Neutrino Astronomy

(almost not detectable) (all about detection)

John Beacom, The Ohio State University

The Ohio State University's Center for Cosmology and AstroParticle Physics

CCAPP

NSF

Plan of the Talk

What are neutrinos?
Astrophysical neutrinos must exist

What is IceCube?
What has IceCube discovered?

What does it mean for particle physics?

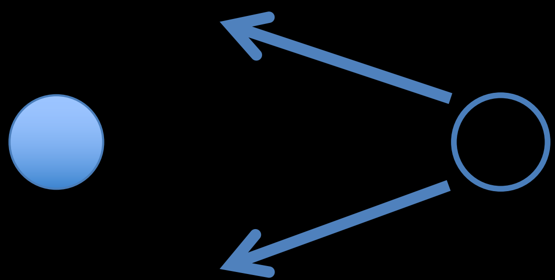
Concluding Remarks

What Are Neutrinos?

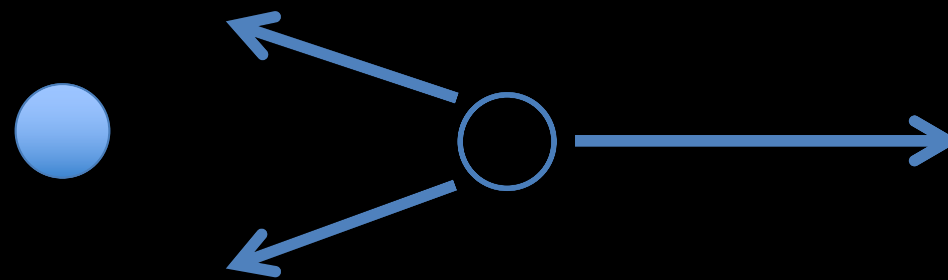
Neutrinos – As Concepts

$$n \to p + e^-$$

$$n \to p + e^- + \bar{\nu}_e$$



before after



before after

Violates conservation of momentum and energy

Respects conservation of momentum and energy

Pauli (1930): *I have done a terrible thing. I have postulated a particle that cannot be detected.*

What About Other Unsolved Problems?

Other particle and nuclear decays?	*Neutrinos!*
Formation of chemical elements?	*Neutrinos!*
Cooling of white dwarfs and neutron stars?	*Neutrinos!*
Radiation energy density of universe?	*Neutrinos!*
What is the dark matter?	*Neutrinos!*
Where does lost computer data go?	*Neutrinos!*
Calculations don’t quite work?	*Neutrinos!*

Neutrinos – As Realities

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Neutron decay happens

$$p + e^- \rightarrow n + \nu_e$$

Electron capture happens

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

What about neutrino capture?

Required by time-reversal invariance of microscopic processes

Bethe and Peierls (1934): *If [there are no new forces] one can conclude that there is no practically possible way of observing the neutrino*

What About Detection?

Reines and Cowan (1956): *antineutrinos detected anyway!*

Neutrinos – As Messengers

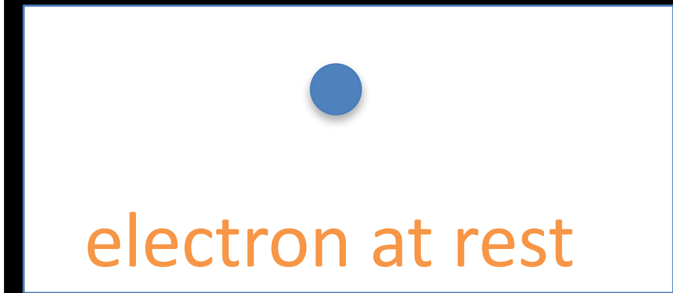
Wherever conditions are hot and dense, or creating chemical elements, or accelerating particles, neutrinos are made

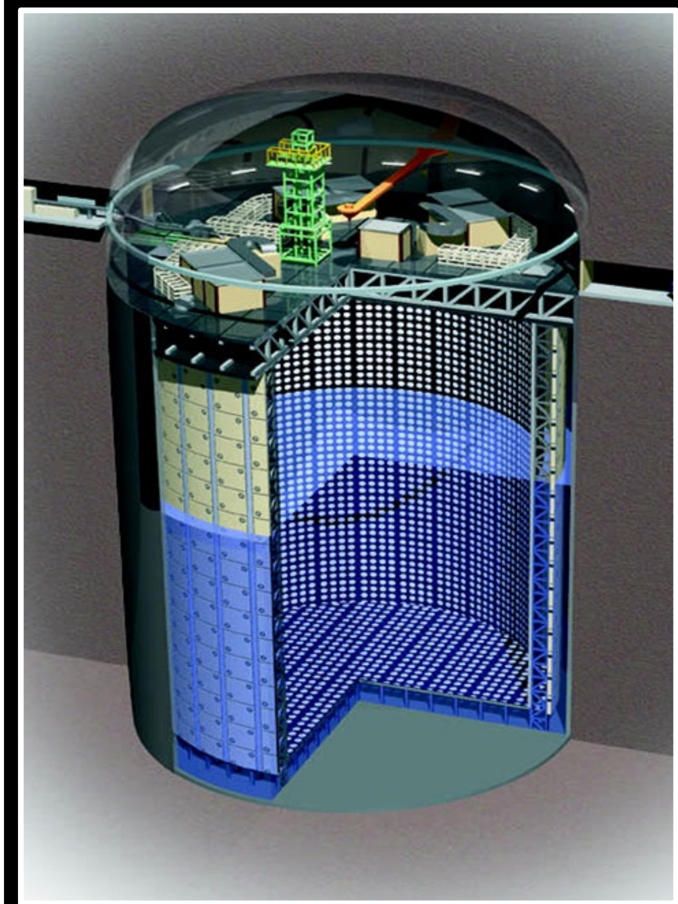
Neutrinos can reveal:

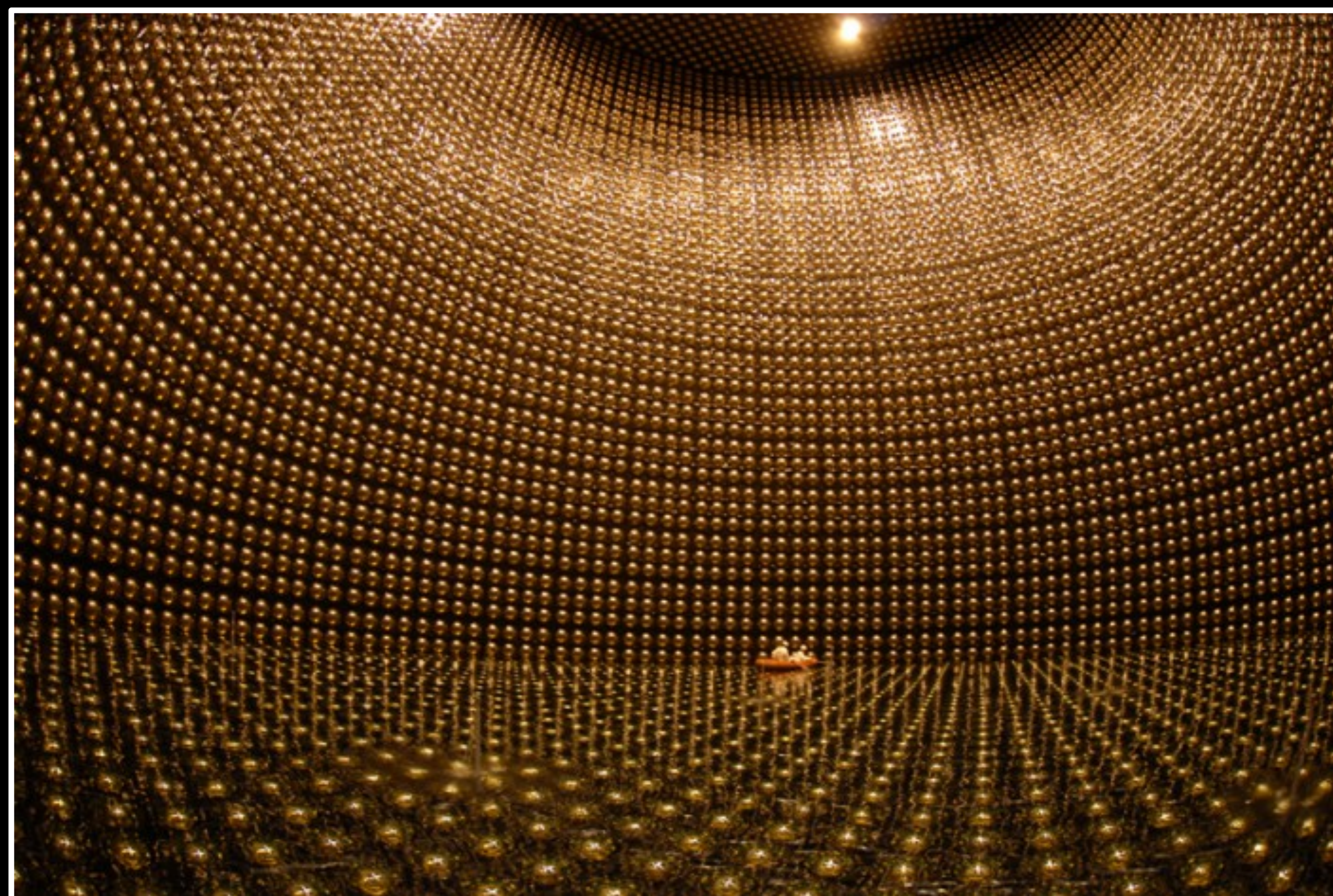
- deep insides of sources, not the outsides
- initial energies, not reduced by scattering
- original timescales, not delayed by diffusion
- distant sources, not attenuated en route

The only thing is that neutrino signal detection is hard

What Makes a Neutrino Observatory?





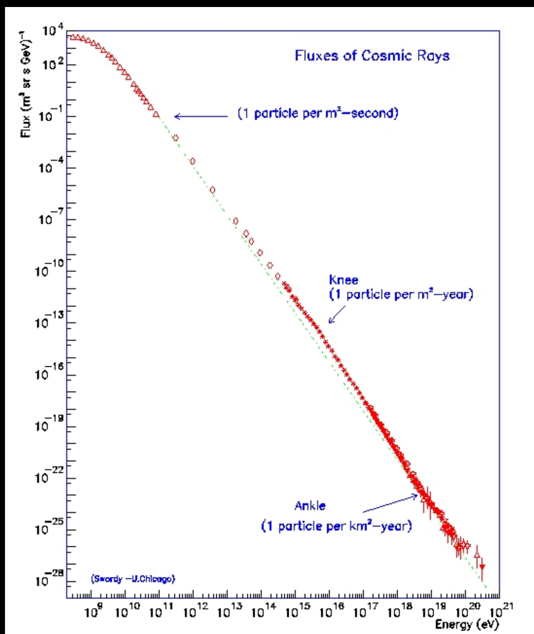


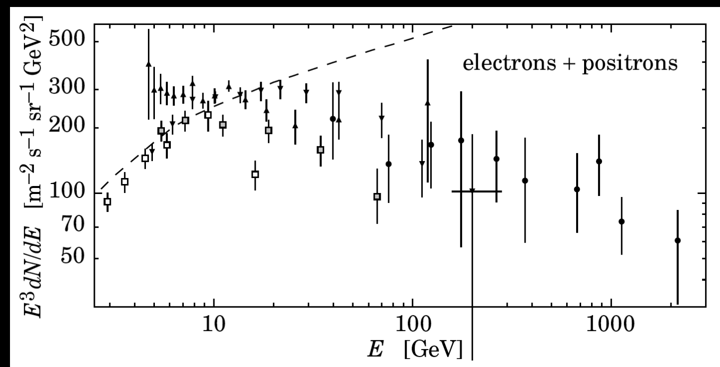
HE astrophysical neutrinos must exist

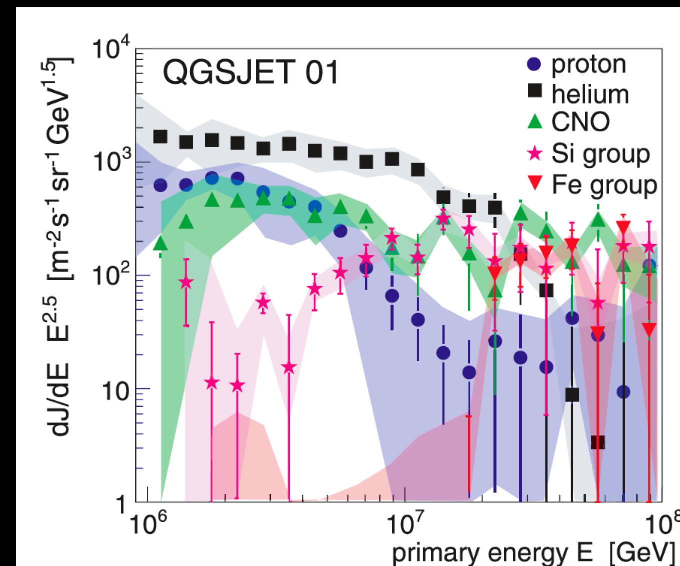
Energetic and Luminous CR Sources Exist

Charged cosmic rays first detected 100 years ago

protons | electrons and positrons | nuclei







Cosmic rays produced with high energies (up to 10^{20} eV) and high densities ($U_{CR} \sim U_{starlight}$ in MW), but do not point back

