The Birth of Neutrino Astrophysics

Naoko Kurahashi Neilson
University of Wisconsin, Madison
IceCube Collaboration

CosPA – Nov 15th, 2013

Outline

- The Case for Neutrino Astrophysics
- First Evidence
- Neutrino Astronomy v1.0
- Beyond v1.0

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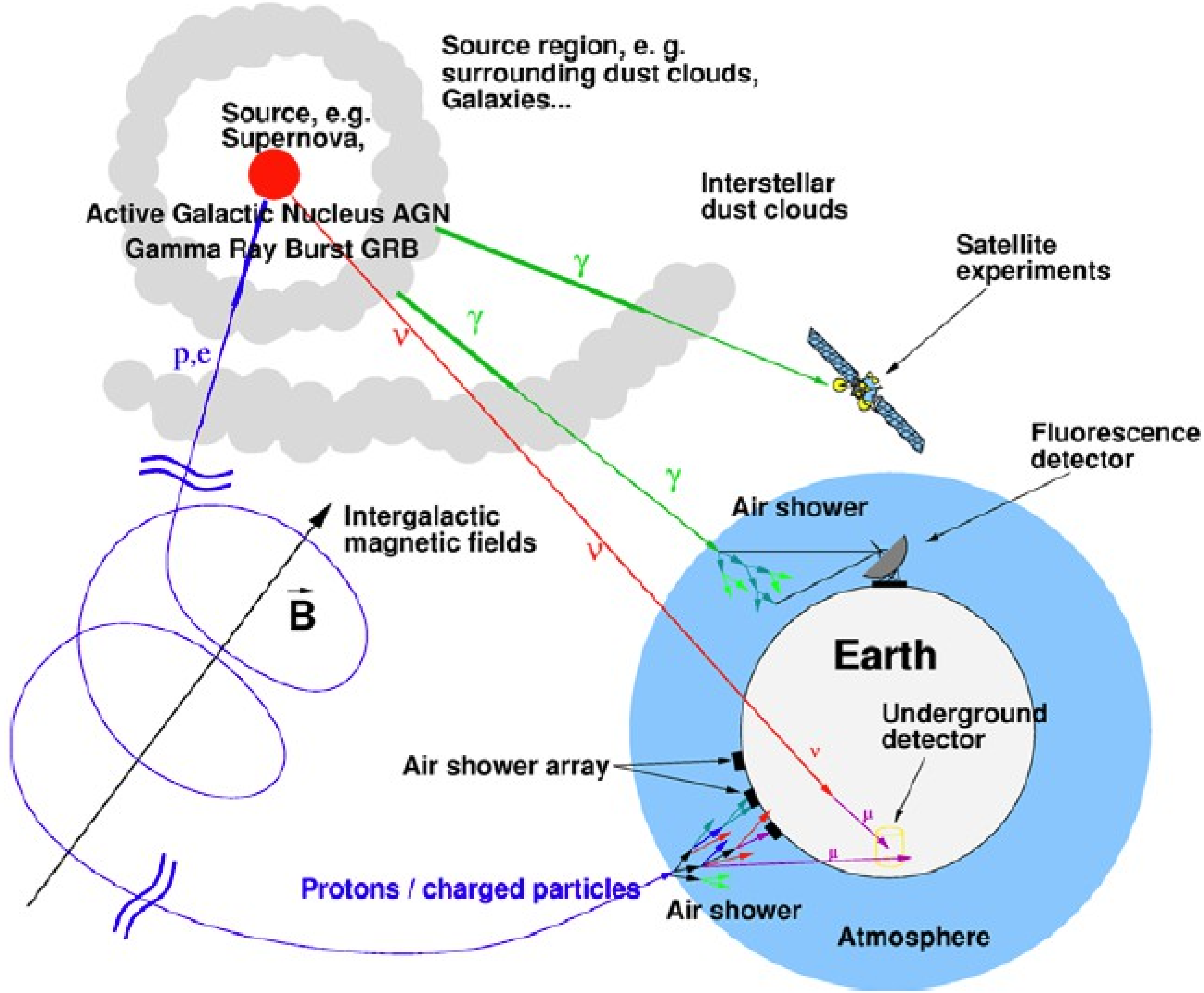
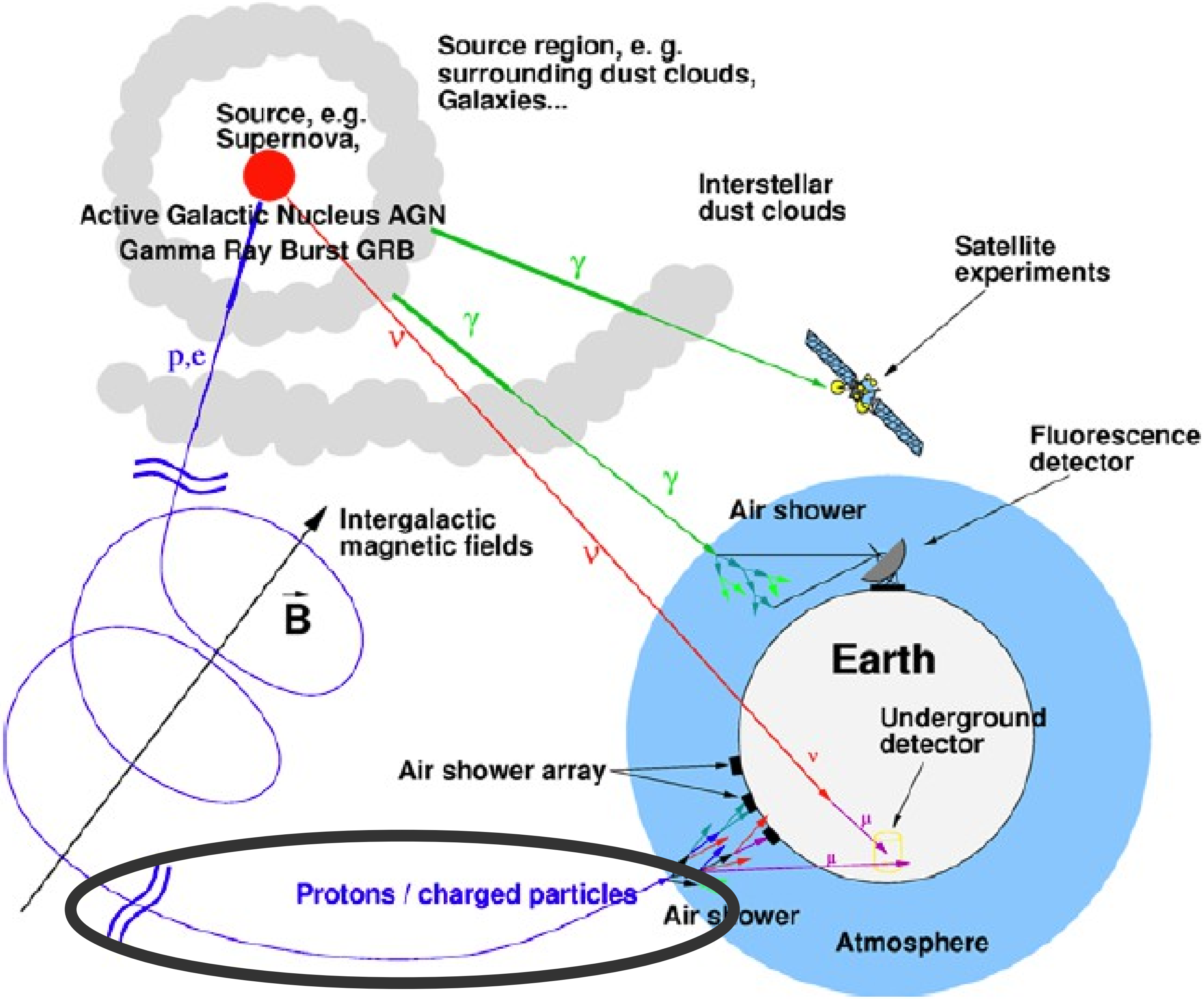
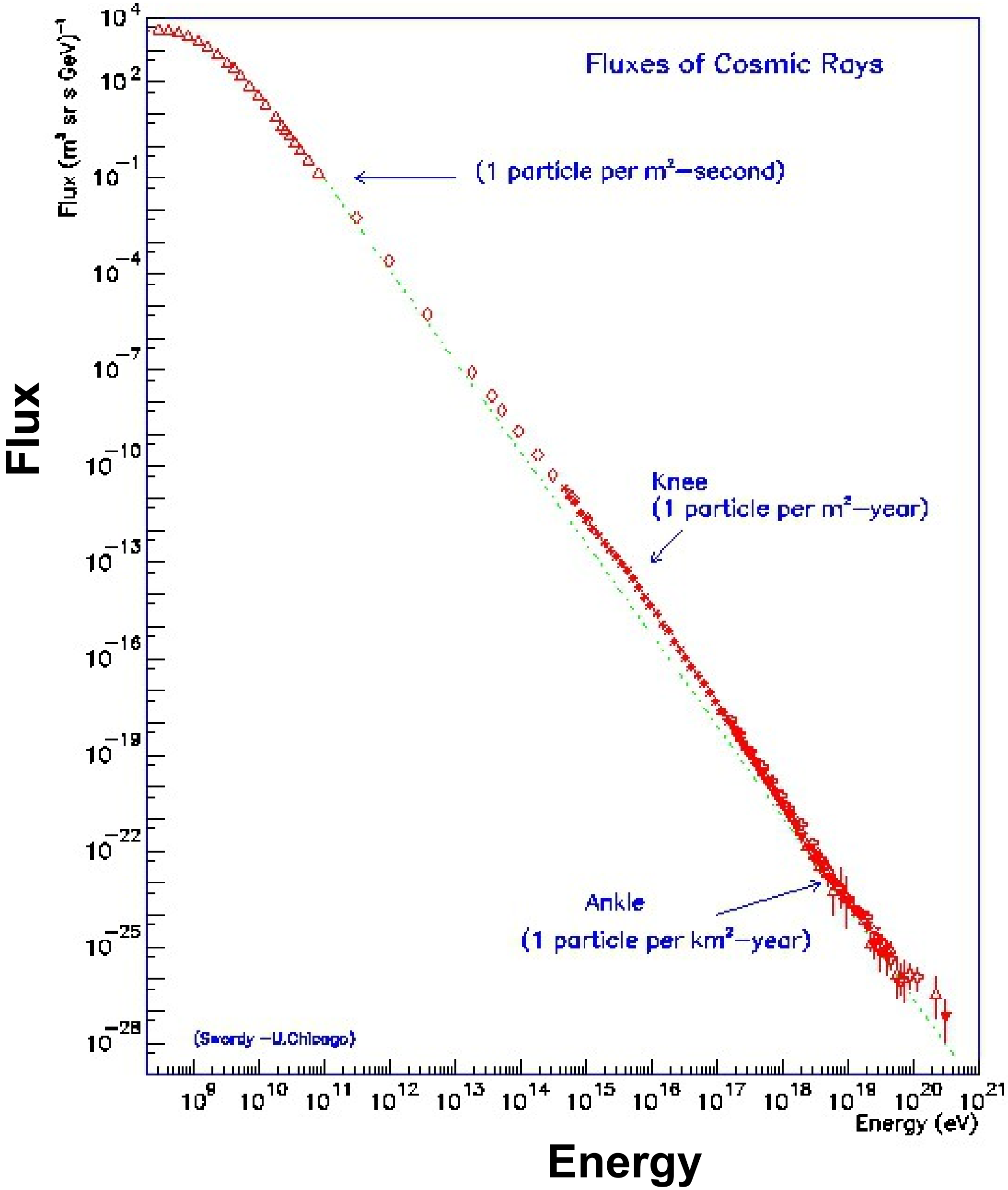
Neutrino Astronomy



Neutrino Astronomy





J. Cronin, T.K. Gaisser, and S.P. Swordy, Sci. Amer. v276, p44 (1997)

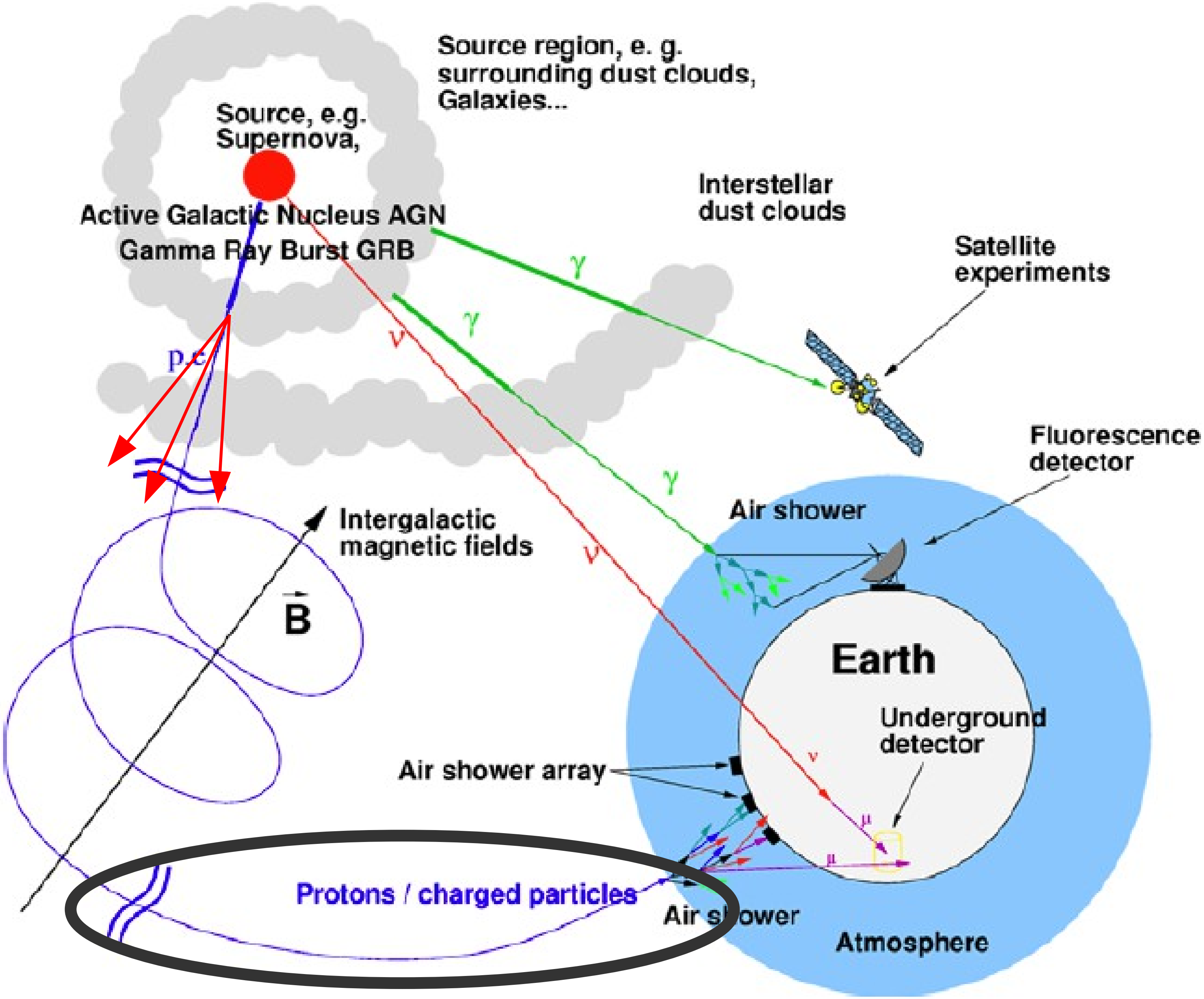
- Low energy cosmic-rays can't escape local magnetic fields
- High-energy cosmic rays hitting gas clouds or interstellar dust interact and deplete

- p+p or nucleon+p type interactions give neutrinos

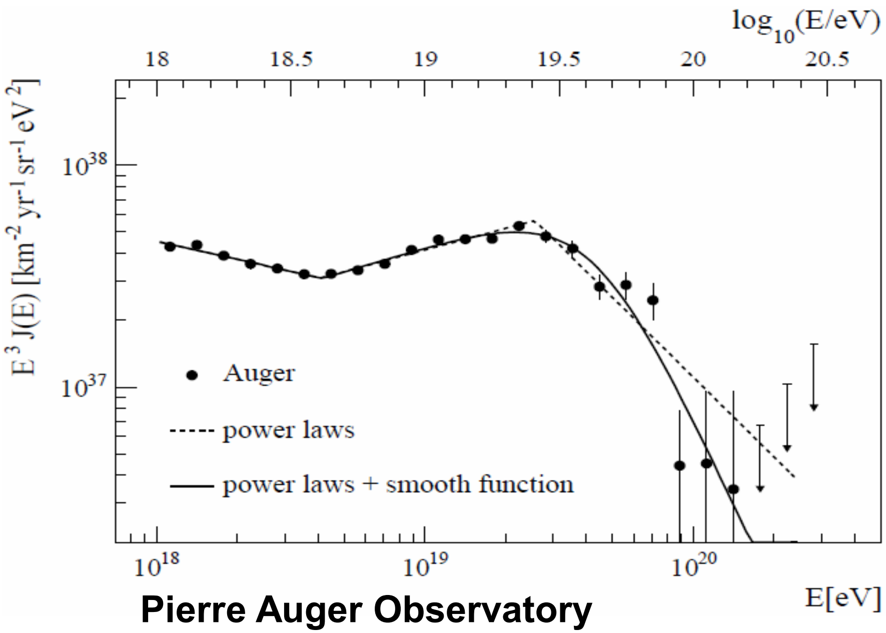
⬇

Absorption of cosmic rays means creation of neutrinos

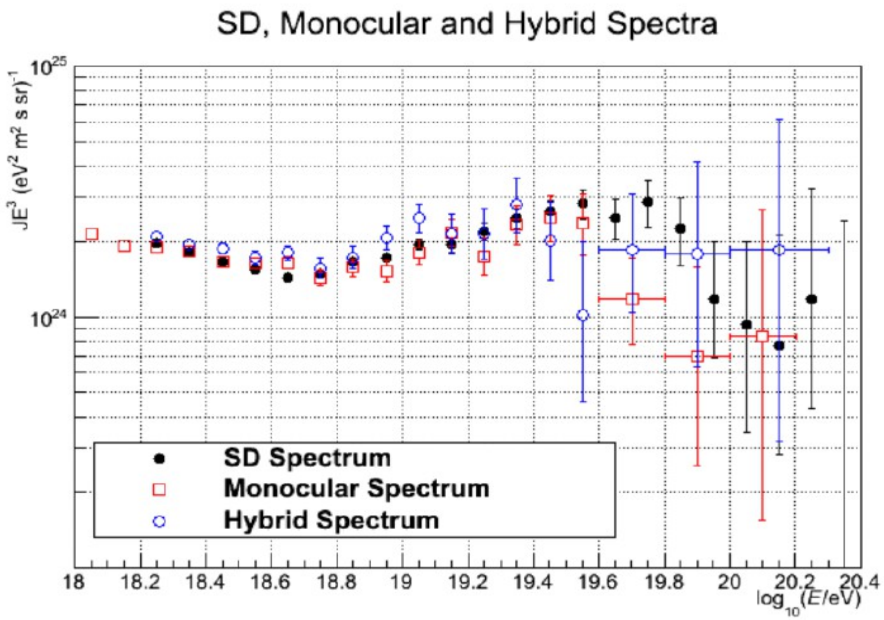
Neutrino Astronomy



10's and 100s of EeV cosmic rays have been observed

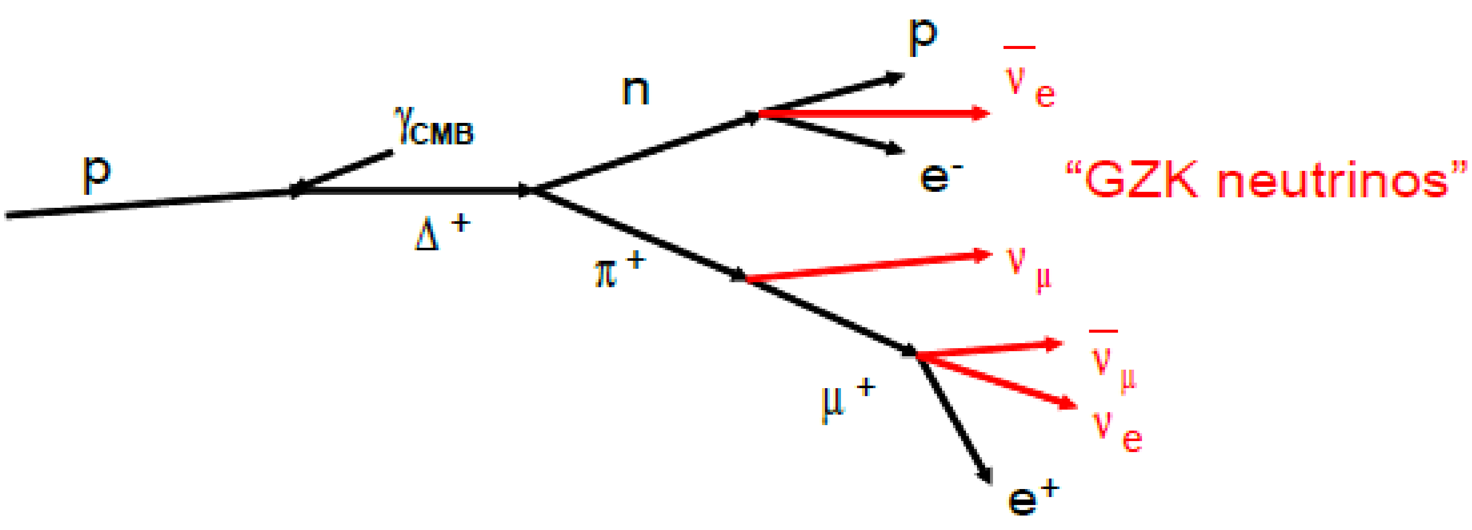


Pierre Auger Observatory
2011, arXiv:astroph/1107.4809



TA talk from yesterday, T. Okuda

Above ~5 x 10^{19} eV, cosmic rays interact with CMB to produce pions:



