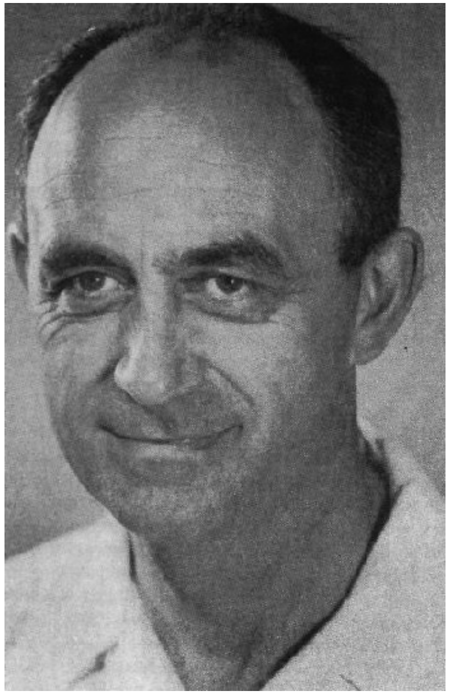
The rates at which various atomic nuclei spin had been measured and showed that a nucleus of nitrogen must contain an even number of spinning constituents. Chemistry showed that a nitrogen atom contains seven electrons, and so its nucleus must have seven protons to counterbalance the electric charge.

If this had been the whole story, a nitrogen nucleus would only have been half as massive as in reality. So seven neutrons were called for. If neutrons were single beasts, like protons, this 7 + 7 = 14 would satisfy the even-number rule. However, if each neutron was really a pair, the total number of constituents would become 21, an odd number. Rutherford's picture of a proton-electron combination simply didn't fit the facts.

This is where Wolfgang Pauli enters the story, inventing a new neutral particle which, he initially thinks, can solve two puzzles for the price of one particle.

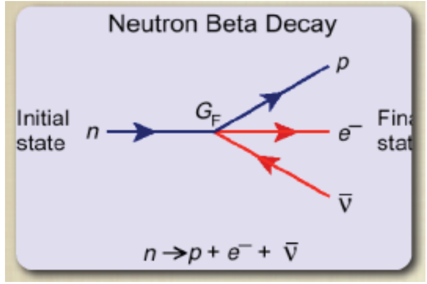
From *Neutrino*, F. Close, Oxford University Press, 2010

1933: Fermi theory (β)



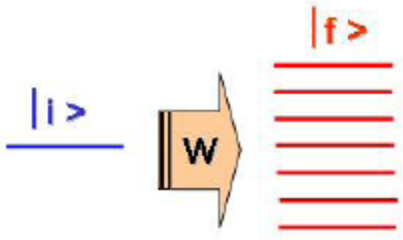
1901 - 1954

📖Nuovo Cimento 11 (1934) 1; Z Physik 88 (1934) 161.



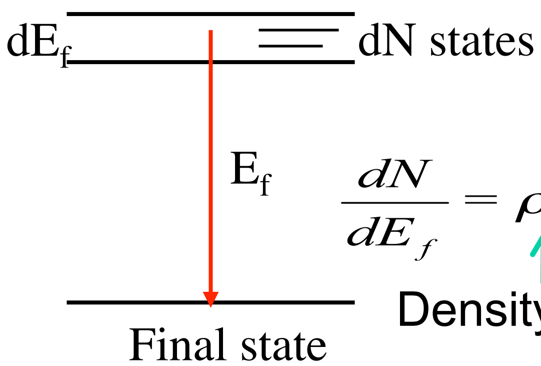
- A nuclear transition takes place when a neutron is destroyed and a proton is created. An electron and a neutrino are emitted. Local interaction.
- Neither the electron nor (anti)neutrino pre-exist in the nucleus. Both are created in the decay process.

- The neutrino is formally treated as a ½ spin particle
- Fermi inspires from the **theory of perturbations at first order**
- **Fermi's Golden Rule**



$$\delta P_{i\to f} = \frac{2\pi}{\hbar} |\langle f|\, W \,|i\rangle|^2 \rho(E_f) \quad \text{sec}^{-1}$$

$$\lambda = \frac{2\pi}{\hbar} |\langle f|\, W \,|i\rangle|^2 \rho(E_f) \quad \text{sec}^{-1}$$



$$\frac{dN}{dE_f} = \rho(\mathrm{E})$$

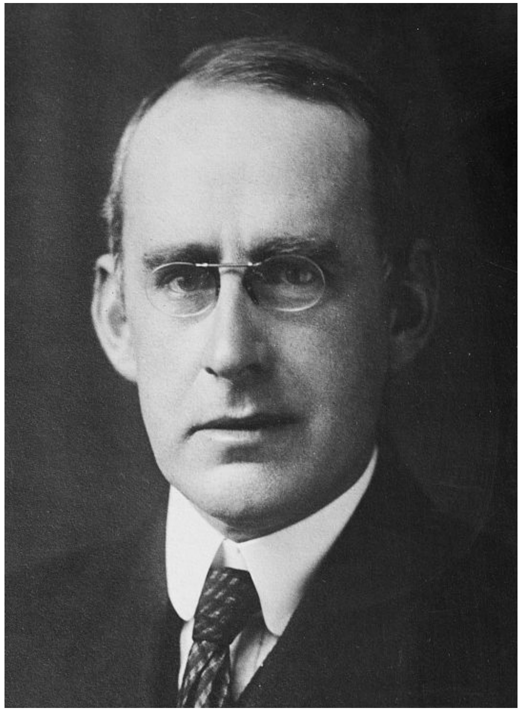
Density of final states

$$\lambda = \frac{1}{\tau} \ll \frac{\Delta E}{\hbar}$$

Slowness of weak interactions justifies treatment at 1st order

Debate and controversy

Amusing to notice that Fermi article "Tentative Theory of beta rays" was rejected by *Nature* *because it "contained speculations too remote from reality to be of interest to the reader" …*



1882 - 1944

Just now nuclear physicists are writing a great deal about hypothetical particles called neutrinos supposed to account for certain peculiar facts observed in ß-ray disintegration. We can perhaps best describe the neutrinos as little bits of spin-energy that have got detached. I am not much impressed by the neutrino theory. In an ordinary way I might say that I do not believe in neutrinos... But I have to reflect that a physicist may be an artist, and you never know where you are with artists. My old-fashioned kind of disbelief in neutrinos is scarcely enough. Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos? Whatever I may think, I am not going to be lured into a wager against the skill of experimenters under the impression that it is a wager against the truth of a theory. If they succeed in making neutrinos, perhaps even in developing industrial applications of them, I suppose I shall have to believe—though I may feel that they have not been playing quite fair.

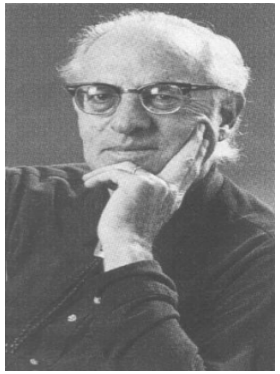
Sir Arthur Stanley Eddington
The Philosophy of Physical Science (1939)

Still, if Fermi's theory is correct…it opens up a possibility for the neutrino to be revealed !

Reines and Cowan

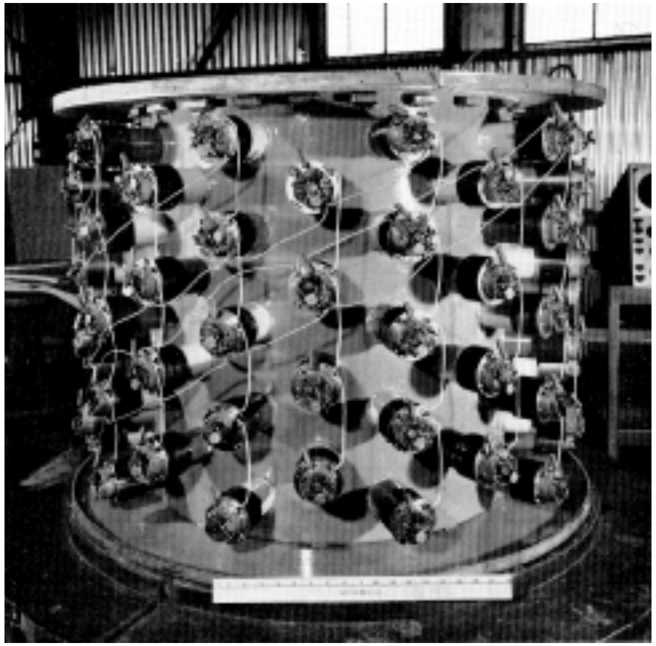
$$p+\overline{\nu} \rightarrow n+e^{+}$$

Reaction threshold = 1,8 MeV



1953 : Hanford
300 liters of scintillators only.
Encouraging results, but too high background

'Poltergeist ' project



1956 : Savanah River
Target made of 400 liters of water and Cadmium Chlorure.
The neutrino interacts with a proton and undergo a positon (e+) and un neutron (n).

$$e^{+}+e^{-} \rightarrow \gamma+\gamma$$

$$\mathrm{n} + {}^{108}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd}^{*} \rightarrow {}^{109}\mathrm{Cd} + 3\gamma$$

$$\gamma+e^{-} \rightarrow \gamma+e^{-} \text{ (compton)}$$

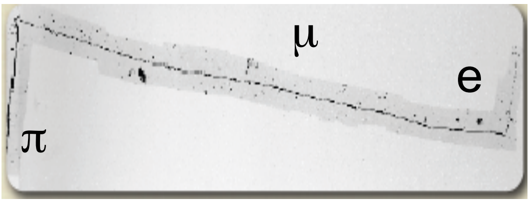
~ μs later

Are ν_μ and ν_e different?

Interrogation motivated by the absence of observation of some processes (conservation of the leptonic number)

$$\mu^+ \to e^+ + \gamma \qquad \mu^+ \to e^+ + e^+ + e^- \qquad \mu^+ + N \to e^+ + N$$

This would imply that neutrinos from pion decay are different from β induced neutrinos



$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\nu_\mu + n \to \mu^- + p \quad \text{allowed}$$

$$\nu_\mu + n \to e^- + p \quad \text{not allowed}$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\bar{\nu}_\mu + p \to \mu^+ + n \quad \text{allowed}$$

$$\bar{\nu}_\mu + p \to e^+ + n \quad \text{not allowed}$$

1962: Brookhaven experiment

As a consequence, the 2 neutrinos from μ decay are of different species

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

Discovery of muon neutrino

📖 PRL 9, 36-44, 1962

AGS 15 GeV Proton Beam

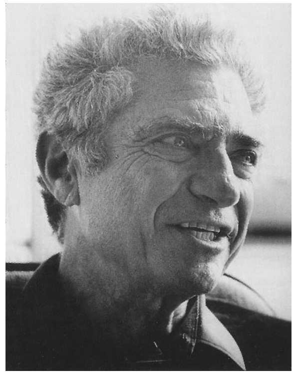
34 evts (P_μ>300MeV)

Expected background (atm) = 5

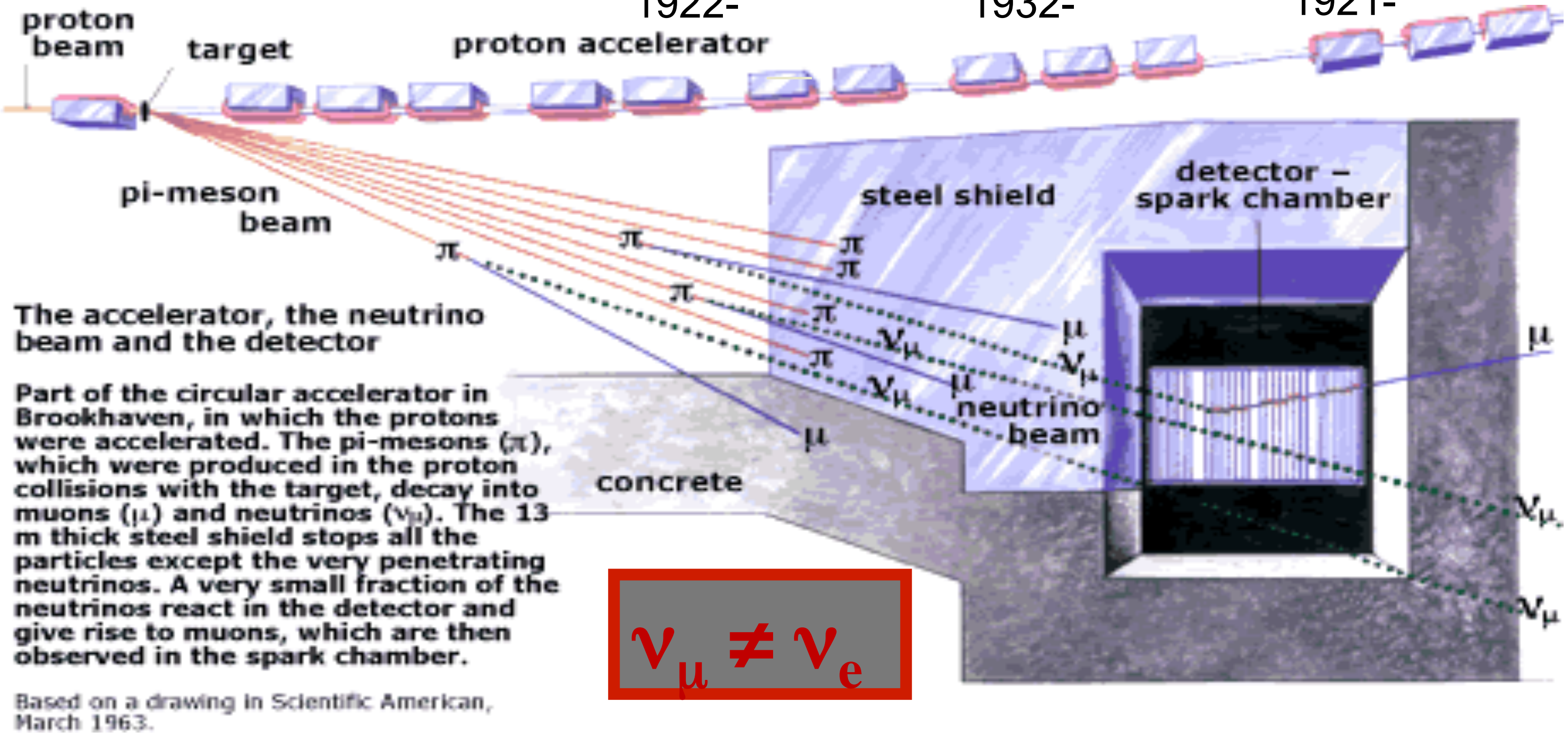
Nobel price 1988

L. Lederman
1922-

M. Schwartz
1932-



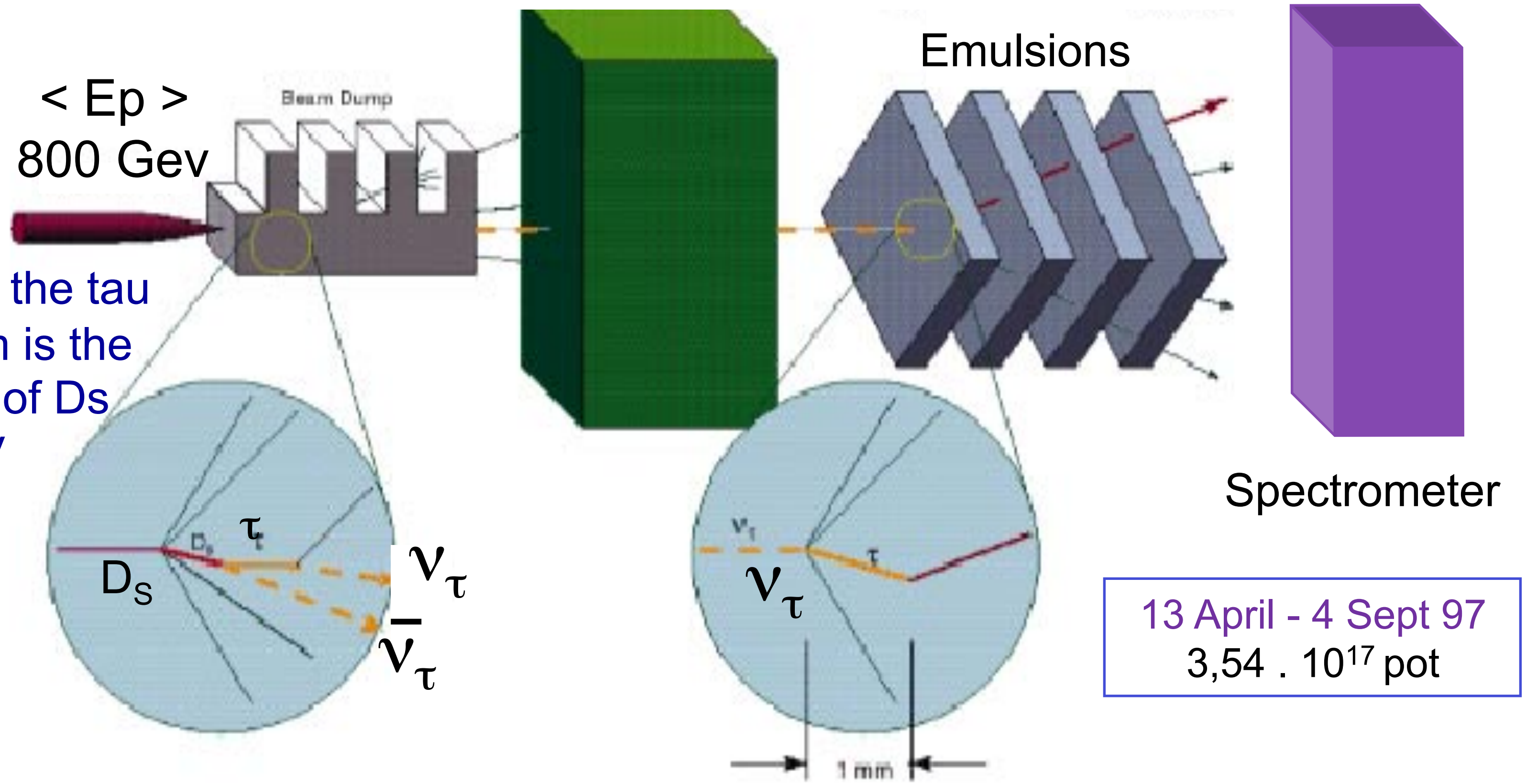
J. Steinberger
1921-



$\nu_\mu \neq \nu_e$

Direct observation of tau neutrino

2000: Results of the **DONUT (E872)** experiment at Fermilab
Observation of the charged current interaction of tau neutrino —> detection of τ lepton



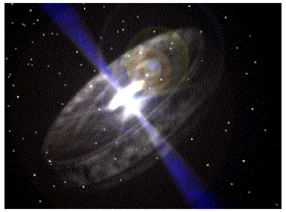
The source of the tau neutrino beam is the disintegration of Ds
$<E_\nu>=111$GeV

13 April - 4 Sept 97
3,54 . 10^{17} pot

Typical event:
One track (tau lepton) + disintegration kink with high transverse momentum Pt + missing energy

$\tau \to e\ \nu_\tau\ \nu_e\ \ (18\%)\ \ \tau \to \mu\ \nu_\tau\ \nu_\mu\ \ (18\%)\ \ \tau \to h + \text{neutral}\ (50\%)$

Outline

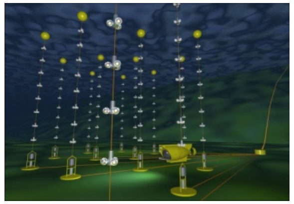


Neutrino astronomy

Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

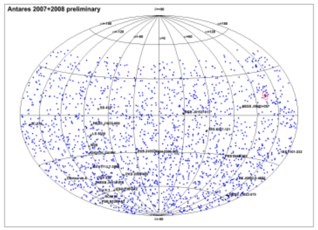


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

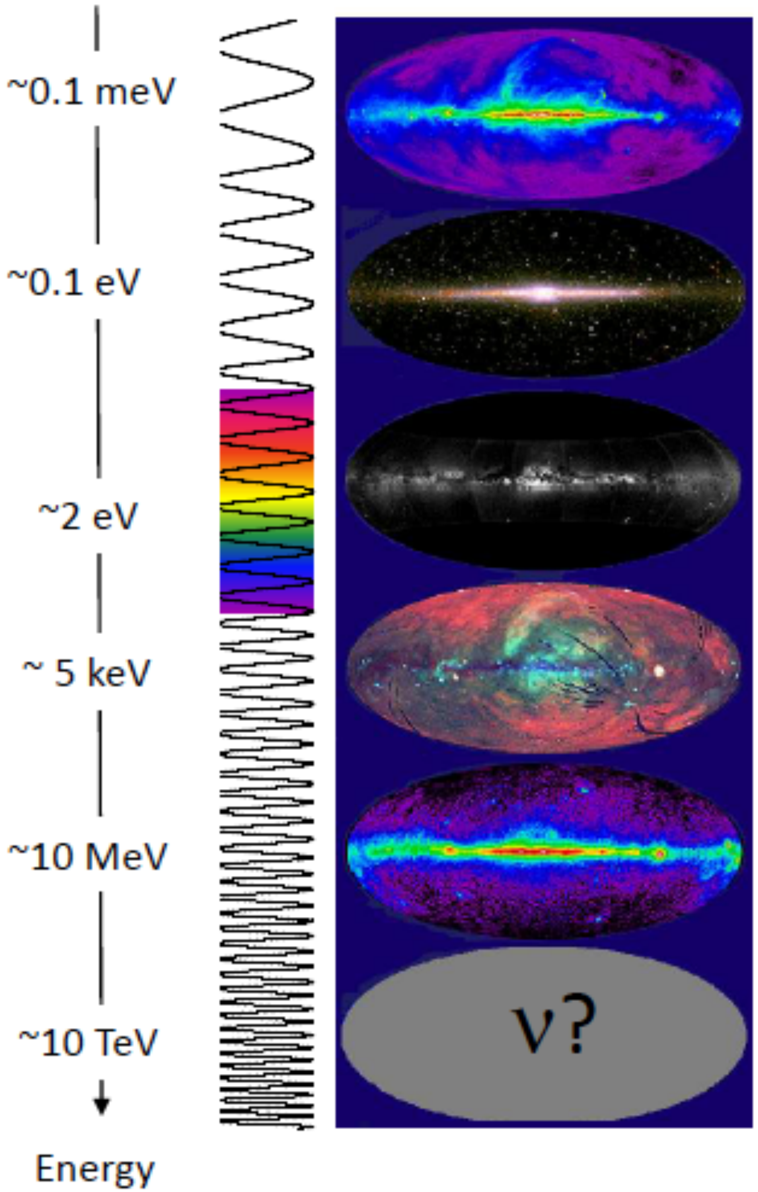
Diffuse Flux

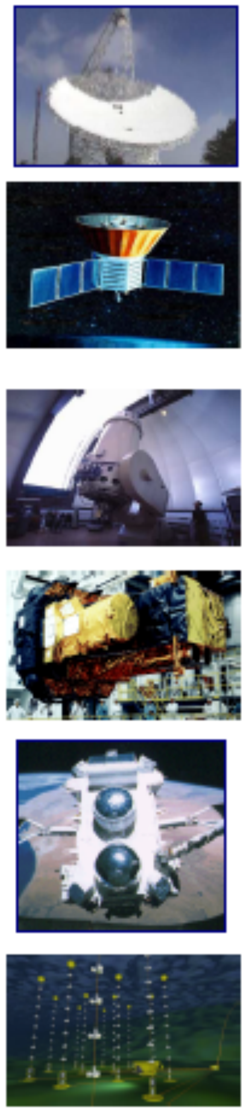
Search for point sources

Multi-messenger search

KM3NeT project

Motivations





Multi-messenger astronomy
Open a new window at
High energy
(>100 GeV)

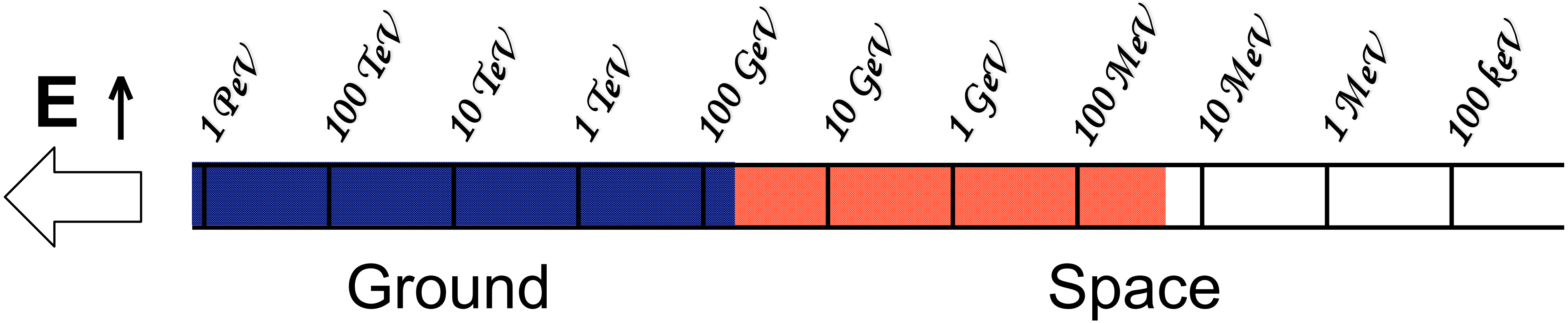
More comprehensive picture
of the most violent
objects in the Universe

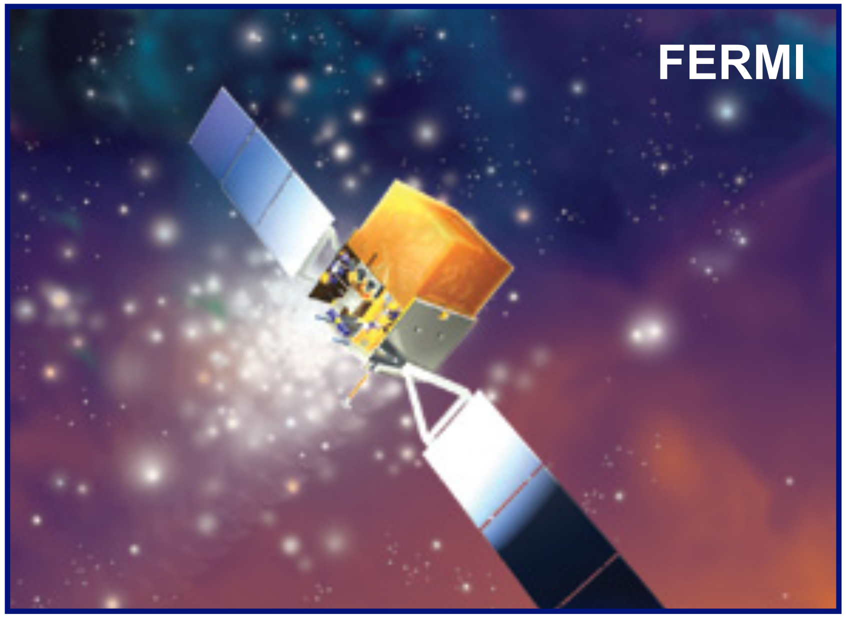
Origin of UHECRs

Dark matter

High-energy gamma-rays

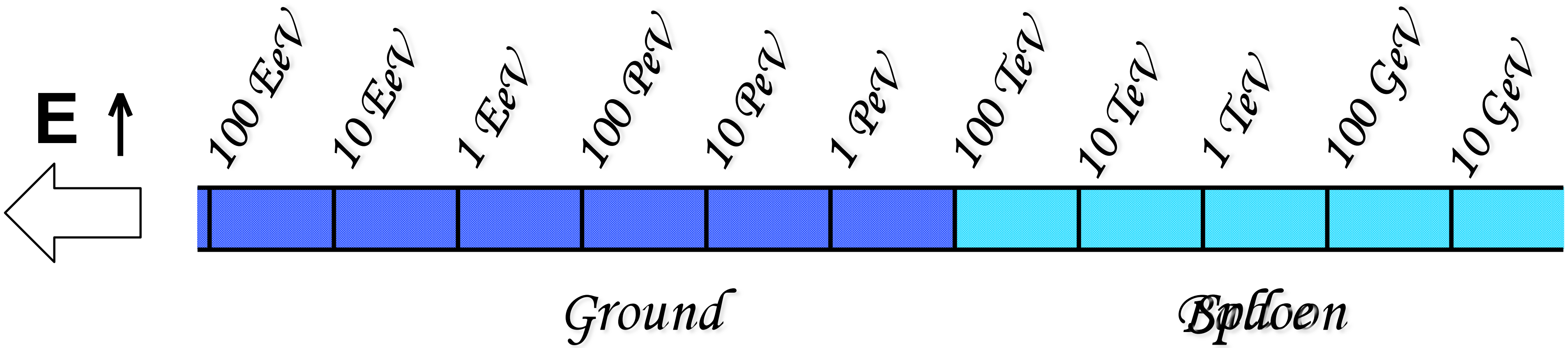
Crédit :J. Paul





Charged cosmic rays

Crédit :J. Paul



Gravitational waves

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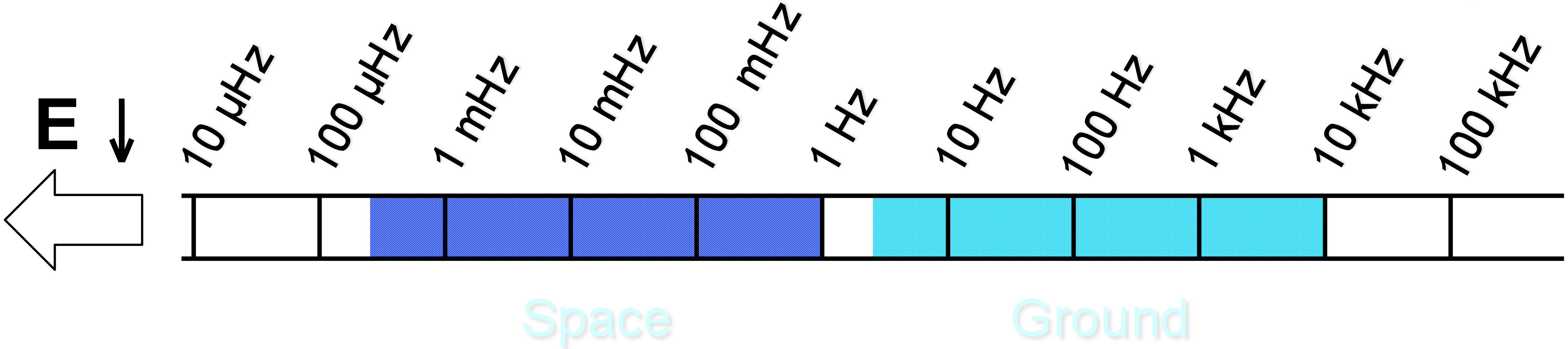
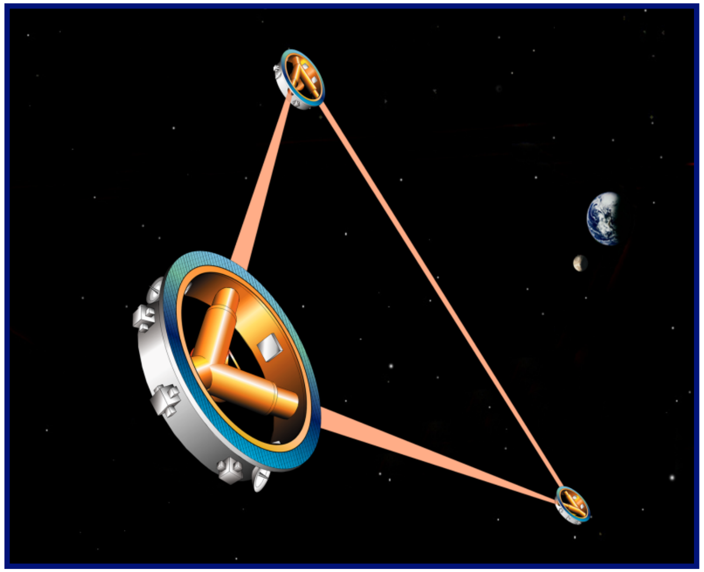
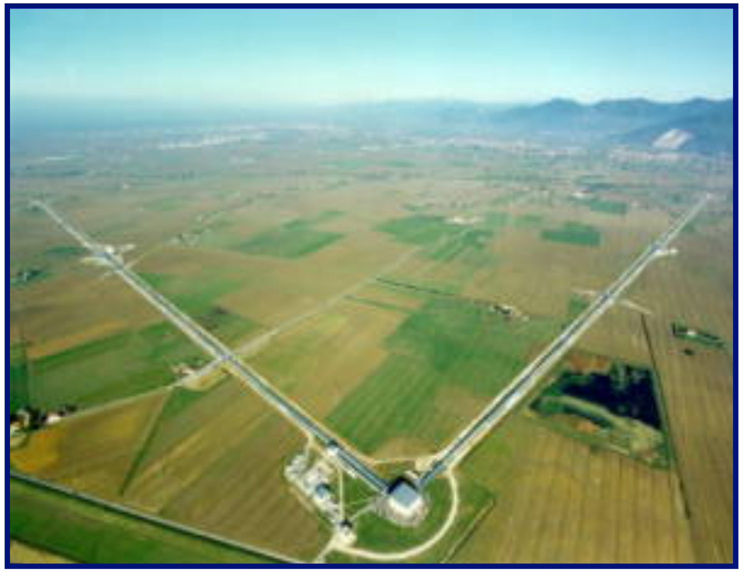
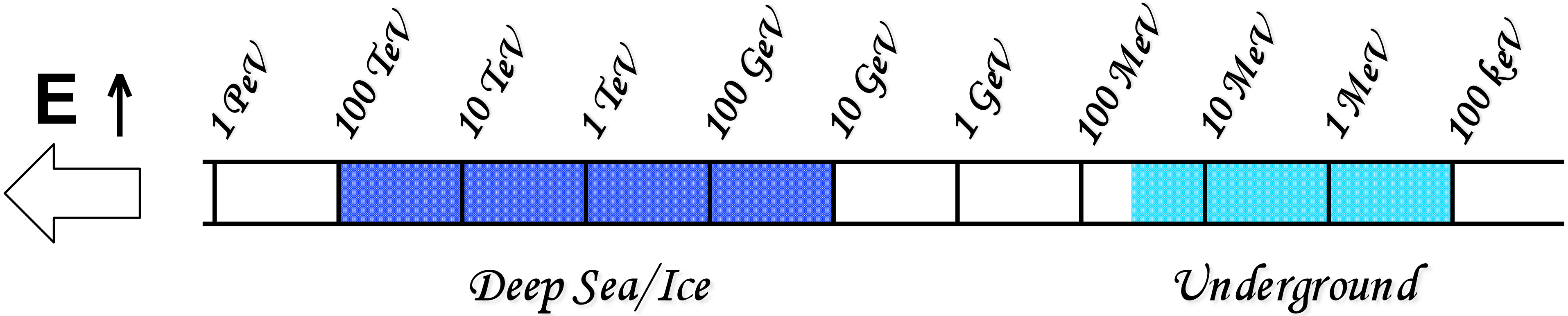


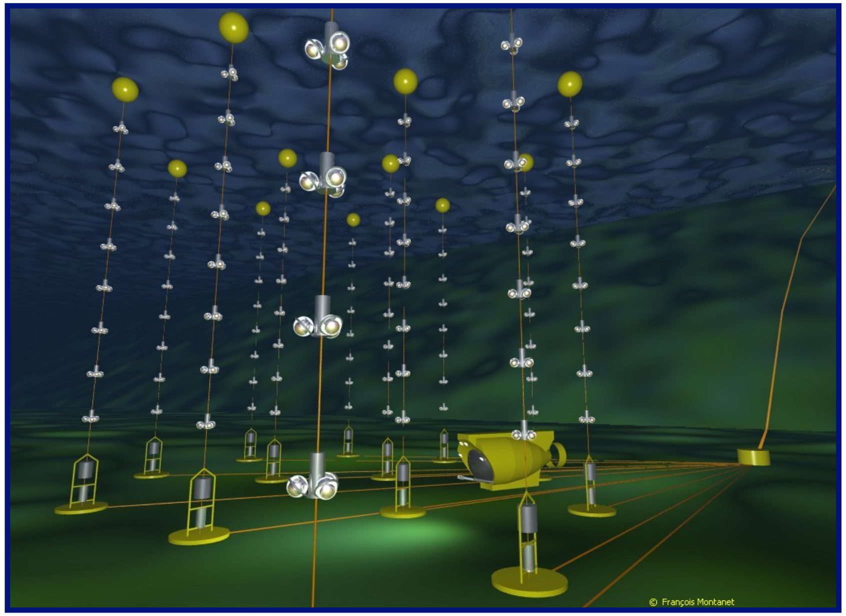


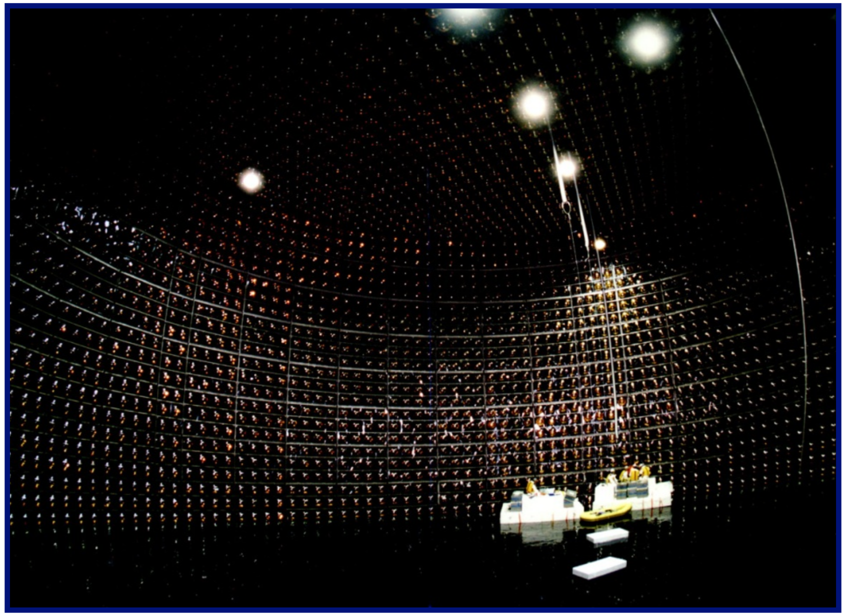


Neutrino telescopes

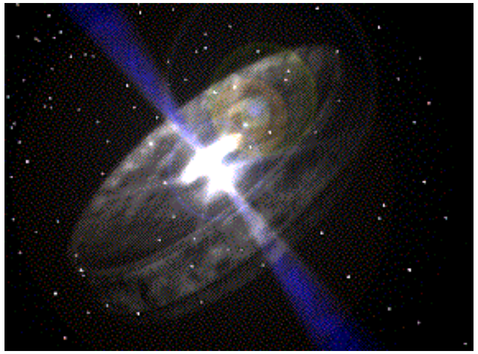
Crédit :J. Paul

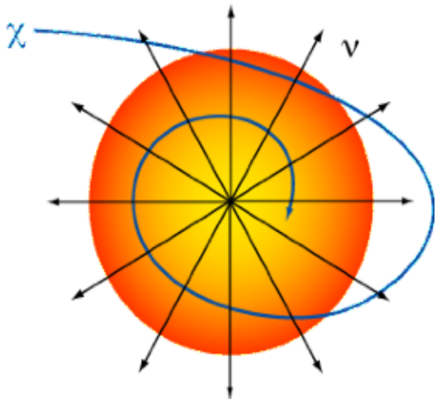


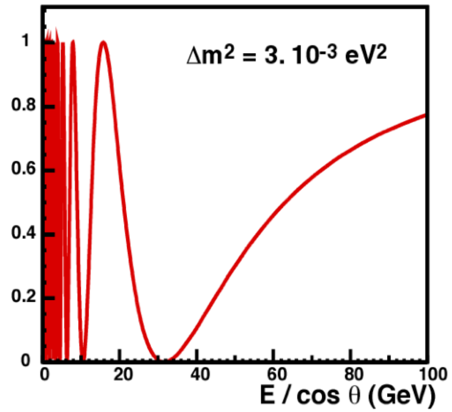




Neutrino telescopes science scope







High Energy	Medium Energy	Low Energy
E_ν > 1 TeV	10 GeV < E_ν < 1 TeV	10 GeV < E_ν < 100 GeV

ν from extra-terrestrial sources

Dark matter search

ν oscillations

Origin and production mechanism of HE CR

→ Primary goal

Exotic particle physics
Monopoles, nuclearites,…

Marine sciences: oceanography, biology, geology…

First ideas early 60's

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

NEUTRINO INTERACTIONS[1]

BY FREDERICK REINES[2]

IV. COSMIC AND COSMIC RAY NEUTRINOS

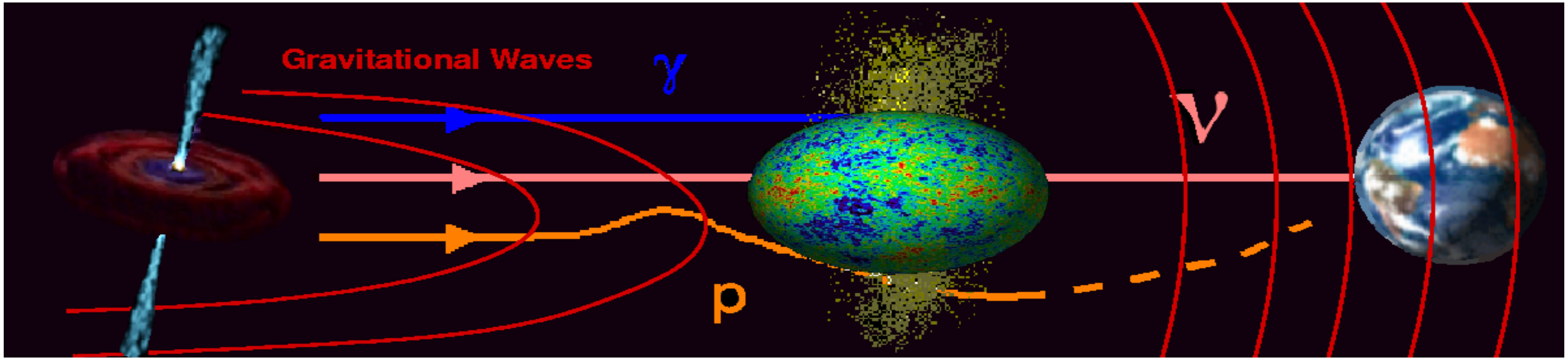
As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems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

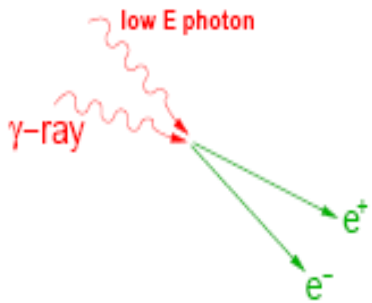
The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

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

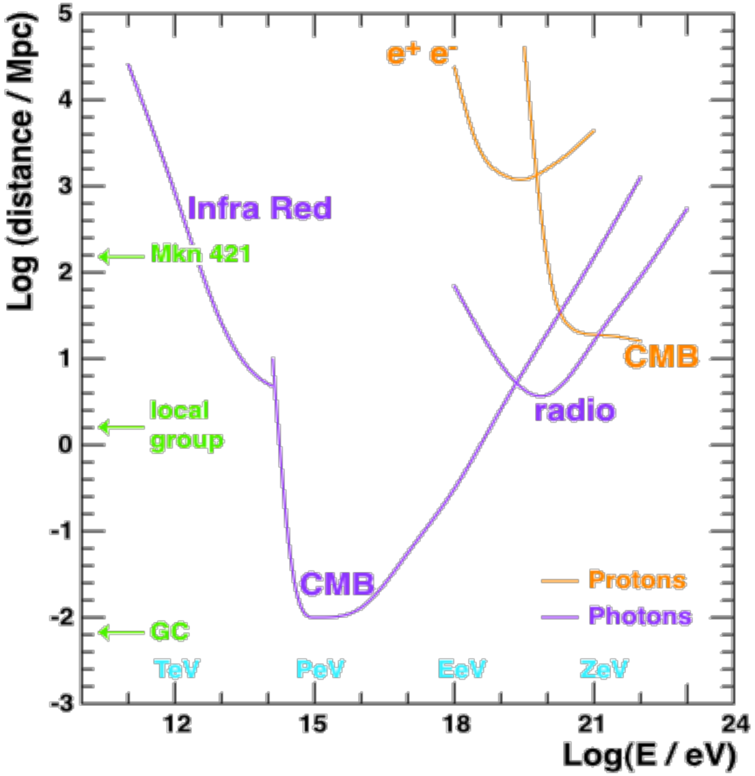
On may even anticipate eventual high-energy neutrino astronomy, since neutrino travel in straight lines, unlike the usual primary cosmic rays, and the neutrinos will convey a new type of astronomical information quite different from that carried by visible light and radio waves

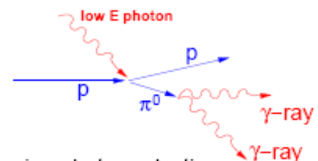
Multi-messenger astronomy



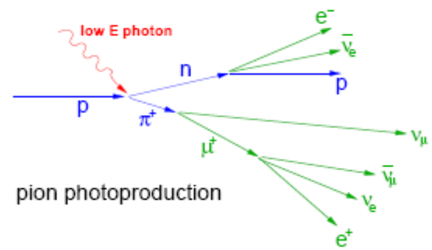


photon−photon pair production





pion photoproduction



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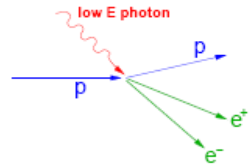


Bethe−Heitler pair production

Horizons of HE astroparticle astronomy

EXERCICES:

1.What is the distance that a neutron of 10^{18} eV would travel?

$$\tau_0 = 885.7s \approx 15\min \Rightarrow \tau_{lab} = \gamma\tau_0 = \frac{E}{m}\tau_0 \approx \frac{10^{18}}{10^9}\tau_0$$

$$D = \frac{\tau_{lab}}{c} \approx 9\text{kpc}$$

2.Consider the process $\gamma_{HE}\gamma_{CMB}\rightarrow e^-e^+$. Try to estimate the energy of the HE photon for which the interaction length will be minimal. Is it compatible with the plot shown before?.

$$\left\{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2\right\}_{lab} = \left\{(m_1 + m_2)^2 - (\vec{0} + \vec{0})^2\right\}_{cm} = 4m_e^2$$

$$2(E_1E_2 - \vec{p_1}.\vec{p_2}) = 2E_1E_2(1 - \cos\theta)$$

The minimum energy is required for head-on collision ($\theta=\pi$) $\Rightarrow E_2 \geq \frac{m_e^2}{E_1}$

Energy of black body spectrum $h\nu/kT$ =2.8 $\Rightarrow E_1 \approx 6.10^{-4}\,\text{eV} \Rightarrow E_2 \approx 4.10^{14}\,\text{eV}$

But we should consider the increase of the cross section near the threshold, that will slightly shift the result towards higher value. Far above threshold: $\sigma_{\gamma\gamma} \propto \frac{1}{E_1}$

3. What can you say about the $\gamma_{HE}\gamma_{CMB}\rightarrow\mu^-\mu^+$.process ?

Same as above with $m_\mu \approx$ 200 m $\Rightarrow E_2 \approx (200)^2\, 4.10^{14}\,\text{eV} \approx 1.6.10^{19}\,\text{eV}$

Competion with $\gamma_{HE}\gamma_{radio}\rightarrow e^-e^+$ but cross section and photon density smaller.

What horizon for charged particles?

Charged particles also interact with radiation fields: **GZK cut-off**

- absorbed by photo production of Δ resonance:

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi + p$$

- At energy threshold:

$$2E_p E_{CMB} > (m_\Delta^2 - m_p^2) = 50x10^{18} = 5x10^{19}\, eV$$

- Absorption length:

$(n_{CMB} = 400/cm^3; \sigma_p \gamma_{CMB} = 10^{-28} cm^2)$

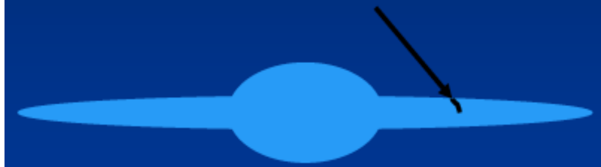
$$\lambda_{\gamma p} = (n_{CMB} \sigma_{p+\gamma_{CMB}})^{-1} \cong 10 Mpc$$

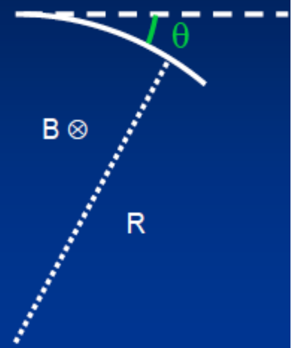
And are deflected by magnetic fields…

Gyromagnetic (Larmor) radius $\propto$ E / Z B

R(kpc) = E(10^{18} eV) / Z B(μG)

θ(rad)= L(kpc) Z B(μG) / E(10^{18}eV)





Galaxy B=2μG, Z=1, L=1kpc

θ = 120° at 10^{18} eV

= 12° at 10^{19} eV

= 1.2° at 10^{20} eV

The window for CR astronomy is small around 10^{19} eV (but exists, see AUGER experiment)

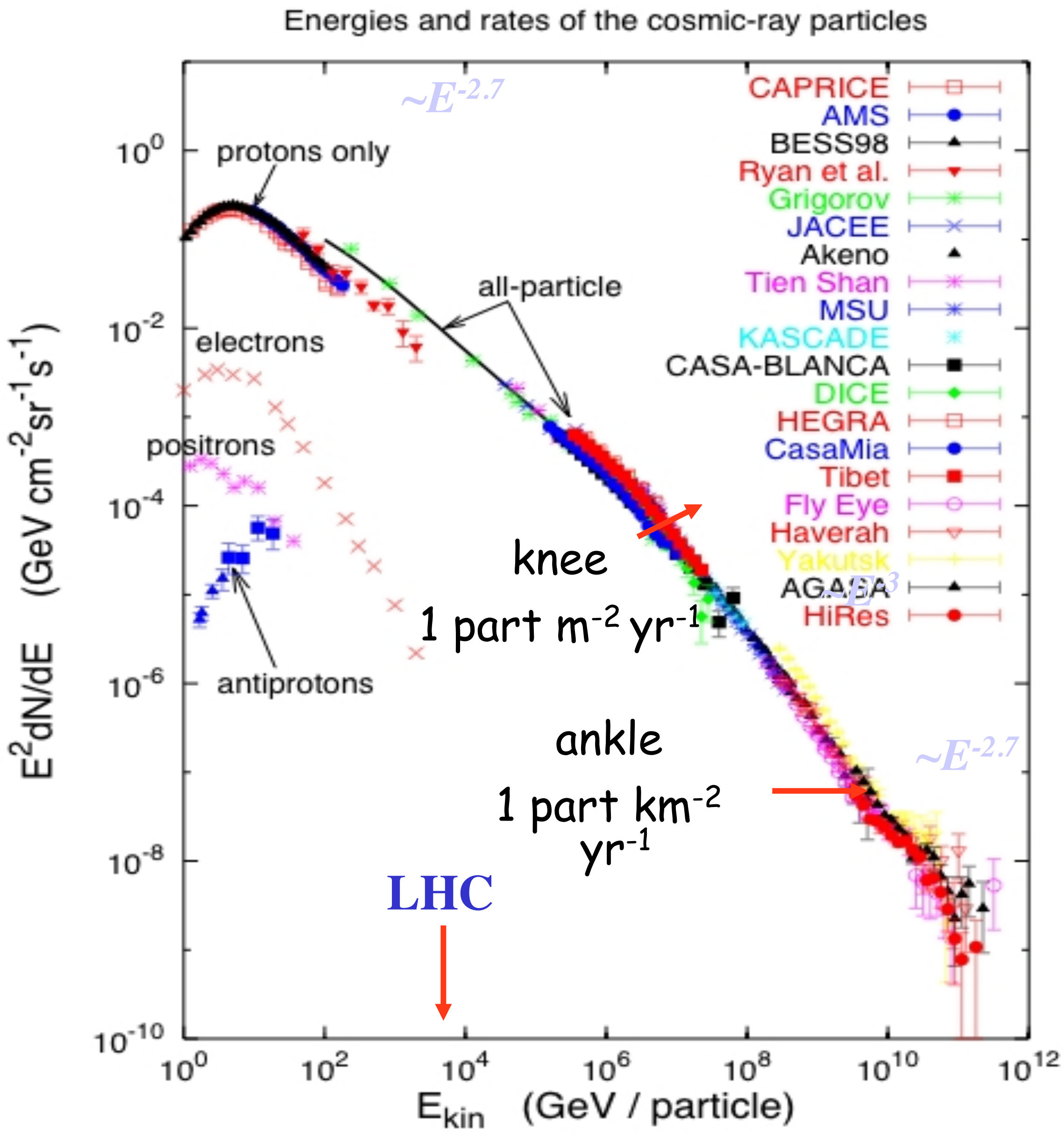
UHE cosmic rays

Nature accelerates particles 10 ⁷ times the energy of LHC!

