Neutrino Telescopes

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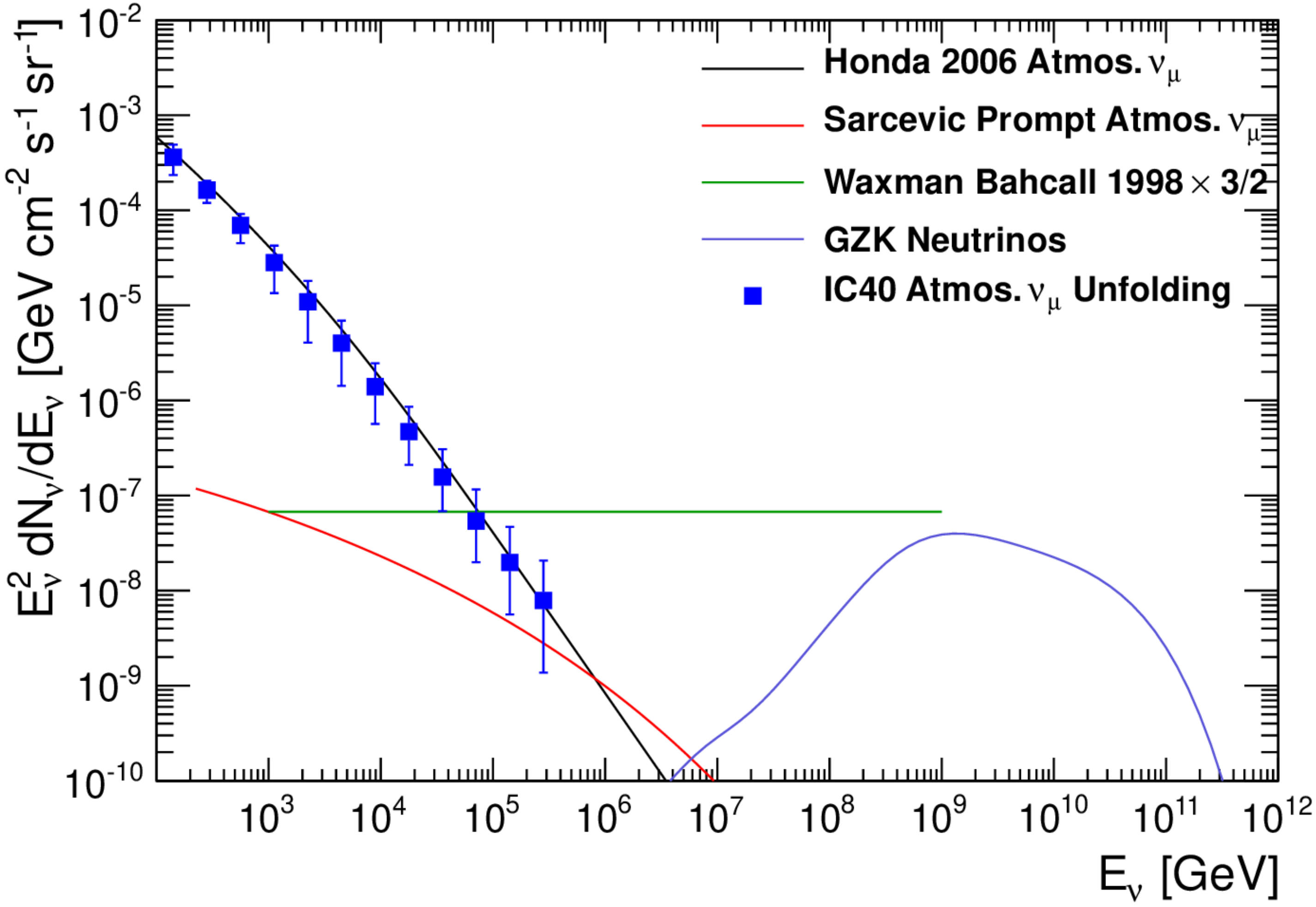
Sept. 3, 2019

UCLA

Landscape of High-Energy Neutrinos



Atmospheric Neutrinos: “Conventional” and Charm

Conventional:

- Pion and Kaon decays in the atmosphere
- Spectrum related to cosmic rays, suppressed by long lifetimes of pion/kaons at high energies
- Overwhelming muon neutrinos

Charm:

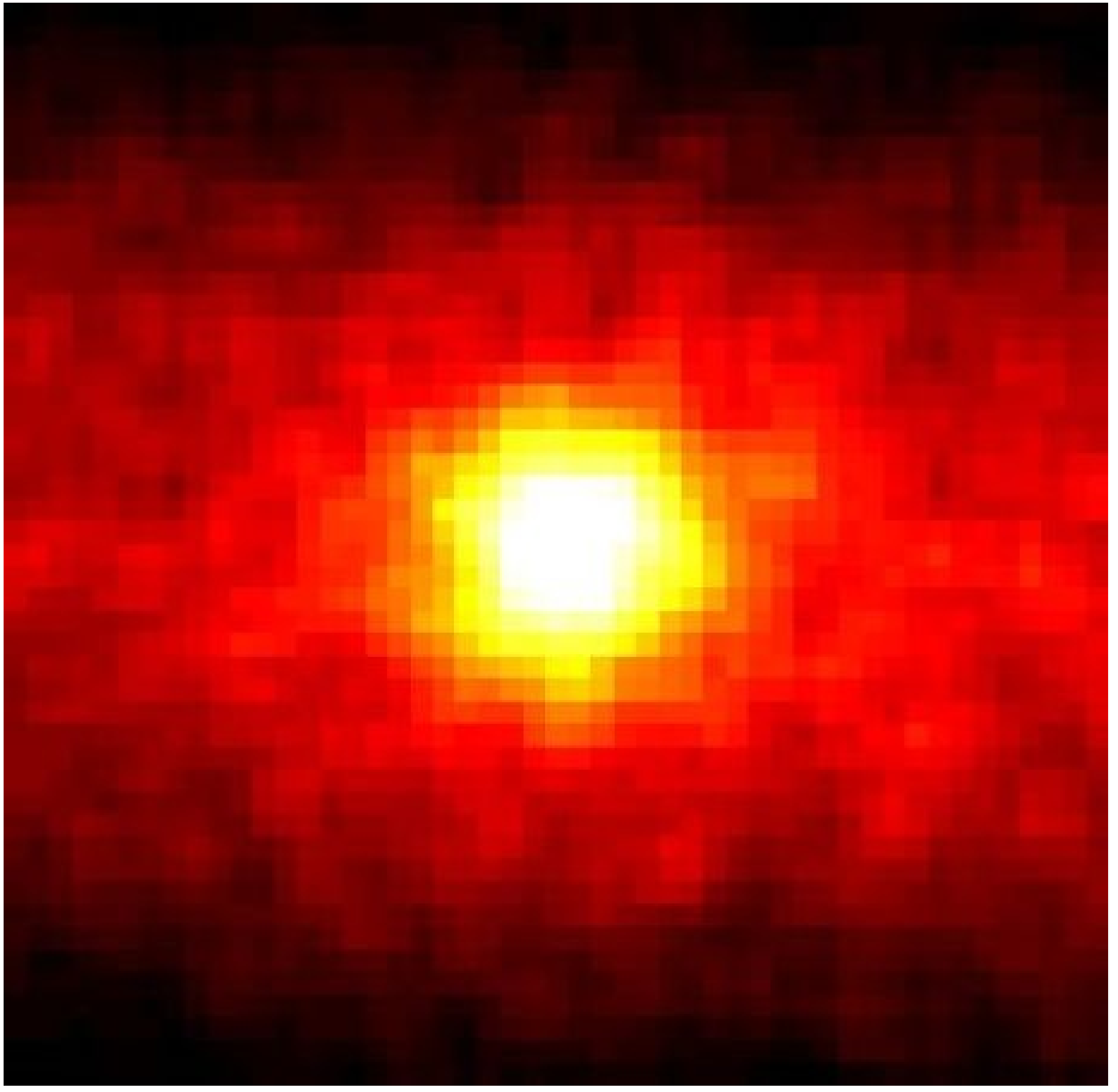
- Decay of charmed mesons (principally D mesons)
- Much shorter lifetime eliminates suppression, traces cosmic ray spectrum precisely
- Order-of-magnitude uncertainty on flux

Sources of Astrophysical Neutrinos

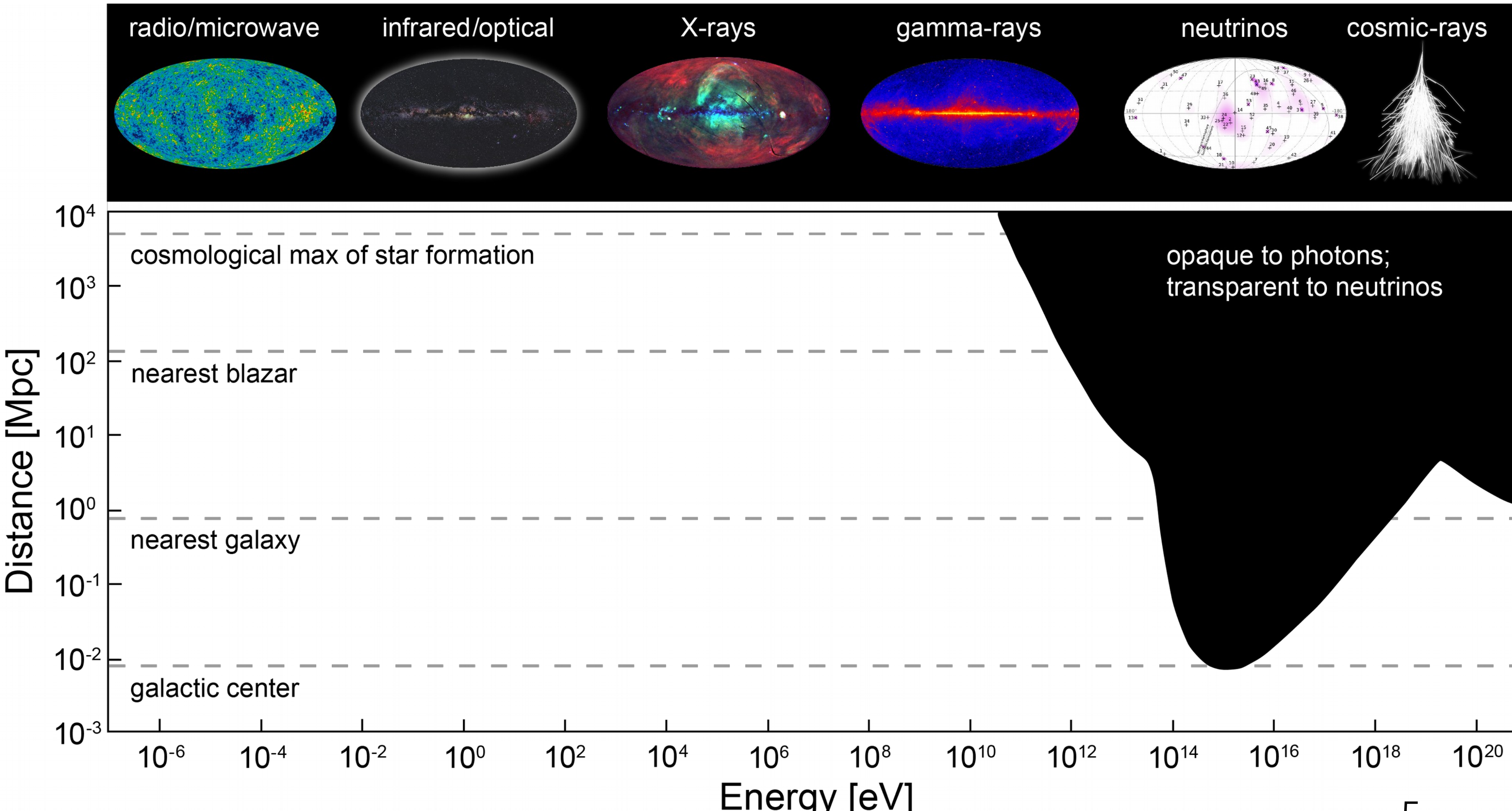
Nuclear interactions (right) – MeV

Pion/Kaon decay – GeV+

Dark Matter decay (?)

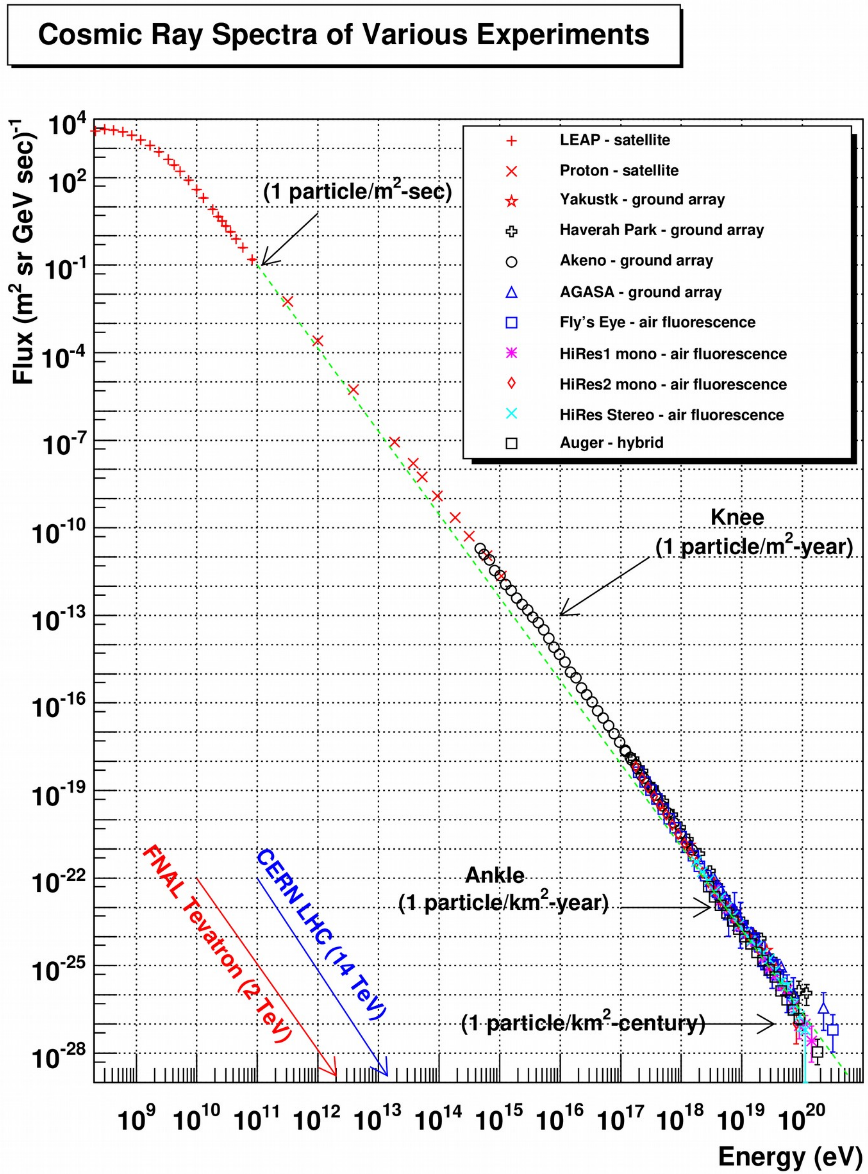


Missing Pieces: What You Can't See



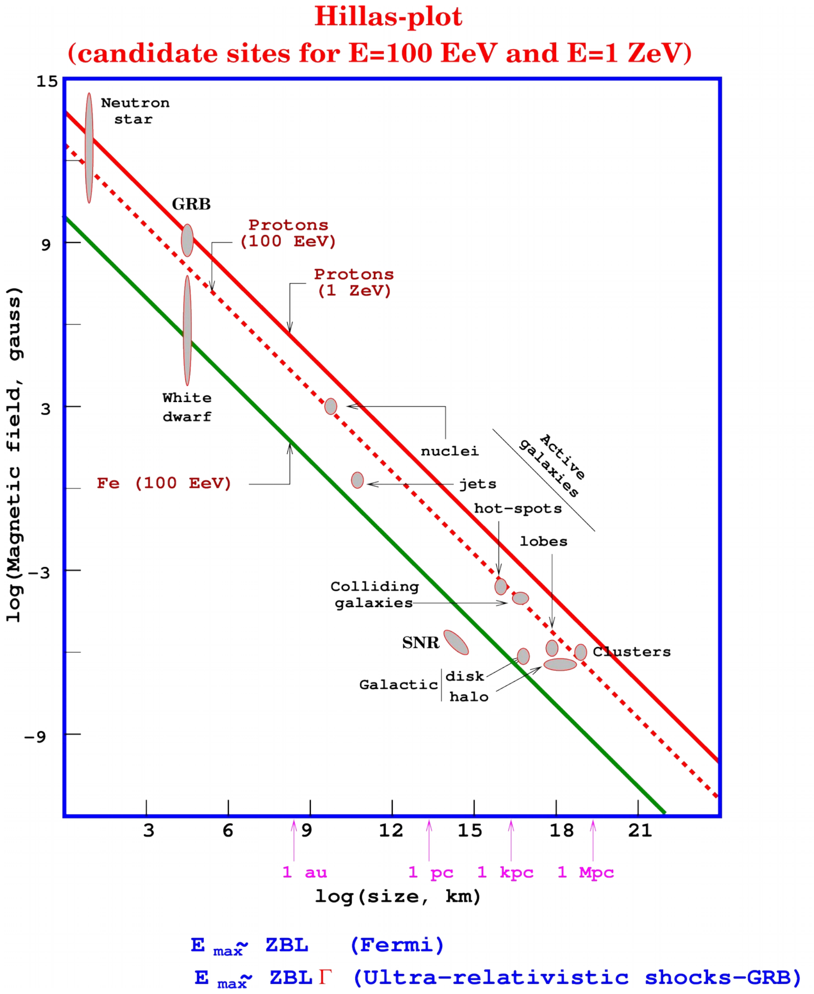
Cosmic Rays: A 100-year-old mystery

- Hadronic matter reaching energies above 10^{20} eV
- How are they made?
- Where do they come from?



