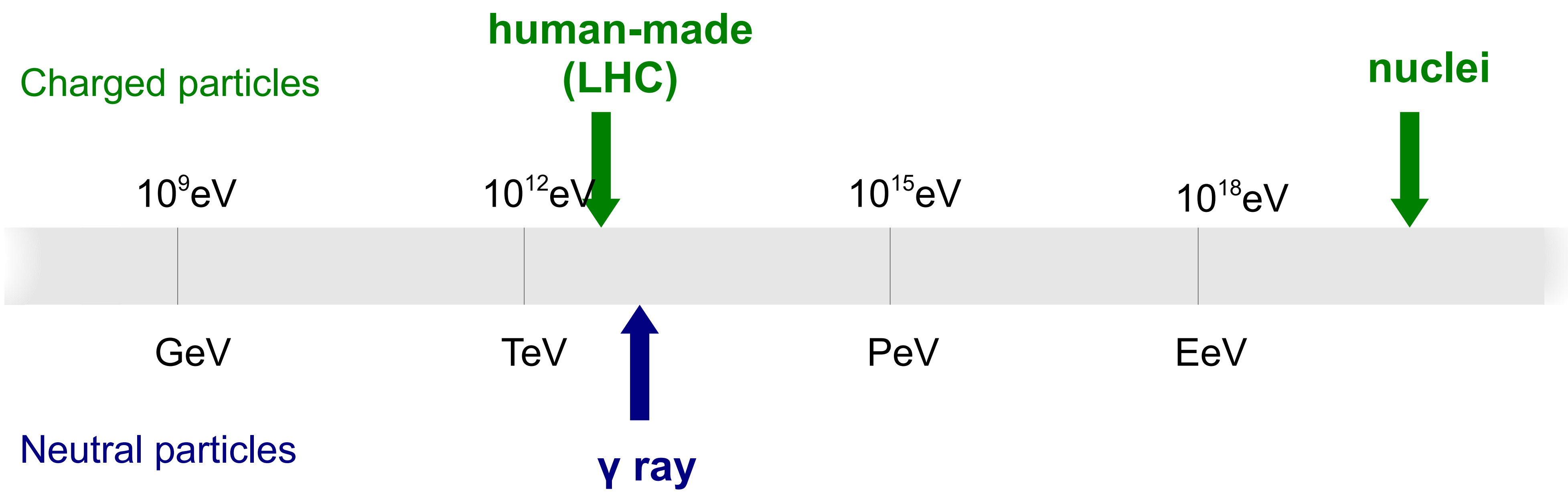
Cosmic Neutrinos in IceCube

Naoko Kurahashi Neilson
University of Wisconsin, Madison
IceCube Collaboration

APS April Meeting – 4/7/2014

Highest energy particles observed



111

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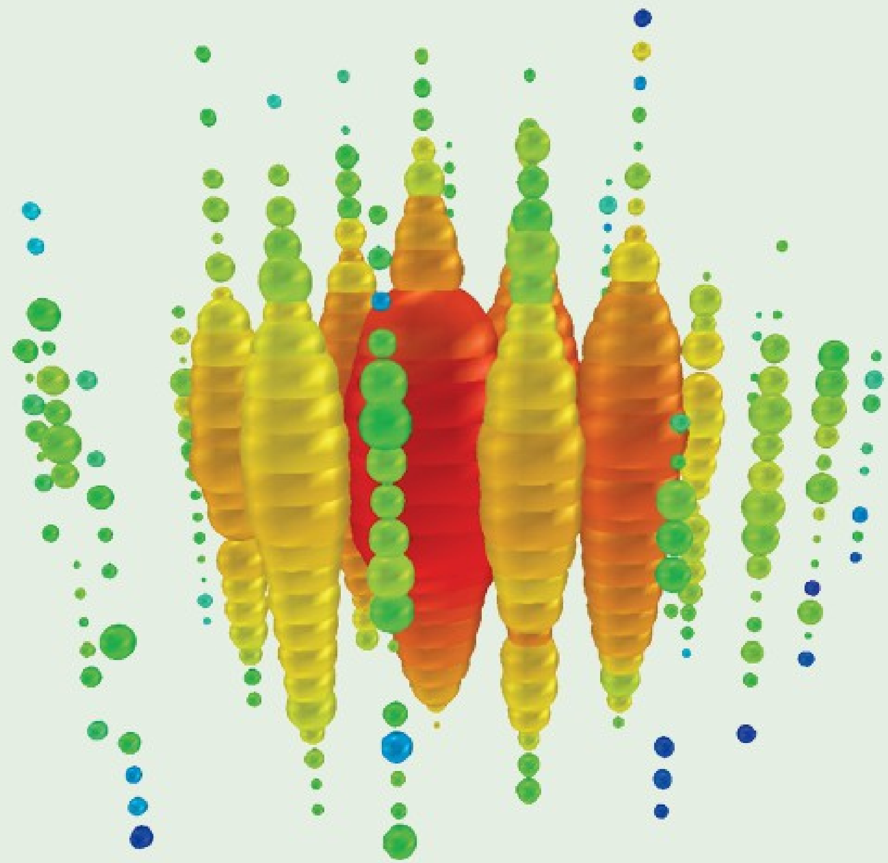

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Volume 111, Number 2

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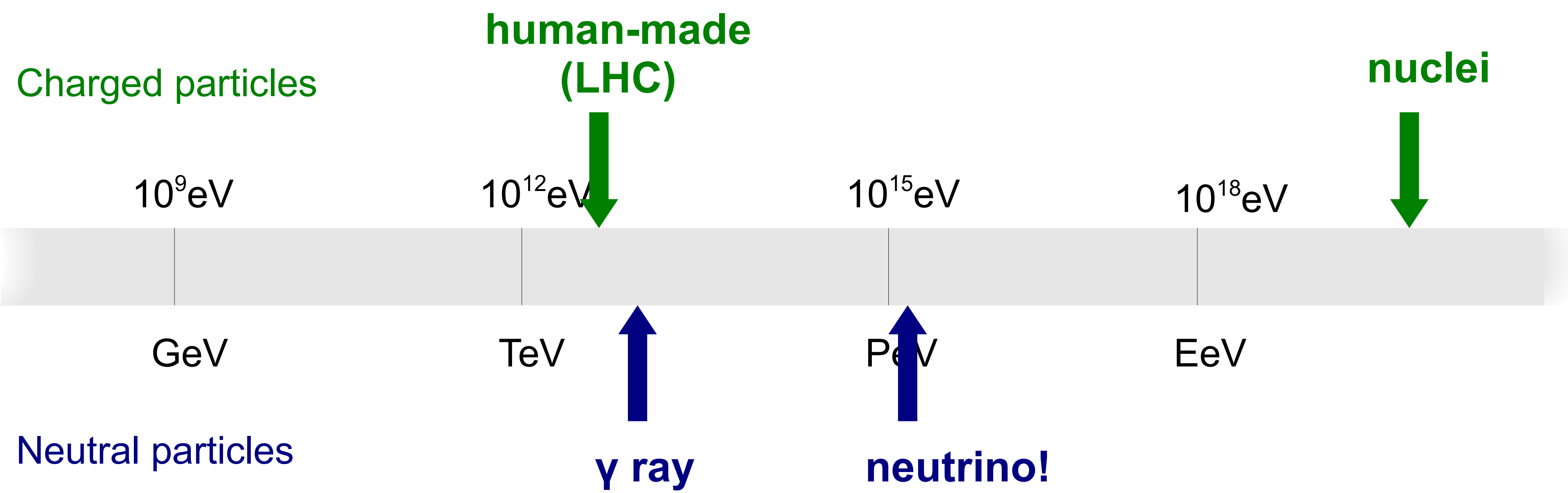

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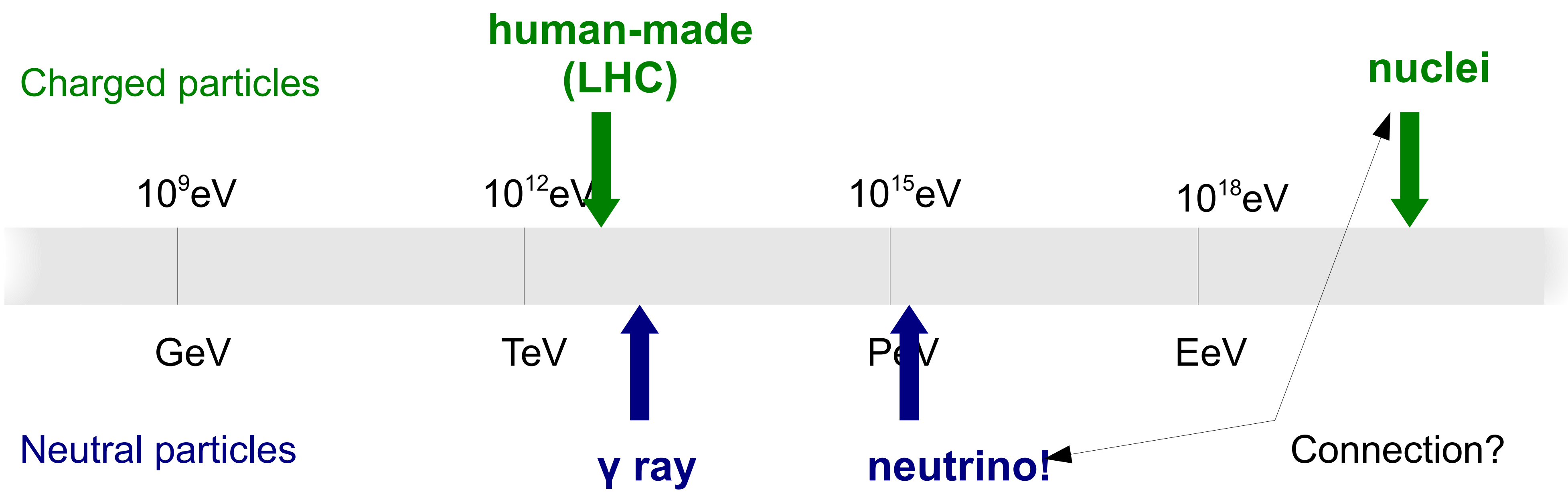
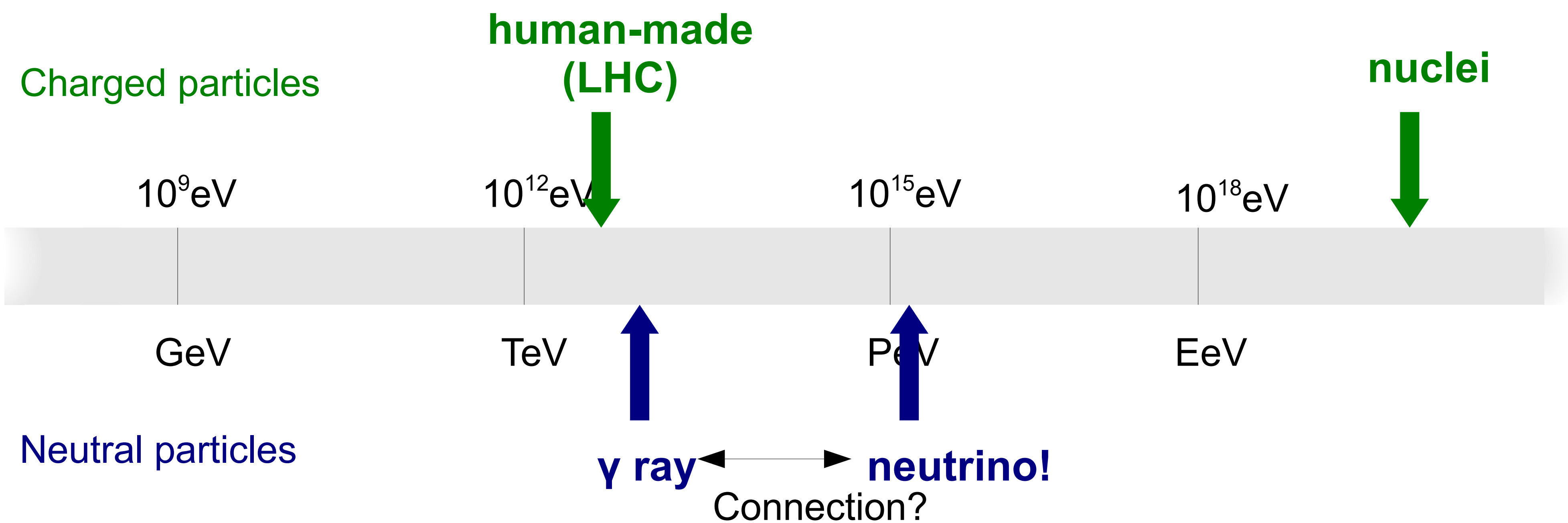


- How are neutral particles created at such high energies?

Highest energy particles observed



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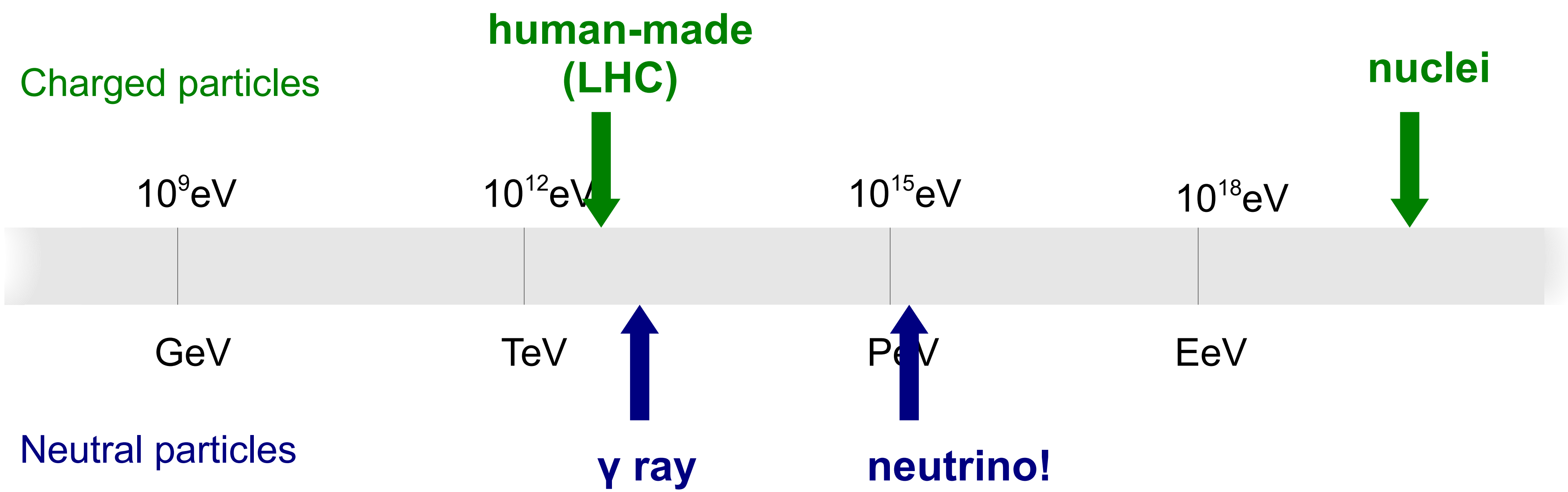
- Can neutrinos be created the same way γ-rays are?

Highest energy particles observed



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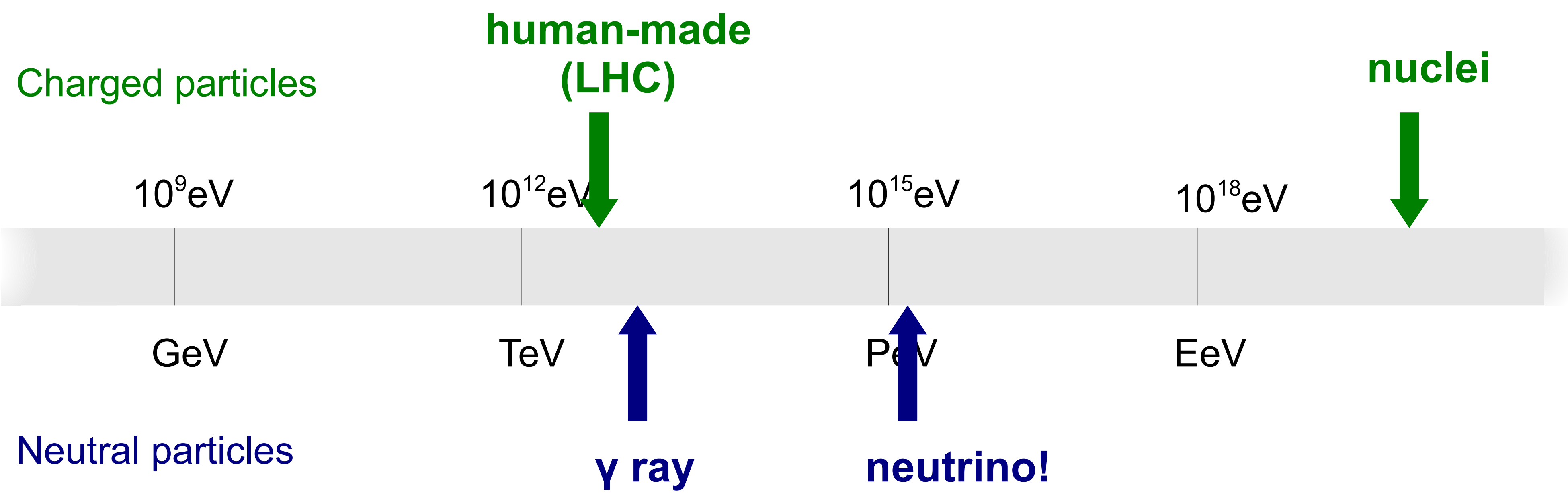
Highest energy particles observed



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- Can neutrinos be created the same way γ-rays are?
- What are the most likely sources of these observed neutrinos? Background? Signal?
- Where do they come from? What do they tell us?

