Neutrino Astronomy

PENNSTATE

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XXVI Rencontres de Blois
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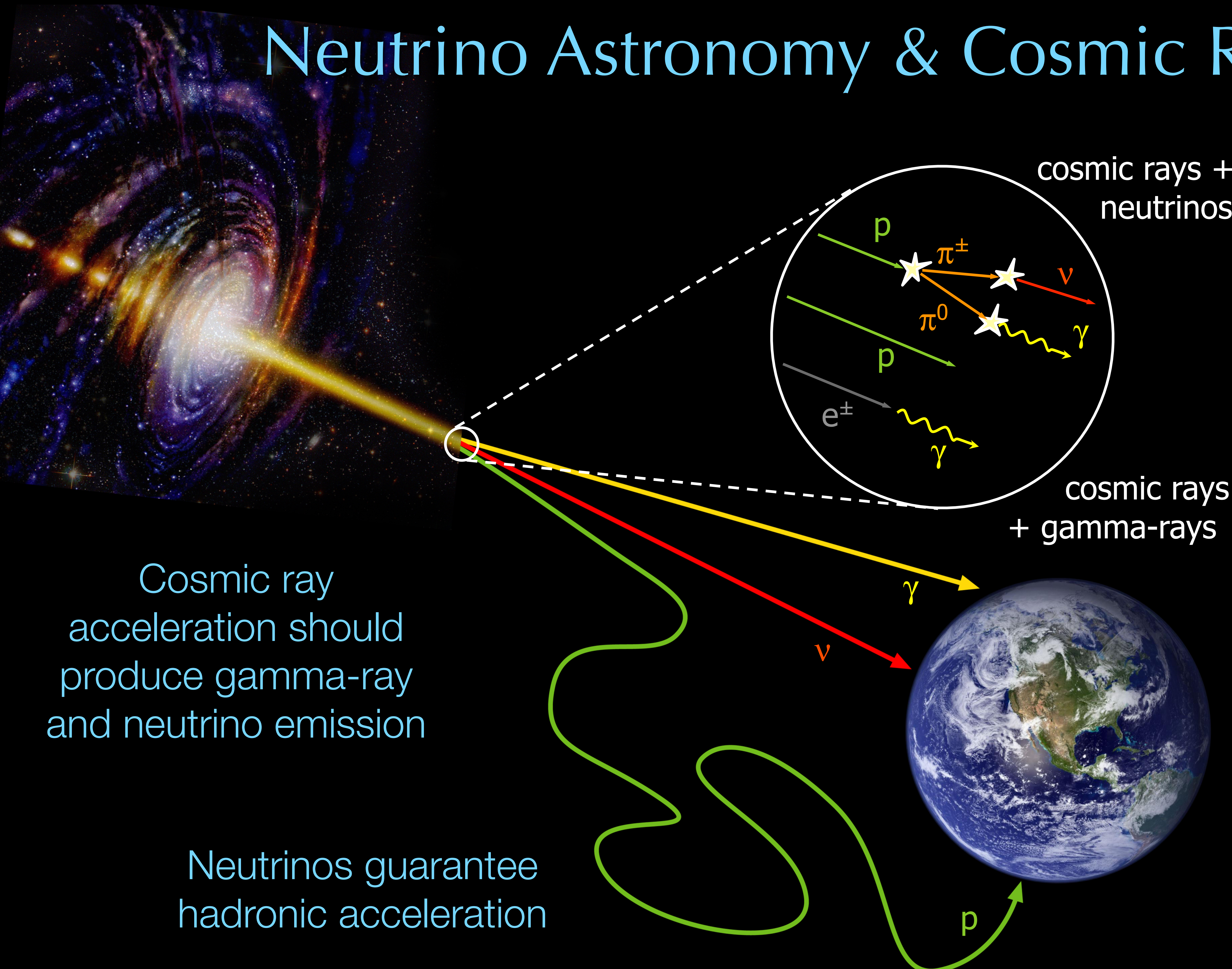
Neutrino Astronomy & Cosmic Rays

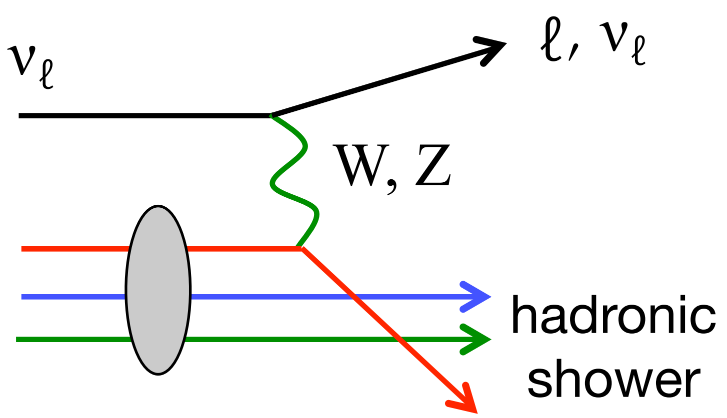


Cosmic ray acceleration should produce gamma-ray and neutrino emission

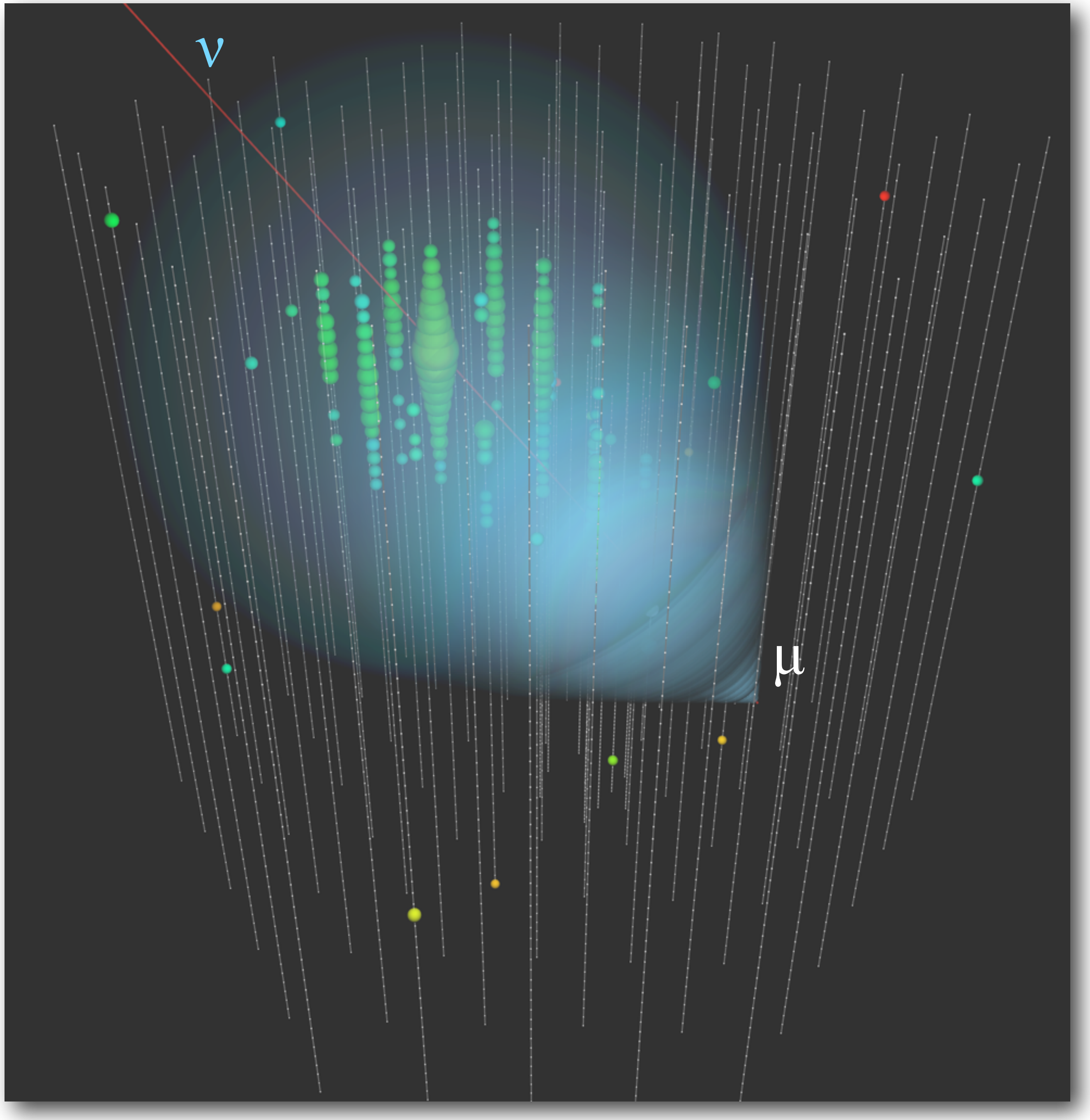
Neutrinos guarantee hadronic acceleration

High Energy Neutrino Telescopes

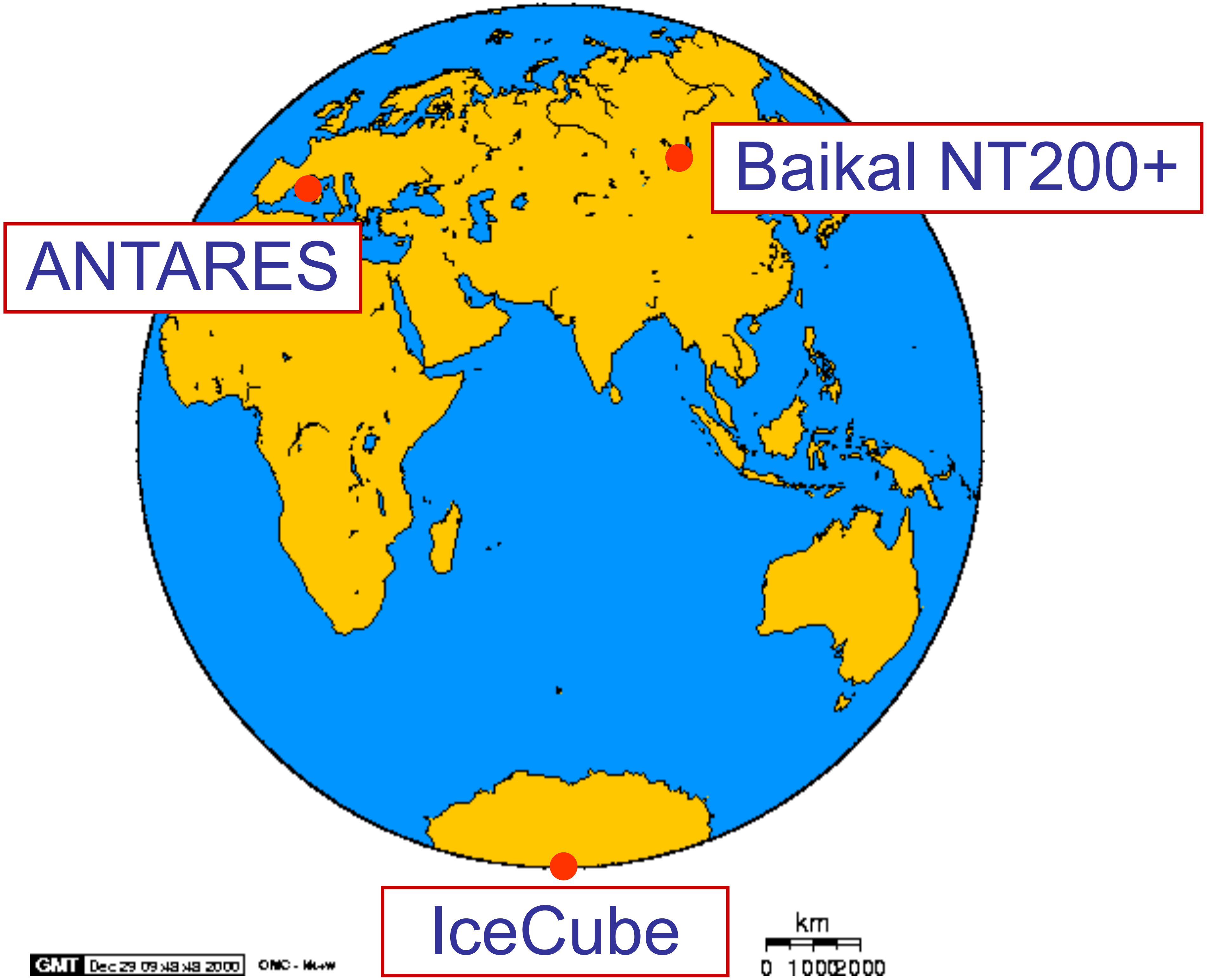
- Use transparent natural material as both target and Cherenkov medium
  - Substantial overburden to reduce atmospheric muon background
- Neutrinos interact in or near detector

