Neutrino telescopes: results and prospects

Pontecorvo Neutrino School

Alushta, Crimea, Ukraine

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MultiDark

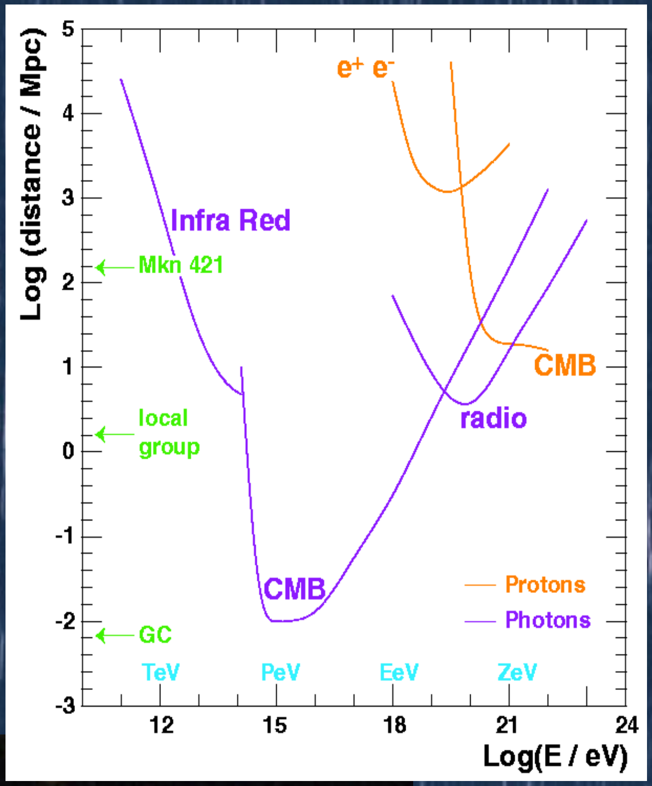
Multimessenger Approach for Dark Matter Detection

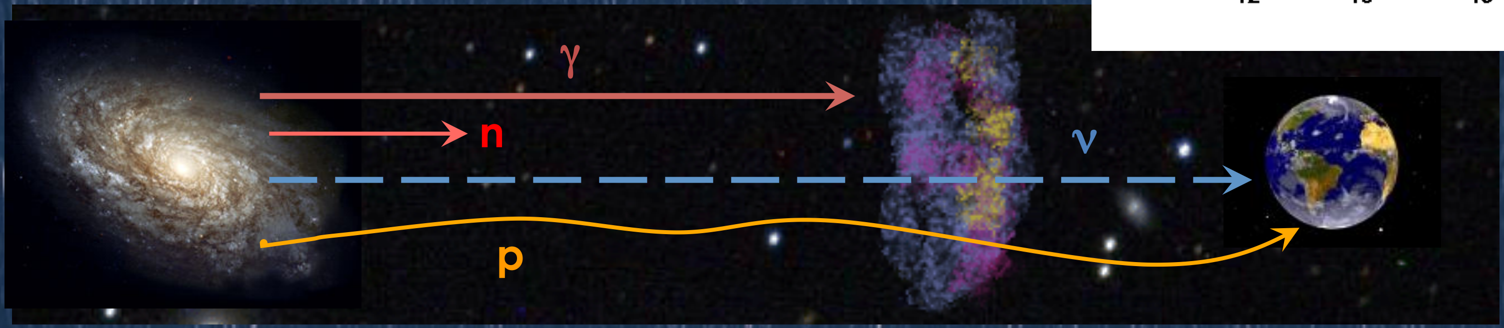
Neutrino astronomy

- Advantages w.r.t. other messengers:
  - Photons: interact with CMB and matter
  - Protons: interact with CMB and are deflected by magnetic fields

- Drawback: large detectors (~GTon) are needed.

Photon and proton mean free range path





Production mechamism

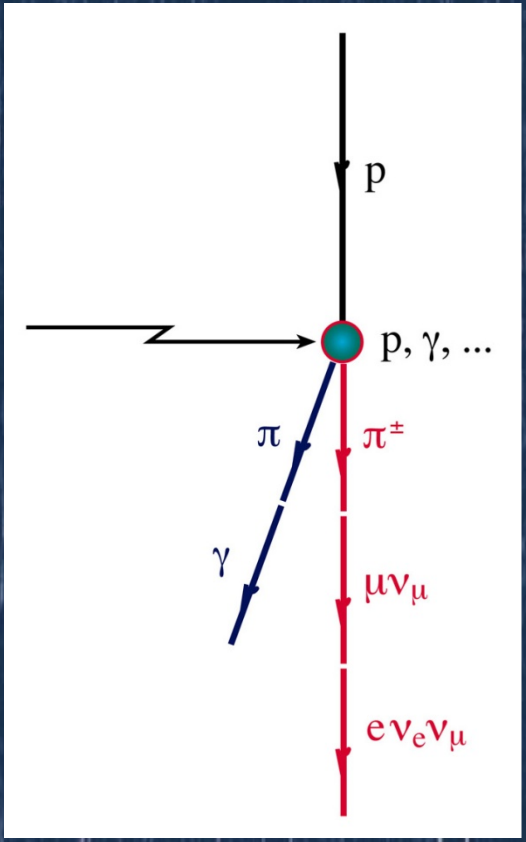
- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}\ldots) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

$$\downarrow$$

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

Cosmic rays

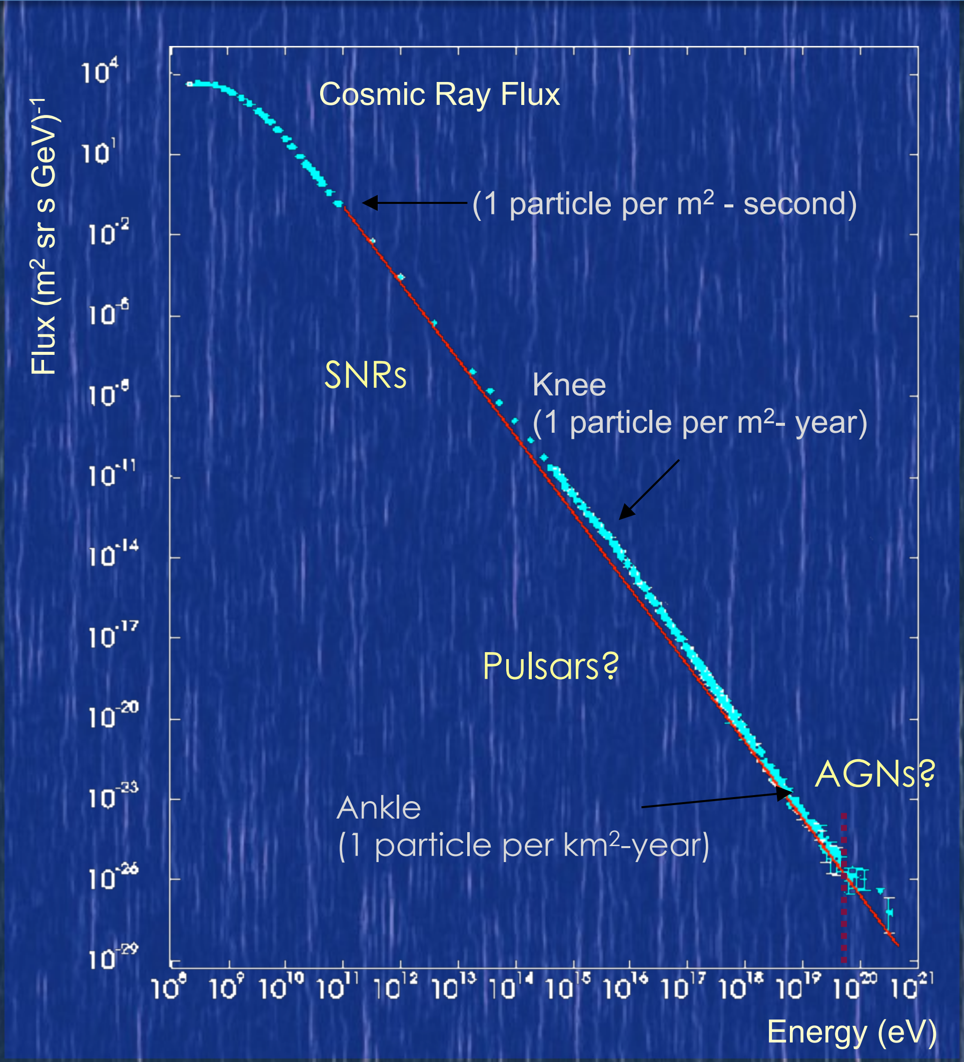


- Moreover, gammas are also produced in this scenario:

$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\ \gamma + Y$$

Gamma ray astronomy

Cosmic rays



- Cosmic rays follow a broken power-law:

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

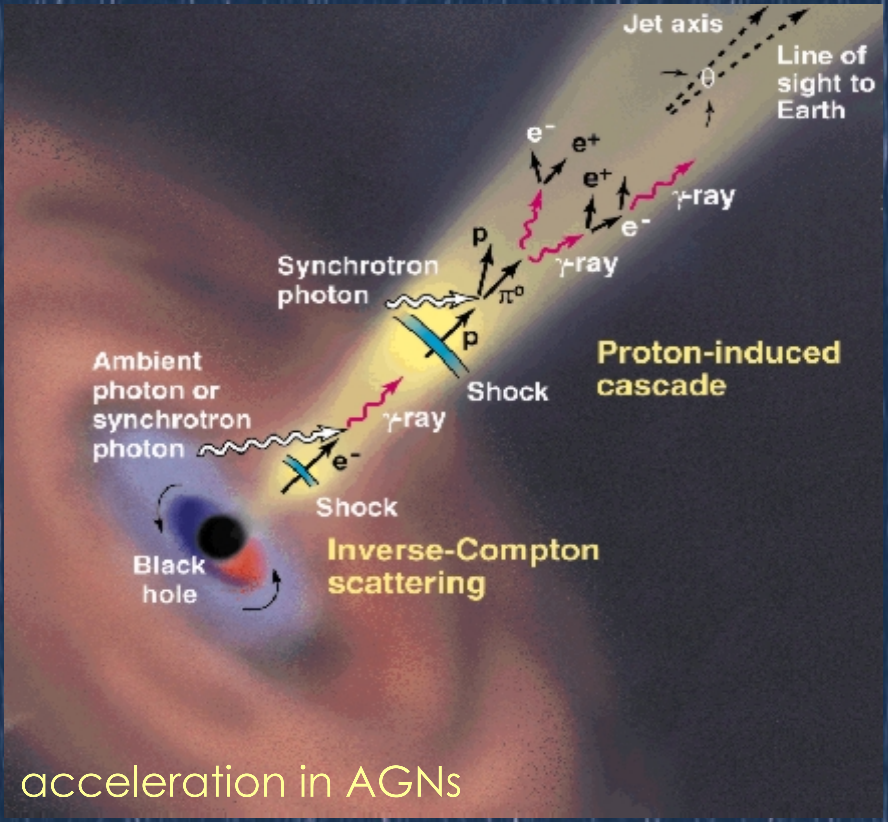
the knee
the ankle

- 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).



Galactic sources

- Supernova remnants
  - Different scenarios: plerions (center filled SNRs), shell-type SNRs, SNRs with energetic pulsars…
- Micro-quasars
  - a compact object (BH or NS) accreting matter from a companion star. Neutrino beams could be produced in the MQ jets
- Magnetars
  - Isolated neutron stars with surface dipole magnetic fields $\sim 10^{15}$ G, much larger than ordinary pulsars
  - Seismic activity in the surface could induce particle acceleration in the magnetosphere

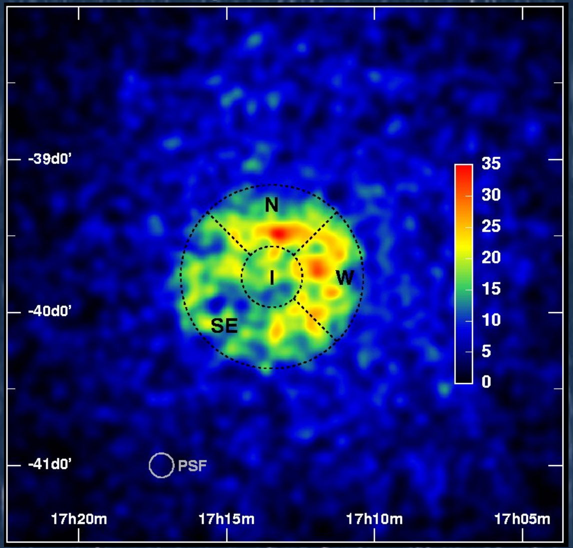
Extragalactic sources

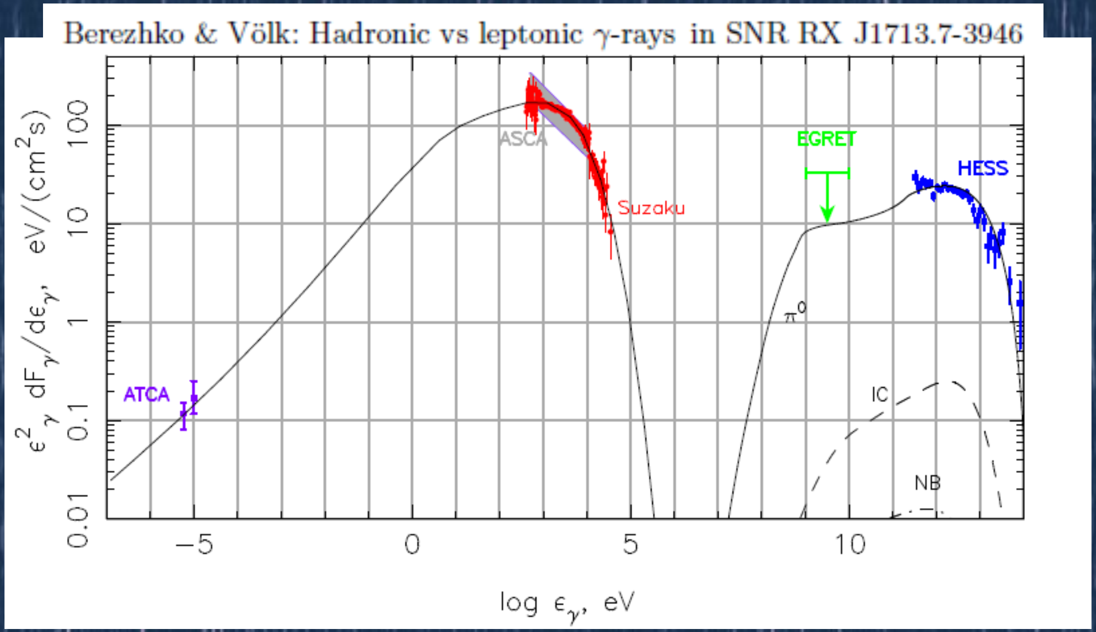
- Active galactic nuclei
  - It includes Seyferts, quasars, radio galaxies and blazars
  - Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted
  - Time-variable emission would enhance chances of detection
- Gamma-ray bursters
  - GRBs are brief 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 or NS merging
  - Neutrinos could be produced in several stages: precursor (TeV), main-burst (100 TeV-10 PeV), after-glow (EeV). The time information makes detection almost background free

RXJ1713-3946

- Data from HESS indicate that the emission of the shell-type supernova remnant RXJ1713-3946 seem to favor hadronic origin:
  - Increase of the flux in the directions of the molecular clouds
  - Unnaturally low B fields have to be assumed to avoid too high synchroton radiation B ≤ 10 μG, even interstellar fields are higher and shocks are expected to amplify fields; measurements in other SNRs indicate B ~ 100 μG)
- Spectrum up to several tens of TeV. If gammas come from π0, then protons are accelerated at E > several hundreds of TeV.
- Another interesting case: W28

HESS image of RXJ1713-3946





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

Ultra-high energy neurinos

- 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 $p\,\pi^0$)

$$\lambda_{\gamma p} = \frac{1}{n_{CMB} \cdot \sigma_{p\gamma_{CMB}}} \cong 10\ \mathrm{Mpc}\ \ @\ \mathrm{E_p} = 5\times 10^{19}\ \mathrm{eV}$$

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

$$\pi \rightarrow \mu + \nu_\mu \rightarrow e + \nu_\mu + \nu_e + \nu_\mu$$

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

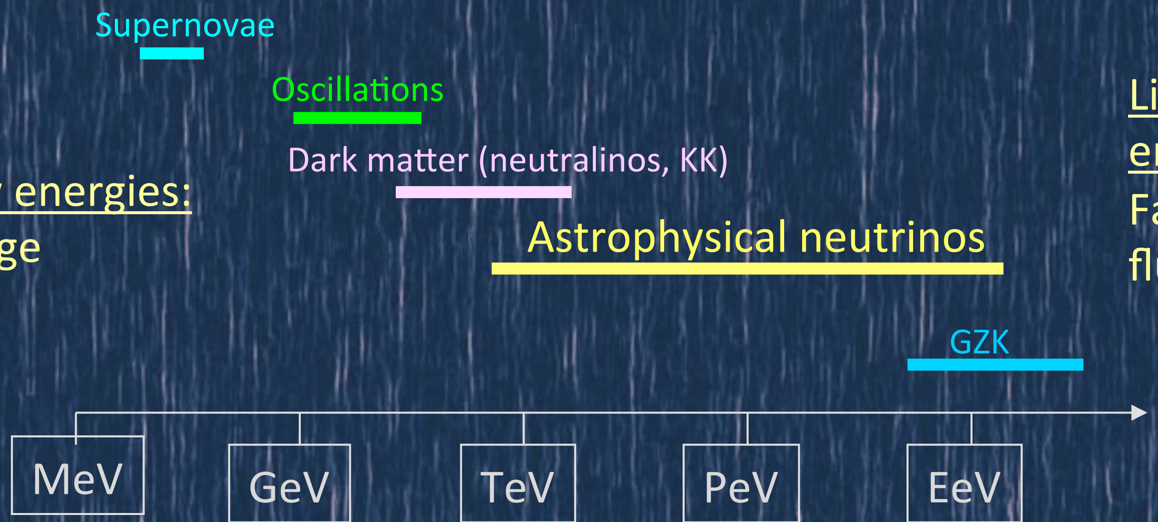
Scientific scope

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

Detector size

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

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

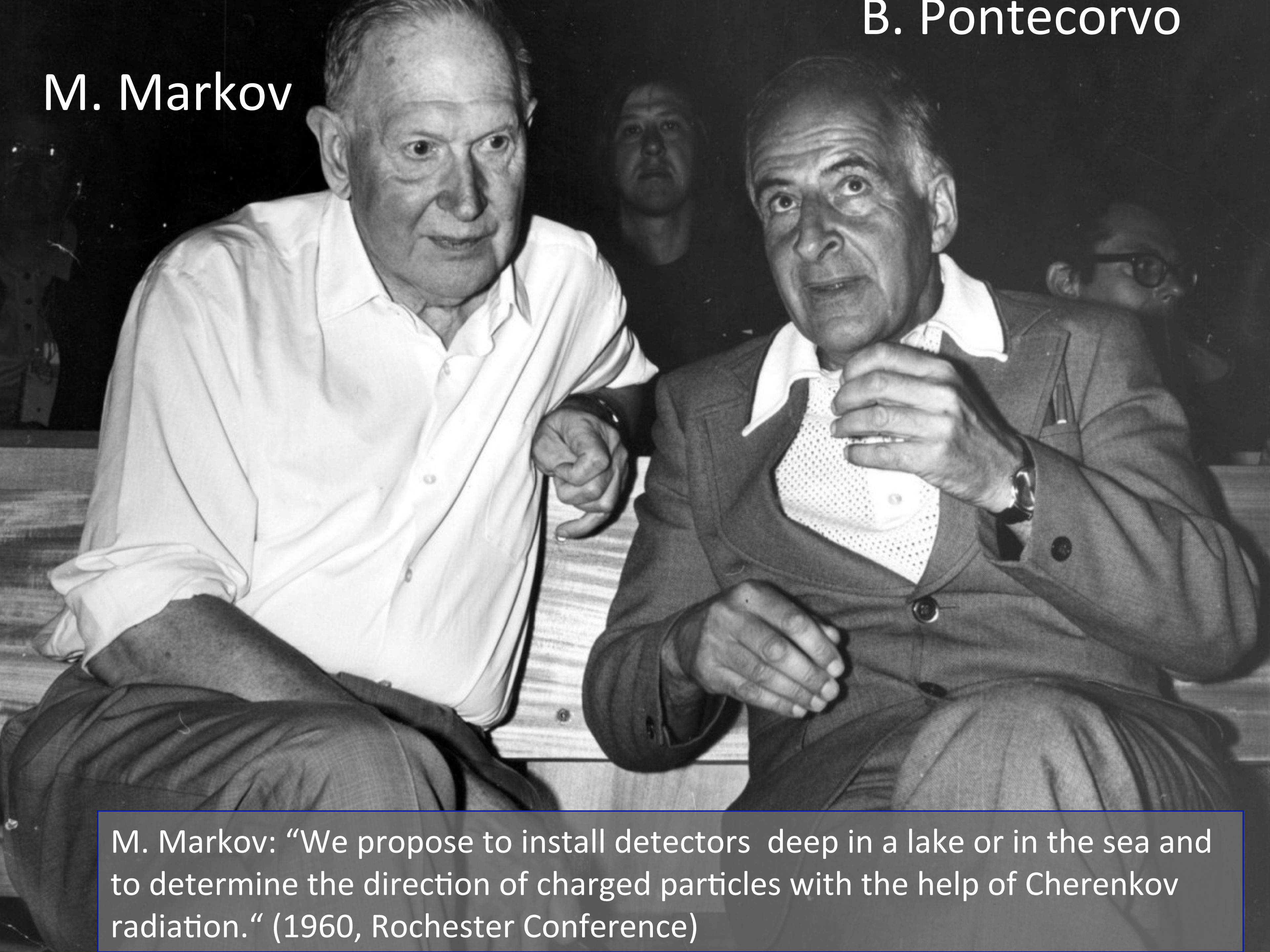


Detector density

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

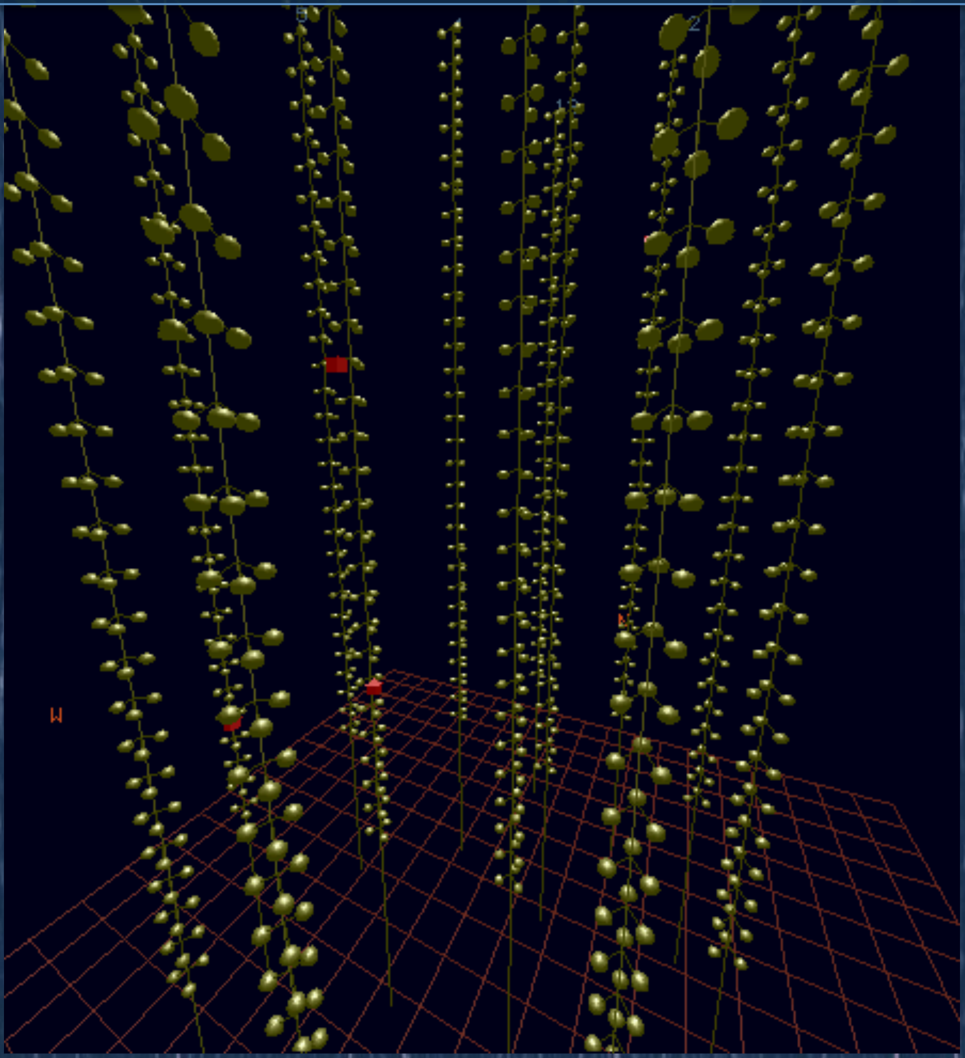
Neutrino detection techniques

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



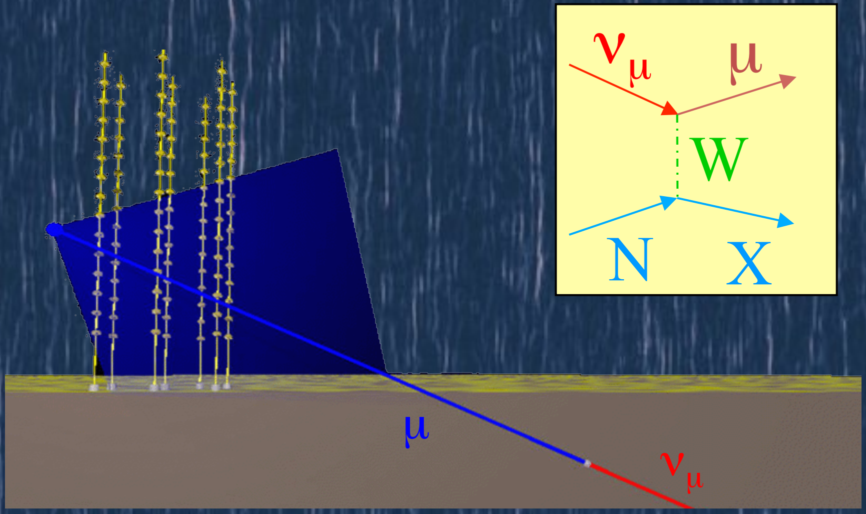
M. Markov: “We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.“ (1960, Rochester Conference)

Detection principle of NTs



1.2 TeV muon traversing ANTARES

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

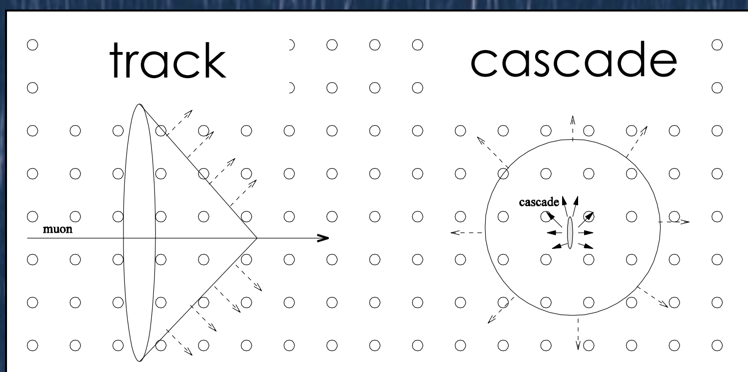


- Position and time information of hits in the PMTs allows us to reconstruct the original direction

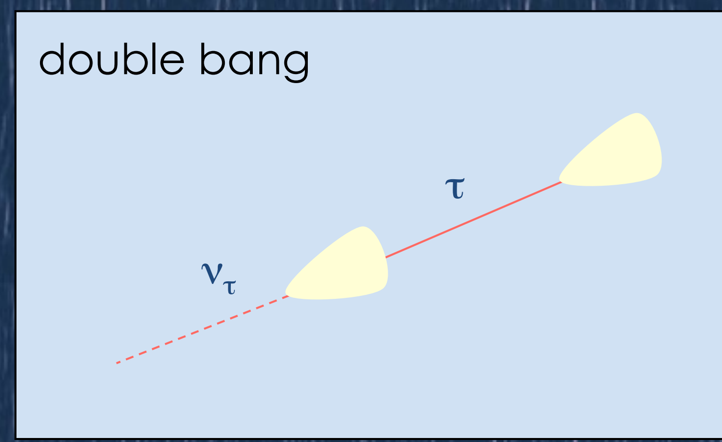
Other signatures

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

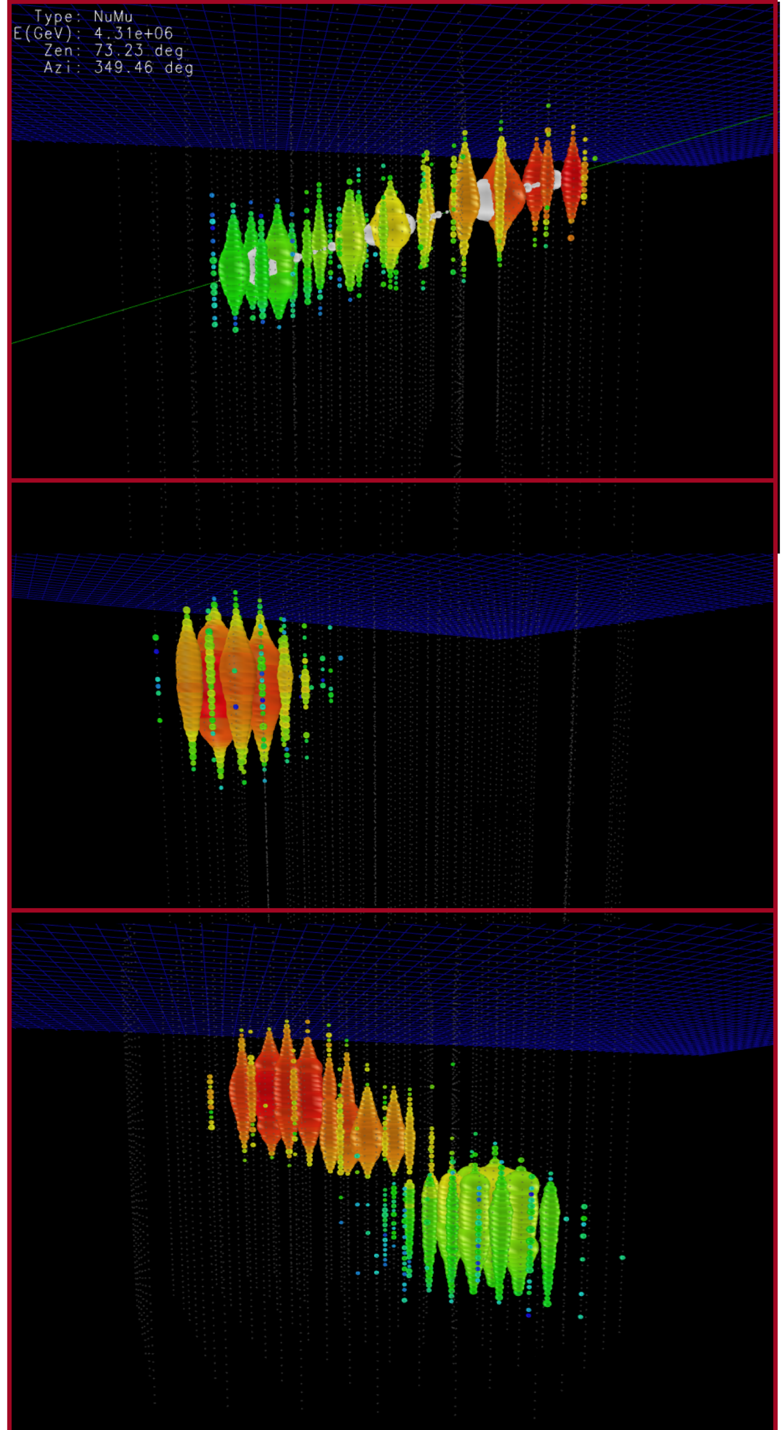
- Clear signature of oscillations.
- ANTARES & AMANDA are too small to detect double bang signature (they are too rare)
- However, cubic-kilometer telescopes could detect them.
- Maximum sensitivity at 1-10 PeV



1 km at 300 GeV	5-10 m long
25 km at 1 PeV	diameter ~ 10 cm



IceCube simulation



(a)

(b)

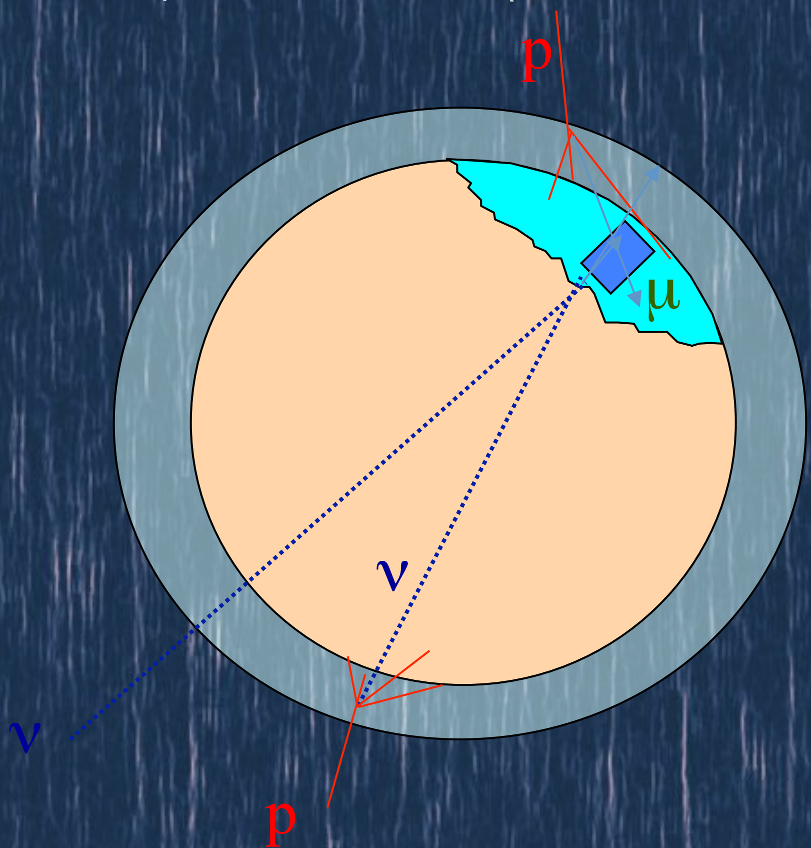
(c)

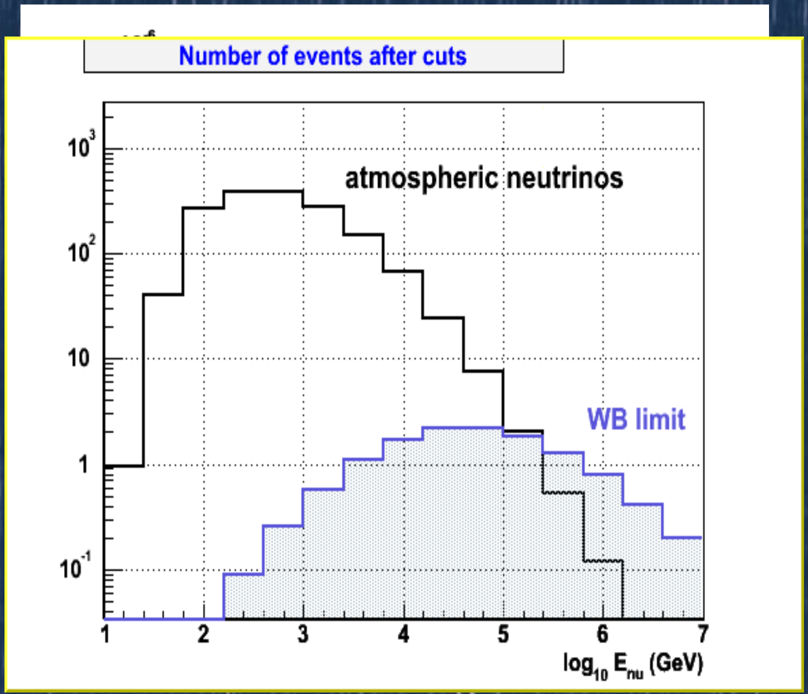
Physical background

- 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).

