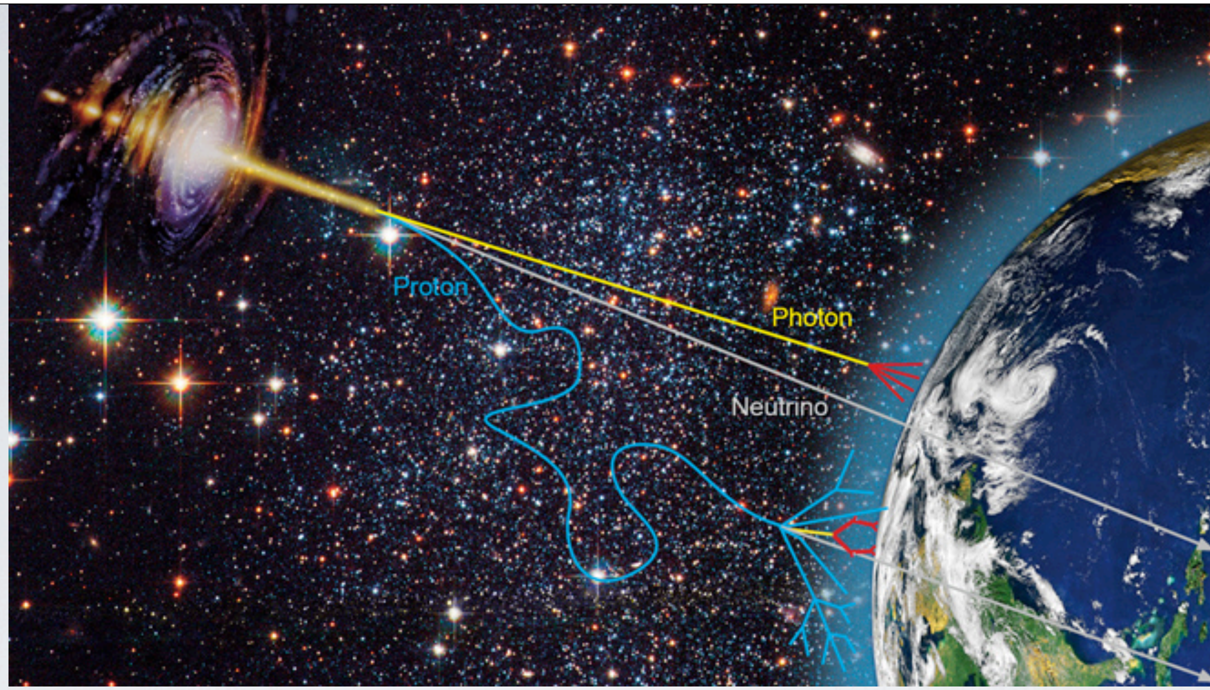

NEUTRINO TELESCOPES

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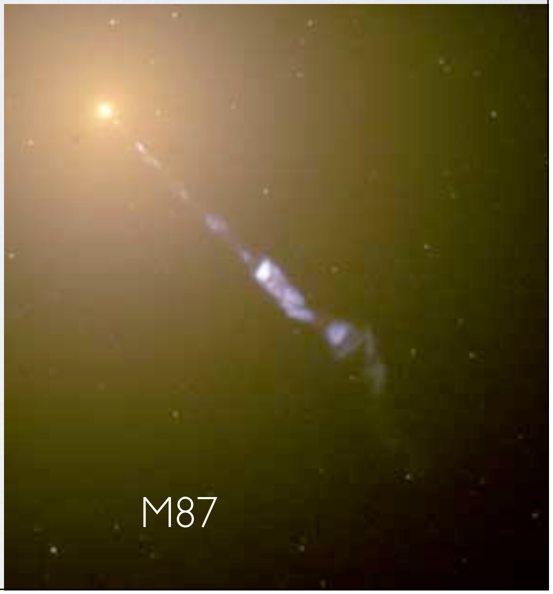
CONTENTS Lecture 1

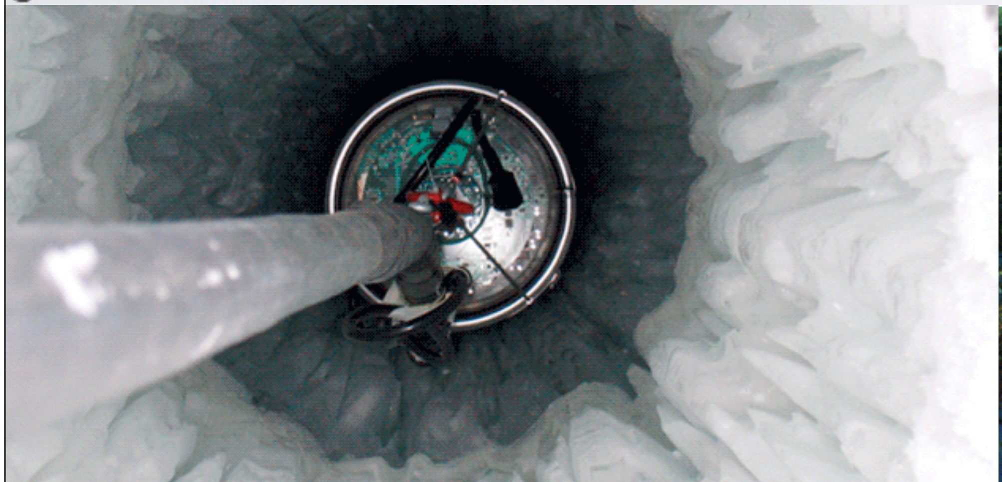
SSI 2010, Aug 9



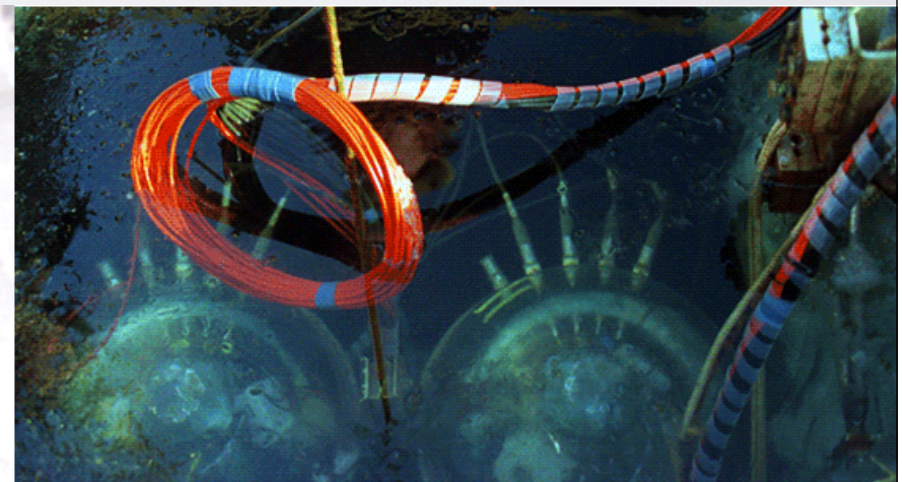
CONTENTS

Lecture 2

- Mediterranean Detectors
- Detection medium
- Detector Parameters
- Analysis Techniques
- Point sources
- Diffuse Fluxes
- Dark Matter
- SN detection



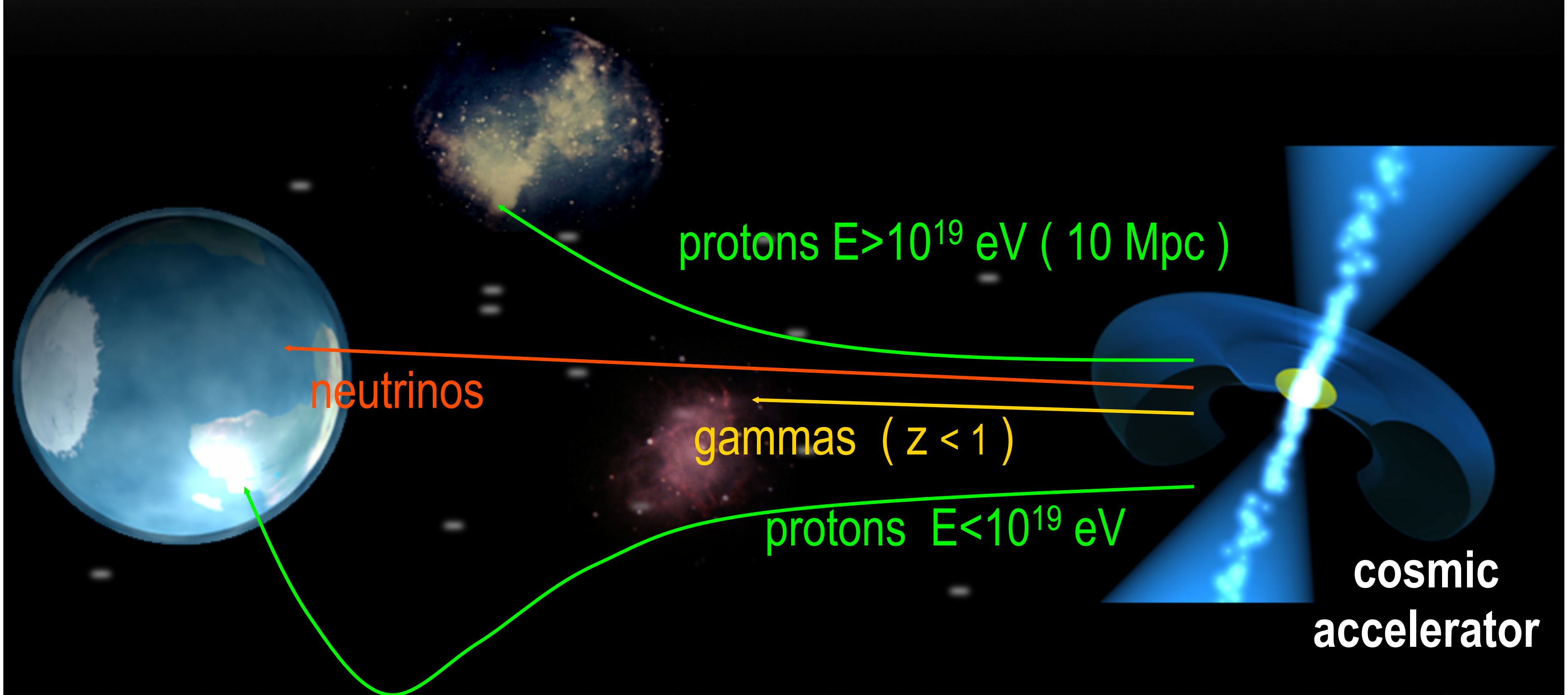
Installation of an optical module in the 2450 m deep hole



Lightsensors before lowering down to 1100 m depth in Lake Baikal

SSI 2010, Aug 10

MESSENGERS FROM THE UNIVERSE



photons: absorbed on dust and radiation; reprocessed at source

protons/nuclei: deviated by magnetic fields, absorbed on radiation (GZK)

Discovery messengers: Neutrinos and Gravitational Waves

OBSERVABLE UNIVERSE

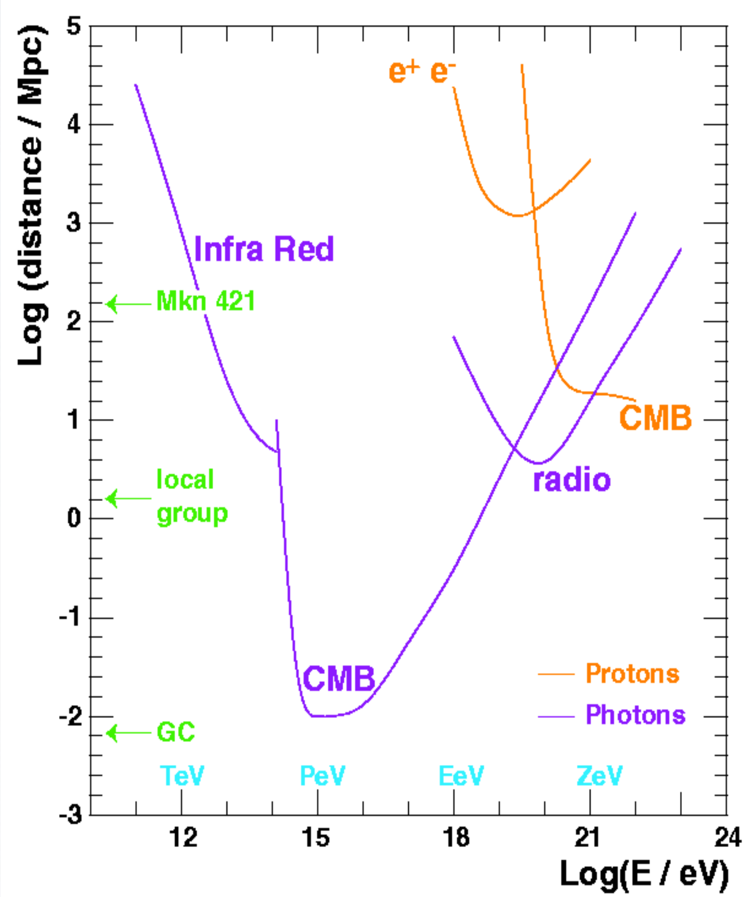
Reference values:

Galactic Centre	8 kpc
Local group (Andromeda M31)	0.725 Mpc
Mrk 421	~ 136 Mpc

Universe c/H_0 = 13.7 billion yrs
(for a reference scale: eg z=1 ~ 6.6 Gpc)

neutrons decay: $\Upsilon ct = E/m\, ct \sim 10$ kpc for E ~ 10^{18} eV

1Mpc = 3.26 Mly = 3.1 10^{24} cm



Interaction on cosmological backgrounds:

Interactions on cosmic backgrounds		threshold	mean free path
γ-rays:	$\gamma + \gamma_{2.7k}$	$>10^{14}$eV	10 Mpc
proton:	$p + \gamma_{2.7k} \rightarrow \pi^0 + X$	$>5.10^{19}$eV	50 Mpc
neutrinos:	$\nu + \nu_{1.95K} \rightarrow Z+X$		

$$E_{res} = \frac{M_Z^2}{2m_\nu} \cong 4 \times 10^{21} \left(\frac{1\text{eV}}{m_\nu}\right) \text{eV}$$

GZK horizon:

$$L_\gamma = \frac{1}{\sigma_{p-\gamma_{CMB}} n_\gamma} \sim \frac{1}{10^{-28}\text{cm}^2 \times 400\text{cm}^{-3}} \sim 10 \text{ Mpc}$$

The neutrino horizon is comparable to the universe!

$$L_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6Gpc$$

T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)
Beacom's Lectures

THE BIRTH OF NEUTRINO ASTRONOMY

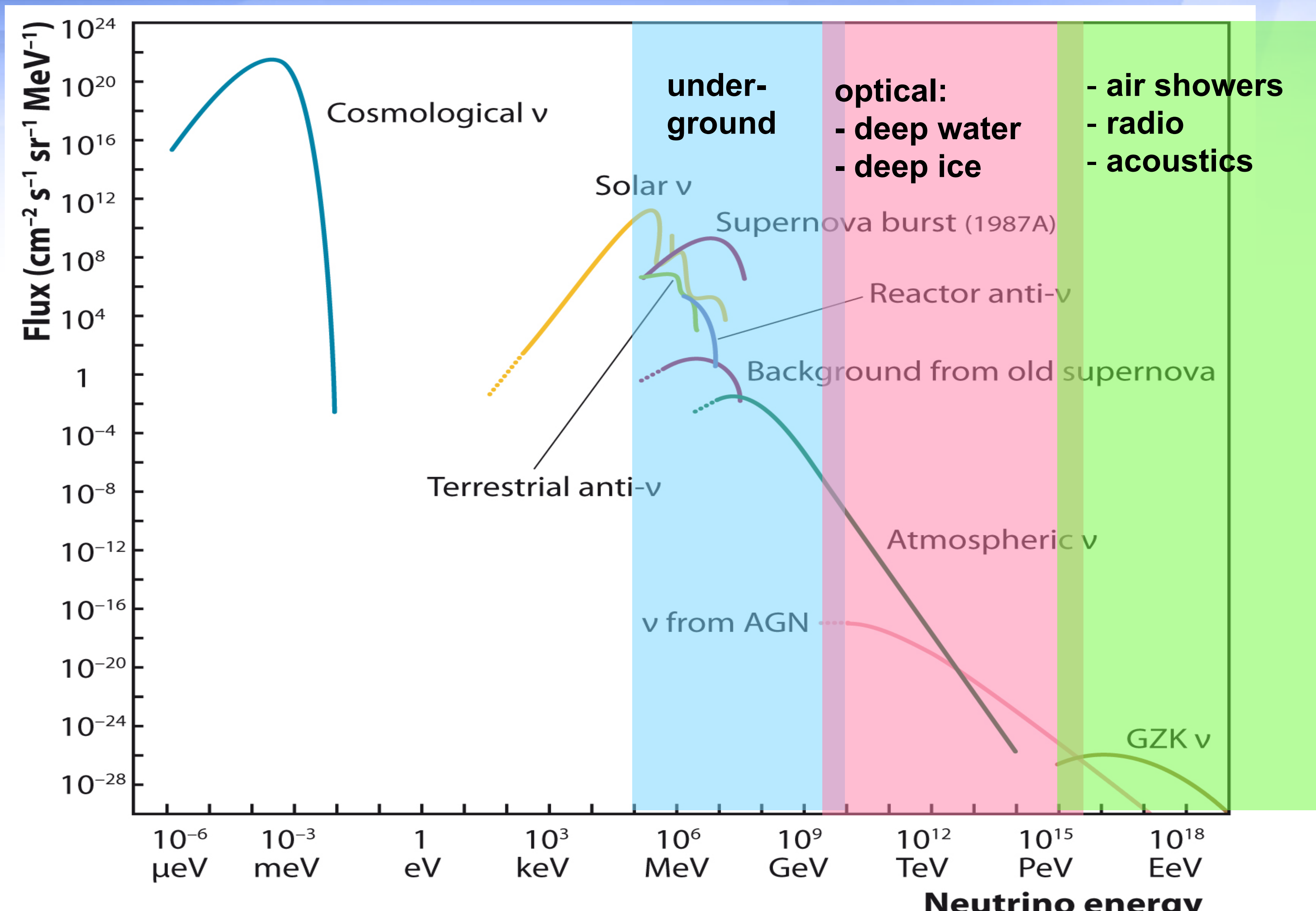
First extra-terrestrial neutrino signals (~10 MeV range)

solar neutrinos (Haxton's Lectures)

Nobel Prize in Physics 2002

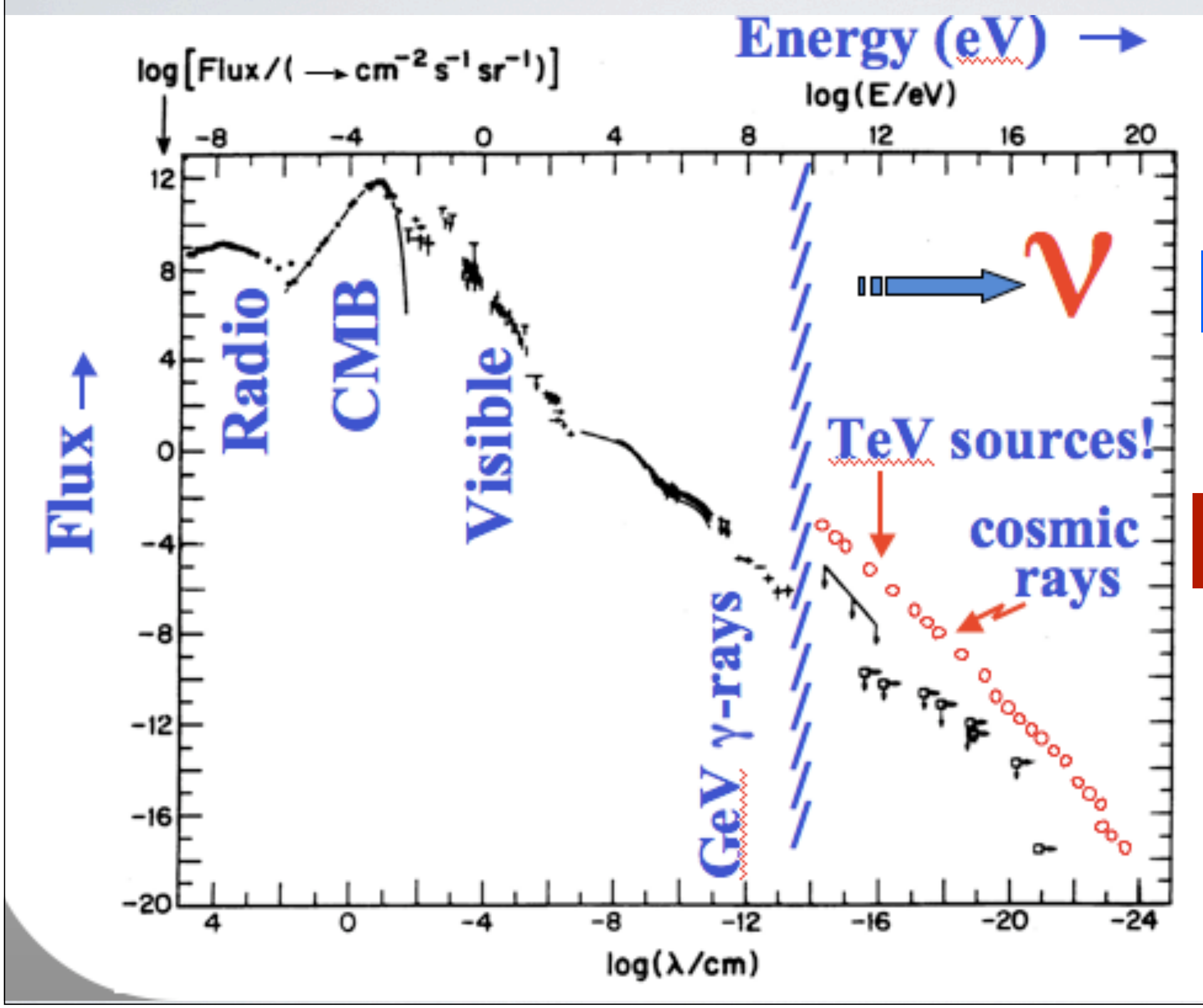
SN1987A (Mezzacappa's Lectures)

SUMMARY OF NEUTRINO FLUXES



Fermi acceleration predicts $dN/dE \sim E^{-2}$. CRs undergo interactions during propagation resulting in softer spectra while neutrinos preserve this dependency.

