International School of Nuclear Physics

35th Course, Neutrino Physics: Present and Future

Erice-Sicily, September 16-24, 2013

News on Neutrino Astrophysics

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Outlook

1) Neutrino Astrophysics

2) Neutrino search and detection

3) Neutrino event results

4) Research and future

ν types (and related physics)

cosmological ν

geo-ν

(natural radioactivity),

artificial ν

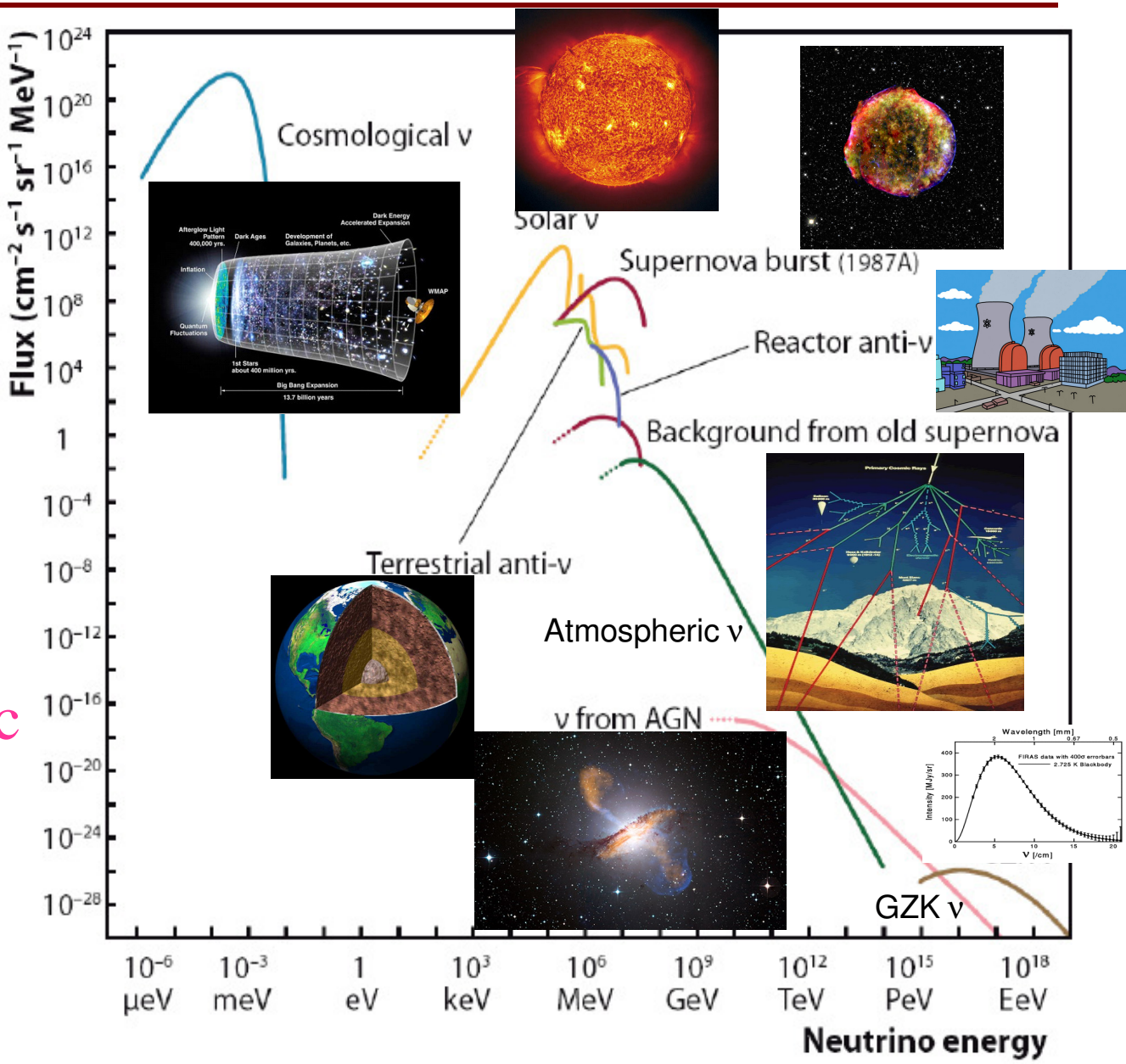
(reactor, accelerator),

atmospheric ν

(CR in atmosphere),

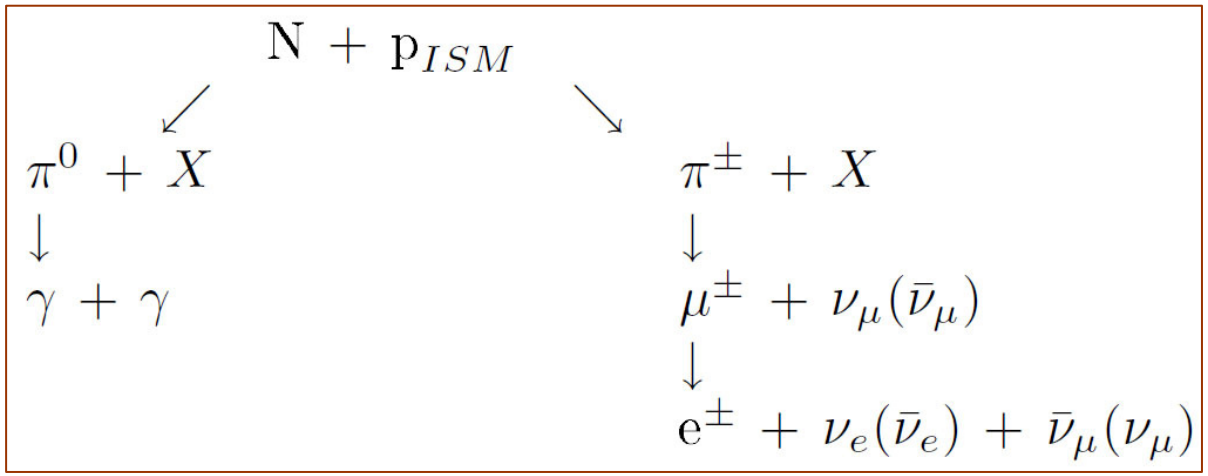
<u>astrophisical ν</u>:

solar, SN, cosmic accelerator, cosmogenic, exhotic



CRs, γs and νs

- ϕ_{CR}, ϕ_γ and ϕ_ν, strictly related: main interaction/decay channels/chain4s (hadronic model)

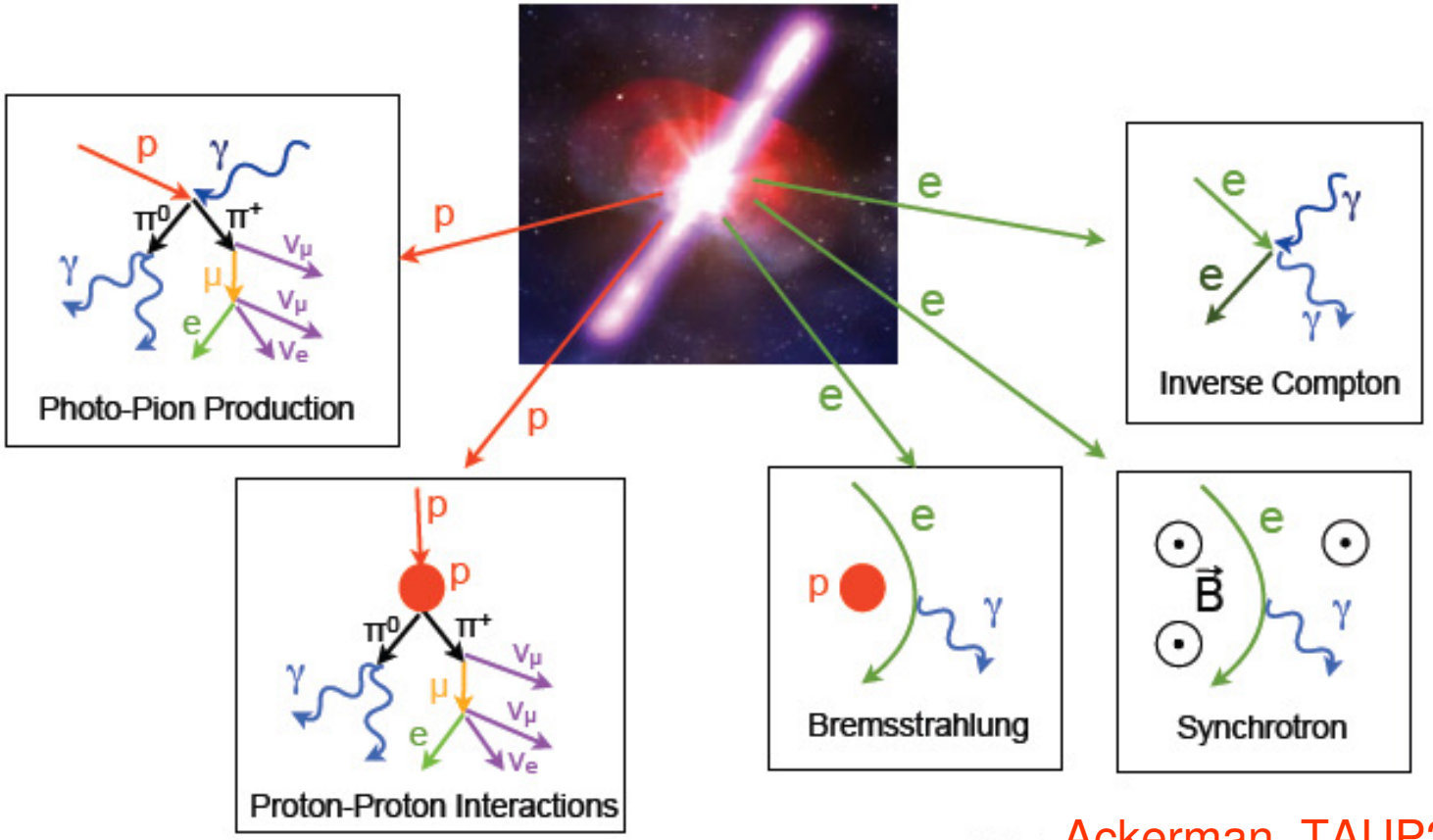


ϕ_{CR} & ϕ_γ: ϕ_ν for comparison (mainly π, η, K produced mesons)

- e&γ populations: leptonic model (brems., synchr., IC, SSC)
- CR & gamma observed
- Aim: obtain a ν flux detailed calculation in analogy to γ-ray flux
- Hadronic (and leptonic) interaction model: universal (e.g. how many νs poroduced from an energetic p)

The power of neutrino observations.