Sources assumed astrophysical, but may also be exotic

Cosmic Rays Inevitably Make Secondaries

Hadronic mechanism

$$p + p \rightarrow p + p + \pi^0,\ p + n + \pi^+$$

$$\pi^0 \rightarrow \boxed{2\gamma},\ \pi^\pm \rightarrow e^\pm + \boxed{3\nu}$$

Leptonic mechanism

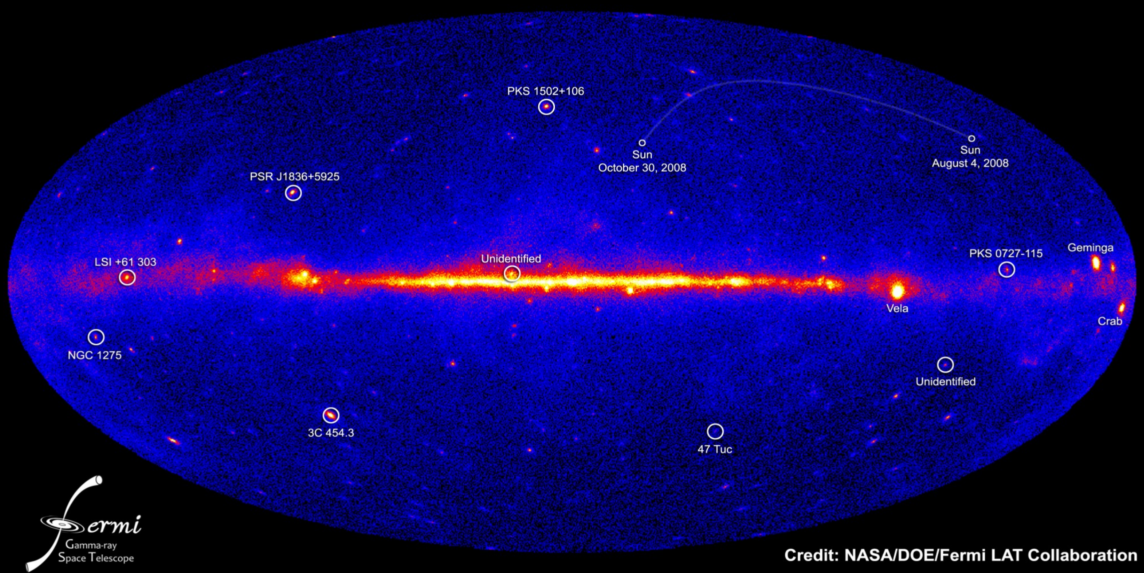
$$e^- + \gamma \rightarrow \boxed{\gamma} + e^-$$

Leptonic sources: versus Hadronic sources:

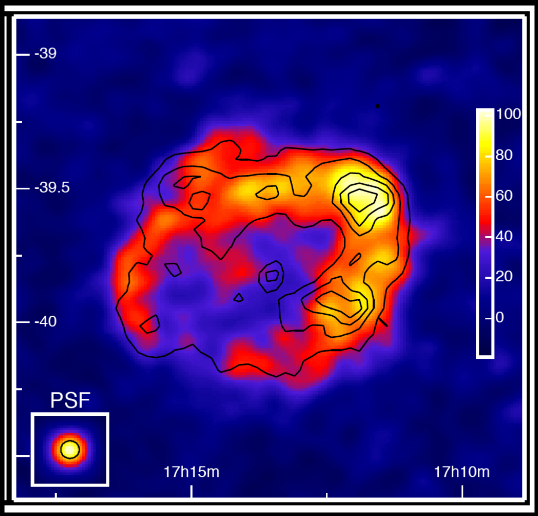
$$\Phi_\nu \sim 0 \qquad \Phi_\nu \sim \Phi_\gamma$$

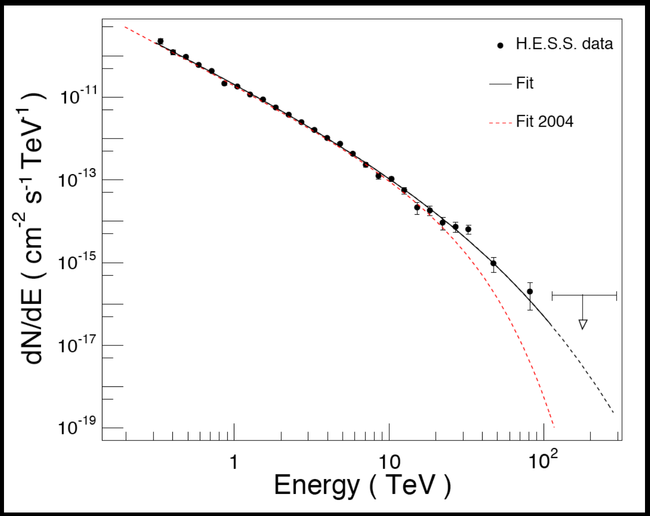
Production always makes a mess; propagation makes more

Energetic and Luminous Gamma Sources Exist



Wide variety of point and diffuse sources, high fluxes





Energies up to ~ 100 TeV

Gammas do point, but they do attenuate, don't reveal parents

Energetic and Luminous Neutrino Sources Exist

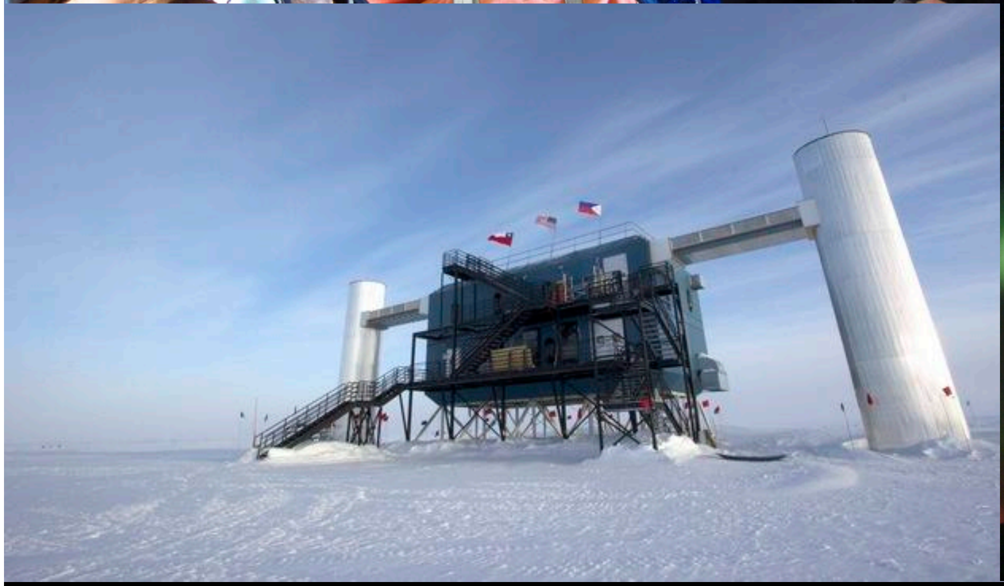
Speculation about high-energy neutrino astronomy since 1960s (Reines; Ruderman; Markov; Pontecorvo; Berezinsky; etc.), now greatly strengthened and directed by gamma-ray data

Large neutrino fluxes expected from a variety of diffuse, point, and transient sources in the Milky Way and cosmos … and neutrino-bright surprises are possible

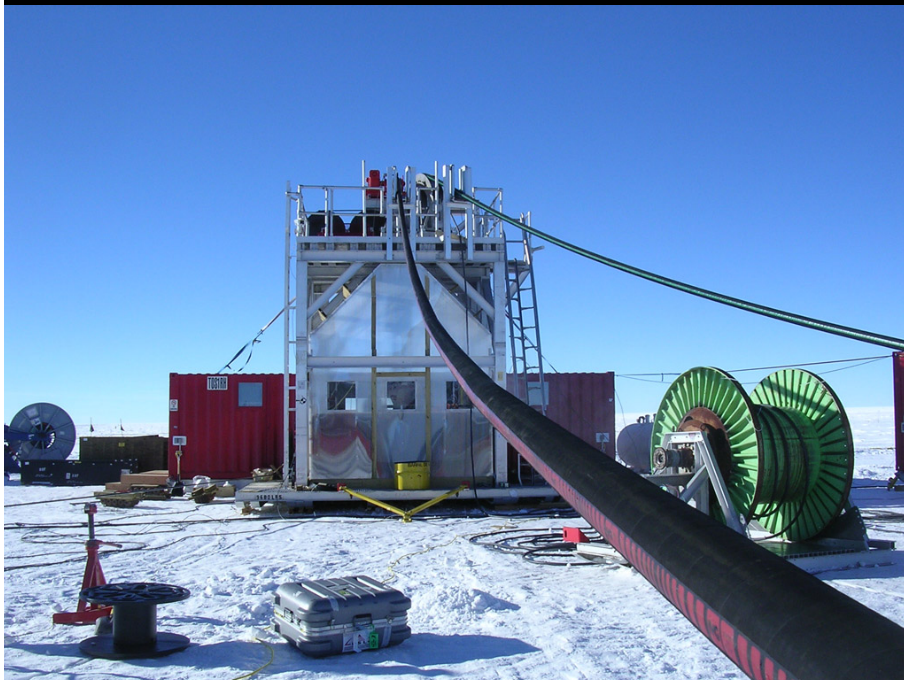
But can they be detected?