Cast of Characters

- Need to keep protons in accelerator while accelerating them
- Particularly violent astrophysical environments



Neutrinos as a Solution

- Neutrinos made at the same time
- Fly directly to Earth without magnetic deflection
- Should be perfect tracers of acceleration
- Neutrinos end up at ~5% the energy of protons

$$
\begin{aligned}
p + \gamma \quad &\rightarrow \quad \pi^0 + p \\
&\qquad \hookrightarrow \gamma + \gamma + p \\
&\rightarrow \quad \pi^+ + n \\
&\qquad \hookrightarrow \mu^+ + \nu_\mu + n \\
&\qquad \hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n
\end{aligned}
$$

Cosmogenic/GZK Neutrinos

- Exactly the same proces
- Away from the source
- Target photons now the CMB
- High energy threshold (10^{19} eV) to make pions
- Tells you about otherwise-invisible cosmic rays

$$
\begin{aligned}
p + \gamma \quad &\rightarrow \quad \pi^0 + p \\
&\qquad \hookrightarrow \gamma + \gamma + p \\
&\rightarrow \quad \pi^+ + n \\
&\qquad \hookrightarrow \mu^+ + \nu_\mu + n \\
&\qquad \hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n
\end{aligned}
$$

Neutrinos from Dark Matter Interactions

- Variety of mechanisms to make neutrinos in DM annihilations, generally from quark hadronization
- N^2 process traces density of DM – standard indirect search
- (Probably) monochromatic neutrinos
- Can also look at DM/nucleon scattering (unique)

Two Mechanisms

Solar Annihilation

- DM density in equilibrium when proton capture rate = annihilation rate
- Sensitive to proton/DM scattering cross-section only
- Directly comparable to laboratory direct detection with Hydrogen target

Extrasolar Annihilation

- Same as other indirect measurements: look for lines in regions with high DM density
- Targets are dwarf spheroidals, galactic center, etc.
- Better foreground situation than gamma rays (no known astrophysical sources of neutrinos)

Exotic Topics

- Non-thermal relic neutrinos
- Neutrino/dark-matter cross-section
- 3x3 PMNS unitarity tests (Baselines of 10^{22} m!)
- Lorentz-invariance violation
- Non-standard interactions at ultra-high energies
- …

Goals of the Field

New ground!
Always room for surprises

GeV+:

- Measurement of $\boldsymbol{\theta}_{23}$
- Indirect detection of dark matter

TeV+:

- Very forward p-p physics
- Sterile neutrino searches

PeV+:

- Direct detection of neutrinos from (ultra-)high-energy cosmic ray sources (concealed, internal dynamics)
- Probes of neutrino propagation over long distances

EeV+:

- Indirect detection of distant high-energy proton sources through pion production on CMB

Measurement Techniques

Large scale anisotropies:

- Measurement of θ_{23}
- Sterile neutrino searches

Astrophysical point sources:

- Particle acceleration mechanism/source identification
- Indirect detection of dark matter

Energy spectrum:

- Direct detection of neutrinos from (ultra-)high-energy cosmic ray sources (concealed, internal dynamics)
- Very forward p-p physics
- Probes of neutrino propagation over long distances

Flavor:

- Sterile neutrino searches
- Measurement of θ_{23}
- Astrophysical particle acceleration mechanism

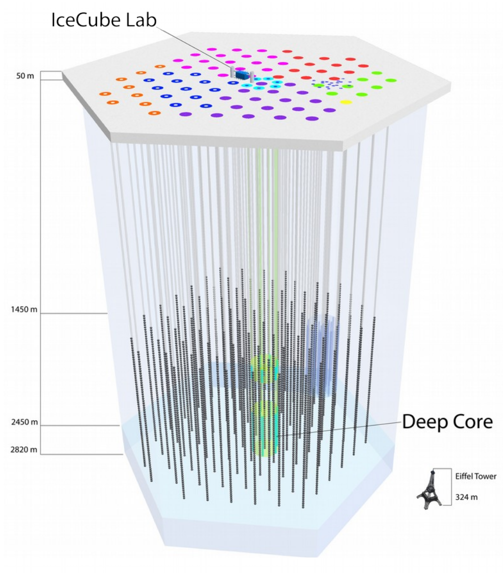
Instrumental Needs: Angular Resolution, Size, Energy, Flavor

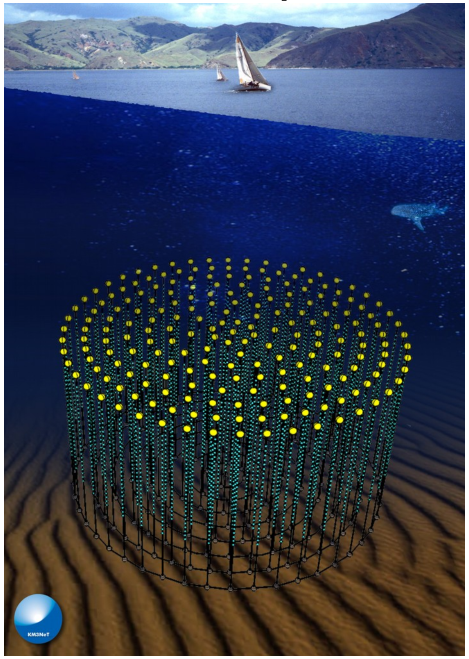
Angular Resolution:	Correlate neutrinos
Size:	Event rate >> 0
Energy Resolution:	Spectral measurements
Flavor:	Production mechanism/distortions

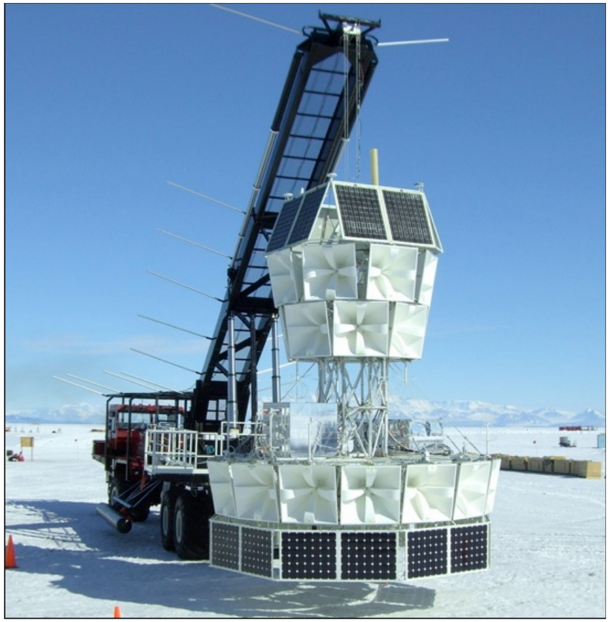
Need huge detector with reasonably dense instrumentation, deep underground

Natural Detectors: the Size Frontier

Common theme: flux low at > 1 TeV, need giant natural detectors







IceCube(-Gen2), KM3net, Baikal/GVD, ANITA, ARA, ARIANNA, ANTARES

Two Techniques

Water/Ice Cherenkov

- Energy threshold of 10s of GeV
- Clear, low-background water
- Instrumentation spacing < ~150 meters

Askaryan Radio

- Radio pulse from charge imbalance in EM shower in matter
- Energy threshold of 10^{16} eV
- Low radio noise site
- Instrumentation spacing of 10s of km

Water: Fresh and Salt, Liquid and Frozen

- Big PMT array in natural water (deep and big)
- PMT[s] in a pressure sphere

Fresh Water

- Low scattering
- High absorption (silt)
- Hard to get deep
- Low radioactivity

Sea Water

- Low scattering
- Moderate absorption (silt)
- Can be very deep
- High radioactivity (salt)
- Bioluminescence

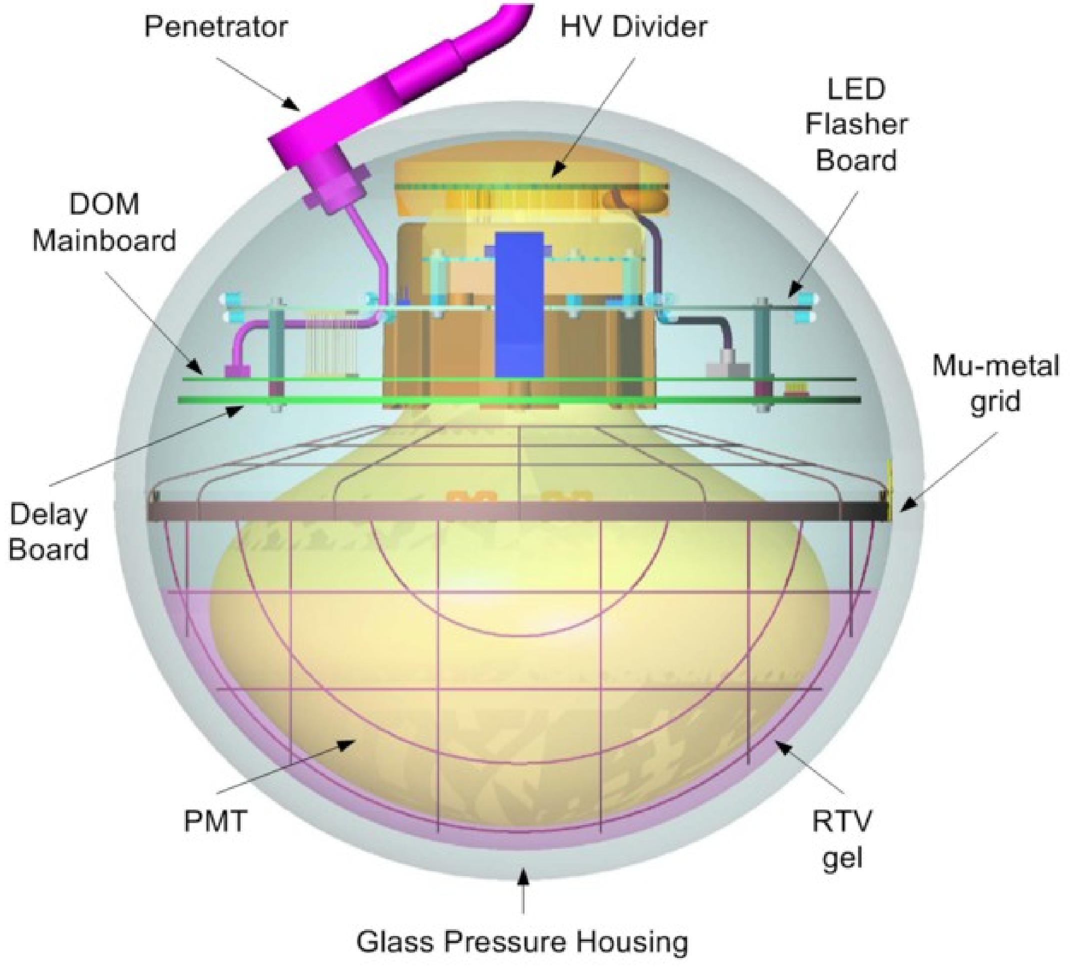
Glacial Ice

- High scattering
- Low absorption
- Moderate depths
- Low radioactivity
- Nothing alive or moving

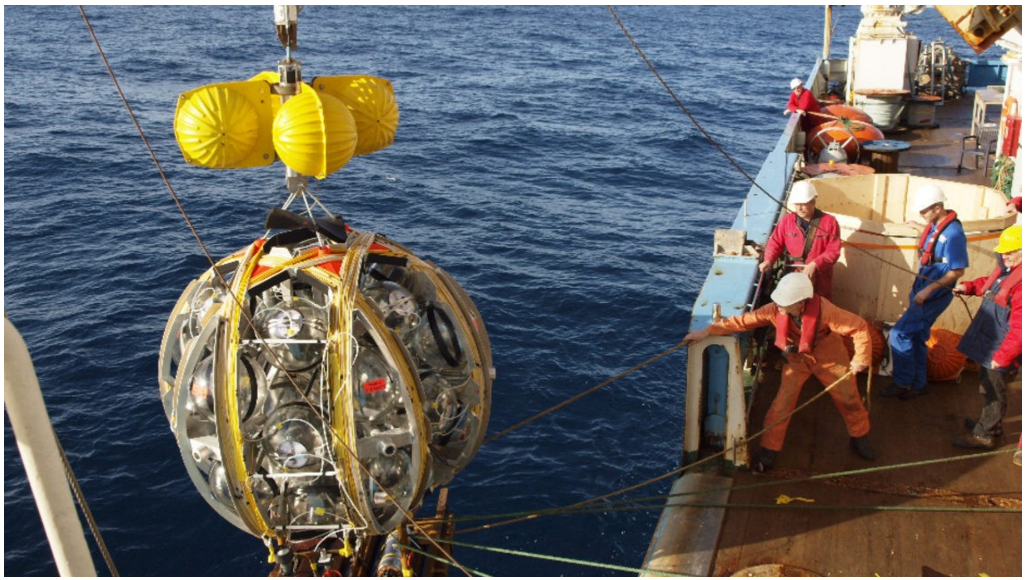
Movie of Muon in Ice

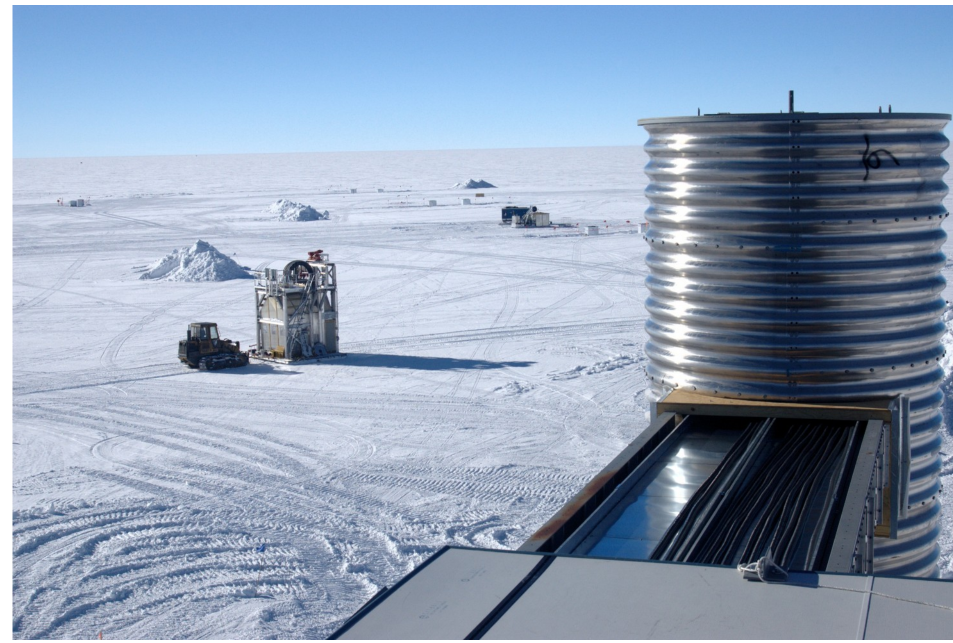
Movie of Muon in Water

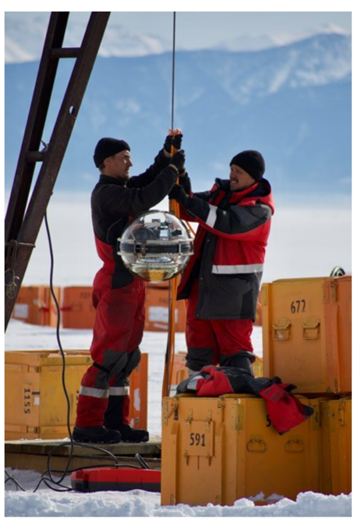
Picture of Detector Modules (example from IceCube)



