Not of this Earth:
the advent of neutrino astronomy

Darren R. Grant
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So what is this all about?

It could be this…

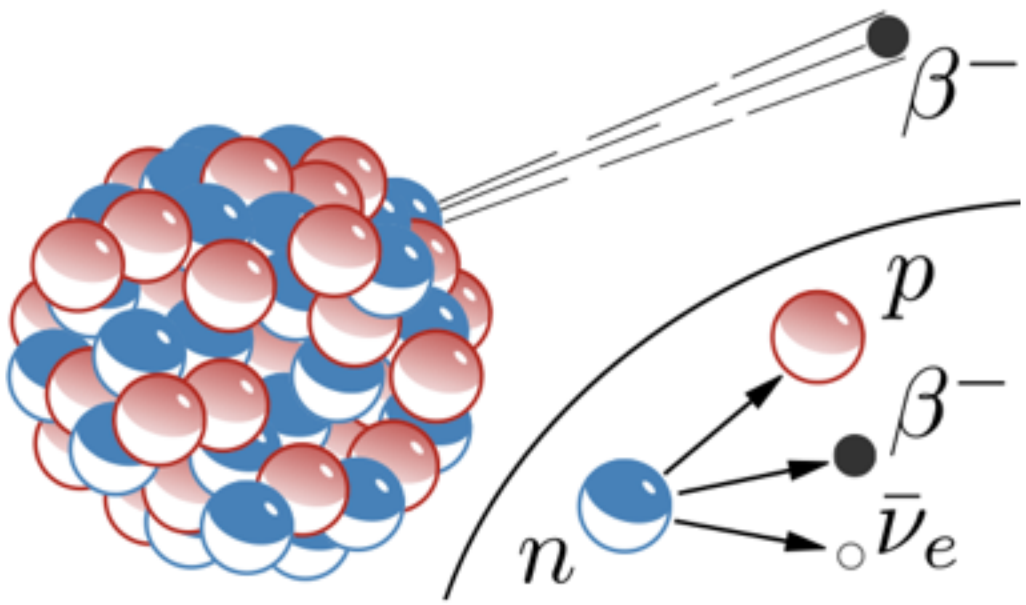
It could be this…but it isn’t

It's the tale of the "ghost particle"

… in the beginning…

• In 1930 Wolfgang Pauli composes a famous letter as a "desperate attempt" to save the law of conservation of energy for the beta decay process. He suggests, in addition to electrons and protons, atoms contain an extremely light neutral particle which he called the neutron. He suggests this "neutron" is also emitted during beta decay and has simply not yet been observed.

• In 1931 Enrico Fermi renames Pauli's "neutron" to neutrino, meaning "little neutral one". Fermi publishes the first successful model of beta decays in which neutrinos are produced in 1934.



http://en.wikipedia.org/wiki/Beta_decay

Wolfgang Pauli

“We aren’t afraid of no ghost”

- A neutrino “Rule of Thumb” - neutrinos interact with only the weak force in nature, meaning they can pass through large amounts of matter with very little probability for interaction 10 billion through your thumb nail per second.

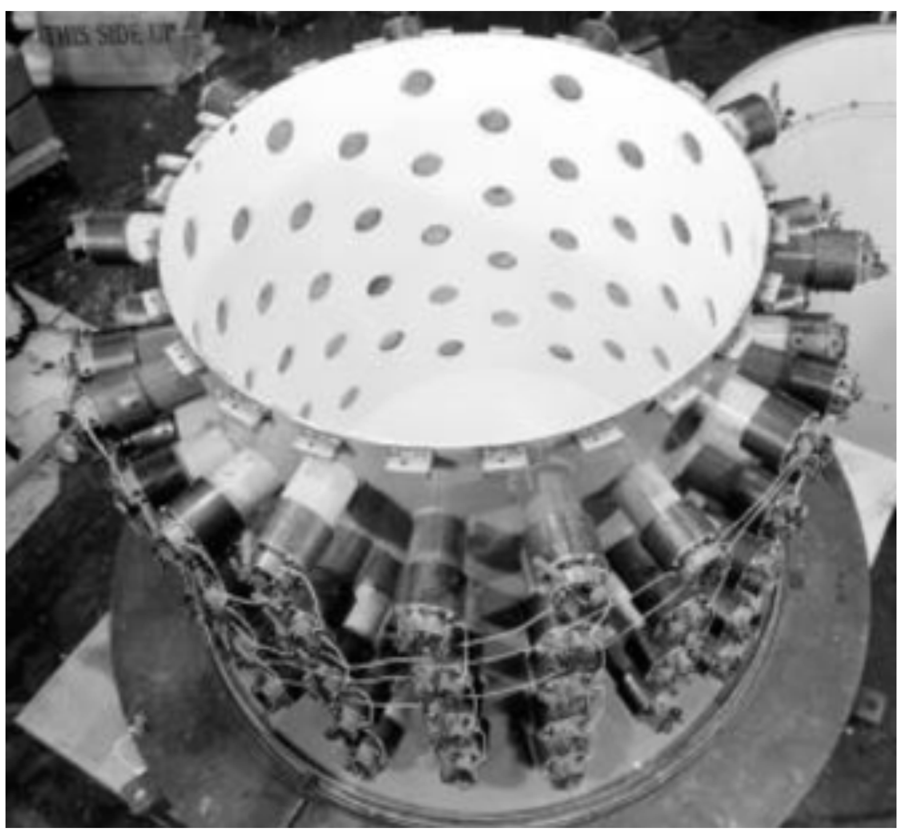
- To guarantee an interaction you would require a column of lead approximately 1 light-year in length.

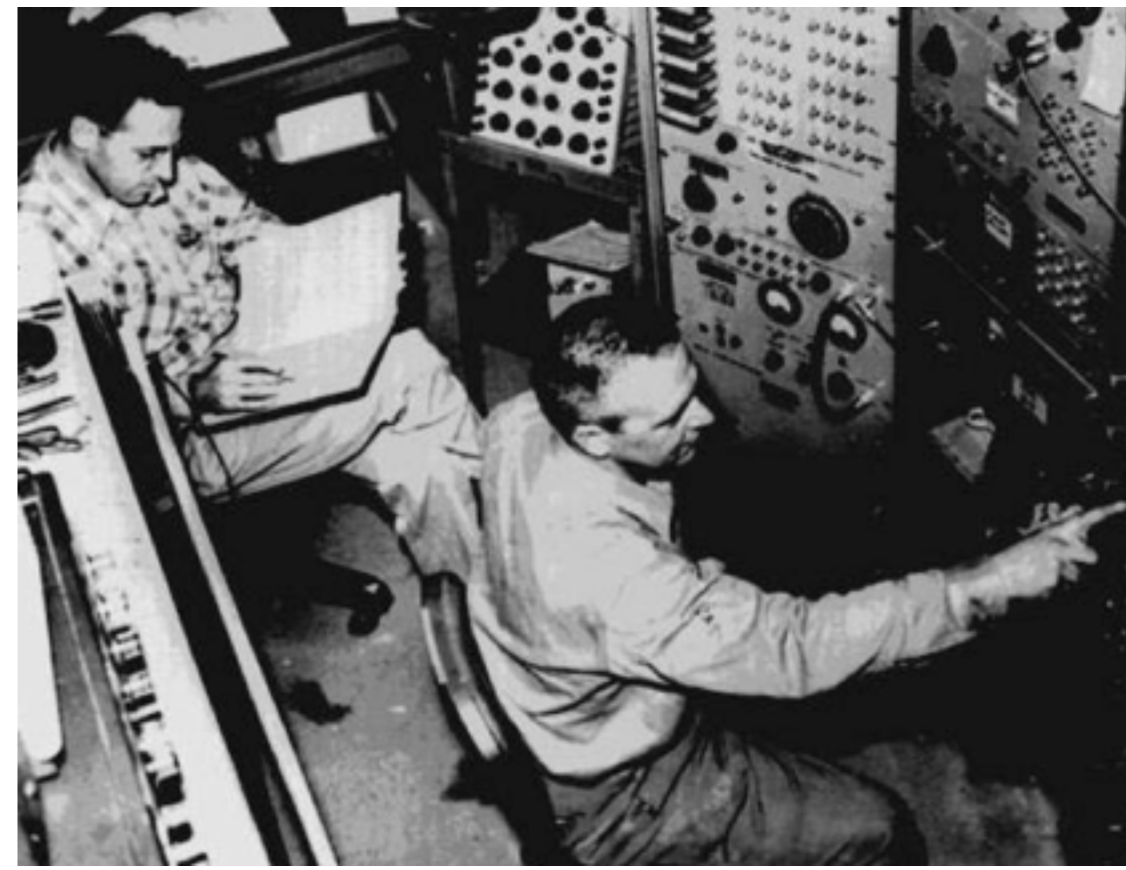
Ghostbusters: Harold Ramis, D. Aykroyd, B. Murray and E. Hudson. Courtesy of Columbia Pictures.

“Ghost” hunting 101

1930s  

- In 1953 Fred Reines and Clyde Cowan set up for the first detection of the neutrino at a reactor with the Hanford Experiment (**Project Poltergeist**). In 1956 at Savannah River they observe the first tentative evidence of the neutrino.





The first physics “Ghostbusters”: Reines and Cowan

"Ghost" hunting 101

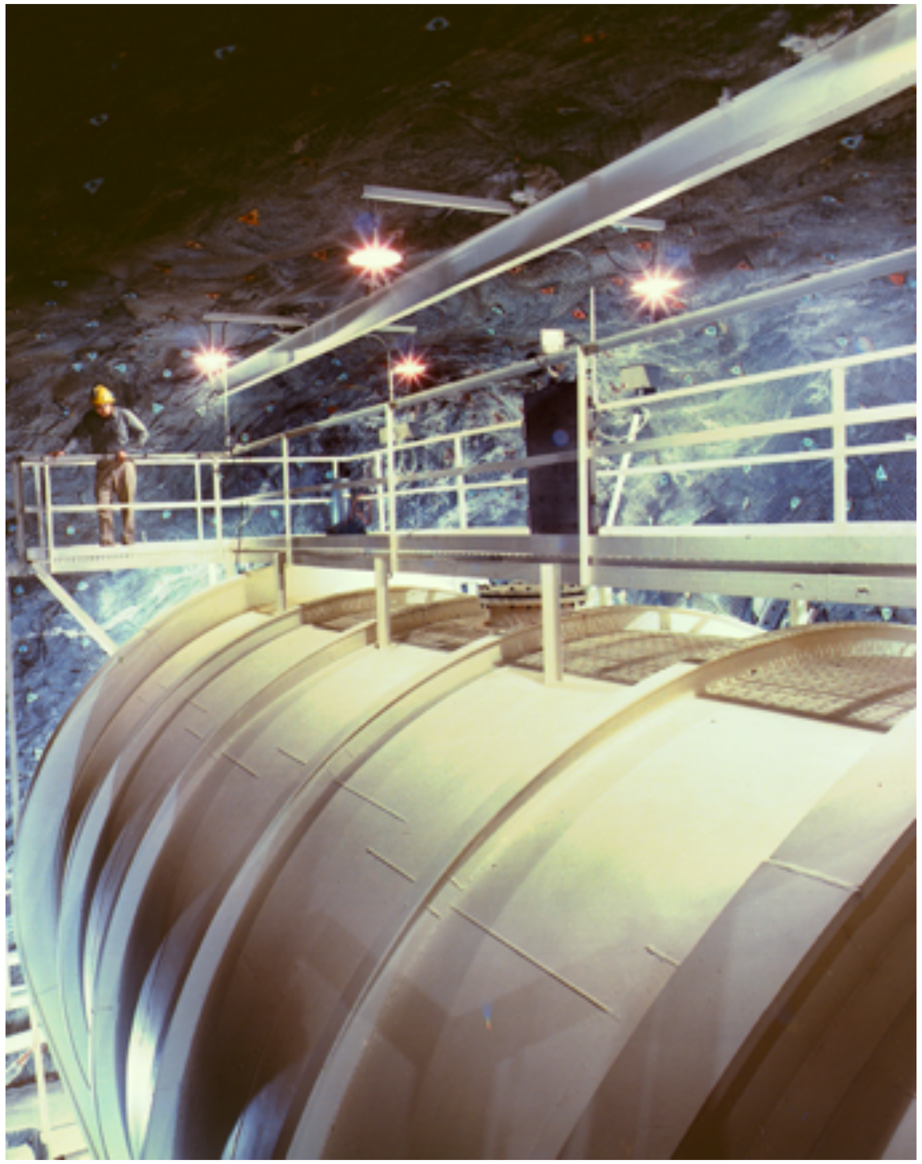
1930s

1950s

1960s, 70s

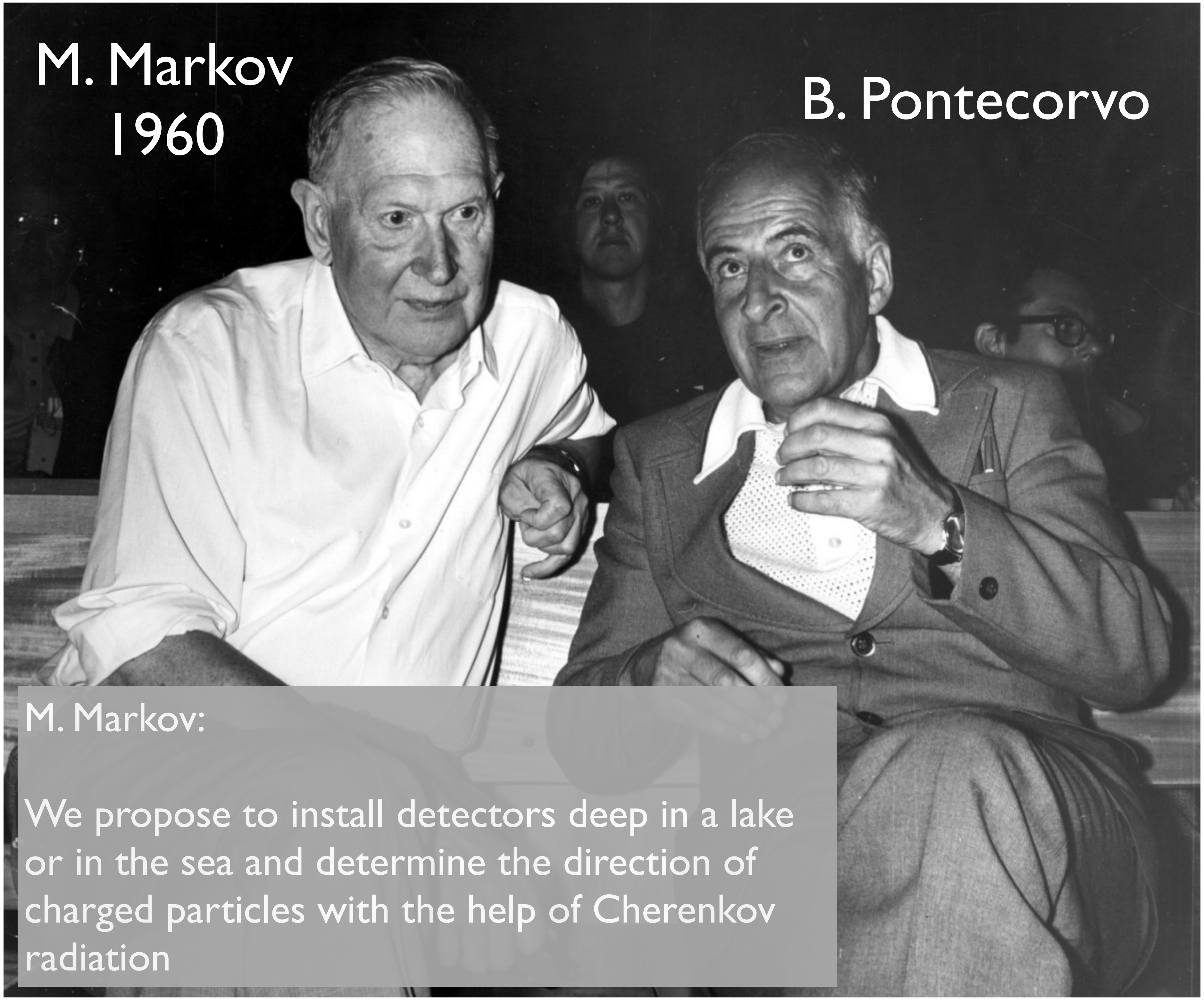
- Ray Davis Jr. constructs and operates the first solar neutrino detector with 100,000 gallons of dry cleaning fluid (neutrinos convert the chlorine to a short-lived argon, which is then counted)

- A deficit of the total number of neutrinos detected (1/3 that predicted by the Solar Model) leads to the 30+ year solar neutrino problem.



Ray Davis Jr. at Homestake

“Ghost” hunting 101 - back to basics



M. Markov:

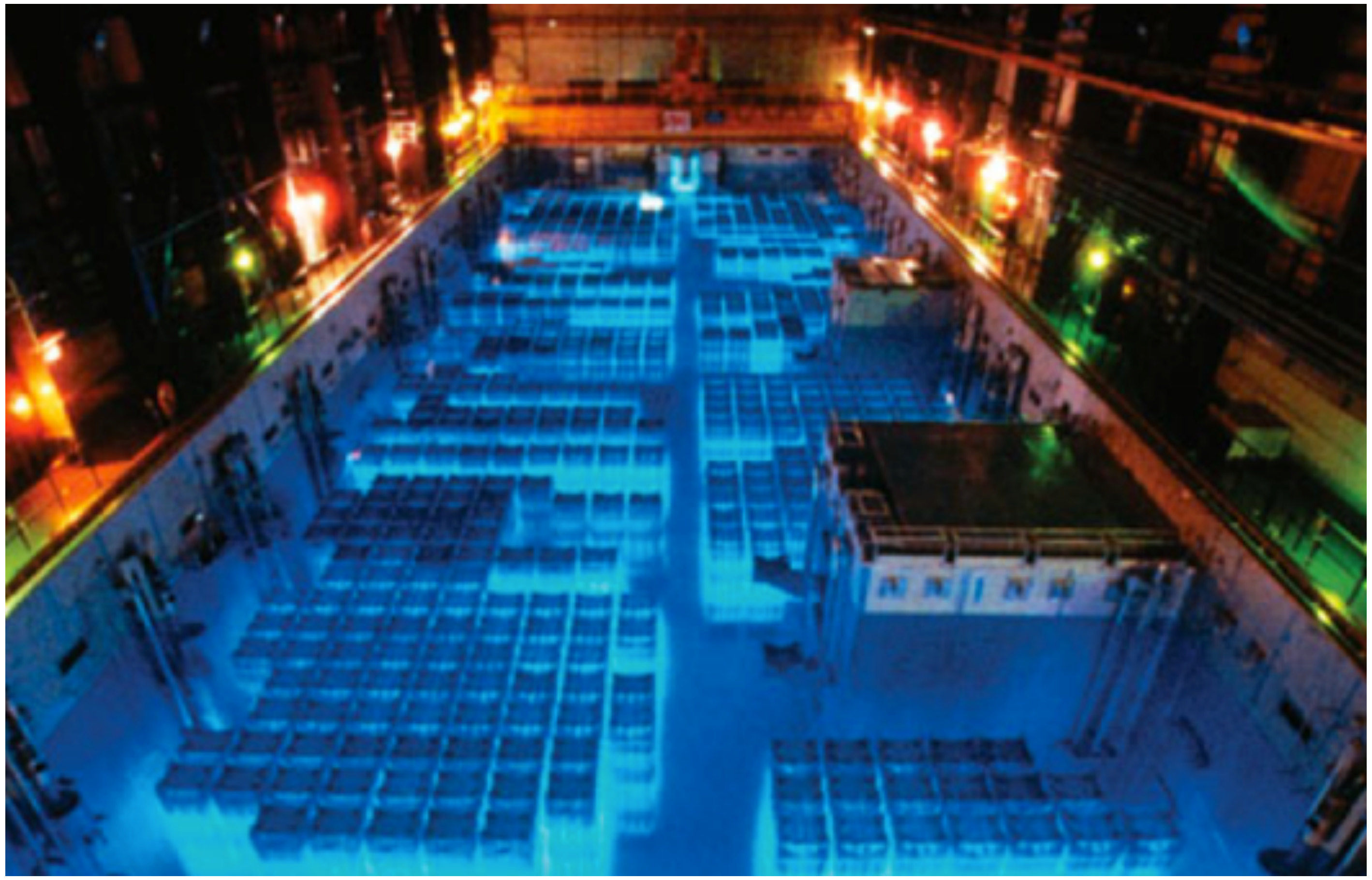
We propose to install detectors deep in a lake or in the sea and determine the direction of charged particles with the help of Cherenkov radiation

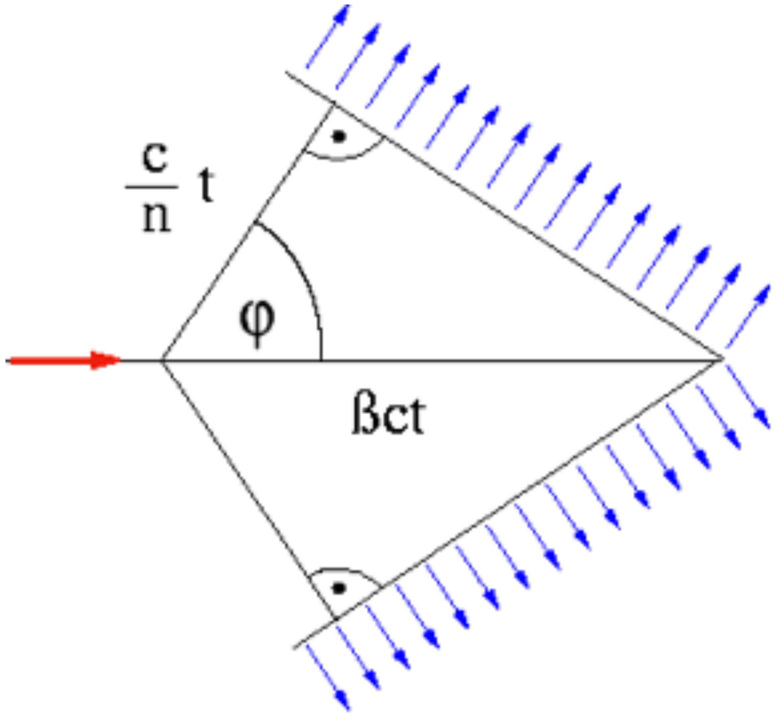
Cherenkov radiation - an aside

A duck in water…

- A charged particle moving fast enough to break the speed of light in a medium produces the equivalent of a sonic-boom in light (violet-blue wavelength) along the track the particle traverses.

