Meeting on Fundamental Physics, Benasque, March 2015

Status report on IceCube, ANTARES and KM3NeT

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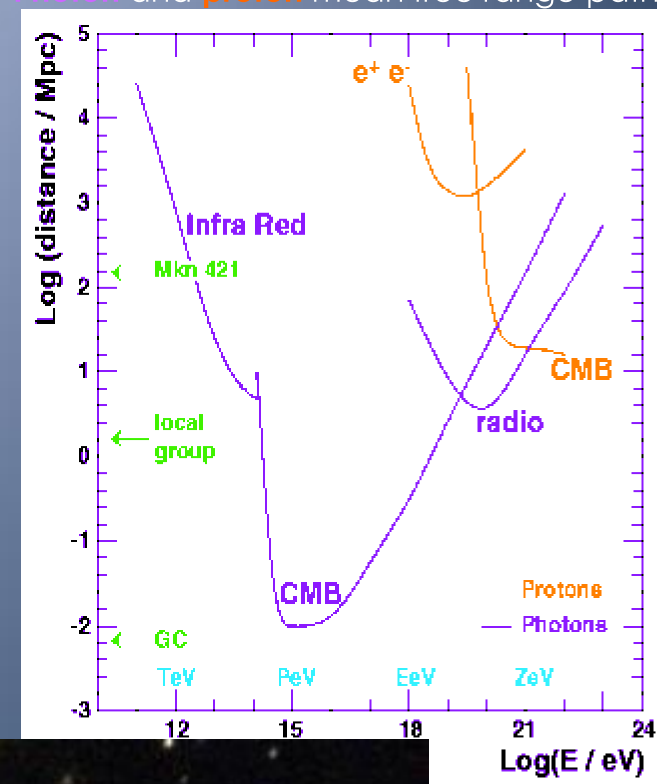
Introduction

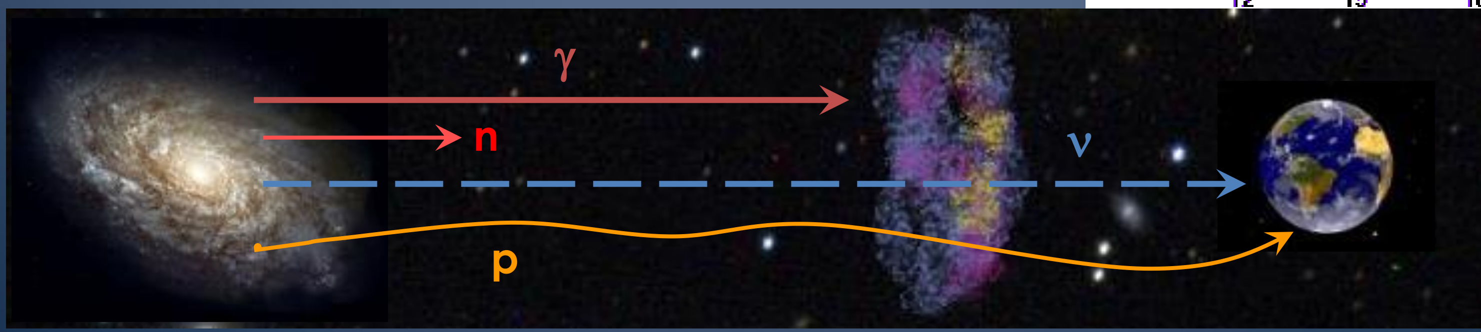
- Motivation
- Detection principle
- Projects
  - Pioneers
  - IceCube
  - ANTARES
  - KM3NeT
  - Conclusions

Neutrino Astronomy

- Advantages:
  - Photons: interact with CMB and matter
  - Protons: interact with CMB and are deflected by magnetic fields
- Drawback: large detectors (~GTon) are neded

Photon and proton mean free range path





Production Mechanism

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \to p^{\pm}(K^{\pm}...) + Y \to m^{\pm} + n_m(\bar{n}_m) + Y$$

$$\downarrow$$

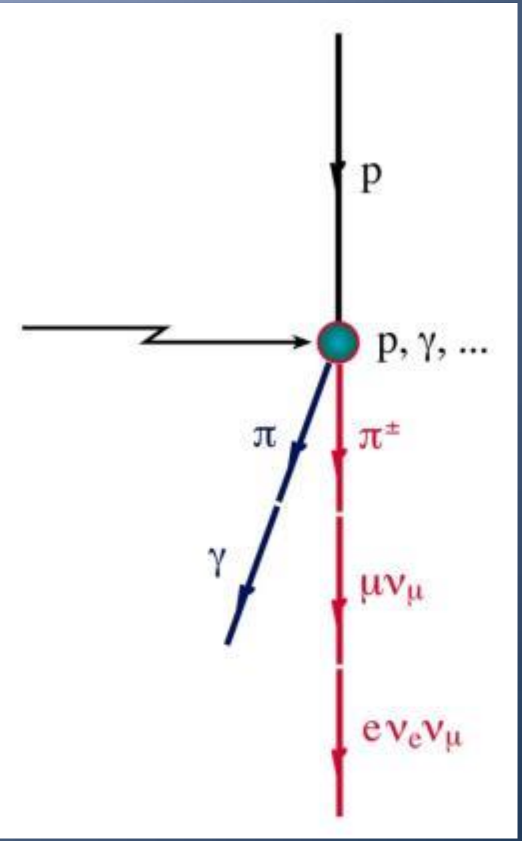
$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_\mu(\nu_\mu)$$

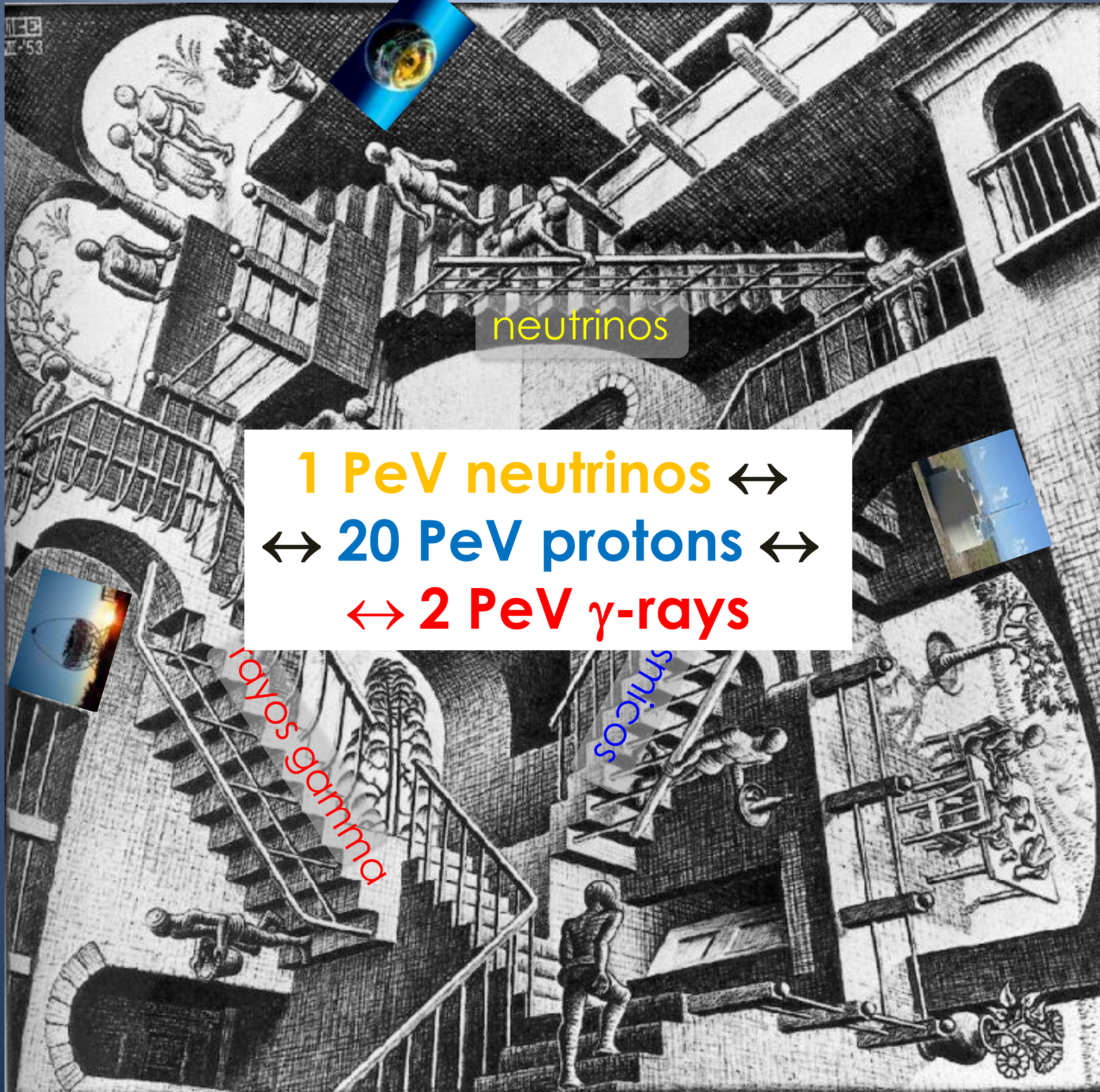
Cosmic rays

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

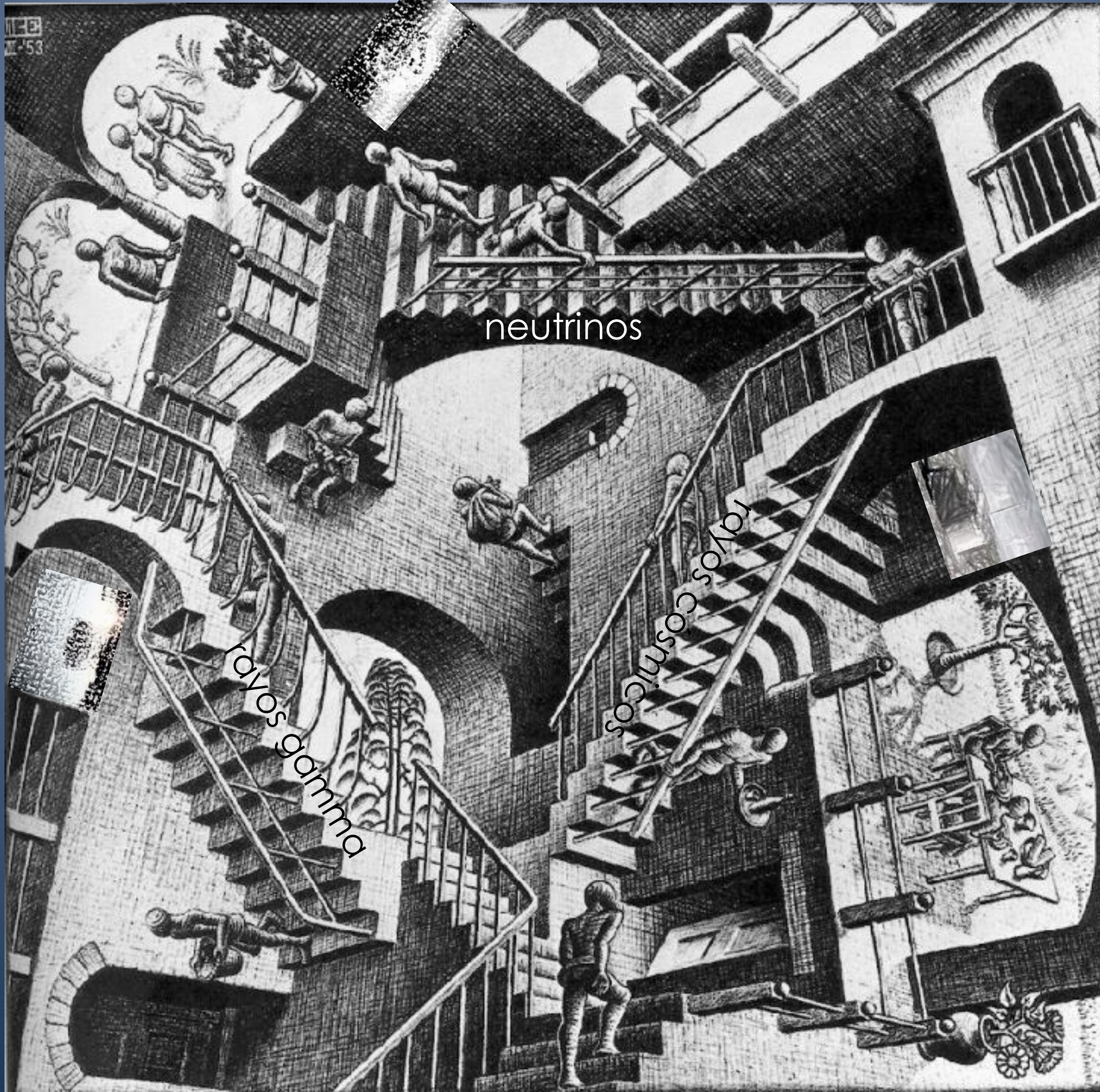
$$N + X \to p^0 + Y \to g\,g + Y$$

Gamma ray astronomy

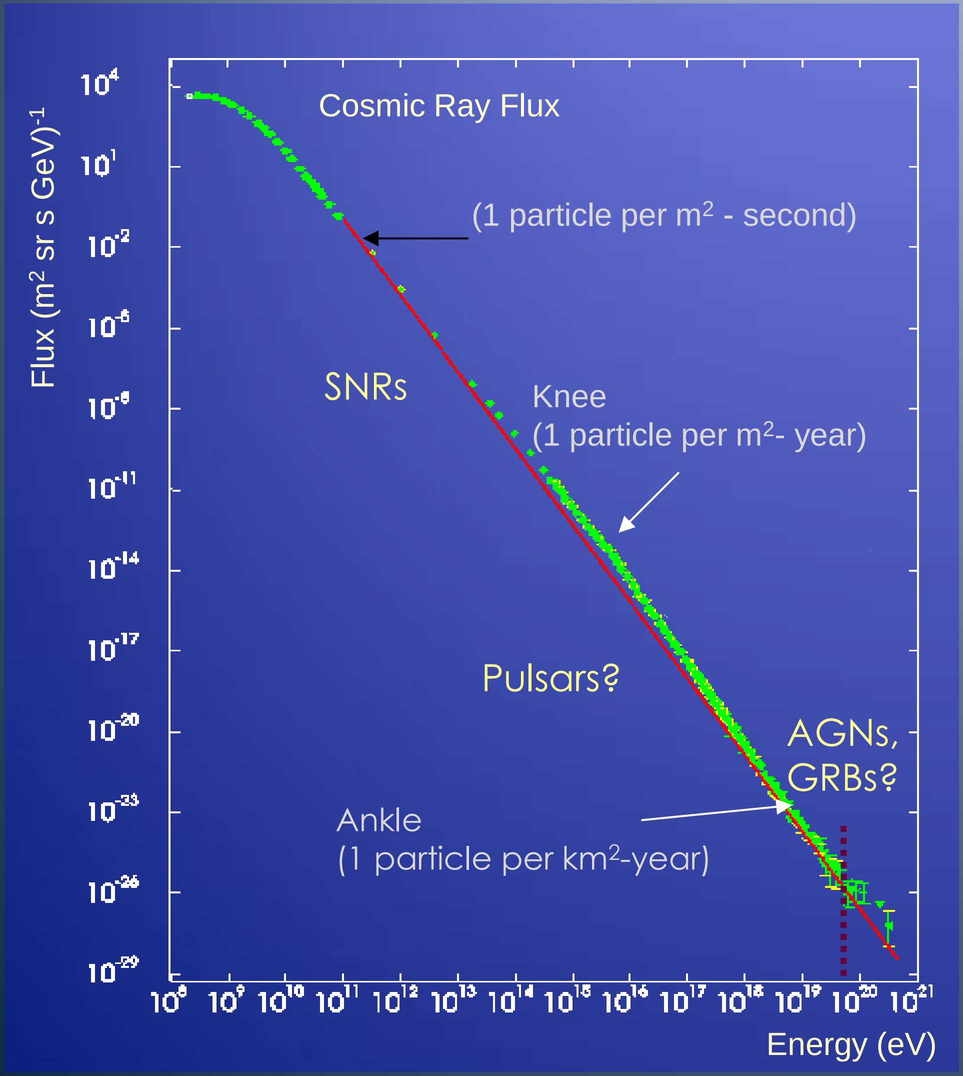




neutrinos
1 PeV neutrinos ↔
↔ 20 PeV protons ↔
↔ 2 PeV γ-rays
rayos gamma
smicos


neutrinos
rayos cósmicos
rayos gamma

Cosmic Rays



- Cosmic rays follow a power law:

$$\frac{dN}{dE} \propto E^{-\gamma} \begin{cases} \gamma = 2.7 \\ \gamma = 3.0 \\ \gamma = 2.7 \end{cases}$$

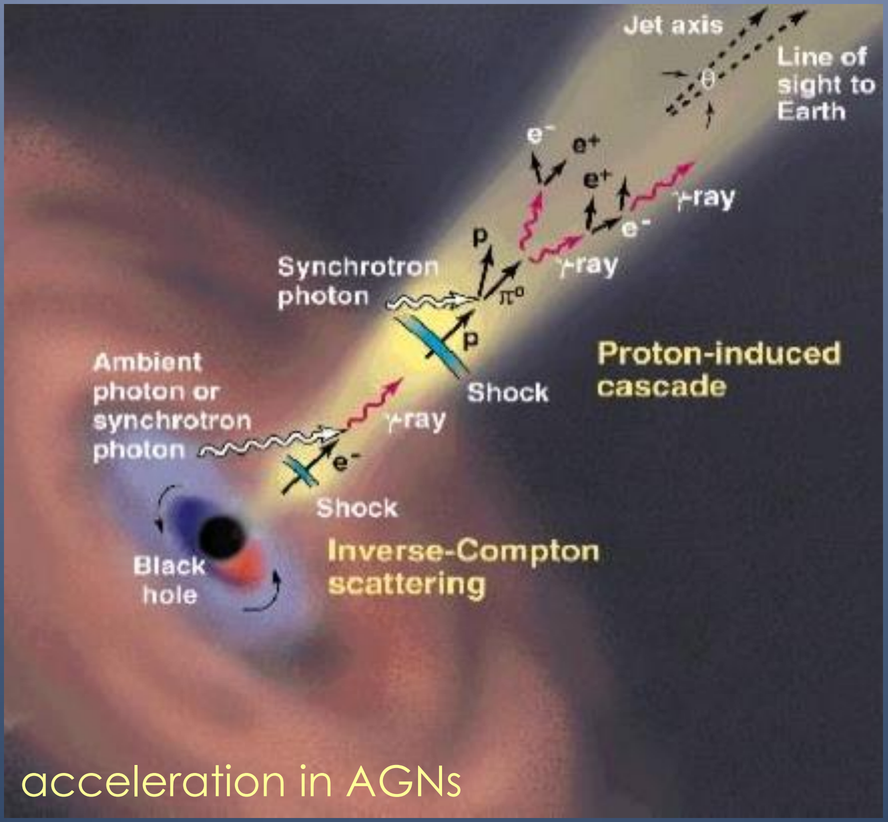
the knee

the ankle

- Beyond ~5×10^{19} eV, the flux should vanish due to the interaction of protons with the CMB (GZK limit).
- High energy neutrinos could give information about the origin of cosmic rays.

High energy photons

- The observation of TeV photons can be explained by
  -leptonic processes (inverse Compton, bremsstrahlung) or
  -the decay of neutral pions produced in hadronic interactions (→neutrino production).

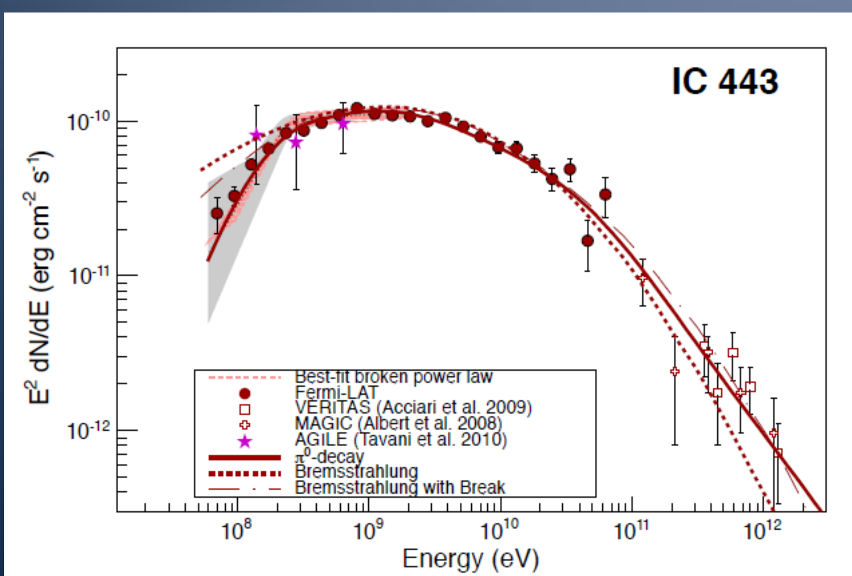


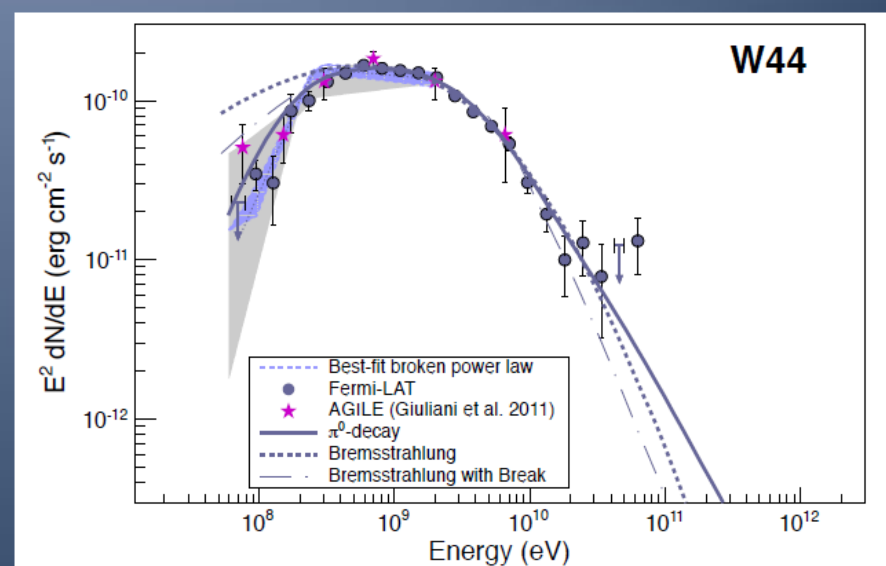
Supernova Remnants

- Formed after the explosion of a supernova by the expelled material colliding with the interstellar medium
- Two main categories:
  - Pulsar Wind Nebulae (or plerions), which have a pulsar in its center
  - Shell-type SNRs

Galactic Cosmic Rays

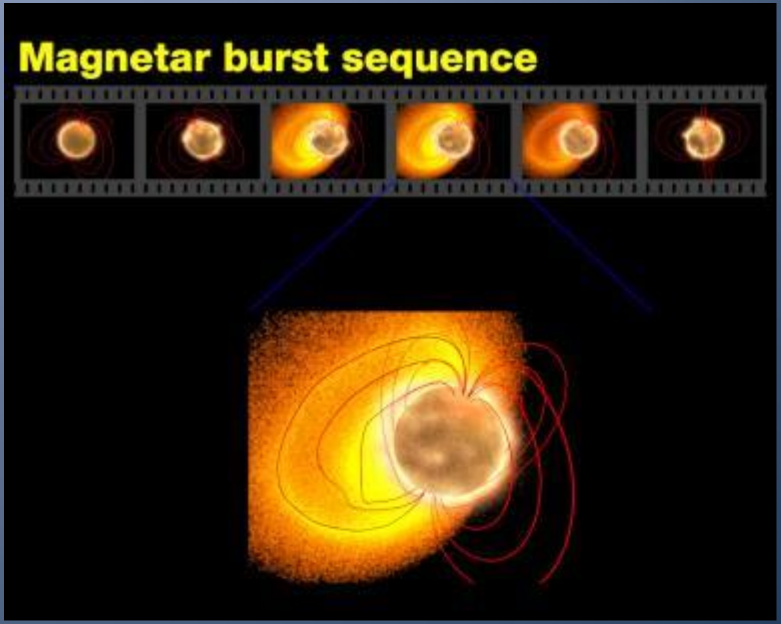
- Fermi (γ-rays) results on IC 443 W44 supernova remnants seem to indicate a better agreement of hadronic models for low energy → origin of low energy CRs?