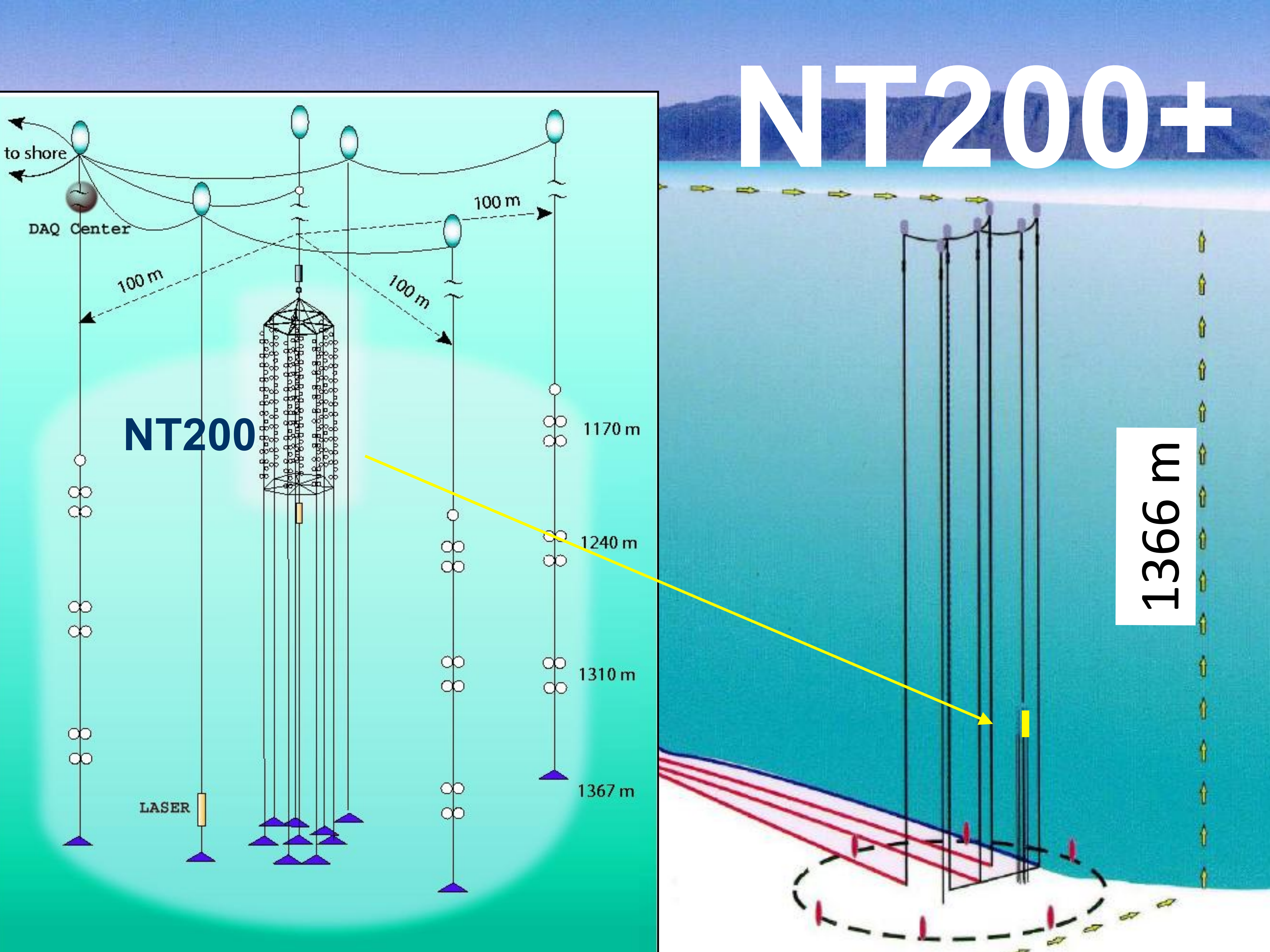


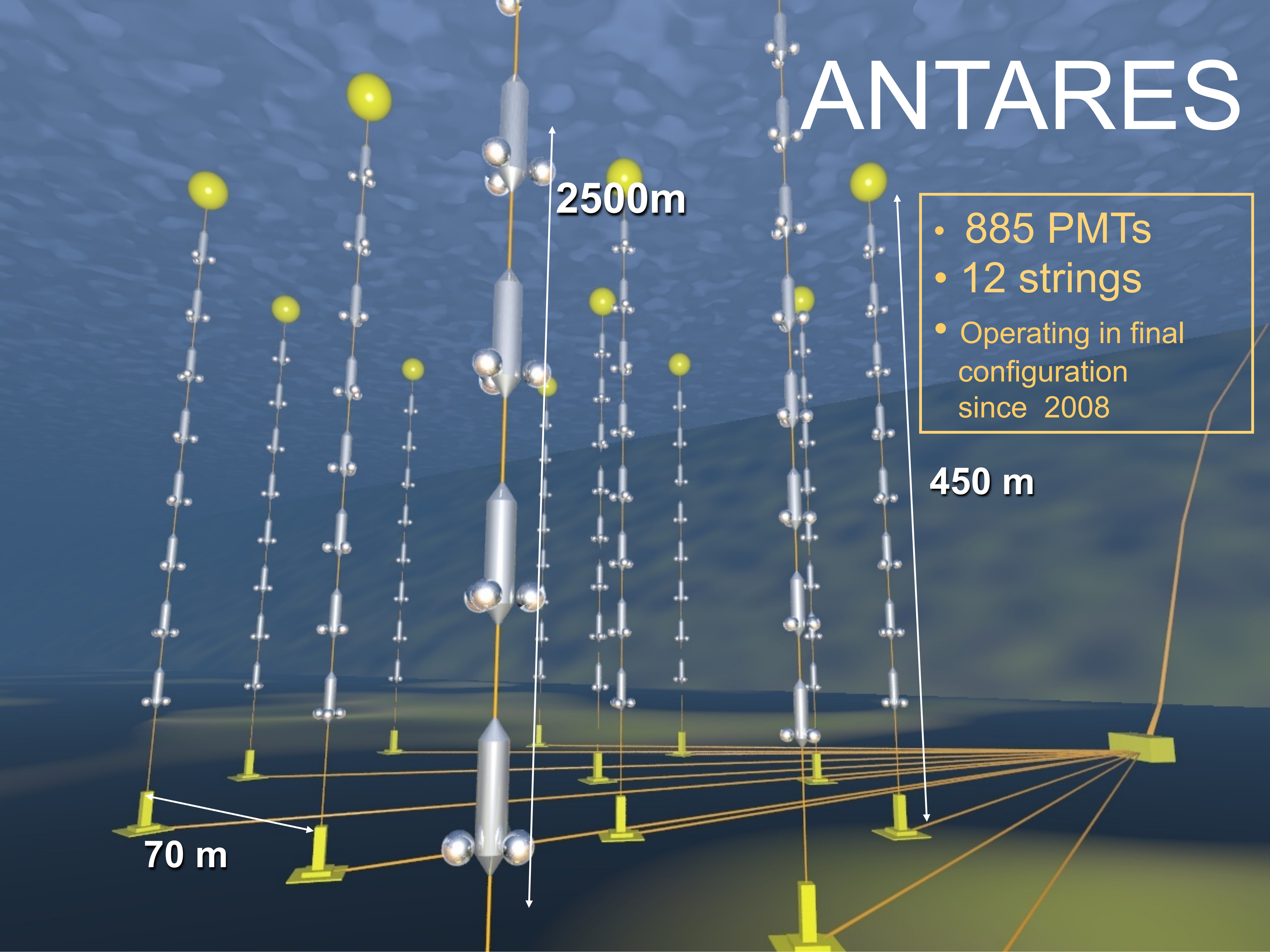
  - Cherenkov radiation detected by 3D array of optical sensors (OMs)
- Suitable materials available in bulk: deep ocean, polar ice caps



Existing Neutrino Telescopes

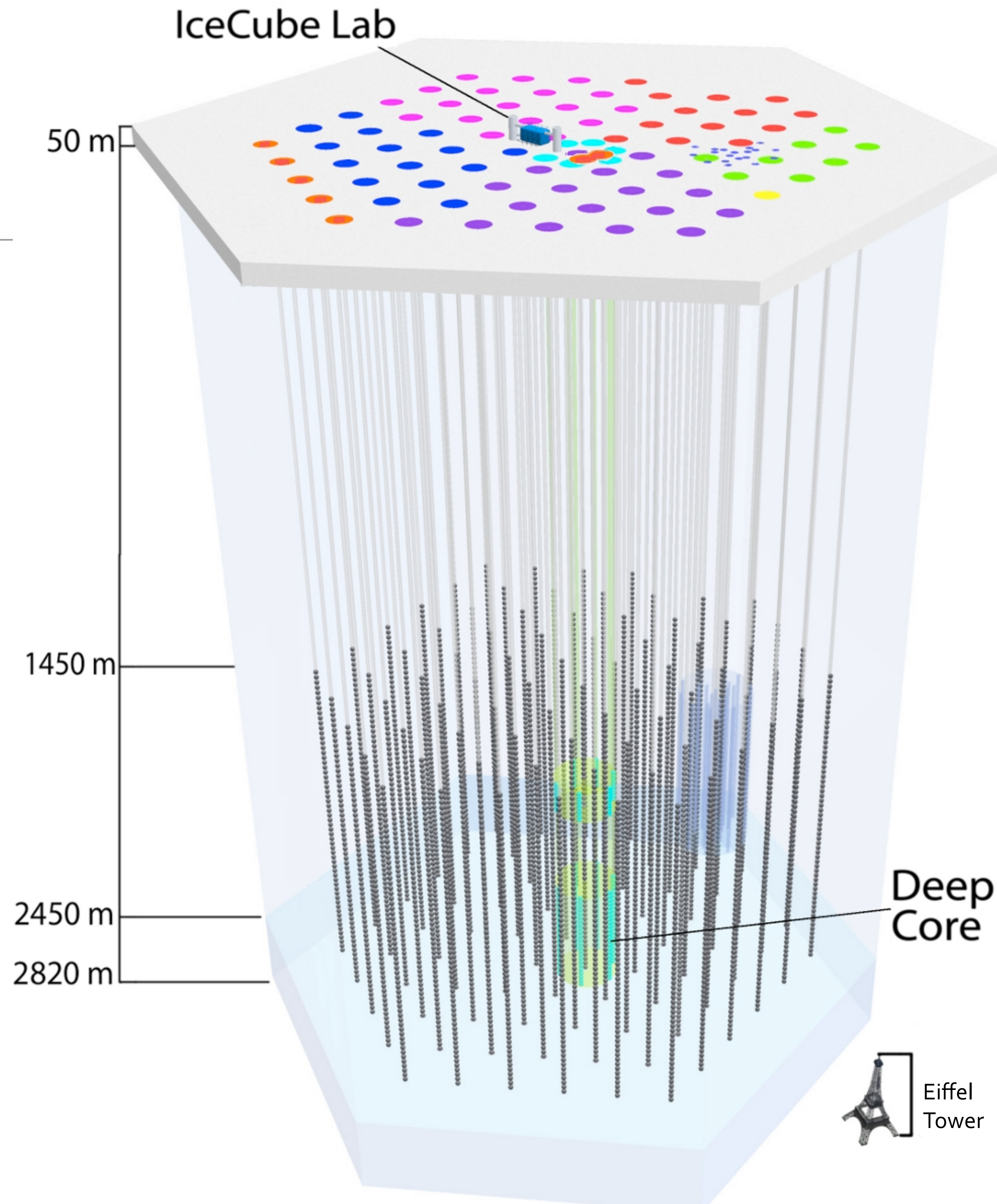



NT200+
to shore
DAQ Center
100 m
100 m
100 m
NT200
1170 m
1240 m
1310 m
1367 m
LASER
1366 m


ANTARES
2500m
• 885 PMTs
• 12 strings
• Operating in final configuration since 2008
450 m
70 m