- Observed, for example, in the cooling pools of nuclear reactors.





Cherekov radiation - an aside

- A charged particle moving fast enough to break the speed of light in a medium produces the equivalent of a sonic-boom in light (violet-blue wavelength) along the track the particle traverses.

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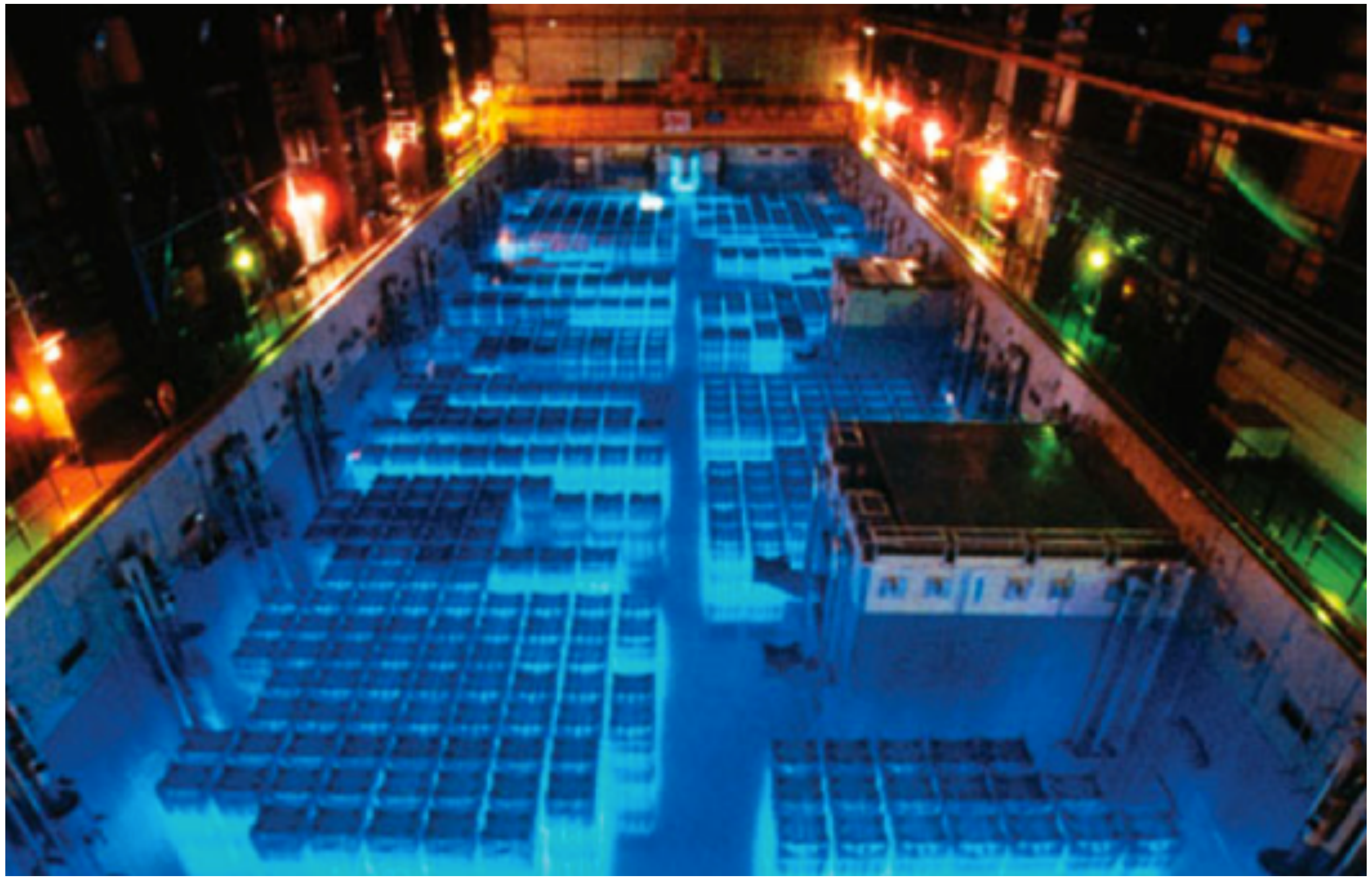
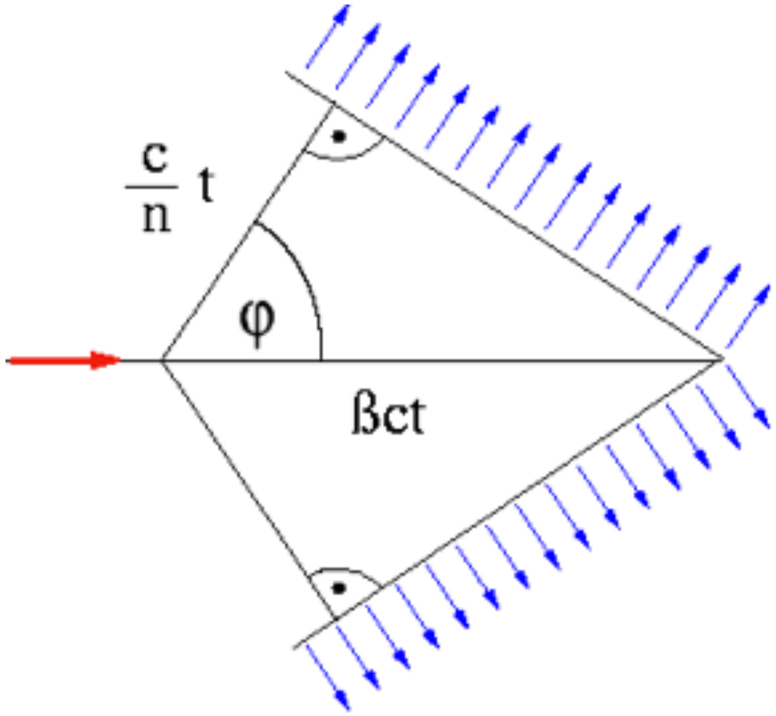
A supersonic "duck" in air…

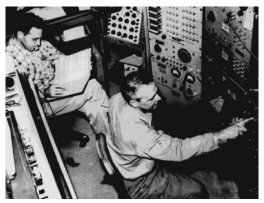




Neutrino detection: A new hope

1930s

1950s



1960s, 70s

1980s

present day

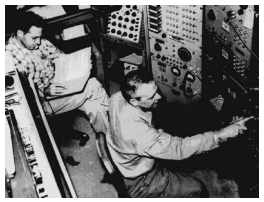
- In the 1980s a revolution in the neutrino field begins with the development of huge Cherenkov detectors.

image Lucasfilms Ltd.

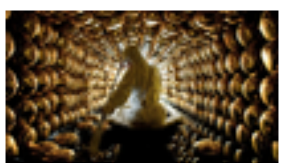
- The Kamiokande detector (8 kT ultra pure water originally designed to detect proton decay) measures the first neutrinos from outside the solar system from supernova 1987A.

Neutrino detection: rise of the machines

1930s  

1950s 

1960s, 70s 

1980s 

1990s & 2000s

present day

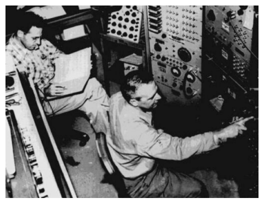
- In the 1990s things really got big…

image Warner Bros.

Neutrino detection: rise of the machines

1930s

1950s



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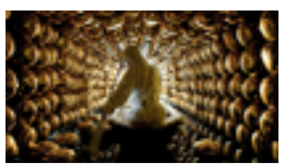
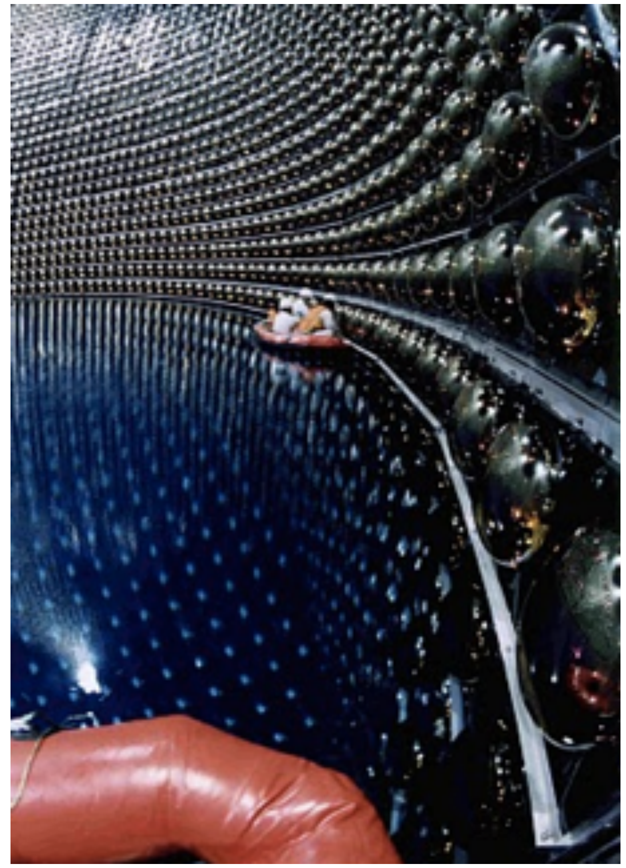
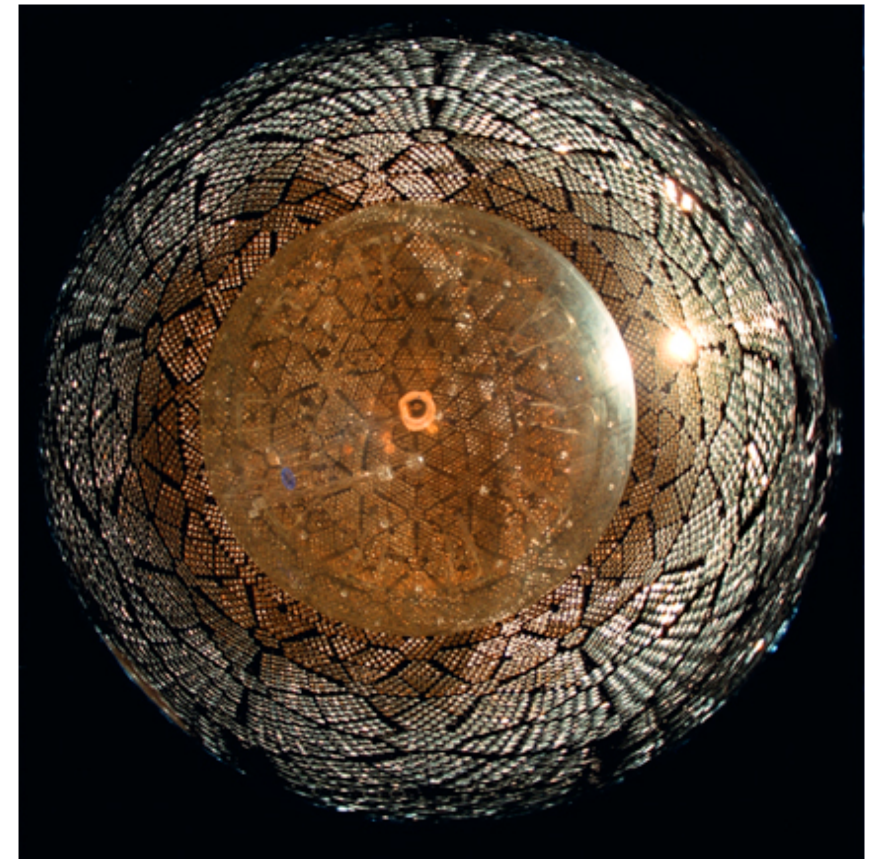


1990s & 2000s

present day



The Super Kamiokande Detector



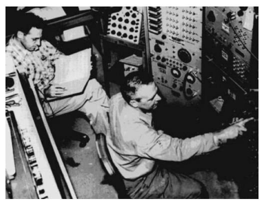
The Sudbury Neutrino Observatory

- Super-Kamiokande (50 kT ultra-pure water) detects first evidence for atmospheric neutrino oscillations implying neutrinos have non-zero mass (1998).

- The Sudbury Neutrino Observatory (1 kT heavy water) measures solar neutrino oscillations (2001) solving the 30+ year Solar Neutrino Problem.

Neutrinos in the modern day

1930s

1950s



1960s, 70s

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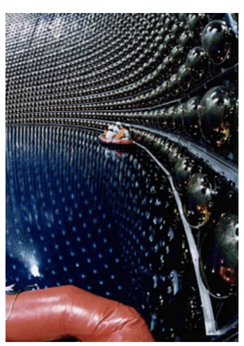
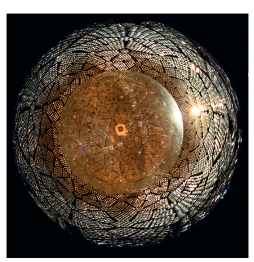
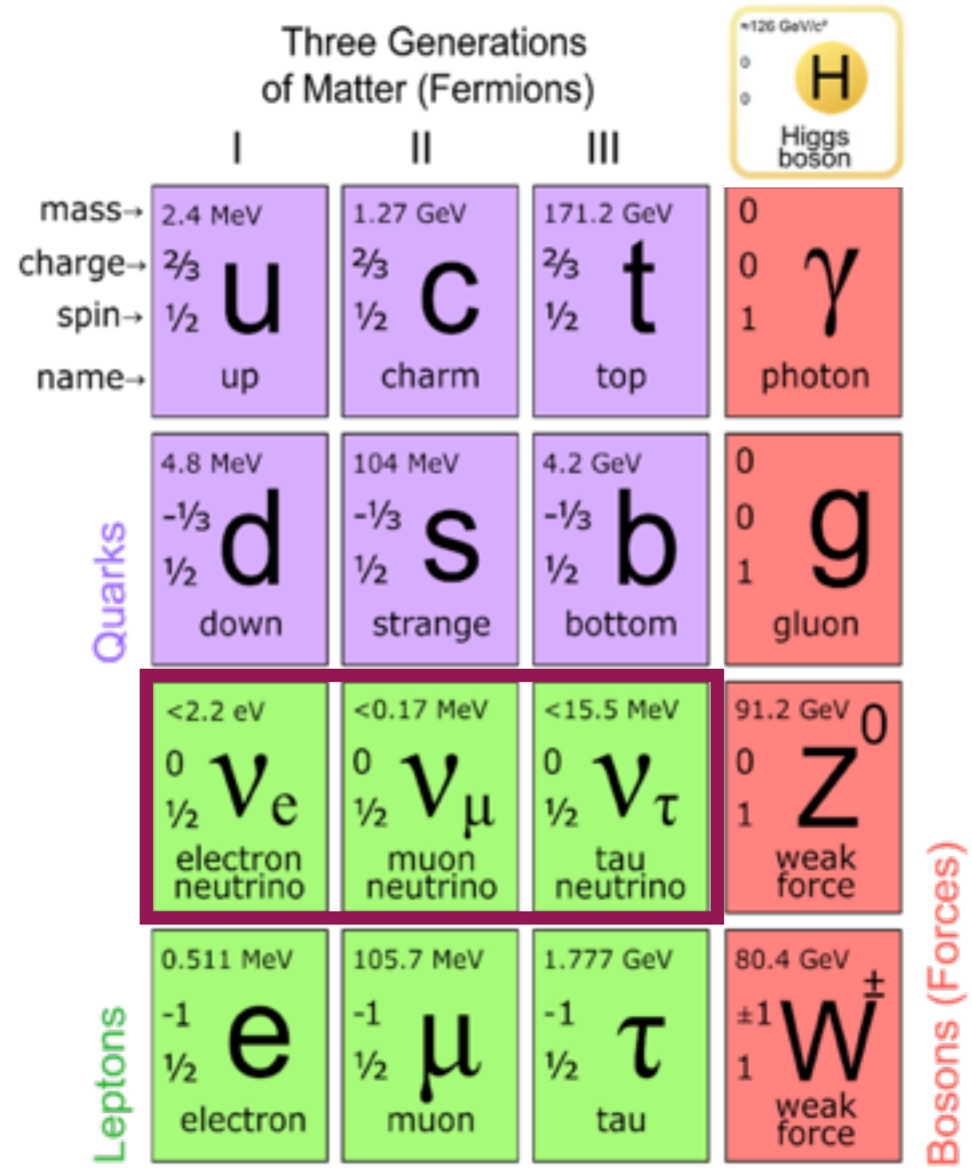
1990s & 2000s



present day

The Standard Model of Particle Physics

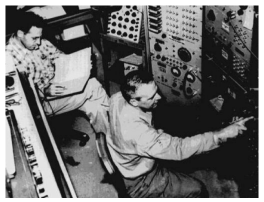


- are 2nd in abundance only to photons in number in the Universe
- have 3 active flavors which have also been produced and detected directly in accelerator experiments
- have learned they have mass and mostly how they mix…. but many of their properties remain a mystery.

