



# Not of this Earth: the advent of neutrino astronomy

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Darren R. Grant  
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So what is this all about?



It could be this...



SOMEWHERE  
IN  
THIS  
WORLD  
STALKS  
A  
THING  
THAT  
IS...

# NOT OF THIS EARTH

starring

PAUL BIRCH · BEVERLY GARLAND · MORGAN JONES · A ROGER CORMAN PRODUCTION

Screenplay by CHARLES B. GRIFFITH and MARK HANNA · Produced and Directed by ROGER CORMAN · AN ALLIED ARTISTS PICTURE

Country of origin U. S. A. 1958



It could be this...but it isn't



SOMEWHERE  
IN  
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STALKS  
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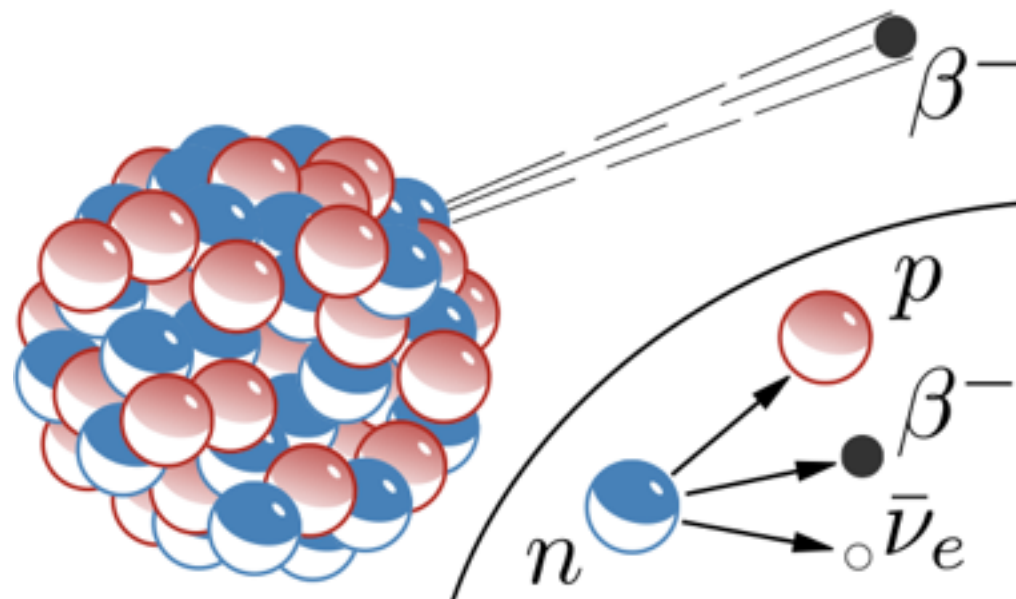
Country of origin U. S. A. 1958



# 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.

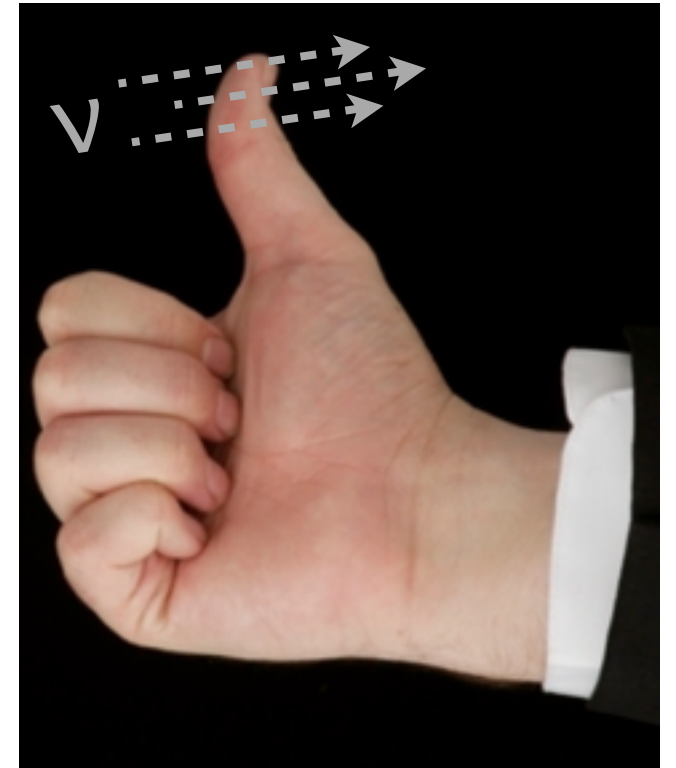


Wolfgang Pauli

# “We aren’t afraid of no ghost”

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- 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.

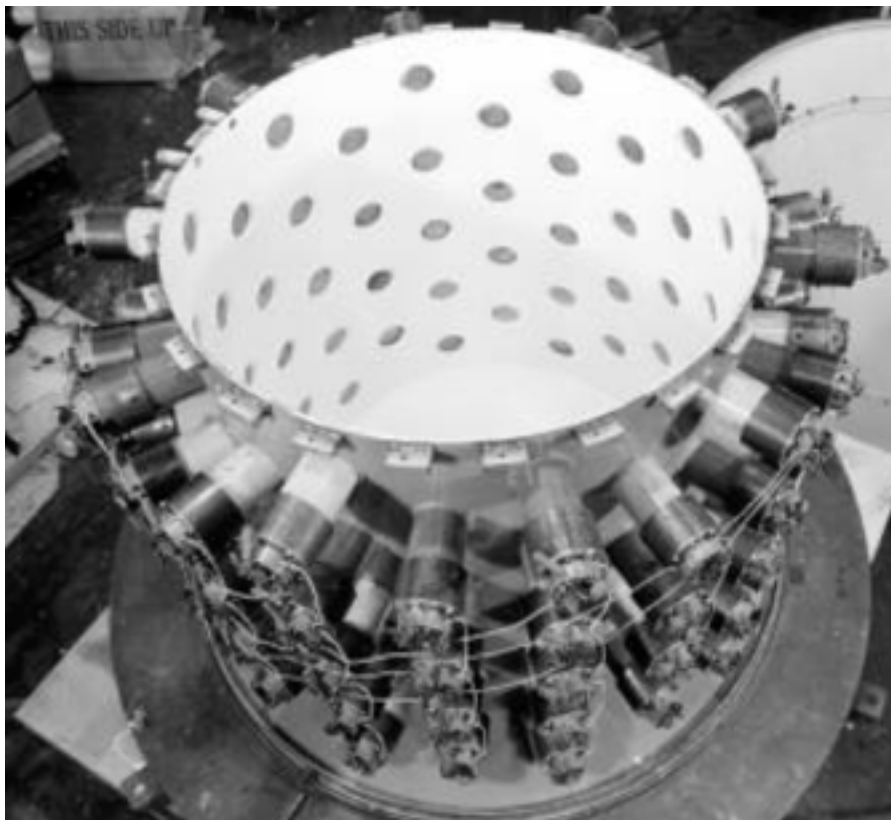


# “Ghost” hunting 101

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.



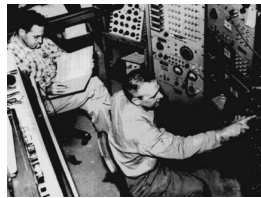
The first physics “Ghostbusters”:  
Reines and Cowan

# “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.

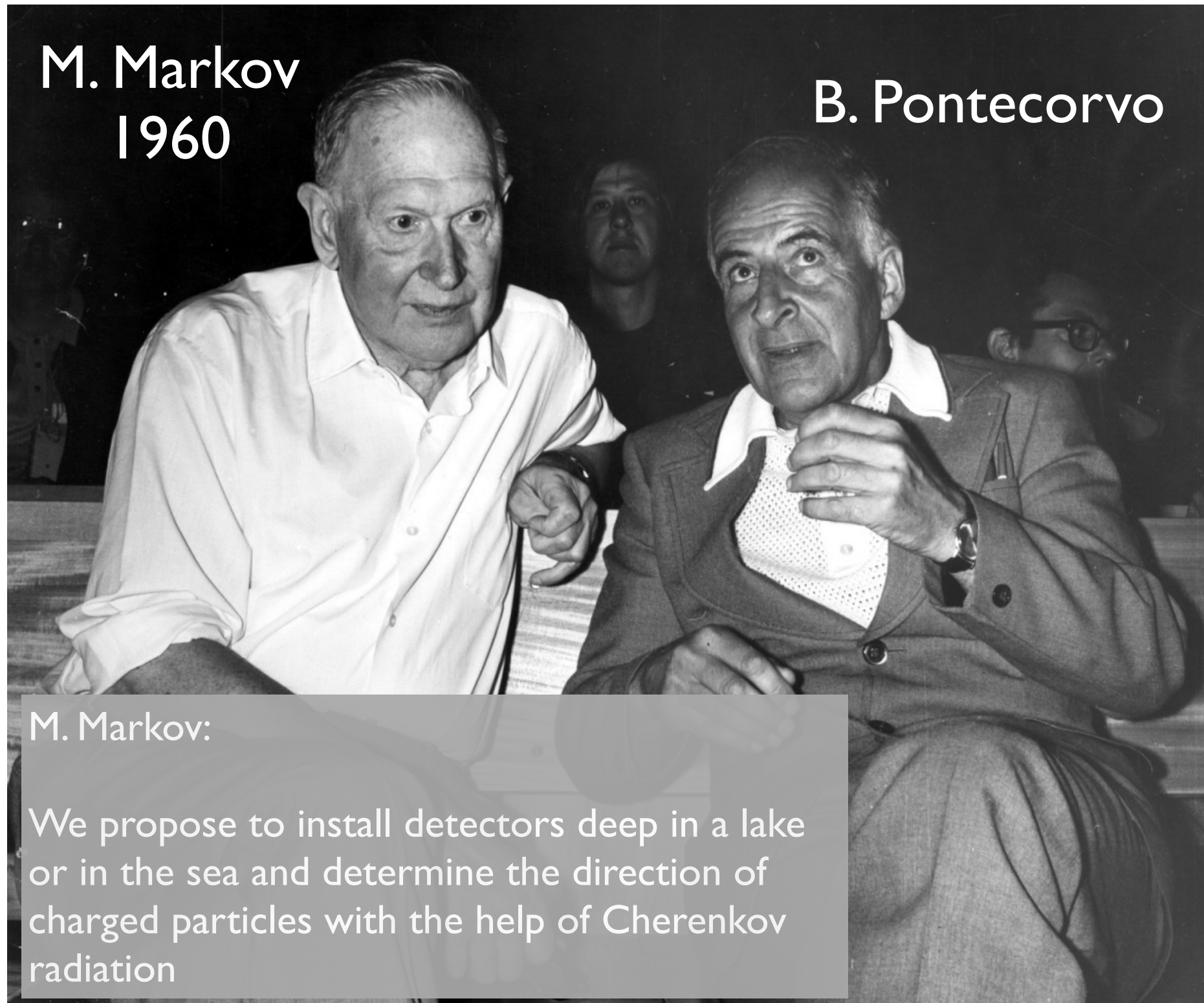


Ray Davis Jr. at Homestake



# “Ghost” hunting 101 - back to basics

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M. Markov  
1960

B. Pontecorvo

M. Markov:

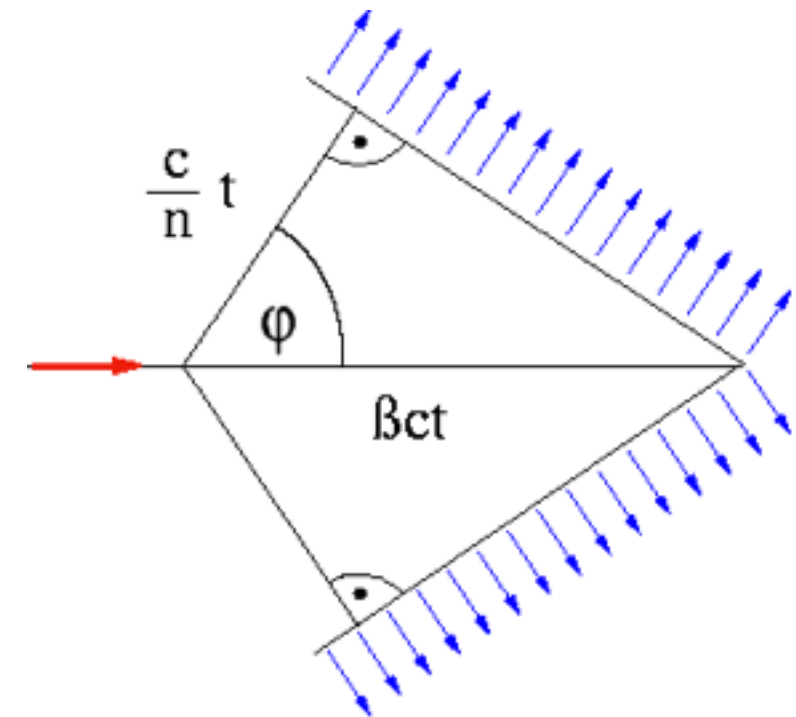
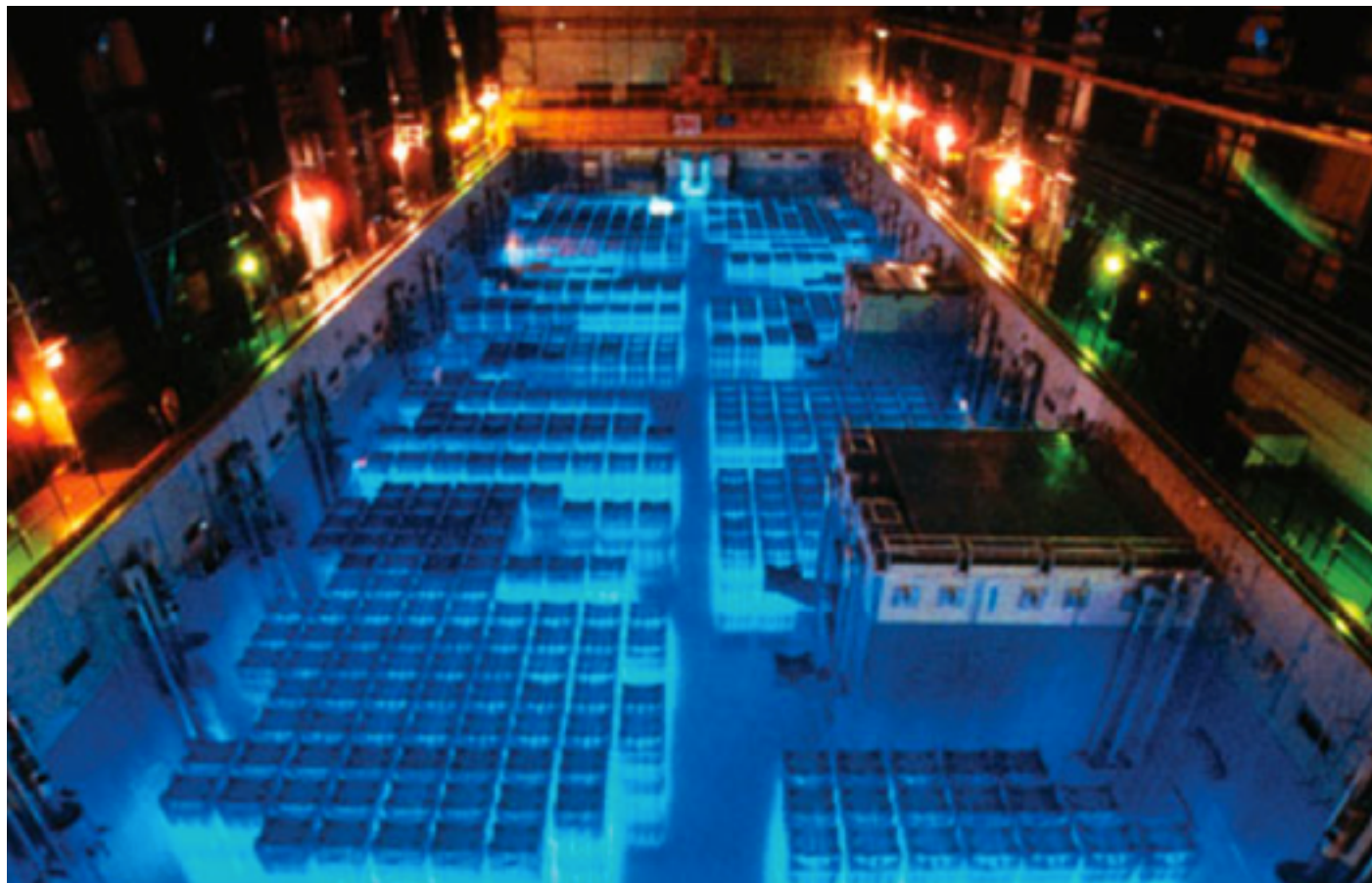
We propose to install detectors deep in a lake or in the sea and determine the direction of charged particles with the help of Cherenkov radiation