UNDERSTANDING ACCELERATION PROCESSES IN THE UNIVERSE



Gamma astronomy

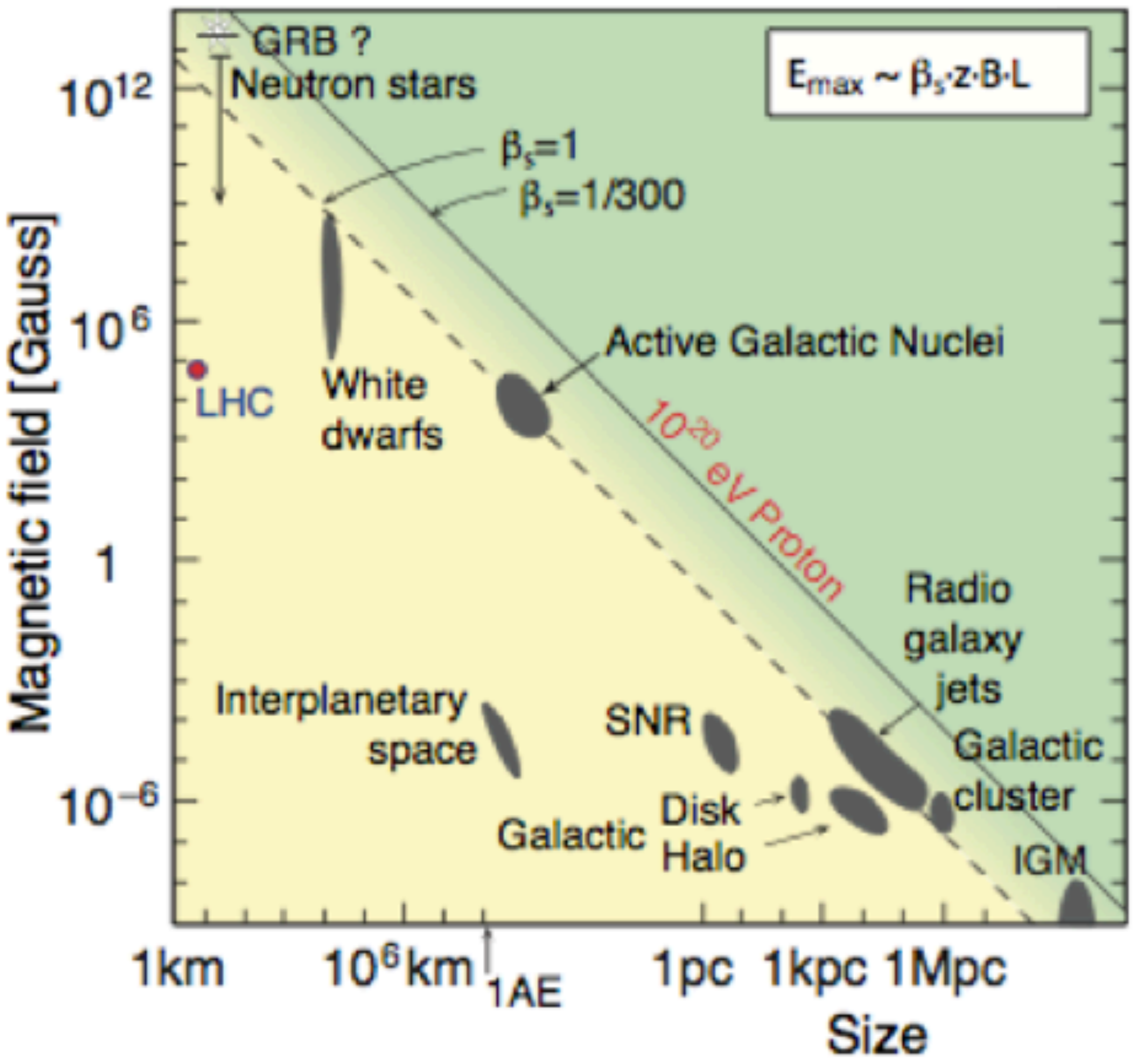
< 100 TeV

Neutrino astronomy

> 10 EeV

Proton astronomy

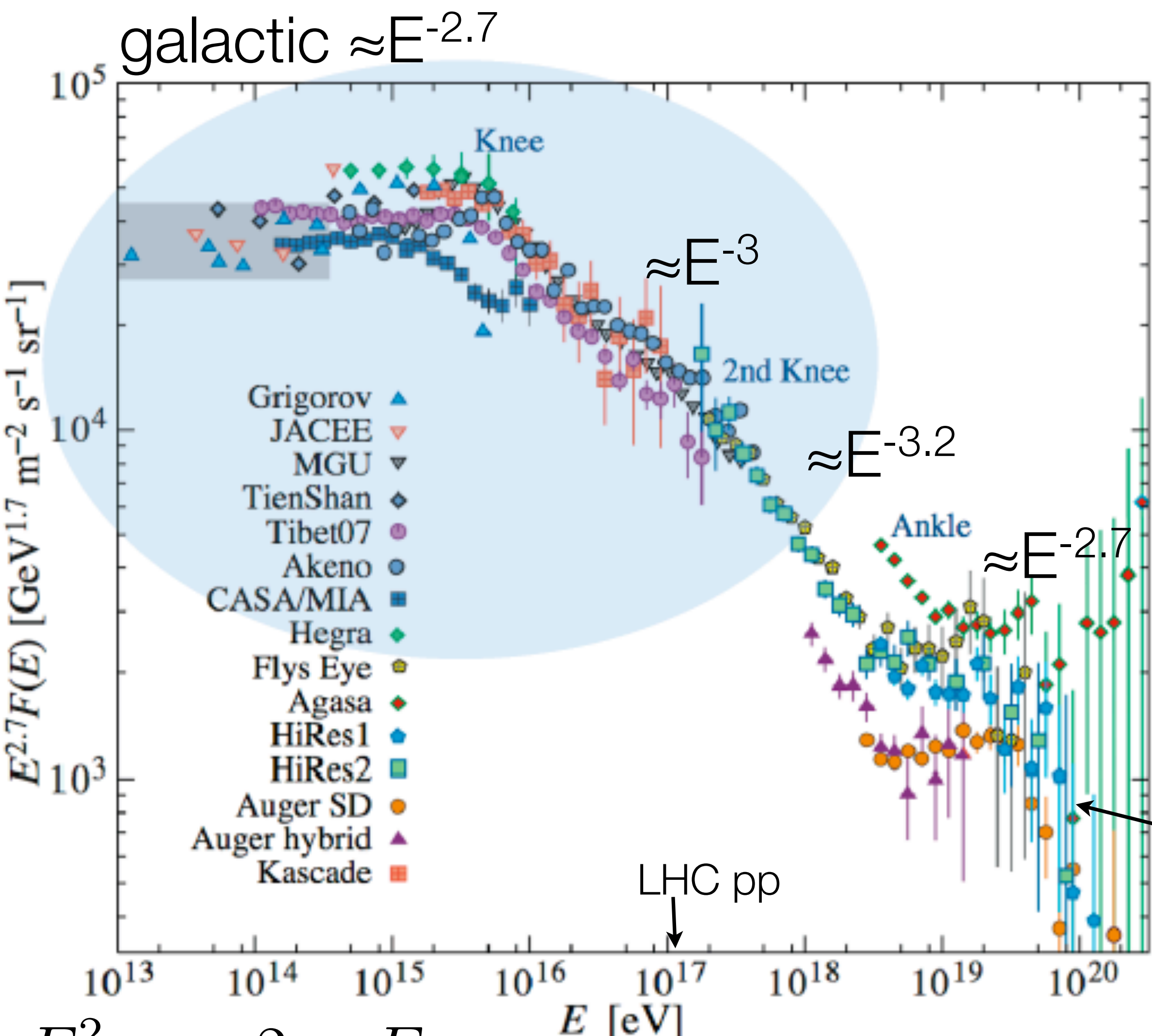
CR sources: Hillas plot



$$E_{\max} \simeq 10^{18}\,\mathrm{eV}\;Z\;\beta_s\;\left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right).$$

Blanford on Cosmic Accelerators
Meszaros on GRBs

Cosmic Ray Spectrum



Luminosity of the CR beam decreases steeply with energy

Galaxy containment (B ~ 4 uG)

R ~ 400 pc @ 10^{18} eV
R ~ 0.4 pc @ 10^{15} eV

1 TeV = 1.6 erg
1 EeV = 0.16 Joule

extra-galactic

What sources for $>10^{17}$ eV CRs?

$$E_{CM}^2 \sim 2 m_p E_{Lab}$$

For LHC: $E_{CM} = 14$ TeV, $m_p \sim 1$ GeV $\rightarrow E_{Lab} \sim 10^{17}$ eV

POWER OF SOURCES OF CRS AND W&B LIMIT

energy density flux = velocity x density

$$4\pi \int dE \left(E \frac{dN}{dE} \right) = c\, \rho_E$$

Galactic

galactic CR: $\rho_E \sim 10^{-12}$ erg/cm^3
Power needed: $\rho_E / T_{esc} \approx 10^{-26}$ erg/cm^{3}s
$T_{esc} \approx 3\times10^6$ yrs escape time from Galaxy

10^{51} erg/SN every 30 years $\sim 10^{-25}$ erg/cm^3 s
for Galactic disk volume $\sim 10^{67}$ cm^3

10% of SN provides the environment and energy to explain the galactic CRs!

1934 Baade and Zwicky
Acc mechanism then proposed by Fermi in 1949

Extragalactic

Above the ankle:

$$E\left\{E\frac{dN_{CR}}{dE}\right\} = \frac{3\times10^{10}\,\mathrm{GeV}}{(10^{10}\,\mathrm{cm}^2)(3\times10^7\,\mathrm{s})\,\mathrm{sr}} = 10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Energy density in extra-galactic CRs:

$$\rho_E = \frac{4\pi}{c}\int_{E_{min}}^{E_{max}} \frac{10^{-7}}{E} dE \frac{\mathrm{GeV}}{\mathrm{cm}^3} \simeq 3\times10^{-19}\frac{\mathrm{TeV}}{\mathrm{cm}^3}$$

$$E_{max}/E_{min} \simeq 10^3$$

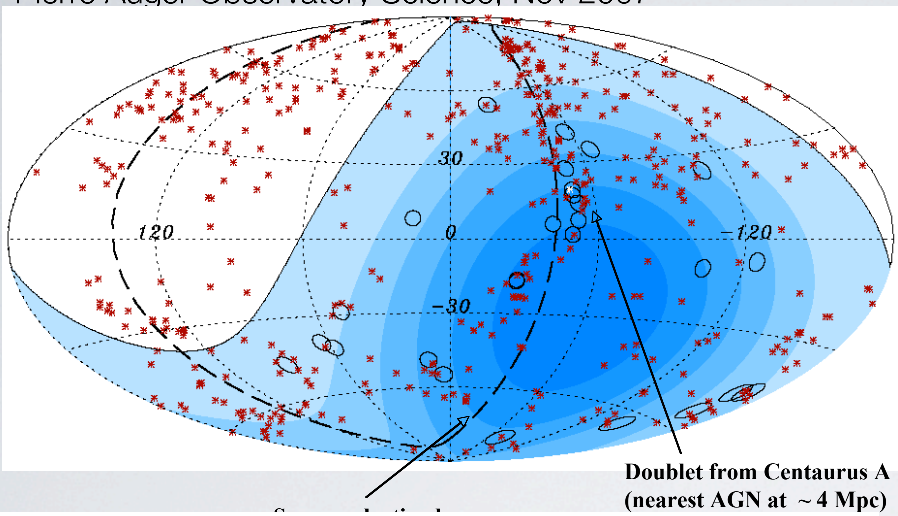
Power needed by a population of sources of p with E^{-2} to generate ρ_E over the Hubble time = 10^{10} yrs $\approx 10^{44}$ erg Mpc^{-3} yr^{-1}

3×19^{39} erg/s per galaxy
3×10^{42} erg/s per cluster of galaxies
2×10^{44} erg/s per AGN
2×10^{52} erg per cosmological GRB.

According to this reasoning W&B produced an upper limit to extragalactic neutrino fluxes http://arxiv.org/abs/hep-ph/9807282

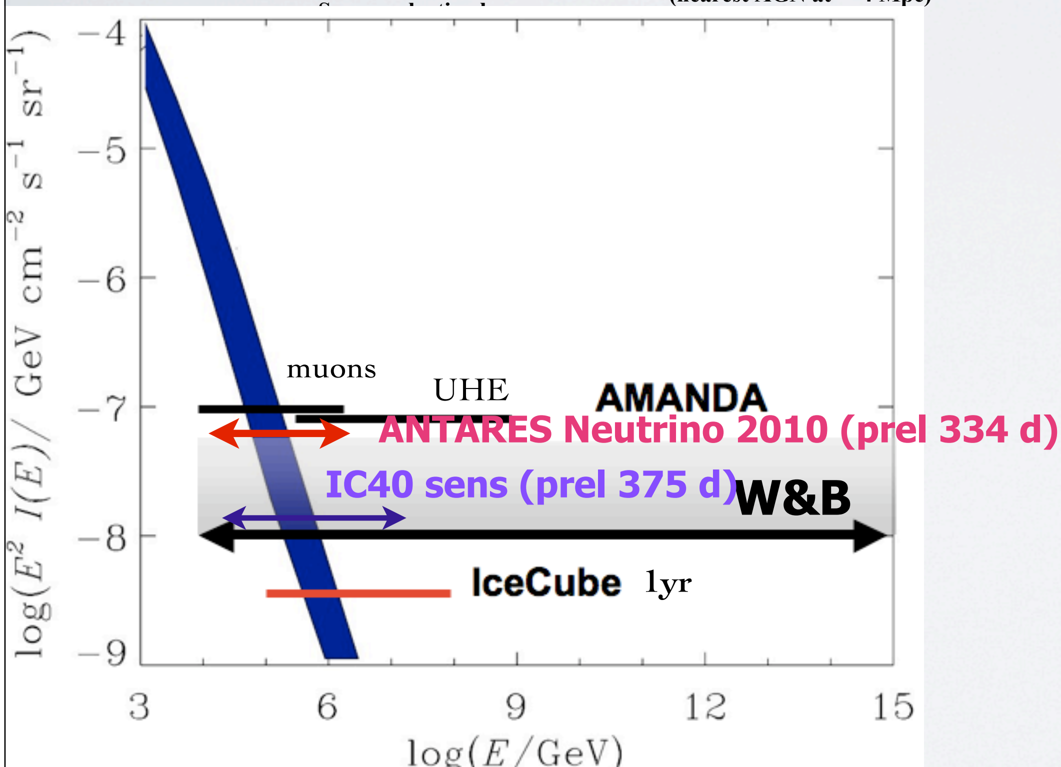
Neutrino - Pierre-Auger UHECR

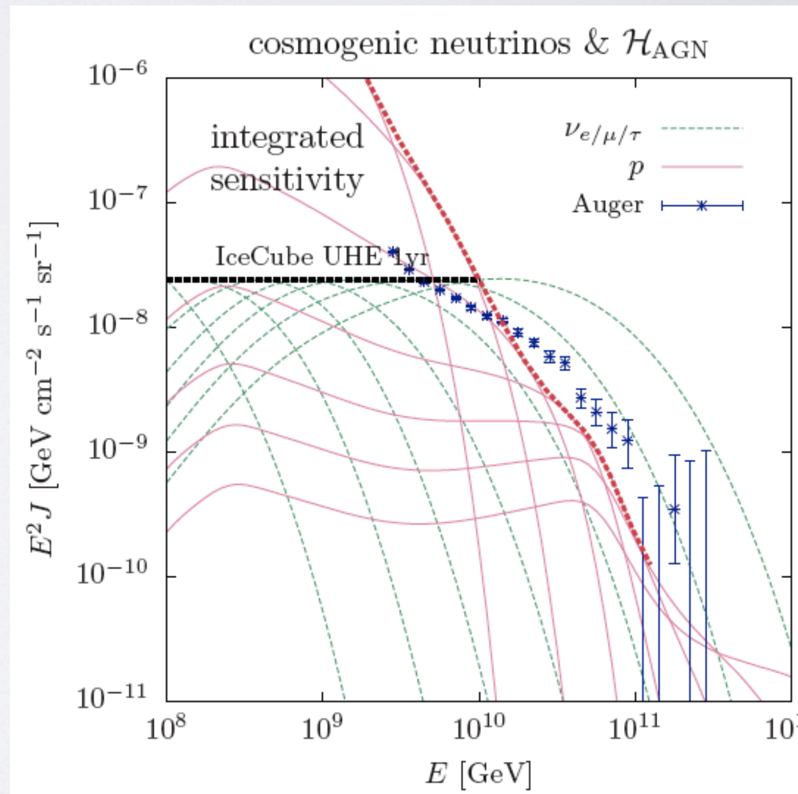
Pierre Auger Observatory Science, Nov 2007



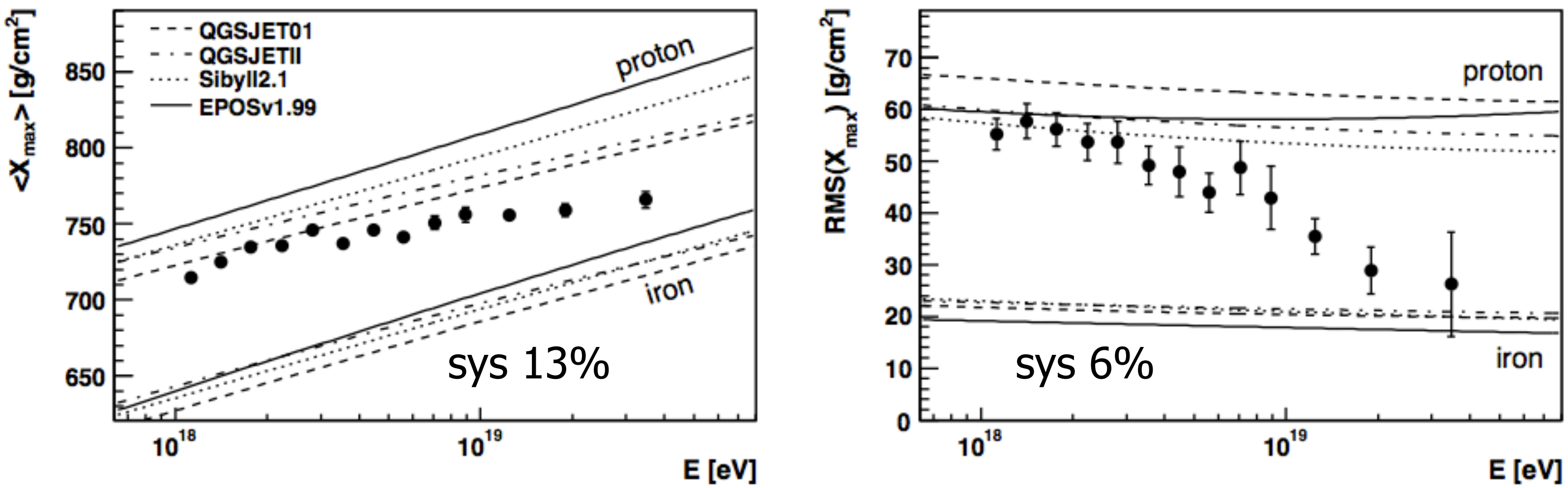
Cosmogenic neutrino fluxes from a population of AGNs with strong source evolution ∝(1+z)[5] Green curves: cosmogenic neutrinos with E_{max} between 10^8-10^{12} GeV. Solid red curves: protons producing the neutrinos. Red dashed curve = proton envelope

(Ahlers et al, 2009).