Outline

- The Case for Neutrino Astrophysics
- IceCube Neutrino Observatory
- Observation of Astrophysical Neutrinos
- Looking Forward

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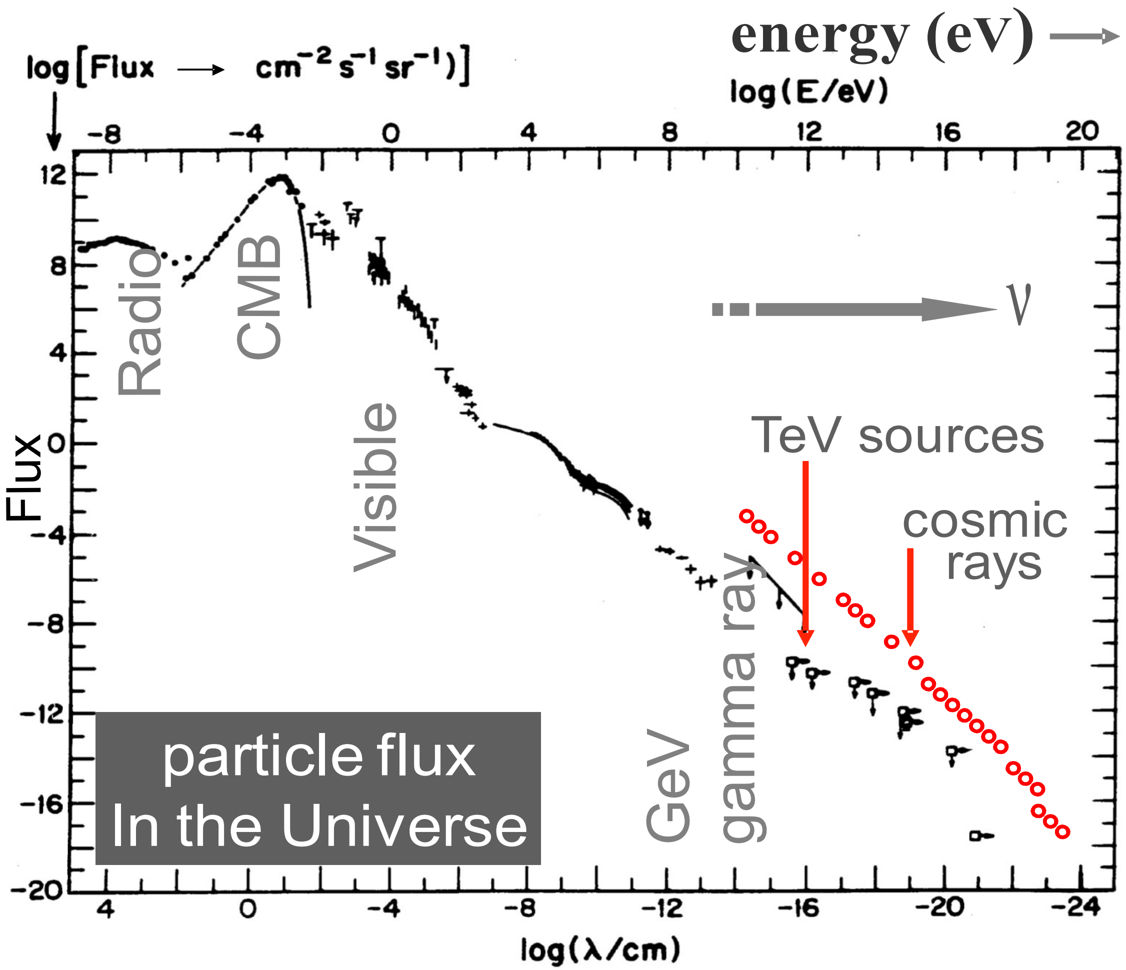
A case for multi-messenger astronomy

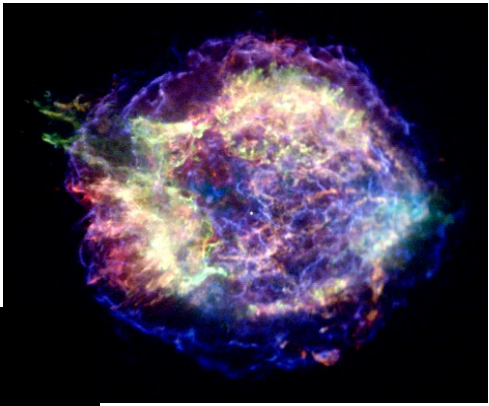
<u>WHERE</u> and HOW do cosmic rays get accelerated?
HOW do gamma rays get created?

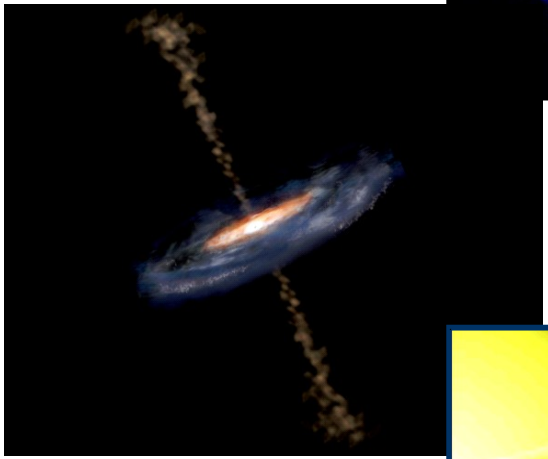
Are cosmic rays made where we see γ ray emission?



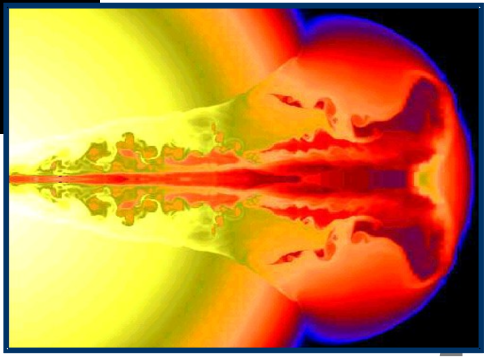
Ressell, T., & Turner, M. 1990,
Comments Astrophys., 14, 323

Supernova Remnants





Active Galactic Nucleus



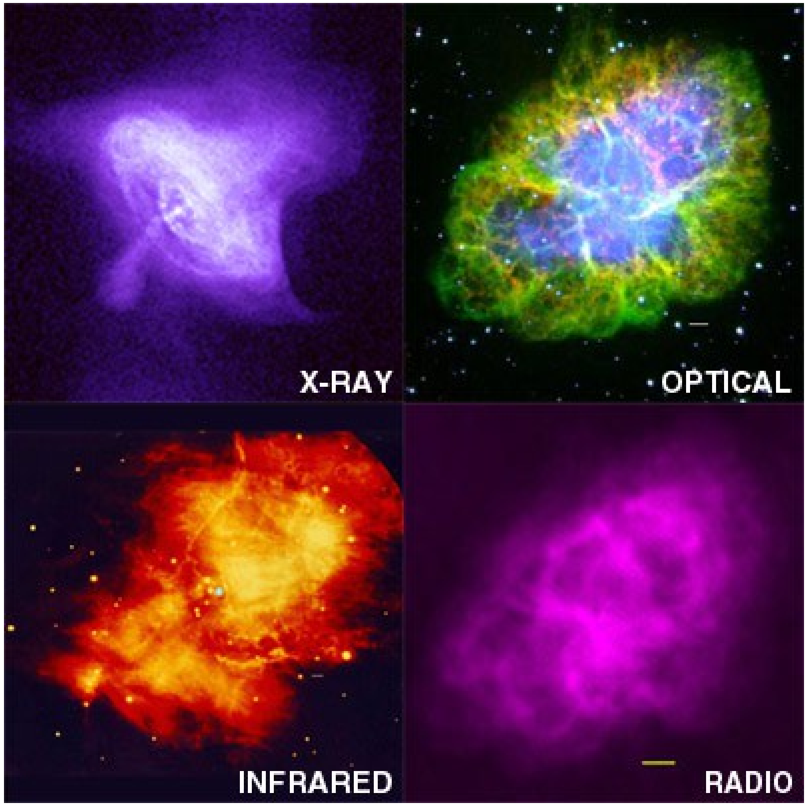
Gamma-ray Bursts

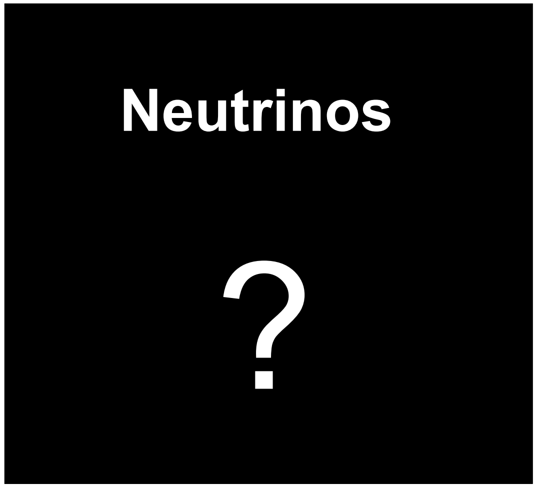
A case for multi-messenger astronomy

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

What happens at the source?

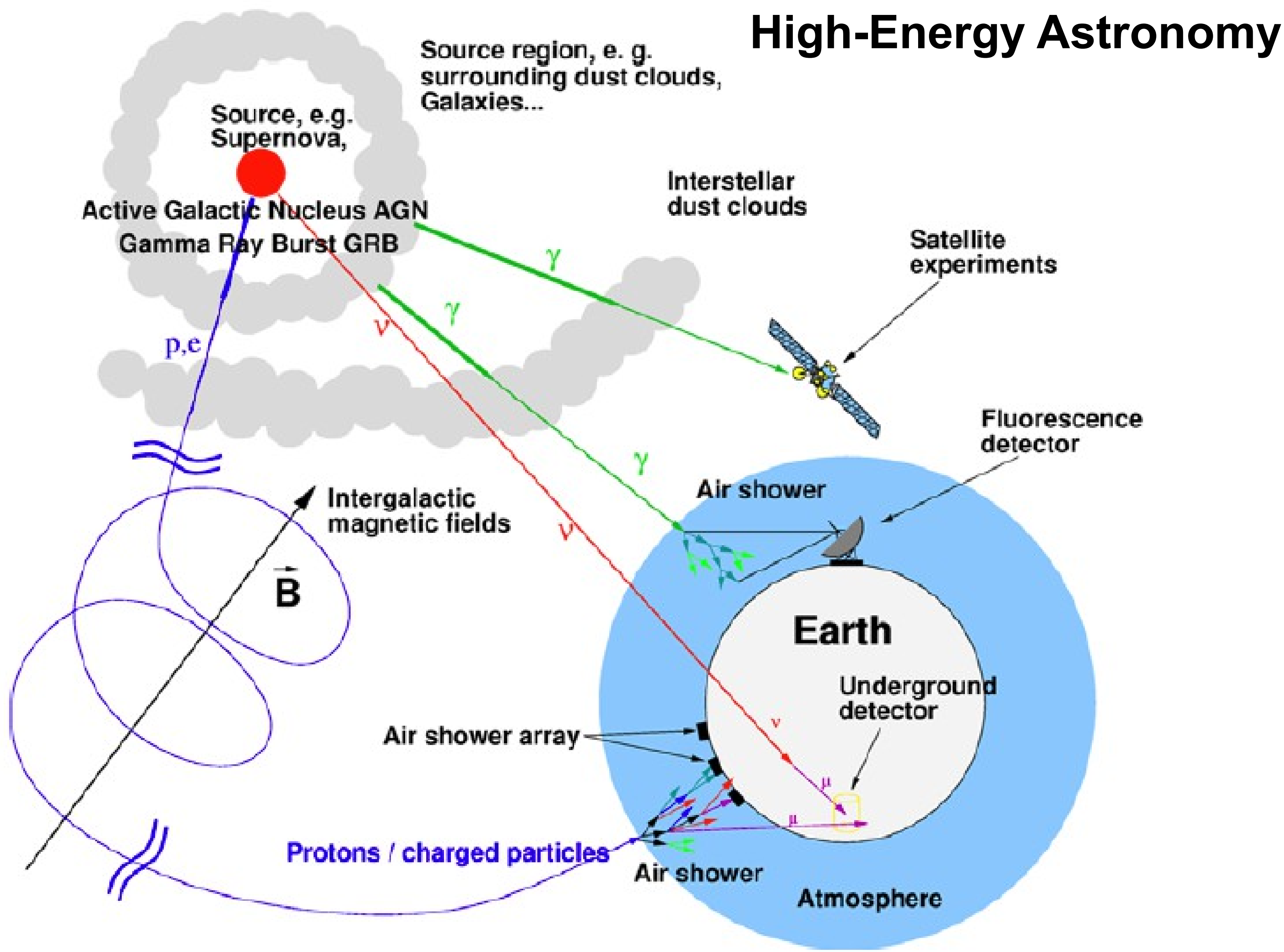
Crab Nebula
A supernova remnant



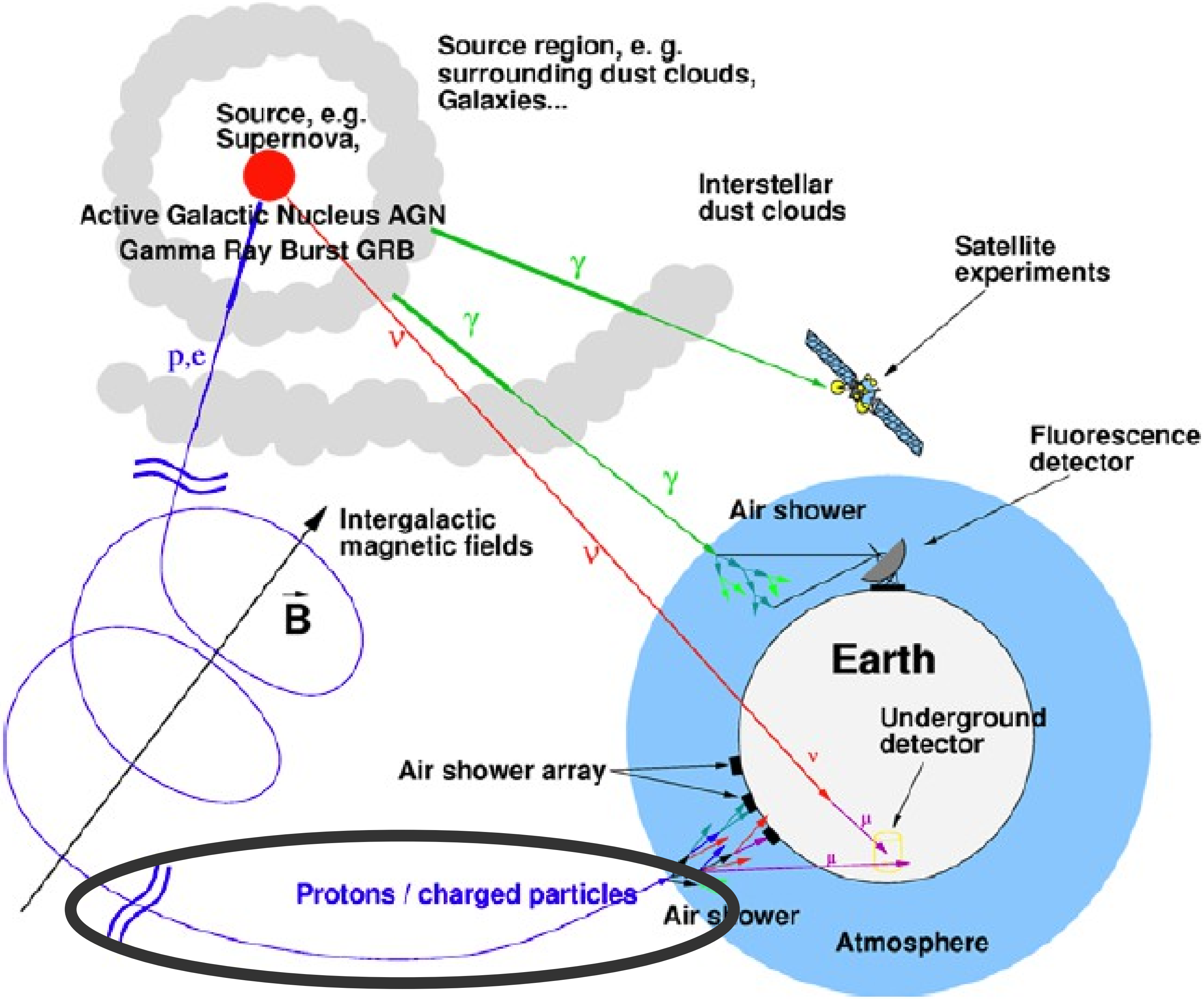


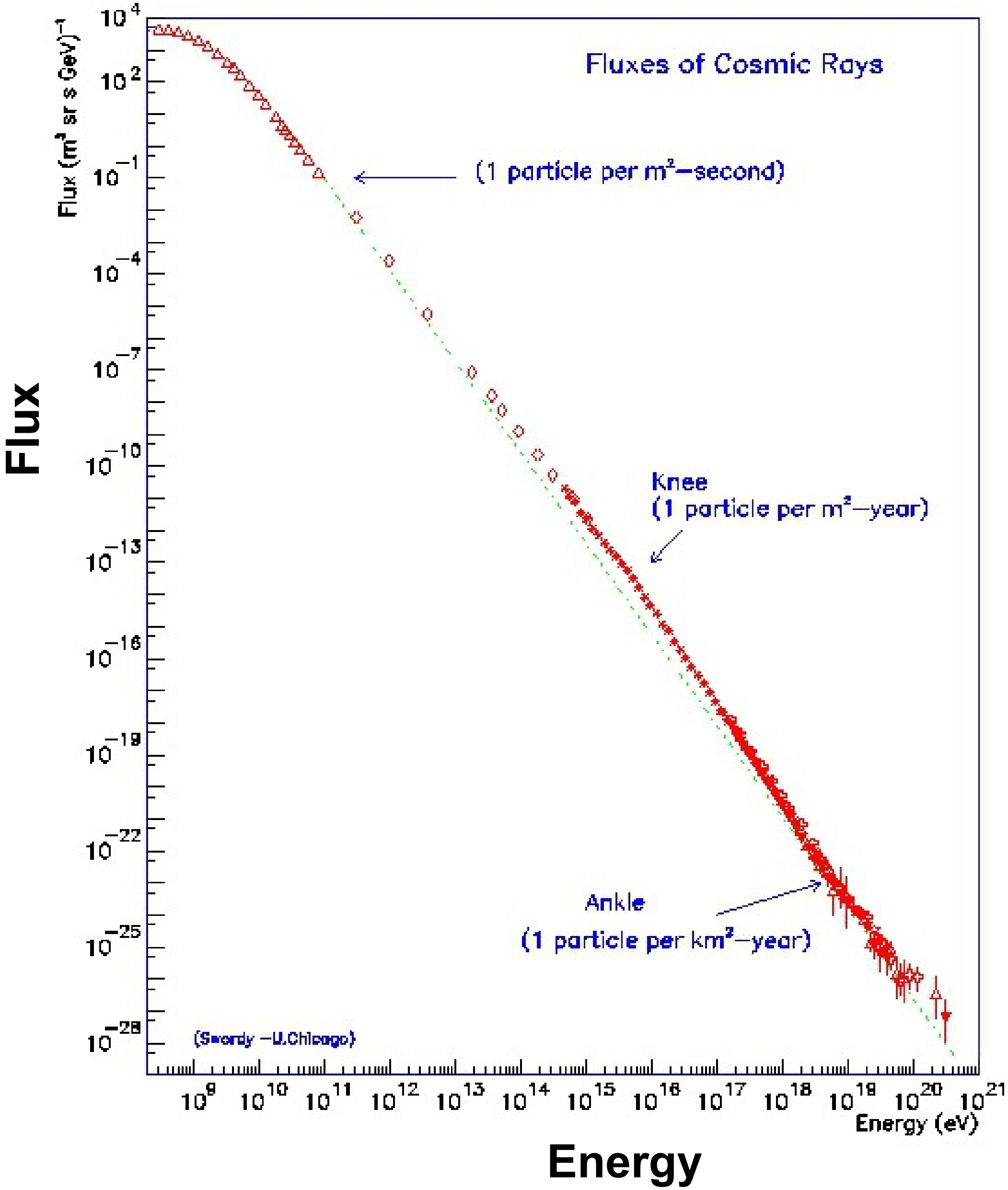
x- ray (Chandra)
optical (Palomar)
infrared (Keck)
radio (VLA)