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

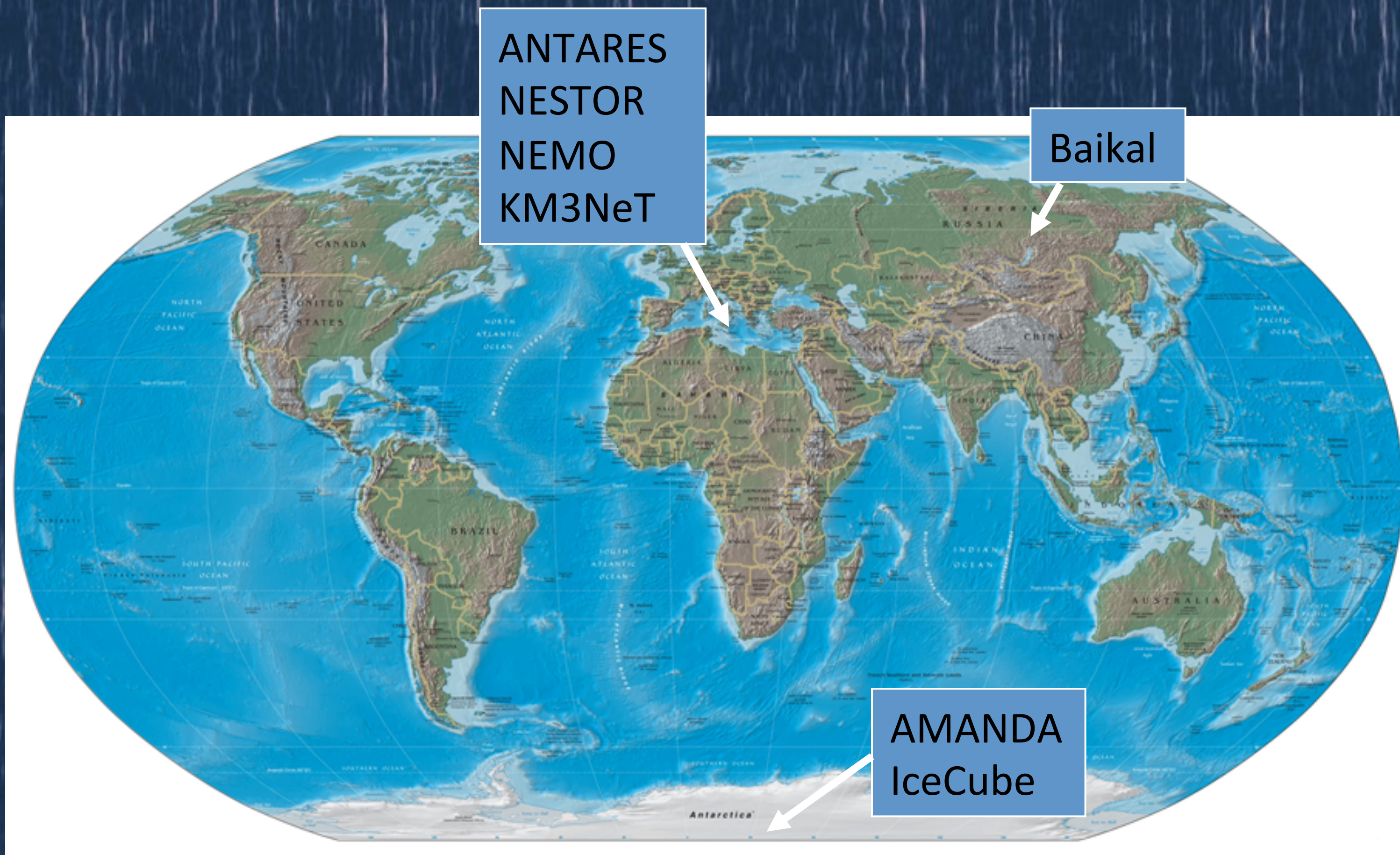
$$n \to \pi^-(+K^-\ldots) \to \mu^- + \bar{\nu}_\mu$$
$$\mapsto e^- + \nu_\mu + \bar{\nu}_e$$





NTs in the world

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

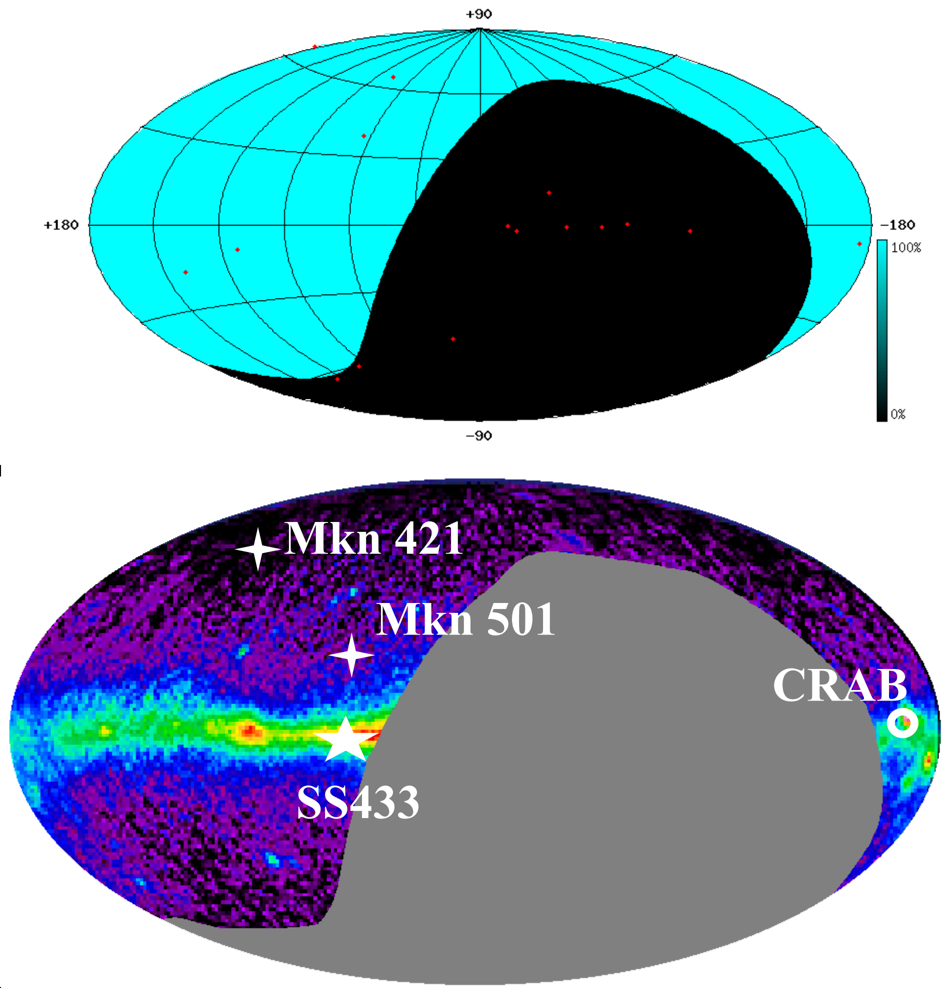


Water vs Ice

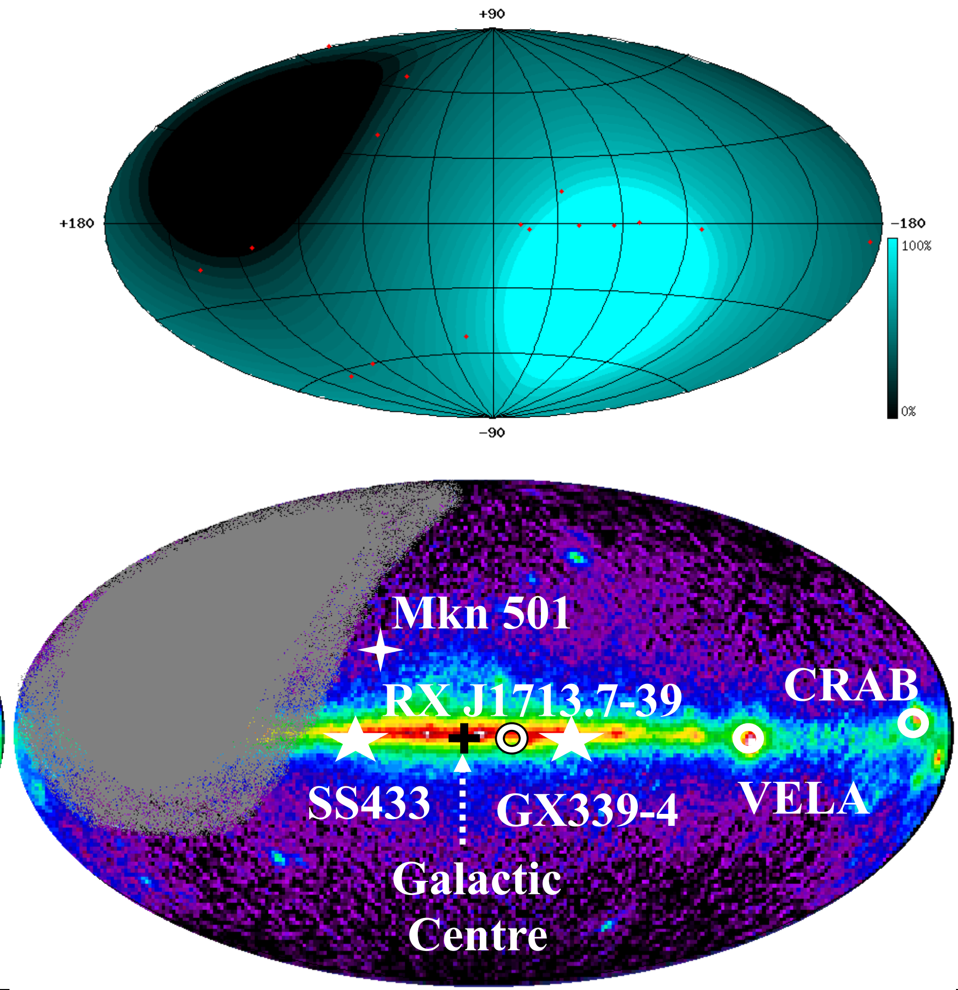
- Very large volumes of medium transparent to Cherenkov light are needed:
  - Ocean, lakes…
  - Antarctic ice
- Advantages of <u>oceans</u>:
  - Larger scattering length → better angular resolution
  - Weaker depth-dependence of optical parameters
  - Possibility of recovery
  - Changeable detector geometry
- 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 of the sky observed by NTs

AMANDA/IceCube (South Pole)
(ang. res.: ~2°/0.6°)

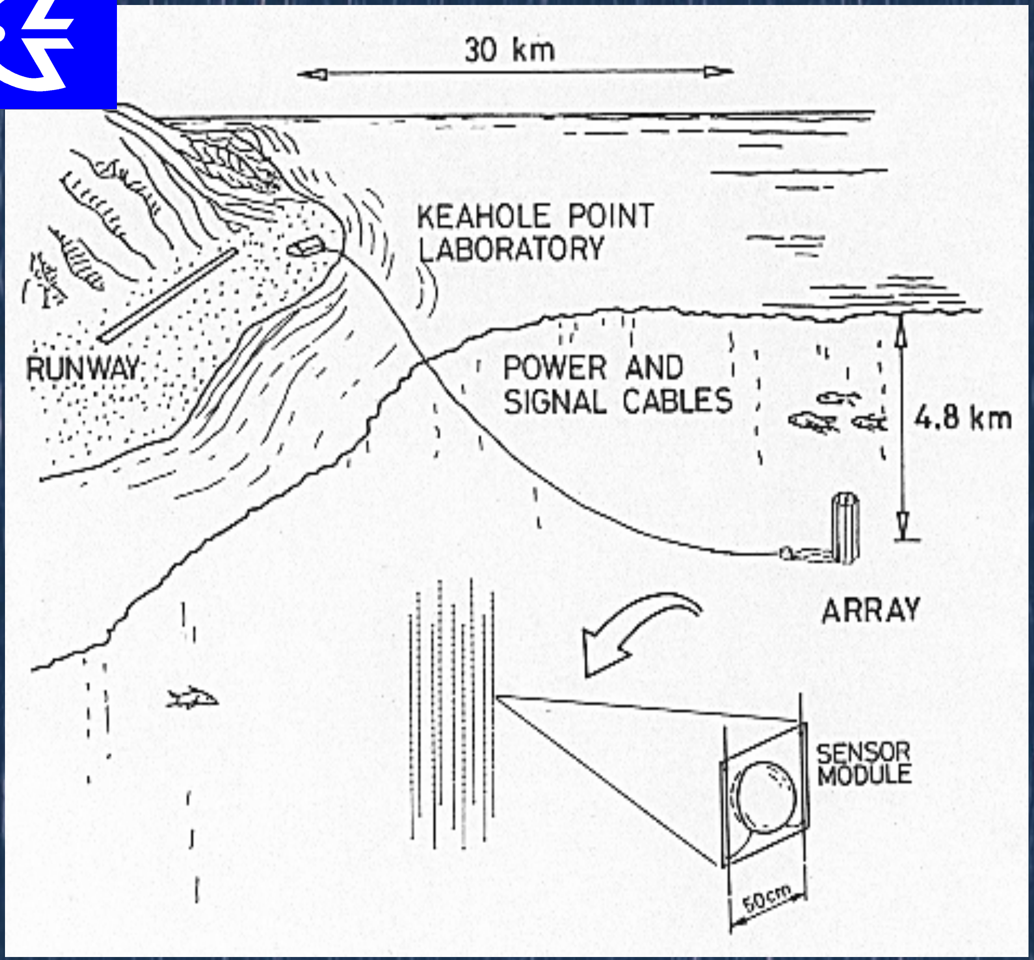


ANTARES (43° North)
(ang. res.: ~0.3°/0.1°)



Pioneers

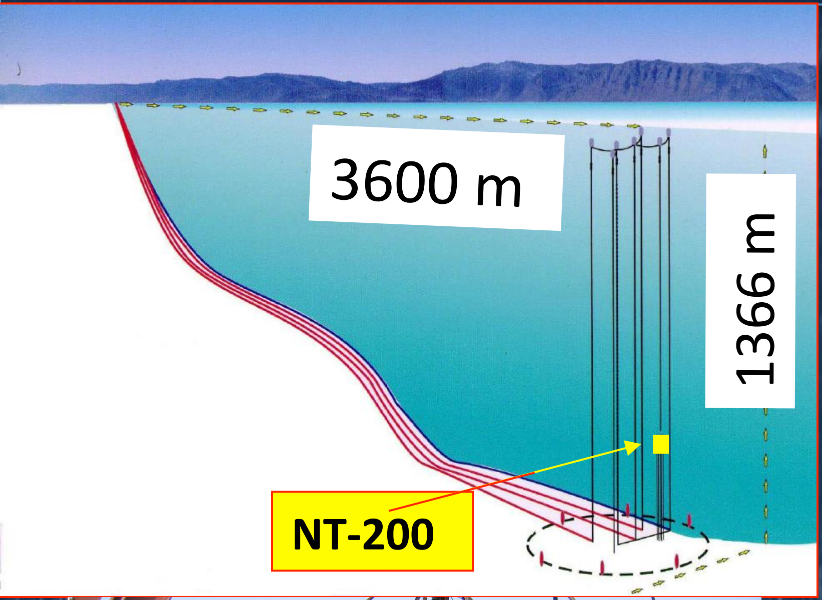
DUMAND



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

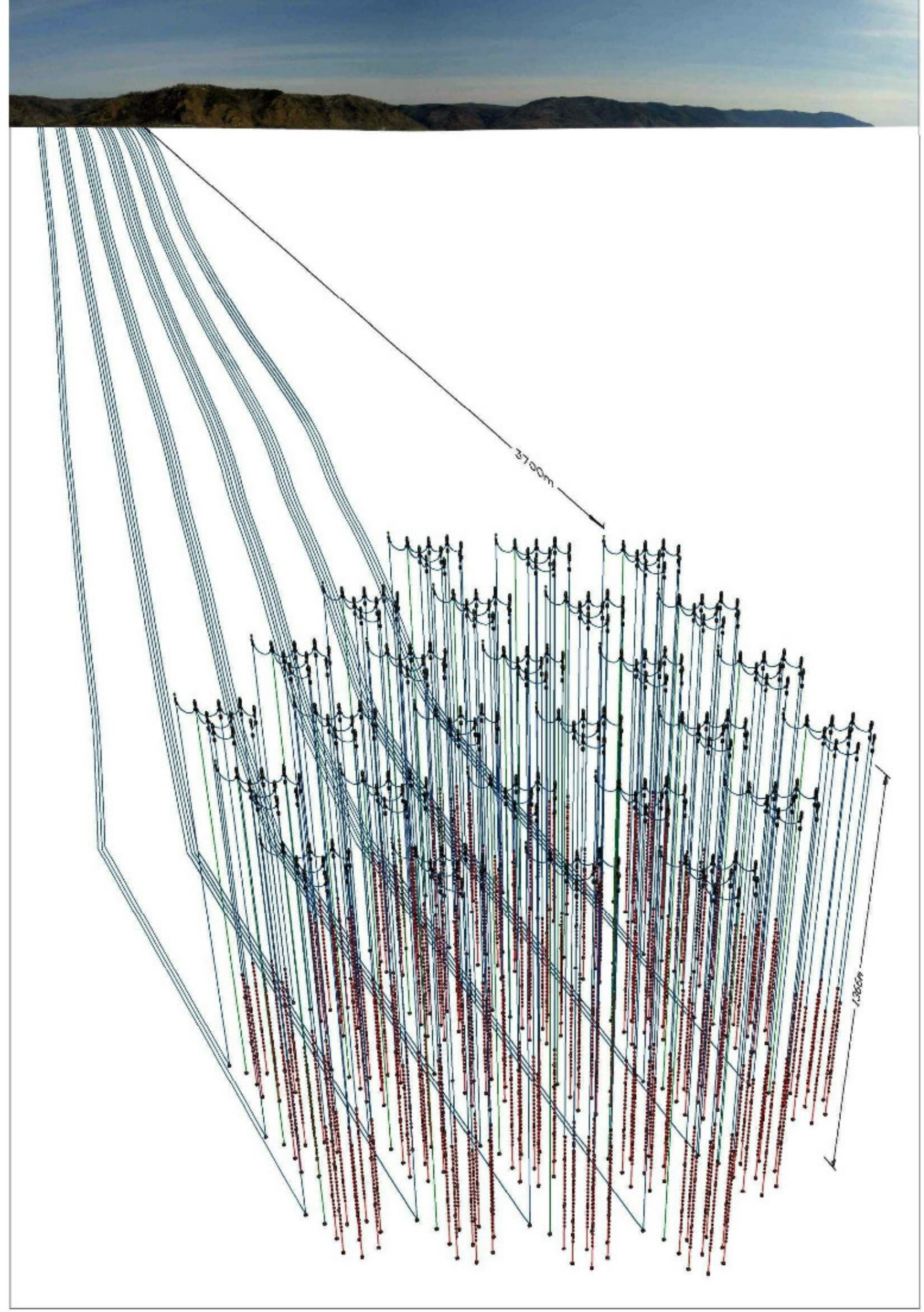
- since 1980: site studies
- 1984 first stationary string
- 1993 NT-36 started
- 1994 first atmospheric neutrino identified
- 1998 NT-200 commissioned
- 2005: NT200+ commissioned

Baikal

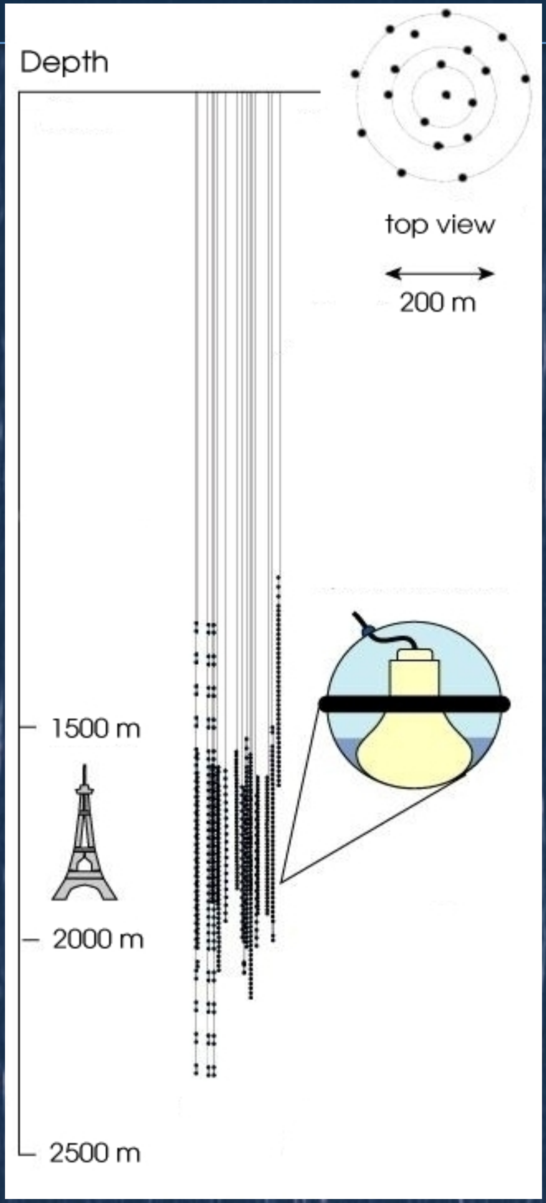
Upgrades and plans for the future:

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

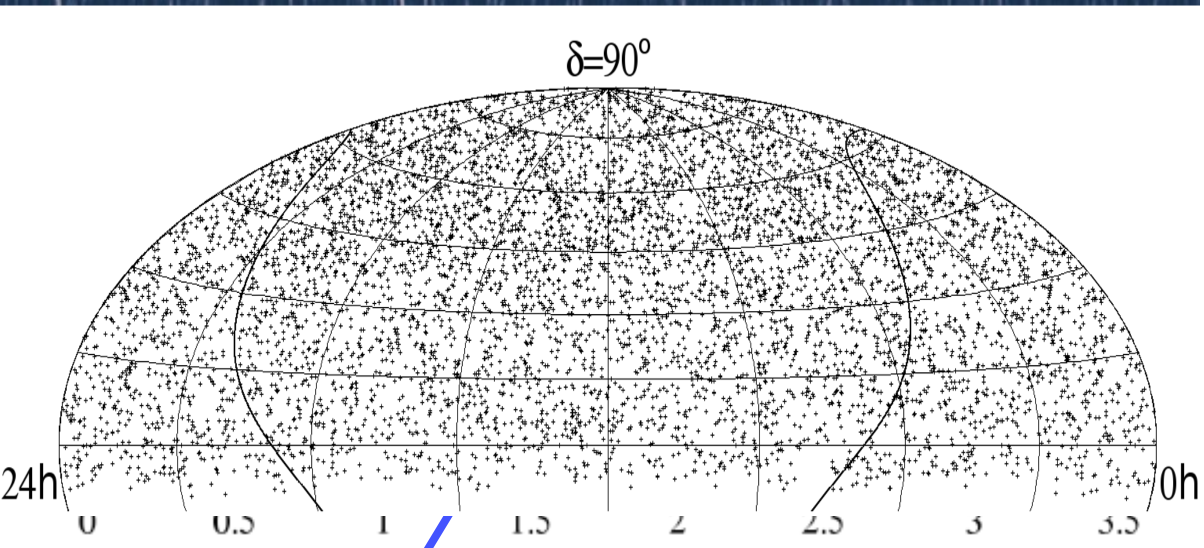
Latter merged into IceCube

- 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

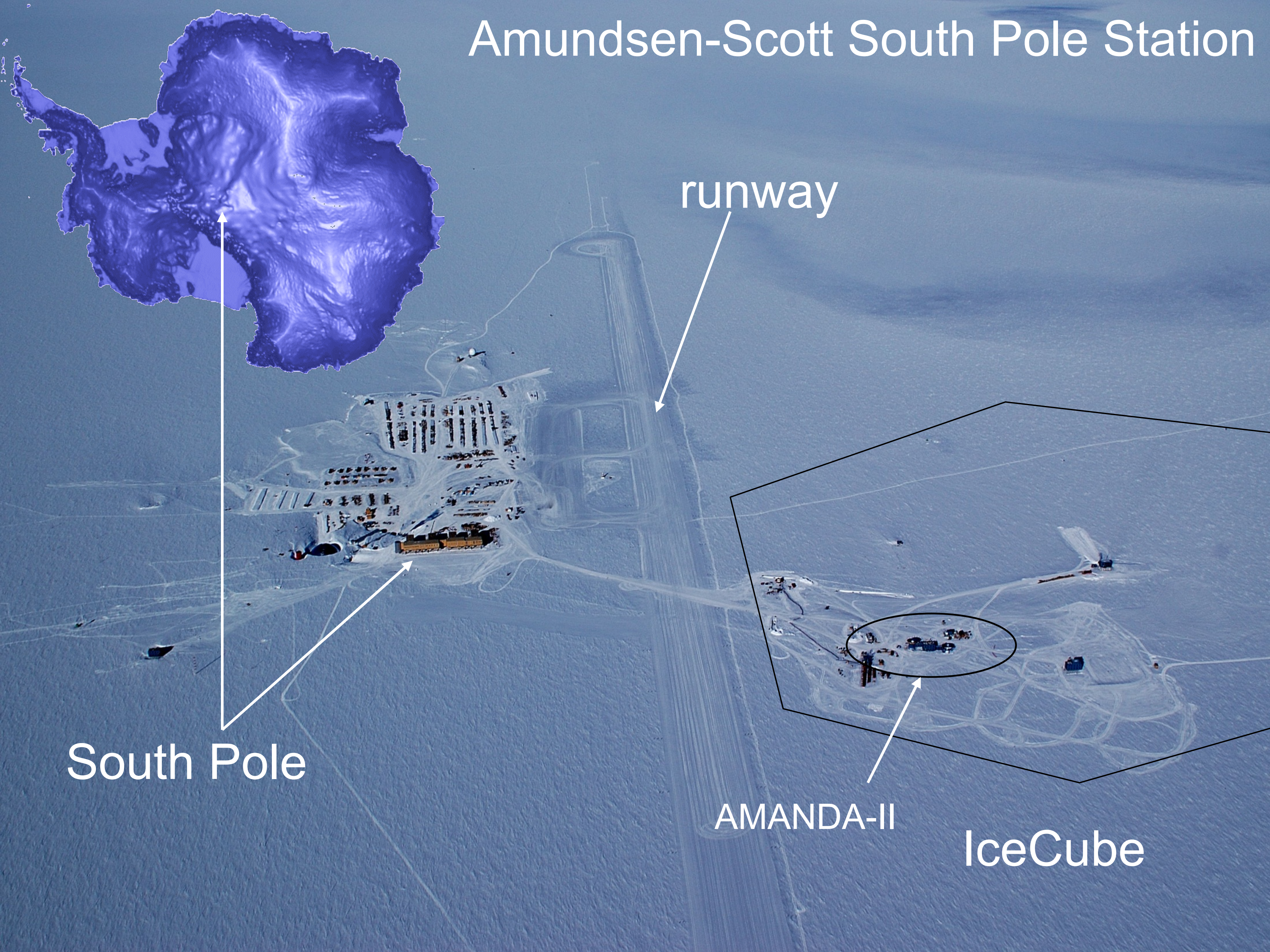


Equatorial sky map of 6595 events recorded by AMANDA II in 2000-2006

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

For 26 sources, p ≤ 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

IC86:

~ 5×10^{10} muons/year

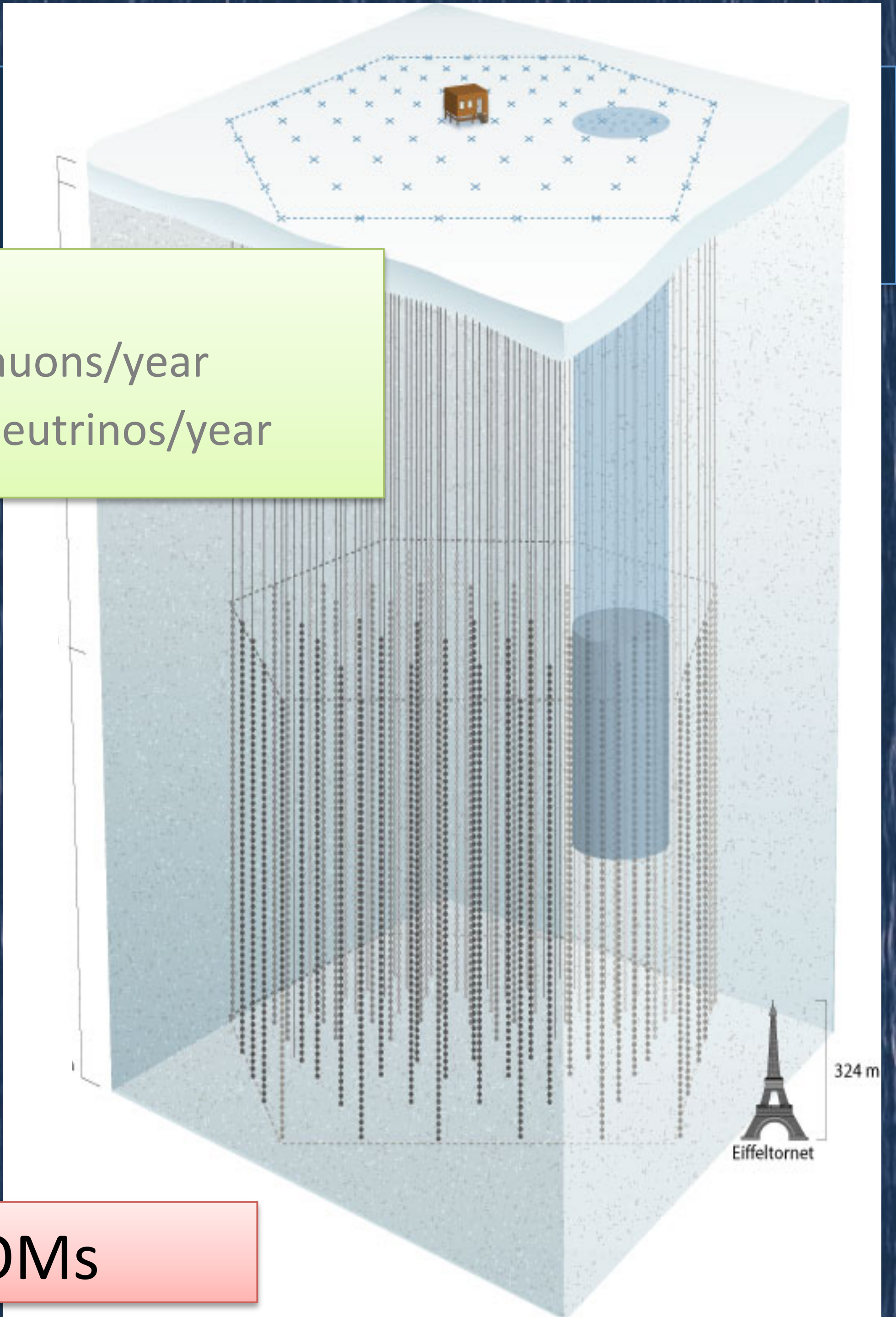
~ 20,000 neutrinos/year

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

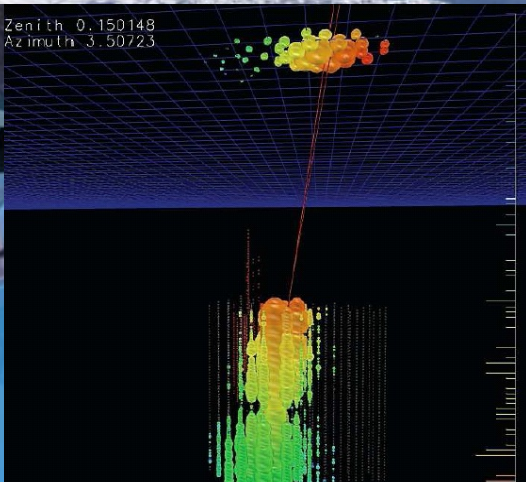


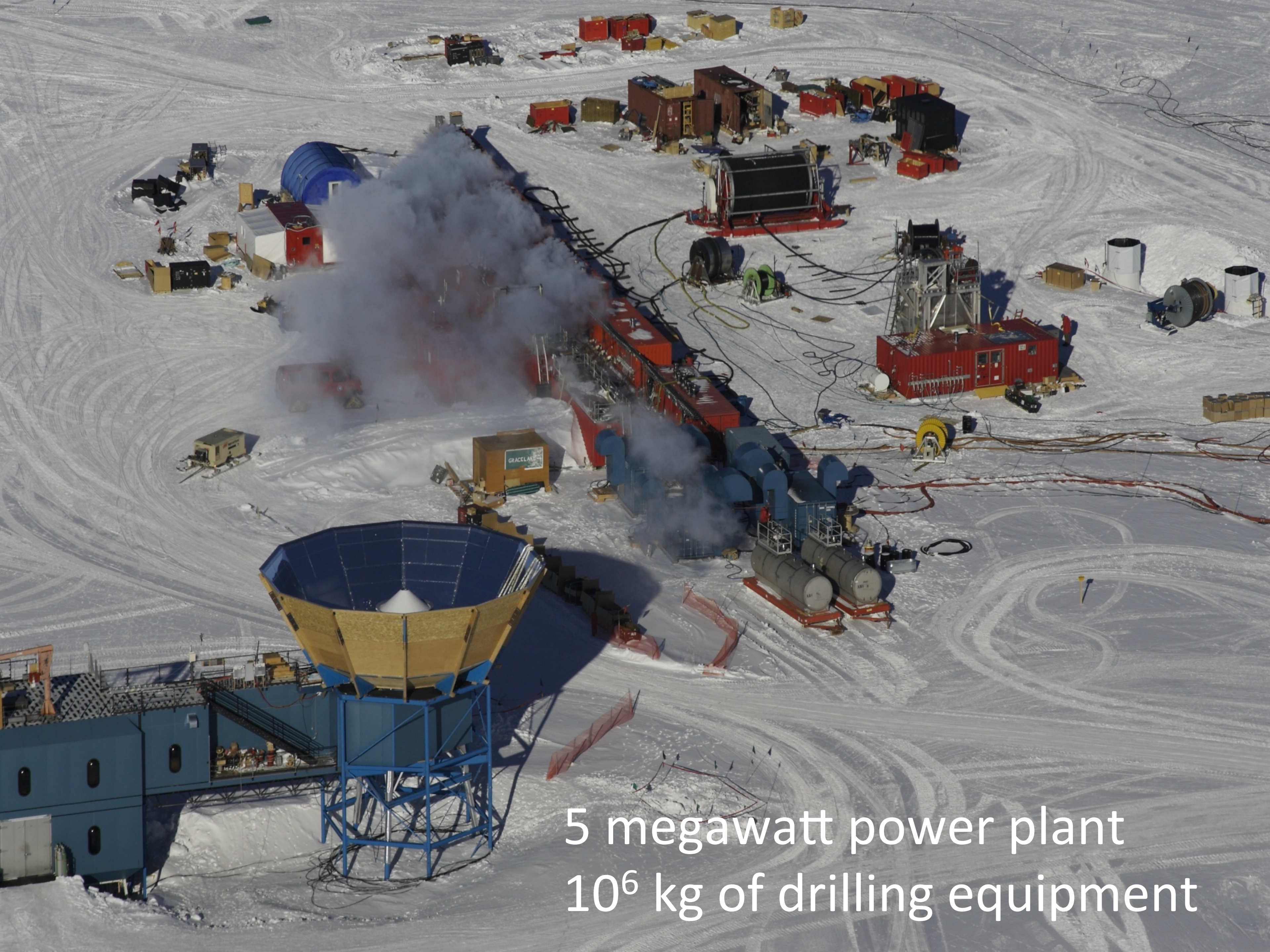
IceCube + Deep Core = 5160 OMs

IceTop

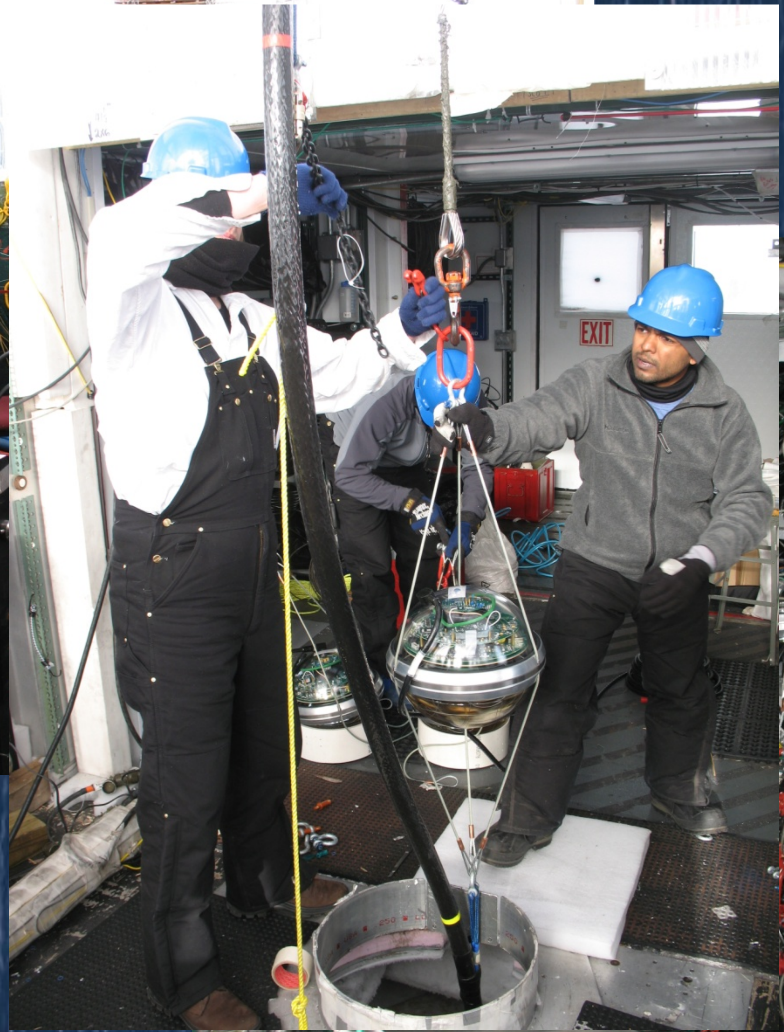
- 80 stations
  - 2 tanks per station
  - 2 DOMs per tank
- Cosmic ray studies
  - 2.8 km altitude
- Use as veto for below ice detector




5 megawatt power plant
10^6 kg of drilling equipment

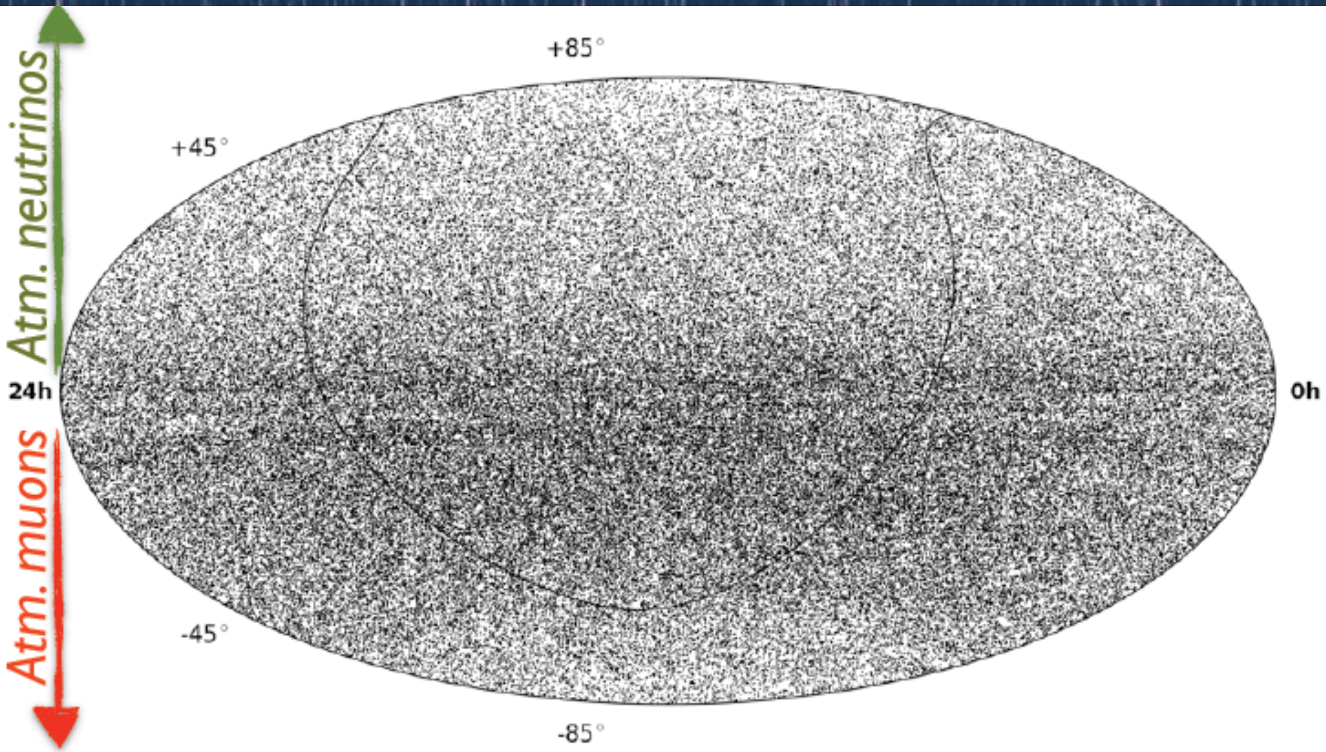
String deployment

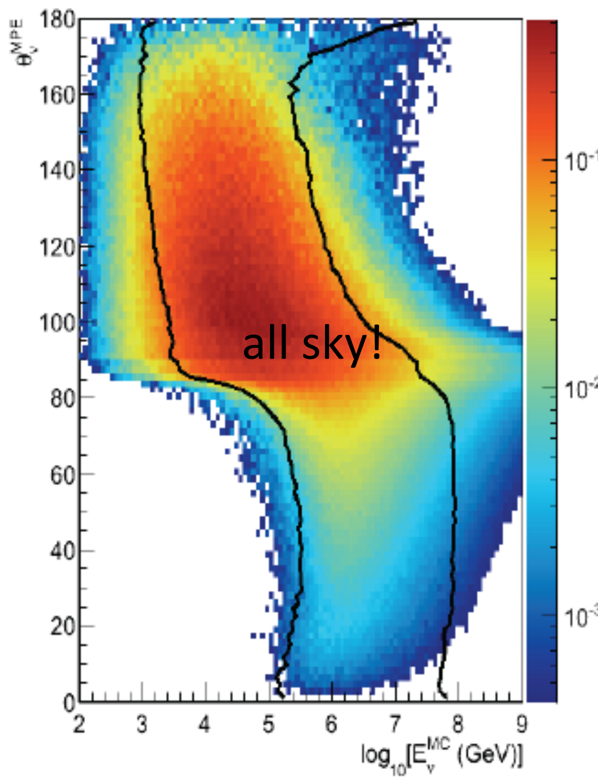


about 2 days to drill
the 2.5 km hole

Point source search

43339 upgoing + 64236 down-going from 723 days (IC40+IC59)





unbinned likelihood

No excess found

Candidate list

13 SNRs + 30 AGNs + … No significant excess… yet

Source	RA (deg)	Dec (deg)	Type	Distance	P-value
Cyg OB2	308.08	41.51	UNID	-	--
MGRO J2019+37	305.22	36.83	PWN	-	--
MGRO J1908+06	286.98	6.27	SNR	-	0.38
Cas A	350.85	58.81	SNR	3.4 kpc	--
IC443	94.18	22.53	SNR	1.5 kpc	--
Geminga	98.48	17.77	Pulsar	100 pc	--
Crab Nebula	83.63	22.01	SNR	2 kpc	--
1ES 1959+650	300.00	65.15	HBL	z = 0.048	--
1ES 2344+514	356.77	51.70	HBL	z = 0.044	--
3C66A	35.67	43.04	Blazar	z = 0.44	0.42
H 1426+428	217.14	42.67	HBL	z = 0.129	--
BL Lac	330.68	42.28	HBL	z = 0.069	0.4
Mrk 501	253.47	39.76	HBL	z = 0.034	0.19
Mrk 421	166.11	38.21	HBL	z = 0.031	--
W Comae	185.38	28.23	HBL	z = 0.1020	--
1ES 0229+200	38.20	20.29	HBL	z = 0.139	0.39
M87	187.71	12.39	BL Lac	z = 0.0042	0.38
S5 0716+71	110.47	71.34	LBL	z > 0.3	0.49
M82	148.97	69.68	Starburst	3.86 Mpc	--
3C 123.0	69.27	29.67	FRII	1038 Mpc	--
3C 454.3	343.49	16.15	FSRQ	z = 0.859	0.48
4C 38.41	248.81	38.13	FSRQ	z = 1.814	0.3
PKS 0235+164	39.66	16.62	LBL	z = 0.94	0.18
PKS 0528+134	82.73	13.53	FSRQ	z = 2.060	0.49
PKS 1502+106	226.10	10.49	FSRQ	z = 0.56/1.839	--
3C 273	187.28	2.05	FSRQ	z = 0.158	--
NGC 1275	49.95	41.51	Seyfert Galaxy	z = 0.017559	--
Cyg A	299.87	40.73	Radio-loud Galaxy	z = 0.056146	0.44
Sgr A*	266.42	-29.01	Galactic Center	8.5 kpc	0.49
PKS 0537-441	84.71	-44.09	LBL	z = 0.896	0.44
Cen A	**201.37**	**-43.02**	**FRI**	**3.8 Mpc**	**0.14**
PKS 1454-354	**224.36**	**-35.65**	**FSRQ**	**z = 1.42**	**0.14**
PKS 2155-304	329.72	-30.23	HBL	z = 0.116	--
PKS 1622-297	246.53	-29.86	FSRQ	z = 0.815	0.27
QSO 1730-130	263.26	-13.08	FSRQ	z = 0.902	--
PKS 1406-076	212.24	-7.87	FSRQ	z = 1.494	0.36
QSO 2022-077	306.42	-7.64	FSRQ	z = 1.39	--
3C279	194.05	-5.79	FSRQ	z = 0.536	0.45
TYCHO	6.36	64.18	SNR	2.4 kpc	--
Cyg X-1	299.59	35.20	MQSO	2.5 kpc	--
Cyg X-3	308.11	40.96	MQSO	9 kpc	--
LSI 303	40.13	61.23	MQSO	2 kpc	--
SS433	287.96	4.98	MQSO	1.5 kpc	0.48

GRBs

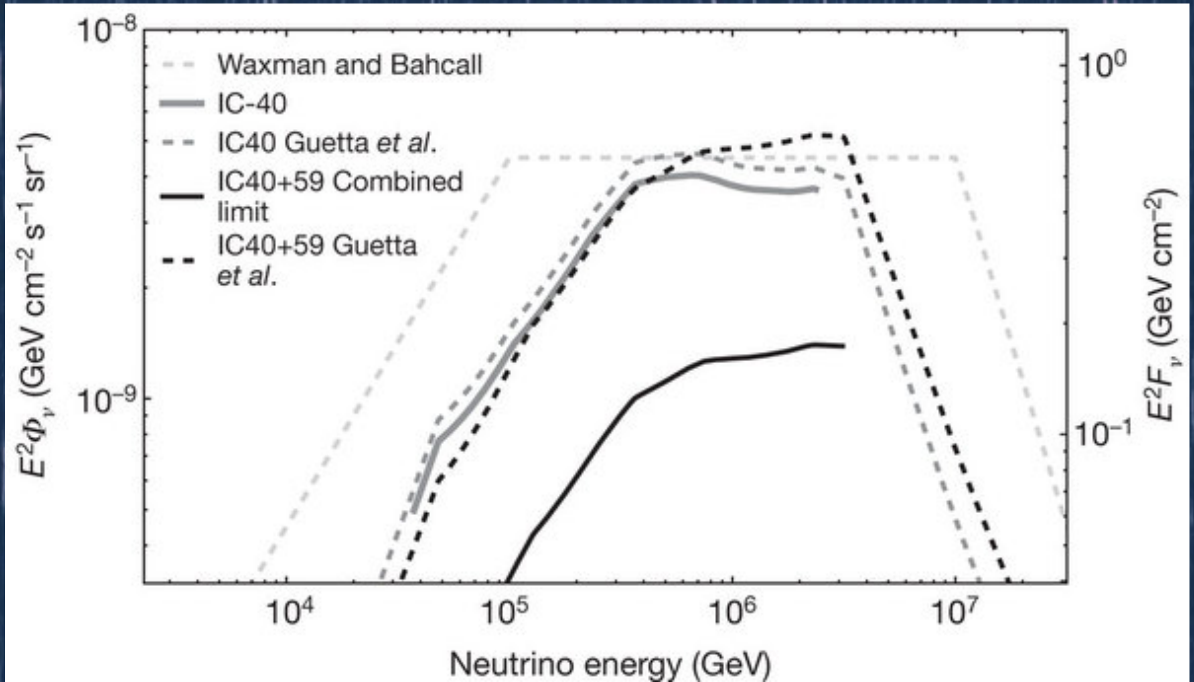
Two strategies:

-model-dependent search: during the period of gamma emission

- no event seen, 8.4 events expected

-model-independent search: wider time scales

- 2 events seen (ev1: 30s after, ev2 14h after), very likely muons from cosmic ray showers



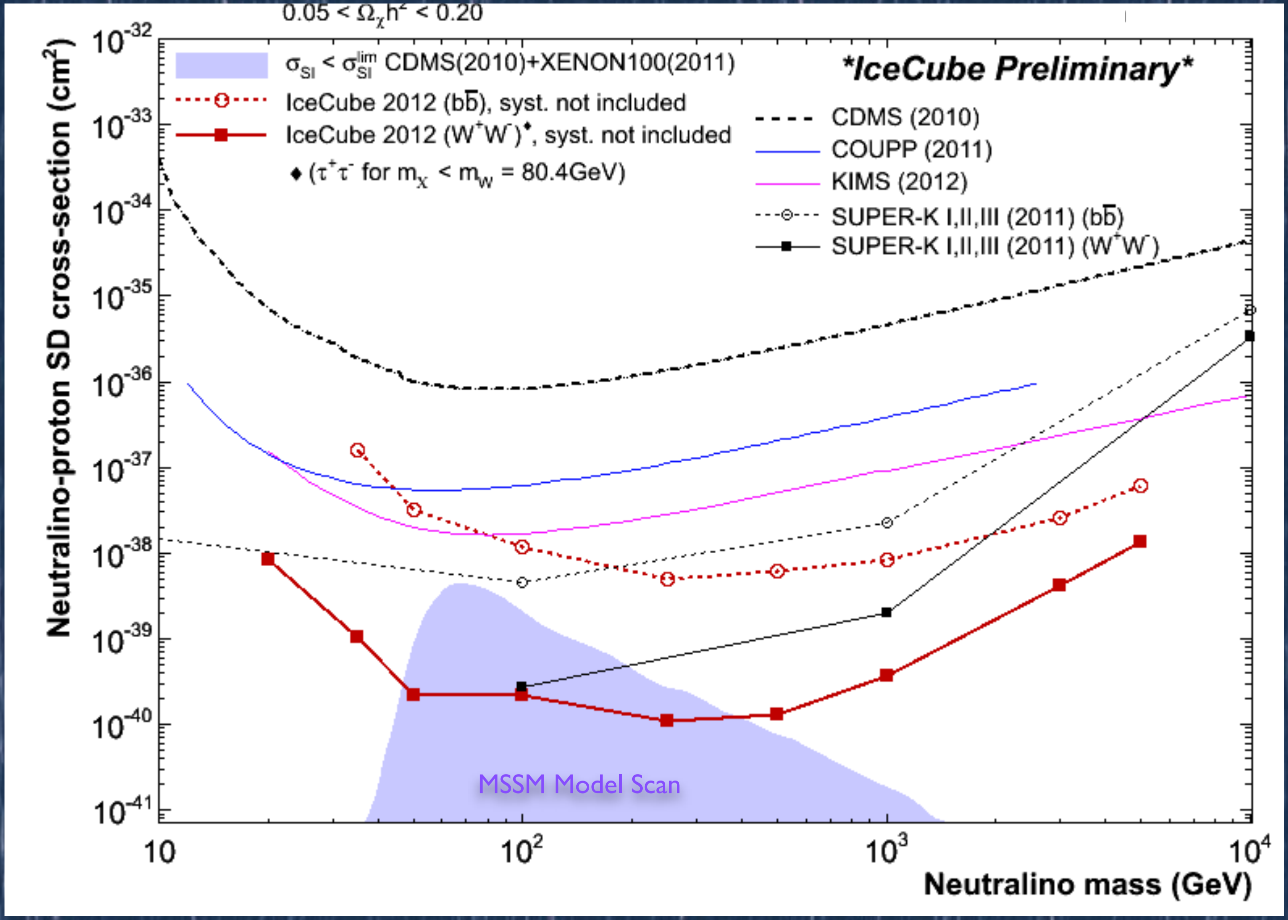
Factor 3.7 below predictions:

-proton density not enough to explain UHECR

-or physics in GRB shocks not well described by models

Dark matter

The search for dark matter in the Sun has the advantage that the signal would be very clean (the astrophysics are well known), compared with other indirect searches (which can be also interpreted as pulsars, etc.)

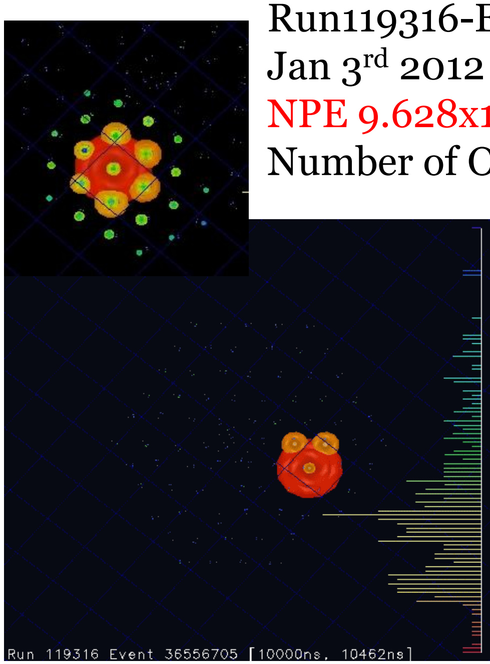


Two events passed the selection criteria

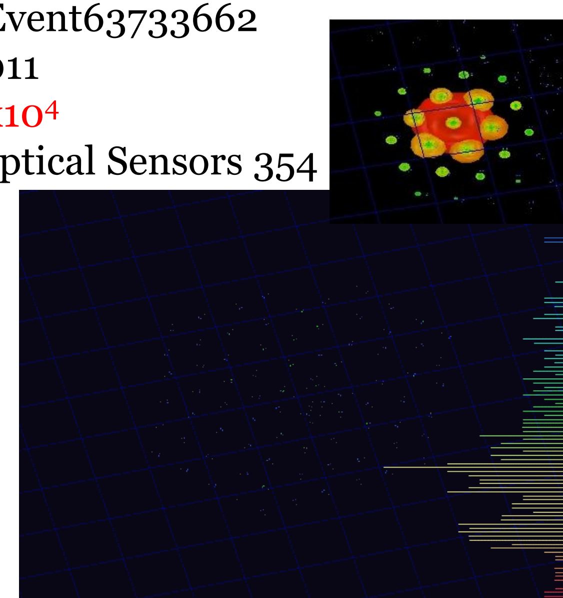
2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events

preliminary p-value: 0.0094 (2.36σ)

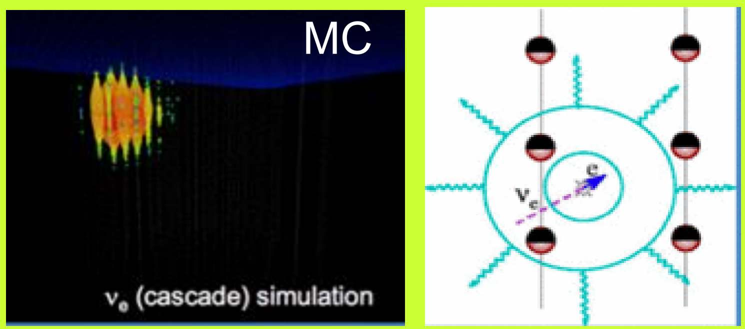
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628×10^4
Number of Optical Sensors 312

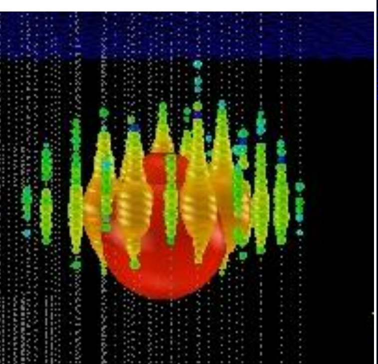


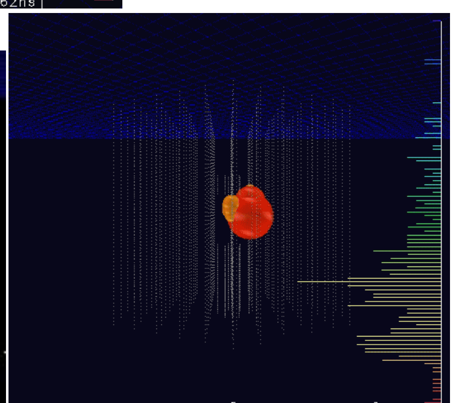
Run118545-Event63733662
August 9th 2011
NPE 6.9928×10^4
Number of Optical Sensors 354