Working on Water and Ice







One more optical module is prepared for immersion

Central module of the section

Underwater acoustic modem

Pulsed semiconductor laser

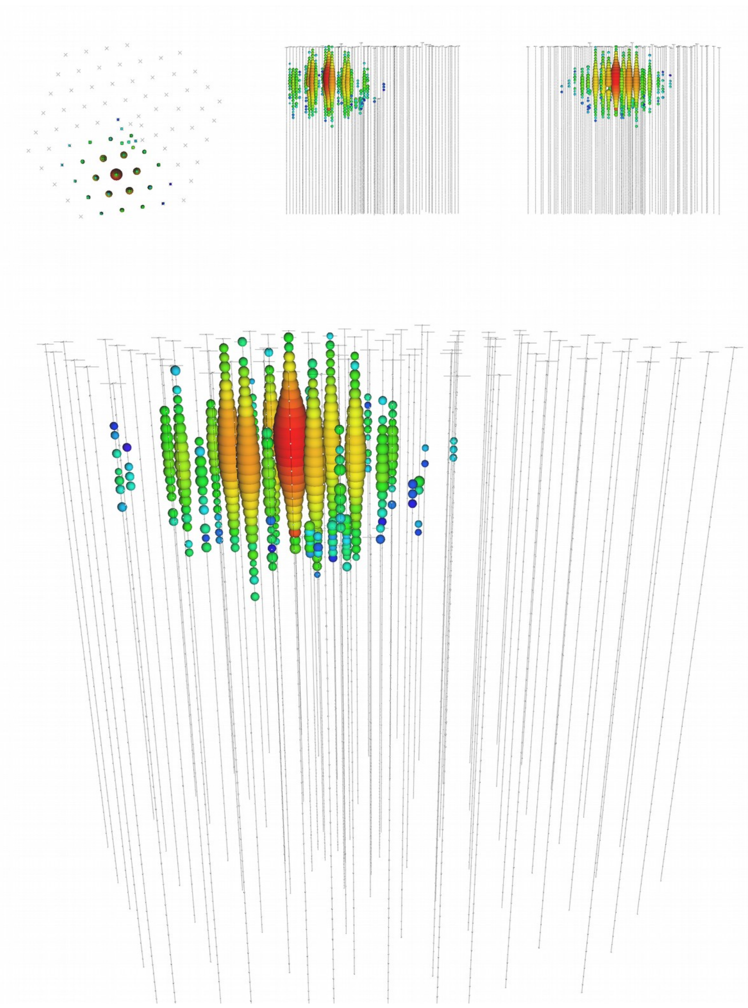
Status of current instruments

First generation mature:

- IceCube (completed 2011)
- ANTARES (2008)
- ANITA (flights 2006-2016)
- Baikal (NT200 1998, NT200+ 2005)

Second generation coming:

- GVD (under rapid construction)
- IceCube-Gen2 (initial upgrade work started, mid-2020s)
- KM3Net (under construction)
- ARA/ARIANNA (construction)



Detector Figures of Merit

Instrumented Volume: ~ cubic kilometer scale

Effective Area: 100 m^2

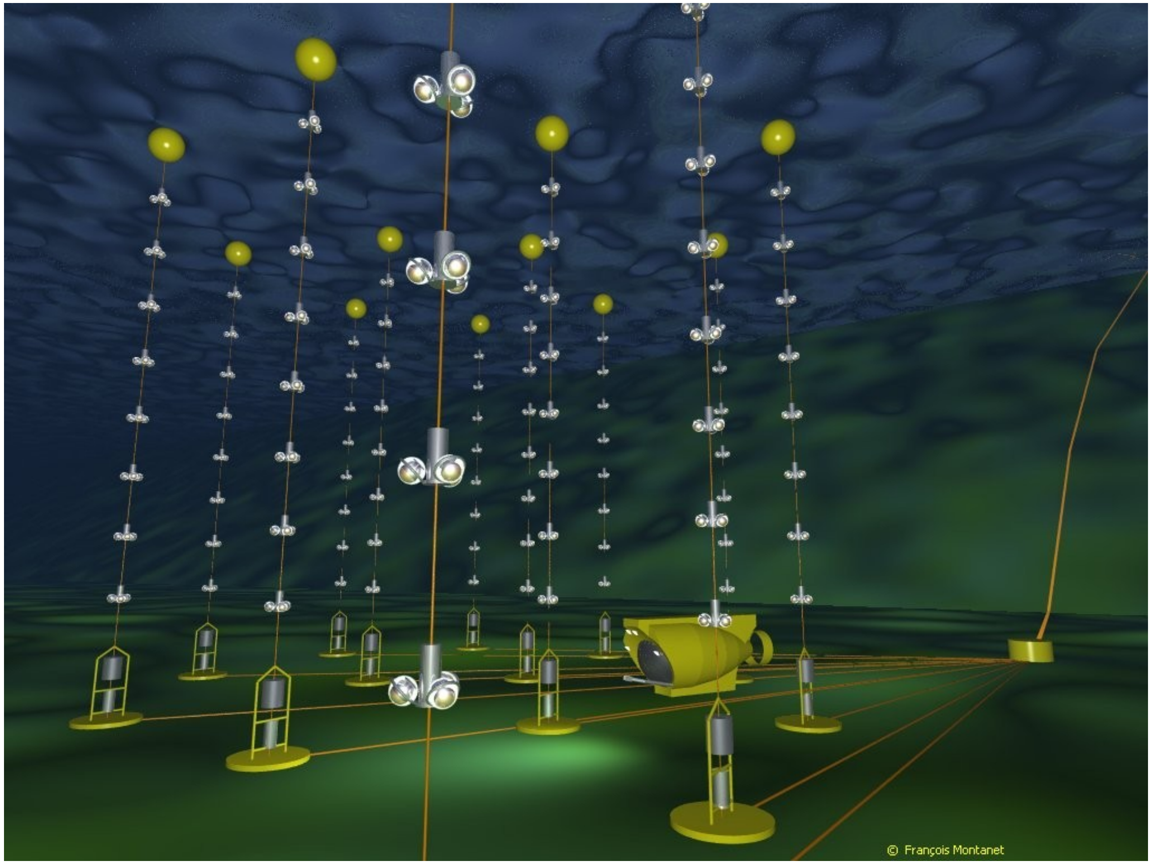
Threshold: <= 10 TeV

Angular Resolution: < 1 degree

Energy Resolution: < factor of 2

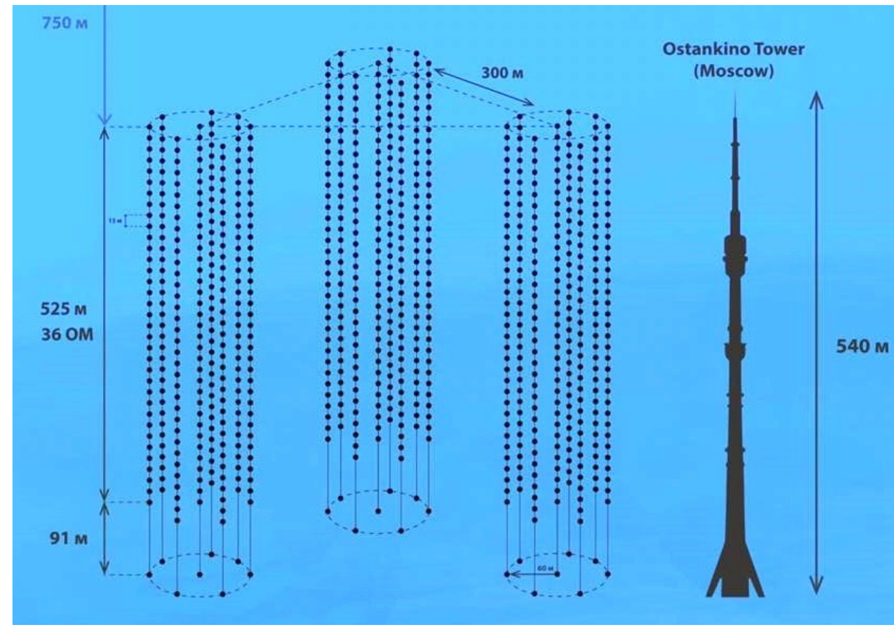
ANTARES

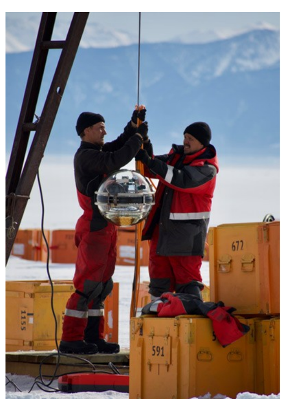
- 900 PMTs
- Deep Mediterrean off French coast
- Completed 2008
- 0.03 km^3
- .2 degree resolution
- 3 m^2 effective area
- Upgrade in progress (KM3net)



Baikal GVD

- In Lake Baikal, Russia (freshwater)
- Follows NT200[+]
- 1440 PMTs
- .25 km^3, 30 m^2 effective area
- 0.3 degree resolution
- Growing (very) fast!

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Central module of the section


Underwater acoustic modem


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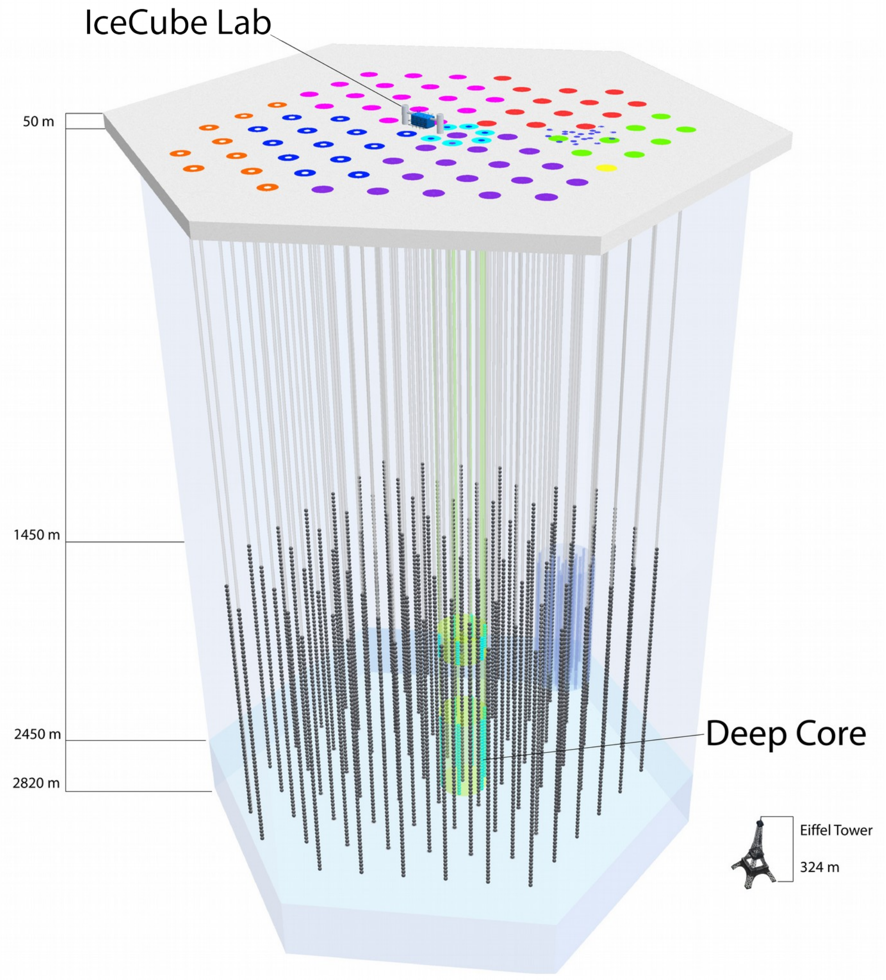
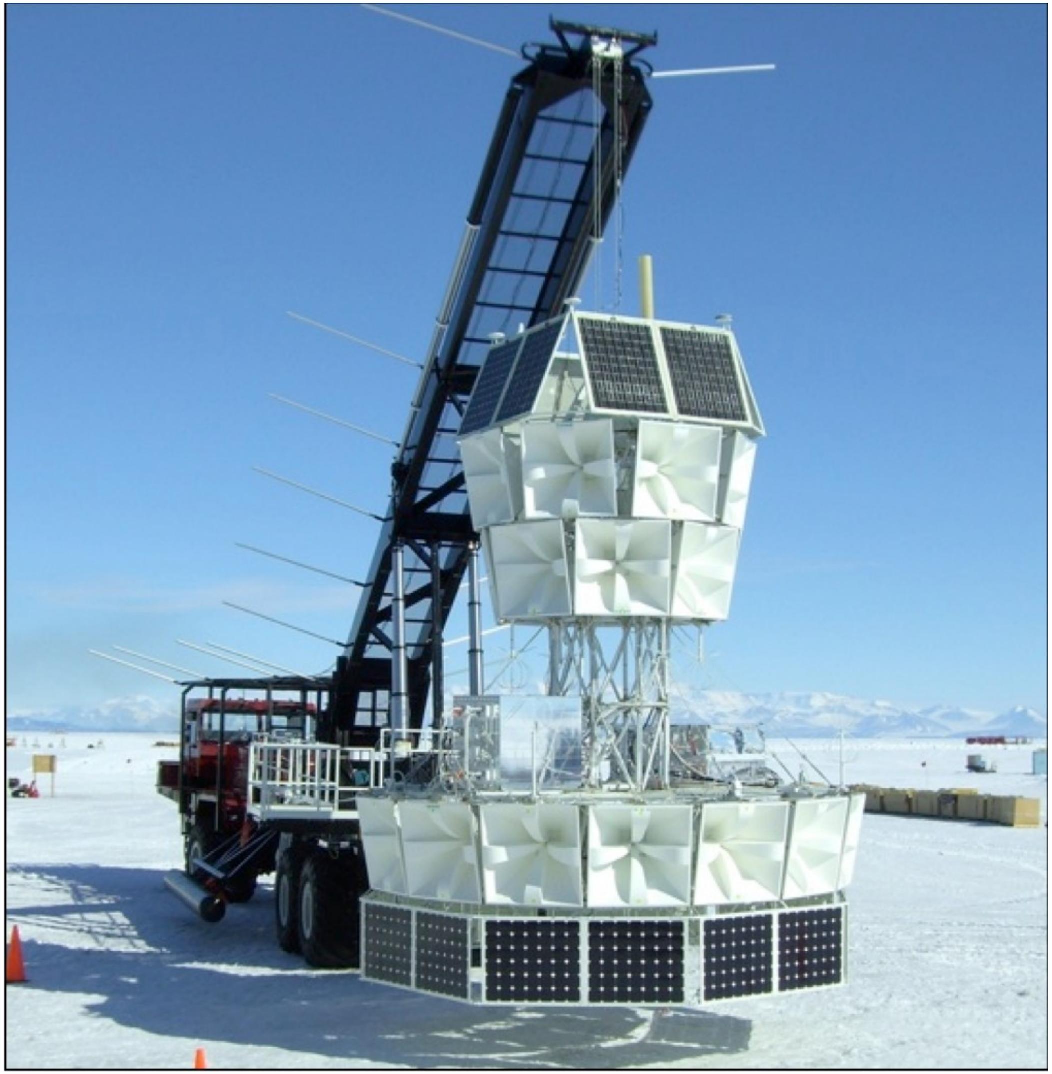
IceCube

- 1 km^3
- 5160 PMTs
- Bottom of South Pole glacier
- 0.5 degree angular resolution
- Completed in 2011
- High-energy effective area of 100 m^2



