High-energy Neutrino Astronomy

An overview oriented towards the Cherenkov Technique

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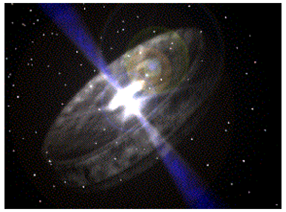
Laboratoire APC

Credits: Ch. Spiering, L. Moscoso, F. Halzen, A. Karle, G. Sullivan, P. Coyle, Th. Patzak, D. Vignaud, E. Resconi…many others

Outline

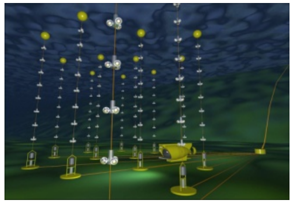


Neutrino astronomy

Historical aspects

Scientific motivations

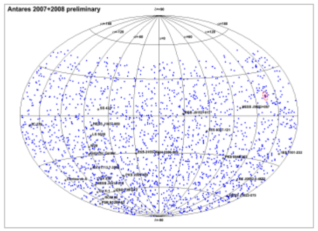
S. Drappeau & P. Baerwald → Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



P. Gay → **Selected results**

Diffuse Flux

Search for point sources

V. Van Elewyck → Multi-messenger search

KM3NeT

K. Clarke → **Future prospects**

First ideas early 60's…science

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

NEUTRINO INTERACTIONS[1]

By Frederick Reines[2]

IV. COSMIC AND COSMIC RAY NEUTRINOS

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

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

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

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

First ideas early 60's…method

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

COSMIC RAY SHOWERS[1]

By Kenneth Greisen

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

For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6 \cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with the lower of the theoretical cross sections—rather marginal, though the background from other particles than neutrinos can be made just as small. The detector has the virtue of good angular resolution to assist in distinguishing rare events having unique directions.

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

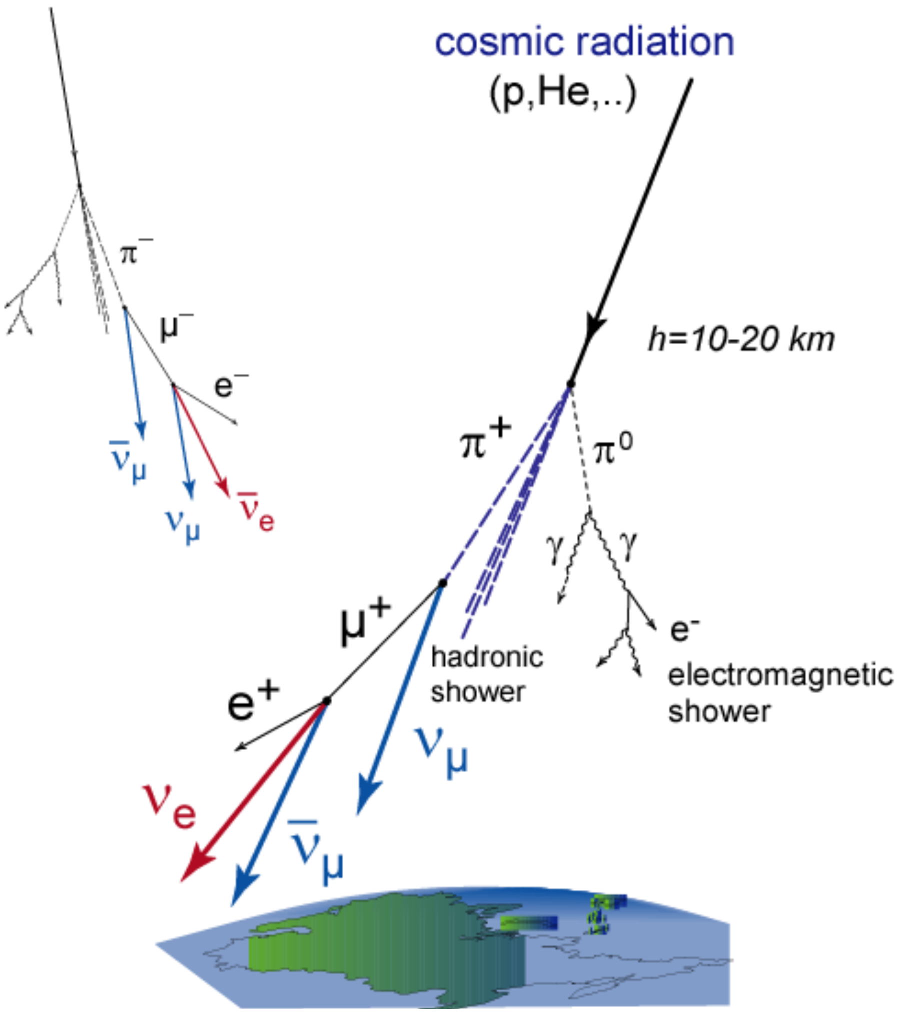
First atmospheric neutrinos

Detection of nearly horizontal atmospheric neutrinos in a South African Gold mine.

F. Reines, 1965

… one of the main motivations for **Reines' South Africa detector**, the **Kolar Gold Field Detector** (India) and the **Baksan scintillation detector**(Russia).
<u>Early sixties:</u> does the neutrino cross section saturate beyond 1 GeV (i.e. one would never measure atm. neutrinos with energies higher than a few GeV).

First atmospheric neutrinos…



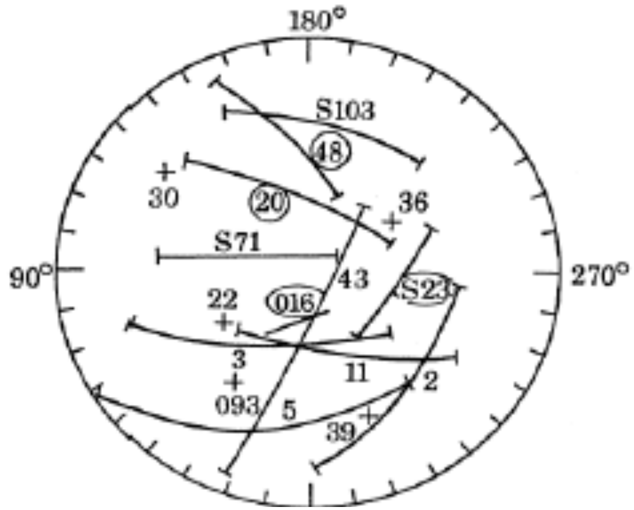
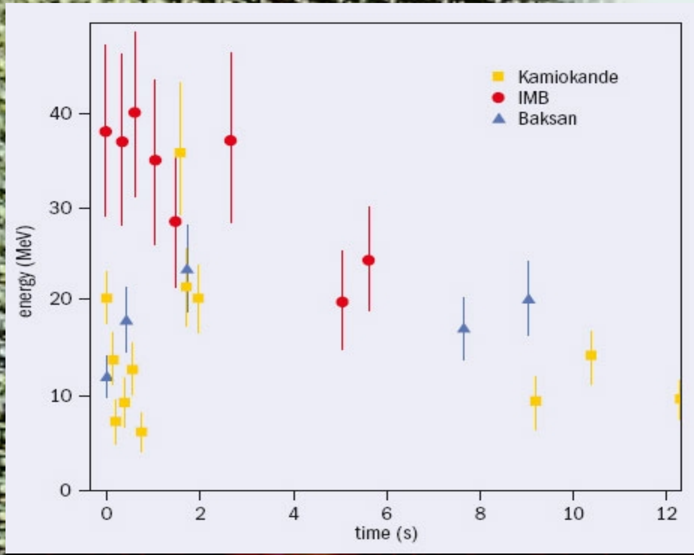


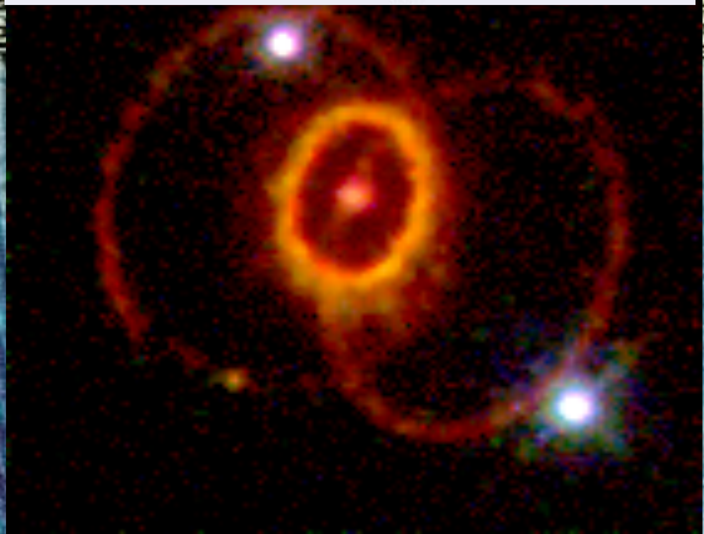
Fig. 2. The first neutrino sky map with the celestial coordinates of 18 KGF neutrino events [Krishnaswamy 1971]. Due to uncertainties in the azimuth, the coordinates for some events are arcs rather than points. The labels reflect the numbers and registration mode of the events (e.g. "S" for spectrograph). Only for the ringed events the sense of the direction of the registered muon is known.

First extraterrestrial neutrinos

cf G. Raffelt
D. Vignaud

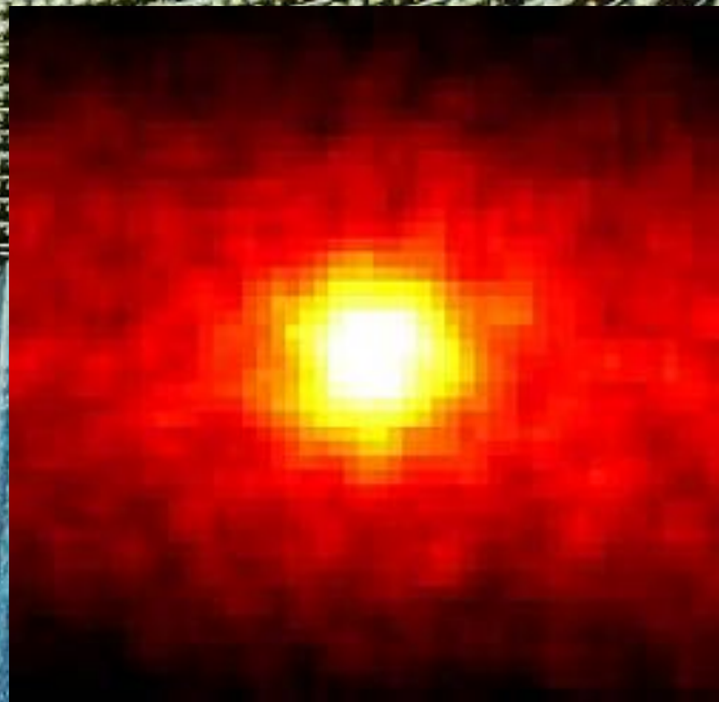


Kamiokande then SuperKamiokande



Neutrinos from
SN1987A
25 events in 12 s

~MeV



The Sun seen by
SuperKamiokande

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.	**Masatoshi Koshiba**	**Riccardo Giacconi**
1/4 of the prize	1/4 of the prize	1/2 of the prize
USA	Japan	USA
University of Pennsylvania Philadelphia, PA, USA	University of Tokyo Tokyo, Japan	Associated Universities Inc. Washington, DC, USA
b. 1914	b. 1926	b. 1931 (in Genoa, Italy)

Solar neutrinos

(MeV energies)

Davis et al. 1955 – 1978

Koshiba et al., 1987 – 1988

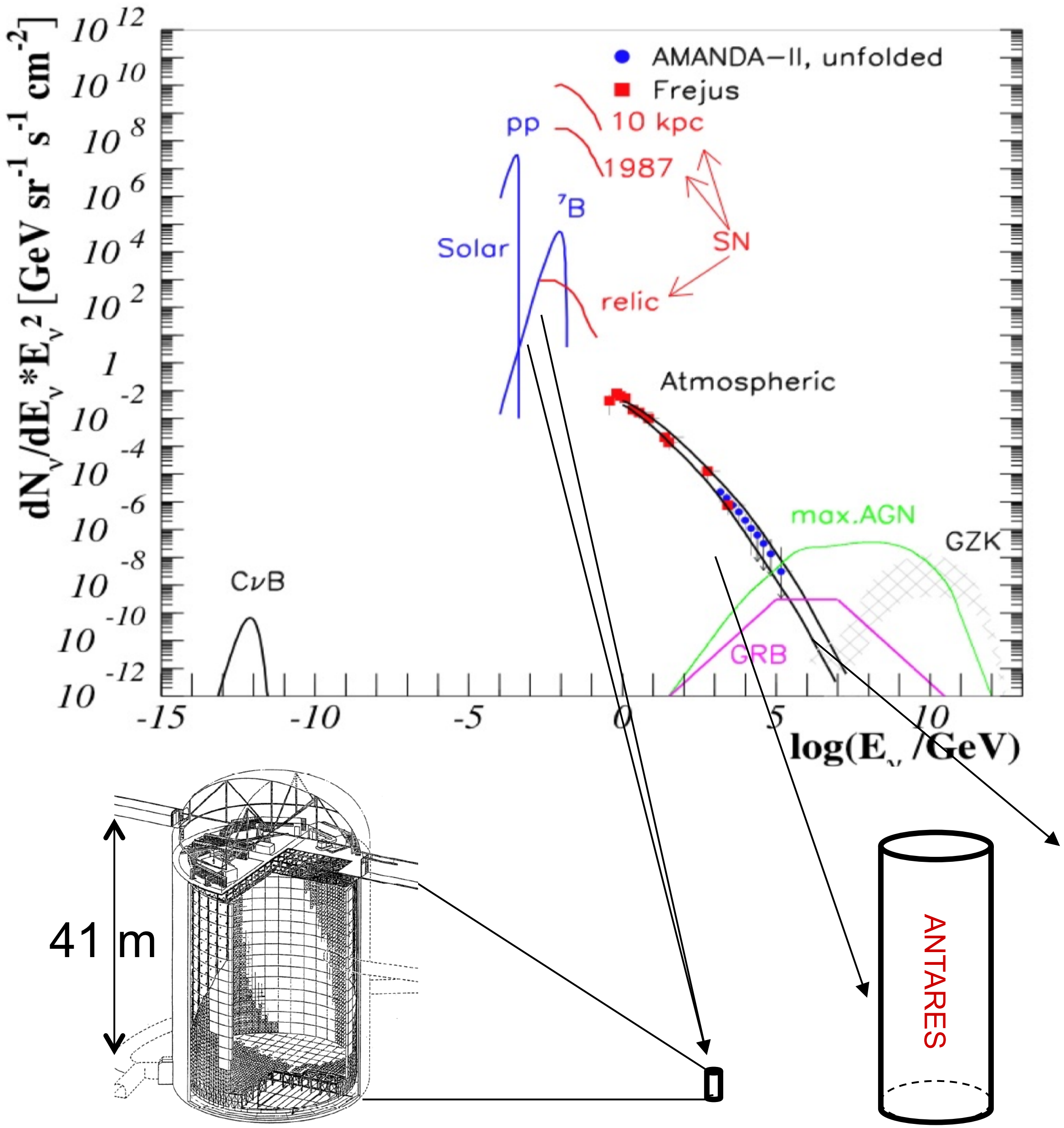
Presence of cosmic neutrinos E > GeV?

Galactic
Extragalactic

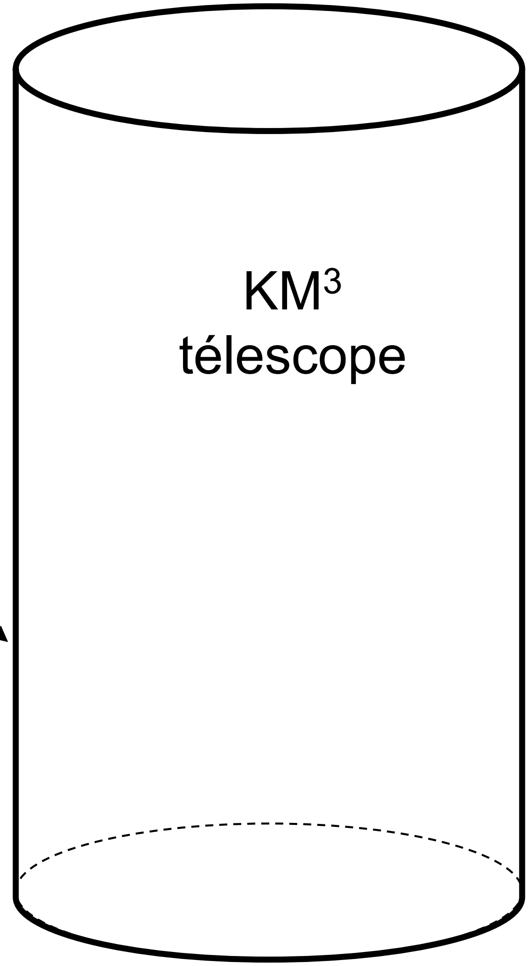
« These neutrino observations are so exciting and significant that I think we're about to see the birth of an entirely new branch of astronomy: neutrino astronomy.»

J.Bahcall
New York Times (3 Apr 1987)

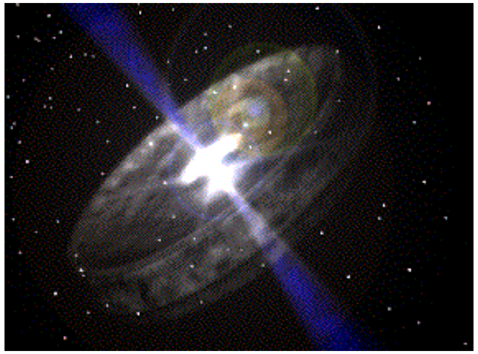
From MeV ν to PeV ν

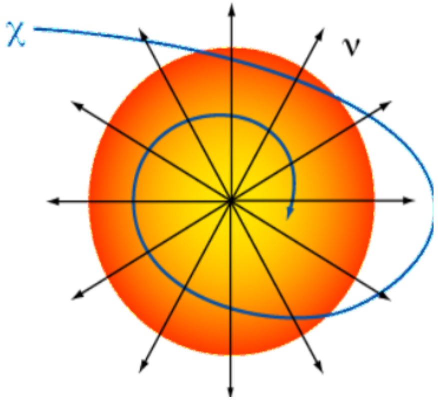


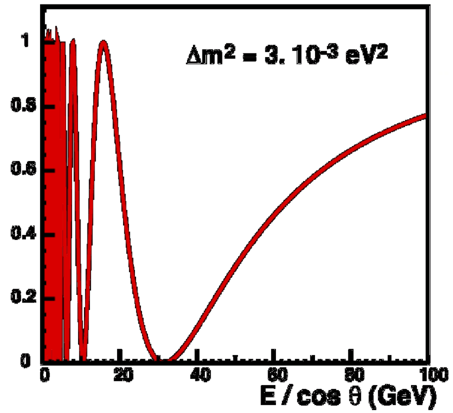
High energy neutrino:
Small fluxes
Need large detectors
for wide energy range



Neutrino telescopes: science scope







High Energy	Medium Energy	Low Energy
$E_\nu > 1$ 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

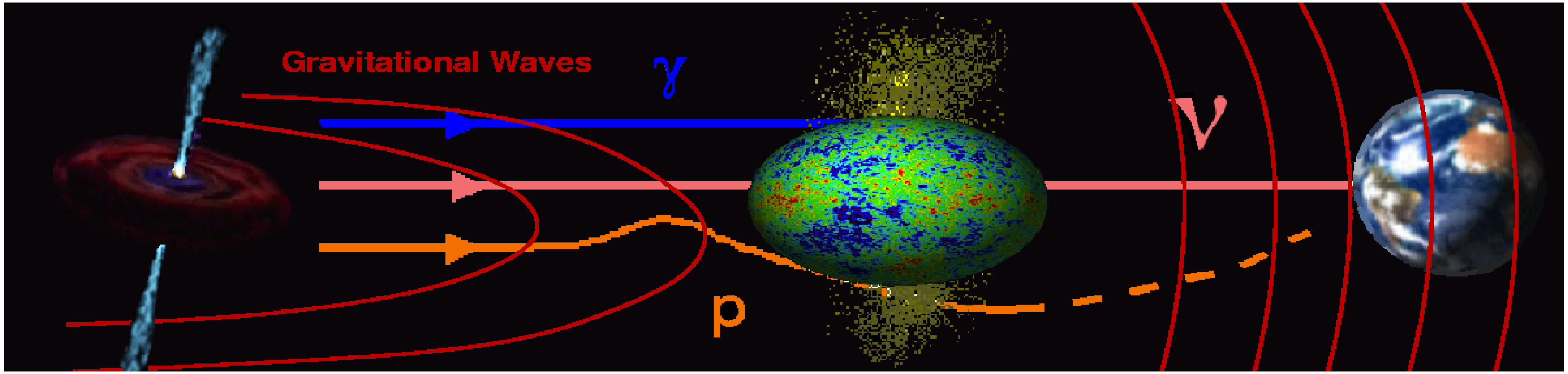
↓

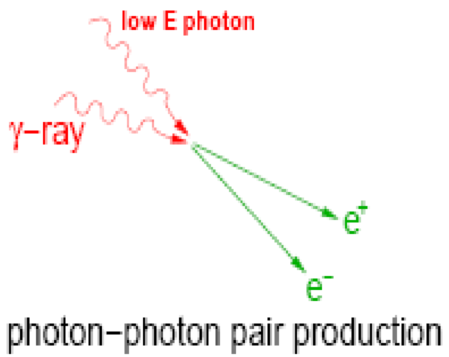
Primary goal

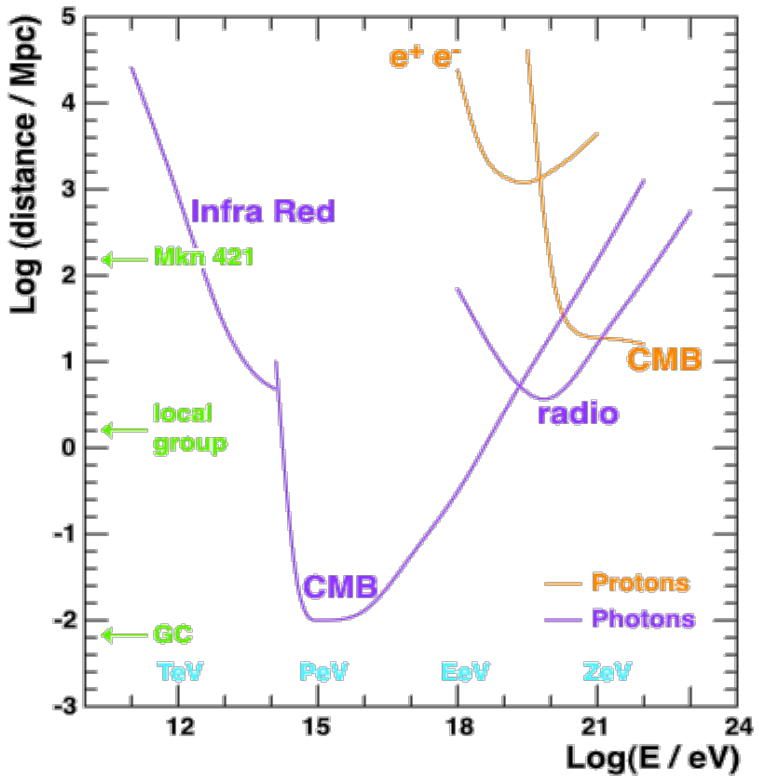
Exotic particle physics
Monopoles, nuclearites,…

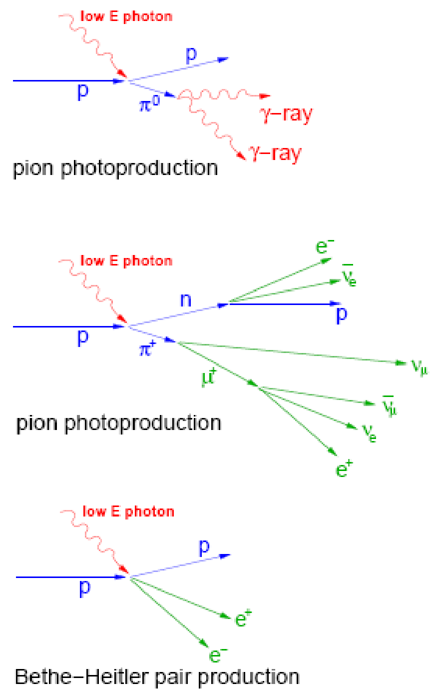
Marine sciences: oceanography, biology, geology…

Multi-messenger astronomy









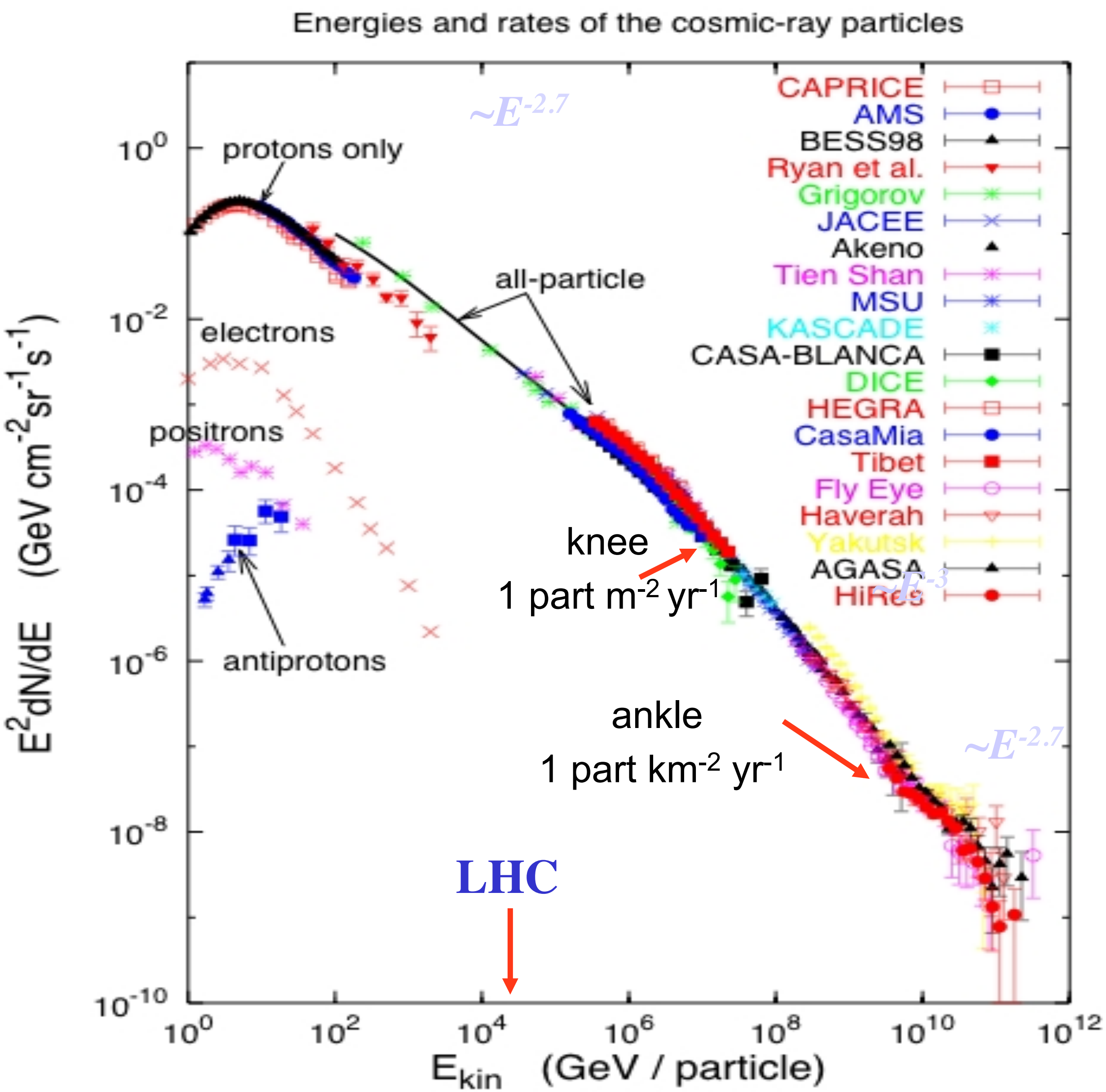
UHE cosmic rays

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

Cutoff now confirmed
But…

where?

