High Energy Neutrino Astronomy

First Light, New Questions

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SCIENTIFIC AMERICAN™

from outside our local group

#5: The First Neutrinos ~~from Outside the Solar System~~

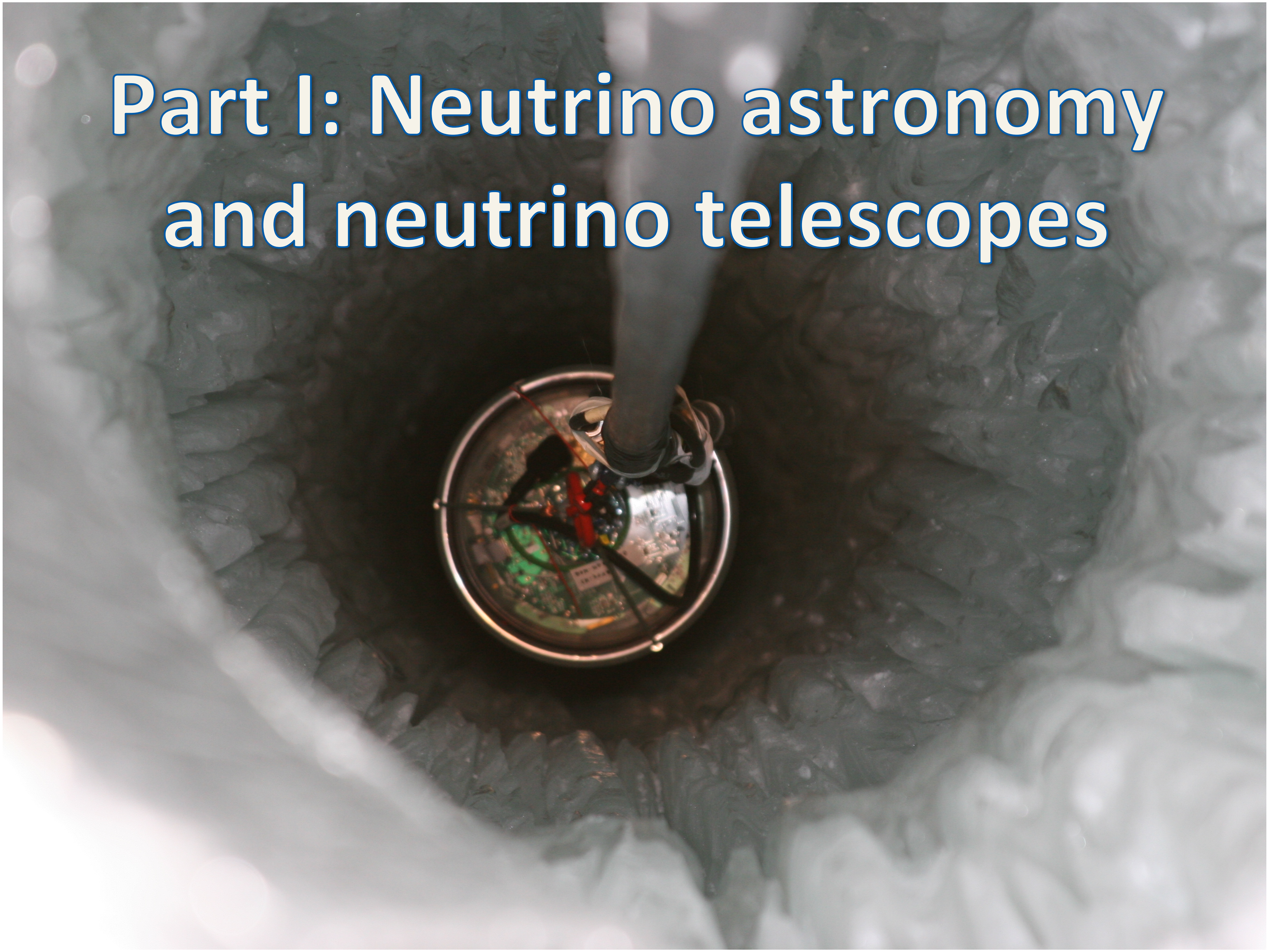
For the first time this year astronomers caught neutrinos originating in distant galaxies, an advance that heralds the start of a new era in astronomy—~~the era of seeing with particles, not just light.~~

Scientists have been studying neutrinos for decades, but almost all of the neutrinos here on Earth come from nearby sources—either our own sun or from high-energy cosmic rays hitting the atmosphere. This year astronomers using the IceCube detector at the South Pole reported the discovery of 28 neutrinos that were so energetic they could not have possibly originated in these local sources. (Researchers named the two most powerful neutrinos "Ernie" and "Bert" after the beloved Sesame Street characters.)

highest energy neutrinos observed—ever.

As for what spawned these ultrapowerful neutrinos, speculation abounds—the particles didn't all arrive in a single spurt and appear to come from random directions on the sky. Once scientists can correlate the location of a neutrino burst to an optical counterpart—possibly coming from an energetic, short-lived object like a supernova—the era of neutrino astrophysics will begin in earnest. —*Michael Moyer*

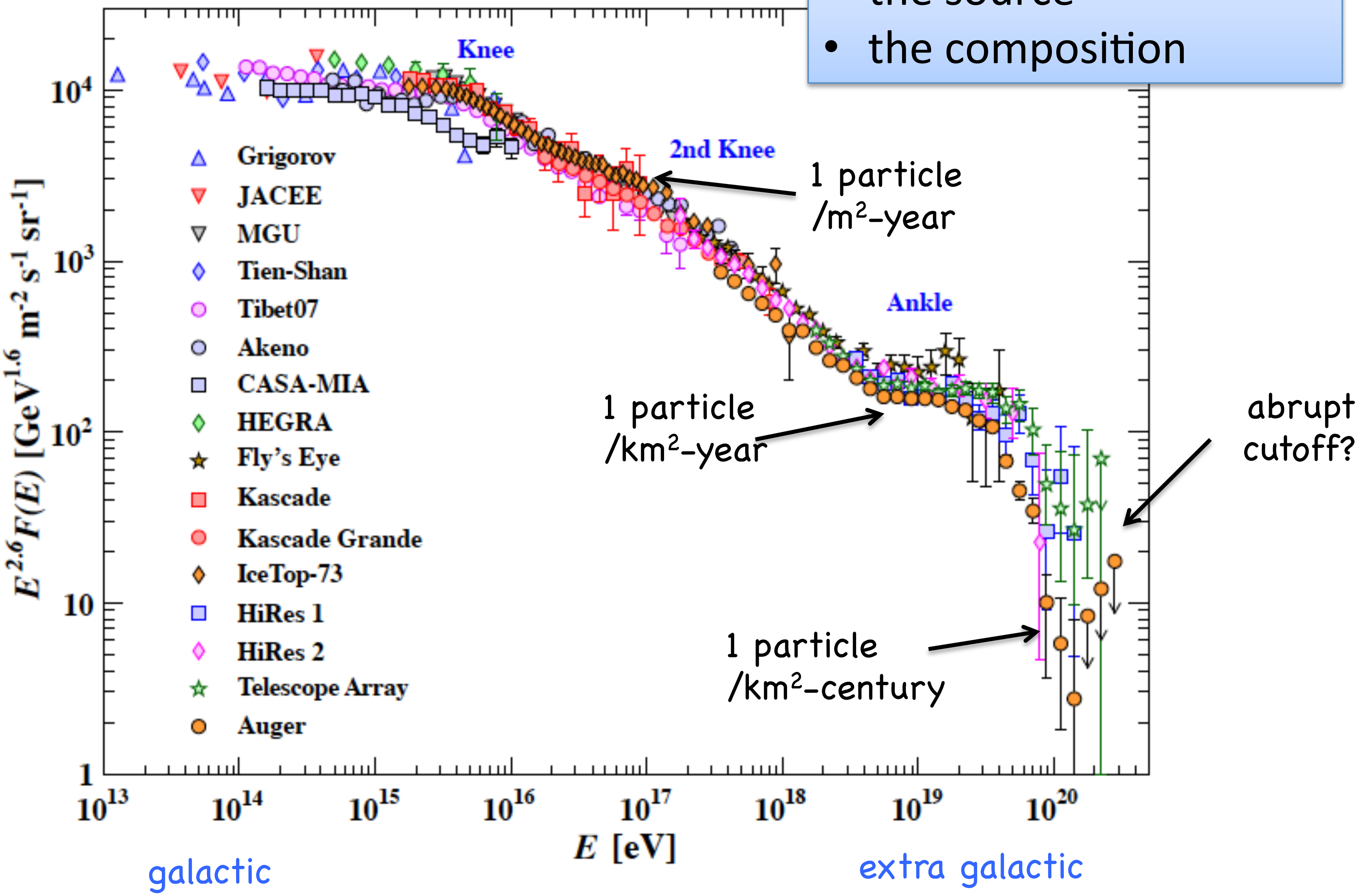
Part I: Neutrino astronomy and neutrino telescopes



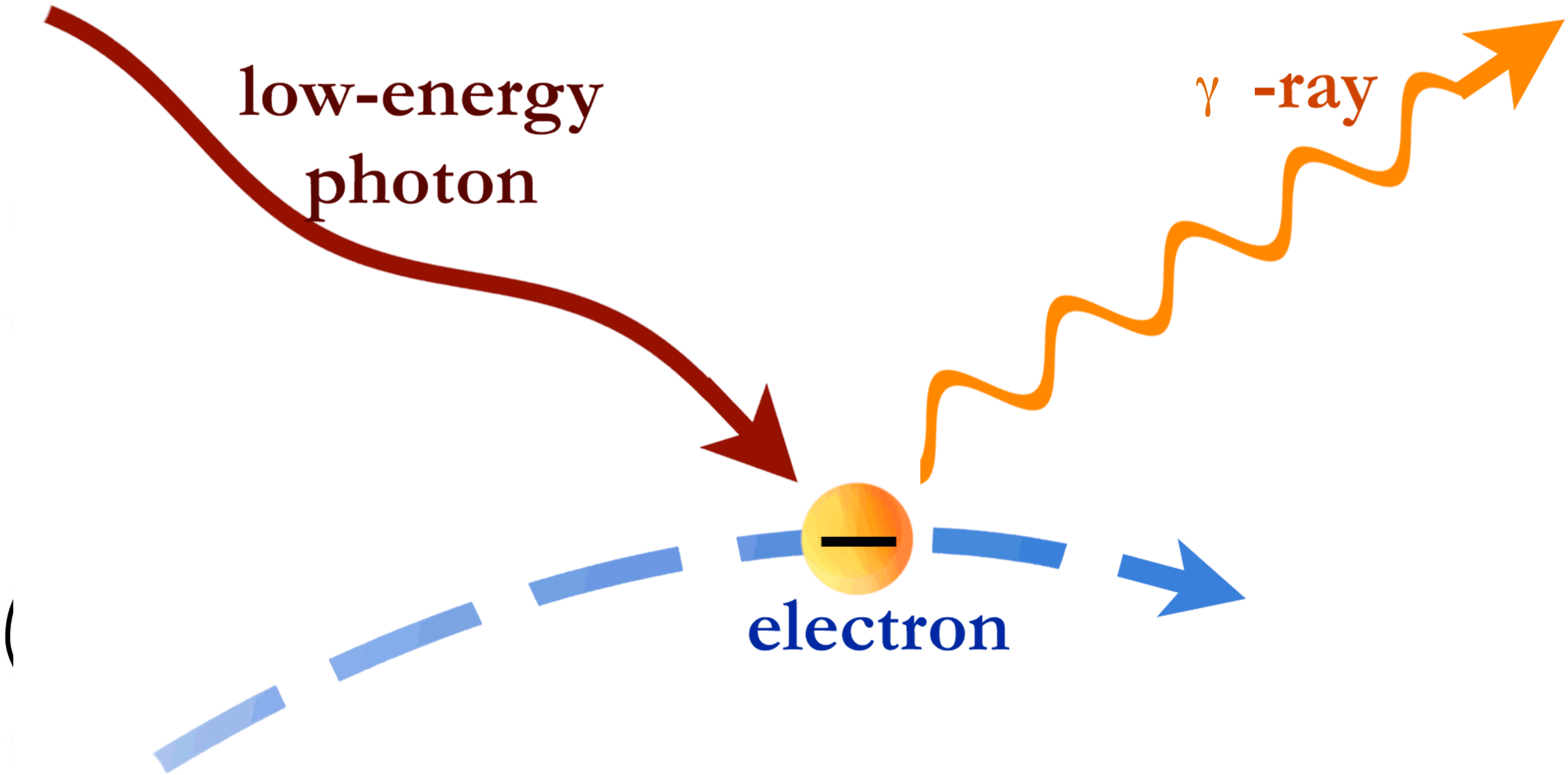
Cosmic rays

We still don't know:

- the source
- the composition

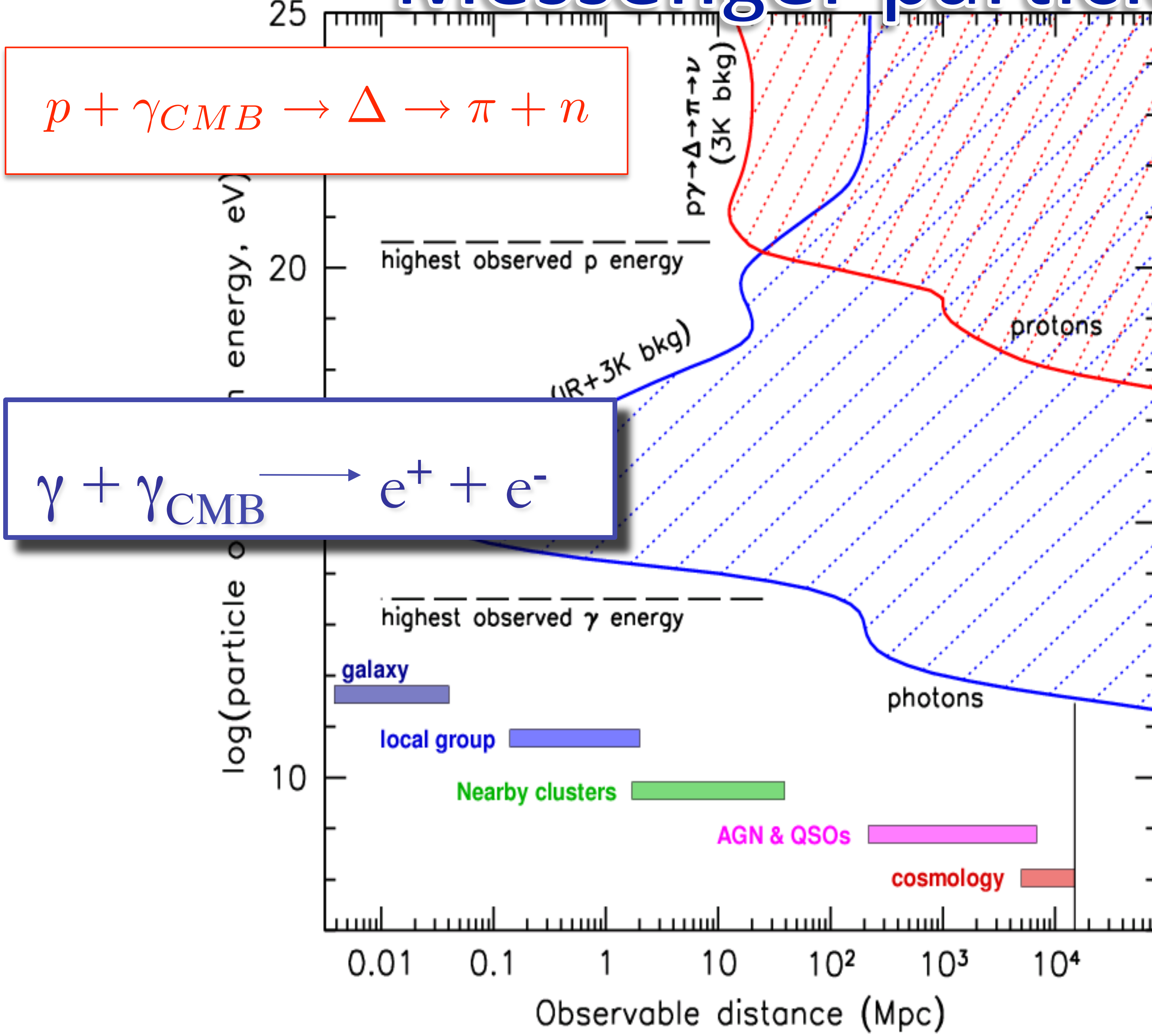


Neutrinos



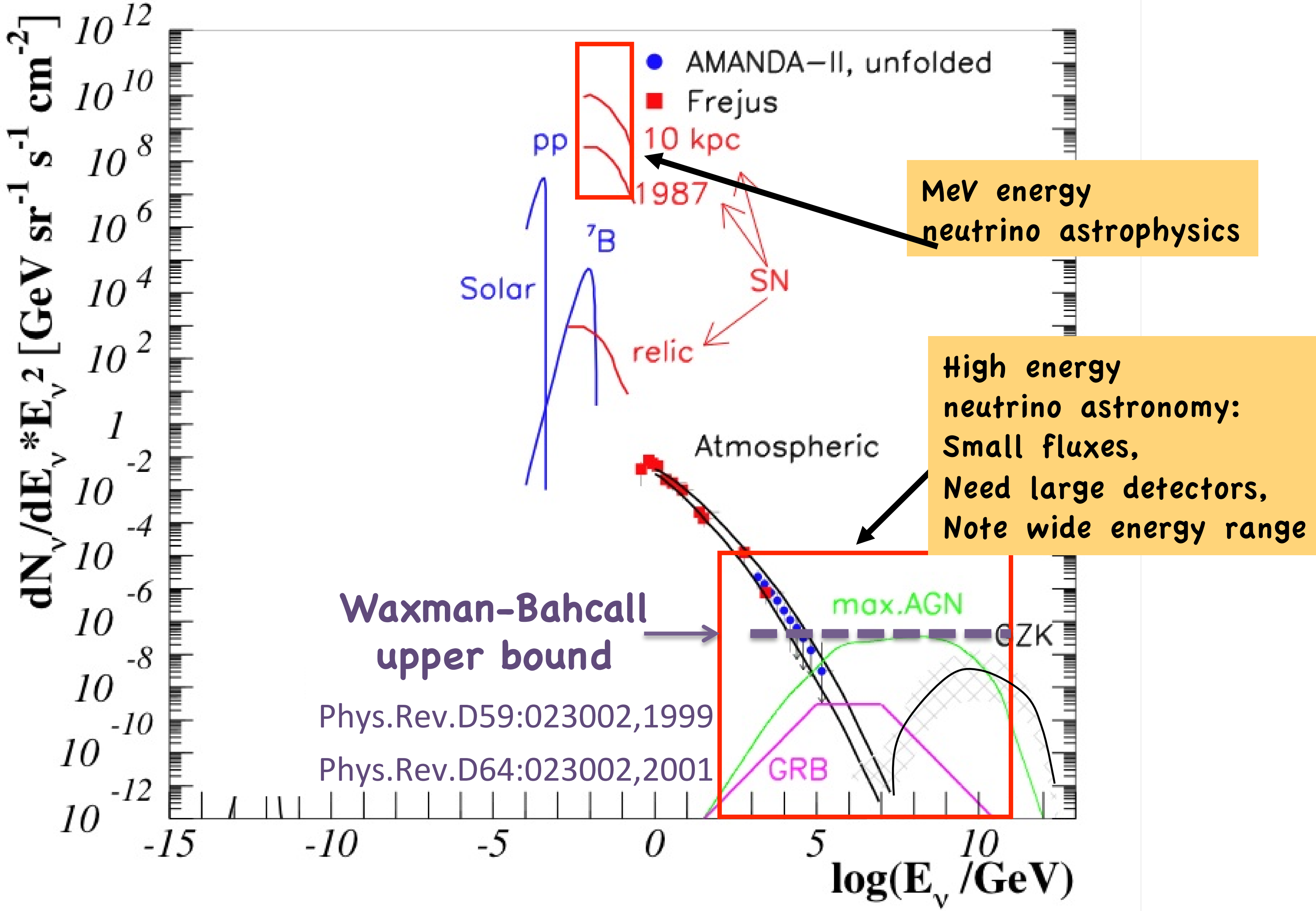
Accelerated electrons can produce gamma rays, but neutrinos are a unique signature of hadronic (proton/ ion) acceleration. (And neutrinos point back…)

Messenger particles



"GZK" cutoff

Astrophysical ν's: Sources, energies and fluxes



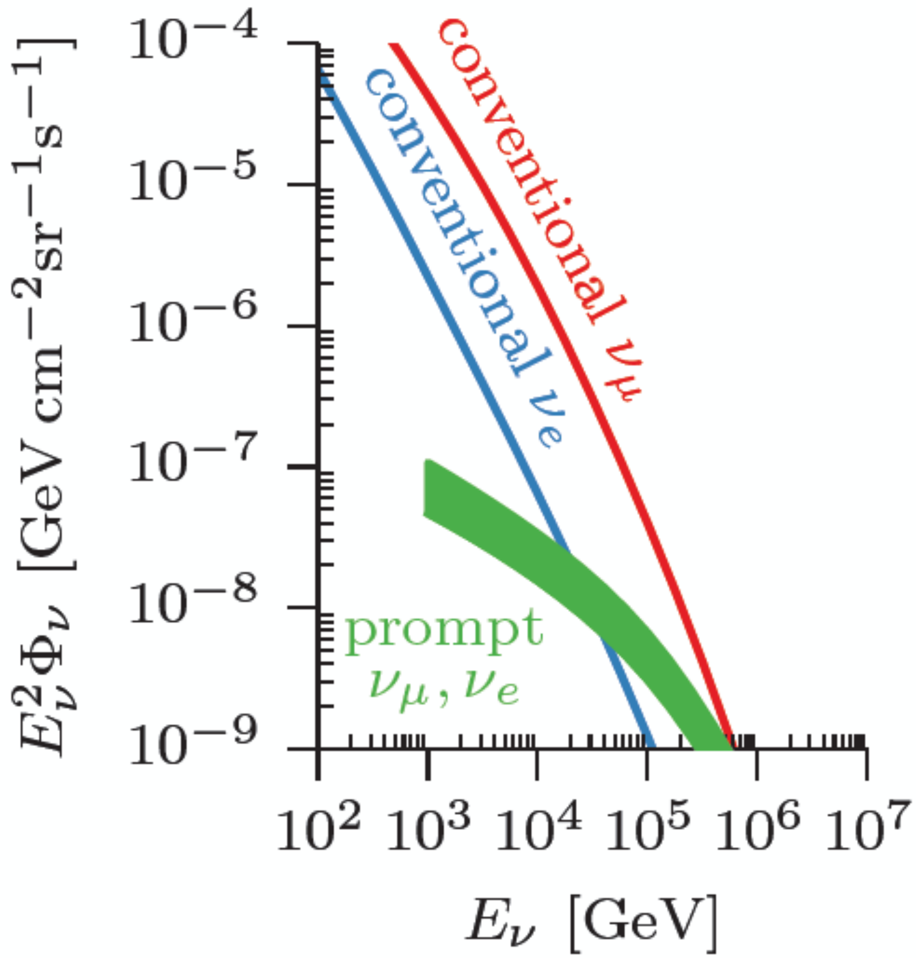
Sources of νs

"conventional atmospheric" pion and kaons- steeper than cosmic ray spectrum since higher energy particles will reinteract before decay- primarily ν_μ

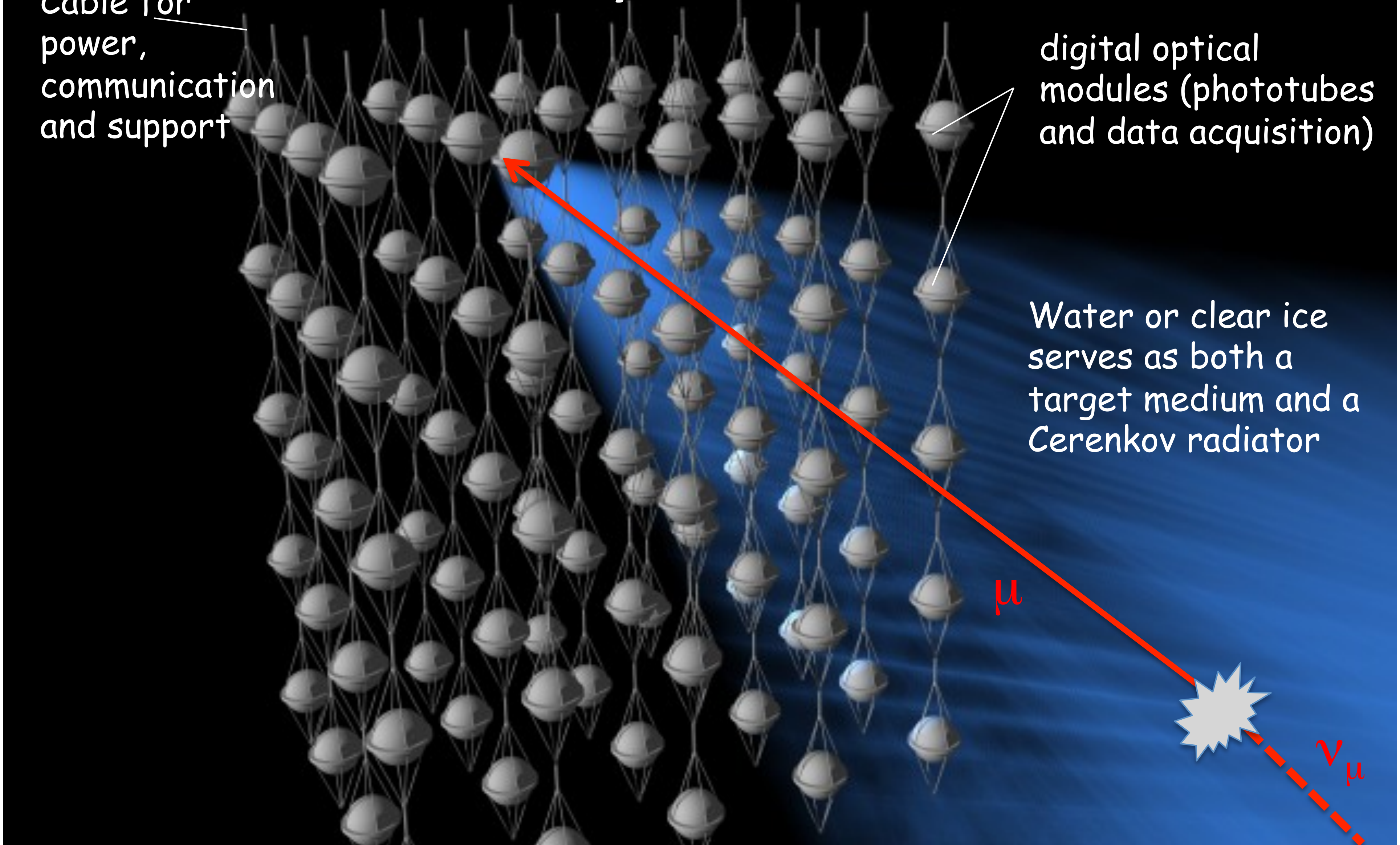
"astrophysical"- steep ($\sim E^{-2}$) due to Fermi acceleration. Long baseline implies equal parts ν_e, ν_μ, ν_τ

"prompt atmospheric" component from charm decay-less steep than conventional- equal parts ν_μ and ν_e. Not yet observed.