Dedicated GZK Neutrino Searches

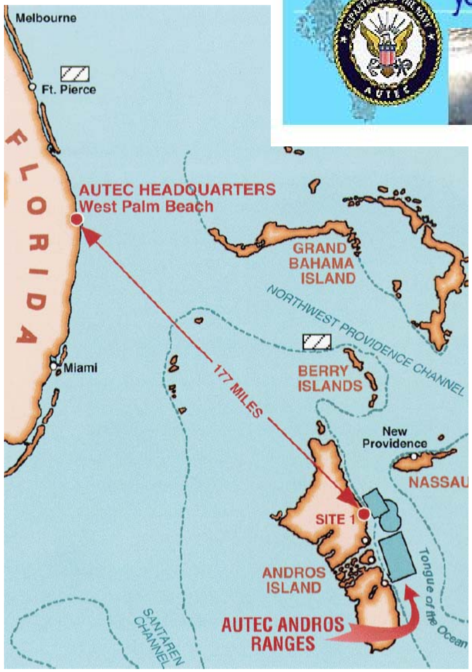
Askaryan Radio Array

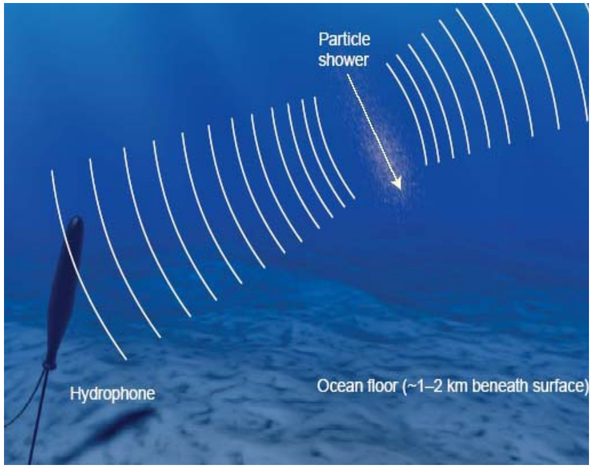
Pierre Auger Observatory

IceCube

SAUND

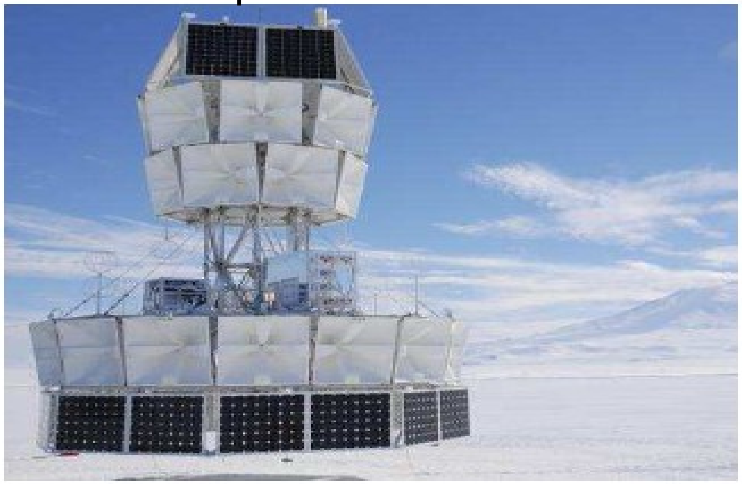
Study of Acoustic Ultra-high energy Neutrino Detection





ANITA

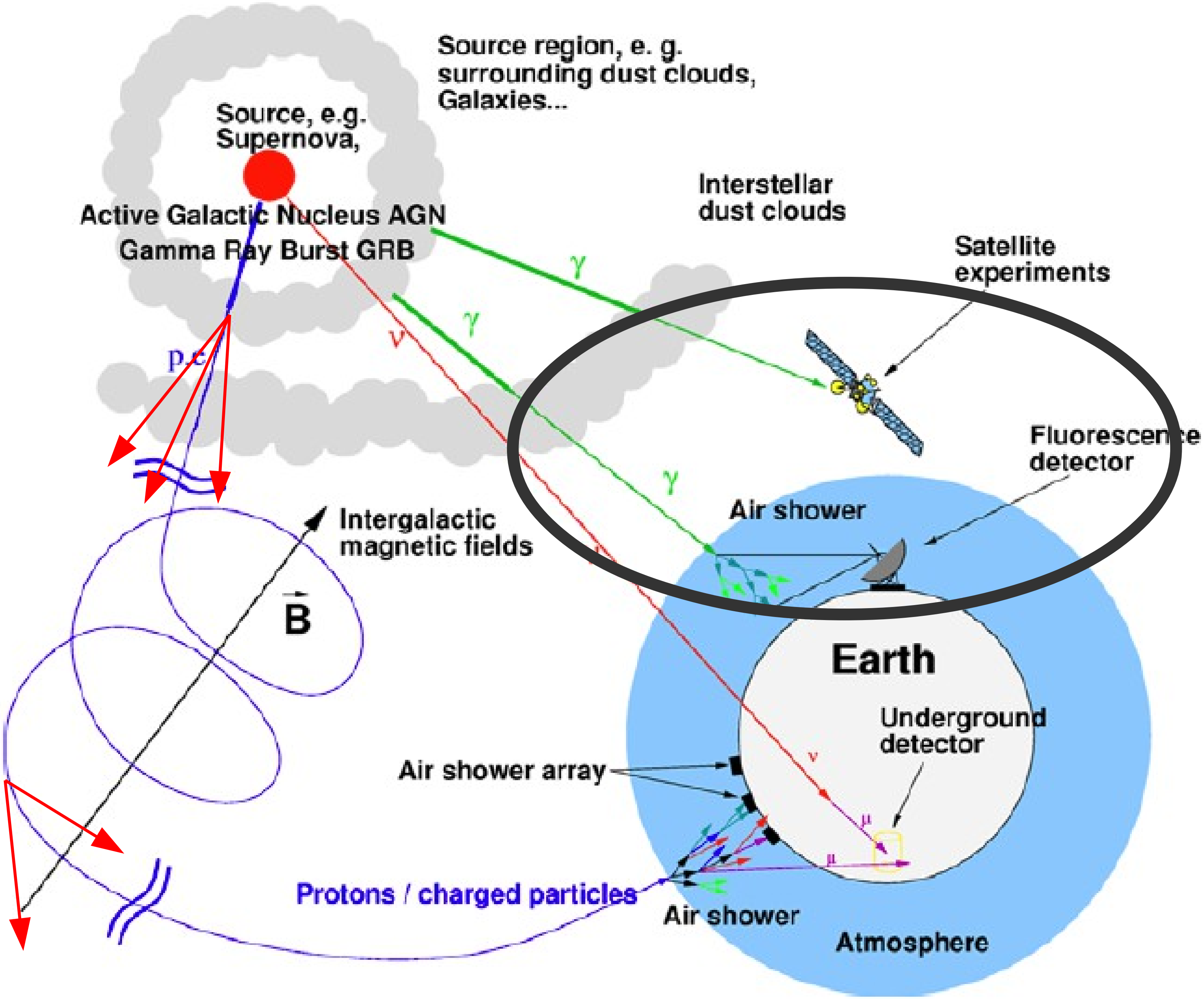
Antarctic Impulsive Transient Antenna



Search for Acoustic Signals from Ultrahigh Energy Neutrinos in 1500 km^3 of Sea Water, N. Kurahashi, J. Vandenbroucke, and G. Gratta, *Physical Review D* 82, 073006 (2010)

Oceanic Ambient Noise as a Background to Acoustic Neutrino Detection, N. Kurahashi and G. Gratta, *Physical Review D* 78, 092001 (2008)

Neutrino Astronomy

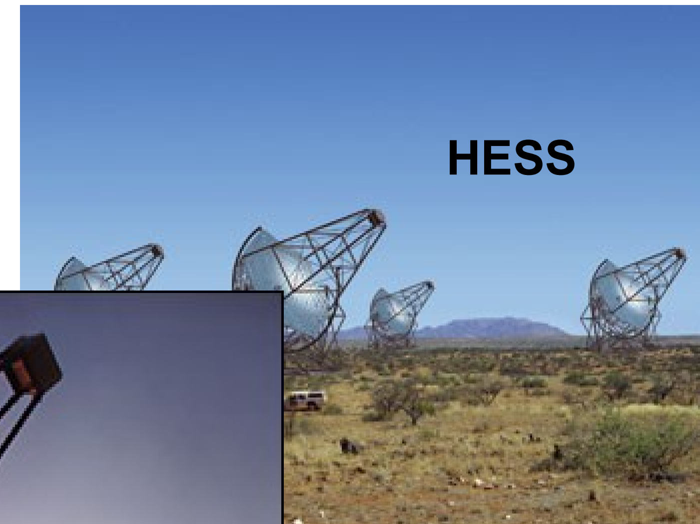


γ ray Telescopes

Ground based imaging air Cherenkov telescopes 100 GeV – tens of TeV

Space satellite telescopes
0.1 GeV – few hundred GeV

Fermi

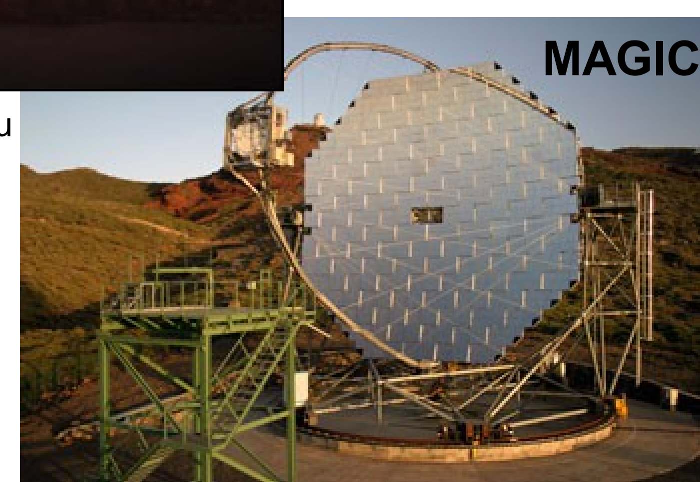


Images: phys.org

Images from NASA

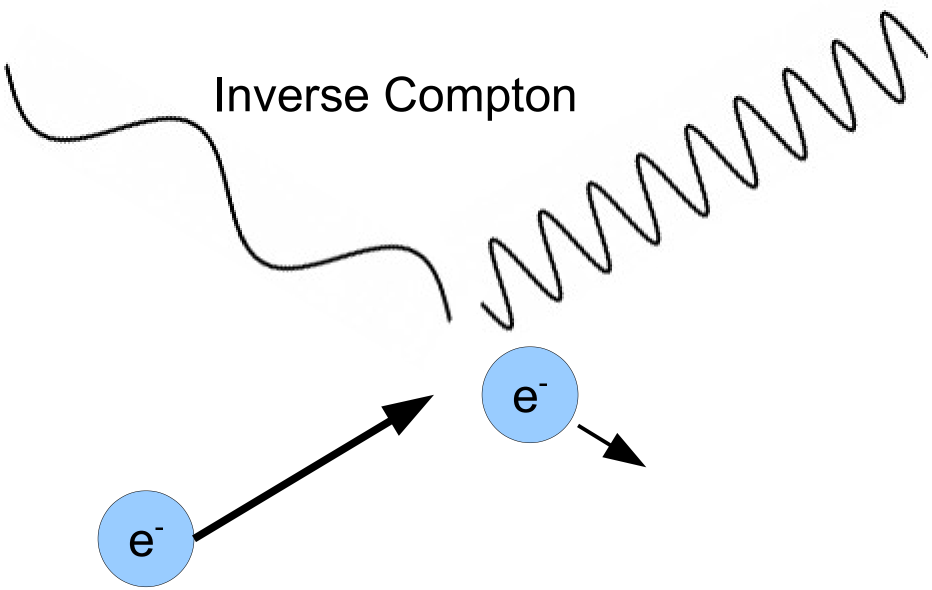
EGRET

Image:kicp.uchicago.edu



Producing γ rays

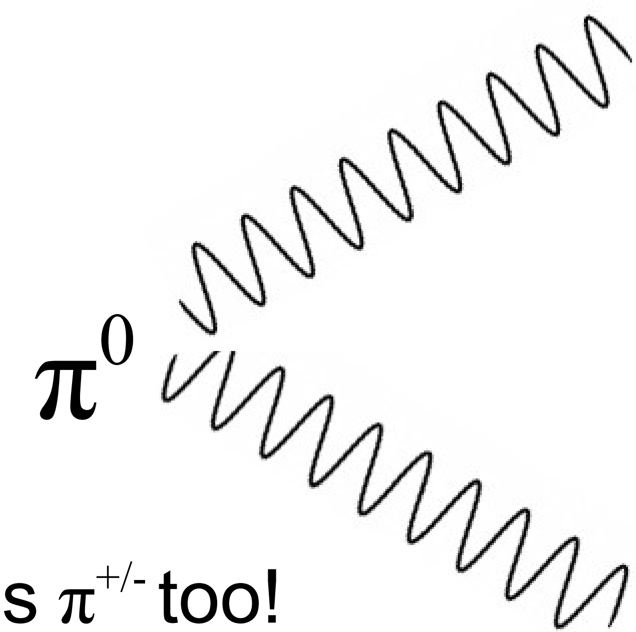
Leptonic Processes



Bremsstrahlung, etc

Hadronic Processes

$P + P$ or $P + \gamma$ creates π^0

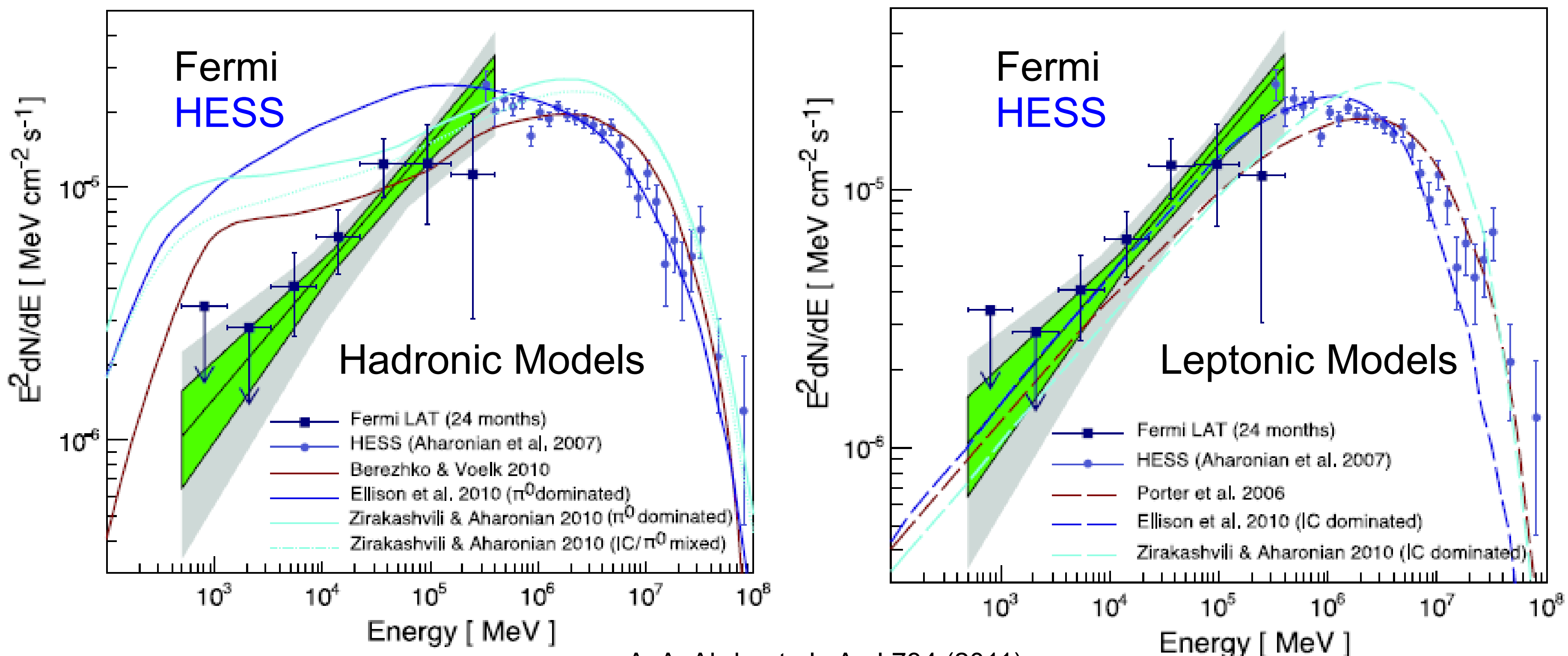


creates $\pi^{+/-}$ too!

<u>Produces ν too</u>

Leptonic or Hadronic?

Supernova Remnant RX J1713



A. A. Abdo et al., ApJ 734 (2011)

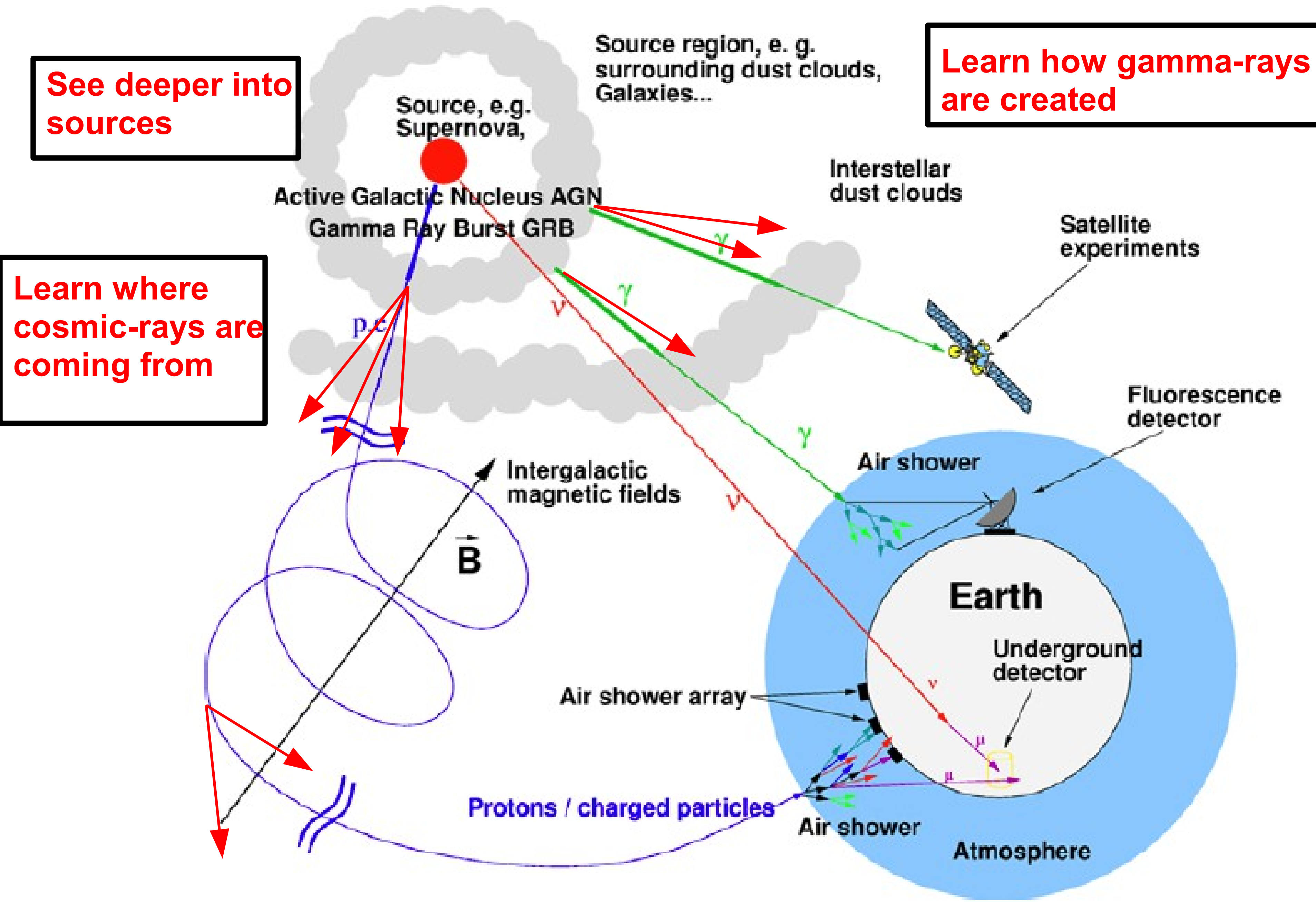
<u>Neutrinos would be definitive evidence of hadronic emission</u>

If neutrinos are observed → Confirmation of hadronic emission

If neutrinos are not observed → Limit on the hadronic emission

Neutrinos do not attenuate at high energies! Spectrum keeps going....