Neutrinos in the modern day

1930s

1950s



1960s, 70s

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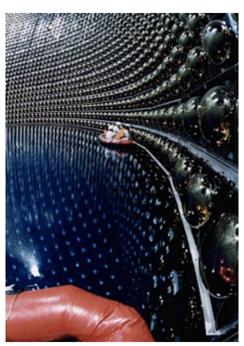
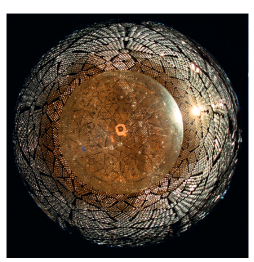
1990s & 2000s





present day

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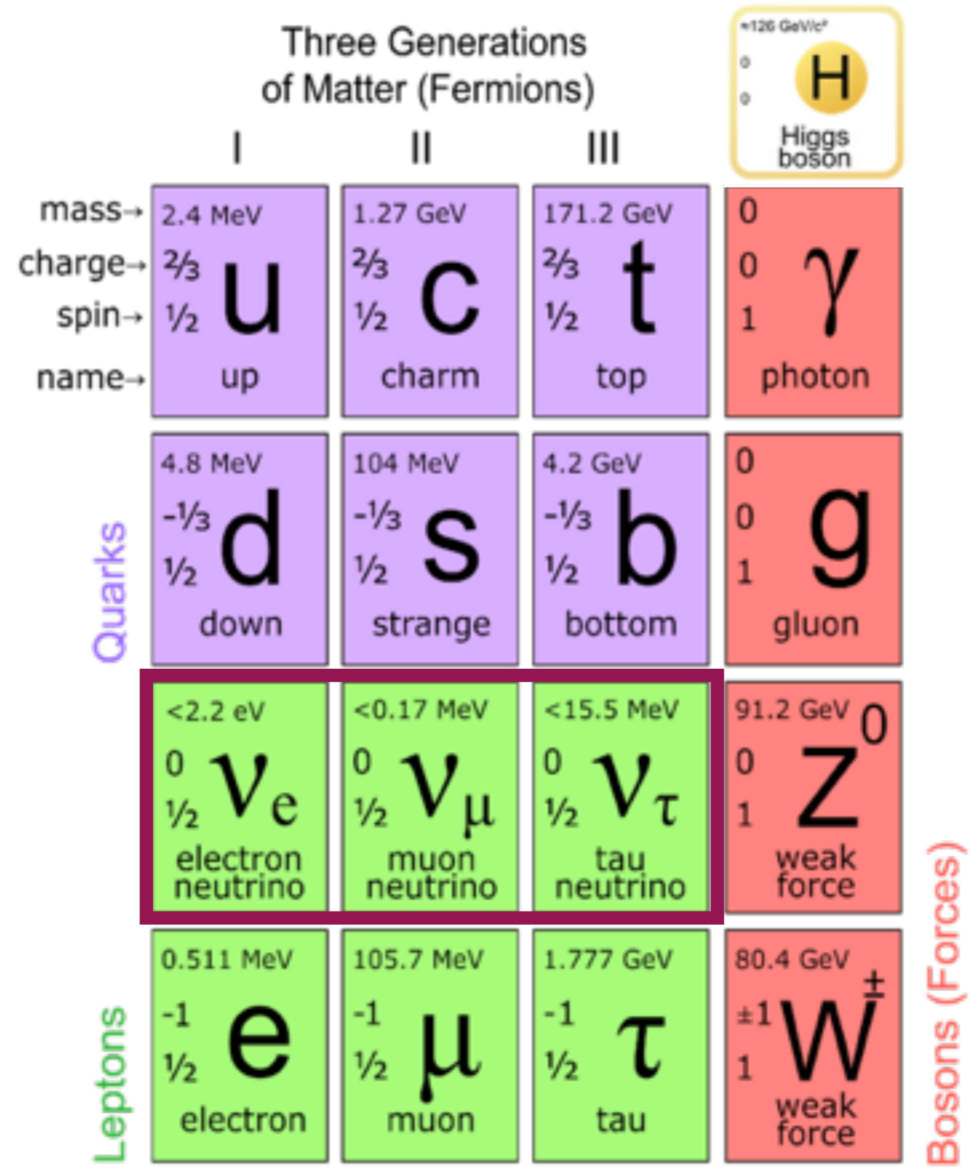
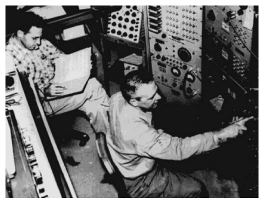
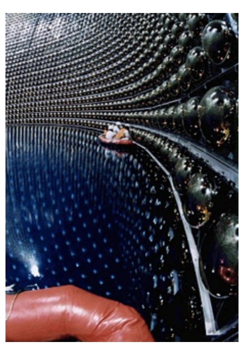
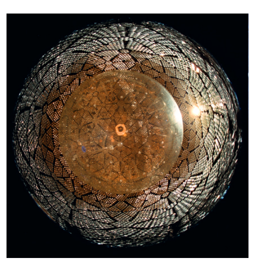
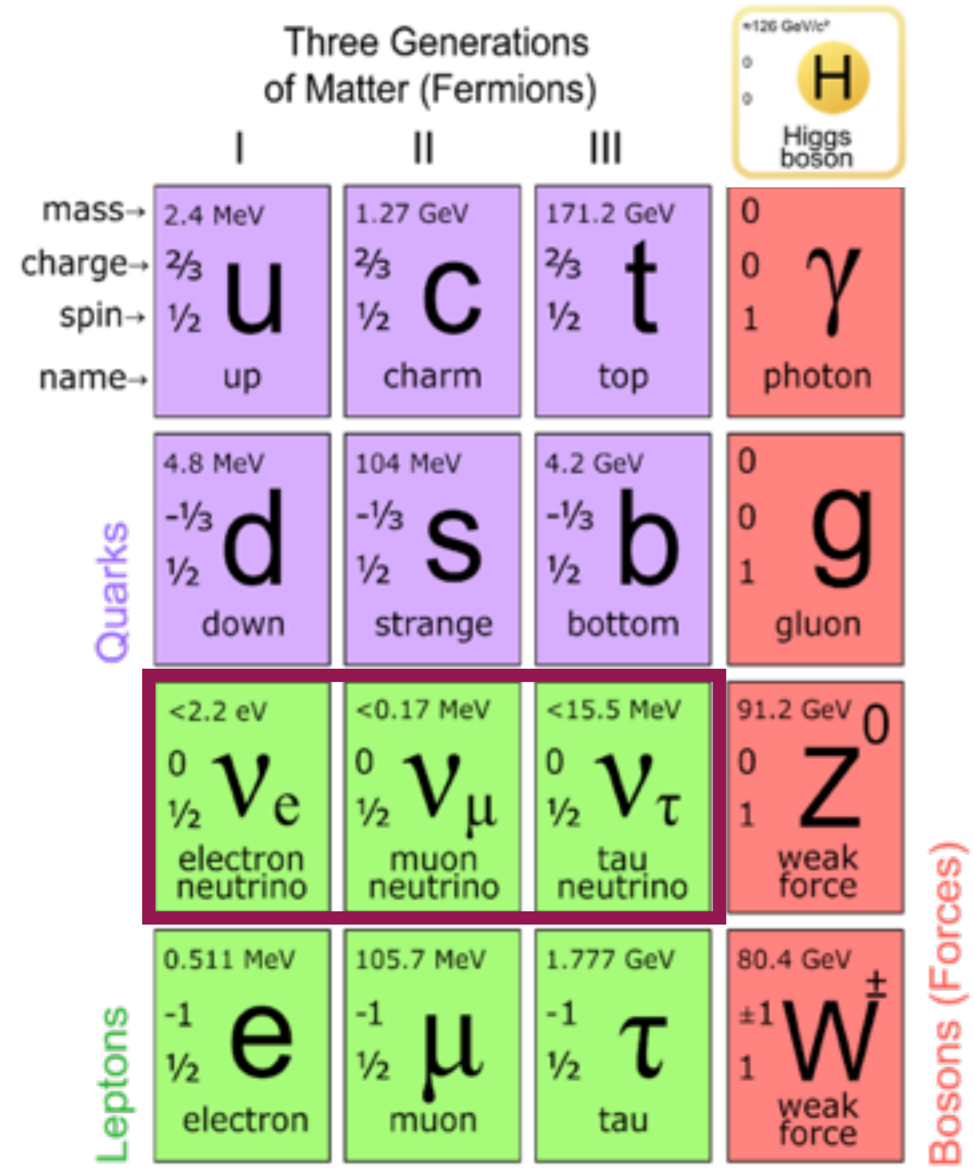


$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Neutrinos in the modern day

- 1930s  
- 1950s  
- 1960s, 70s  
- 1980s  
- 1990s & 2000s  
- present day

The Standard Model of Particle Physics



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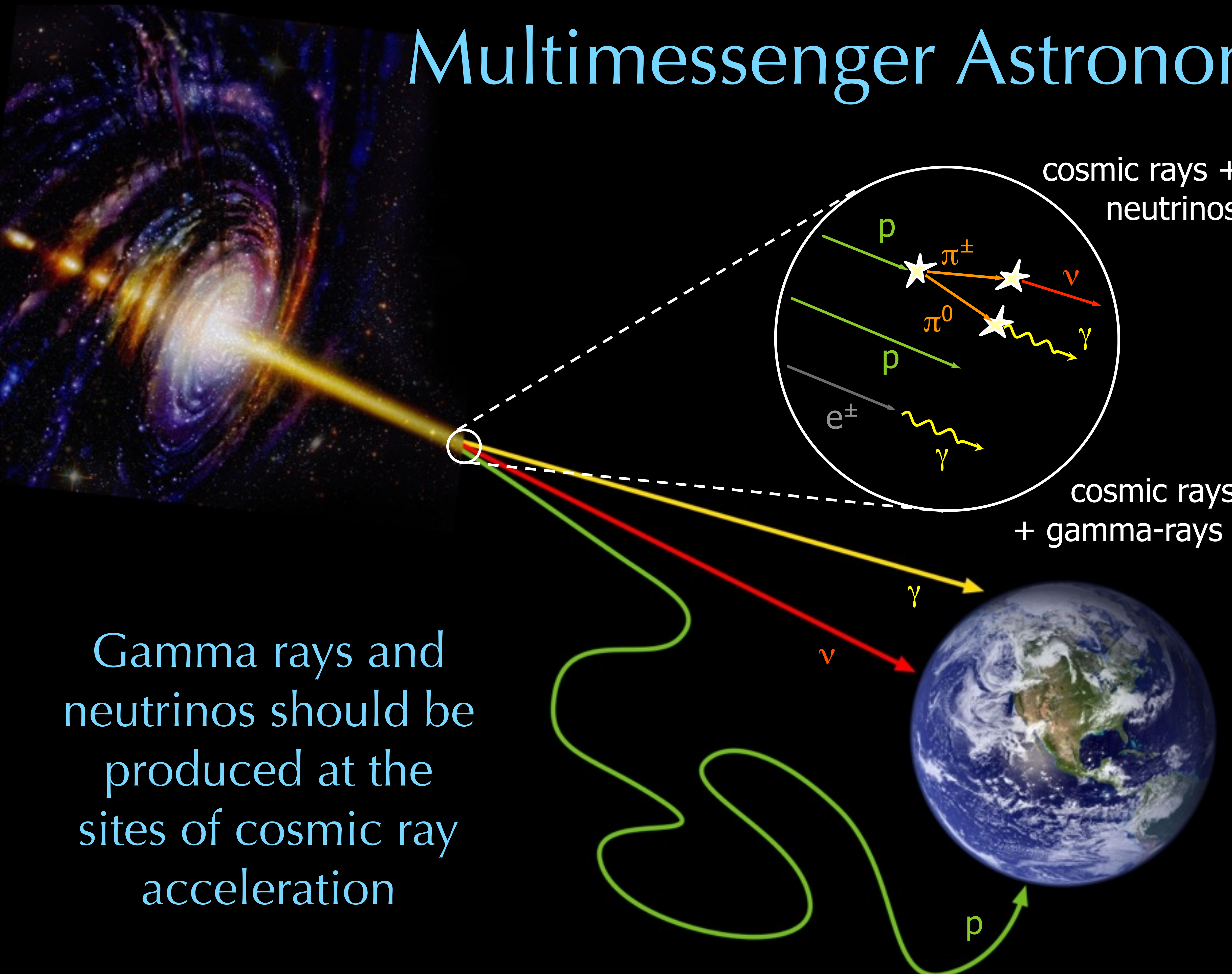
Multimessenger Astronomy



Gamma rays and neutrinos should be produced at the sites of cosmic ray acceleration

How can we make this work?

…we’re gonna need a bigger ~~boat~~ detector

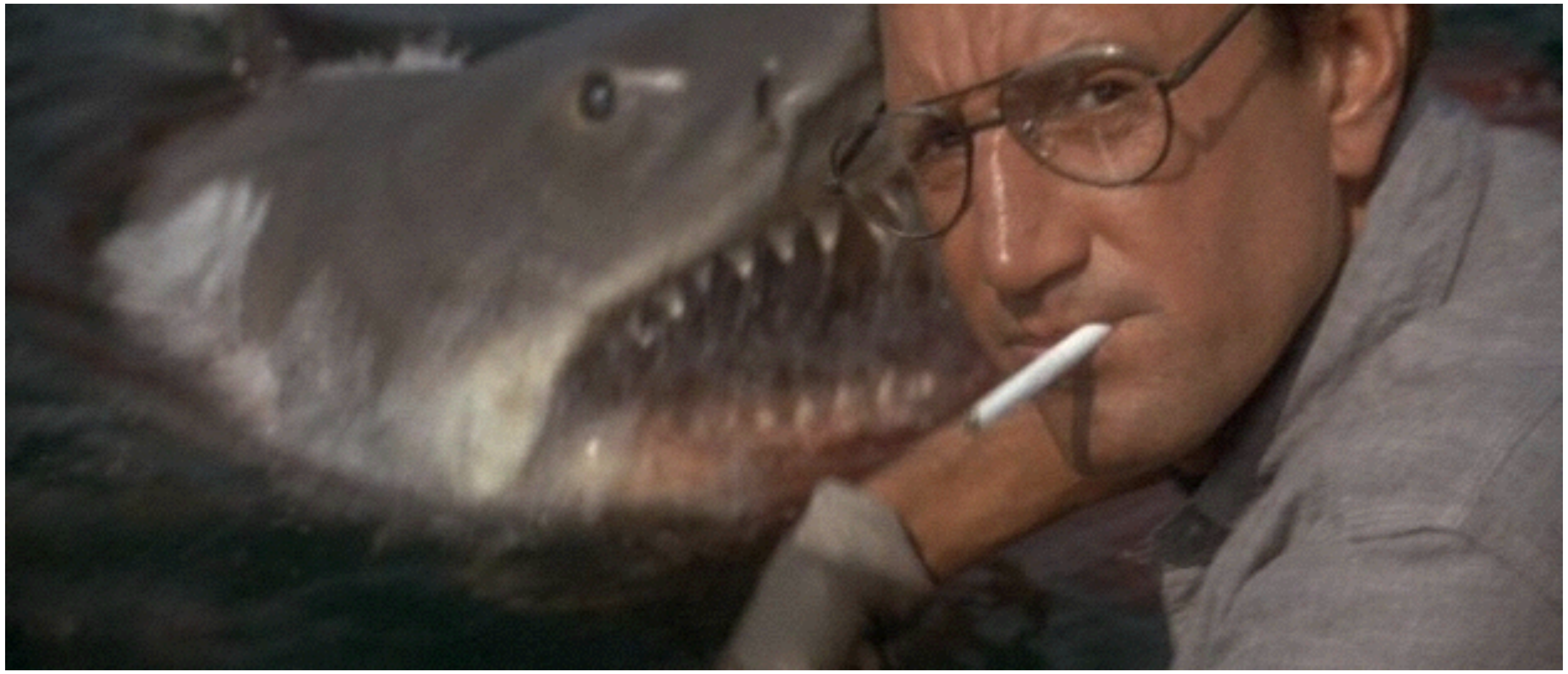


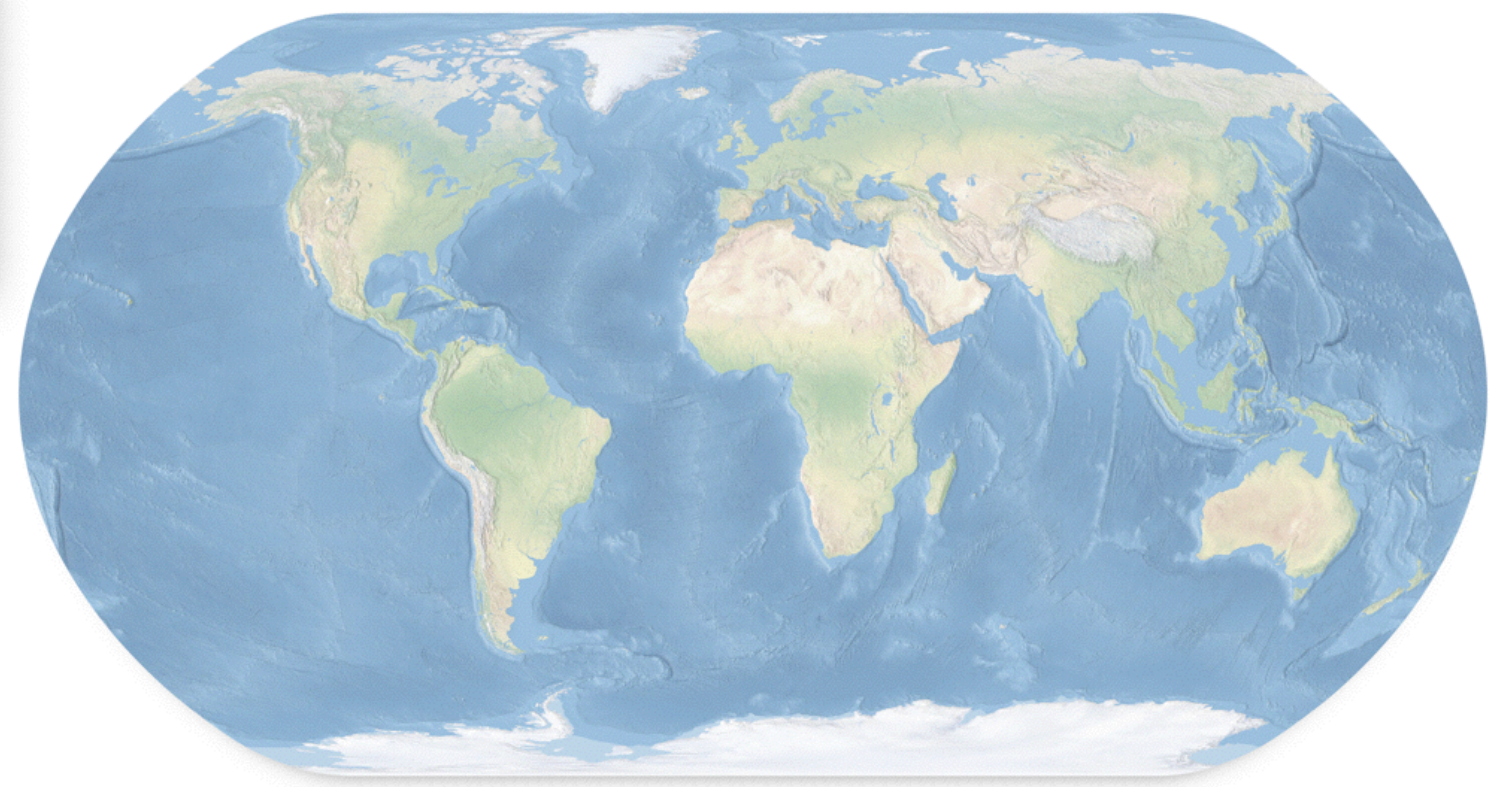
image Jaws; Universal Pictures

- the astrophysical neutrino events are expected to be millions of times higher in energy than those previously detected. We therefore need a huge volume (~1 km^3 or more) to measure the Cherenkov light from the full events

- the challenge in detecting these astrophysical neutrino events remains the same; reducing the backgrounds (cosmic rays) to extract the rare signal

Where in the world?