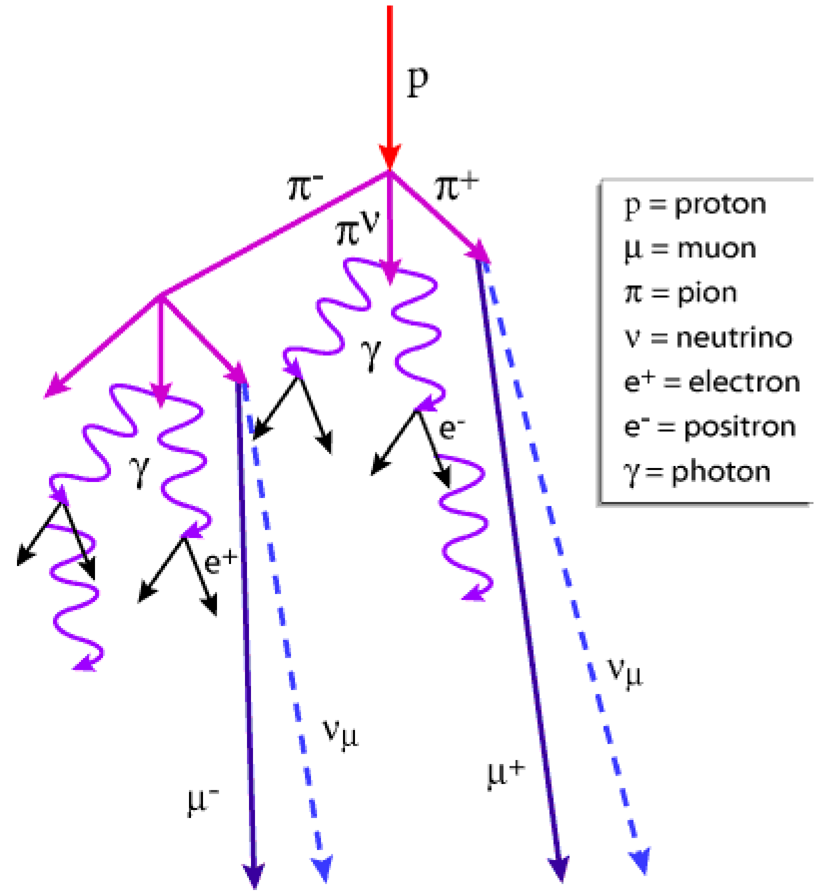
ANITA

- Askaryan Effect instrument
- Balloon-borne
- 4 flights so far over Antarctica
- Threshold 10^{18} eV (GZK only)
- 10^5 m^2 effective area



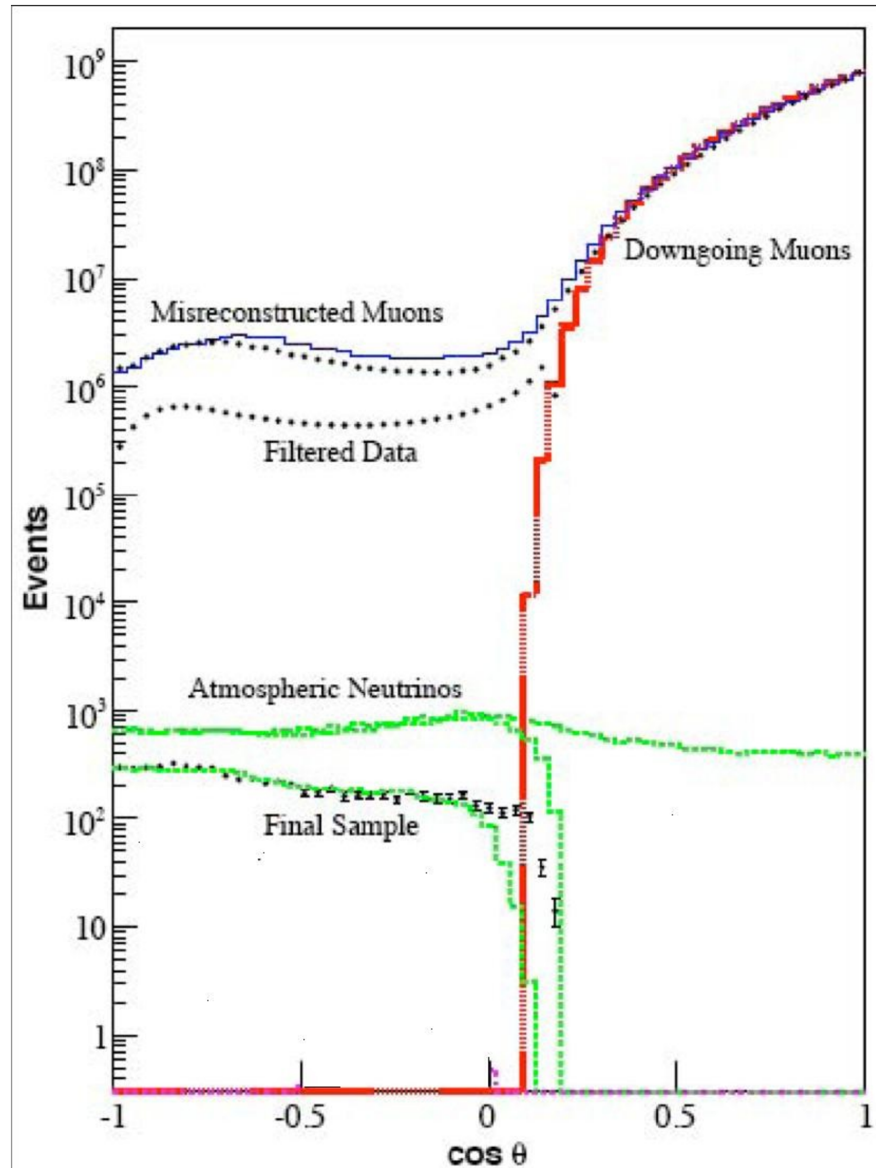
Background Rejection

- All backgrounds from cosmic-ray air showers
- Muons (down-going)
- Atmospheric neutrinos (up- and down-going, sometimes the signal)
- Down-going neutrinos *correlated* with muons



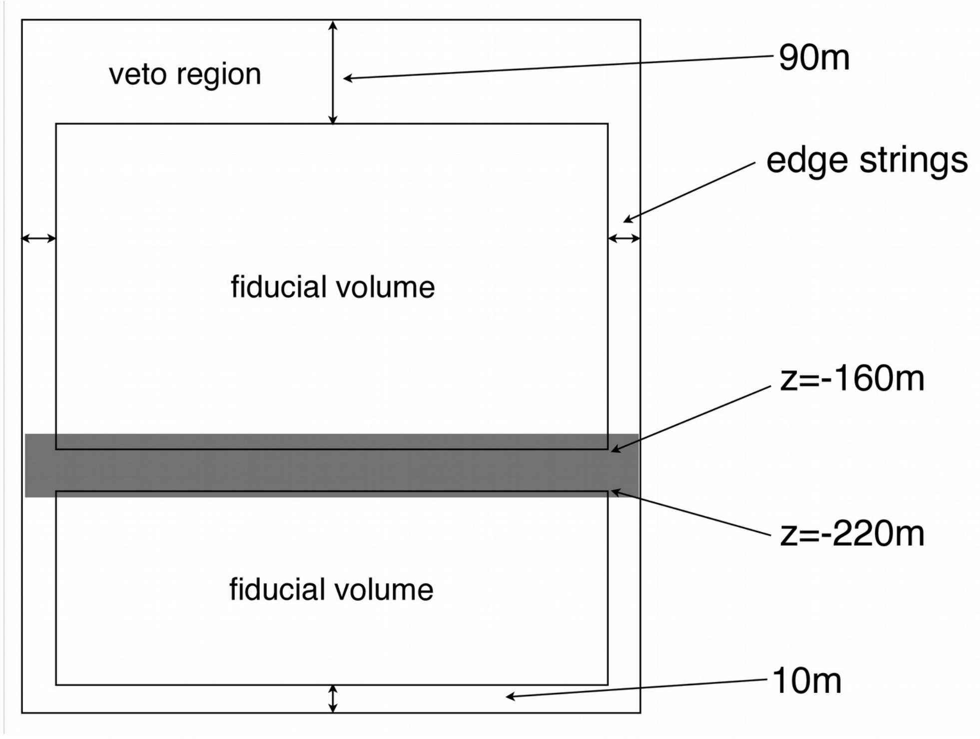
Option 1: Up-going events only

- Use up-going muons
- CR muons blocked by the Earth, leaving only neutrino-induced muons
- Substantial increase in effective volume from 10+ km muon track length



Option 2: Containment

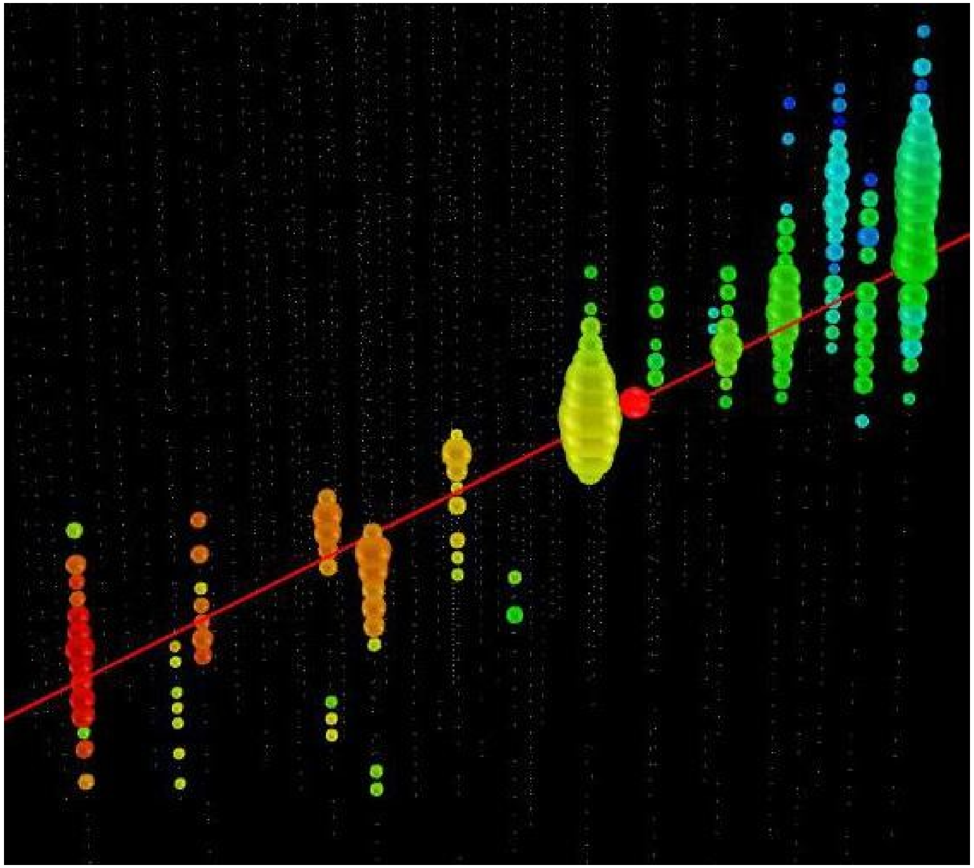
- Use events only with visible vertex
- Can see all directions
- Small effective volume (veto region, lose uncontained muons)
- All-flavor



Event Reconstruction

Goal is to match PMT data up to predictions. Some simplifications:

- Muons move in straight lines
- Muon and electron energy loss is proportional to energy



Some things are trickier…

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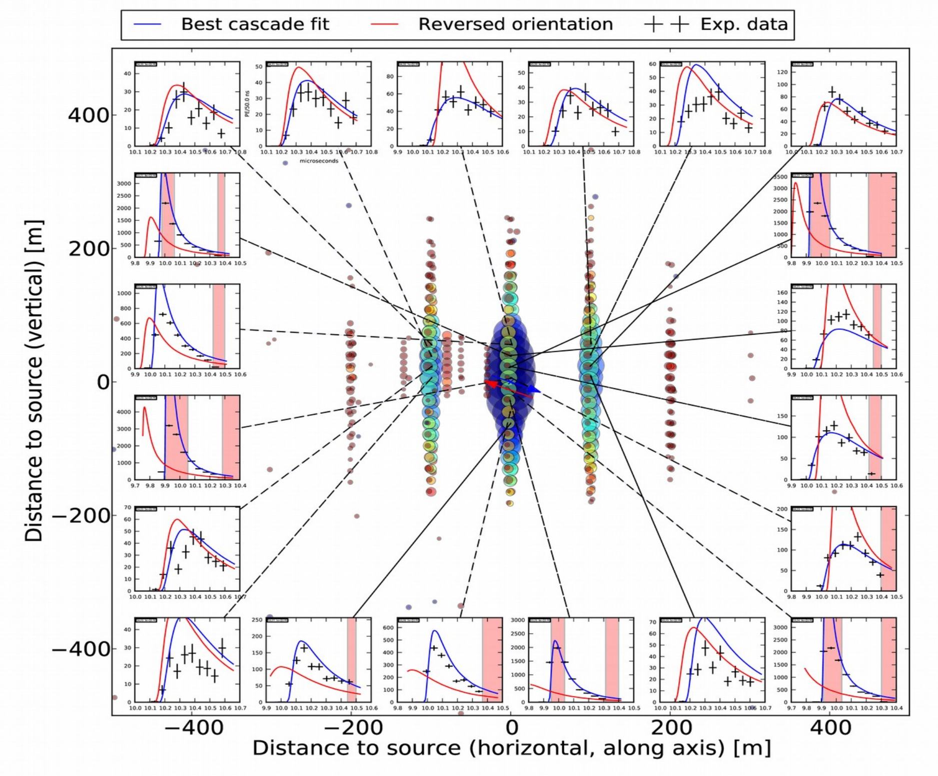
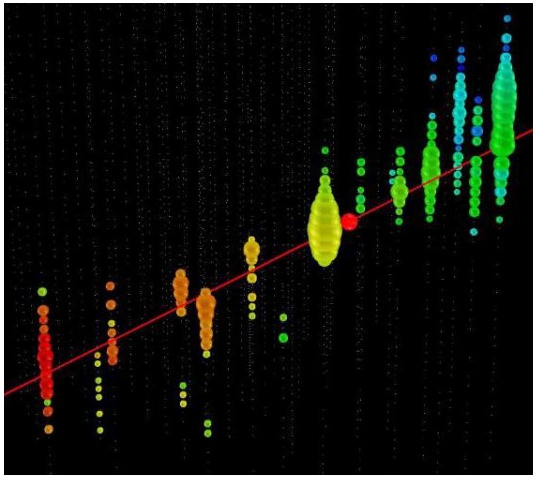
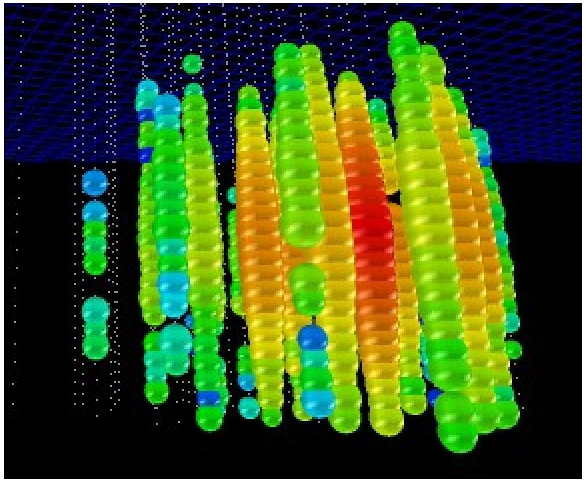


Some things are trickier…

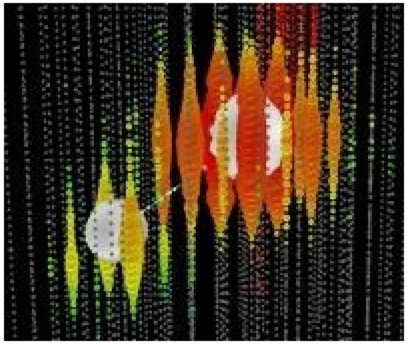
Flavor Identification



Muon (“track”)



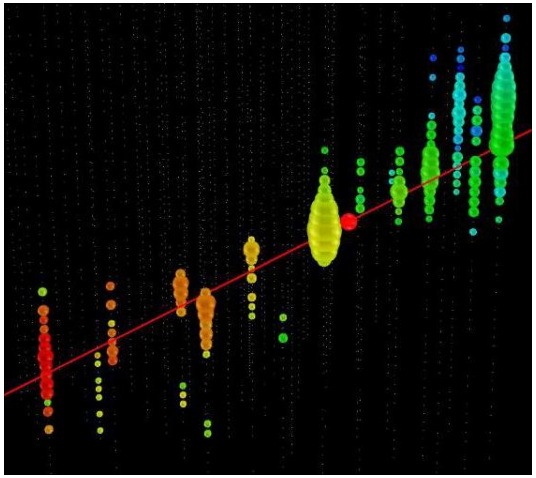
Electron (“cascade”)



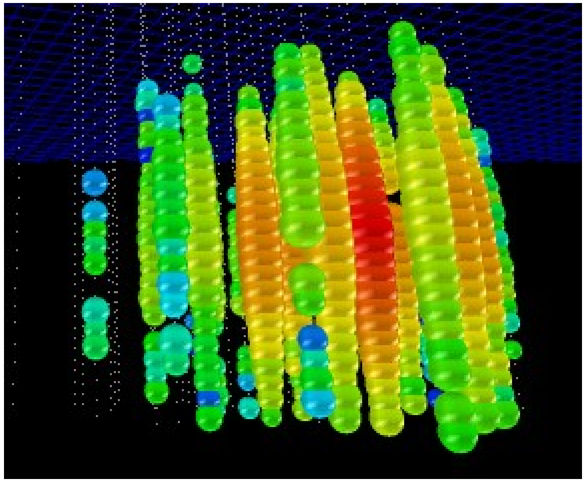
Tau (rare, not yet seen)

