High Energy Neutrinos from the Sky

Lepton-Photon 2013

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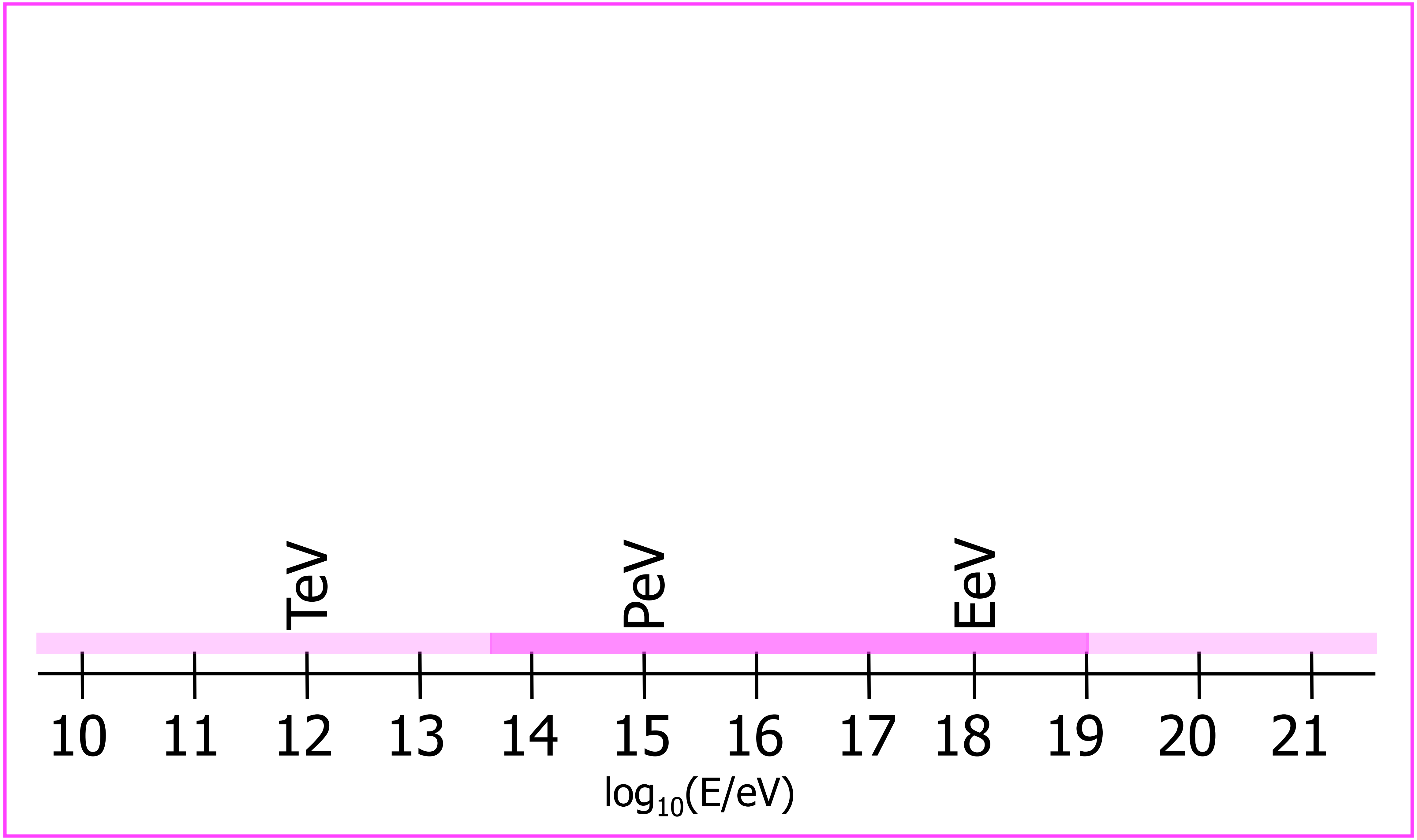
UNIVERSITY OF ALBERTA

Astronomical Messengers



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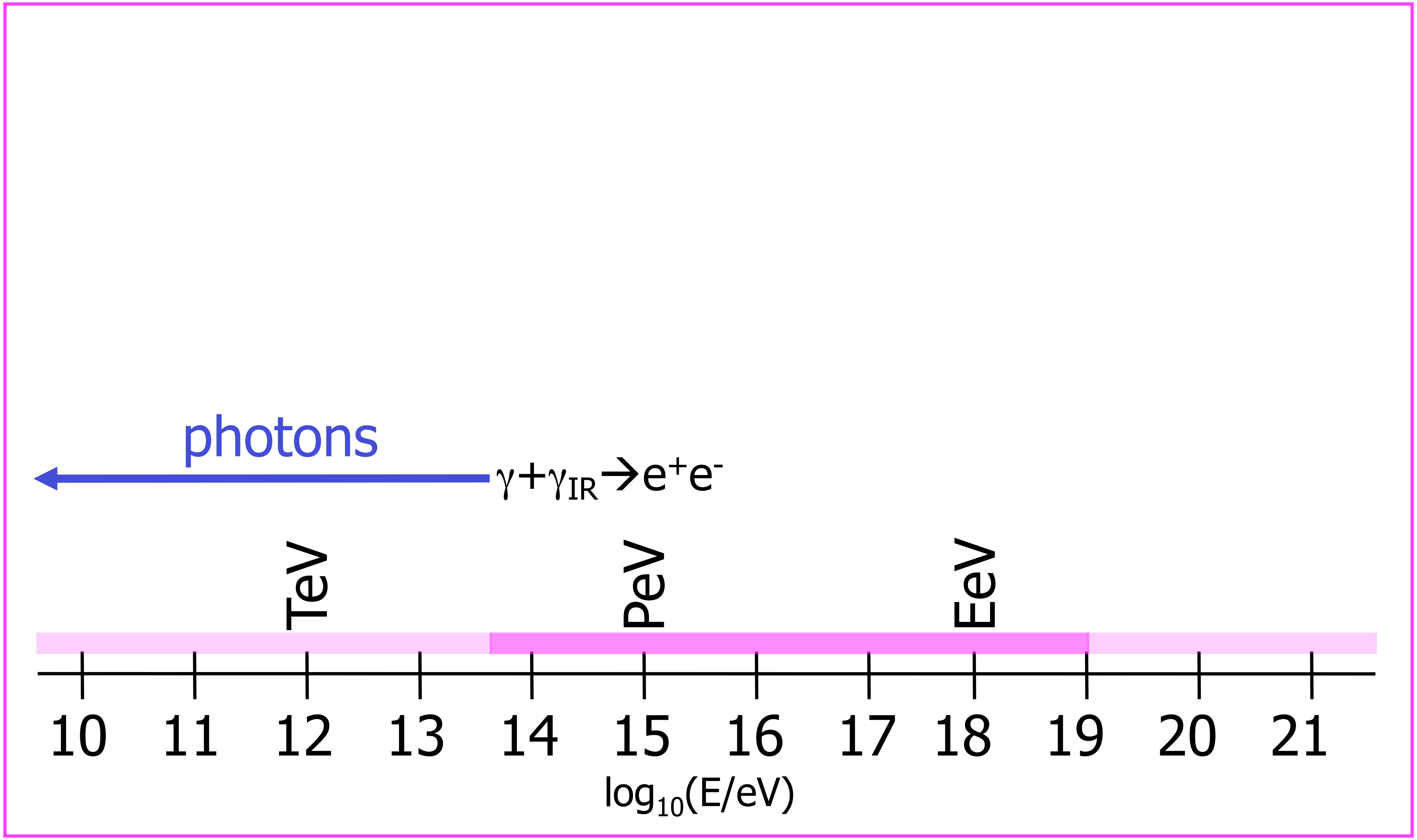

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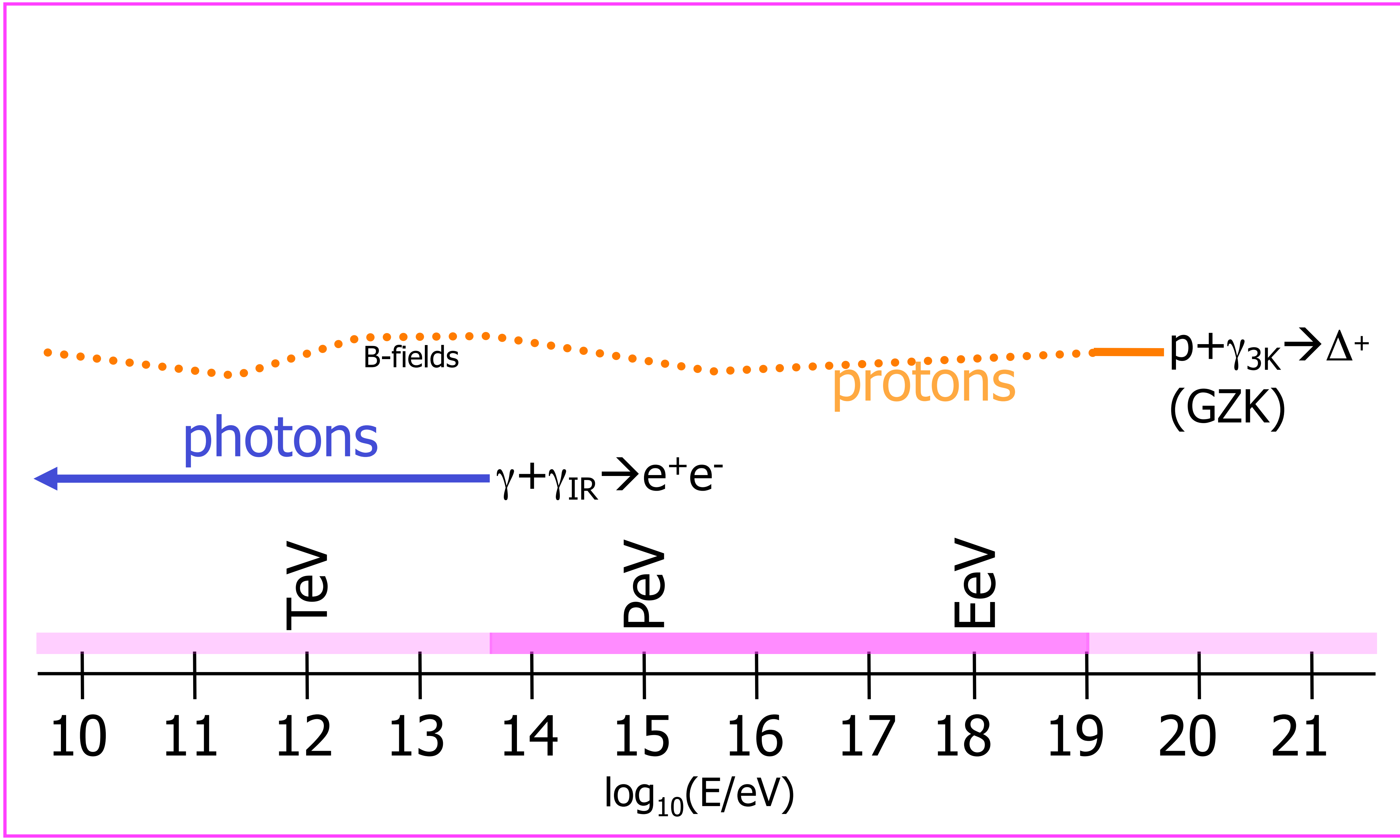

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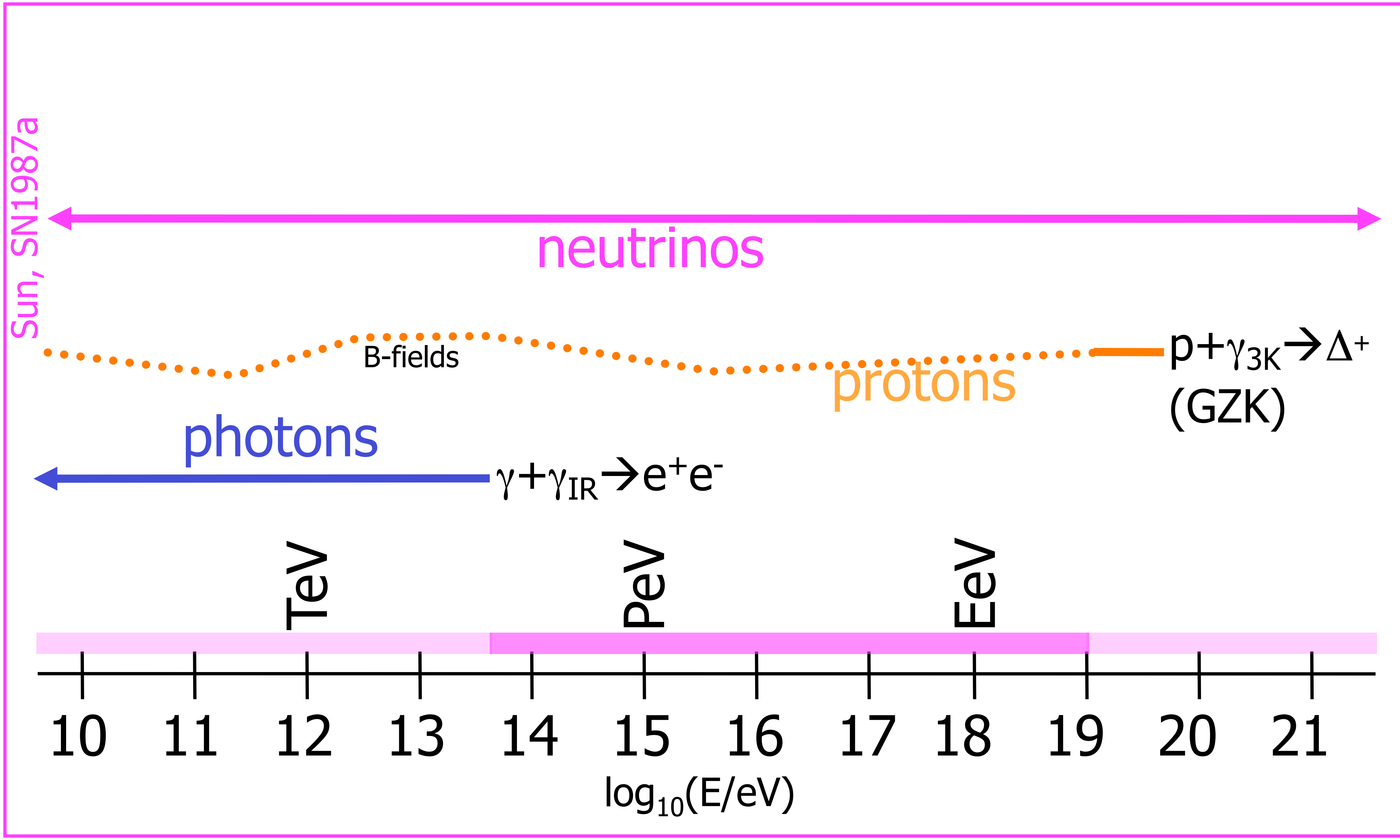

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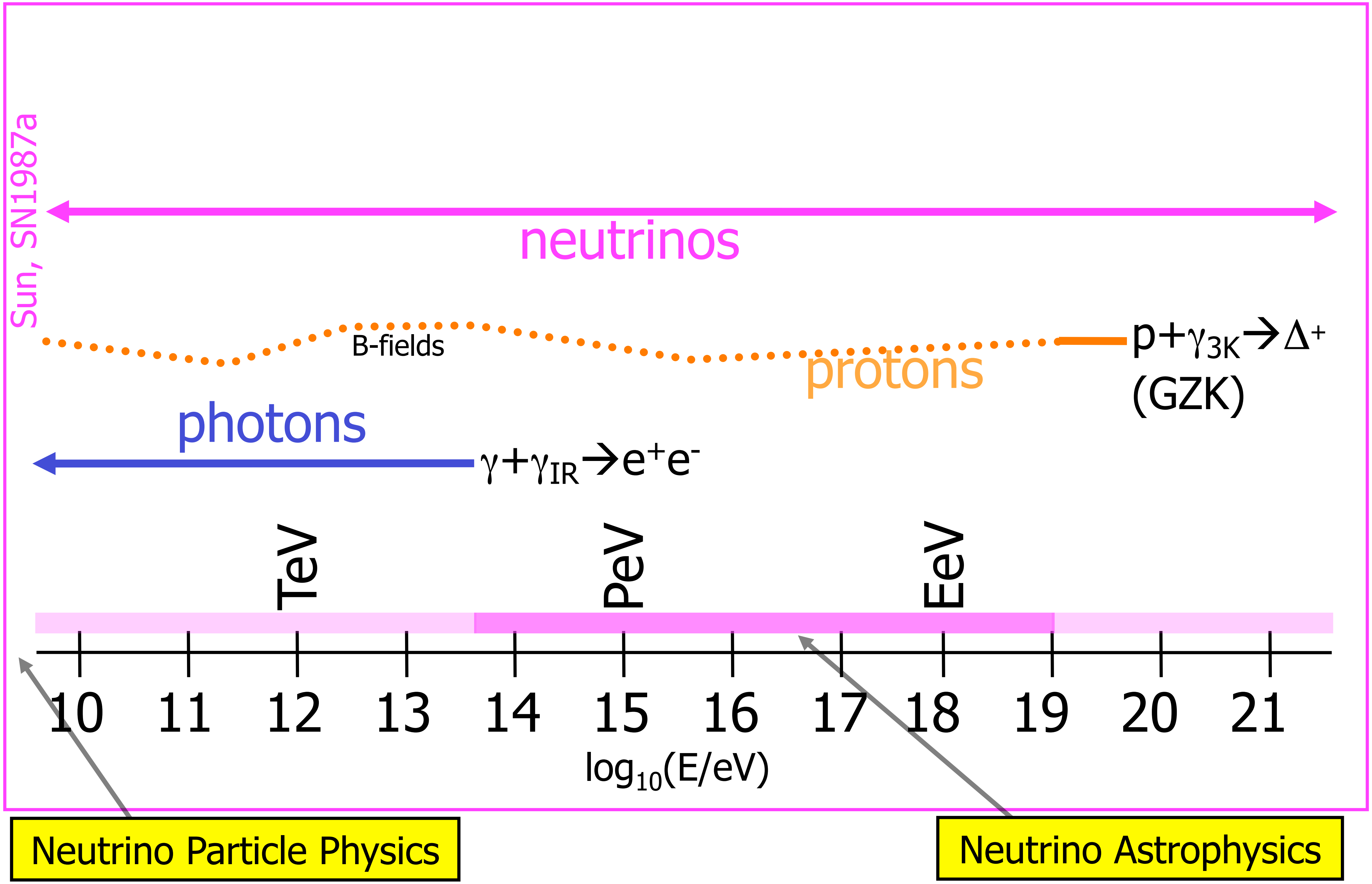
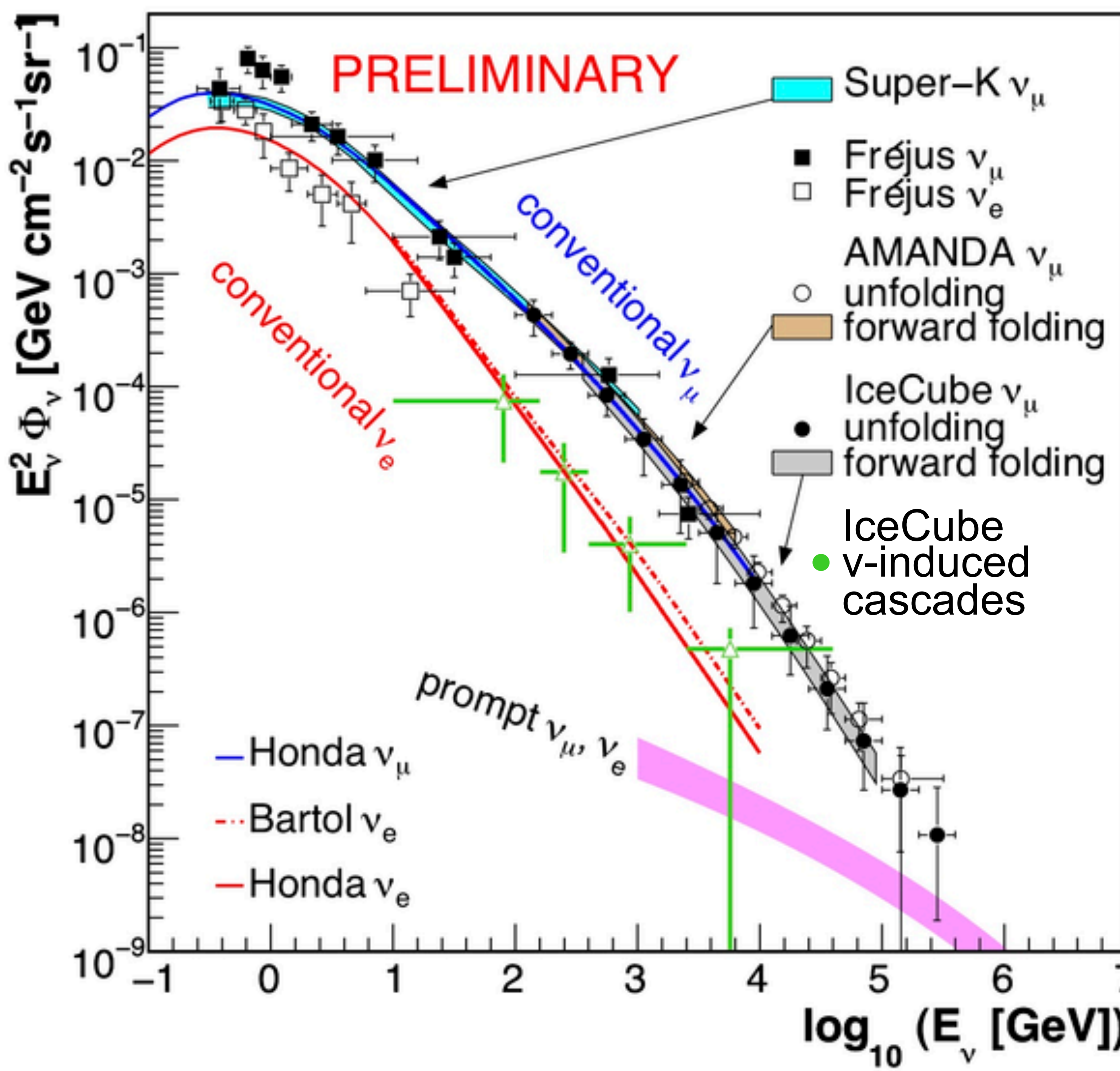


Neutrinos from the sky: known sources

- Neutrinos are produced in collisions of cosmic ray protons and other nuclei with atmospheric nuclei
  - pions, kaons→ν's
  - 4π
- Neutrino energies extend up to ~100 TeV
- Higher energy contribution from "prompt" ν's from charm decays not yet observed
  - $(D^0, D^\pm, D_S^\pm, \Lambda_C^\pm) \rightarrow \nu$'s



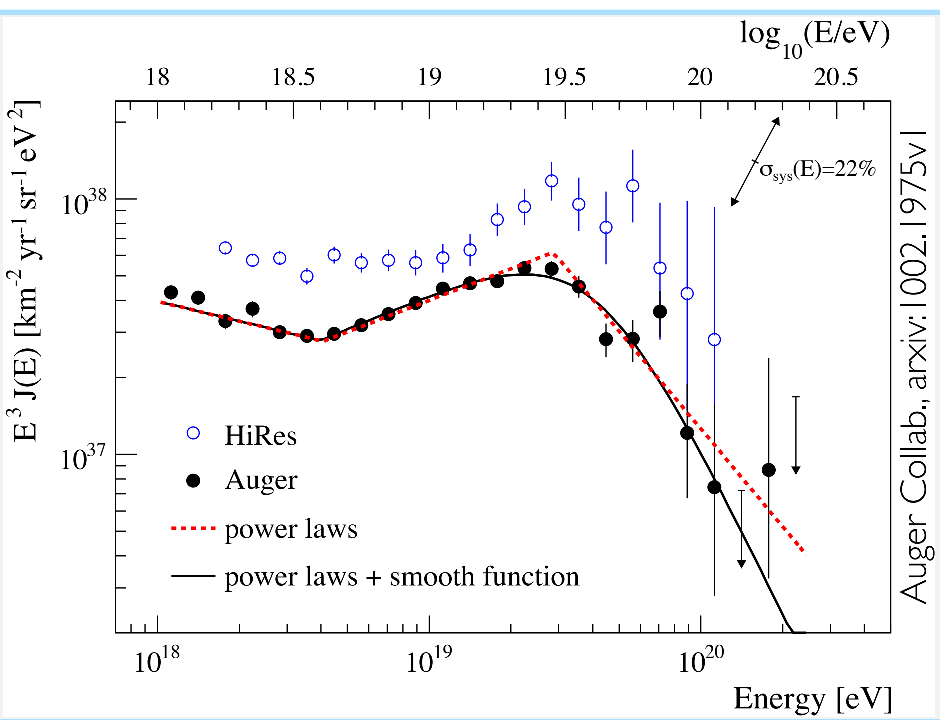
Neutrinos from the sky: potential astrophysical sources

