The IceCube Experiment

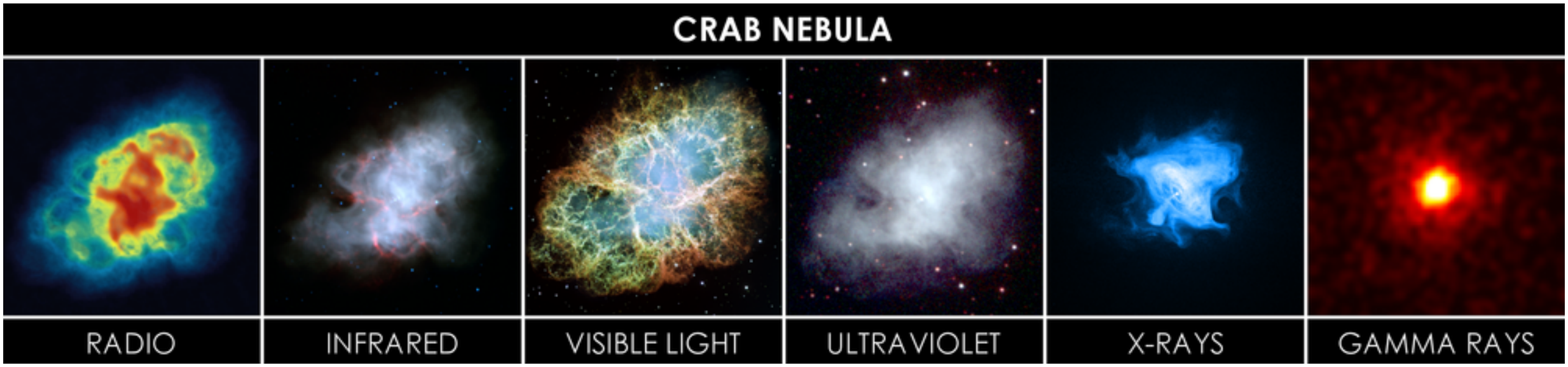
Madison BootCamp 2015
Nancy Wandkowsky

Outline

- Why neutrinos?
- Why IceCube?
- How does IceCube work?
- What do neutrinos look like in IceCube?
- What are the physics goals of IceCube?
  - Astrophysical Neutrinos
  - Point Sources
  - Neutrino Oscillation

Why neutrinos?

- Crab Nebula: Supernova remnant (SN1054)
- emits light of all wavelengths



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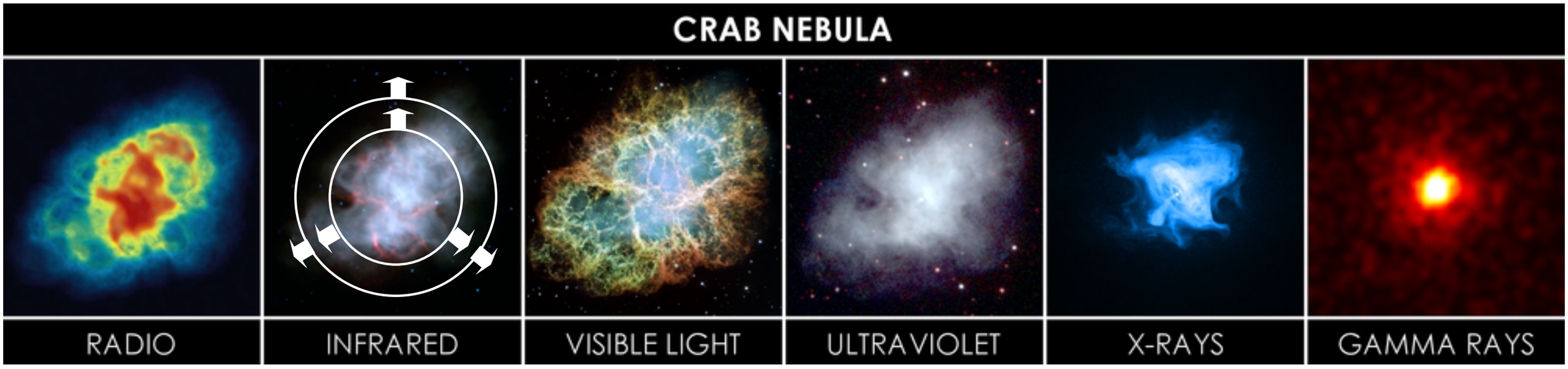
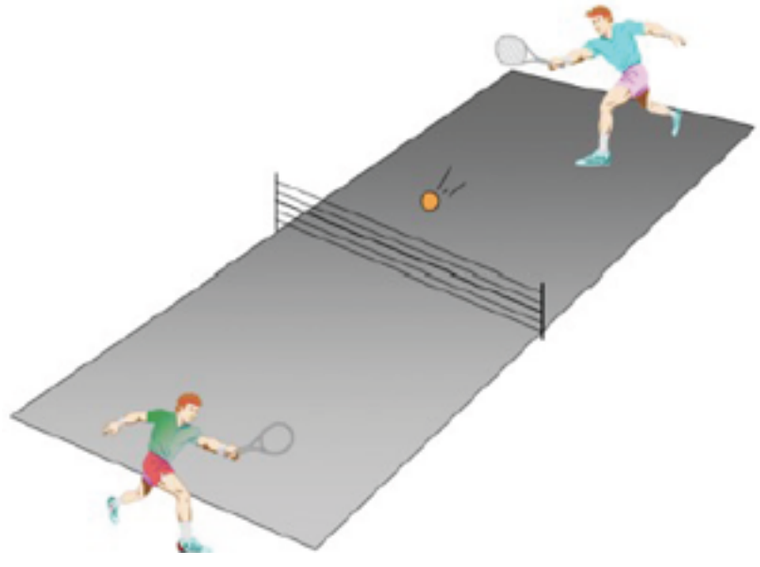
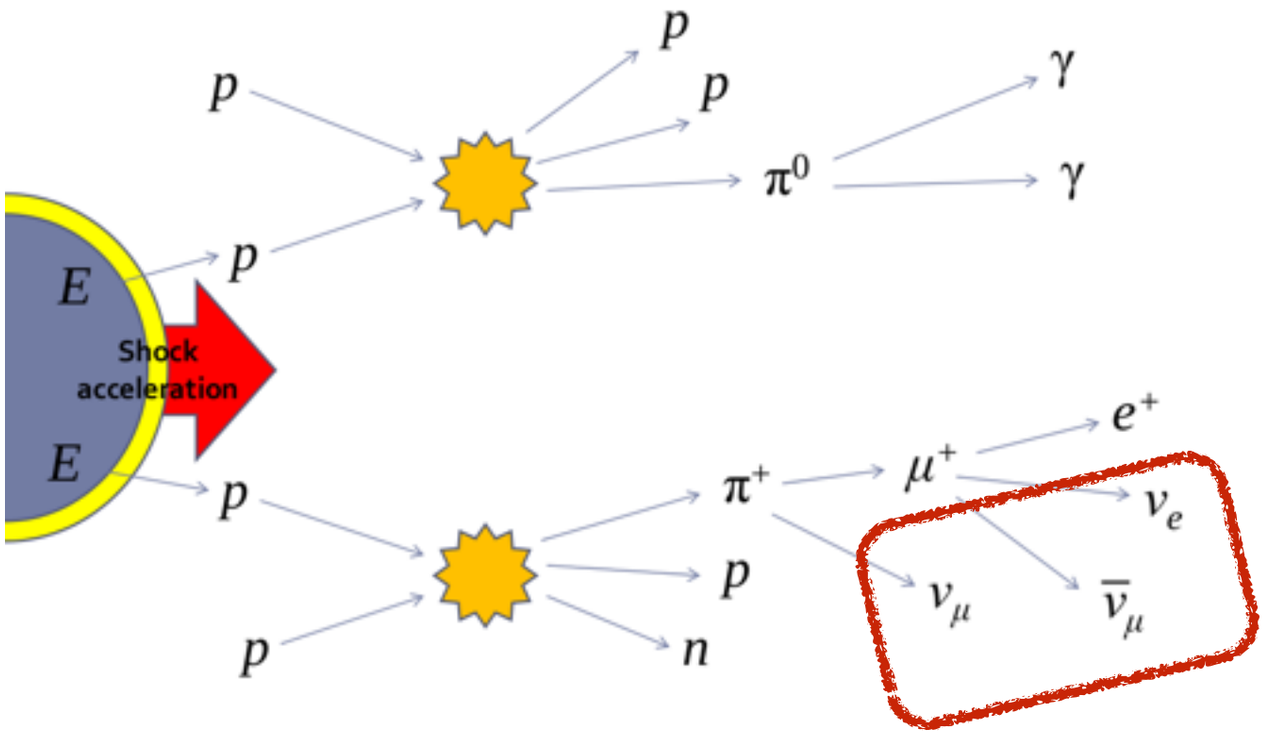


- gravitational energy released is transformed into acceleration of electromagnetic particles
- also acceleration when em particles cross magnetic fields



Cosmic Messengers

- Molecular clouds close to SN act as beam dumps



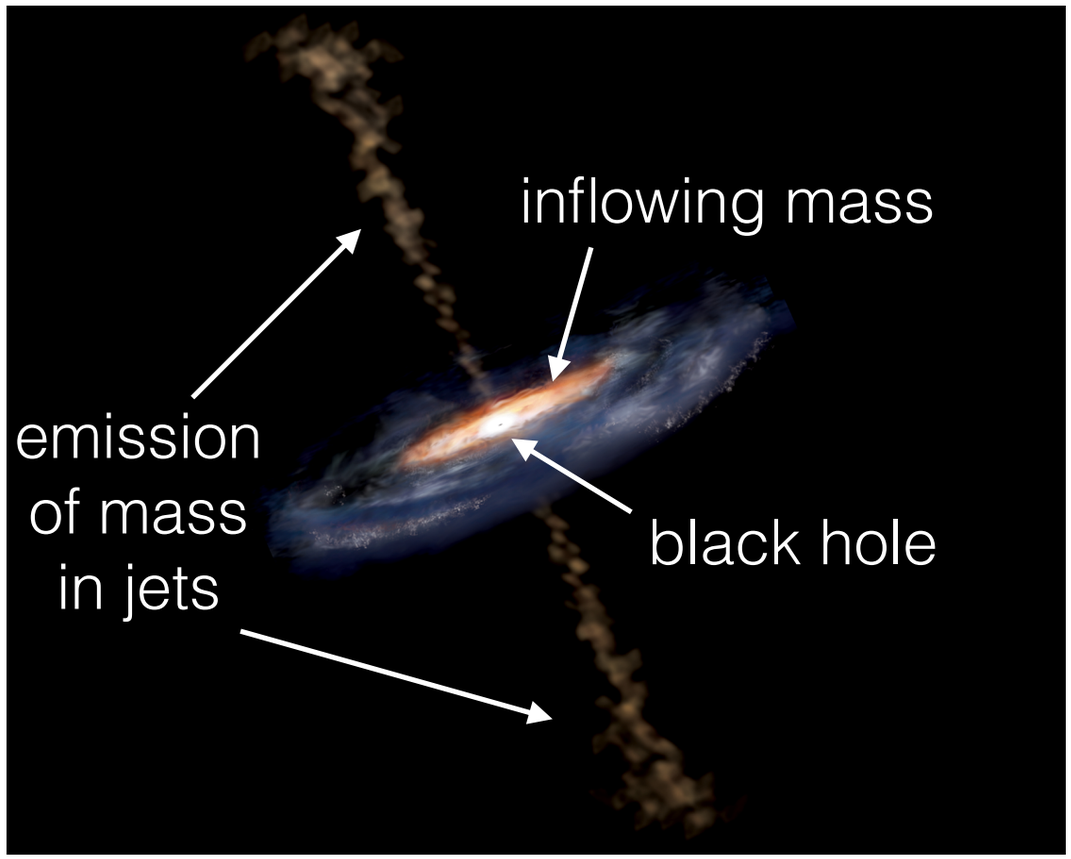
- neutral pions ➙ protons, gammas
- charged pions ➙ neutrons, neutrinos

} with up to PeV energies!

Supernovae as galactic neutrino sources!

Cosmic Messengers

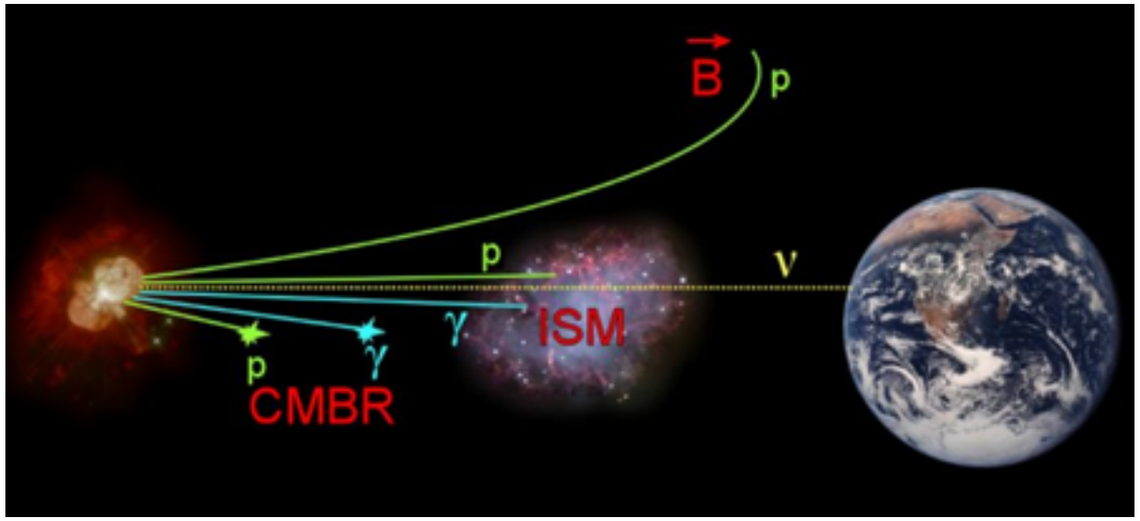
- Active Galactic Nuclei (AGN)



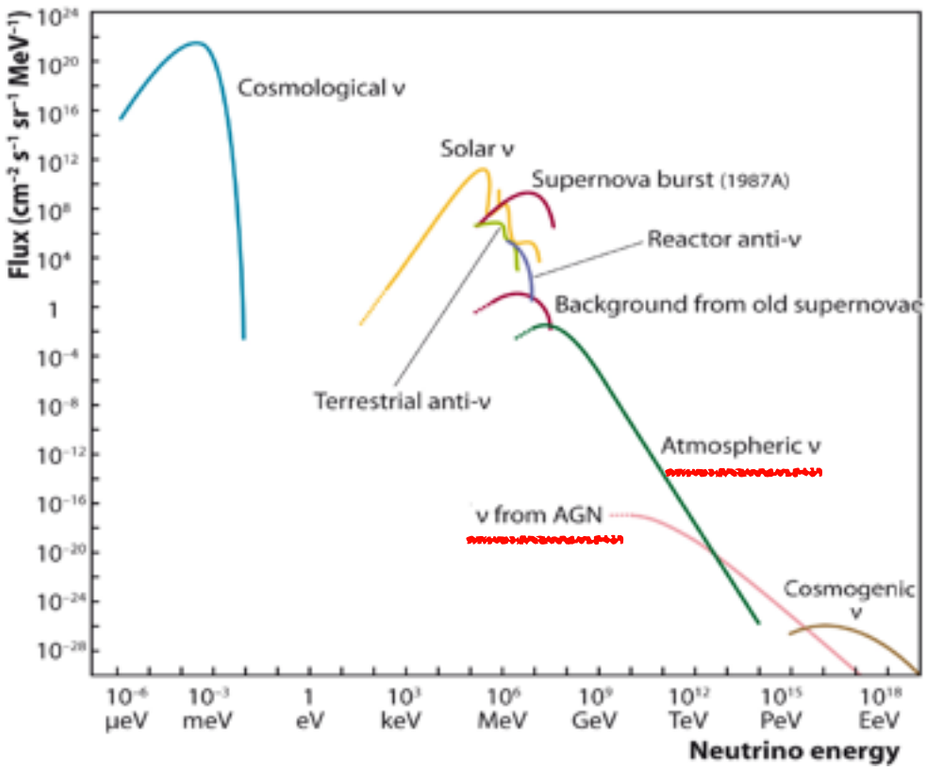
- acceleration stronger than in SN ➙ above PeV energies possible!

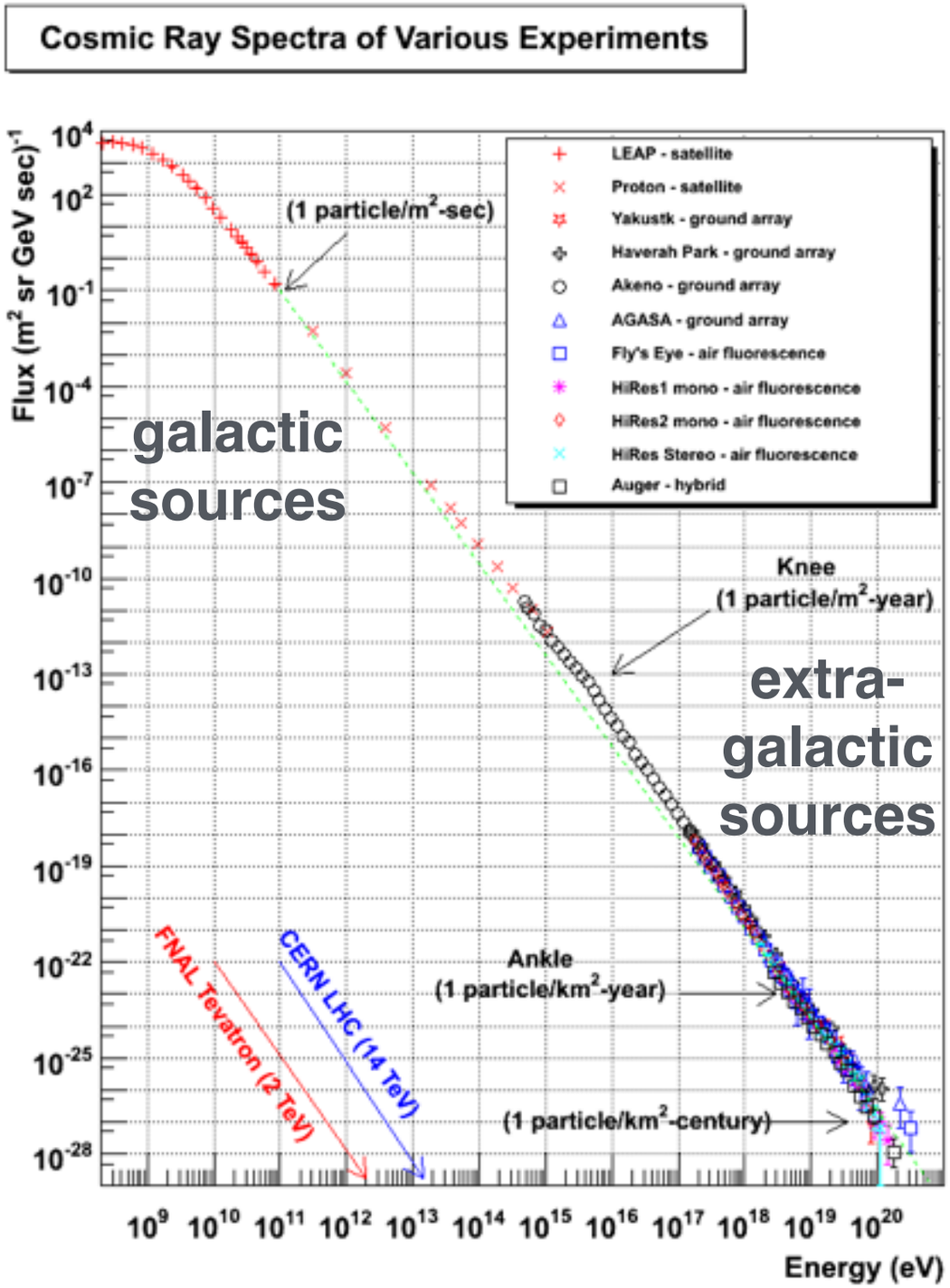
AGN as extra-galactic neutrino sources!