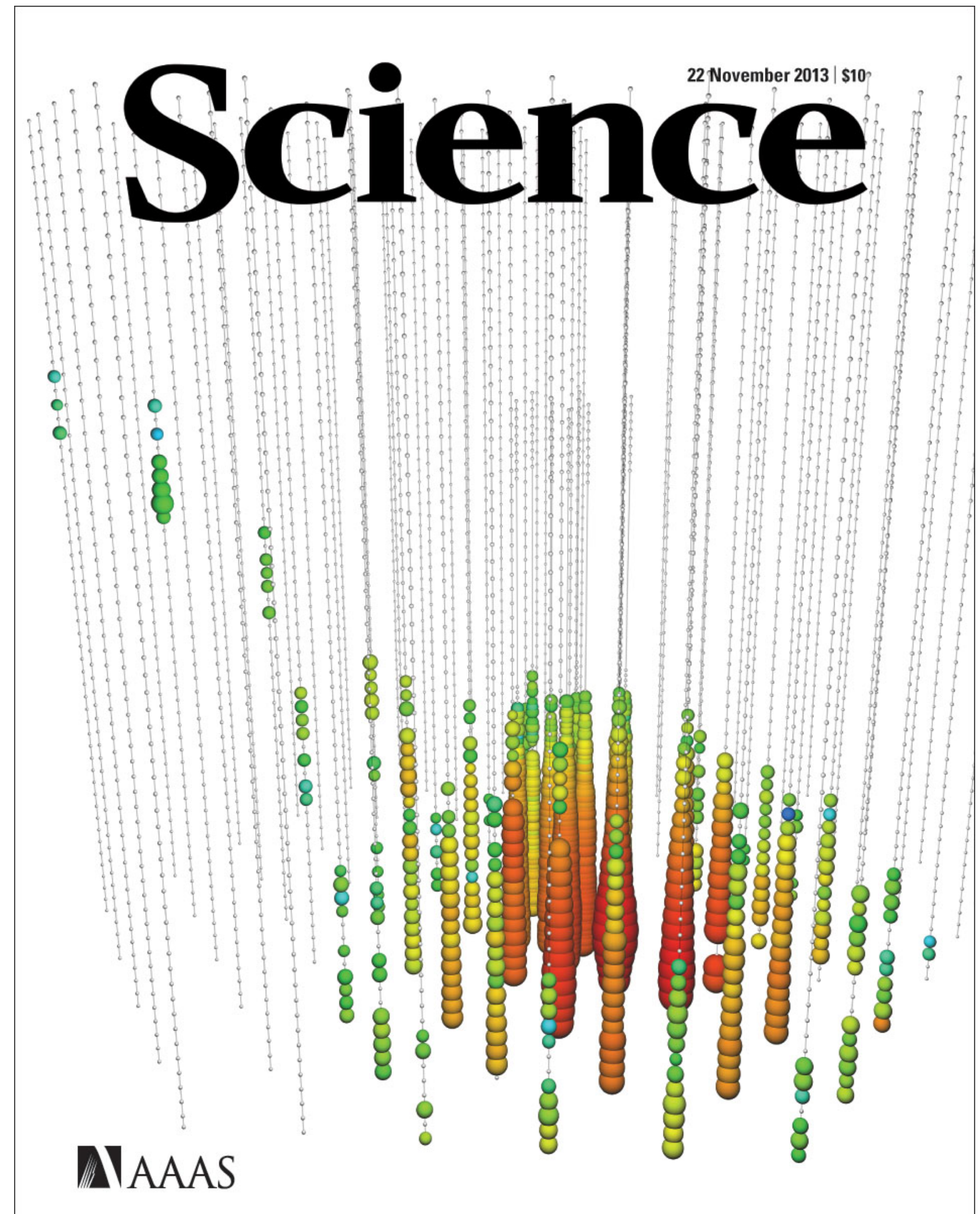
The IceCube Observatory

- One gigaton of South Pole ice instrumented, completed in 2010
- 86 strings of 60 DOMs
  - 125 m string spacing
  - 17 m spacing between DOMs on a string
- DeepCore infill array for low energy physics
  - 8 strings on closer spacing in deep, clear ice



Neutrinos from Astrophysical Sources

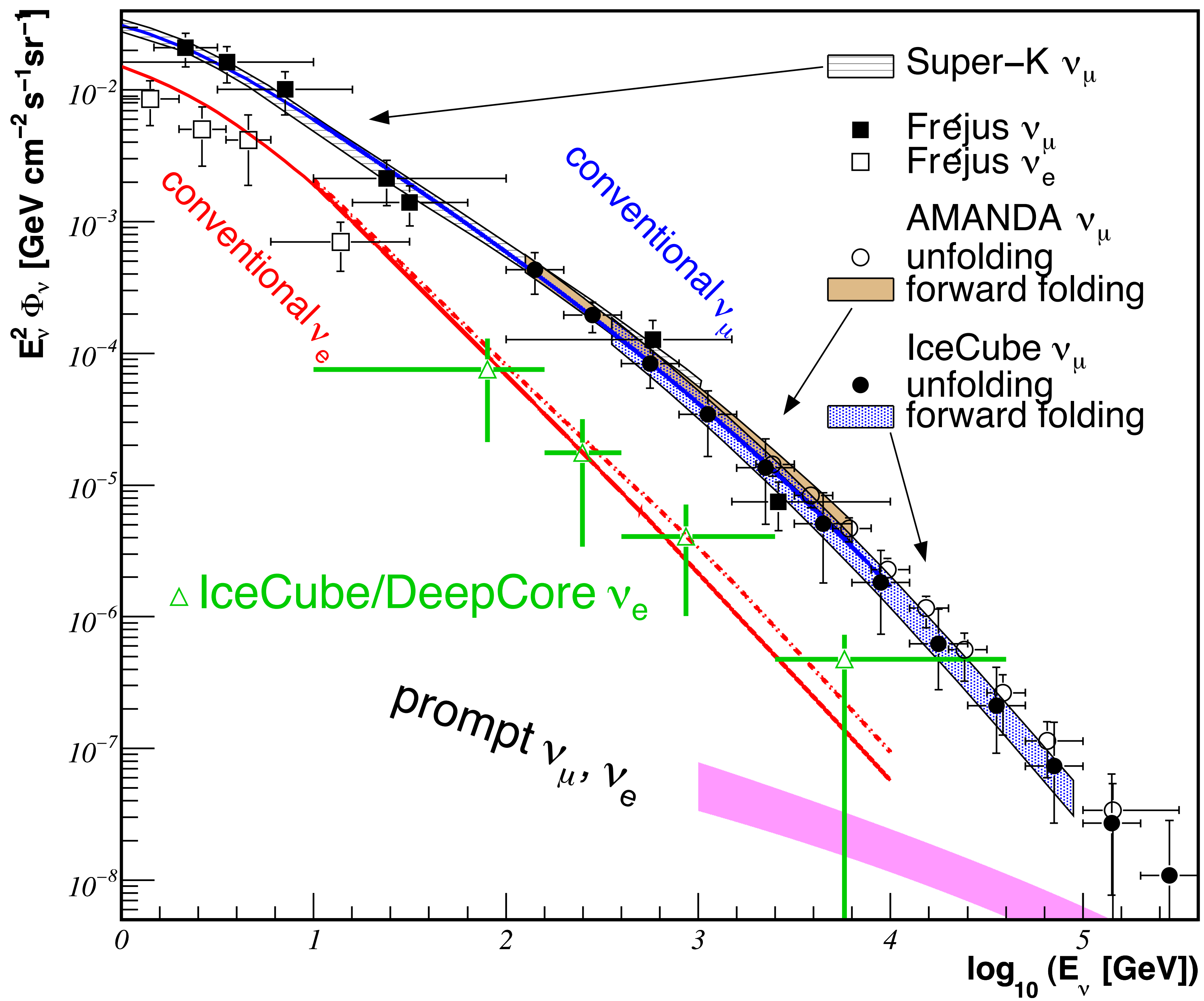
- Neutrino telescopes are multi-purpose instruments with a broad science portfolio
  - Neutrino oscillations
  - Indirect dark matter searches (parallel talk by Jan Lünemann)
  - Cosmic ray physics
  - Exotic particle direct searches
- Focus in this talk on recent results in the search for the sources of the cosmic rays
  - See also talk by Christophe Hugon



Calibration Flux: Atmospheric Neutrinos

- A background in searches for sources of astrophysical neutrinos…
  - …but useful for calibrating detector response
  - …and interesting for studies of particle production
  - …and a source of a few hundred thousand neutrino events per year

M. G. Aartsen et al., *Phys. Rev. Lett*. 110, 151105 (2013)



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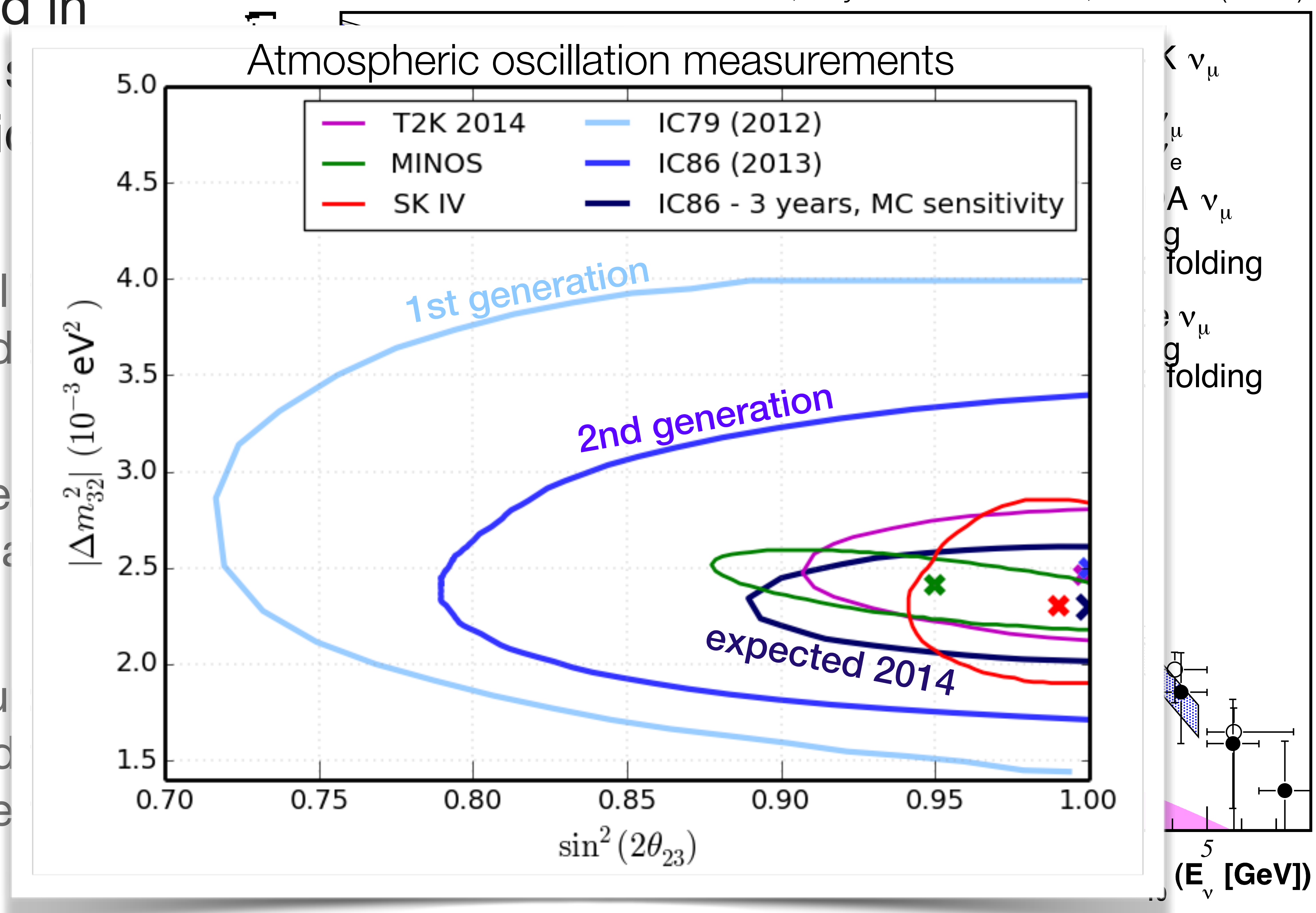
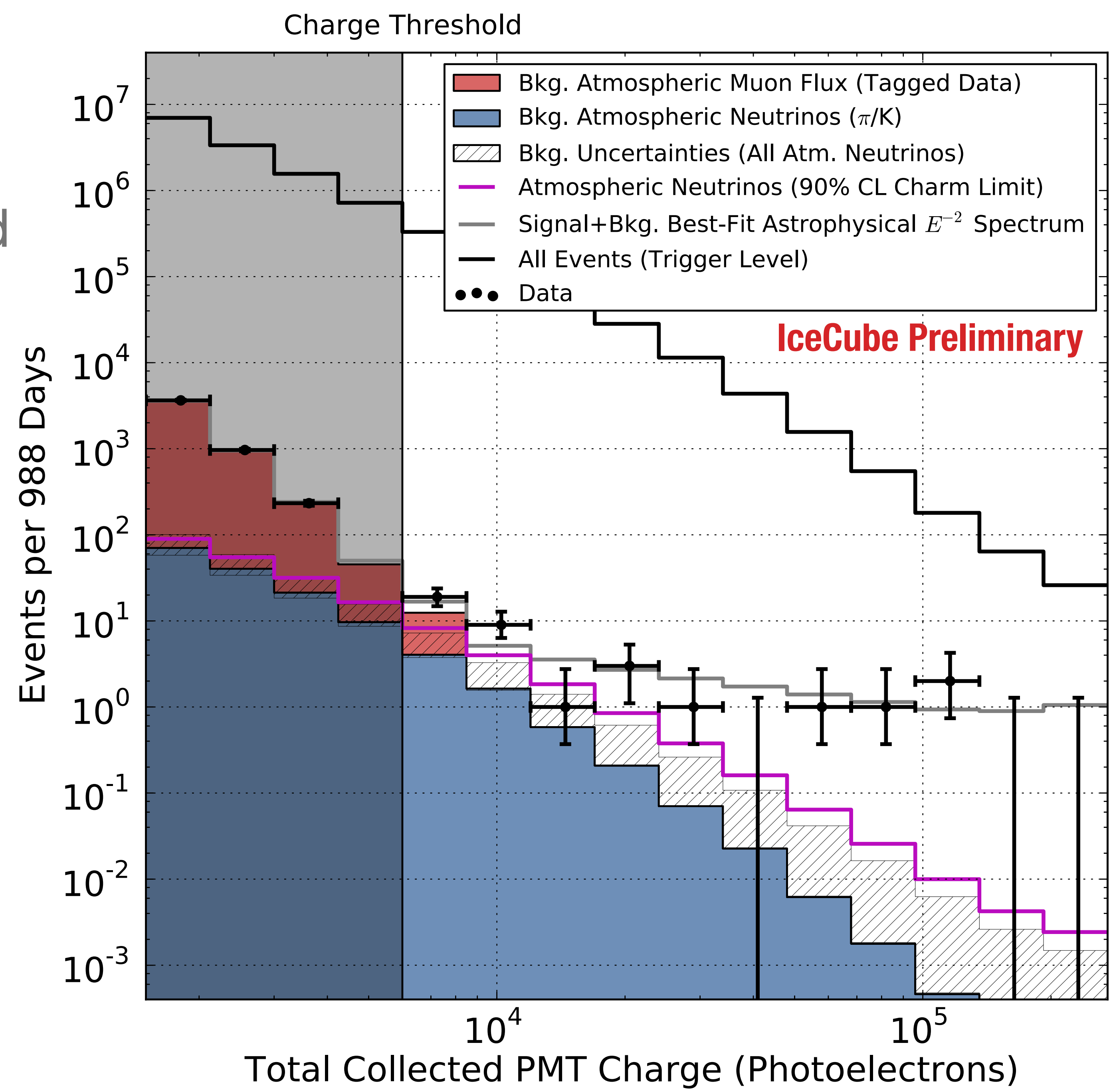