UHECR Composition?



P. Auger hybrid events

FIG. 3: $\langle X_{\max}\rangle$ and RMS($X_{\max}$) compared with air shower simulations [20] using different hadronic interaction models[21].

Fe (λ_{int} ~2.3 g/cm^2) interacts before in the atmosphere than p (λ_{int} ~90 g/cm^2)

Superposition principle: A nucleons sharing primary energy E_0/A

Shower maximum depth and magnitude of the shower-to-shower fluctuations of the maximum depth which is expected to decrease with the number of primary nucleons A and to increase with the interaction length of the primary particle.

Less cosmogenic neutrinos if UHECR are nuclei

http://arxiv.org/pdf/1002.0699v1

Are there neutrinos in UHECR directions?

- 1) 22 P.Auger + 13 HiReS events in IceCube-22 string FoV; similar search in ANTARES

- 2) UHECR deflections with respect to neutrino sources unknown: assume gaussian smear with sigma= 3 deg

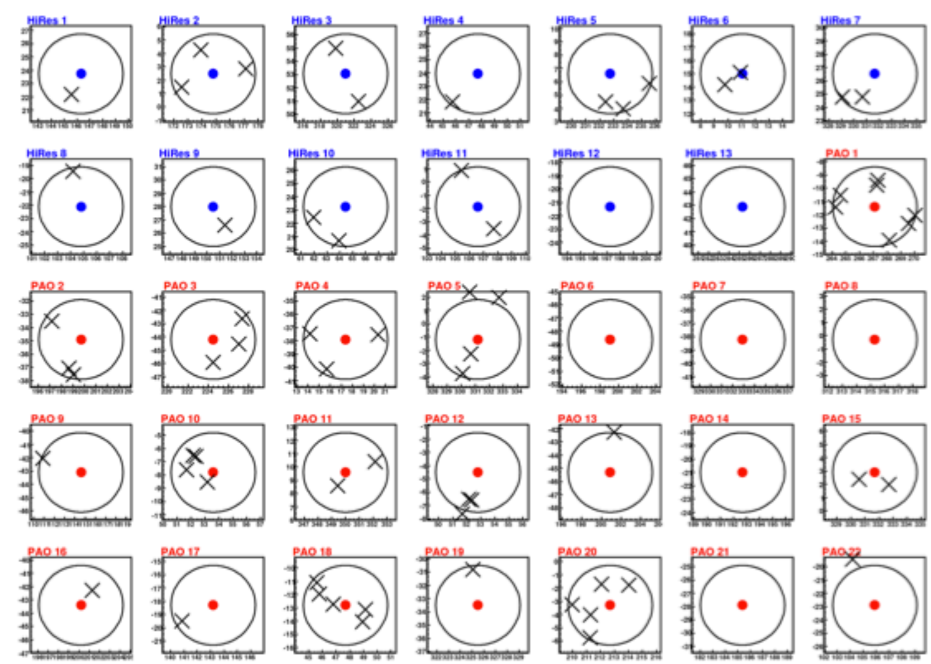
R. Lauer PhD Thesis
IceCube Coll, Vulcano 2010
and Neutrino 2010

IceCube-22 events: 60

Expected from backg: 43.7

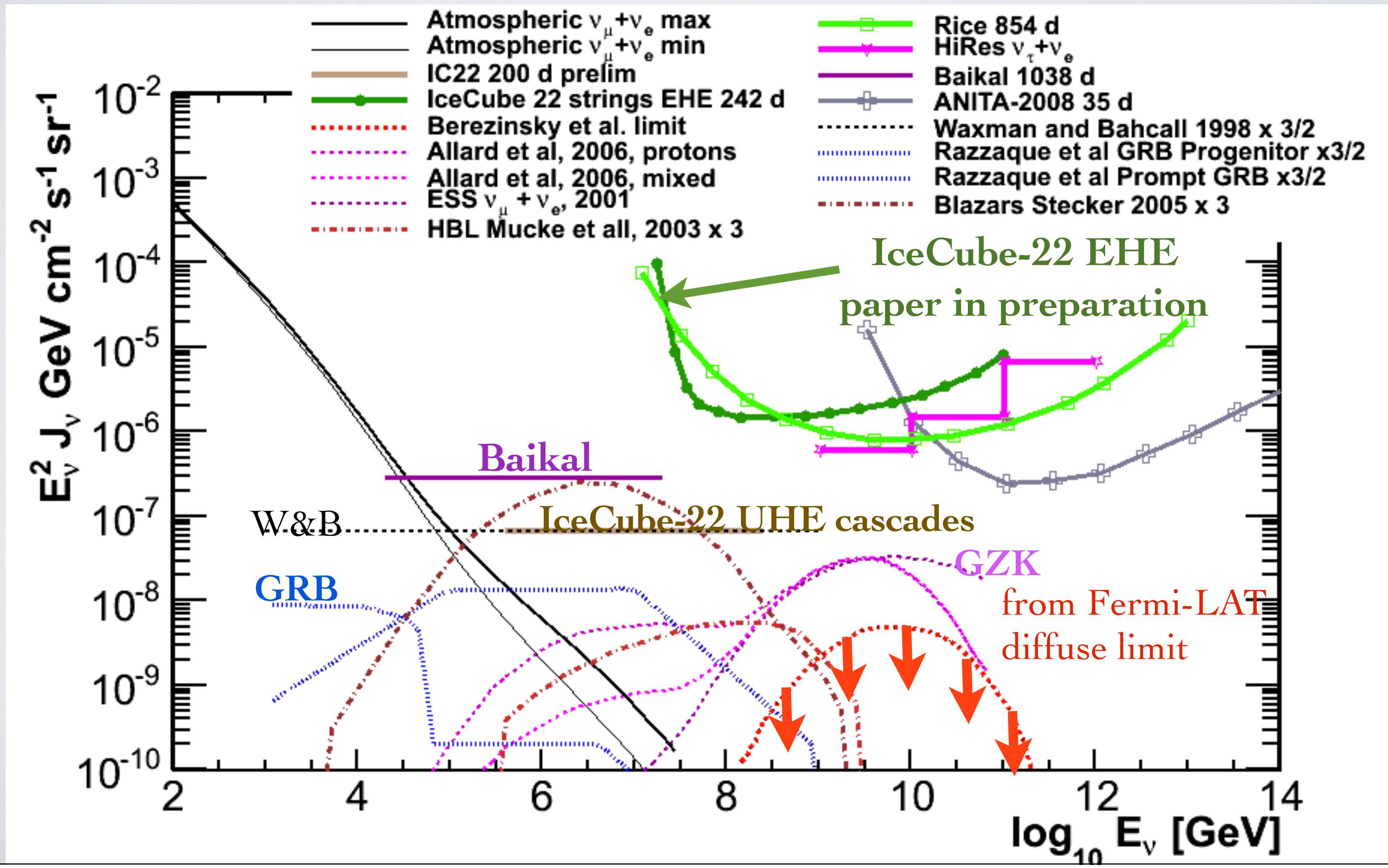
Excess prob.: 0.98% (2.33 σ)

Compatible with background



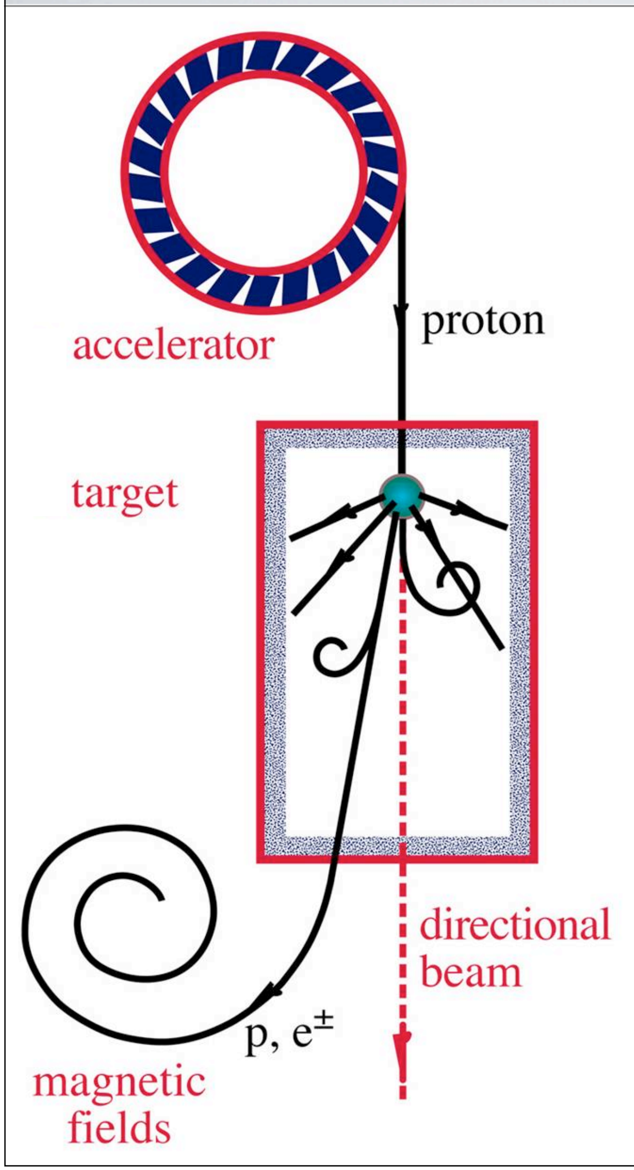
UHE-Neutrino-gamma connection

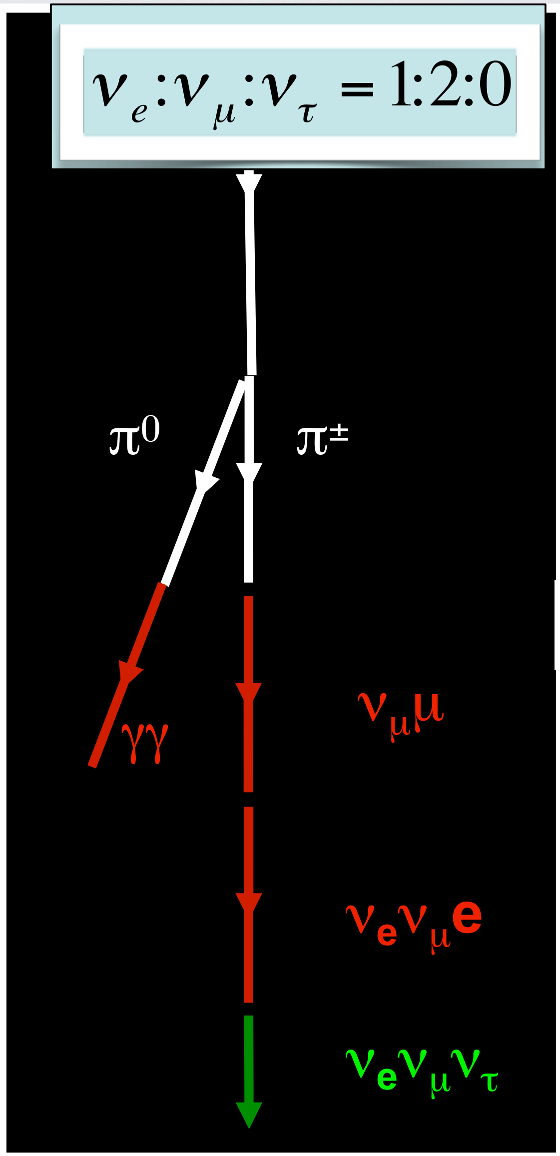
UHECR interactions on CMB produce neutrinos and gammas. Gammas cascade down unlike neutrinos. **Fermi-LAT extra-galactic diffuse bound**(arXiv:1002:3603) limits the energy density in cascades which in turn limits the expected UHE neutrino flux (Berezinski et al., arXiv:1003.4959). This excludes most models with strong evolution detectable by present experiments.



THE GENERIC NEUTRINO SOURCE

Beam Dump model: the cosmic-ray - gamma - neutrino connection





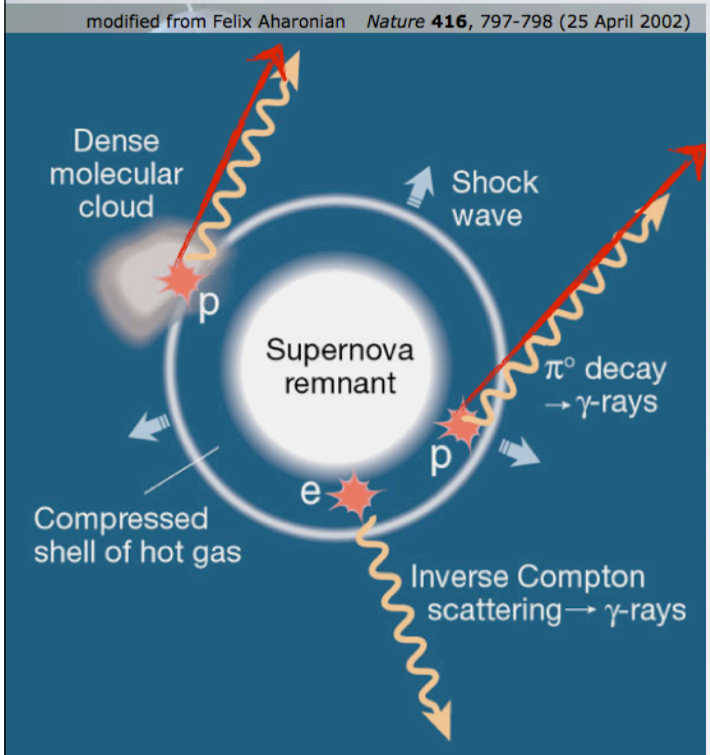
At source.

After propagation:

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

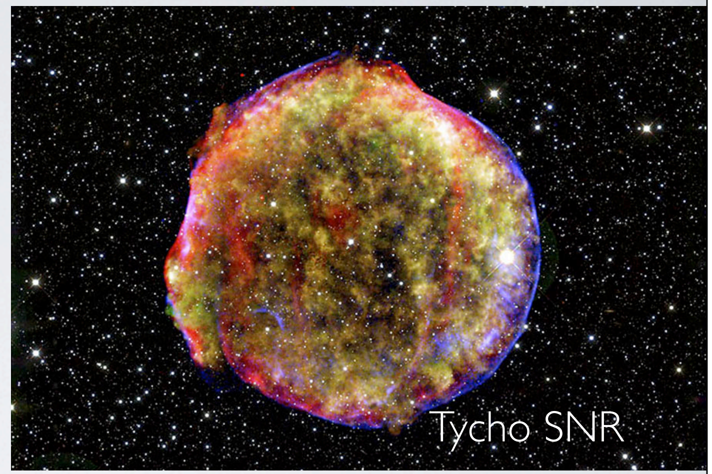
ν/γ after oscillations ~ 0.5

SNR BEAM DUMP



$\pi^{\pm}$ decay $\rightarrow \nu$

ν NOT produced in leptonic interactions



$$p + p \rightarrow p + p + \pi^0$$

$$p + p \rightarrow p + n + \pi^+$$

$$p + A \rightarrow \pi^0 + \pi^+ + \pi^-$$

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

$\pi^{\pm} \rightarrow \mu\nu_\mu$, $e + 2\nu_\mu + \nu_e$

CRs +

2 γ's with $E_\gamma \approx E_\pi/2 \approx E_p/6$

4 νμ with $E_\nu \approx E_\pi/4 \approx E_p/12$

$$E_{p,th} = \frac{(2m_p + m_\pi)^2 - 2m_p^2}{2m_p} \sim 1.23 \text{ GeV}$$

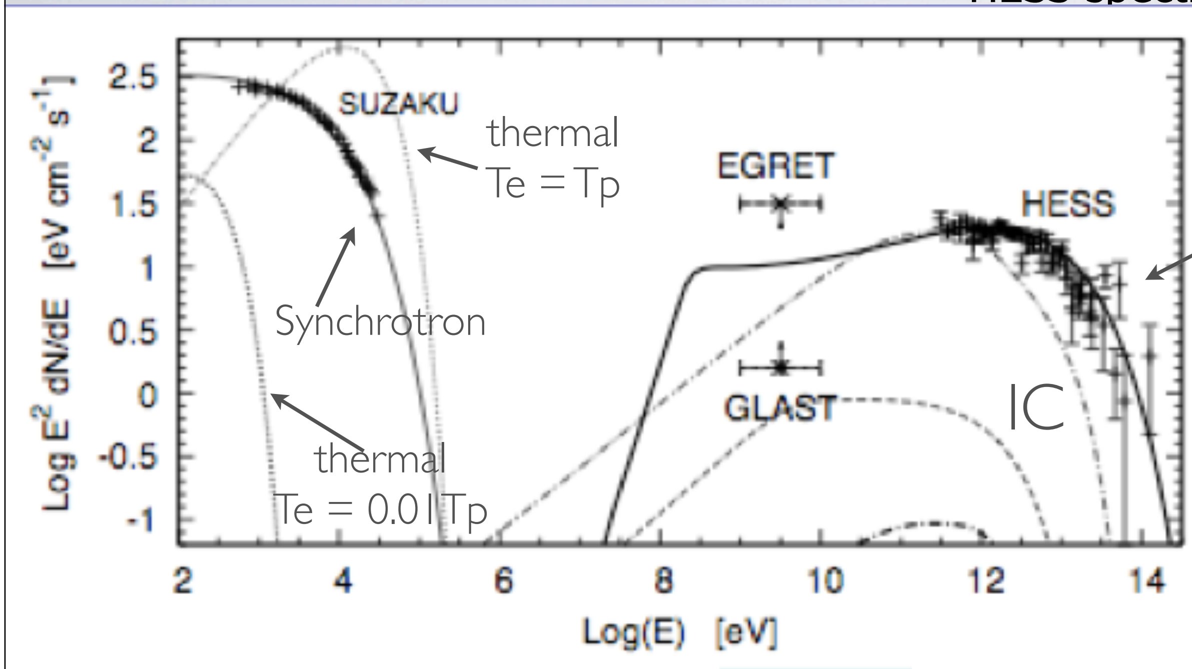
K~0.5 after oscillations

$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu,$$

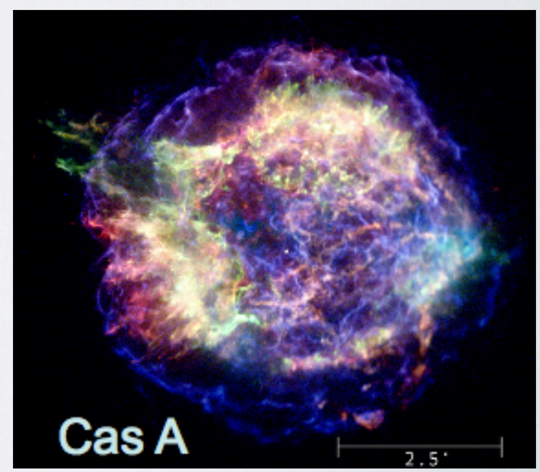
HADRONIC LEPTONIC SCENARIOS: RXJ 1713.7-3946

Morlino et al
http://arxiv.org/abs/0810.0094v1

CANGAROO: hadronic model preferred (Nature 2002)
HESS spectrum harder (A&A 464(2007) 235)



