Neutrino's signatures of GW sources

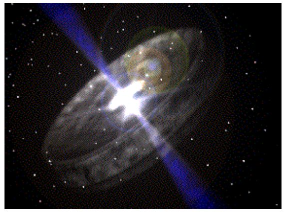
An overview oriented towards the Cherenkov Technique

Antoine Kouchner
Université Paris 7 Diderot
Laboratoire APC

Credits: Ch. Spiering, L. Moscoso, F. Halzen, A. Karle, G. Sullivan, P. Coyle, Th. Patzak, Th. Pradier, G. Raffelt, N. Whitehorn,…

IVth School of Astroparticle Physics Saint Michel l'Observatoire, May, 2013

Outline

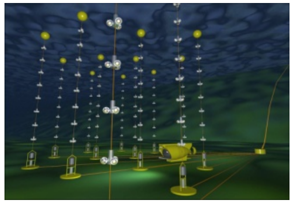


Neutrino astronomy

Historical aspects

Scientific motivations

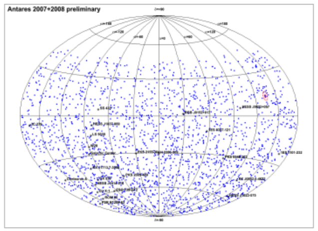
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

First Discovery by IceCube? ← Diffuse Flux

Search for point sources

Multi-messenger search

GWHEN searches

Future prospects

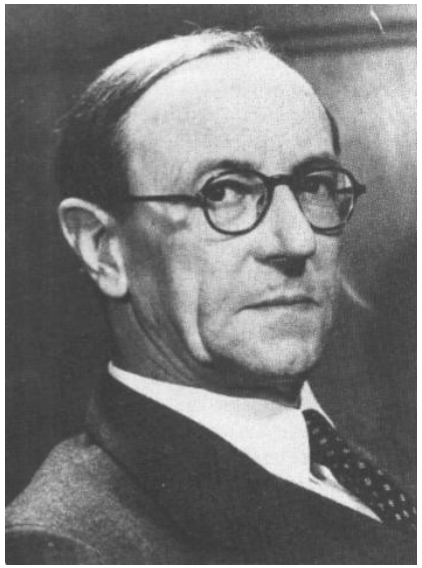
β Radioactivity

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

1878 - 1968

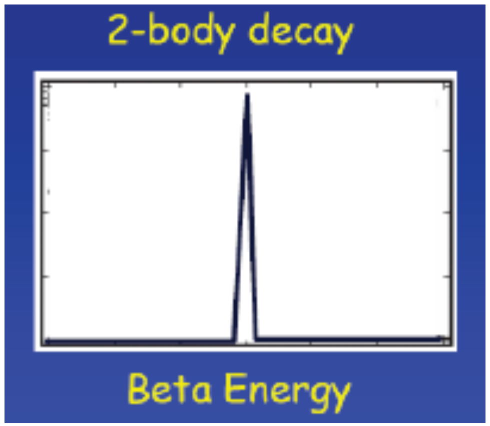
Compatible with interpretations of that time:
nucleus = A protons + (A- Z) electrons [+Z orbital electrons]
β disintegration : (A, Z) —> (A, Z-1) + e^-

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

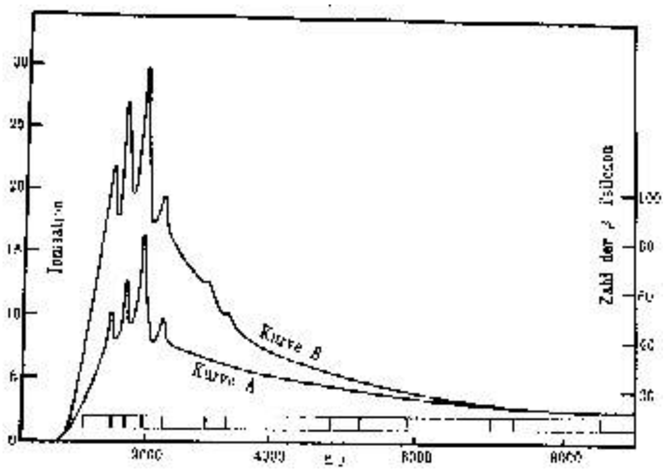


1891 - 1974

Expected



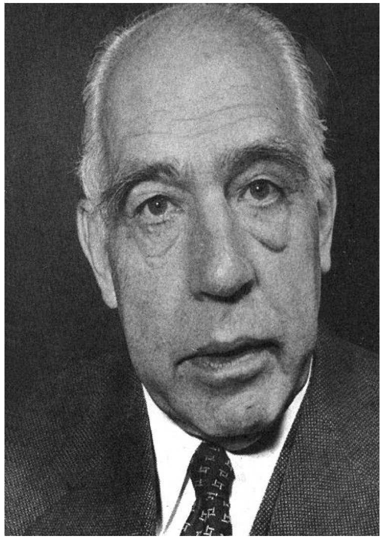
Measured



"there is probably some silly mistake somewhere"

Possible theoritical solutions

Niels Bohr (1885-1962)



« Energy is conserved only statistically » (on average)

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

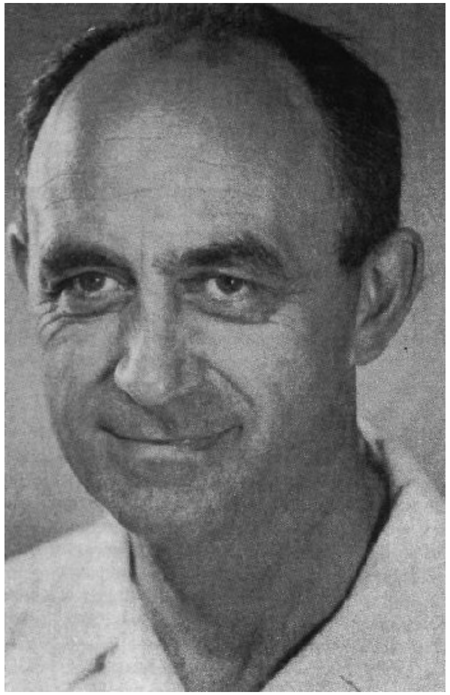
Wolfgang Pauli (1900-1958)

« 1930: another neutral and light particle is emitted »

Letter to « radioactive» physicists meeting in Tübingen.

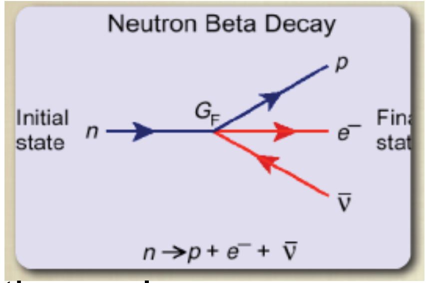
This is the neutrino birth, first called "neutron".

1933: Fermi theory (β)



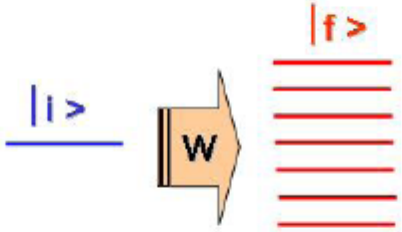
1901 - 1954

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



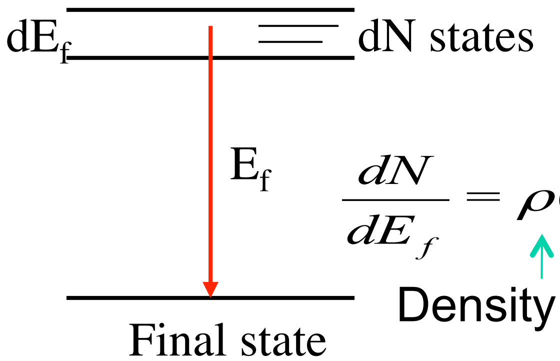
- A nuclear transition takes place when a neutron is destroyed and a proton is created. An electron and a neutrino are emitted. Local interaction.
- Neither the electron nor (anti)neutrino pre-exist in the nucleus. Both are created in the decay process.

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



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

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



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

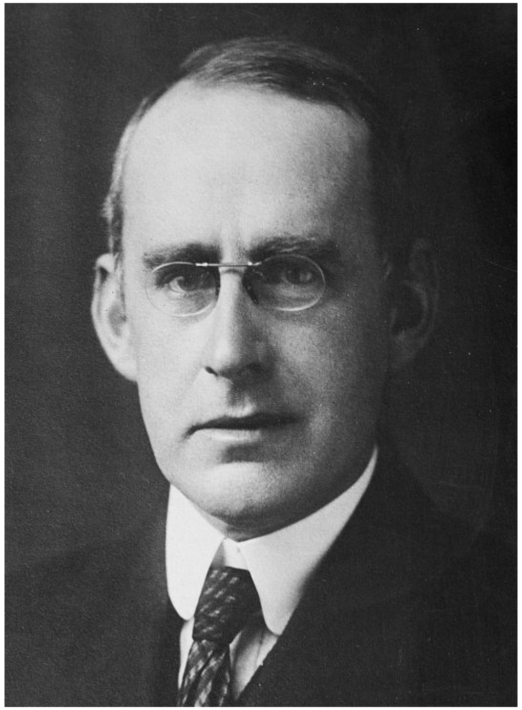
Density of final states

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

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" …*



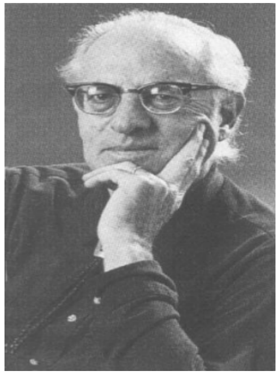
1882 - 1944

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



$$p+\bar{\nu} \rightarrow n+e^{+}$$ Reaction threshold = 1,8 MeV

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

'Poltergest ' project

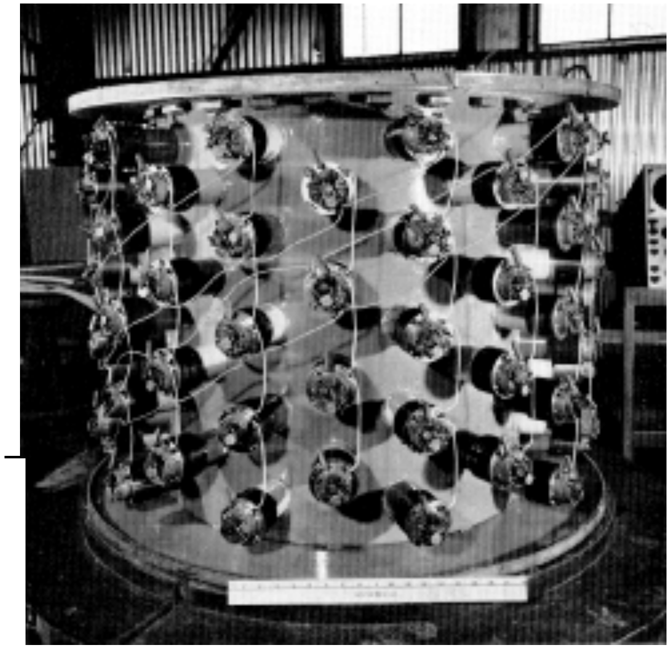
The neutrino interacts with a proton and undergo a positon (e+) and un neutron (n).

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

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

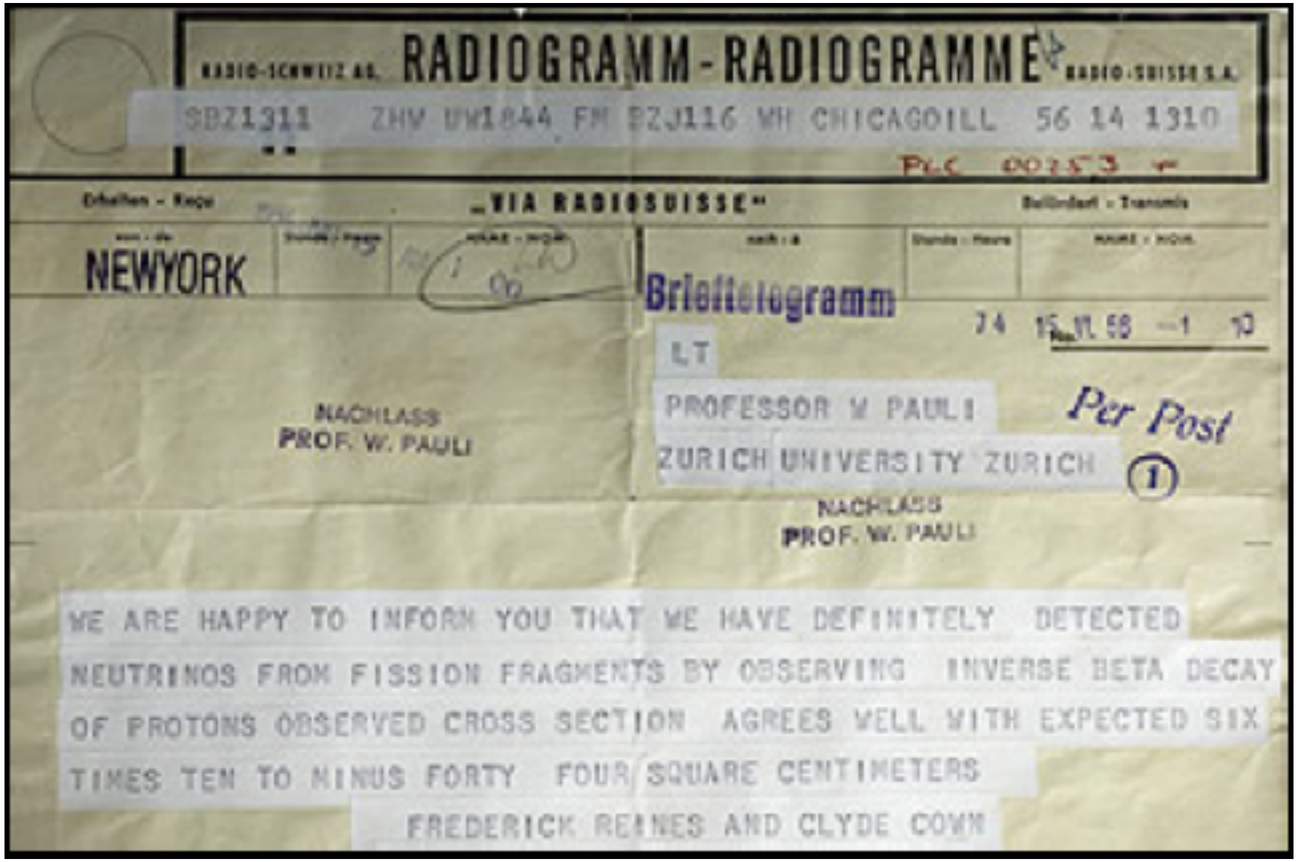
$$\gamma+e^{-} \rightarrow \gamma+e^{-} \text{ (compton)}$$

~ 5 μs later



1956 : Savanah River
Target made of 400 liters of water and Cadmium Chlorure.

Telegram sent to Pauli on June 14th 1956



RADIO-SCHWEIZ AG. RADIOGRAMM - RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHV UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

"VIA RADIOSUISSE"

NEWYORK

Briefteleqramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

📖 C.L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire, « Detection of the Free Neutrino :a Confirmation », SCIENCE, 20 July 1956, Volume 124, Number 3212

Prix Nobel 1995 (Cowan deceased)

Discovery of muon neutrino

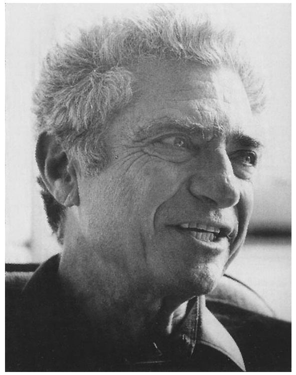
📖 PRL 9, 36-44, 1962

AGS 15 GeV Proton Beam

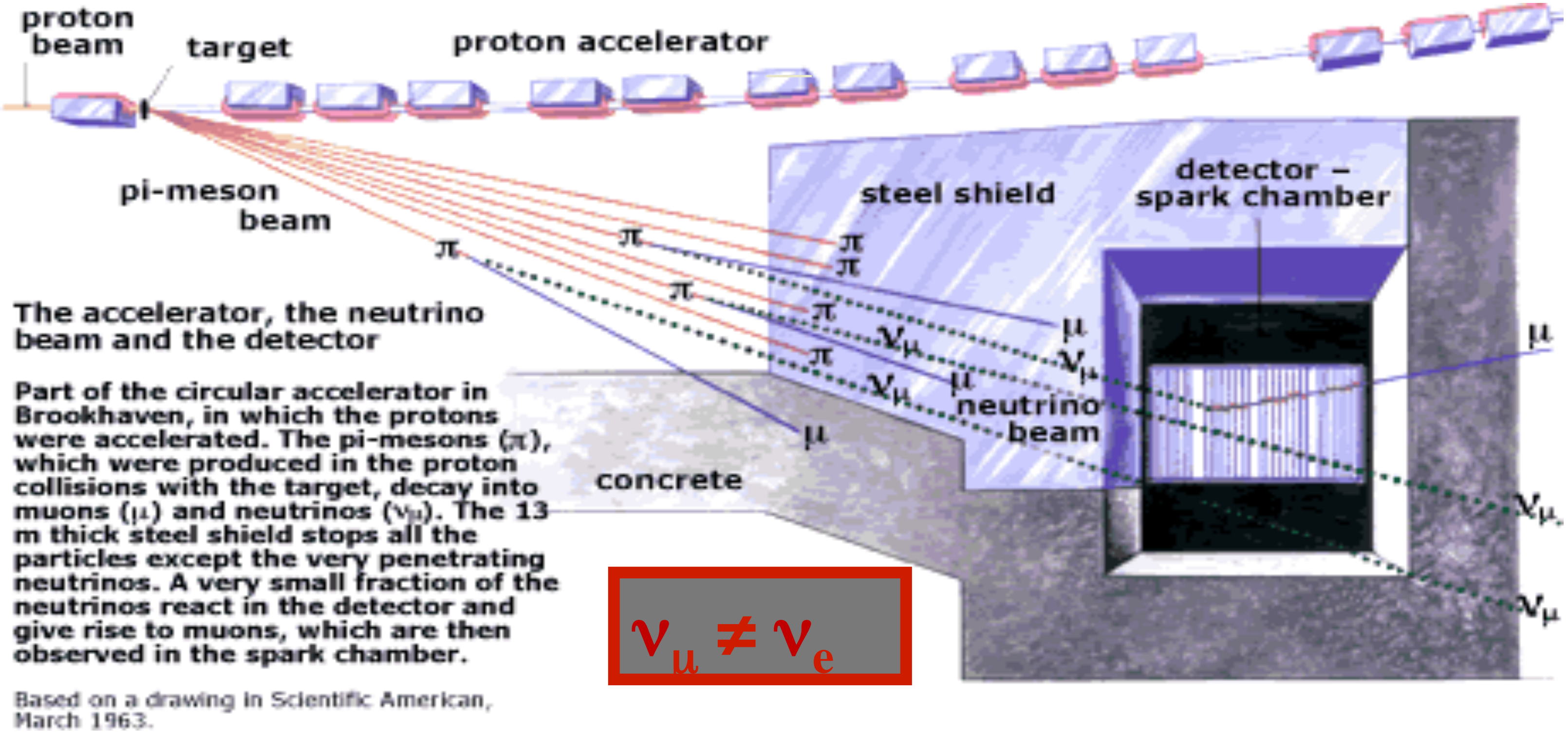
34 evts (P_{μ}>300MeV)
Expected background (atm) = 5
Nobel price 1988

M. Schwartz
1932- 2006

L. Lederman
1922-



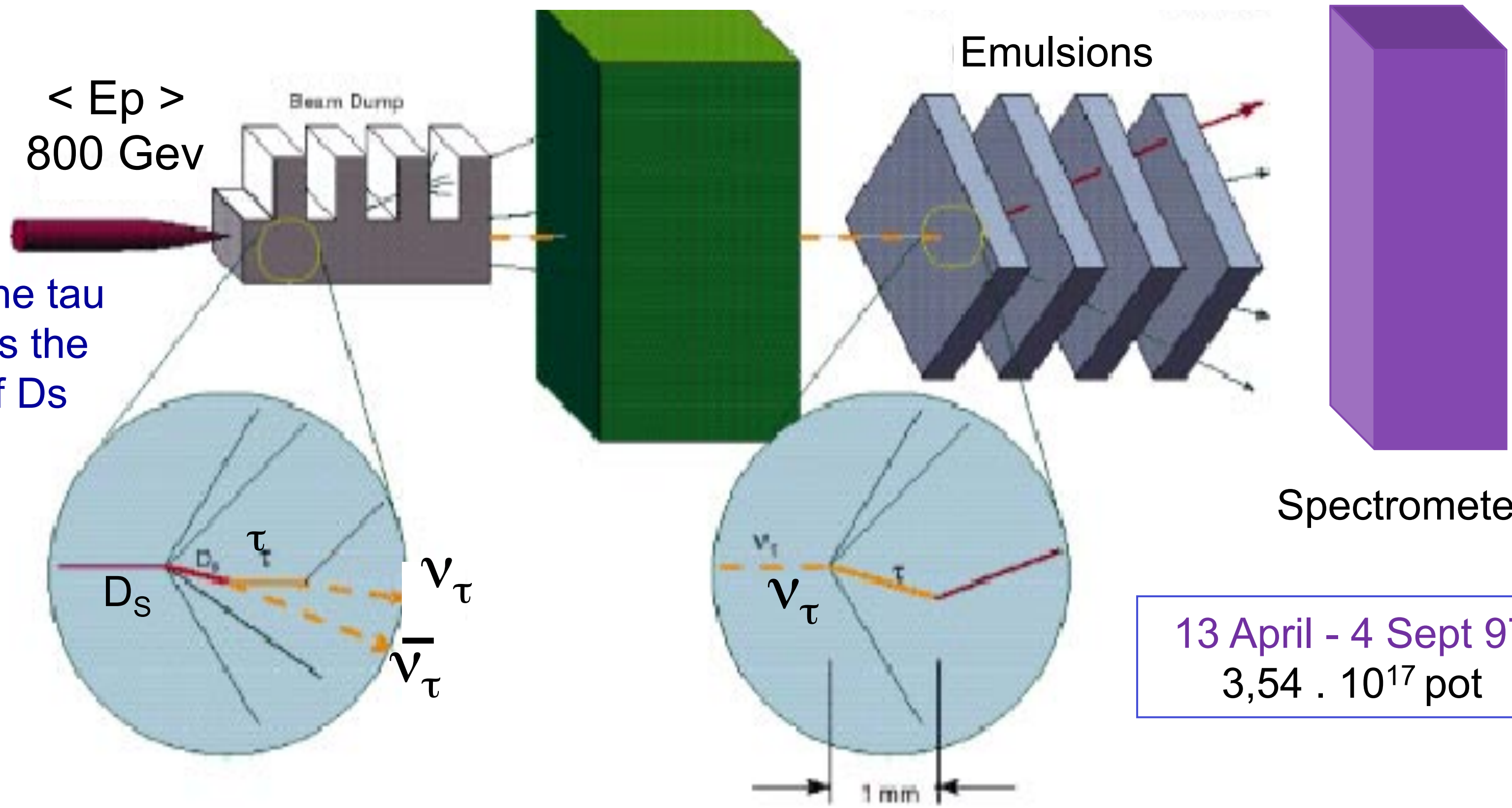
J. Steinberger
1921-



$\nu_\mu \neq \nu_e$

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
$<E_\nu>=111GeV$

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

$\tau \rightarrow e\ \nu_\tau\ \nu_e$ (18%) $\tau \rightarrow \mu\ \nu_\tau\ \nu_\mu$ (18%) $\tau \rightarrow h$ + neutral (50%)

Detection of solar neutrinos

2 types of methods:

Radiochemical experiments

ν_e + (A,Z) —> e$^-$ + (A,Z+1)*

• One counts the number of daughter nuclei
The production rare is $R = N\int \Phi(E)\sigma(E)dE$

Number of target atoms $\sim 10^{-45}$ cm^{-2}

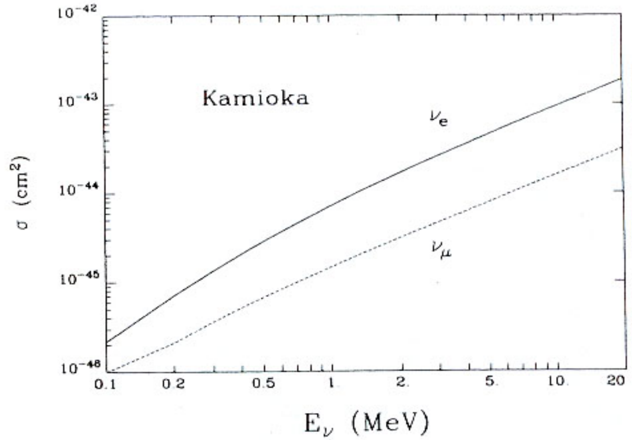
☞~ 10^{30} atoms needed for 1 detection per day
⇒ target : tons

1 SNU = 10^{-36} capture atom^{-1} sec^{-1}

No information on time, E, direction of ν's

Real time experiments

ν_x + e$^-$ —> ν_x + e$^-$



• The scattered electron is detected thanks to the emitted Cherenkov light.
• Forward scattering: energy E estimate.
• $E_{threshold}$ ⇒ only neutrinos from B
⇒ target : kilo ton

The Homestake experiment

1968 : First experiment detecting solar neutrinos
Homestake gold mine, South Dakota, USA
1480m underground

615 tons de C_2Cl_4 (Perchloroethylene)
~ 380 000 litres

Liquid (cheap, commercially available)

$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$

$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow$ **${}^{37}Cl$ $(T_{1/2}=35\ d)$**

$E_{thresl}=0.8\ MeV > E_{pp}$

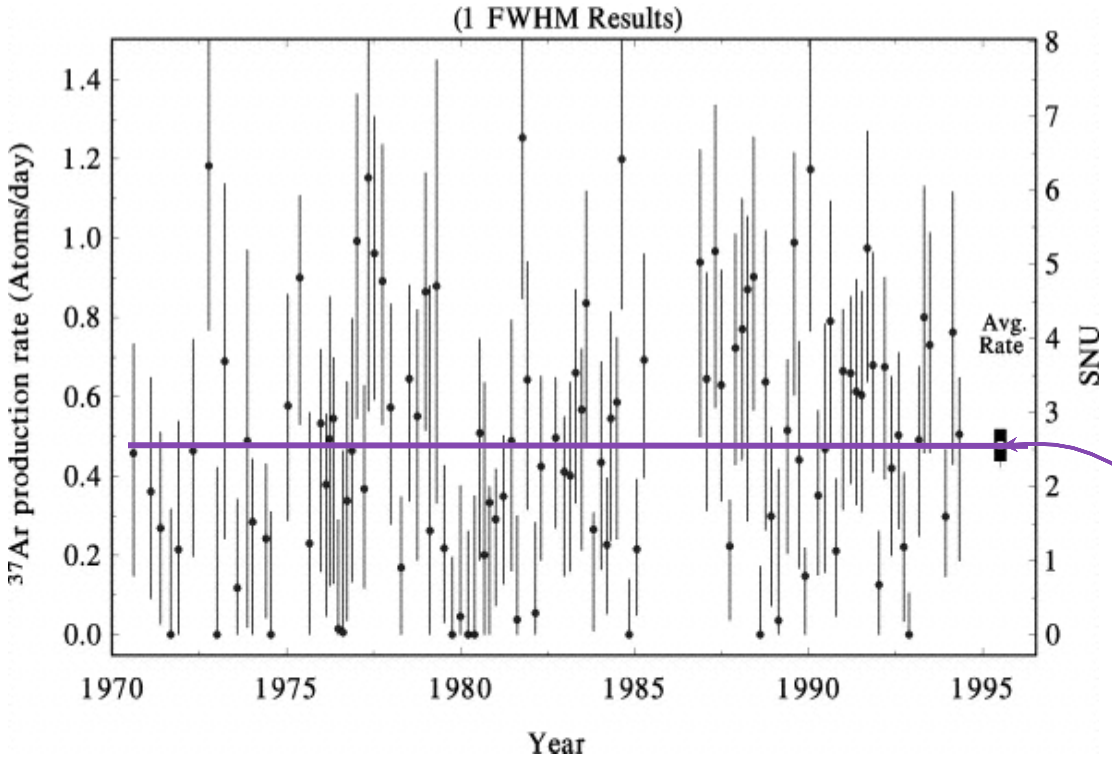
Principle of a cycle :

- -Exposition (~2 months)
- -Extraction of the produced Ar
  - He flushing, Ar trapping (charcoal)
  - Controlled by adding inert ^{38}Ar
- -Counting
  - Mini proportional counters < ~ cm^3
  - Observation of Ar disintegration (e_{AUGER})
  - Energy deposit and signal rise time

The Homestake experiment

📖 **B.T.Cleveland et al., Ap. J. 496 (1998) 505**

- **25 years of data (108 runs)**



R. Davis, Nobel price in 2002

Average result:
2.56 ± 0.20 SNU
so 1/3 of
predictions
(7.6 ± 1.2 SNU)

Around 750 disintegrations have been observed, which make ~0.5 per day

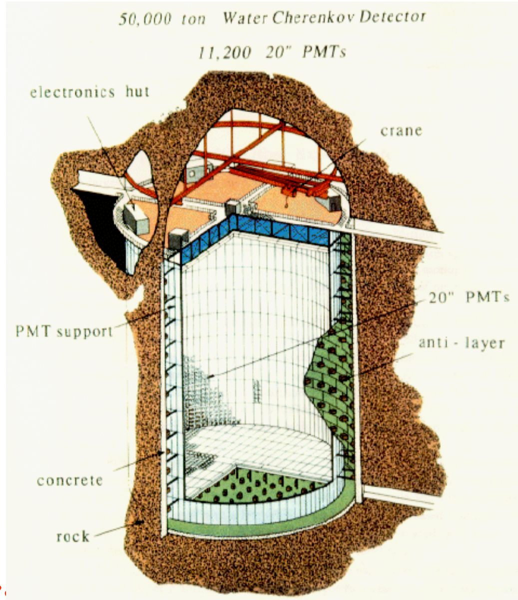
Early 1970 (~10 extractions): the birth of the "solar neutrino problem"

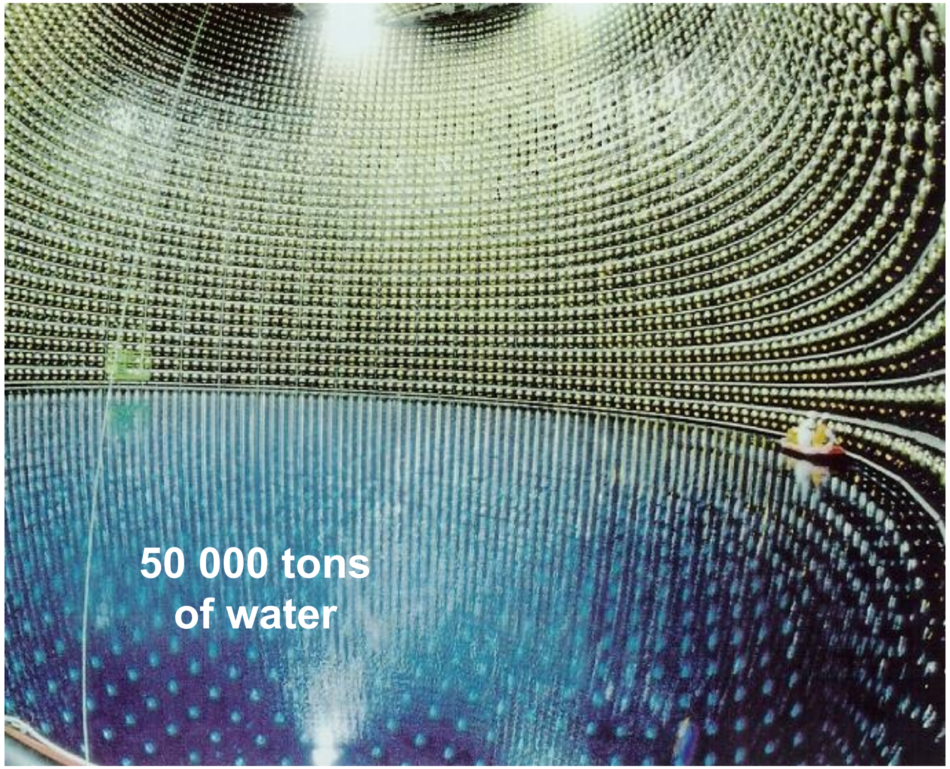
A confirmation was mandatory

Problem solved today with neutrino oscillations

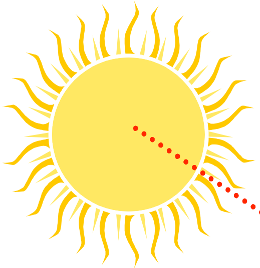
Real time experiments

Kamiokande 1987-1996
SuperKamiokande 1996 -
2700m we





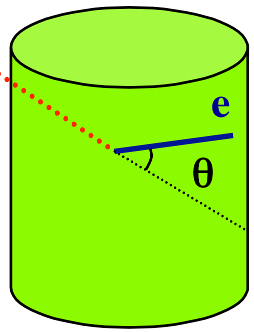
11 146 PMTs 20 ”



neutrino

$$\nu_e + e^- \longrightarrow \nu_e + e^-$$

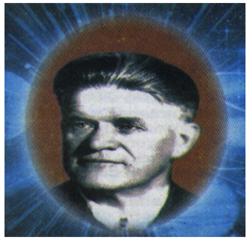
Threshold~6.5 MeV

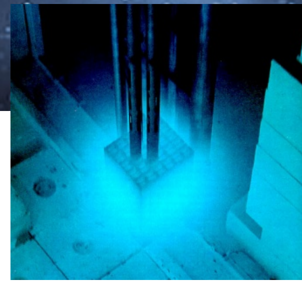


The diffusion allows to know the direction of the incoming neutrino thanks to:

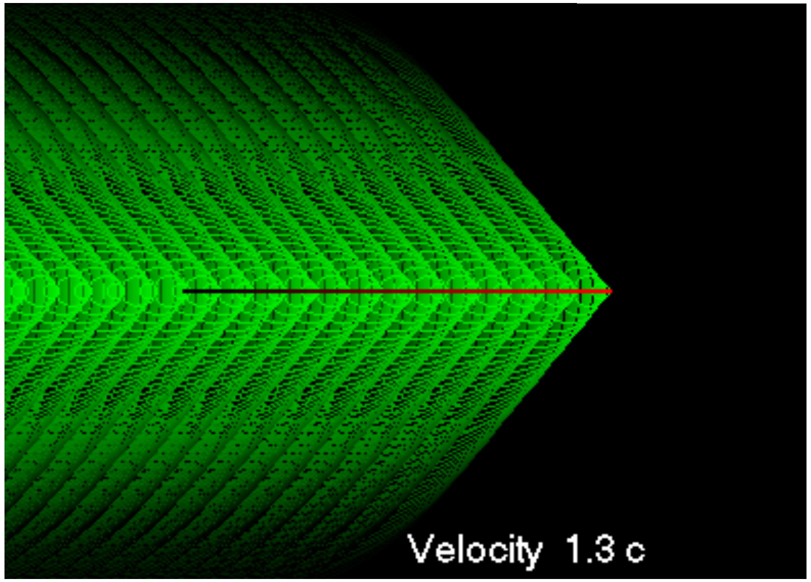
- The exact arrival time
- The recoil electron energy spectrum which is correlated to the one of the neutrino

Cherenkov radiation

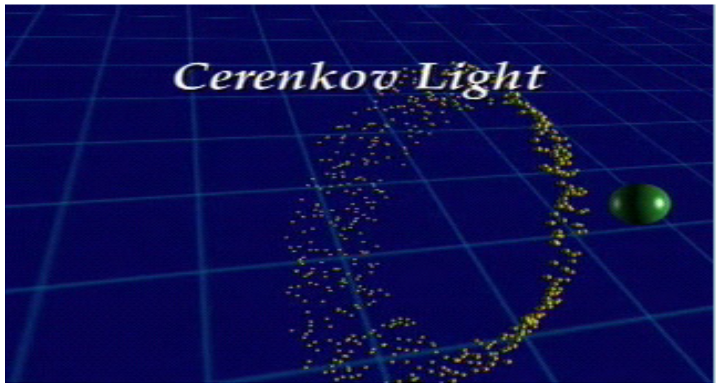




Coherent emission of light produced by relativistic charged particles, observable in a transparent medium



The charged particles polarize the molecules of that medium, which then turn back rapidly to their ground state, emitting radiation in the process



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]

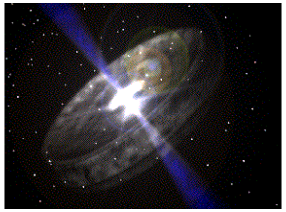
By Kenneth Greisen

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.