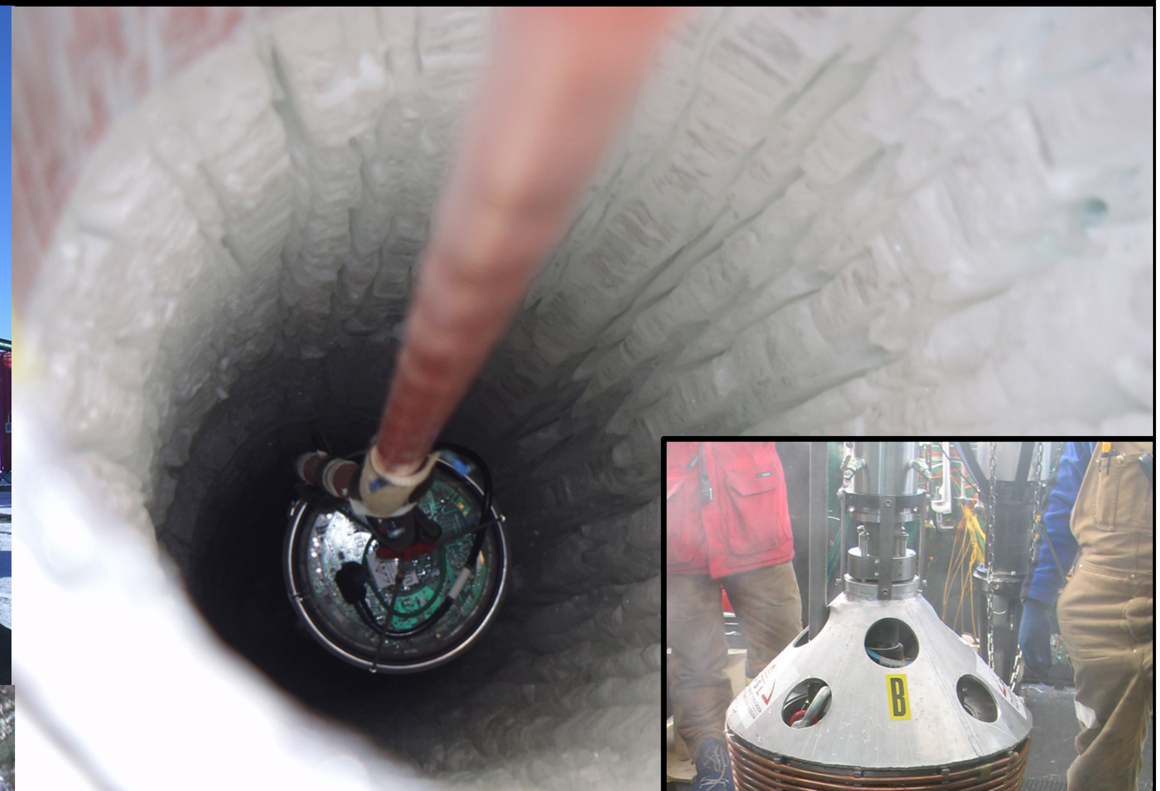
What is IceCube?

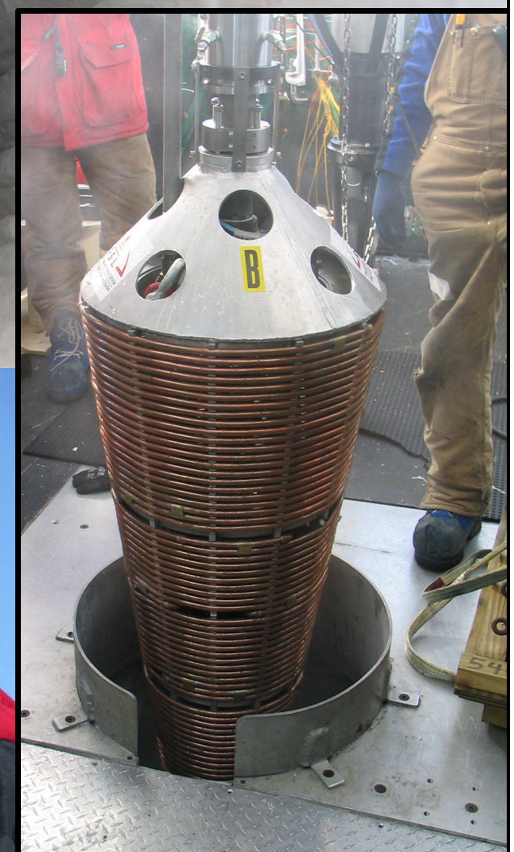
The Location



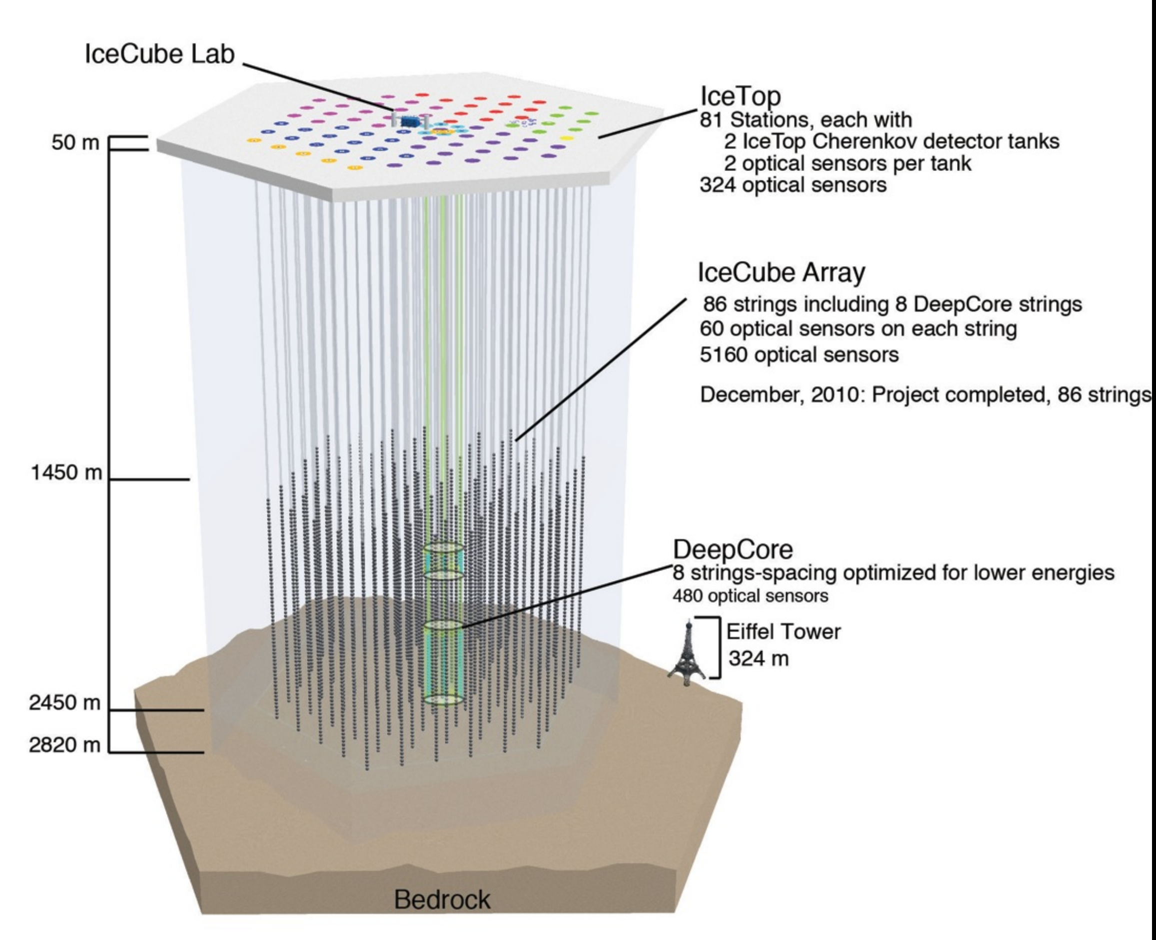
The Construction

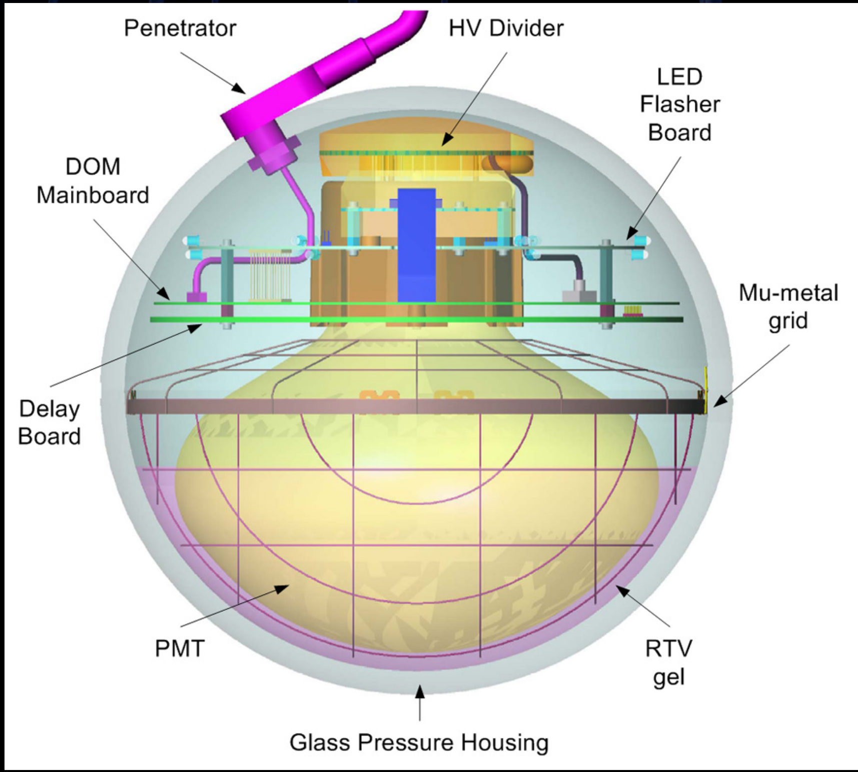






The Design





Needs 86 strings of PMTs buried in 1 km^3 of clear ice

The Detection Principles

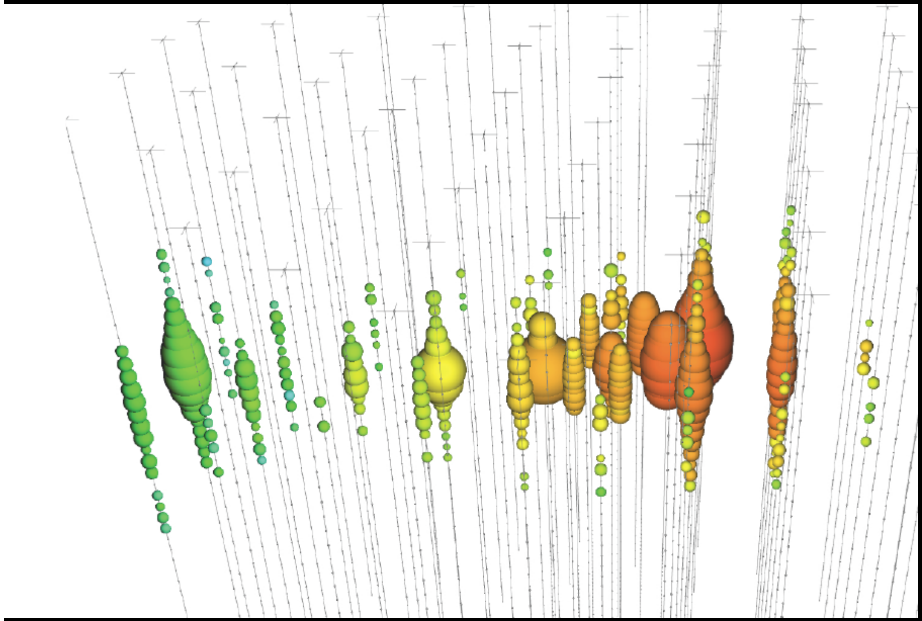
Track events
Few km in length
Planned focus of IceCube