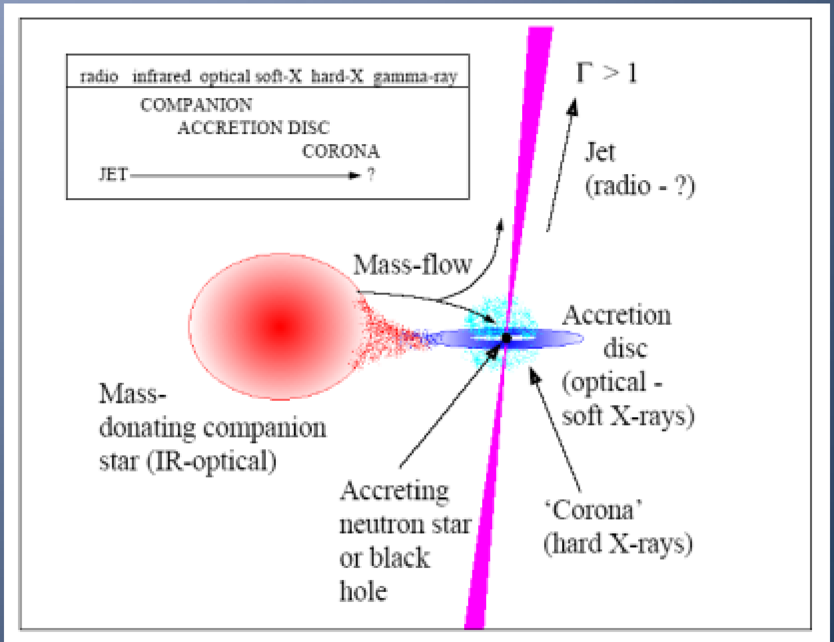
Magnetars

- Isolated neutron stars with surface dipole magnetic fields ~1015 G, much larger than ordinary pulsars.
- Seismic activity in the surface could induce particle acceleration in the magnetosphere



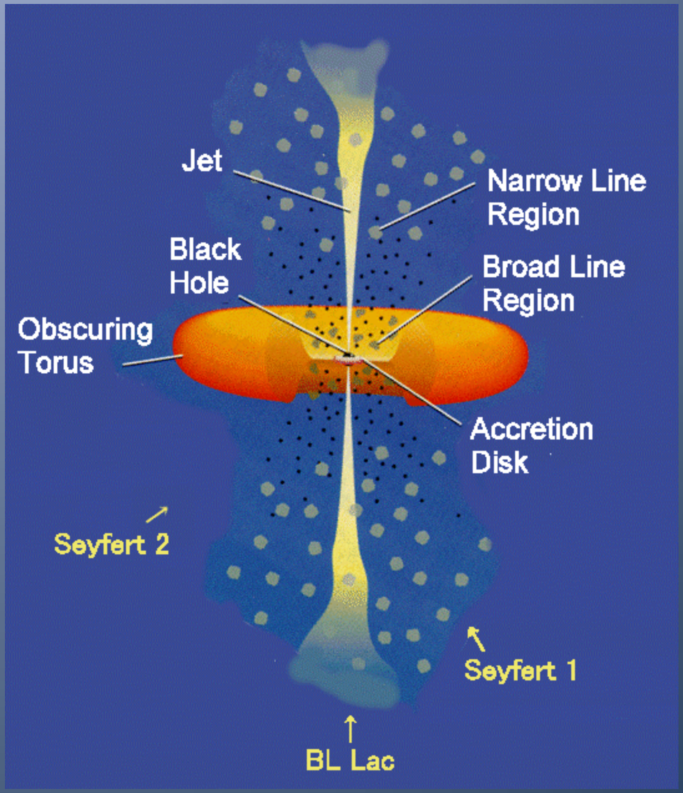
Microquasars

- Micro-quasars: a compact object (BH or NS) towards which a companion star is accreting matter
- Particle acceleration up to high energies in the jets



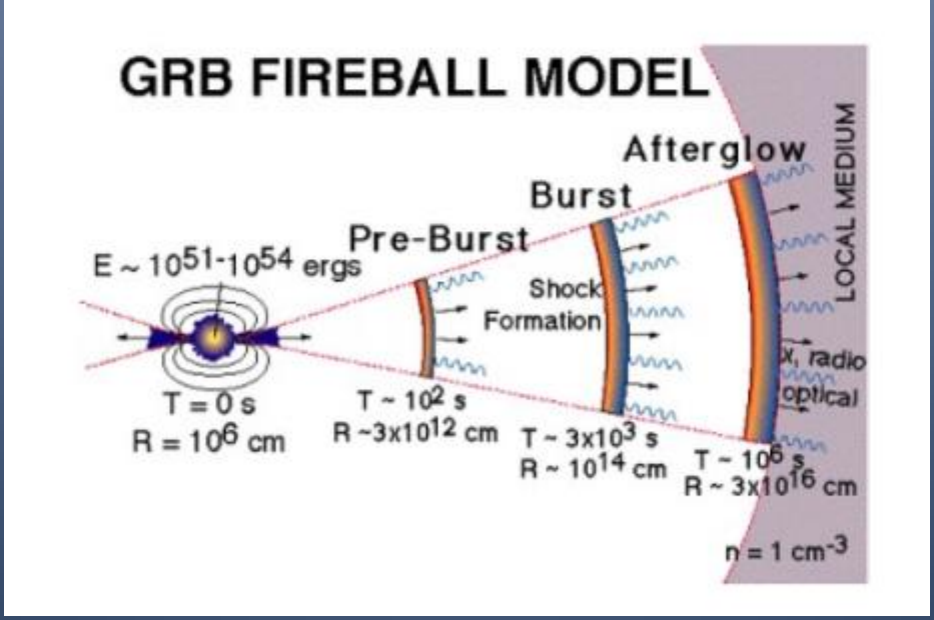
Active Galactic Nuclei

- Active Galactic Nuclei includes Seyferts, quasars, radio galaxies and blazars.
- Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted.



Gamma Ray Bursts

- GRBs are brief explosions of γ rays (often + X-ray, optical and radio).
- In the fireball model, matter moving at relativistic velocities collides with the surrounding material. The progenitor could be a collapsing super-massive star (short GRBs, 0.5 s) or the merging of two compact objects (long GRBs, 30 s)



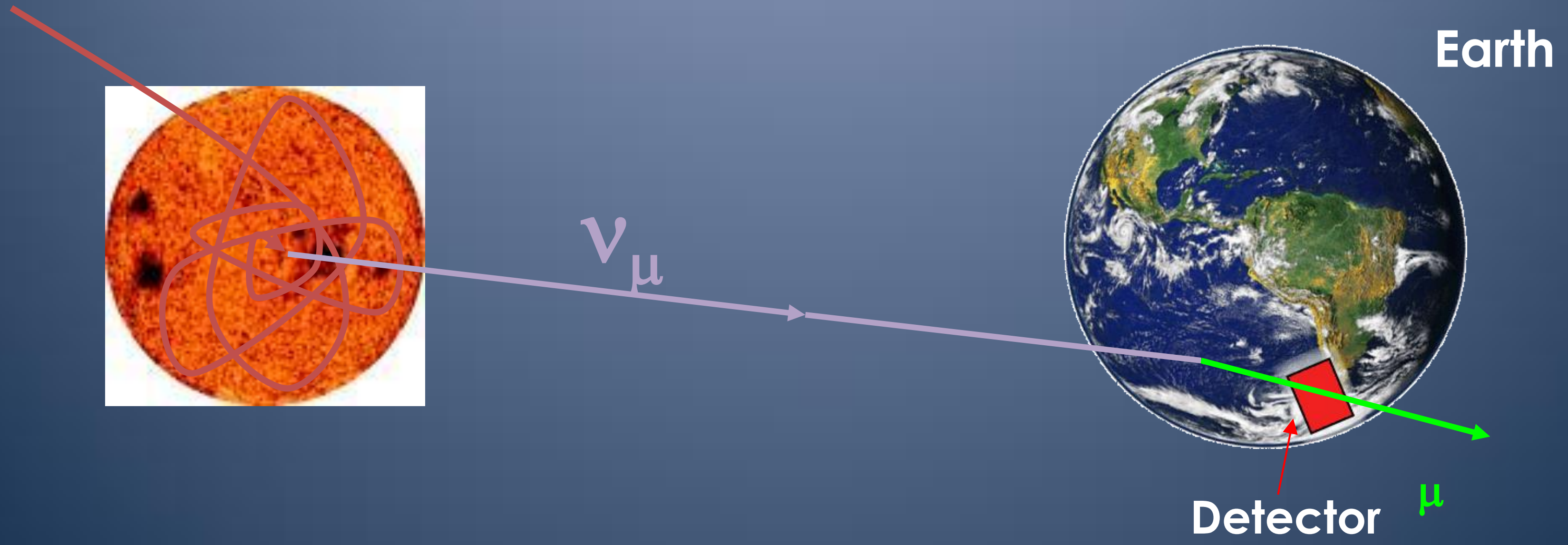
Starbust Galaxies

- Starburst galaxies are characterized by the existence of regions with a very high star formation rate
- A galactic scale wind blows out large amounts of mass into the intergalactic medium driven by the collective effect of supernova explosions and massive star winds

Composite image (HST/WIYN) of M82 and its optical bright superwind

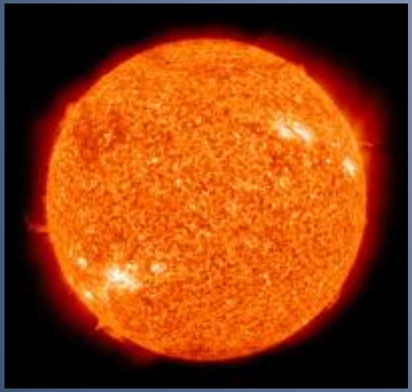
Dark matter

- WIMPs (neutralinos, KK particles) are among the most popular explanations for dark matter
- They would accumulate in massive objects like the Sun, the Earth or the Galactic Center
- The products of such annhiliations would yield "high energy" neutrinos, which can be detected by neutrino telescopes



Sources for DM searches

Sun



Galactic Centre

Dwarf galaxies

Earth

Galactic Halo

Galaxy clusters

Ultra-high energy neutrinos

- Protons interact with cosmic microwave background, which limits its range at high energies (GZK cut-off): $p\,\gamma_{CMB} \rightarrow \Delta^+ \rightarrow n\,\pi^+$ (or $p\,\pi^0$)

$$l_{gp} = \frac{1}{n_{CMB} \times s_{pg_{CMB}}} @ 10\ \mathrm{Mpc}\ \ @\ E_p = 5´\ 10^{19}\ \mathrm{eV}$$

- The GZK cut-off also leads to a measurable to neutrinos

$$p \rightarrow m + n_m \rightarrow e + n_m + n_e + n_m$$

~1 neutrino (E_ν > $2\mathrm{x}10^{18}$ eV) per km^3 year

Scientific Scope

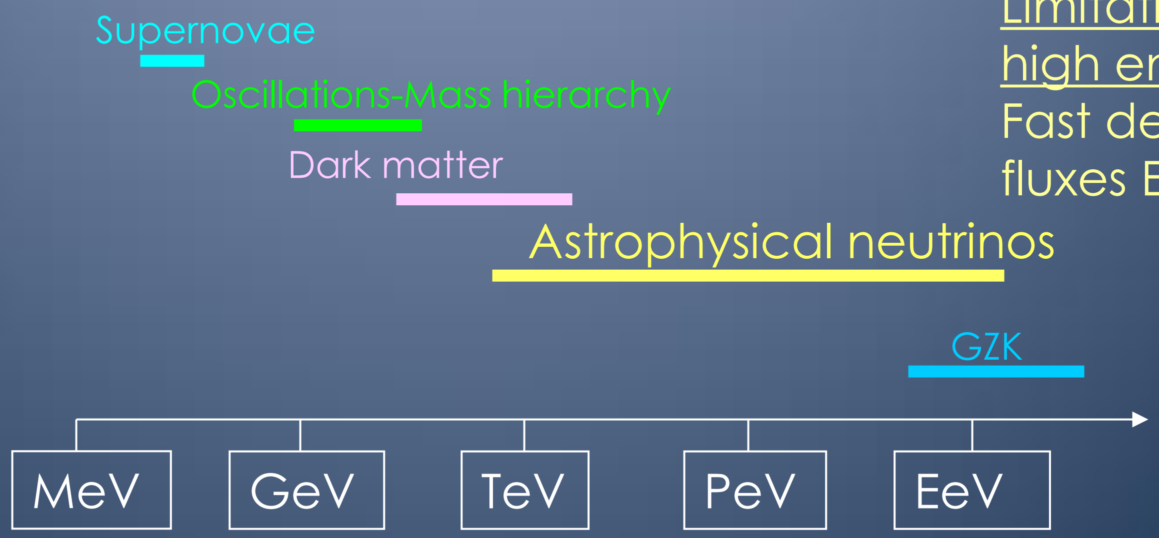
- Origin of cosmic rays
- Hadronic vs. leptonic signatures
- Neutrino mass hierarchy
- Dark matter

Detector size

<u>Limitation at high energies:</u>
Fast decreasing fluxes E^{-2}, E^{-3}

<u>Limitation at low energies:</u>
-Short muon range
-Low light yield
-^{40}K (in water)

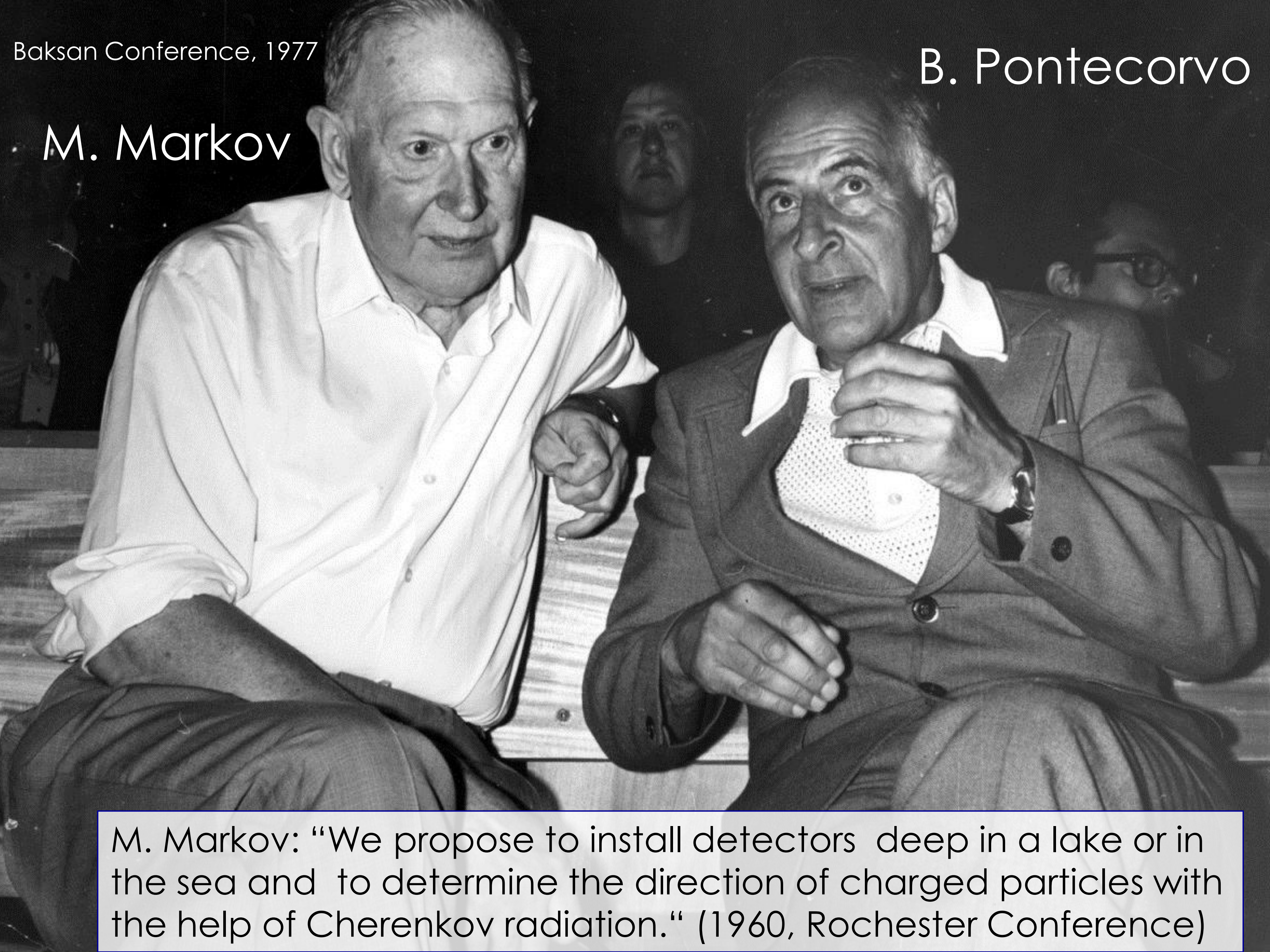
Detector density



Other physics: monopoles, nuclearites, Lorentz invariance, etc...

Neutrino detection techniques

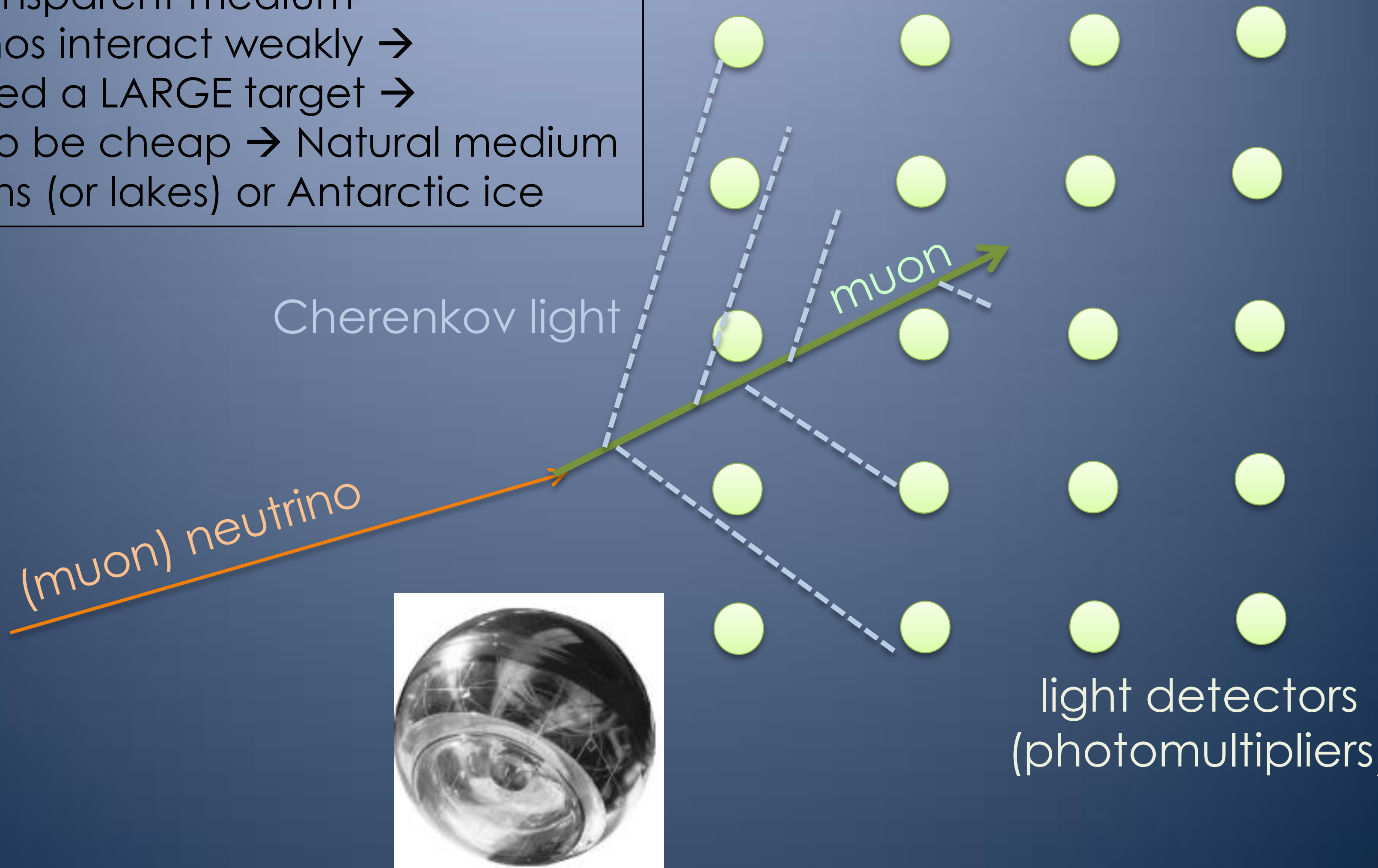
- Optical Cherenkov:
  - In Ice: AMANDA, IceCube
  - In water: Baikal, ANTARES, KM3NeT
- Atmospheric showers:
  - On earth: Auger
  - In space: JEM-EUSO
- Radio:
  - On earth: RICE, ARIANNA, LOFAR
  - Balloon: ANITA
- Acoustic:
  - AMADEUS, SPATS



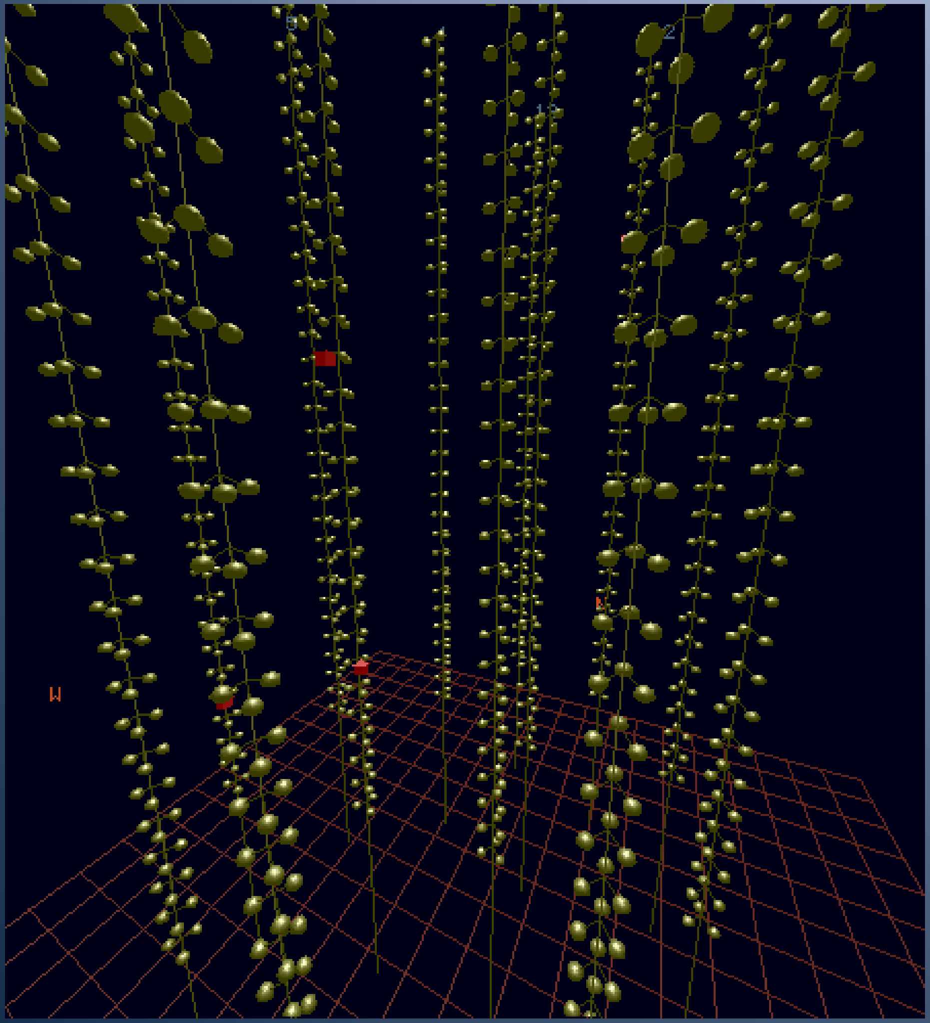
M. Markov: “We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.“ (1960, Rochester Conference)

Detection Principle

Where to put the detector?
1) In a transparent medium
2) Neutrinos interact weakly →
→ We need a LARGE target →
→ It has to be cheap → Natural medium
→ Oceans (or lakes) or Antarctic ice

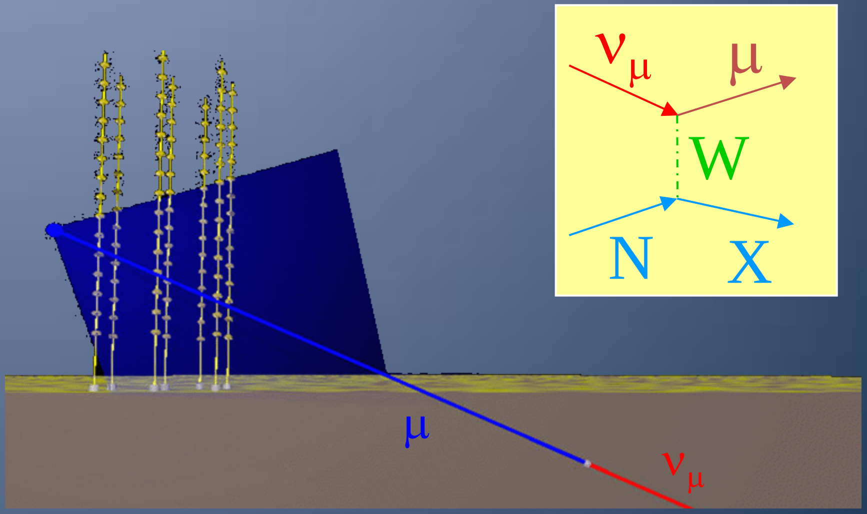


Detection Principle



1.2 TeV muon traversing ANTARES

- The neutrino is detected by the Cherenkov light emitted by the muon produced in the CC interaction.