Cosmic Messengers



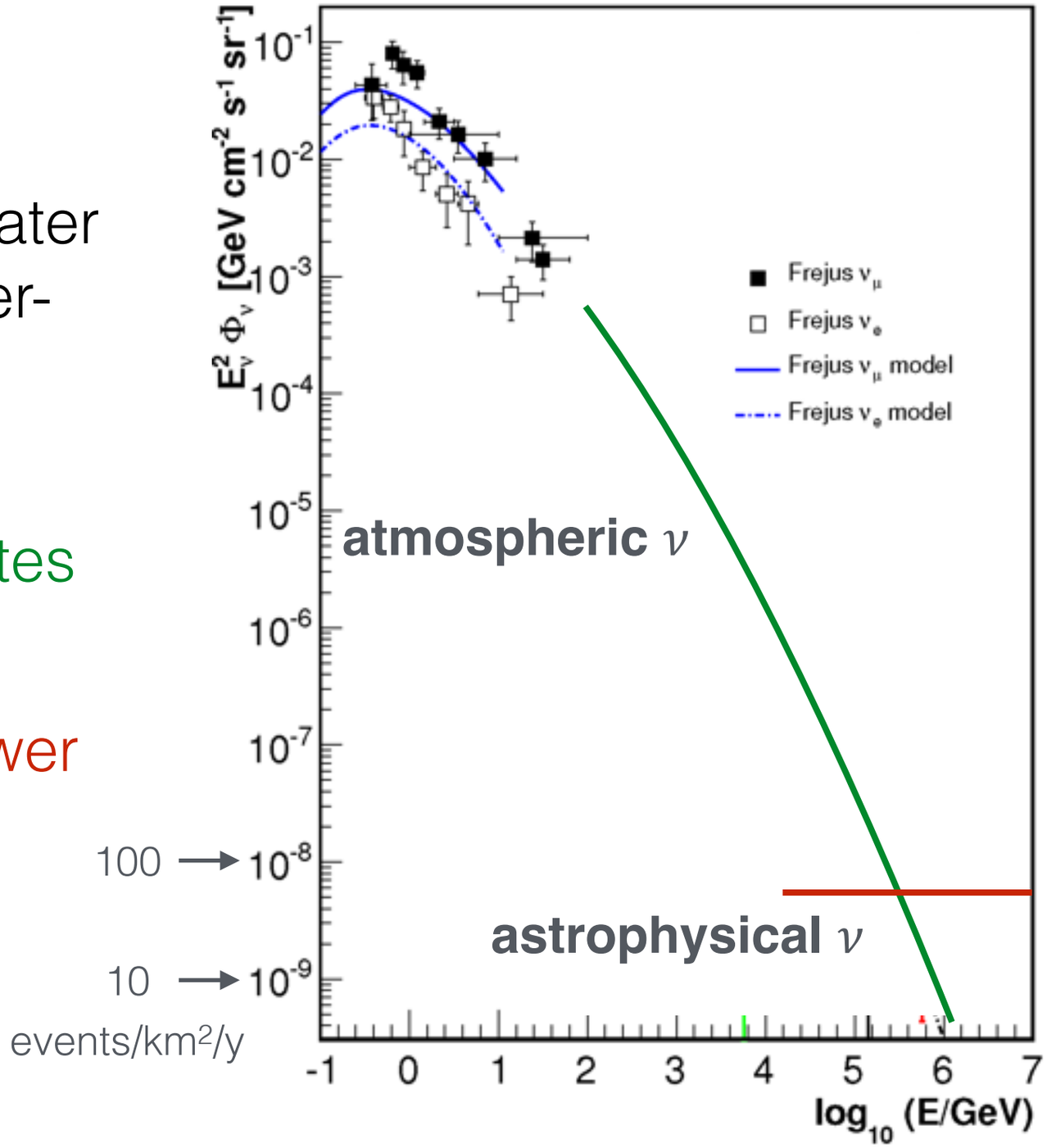
- Neutrinos ν are ideal messengers!
- CR and ν abundance tightly coupled





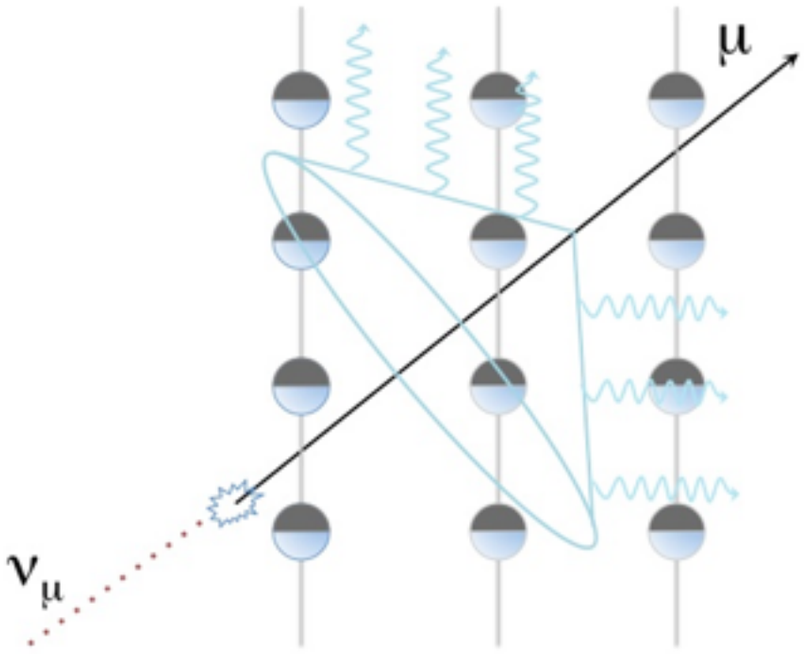
Why IceCube?

- steeply falling spectrum
- low-energy atmospheric neutrinos measured with water Cherenkov detectors (Super-Kamiokande: ~50 kt)
- high-energy atmospheric neutrinos ➙ lower count rates
- extraterrestrial neutrinos at higher energies ➙ even lower count rates



How does IceCube work?

- What we need for a high-energy neutrino detector:
  - ➡ a huge volume of a transparent medium: antarctic ice

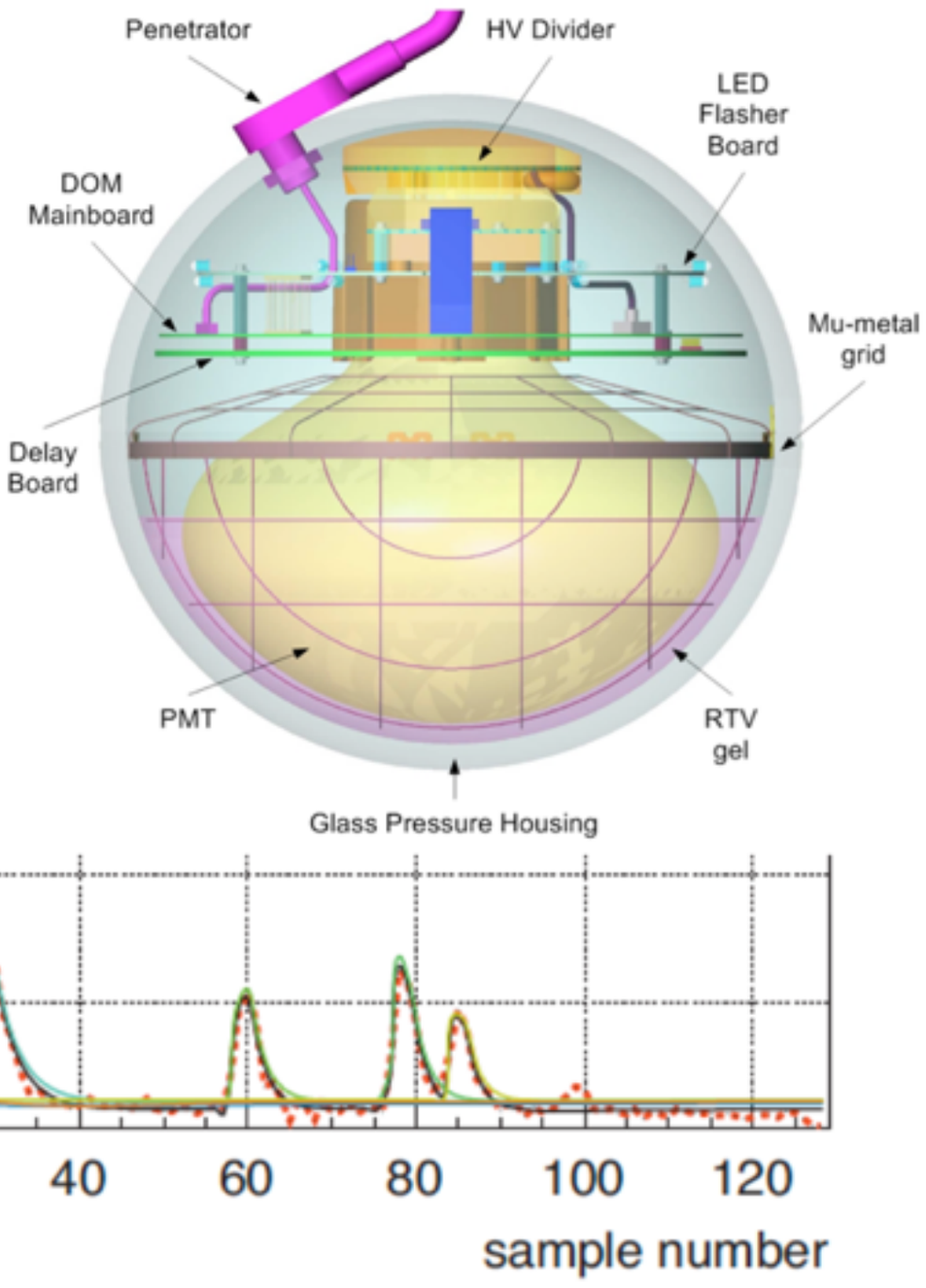


charged particles traveling faster than speed of light in a dielectric medium produce a Cherenkov cone

How does IceCube work?

- What we need for a high-energy neutrino detector:
  - ➡ photon detectors to capture the light: Digital Optical Modules (DOM)

more on DOMs and data acquisition:
J. Kelley, Tue 9am



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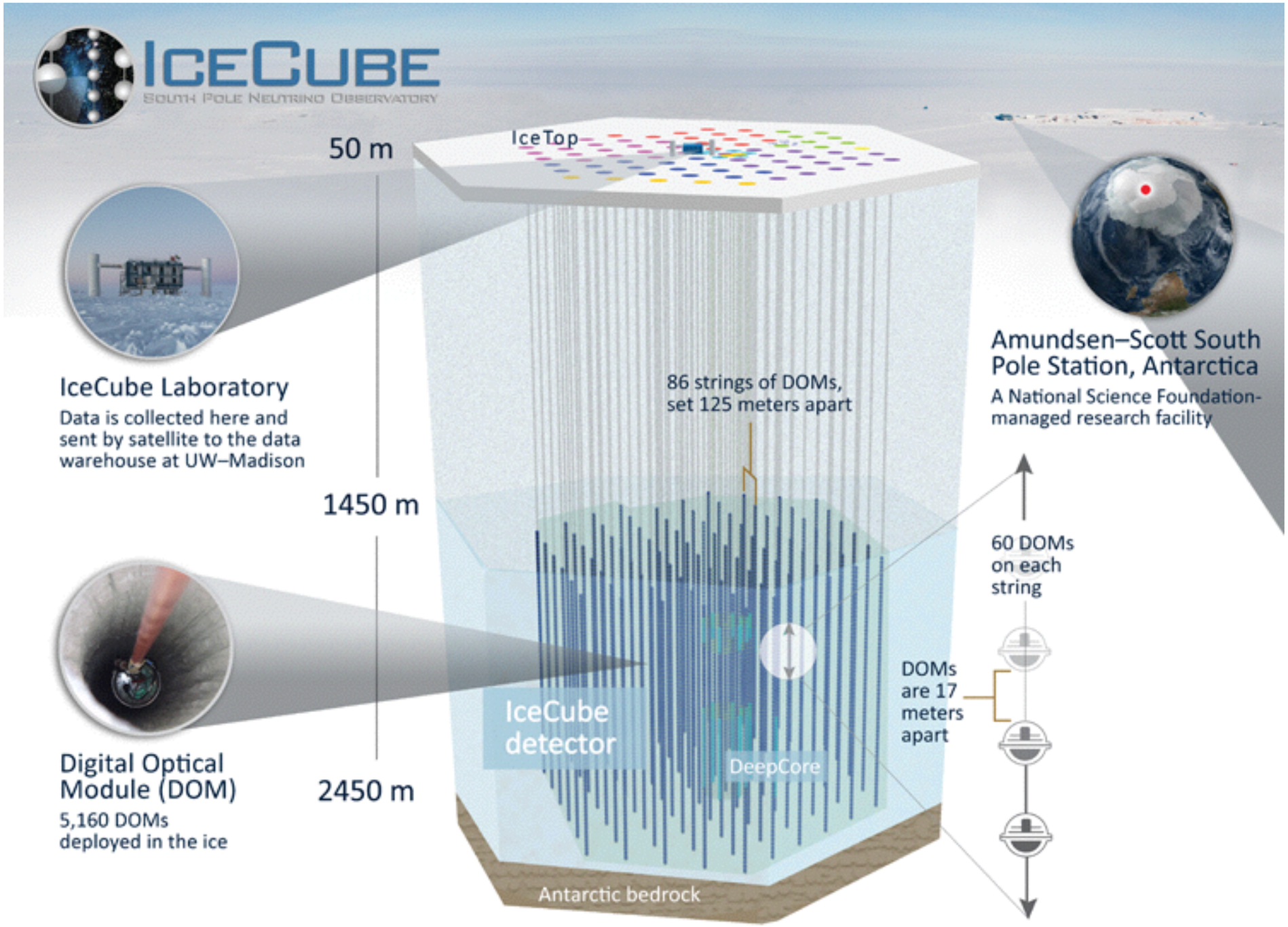
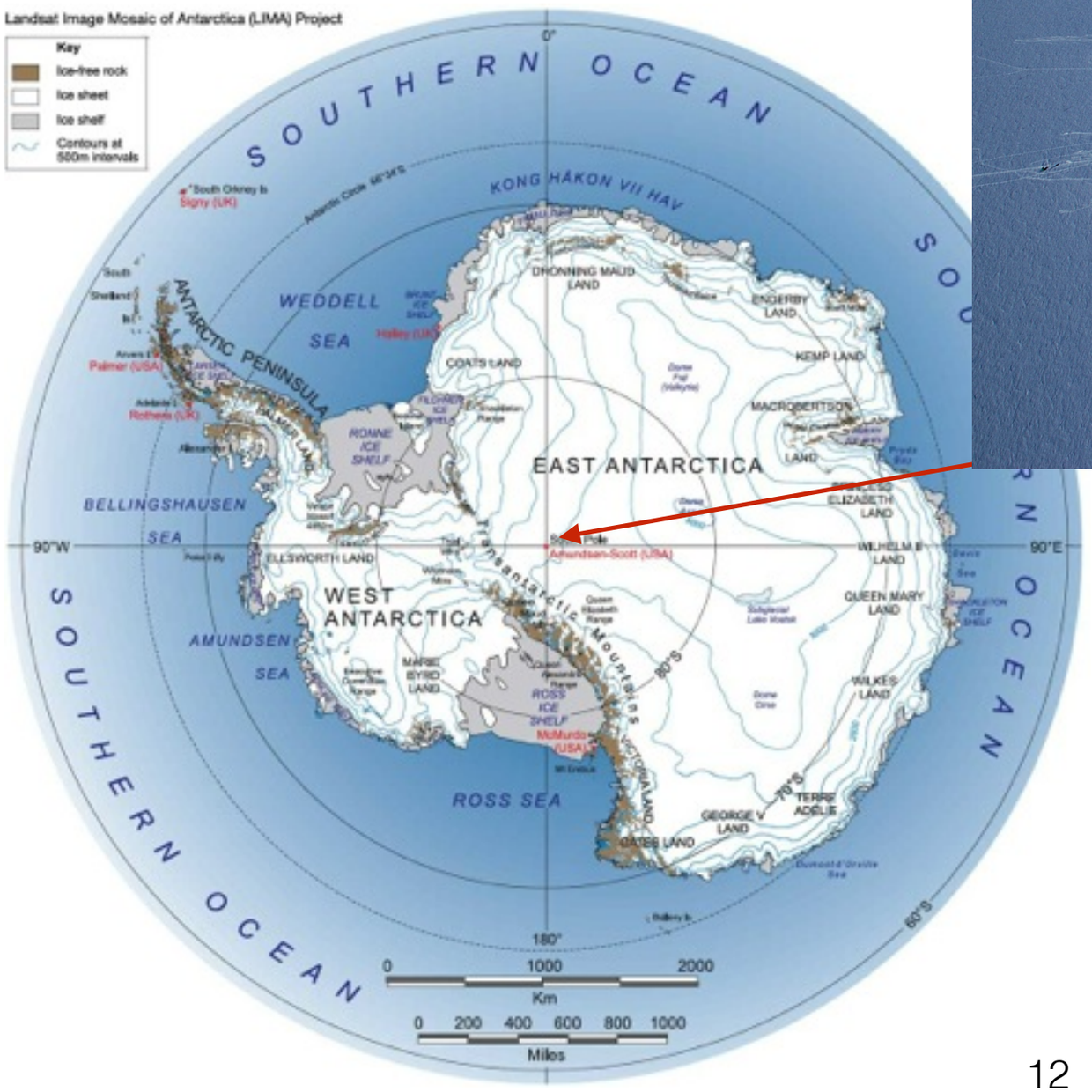
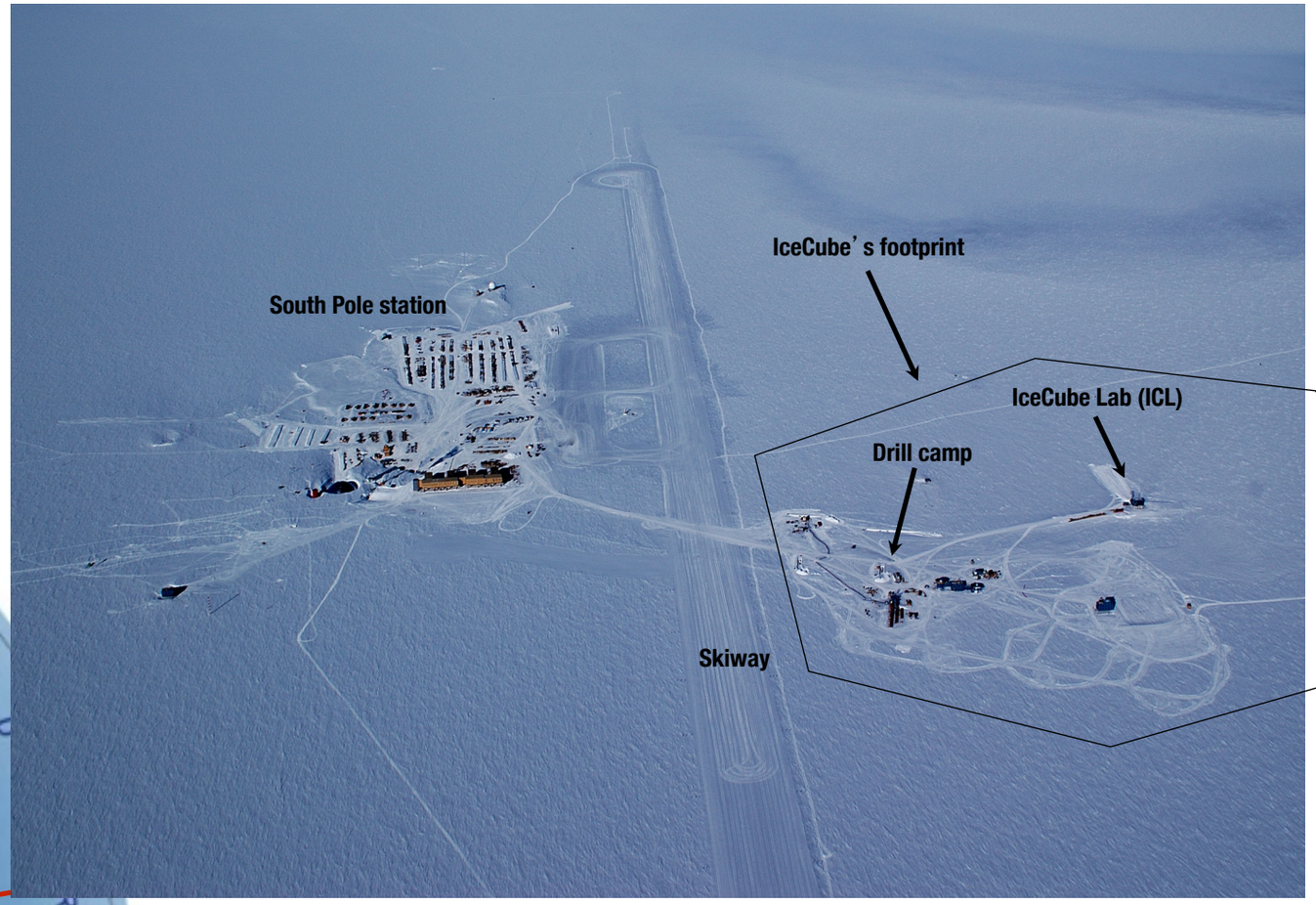
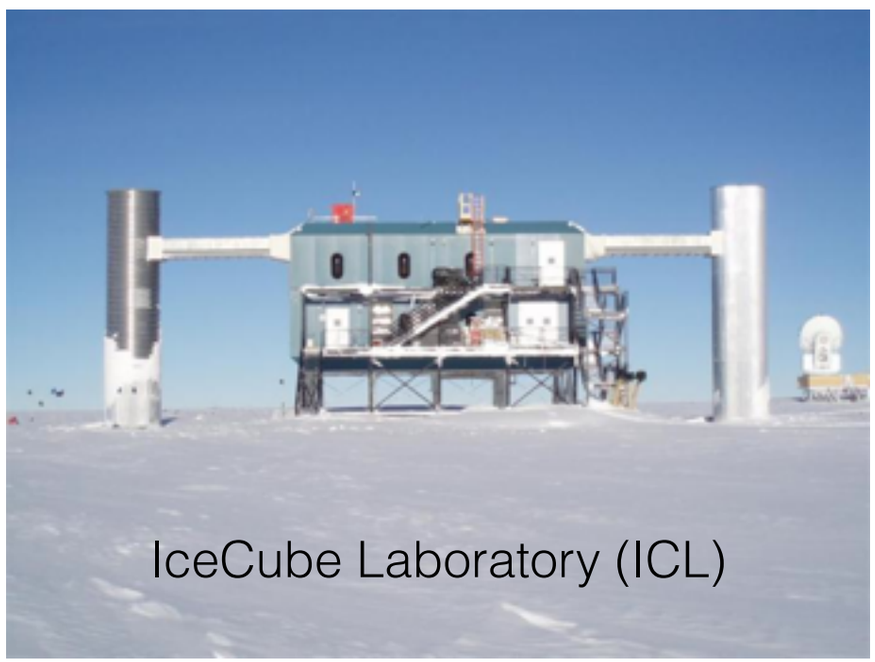