Enberg, Reno, Sarcevic
arXiv: 0806.0418
Phys.Rev. D78:043005 (2008)



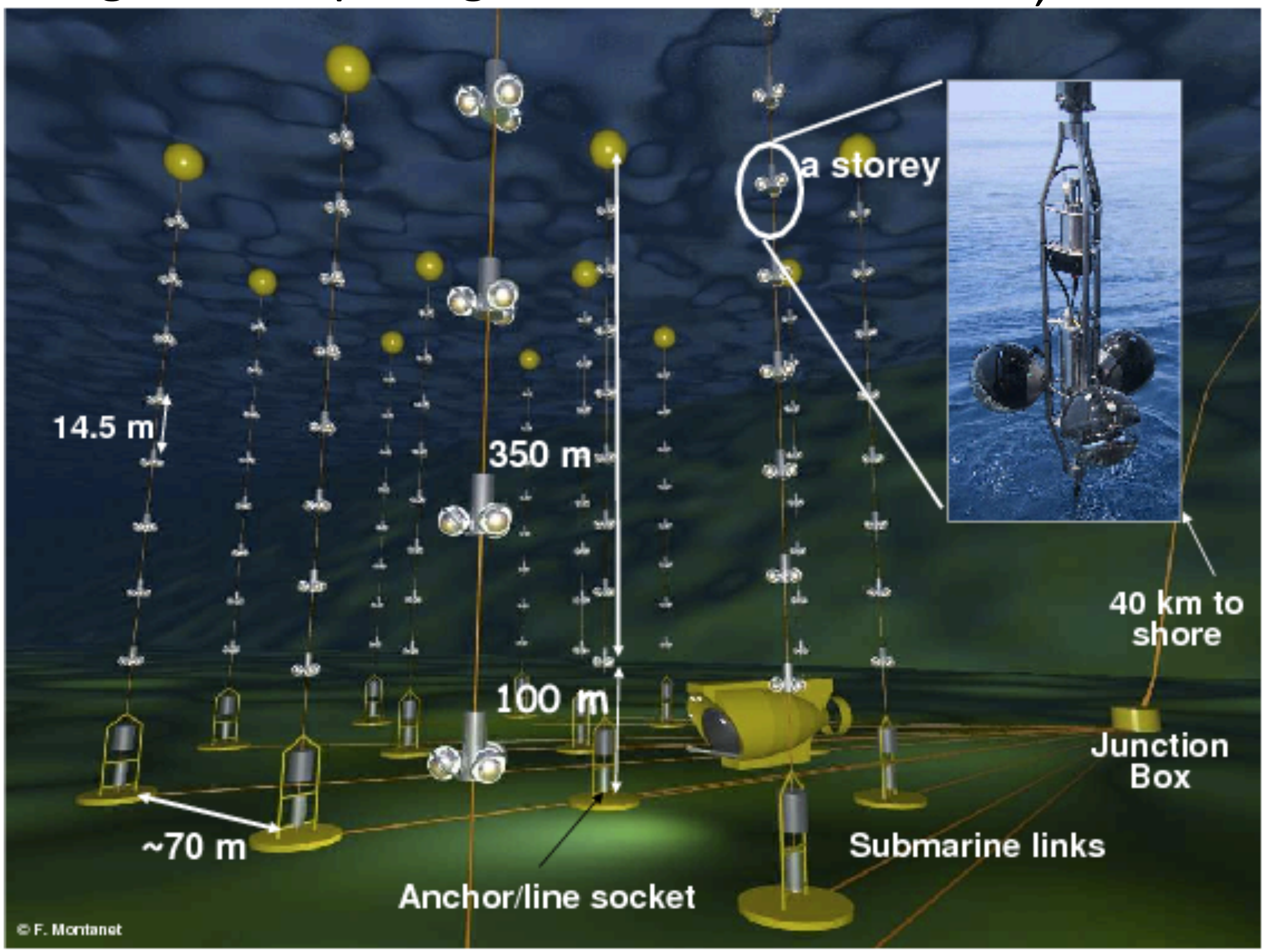
Anatomy of a Neutrino Detector



Due to the scale required for a high energy neutrino detector, man-made tanks are impractical. Large natural reservoirs are needed.

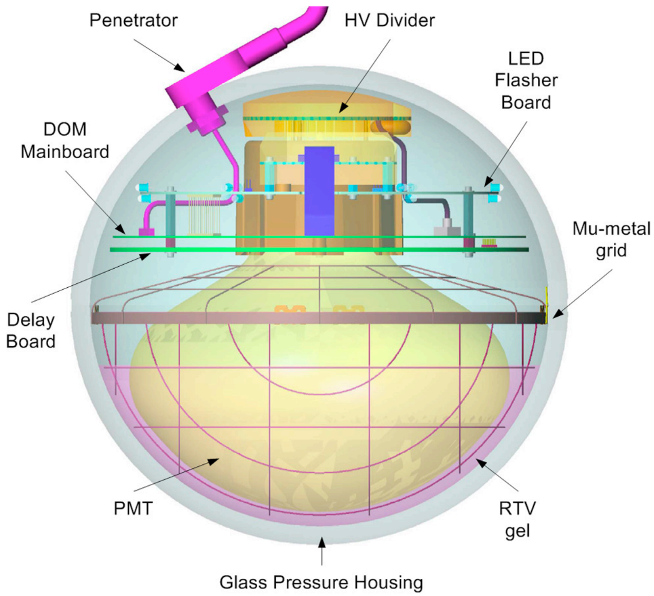
ANTARES

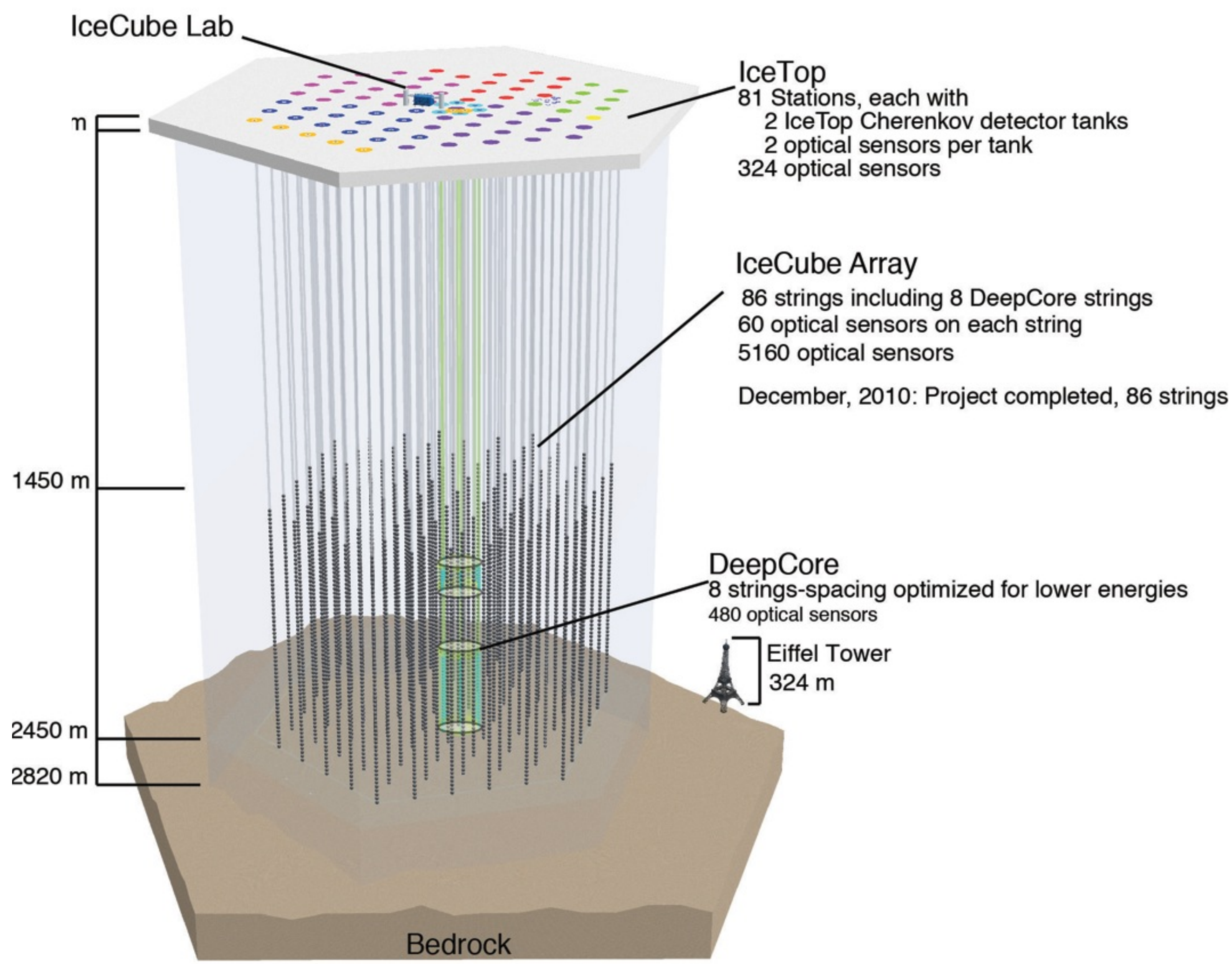
- Mediterranean Sea
- 0.01 km3
- 12 strings, 70 m spacing
- 885 photomultiplier tubes
- Sea floor ~2400m
- near Toulon, France



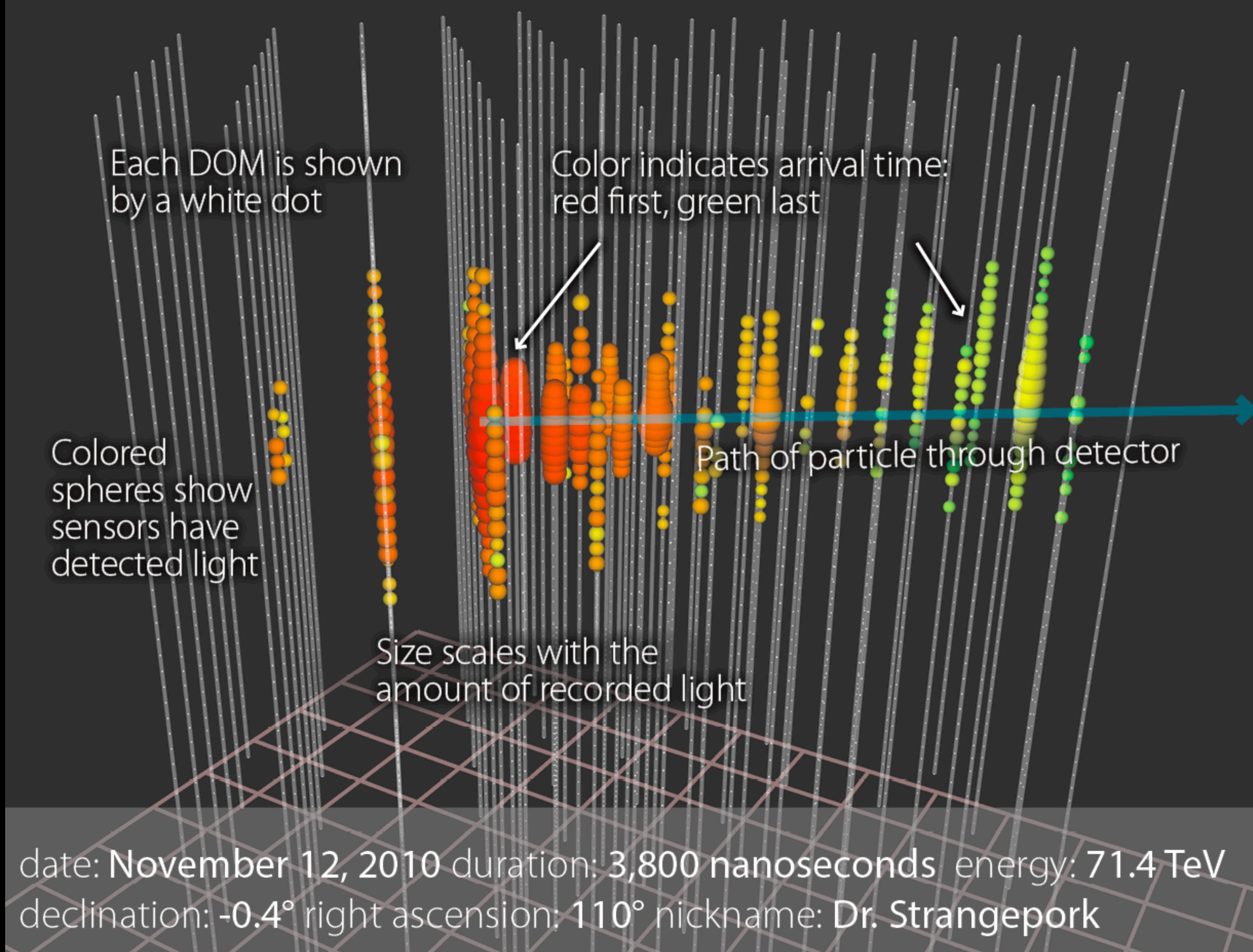
ICECUBE

86 strings
5160 photomultiplier tubes
1 cubic kilometer of instrumented area





IceCube Events

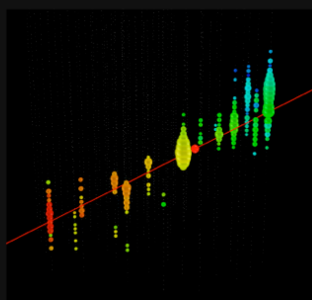


Neutrino Event Signatures

Signatures of signal events

time

CC Muon Neutrino

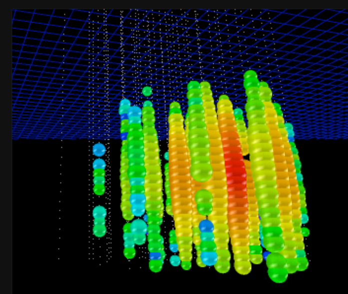


$$\nu_\mu + N \to \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

Neutral Current /Electron Neutrino



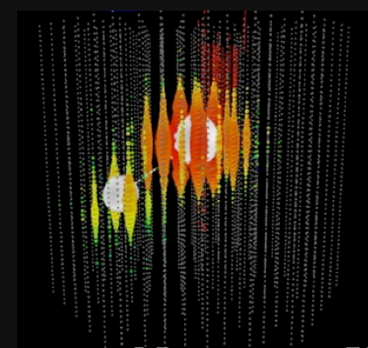
$$\nu_{\mathrm{e}} + N \to \mathrm{e} + X$$

$$\nu_{\mathrm{x}} + N \to \nu_{\mathrm{x}} + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution
(at energies $\gtrapprox 100$ TeV)

CC Tau Neutrino



$$\nu_\tau + N \to \tau + X$$

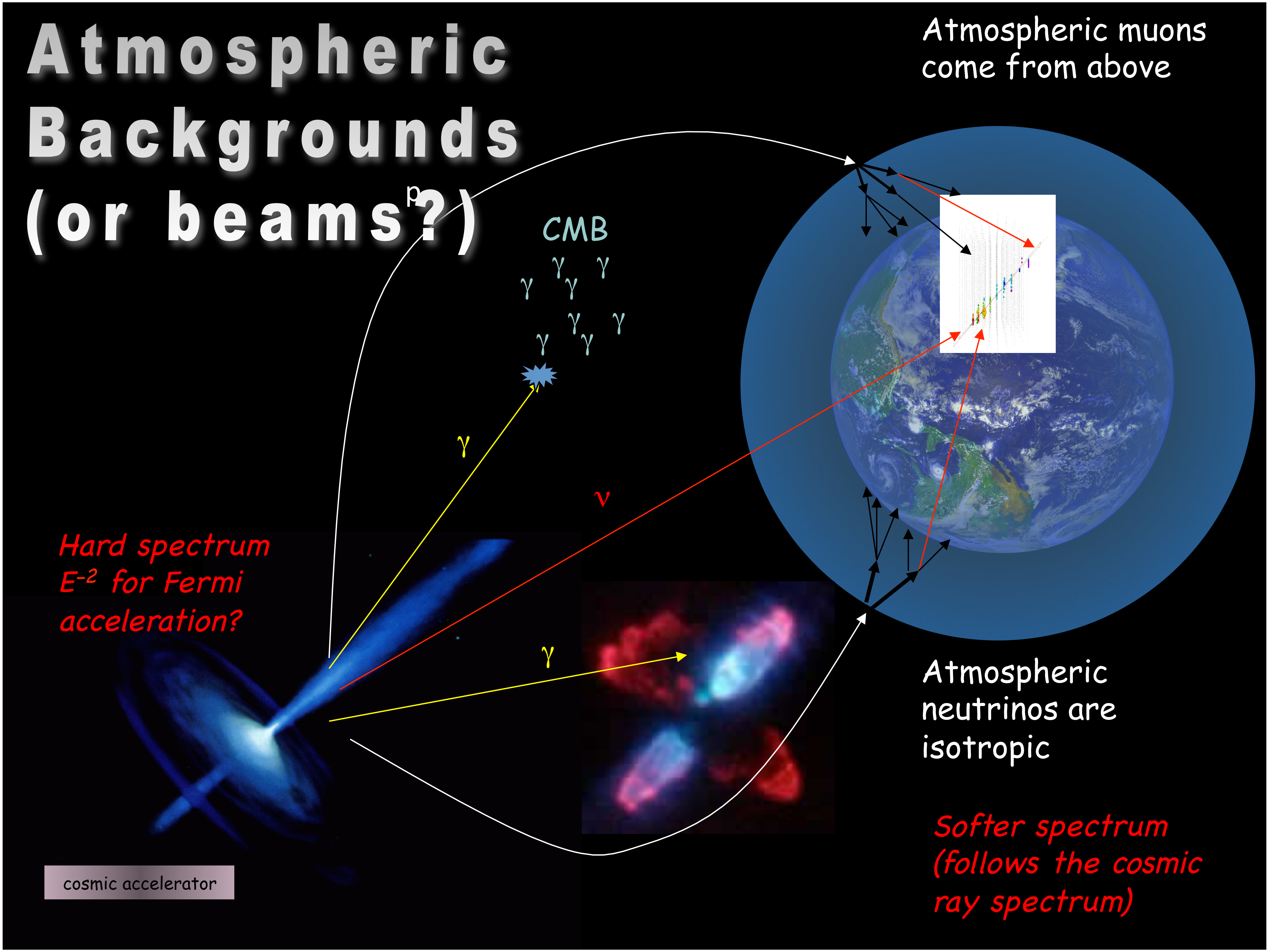
"double-bang" and other signatures (simulation)

(not observed yet)

IceCube Preliminary

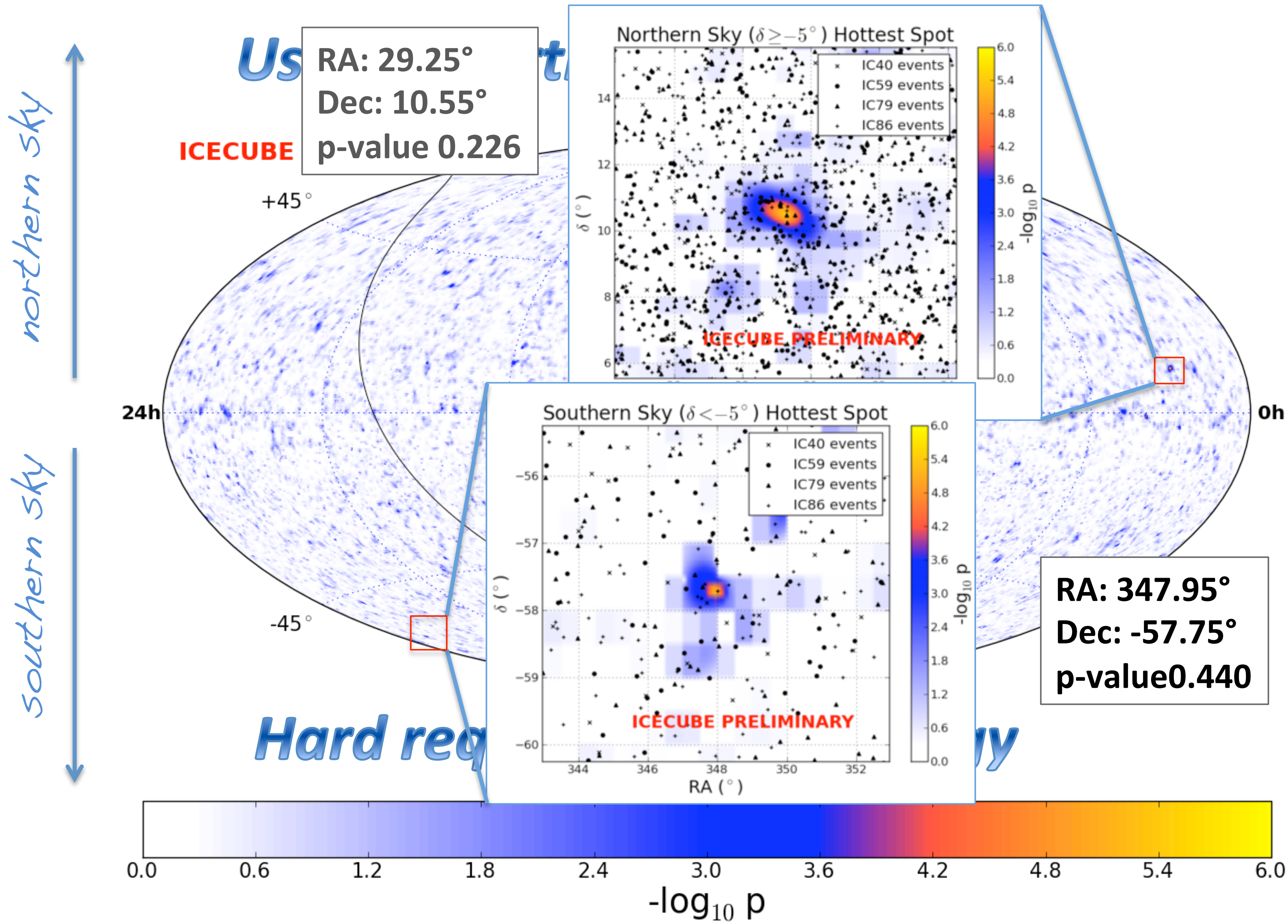
Over a very long baseline flavor ratios of 1:1:1 are expected due to oscillations


Part II: A signal!!!


Atmospheric Backgrounds (or beams?)
Atmospheric muons come from above
p
CMB
γ
ν
Hard spectrum E-2 for Fermi acceleration?
Atmospheric neutrinos are isotropic
Softer spectrum (follows the cosmic ray spectrum)
cosmic accelerator

Point source search

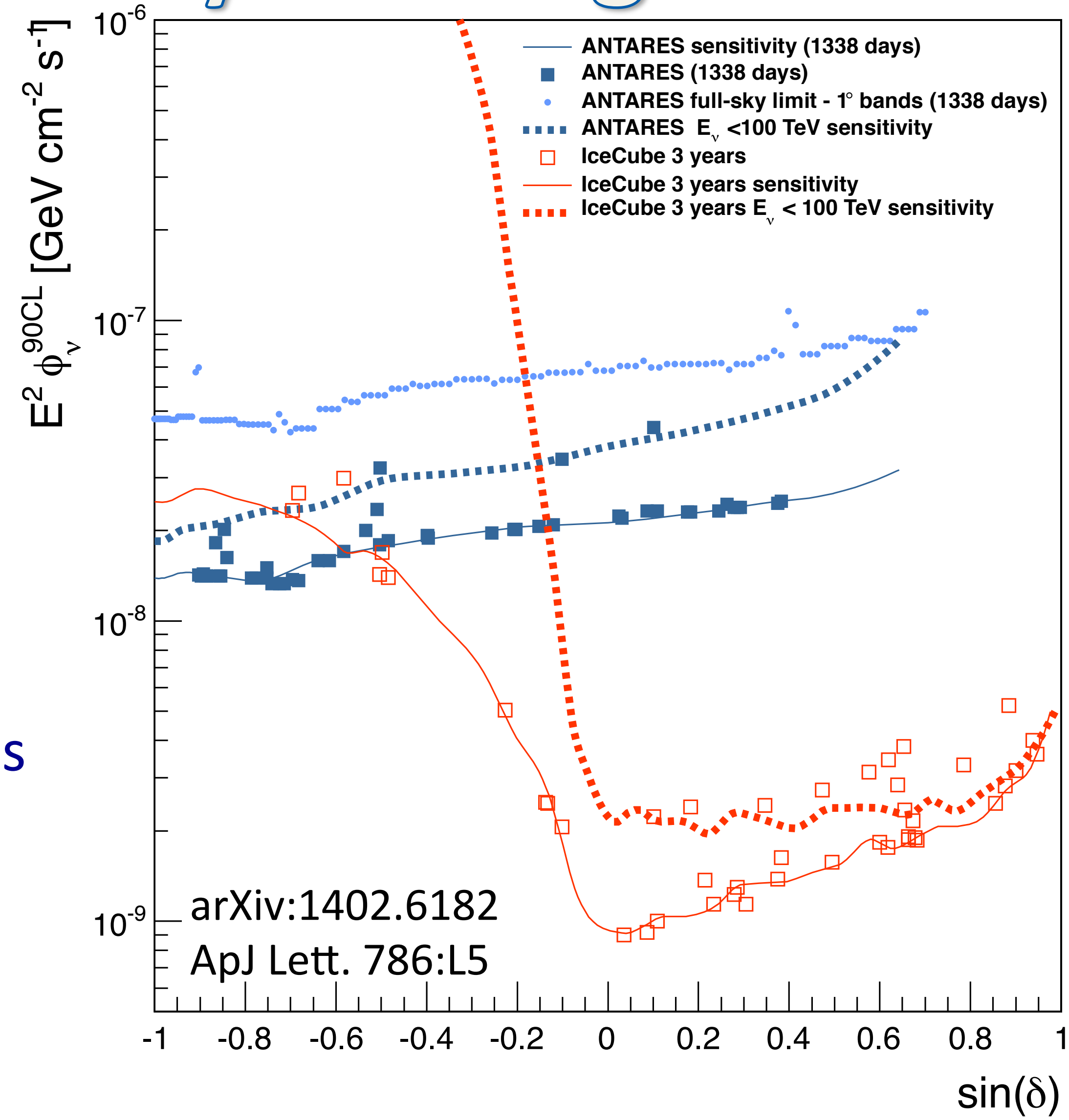
Using all muon neutrino candidates (including non-contained)



Neutrino sky coverage

- IceCube has a larger effective area, and a shielded view of the Northern hemisphere, Southern hemisphere sensitivity mostly due to high energy events.