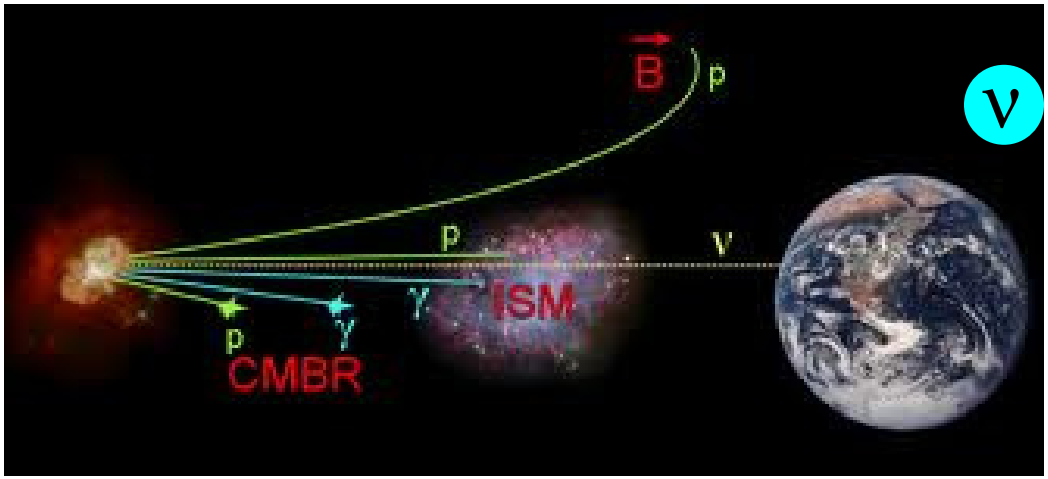
> Neutrinos are a diagnostic of **hadronic acceleration sites and processes.**



Ackerman, TAUP2013

ν Astronomy

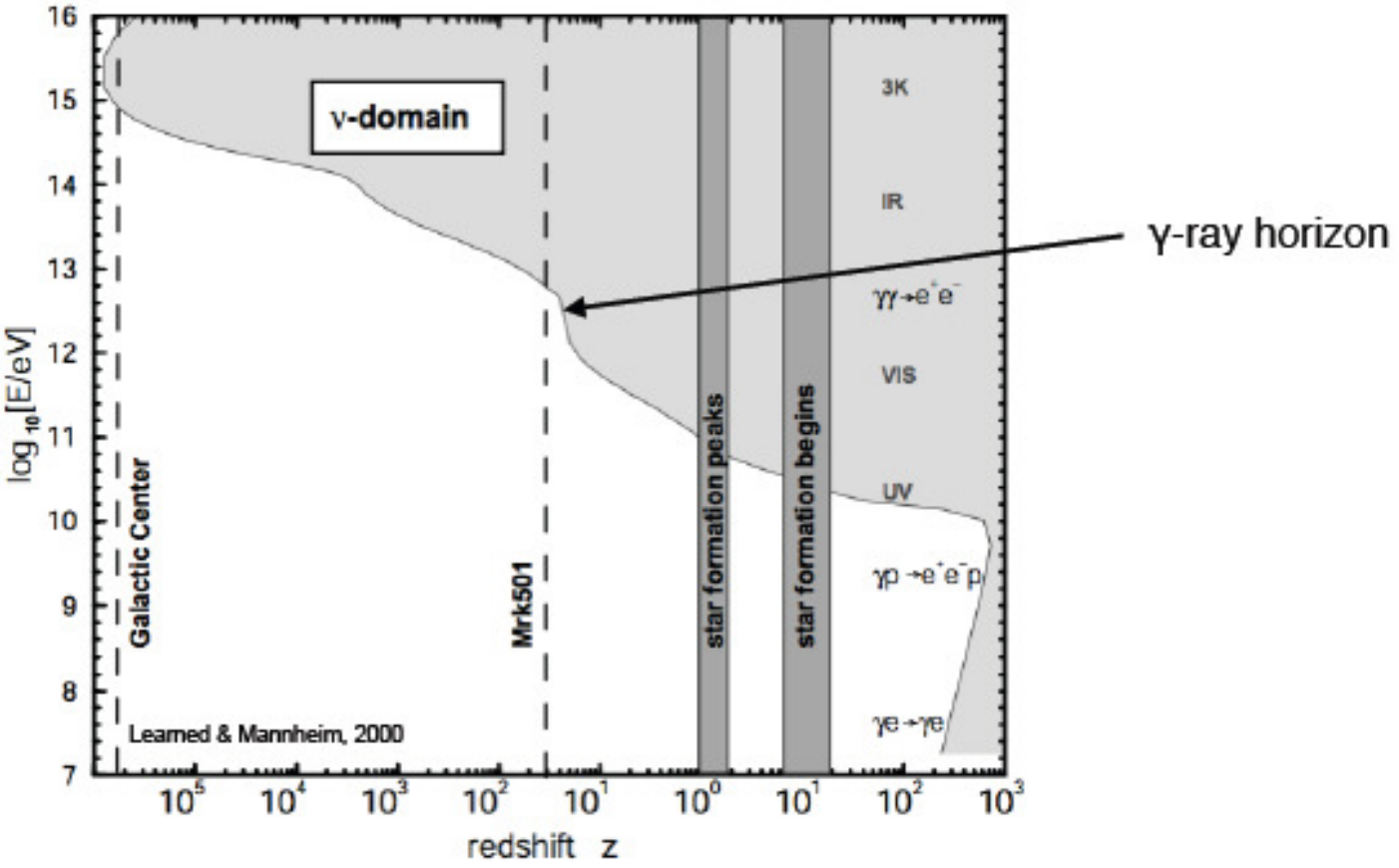
- With photons (and gravitational waves): better comprehension of universe
  - in many scales and energies
  - simultaneous/correlated detection



- ν spectrum → main detection problems:
  1- fleble interaction
  2- atmospheric noise (other?)

The neutrino domain: PeV astronomy.

- Above 100 GeV the **universe** starts to turn **opaque for γ-rays**.
- Only neutrino telescopes can do **PeV/EeV astronomy.**



Gal-extragal High Energy ν

- Galactic flux contributions: point, diffuse disk (&halo)
- Extra-galactic flux contributions:

  Gamma point sources ↔ nu "stars" (candidate AGNs, GRBs –not proven)

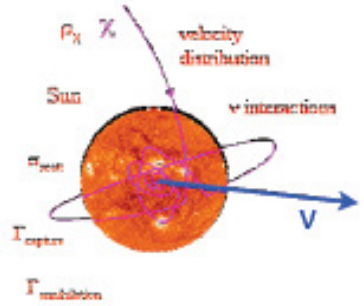
  Isotropic diffuse (from galaxies, GZK ν)
- knowledge problems: source&leptonic (mainly IC in diffuse) contributions
- As for γs → TeV CAT map for νs

The power of neutrino observations.

Neutrinos can **escape dense environments:**

> High-energy neutrinos from core-collapse SNe.
(e.g. Ando & Beacom, 2005)

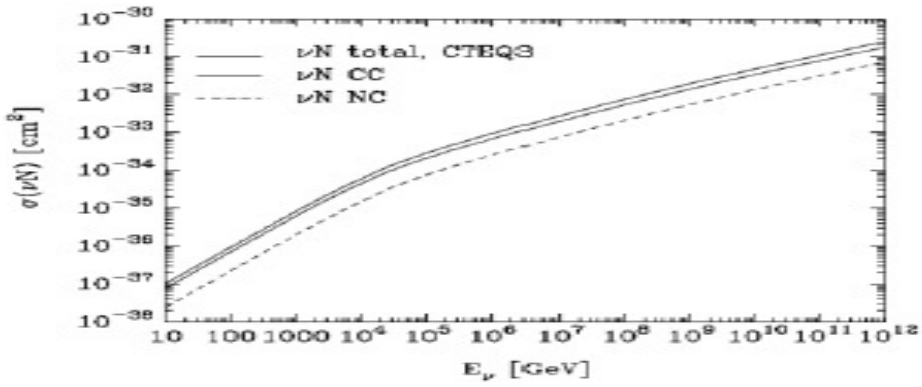
> Neutrinos from the cores of active galactic nuclei
(e.g. Stecker et al., 1991)



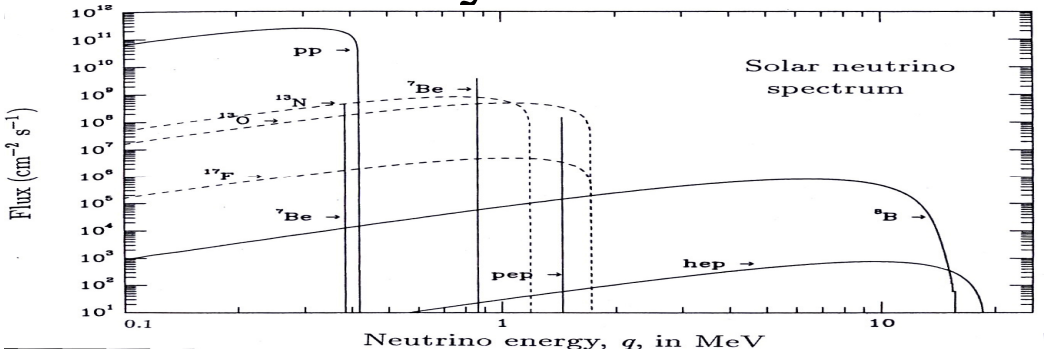
> High-energy neutrinos from dark matter annihilation in the sun.

Actual astrophysical context

- Neutrino telescopes: low noise and large volumes experiments (Ice Cube, Antares, km3Net, Auger)

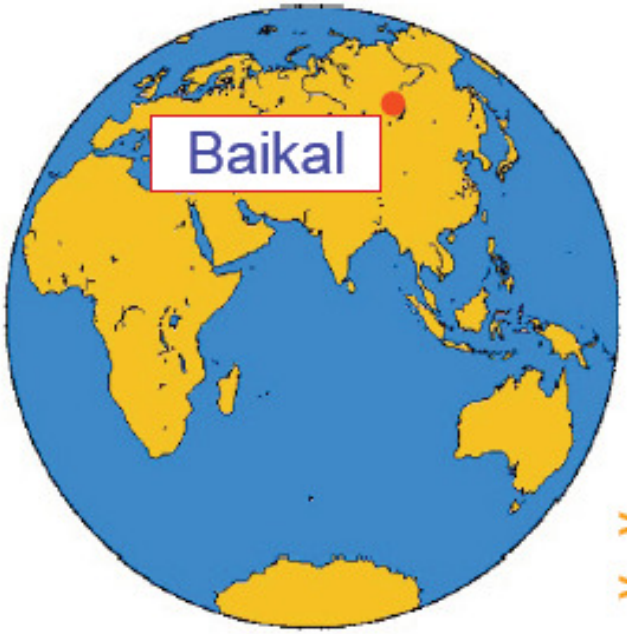


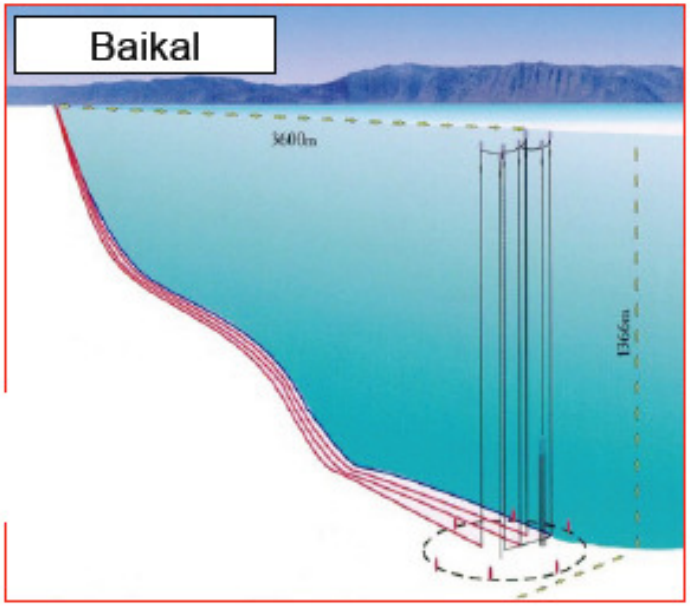
- Detected only solar & SN1987a



- Why no other astro-ν, while already detected many terrestrial νs?

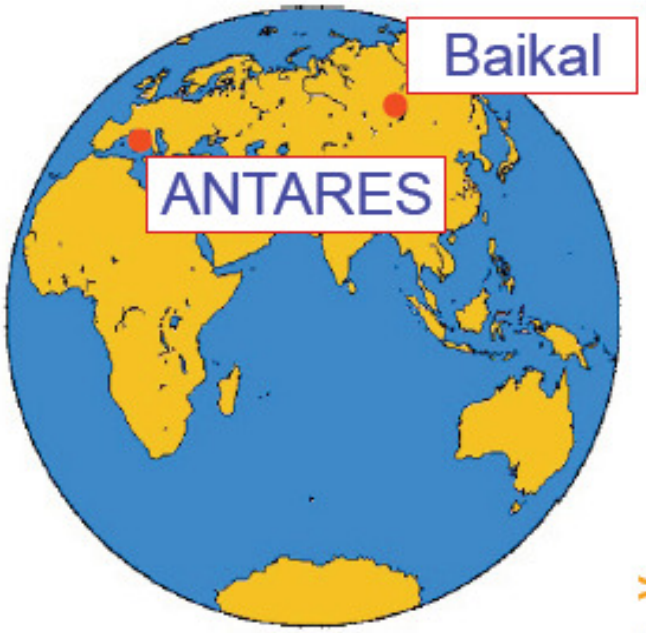
Operating neutrino telescopes: Baikal

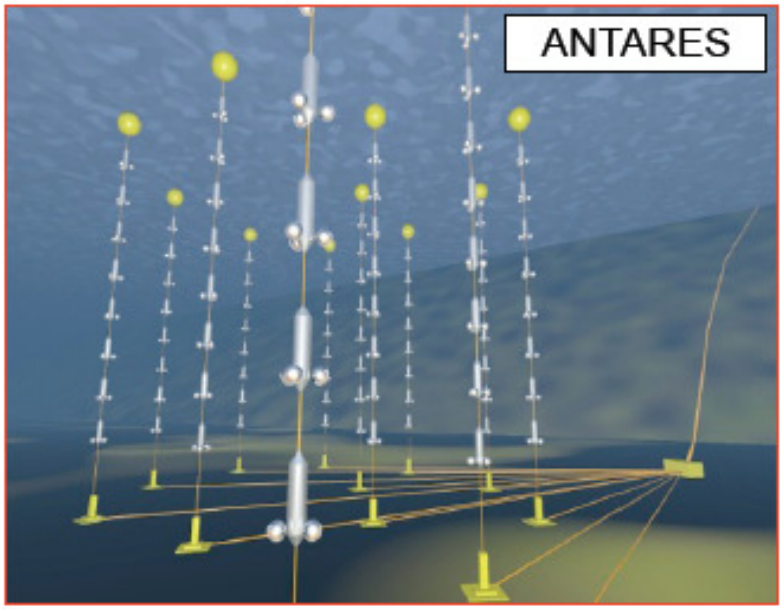




- ~ 4km off the shore of **Lake Baikal**
- **Completed** in **1998**
- 192 optical sensors on 8 strings (**10^{-4} km^3** instrumented volume)
- Upgraded to NT200+ configuration in 2007 (+18 sensors on 3 strings)