Intermezzo: IceCube construction

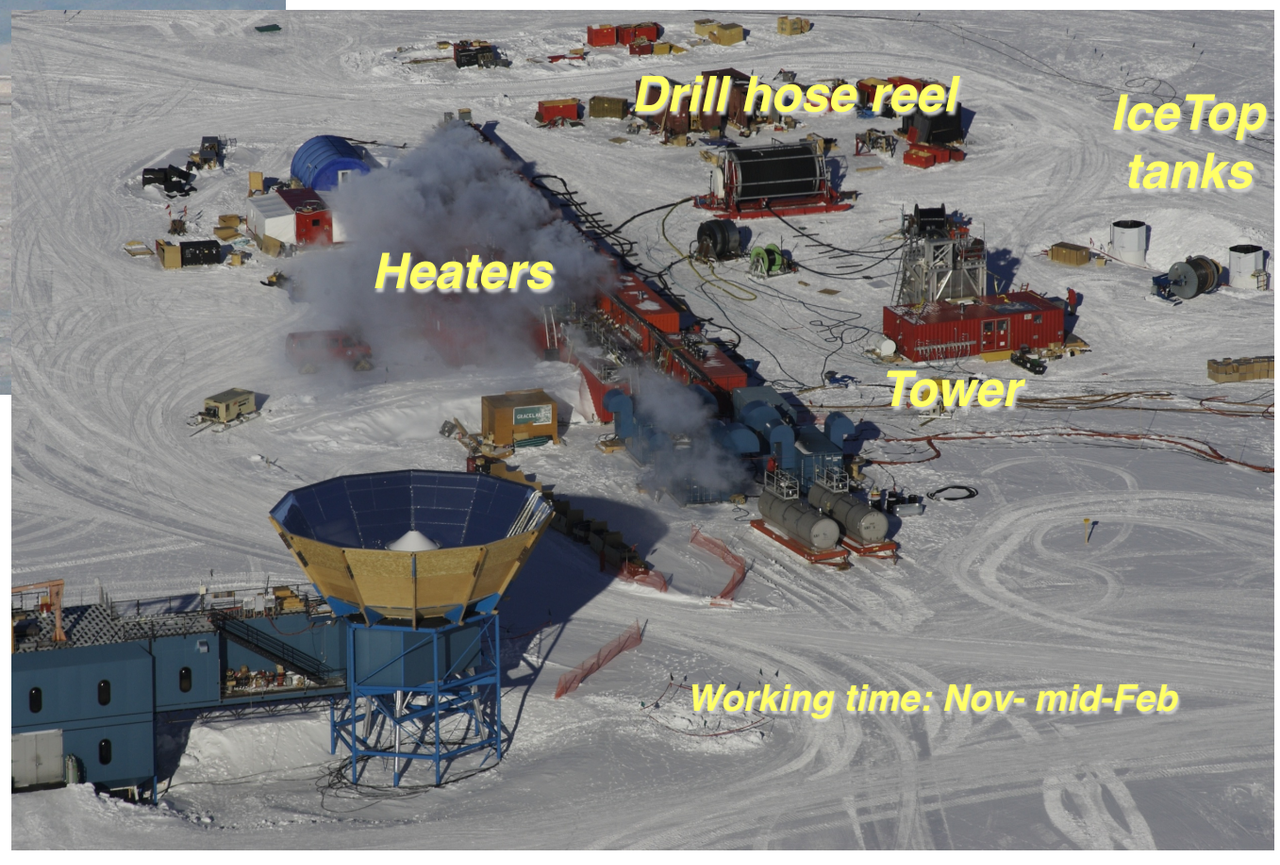






Intermezzo: IceCube construction

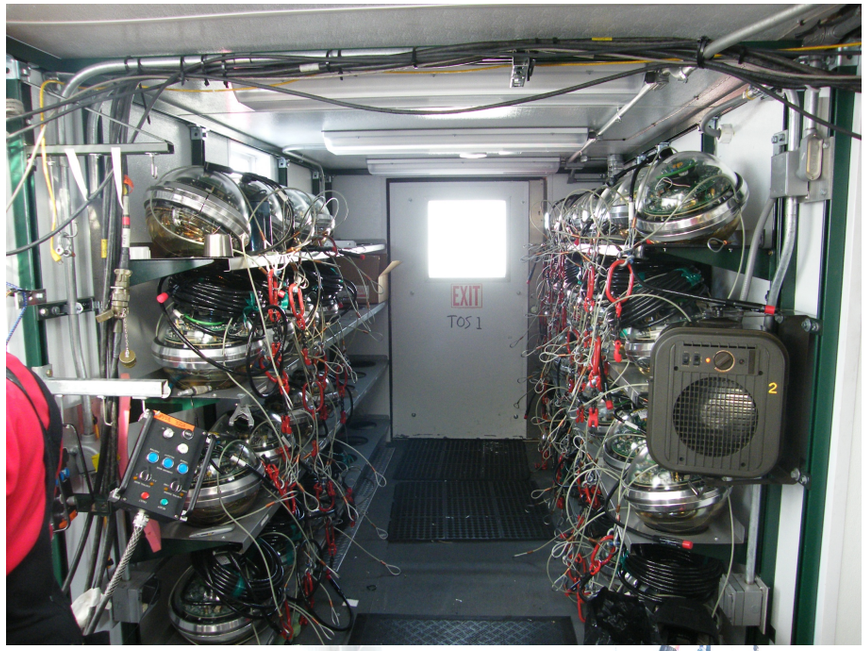
- Construction between Dec 2004 - Dec 2010

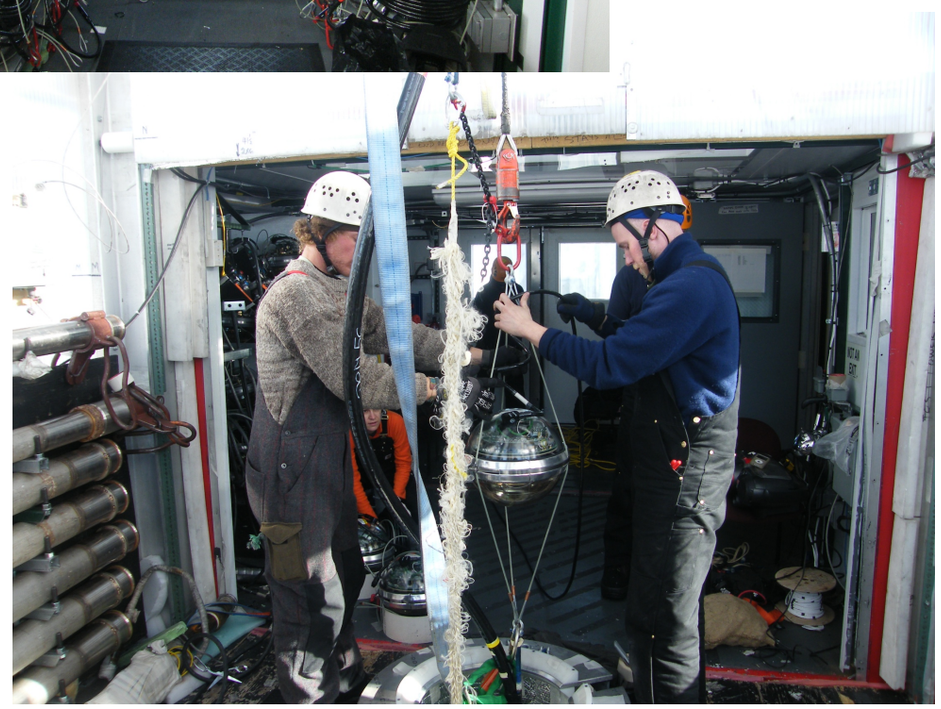


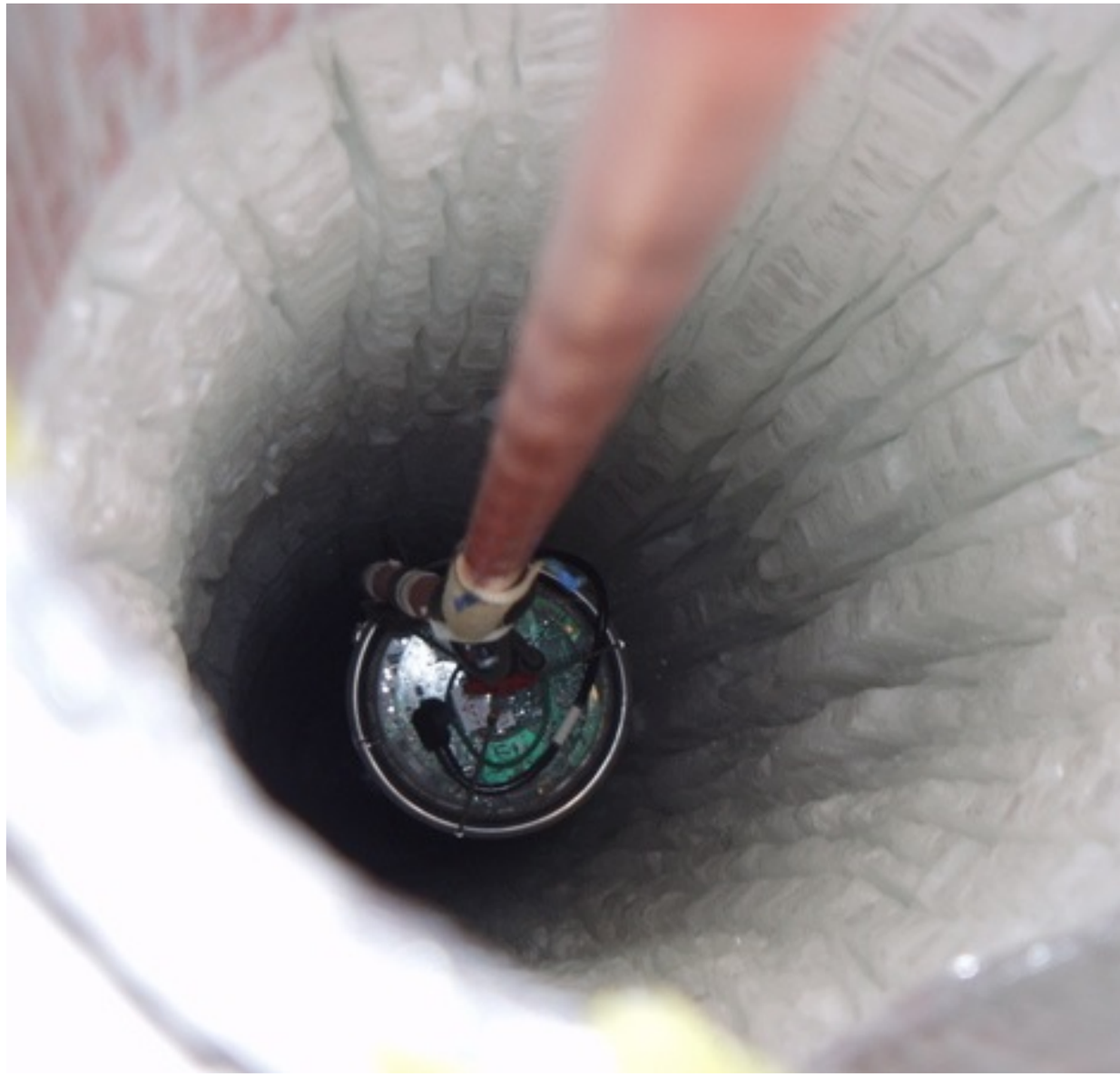
- hot water drilling
- only limited number of holes per season (~12)