Outline

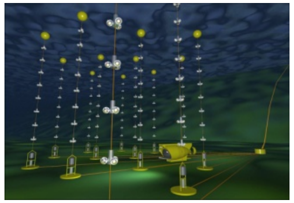


Neutrino astronomy

Historical aspects

Scientific motivations

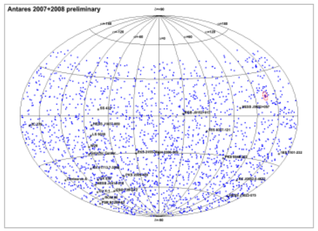
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux

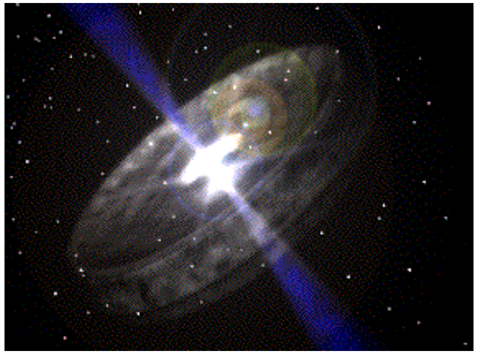
Search for point sources

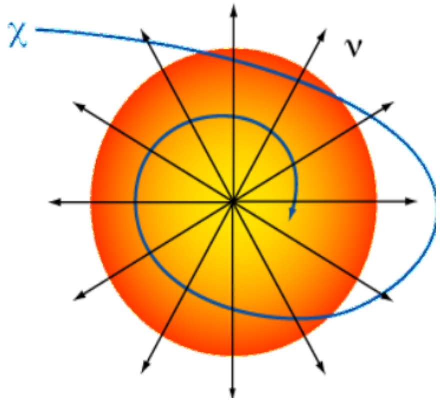
Multi-messenger search

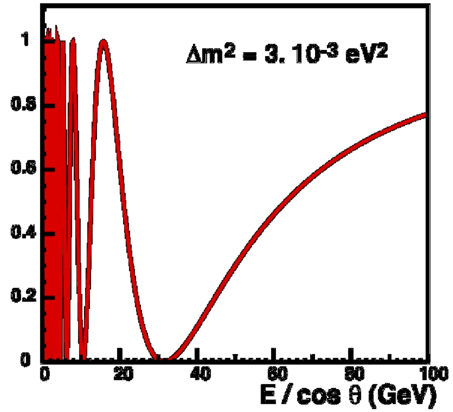
GWHEN searches

Future prospects

Neutrino telescopes: science scope







High Energy $E_\nu > 1$ TeV	Medium Energy 10 GeV $< E_\nu <$ 1 TeV	Low Energy 10 GeV $< E_\nu <$ 100 GeV

ν from extra-terrestrial sources

Dark matter search

ν oscillations

Origin and production mechanism of HE CR

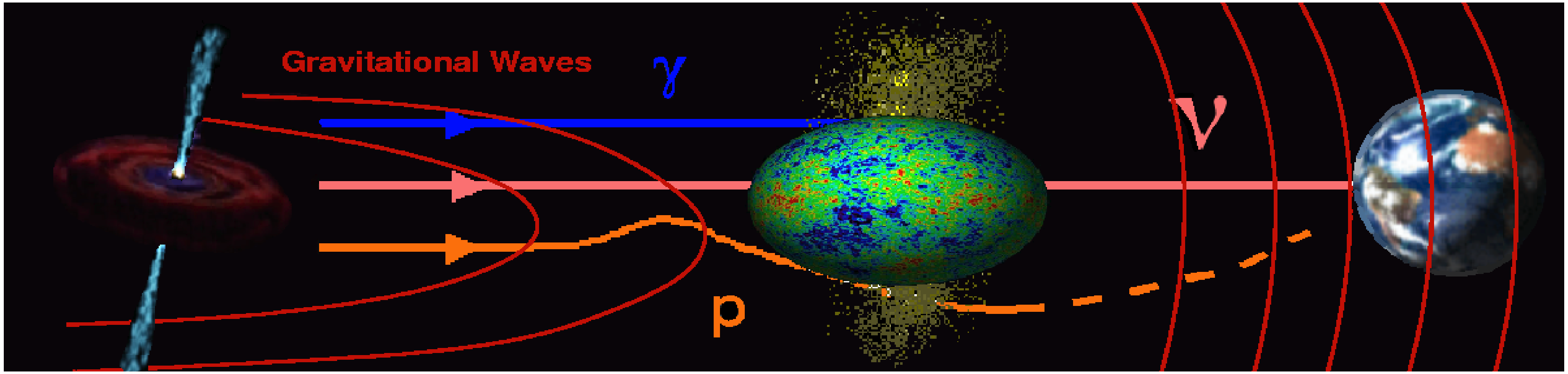
↓

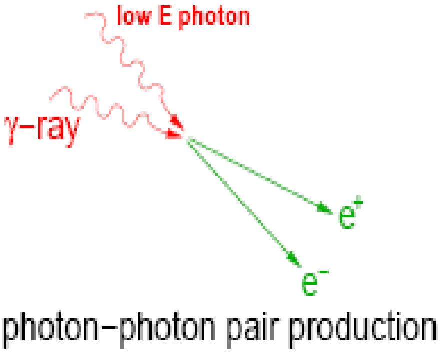
Primary goal

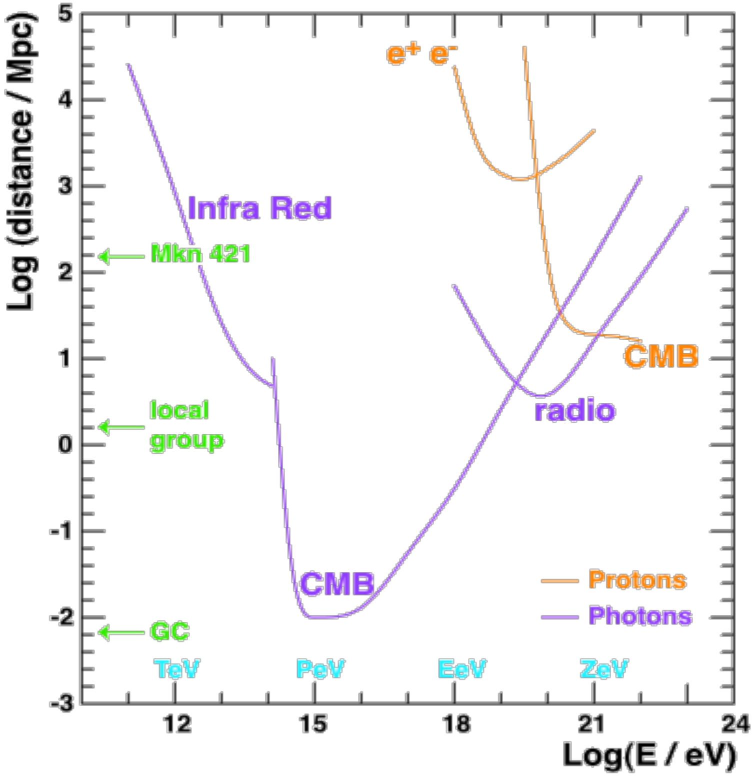
Exotic particle physics
Monopoles, nuclearites,…

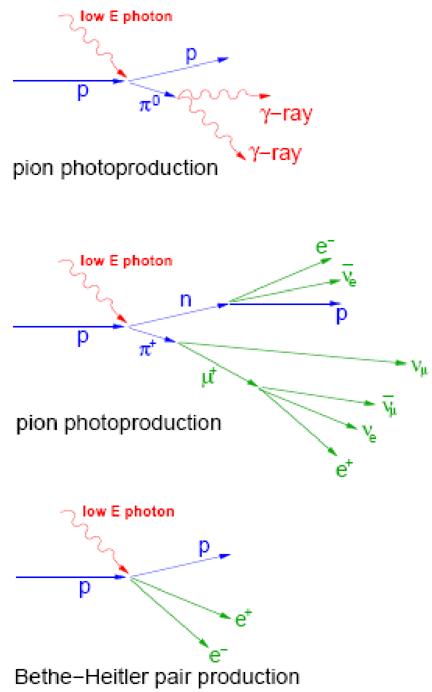
Marine sciences: oceanography, biology, geology…

Multi-messenger astronomy









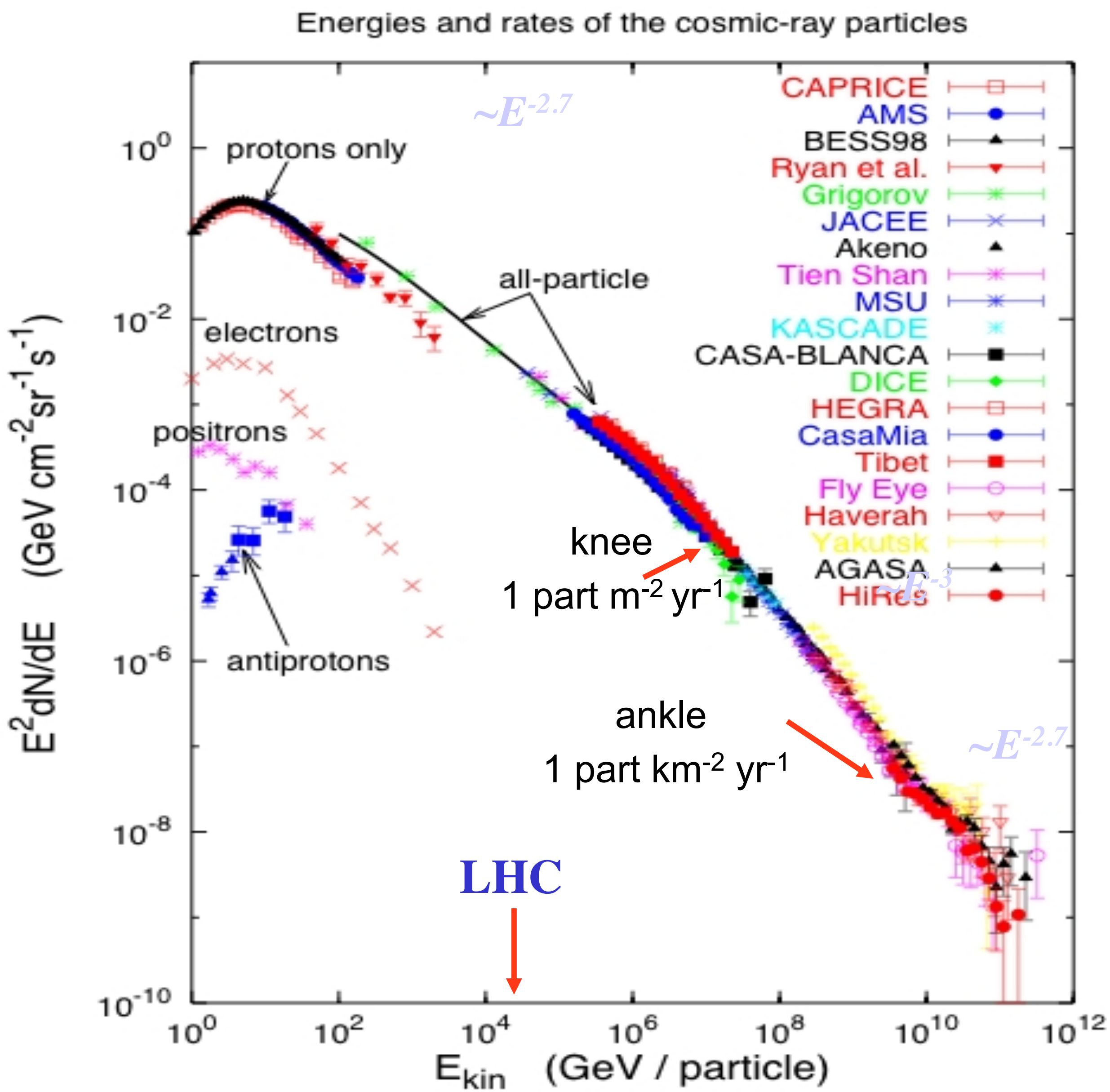
UHE cosmic rays

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

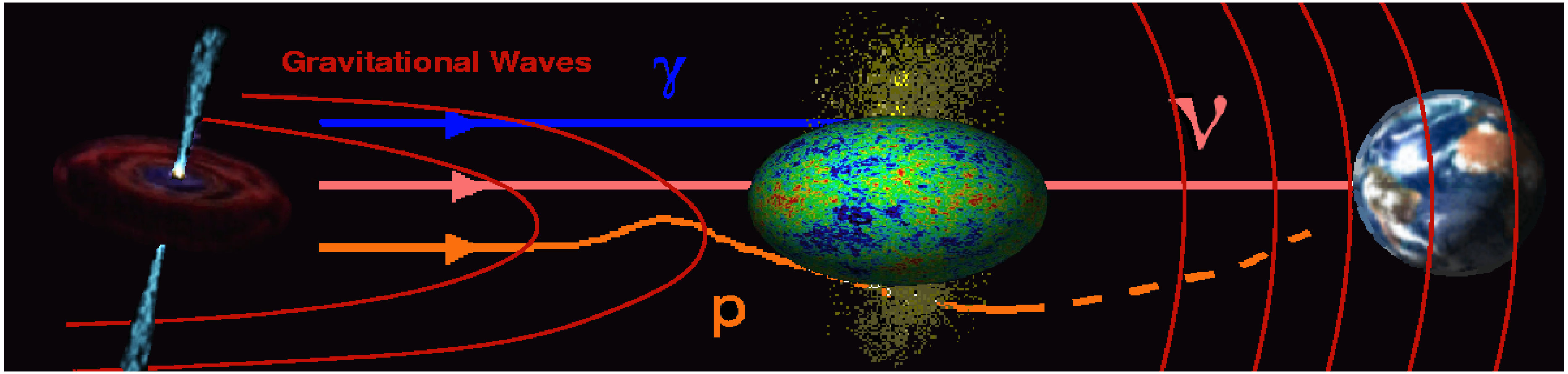
Cutoff now confirmed
But…

where?

how?



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)

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

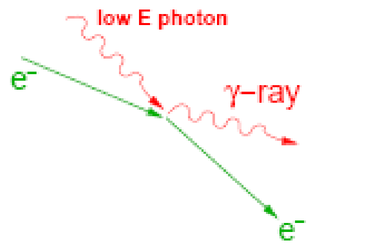
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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

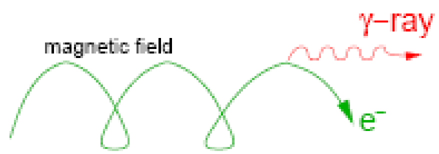
$\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ source $\qquad$ $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ Earth

- 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:

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

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

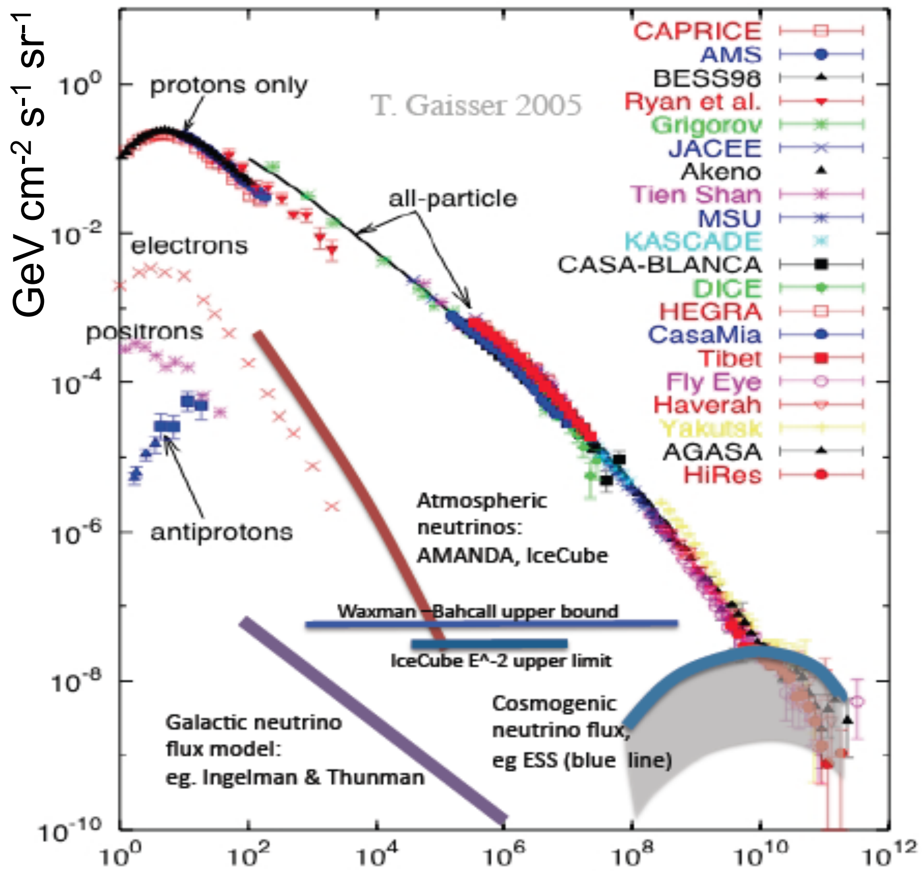
Hypothesis: UHECR are protons,
if not scales with p fraction

- Cosmogenic neutrino flux

Berezinsky & Zatsepin, 1969
UHECR p interact with CMB =>GZK cut off

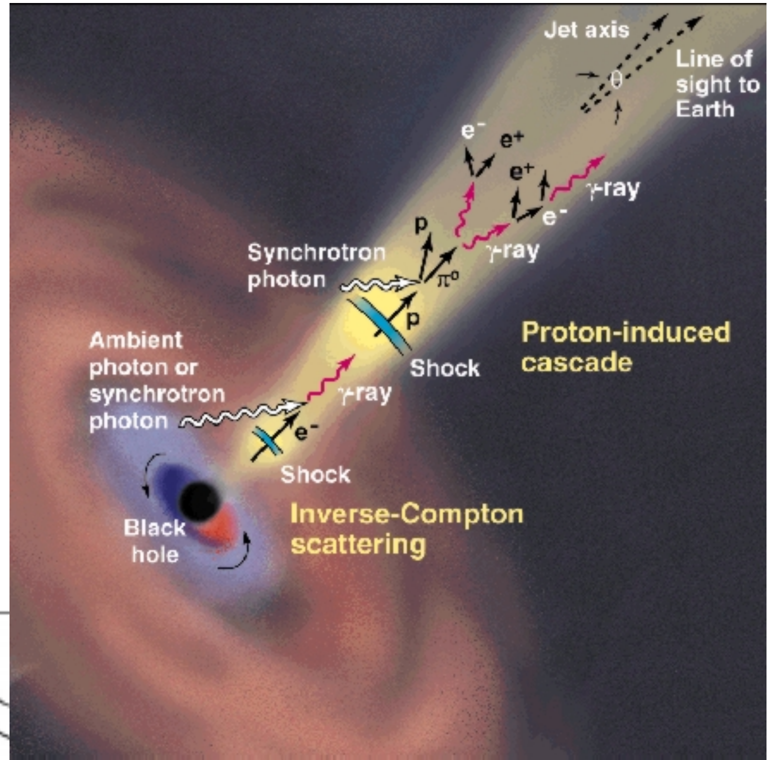
$$p^+ + \gamma_{bkg} \longrightarrow \Delta^+ \longrightarrow \pi^+ + n^0$$

→ UHE ν



Models currently being probed by existing neutrino telescopes

Potential extragalactic sources

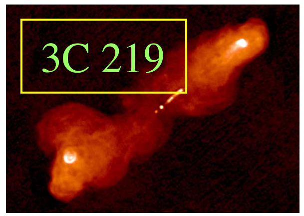


Starburst Galaxies

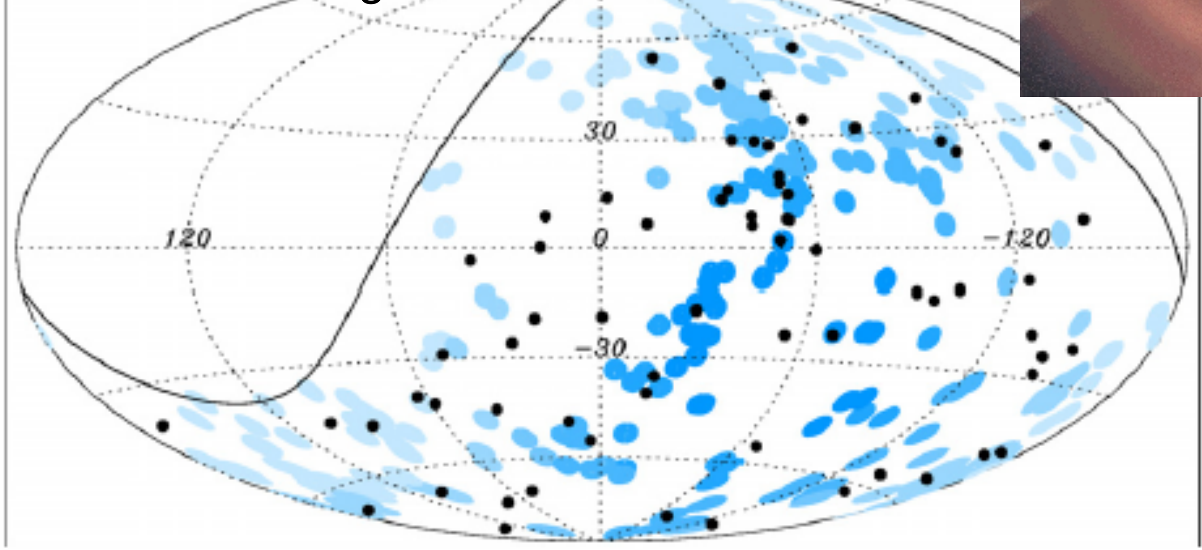
Active Galactic Nuclei (AGN)

Steady (though variable) emissions

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



AUGER events 69 evts E>55 EeV correlate with VCV catalogue



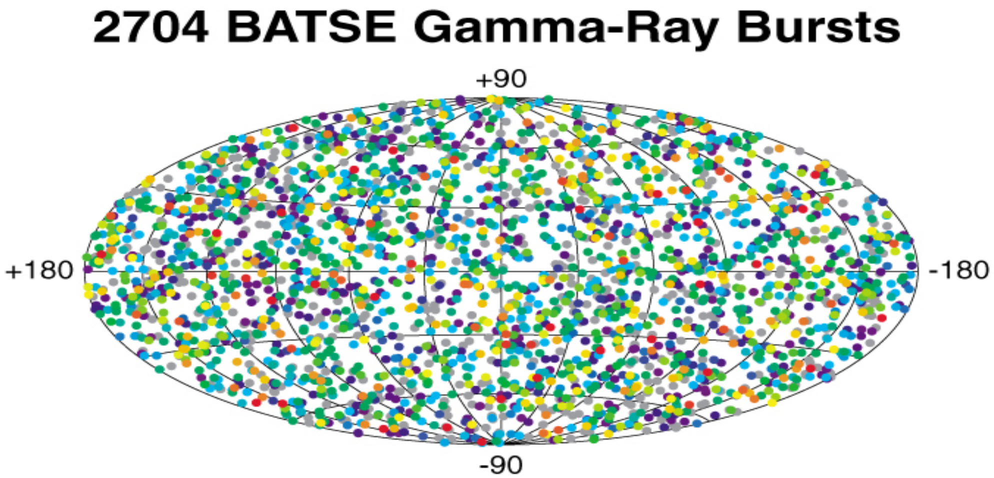
📖 Astropart. Phys. 34 (2010)

The correlation rate has decreased from 68% (2007) to 38% (2010)
More statistics is required

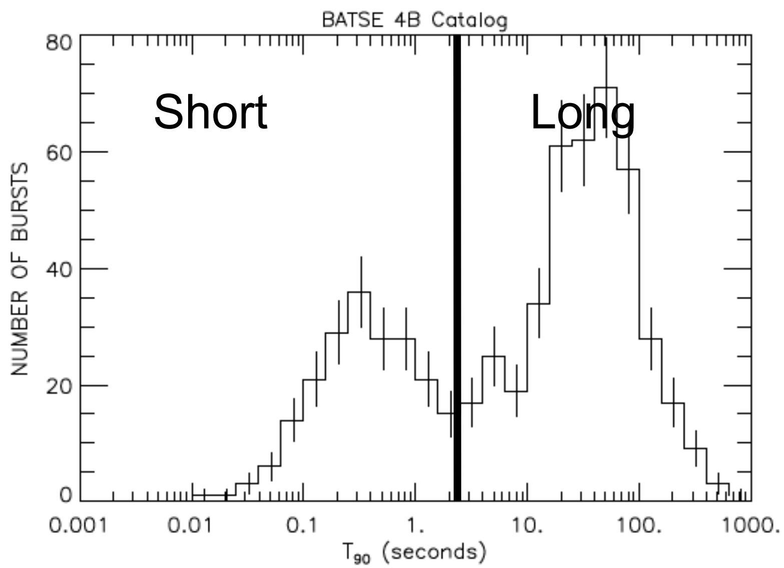
Gamma-ray Bursts

See F. Daigne's lectures

- GRBs are intense and short-lived flashes of gamma-rays
- Tens of keVs to tens of GeVs



- Two populations
  - Long duration (t≥2s)
    - Typical distance ~ 1 Gpc
  - Short duration (t≤2s):
    - Typical distance ~ few 100 Mpc



- Candidates for:
  - Acceleration of cosmic rays,
  - Emission of HE neutrinos (rich in baryon?)
  - Gravitational waves (massive progenitor?)

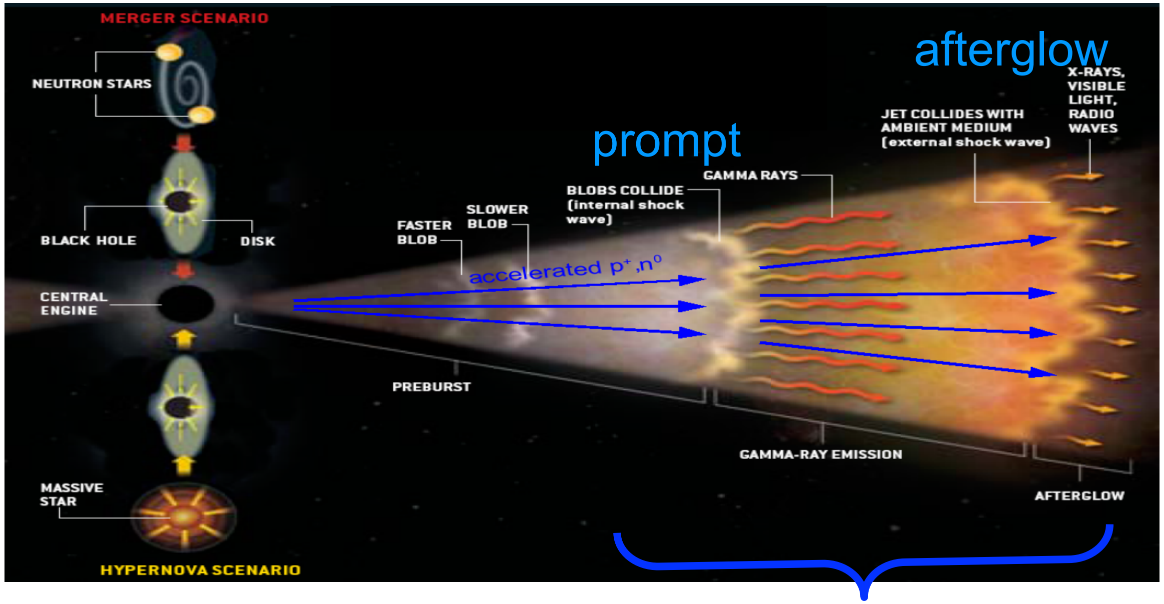
GW and HE neutrinos from GRBs

The fireball model:

Ejection of ultra relativistic plasma of shock-accelerated particles

Short GRB progenitor:
coalescing binaries involving BH and/or neutron stars.
→ GW associated to coalescence process (inspiral)

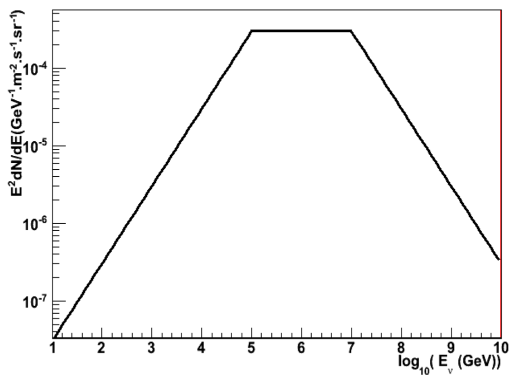
Long GRBs progenitors:
associated to core-collapse supernovae (collapsars)
→ GW burst during collapse



HEN emitted in baryon-loaded jets during prompt (TeV-PeV) & afterglow (PeV – EeV) phases

- Waxman and Bahcall estimated the diffuse flux of neutrinos from GRBs

📖 Phys. Rev. D64, 023002 (2001). 27



Coincidence window

📖 *GWHEN group, Astropart. Phys. 35 (2011) 1-7*

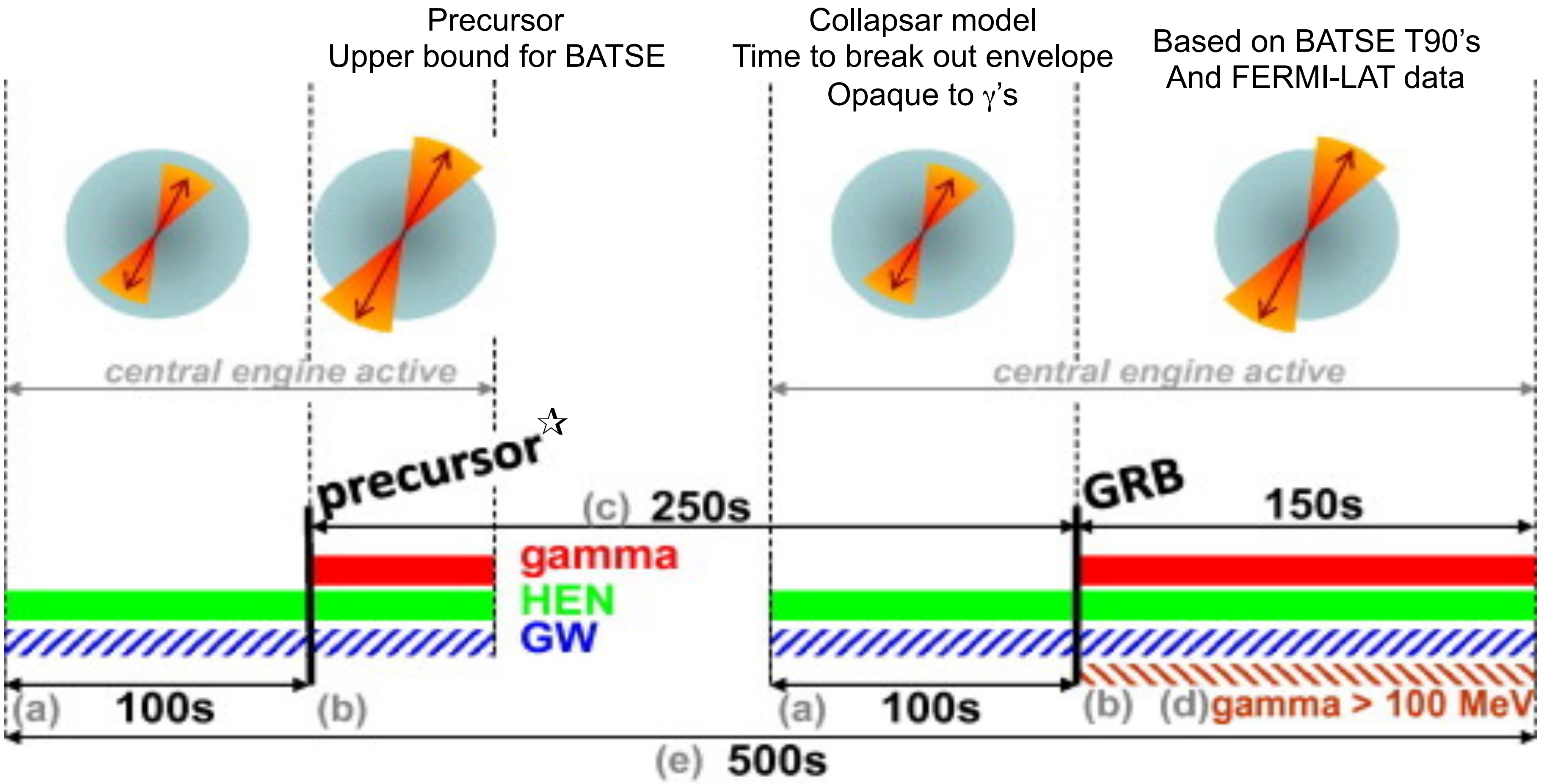


Fig. 1. (a) active central engine before the relativistic jet has broken out of the stellar envelope; (b) active central engine with the relativistic jet broken out of the envelope; (c) delay between the onset of the precursor and the main burst; (d) duration corresponding to 90% of GeV photon emission; (e) time span of central engine activity.

☆ Precursors were observed for ~15% of GRBs (long and short (8%))
Emission mechanisms might be that of prompt GRBs same model

More (speculative) candidates among GRBs

Observational evidence for Low-Luminosity GRBs (LLGRBs)

- γ-ray luminosity few orders of magnitude smaller
- often associated with SN events
- 10 x more frequent than long GRBs in local universe

→ produced by a particularly energetic population of core-collapse SNe ?

- mechanism still debated ! proposed models include

- Choked GRBs: successful jets unable to break through the stellar envelope
(Eichler & Levinson, 1999; Mészaros & Waxman, 2001)

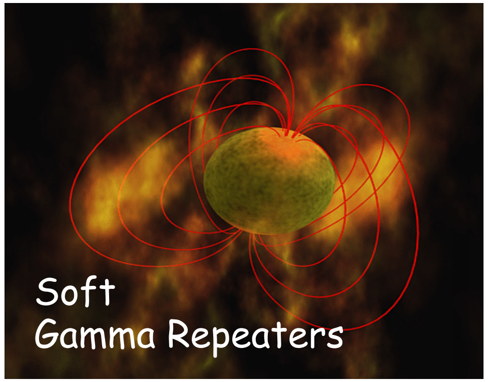
- Failed GRBs: mildly relativistic, baryon-rich and optically thick jets
(Razzaque, Meszaros & Waxman, 2003 ; Ando & Beacom, 2005)

	SN	"Failed" GRBs	GRB
Energy (erg)	10^{51}	10^{51}	10^{51}
Rate (yr^{-1})	$\sim 10^{-2}$	$\sim 10^{-5}$ - 10^{-2}	$\sim 10^{-5}$
Γ	~1	~3-100	~100-10^3

From Ando (2009)

→ potential missing link between SN and regular GRBs
→ similar energy budget BUT higher rate
→ GW/HEN observations are crucial to constrain the models

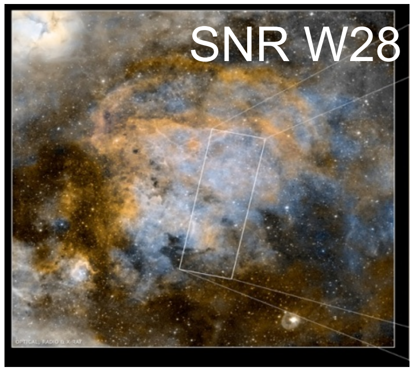
Potential Galactic sources



• **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

• Supernovae Remnants
Evidence for hadron acceleration
SN1006, W28, W44, W49B, W51C …



• Dense regions
Sun, Galactic Centre, Interstellar medium

→ Mostly seen by Northern Hemisphere NT

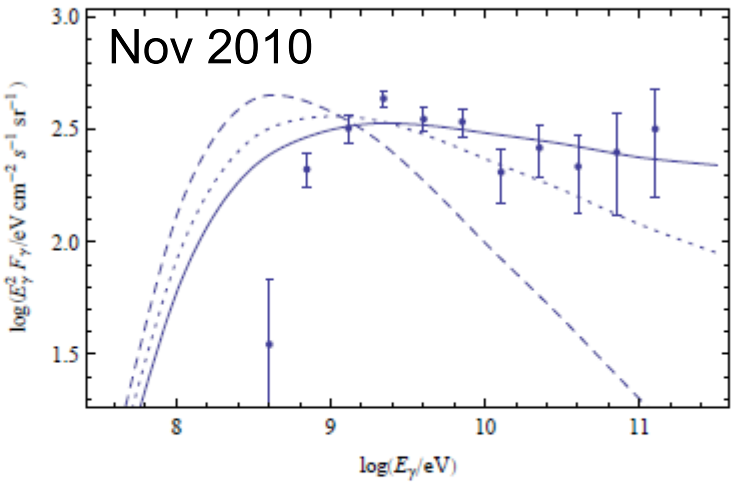
Fermi Bubbles

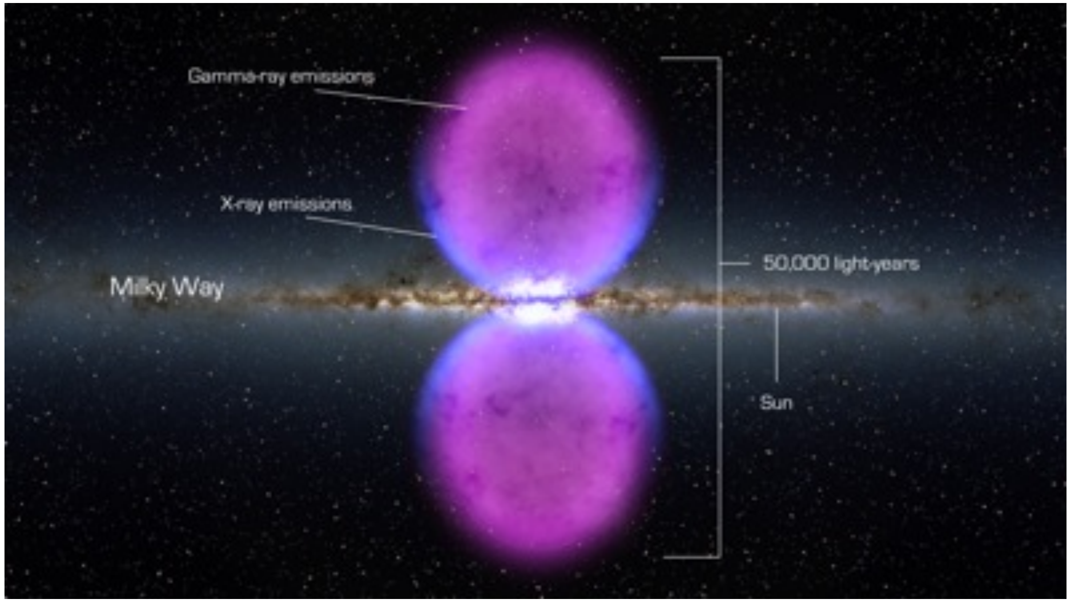
“Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays”

🕮 M. Crocker and F. Aharonian Phys. Rev. Lett. 106 (2011) 11102

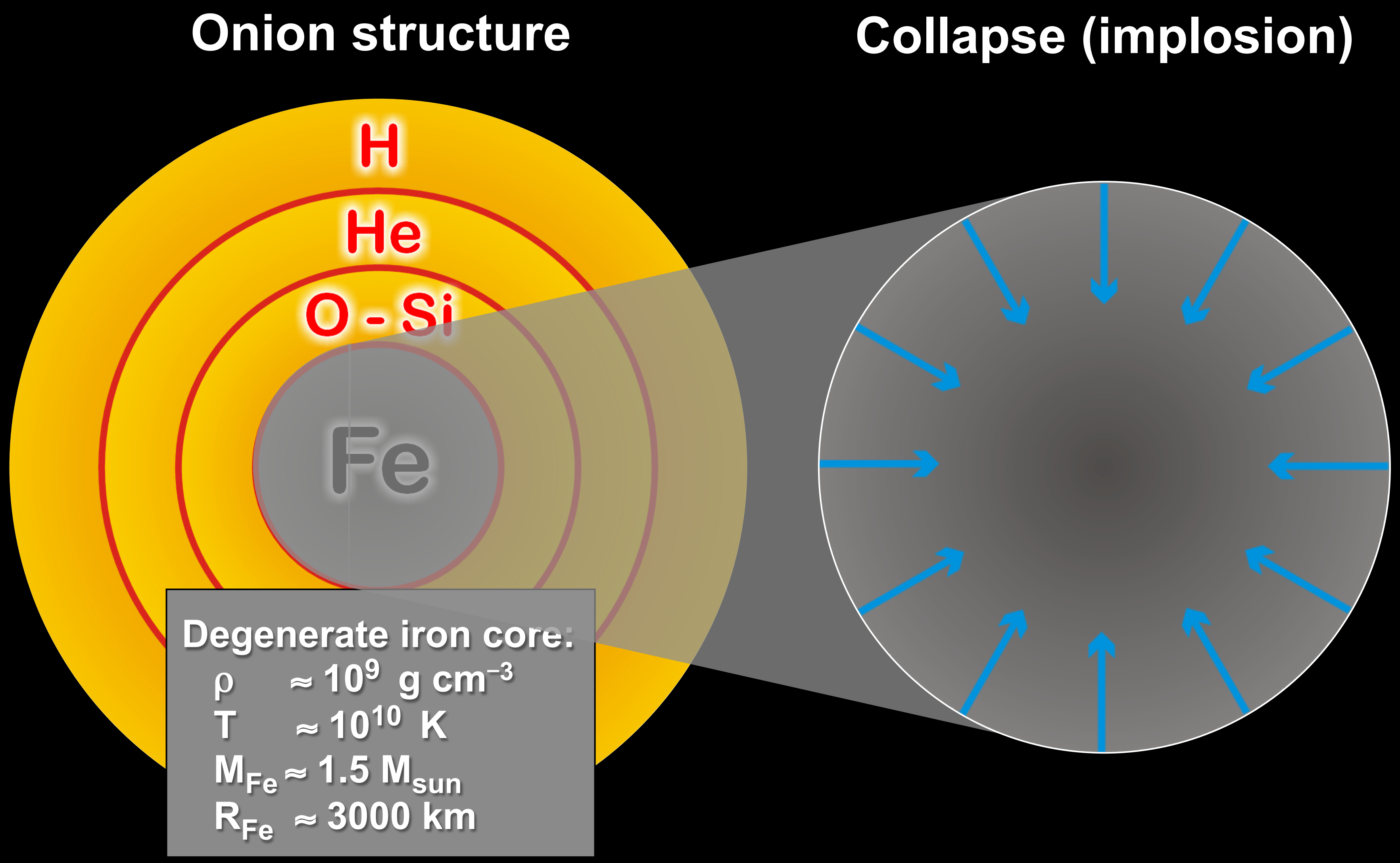
“Bilateral ‘bubbles’ of emission centered on the core of the Galaxy and extending to around 10 kpc above and below the Galactic plane. These structures are coincident with a non-thermal microwave ‘haze’ found in WMAP data and an extended region of X-ray emission detected by ROSAT.”