$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

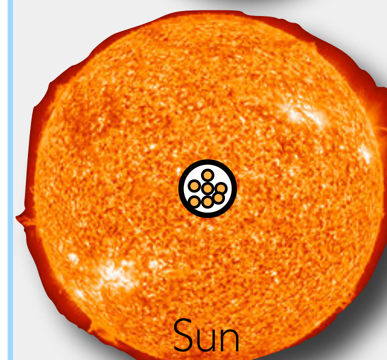
Gamma-ray Bursts

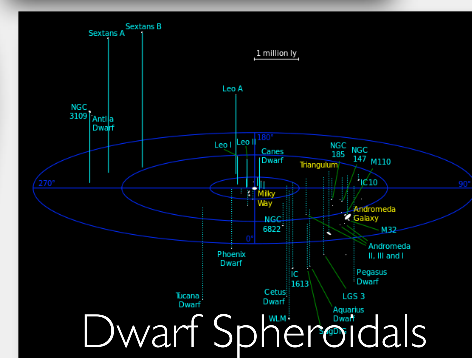
Active Galactic Nuclei

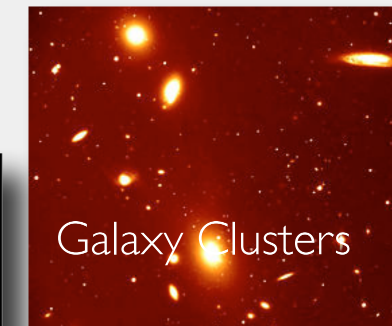
$p+\gamma_{3K} \rightarrow \Delta^{+}$ (GZK)

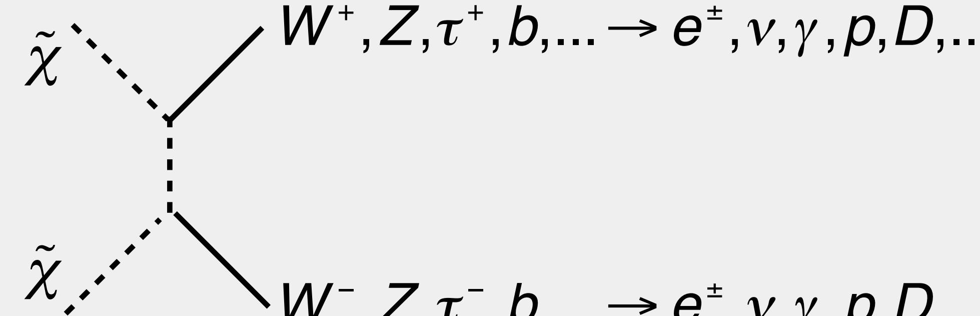


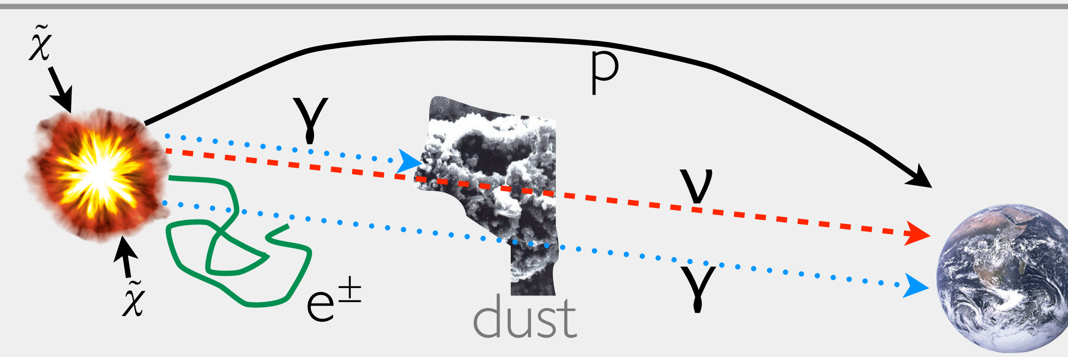
WIMPs







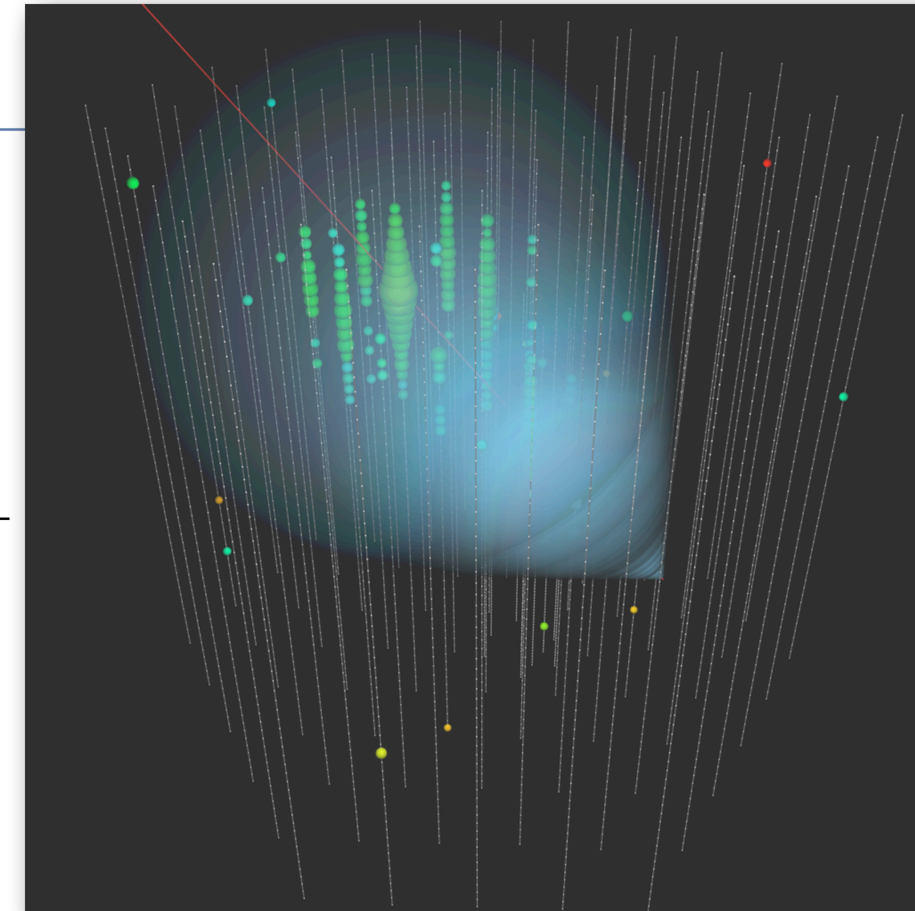




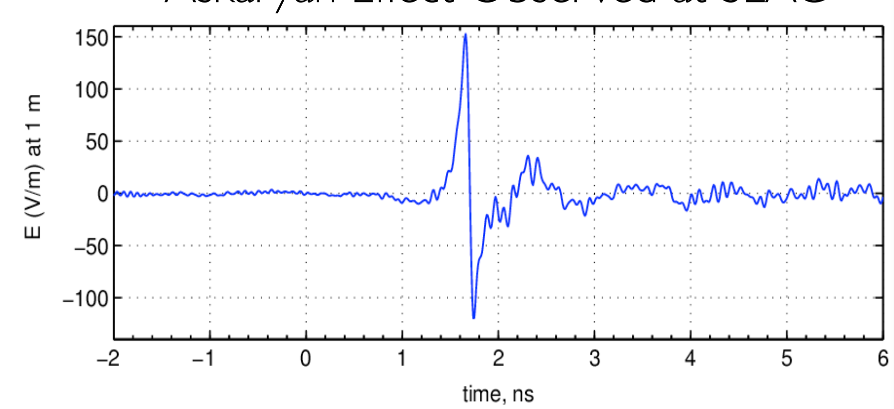
Principles of high energy ν detection

- Water Cherenkov
  - ν-induced charged particles emit a detectable pattern of Cherenkov radiation
  - backgrounds from cosmic ray μ and atmospheric ν reduced via event timing, direction, energy and vetoing techniques
- Radio Askaryan
  - radio λ's are comparable to size of ν-induced shower of charged particles; resulting coherent radiation can be very powerful
  - demonstrated at SLAC with 28 GeV shower × 10^9 particles/shower directed into a block of ice
- Penetrating or upward-going air shower
  - air Cherenkov (Auger)
- Acoustic
  - localized ν-induced heating: sharp sonic pulse
  - tests in polar icecap yielded too small λ_{att}
    - water could be better, but need water without noisy sea creatures & boats (the Dead Sea?)

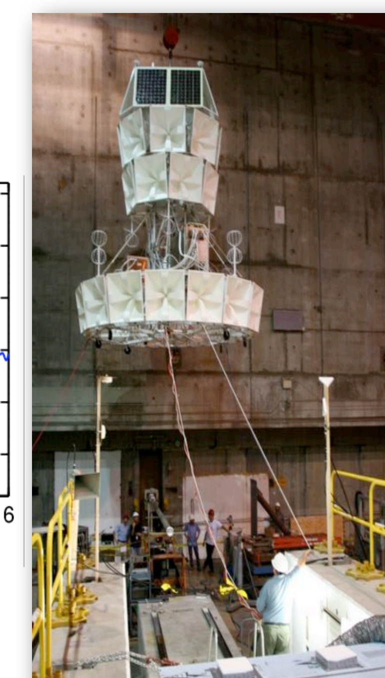
Simulated downward-going cosmic-ray muon in IceCube



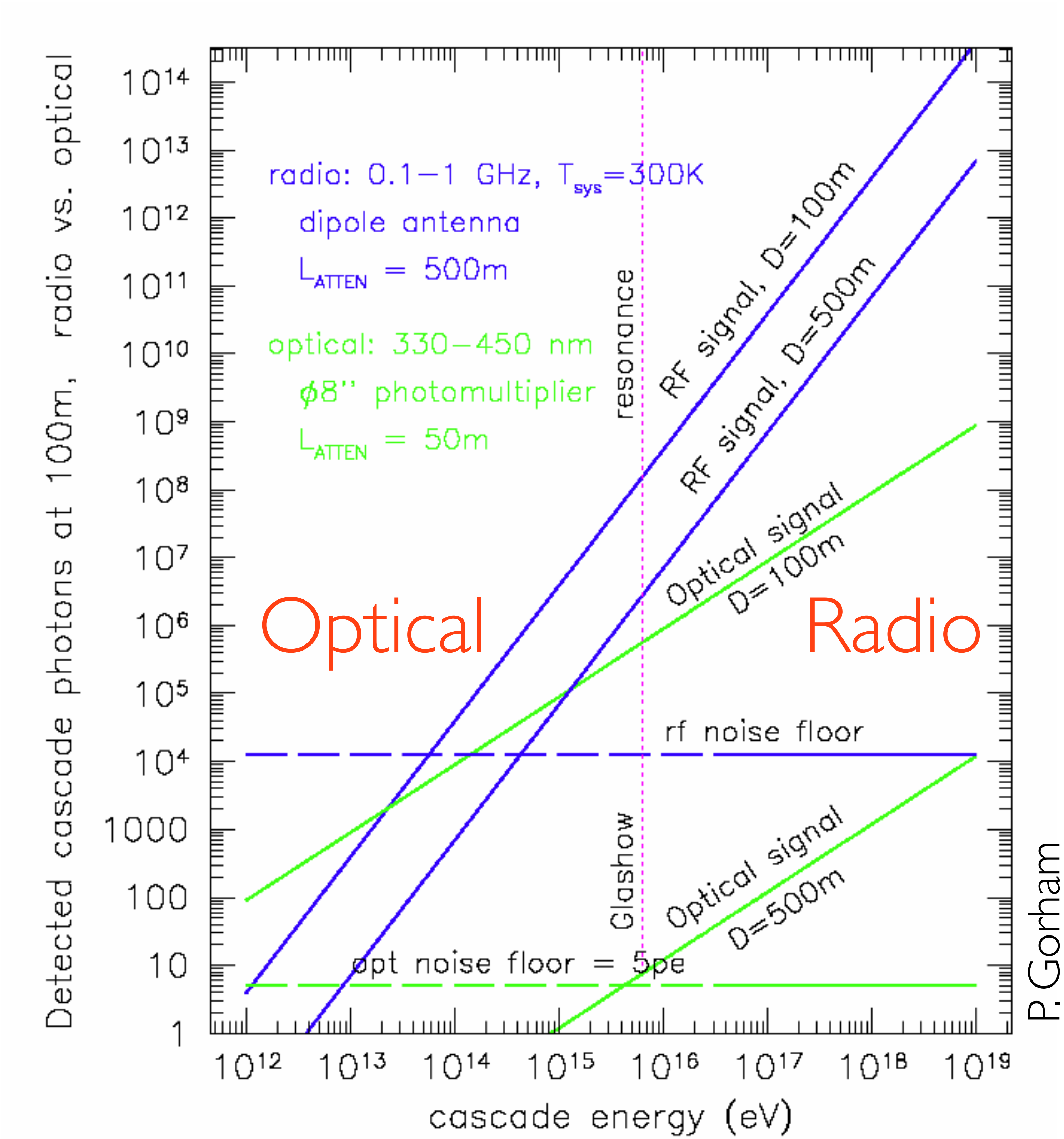
Askaryan Effect Observed at SLAC



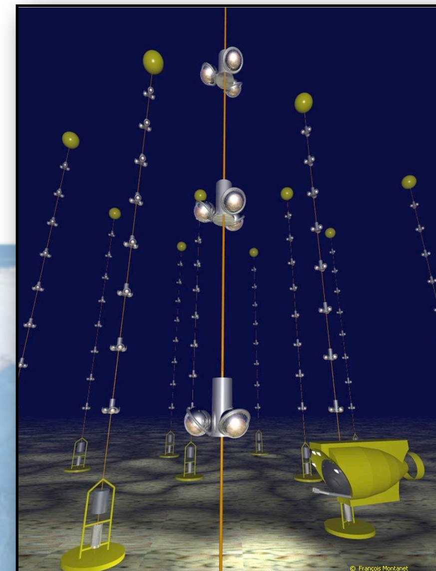
ANITA Coll. PRL (2007)



Detector regimes: optical vs. radio



Operating large optical water Cherenkov detectors



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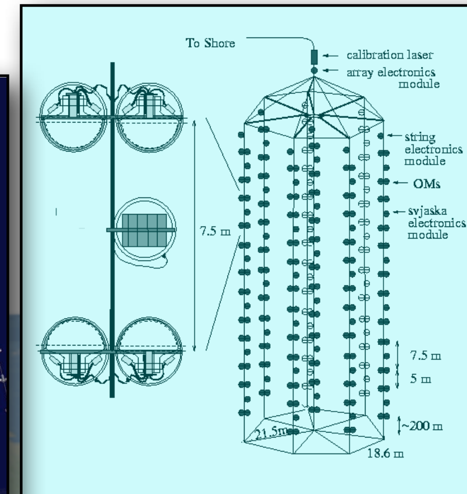
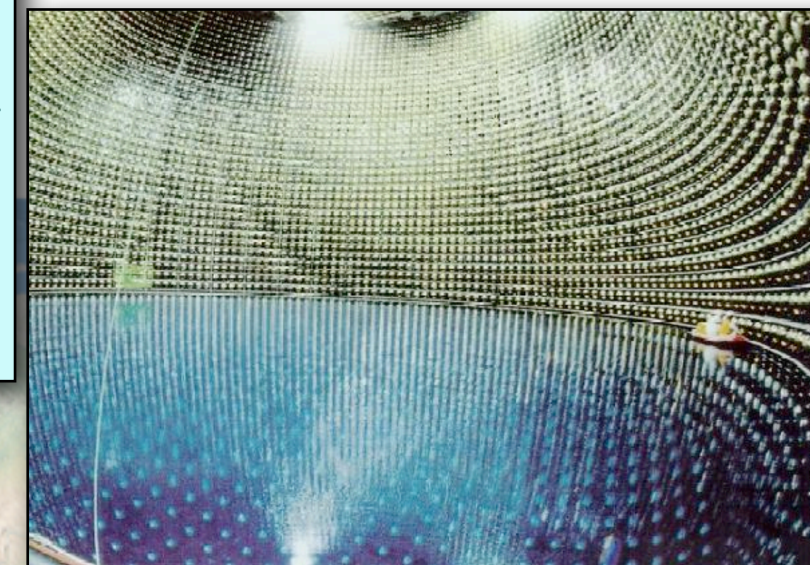
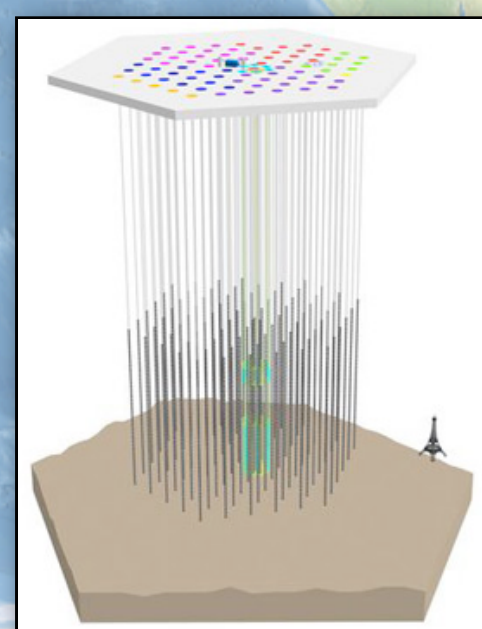


Lake Baikal



Super-Kamiokande

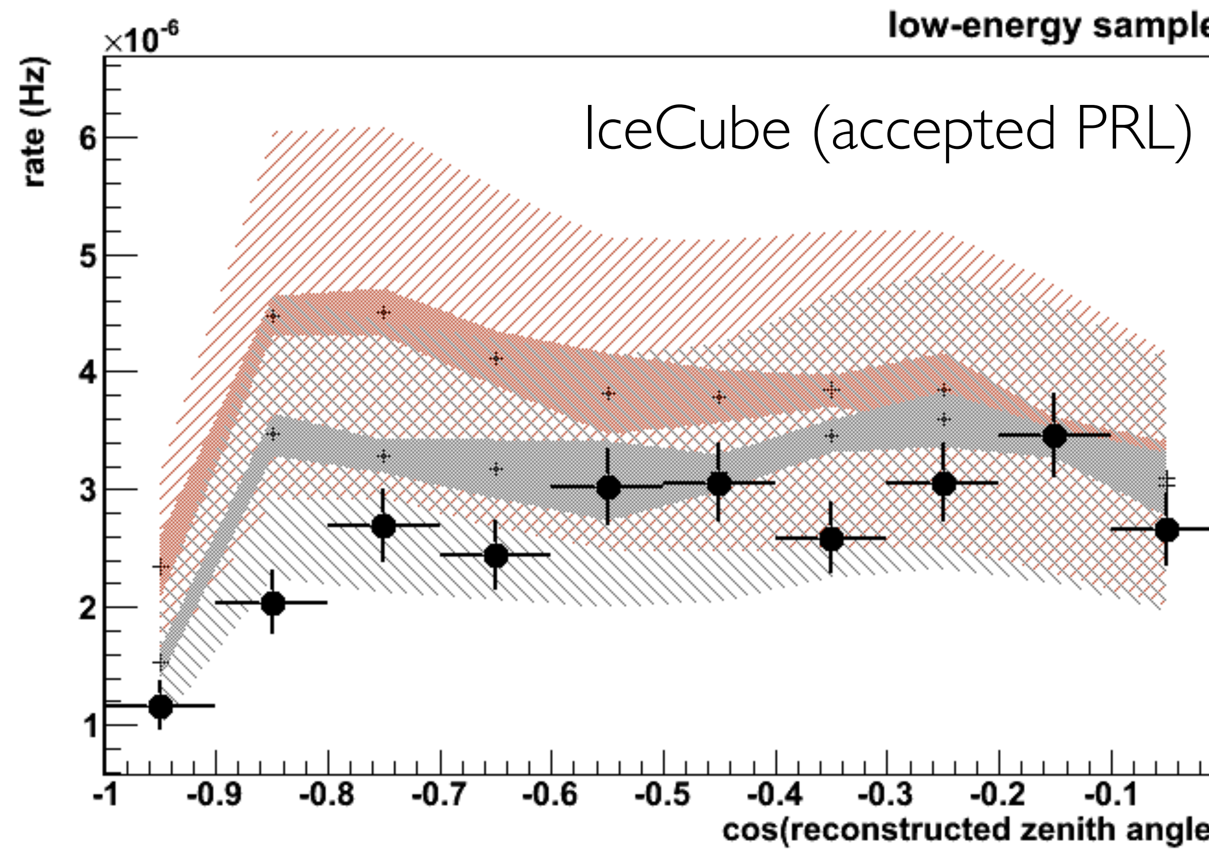


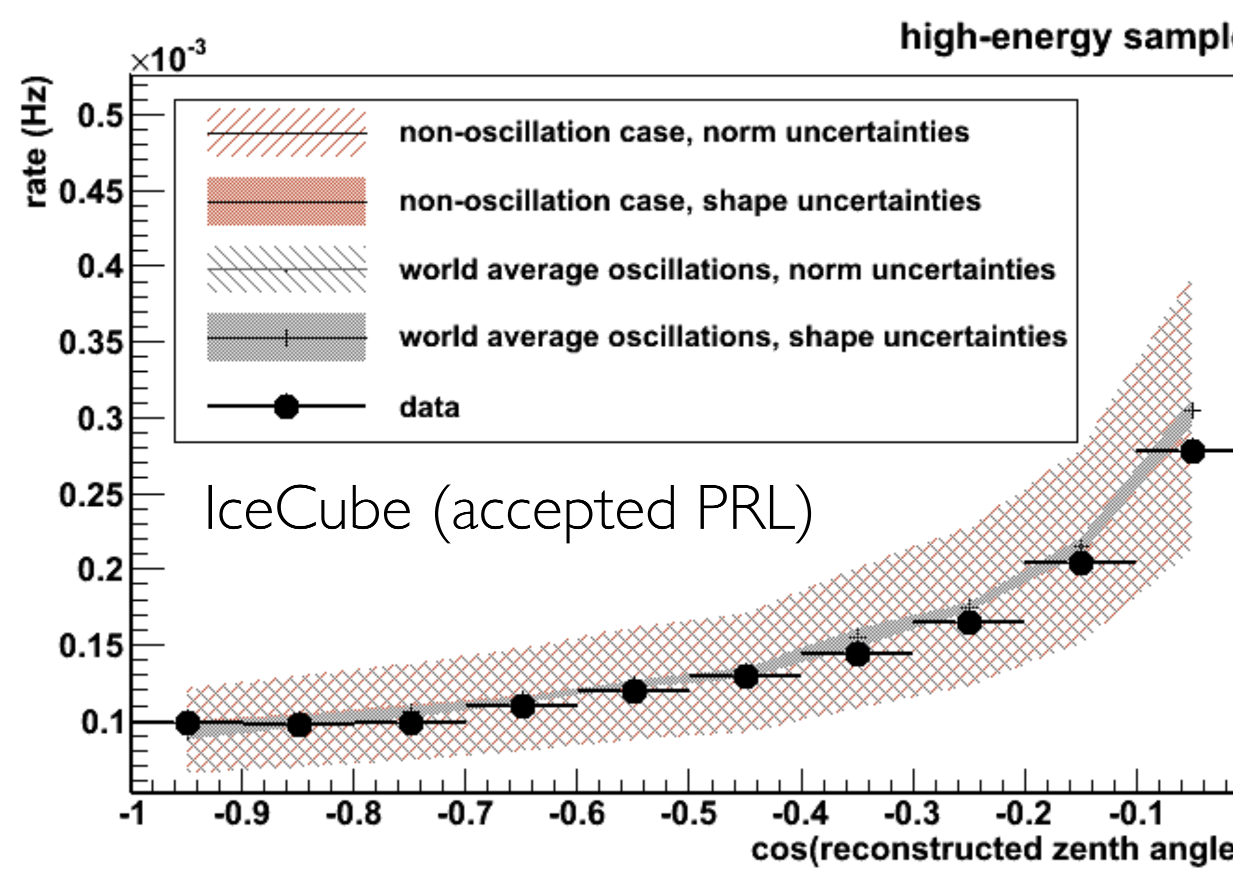
IceCube & DeepCore

Darren R. Grant - University of Alberta

Some results from the known (atm.) ν source (water Ch. dets.)