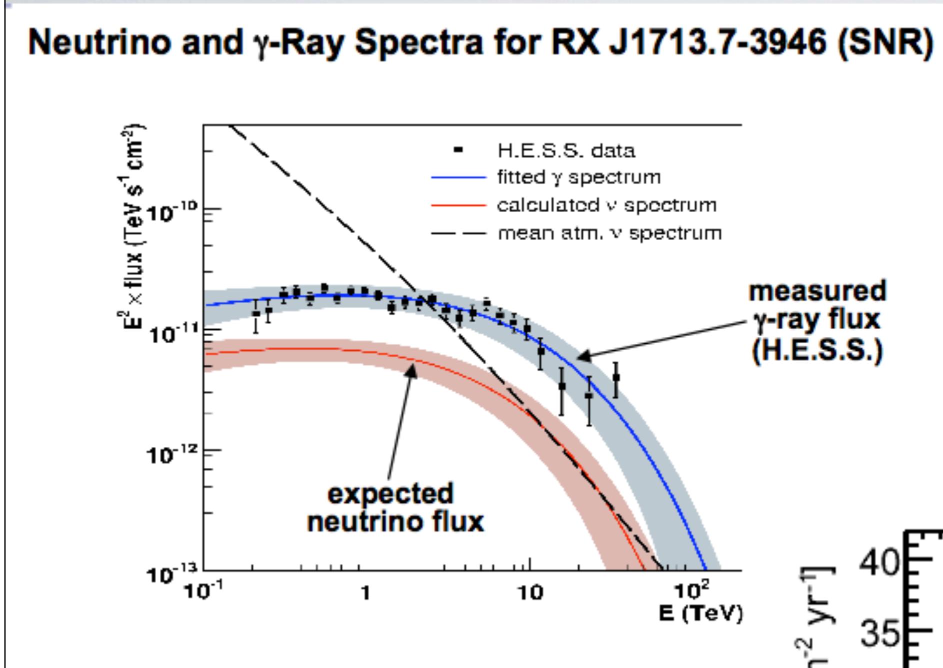
pion decay



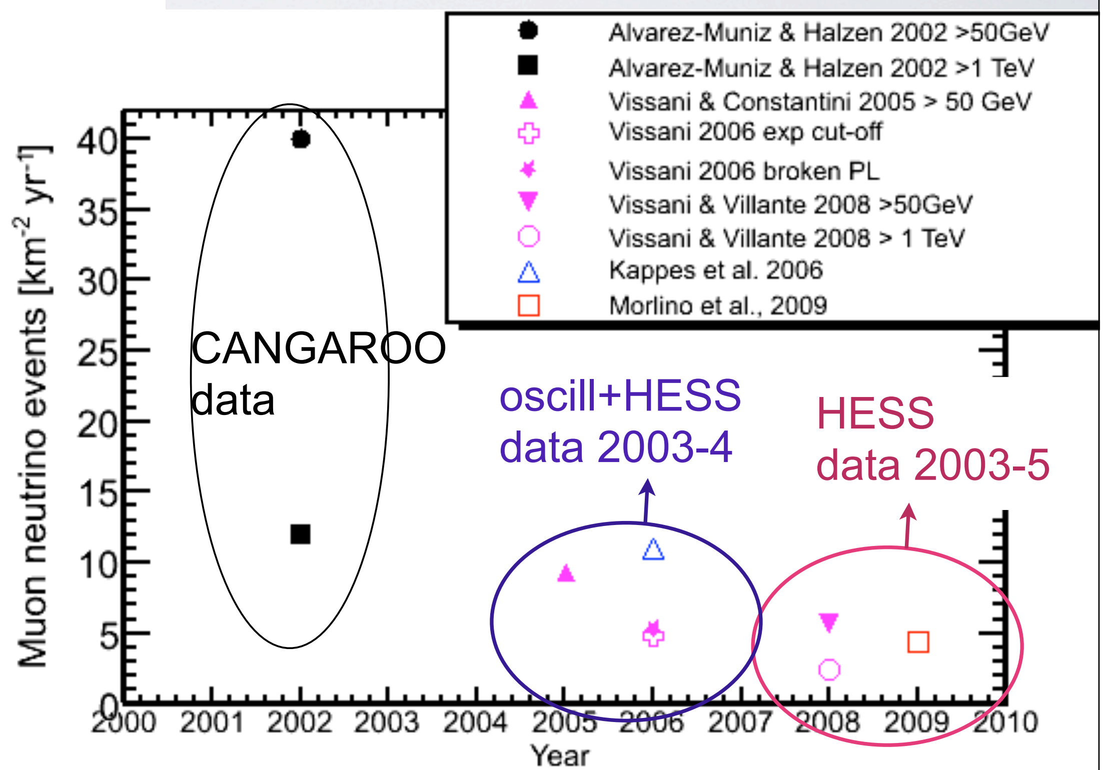
The width of the filaments require B_{ds} ~ 100 uG

NEUTRINO EVENTS FROM SNR

Neutrino-gamma fluxes can be estimated using measured γ fluxes.



gamma absorption often neglected



Neutrino- Gamma-Astronomy connection

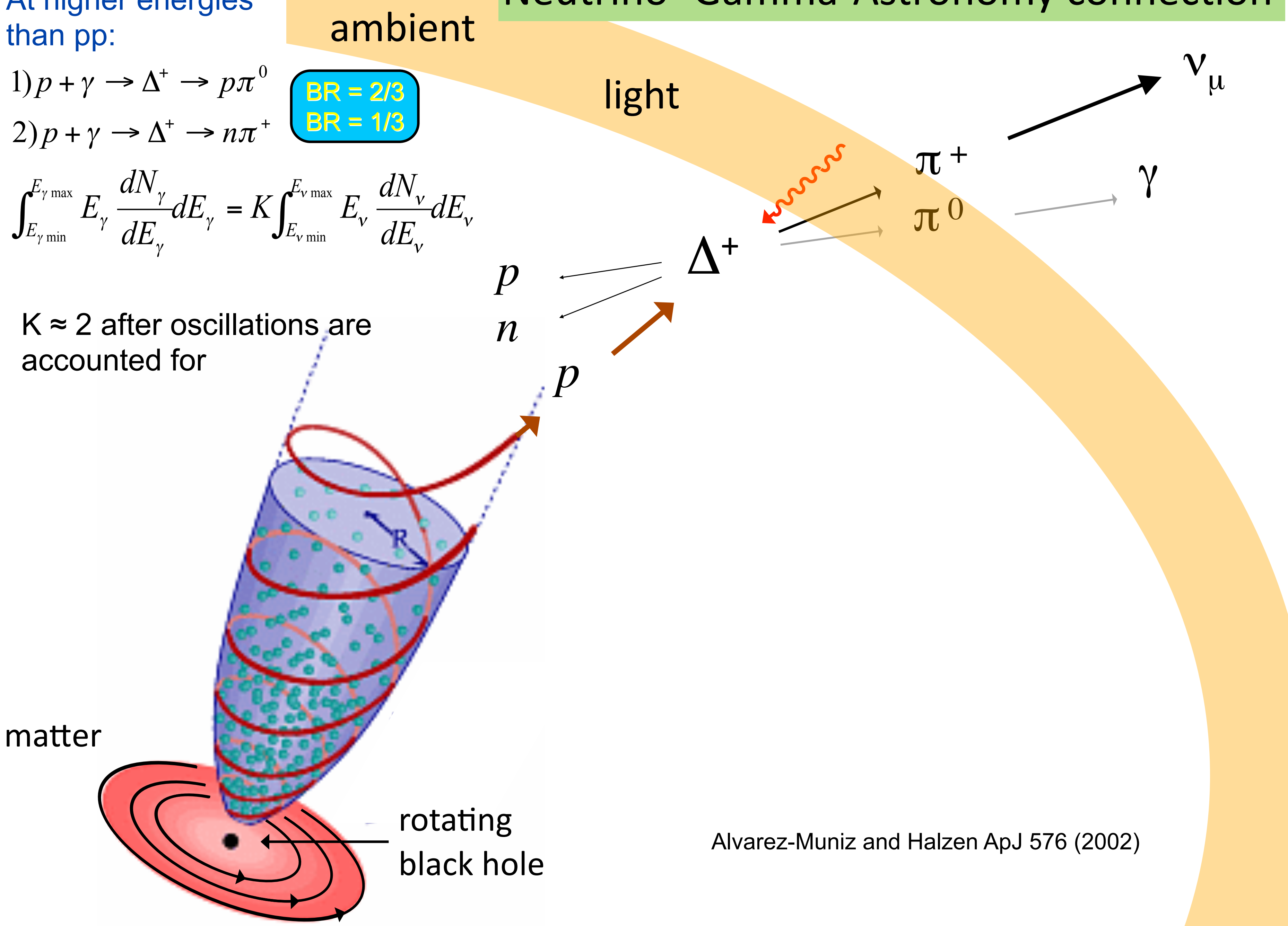
At higher energies than pp:

$$1)\ p+\gamma \rightarrow \Delta^+ \rightarrow p\pi^0$$ BR = 2/3

$$2)\ p+\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$$ BR = 1/3

$$\int_{E_{\gamma\,\min}}^{E_{\gamma\,\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_{\nu\,\min}}^{E_{\nu\,\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

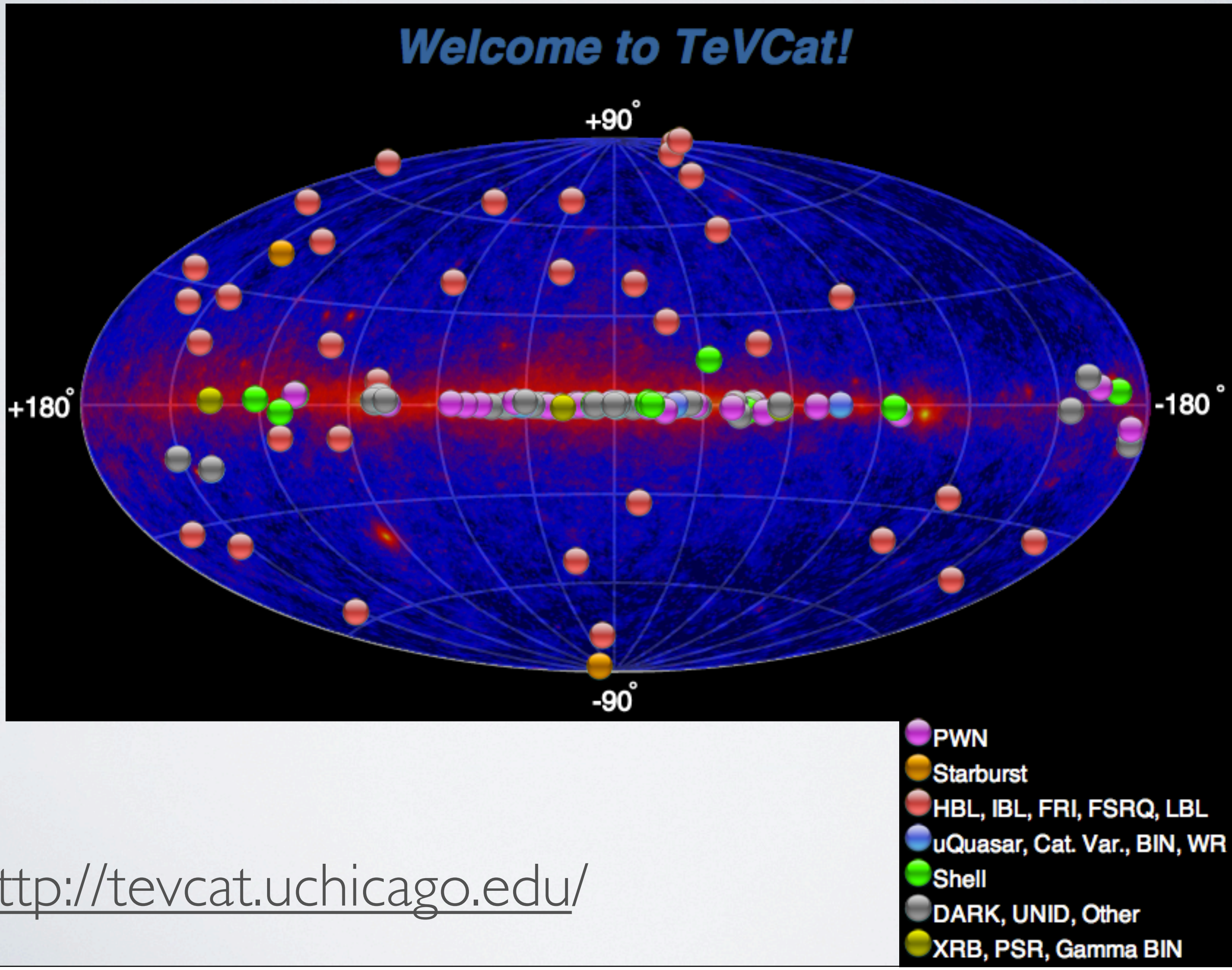
K ≈ 2 after oscillations are accounted for



Alvarez-Muniz and Halzen ApJ 576 (2002)

CURRENT TEV SKY

More than 100 sources



http://tevcat.uchicago.edu/

NEUTRINO OSCILLATION REMINDER

Conversion probability (3 neutrino flavors and in vacuum):

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - \sum_{j\neq k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \left(1 - e^{-i\Delta E_{jk} L}\right)$$

Langacker's lectures

Where the mixing matrix is:

solar U_{e1}, $U_{e2} \leftrightarrow \theta_{12}$ CHOOZ $U_{e3} \leftrightarrow \theta_{13}$

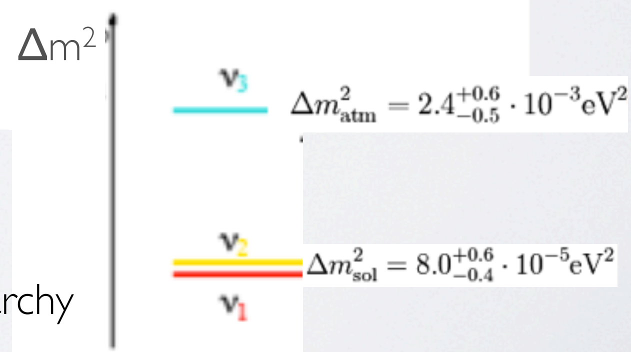
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

atmospheric $U_{e3} \leftrightarrow \theta_{13}$ $U_{\mu 3}, U_{\tau 3} \leftrightarrow \theta_{23}$

$s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$.

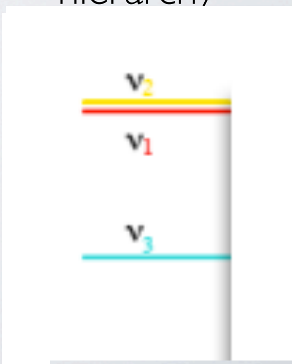
Observed values of oscillation parameters

- $\sin^2(\theta_{13}) < 0.032$ at 95% confidence level ($\theta_{13} < 10.3°$) [4] CHOOZ
- $\tan^2(\theta_{12}) = 0.45^{+0.09}_{-0.07}$. This corresponds to $\theta_{12} \equiv \theta_{\rm sol} = 33.9^{\circ}{}^{+2.4°}_{-2.2°}$ ("sol" stands for solar) [6]
- $\sin^2(2\theta_{23}) = 1^{+0}_{-0.1}$, corresponding to $\theta_{23} \equiv \theta_{\rm atm} = 45 \pm 7°$ ("atm" for atmospheric)[7]
- $\Delta m^2_{21} \equiv \Delta m^2_{\rm sol} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5}{\rm eV}^2$ [6]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\rm atm} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3}{\rm eV}^2$[7]



direct hierarchy

inverted hierarchy



ASTROPHYSICAL NEUTRINO OSCILLATIONS

In the limit $L \to \infty$, we have

$$P(\nu_\alpha \to \nu_\beta; L = \infty) = \delta_{\alpha\beta} - \sum_{j \neq k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2,$$

average over rapid oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2$$

$$P(\nu_e \to \nu_e) = \sum_i |U_{ei}|^2 |U_{ei}|^2 = |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 = 0.82^4 + 0.57^4 + 0 = 0.56$$

$$P(\nu_e \to \nu_\mu) = \sum_i |U_{ei}|^2 |U_{\mu i}|^2 = |U_{e1}|^2 |U_{\mu 1}|^2 + |U_{e2}|^2 |U_{\mu 2}|^2 + |U_{e3}|^2 |U_{\mu 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$$P(\nu_e \to \nu_\tau) = \sum_i |U_{ei}|^2 |U_{\tau i}|^2 = |U_{e1}|^2 |U_{\tau 1}|^2 + |U_{e2}|^2 |U_{\tau 2}|^2 + |U_{e3}|^2 |U_{\tau 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

At source: $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$

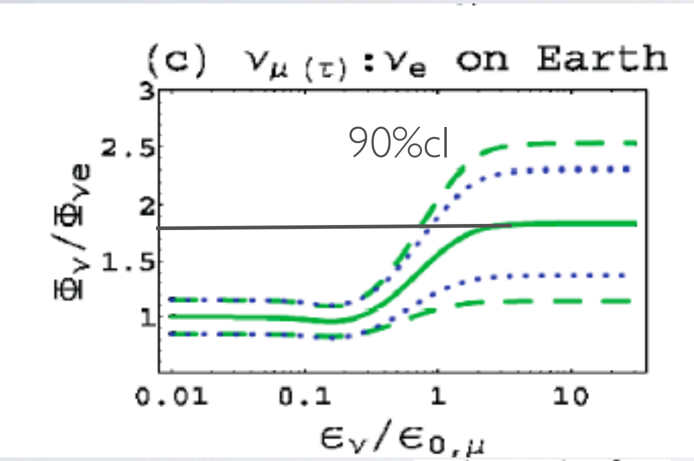
60% of ν_e survive and 2x20% come from 2xν_μ = 100%
2x40%=80% of 2xν_μ survive and 20% come from ν_e= 100%
20% of ν_τ come from ν_e and 2 x 40% from ν_μ= 100%

At Earth: 1: 1: 1

http://arXiv.org/pdf/hep-ph/0005104

BUT THERE ARE CAVEATS...

1) In come (galactic) sources n decay contributes
2) Kashti & Waxman (PRL 95, 2005) pointed out that muons may sto decaying for extragalactic sources where the energy of p is very high

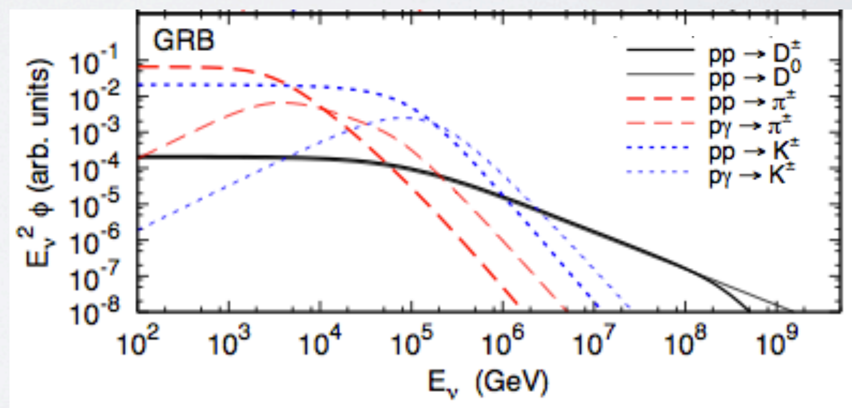


ϵ_0 = energy at which $\tau_{x,\mathrm{cool}} = \tau_{x,\mathrm{decay}}$

Ratio becomes 1:1.8:1.8 @ > 100 TeV

3) charm production is normally neglected but at high energy it can dominate due to prompt decays. This is also a source of ν_τ.

Muon neutrinos+antineutrinos



http://arxiv.org/abs/0808.2807v1

THE EVOLUTION OF NEUTRINO TELESCOPES

…a long march
which has not
yet reached
its end.

It originated from ideas in the 60s

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

COSMIC RAY SHOWERS[1]

By Kenneth Greisen
Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y.

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.