Very deep site
Stable and clean (low-background) environment
Readily Accessible and Scientifically Ready



Where in the world?

Very deep site
Stable and clean (low-background) environment
Readily Accessible and Scientifically Ready

Oh... and let's choose something warm and exotic so we want to visit...

Where in the world?

Very deep site
Stable and clean (low-background) environment
~~Readily Accessible~~ and Scientifically Ready

~~Oh… and let's choose something warm and exotic so we want to visit…~~

Where in the world?

coastal Antarctica....
sunny
exotic
warm

Where in the world?

coastal Antarctica....

sunny ✔

exotic

warm

Where in the world?

coastal Antarctica....

sunny ✔

exotic ✔

warm

Where in the world?

coastal Antarctica....

sunny ✔

exotic ✔

warm... relatively (think about where we are planning to head next) ✔

Welcome…

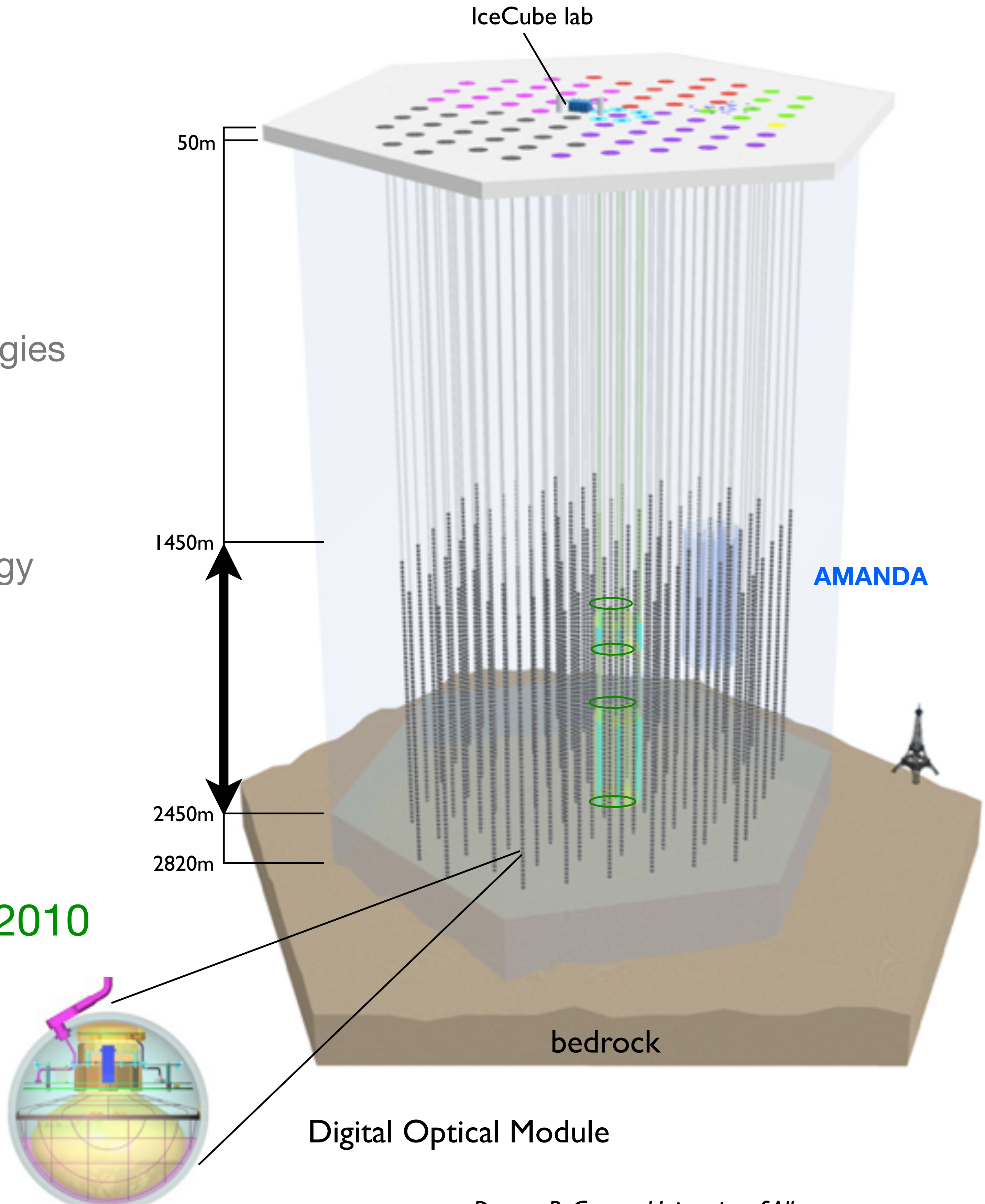
to South Pole Station Antarctica!

University of Alberta Graduate Student Tania Wood
“Summer” 2014

The IceCube Neutrino Observatory

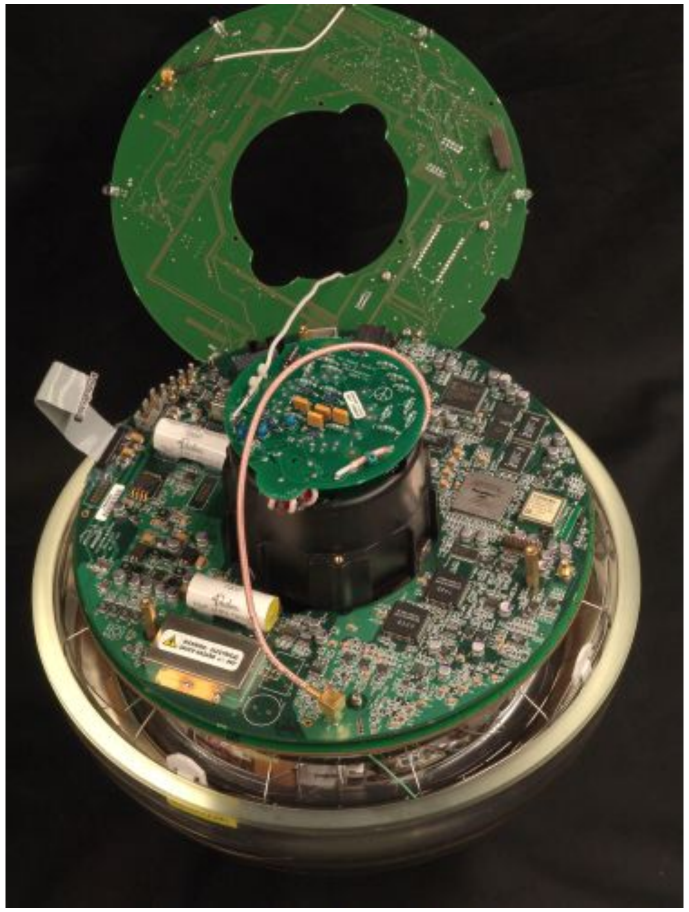
- Very large scale "hybrid" observatory
  - ~$272M to construct (NSF, Sweden, Germany, Belgium)
- IceCube:
  - ~1 cubic-km instrumented volume
  - Designed to detect neutrinos with energies between 200 GeV and 10 EeV.
- DeepCore extension:
  - 8 new strings ~$4M addition.
  - Dense instrumentation lowers the energy threshold to 10 GeV
  - (my pride and joy)
- IceTop:
  - Surface air shower detector array.
  - Threshold approx. 300 TeV

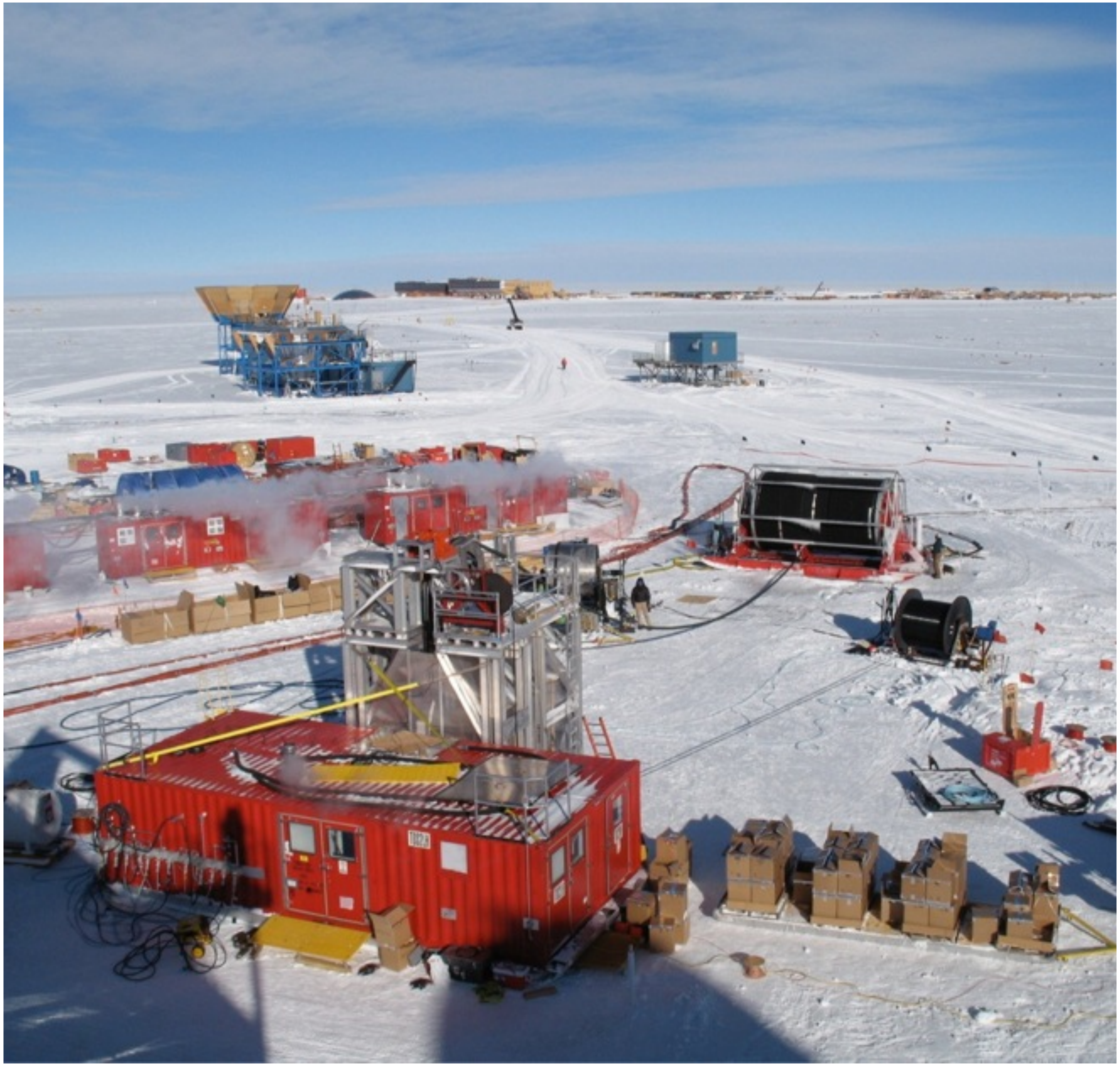
Completed December 18, 2010

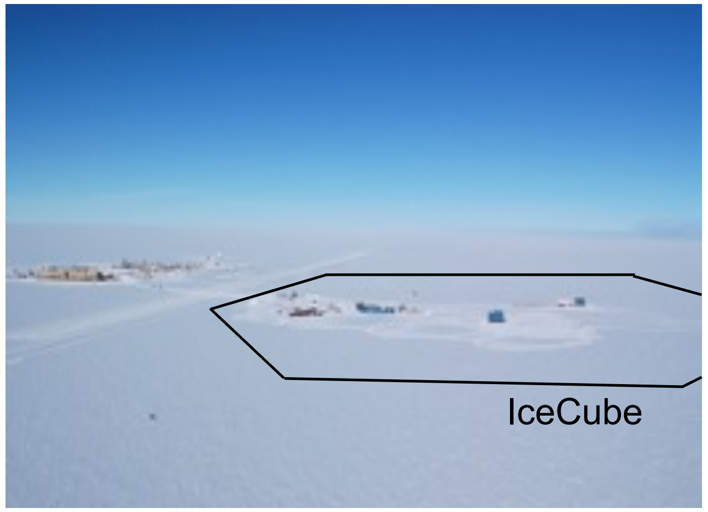


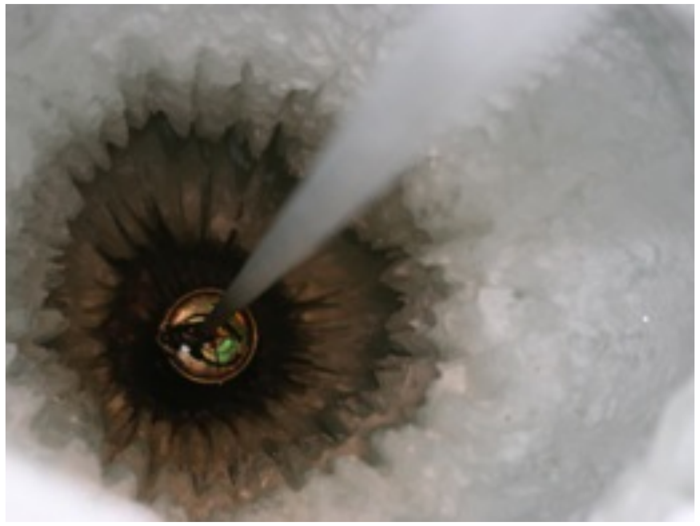
The Digital Optical Module (DOM)

- Digital Optical Module
  - Ultra-sensitive light sensors (photomultiplier tubes) with complete on-board high voltage and data acquisition.
  - Complete signal digitization within the ice.

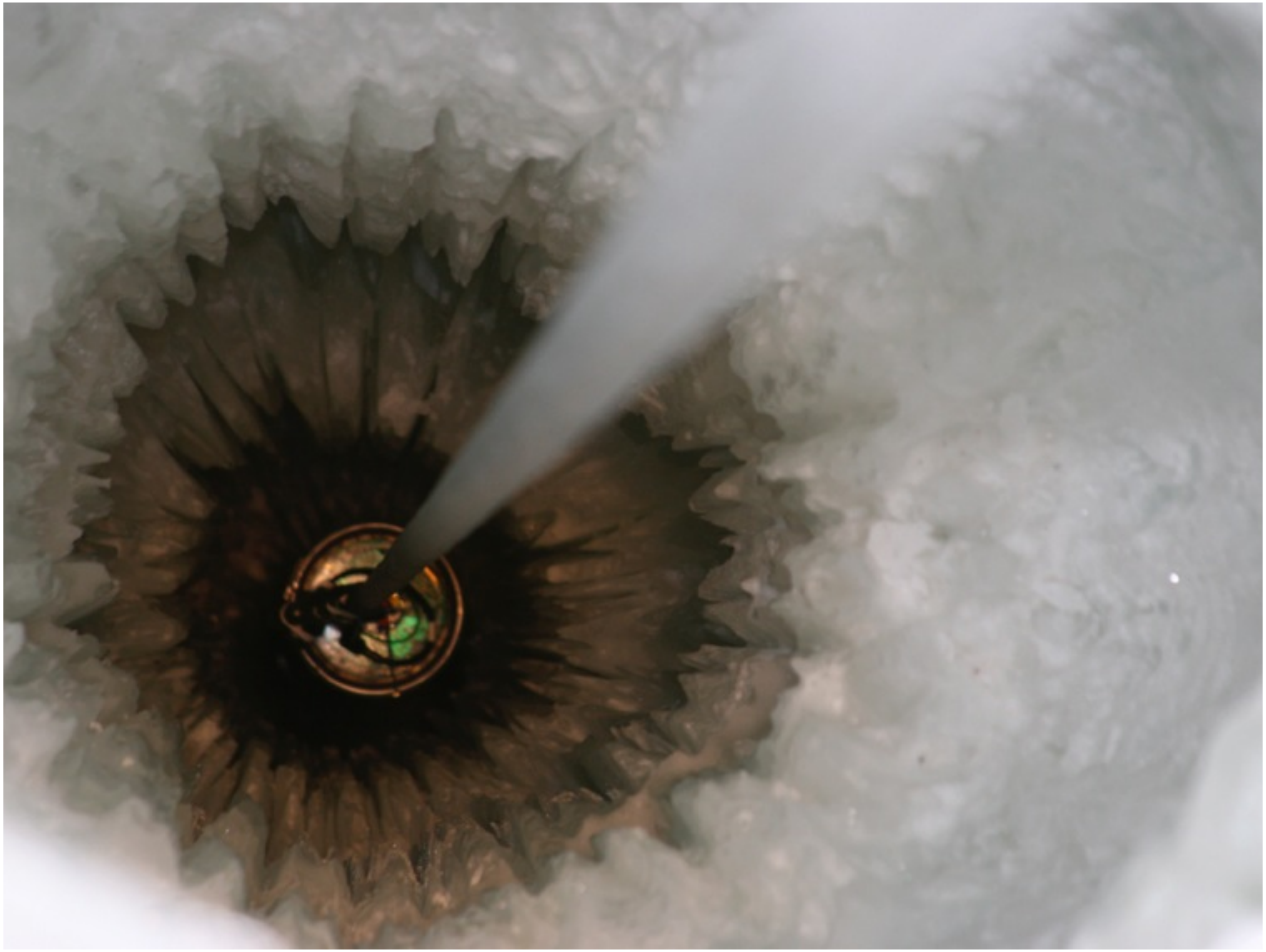






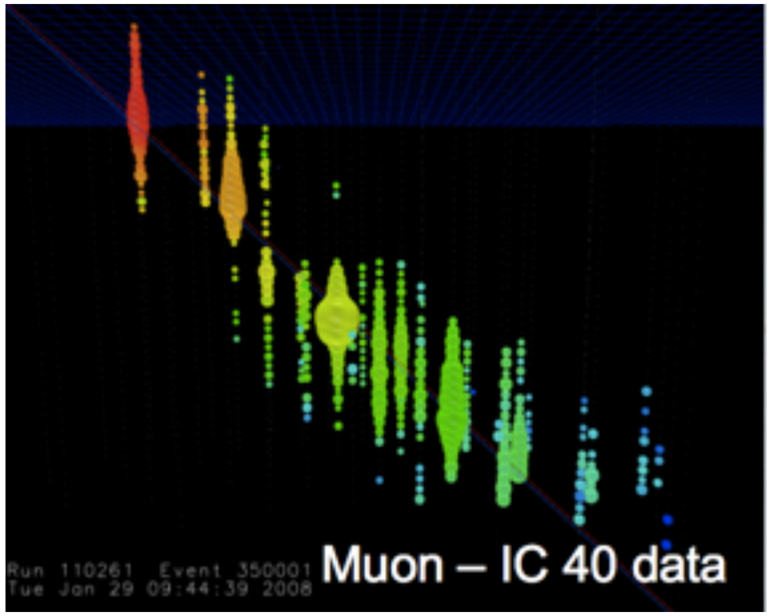


Amundsen-Scott South Pole Station, Antarctica



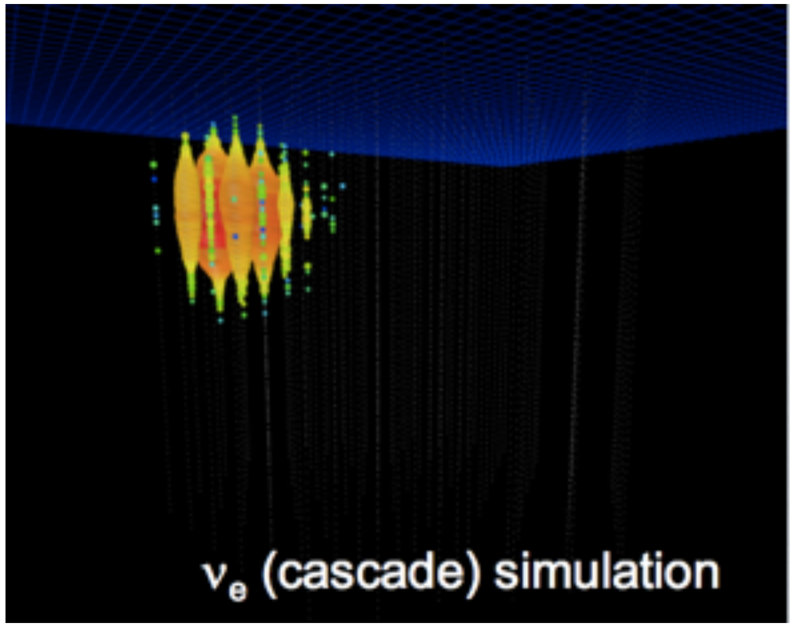
Darren R. Grant - University of Alberta

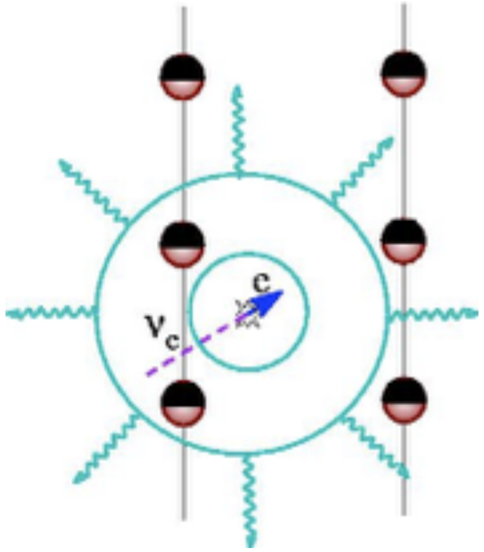
Neutrino Telescopes - Principle of Detection