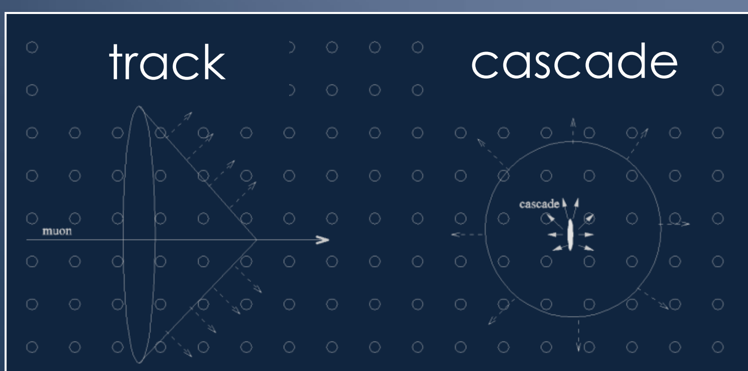


- Position and time information of hits in the PMTs allows us to reconstruct the original direction

Other signatures

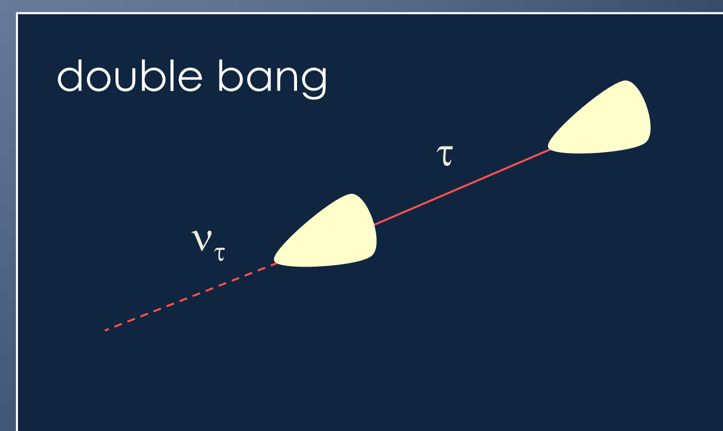
- Cascades are an important alternative signature: detection of electron and tau neutrinos.
- Also neutral interaction contribute (only hadronic cascade)

- Clear signature of oscillations.
- ANTARES is too small to detect double bang signature (they are too rare)
- However, cubic-kilometer telescopes could detect them
- Maximum sensitivity at 1-10 PeV

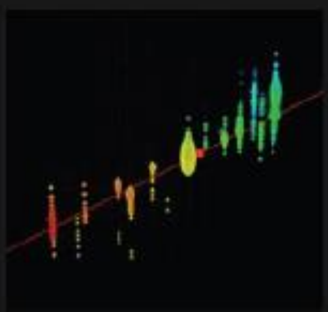
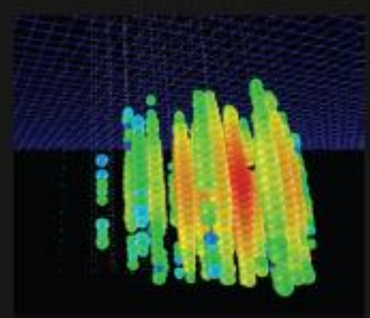
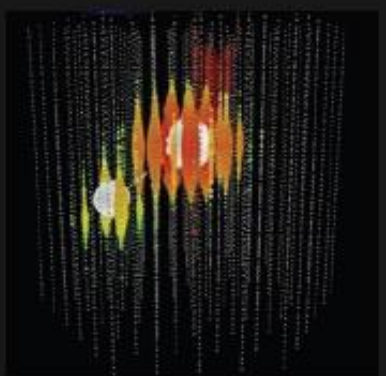


1 km at 300 GeV
25 km at 1 PeV

5-10 m long
diameter ~ 10 cm



Channels

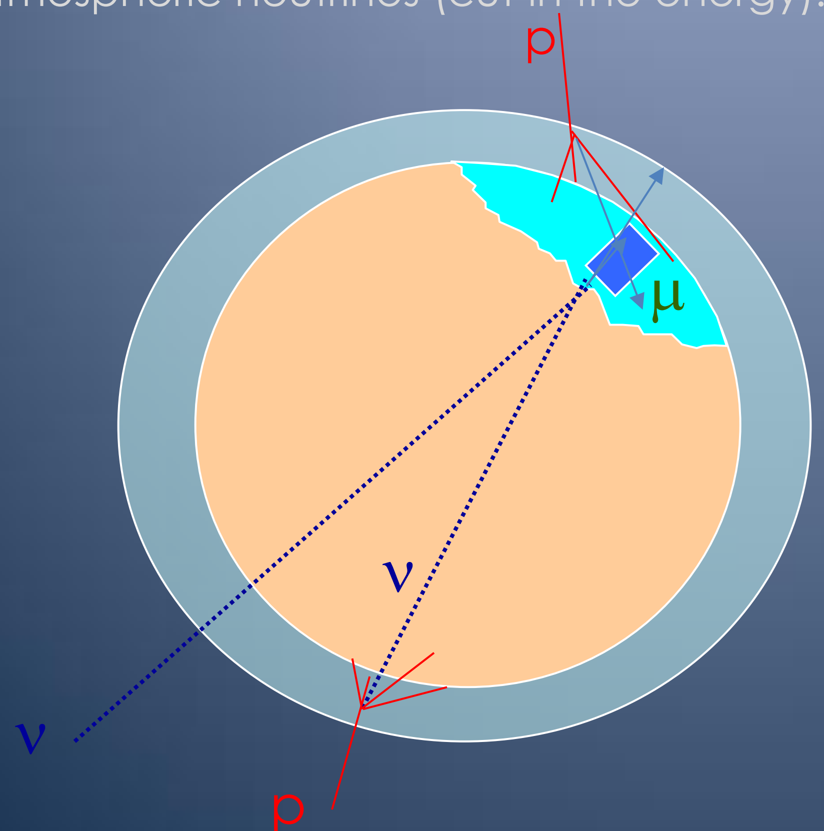
CC Muon Neutrino	Neutral Current / Electron Neutrino	CC Tau Neutrino
		
$\nu_\mu + N \rightarrow \mu + X$	$\nu_e + N \rightarrow e + X$ $\nu_x + N \rightarrow \nu_x + X$	$\nu_\tau + N \rightarrow \tau + X$
track (data)	cascade (data)	"double-bang" and other signatures (simulation)
factor of ≈ 2 energy resolution < 1° angular resolution	≈ ±15% deposited energy resolution ≈ 10° angular resolution (at energies ≳ 100 TeV)	(not observed yet)

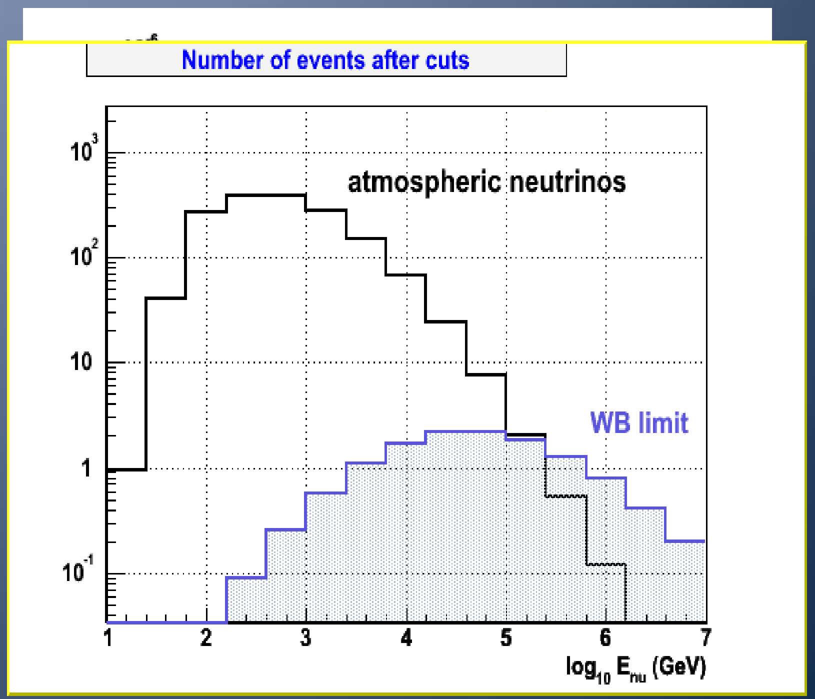
Physical Background

- There are two kinds of background:
  - -Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events).
  - -Atmospheric neutrinos (cut in the energy).

$$p \to \pi^+(+K^+ ...) \to \mu^+ + \nu_\mu$$
$$\mapsto e^+ + \bar{\nu}_\mu + \nu_e$$

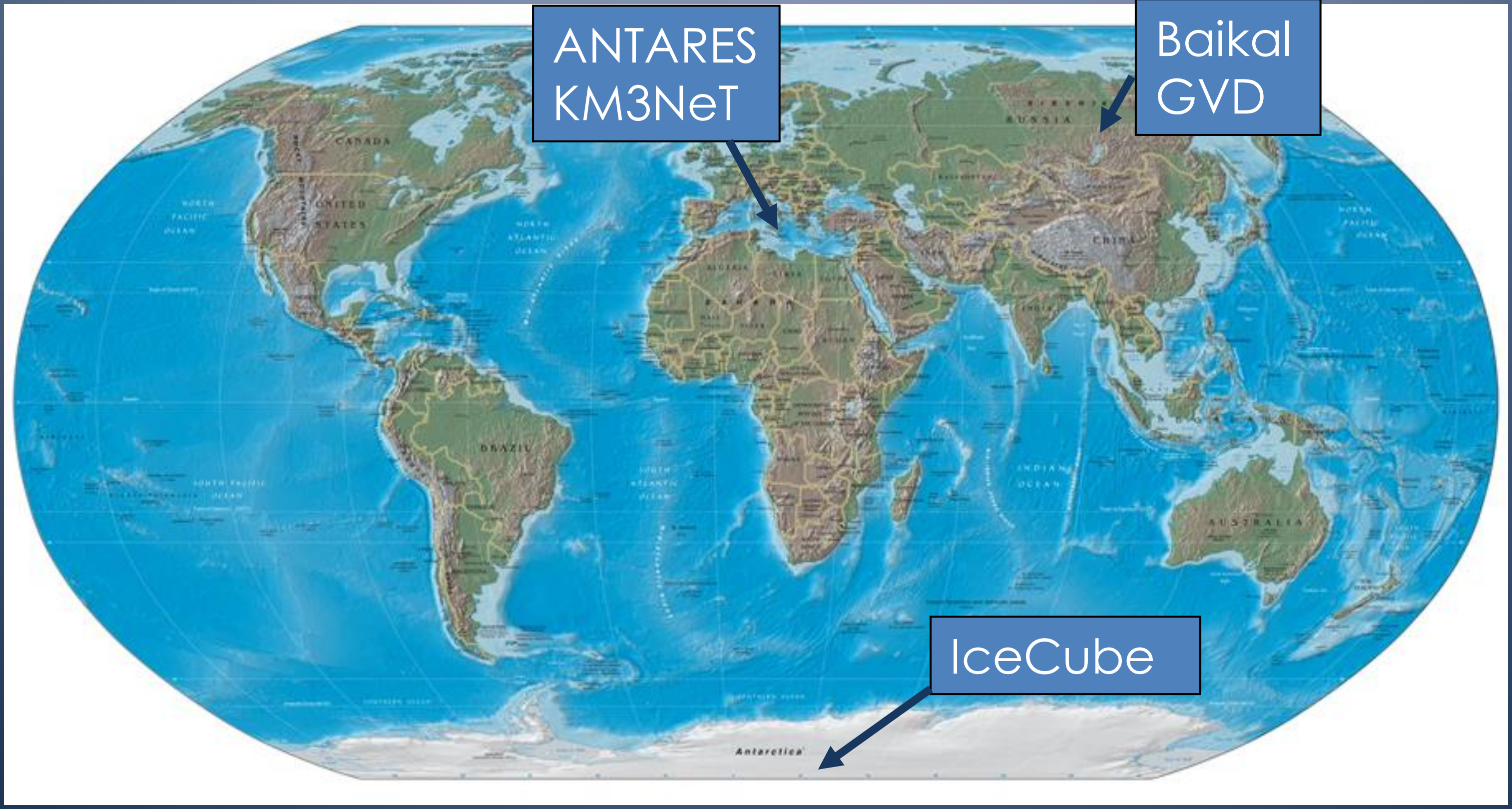
$$n \to \pi^-(+K^- ...) \to \mu^- + \bar{\nu}_\mu$$
$$\mapsto e^- + \nu_\mu + \bar{\nu}_e$$





NTs in the world

- Several projects are working/planned, both in ice and ocean and lakes.

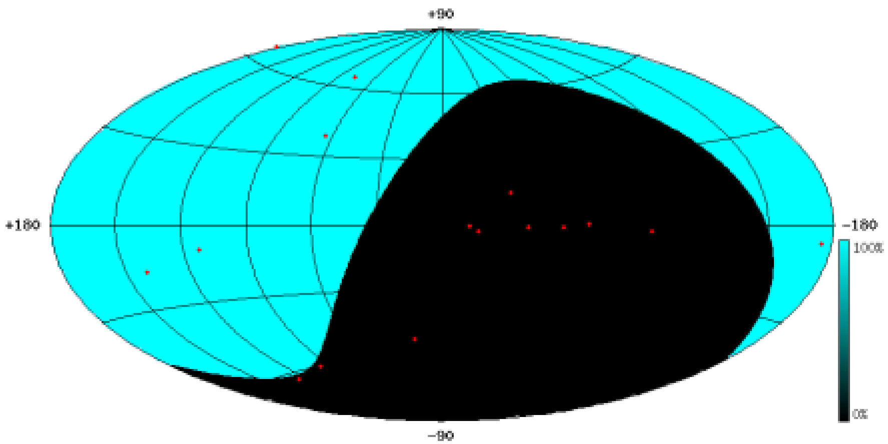


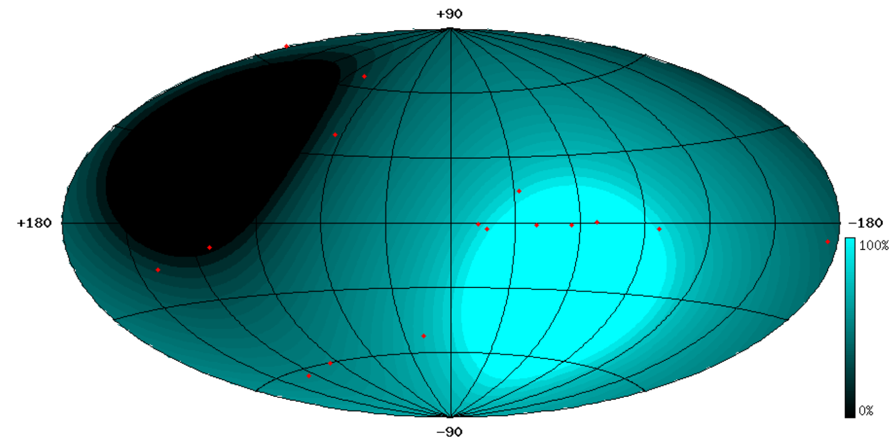
Water vs Ice

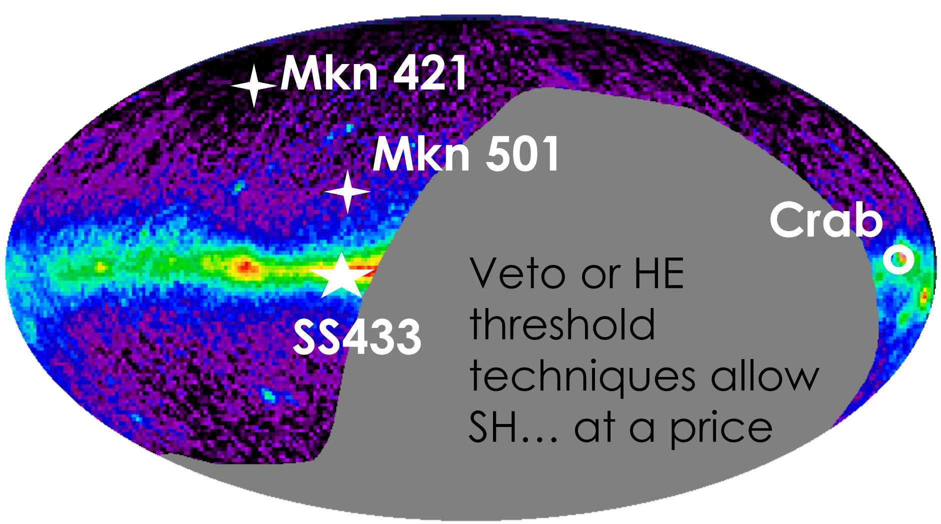
- Very large volumes of medium transparent to Cherenkov light are needed:
  - Ocean, lakes…
  - Antarctic ice
- Advantages of <u>oceans</u>:
  - Larger scattering length $\rightarrow$ better angular resolution
  - Weaker depth-dependence of optical parameters
  - Possibility of recovery
  - Changeable detector geometry
- Advantages of <u>ice</u>:
  - Larger absorption length
  - No bioluminescence, no ^{40}K background, no biofouling
  - Easier deployment
  - Lower risk of point-failure
- Anyway, a detector in the Northern Hemisphere in necessary for complete sky coverage (Galactic Center!), and it is only feasible in the ocean.

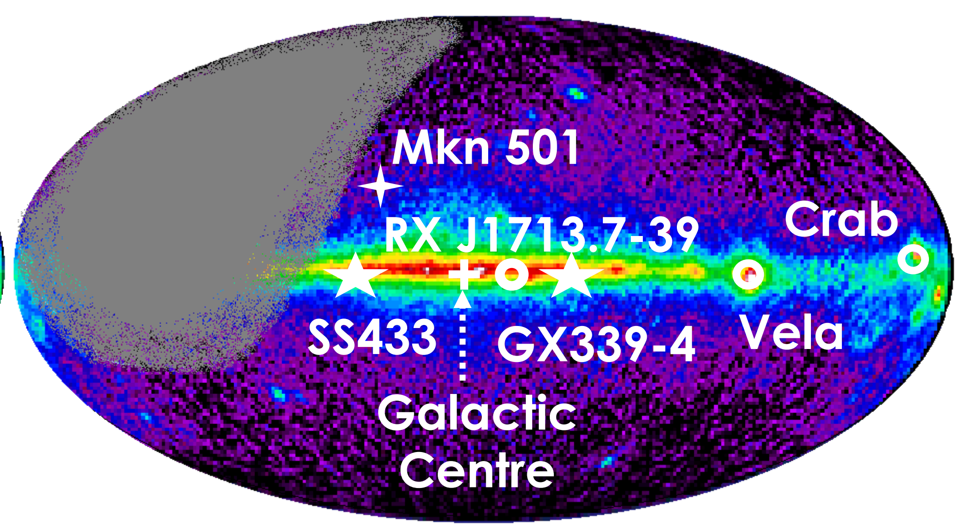
Regions observed by NTs

IceCube (South Pole) (ang. res.: 0.6°)	ANTARES/KM3NeT (43° North) (ang. res.: ~0.3°/0.1°)



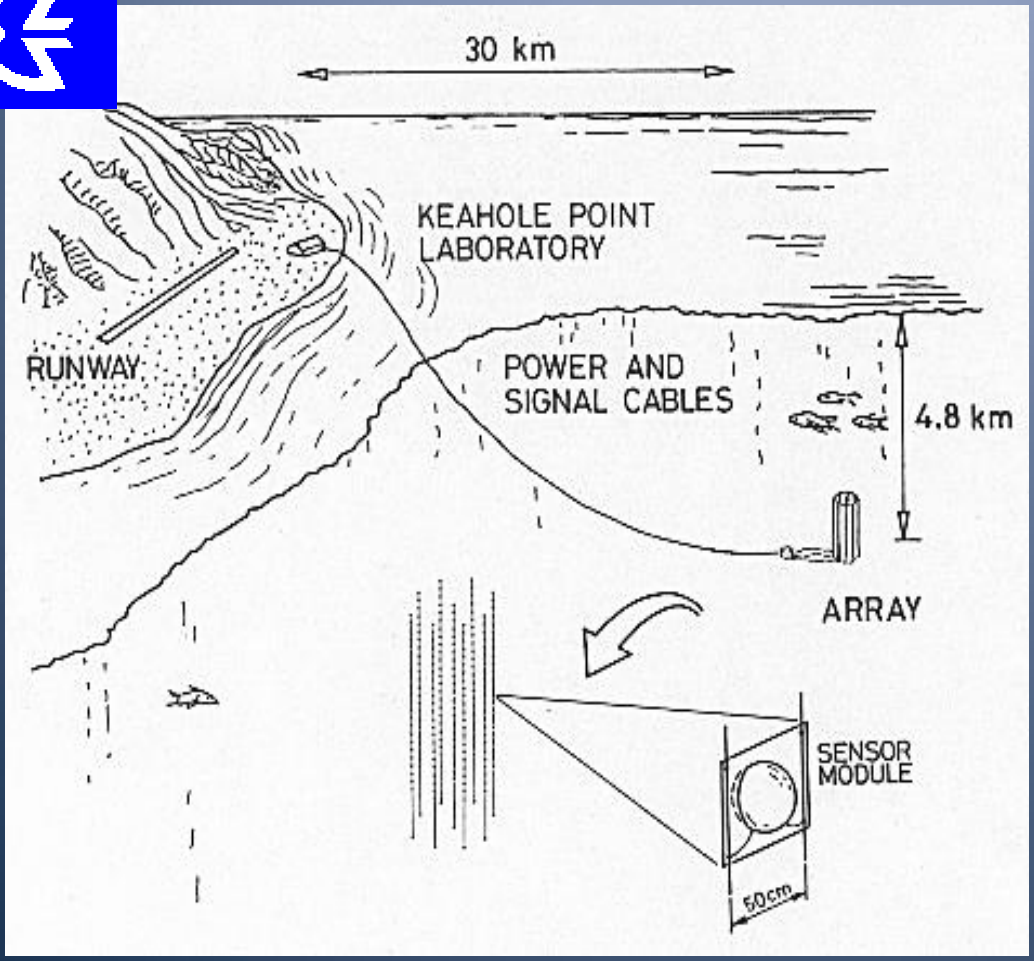






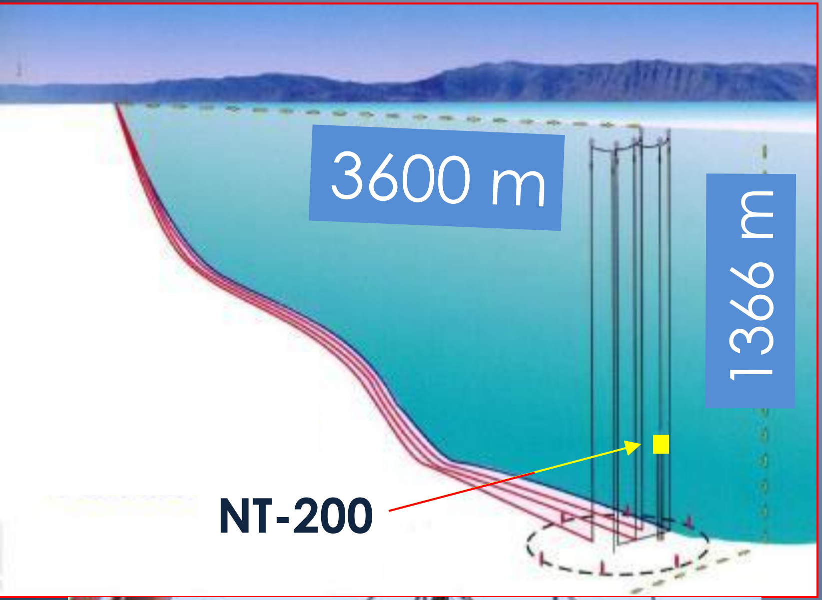
Pioneers

DUMAND



- History of the project:
- 1975: first meetings for underwater detector in Hawaii
- 1987: Test string
- 1988: Proposal: "The Octagon" (1/3 AMANDA)
- 1996: Project cancelled

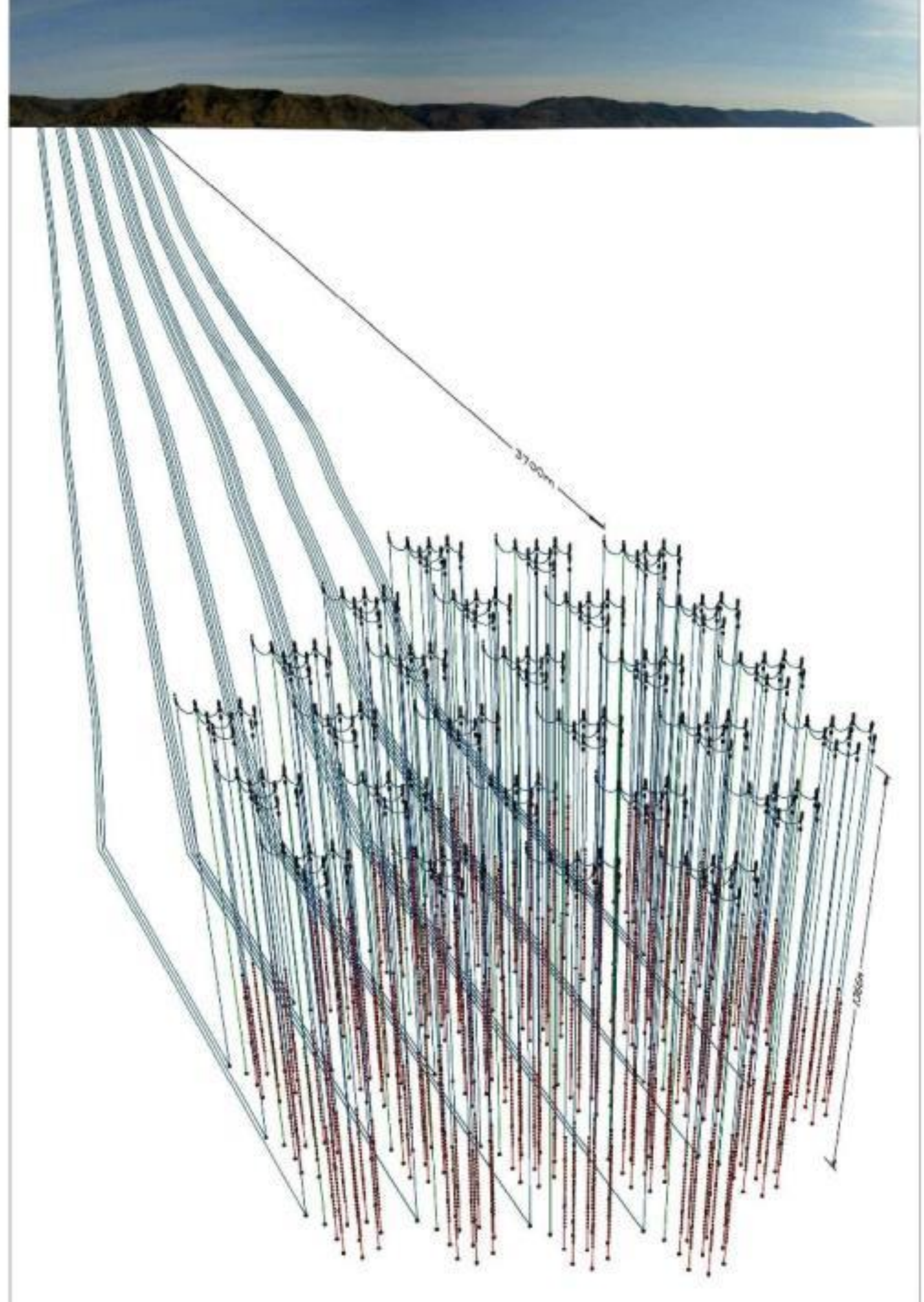
Baikal

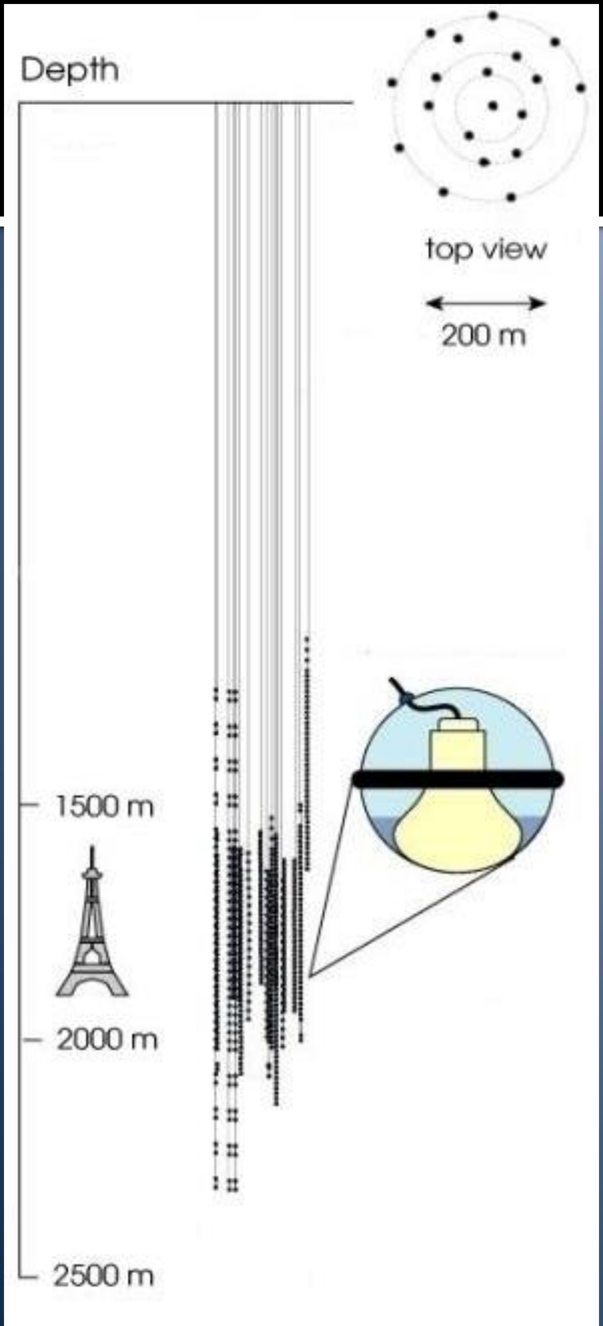


- History of the project
- since 1980: site studies
- 1984 first stationary string
- 1993 NT-36 started
- 1994 first atmospheric neutrino identified
- 1998 NT-200 commissioned
- 2005: NT200+ commissioned

GVD

- Upgrades and plans for the future:
- GVD
  - Instrumented volume ~0.3 km3
  - 2304 OMs
  - 96 strings/ 12 clusters
  - Prototype line deployed in 2011
  - 2014-2018: construction data taking
  - Also plans for acoustic detection