- Antares' Northern hemisphere location means a lower threshold for Southern Hemisphere events. Superior angular resolution due to higher instrument density.

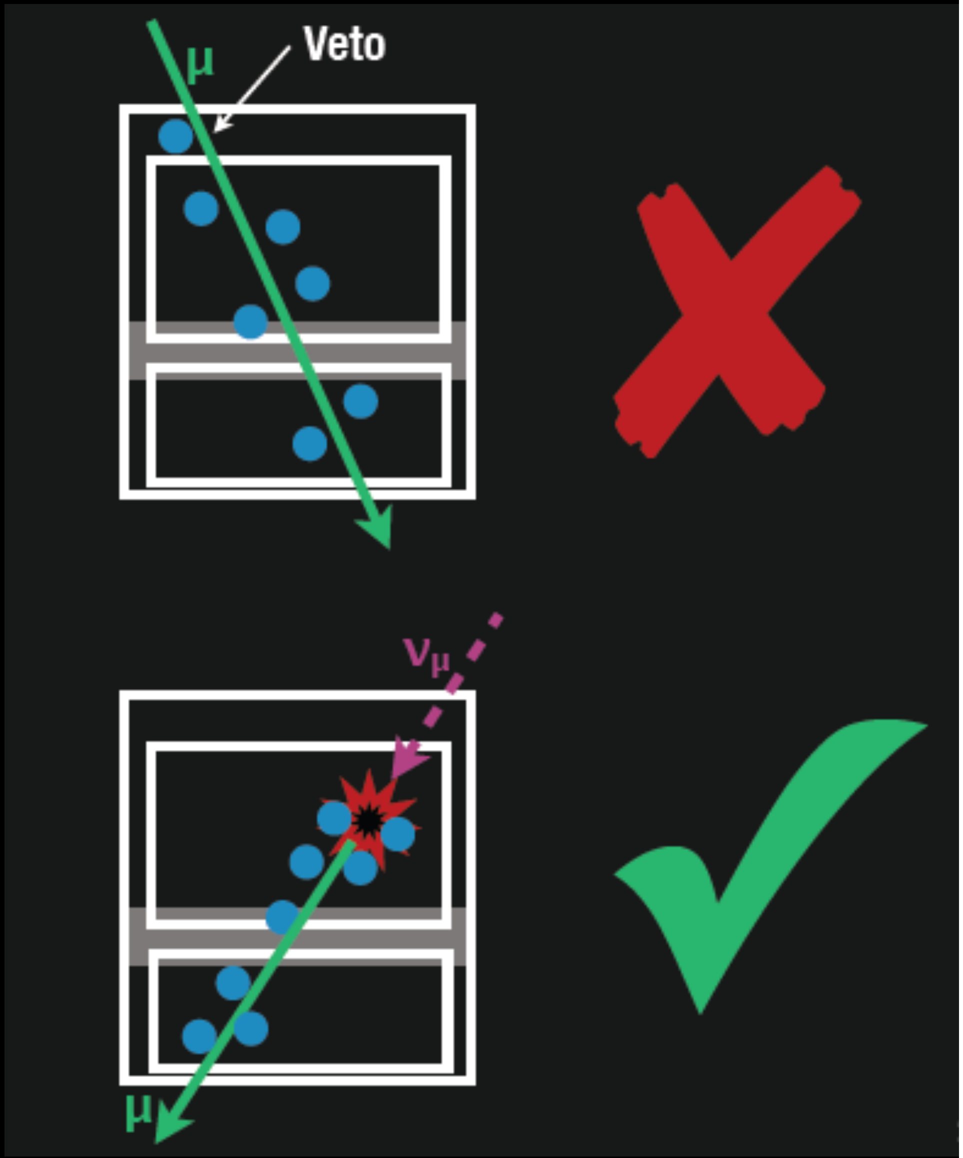


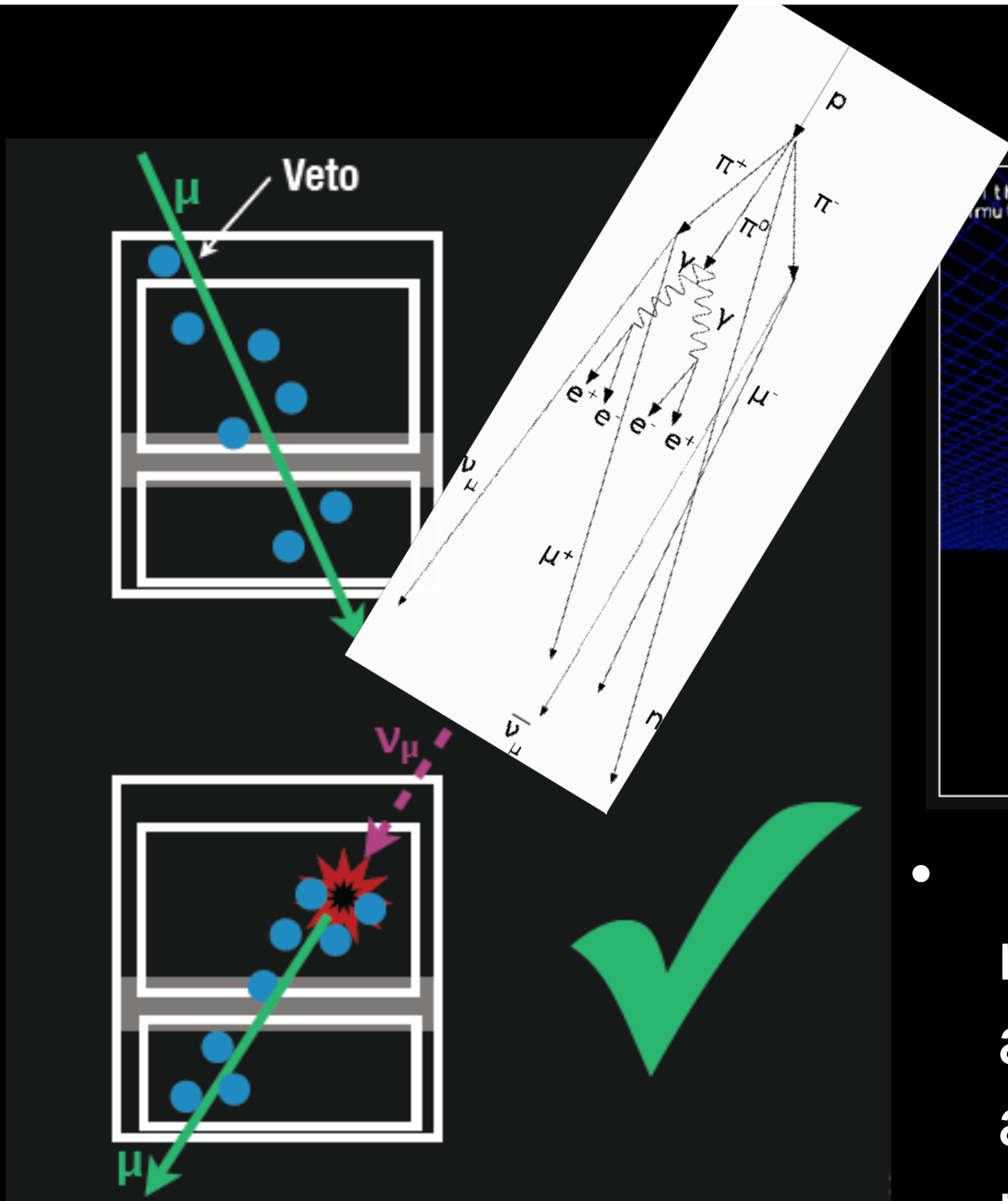
IceCube and ANTARES are complementary

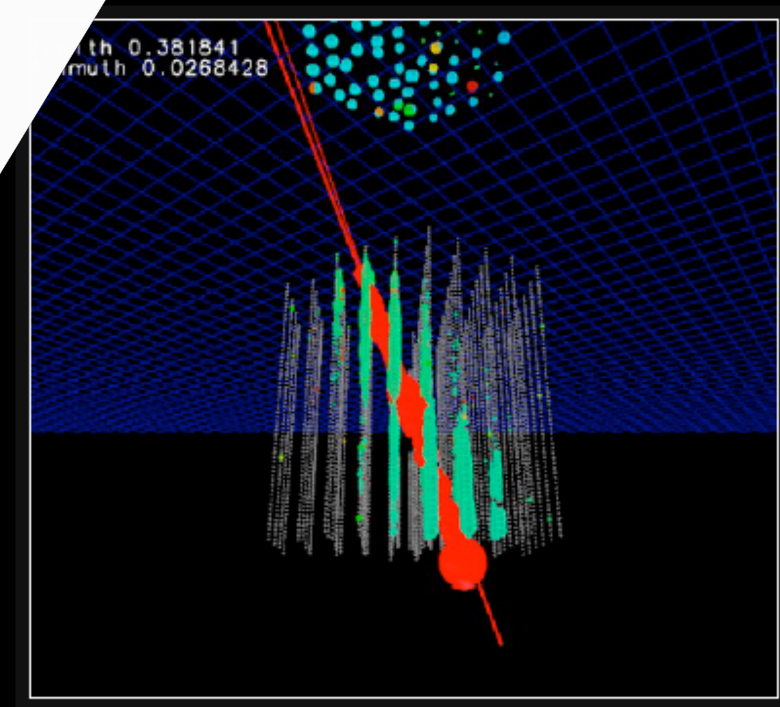
Cosmic or terrestrial?

- suppress atmospheric muons by looking for events that start in the detector

- discard any events whose earliest energy deposits are in the outer layer of the detector





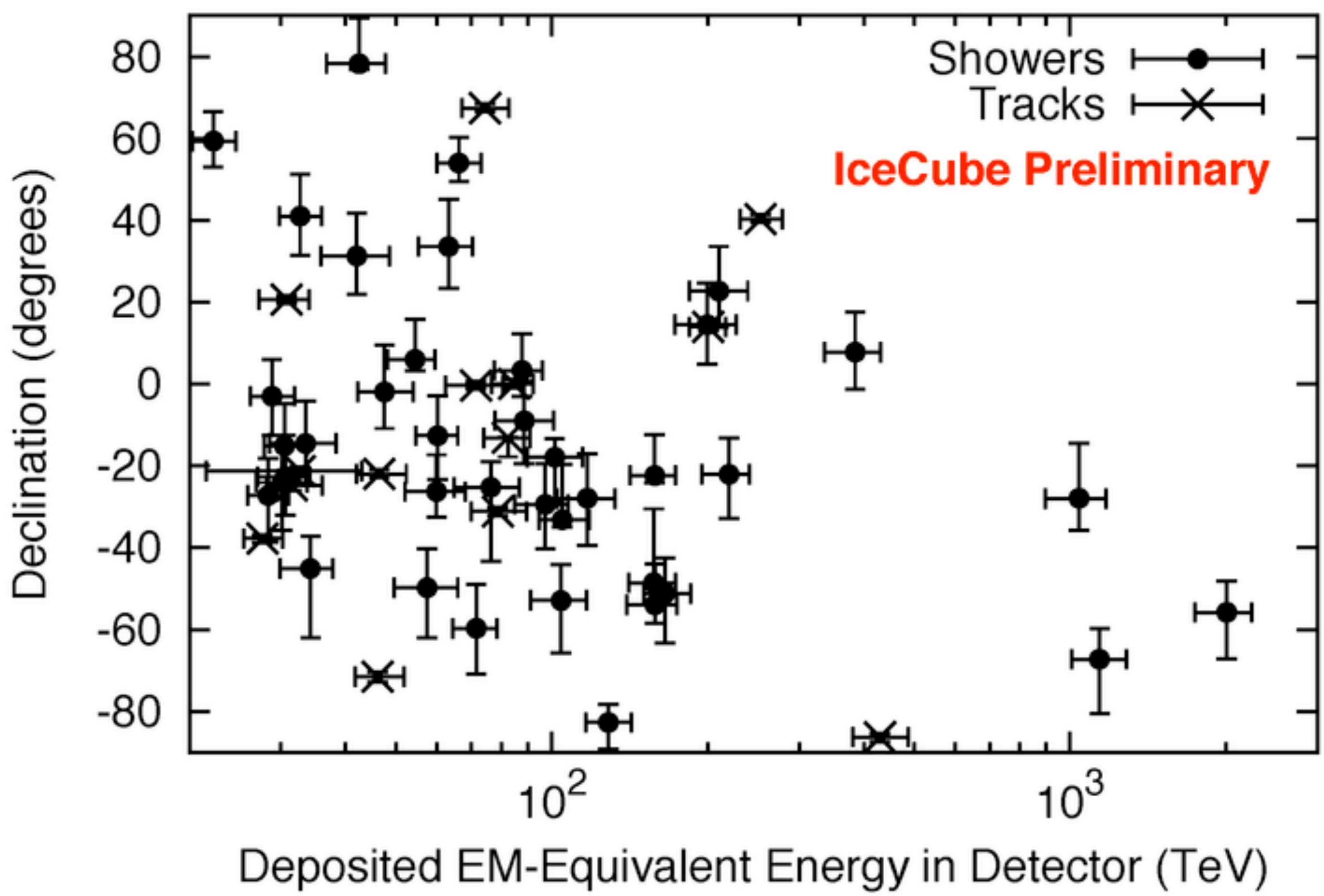


- atmospheric neutrinos produced in air showers will have accompanying muons

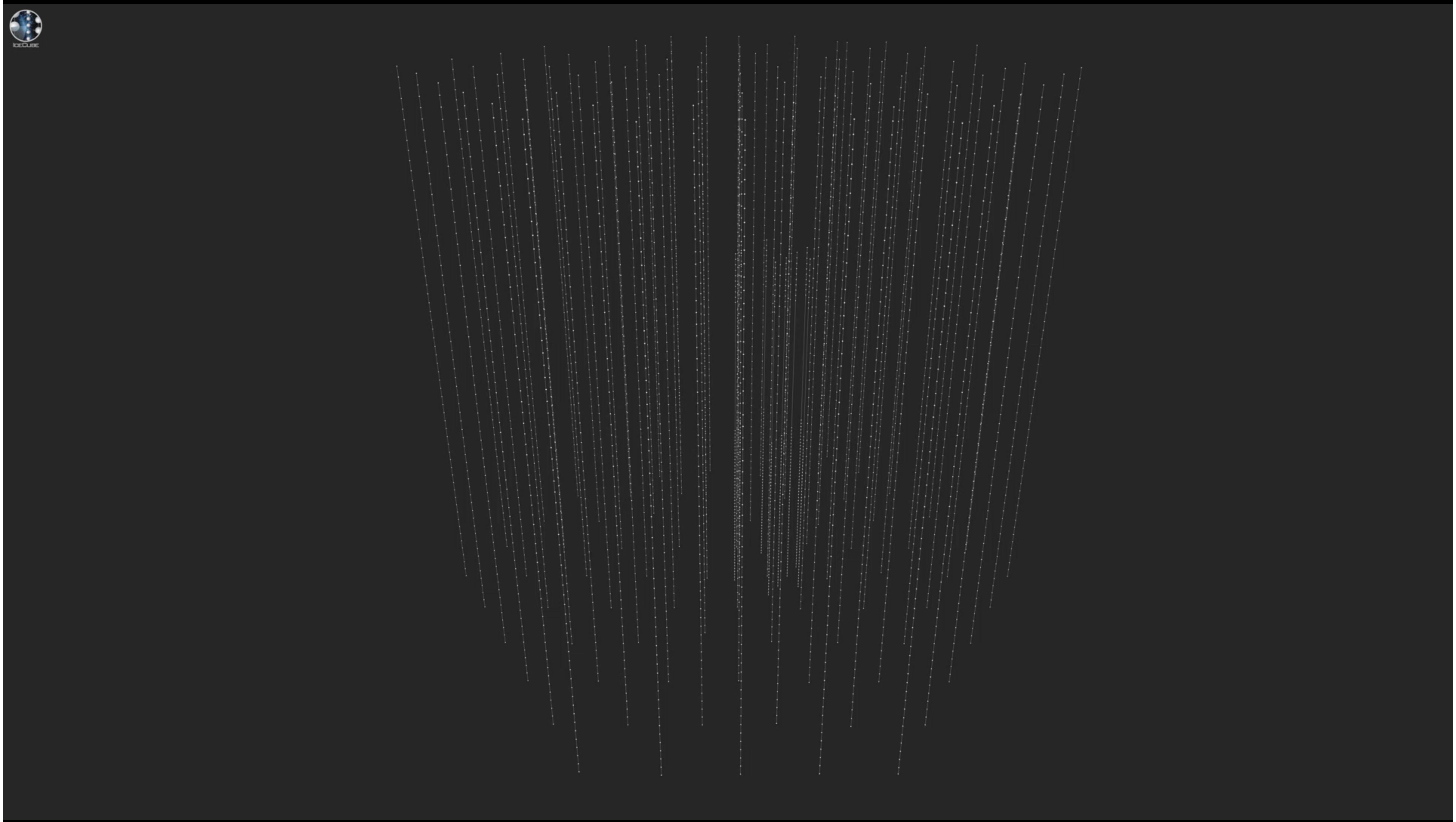
Opening the box…

53 events found in 4 years
6.5 σ discovery

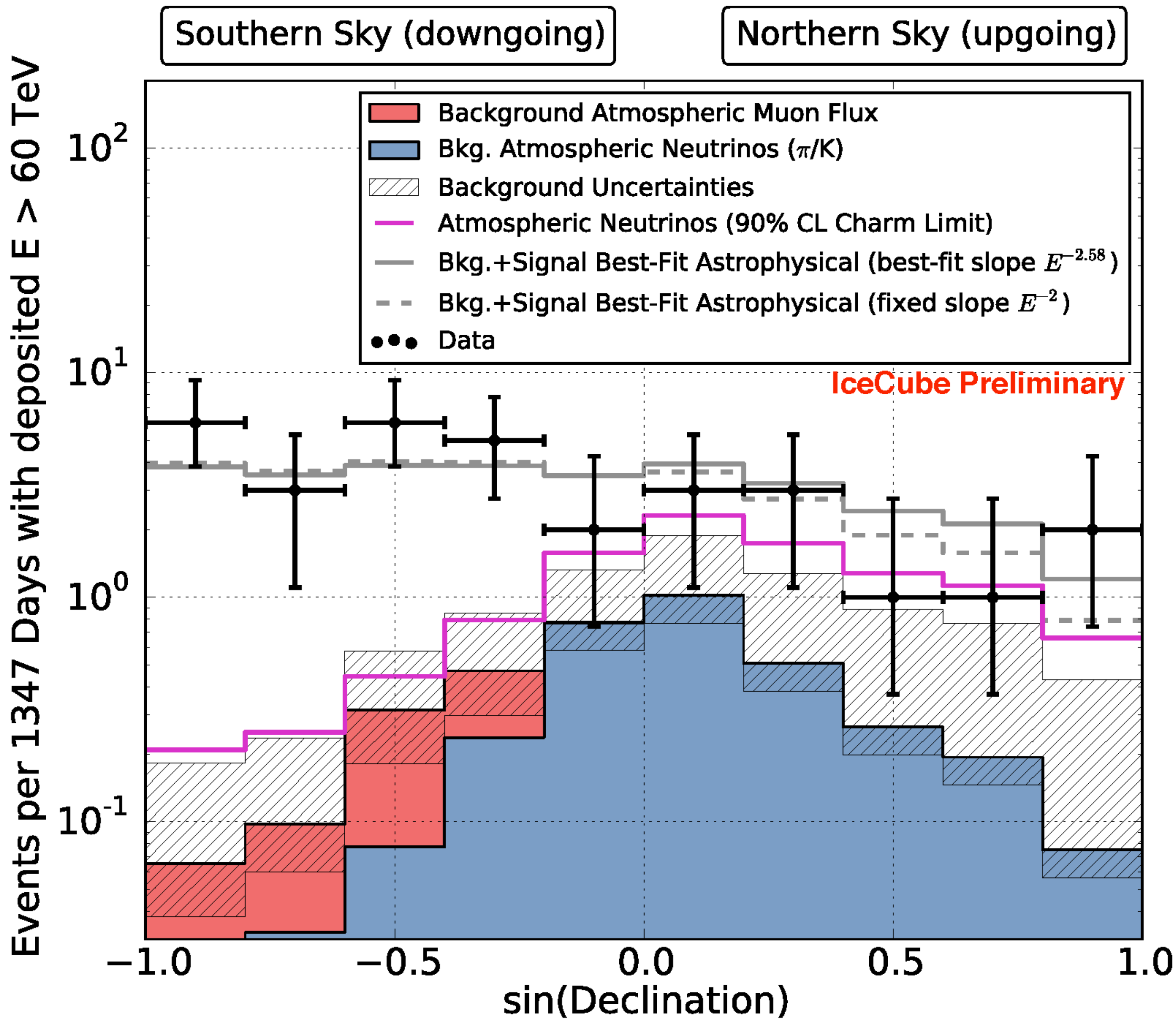
Estimated backgrounds:
$9.0^{+8.0}_{-2.2}$ atm. neutrinos
12.6+/-5.1 atm. muons