Spectre de Fermi $E^{-2.1}$





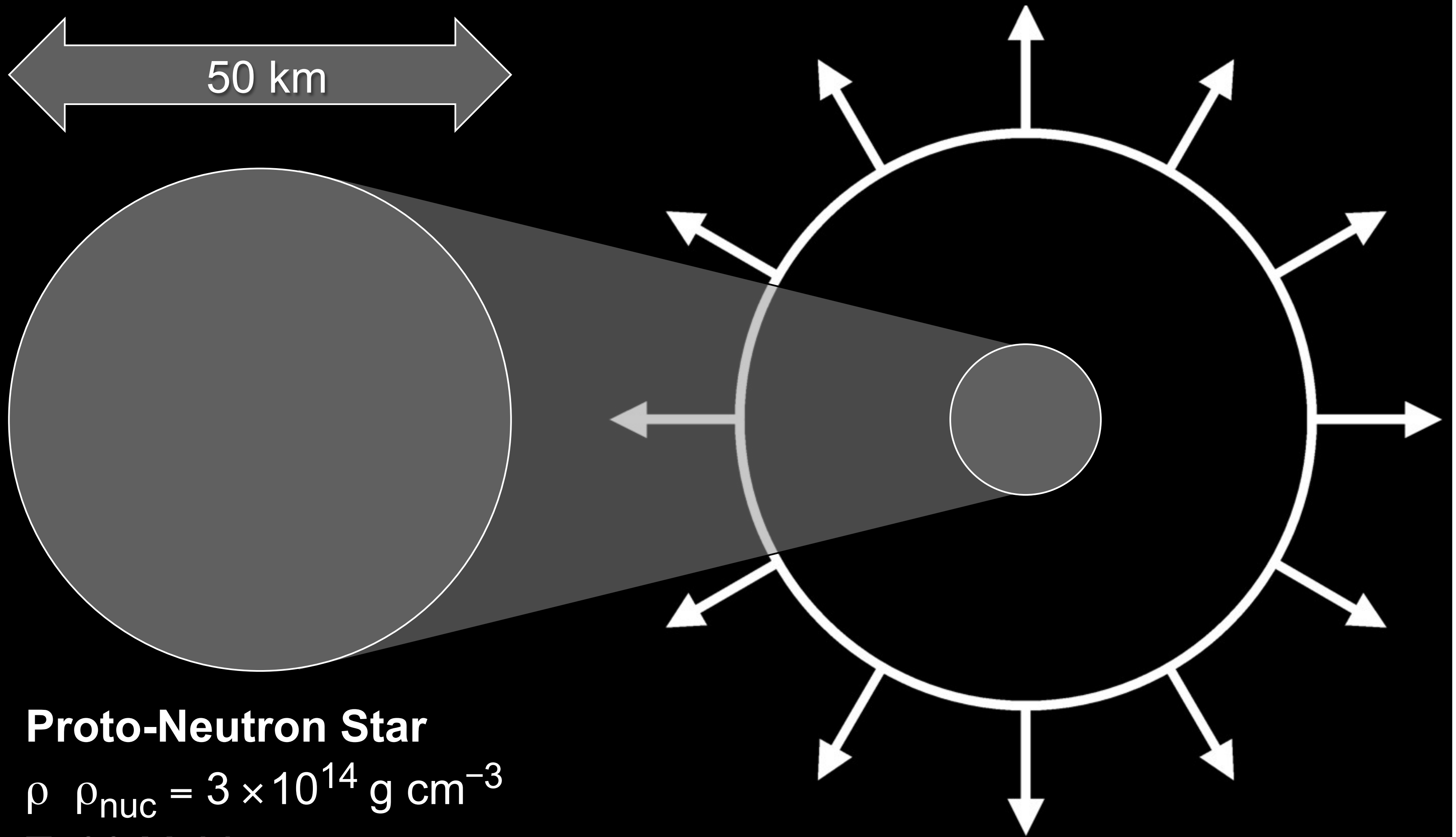
Stellar Collapse and Supernova Explosion



From G. Rafflet

Stellar Collapse and Supernova Explosion

Newborn Neutron Star **Explosion**



Proto-Neutron Star

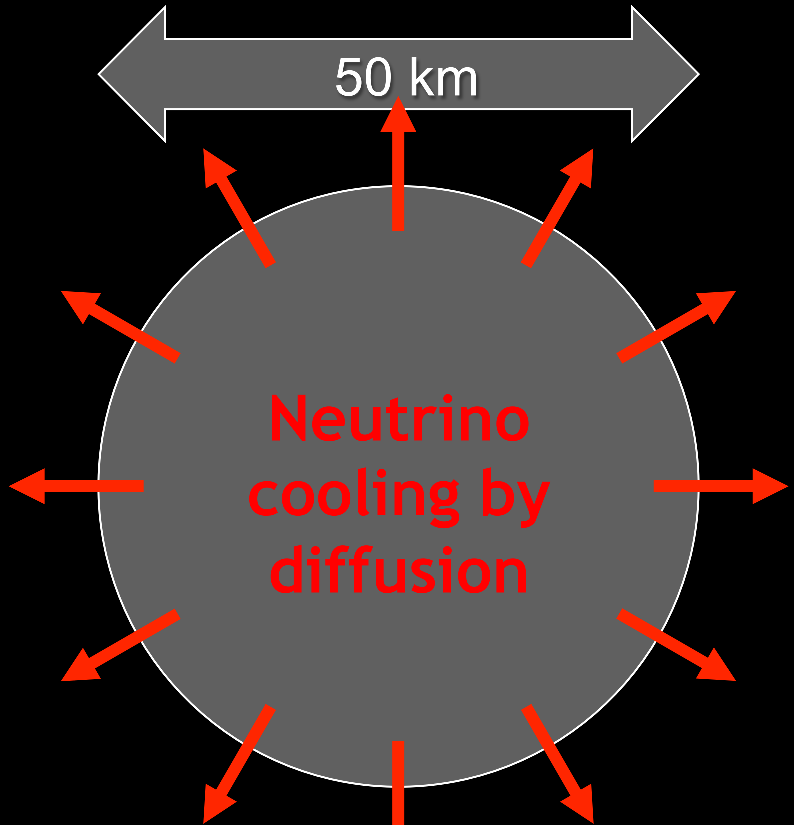
$\rho \quad \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

T 30 MeV

From G. Rafflet

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \quad \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

T 30 MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion

0.01% Photons, outshine host galaxy

Neutrino luminosity

$L_\nu \quad 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

$3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

From G. Rafflet

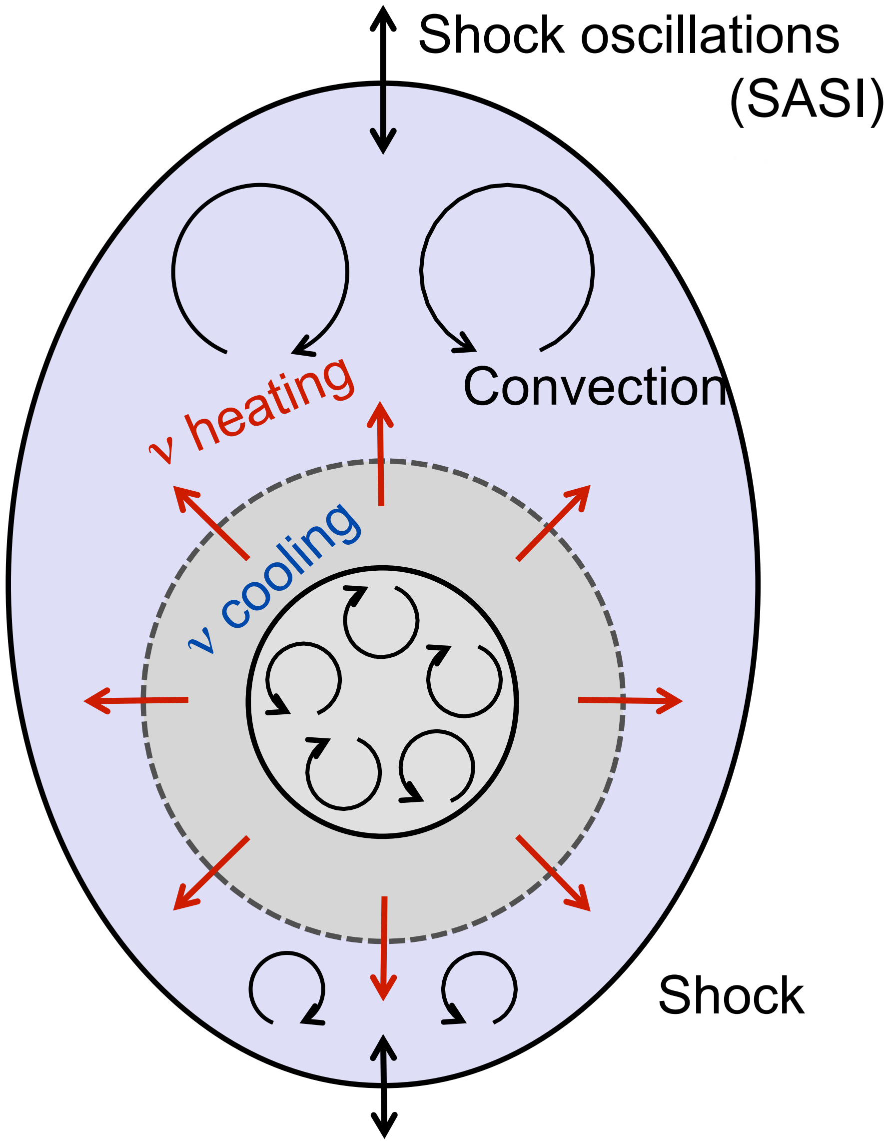
Neutrino-Driven Mechanism – Modern Version

- A more complex reality….

- Successful explosions in 1D and 2D for different progenitor masses (e.g. Garching group)

- Details important (treatment of GR, ν interaction rates, etc.)

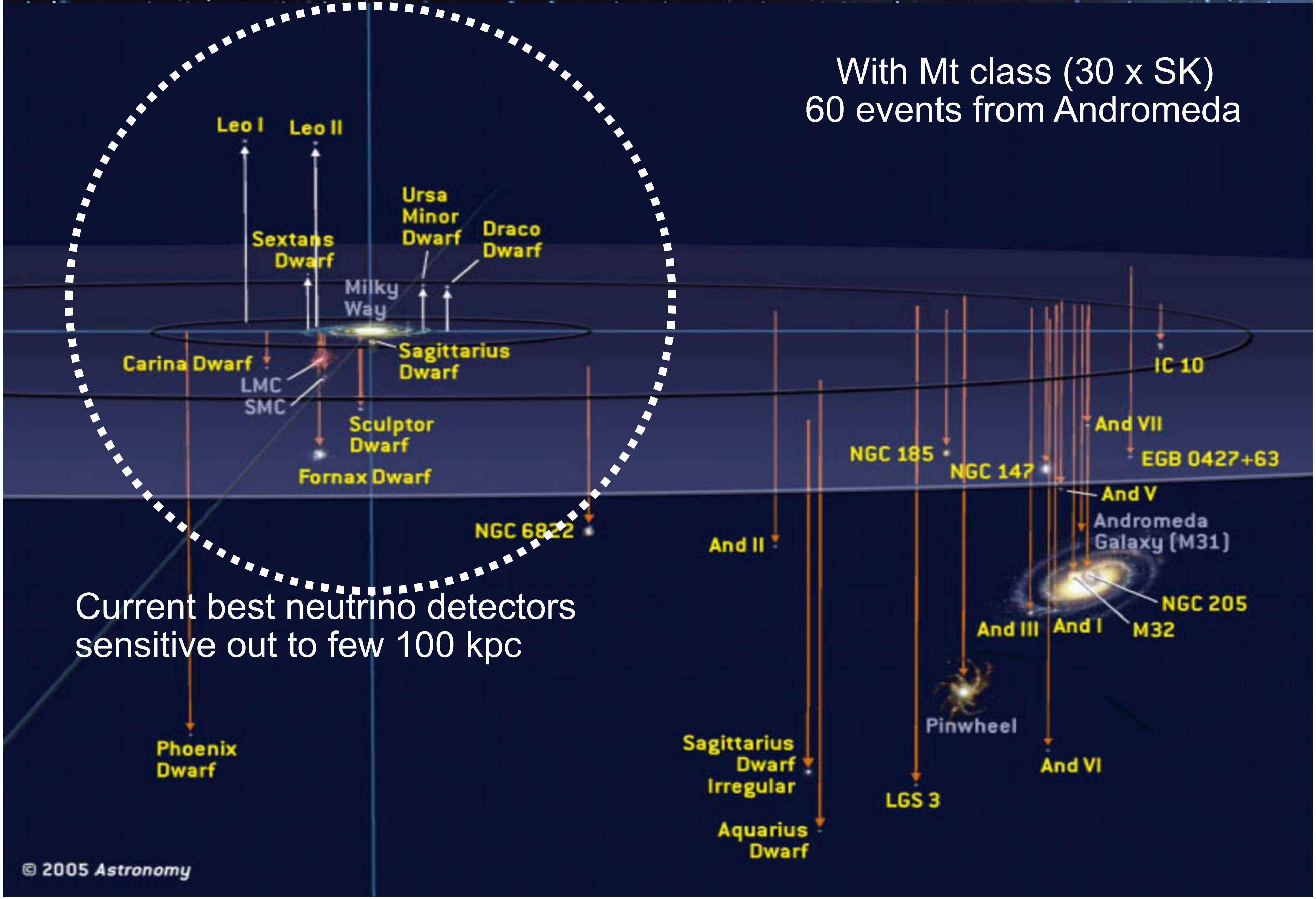
More data needed…



From G. Raffelt

Local SN rate

With Mt class (30 x SK)
60 events from Andromeda

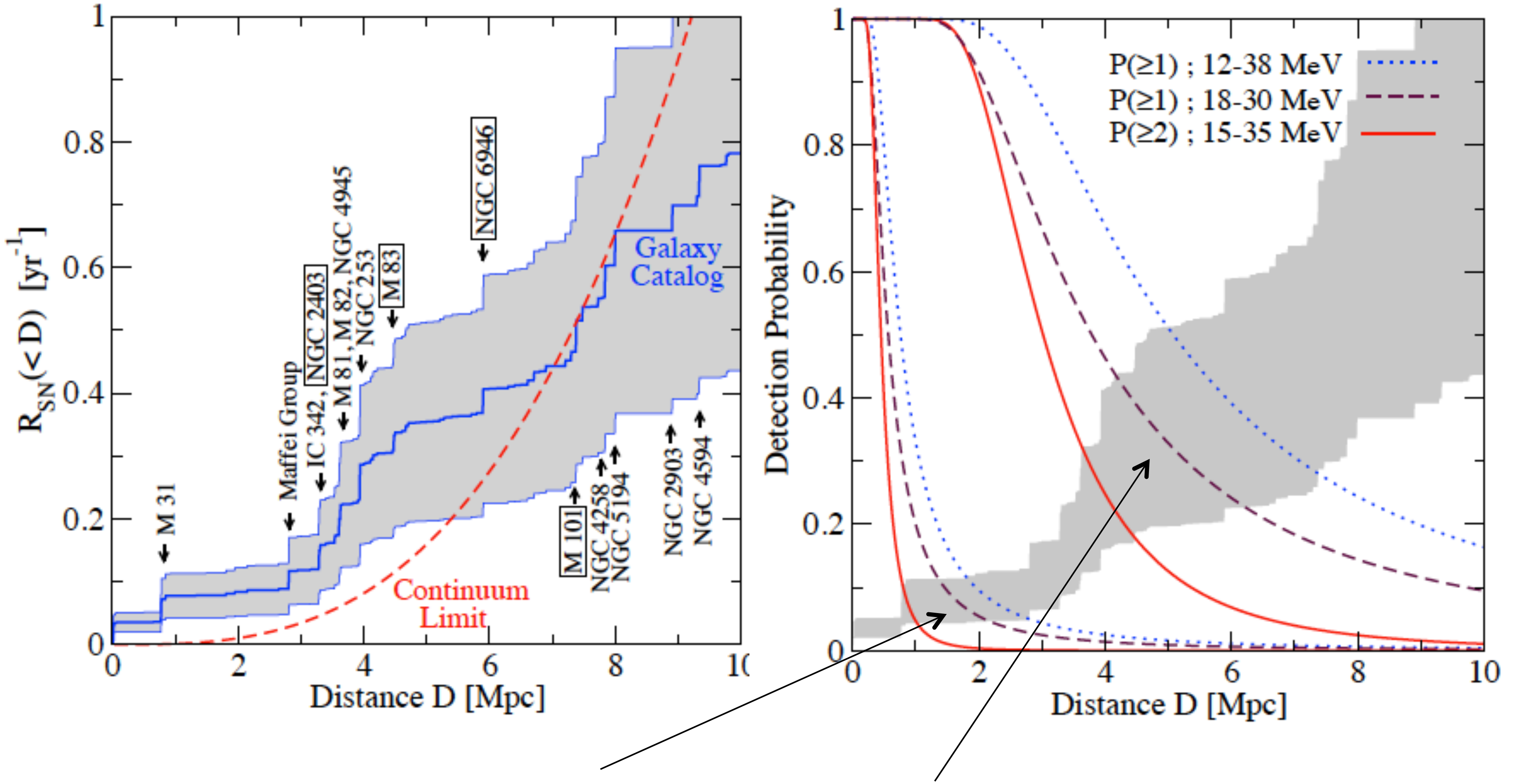


Current best neutrino detectors
sensitive out to few 100 kpc

Searching further away

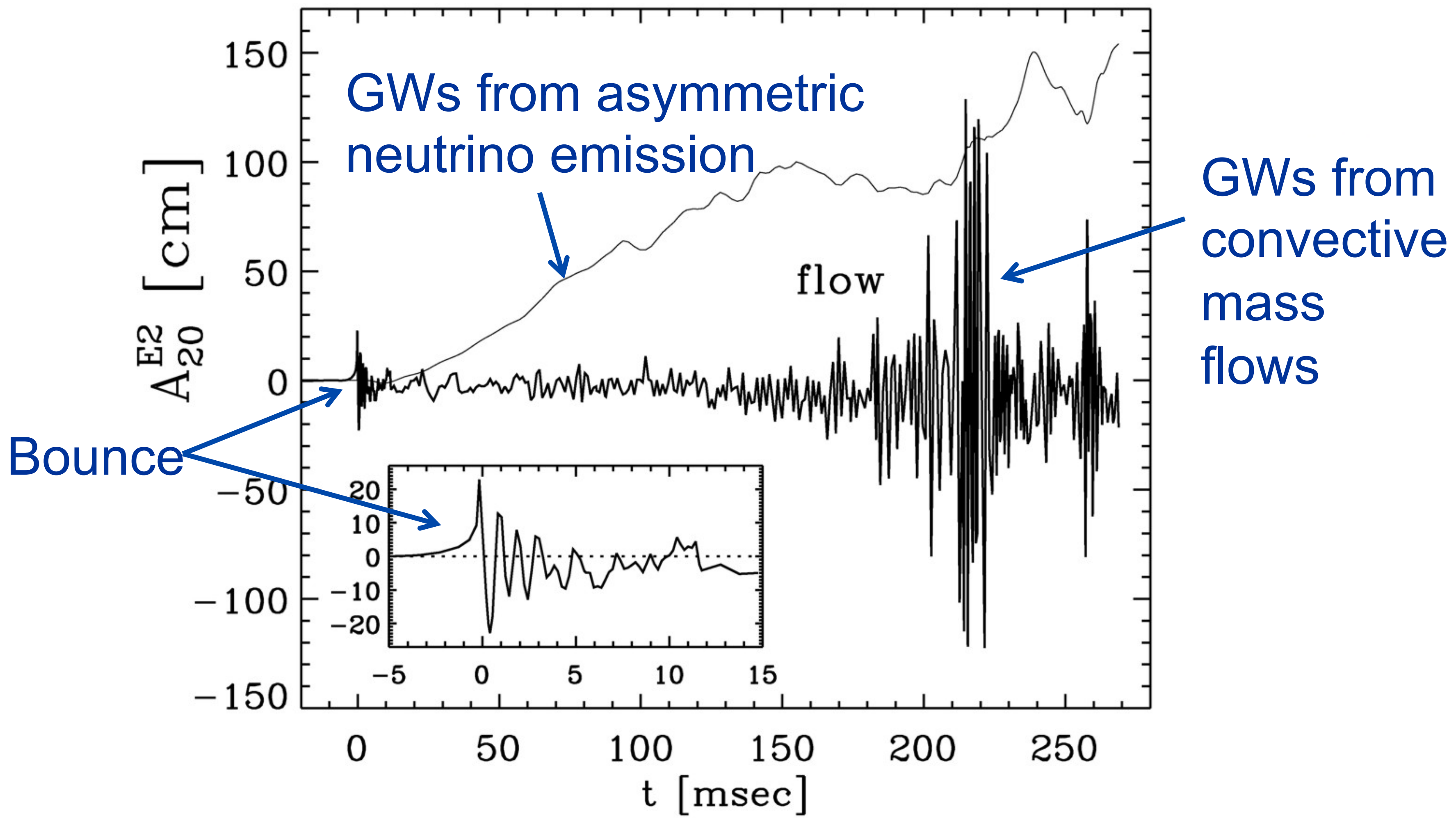
📖 Ando, Beacom, Yuksel, Phys Rev Lett 95 (2005) 171101

Prob. to detect at least one SN neutrino



Numbers stand for SK (22.5 kt) and 1-Mton scale water-Cherenkov detector

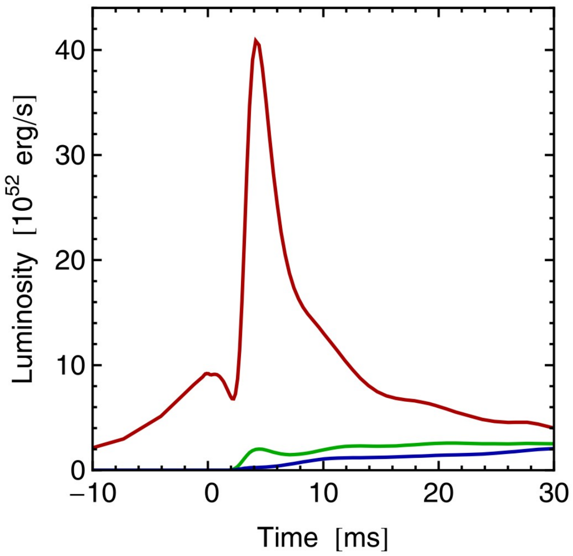
Gravitational Waves emission



📖 Müller, Rampp, Buras, Janka, & Shoemaker, Astrophys.J.603:221-230, 2004

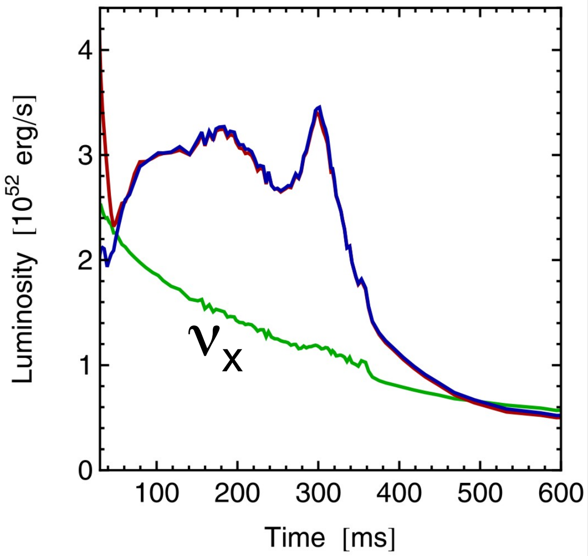
Neutrino emission

Prompt ν_e burst



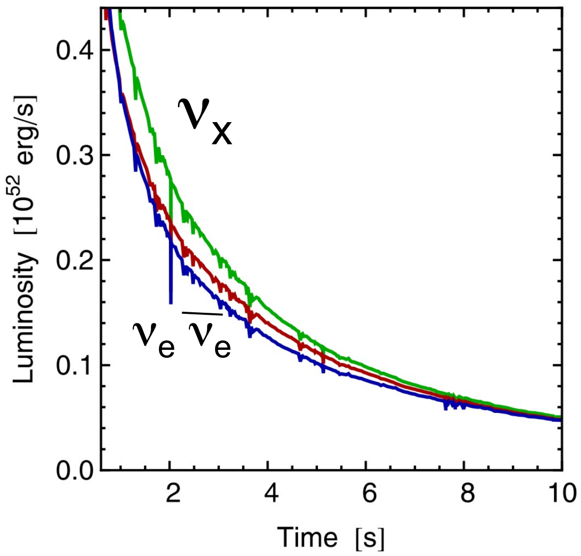
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls 150 km
- Neutrinos powered by infalling matter

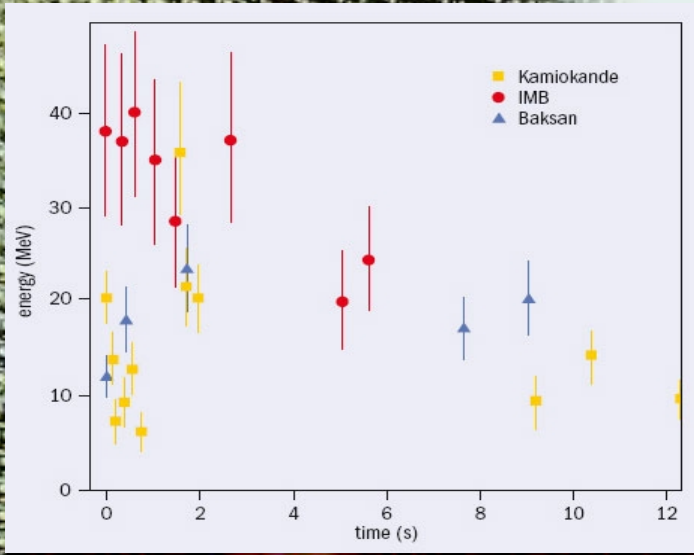
Cooling



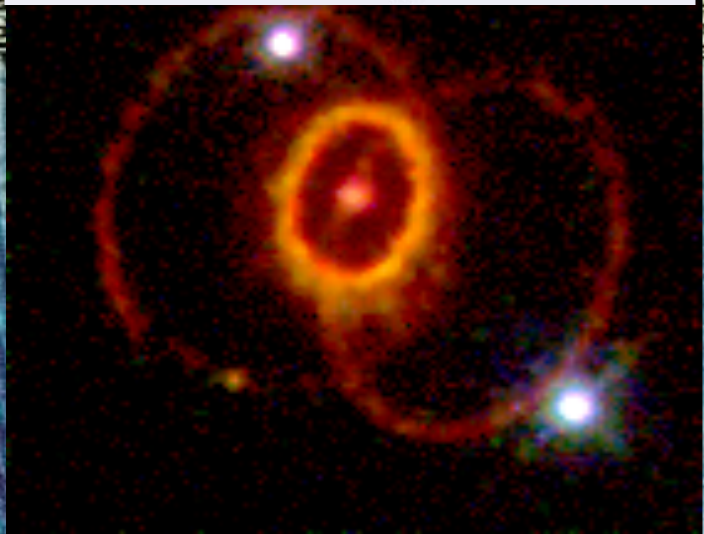
Cooling on neutrino diffusion time scale

📖 Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

First extraterrestrial neutrinos…

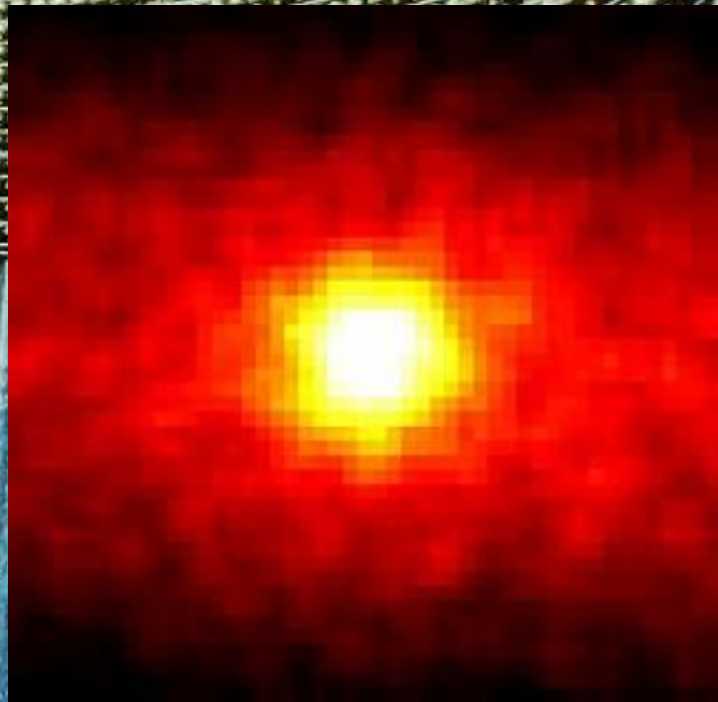


Kamiokande then SuperKamiokande



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.
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

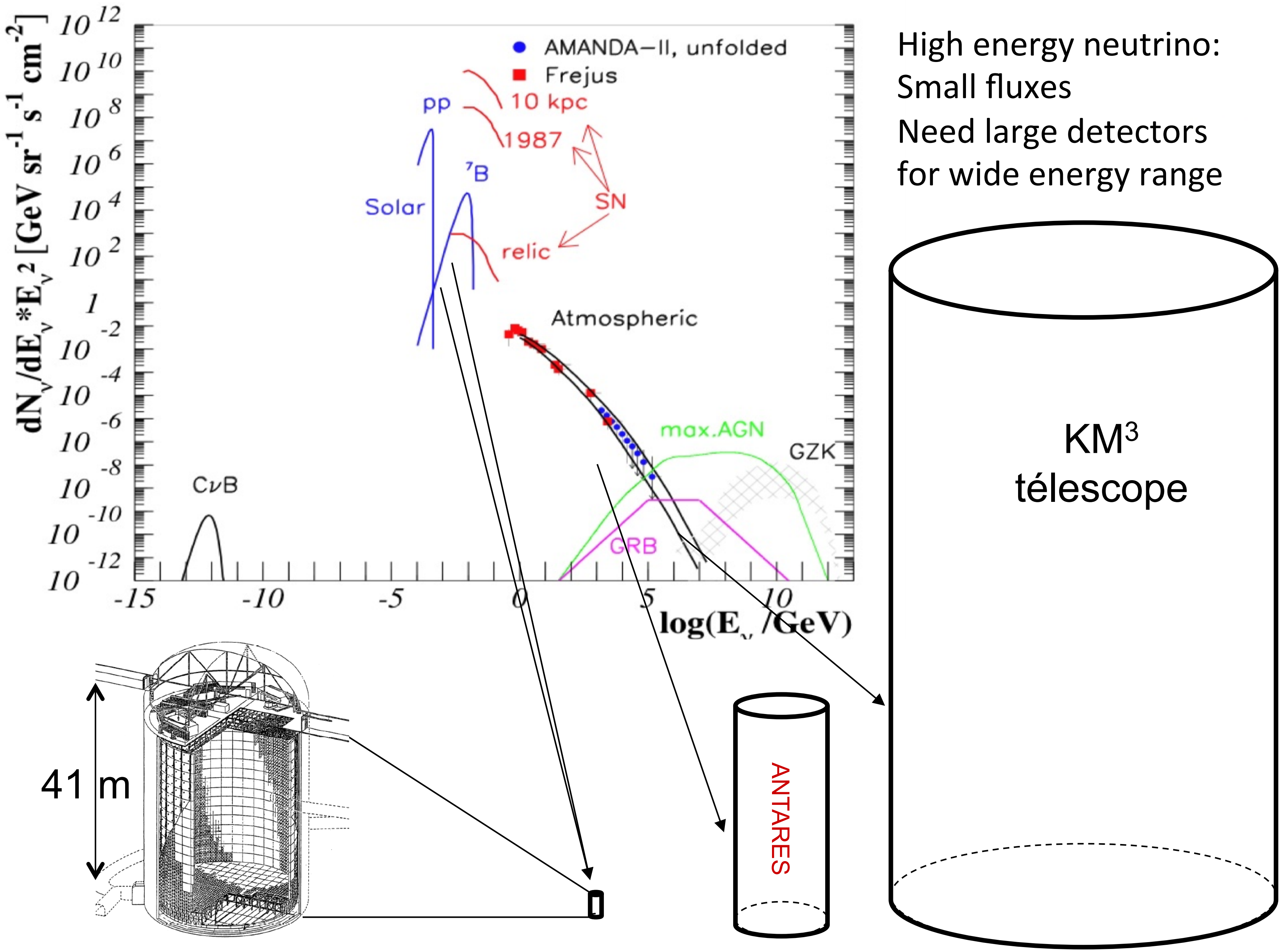
Presence of cosmic neutrinos E > GeV?

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.»

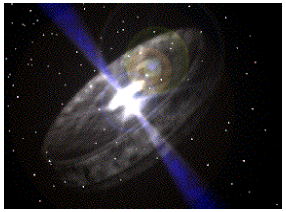
J.Bahcall
New York Times (3 Apr 1987)

From MeV ν to PeV ν



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

Outline

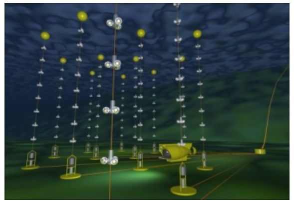


Neutrino astronomy

Historical aspects

Scientific motivations

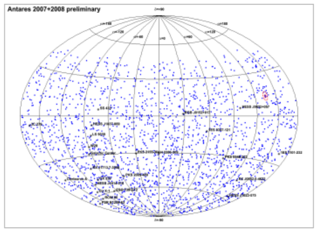
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux

Search for point sources

Multi-messenger search

GWHEN searches

Future prospects

Markov idea: muon neutrino

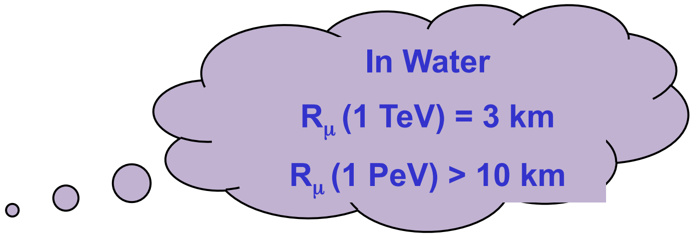
S.B:9.A
Nuclear Physics 27 (1961) 385—394; © *North-Holland Publishing Co., Amsterdam*

ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

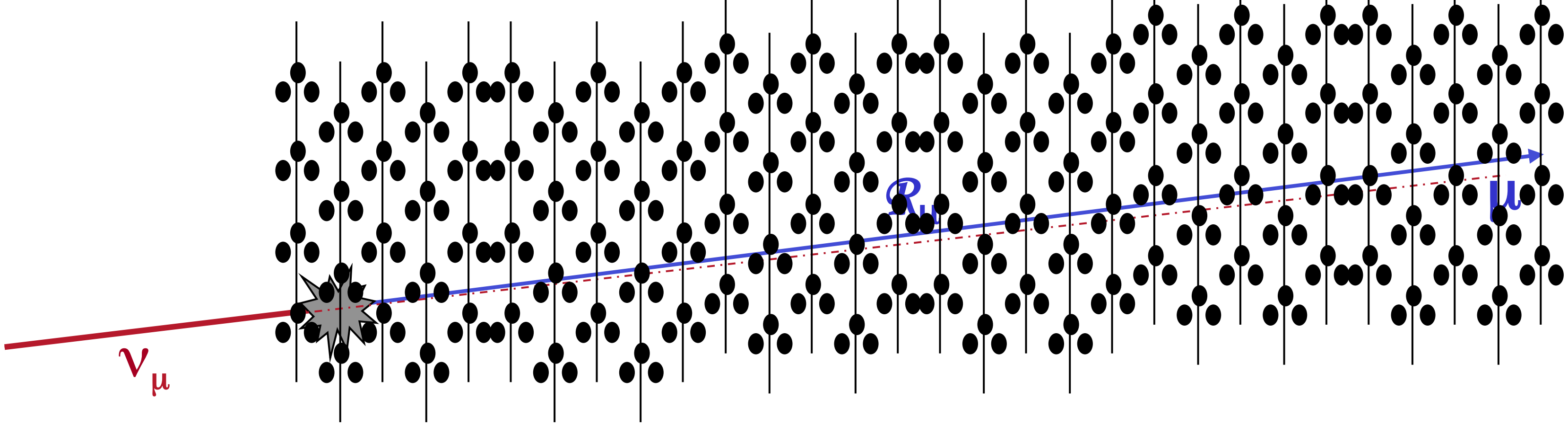
M. A. MARKOV and I. M. ZHELEZNYKH
P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

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.