Neutrino Astronomy



Neutrino Astronomy





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

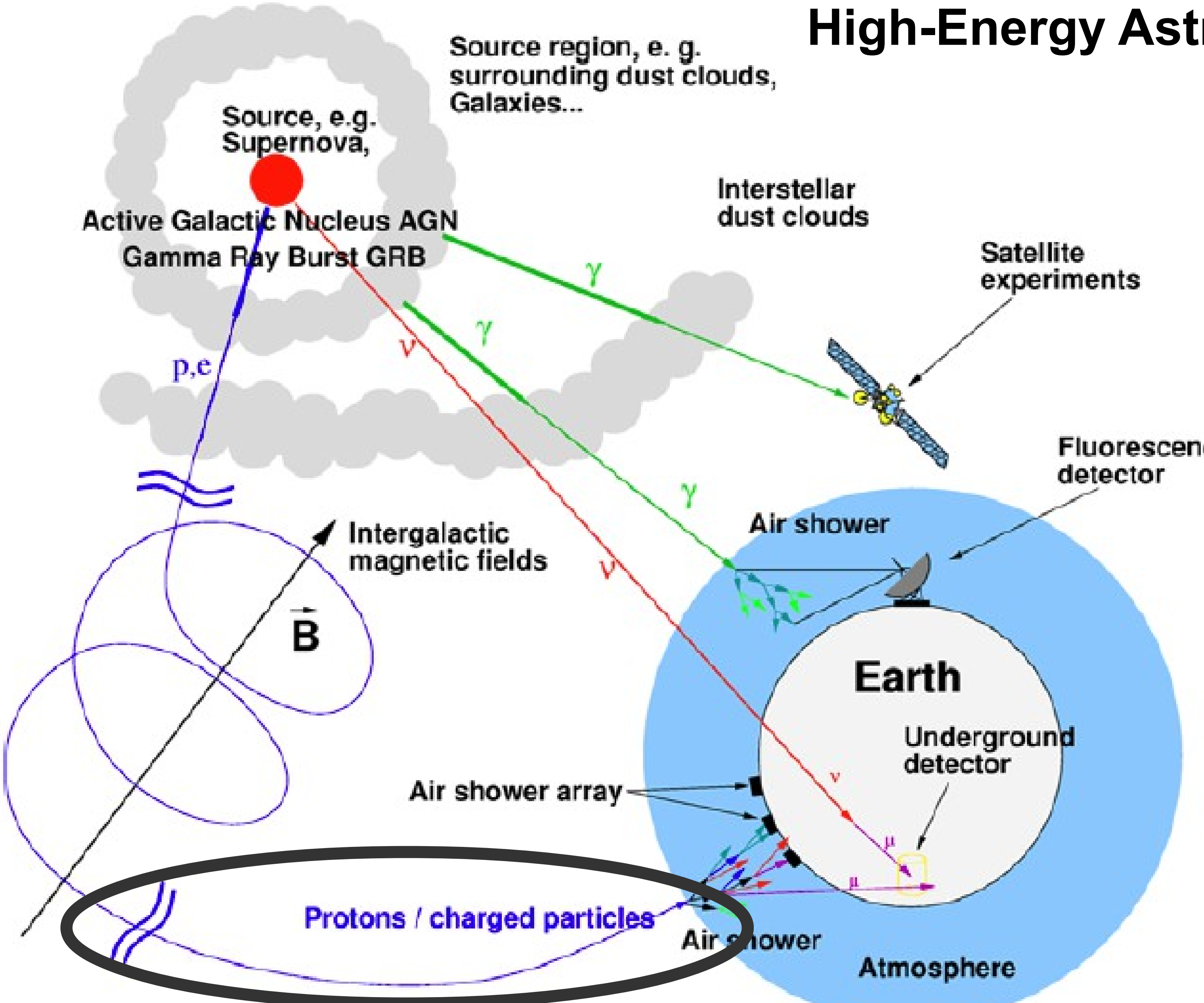
- Low energy cosmic-rays can't escape local magnetic fields
- High-energy cosmic rays hitting gas clouds or interstellar dust interact and deplete

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

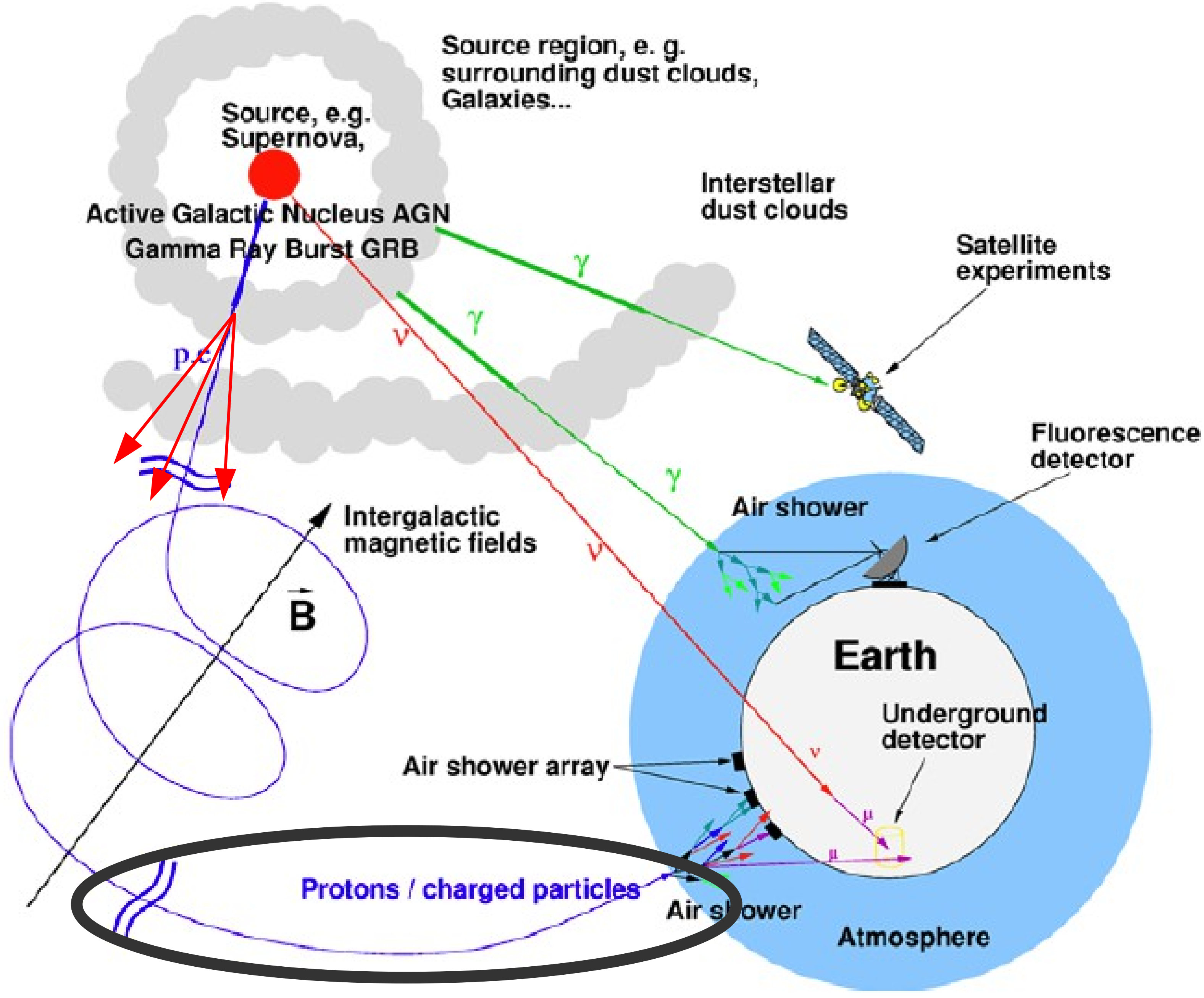
Interaction of cosmic rays means creation of neutrinos

Neutrino Astronomy

High-Energy Astronomy

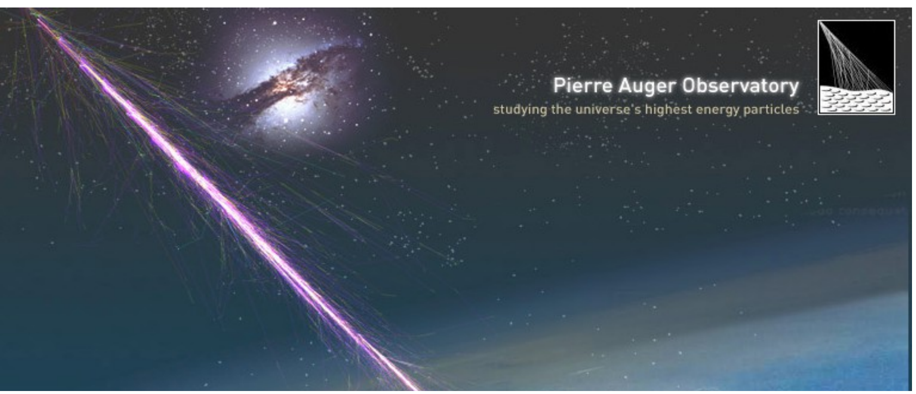


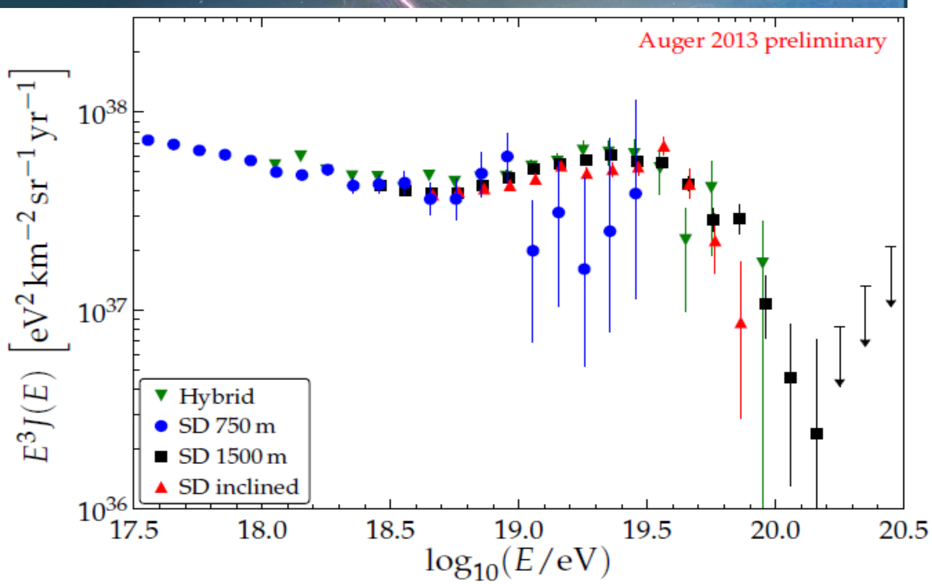
Neutrino Astronomy



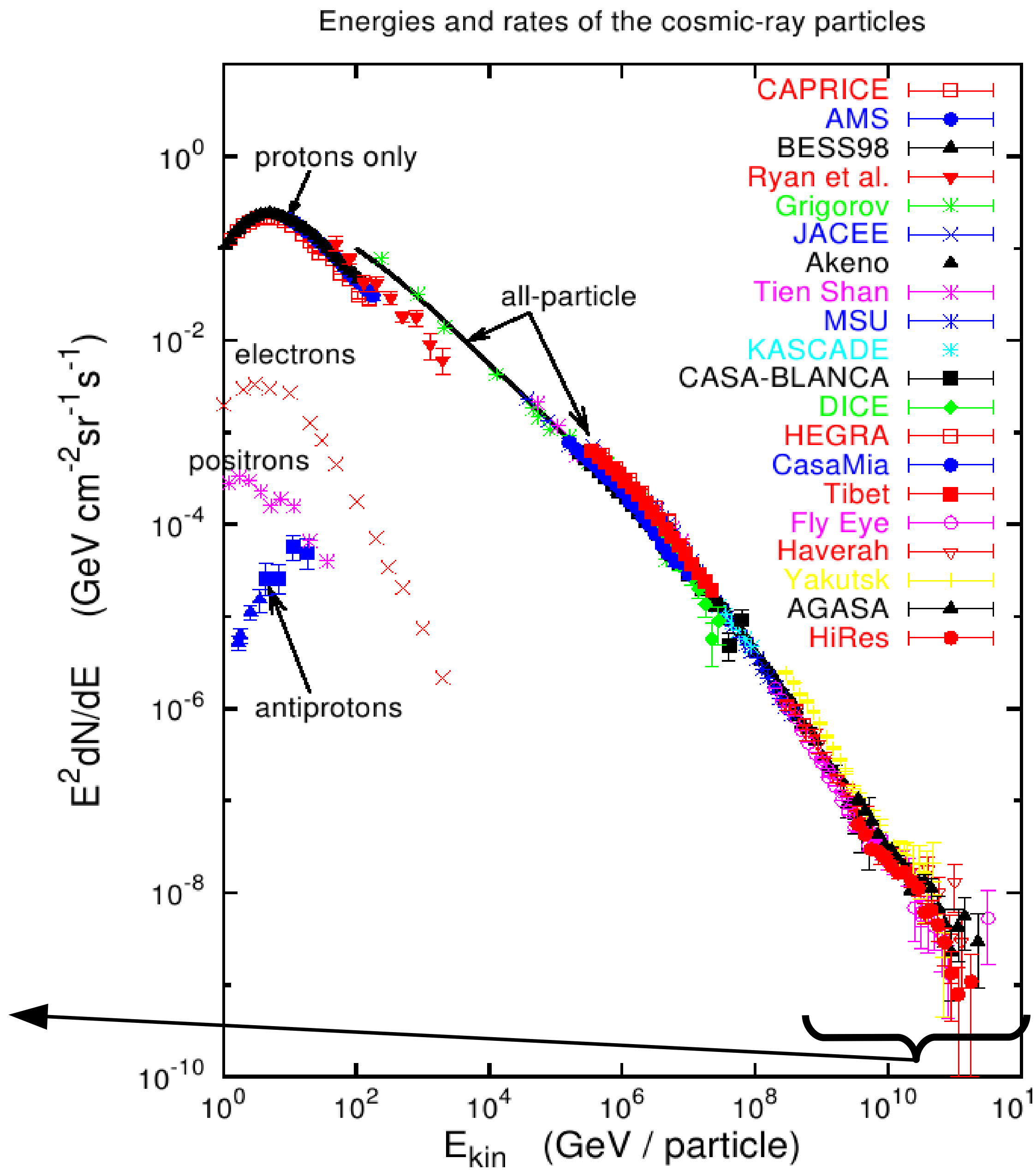
Measured charged particle spectrum

What's happening at Extremely High Energies (>10^{18}eV)?