Cutoff now confirmed
But…

where?

how?



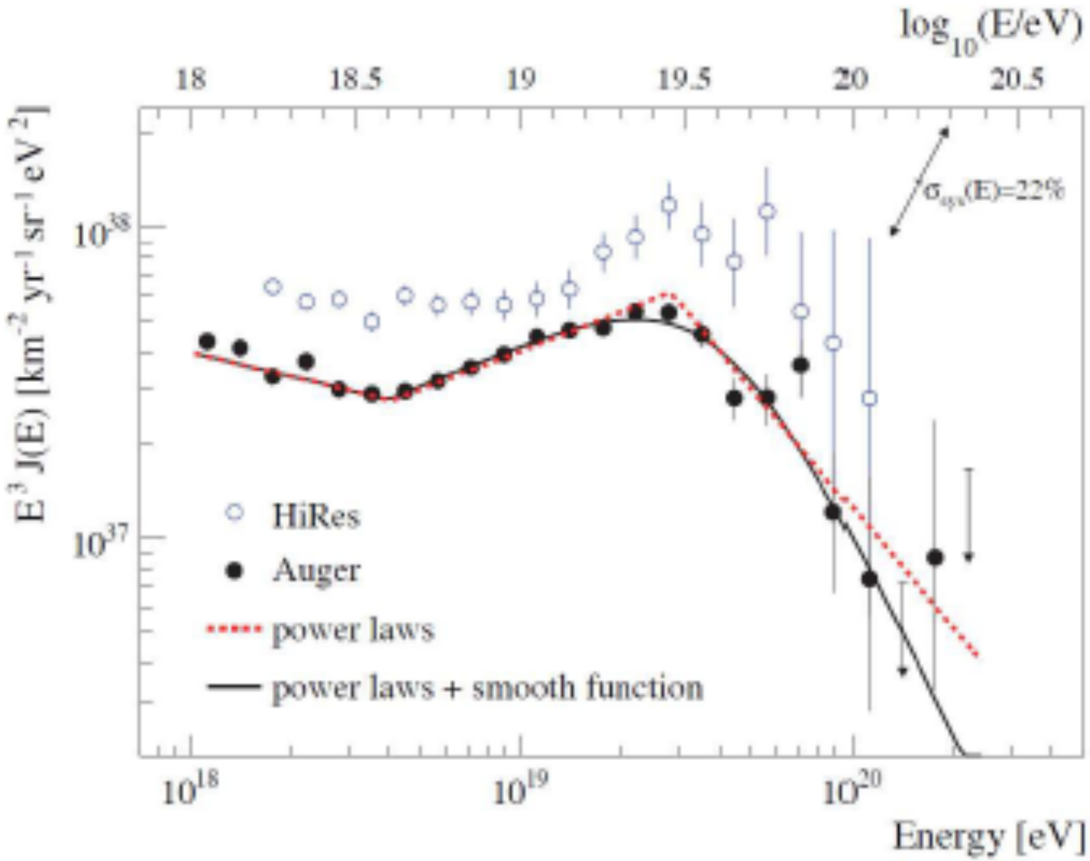
UHE cosmic rays

Nature accelerates particles 10^7 times the energy of LHC!

Cutoff now confirmed
But…

where?

how?



Hillas Diagram

📖 Hillas, Ann. Rev.Astron. Astrophys. 1984.22:425-44

Scénario bottom-up

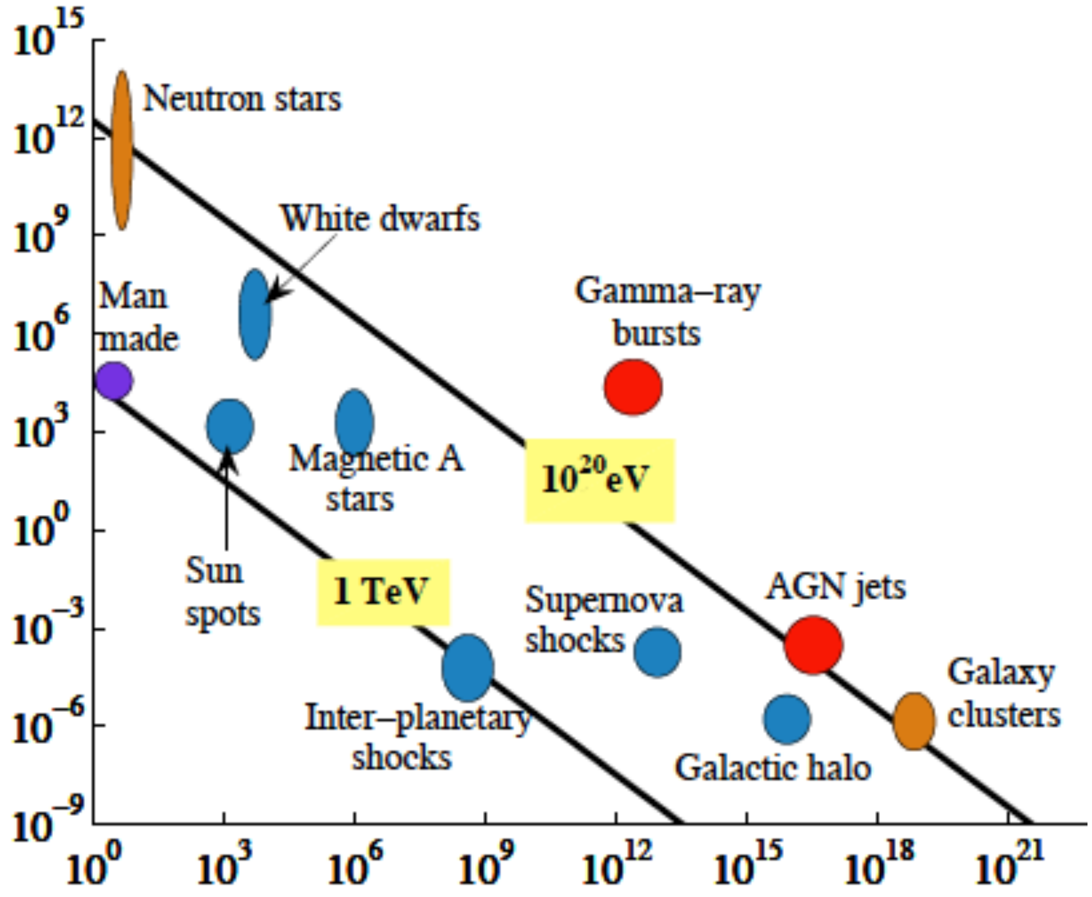
Accélération (de type Fermi) de particules chargées dans des processus astrophysiques violents

<u>Critère de Hillas:</u>

$$\Rightarrow E_{max} = Z.\left(\frac{L}{1\,\text{kpc}}\right)\left(\frac{B}{1\,\mu\text{G}}\right).10^{18}\ \text{eV}$$

Ex: pulsars, noyaux actifs de galaxie, sursauts gamma…

Champ magnétique (Gauss)

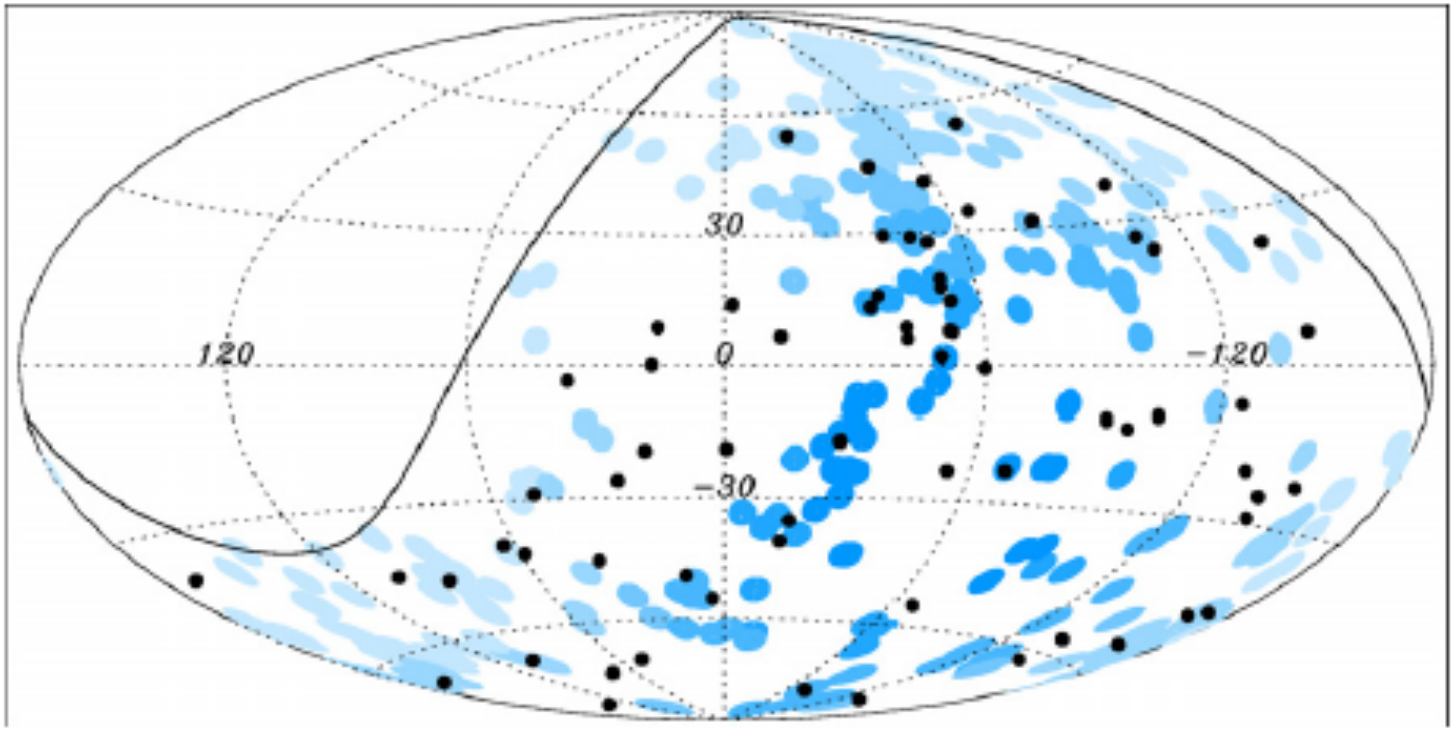


Taille (km)

Only (controversial) indications

📖 Astropart. Phys. 34 (2010)

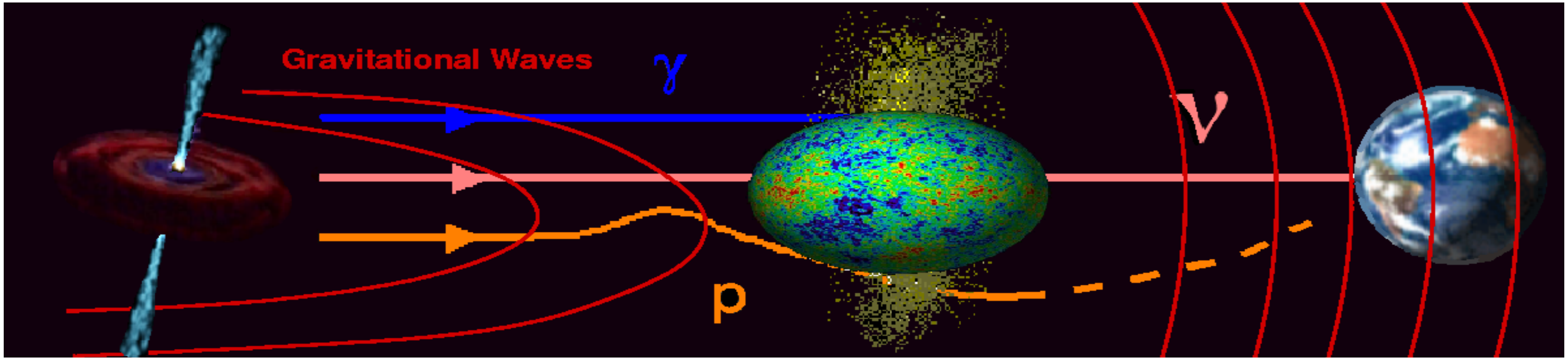
Corrélations AUGER 69 evts E>55 EeV
VCV catalogue



The correlation rate dropped from
68% (2007) to 38% (2010)
More data are needed…

Small window
for astronomy
~ 10^{20} eV

Multi-messenger astronomy



Neutrino

⇒Transient sources

⇒ Cosmological distances

⇒Core of astrophysical bodies

⇒ Point source

Cosmic ray connection

- Hadronic cascades (as for atmospheric showers)

HE CR & γ observed on Earth

$$p/A + p/\gamma \rightarrow \pi^0 + \pi^+ + \pi^- + N + \dots$$

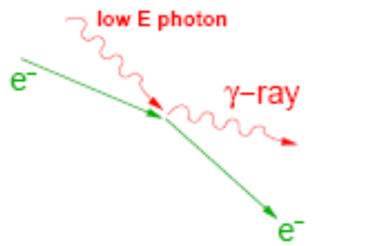
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

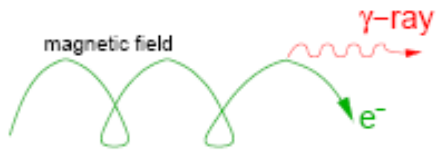
$$\nu_e:\nu_\mu:\nu_\tau = 1:2:0 \text{ source} \xrightarrow{\text{oscillations}} \nu_e:\nu_\mu:\nu_\tau = 1:1:1 \text{ Earth}$$

- Primary acceleration («Bottom-Up»)
  - Stochastics shocks (Fermi mechanism)
  - Explosion /Accretion / Core collapse



inverse Compton scattering

- Benchmark EG neutrino flux Waxman-Bahcall
  - ~ 500 events /yr/ km^2



synchrotron radiation

- But HE γ also from electromagnetic processes
  - Synchrotron Inverse Compton

Synchrotron emission

When electrons encounter a magnetic field, they spiral along the field

lines in a helical path. This means that their direction is constantly changing, (i.e. they are accelerating) and they therefore emit radiation

Classical energy loss per revolution:

$$\delta E \text{ (in MeV)} \approx 0.0885 \; [E(\text{in GeV})]^4 / R(\text{in m}) \; . \qquad (7.11)$$

For $\gamma \gg 1$, the energy radiated per revolution into the photon energy interval $d(\hbar\omega)$ is

$$dI = \frac{8\pi}{9} \alpha \, \gamma \, F(\omega/\omega_c) \, d(\hbar\omega) \; , \qquad (7.12)$$

where $\alpha = e^2/\hbar c$ is the fine-structure constant and

$$\omega_c = \frac{3\gamma^3 c}{2R} \qquad (7.13)$$

is the critical frequency. The normalized function $F(y)$ is

$$F(y) = \frac{9}{8\pi}\sqrt{3}\, y \int_y^\infty K_{5/3}(x) \; dx \; , \qquad (7.14)$$

From PDG

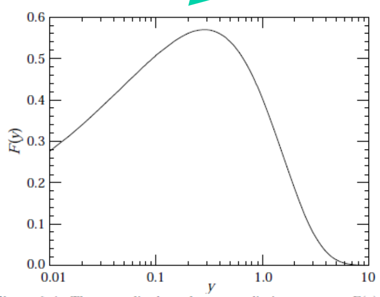
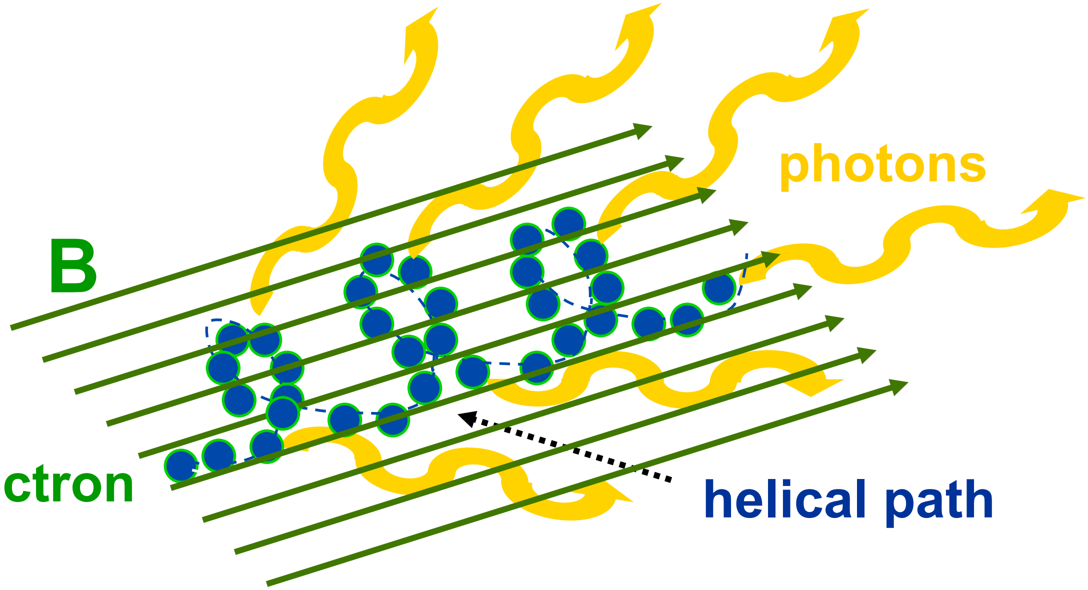
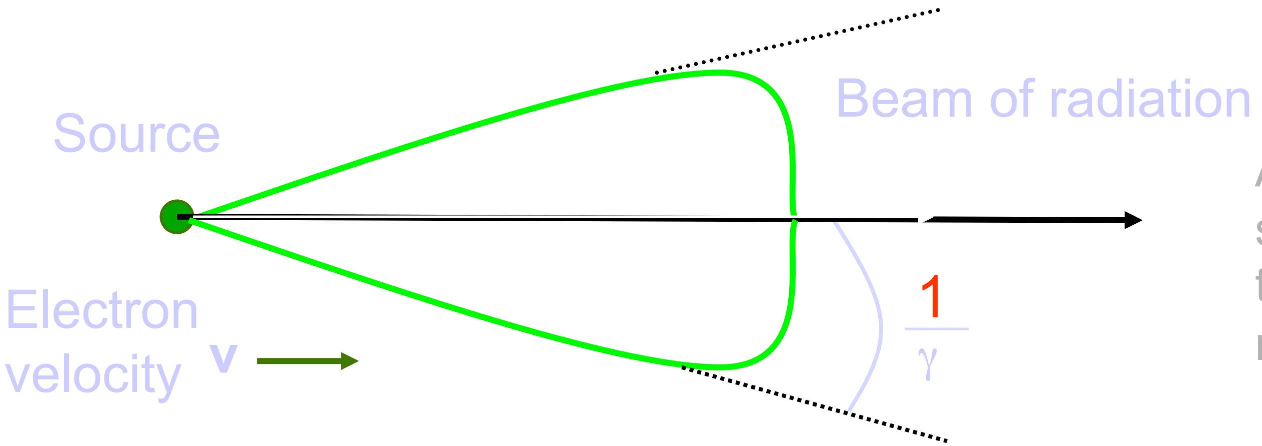


Figure 7.1: The normalized synchrotron radiation spectrum $F(y)$.



Synchrotron radiation

- Due to relativistic effects, synchrotron radiation is highly collimated in the direction of the velocity of the charged particles.

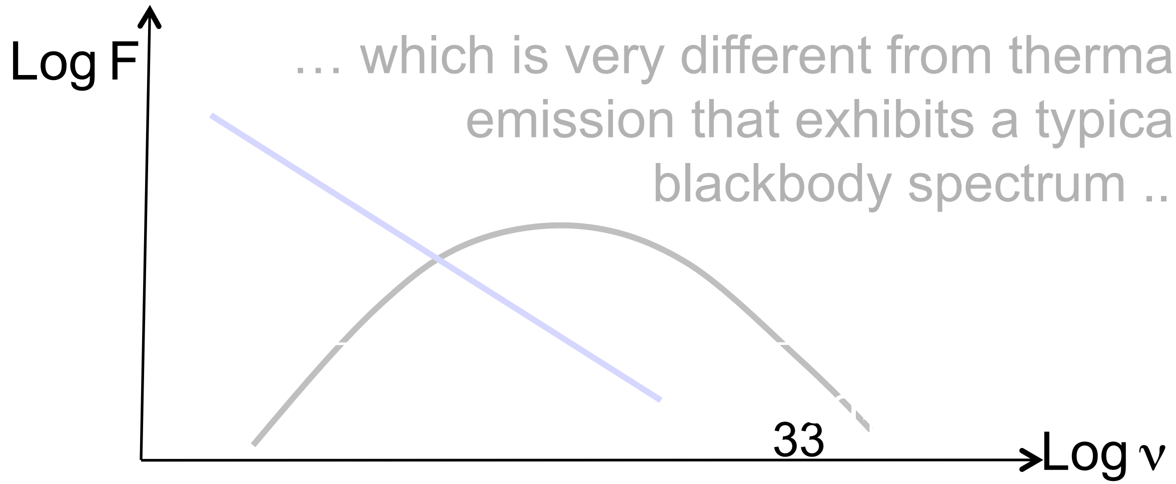


As $v \rightarrow c$, γ increases, so $1/\gamma$ decreases and the beam becomes more collimated.

- Since the electrons which encounter the magnetic field will have a range of energies, the radiation emitted will cover a wide frequency range. This means that synchrotron radiation is seen as continuum emission.

F = flux density
ν = frequency

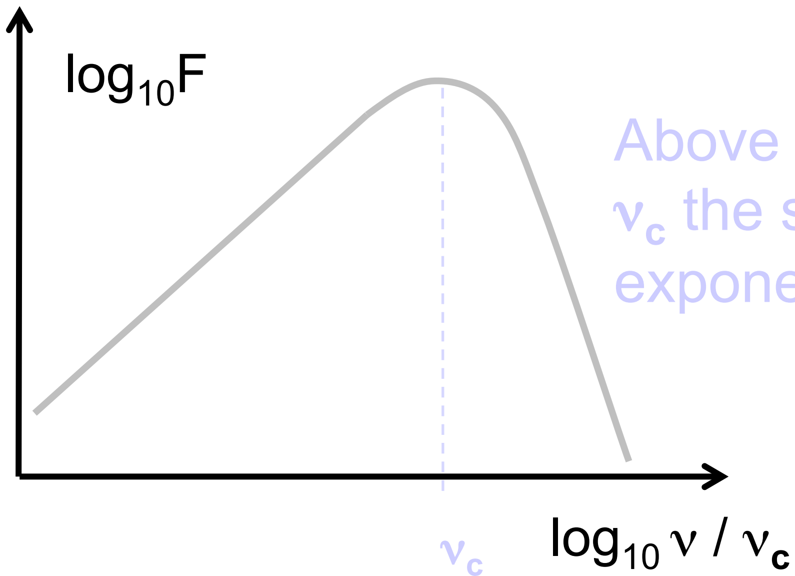
$$F \sim \nu^{-\alpha}$$



… which is very different from thermal emission that exhibits a typical blackbody spectrum ...

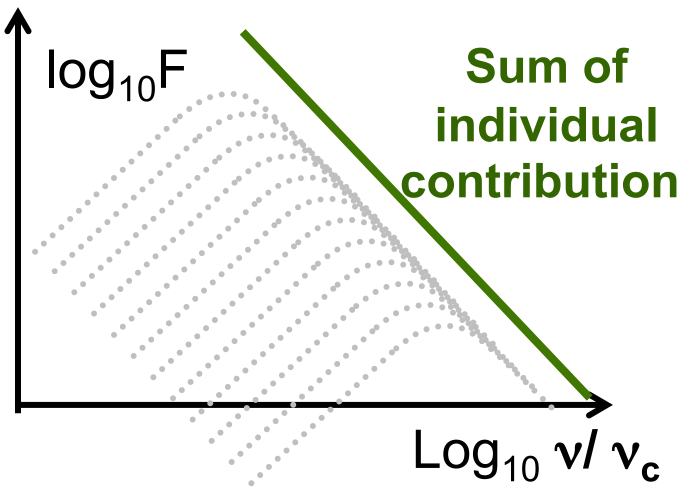
Synchrotron spectrum

The shape of the overall spectrum actually comes from the sum of each electron's contribution. Individual electrons spiraling around the magnetic field lines emit a spectrum that peaks at one particular frequency, ν_c:

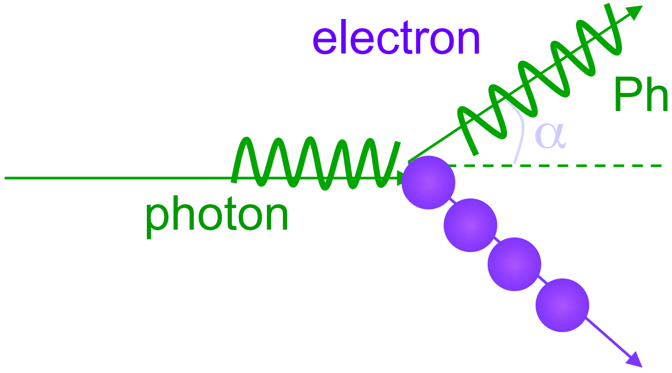


Above the critical frequency ν_c the spectrum drops exponentially.

Summing the individual contributions of many electrons gives the resulting synchrotron spectrum:



Compton scattering

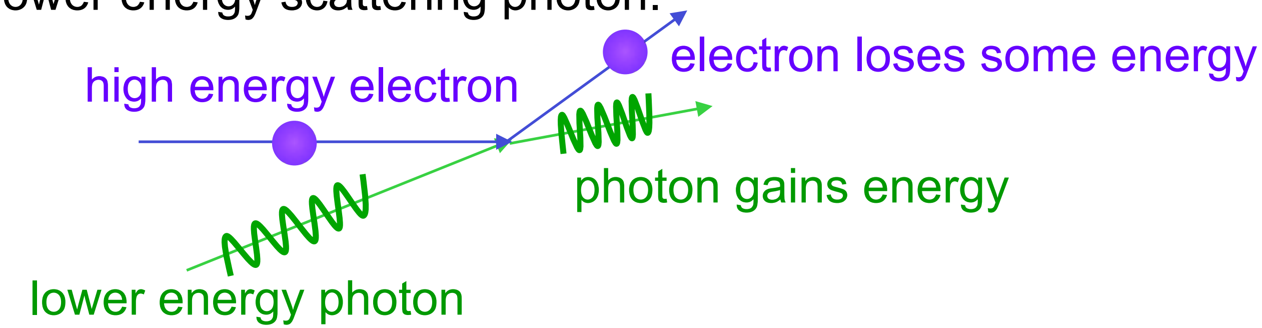


for $h\nu \ll m_e c^2$ with it is called *Thomson scattering*, **which is actually low energy scattering between a photon and an electron.**

In Compton scattering, a photon of high energy collides with a stationary electron and transfers part of its energy and momentum to the electron. The photon's frequency decreases in the process.

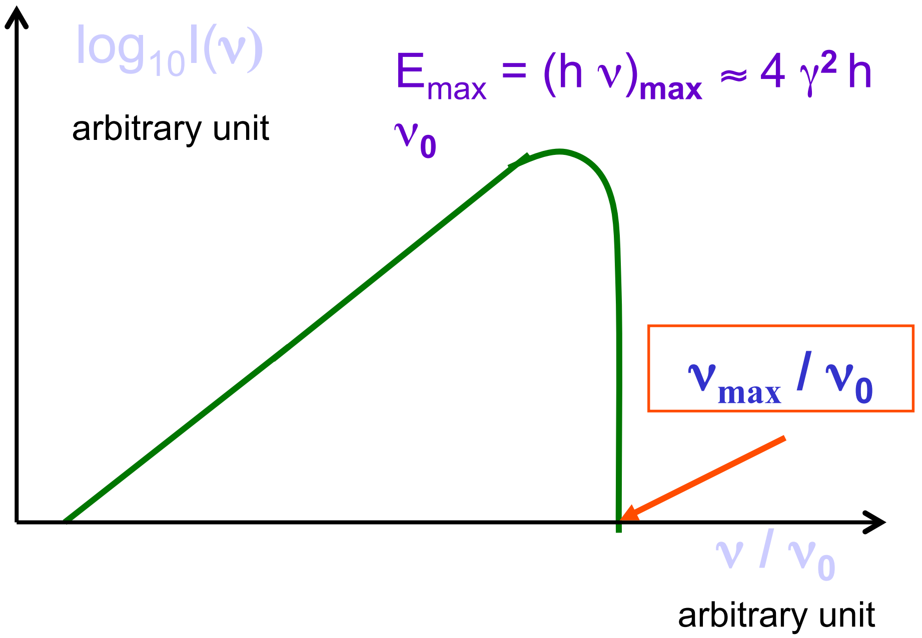
Inverse Compton scattering

In inverse Compton scattering, a high energy electron transfers both energy and momentum to a lower energy scattering photon.

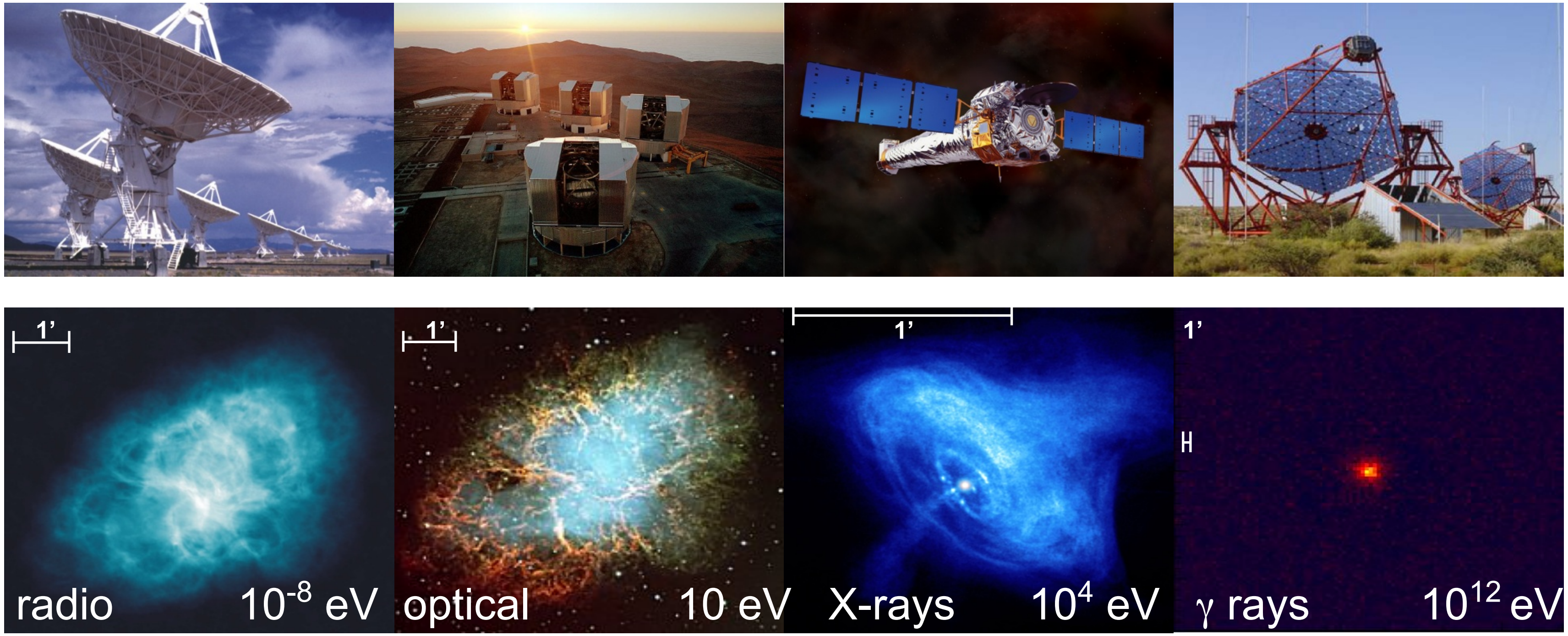


In general, the frequency of the scattered photon is approximately given by $\nu \approx \gamma^2 \nu_0$. In many astronomical sources there are electrons with $\gamma \approx 100$ –1000, and therefore inverse Compton scattering is the main radiation process, scattering low energy photons up to very high energies.

At low frequencies, the scattered radiation increases proportionally with frequency, while at high frequencies, it drops down below a maximum frequency.

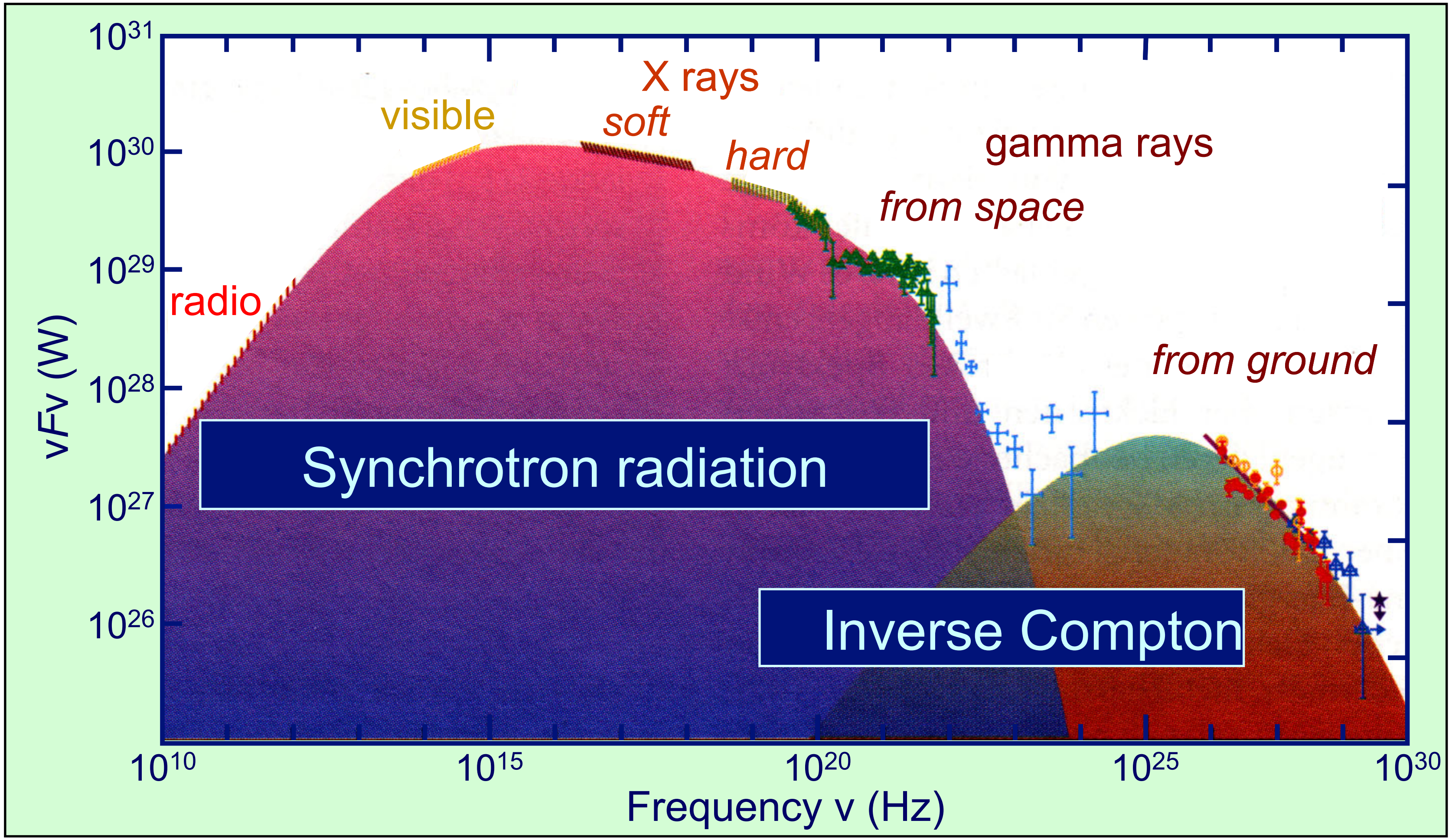


Ex: Crab Nebula

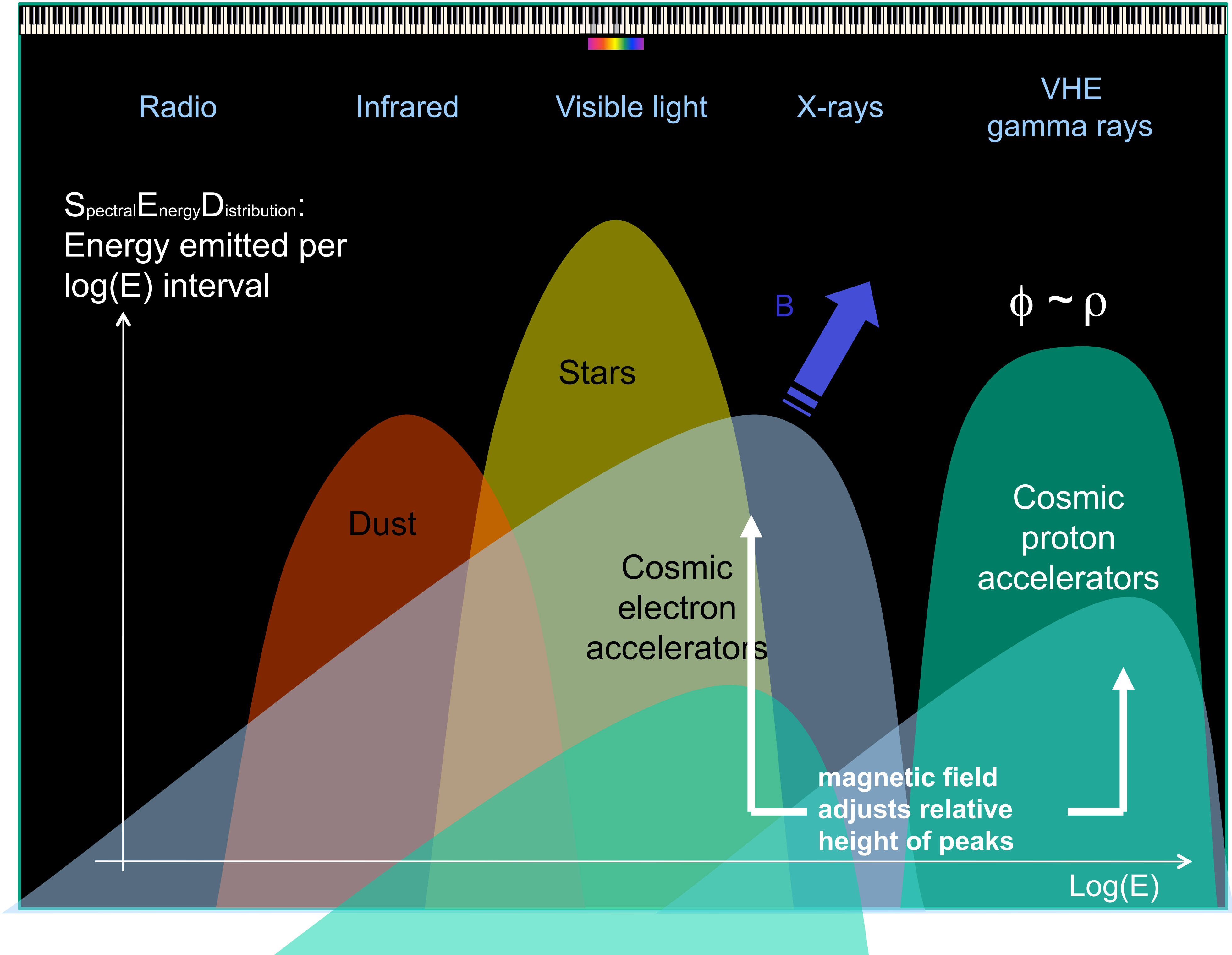


Standard candle for γ-ray astronomy
1st TeV gamma-ray source observed
by WHIPPLE in 1989 (50h)
HESS 2003 30s

Ex: Crab Nebula



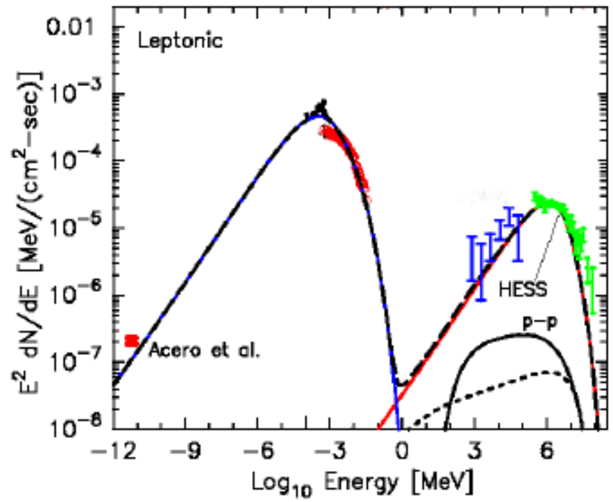
Mutli-wavelength analysis → Modeling of the source



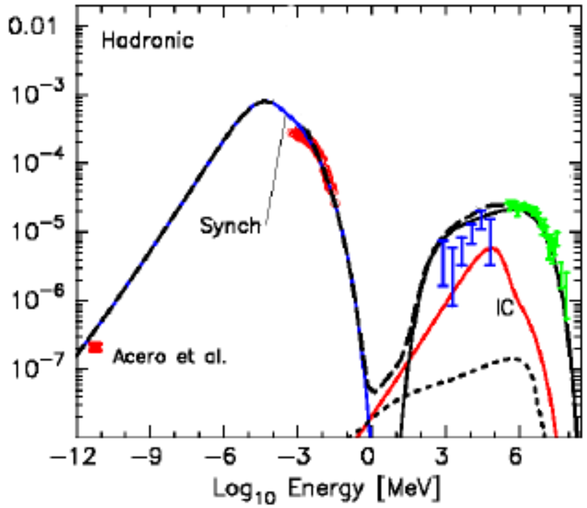
Radio
Infrared
Visible light
X-rays
VHE gamma rays
SpectralEnergyDistribution:
Energy emitted per log(E) interval
Stars
Dust
B
ϕ ~ ρ
Cosmic electron accelerators
Cosmic proton accelerators
magnetic field adjusts relative height of peaks
Log(E)

Ex: SNR RXJ1713.7-3946

«Leptonic» model best fits



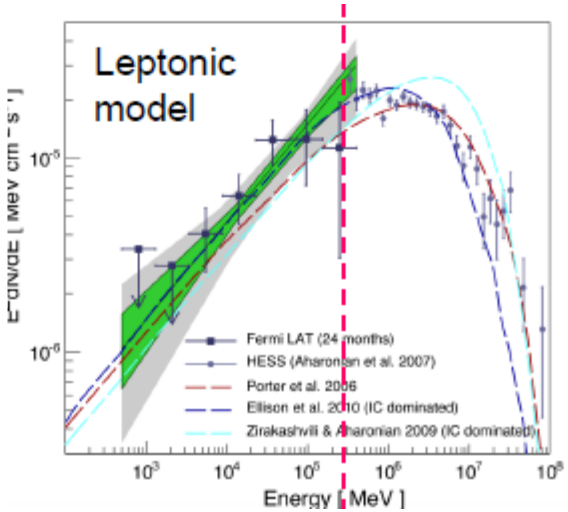
«Hadronic» model best fits

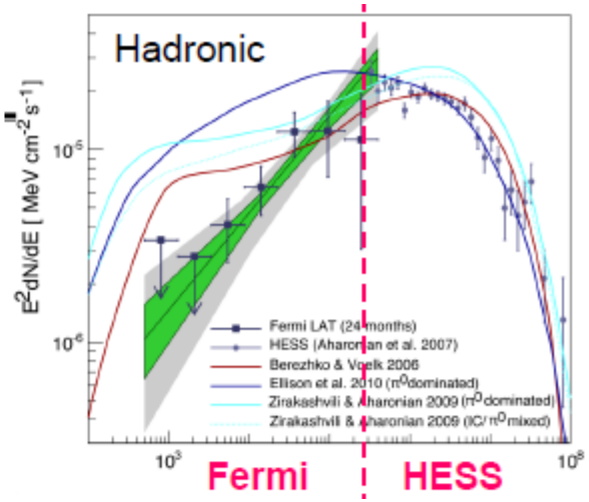


📖 D. C. Ellison et al. ApJ, 712, 287 (2010)

Observations from FERMI now favour ICS production of γ

📖 Abdo et al. ApJ, 734, 28, 2011





Fermi mechanism

Transfer of macroscopic kinetic energy of moving magnetized plasma to individual charged particle

EXERCICES:

1.Consider a process in which a test particle increases its energy by an amount proportional to its energy at each "encounter": $\Delta E = \xi E$. What is energy after n encounters? E_0 being the Injection energy.

$$E = E_0(1+\xi)^n$$

2.Let's define P_{esc} the probability to escape the acceleration region after each encounter. What is the probability of remaining in the acceleration region after n encounters? What is the number of encounters needed to reach an energy E?

$$P_{remain} = (1-P_{esc})^n$$

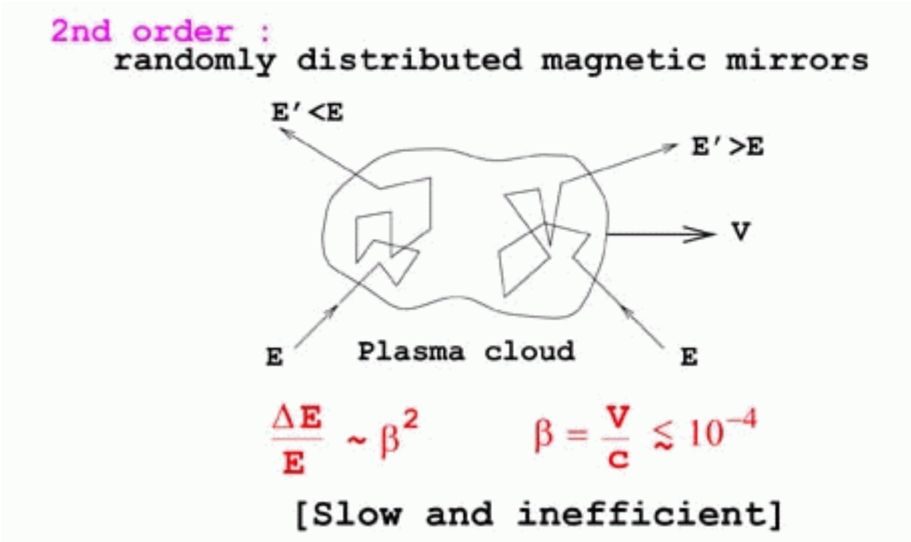
$$\ln\frac{E}{E_0} = \ln(1+\xi)^n \Rightarrow n = \frac{\ln E/E_0}{\ln(1+\xi)}$$

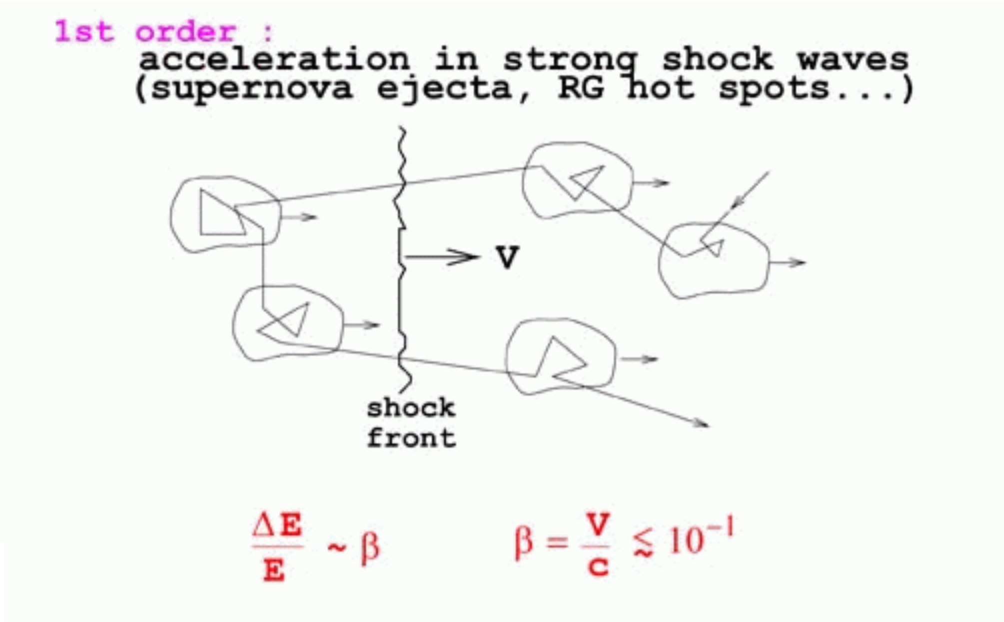
3. What is the proportion of particles accelerated to energies greater than E?

$$N(>E) \propto \sum_{n\geq m}(1-P_{esc})^m \quad \text{using} \sum_{n=0}^{N} q^n = \frac{1-q^{N+1}}{1-q} \Rightarrow N(>E) \propto \frac{(1-P_{esc})^n}{P_{esc}}$$

$$\Rightarrow \boxed{N(>E) \propto \frac{1}{P_{esc}}\left(\frac{E}{E_0}\right)^{-\gamma}} \quad \text{with} \quad \gamma = \frac{\ln(1-P_{esc})^{-1}}{\ln(1+\xi)} \approx \boxed{\frac{P_{esc}}{\xi}}$$

Fermi mechanism (1st and 2nd order)





Original Fermi mechanism
📖 Fermi, E. *Phys. Rev., 75, 1169 (1949)*

Particle can gain or loose velocity at each encounter
Depending on the angle, but after several encounters, there is a net gain.

Gain of energy at each encounter

$$\gamma \approx \frac{P_{esc}}{\xi} \Rightarrow \gamma \approx 1 \Rightarrow \frac{dN}{dE} \propto E^{-2}$$

Compatible with observations!