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

Reconstruction of muon trajectory

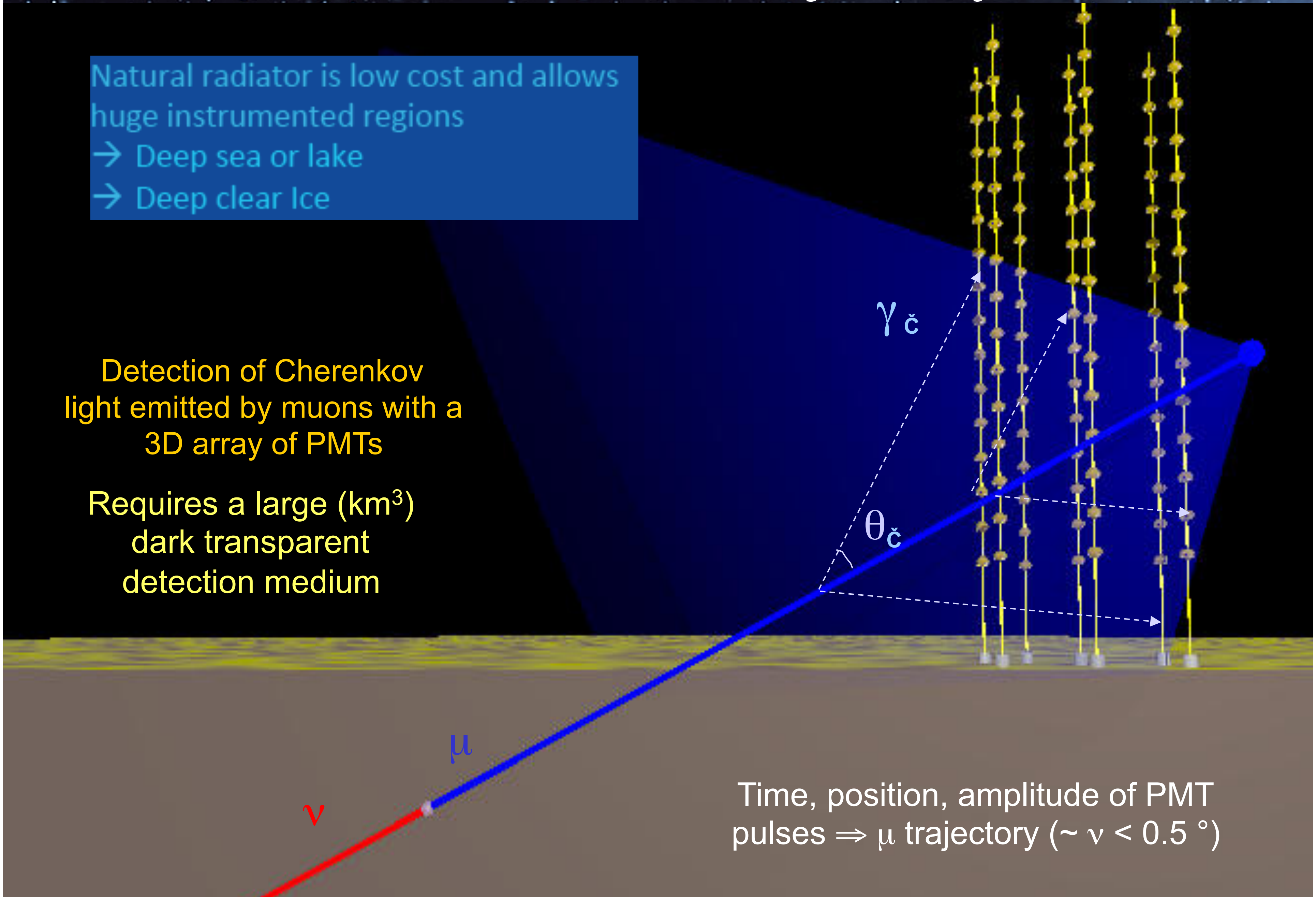
Natural radiator is low cost and allows huge instrumented regions

→ Deep sea or lake

→ Deep clear Ice

Detection of Cherenkov light emitted by muons with a 3D array of PMTs

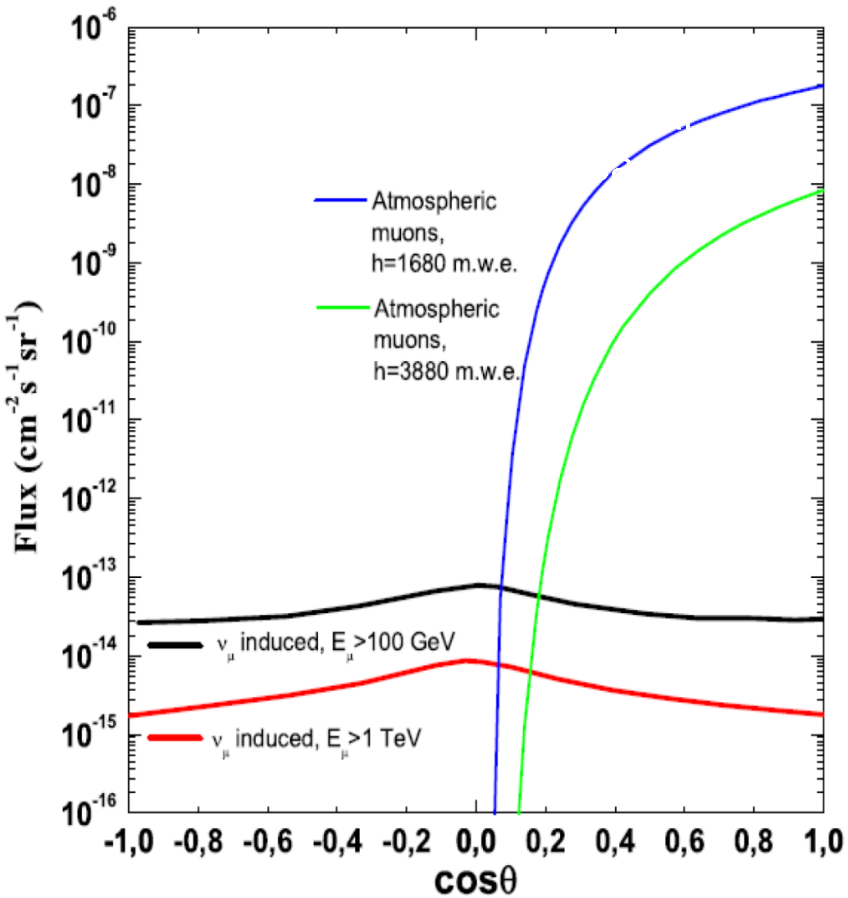
Requires a large (km^3) dark transparent detection medium

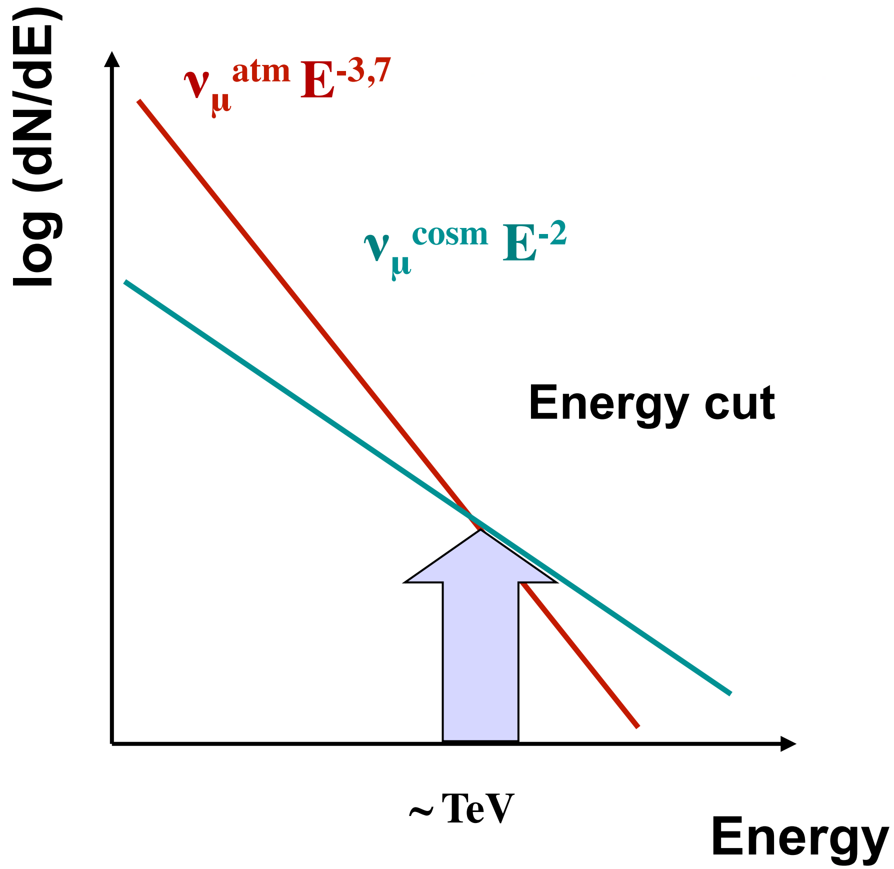


Time, position, amplitude of PMT pulses ⇒ μ trajectory (~ ν < 0.5 °)

Atmospheric background vs cosmic ν's

Atmospheric muons: **shield detector & define signal as upward muons**



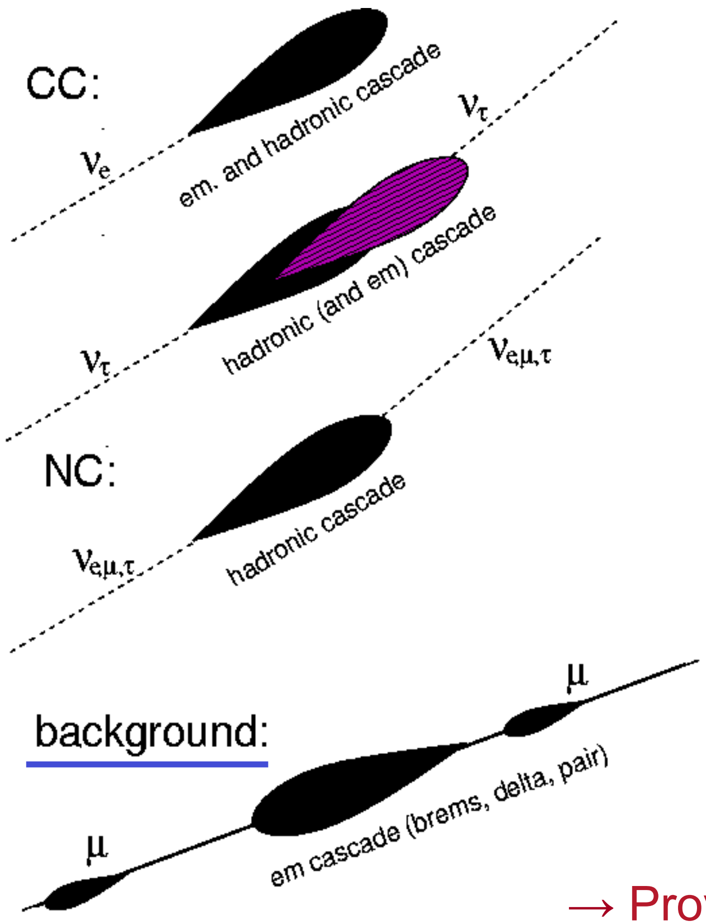


Atmospheric neutrinos: **search for**

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

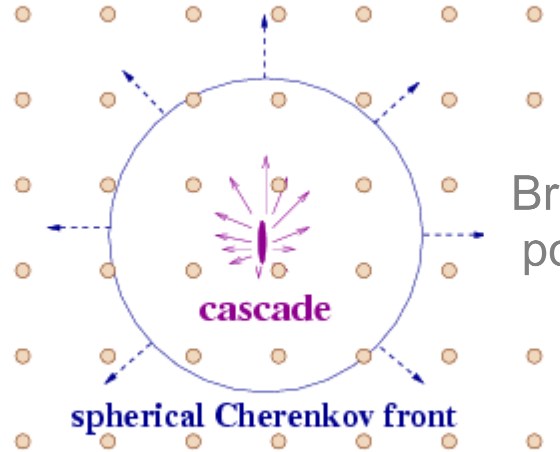
Other neutrino interaction topologies

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



So-called "cascade" events

Generic reconstruction:

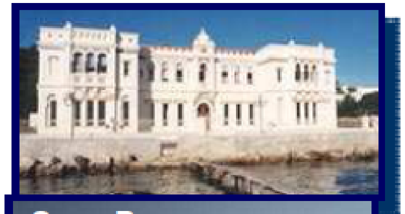


Bright point

→ Provide sensitivity to all neutrino flavors

Neutrino telescopes (TeV)

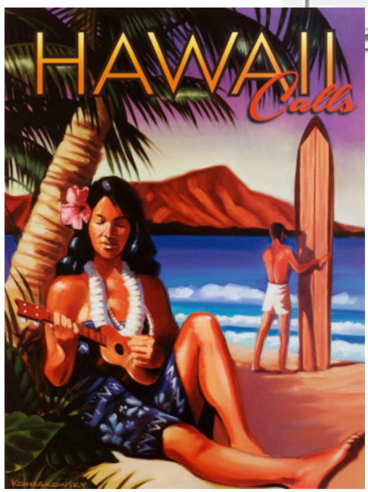
{ANTARES, BAIKAL, ICECUBE} currently working



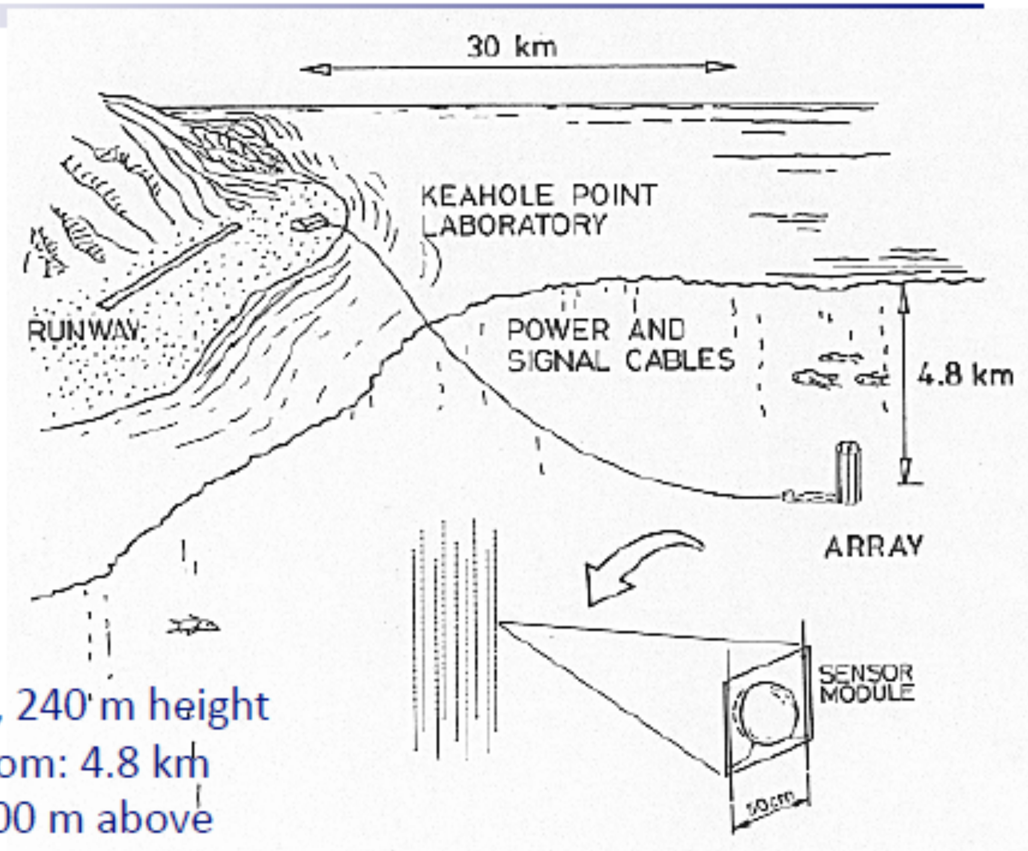
{ANTARES, NEMO, NESTOR} ∈ Consortium KM3NeT

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.

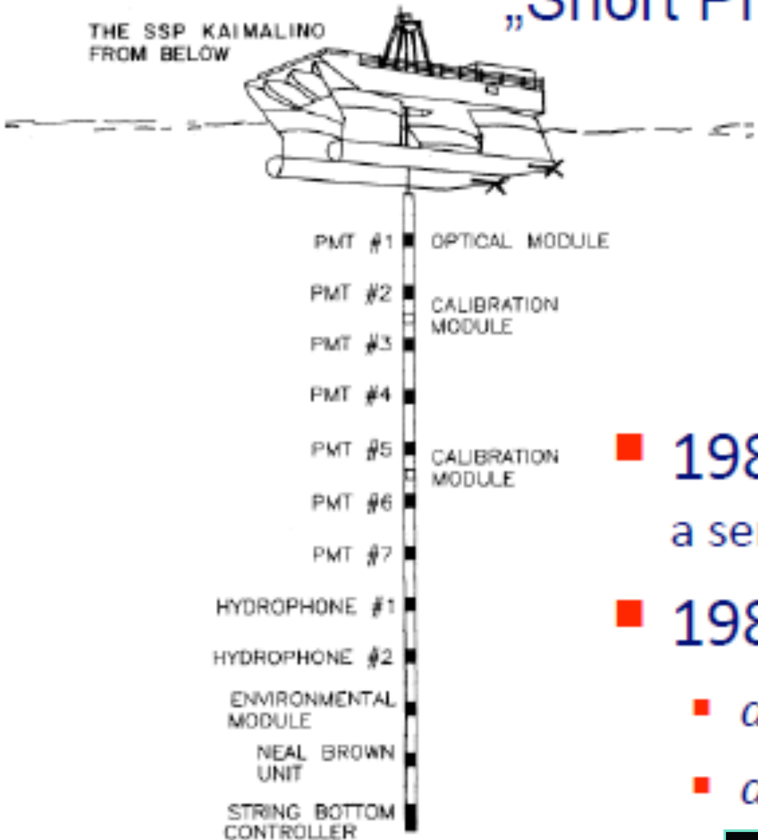


DUMAND-II (The Octagon)



- 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

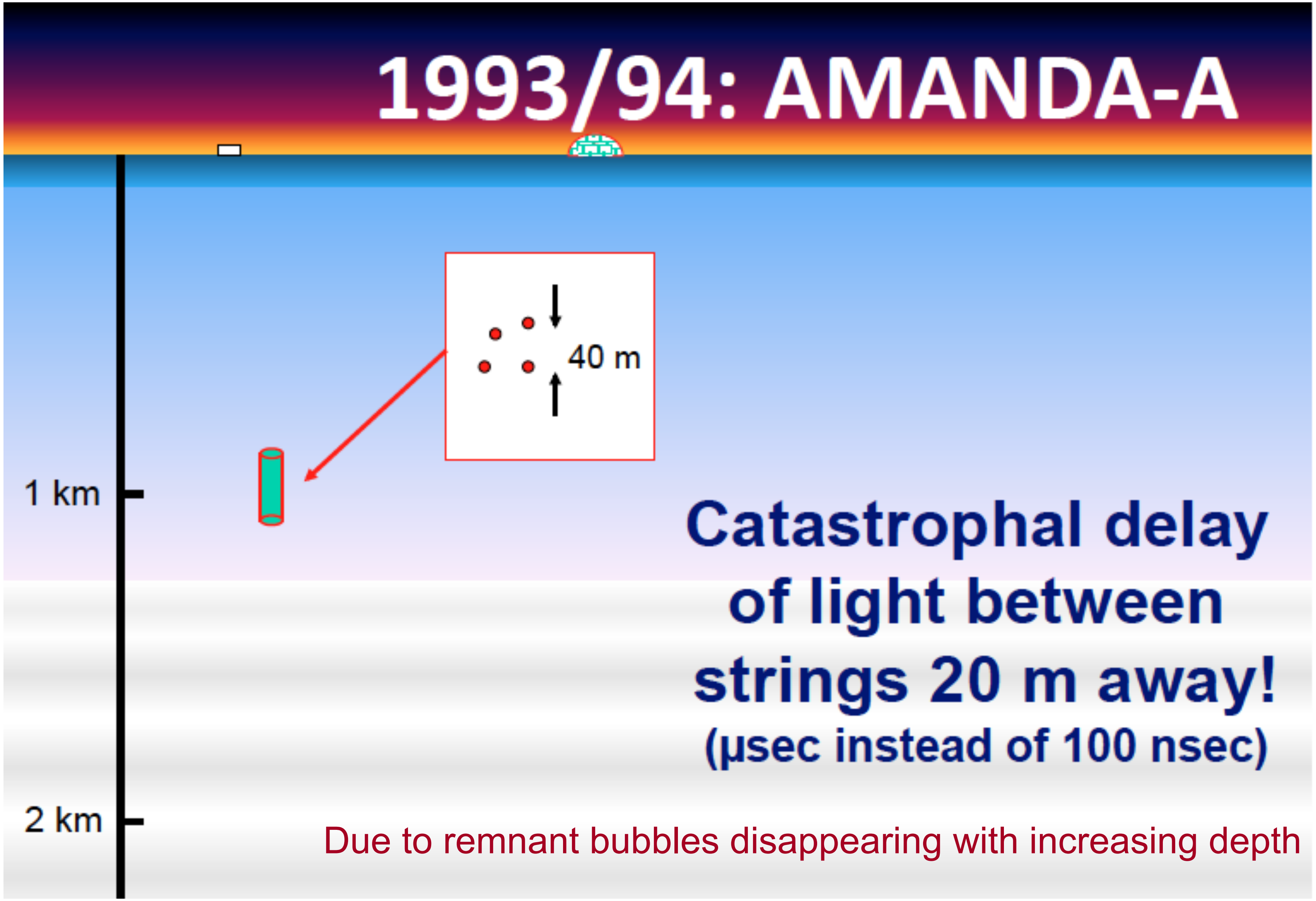
D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

* 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 !

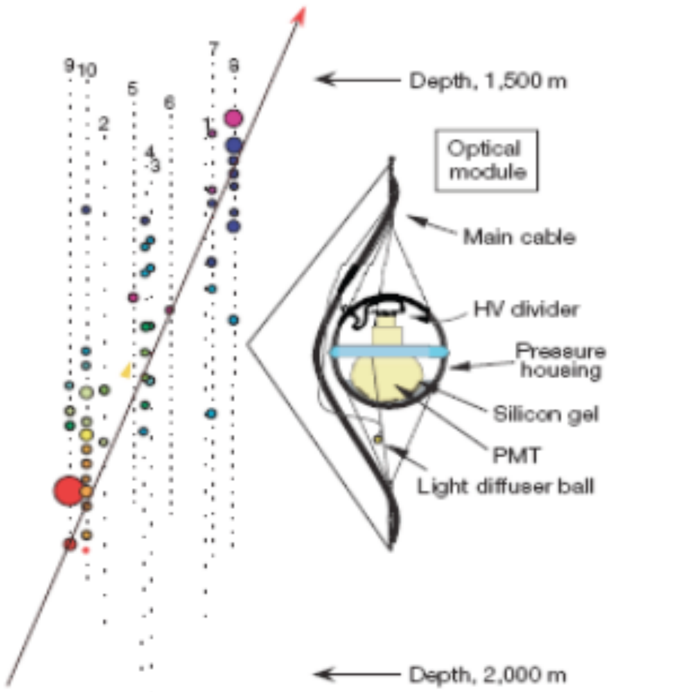
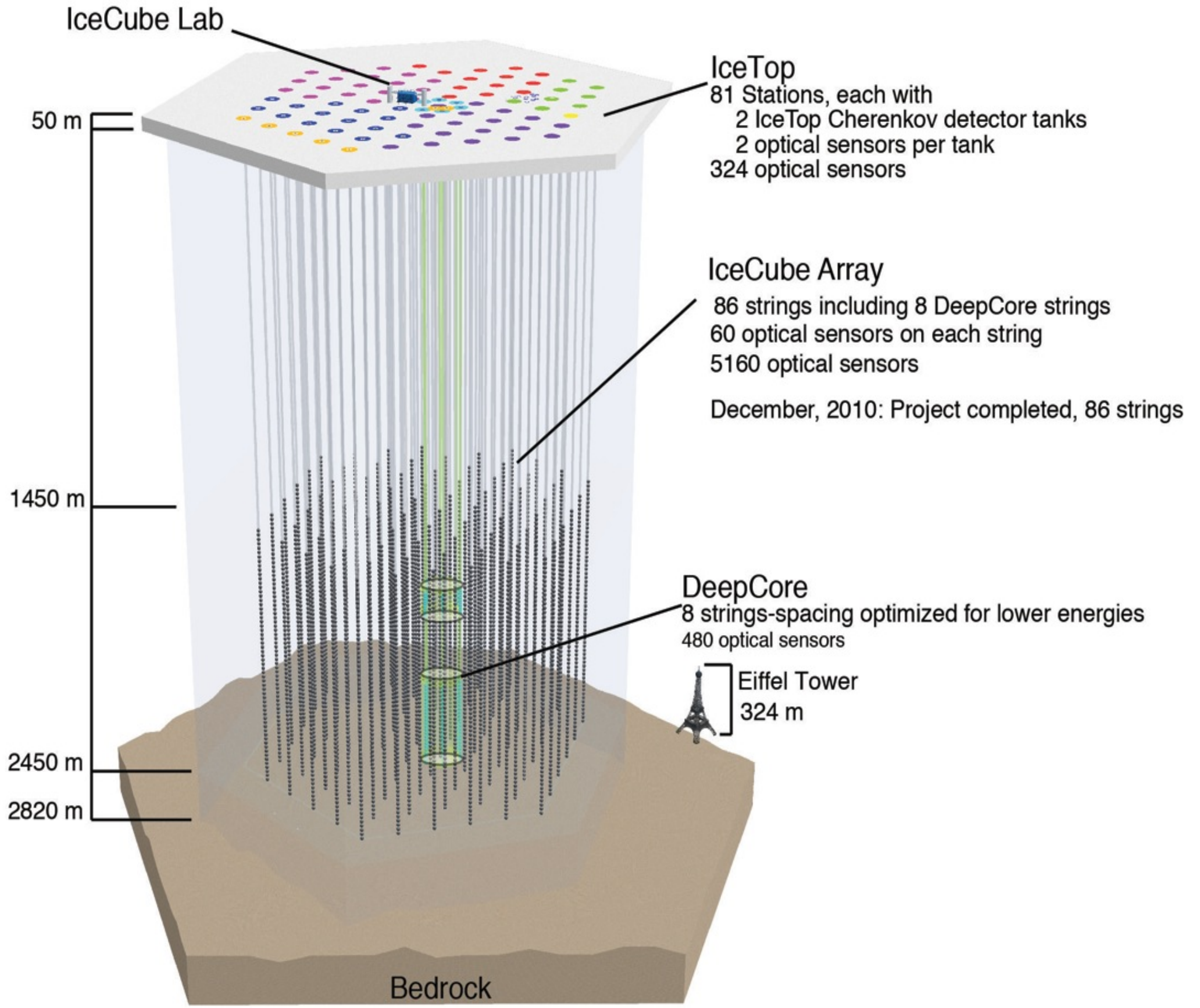
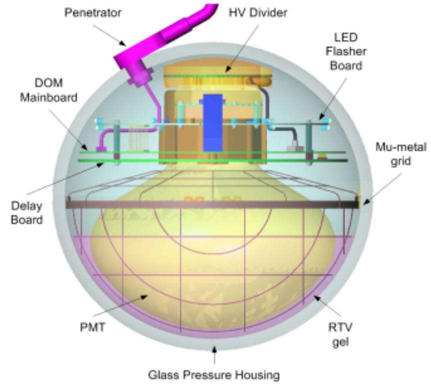


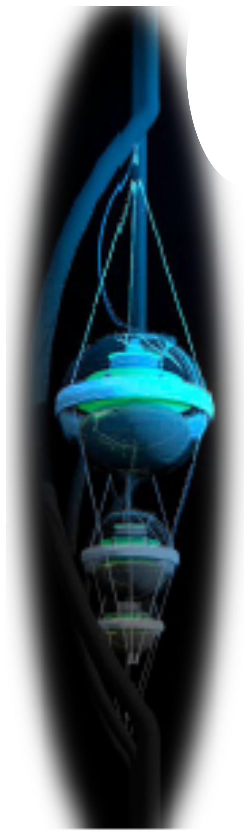
Figure 1 The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular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

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

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

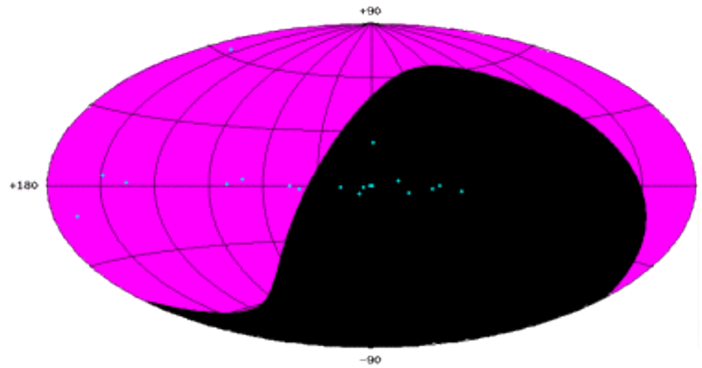
- Logistically attractive

  Close to shore (deployment / repair)

- ☹ Optical activity

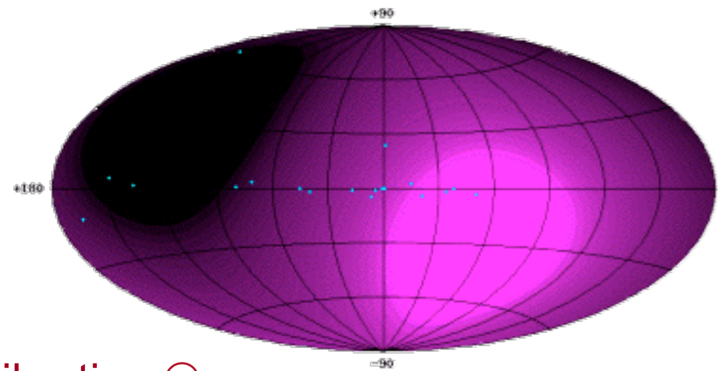
  Requires causality filters but can be used for calibration ☺

South Pole visible sky

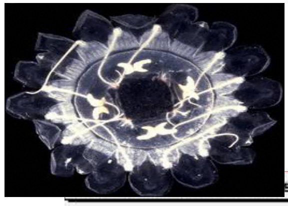


Most of the HESS TeV Sources visible by Northern NT

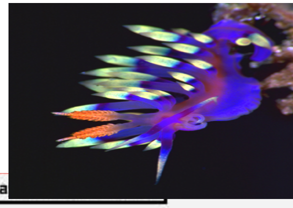
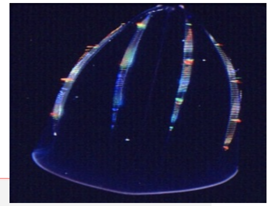
Mediterranean visible sky

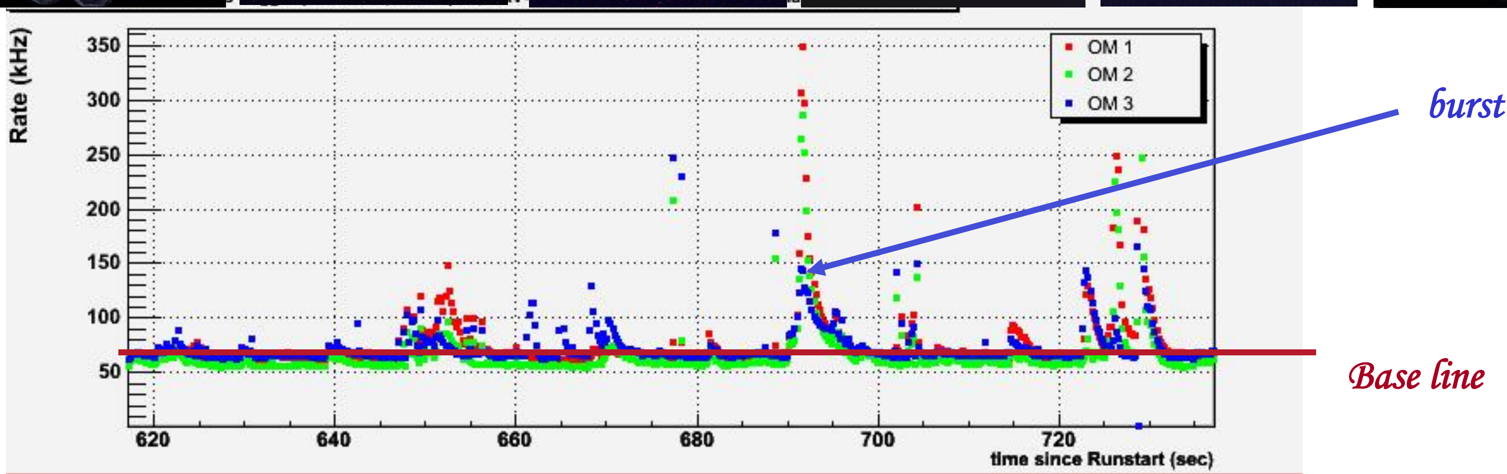


ANTARES Optical background



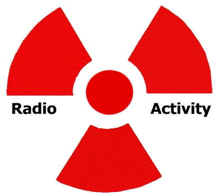


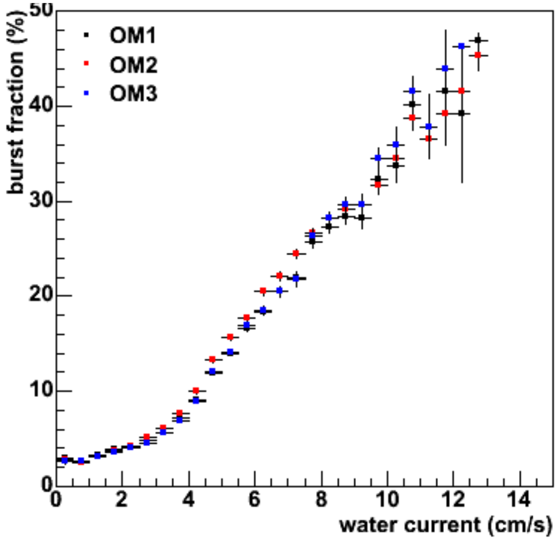



Base line ^{40}K

Bio-luminescence



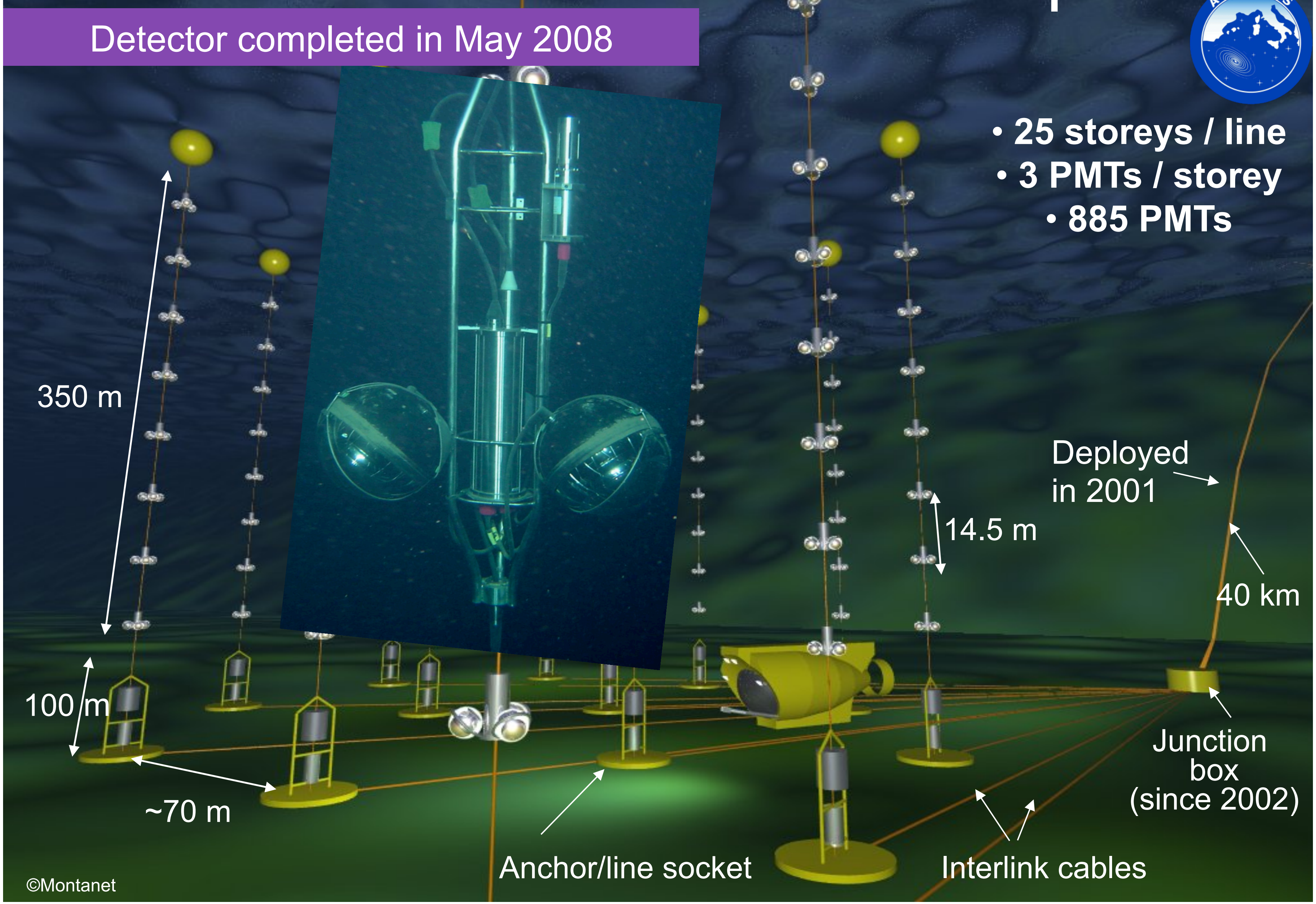


Bio-luminescence burst:

photo-emitter animals

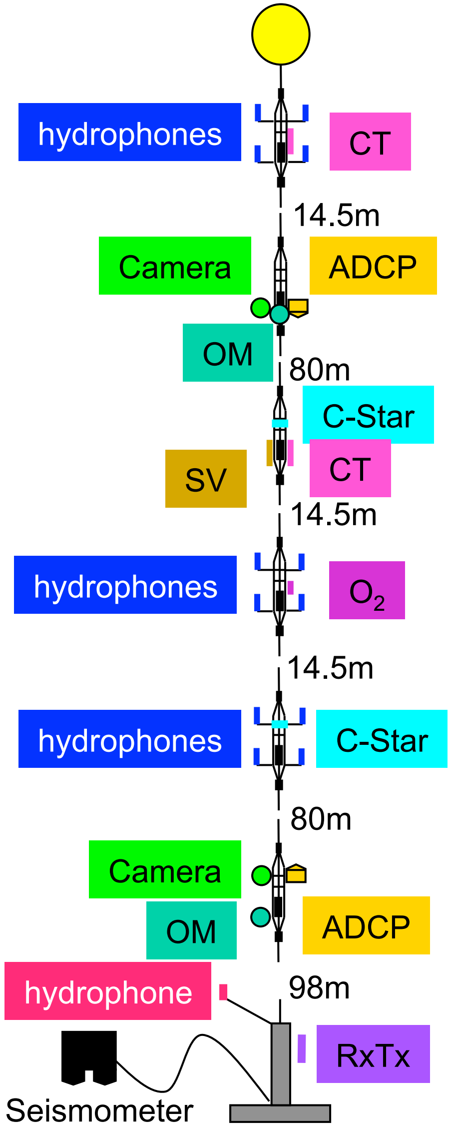

Toulon
M.Pacha
Antares
Electro-optical
Cable of
40 km
42 50'N, 6 10'E
Google
© 2008 Cnes/Spot Image
Image © 2008 DigitalGlobe
Image NASA

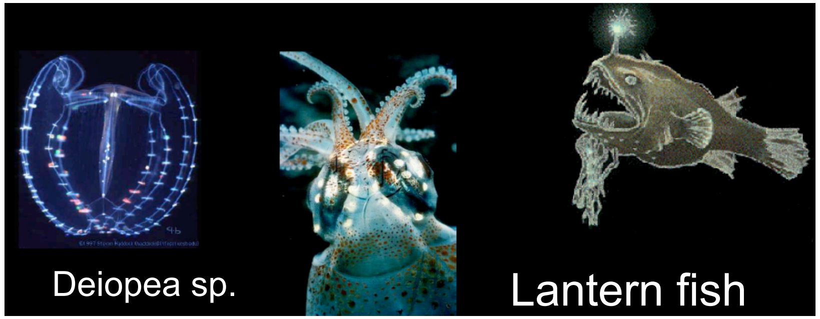
The ANTARES neutrino telescope



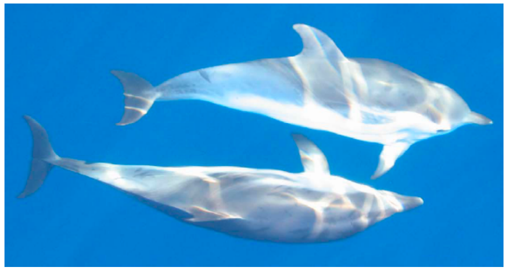
Sea science and Earthquakes

Instrumentation Line

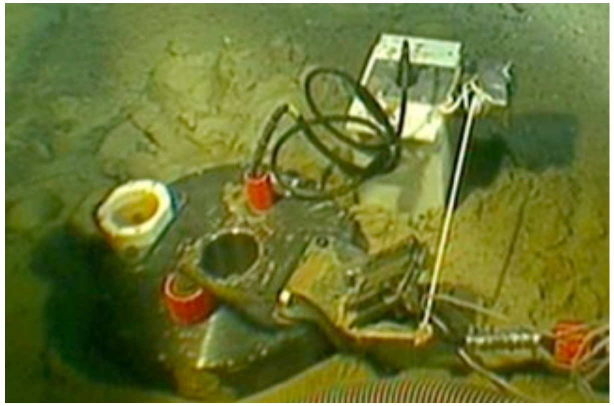




Acoustic noises



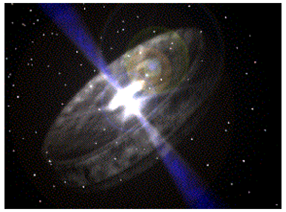
seismometer



Video-monitoring

ANTARES is a multidisciplinary observatory

Outline

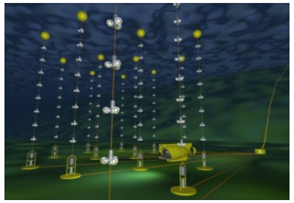


Neutrino astronomy

Historical aspects

Scientific motivations

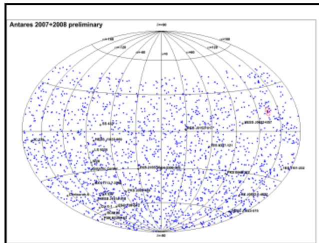
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux

Search for point sources

Multi-messenger search

GWHEN searches

Future prospects

The punch line:
“Evidence for high energy extraterrestrial neutrinos”

Two events beyond 1 PeV observed (Ernie & Bert) in a cosmogenic neutrino search. arXiv:1304.5356

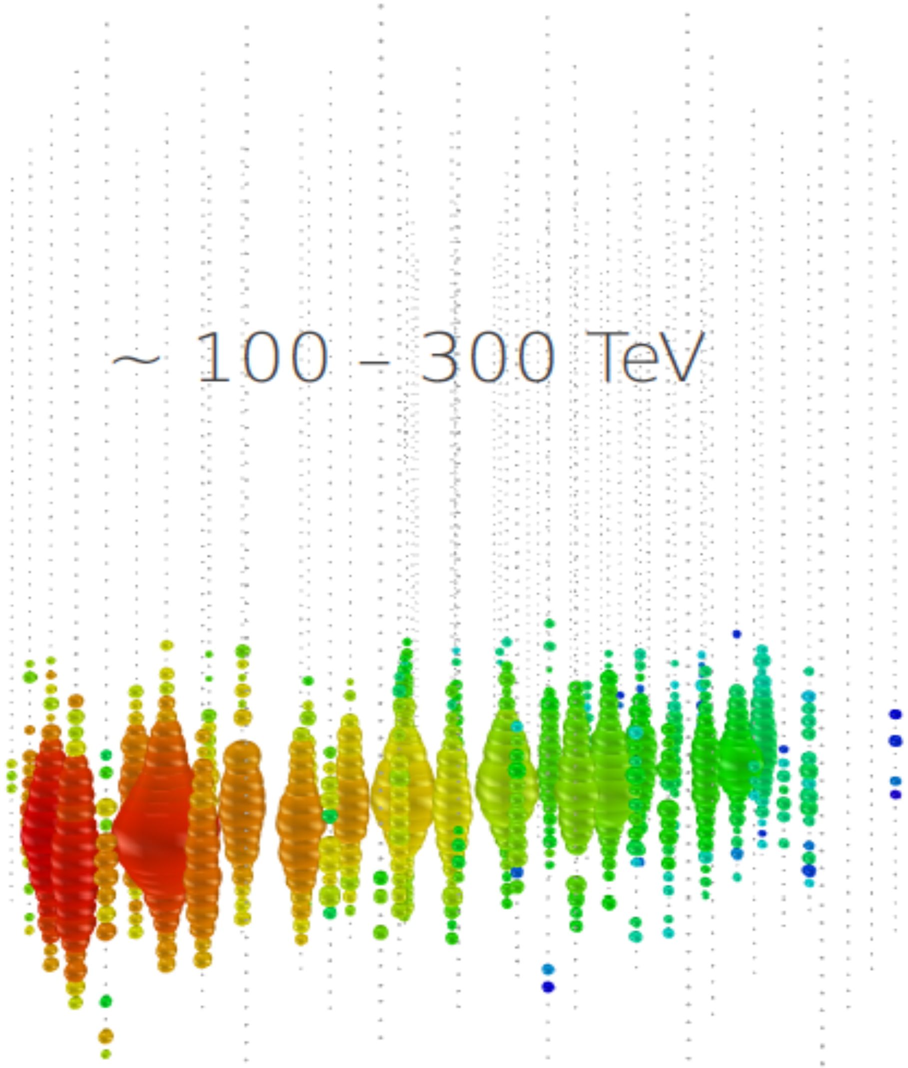
A follow up analysis has uncovered an additional 26 events. Joint observations are inconsistent with atmospheric origin at the 4.3 σ level.