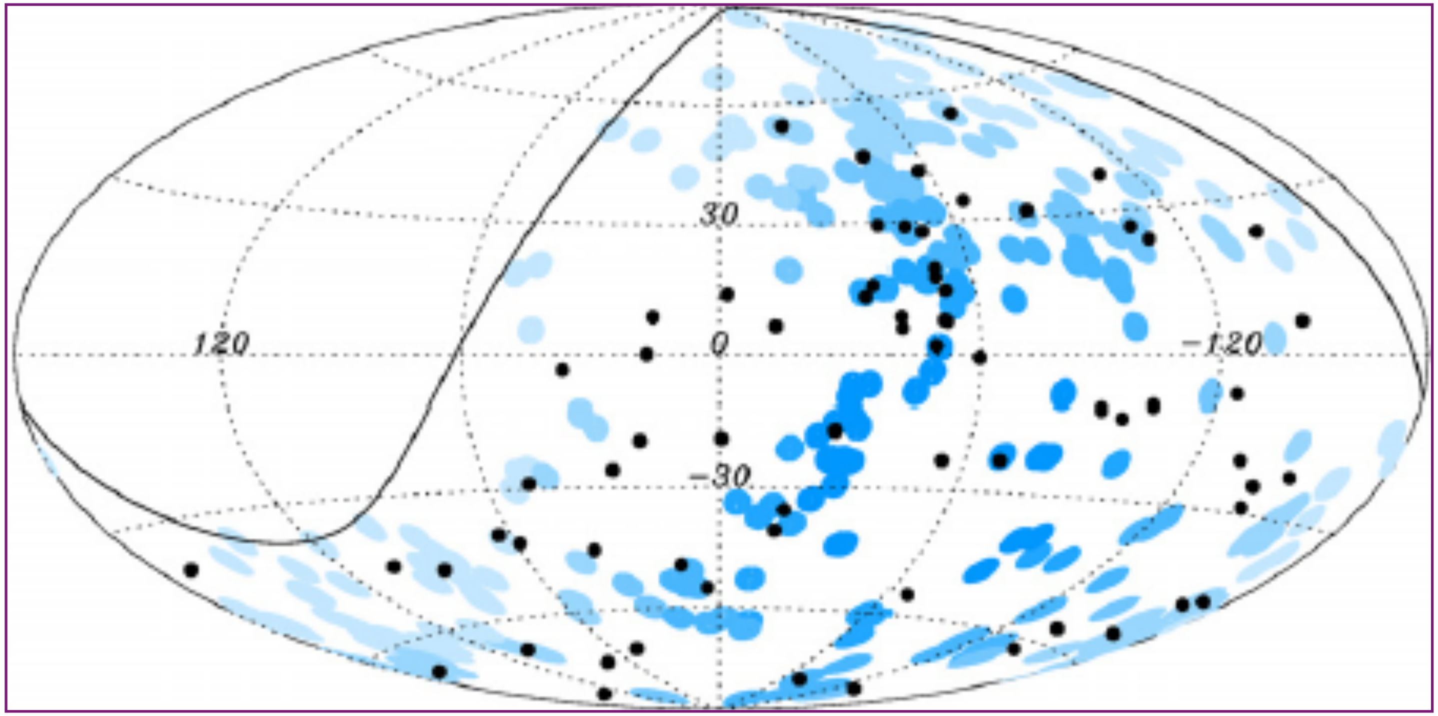
how?



Only (controversial) indications

📖 Astropart. Phys. 34 (2010)

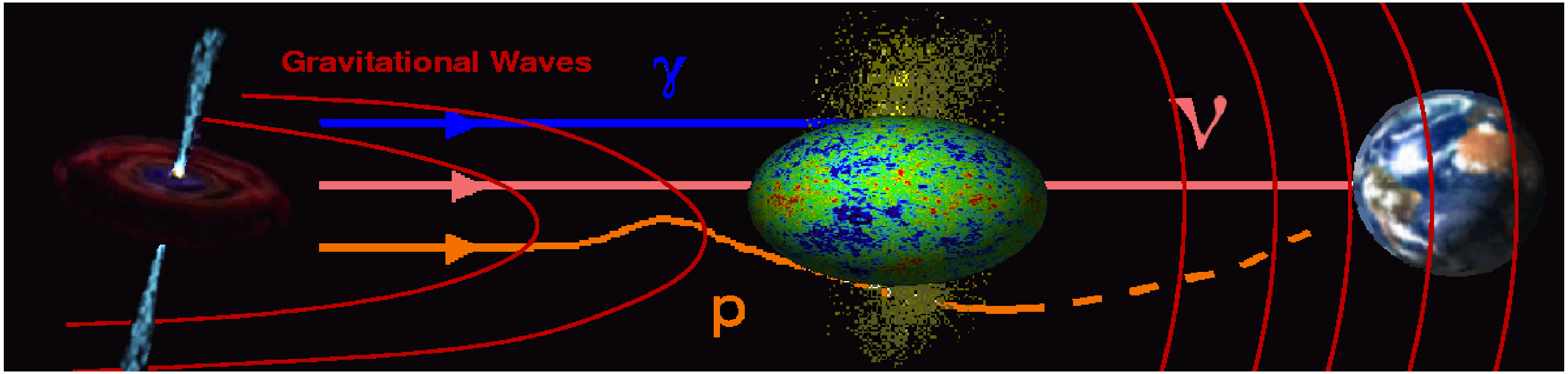
AUGER 69 evts E>55 EeV
VCV catalogue



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

Mutli-wavelength/messenger analysis → Modeling of the source

Cosmic ray connection

- Hadronic cascades (as for atmospheric showers)

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

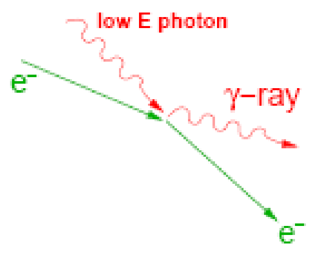
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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

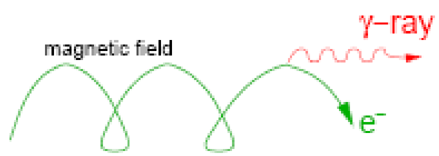
$$\nu_e:\nu_\mu:\nu_\tau = 1:2:0 \ \text{source} \xrightarrow{\text{oscillations}} \nu_e:\nu_\mu:\nu_\tau = 1:1:1 \ \text{Earth}$$

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



inverse Compton scattering

- But HE γ also from electromagnetic processes
  Synchrotron Inverse Compton



synchrotron radiation

« Guaranteed » Flux / Upper Bounds

- Benchmark extragalactic muon neutrino flux

  Waxman & Bahcall, 1999

Estimated energy density of UHECR:

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

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 total ν flux:

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

$E^{-2}\ I(E) = 4.5\ 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
~ 500 events /yr/ km^2

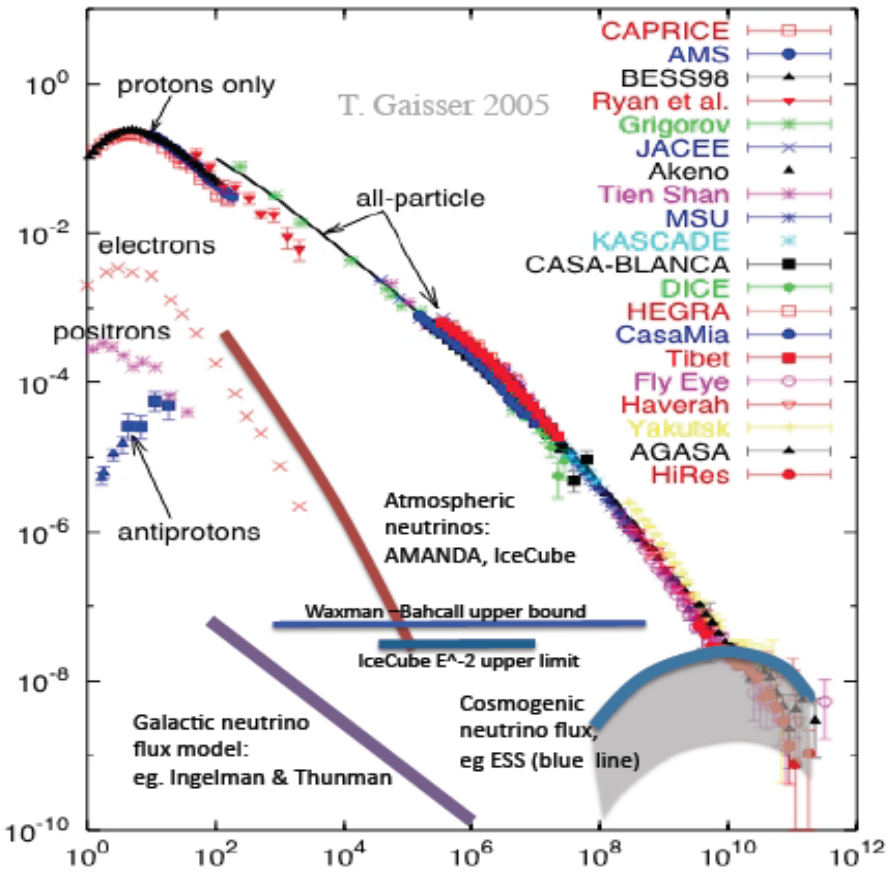
Hypothesis: UHECR are protons,
if not scales with p fraction

- 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



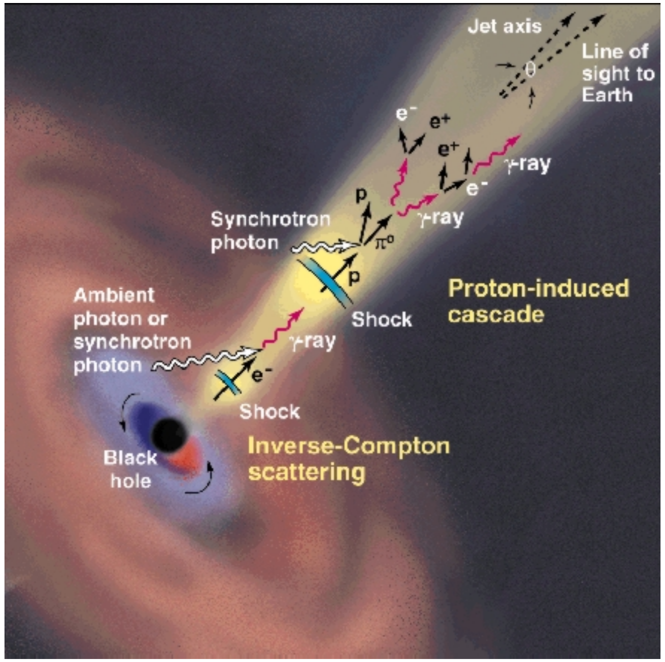
Models currently being probed by existing neutrino telescopes

Potential extragalactic sources

Active Galactic Nuclei (AGN)

Steady (though flaring) sources

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

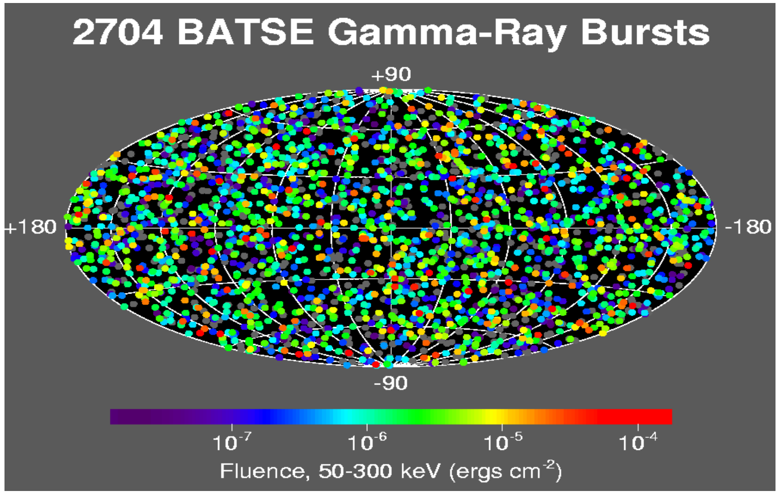


Gamma Ray Bursters (GRB)

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

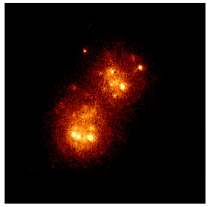
Counterparts : z up to 8.3

BATSE : 1 burst/day



Starburst Galaxies

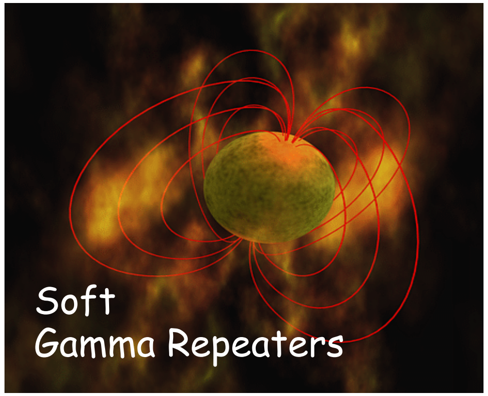
supernovae -> cosmic rays + dense gas -> pions



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.

→ 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

→ HEN from GRB-like flares

Galactic Center
seen with TeV photons

- *Supernovae remmants*

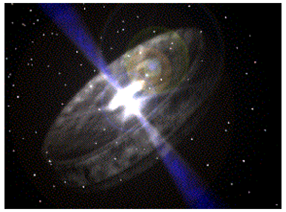
  pulsars, neutron stars

- *Dense regions*

  Sun , Galactic Centre, Interstellar medium

→ Mosty seen by Northern Hemisphere neutrino telescopes

Outline

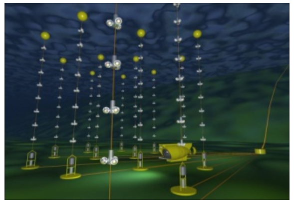


Neutrino astronomy

Historical aspects

Scientific motivations

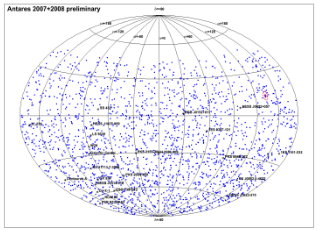
S. Drappeau & P. Baerwald → Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



P. Gay → Selected results

Diffuse Flux

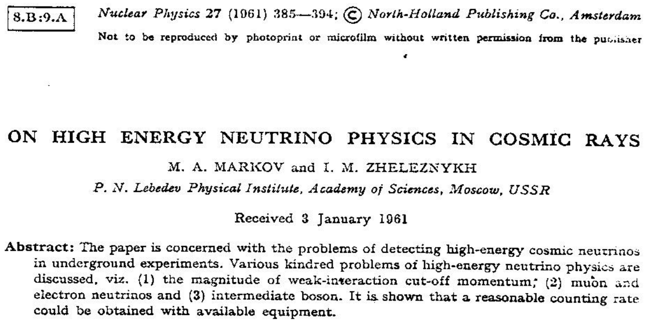
Search for point sources

V. Van Elewyck → Multi-messenger search

KM3NeT

K. Clarke → Future prospects

Markov idea: muon neutrino



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

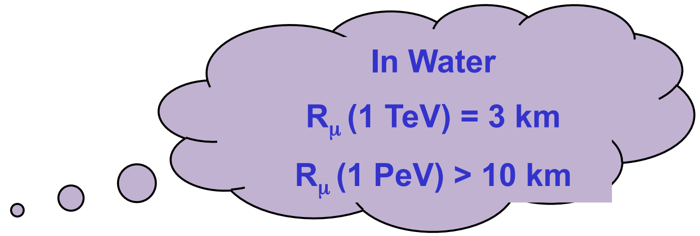
ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH

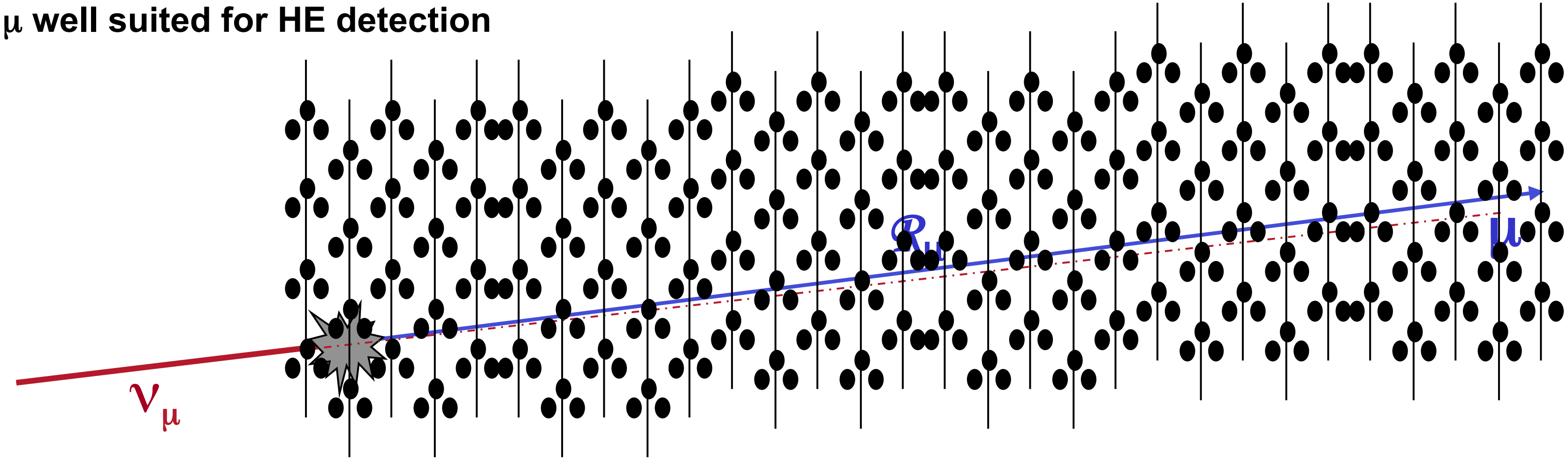
P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

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.



μ well suited for HE detection



- 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

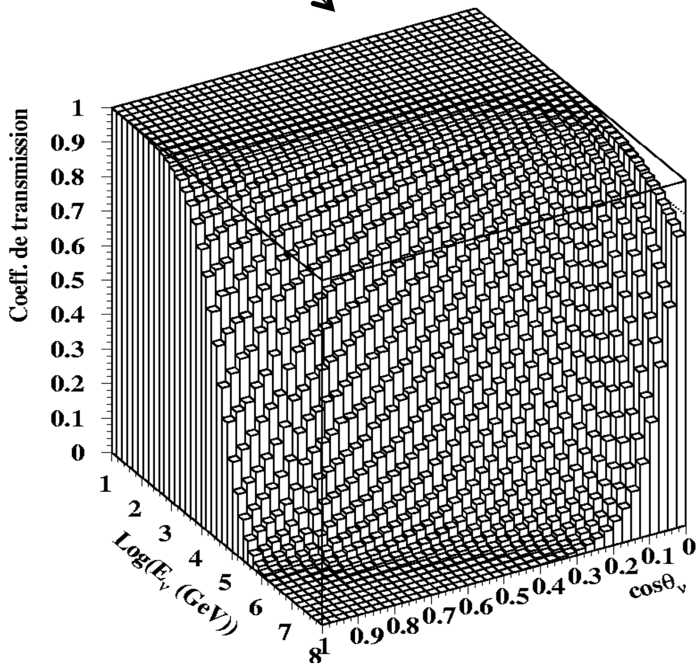
The number of muon events in units of detection area A and observation time T is:

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

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

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

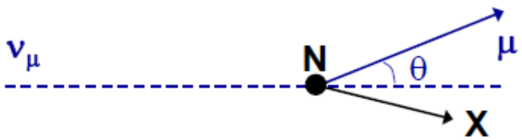
Range of
lepton of energy
El before it reaches E_{min}



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

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

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



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

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

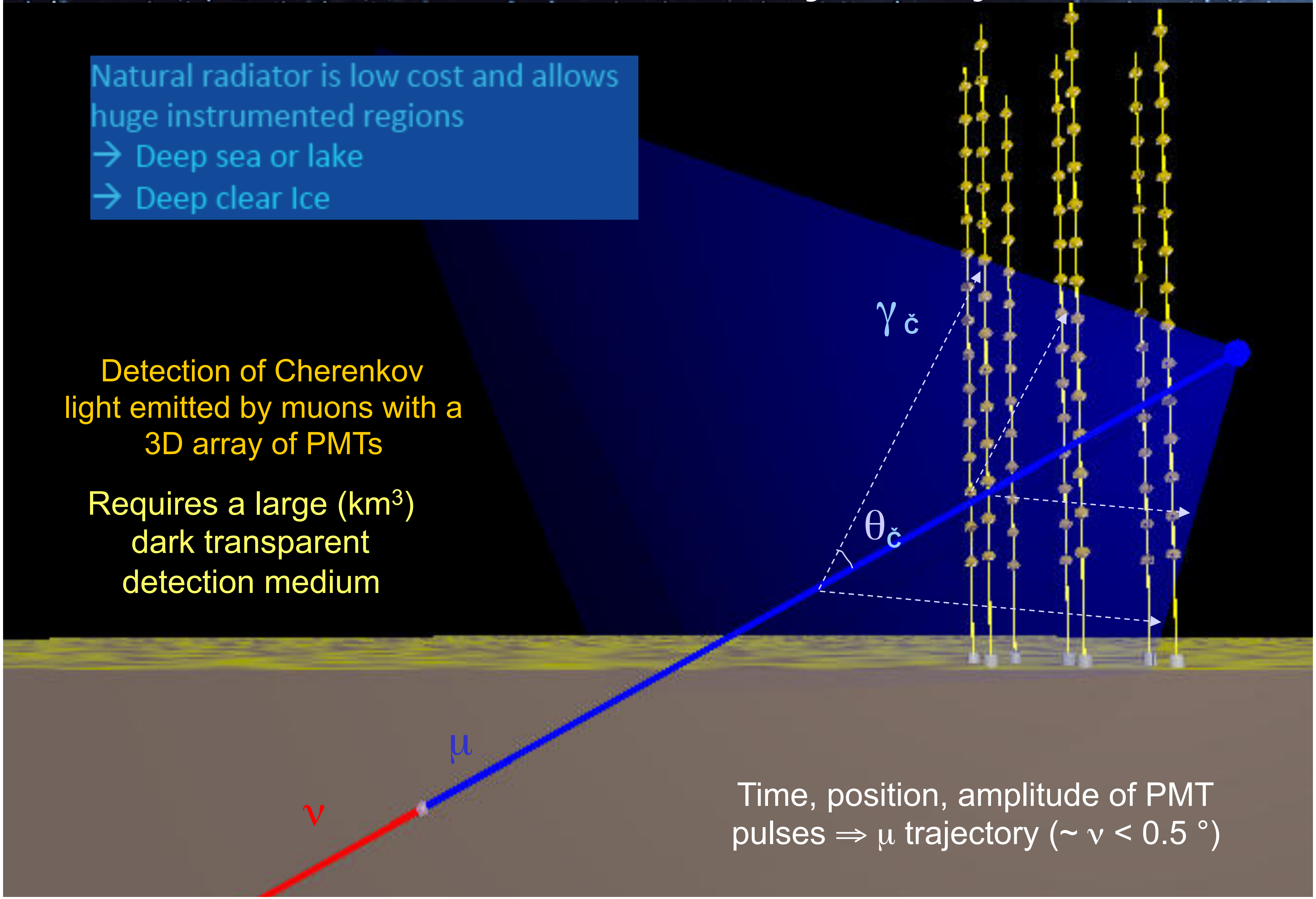
Pair creation, Bremsstrahlung, photo-nuclear interactions

Energy estimated from the total amount of colllected light.