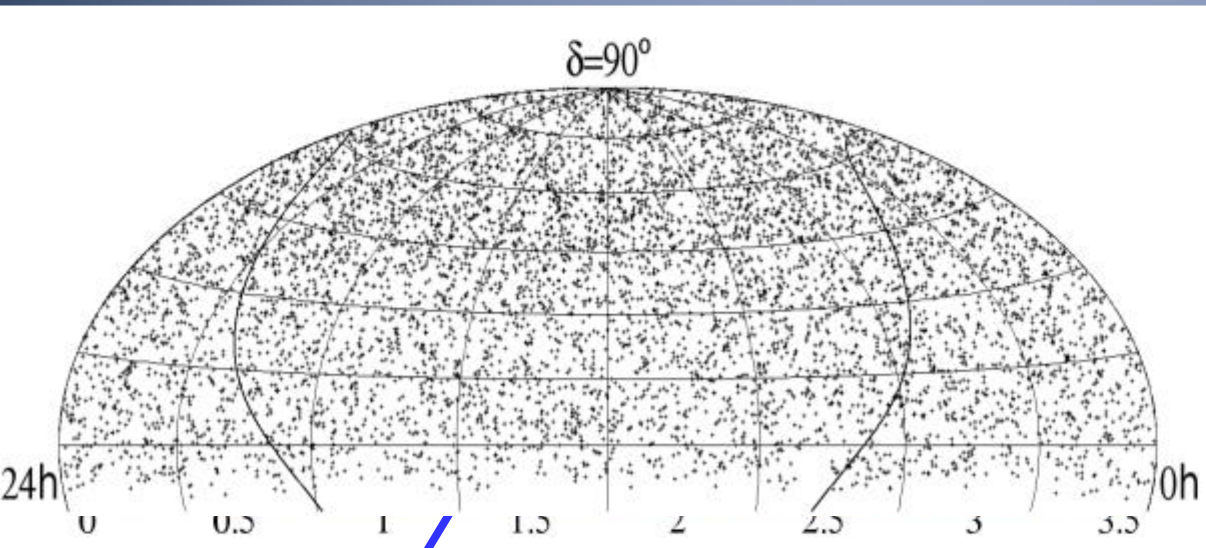


AMANDA

- 1997-99: AMANDA-B10
- (inner lines of AMANDA-II)
  - 10 strings
  - 302 PMTs
- Since 2000: AMANDA-II
  - 19 strings
  - 677 OMs
  - 20-40 PMTs / string
- Latter merged into IceCube
- May 2009: switched off

AMANDA

26 sources selected for search



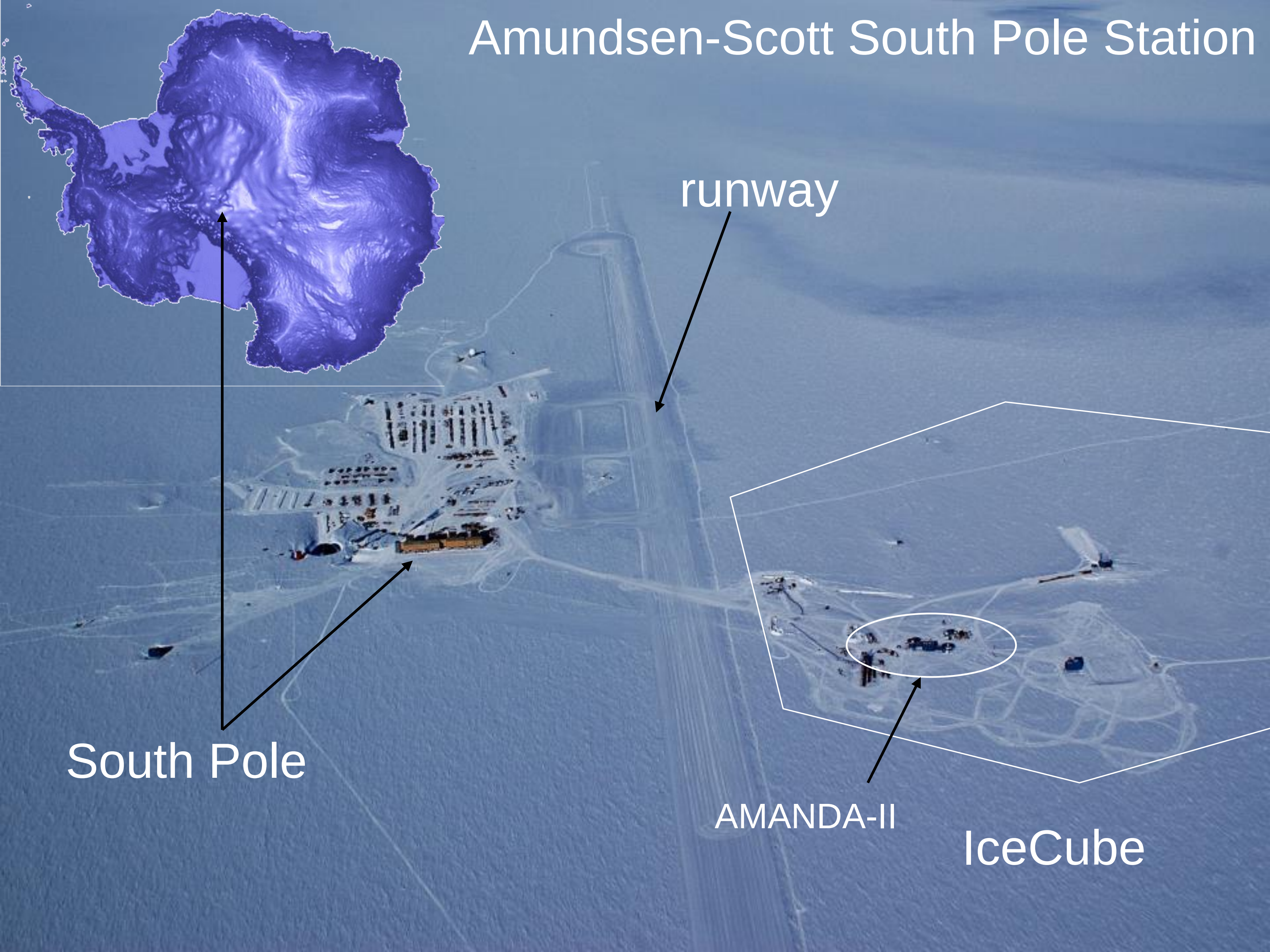
Source	Φ_{90}	p-value
Crab Nebula	9.27	0.10
MGRO J2019+37	9.67	0.077
Mrk 421	2.54	0.82
Mrk 501	7.28	0.22
LS I +61 303	14.74	0.034
Geminga	12.77	0.0086
1ES 1959+650	6.76	0.44
M87	4.49	0.43
Cygnus X-1	4.00	0.57

Equatorial sky map of 6595 events recorded by AMANDA II in 2000-2006

The most significant point has 3.4σ but this should happen 95% of the time with the present statistics.

For 26 sources, $p \leq 0.0086$ occurs 20% of the time for at least one source.

IceCube


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

IceCube

IceTop

80 pairs of ice Cherenkov tanks
Threshold ~ 300 GeV

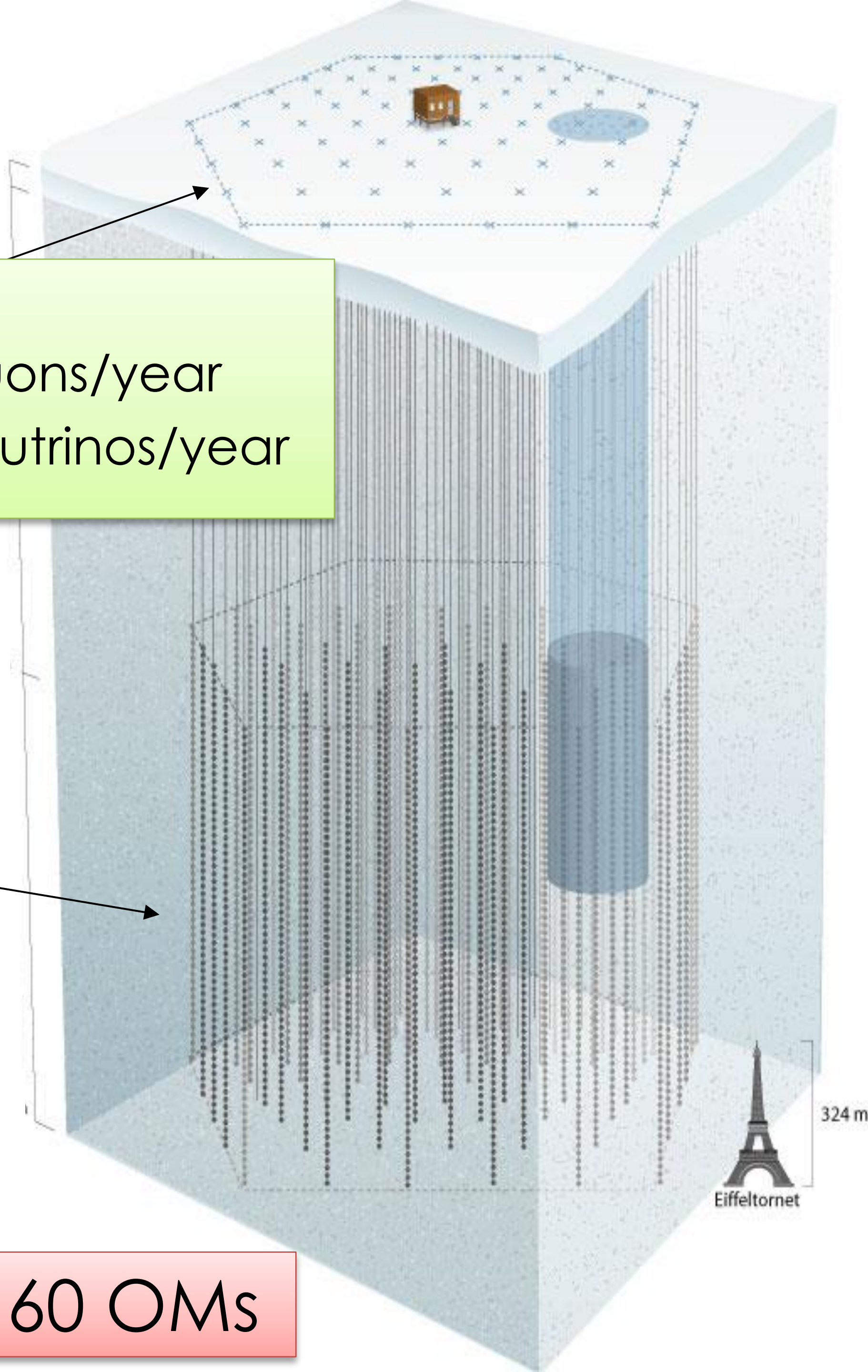
IceCube Array

80 strings with 60 OMs
17 m between OMs
125 m between strings
1 km^3. A 1-Gton detector

Deep Core

6 strings with 60 HQE OMs
Inner part of the detector

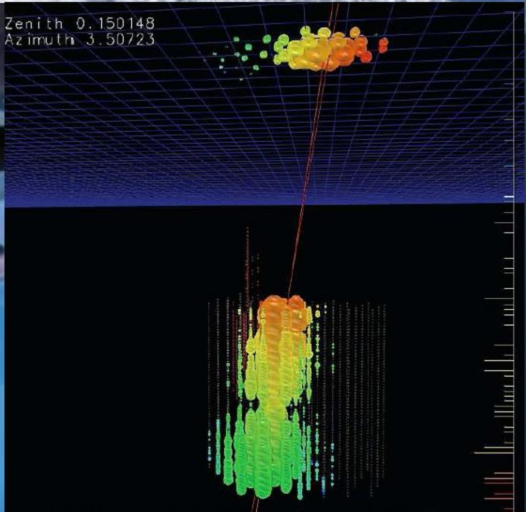
IC86:
~ 5×10^{10} muons/year
~ 20,000 neutrinos/year



IceCube + Deep Core = 5160 OMs

IceTop

- 80 stations
  - 2 tanks per station
  - 2 DOMs per tank
- Cosmic ray studies
  - 2.8 km altitude
- Use as veto for below ice detector

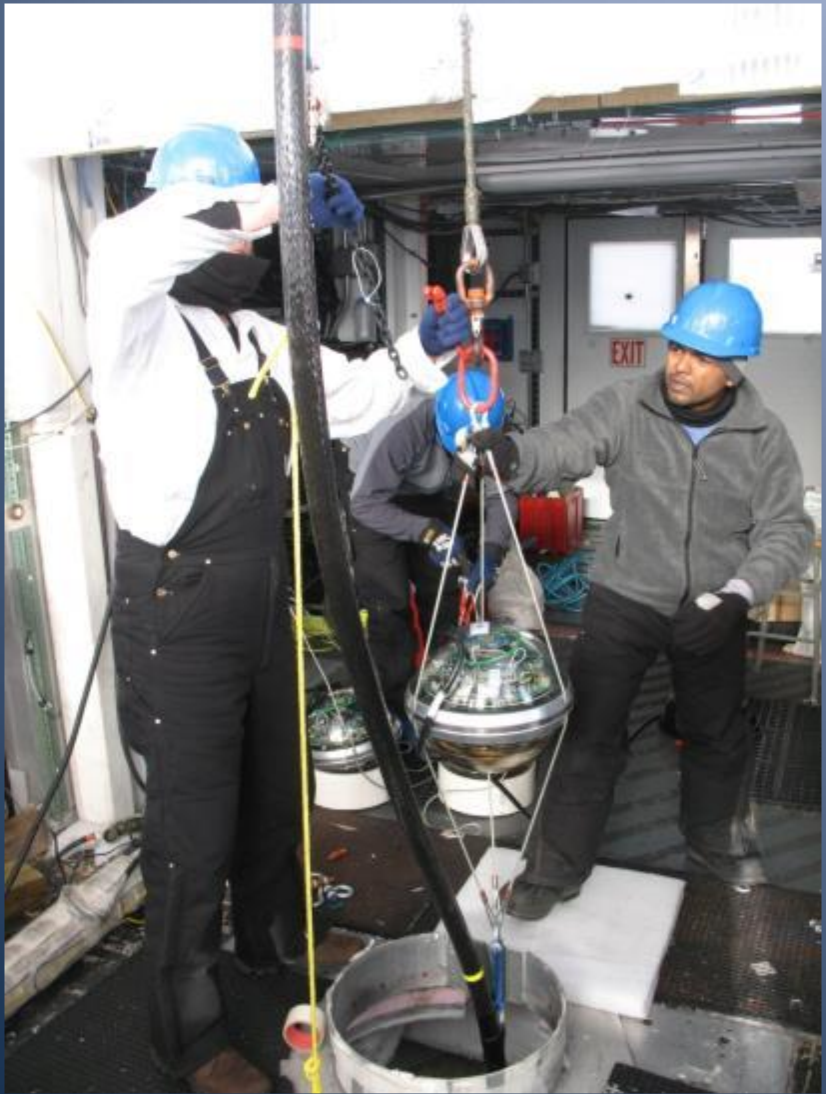


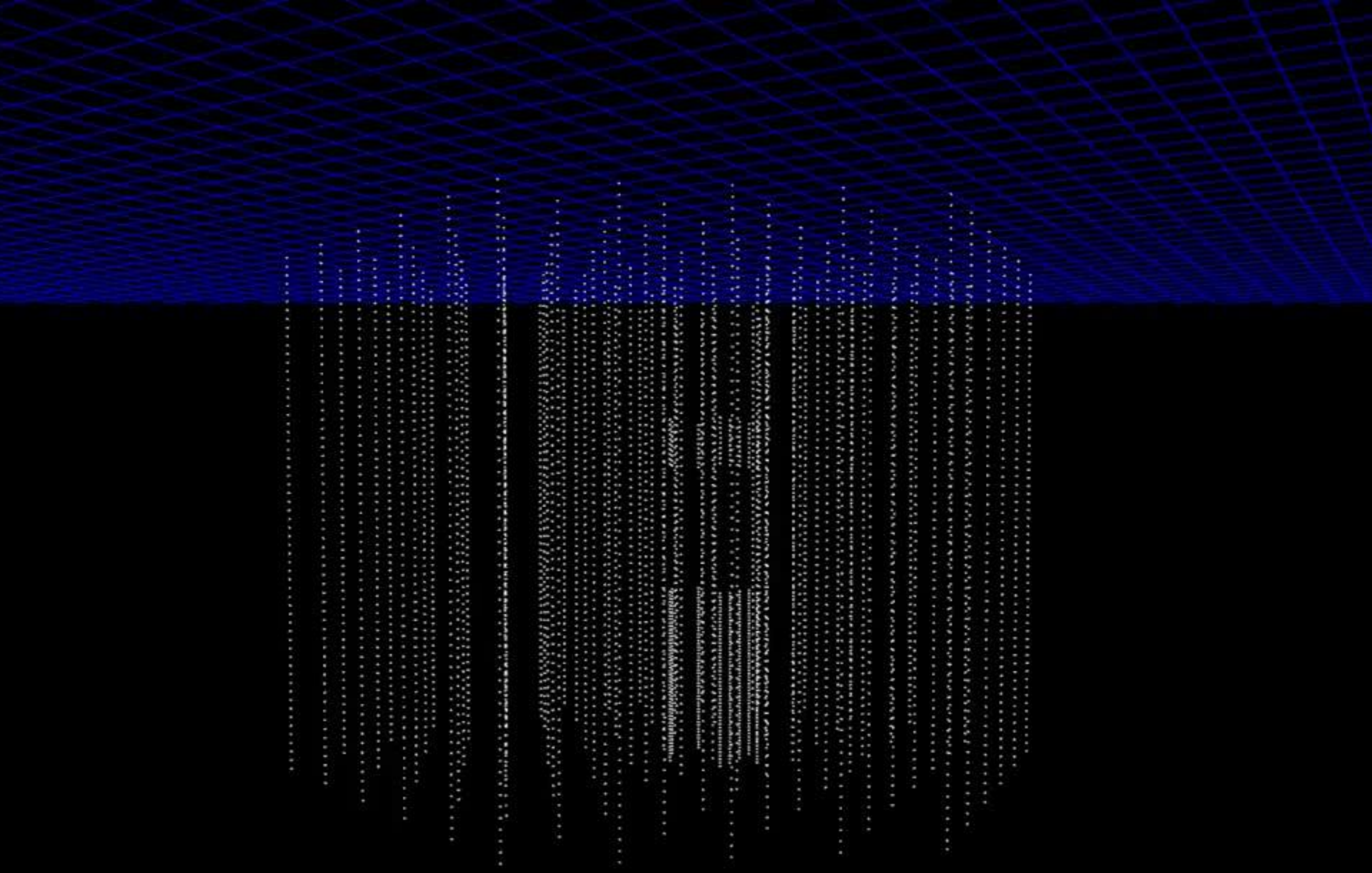

5 megawatt power plant
10^6 kg of drilling equipment

String deployment

about 2 days to drill the 2.5 km hole

String installation

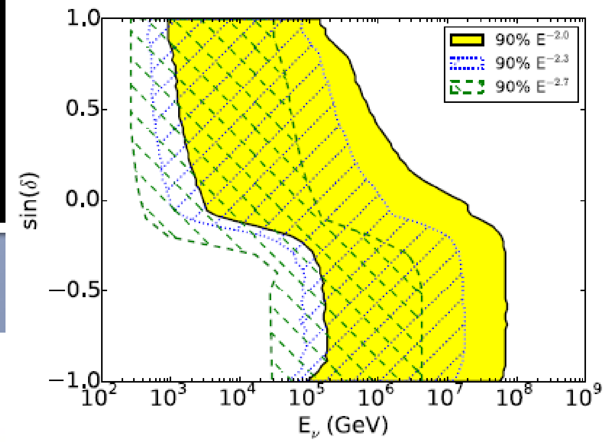


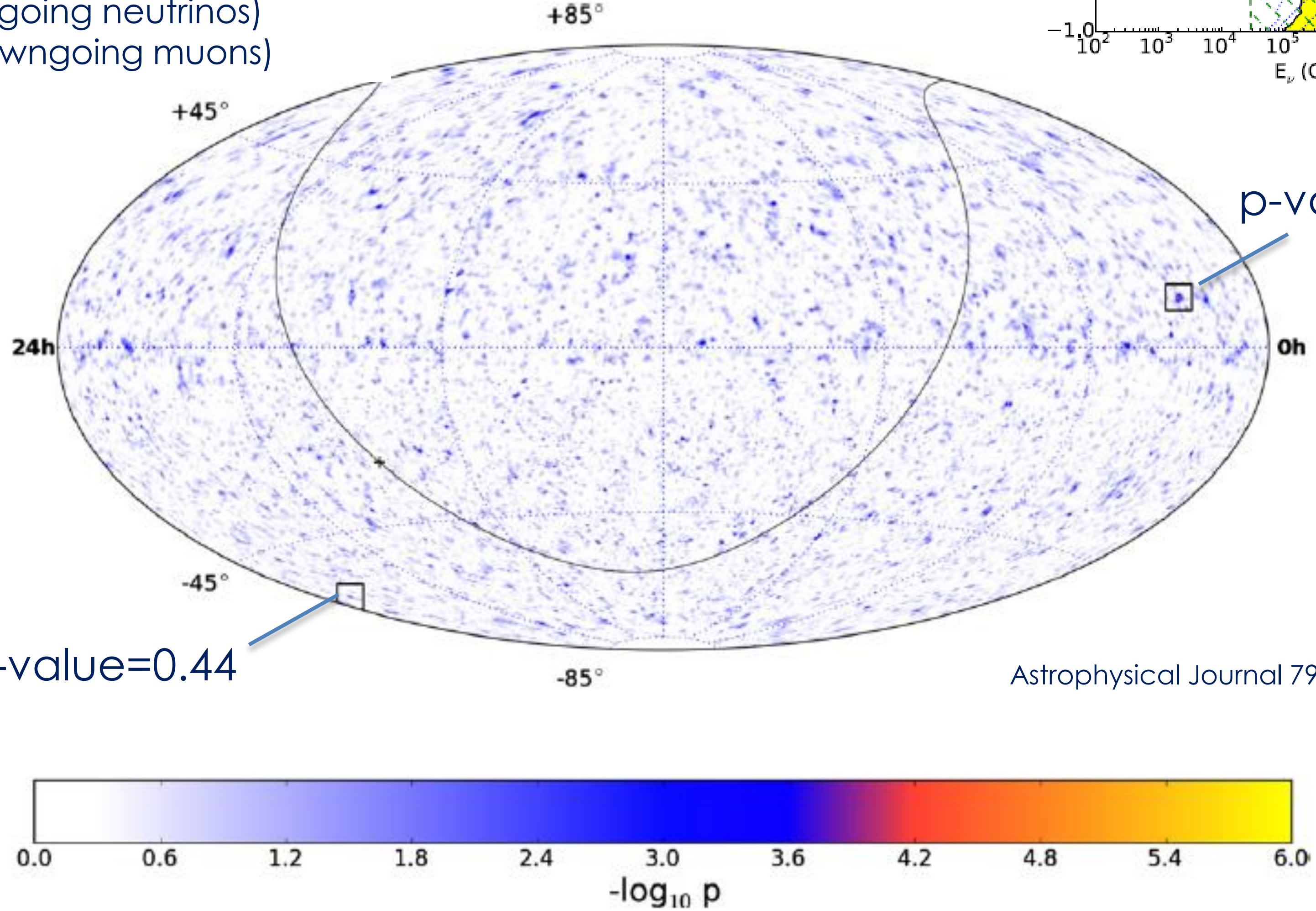


This is just 10 miliseconds

Point Source Search

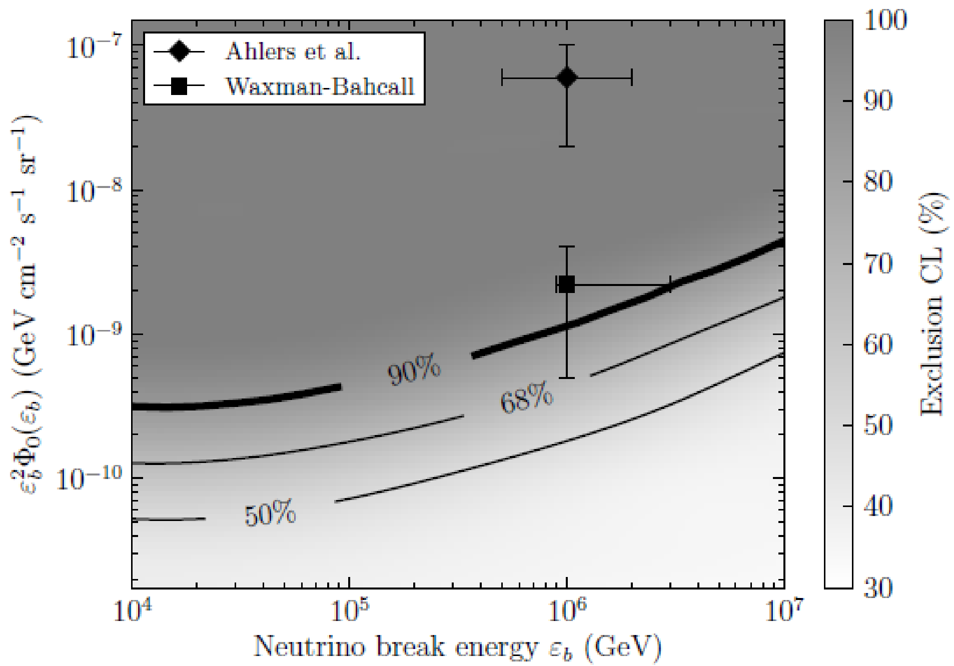
2008-2011 data:
Livetime 1371 days
178k (upgoing neutrinos)
216k (downgoing muons)