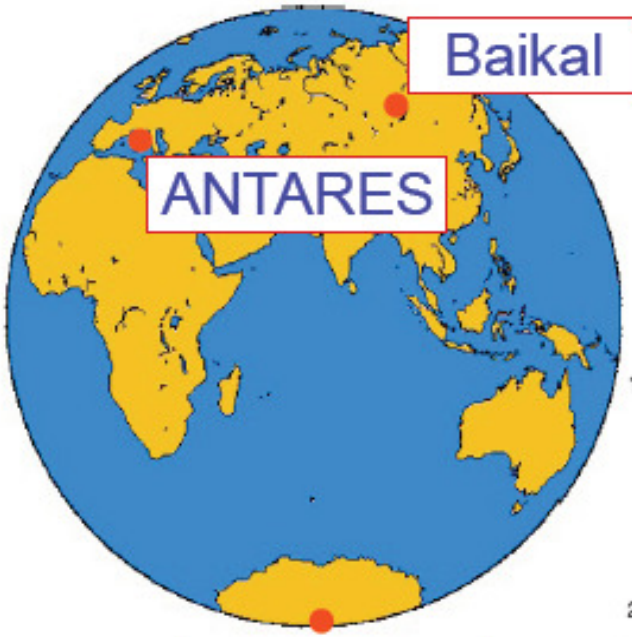
Operating neutrino telescopes: ANTARES

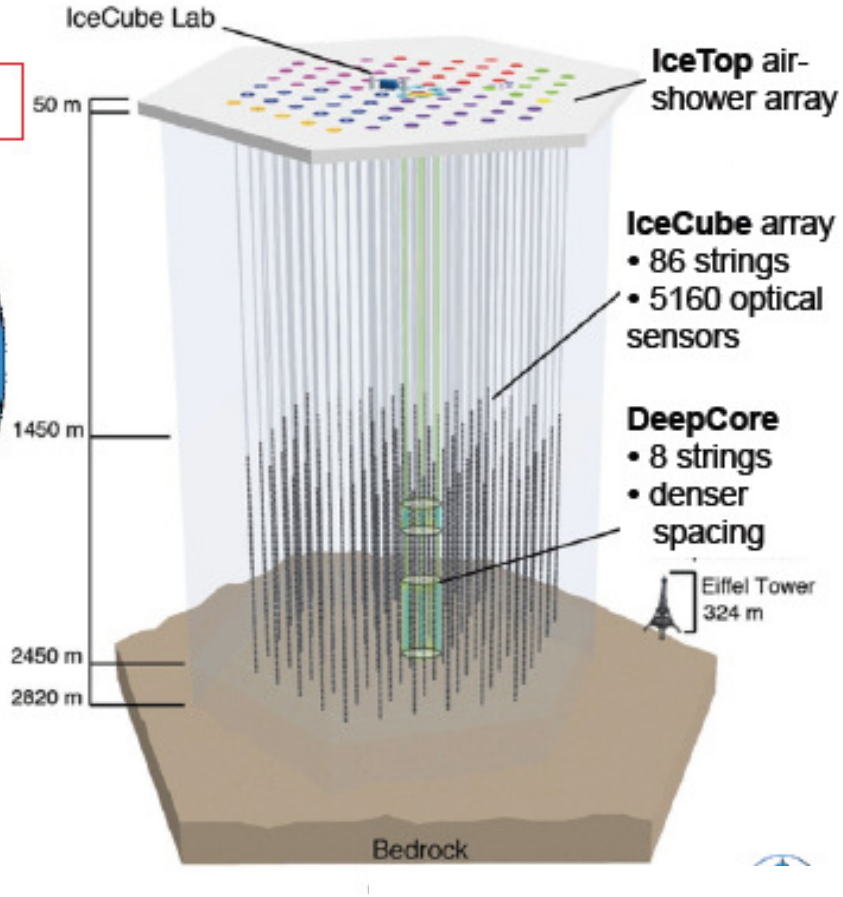




- Mediterranean sea, off **Toulon, France**
- **Operating since 2008** in final configuration
- 885 PMTs on 12 strings (~**10^{-2} km^3** instrumented volume)

Operating neutrino telescopes: IceCube





> **Completed** in Dec **2010**.