Intermezzo: IceCube construction

- Construction between Dec 2004 - Dec 2010

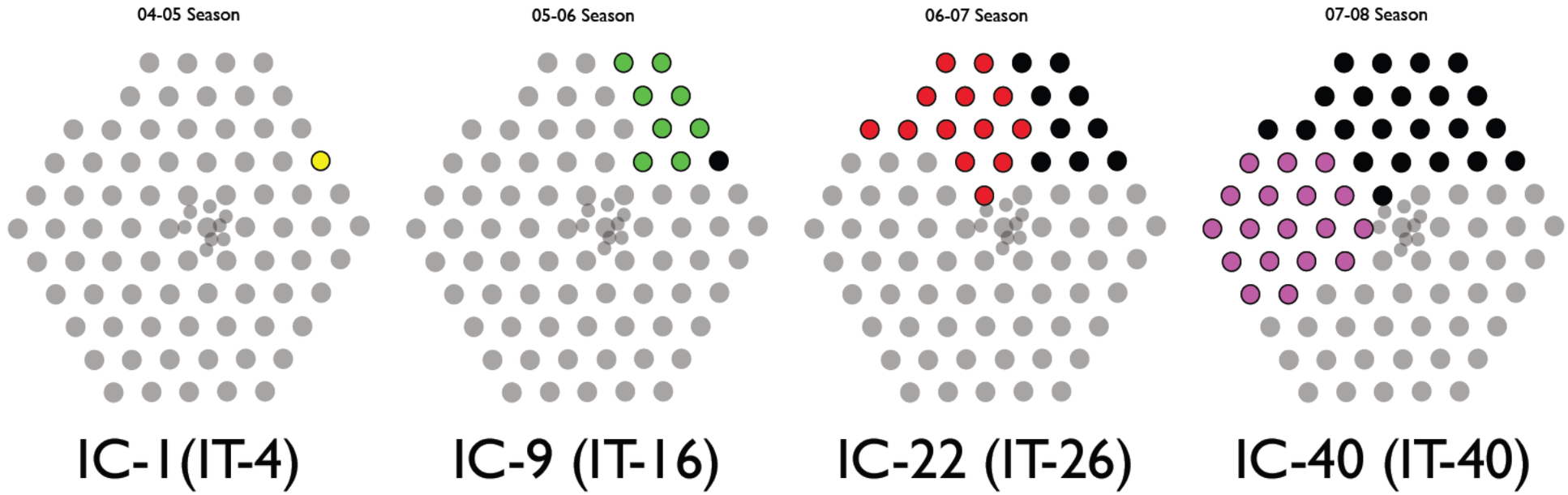


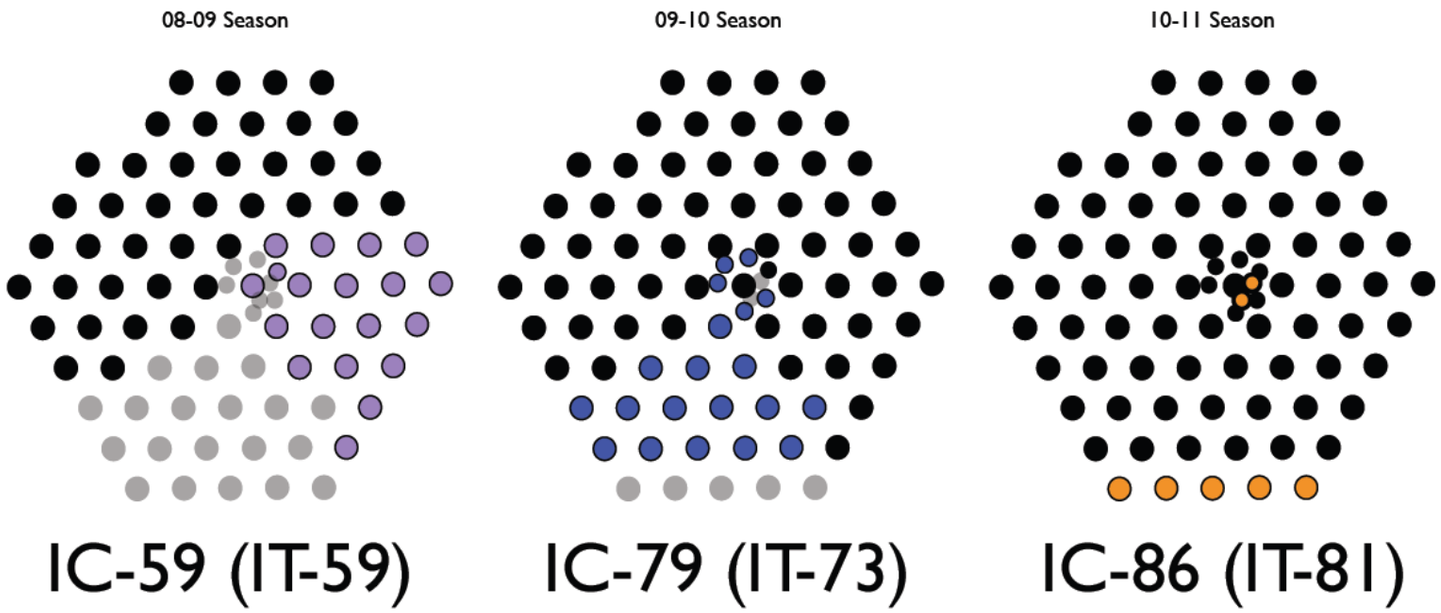




Intermezzo: IceCube construction

The IceCube Observatory





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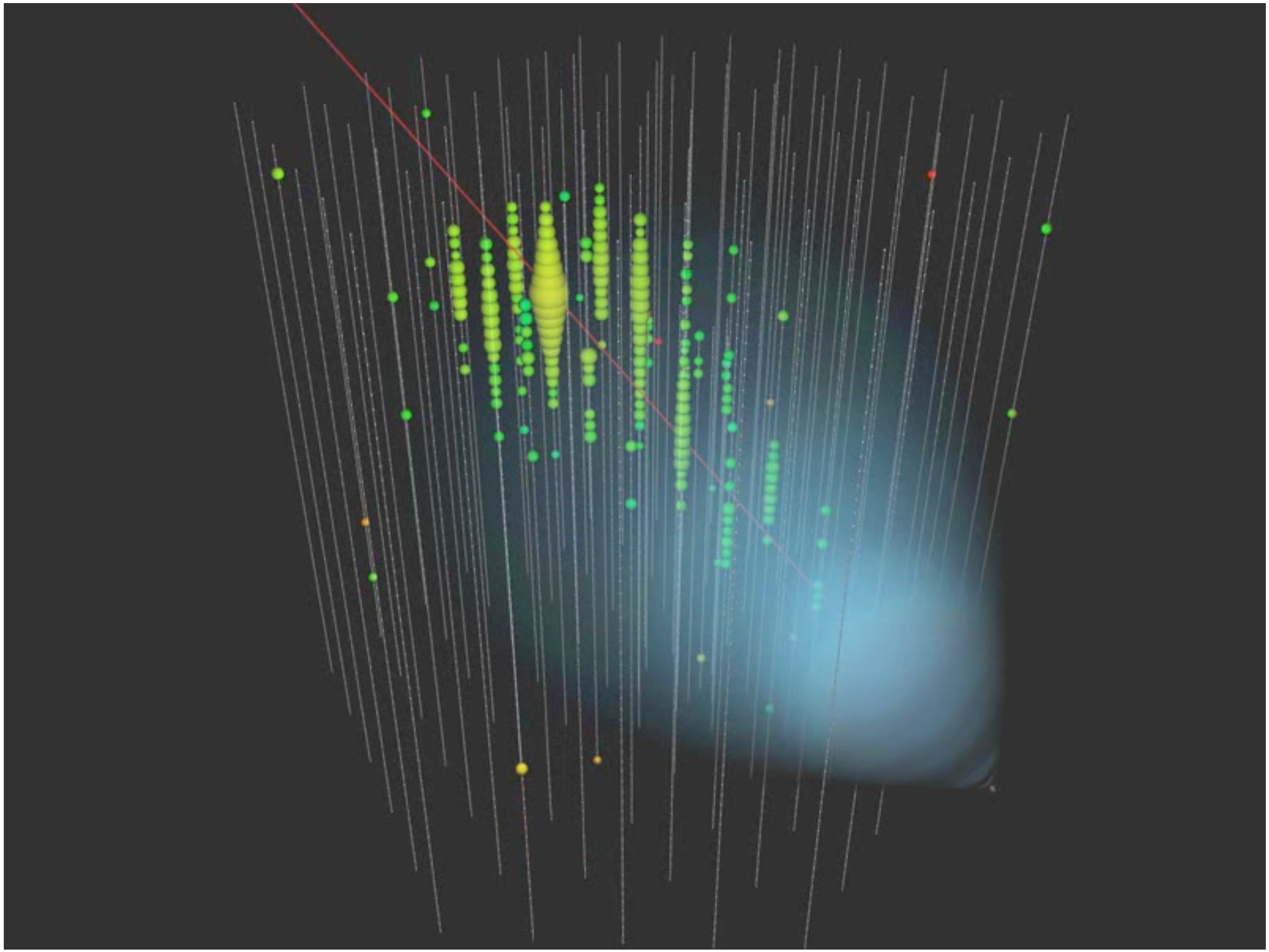

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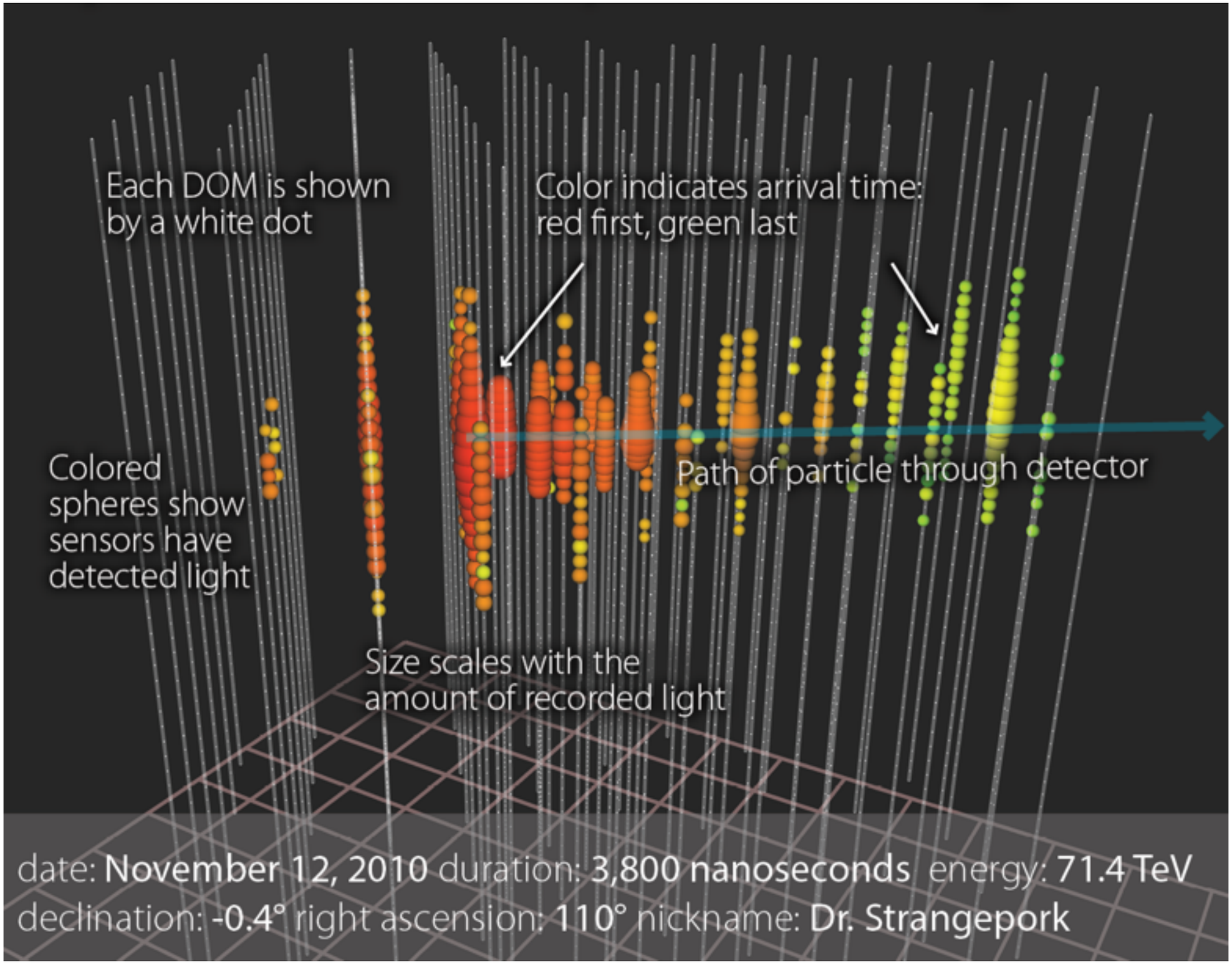

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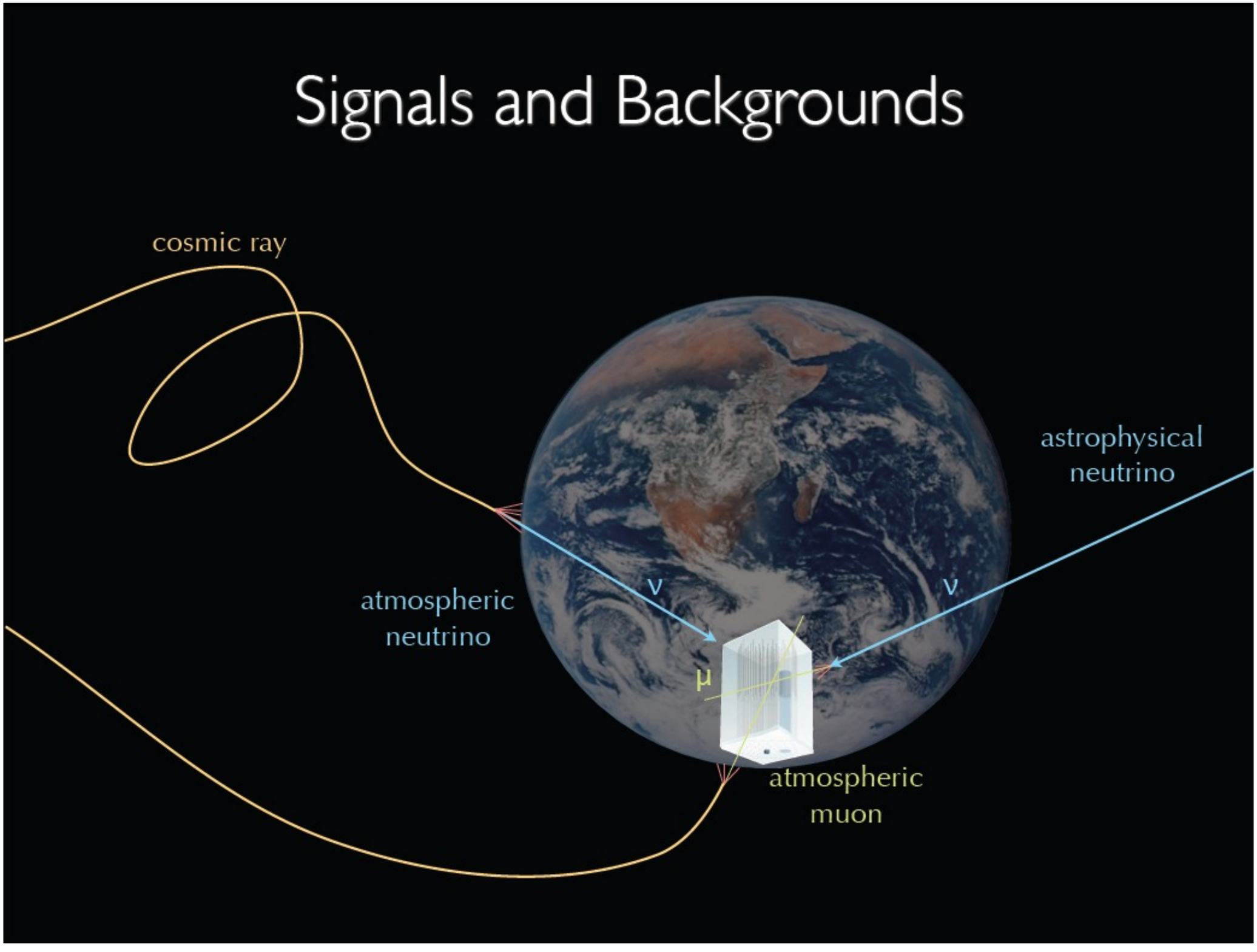
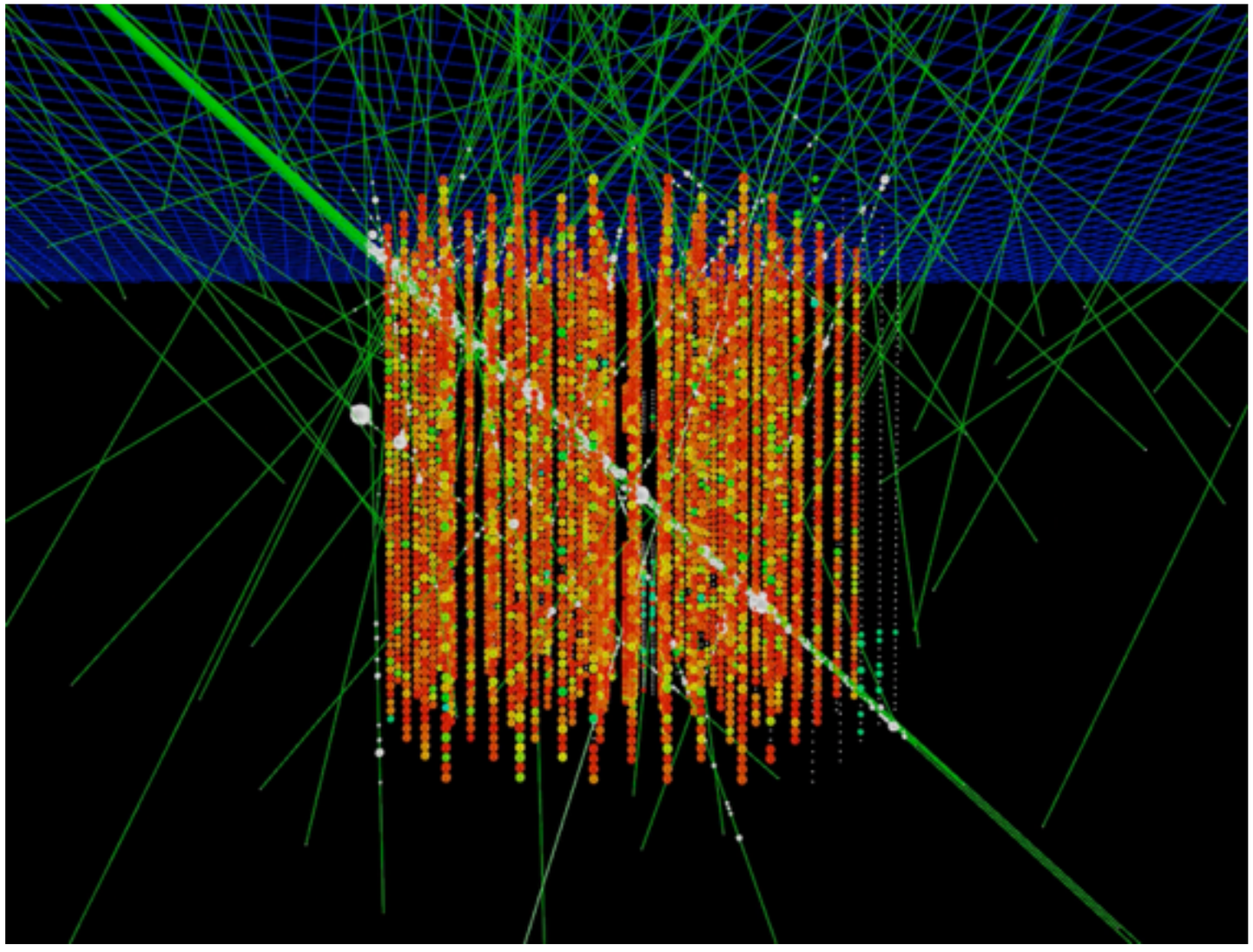


What do neutrinos look like in IceCube?

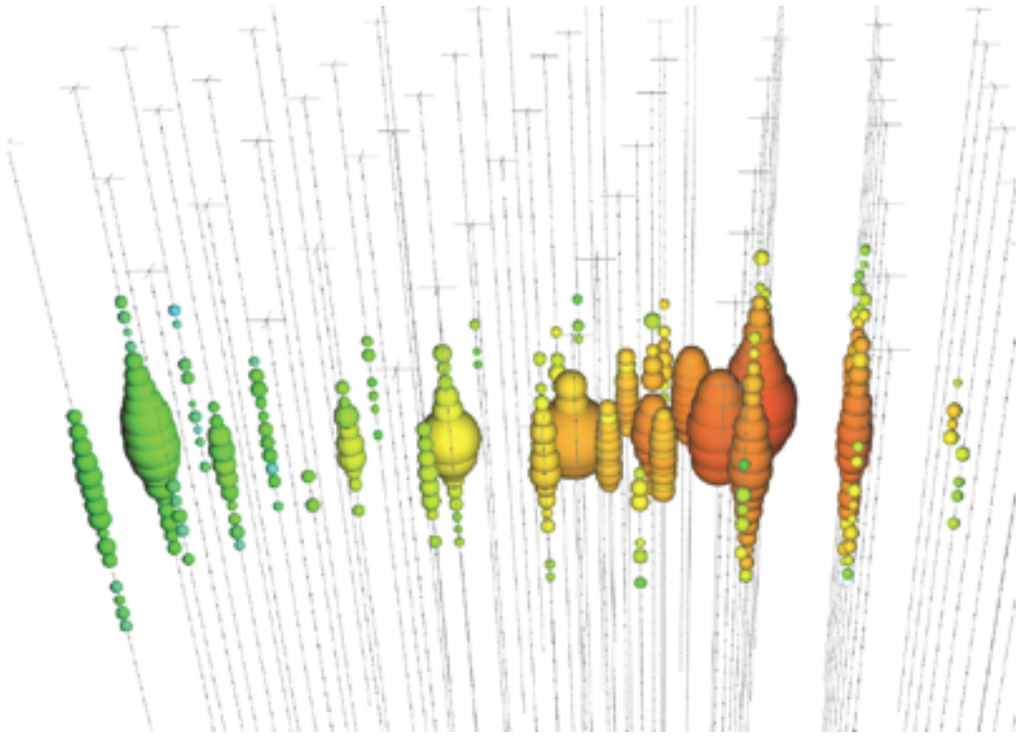
- 10 ms of IceCube data:
- ~275 mio atm. μ per day
- ~8250 atm. ν per month
- ~10 astroph. ν per year



challenge: find astrophysical neutrinos within a large background

What do neutrinos look like in IceCube?

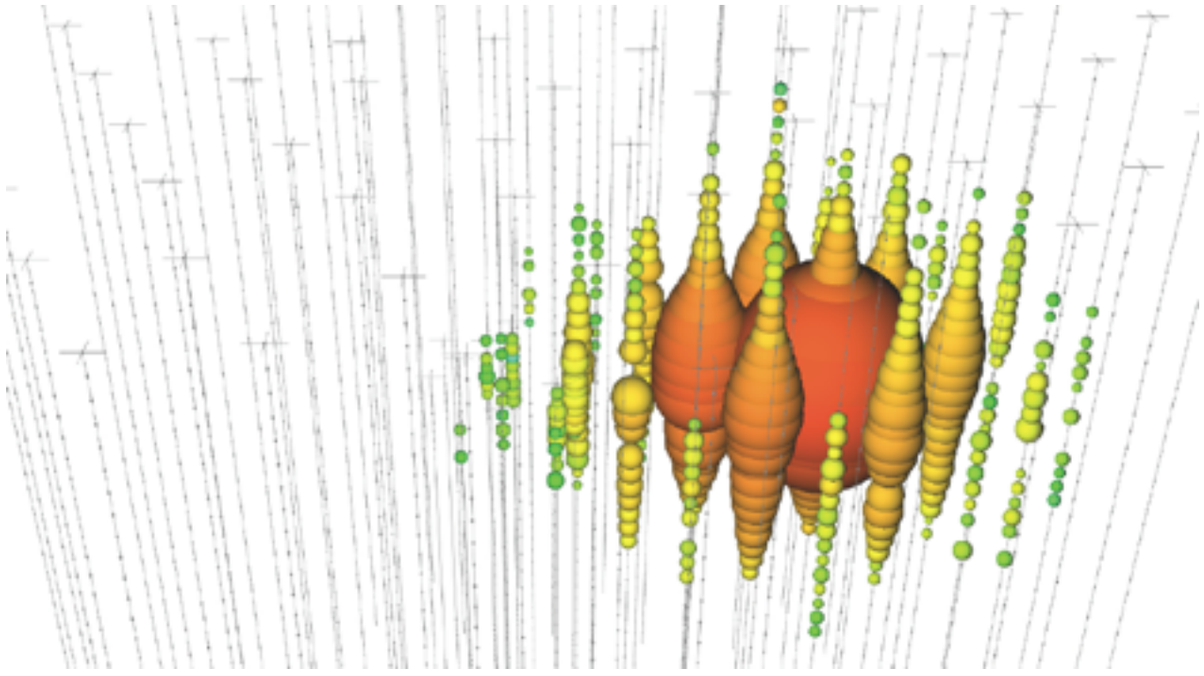
track



$$\nu_\mu + N \rightarrow \mu + X$$

- upgoing: signal
- downgoing: likely background

cascade



$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + N$$

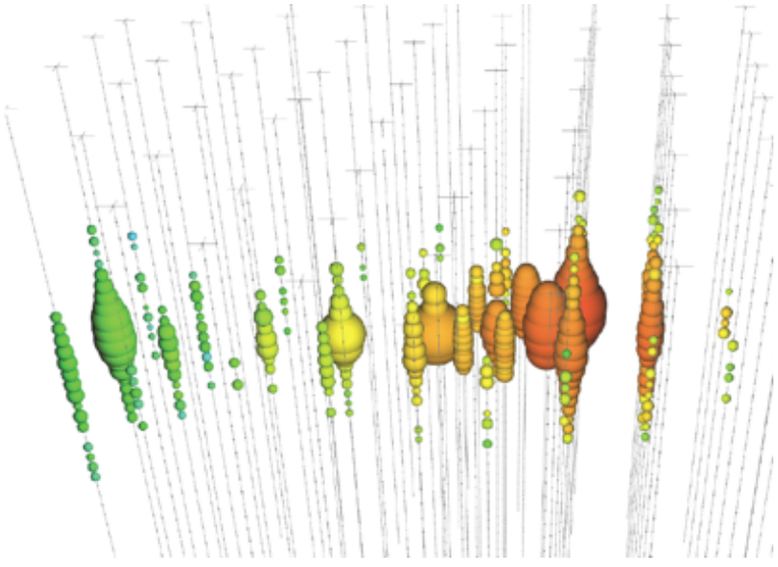
- likely signal

x = any flavor

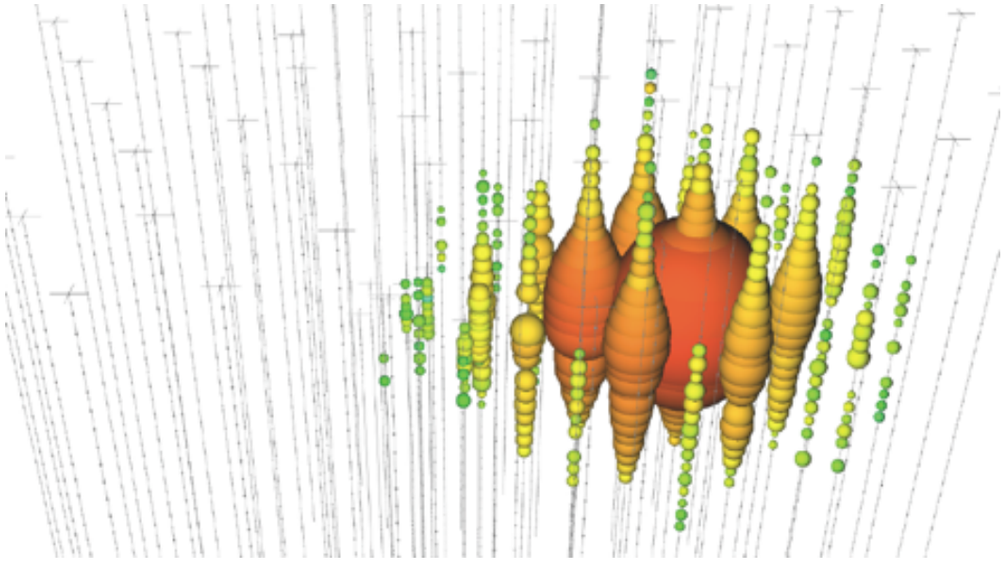
What do neutrinos look like in IceCube?