Observations compatible with an astrophysical origin.

More data and analyses coming up soon.

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

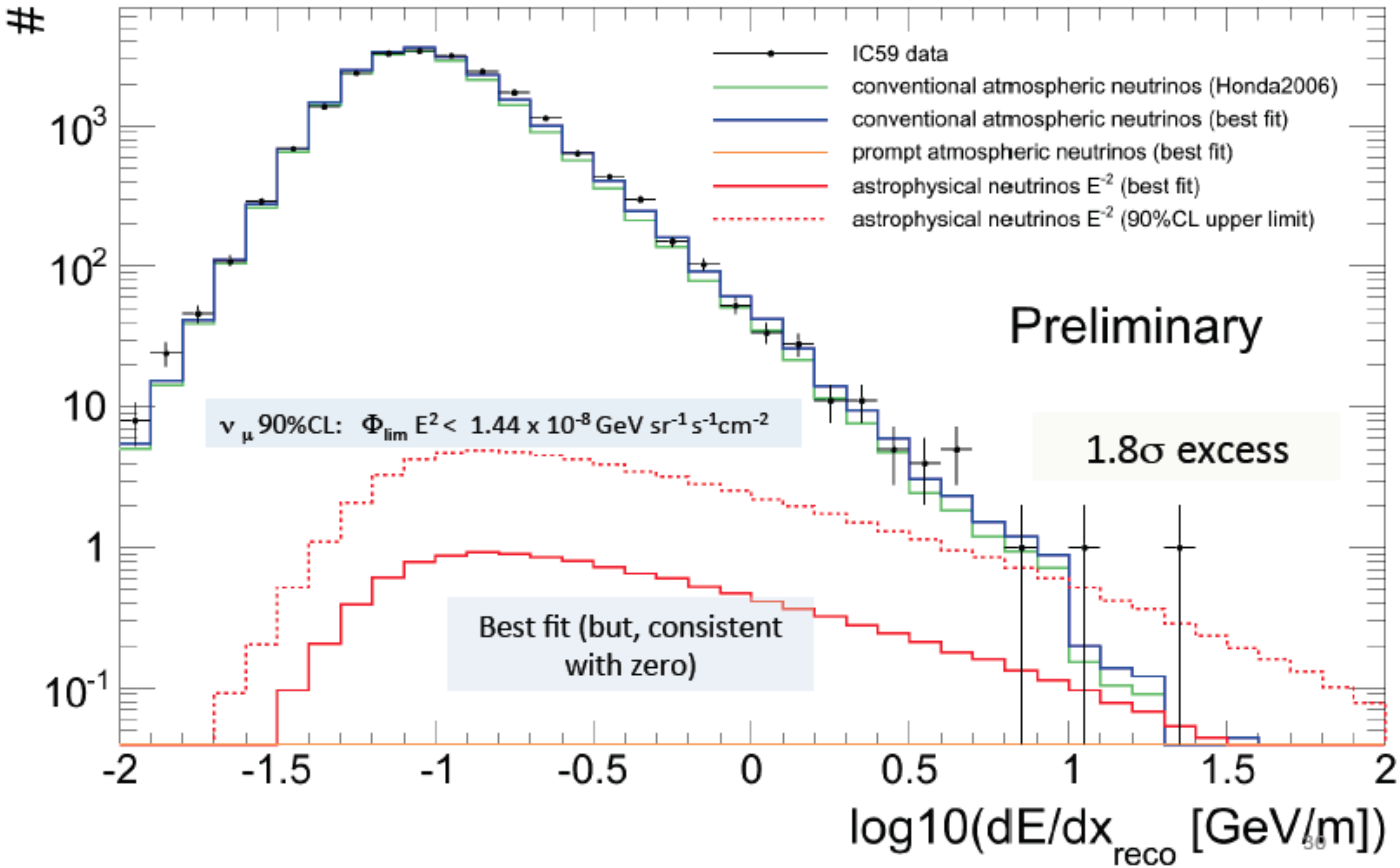
Conventional ν_μ:	~ 21 000
Prompt ν_μ:	~ 150
Astrophysical ν_μ:	< 40

Conv. atms. muon background:

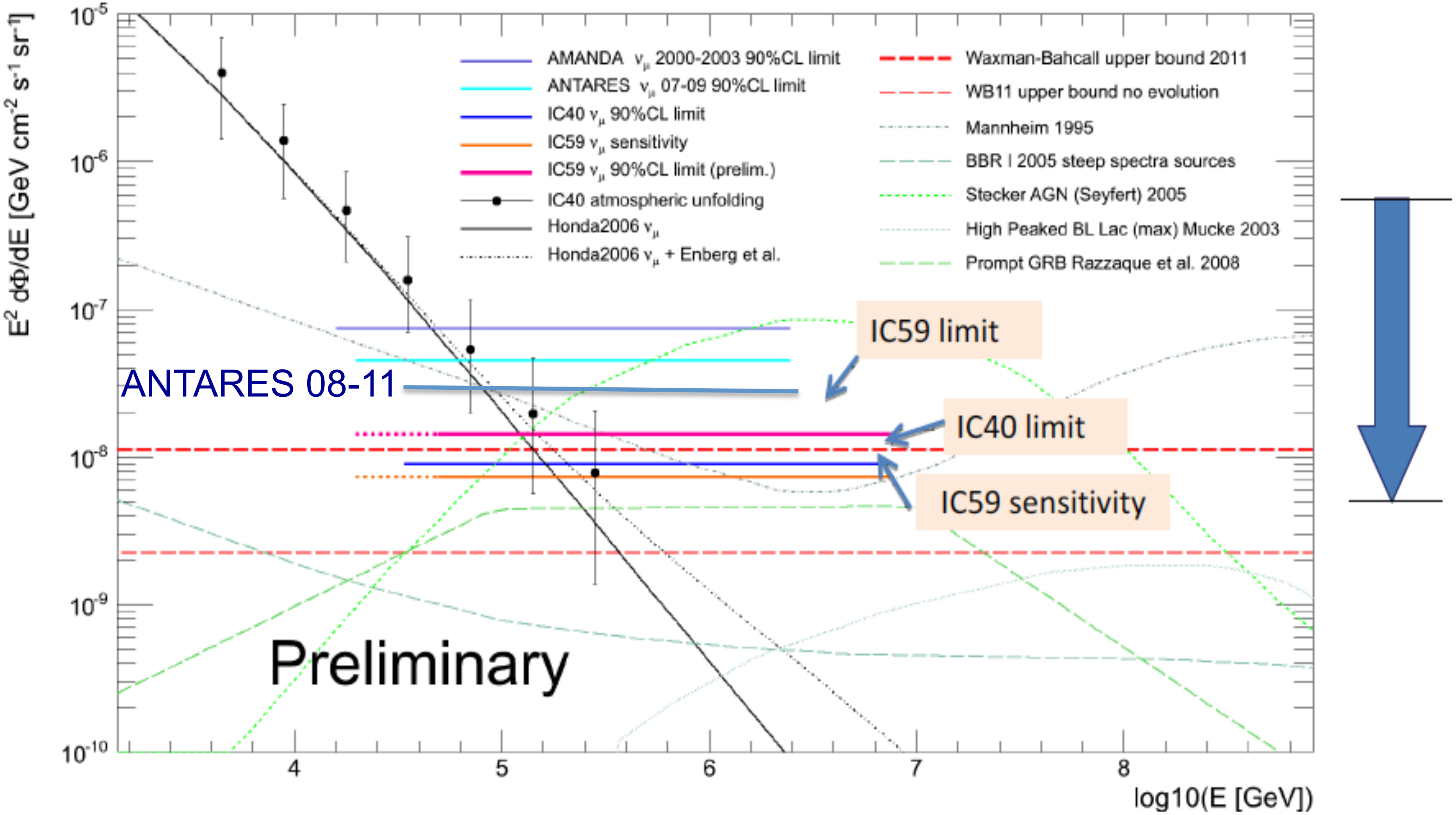
~ 30

Diffuse IC 59 search (muons)

348 days



Current limits



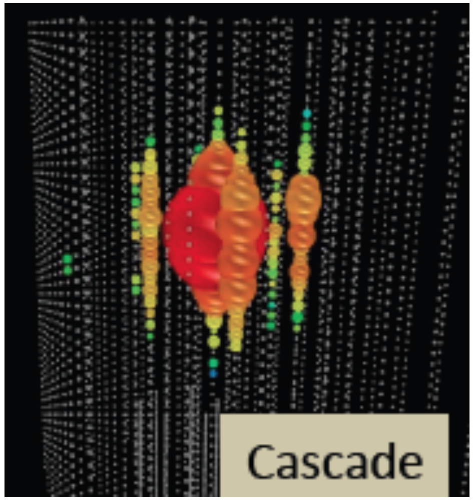
Almost 3 orders of magnitude w.r.t underground experiments
1-2 orders of magnitude below most optimistic predictions

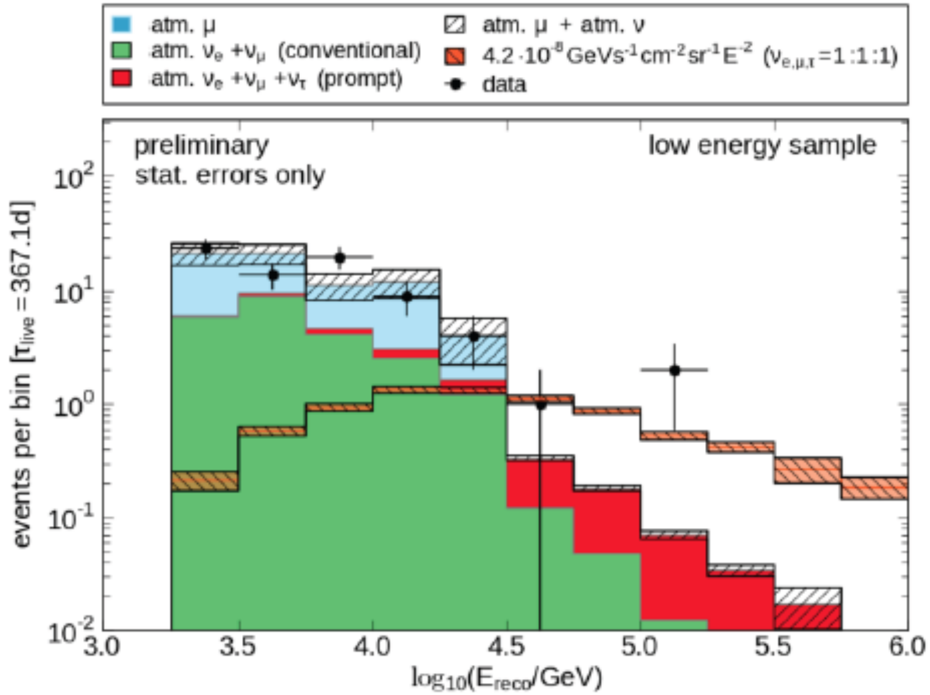
IC40 ν Cascade Diffuse Search

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

background: atm. μ

difficult background: atm. μ with catastrophic energy losses



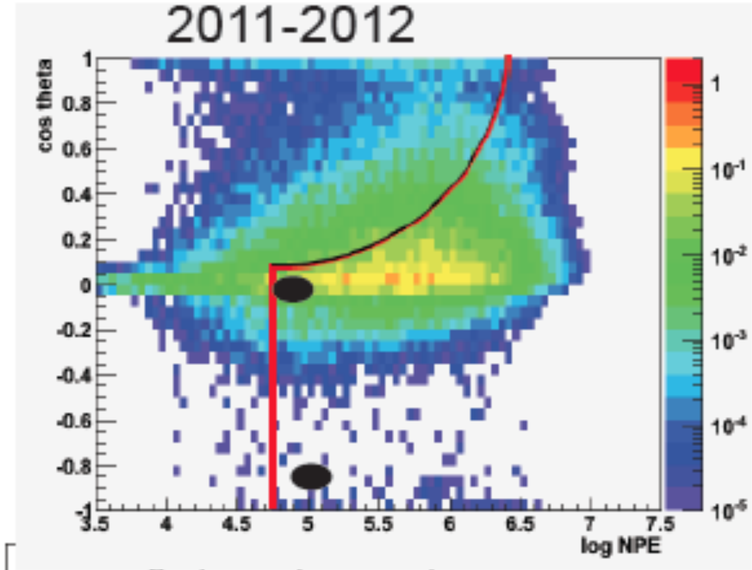


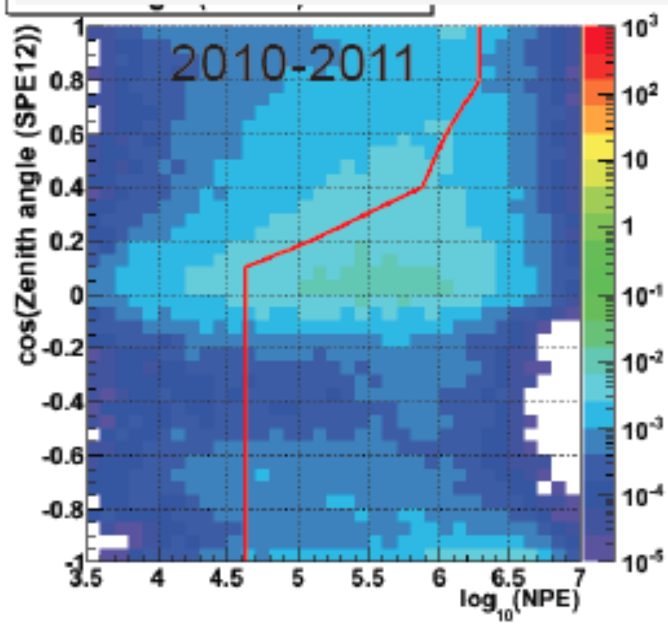
More events observed than expected for E>100 TeV

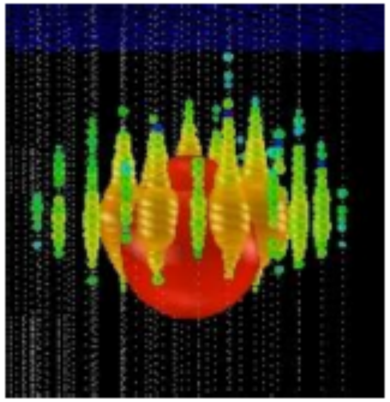
2.4 σ above expectation…

IC79+IC86 ν UHE Search

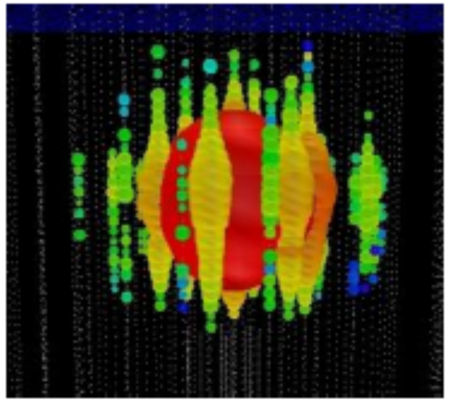
2 events are observed in the PeV energy region in IC 86 sample



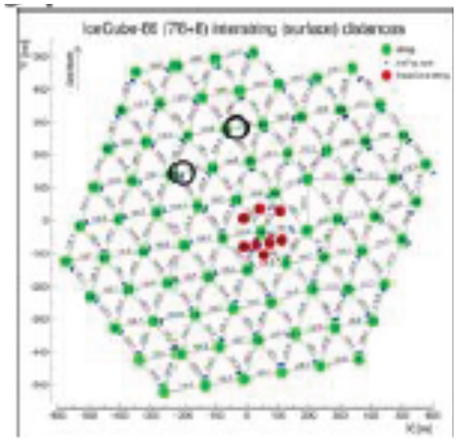




Ernie
GMT: 2012/1/3 9:34:01



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



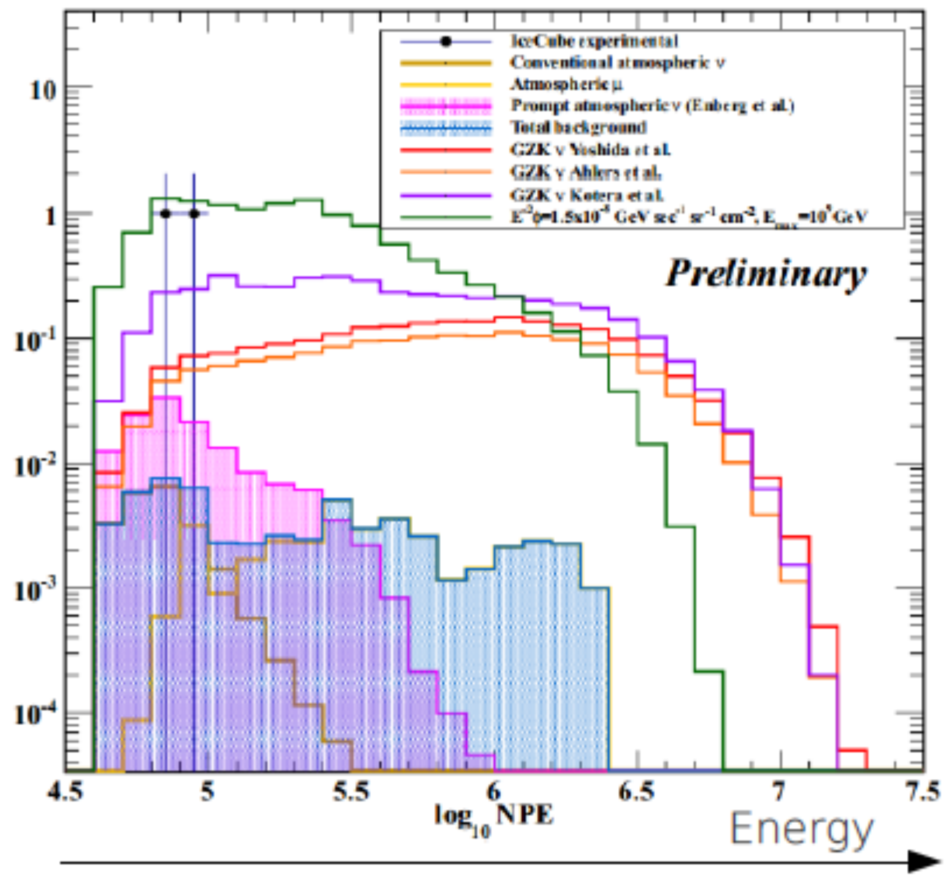
“No counter arguments to the hypothesis of neutrino induced cascades so far”

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

Nb of events per bin (670 days)



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.

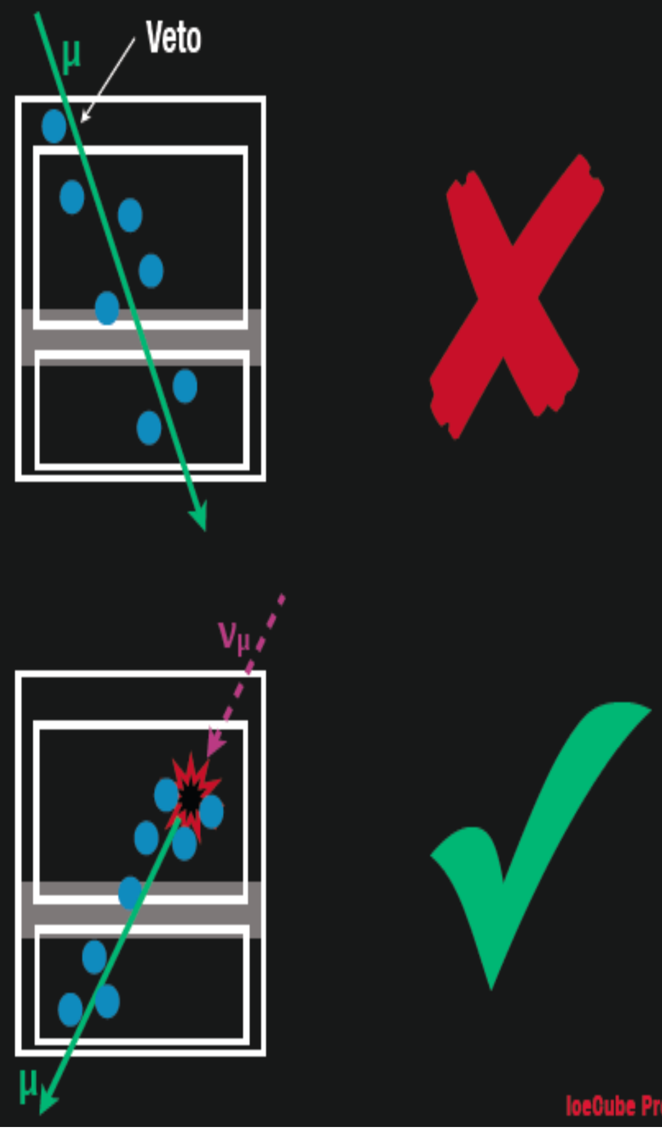
p-value 1.9×10^{-3} (2.9σ) beyond conventional background

Follow up analysis

Specifically designed to find these contained events

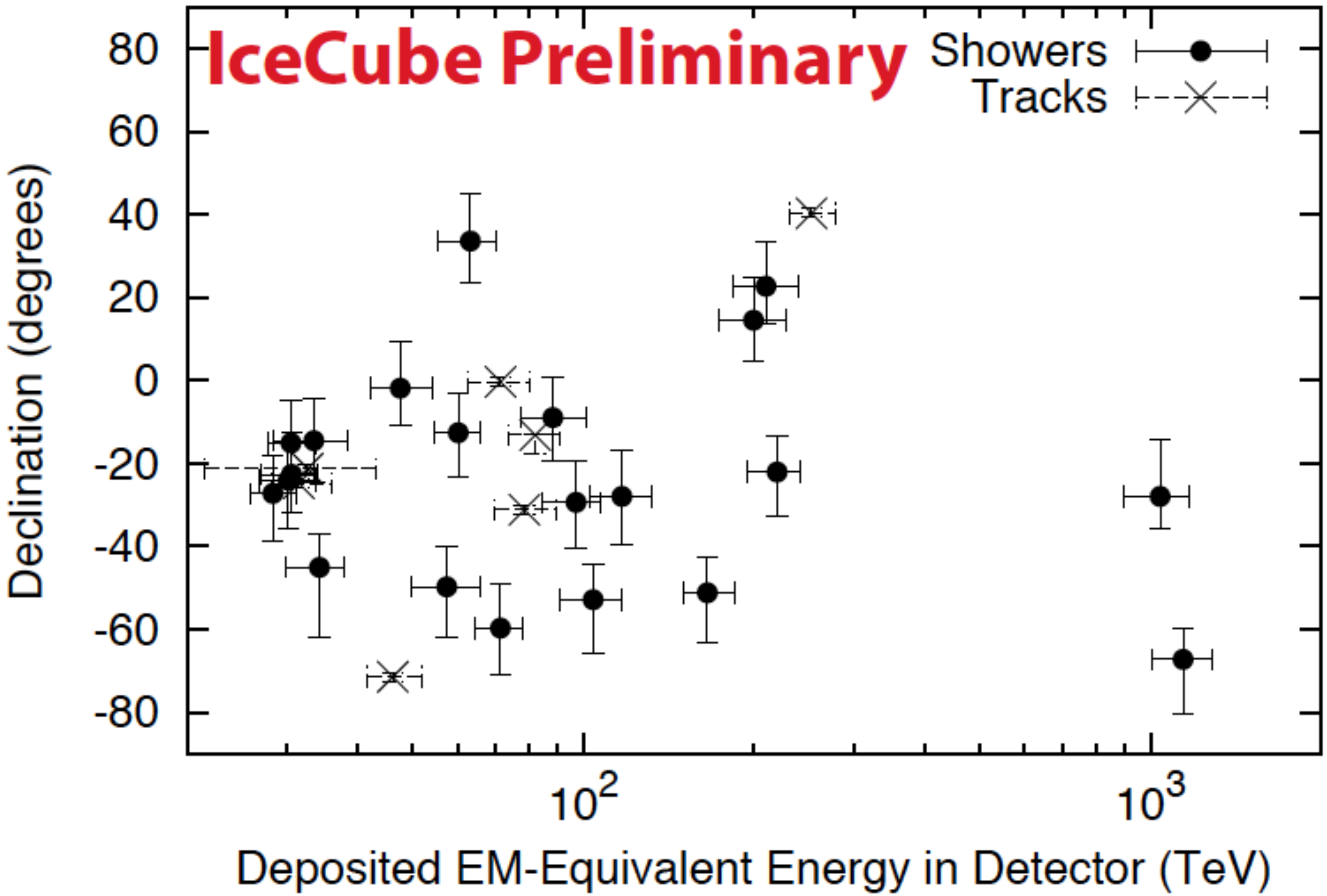
Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

- Explicit contained search at high energies (cut: Q_{tot}>6000)
- 400 Mton effective fiducial mass
- Use atmospheric muon veto
- Sensitive to all flavors in region above 60TeV
- Three times as sensitive at 1 PeV
- Estimate background from data



IceCube Preliminary

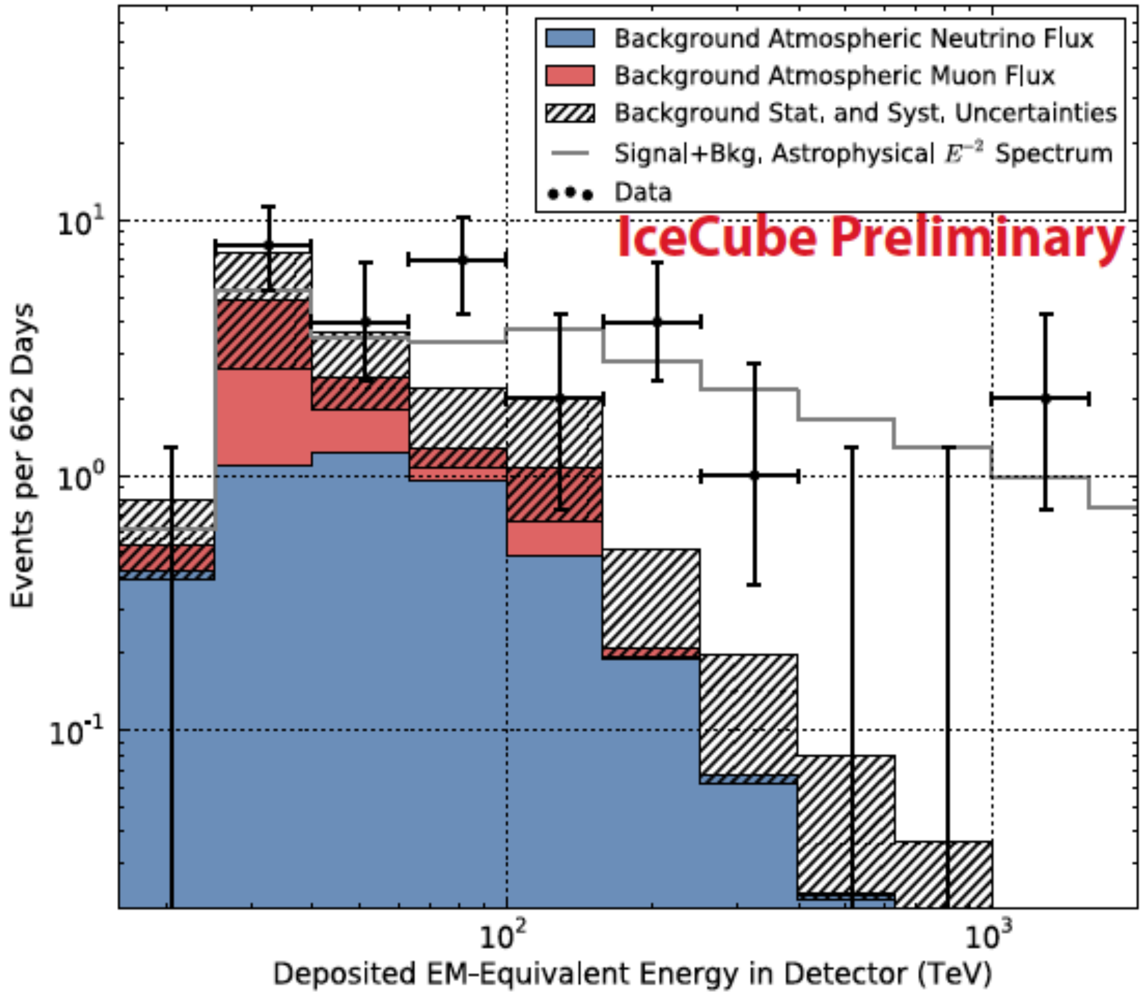
Results of Contained Vertex Event Search (4.3σ)



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

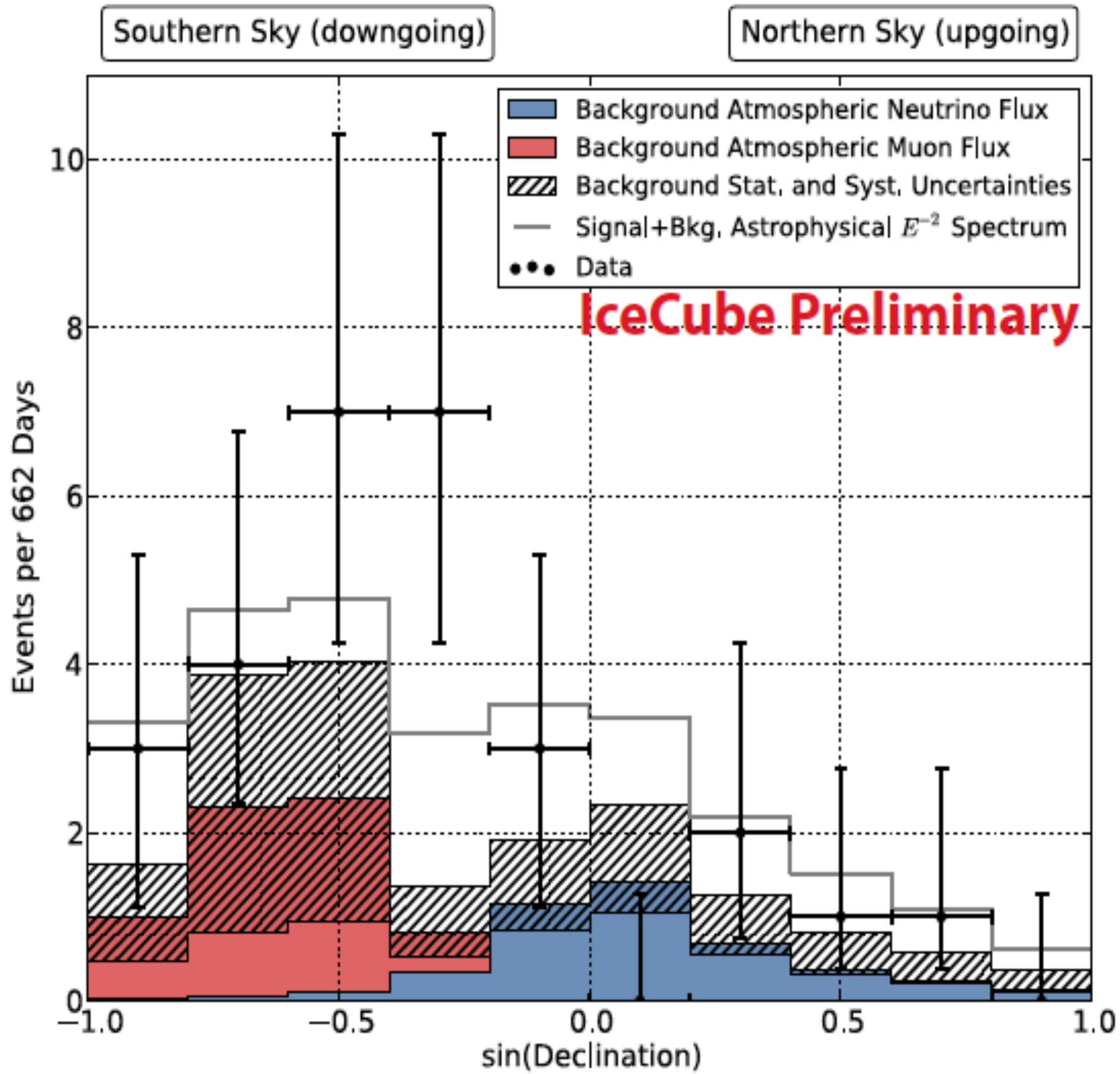
Energy Spectrum

- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff at $1.6^{+1.5}_{-0.4}$ PeV

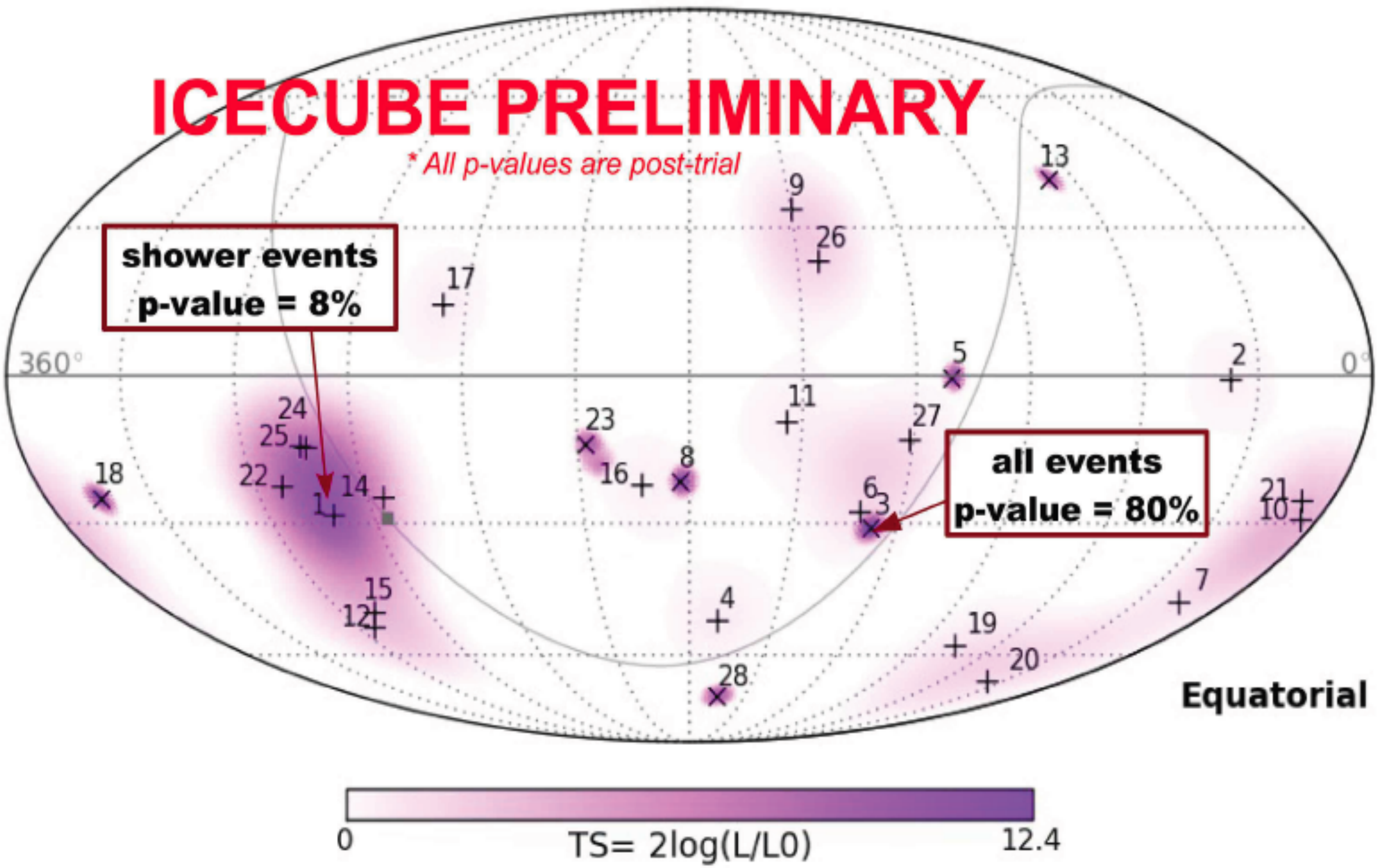


Zenith Distribution

- Compatible with Isotropic Flux
- Events from North absorbed in Earth
- Minor excess in south compared to isotropic, but not significant