Astrophysical Journal 796 (2014) 109

Gamma Ray Bursts



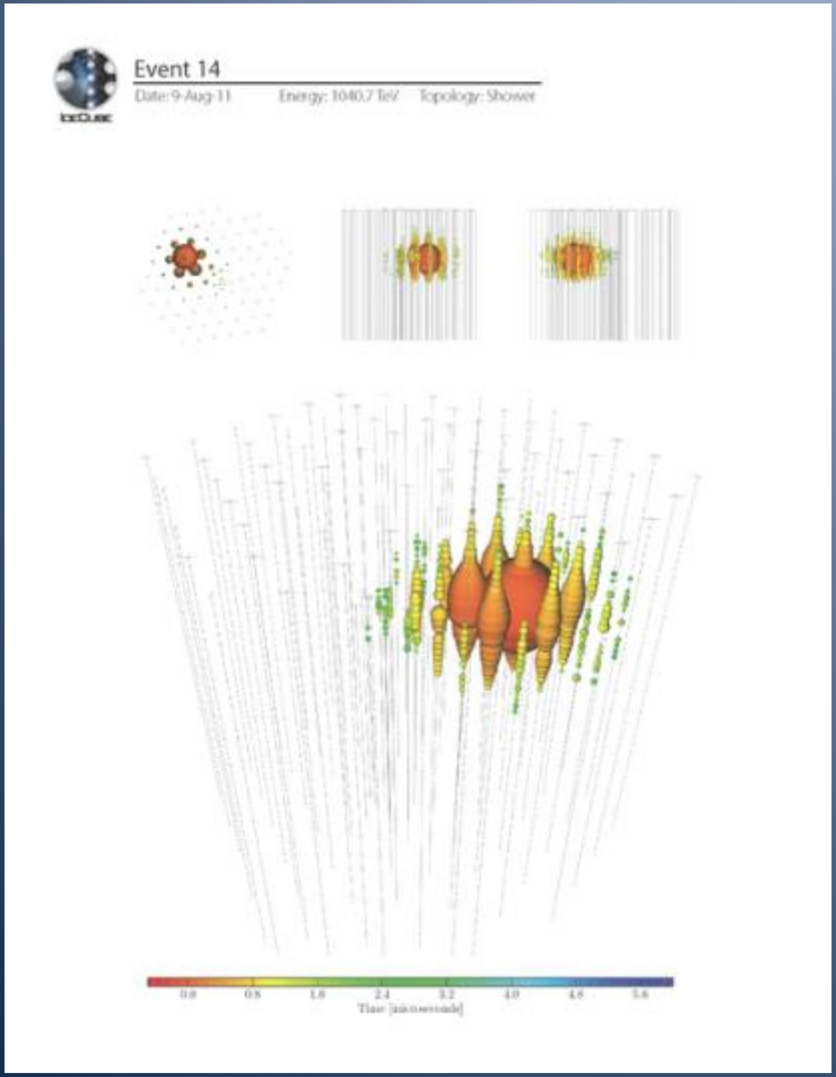
arXiv:1412.6510

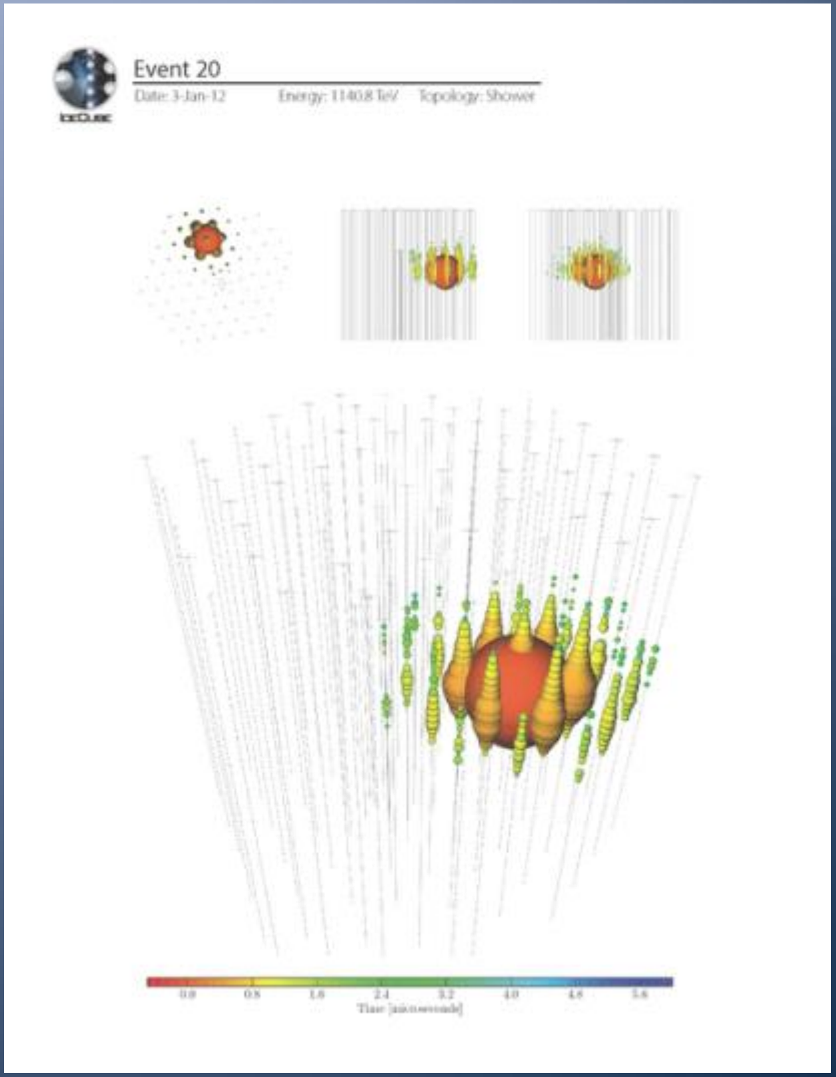
Ahlers et al.: only neutrons contribute
Waxman-Bahcall: protons are allowed to escape and contribute to the UHECR flux

- Four years of data
- 506 bursts studied
- Only 1 coincidence (non significant)
- Strong constrains in GRBs models
- No more than ~1% of the IC neutrino flux consists of prompt emission from GRBs

Ernie and Bert

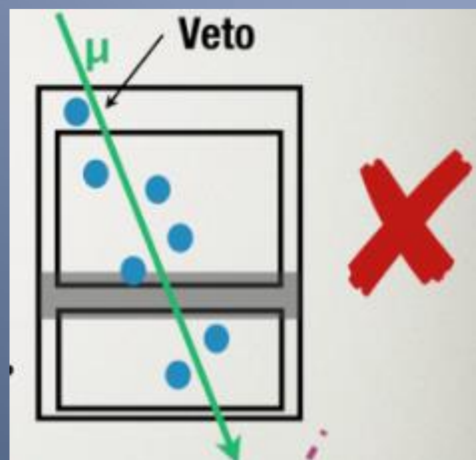
2012: Looking for UHE neutrinos, two events (cascades) appeared with E ~ 1 PeV (0.14 expected, 2.36σ)…

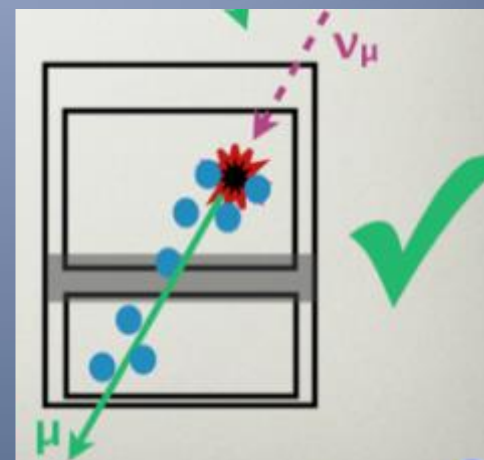




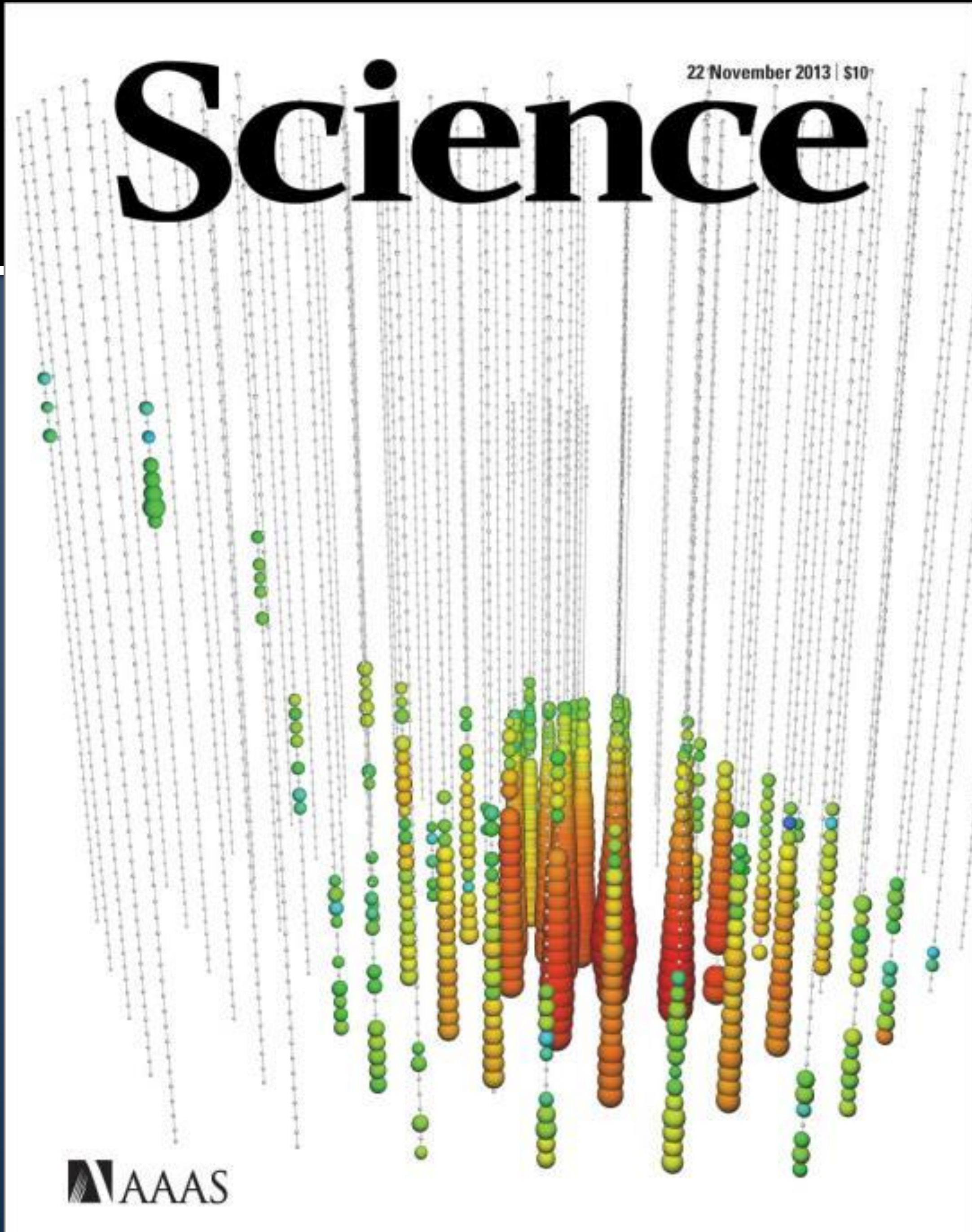
HESE events

- HESE (High Energy Starting Events): Events of high energy (>30 TeV) starting inside the detector





- This strategy allows to reduce the background due to atmospheric muons because they would have left a signal in the external part of the detector (veto)
- It also helps to filter atmospheric neutrinos, since they are usually accompanied by muons
- Disadvantage: the volume is greatly reduce (only “contained” events)

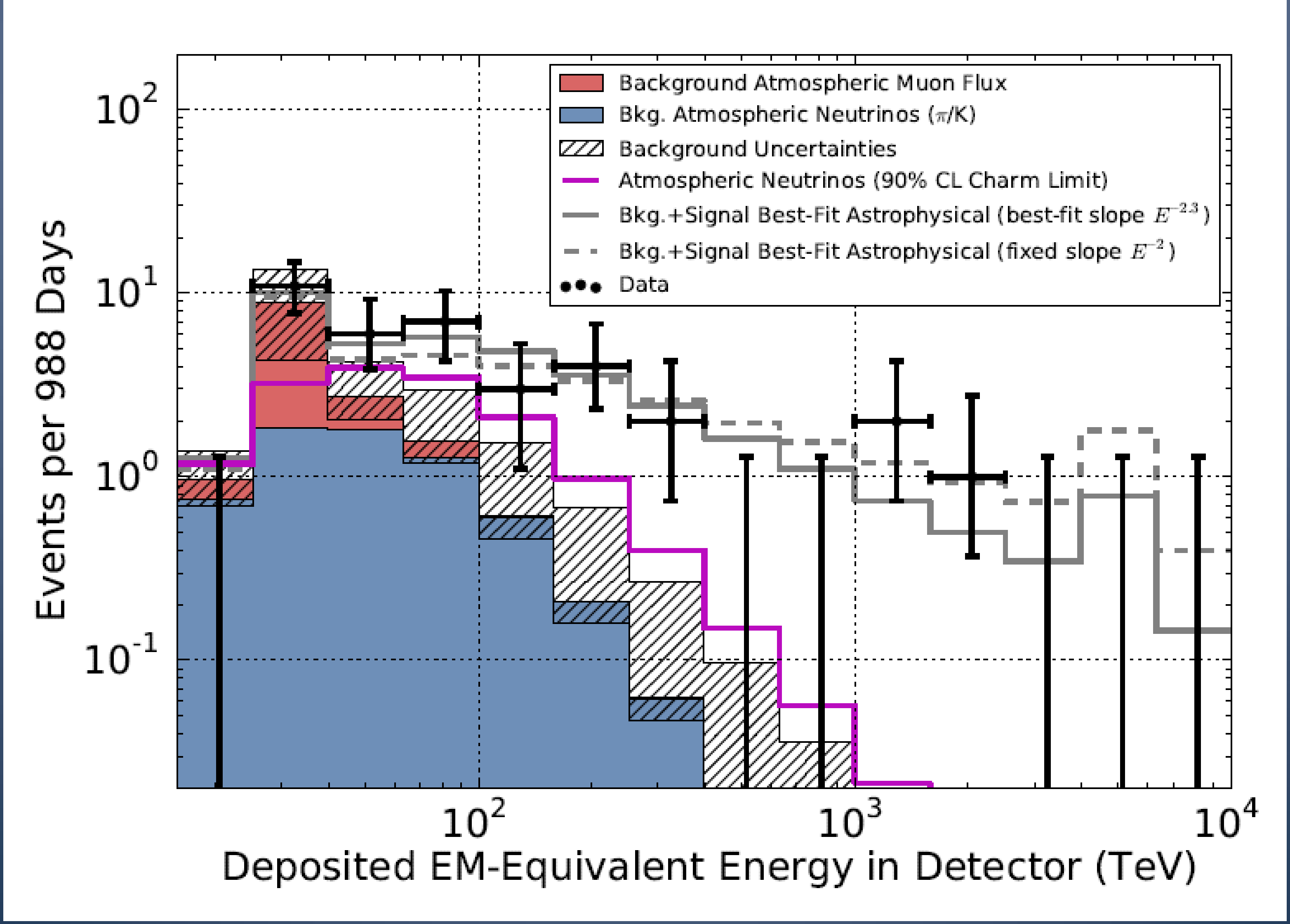


Science 342 (2013) 1242856, 22

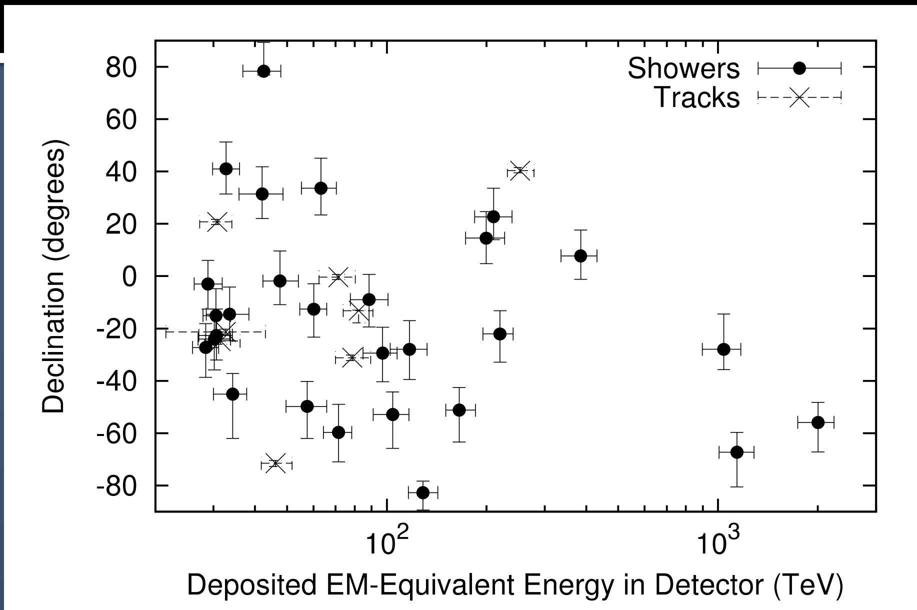
- 28 events in total (including Ernie and Bert)
- Expected background:
  - 6.0±3.4 atm. muons
  - 4.6±1.5 atm. neutrinos
- Significance: 4.9σ

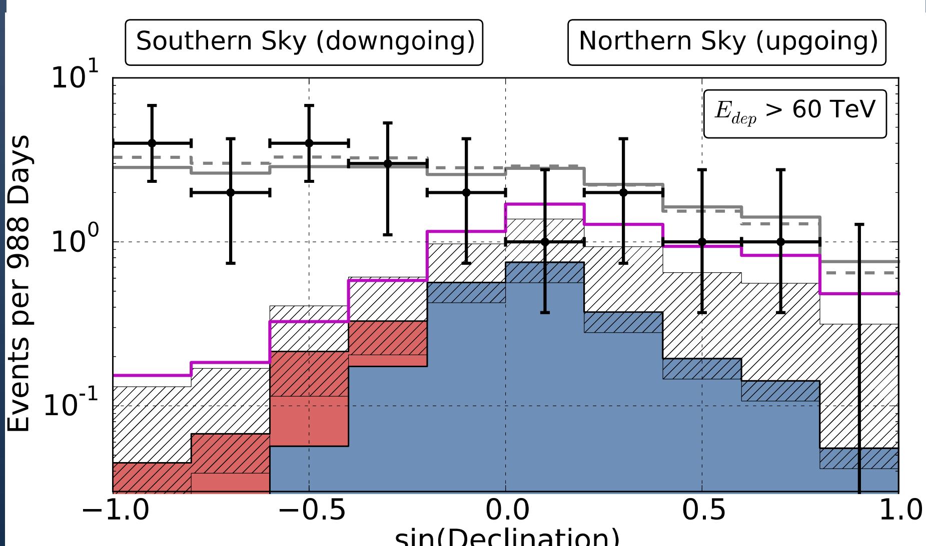
Discovery!

in three years, 37 events



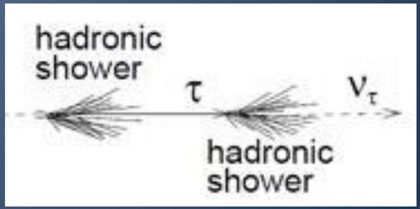
HESE events

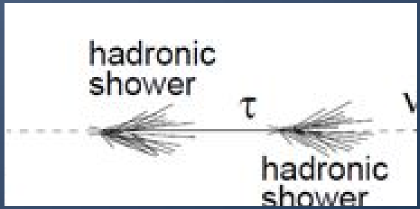


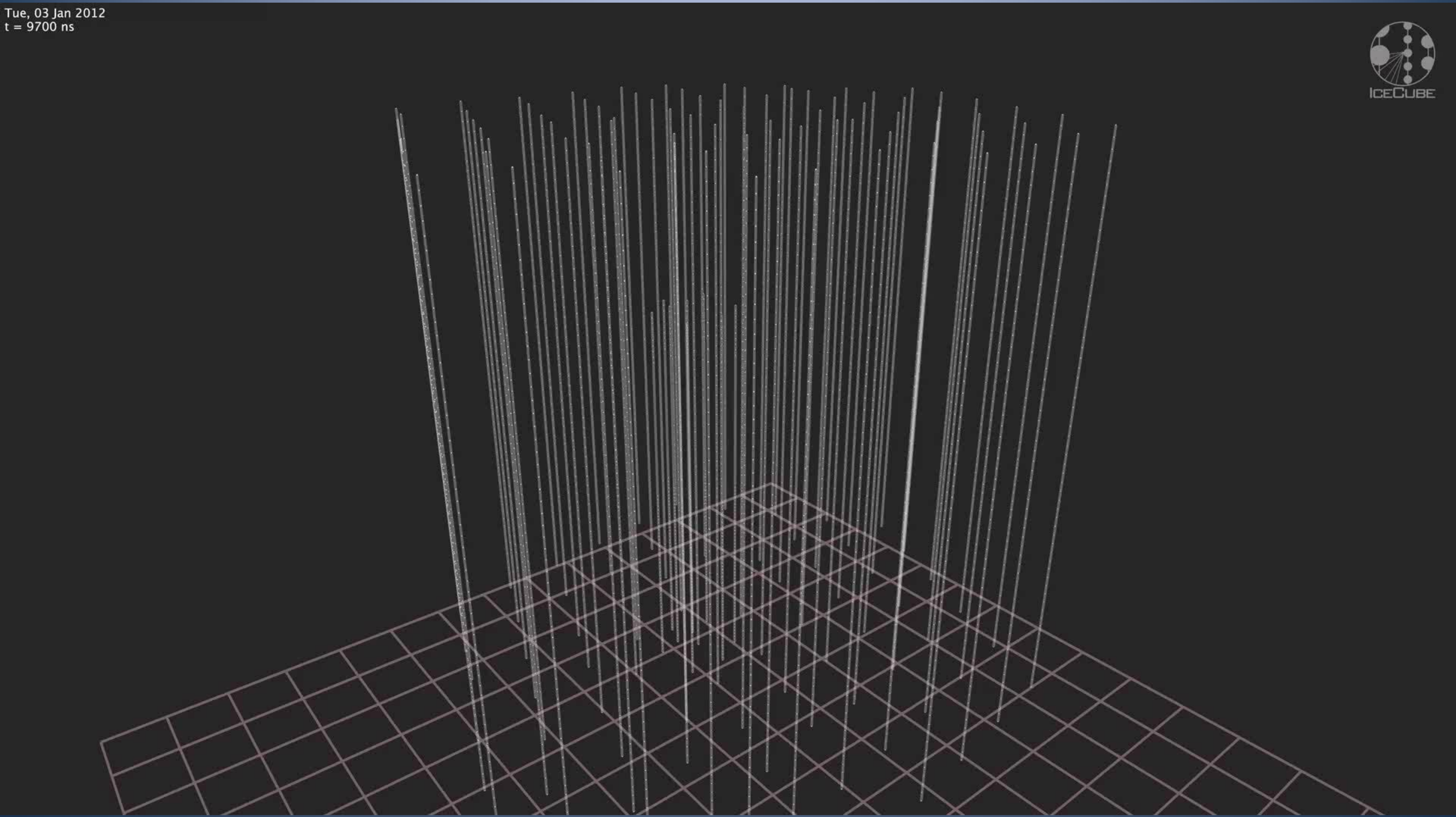


- 9 tracks (muons), angular resolution < 1 deg, to reconstruct the energy is harder since the muon takes part of energy out

- 28 showers, angular resolution 10-30 deg, good energy resolution (15%)

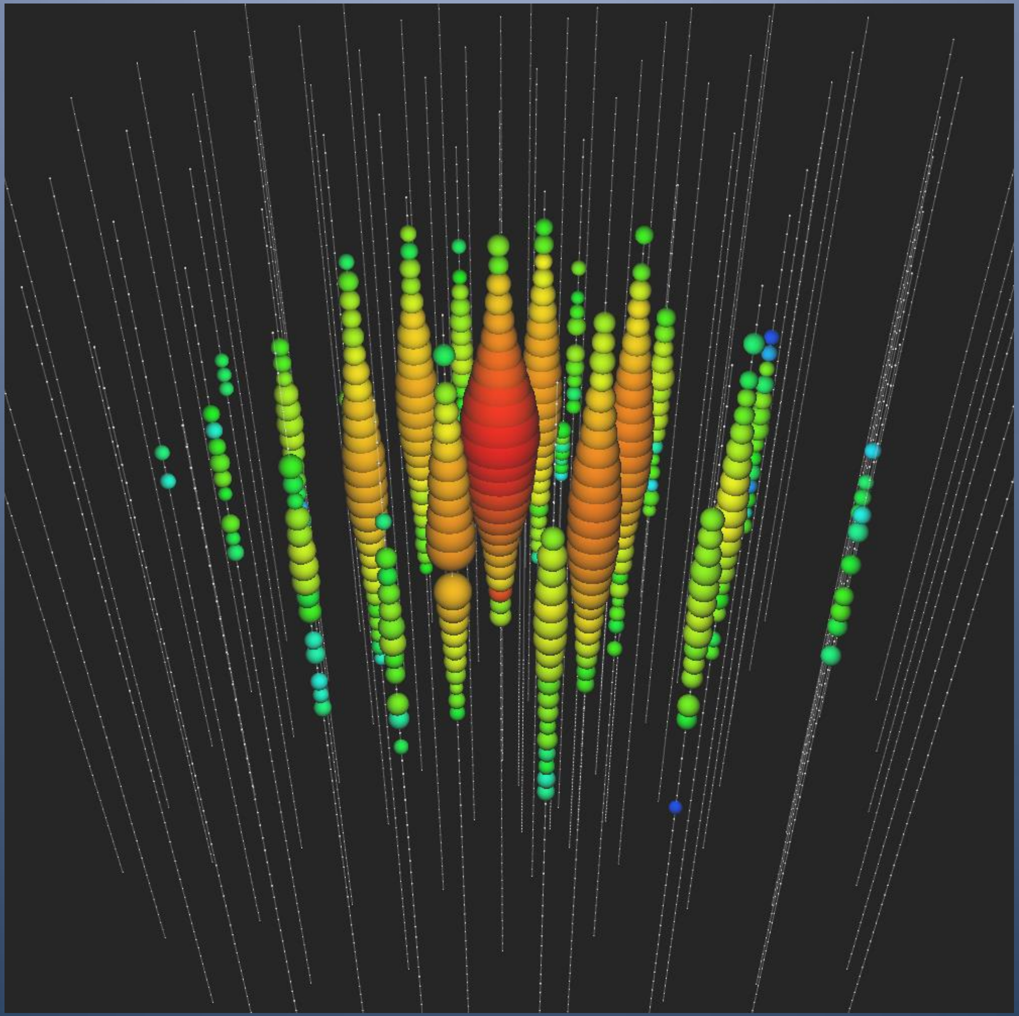




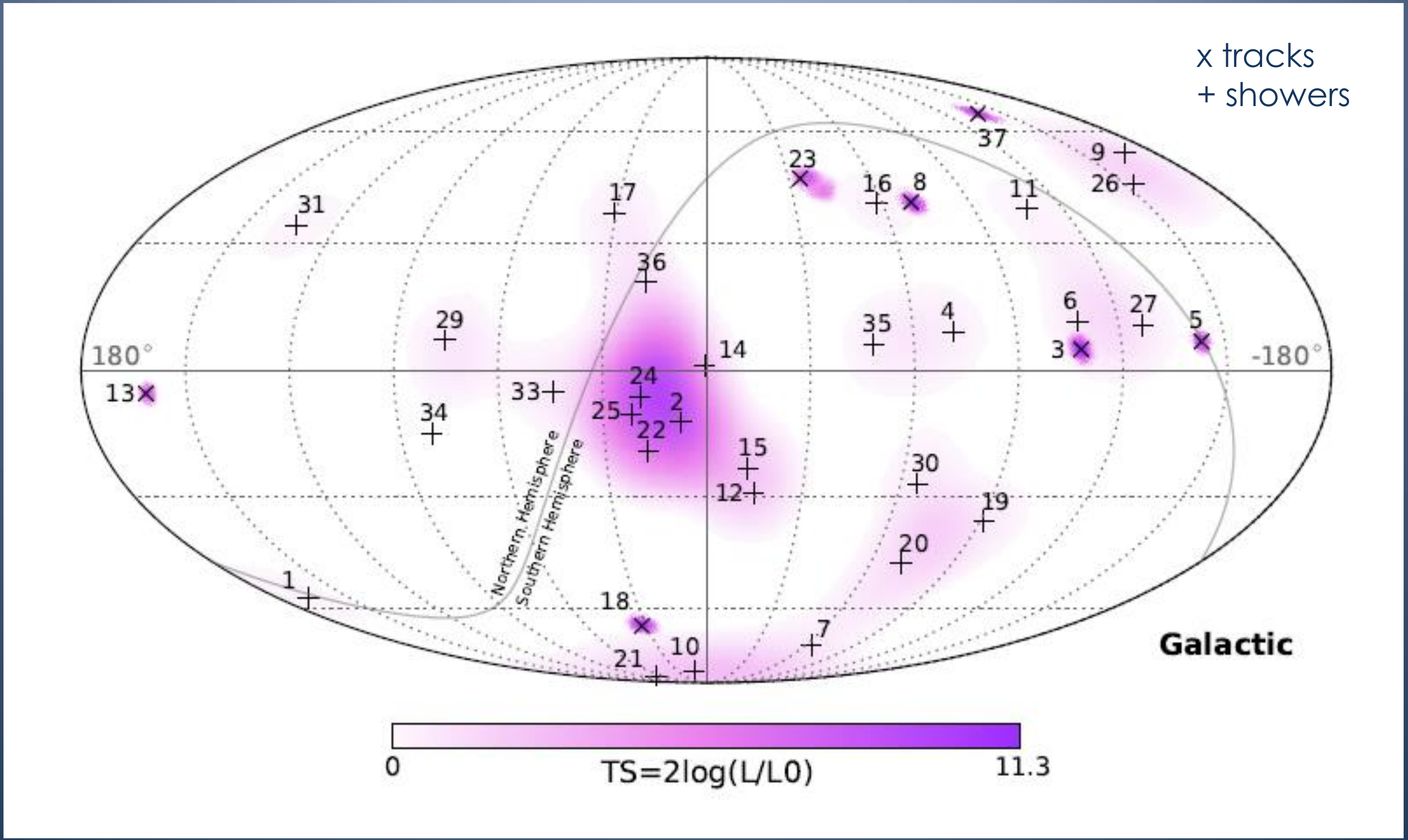

Tue, 03 Jan 2012
t = 9700 ns
ICECUBE

Big Bird

Energy ~2 PeV (highest energy neutrino ever observed!)