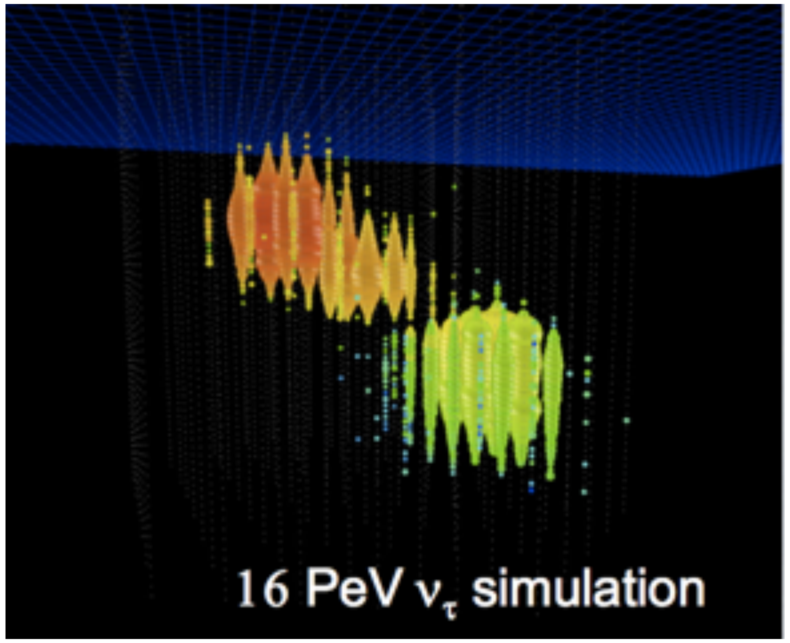


Tracks:
- through-going muons
- pointing resolution ~1°

Cascades:
- Neutral current for all flavors
- Charged current for ν_e and low-E ν_τ
- Energy resolution ~10% in log(E)

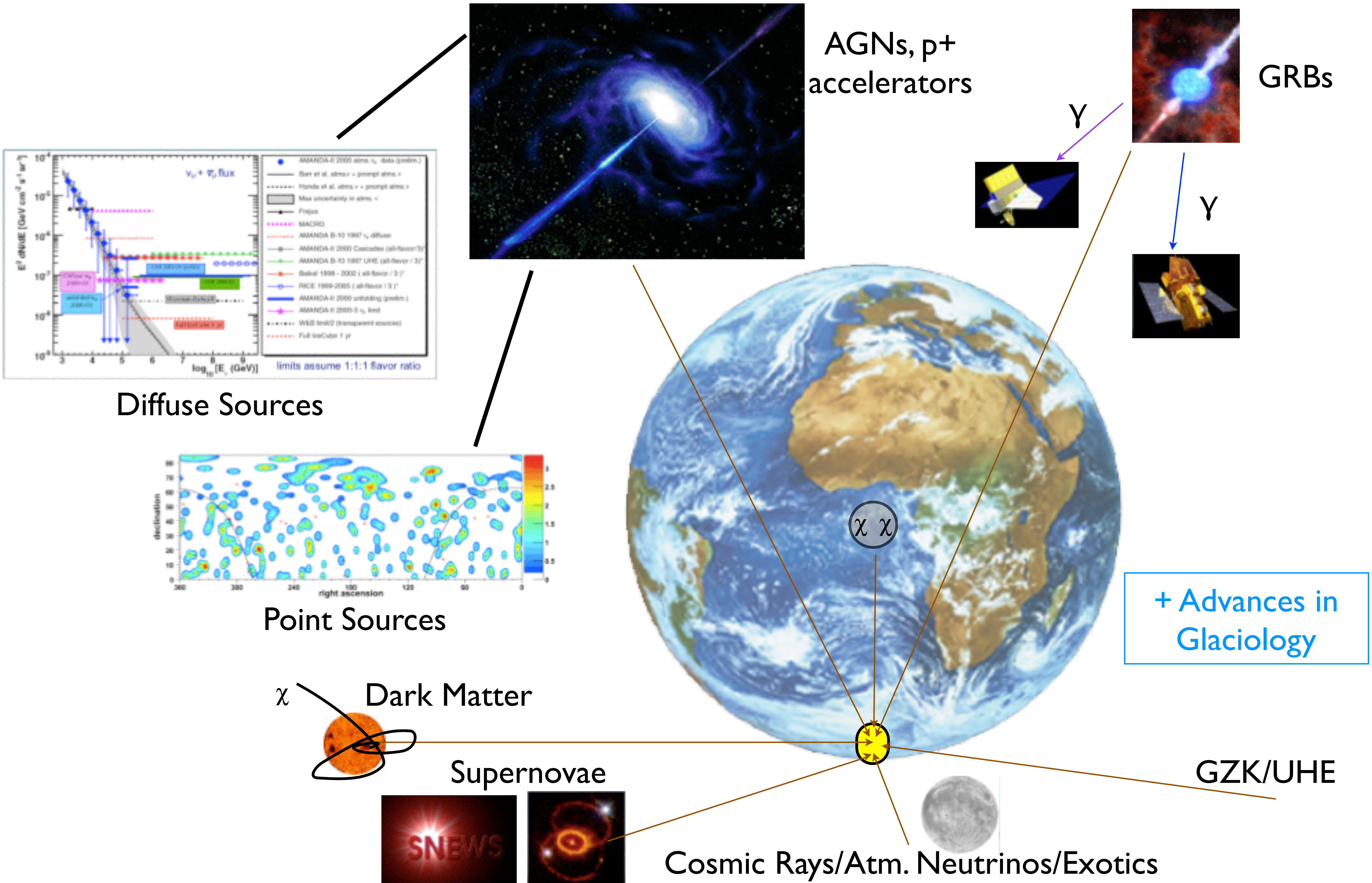






Composites:
- Starting tracks
- high-E ν_τ (Double Bangs)
- Good directional and energy resolution

The IceCube Neutrino Observatory - A Wealth of Science...



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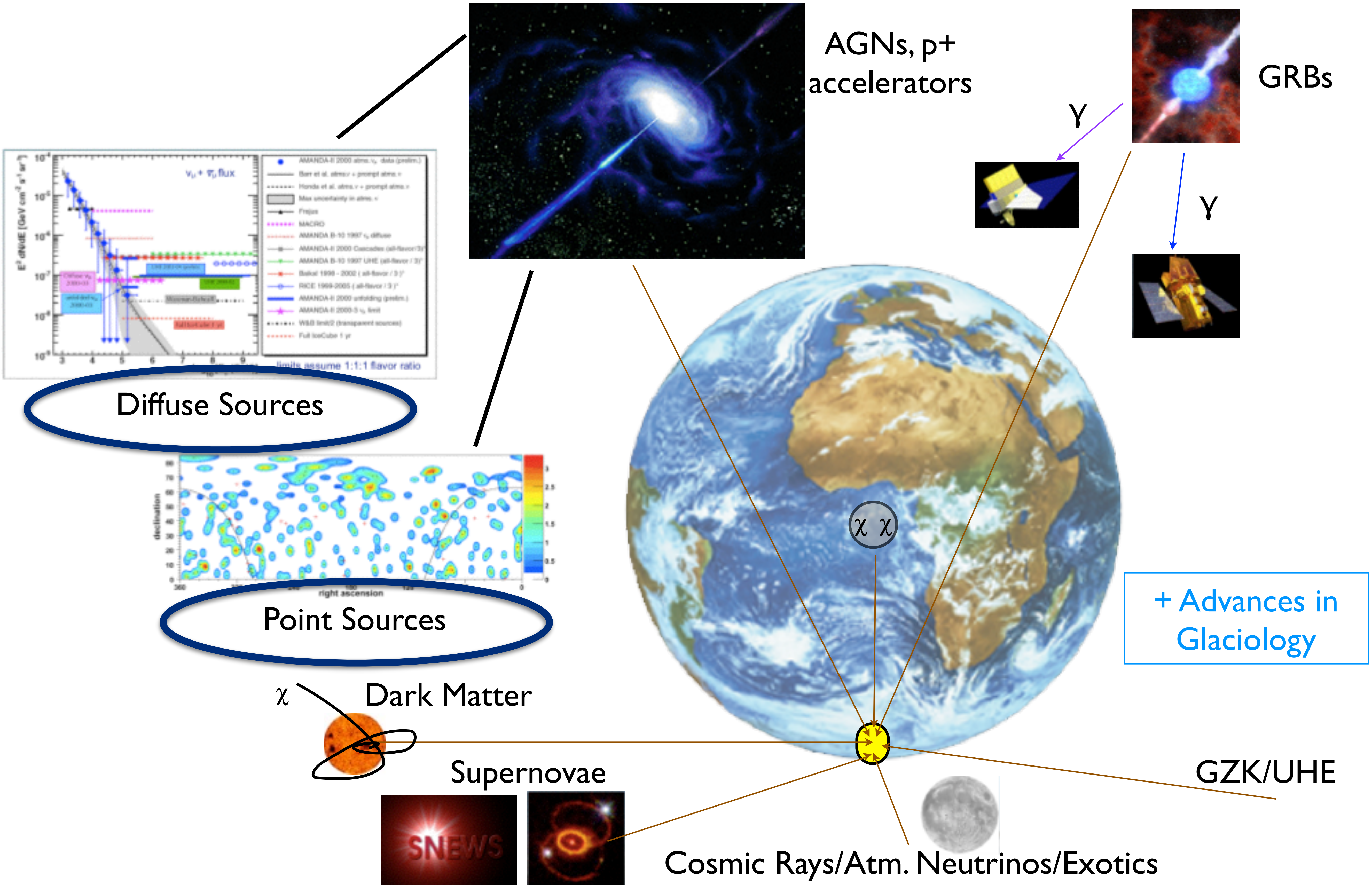
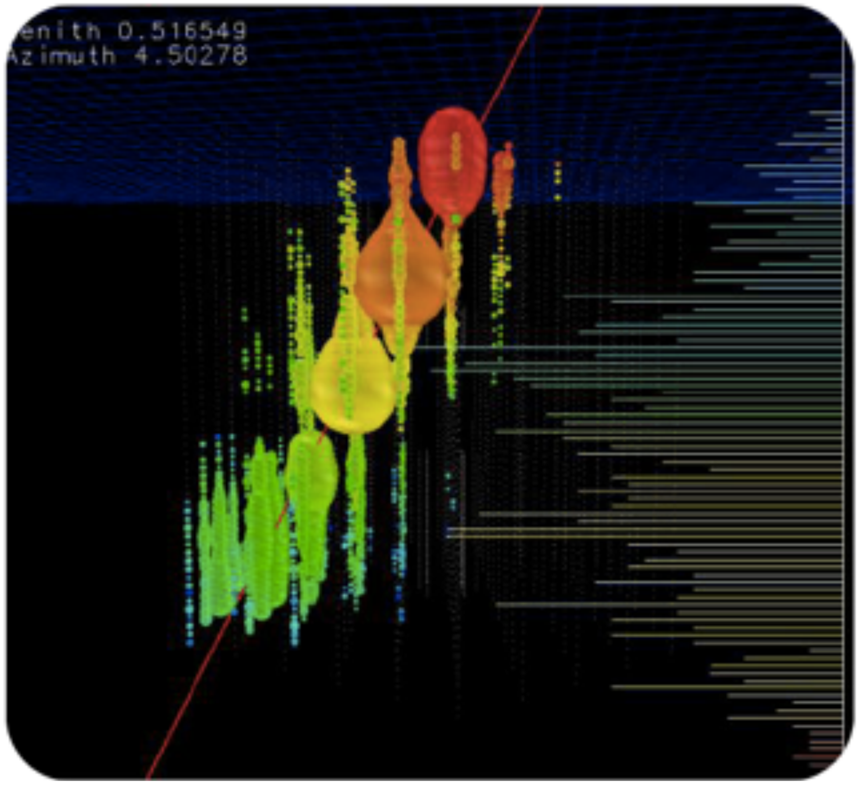
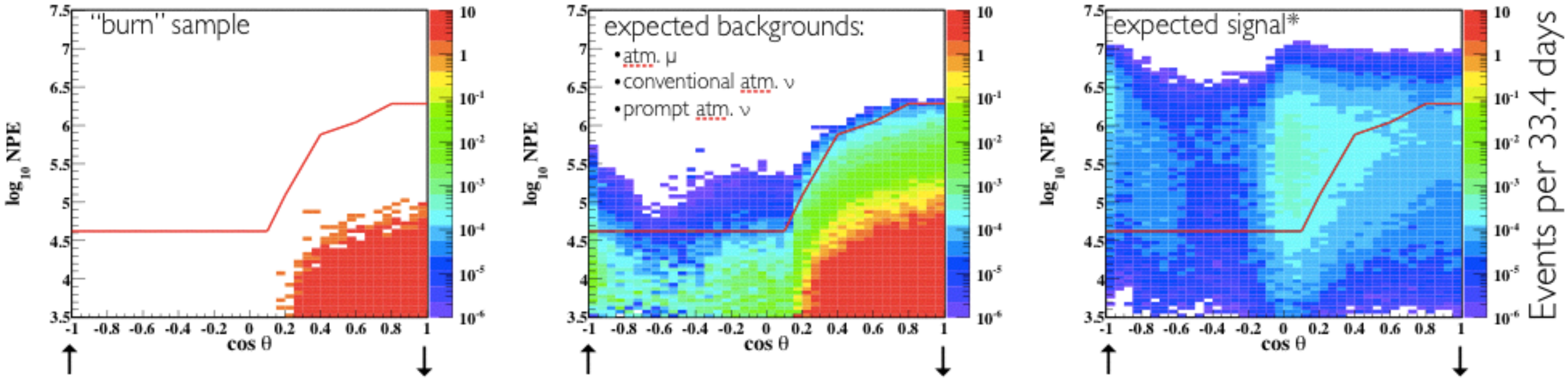


The IceCube ultra high energy neutrino search

- 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

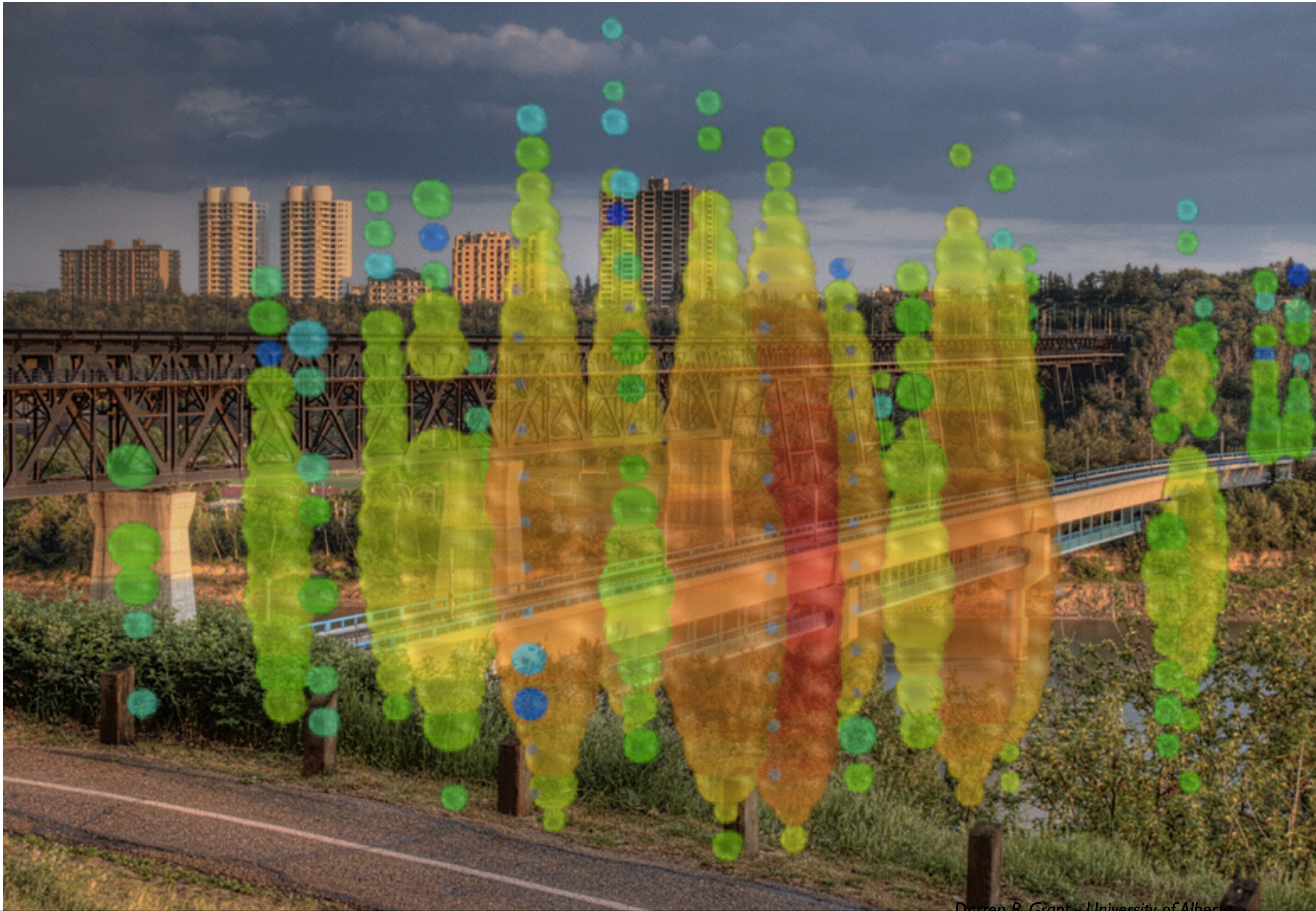




http://arxiv.org/abs/1304.5356 (accepted PRL)

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

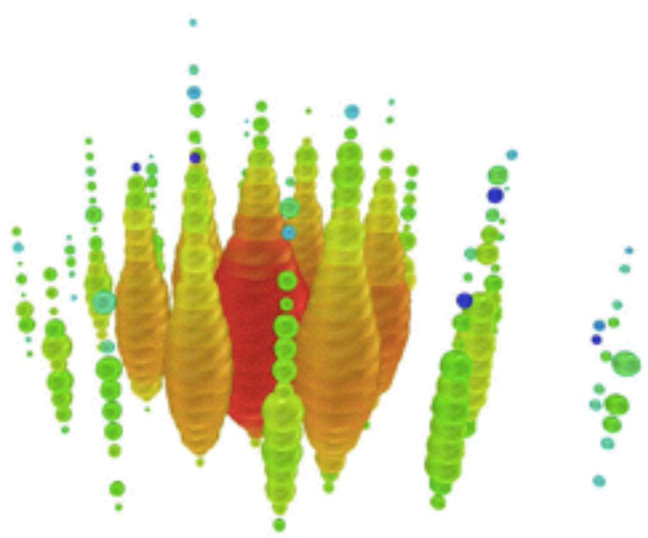
A PeV neutrino visits the High Level Bridge...