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

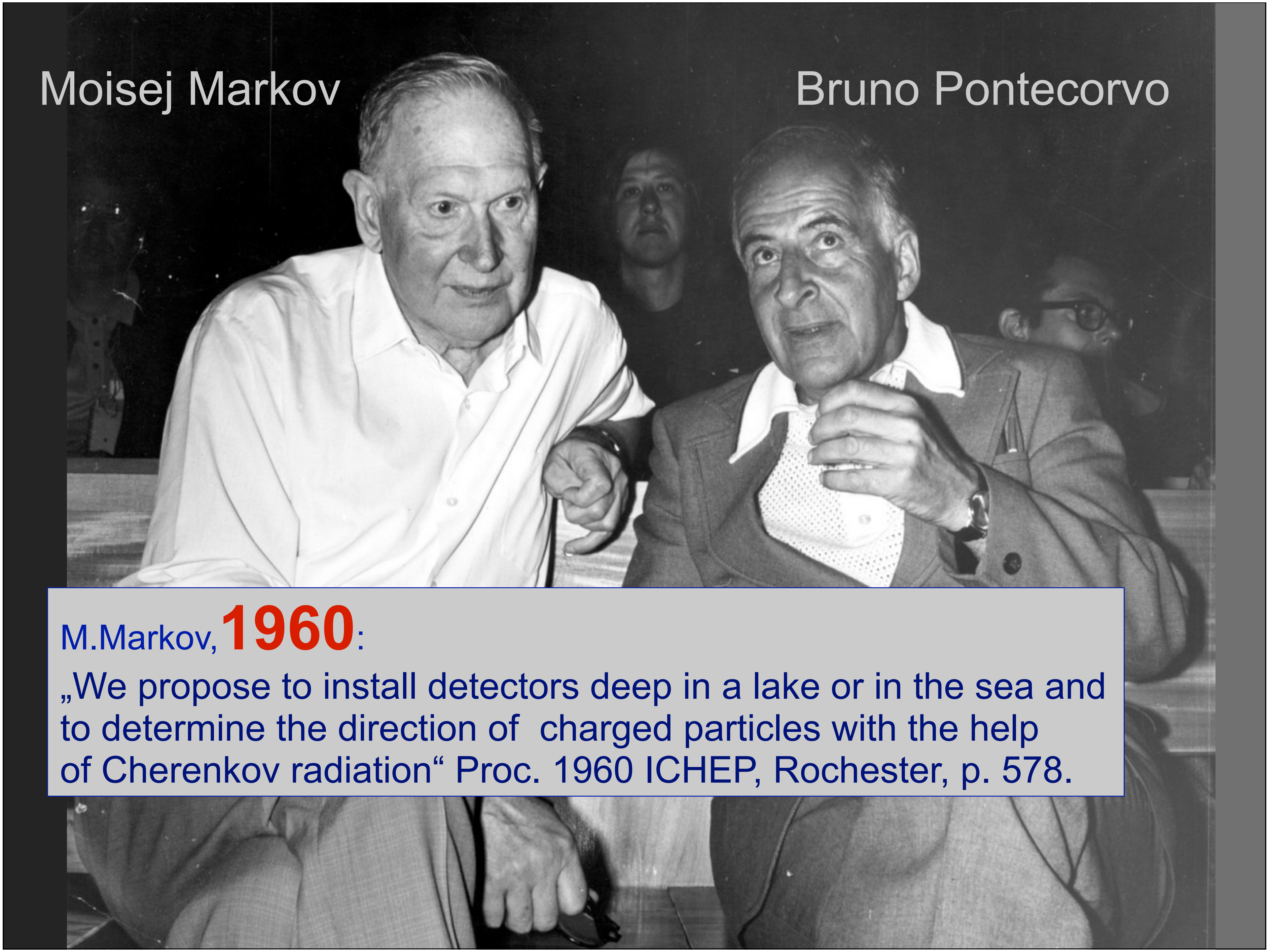
NEUTRINO INTERACTIONS[1]

By Frederick Reines[2]
Physics Department, Case Institute of Technology, Cleveland, Ohio

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

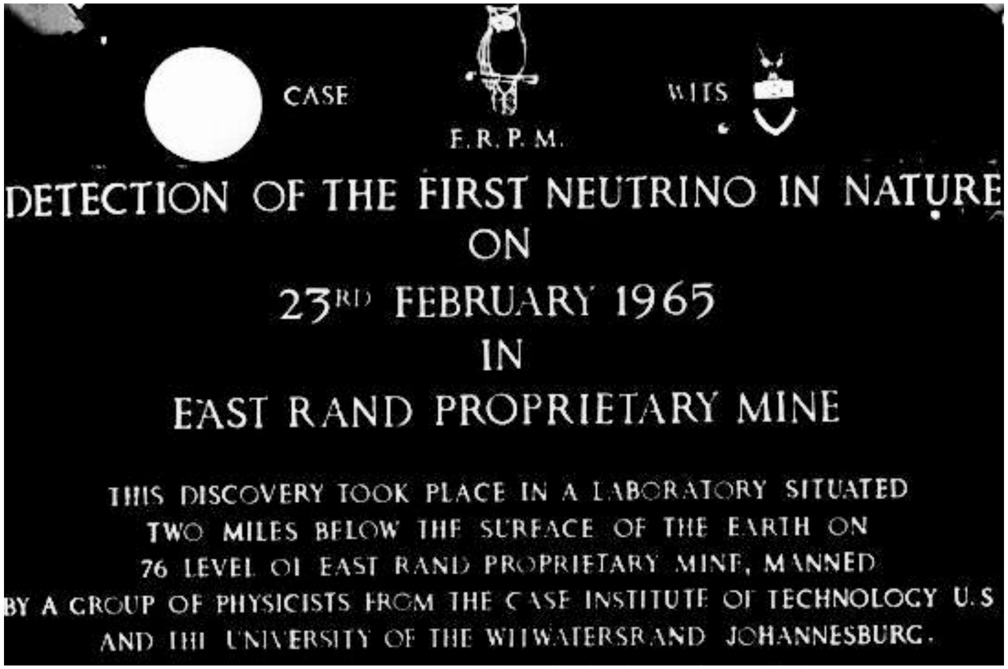


M.Markov, **1960**:

„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“ Proc. 1960 ICHEP, Rochester, p. 578.

First neutrino detection

in 1965 detection of nearly horizontal atmospheric neutrinos by F. Reines in a South African Gold mine.

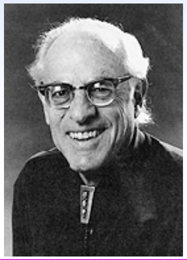


http://www.ps.uci.edu/physics/reinesphotos.html

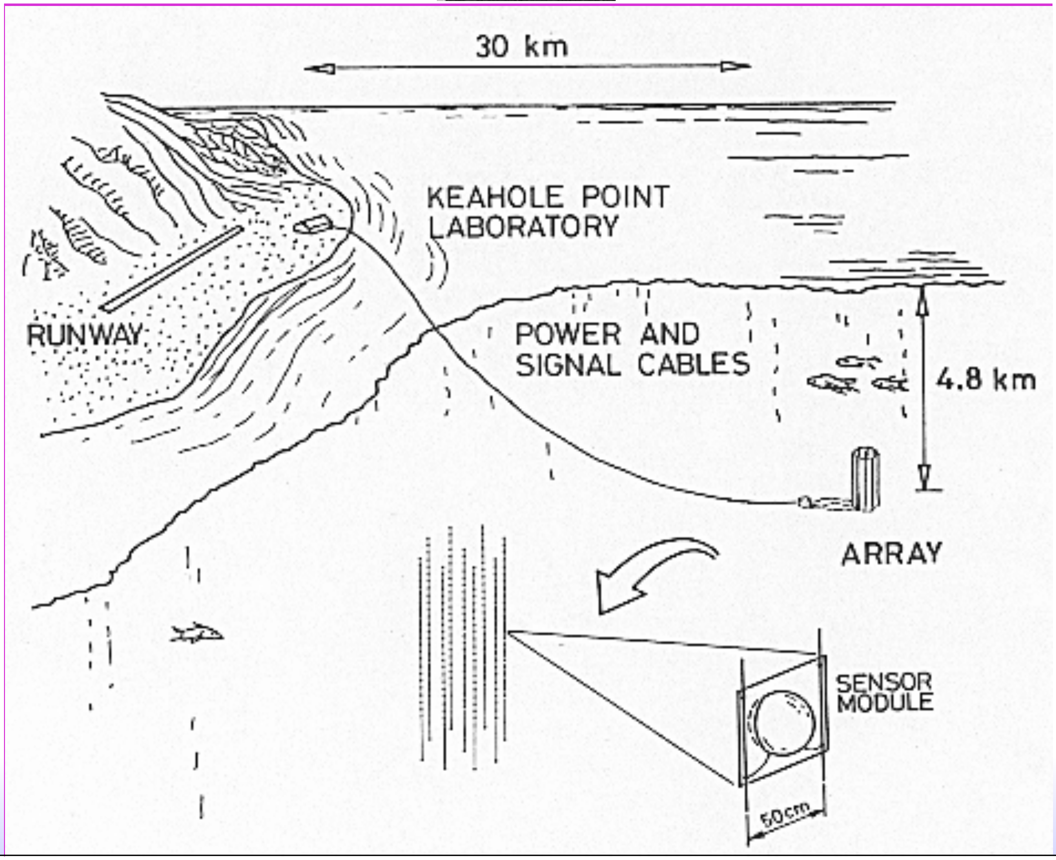
DUMAND

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

- The name: DUMAND (Deep Underwater Muon And Neutrino Detector), proposed by Fred Reines
- 1975: First DUMAND Workshop in Washington State College
- DUMAND Steering Committee, chaired by F.Reines, J. Learned, A.Roberts



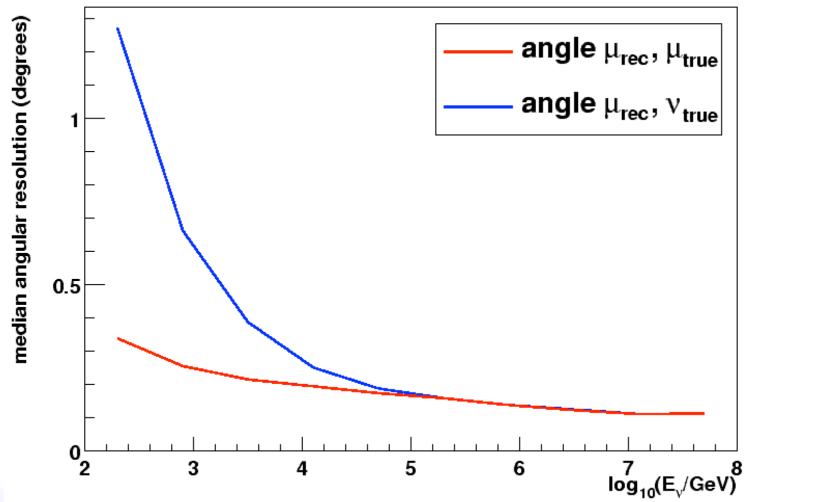
- 9 strings
- 216 OMs
- 100 diameter, 240 m height
- Depth of bottom: 4.8 km
- Lowest OM 100 m above bottom

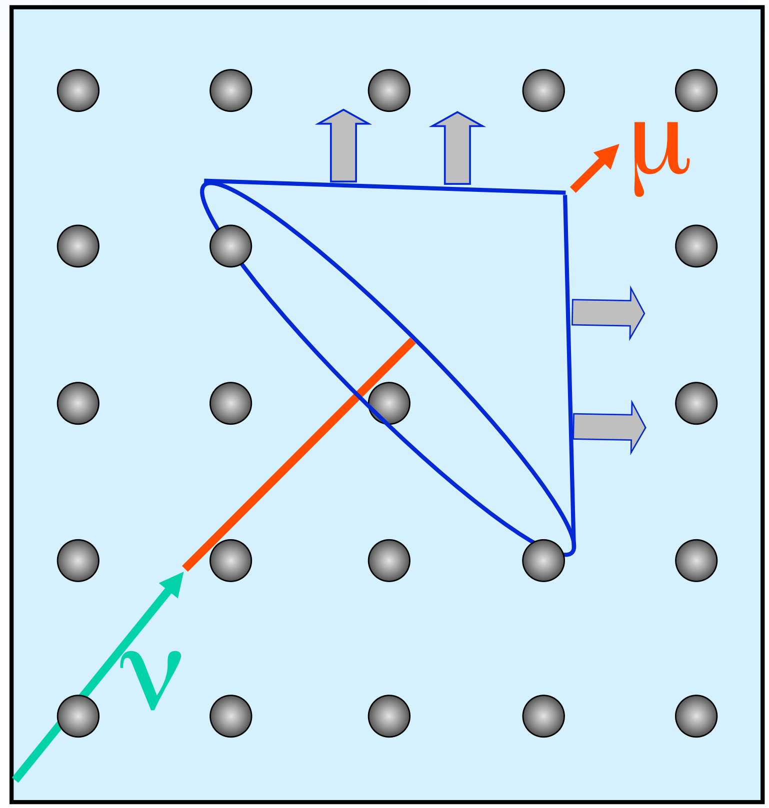


Principle and capabilities

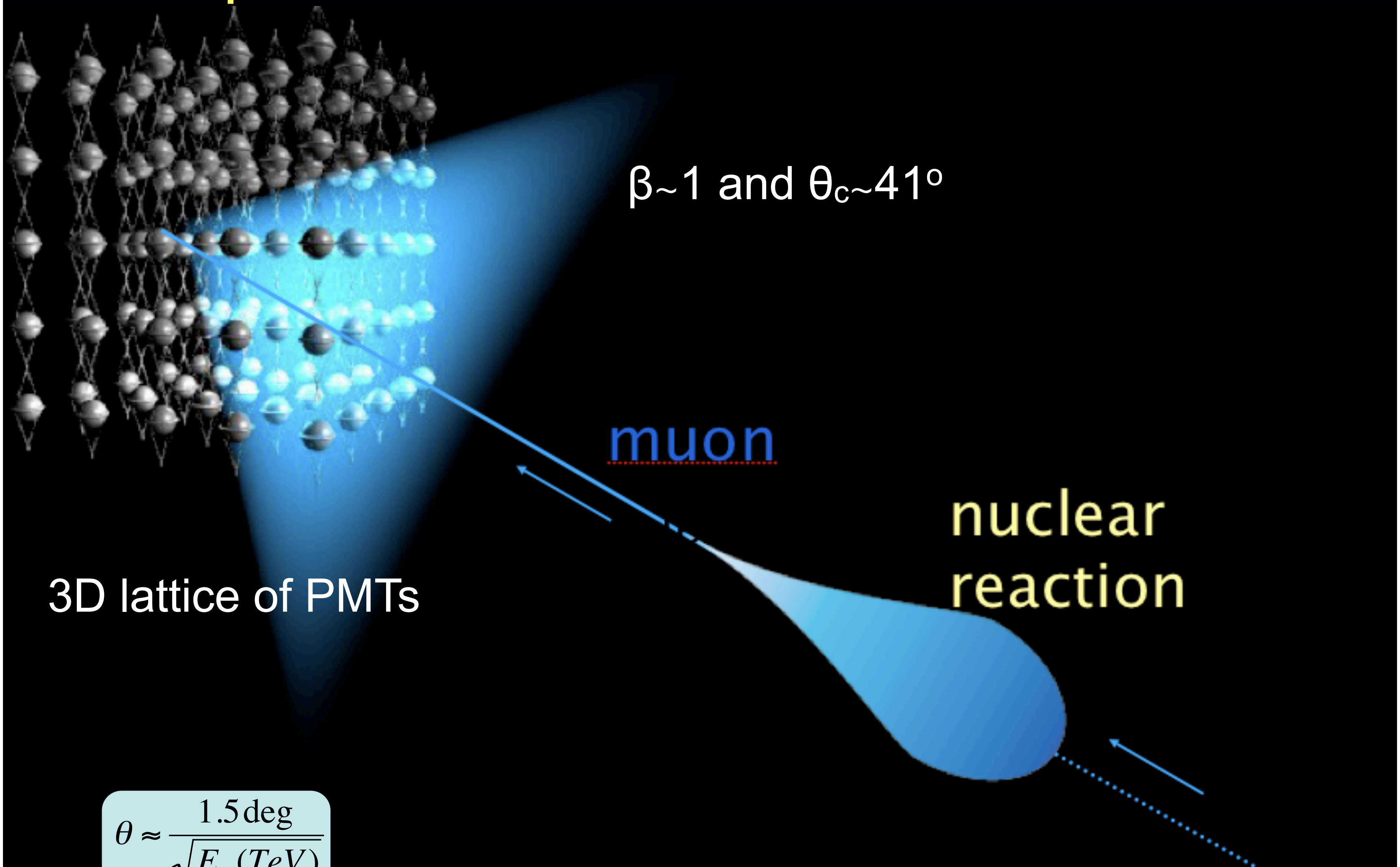
- Angular resolution of 1° possible → astrononomy

- Energy resolution for muons is 50% at best, for 1 km track length



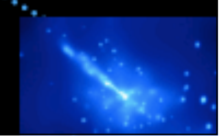


Concept of Neutrino

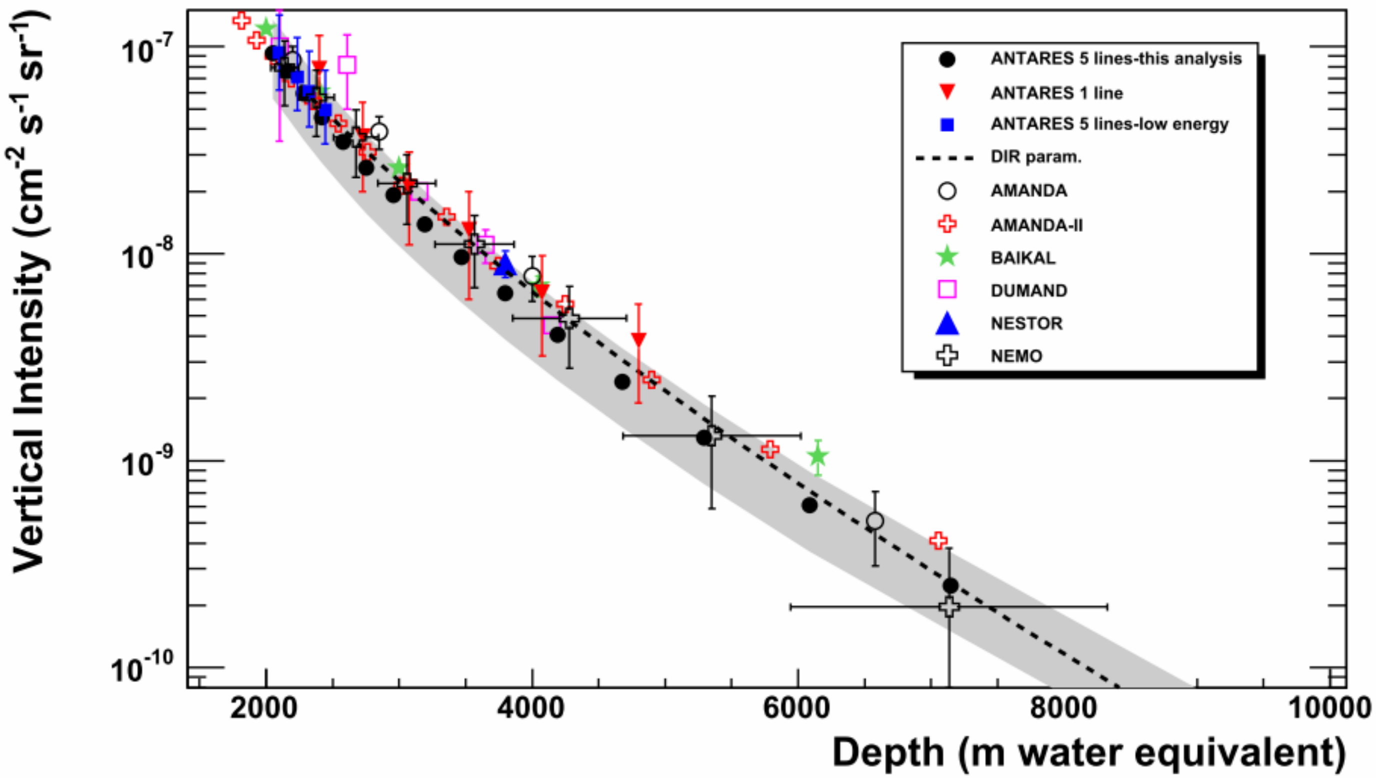


$$\theta \approx \frac{1.5\,\deg}{\sqrt{E_\nu(TeV)}}$$

Between 300-600 nm about 3.5×10^4 Cherenkov photons/m of a muon track

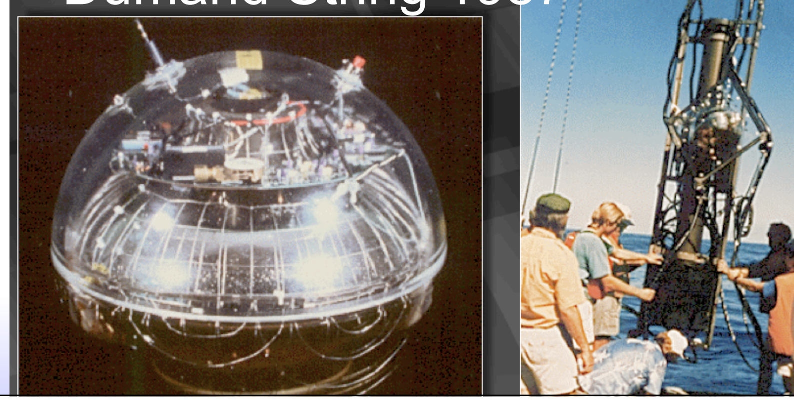


Depth and Muon Intensity

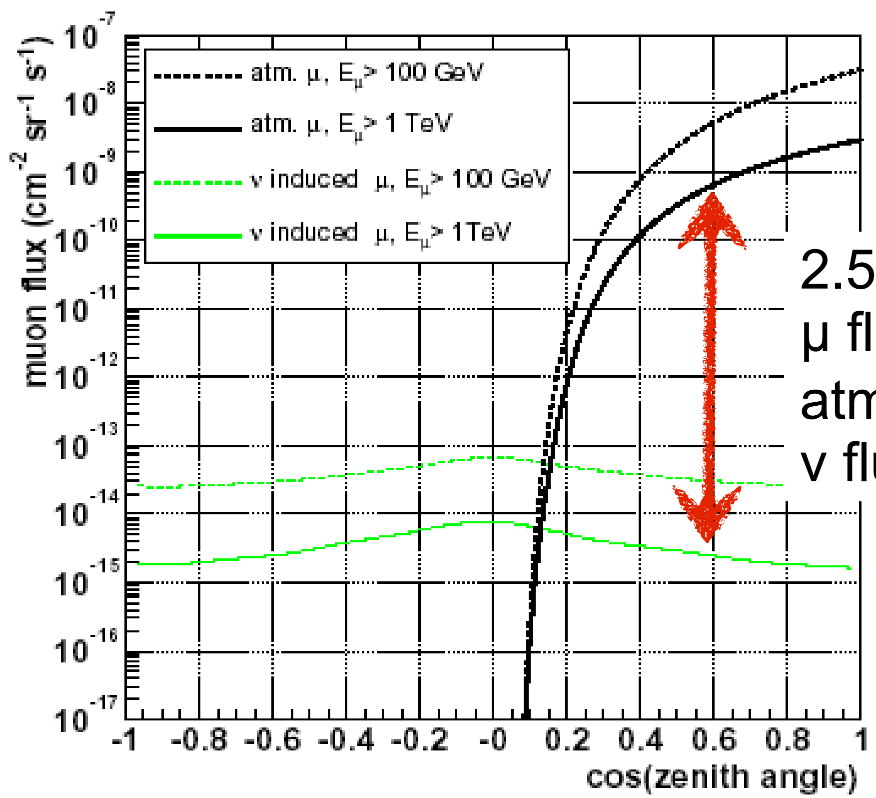


After the successful measurement of the test string, in 1993 the shore cable is laid and the 1st string is deployed and connected to the junction box.
Failure due to a water leak...
1995 DUMAND is terminated.