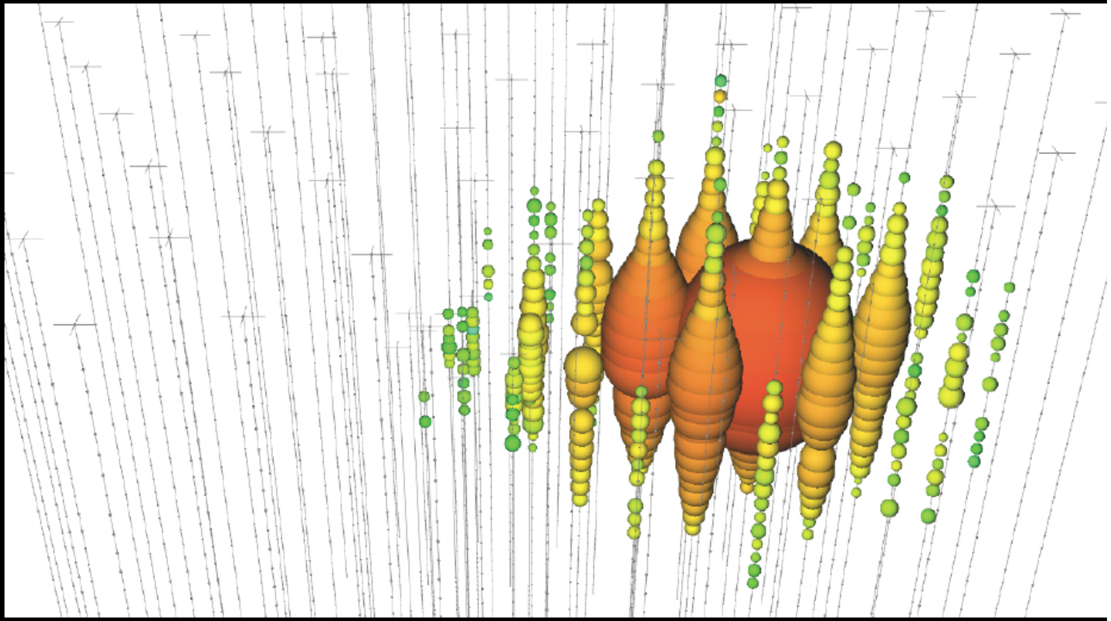
e.g., $\nu_\mu + n \rightarrow \mu^- + p$

Cascade (shower) events
Few m in length
See Beacom and Candia (2004)

e.g., $\nu_e + n \rightarrow e^- + p$

$\nu_\tau + n \rightarrow \tau^- + p$

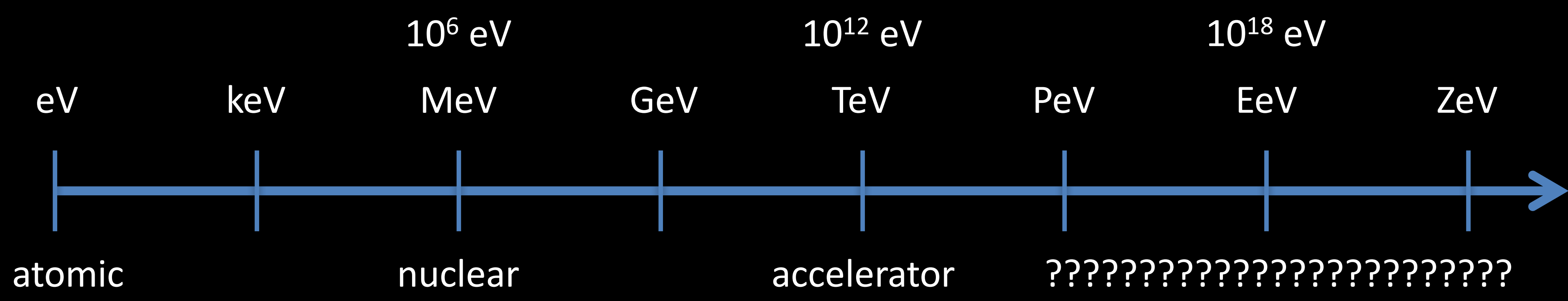




First Difficulty: Beseeching Nature

Requires: sources that reach high energies
sources that are luminous
sources of different types
particles that can reach us
particles that can point back
particles that can be detected
results that can be understood

Our part

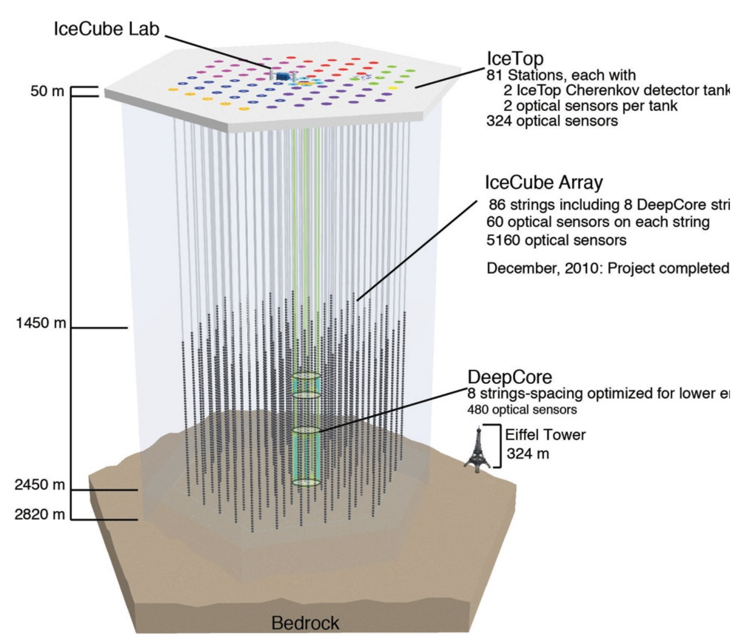


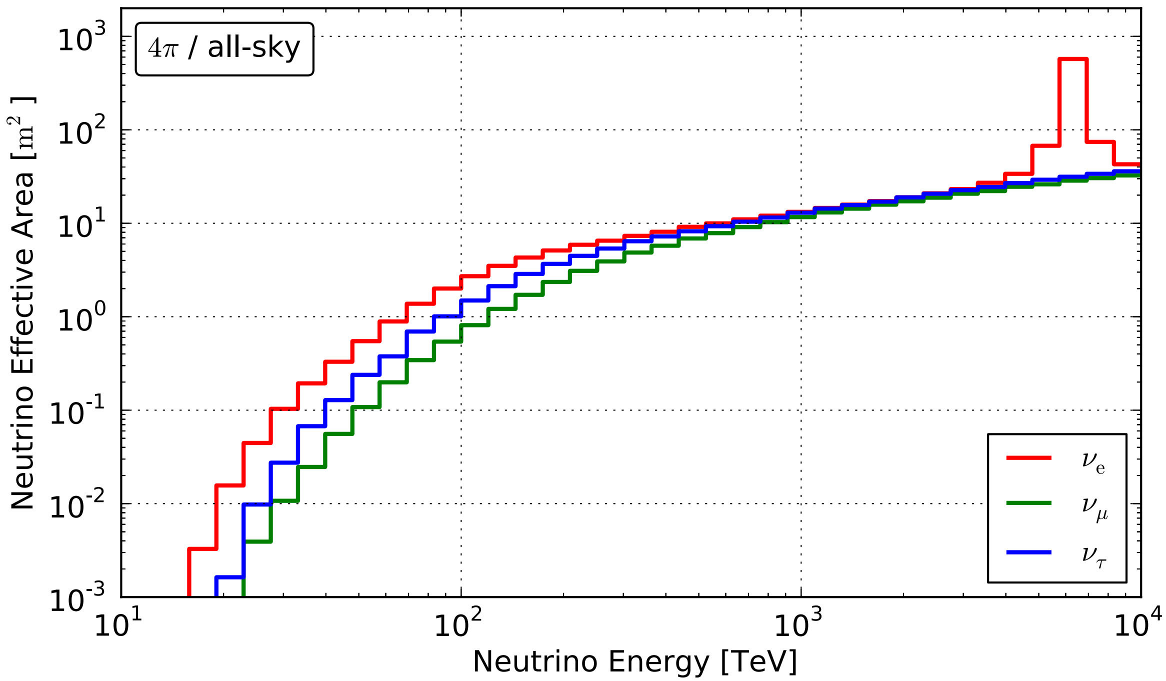
Second Difficulty: Measuring Signals

$$N_{events} \sim 4\pi \,.\, N_{targets}\, \sigma \,.\, T \,.\, \Phi \sim 4\pi \,.\, A_{effective} \,.\, T \,.\, \Phi$$

Volume ~ 1 km^3

$A_{effective}$ ~ 1 m^2 at 100 TeV



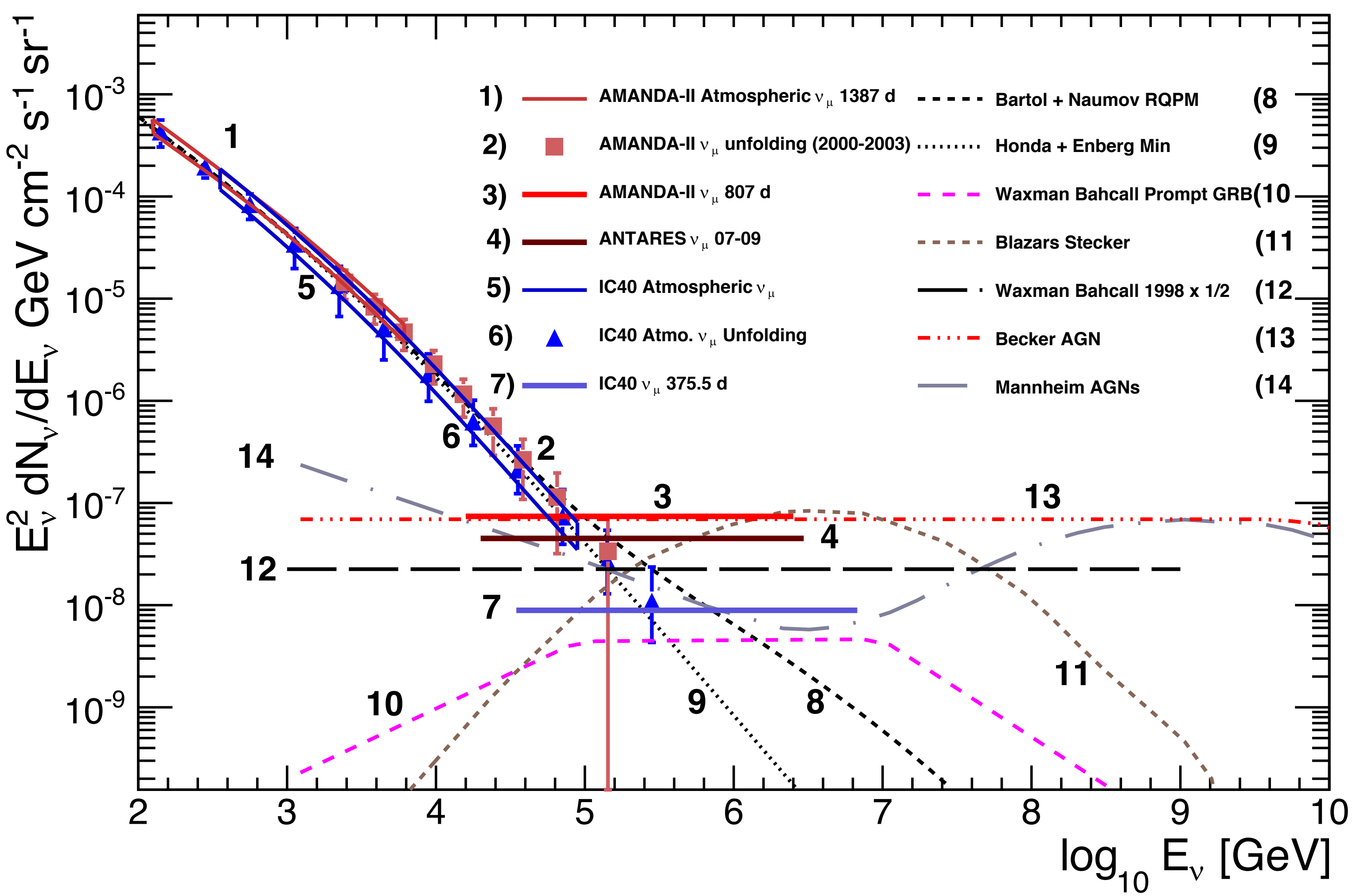


For many sources, ~ 1 km^3 is the minimum required

Third Difficulty: Rejecting Backgrounds

Atmospheric muons: enormous but greatly reducible *background*

Atmospheric neutrinos: big but reducible (Schonert+ 2008) *foreground*



IceCube 2011:

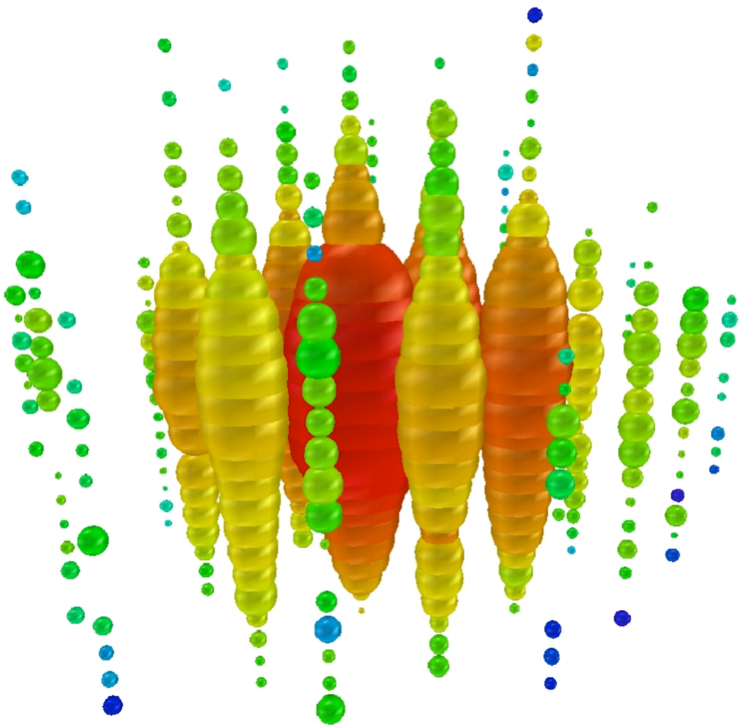
Atm. nu measured up to ~ 200 TeV

Astro. nu strong limits at higher energies

What has IceCube Discovered?

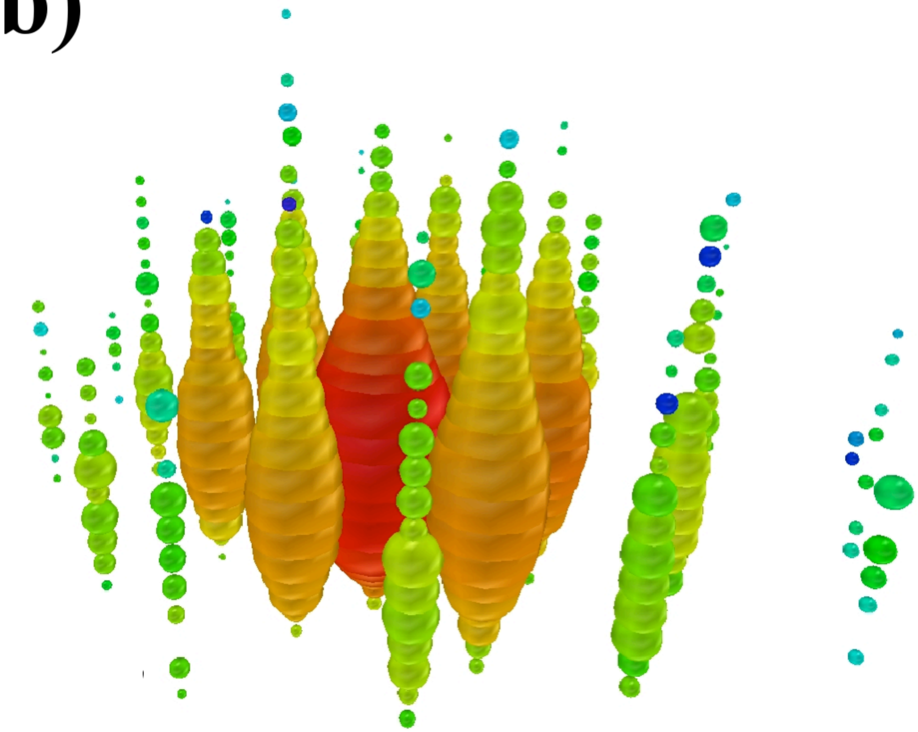
The Pevatrons Uncloak

(a)



2011: ~ 1 PeV cascade

(b)

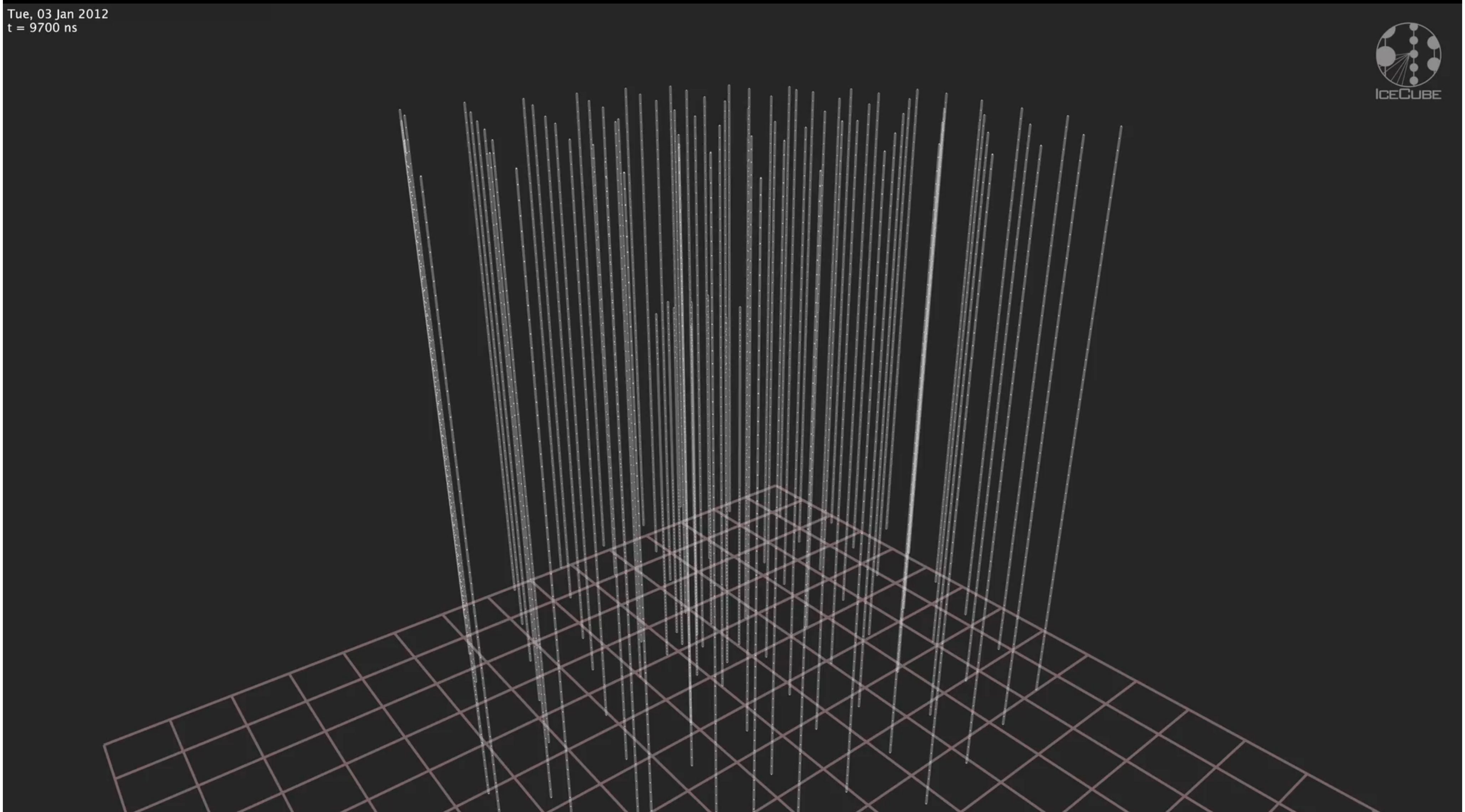


2012: ~ 1 PeV cascade

Great fortune in finding these events in this search (2013)

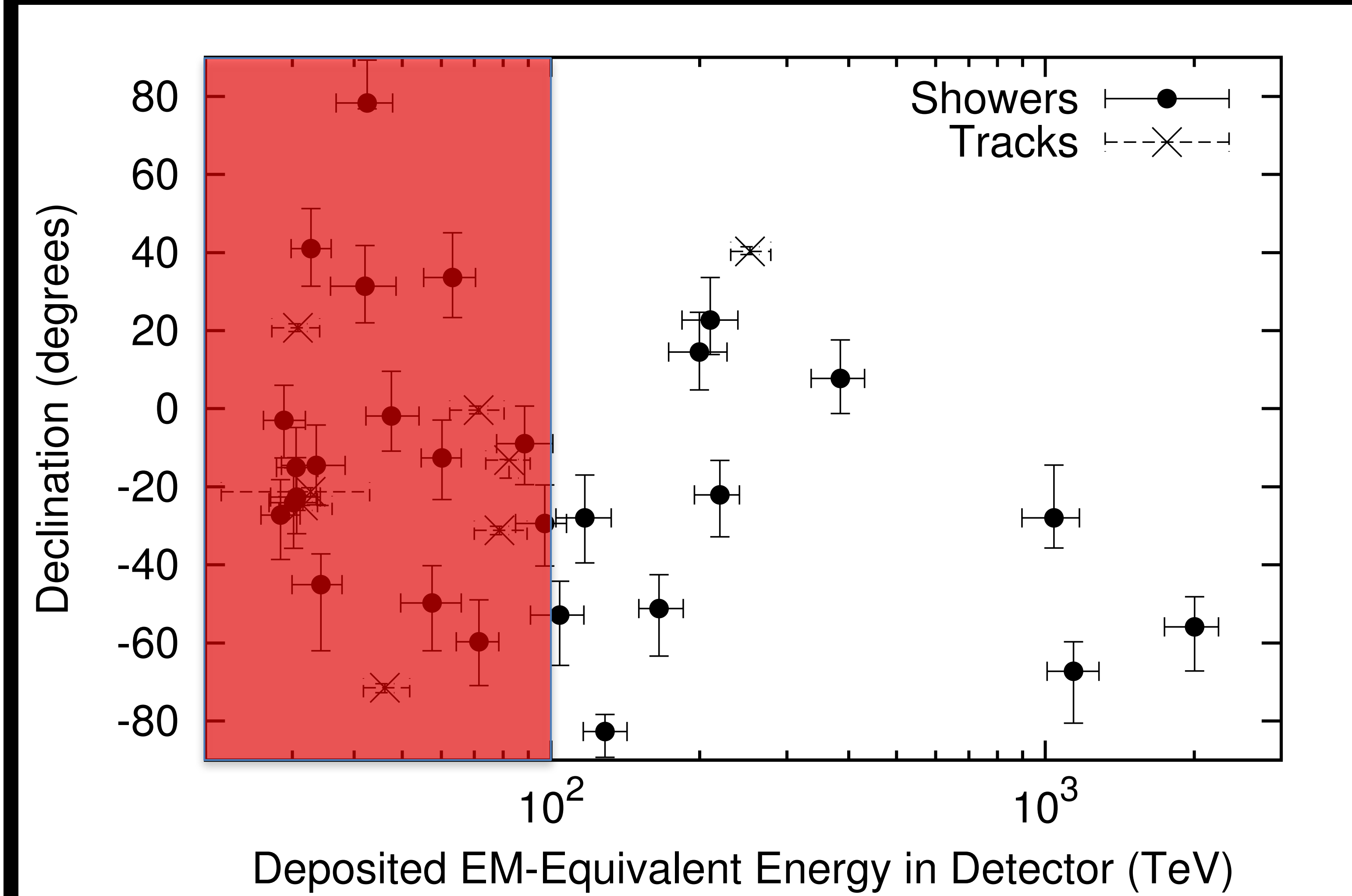
Many surprised; Laha+ (2013) demystified and showed tests