Neutrino Astronomy



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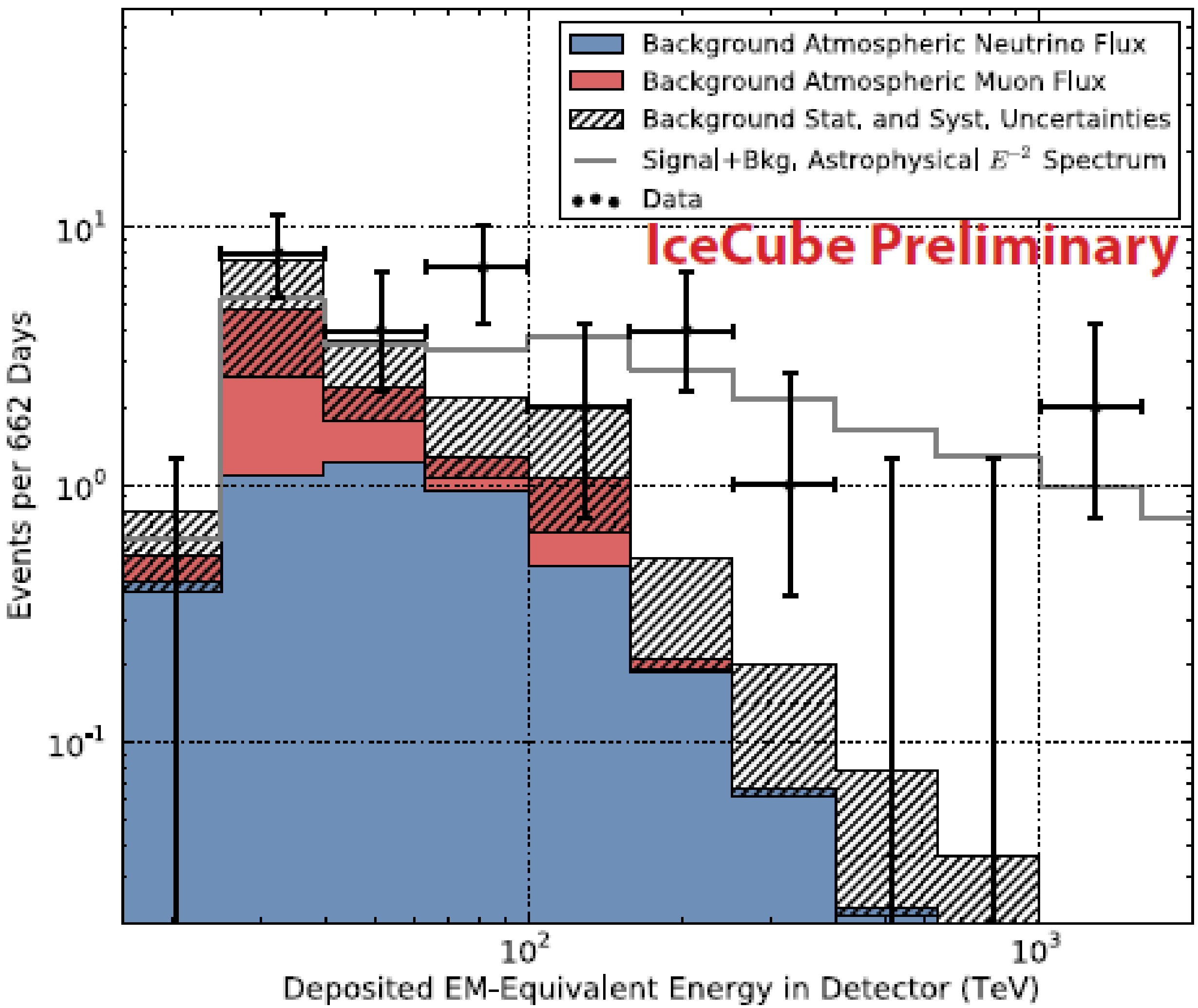
IceCube Sees Excess Events at High Energies Using Contained Events!



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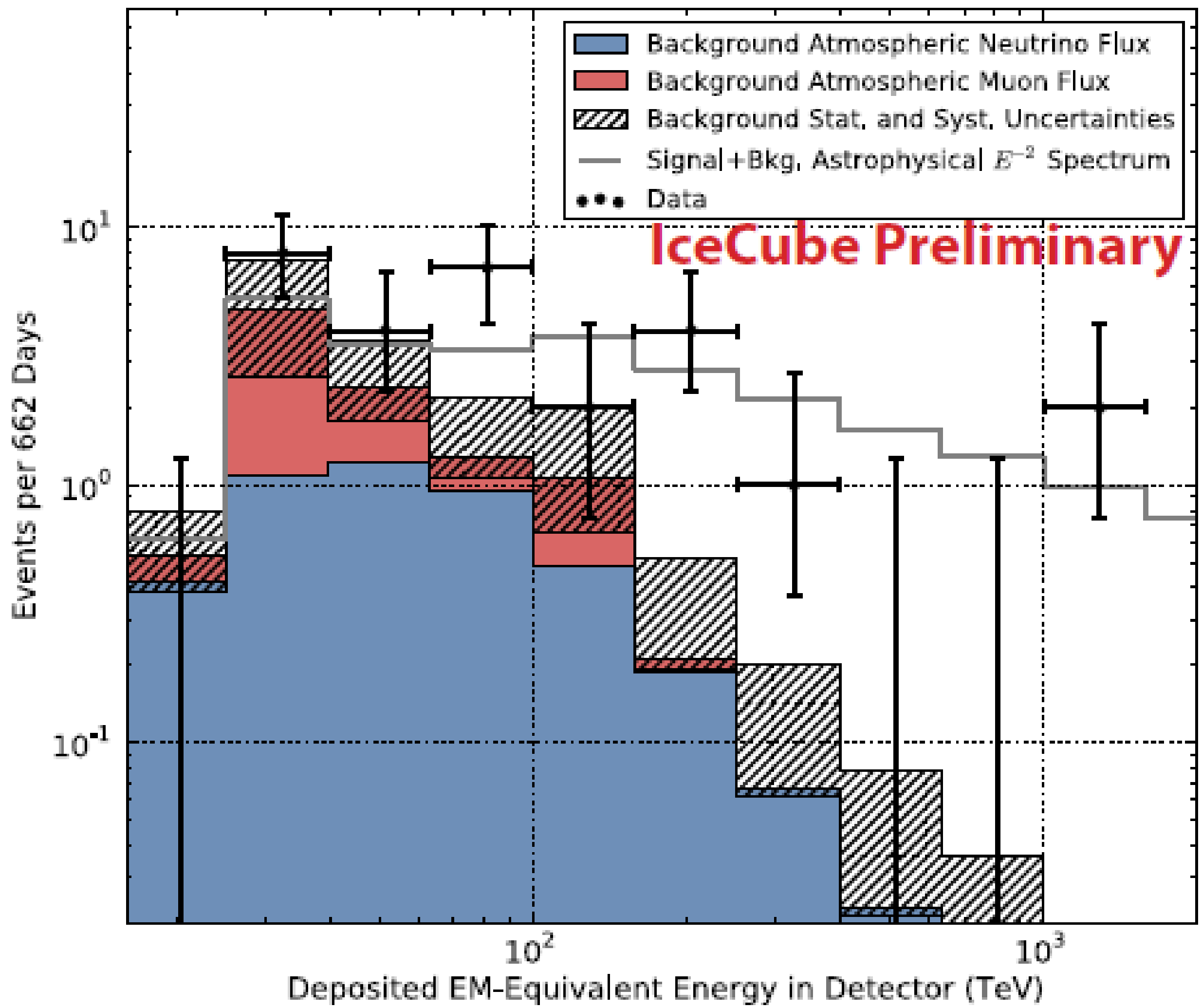
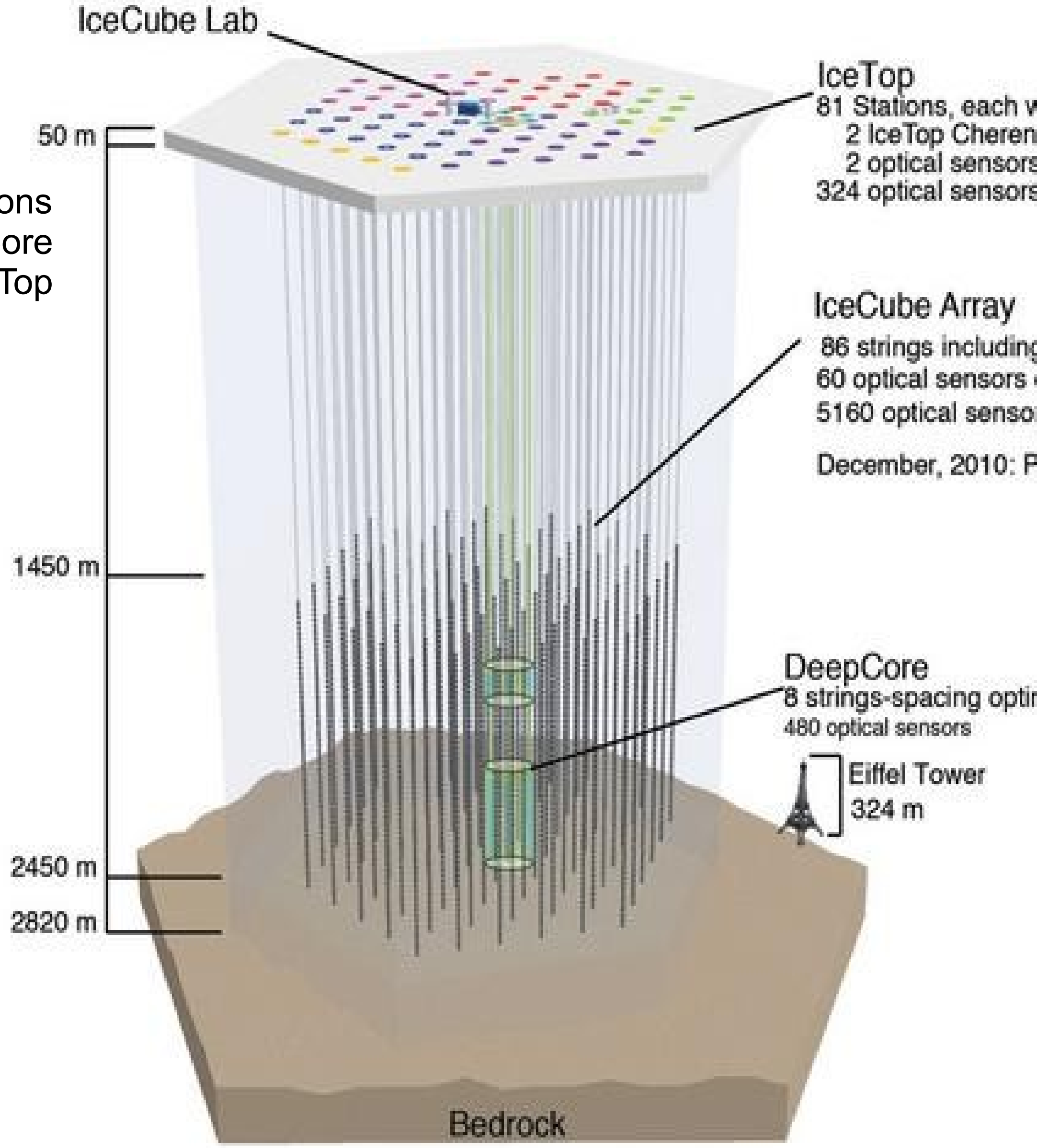


The IceCube Detector

IceCube and its two extensions
DeepCore
IceTop

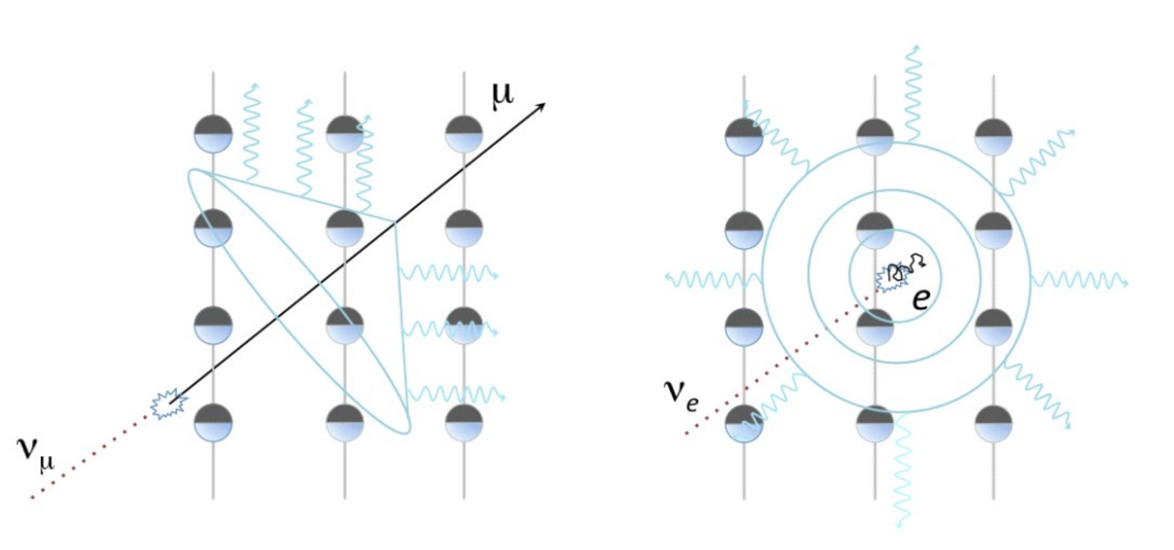
17m vertical spacing
125 m String spacing

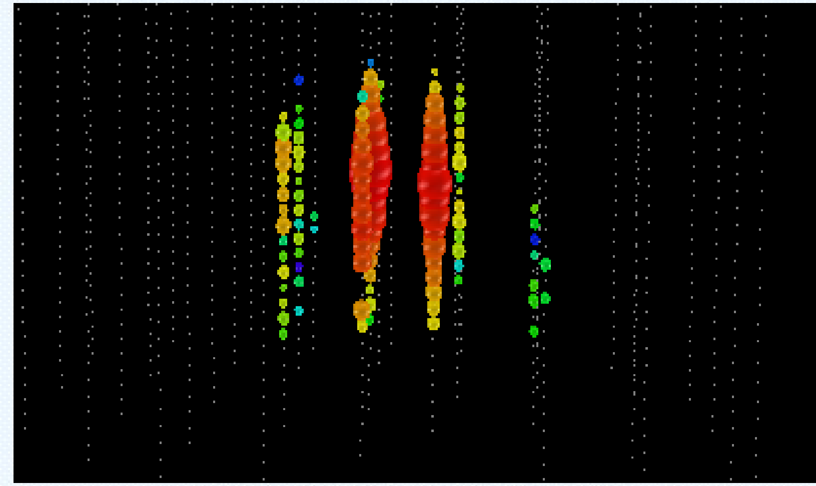


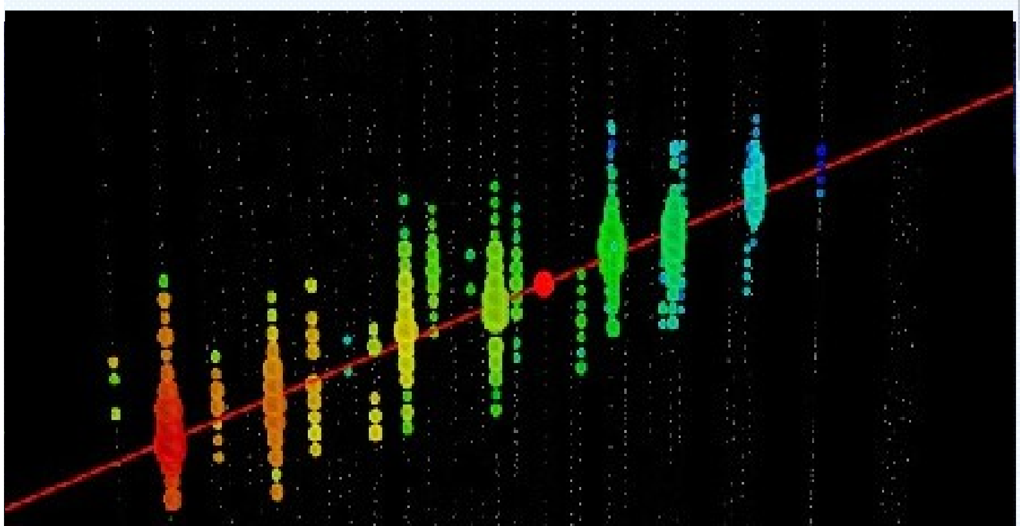
Digital Optical Module (DOM)

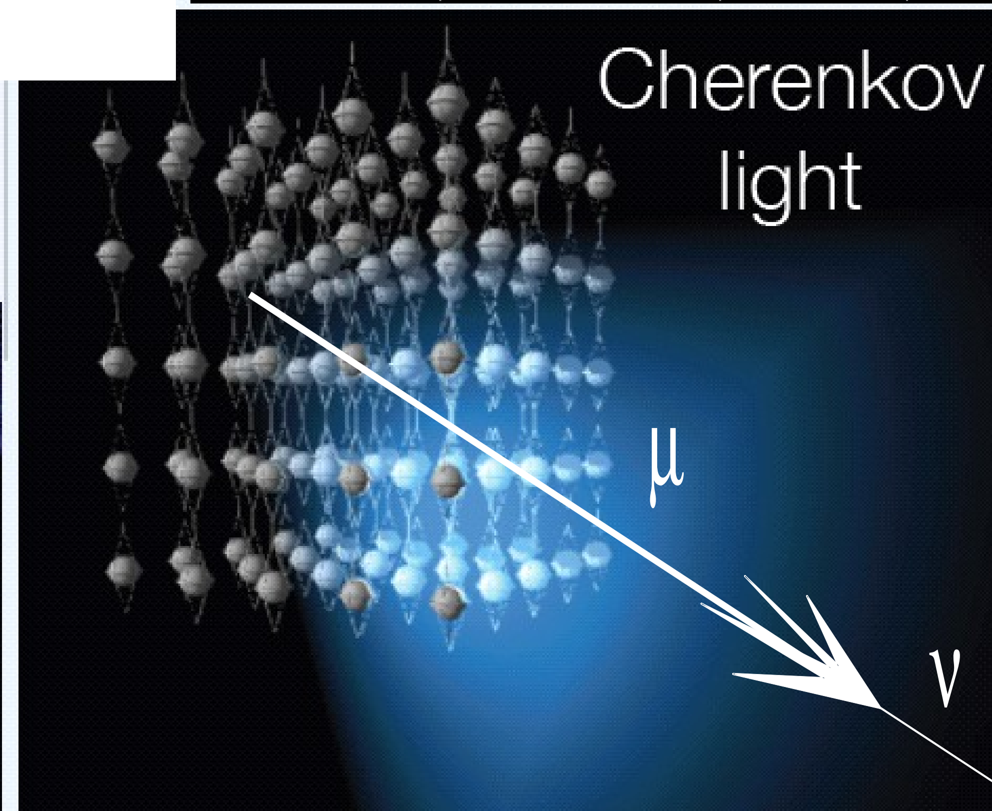
Completed almost 3 years ago!

detection principle

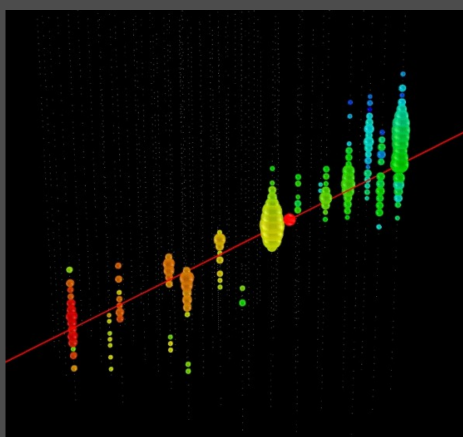
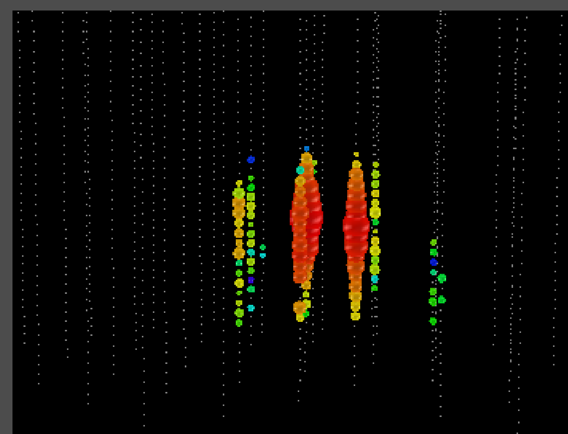
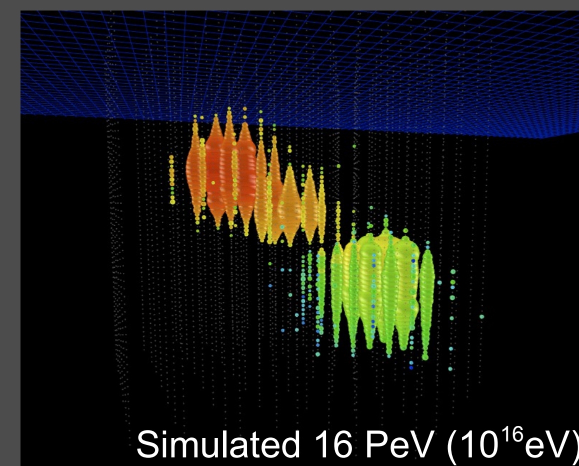