# 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.

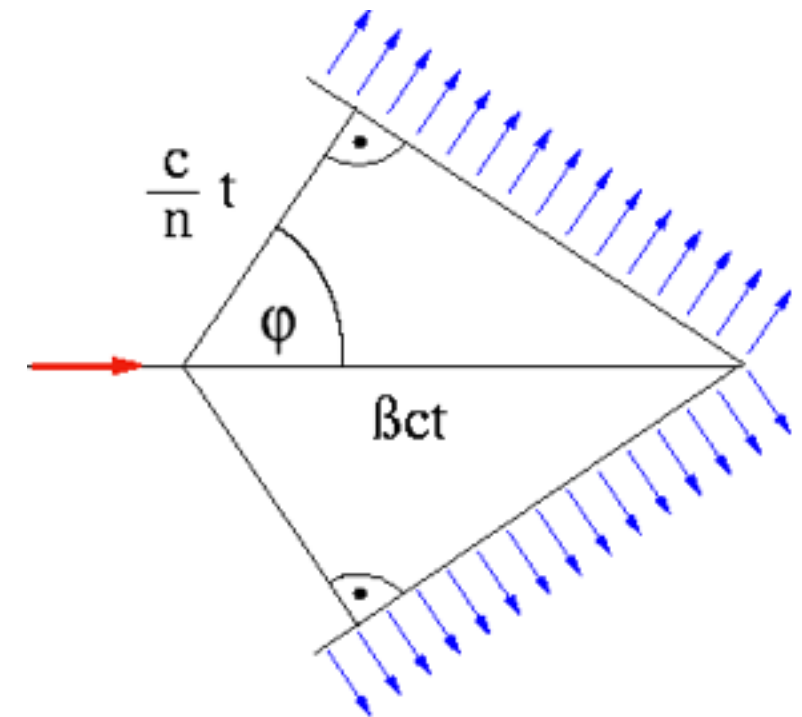
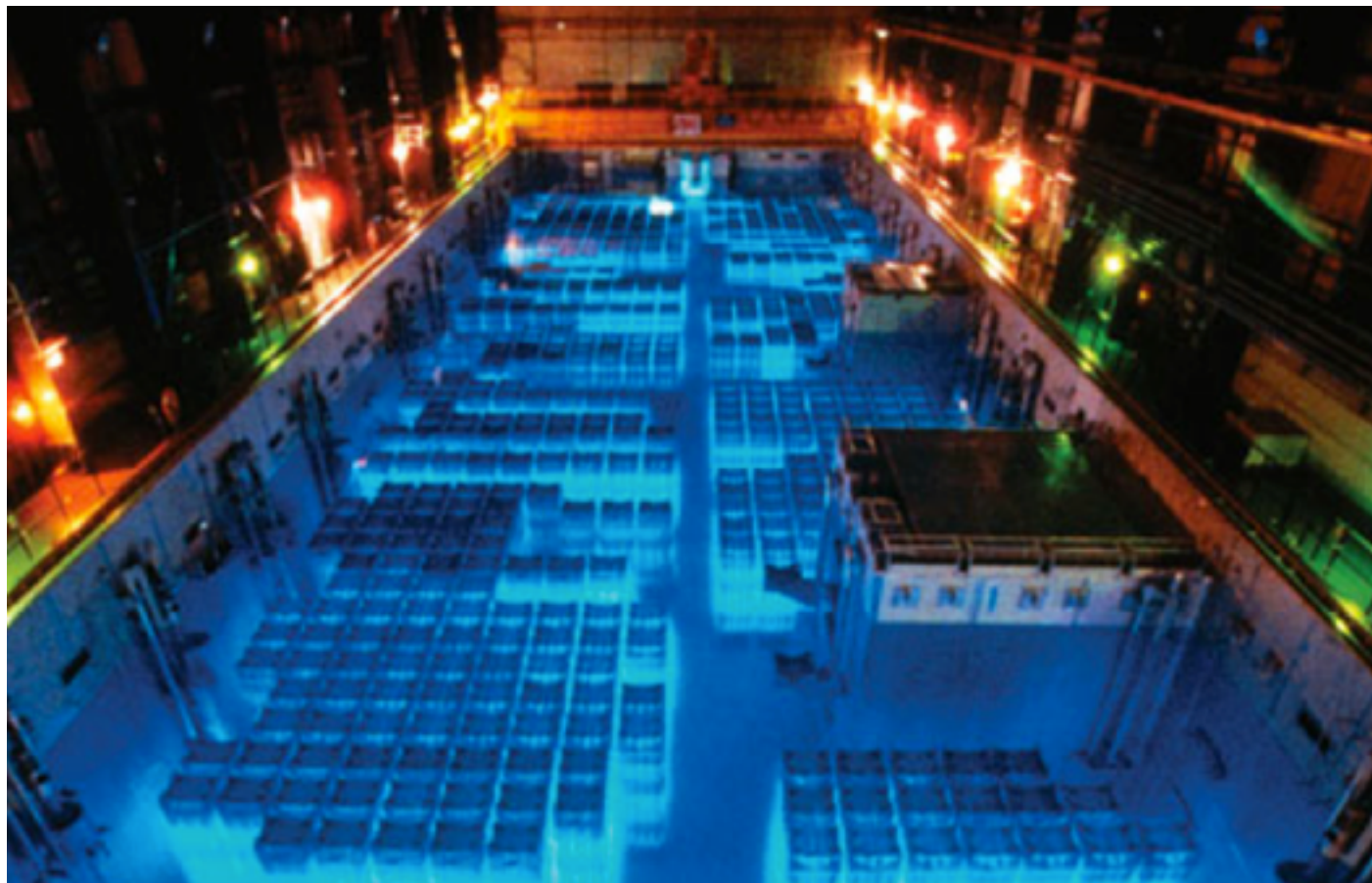




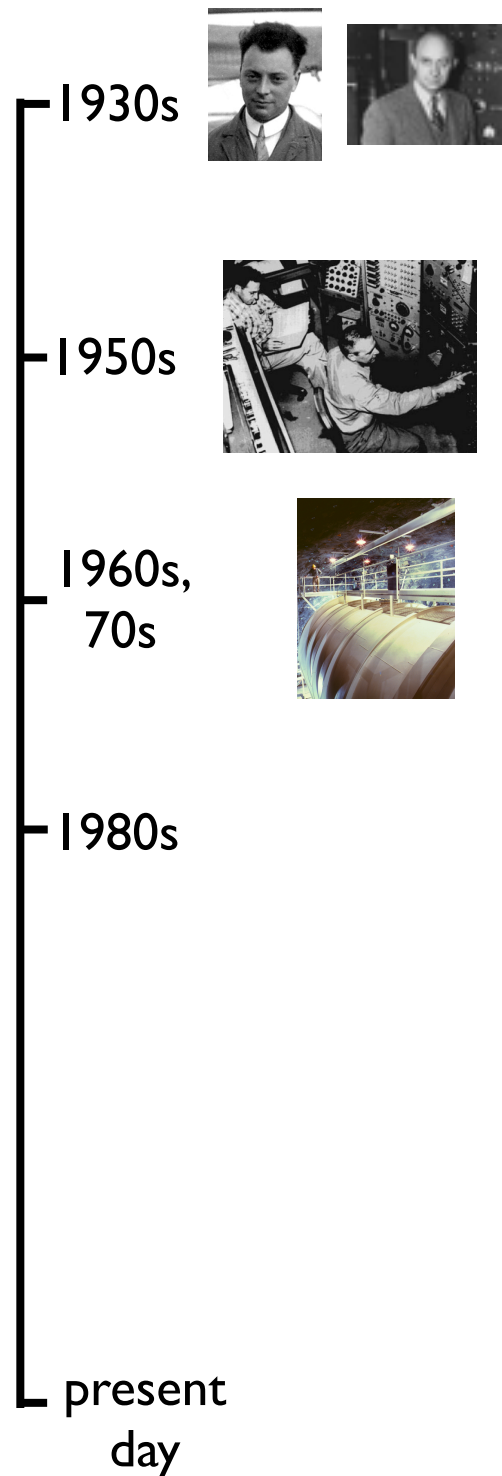
# Cherekov radiation - an aside

A supersonic “duck” in air...

- 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.



# Neutrino detection: A new hope



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

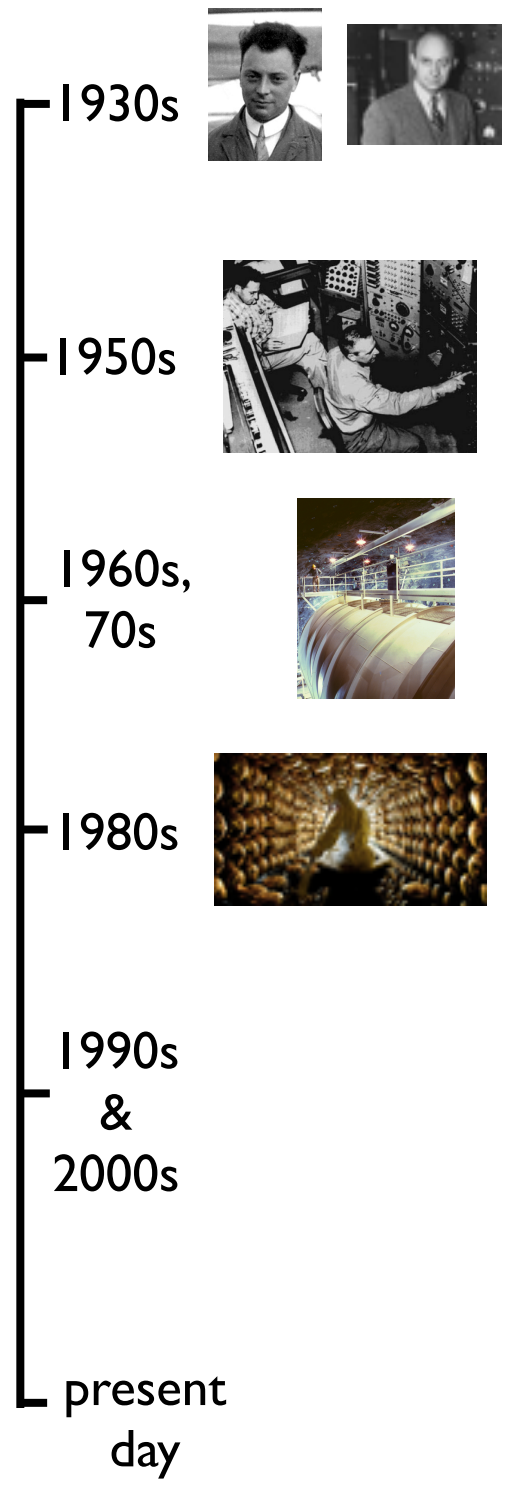


image Lucasfilms Ltd.

- 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



- In the 1990s things really got big...

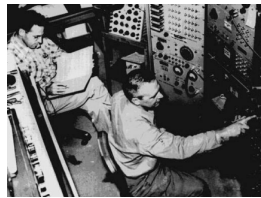
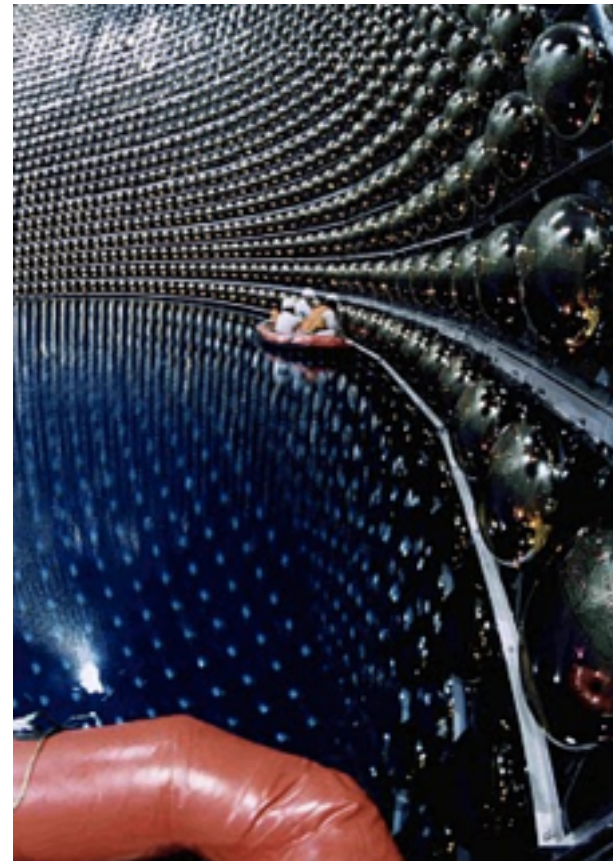
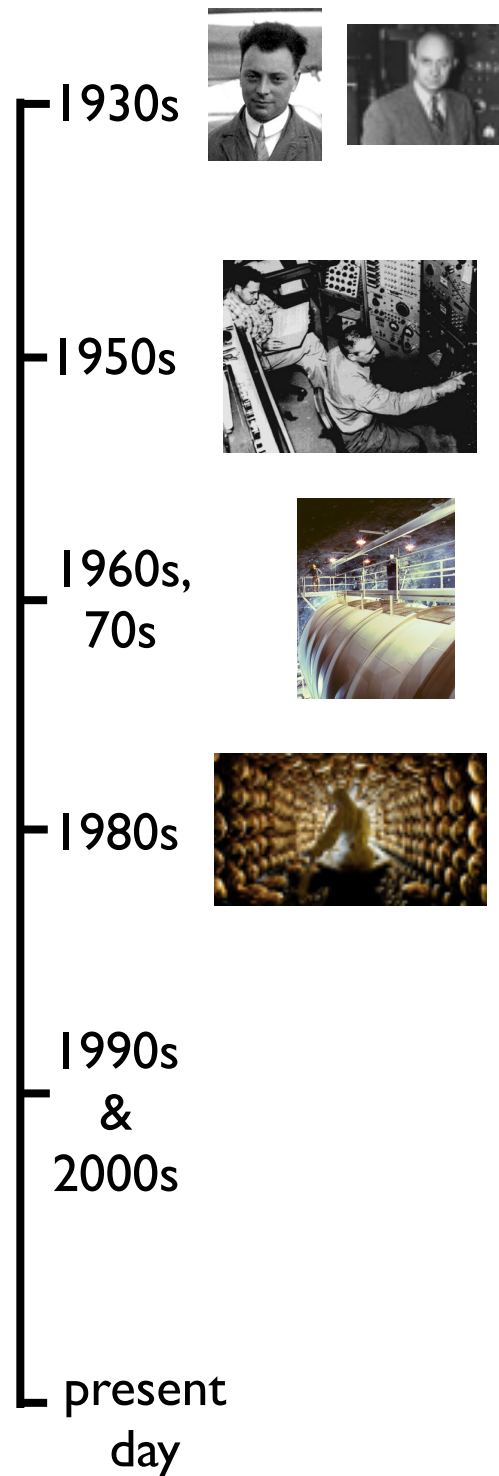
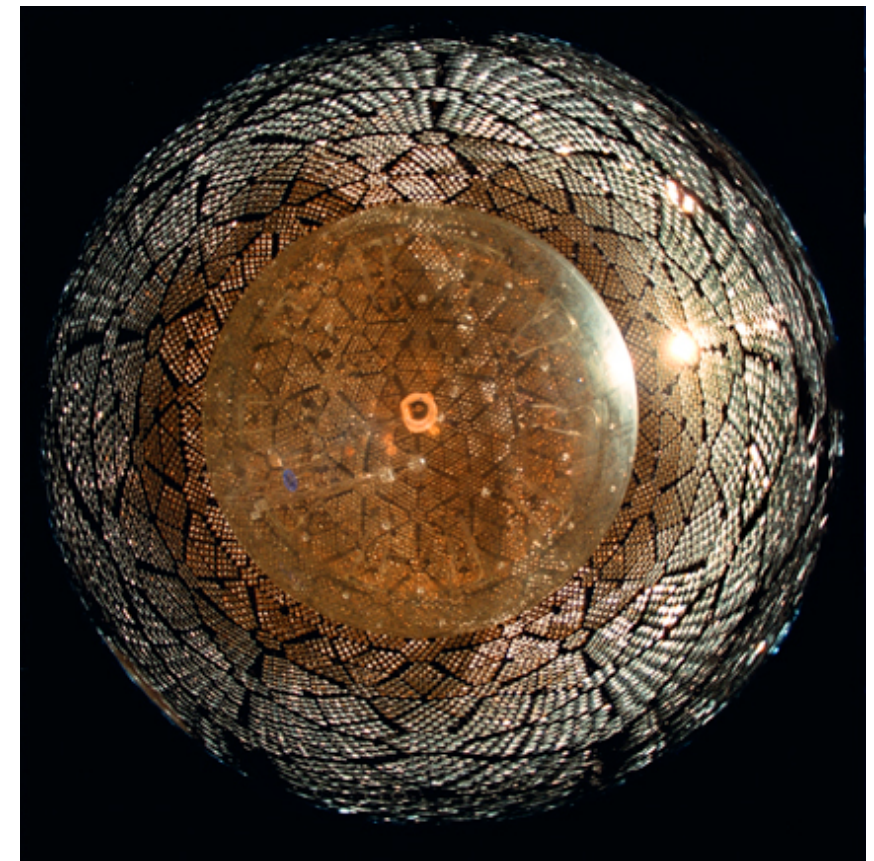


image Warner Bros.

# Neutrino detection: rise of the machines



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

Timeline of neutrino discovery and research:

- 1930s:** Wolfgang Pauli (1930) and Enrico Fermi (1934) proposed the neutrino.
- 1950s:** Clyde L. Cowan and Frederick Reines (1956) first detected neutrinos.
- 1960s, 70s:** Development of neutrino detectors like Super-Kamiokande.
- 1980s:** Discovery of neutrino oscillation by T. Kobayashi and M. Tanimoto (1982).
- 1990s & 2000s:** Large-scale experiments like Super-Kamiokande and SNO.
- present day:** Ongoing research into neutrino mass and properties.