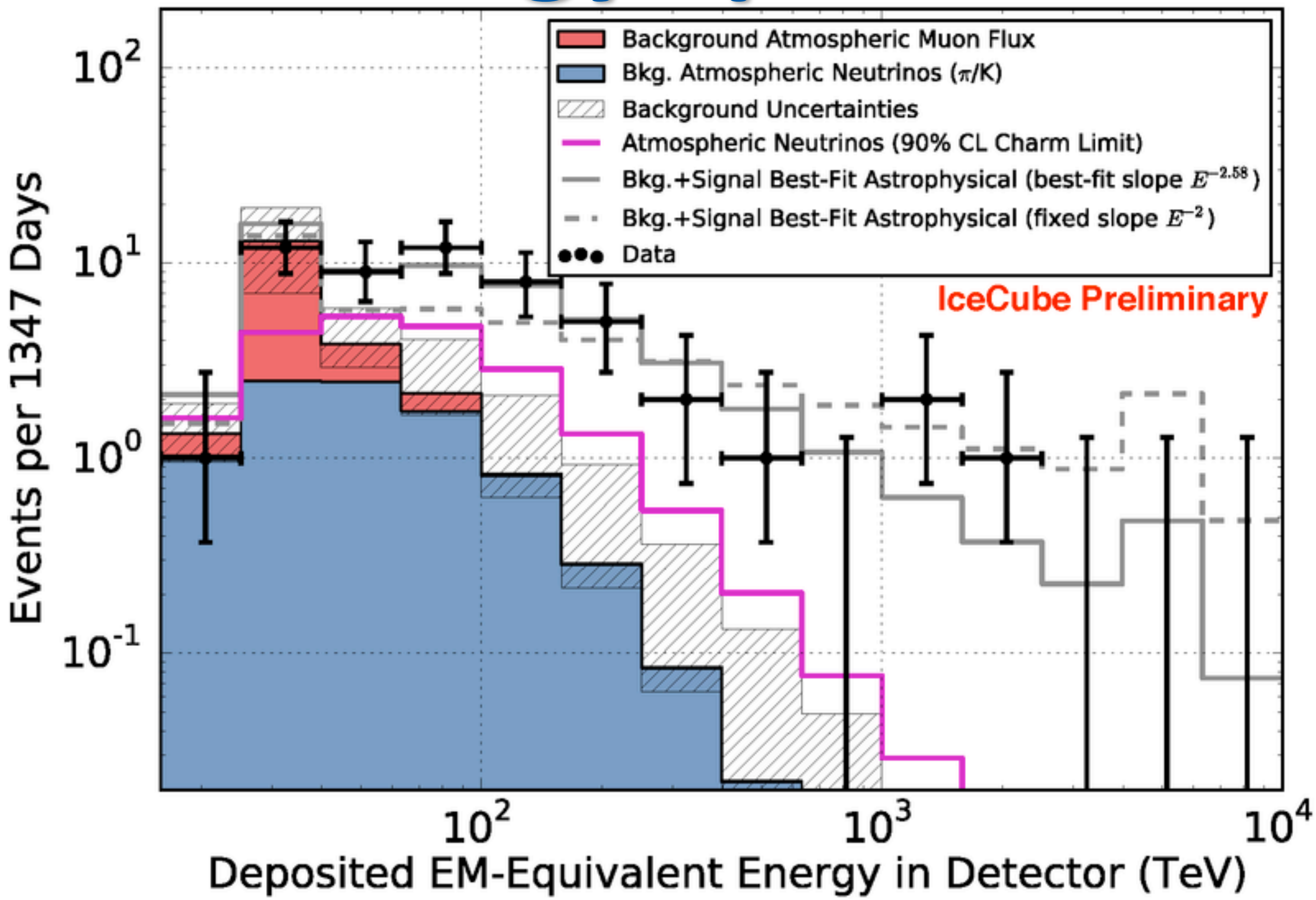
The Highest Cascade Event Ever Observed



Angular distribution



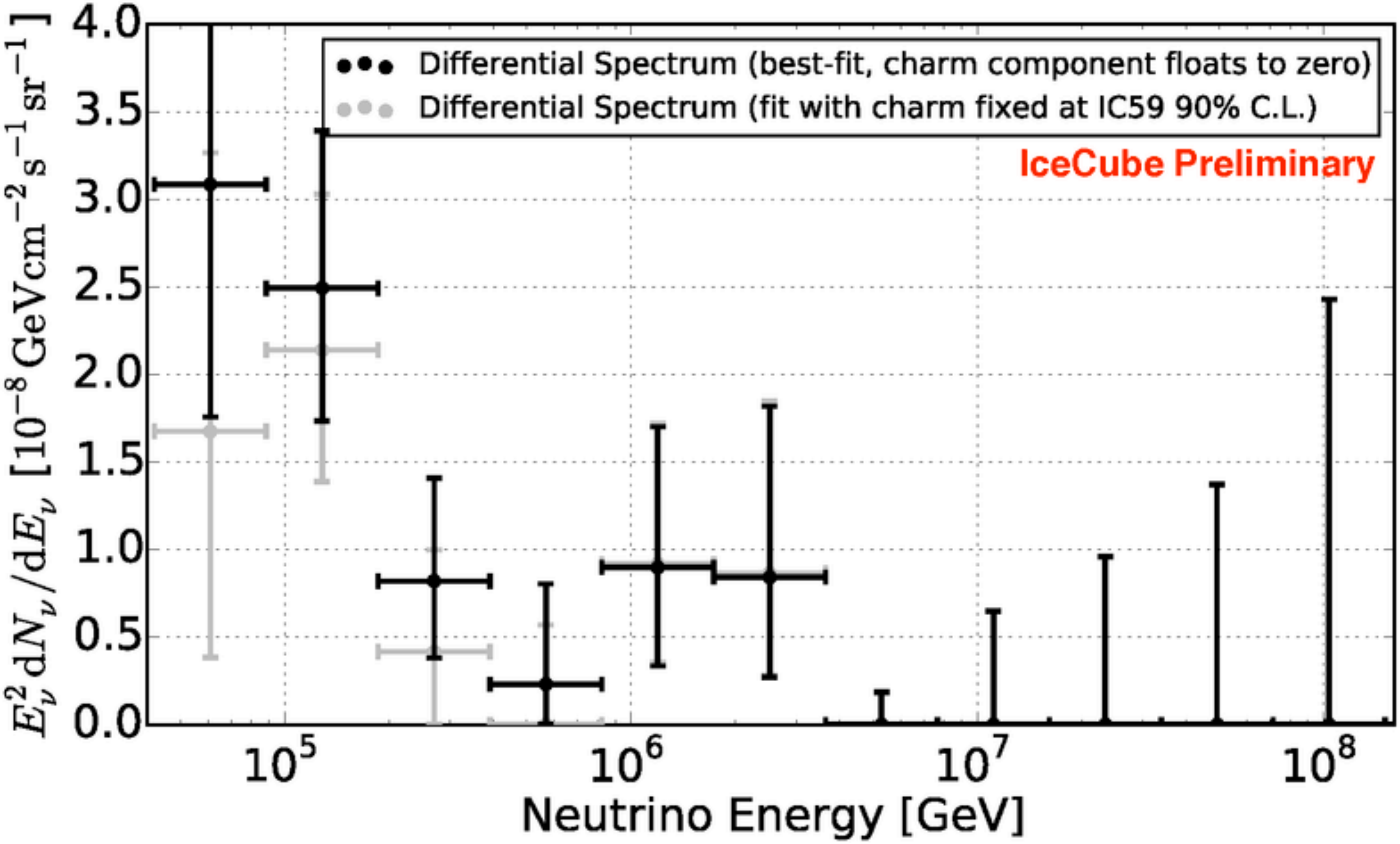
Energy Spectrum



4 years

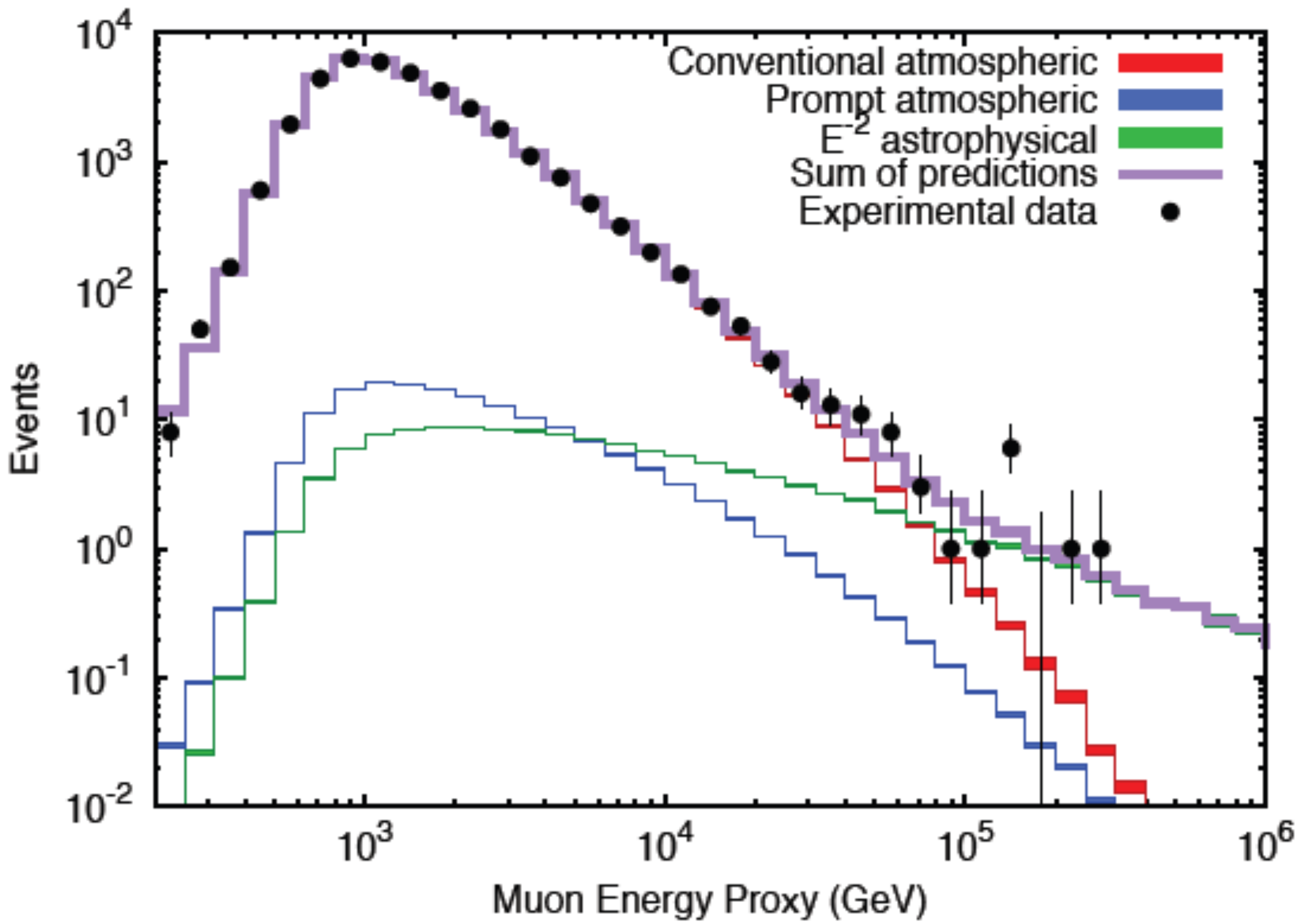
best-fit per-flavor astrophysical (E^{-2}) flux

$E^2\phi(E) = 0.84 \pm 0.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}



Differential Spectrum (best-fit, charm component floats to zero)
Differential Spectrum (fit with charm fixed at IC59 90% C.L.)
IceCube Preliminary
$E_\nu^2 \mathrm{d}N_\nu/\mathrm{d}E_\nu$ $[10^{-8}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}]$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]

An independent analysis



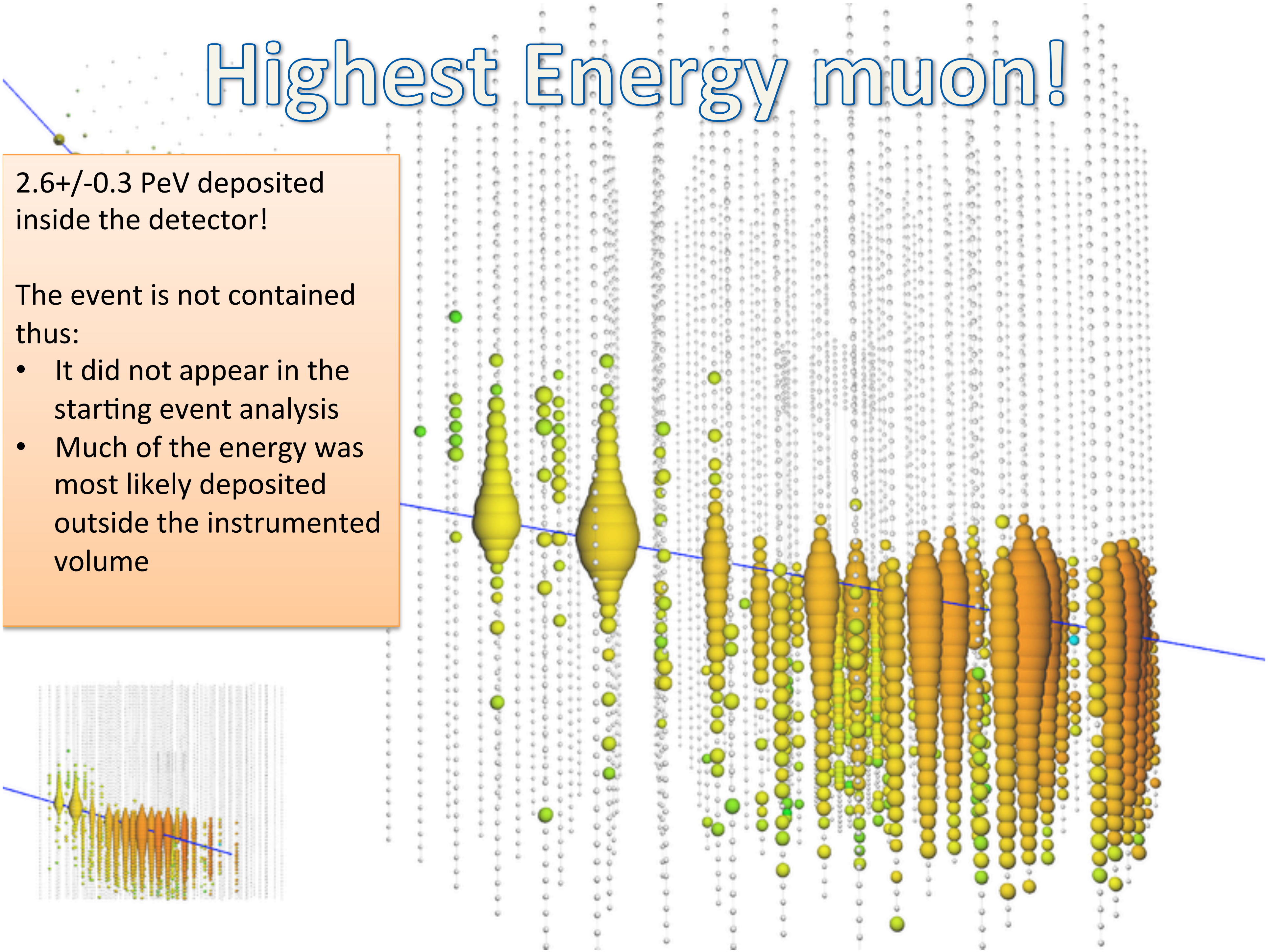
- Look at all muons from the northern hemisphere (no veto)
- Look only at the northern sky so atmospheric muons are removed
- You are left with atmospheric plus astrophysical neutrinos
- See if the spectrum of atmospheric neutrinos alone can explain what you see

Highest Energy muon!

2.6+/-0.3 PeV deposited inside the detector!

The event is not contained thus:

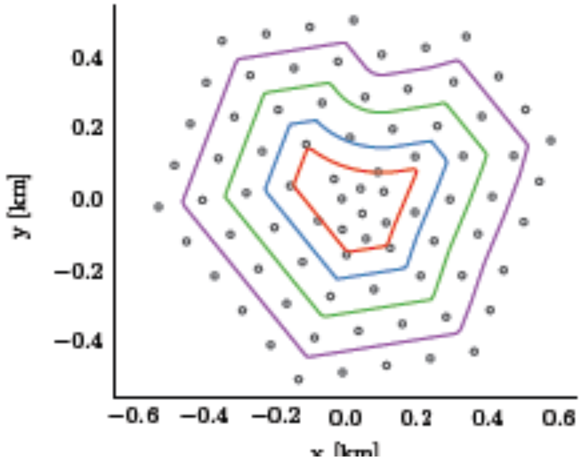
- It did not appear in the starting event analysis
- Much of the energy was most likely deposited outside the instrumented volume

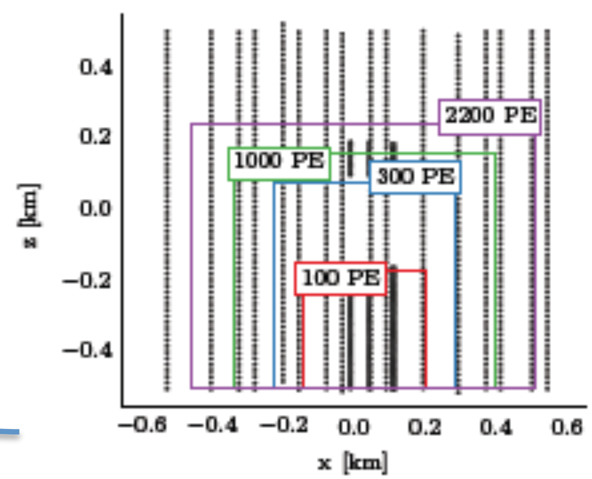


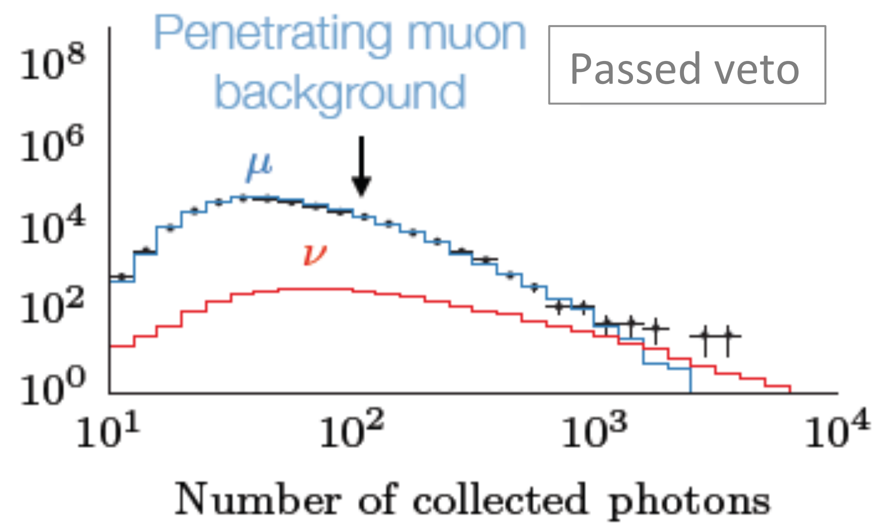
Veto Approach: extending to lower energies

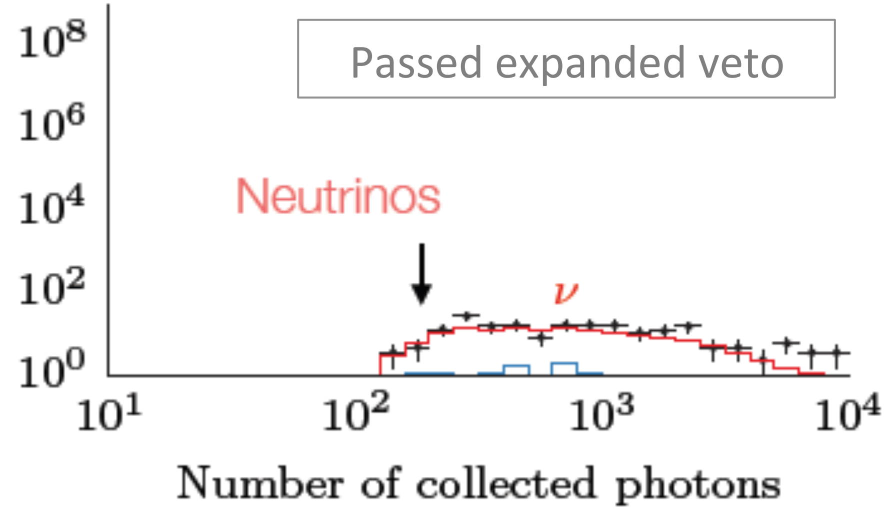
to further study astrophysical flux, and constrain charm

Widen veto region for lower energy events

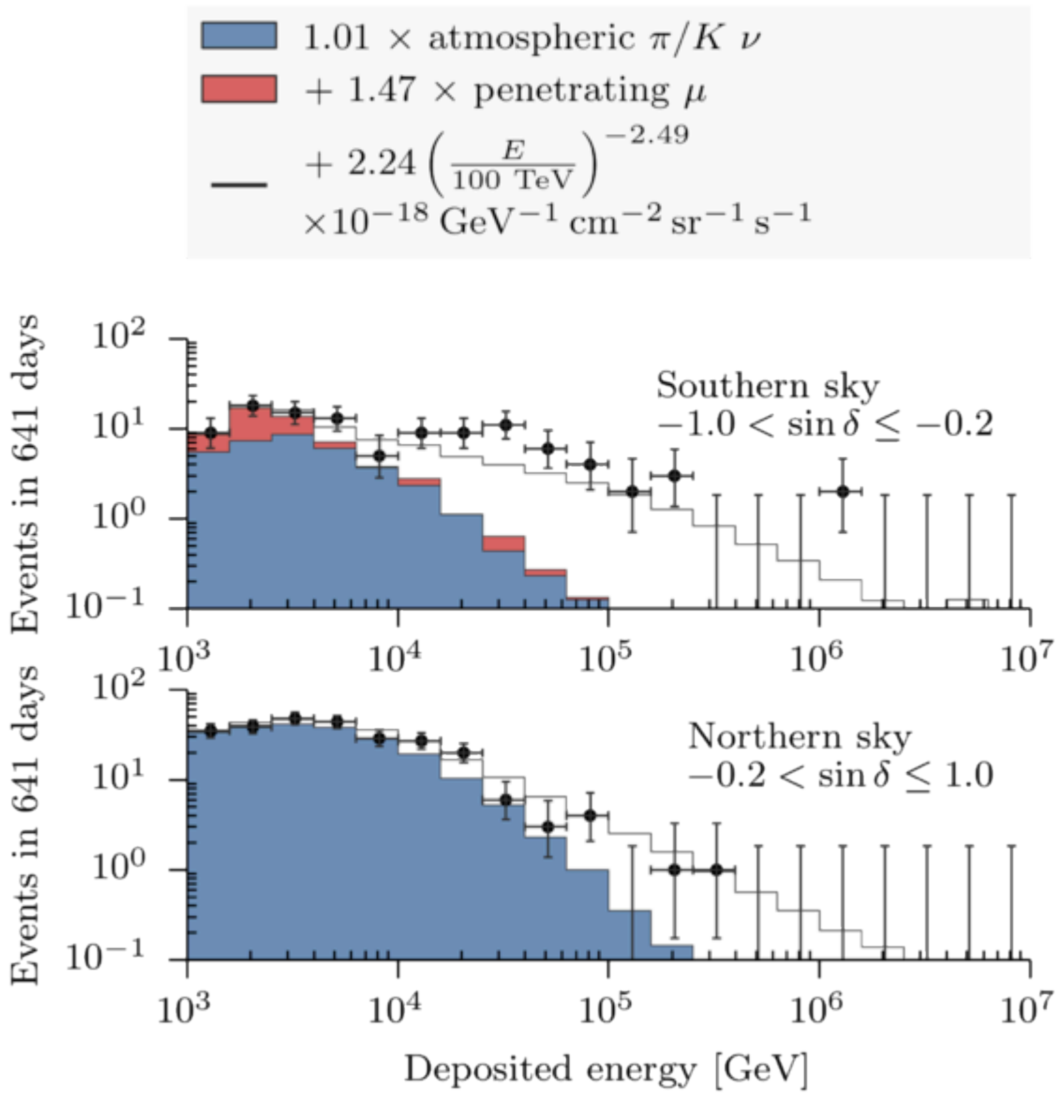








Medium Energy Event Veto



283 cascades
105 tracks

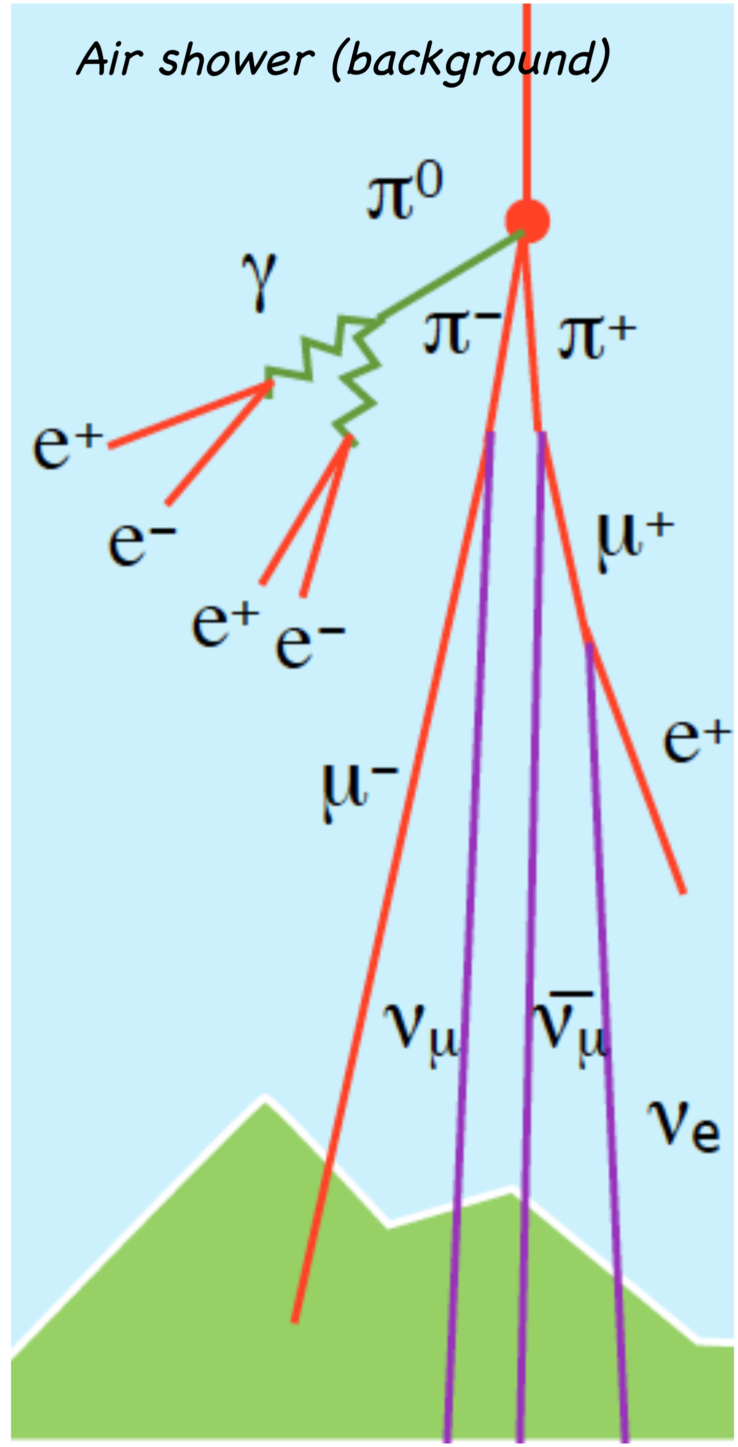
Steeper spectral index favored (if no break in the power law).

Astrophysical excess extends down to 10 TeV in Southern sky.

Upper limit on charmed mesons: 1.4 ERS (PRD78:43005)

Why do we think this flux is astrophysical?