→ Through going events

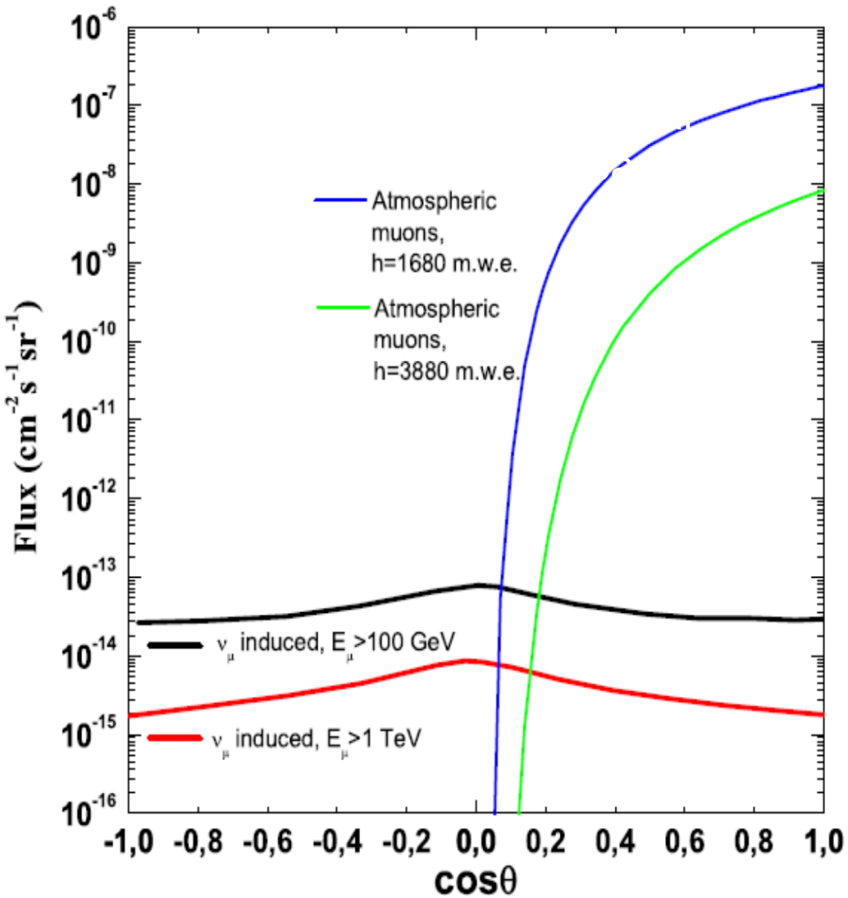
Astrophysics

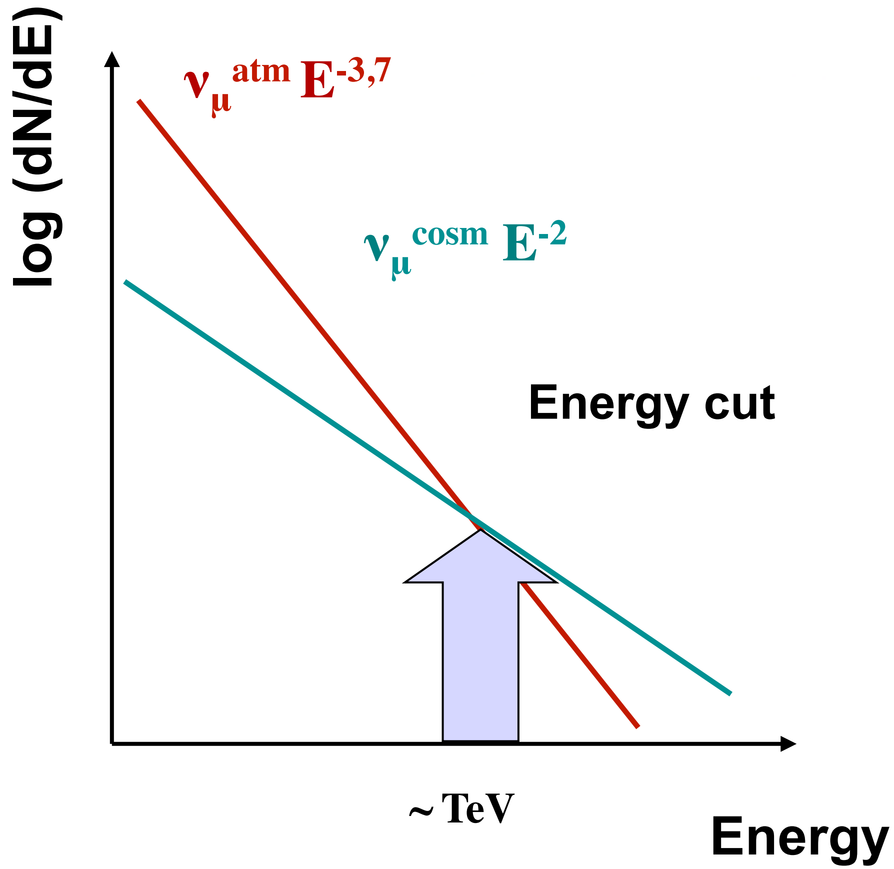
Reconstruction of muon trajectory



Atmospheric background vs cosmic ν's

Atmospheric muons: shield detector & define signal as upward muons



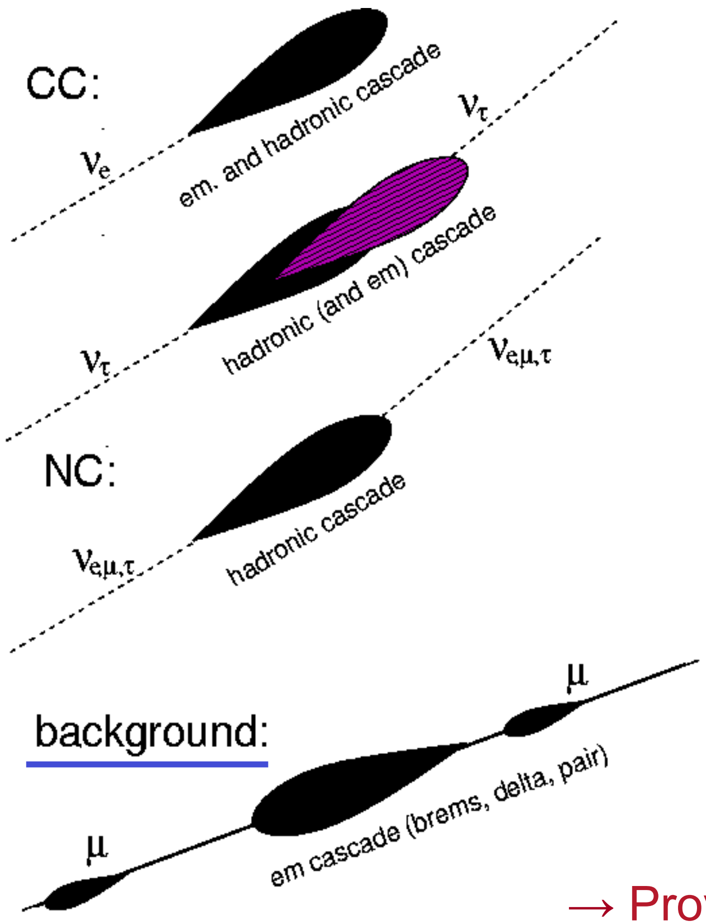


Atmospheric neutrinos: search for

- An excess at High Energy
- Anisotropies
- Time / space coincidence with other cosmic probes

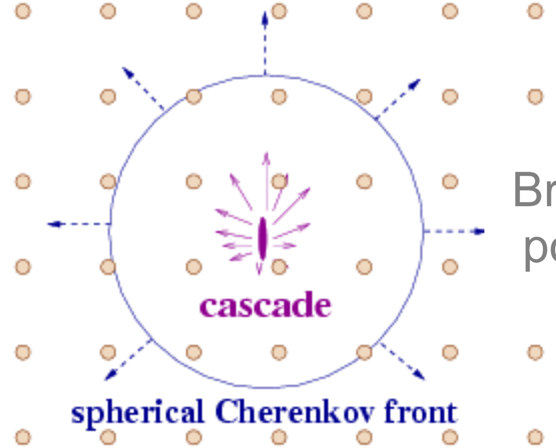
Other neutrino interaction topologies

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



So-called "cascade" events

Generic reconstruction:

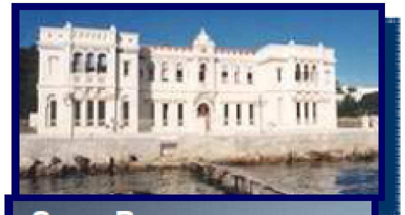


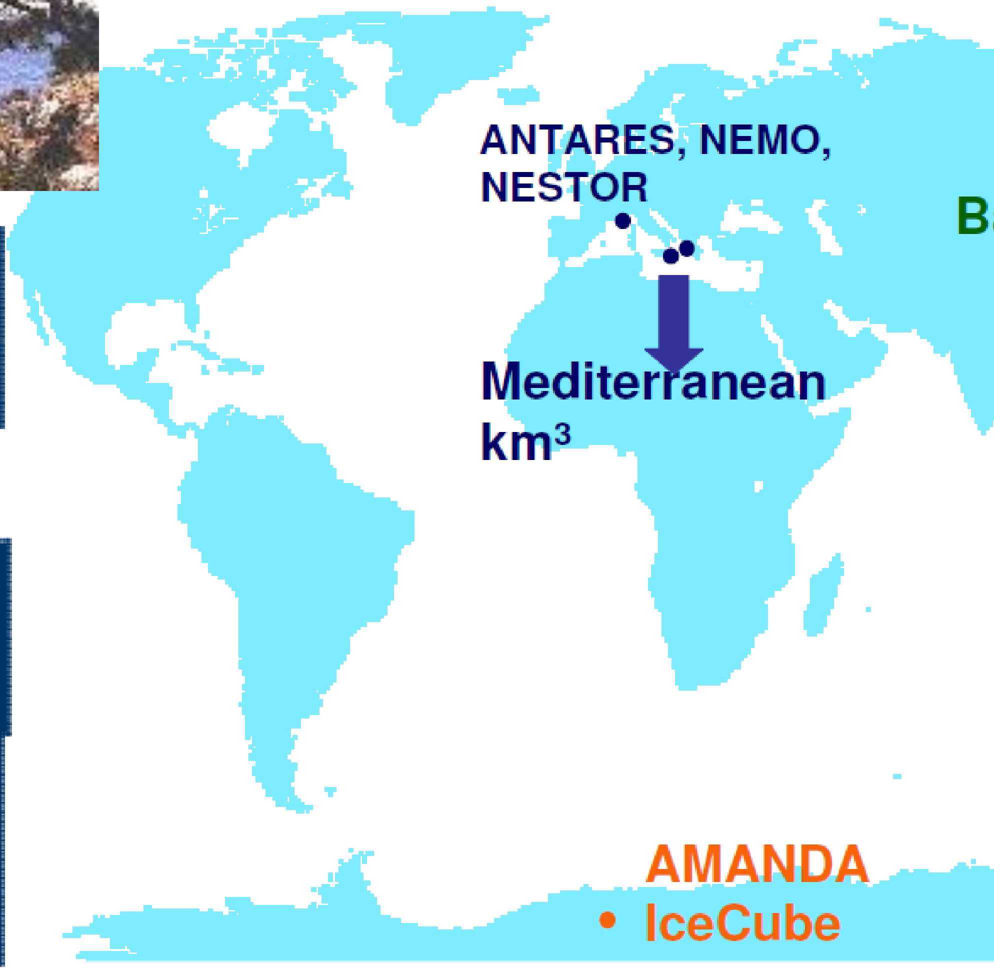
Bright point

→ Provide sensitivity to all neutrino flavors

Neutrino telescopes (TeV)

{ANTARES, BAIKAL, ICECUBE} currently working

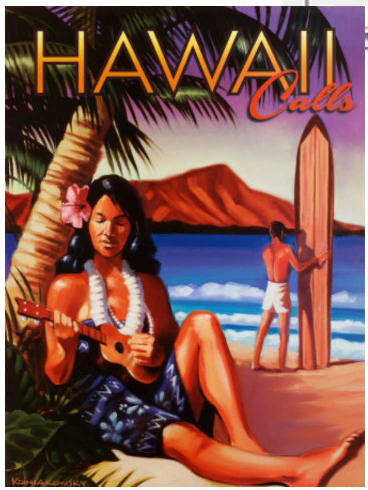




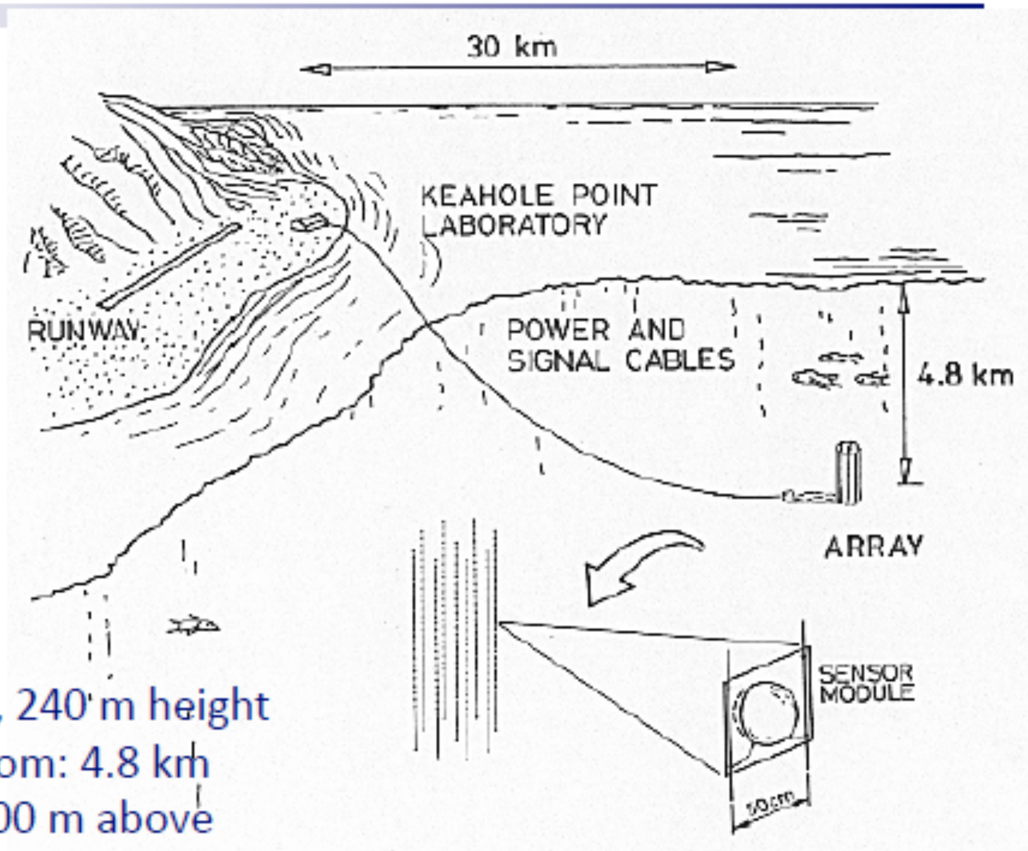
{ANTARES, NEMO, NESTOR} ∈ Consortium KM3NeT

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.

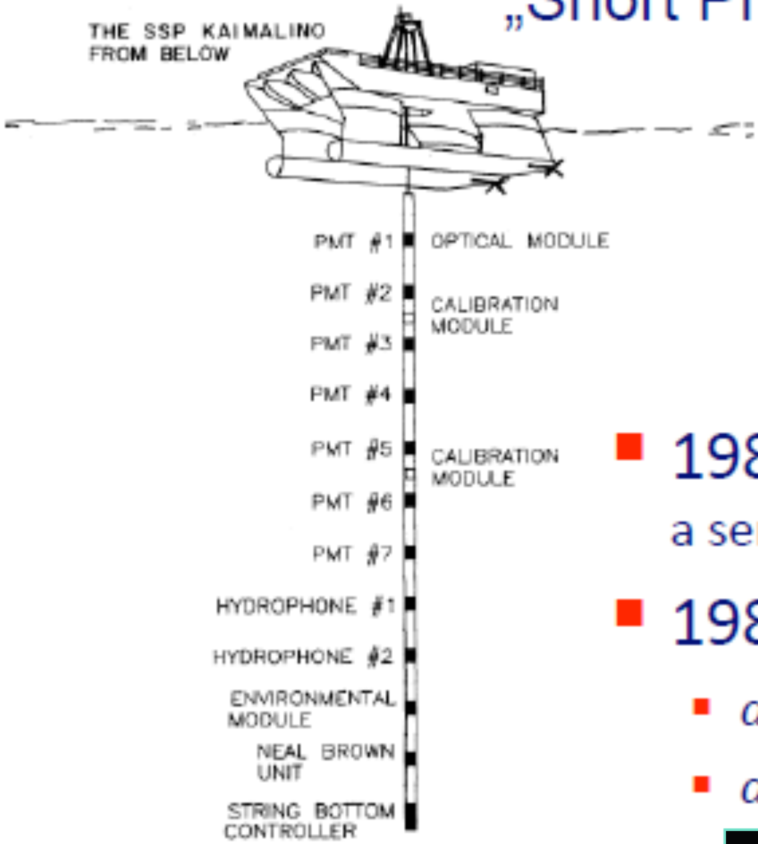


DUMAND-II (The Octagon)



- 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)

First steps in the Ice…

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

Nature Sept 91

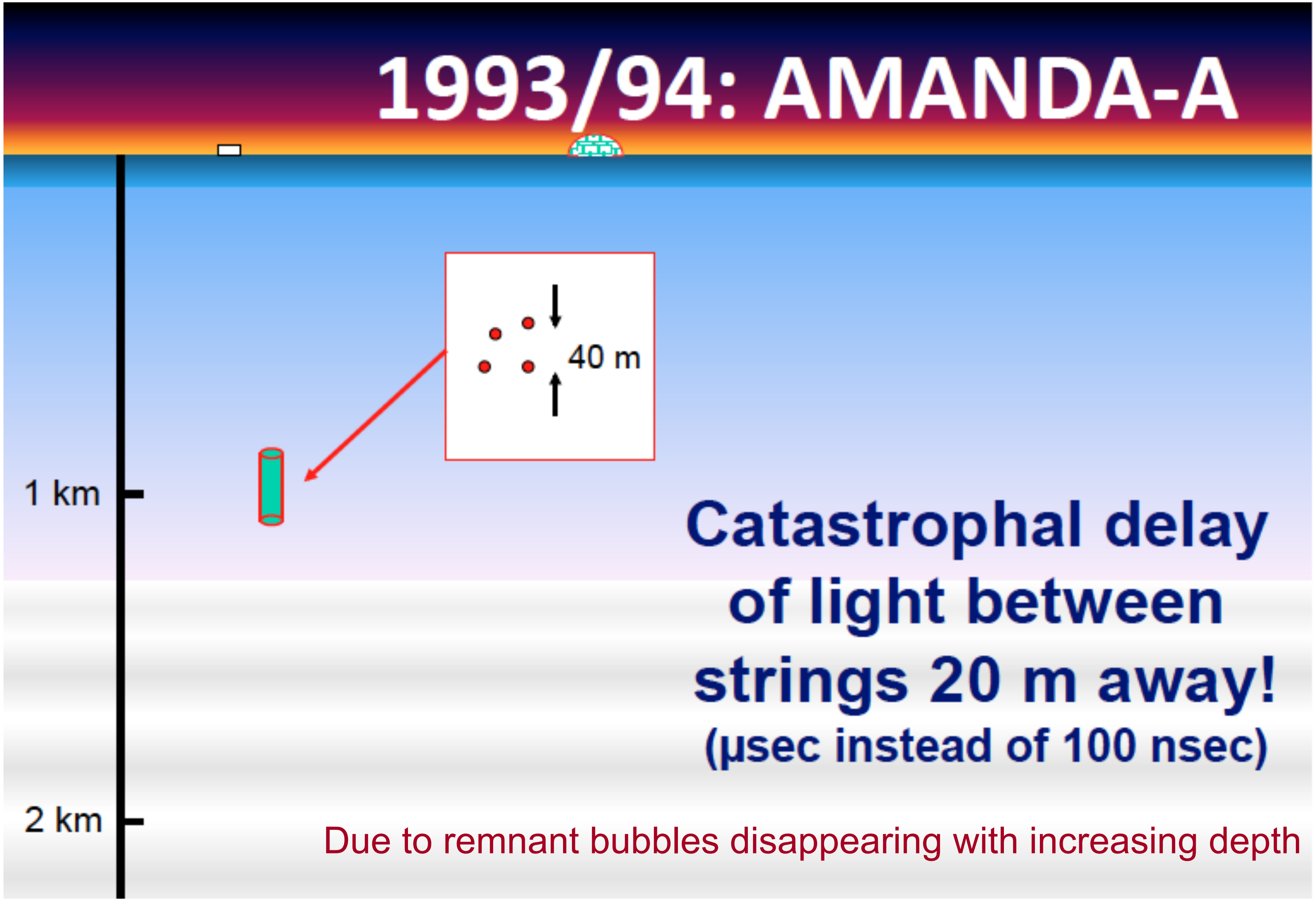
D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

* 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

...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 !

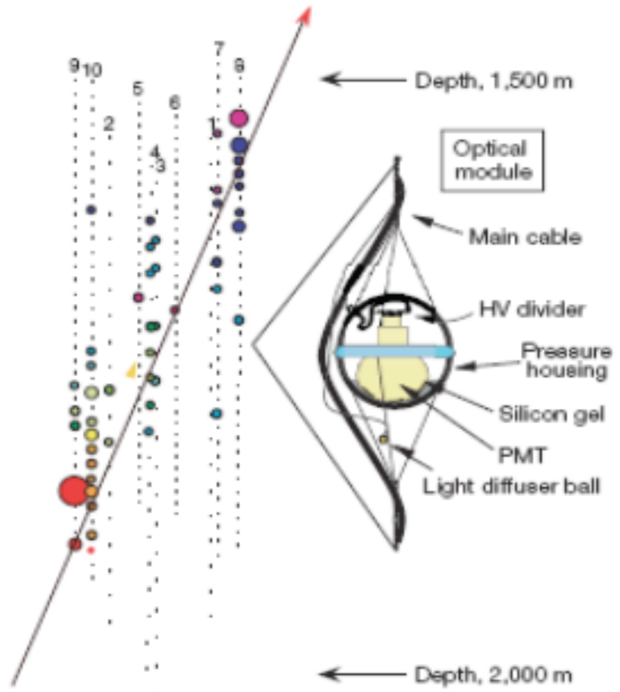
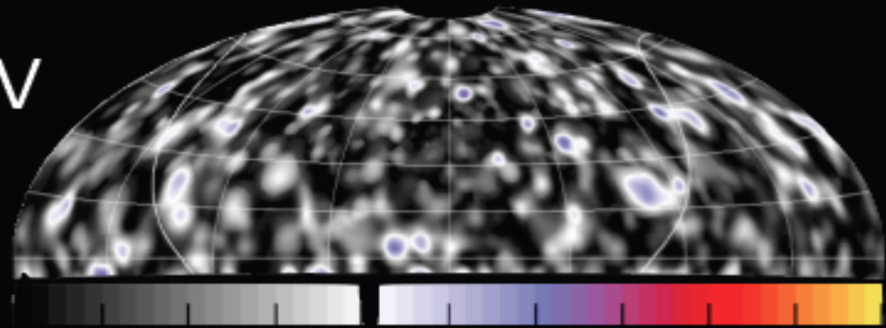


Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular 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.