Pierre Auger Observatory
ICRC 2013 proceedings



Hillas 2006, arXiv:astro-ph/0607109

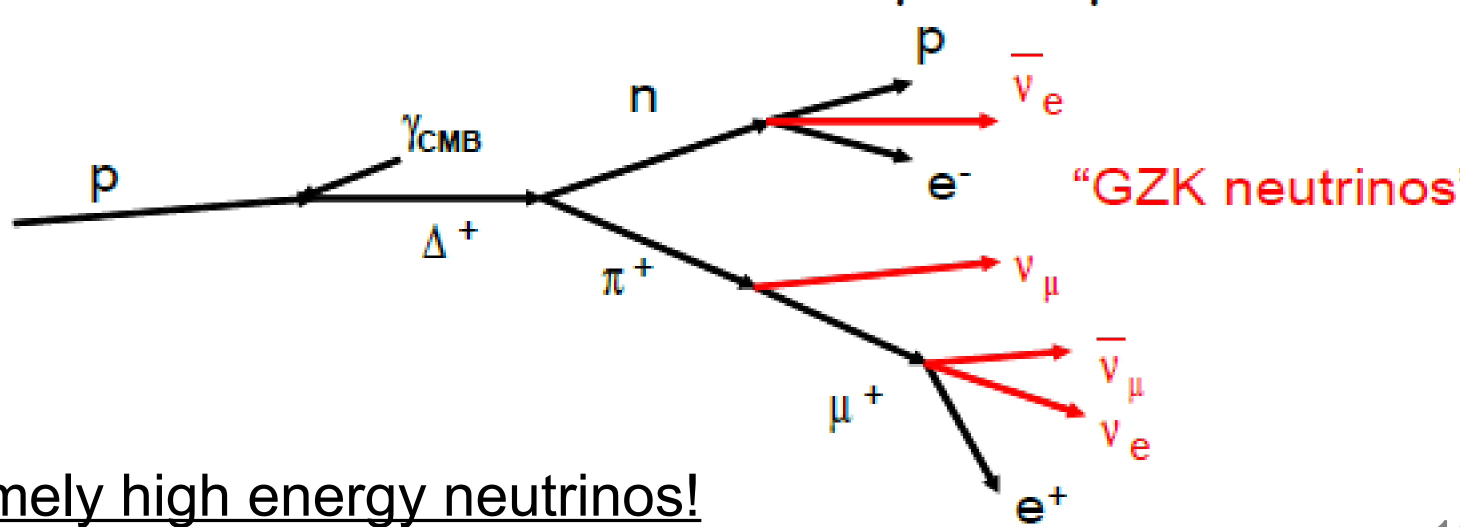
The GZK Mechanism
(Greisen-Zatsepin-Kuzmin)

Cosmic Microwave Background Radiation Acts To Deplete The Density Of High Energy Cosmic Rays

Low energy photons from the early universe

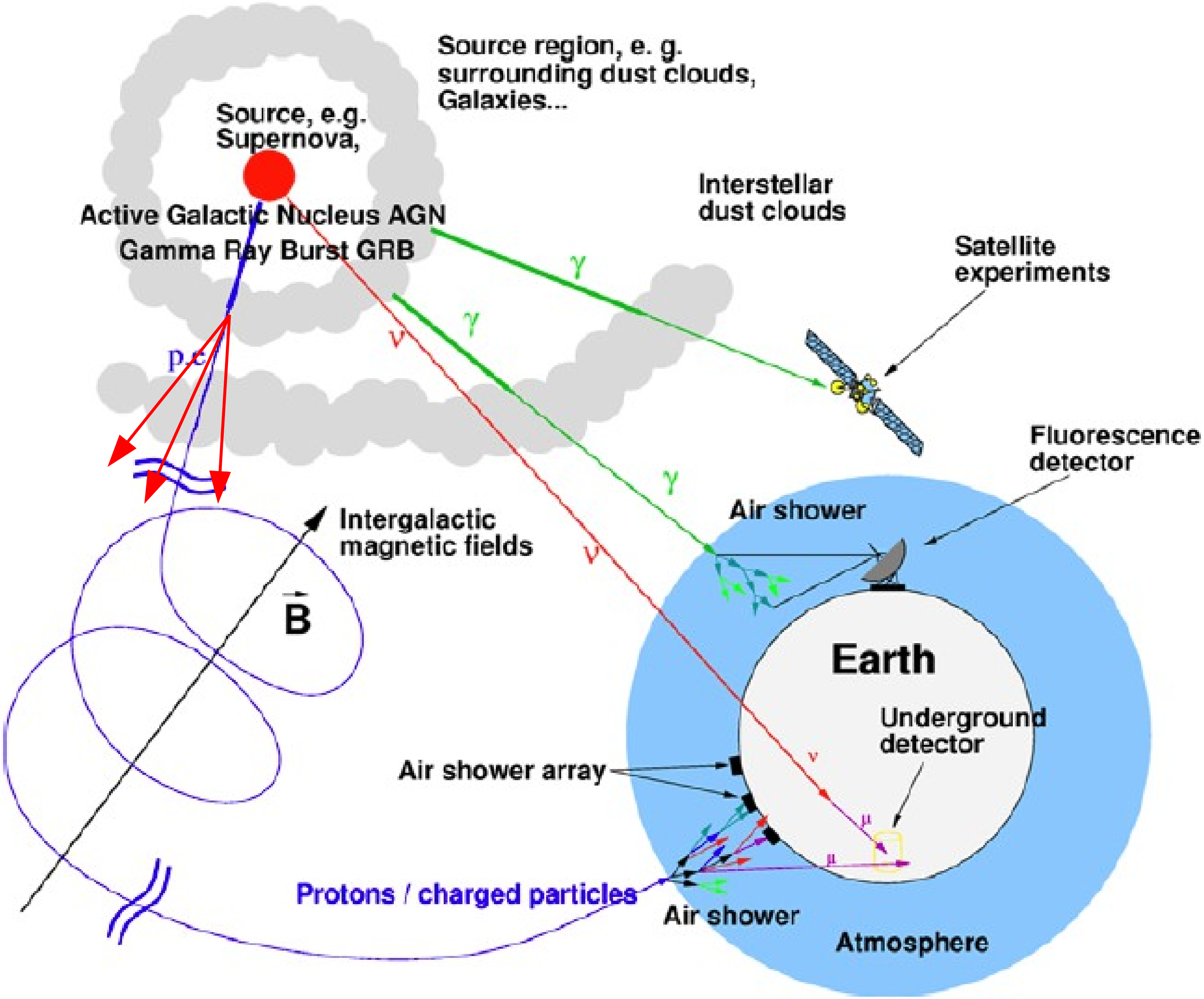
$$\gamma_{CMB} + p \rightarrow n + \pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu}$$

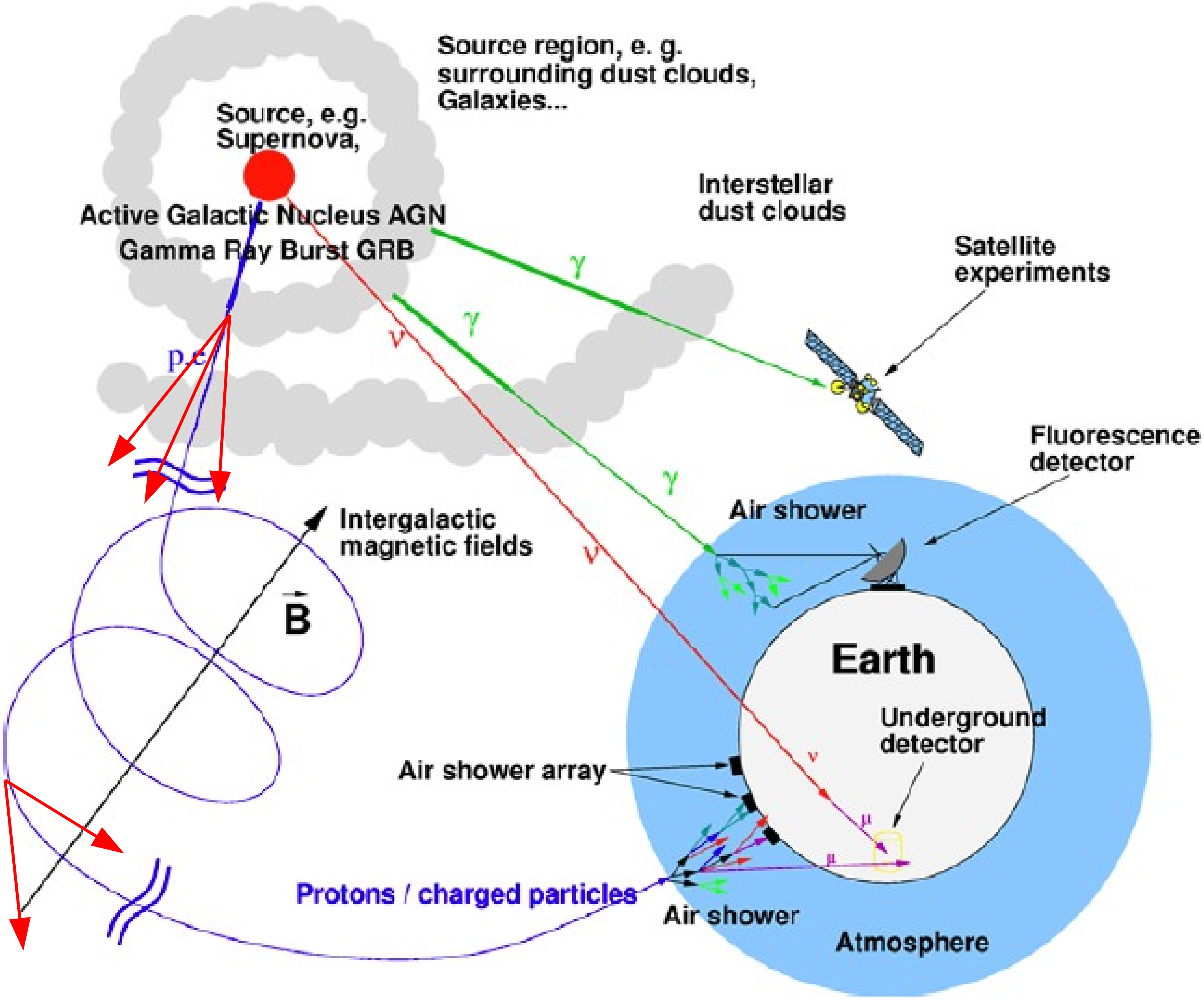


<u>GZK produces extremely high energy neutrinos!</u>

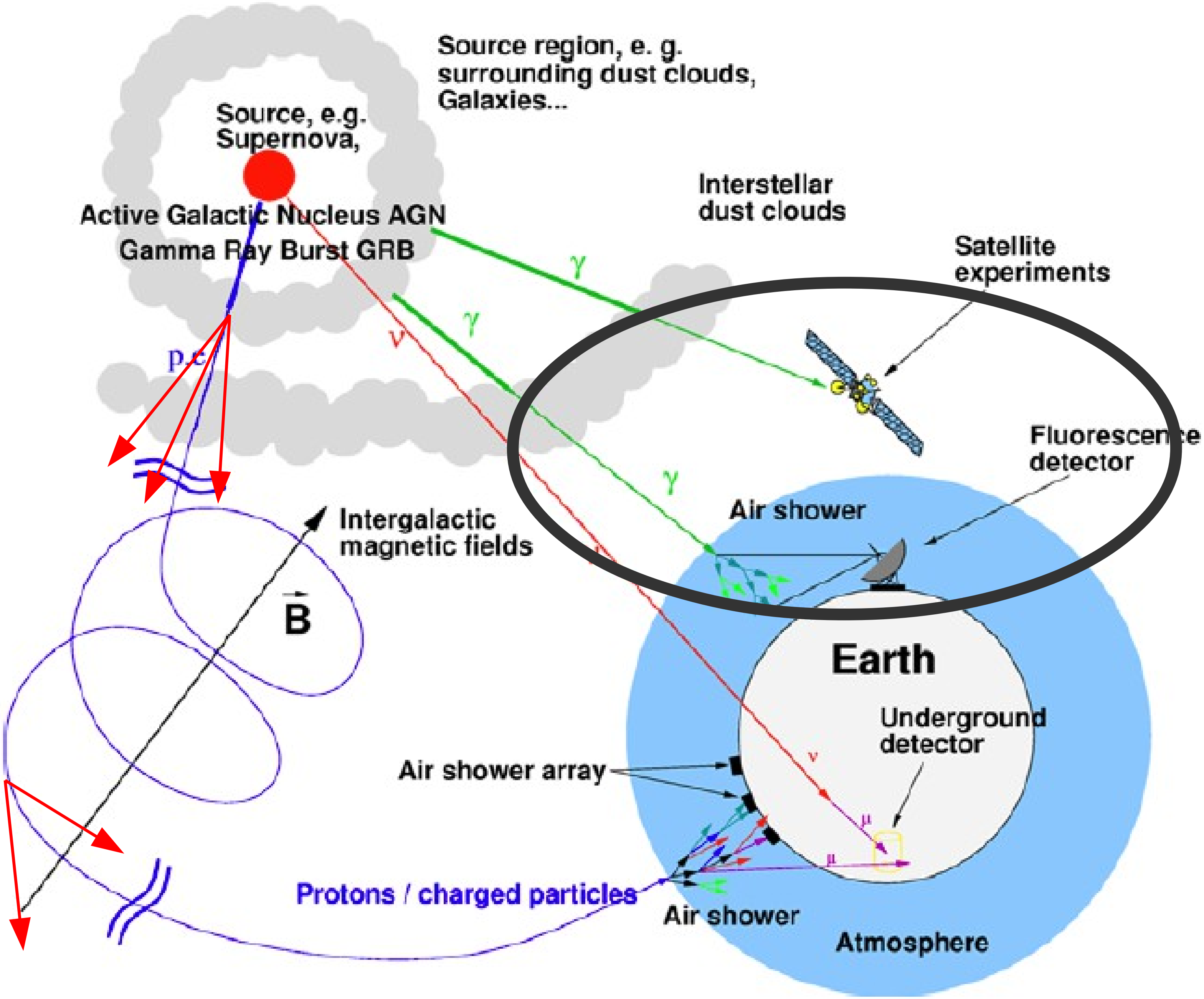
Neutrino Astronomy



Neutrino Astronomy



Neutrino Astronomy



γ ray Telescopes

Space satellite telescopes
0.1 GeV – few hundred GeV

Fermi

Images from NASA

EGRET

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

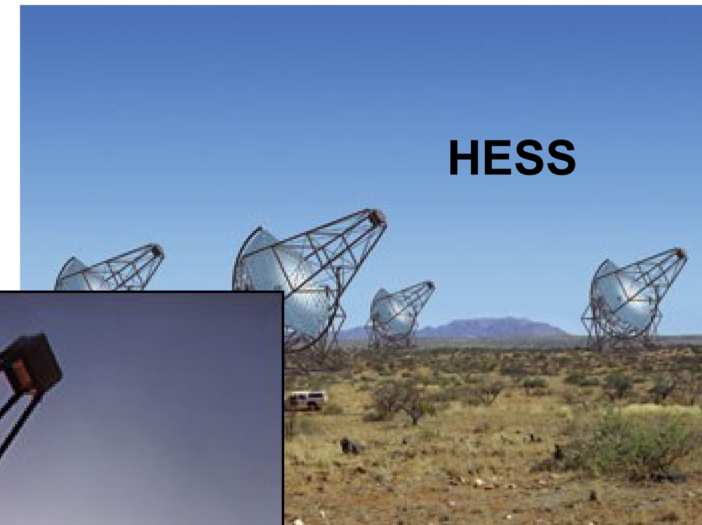
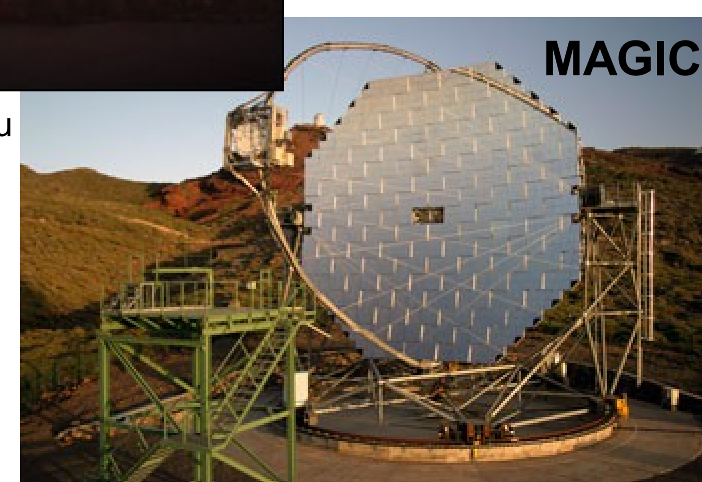