- Following in the footsteps of SuperK, high energy neutrino telescopes have made their first atmospheric neutrino oscillation measurement near 25 GeV
- no oscillation hypothesis rejected at 5.6σ





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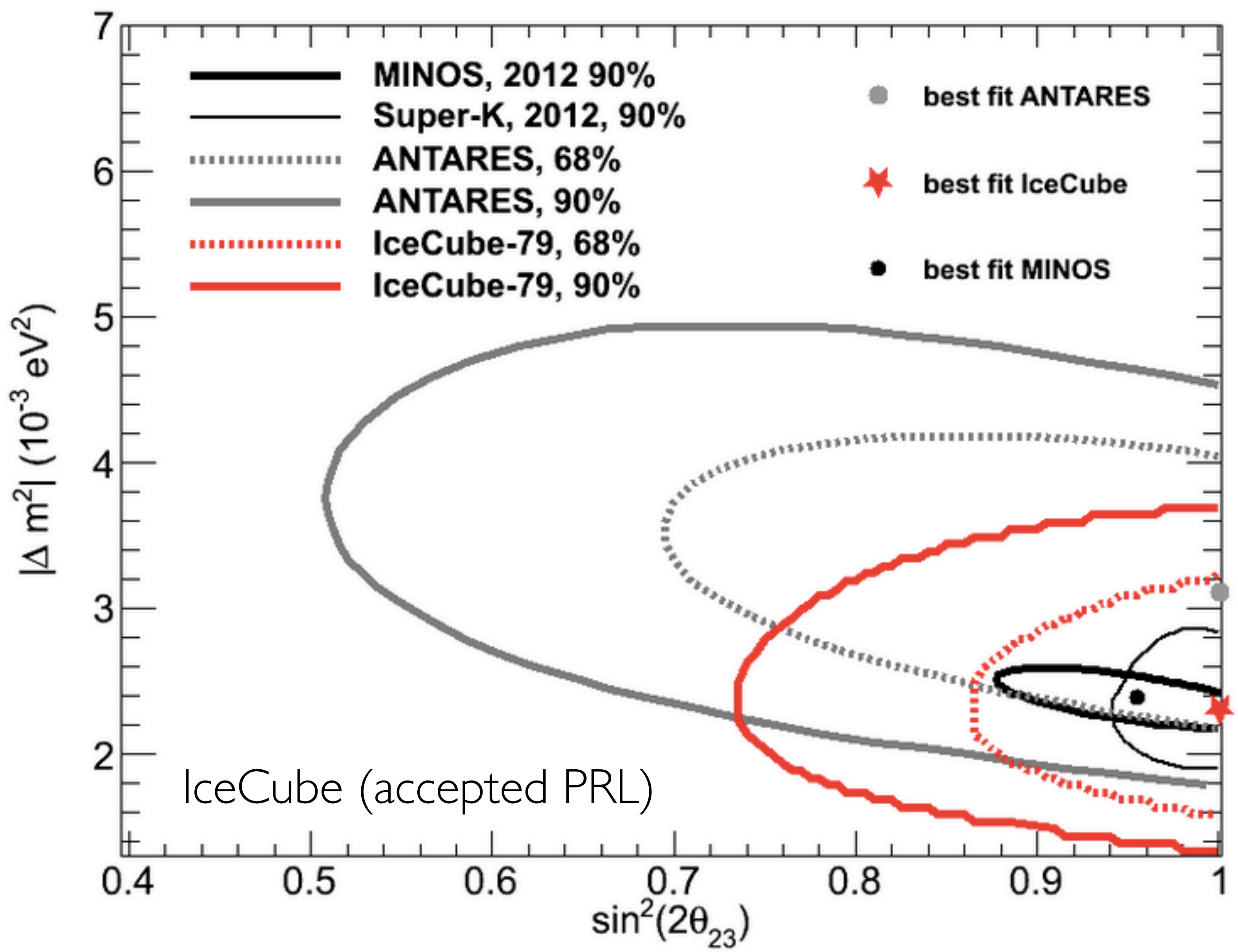
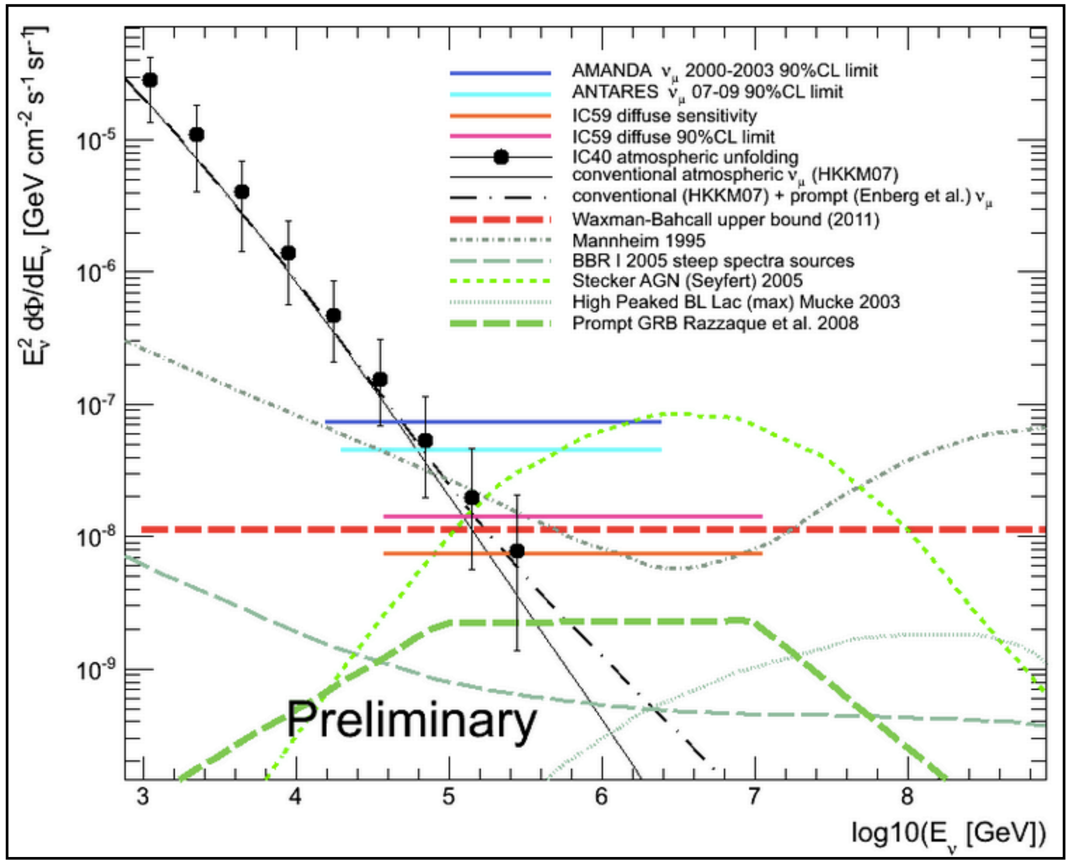
- oscillation parameters have been extracted; in good agreement with the global best fits

- high statistics analyses are now being refined on 2.5 years of DeepCore (IceCube low-energy extension) data

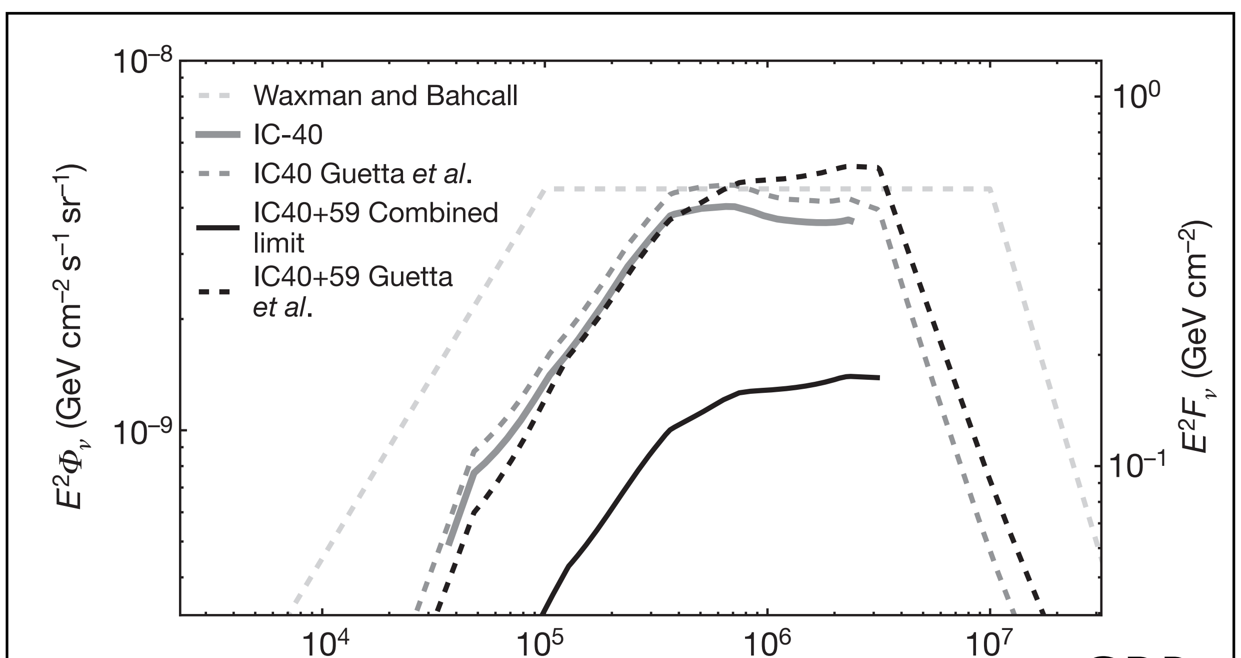


Some results from the proposed (atm.) ν sources (water Ch. dets.)

- Search for ν's from:
  - diffuse sources:



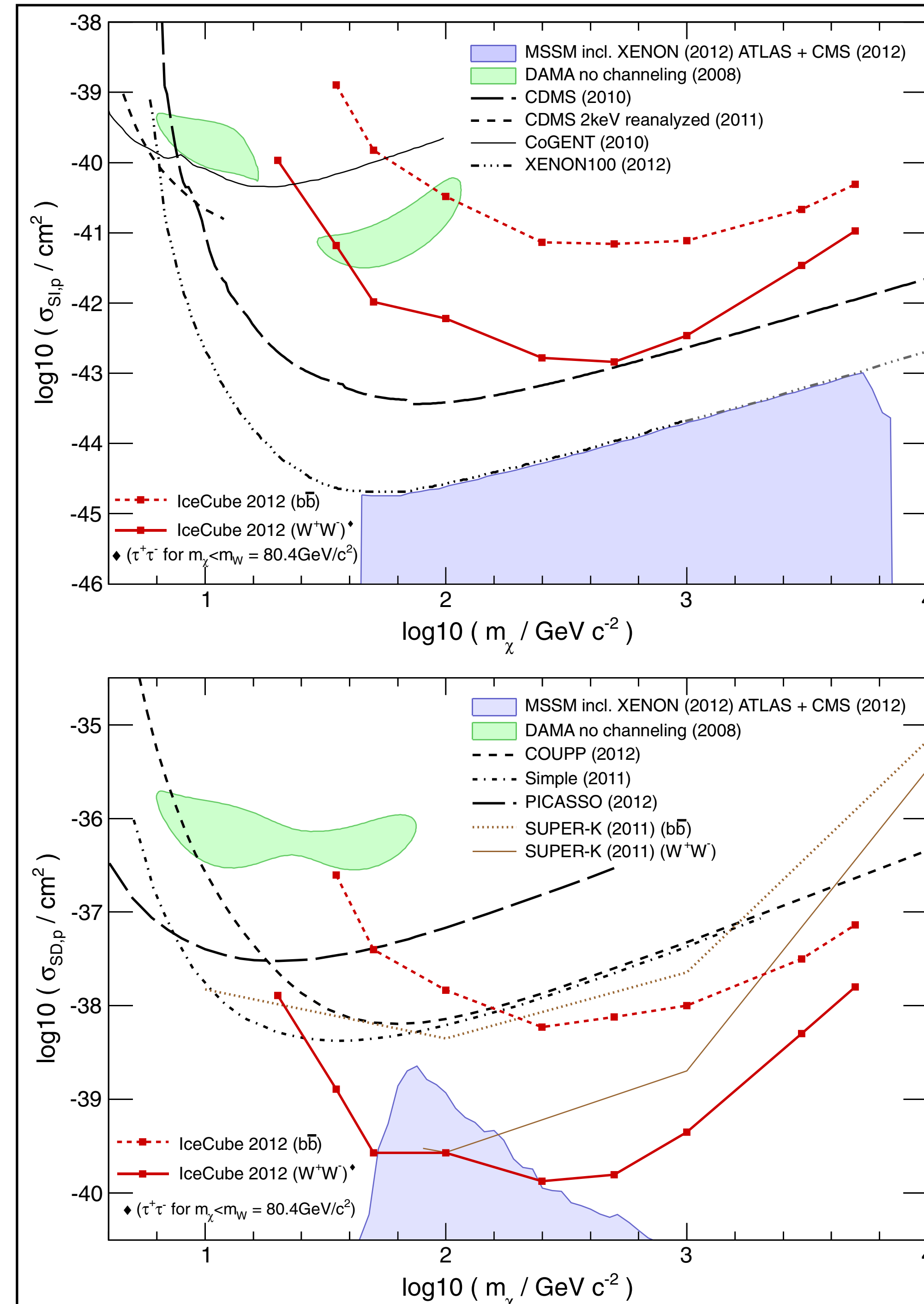
  - point sources:



doi:10.1038/nature11068

GRBs

- WIMP annihilations: PRL 110, 131302 (2013)

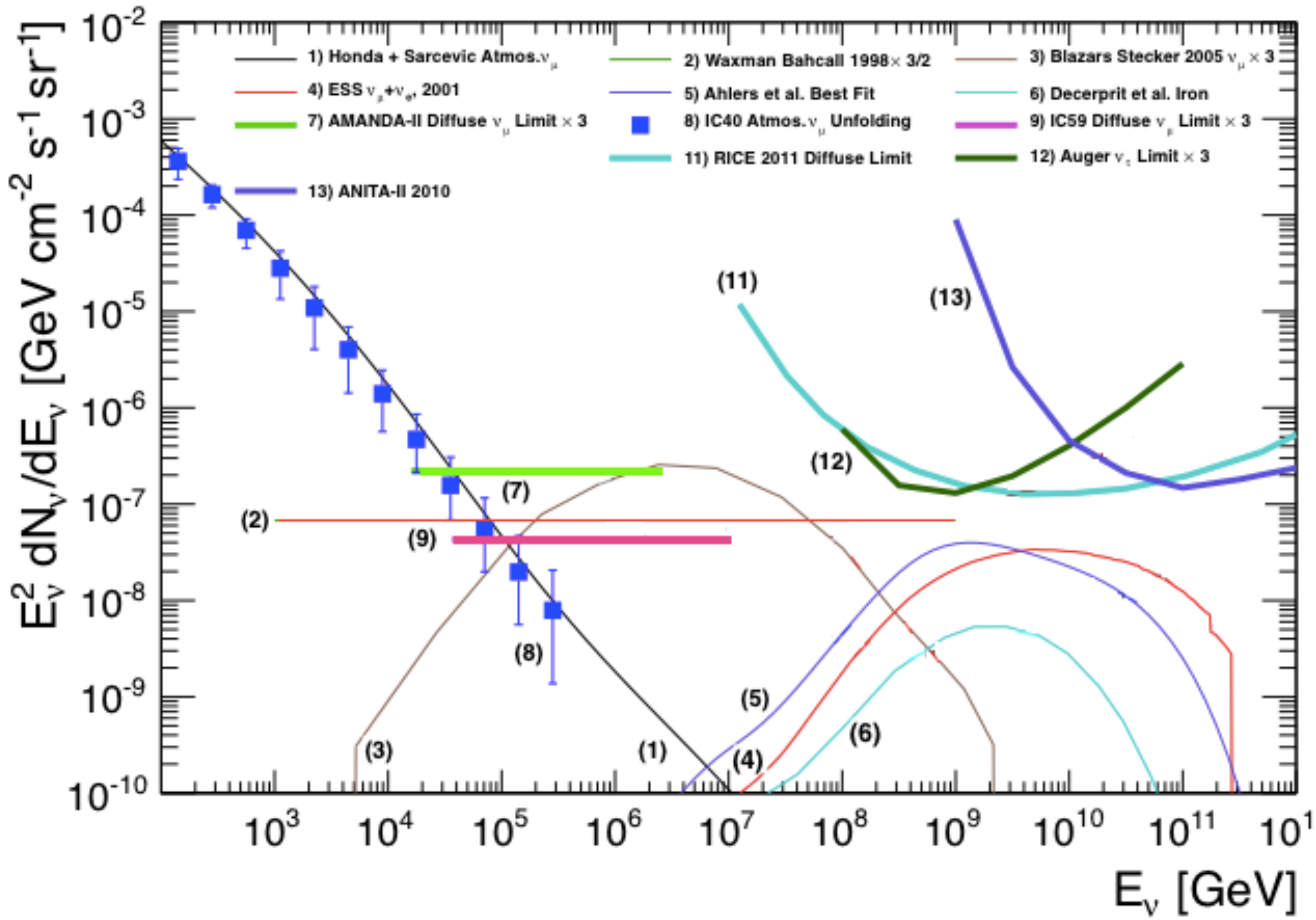


- Nothing was found

Search for GZK ultra-high energy neutrinos and radio pulse detectors

- ANITA, RICE, Auger

	ANITA-I	ANITA-II
Isolated Vertically Polarized Events	1	1
Expected Background	1.1	0.97 +/- 0.42



Status high energy neutrino searches (circa 2011)

With continuing occurrence of null results the community had started to become quite good a placing stringent limits on leading theories...

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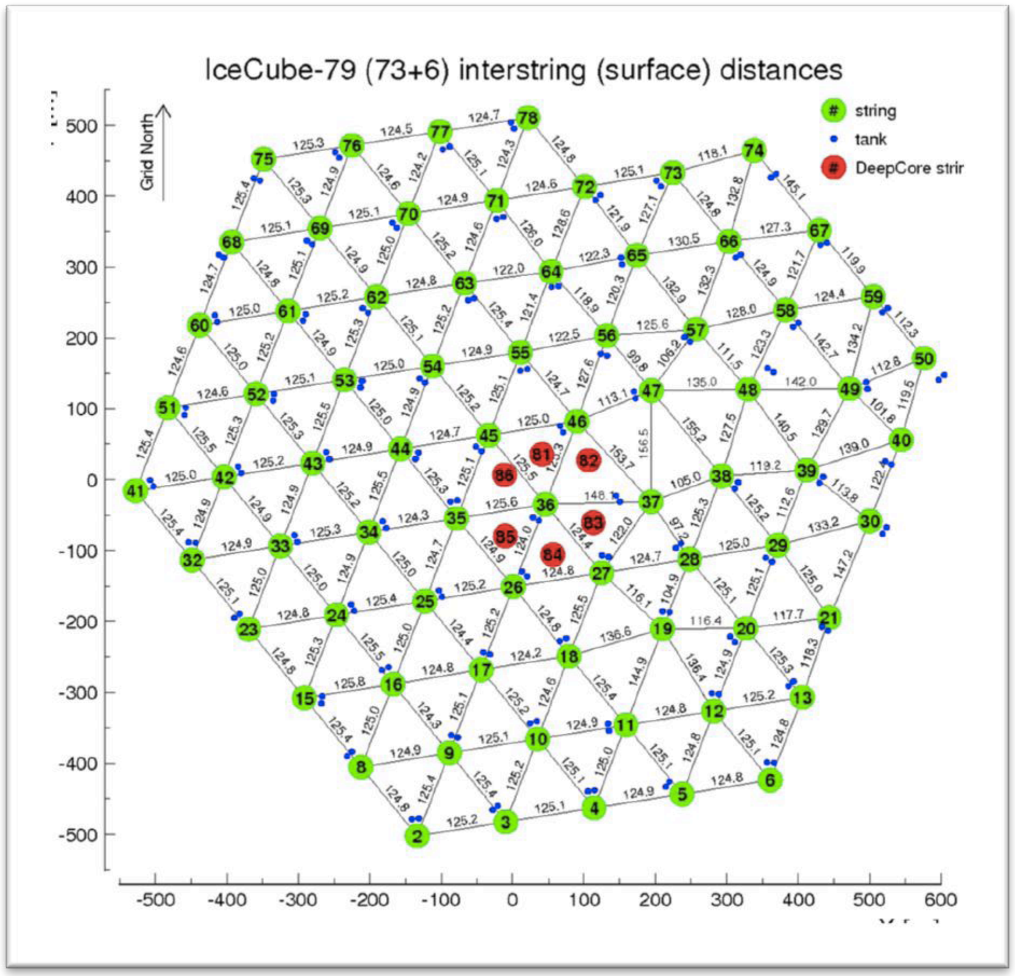
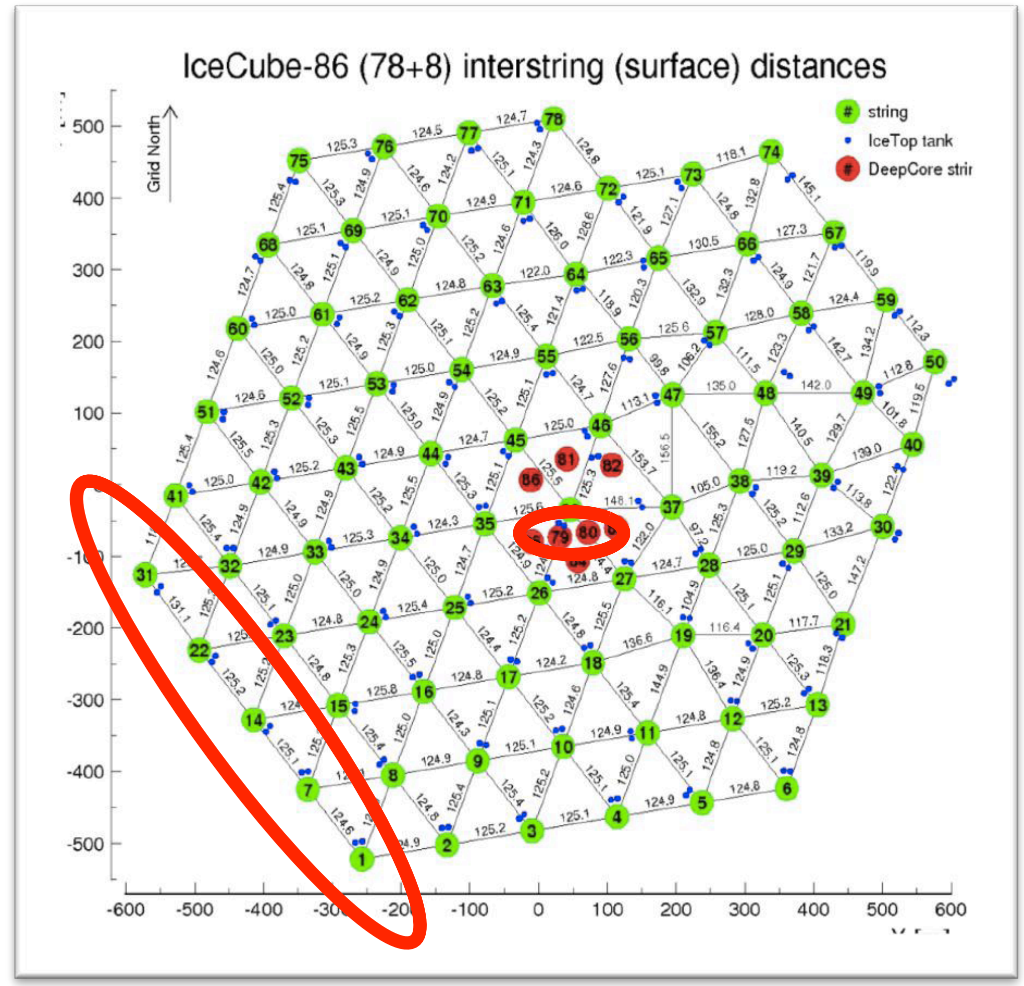