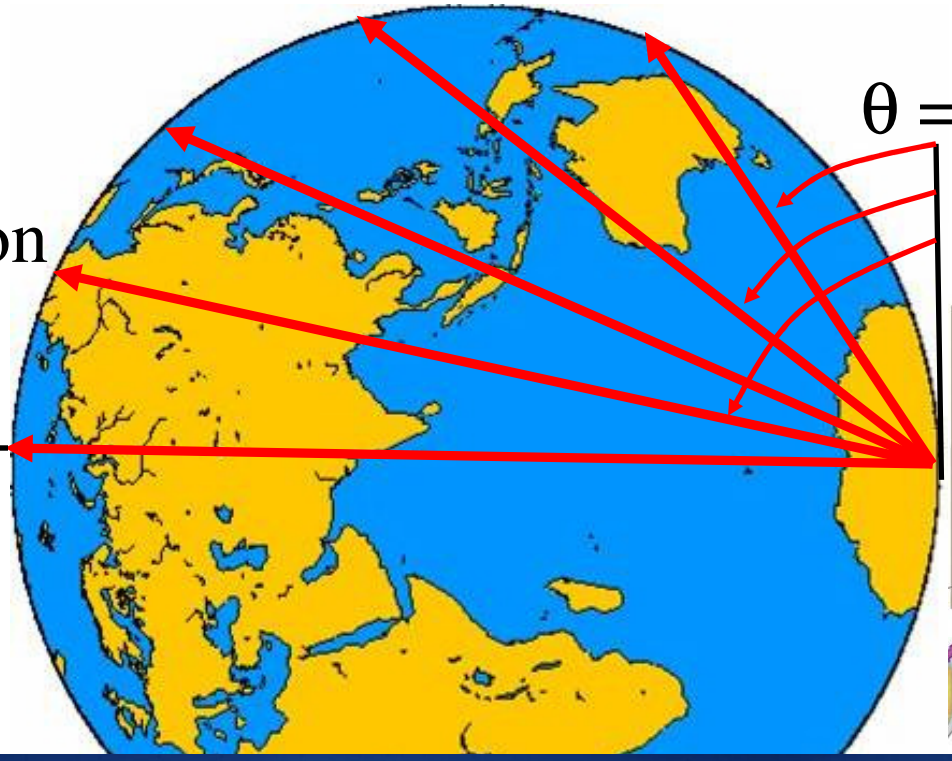
> Instrumented volume: ~ **1km³**

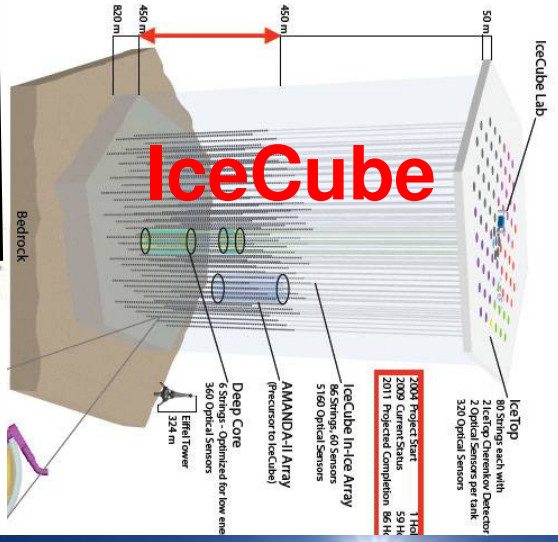
Visual concept

Lines of sight through the Earth

$\theta = \pi/2$ – zenith angle

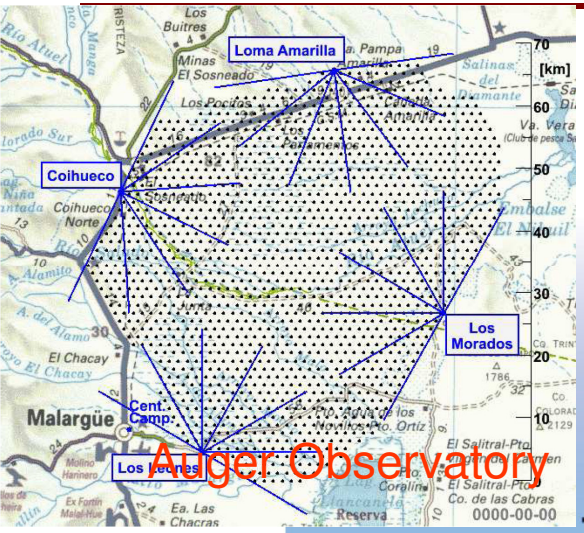
Rotation axis

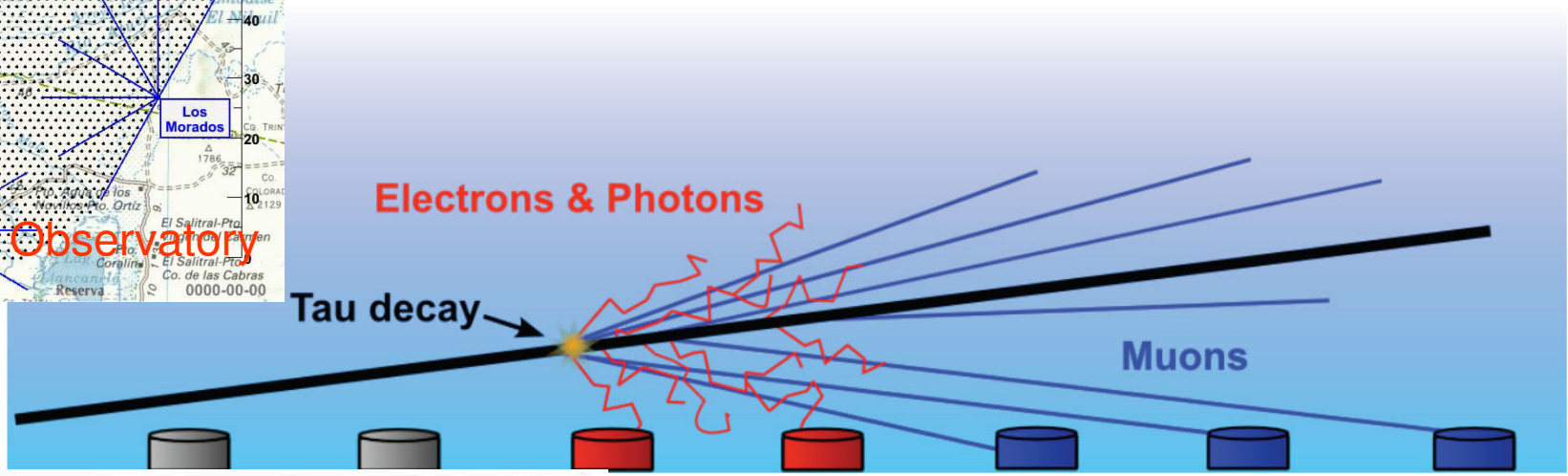


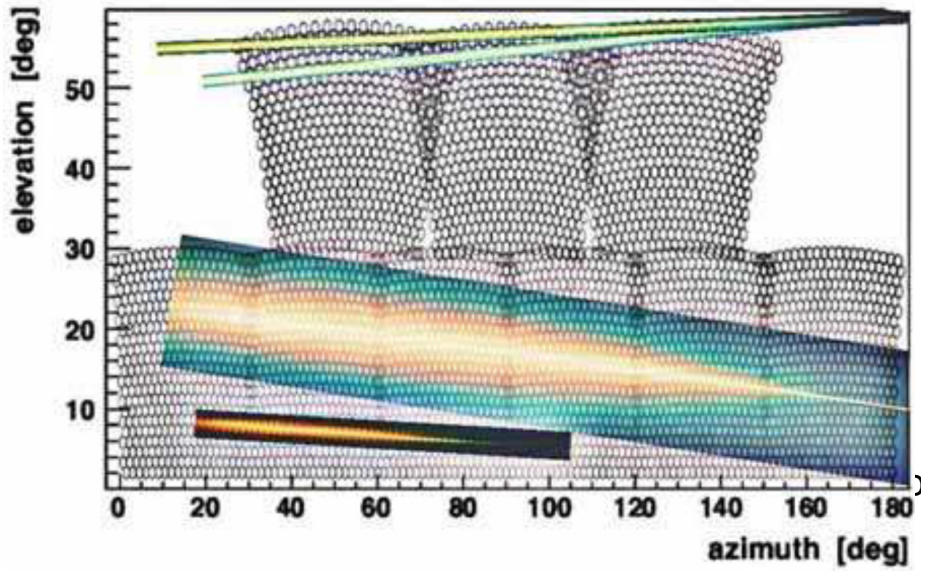


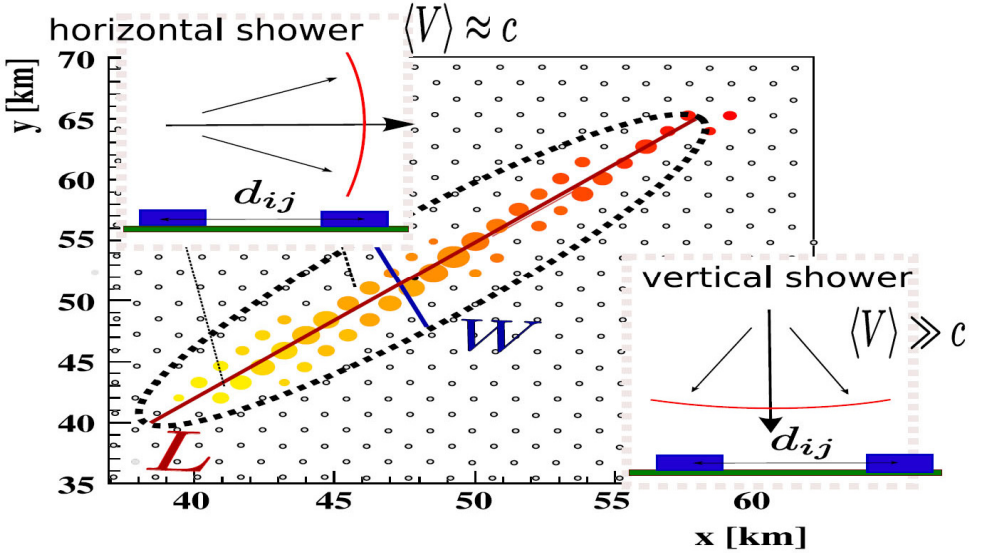
Ice Cube website

EAS array


Loma Amarilla
Coihueco
Los Morados
Malargüe
Cent. Camp.
Los Leones
Auger Observatory
70
[km]
60
50
40
30
20
10

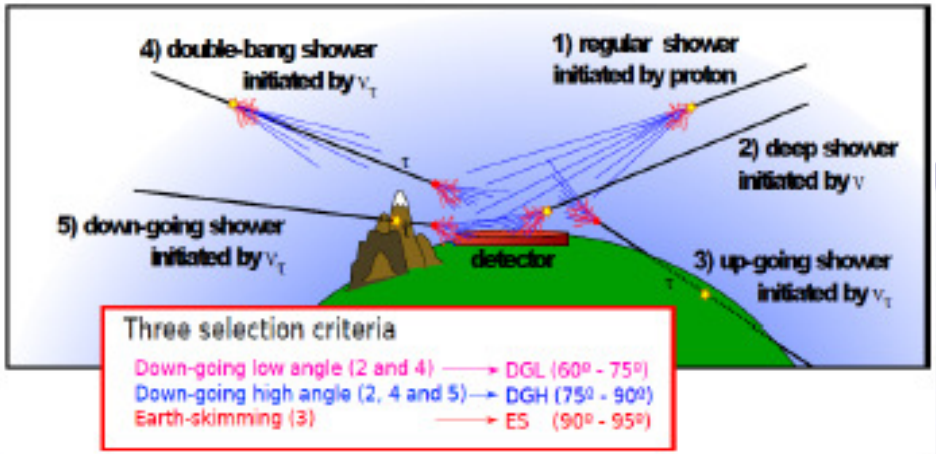

Electrons & Photons
Tau decay
Muons


elevation [deg]
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
azimuth [deg]

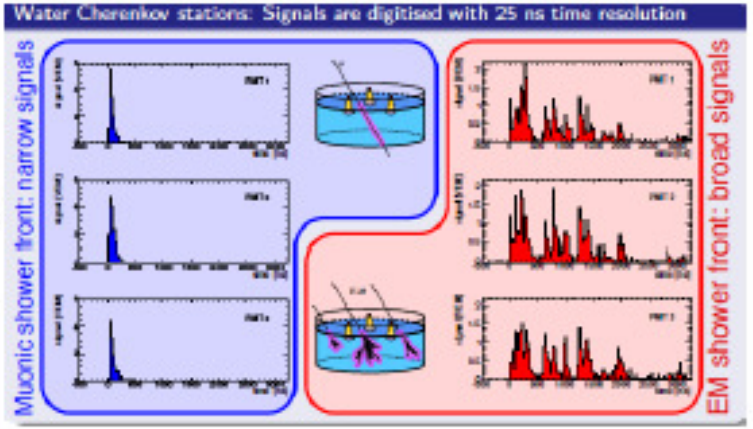

horizontal shower
$\langle V \rangle \approx c$
d_{ij}
L
W
vertical shower
$\langle V \rangle \gg c$
d_{ij}
y [km]
70
65
60
55
50
45
40
35
40
45
50
55
60
x [km]

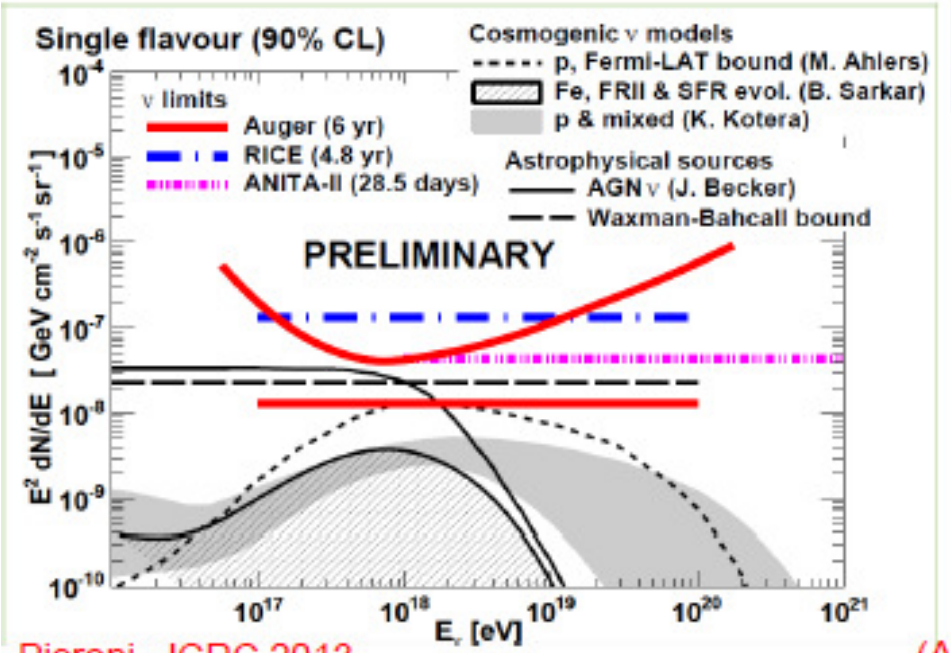
EAS array: Auger

COMPOSITION: BOUNDS ON NEUTRINOS



Neutrinos, unlike hadrons, can induce "young" showers close to the ground





CANDIDATES: 0 → Bounds

Predictions for cosmogenic neutrinos are sensitive to composition (more for lighter nuclei)

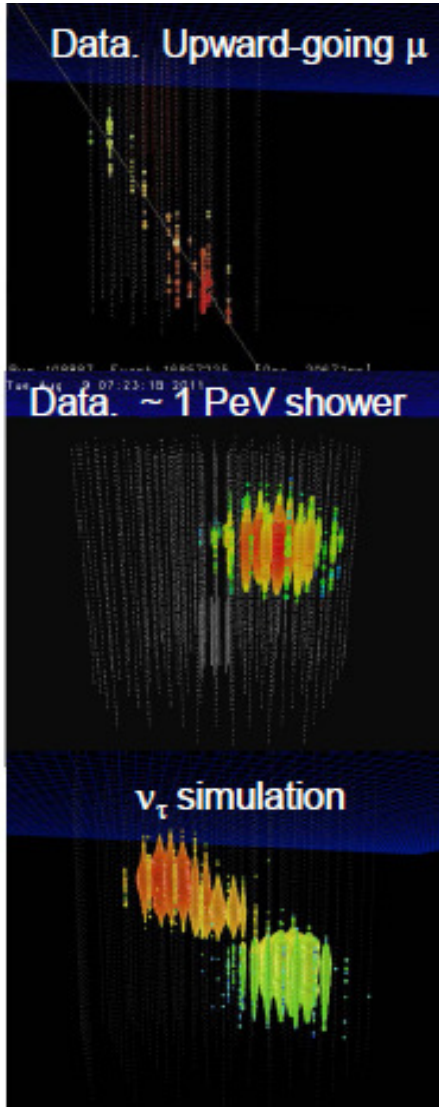
Model	Expected number of events
AGN (Becker)	~ 3.1
Cosmogenic (Ahlers) proton (Fermi-LAT bound)	~ 1.4
Cosmogenic (Kotera) proton & mixed compos.	~ 0.2 - 0.6
IceCube PeV flux, E^{-2} extrapolation	~ 2.2

Pieroni ICRC 2013

(Also Kopper, Mohrmann, Ahlers@TAUP2013)