First Detection: Events Interacting in IceCube

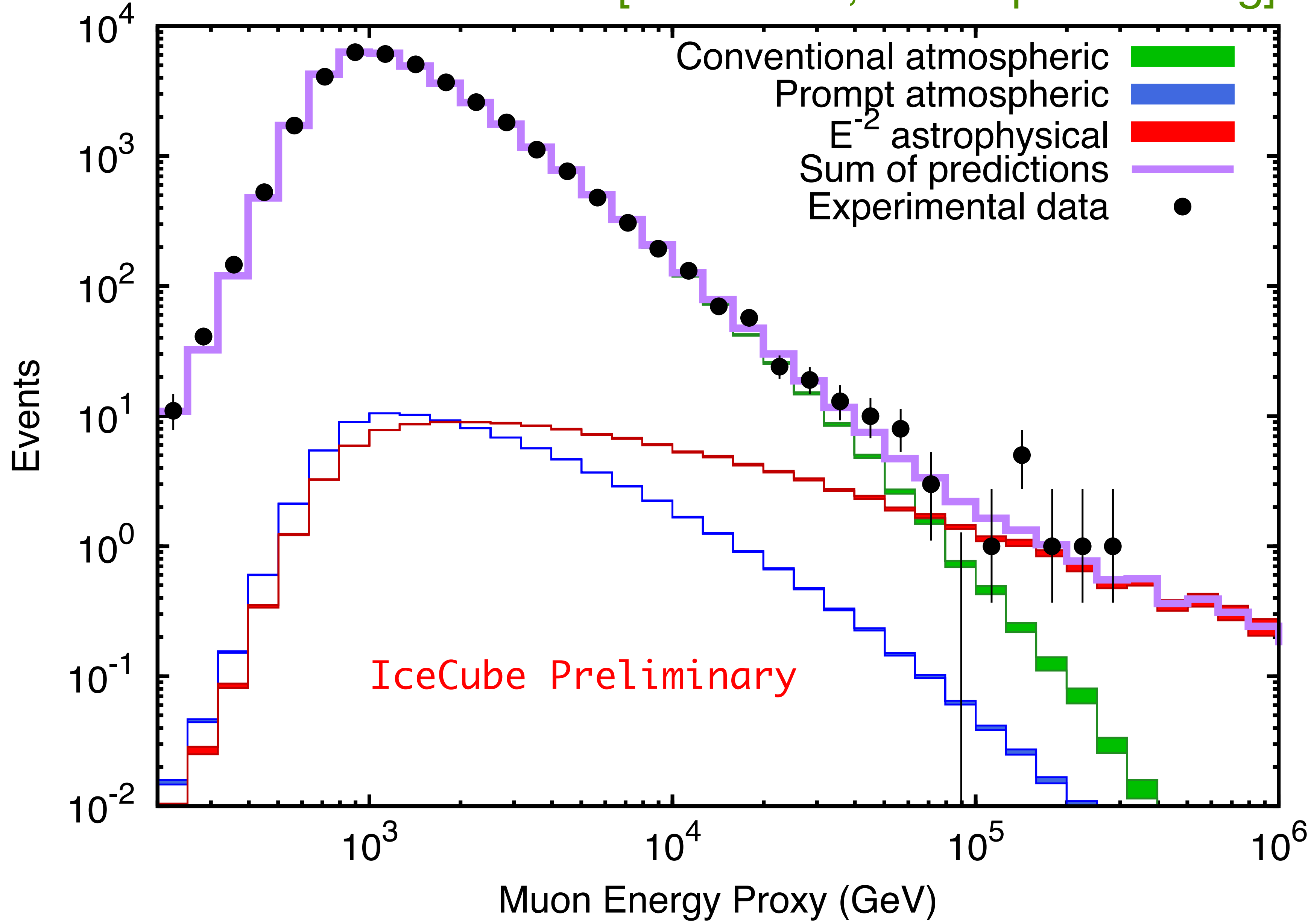
- 37 events observed in 3 years with min. charge of 6000 PE
  - Approx. 60 TeV energy threshold
- Estimated background 1: $6.6^{+5.9}_{-1.6}$ atm. neutrinos
- Estimated background 2: 8.4±4.2 atm. muons
- Combined significance: 5.7σ
- Note: no events above 3 PeV (Glashow resonance: $\bar{\nu}_e e \rightarrow W$)



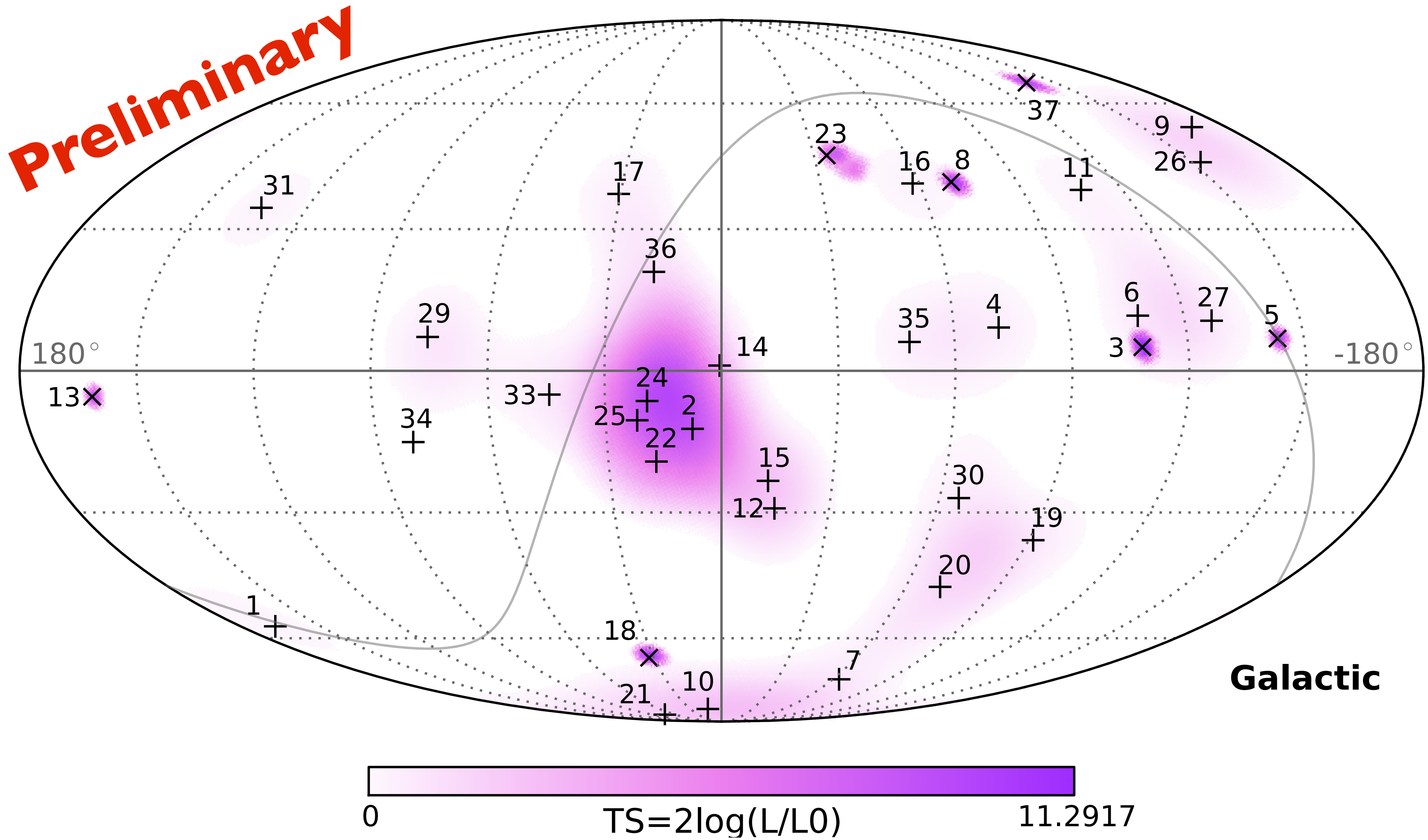
Confirmation: Muon Netrinos

- Similar high energy excess observed in through-going muon neutrinos from northern sky
  - Flux level agrees with that from starting event search
  - Apparently equal flux of all flavors
  - Still no events above ~2 PeV

[C. Weaver, APS April Meeting]



IceCube Sky Map (Contained Event Search)



[Claudio Kopper, Moriond EW 2014]

Proposed Explanations

Extragalactic sources

On the origin of IceCube's PeV neutrinos
– Cholis, Hooper [1211.1974]

Diffuse PeV Neutrinos from Gamma-ray Bursts
– Liu, Wang [1212.1260]

Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons
– Kistler, Stanev, Yuksel [1301.1703]

PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei
– Kalashev, Kusenko, Essey [1303.0300]

Diffuse PeV neutrino emission from ultraluminous infrared galaxies
– He, Wang, Fan, Liu, Wei [1303.1253]

PeV neutrinos observed by IceCube from cores of active galactic nuclei
– Stecker [1305.7404]

TeV-PeV neutrinos from Low-Power Gamma-ray Burst Jets inside Stars
– Murase, Ioka [1306.2274]

Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube
– Murase, Ahlers, Lacki [1306.3417]

Photohadronic Origin of the TeV-PeV Neutrinos Observed in IceCube
– Winter [1307.2793]

Long-lived PeV-EeV Neutrinos from GRB Blastwave
– Razzaque [1307.7596]

Long-
– Liu et al. [1310.1263]

Long-
– Murase, Inoue, Dermer [1403.4089]

Galactic sources

Galactic PeV Neutrinos
– Gupta [1305.4123]

Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy
– Fox, Kashiyama, Meszaros [1305.6606]

Pinning down the cosmic ray source mechanism with new IceCube data
– Anchordoqui et al. [1306.5021]

The Galactic Pevatron
– Neronov, Semikoz, Tchernin [1307.2158]

The Galactic Center Origin of a Subset of IceCube Neutrino Events
– Razzaque [1309.2756]

Probing the Galactic Origin of the IceCube Excess with Gamma-Rays
– Ahlers, Murase [1309.4077]

Two source populations

TeV-PeV neutrinos over the atmospheric background: originating from groups of sources?
– He, Yang, Fan, Wei [1307.1450]

Exotica

Neutrino decays over cosmological distances and the implications for neutrino telescopes
– Baerwald, Bustamante, Winter [1208.4600]

Explanation for the Low Flux of High-Energy Astrophysical Muon Neutrinos
– Pakvasa, Joshipura, Mohanty [1209.5630]

Neutrinos at IceCube from heavy decaying dark matter
– Feldstein et al. [1303.7320]

Superheavy Particle Origin of IceCube PeV Neutrino Events
– Barger, Keung [1305.6907]

Pseudo-Dirac neutrinos via mirror-world and depletion of UHE neutrinos
– Joshipura, Mohanty, Pakvasa [1307.5712]