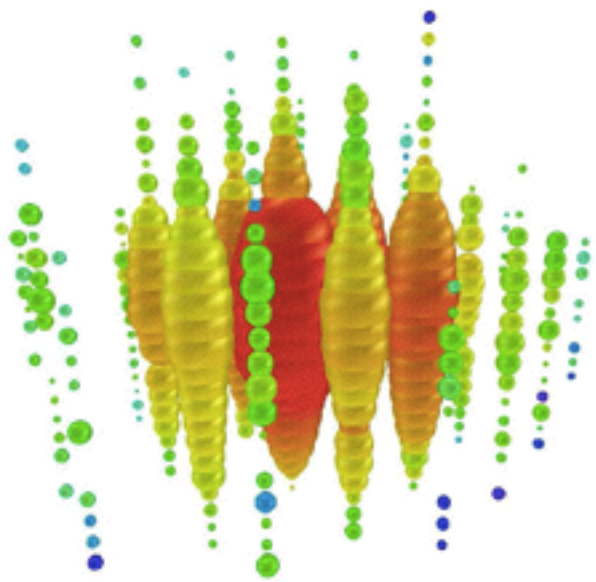
The IceCube ultra high energy neutrino search

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

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



1.04±0.16 PeV

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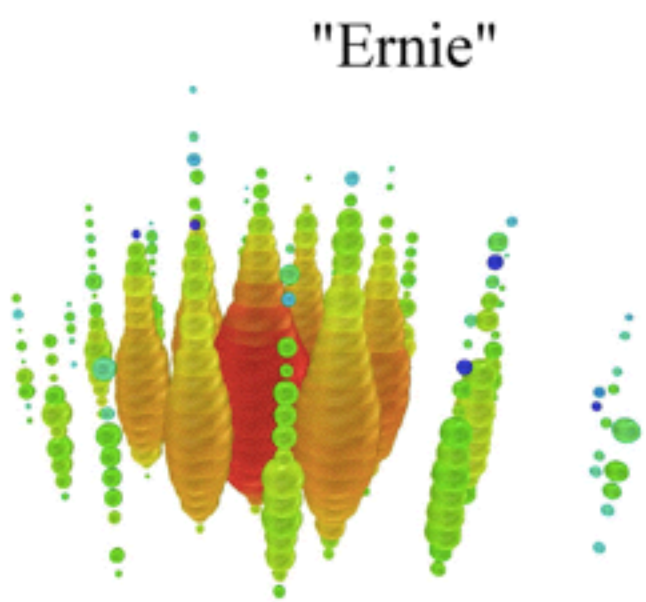
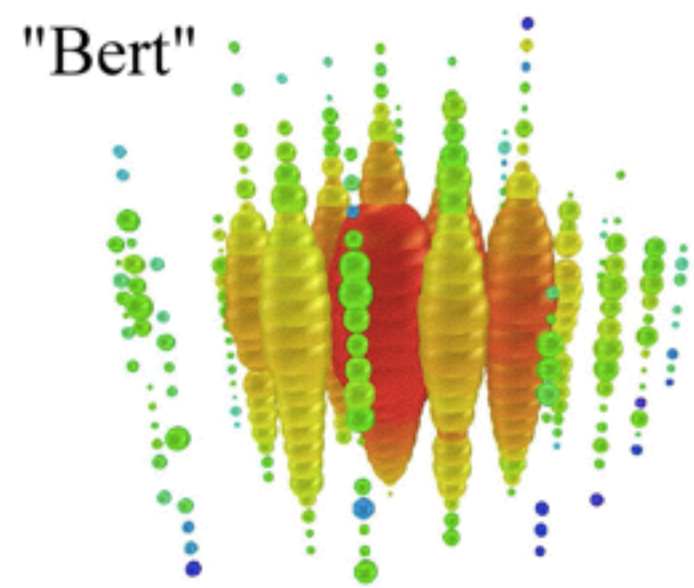


1.14±0.17 PeV

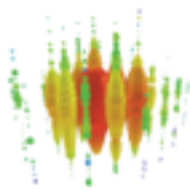
©2013 Sesame Workshop



1.04±0.16 PeV

“Bert” becomes a cover model...

NEWSPAPER



Observation of a high-energy particle shower event from August 2011, identified as a PeV-energy neutrino. Each sphere represents a digital optical module sensor in the IceCube detector. Sphere size is a measure of the recorded number of photoelectrons. Colors represent arrival times of photons (red, early; blue, late). Selected for a Synopsis in *Physics* and an Editors' Suggestion. [M. G. Aartsen *et al.*, IceCube Collaboration, Phys. Rev. Lett. 111, 021103 (2013)]

PHYSICAL REVIEW LETTERS™

Contents

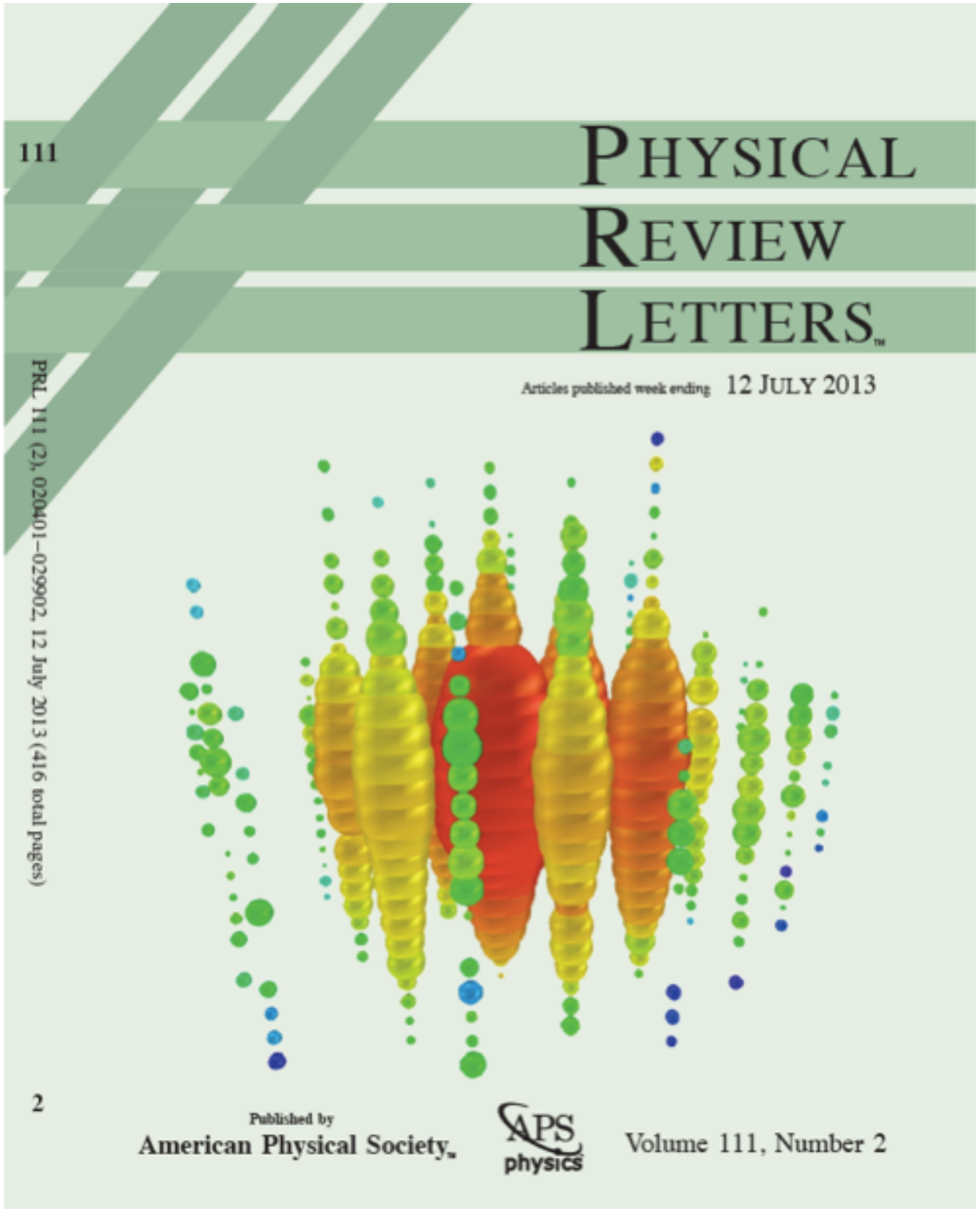
Articles published 6 July–12 July 2013

VOLUME 111, NUMBER 2 12 July 2013

(Continued Inside)

Selected for a Viewpoint in *Physics*. Please visit http://physics.aps.org/.
By suggesting a few manuscripts each week, we hope to promote reading across fields. Please see our Announcement Phys. Rev. Lett. 98, 010001 (2007).

0031-9007(20130712)111:2;1-2



The next logical step...

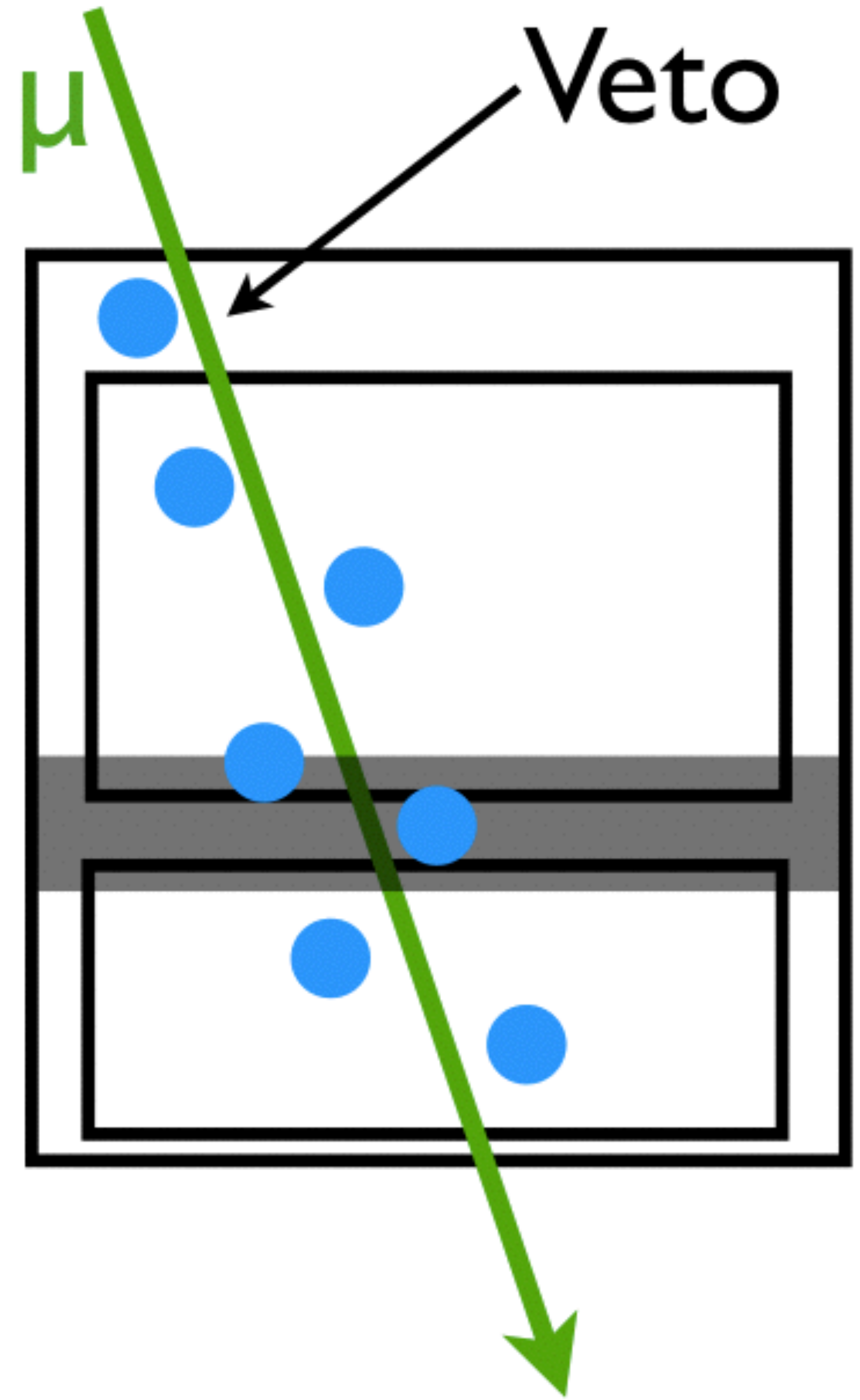
- Extend the search to lower energies for the same 2 year dataset
  - the two observed were at the search lower acceptance window, and higher energies showed no events
  - previous IceCube analyses had hints for astrophysical neutrino events above 100 TeV at approximately 2σ
- Challenges with this approach:
  - 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 ($\lambda_{abs.} \sim d_{Earth}$ at $E_{\nu} \sim 100$ 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)



The IceCube high energy “starting events” analysis

The result of the search...

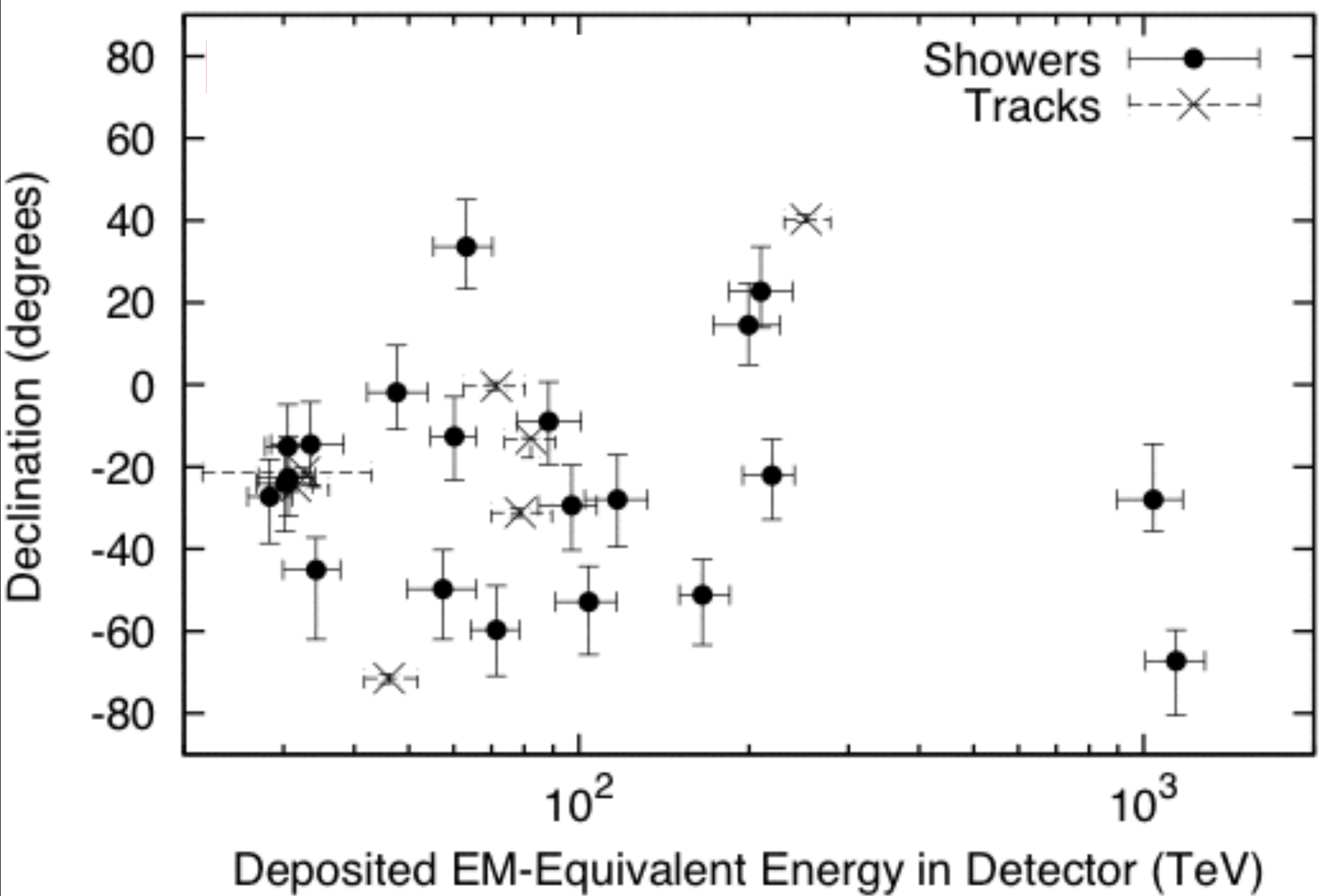
The IceCube high energy starting events analysis

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

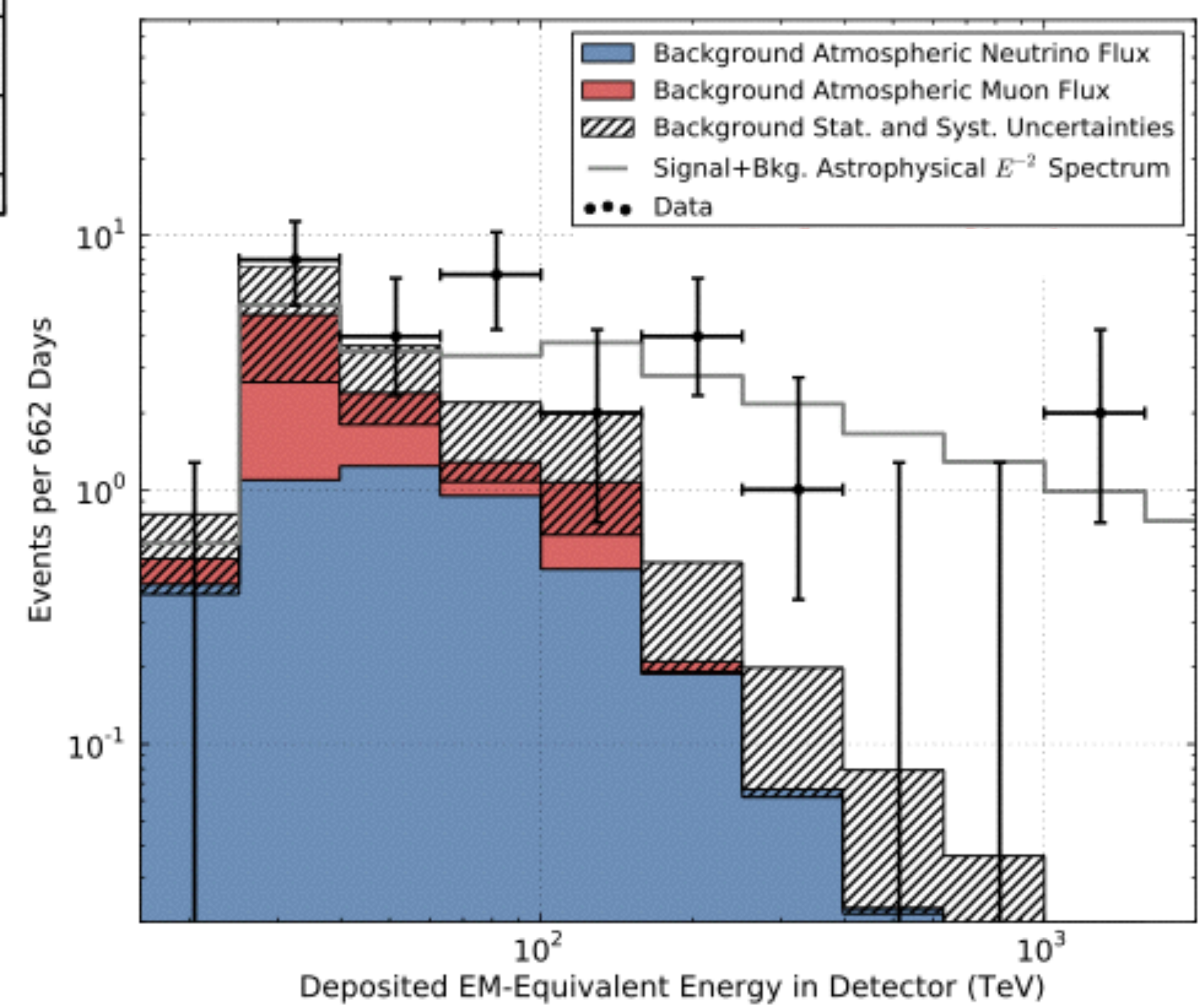
>4.3σ in excess of expected terrestrial background signal