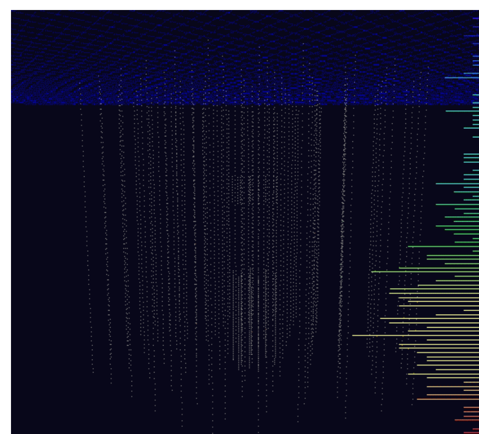


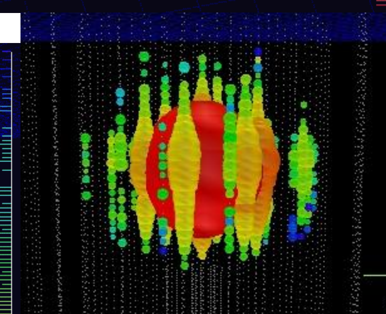
CC/NC interactions in the detector



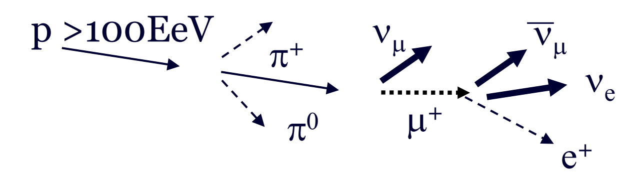


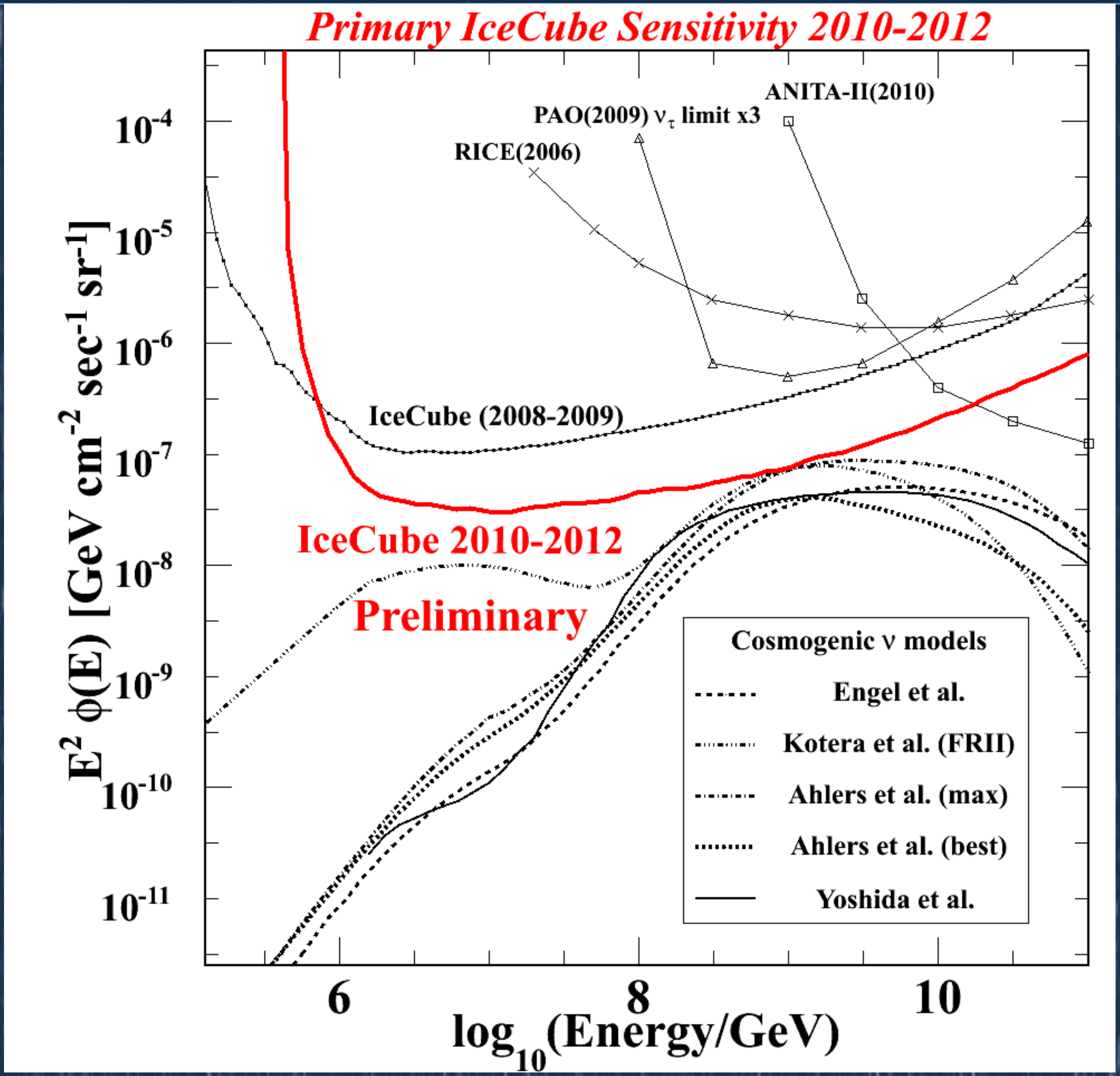






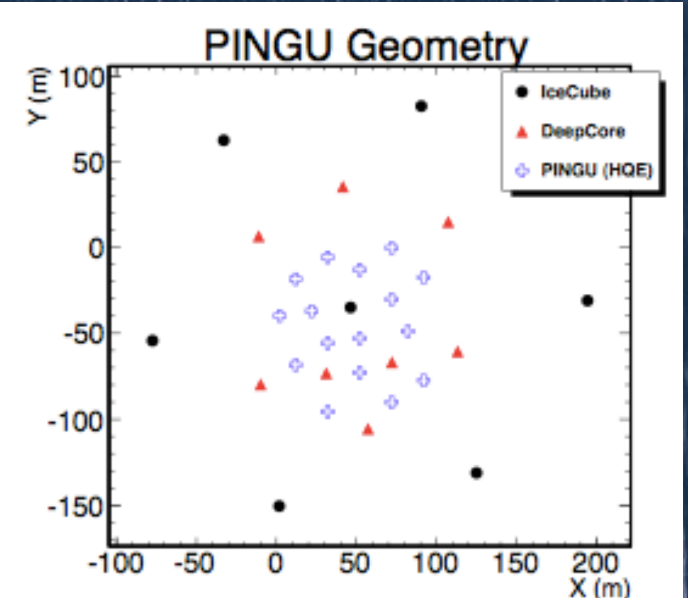
UHE neutrinos



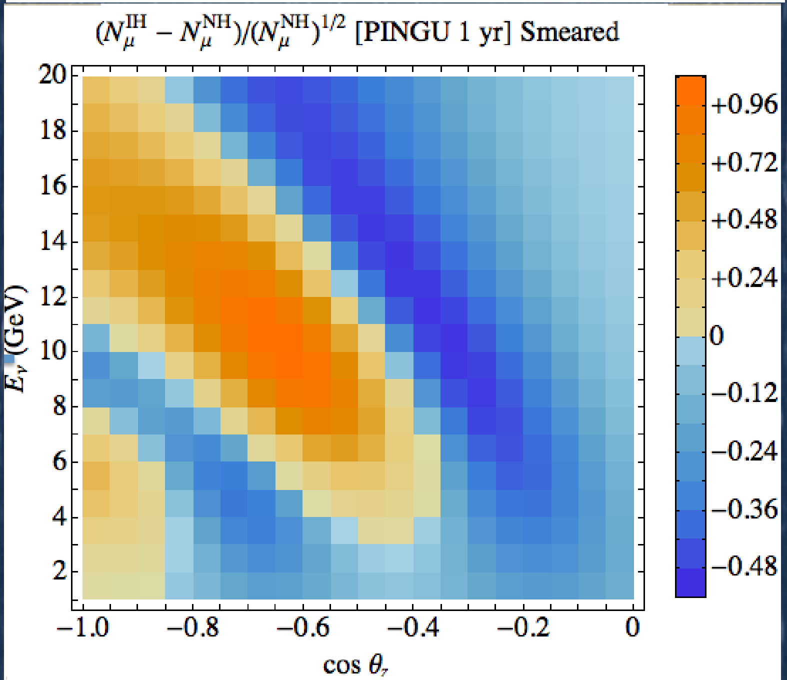


PINGU

- 20 additional strings, 50-60 Oms each (10 MT)
- Low energy frontier (E_{thres} ~ 1GeV)
- Neutrino oscillations, mass hierarchy, WIMPs…



Akhmedov et al, arXiv:1205.7071 [hep-ph]



σ_E = 2 GeV, σ_θ = 11.25°

3σ – 11σ in 5 Years of running

Includes systematic error ≤ 10%

(G. Sullivan, Neutrino 2012)

MSW effect

- Oscillation probabilities in

vacuum: $P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$

matter: $P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \, \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$

$$\Delta\tilde{m}^2 = \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},$$

$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

$$\hat{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E \, G_F \, n_e}{\Delta m^2} \Rightarrow \text{MH}$$

Resonance energy:

$$E_{\text{res}}\,[\text{GeV}] \sim 13\,200 \, \cos 2\theta \, \frac{\Delta m^2\,[\text{eV}^2]}{\rho\,[\text{g/cm}^3]}$$

Matter resonance: $\hat{A} \to \cos 2\theta$

In this case:

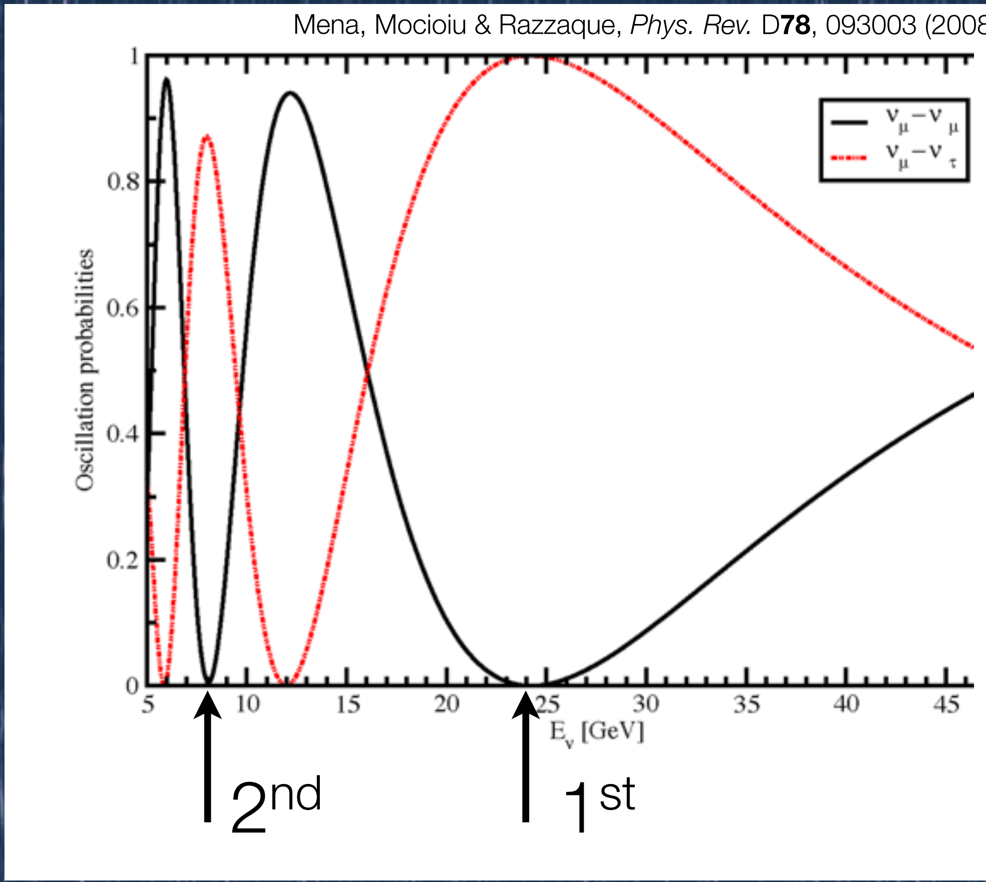
- Effective mixing maximal
- Effective osc. frequency minimal

For ν_μ appearance, Δm_{31}^2:

- ρ ~ 4.7 g/cm³ (Earth's mantle): E_{res} ~ 7 GeV
- ρ ~ 10.8 g/cm³ (Earth's outer core): E_{res} ~ 3 GeV

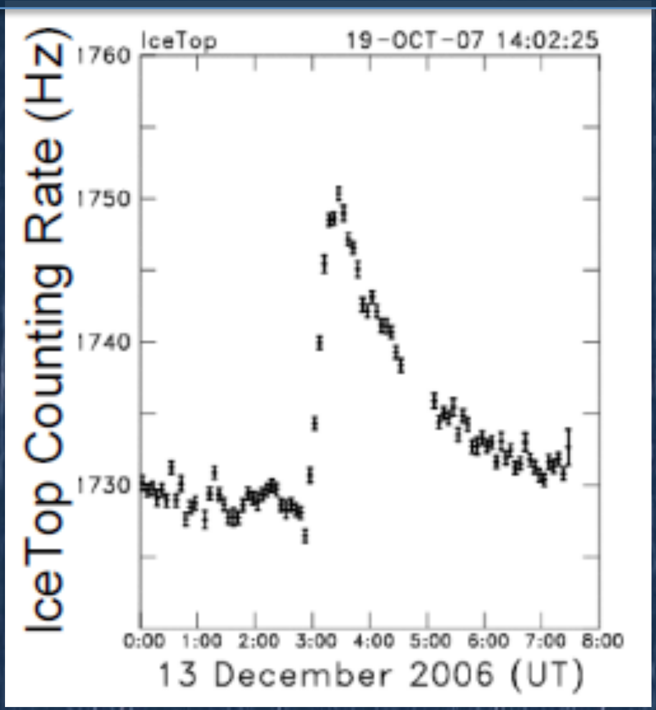
Neutrino oscillations

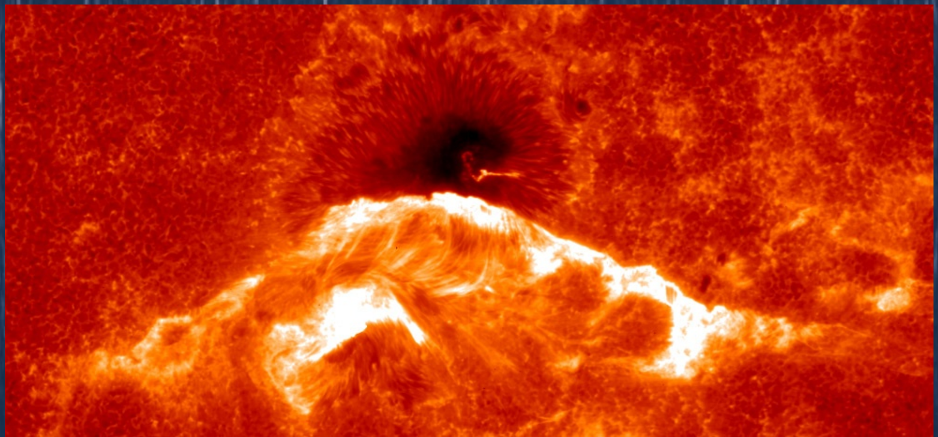
- Second oscillation minimum accessible with a ~GeV threshold



Solar physics

- IceTop tanks able to measure measure 1-10 GeV spectrum
- The giant solar flare of 13th December 2003 detected by IceTop





Other science by IceCube

- Cosmic ray physics (with IceCube + IceTop):
  - IceTop detects showers, IceCube detects the associated muons→ cosmic ray composition studies (heavier CRs produce more muons at a given energy)
  - IceCube can observe muons hundreds meters away from the shower core (high transverse-momentum interactions in the air shower)
- Neutrino oscillations
- Multi-messenger astronomy
  - Correlations with ROTSE, AGILE, MAGIC, and LIGO, ANTARES
- New technologies
  - 3 prototype digital radio strings deployed with IceCube strings
  - 4 Hydrophones deployed above IceCube
- Glaciology, South Pole atmosphere, Earth tomography?

ANTARES

The ANTARES collaboration

- NIKHEF, Amsterdam
- KVI Groningen
- NIOZ Texel

- University of Erlangen
- Bamberg Observatory

- IFIC, Valencia
- UPV, Valencia
- UPC, Barcelona

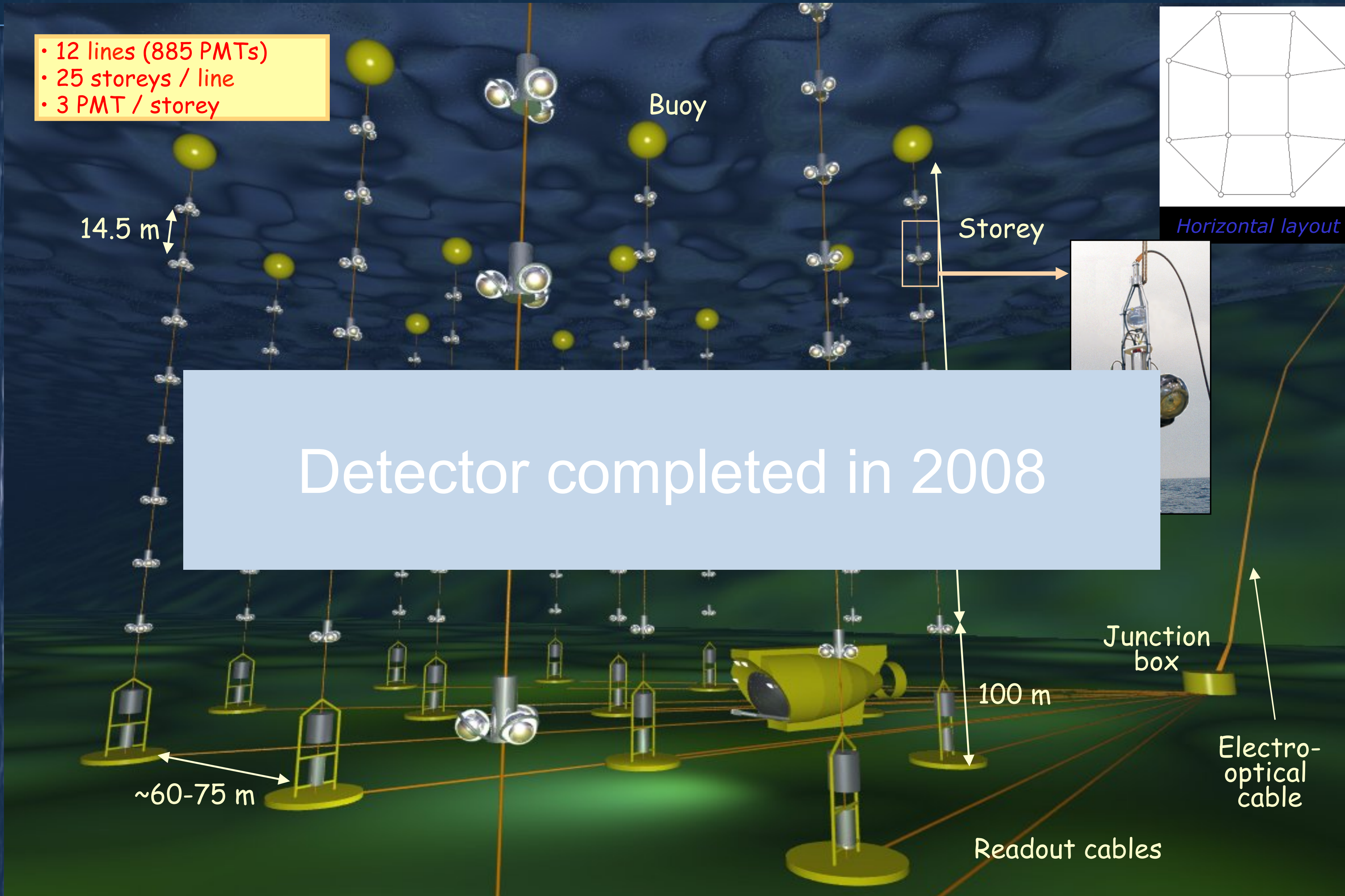
- CPPM, Marseille
- DSM/IRFU/CEA, Saclay
- APC Paris
- IPHC (IReS), Strasbourg
- Univ. de H.-A., Mulhouse
- IFREMER, Toulon/Brest
- C.O.M. Marseille
- LAM, Marseille
- GeoAzur Villefranche

- ITEP,Moscow

- ISS, Bucarest

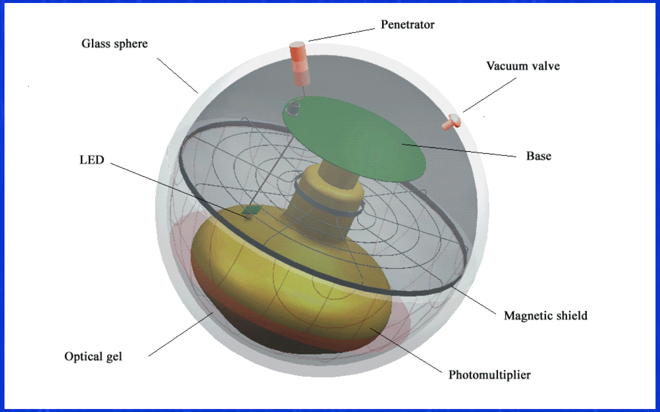
- University/INFN of Bari
- University/INFN of Bologna
- University/INFN of Catania
- LNS – Catania
- University/INFN of Pisa
- University/INFN of Rome
- University/INFN of Genova
- University/INFN of Napoli

The ANTARES detector



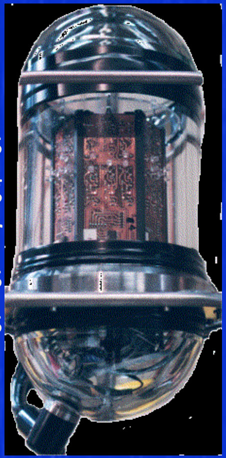
Detector completed in 2008

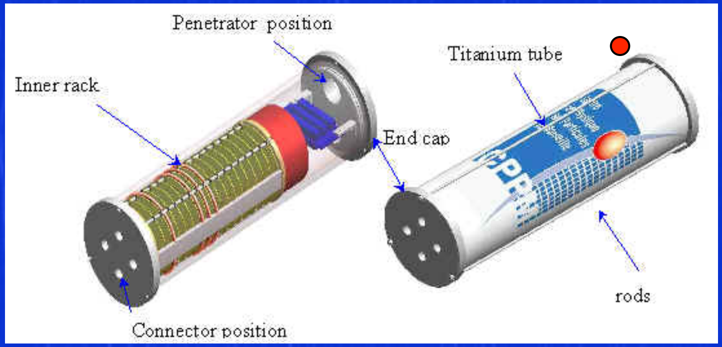
Detector elements



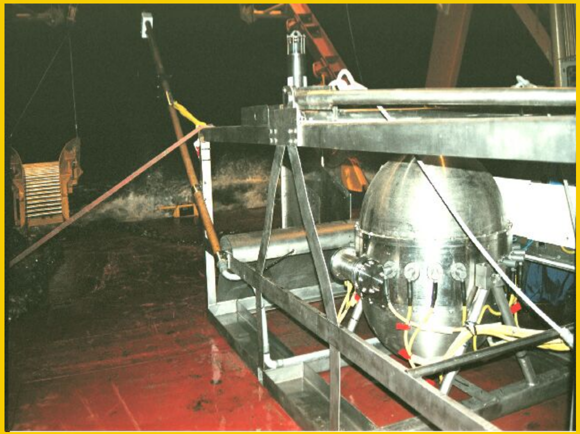
The Optical Module contains a 10” PMT and its electronics

The Optical Beacons allows timing calibration and water properties measurements

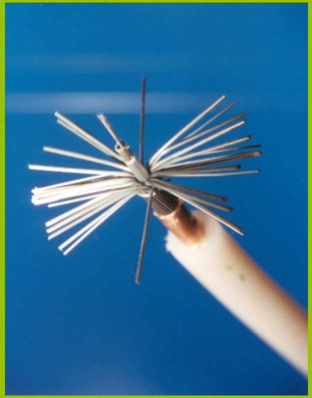




The Local Control Module contains electronics for signal processing

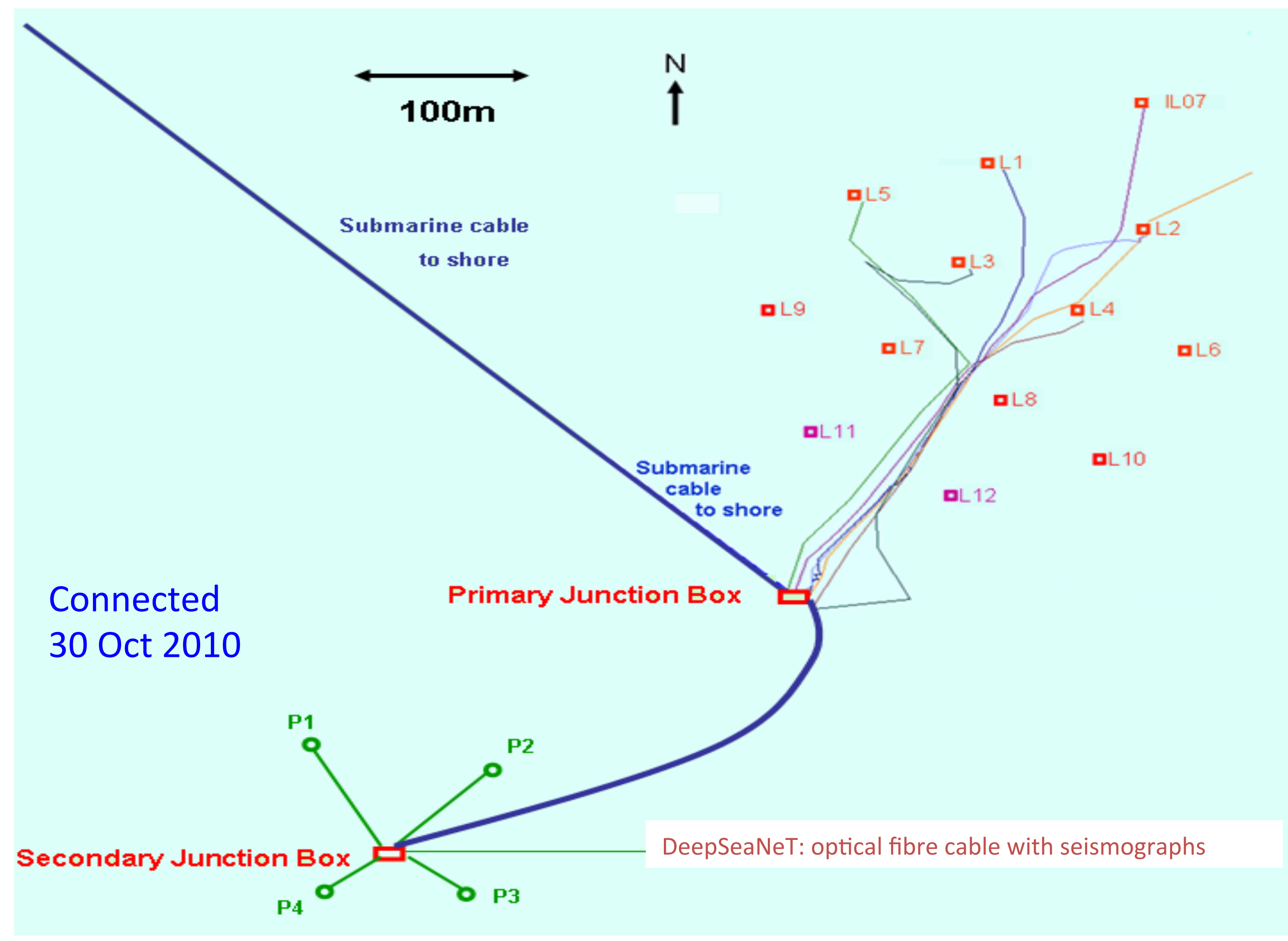


It receives power from shore station and distributes it to the lines. Data and control signals are also transmitted via the JB.



It provides power and data link between the shore station and the detector (40 km long)

ANTARES infrastructure



Milestones

2001 – 2003:

- *Main Electro-optical cable* in 2001
- *Junction Box* in 2002
- *Prototype Sector Line (PSL)* &
  Mini Instrumentation Line (MIL) in 2003

2005 – 2006:

- *Mini Instrumentation Line with OMs (MILOM)* running since April 2005
- *Line 1* running since March 2006,
  first complete detector line
- *Line 2* running since September 2006

First Physics analysis
started with first line

2007 – 2008:

- *Line 3-5* running since Jan 2007
- *Line 6-10+IL07* since Dec 2007
- *Line 11-12* since May 2008

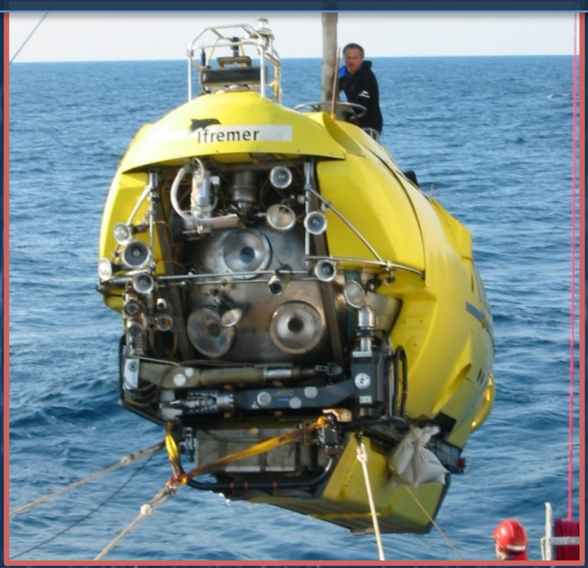
2008+: Physics with full detector !

Livetime of lines

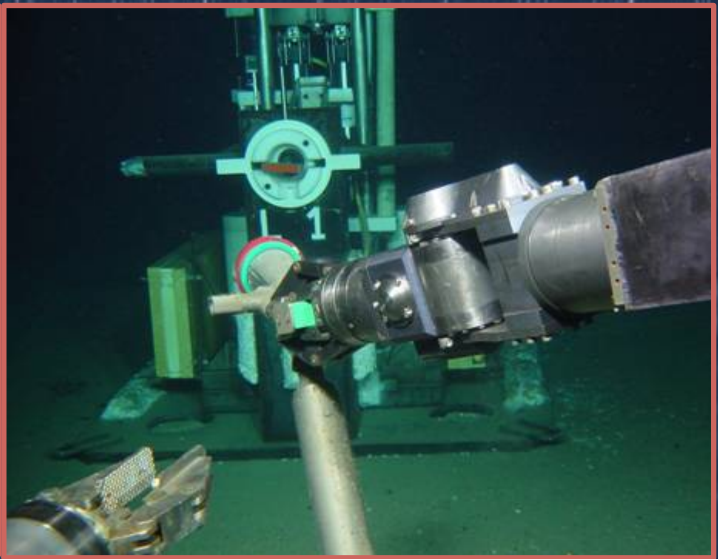
Deployment

Connection

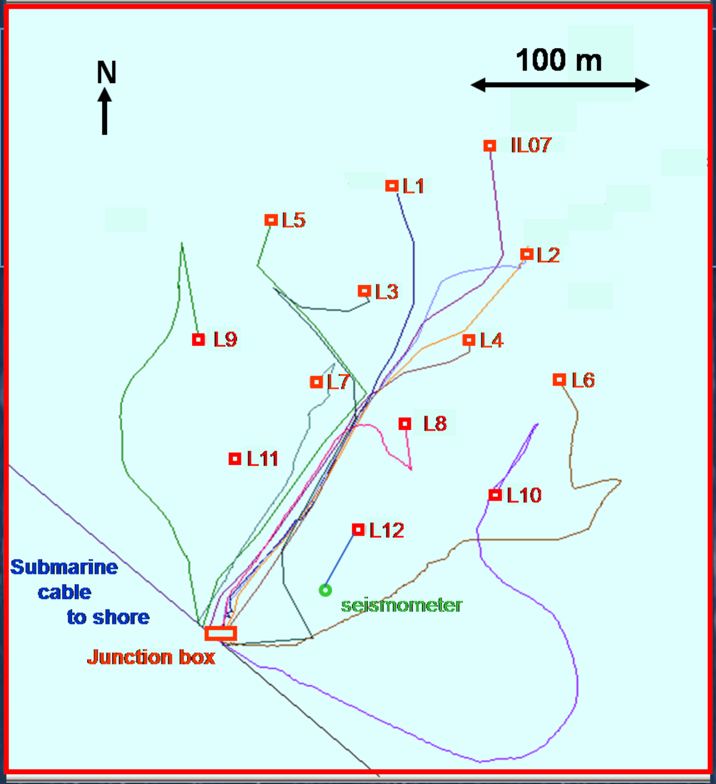
Nautile (manned)

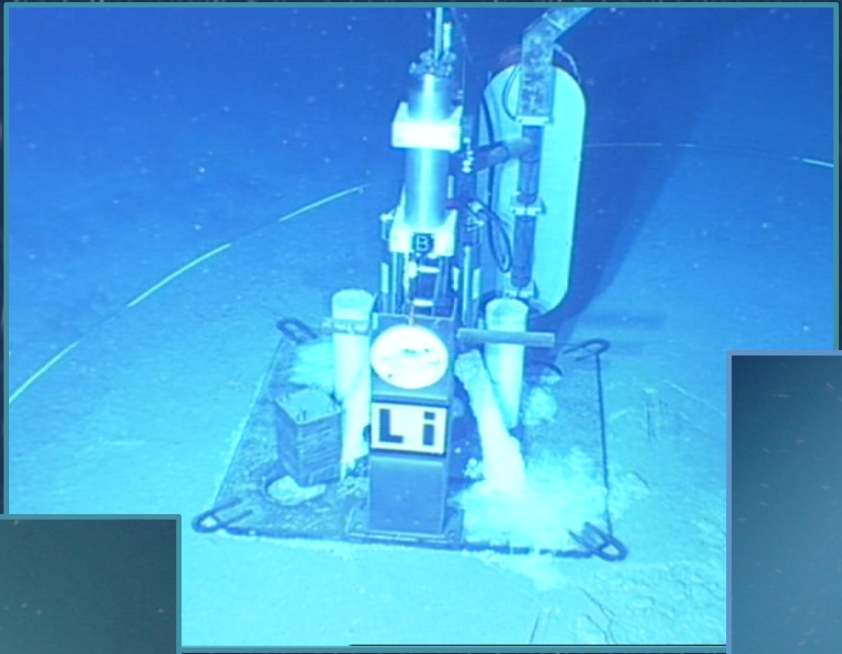


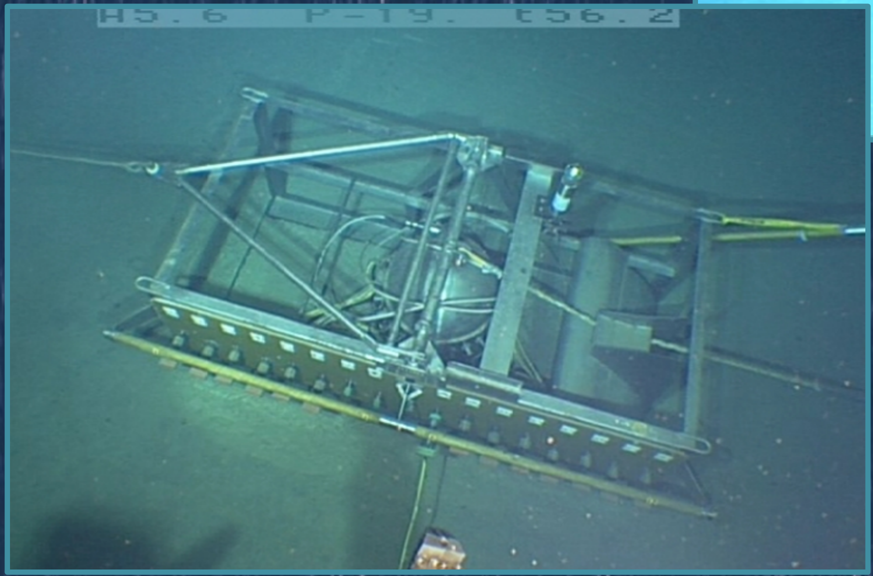
Victor (ROV)