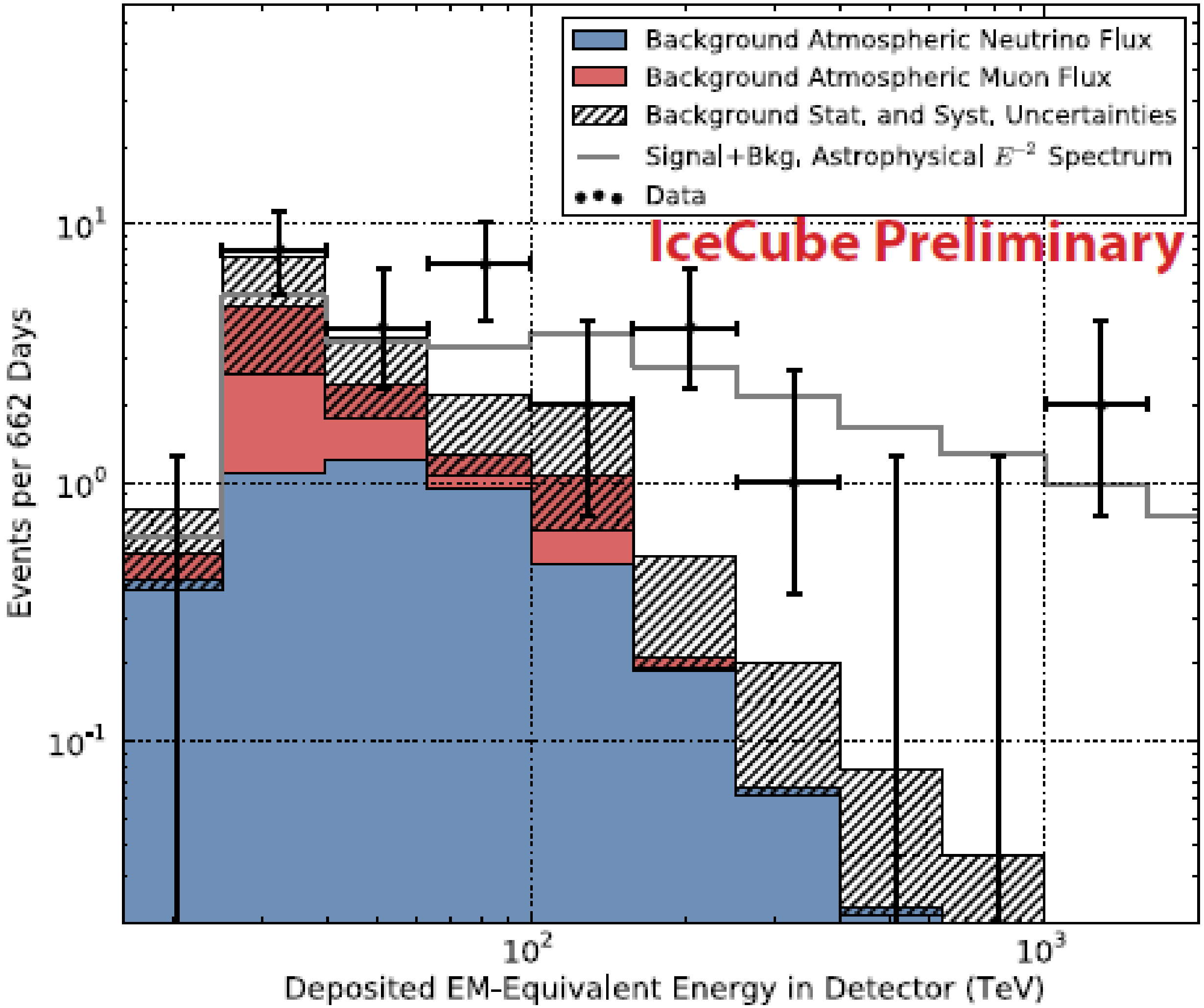




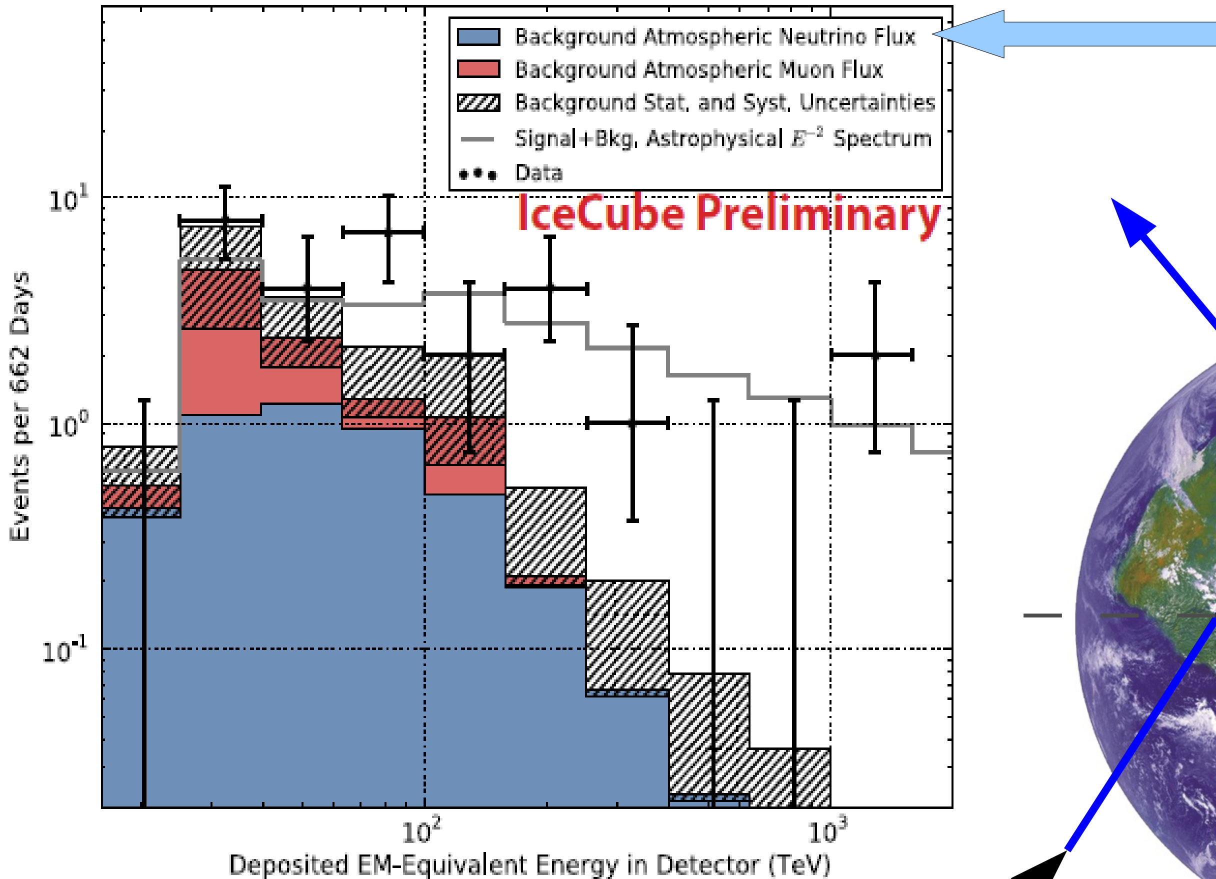
Topologies of different event types

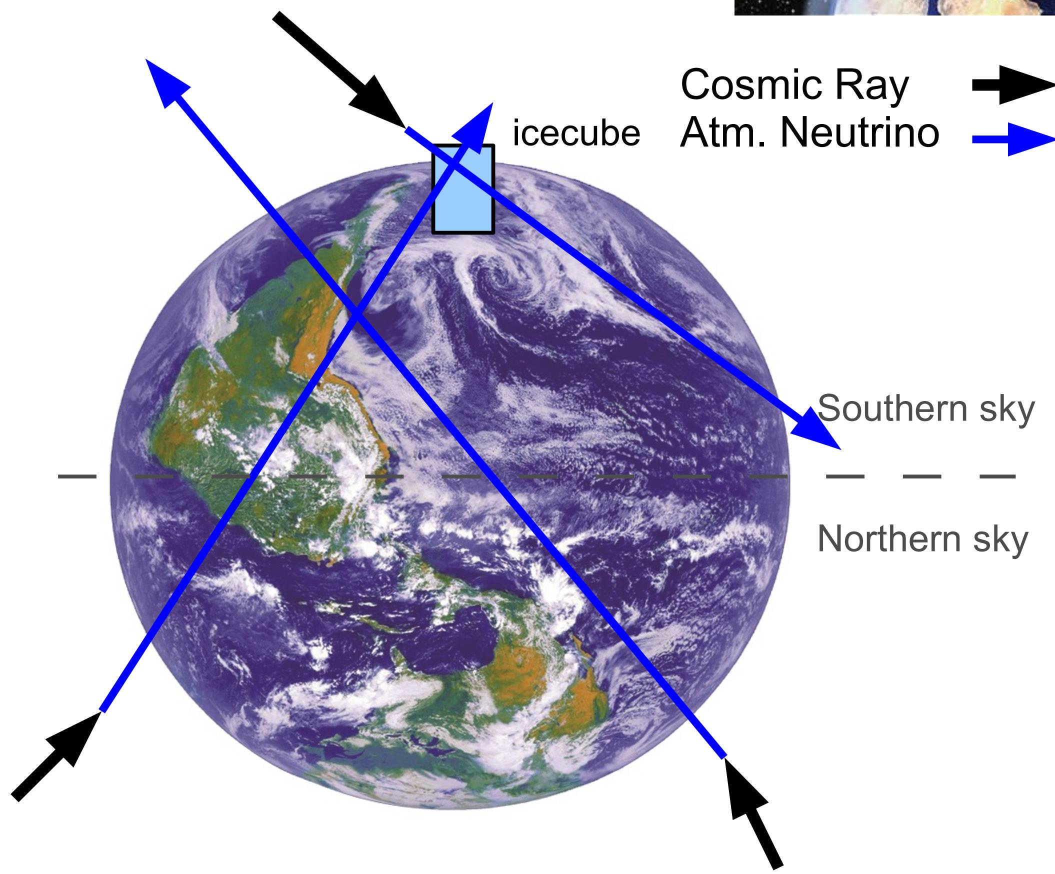
CC Muon Neutrino	Neutral Current /Electron Neutrino	CC Tau Neutrino
		
$\nu_\mu + N \to \mu + X$	$\nu_e + N \to e + X$ $\nu_x + N \to \nu_x + X$	$\nu_\tau + N \to \tau + X$
Track	**Shower**	**Double-Shower (not observed yet)**

IceCube Sees Excess Events at High Energies Using Contained Events!



What should IceCube see?





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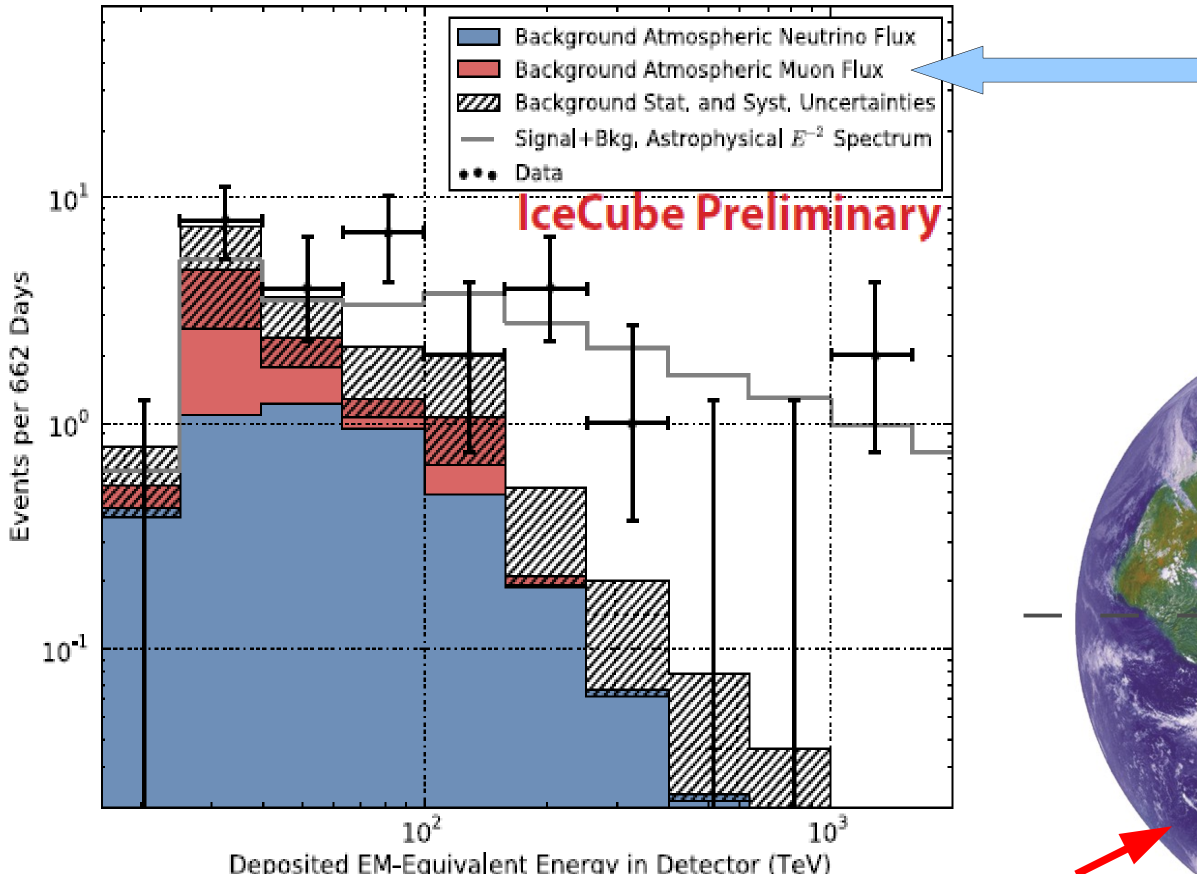