- Muon CC vs. Other is easy with optical detectors (some issues with muon bremsstrahlung)
- Everything else is hard (sometimes possible)
- Flavor ID basically not possible in radio

Cascades and Tracks (Optical Only)



- Good angular resolution
- Poor energy resolution (uncontained vertex, giant stochastic losses)

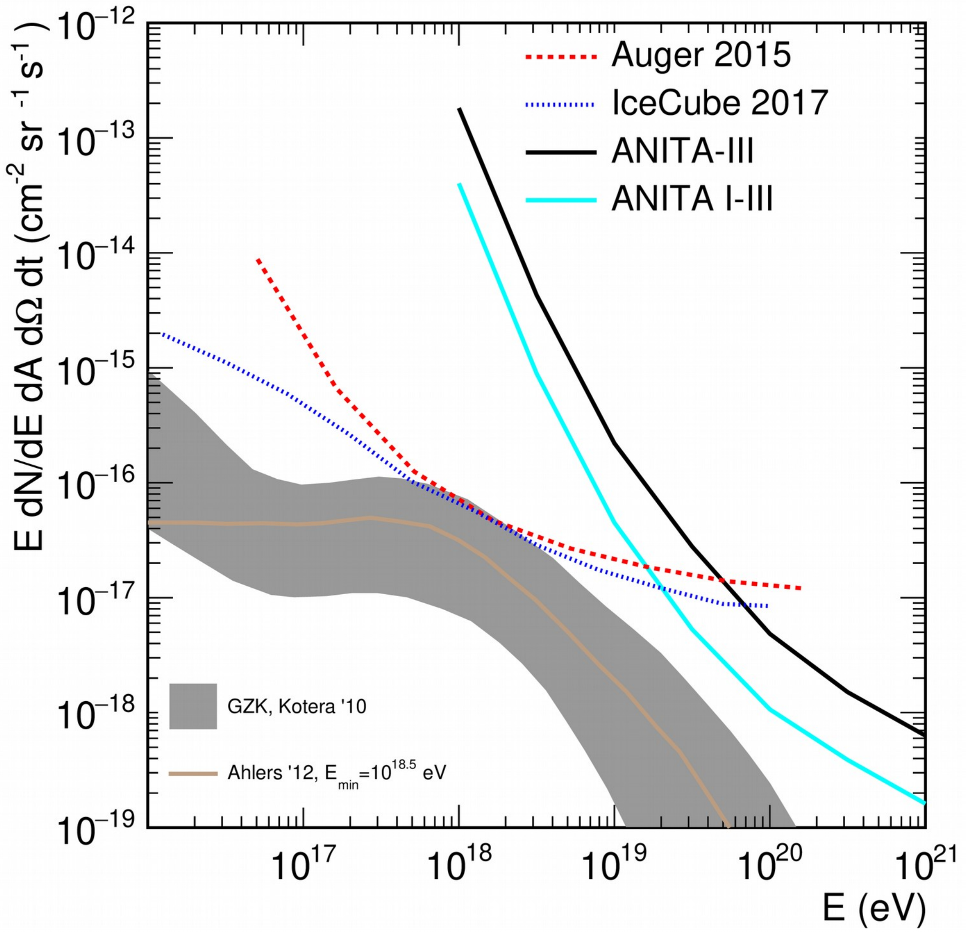


- Good (deposited) energy resolution
- Poor angular resolution (especially in ice, not so bad in water)

Some (high-energy) results

GZK Neutrinos

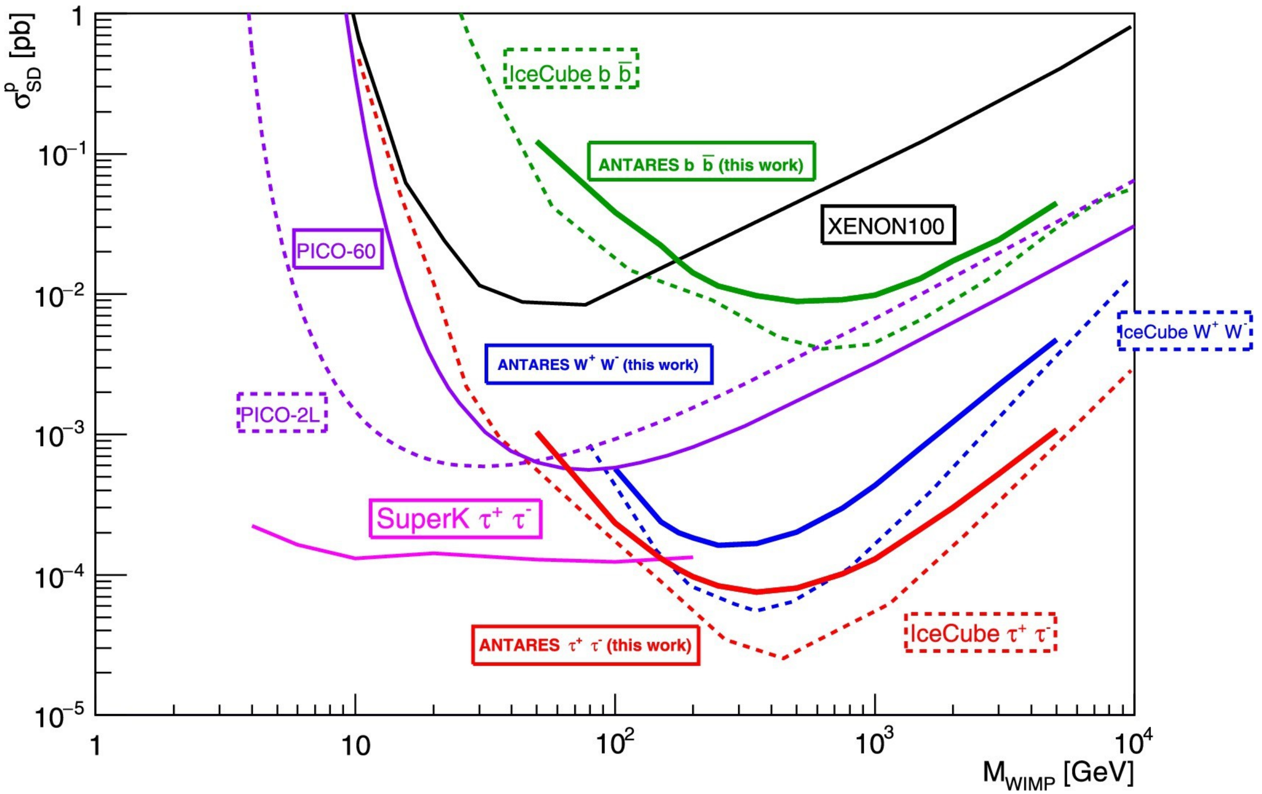
- Not yet seen, edging into model space
- Not quite concerning yet
- Some interesting anomalous events from ANITA



ANITA, 1803.02719

Status of Dark Matter Searches

- Unique ability to probe high-mass dark matter (indirectly)
- Particularly sensitive to spin-dependent interactions in the Sun



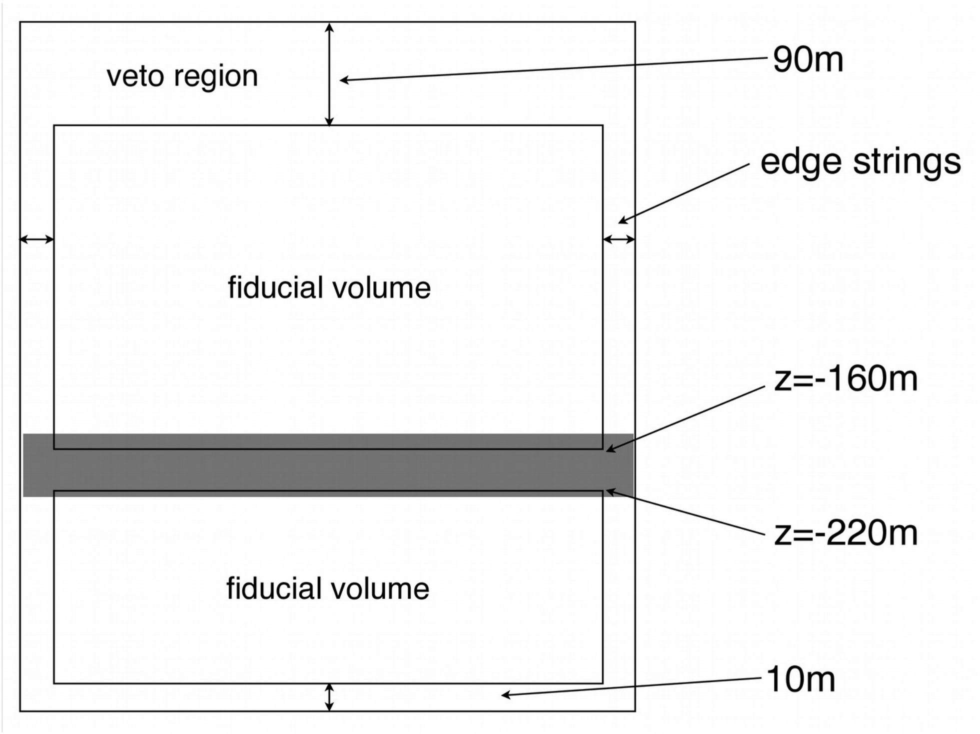
ANTARES, PLB 2016

Limited by angular resolution, statistics

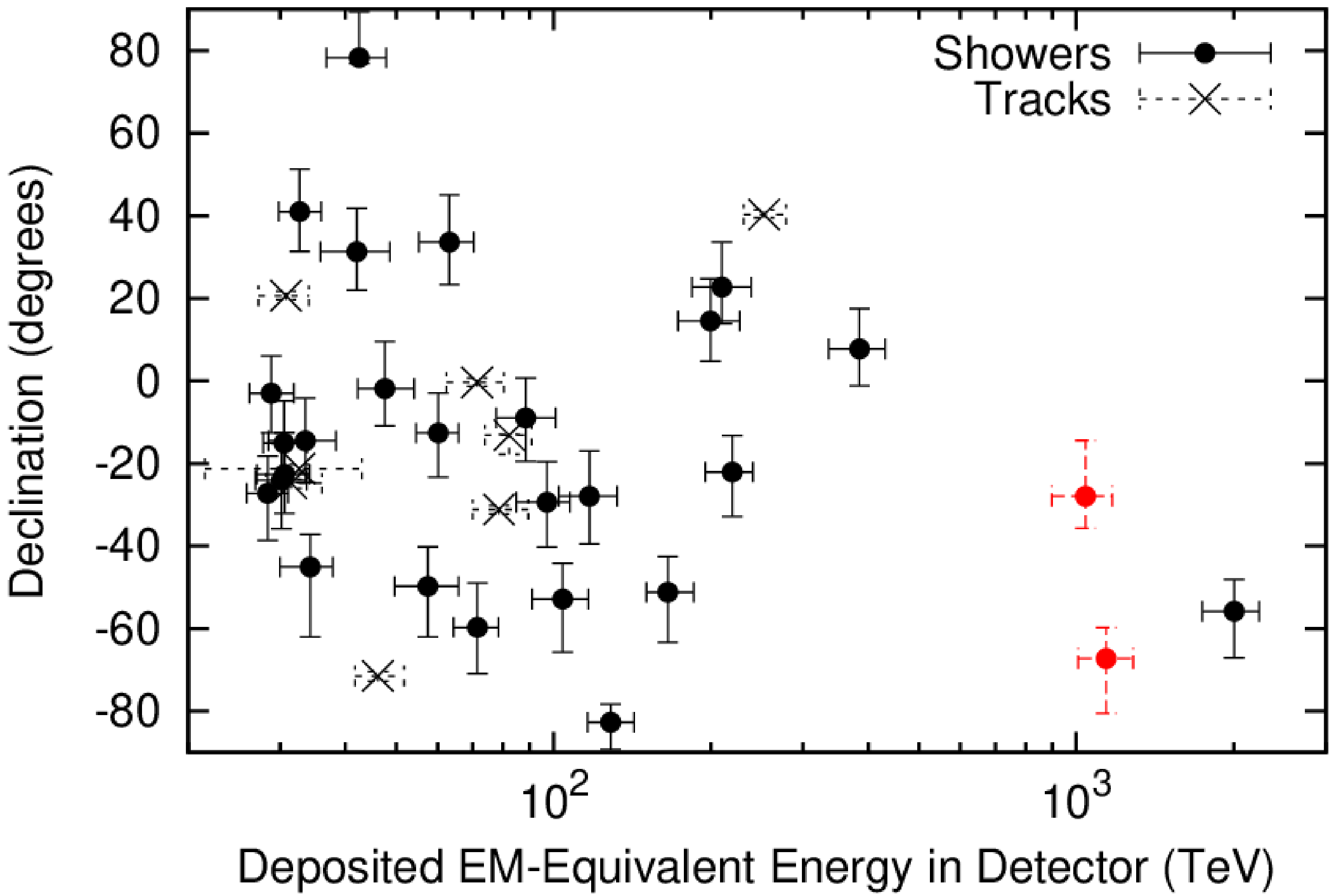
HESE: Example IceCube Analysis

Select neutrinos with contained vertex and sufficiently high energy to make containment cut effective

- Removes muons
- Removes downgoing atmospheric neutrinos
- Keeps astrophysical neutrinos from all directions



Events from HESE (2013)

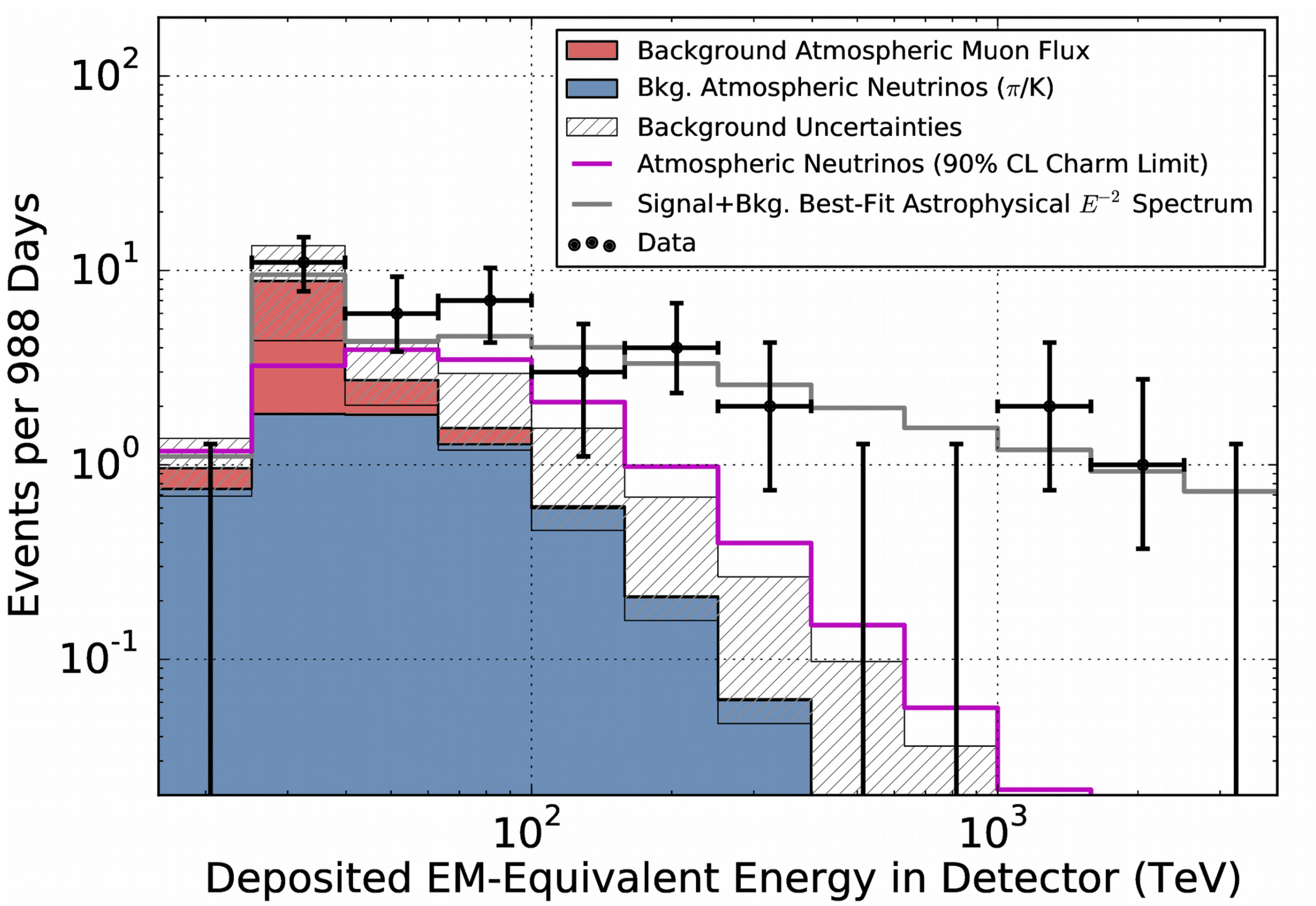


1311.5238

Implications of Events

Signal Expectations:	Bkg. Expectations:	Data:
✔ Cascade-dominated (~80%) from oscillations	✗ Largely track-like (CR muons and atmospheric neutrinos)	✔ 28/37 are cascades
✔ High-energy (expect hard spectrum)	✗ < 1 event/year above 100 TeV	✔ Extends above 1 PeV
✔ Mostly (2/3) in southern sky from Earth absorption	✗ Atmospheric neutrinos mostly in North	✔ 28/37 from Southern sky