From Darkness, Light



Then Comes the Flood

2014 IceCube TeV-PeV search, using 2010—2013 data



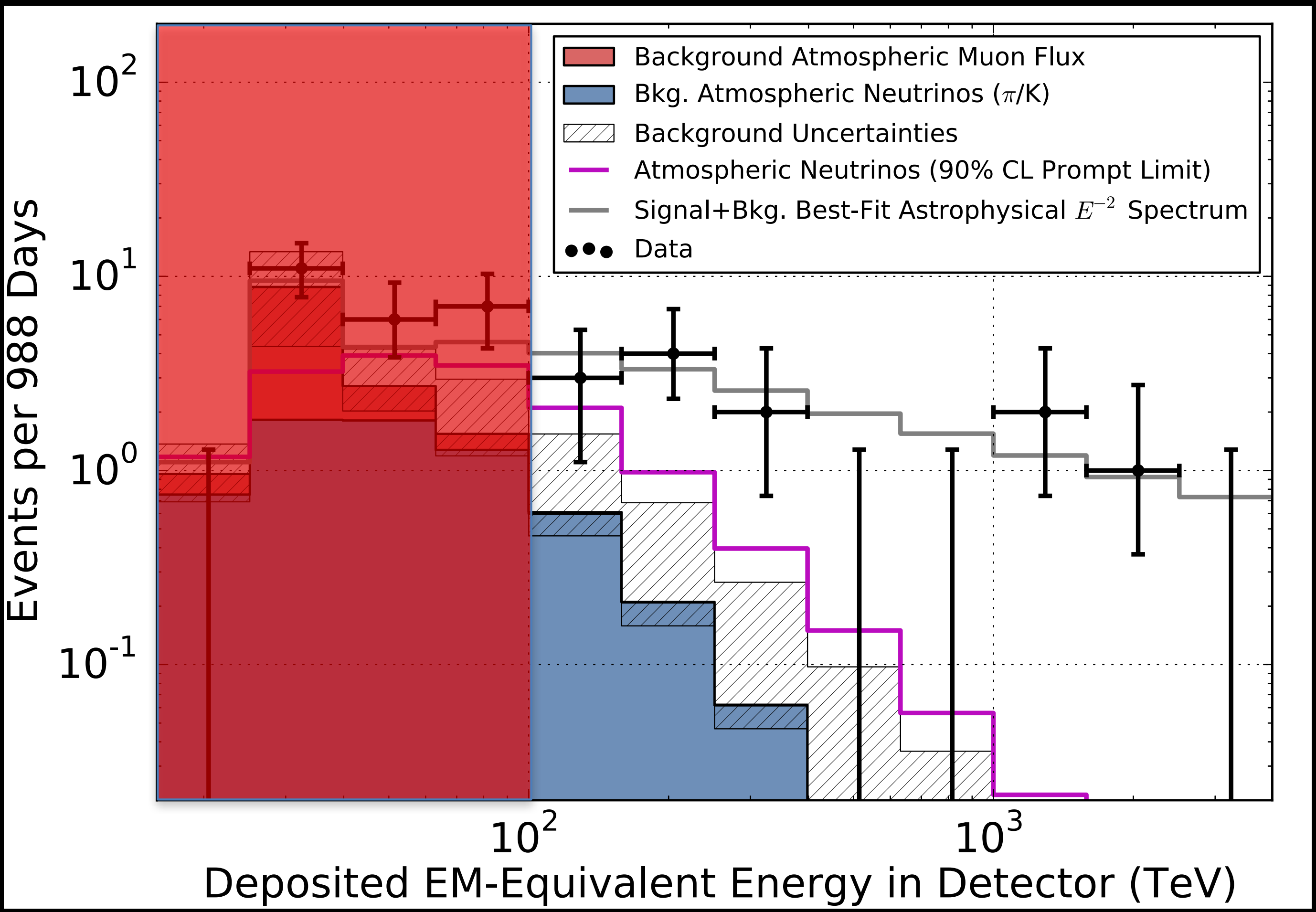
My opinion: focus above 100 TeV on "Clean Dozen" events with negligible atmospheric backgrounds

Conservative analysis: 37 candidates, ~ 15 background, 5.7σ

What Does the Energy Spectrum Tell Us?

Sum of cascade (all flavors), starting track (muon) channels

True significance is *much higher* than reported

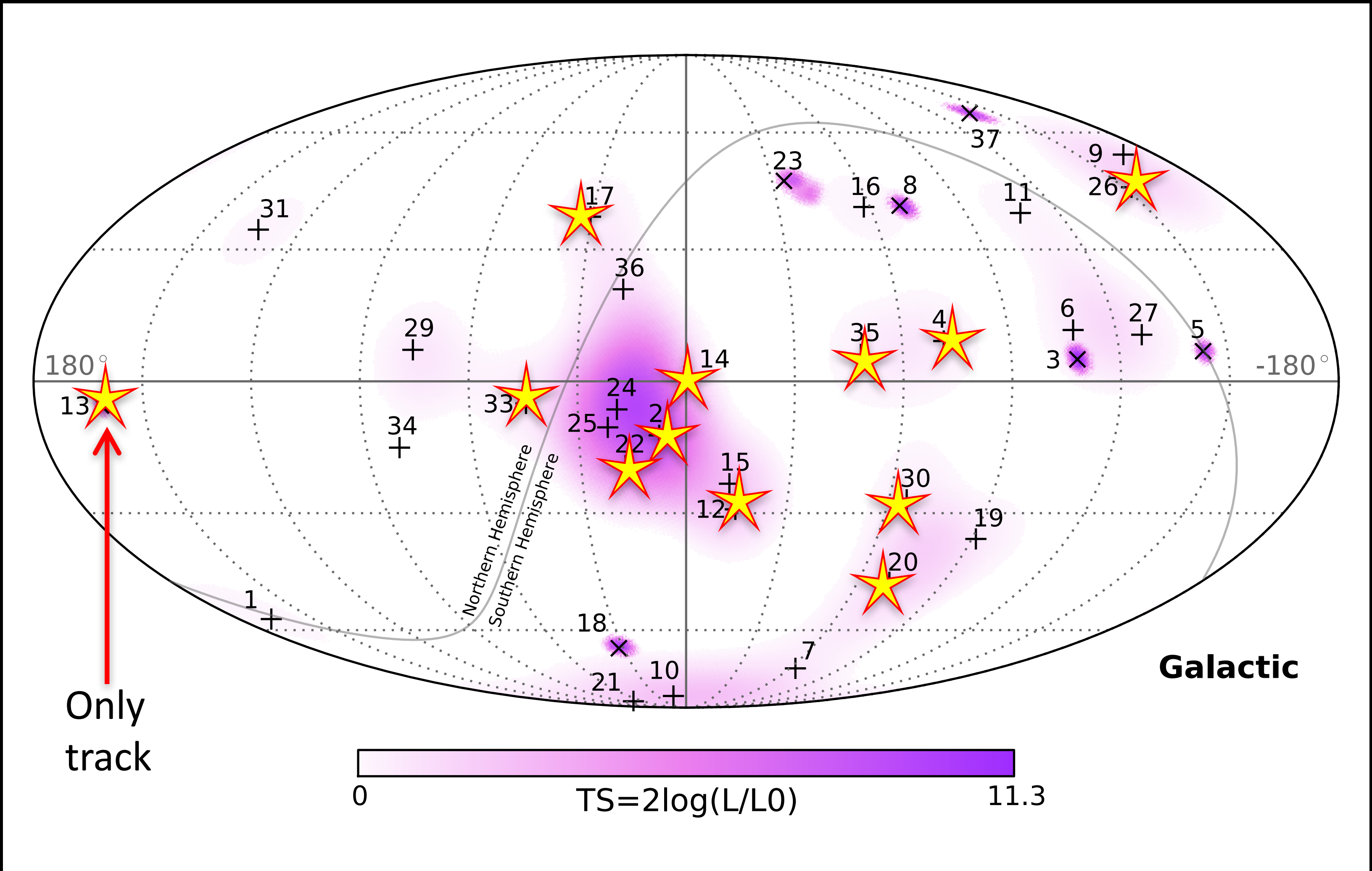


For "Clean Dozen" events, ignore the backgrounds shown because cascade channel dominates

Easy to see (!): astrophysical neutrinos with spectrum ~ E^{-2}

What Does the Angular Distribution Tell Us?

First HE neutrino skymap; some caveats for interpretation



Isolating "Clean Dozen" changes picture

Easy to see (!): sources mostly isotropic, extragalactic

Certainties, Probabilities, Mysteries

Signal origin: definitely observed extraterrestrial neutrinos
likely no UHE, Galactic, or exotic sources

Energy spectrum: $E^2 \Phi \sim$ 10^-8 GeV cm^{-2} s^{-1} sr^{-1}
shape E^-2 with cutoff or a bit steeper

Angular distribution: likely isotropic with Earth attenuation
no obvious clustering or correlations

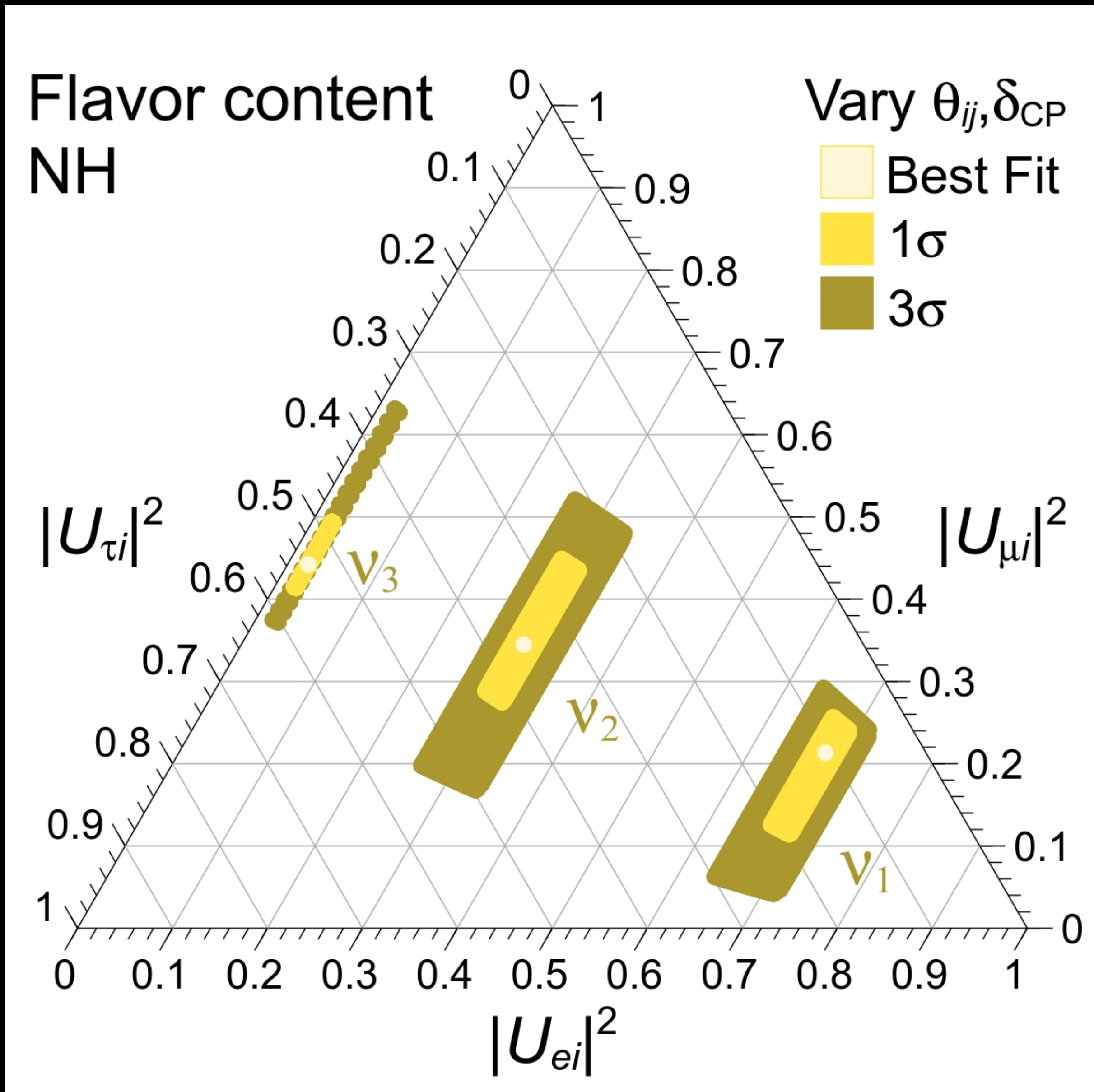
Flavor ratios: maybe consistent with 1:1:1, but a little weird
where are the muon tracks at high energy?