## The Standard Model of Particle Physics

				Three Generations of Matter (Fermions)			Higgs boson
				I	II	III	~126 GeV/c <sup>2</sup>
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0	0	0	H
charge→	2/3	2/3	2/3	0	0	0	γ
spin→	1/2	1/2	1/2	1	1	1	photon
name→	u up	c charm	t top				
	4.8 MeV	104 MeV	4.2 GeV	0	0	0	g
	-1/3	-1/3	-1/3	0	0	0	Z <sup>0</sup>
	1/2	1/2	1/2	1	1	1	W <sup>±</sup>
	d down	s strange	b bottom				
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV	0	0	
	0	0	0	0	0	0	
	1/2	1/2	1/2	1	1	1	
	ν <sub>e</sub> electron neutrino	ν <sub>μ</sub> muon neutrino	ν <sub>τ</sub> tau neutrino				
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV	±1	1	
	-1	-1	-1	±1	±1	±1	
	1/2	1/2	1/2	1	1	1	
	e electron	μ muon	τ tau				

**Quarks** (purple boxes), **Leptons** (green boxes), **Bosons (Forces)** (red boxes)

- 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

Timeline of neutrino research:

- 1930s:** Pauli (1930), Fermi (1934)
- 1950s:** Cowan and Reines (1956), Nobel Prize (1962)
- 1960s, 70s:** Super-Kamiokande (1986), Nobel Prize (1987)
- 1980s:** Kamiokande (1987), Nobel Prize (1988)
- 1990s & 2000s:** SNO (1999), Nobel Prize (2015)
- present day:** IceCube (2010)

## The Standard Model of Particle Physics

Three Generations of Matter (Fermions)

	I	II	III	Higgs boson
mass →	2.4 MeV	1.27 GeV	171.2 GeV	~126 GeV/c <sup>2</sup>
charge →	2/3	2/3	2/3	0
spin →	1/2	1/2	1/2	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
	4.8 MeV	104 MeV	4.2 GeV	0
	-1/3	-1/3	-1/3	0
	1/2	1/2	1/2	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	1/2	1/2	1/2	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	±1
	1/2	1/2	1/2	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force

**Quarks** (purple/green labels)  
**Leptons** (green labels)  
**Bosons (Forces)** (red labels)

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



# Neutrinos in the modern day

Timeline of neutrino research:

- 1930s:** Pauli (1930), Fermi (1934)
- 1950s:** Cowan and Reines (1956), Gold Medal (1958)
- 1960s, 70s:** Super-Kamiokande (1986), Gold Medal (1987)
- 1980s:** Kamiokande (1986), Gold Medal (1987)
- 1990s & 2000s:** Super-Kamiokande (1996), SNO (2001)
- present day:** IceCube (2011)

## The Standard Model of Particle Physics

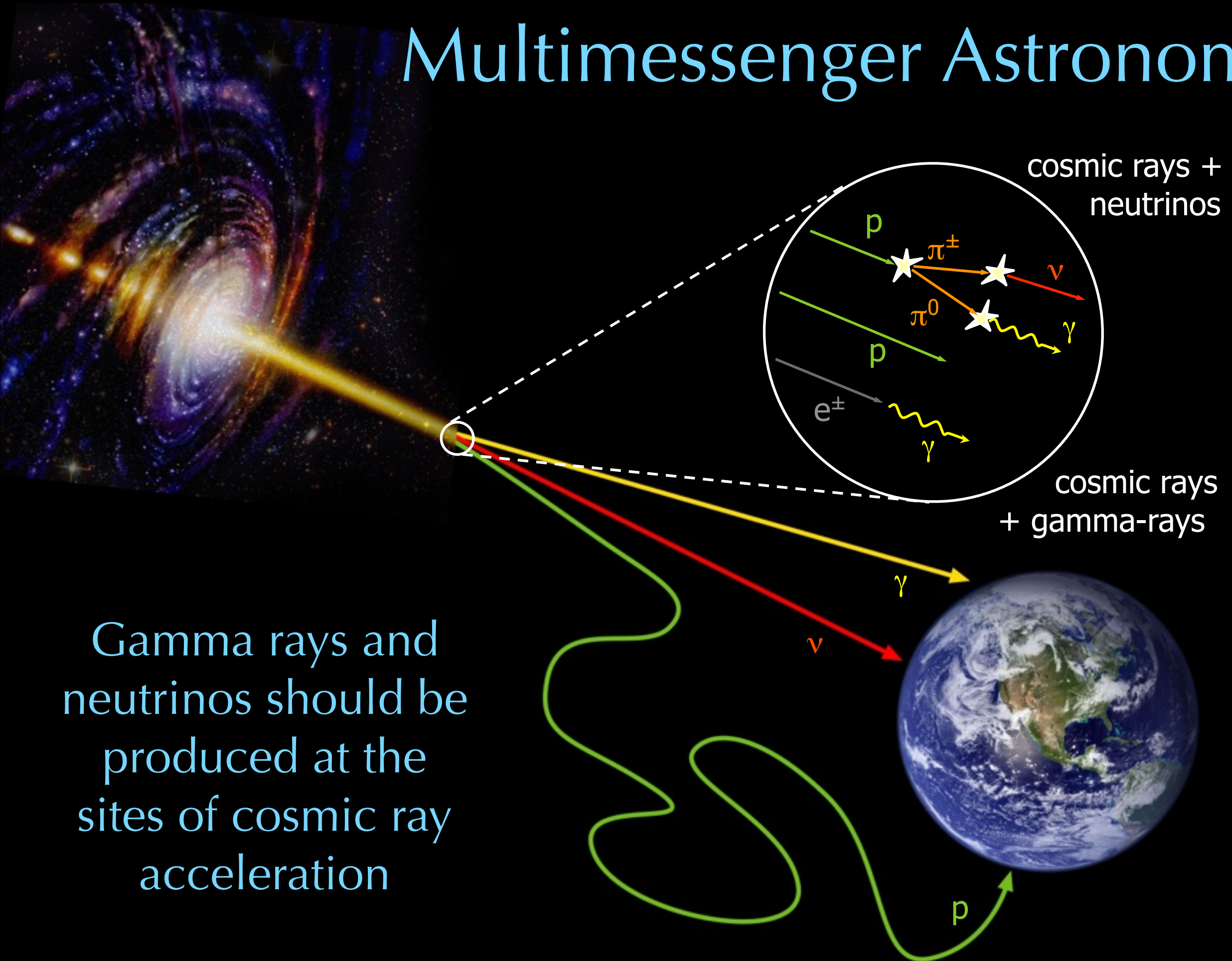
Three Generations of Matter (Fermions)

	I	II	III	Higgs boson
mass	2.4 MeV	1.27 GeV	171.2 GeV	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b><math>\gamma</math></b> photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
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	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>W<sup>±</sup></b> weak force

Quarks (purple), Leptons (green), Bosons (Forces) (red)

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

# Multimessenger Astronomy



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



# How can we make this work?

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...we're gonna need a bigger ~~boat~~ detector



image Jaws; Universal Pictures

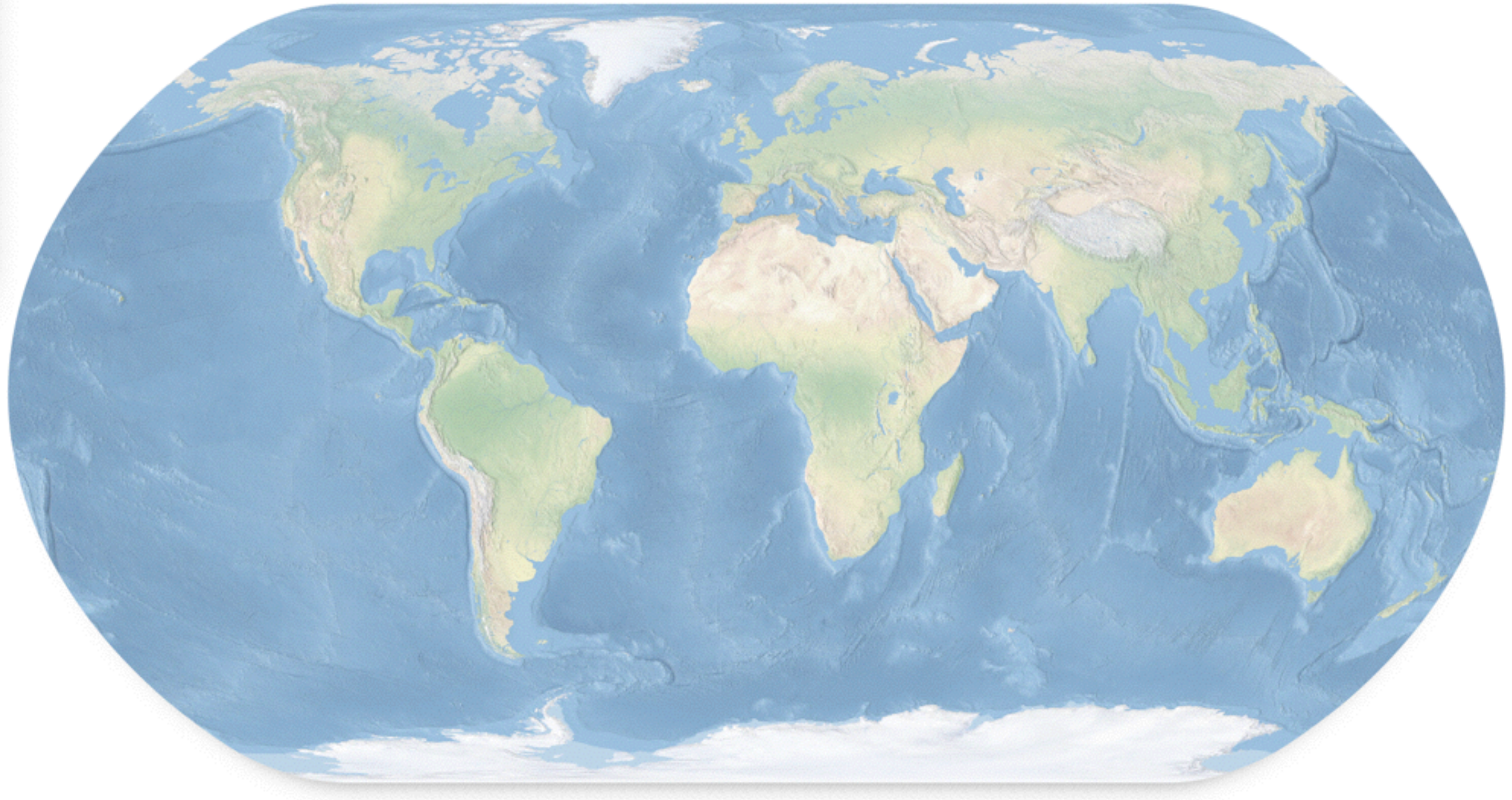
- the astrophysical neutrino events are expected to be millions of times higher in energy than those previously detected. We therefore need a huge volume ( $\sim 1 \text{ km}^3$  or more) to measure the Cherenkov light from the full events
- the challenge in detecting these astrophysical neutrino events 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

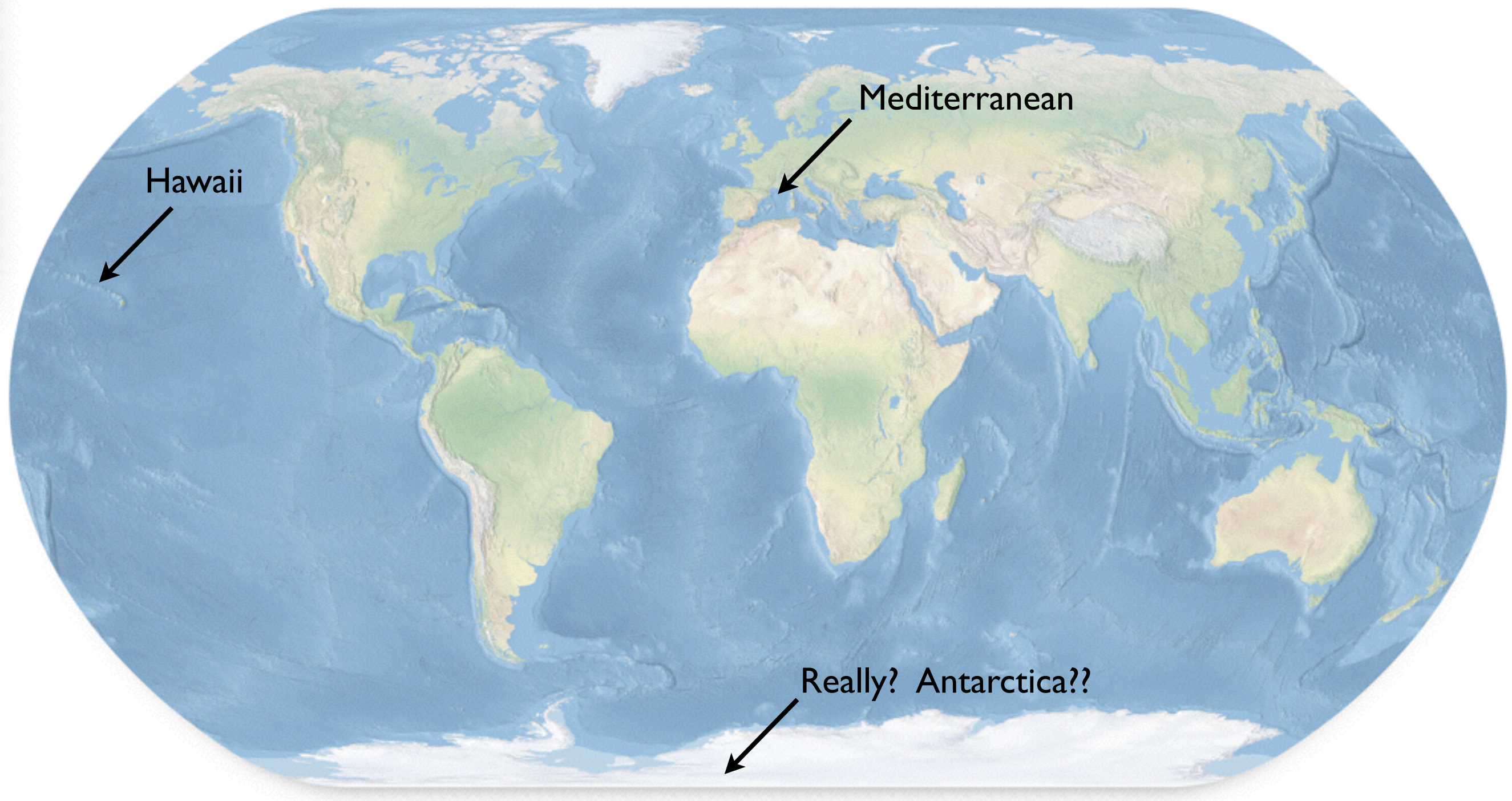


Oh... and let's choose something warm and exotic so we want to visit...



# 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!

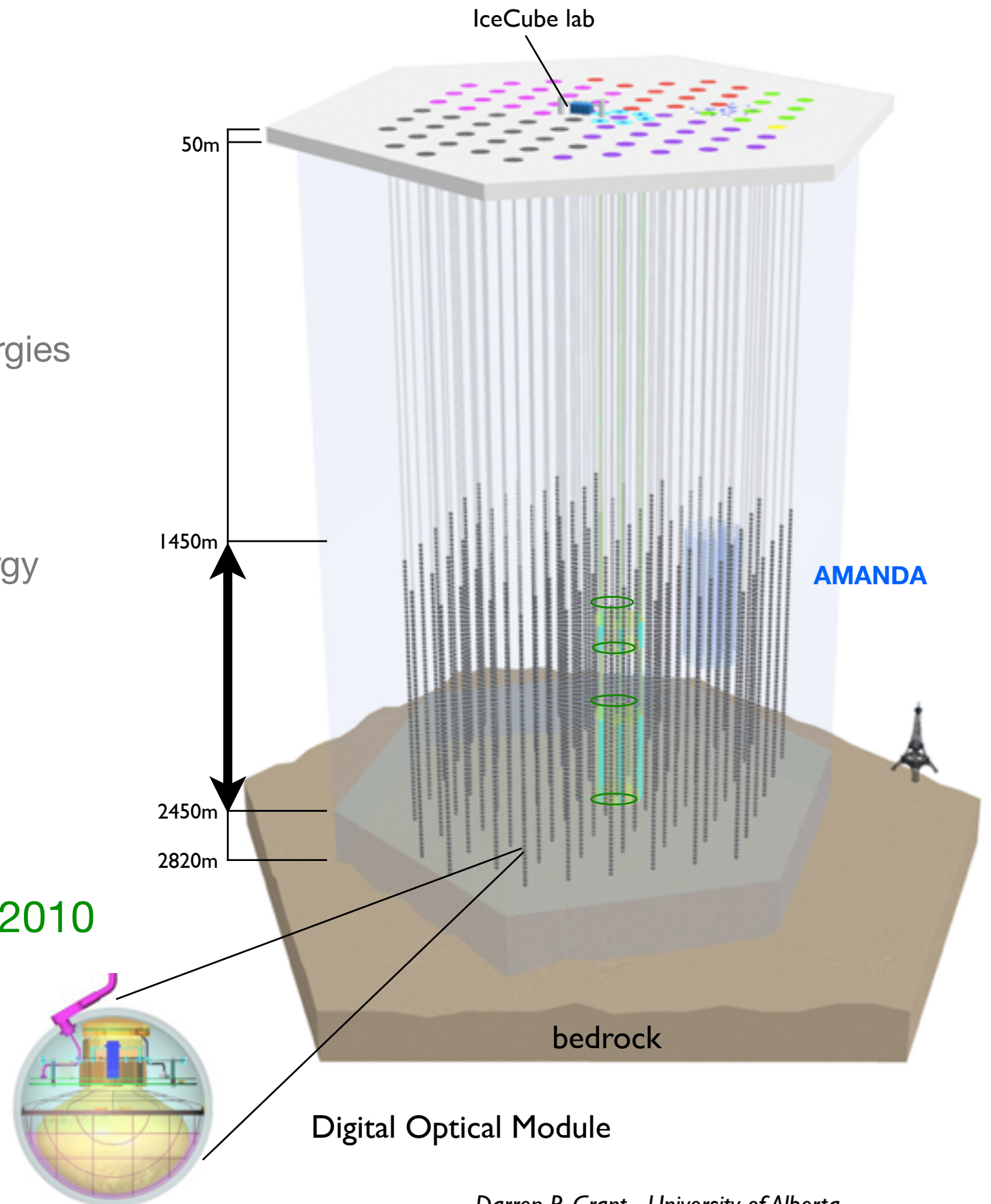


University of Alberta Graduate Student Tania Wood  
"Summer" 2014  
*Darren R. Grant - University of Alberta*