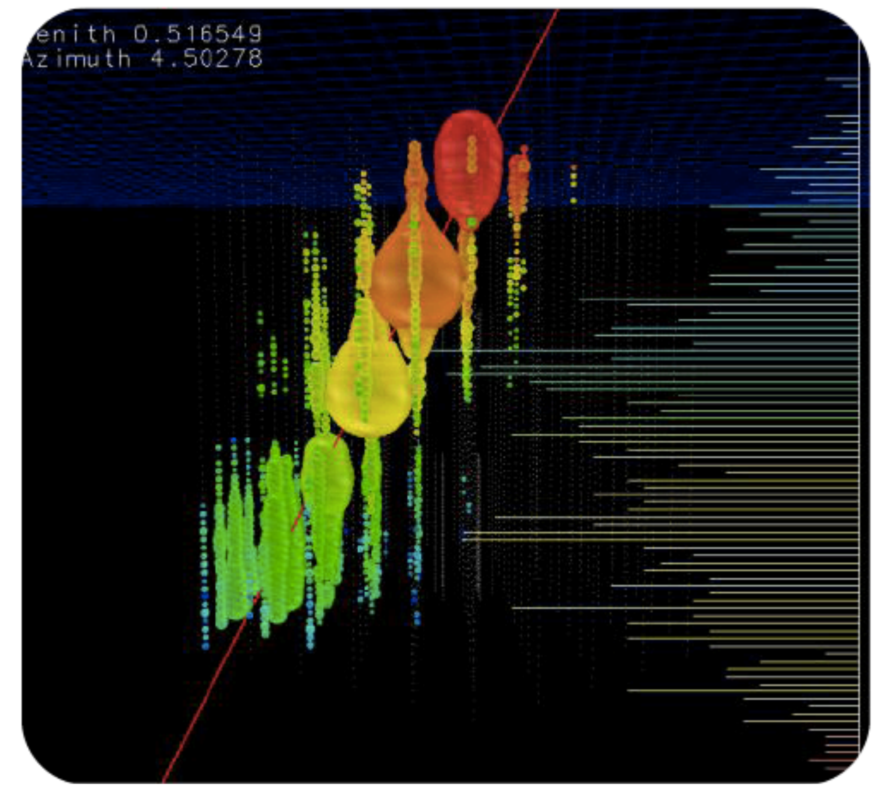
new strings

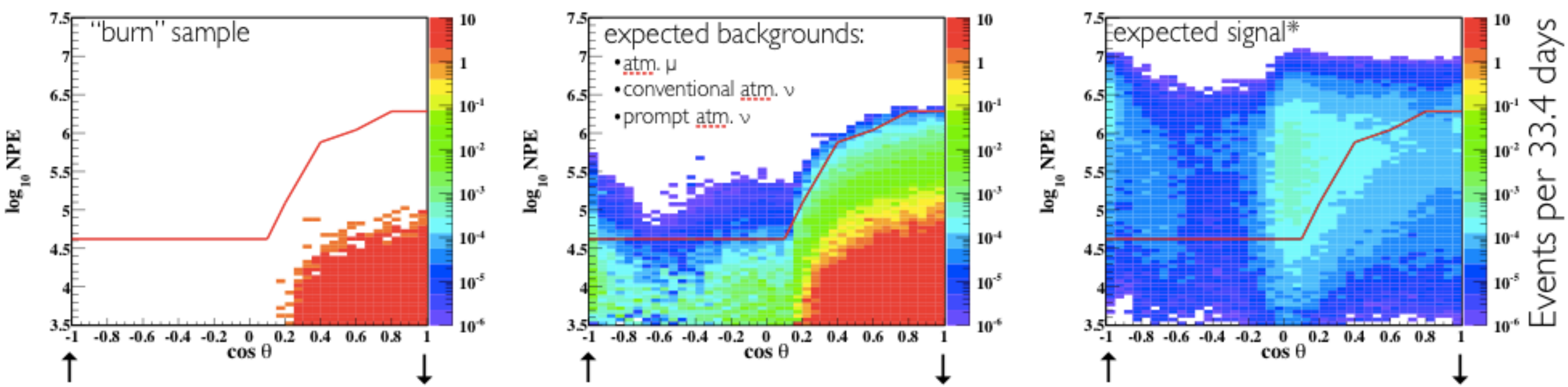
...and then the ultra-high energy analysis from the first cubic-km datasets occurred (IceCube 79 and 86 strings; 615.9 days)

The IceCube ultra high energy neutrino search

- An analysis tuned to independently sample muon and cascade events up to 10^9 GeV.

- Designed to remove backgrounds:
  - atmospheric neutrinos below 500 TeV with a cut on number photoelectrons (NPE)
  - atmospheric muons with an entering track hypothesis from the reconstruction and a directionally dependent NPE cut



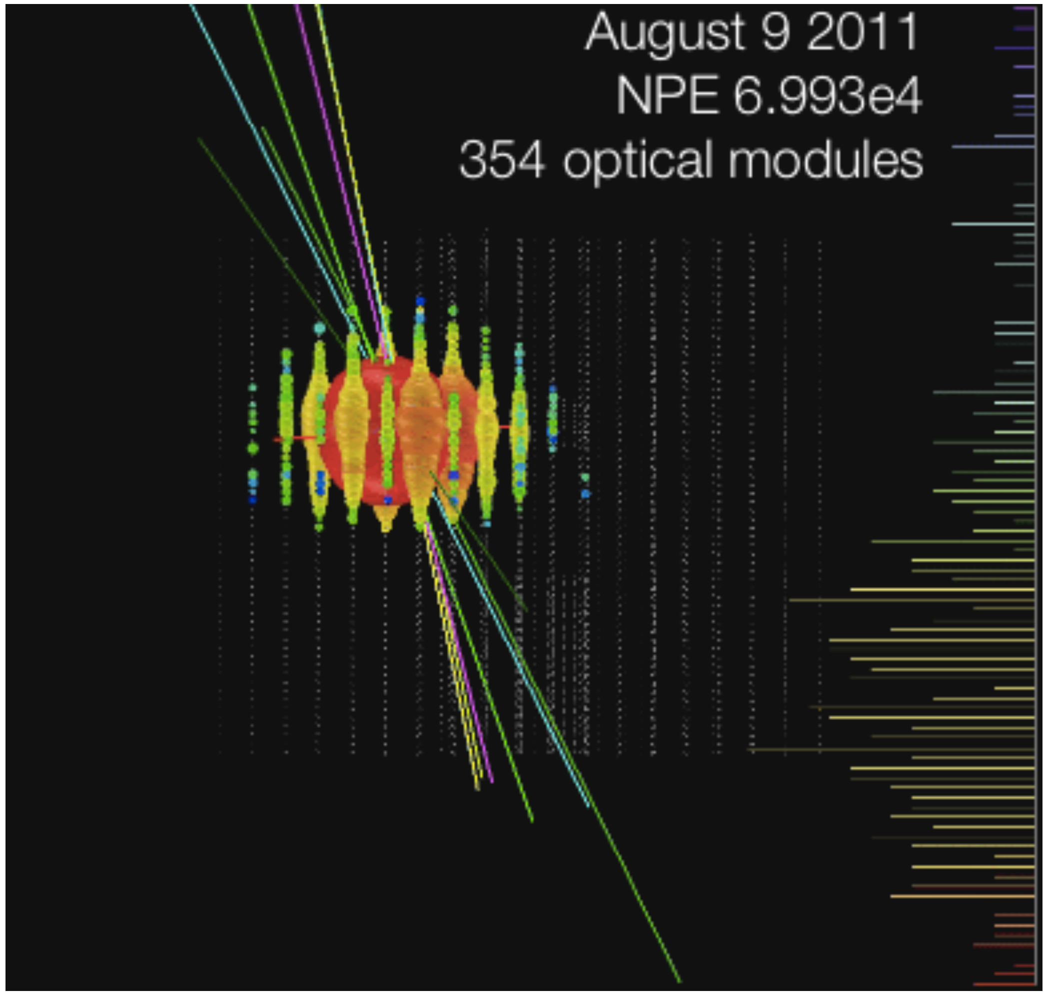


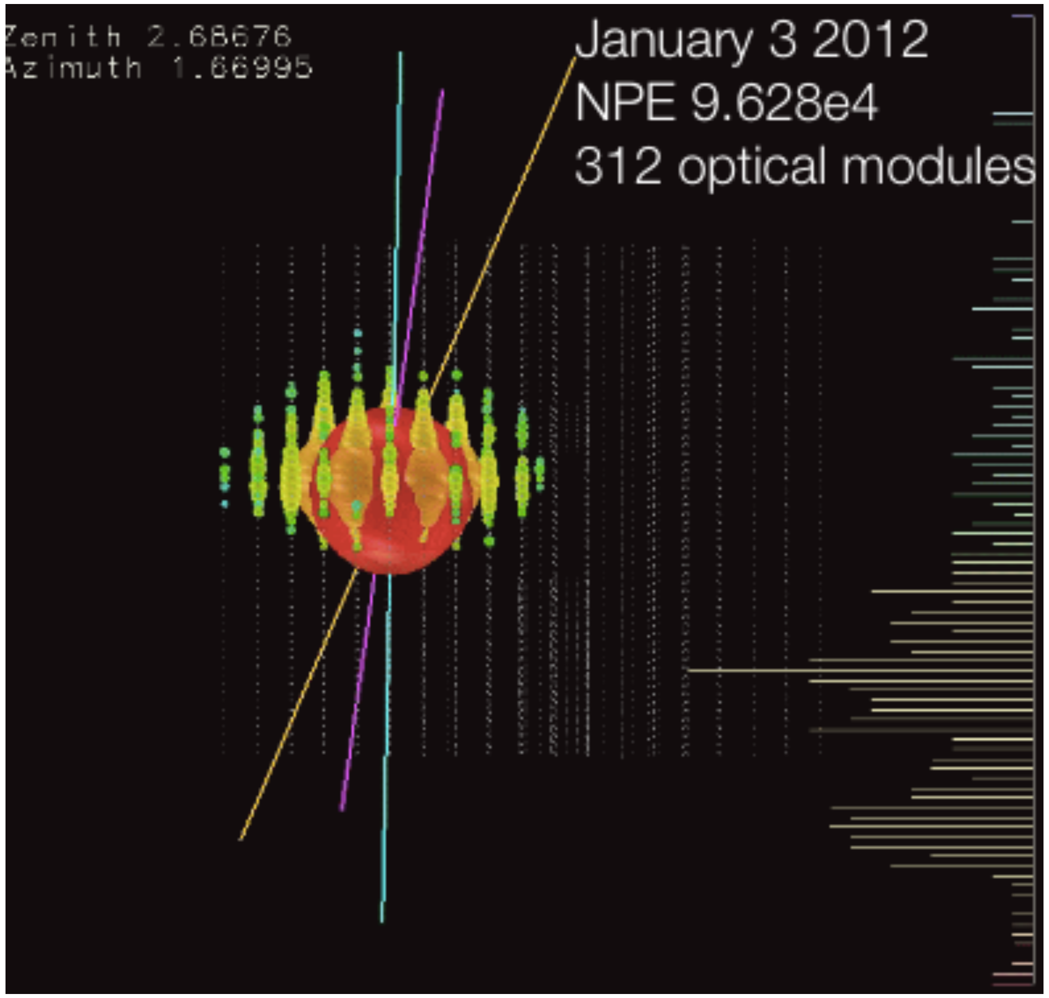
http://arxiv.org/abs/1304.5356 (accepted PRL)

*Yoshida and Teshima, Prog. Theor. Phys. 89, 833 (1993)

The IceCube ultra high energy neutrino search

- Fortunately, there is sometimes a bit of the unexpected in an analysis
    - Fitting tracks to spherical "cascade" events yields unpredictable results
    - Two down-going cascades reconstructed as upward tracks, sneaking into final muon sample





A PeV Neutrino near the Golden Gate Bridge

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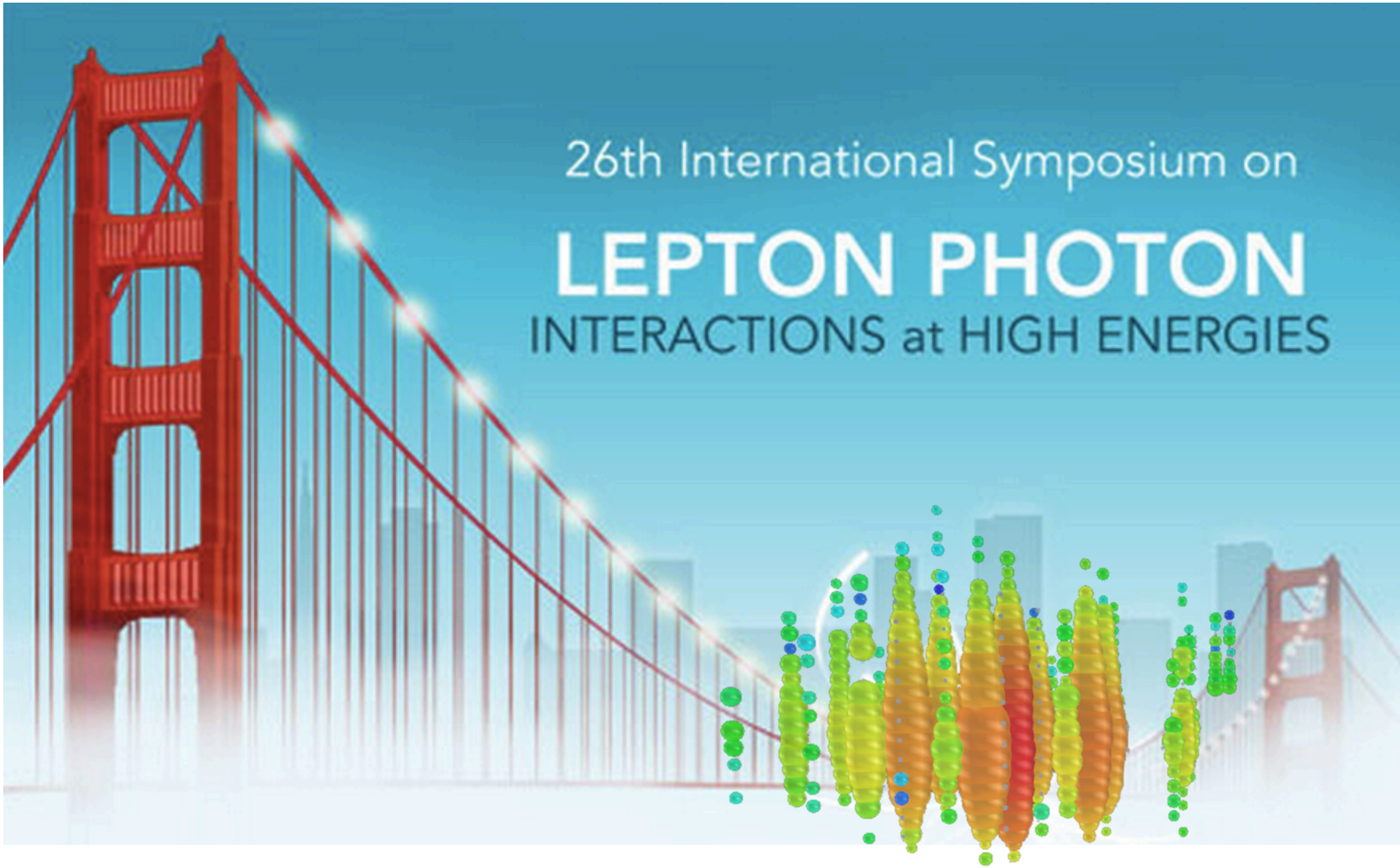

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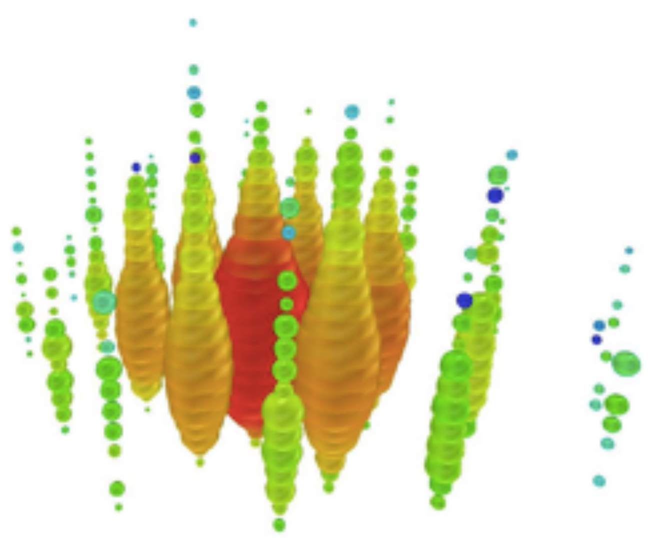
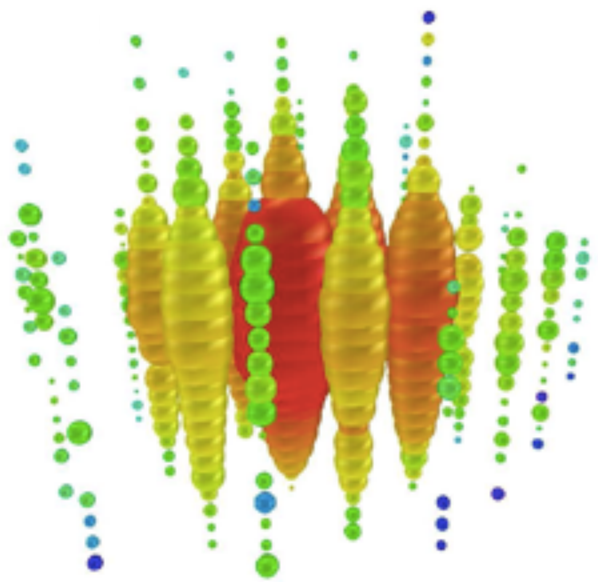
These 2 events were at the lower end of the energy sensitivity for the analysis. They were given names fitting for such giant high energy neutrinos...



1.14±0.17 PeV



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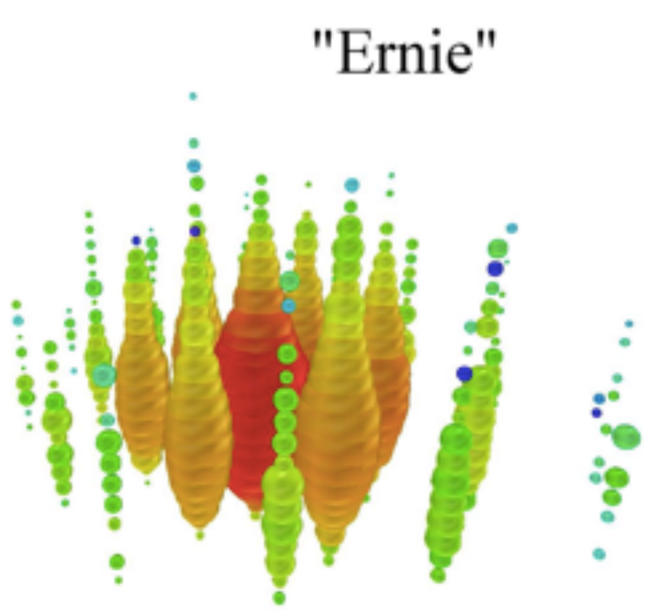

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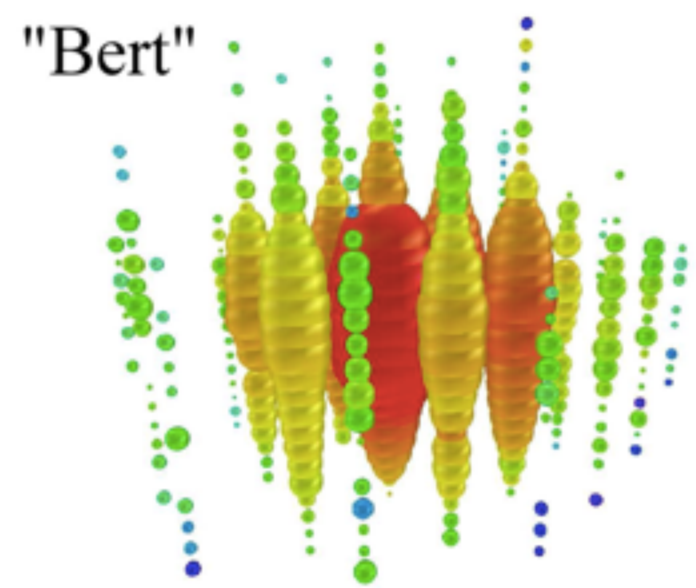

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The IceCube ultra high energy neutrino search

- The energy for the Bert and Ernie are too low to be GZK and too high to be atmospheric
- The spectrum may be broken; the flux for an E-2 spectrum should have produced 8-9 more events with energy greater than 1 PeV
- The p-value for the background only hypothesis is 2.9e-3 (2.8σ)

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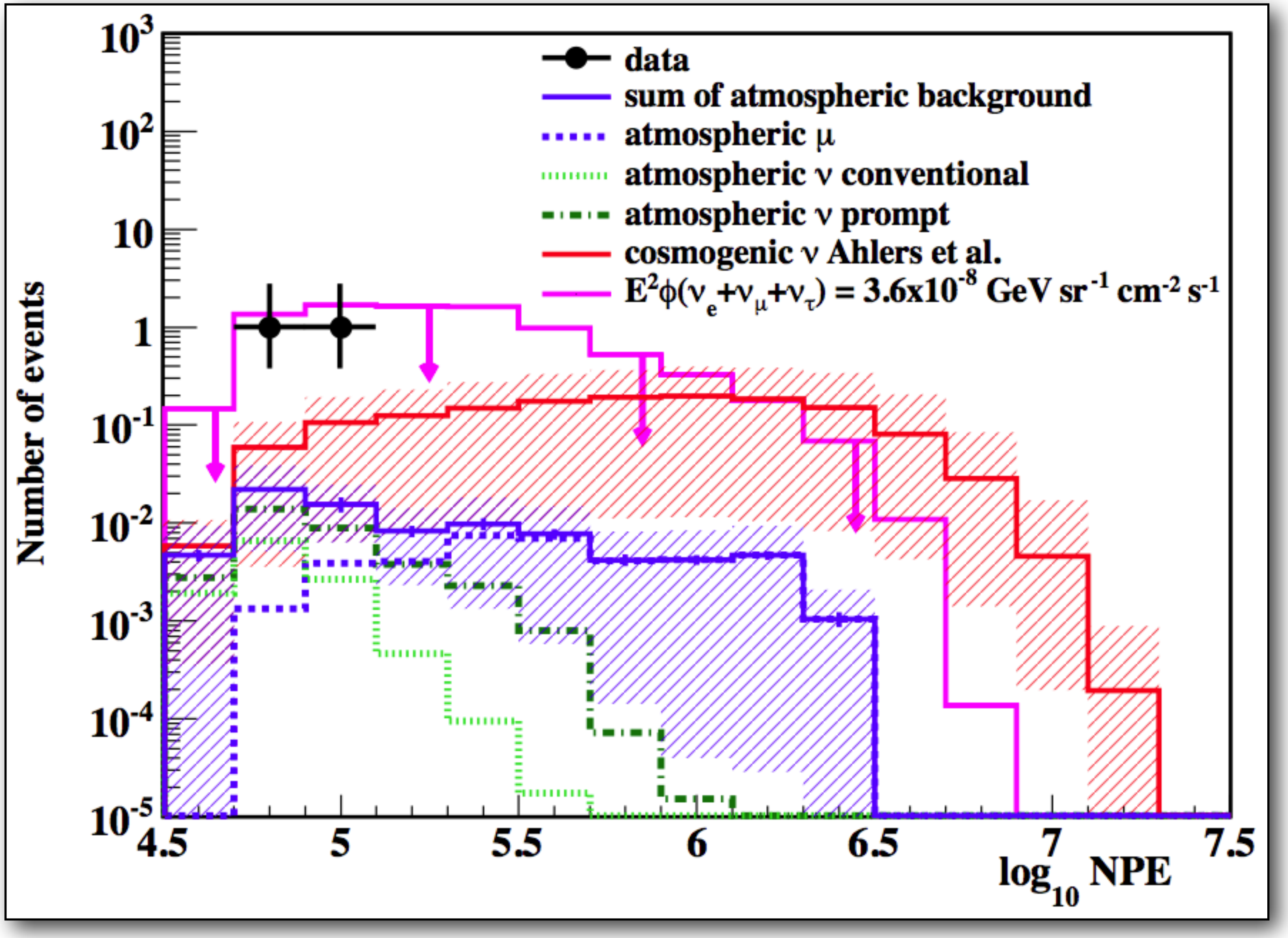

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- The spectrum may be broken; the flux for an E-2 spectrum should have produced 8-9 more events with energy greater than 1 PeV
- The p-value for the background only hypothesis is 2.9e-3 (2.8σ)
- stringent limits placed for the highest energies given lack of events