« Guaranteed » Flux / Upper Bounds

- Benchmark extragalactic muon neutrino flux

Waxman & Bahcall, 1999

Estimated energy density of UHECR:

$$E^2 \left. \frac{d\dot{N}_{\rm CR}}{dE} \right|_{E_{\rm min}} \approx 10^{44}\,{\rm erg\,Mpc^{-3}yr^{-1}}$$

Energy lost to ν in pγ interactions over Hubble time:

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx \frac{3}{8}\epsilon_\pi\, t_{\rm H}\, E^2 \frac{d\dot{N}_{\rm CR}}{dE}.$$

Resulting maximum ν flux:

$$[E_\nu^2 \Phi_\nu]_{\rm WB} \approx 2.3 \times 10^{-8} \epsilon_\pi \xi_z \ {\rm GeV cm^{-2} s^{-1} sr^{-}}$$

$E^{-2}\, I(E) = 4.5\ 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

~ 500 events /yr/ km^2

Hypothesis: UHECR are protons,
if not scales with p fraction

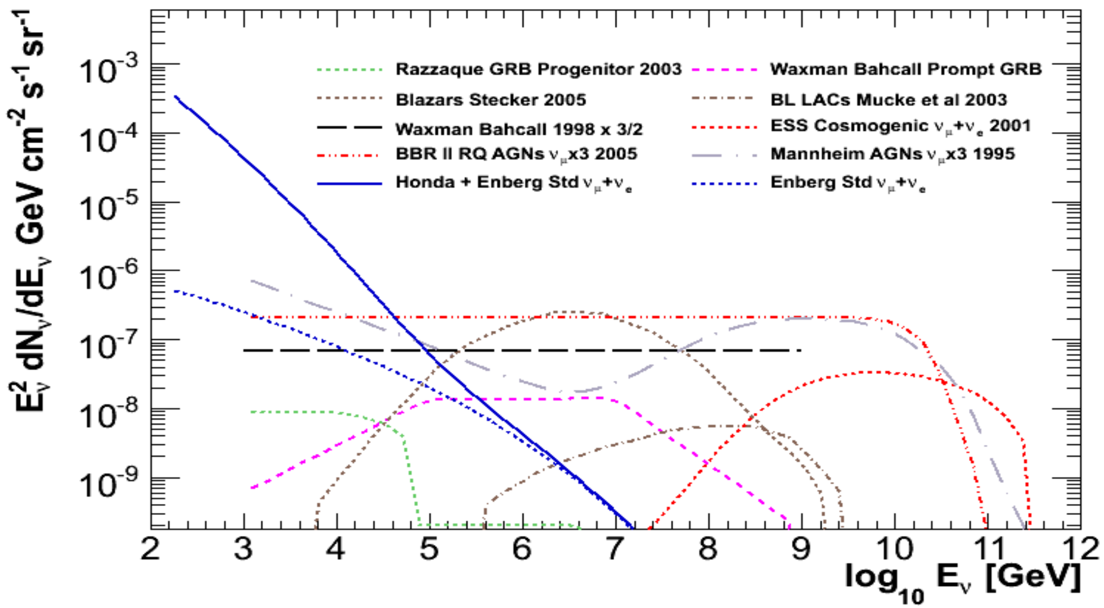
- Cosmogenic neutrino flux

Berezinsky & Zatsepin, 1969

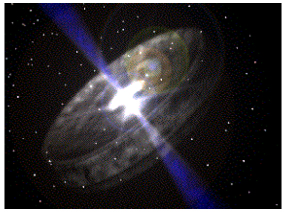
UHECR p interact with CMB =>GZK cut off

$$p^+ + \gamma_{bkg} \longrightarrow \Delta^+ \longrightarrow \pi^+ + n^0$$

→ UHE ν



Outline

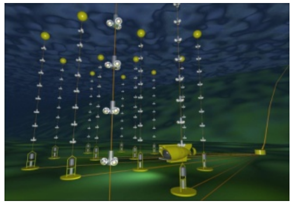


Neutrino astronomy

Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

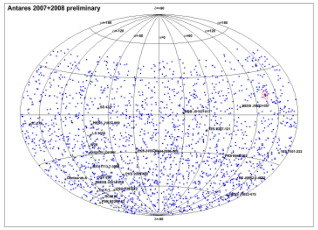


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

Diffuse Flux

Search for point sources

Multi-messenger search

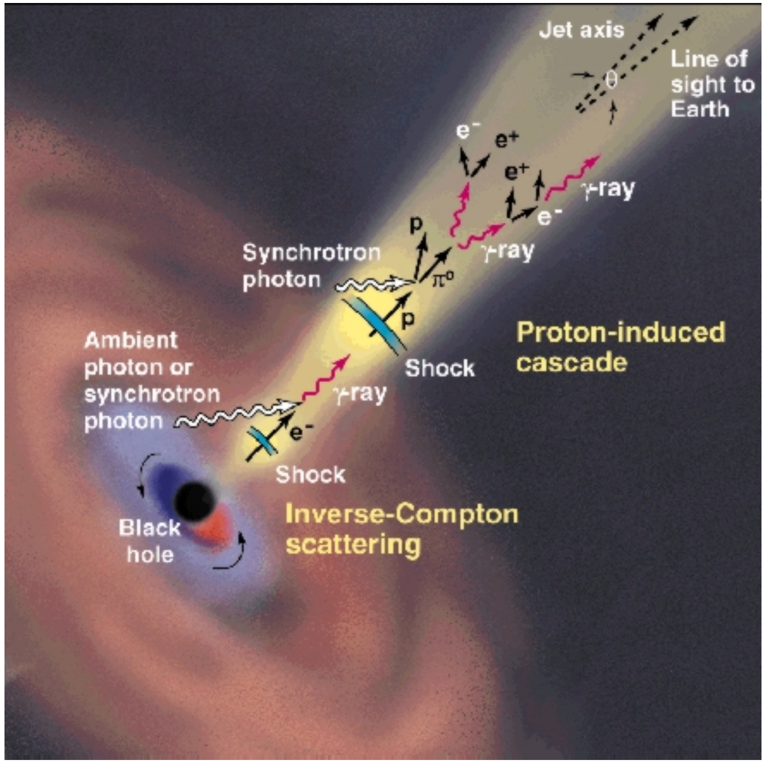
KM3NeT project

Potential extragalactic sources

Active Galactic Nuclei (AGN)

Steady (though flaring) sources

Observed luminosities
10^9 - $10^{15} \times L_\odot$

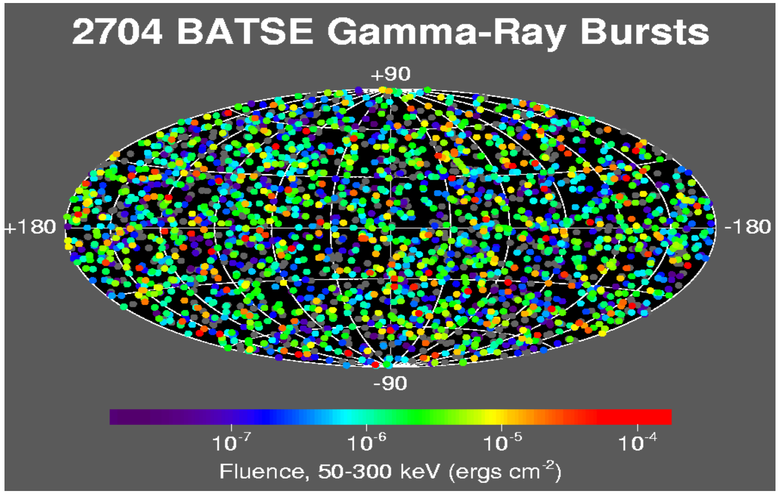


Gamma Ray Bursters (GRB)

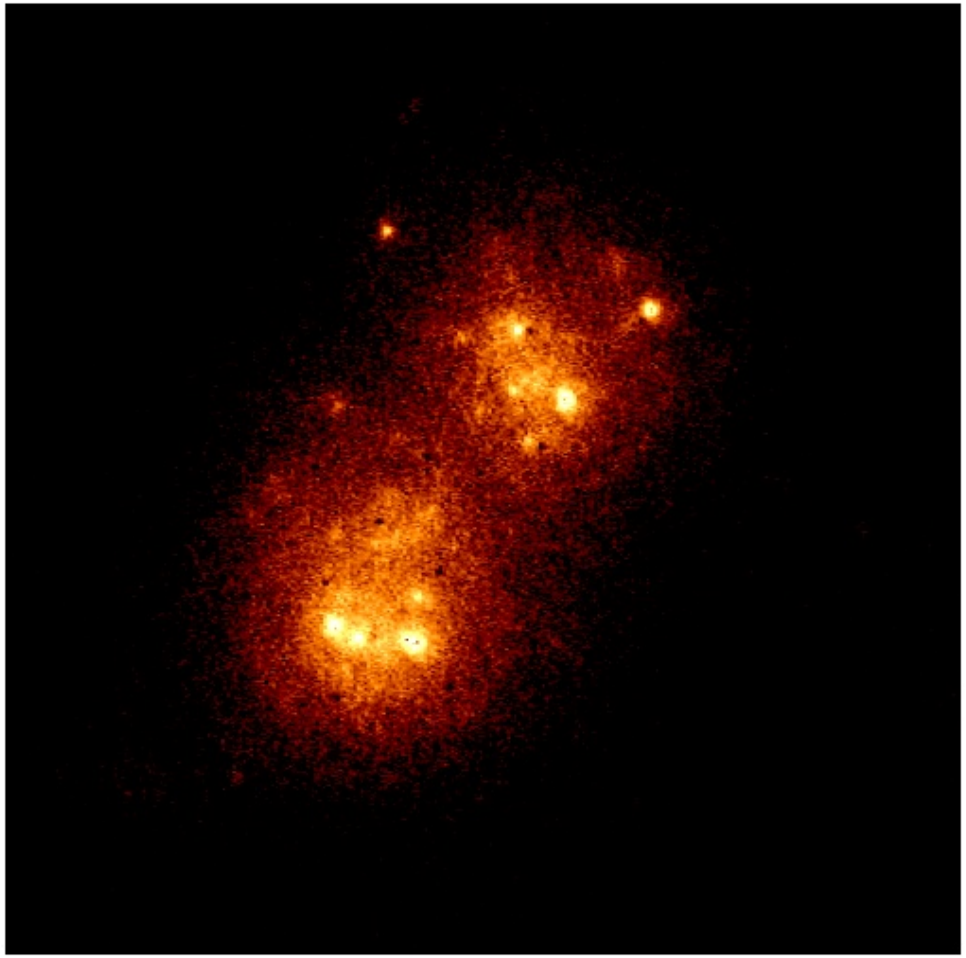
Short emissions (~1s)
Very bright ~ $10^{18} \times L_\odot$

Counterparts : z up to 8.3

BATSE : 1 burst/day



Starburst galaxies



merging galaxies

- $v \sim 100$ km/s
- $t \sim 10^6$ years
- $\rho \sim 0.2$ g cm^{-2}
- $B \sim 0.1$ mGauss

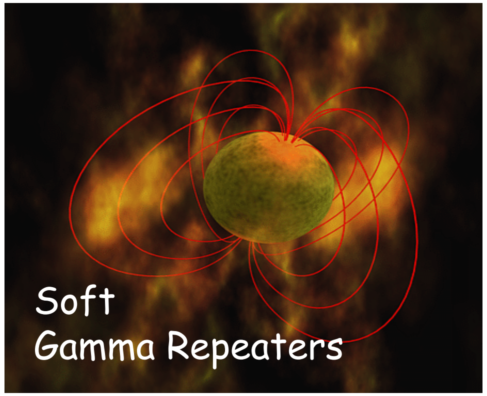
supernovae

→ cosmic rays

+ dense gas

→ pions

Potential Galactic sources



Microquasars X-ray binaries with compact object (neutron star or black hole) accreting matter and re-emitting it in relativistic jets (intense radio & IR) flares.

→ GW in accretion/ejection phases?
→ HEN from jets

SGRs X-ray pulsars with a soft γ-ray bursting activity.
Magnetar model: highly magnetized neutron stars whose outbursts are caused by global star-quakes

→ GW from star deformation
→ HEN from GRB-like flares

- *Supernovae remmants*

pulsars, neutron stars

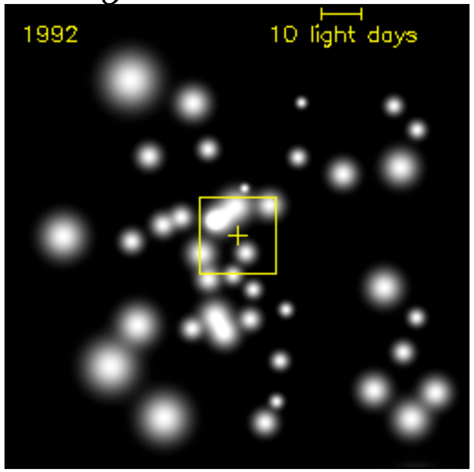
- *Dense regions*

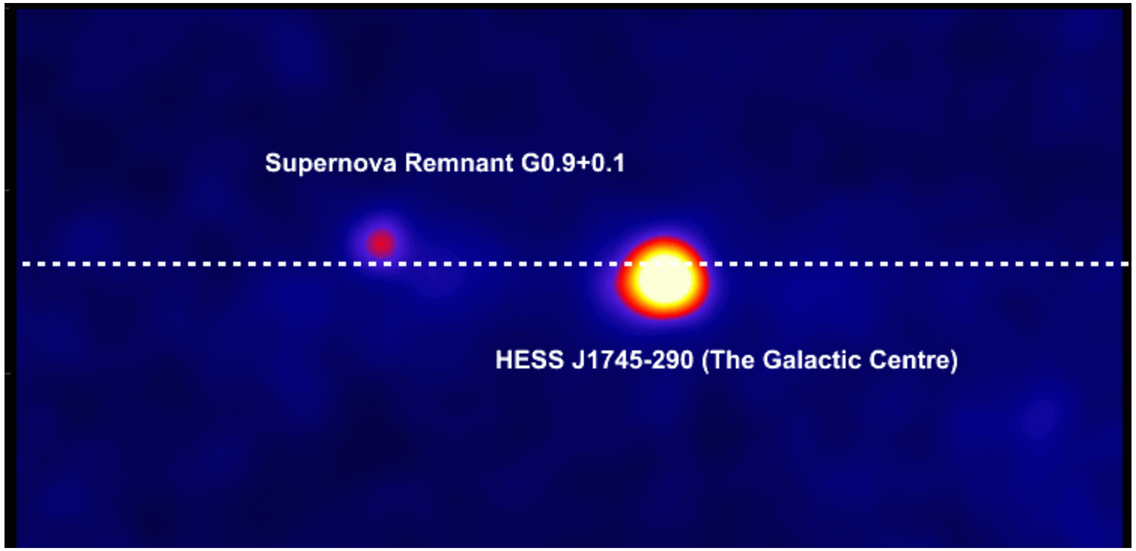
Sun , Galactic Centre,
Interstellar medium

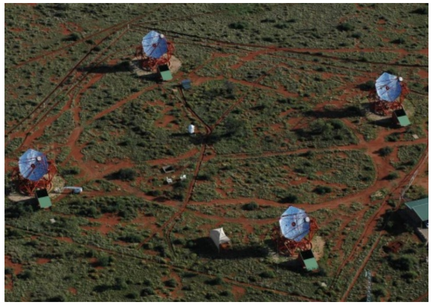
→ Mosty seen by Northern Hemisphere neutrino telescopes

The Galactic center region

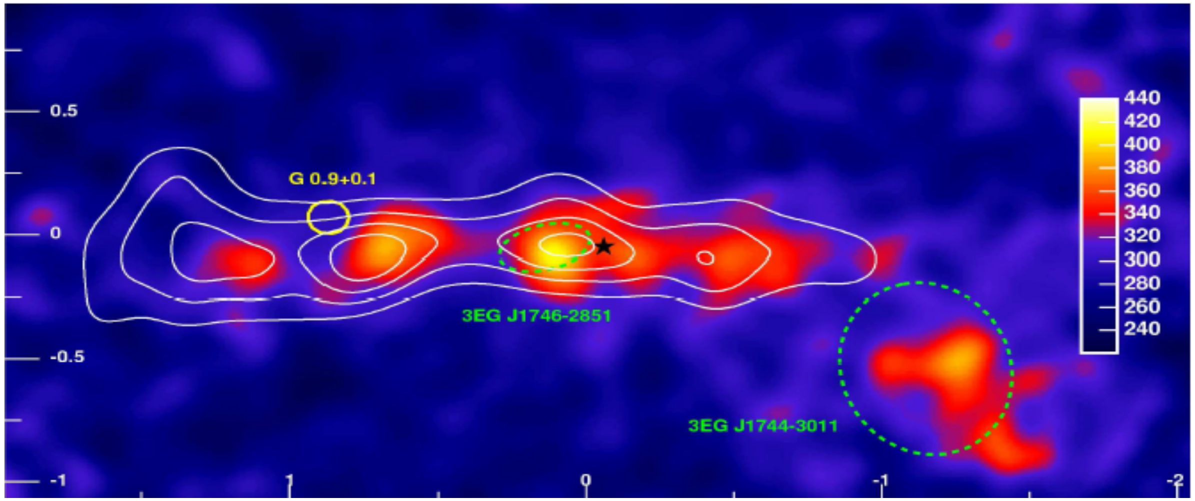
- *High densities*
- *Compact source Sgr A**
  Black hole ~3 10^6 $M_\odot$
- *Sgr A East SNR*







HESS

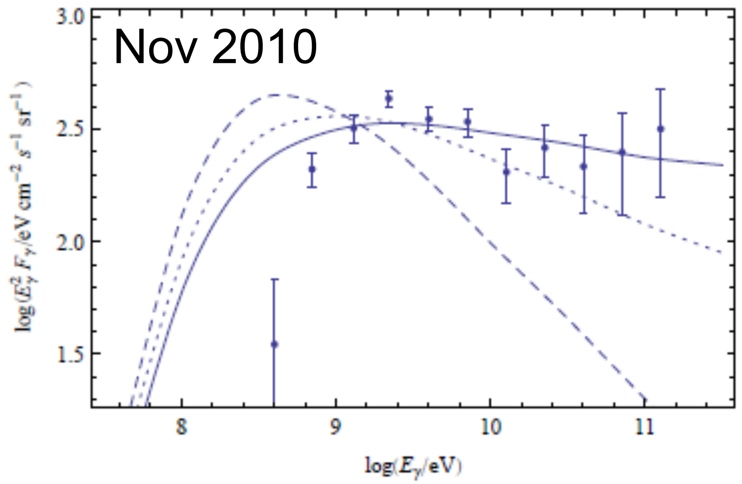


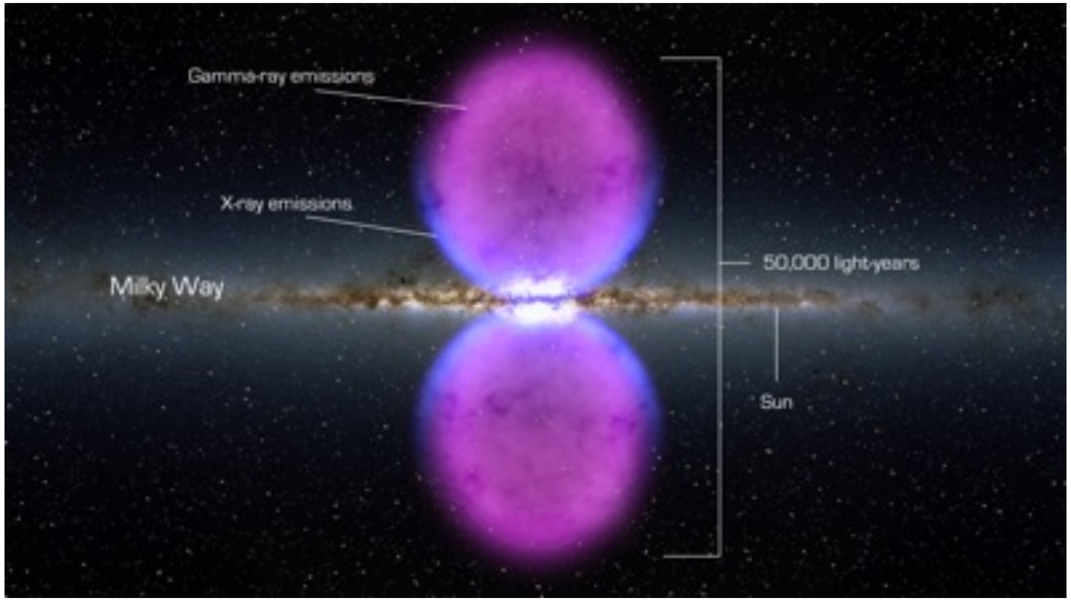
Fermi Bubbles

"Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays"
📖 M. Crocker and F. Aharonian Phys. Rev. Lett. 106 (2011) 11102

"Bilateral 'bubbles' of emission centered on the core of the Galaxy and extending to around 10 kpc above and below the Galactic plane. These structures are coincident with a non-thermal microwave 'haze' found in WMAP data and an extended region of X-ray emission detected by ROSAT."

Spectre de Fermi $E^{-2.1}$



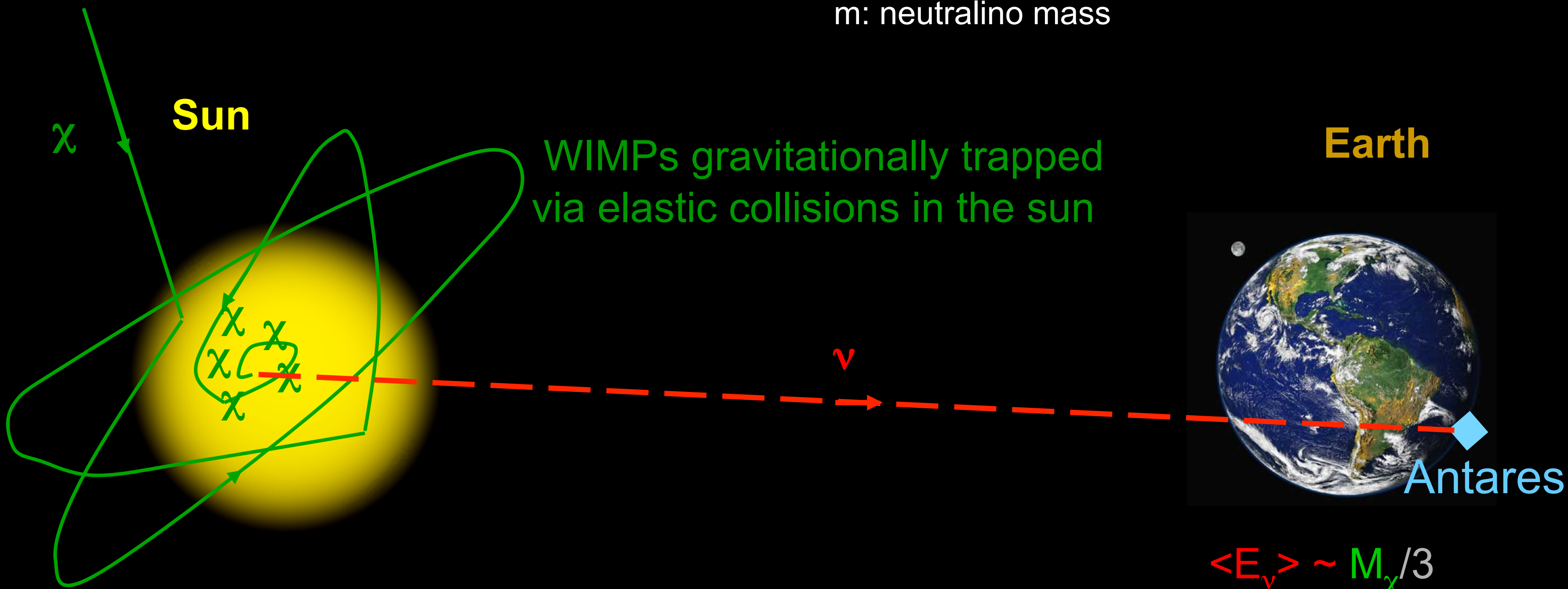


Indirect searches of dark matter WIMPs

Annihilations of DM particles inside dense bodies

$$\Gamma_{ann} = \frac{\sigma_{ann} v \rho^2}{m^2}$$

Γ_{ann}: annihilation rate per unit of volume
σ_{ann}: neutralino-neutralino cross-section
v: relative speed of the annihilating particles
ρ: neutralino mass density
m: neutralino mass



$\langle E_\nu \rangle \sim M_\chi/3$

$\chi \;\; \chi \;\; \rightarrow \;\; WW, \; ff$

$W, f \rightarrow \; \nu \; X$

Neutralino annihilations in the Sun in mSUGRA

Study of **neutralino Dark Matter** sensitivity within SUSY mSUGRA framework

Random walk scan within

mSUGRA parameter space :

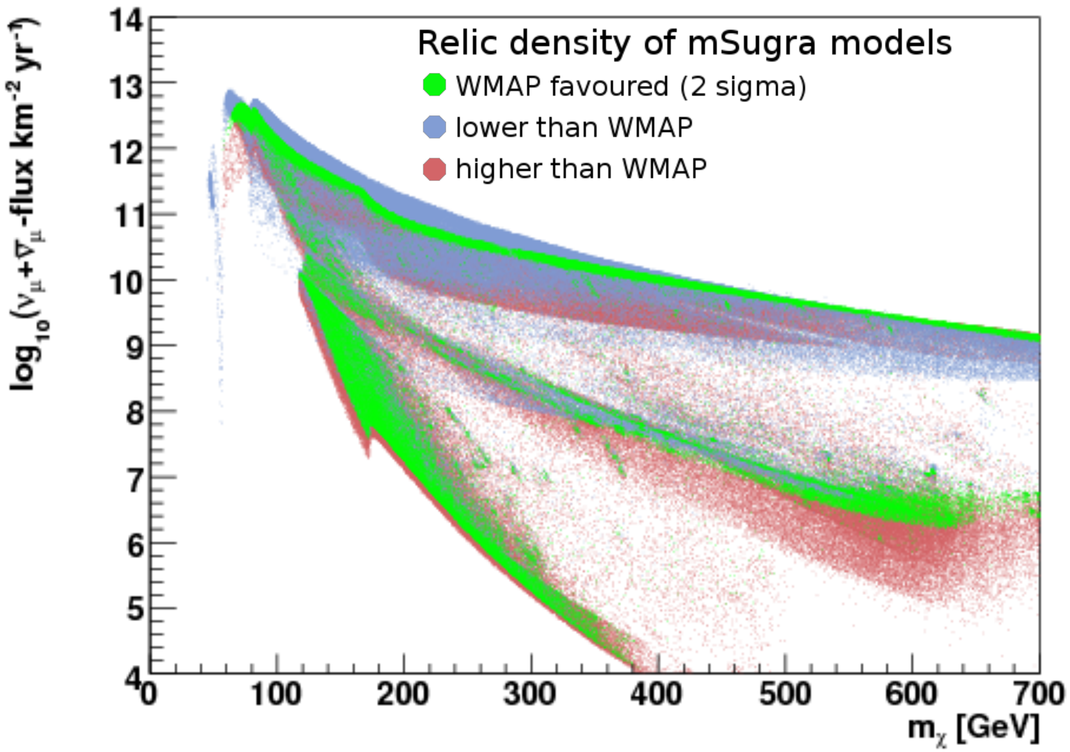
$0 < m_{1/2} < 2000$ GeV

$0 < m_0 < 8000$ GeV

$0 < \tan\beta < 60$

$-3\, m_0 < A_0 < 3\, m_0$

Integrated neutrino flux for $E\nu > 10$ GeV



Calculated with DarkSUSY

and ISASUGRA (RGE code) with

$m_{top} = 172.5$ GeV

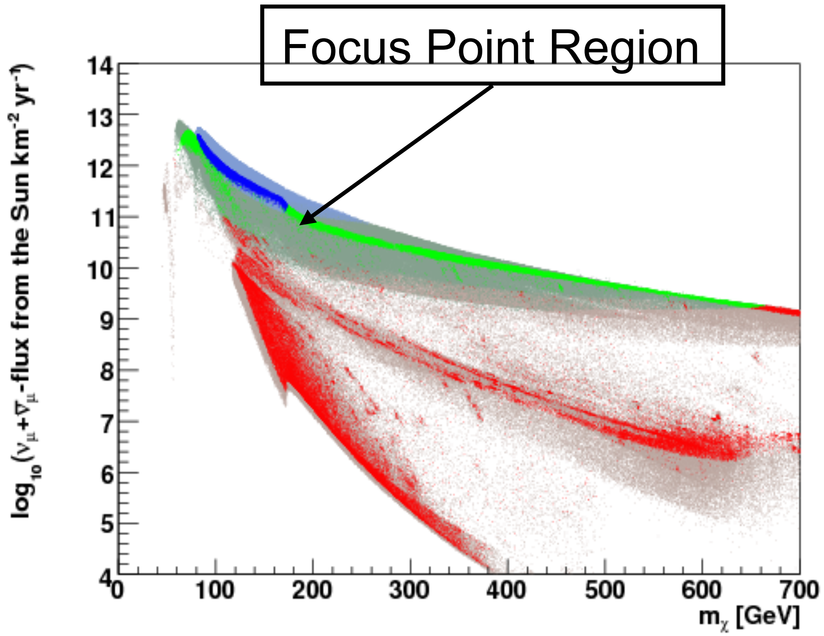
Local halo density: 0.3 GeV/cm^3

$\langle v_\chi \rangle = 270$ km/s

Includes ν oscillation effects in the Sun and in vacuum

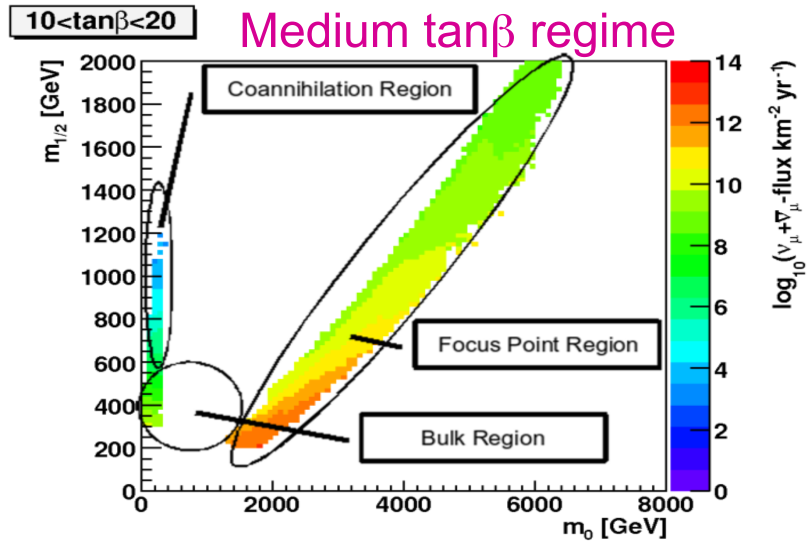
Neutralino annihilations in the Sun in mSUGRA

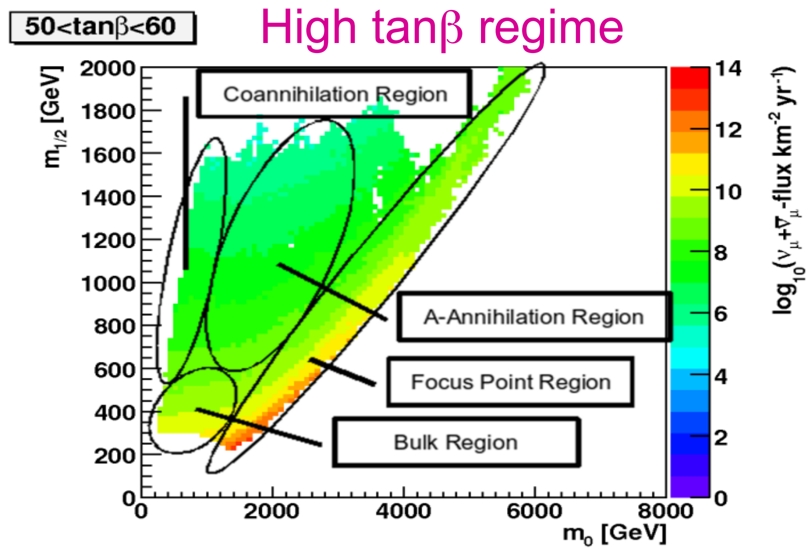
mSugra Parameter Space



mSugra models favoured by WMAP
- 90% CL excudable by ANTARES
- 90% CL excludable by KM3NeT
- not excludable

mSugra models disfavoured by WMAP
- 90% CL excludable by ANTARES
- 90% CL excludable by KM3NeT
- not excludable

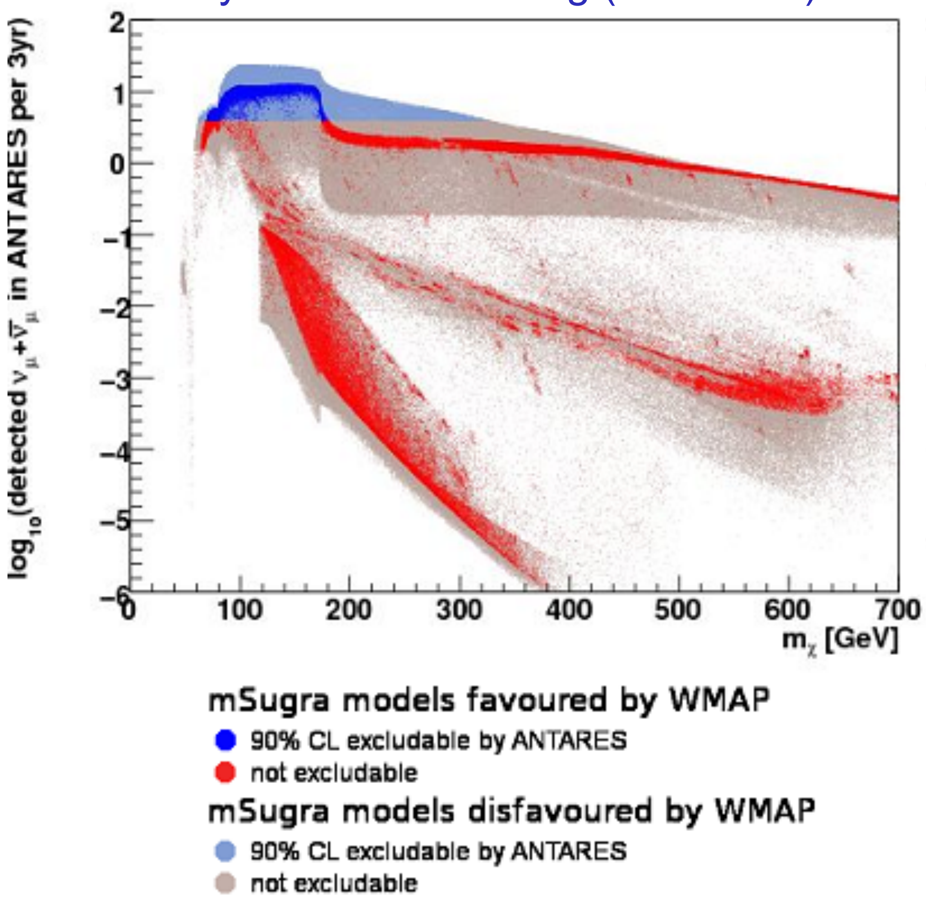




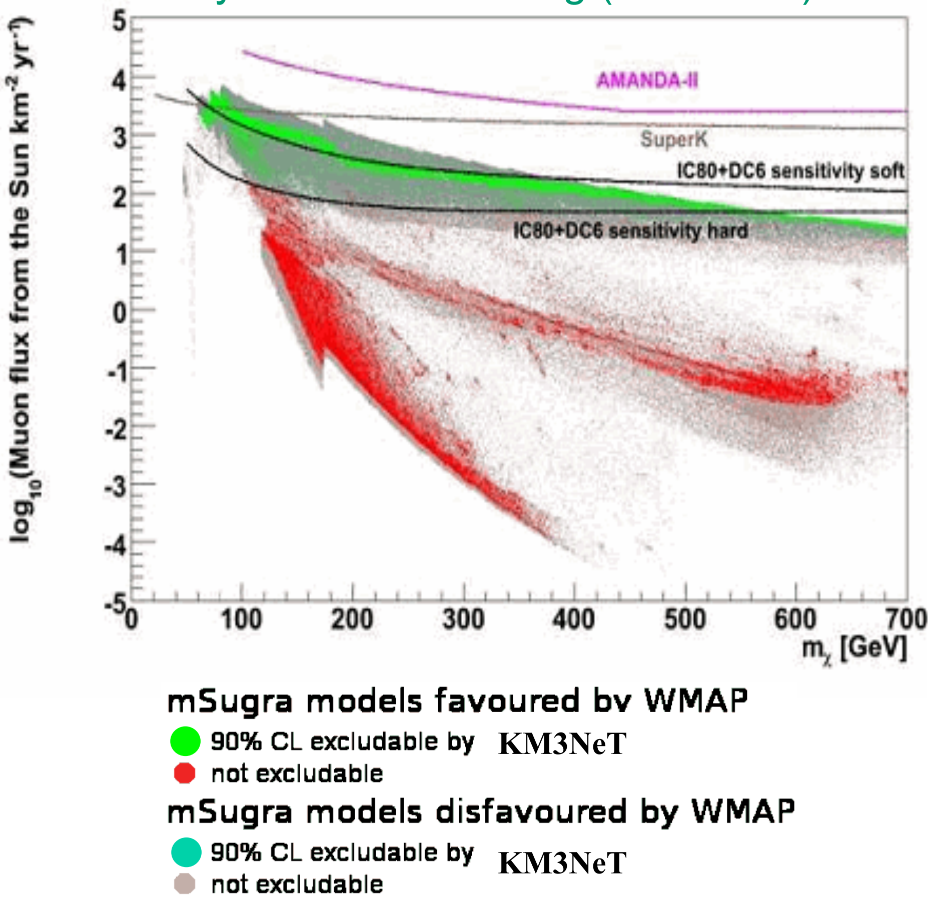
Perspectives for DM searches

- Current limits do not constrain the WMAP favored models ($0.094 < \Omega_\chi h^2 < 0.129$)

ANTARES sensitivity calculated for 3 years of data taking (mSUGRA)



KM3NeT Sensitivity calculated for 10 years of data taking (mSUGRA)



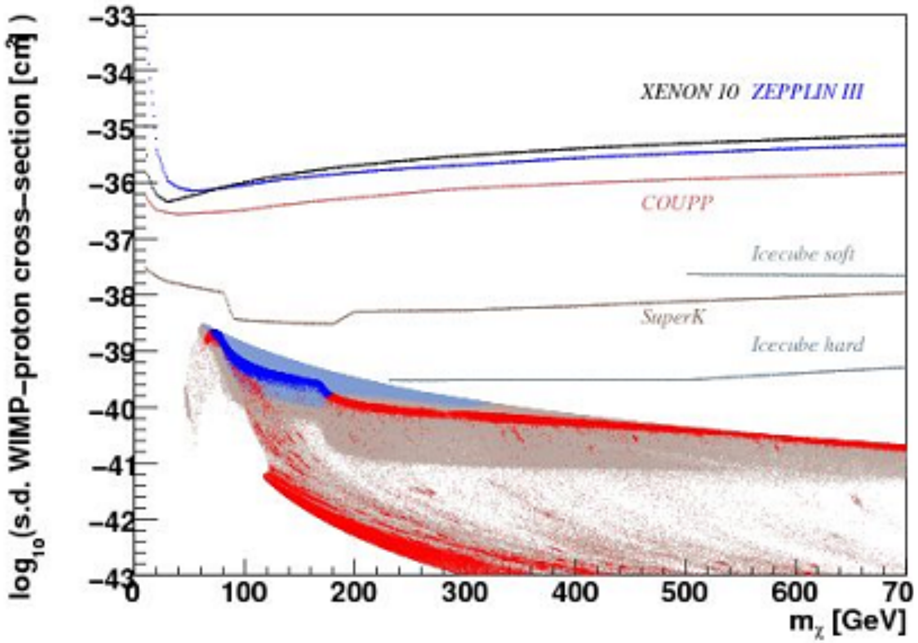
Exclusion capabilities : mainly Focus Point region (good complementarity to LHC)

- Other models (e.g. mUED) have better prospects (direct LKP annihilation into neutrinos)

Spin-dependent scenarios

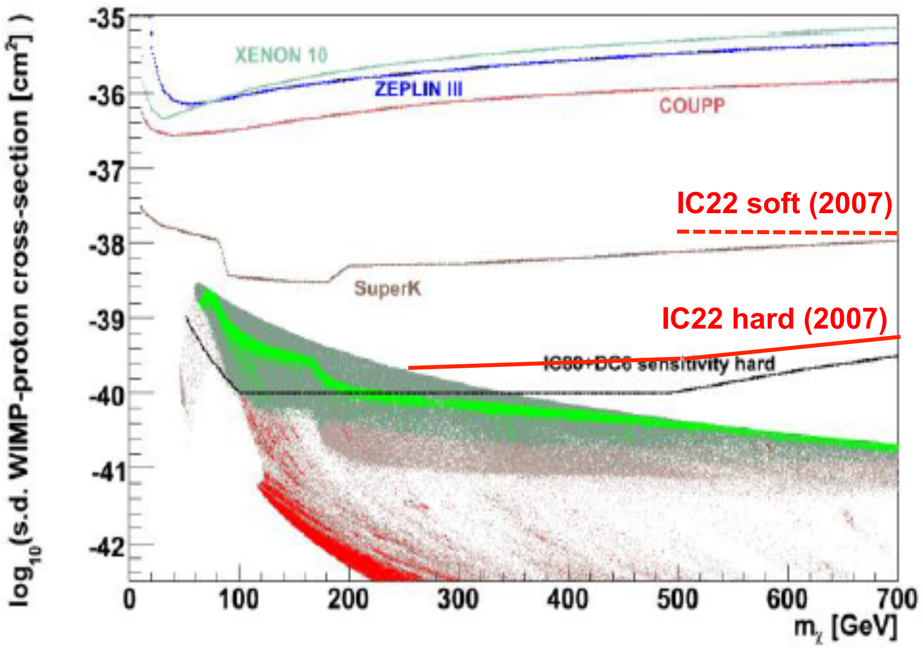
Very competitive sensitivity compared to direct detection experiments in the case of spin-dependant neutralino interaction

ANTARES sensitivity calculated for 3 years of data taking (mSUGRA)

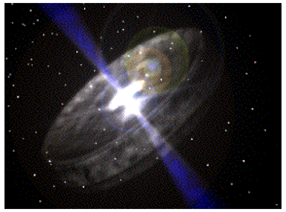


Current limits

Km-scale Sensitivity (10 years)



Outline

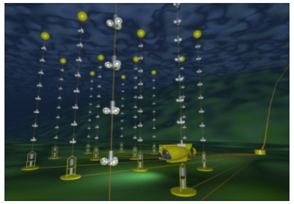


Neutrino astronomy

Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

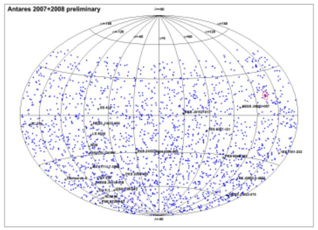


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

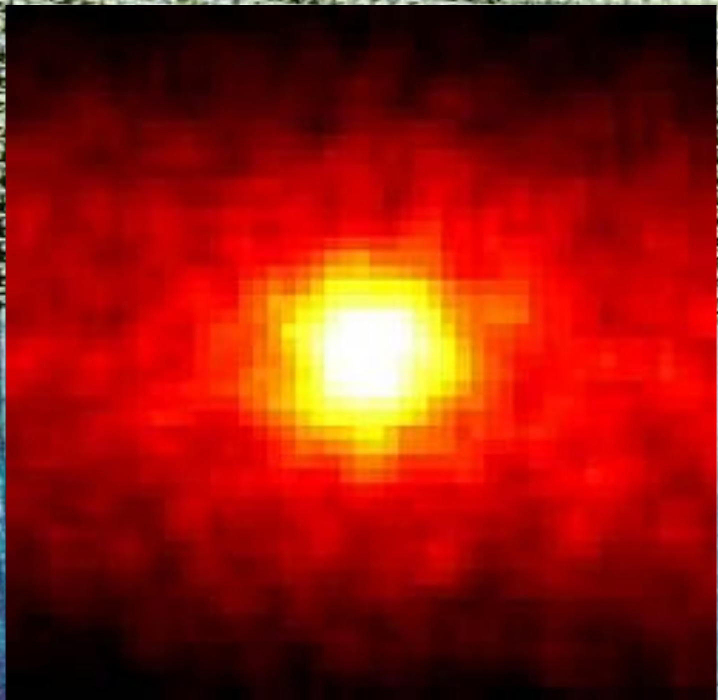
Diffuse Flux

Search for point sources

Multi-messenger search

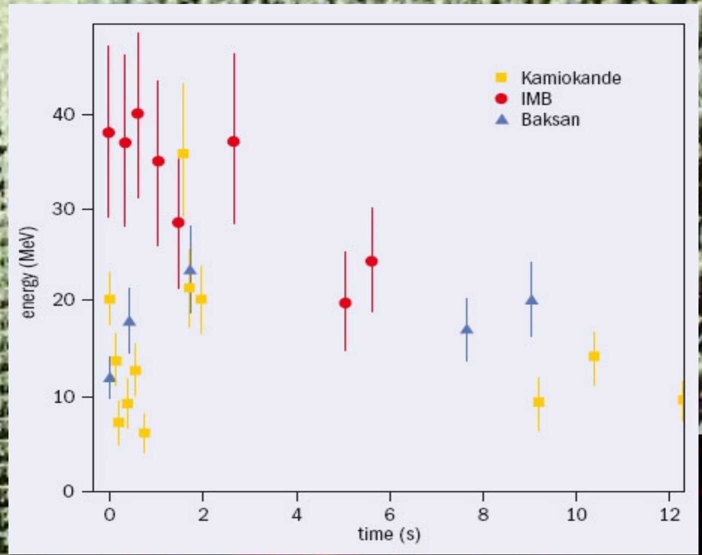
KM3NeT project

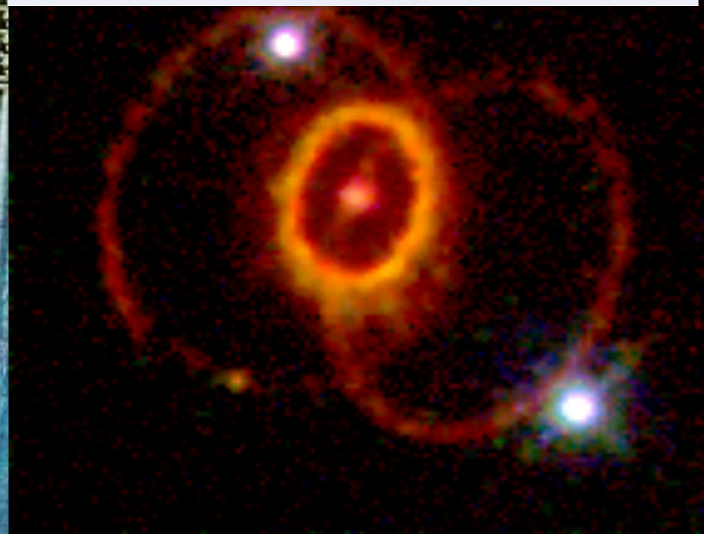
First extraterrestrial neutrinos



The Sun seen by SuperKamiokande

~MeV





Neutrinos from SN1987A
25 events in 12 s

Neutrinos from space: the long quest

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.
1/4 of the prize
USA
University of Pennsylvania
Philadelphia, PA, USA
b. 1914

Masatoshi Koshiba
1/4 of the prize
Japan
University of Tokyo
Tokyo, Japan
b. 1926

Riccardo Giacconi
1/2 of the prize
USA
Associated Universities Inc.
Washington, DC, USA
b. 1931
(in Genoa, Italy)

Solar neutrinos

(MeV energies)

Davis et al. 1955 – 1978

Koshiba et al., 1987 – 1988

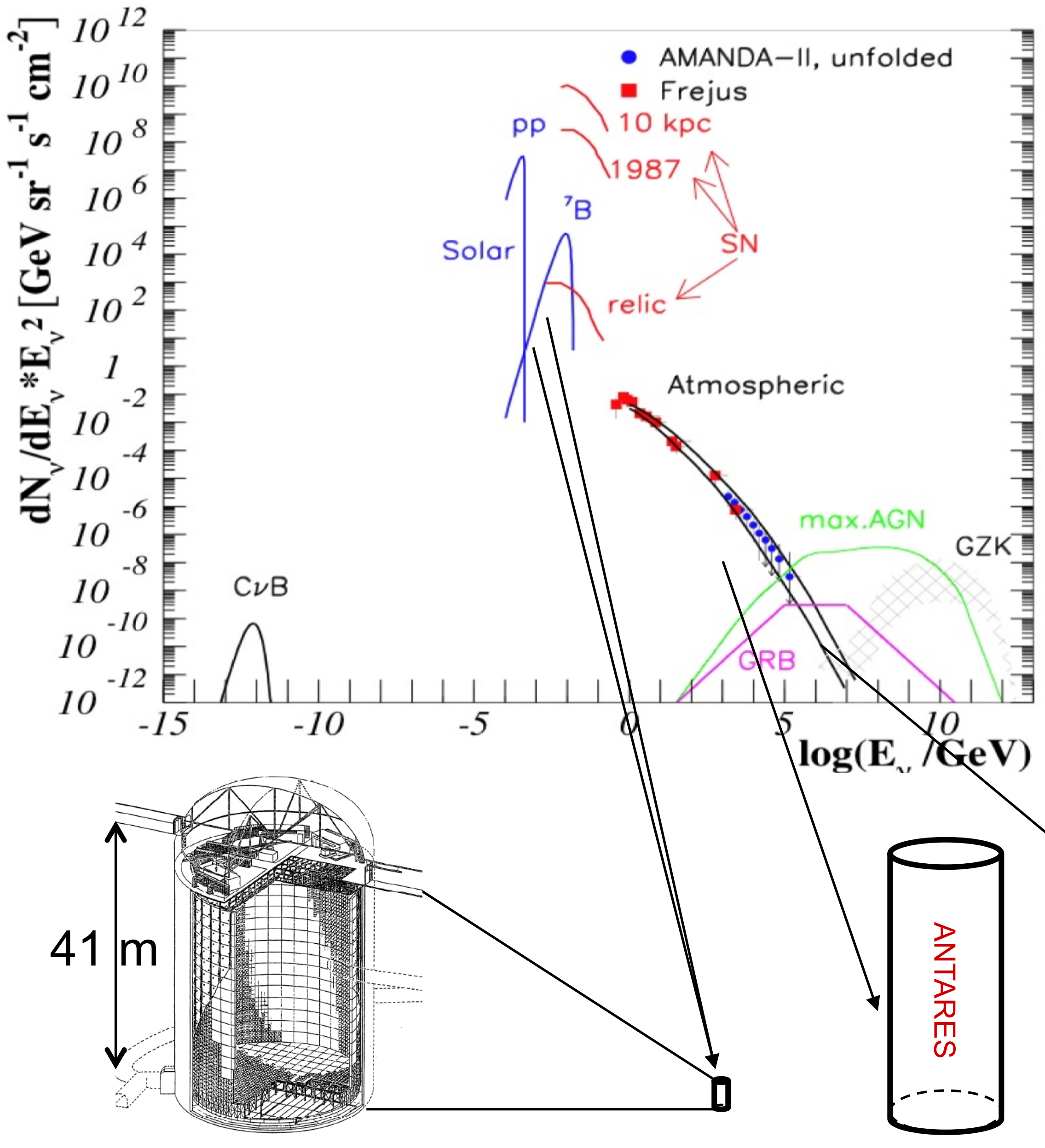
Presence of cosmic neutrinos E > GeV?