Skymap: No Significant Clustering

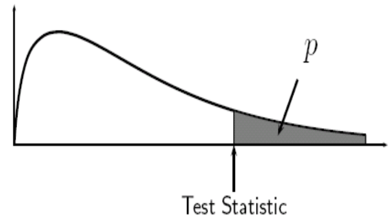


Point source searches

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)

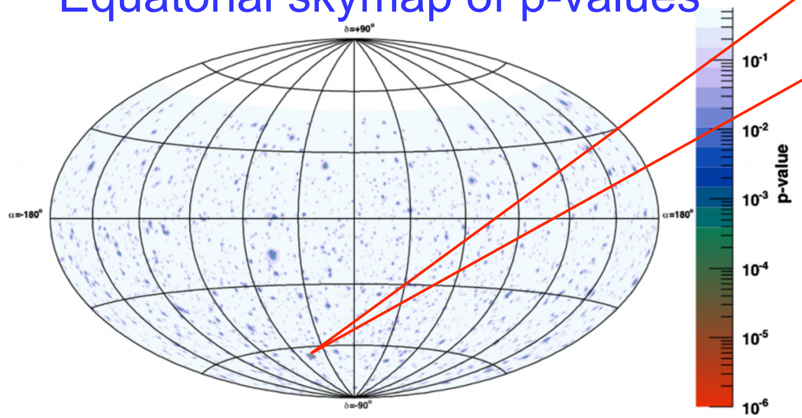
- Use Clusterization algorithm
- Calculate a statistic given data (eg. Likelihood ratio)
- Compute *p-value* (probability to observe such statistic from bkg)
- Compute post-trial significance probability to observe *p-value* from many experiments



These analyses can be performed for :

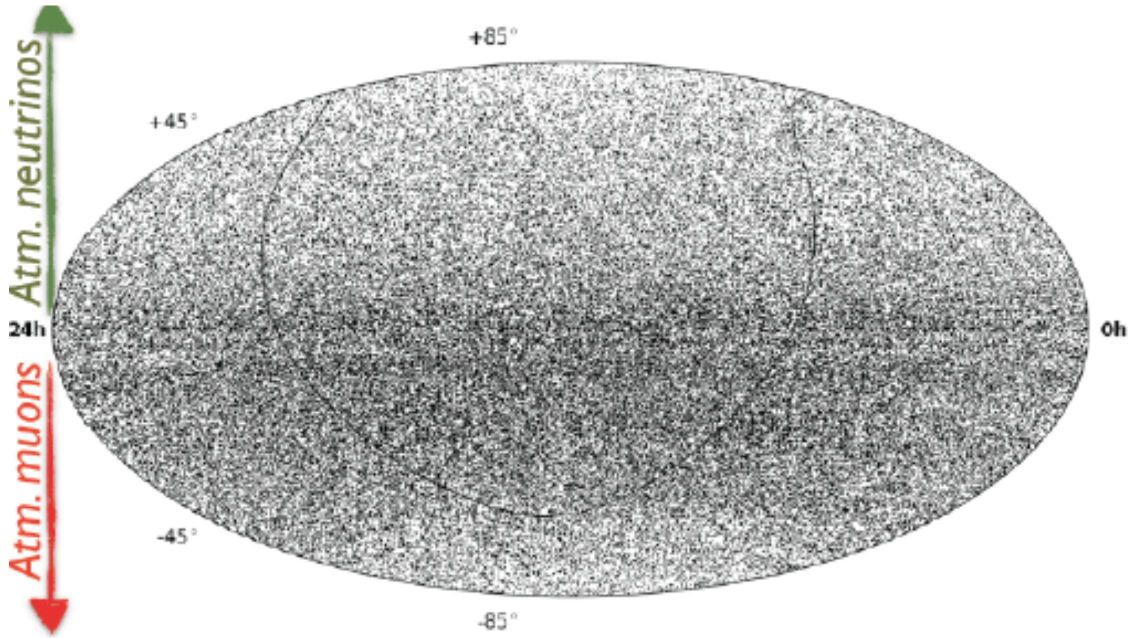
- All sky search
- Predefined list of known sources
- Collection of sources of same kind summed up (stacking analysis)

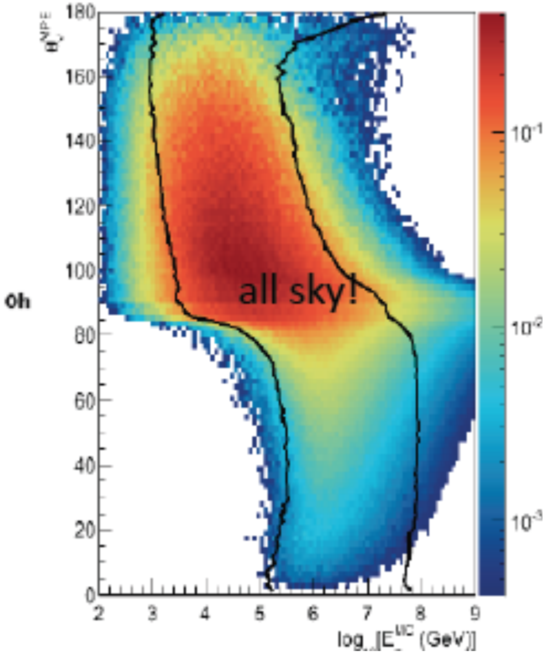
Equatorial skymap of p-values

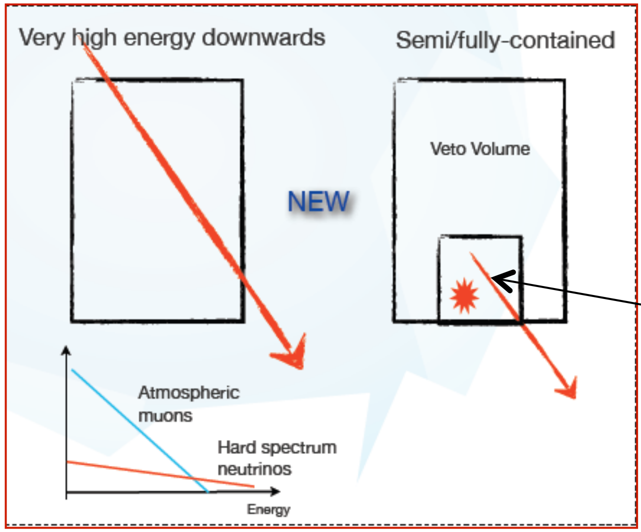


ANTARES results
Hottest spot: RA: −46.5°, δ= −65.0°
N_{sig} = 5, p-value = 0.026 Significance = 2.2 σ

IceCube sky map (IC 40+59)



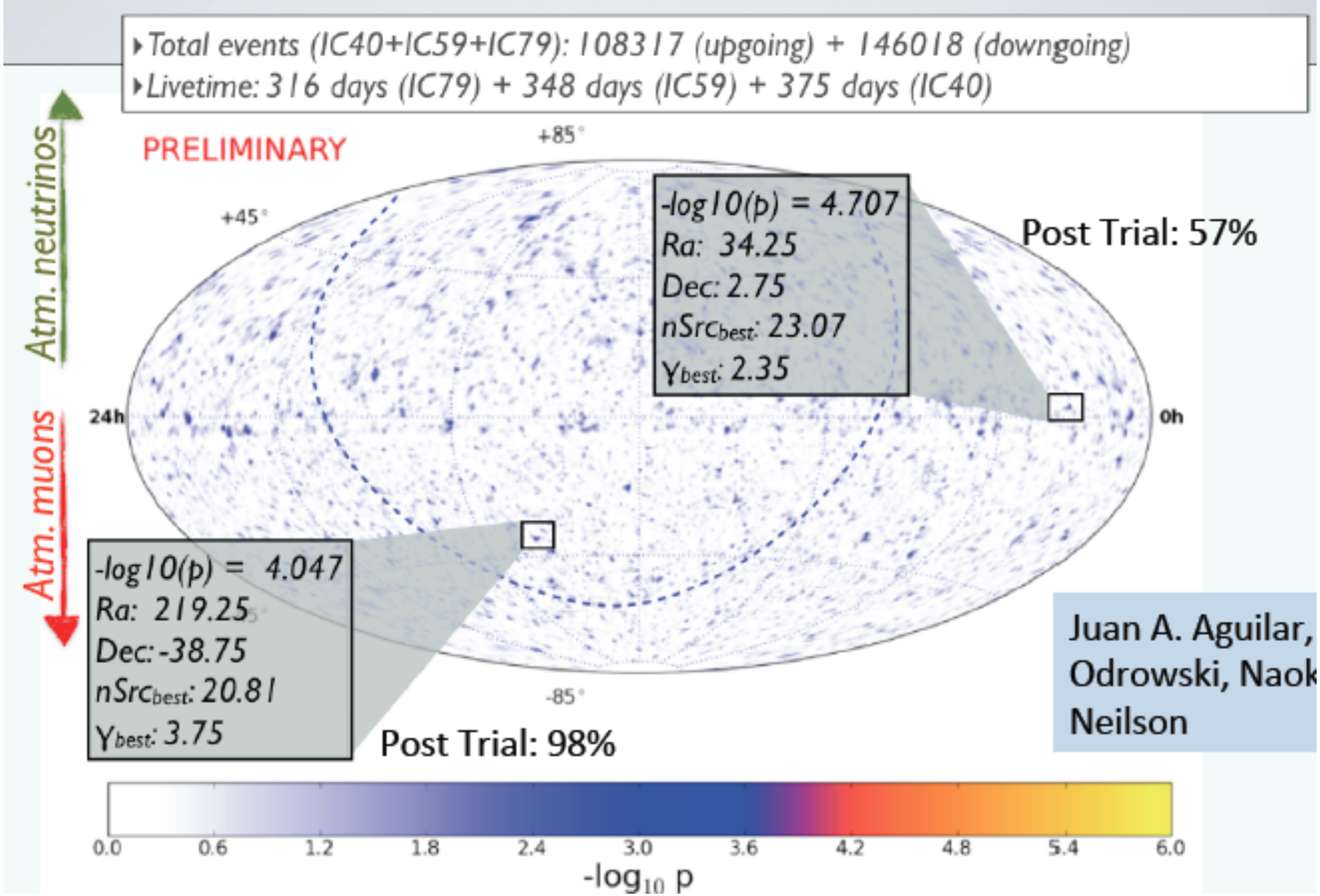




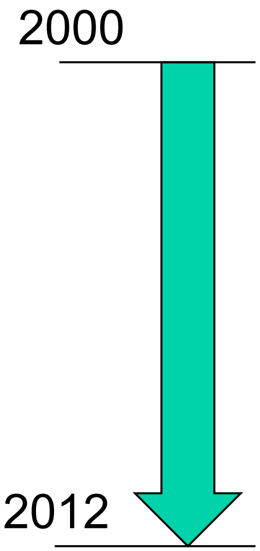
43339 up-going + 64230 down-going
723 days

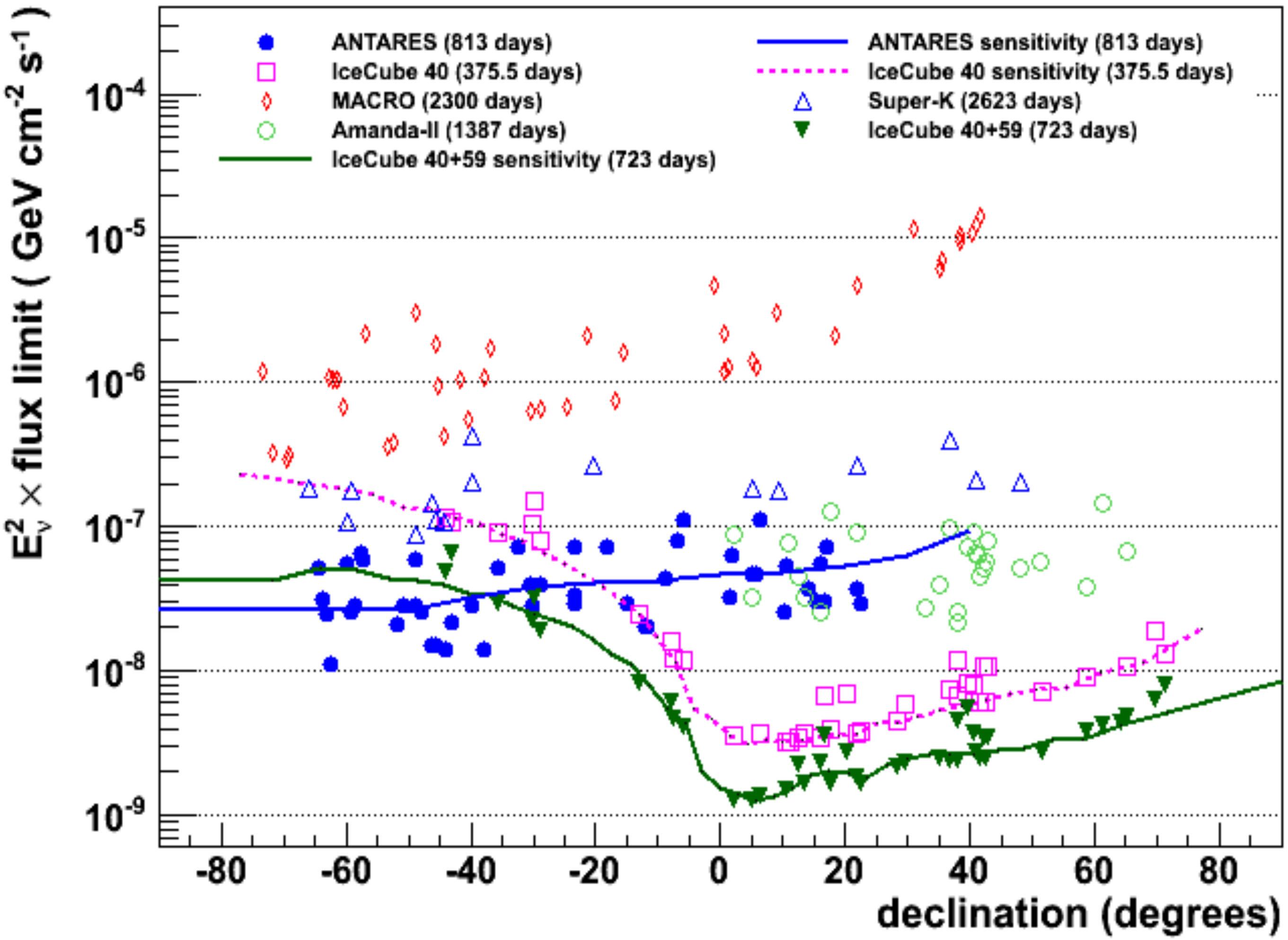
Includes Deep Core array

IceCube sky map…latest?



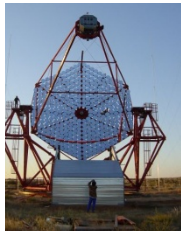
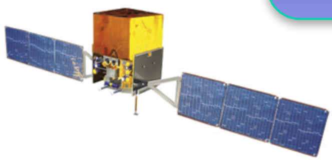
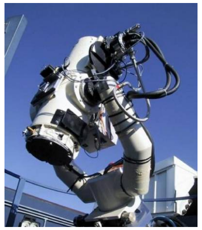
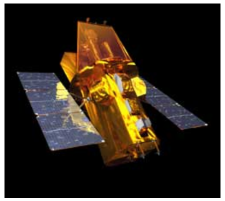
Current Upper limits

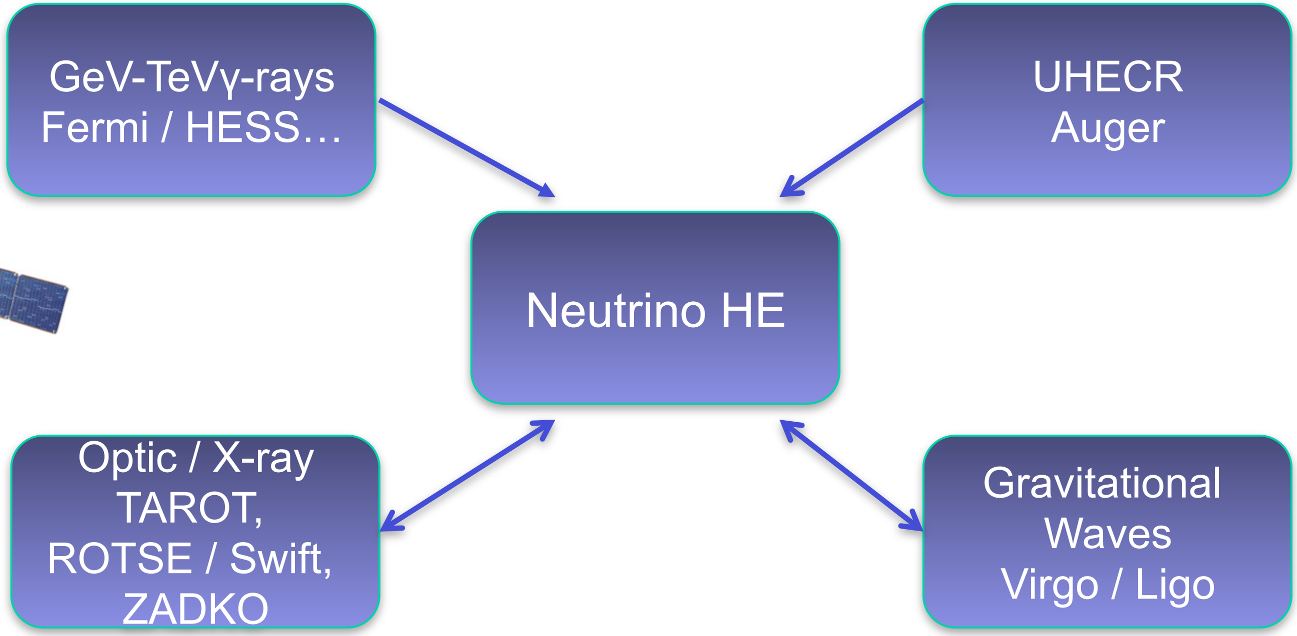




📖 Antares, S. Adrian-Martinez et al., ApJ, 760, 53, 2012

The multi-messenger program



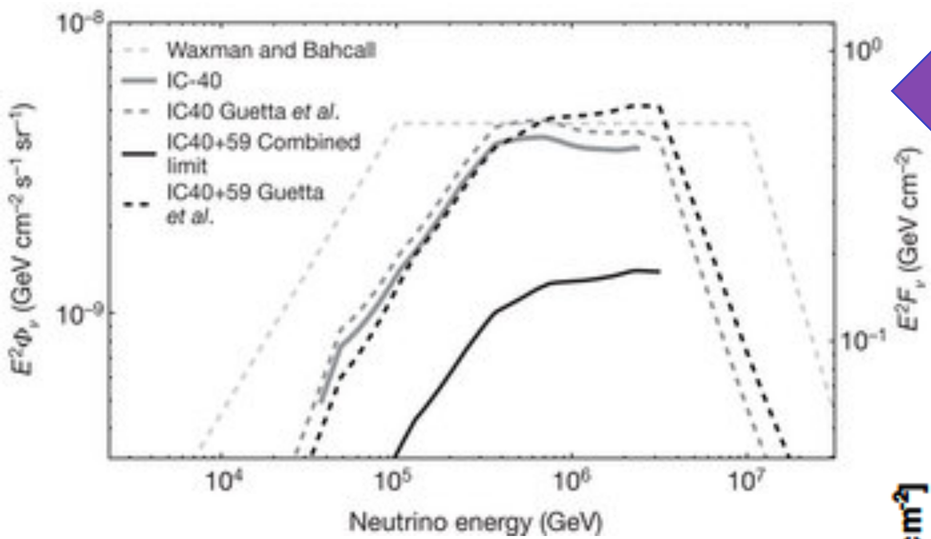


⇒ A way to better understand the sources and the related physics mechanisms

⇒ A way to increase the detector sensitivities (uncorrelated backgrounds)

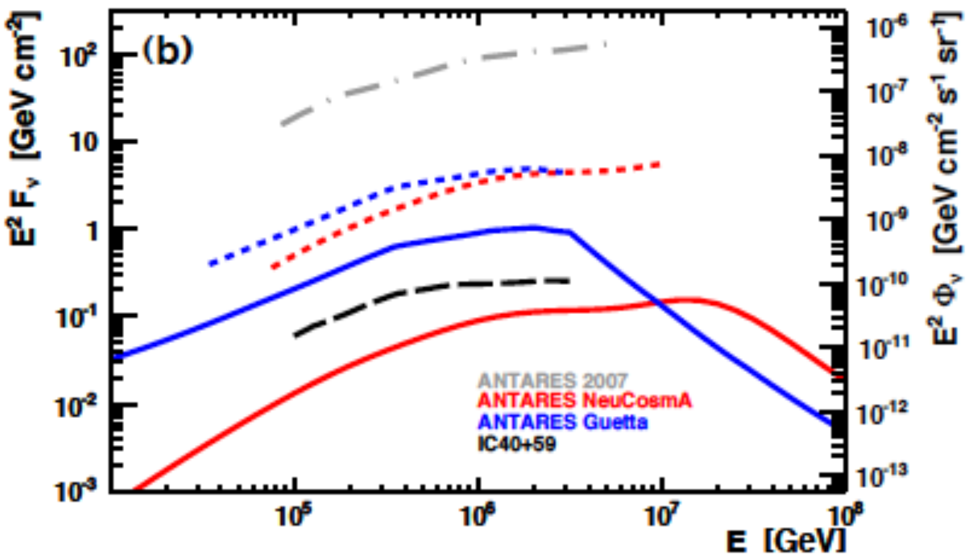
Alert programs

- 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 limits



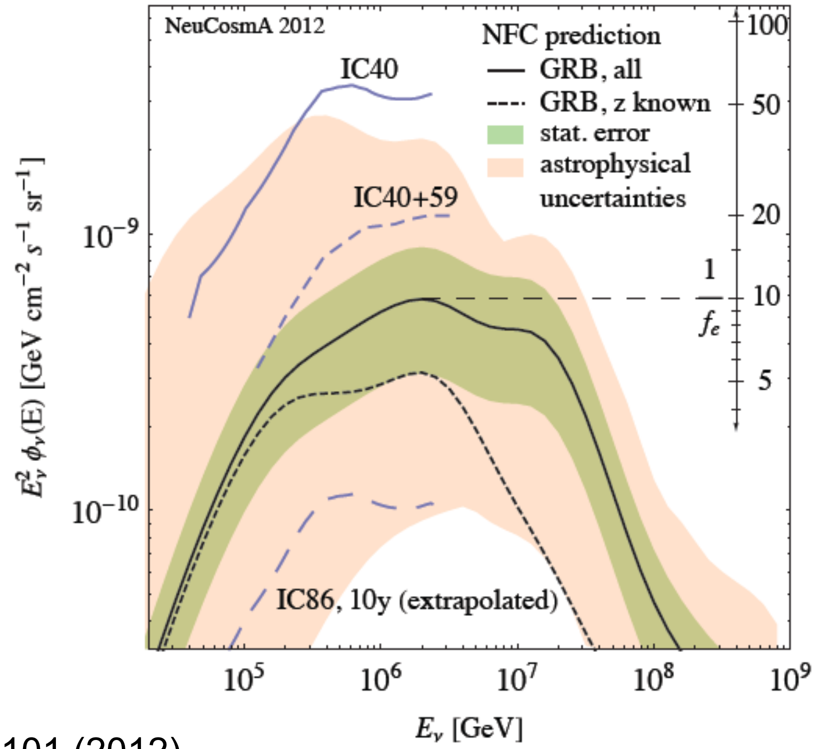
Fireball model challenged by IceCube?

Basic approach: $p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$

The normalization (IceCube approach)

$$\int_0^\infty \mathrm{d}E_\nu \, E_\nu F_\nu(E_\nu) = \overbrace{\frac{1}{8}}^{x_{\pi\to\nu} = \frac{1}{2}\cdot\frac{1}{4}} \underbrace{\left(1 - (1 - \langle x_{p\to\pi}\rangle)^{\Delta R/\lambda_{p\gamma}}\right)}_{f_\pi} \overbrace{\frac{1}{f_e} \int_{1\,\mathrm{keV}}^{10\,\mathrm{MeV}} \mathrm{d}E_\gamma \, E_\gamma F_\gamma(E_\gamma)}^{\text{energy in protons}}$$

Numerical approach:
f_π can be much reduced

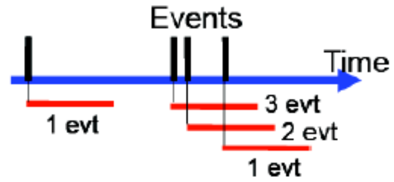


- Significantly reduced prediction
- Uncertainties of astrophysical parameters; tested ranges: $t_v = 0.001 - 0.1$ s, $\Gamma = 200 - 500$, $\alpha_p = 1.8 - 2.2$, and $\epsilon_B/\epsilon_e = 0.1 - 10$
- Conservative bounds only with known parameters, here: known redshifts
- Additional uncertainty from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

Hümmer et al. PRL 108 231101 (2012)

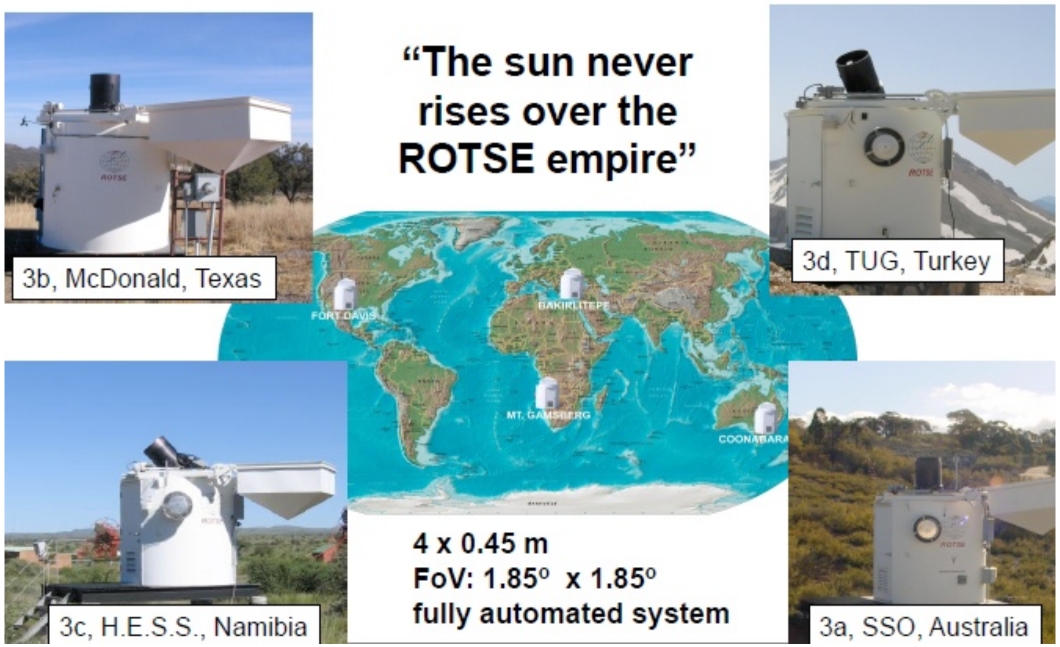
Neutrino's Alerts Follow Up

- 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



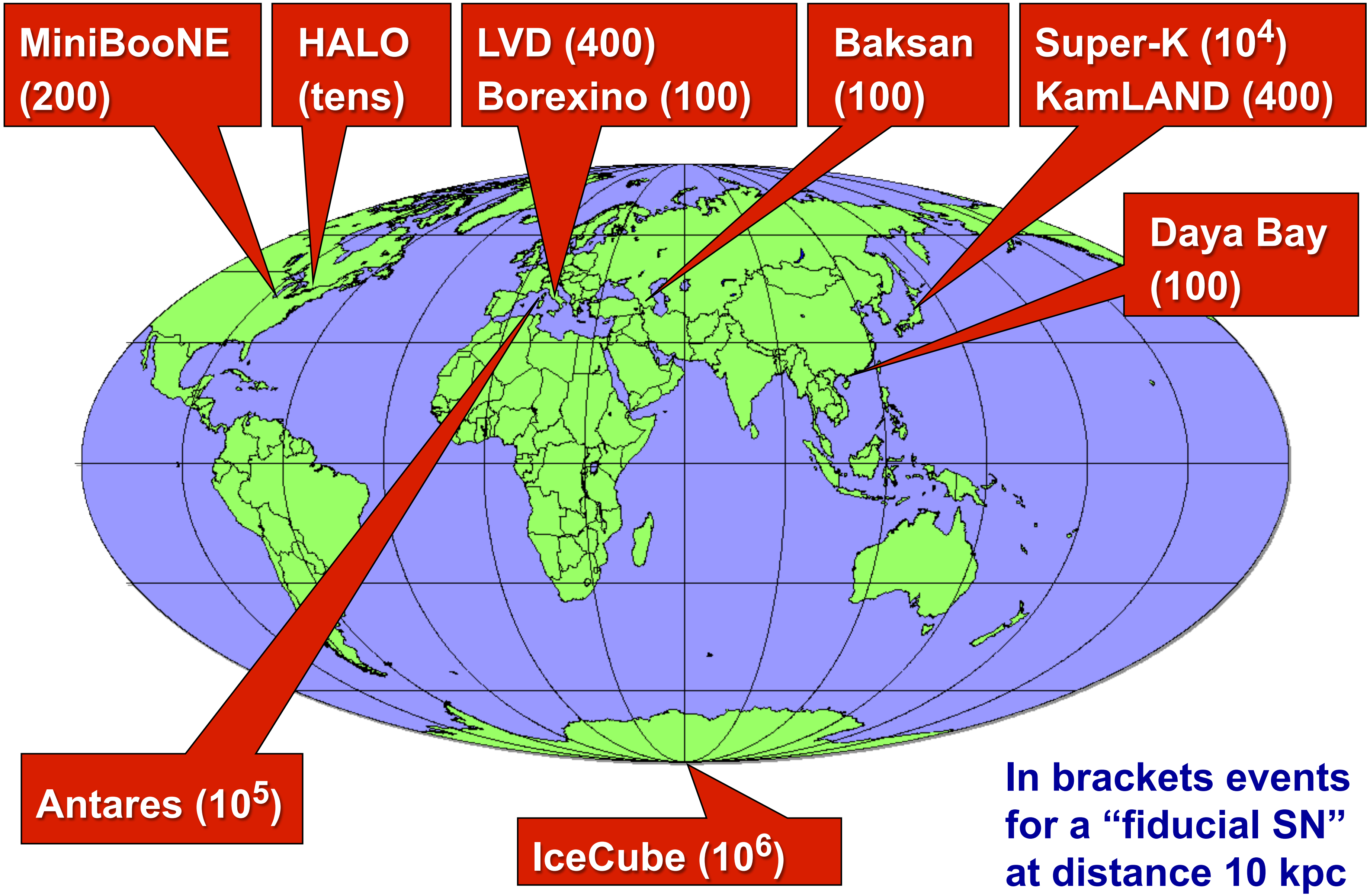
Antares

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, ZADKO
- SWIFT/XRT

See E. Chassande-Mottin's lectures

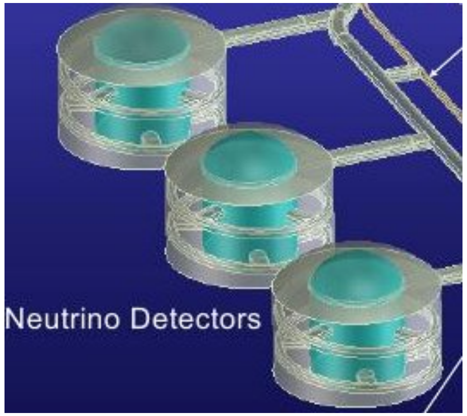
Operational Detectors for Supernova Neutrinos



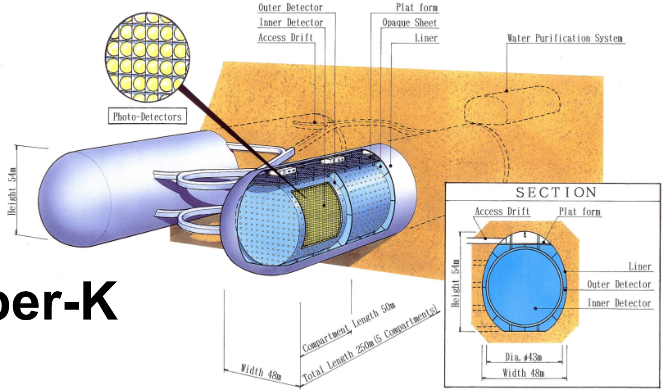
In brackets events for a "fiducial SN" at distance 10 kpc

Next Generation Large-Scale Detector Concepts

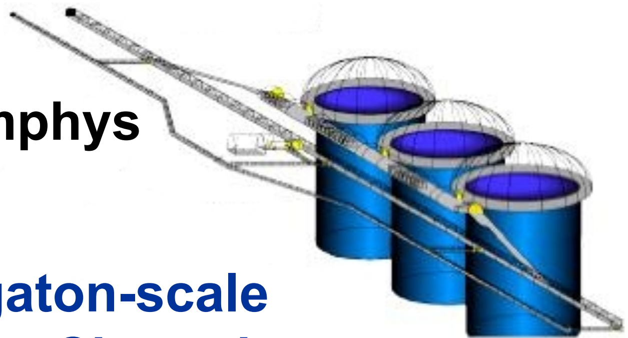
DUSEL
LBNE



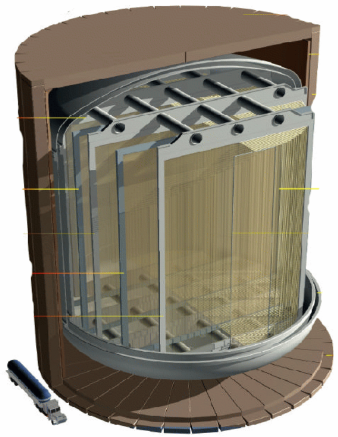
Hyper-K



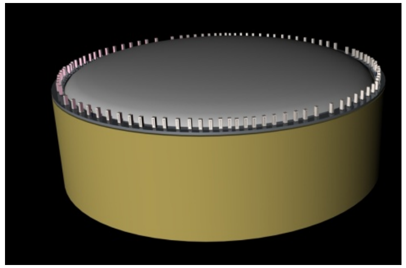
Memphys

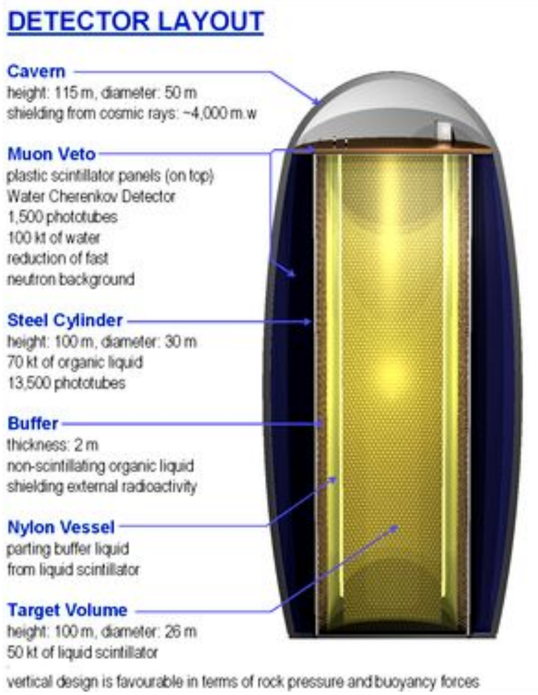


Megaton-scale water Cherenkov



5-100 kton liquid Argon

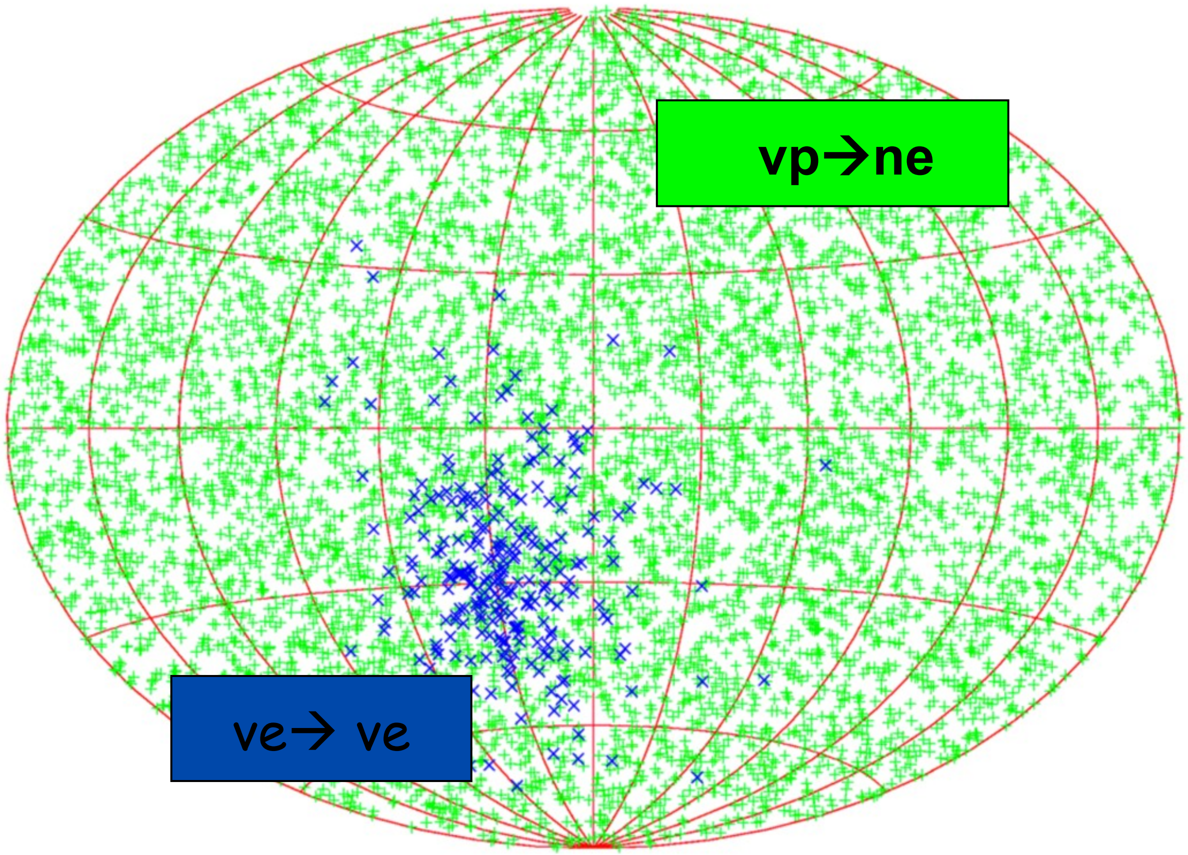




100 kton scale scintillator

LENA
HanoHano

Supernova Pointing with Neutrinos



Neutron tagging efficiency		
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30
95% CL half-cone opening angle		

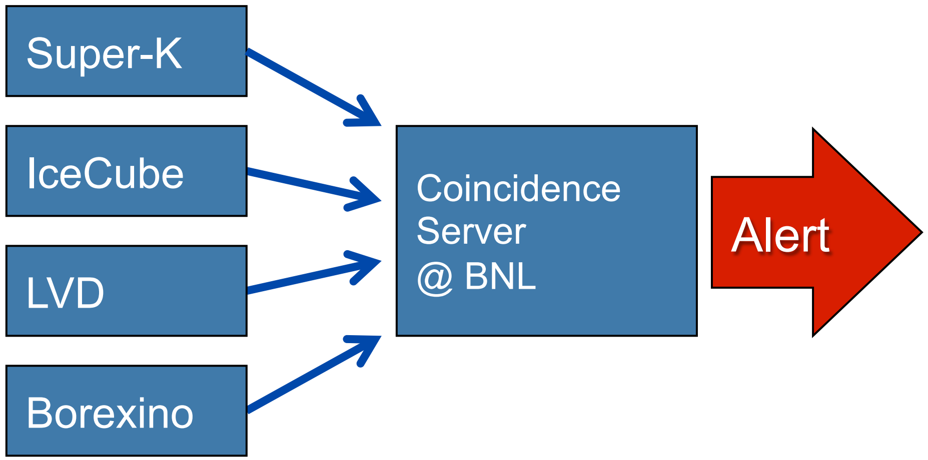
📖 Tomàs, Semikoz, Raffelt, Kachelriess & Dighe: Supernova pointing with low- and high-energy neutrino detectors [hep-ph/0307050]

SuperNova Early Warning System (SNEWS)

The detection of even a single neutrino in association with a nearby supernova would reduce the uncertainty on the start time from ~ 1 day to ~ 10 seconds, which would help for GW searches for instance.