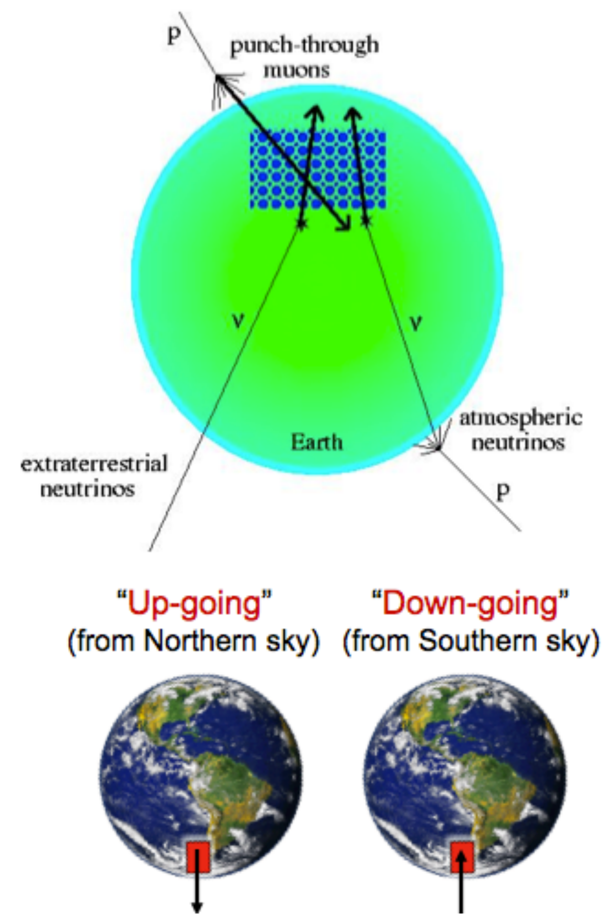
Dumand String 1987



Going Deep to see upgoing neutrino induced events



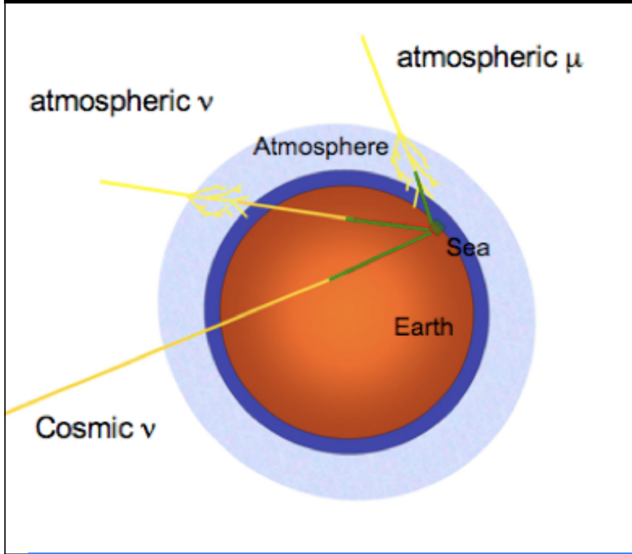
2.5 km deep
μ flux~$10^{5.5}$ atmospheric ν flux



Dark and transparent media for Cherenkov detection

Atmospheric neutrinos are a background and a signal themselves for NTs!

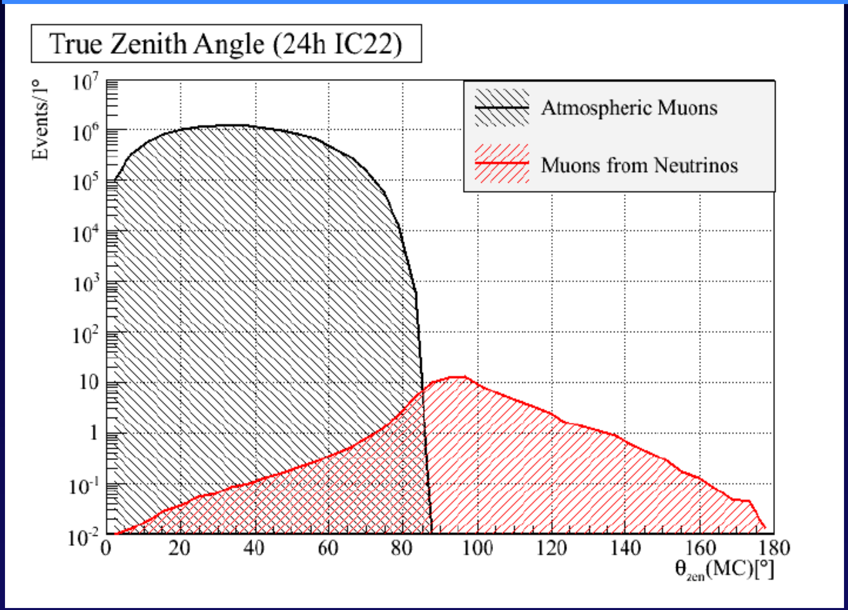
http://lanl.arxiv.org/abs/0906.2634v1



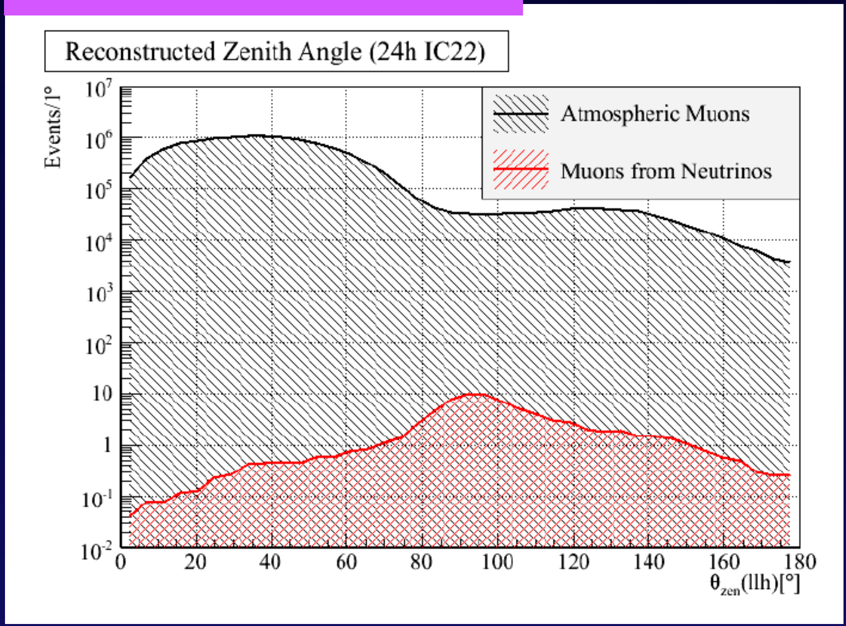
Ideal/Real life

Quality cuts required to remove atmospheric muon background

True zenith dr from simulation

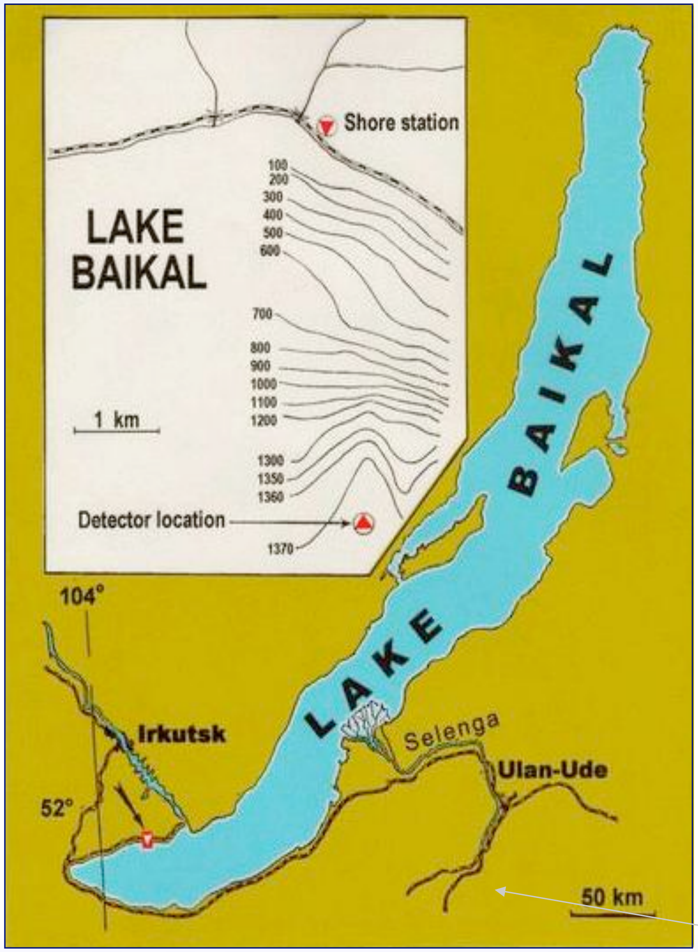


Reconstructed



The Lake BAIKAL experiment

Bezrukov, Domogatsky, Berezinsky, Zatsepin

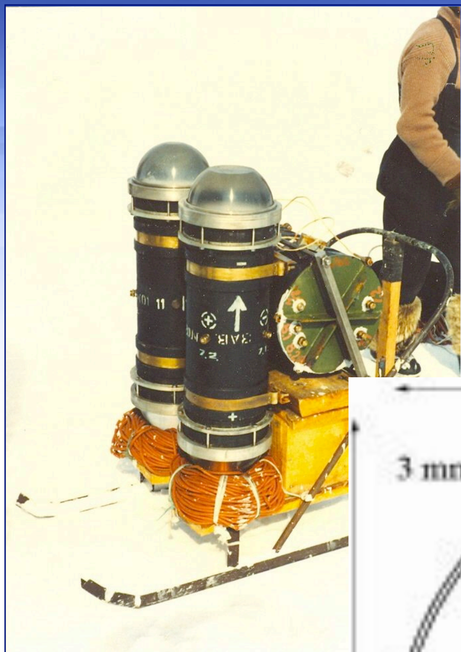


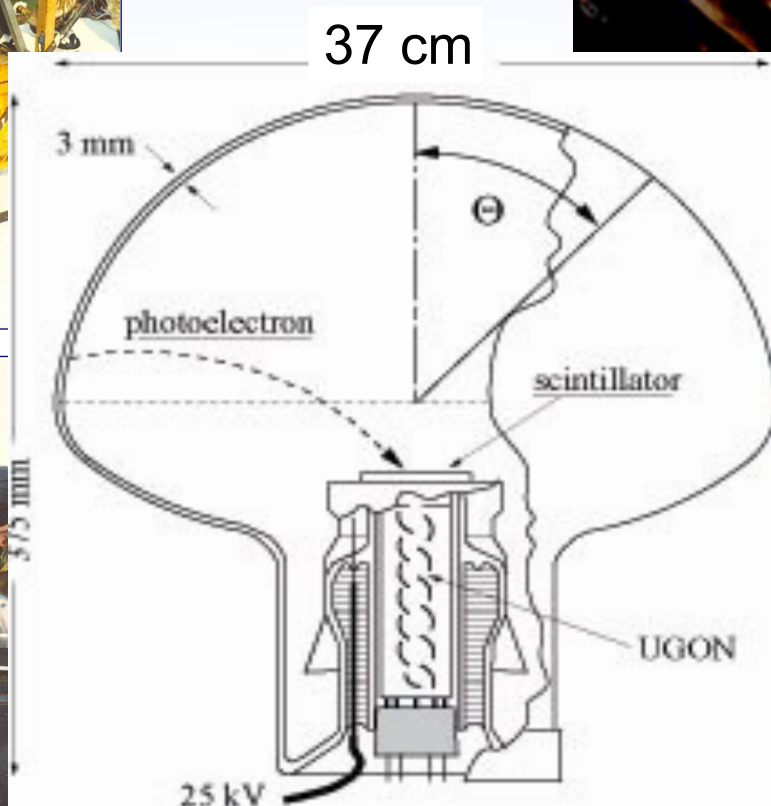
G. Domogatsky

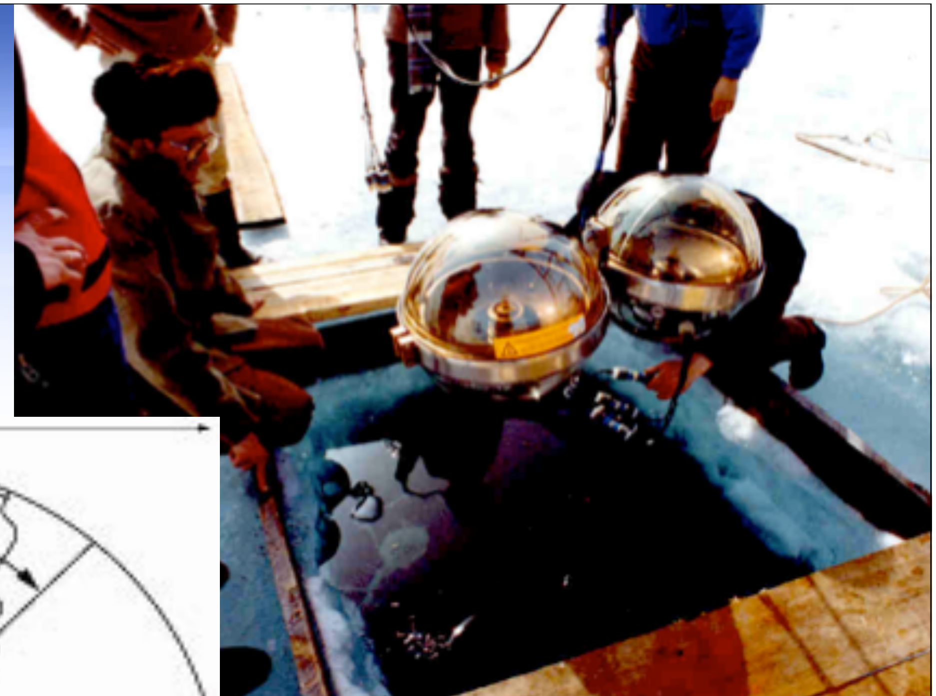
- Largest fresh water reservoir in the world
- Deepest Lake (1.7 km)
- 1981: first site explorations & R&D
- Choosen site 3.6 km from shore, 1.3 km depth

Ice as a natural deployment platform

The Quasar

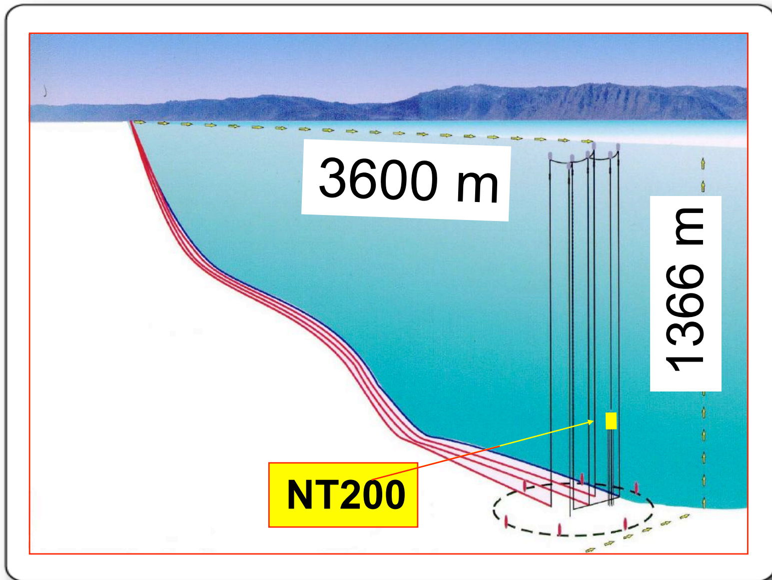






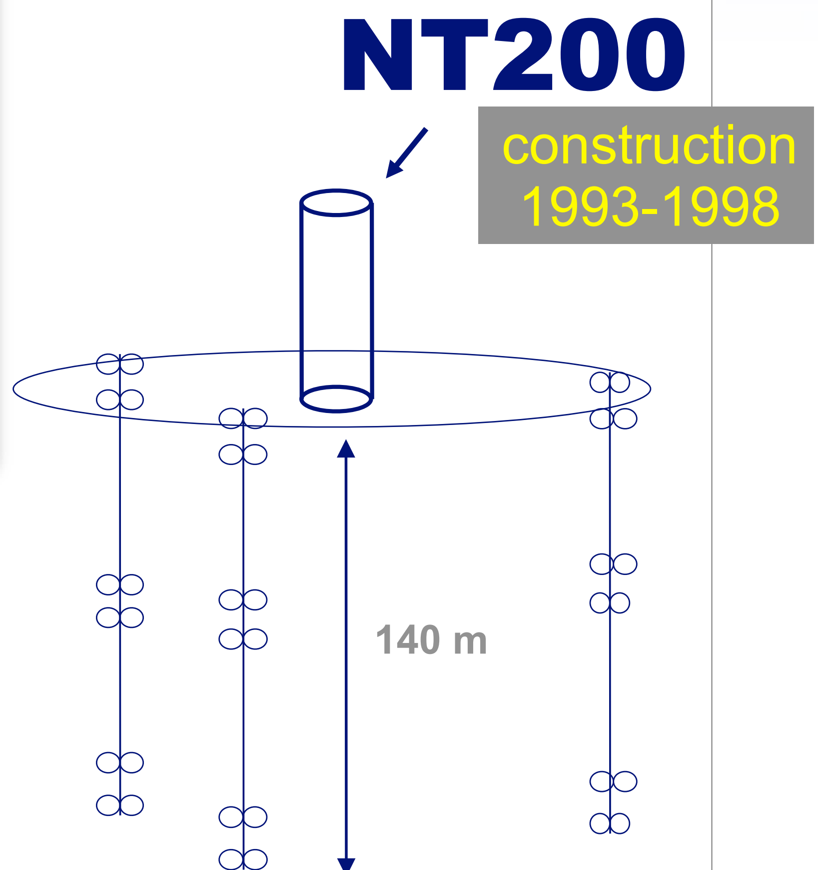
NT200+

Various configurations until they reached NT200+



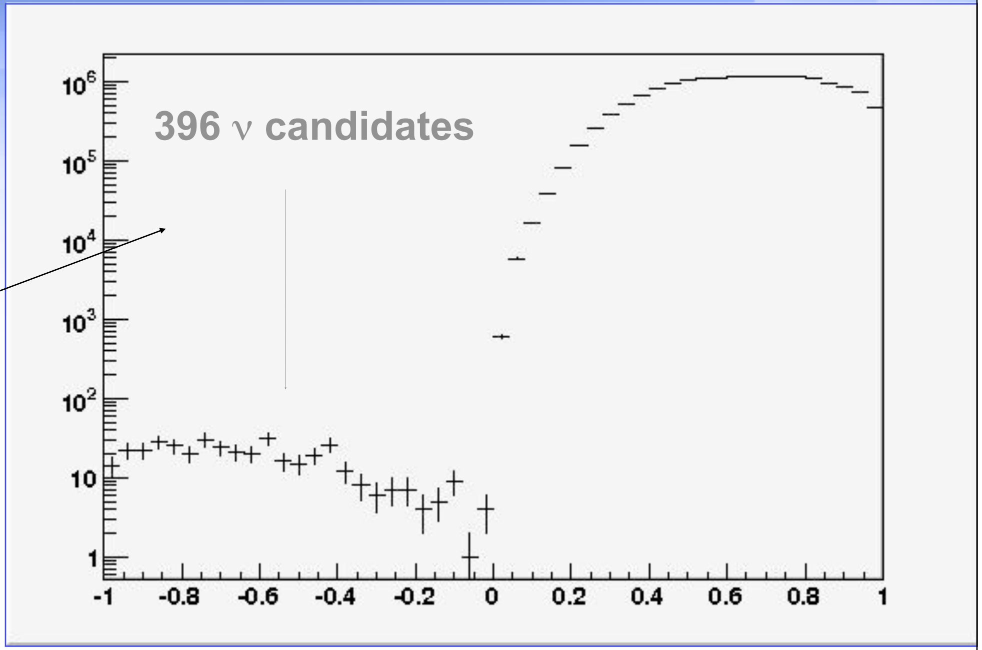
NT200+

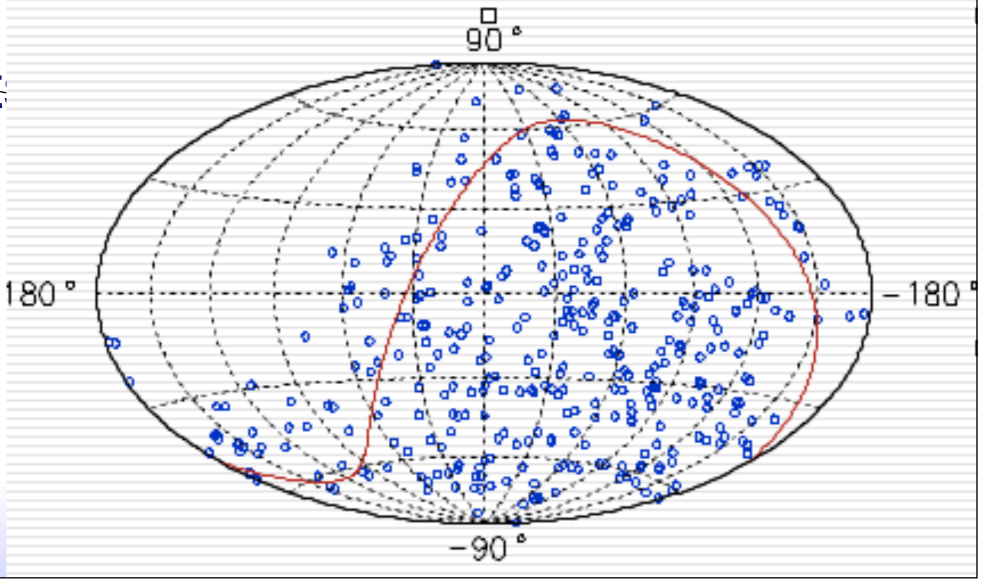
- upgrade 2005/06
- 4 times better sensitivity than NT200 for PeV cascades
- basic cell for km3 scale detector