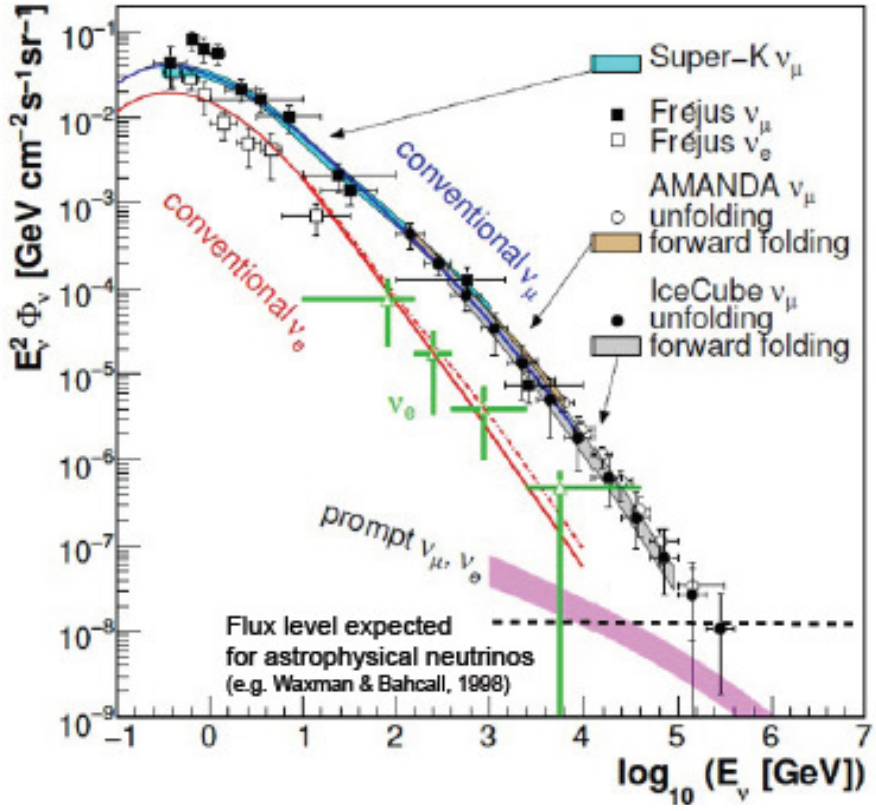
Flavor identification

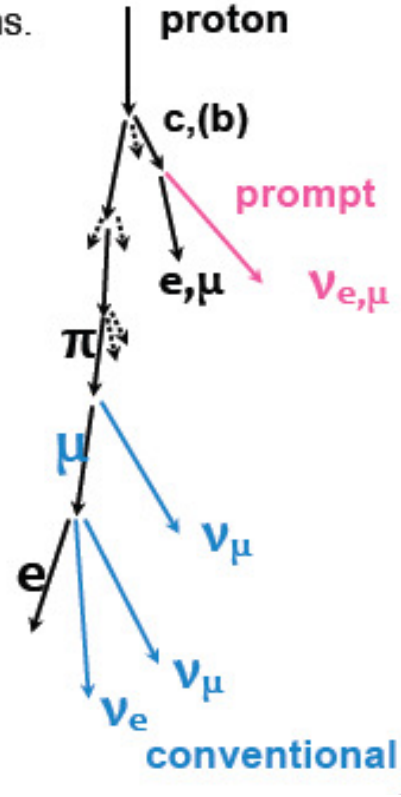
- 3 distinctive topologies
- ν_μ charged current
  - ~<1^0 angular resolution
  - factor of 2 energy resolution
- showers: charged current ν_e, ν_τ, or any flavor neutral-current
  - 15% energy resolution at high energies
    - 10% difference for hadronic/EM showers
  - ~15^0 angular resolution (energy dependent)
- ν_τ double bang: not yet seen
- Ongoing improvements in reconstruction algorithms for all 3 topologies
  - Direct Reconstruction (Paper 0581)
  - Robust Statistics – first guess (Paper 0807)



The atmospheric neutrino background.

- **Most neutrinos** seen by neutrino telescopes are of **atmospheric origin**.
- Atmospheric-ν are produced in **CR air shower interactions**.
- **"Prompt" component** from the decay of charm mesons.





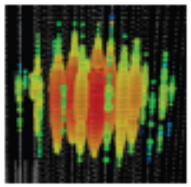
Backgrounds

- Atmospheric muons passing the veto
  - This background is determined experimentally by defining a smaller, inner veto region and checking the rate at which tagged muons leak through
- Atmospheric neutrinos
  - "Conventional" ν (from π, K decay)
  - "Prompt" ν (from decay of charm)
  - Muons produced in the same shower as ν provide a partial self-veto in Southern sky

High-energy neutrino astrophysics.

> Search for the **sites of hadronic acceleration.**

- Galactic and extragalactic sources.
- Transients (Gamma-ray bursts, flares of AGNs, periodic emission from binaries)

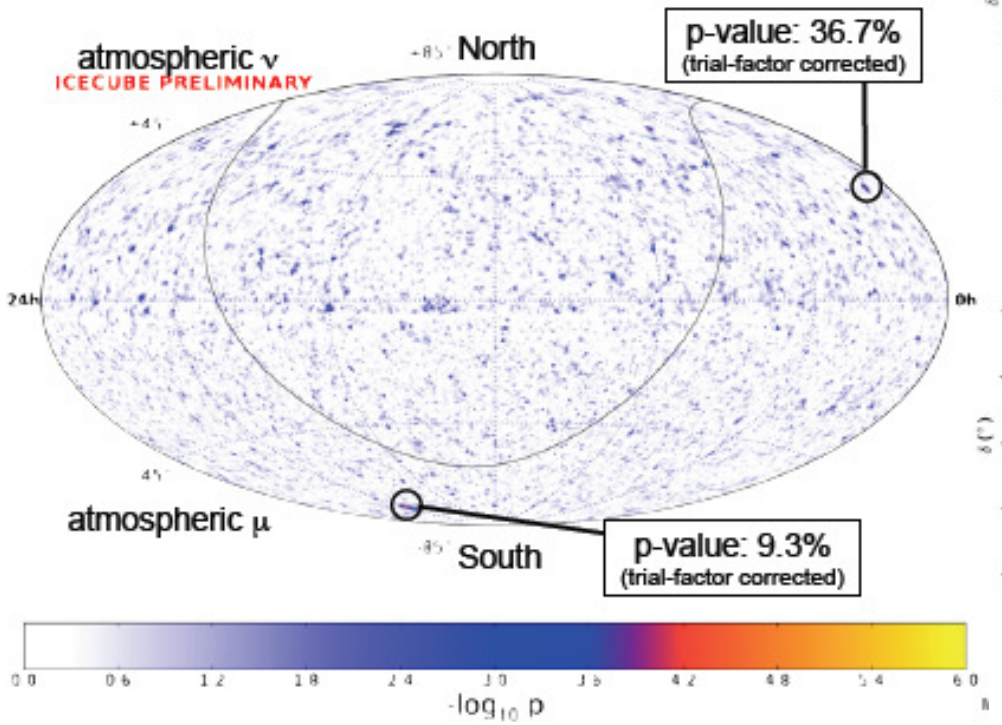


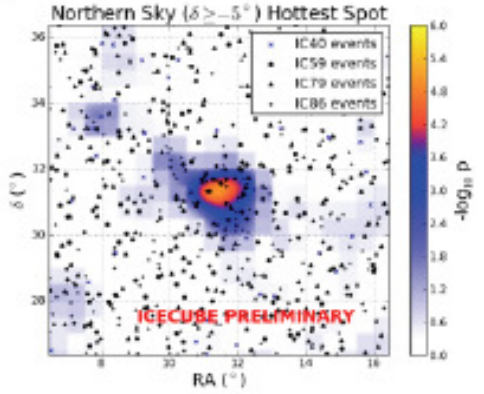
> Search for a **diffuse neutrino flux** from throughout the universe

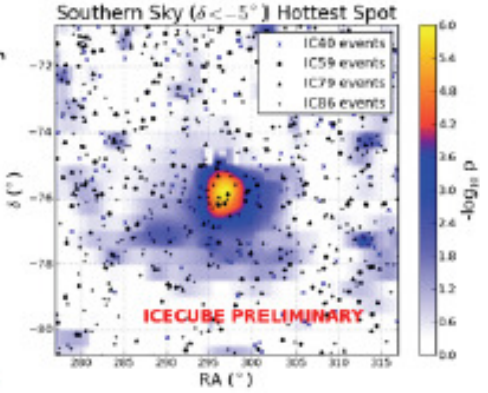
- from unresolved sources
- from the interactions of ultra-high-energy CR

Search for individual neutrino sources: IceCube

- **4 years** of IceCube data (construction phase + full array)
- 1371 days of livetime, **394,000 events** total
  - **178,000 neutrino** candidates in the North
  - **216,000 atmospheric muons** in the South

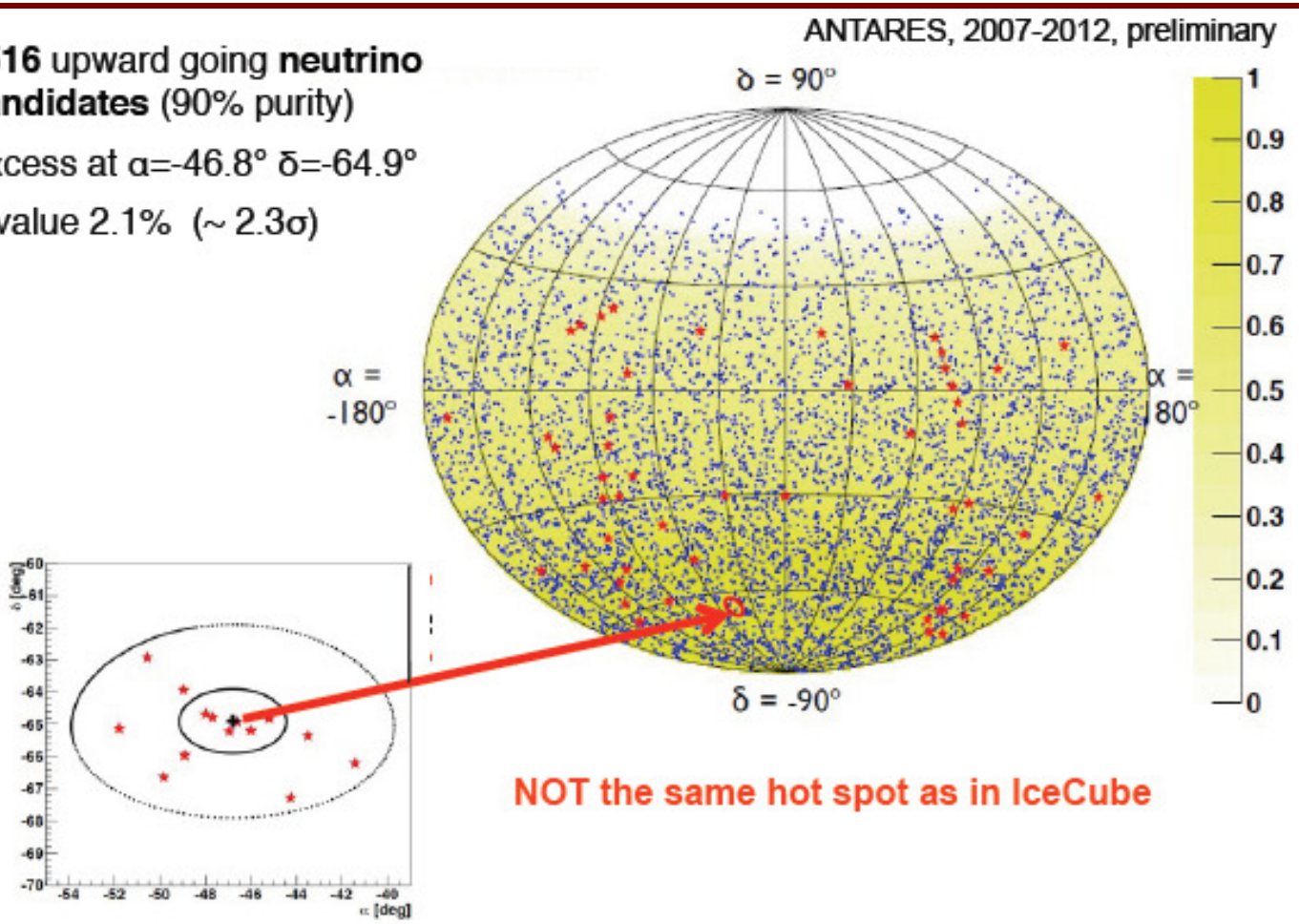






Search for individual neutrino sources: ANTARES

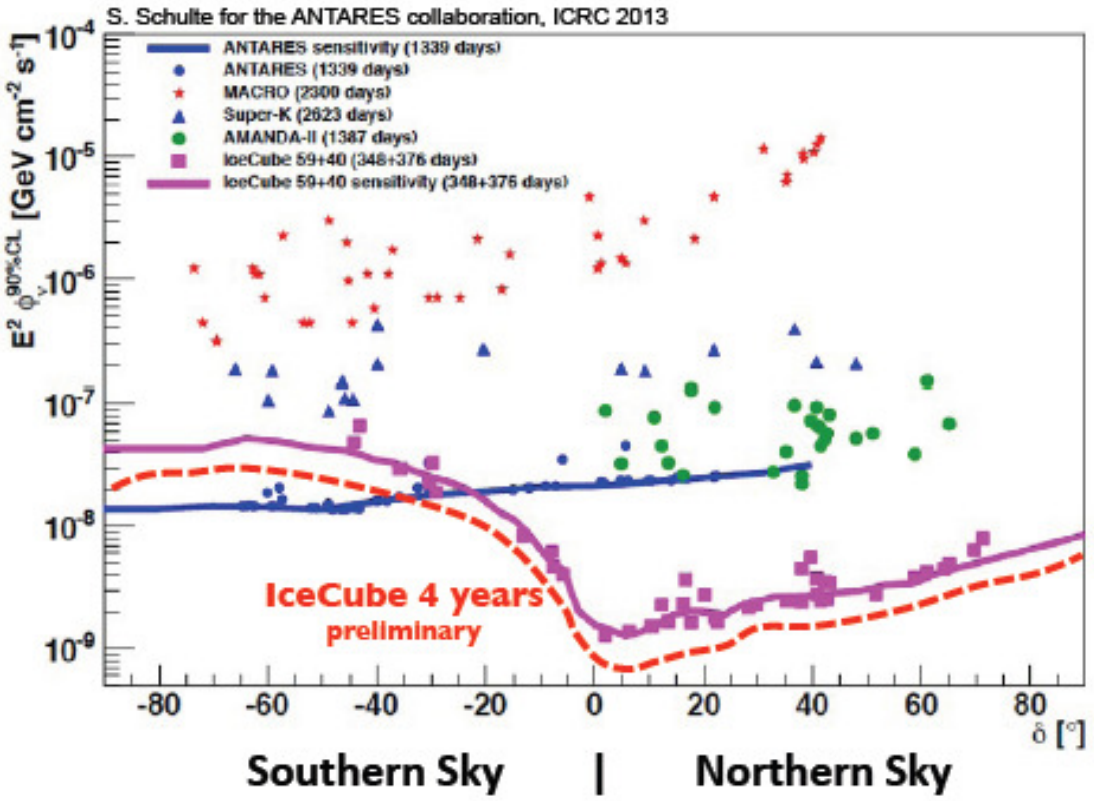
- **5516** upward going **neutrino candidates** (90% purity)
- Excess at α=-46.8° δ=-64.9°
- p-value 2.1% (~ 2.3σ)