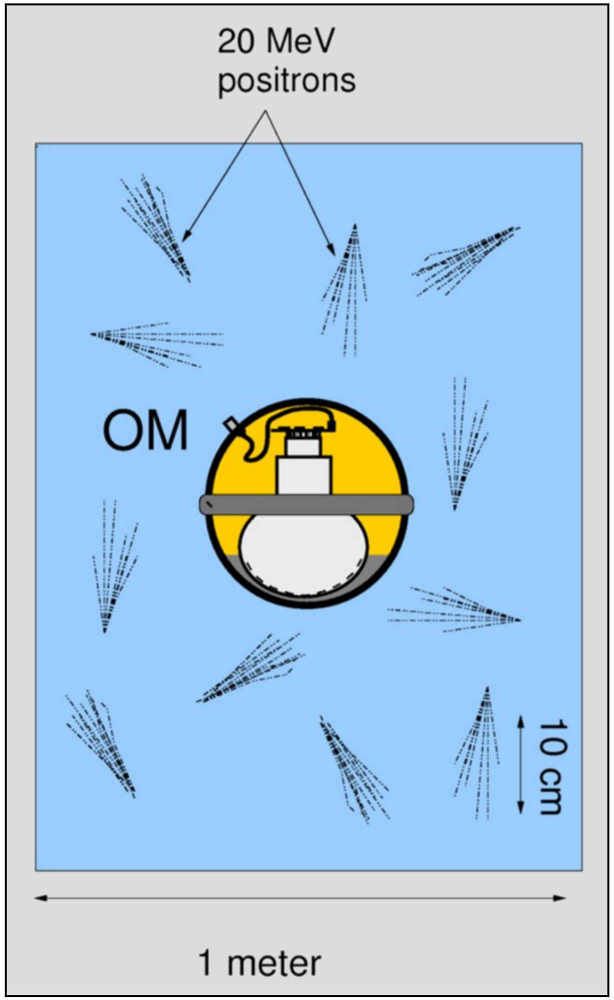
http://snews.bnl.gov

- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance



IceCube as a Supernova Neutrino Detector

- Each optical module (OM) picks up Cherenkov light from its neighborhood
- 300 Cherenkov photons per OM from SN at 10 kpc
- Bkgd rate in one OM < 300 Hz
- SN appears as "correlated noise" in 5000 OMs



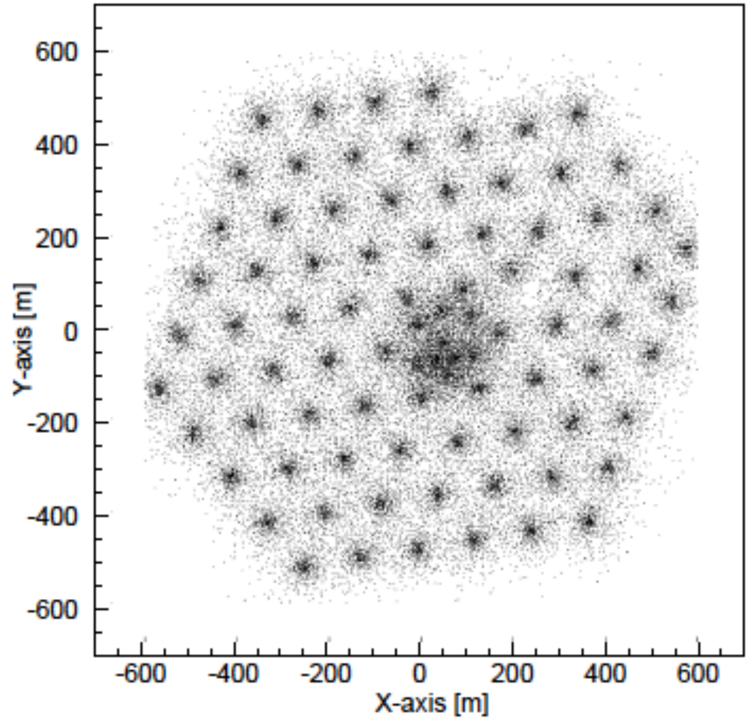


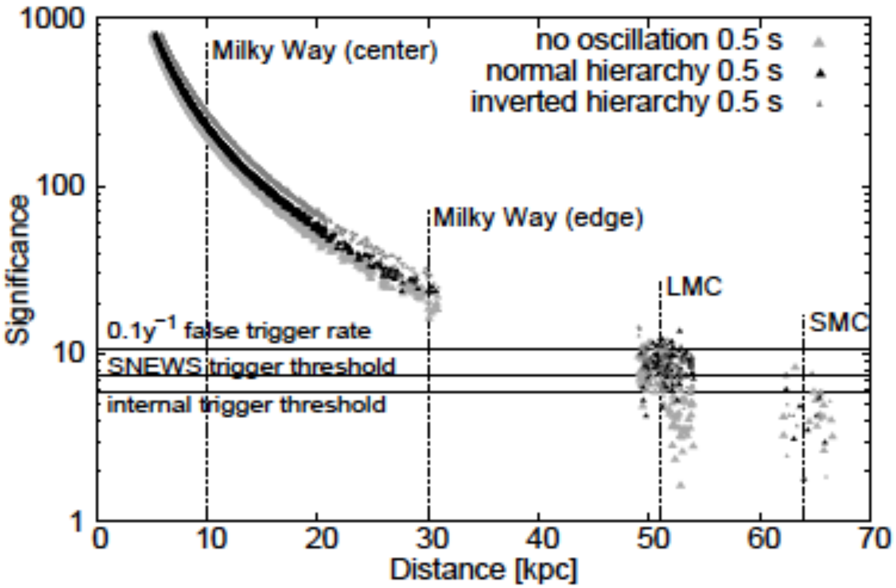
Fig. 6. Detected neutrino inverse beta decay interaction vertices projected onto the horizontal plane based on a GEANT-3.21 simulation with 10 million neutrino interactions.

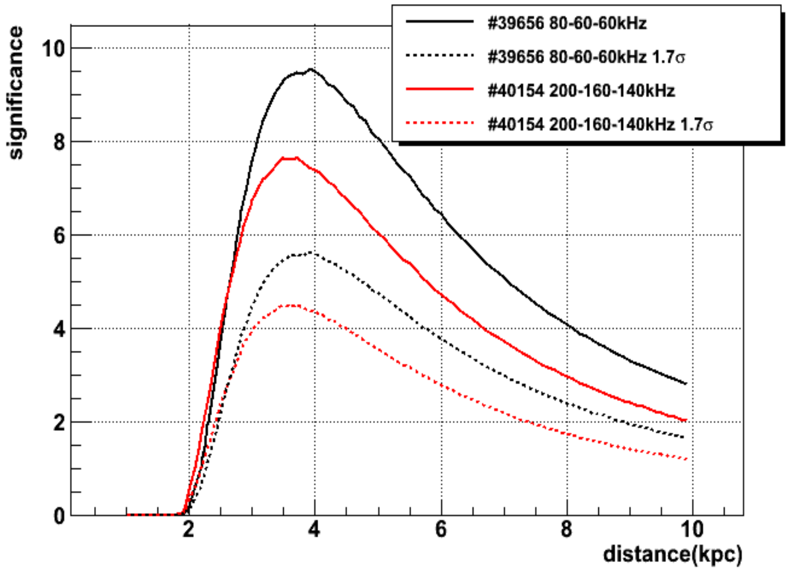
📖 IceCube collaboration, A&A 535 A109 2011

IceCube and ANTARES performances

$$Significance = \frac{Signal}{\sigma_{measurement}}$$

Single rate method





📖 IceCube collaboration, A&A 535 A109 2011

📖 Antares , 32 ICRC proceedings ArXiv 1112.0478

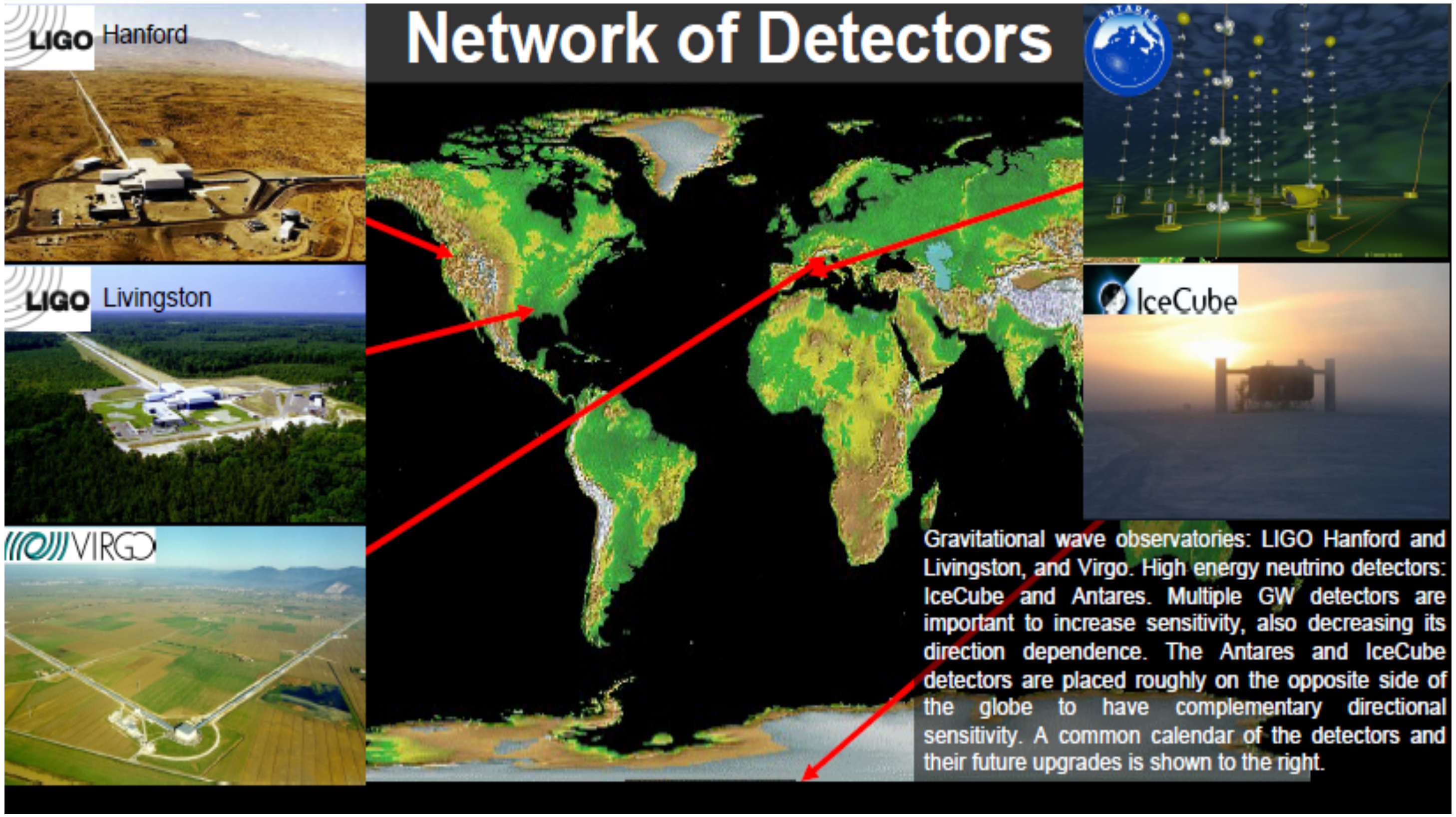
The GWHEN working group

Objective: conduct a joint search for HE Neutrinos and Gravitational Waves
→ A triggered search increases the discovery potential

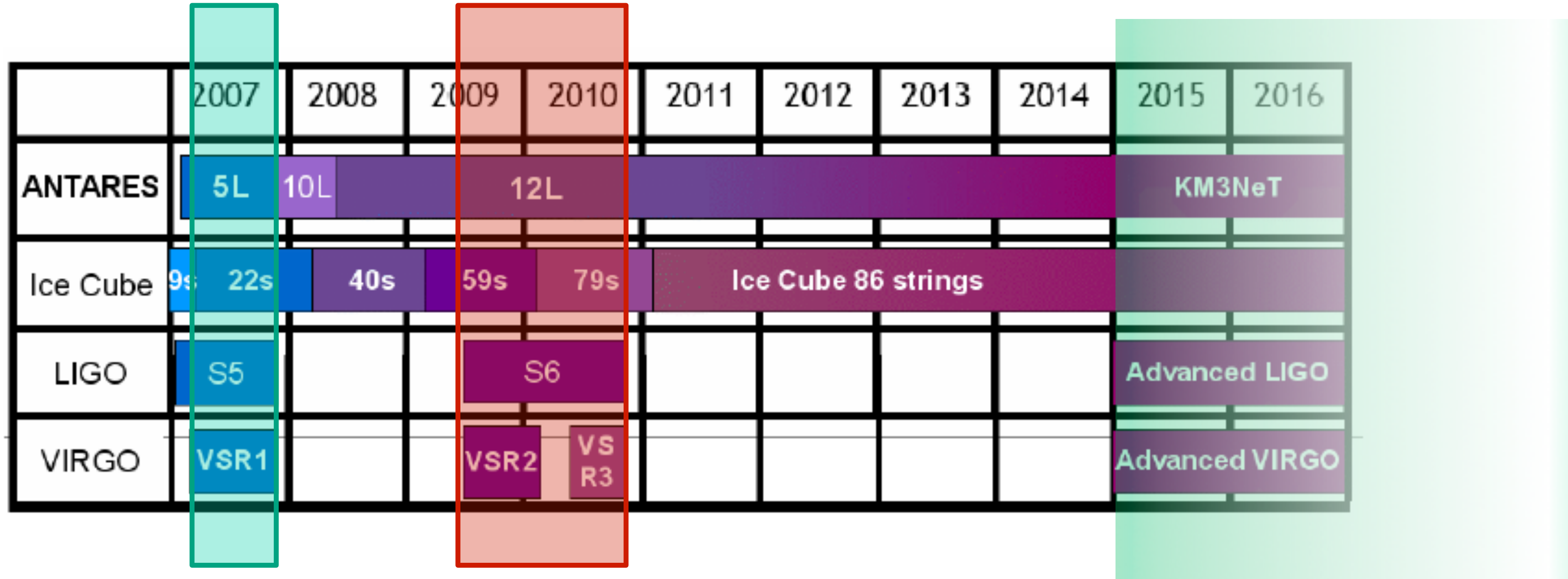
Effective collaboration (MoU) between LSC and ANTARES since Sept 2009

IceCube has joined the GWHEN group in March 2010

GWHEN team leaders :
T. Pradier(Antares)
E. Chassande Mottin (Virgo)
S. Marka (LIGO)

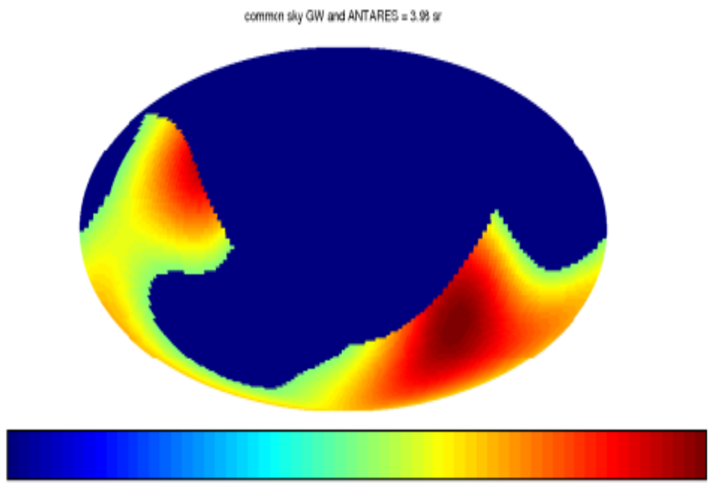


Common data set



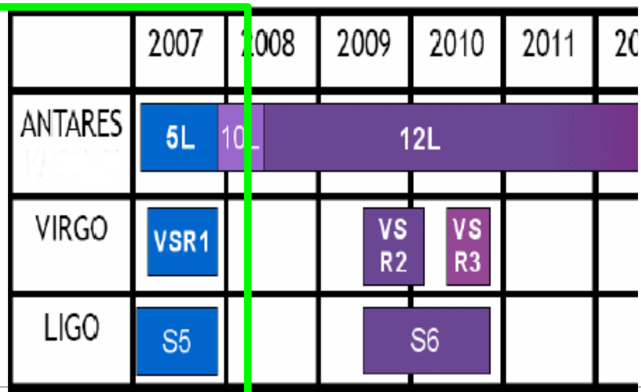
Common sky coverage for
VIRGO+LIGO+ANTARES
in geocentric coordinates ~ 30%

Assumes ANTARES has 100% visibility in its antipodal hemisphere and 0% elsewhere



Data analyses

📖 PhD Thesis B. Bouhou, APC

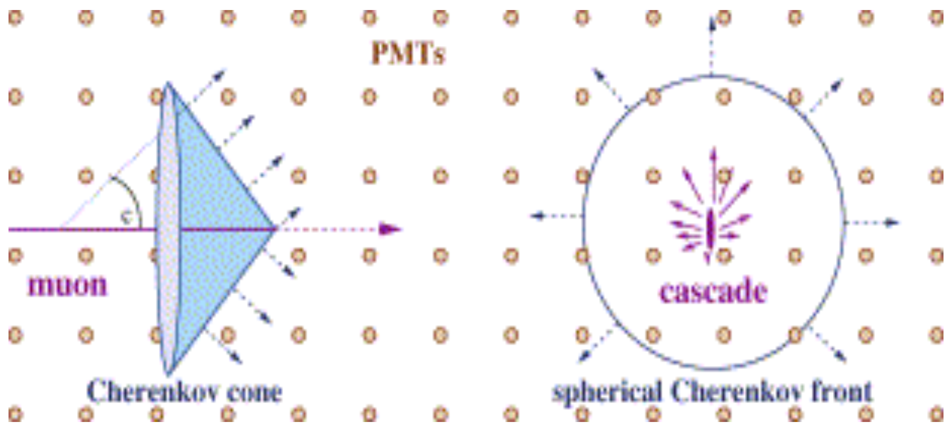


Data	2007	2009-2010
ANTARES	Partial (5L)	Complete (12L)
Virgo/LIGO	Initial	enhanced
Lifetime (days)	104	129
HEN selection method	point-source	Jointly Optimized
HEN Rec. algorithm	Bbfit (robust)	Aafit (likelihood)
GW follow-up pipeline	X-pipeline	s-cWB
Neutrino candidates tools	O(100) Used available tools	O(1000) Dedicated tools
status	complete	Final phase

📖 To appear in JCAP

Analysis of the 2007 data (104 days)

- Robust neutrino track reconstruction: Bbfit
  - Simplified detector geometry (straight lines, 1 single OM at the center of storey)
  - Minimization of χ^2-function (on time hit distribution)
  - Two reconstruction hypothesis:

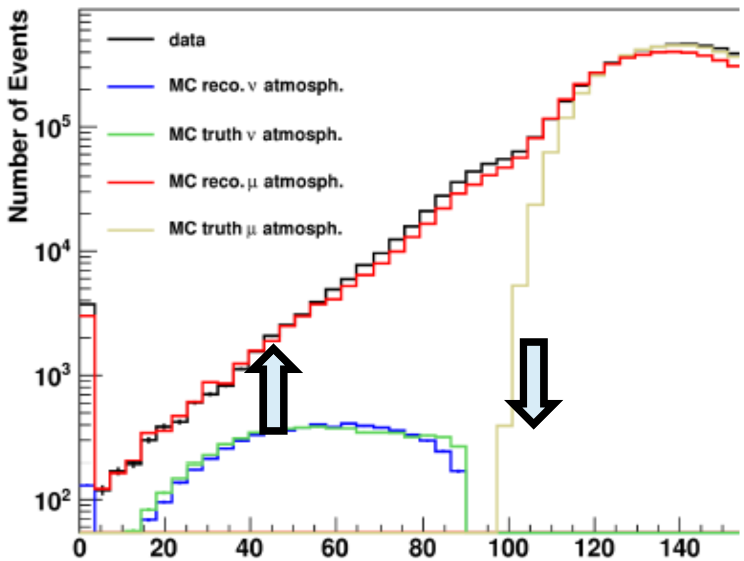


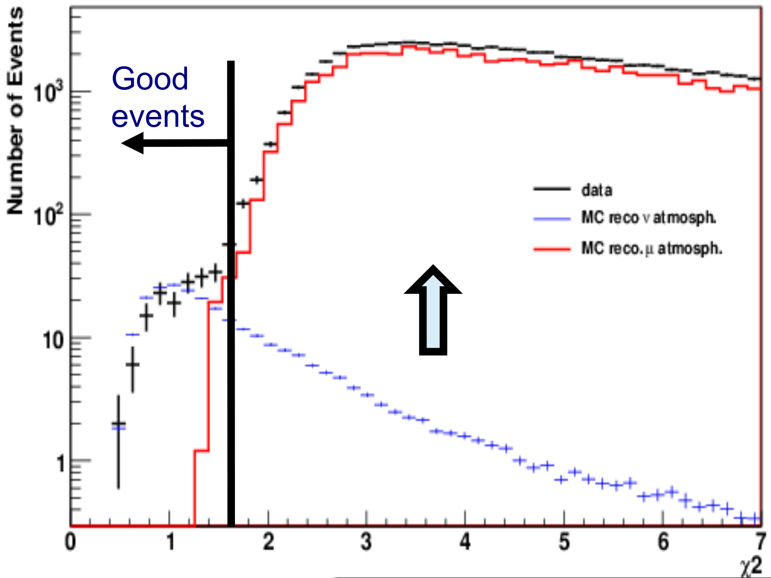
Good χ^2 Good $b\chi^2$

→ Select good χ^2 bad $b\chi^2$

HEN selection criteria (1)

- Selection parameters
  - Direction of the track θ (signal $\leftrightarrow \theta \leq 0$)
  - Track fit quality parameters: χ^2 cut





- Selection (optimizations) procedure:
  - Maximize the discovery potential for a steady point-source search of neutrino (E^{-2} spectrum)

Final cuts

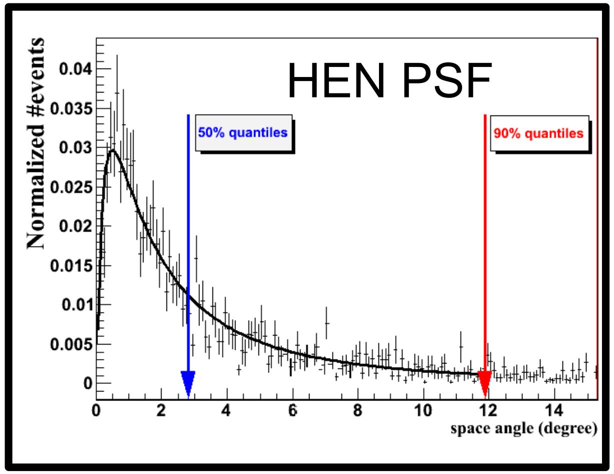
$b\chi^2 \geq 2.2$

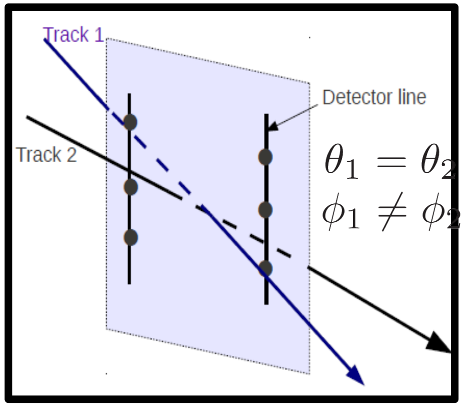
$\chi^2 \leq 1.8$ if $\theta \leq 80^\circ$

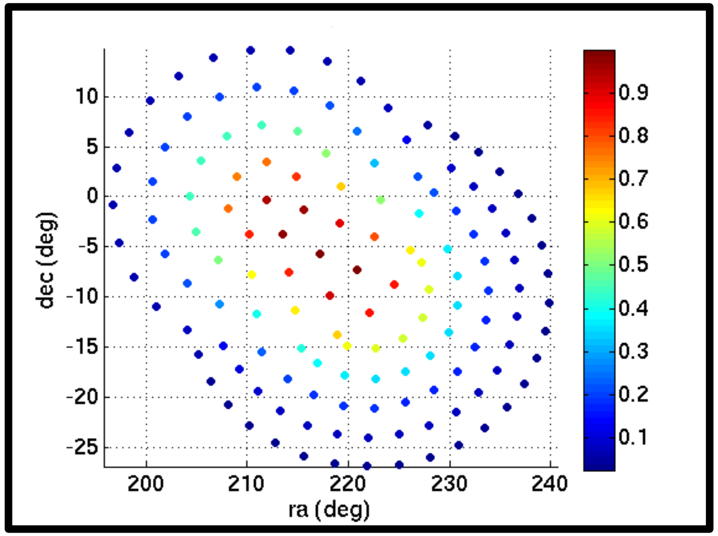
$\chi^2 \leq 1.4$ if $80^\circ \leq \theta \leq 90^\circ$

Angular search window

- Error distribution of the HEN direction
- The radius used for the joint analysis is defined as the 90% quantile of this distribution $ASW^{90\%}$
- Provide the probability distribution of the neutrino direction event-by-event







(mirror tracks are processed together)

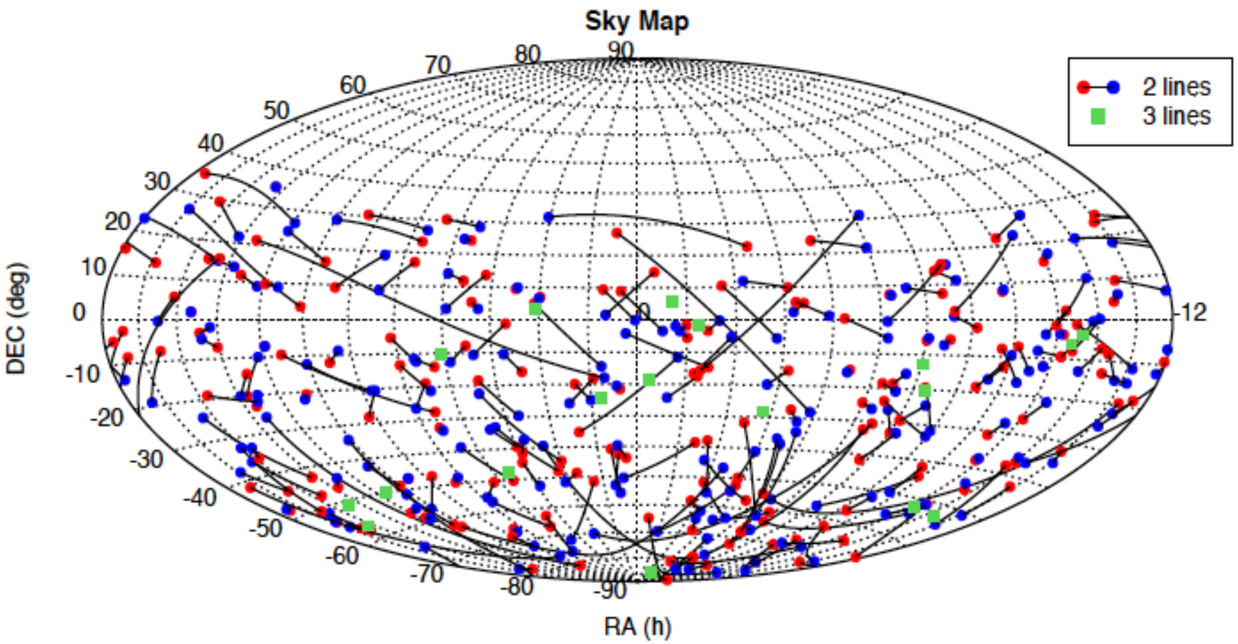
$< ASW^{90\%} >= 30^\circ$ Encompassing the two mirror tracks

$< ASW^{90\%} >= 12.5^\circ$ For the individual mirror track $d\Omega \propto (ASW90\%)^2$

HEN selection

- 216 neutrino candidates are selected
  - 198 with 2 lines (two directions)
  - 18 with 3lines and more

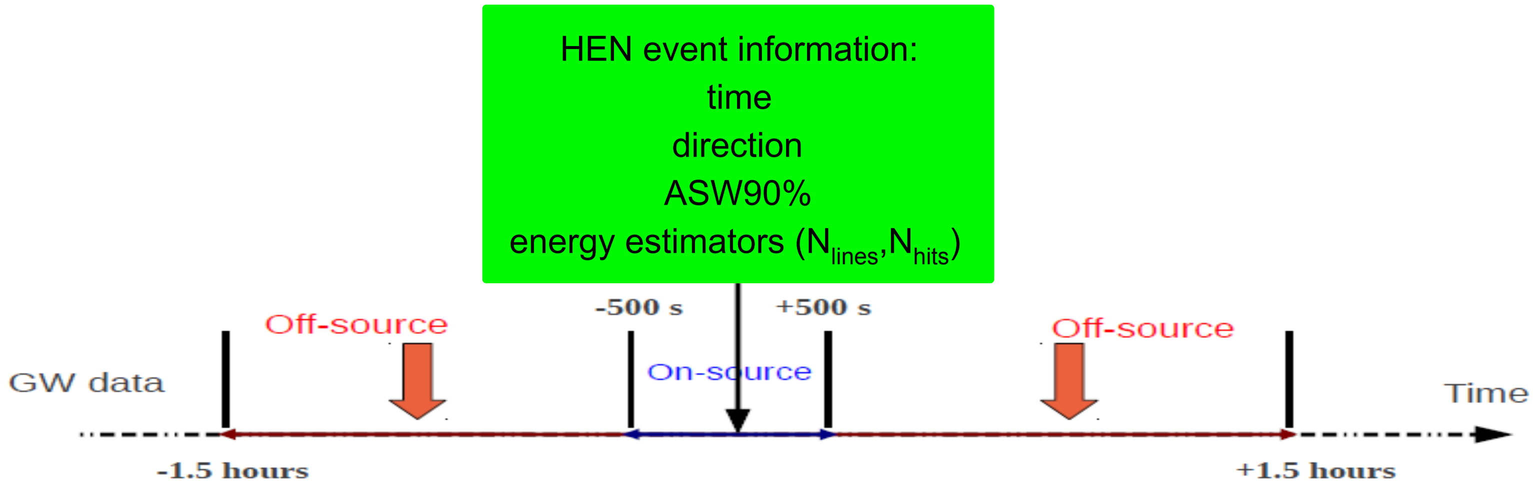
time (JD)	RA	dec	Nline	Nhits	AW(50)	AW(90)	weight	Theta	m	sigma	Norm. param
2454141.13935377	269.727	-5.896	2	13	2.2	12.1	0.5	2.4311e-02	2.3902e+00	1.2096e+00	3.9455e-02
2454141.13935377	269.100	-5.225	2	13	2.2	12.1	0.5	2.4311e-02	2.3902e+00	1.2096e+00	3.9455e-02
2454151.91867849	241.835	-44.333	2	11	2.7	14.3	0.5	4.8647e-03	2.8349e+00	1.3092e+00	4.0219e-02
2454151.91867849	268.385	-56.735	2	11	2.8	13.7	0.5	1.6306e-09	2.8663e+00	1.1820e+00	3.9580e-02
2454151.92226114	171.514	-2.570	2	8	2.5	11.5	0.5	1.2544e-02	2.7238e+00	1.2775e+00	4.1272e-02
2454151.92226114	182.212	-12.105	2	8	2.3	10.8	0.5	3.5758e-02	3.9985e+00	1.6663e+00	5.1689e-02
2454154.89607324	141.656	-3.301	2	12	2.4	11.5	0.5	1.5397e-08	2.4227e+00	1.1788e+00	3.9576e-02
2454154.89607324	137.665	-1.898	2	12	2.4	11.5	0.5	1.5397e-08	2.4227e+00	1.1788e+00	3.9576e-02
2454155.36216981	265.427	13.870	2	8	2.7	13.2	0.5	8.6629e-08	2.8099e+00	1.2090e+00	3.9895e-02
2454155.36216981	258.866	11.161	2	8	2.7	13.2	0.5	8.6629e-08	2.8099e+00	1.2090e+00	3.9895e-02
2454157.10113550	1[illegible].784	15.958	2	8	2.7	13.2	0.5	8.6629e-08	2.8099e+00	1.2090e+00	3.9895e-02
2454157.10113550	195.050	18.397	2	8	2.7	13.2	0.5	8.6629e-08	2.8099e+00	1.2090e+00	3.9895e-02
2454157.47628597	37.369	9.441	2	11	2.6	13.4	0.5	8.3305e-12	2.7292e+00	1.1952e+00	3.9518e-02
2454157.47628597	36.844	9.913	2	11	2.6	13.4	0.5	8.3305e-12	2.7292e+00	1.1952e+00	3.9518e-02
					.9	12.7	0.5	3.3971e-02	3.9998e+00	1.4631e+00	4.8543e-02
					.9	12.7	0.5	3.3971e-02	3.9998e+00	1.4631e+00	4.8543e-02
					.8	12.0	0.5	3.3575e-02	3.2989e+00	1.3087e+00	4.2303e-02
					.2	11.9	0.5	1.8175e-08	2.3217e+00	1.2413e+00	3.9633e-02
					.4	11.9	0.5	3.5170e-09	2.6909e+00	1.3369e+00	4.1404e-02
					.4	11.9	0.5	3.5170e-09	2.6909e+00	1.3369e+00	4.1404e-02
					.7	12.6	0.5	7.4600e-07	2.6143e+00	1.1803e+00	3.9572e-02



Coincidence with GWs (1): method

See M.A Bizouard & M. Was lectures

- GW analysis: X-pipeline
  - Initially developed for GW follow-up with GRBs
  - Uses neutrino triggers to search for GW
  - Nominal frequency band [64, 500]Hz, extended to 2 kHz for 3 line neutrinos
  - Coherent combining of data + time-frequency excess power search



- 158 (among 216 neutrinos) with GW data

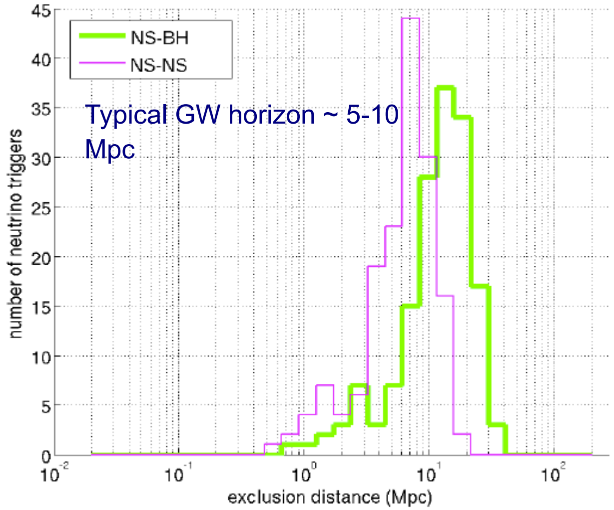
- Closed-box (blind) analysis:

  background estimation & parameter tuning on off-source region

No excess →Upper limits: exclusion distances

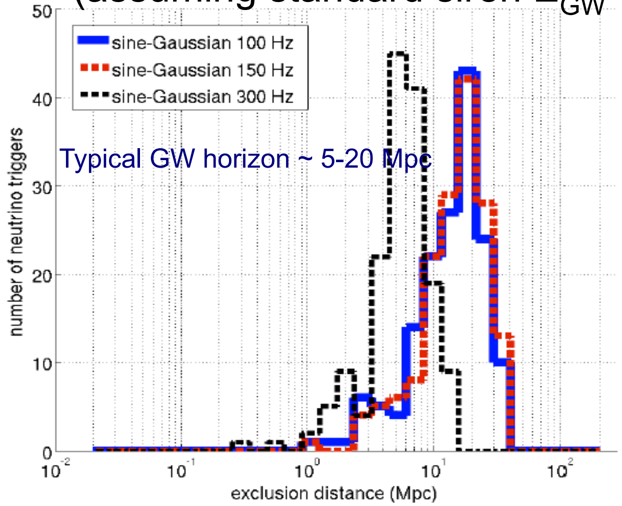
- Estimate the detection horizon for each injected GW template signal:

Inspiral (short GRB)

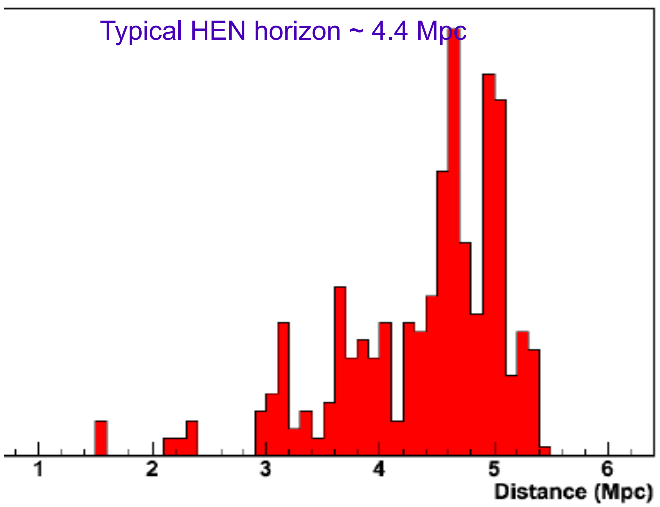


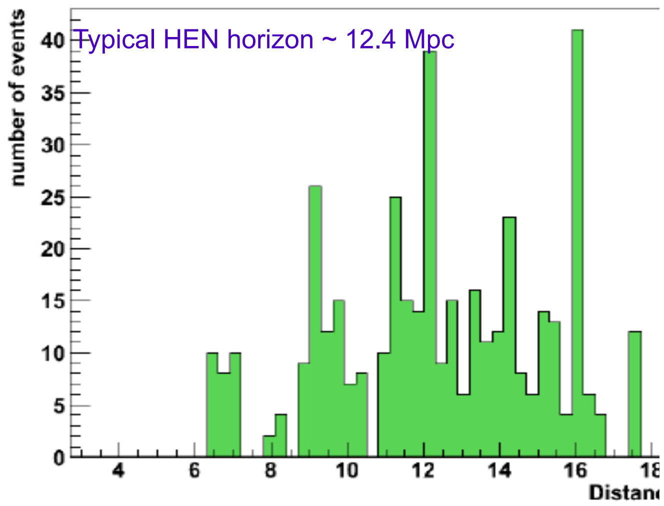
sine-gaussian (long GRB)

(assuming standard siren $E_{GW} = 10^{-2} M_O c^2$)



Distance for 50% probability to detect at least one neutrino event





Upper limits: population density

- No joint detection implies

$N_{GW\text{-}HEN} \leq 2.3$ at 90% C.L.