Result from 7 years of AMANDA II

- 6595 neutrinos up to record energy of 200 TeV
- Record limits on fluxes for cosmic neutrinos (diffuse, point sources, GRB)

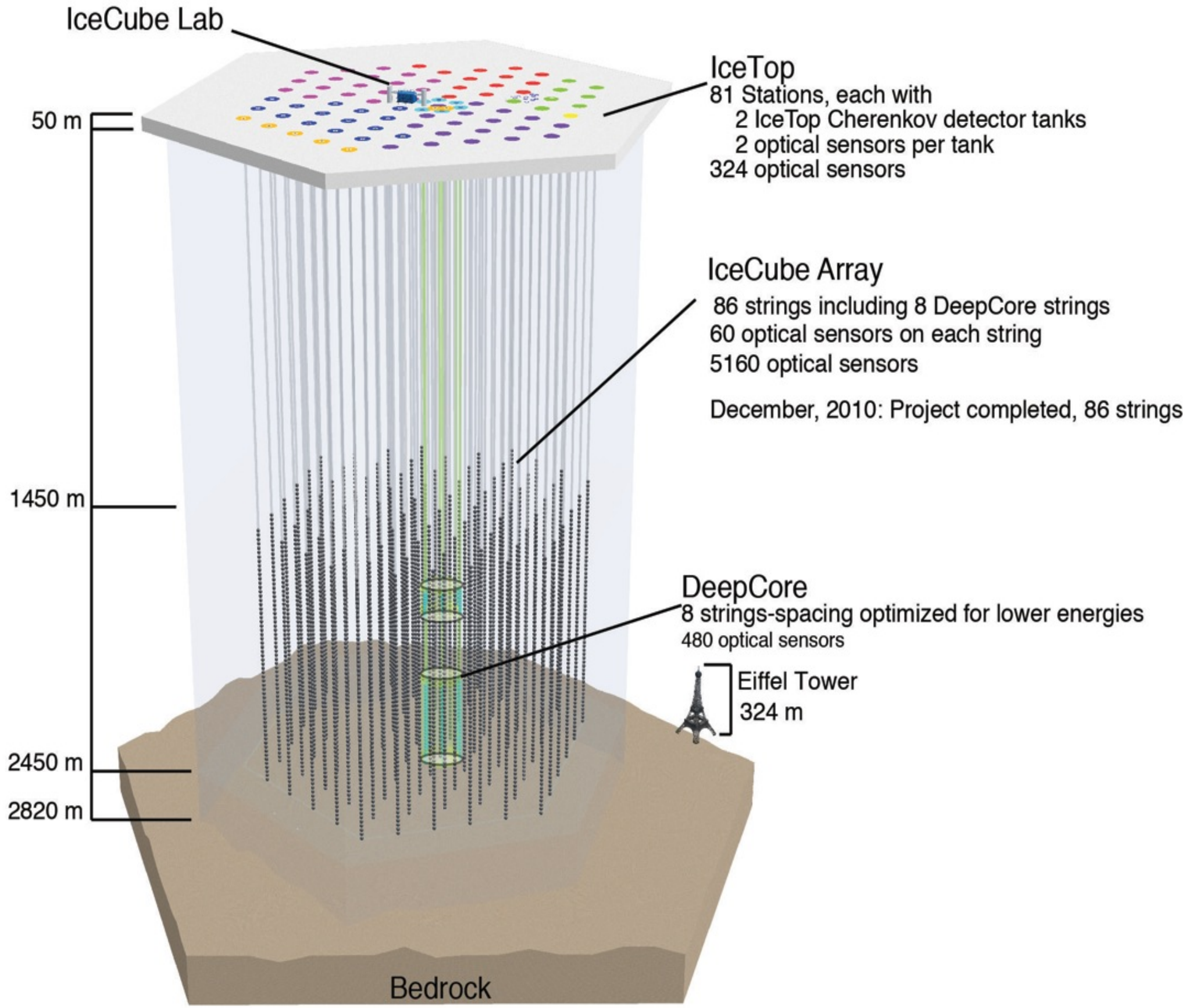


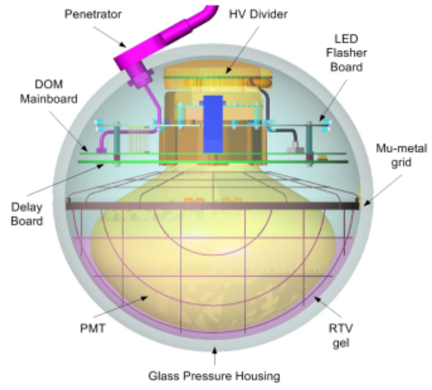
- Record limits on indirect dark matter search, magnetic monopoles, tests of Lorentz invariance
- Monitoring the galaxy for supernova bursts
- Spectrum and compositon of cosmic rays

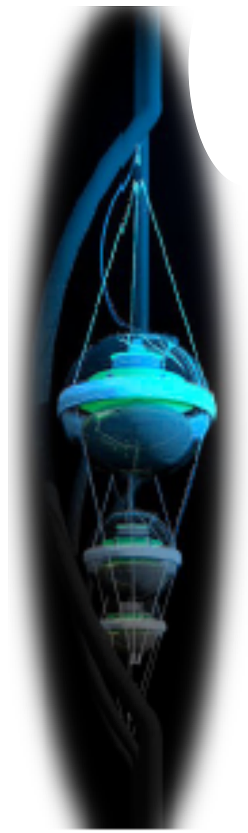
Now superseded by current IceCube results

IceCube : the biggest NT in the world

Completed since December 2010.







IceCube construction/data phases

Strings	Data (year)	Livetime	trigger rate (Hz)	HE ν rate (per day)
AMANDAII(19)	2000-2006	3.8 years	100	~5 / day
IC40	2008-09	375 days	1100	~40/ day
IC59	2009-10	350 days	1900	~70/ day
IC79	2010-11	320 days	2250	~100/day
IC86-I	2011- 2012	~ year	2700	processing
IC86-II	current		2700	running

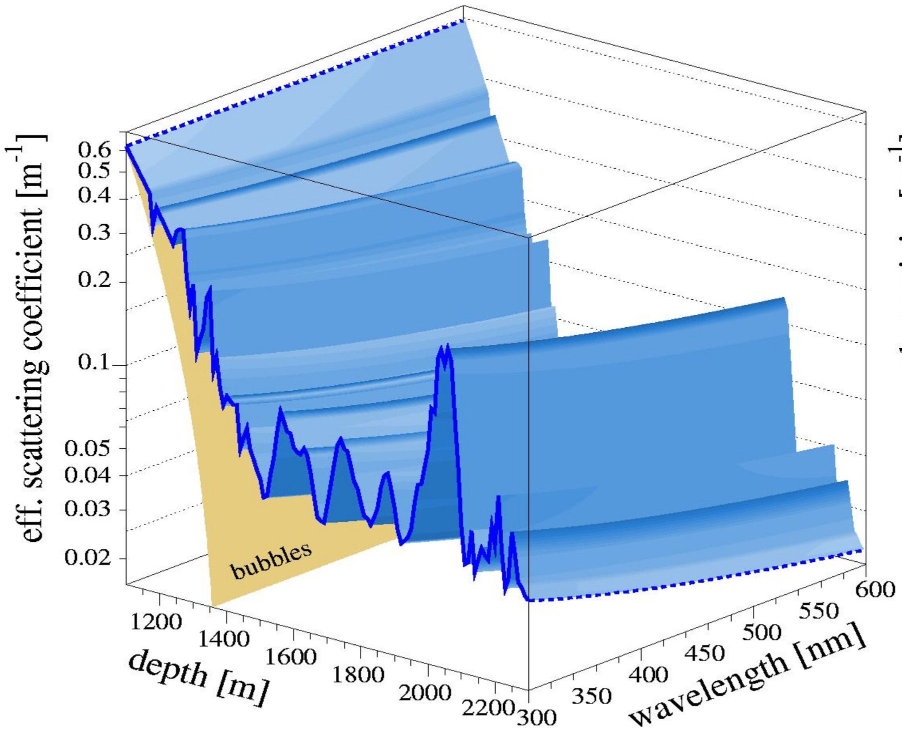
DeepCore Installed → IC79

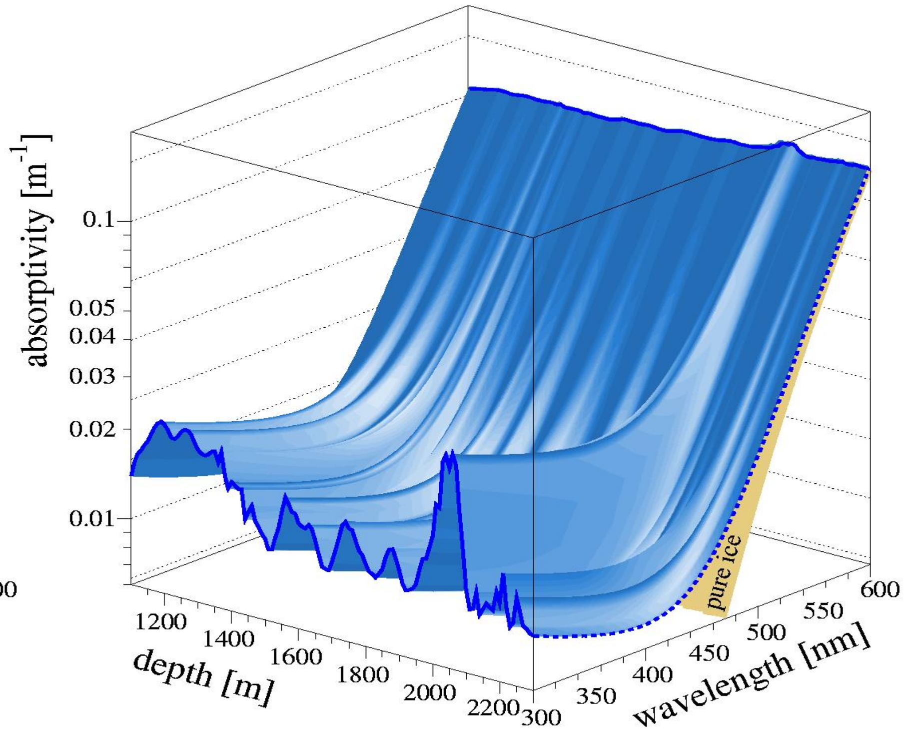
Run transition typically mid May

- Detector performance parameters increase faster than the number of strings
  - Longer muon tracks (km scale)
  - Improved analysis techniques

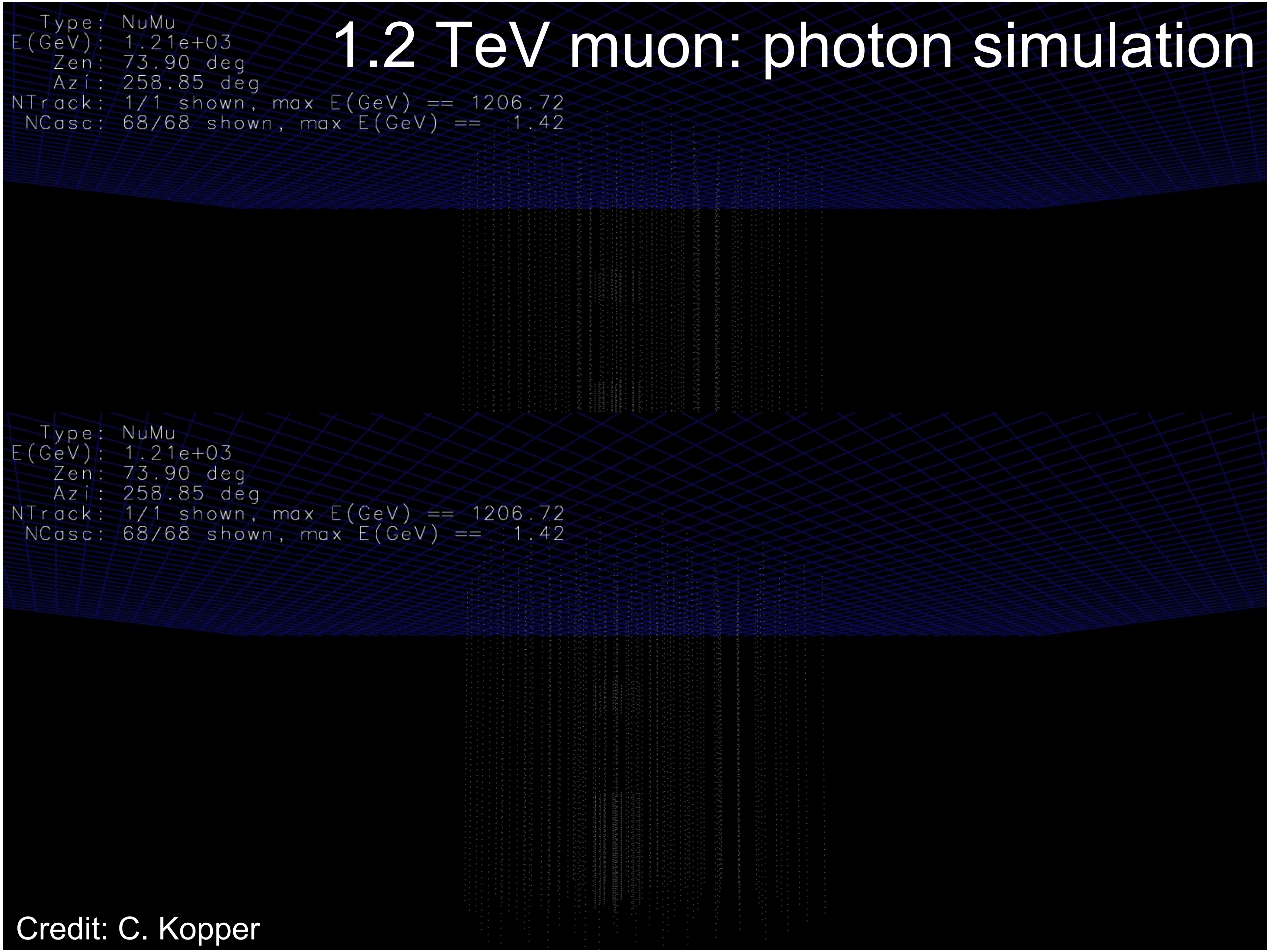
IC86 achieving ~ 99% uptime

The Ice optics





1.2 TeV muon: photon simulation



Credit: C. Kopper

Why the Mediterranean Sea?

- Obvious complementarity to South Pole

  Galactic centre

- Long (homogeneous) scattering length

  Good pointing accuracy

- Deep sites - up to ~5000m

  Detector shielding

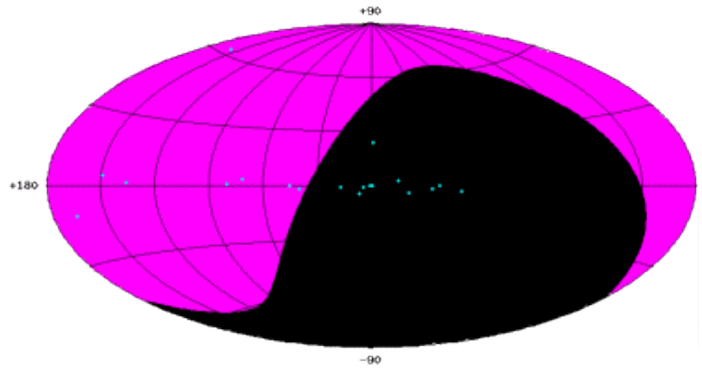
- Logistically attractive

  Close to shore (deployment / repair)

- ☹ Optical activity

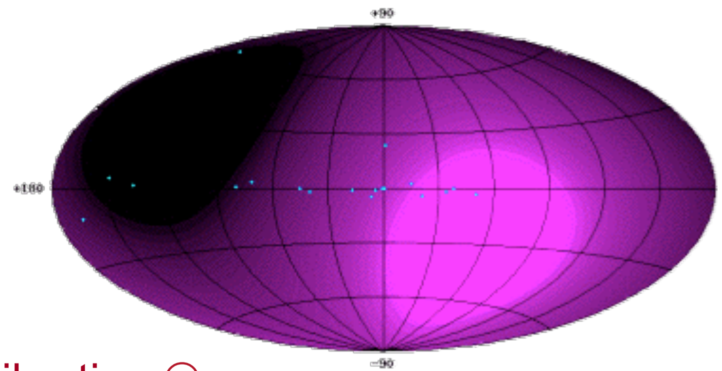
  Requires causality filters but can be used for calibration ☺

South Pole visible sky

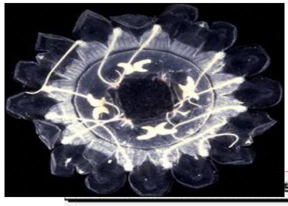


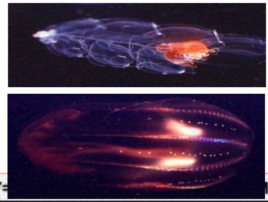
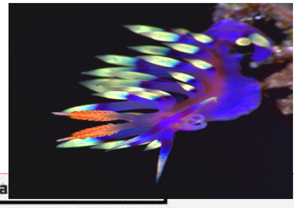
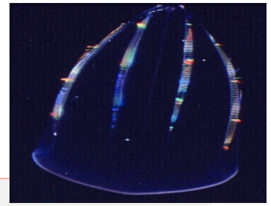
Most of the HESS TeV Sources visible by Northern NT

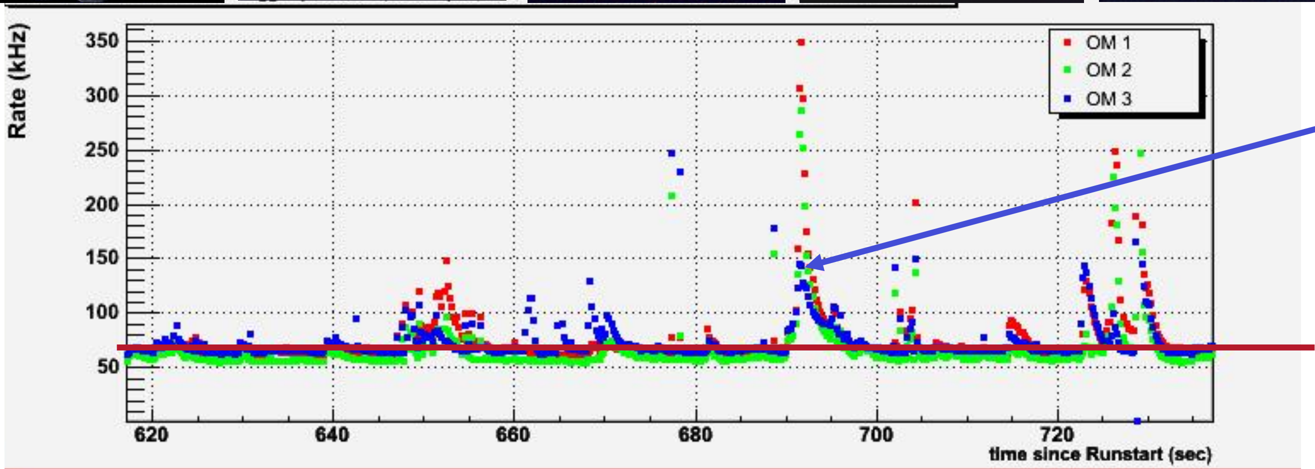
Mediterranean visible sky



ANTARES Optical background



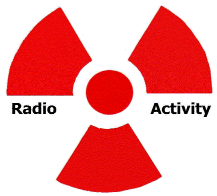
burst

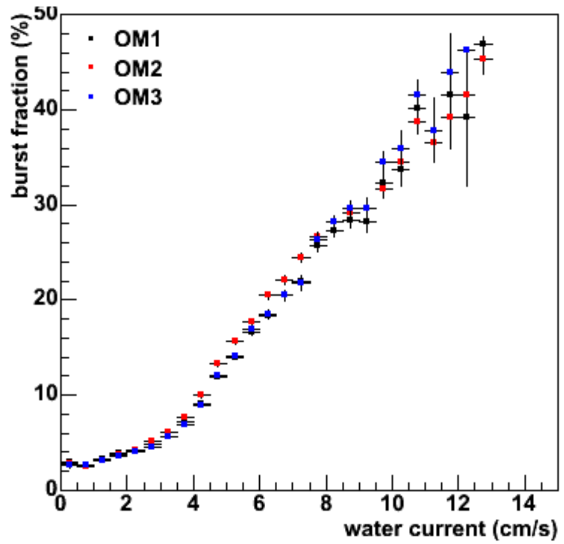
Base line

Base line

^{40}K

Bio-luminescence





Bio-luminescence burst:

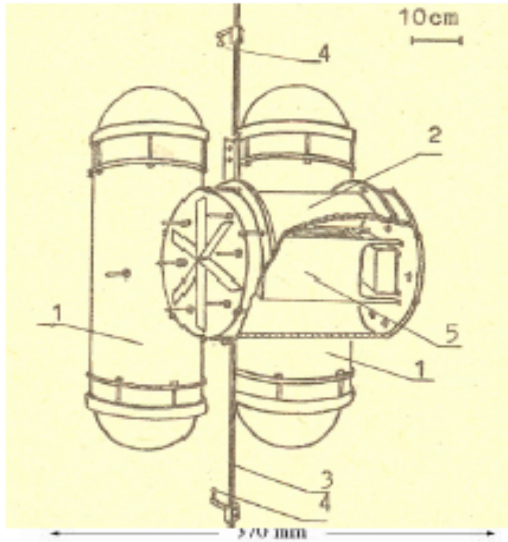
photo-emitter animals

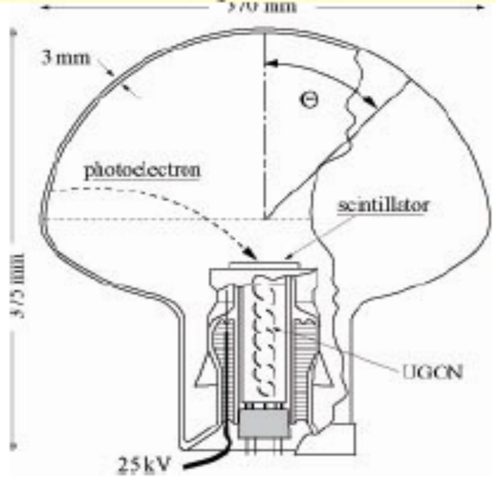
The 80's : first successes in water

The lake Baikal detector

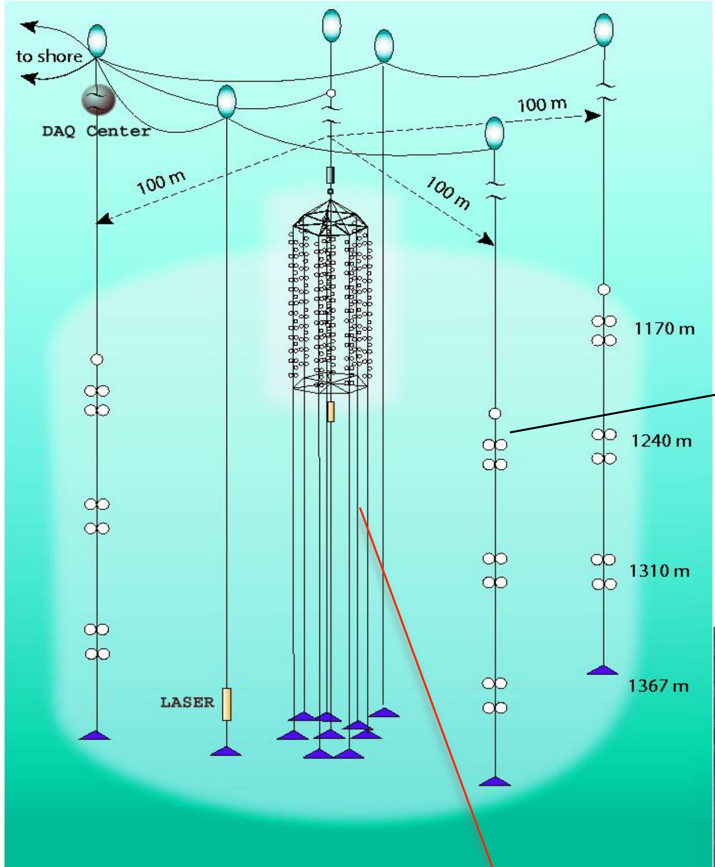
→ deepest lake (1.7 km), largest fresh water reservoir in the world