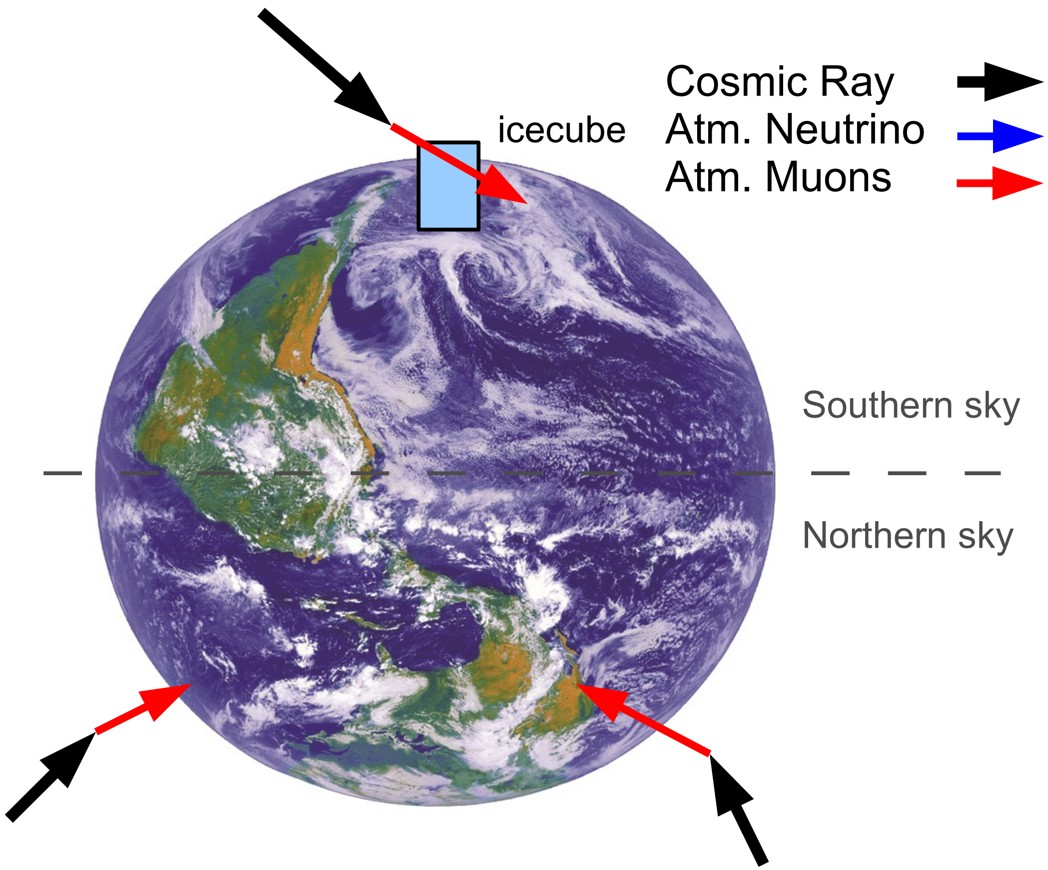

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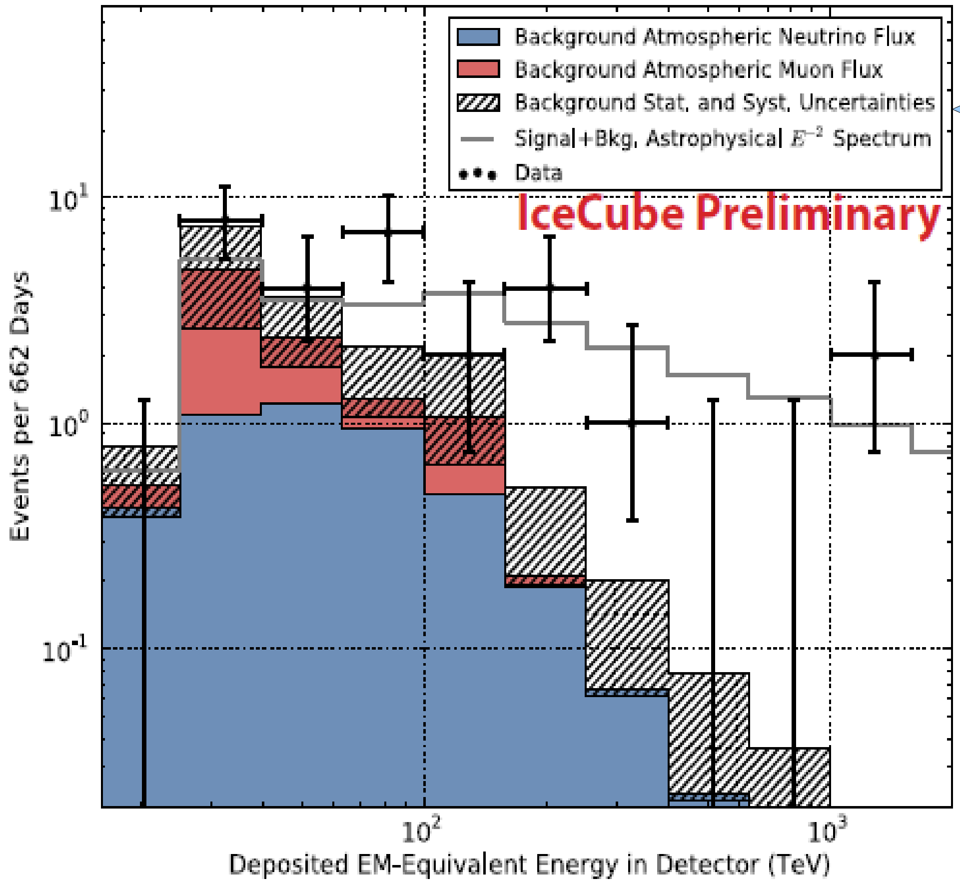
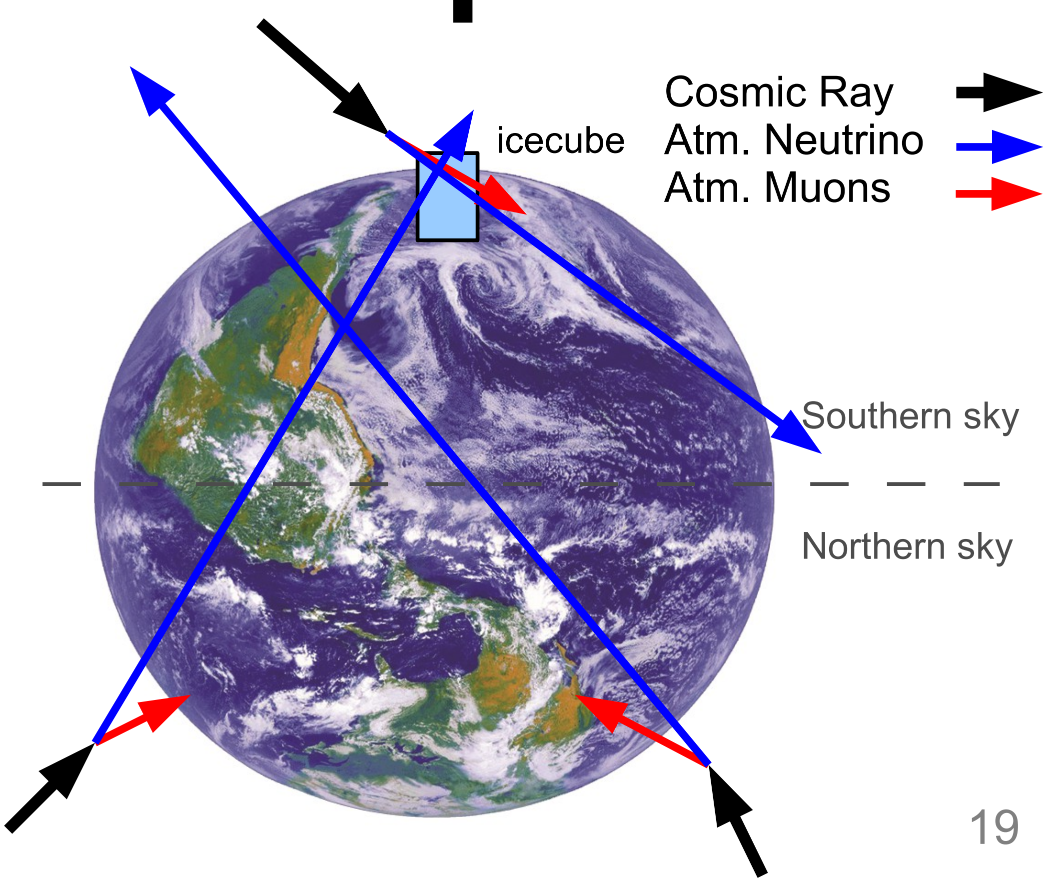
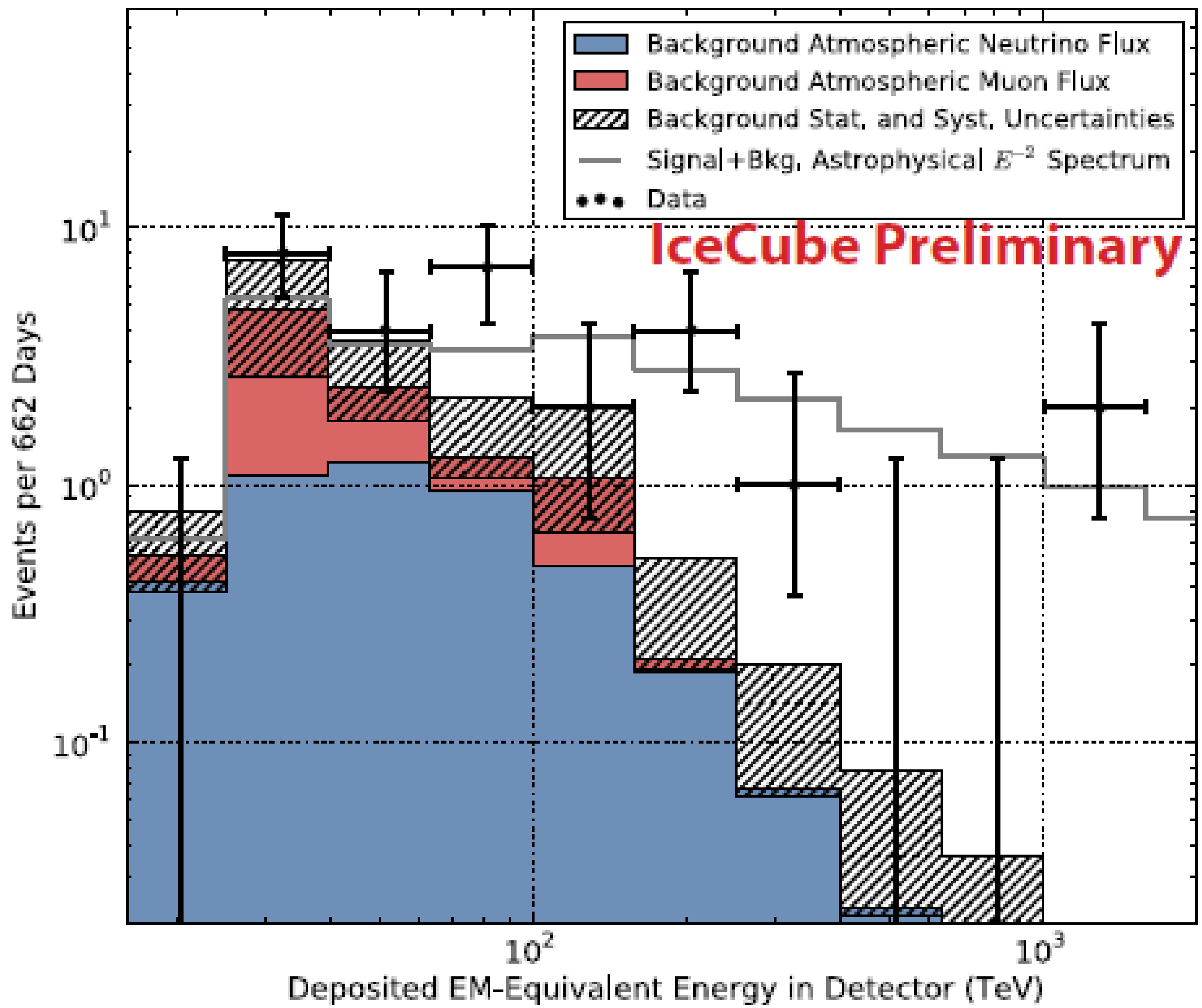


Uncertainties on neutrino products in the shower from fast decaying mesons ("prompt" component of atmospheric neutrinos)

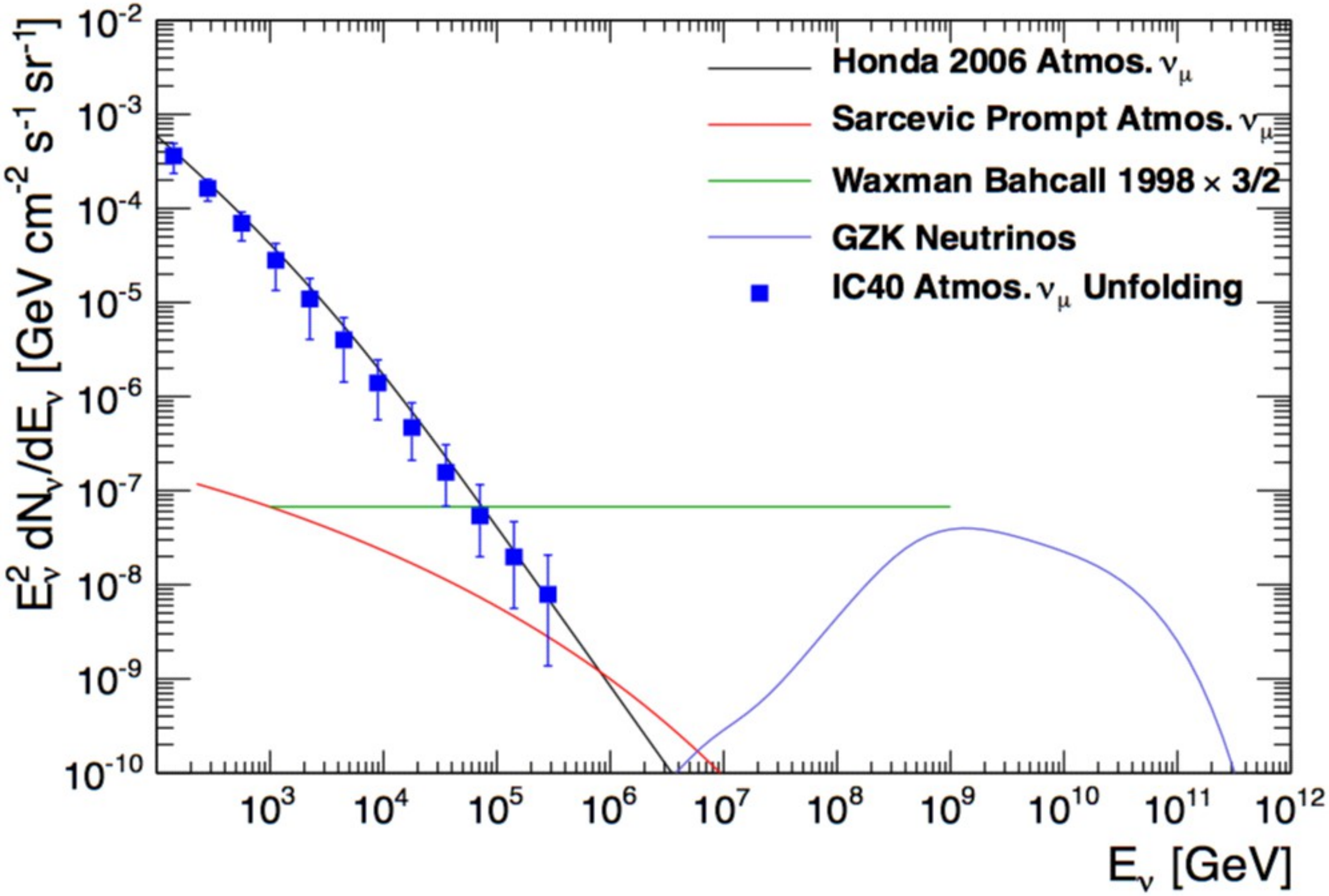
+



IceCube Sees Excess Events at High Energies Using Contained Events!



Why is high-energy important?



π/K Atmospheric Neutrinos (dominant < 100 TeV)
Prompt Atmospheric Neutrinos (expected > 300 TeV)
Astrophysical Neutrinos (maybe dominant > 100 TeV)
GZK Neutrinos (10^6 TeV)

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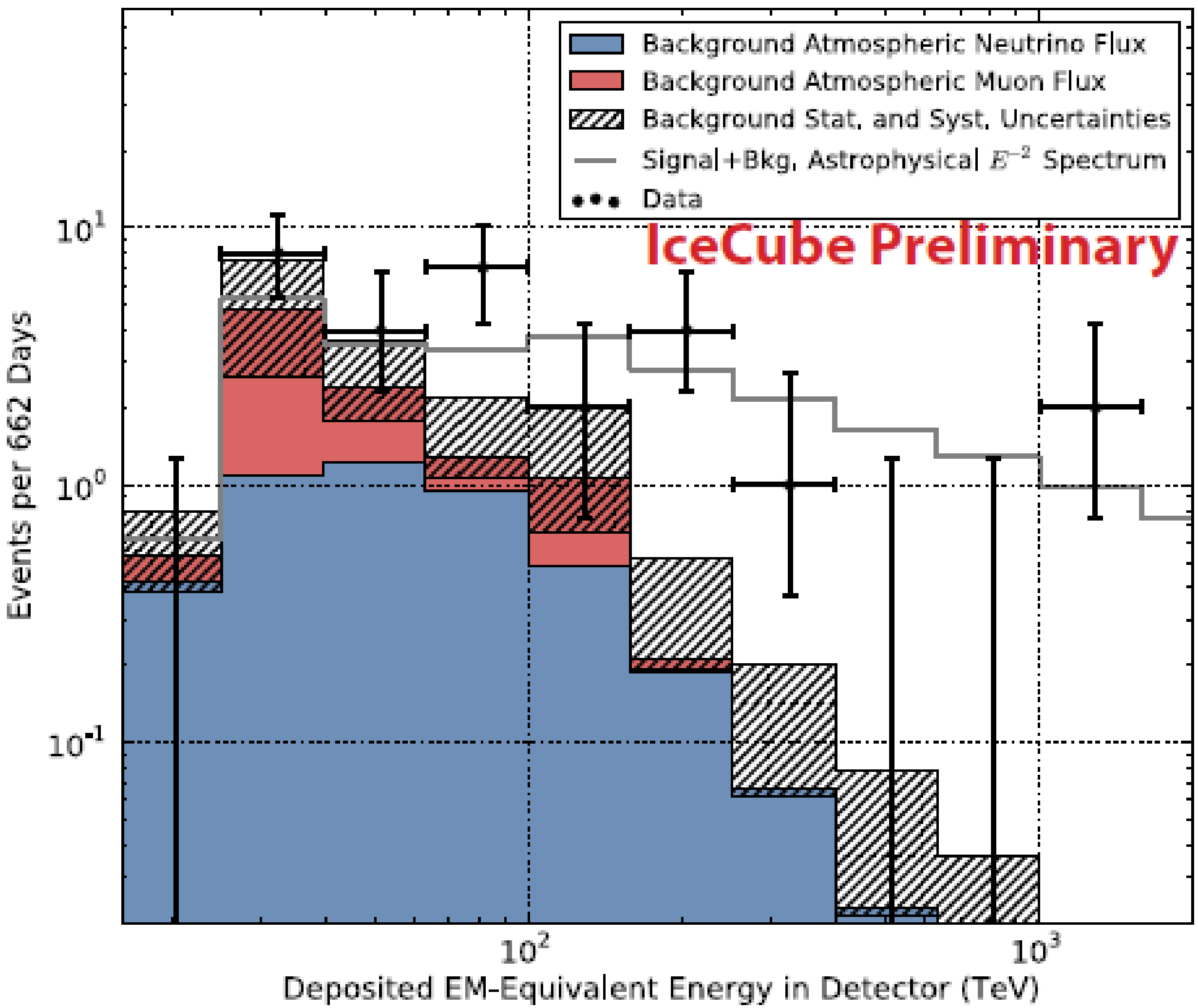
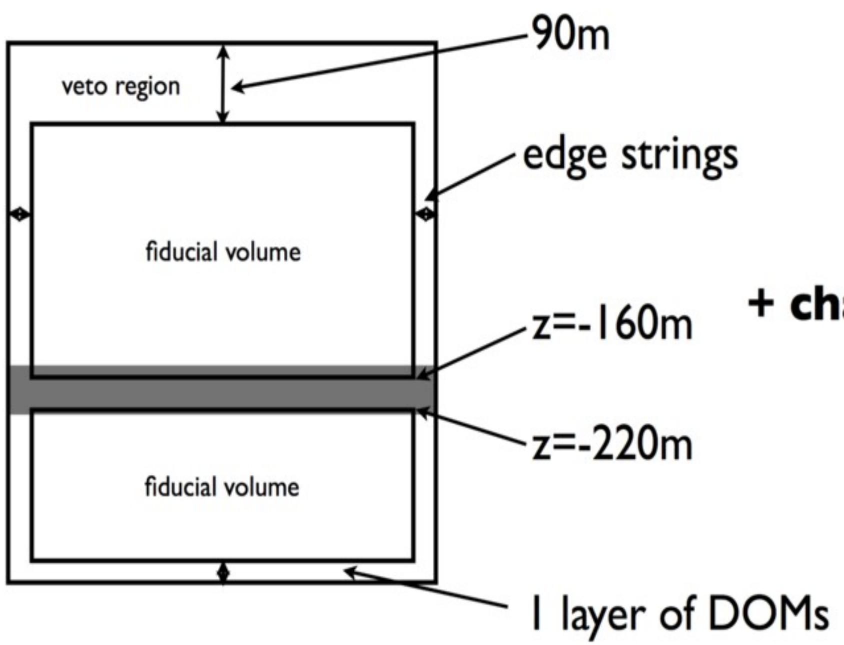


Events with interaction vertices contained inside the IceCube detector → More likely to be neutrino events

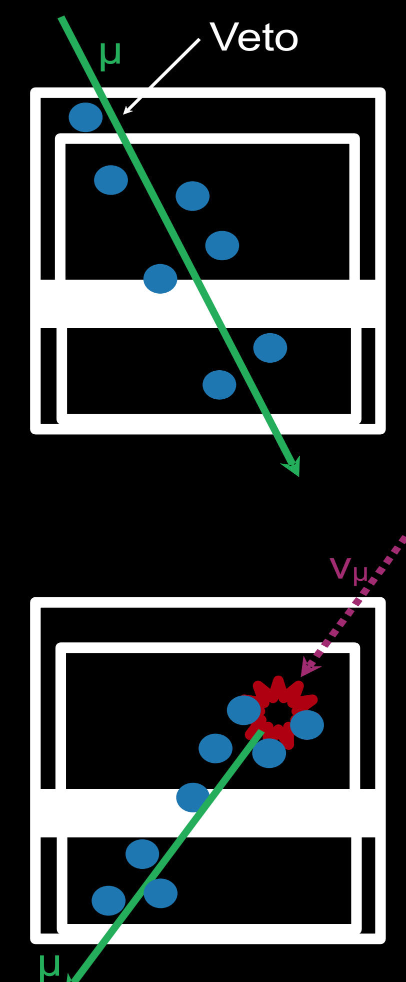


+ charge cut

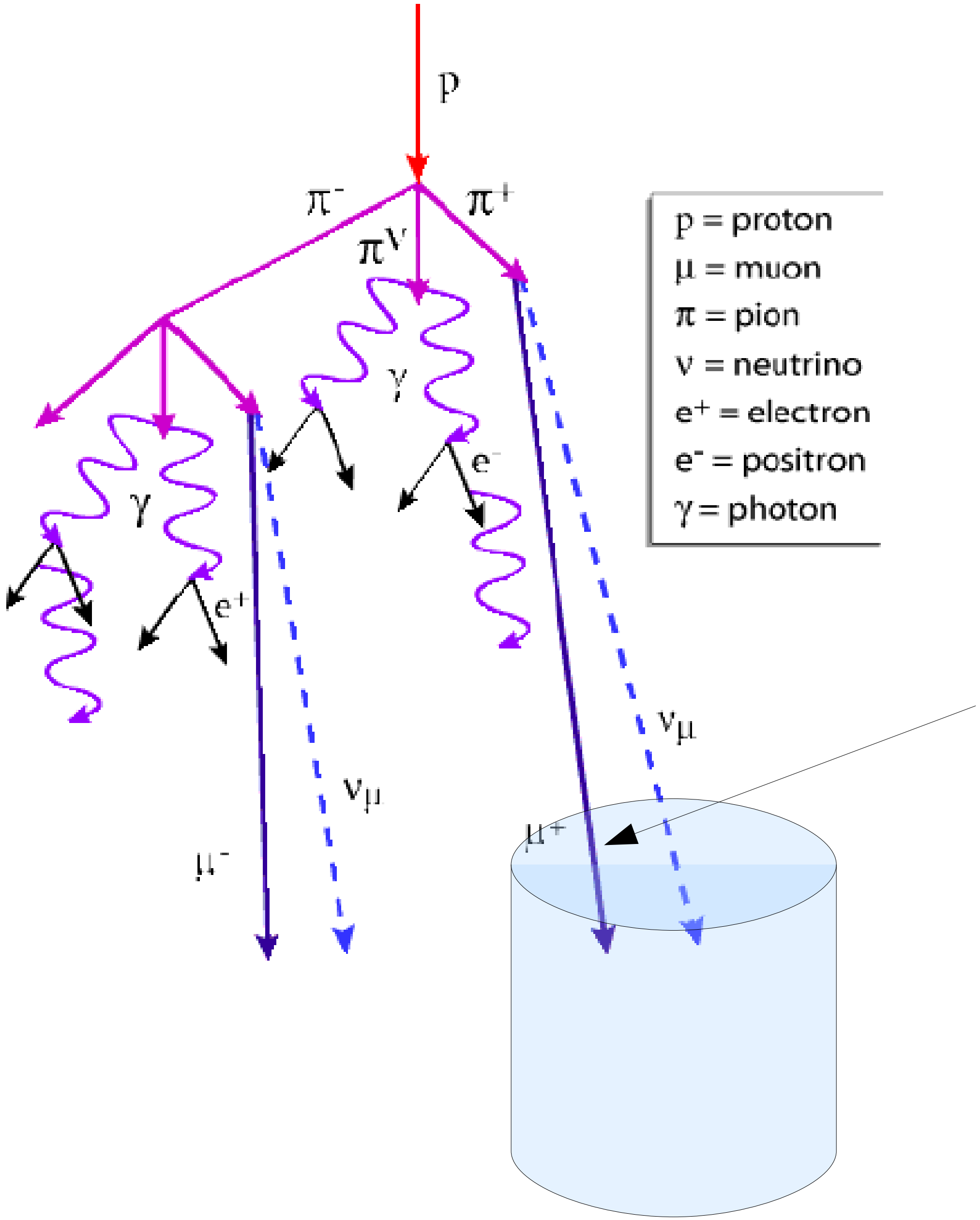
The higher the energy, the better this works!

Could be an atmospheric muon or could be a muon caused by neutrinos

Most likely a neutrino



Tagging atmospheric neutrinos



The accompanying muon trips the veto!