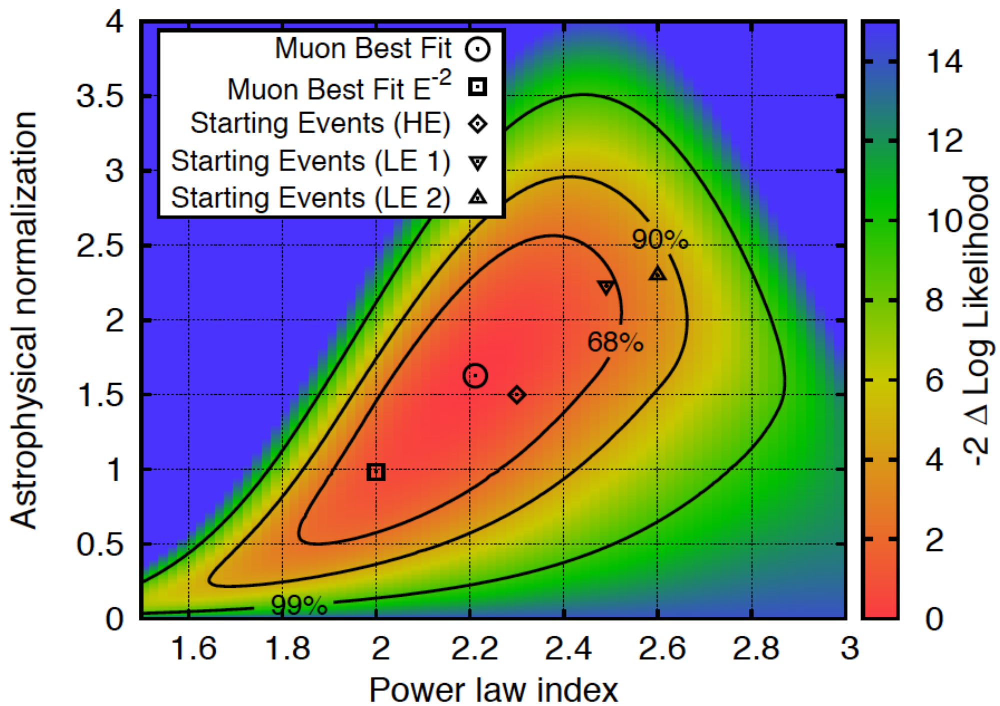
- Neutrinos produced in the atmosphere in the Southern hemisphere would be accompanied by muons
- The Earth is neutrino absorbing at high energies, and there are slightly more events in the South
- Neutrinos produced in atmospheric interactions are preferentially ν_μ and we see mostly cascades (from ν_e, ν_τ?)
- The rate/energy is too high
- The flux is what we expected it to be (that's why we built a km^3 detector)
- We have corroborating evidence in an independent analysis



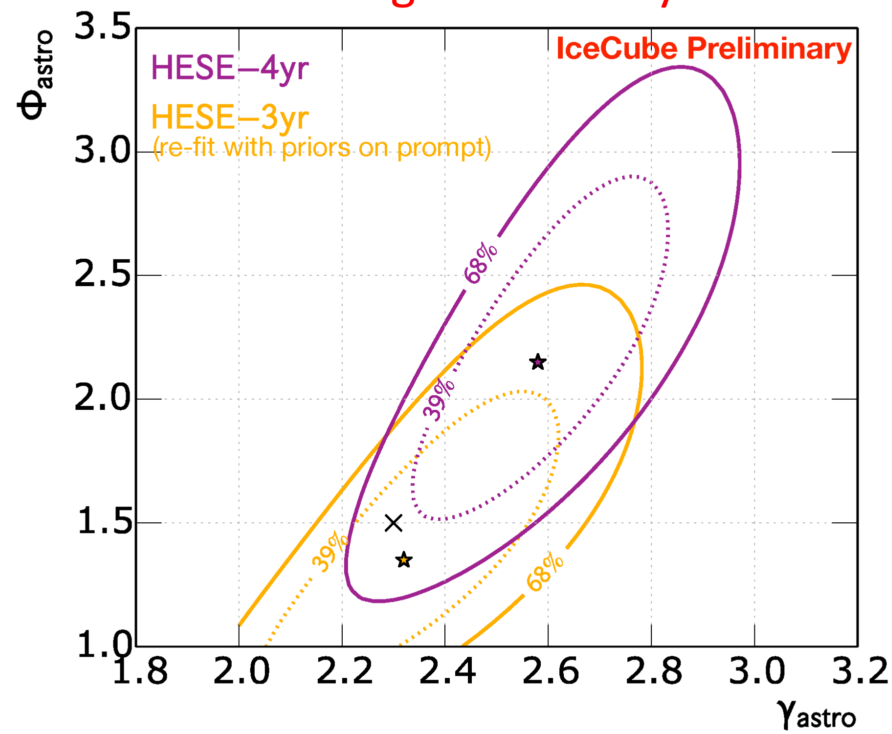
Fits: Normalization & Spectral Index

What is the flux?

Recently published (1507.04005)



New starting event analysis

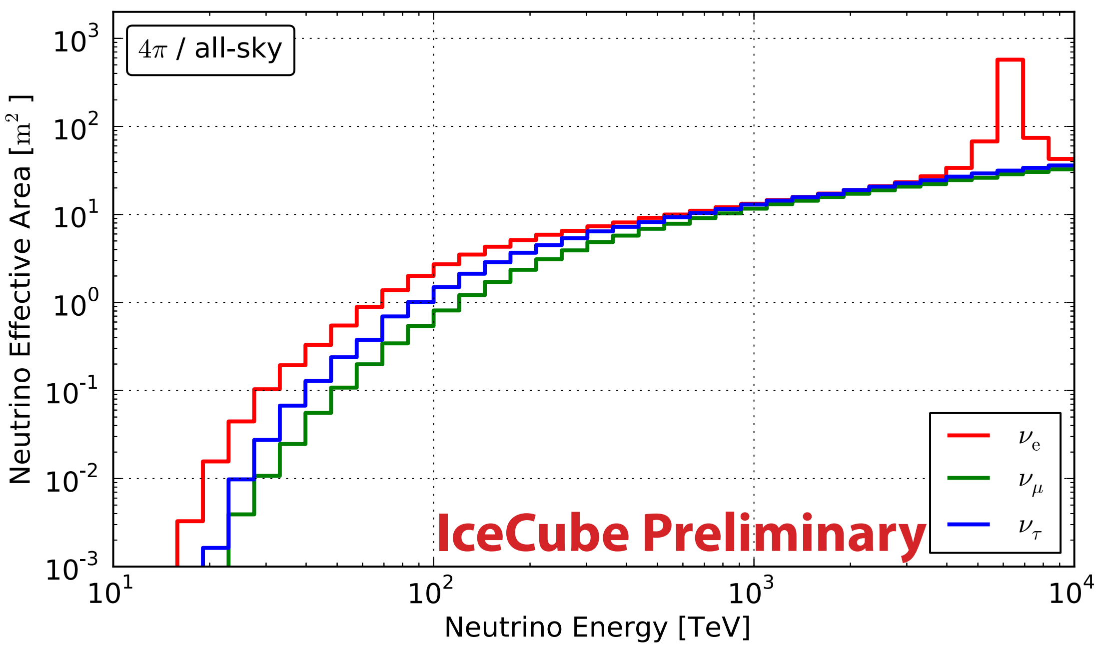


What we (don't) know:

- Observed events have a hard spectrum.
- At energies just above the end of our spectrum (E_ν=6.3 PeV), we expect an increased rate due to the Glashow resonance

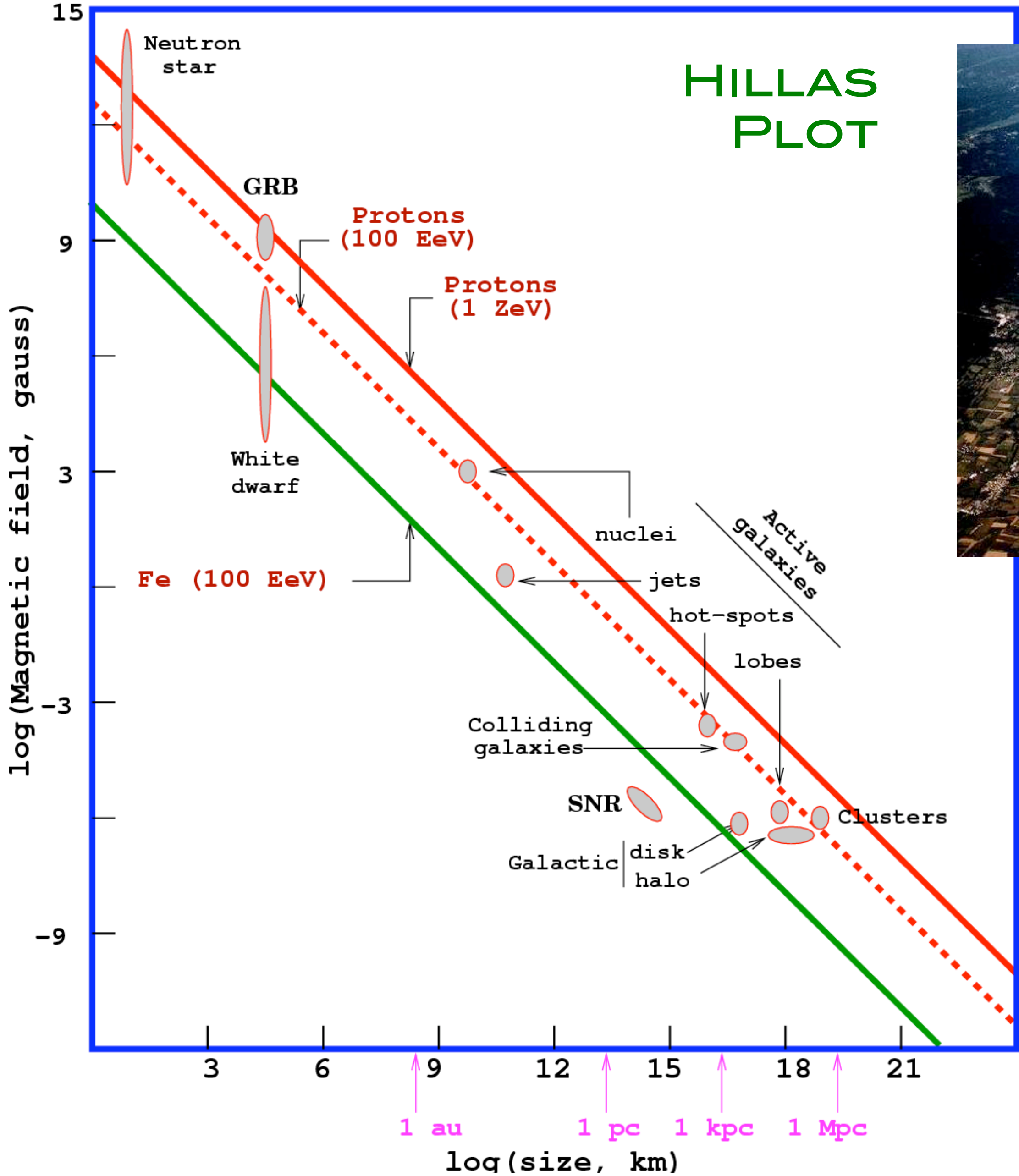
$$\overline{\nu}_e e^- \rightarrow W^-$$

- The lack of observation of events at the Glashow resonance implies that either the spectrum ends at a few PeV, or the spectrum is steeper than E^{-2}…




Part III: What is it?

Candidate accelerators

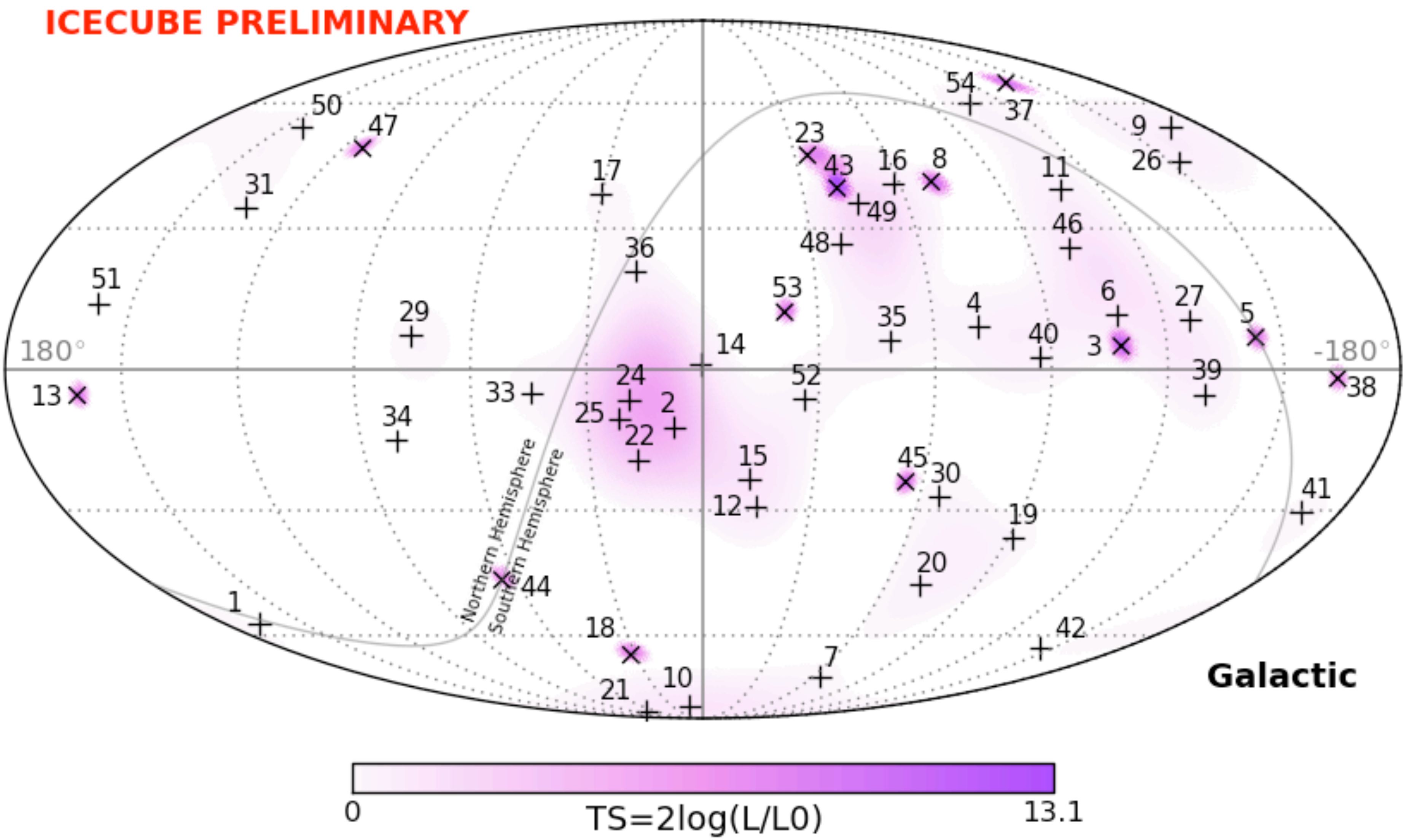


Requirements:

large radius

large magnetic field

Where do they come from?



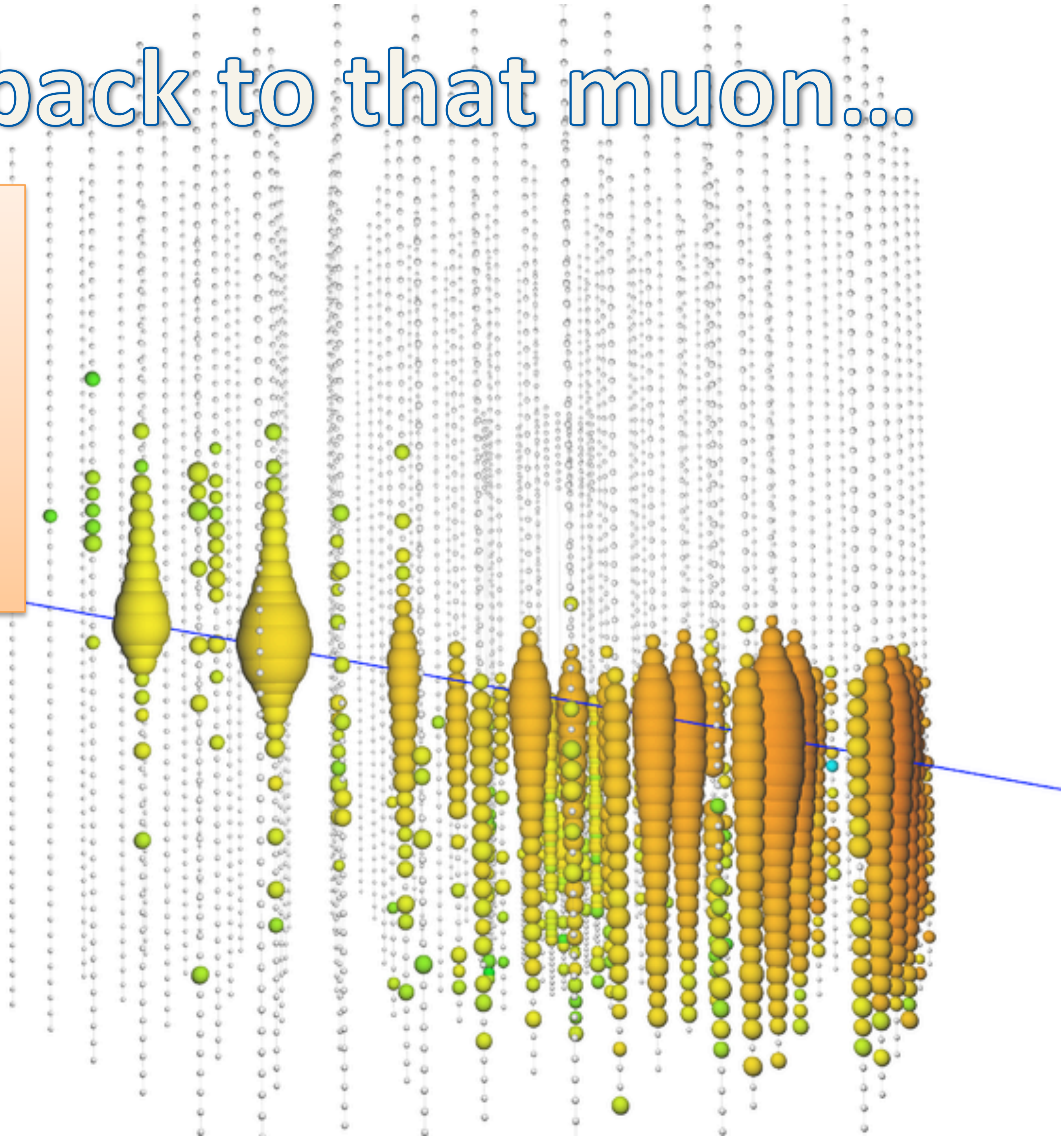
We need more statistics and/or a multimessenger approach

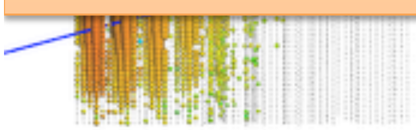
Now, back to that muon…

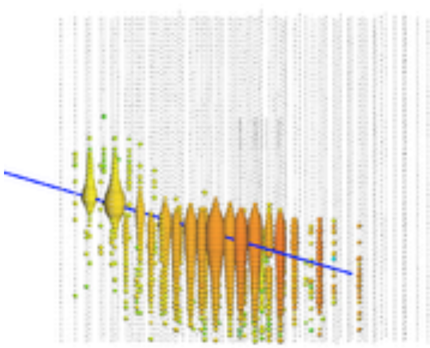
2.6+/-0.3 PeV deposited inside the detector!

A muon event so it points!

- Most similar events have an angular error of less than 1 degree
- There's "a lot of stars in the sky"…*sigh*







Multimessenger astronomy

M. Ahlers, ICRC 2015

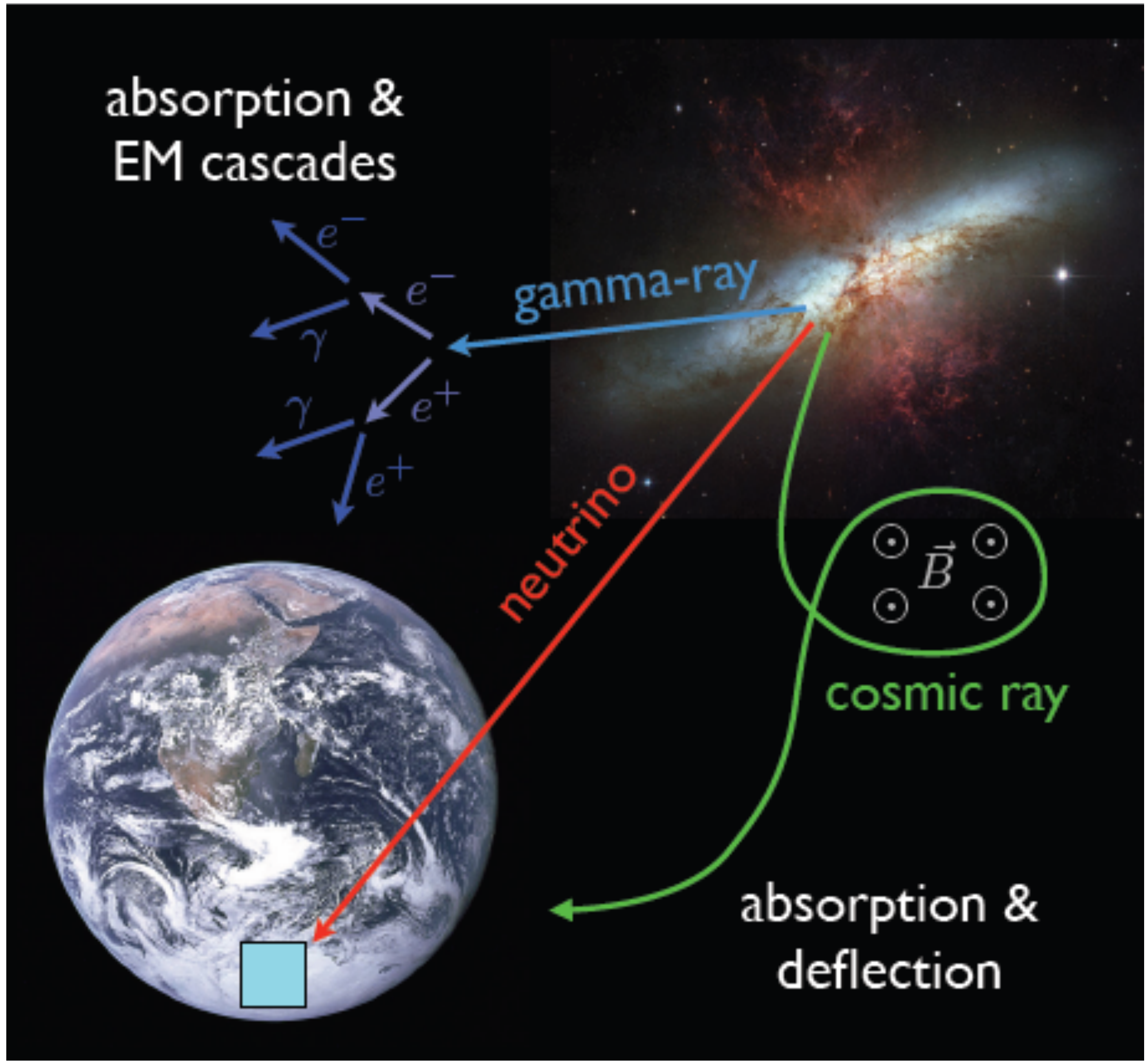
Messengers:

- Cosmic rays
- Gamma-rays
- Neutrinos
- Gravitational waves

Pion production in CR interactions with "gas" (pp) or "radiation" (pγ)

Neutrinos carry ~ 5% of the CR nucleon energy

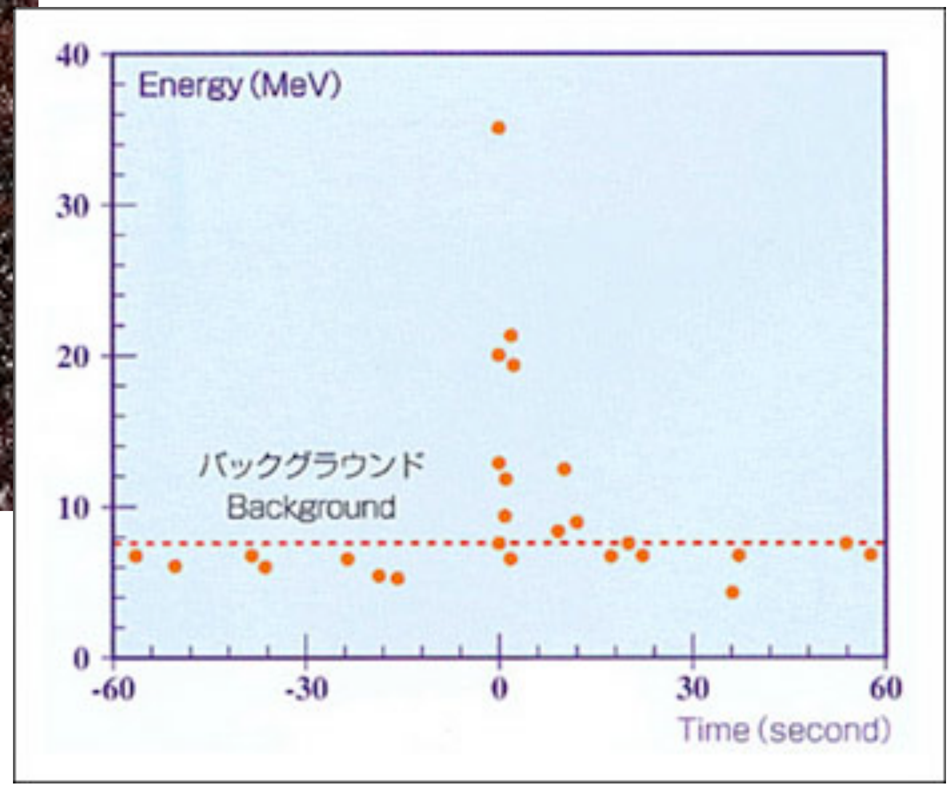
1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays



Supernova 1987A

After Before

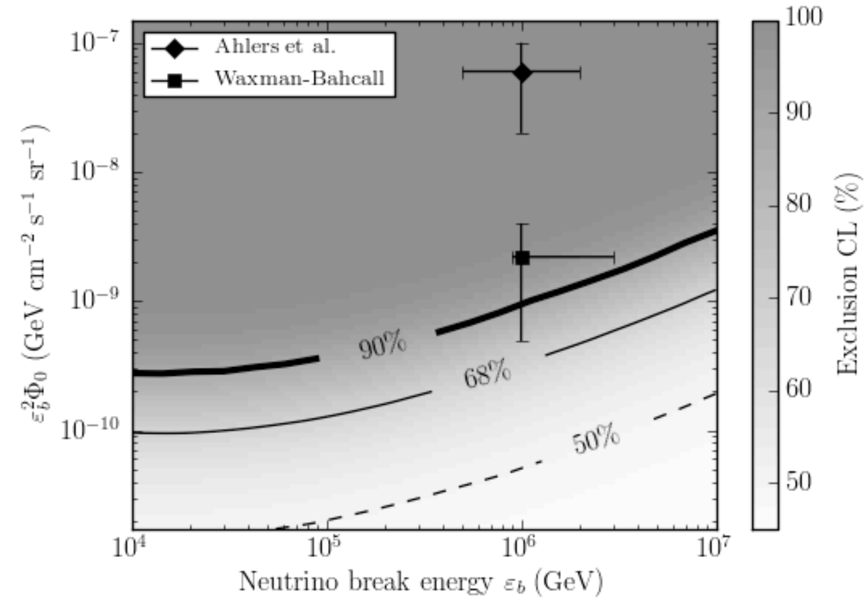
- Occurred in the Large Magellanic Cloud 170,000 ly away
- Low energy (~15 MeV) neutrinos
- Proper time: 1hour

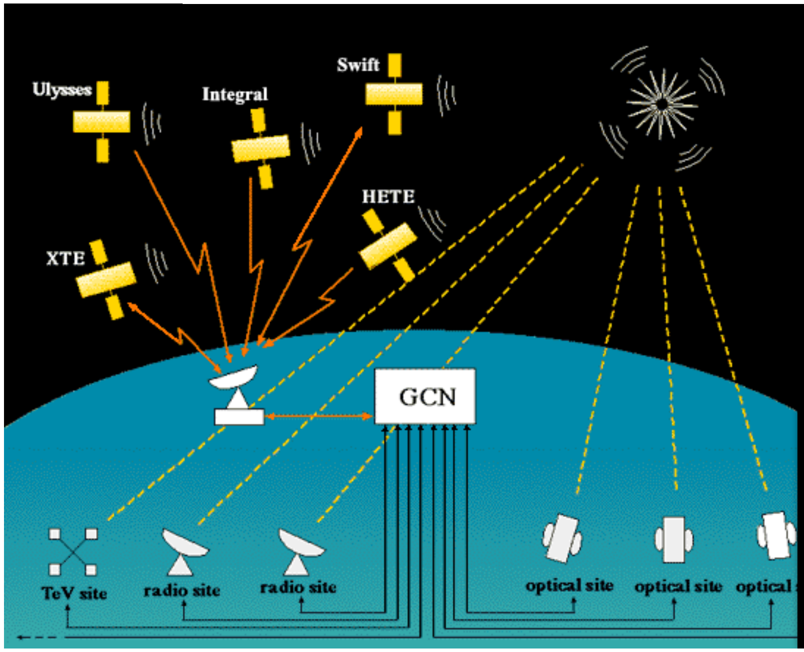


- Confirmed models of the core collapse of a massive star
- Yielded upper limits on neutrino mass and lifetime.