- 1984: first stationary string
  - Muon flux measurement
- 1986: second stationary string (Girlyanda 86)
  - Limits on GUT magnetic monopoles
- All that with 15-cm flat-window PMT FEU-49
- Development of a Russian smart phototube (Quasar)

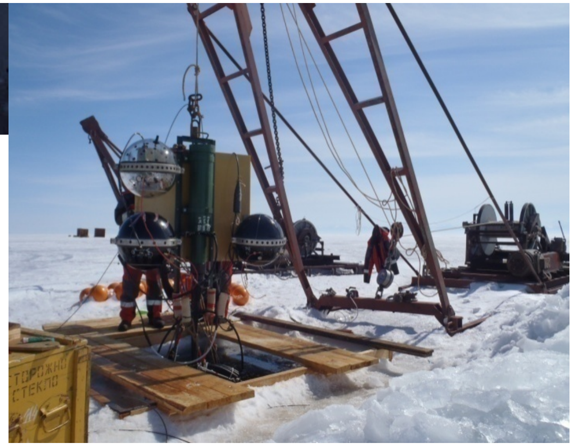


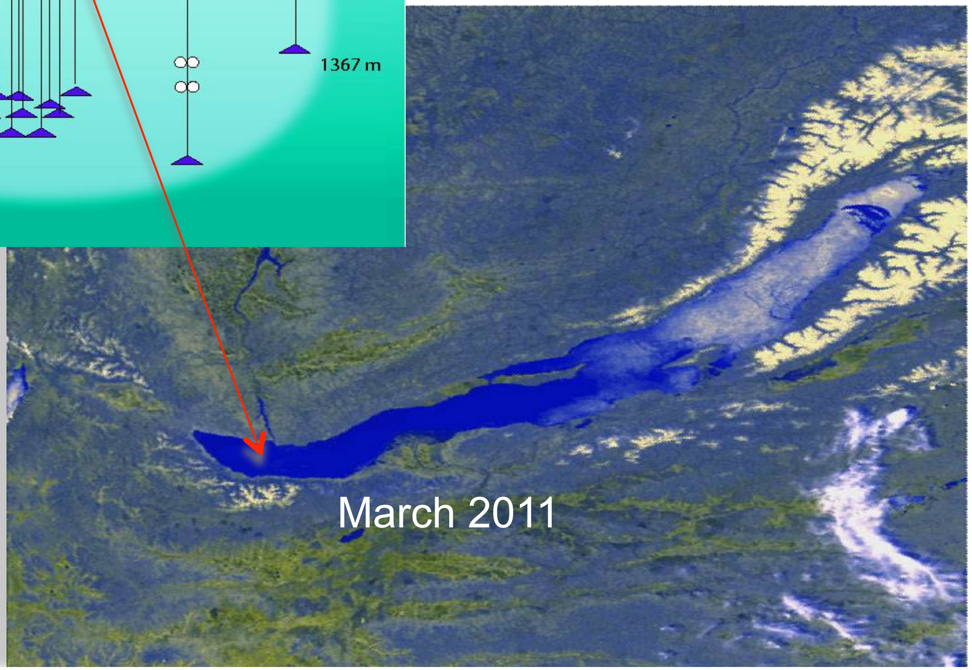


Baikal NT status



NT200+ is now operating





~ 3.6 km
to shore
1070m depth

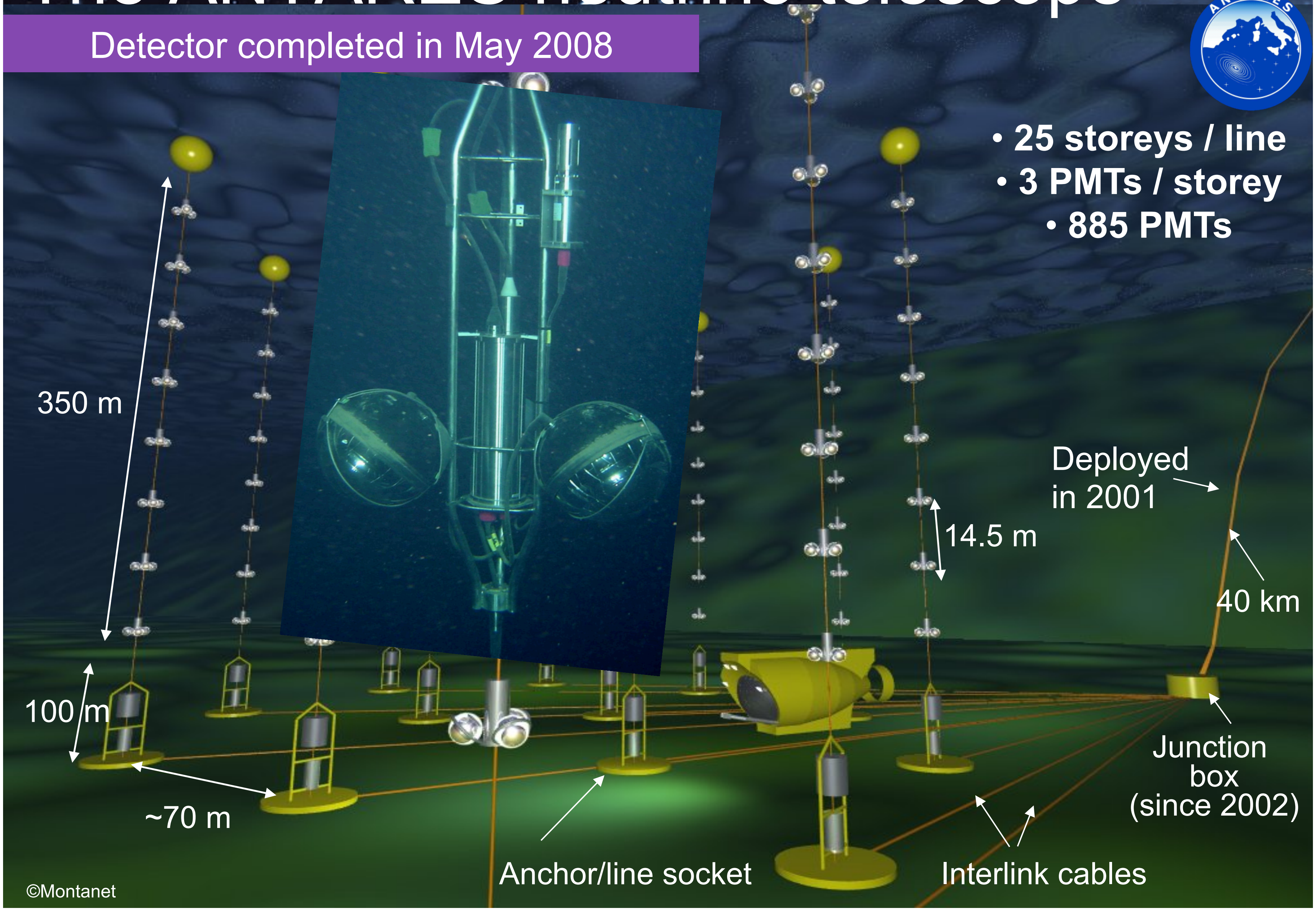
NT200 +
8 strings (192 OMs) + 3 outer strings (36 OMs)
Height x ∅ 210m x 200m $V_{inst} = 4\times10^6 m^3$
Eff. shower volume: 10 PeV ~ 10 Mton
Includes 2 prototype strings for GVD New OM, DAQ, cabling triggering systems


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

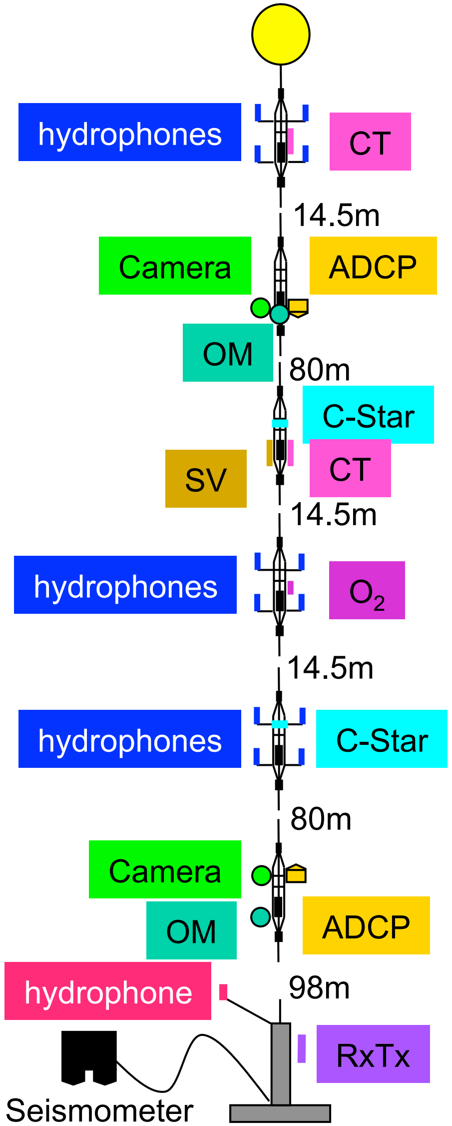
Detector completed in May 2008

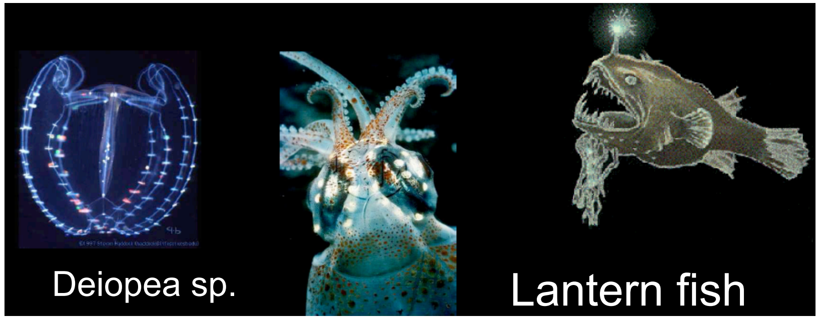
- **25 storeys / line**
- **3 PMTs / storey**
- **885 PMTs**



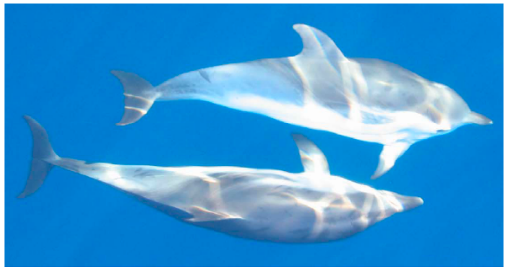
Sea science and Earthquakes

Instrumentation Line

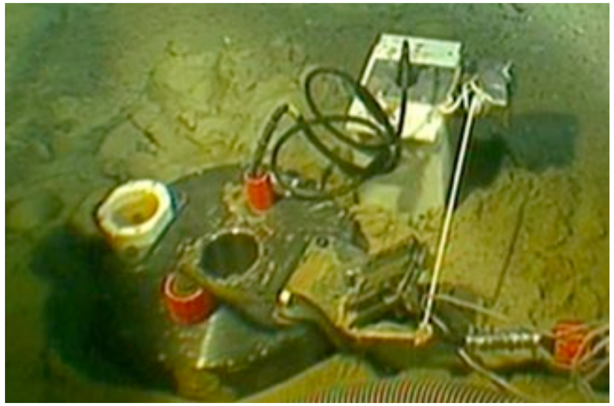




Acoustic noises



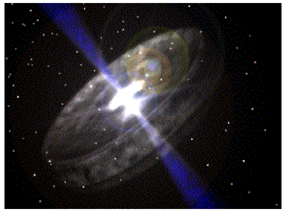
seismometer



Video-monitoring

ANTARES is a multidisciplinary observatory

Outline

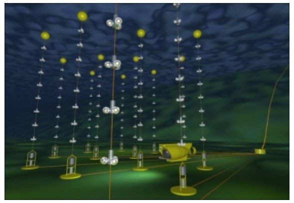


Neutrino astronomy

Historical aspects

Scientific motivations

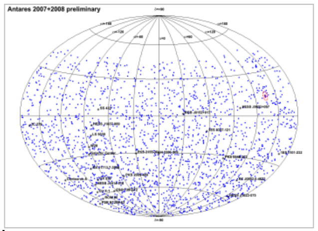
S. Drappeau & P. Baerwald → Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



P. Gay → **Selected results**

Diffuse Flux

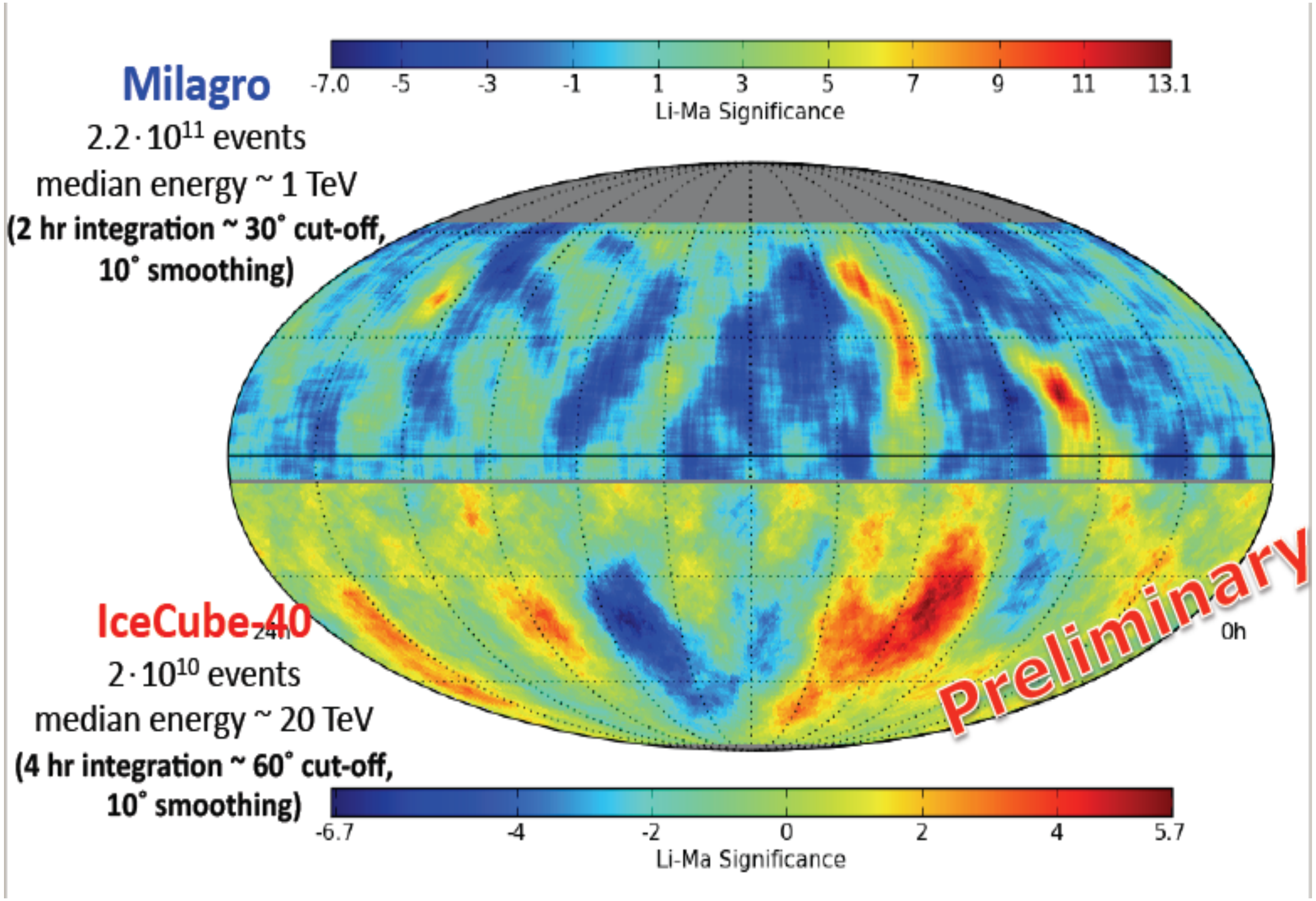
Search for point sources

V. Van Elewyck → Multi-messenger search

K. Clarke → **Future prospects**

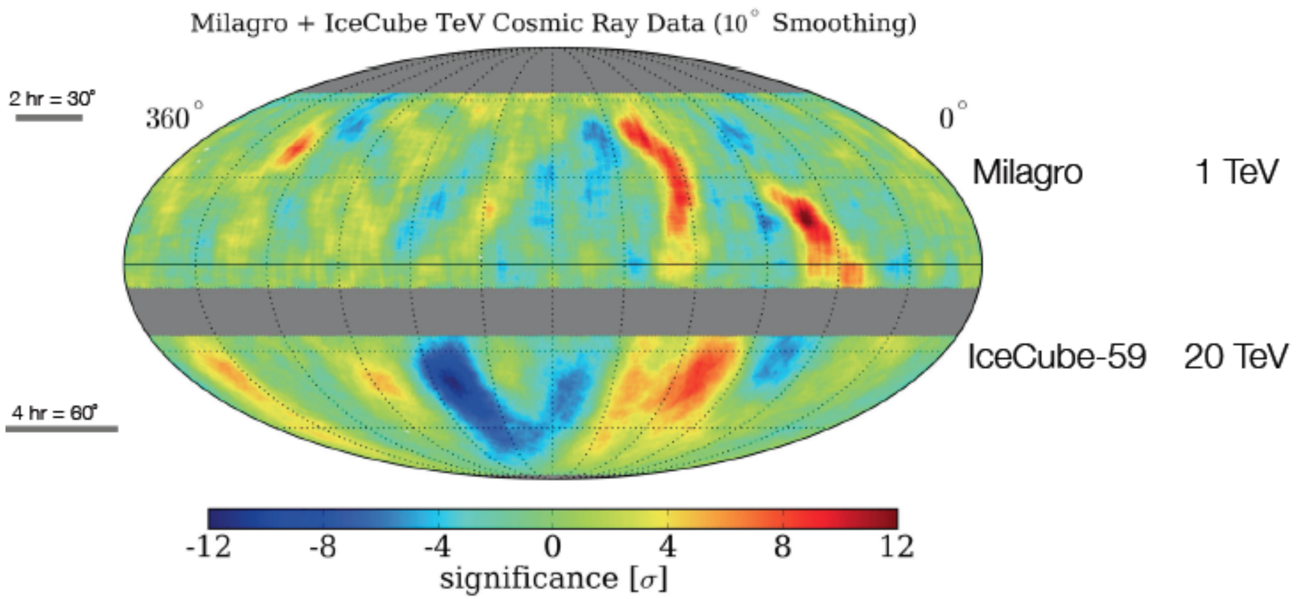
IceCube : Cosmic ray studies

📖 ApJ (2011) 740 16

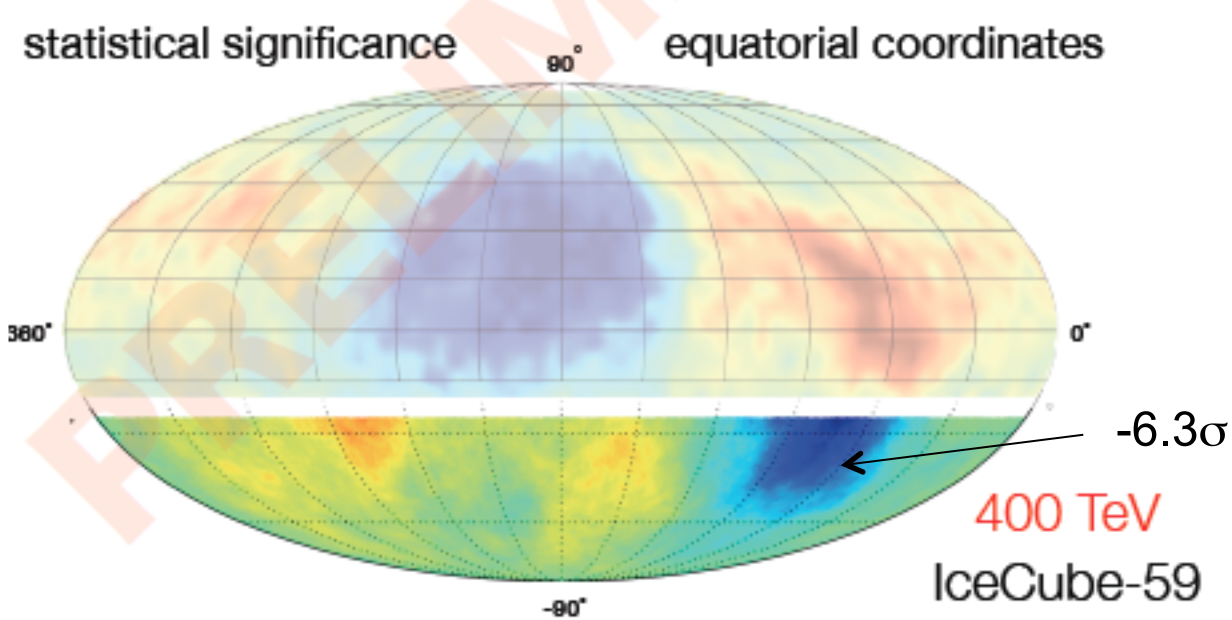


Unexplained anisotropy…

IceCube : Cosmic ray studies



Anisotropy confirmed with IC59



Evolution with energy
Different effect at 400 TeV?

arXiv:1205.3969

IceCube Diffuse Neutrino Searches

• Look for high-energy neutrino events above the rapidly falling atmospheric neutrino spectrum

- Upward muon neutrinos
- Cascade events (CC ν_e and ν_τ , NC all flavors)

• ν_μ diffuse search

- IC 40 published 📖 PRD 84, 082001 (2011)
- New results from IC59

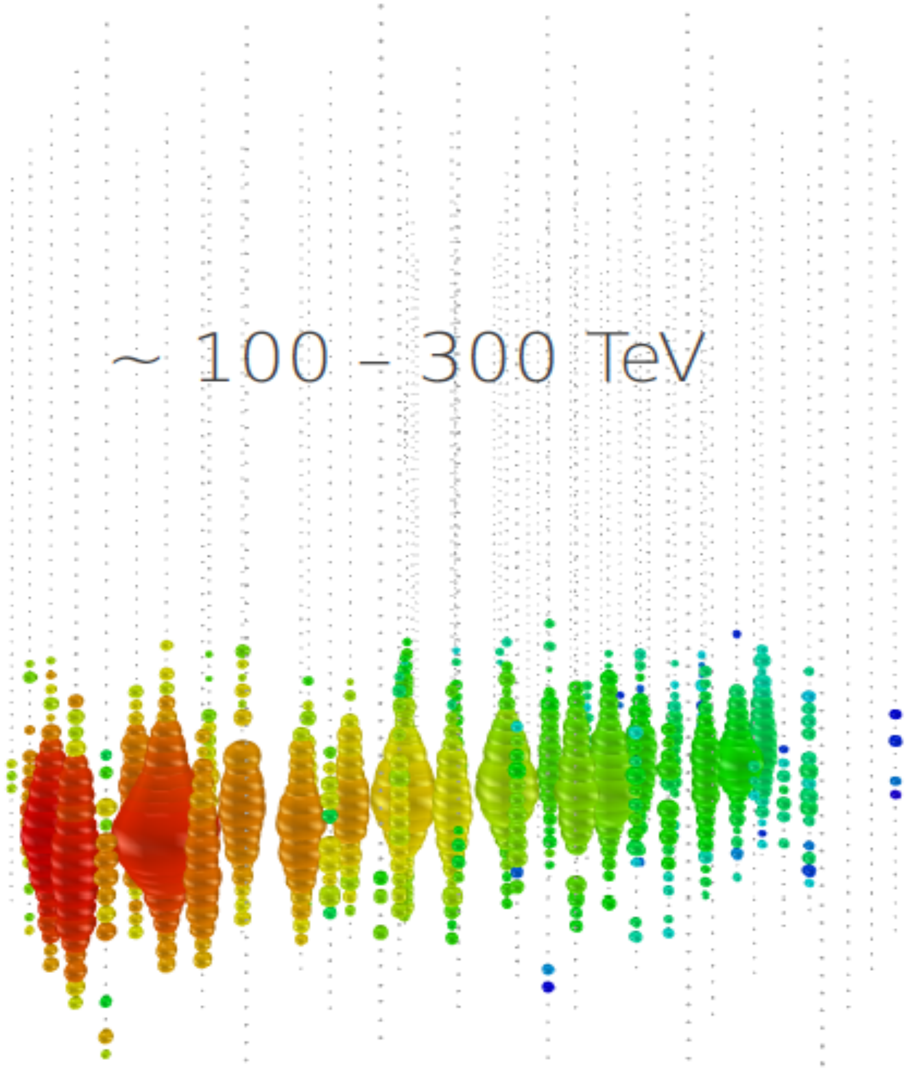
• Cascade search

- Analysis with IC40 not yet published
- IC79+IC86 [2011] search for cosmogenic neutrinos

➔ 2 events near threshold…

Diffuse IC 59 search (muons)

The highest energy event in the sample



Selection of upgoing, high-energy neutrino induced muon events to remove background from downgoing atmospheric muons.