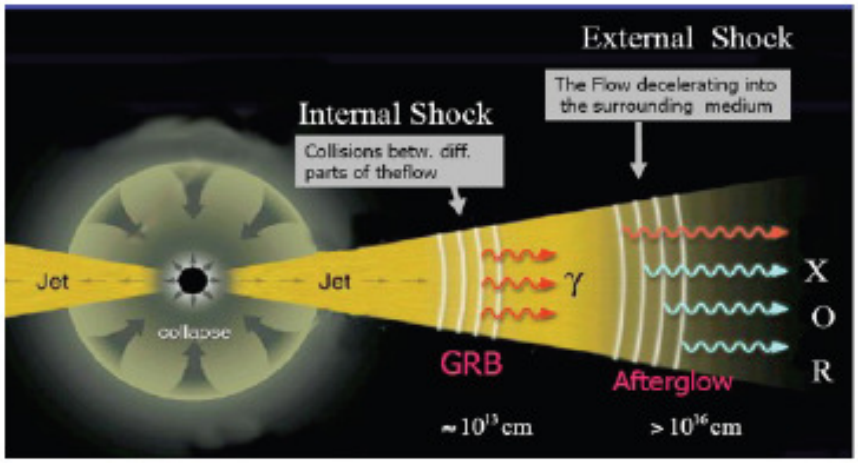
NOT the same hot spot as in IceCube

Upper limits on the neutrino flux from sources.

- **Factor 1000 increase** in sensitivity over 13 years.
- **No detections.**
- **ANTARES and IceCube** observations are **complementary**.



Search for neutrinos from transients: GRBs



- **GRBs** have been proposed as the **dominant acceleration site** for CRs up to energies > 10^{20} eV.
- Accompanying **neutrino emission** should be **visible in km³-sized** neutrino telescopes in a wide variety of scenarios.
- Search for **cumulative signal** from all observable bursts.

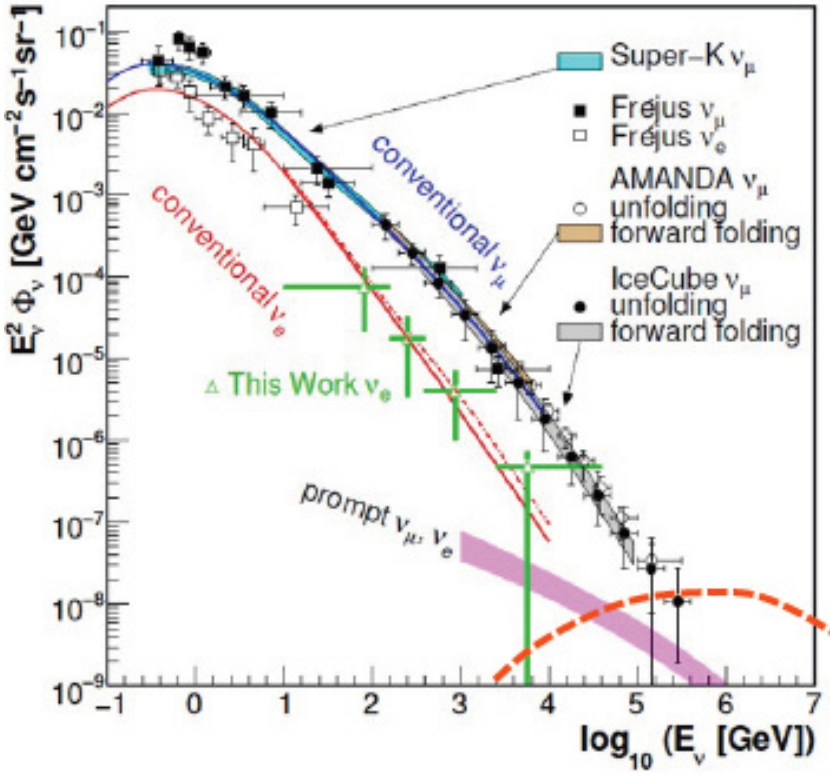
IceCube

- **225 GRB** at Northern sky
- 2 years of IceCube construction phase data
- No significant correlation found between IceCube events and GRBs.

ANTARES

- **296 GRB at** Southern sky
- No ANTARES event in time and direction coincidence (arXiv:1307.0304)

Search for diffuse astrophysical neutrinos.

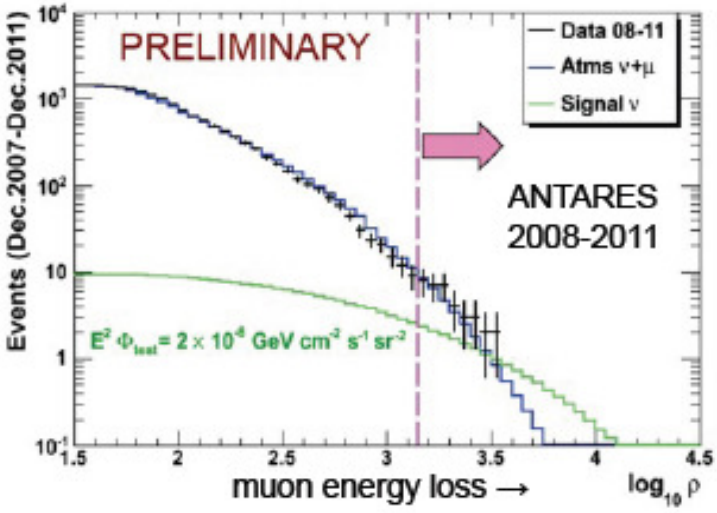


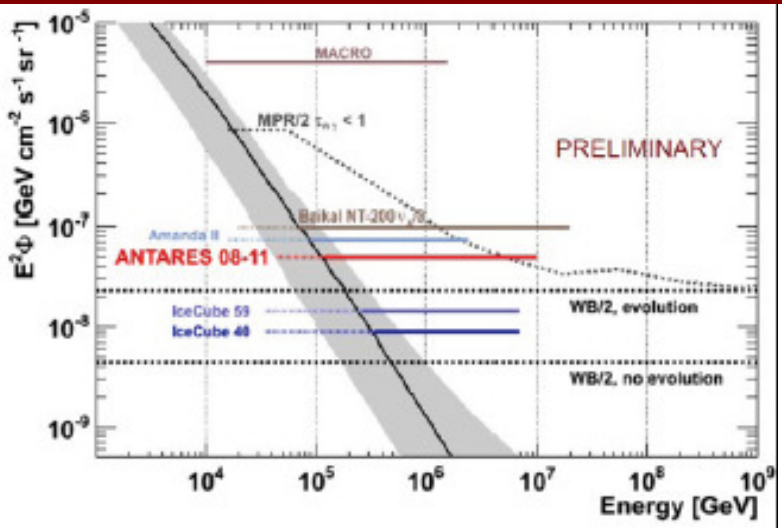
> Search for a **diffuse excess** of neutrinos over background from atmosphere at high energies.
  - From unresolved neutrino sources
  - From the interactions of CR with the extragalactic background light

> **Lower** atmospheric **background** for **shower-type** events (ν_e + NC ν_μ only)

extraterrestrial neutrinos ?

Upper limits on the diffuse flux of atmospheric neutrinos.





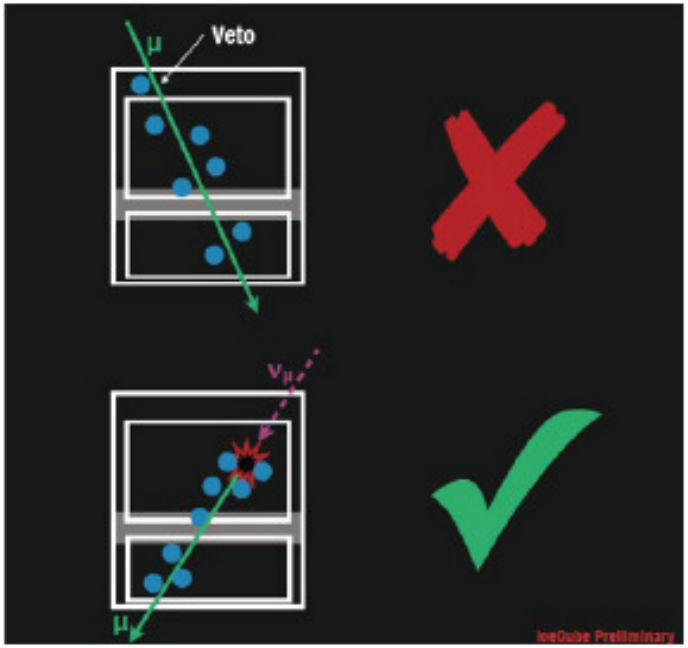
> Search for high-energy excess in the muon energy loss spectrum.

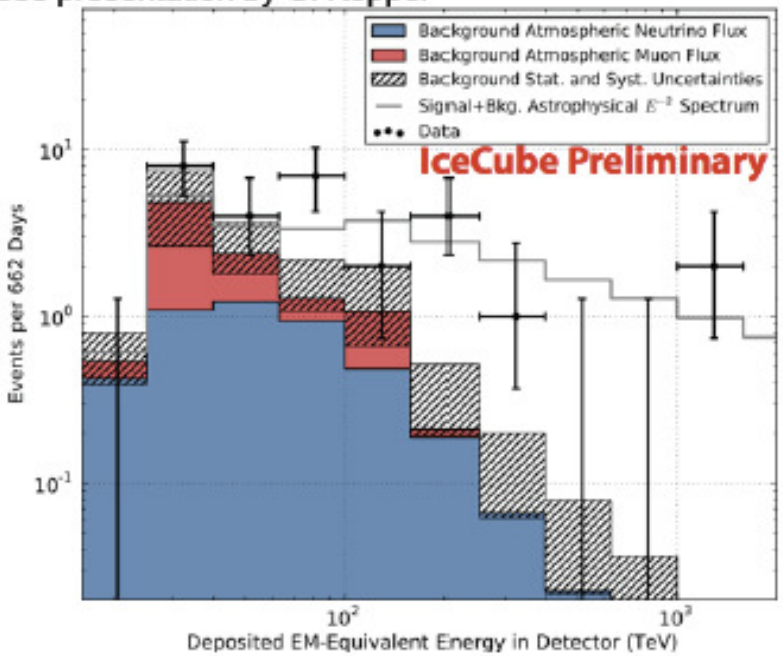
> Upper limits on astrophysical flux:

- ANTARES (2008 - 2011)
- IceCube construction phase

Search for a diffuse astrophysical flux.