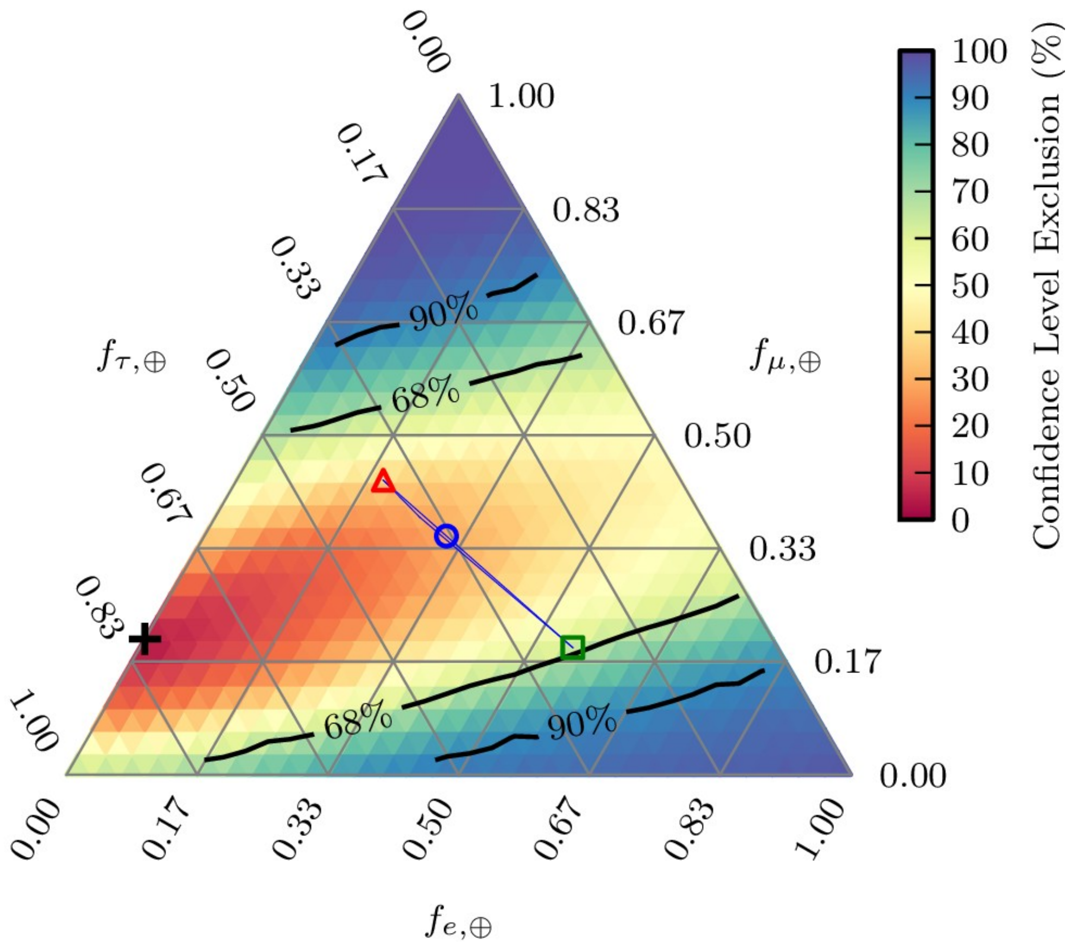
Energy Spectrum of the Diffuse Background



1405.5303

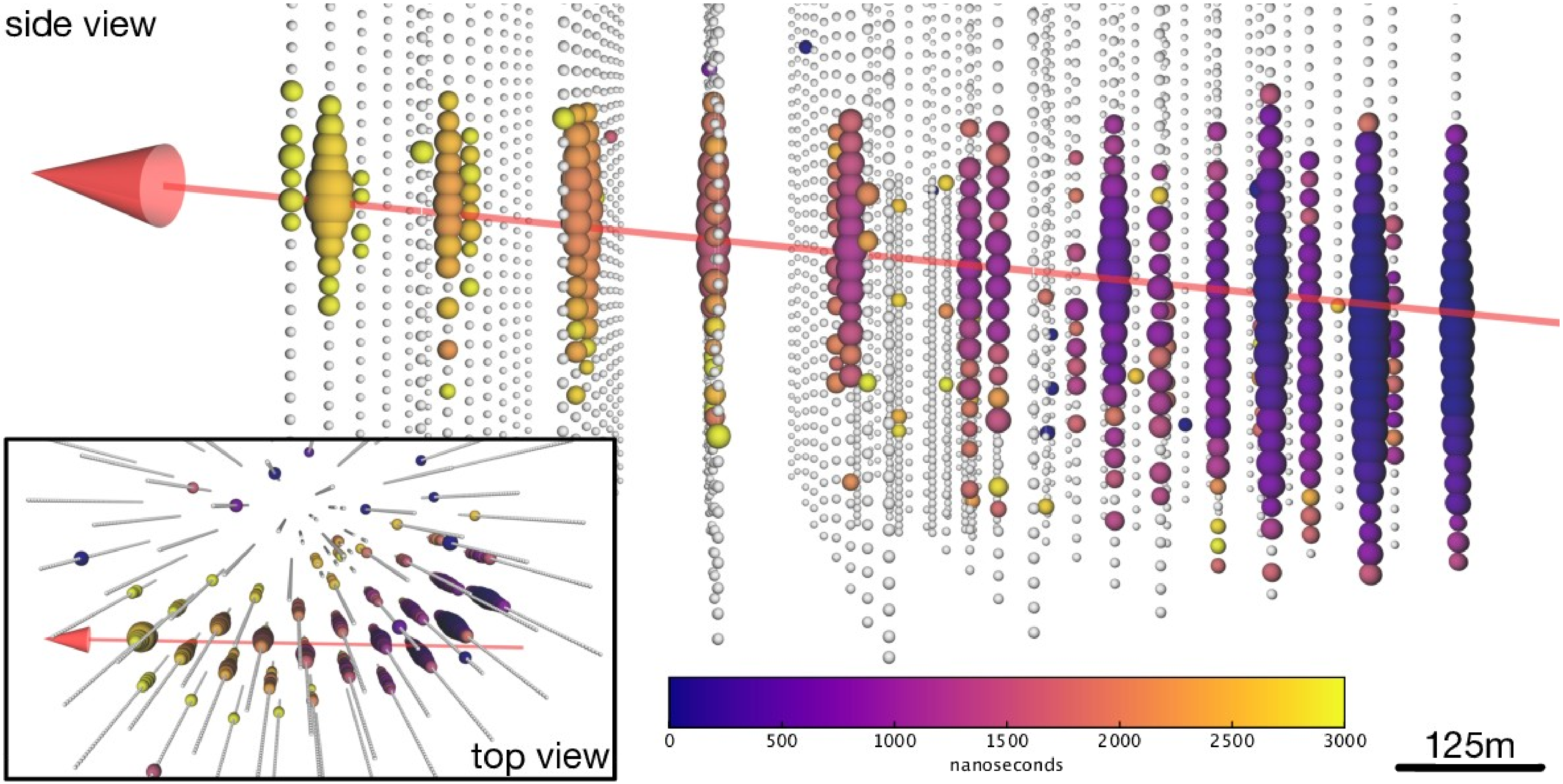
Flavor Composition of the Diffuse Background

- Compatible with flavor equiparition
- No new physics, compatible with expectations from pion decay in astrophysical sources