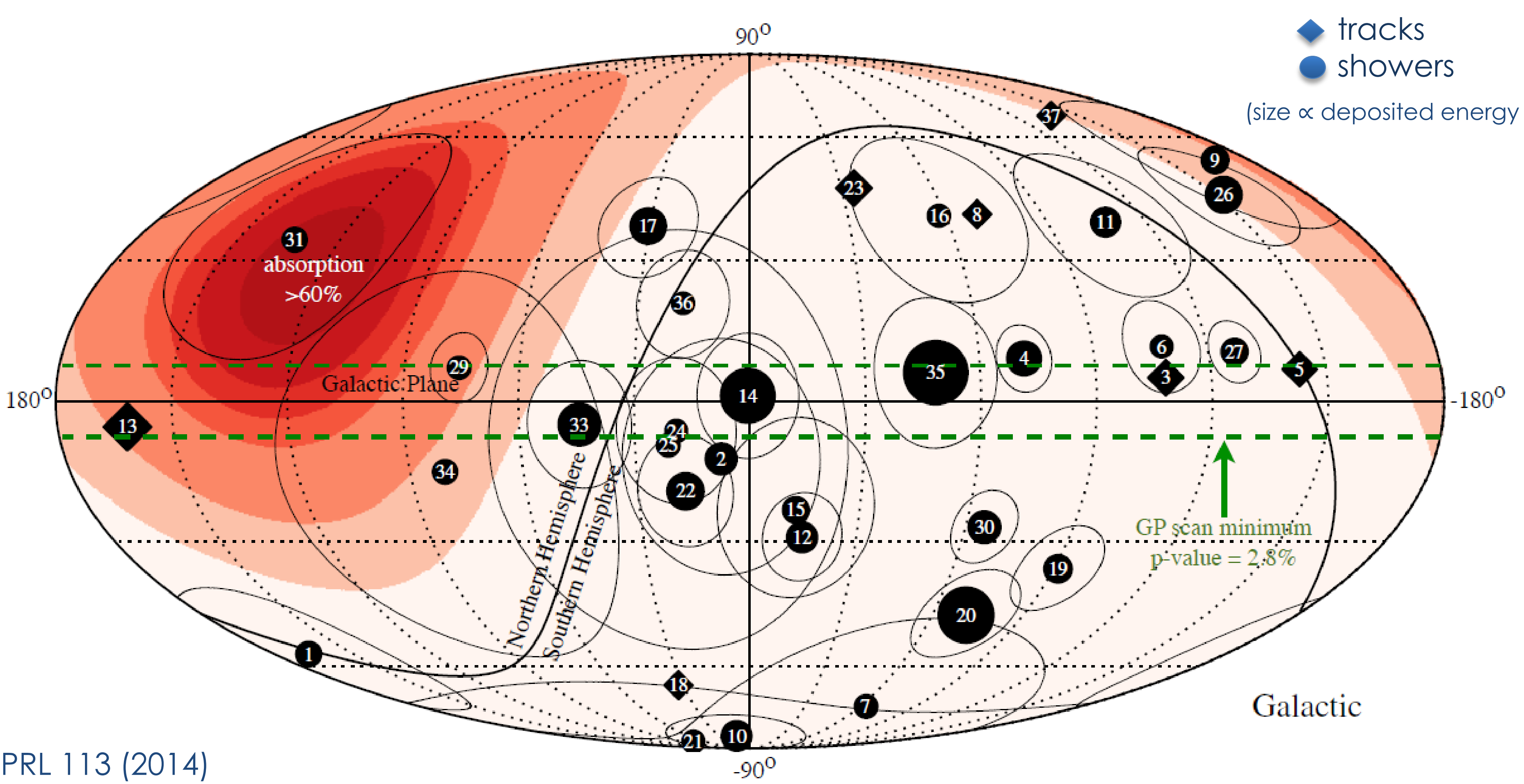


HESE skymap



- All events: p-value 84%
- Shower events: p-value 7.2%

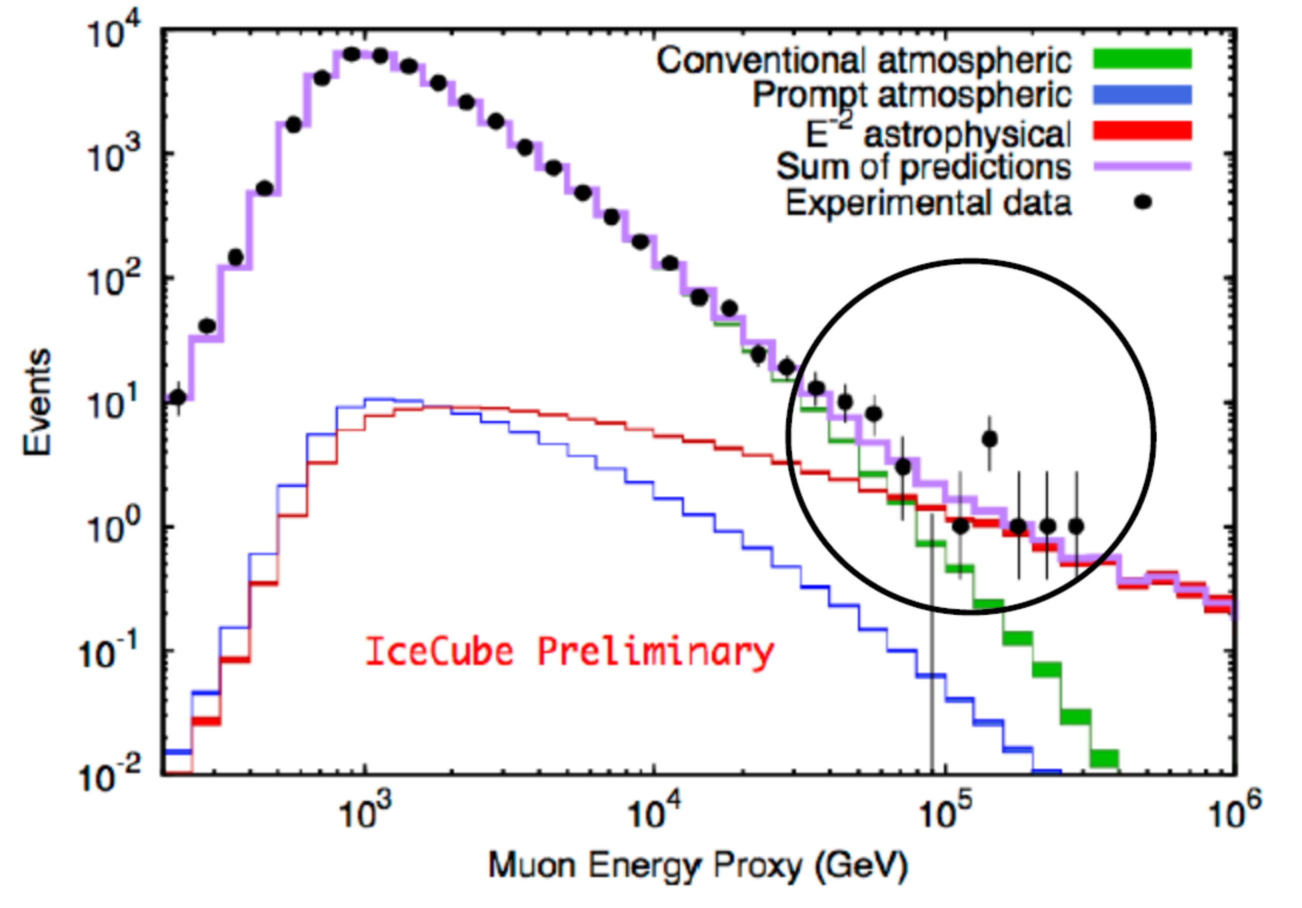
HESE skymap



PRL 113 (2014)

- All events: p-value 84%
- Shower events: p-value 7.2%

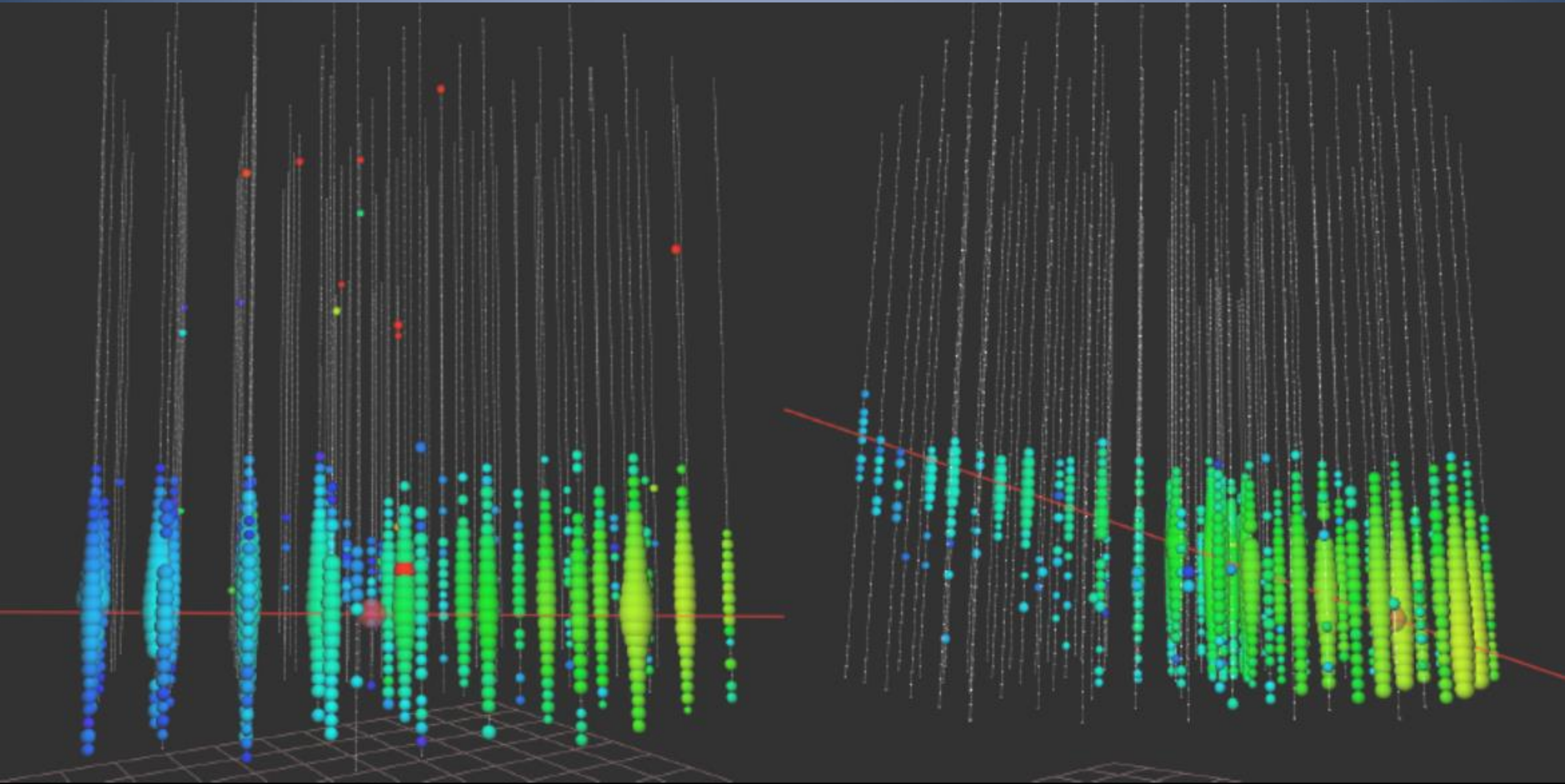
Diffuse fluxes



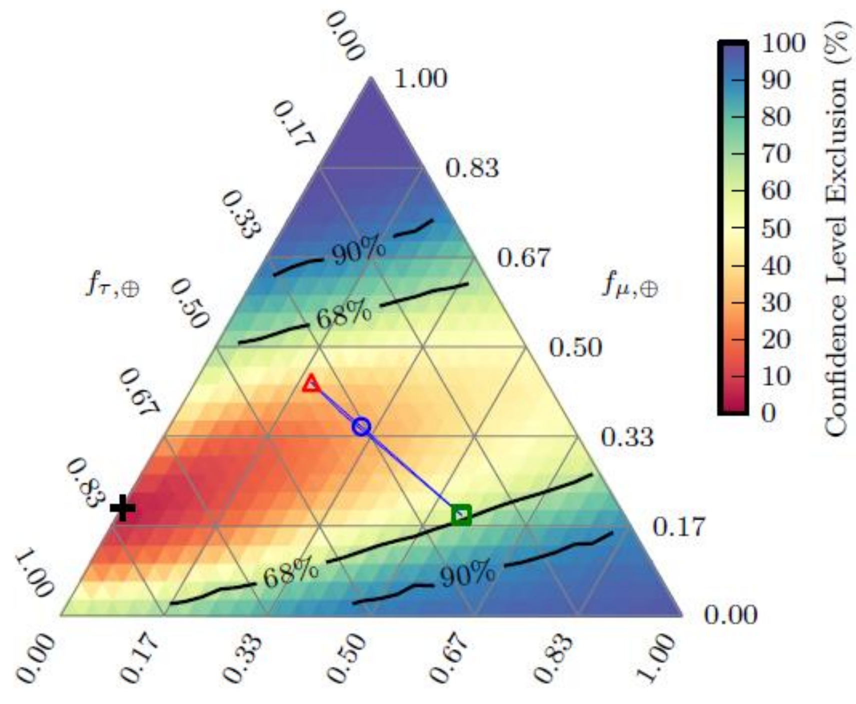
- "Standard" search for a diffuse of upgoing muon neutrinos
- Two years of data
- 3.7 sigma – Measured flux compatible with HESE analysis

Diffuse flux

- Highest energy observed in muon: 560 TeV → 1 PeV neutrino



Flavour ratios



arXiv:1502.03376

- △ muon-suppressed pion decay (0:1:0)
- ○ pion & muon decay (1:2:1)
- □ neutron decay (1:0:0)
- + best fit (0:0.2:0.8)

- 3 year sample
- 129 showers and 8 tracks (superset of HESE sample)
- Best fit:

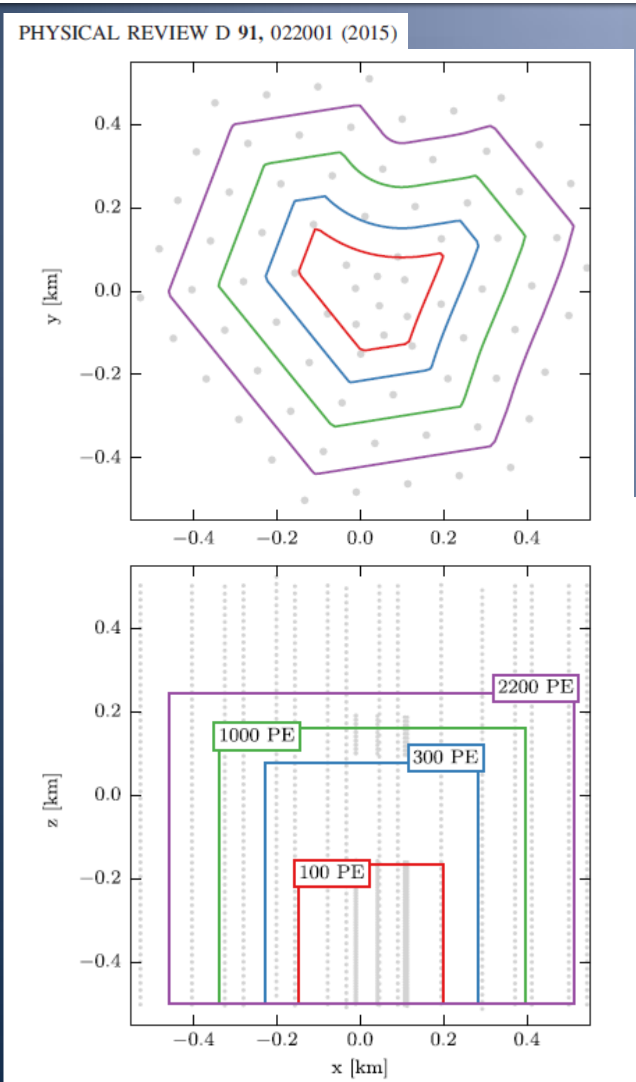
$$\gamma = 2.6 \pm 0.15$$

$$\Phi_0 = (2.3 \pm 0.4) \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}$$

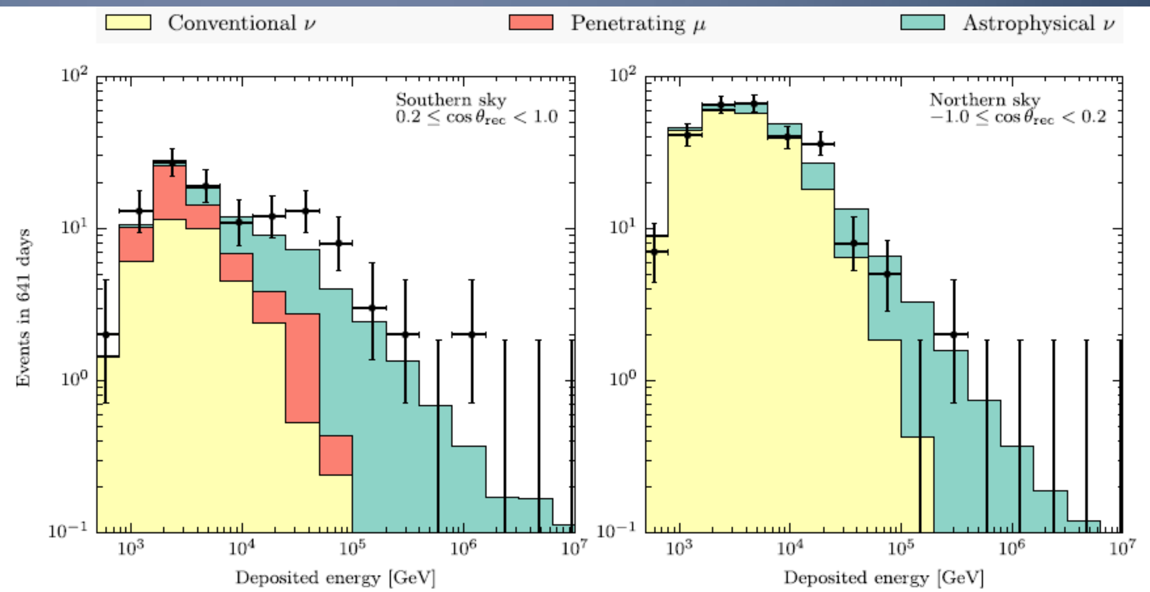
(spectrum with HE cutoff also disfavoured)

- Best composition at Earth is (0:0.2:0.8), but the limits are compatible with all compostions possible under averaged oscillations

MESE analysis

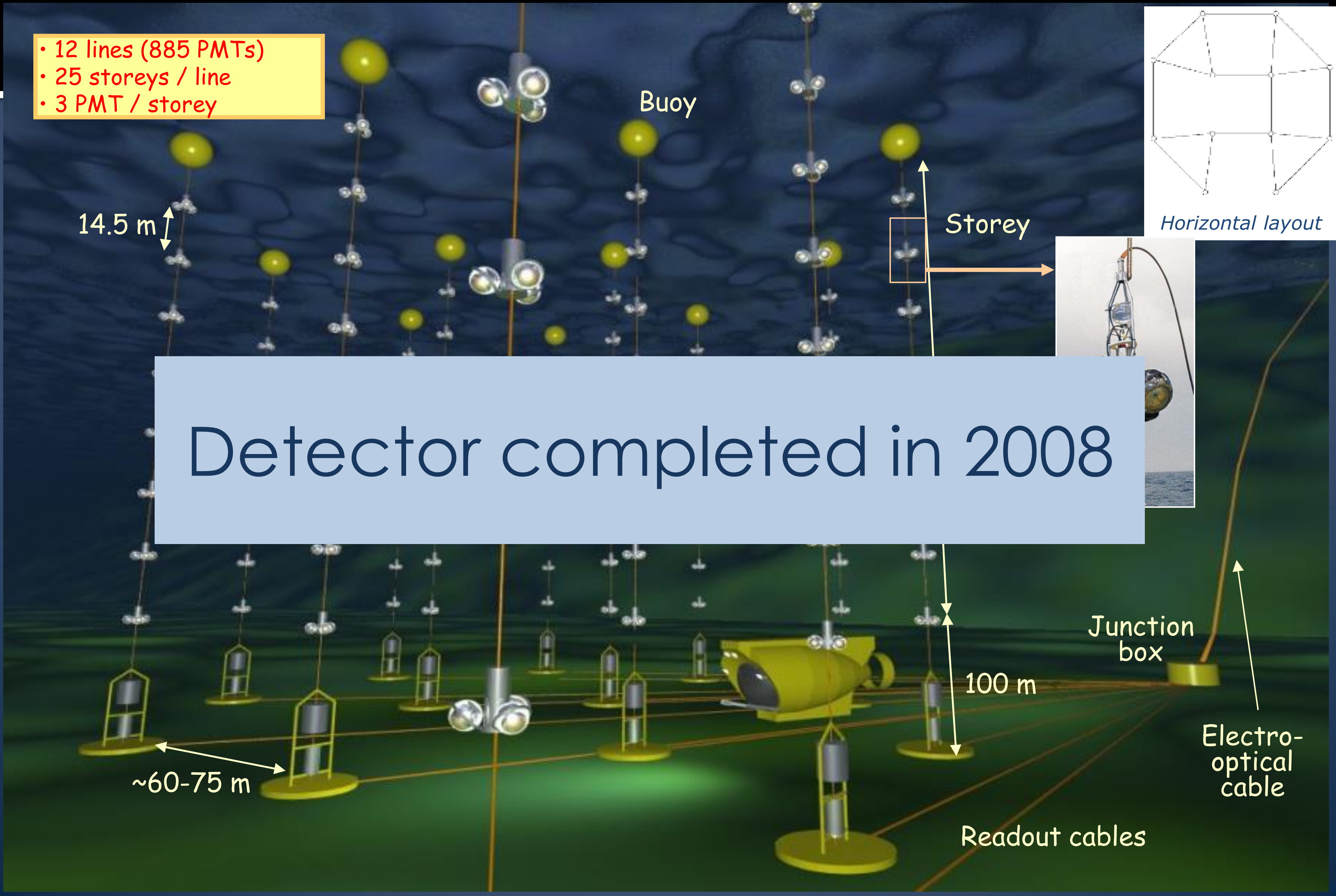


- MESE: Medium Energy Starting Events (>1 TeV)
- Veto condition more restrisctive for lower energies
- 641 days: 283 cascades and105 tracks
- Measured spectral index γ= 2.46±0.12 (γ=2 rejected at 99% CL) in the 10-100 TeV range



ANTARES

The ANTARES Detector

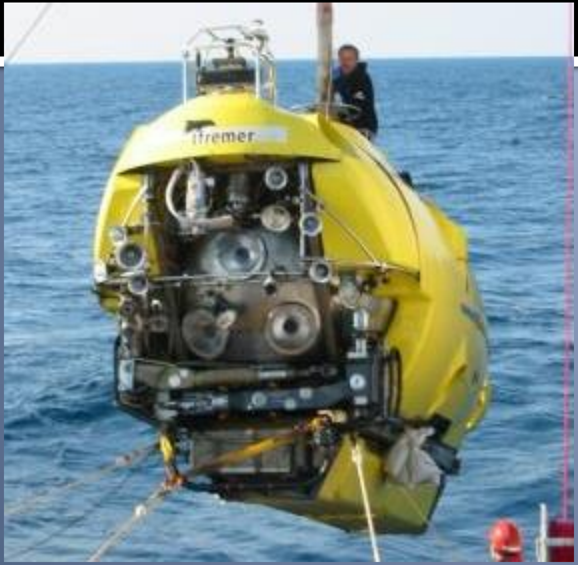


Detector completed in 2008

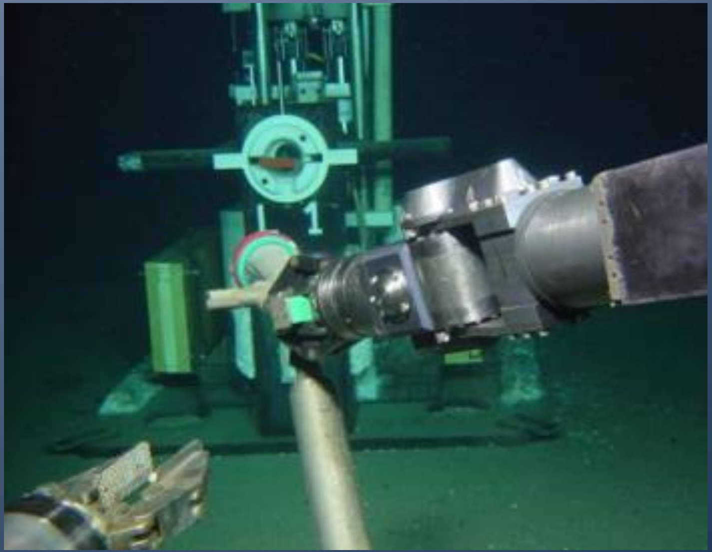
Deployment

Connection

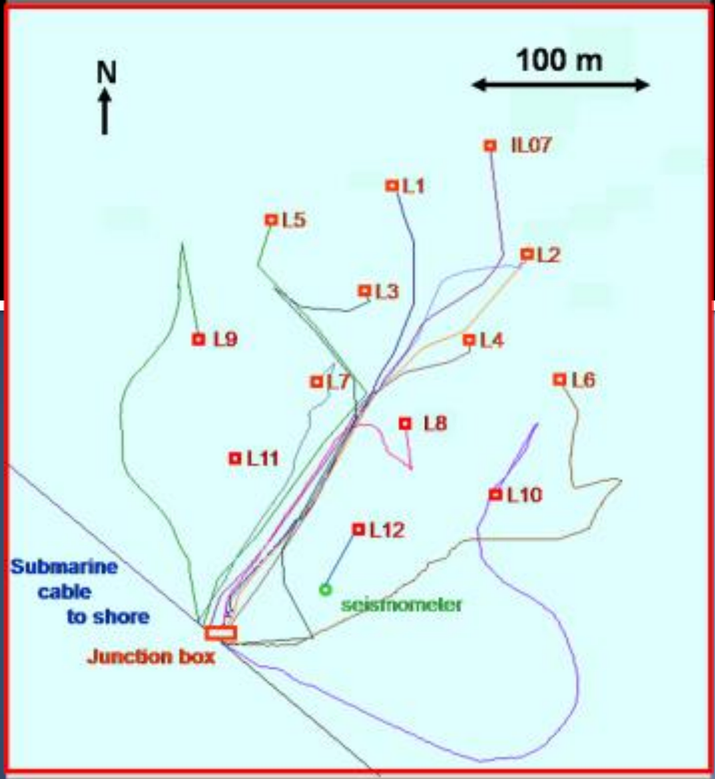
Nautile
(manned)