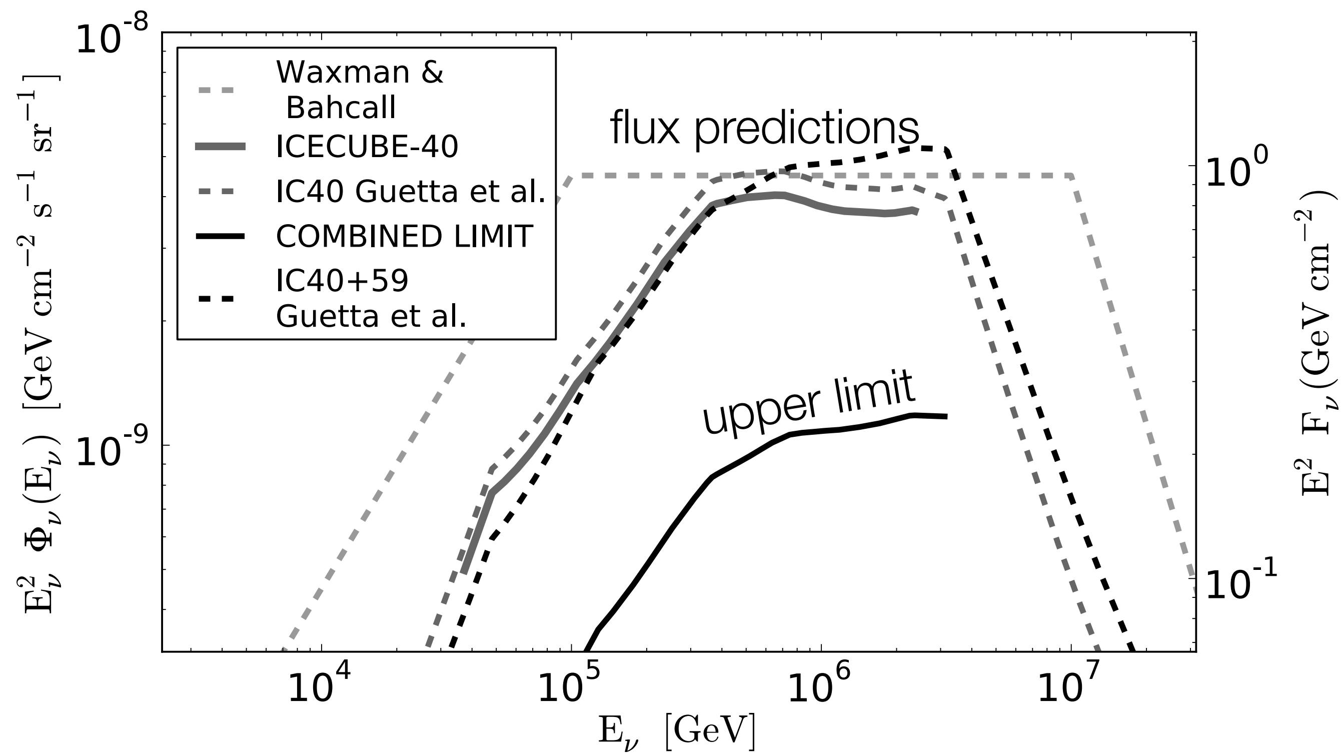
Are IceCube neutrinos unveiling PeV-scale decaying dark matter?
– Esmaili, Sercipo [1308.1105]

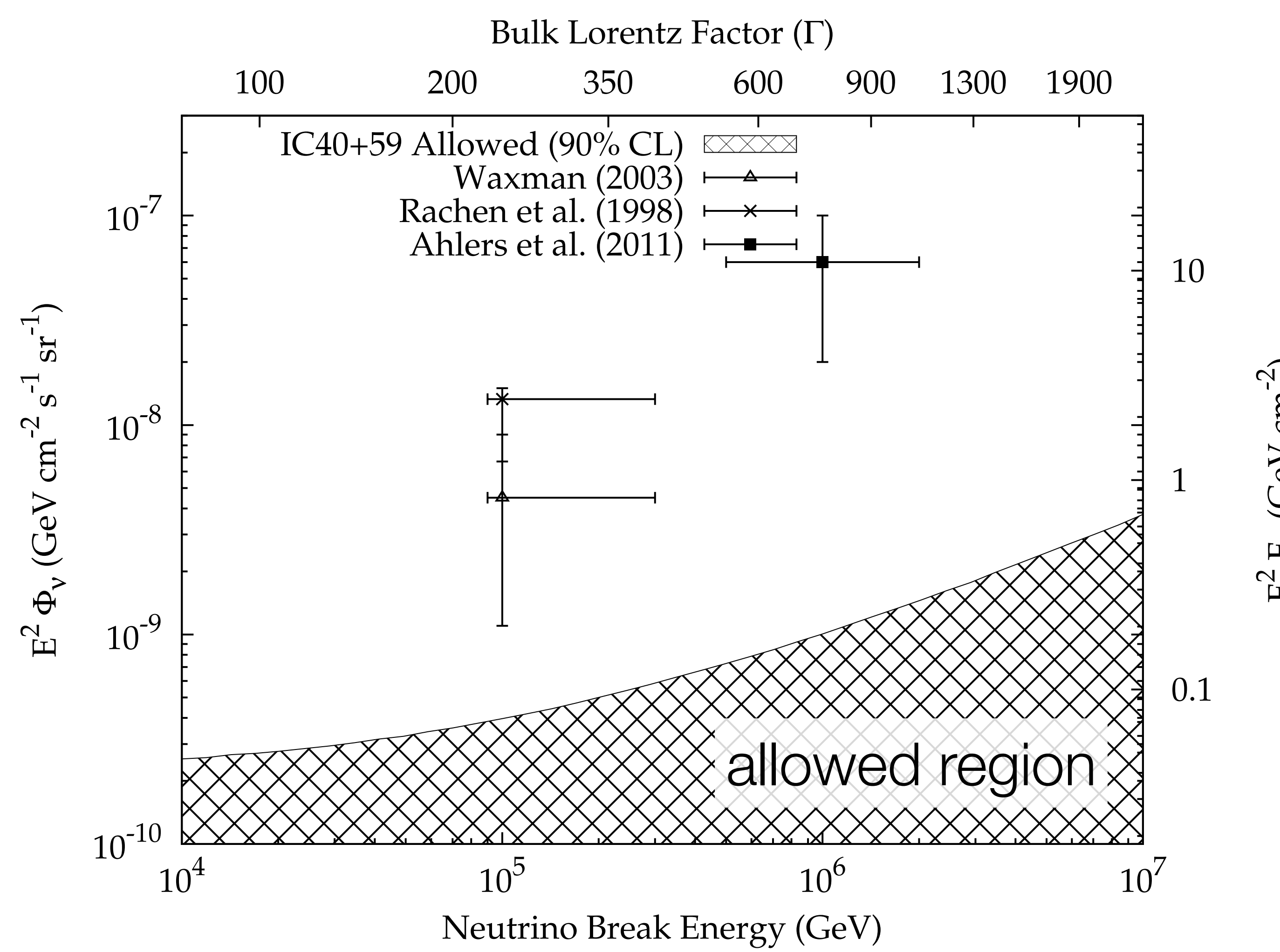
...and growing

Candidate Sources: GRBs

- IceCube has searched for neutrinos in coincidence with 300 GRBs recorded 2008 – 2010
  - 40 and 59 string configurations
- No neutrinos observed in coincidence with these GRBs
  - Upper limits at approximately 20% the predicted flux, if GRBs are the (sole) sources of the observed UHE cosmic rays
- Limits dependent on modeling of GRBs, but well below level of observed IceCube flux
  - Caveat: low-power jets…

R. Abbasi et al., *Nature* 484, 351-354 (2012)





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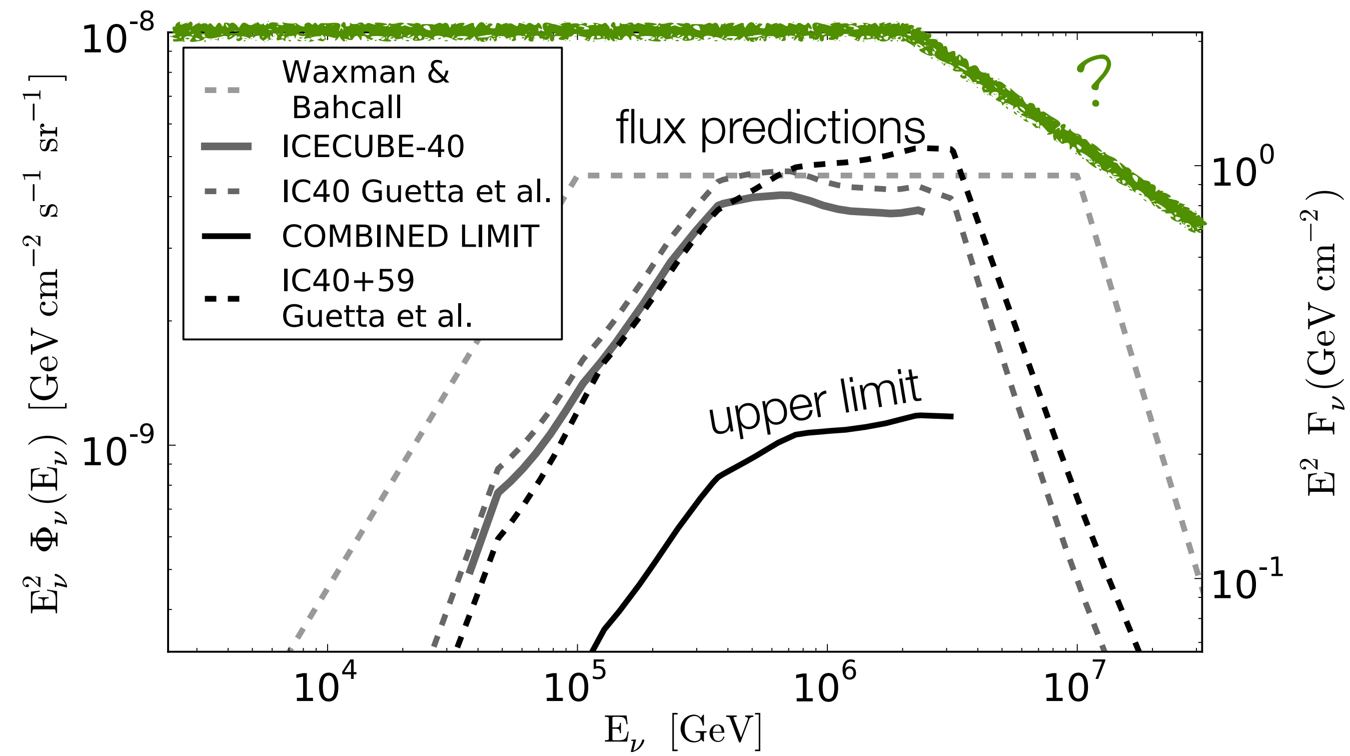
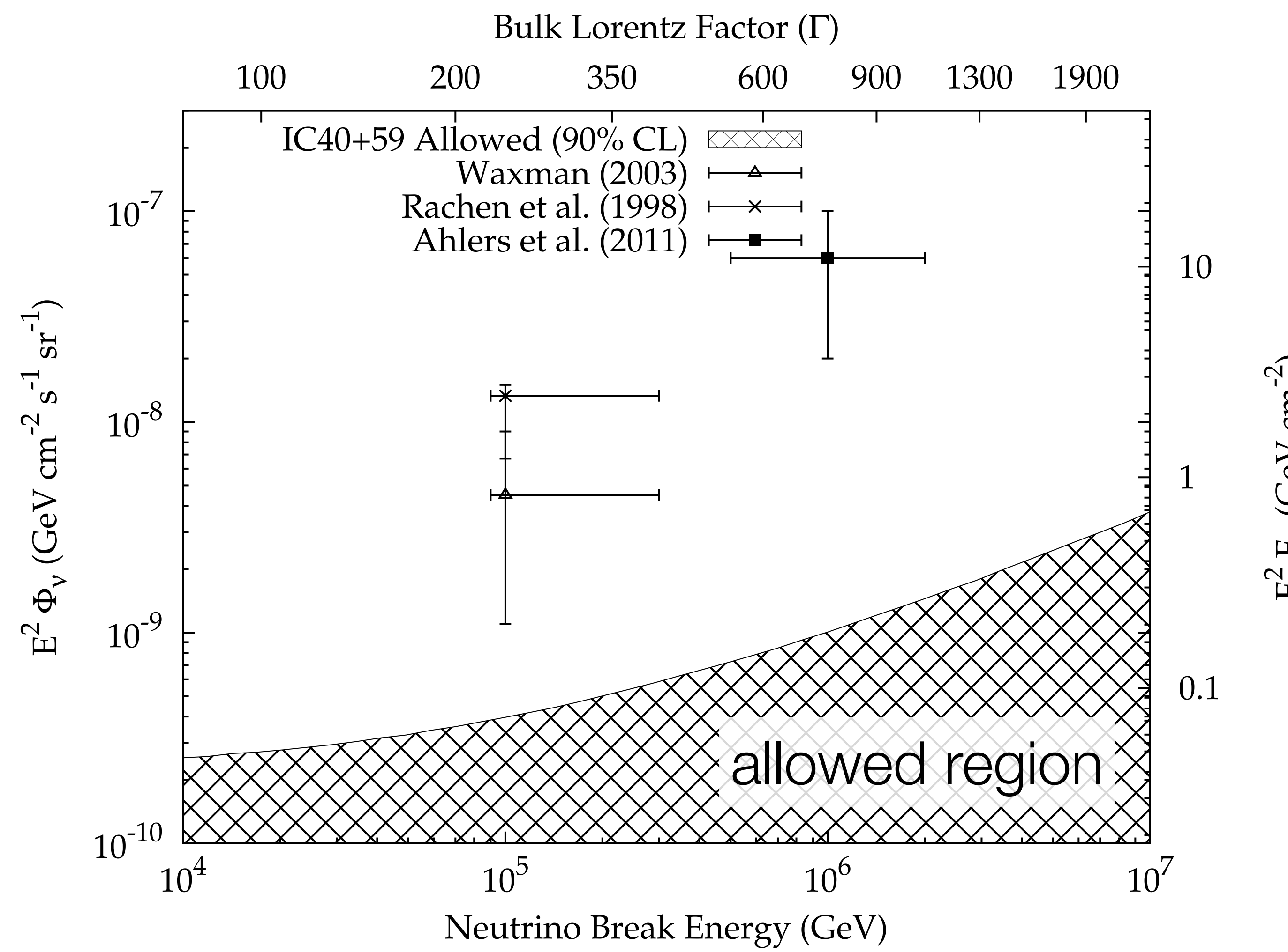
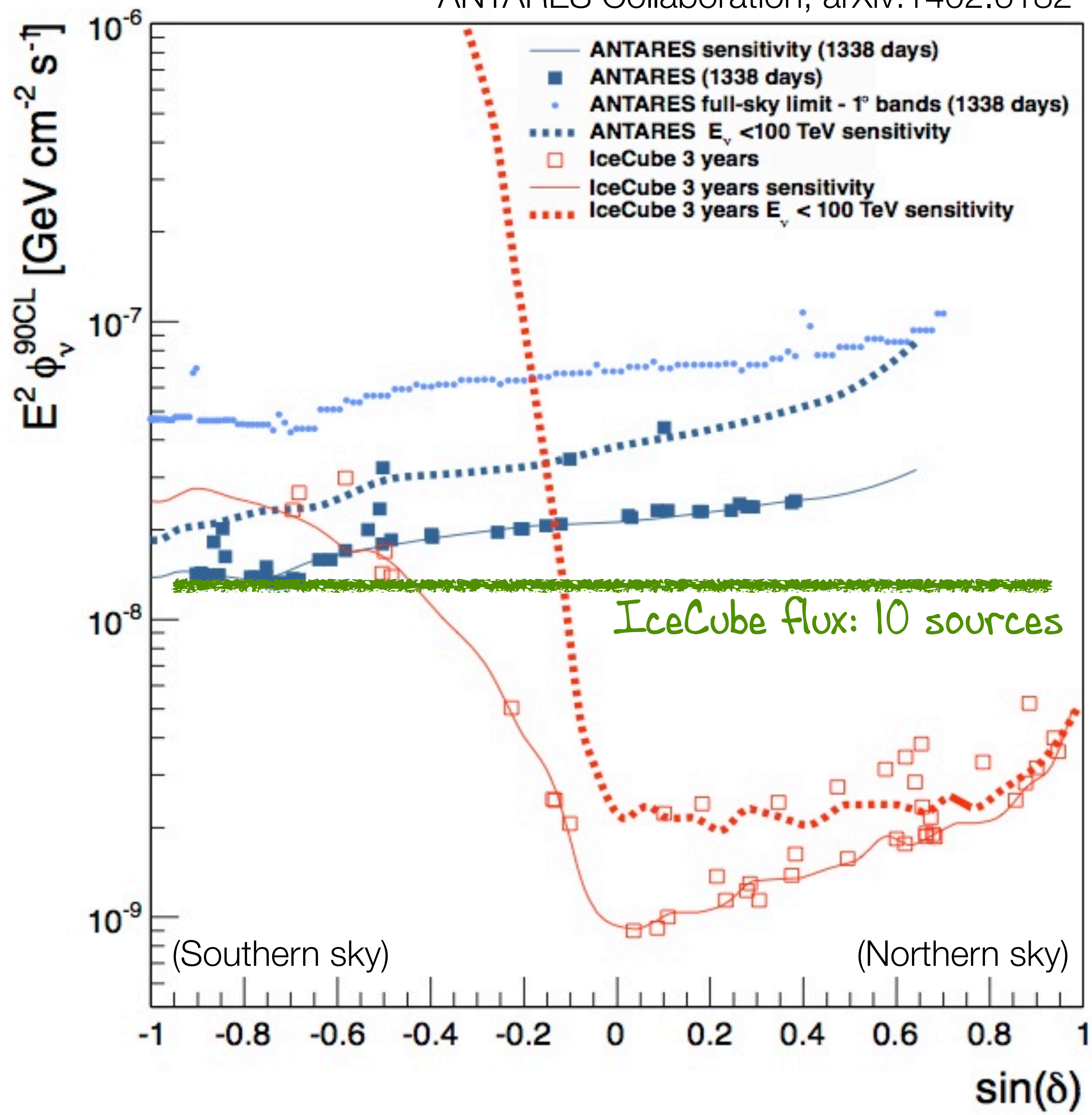