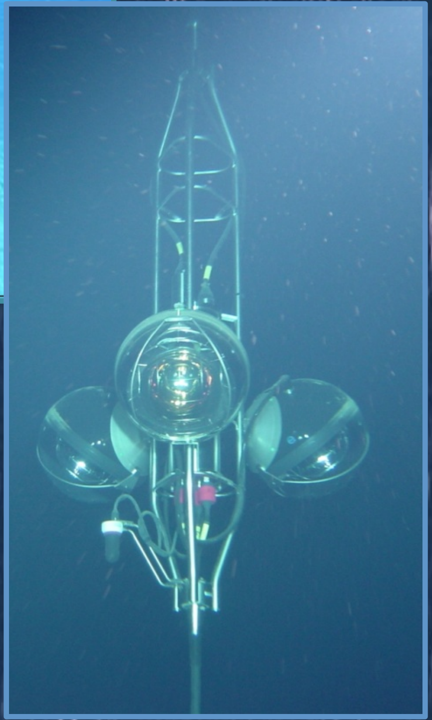


Pictures from seabed

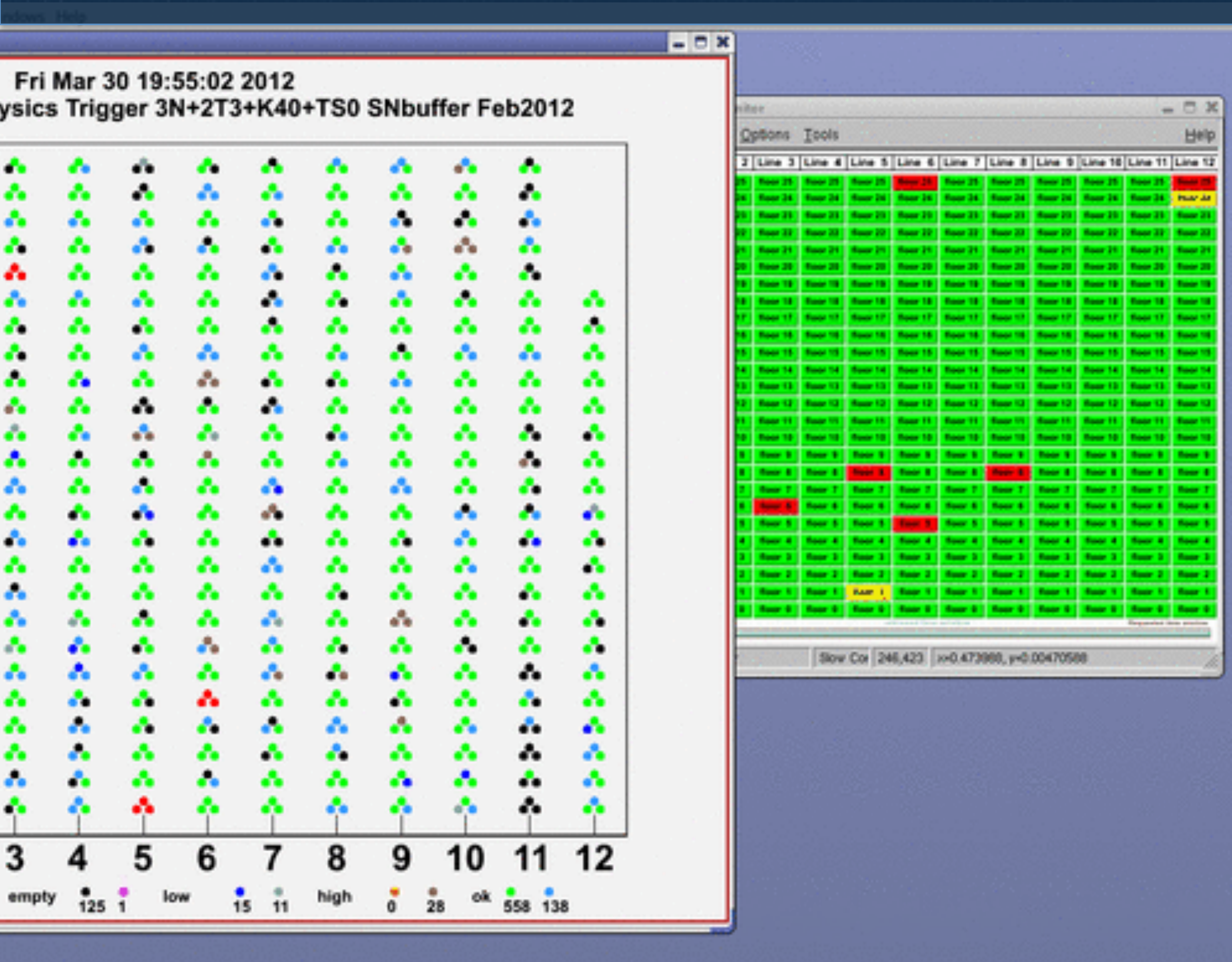




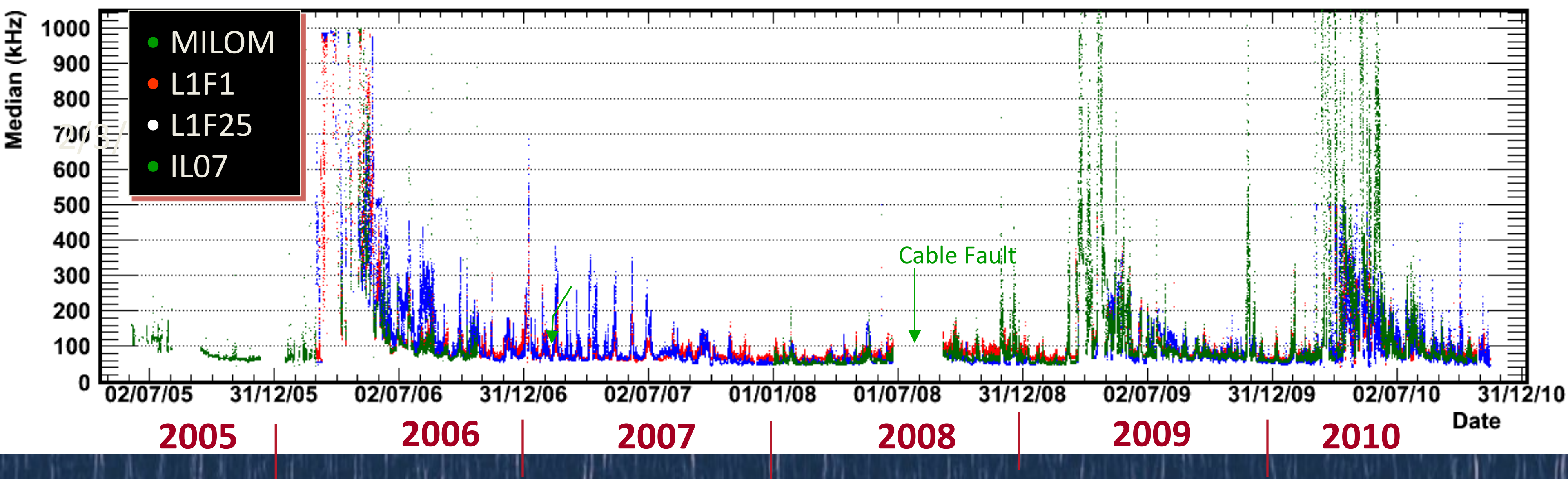




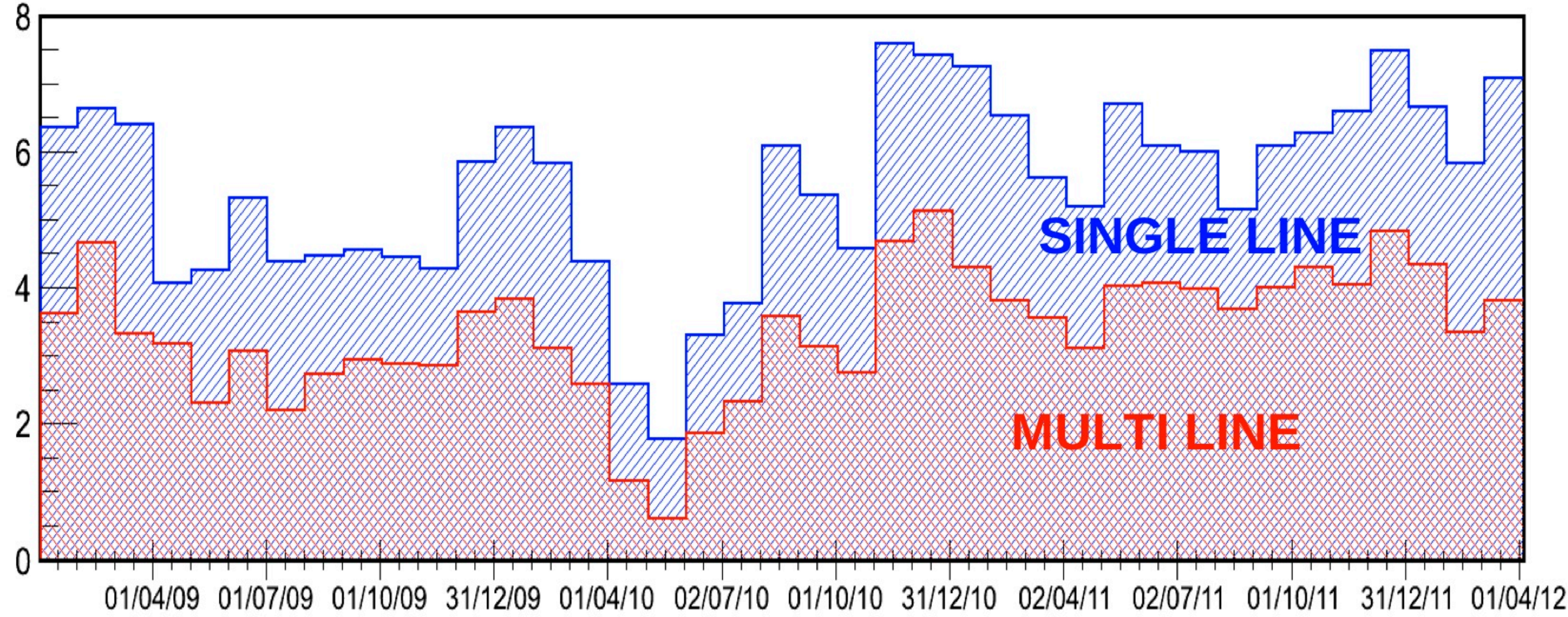
Detector operation



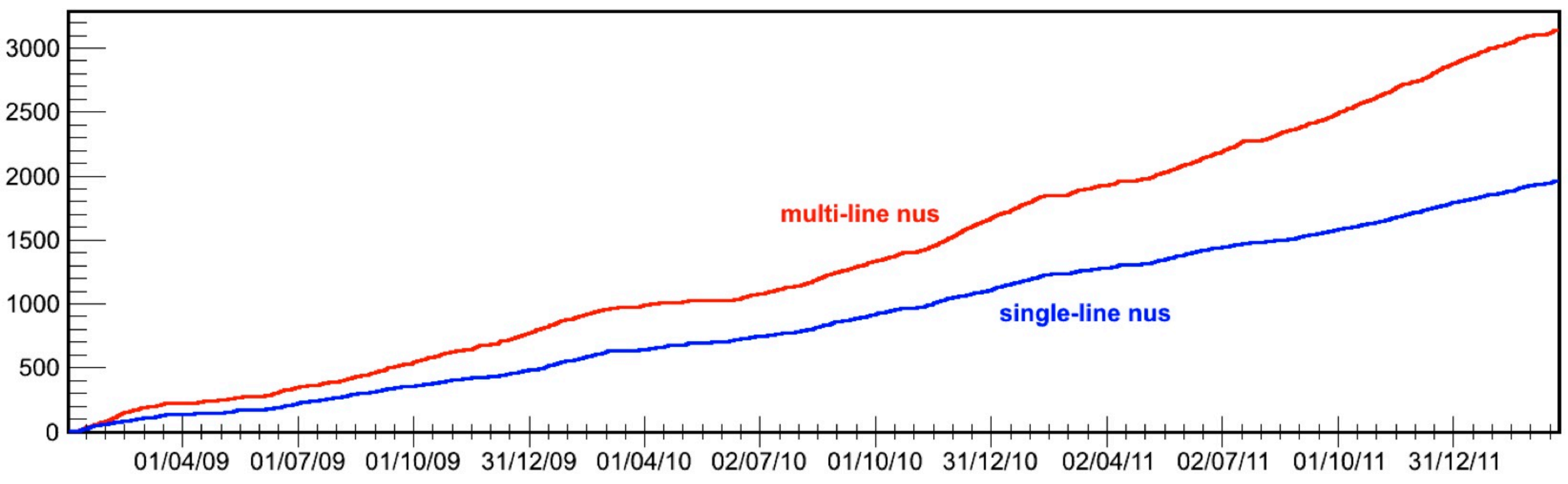
Median rate



- Some years (2006, 2010), high rates of bioluminescence in spring, maybe correlated to particularly cold winters.



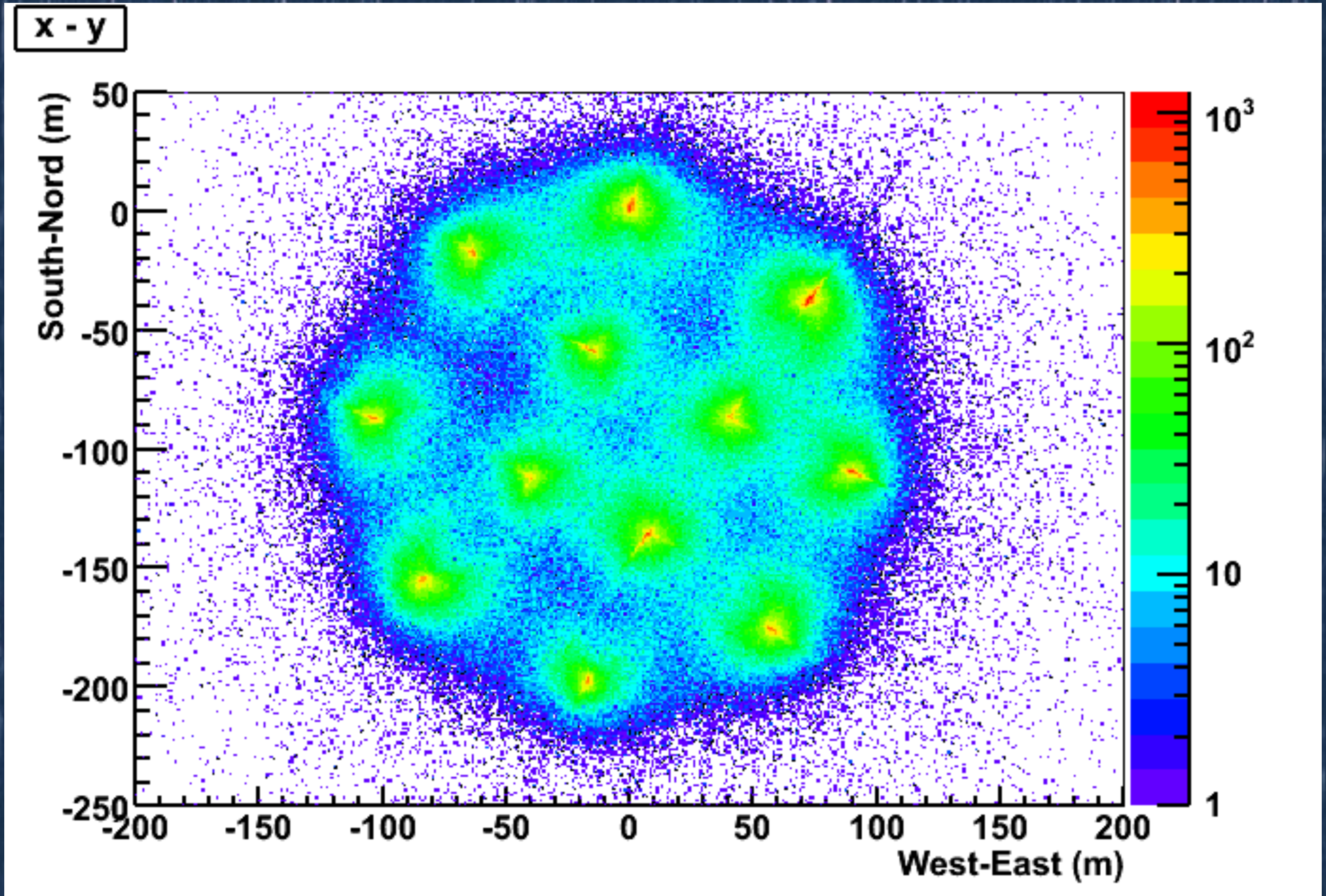
SINGLE LINE
MULTI LINE
0
2
4
6
8
01/04/09
01/07/09
01/10/09
31/12/09
01/04/10
02/07/10
01/10/10
31/12/10
02/04/11
02/07/11
01/10/11
31/12/11
01/04/12



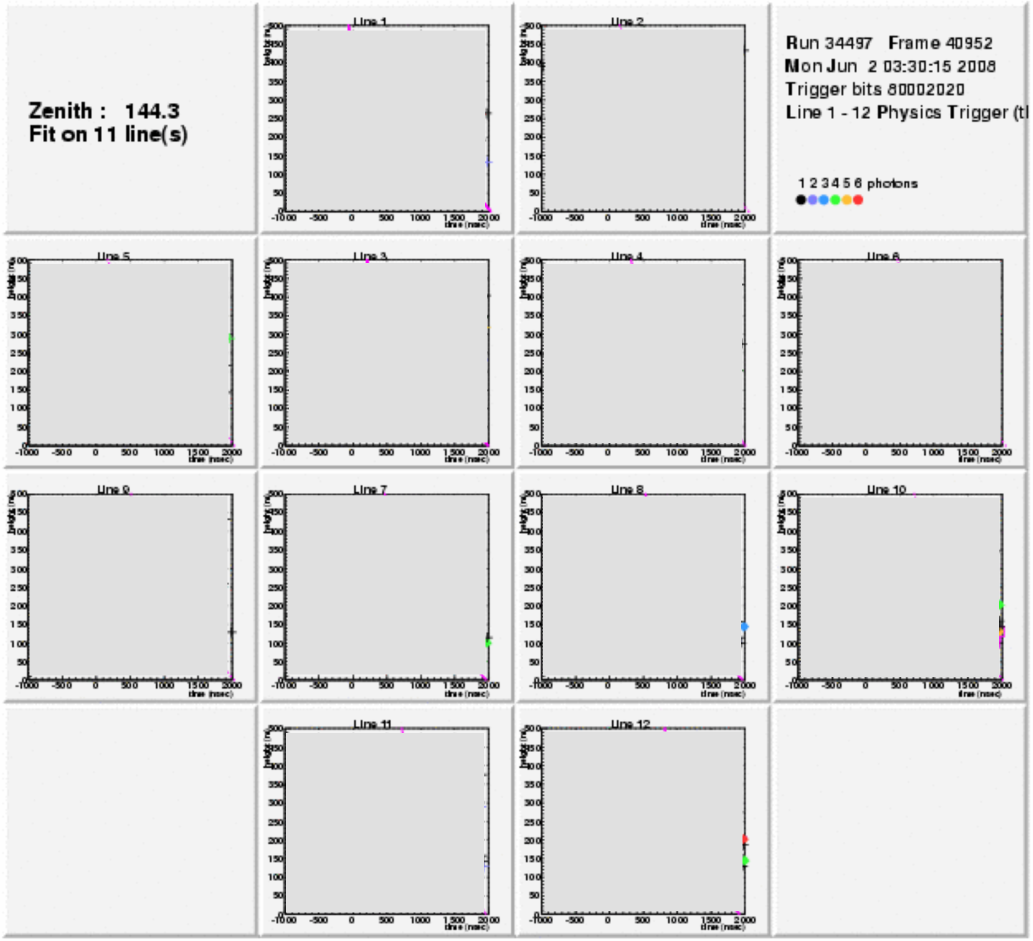
multi-line nus
single-line nus
0
500
1000
1500
2000
2500
3000
01/04/09
01/07/09
01/10/09
31/12/09
01/04/10
02/07/10
01/10/10
31/12/10
02/04/11
02/07/11
01/10/11
31/12/11

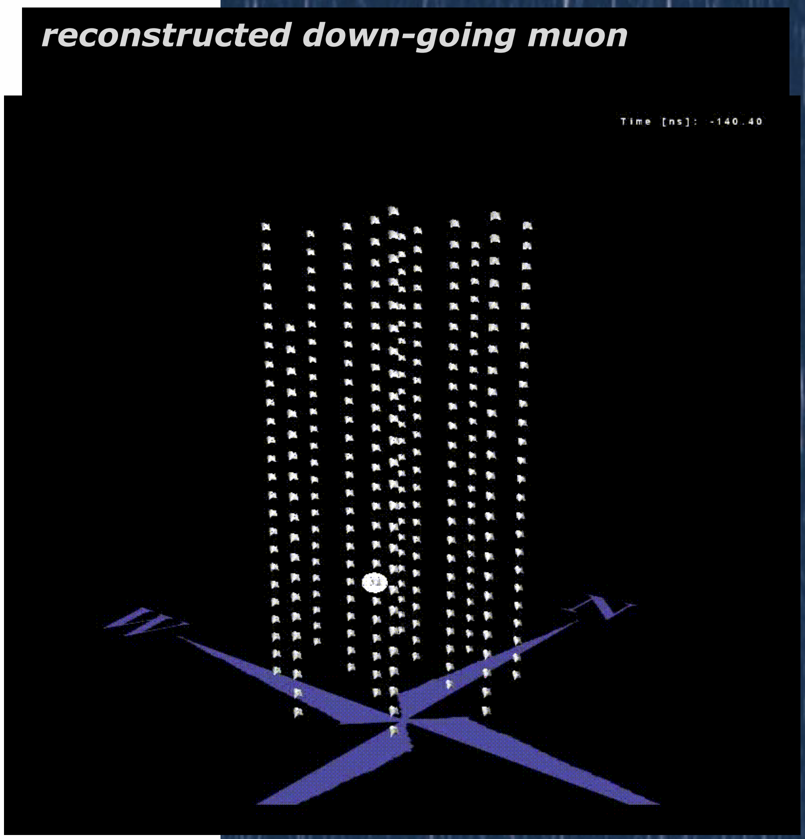
Detector footprint

- Detector as seen by atmospheric muons: position of the first triggering hit

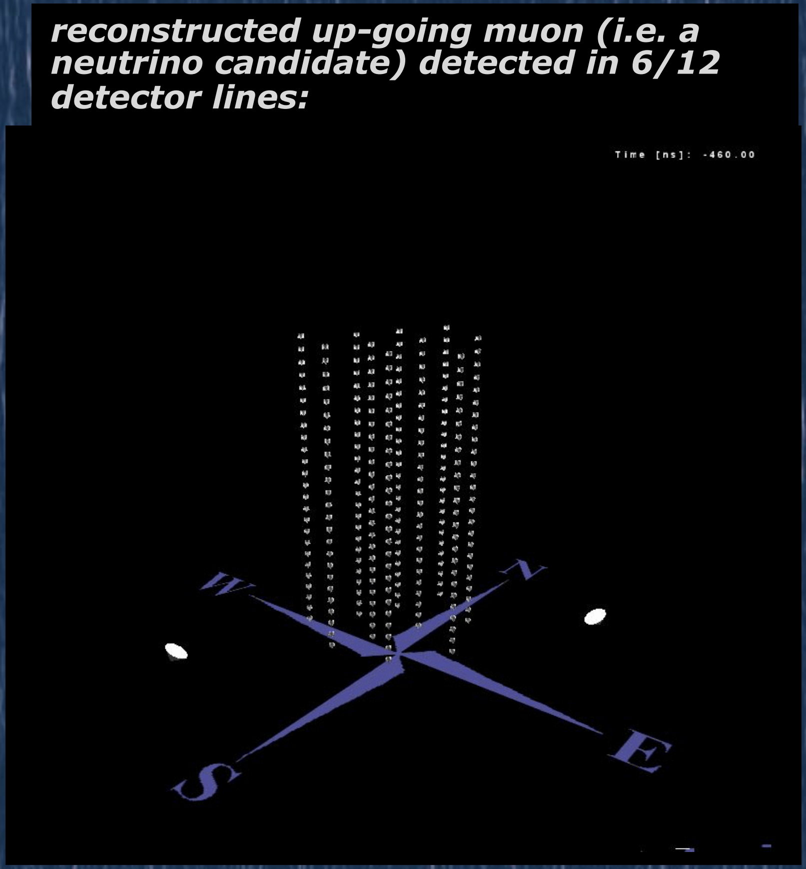


Multi muon event



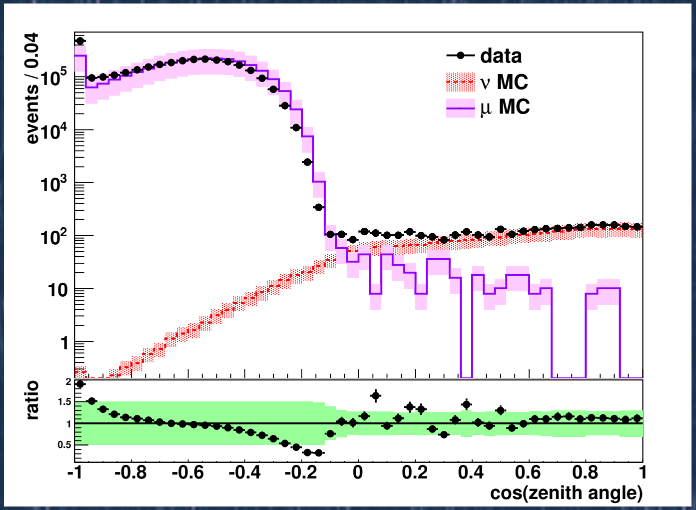


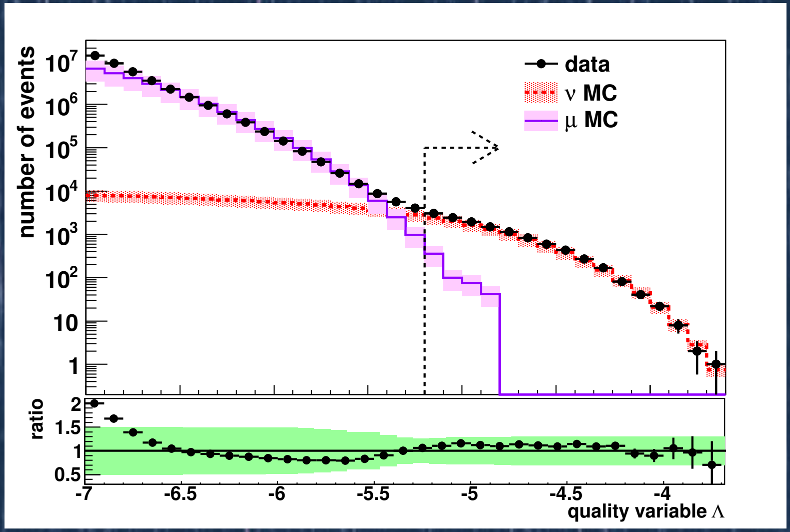
Neutrino candidate

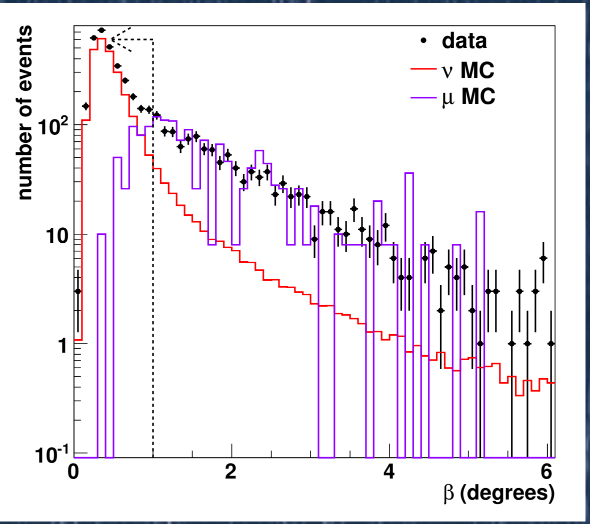


Point source search: selection cuts

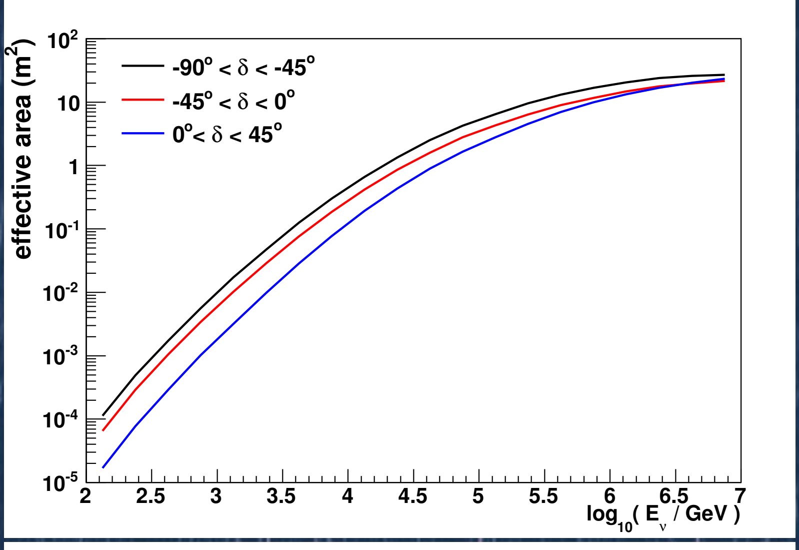
- Good agreement between data and Monte Carlo (detector understood!)
- For PS analysis, selection based on
  - Zenith angle (upgoing events)
  - Quality of reconstruction
  - Estimated angular error in reconstructed track
- Energy information (number of hits) used in the PDF





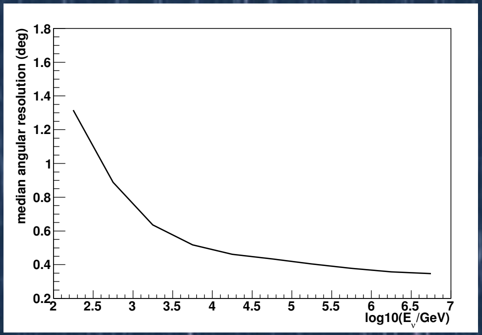


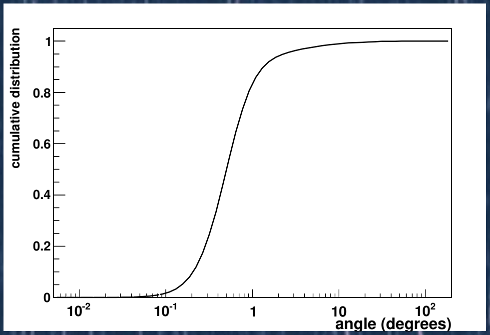
Point source search: detector performance



Effective area

- For E_ν<10 PeV, A_{eff} grows with energy due to the increase of the interaction cross section and the muon range.
- For E_ν>10 PeV the Earth becomes opaque to neutrinos.