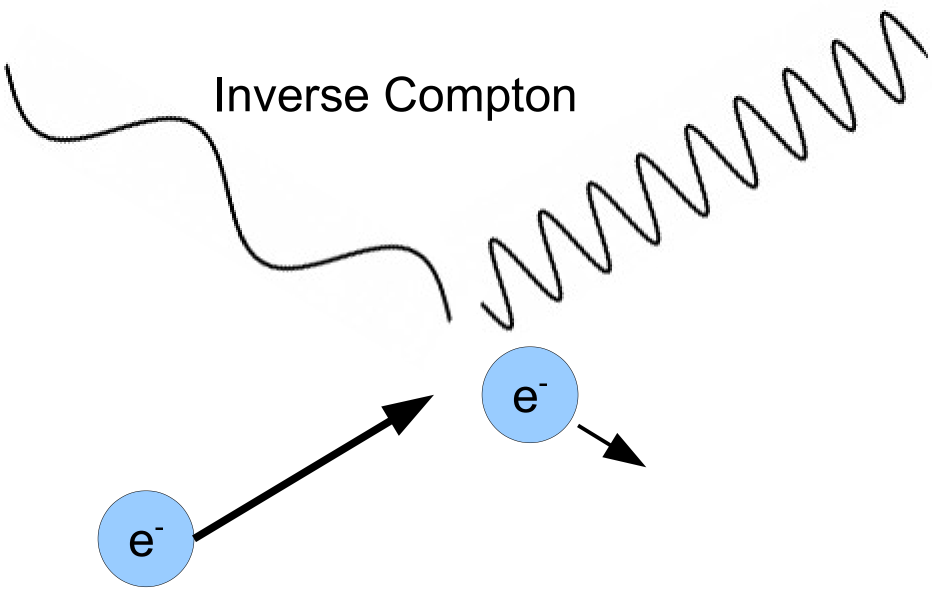
Image:kicp.uchicago.edu

Images: phys.org



Producing γ rays

Leptonic Processes

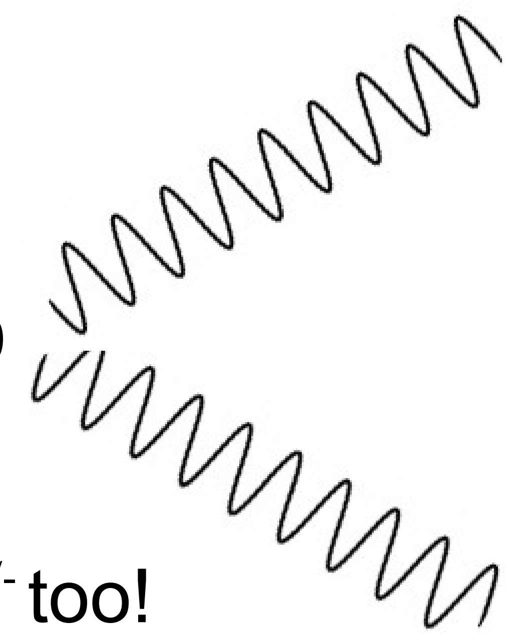


Bremsstrahlung, etc

Hadronic Processes

$P + P$ or $P + \gamma$ creates π^0

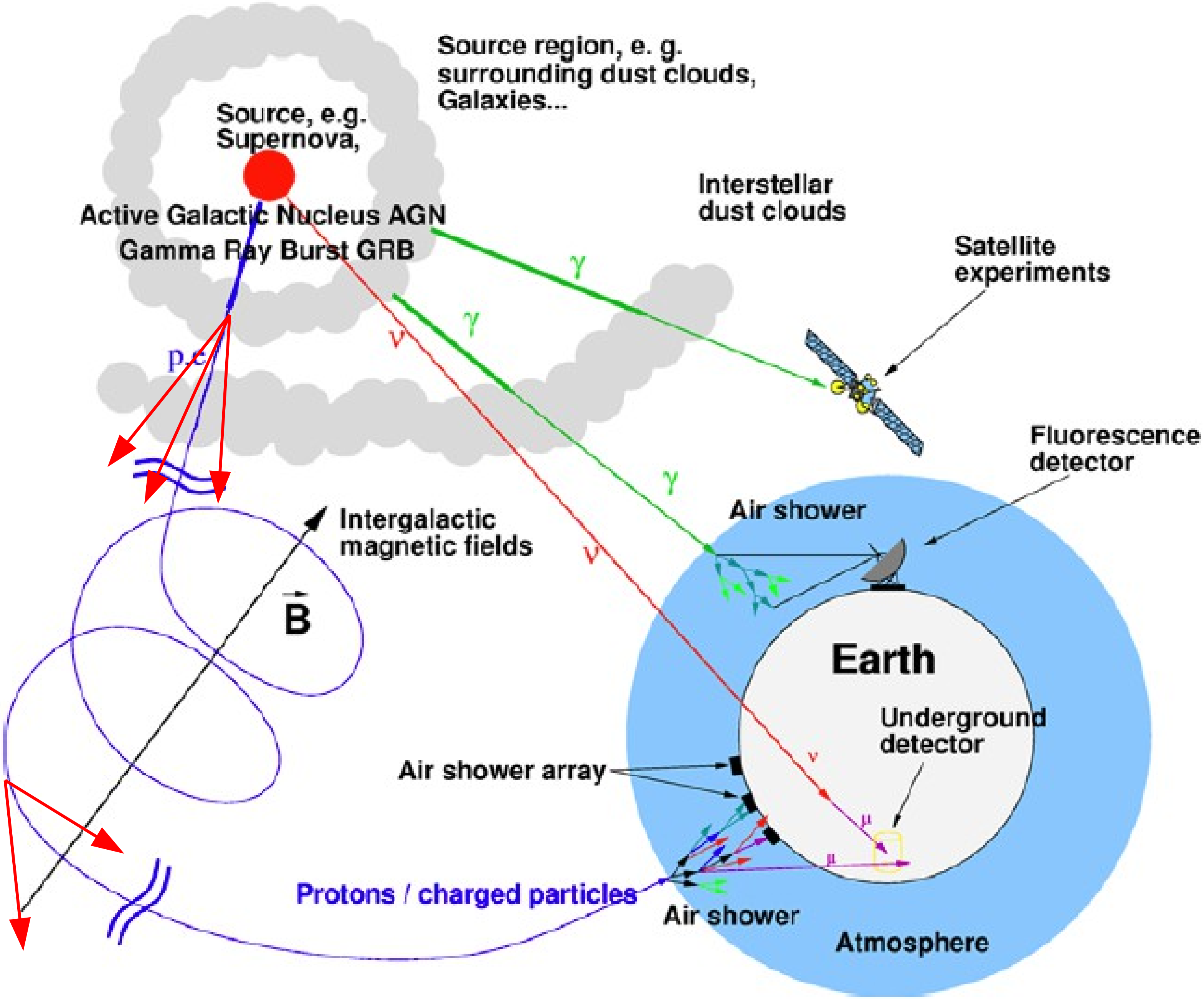
π^0



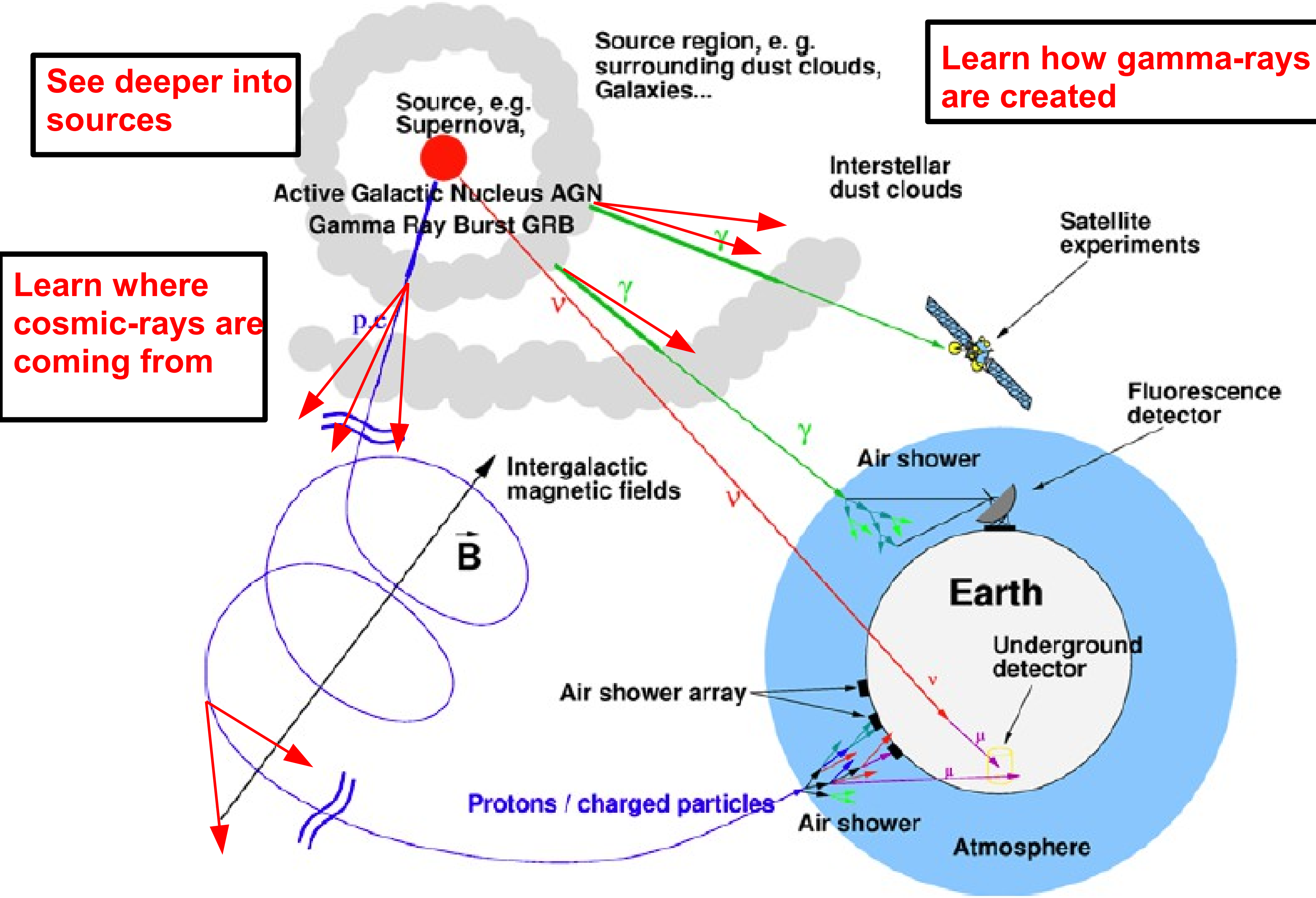
creates $\pi^{+/-}$ too!

Produces ν too

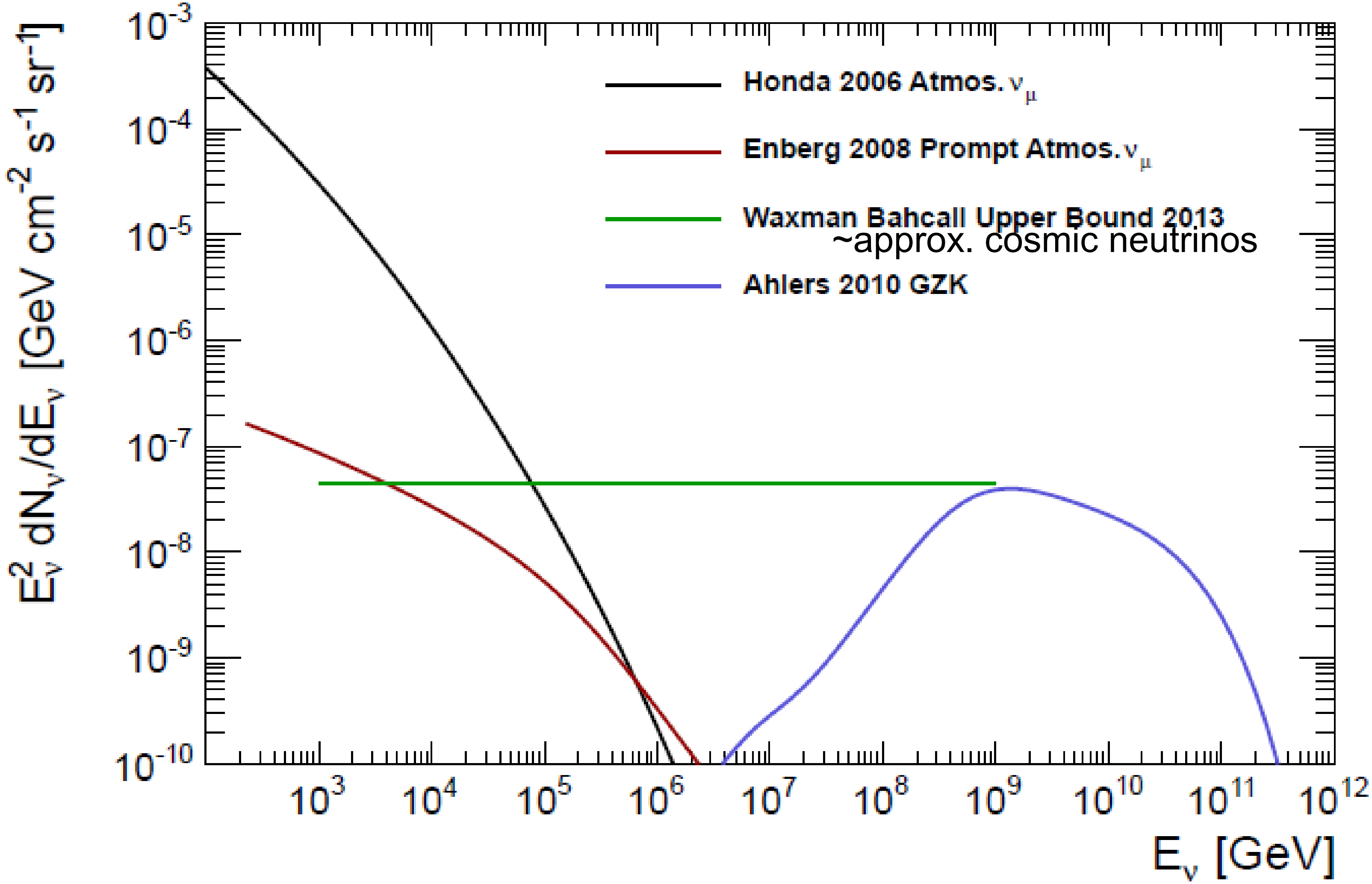
Neutrino Astronomy



Neutrino Astronomy



Why High Energy?



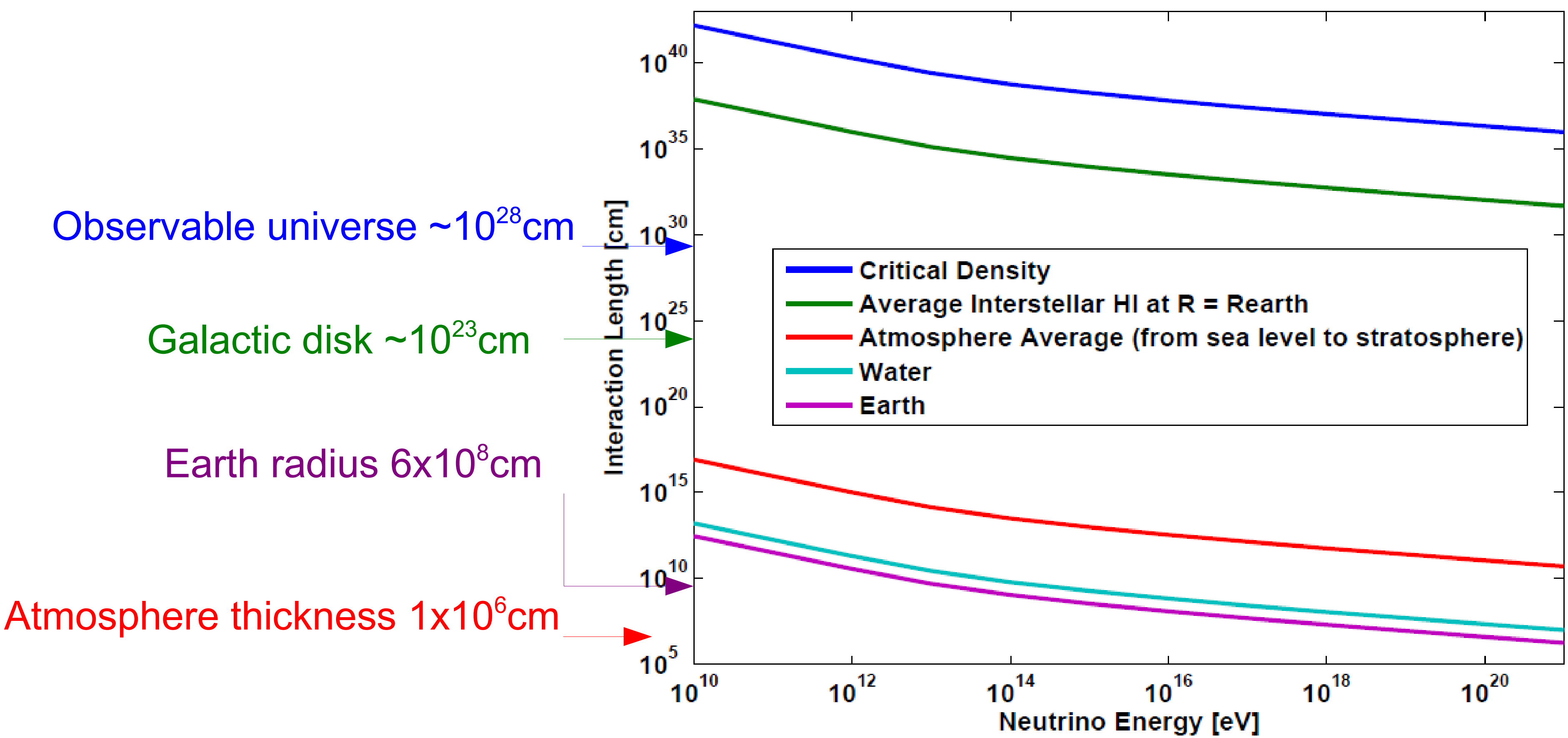
π/K Atmospheric Neutrinos (dominant < 100 TeV)
Prompt Atmospheric Neutrinos (expected > 300 TeV)
Astrophysical Neutrinos (maybe dominant > 100 TeV)
GZK Neutrinos (10^6 TeV)

Challenges of Neutrino Astronomy

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



Cross section from **Gandhi et al., Phys. Rev. D 58 (1998) 093009**

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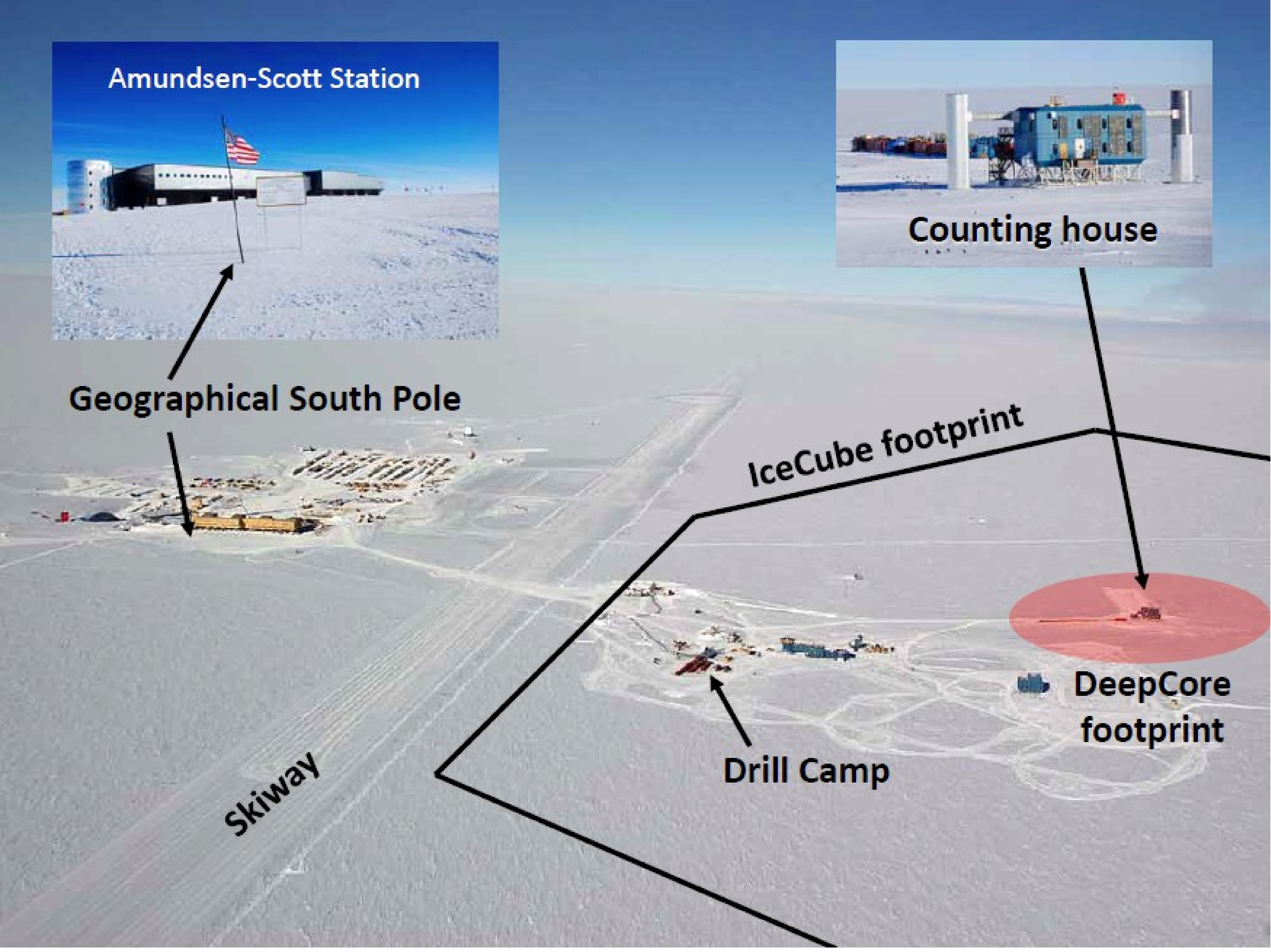
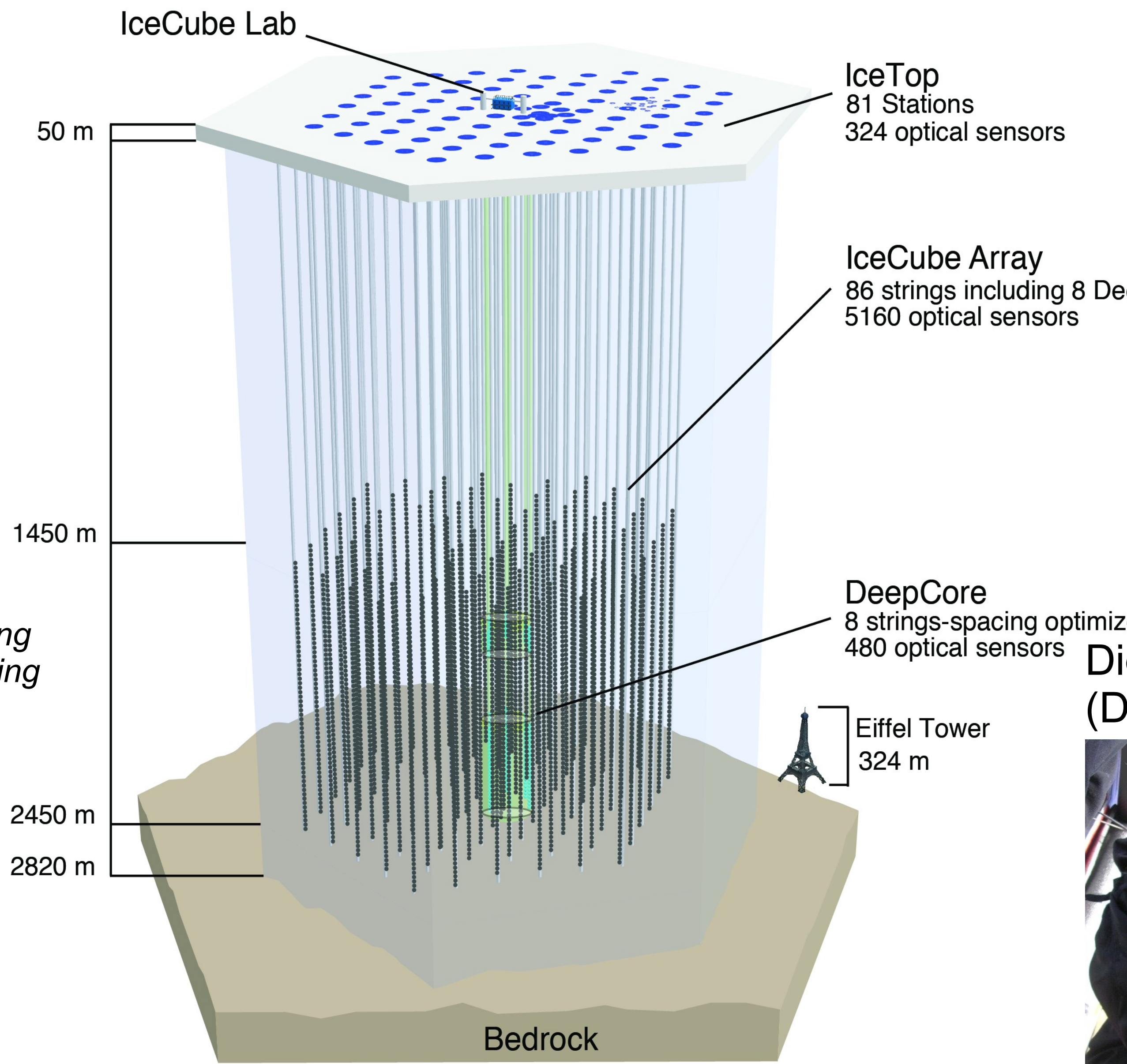