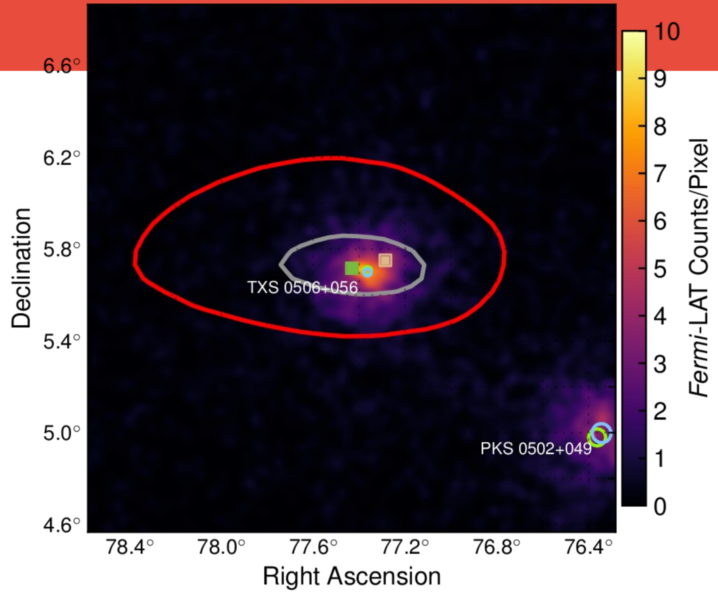
1502.03376

September 22, 2017



Detection of an interesting 300 TeV neutrino by IceCube

Follow-ups from Ground and Sky

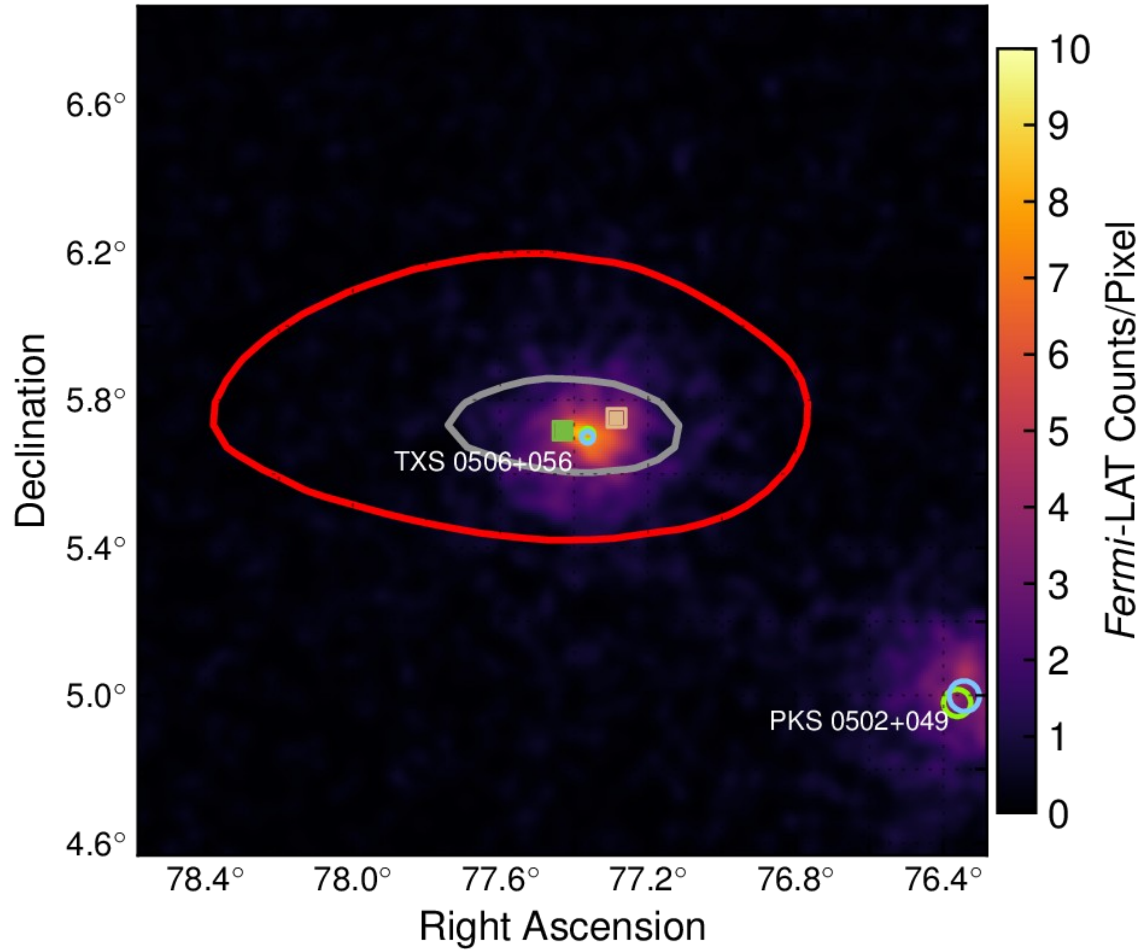


Space and Ground-based telescopes follow up quickly

Follow-up results

Neutrino points to the blazar TXS 0506+056, 4.5 billion light years away

97th-brightest gamma-ray blazar

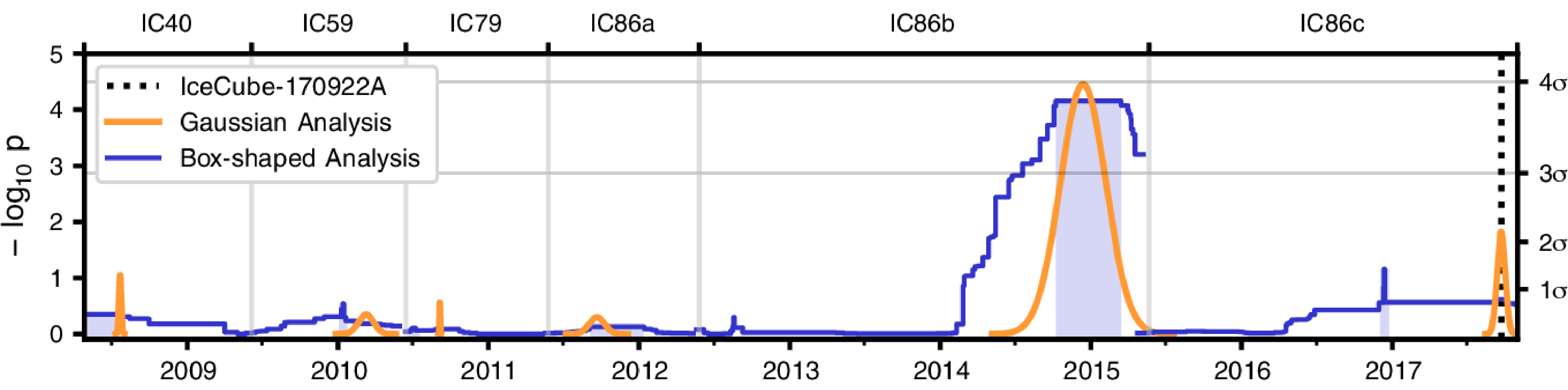


December 2014

Many more neutrinos (13) in December 2014

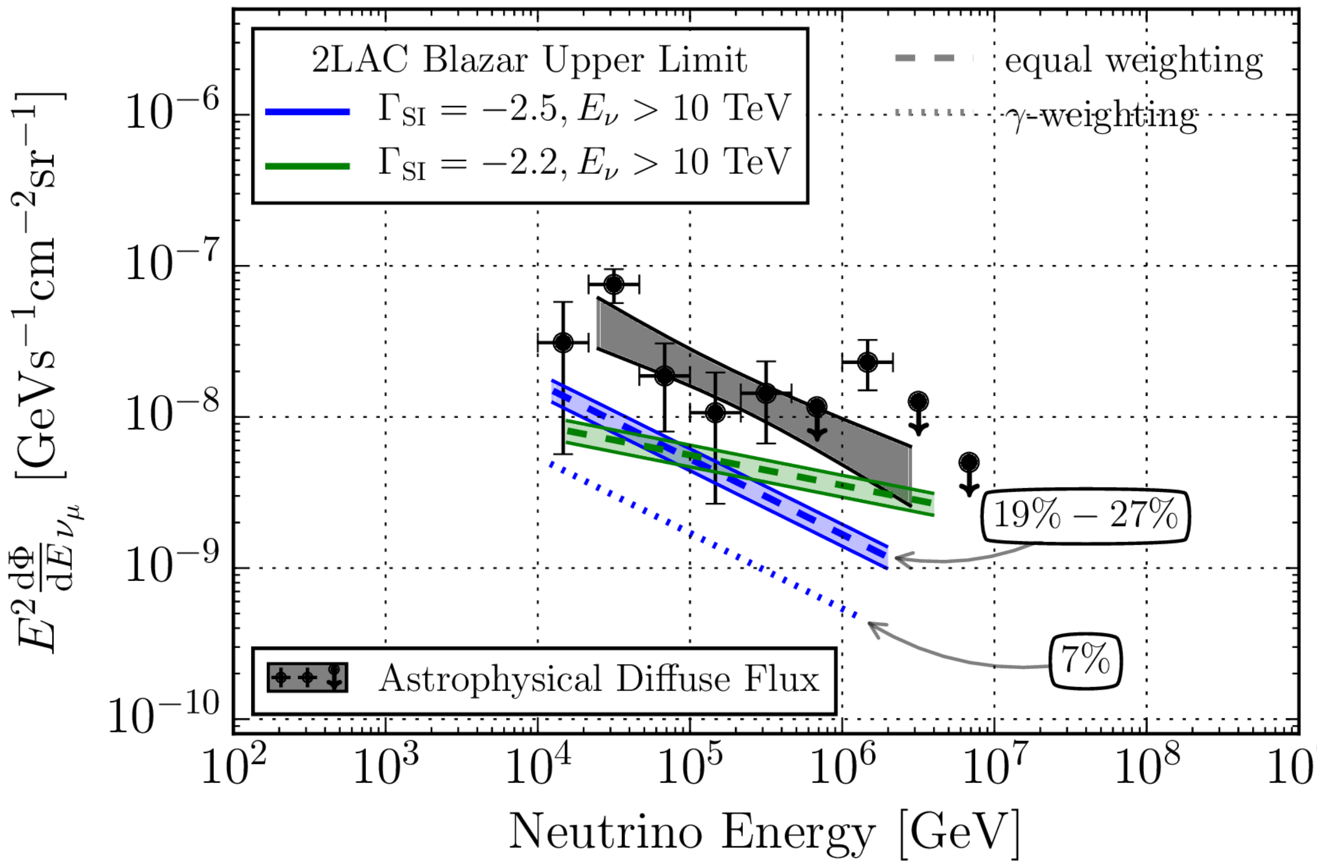
But no gamma rays!

Simple story is not good enough



So: Blazars?

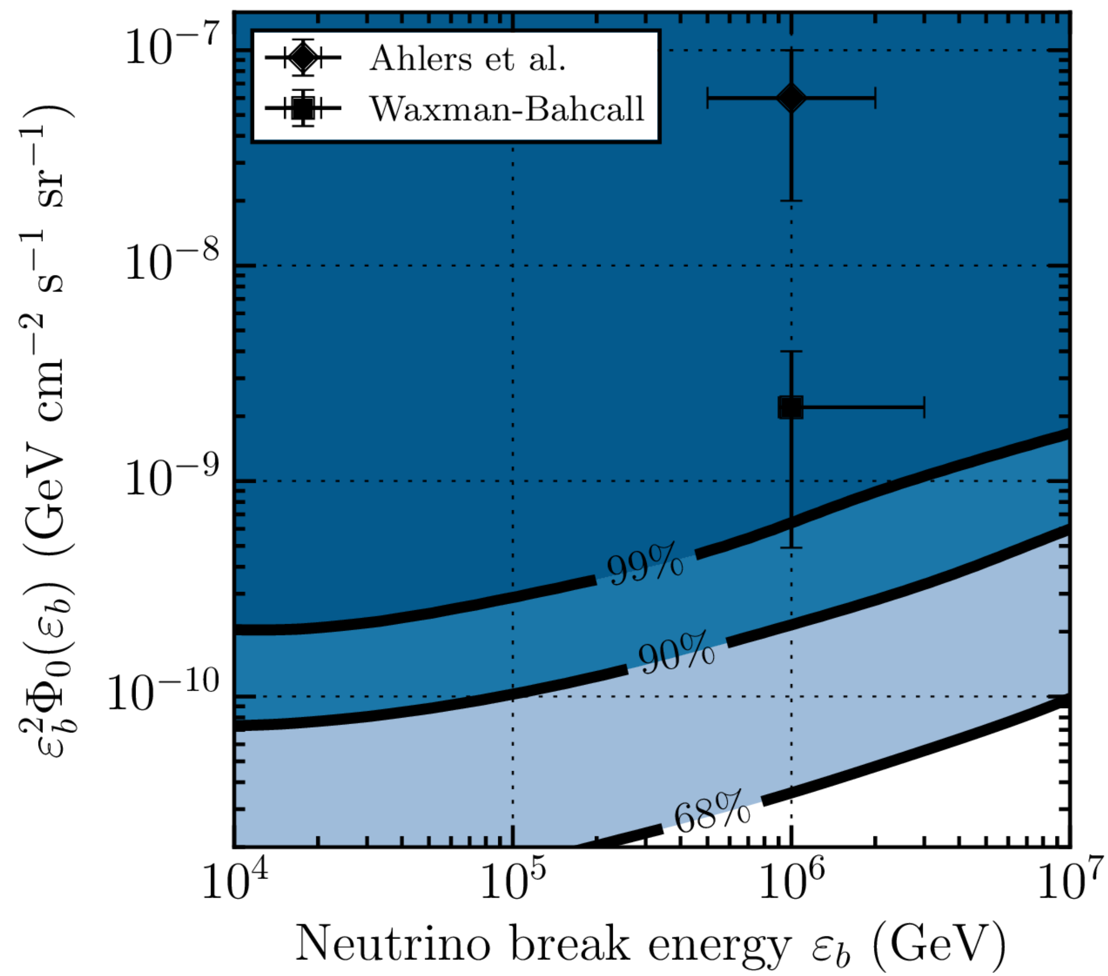
- Like this blazar
- Largest contribution to diffuse gamma-ray background
- **< 10% of diffuse background**



1611.03874

So: GRBs?

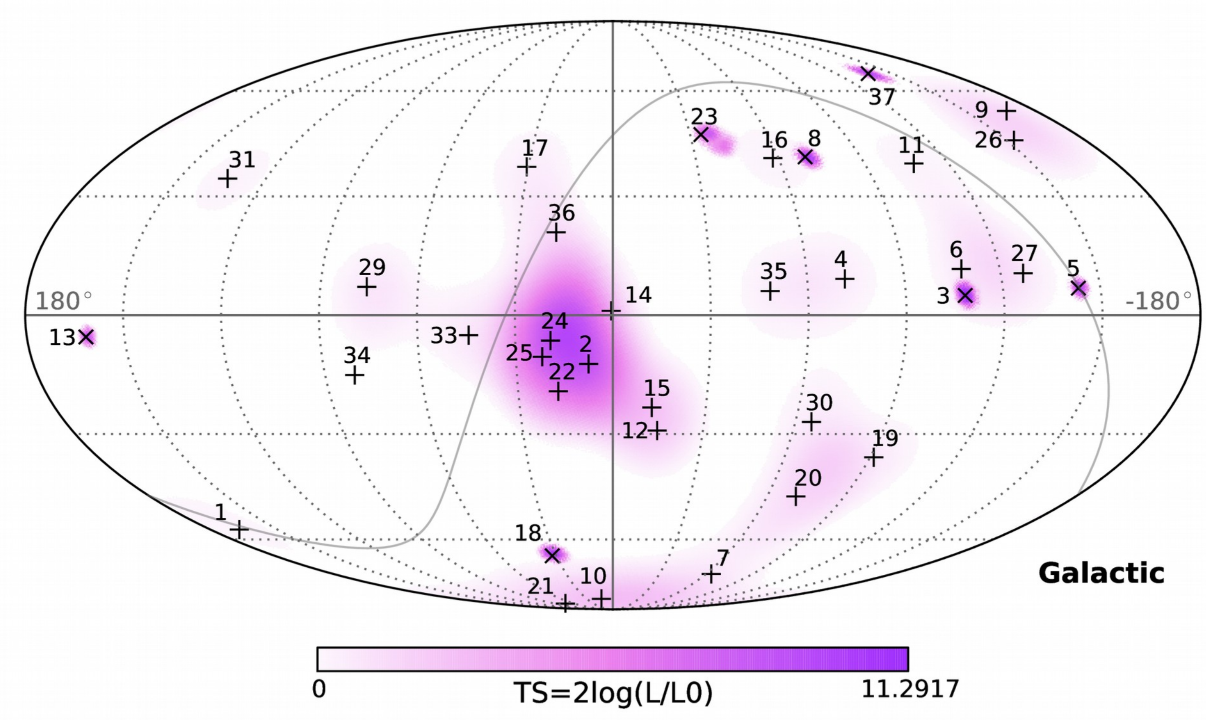
- Biggest explosions in universe
- Similar energy density in photons to neutirnos
- **< 1% of diffuse background**



1702.06868

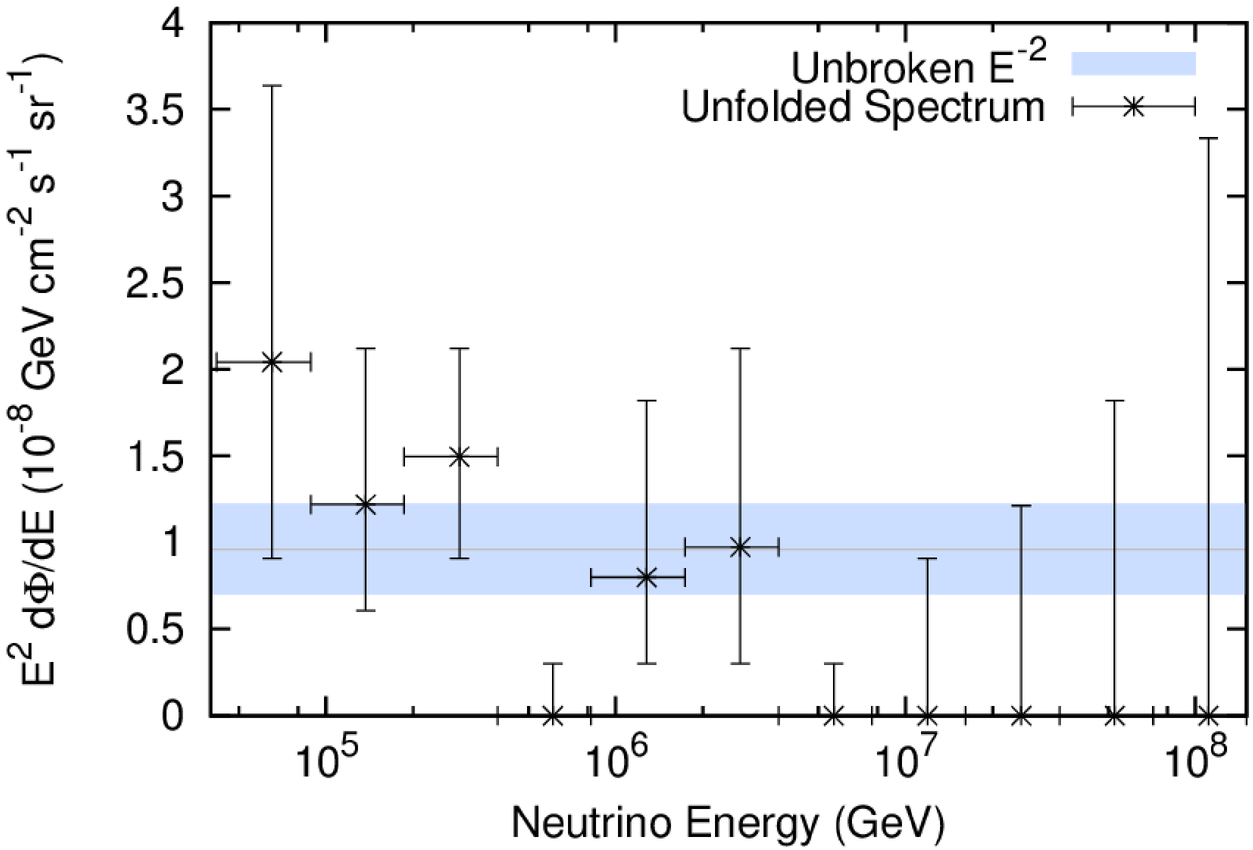
So: Our Galaxy?

- Dominates electromagnetic sky at all energies
- No obvious correlation to the galaxy, though...
- **< 10% of diffuse flux**



Dark Matter?

- Usually (not always!) makes monochromatic neutrinos, some spread from redshift
- **Data clearly not monochromatic**



1405.5303

Things We Know

- There is a large, diffuse TeV—PeV neutrino background of (at least largely) extragalactic origin
- It seems to be well-mixed between flavors
- It is apparently isotropic and correlated with (almost) nothing
- At least one blazar makes at least some neutrinos, but blazars don't explain the diffuse background

???????????????????????????

- How is the first high-energy neutrino source so far away?
- How was it making neutrinos? (and what was it doing in 2014?)
- Does anything interesting happen to neutrinos when they fly for 5 billion years?
- How is the diffuse background so isotropic?
- If not all the things we think about, where is it coming from?
- Is it just astrophysics being complicated? Or something more exotic (non-thermal relic, etc.)?

Keys to improve: the measurement regime

Effective area

- 1^{st} generation targeted the first events
- More required, scaling between sqrt(N) and linear
- 1 km^3 → 5-10 km^3

Angular resolution

- Limits source searches (dark matter and astrophysics)
- Scaling linear
- .5 degree → .1 degree

Systematics

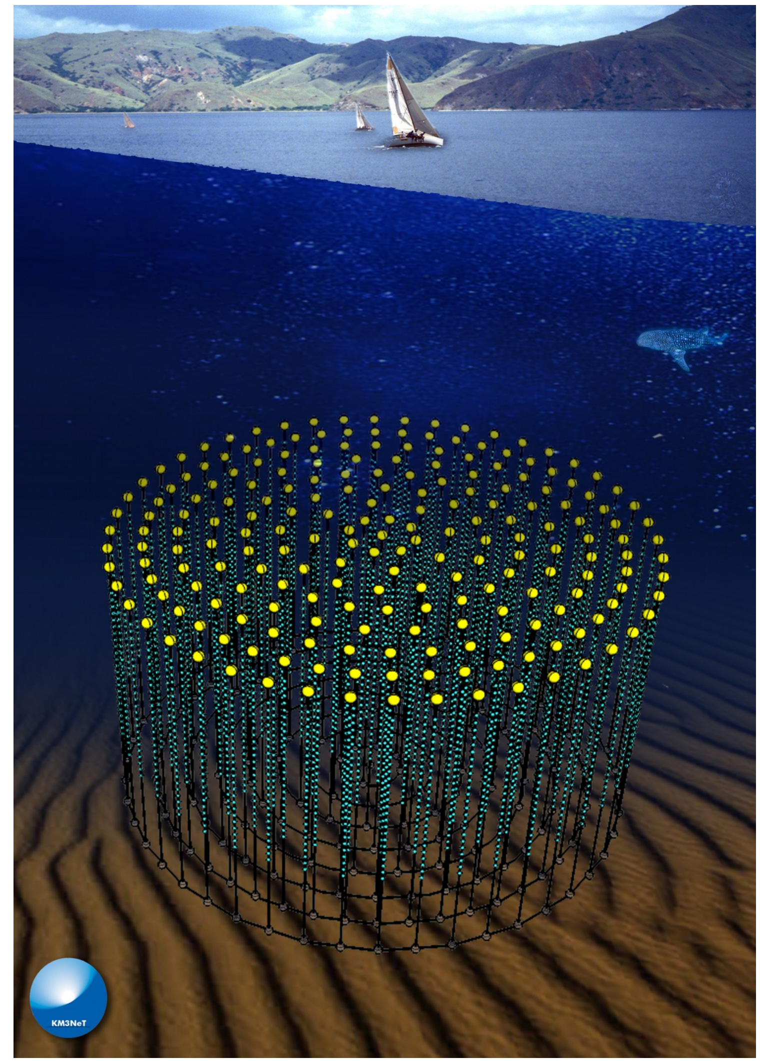
- Limits spectral measurement, low energies

Flavor ID

- Powerful constraint on neutrino physics, source dynamics
- Better reconstruction, more fine-grained data

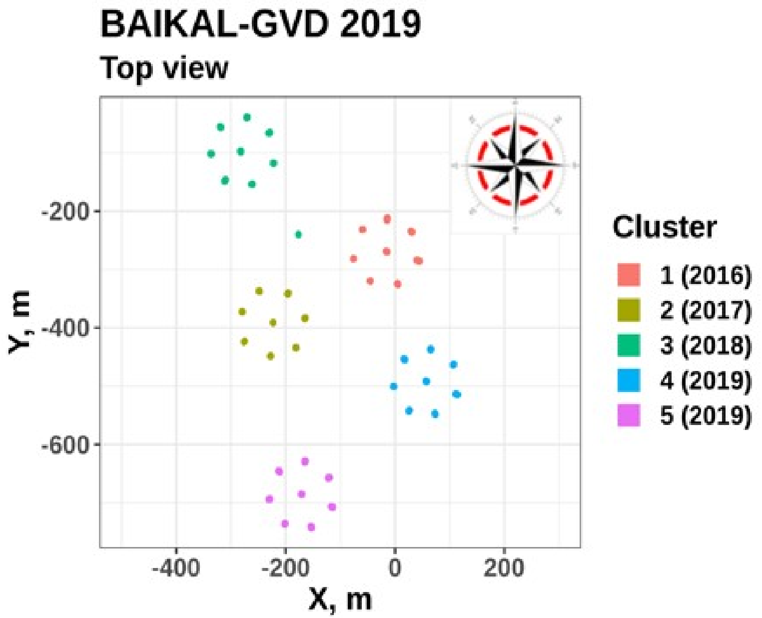
On the Horizon: KM3net

- Multi-km^3 water detector
- Superb angular resolution
- Very of large areas of sky
- Interesting new multi-PMT modules
- Under construction!