Schoenert et al.
Phys.Rev. D79 (2009) 043009

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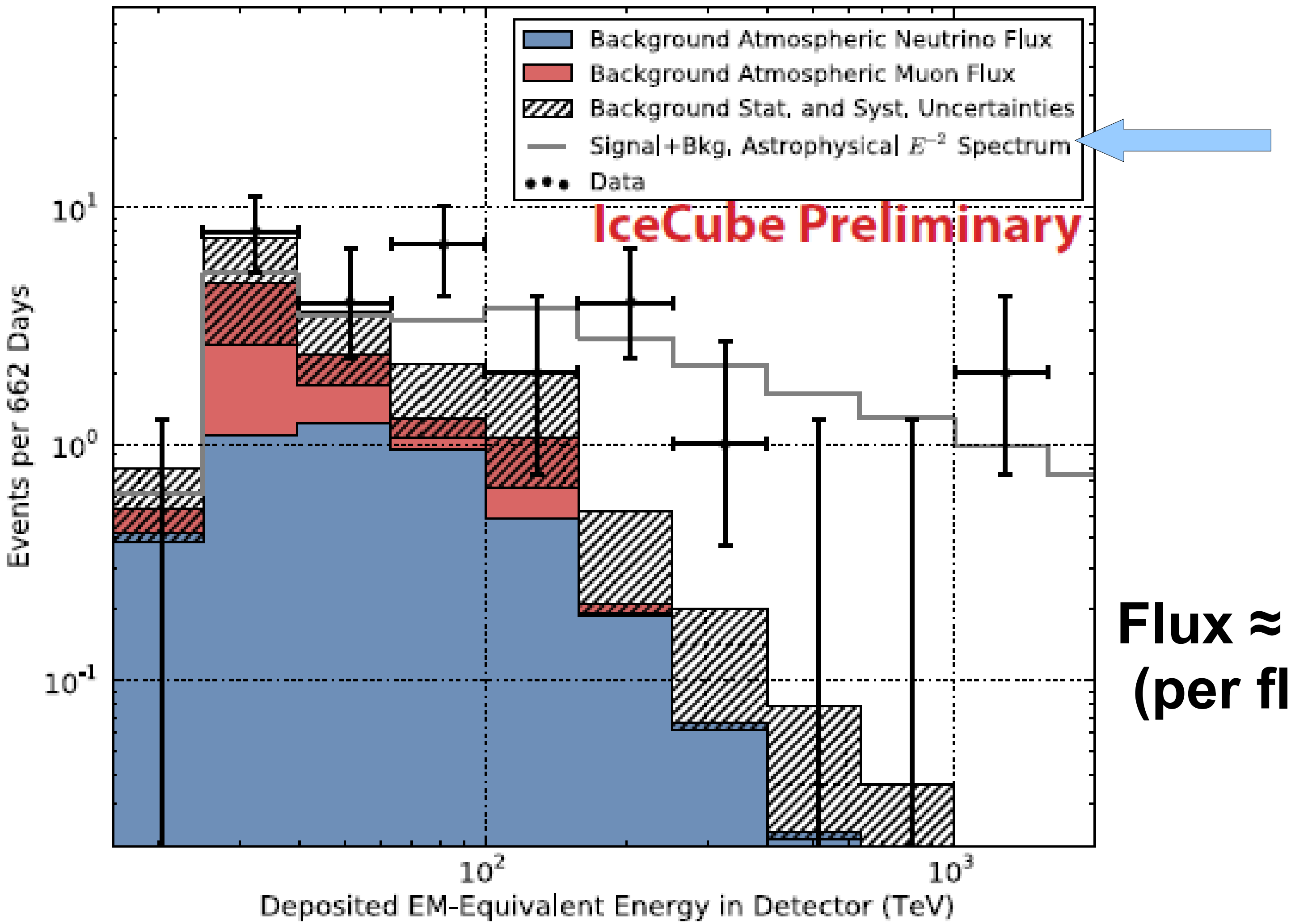


Predicted background + Flux ~ E^{-2} fit

Flux ≈ $10^{-8}E^{-2}$[GeV/cm^2/s/str] (per flavor, assuming 1:1:1)

The Numbers

28 events observed (21 showers, 7 tracks)
expected background of 10.6 +5.0/-3.6 (sys+stat)

A flux level of $\sim 10^{-8} E^{-2}$[GeV/cm^2/s/str] predicts another 3-6 events in 2-10PeV range

Speculation of a cutoff at ~couple PeV or a slightly softer spectrum

To first order.....

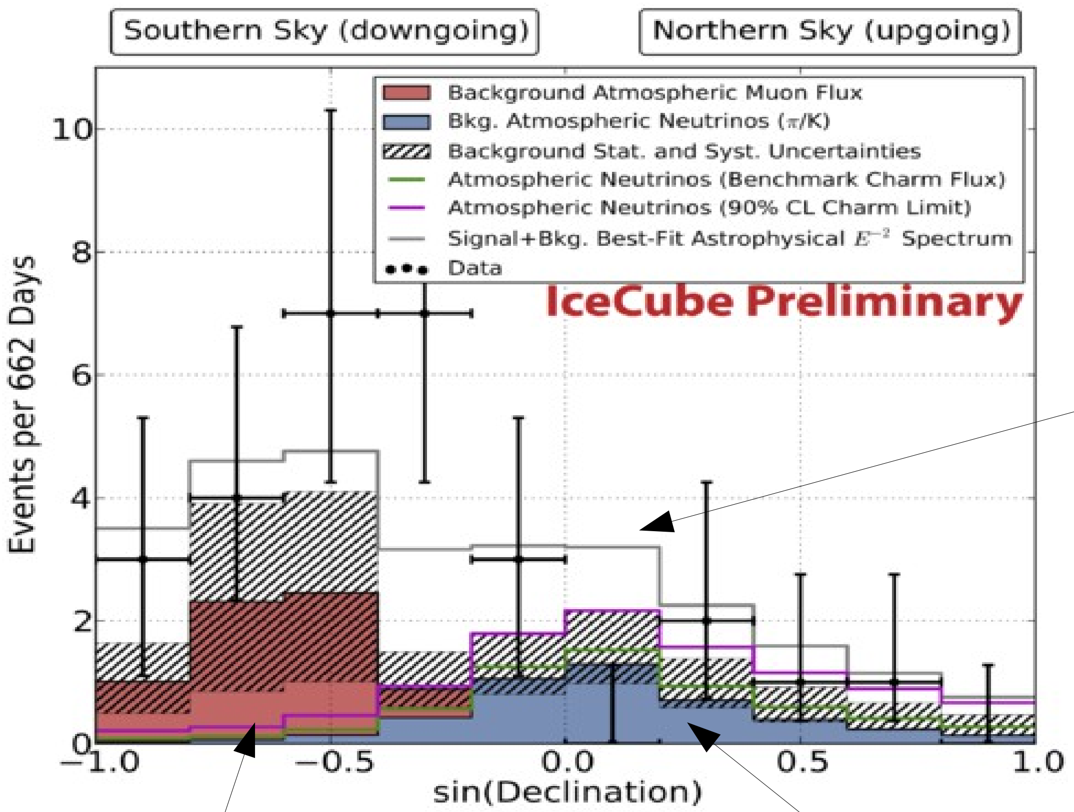
All Neutral Current
νe, $\nu\tau$, Charge Current } shower

$\nu\mu$ Charge Current — track

Track-Shower ratio seen is consistent with a 1:1:1 neutrino flavor signal

Declination Distribution of Events

= zenith



Diffuse signal

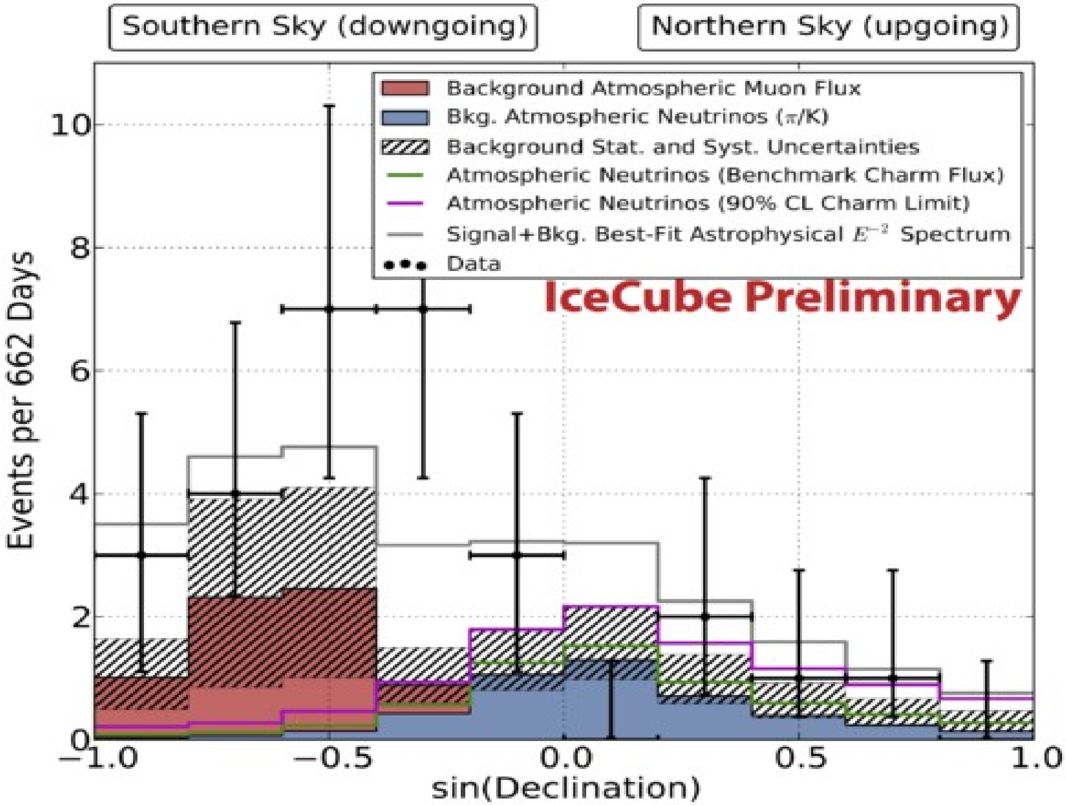
Muon background only in the southern sky

Atm. Neutrino background dominant
- in northern sky (tagging shower muons)
- but near the horizon (earth absorption)

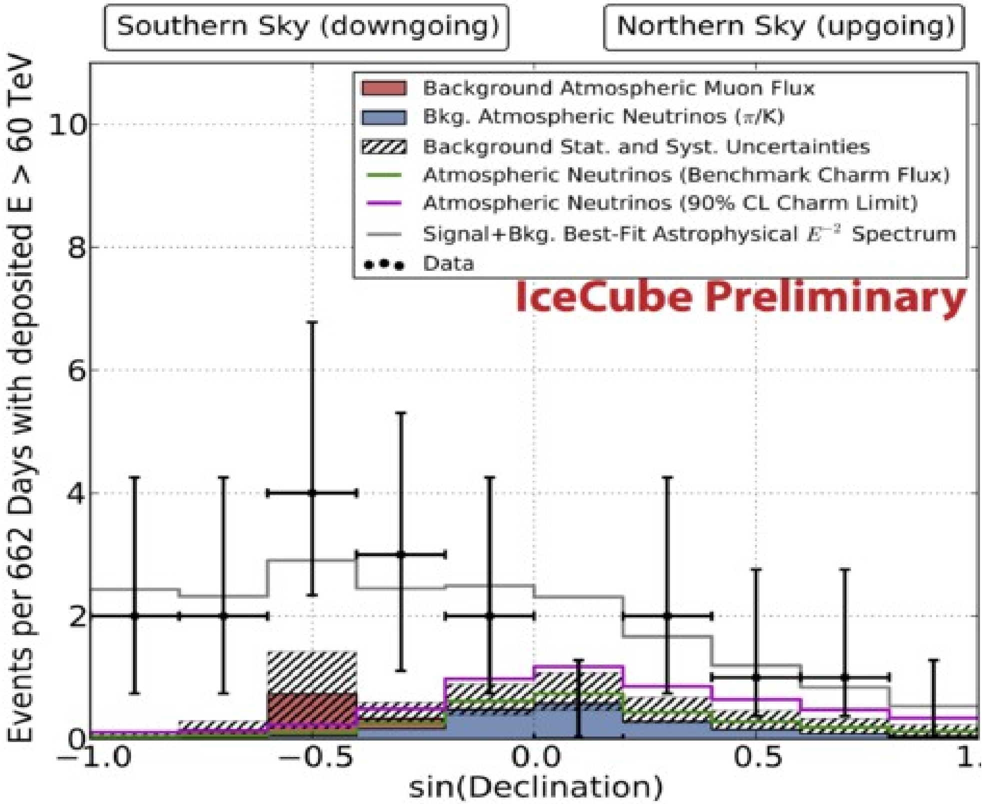
Declination Distribution of Events

= zenith

ALL EVENTS



EVENTS > 60 TeV



Summary So Far

- Above 4σ evidence of astrophysical flux
- Consistent with 1:1:1 flavor ratio
- Flux at $\sim 10^{-8} E^{-2}$[GeV/cm^2/s/str]
- There seems to be a cutoff at a few PeV or a slightly softer than E^{-2} spectrum
- Declination distribution of events compatible with a diffuse source → similar flux level at northern and southern hemisphere

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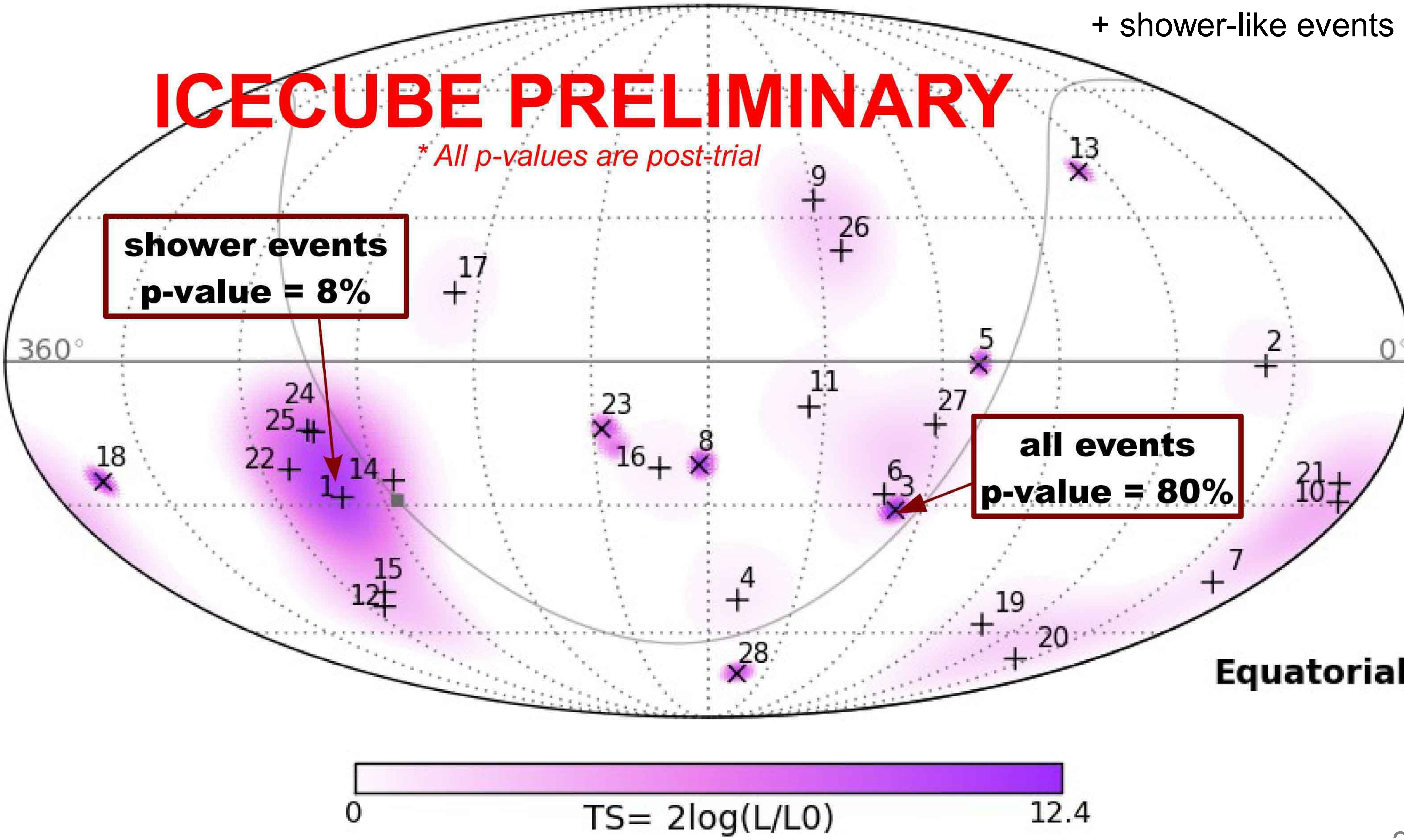
So what are the source(s) of these events?

Test Statistic Map

Most likely event direction
x track-like events
+ shower-like events

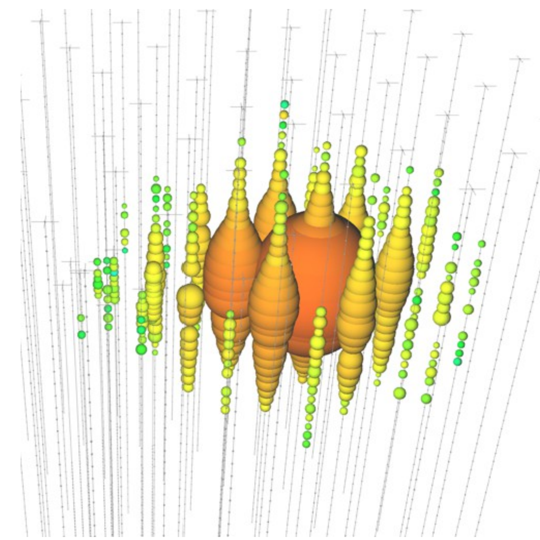


Reconstruction Capabilities

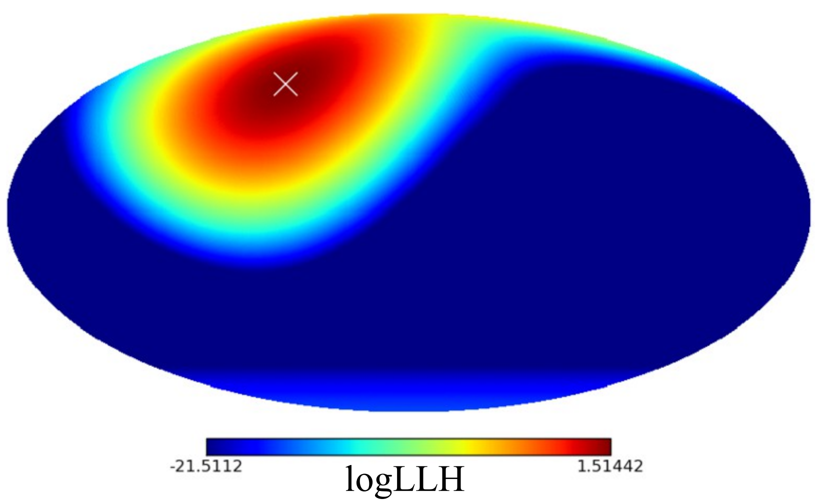
@ 100 TeV energies

	Energy Reconstruction*	Directional Reconstruction*
Tracks	**Okay**	**Good**
Showers	**Good**	**Okay**

* against primary neutrino energy and direction



Reconstruction map of a ~60 TeV shower-like event in local coordinates



Likelihood Search for a Point Source
- Test Statistic (TS) Calculation -

Maximize the likelihood L at every point in the sky x

Total # of events = 28

# of events from source
Varied to maximize L

$$L(x) = \prod_{i}^{n_{tot}} \left[\frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

Reconstruction map
value at position x
from event i

Uniform value
for each event
at every position

** Events' energies not used in the likelihood*

TS is calculated for every point in the sky x

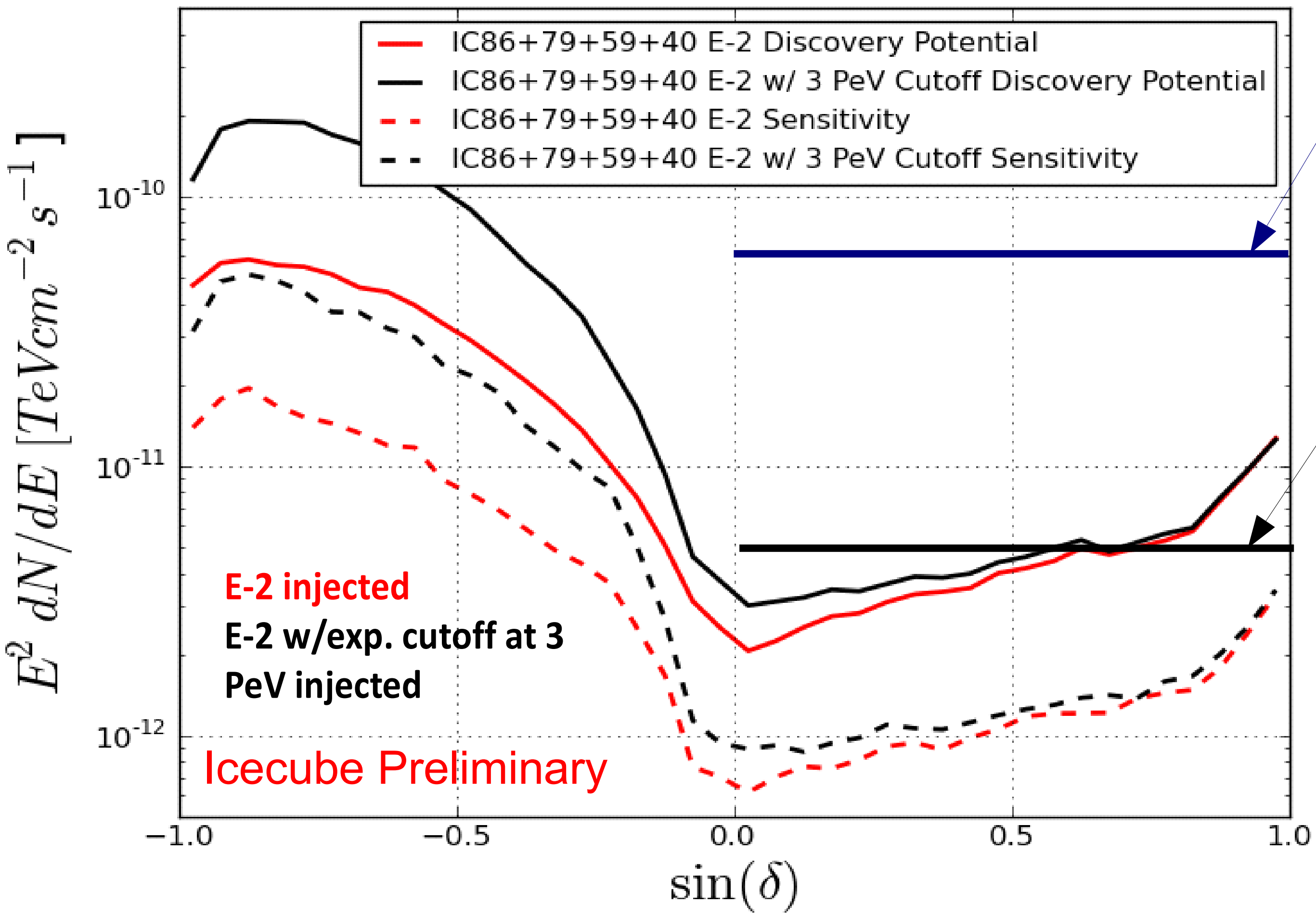
$$TS(x) = 2 \times \log\left(L(x) \Big/ L_0(x) \right)$$

where $L_0 = L(x, n_s = 0)$

How many sources?