Amundsen-Scott Station
Counting house
Geographical South Pole
IceCube footprint
DeepCore footprint
Drill Camp
Skiway

The IceCube Detector



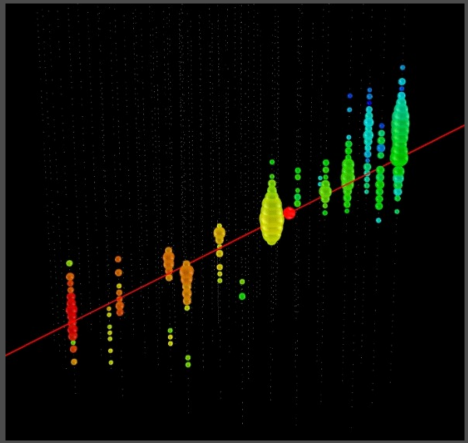
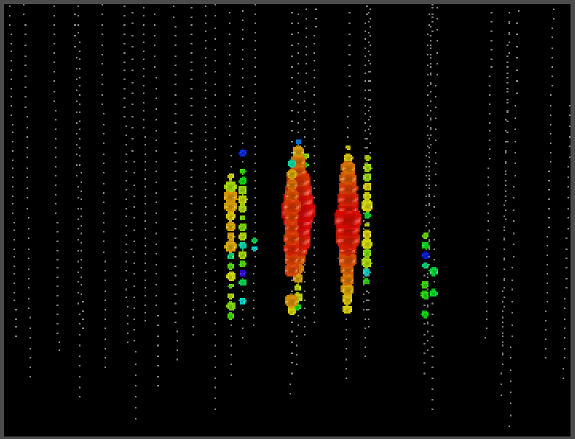
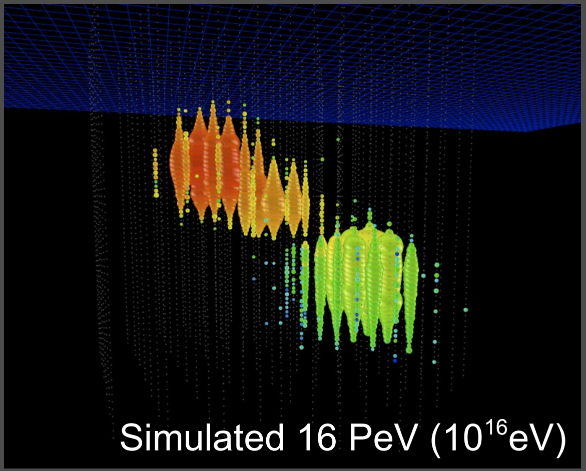
17m vertical spacing
125 m String spacing

Completed 3 years ago!

Digital Optical Module (DOM)

Topologies of different event types

time

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 Physics Programs

Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology
Cosmic ray composition	Atmospheric neutrino spectrum	Dark Matter	Supernovae monitoring	Earth density profile	GZK neutrinos
Arrival directions	Charm production	Neutrino oscillations	Transient events, GRBs, AGNs	Glaciology	
Origin	neutrino cross sections	Neutrino velocities	Neutrino Point Sources	Atmospheric conditions	

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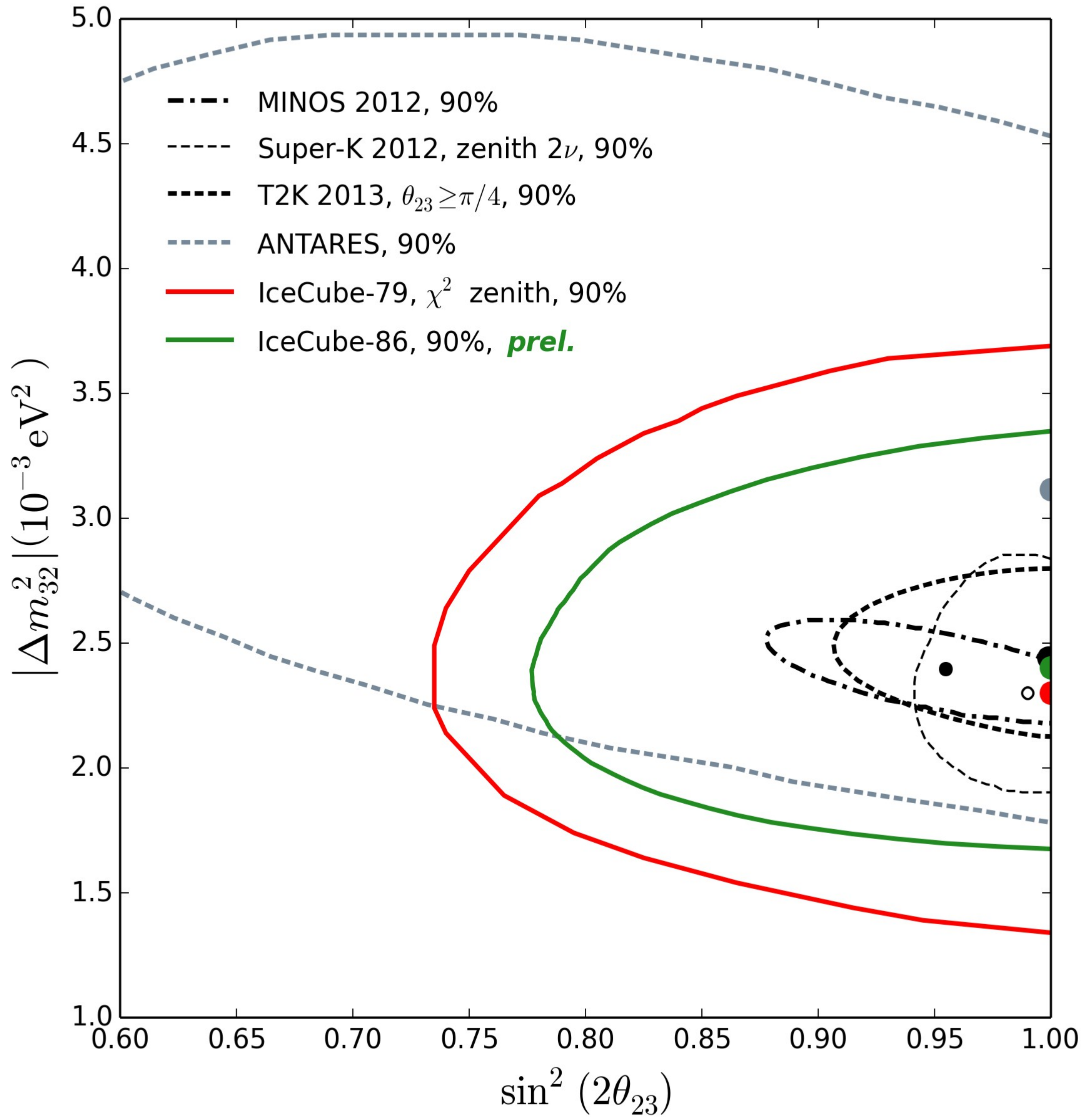
IceCube measures neutrino oscillation at 20-30 GeV energies!



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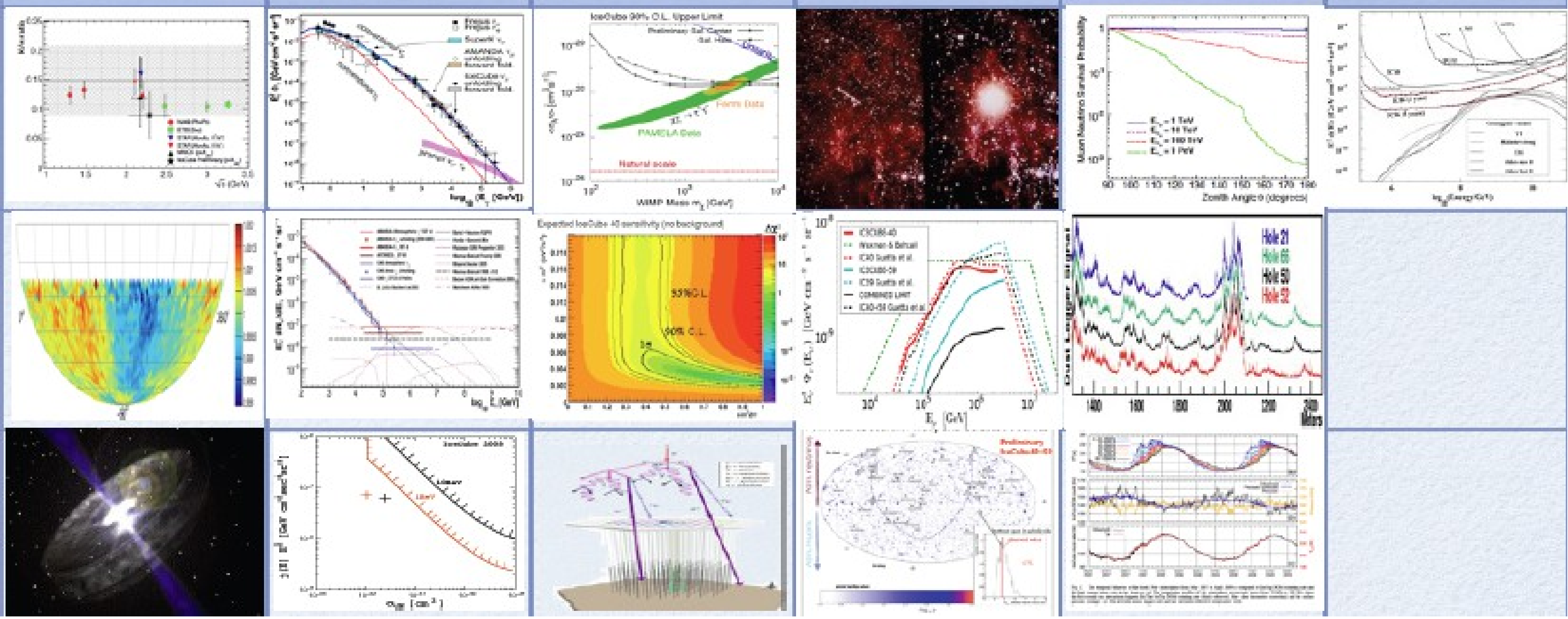

The IceCube Collaboration

~250 people for ~40 institutions

Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

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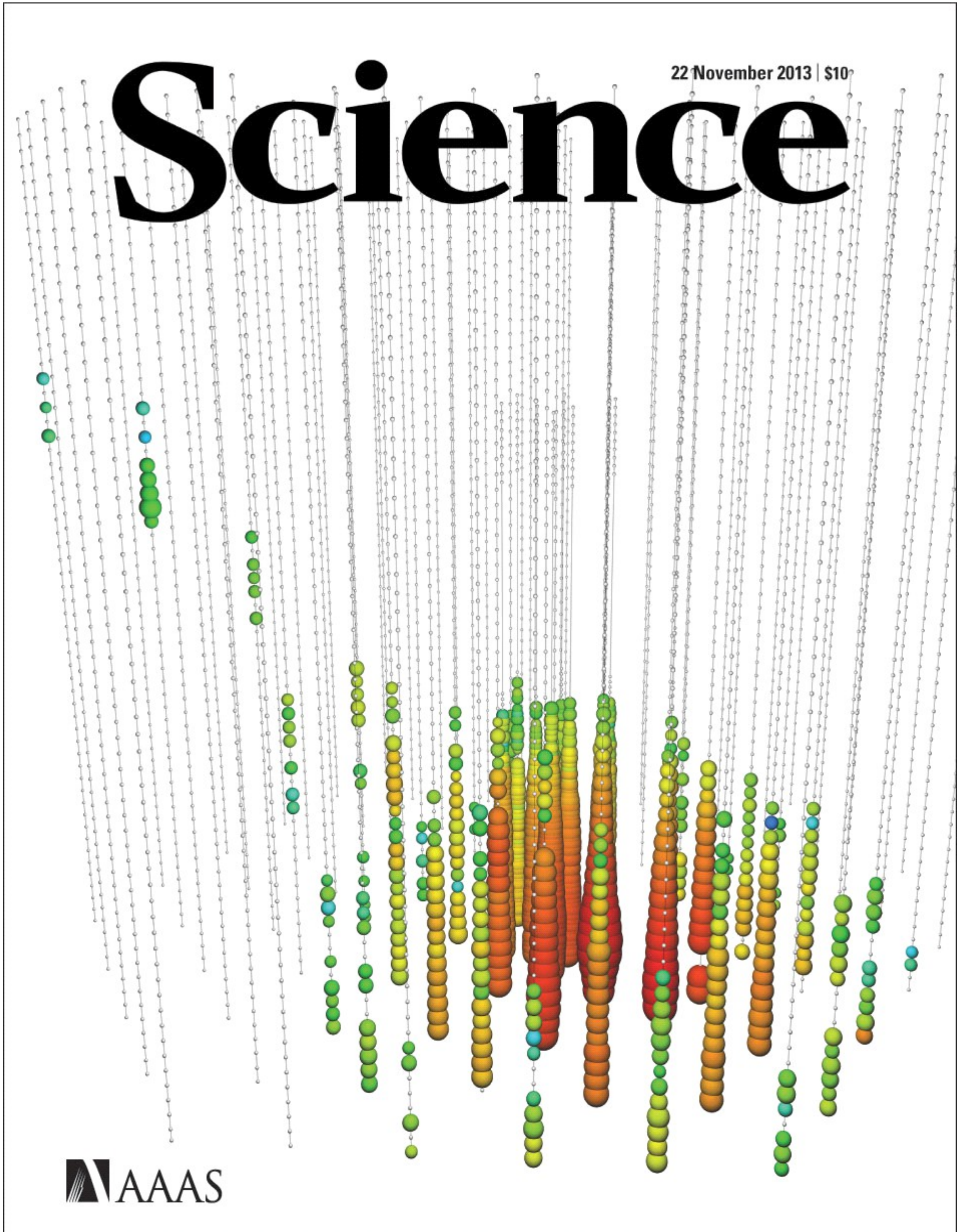
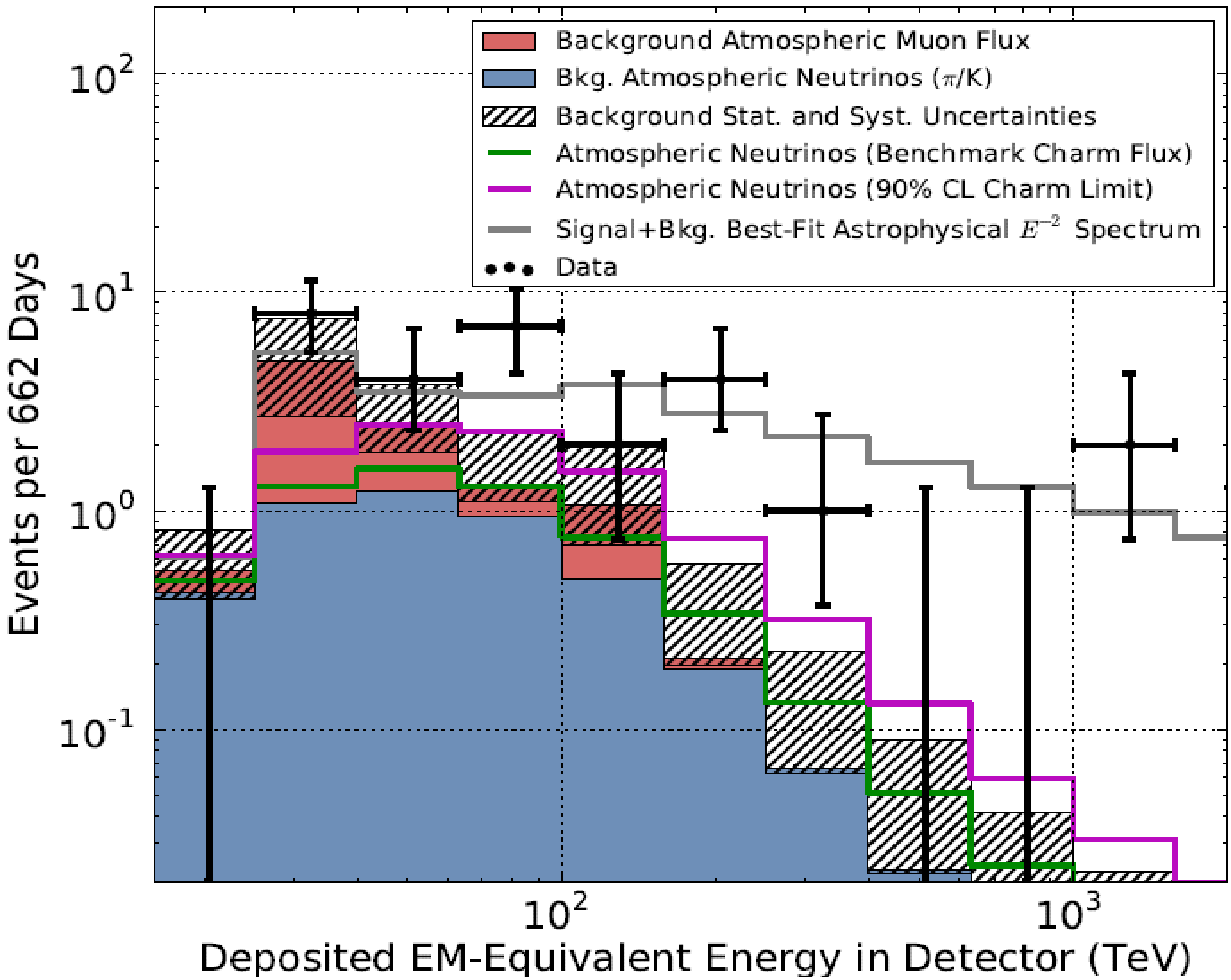
- The Case for Neutrino Astrophysics
- IceCube Neutrino Observatory
- Observation of Astrophysical Neutrinos
  - Low Statistics, Low Background
  - High Statistics, High Background
- Looking Forward