Darren R. Grant - University of Alberta

The IceCube high energy starting events analysis

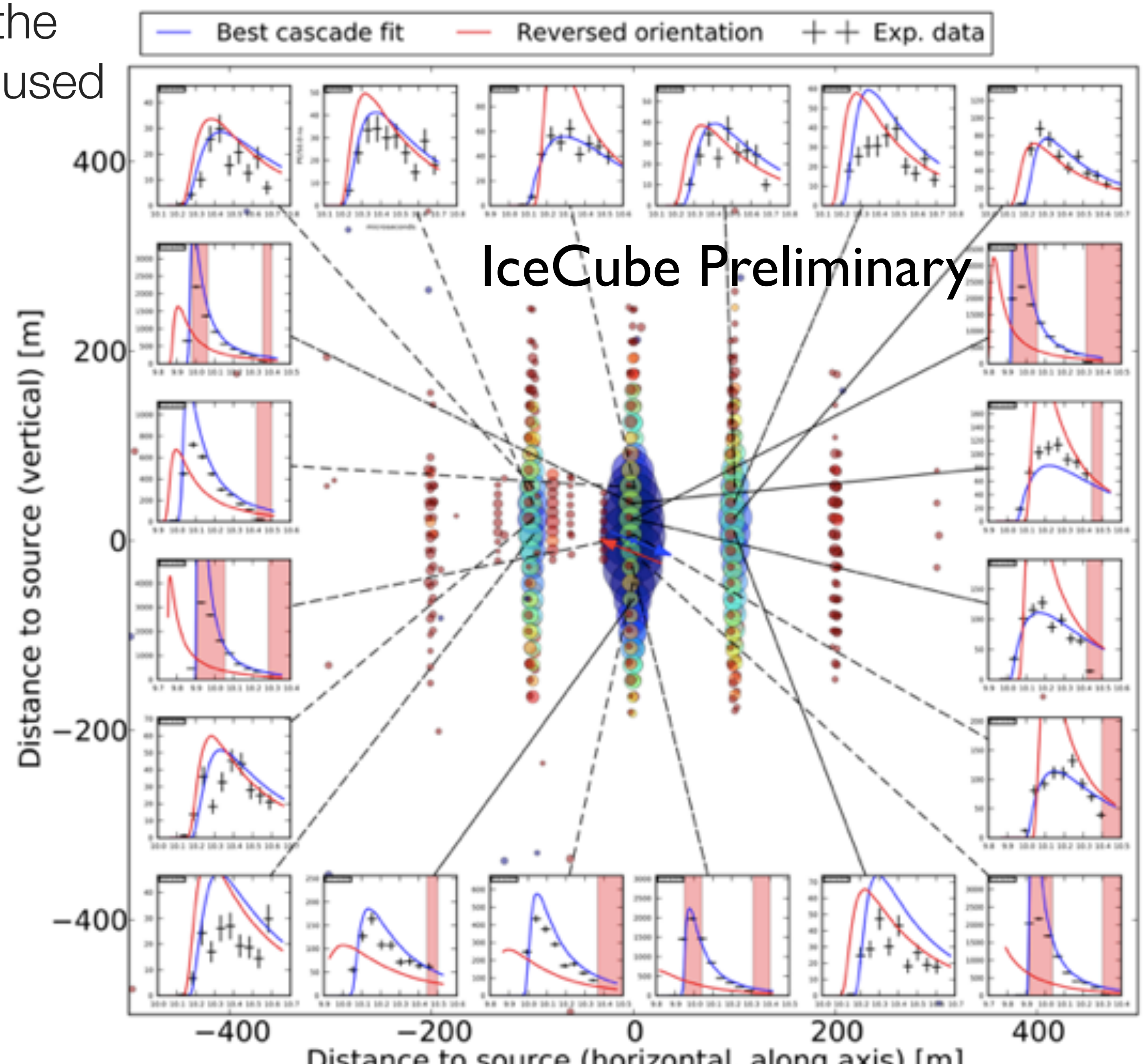


Note:
a) "EM-equivalent energy" underestimates the E of ν_x NC and ν_τ CC interactions
b) Energy gap is not statistically significant
c) For showers σ(E)~10% & σ(ϕ)~10°-15°

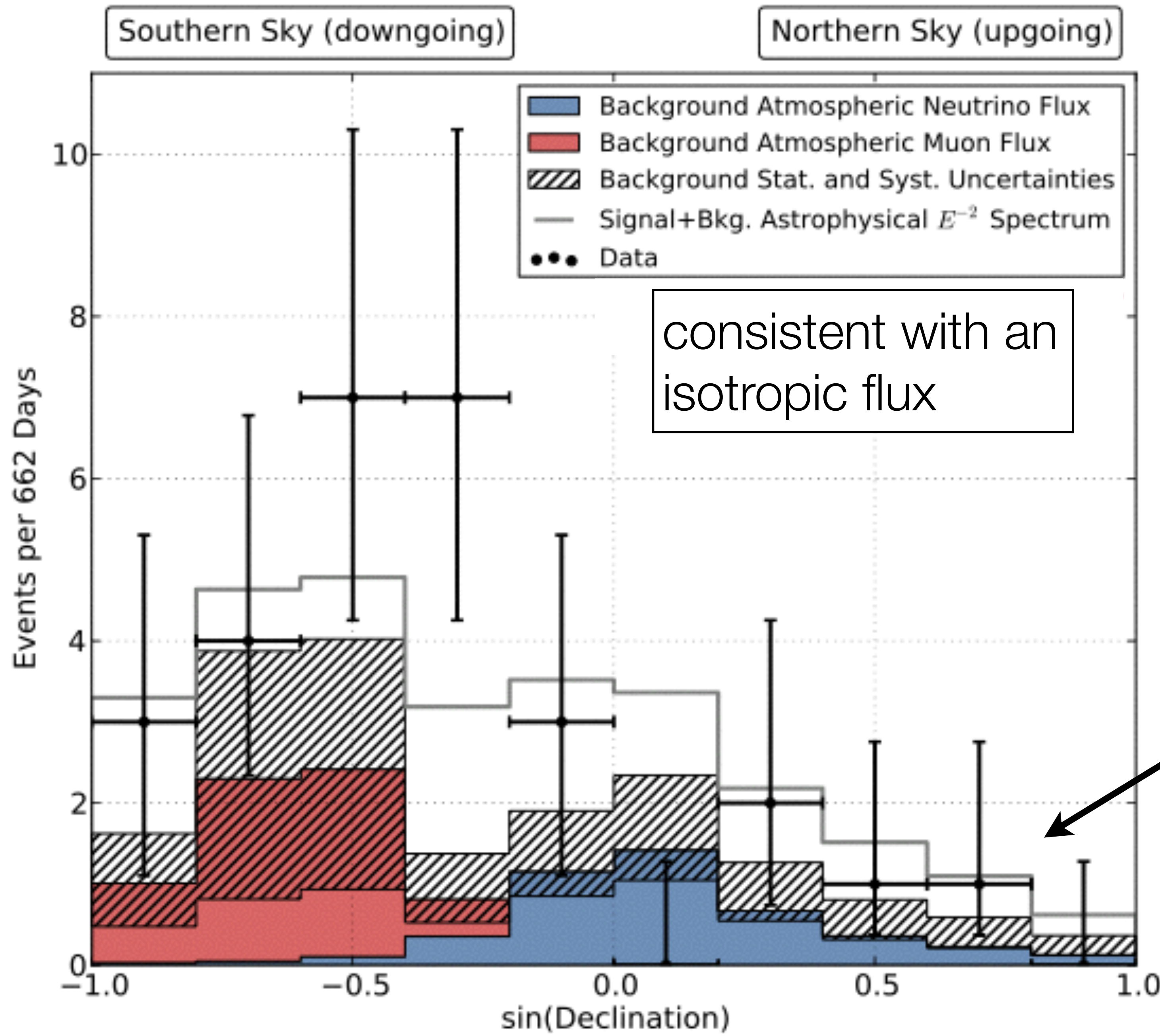


The IceCube high energy starting events analysis

- 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)



The IceCube high energy starting events analysis

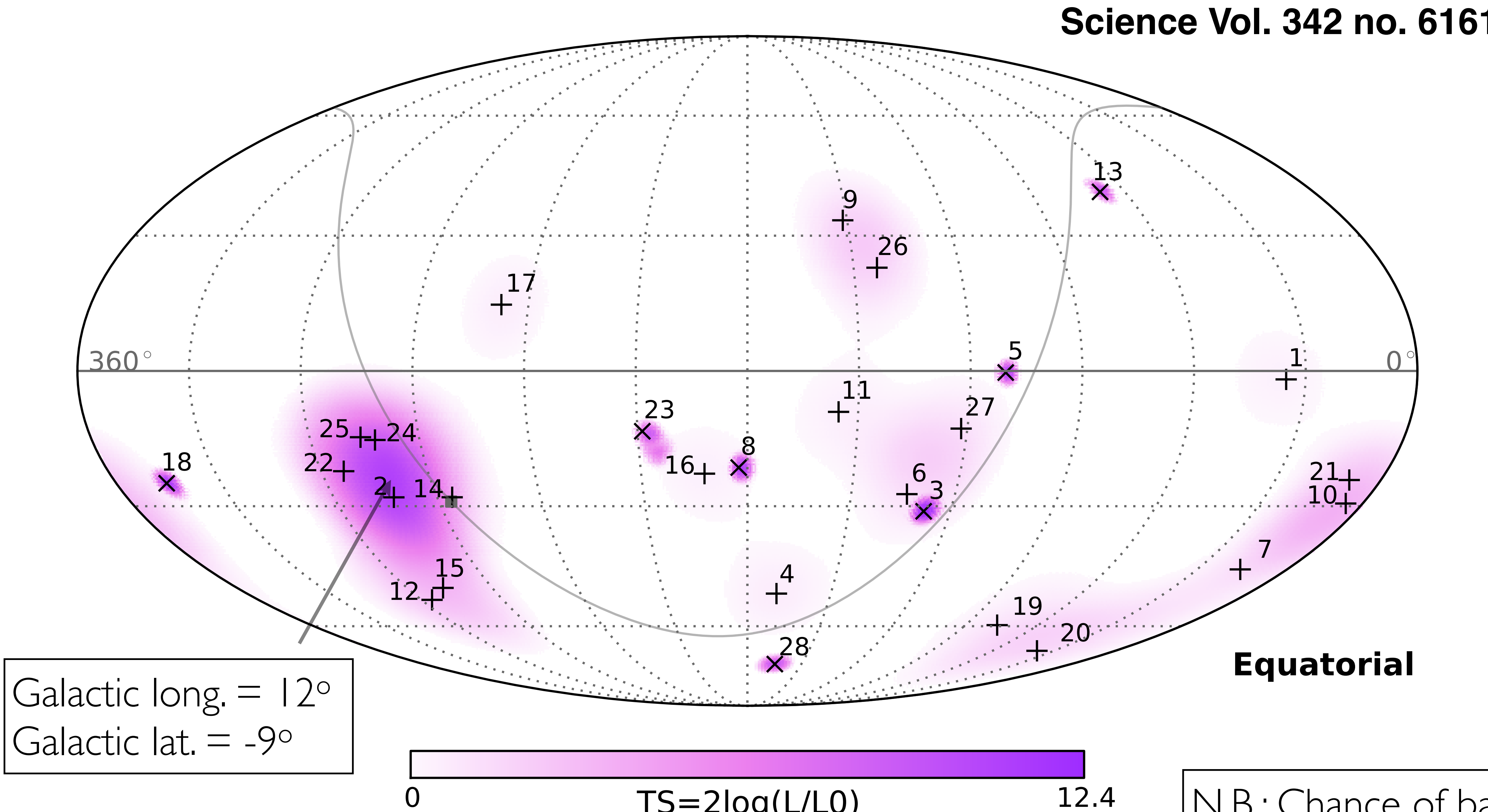


consistent with an isotropic flux

At these energies events here are absorbed

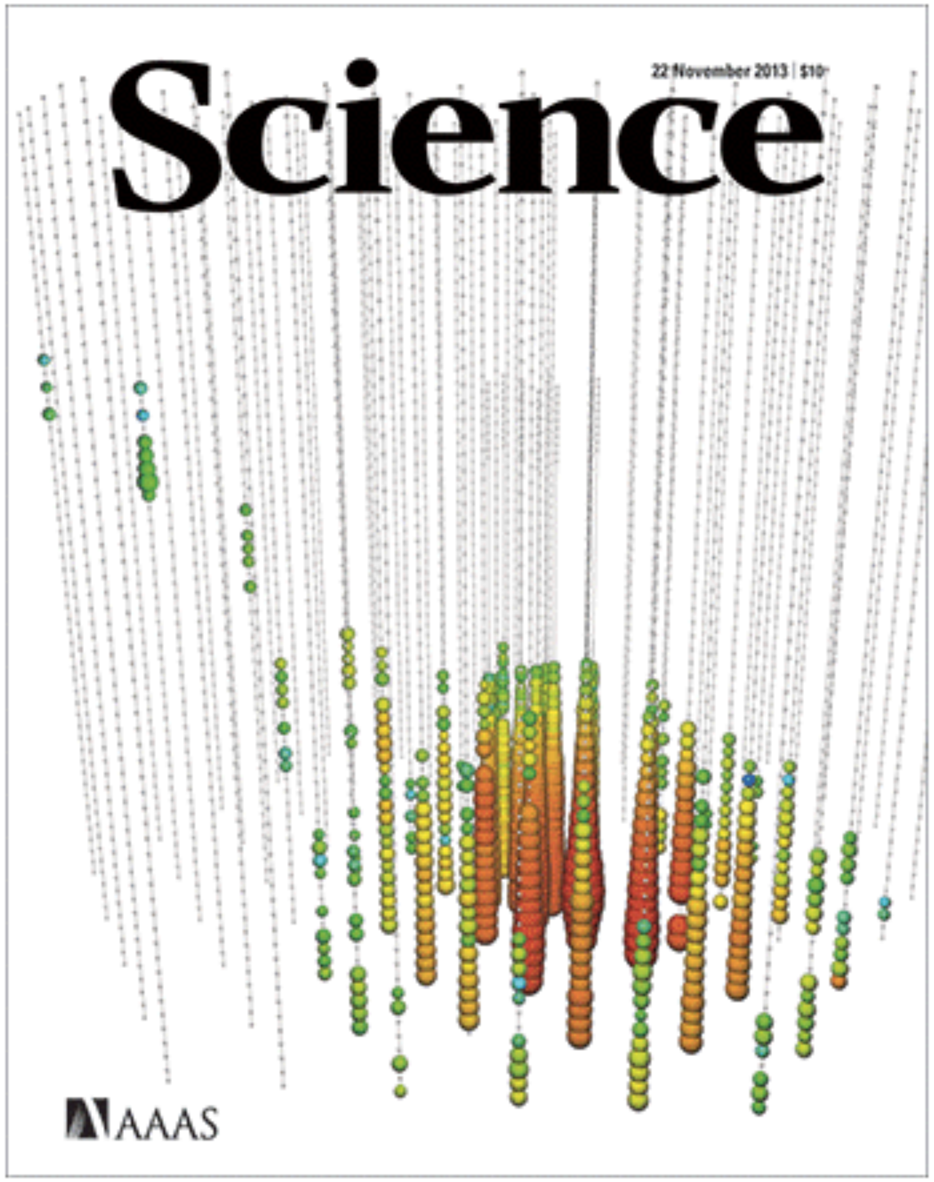
The IceCube high energy starting events analysis

- Skymap: no significant clustering of events in space (or time)



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

And the world took notice…



And the world took notice…

Antarctica Invaded by Extraterrestrials

The Guardian Liberty Voice

Tiny, invisible EXTRATERRESTRIAL INVADERS appear at South Pole

Dozens travelled here almost at warp speed to hit beneath stilt base

The Register, UK

Extraterrestrials on Earth: Scientists find outer space stuff at South Pole FoxNews

What is coming next?