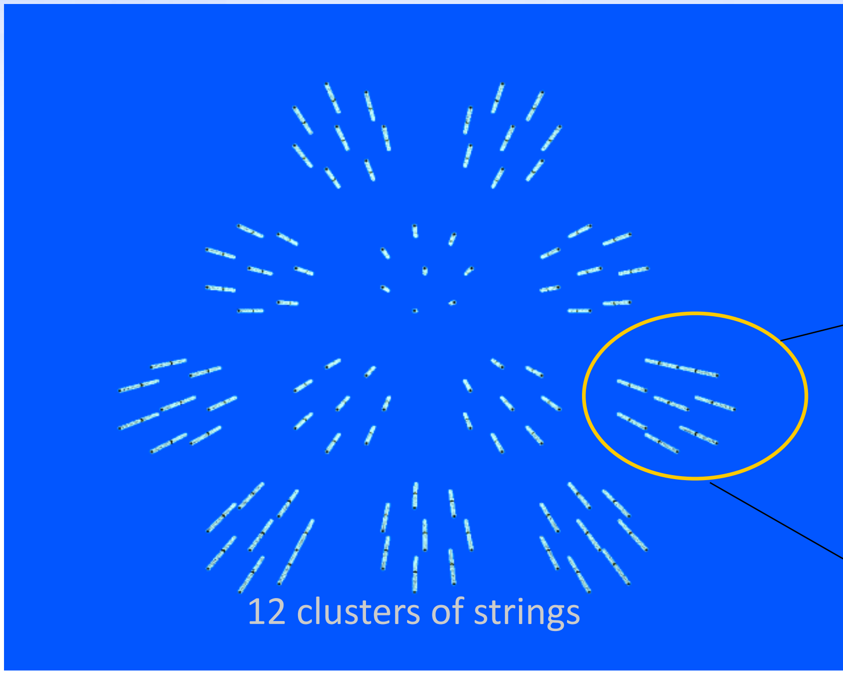
NT200 results

- Atmospheric neutrinos
- WIMP search
- Diffuse neutrino fluxes
- Skymap: 372 neutrino events in 1038 d
- GRB coincidences
- Magnetic monopoles

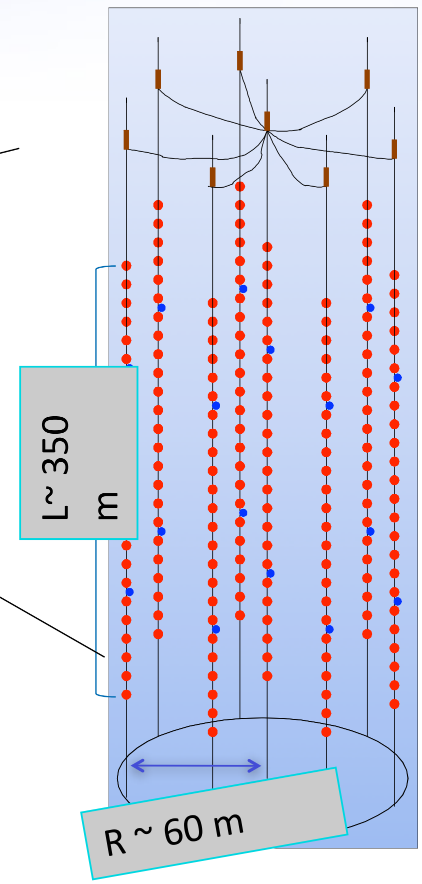




Proposal of Gigaton Volume Detector, GVD



NT1000: top view



- Sacrifice low energies (muon threshold ~ 10 TeV)
- Protoype strings being tested
- Modular clusters, stepwise installation > 2012
- ~ 2000 optical modules (conventional PMs)

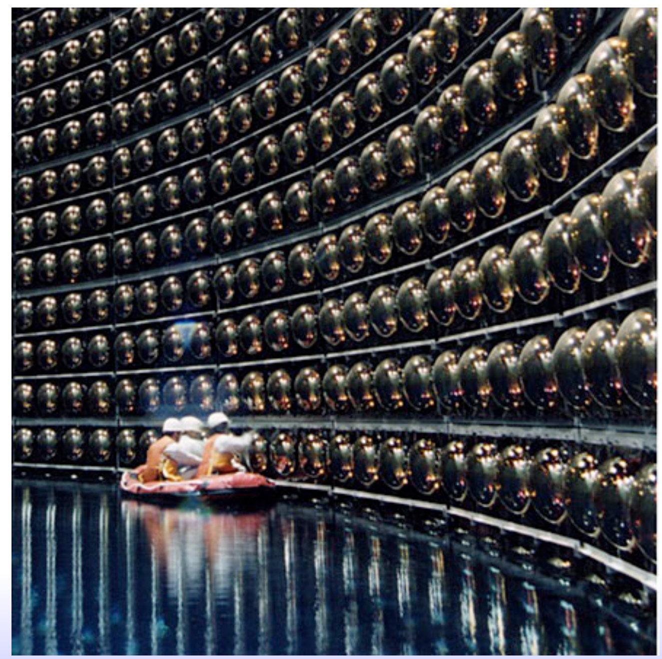
The 80's and 90's

Deep underground detectors (Kolar Gold Field, Bakdan, Frejus, Soudan, IMB, Kamiokande ➙ Super-Kamiokande, MACRO) reached their full blossom:

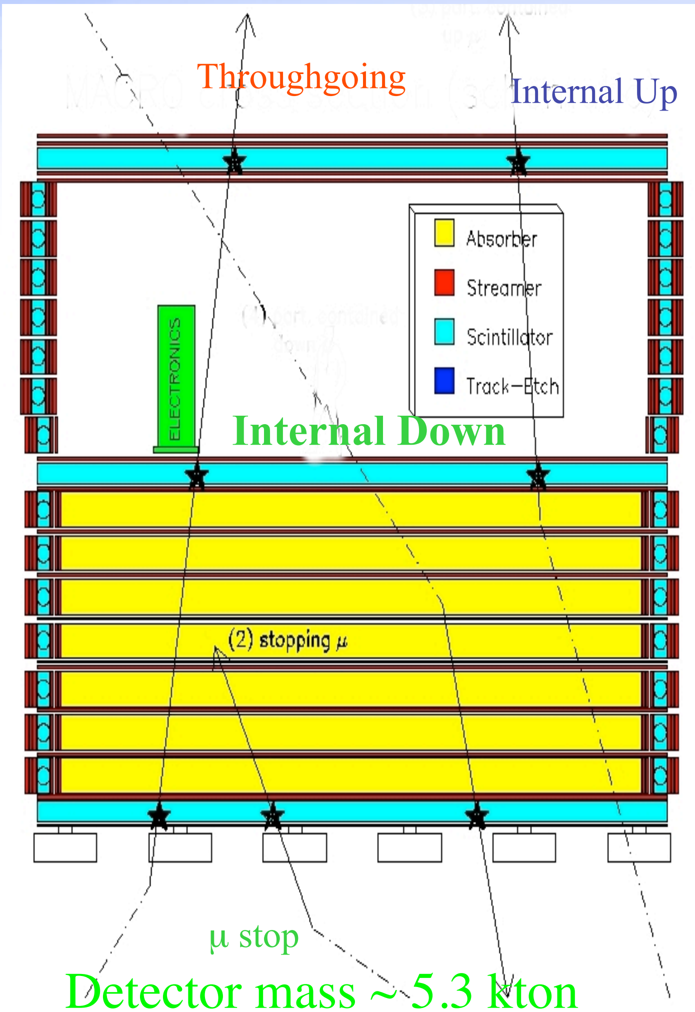
- solar neutrino oscillations
- atmospheric neutrino oscillations
- supernova neutrinos
- proton decay and monopoles
- skymaps

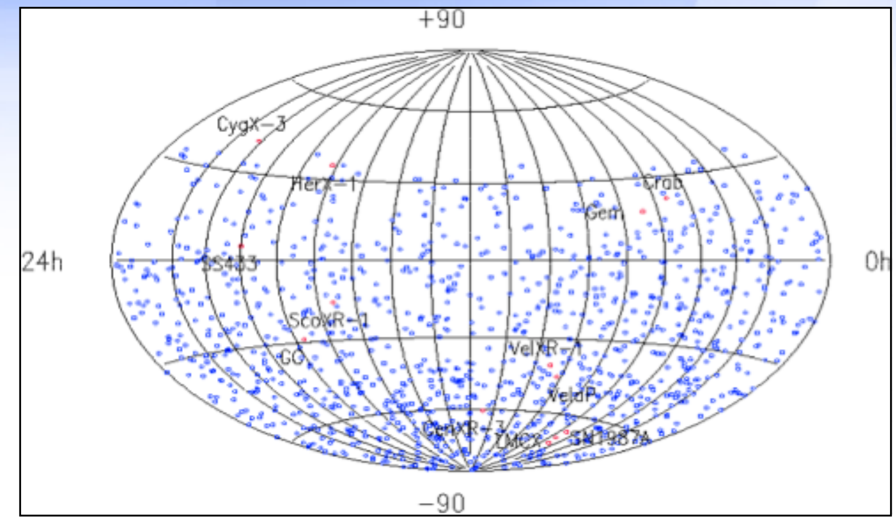
MACRO

Super-Kamiokande

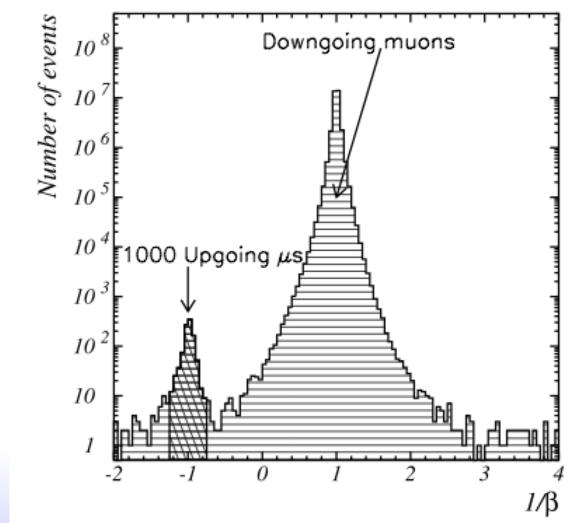


Neutrino Astronomy with MACRO





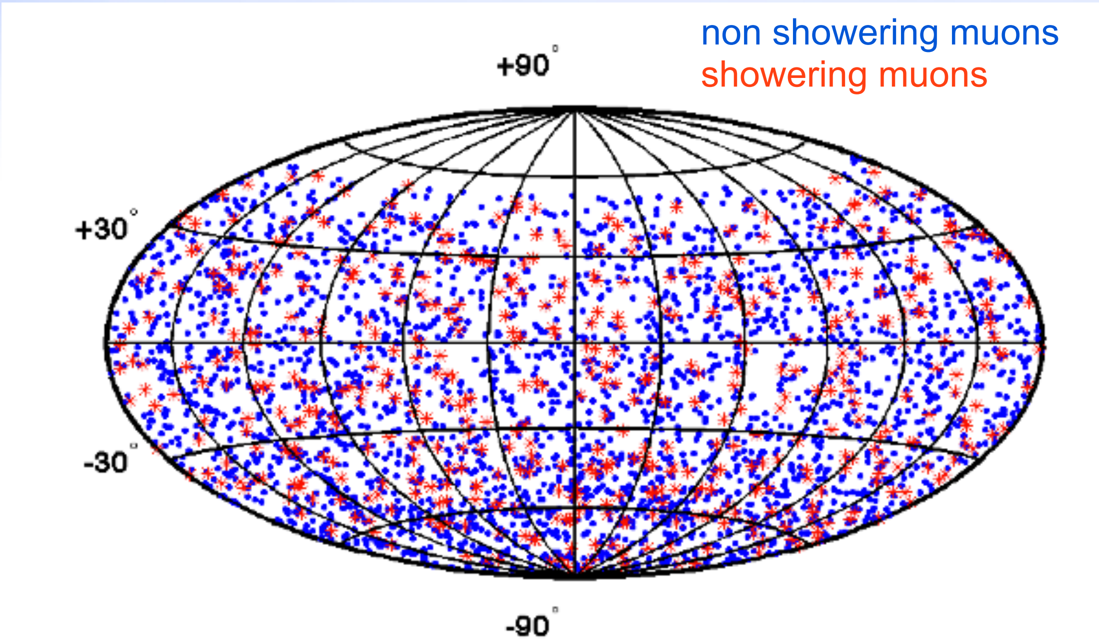
MACRO, 1356 upgoing muons (ApJ 546 (2001) 1038, my PhD thesis!)

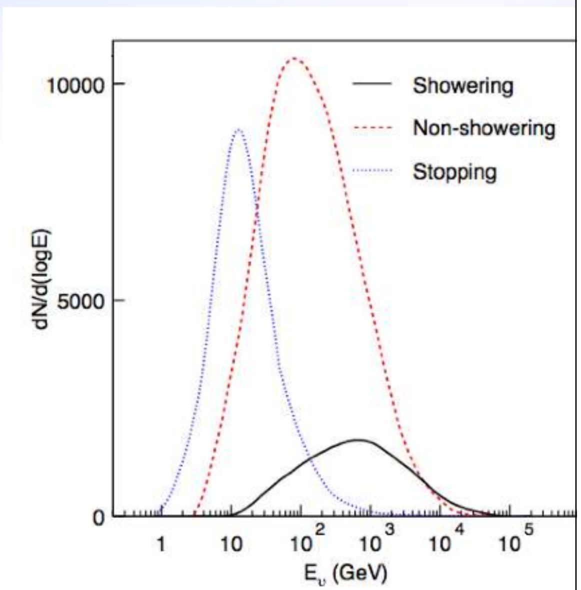


Only now surpassed by SK and ANTARES

Super-Kamiokande

3134 neutrino events between Apr. 96-Aug. 07 (2623 d) Eth = 1.6 GeV



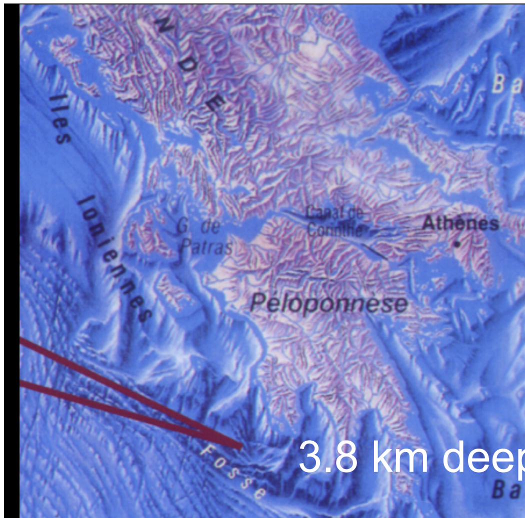


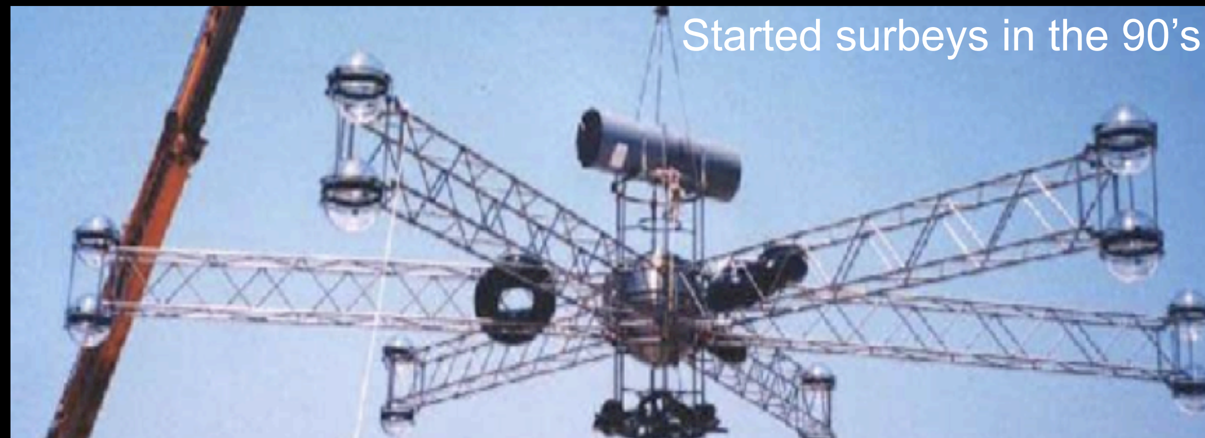
5 events around RXJ 1713.7-3946 ➙ probability that the background can produce this signature is 2.5% (after trials)

One upgoing muon 411 s after GRB 991004D (34 s) in 8° search cone ➙ probability that the background can produce this signature is 4.7%