- For each event, we want to know the energy and direction
- How good does this work for tracks/cascades?

track



cascade



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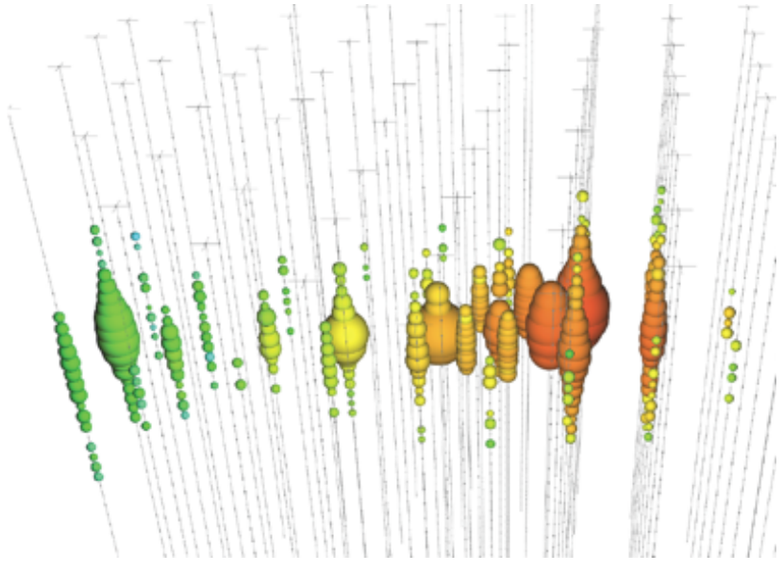
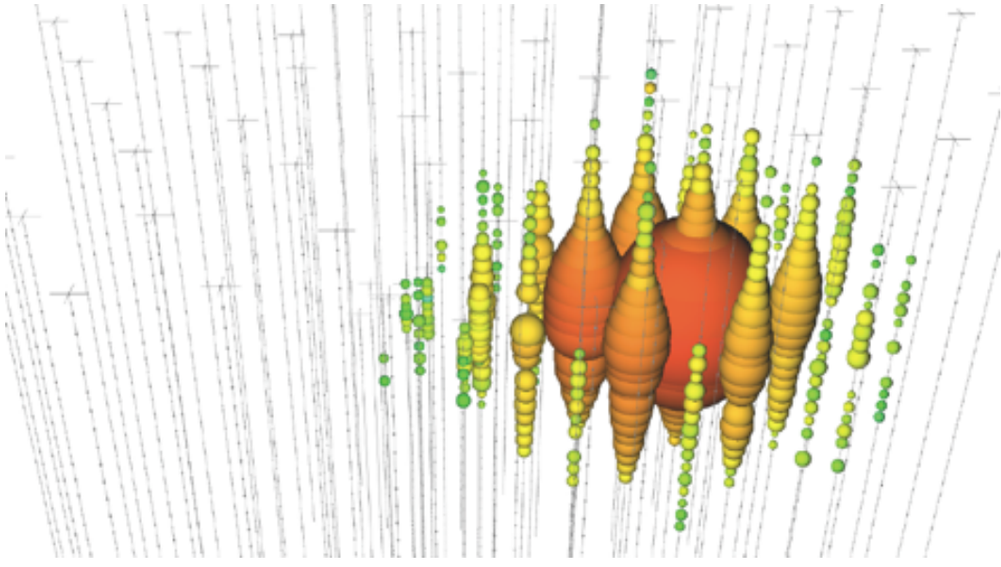


good direction resolution
bad energy resolution

cascade



good energy resolution
bad direction resolution

What are the physics goals of IceCube?

- Do astrophysical neutrinos exist?
- Where do astrophysical neutrinos (and CR) come from?
- How are they accelerated?
- What are the oscillation properties?

- Does dark matter exist?
- Do sterile neutrinos exist?
- many more…

What are the physics goals of IceCube?

- Do astrophysical neutrinos exist?
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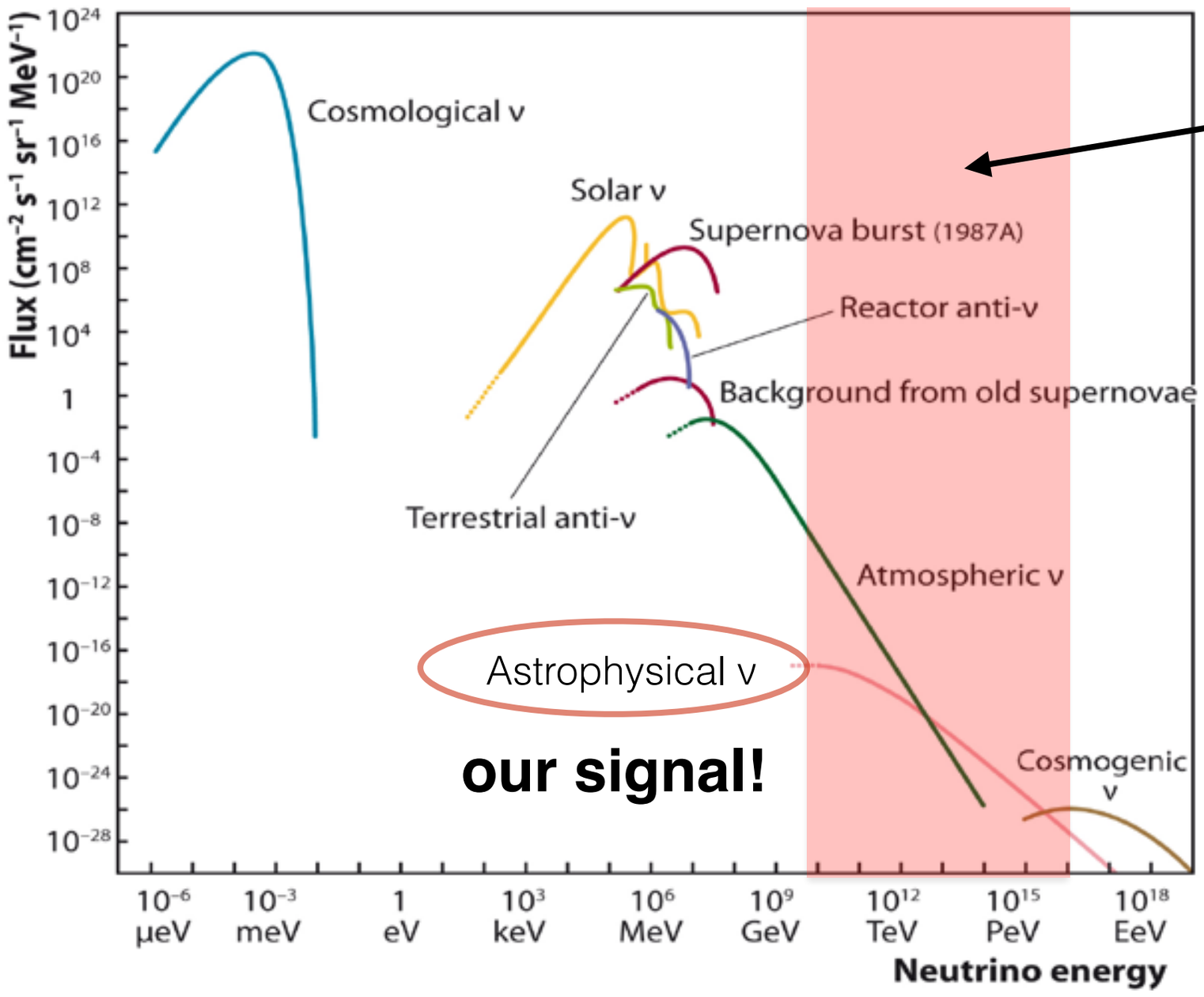
- Does dark matter exist?
- Do sterile neutrinos exist?
- many more…

Anatomy of an IceCube analysis:

- Goal: **Observe Something**
- Steps:
  - Detector takes data
    - PMT, DOM, DAQ, Trigger
  - Separate signal from background
    - Apply algorithms to get particle's identity, energy, position direction
    - Throw away particles that don't look like signal
  - Apply statistical test to test if you observe signal

Do astrophysical neutrinos exist?

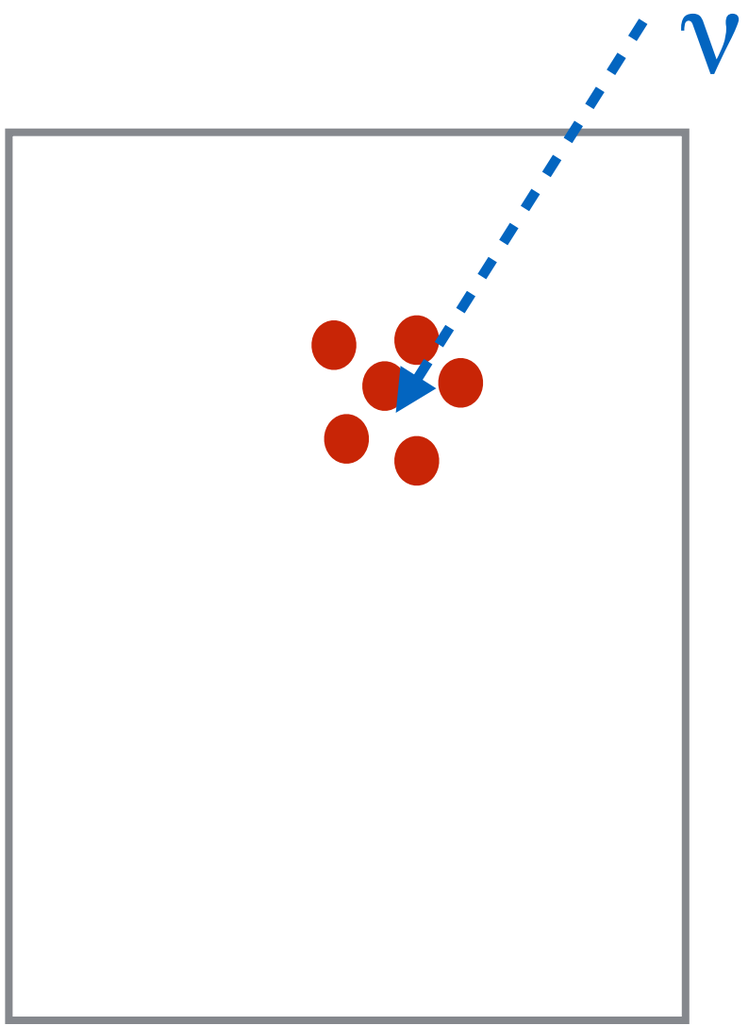


can be detected by IceCube

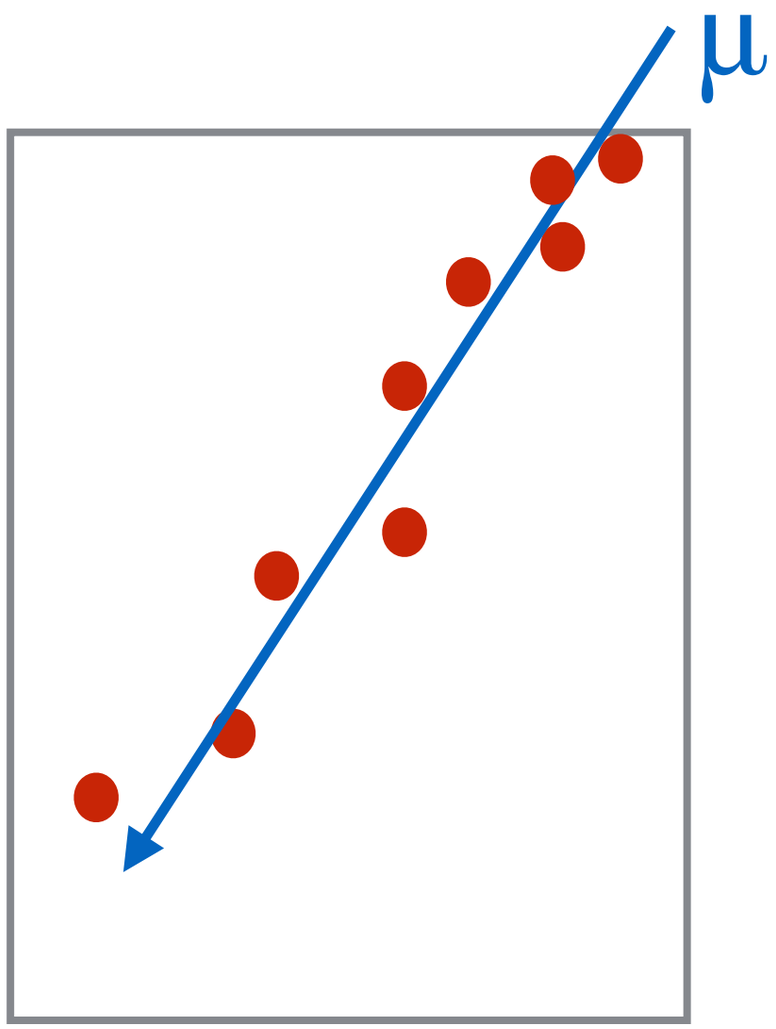
signal: astrophysical ν; **background**: everything else

Do astrophysical neutrinos exist?

typical signal



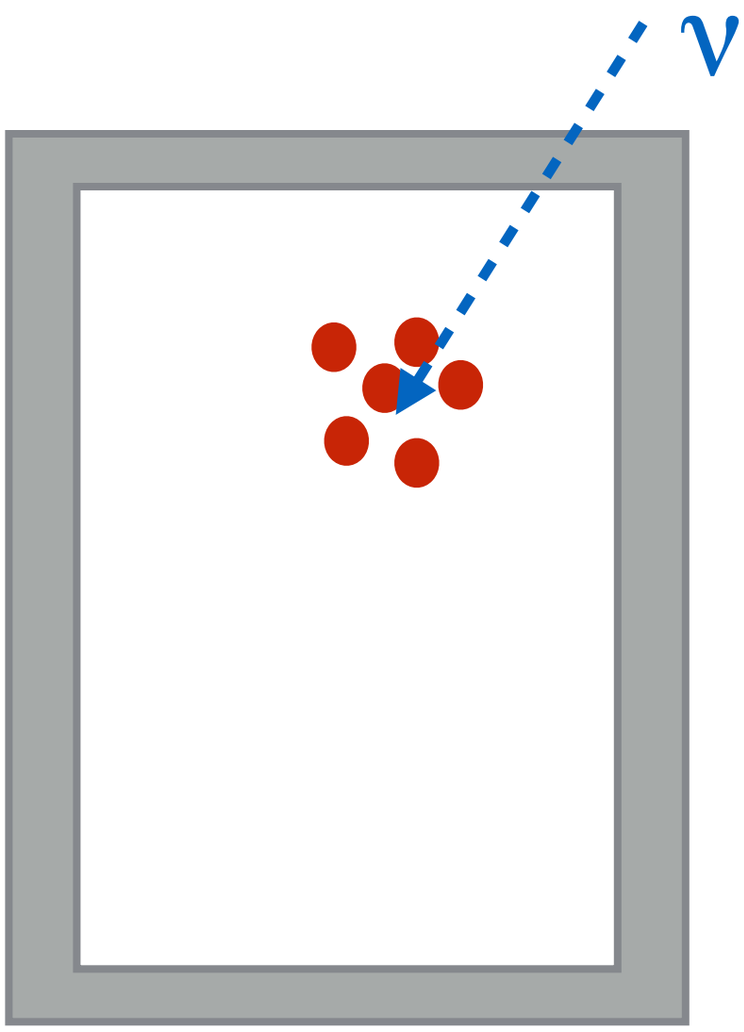
typical background



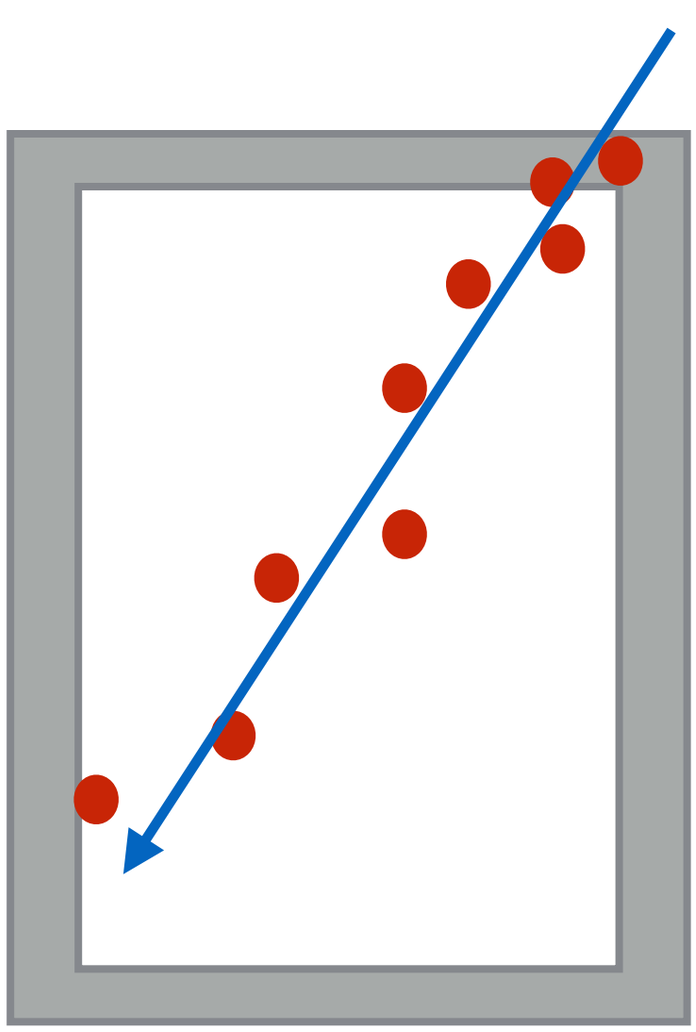
Idea: events starting in the detector have to be neutrinos
➞ HESE (High Energy Starting Event) analysis