Galactic
Extragalactic

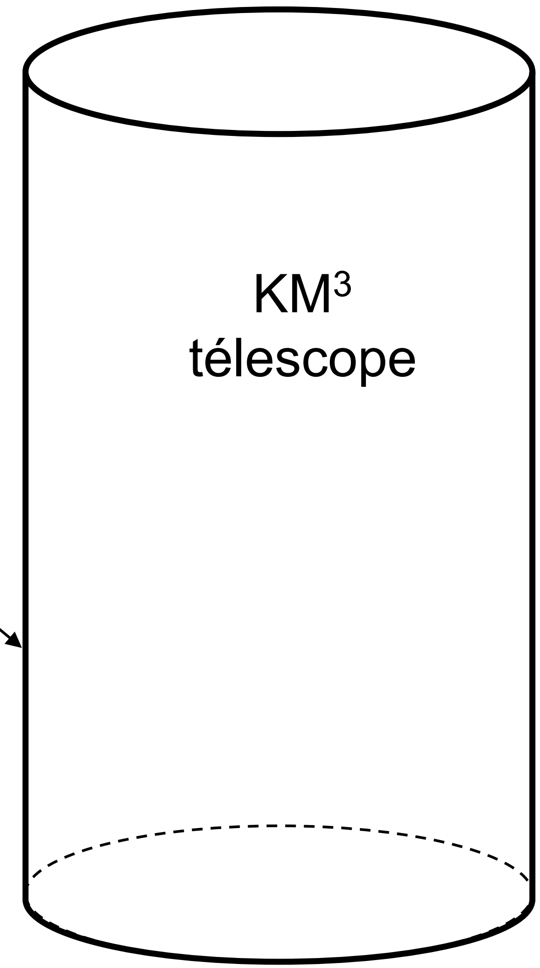
« These neutrino observations are so exciting and significant that I think we're about to see the birth of an entirely new branch of astronomy: neutrino astronomy.»

J.Bahcall
New York Times (3 Apr 1987)

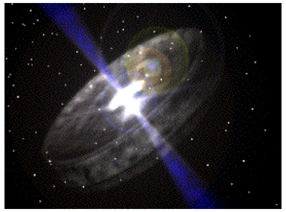
From MeV ν to PeV ν



High energy neutrino:
Small fluxes,
Need large detectors
for wide energy range



Outline



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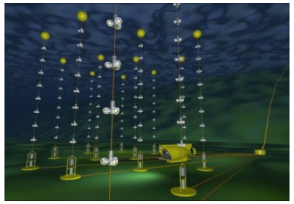
Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

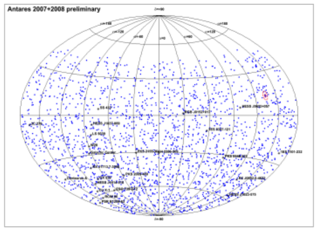


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

Diffuse Flux

Search for point sources

Multi-messenger search

KM3NeT project

Markov’s idea: muon neutrino

ИЯИ зак. № 2768

8.B:9.A

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

ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH

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

Received 3 January 1961

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

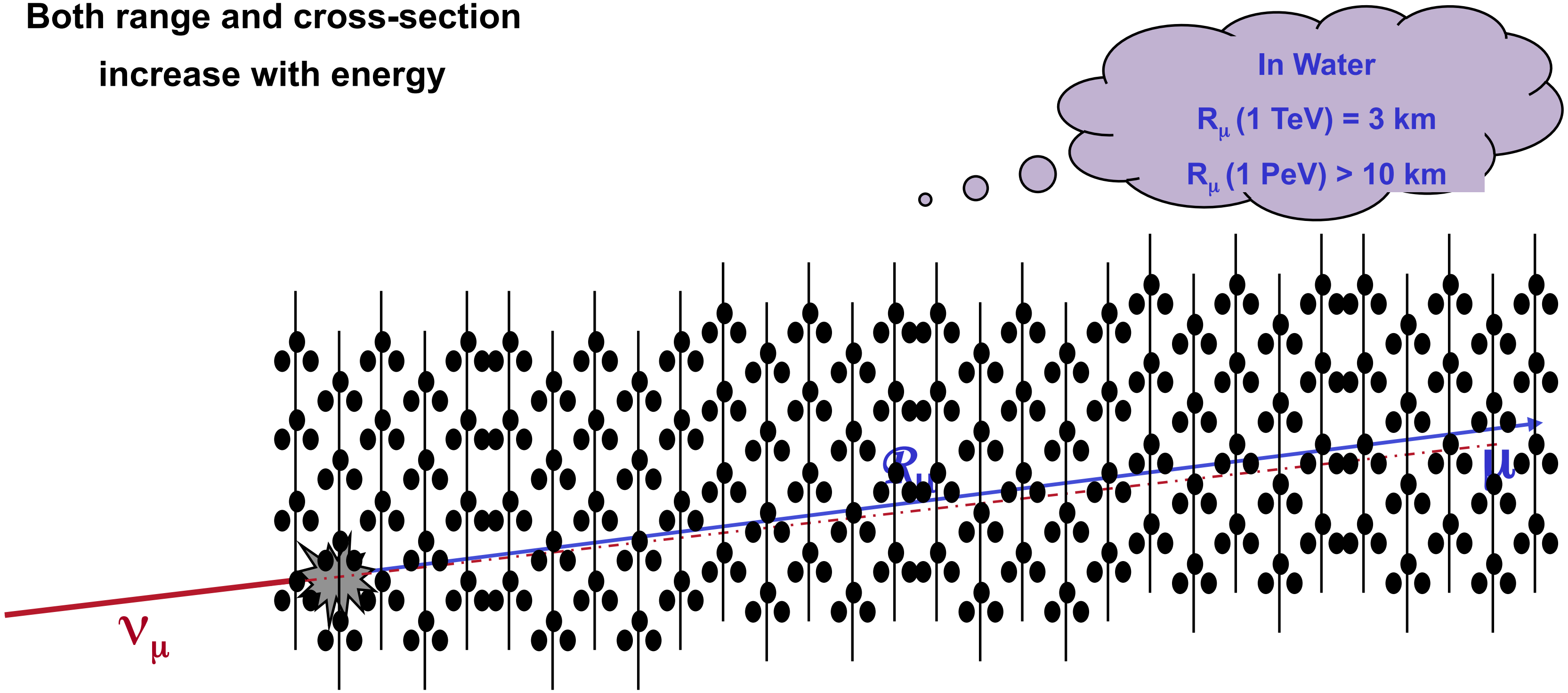
In 1960 M.A. Markov and I.M. Zheleznikh understand that the ν_μ detection is easier than the ν_e detection due to the induced muon path length.

Published in Nuclear Phys. 27 (1961) 385.

Markov idea: muon neutrino

μ well suited for HE detection

Both range and cross-section increase with energy



- Detection effective volume increases with E_ν
- Angle between ν and μ decreases with E_ν
- Interaction cross section increases with E_ν

Detection of HE muon neutrinos is favoured

Detection rate

The number of muon events in units of detection area A and observation time T is:

$$\frac{N_\mu(E_{\mu,min},\vartheta)}{AT} = \int_{E_{\mu,min}}^{E_\nu} dE_\nu \Phi_\nu(E_\nu,\vartheta) P_{\nu\mu}(E_\nu,E_{\mu,min}) e^{-\sigma_{tot}(E_\nu)N_A Z(\vartheta)}$$

- **Neutrino flux spectrum**
- **Probabilty to produce a detectable ($E_\mu > E_{min}$) muon**
- **Earth transparency to HE neutrinos → >PeV neutrinos search for "horizontal" tracks**

$$P_{\nu\to l} = \mathcal{N}\int_{E_{min}}^{E_\nu} dE_l \frac{d\sigma}{dE_l} R_l(E_l, E_{min})$$

Range of lepton of energy El before it reaches E_{min}

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 m_N E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \left[xq\left(x,Q^2\right) + x\bar{q}\left(x,Q^2\right)(1-y)^2\right]$$

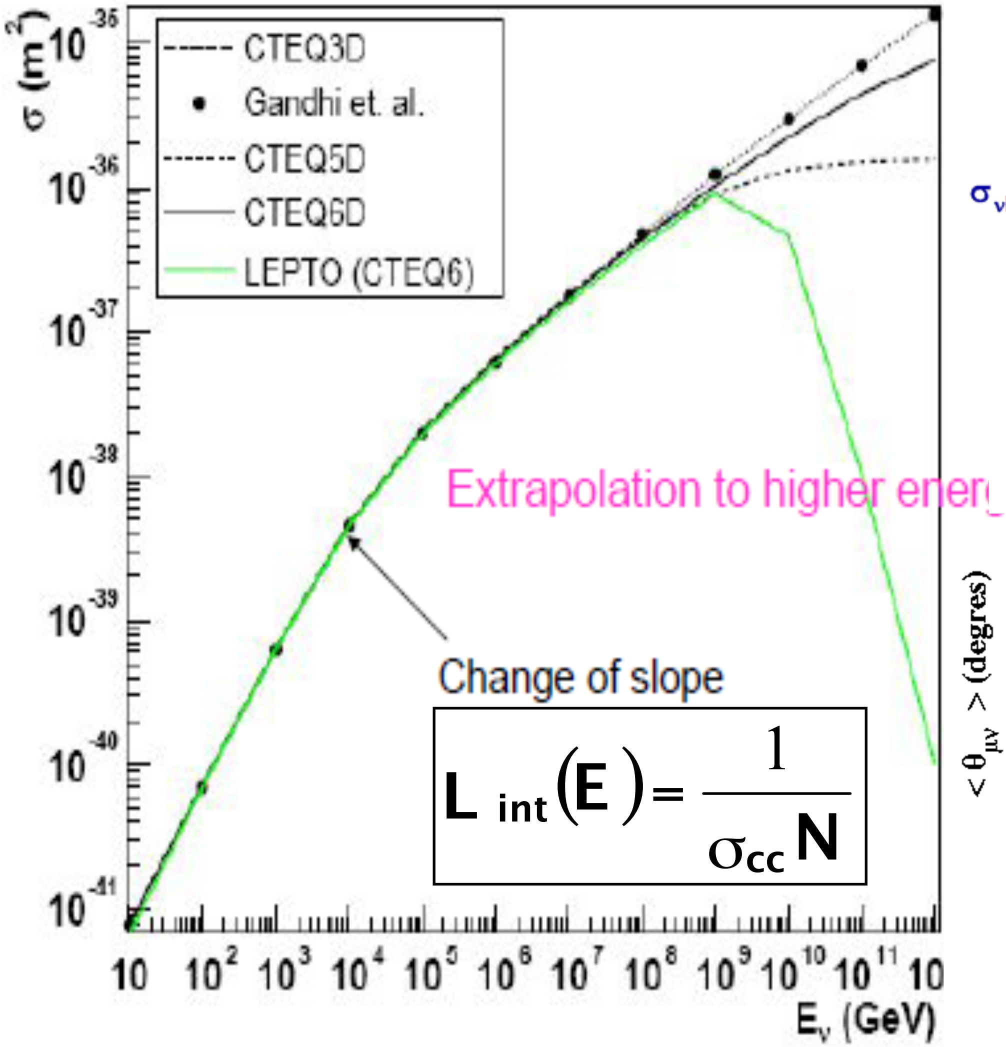
Bjorken scaling $x = Q^2/2M\nu$: fraction of the target nucleon's momentum carried by the quark

where $\nu = E_\nu - E' = E_x - M_{target}$ (energy of hadronic final state X)

x and Q^2 are measured event by event

Inelasticity (Bjorken) $y = \nu/E$: fraction of the lepton's energy lost in the lab

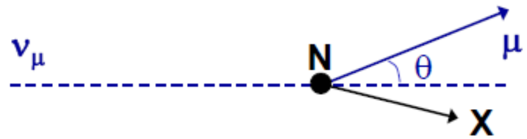
Deep inelastic scattering



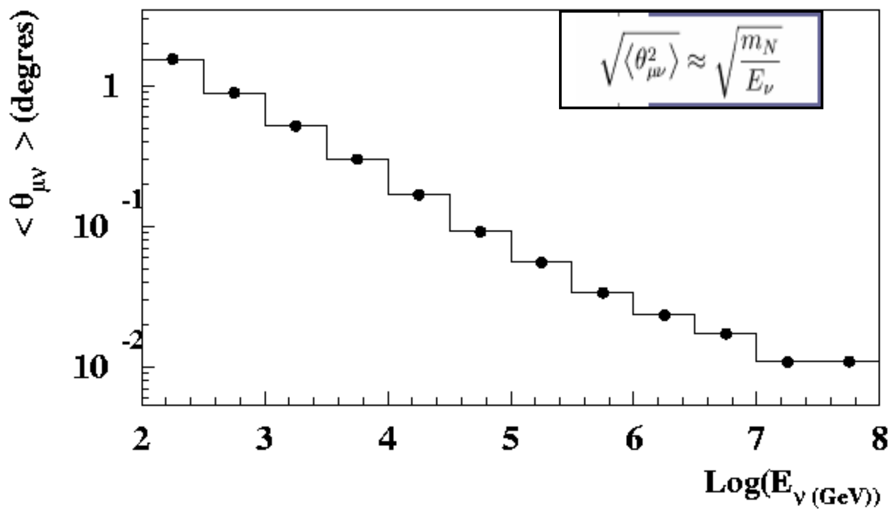
$$\nu_\ell + N \rightarrow \ell^- + X$$

$$\sigma_{\nu N} \begin{cases} \propto E_\nu & E_\nu \leq 5\,\mathrm{TeV} \\ \propto E_\nu^{0.4} & E_\nu > 5\,\mathrm{TeV} \end{cases}$$

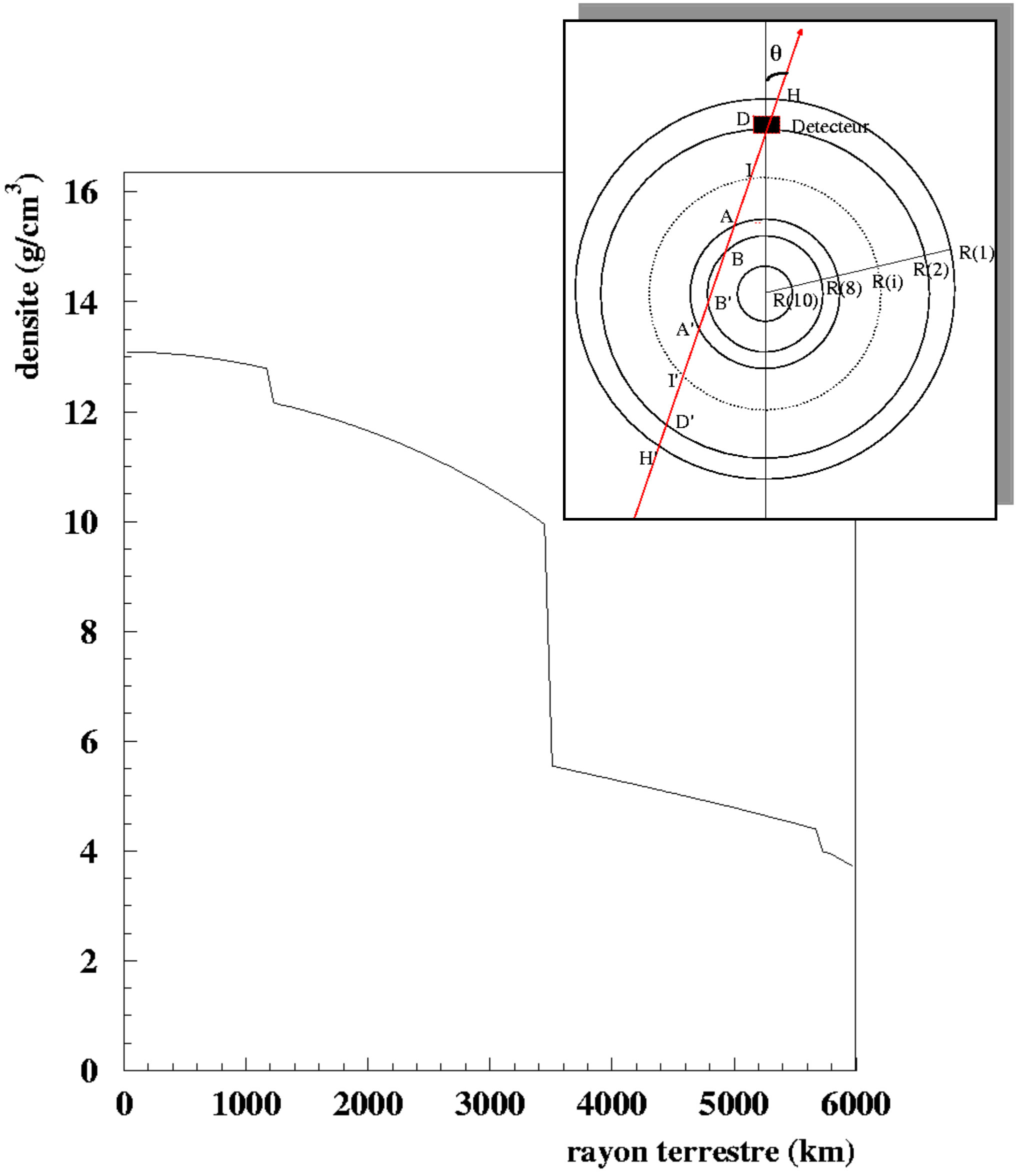
At >TeV energies the muon and the neutrino are co-linear



$$\langle \theta \rangle \approx \frac{1.5^\circ}{\sqrt{E_\nu[\mathrm{TeV}]}}$$

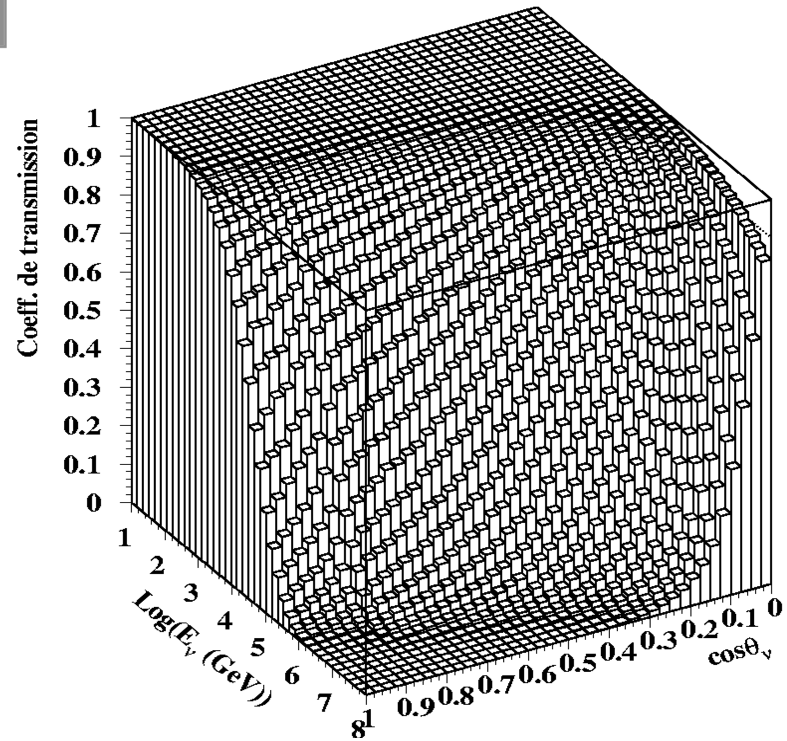


Neutrino absorption in the Earth



Preliminary Earth model (10 layers)

$$A(\theta,E) = e^{-\frac{\int \rho(\theta)dl}{L_{int}}}$$



Neutrino absorption in the Earth

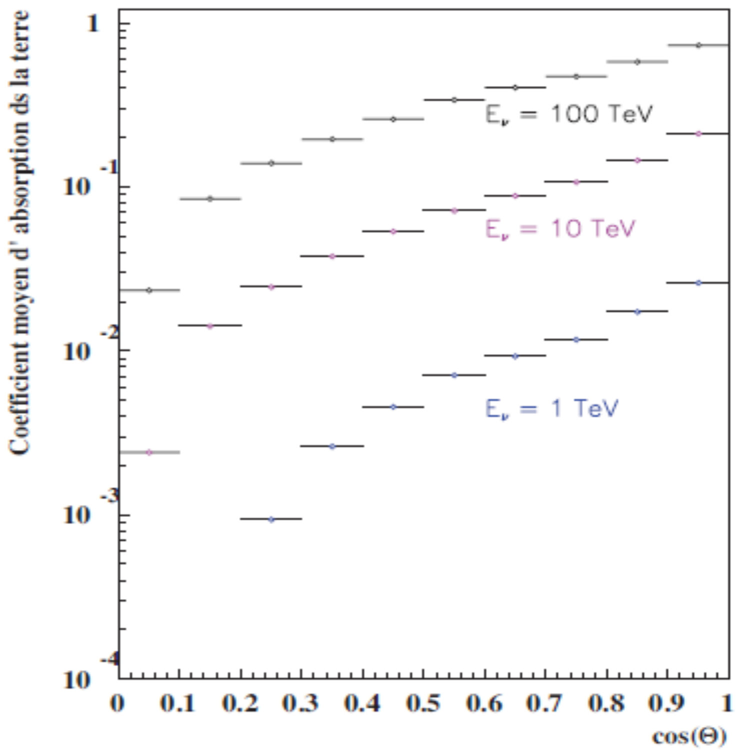


FIG. 1.17: *Effet moyen de l'absorption de neutrinos d'énergie de 1, 10 et 100 TeV en fonction de leur angle zénithal.*

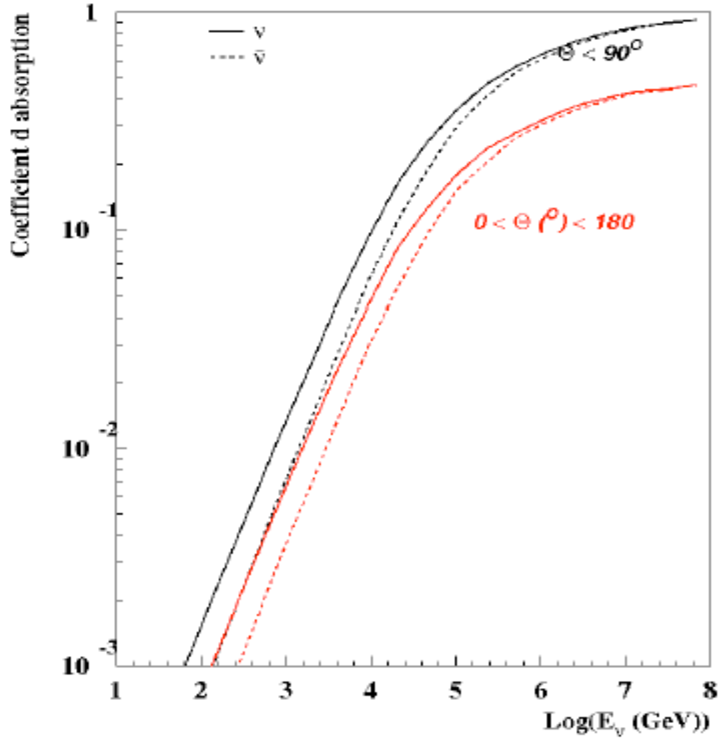
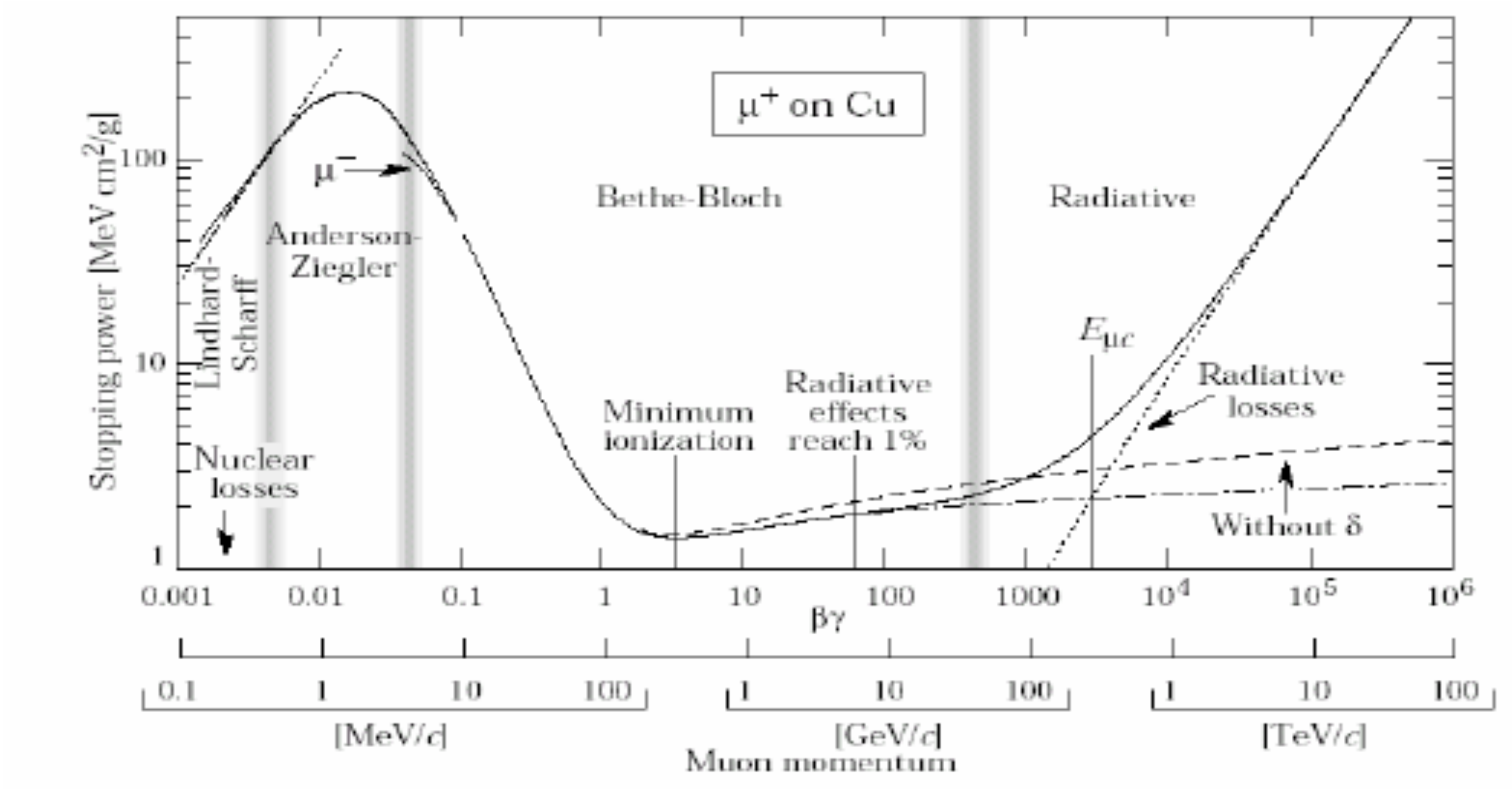


FIG. 1.18: *Absorption moyennée pour les neutrinos montants (en noir) et pour les deux hémisphères (en rouge) en fonction de l'énergie.*

Muon energy loss

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



Muon energy loss

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

Dominant for energy of 5 GeV - 1 TeV

Ionization

Energy loss proportional to the muon range

Contained or semi-contained events

Dark matter and oscillation studies

Dominant at hight energy > 1 TeV

Pair creation, Bremsstrahlung, photo-nuclear interactions

Energy estimated from the total amount of colllected light.

Through going events

Astrophysics

Muon energy loss

$$\left\langle \frac{dE}{dX} \right\rangle \approx \alpha(E) + \beta(E)E$$

$$\alpha \approx 2,2\ \mathrm{MeV.g^{-1}.cm^2}$$

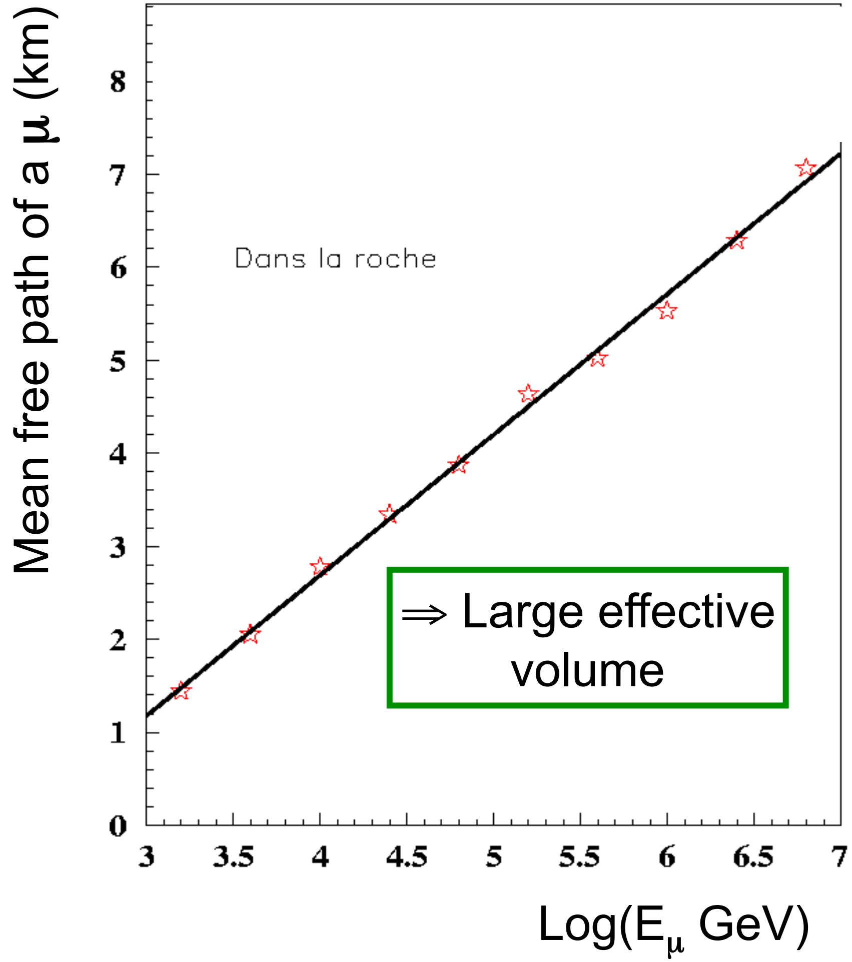
$$\beta \approx 4 \times 10^{-6}\ \mathrm{g^{-1}.cm^2}$$

EXERCICES:

1.Compute the path length of muon of energy E before if reaches the energy E_{min} based on the approximate d values of α and β .

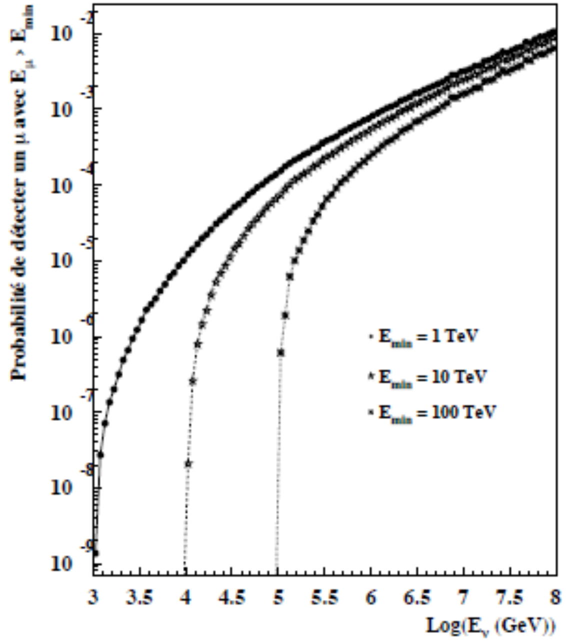
$$\mathrm{R}_\mu(\mathrm{E}_\mu, \mathrm{E}_{\min}) = \int_{\mathrm{E}_{\min}}^{\mathrm{E}_\mu} \frac{1}{\left\langle \frac{\mathrm{dE}}{\mathrm{dX}} \right\rangle} \mathrm{dE} \approx \frac{1}{\beta} \ln \frac{(\alpha/\beta) + \mathrm{E}_\mu}{(\alpha/\beta) + \mathrm{E}_{\min}}$$

2.AN: What is the total range of a 10 TeV muon in the rock (ρ_r=2.65 g. cm^{-3}), in sea water (ρ_r=1.02 g. cm^{-3}) ?



Detection probability and rate

$$P_{\nu \to l} = \mathcal{N} \int_{E_{min}}^{E_\nu} dE_l \frac{d\sigma}{dE_l} R_l(E_l, E_{min})$$

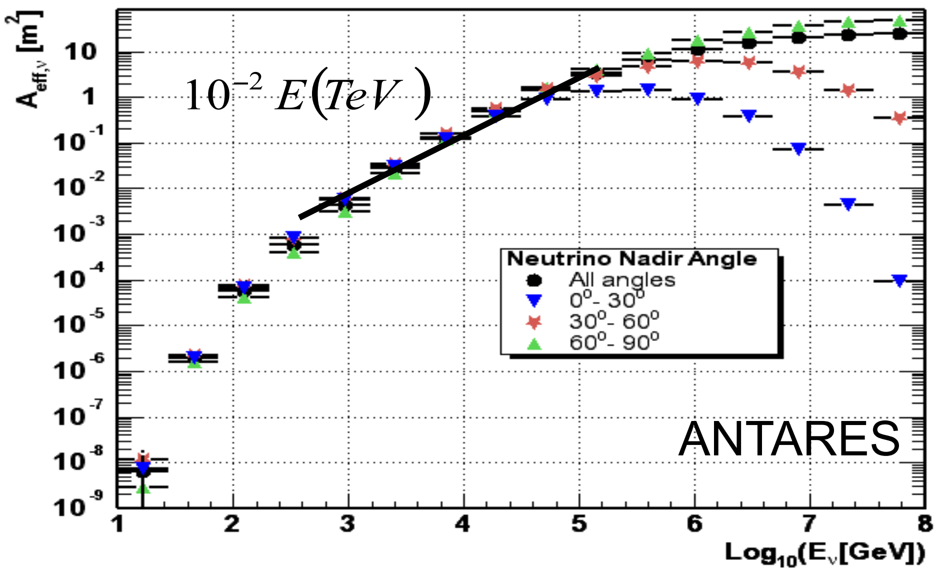


Here the Earth absorption is not taken into account

Event rate: $\frac{N_\mu}{T} = \int dE \cdot \frac{d\Phi_\nu}{dE_\nu} \cdot A_{eff}(E_\nu)$

$$A^{eff}(\theta, E_\nu) = \frac{N_{rec}}{N_{gen}} \times V_{gen} \times (\rho N_A) \times \sigma(E_\nu) \times e^{-\sigma(E_\nu)\rho N_A z(\theta)}$$

Neutrino Effective Area

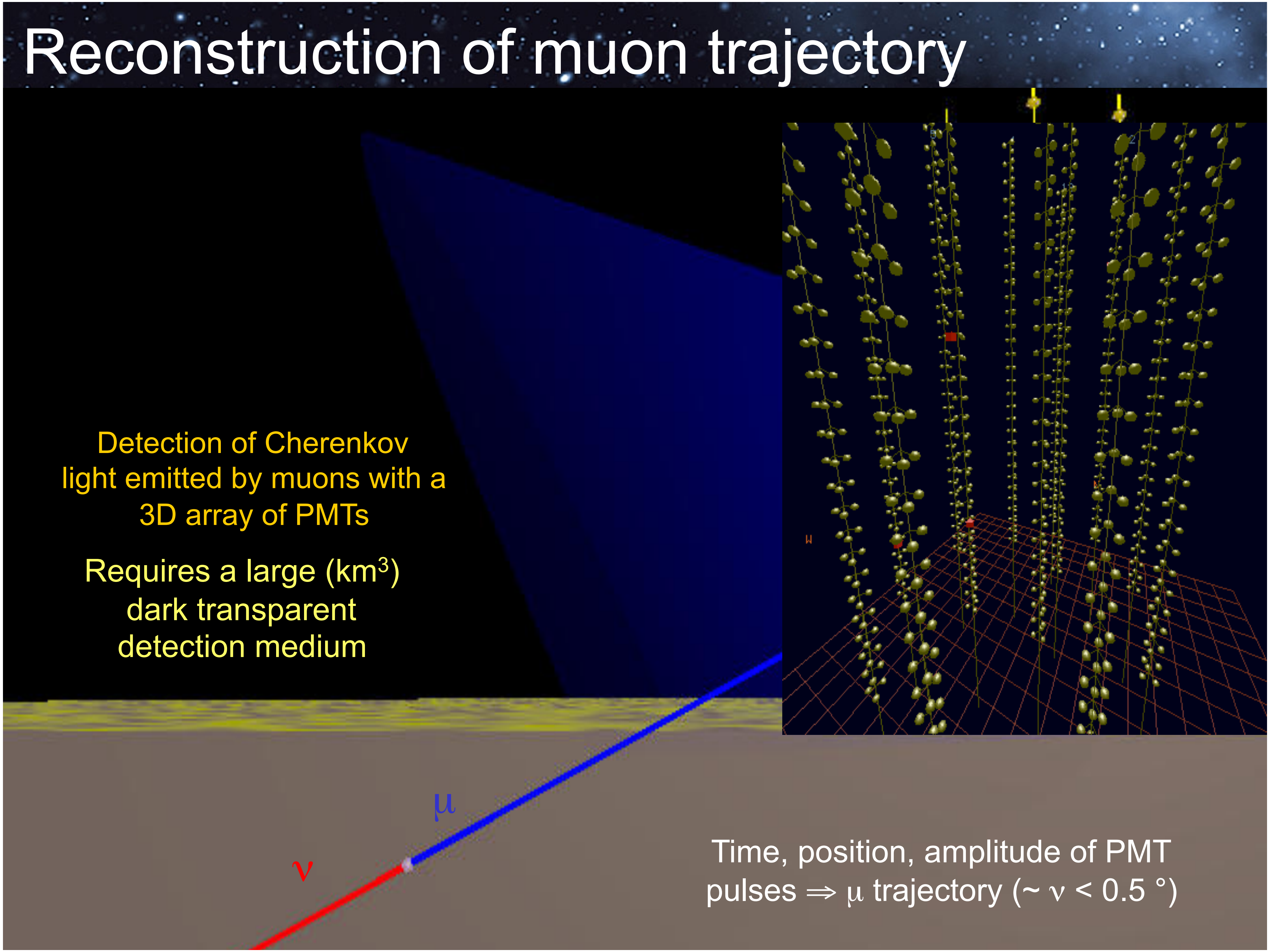


oscillations

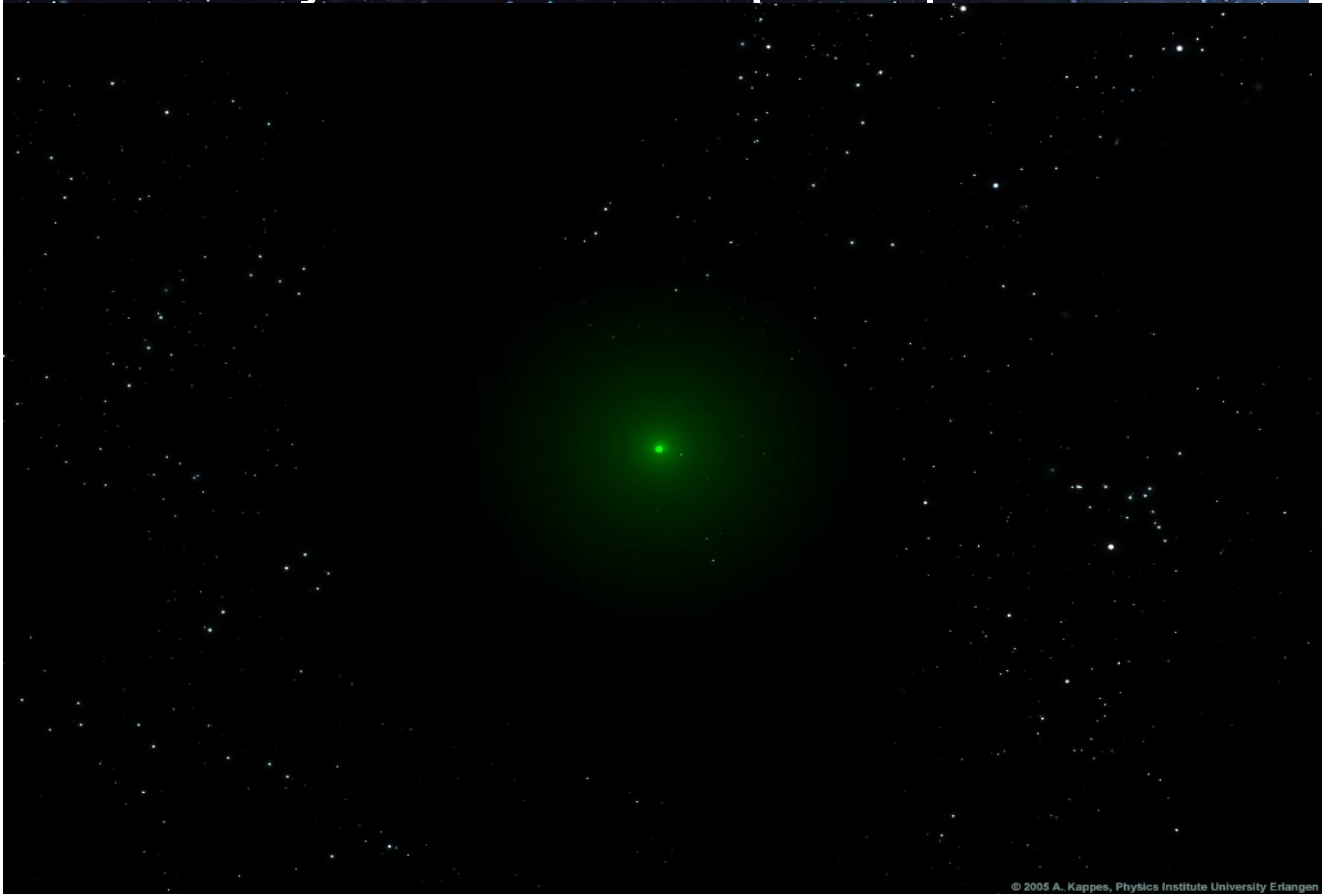
$$N = 2\pi \times \Delta t \times \int_{1TeV}^{1PeV} \frac{dN}{dE} A_{eff,\nu}(E)\, dE \times \frac{1}{2}$$

WB: $\frac{dN}{dE} = \frac{4.5 \times 10^{-11}}{E^2} TeV^{-1}\, cm^{-2}\, s^{-1}\, sr^{-1}$

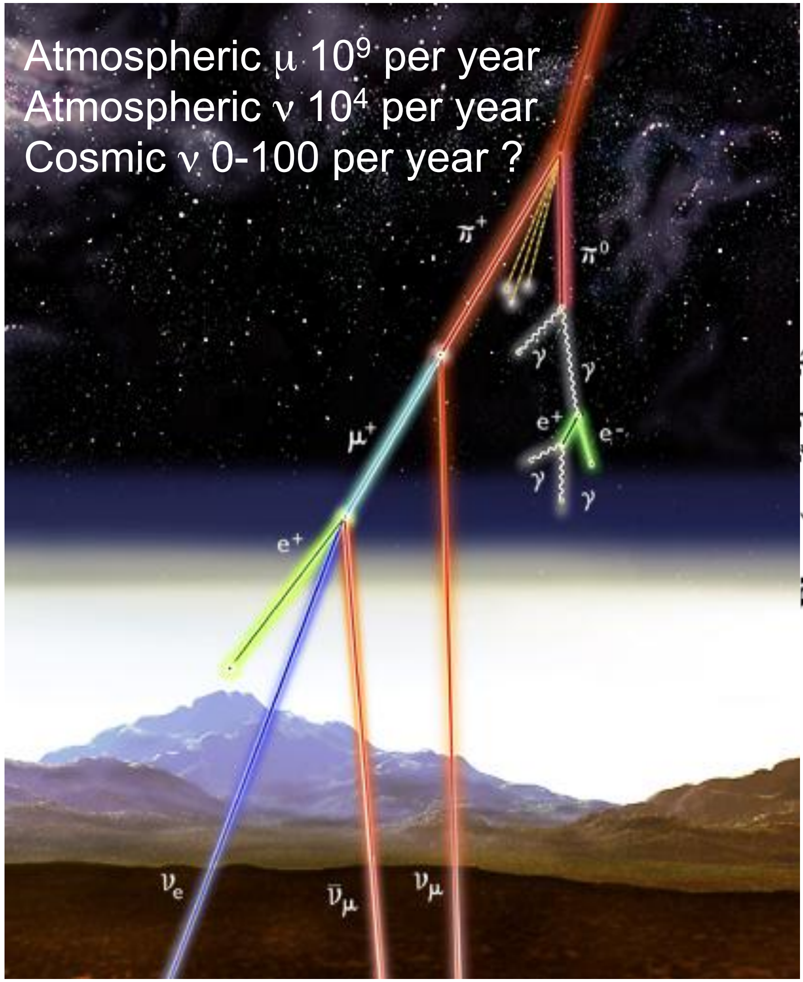
N ~ 3 / an

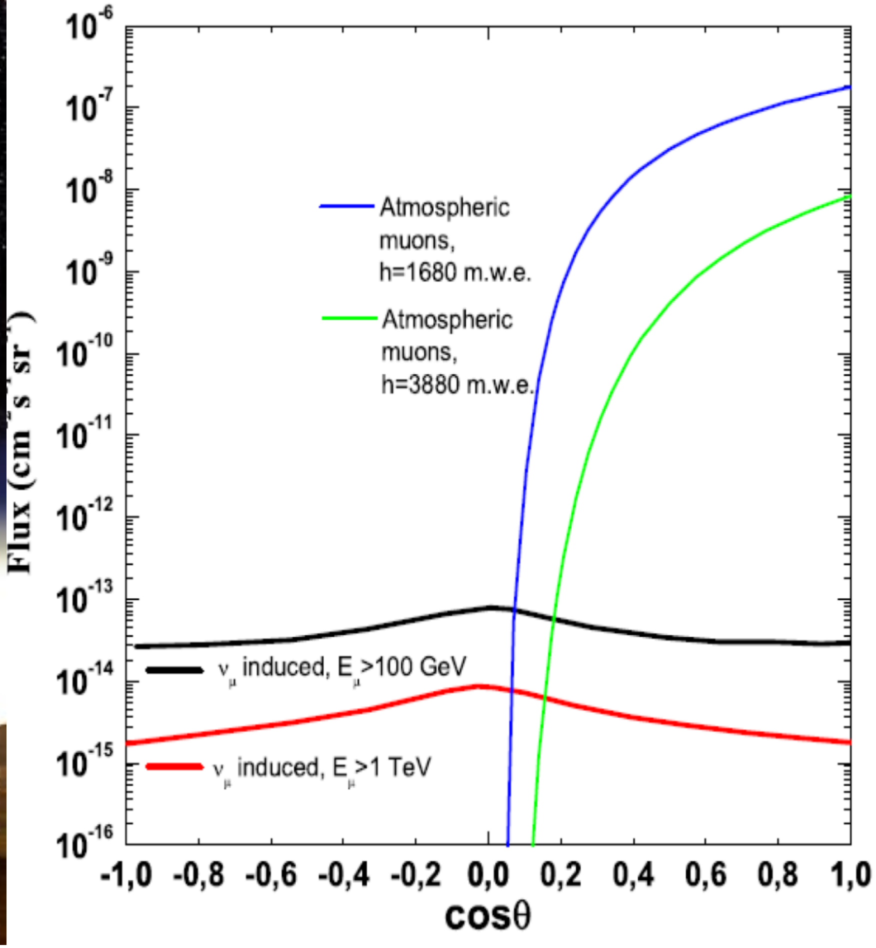

Reconstruction of muon trajectory
Detection of Cherenkov light emitted by muons with a 3D array of PMTs
Requires a large (km³) dark transparent detection medium
μ
ν
Time, position, amplitude of PMT pulses ⇒ μ trajectory (~ ν < 0.5 °)

Summary of detection principle



Atmospheric background



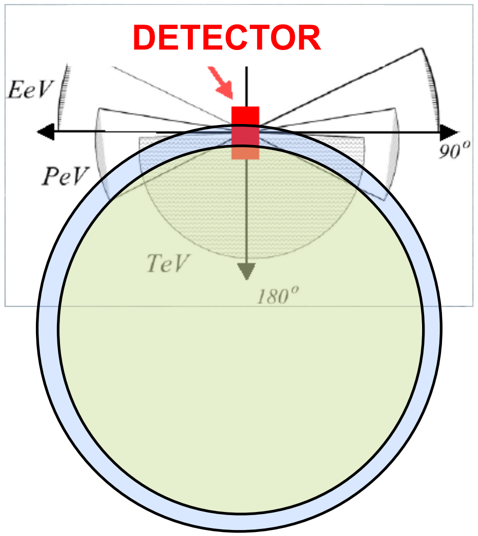


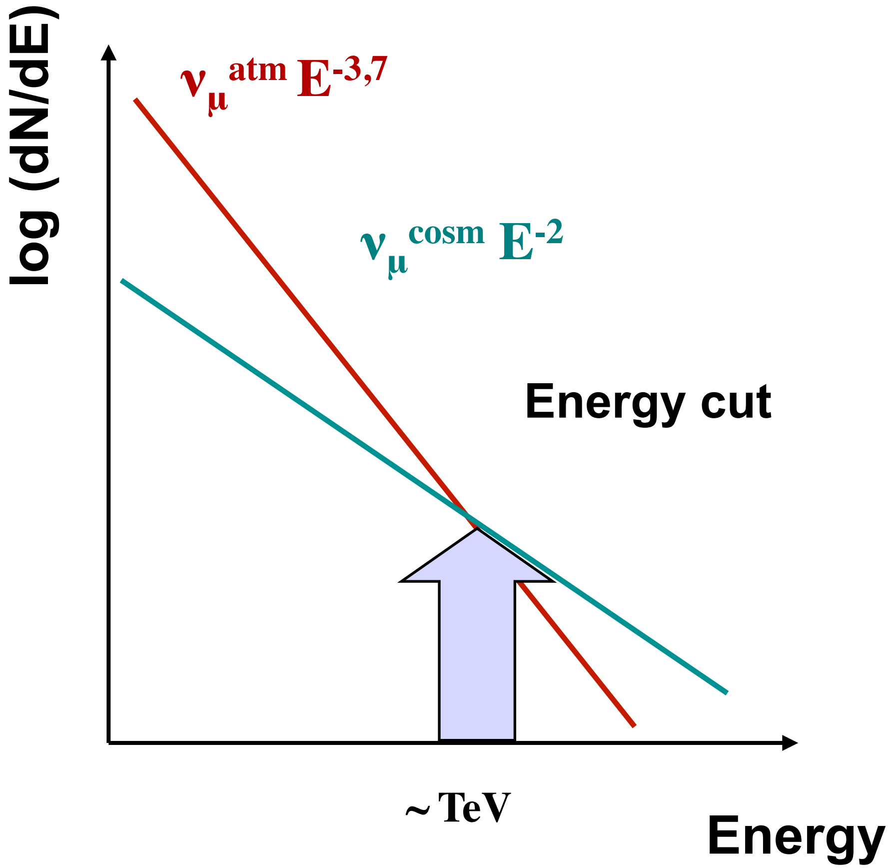
Atmospheric muons: only downgoing

Shield detector & define signal as upward muons

Atmospheric vs cosmic neutrinos

- **Cosmic neutrinos**: can be selected through dedicated cuts
- Search for anisotropy
- Time coincidence with other cosmic probes

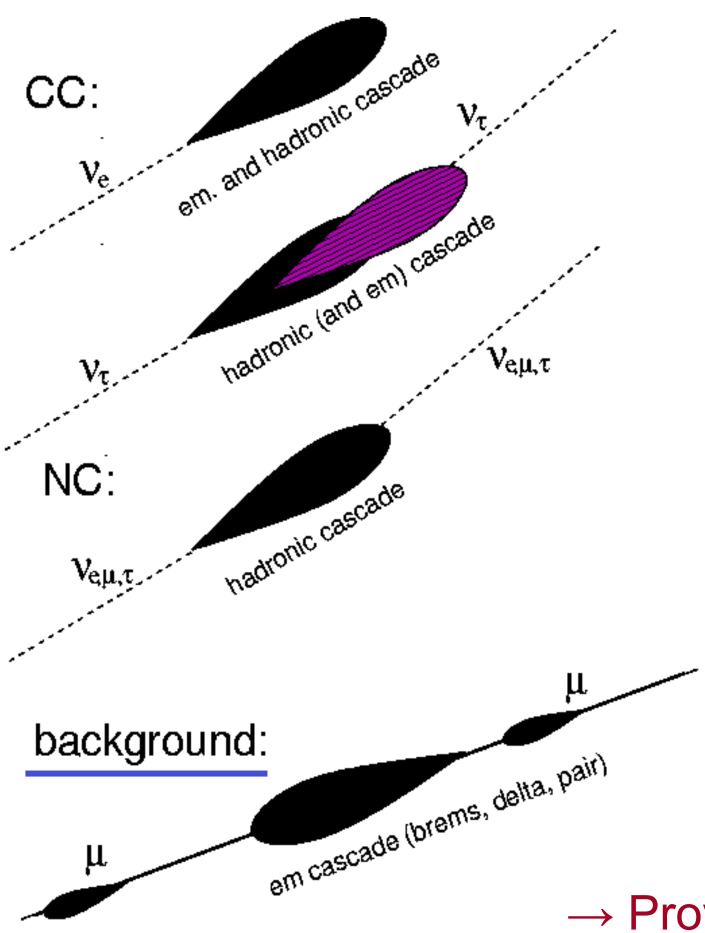




First signal for NT is atmospheric neutrinos

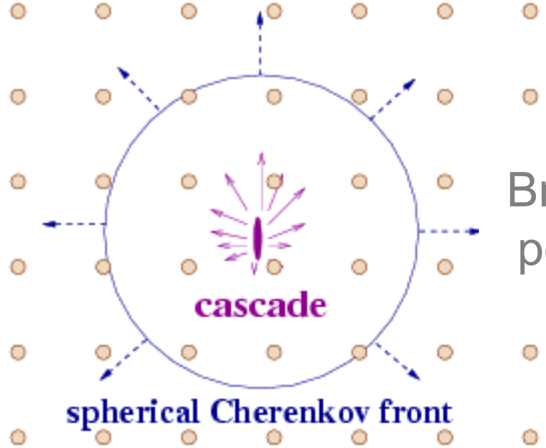
Other neutrino interaction topology

$\nu_e:\nu_\mu:\nu_\tau$ =1:2:0 at source —*oscillation*→ $\nu_e:\nu_\mu:\nu_\tau$ =1:1:1 at Earth !