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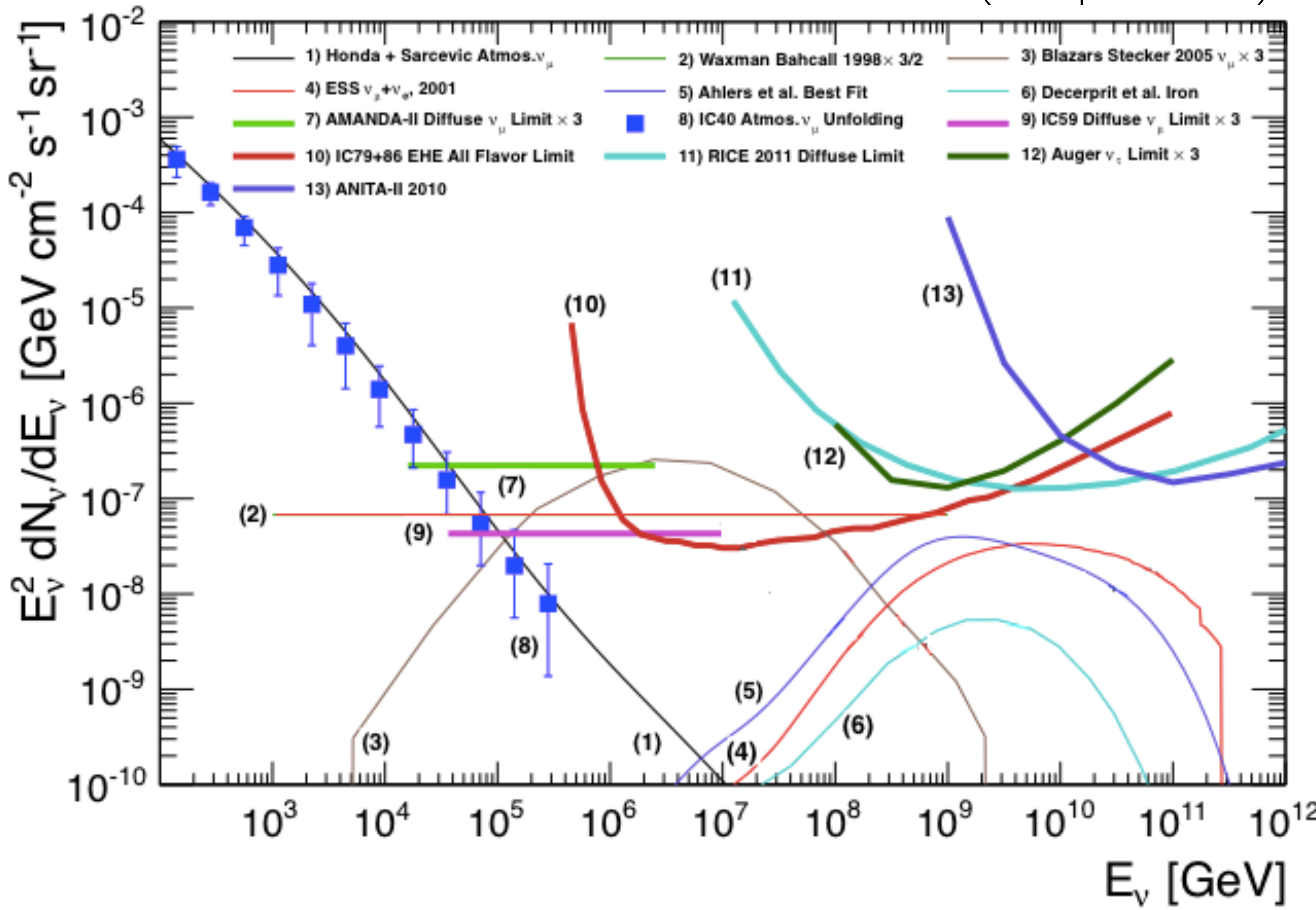
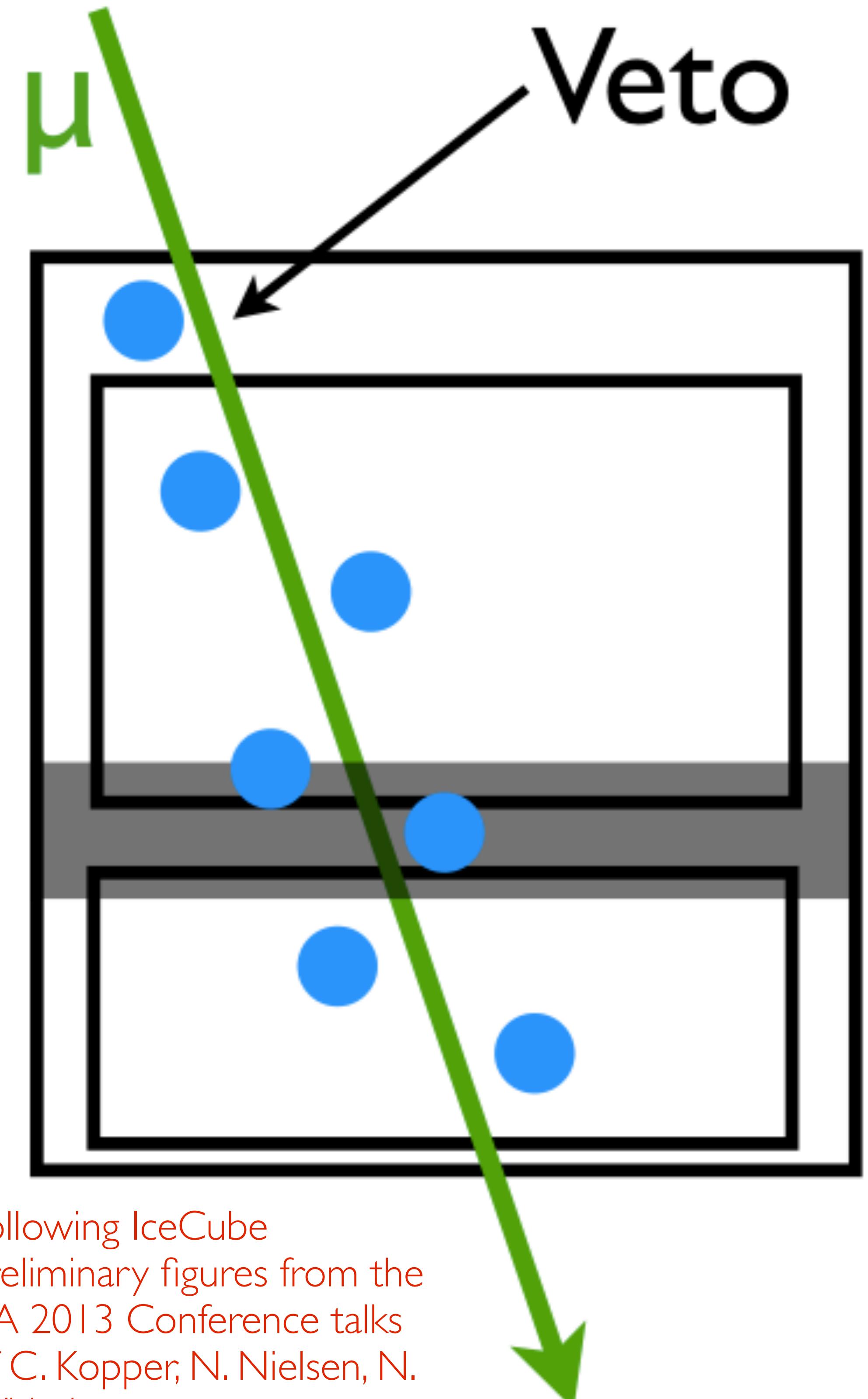


The next logical step...

- Extend the search to lower energies for the same 2 year dataset
  - the two observed were at the search lower acceptance window, and higher energies showed no events
  - previous IceCube analyses had hints for astrophysical neutrino events above 100 TeV at approximately 2σ
- Challenges with this approach:
  - at lower energies one is more susceptible to backgrounds; atmospheric neutrinos will be an irreducible source in the absence of a clear point source since they will not be fully absorbed ($\lambda_{abs.}$~d_{Earth} at E_{ν}~100 TeV)
  - these first 2 events were downward-going; if the source is above the horizon there is a background of 1e11 atmospheric muons per year potentially masking the signal

The IceCube high energy starting events analysis

- The solution is to identify starting events in the detector by applying an active veto to remove the down-going backgrounds:
  - atmospheric muons identified by using part of the detector in anti-coincidence; can estimate potential contamination by using subsequent detector regions to measure number of muons that evade the other veto layer (expect 6 ± 3.4 energetic muons in 2 years)
  - atmospheric neutrinos: starting outside the detector see above; starting inside the detector tag with a parent atmospheric muon (expect 4.6 +2.9/-1.9 events in 2 years)



Following IceCube preliminary figures from the IPA 2013 Conference talks of C. Kopper, N. Nielsen, N. Whitehorn

The IceCube high energy starting events analysis

The result of the search...

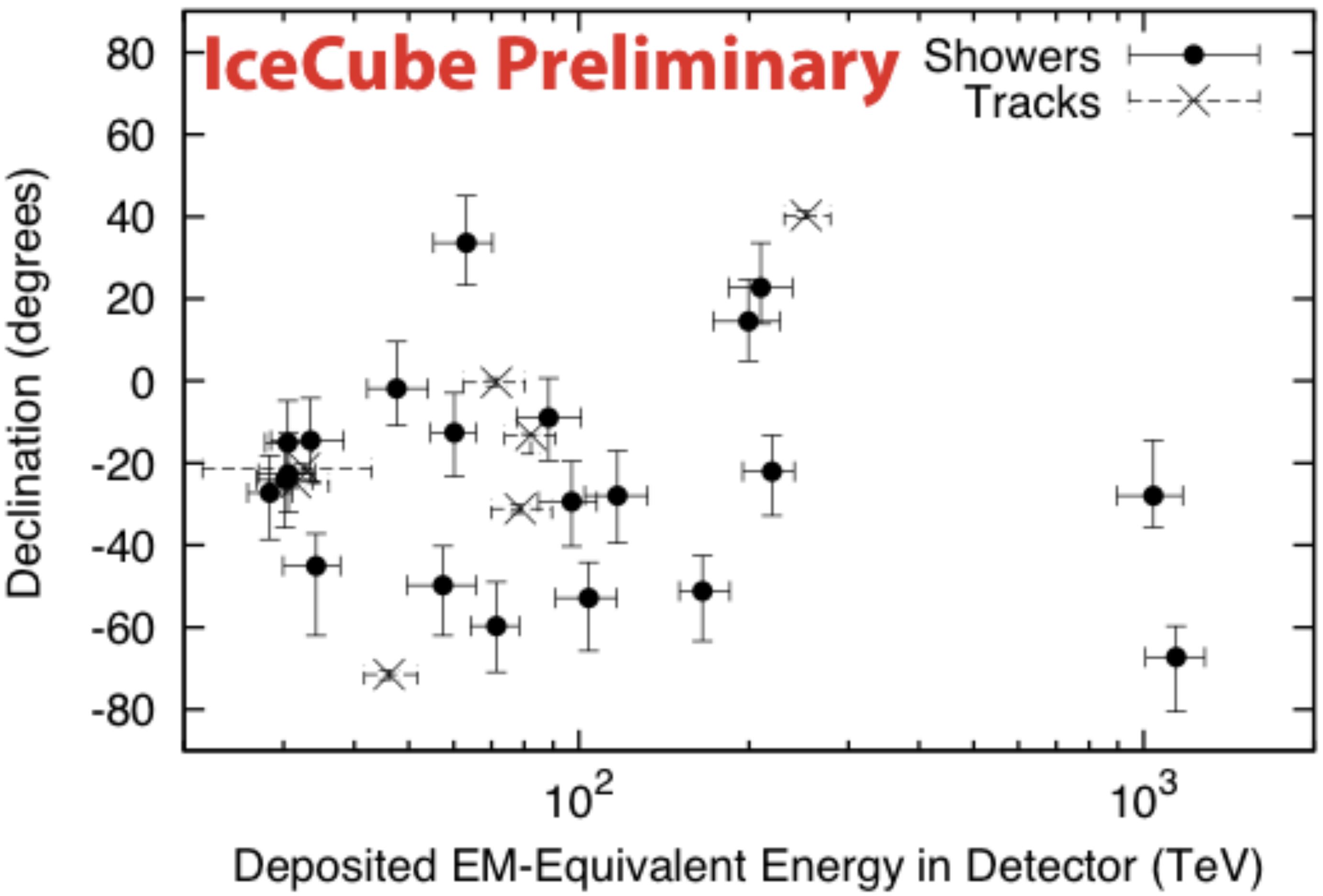
The IceCube high energy starting events analysis

The result of the search... 28 events! (each named after a Muppet; shown in order of appearance)

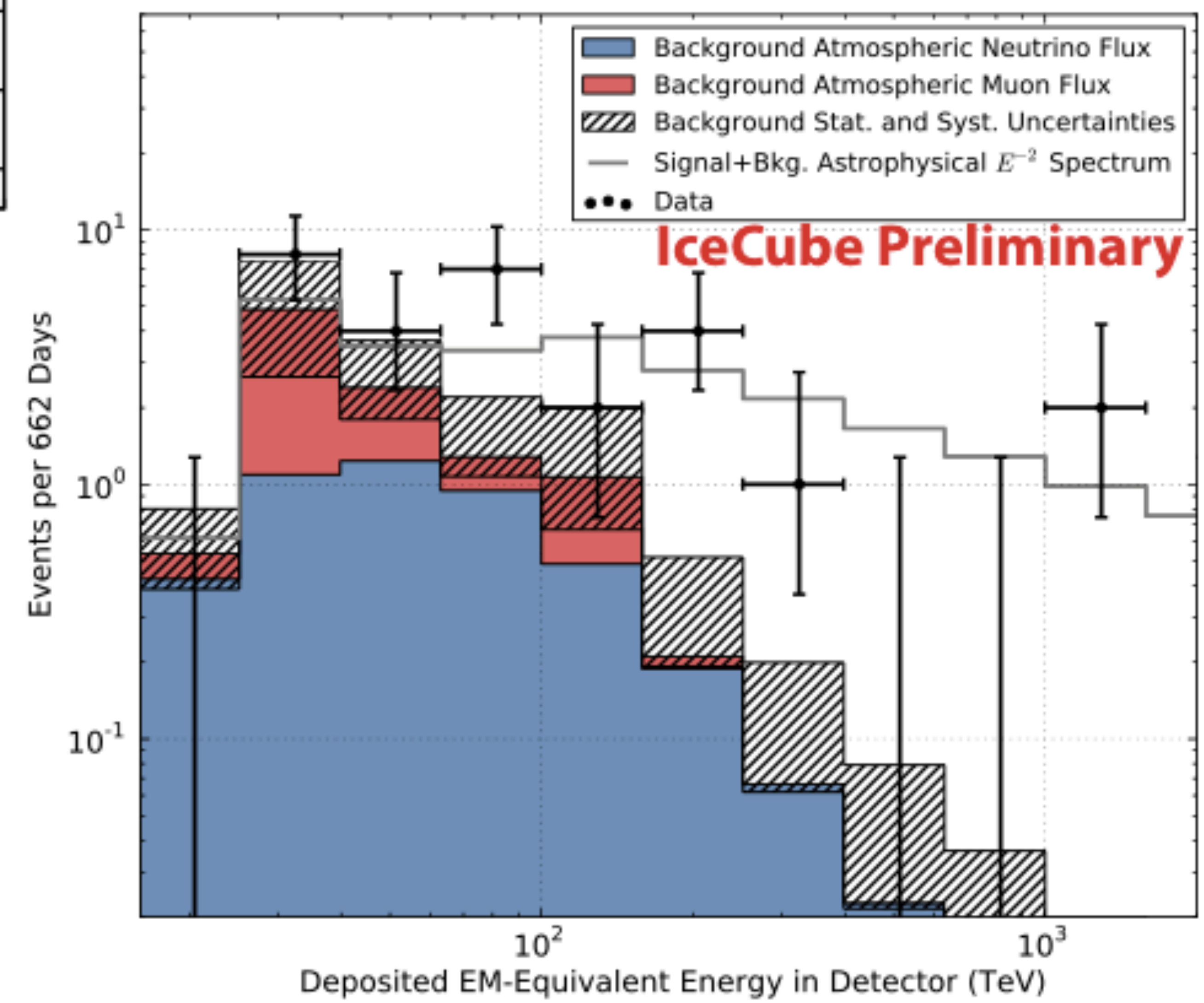
The IceCube high energy starting events analysis

- Details of the 28 events:
  - energies range from 30 TeV and 1.1 PeV
  - 24 were downward; 4 upward
  - 7 have a visible muon in the event; 4 are consistent with down-going muons including 1 with hits in the IceTop surface array
  - Expected background, including prompt charm production, is 12.1 ± 3.4 events. Signal is inconsistent with this background at 4.3σ (2.8σ sigma Bert and Ernie alone; 3.6σ the other 26 Muppets alone)
- For an all-flavor flux:
  - $E^2\Phi(E) = (3.6 \pm 1.2) \times 10^{-8}$ GeV/(cm^2 s sr)
  - E_{cutoff} = 1.6(+1.5, -0.4) PeV

The IceCube high energy starting events analysis

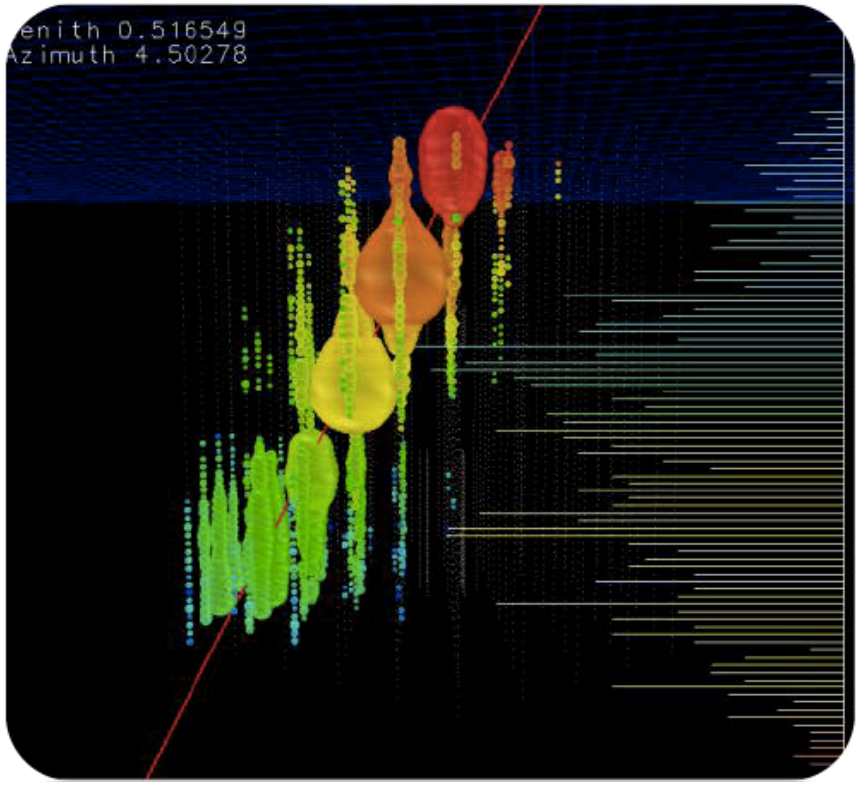


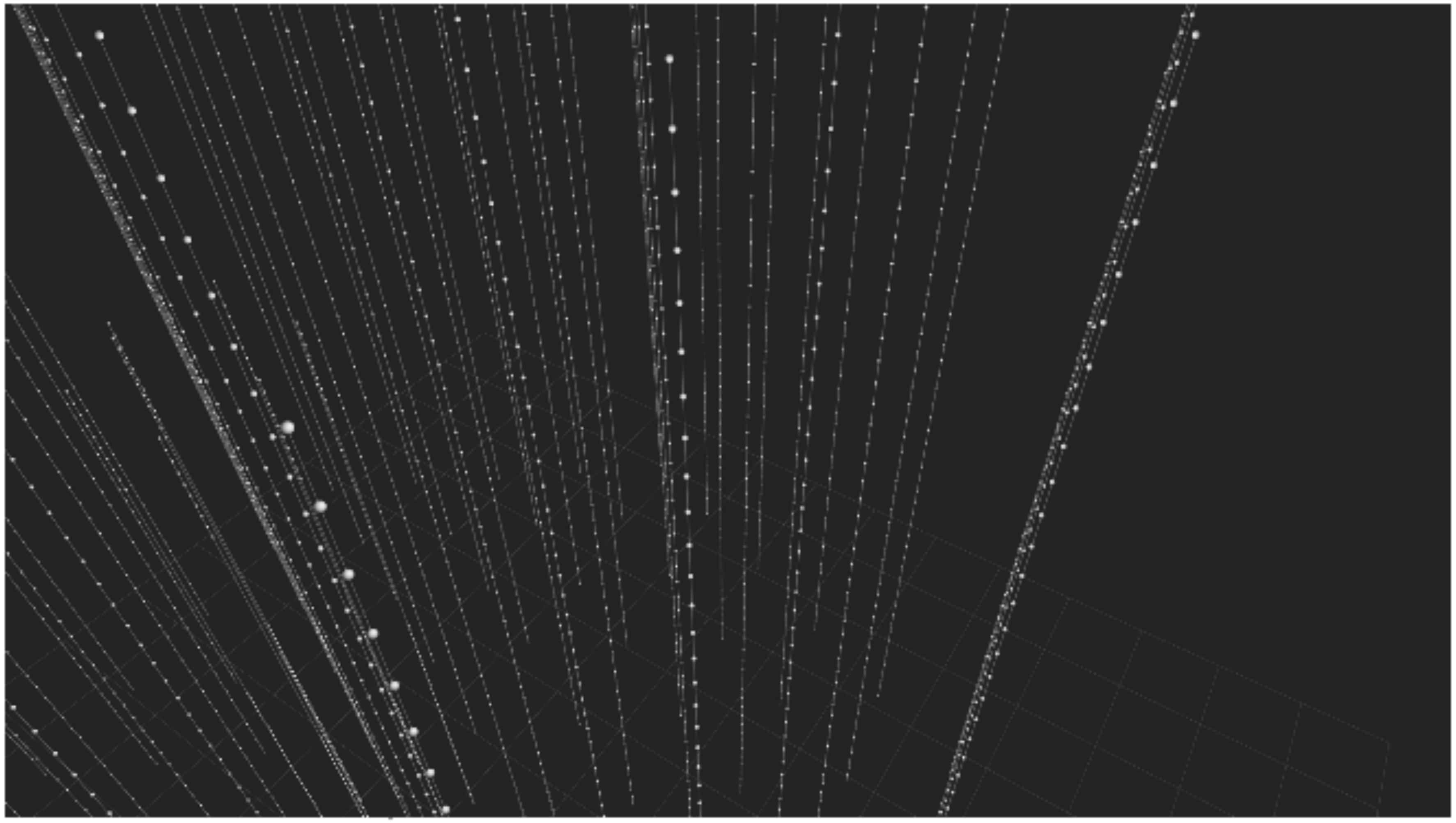
Note:
a) "EM-equivalent energy" underestimates the E of ν_x NC and ν_τ CC interactions
b) Energy gap is not statistically significant
c) For showers σ(E)~10% & $\sigma(\varphi)$~10°-15°



The IceCube high energy starting events analysis

- Angular reconstruction of the events:
  - muons are fairly straightforward (energetic events provide long tracks with a large lever arm)
  - cascades can be more challenging since their light distribution appears spherical (arrival time of the photoelectrons in the PMT waveform can be used to obtain direction)





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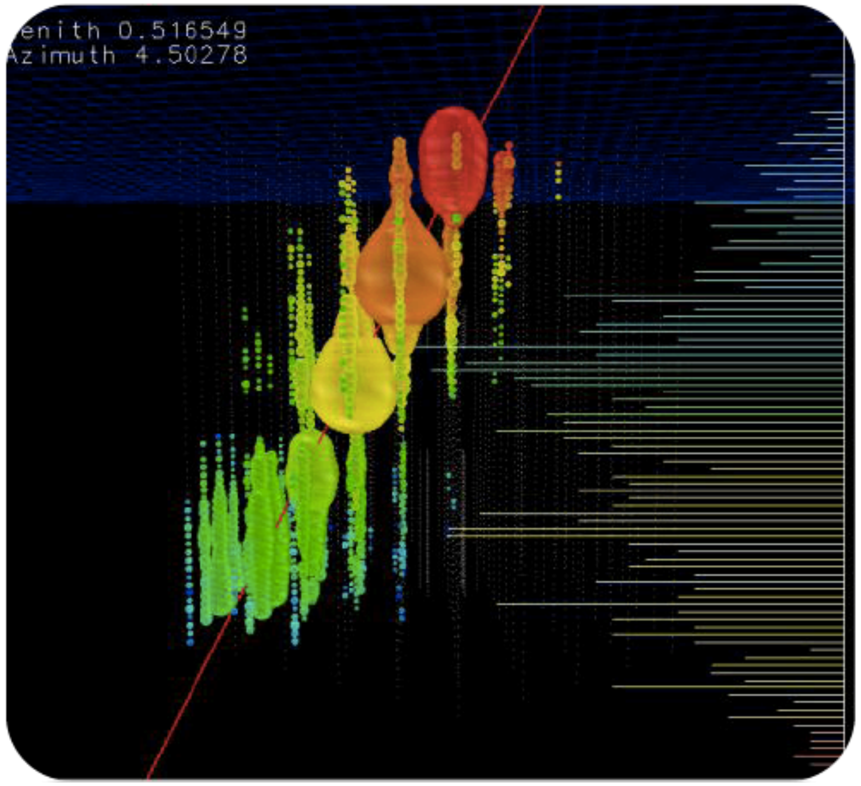