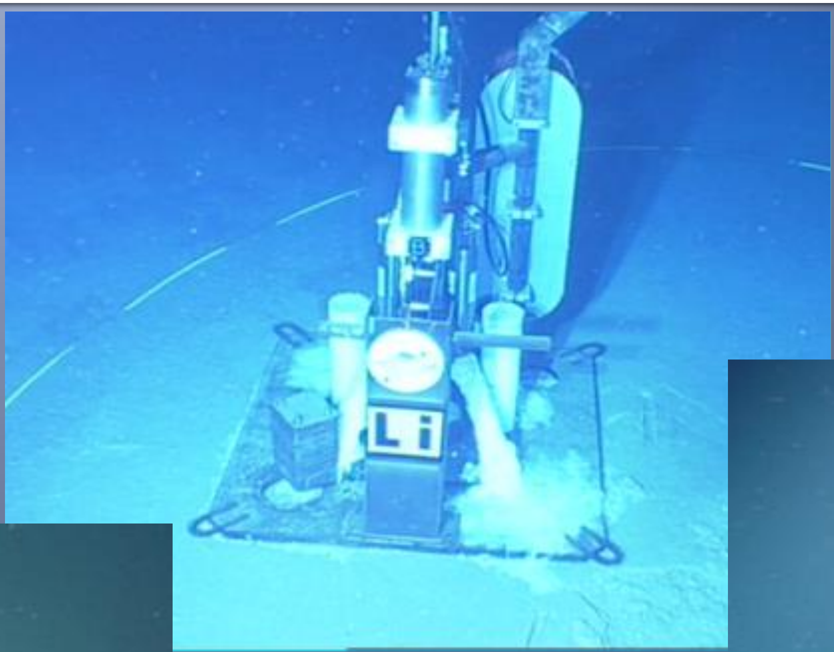


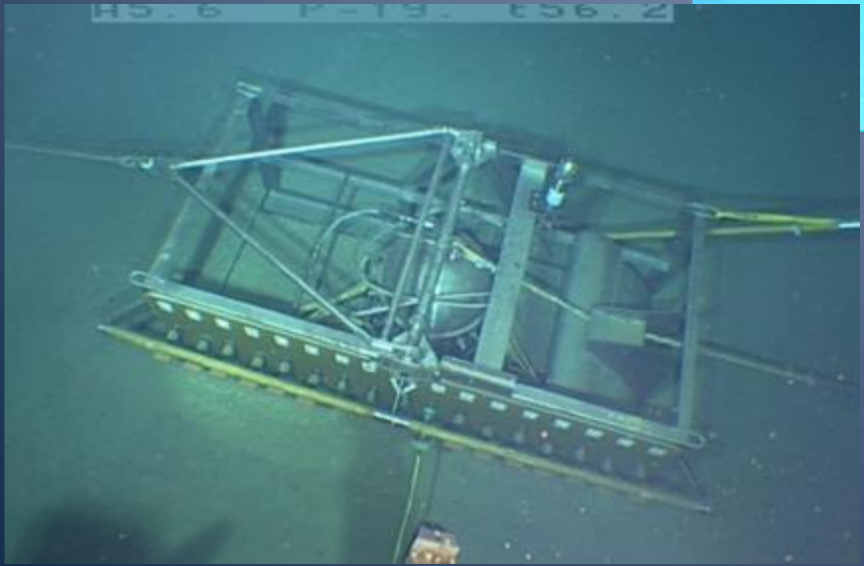
Victor
(ROV)



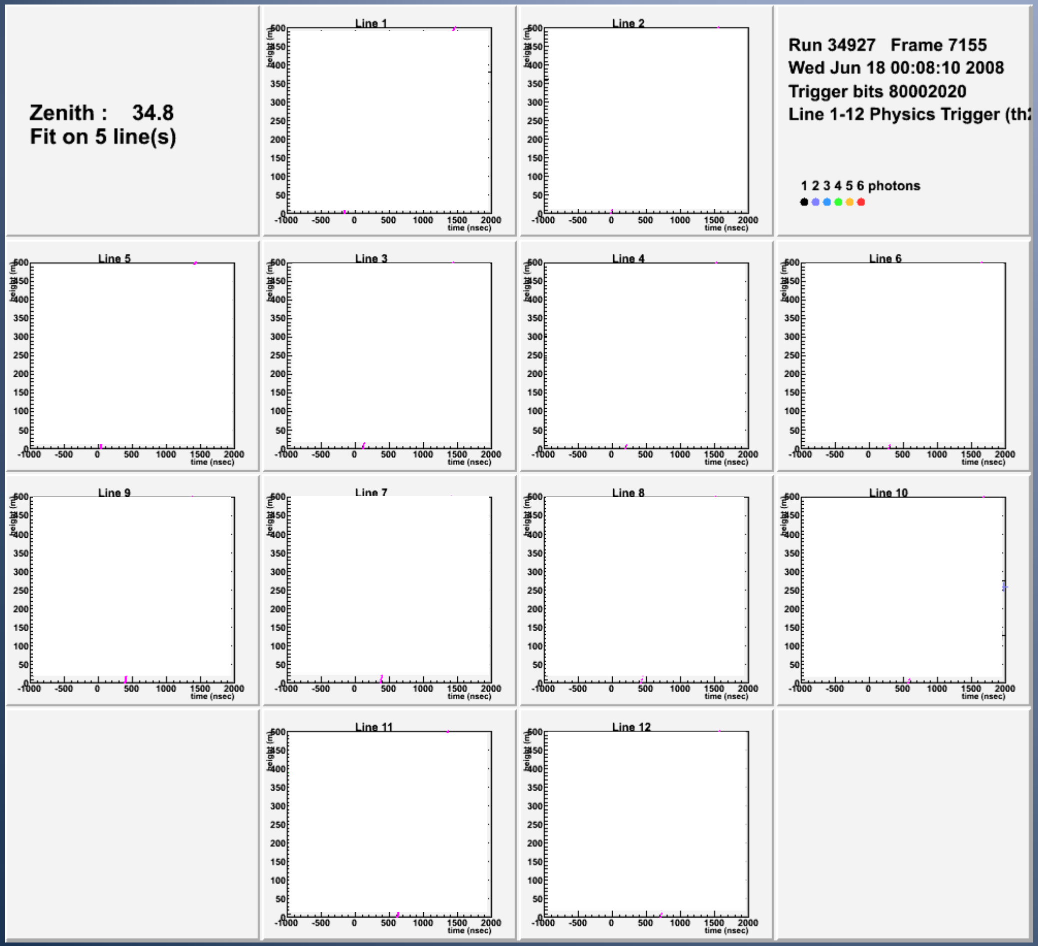
Pictures from the sea



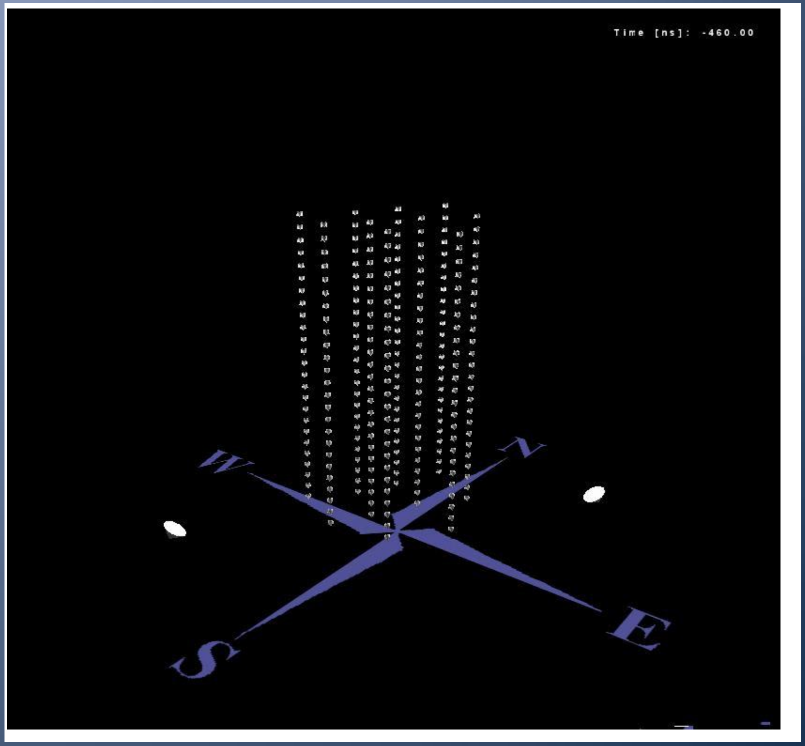




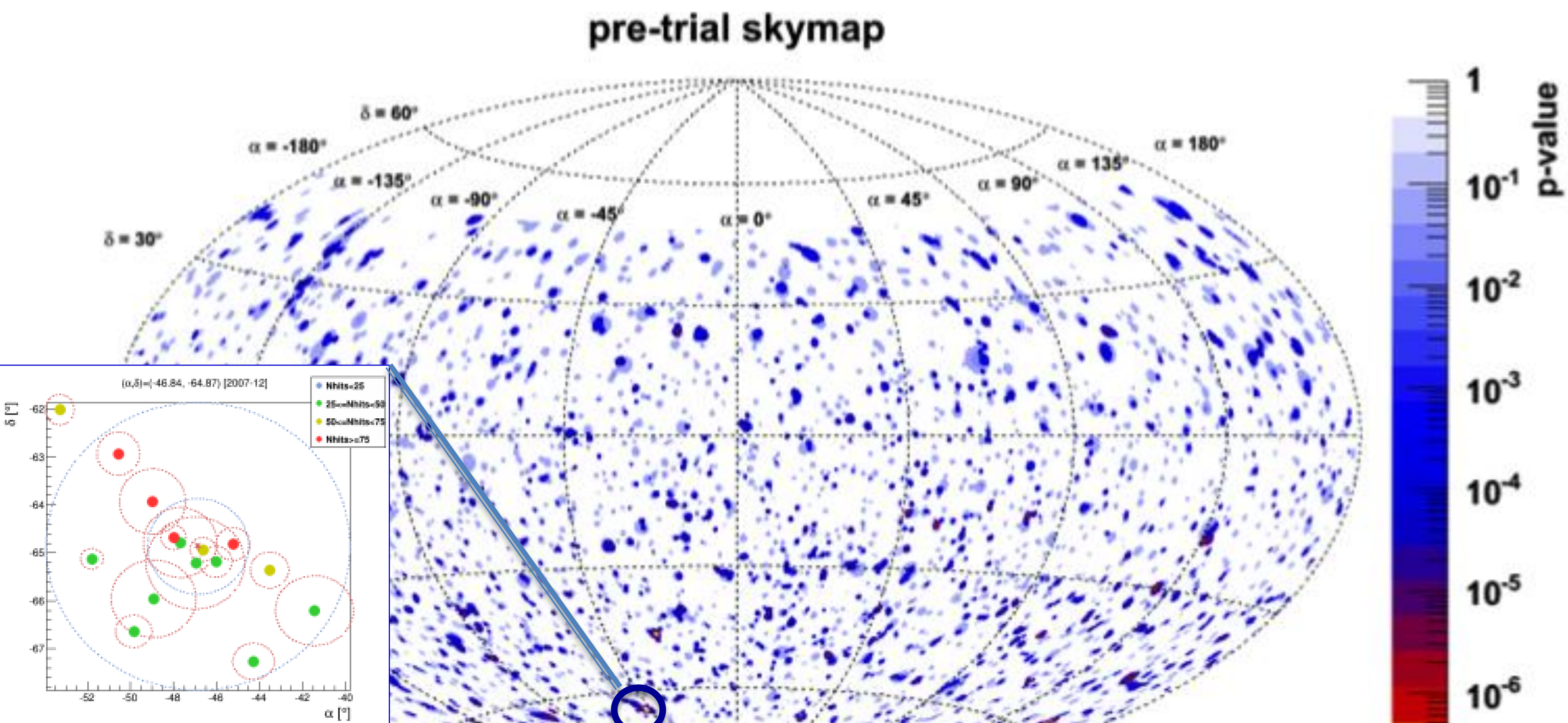
Neutrino candidate



reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:

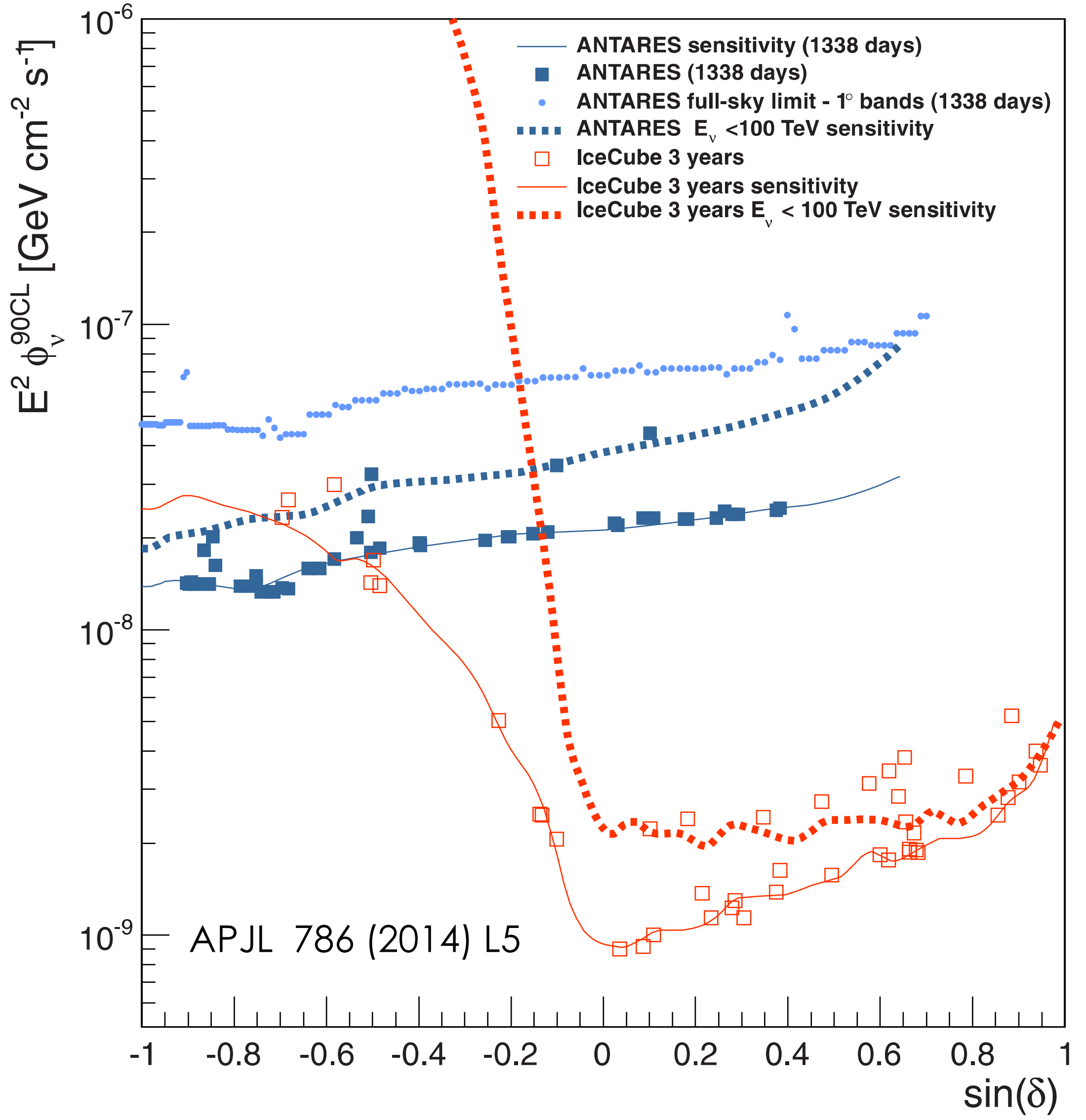


ANTARES neutrino sky



Most significant cluster:
6 (14) events in 1° (3°)
p-value = 2.7% (2.2 σ)

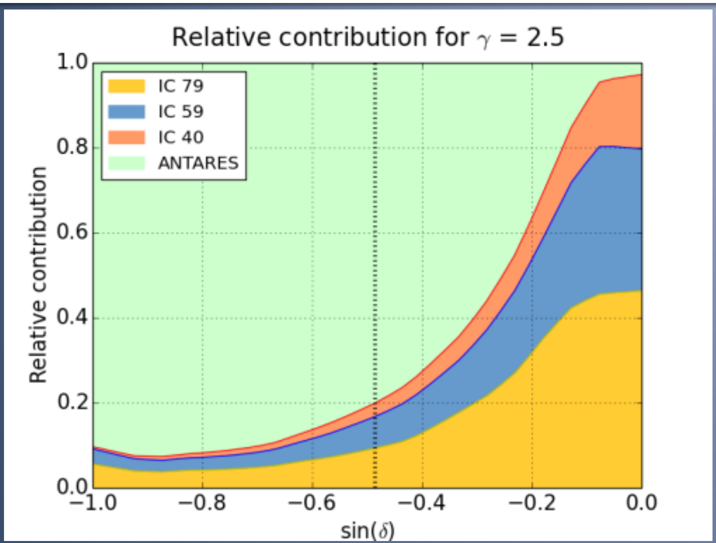
Flux limits



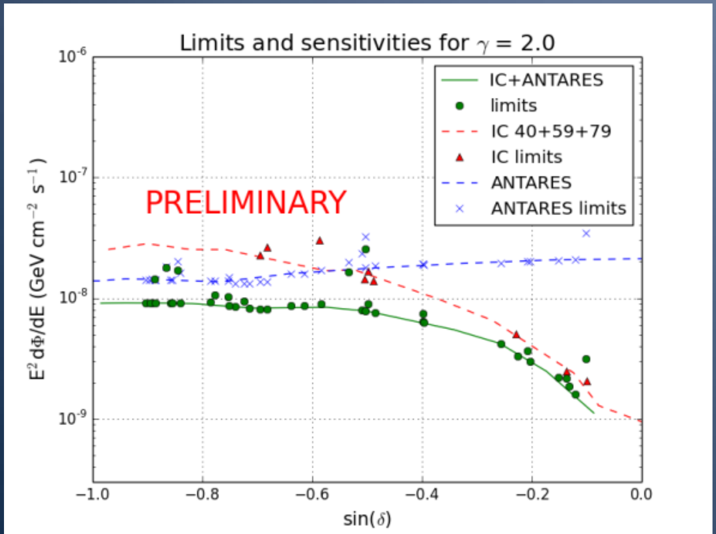
Name	$\alpha(^\circ)$	$\delta(^\circ)$	n_s	p-value	$\phi^{90\,\%CL}$
HESSJ0632+057	98.24	5.81	1.60	0.07	4.40
HESSJ1741-302	265.25	-30.20	0.99	0.14	3.23
3C279	194.05	-5.79	1.11	0.39	3.45
HESSJ1023-575	155.83	-57.76	1.98	0.82	2.01
ESO139-G12	264.41	-59.94	0.79	0.95	1.82

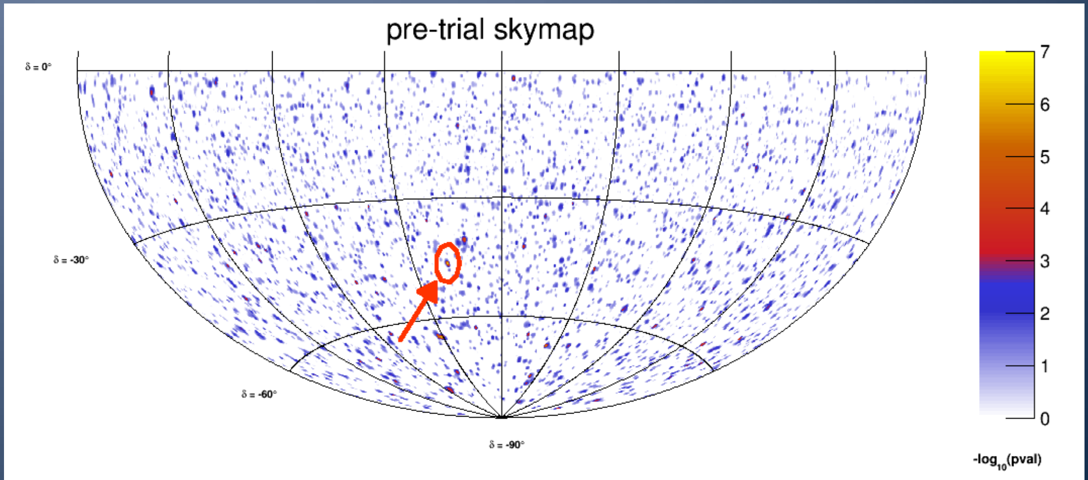
- Best limits for TeV-PeV energiesin the Sourthern Hemisphere
- IceCube threshold for SH is ~1 PeV

ANTARES+IceCube Combined



- An analysis has been done looking for point sources combining ANTARES and IceCube data
- There is an improvement in the declination region corresponding to the crossing of sensitivities, whose position depends on the spectral index and a potential energy cutoff
- Data (ANTARES 6y + IceCube 3y) has been unblinded and a common skymap produced (no excess found)





Diffuse fluxes

Multimessenger

GeV-TeV γ-rays
Fermi / HESS…

- 🕮 JCAP 03(2013) 006
- 🕮 A&A 559 (2013) A9
- 🕮 JCAP 05 (2014) 001

UHECR
Auger

- 🕮 APJ 774 (2013) 19

High energy neutrinos

Optical / X-rays
TAROT, ROTSE /
Swift, ZADKO

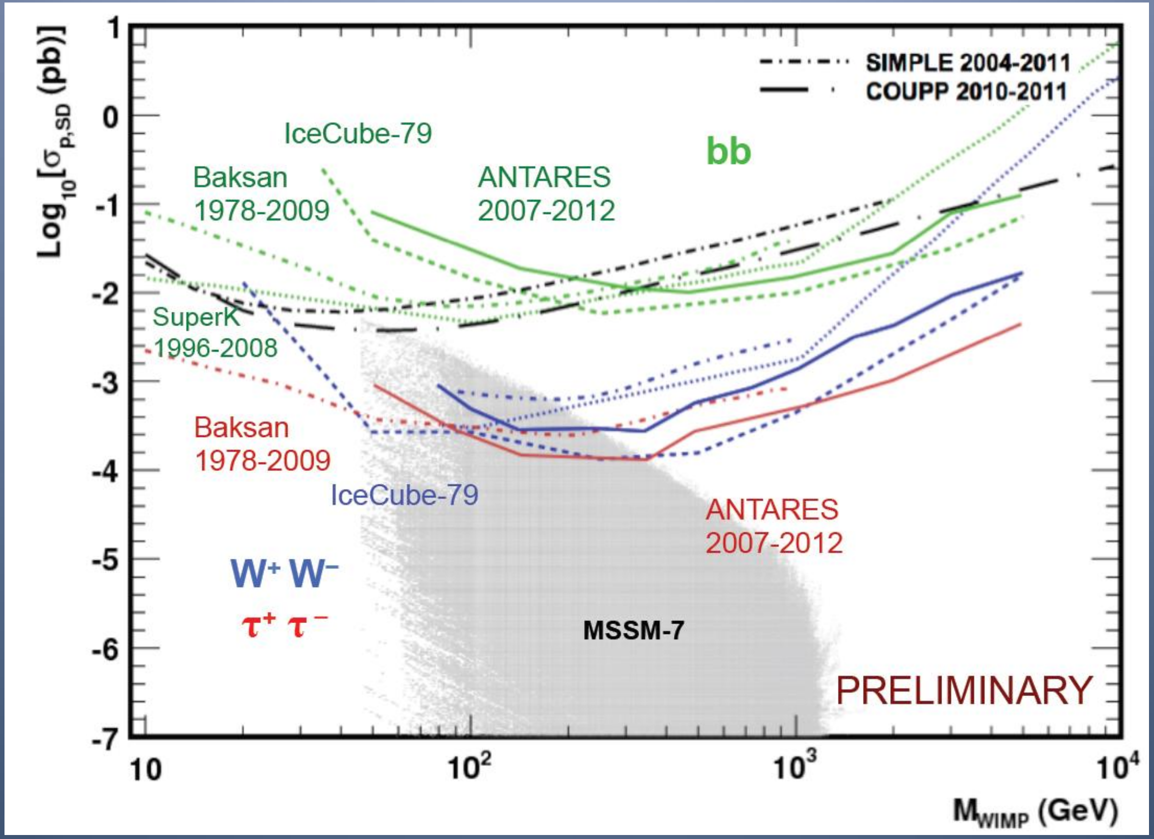
- 🕮 APP 36 (2012) 204
- 🕮 A&A 559 (2013) A9