Time distribution: appears to be constant, not bursty

Pause: Order Of Magnitude Estimates

What Does it Mean for Particle Physics?

Flavor Composition of Mass Eigenstates

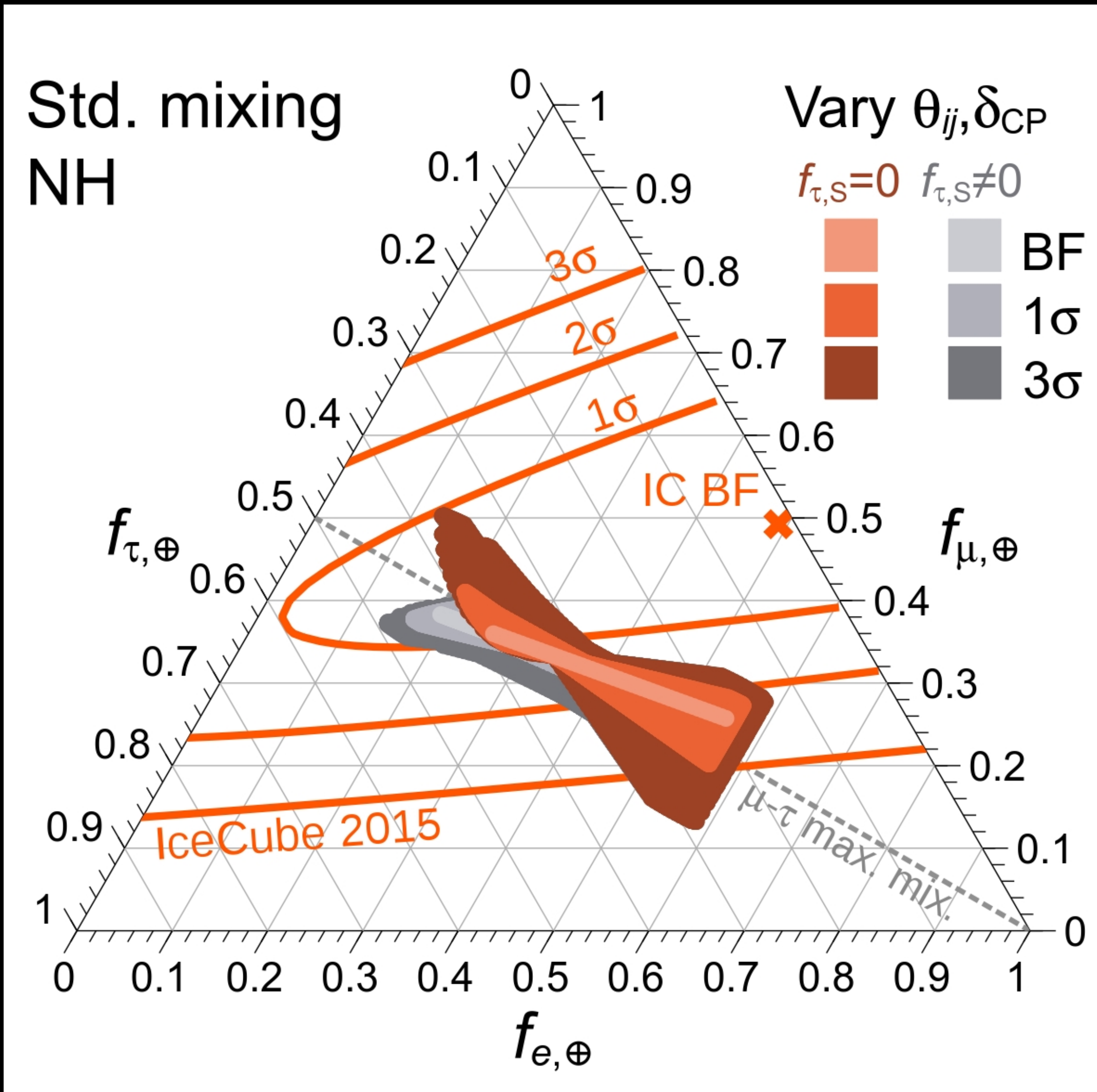


Neutrino mixing angles are all large, well known

(and similar for both hierarchies)

Bustamante, Beacom, Winter (2015, PRL)

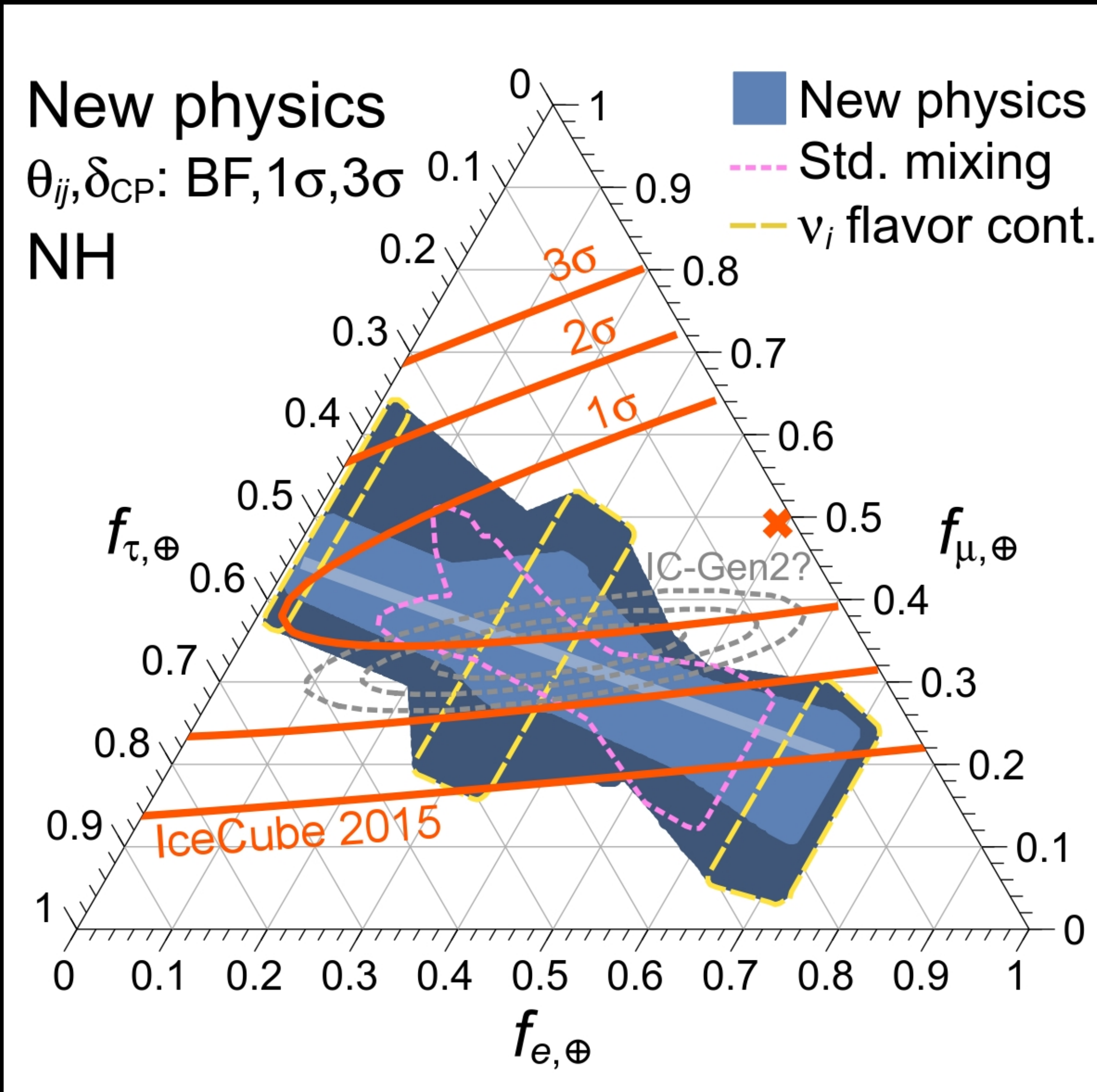
Flavor Ratios – No New Physics



For no new neutrino physics beyond standard mixing:

The full space of flavor ratios at Earth is tightly restricted for all initial ratios

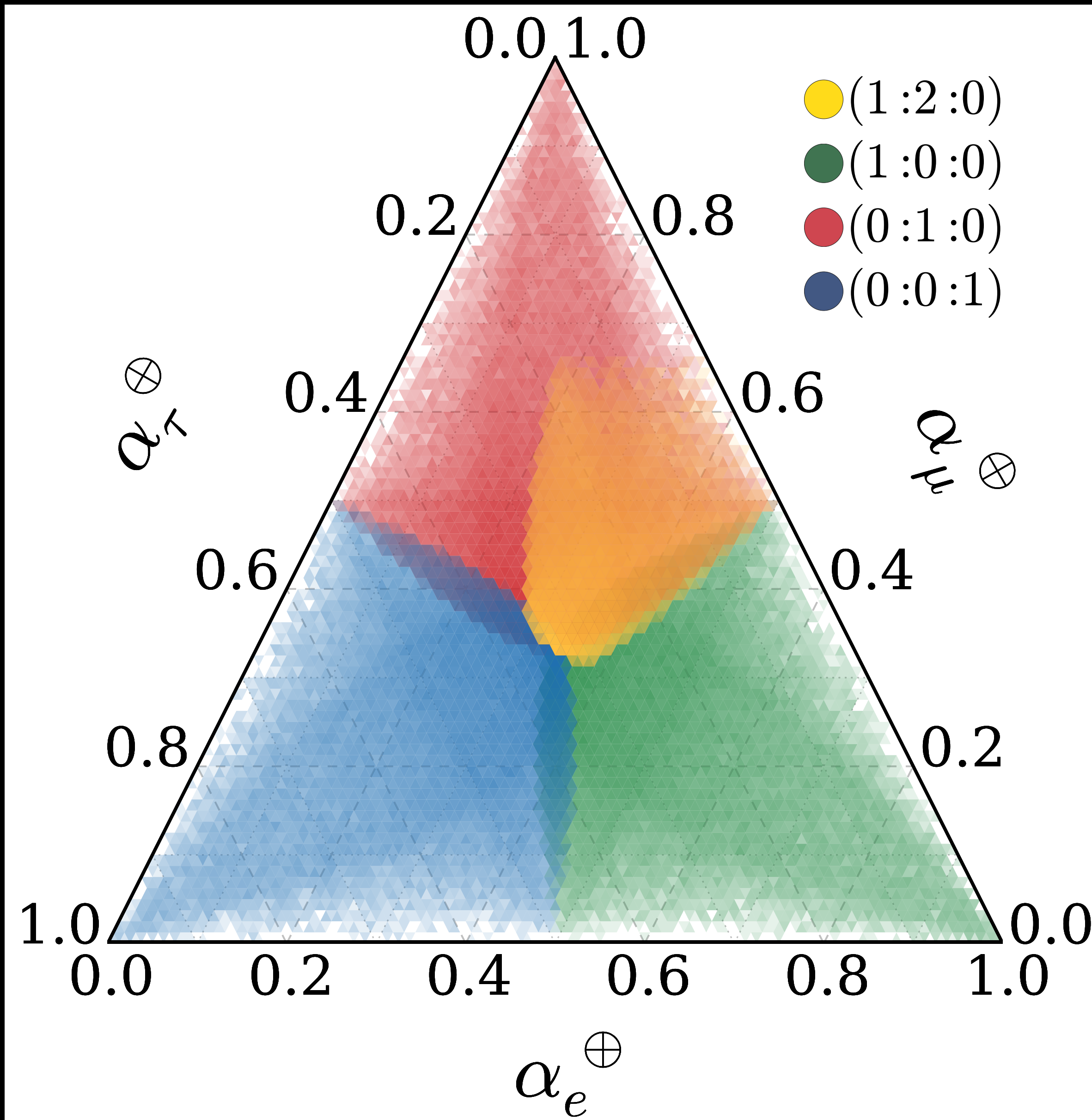
Flavor Ratios – Broad Class of New Physics