“traditional” point source analysis
using clean muons in the detector

In the Northern hemisphere:
Astrophysical Flux ~ 10^{-8} GeV/cm^2/s/sr x 2π
~6 x 10^{-11} TeV/cm^2/s



“traditional” PS analysis
discovery potential is
~2-6 x 10^{-9} GeV/cm^2/s

$N_{sources} \geq 15$

Many ways around it
- extended sources
- much softer spectrum
- different flavor ratio

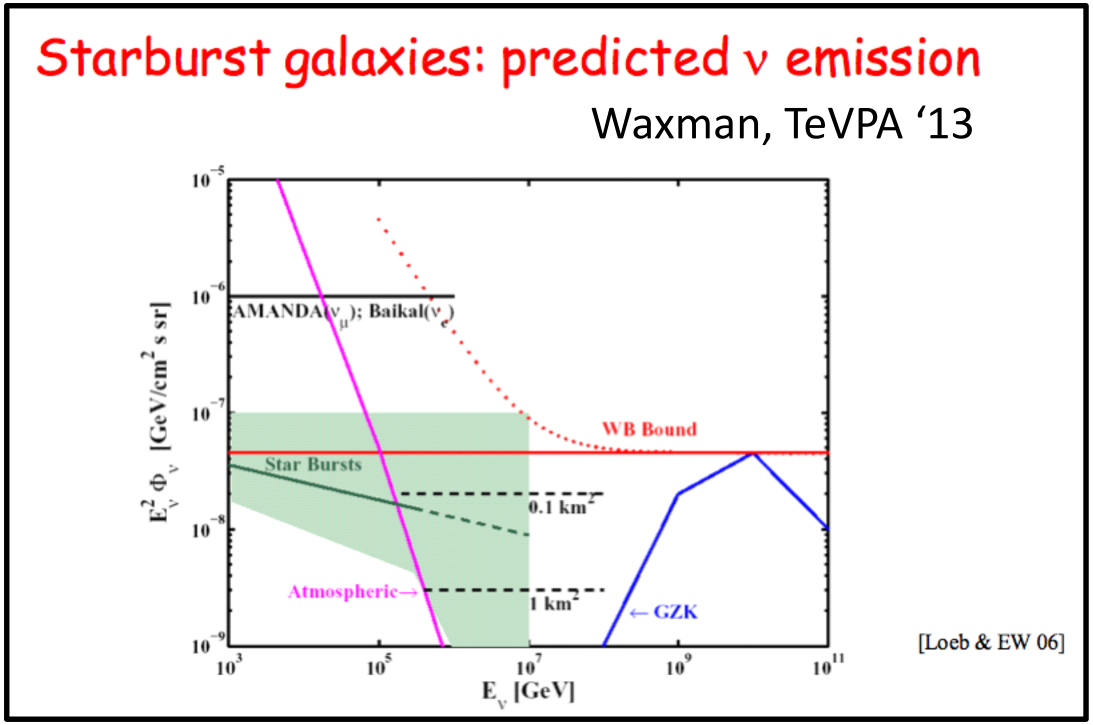
Could it be Starburst Galaxies?

IceCube does a stacking analysis on close-by starburst galaxies using clean muons and has a strong upper limit

arxiv:1307.6669

Stacking of catalog of 127 starbursts

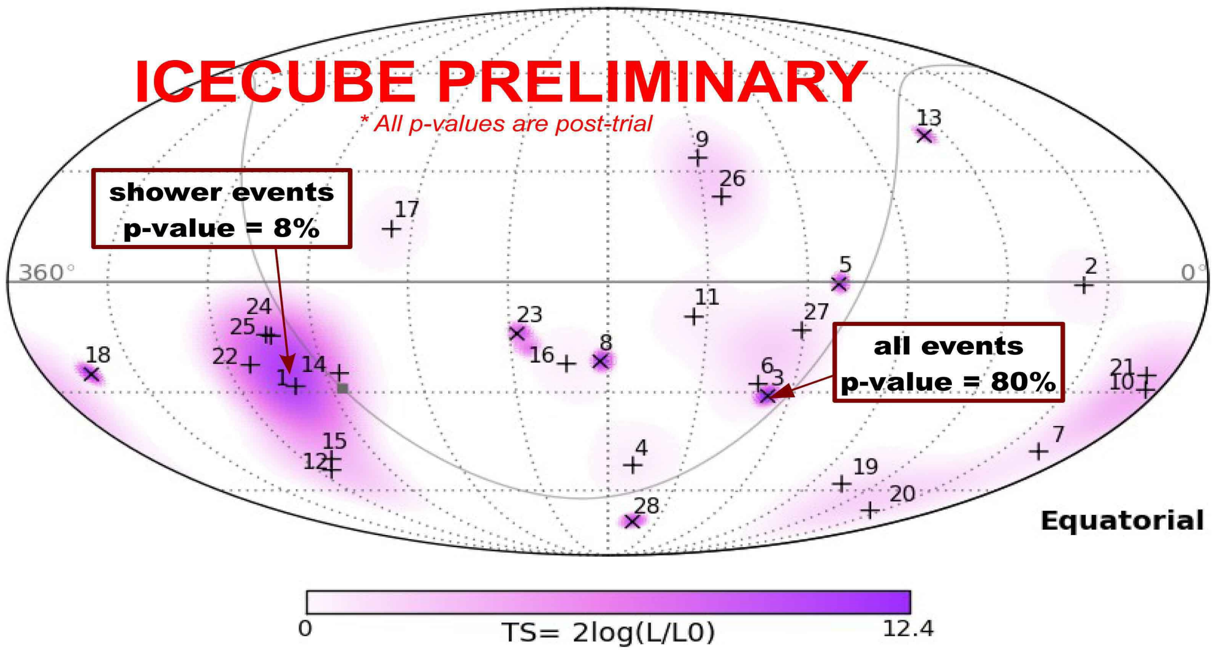
- Within $z < 0.03$
- F_{FIR}(60 micron) > 4 Jy
- F_{radio}(1.4 GHz) > 20 mJy



Unbroken E^{-2} flux limit: 7×10^{-10} E^2 GeV cm^{-2}s^{-1}sr^{-1}

Bright, nearby starbursts can only be responsible for ~< 10% of HESE flux

Do the events cluster around the Galactic Plane?



P-values for chance correlation	All 28 Events	21 Cascade Events
+/- 2.5 degrees (unblinding)	> 50%	41%
+/- 5 degrees	14%	41%
+/- 10 degrees	5%	43%

Only +/- 2.5 deg is *a priori

Summary of Neutrino Astronomy v1.0

- No clustering in space (or time)
- No clustering in Galactic Plane
- Not from close by starburst galaxies
- “Traditional” point source search limits suggest many sources contributing to the flux
- Everything so far points to diffuse sources

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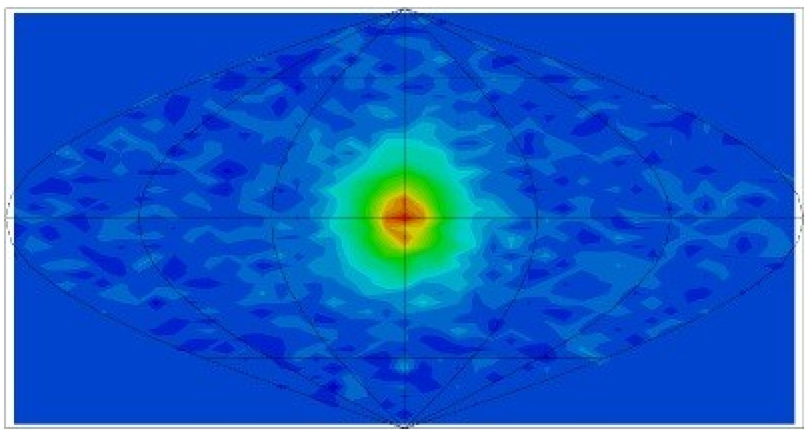
Challenges of Neutrino Astronomy

The Neutrino Astronomy Catalog

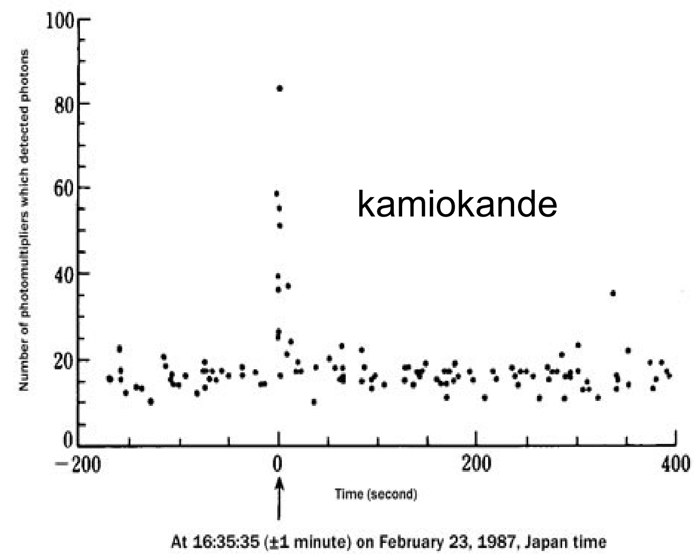
The Sun



super-kamiokande

VERY close by source

Supernova 1987A



No direction, just timing

Challenges of Neutrino Astronomy

- The higher the energy, the fewer there are
  - True for any high-energy telescope

Challenges of Neutrino Astronomy

- The higher the energy, the fewer there are
- Neutrinos don't interact much until very high energies
  - Same characteristics that make neutrinos great messengers make them hard particles to detect

In some ways, this is front-loading the problem.
- Cosmic-rays & gamma-rays: easier to detect, but harder to interpret (source? Spectrum at source?)
- Neutrinos: harder to detect but easier to interpret

- High statistics of events is crucial!

To go beyond v1.0....

- The higher the energy, the fewer there are
- Neutrinos don't interact much until very high energies

→

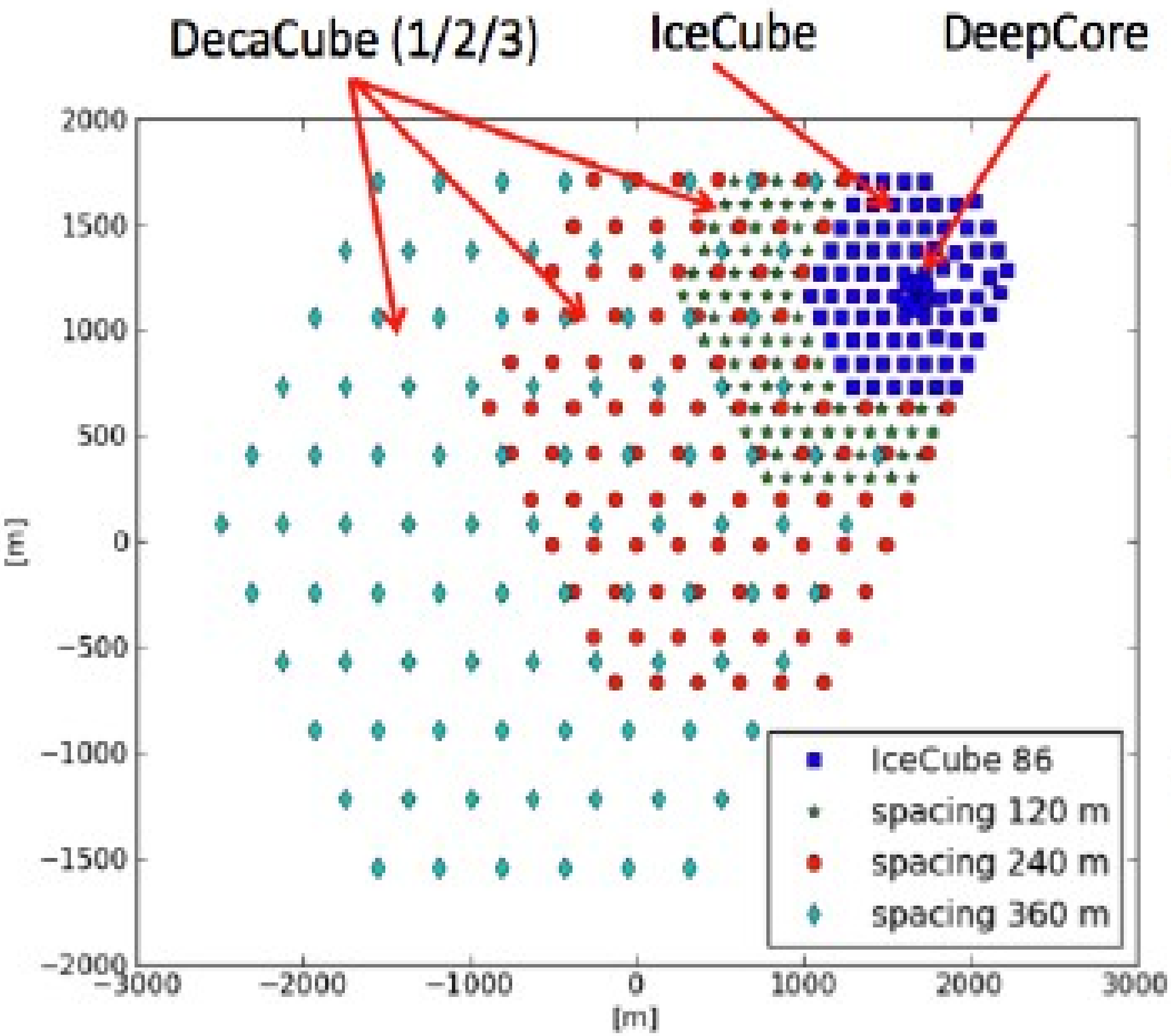
- Only first 2 years of IceCube data, IceCube will run a lot longer → we will have many more events!
- Future: Maybe a bigger IceCube?

- Still need to “point” - otherwise it's not astronomy

→

- We need tracks! Tracks are crucial for the discovery of the first source!
- Spacing of array need not be so dense for very high energy track reconstruction → bigger IceCube could be sparser!

DecaCube, the future of IceCube?



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

The Birth of Neutrino Astrophysics

- The Case for Neutrino Astrophysics
  → is convincing
- First Evidence
  → clearly shows astrophysical neutrinos!
- Neutrino Astronomy v1.0
  → too early to discover their sources
- Beyond v1.0
  → The hunt for sources is on!

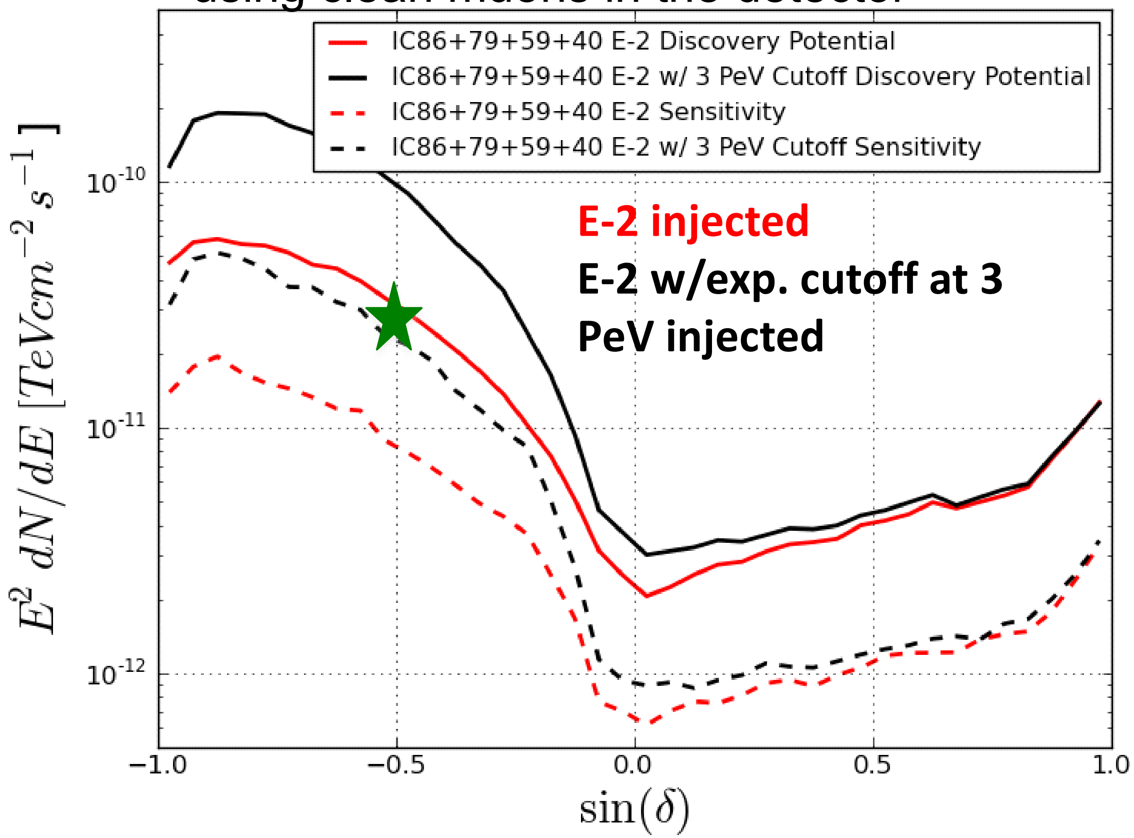
Backups

Could it be a Point Source?