see presentation by C. Kopper

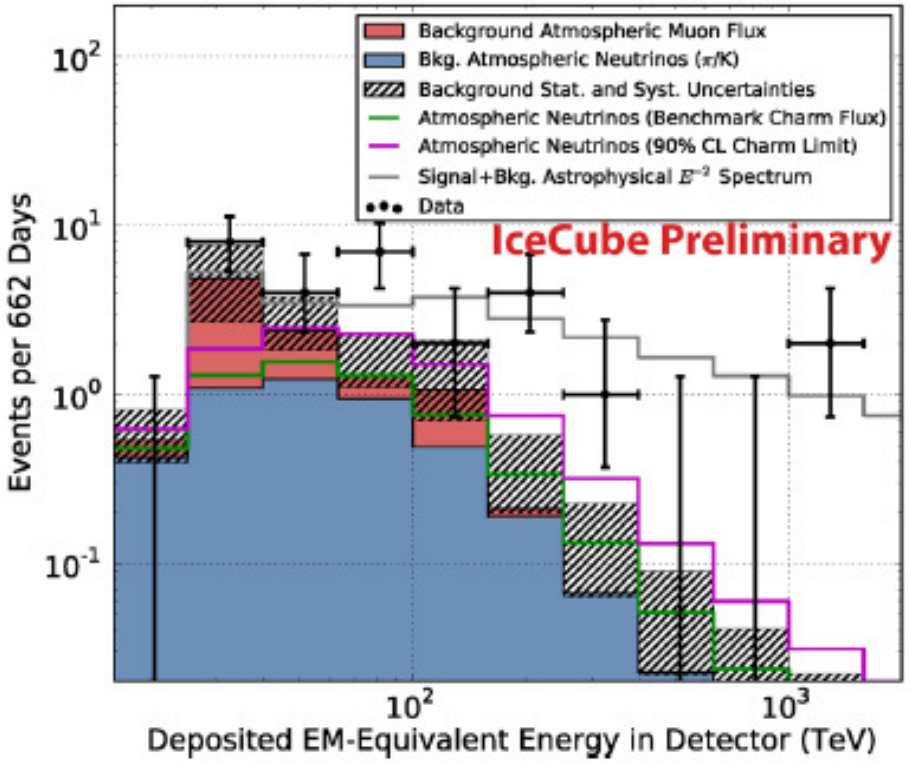




- **Extension** of previous search to **lower energies** (~ 30 TeV energy threshold)
- **New strategy** to reject CR background.
- **28 events** found in 2010-2012 dataset.
- **4.1σ excess** over expected backgrounds from atmospheric μ / ν

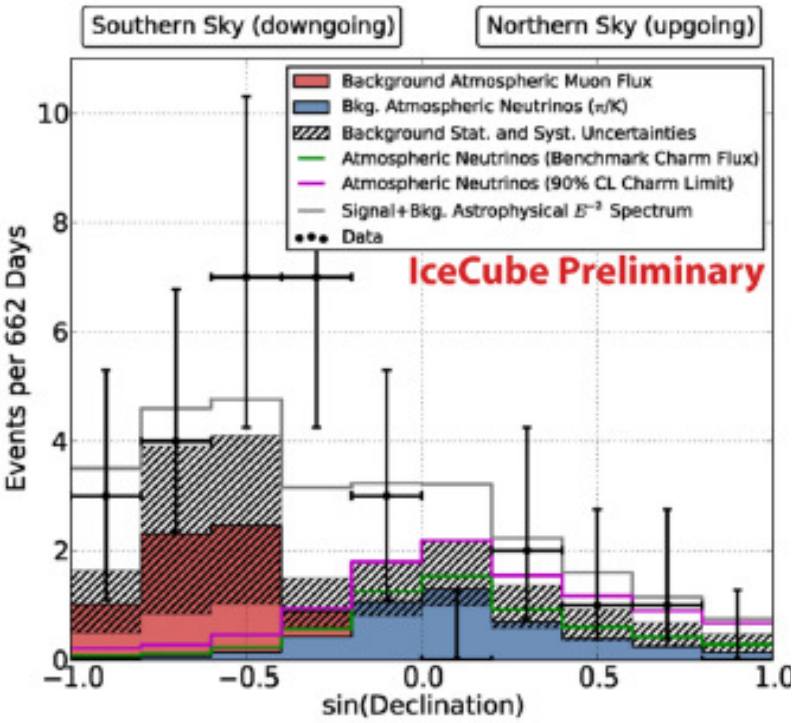
Energy spectrum & event characteristics

- Deposited energy
  - Electromagnetic process assumed
  - ~ 10-15% less light from hadronic showers
- 21 of 28 events are shower-like
  - Fraction is consistent with astrophysical or prompt ν

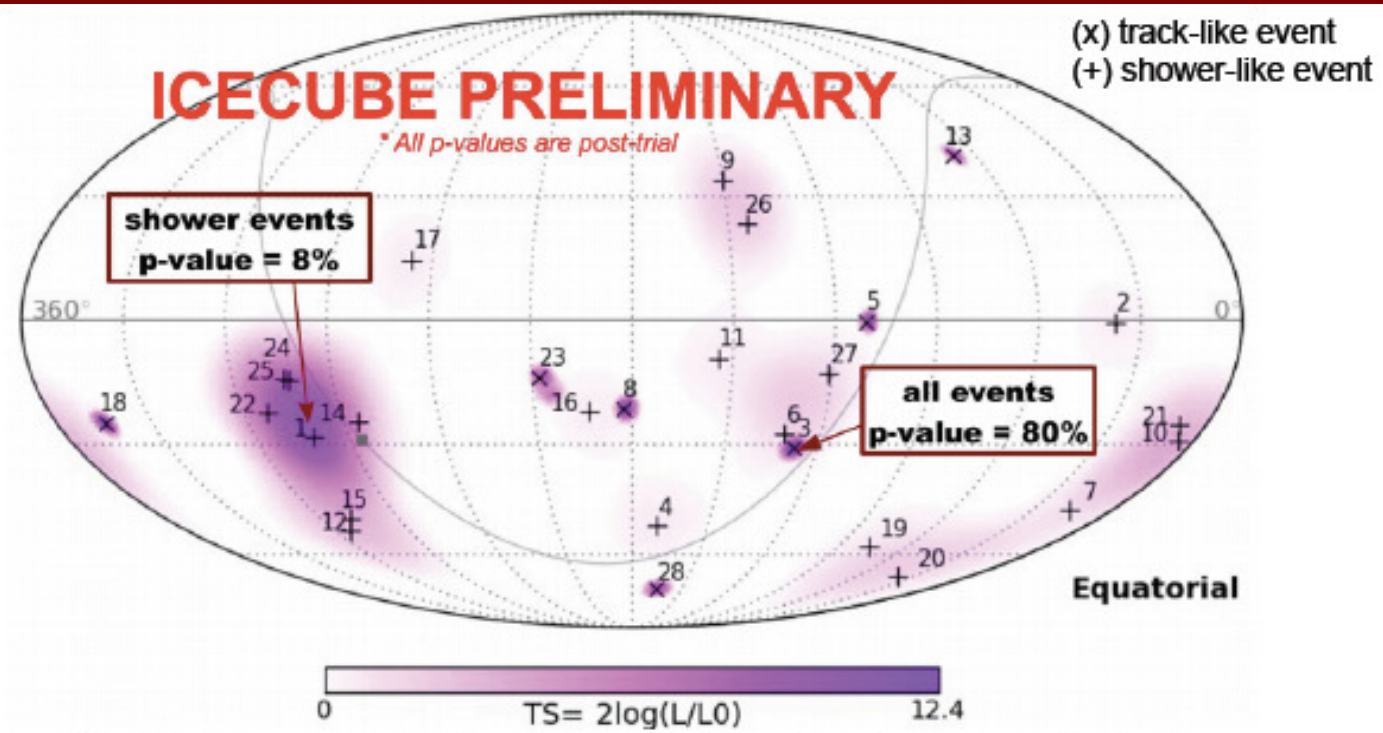


Zenith angle distribution

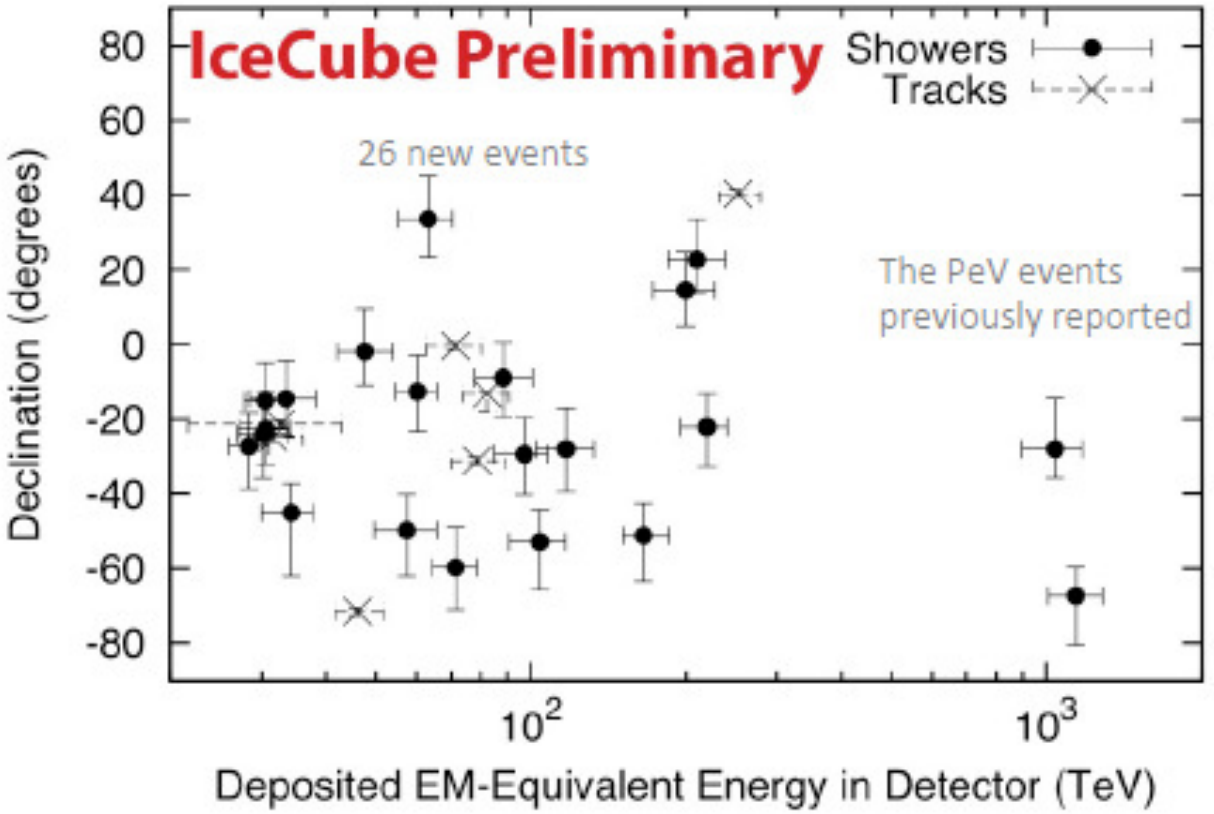
- 24 of 28 events are downward-going
- Most atmospheric ν should be upward-going
  - Effect of veto
- Astrophysical ν should be somewhat more downward-going
  - Acceptance and absorption
- 1.5 σ away from astrophysical prediction; inconsistent with atmospheric



Distribution of high-energy neutrinos on the sky.



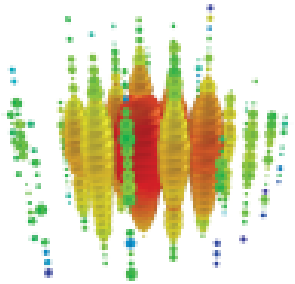
- **Event distribution** compatible with expectations from background + isotropic astrophysical flux.
- **No significant correlation** in space/time with GRBs found.
- **More statistics needed** to distinguish different hypotheses of astrophysical origin.