So-called "cascade" events

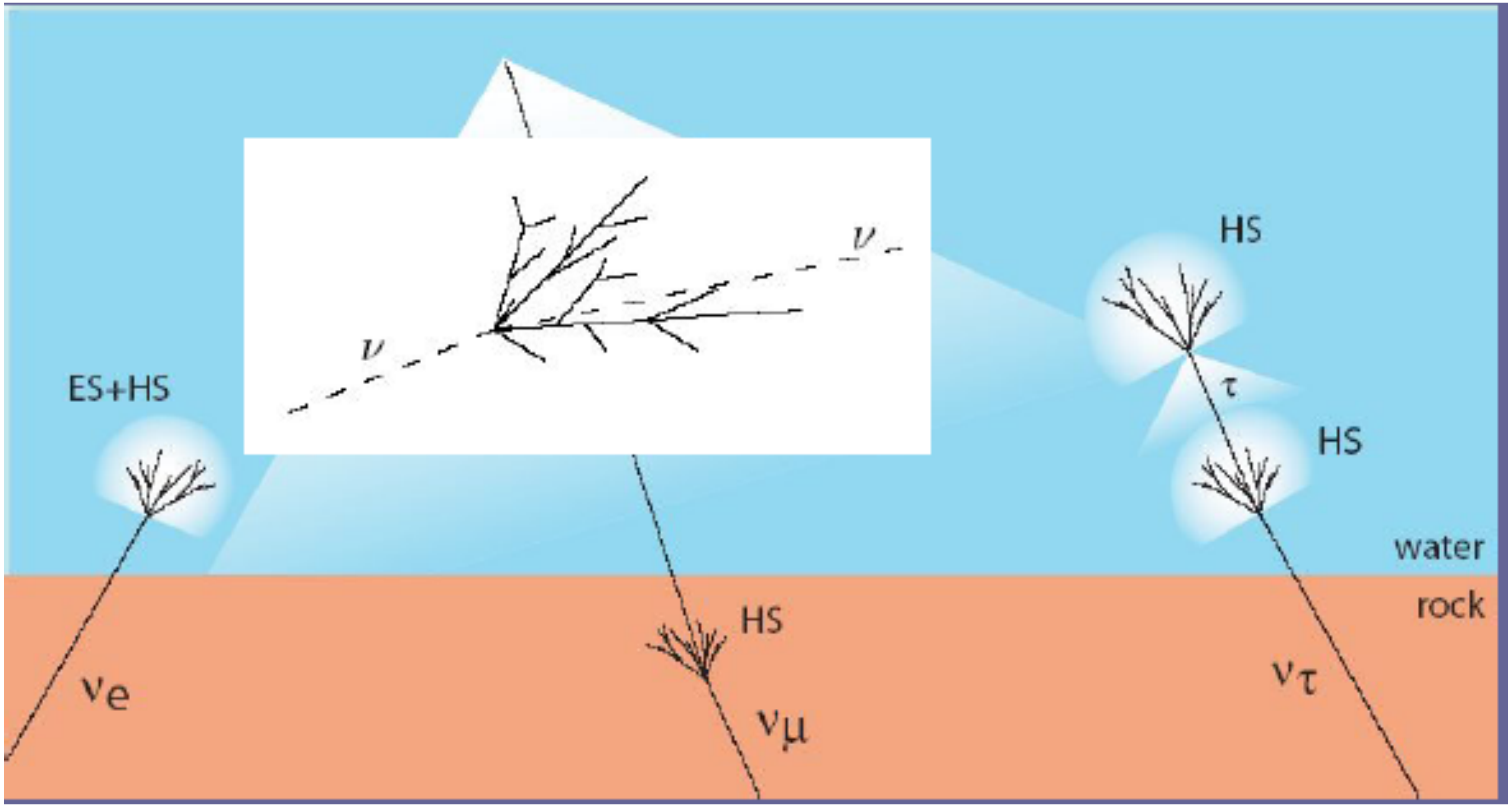
Generic reconstruction:



Bright point

→ Provide sensitivity to all neutrino flavors

Other neutrino interaction topology

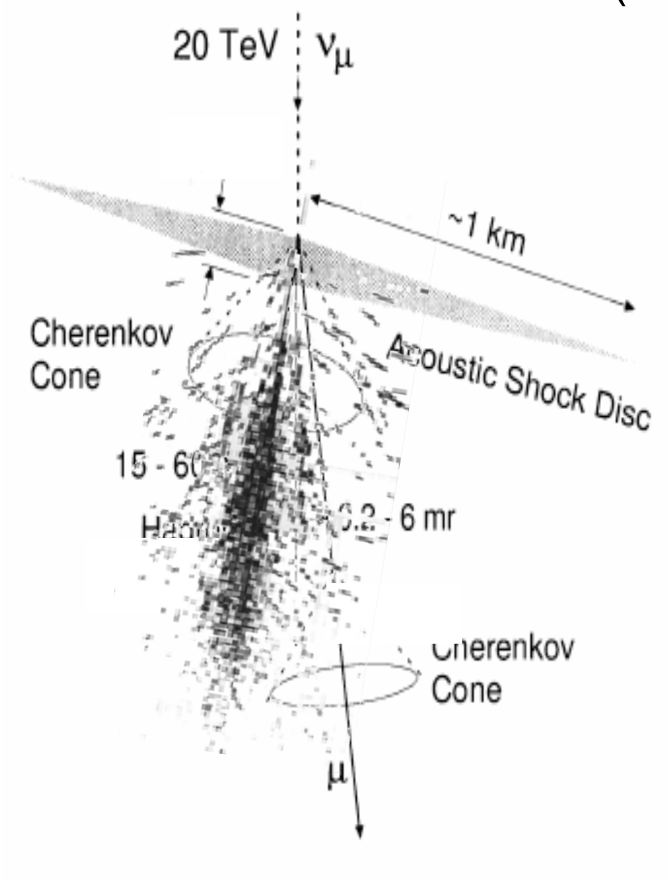


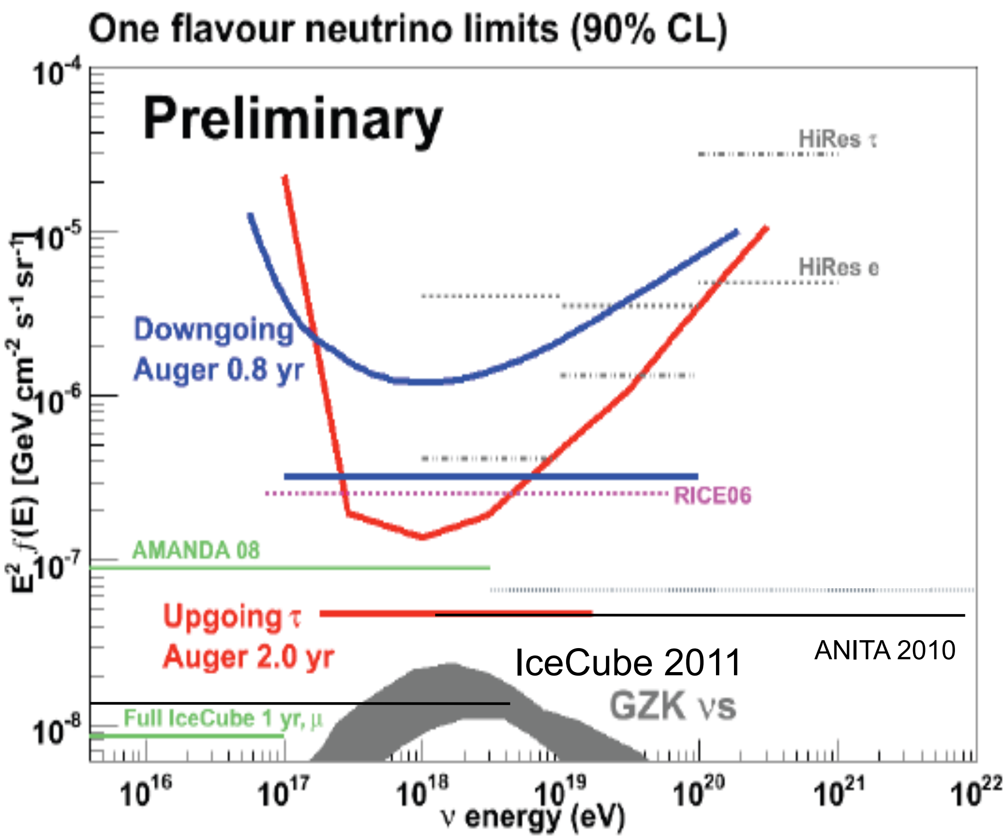
Other detection techniques

Acoustic shock, Optical, Radio (Askaryan Cherenkov), E.A.S, fluorescence

UHE neutrinos (not suited for TeV neutrinos)

📖 AUGER arXiv:0906.2347
📖 IceCube arXiv:1103.4250





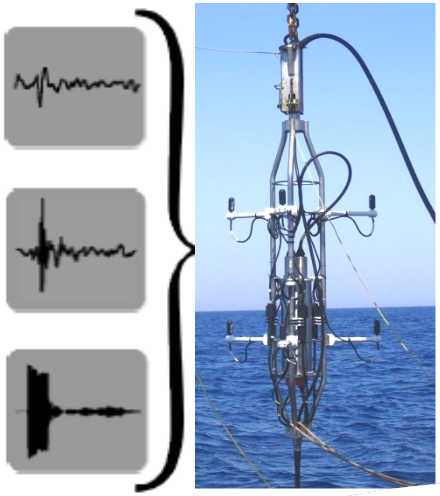
Current limits disfavor « Top-Down » models

Exclude saturated model of GZK

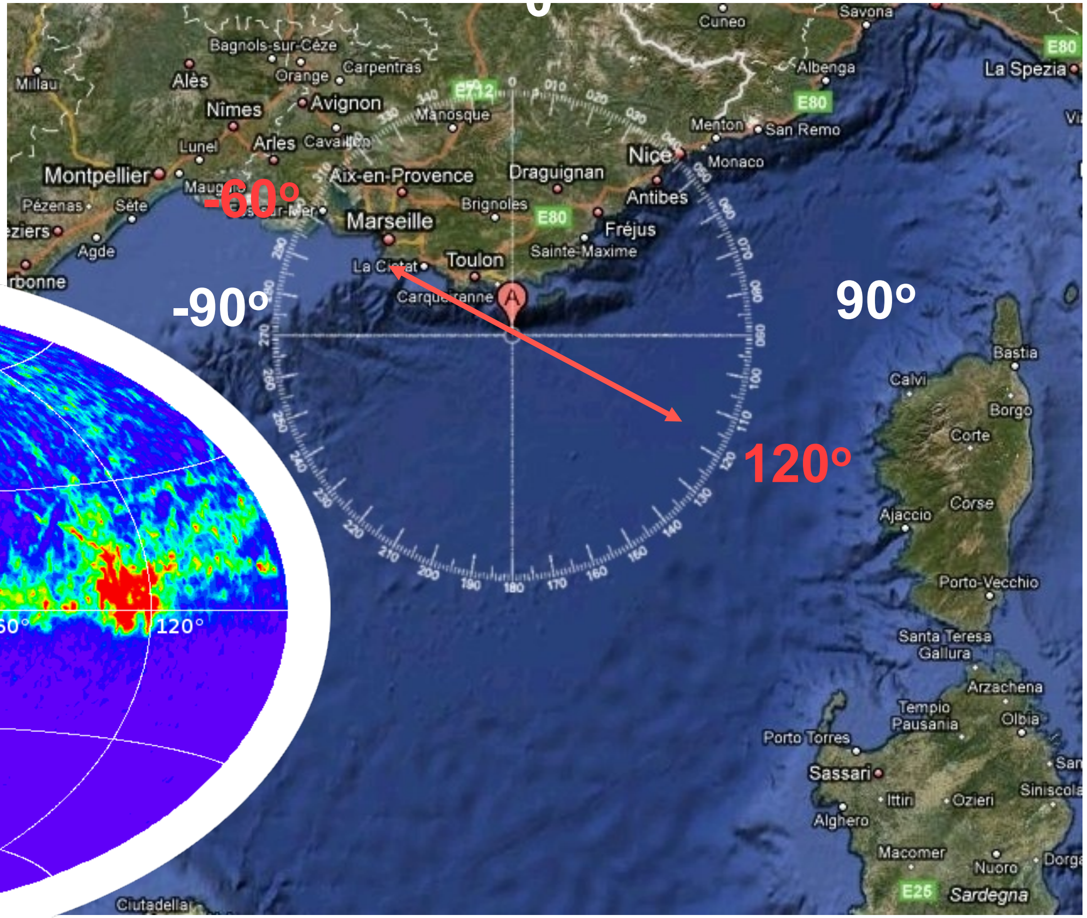
Acoustic detection R&D studies

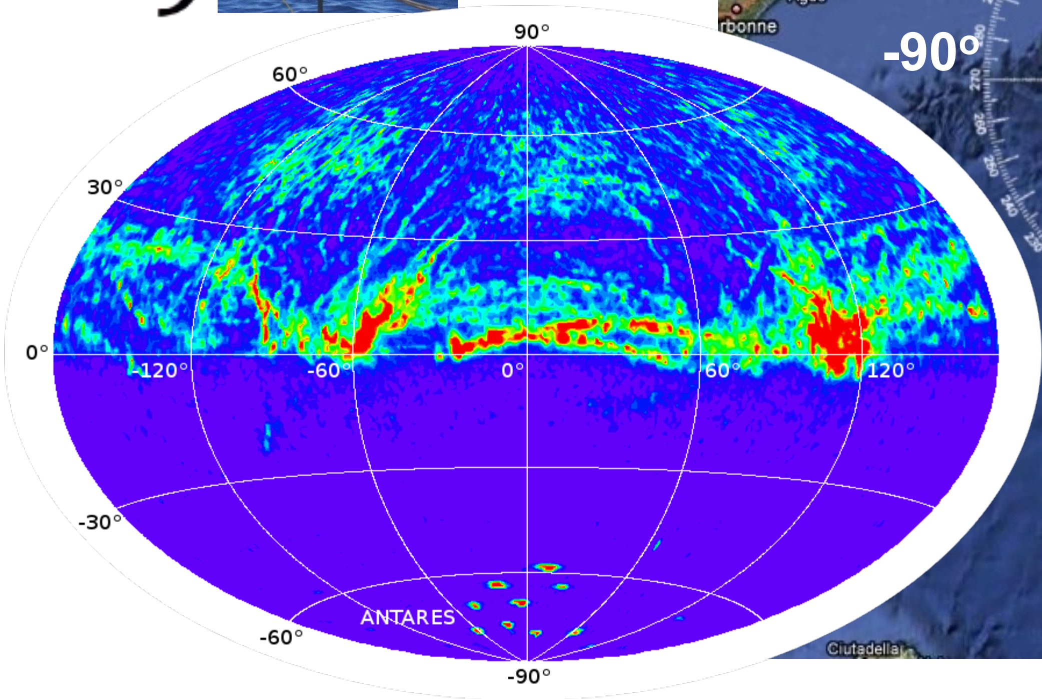
Example : AMADEUS detector as part as ANTARES NT
But also SPATS in the South Pole…

📖 NIM A 626-627 (2011) 128-143

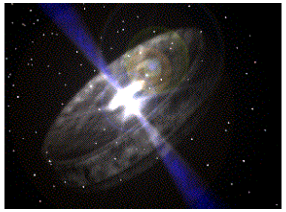


Direction reconstruction for one storey
All types of transient signals included, sea mammals, ships etc.
Origin points north to horizon





Outline

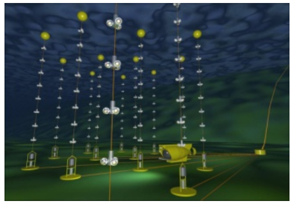


Neutrino astronomy

Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

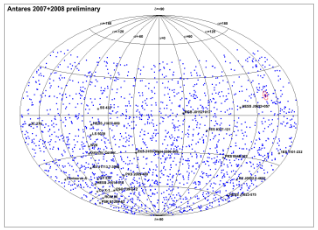


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

Diffuse Flux

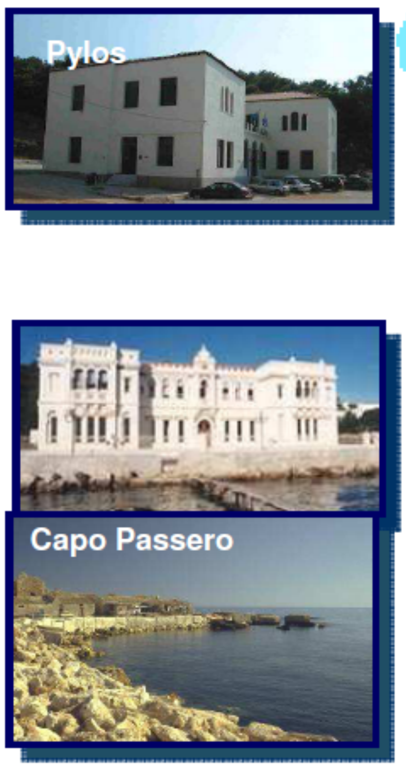
Search for point sources

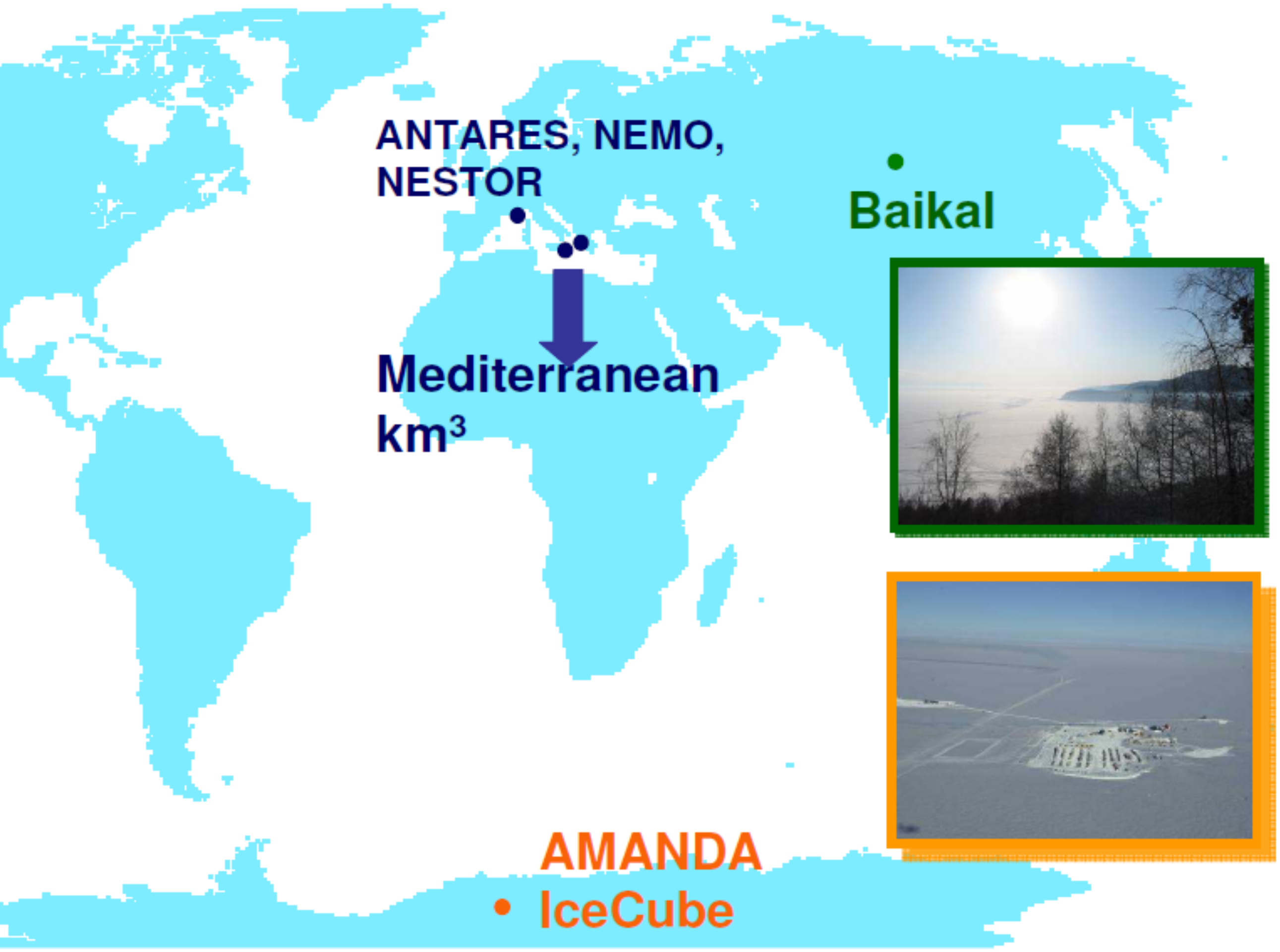
Multi-messenger search

KM3NeT project

Neutrino telescopes (TeV)

{ANTARES, BAIKAL, ICECUBE} currently working

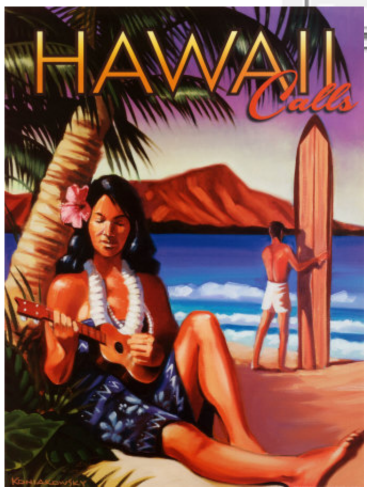




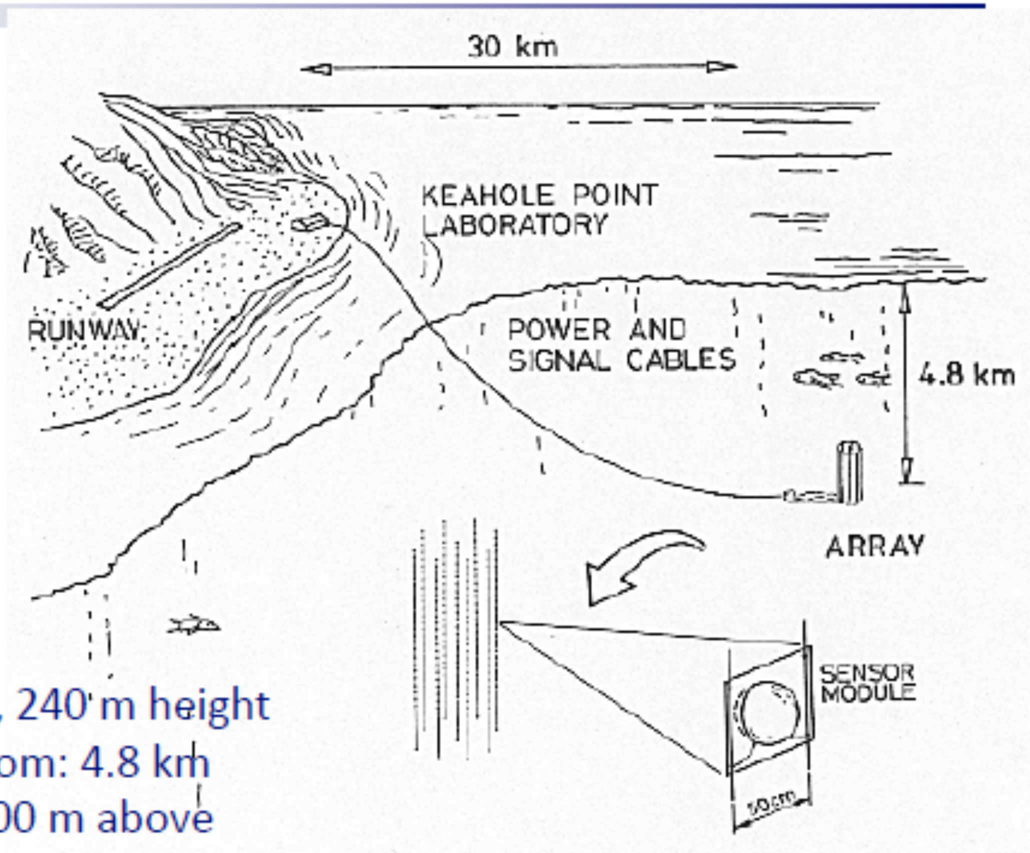
{ANTARES, NEMO, NESTOR} ∈ Consortium KM3NeT

Years 80's : the first project

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

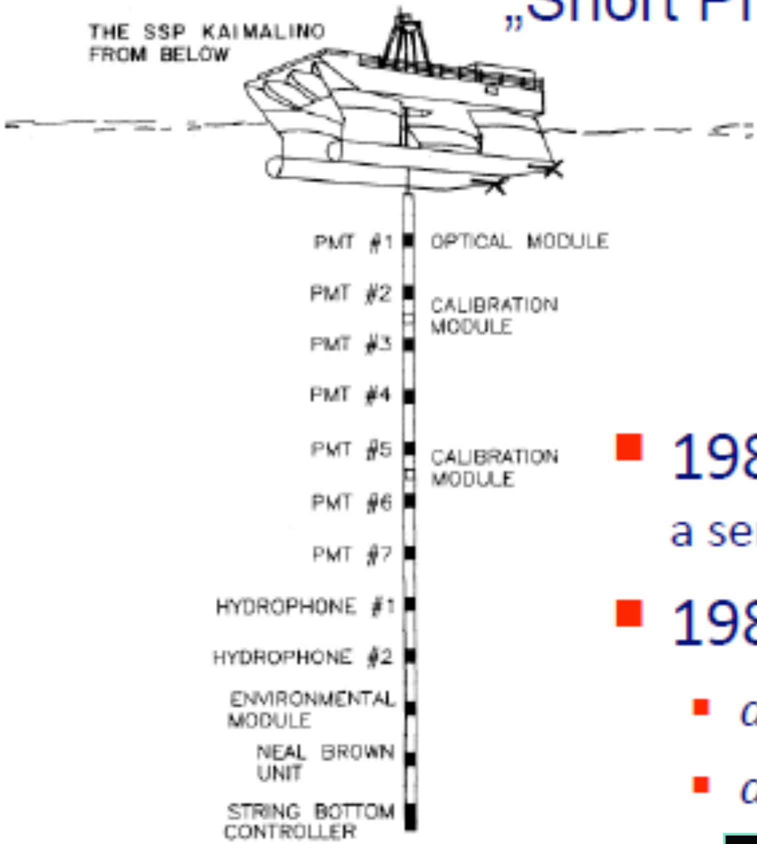


DUMAND-II (The Octagon)



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

R&D in Hawaii



„Short Prototype String"

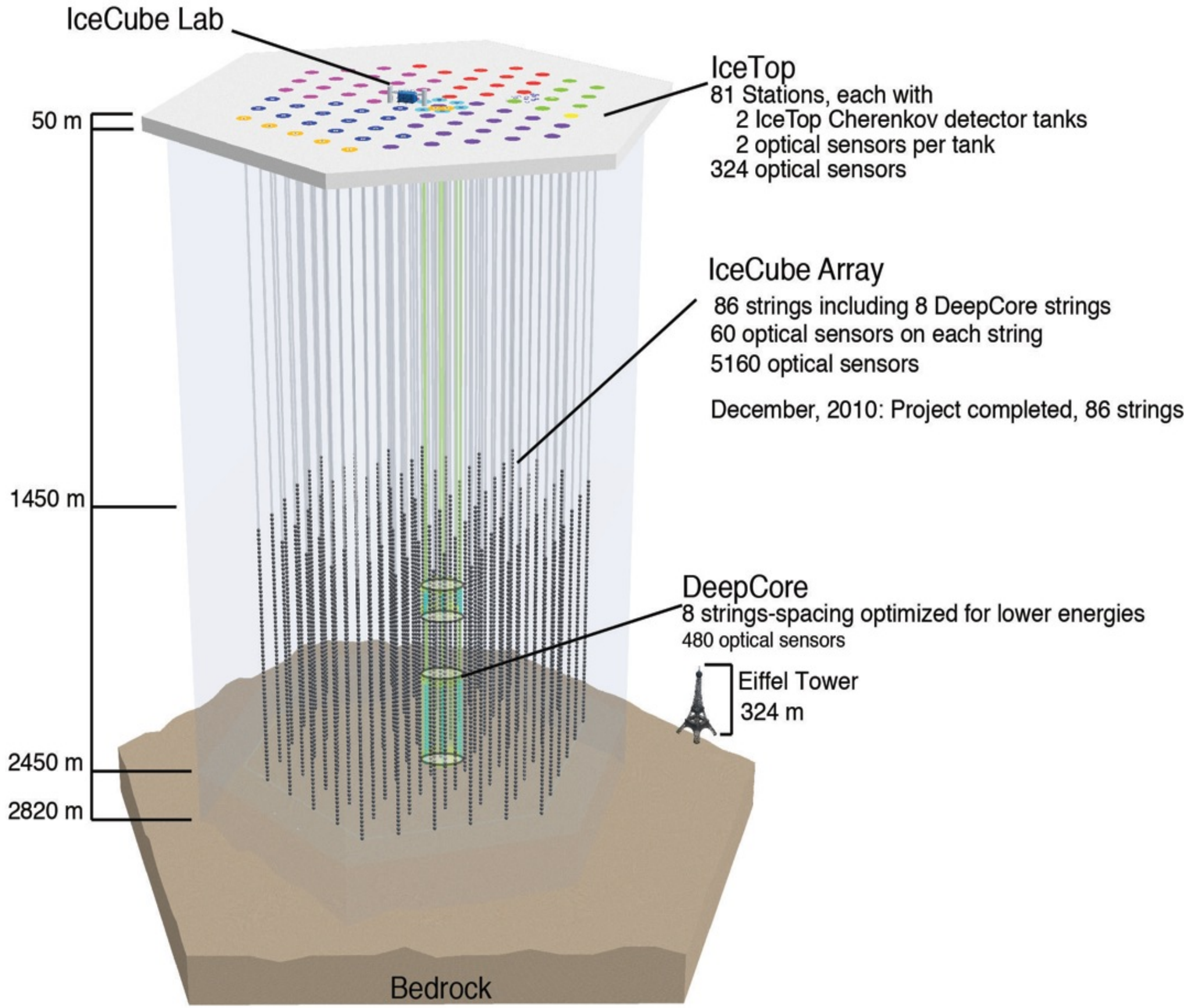
- 1982-87:
  a series of 14 cruises, with two lost strings
- 1987: success !
  - *depth-intensity curve*
  - *angular distributions*
  - December 1993: deployment of first string and connection to junction box. Failure after several hours

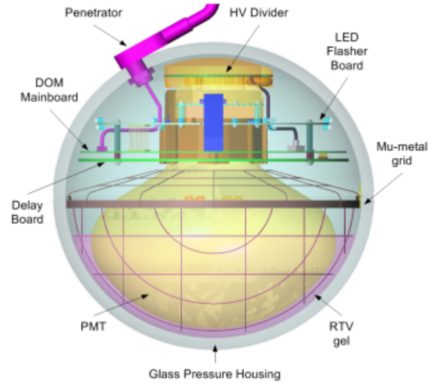
    1995: DUMAND project is terminated

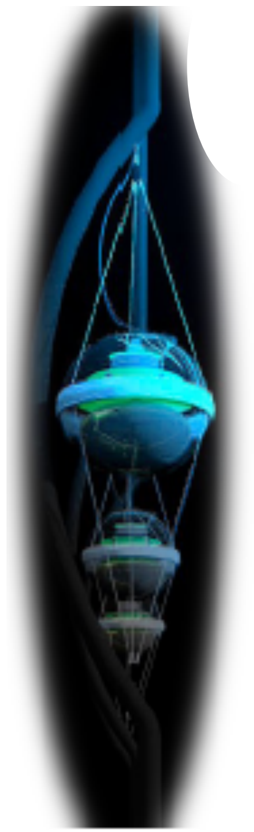
"At first, when we talked about DUMAND our accelerator friends laughed and said we were crazy. Now they ask why have you not got it operating yet !"
J G Learned (1992)

IceCube : the biggest NT in the world

Completed since December 2010.







First steps…

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

Nature Sept 91

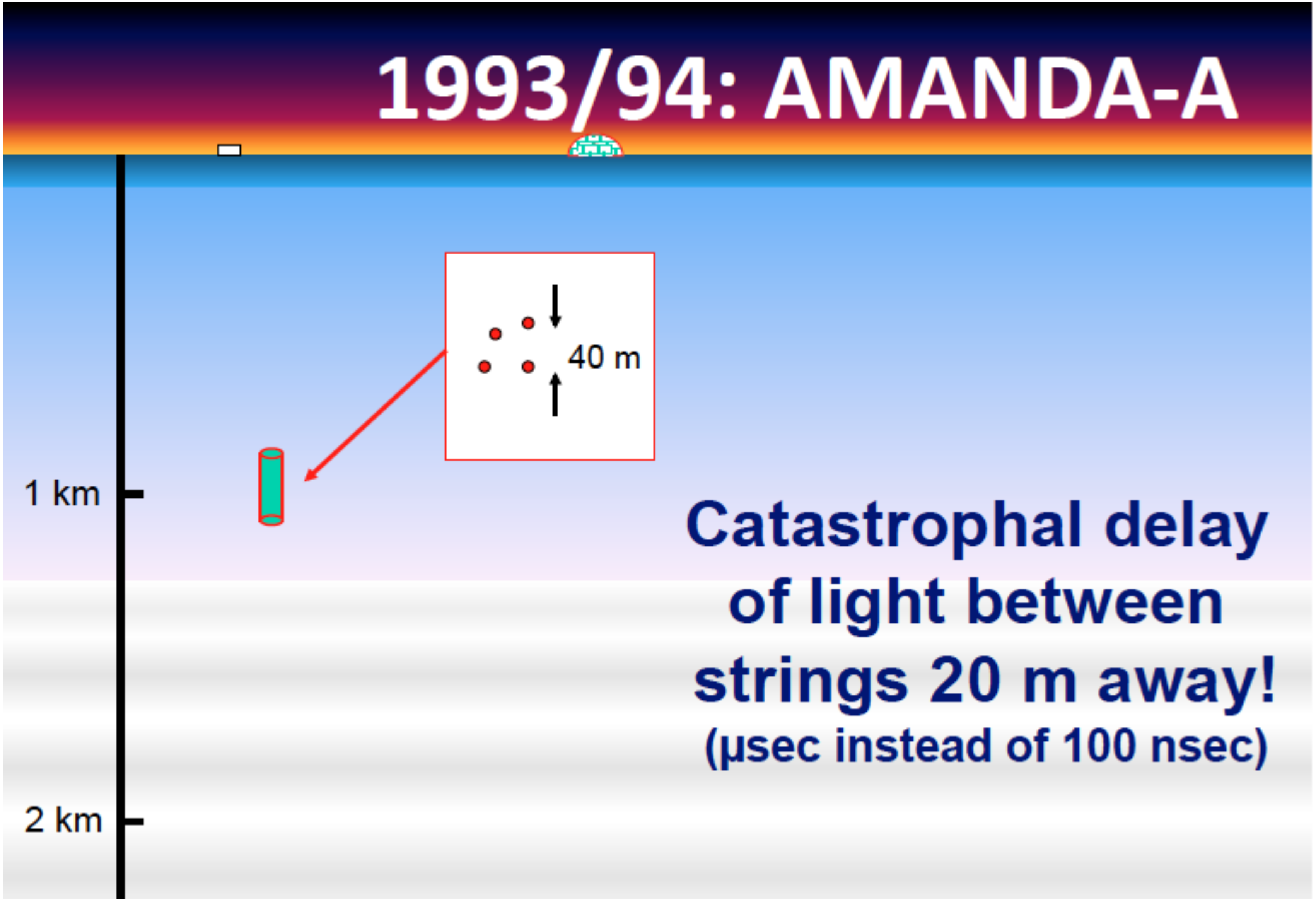
D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

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

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

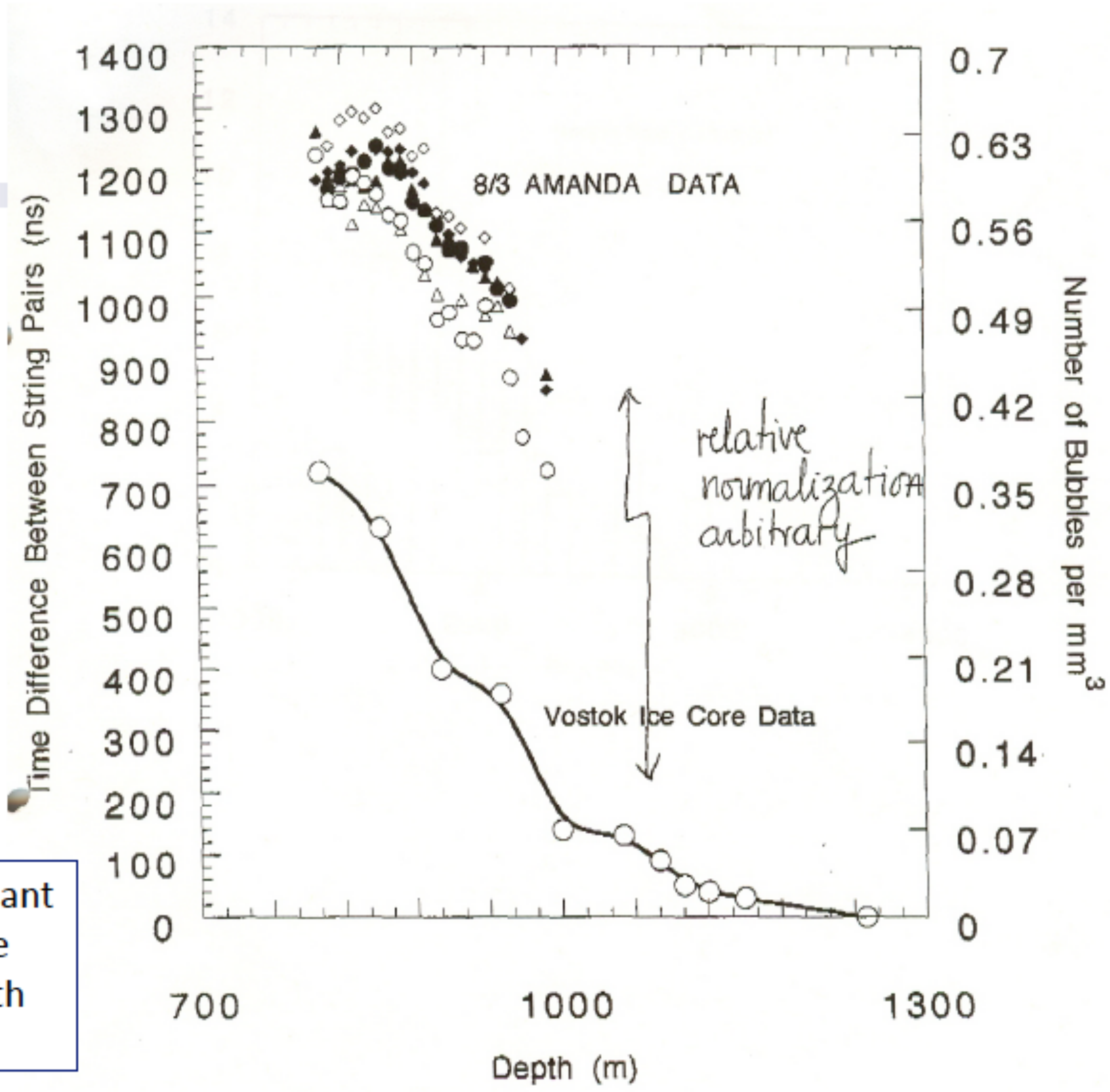
F. Halzen

...were difficult



Crédit : Ch. Spiering

…were difficult



Explanation remnant bubbles which are disapppearing with increasing depth.

...but conclusive !

Observation of high-energy neutrinos using Čerenkov detectors embedded deep in Antarctic ice

E. Andrés*, P. Askebjer†, X. Bai‡, G. Barouch*, S.W. Barwick§, R.C. Bay‖, K.-H. Becker¶, L. Bergström†, D. Bertrand#, D. Bierenbaum§, A. Biron☆, J. Booth§, O. Botner**, A. Bouchta☆, M.M. Boyce*, S. Carius††, A. Chen*, D. Chirkin‖¶, J. Conrad**, J. Cooley*, C.G.S. Costa#, D.F. Cowen‡‡, J. Dailing§, E. Dalberg†, T. DeYoung*, P. Desiati☆, J.-P. Dewulf#, P. Doksus*, J. Edsjö†, P. Ekström†, B. Erlandsson†, T. Feser§§, M. Gaug☆, A. Goldschmidt‖, A. Goobar†, L. Gray*, H. Haase☆, A. Hallgren**, F. Halzen*, K. Hanson‡‡, R. Hardtke*, Y.D. He‖, M. Hellwig§§, H. Heukenkamp☆, G.C. Hill*, P.O. Hulth†, S. Hundertmark§, J. Jacobsen‖, V. Kandhadai*, A. Karle*, J. Kim§, B. Koci*, L. Köpke§§, M. Kowalski☆, H. Leich☆, M. Leuthold☆, P. Lindahl††, I. Liubarsky*, P. Loaiza**, D.M. Lowder‖, J. Ludvig‖, J. Madsen*, P. Marciniewski**, H.S. Matis‖, A. Mihalyi‡‡, T. Mikolajski☆, T.C. Miller‡, Y. Minaeva†, P. Miočinović‖, P.C. Mock§, R. Morse*, T. Neunhöffer§§, F.M. Newcomer‡‡, P. Niessen☆, D.R. Nygren‖, H. Ögelman*, C. Pérez de los Heros**, R. Porrata§, P.B. Price‖, K. Rawlins*, C. Reed§, W. Rhode¶, A. Richards‖, S. Richter☆, J. Rodríguez Martino†, P. Romenesko*, D. Ross§, H. Rubinstein†, H.-G. Sander§§, T. Scheider§§, T. Schmidt☆, D. Schneider*, E. Schneider§, R. Schwarz*, A. Silvestri¶☆, M. Solarz‖, G.M. Spiczak‡, C. Spiering☆, N. Starinsky*, D. Steele*, P. Steffen☆, R.G. Stokstad‖, O. Streicher☆, Q. Sun†, I. Taboada‡‡, L. Thollander†, T. Thon☆, S. Tilav*, N. Usechak§, M. Vander Donckt#, C. Walck†, C. Weinheimer§§, C.H. Wiebusch☆, R. Wischnewski☆, H. Wissing☆, K. Woschnagg‖, W. Wu§, G. Yodh§ & S. Young§

NATURE 2001

AMANDA B10 (1996/97)

IceCube will work !

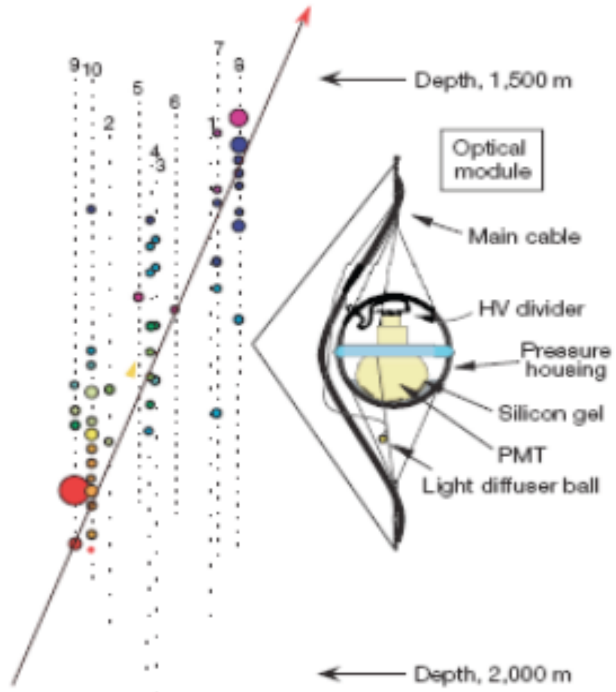


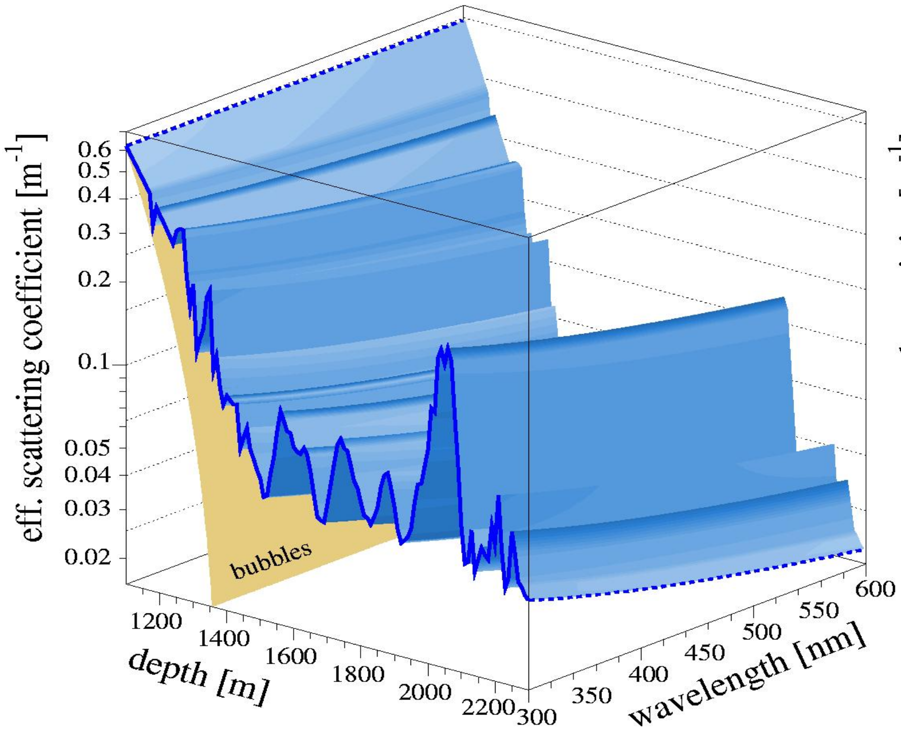
Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular event; the sizes of the circles indicate the amplitudes of the pulses and the colours correspond to the time of a photon's arrival. Earlier times are in red and later ones in blue. The arrow indicates the reconstructed track of the upwardly propagating muon.