Do astrophysical neutrinos exist?

typical signal

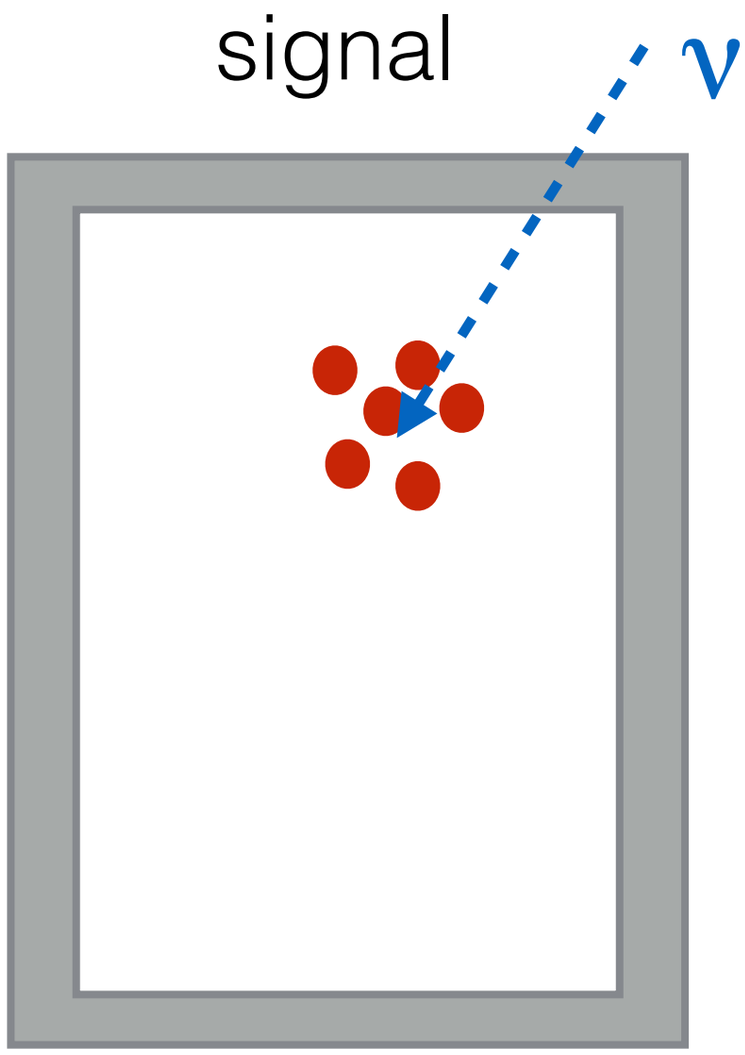


typical background



use DOMs on outer layer as veto!

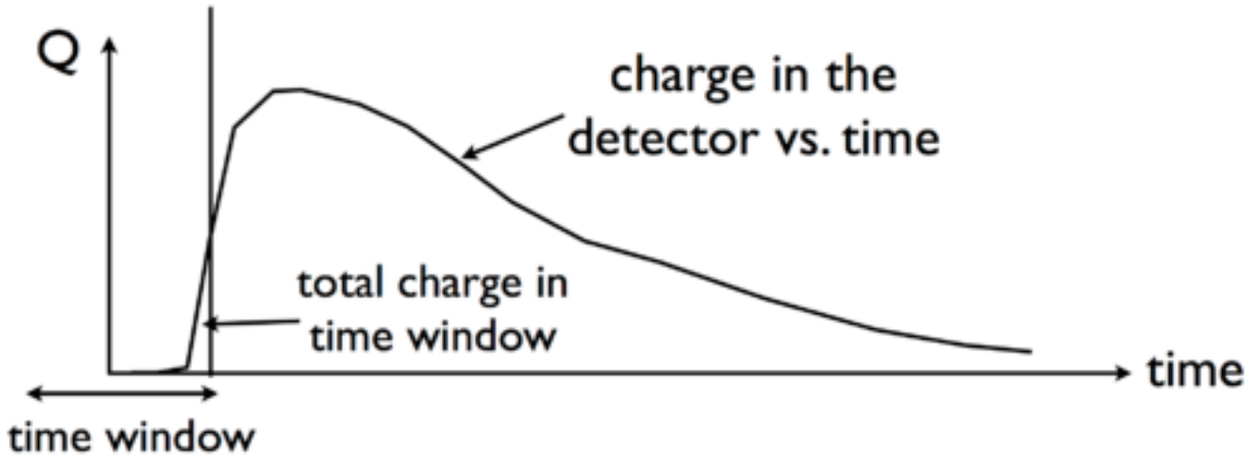
Do astrophysical neutrinos exist?



an event is marked as signal if:

- less than 3 of the first 250 photoelectrons were recorded in the veto region

→ removes atmospheric muon background



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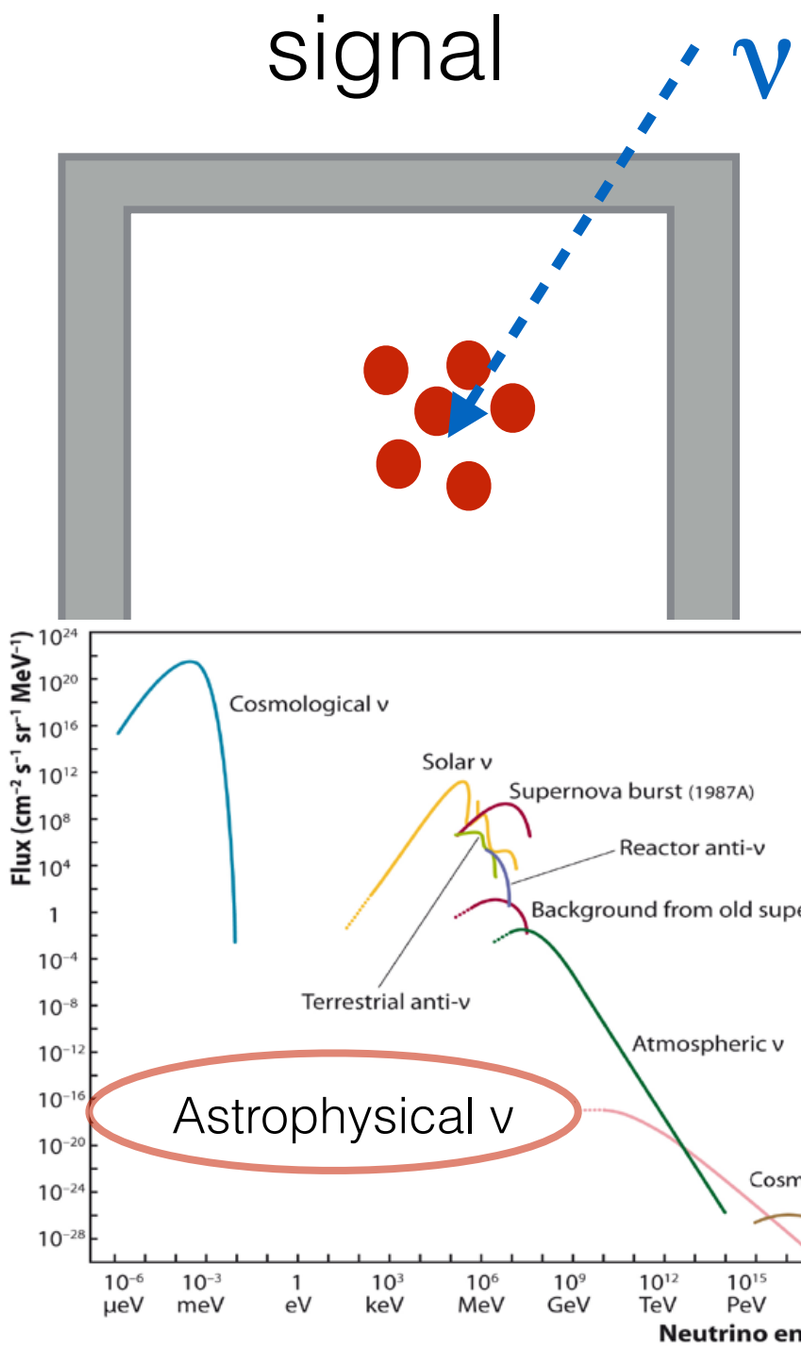


an event is marked as signal if:

- less than 3 of the first 250 photoelectrons were recorded in the veto region

  → removes atmospheric muon background

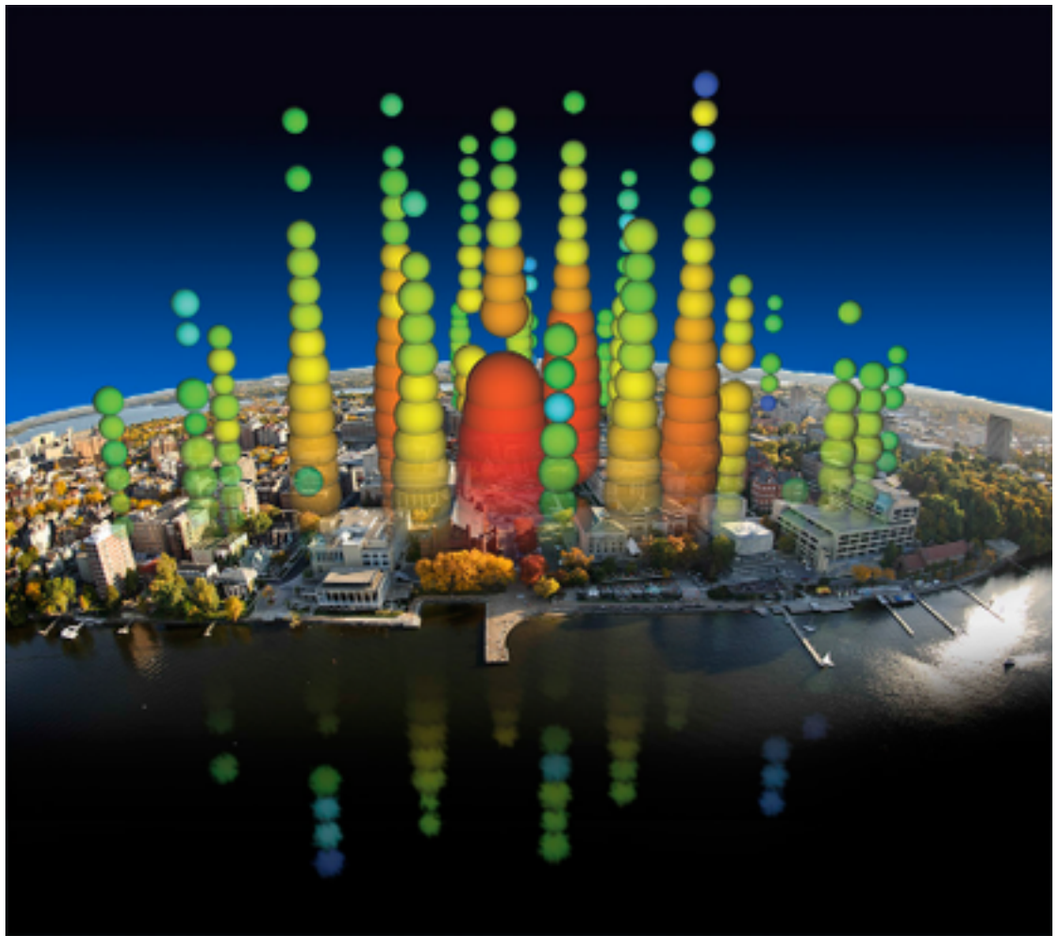
- it deposits more than 6000 PE

  → removes some atmospheric neutrino background

Do astrophysical neutrinos exist?

Opening the 3y box: what did we find?

- HESE analysis reveals 37 neutrino event candidates
- Big Bird: highest energy neutrino (2.2 PeV)

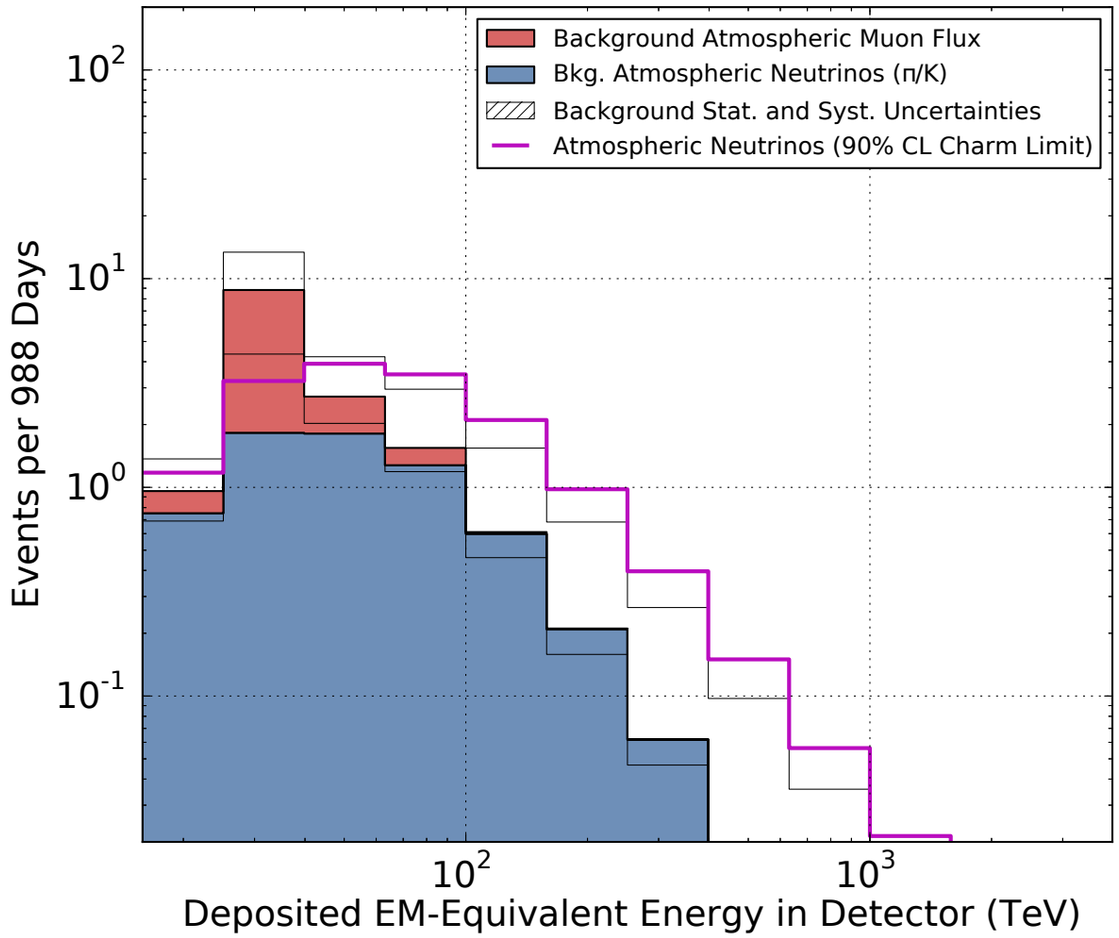


Bert

Do astrophysical neutrinos exist?

"How significant is our result?"

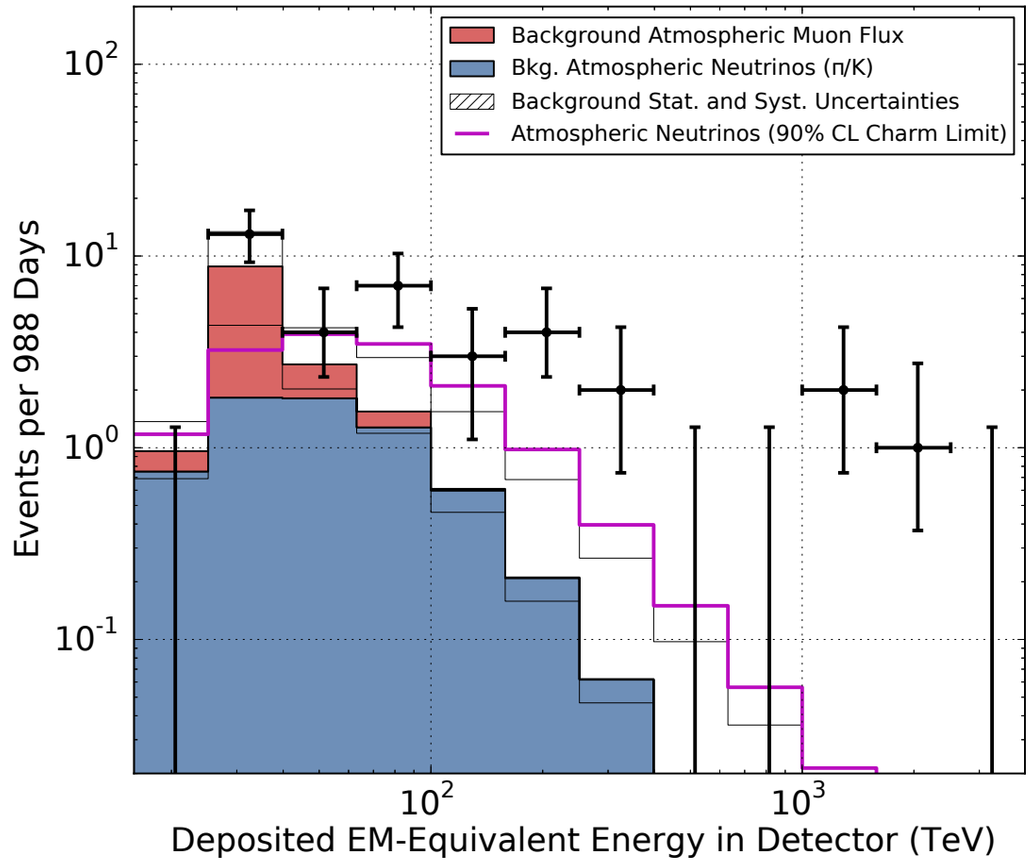
How much background did we expect?
→ needs precise computer models!



Do astrophysical neutrinos exist?

"How significant is our result?"