Expected event numbers

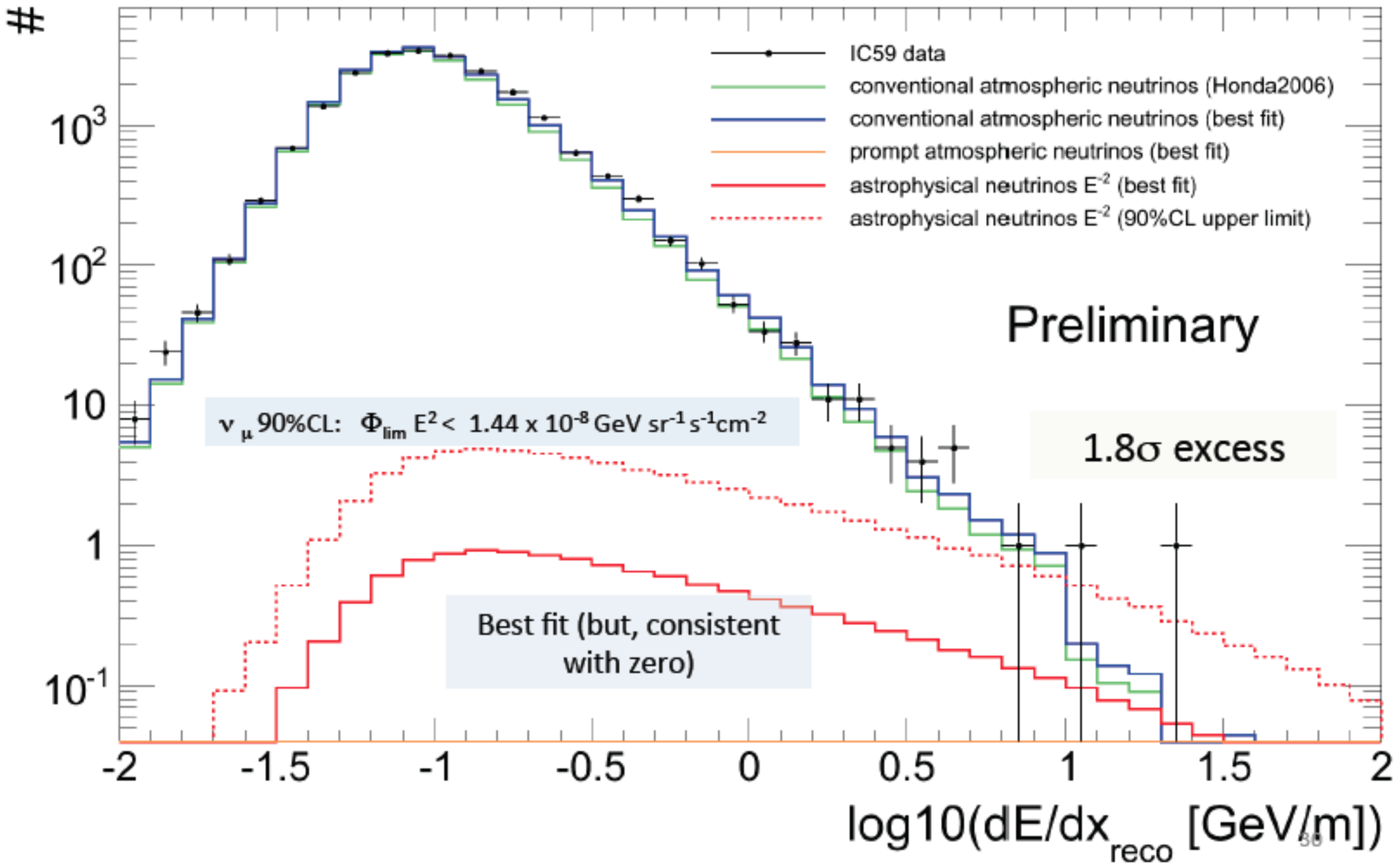
Conventional ν_μ:	~ 21 000
Prompt ν_μ:	~ 150
Astrophysical ν_μ:	< 40

Conv. atms. muon background:

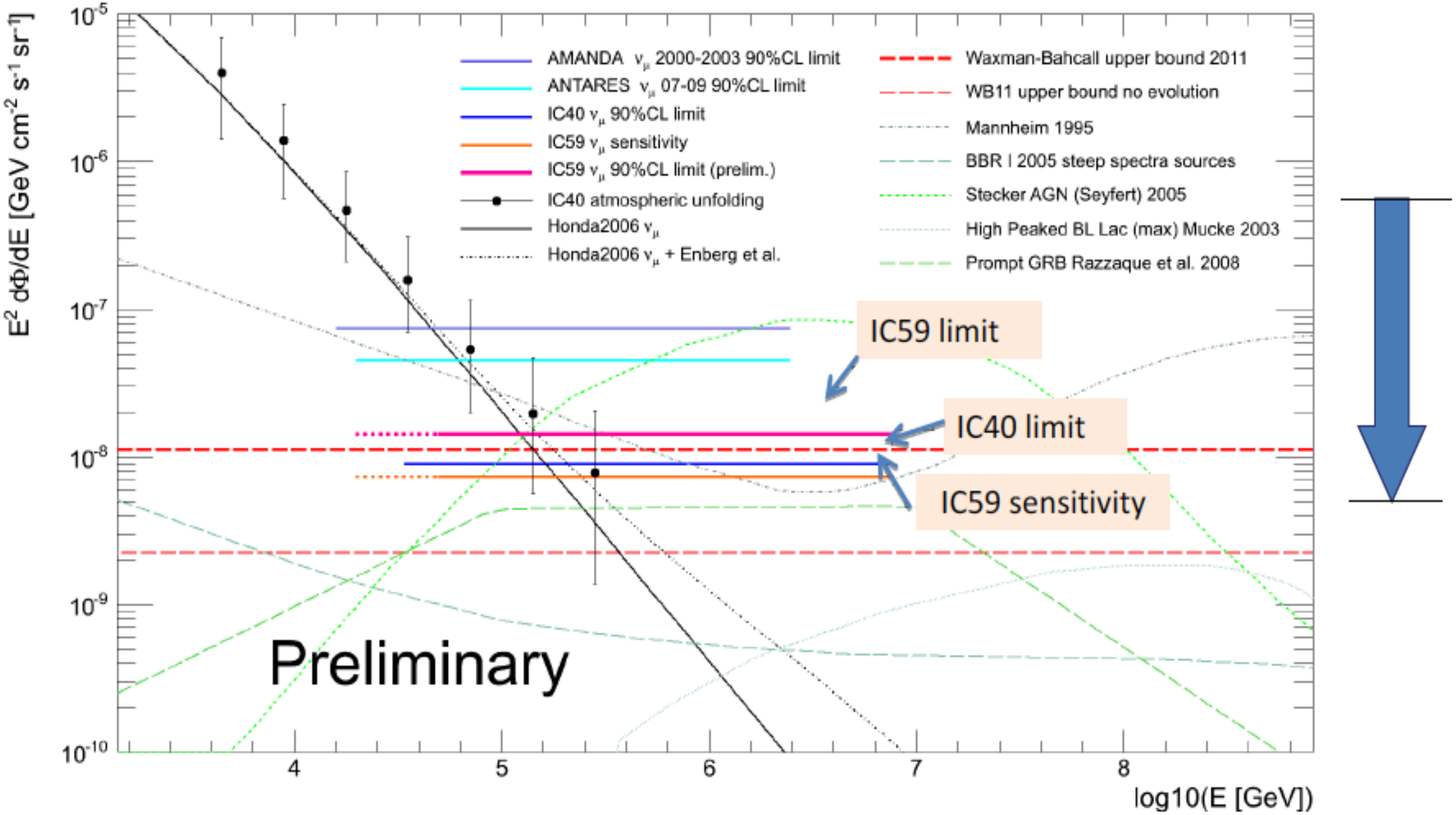
~ 30

Diffuse IC 59 search (muons)

348 days



Current limits



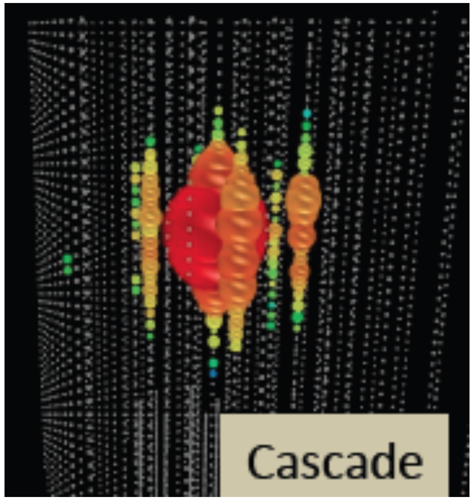
Almost 3 orders of magnitude w.r.t underground experiments
1-2 orders of magnitude below most optimistic predictions

IC40 ν Cascade Diffuse Search

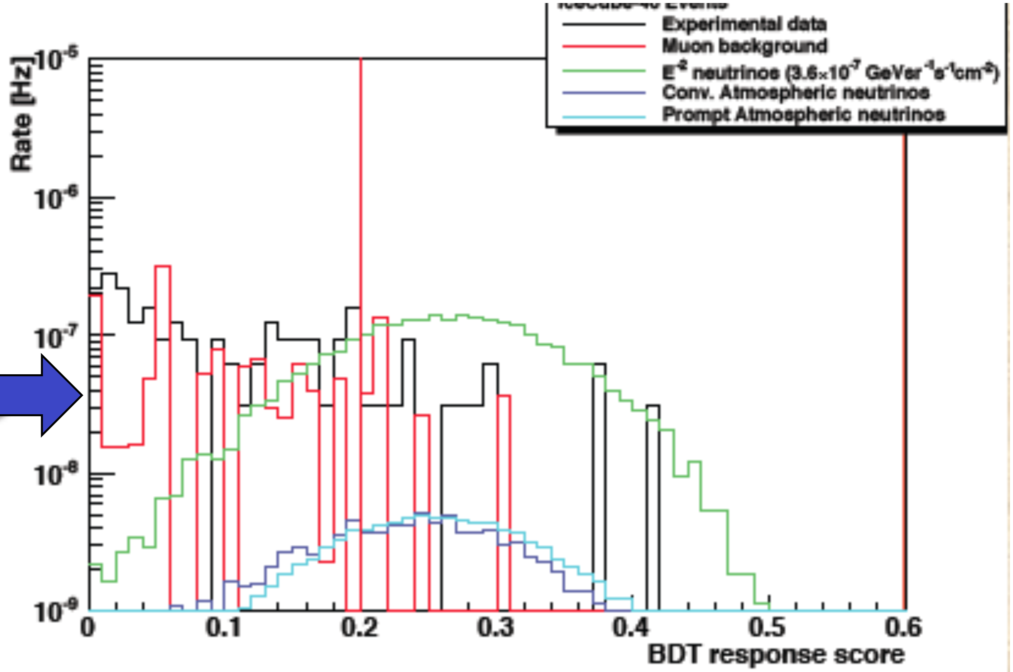
signal: ν induced particle showers (ν_e CC + all-flavor NC)

background: atm. μ

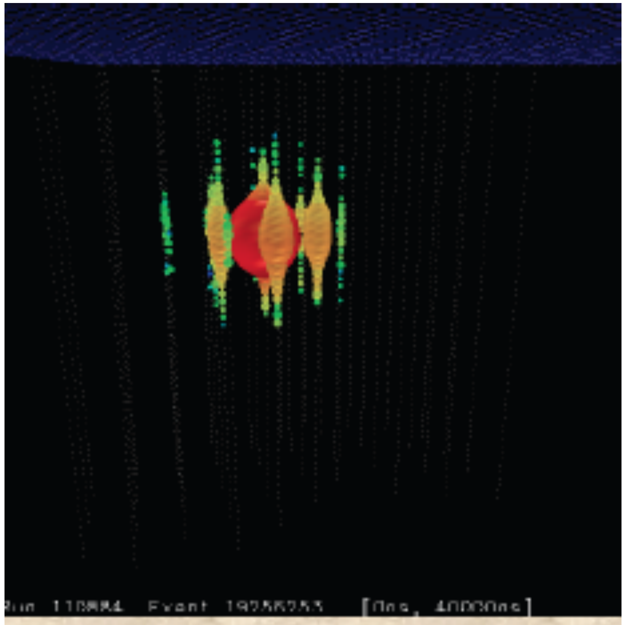
difficult background: atm. μ with catastrophic energy losses

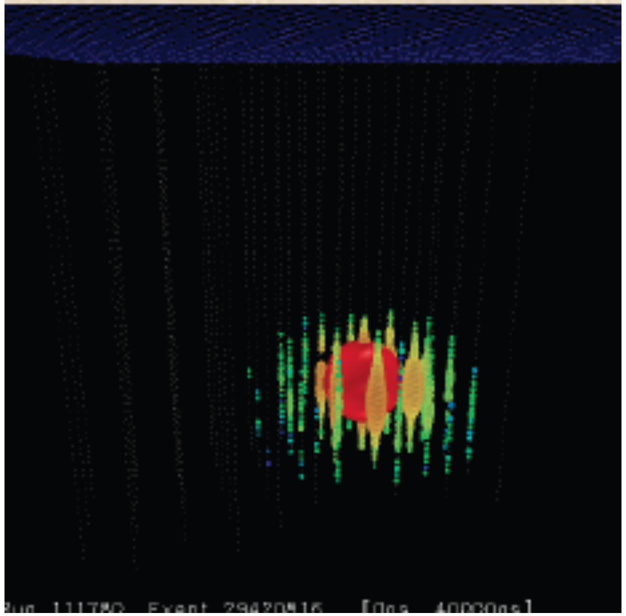


The analysis uses a Boosted Decision Tree optimized for removing atmospheric μ's



IC40 ν Cascade Diffuse Search





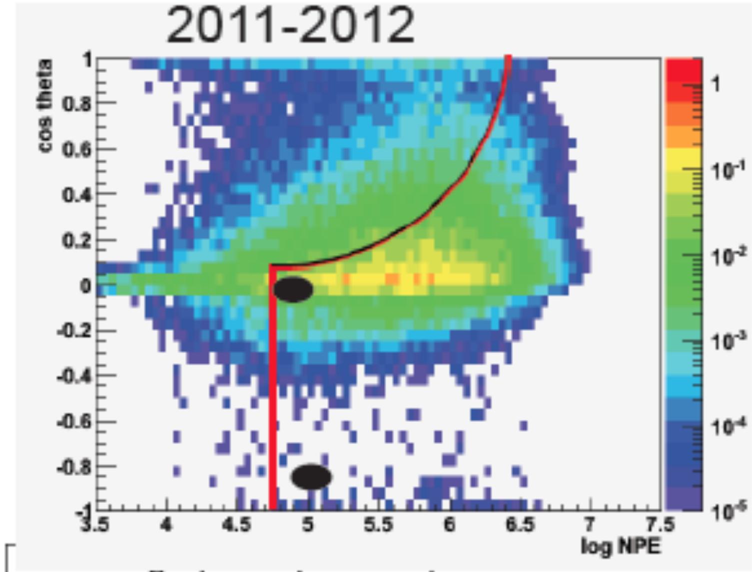
14 events found after cuts in a total livetime of 373.6 days (11.6 excepted from background)

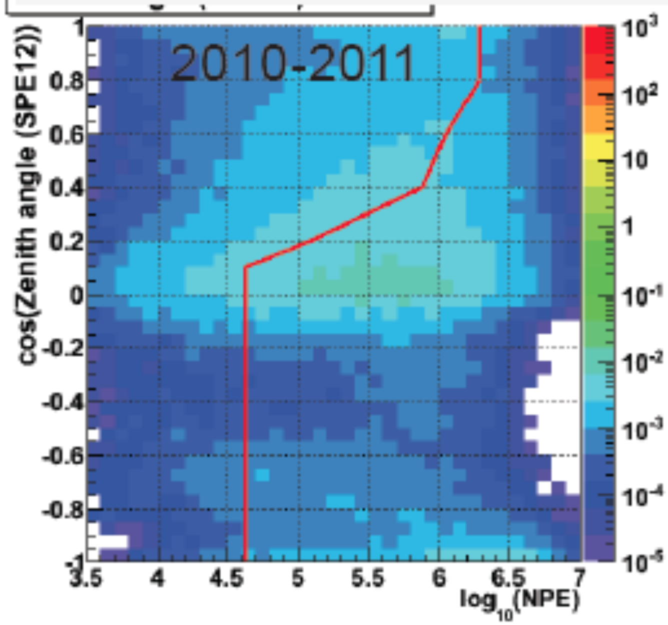
HE vs LE sample analysis under study

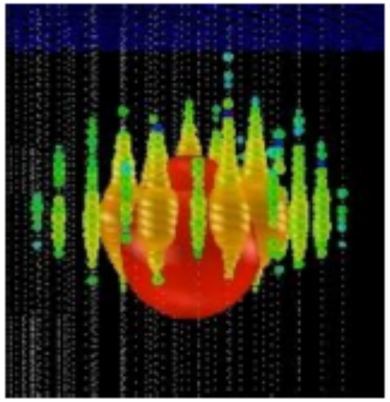
Run	Date	BDT response	Energy
110860	18th April 2008	0.268	29 TeV
110862	19th April 2008	0.375	31 TeV
110884	23rd April 2008	0.416	175 TeV
110964	10th May 2008	0.230	27 TeV
111076	29th May 2008	0.225	41 TeV
111113	5th June 2008	0.380	174 TeV
111281	7th July 2008	0.293	31 TeV
111558	30th August 2008	0.232	45 TeV
111780	16th October 2008	0.236	144 TeV
111917	8th November 2008	0.279	32 TeV
112406	14th January 2009	0.203	47 TeV
112782	6th February 2009	0.219	57 TeV
113693	12th May 2009	0.295	40 TeV
113802	17th May 2009	0,281	27 TeV

IC79+IC86 ν UHE Search

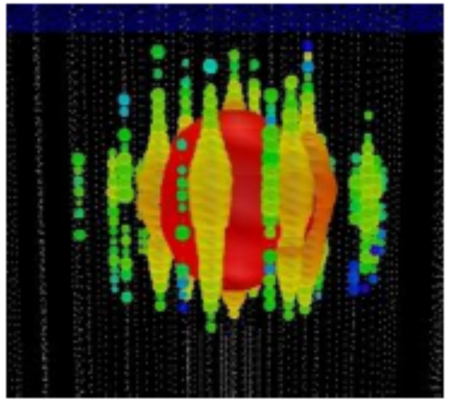
2 events are observed in the PeV energy region in IC 86 sample



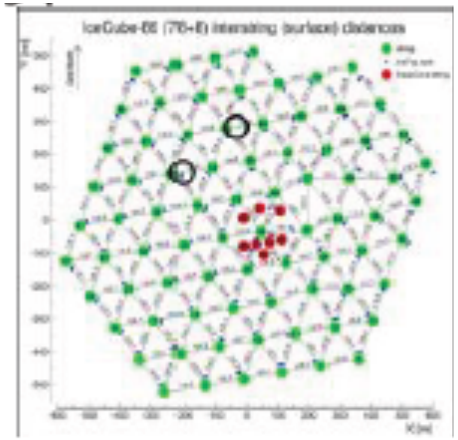




Ernie
GMT: 2012/1/3 9:34:01



Bert
GMT: 2012/8/8 12:23:18



"No counter arguments to the hypothesis of neutrino induced cascades so far"

IC79+IC86 ν UHE Search

Expected event numbers

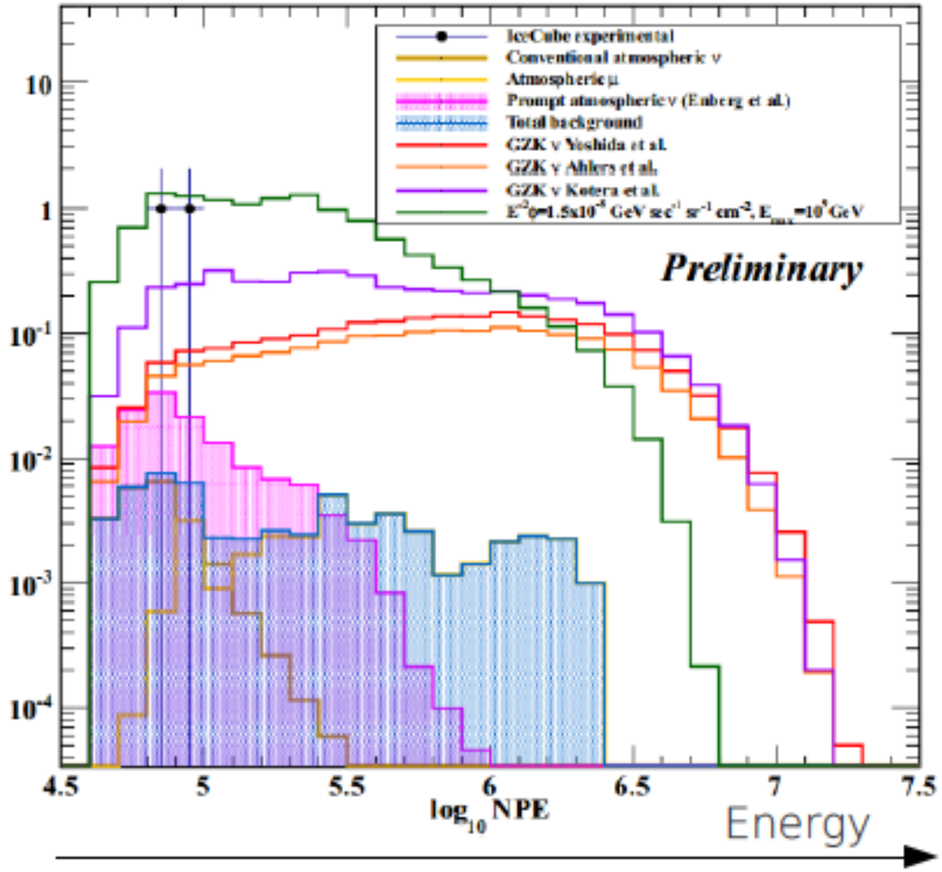
Atms. Background (conv. ν + μ)	0.06
Prompt atms. ν (Enberg et al. + knee)	0.13
Prompt (IC59 limit)	0.30
Astrophysical (IC59 best fit) 0.3×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}	1.7
Astrophysical (IC59 limit) 1.4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}	9.1
GZK (various models)	0 – 4
Data	2

First PeV-events detected at the low-energy threshold of the IC86 EHE analysis!

Events look like good neutrino cascades.

Probability to be consistent with conv. atms. or prompt is very small.