Searches for Individual Sources

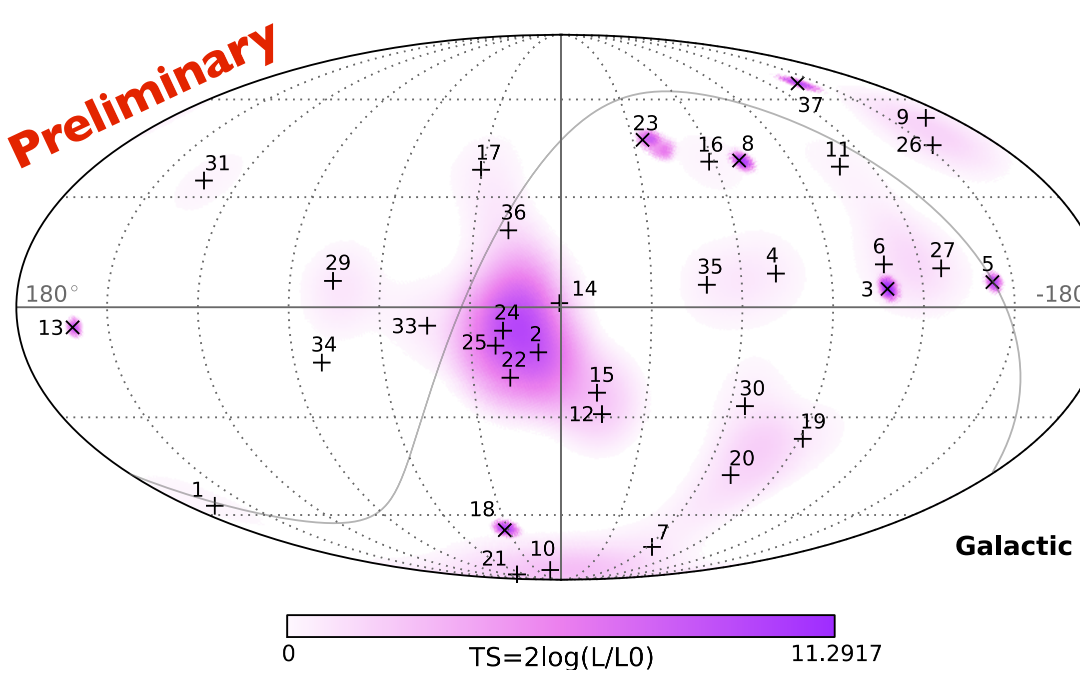
- IceCube is most sensitive to sources in the Northern sky
  - Look through the Earth to remove cosmic ray muon background
  - Only high energies visible in Southern sky
- In the Southern sky, ANTARES has best limits – assuming spectrum extends to lower energies

ANTARES Collaboration, arXiv:1402.6182



ANTARES Source Search

- Current IceCube data set is dominated by cascades (ν_e, ν_τ, or NC), with poor angular resolution
  - Hottest spot is not significant (p-value ~8%), but *could* be a hint of a (Galactic?) source



[Claudio Kopper, Moriond EW 2014]

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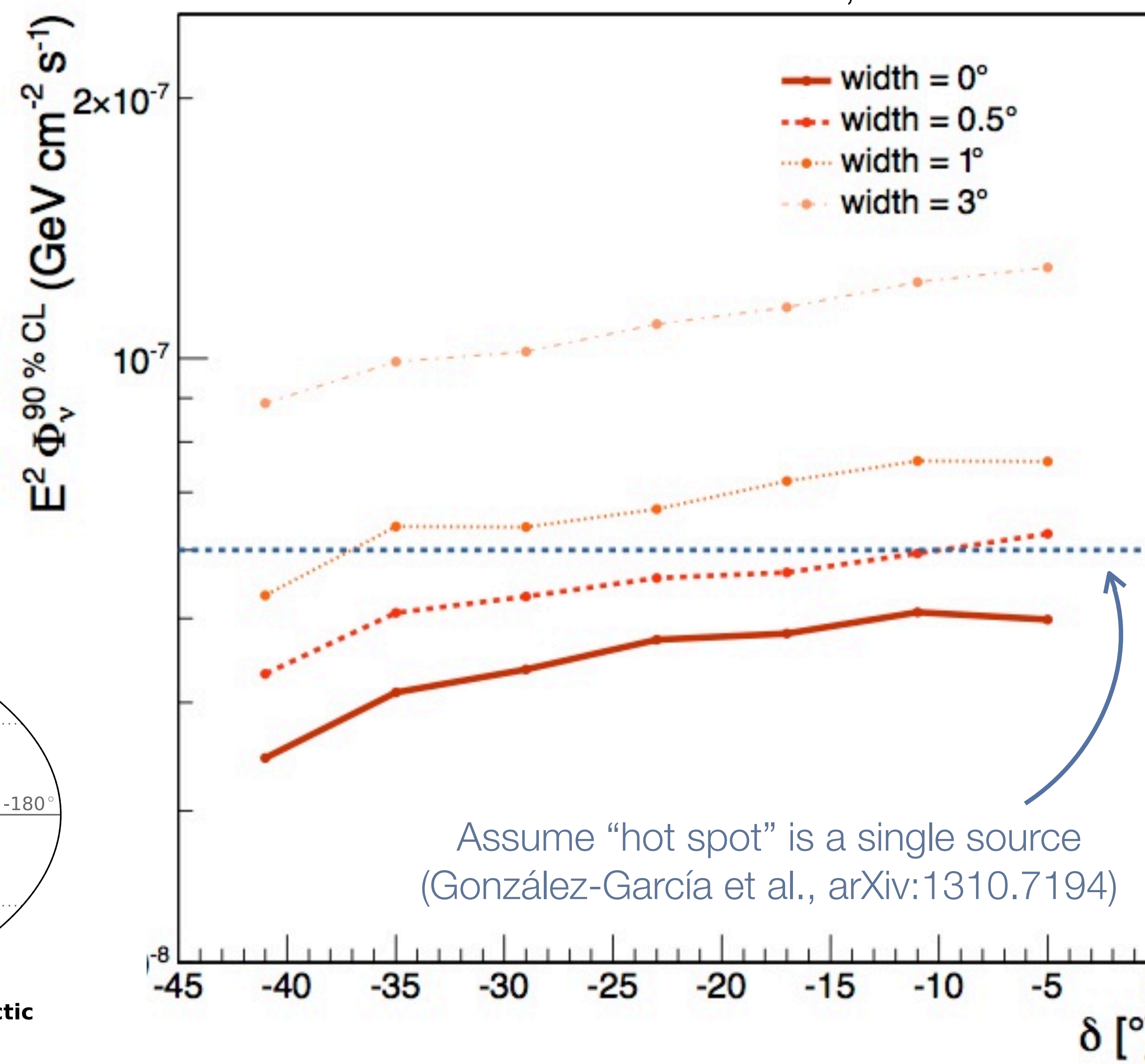