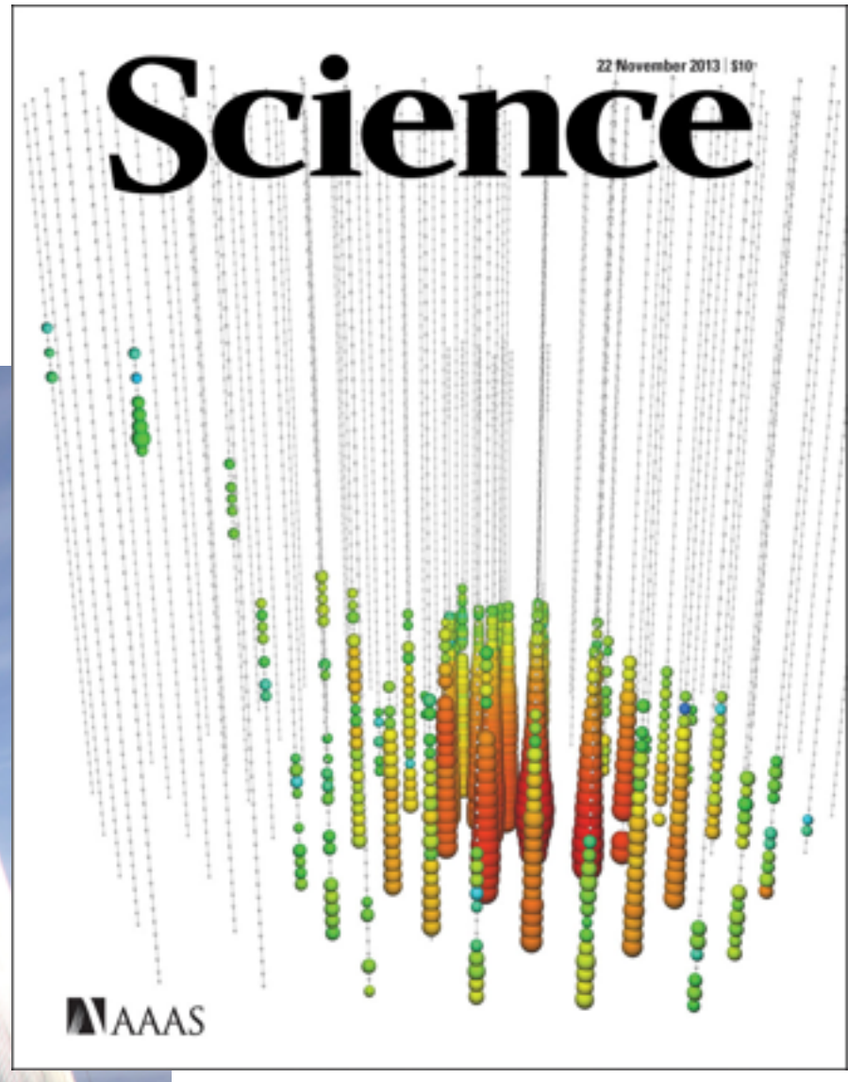
How many events did we actually find?
→ can this be explained by a background-only hypothesis?



purely atmospheric origin rejected at 5.7σ

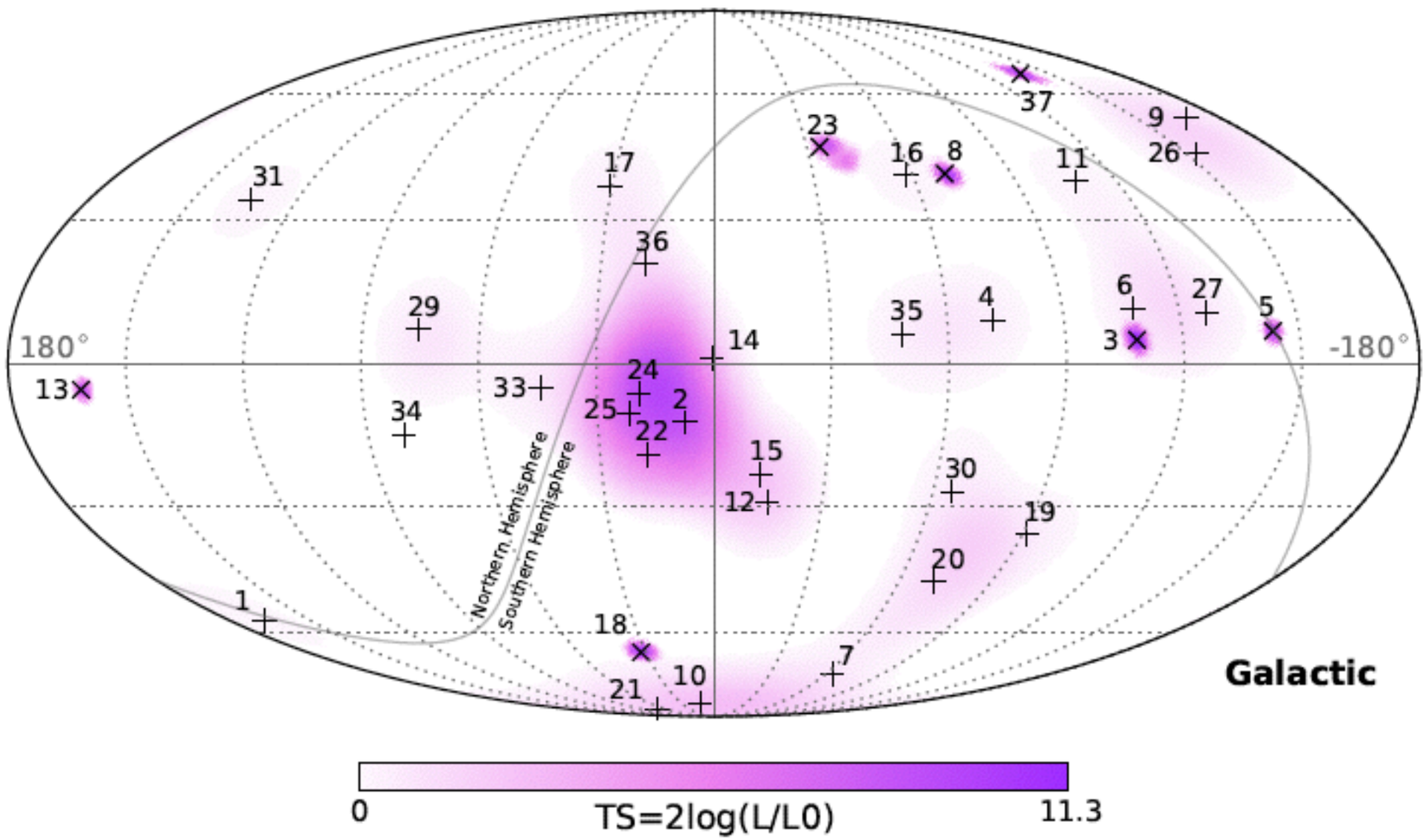
Do astrophysical neutrinos exist?

Yes, they do!



Where do astrophysical neutrinos come from?

- Goal: find a point source of neutrinos
- Let's look at the 3y HESE events on a sky map



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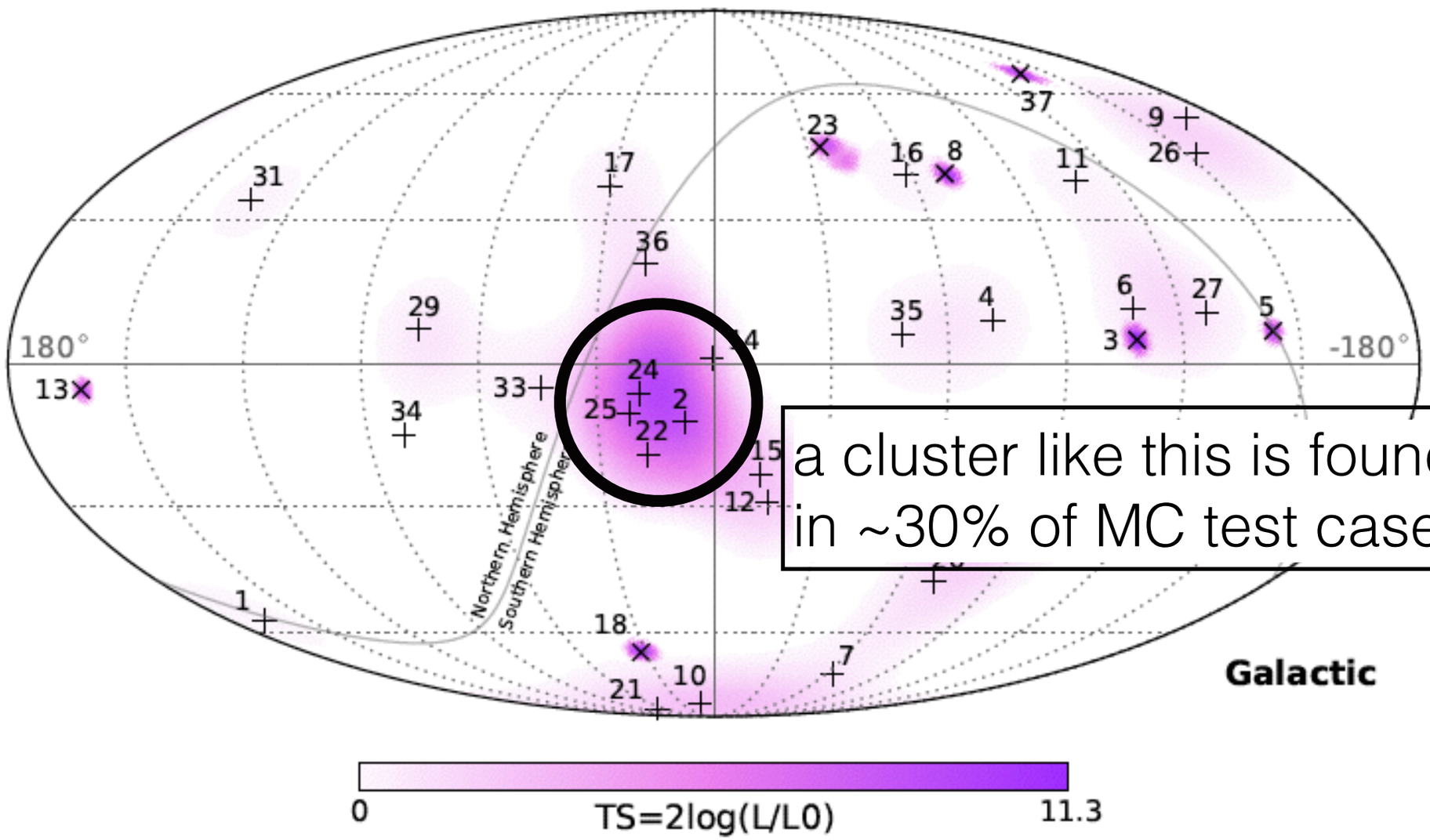

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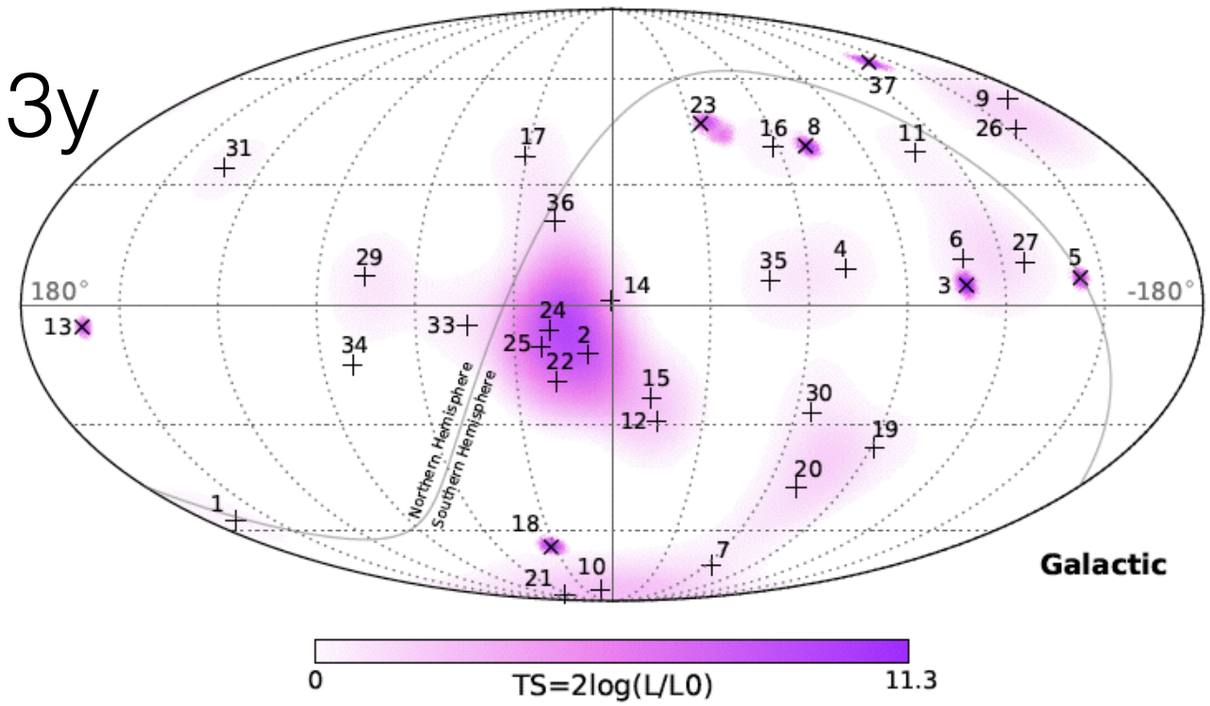
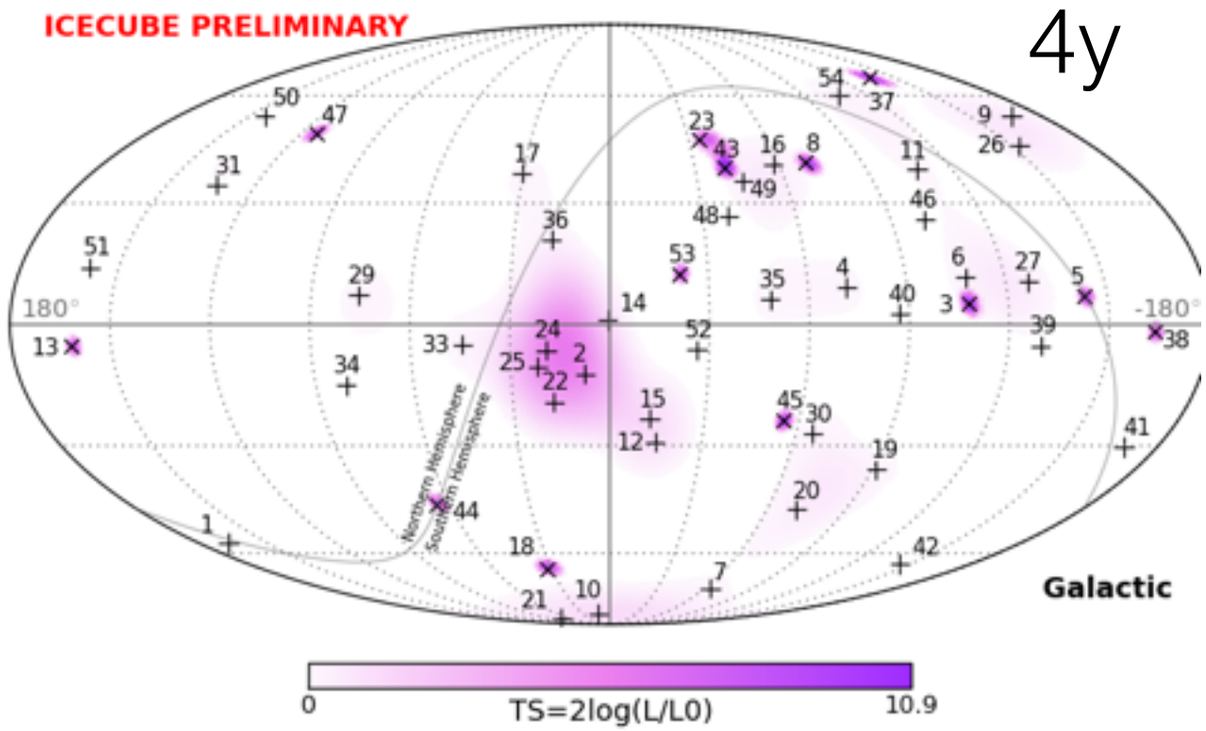


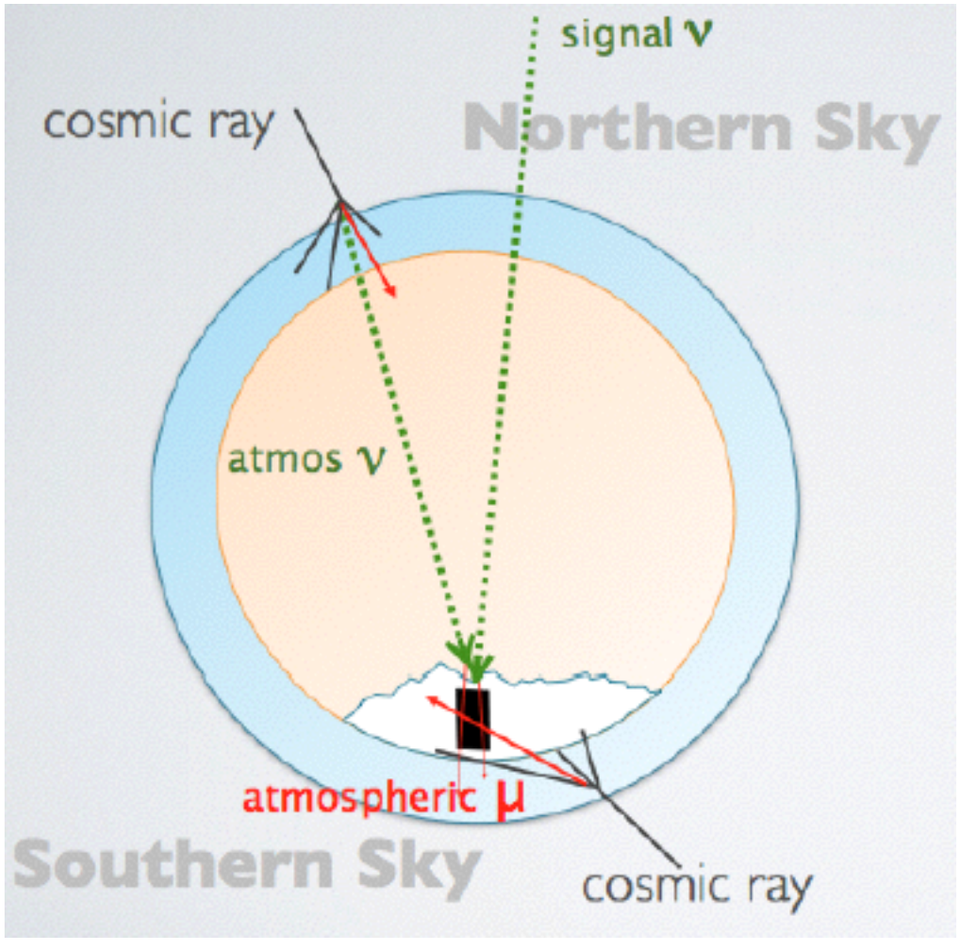
x tracks
+ cascades



HESE disadvantage: mostly cascades ➙ bad pointing

Where do astrophysical neutrinos come from?