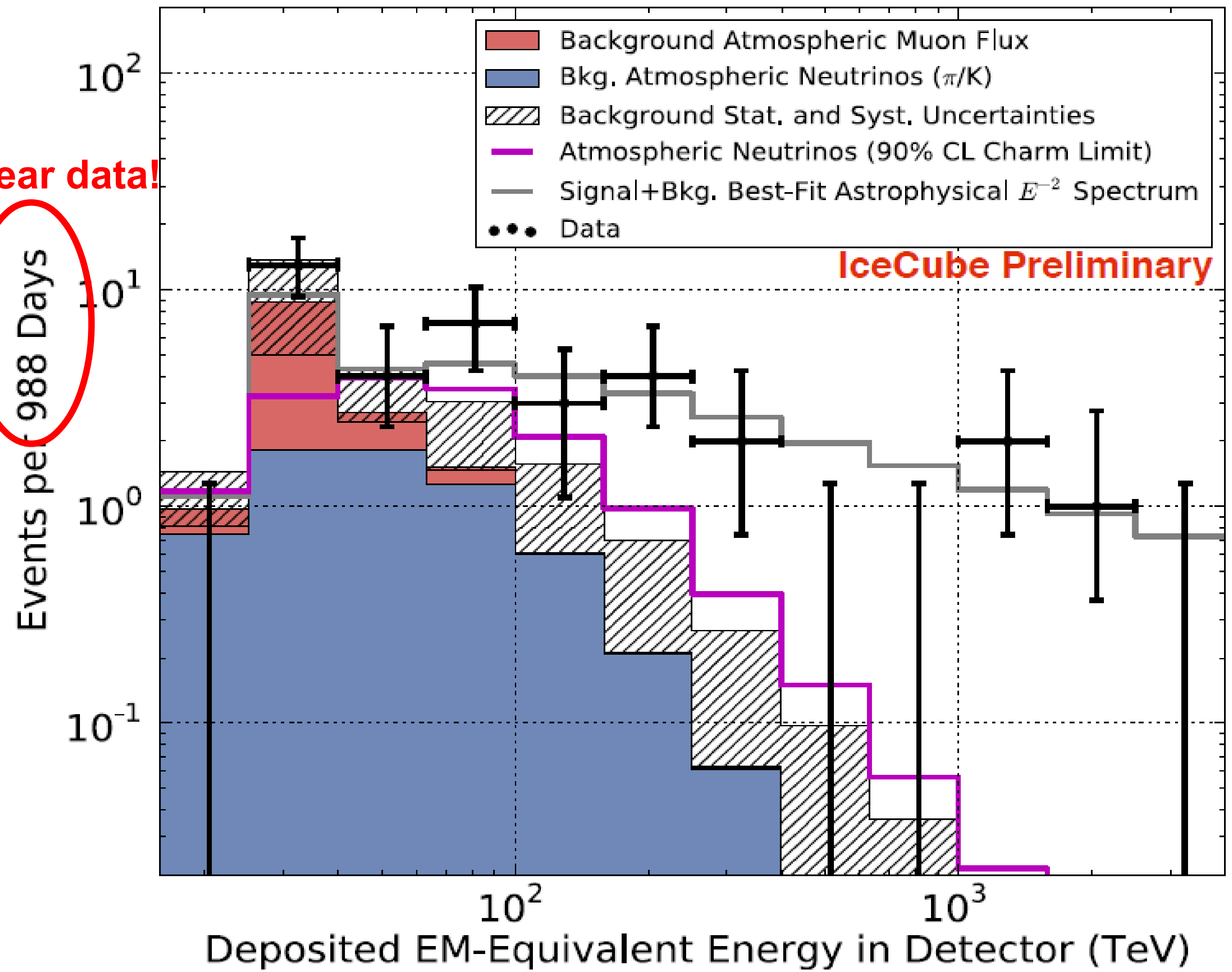

Science
22 November 2013 | $10
AAAS

IceCube Discovers Excess Events at High Energies Using Contained Events!

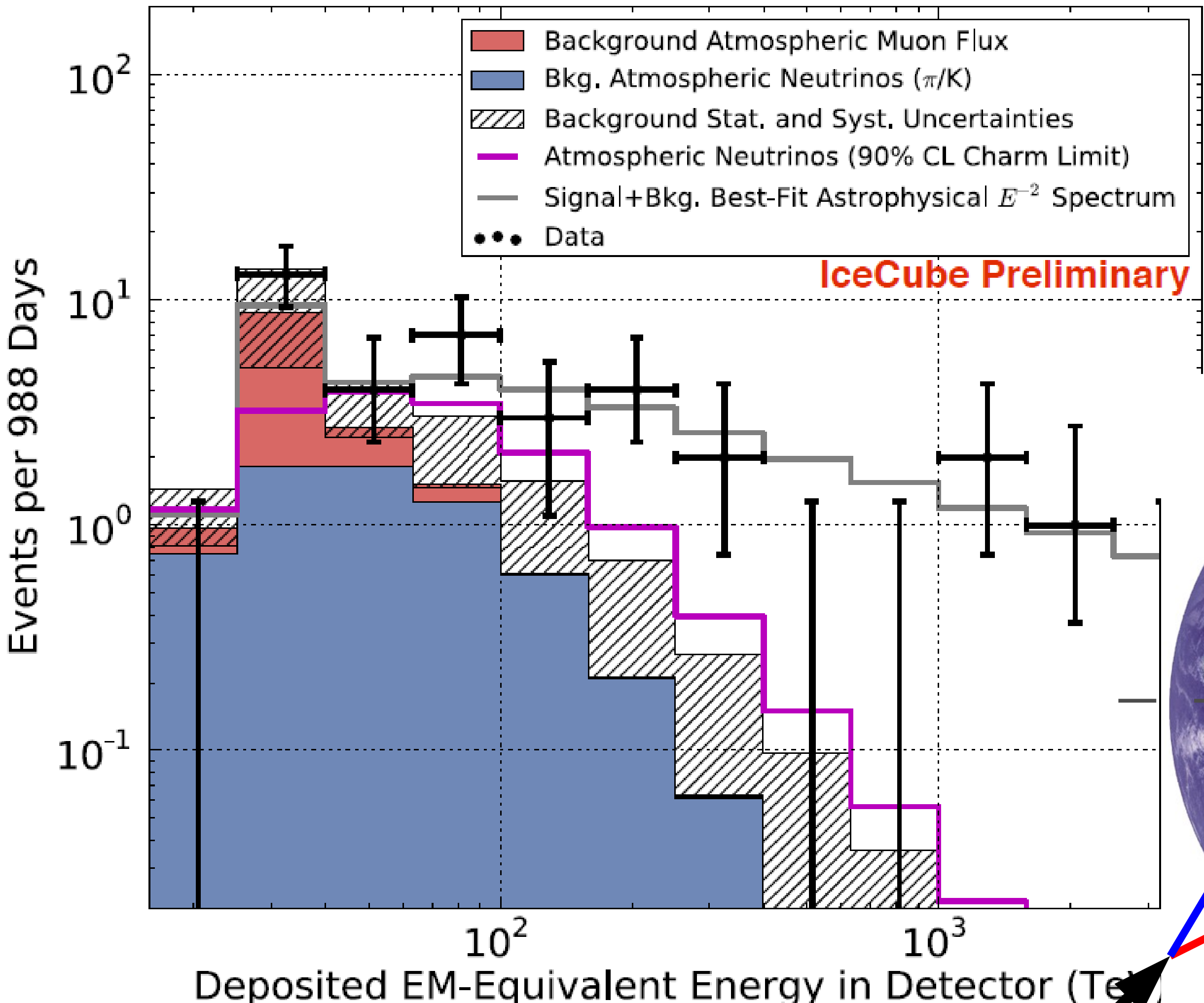


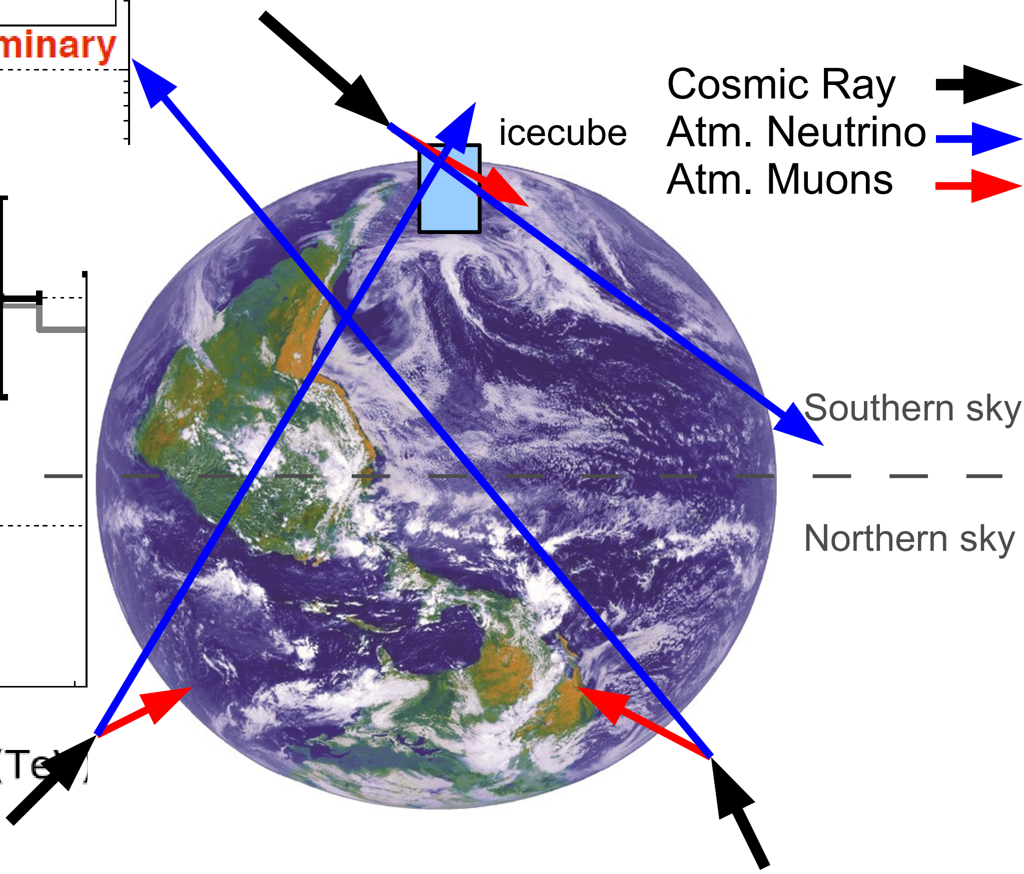
IceCube Discovers Excess Events at High Energies Using Contained Events!

New! 3-year data!



What should IceCube see?





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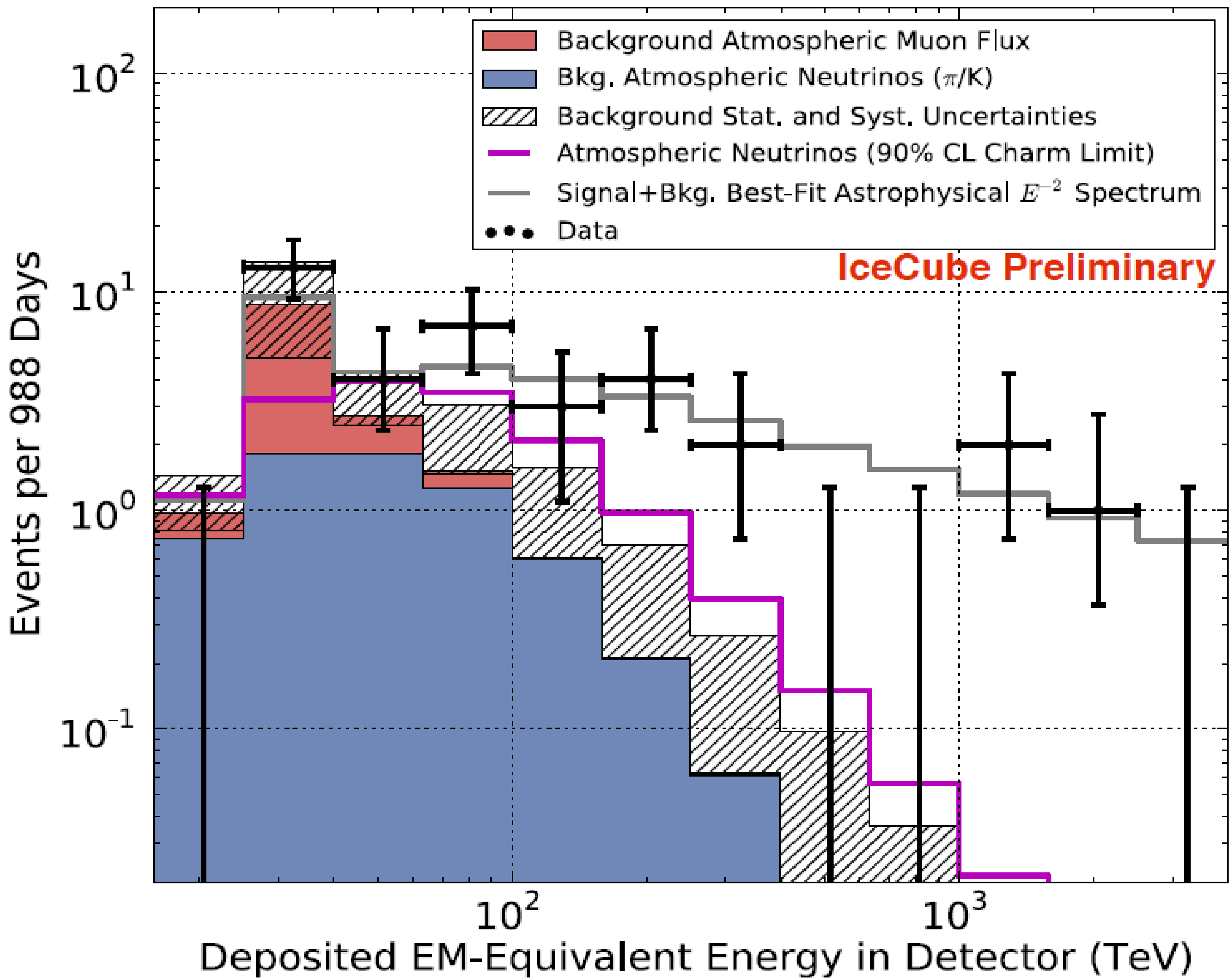
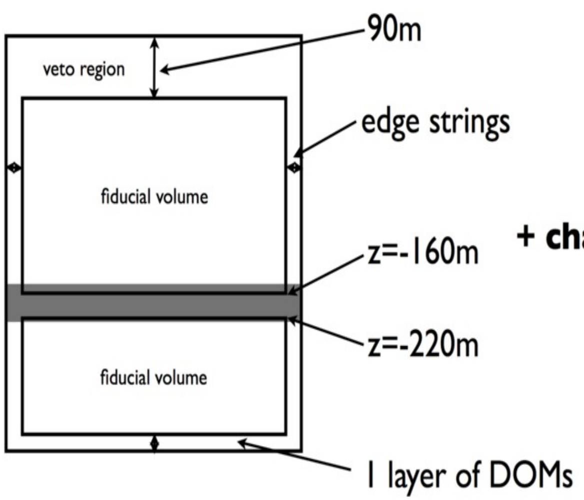


Details of this analysis that discovered cosmic neutrinos

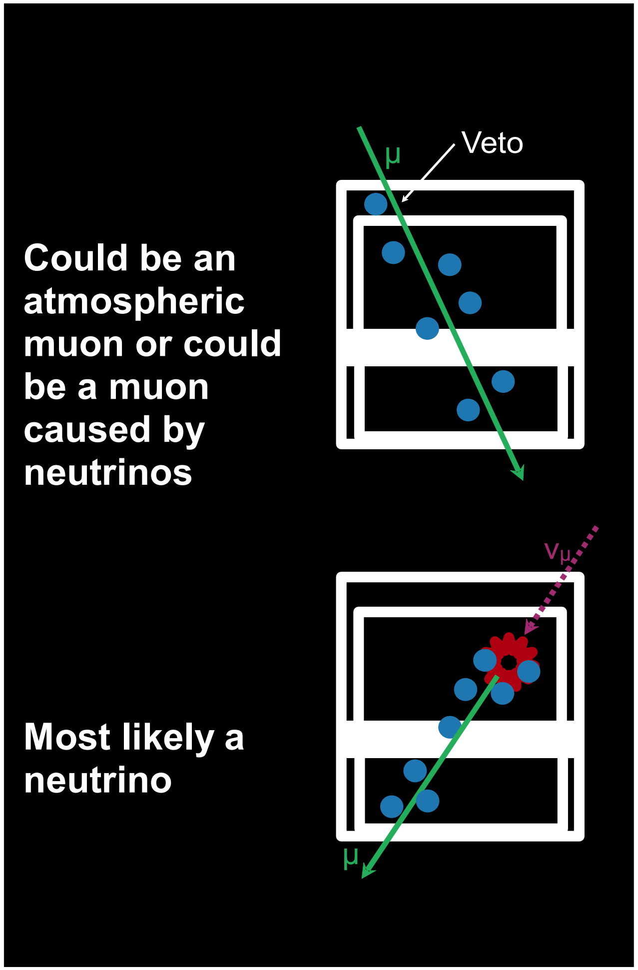
Nathan Whitehorn's talk: This Afternoon

Session U4 (3:30pm, Chatham Ballroom C)



+ charge cut

The higher the energy, the better this works!