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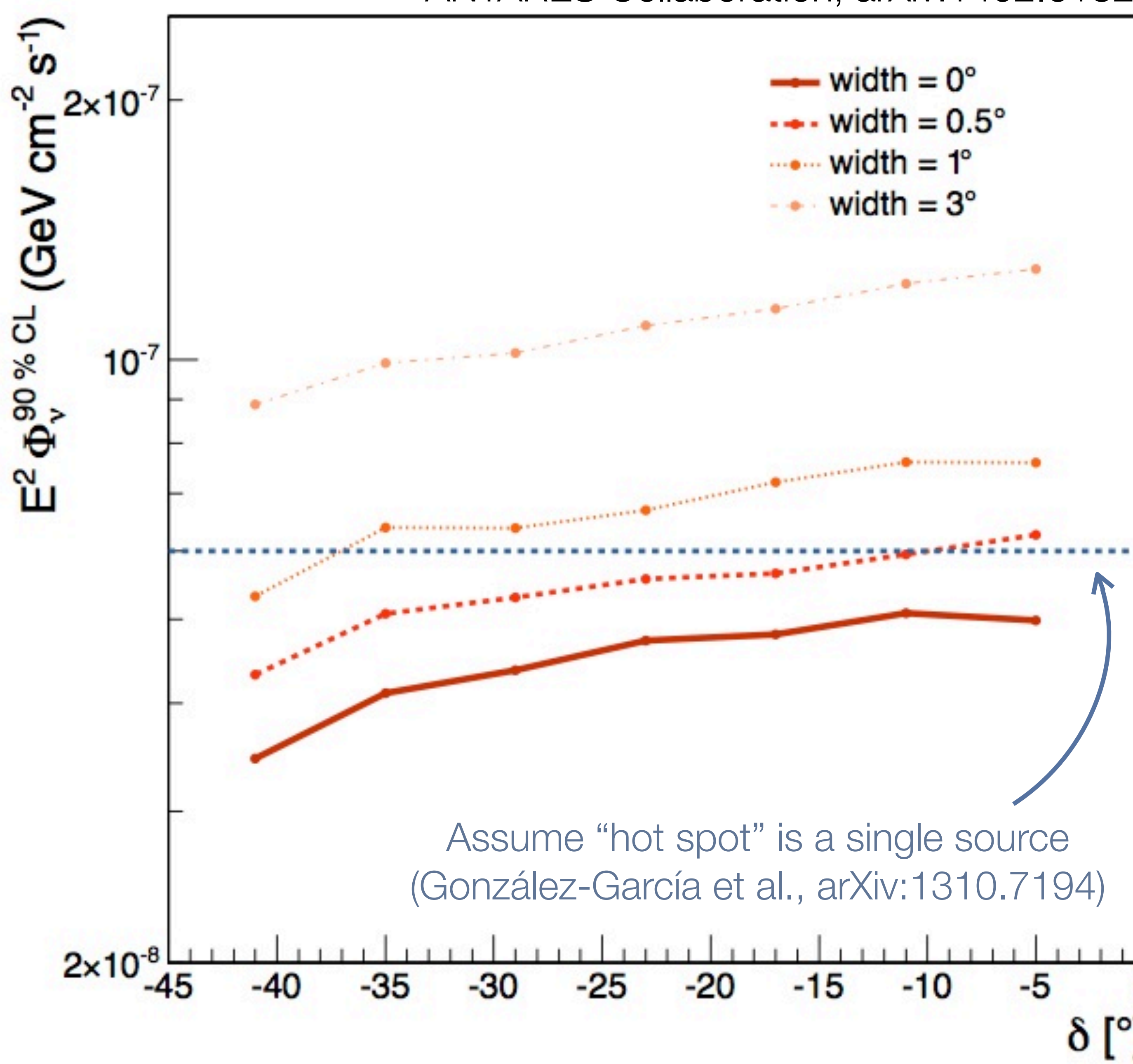
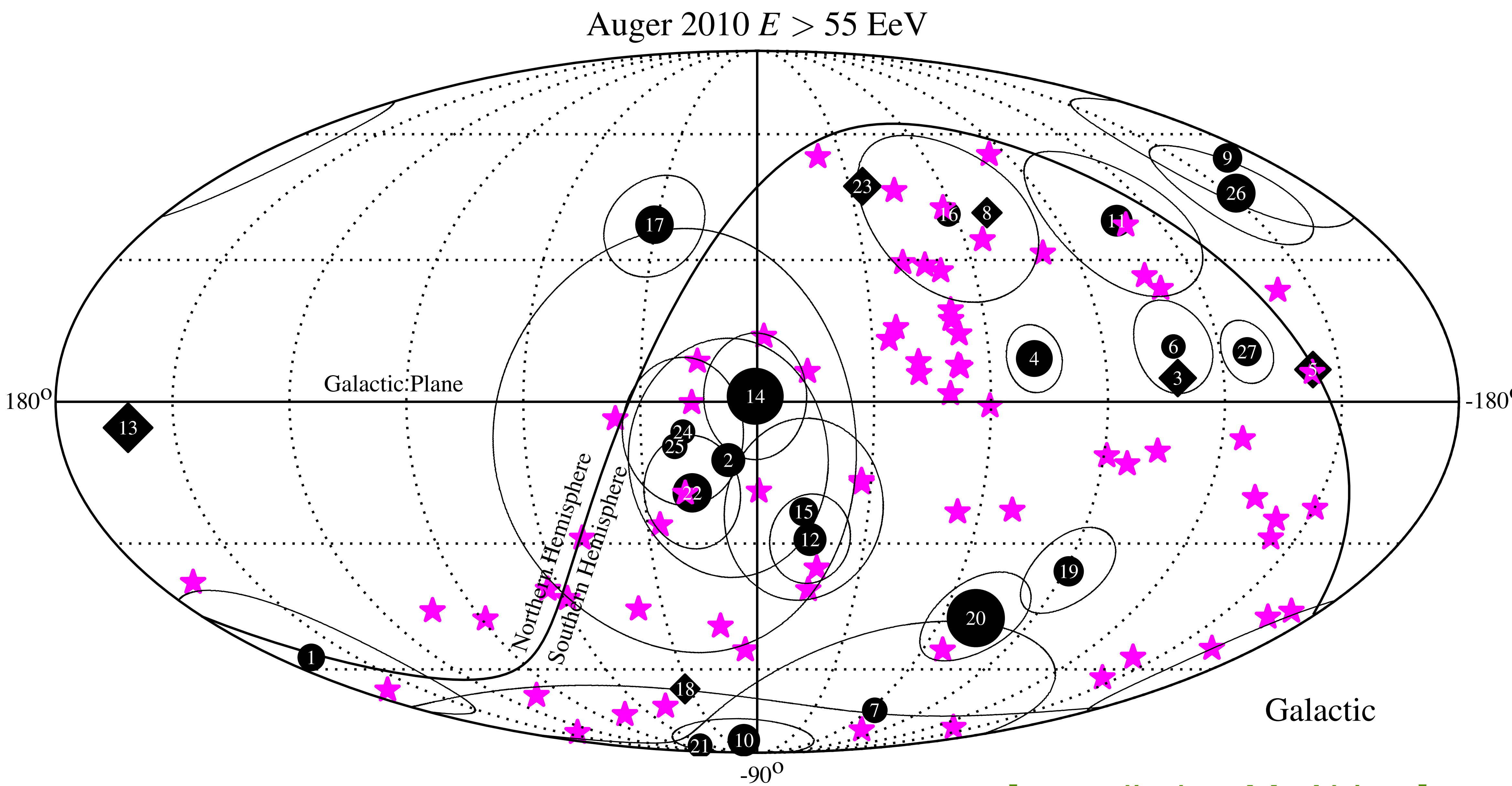
- Current IceCube data set is dominated by cascades (ν_e, ν_τ, or NC), with poor angular resolution
  - Hottest spot is not significant (p-value ~8%), but *could* be a hint of a (Galactic?) source
- ANTARES search for a ν_μ source in the inner Galaxy (at lower energies)
  - If there is a single source, it must be spatially extended, or have a spectrum peaked at a few hundred TeV

ANTARES Collaboration, arXiv:1402.6182



Multimessenger Counterparts: UHE Cosmic Rays

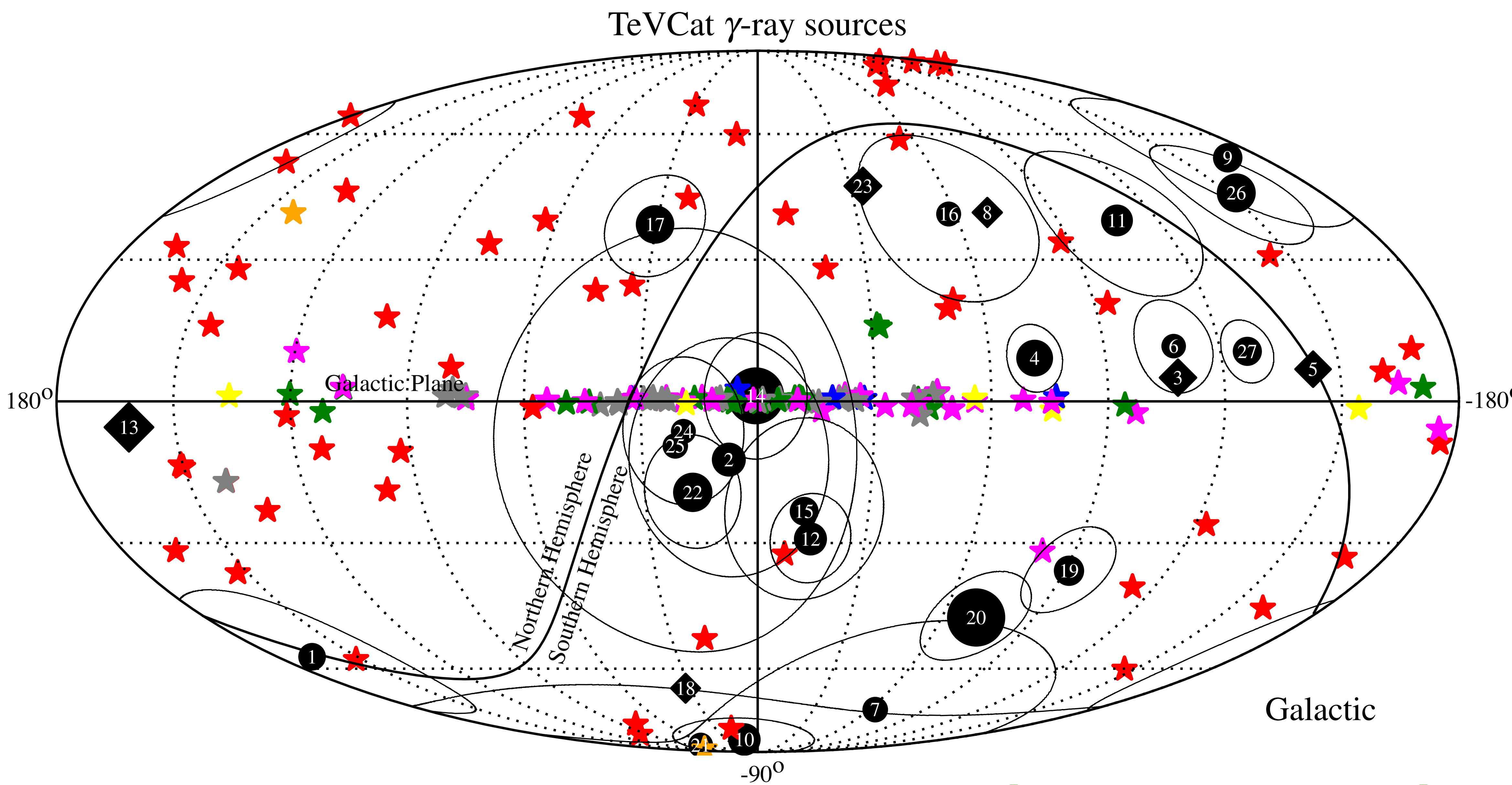


[compilation M. Ahlers]

$$\langle\theta\rangle \simeq 1^\circ \left(\frac{D}{\lambda_{\rm coh}}\right)^{\frac{1}{2}} \left(\frac{E}{55\rm EeV}\right)^{-1} \left(\frac{\lambda_{\rm coh}}{1\rm Mpc}\right) \left(\frac{B}{1\rm nG}\right)$$

[Waxman & Miralda-Escude'96]