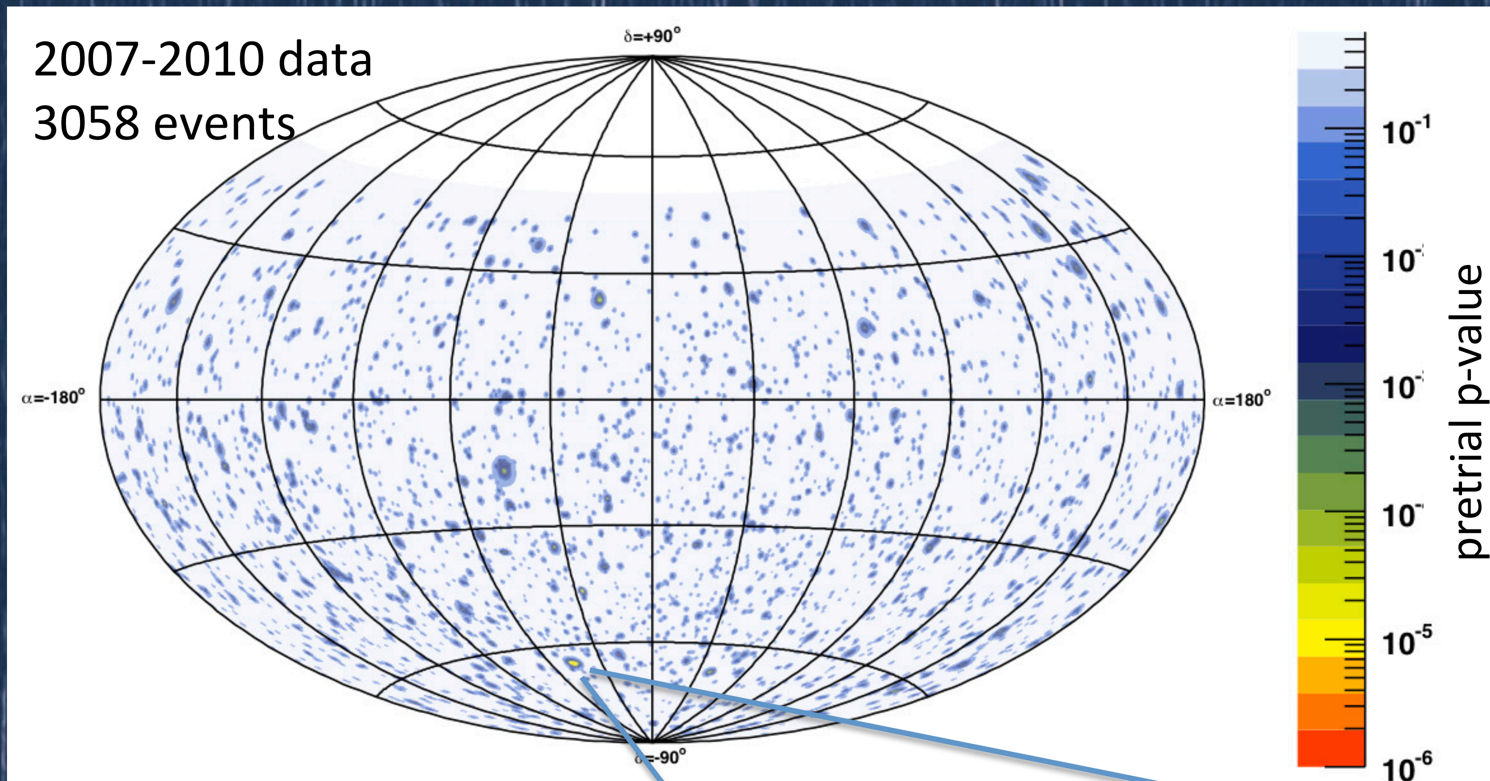


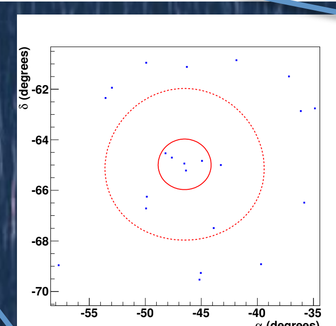


Angular resolution

- For E_ν < 10 TeV, the angular resolution is dominated by the ν-μ angle.
- For E_ν > 10 TeV, the resolution is limited by track reconstruction errors
- For E^{-2}: median=0.46 ± 0.10 deg

Point source search: skymap





Most significant cluster at:
RA = −46.5°
δ = −65.0°

N_{sig} = 5
Q = 13.02
p-value = 0.026
Significance = 2.2 σ

Point source search: list of candidates

- We look in the direction of a list of 51 candidate sources.
- Selection criteria: mostly based on γ-ray flux + visibility)
- Result compatible with only-background hypothesis

Flux upper limit on E^{-2} spectrum (in 10^{-8} GeV^{-1} cm^{-2} s^{-1} units)

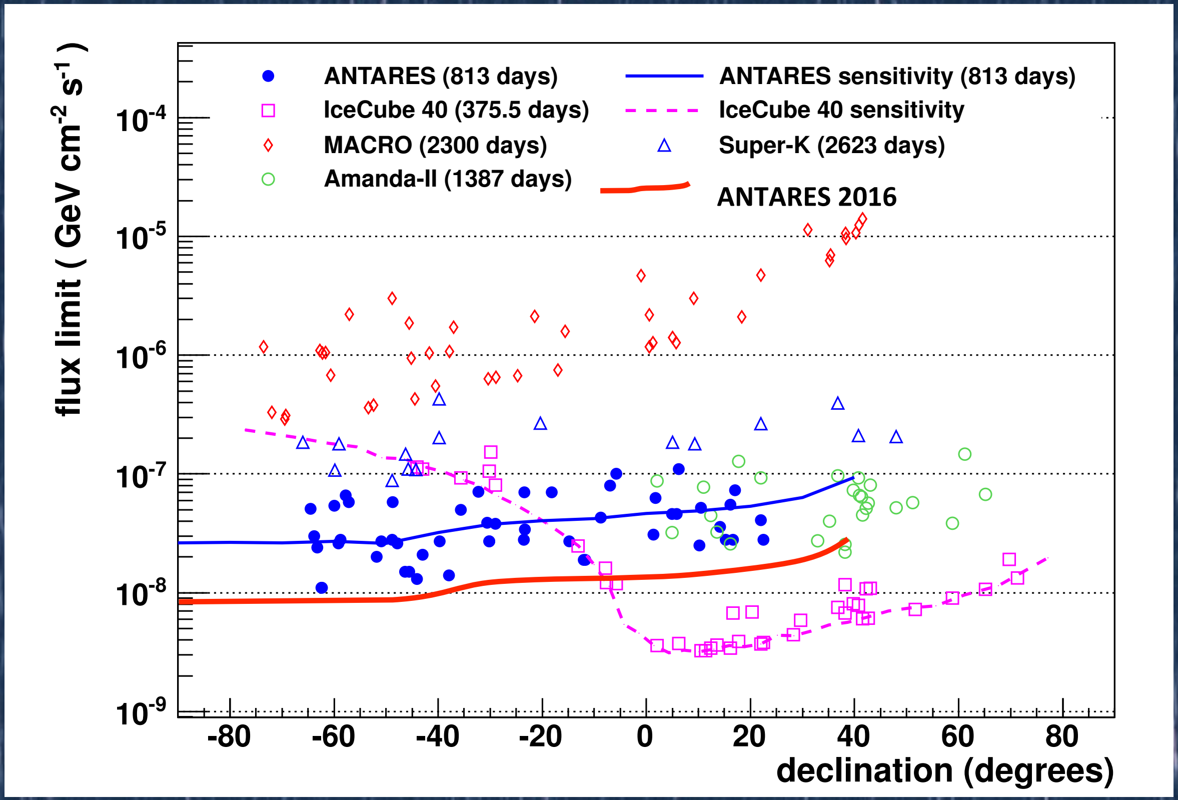
Sources with lhte owest p-values

Source name	$\alpha_s\,[°]$	$\delta_s\,[°]$	p	ϕ_ν^{90}
HESS J1023-575	155.83	-57.76	0.41	6.6
3C 279	-165.95	-5.79	0.48	10.1
GX 339-4	-104.30	-48.79	0.72	5.8
Cir X-1	-129.83	-57.17	0.79	5.8
MGRO J1908+06	-73.01	6.27	0.82	10.1
ESO 139-G12	-95.59	-59.94	0.94	5.4
HESS J1356-645	-151.00	-64.50	0.98	5.1
PKS 0548-322	87.67	-32.27	0.99	7.1
HESS J1837-069	-80.59	-6.95	0.99	8.0

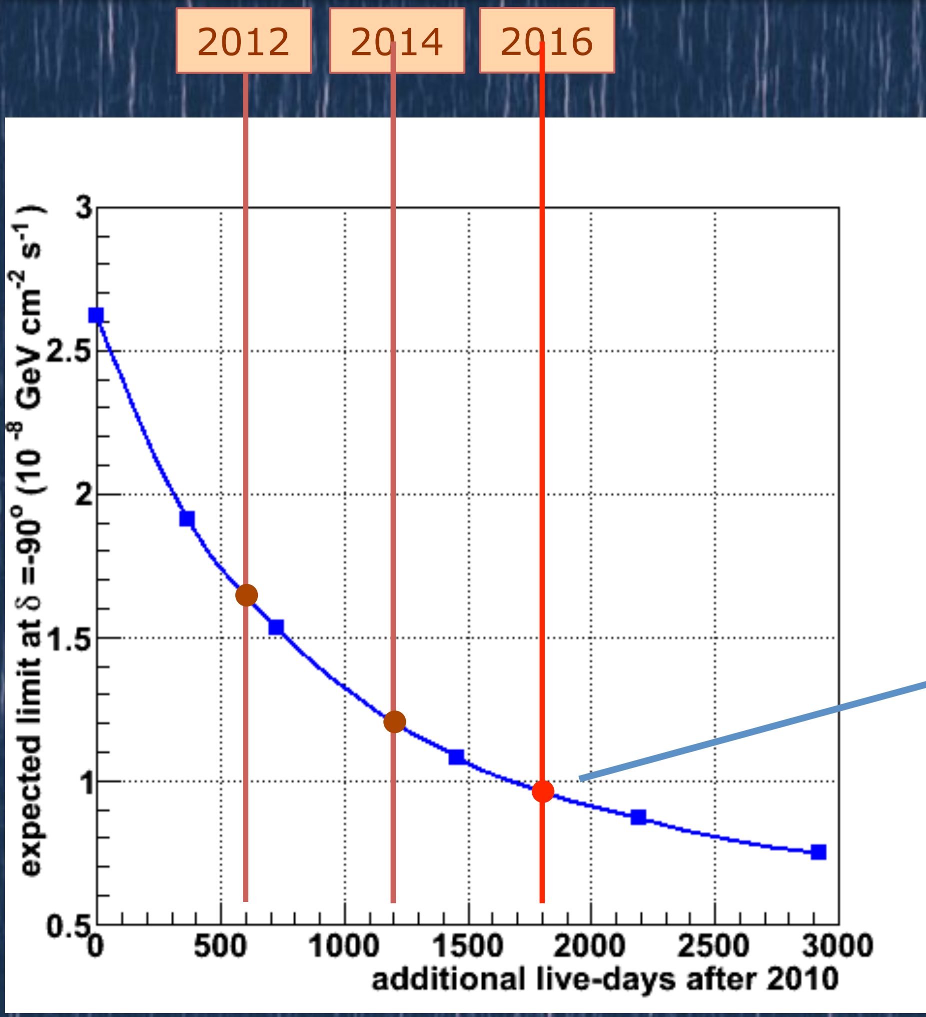
Most significant case: HESSJ1023-575 (p-value=41%)

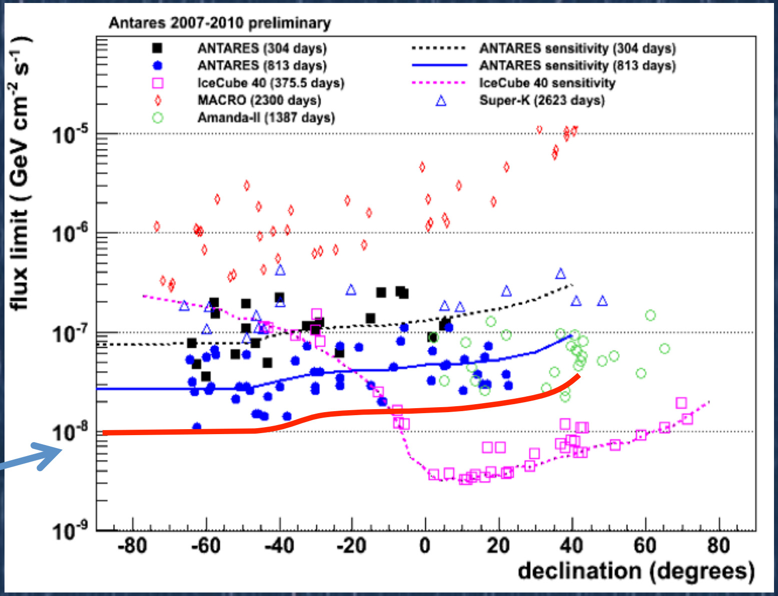
Point source search: flux limits

- For most of the Southern-sky, ANTARES has the best limits
  (Moreover: IceCube threshold for SH ~1 PeV, while for Galactic sources, a cut-off in the energy spectrum is expected)
- By 2016, limits expected to improve by a factor 2.5



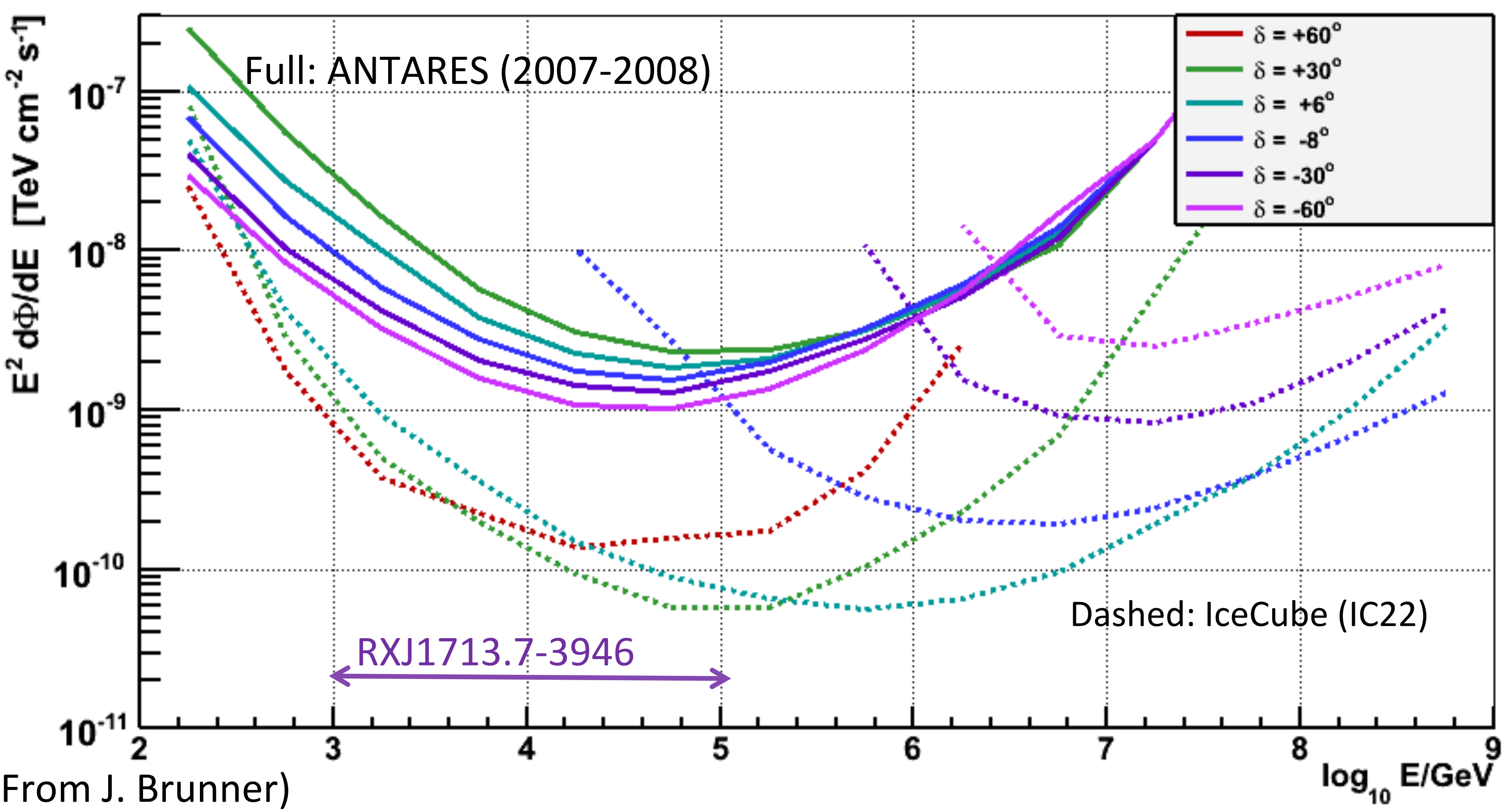
PS search: additional data





Assuming 300 live days/year

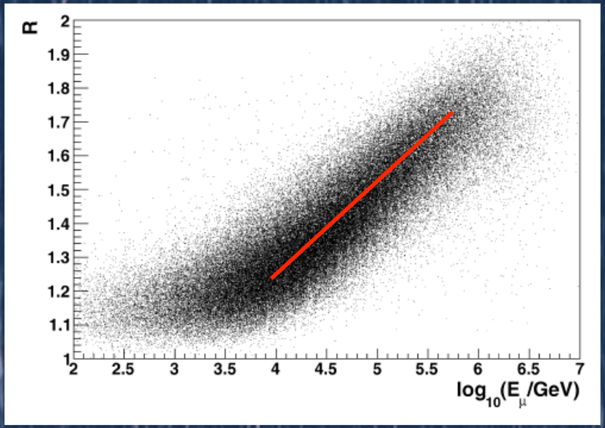
Limits vs Energy

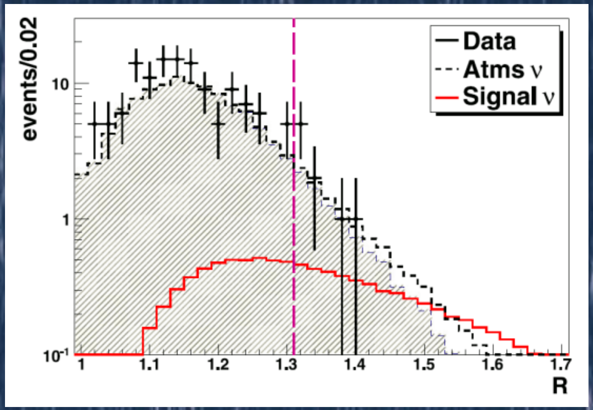


(From J. Brunner)

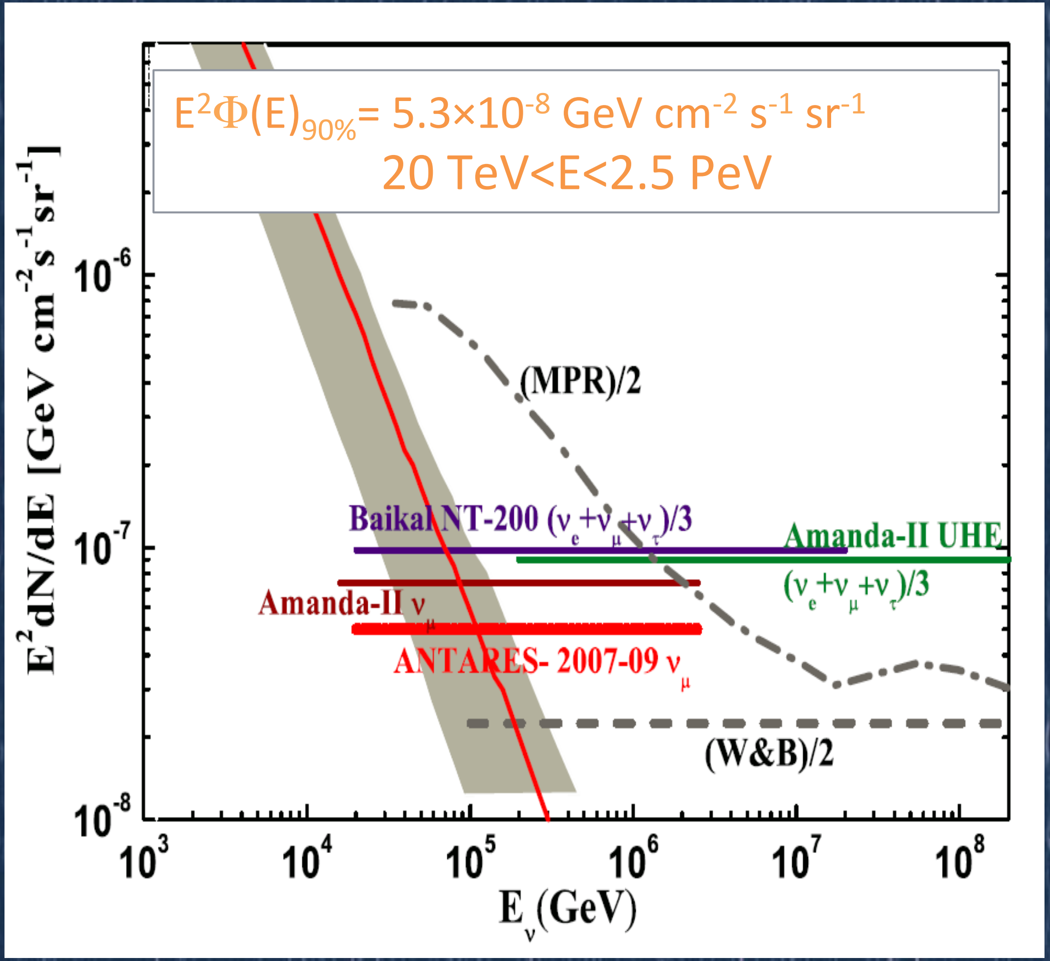
Diffuse flux

2007-2009 data

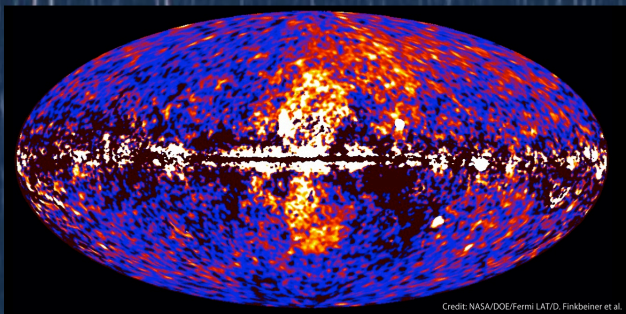




$$R = \frac{\sum number\_of\_hits\_in\_PMT\_i}{Total\_number\_of\_PMTs\_in\_event}$$



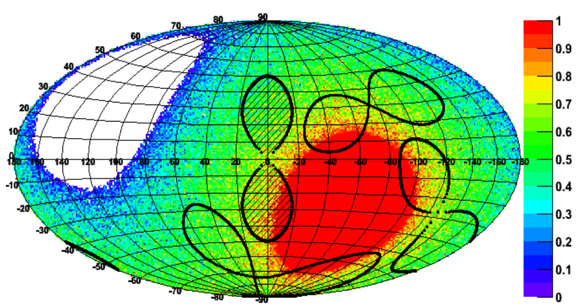
Fermi Bubbles



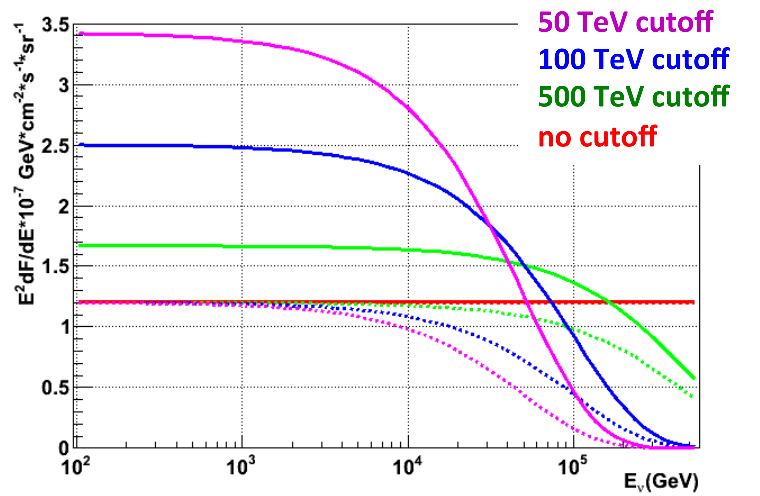
According to Villante & Vissani [Phys. Rev. D 78 (2008) 103007]

- $\Phi_{nu} \sim 1/2.5 \Phi_{gamma} \sim E^{-2} 1.2 * 10^{-7} GeV\ cm^{-2}\ s^{-1}\ sr^{-1}$
- Neutrino cutoff may be obtained from the proton cut off $x_{nu} \sim x_p/20$ (50 TeV-500 TeV)

On/OFF source analysis: background estimated from average of three "bubbles" shifted in time



preliminary



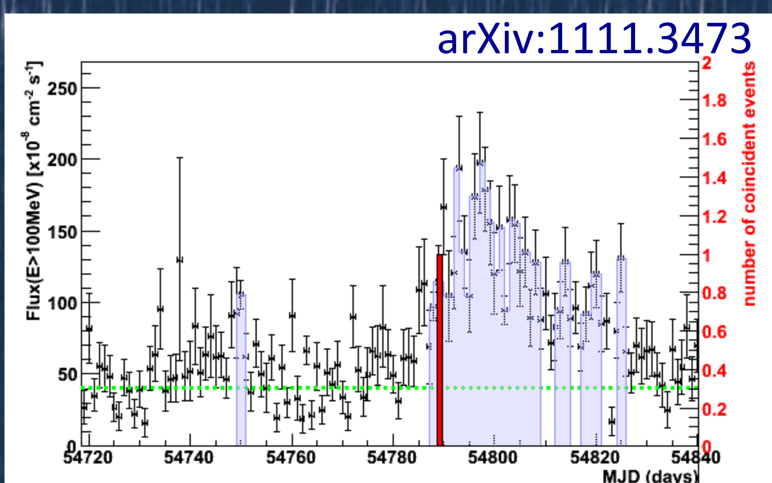
Nback (OFF) = 90±5(stat)±3(sys)
N_{ON} = 75 events → NO SIGNAL

Fully hadronic scenario with no cutoff excluded

Correlations with γ and X-ray flares

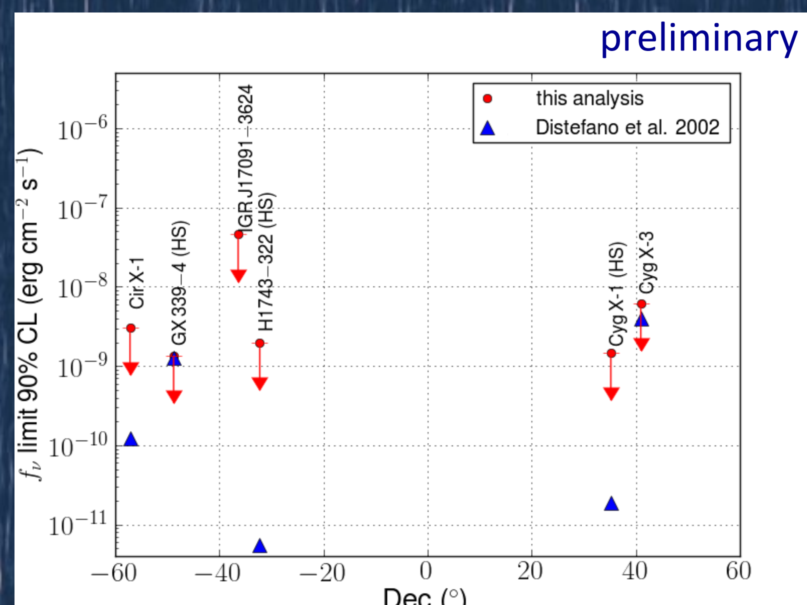
Blazars: AGNs with a jet pointing to us

- 10 flaring blazars in 2008: PKS0208-512, AO0235+164, PKS1510-089, 3C273, 3C279, 3C454.3, OJ287, PKS0454-234, Wcomae, PKS2155-304
- For 9 sources: 0 events
- 3C279: 1 event compatible with the source direction ($\Delta\alpha$=0.56^{o}) and time distribution
- Post trial value 10%
- Upper-limit on the neutrino fluence



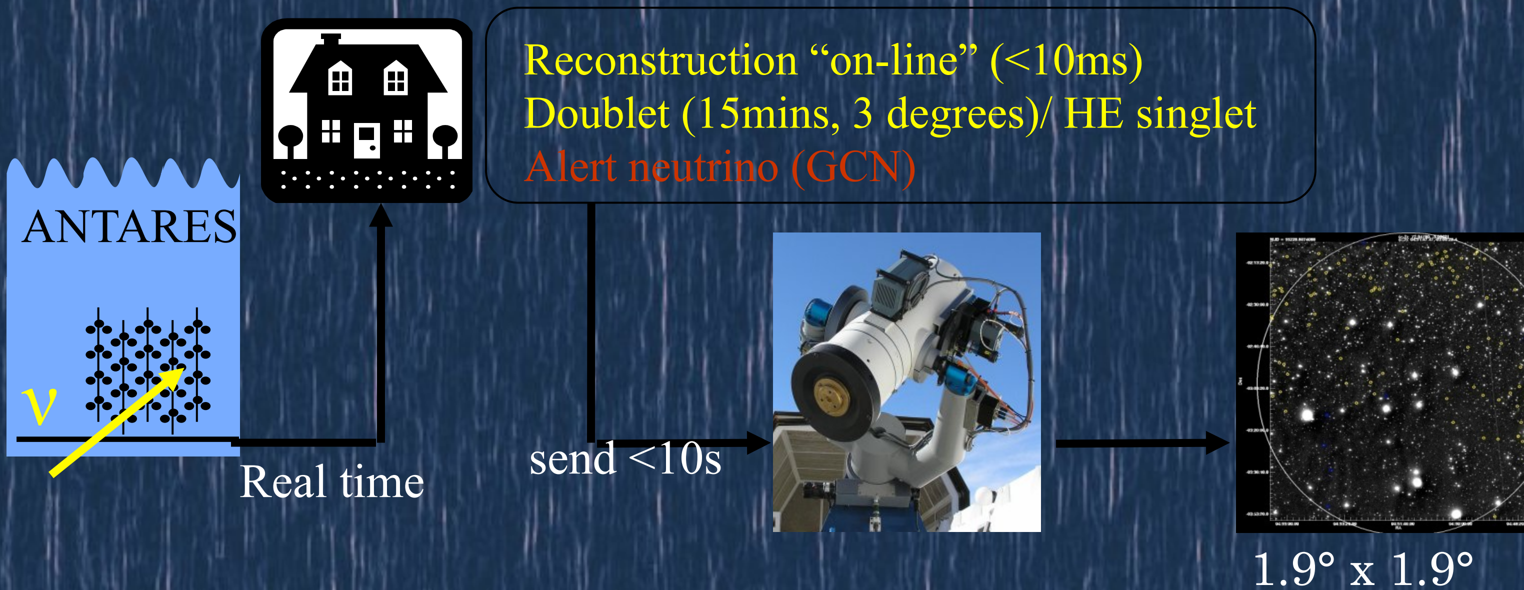
Microquasars: Binary system of compact star + normal star accreting to the former

- 6 flaring microquasars in 2007-2010: Circinus X-1, GX339-4, H 1743-322, IGRJ17091-3624, Cygnus X-1, Cygnus X-3
- No neutrinos found in coincidence with outbursts



TaToO: Telescopes and ANTARES Target of Opportunity

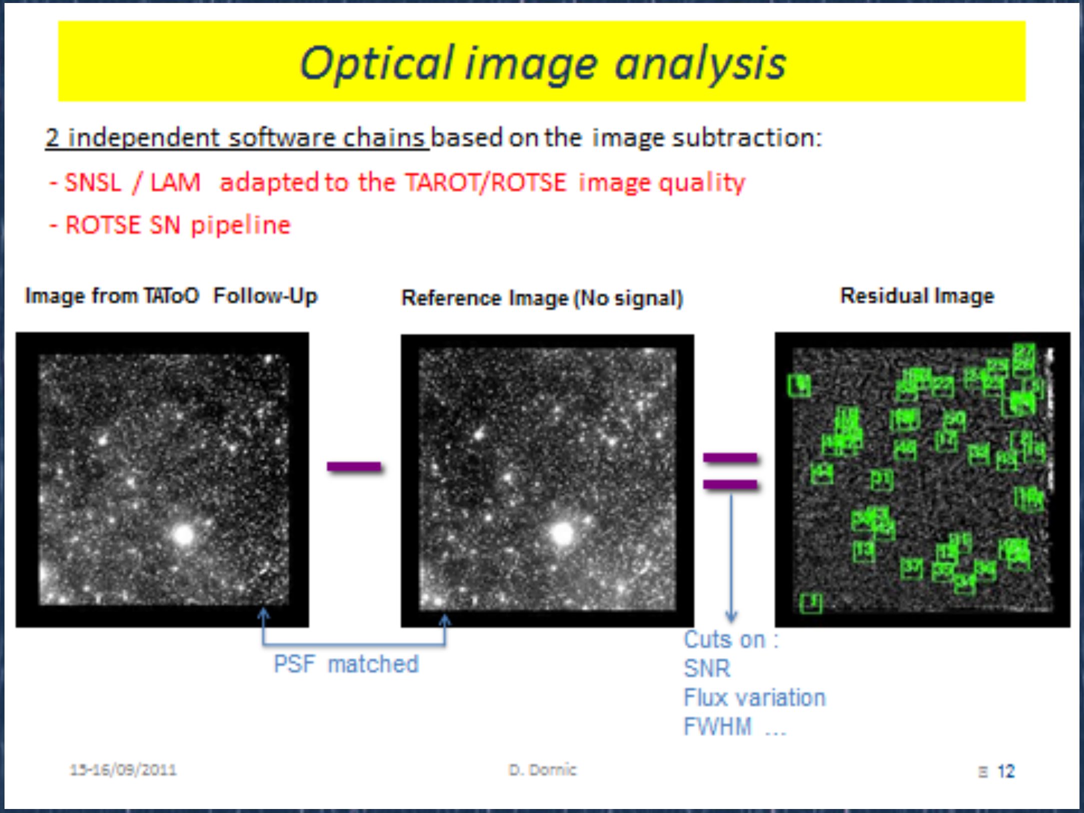
TAToO: optical follow-up of neutrino alerts in order to search for transient sources (GRBs, choked GRBs, AGN flares…)