Astrophys.J.704:503-512,2009

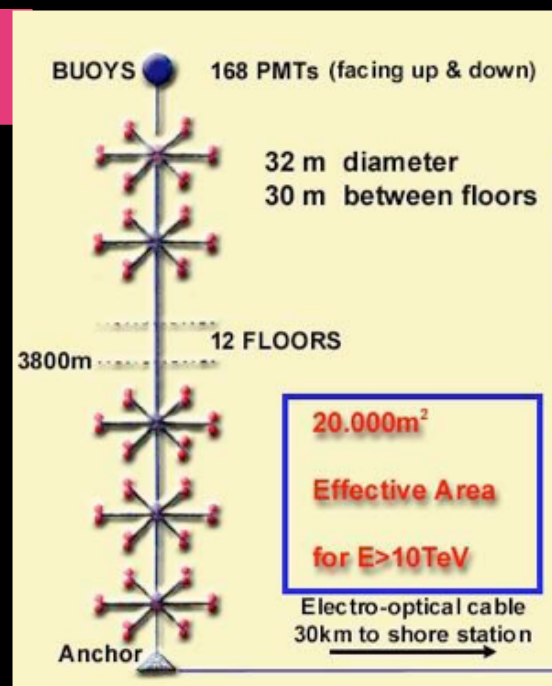
NESTOR





Hexagonal floor prototype measured muon flux

Vision: towers with 12 floors,144 PMTs/foor, 32 m diameter, 30 m between floors



THE ICE OPTION

F. Halzen

E. Zeller (Kansas) suggests to F. Halzen radio detection of neutrinos in Antarctic ice

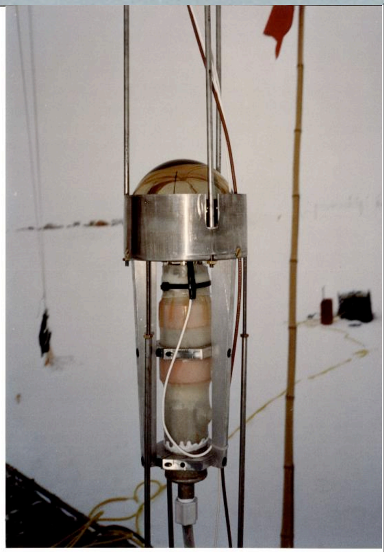
Jan. 89, ICRC, Adelaide: Decide to propose AMANDA (B. Price, D. Lowder, S. Barwick, B. Morse, F. Halzen, A. Watson)

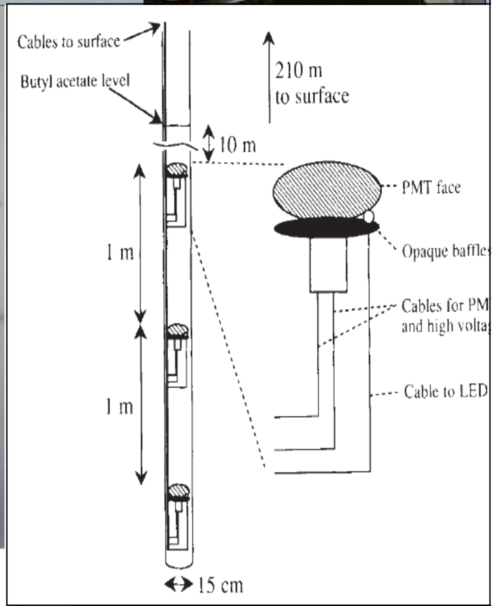
1990: Morse et al. deploy PMTs in Greenland ice:

absorption length > 18 m

1991 first small PMTs deployed

Results consistent with 25 m absorption length





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

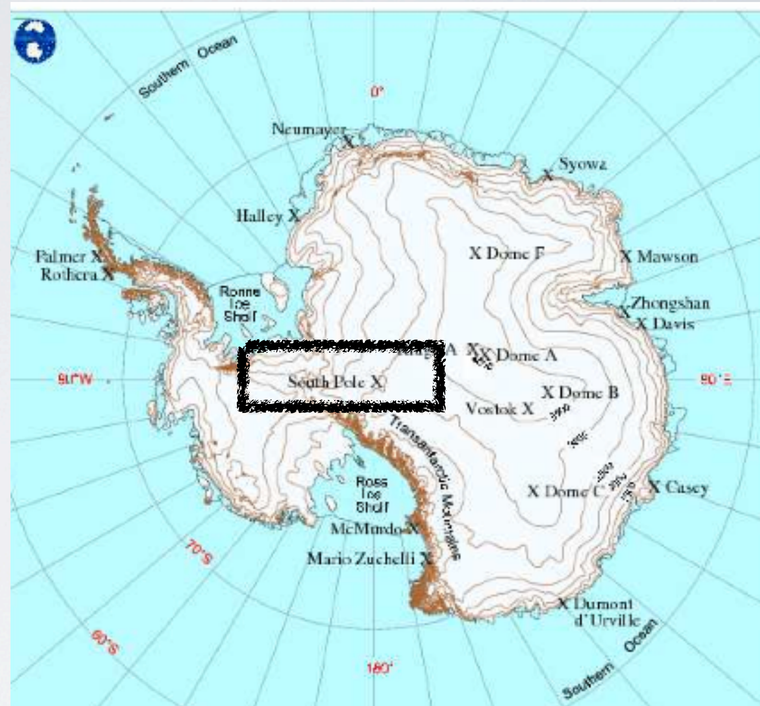
D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

ACKNOWLEDGEMENTS. We thank B. Koci and the entire PICO organizati 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.

Nature Sep 91

ASTRONOMY IN ANTARCTICA

US-Amundsen-Scott Soth Pole Station (1957) 2,835 m asl
Named after

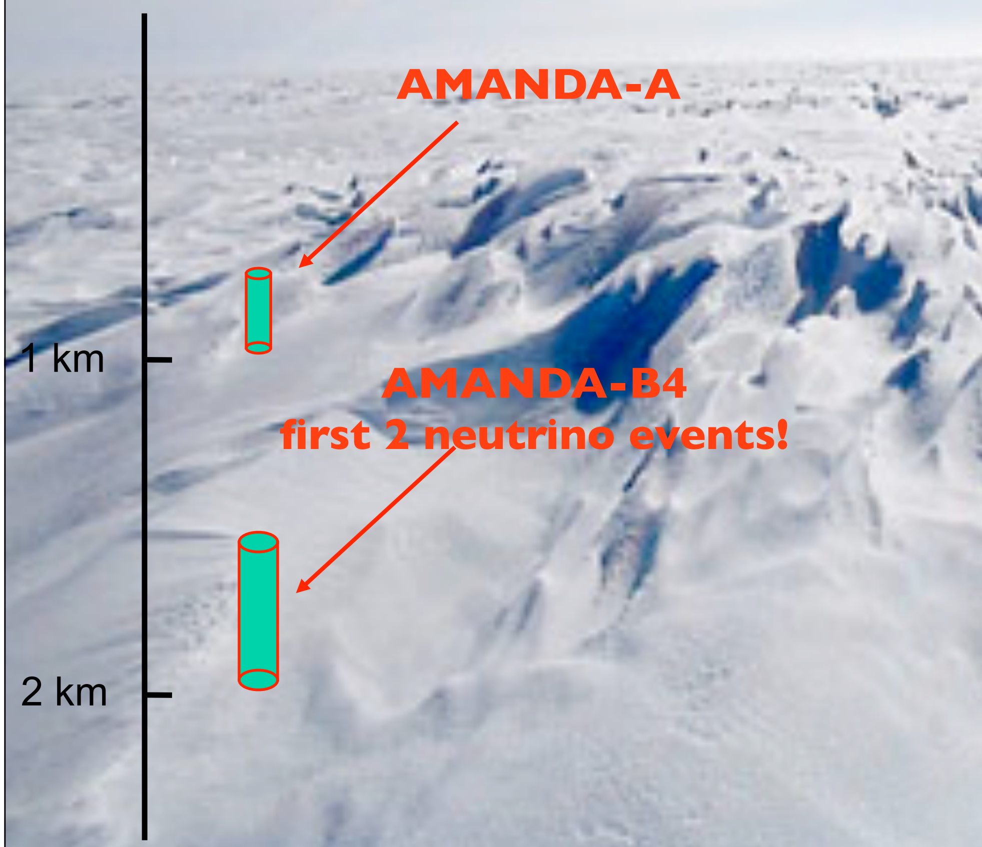


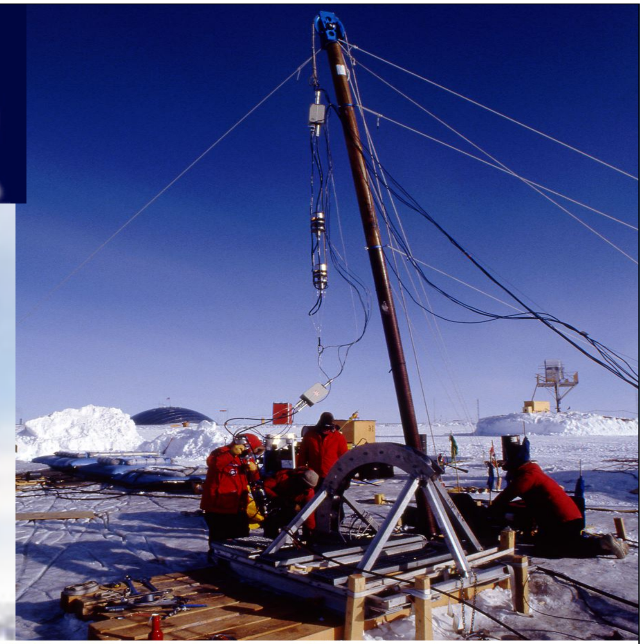

The new station

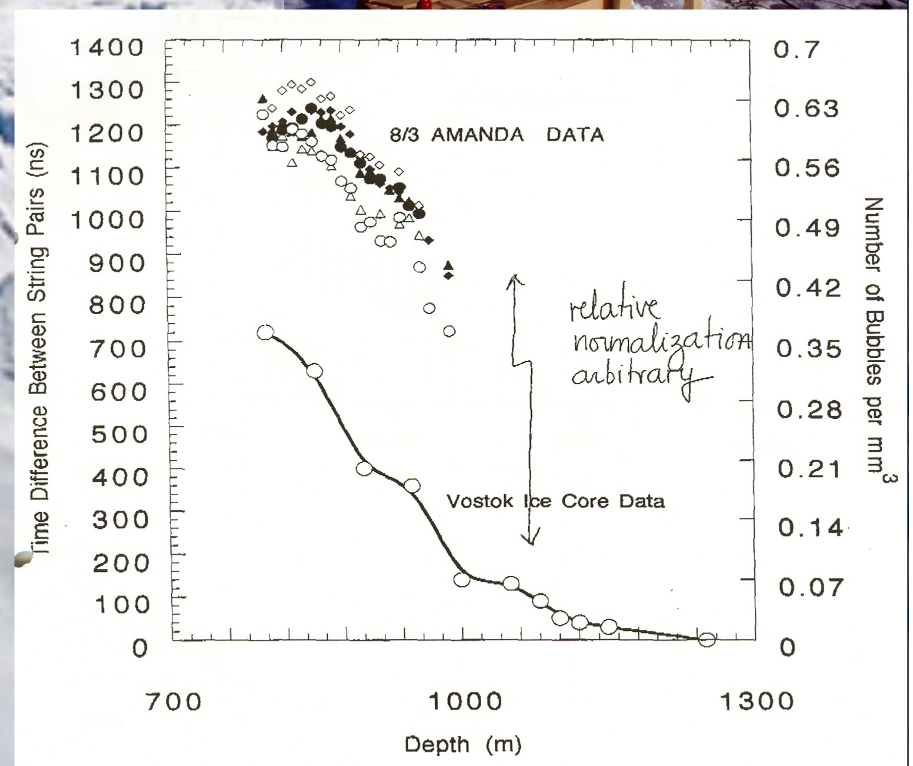
History of Astronomy in Antarctica by Burton http://arxiv.org/pdf/1007.2225v1

AMANDA

- 1993/94 AMANDA-A: us delays of photons instead ns between strings 20 m away
- Bet: go deeper! bubbles disappear with depth
- 95/96: AMANDA B-4 between 1450-1950 m ➙ 96/97 AMANDAB-10 ➙ AMANDA-II



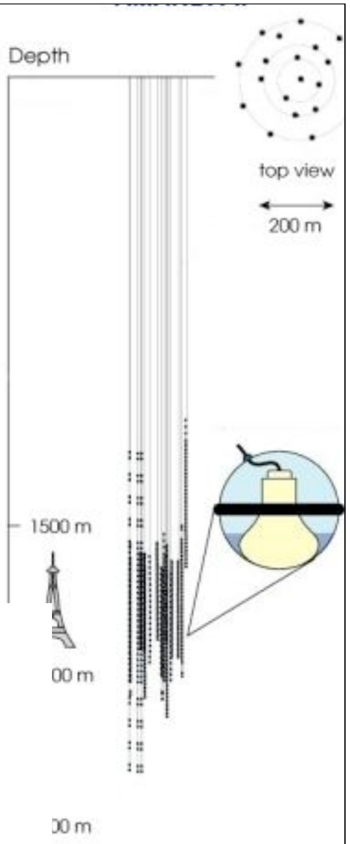




AMANDA Sky map

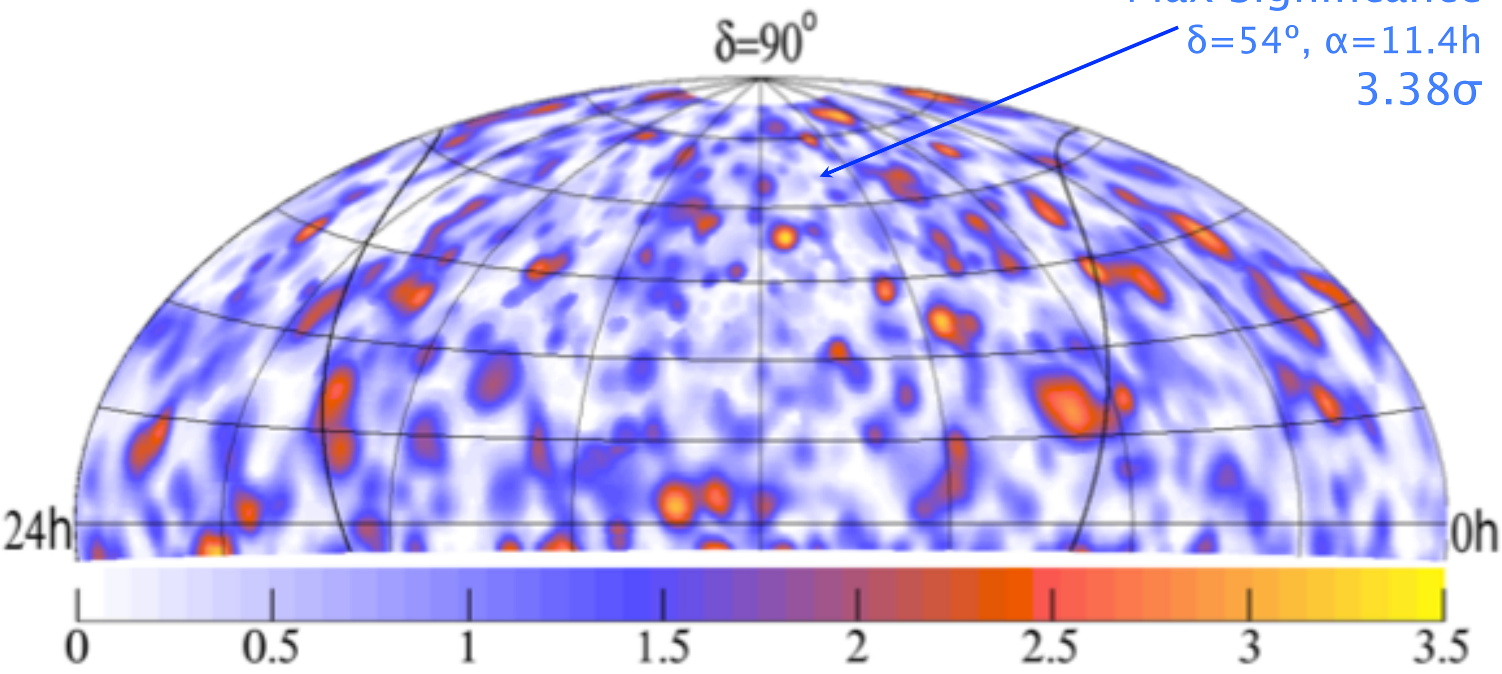
AMANDA (1996-2009),completed in 2000

19 Strings,677 Modules, 8 inch PMTs



6595 ev/3.8 yr of livetime
data public at *http://www.icecube.wisc.edu/science/data*

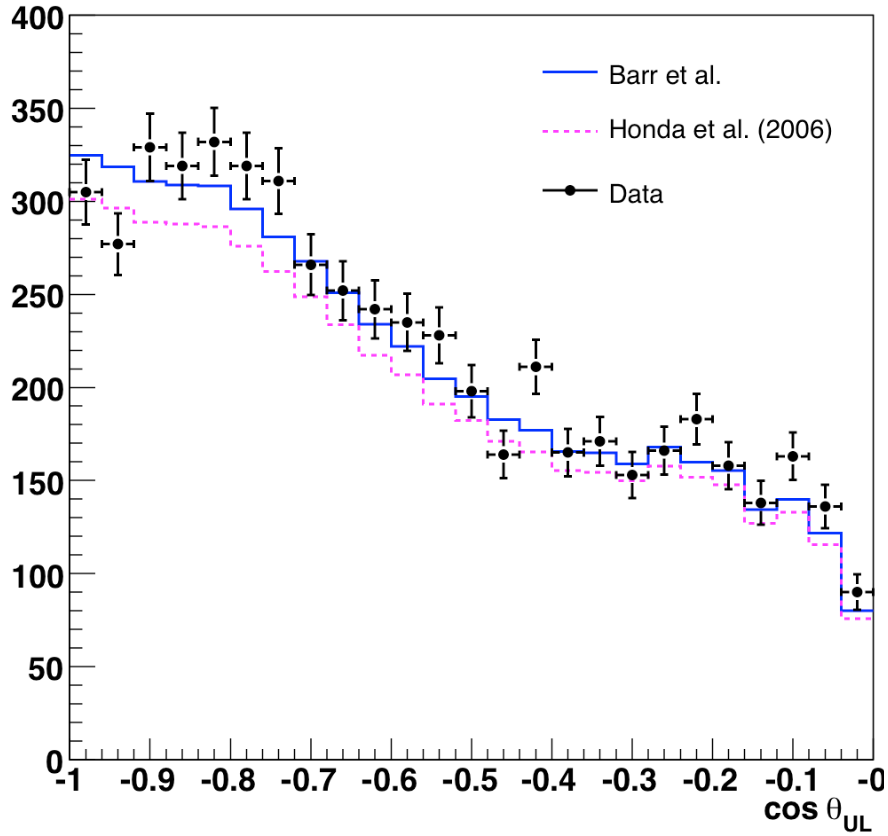
Max Significance
δ=54°, α=11.4h
3.38σ

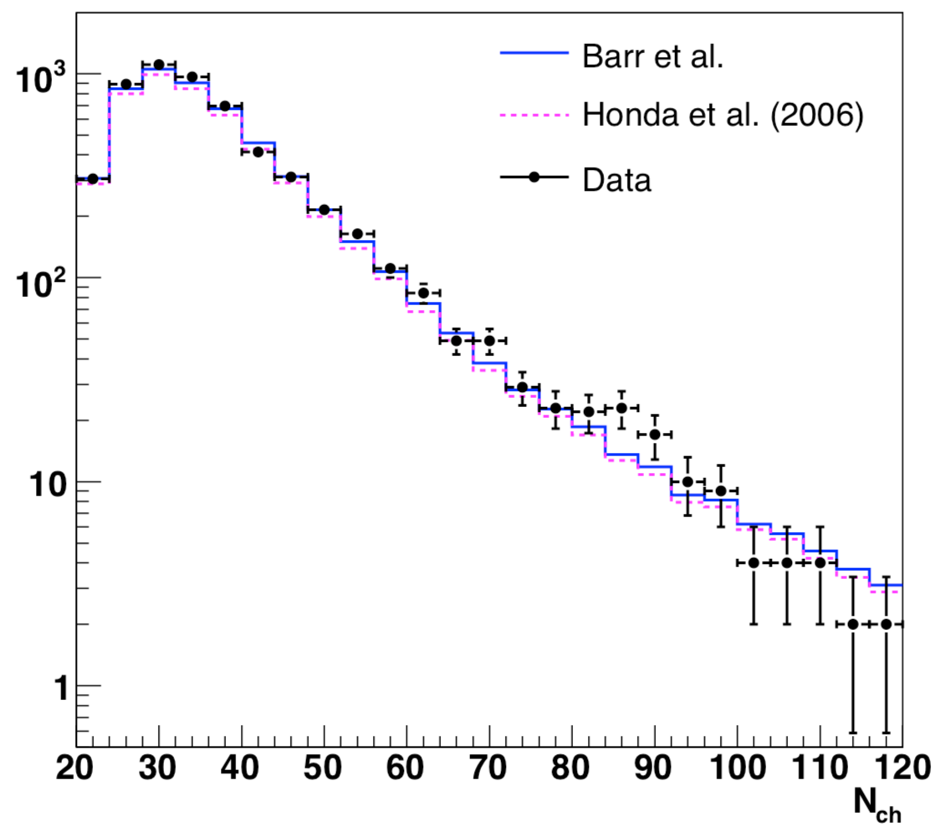


Skymap from 7years AMANDA: no significant excess

significance

AMANDA full sample





zenith angle

number of PMT

Phys. Rev. D79 (2009) 062001
Phys. Rev. D79 (2009) 102005