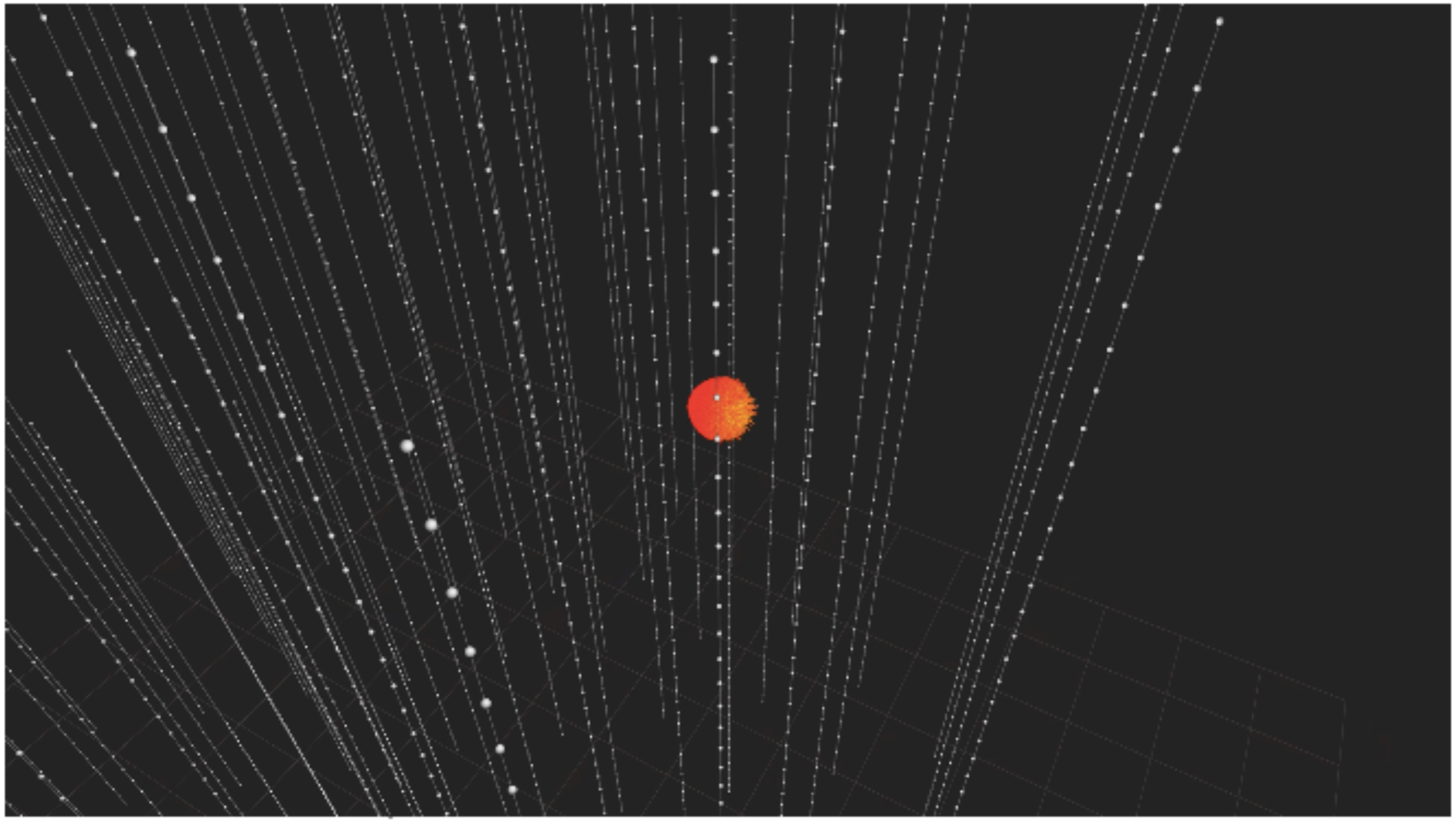

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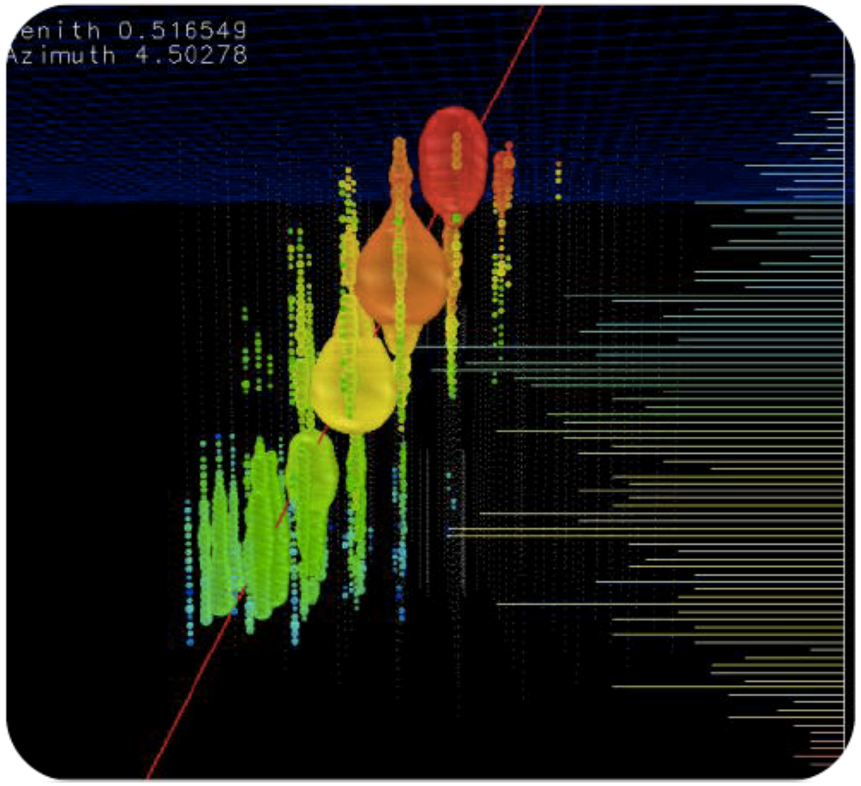

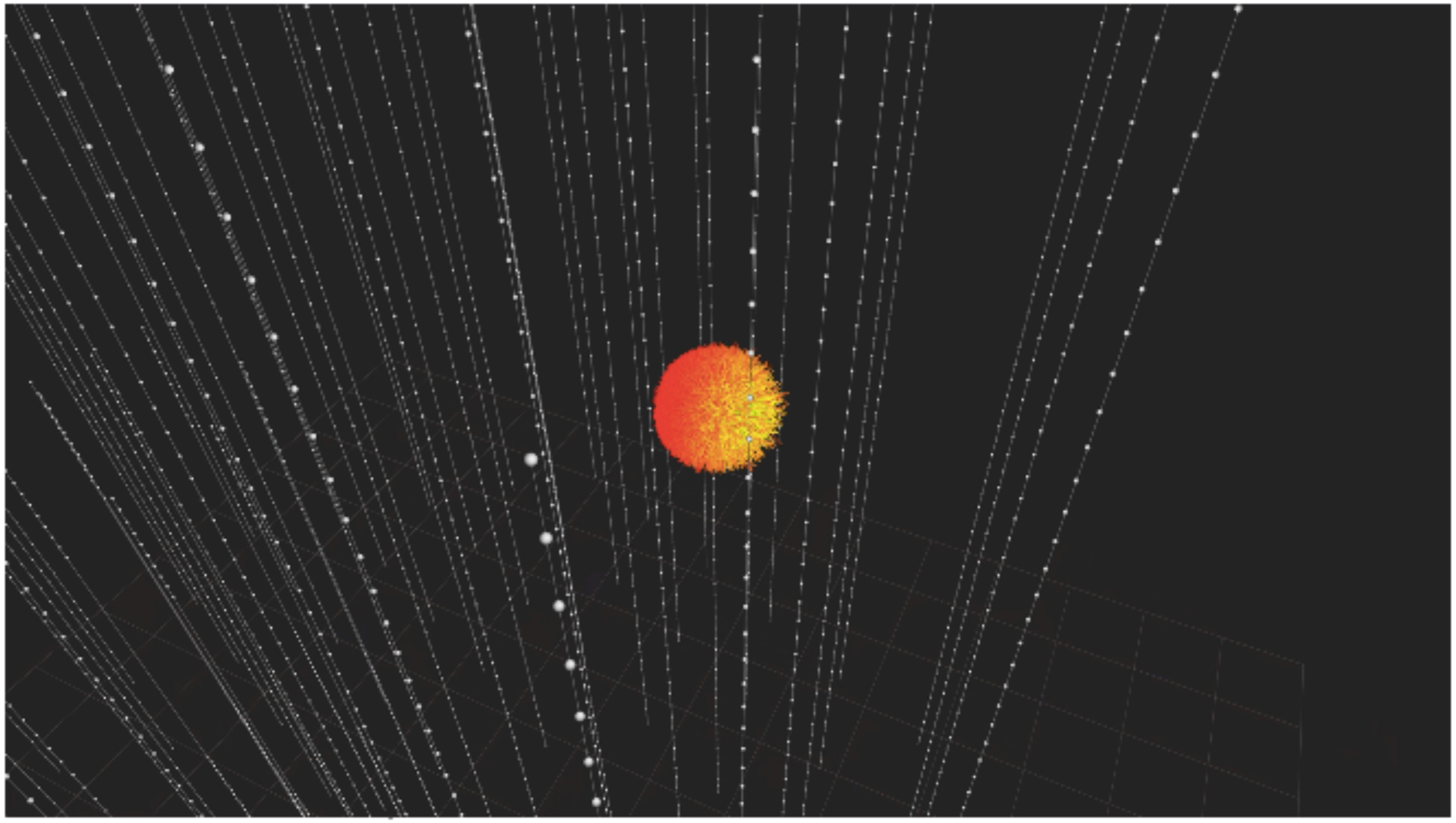

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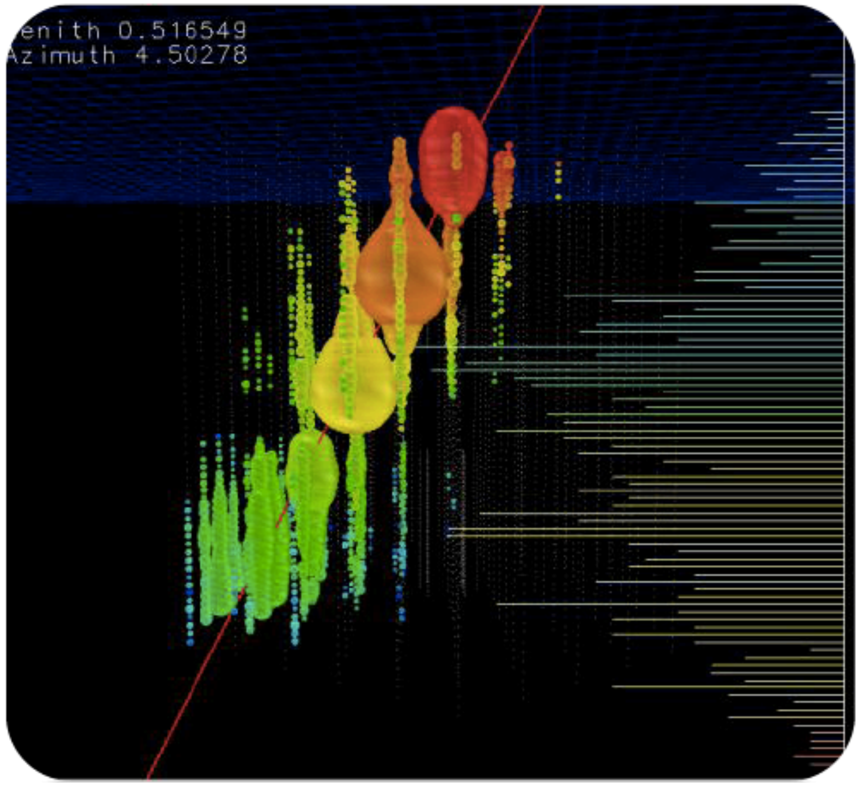

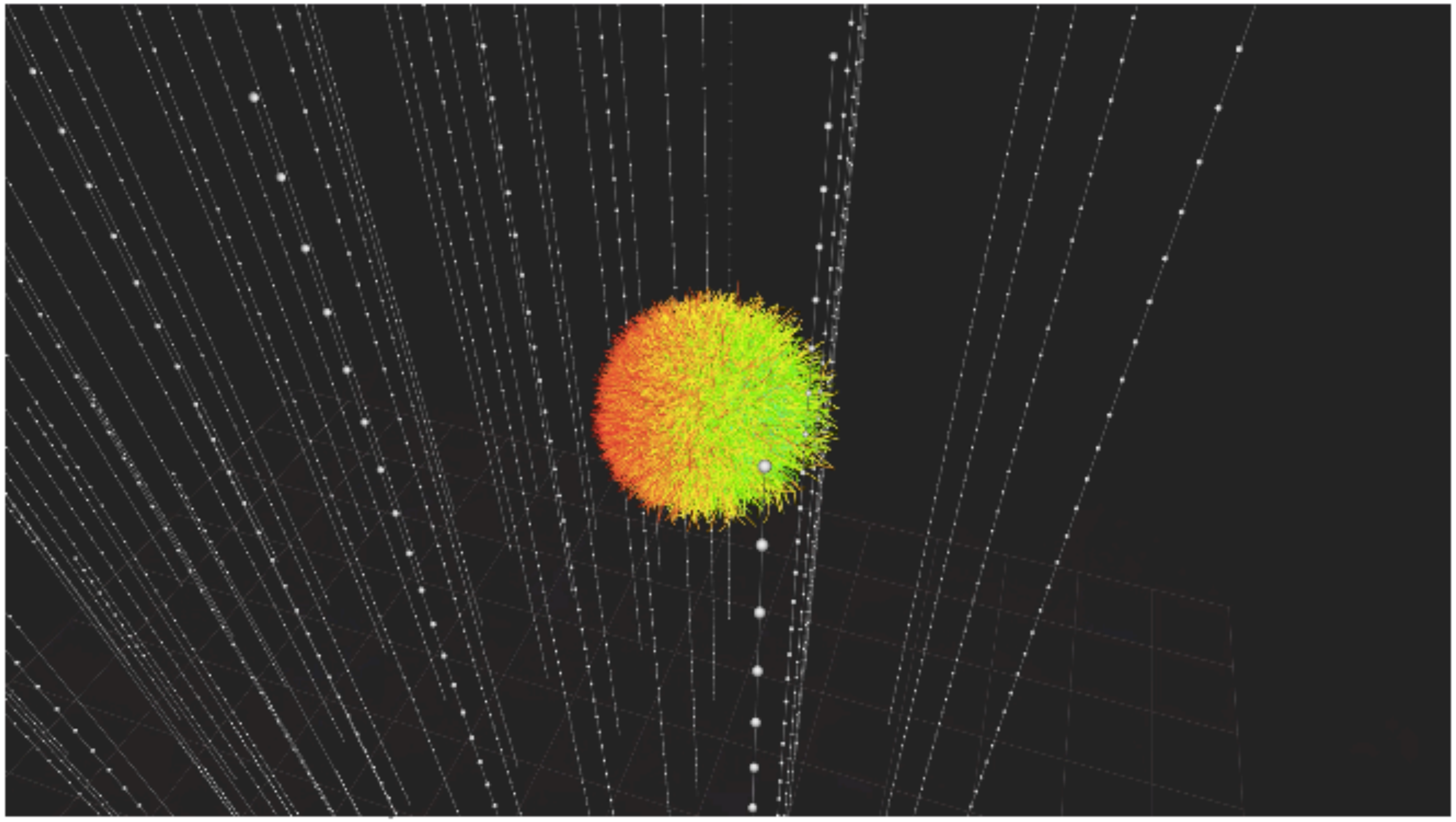

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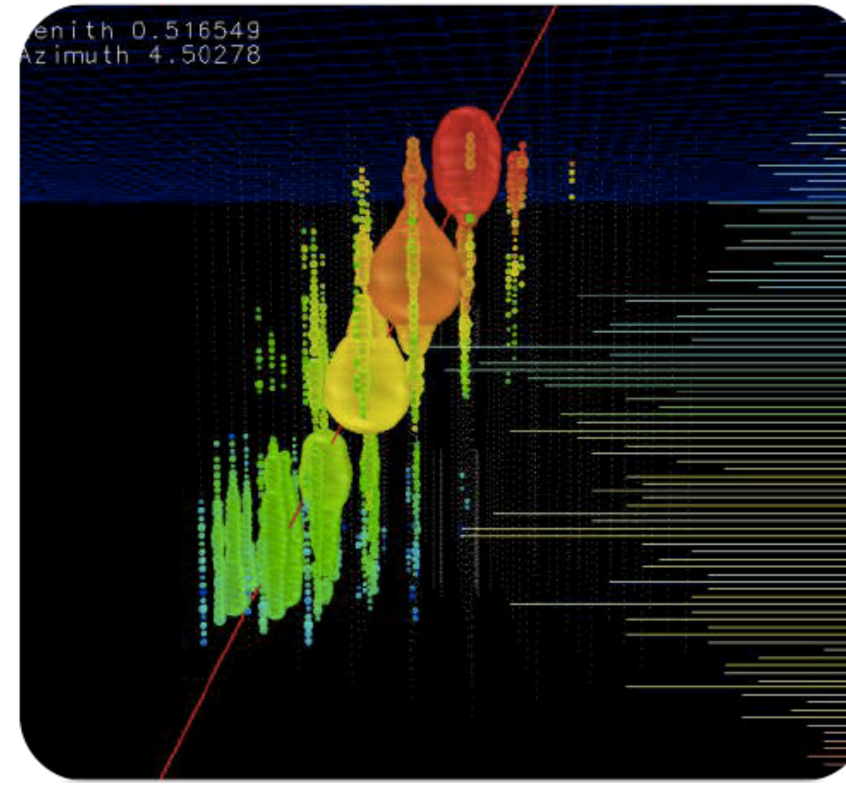
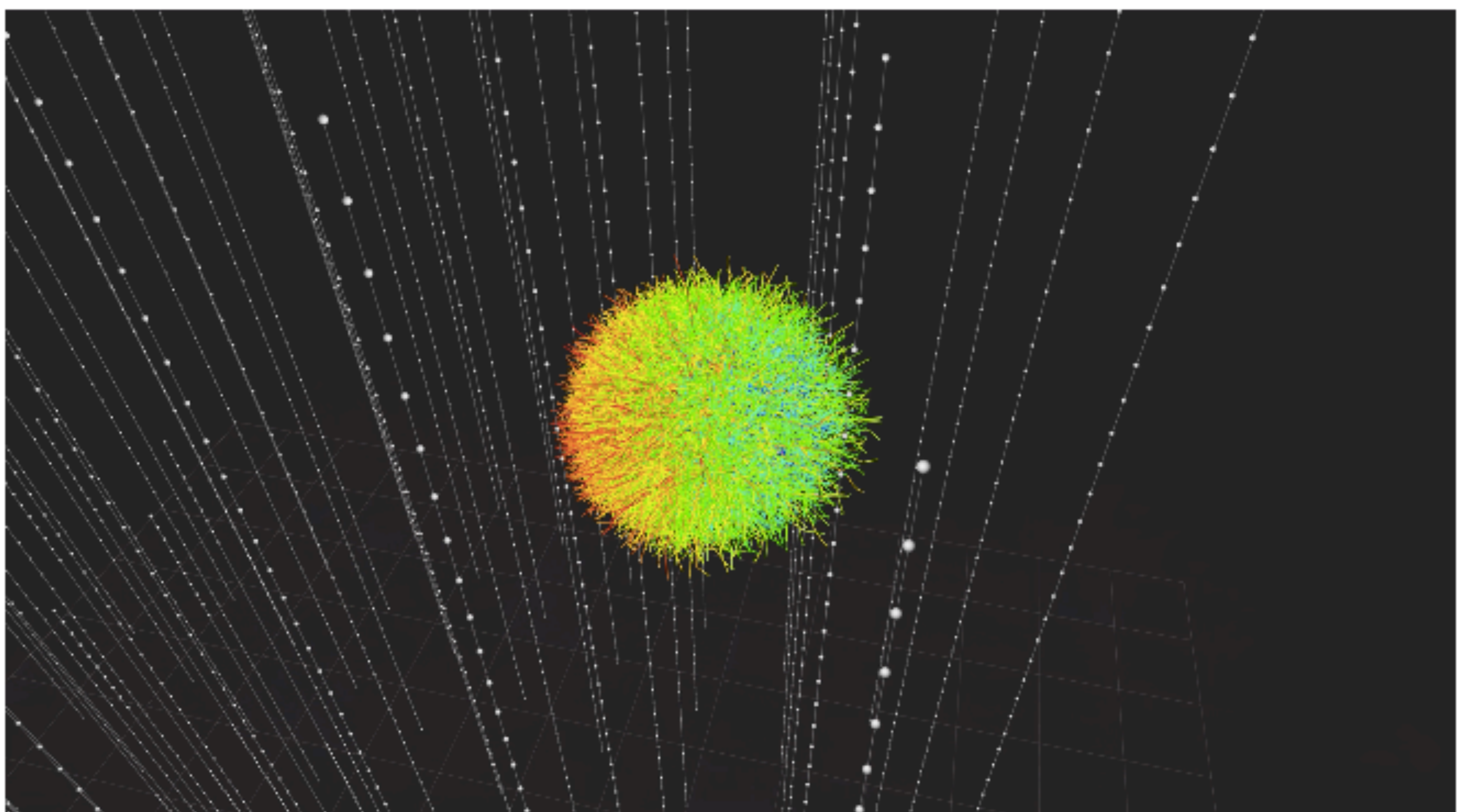
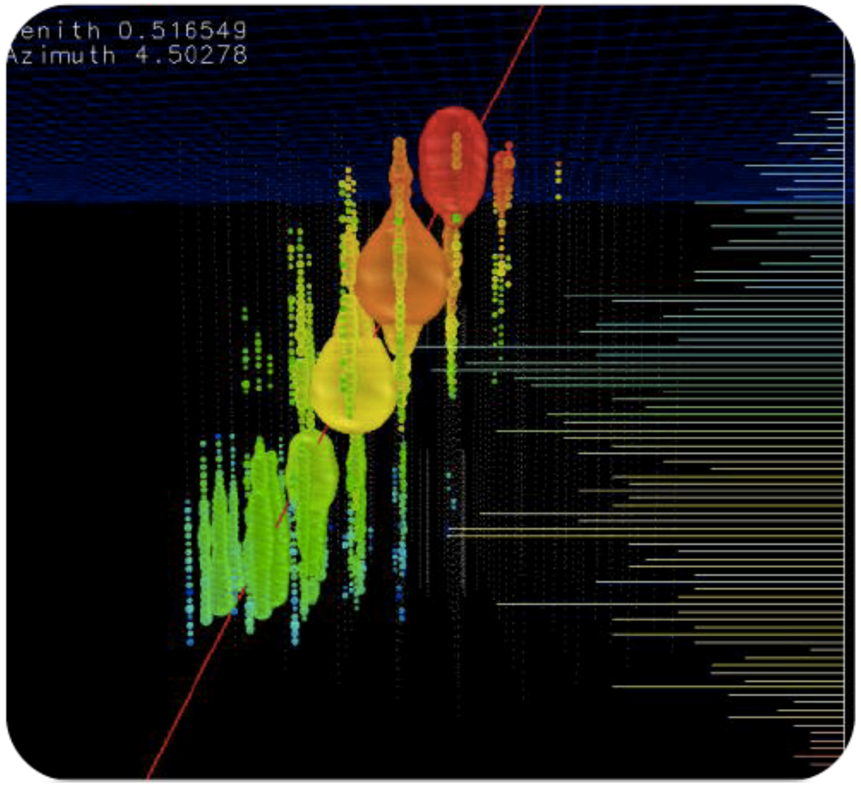
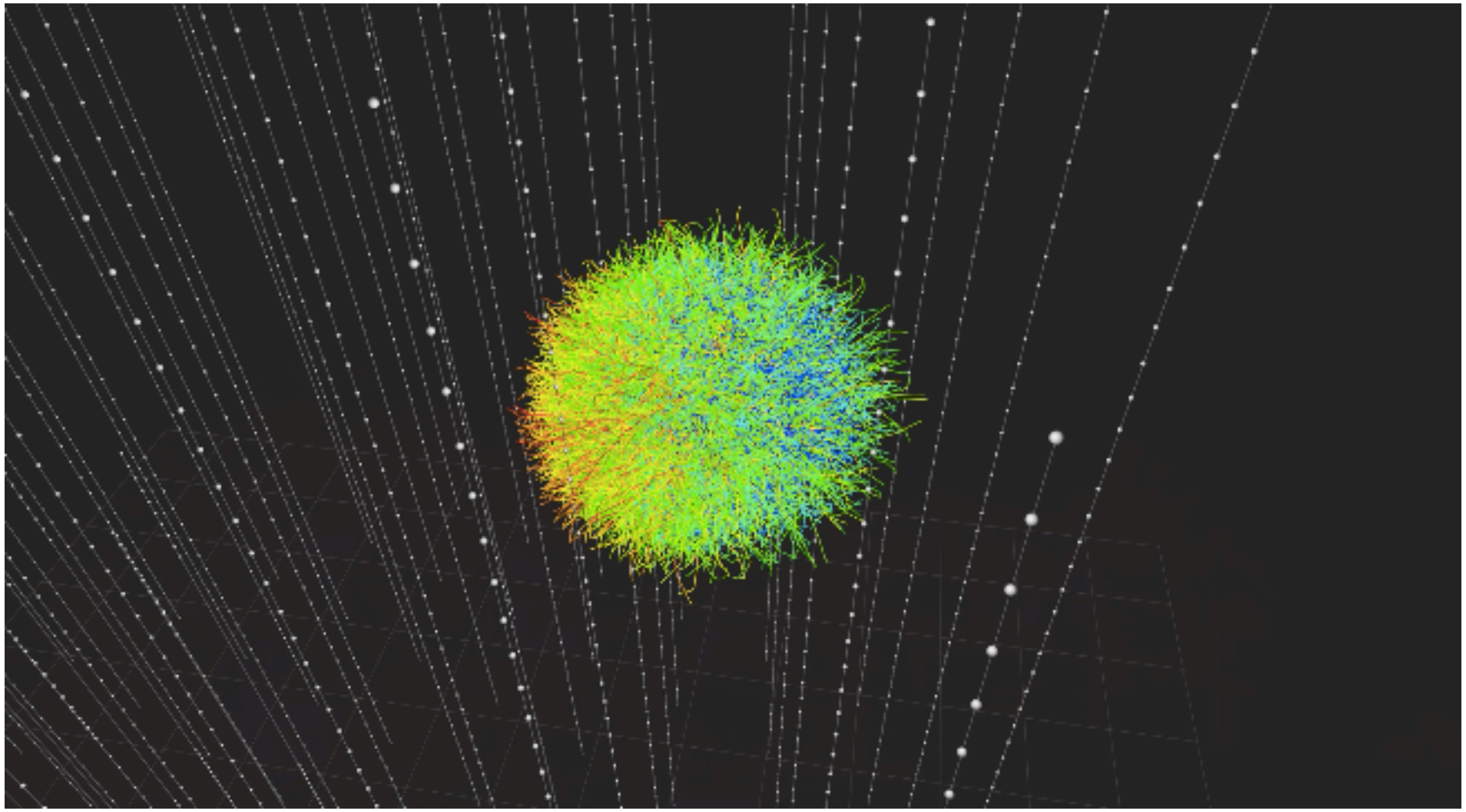