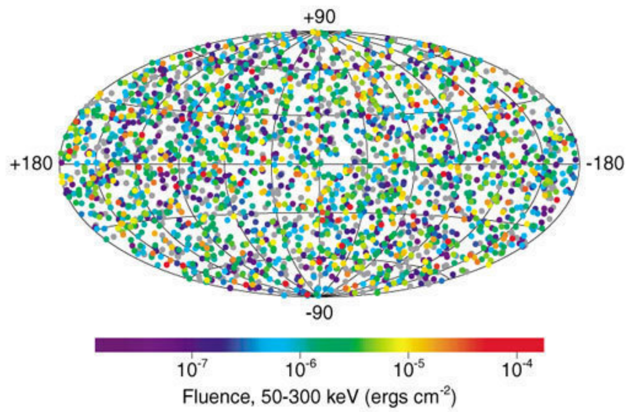
Origin of neutrinos determined due to correlated observations with optical telescopes!

Gamma-ray bursts





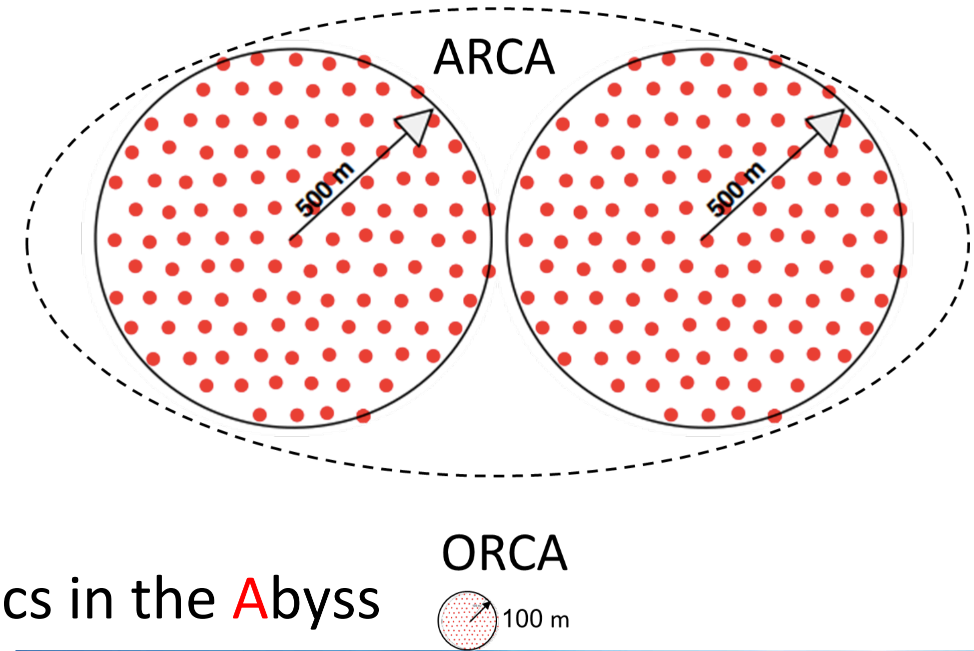
Look for neutrinos that are on time and on source for reported GRBs. (No events seen.)



Part IV: The Quest for More Statistics & Higher Energies

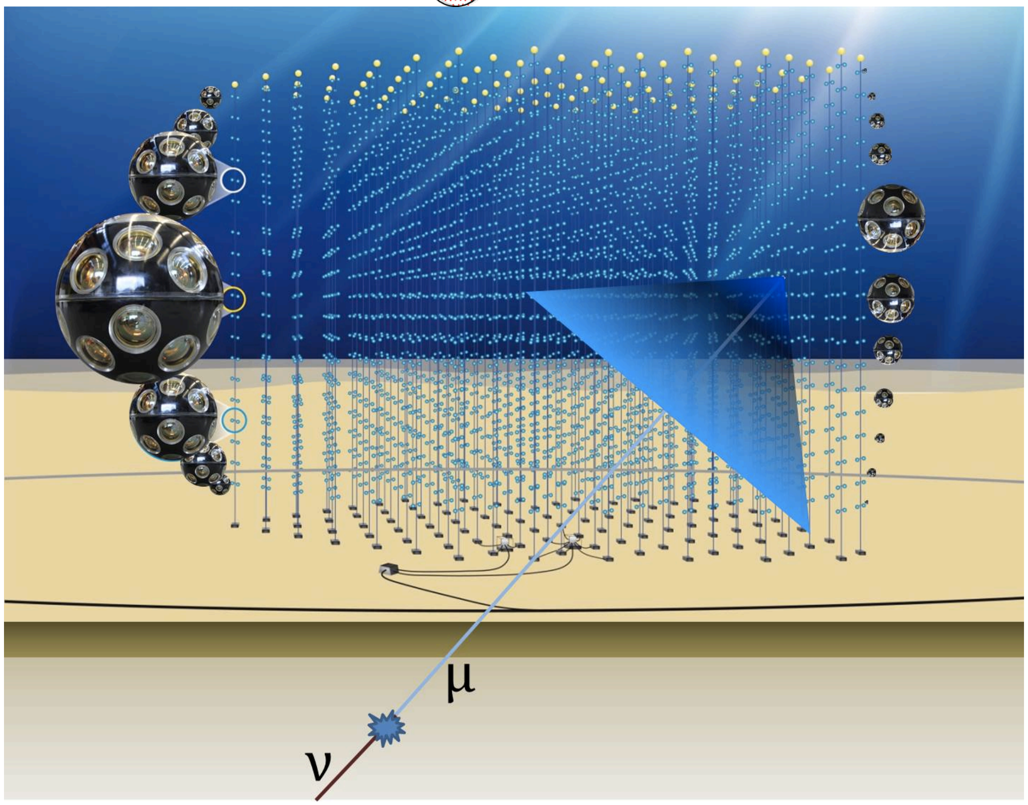
KM3Net

Successor to ANTARES in the Mediterranean



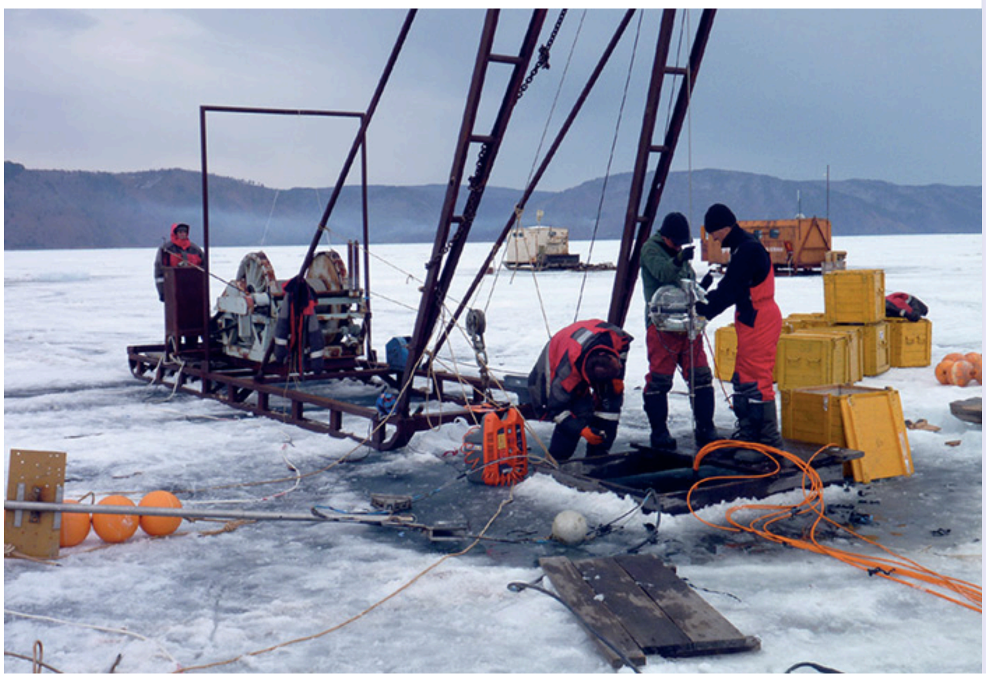
2 components:
Astroparticle &
Oscillations Research with Cosmics in the Abyss

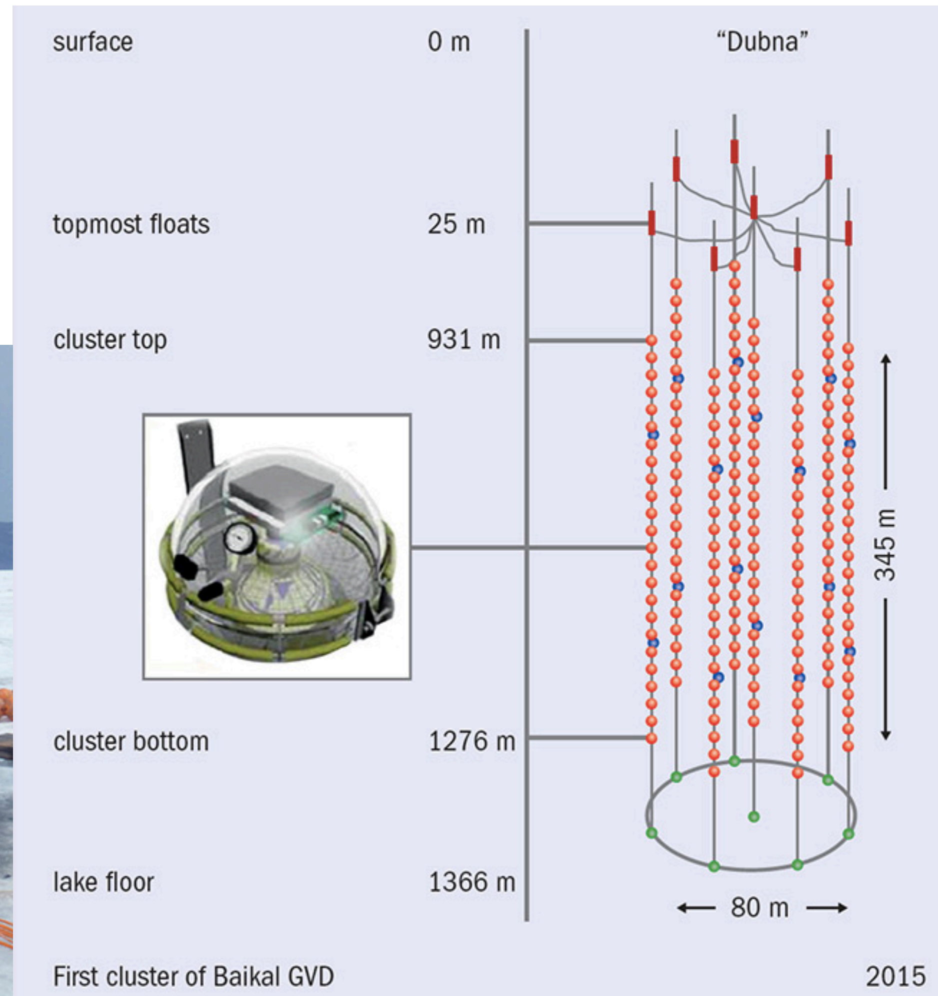
- KM3Net 'detection unit'
  - Line anchored to the sea floor
  - 18 equally spaced modules
- 2 ARCA blocks
  - 115 lines
  - 90m horizontal
  - 36m vertical
- 1 ORCA block
  - 115 lines
  - 20 horizontal spacing
  - 6m vertical spacing



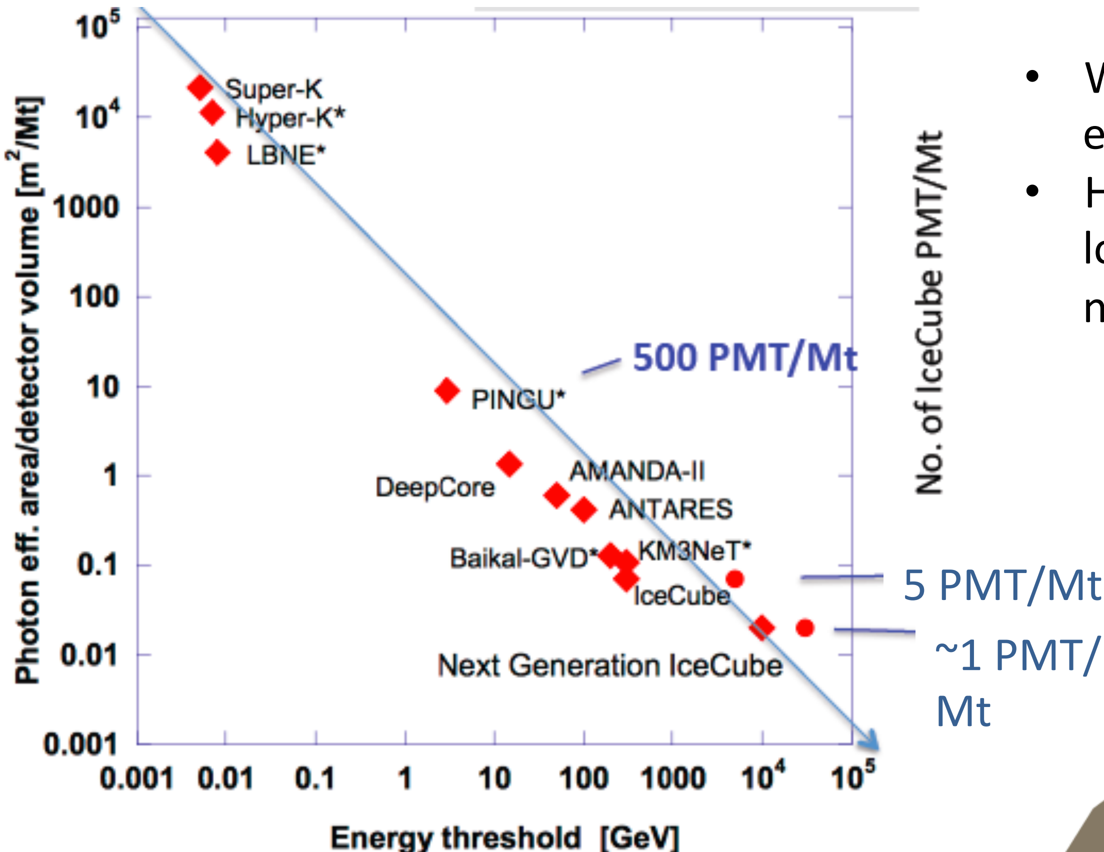
Baikal GVD (Gigaton Volume Detector)

- Planned for a deep Siberian lake which was the site of one of the pioneering neutrino telescopes
- First "cluster" installed in early April
- Phase I: 10-12 clusters covering 0.4 km^3 by 2020
- Phase II: 25 clusters covering 1.5 km^3

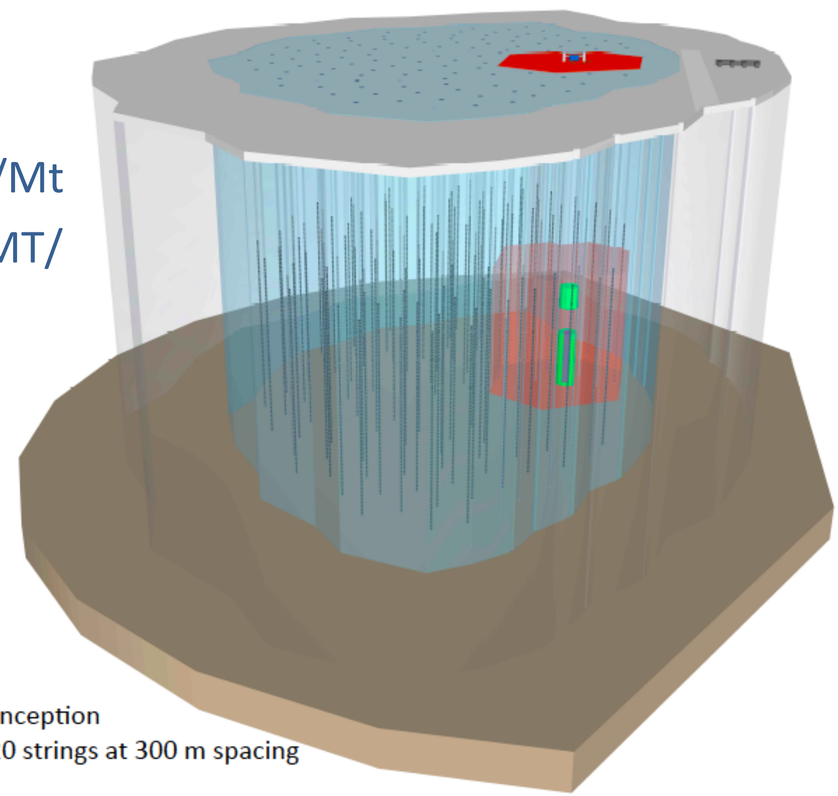




A Next Generation IceCube



- We need to increase statistics at high energies
- Higher energy events are larger -> lower density of instrumentation needed



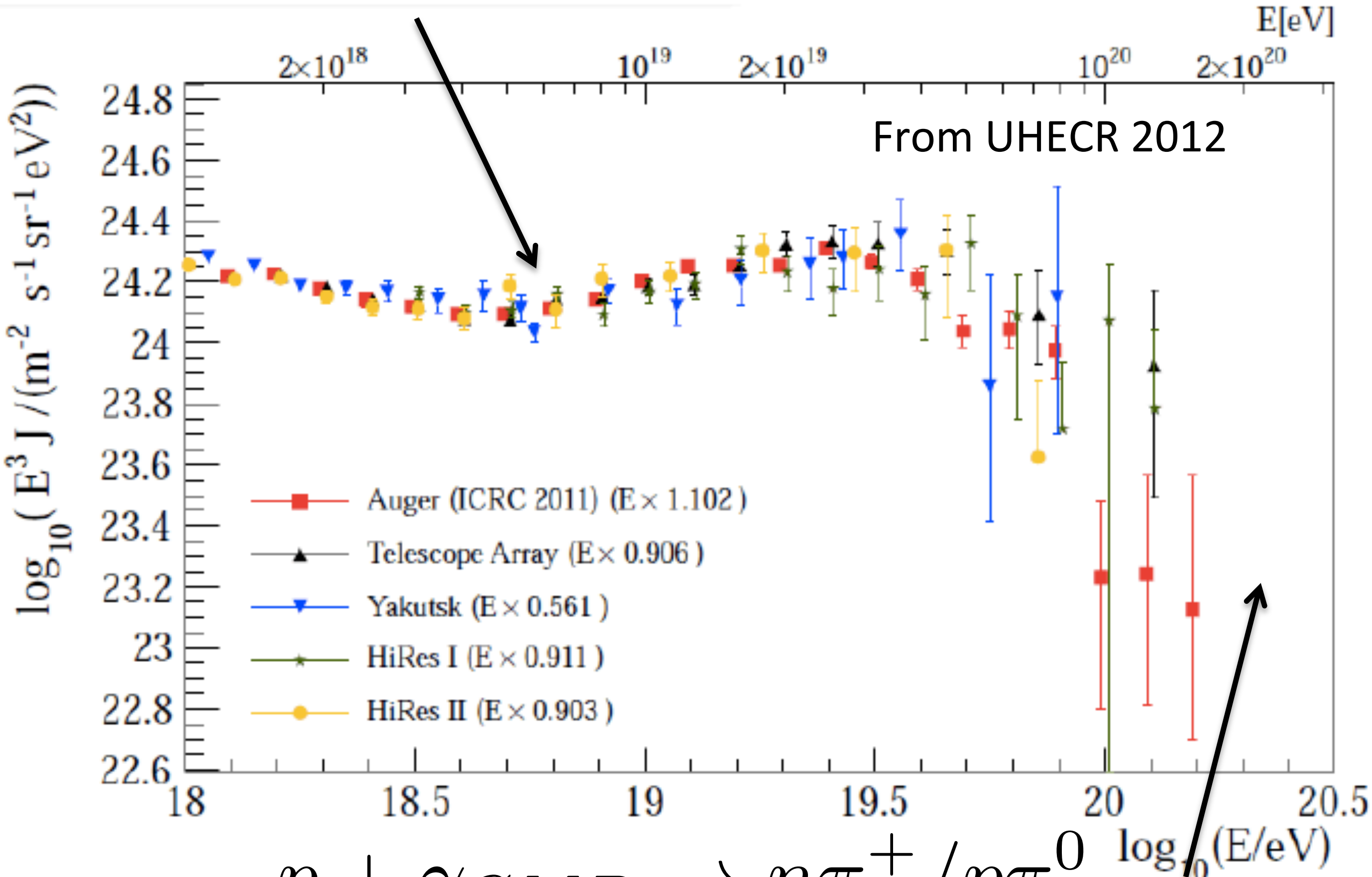
Artist conception
Here: 120 strings at 300 m spacing

- Install a similar amount of instrumentation as is in IceCube, but more sparsely spaced
- Extend IceCube by 1 order of magnitude

The GZK effect

$$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$$?

Greisen, Zatsepin, and Kuzmin (GZK) observed in the 1960's that the propagation of UHE protons with energies above the threshold for pion photproduction on the CMB would be limited.



The observation of a cutoff tells us that cosmic ray accelerators are outside of 50 Mpc… or that the accelerators are running out of juice

$$p + \gamma_{CMB} \rightarrow n\pi^+ / p\pi^0$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$?

Charged pion decay produces neutrinos!!