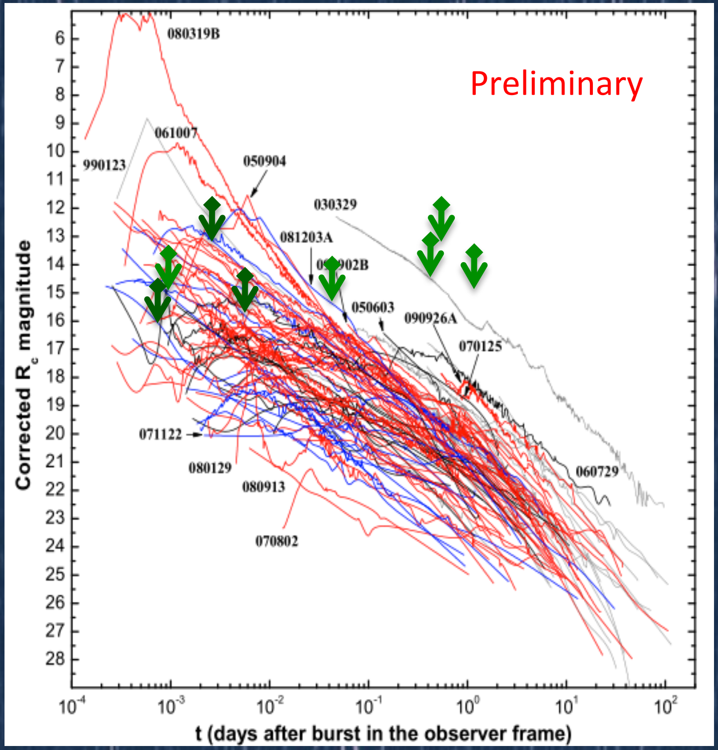


Large sky coverage ($>2\pi$ sr) + high duty cycle
Improved sensitivity (1 neutrino $\Rightarrow$ 3 sigma discovery)
No hypothesis on the nature of the source
Independent of availability of external triggers

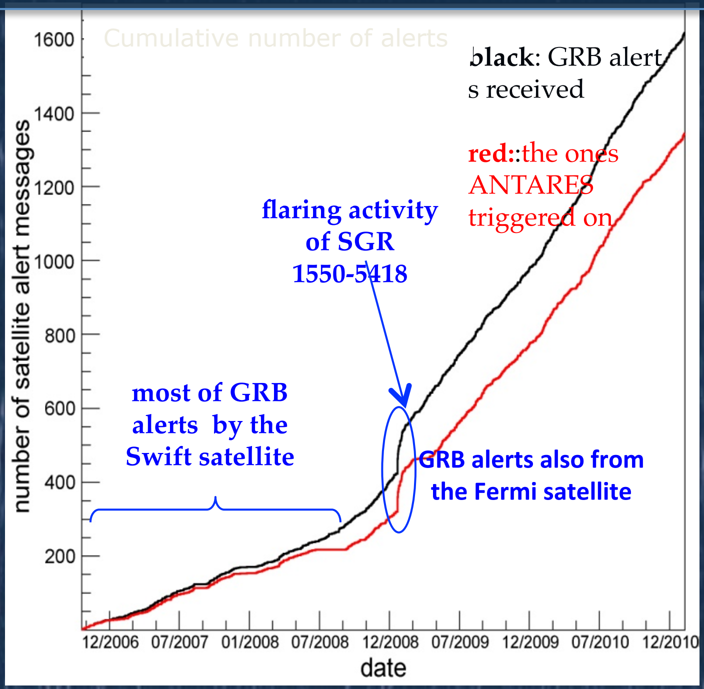
TAToO: GRB analysis

For each neutrino alert -> search for counterpart in optical originating from GRB (54 alerts sent since mid 2009)

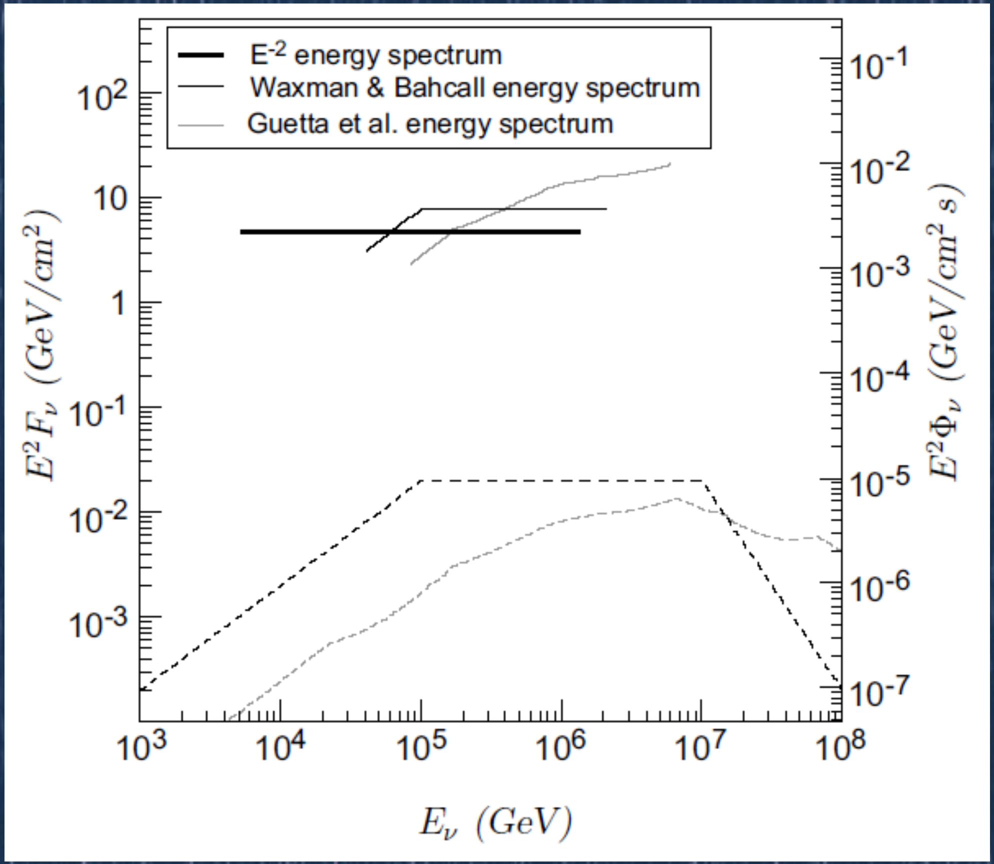




GRB triggered search



90% CL Upper limits on fluxes from 40 stacked GRBs

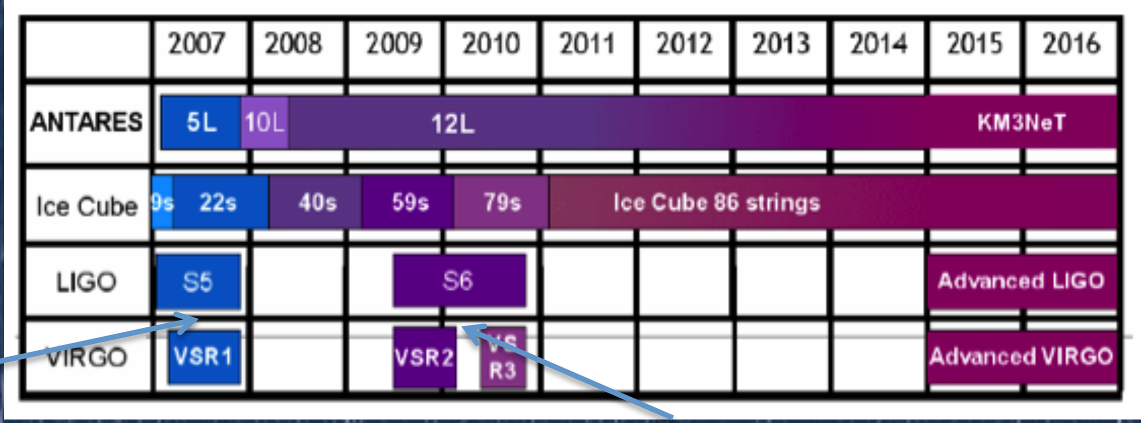


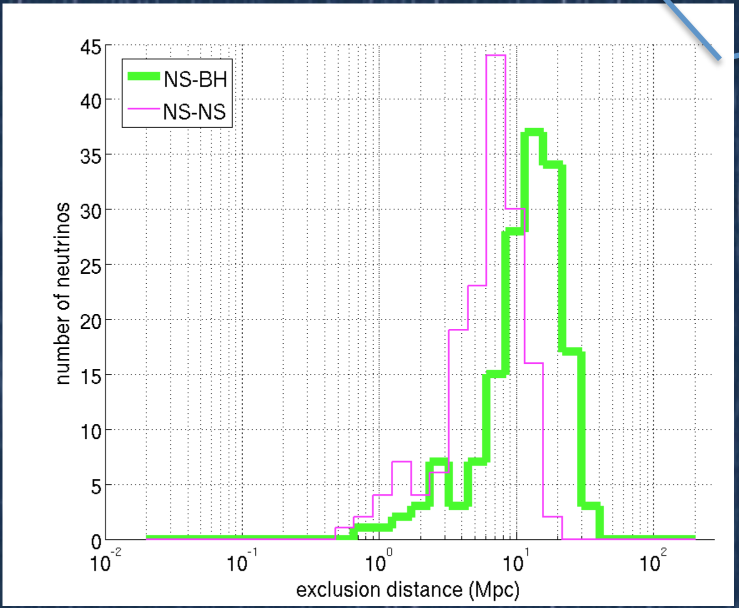
- > 1300 alerts from GCN have been recorded (Jan 2011)
- Lines 1-5 data unblinded: 40 GRB alerts
- The total prompt emission duration of the 40 GRBs is 2114 s

Correlation with GWs

Main motivations:
- plausible common sources (microquasars, SGR, GRBs)
- discovery potential for hidden sources (e.g. failed GRBs)

First analysis of 2007 data performed and reviewed by both collaborations
No detection→limits.



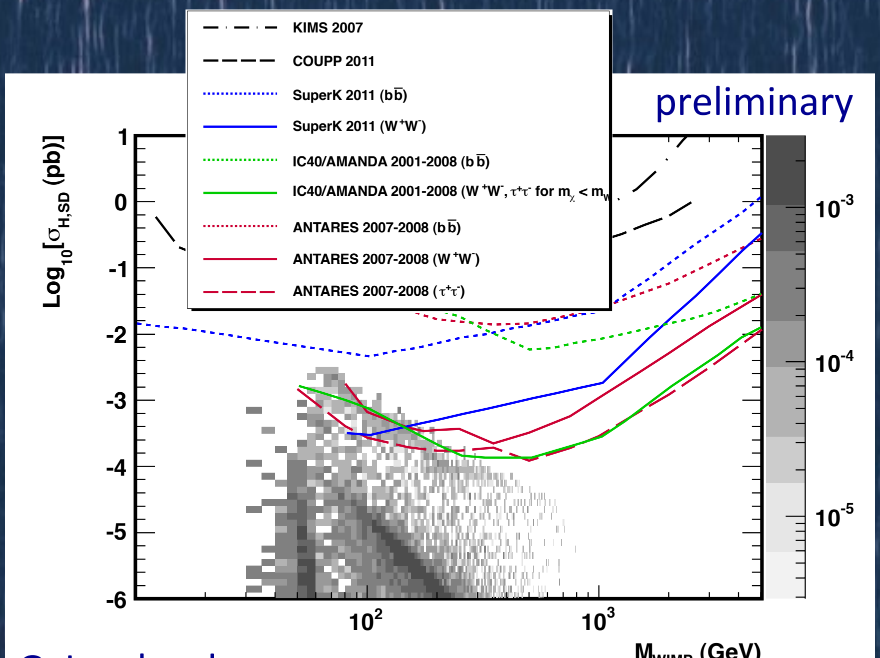


Analysis of remaining data ongoing with improved reconstruction and dedicated GW pipeline

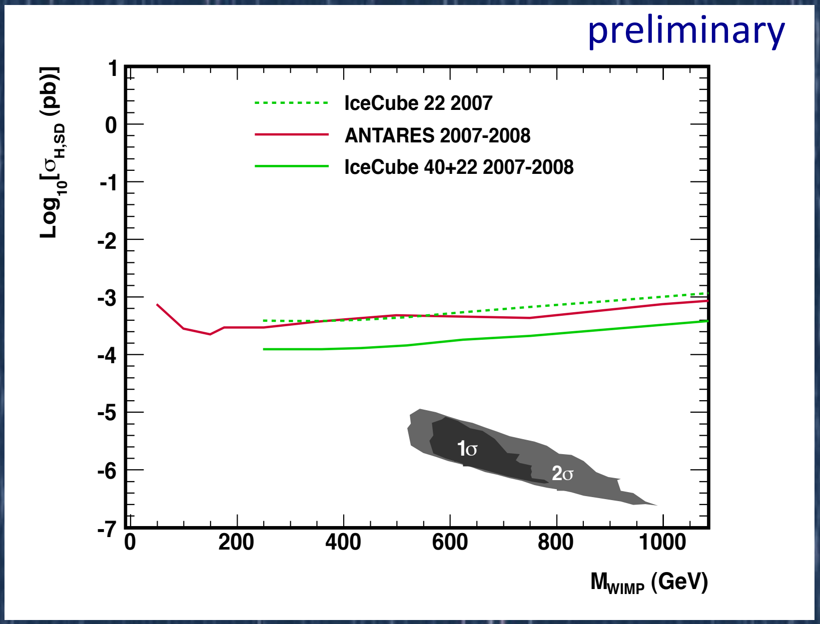
The MoU between Antares and VIRGO-LIGO has been extended until late 2013.

Dark matter

- WIMPs (neutralinos, KK particles) accumulate in massive objects like the Sun, the Galactic Center, dwarf galaxies…
- The products of such annihilations would yield "high energy" neutrinos, which can be detected by neutrino telescopes
- A signal would be a clean indication of DM (no plausible astrophysical explanation)



G. Lambard



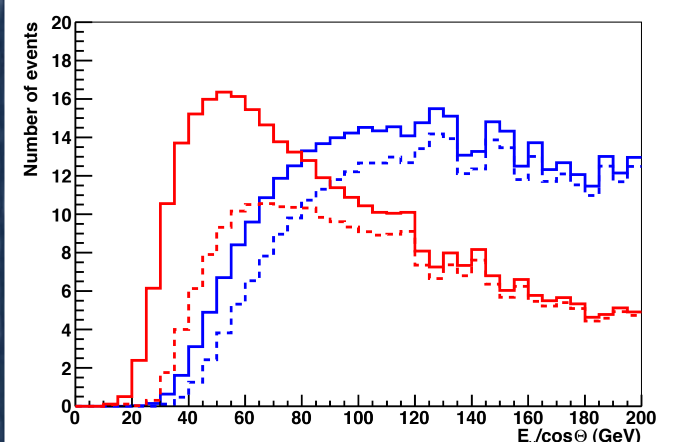
Oscillations: method

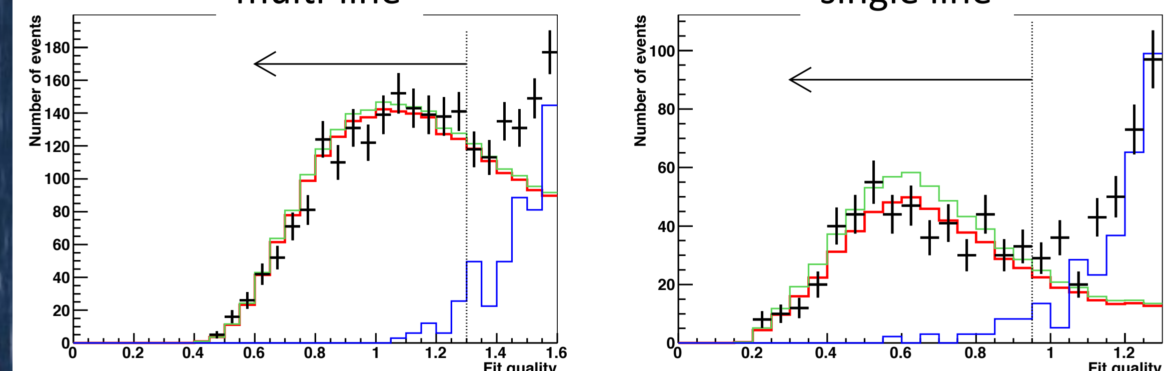
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right) = $$
$$= 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m^2_{32} \cos\Theta}{E_\nu}\right).$$

No azimuth information is needed →
single-line reconstruction is enough →
lower energy threshold (20 GeV) →
oscillation effect observable!

solid: no osc
dashed: osc

red: single-line
blue: multi-line





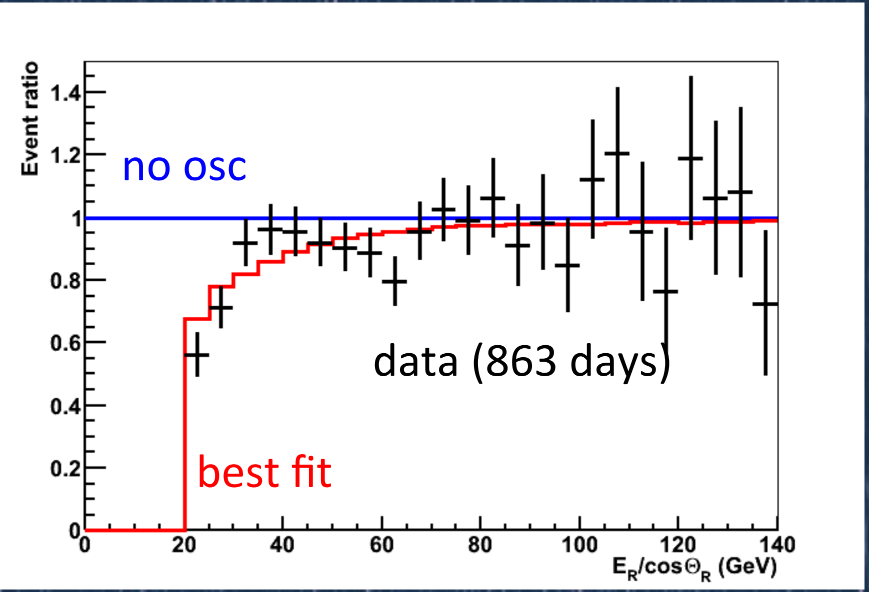
	Multi-line			Single-line		
	Data	ν MC	μ MC	Data	ν MC	μ MC
All	$1.42 \cdot 10^8$	8755	$1.23 \cdot 10^8$	$1.51 \cdot 10^8$	8242	$1.10 \cdot 10^8$
Nstorey > N_{cut}	$1.33 \cdot 10^8$	8248	$1.18 \cdot 10^8$	$4.44 \cdot 10^7$	1260	$3.03 \cdot 10^7$
Fit boundary	$1.32 \cdot 10^8$	8150	$1.17 \cdot 10^8$	$4.31 \cdot 10^7$	1242	$2.93 \cdot 10^7$
$\cos\Theta_R > 0.15$	$2.74 \cdot 10^6$	5512	$1.84 \cdot 10^6$	$7.97 \cdot 10^5$	1116	$6.96 \cdot 10^5$
Fit quality cut	1632 ± 40	1971 ± 6 1910 ± 6	52 ± 12	494 ± 22	651 ± 3 557 ± 3	28 ± 9

Oscillations: result

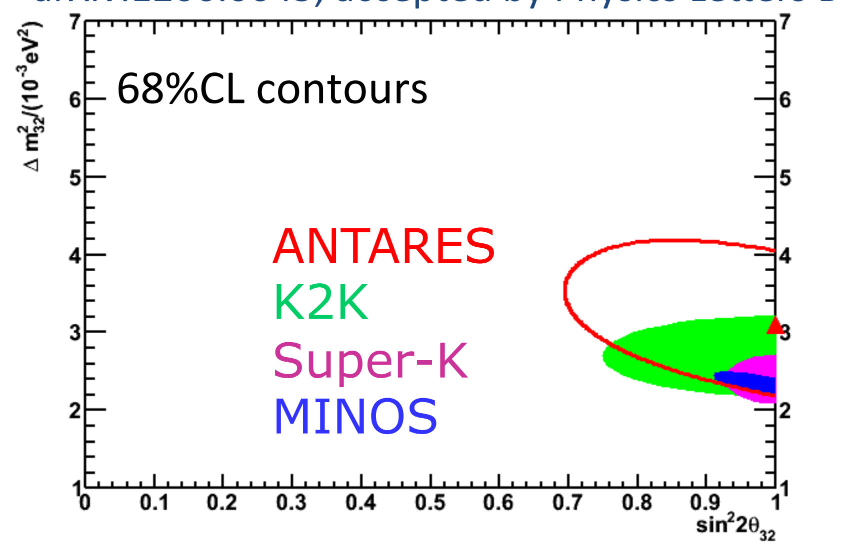
Systematic uncertainties:

- Absorption length: ±10%
- Detector efficiency: ±10%
- OM angular acceptance
- Spectral index of ν flux: ±0.03%

5% error on slope vs $E_R/\cos\Theta_R$



arXiv:1206.0645, accepted by Physics Letters B



$\Delta m^2 = (3.1 \pm 0.9)\ 10^{-3}\ eV^2$ (assuming maximal mixing)

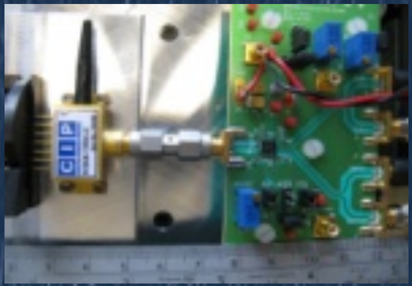
KM3NeT

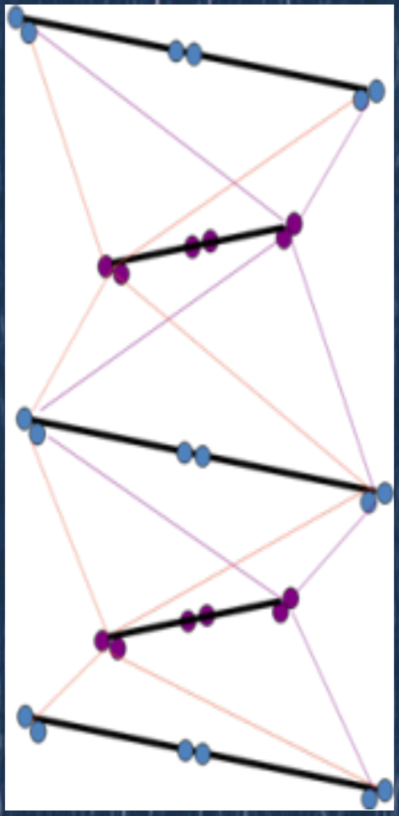
KM3NeT

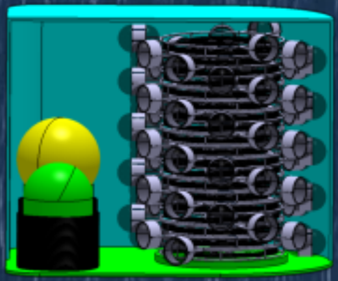
- KM3NeT us the project of joint effort for the construction of a cubic kilometer neutrino detector in the Mediterranean Sea
- The first step is R&D phase, in which the experience of present projects will be an important input
- The expansion from 0.1 km^2 to 1 km^3 is not straight-forward
- Parallel contributions to marine biology, geophysics, oceanography, etc. will be important.
- 40 Particle/Astroparticle and Sea science/technology (11 European countries)
- Design Study and Preparatory Phase funded by European Framework Programs

R&D phase

… + studies on data transmission, power distribution, time calibration and positioning, marine operations,



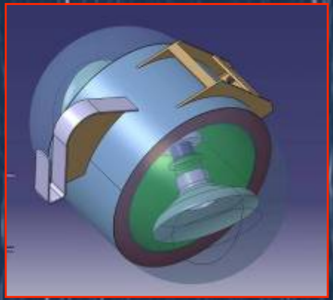


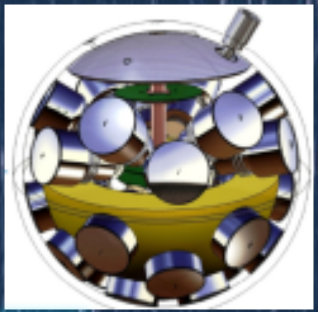


Self-unfolding structures for massive deployment

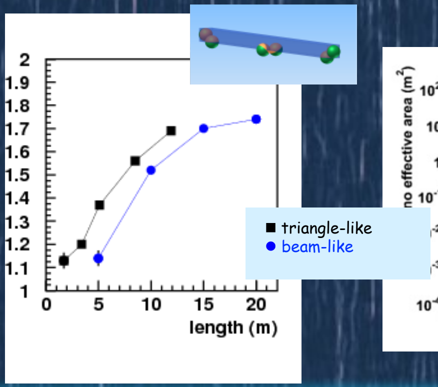
KM3NeT R&D

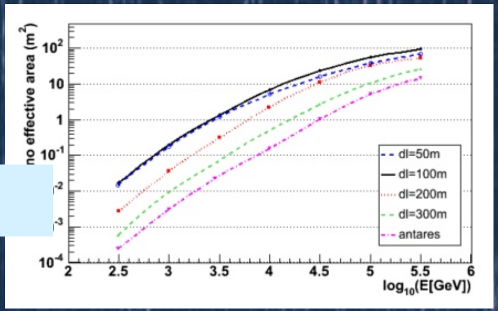
Several photo-sensors and optical module arrangements studied.

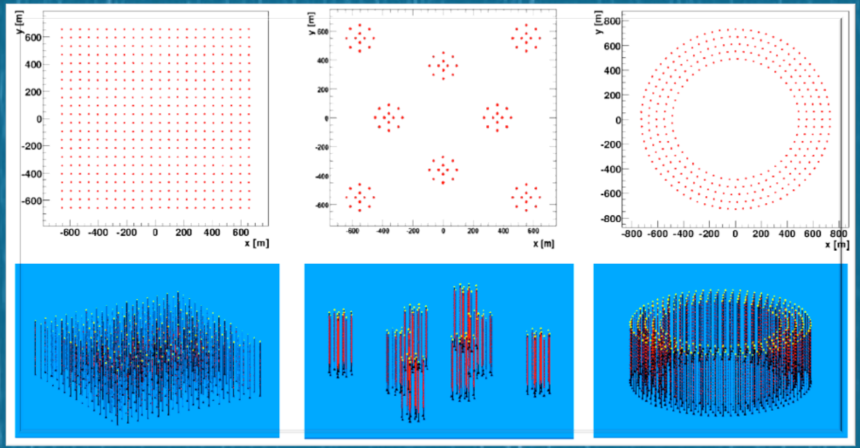




Performance in terms of effective area and resolution for different configurations have been studied





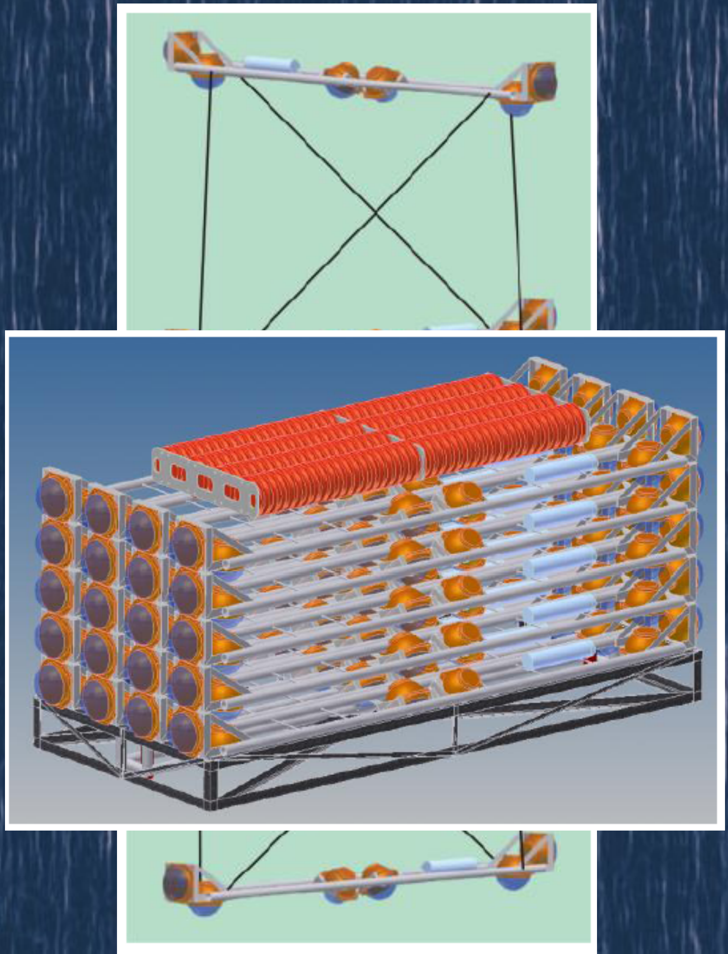


Multi-PMT Optical Module

- 31 3” PMTs inside a 17” glass sphere with 31 bases (total ~140 mW)
- Cooling shield and stem
- With respect to single large PMT:
  - Single vs multi photon hit separation
  - Larger photocade area per OM

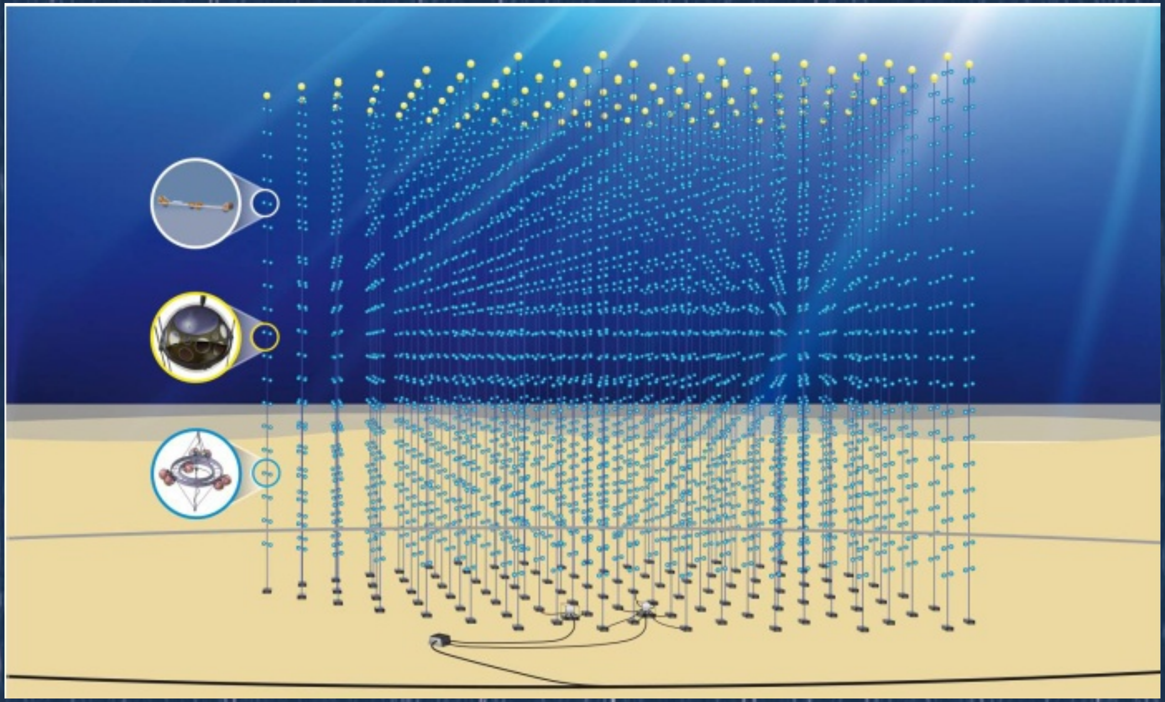
Bar

- 300 x Self-unfolding structure
- 6 meters long
- 20 floors
- Made of aluminium



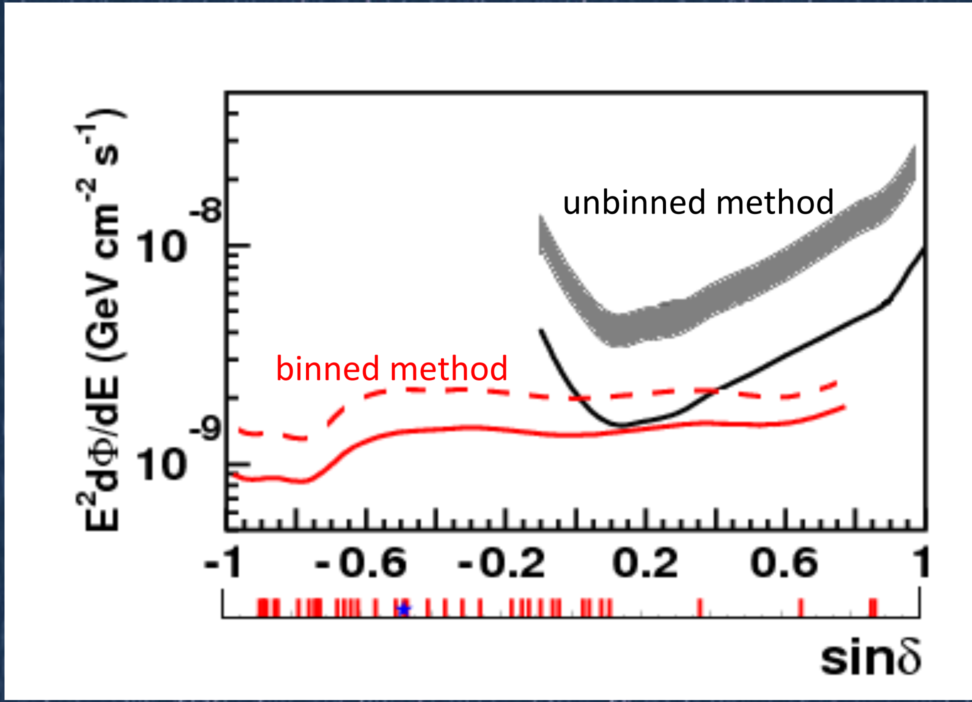
KM3NeT

- Technical design report (TDR) approved
- Preproduction model (a full detector line) under construction to be deployed in 2012 (with multi-PMT OM on horizontal bars)
- 40 M€ already on the table from France, Italy and the Netherlands
- Data taking would start in 2014. By 2015 the sensitivity will surpass ANTARES