⇨ limits on the population density of joint GW+HEN emitters:

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

← Volume of universe probed by the present analysis for typical GW-HEN sources

$$d_{GW-HEN} \simeq min(d_{HEN}, d_{GW})$$

- Short GRB-like: d_{HEN} = 4.4 Mpc, d_{GW} = 5-10Mpc

  $\rho_{GWHEN} \leq 10^{-2}$ Mpc^{-3} yr^{-1}

  ...to be compared with estimated density of NS-NS mergers:

  $\rho_{NS\text{-}NS} \approx 10^{-6}$ Mpc^{-3} yr^{-1} (Kalogera et al. 2004 ; Belczynski et al. 2011)

- Long GRB-like: d_{HEN} = 12.4 Mpc, d_{GW} = 10-20 Mpc

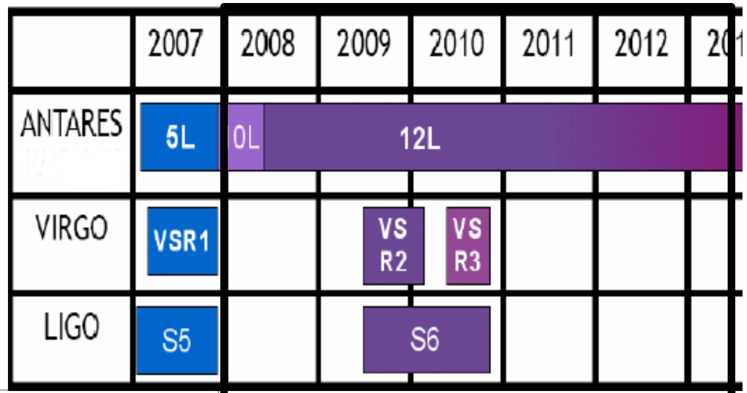
  $\rho_{GWHEN} \leq 10^{-3}$ Mpc^{-3} yr^{-1}

  ...to be compared with estimated density of Type II/Ibc core-collapse SN :

  $\rho_{SNII} \approx 2 \times 10^{-4}$ Mpc^{-3} yr^{-1} (Bazin et al. 2009)

  $\rho_{SNIbc} \approx 2 \times 10^{-5}$ Mpc^{-3} yr^{-1} (Guetta & Valle 2007)

Data analyses

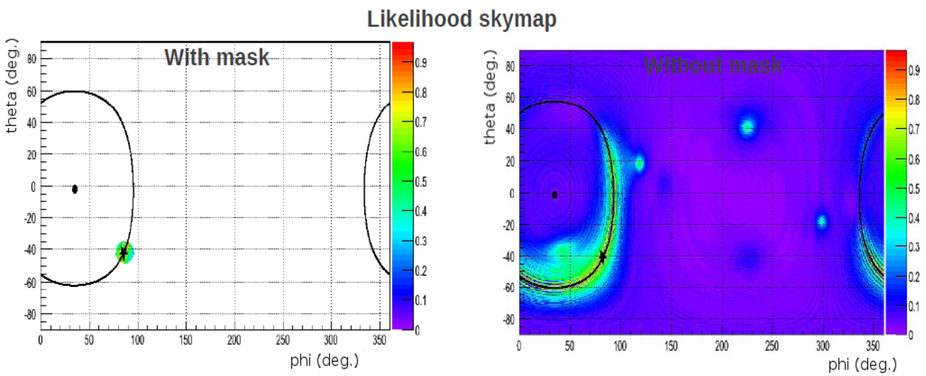


Data	2007	2009-2010
ANTARES	Partial (5L)	Complete (12L)
Virgo/LIGO	Initial	enhanced
Lifetime (days)	104	129
HEN selection method	point-source	Jointly Optimized
HEN Rec. algorithm	Bbfit (robust)	Aafit (likelihood)
GW follow-up pipeline	X-pipeline	s-cWB
Neutrino candidates tools	O(100) Used available tools	O(1000) Dedicated tools
status	complete	Final phase

Improved algorithms

- GW
  - Coherent Wave burst (used in the all-sky GW search)
  - Search in skymask from neutrino direction and ASW90 %
  - Select data segments of 1000 sec (use time of neutrino candidates)
  - Frequency band [64, 2048] Hz
  - Less CPU time (1000 ν /week) vs 100 ν /month for X-pipeline

→ Skymask-coherent WaveBurst



- Muon neutrino reconstruction algorithm:
  - Maximum likelihood $\Lambda \sim \frac{log\mathcal{L}}{N_{dof}}$
  - Based on full PDF of time residuals (all hits)
  - Better angular accuracy
  - Real time detector geometry → no mirror track

Optimization of the joint search sensitivity (1)

A novel approach

GW FAR rate — Time window (1000 sec)

False Alarm Probability

$$FAP = FAR(\rho) \times N_\nu(\Lambda) \times \Delta t$$

$\rho \propto SNR$

number of HEN candidates

- Adjust HEN and GW cuts to keep FAP fixed

  Lower Λ implies:

  - Larger neutrino signal efficiency
  - Number of HEN candidates increases
  - More stringent GW threshold ρ
  - Lower GW efficiency

- Find trade-off between ρ and Λ at a given FAP

Optimization of the joint search sensitivity (2)

Objective: maximize the number of "observable" sources

- Write the number of detectable GWHEN sources as follows

$$\mathcal{N}_{\mathrm{gw}\nu}(\Lambda,\rho) \propto \int_0^\infty 4\pi r^2 dr \, \frac{1}{r^2} \epsilon_\nu(\Lambda)\epsilon_{gw}(\rho; E_{gw}, r),$$

- $\epsilon_{gw}(\rho; E_{gw}, r)$ and $\epsilon_\nu(\Lambda)$ are the efficiencies for a given model

- Approximate GW efficiency as a step function

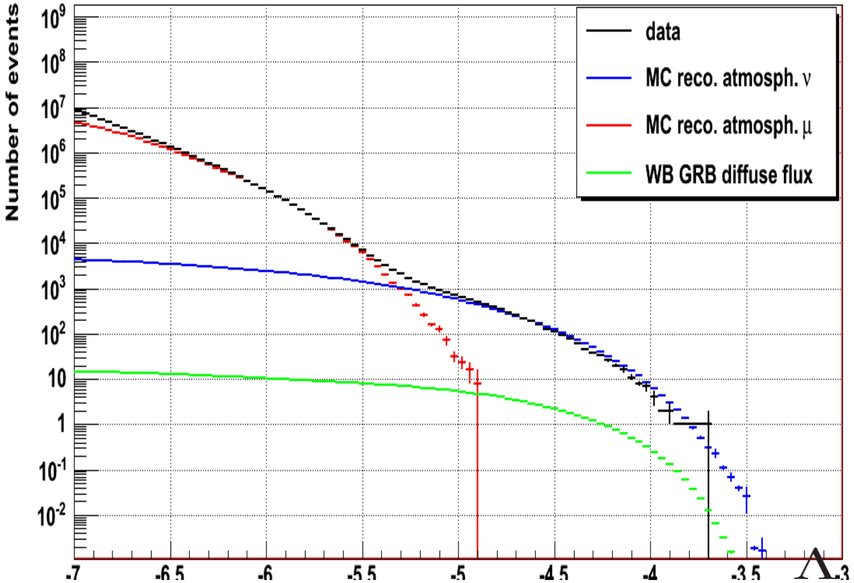
$$\mathcal{N}_{\mathrm{gw}\nu}(\Lambda,\rho) \propto \epsilon_\nu(\Lambda) D(\rho).$$

- ρ is inversely proportional to horizon distance

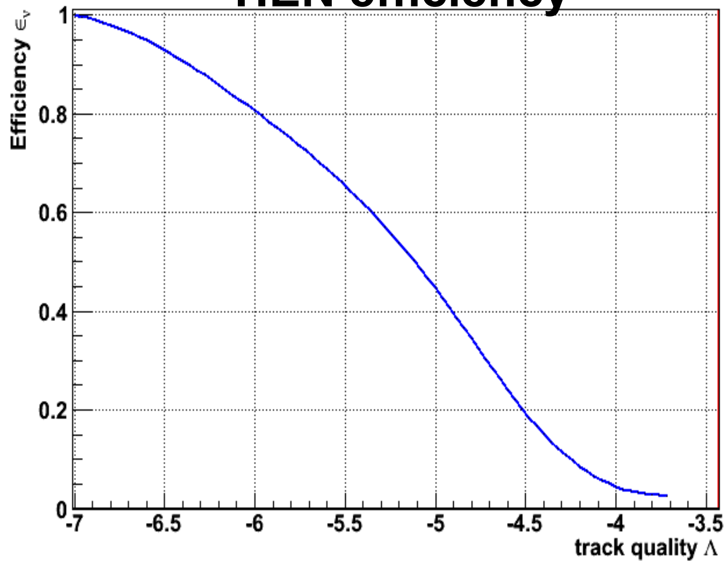
$$\mathcal{N}_{\mathrm{gw}\nu}(\Lambda,\rho) \propto \epsilon_\nu(\Lambda)/\rho \equiv FOM$$

Optimization of the joint search sensitivity (3)

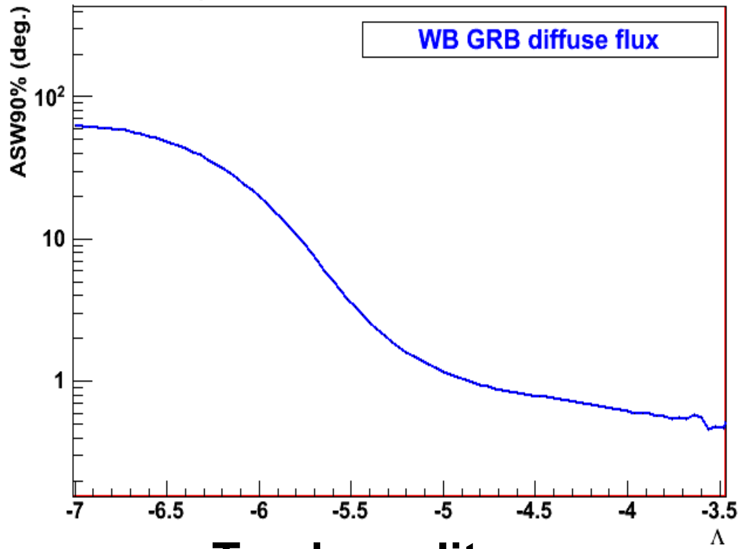
Cumulative distribution of Lambda



HEN efficiency



Angular search window

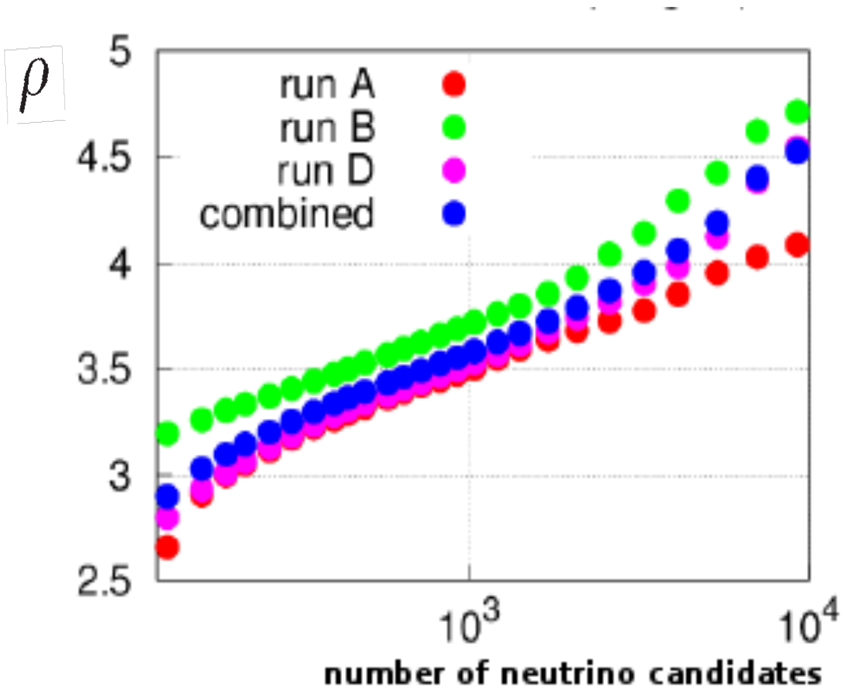


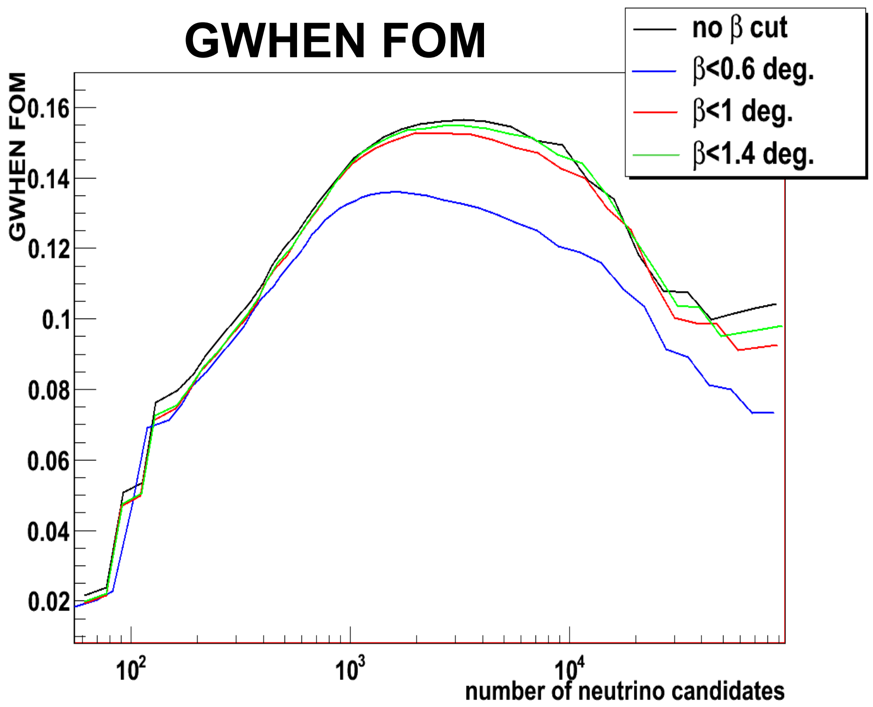
Track quality

- Use MC simulation and data
- Select only upgoing events
- Use W&B GRB diffuse flux

Optimization of the joint search sensitivity (4)

- Optimize for 3-detector network
- Fix false alarm probability (FAP) at 4.7×10^{-3} (2 sigma)
- Find Λ maximazing FOM

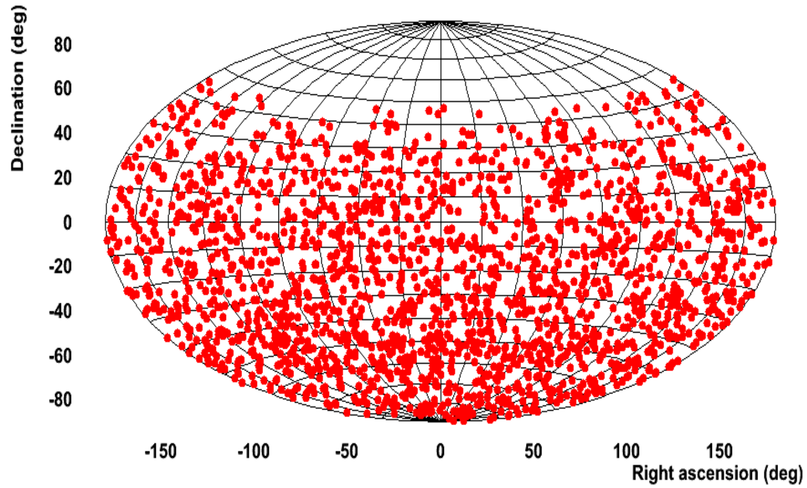




Current status

Final cuts

$$\Lambda > -5.44$$
$$\beta < 1^\circ$$



- Selected 1986 HEN candidates
- Selection has been approved by the ANTARES collaboration
- GW Background computed
- Statistical treatment of joint candidates defined

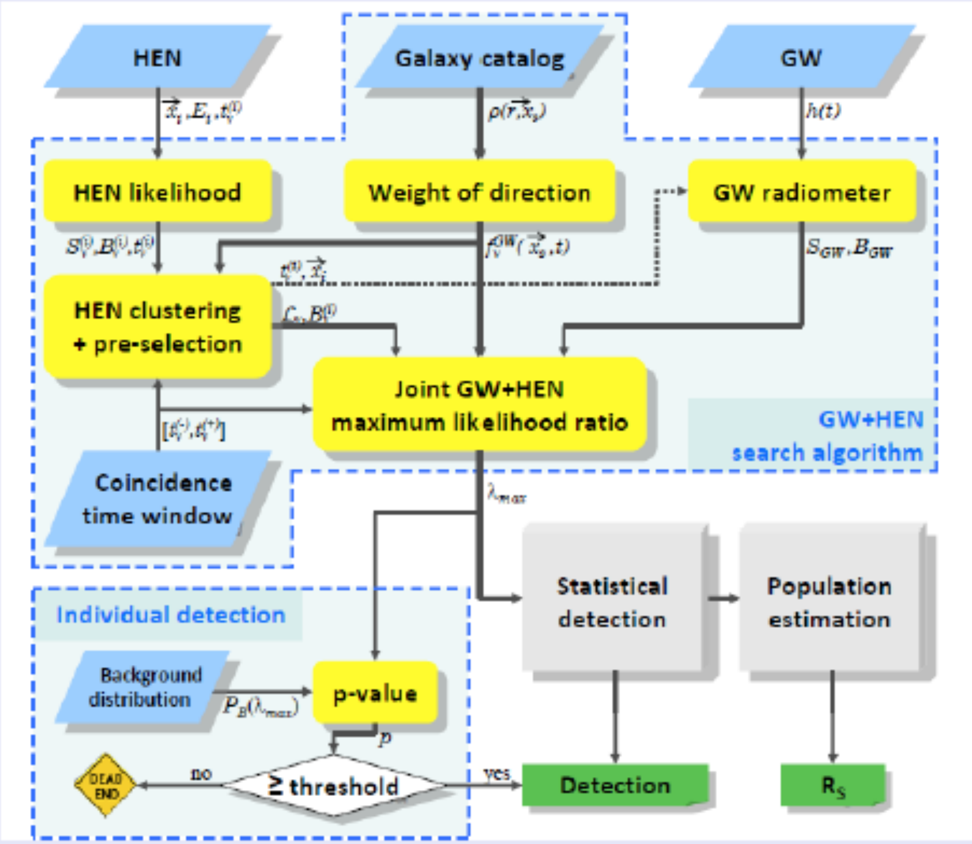
- In the hypothesis of no detection for this analysis the upper limit on the population density can be improved by :
  - Gain of factor 1.4 on observation time
  - Gain of factor 3 on the effective area ($\sqrt{3}$ on the distance)
    - Gain of factor ~ 7 on the population density w.r.t 2007 analysis

IceCube & Virgo-LIGO joint search

Ongoing analysis

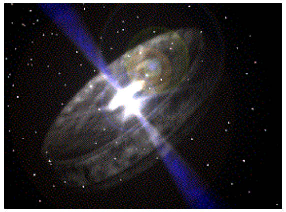
IC22 + VSR1/S5 in 2007

- $\sim$ 100 days of concomittant data, 1200 HEN candidates
- Re-weighting of events wrt Galaxy Catalogue



Request from Virgo-LIGO : Include 2009-2010 data set.

Outline

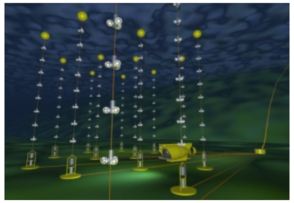


Neutrino astronomy

Historical aspects

Scientific motivations

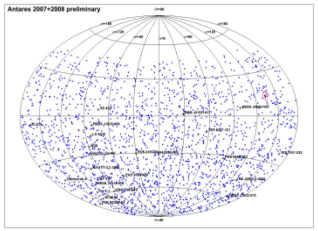
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux

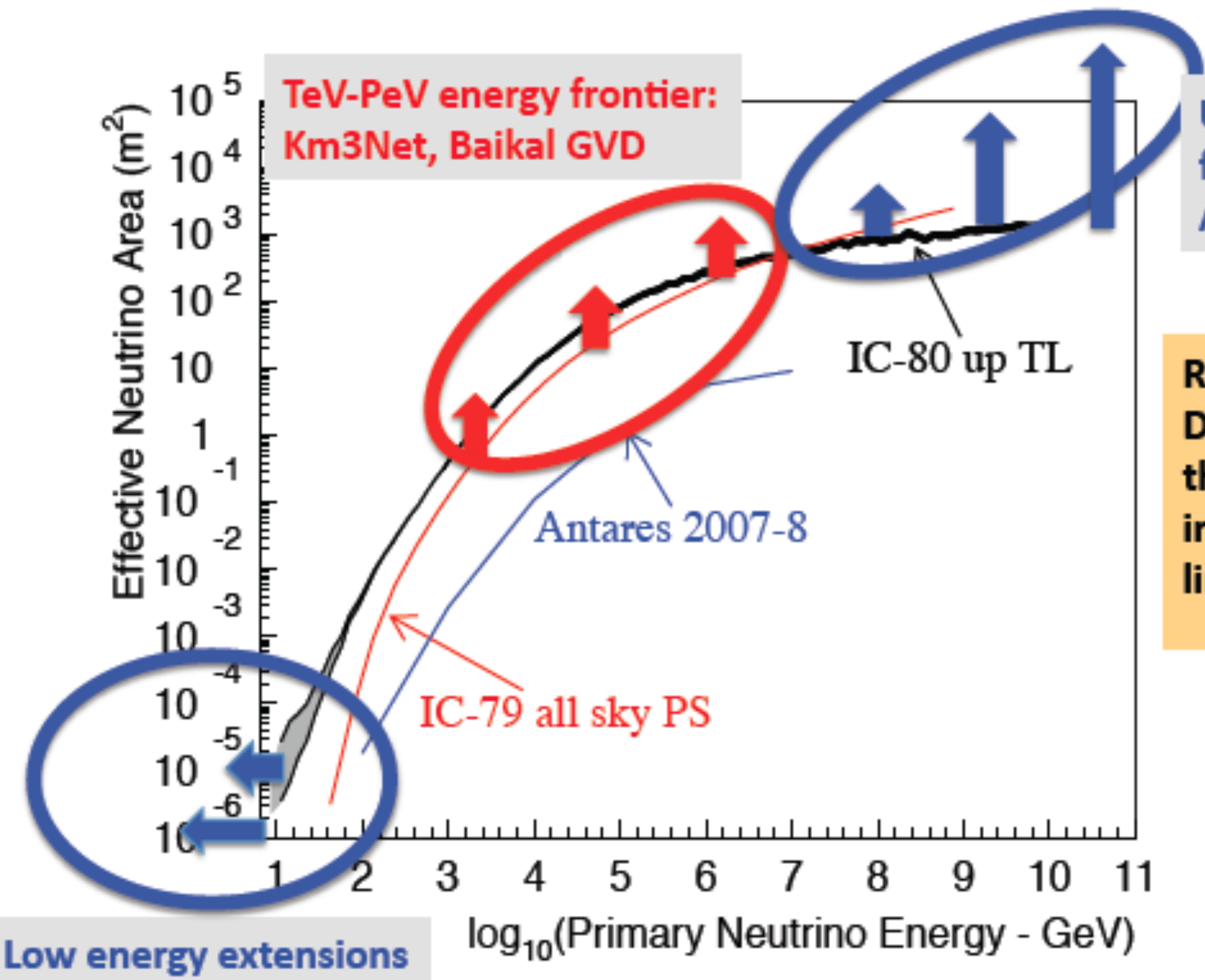
Search for point sources

Multi-messenger search

GWHEN searches

Future prospects

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

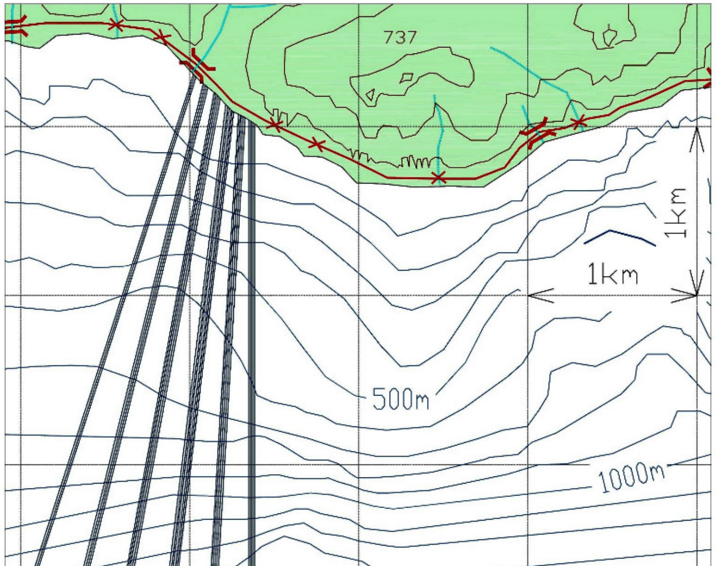
Gton Volume Detector (Lake Baikal)

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

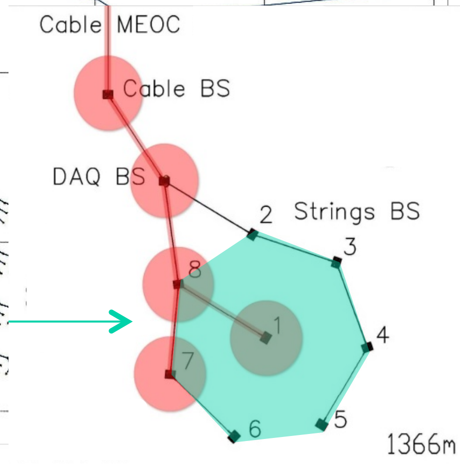
Instrumented water volume
V= 1.5 km^3 S = 2 km^2

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

Full first cluster 2014 ?

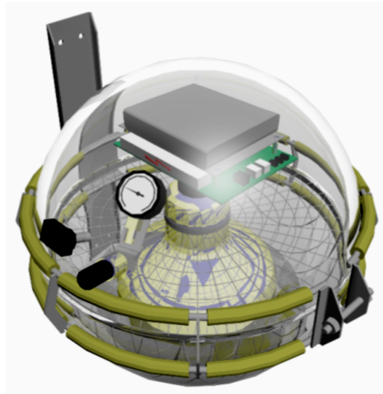


GVD array



1st GVD cluster: 8 strings

- Installed strings and cable stations



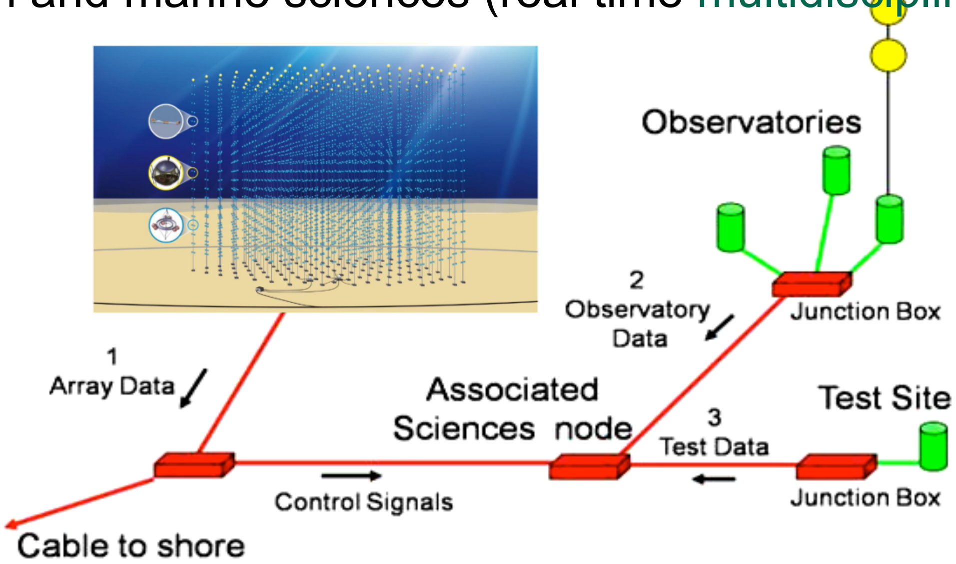
Optical module

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

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

The detector layout

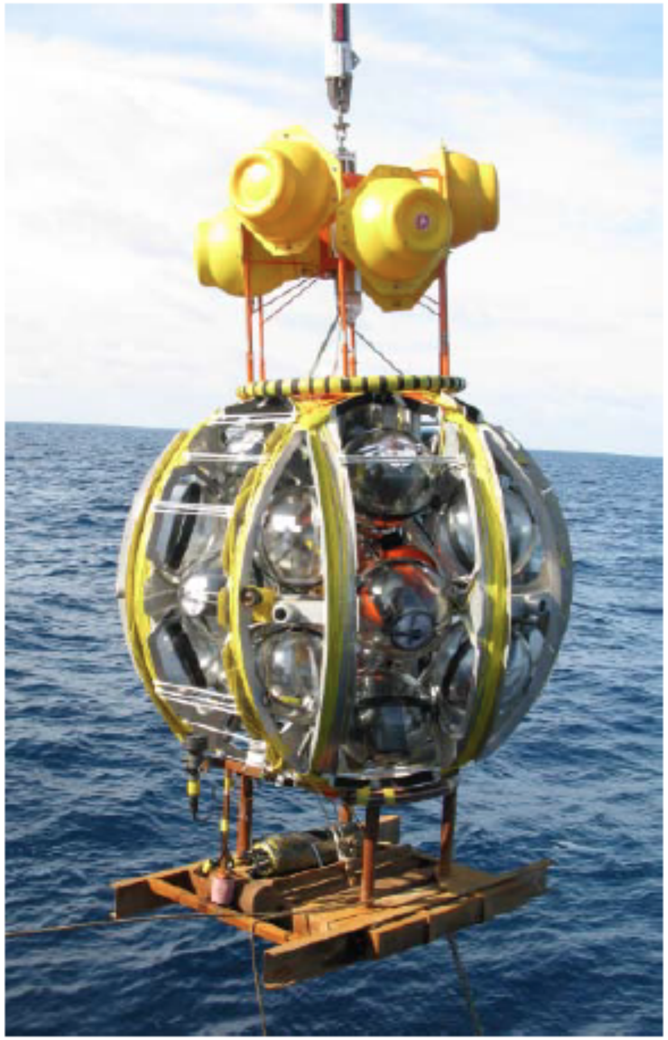
The String Technology

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

Detection Unit with 20 storeys

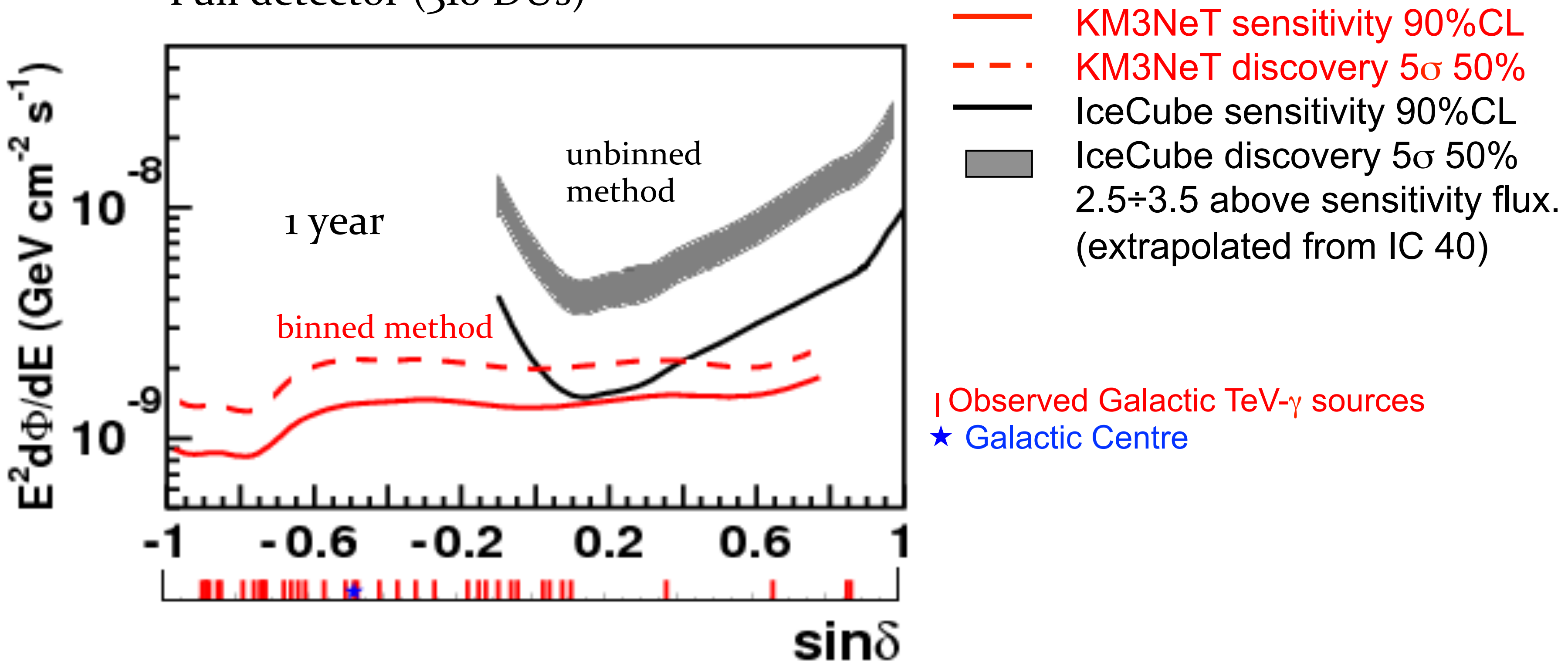
40 m inter-storey distance

Compact deployment



Expected sensitivity E^{-2} spectrum

Full detector (310 DUs)



The case for RXJ 1713

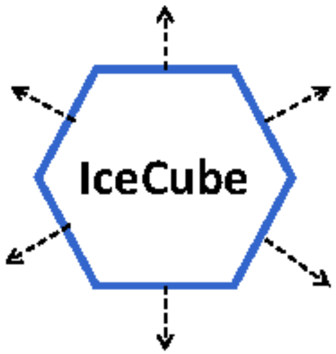
- 2-2.5 years for 3 σ discovery
- 5-6 years for 5 σ discovery

Anticipated Improvements

- Unbinned analysis, source morphology, improved reconstruction

Towards a futur Global Neutrino Observatory?

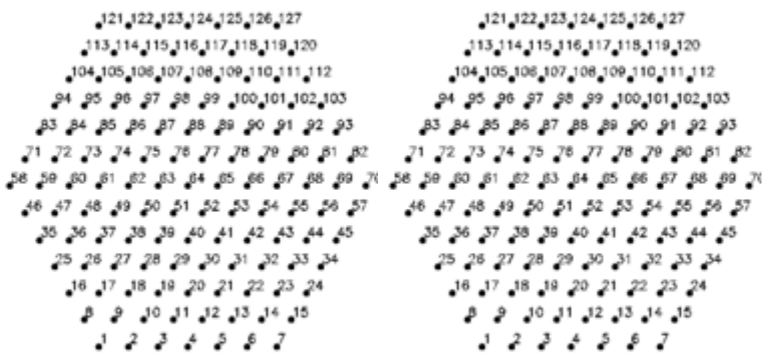
South hemisphere: – 1km^3

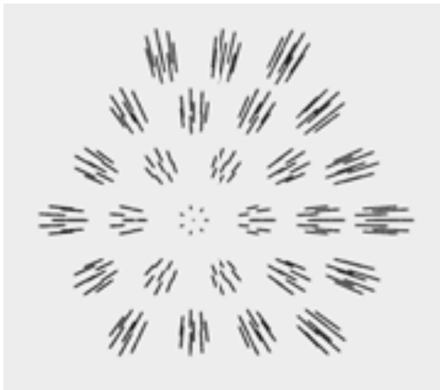


Already common meeting once a year since 2008… "MANTS symposium"

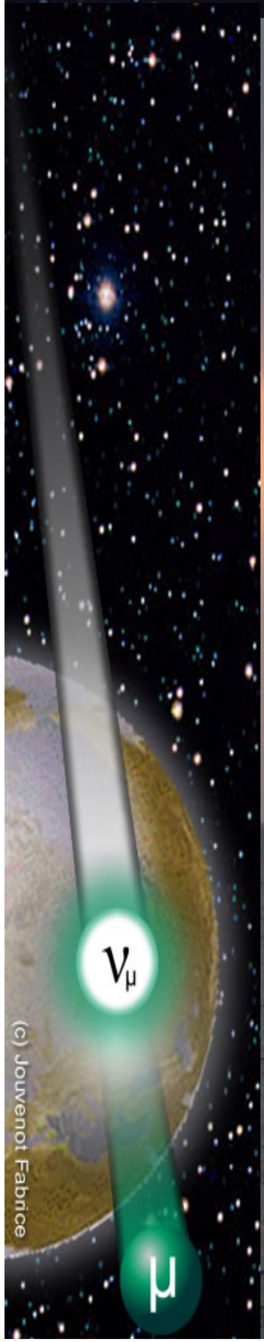
Northern hemisphere:

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





Conclusions



- Neutrino astronomy has made great progress
- First observation of HE astrophysical neutrinos reported 10 days ago by IceCube.
- ANTARES has demonstrated the feasibility of a deep-sea detector. Currently the larger NT in the Northern hemisphere…

  A platform for associated sciences.
- A rich multi-messenger program
  - First GWHEN study published
  - More is expected soon (ANTARES+IceCube)
- A joint discovery with the advanced generation of interferometers?