IceCube Preliminary
Showers
Tracks
26 new events
The PeV events
previously reported
Declination (degrees)
80
60
40
20
0
-20
-40
-60
-80
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)

Some papers explaining IceCube neutrinos

Galactic

- "Galactic PeV Neutrinos," Gupta, arXiv: 1305.4123
- "Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy," Fox, Kashiytama, Mészarós, arXiv:1305.6606
- "Pinning down the cosmic ray source mechanism with new IceCube data," Anchordoqui et al., arXiv:1306.5021
- "The Galactic Pevatron," Neronov, Semikoz, Tchernin, arXiv:1307.2158



Extragalactic

- "PeV neutrinos from the propagation of ultra-high energy cosmic rays," Roulet et al., arXiv:1209.4033
- "On The Origin of IceCube's PeV Neutrinos," Cholis, Hooper, arXiv:1211.1974
- "Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons," Kistler, Stanev, Yuksel , arXiv: 1301.1703
- "PeV neutrinos from intergalactic interactions of cosmic rays emitted by active galactic nuclei," Kalashev, Kusenko, Essey, arXiv:1303.0300
- "Neutrinos at IceCube from Heavy Decaying Dark Matter," Feldstein et al., arXiv:1303.7320
- "Ice Cube Observed PeV Neutrinos from AGN Cores," Stecker, arXiv:1305.7404
- "Demystifying the PeV Cascades in IceCube: Less (Energy) is More (Events) ," Laha et al., arXiv: 1306.2309
- "On the Hadronuclear Origin of PeV Neutrinos Observed with IceCube," Murase, Ahlers, Lacki, arXiv:1306.3417
- "Photohadronic Origin of the TeV-PeV Neutrinos Observed in IceCube," Winter, arXiv:1307.2793

Conclusions

- Neutrino telescope have improved the sensitivity for observation of astrophysical neutrino by a factor of 1000 in 13 years
- So far no discovery of an individual neutrino source
- νe more than νmu, donward going more than upward going => hints for astrophysical neutrinos
- IceCube observes the first strong evidence for astrophysical neutrinos

  data incompatible with atmospheric expectations on the > 4sigma level

  compatible with a diffuse & isotropic astrophysical flux (no significant clustering observed)

  additional studies and data needed to constraint the spectral paramenter of this flux
- 'Berte' and 'Ernie' are the not only PeV neutrinos (IceCube top secret)
- More result expected soon (collection and analisys of new data and soon more to say about this excess)

  analisys of 2012/2013 IceCube data – better constraints on atmospheric neutrino fluxes
- Exiting theoretical research on work
- See Daniele Fargion's talk on monday

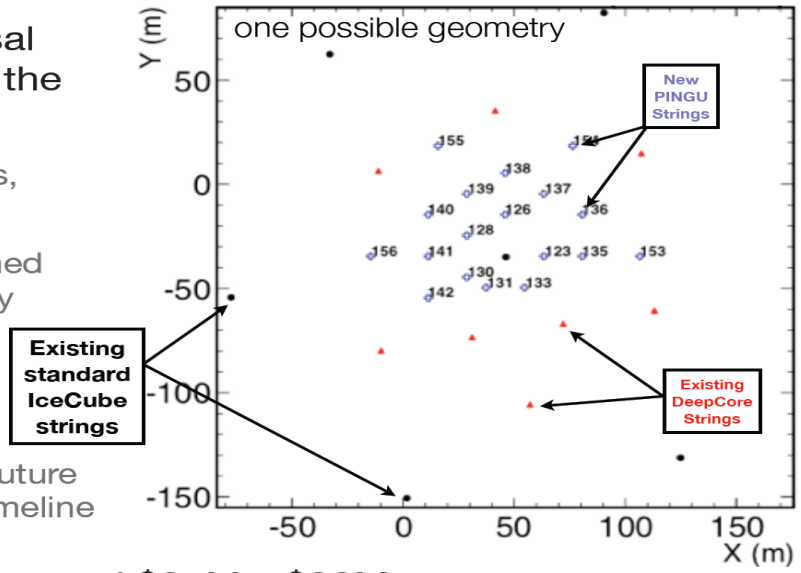

Thanks for your kind attention
Erice Panorama

Backup slides

PINGU & Deep Core

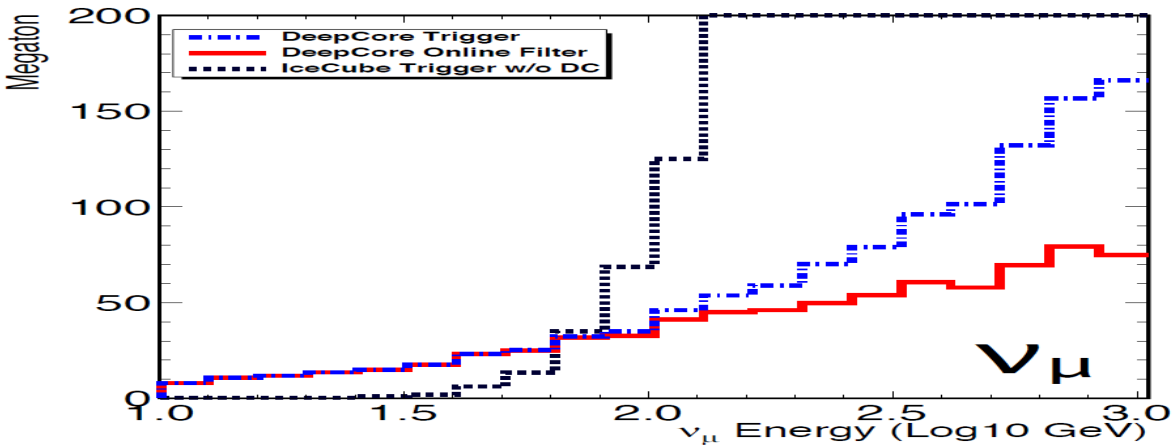
Beyond DeepCore: PINGU

- Now developing a proposal to continue to instrument the DeepCore volume
  - An additional 18-20 strings, 1000-1200 DOMs
  - Make use of well-established IceCube drilling technology
  - Might get to a threshold of ~1 GeV in a ~10 MTon volume
  - Also an R&D platform for future detectors on a ~decade timeline

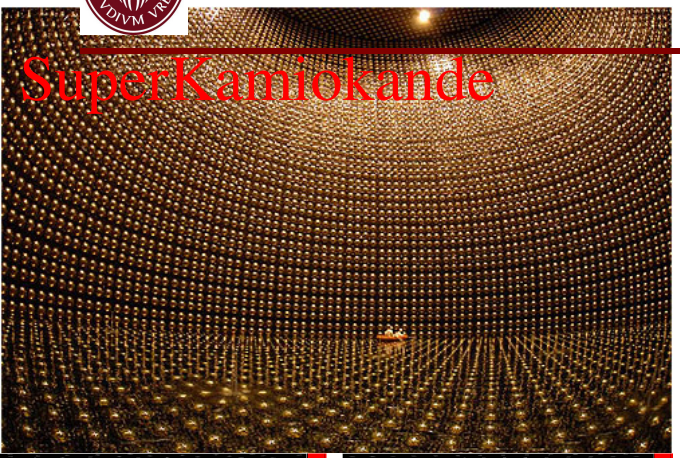


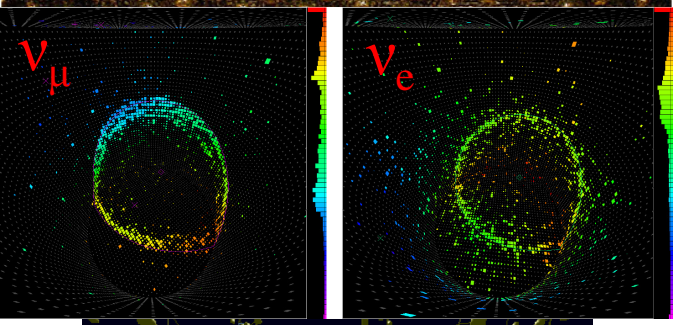
- Price tag expected to be around $25M – $30M

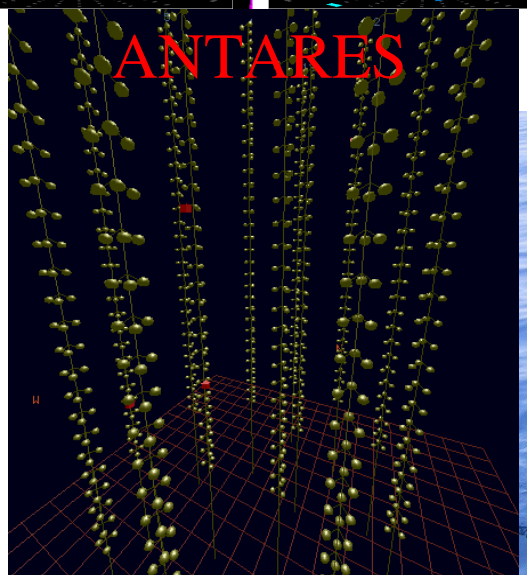
Tyce DeYoung RICAP '11 May 25, 2011

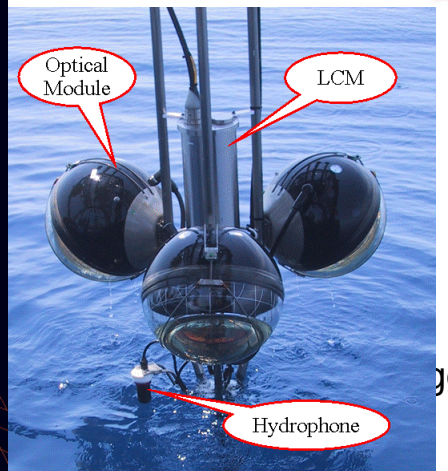


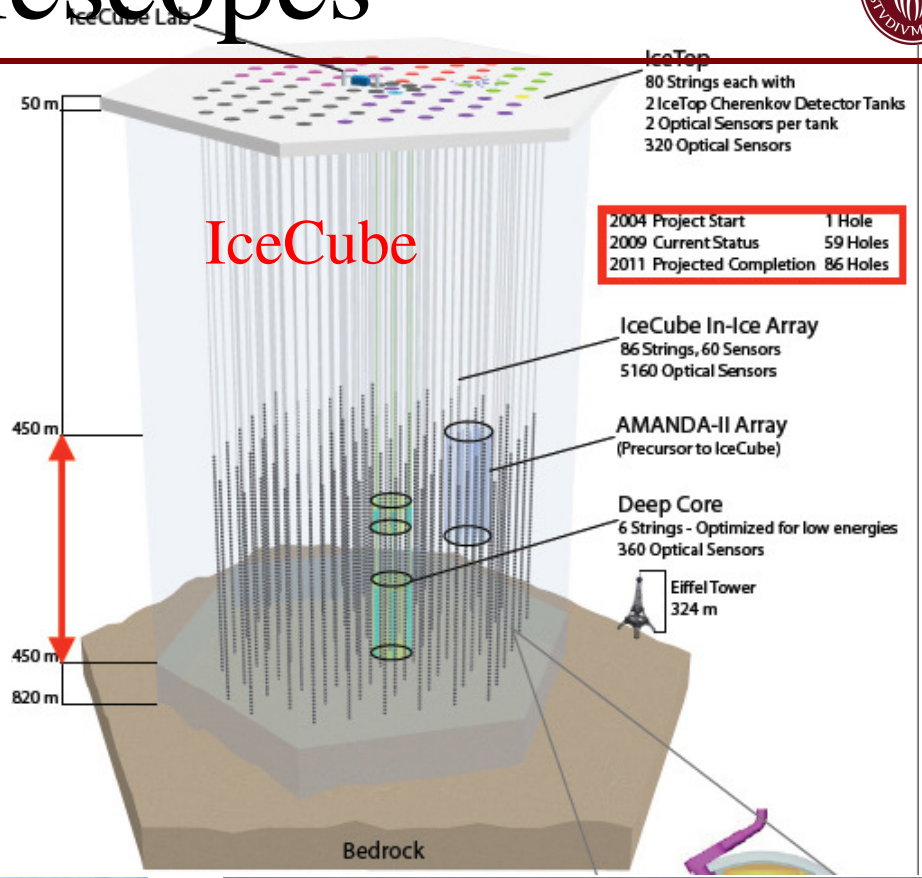
ν telescopes

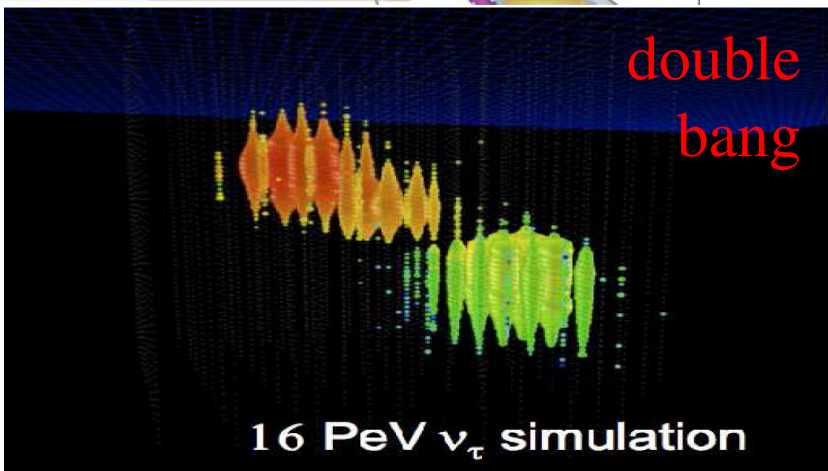












P. Auger Observatory