- Another year of data has been analyzed and added to the full sample
  - nine more events (1 track, 8 cascades) have been observed
  - included is the highest energy event to date…

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image Sesame Workshop

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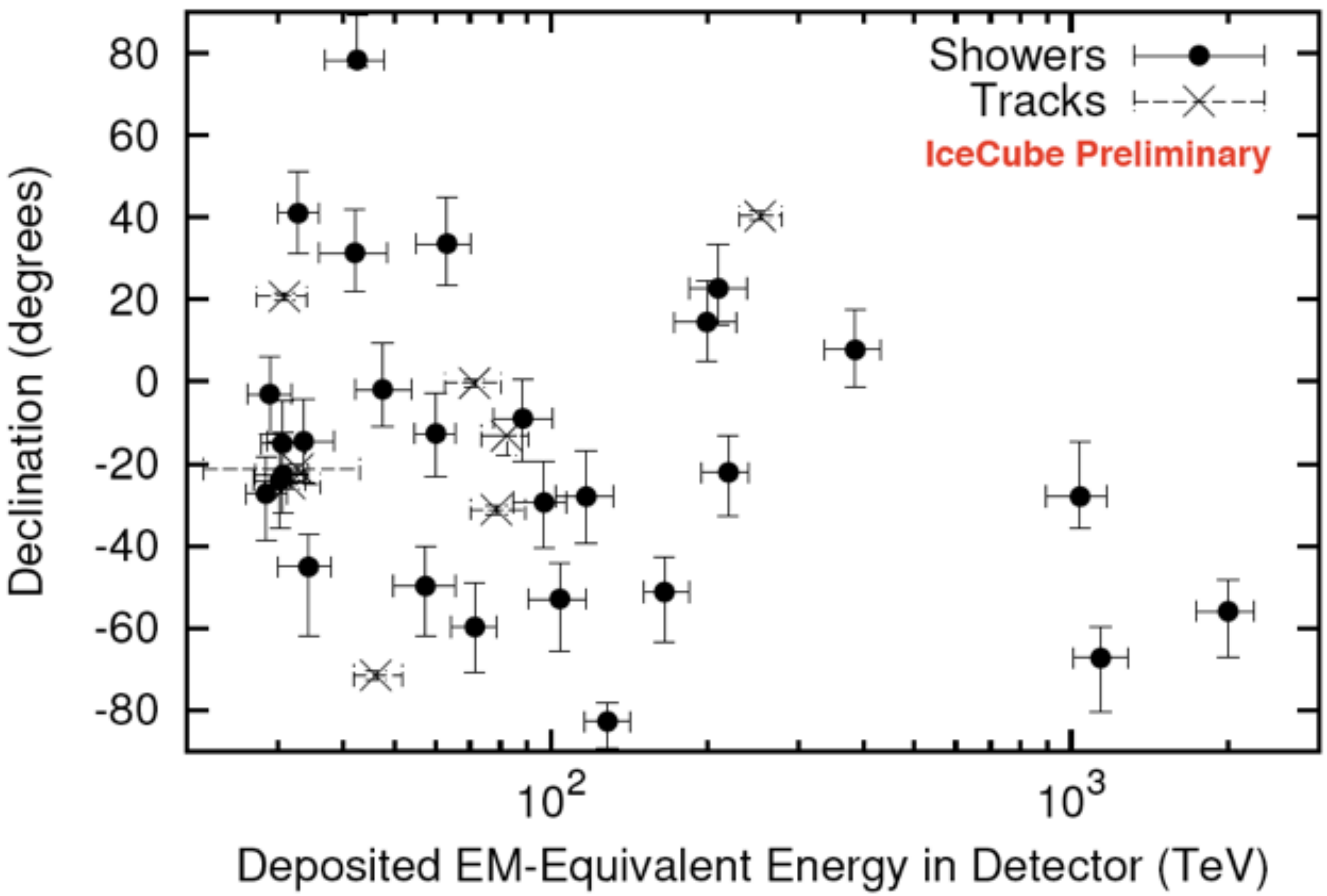

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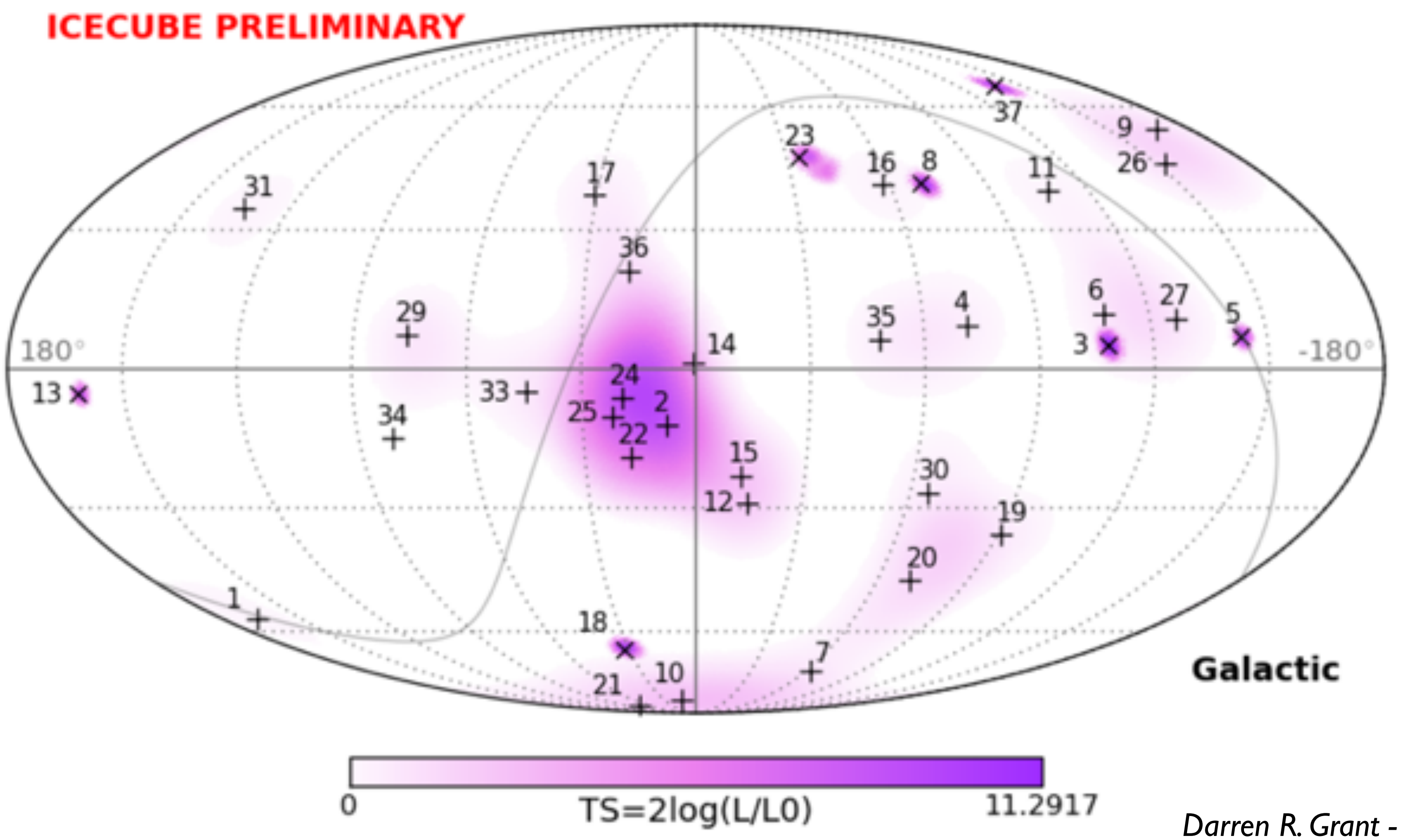

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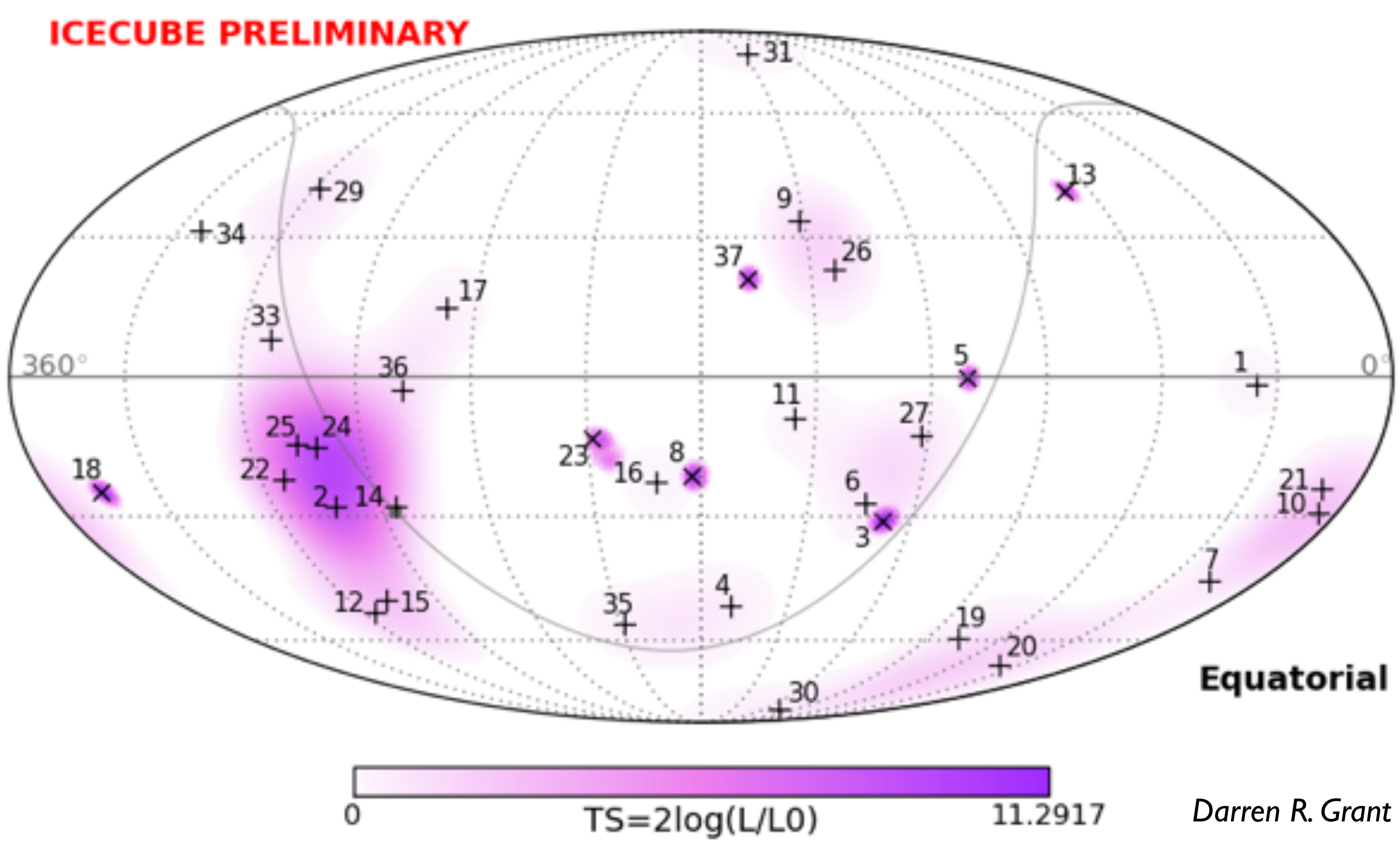

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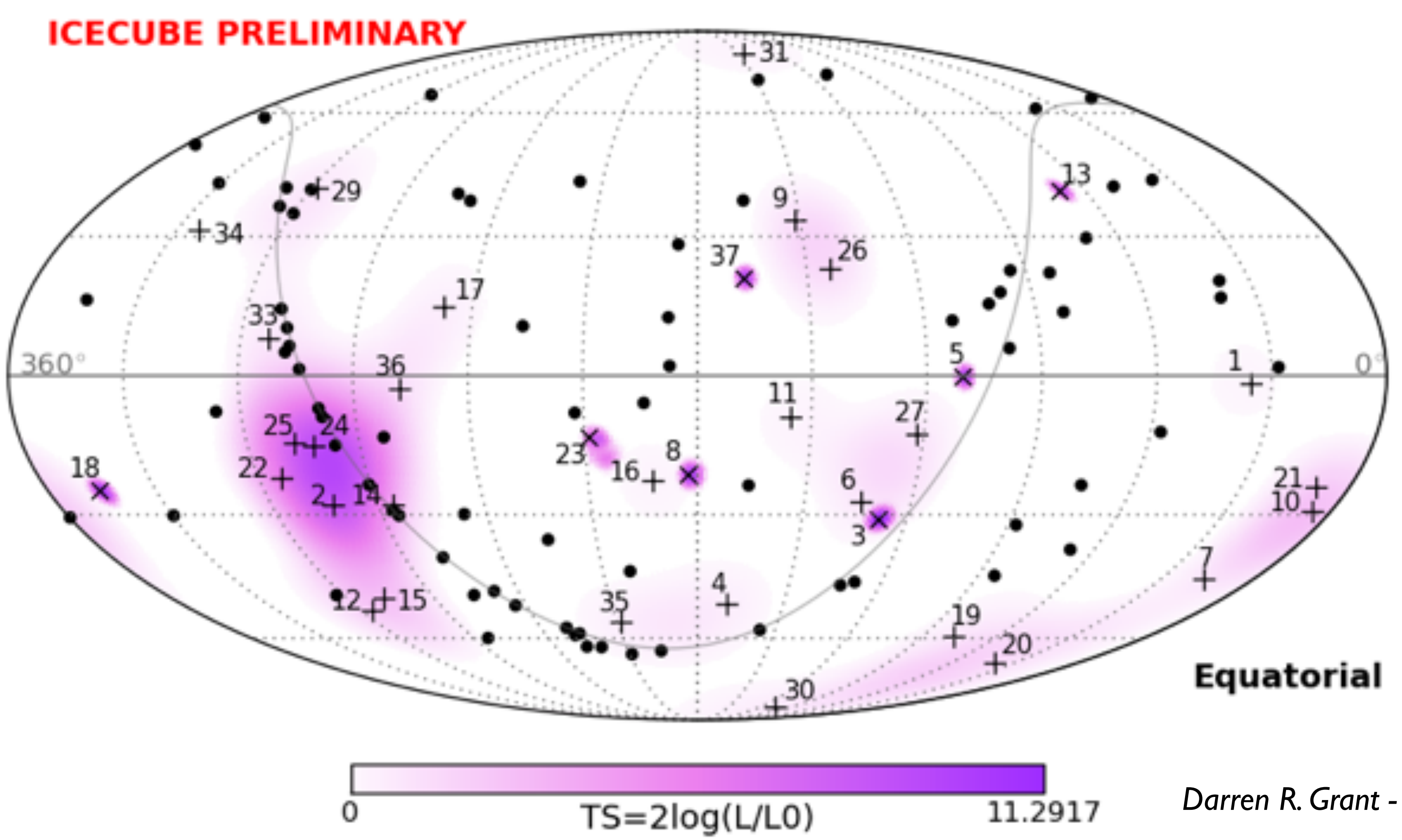


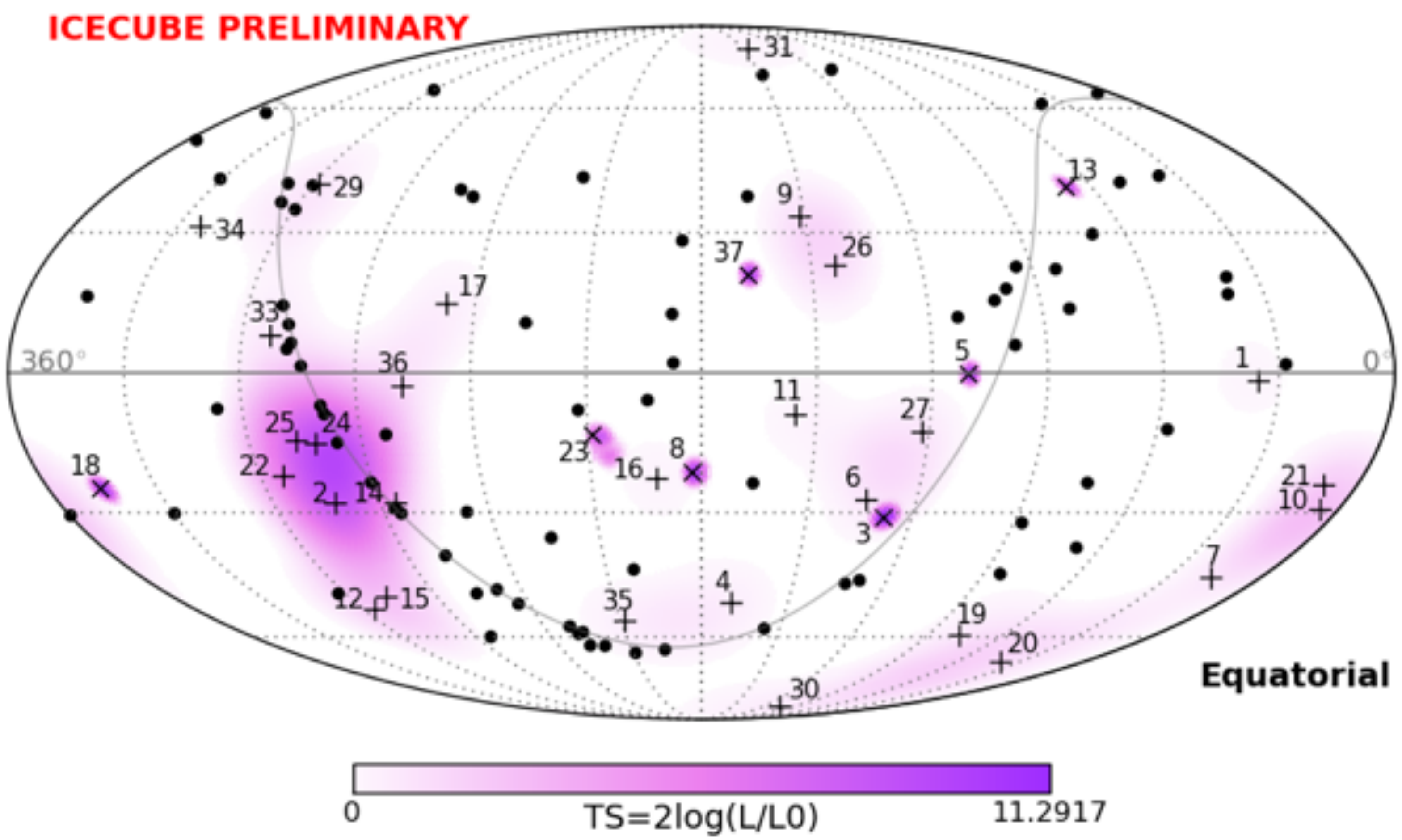
Summary

• IceCube is COMPLETE and actively taking data. It is the world's largest neutrino detector (>1 Gigaton!).

• Analyses are underway... discoveries are happening!

• We are now at the threshold of neutrino astronomy; a unique new window to view our Universe

•Plans developing for future detectors (low and high energy extensions) - stay tuned!



To conclude…

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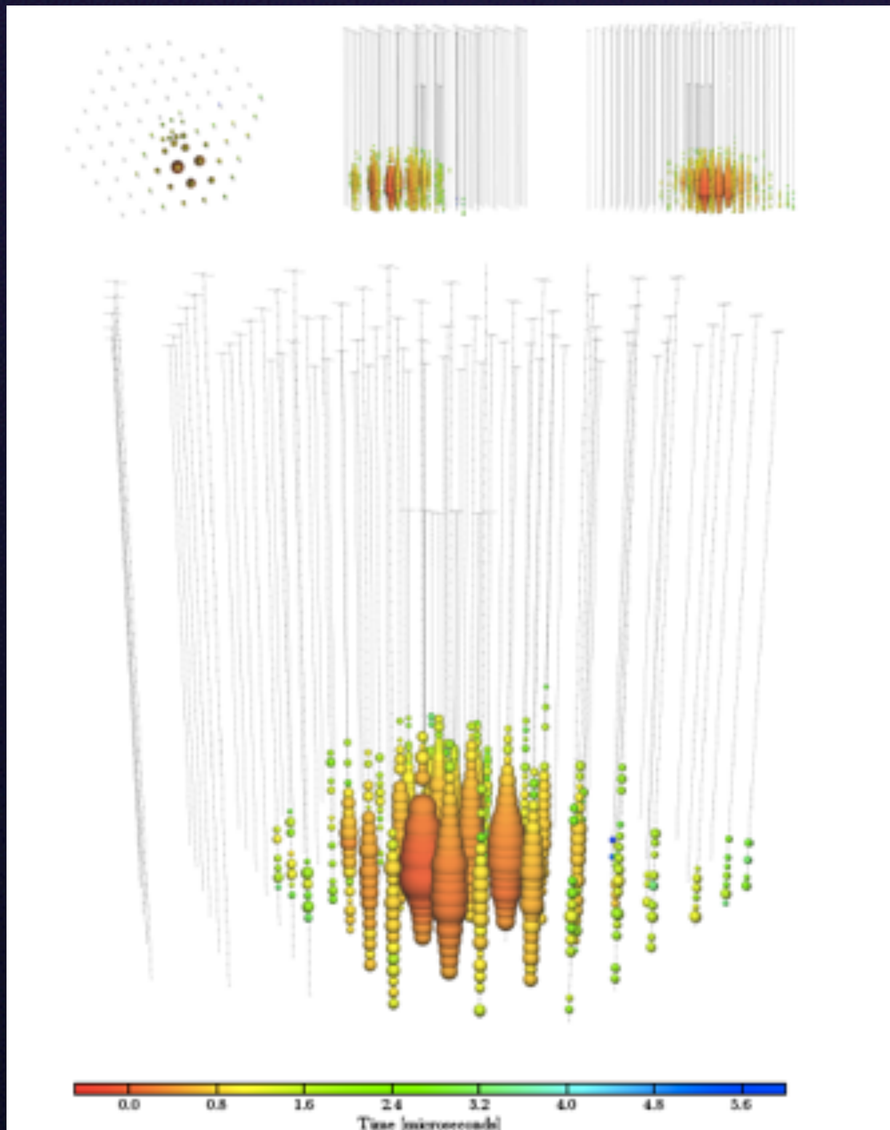
To conclude…they have arrived!



“Gonzo the Great”

image
muppet.wikia.com

Thanks for your attention!

Backup slides