- Back of the envelope:
  - best-fit diffuse flux is ~1 x 10^{-8} GeV/cm^2/s/sr
  - Convert to ν_μ all-sky flux multiply by $4\pi \approx 12 \times 10^{-8}$ GeV/cm^2/s
  - But only ~25% of events near hottest spot: ~3 x 10^{-8} GeV/cm^2/s → **3 x 10^{-11} TeV/cm^2/s**

→ 90% of the times, we should start seeing a hotspot there too with the “traditional” point source analysis
→ We don't
→ many ways around this
Not a point source (extended)
Not equal in flavor
Not a constant source

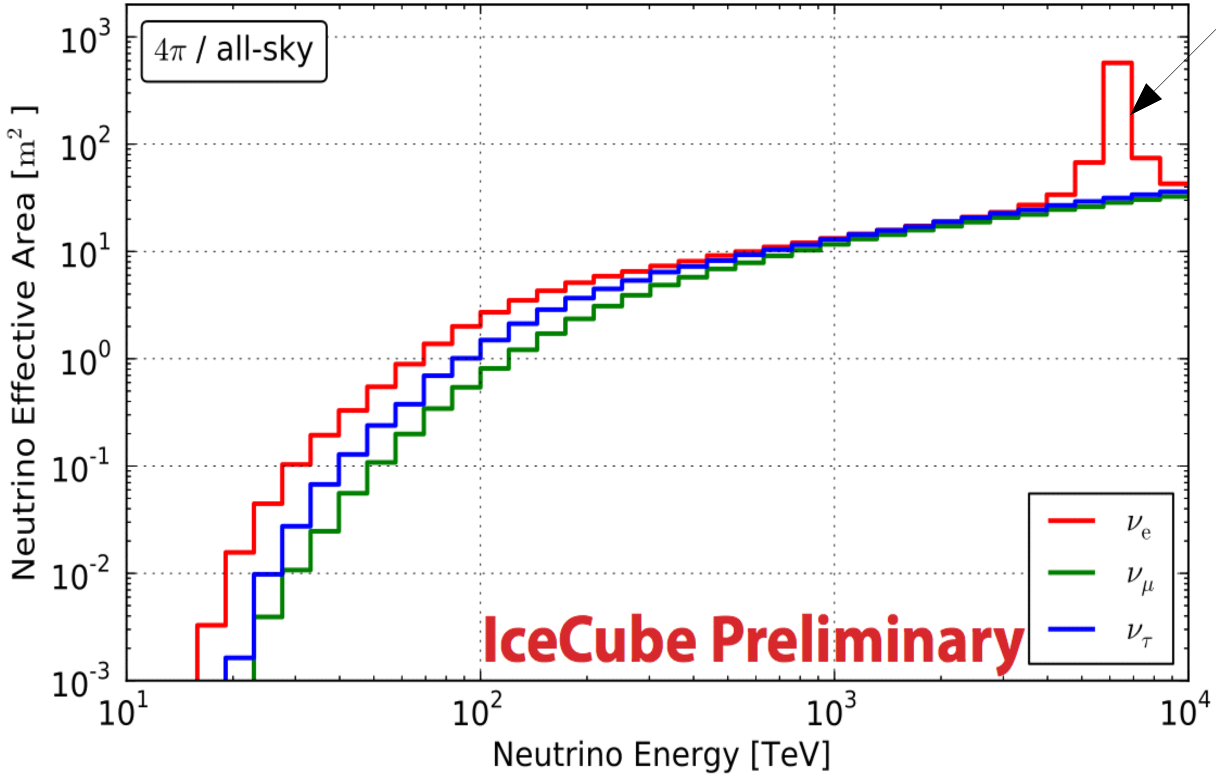
“traditional” point source analysis using clean muons in the detector

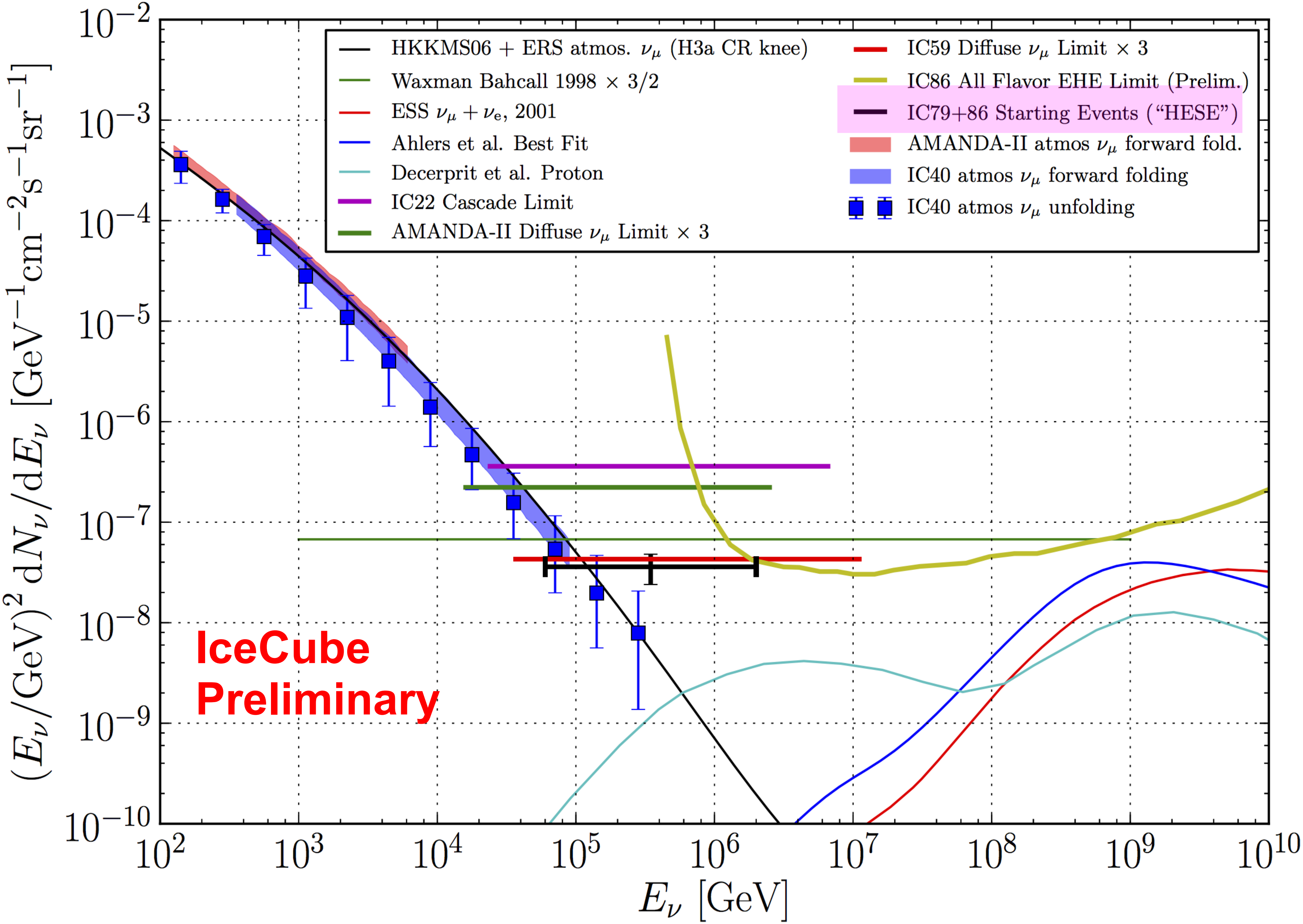


Speculation of a cutoff

A flux level of ~$10^{-8}E^{-2}$[GeV/cm^2/s/str] predicts another 3-6 events in 2-10PeV range

Glashow resonance

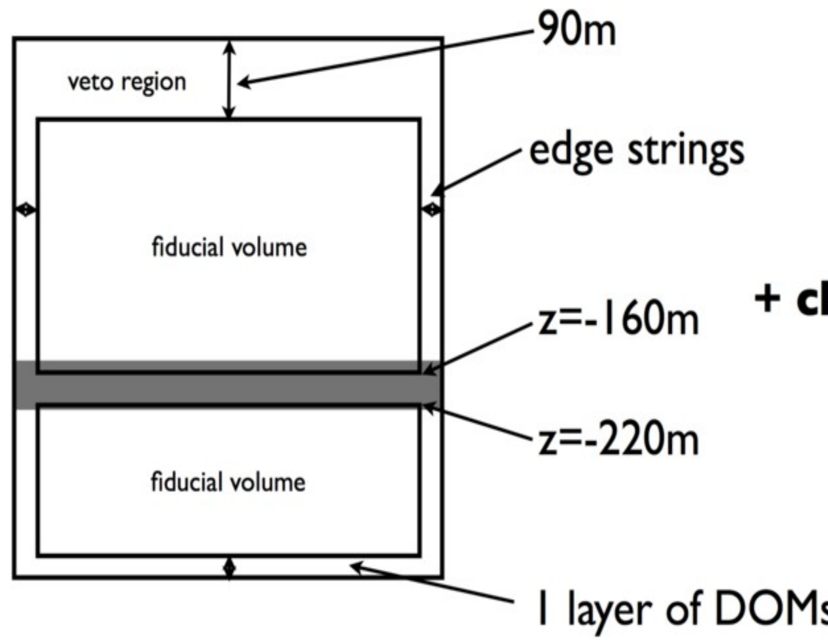




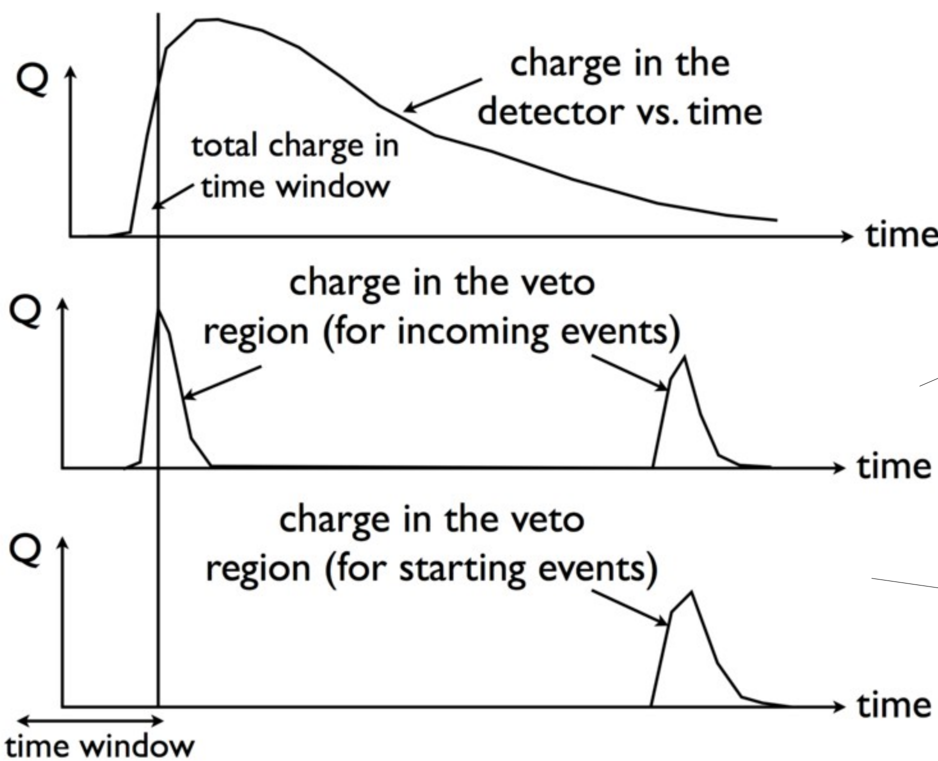
HKKMS06 + ERS atmos. ν_μ (H3a CR knee)
Waxman Bahcall 1998 × 3/2
ESS $\nu_\mu + \nu_e$, 2001
Ahlers et al. Best Fit
Decerprit et al. Proton
IC22 Cascade Limit
AMANDA-II Diffuse ν_μ Limit × 3
IC59 Diffuse ν_μ Limit × 3
IC86 All Flavor EHE Limit (Prelim.)
IC79+86 Starting Events ("HESE")
AMANDA-II atmos ν_μ forward fold.
IC40 atmos ν_μ forward folding
IC40 atmos ν_μ unfolding
IceCube
Preliminary
$(E_\nu/\mathrm{GeV})^2 \mathrm{d}N_\nu/\mathrm{d}E_\nu$ [$\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$]
E_ν [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}

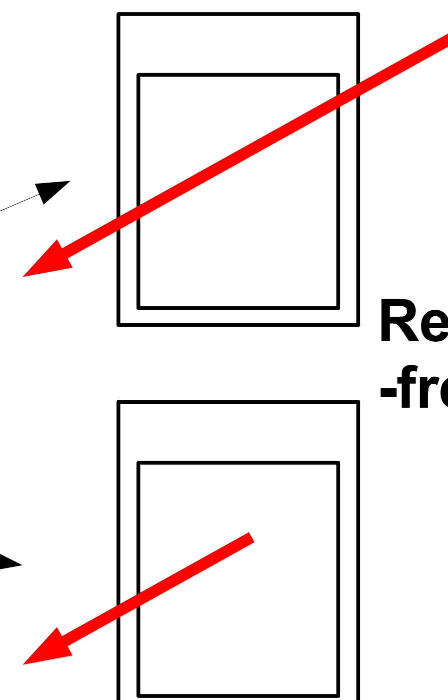
The Event Selection

“High Energy Starting Events” Analysis



+ charge cut



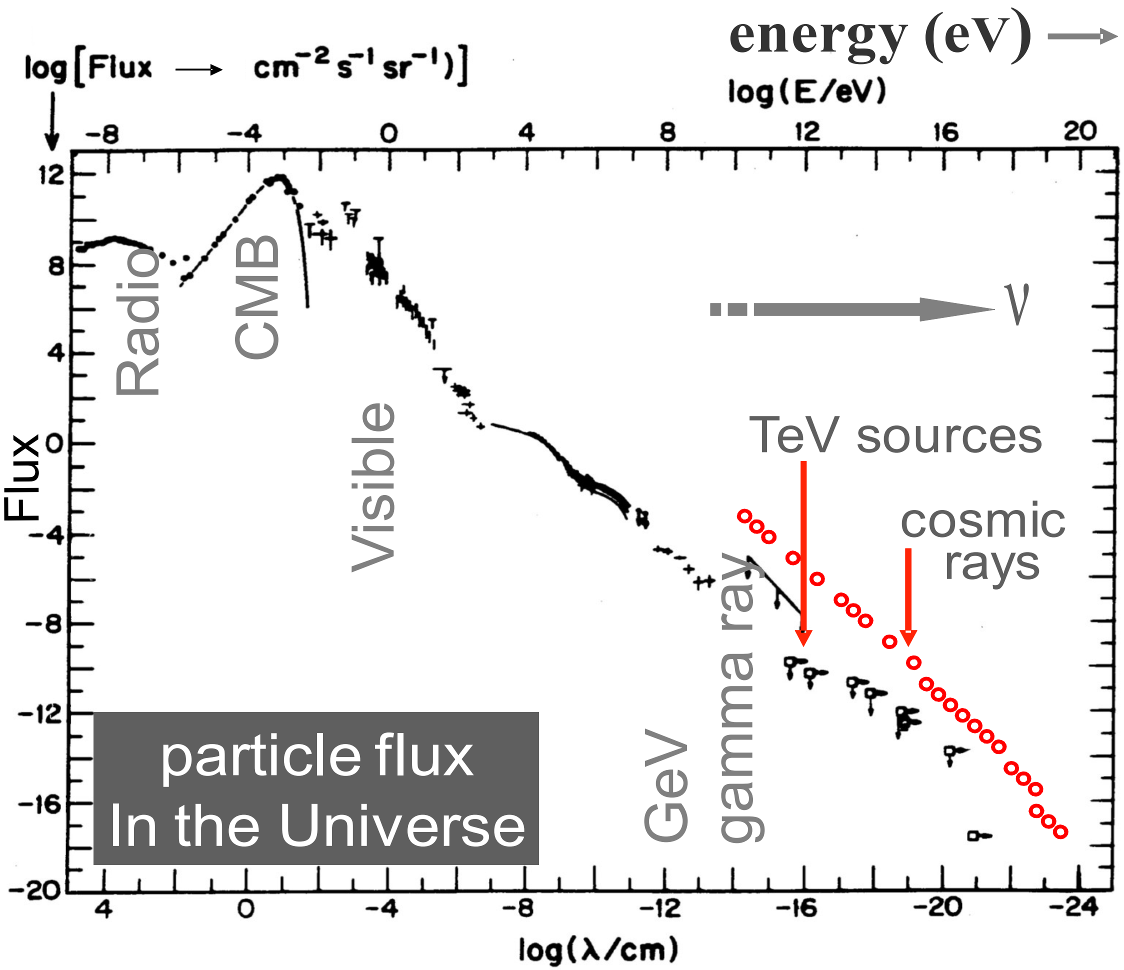


Reconstruction -free veto!

A case for multi-messenger astronomy

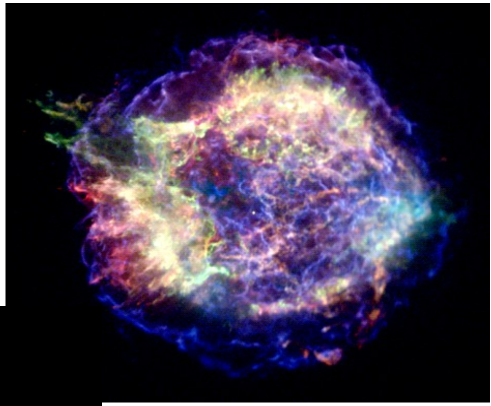
<u>WHERE</u> and HOW do cosmic rays get accelerated?
HOW do gamma rays get created?

Are cosmic rays made where we see γ ray emission?

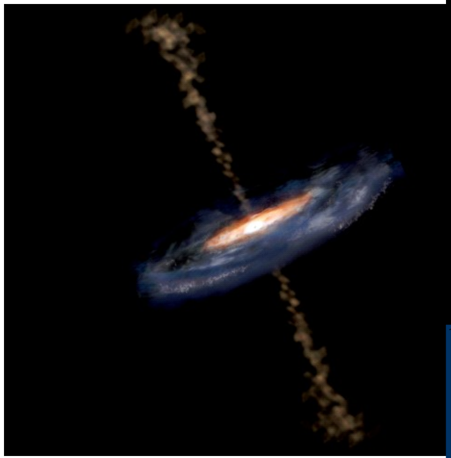


Ressell, T., & Turner, M. 1990,
Comments Astrophys., 14, 323

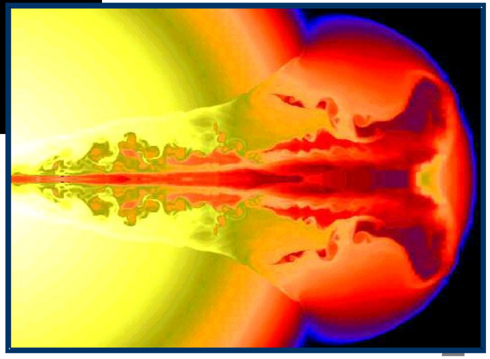
Supernova Remnants



Active Galactic Nucleus



Gamma-ray Bursts

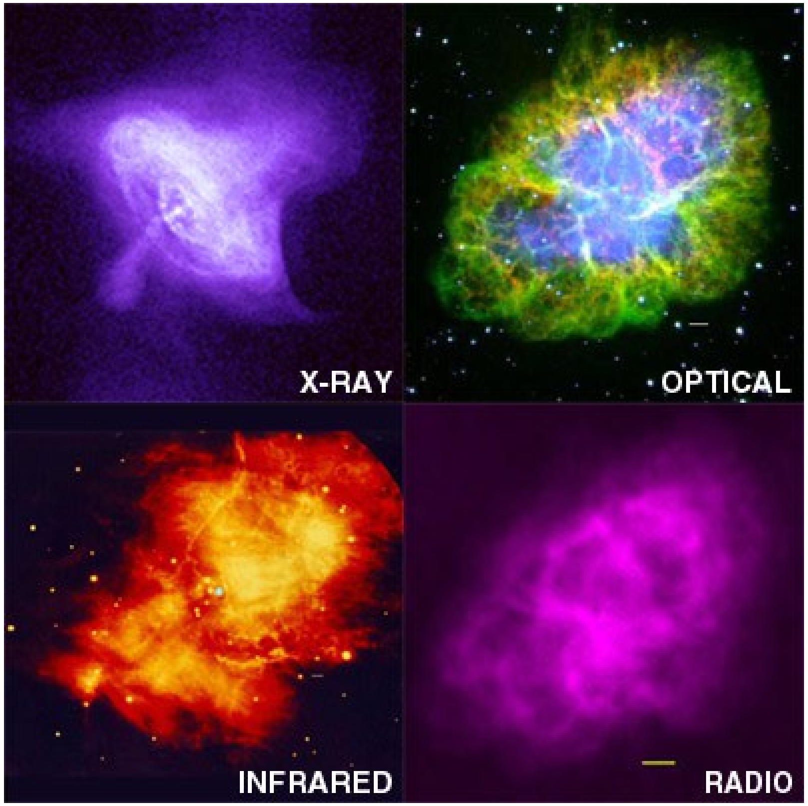


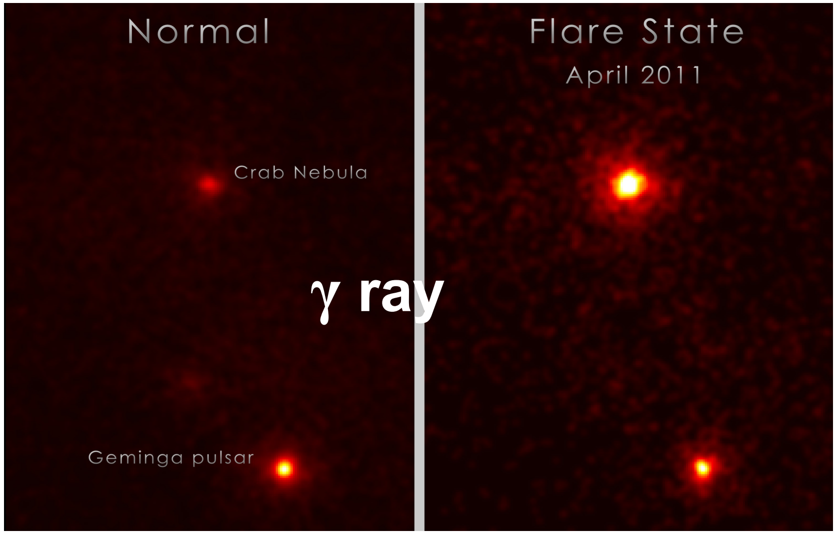
A case for multi-messenger astronomy

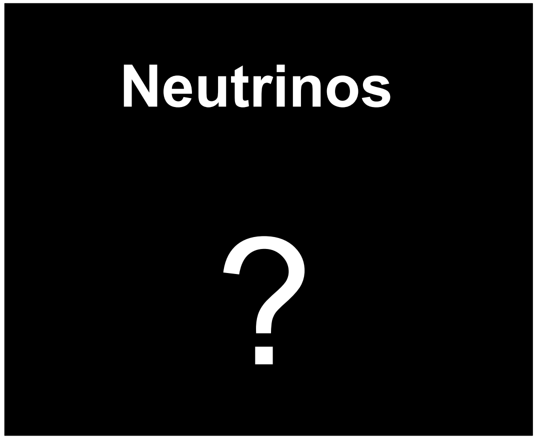
WHERE and <u>HOW</u> do cosmic rays get accelerated?
<u>HOW</u> do gamma rays get created?

What happens at the source?

Crab Nebula
A supernova remnant







x- ray (Chandra)
optical (Palomar)
infrared (Keck)
radio (VLA)
γ ray (Fermi LAT)

Developed cascade direction reconstruction!