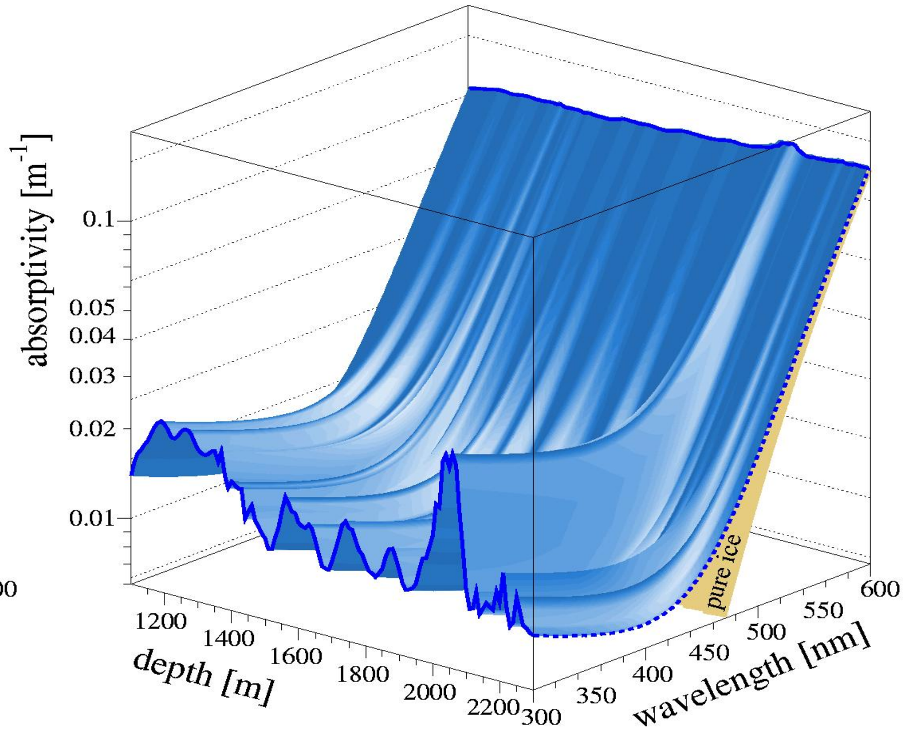
3 challenges

1. deployment

3 challenges

2. Ice's optics



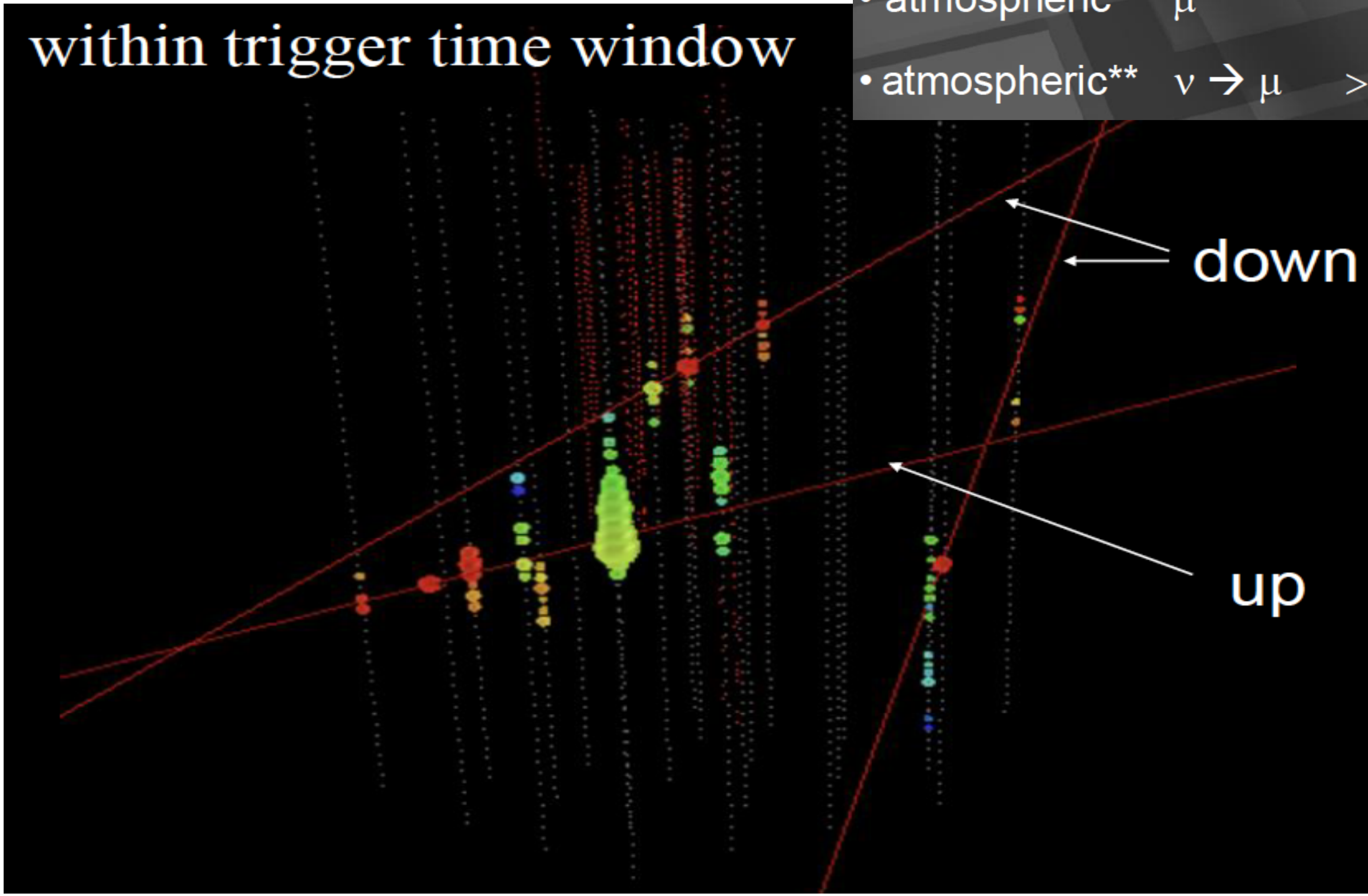


3 challenges

3. rejection of atmospheric muons

muons detected per year:

- atmospheric* μ 7×10^{10}
- atmospheric** $\nu \rightarrow \mu$ $> 8 \times 10^{4}$



Why the Mediterranean Sea?

- Obvious complementarity to South Pole

  Galactic centre

- Long scattering length

  Good pointing accuracy

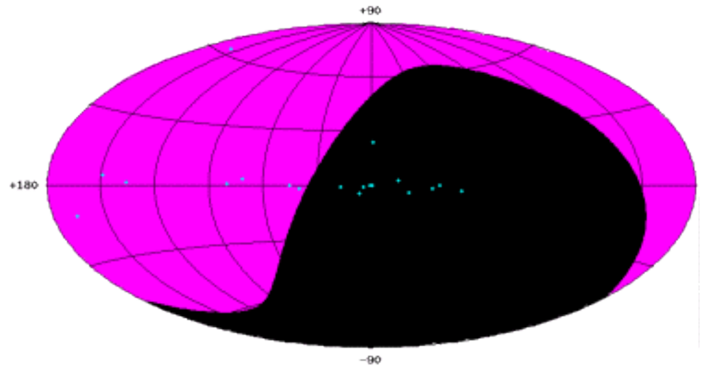
- Deep sites - up to ~5000m

  Detector shielding

- Logistically attractive

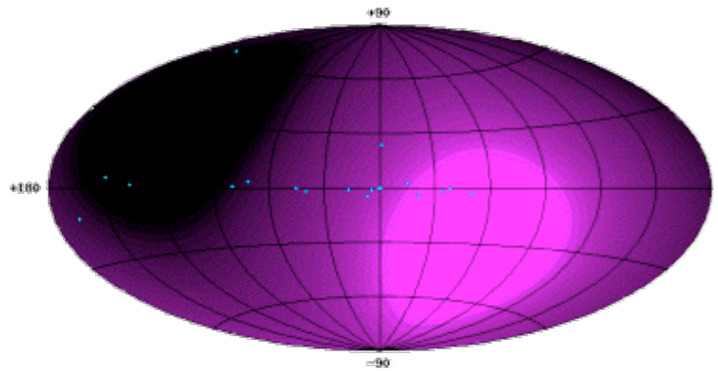
  Close to shore (deployment / repair)

South Pole visible sky



Most of the HESS TeV Sources visible by Northern NT

Mediterranean visible sky



Physical site selection criteria

- Depth → reduces muon background contamination

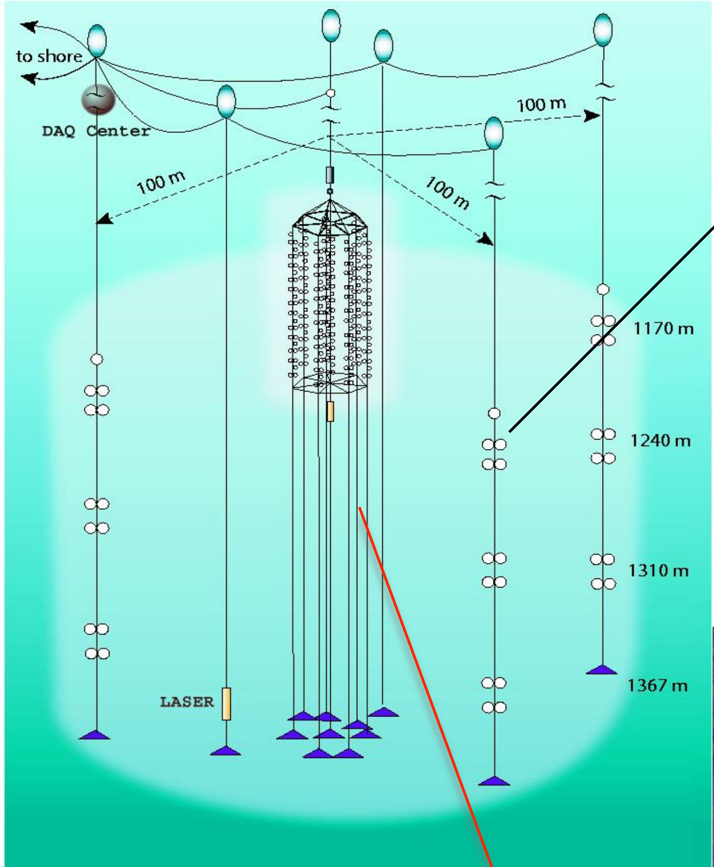
- Absorption length → Detection volume
  Scattering length → Angular resolution

[λ ~ 460 nm] (blue)	Absorption length (m)	Effective Scattering length (m)	Angular resolution (°) (< 0.1km², E>10 TeV)
South Pole	≤ 100	≤ 25	**3°**
Lake Baikal	≥ 15	> 300	**1.5°**
Mediterranean	55	> 300	**0.2°**

- Optical activity [quiet in ice and fresh water]
  - Living creatures
  - ^{40}K decay

  } Require causality filter

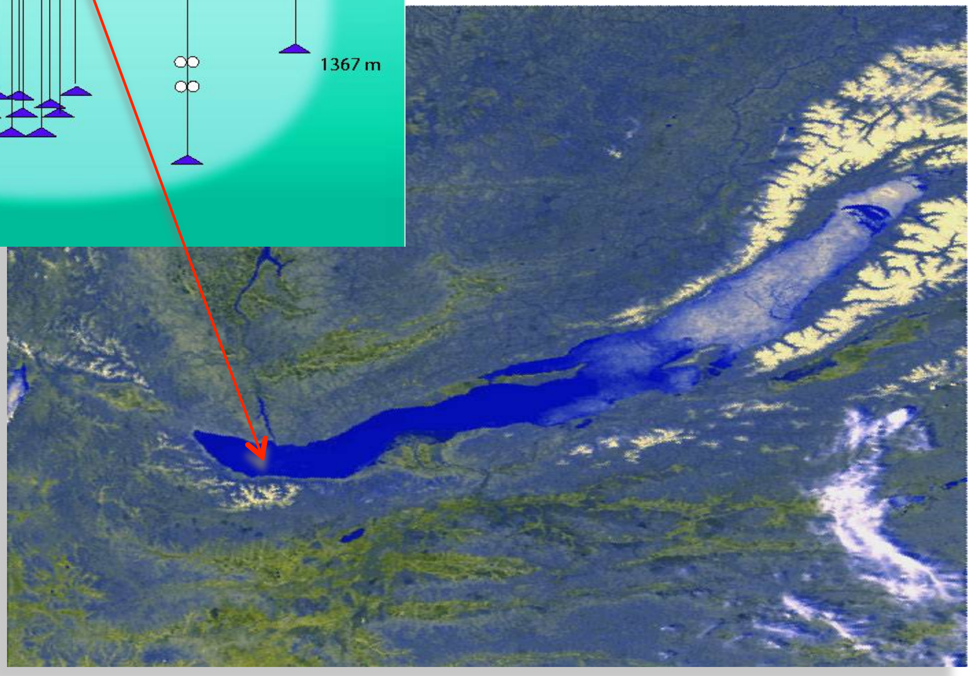
Baikal NT status



NT200+ is now operating

Quasar photodetector ($\varnothing$=37cm)

GVD TDR expected in 2011



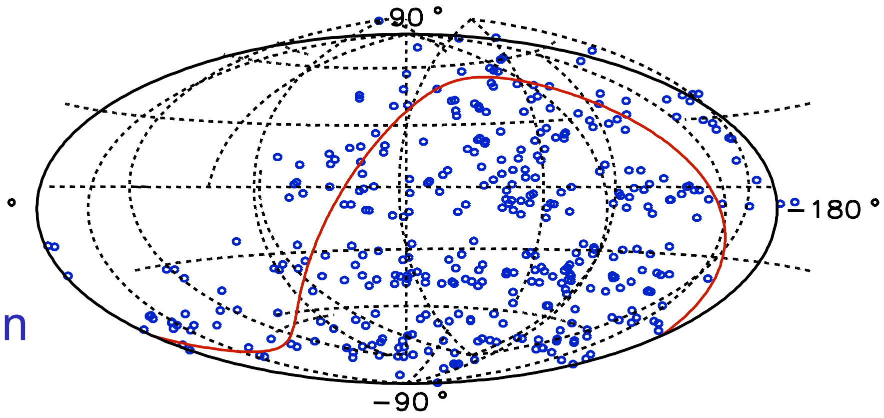
~ 3.6 km
to shore
1070m depth

NT200 +
8 strings (192 OMs) + 3 outer strings (36 OMs)
Height x $\varnothing$ 210m x 200m V_{inst} = $4\times10^6 m^3$
Eff. shower volume: 10 PeV ~ 10 Mton
Includes 2 prototype strings for GVD New OM, DAQ, cabling triggering systems

Baikal physics studies: summary

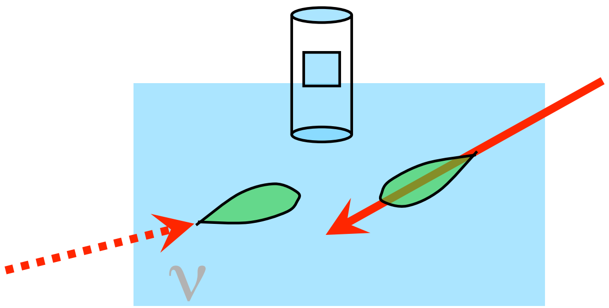
- **Point sources / atmospheric neutrinos**
  - 372 neutrinos in 1038 days (1998-2003)
    Expected 385 from Monte Carlo
  - Search for up-going μ correlated with 155 GRB in time and direction.

  No excess, no significant cluster, no correlation



Skyplot of ν events for 5 years
E_{THR} 15-20 GeV (gal. coord.)

- **Diffuse High Energy Neutrinos**



- Studies of bright cascades detected in the telescope: a search for excess above the expected background from atmospheric muons.

The 90% C.L. "all flavor" (new analysis) limit, $\nu_e:\nu_\mu:\nu_\tau=1:1:1$

$E^2 \Phi_\nu < 2.9 \cdot 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} 20 TeV $< E_\nu <$ 20 PeV

- **Neutrinos from DM annihilations**
  - A search for possible signal from WIMP annihilation in the centres of the Earth, the Sun, the Galaxy ("indirect" WIMP search). ☞ Upper limits

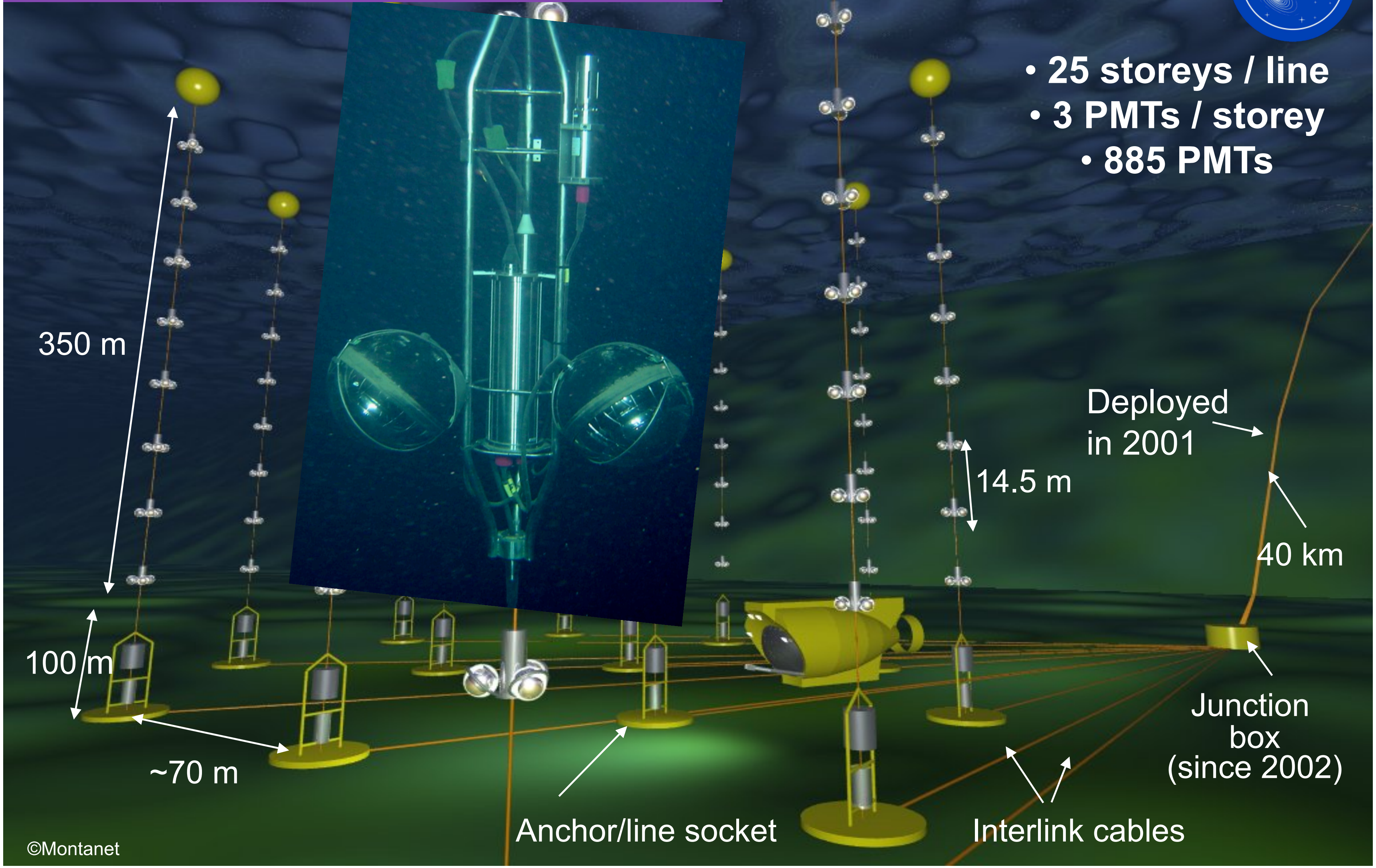
- **Exotic physics** Search for fast and slow moving magnetic monopoles ☞ Upper limits


Toulon
M.Pacha
Antares
Electro-optical
Cable of
40 km
42 50'N, 6 10'E
Google
© 2008 Cnes/Spot Image
Image © 2008 DigitalGlobe
Image NASA

The ANTARES neutrino telescope

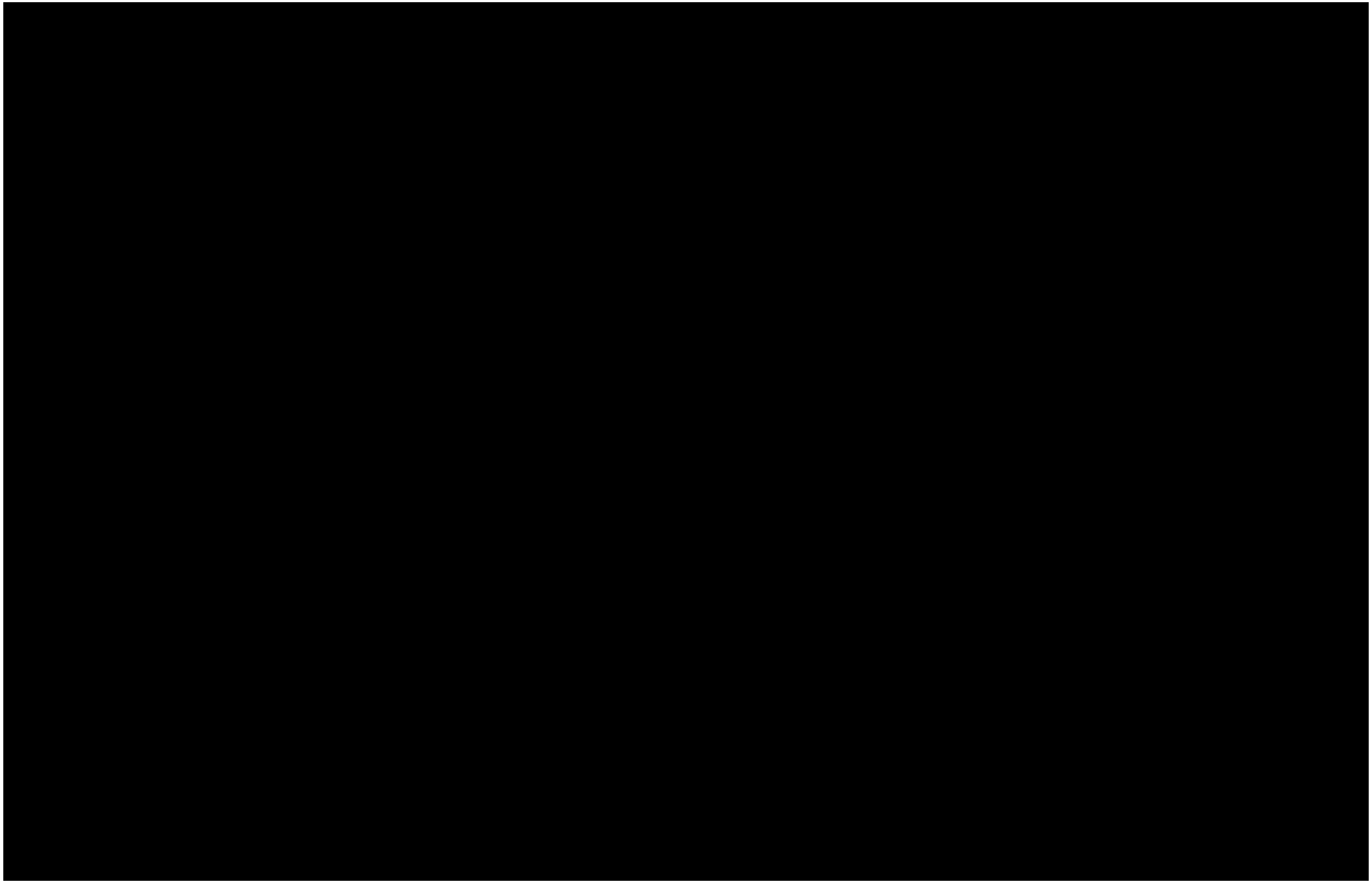
Detector completed in May 2008

- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

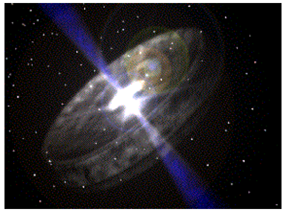


First line connection: march 2006

First line connection: march 2006



Outline

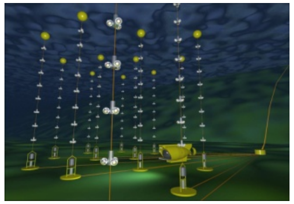


Neutrino astronomy

Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

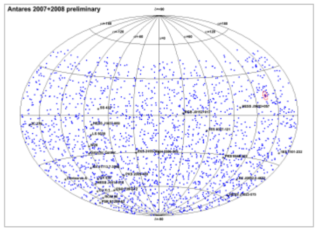


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

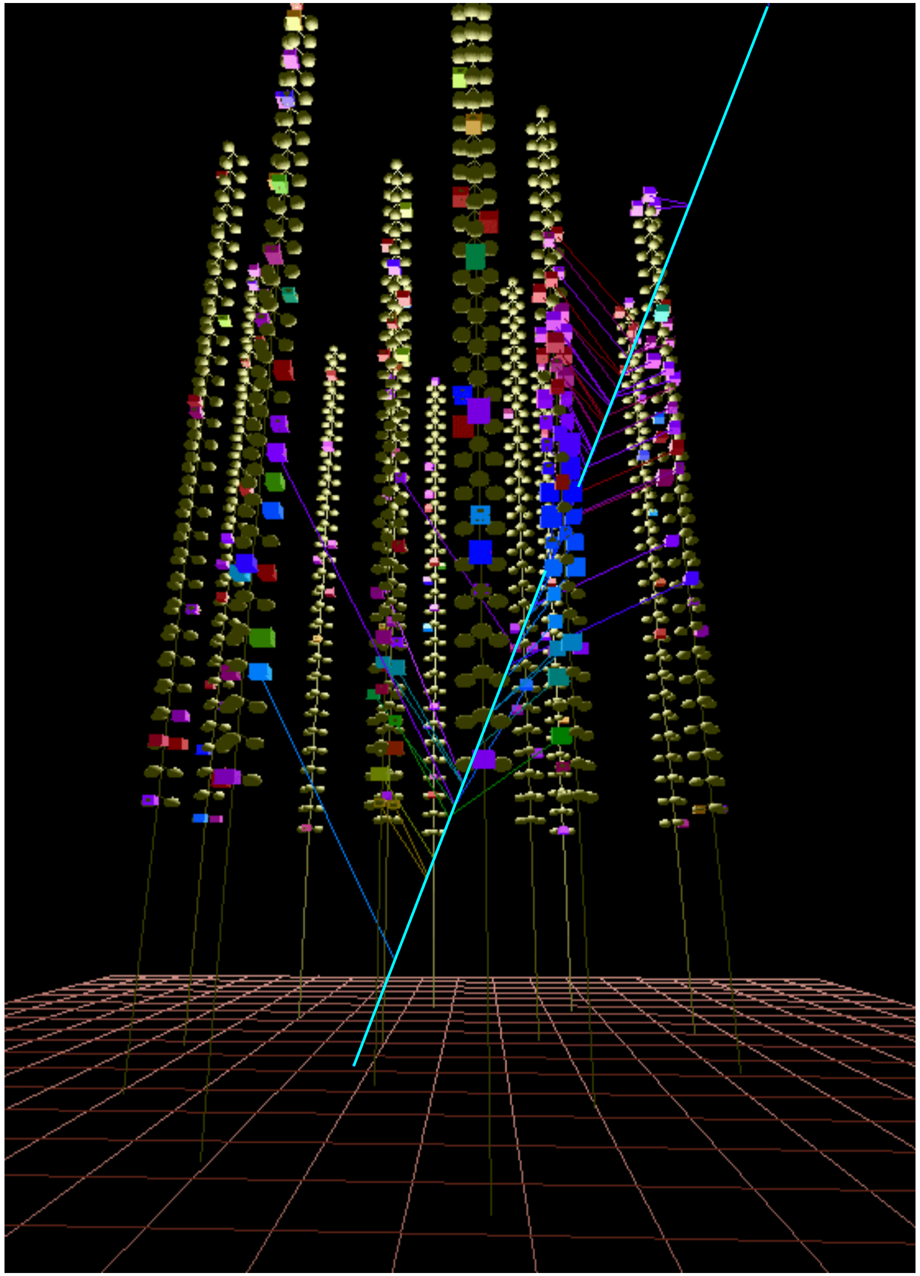
Diffuse Flux

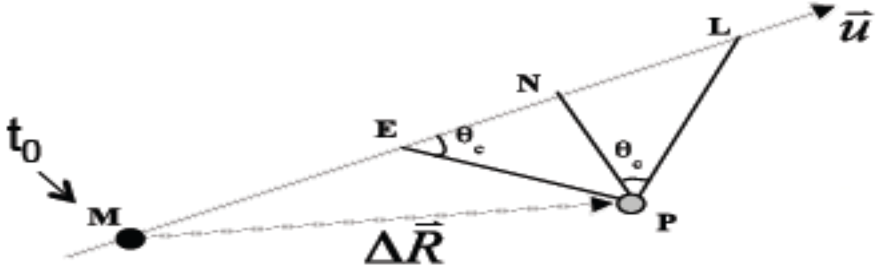
Search for point sources

Multi-messenger search

KM3NeT project

Reconstruction of muon trajectory





$$(t_{theor} - t_0) = \frac{1}{c} ME + \frac{n}{c} EP$$

$$c(t_{theor} - t_0) = \Delta\vec{R}.\vec{u} + \alpha.\sqrt{\Delta\vec{R} - (\Delta\vec{R}.\vec{u})}$$

$$\alpha = \tan\theta_c$$

5 parameters associated to the track:

M (x_0, y_0, z_0) @ t_0
u $(u_x\ u_y\ u_z)$ or $(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$

1. Selection events of interest based on causality criteria

2 Fit based on the time residuals

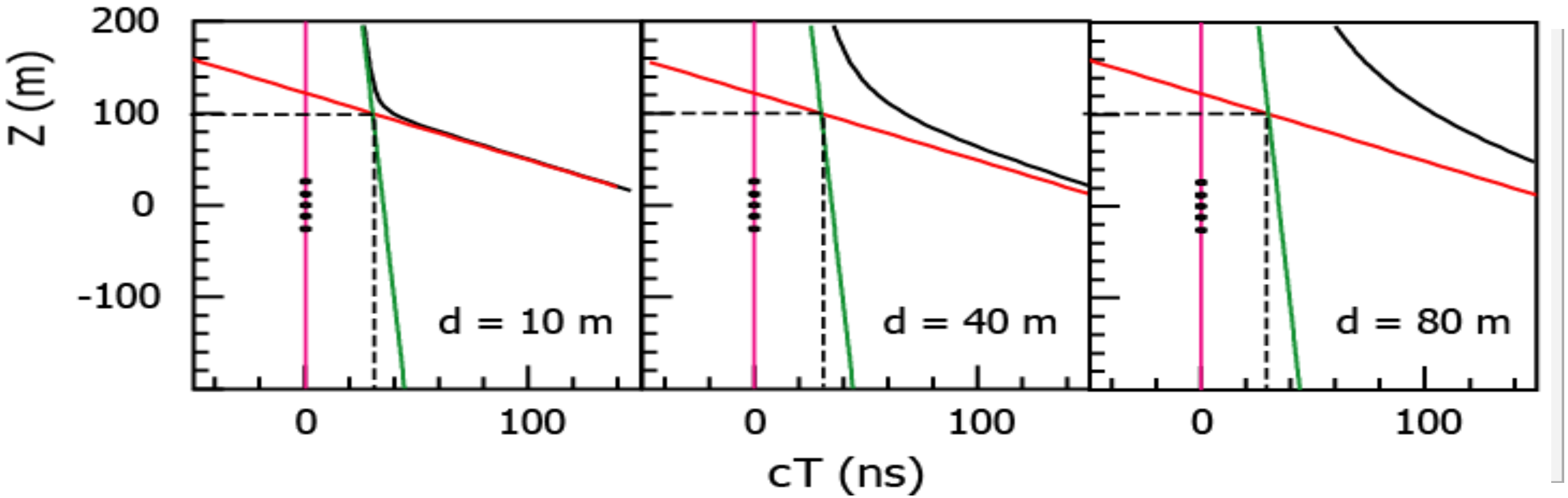
$$\Delta t_i = t_{theor}(\mathbf{M}, \mathbf{u}) - t_i$$

Reconstruction of muon trajectory

Altitude (z) des photons en fonction du temps d'arrivée (t)

⇒ Fonction de l'angle zénithal et de la distance minimale d'approche

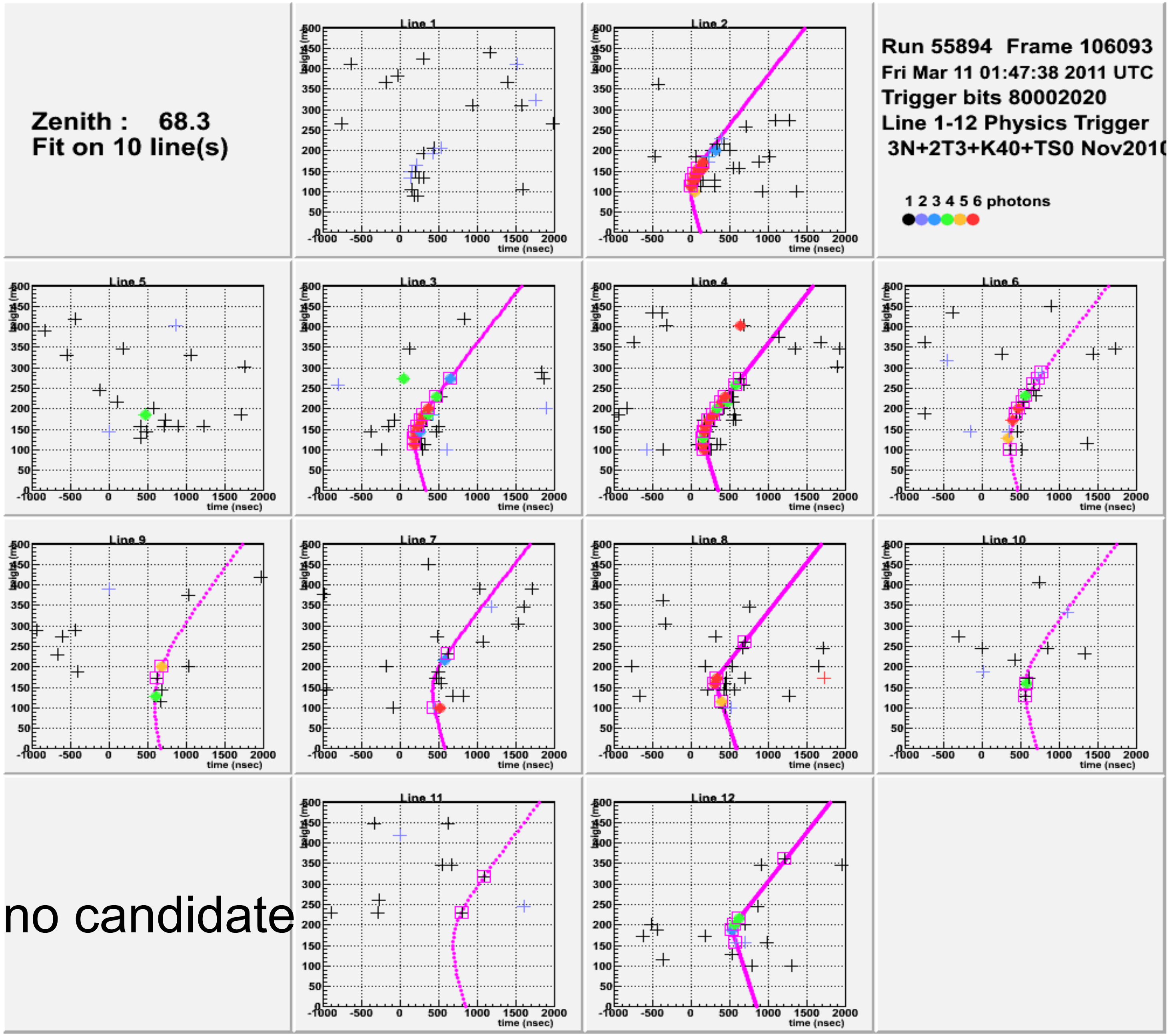
Intersection du plan (z,t) et du cône Tcherenkov ⇒ Hyperbole



- « Aafit »:
  - Maximum de vraisemblance
  - Fonction de densité de probabilité
  - Algorithme sophistiqué
  - Optimisé pour les muons montant (ν)
- « BBFit »: 📖 Astropart. Phys. 34 (2011) 652-662
  - Minimisation d'un χ^2
  - Photons directs
  - Utilisée en ligne
  - Adaptée aux muons descendant

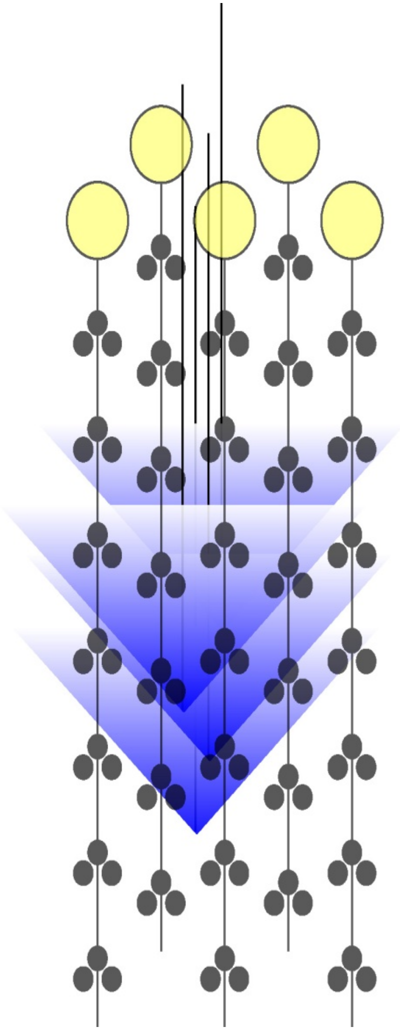
Hypothèse : *Un seul muon dans le détecteur*

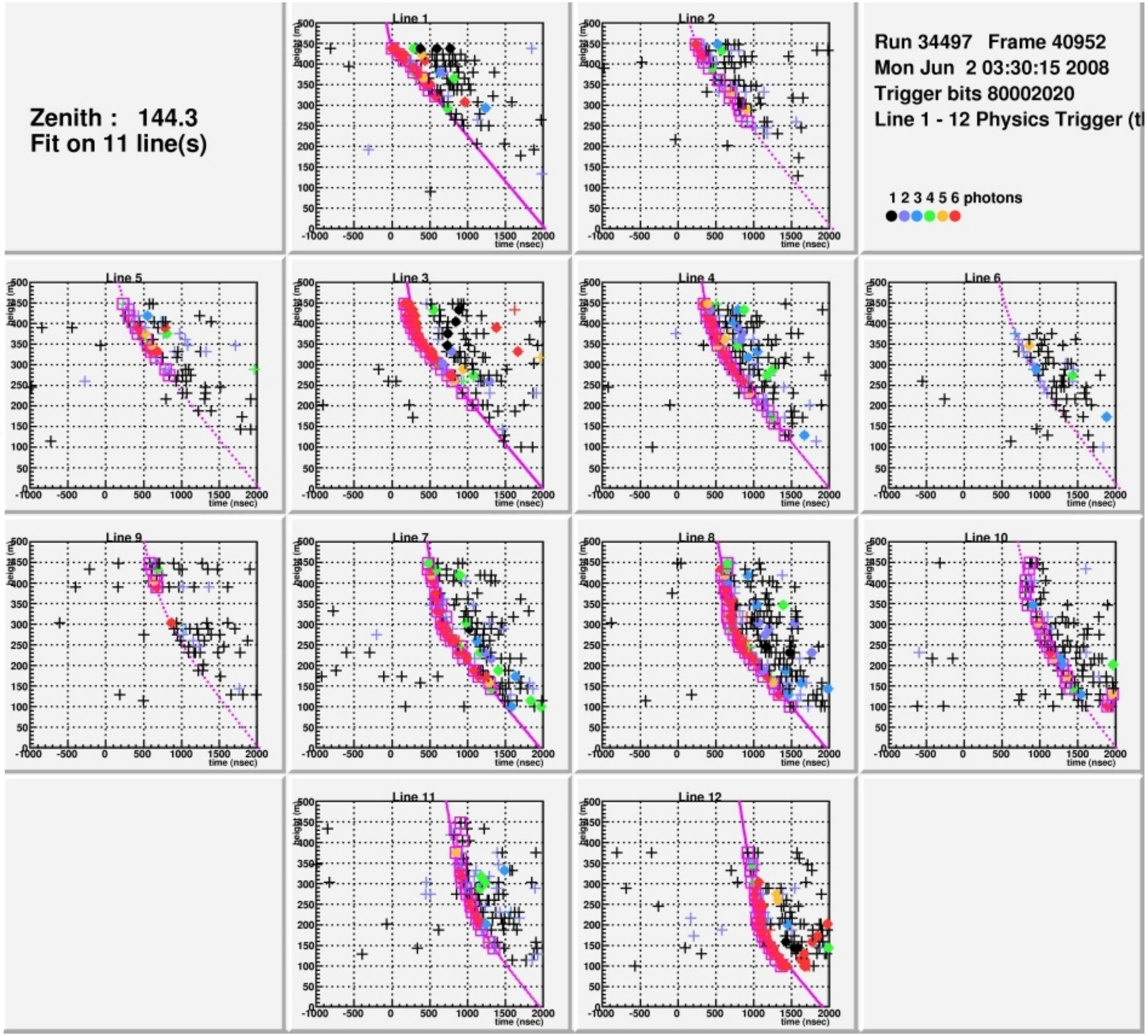
Un muon = $\sum(t_i, q_i, position_i)$



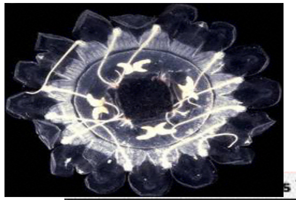
Neutrino candidate

Muon bundles ?

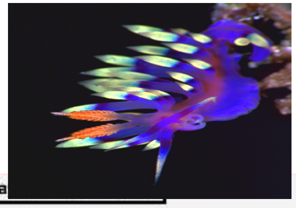
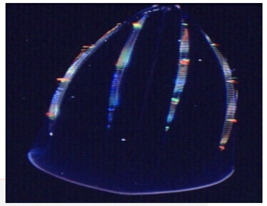


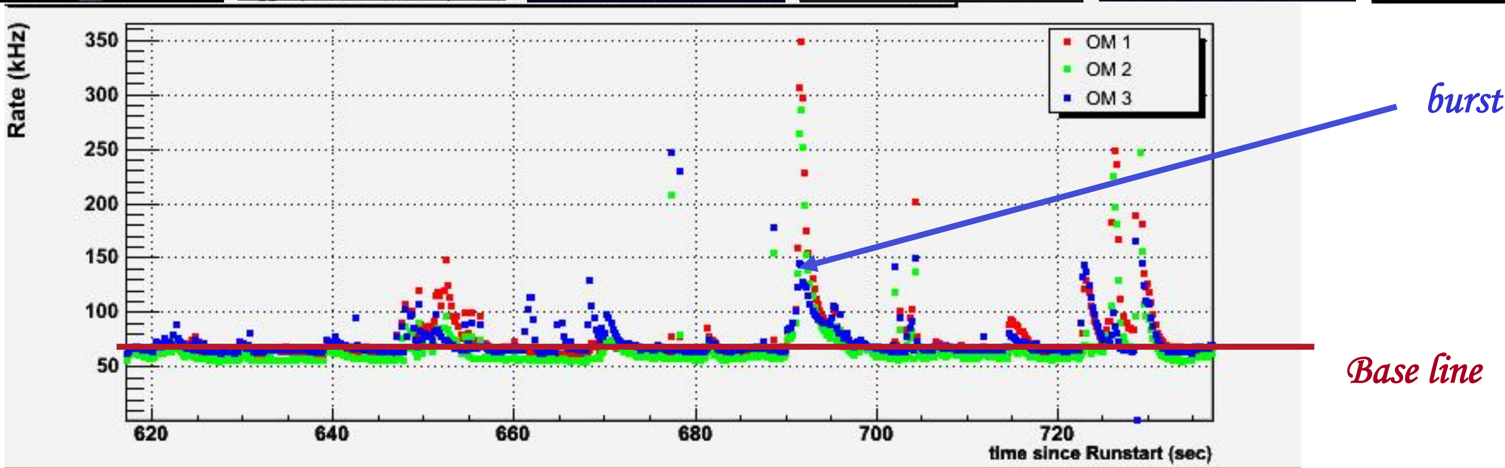


Optical background



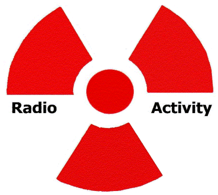


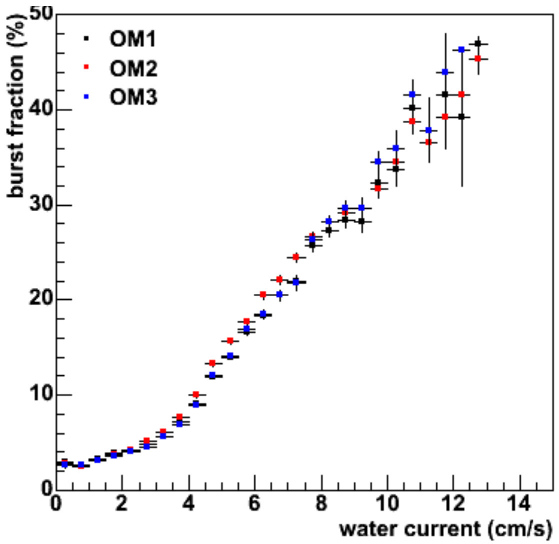



Base line ^{40}K

Bio-luminescence



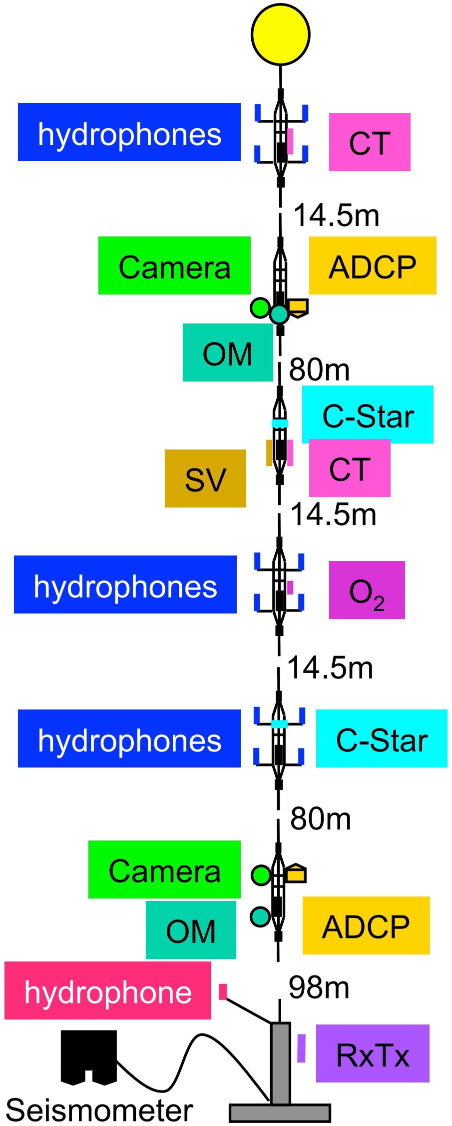


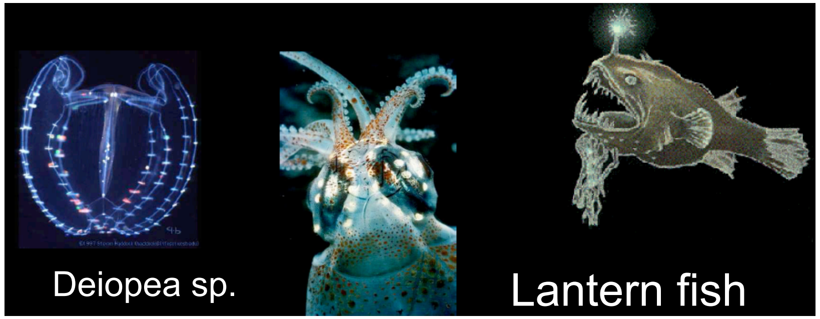
Bio-luminescence burst:

photo-emitter animals

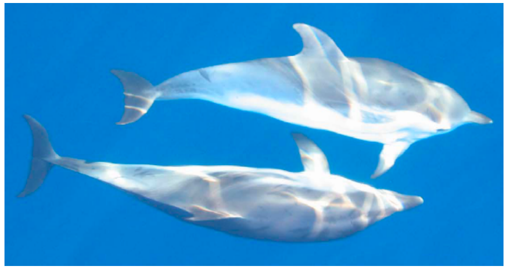
Sea science and Earthquakes

Instrumentation Line

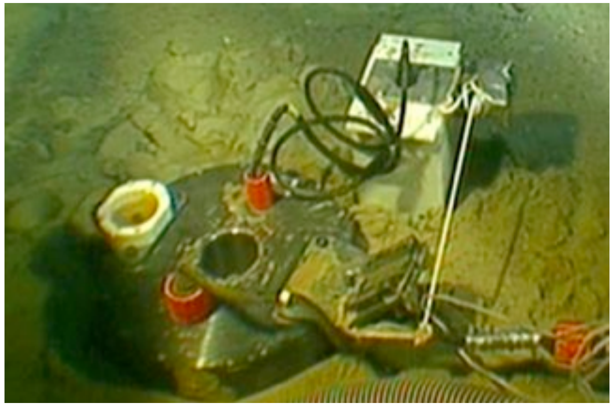




Acoustic noises



seismometer



Video-monitoring

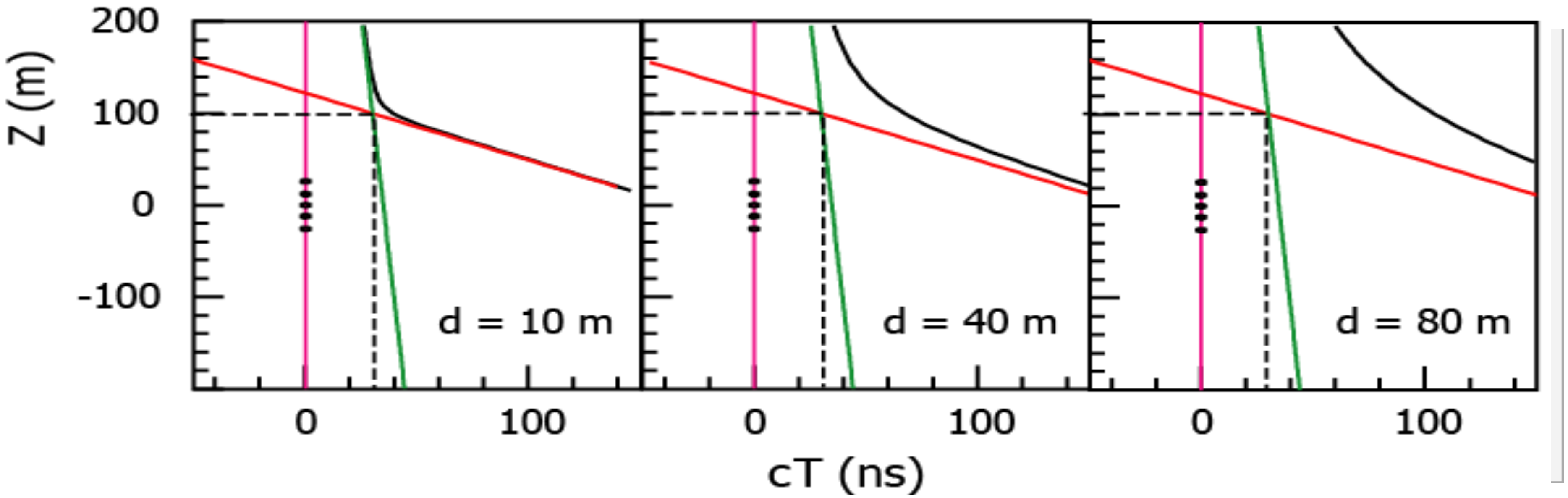
ANTARES is a multidisciplinary observatory

Reconstruction of muon trajectory

Altitude (z) of photons as a function of time arriv   al (t)

⇒ depends on zenith angle and distance of closest approach

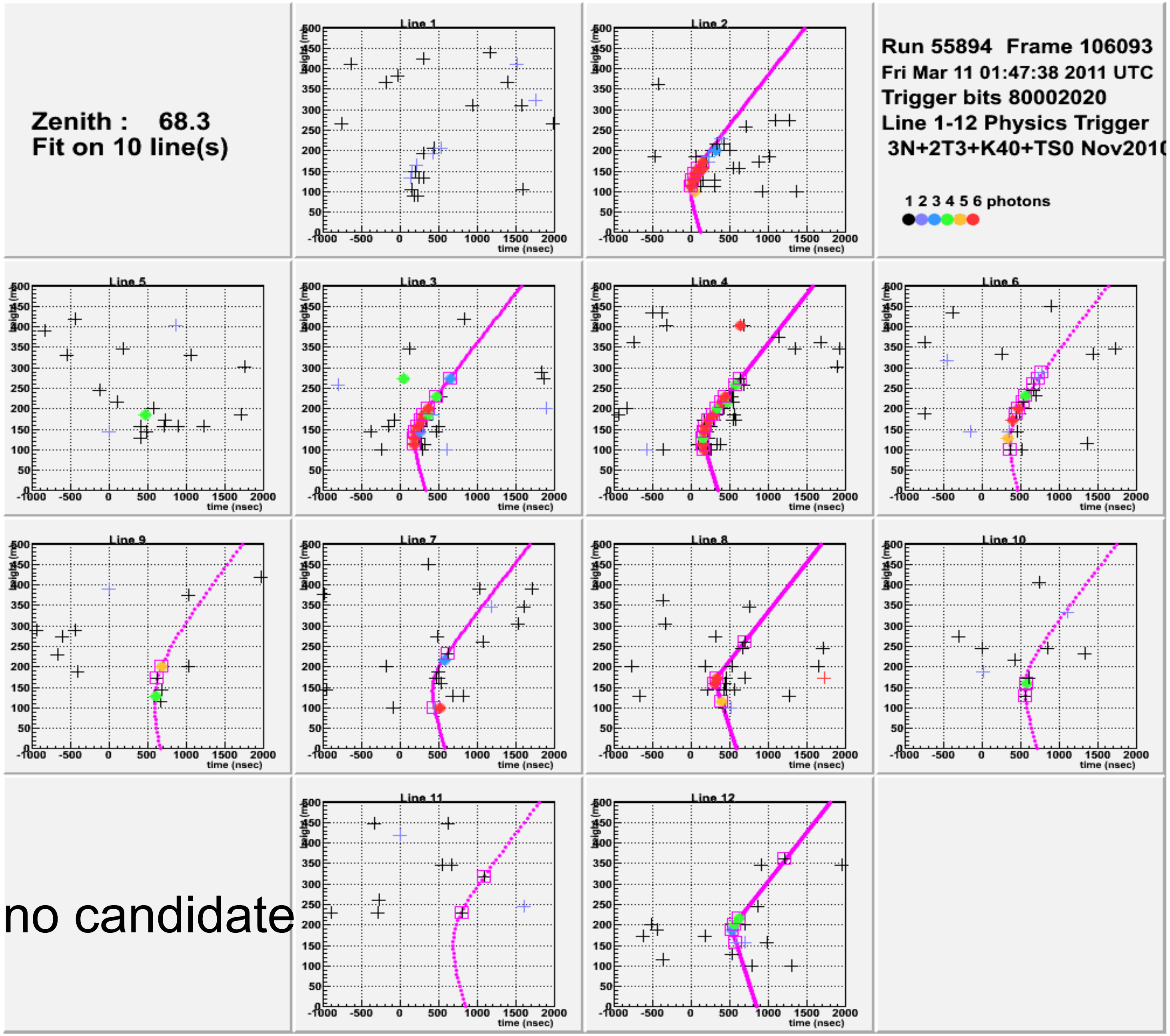
Intersection of plane (z,t) and Cherenkov cone ⇒ Hyperbola