# 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



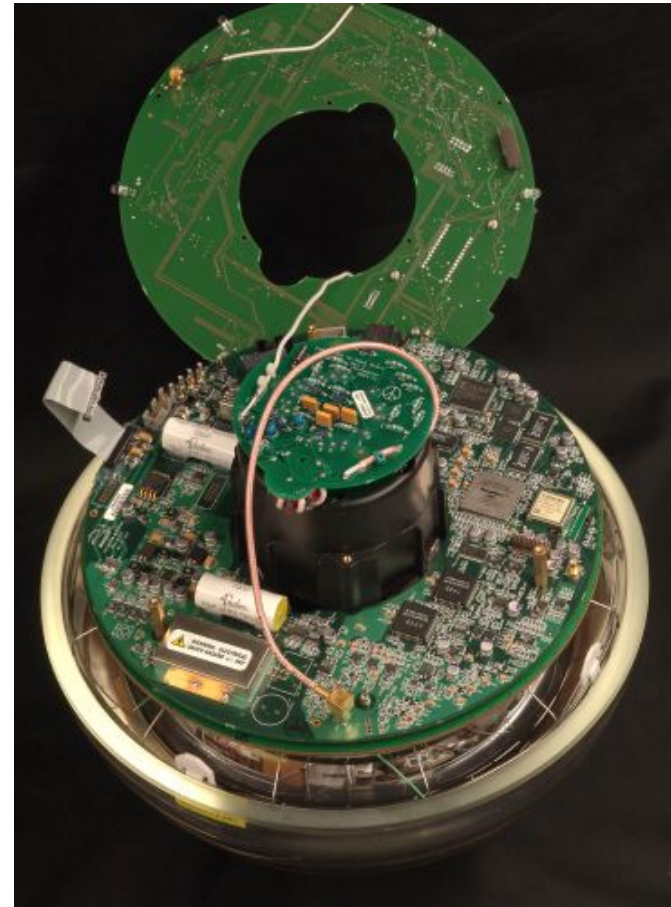


# The Digital Optical Module (DOM)

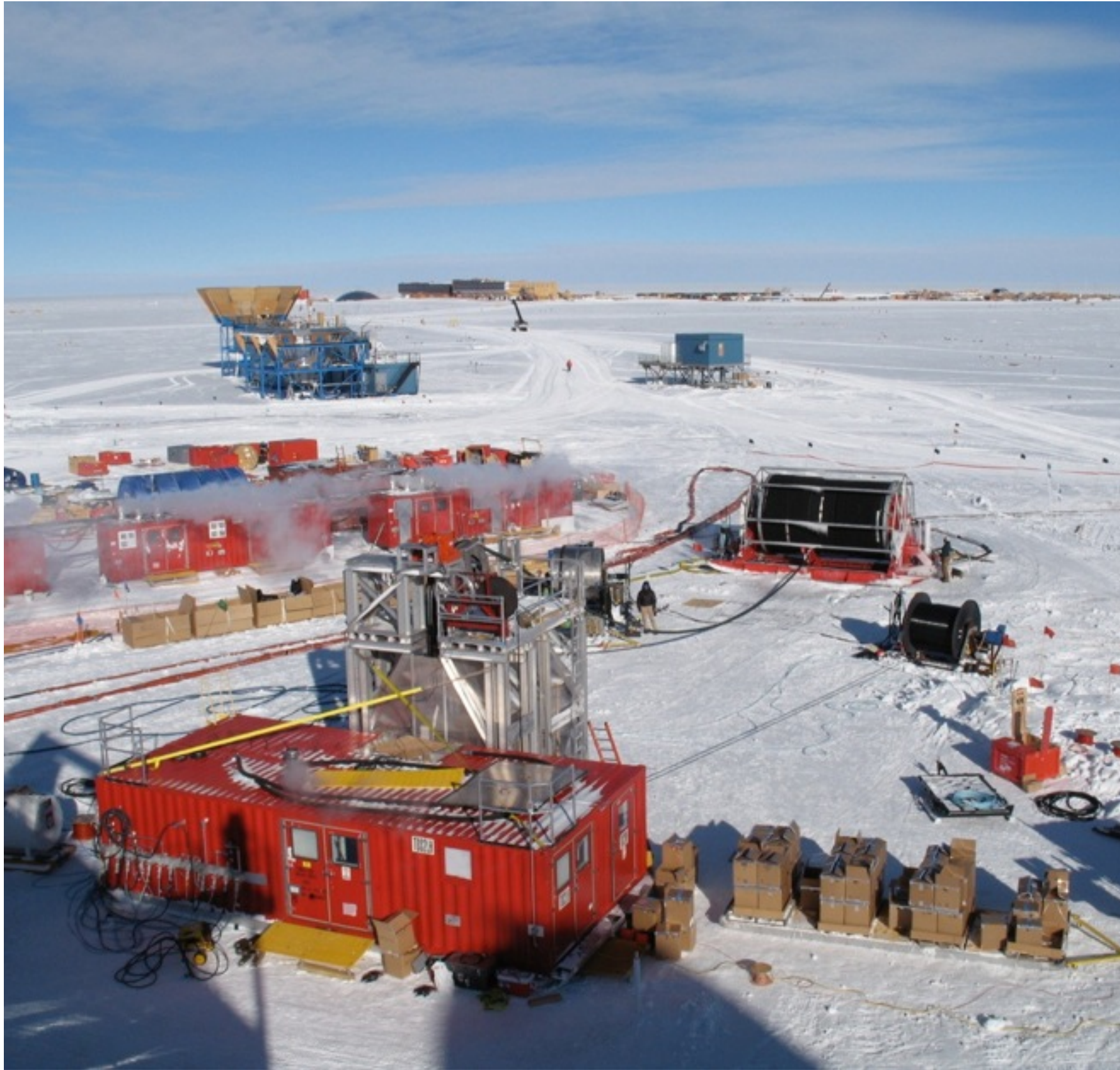
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- Digital Optical Module
  - Ultra-sensitive light sensors (photomultiplier tubes) with complete on-board high voltage and data acquisition.
  - Complete signal digitization within the ice.

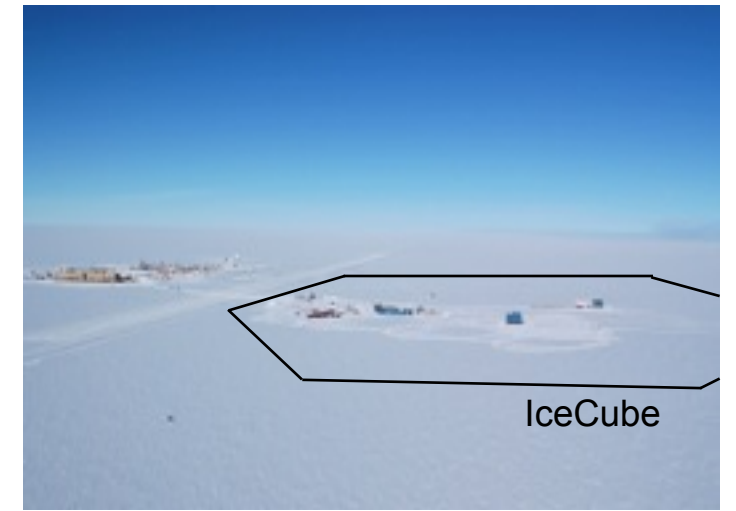
Photomultiplier Tube



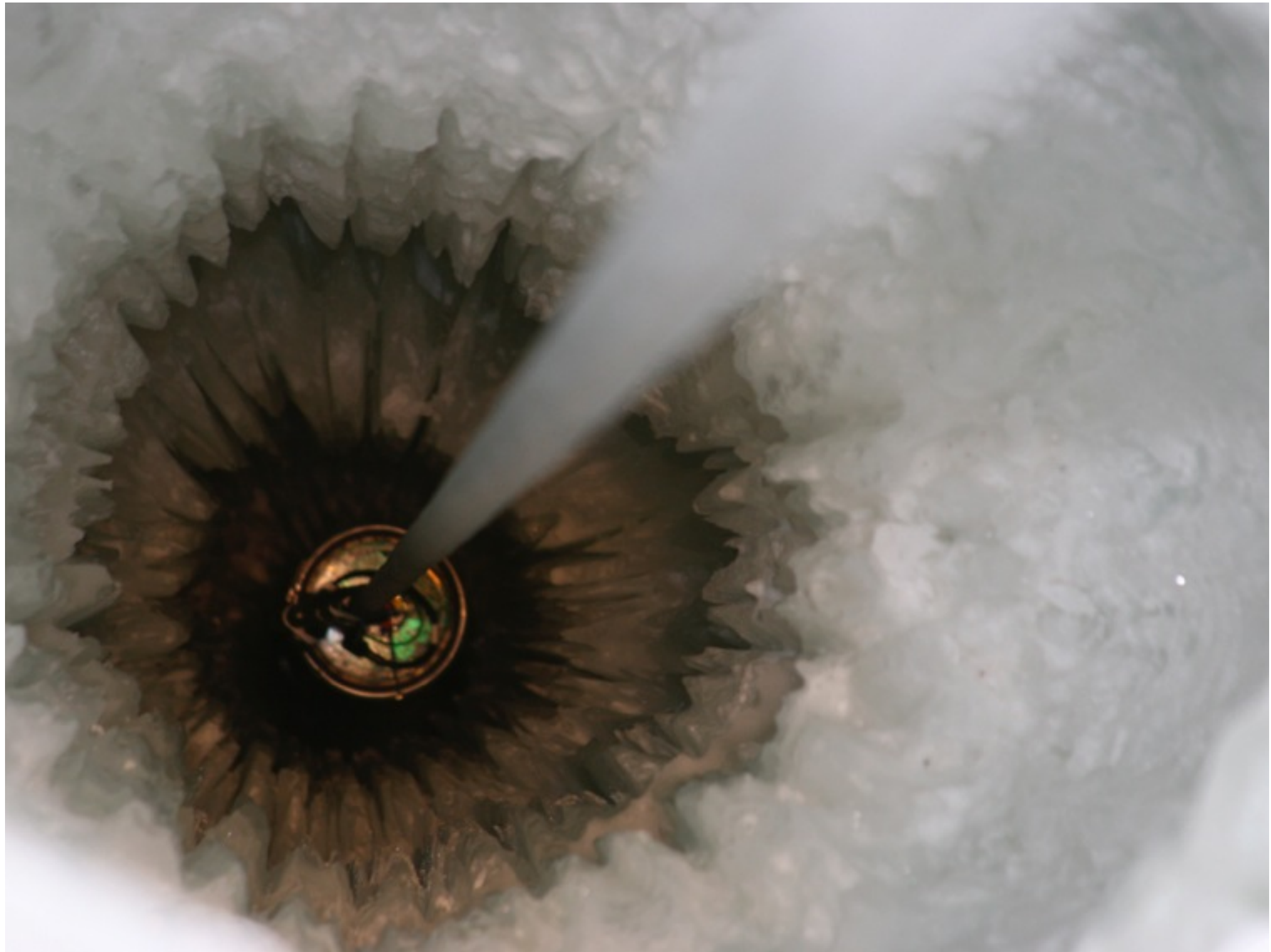




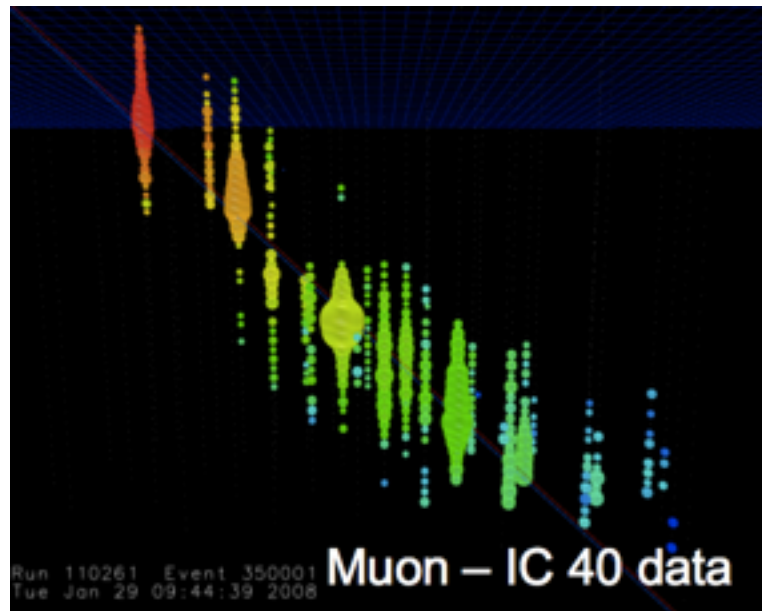
Amundsen-Scott South Pole Station, Antarctica







# Neutrino Telescopes - Principle of Detection

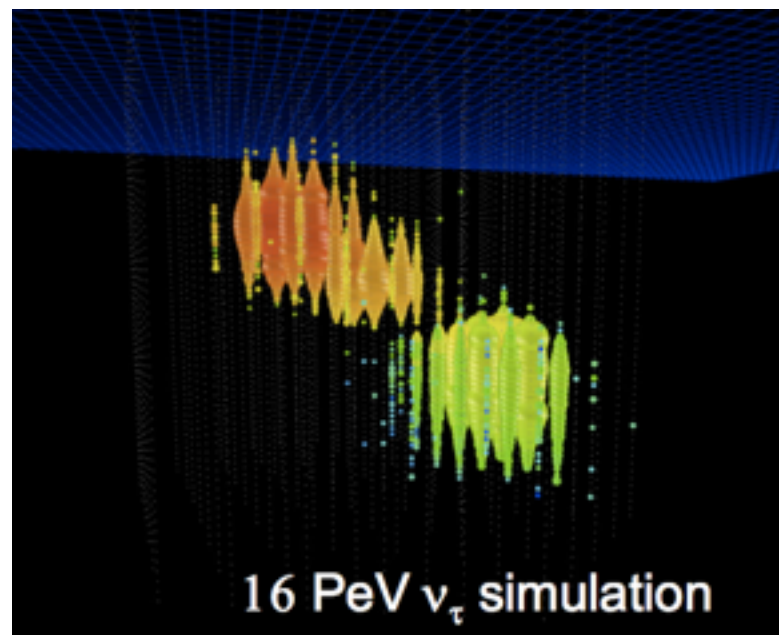


## Tracks:

- through-going muons
- pointing resolution  $\sim 1^\circ$

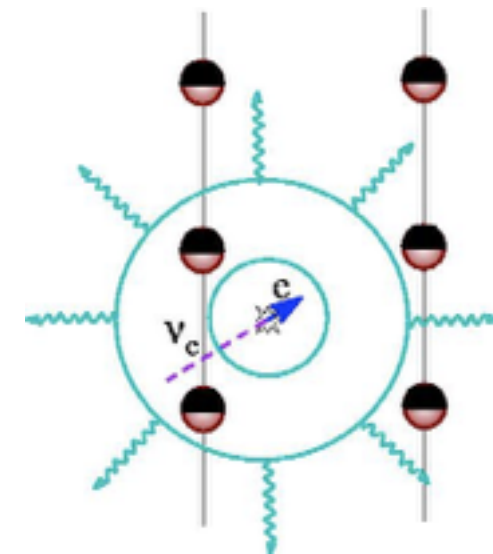
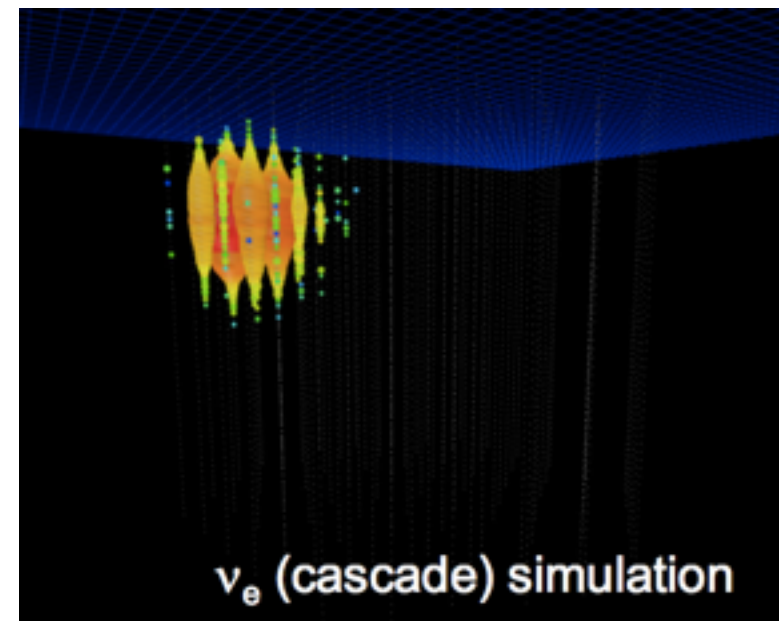
## Cascades:

- Neutral current for all flavors
- Charged current for  $\nu_e$  and low-E  $\nu_\tau$
- Energy resolution  $\sim 10\%$  in  $\log(E)$



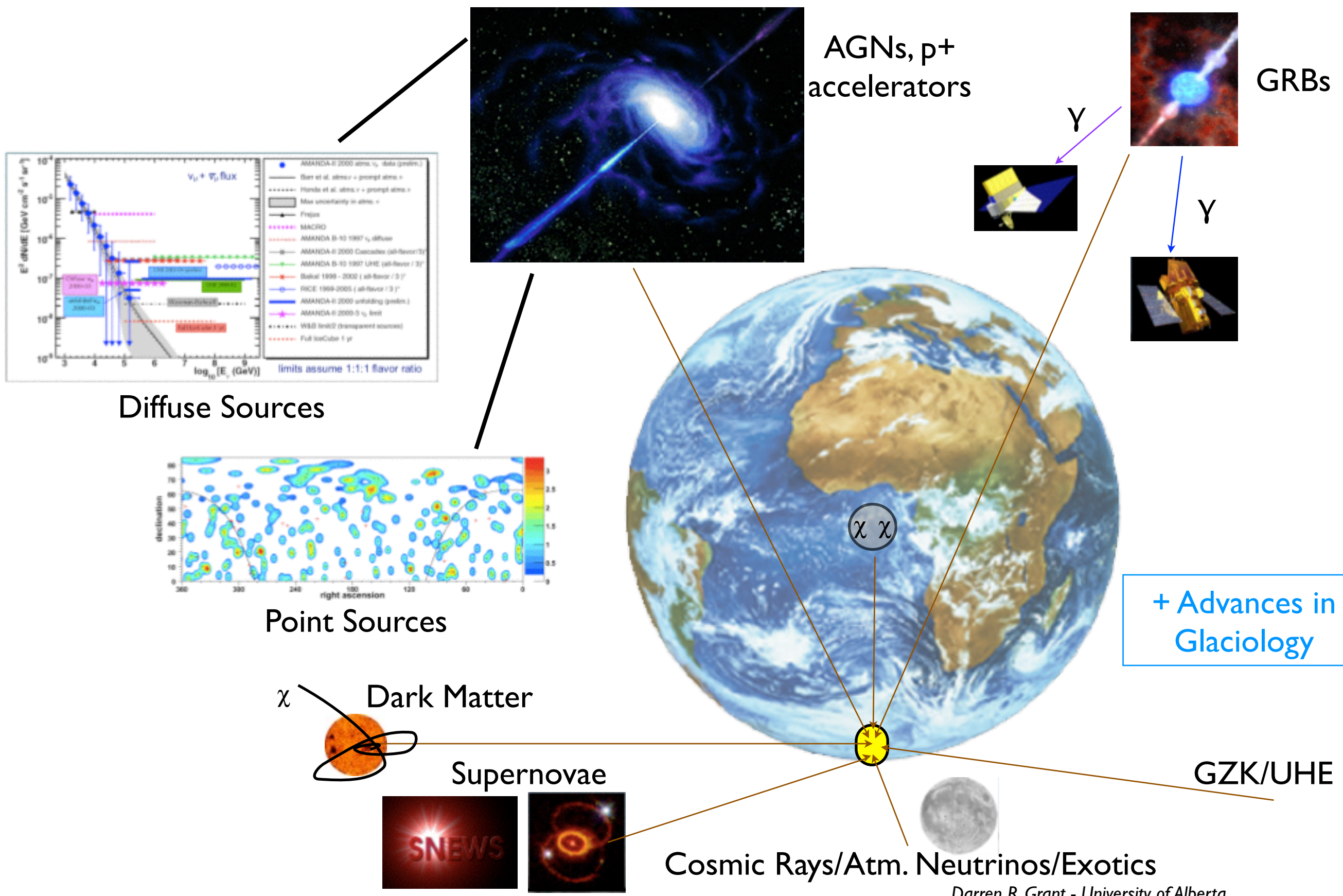
## Composites:

- Starting tracks
- high-E  $\nu_\tau$  (Double Bangs)
- Good directional and energy resolution



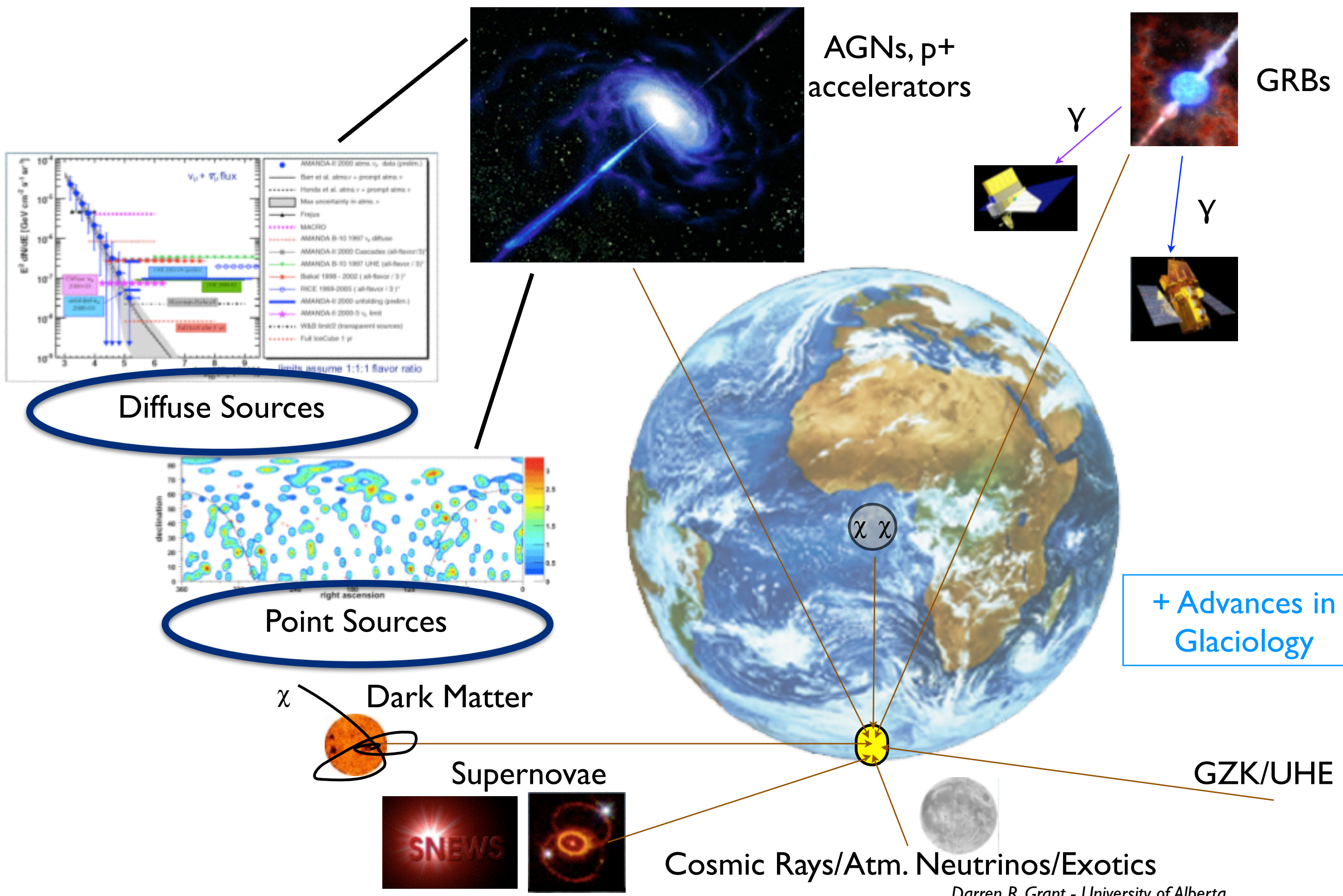


# The IceCube Neutrino Observatory - A Wealth of Science...





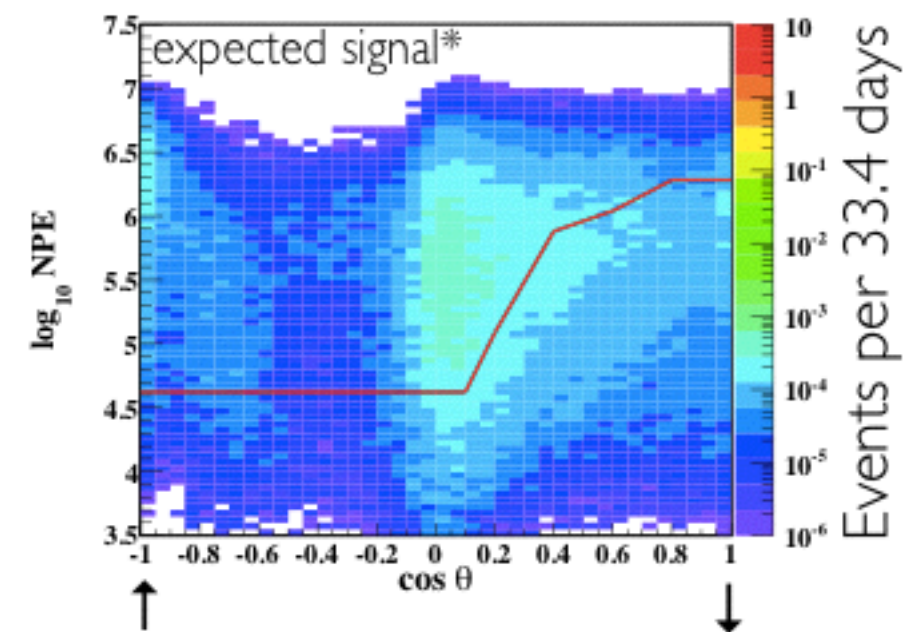
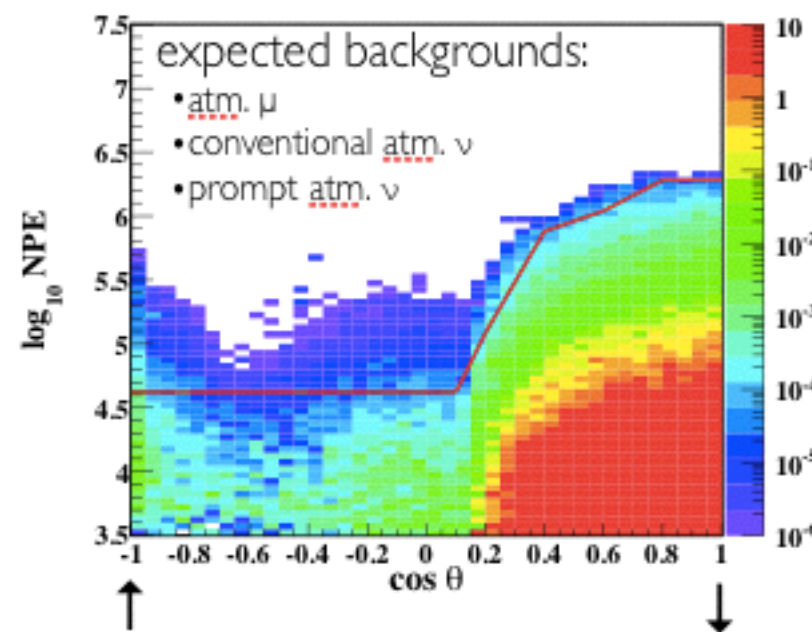
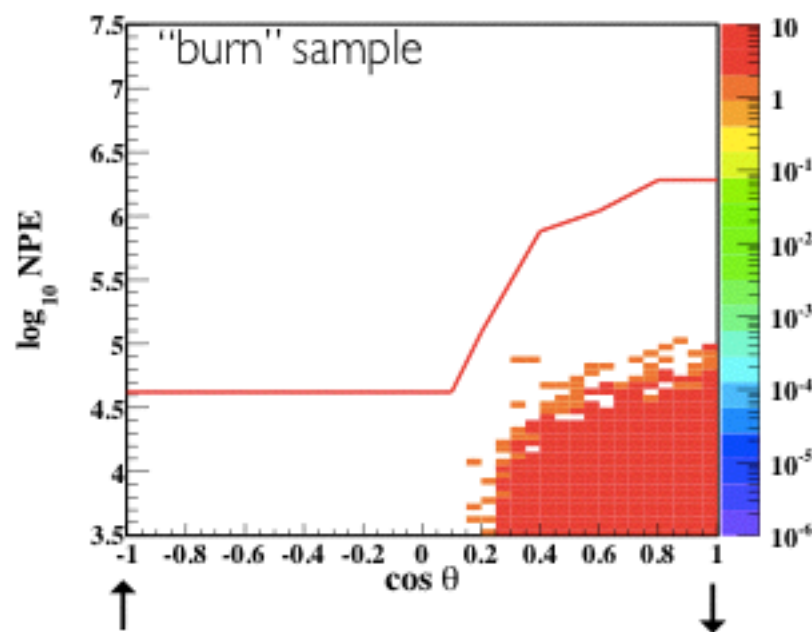
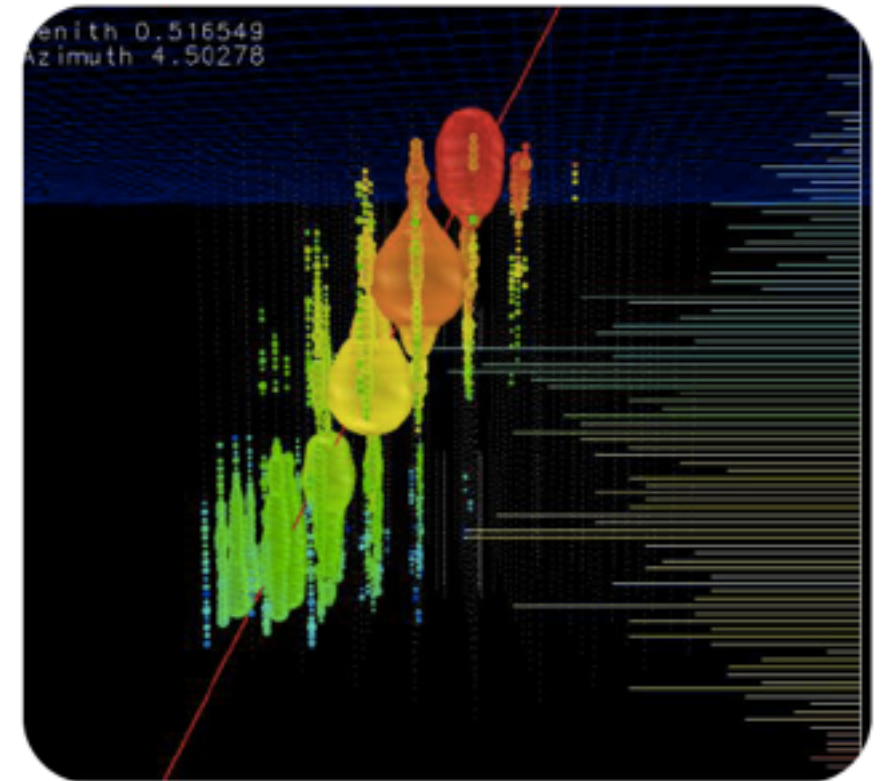
# The IceCube Neutrino Observatory - A Wealth of Science...





# 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

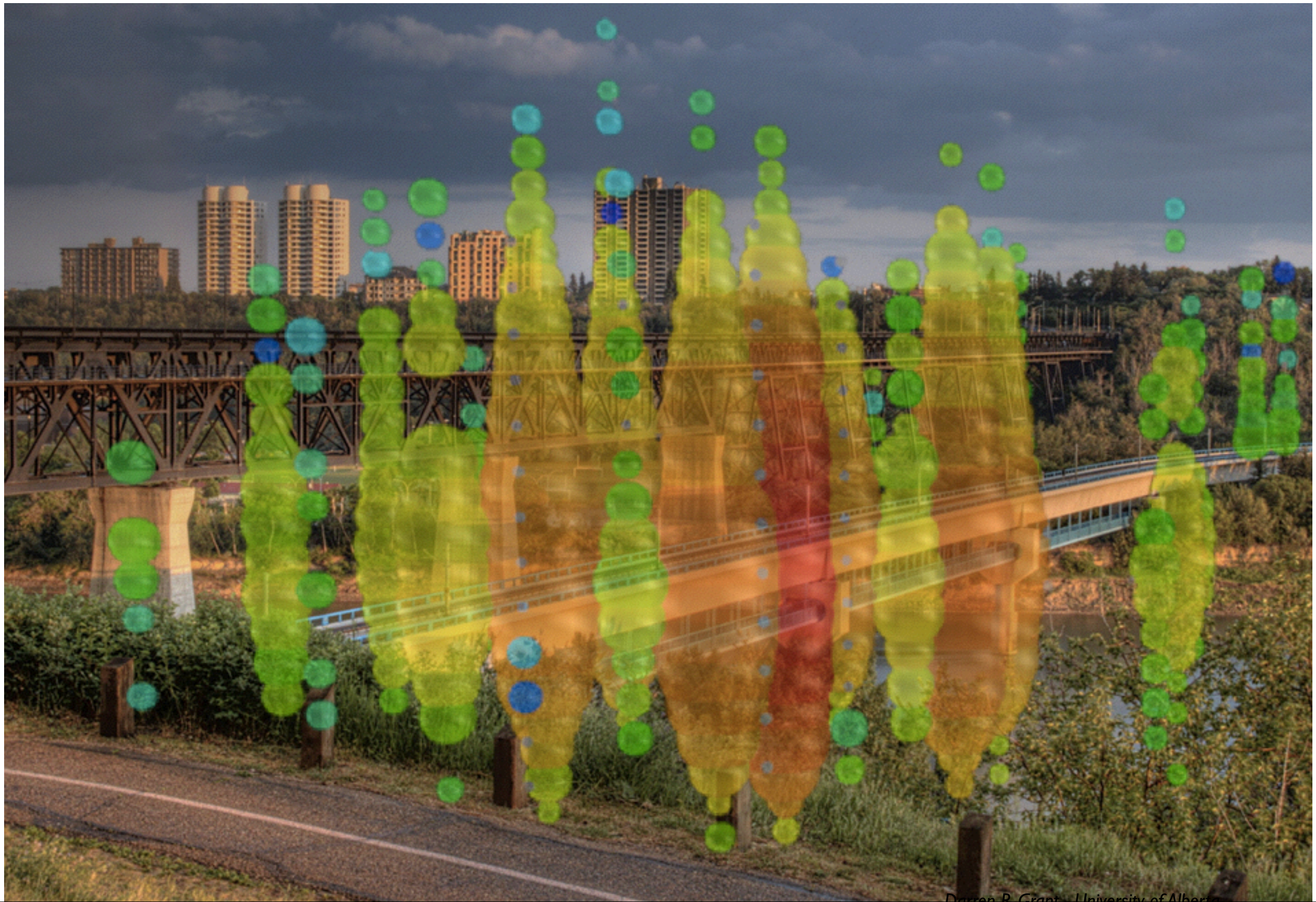


<http://arxiv.org/abs/1304.5356> (accepted PRL)

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



# A PeV neutrino visits the High Level Bridge...

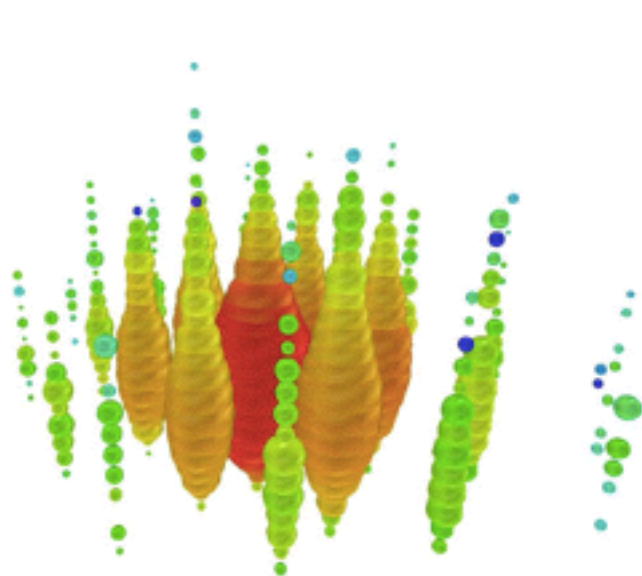




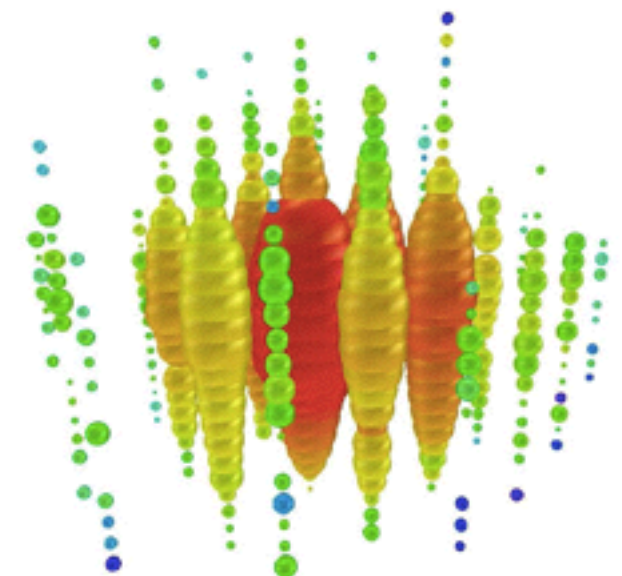
# The IceCube ultra high energy neutrino search

- 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...