The IceCube high energy starting events analysis

- Angular reconstruction of the events:
  - muons are fairly straightforward (energetic events provide long tracks with a large lever arm)
  - cascades can be more challenging since their light distribution appears spherical (arrival time of the photoelectrons in the PMT waveform can be used to obtain direction)





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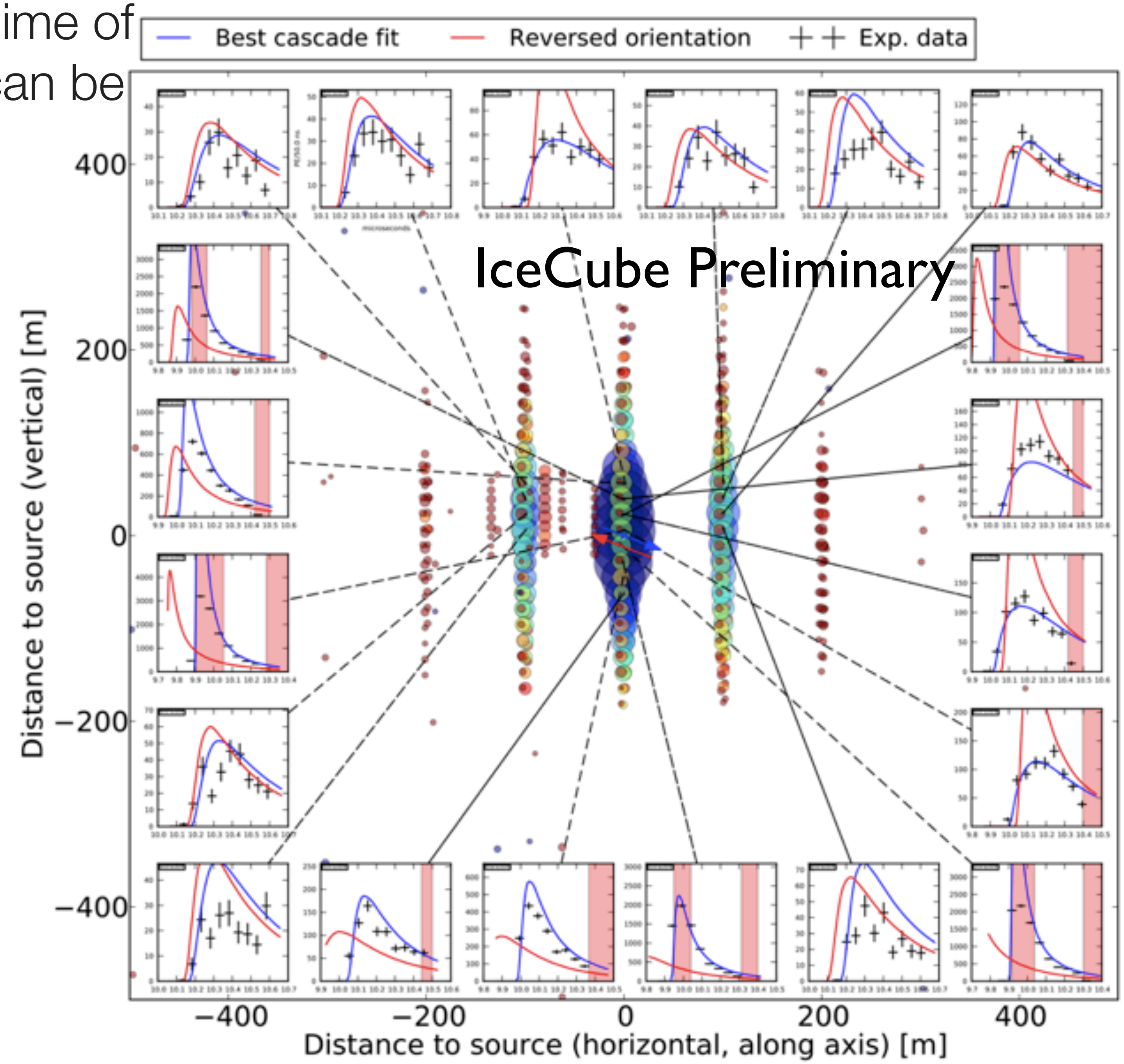
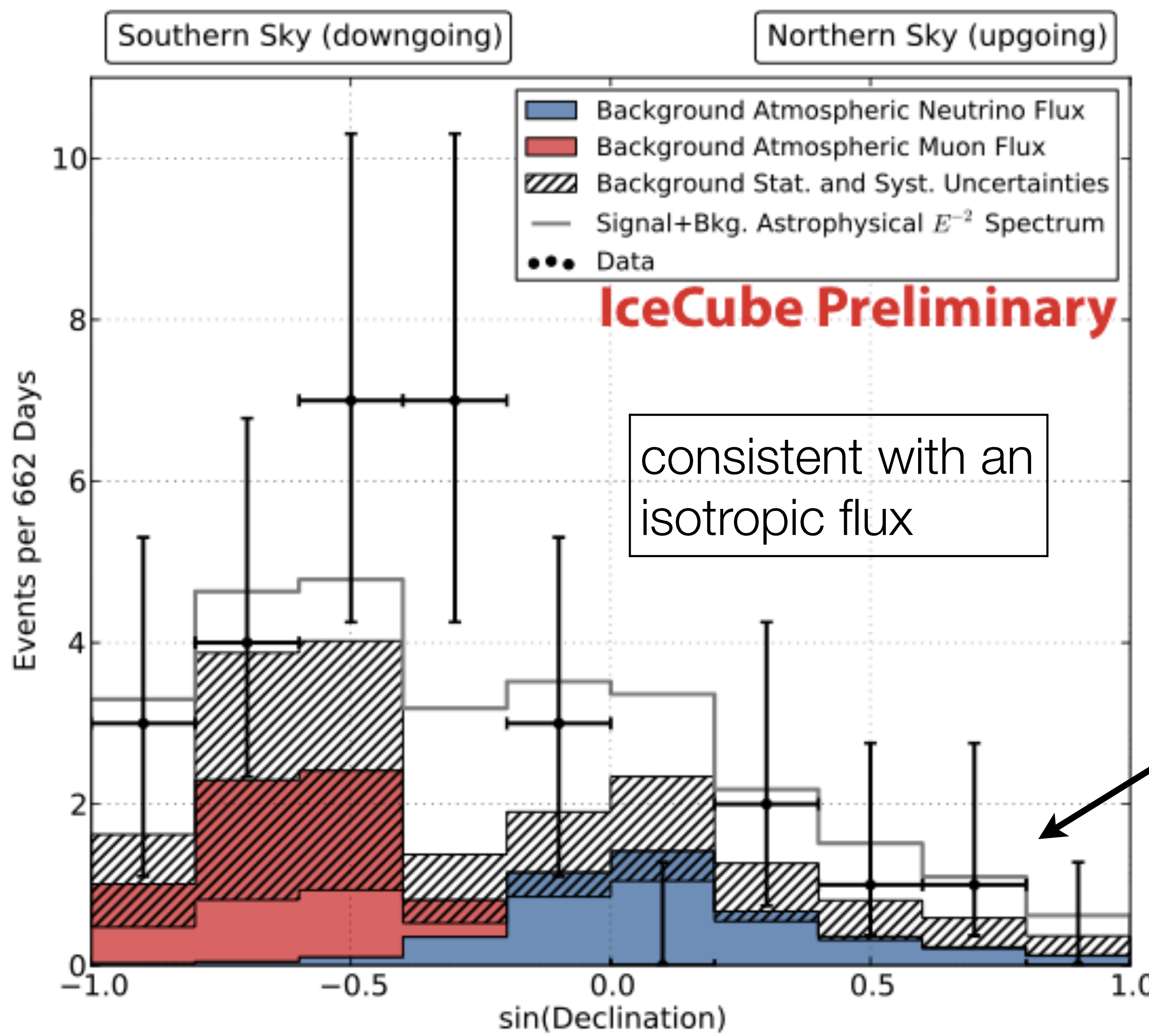


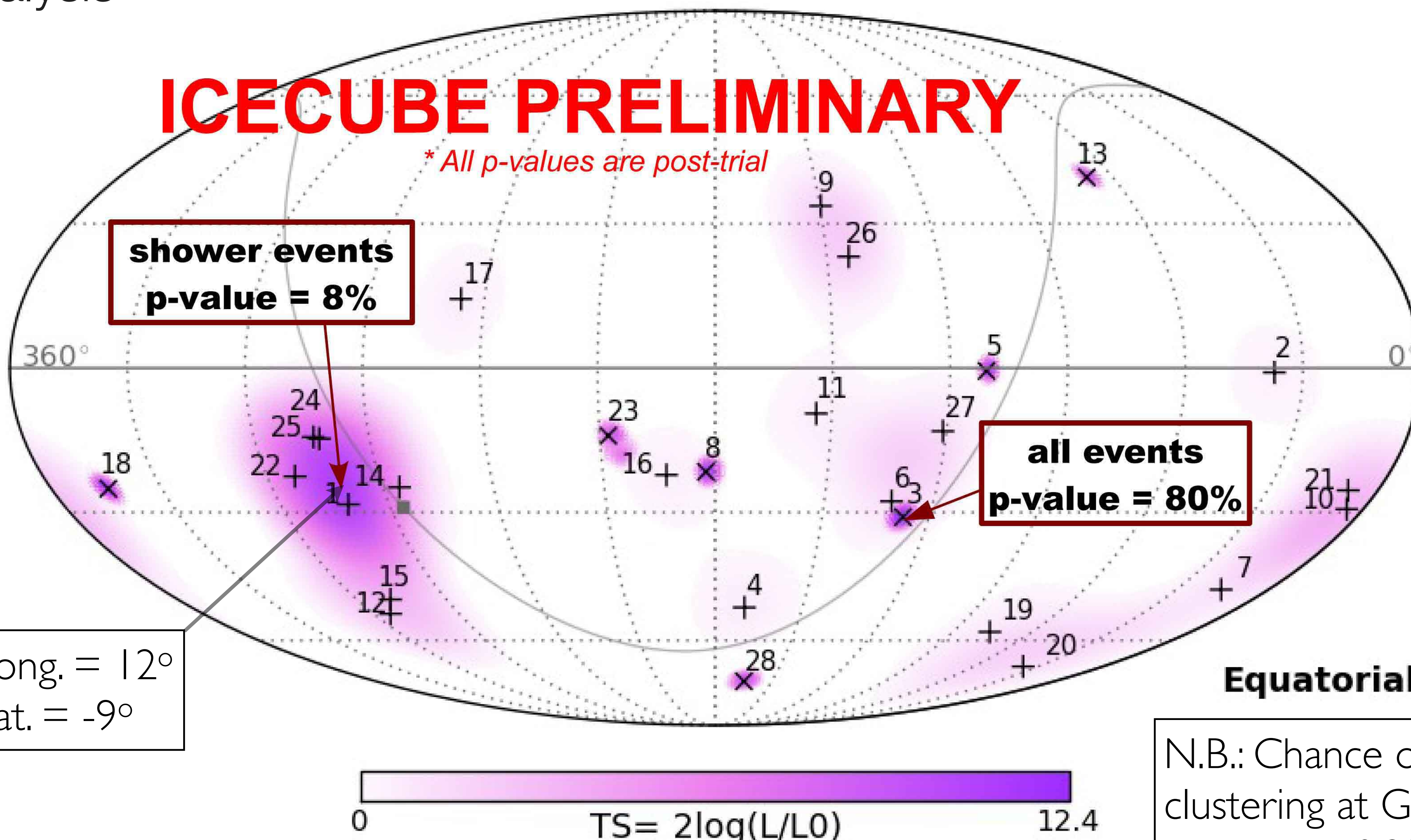
The IceCube high energy starting events analysis



At these energies events here are absorbed

The IceCube high energy starting events analysis

- Skymap: no significant clustering of events in space (or time); GRB coincidence search underway and another year of full detector data under analysis

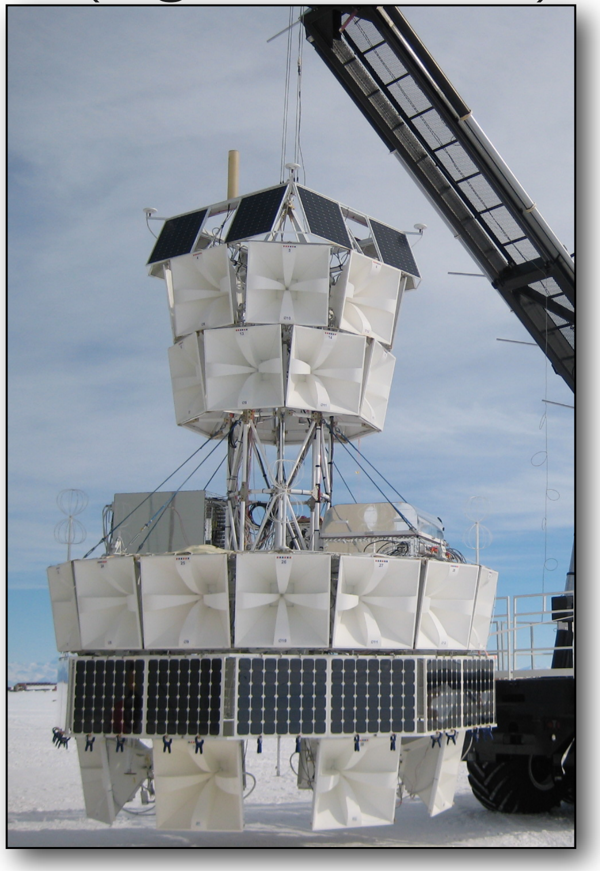


Galactic long. = 12°
Galactic lat. = -9°

N.B.: Chance of background clustering at G.C. < 5.4%; at exact spot 0.2%

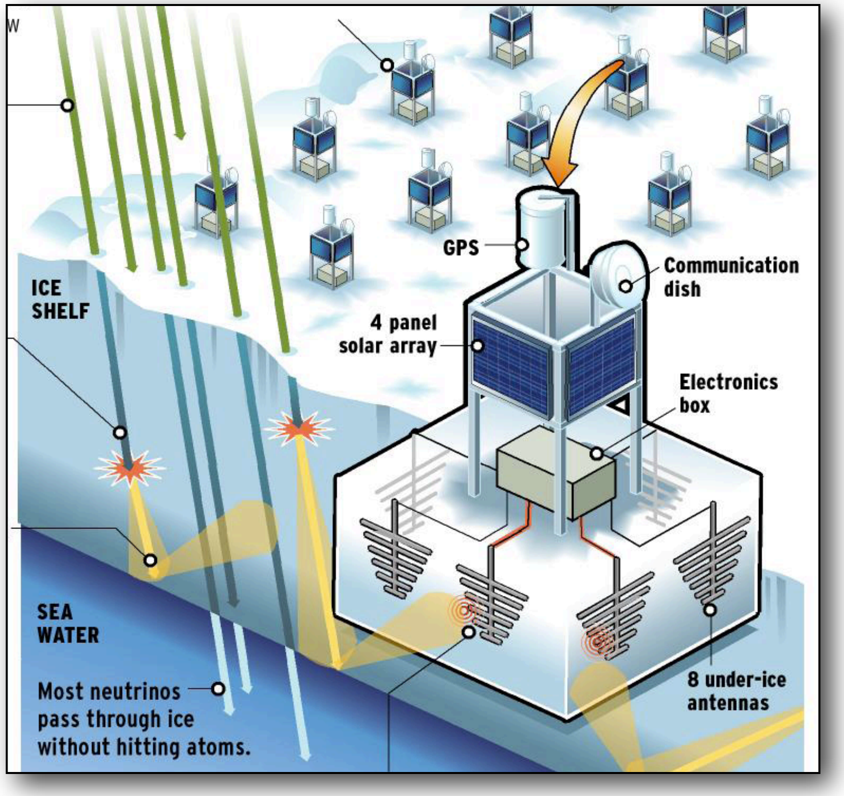
Future neutrino detectors: Askaryan radio pulses

- ANITA III (flight 2013/14)



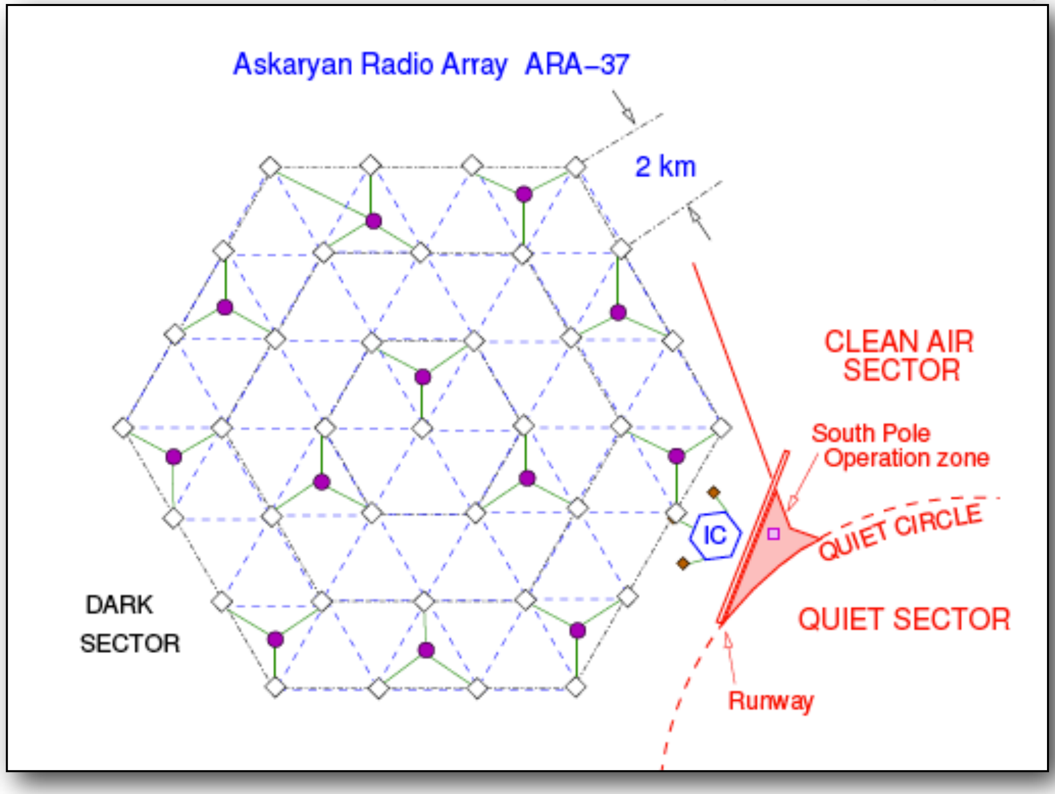
- ARIANNA, ARA (prototype phase)

arXiv:1207.3846



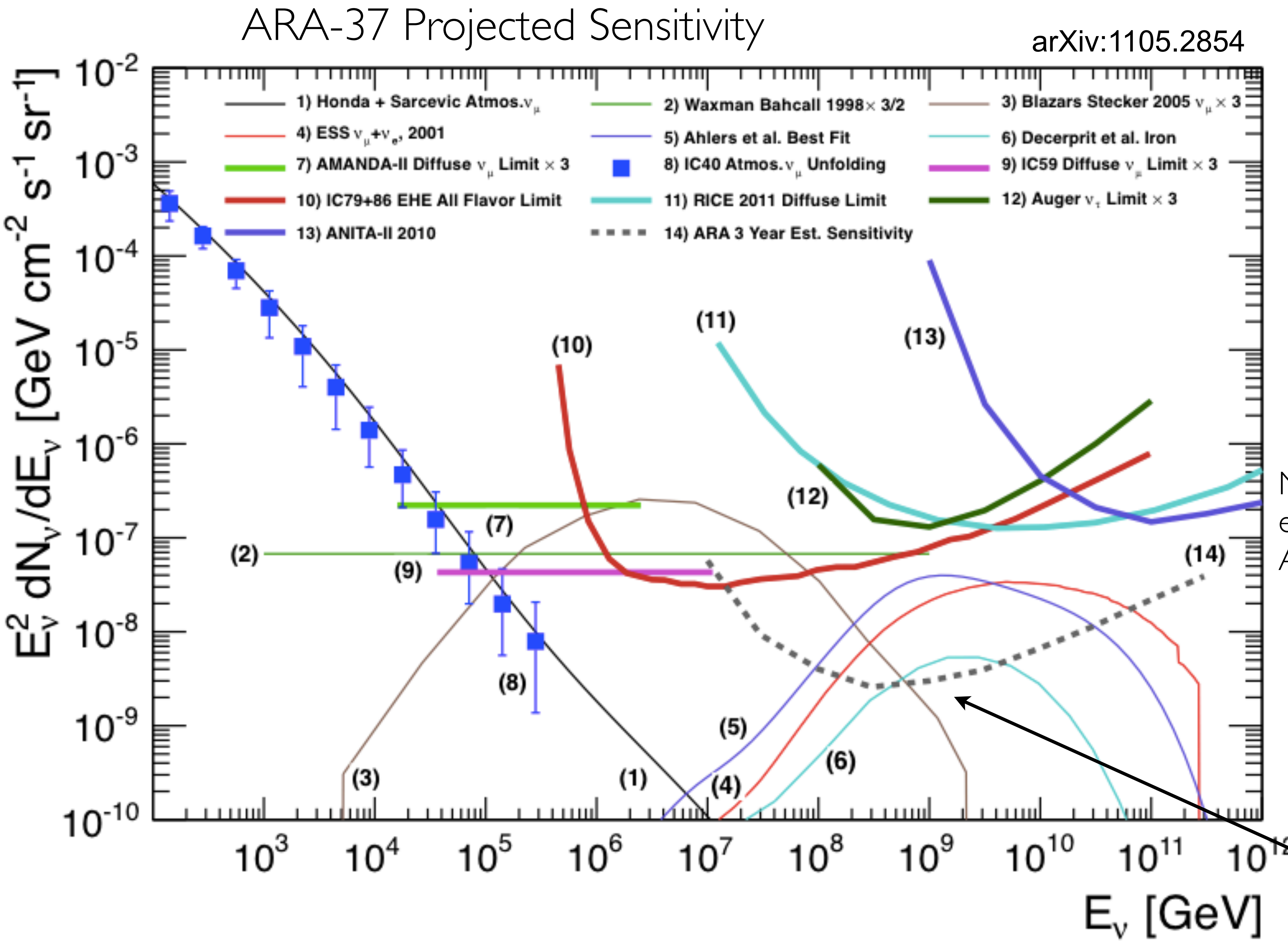
ARIANNA (Ross Ice Shelf, Antarctica) - 4 stations in operation, 3 additional in preparation