On the Horizon: GVD

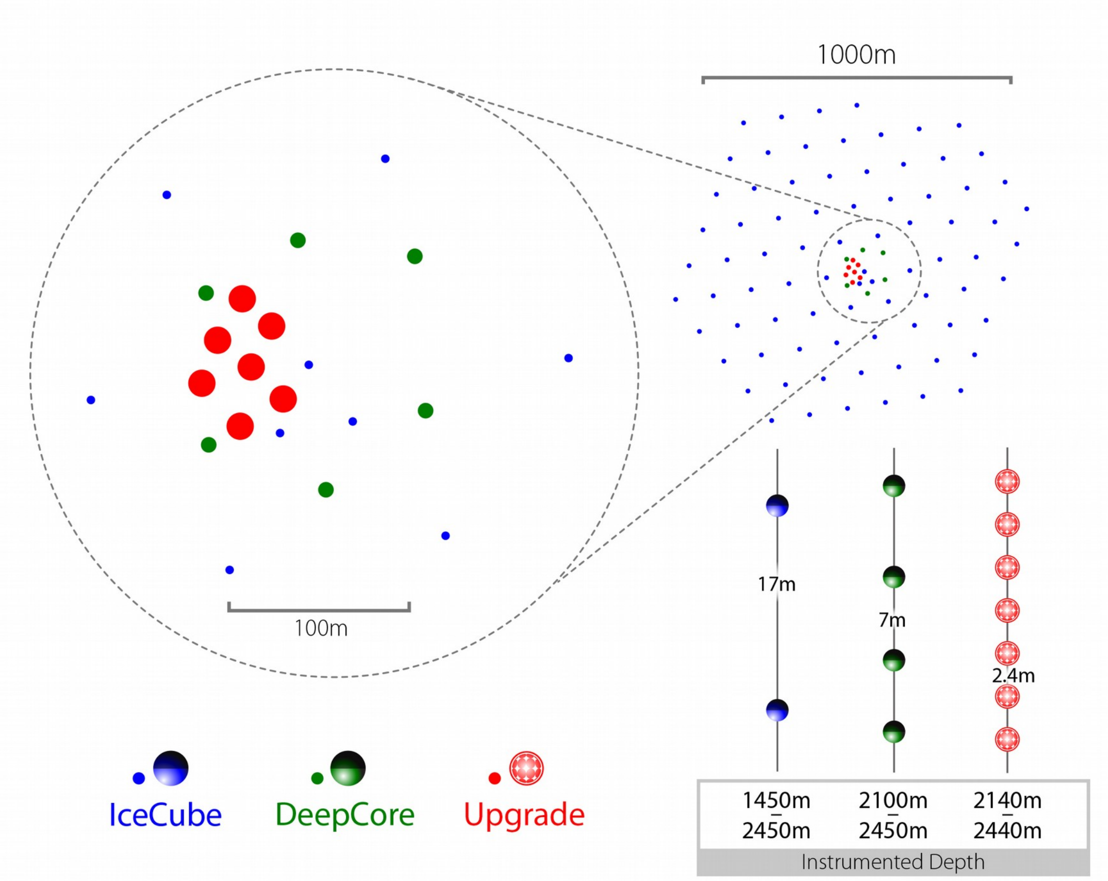
- Multi-km^3 water detector
- Superb angular resolution
- Very large areas of sky
- At Baikal site
- Taking data, right now, during construction!
- Likely first non-IceCube detector to see diffuse background



F. Simkovic, ICRC 2019

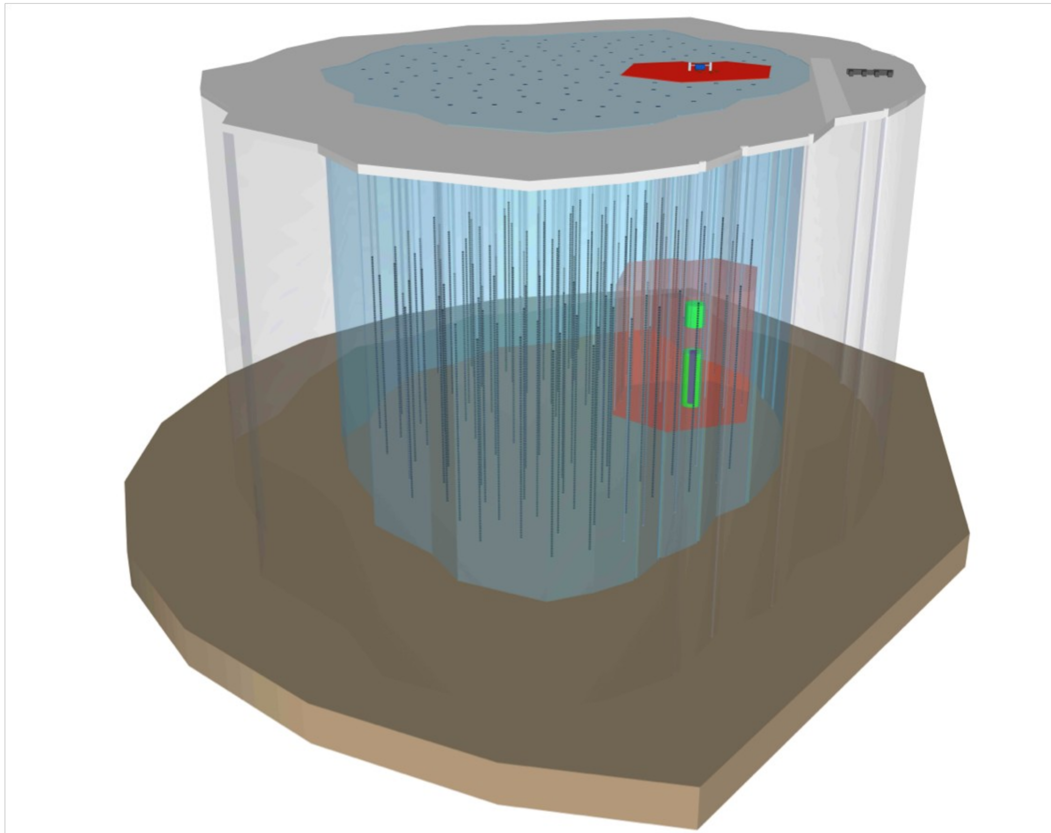
On the Horizon: IceCube Upgrade

- Small in-fill of IceCube
- Better calibration
- Improves all of IceCube's angular resolution
- Sensitivity enhancement at low energies
- R&D Opportunity
- Funded!



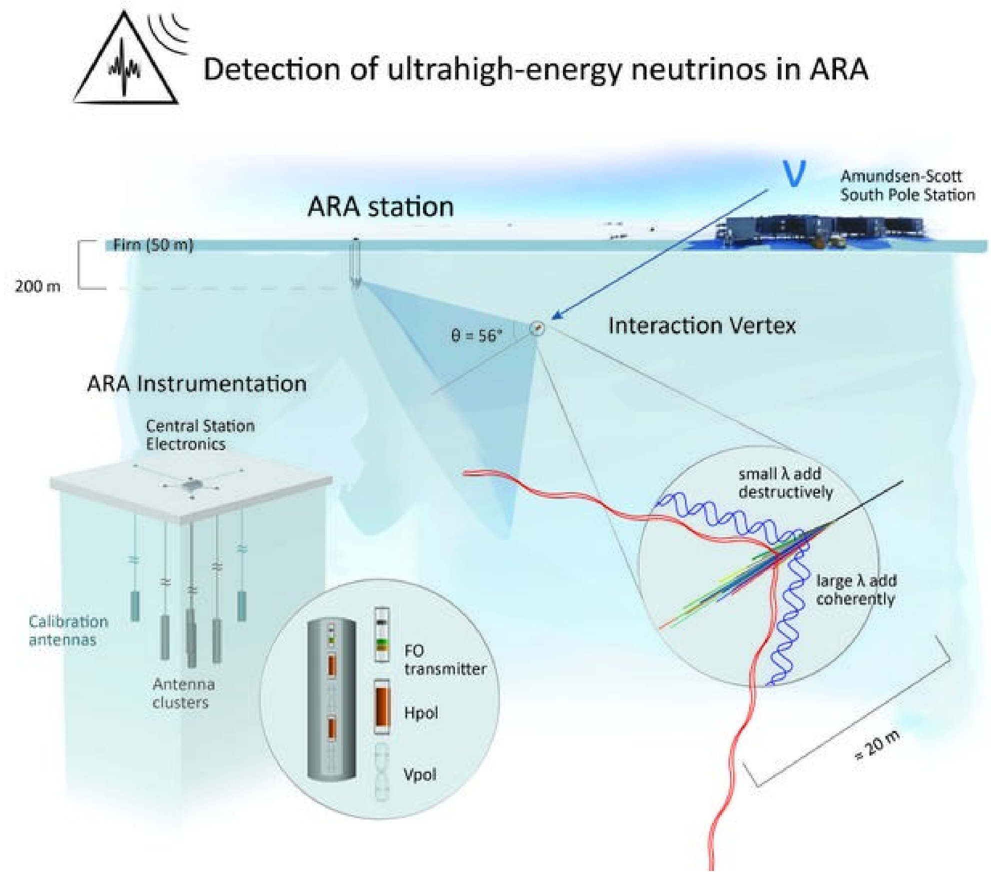
On the Horizon: IceCube Gen2

- 8 km^3
- 0.1 degree resolution
- Early design stage
- New photo-detector designs
- Mid-2020s



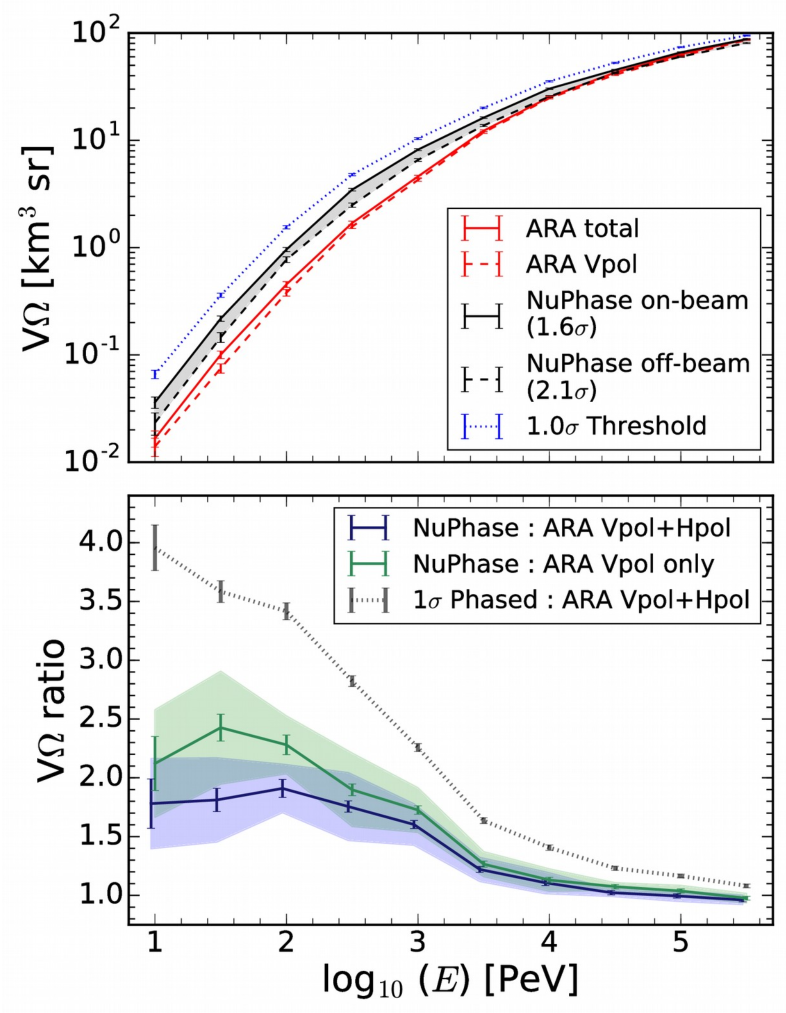
On the Horizon: Ultra-High-Energy Radio

- How to scale to 100 km^3?
- Radio impulses from charge imbalance in showers in matter
- Proven technique (ANITA)
- Two in-ice instruments building out: ARA and ARIANNA
- Threshold of 10^{17} eV



On the Horizon: (Merely) High-Energy Radio?

- Radio is cheap, but energy threshold is high
- Threshold set by trigger noise
- Multi-antenna correlations can pull this down
- Possible 10^{15} eV in reach
- Test module deployed in ARA in 2018



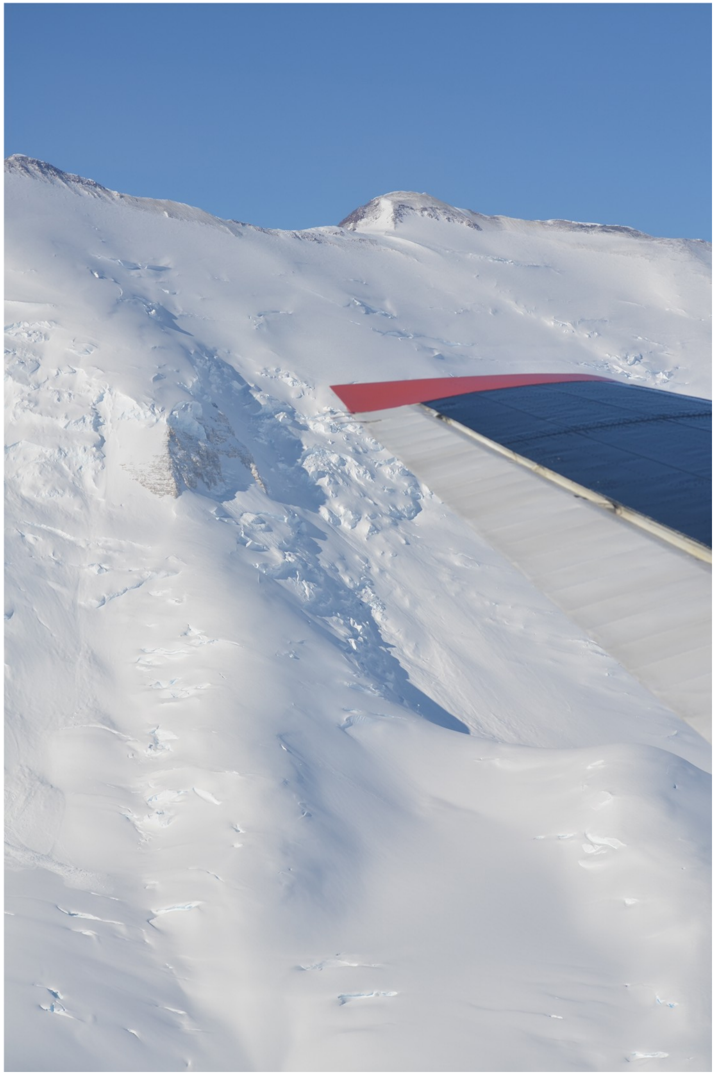
ArXiv: 1809.04573

Prospects for the Next Decade

This decade, we stopped measuring zero:

- First source – distribution normalized, know what to target
- At models for GZK
- Diffuse background detected
- Oscillation capabilities demonstrated

Next 10 years, many new instruments coming online – learn what these things have to tell us



The Beginning