$1.14 \pm 0.17$  PeV

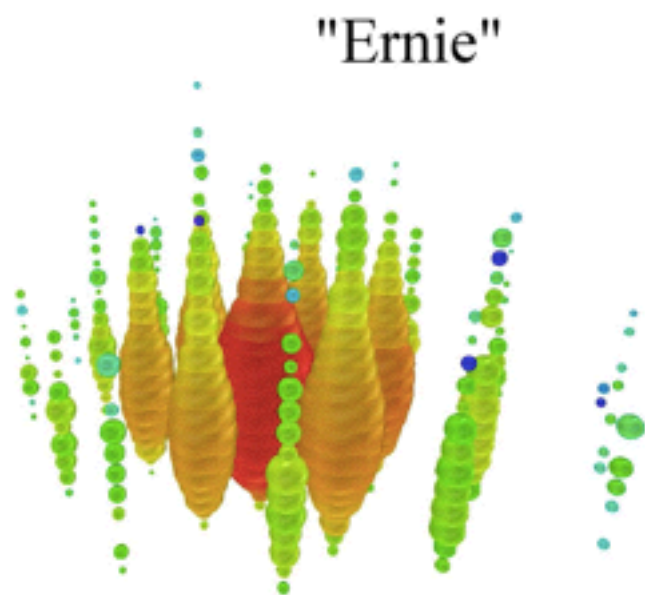


$1.04 \pm 0.16$  PeV

# The IceCube ultra high energy neutrino search

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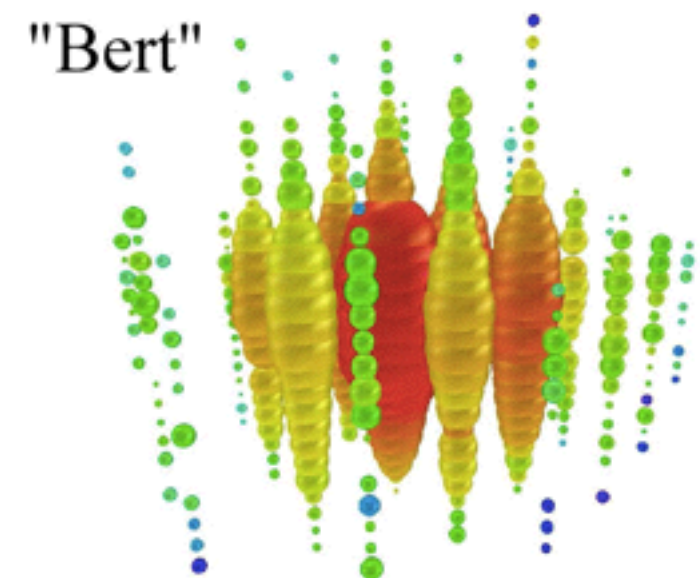
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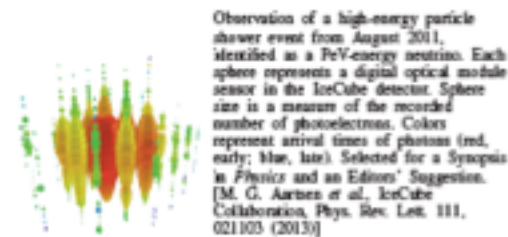
©2013 Sesame Workshop



$1.04 \pm 0.16$  PeV



# “Bert” becomes a cover model...



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™

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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).

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

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PHYSICAL  
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LETTERS™

Articles published week ending 12 JULY 2013

PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

2

Published by  
American Physical Society, APS  
physics

Volume 111, Number 2

# The next logical step...

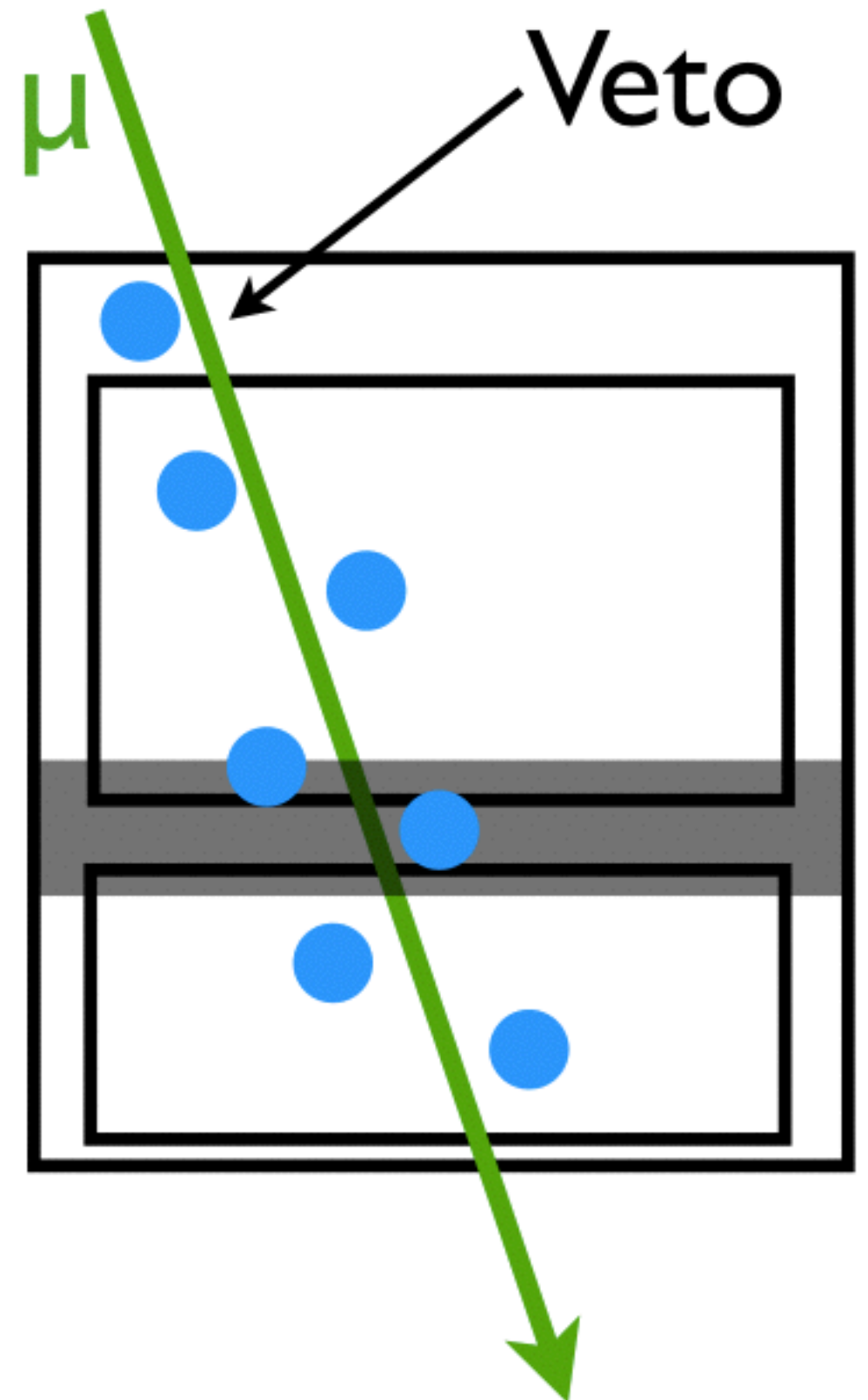
---

- 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  $2\sigma$
- 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 ( $\lambda_{\text{abs.}} \sim d_{\text{Earth}}$  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  $6 \pm 3.4$  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

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The result of the search...



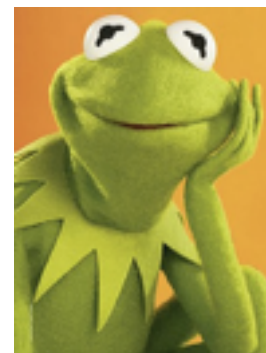
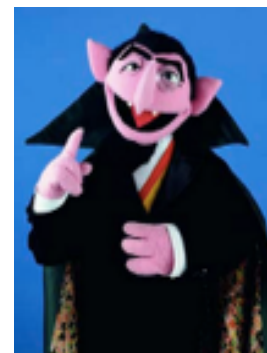
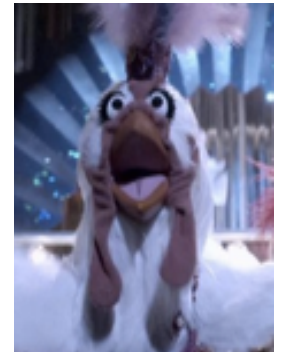
# The IceCube high energy starting events analysis

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

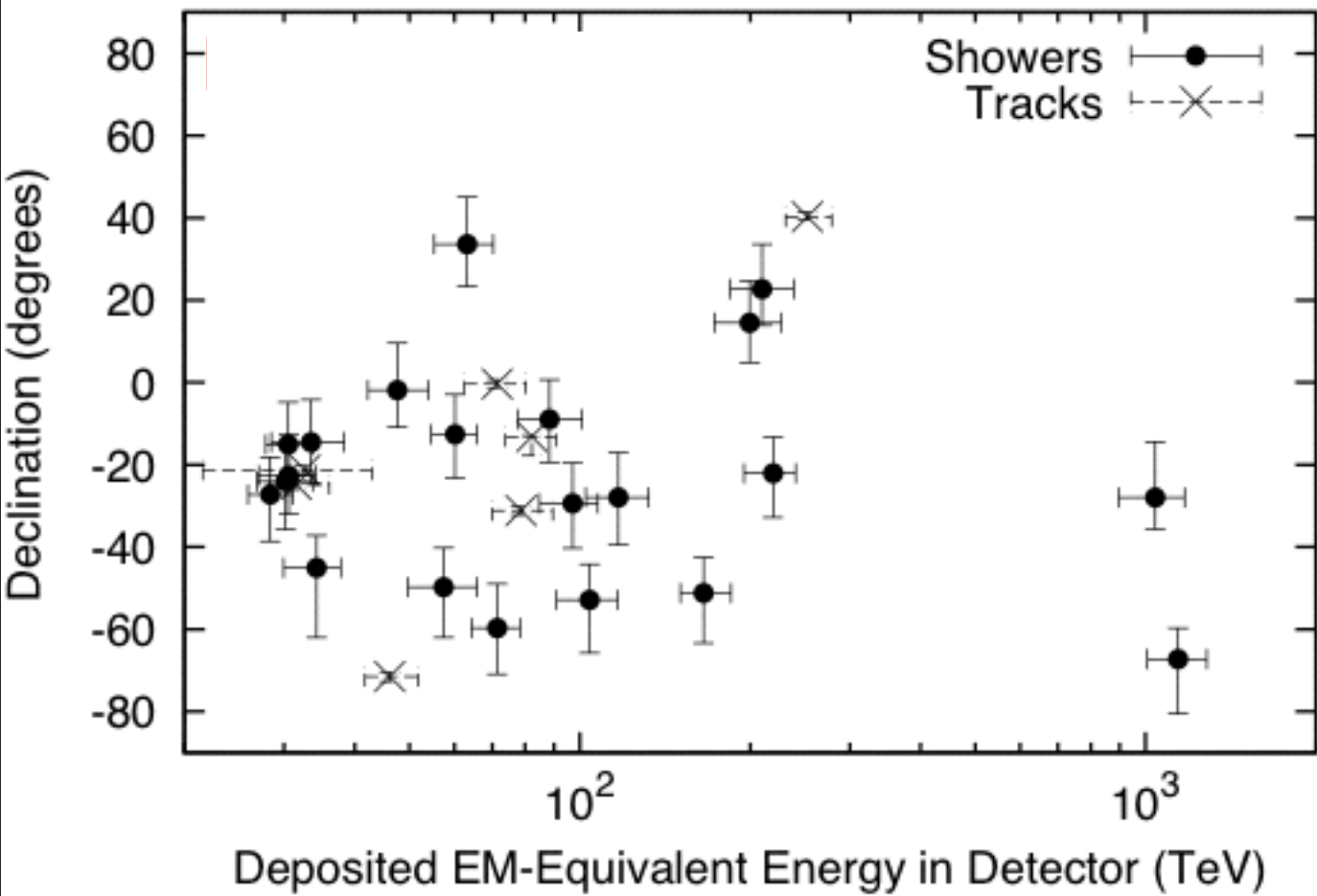
$>4.3\sigma$  in excess of expected terrestrial background signal



Images  
©2013 Sesame Workshop  
©The Walt Disney Company

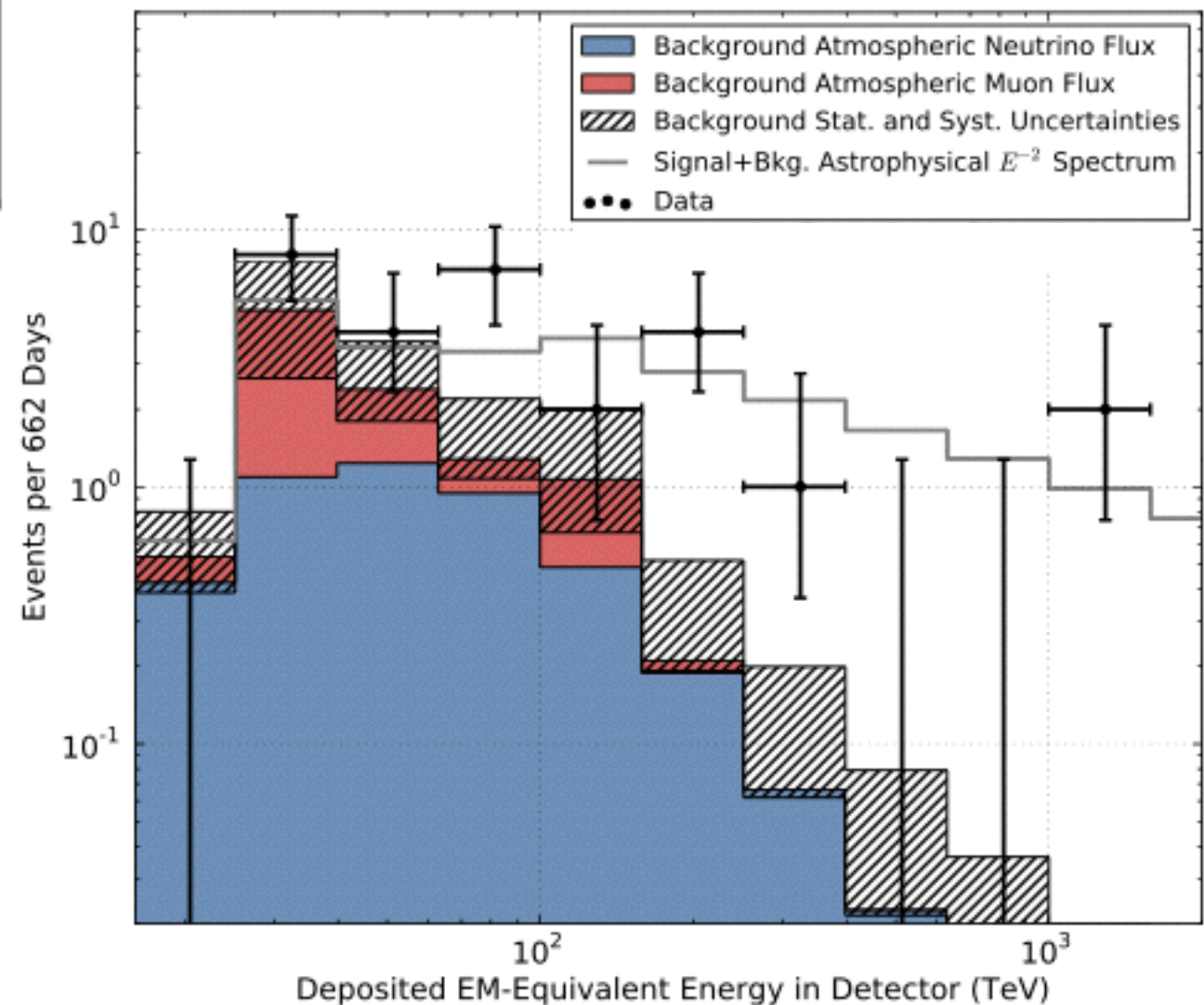


# The IceCube high energy starting events analysis



Note:

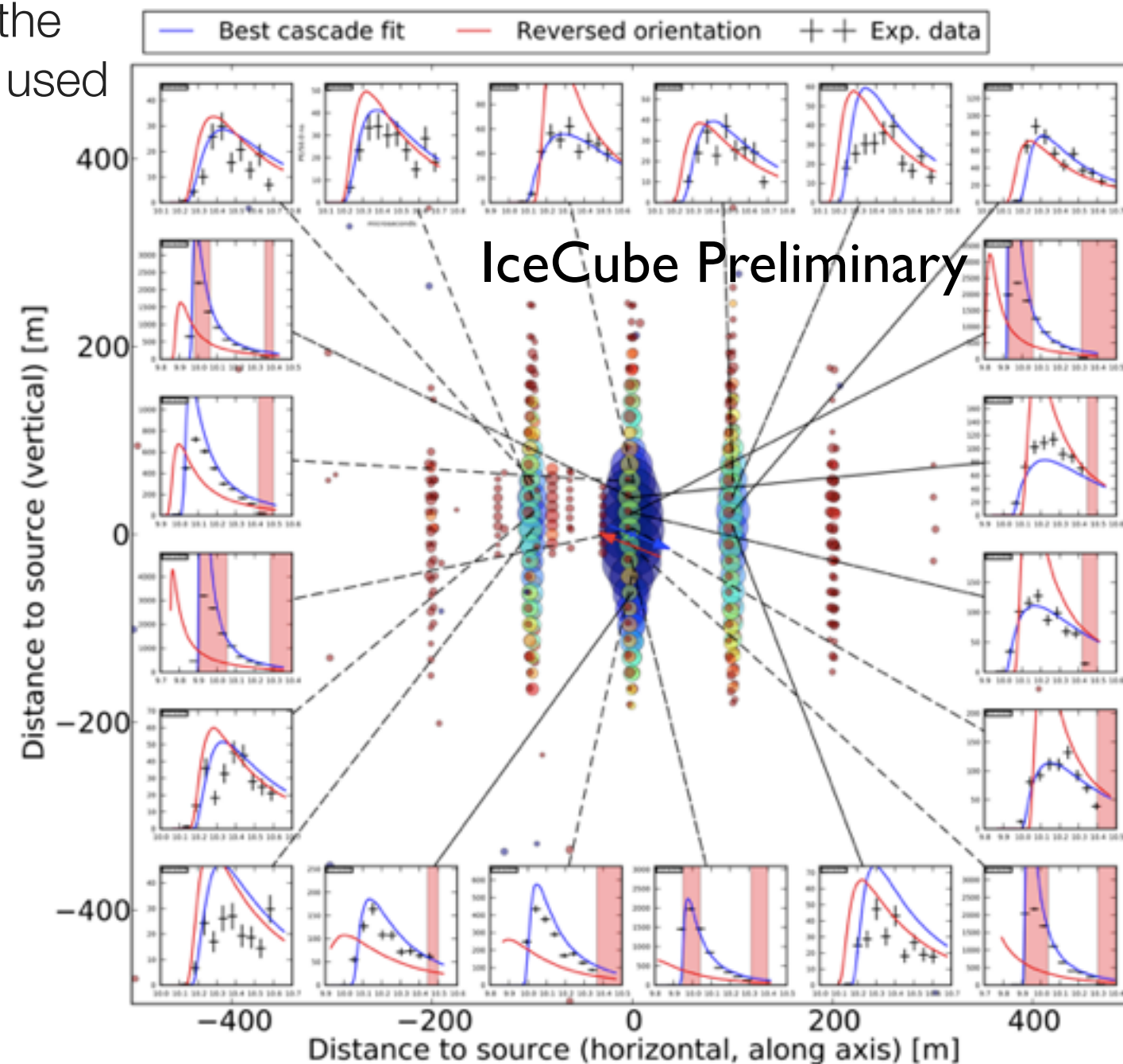
- a) "EM-equivalent energy" underestimates the E of  $\nu_x$  NC and  $\nu_\tau$  CC interactions
- b) Energy gap is not statistically significant
- c) For showers  $\sigma(E) \sim 10\%$  &  $\sigma(\phi) \sim 10^\circ - 15^\circ$



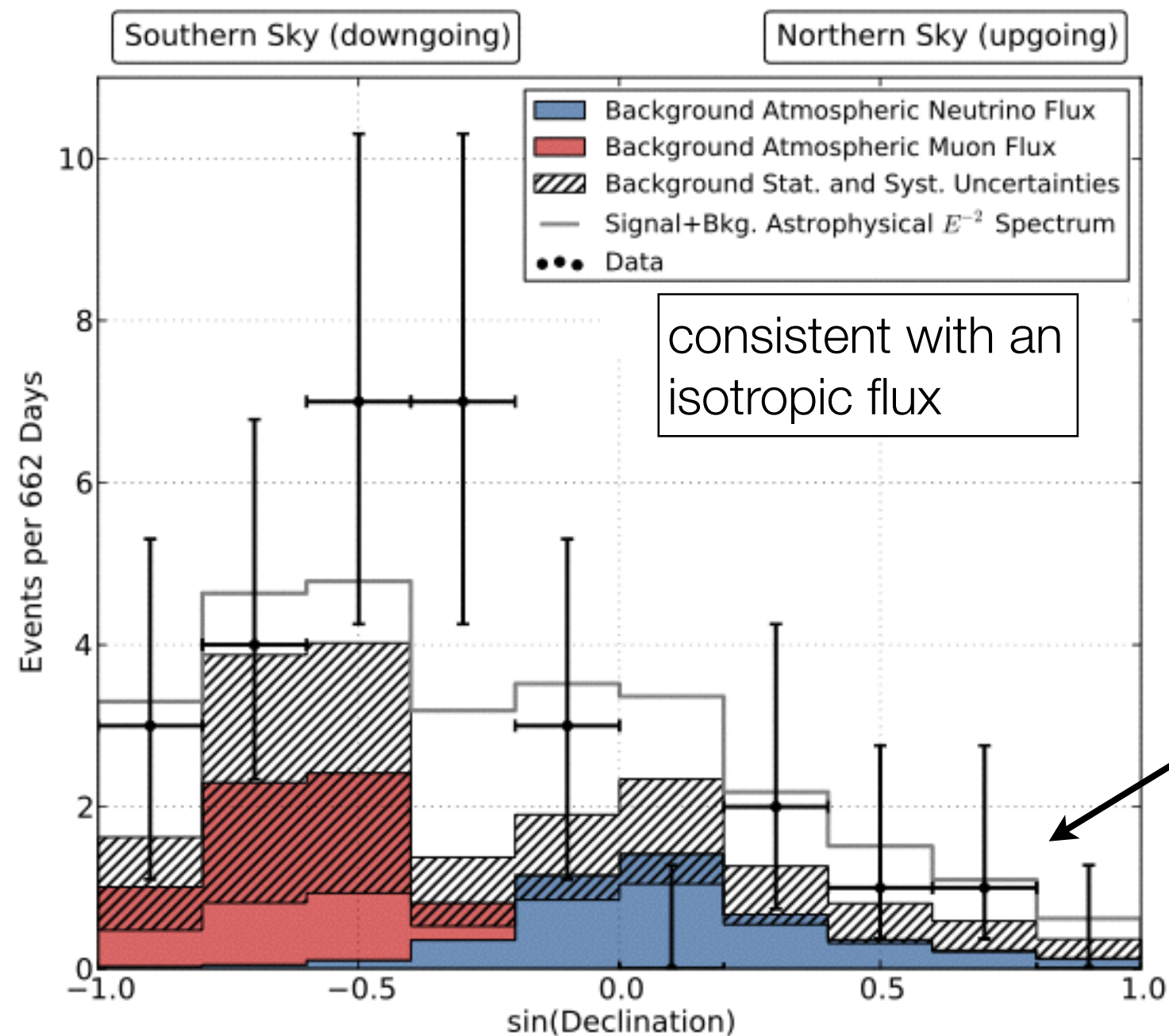


# The IceCube high energy starting events analysis

- 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

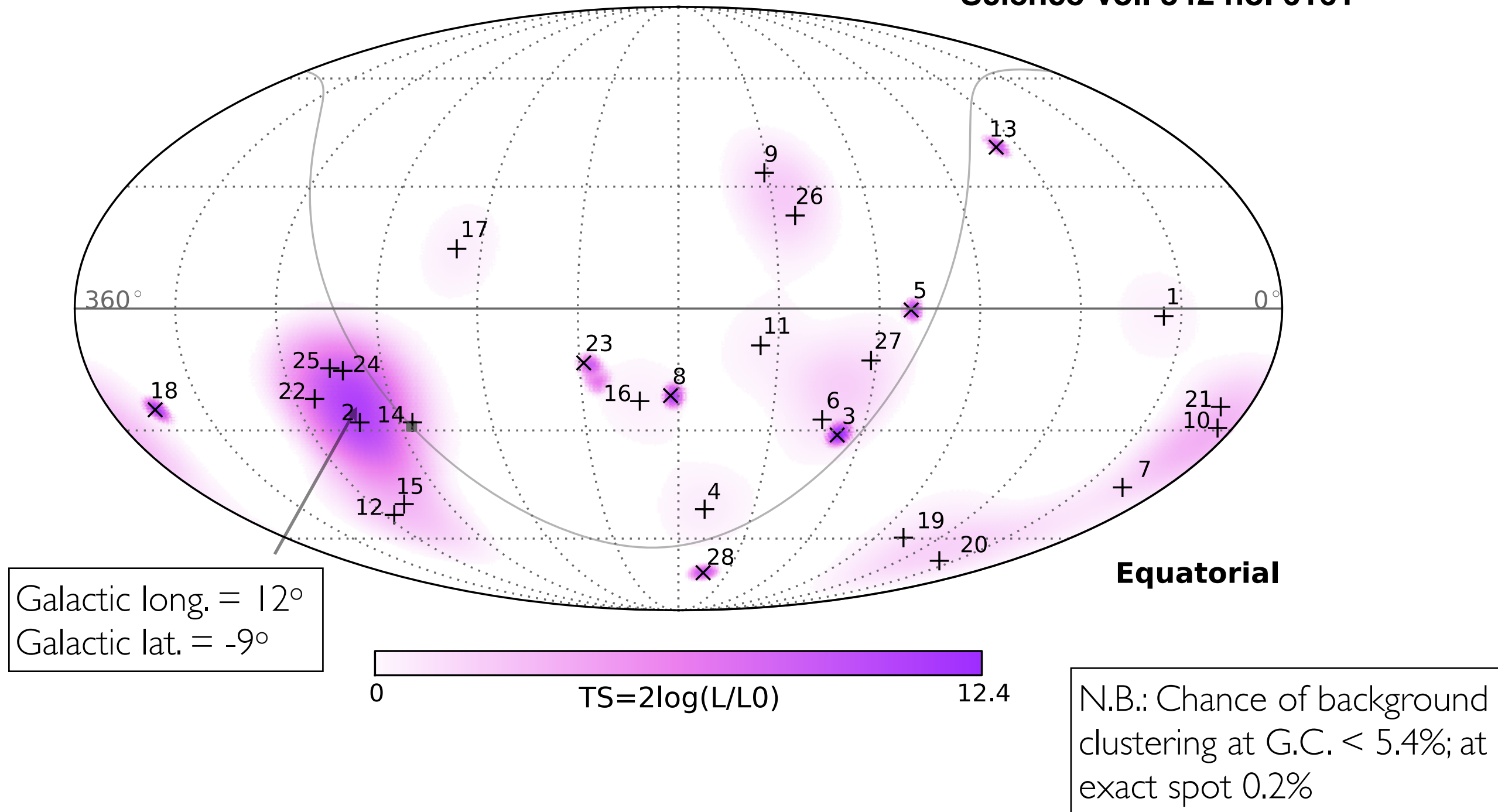
At these energies events here are absorbed



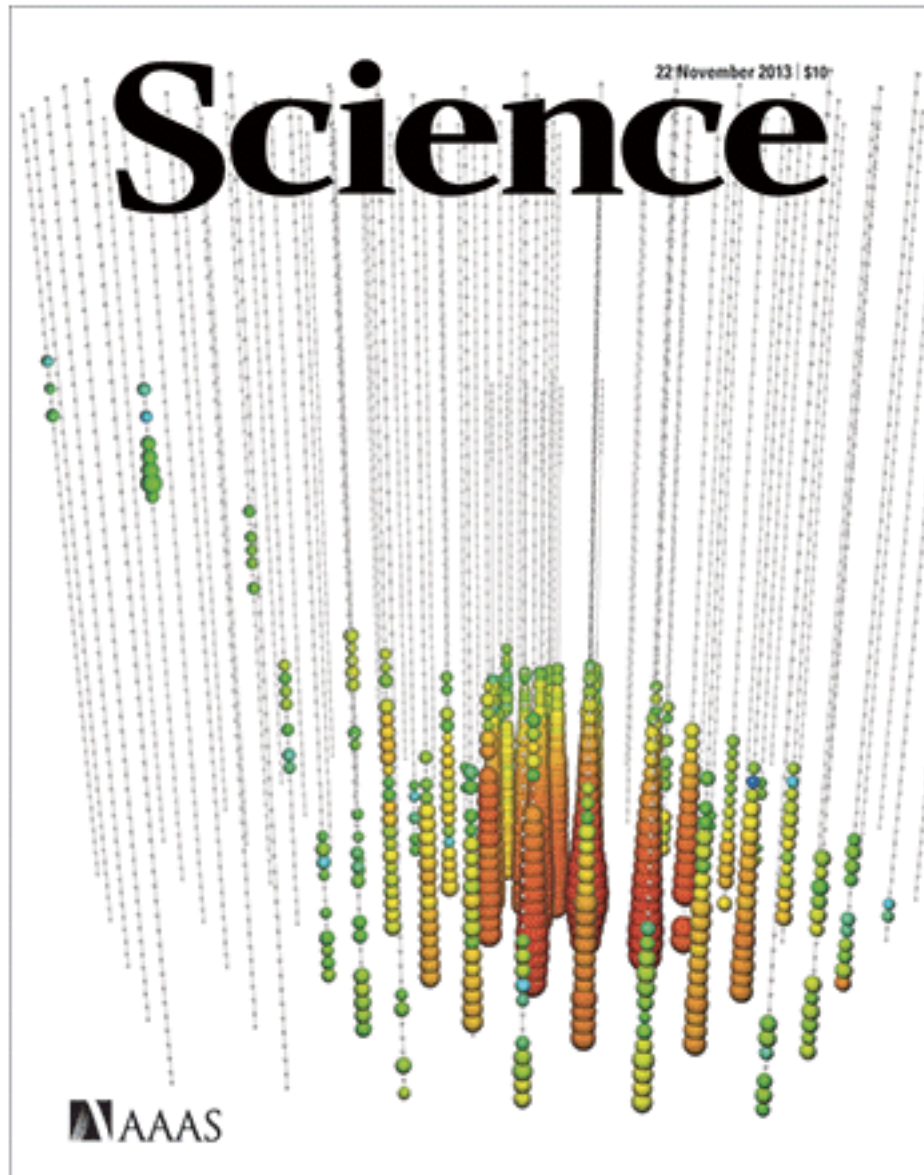
# The IceCube high energy starting events analysis

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

Science Vol. 342 no. 6161



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

Grant - University of Alberta

# 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...



# What is coming next?

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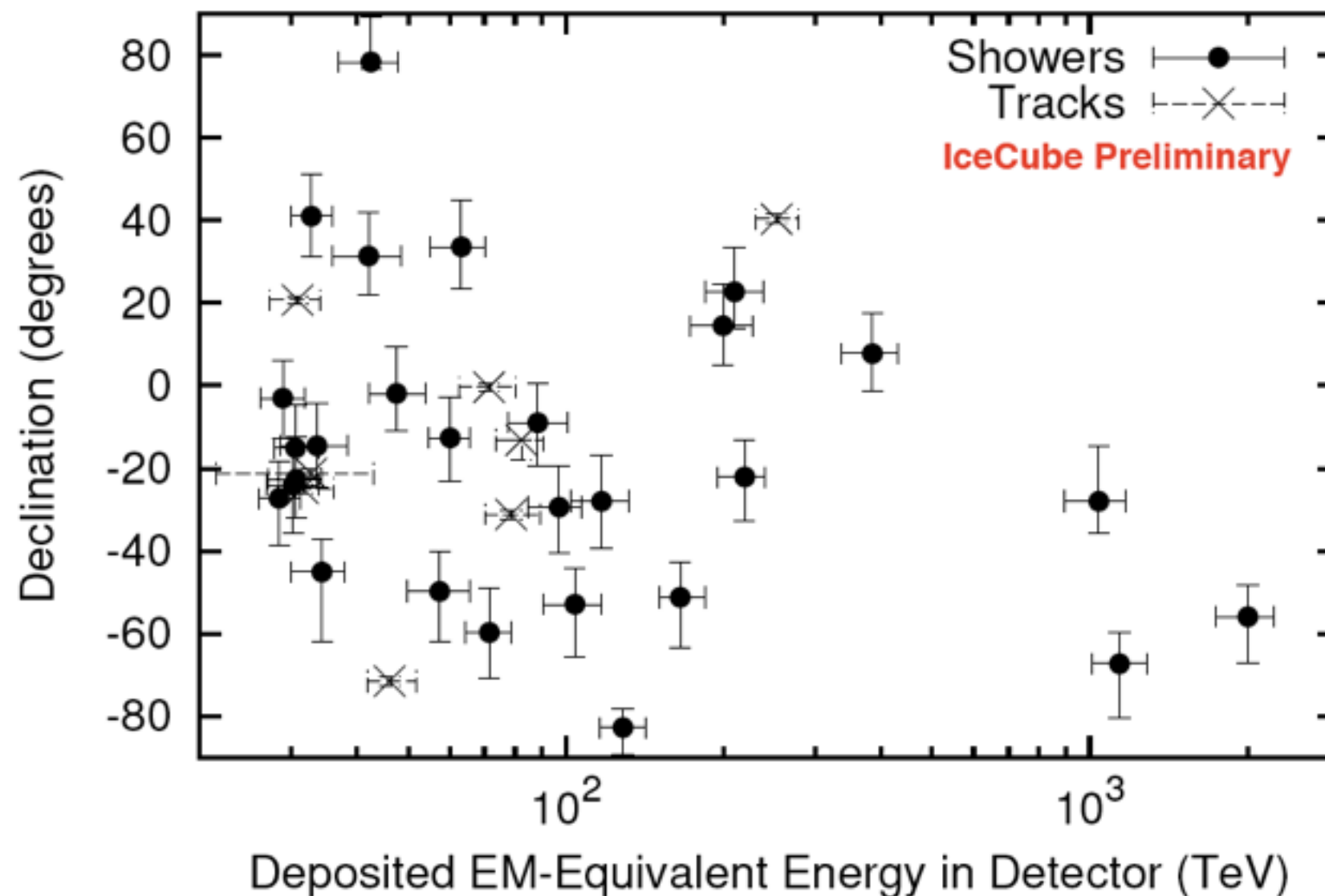
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[image Sesame Workshop](#)