Astropart. Phys. (2011)



ARA (South Pole) - 3 stations operating; 4 additional planned in 2013/14

Future neutrino detectors: Askaryan radio pulses



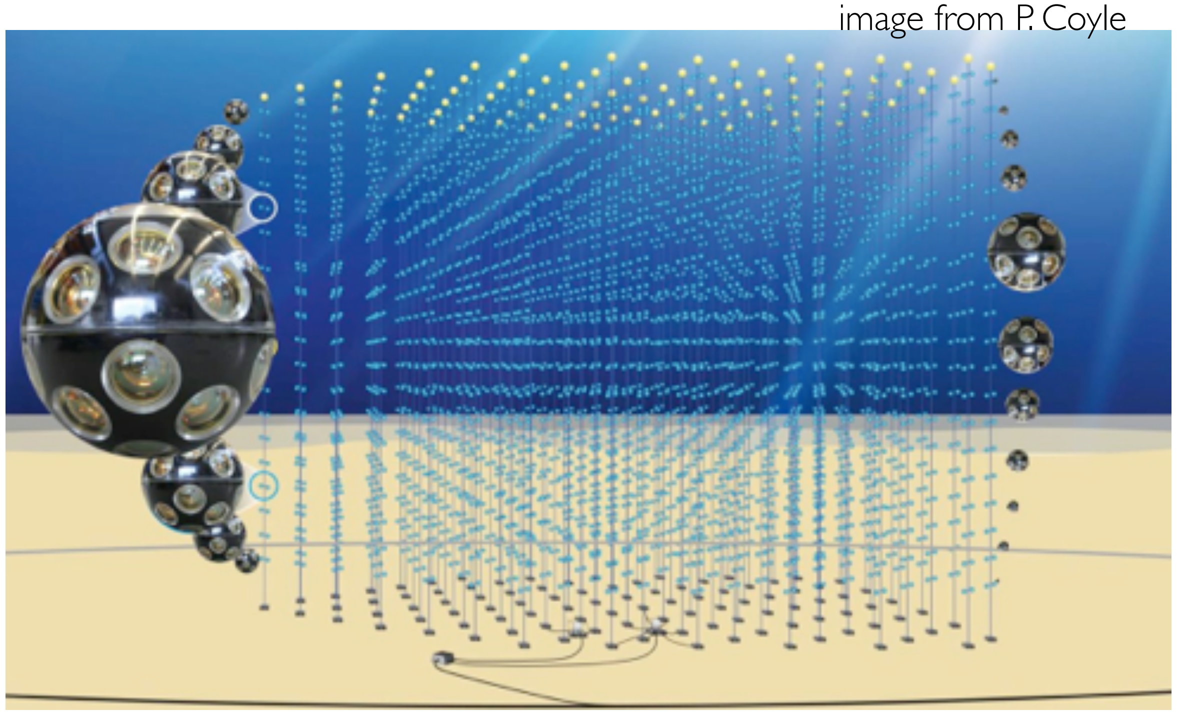
Note: ANITA-III (2013/14) expected 5x better than ANITA-II

Goal is to reach the "guaranteed" neutrino signal from the GZK effect

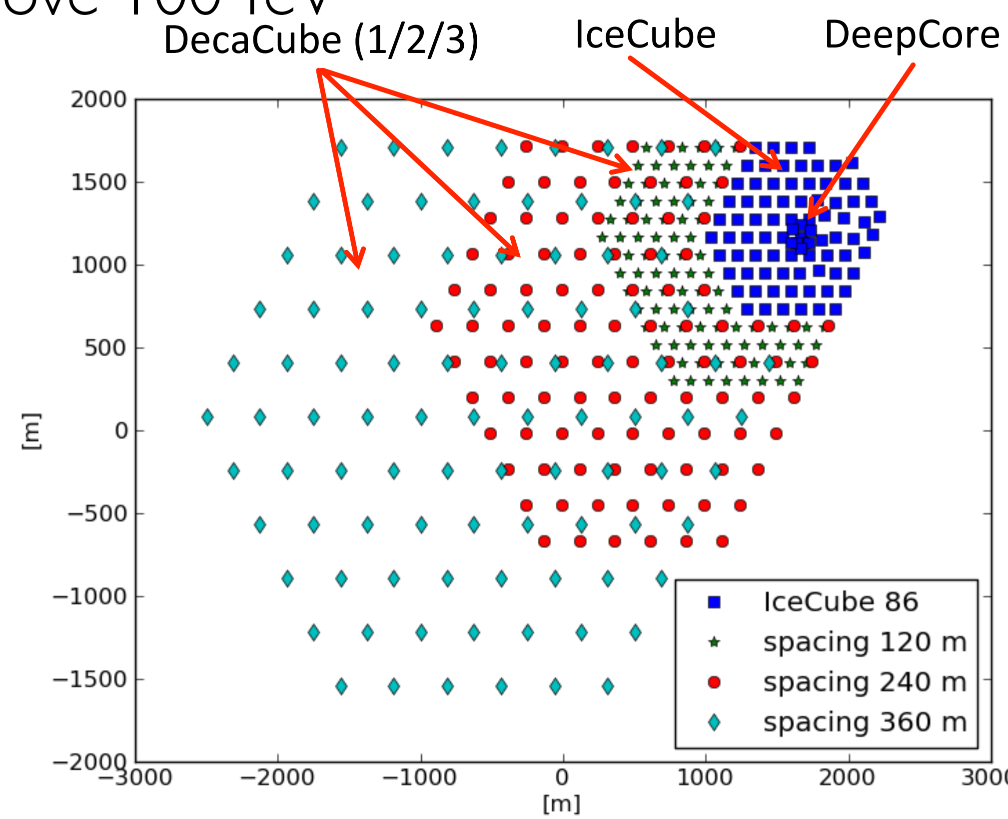
Future neutrino detectors: optical water Cherenkov

Larger (multi cubic-km scale) detectors for energies above 100 TeV

image from P. Coyle

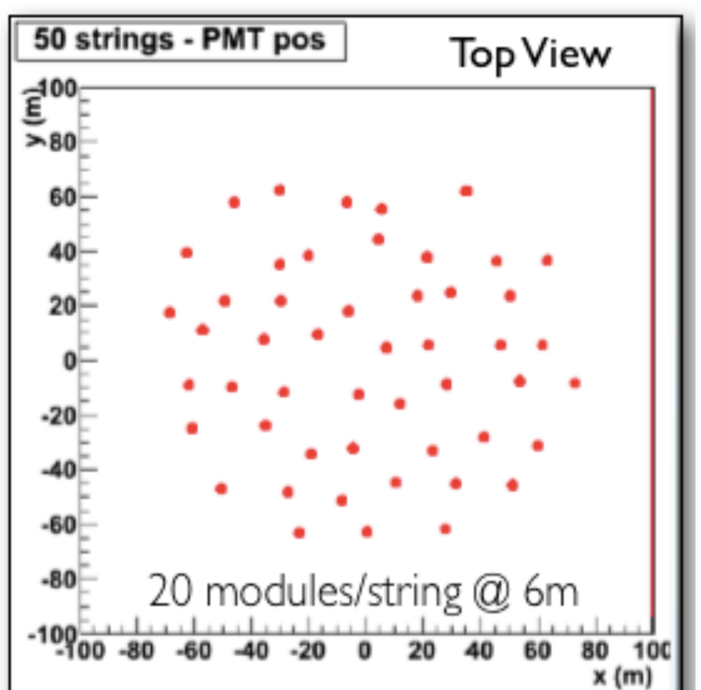


KM3NeT (Mediterranean) - funded and starting construction; excellent sensitivity to Galactic Centre and the “Fermi bubbles”

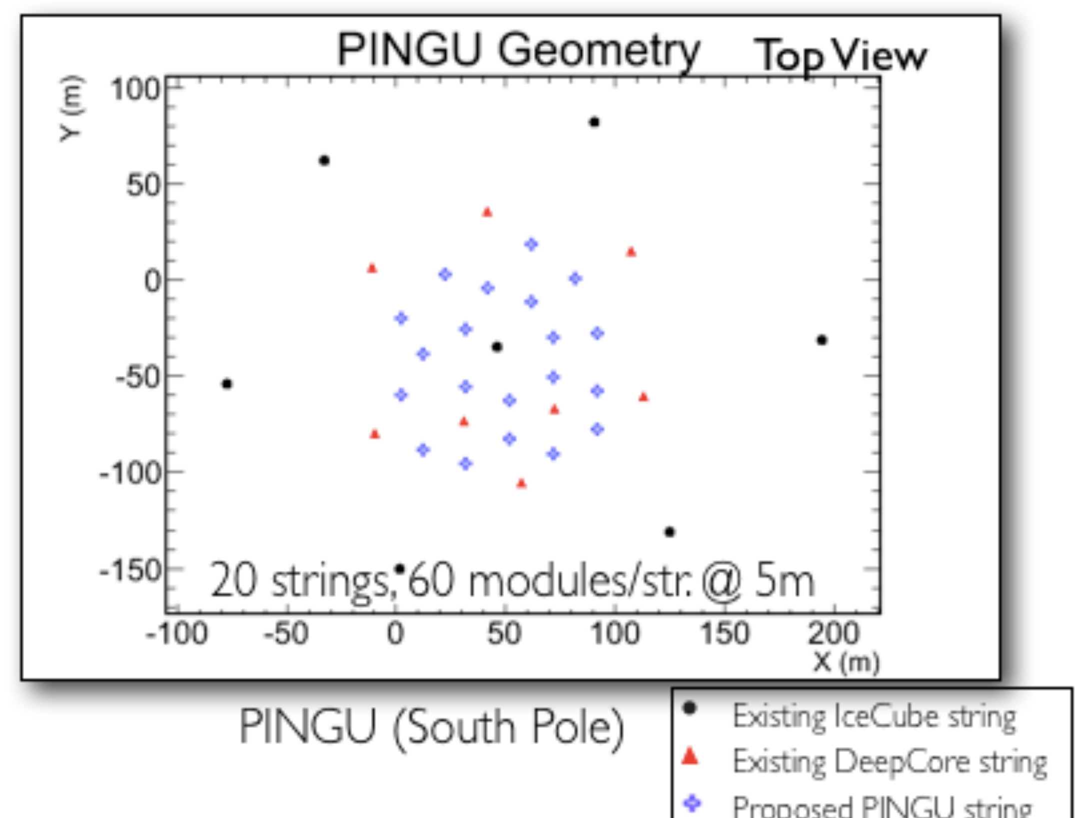


DecaCube (South Pole)

Smaller (sub-)detectors for energies below 15 GeV



ORCA (Mediterranean)

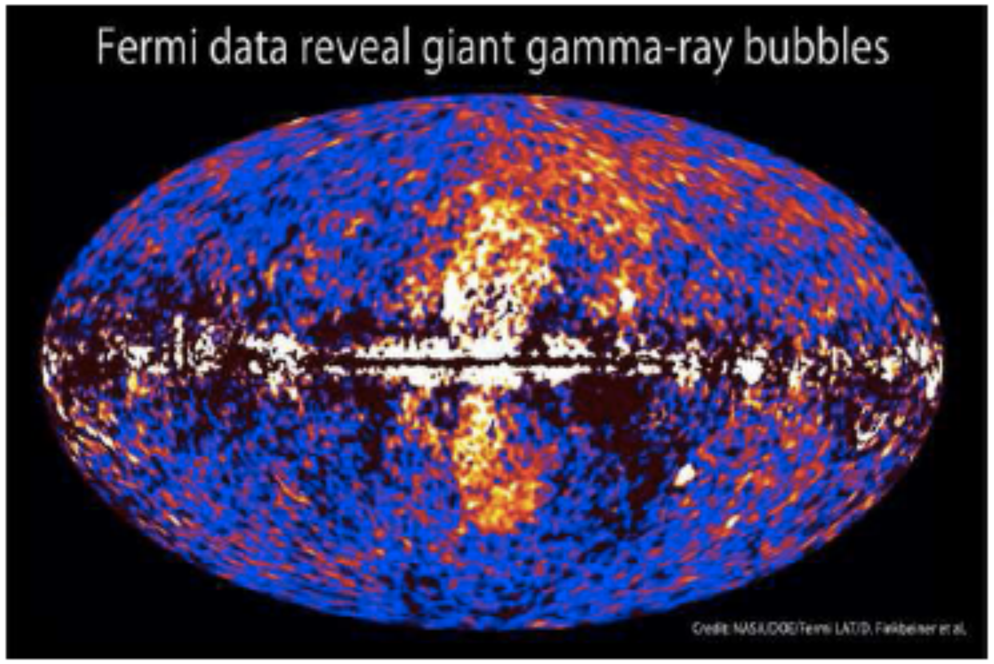


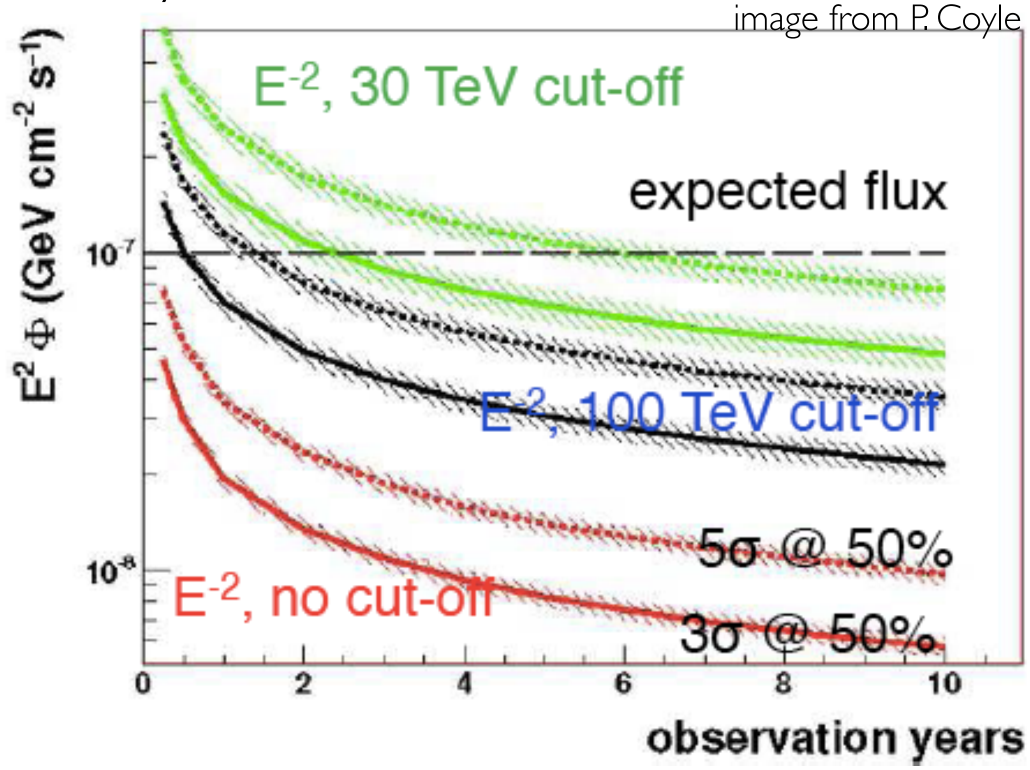
PINGU (South Pole)

Future neutrino detectors: optical water Cherenkov

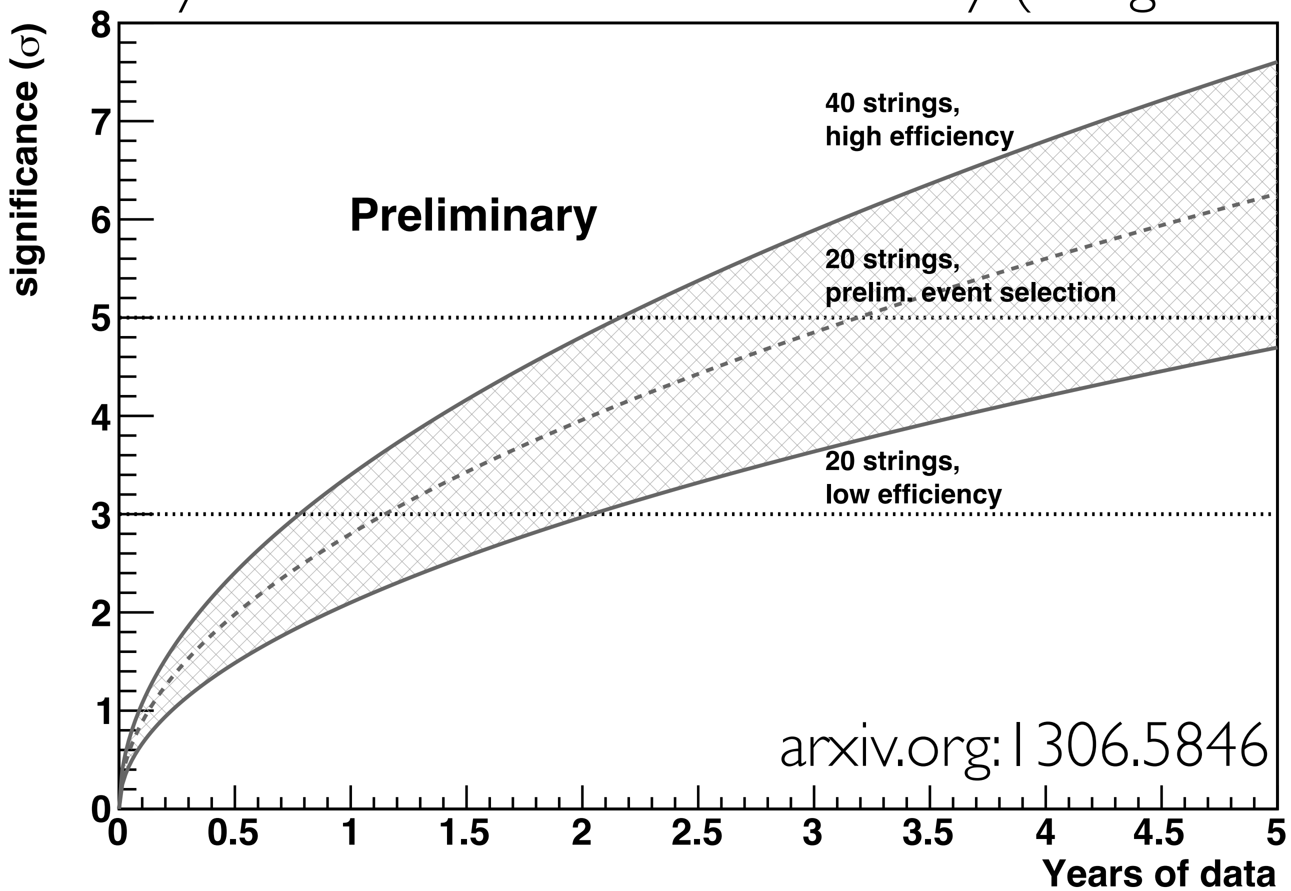
KM3NeT (Mediterranean) and sensitivity to the "Fermi bubbles"

image from P. Coyle



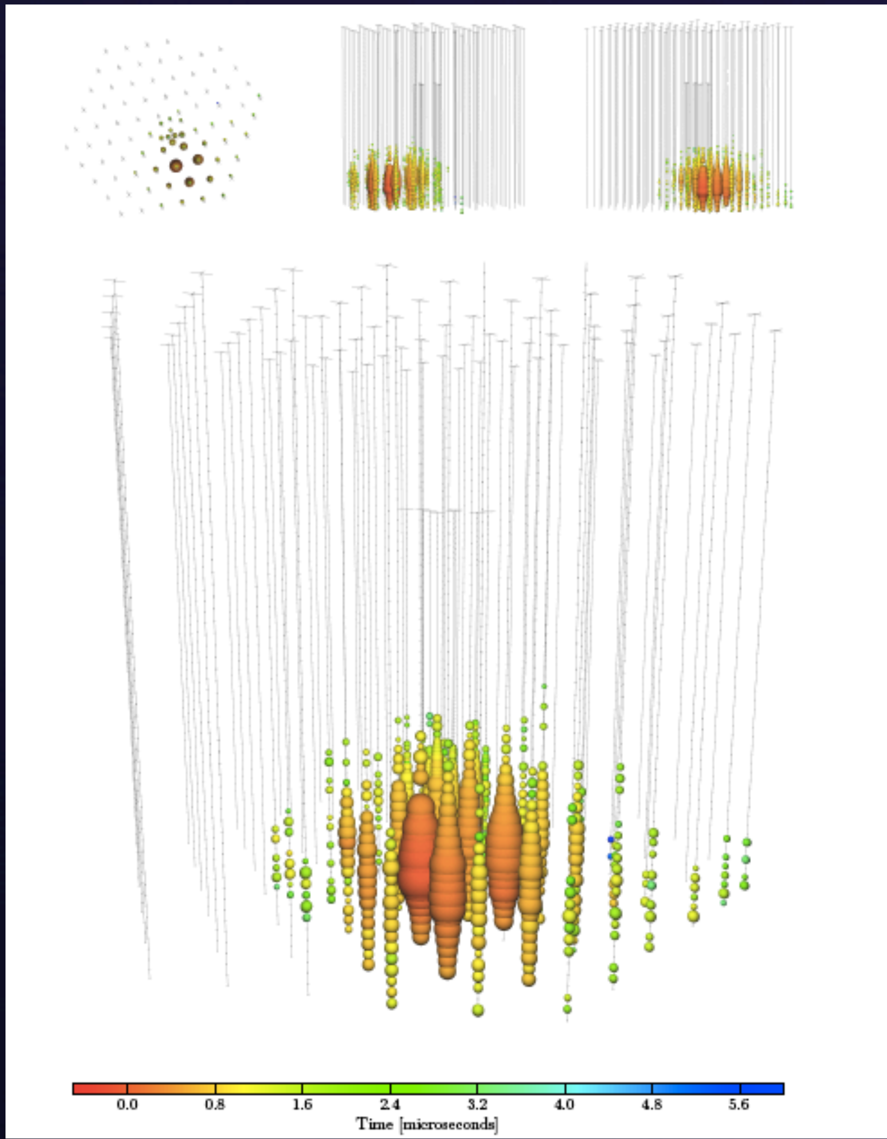


PINGU sensitivity to the neutrino mass hierarchy (using atmospheric neutrinos)



Summary

- Neutrino astrophysics:
  - IceCube has observed a strong excess of neutrino-like events (4.3σ compared to the background expectation)
    - exhibit a hard energy spectrum (with possible cut off; time will tell)
    - are consistent with a flavour ratio of 1:1:1 (mixing and 1:2:0 from pion decay at the production site(s))
    - show no evidence (yet) for spatial or temporal clustering
  - More data in hand; more events are arriving monthly (the dawn of neutrino astronomy?!)
  - very exciting time for the field; existing and planned detectors will add significant sensitivity
- Neutrino particle physics:
  - the same neutrino telescope techniques have now been demonstrated to work at lower energies and measurement of fundamental neutrino properties are feasible (ideal for enormous detector volumes at lower costs)



"Gonzo the Great"

image
muppet.wikia.com

Thanks to the organizers!