For new neutrino physics that only incoherently mixes mass eigenstates:

The full space of flavor ratios at Earth is *also* tightly restricted for all initial ratios

Flavor Ratios – All Possibilities of New Physics



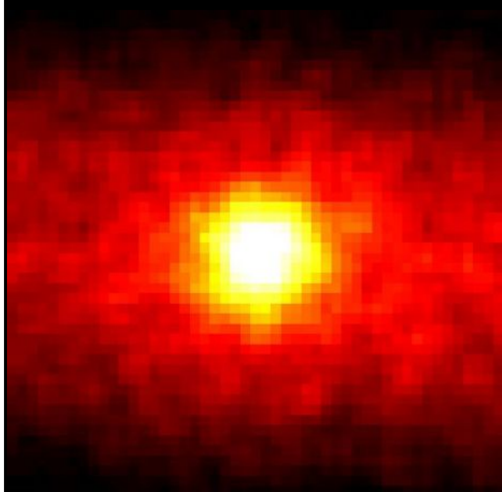
To fill the remainder of the space, the new physics must preserve coherence and/or change the mixing parameters

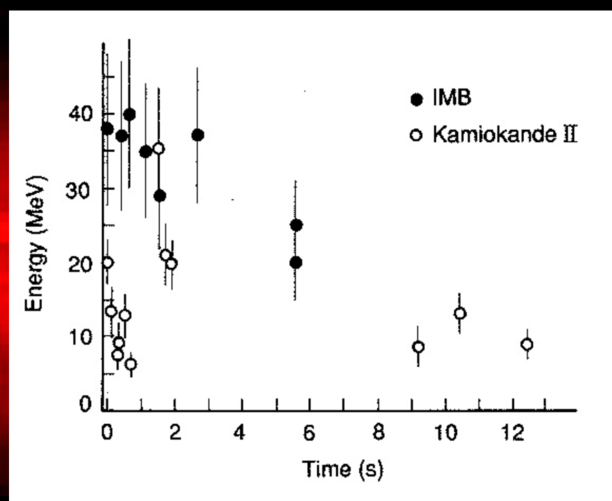
Arguelles, Katori, Salvado (2015, PRL)

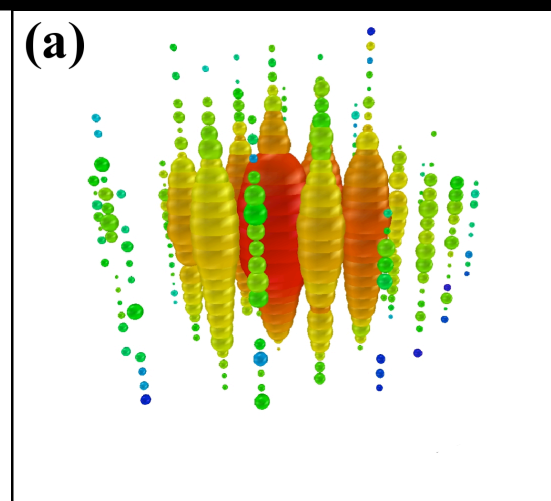
Concluding Remarks

Neutrino Astronomy Is Real

Solar (MeV)	Supernova (MeV)	IceCube (TeV—PeV)	??? (PeV—EeV)



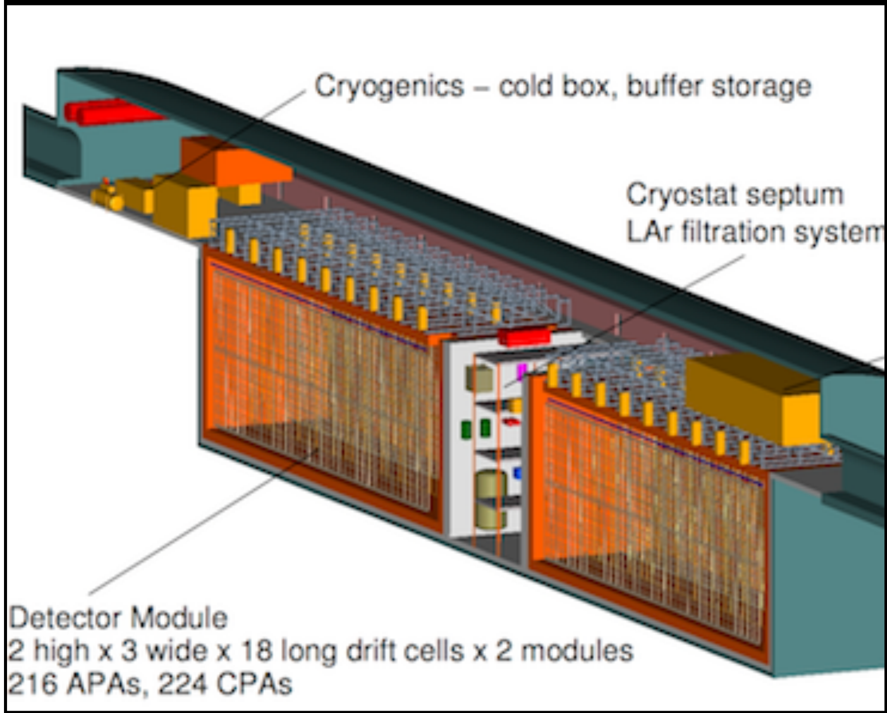


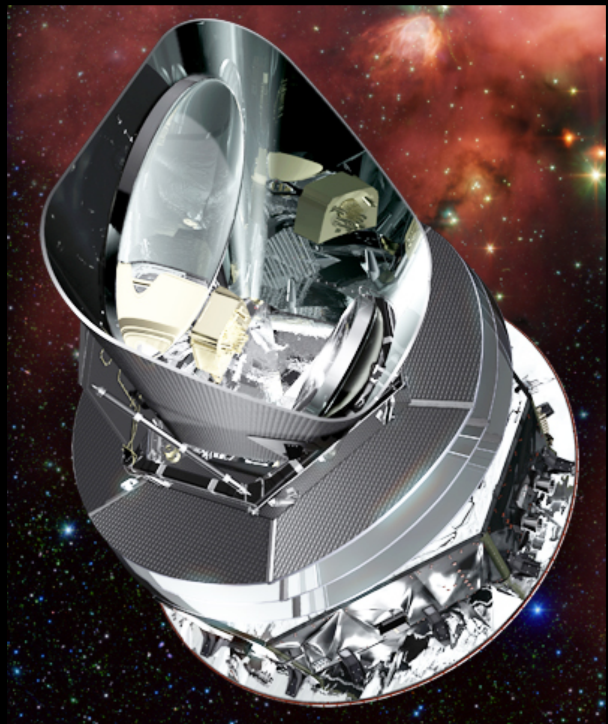


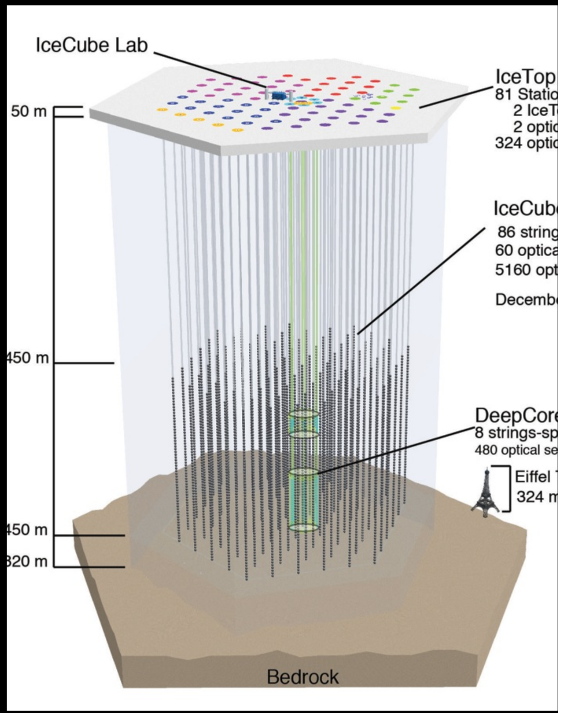
Great start, with much more to discover

Neutrino Science Must Be Broad

Laboratory | Cosmology | Astronomy







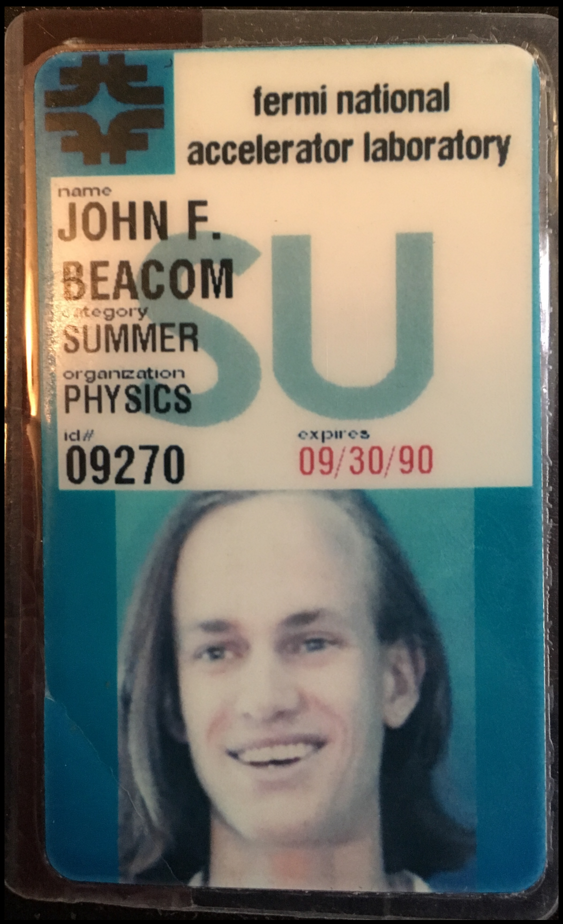
LBNF+DUNE
plus many more

Beyond Planck
plus many more

IceCube+Gen2
plus many more

Each method has a bright future, probing all three of particle physics, cosmological physics, and astrophysics

Becoming A Researcher



Center for Cosmology and AstroParticle Physics

The Ohio State University's Center for Cosmology and AstroParticle Physics

CCAPP

Columbus, Ohio: 1 million people (city), 2 million people (city+metro)
Ohio State University: 56,000 students
Physics: 55 faculty, Astronomy: 20 faculty
CCAPP: 20 faculty, 10 postdocs from both departments
Placements: *In 2014 alone, 12 CCAPP alumni got permanent-track jobs*

Recent faculty hires: Antonio Boveia, Linda Carpenter, Chris Hirata, Adam Leroy, Laura Lopez, Annika Peter
Recent PD hires: Ami Choi, Alexia Lewis, Niall MacCrann, Tuguldur Sukhbold, Michael Troxel, Ying Zu, Francesco Capozzi

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