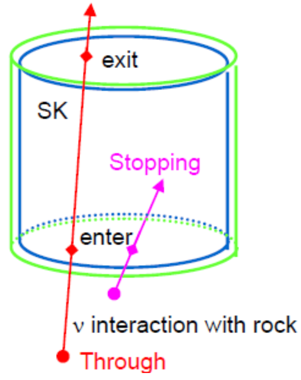
Nb of events per bin (670 days)



p-value 1.9×10^{-3} (2.9σ) beyond conventional background

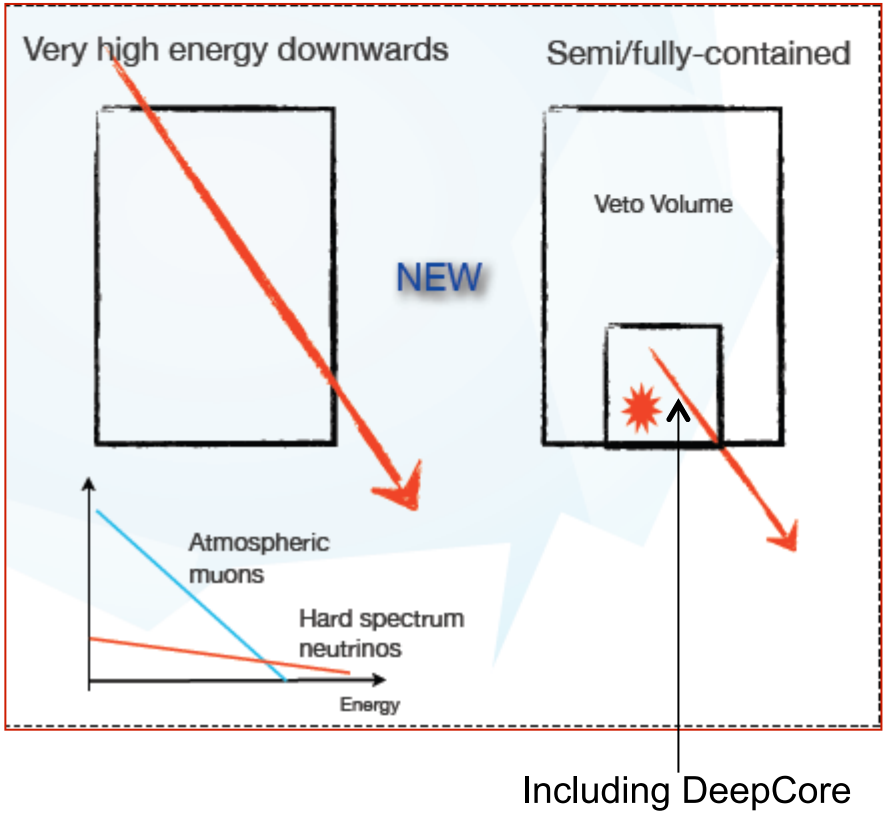
Recent searches for neutrino point sources

• 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+59 data set (723 days) in all sky

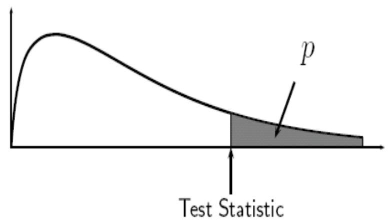


Sky maps

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

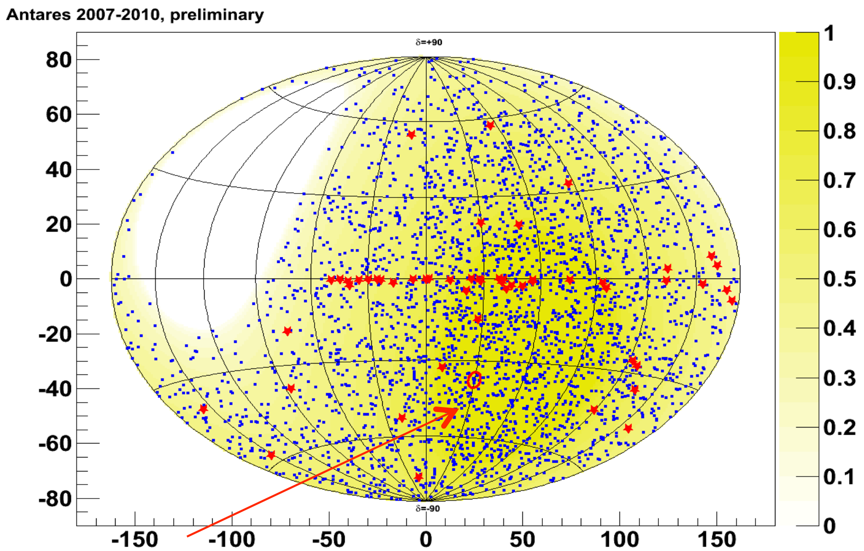
Summarized generic “blind” analysis (Optimized with scrambled data set)

- 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

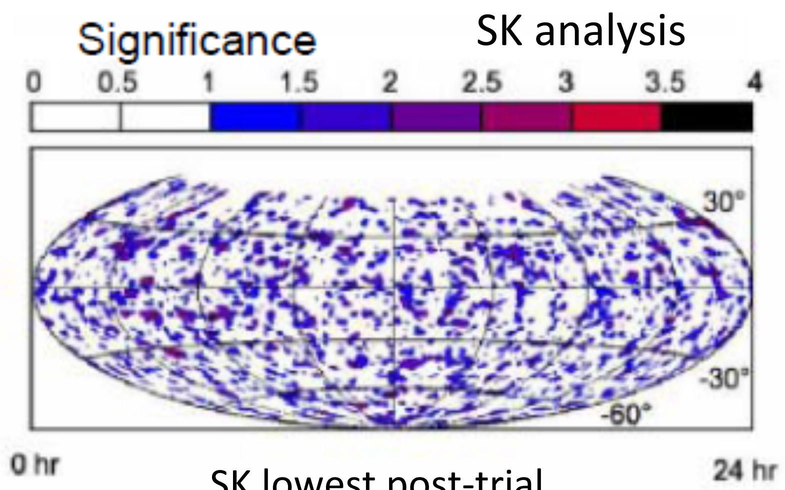


These analyses can be performed for :

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



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

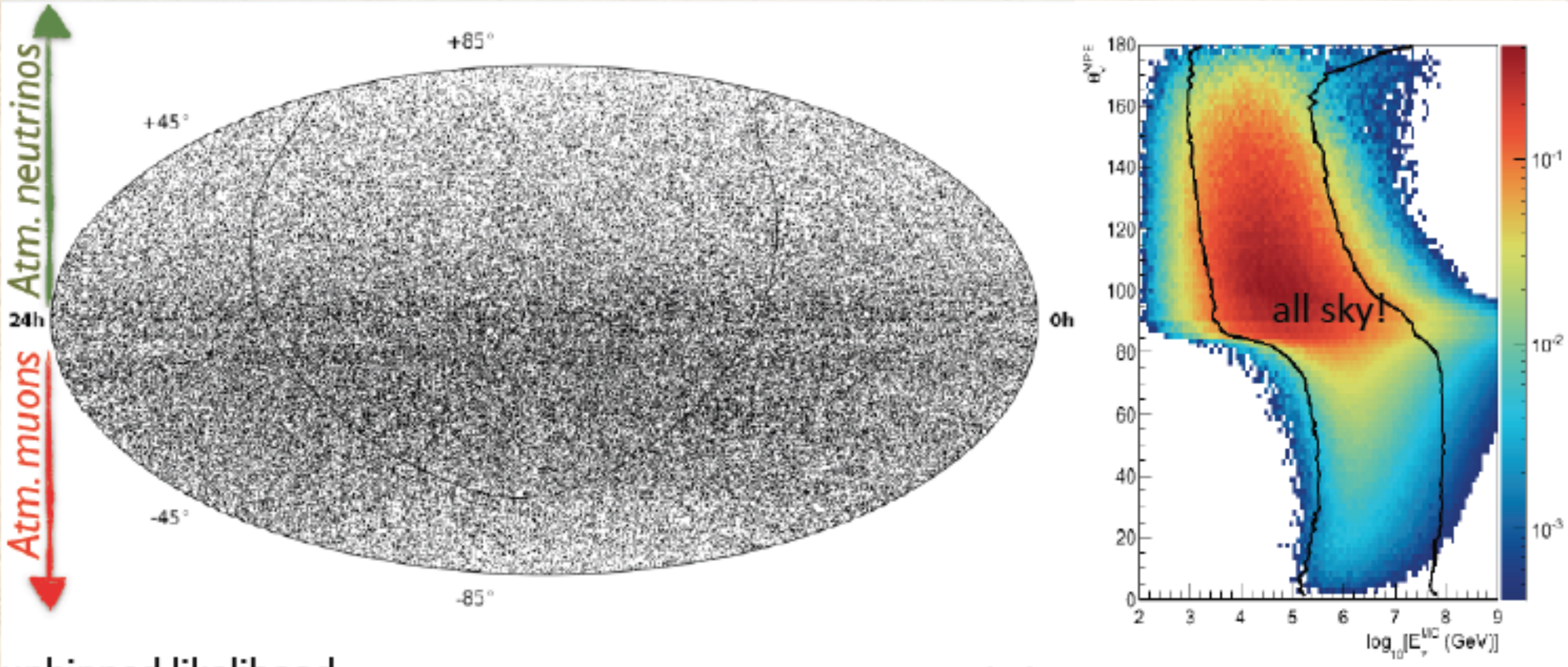


SK lowest post-trial
p-value = 0.025 (~2σ)
RX J1713.7-1946
No significant excess found

IceCube sky map

Point Source Search in Skymap (IC40+59)

43339 up-going + 64230 down-going from 723 days



unbinned likelihood

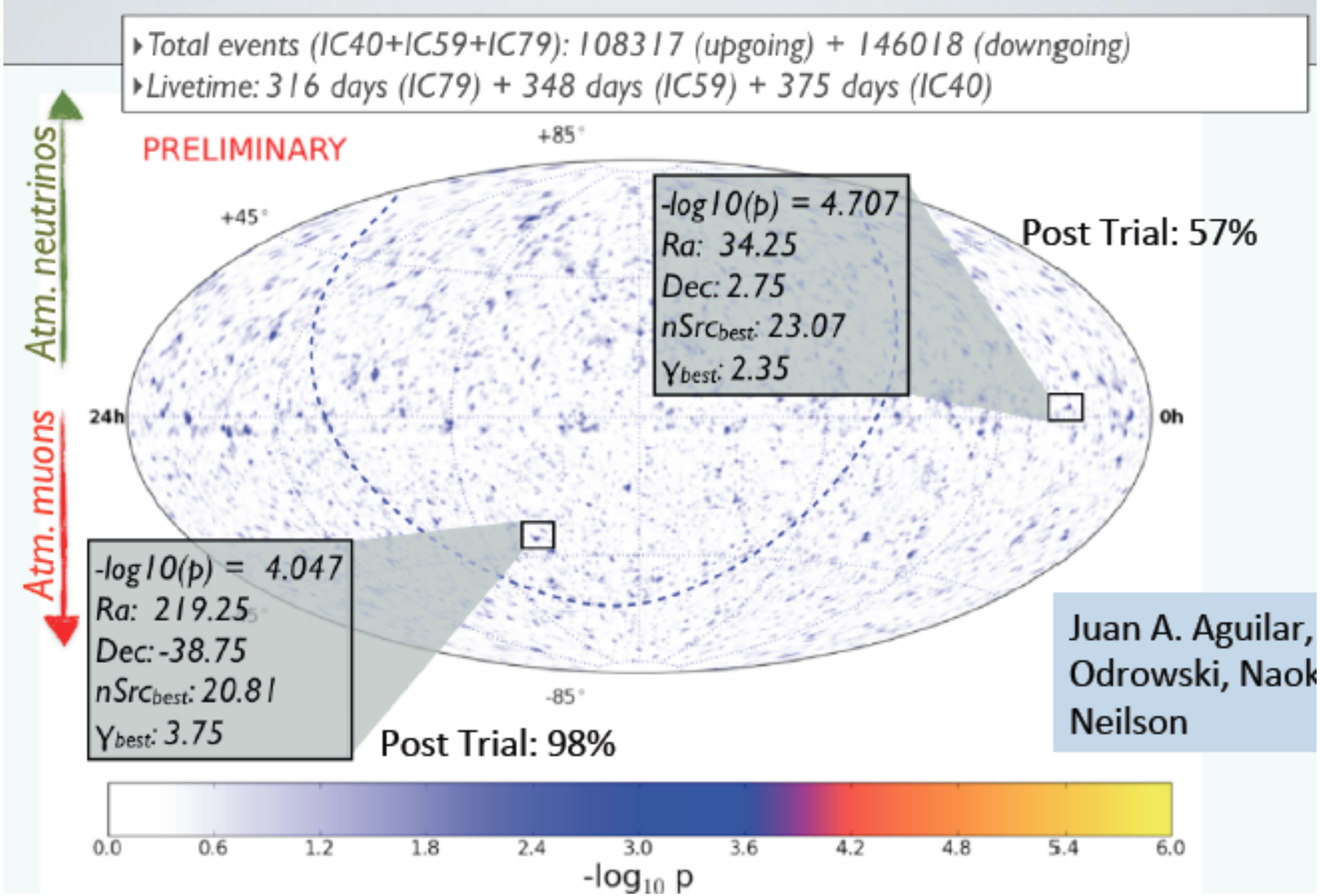
$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

signal term contains angular and energy pdf

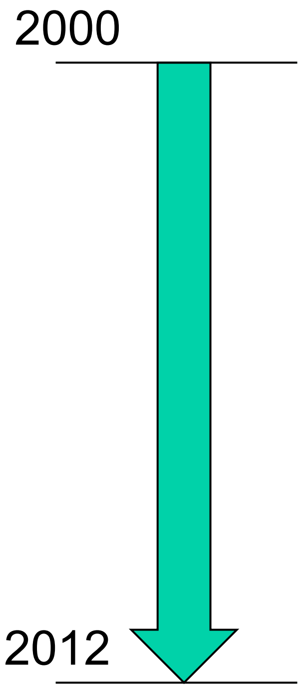
test statistics:

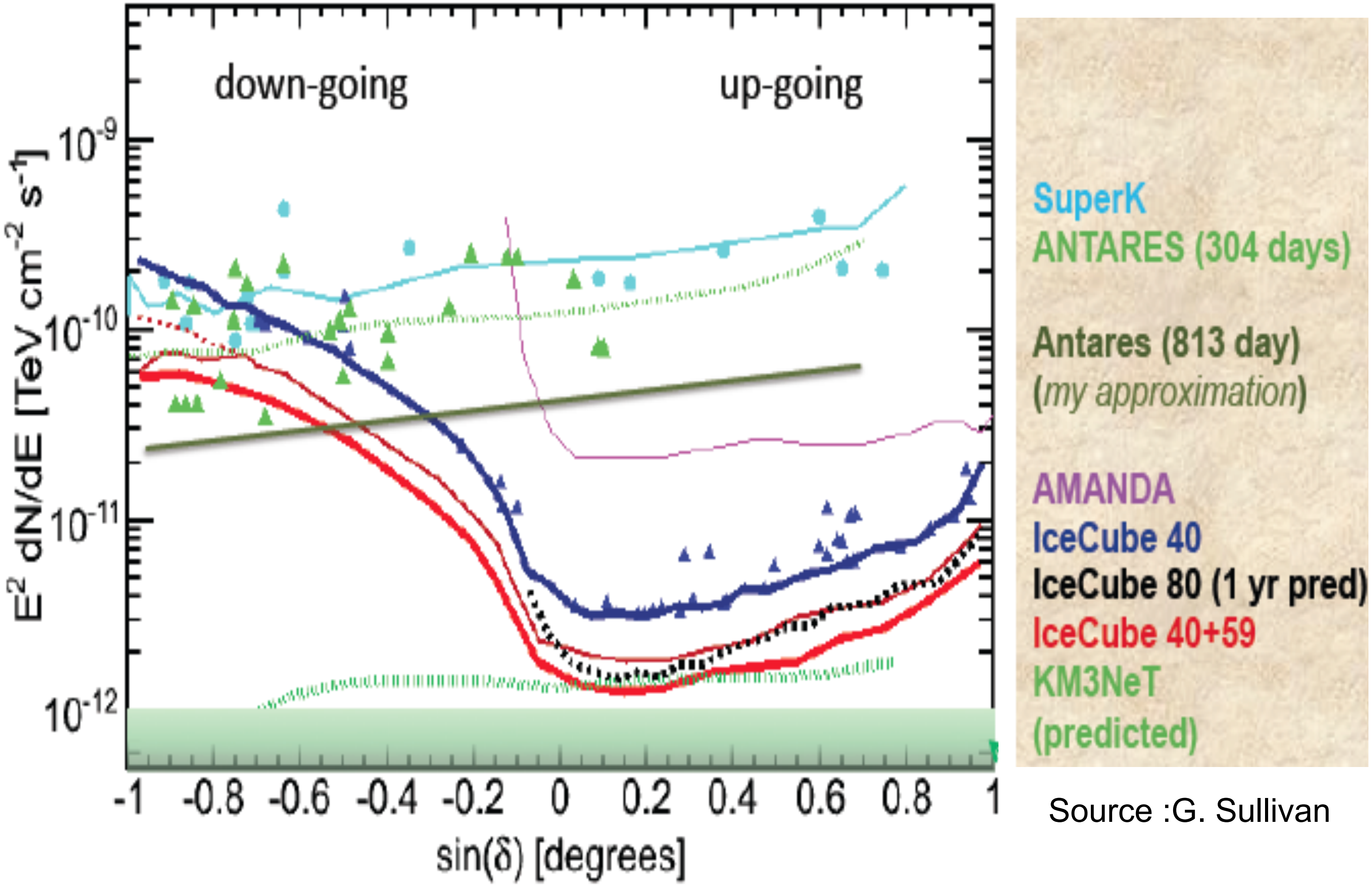
$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \text{p} - \text{value}$$

IceCube sky map….latest?



Current Upper limits



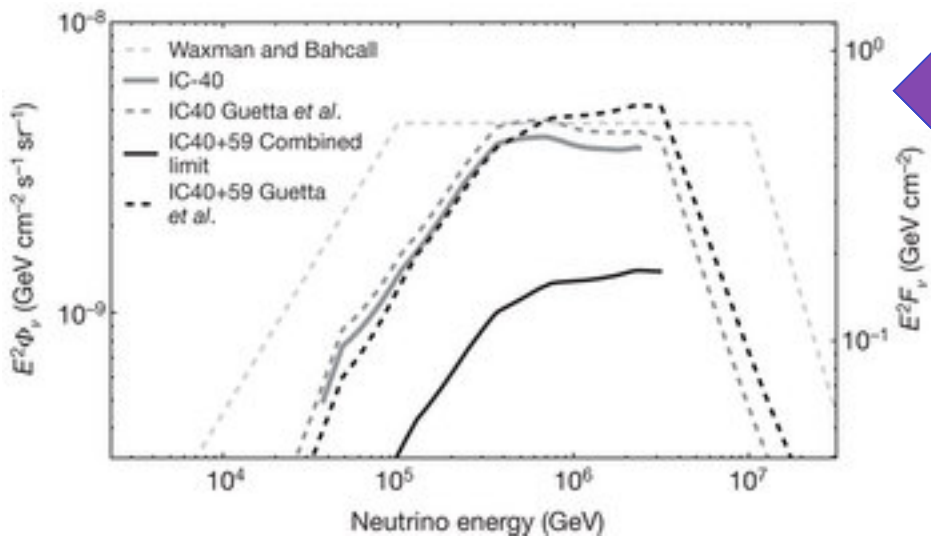


Source :G. Sullivan

Alert programs

cf Philipp Baerwald

- 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)

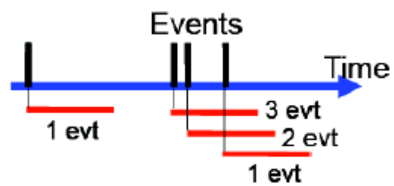


Best limit obtained with IC40+59
Excludes optimistic predictions based on fireball model

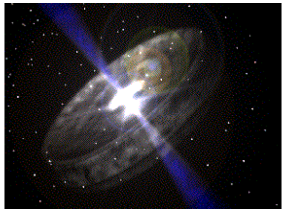
🕮 Nature 484, 351–354 (19 April 2012)

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

- 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)



Outline

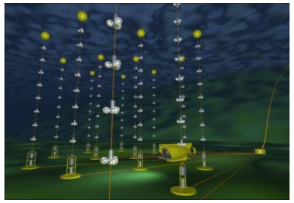


Neutrino astronomy

Historical aspects

Scientific motivations

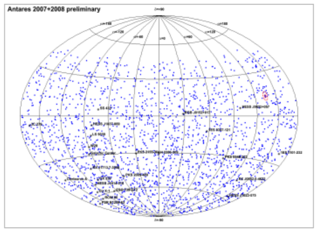
S. Drappeau & P. Baerwald → Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



P. Gay → **Selected results**

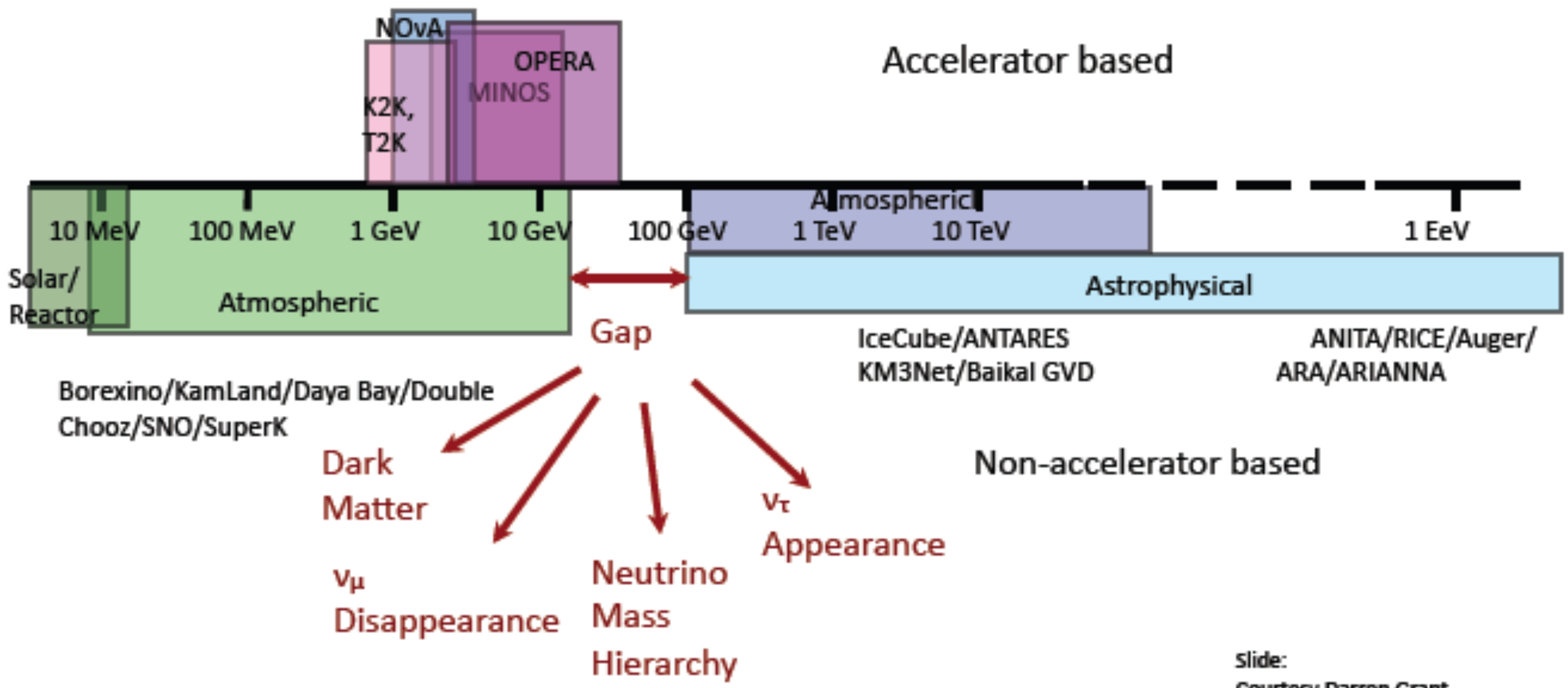
Diffuse Flux

Search for point sources

V. Van Elewyck → Multi-messenger search

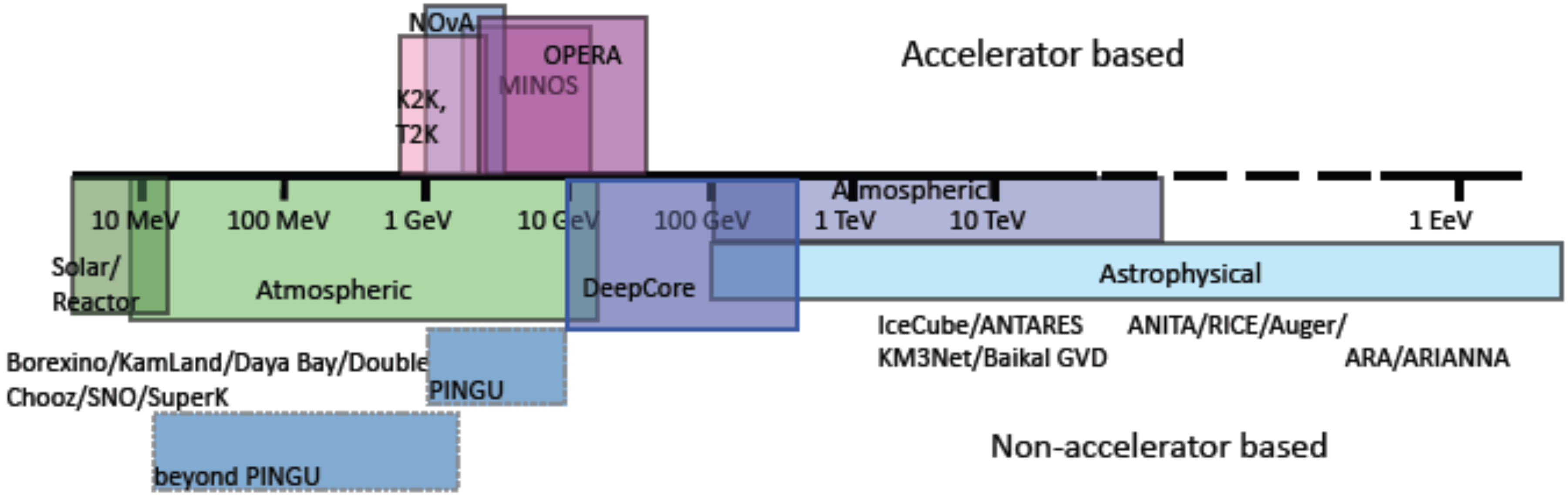
K. Clarke → **Future prospects**

The Neutrino Detector Spectrum



Slide:
Courtesy Darren Grant
NNN 2011

The Neutrino Detector Spectrum



~70 active members in feasibility studies:

IceCube, KM3Net, Several neutrino experiments

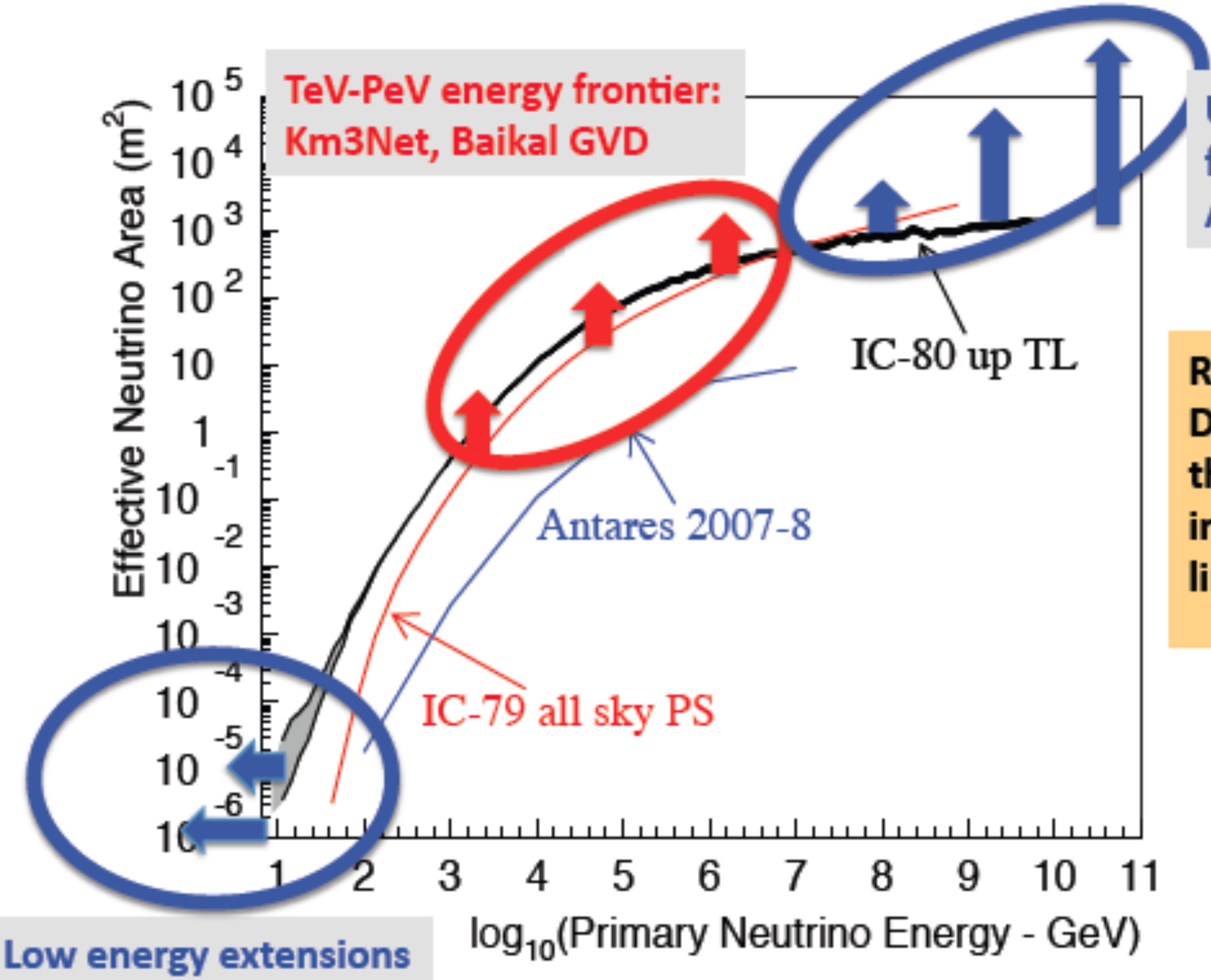
Photon detector developers

Theorists

Slide after:
Darren Grant
NNN 2011

Ken Clarke

Neutrino effective areas



UHE energy detectors for GZK neutrino flux: ARA, ARIANNA

Radio detection in ice: Detection volume and thus sensitivity increases roughly linearly with energy!

Low energy extensions to IceCube, DeepCore: PINGU, MICA

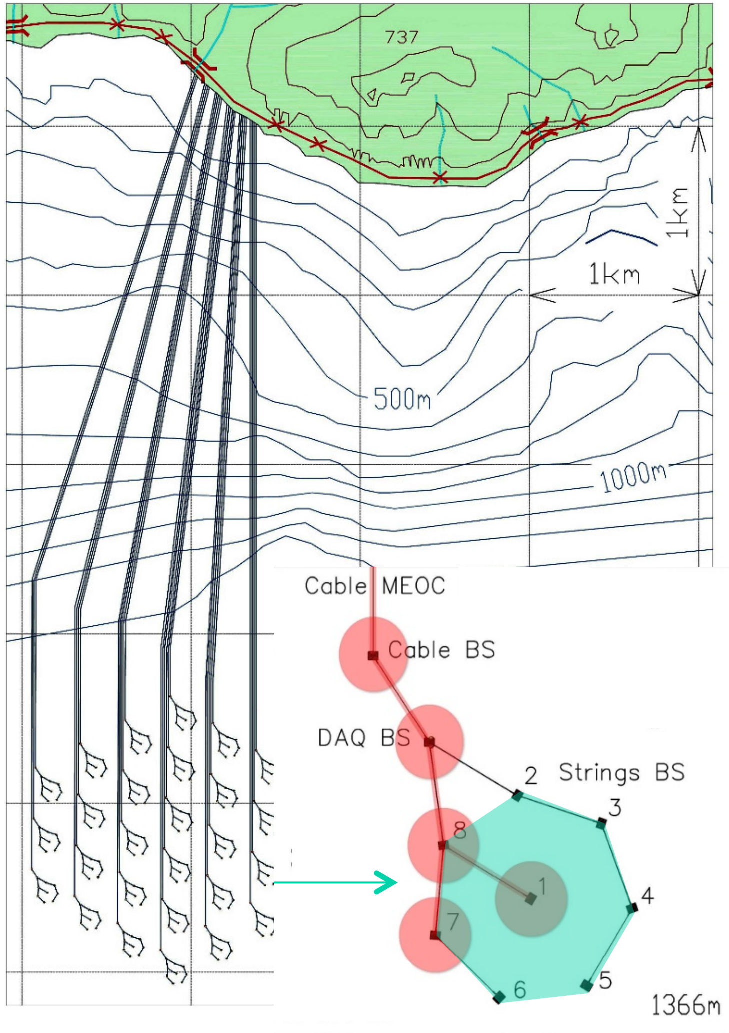
Gton Volume Detector (Lake Baikal)

10368 photo-sensors on 216 strings
27 subarrays (clusters with 8 strings)
String: 4 sections, 48 photo-sensors
Active depths: 600 – 1300 m
To Shore: 4 – 6 km

Instrumented water volume
V= 1.5 km^3 S = 2 km^2

Angular resolution
Muons: 0.25 degree
Showers: 3.5-5.5 degree

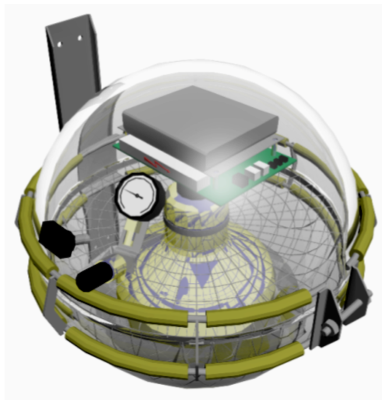
Full first cluster 2014 ?



GVD array

1st GVD cluster: 8 strings

- Installed strings and cable stations

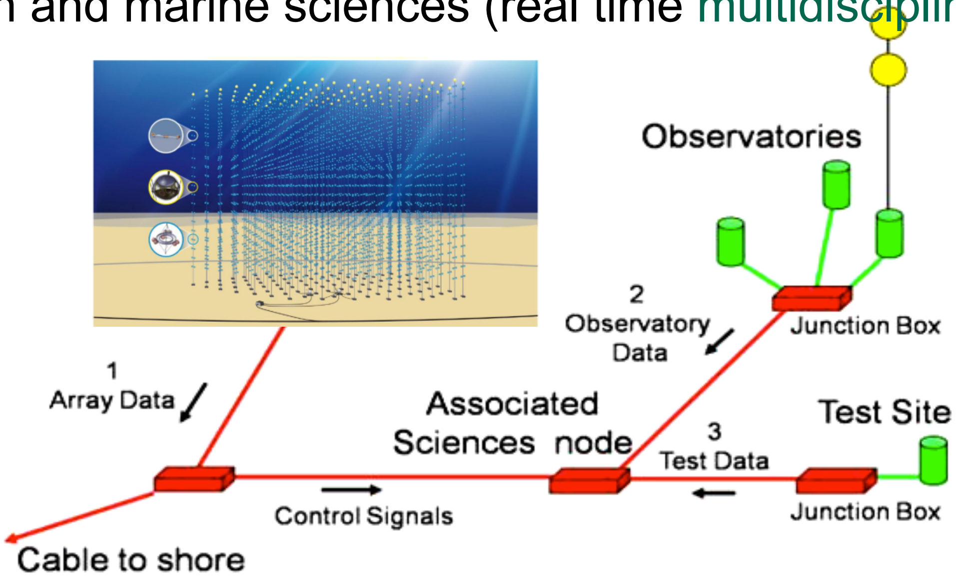


Optical module

KM3NeT activities

Consortium : 40 institutes from 10 European countries

Objectives :
- Built a 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)



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

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

-Towards a multi-site detector
- Secured funds 40 M€

The detector layout

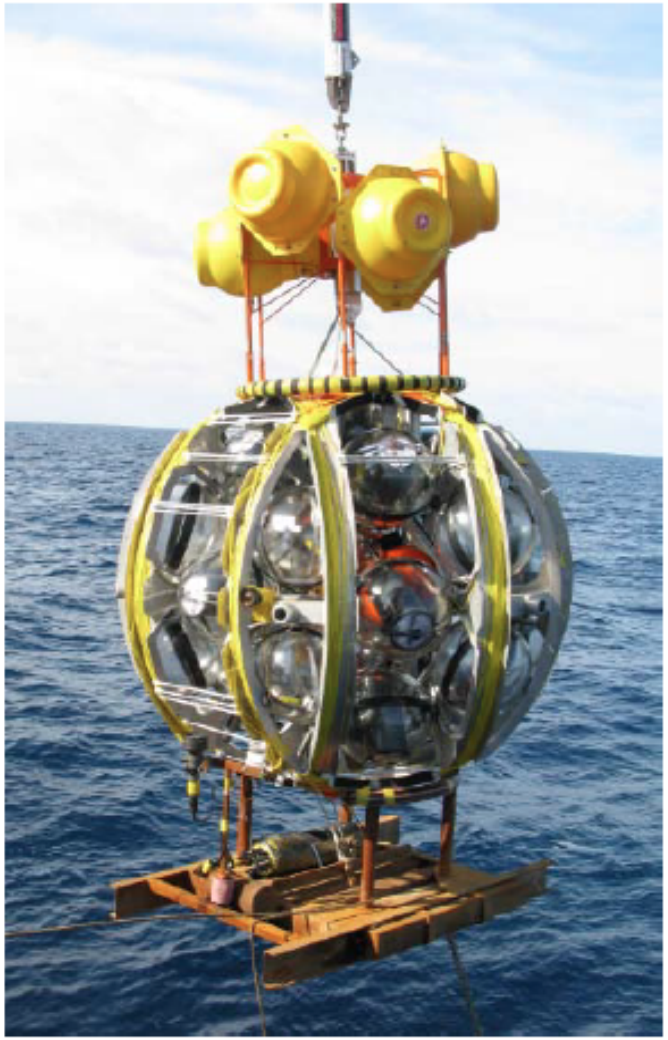
The String Technology

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

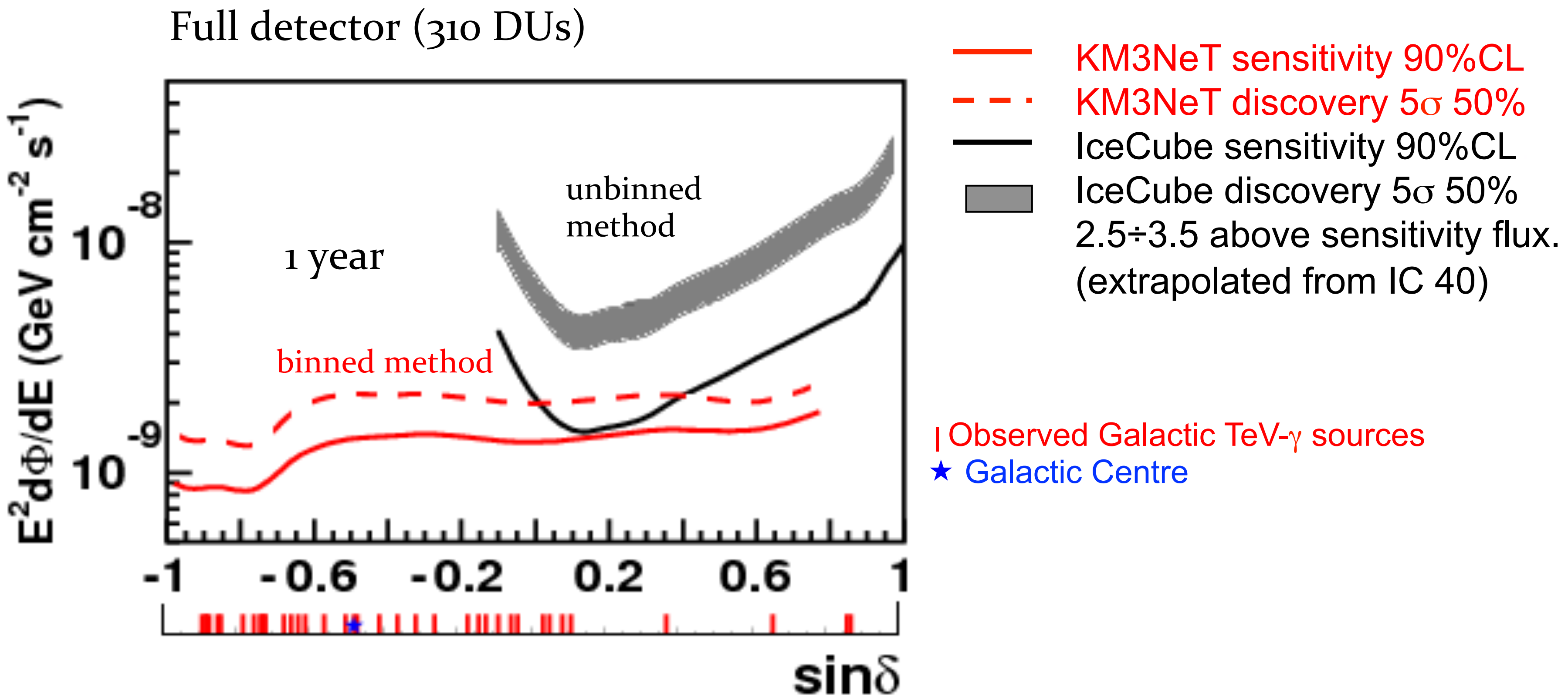
Detection Unit with 20 storeys

40 m inter-storey distance

Compact deployment



Expected sensitivity E^{-2} spectrum



The case for RXJ 1713

- 2-2.5 years for 3 σ discovery
- 5-6 years for 5 σ discovery

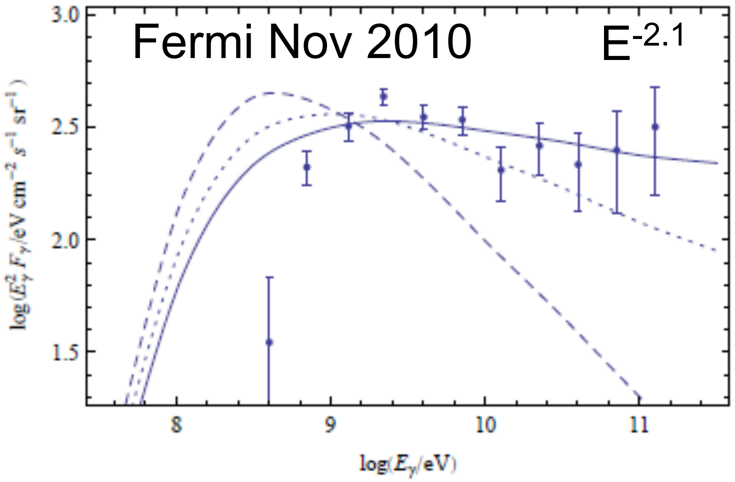
Anticipated Improvements

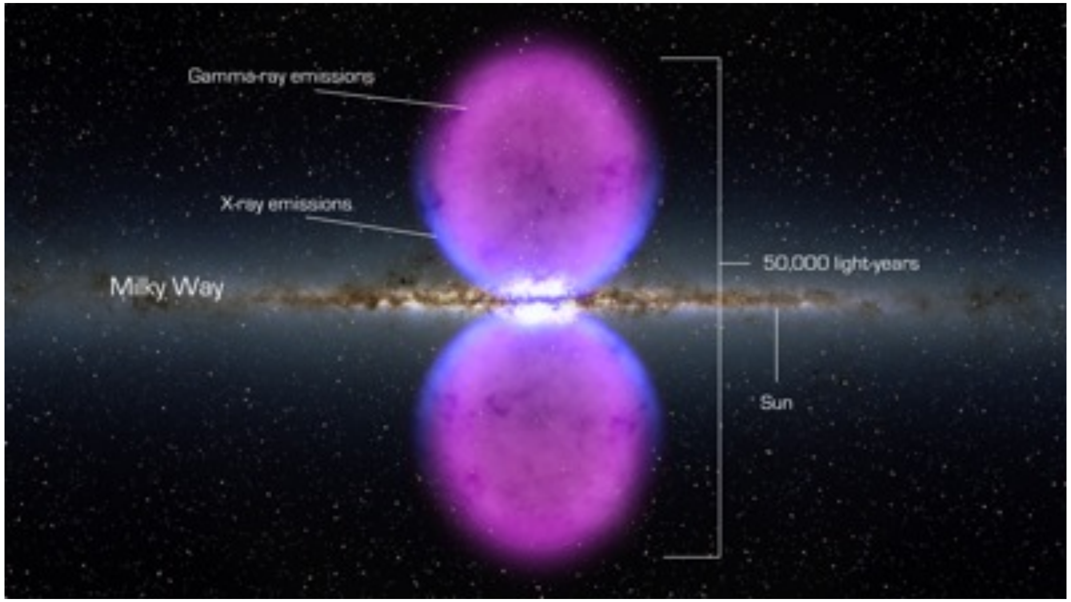
- Unbinned analysis, source morphology, improved reconstruction

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."

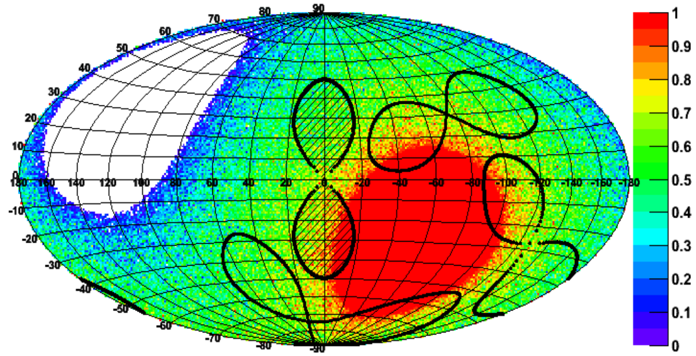




For 100% hadronic models:
$F\nu \sim 1/2.5\ F\gamma$ (Vissani)
$E^2 dF\nu/dE = 1.2 \cdot 10^{-7}$ GeV $cm^{-2} s^{-1} sr^{-1}$
E cutoff protons: 1PeV-10 PeV (Croker&Aharonian)
E cutoff neutrinos = 1/20 cutoff protons

Search for Neutrinos from Fermi Bubbles

Good visibility for ANTARES/KM3NeT

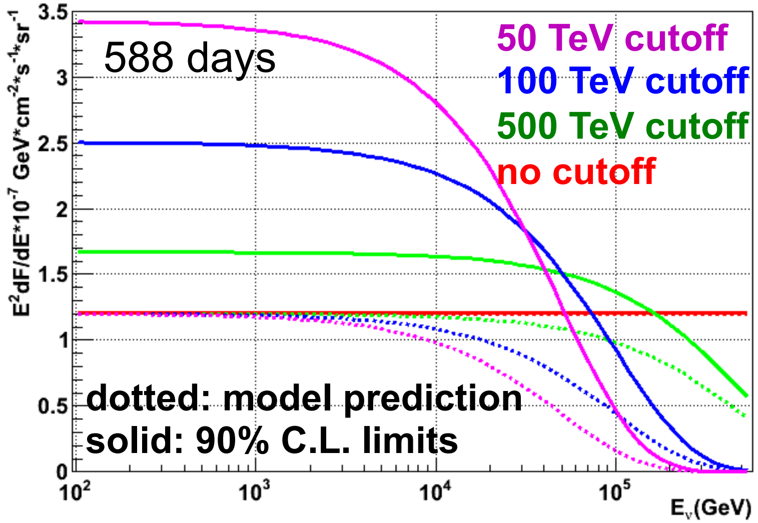


galactic coords

ANTARES

Background estimated from average of three 'OFF' regions (time shifted in local coordinates)

ANTARES preliminary



Nback (OFF) = 90 ± 5 (stat) ± 3(sys)
Nsig (ON) = 75

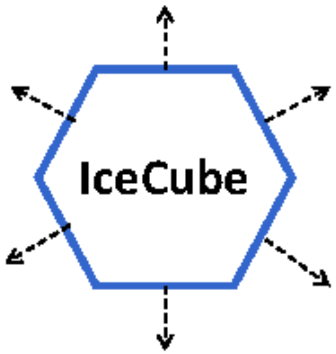
No signal
→ exclude fully hadronic model no cutoff
(90%CL F&C)

KM3NeT
- Few months for 3 σ discovery
- About 1 year for a 5 σ discovery (E^{-2} 100TeV cutoff)

Submitted to Astroparticle Physics
arXiv:1208.12266

Towards a futur Global Neutrino Observatory?

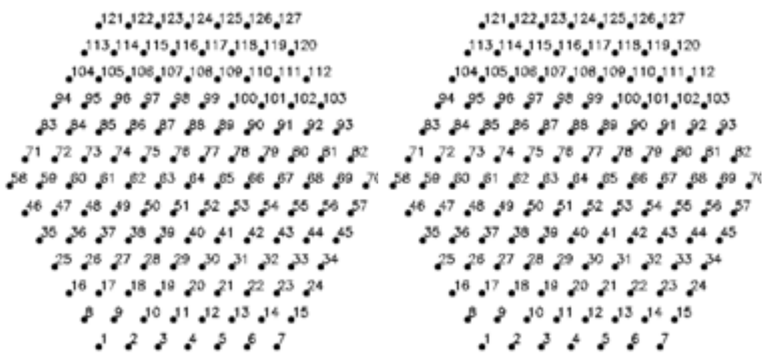
South hemisphere: – 1km^3

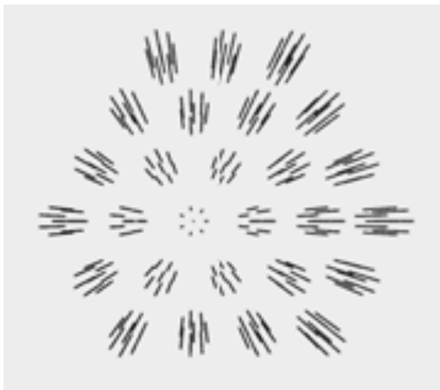


Already common meeting once a year since 2008… “MANTS symposium”

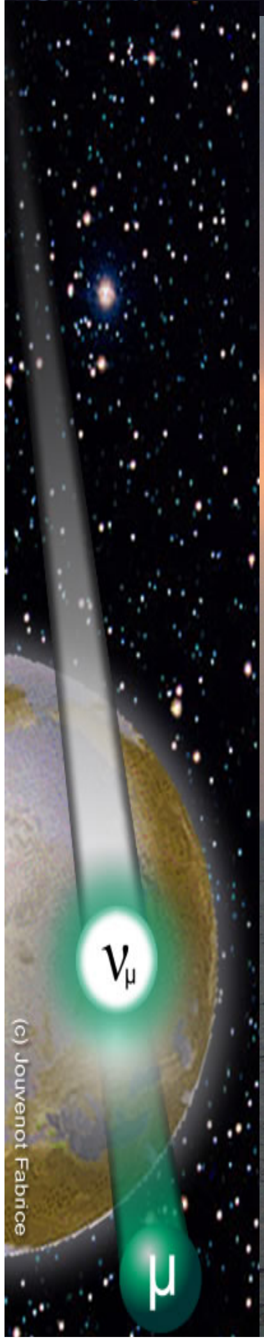
Northern hemisphere:

KM3NeT (2 x 2.5) km^3 + 1.5 km^3 GVD





Conclusions



- Neutrino astronomy has made great progress
- IceCube 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.

- Interesting physics cases being investigated with low/high energy extensions

The best is yet to come!