- « Aafit »:
  - Maximum likelihood
  - Probability density functions
  - Sophisticated algorithm
  - Optimized for up-going muons (ν)
- « BBFit »: 🕮 Astropart. Phys. 34 (2011) 652-662
  - Minimization of χ^2
  - Directs photons
  - Used online
  - Adapted for down-going muons

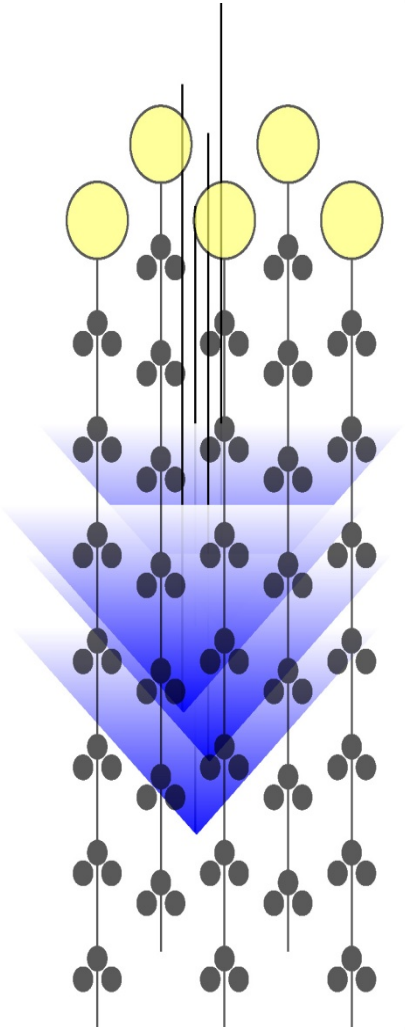
Assumption : *One single muon in the detector*

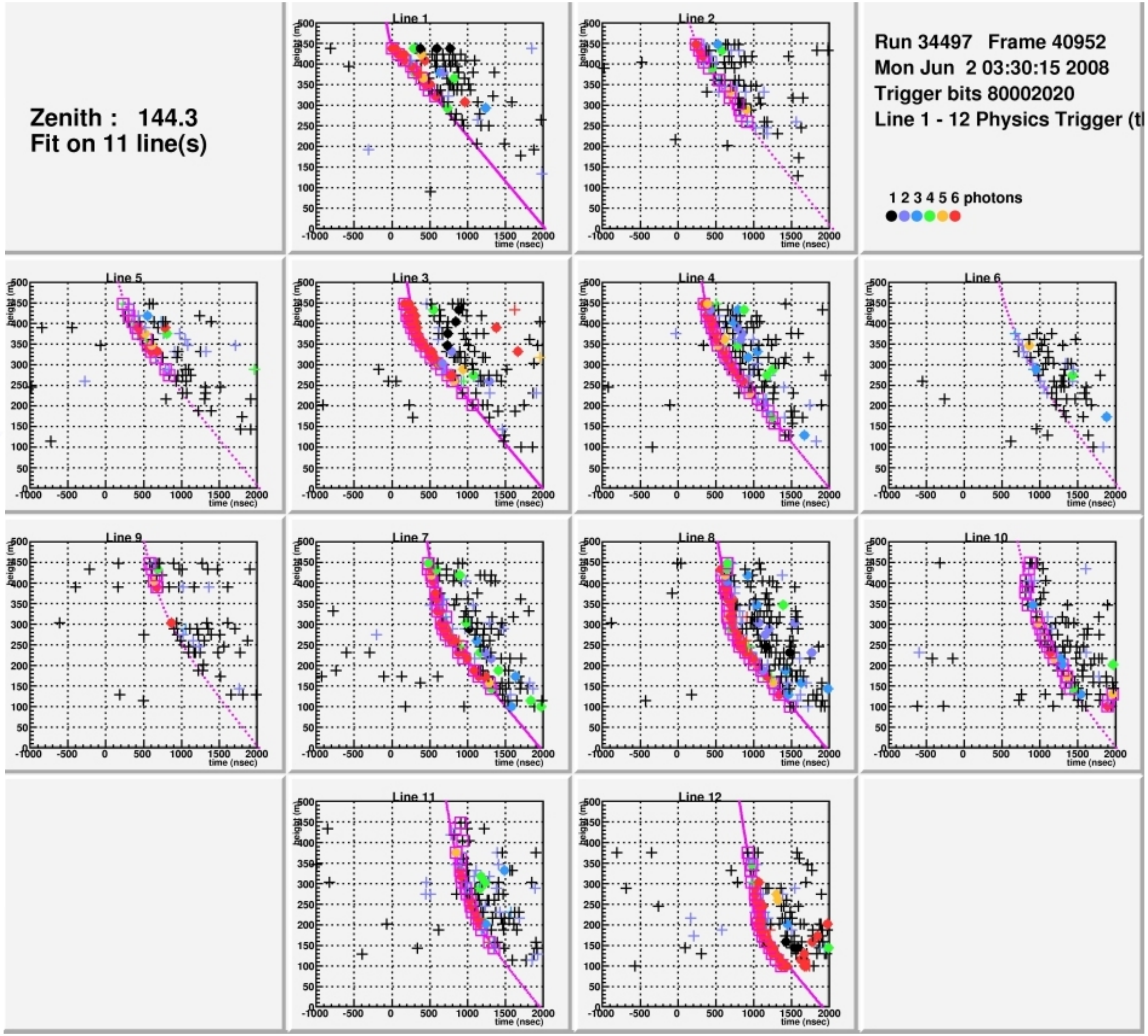
Un muon = $\sum(t_i, q_i, position_i)$



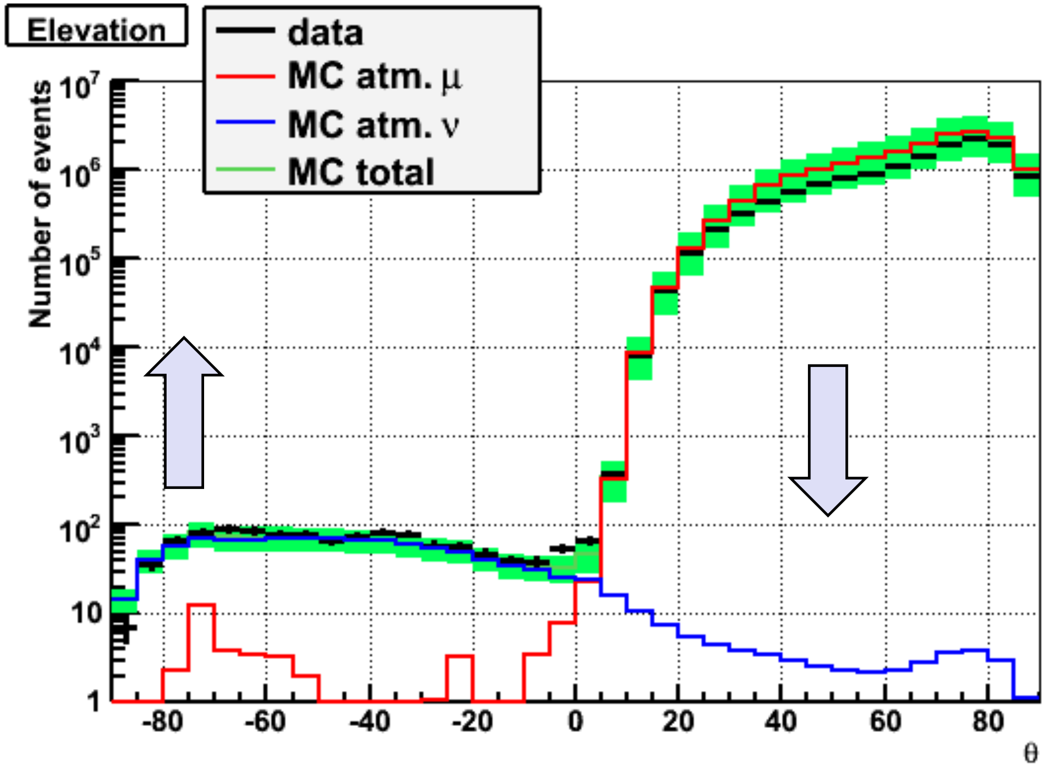
Neutrino candidate

Muon bundles ?





Example of reconstructed data set



ANTARES

5-line data (May-Dec. 2007)
+
9-12 line data (2008)

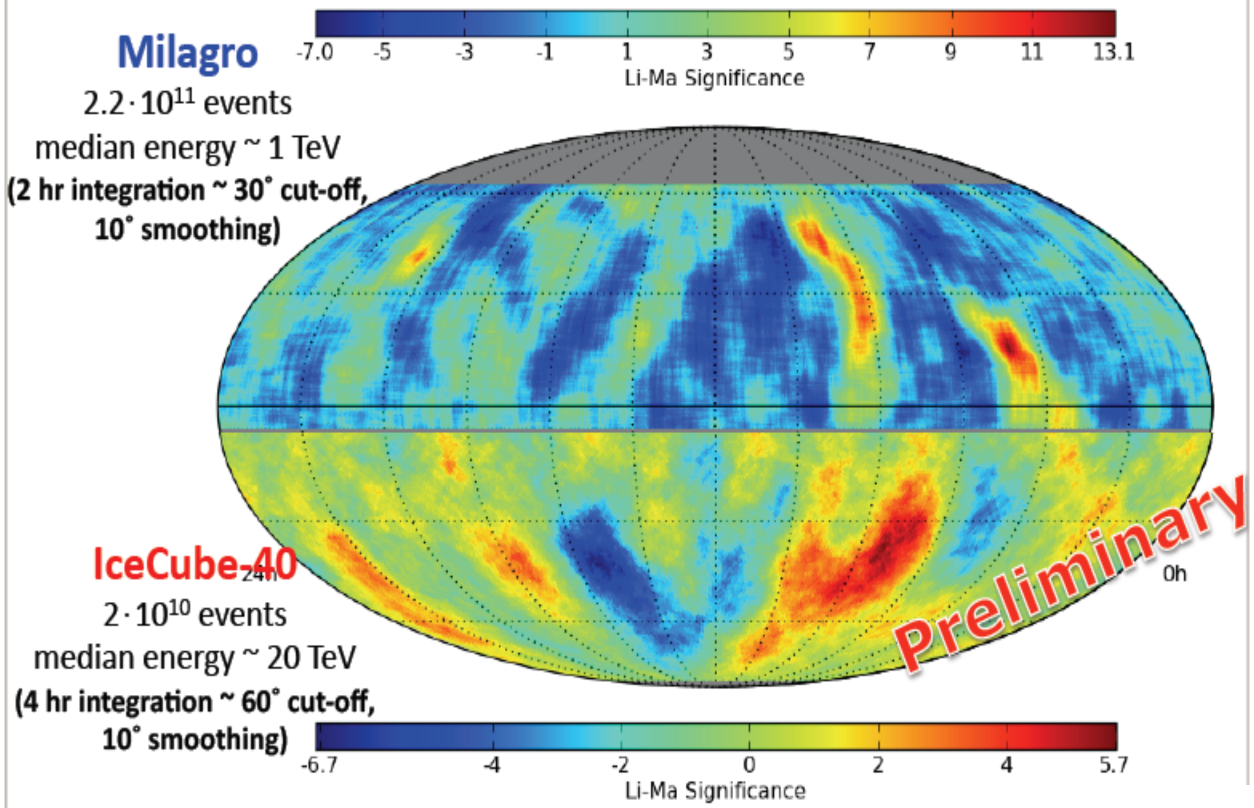
341 days detector live time

1062 neutrino candidates:
3.1 ν candidates/day

Fair agreement with Monte Carlo
atmospheric neutrinos: 916 (30% syst. error)
atmospheric muons: 40 (50% syst. error)

Physics program started. First results presented.

IceCube : Cosmic ray studies

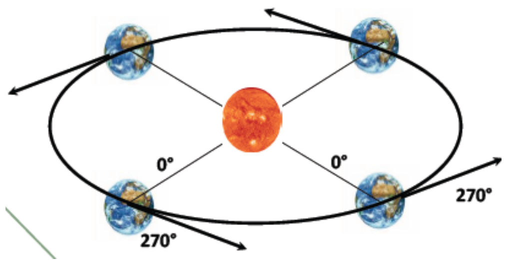


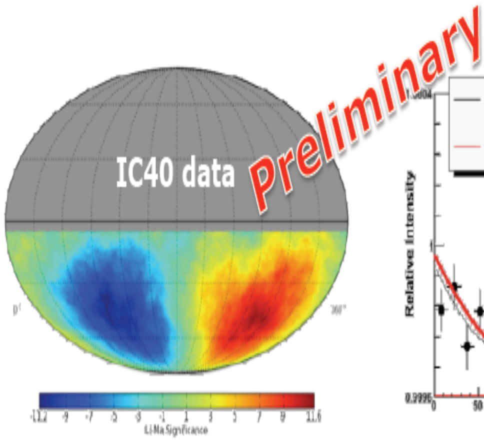
📖 arXiv:1105.2326

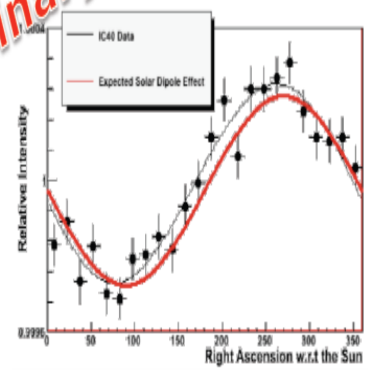
Unexplained anisotropy…

Dipole due to Earth motion
around the Sun
Compton & Getting effect

📖 Phys Rev 47 (1935) 817

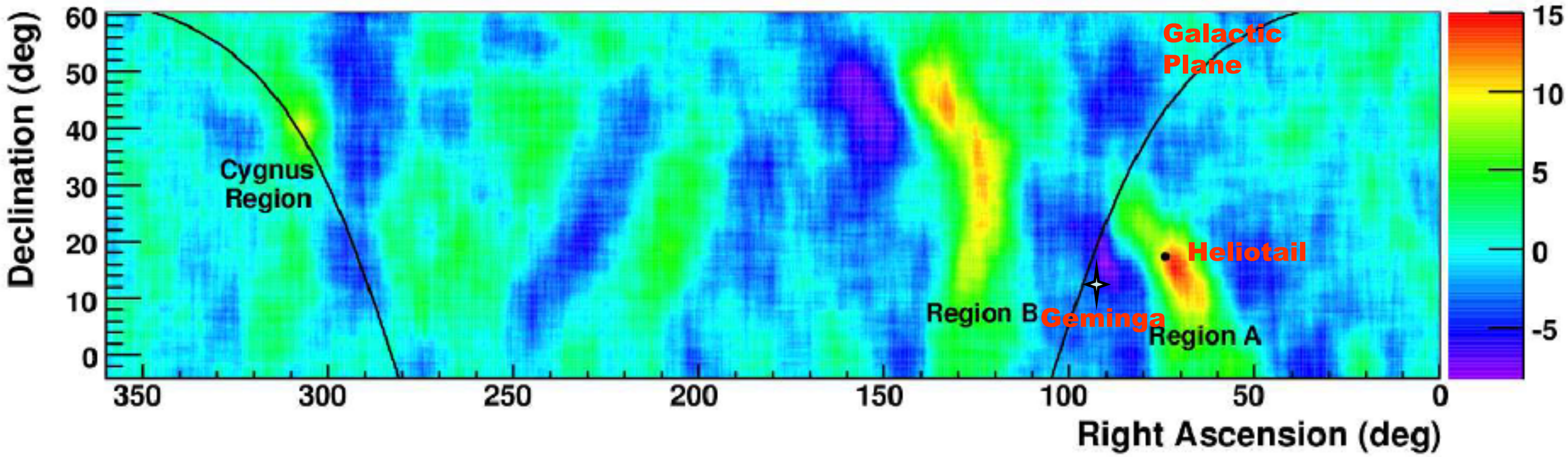




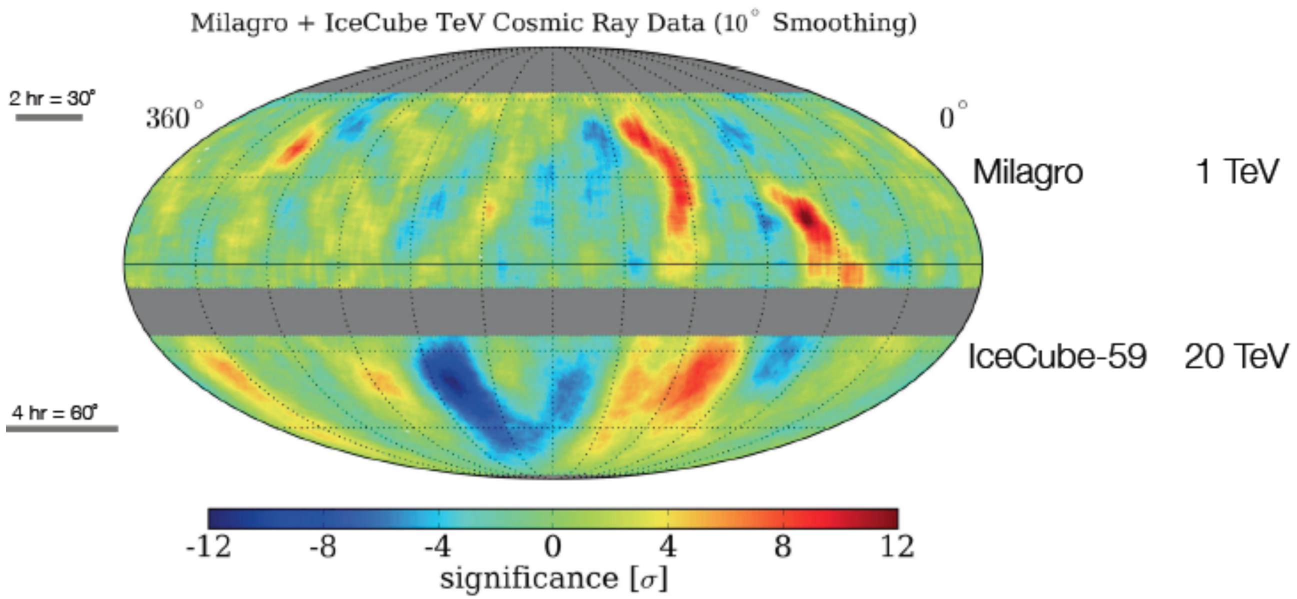


Milagro Observes Anisotropy in 10 TeV Cosmic Rays

- Milagro's standard point-source analysis with a 10º bin size
- Results:
  - Two regions of fractional excess of 6e-4 (Region A) and 4e-4 (Region B) above the cosmic ray background were detected.
- Composition:
  - Excesses are not gamma rays (or electrons), but charged cosmic rays (8.6σ Region A and 6.6σ Region B).
- Energy Spectrum:
  - The spectra of both excesses are inconsistent with the cosmic-ray spectrum (4.6σ and 2.5σ)
  - Spectrum of region A: Broken power-law with index = -1.45 and break energy=9TeV.

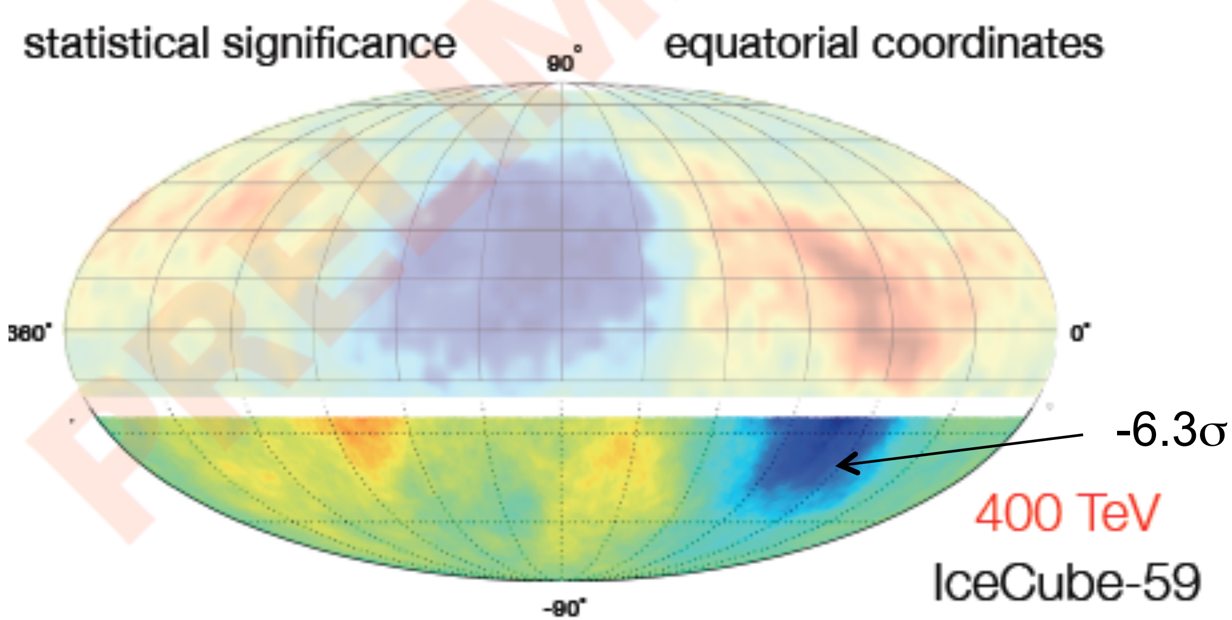


IceCube : Cosmic ray studies



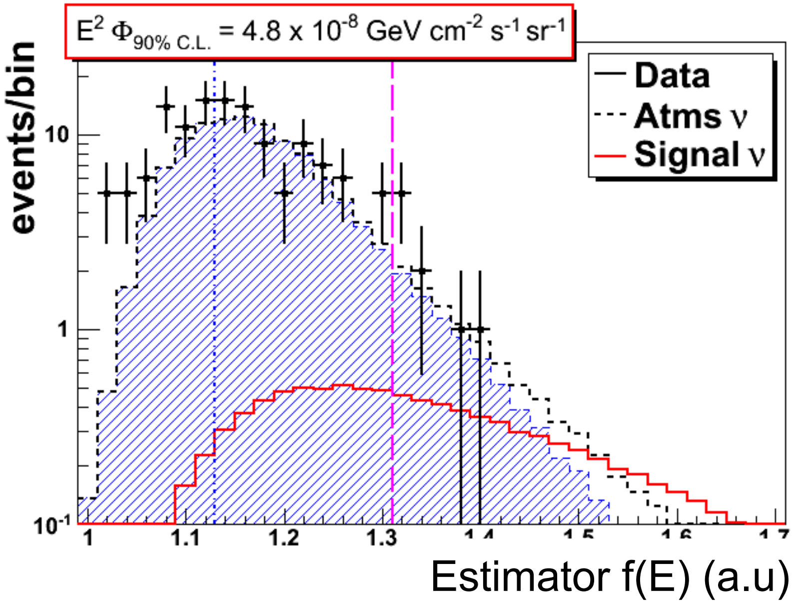
Anisotropy confirmed with IC59

Evolution with energy
Différent effect @400 TeV



arXiv1109.101v1

Diffuse flux – Upper limits (E^{-2})



334 days live time

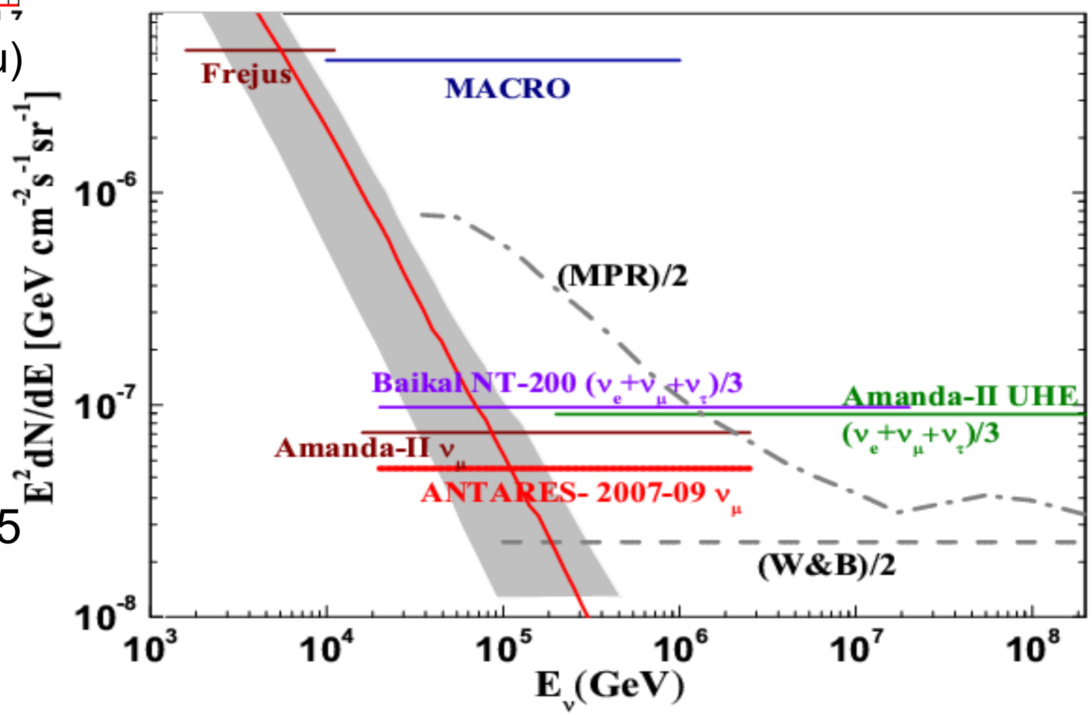
9 observed events for 10.5 ± 2 expected

⇨ $E^2\Phi(E)_{90\%} = 4.8\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
20 TeV<E< 2.5 PeV

ANTARES limit …

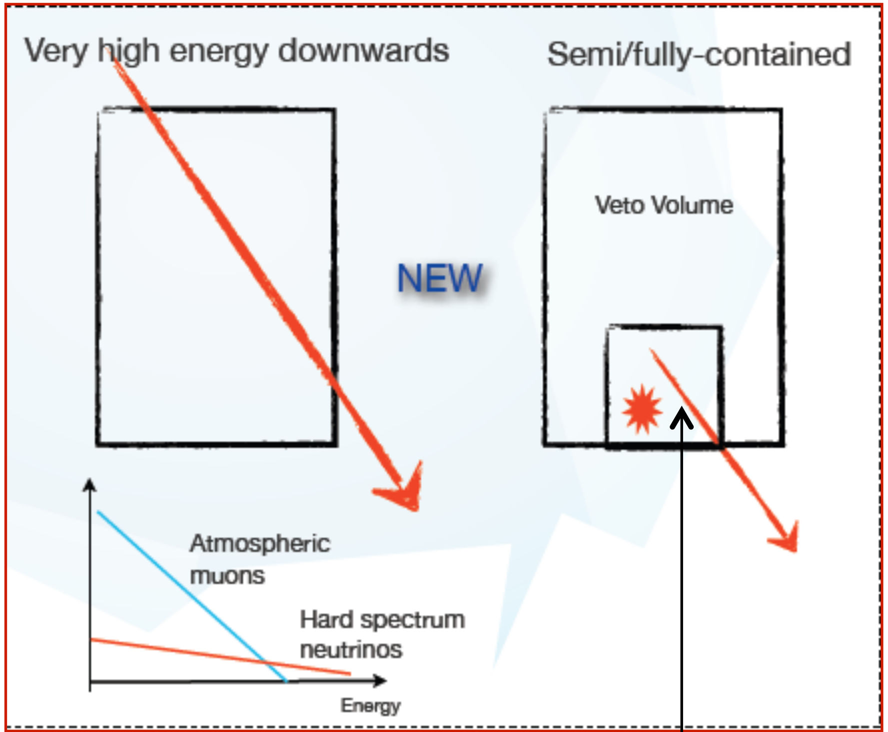
…superseded by IC40 sensitivity (375 days) by a factor ~ 5

☞ below WB flux

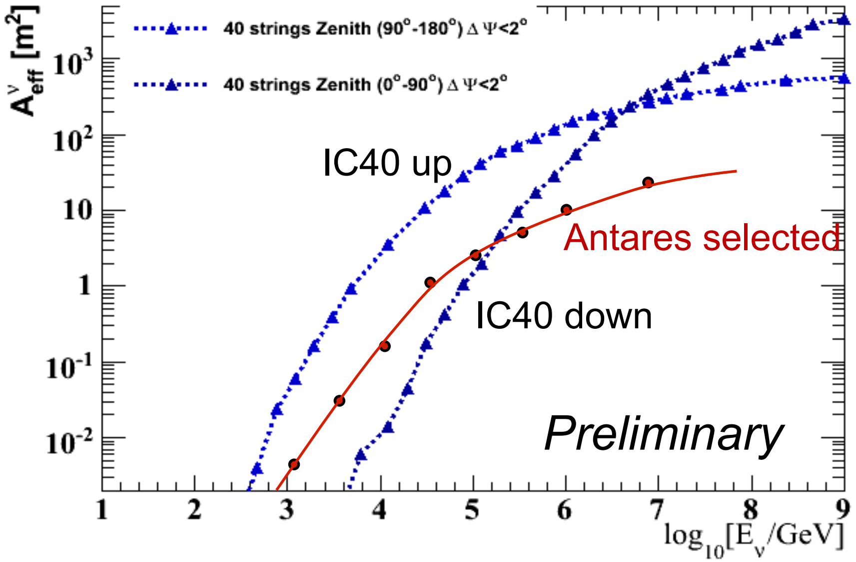


IceCube extension to 4π sky

The size of IceCube now allows to search for down going neutrinos at very high energy



Including DeepCore

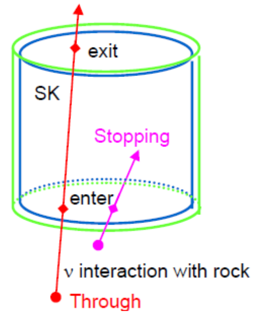


Sensitivity is reduced by:

- HE cut required to kill atmospheric background
- Vetoing against background (contained interactions)
- Difficult for TeV galactic sources like RX J1713.7-1936

Recent searches for neutrino point sources

• SK experiment (low energy threshold E>1.6 GeV)
  • All 3134 upward through going events in 2623 days

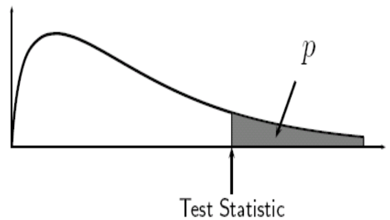


• ANTARES first analysis with 5-10-12 lines (TeV)
  • 2007-2010 (813 days) data analyzed

•ICECUBE with IC40 data set (375.5 days) in all sky

Summarized generic "blind" analysis (Optimized with scrambled data set)

• Use Clusterization algorithm
• Calculate a statistic given data (eg. Likelihood ratio)
• Compute *p-value* (probability to observe such statistic from bkg)
• Compute post-trial significance probability to observe *p-value* from many experiments

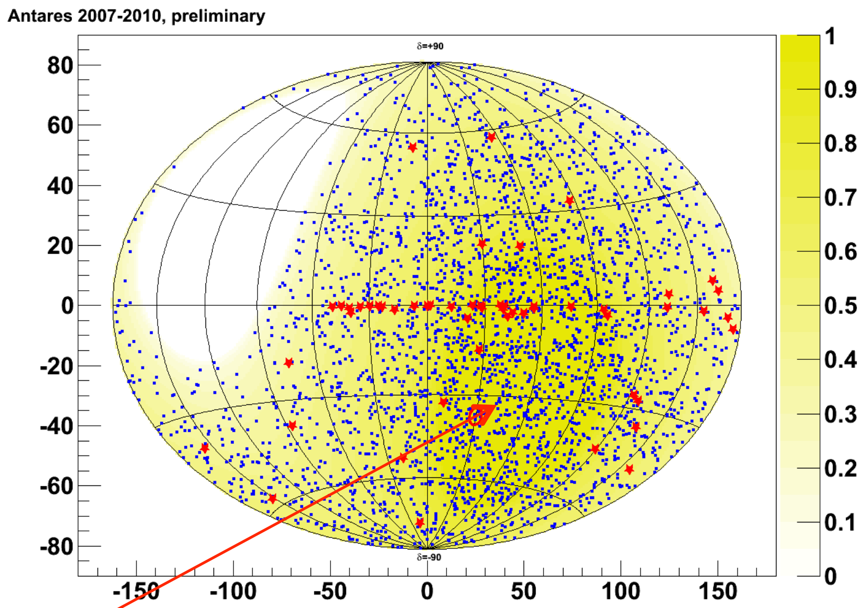


These analyses can be performed for :

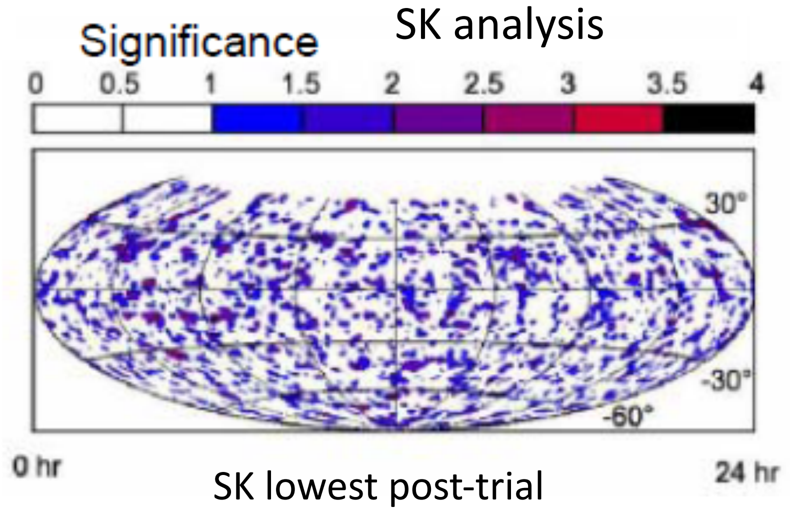
• All sky search
• Predefined list of known sources
• Collection of sources of same kind summed up (stacking analysis)

Methods
Neunhoffer and Kopke NIM A 558 (2006) 561
Hill and Rawlins, Astrop. Phys., 19, 393, (2003)

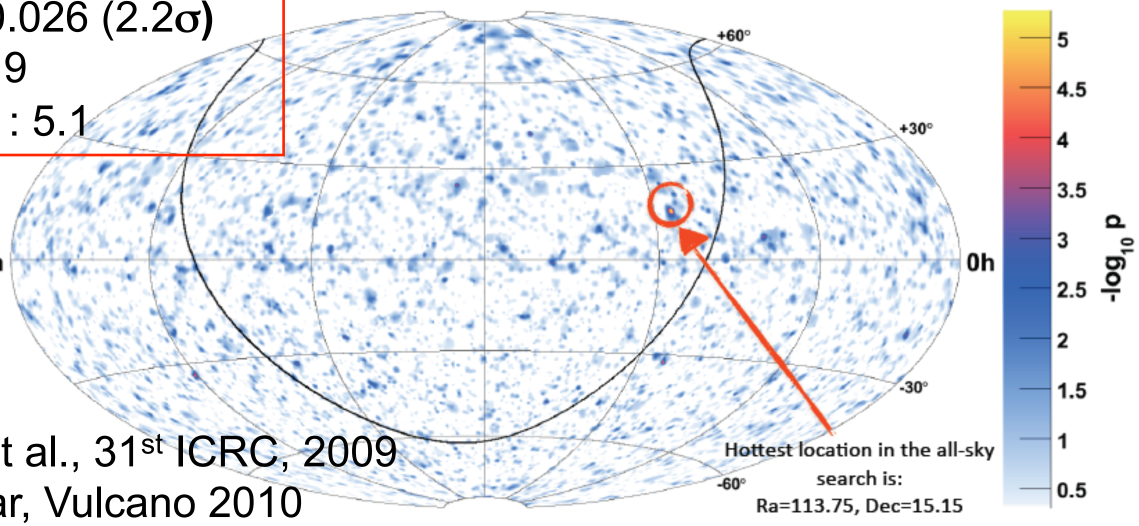
Sky maps



location : **-46.49, -64.97**
p-value : 0.026 (2.2σ**)**
events : 9
Nsig fitted : 5.1



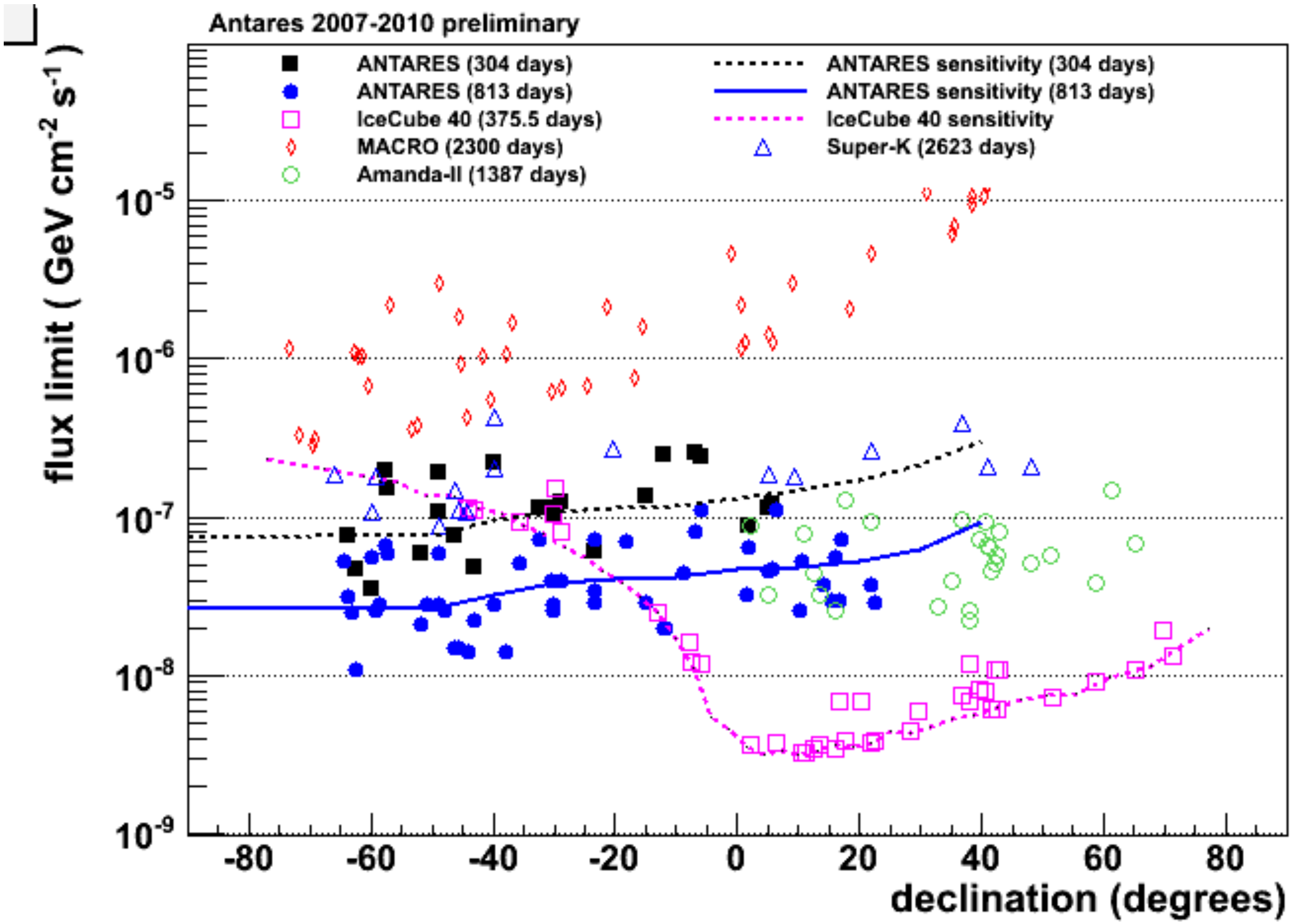
SK lowest post-trial
p-value = 0.025 (~2σ)
RX J1713.7-1946
No significant excess found



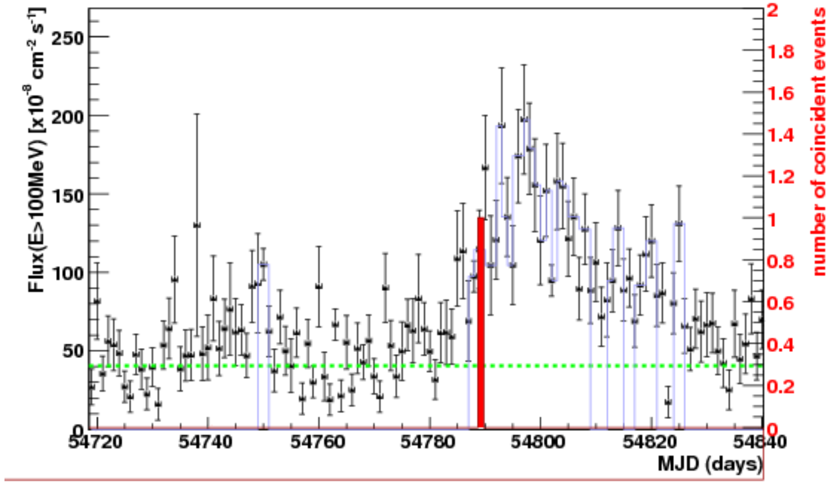
All sky post-trial:
plus basse p-value = 18%
Sources choisies:
Plus basse *p-value* = 10%
Pas d'excès ☞ limites

📖J. Dumm et al., 31st ICRC, 2009
📖 J.A. Aguilar, Vulcano 2010

Current Upper limits



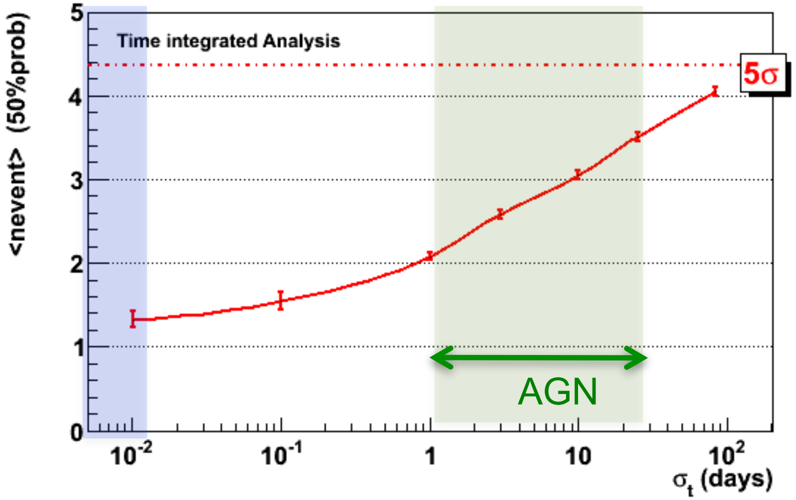
AGN flares



Data Fermi LAT

Identification of active periods

Typical duration: 1-20 jours



ANTARES:

→ Time dependant likelihood method

→ Data from 2008 (4 months)

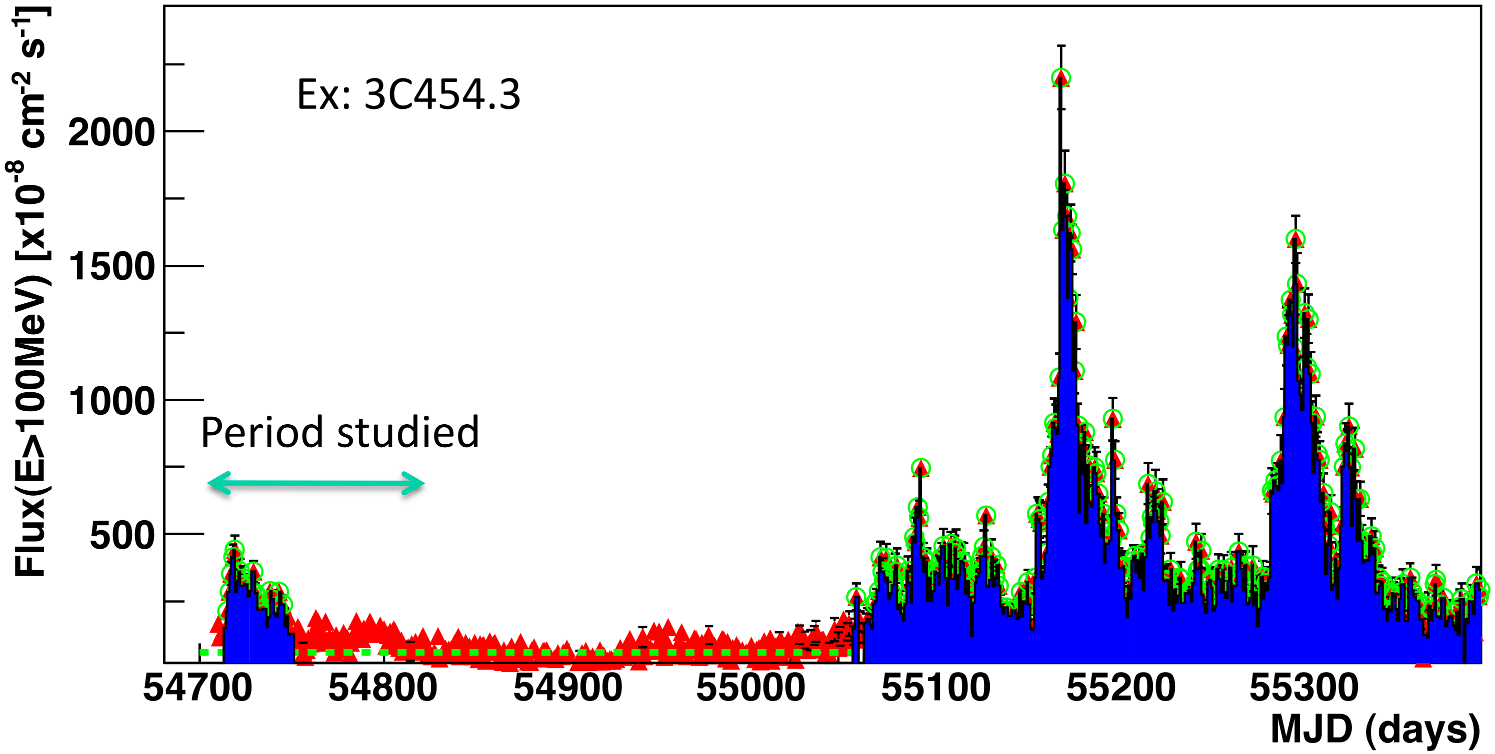
→ Performance: Number of events needed for a discovery at 5σ CL (50 % prob.)

➡ Gain by a factor 2-3 wrt standard analysis

Analysis of 10 Fermi sources :

=>1 neutrino detected for 3C279 (post-trial p-value ≈10%)

More to come



Gamma-ray light curve (red dots) of the blazar 3C454.3 measured by the LAT instrument onboard the Fermi satellite above 100 MeV for almost 2 years of data

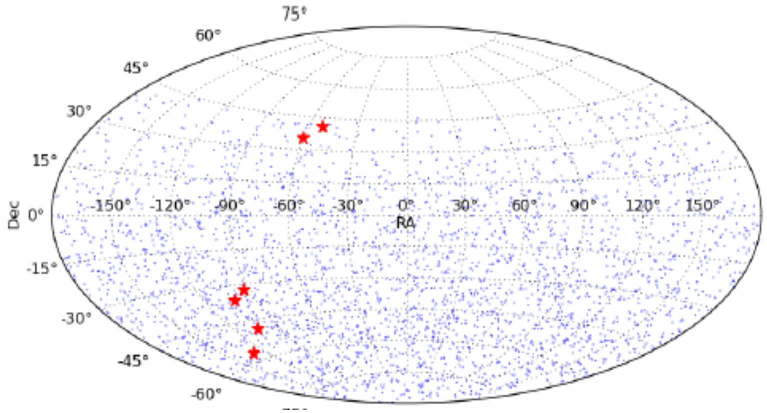
Microquasar flares

Same sort of analysis but selection based on X-rays (RXTE/ASM and Swift/BAT)

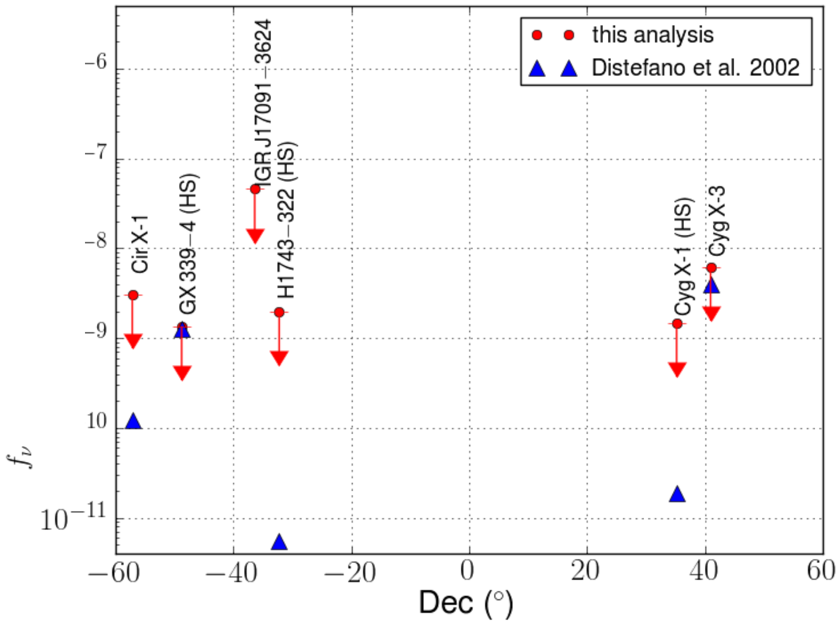
The microquasars selected are:
Cir X-1, GX 339-4, H1742-322, IGR J1709
and Cyg X-1.