The Challenge

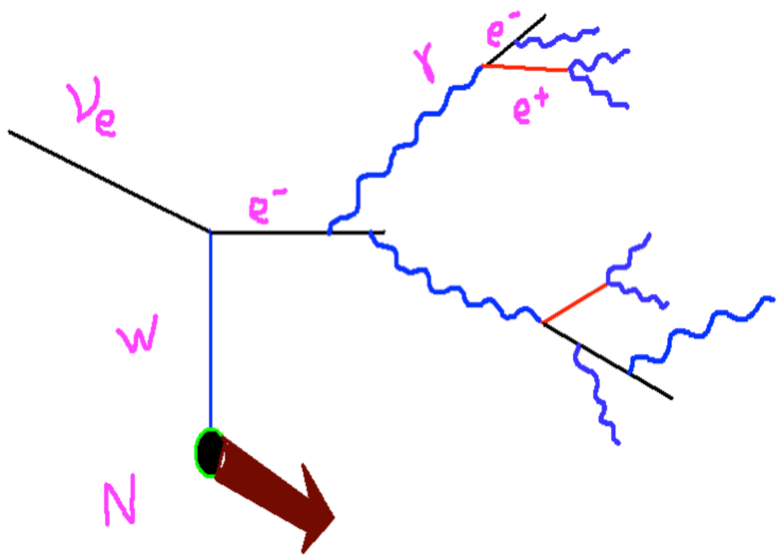
- ~10 νs per kilometer squared from GZK per year
- ~300 km interaction length
- ->0.03 νs per cubic kilometer per year
- Earth is neutrino absorbing so see only above the horizon
- ~0.01 ν /km^2/year

We need >100 km^2 scale detector to see GZK neutrinos

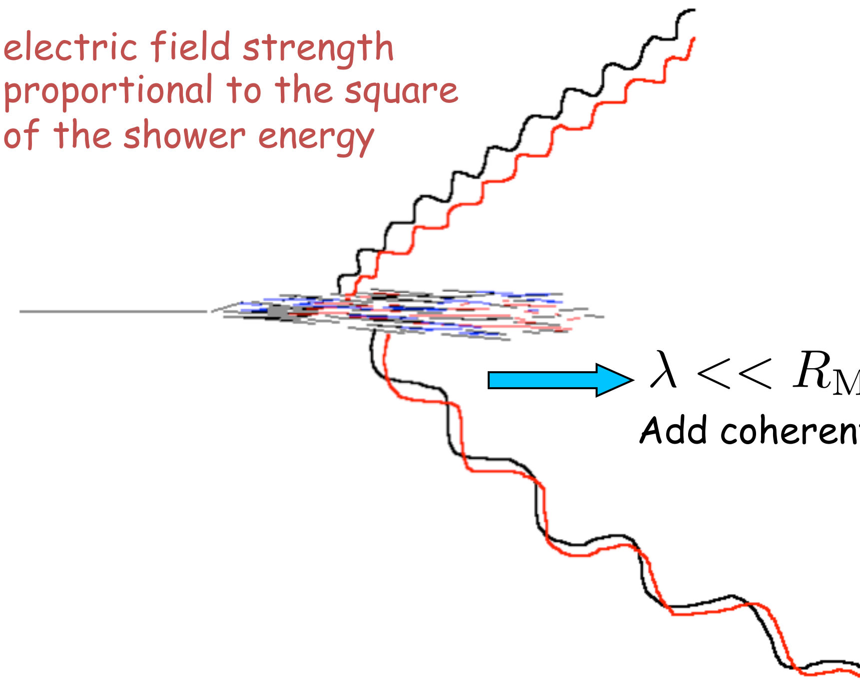
Coherent RF signal from electromagnetic cascade

aka the "Askaryan effect"

charge asymmetry in particle shower development- combined effects of positron annihilation and Compton scattering on atomic electrons result in a 20% excess of electrons over positrons in a particle shower → moves as a compact bunch, a few cm wide and ~1cm thick → wavelengths shorter than the bunch length suffer from destructive interference



electric field strength proportional to the square of the shower energy

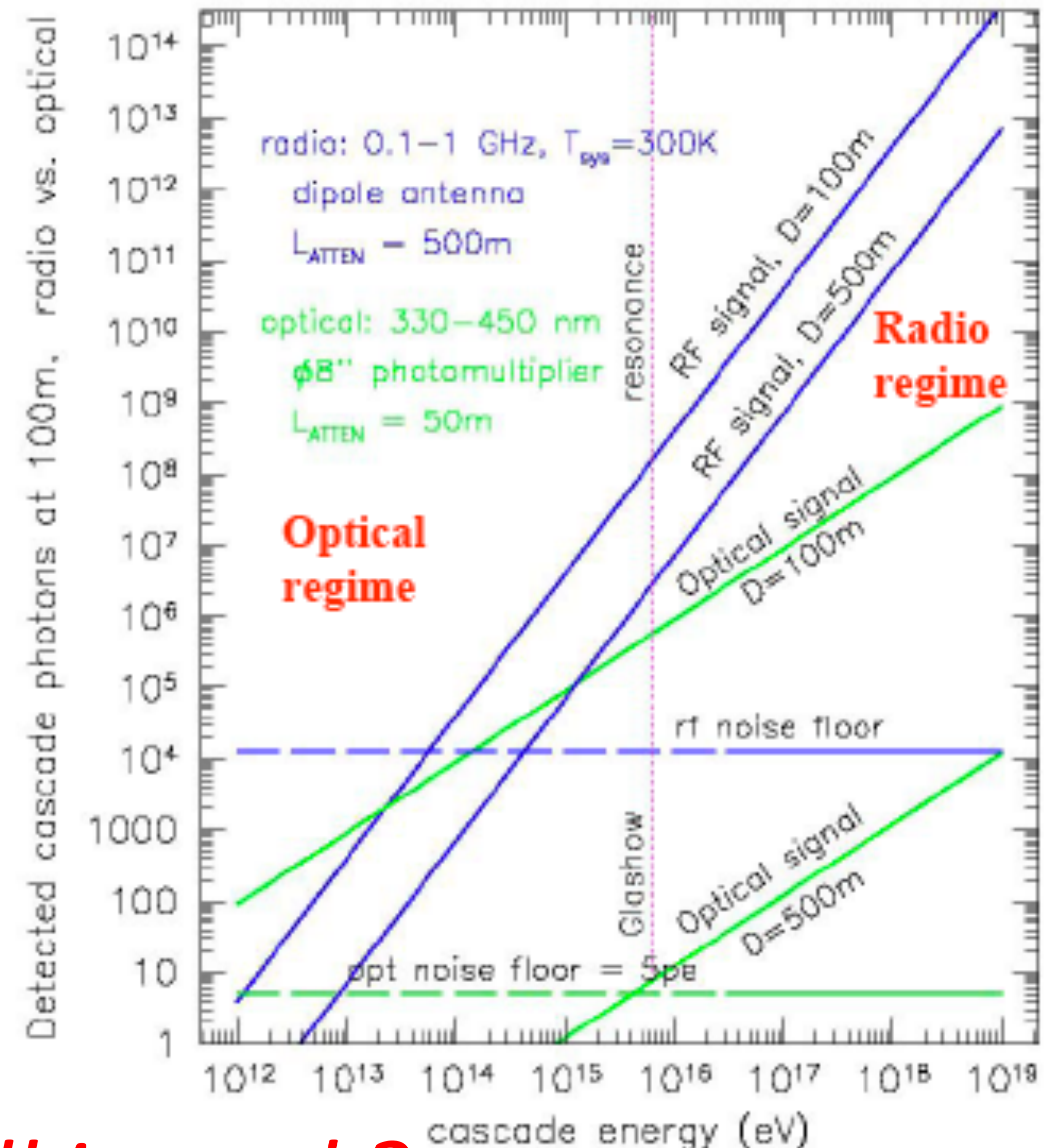


$\lambda << R_{\text{Moliere}}$

Add coherently!

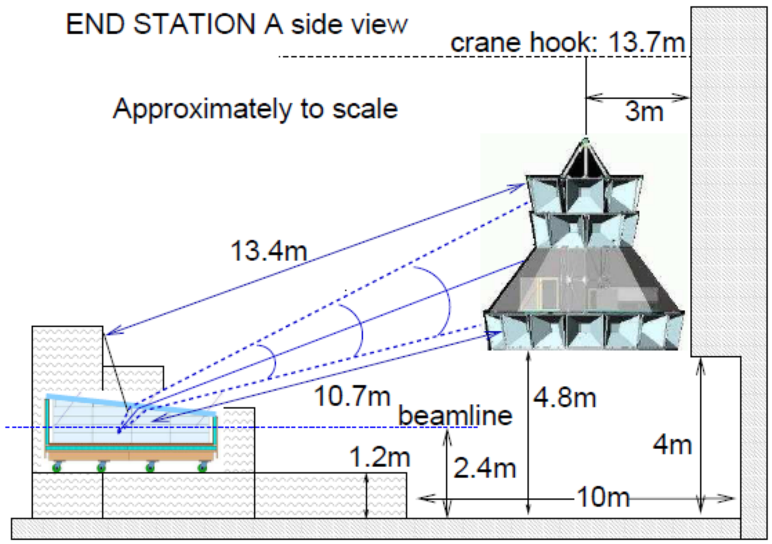
Why radio?

- Power emitted in radio overtakes the optical at high energies
- Spacing of detector components is dictated by the attenuation length in cold ice (~100m for optical, ~1km for radio)
- A large area RF array can be built at lower cost
- Power density increases with frequency, but the thickness of the Cherenkov cone decreases with frequency



...but will it work?

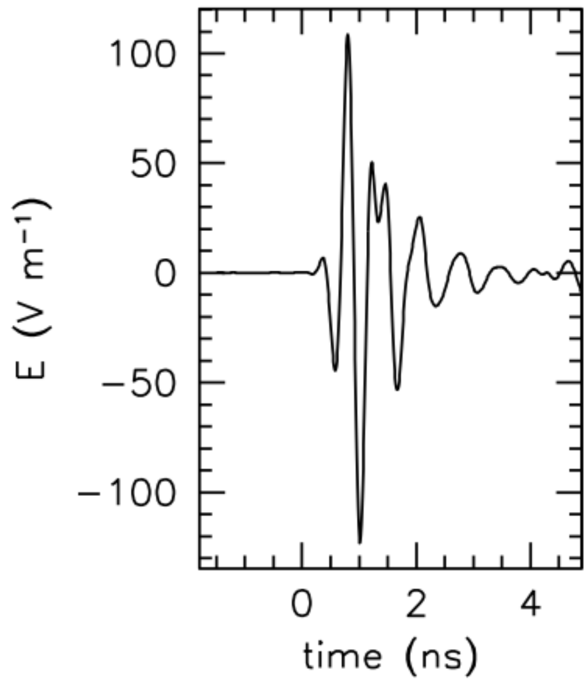
Seeing is believing?



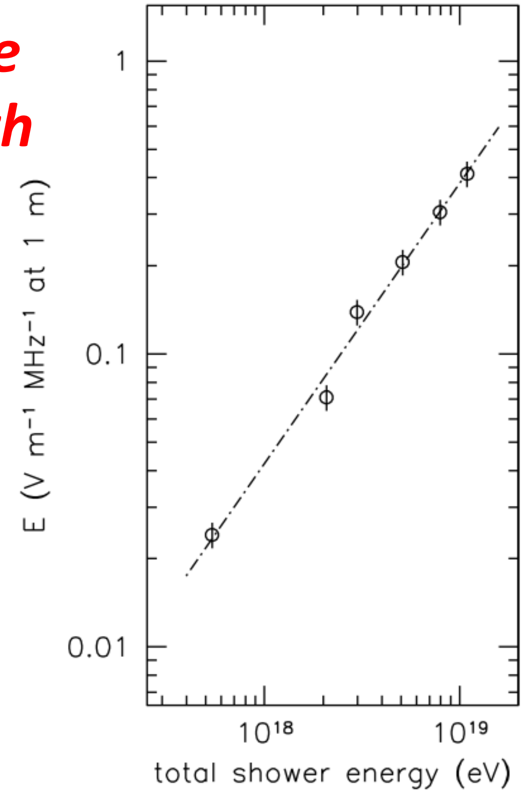
Beam tests

Confirm Askaryan effect in sand, salt, and ice.

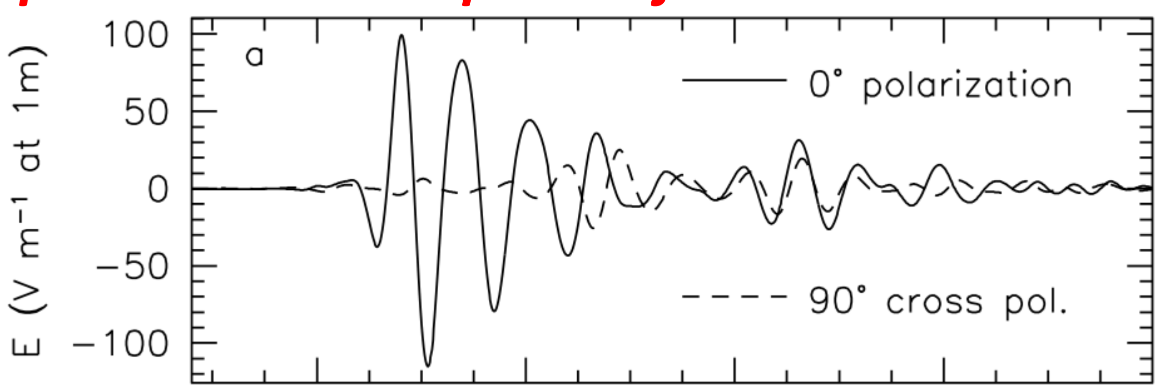
It's impulsive....



It's coherence increases with energy....

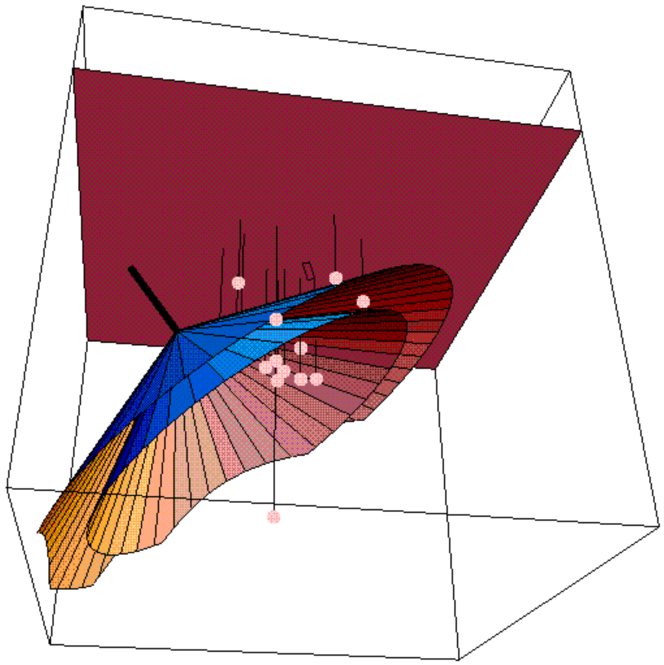


It's polarized....as expected from Cerenkov radiation



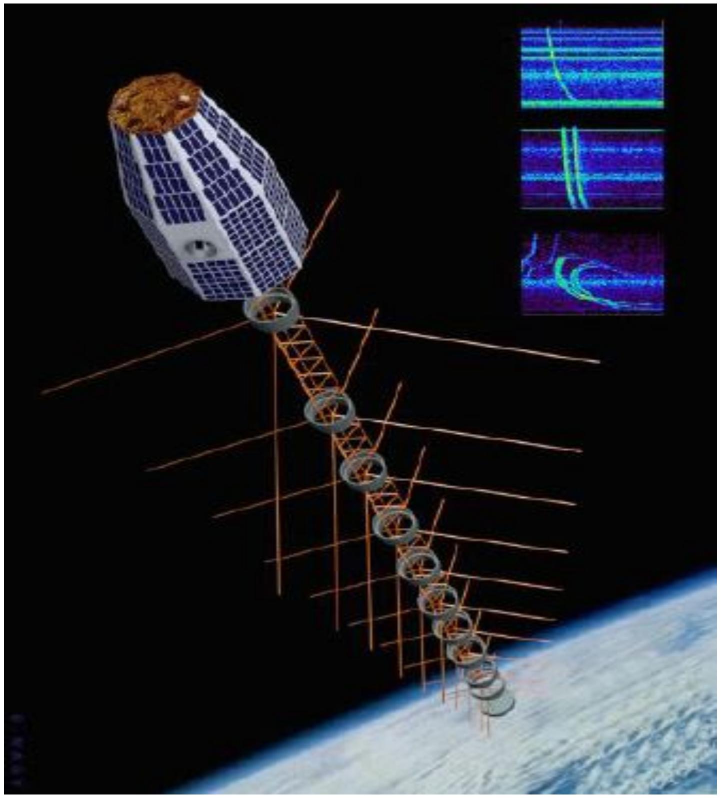
Two Approaches

In-situ



- Smaller area
- Longer observation time
- Lower energy threshold
- Vertex may be reconstructed in the medium (Superior background discrimination)

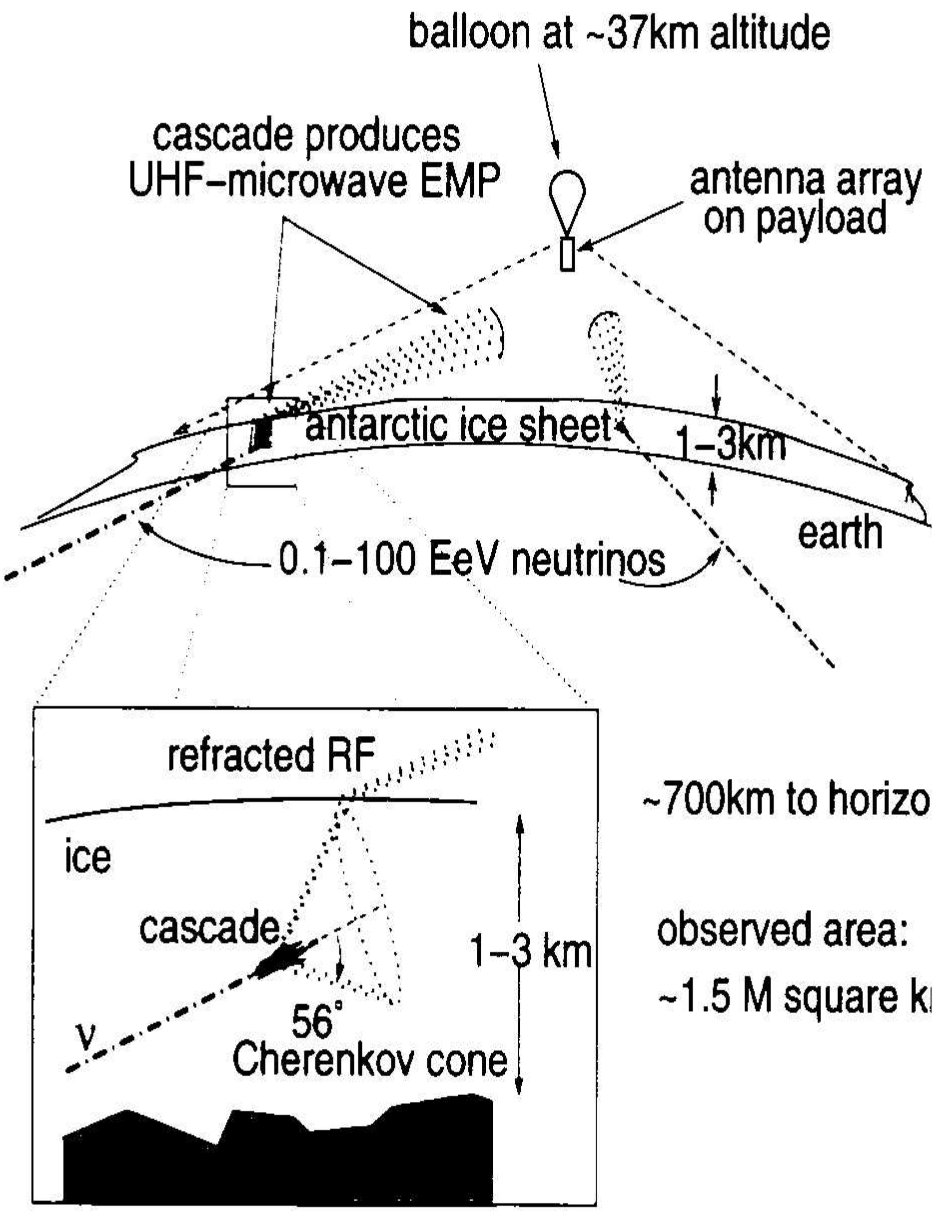
Syntoptic



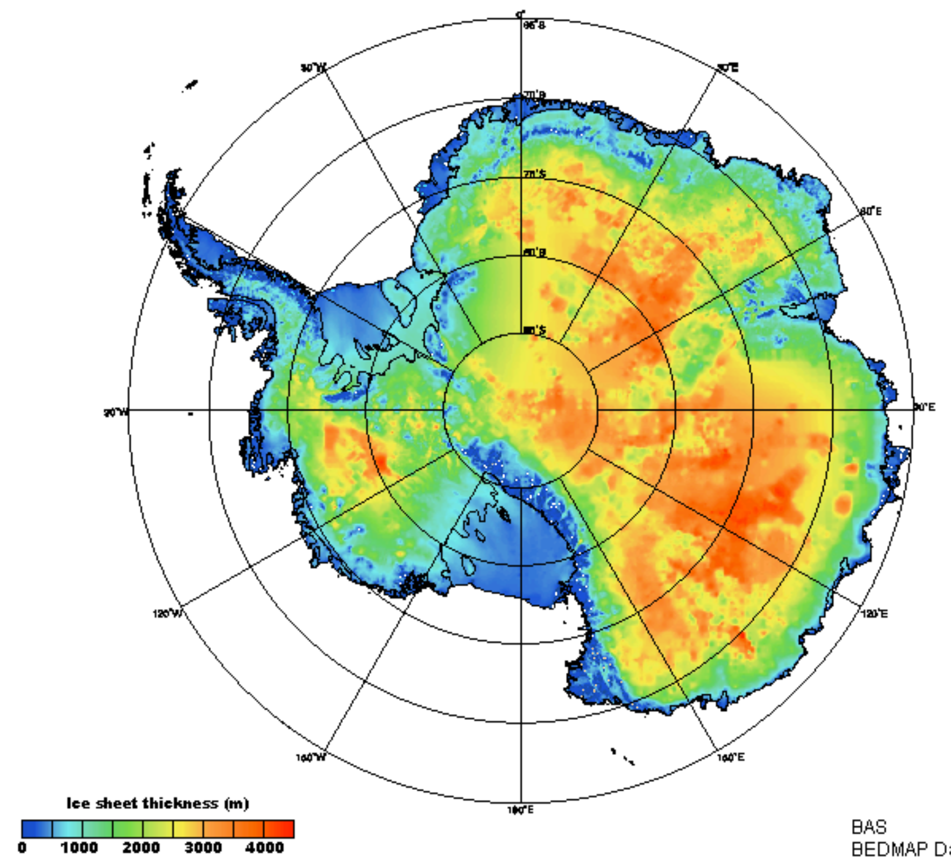
- Larger area
- Higher energy threshold
- Limited by viewing time in most approaches
- Viewing angle limited by total internal reflection
- Surface roughness a concern

ANITA

Antarctic Impulse Transient Antenna

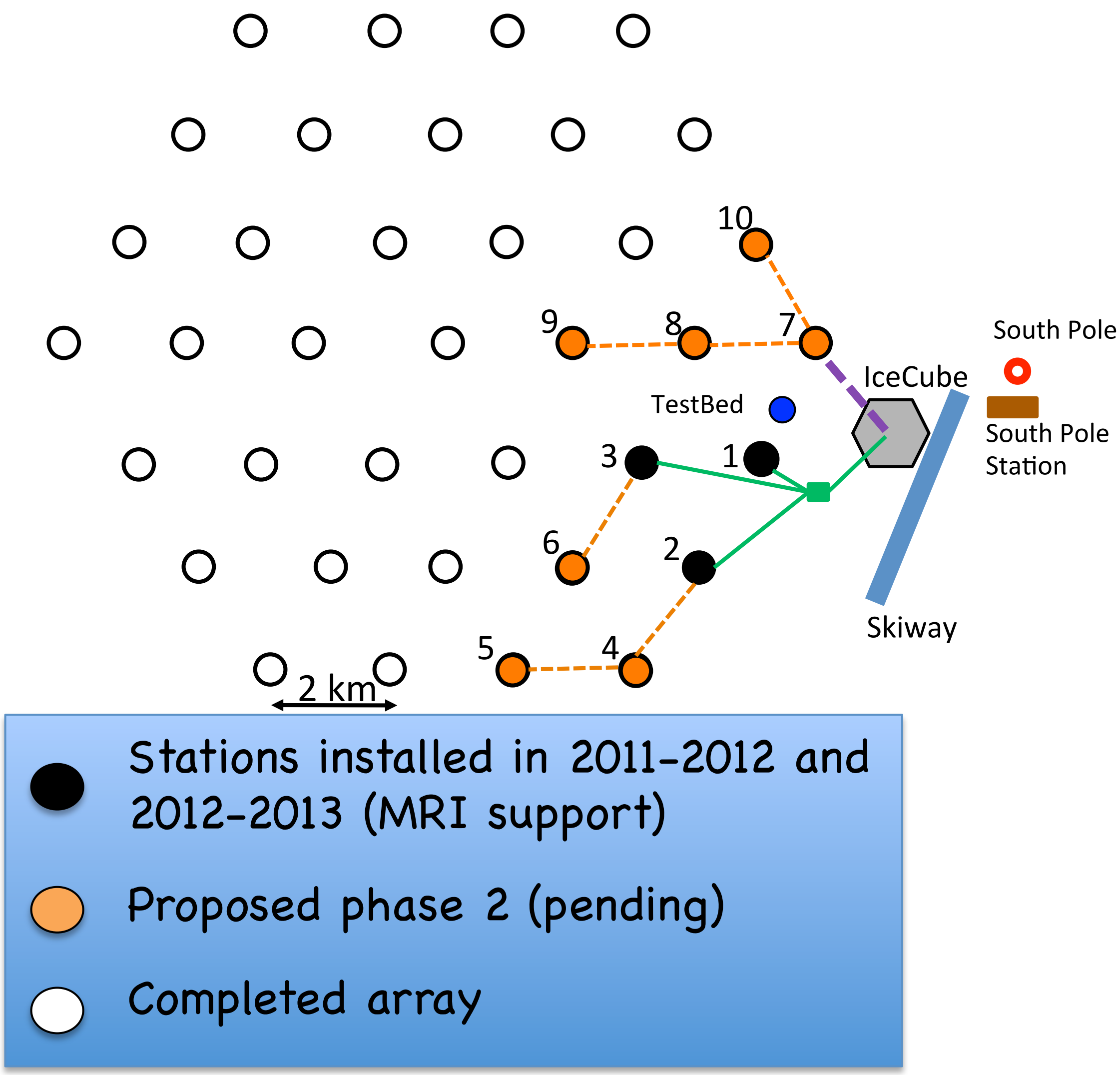


- Views a volume of 1.5 x 10^6 km^3 of ice
- 37 km altitude



A 100 km^3 Neutrino Observatory

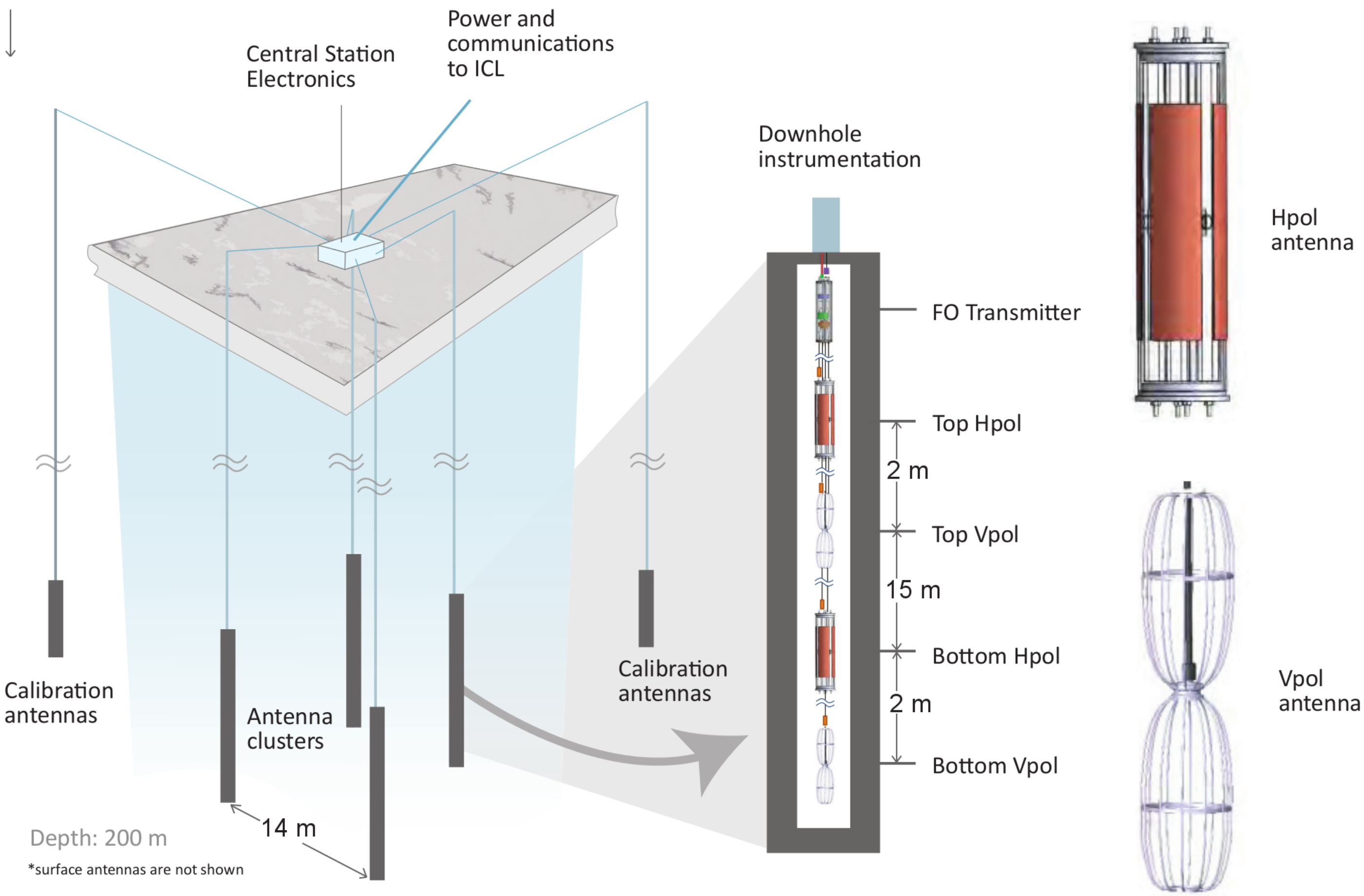
The Askaryan Radio Array



- Large spacing chosen to maximize the exploit the long attenuation length of radio and maximize the covered area
- Energy threshold is ~an order of magnitude larger than "Big Bird"
- Each cluster is autonomous with little overlap in events to maximize the area covered at a fixed cost.