KM3NeT sensitivity

Sensitivity and discovery fluxes for point like sources with a E^{-2} spectrum for 1 year of observation time (full detector 154 DUx2)



KM3NeT sensitivity 90%CL
KM3NeT discovery 5σ 50%
IceCube sensitivity 90%CL
IceCube discovery 5σ 50% 2.5÷3.5 above sensitivity flux. (extrapolation from IceCube 40 string configuration)

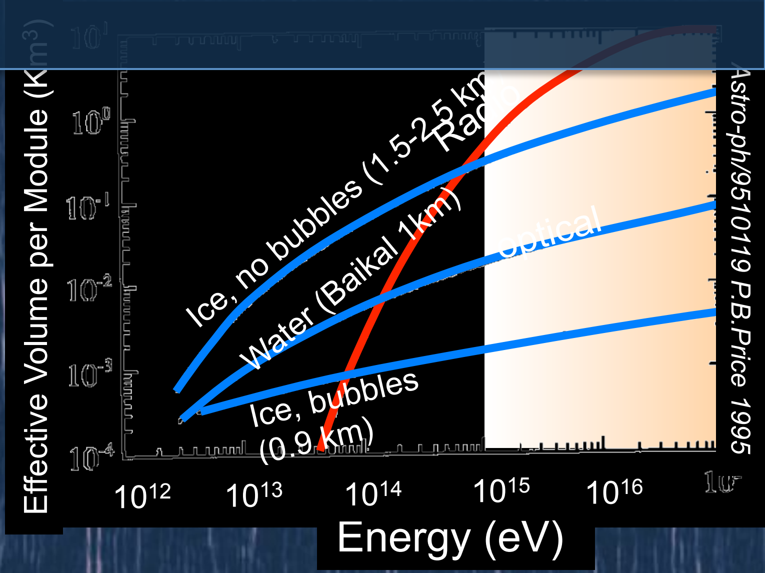
| Observed Galactic TeV γ-sources (SNR, unidentified, microquasars)
F. Aharonian et al. Rep. Prog. Phys. (2008)
Abdo et al., MILAGRO, Astrophys. J. 658 L33-L36 (2007)
★ Galactic Centre

Observation of RXJ1713 at 5σ within about 5 years

Sensitivity and discovery potential will improve with unbinned analysis

Other techniques

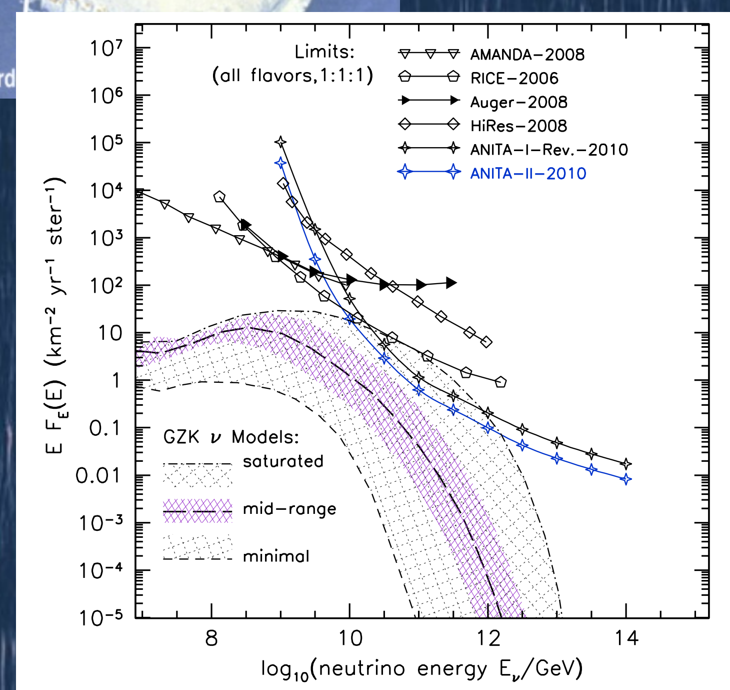
Radio detection



- At UHE, the predicted neutrino fluxes are very low (~1 GZK ev/year in IceCube)
- Larger (cheaper) detectors are needed → radio detection (λ_{att}~km)

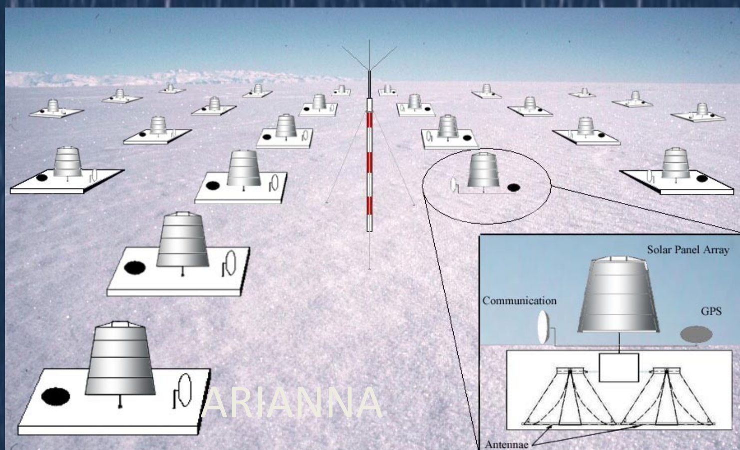
- Askarian Effect:
  - Coherent Cherenkov RF emission of from cascades
  - Electrons are swept in the shower development → negative net charge
  - Signal power ~ E^2
- Apart from being from the λ_{att} advantage, the deployment (for instance in the ice) is easier

ANITA



"Low" threshold (10^{17} eV)
Altitude: 35,000m
35 days + 31 days of flight
Polarization sensitivity (real signal expected vertically polarized)
5 events. Expected bg 1 ev, but:
- 3 Horizontally polarized
- 1 emitted by pulser

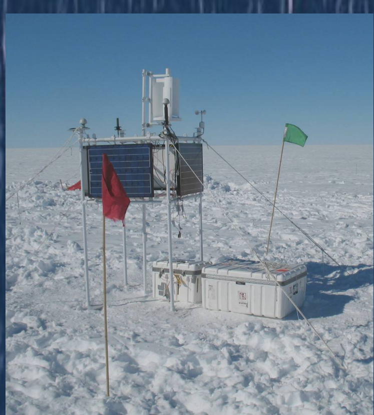
ARIADNA and HRA



Goal:

Instrumented volume: 500 km^3
40 GZK events/year
Threshold 10^{17} eV
→ Antennae in ice (att. lenght ~500 m)

ARIANNA (Antarctic Ross Iceshelf Antenna Neutrino Array): the water-ice interface at the bottom of the Ice Shelf reflects quite well radio signals

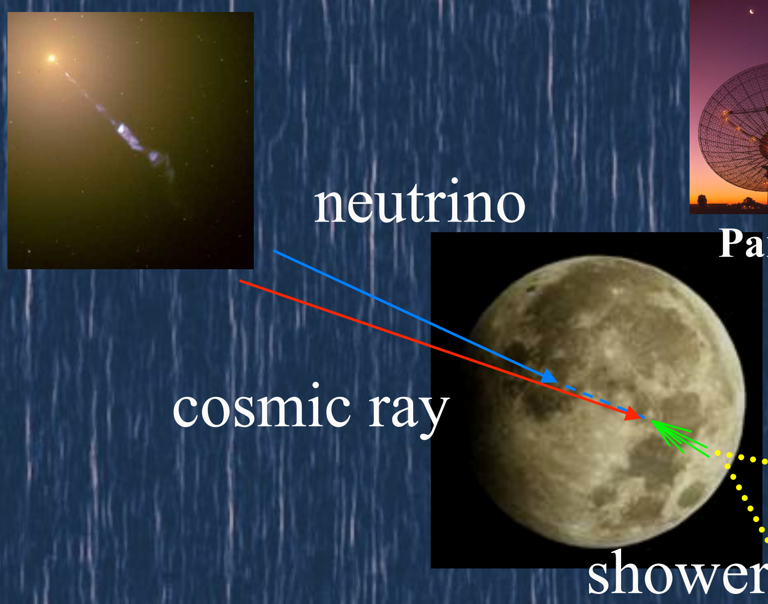


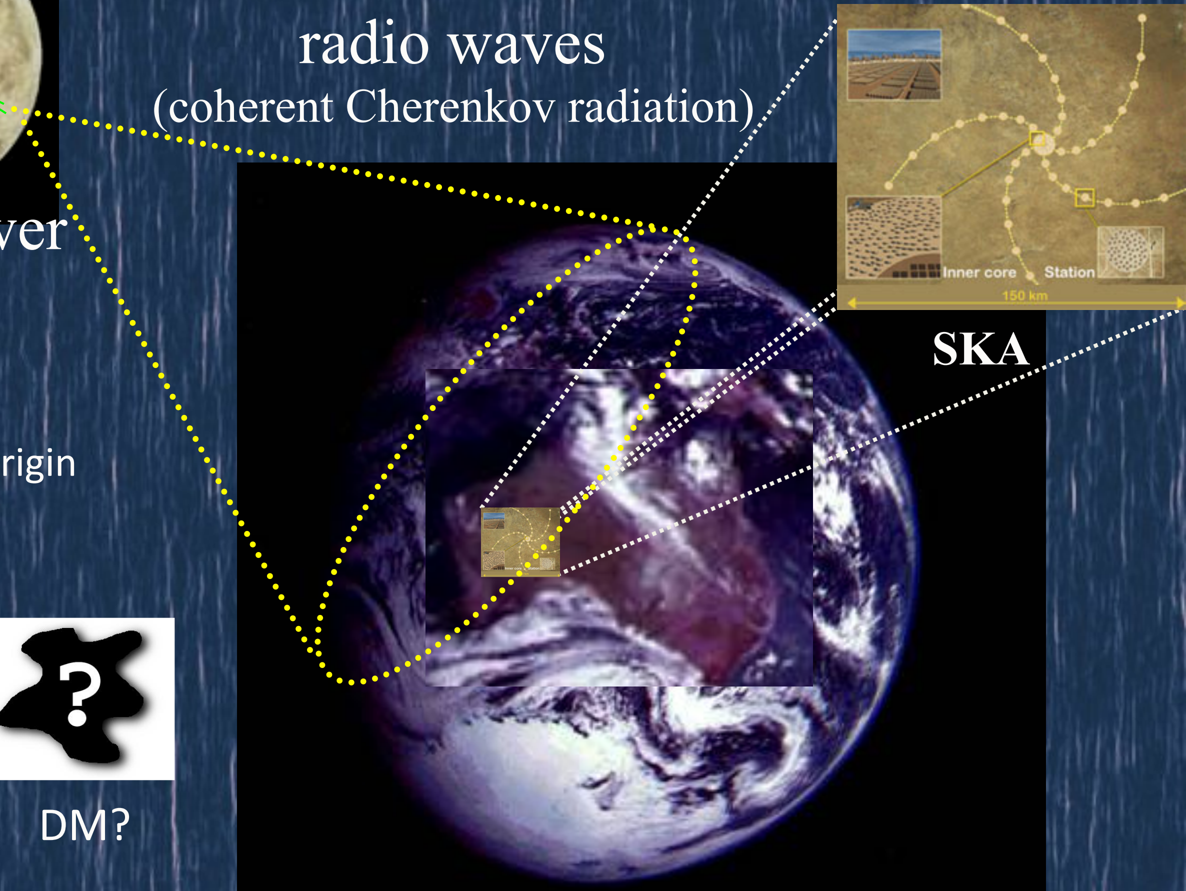
Problems:
how to power (battery performance degraded is so cold environment: windmills?
Data transmission: wireless, but possible interference…

ν Model	N_ν	MRF
Cosmogenic(GZK):		
ESS-Fig 9 [20] -p	40	0.05
Y-QSO [23] -p	23	0.1
Y-GRB [23] -p	51	0.044
WB [24] -p	16	0.14
Ahlers et al. [25] -p	12	0.19
Ave et al. -max [26]- Fe	3	0.75
Non-cosmogenic:		
AGN-MPR [27]	154	0.015
AGN-M [28]	62	0.037

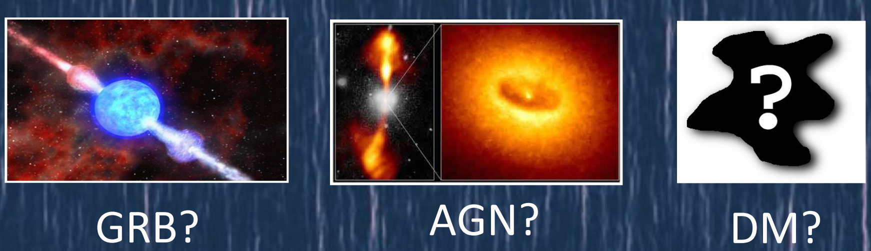
(First stage for Hexagonal Radio Array (seven ARIANNA stations funding approved)

Lunar Cherenkov technique



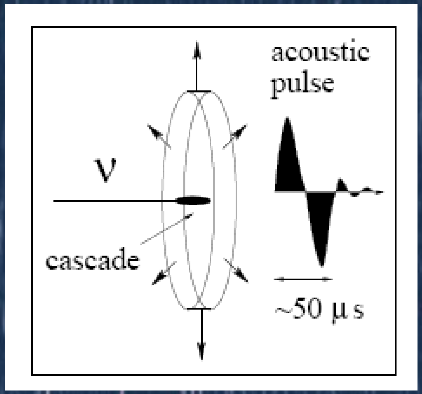


“A radio method to determine the origin of the highest-energy neutrinos and cosmic rays."



Acoustic detection

- A high-energy particle cascade deposits energy in the medium → heat → fast expansion → bipolar acoustic pulse (~10 μs, diameter 10 cm)
- Attenuation length: hundreds of meters
- It could be competitive with optical detection at multi-PeV energies



SPATS

SPATS (South Pole Acoustic Test Setup)

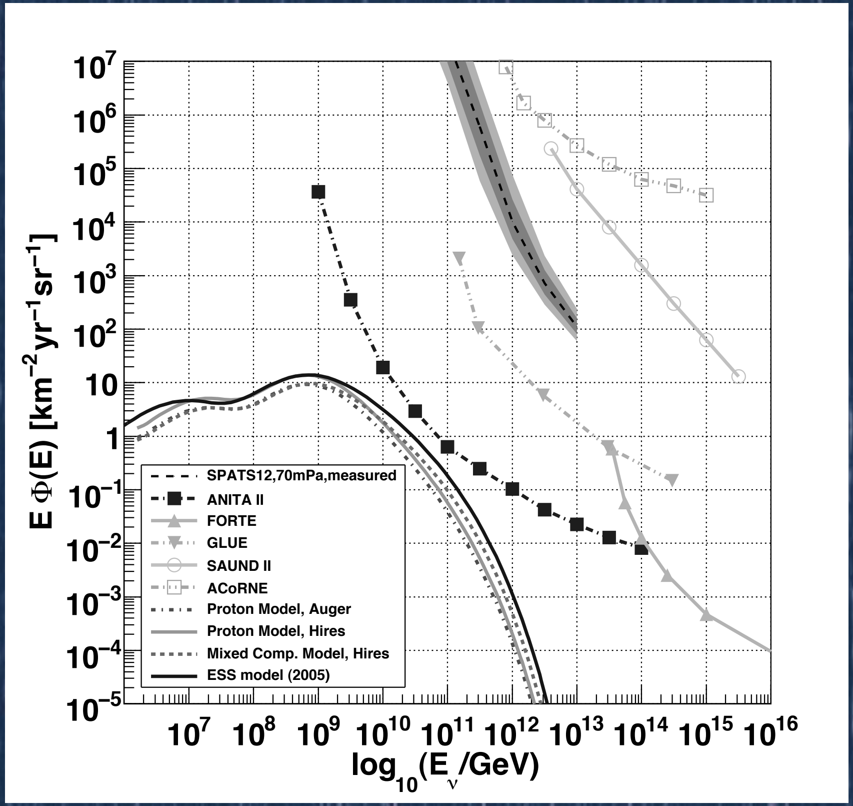
Test for measurement of attenuation length, noise, etc. for acoustic detection in the South Pole

Four strings deployed in the upper 500 m of some IceCube holes

interstring disntace: 125-43m

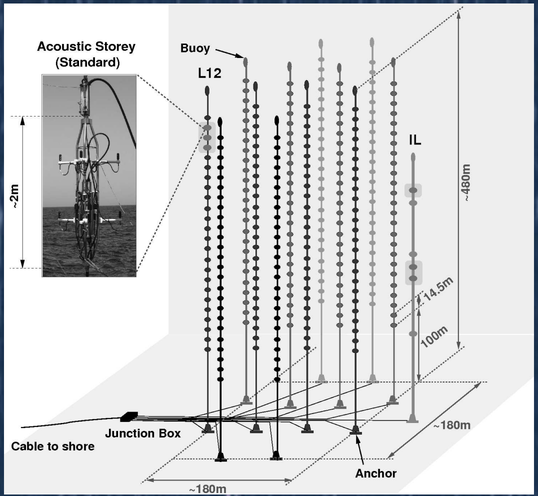
7 transmitters/receivers per string

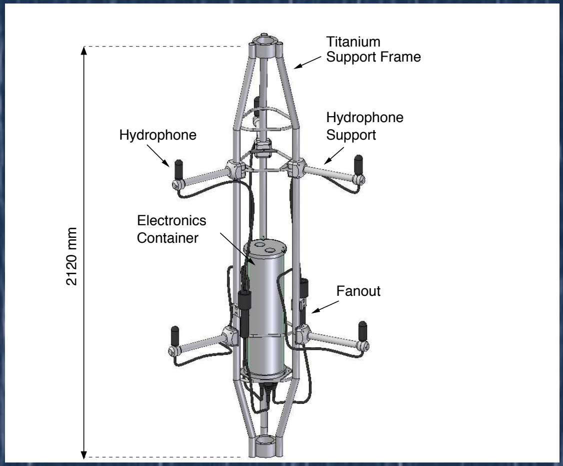
attenuation length ~300 m (shorter than expected)



AMADEUS

- Integrated in ANTARES
- Test bench for acoustic detection in the Mediterranean Sea
- Six acoustic storeys:
  - Three on the Instrumentation Line
  - Three in twelfth line of ANTARES
- Ambient noise measured very stable and at the expected level





Auger

- Detector for UHE CRs. Hybrid technique:
  - Surface detectors
  - Fluorence detectors
- Also works for neutrinos (E > ~ 0.1 EeV)
- Three possibilities:
  - Down-going
  - Earth-skimming
  - Andes-crossing (tau neutrinos)

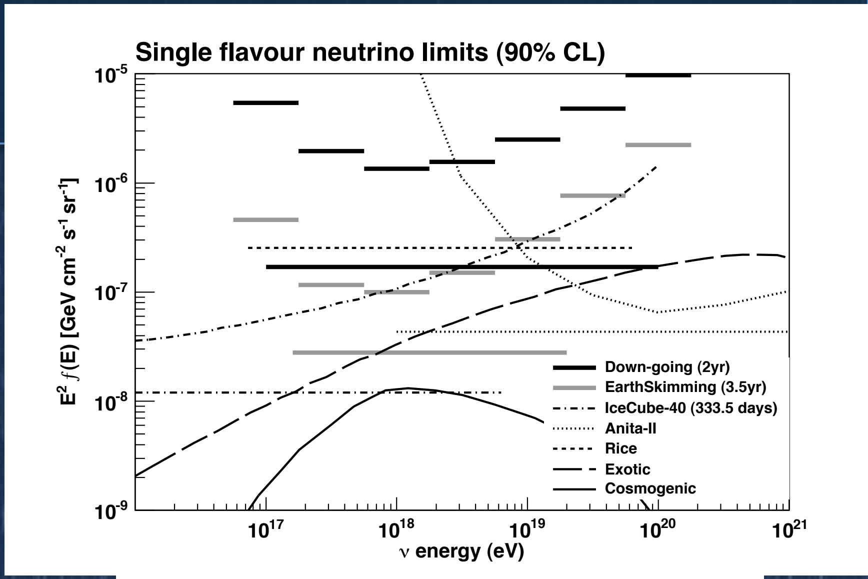
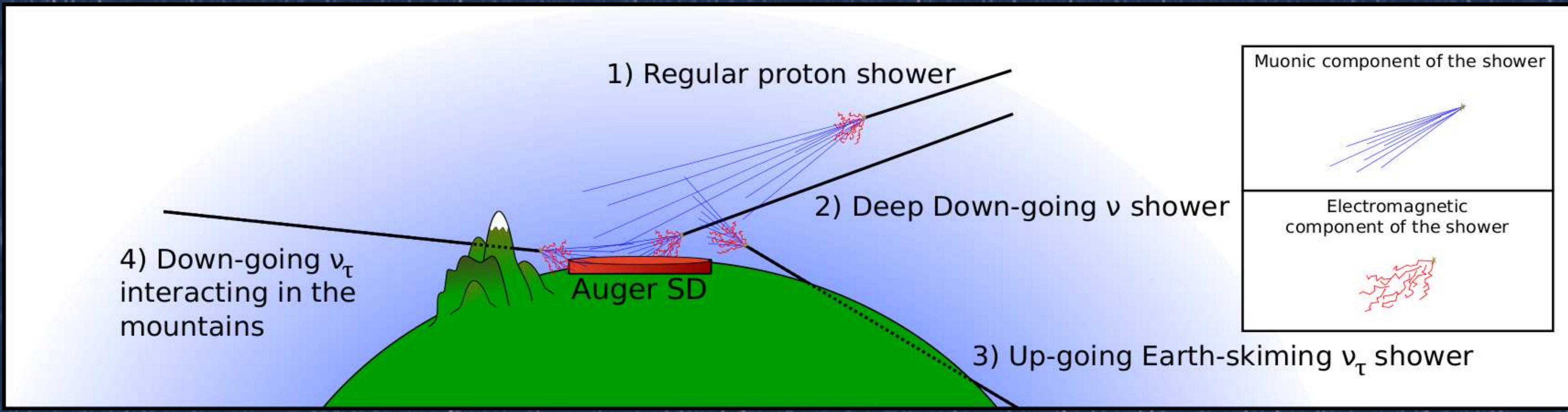
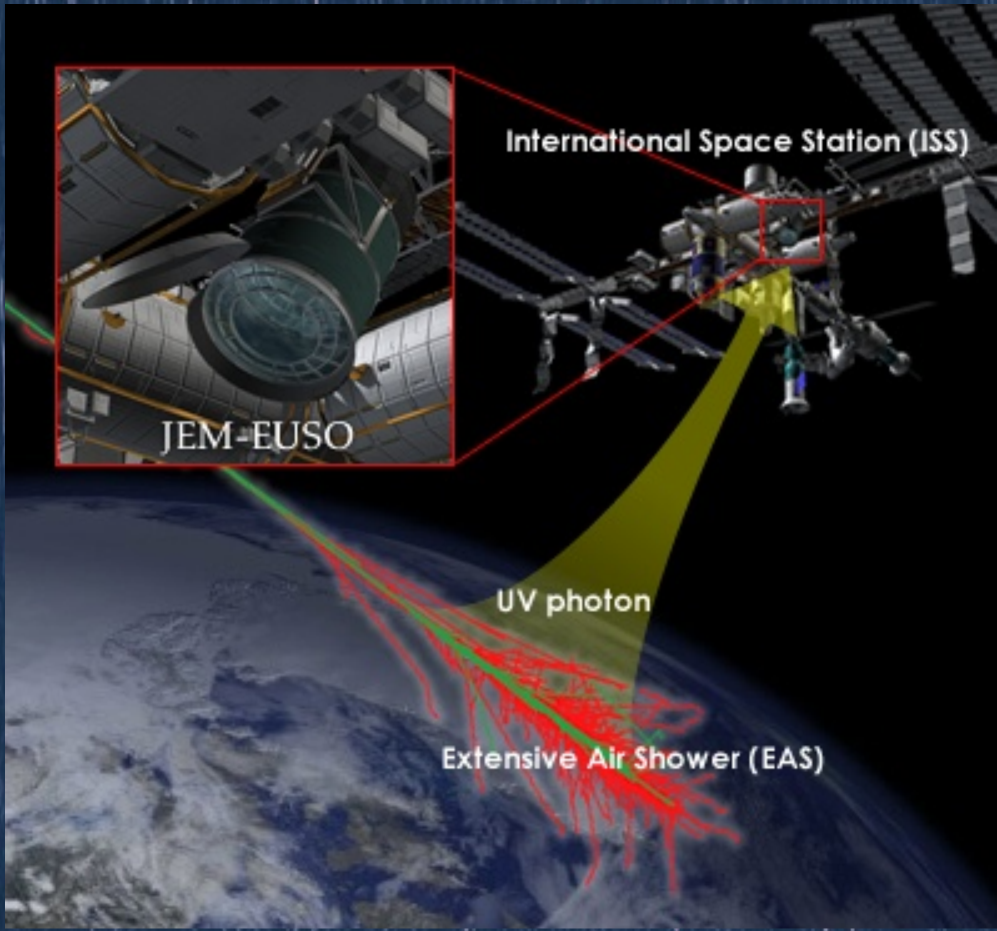


Figure 3: Differential and integrated upper limits (90% C.L.) from the Pierre Auger Observatory for a diffuse flux of down-going ν (2 yr of full Auger) and Earth-skimming ν_τ (3.5 yr of full Auger). Limits from other experiments are also plotted [16]. Expected fluxes are shown for cosmogenic neutrinos [17] and for a theoretical exotic model [18].

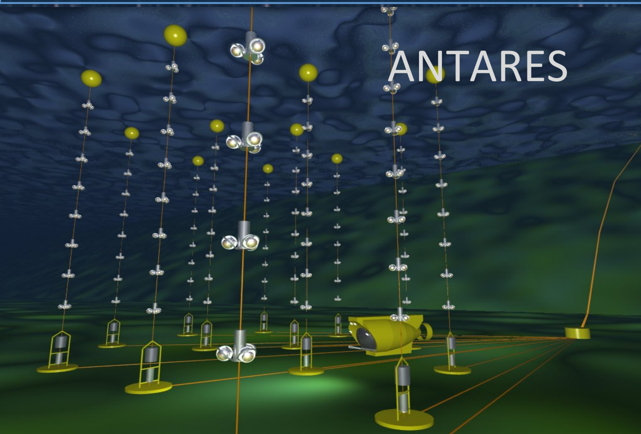


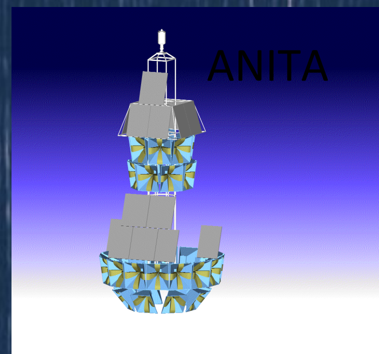
JEM-EUSO

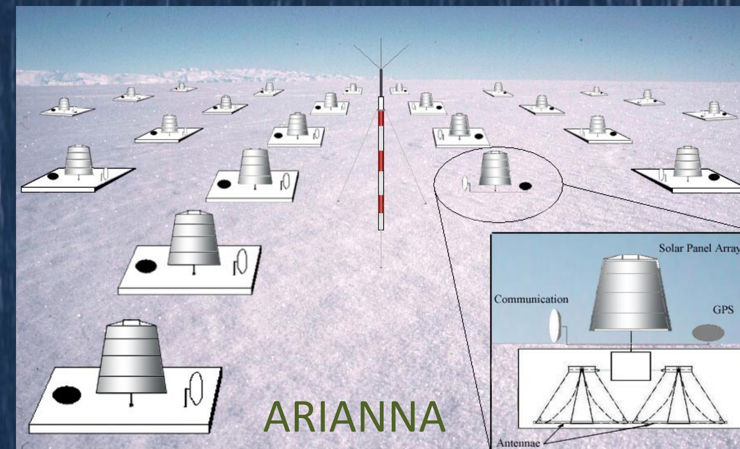
- Space detection (International Space Station)
- Based on fluorescence detection (airshowers initiated by UHE CRs, gammas and neutrinos)
- Huge volume



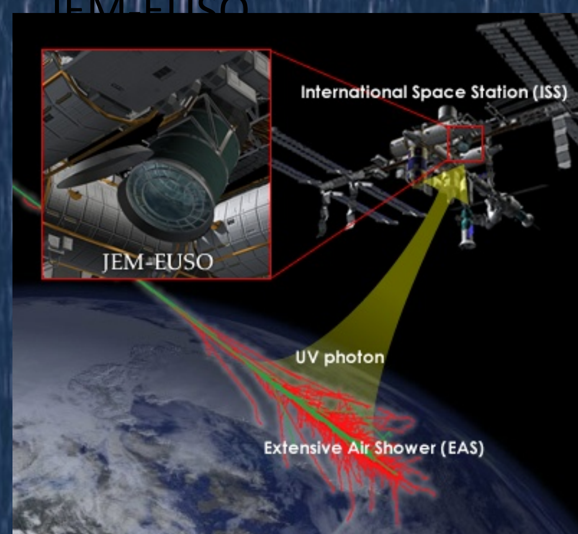
Many, many ideas…

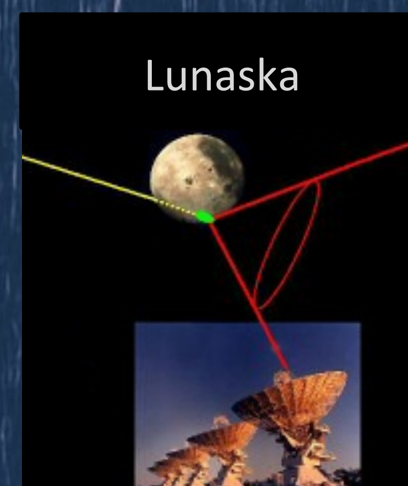






JEM-EUSO





Summary

- Neutrino astronomy is becoming a powerful tool for Astrophysics and Particle Physics
- AMANDA and Baikal pioneered the field
- IceCube, the first cubic kilometer detector, is complete a providing rich data. First severe constrains on astrophysical models have been set. Maybe the first cosmic neutrinos have been already observed
- ANTARES, in the Northern hemisphere, has proven the feasibility of large underwater detectors. It completes the full sky coverage and has its own specific advantages. The technical success of ANTARES paves the way for the cubic kilometer detector in the Mediterranean Sea: KM3NeT