Multimessenger Counterparts: TeV Gamma Rays

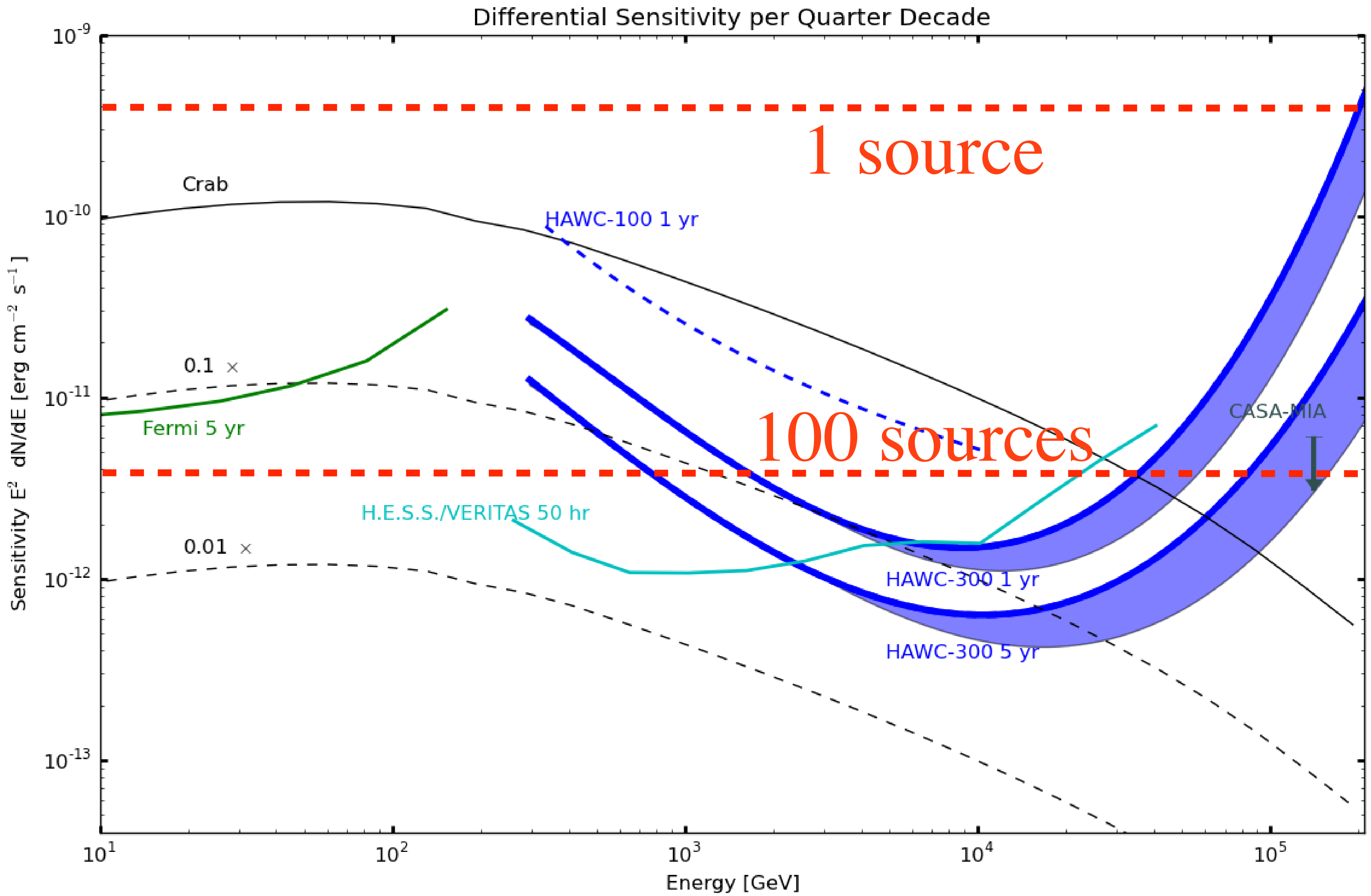


[compilation M. Ahlers]

LBL, IBL, LBL, FRI, FSRQ Globular Cluster, Star Forming Region, Massive Star Cluster
Binary PWN Shell, SNR/Molec.Cloud, Composite SNR Starburst Others [TeVCat'14]

Search for Gamma Ray Counterparts

- TeV gamma ray instruments should have the sensitivity to detect neutrino sources, *if:*
    - Sources not transient
    - Emission extends to lower energy
    - Flux is due to relatively small number of sources



[HAWC Collaboration'13]

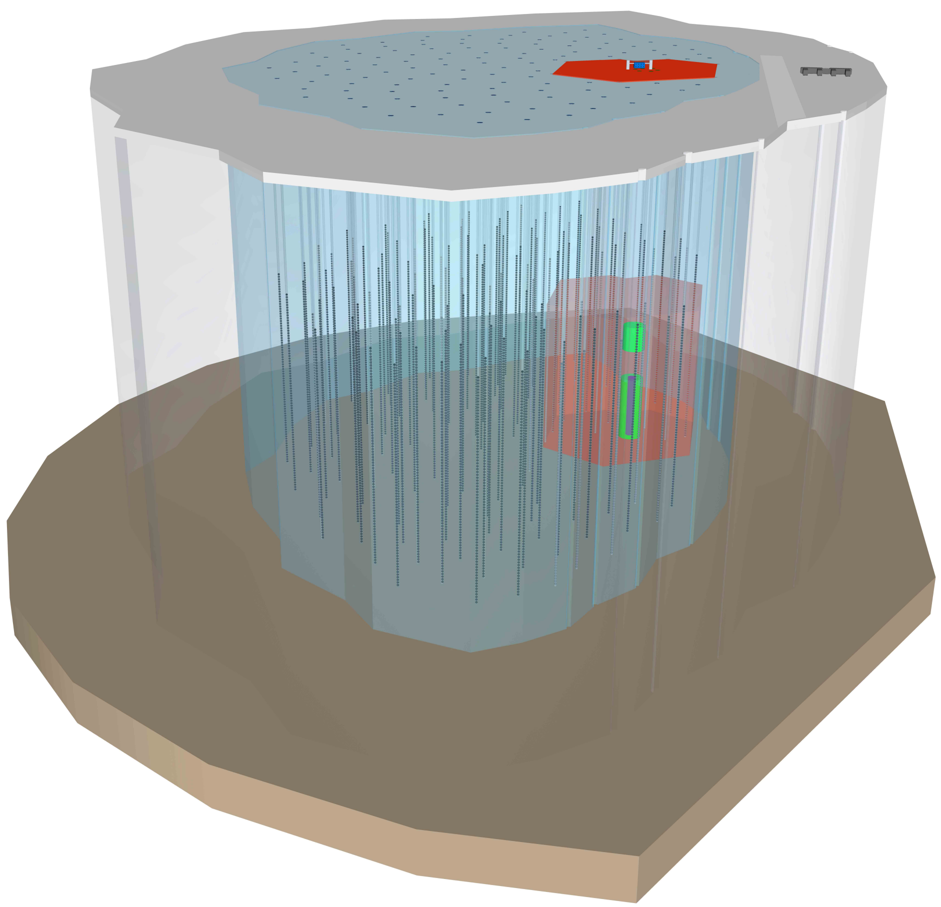
What Do We Know?

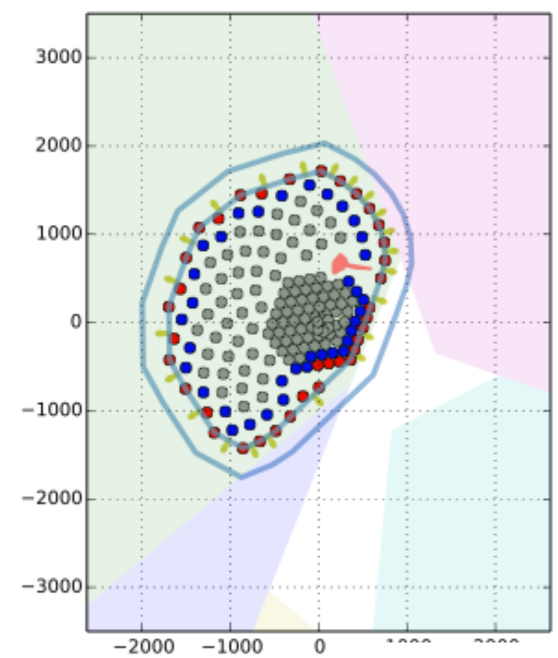
- Compelling evidence for an astrophysical flux of neutrinos at energies of 100 TeV – 2 PeV
  - Energy spectrum around dN/dE ~ $E_\nu^{-2.0}$ to $E_\nu^{-2.4}$ over that range
  - Probably require either the softer spectrum or a cutoff at 3-5 PeV
  - Consistent with equal fluxes of each neutrino flavor
- Consistent with an isotropic flux, although cannot rule out that a substantial part comes from a few bright sources
  - At least some of the flux almost certainly from extragalactic sources
- Working to extend our analyses, but with current instruments, event rates are low and progress will be slow
  - Several proposals for next-generation detectors

Future Instruments

- KM3NeT in the Mediterranean
  - Phase 1: roughly 3 x ANTARES, already funded, completion 2016
  - Phase 1.5: comparable to IceCube but with different view of the sky, potentially complete by 2020
  - Phase 2: several times IceCube sensitivity to ν_μ, potentially mid 2020's
- GVD in Lake Baikal
  - First of 10 clusters in 2015, full array in 2020
- Next-Generation IceCube
  - Proposal in preparation: potential construction start in 2018/19, completion in 2027
  - Would include PINGU neutrino oscillation/dark matter component

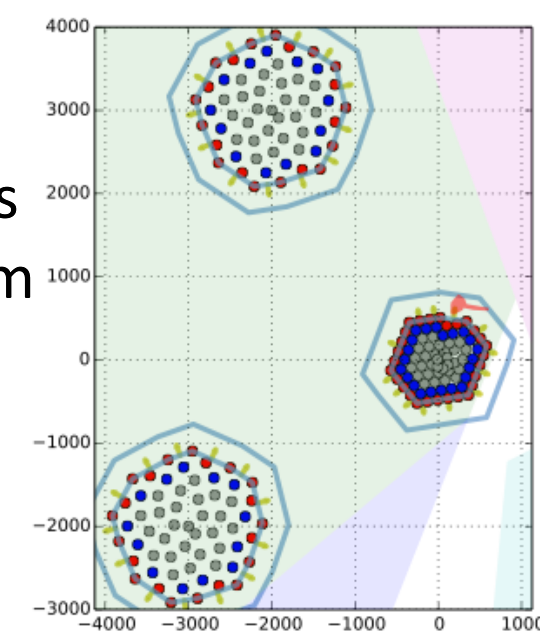
Next-Generation IceCube





IceCube + 96 strings
Spacing 240 m

IceCube +
2 x 60 strings
spacing 240 m



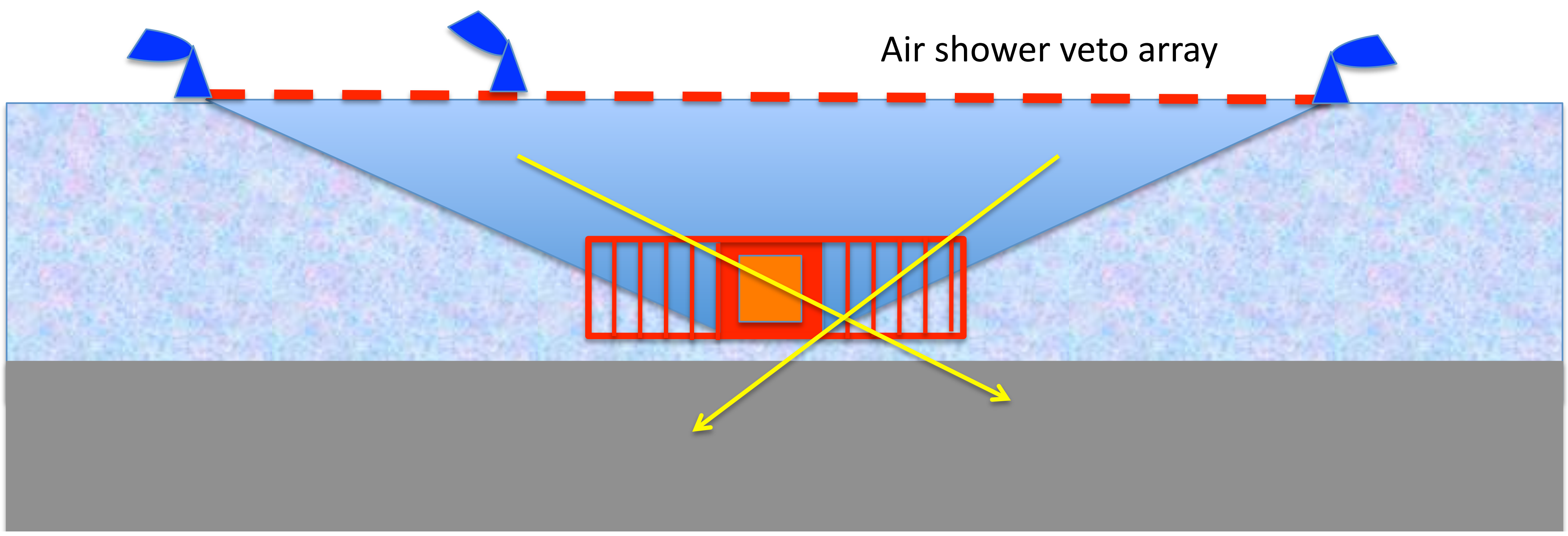
- **~ 100 strings**
- **+ surface veto detector**
- **+ PINGU for oscillations (40 strings)**
- **Start 2018/19?**

Albrecht Karle, Arlington Meeting April 24, 2014

Surface Veto Arrays

- Examining both EAS arrays (surface particle detectors) and air Cherenkov telescopes for tagging cosmic ray air showers

- In addition to lowering energy threshold, surface veto array would allow substantial expansion of fiducial volume for downgoing ν's



PINGU: Measuring the Neutrino Mass Hierarchy

- Several current or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years
  - NB: *median* outcomes shown – large fluctuations possible
- Widths indicate main uncertainty
  - LBNE/NOvA: δ_{CP}
  - JUNO: σ_E (3.0-3.5%)
  - PINGU/INO: θ_{23} (38.7°–51.3°, 40°–50°)
  - Other projections presented here assume worst-case parameters (1st octant)
- PINGU timeline based on aggressive but feasible schedule; LBNE from LBNE-doc-8087-v10, all others from Blennow et al.

after Blennow et al., arXiv:1311.1822