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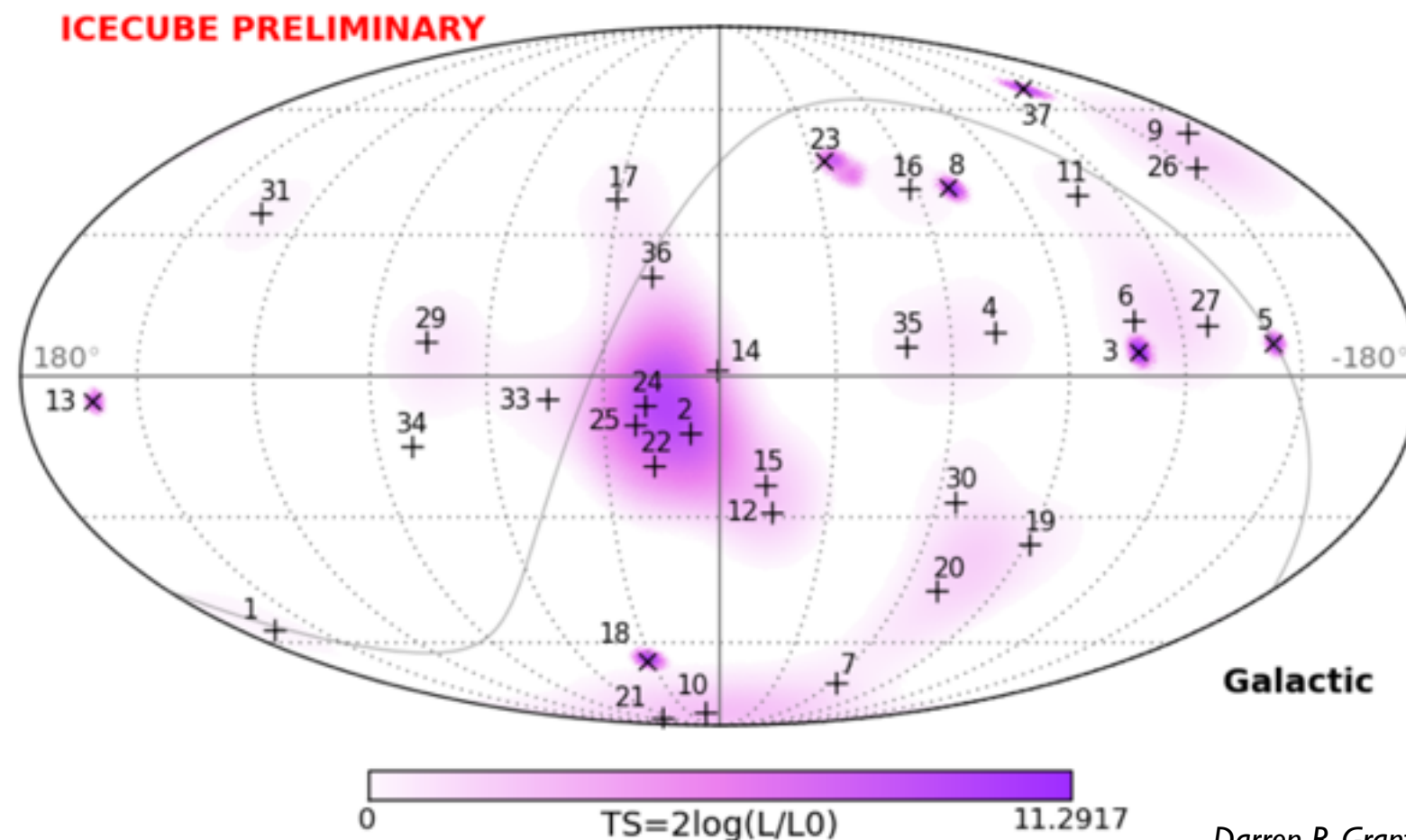
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  - As you add more data it is very much like taking a long exposure... eventually the details of the image become clear



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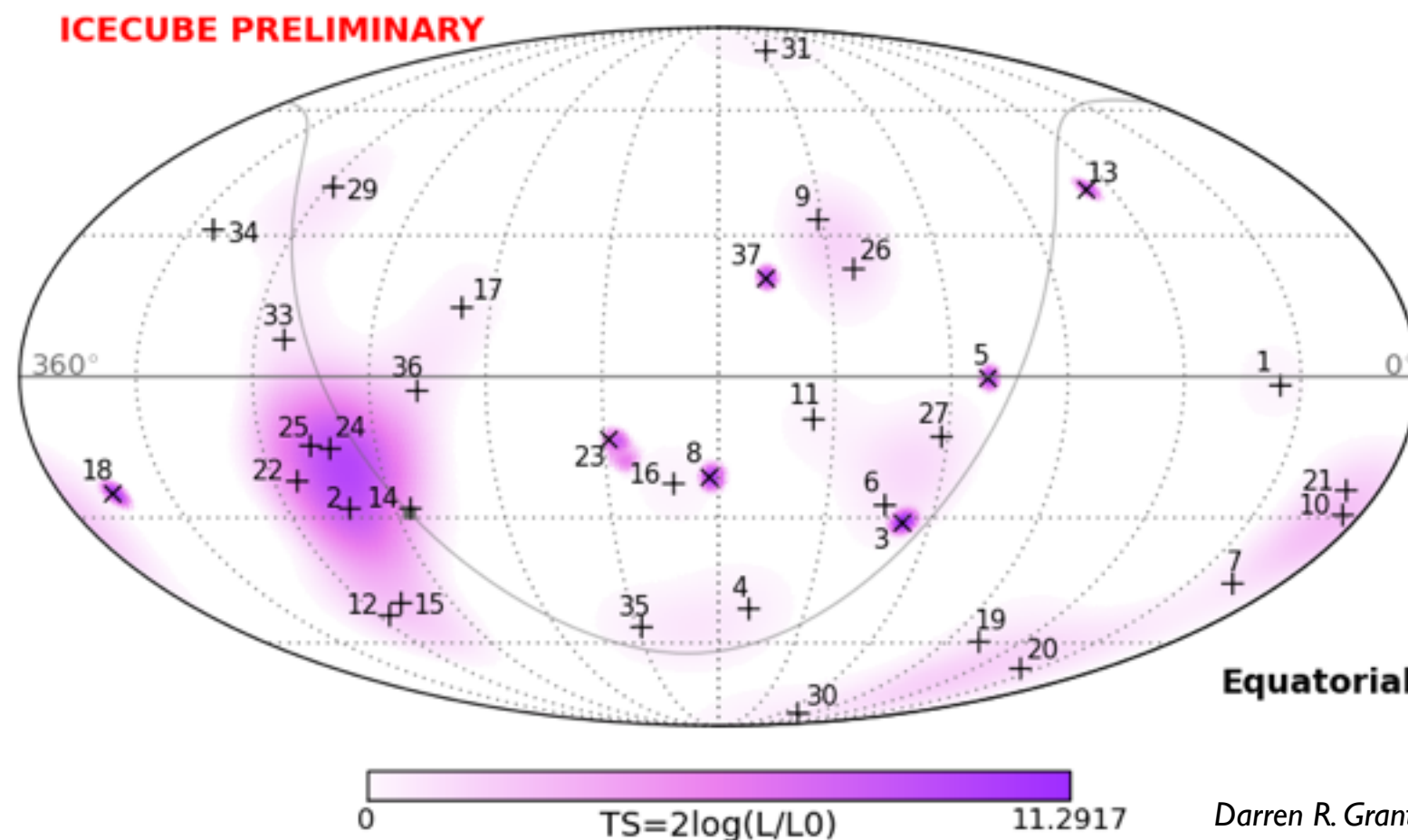
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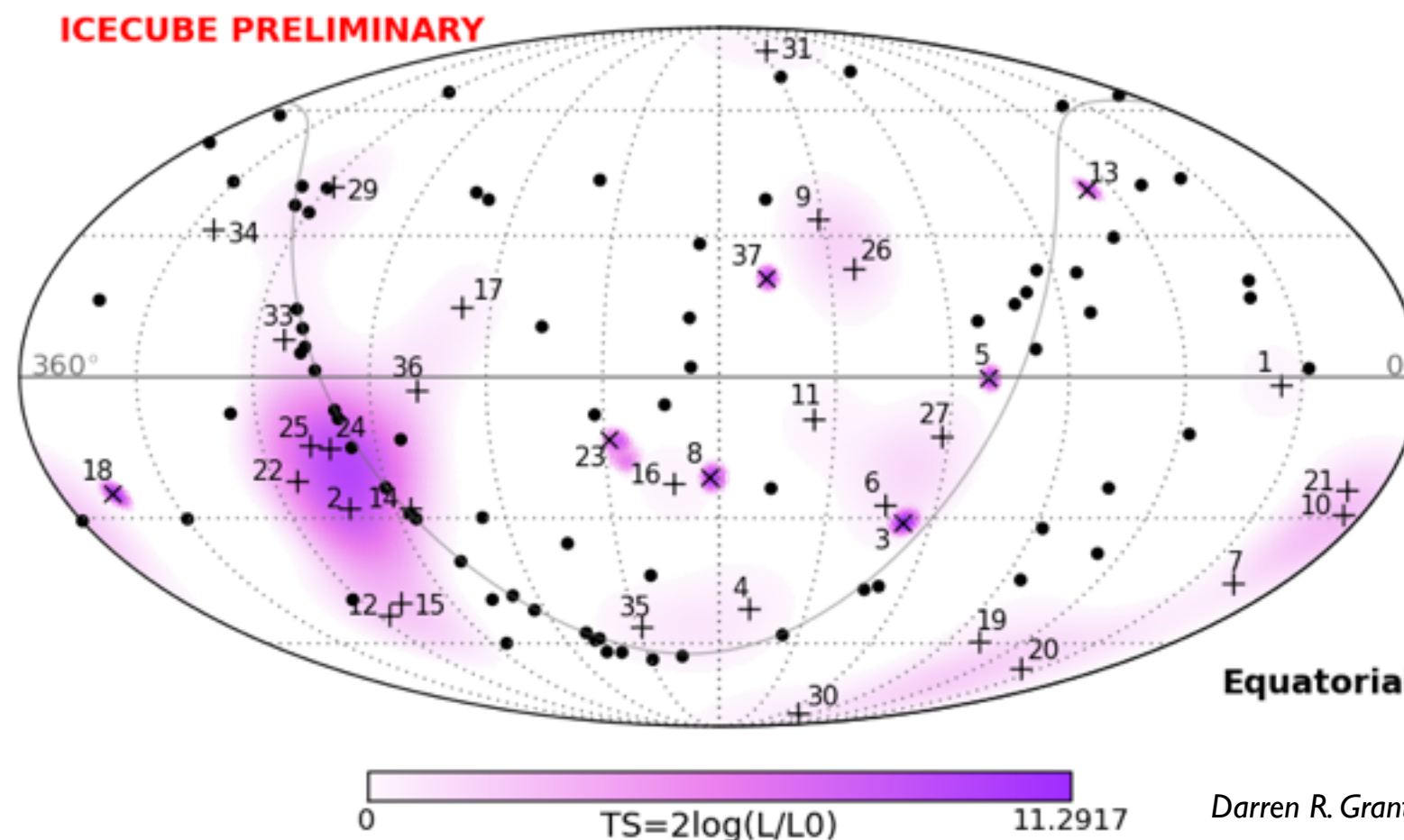
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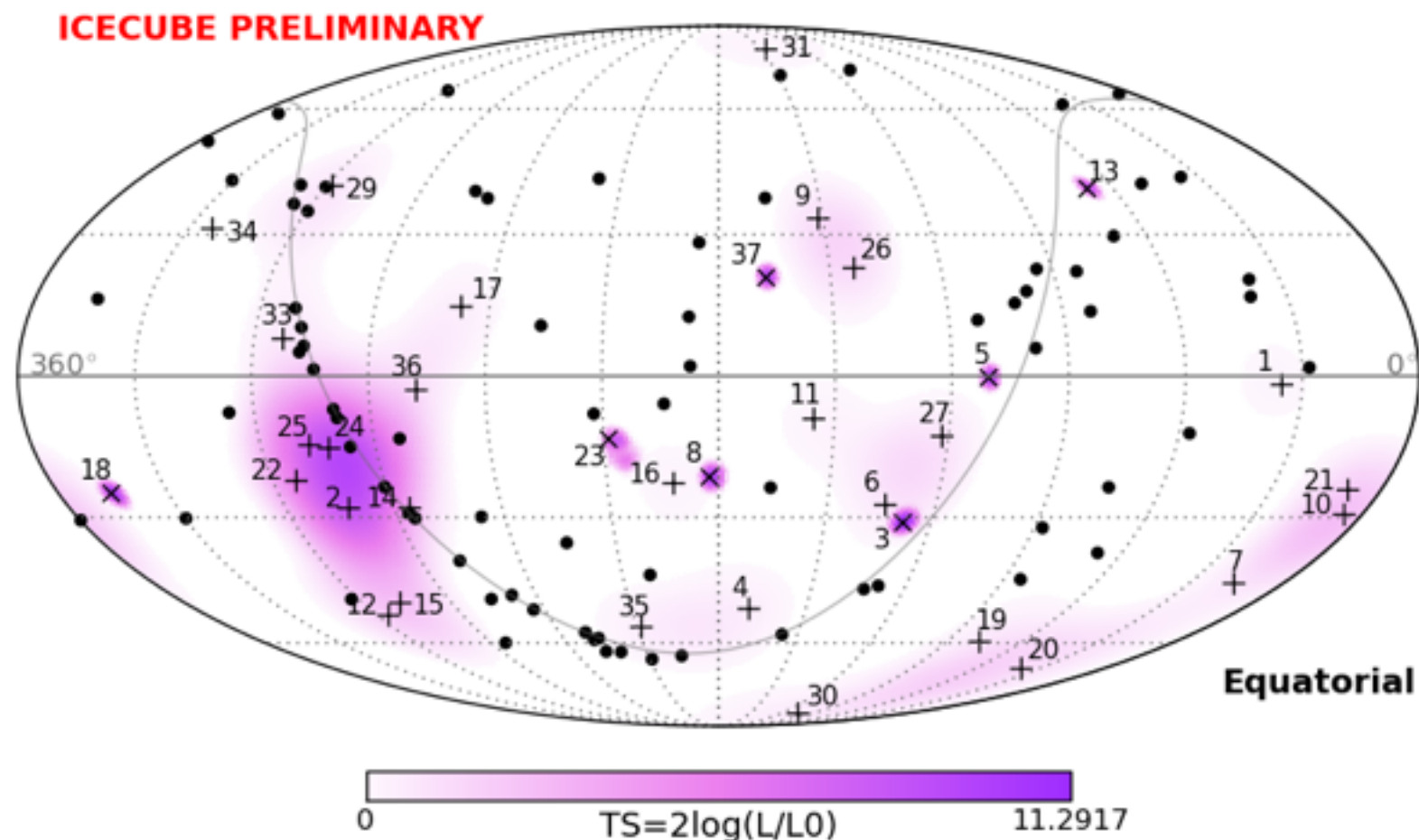
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# Summary

- 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...



SOMEWHERE  
IN  
THIS  
WORLD  
STALKS  
A  
THING  
THAT  
IS...

# NOT OF THIS EARTH

starring

PAUL BIRCH · BEVERLY GARLAND · MORGAN JONES · A ROGER CORMAN PRODUCTION

Screenplay by CHARLES B. GRIFFITH and MARK HANNA · Produced and Directed by ROGER CORMAN · AN ALLIED ARTISTS PICTURE

Darren R. Grant - University of Alberta



To conclude...they have arrived!



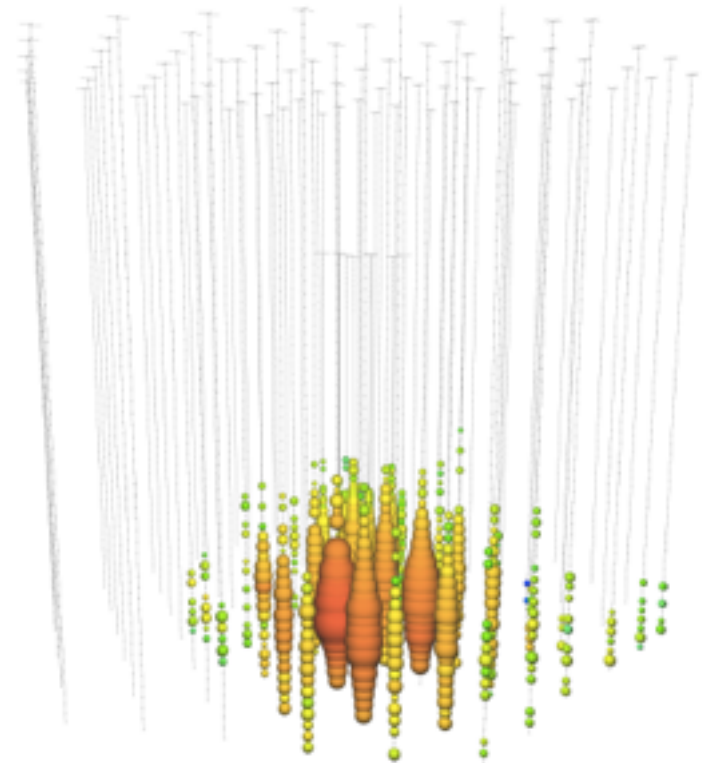
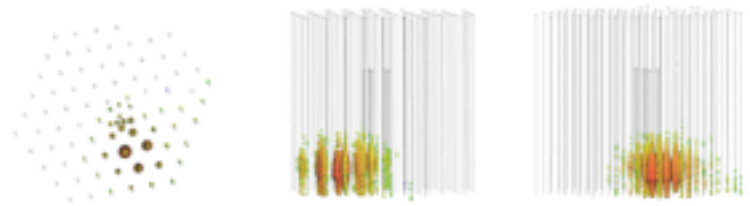
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“Gonzo the Great”



Thanks for your attention!

image  
[muppet.wikia.com](http://muppet.wikia.com)

Darren R. Grant - University of Alberta



# Backup slides

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