Total livetime : 813.3 days

Unbinned likelihood method: LR-test

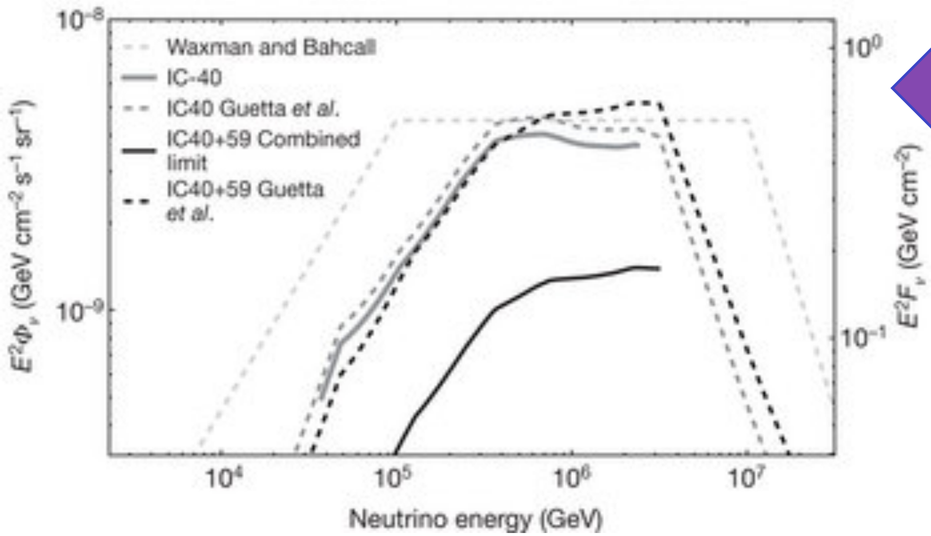


	Q	n_{sig}	closest ν	$N_{bg}^{exp}(< 3°)$
H1743−322(TS)	0.41	0.66	2.3°	0.04
Cyg X-1 (HS)	0.0016	0.08	1.4°	0.86
Cir X-1	0	0	5.7°	0.35
GX 339−4 (HS)	0	0	2.8°	0.66
GX 339−4 (TS)	0	0	11 °	0.02
H1743−322 (HS)	0	0	4.6°	0.61
IGR J17091−3624	0	0	12 °	0.05
Cyg X-1 (TS)	0	0	6.4°	0.27
Cyg X-3	0	0	6.9°	0.20



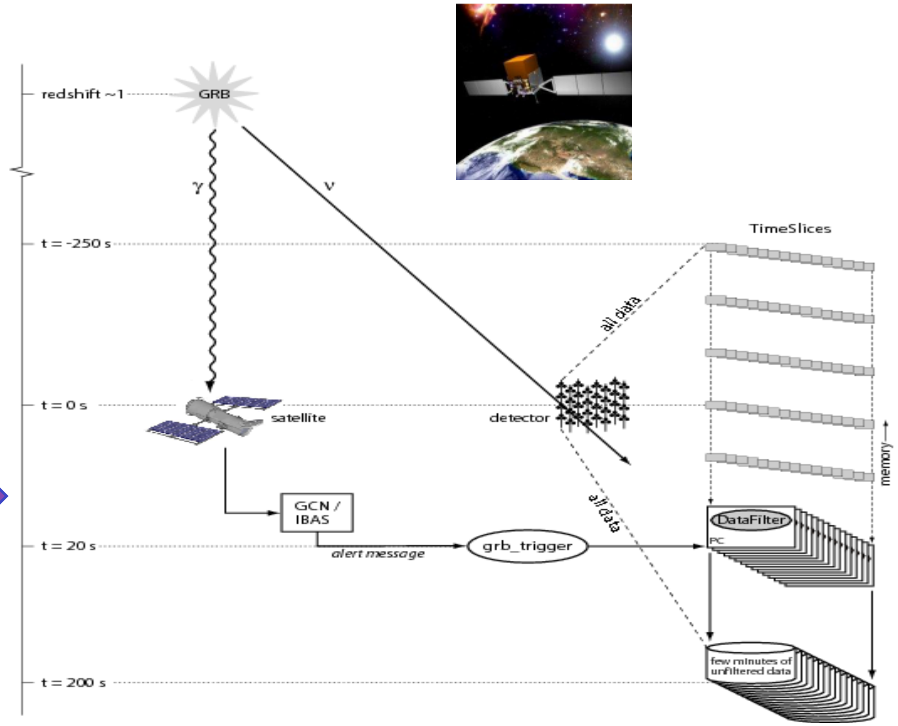
Alert programs (1)

- Search for neutrino events in coincidence with observed GRB
  - Time and direction known ☞ background reduction ☞ improved sensitivity
  - Individual modeling of bursts using satellite data (fireball model)



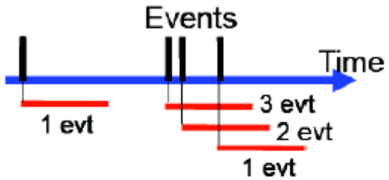
Best limit obtained with IC40+59
Excludes optimistic predictions based on fireball model
📖 Nature 484, 351–354 (19 April 2012)

- ANTARES dumps all buffered unfiltered data when receiving an alert (~1min)
  - Various analysis being performed



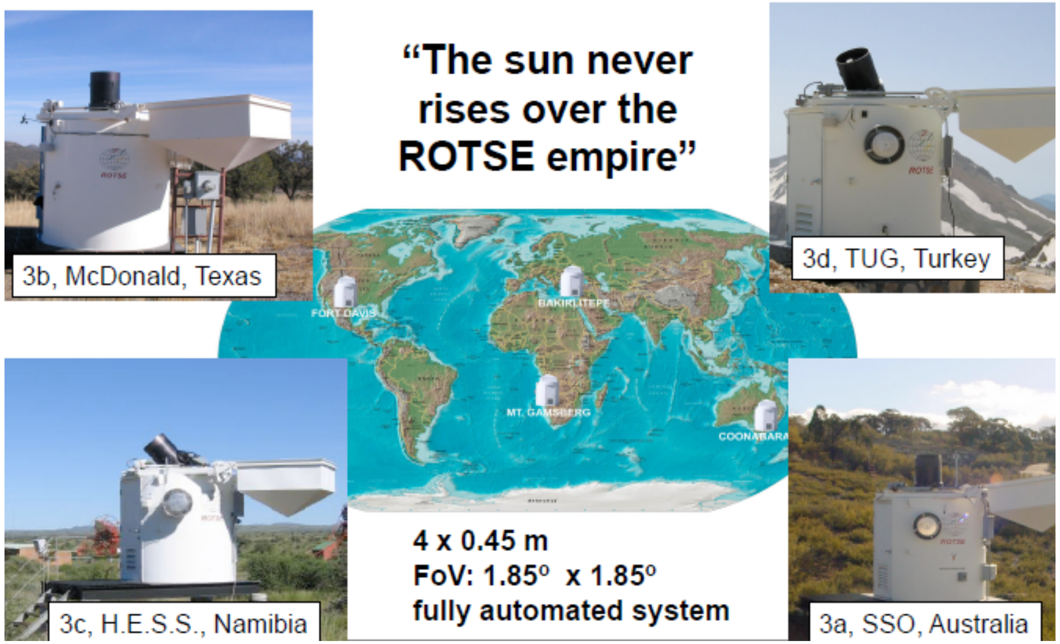
Alert programs (2)

- Reversely, IceCube and ANTARES also send alerts for optical follow up
  - Could give confirmation of a detection
  - Triggers are VHE events or multiplets (rolling searches)



IceCube

Latency has been reduced to ~ minutes
Alarm rate ~ 30 /year
Alerts are sent to ROTSE
T_0, T_0 +1, 2,…14 days



Antares

Latency ~ sec
Alarm rate 1-2 / month
Alerts are sent to :

- TAROT (La Silla, Chile) since Feb 2009
  T_0, T_0 +1, 3, 9 and 27 days
- ROTSE for 3 months

IceCube has a program
with MAGIC (La Palma, E>25GeV)

The GWHEN working group

Objective: conduct a joint search for HE Neutrinos and Gravitational Waves

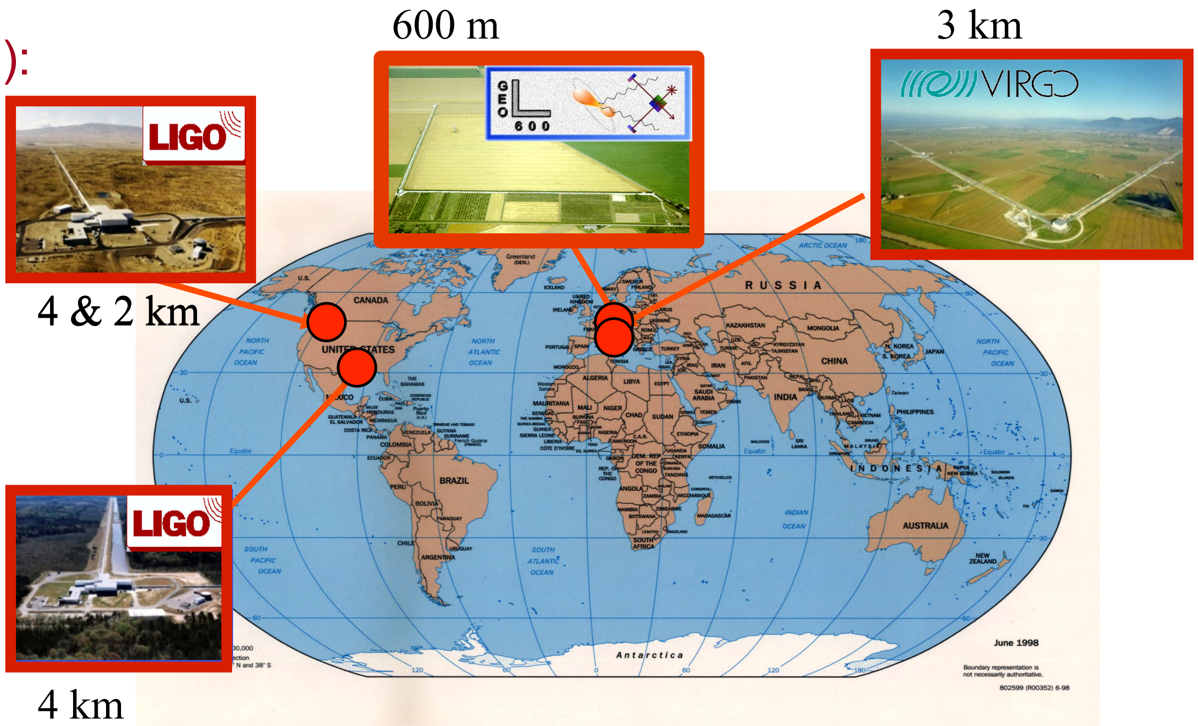
Motivations:

-plausible common sources GRBs (core collapse into BH or coalescing neutron stars), SGRs (magnetars), microquasars...

References : http://www.gwhen-2009.org

- potential for discovery of hidden sources (e.g. failed GRBs)

VIRGO/LIGO/GEO network (LSC):

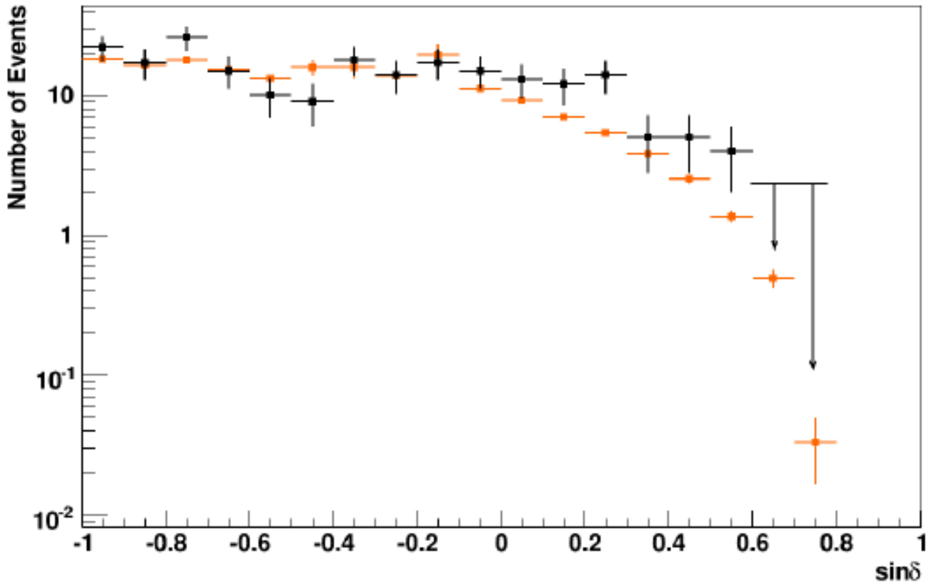


Effective collaboration (MoU) between LSC and ANTARES (analysis started) since Sept 2009

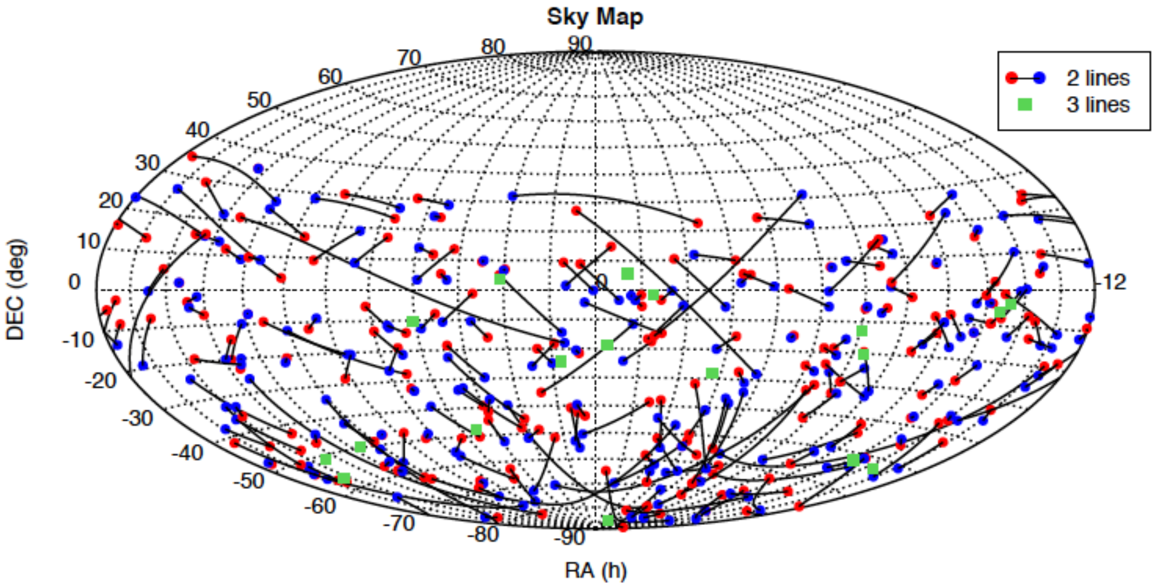
IceCube has recently joined the GWHEN group

Selected events

📖 http://arxiv.org/abs/1205.3018

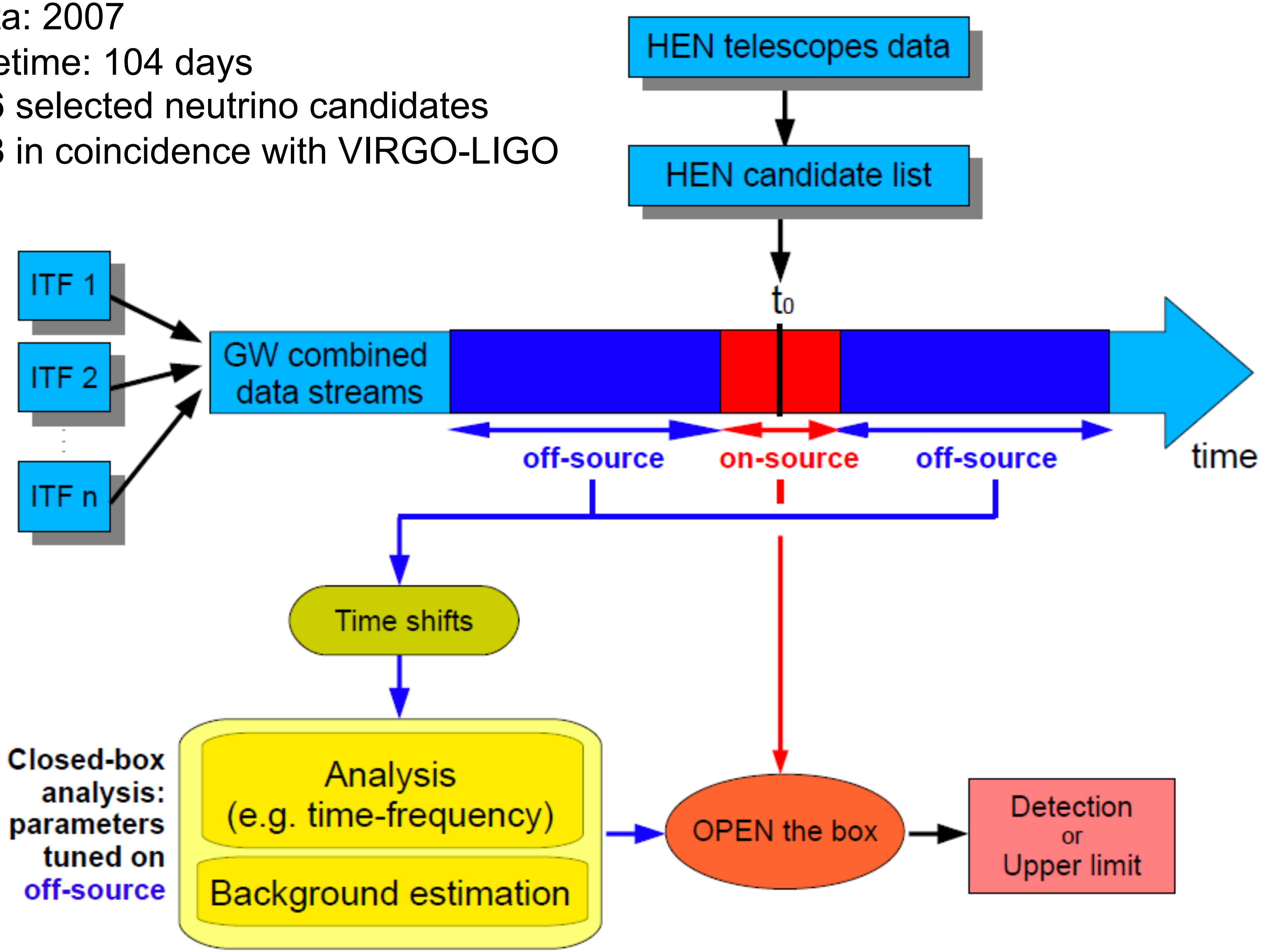


Data: 2007
Livetime: 104 days
216 selected neutrino candidates
158 in coincidence with VIRGO-LIGO



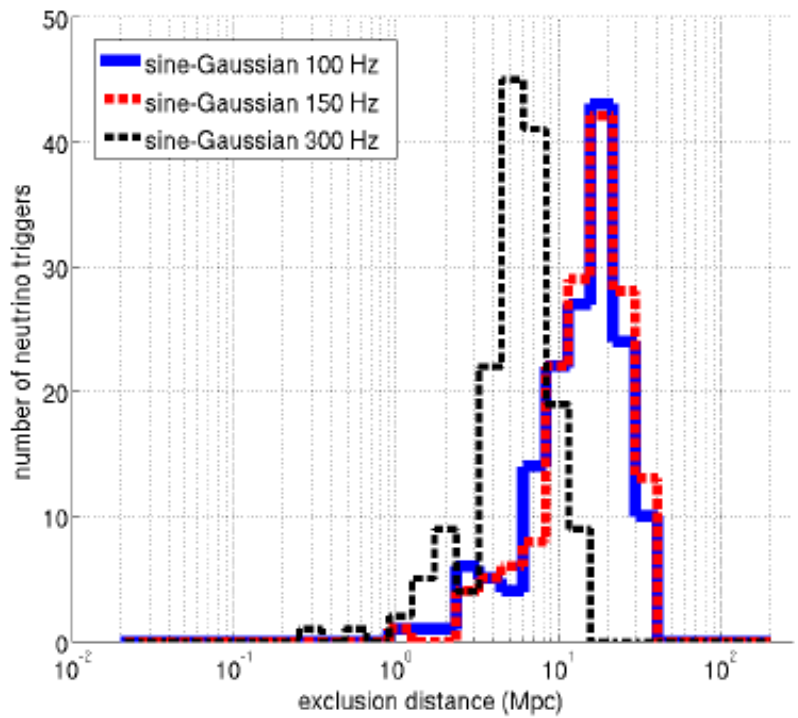
Search principle

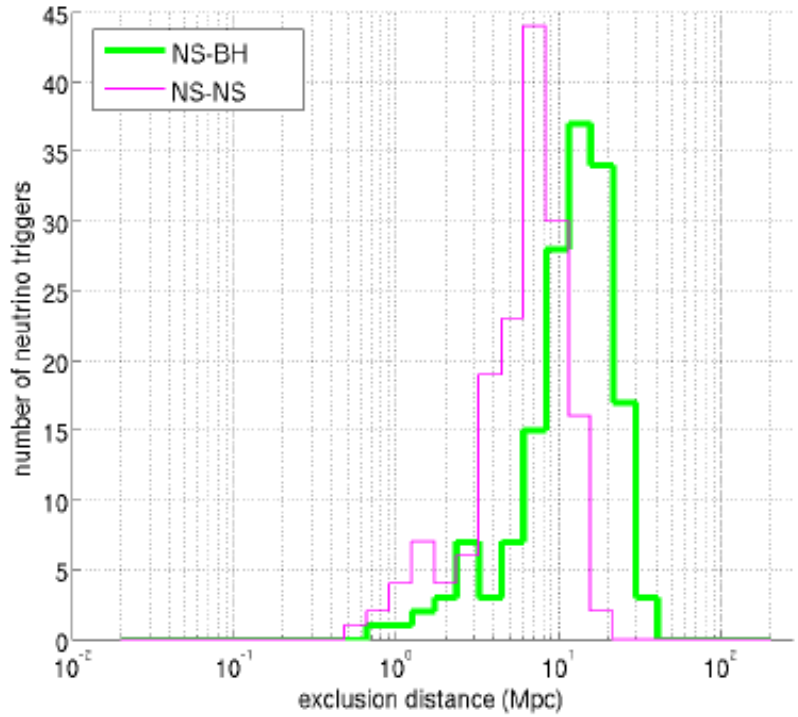
Data: 2007
Livetime: 104 days
216 selected neutrino candidates
158 in coincidence with VIRGO-LIGO



Exclusion distances

📖 http://arxiv.org/abs/1205.3018





$$\rho_{\text{GW-HEN}} V_{\text{GW-HEN}} \leq \frac{2.3}{T_{\text{obs}}}$$

$$\rho^{\text{SGRB}}_{\text{GW-HEN}} \lesssim 10^{-2} \text{Mpc}^{-3}\ \text{yr}^{-1}$$

$$\rho^{\text{LGRB}}_{\text{GW-HEN}} \lesssim 10^{-3} \text{Mpc}^{-3}\ \text{yr}^{-1}$$

$E_{GW} = 10^{-2}\ M_{\odot}\ c^2$

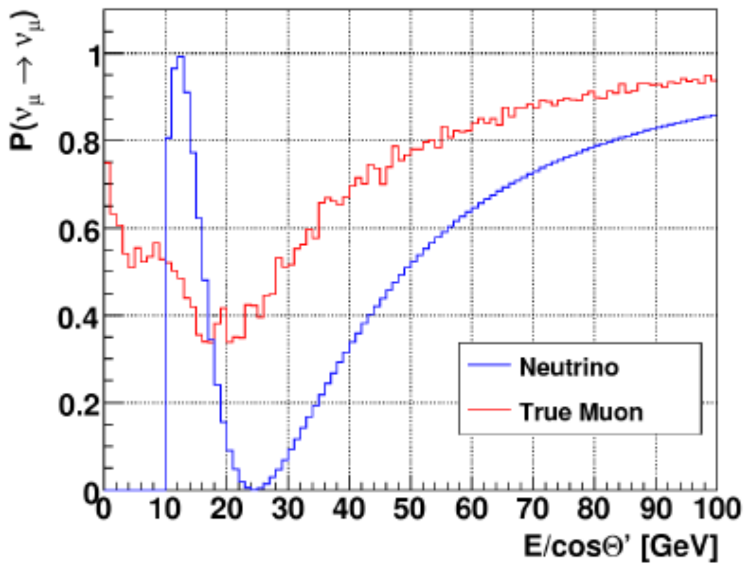
Neutrino oscillations studies

First oscillation study with HE neutrino telescope

Data : from March 2007 to December 2010
Active time 863 days

Method: Oscillation parameters from χ^2 fit
to E/cosθ distribution

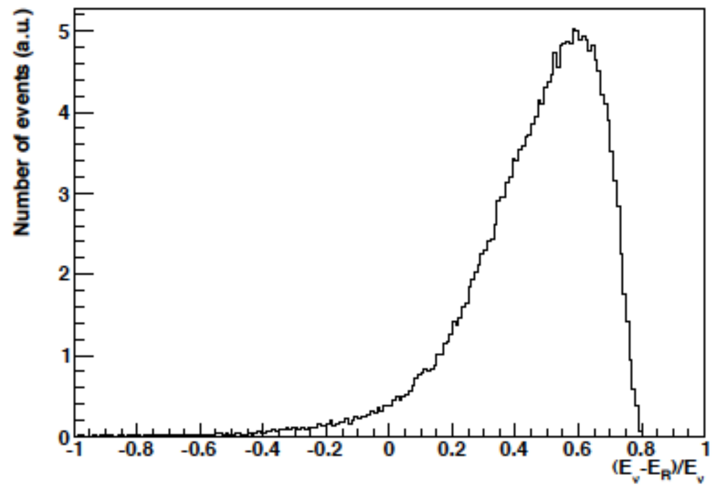
$\Delta m^2_{32} = 2.43 \cdot 10^{-3}\ \mathrm{eV}^2$ and $\sin^2 2\theta_{32} = 1$



Energy estimate : from muon path in the detector

$$S = (z_{max} - z_{min}) / \cos\Theta_R.$$

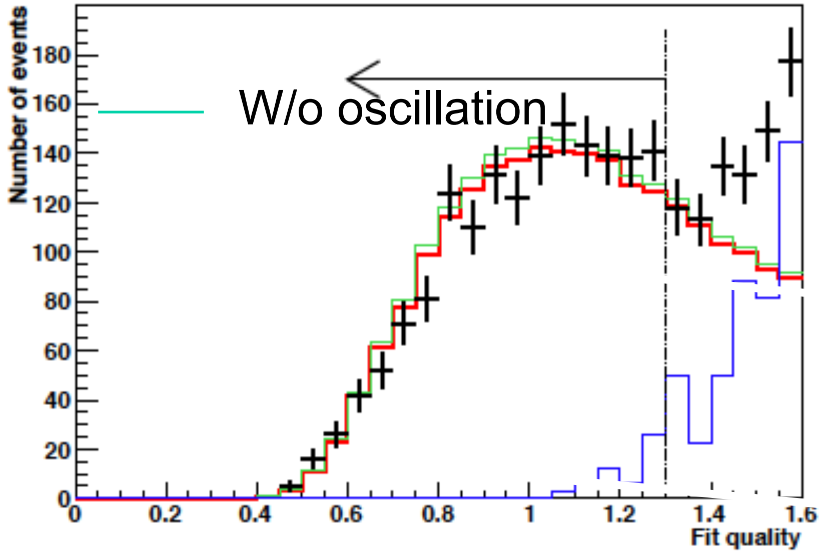
$$E_R = S \cdot 0.2\ \mathrm{GeV/m}.$$



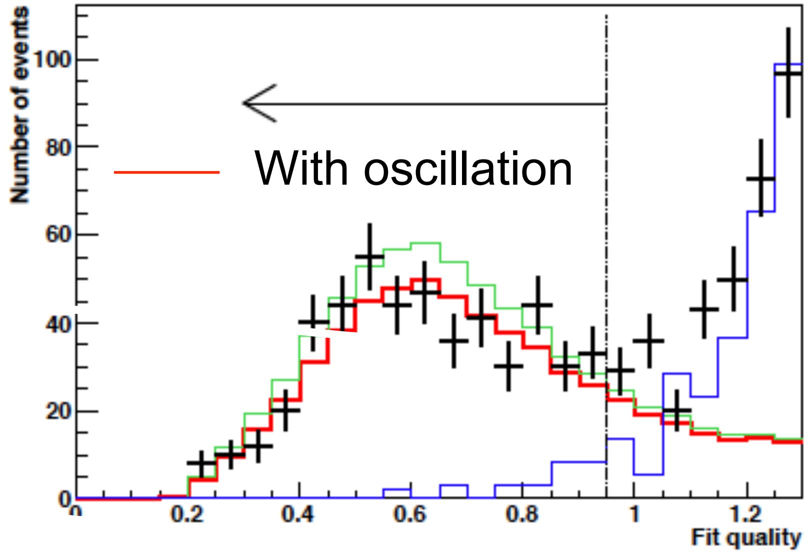
Neutrino oscillations studies

Event selection:

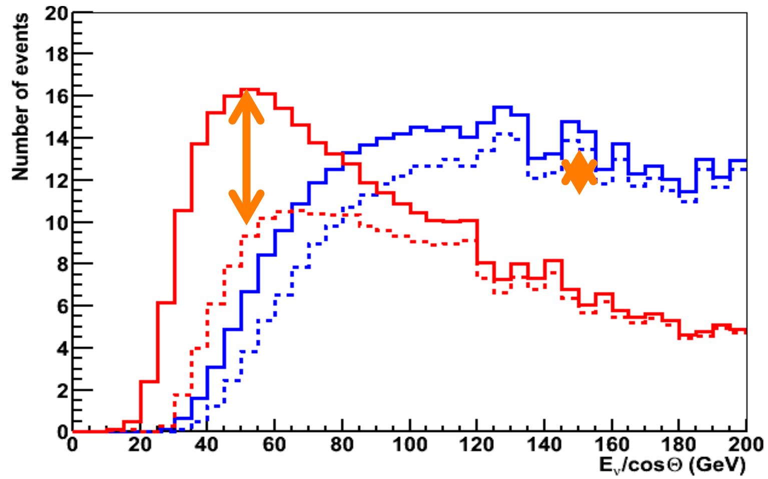
Multiline ML



Single line SL



Analysis strategy:



Total Normalisation
Affects 1L and ML in the same way

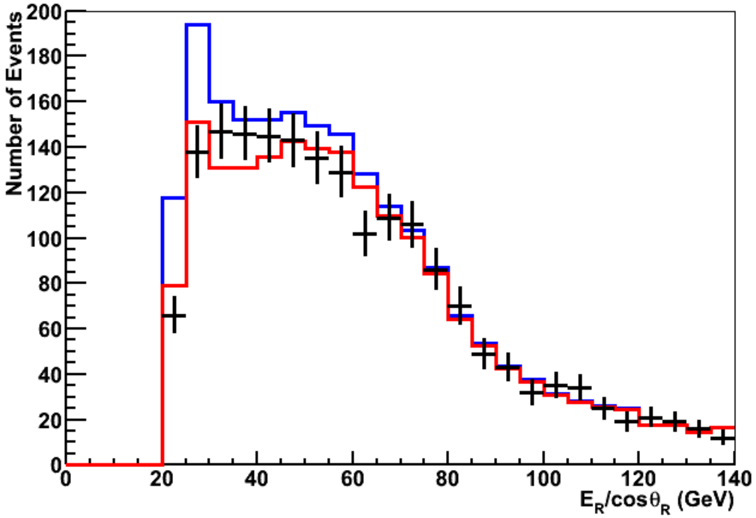
Changes of histogram shape
Affects 1L and ML differently
Modifies ratio R=1L/ML
Similar to effect of oscillations

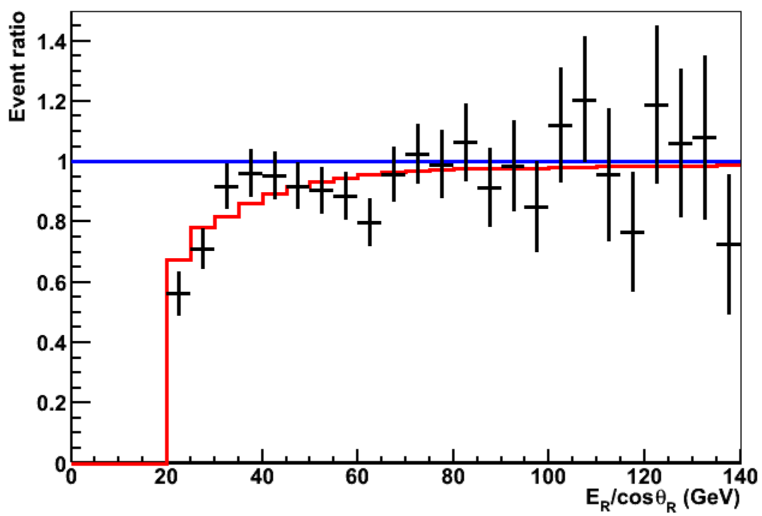
Implementation

$$\chi^2 = \sum_i \left[N_i - (1+\epsilon)MC_i^{1L} - (1+\eta)MC_i^{ML}\right]^2 / \sigma_i^2 + (\epsilon - \eta)^2 / \sigma_R^2.$$

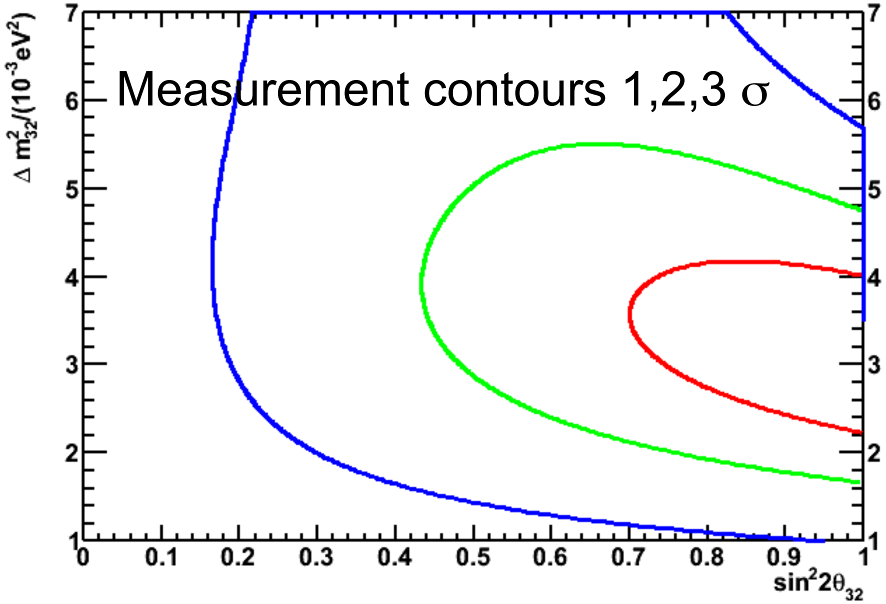
- Correlated systematic effects through pull factors
- ε normalization of 1L sample
- η normalization of ML sample
- Total normalization modifies $\varepsilon = \eta$
- No terms ε^2/σ^2 or η^2/σ^2 → normalization not constrained
- $\varepsilon - \eta$ modifies $R = N_{1L}/N_{ML}$ → constrained by $\sigma_R = 4\%$

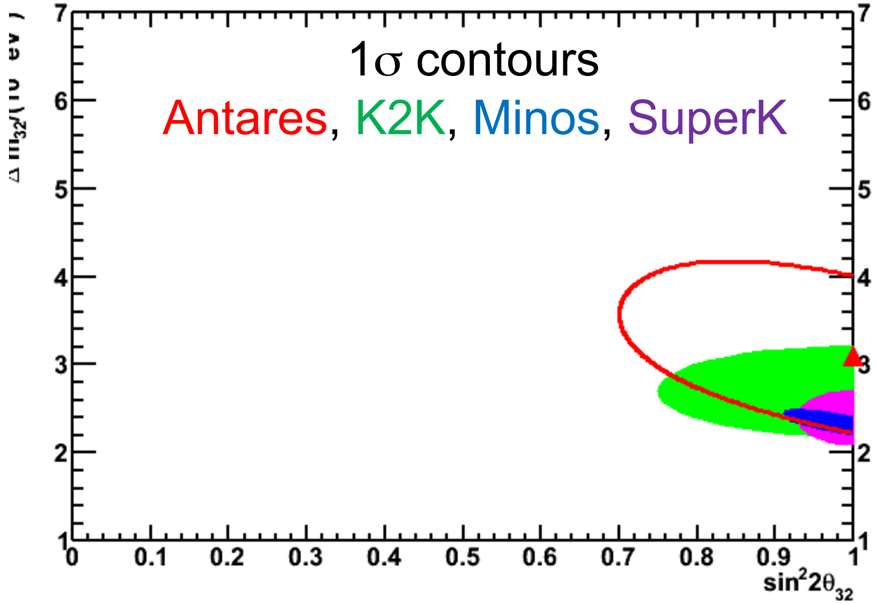
ANTARES Results





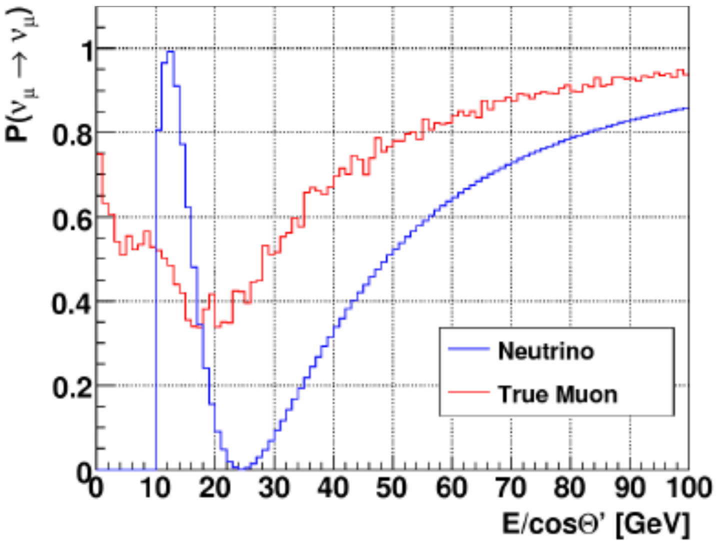
When imposing maximal mixing $\Delta m^2=(3.1\pm0.9)\ 10^{-3}\ eV^2$



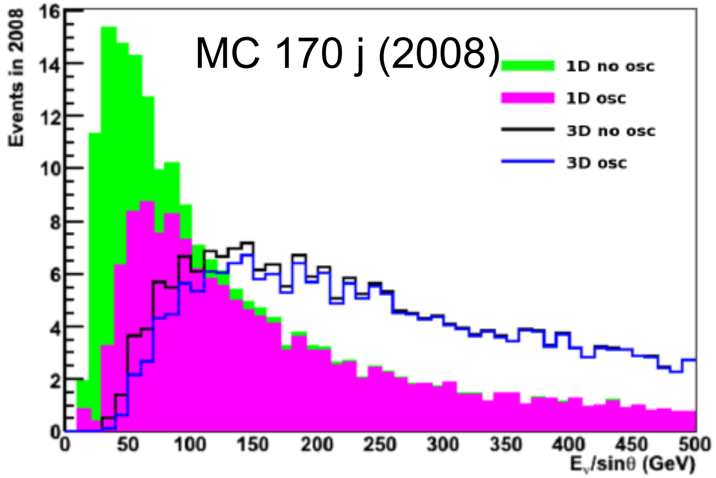


Et les oscillations dans le secteur atmosphérique?

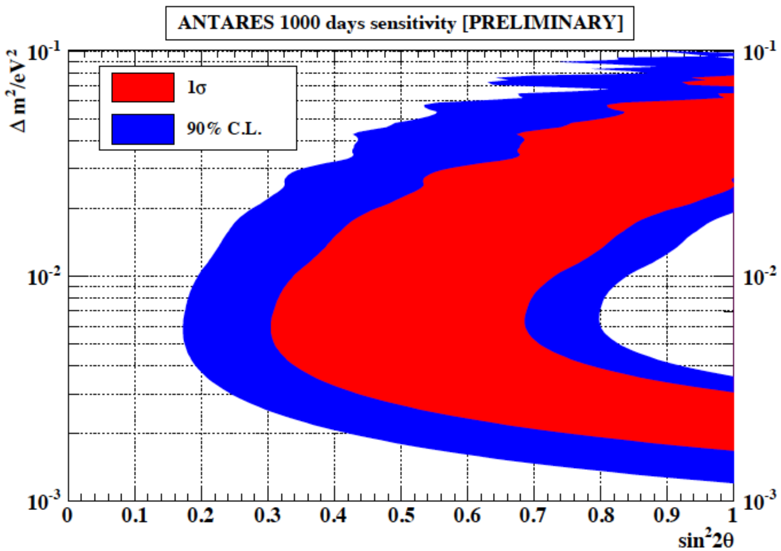
$(\sin^2(2\theta_{23}) = 1$ + MINOS input[1] : $|\Delta m^2_{23}| = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\ \mathrm{eV}^2)$



Méthode : étudier le rapport des evts verticaux (single line) aux evts diagonaux (multiline)

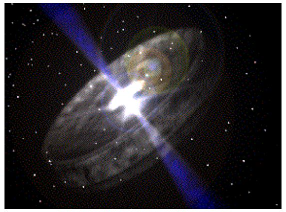


	no osc.	osc.
single line events	186	160 (-14%)
multiline events	522	504 (-3%)



3 year data can exclude (3σ) the non-oscillation hypothesis.
Sensitivity not competitive with MINOS, but first measurement with NT.

Outline

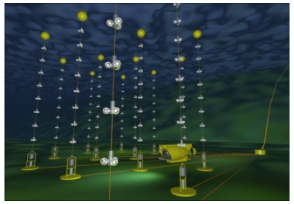


Neutrino astronomy

Lectures of Th. Patzak → Historical aspects

Scientific motivations

Cosmic neutrino sources

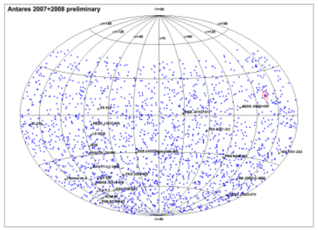


Neutrino telescope

First extraterrestrial neutrinos

Detection principles

Current telescopes



Selected results

Diffuse Flux

Search for point sources

Multi-messenger search

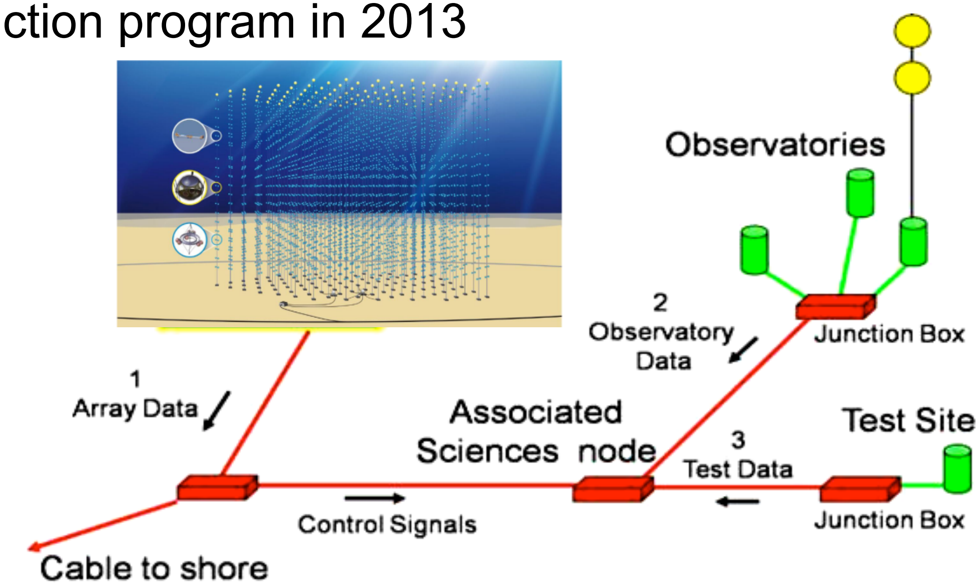
KM3NeT project

KM3NeT activities

Consortium : 40 institutes from 10 European countries

Objectives :

- Built a cubic-km scale NT in the Mediterranean that exceeds IceCube sensitivity by a substantial factor (target TeV galactic sources for an overall budget of ~ 250 M€)
- Provide node for Earth and marine sciences (real time multidisciplinary observatory)
- Start 5 years construction program in 2013



Achievements :

- Constructive gathering of “dispersed” forces
- Conceptual Design Report (CDR) published in 2008
- Technical Design Report (TDR) available

http://www.km3net.org/public.php

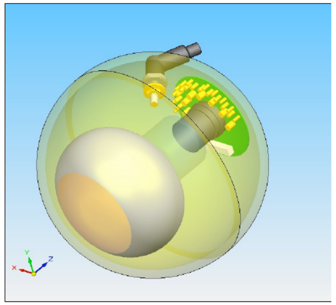
Pending :

- Clarify the question of the site in the coming year

KM3NeT technical activities

- Two alternative solutions OMs

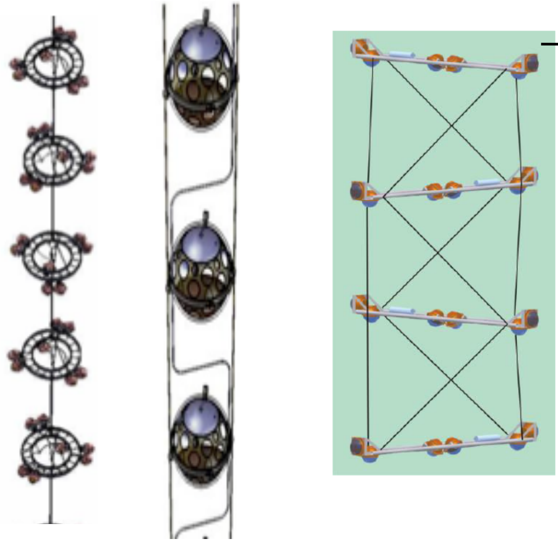
Preferred one



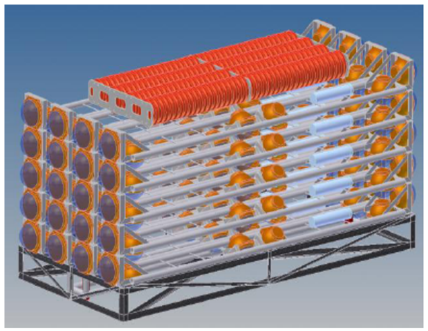
Single-PMT Optical Module
8-inch PMT with 35% quantum efficiency inside a 13 inch glass sphere

Multi-PMT Optical Module
31 small PMTs (3-inch) inside a 17 inch glass sphere

- Three alternative solutions for the detector units



Preferred one
Flexible tower with horizontal bars equipped with 6 Oms
Simulations: 3D OM arrangement resolve ambiguities in the reconstruction of the muon azimuthal angle



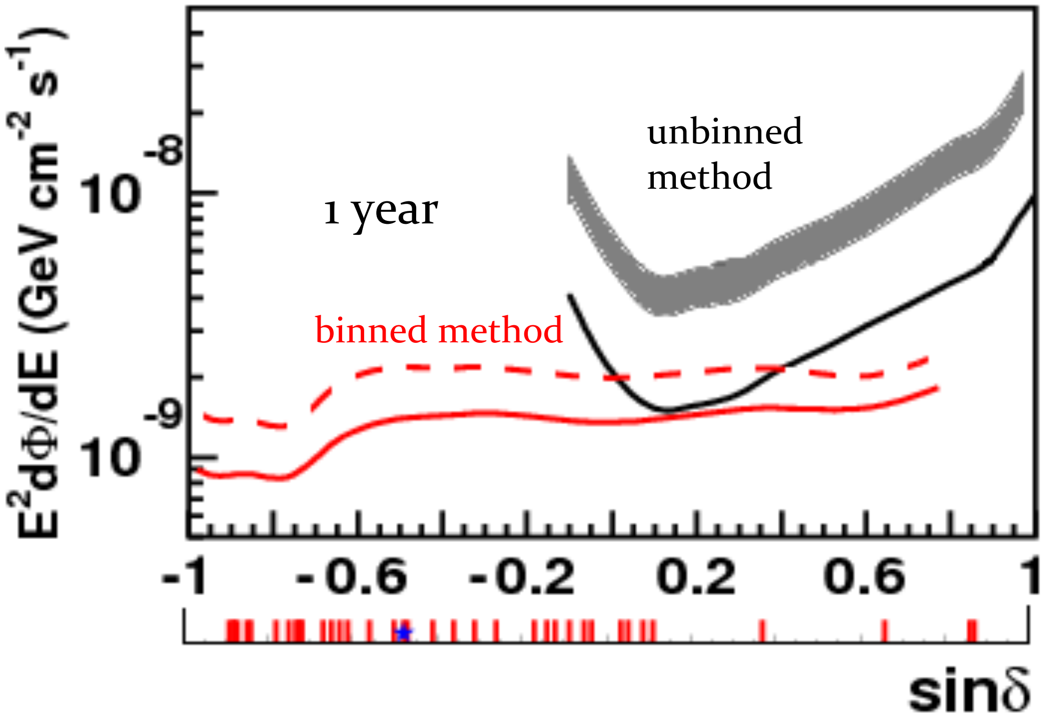
The packed flexible tower (20 storey)

Successful deployment test in February 2010

Expected sensitivity

Sensitivity and discovery fluxes for point like sources with E^{-2} spectrum

Full detector (310 DUs)



KM3NeT sensitivity 90%CL

KM3NeT discovery 5σ 50%

IceCube sensitivity 90%CL

IceCube discovery 5σ 50% 2.5÷3.5 above sensitivity flux. (extrapolation from IceCube 40 string configuration)

| Observed Galactic TeV-g sources (SNR, unidentified, microquazars)

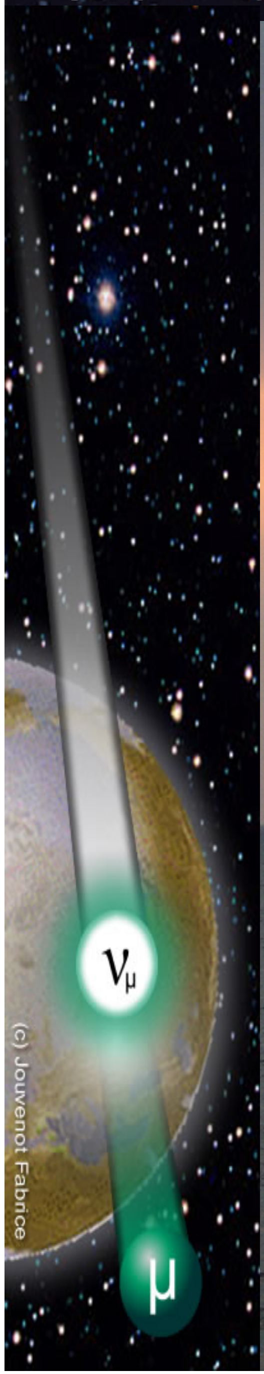
F. Aharonian et al. Rep. Prog. Phys. (2008)

Abdo et al., MILAGRO, Astrophys. J. 658 L33-L36 (2007)

★ Galactic Centre

Sensitivity and discovery will improve with the unbinned analysis

Conclusions



- Neutrino astronomy has made great progress with detectors
- IceCube has been completed for more than 1 year : now sensitive to the region of physical interest.
- ANTARES has demonstrated the feasibility of a deep-sea ANTARES is the larger NT in the Northern hemisphere…A platform for associated sciences.

The best is yet to come!

« Le véritable voyage de découverte ne consiste pas à chercher de nouveaux paysages, mais à avoir de nouveaux yeux .» *M.Proust*