- Goal: find a point source of neutrinos
- Use muon neutrinos!
- upgoing: atm. + astroph. ν
- downgoing: ν + atm. muons



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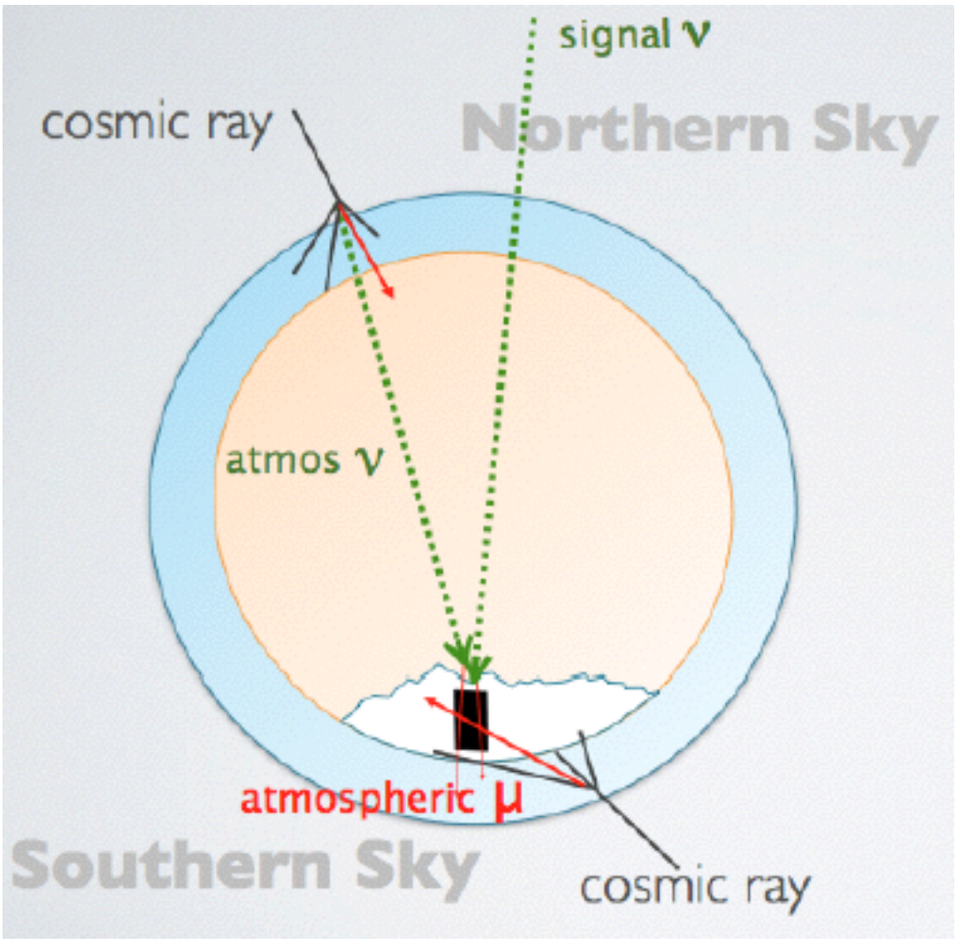
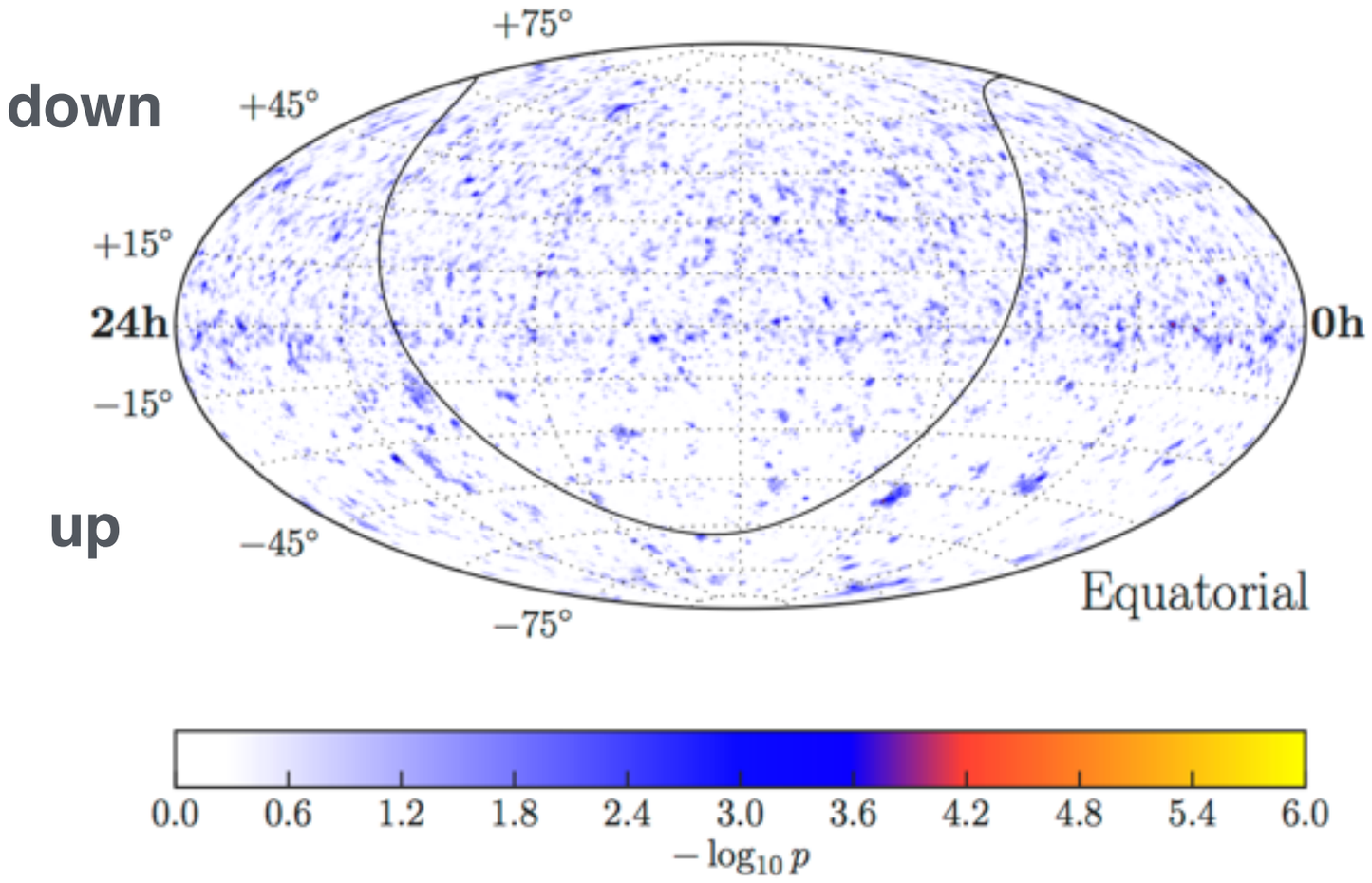
- downgoing: ν + atm. muons





no significant source found!

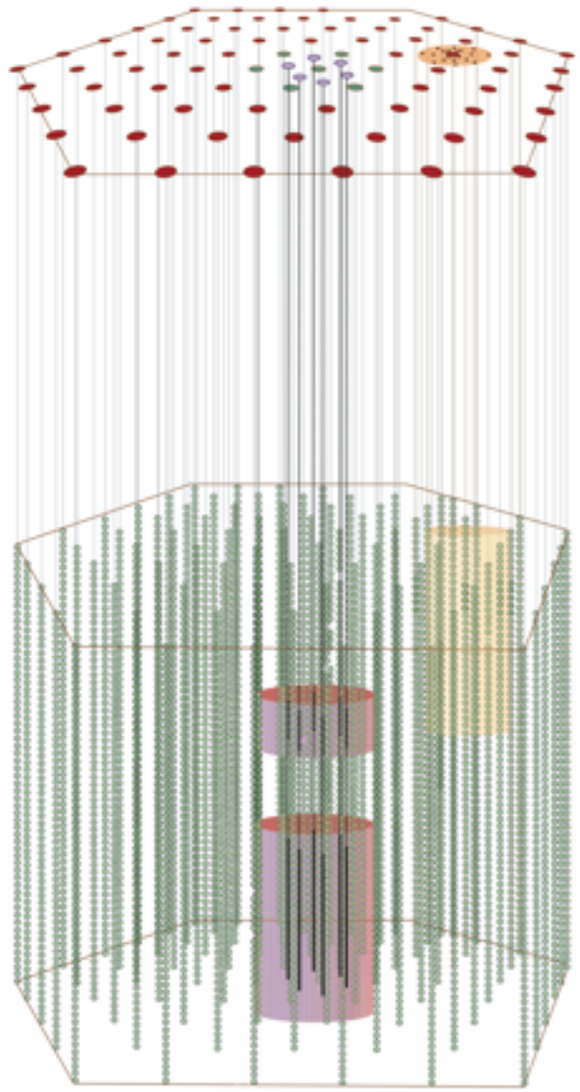
Where do astrophysical neutrinos come from?

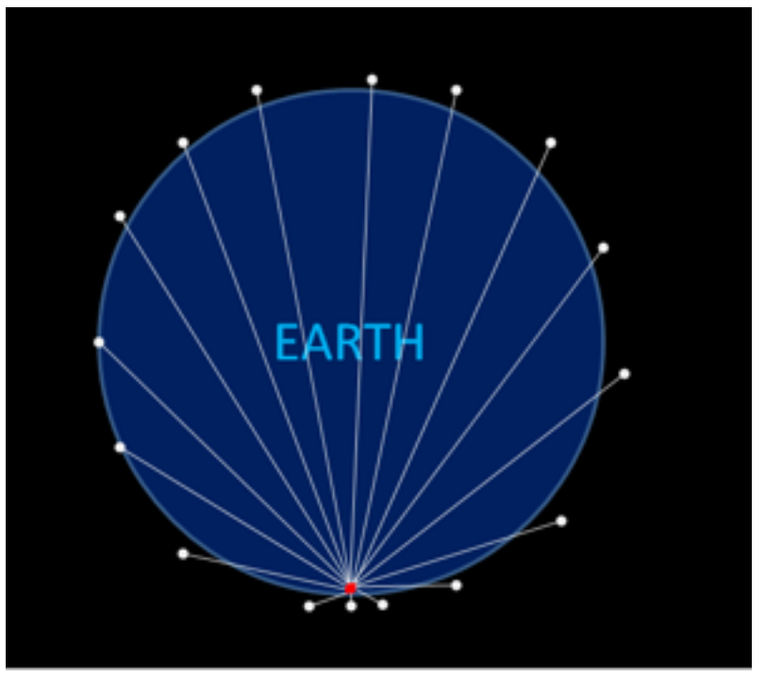
We don’t know yet…

… but the search continues
(with more data and better analysis techniques)

What are the oscillation properties?

- Goal: look for atmosph. muon-ν disappearance
- map parameter space: L/E
- L: arrival direction of ν determines path length
- E: reconstructed energy (O(GeV) ➞ DC)
- background reduction: use IceCube as veto

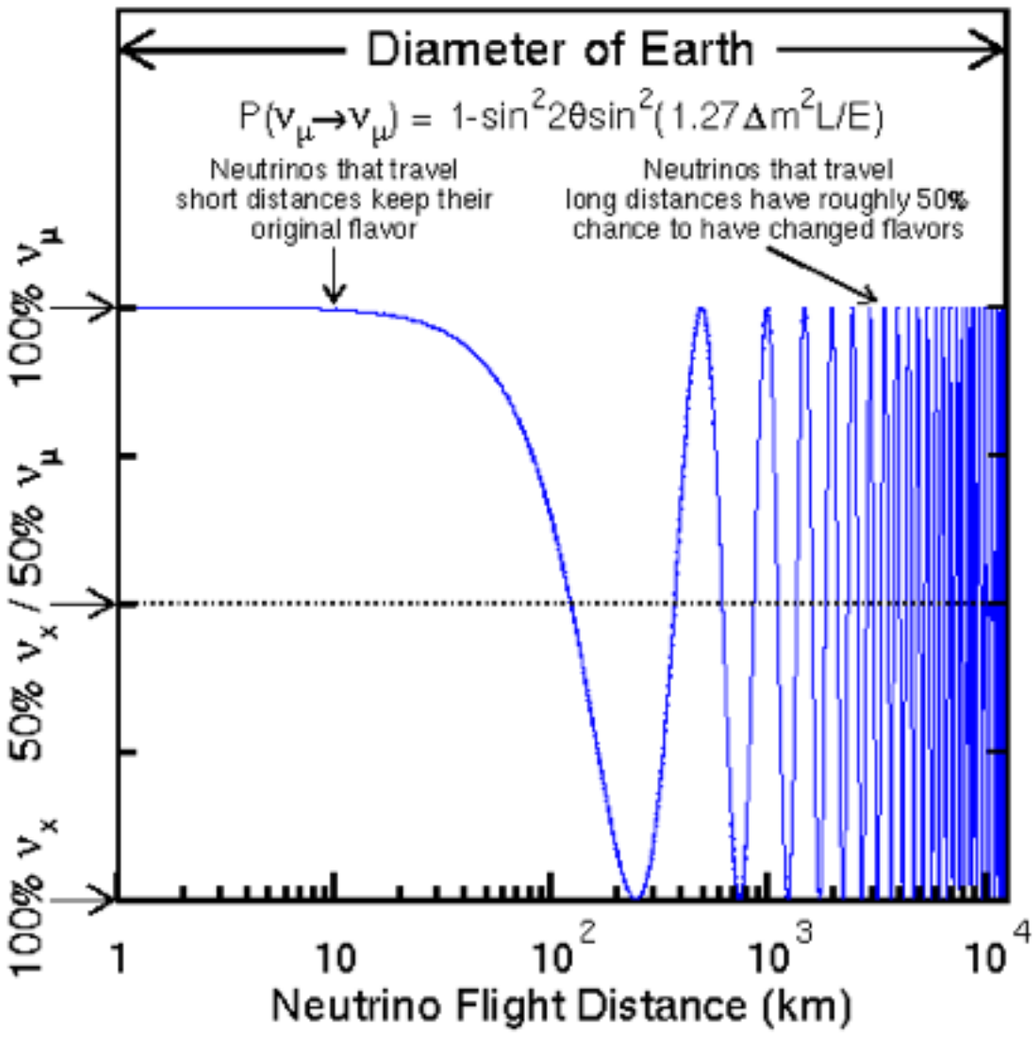


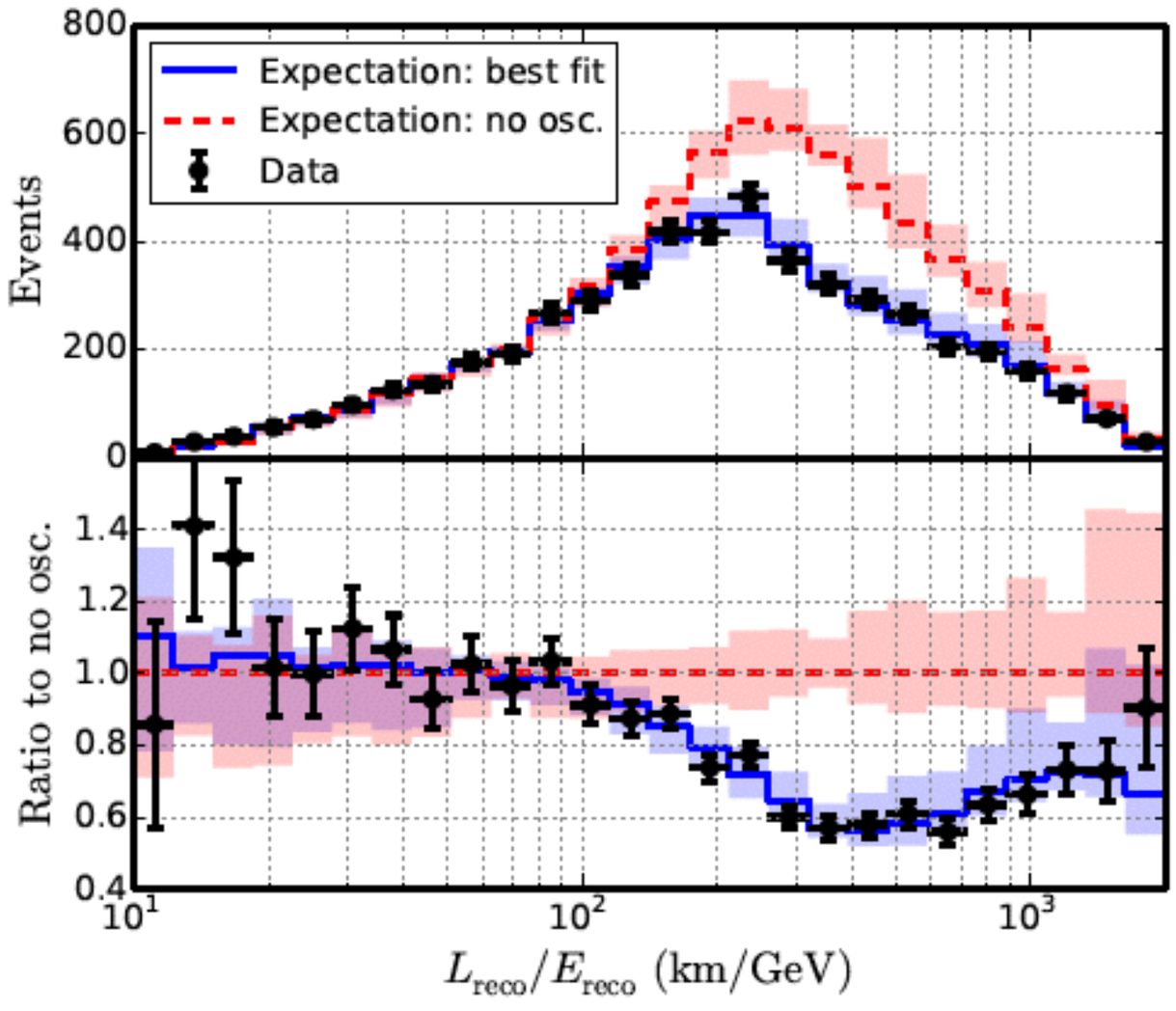


$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

What are the oscillation properties?

- Oscillation signal: disappearance of events in certain region of phase space

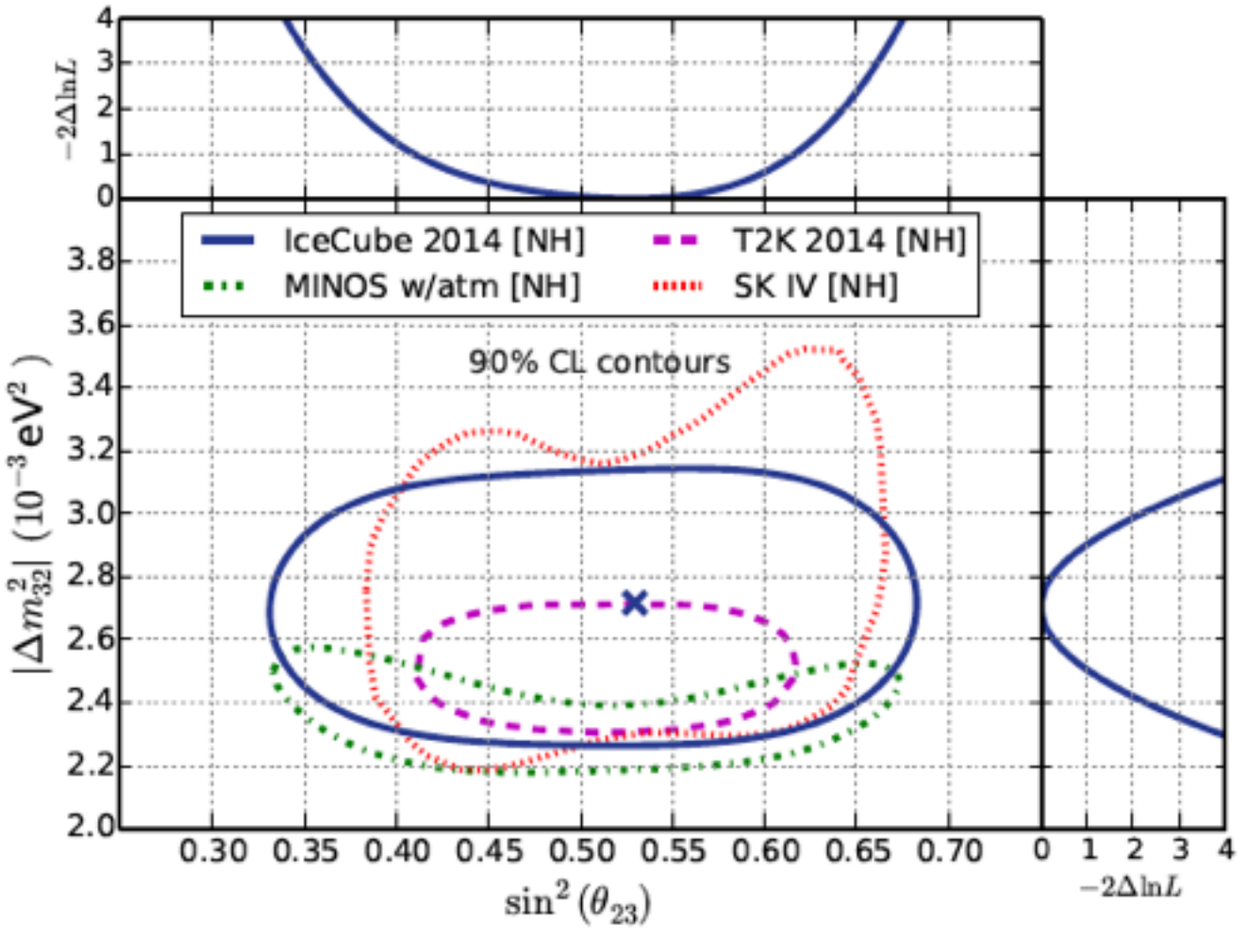




IceCube sees a clear disappearance of ν_μ

What are the oscillation properties?

- The disappearance signal can be translated into the mixing parameters $sin^2(\theta_{23})$ and $|\Delta m_{32}^2|$



IceCube results consistent (and competitive!) with dedicated oscillation experiments

Summary

- IceCube: a 1km^3 neutrino detector in the antarctic ice
- DOMs detect Cherenkov light of neutrino-induced charged particles or cosmic ray muons
- Challenge: discriminate signal from background
- Many interesting analyses:
  - HESE: astrophysical neutrinos exist
  - Point Source: no point sources found yet :(
  - Oscillation: IceCube as competitive oscillation experiment
  - many more: dark matter, magnetic monopoles, Cosmic Ray physics, Supernova, Gamma Ray Bursts…