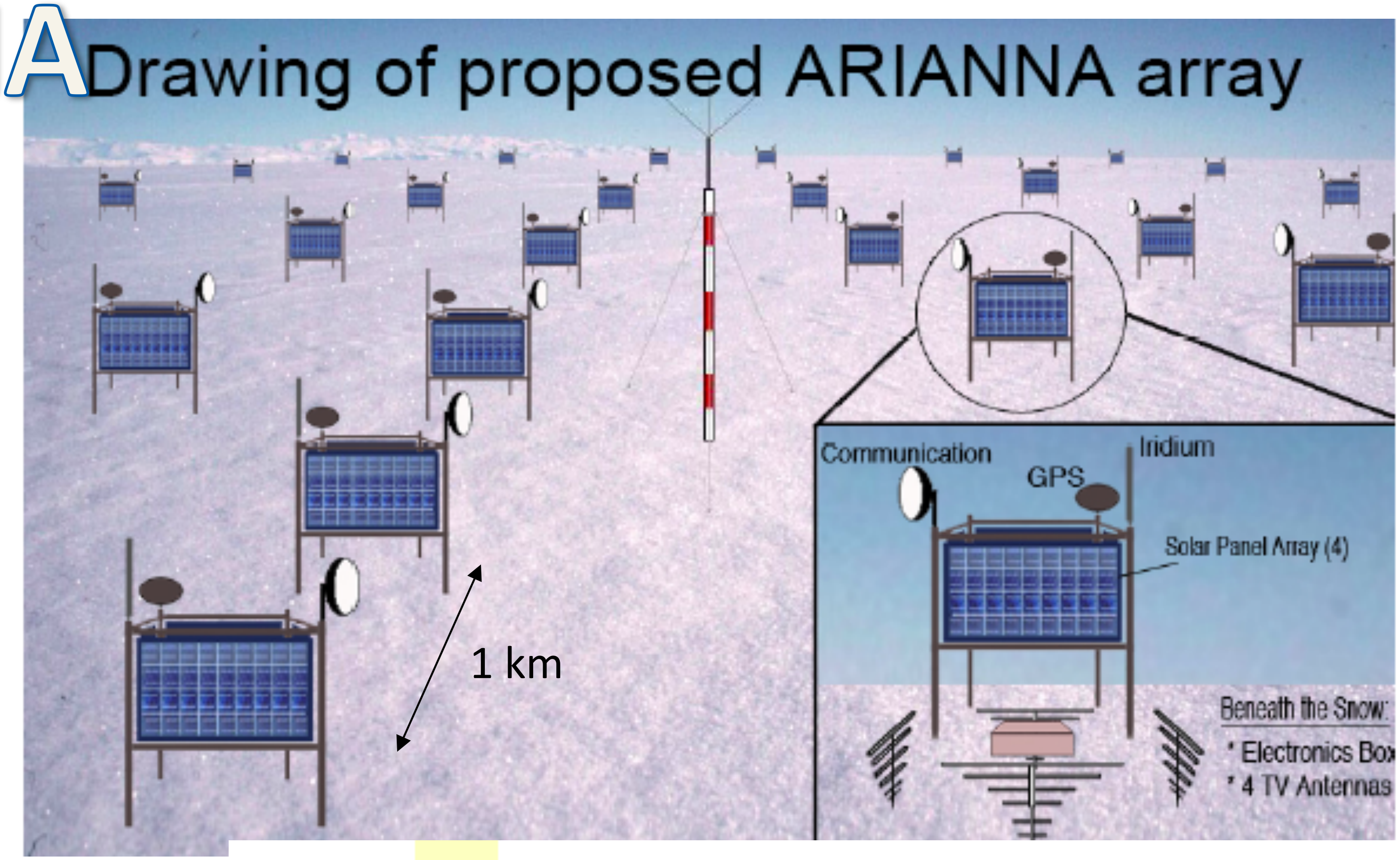
ARA Station Design

See talk by Carl Pfendner, Thursday am



- Each station contains multiple strings and can independently reconstruct an event
- Cherenkov cone is polarized, need both Hpol and Vpol
- Antennas engineered to fit down a narrow hole to save drilling costs

ARIANNA

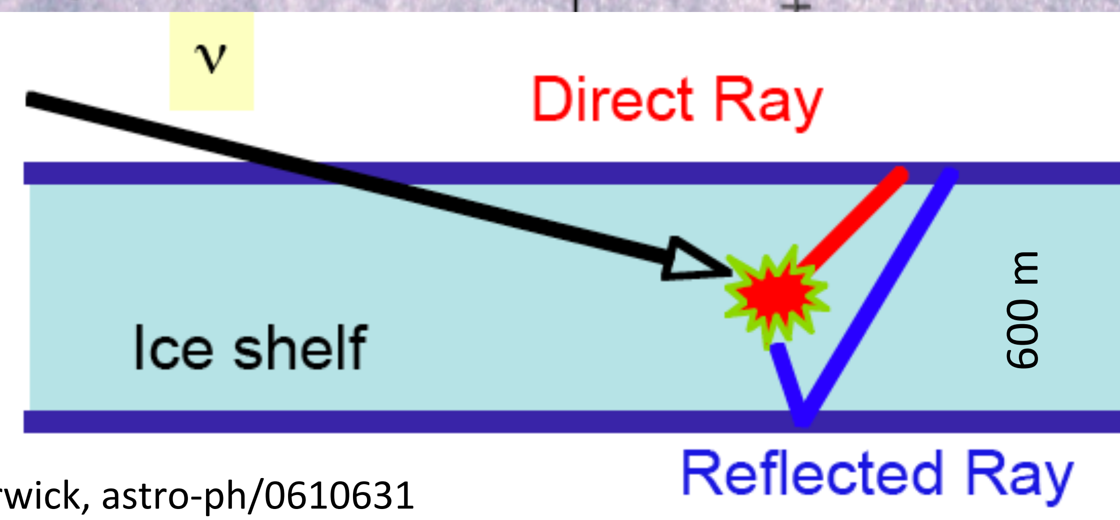


Proposed: 31 x 31 array [30 km x 30 km]

A nine station hexagonal prototype array has been installed

Advantages:

- Wind and solar powered
- Hardware is installed near the surface



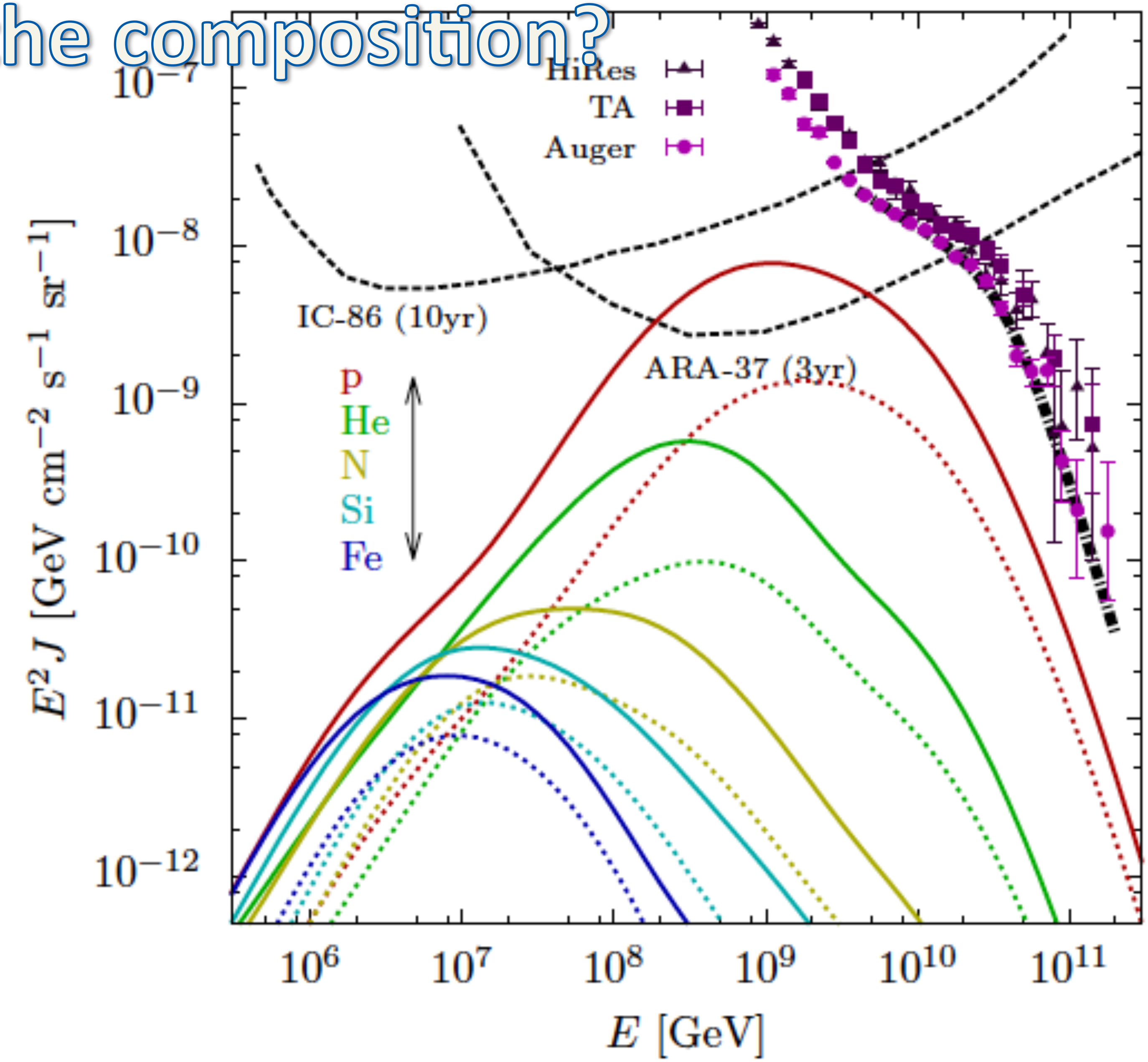
Barwick, astro-ph/0610631

What can Askaryan arrays say about the composition?

Ahlers & Halzen 2012
Arxiv 1208.4181

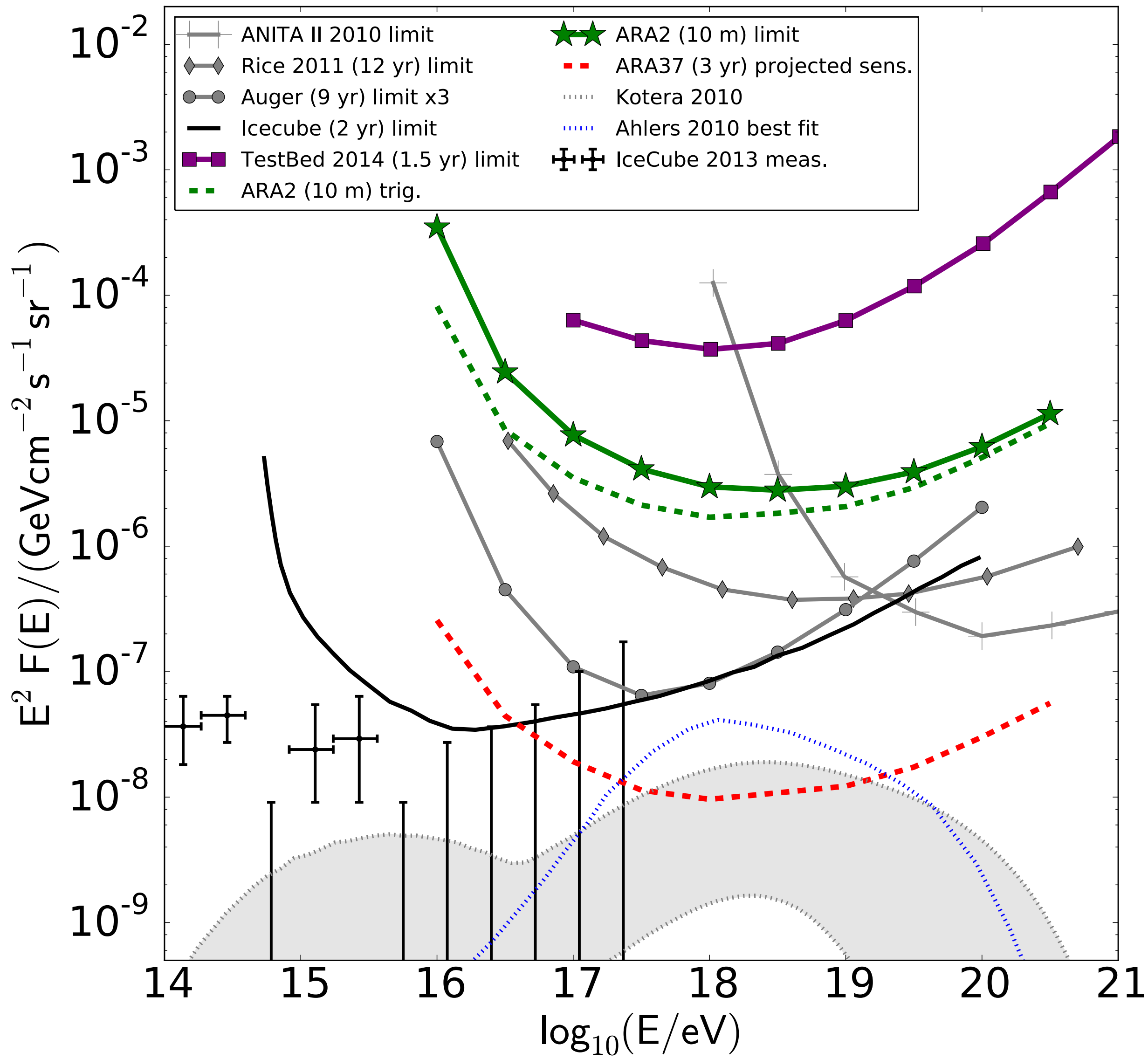
“Best fit” is to the HiRes spectrum

Dashed and dotted lines show different assumptions about the star formation rate.



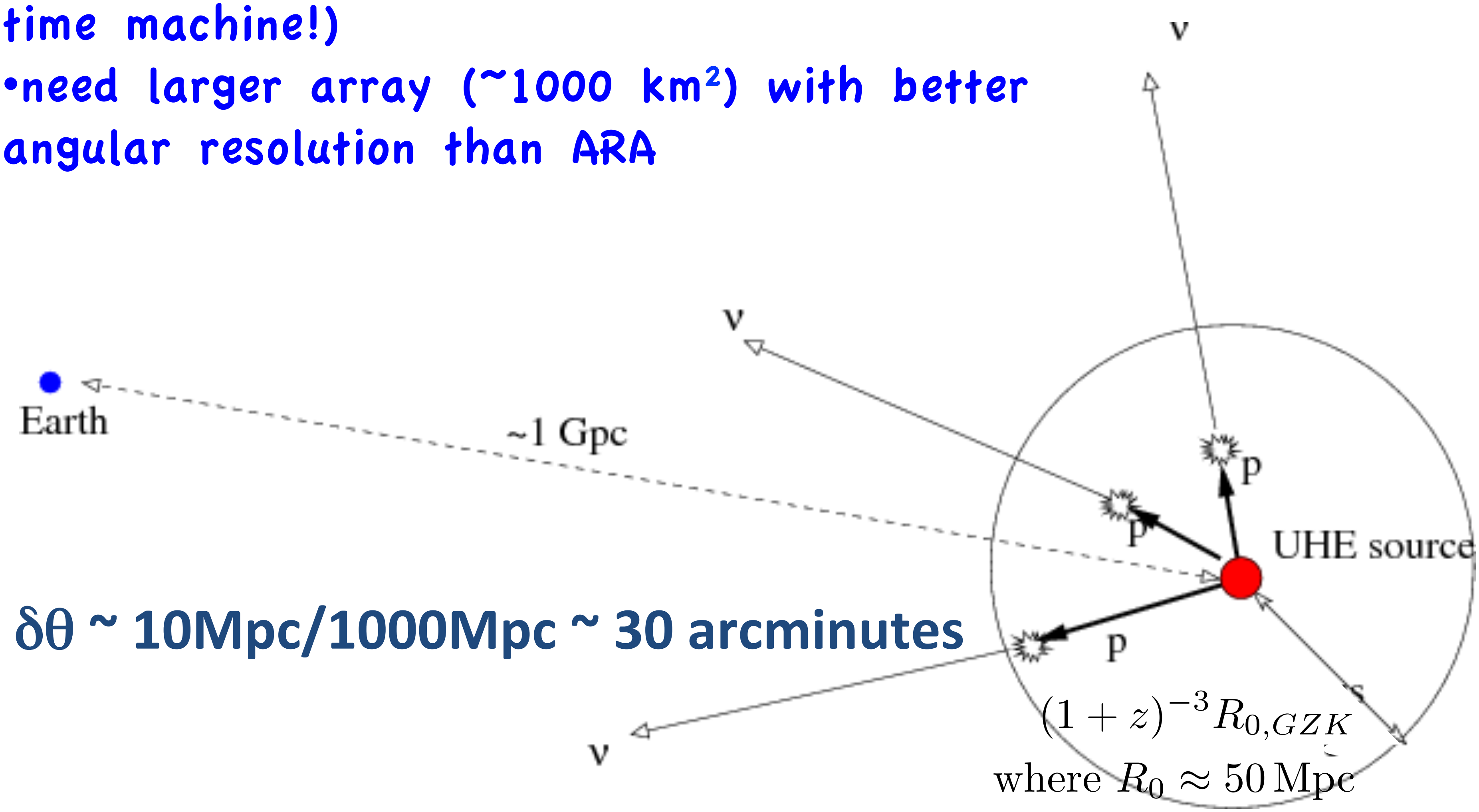
Limits and sensitivities

The current generation of Askaryan arrays under development will either discover or rule out more optimistic scenarios.



astronomy with GZK neutrinos?

- cosmic acceleration mechanisms
- source evolution (neutrinos are the ultimate time machine!)
- need larger array (~1000 km^2) with better angular resolution than ARA



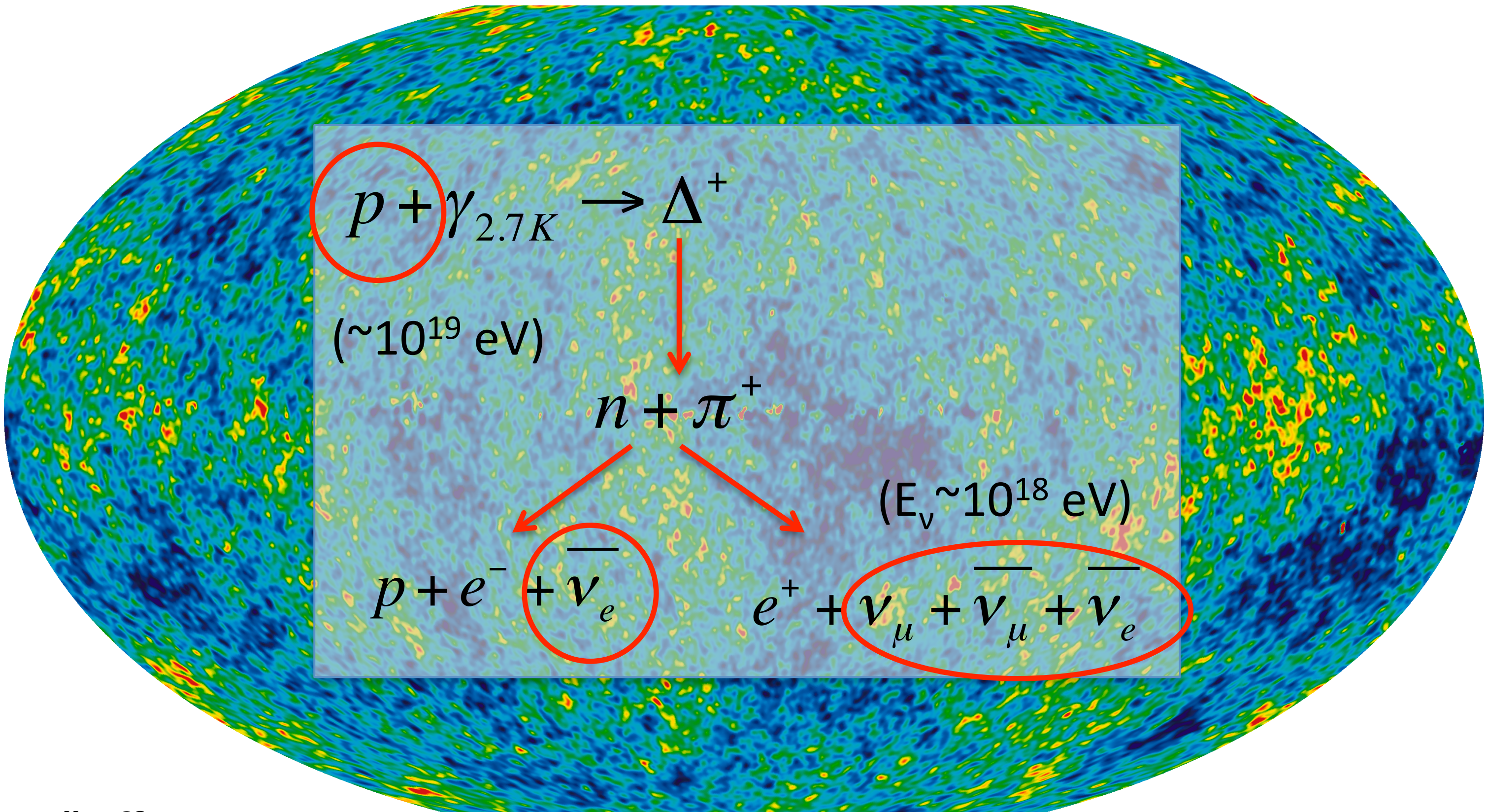
$\delta\theta \sim 10\mathrm{Mpc}/1000\mathrm{Mpc} \sim 30$ arcminutes

Larmor radius of 10^{20} eV proton in 10^{-9} Gauss intergalactic magnetic field ~100 Mpc

The Future

- The first kilometer scale neutrino telescope is operating, and has discovered a flux of astrophysical neutrinos
- The sources remain
- Other kilometer scale neutrino telescopes are under development
- IceCube will continue to accumulate statistics at high energies
- A next generation IceCube of an additional order of magnitude in size needed
- Radio Askaryan Arrays are the most inexpensive path to >100km^2 detectors and "cosmogenic" neutrino detection

A guaranteed source of ultrahigh-energy neutrinos?



"GZK" effect:

Greisen, Zatsepin, Kuzmin 1966: the universe is not transparent to cosmic rays!