Gravitational Waves
Virgo / Ligo

- 🕮 JCAP 06 (2013) 008

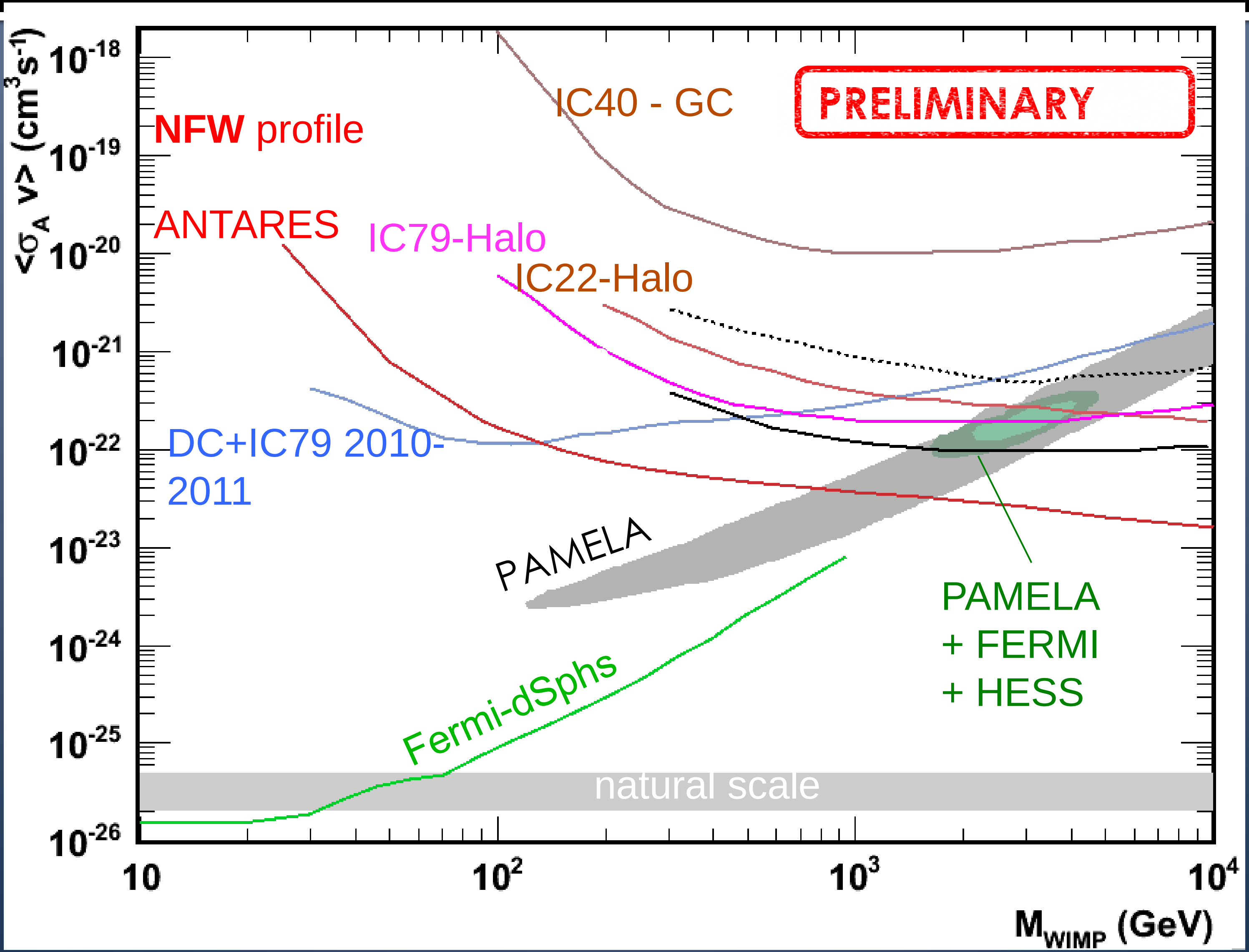
- It increases the chances of detection
  - Common sources for different messengers
  - Backgrounds and systematics non-correlatedos

Dark Matter: Sun

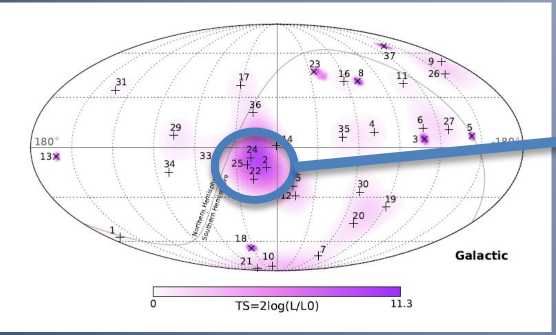


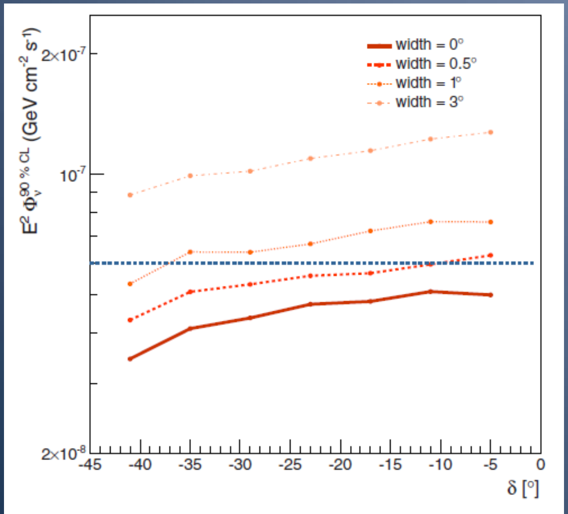
- With only 2007-2008 data, already competitive with IceCube-79:
  - Better angular resolution
  - Better visibility of the Sun
  - Energy threshold

Dark Matter: Galactic Centre



ANTARES on IceCube signal (I)





The Astrophysical Journal Letters, 786:L5 (5pp), 2014

- What can ANTARES say about this? (seven events in the HESE analysis close to the GC)
- In arXiv:1310.7194 (González-García, Halzen, Niro), it is proposed to come from a point source with flux 6x10^{-8} GeV cm^{-2} s^{-1}.
- ANTARES data allows to reject this possibility (it is not a point-like source) at the flux proposed there and limits depending on the size of the source are set

ANTARES on IceCube signal (II)

ATNARES on IceCube signal (III)

A&A 566, L7 (2014)
DOI: 10.1051/0004-6361/201424219

Astronomy & Astrophysics

Letter to the Editor

TANAMI blazars in the IceCube PeV-neutrino fields★

F. Krauß[1,2], M. Kadler[2], K. Mannheim[2], R. Schulz[1,2], J. Trüstedt[1,2], J. Wilms[1], R. Ojha[3,4,5], E. Ros[6,7,8], G. Anton[9], W. Baumgartner[3], T. Beuchert[1,2], J. Blanchard[10], C. Bürkel[1,2], B. Carpenter[5], T. Eberl[9], P. G. Edwards[11],

Astronomy & Astrophysics manuscript no. antares_tanami_aa
January 16, 2015

Letter to the Editor

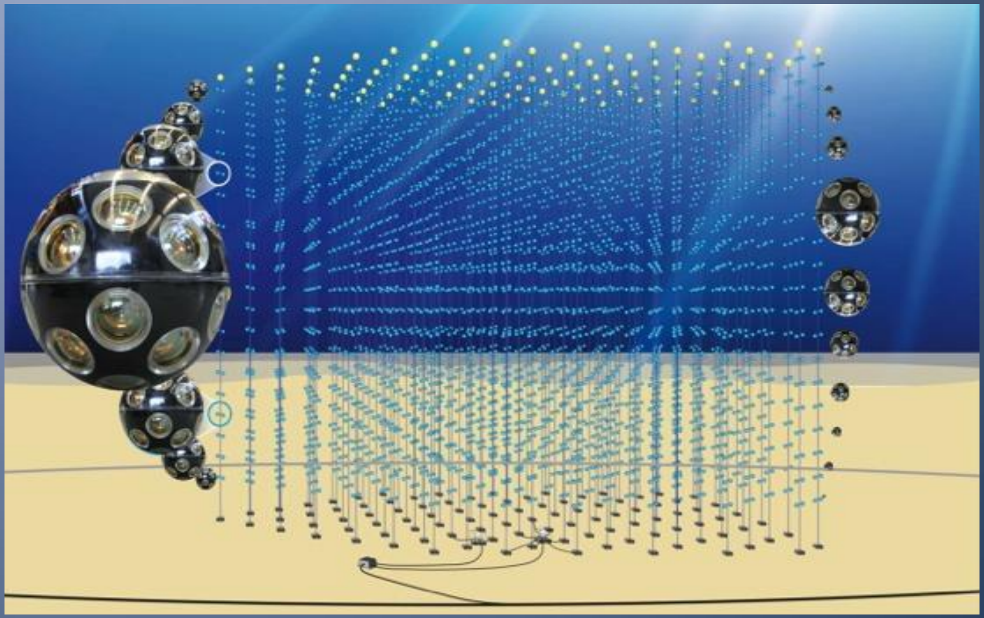
ANTARES Constrains a Blazar Origin of Two IceCube PeV Neutrino Events

The ANTARES Collaboration: S. Adrián-Martínez[1], A. Albert[2], M. André[3], G. Anton[5], M. Ardid[1], J.-J. Aubert[6], B. Baret[7], J. Barrios[8], S. Basa[9], V. Bertin[6], S. Biagi[23], C. Bogazzi[12], R. Bormuth[12,13], M. Bou-Cabo[1], M.C. Bouwhuis[12], R. Bruijn[12,14], J. Brunner[6], J. Busto[6], A. Capone[15,16], L. Caramete[17], J. Carr[6], T. Chiarusi[10]

KM3NeT

KM3NeT

- KM3NeT is a common proyect to construct neutrino telescope in the Mediterranean with an instrumented volume of several cubic kilometers
- It will also be a platform for experiments on sea science, oceanograpy, geophysics, etc.
- 40 groups of Astroparticle Physics and Sea Science from 11 countries are involved



- Prototype lines have already been installed
- The construction of the first lines has started
- The first KM3NeT line will be installed this spring

Phases

PHASE 1:

- Already funded
- 31 lines (24 in Italy, 7 in France)to be deployed in 2015-2016
- Proof of feasibility and first science results

PHASE 2:

- ***ARCA*** (Astroparticle Researche with Cosmic Rays)
  - Test IceCube signal
  - Italy
  - 2x115 lines
  - Sparse configuration
- ***ORCA*** (Oscillation Research with Cosmic Rays)
  - Mass hierarchy (and DM)
  - France
  - 115 lines
  - Dense configuration

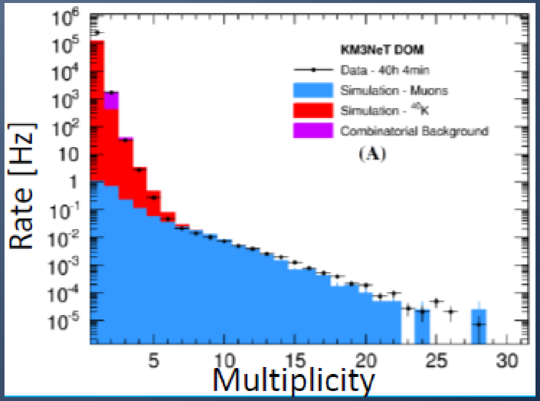
PHASE 3: FINAL CONFIGURATION

- 6x115 lines (in total)
- Neutrino astronomy including Galactic sources

KM3NeT Optical Modules

- (Multi-PMT) Optical Module
  - 31 x 3" PMTs
  - diametre: 17''
  - low power requirements
  - "full" module: no additional electronics vessel needed
  - uniform angular coverage
  - information of the arrival direction of photons
  - better rejection of background

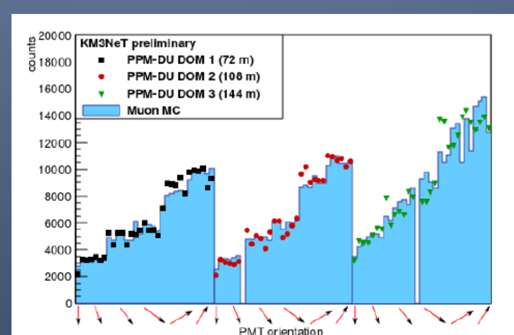
- Prototype at ANTARES intrumentation line since April 2015
- Ref: Eur. Phys. C. (2014) 74:3056



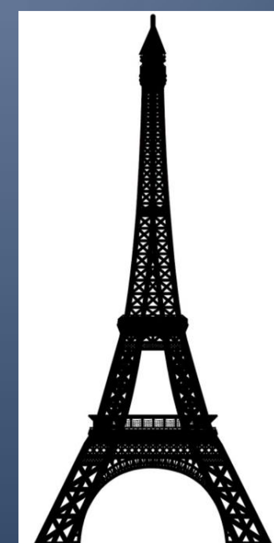
KM3NeT Detector Units

- Detector Units (strings)
  - 18 DOMs, separated vertically by: 6 m (ORCA) or 36 m (ARCA)
  - anchored at sea floor by a dead weight
  - kept vertical by buoys
  - 115 DUs = 1 building block
- Deployable with launching vehicle:
  - fast
  - recoverable
  - safe
  - less dependent on weather conditions

Prototype installed at Capo Passero since May 2014

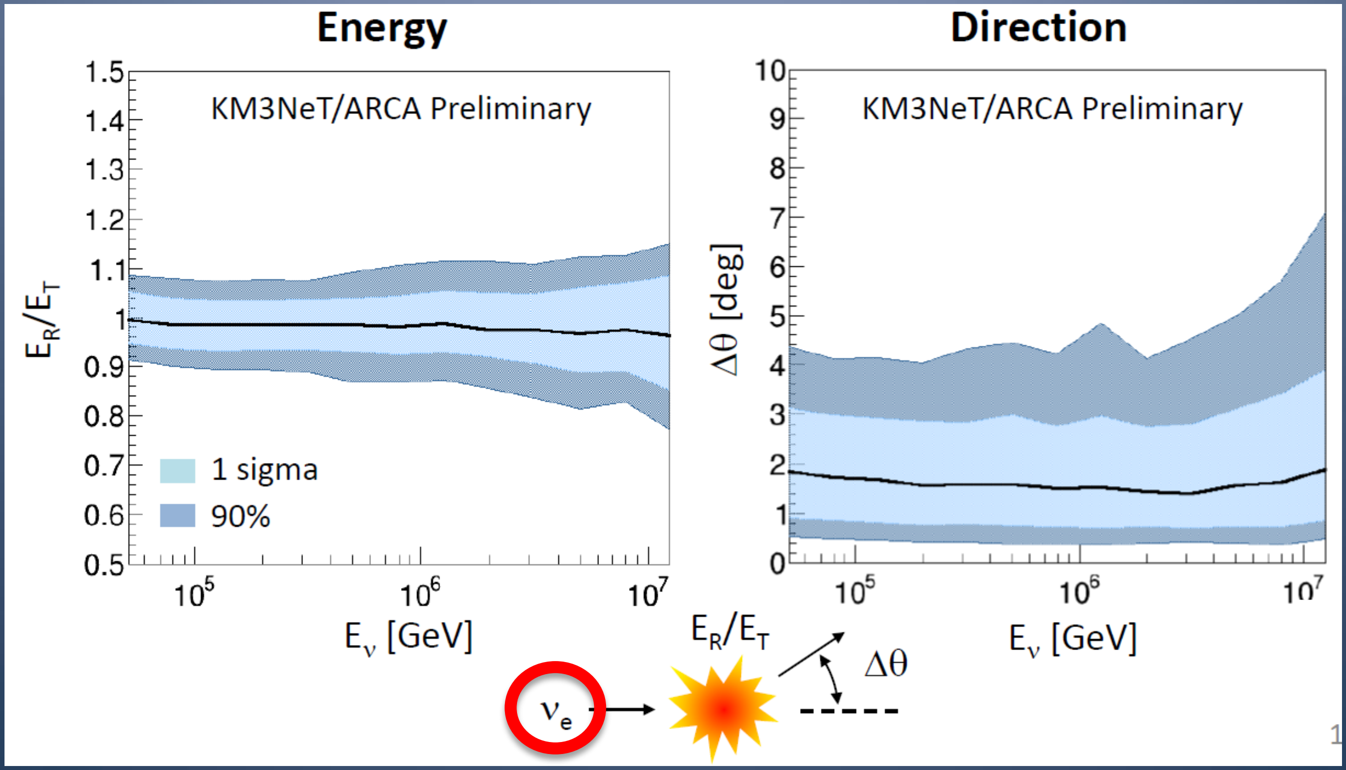


ARCA

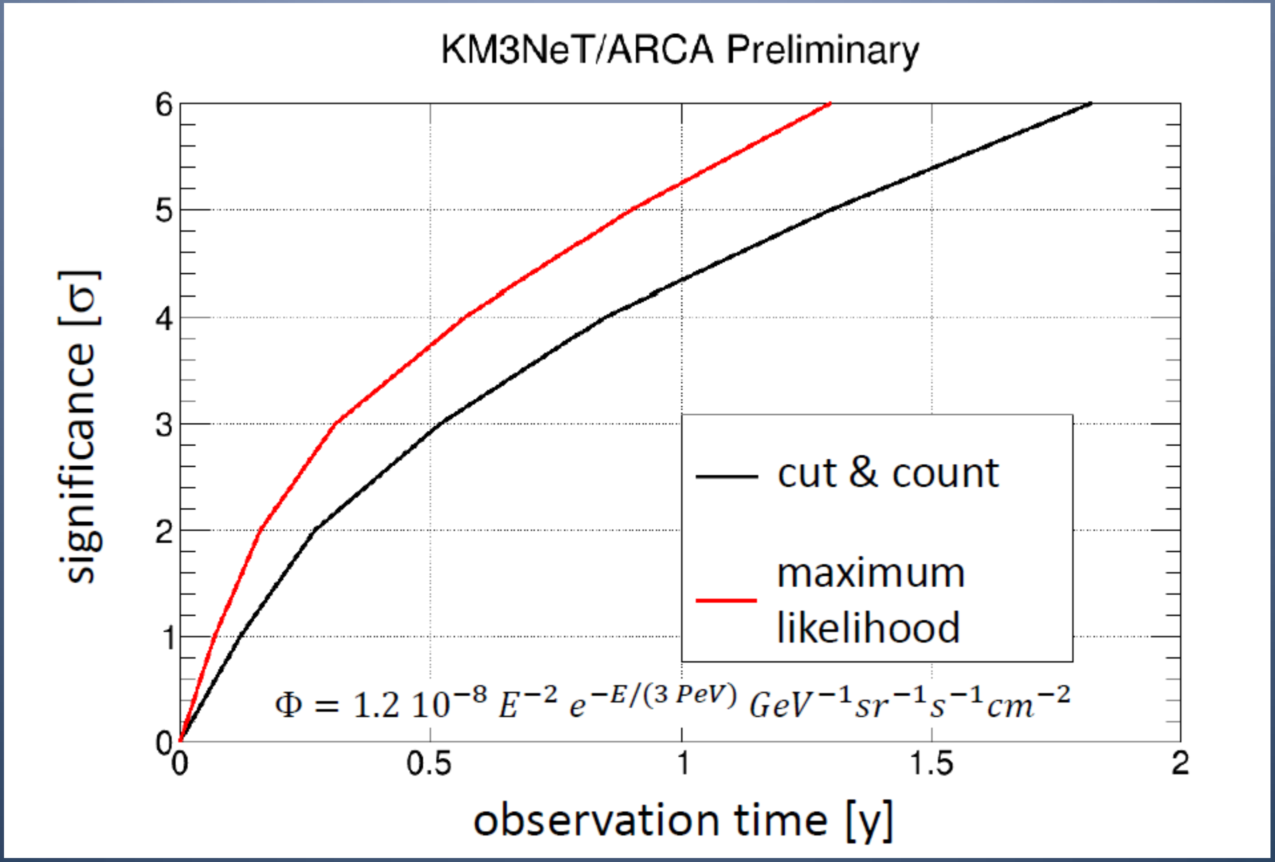


Performance (ARCA)

- Water: best angular resolution
- All flavor astronomy!

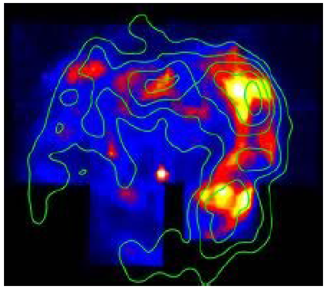


Performance (ARCA)

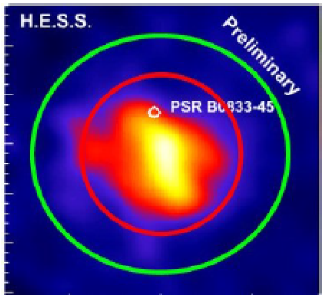


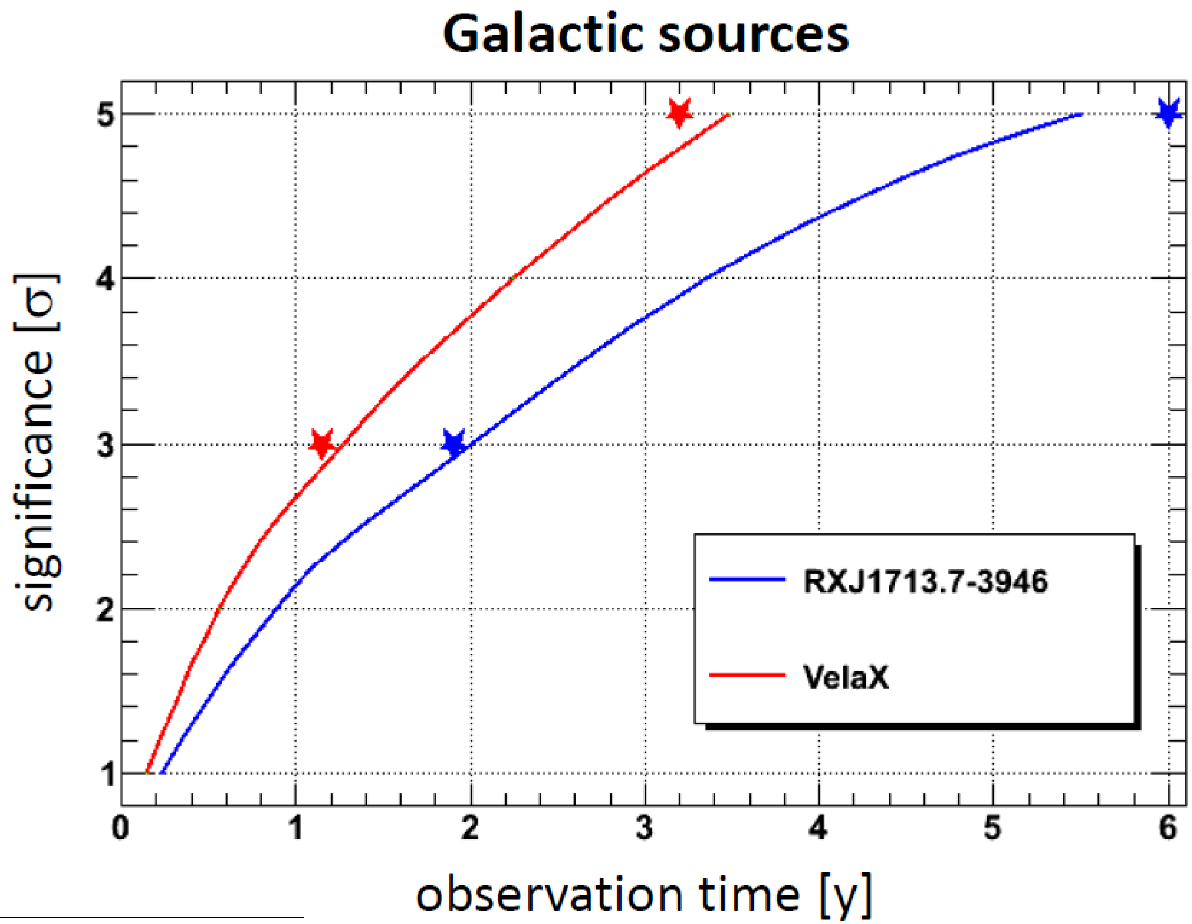
Performance (Phase 3)

RXJ1713[¶]



Vela X[§]



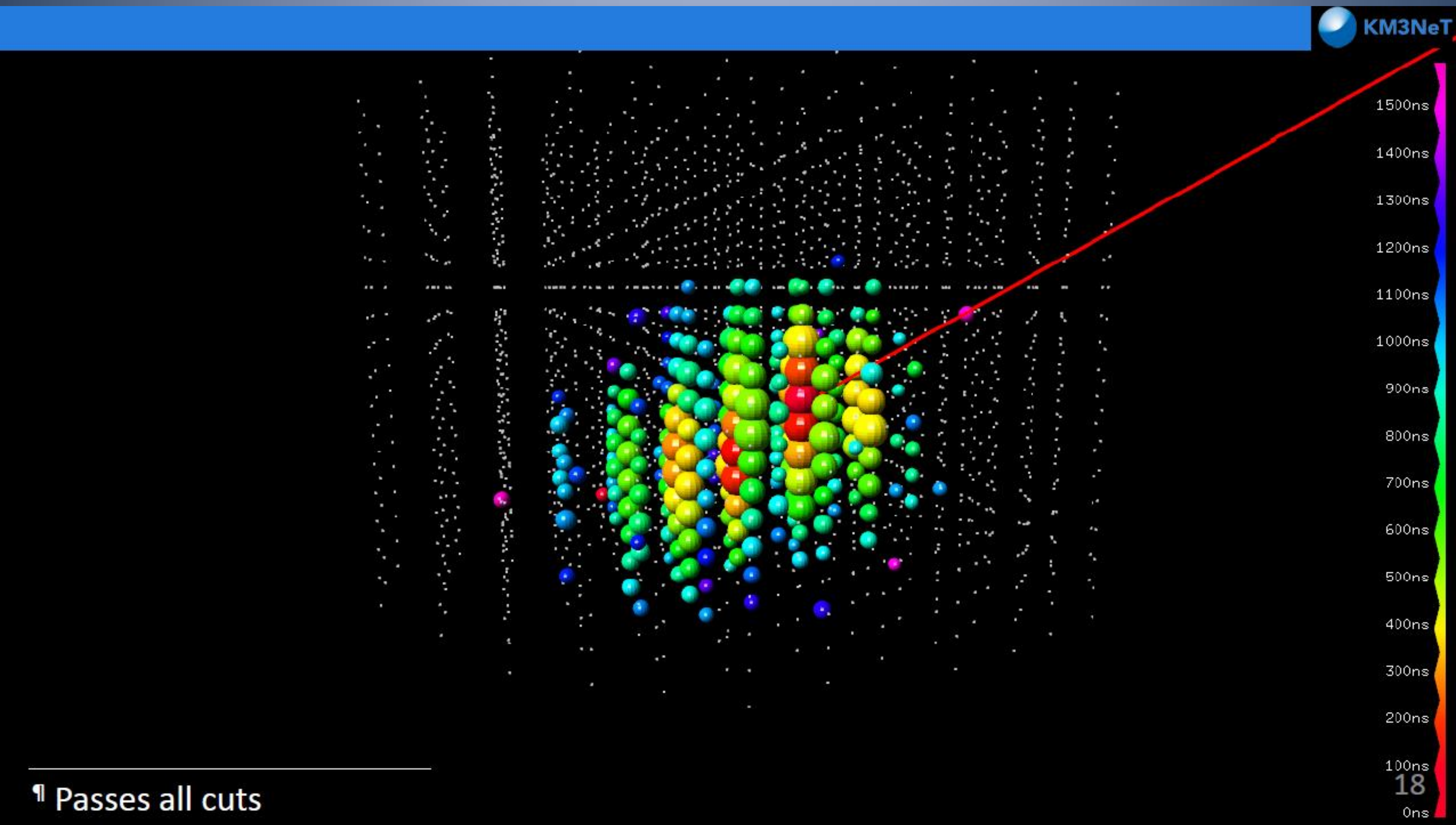


[¶] S.R. Kelner, *et al.*, Phys. Rev. D 74 (2006) 034018.

[§] F.L. Villante and F. Vissani, Phys. Rev. D 78 (2008) 103007.

M. Jong, NeuTel 2015

1.5 PeV event



- Passes all cuts