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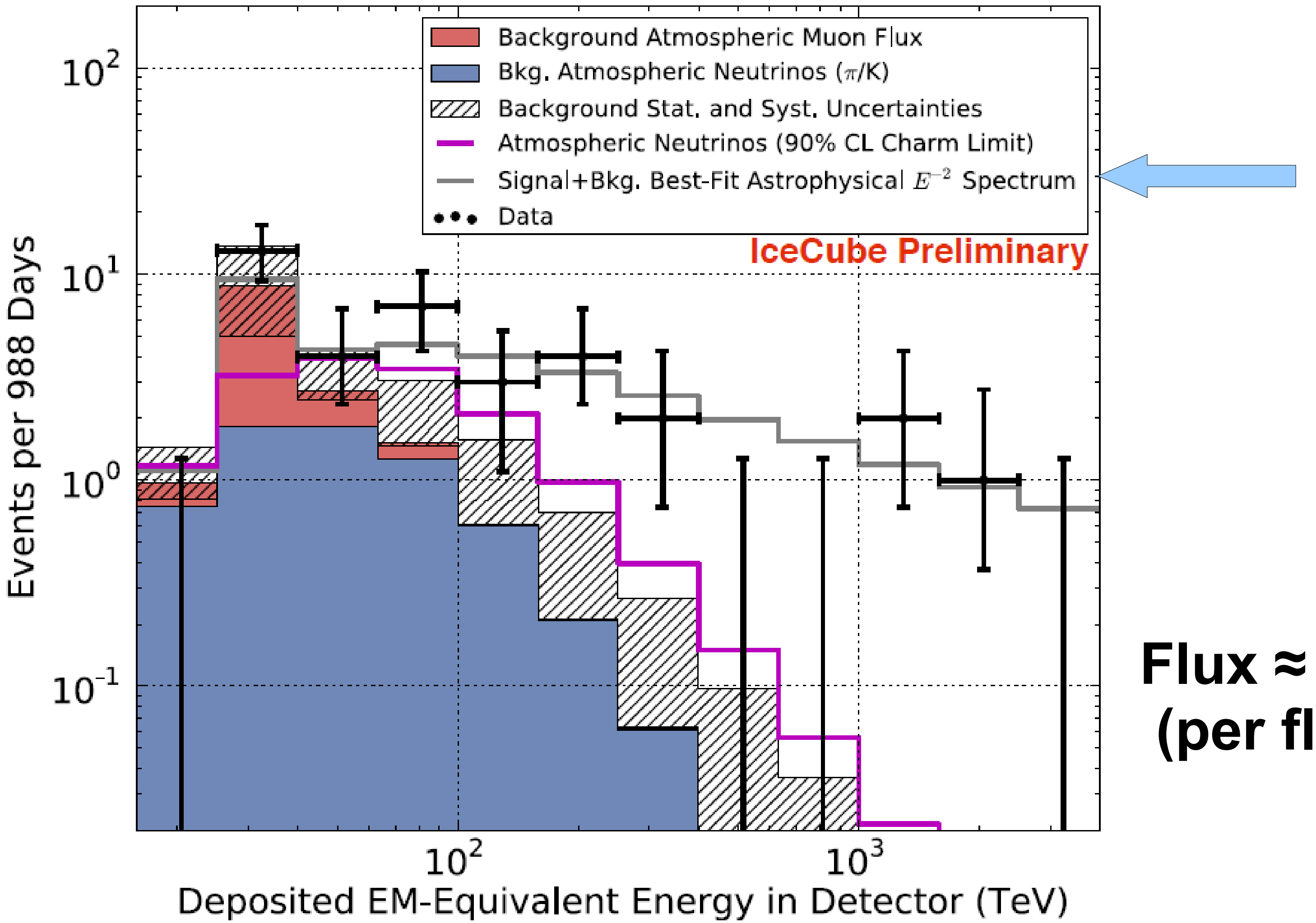


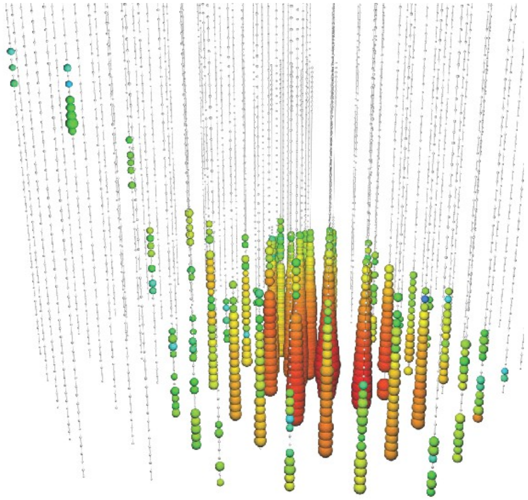
Predicted background + Flux ~ E^{-2} fit

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

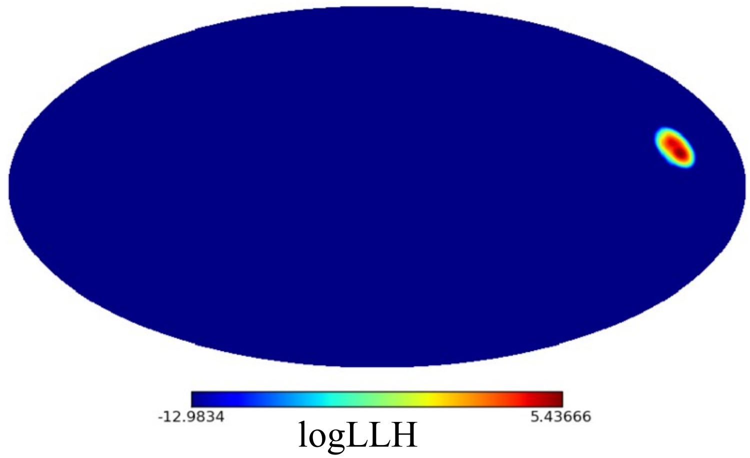
Neutrino Astrophysics:
We found a cosmic neutrino flux!

Neutrino Astronomy:
So what are the source(s) of these events? Where do they come from?

Reconstruction Capabilities



Reconstruction maps in local coordinates



Sample dominated by showers

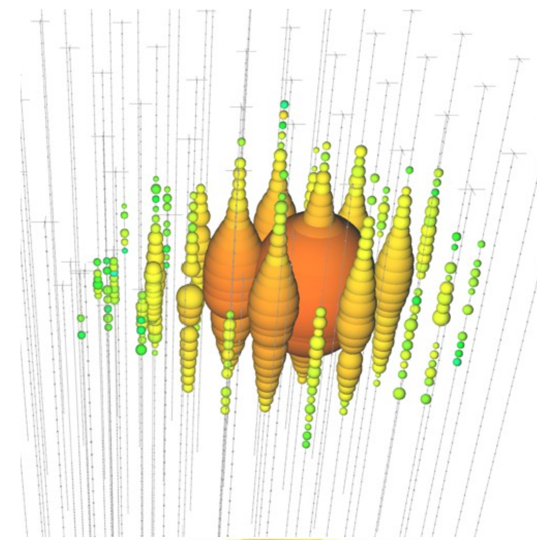
as foreseen by:

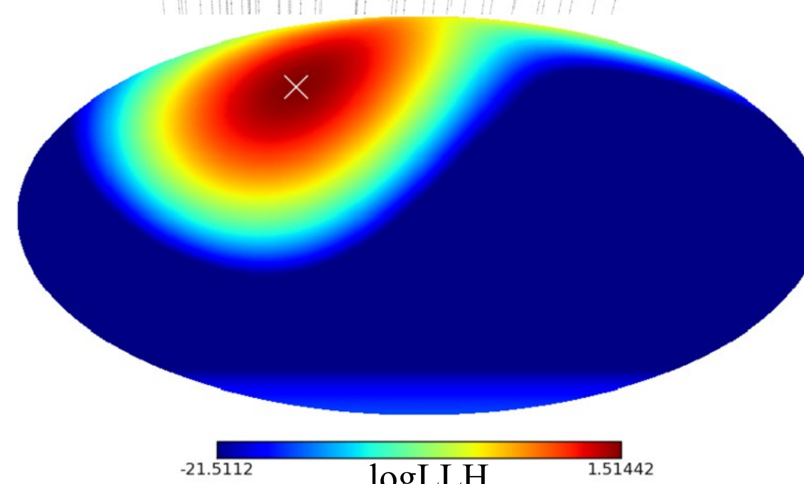
- J. Beacom & J. Candia, JCAP 0411 (2004)
- M. Kowalski, JCAP 0505 (2005)

In fact, originally included in IceCube design goal:

- A. Karle,

icecube.wisc.edu/icecube/static/reports/IceCubeDesignDoc.pdf





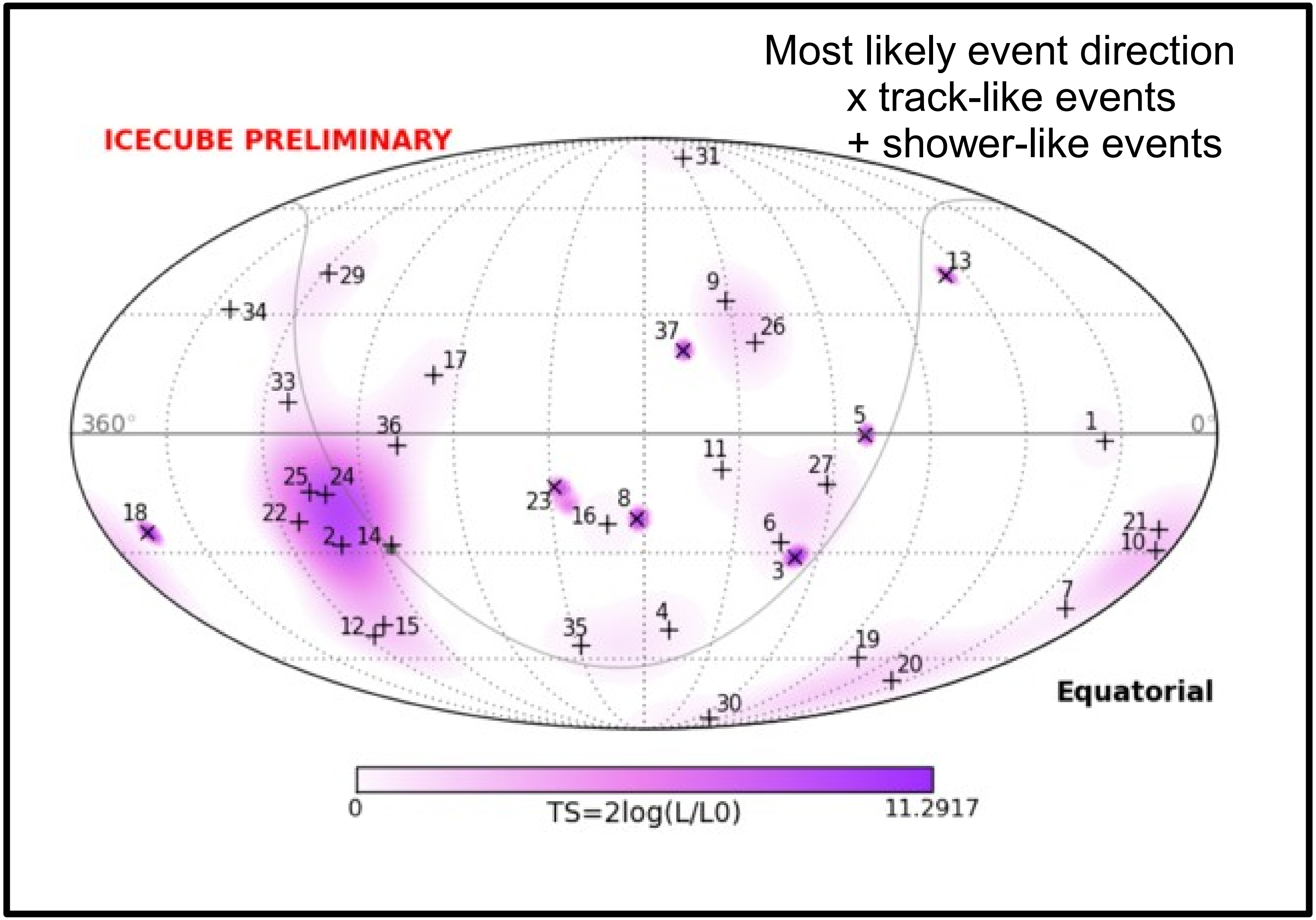
@ 100 TeV energies

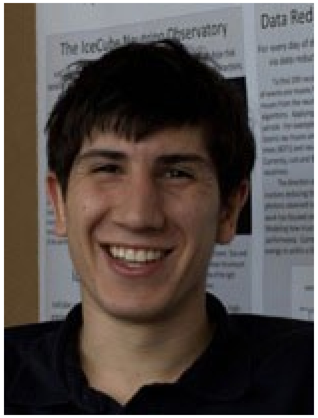
	Energy Reconstruction*	Directional Reconstruction*
Tracks	~factor 2	~0.5 degrees
Showers	10%	~15 degrees

* against primary neutrino energy and direction

Low Statistics Low Background Astronomy Analysis

Jake Feintzeig's talk: Next Session R8 (rm 202)



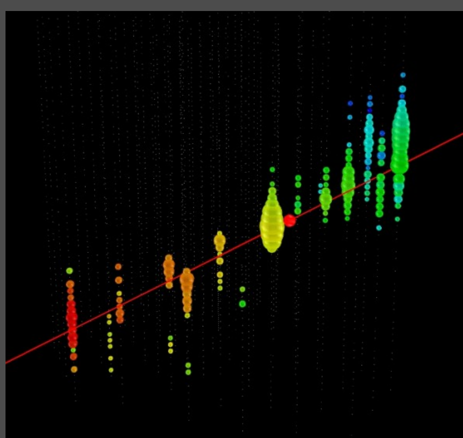


Outline

- The Case for Neutrino Astrophysics
- IceCube Neutrino Observatory
- Observation of Astrophysical Neutrinos
  - Low Statistics, Low Background
  - High Statistics, High Background
- Looking Forward

Topologies of different event types

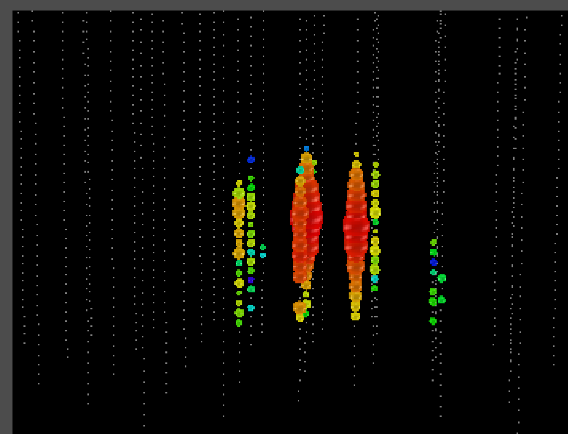
CC Muon Neutrino



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

Track

Neutral Current /Electron Neutrino

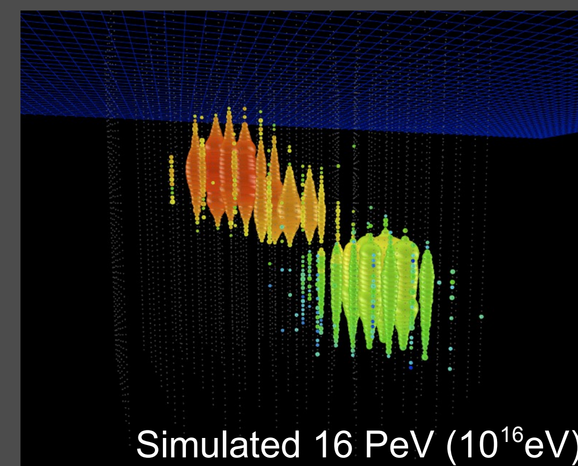


$$\nu_e + N \rightarrow e + X$$

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

Shower

CC Tau Neutrino



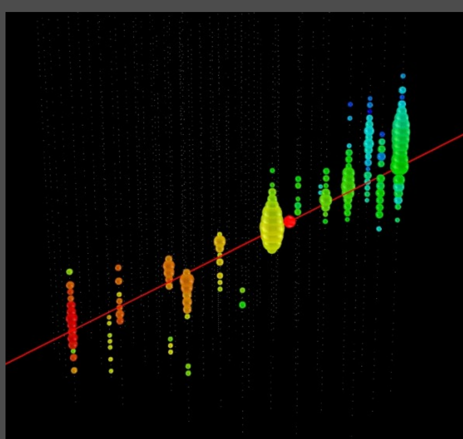
$$\nu_\tau + N \rightarrow \tau + X$$

Double-Shower (not observed yet)

Topologies of different event types

time

CC Muon Neutrino



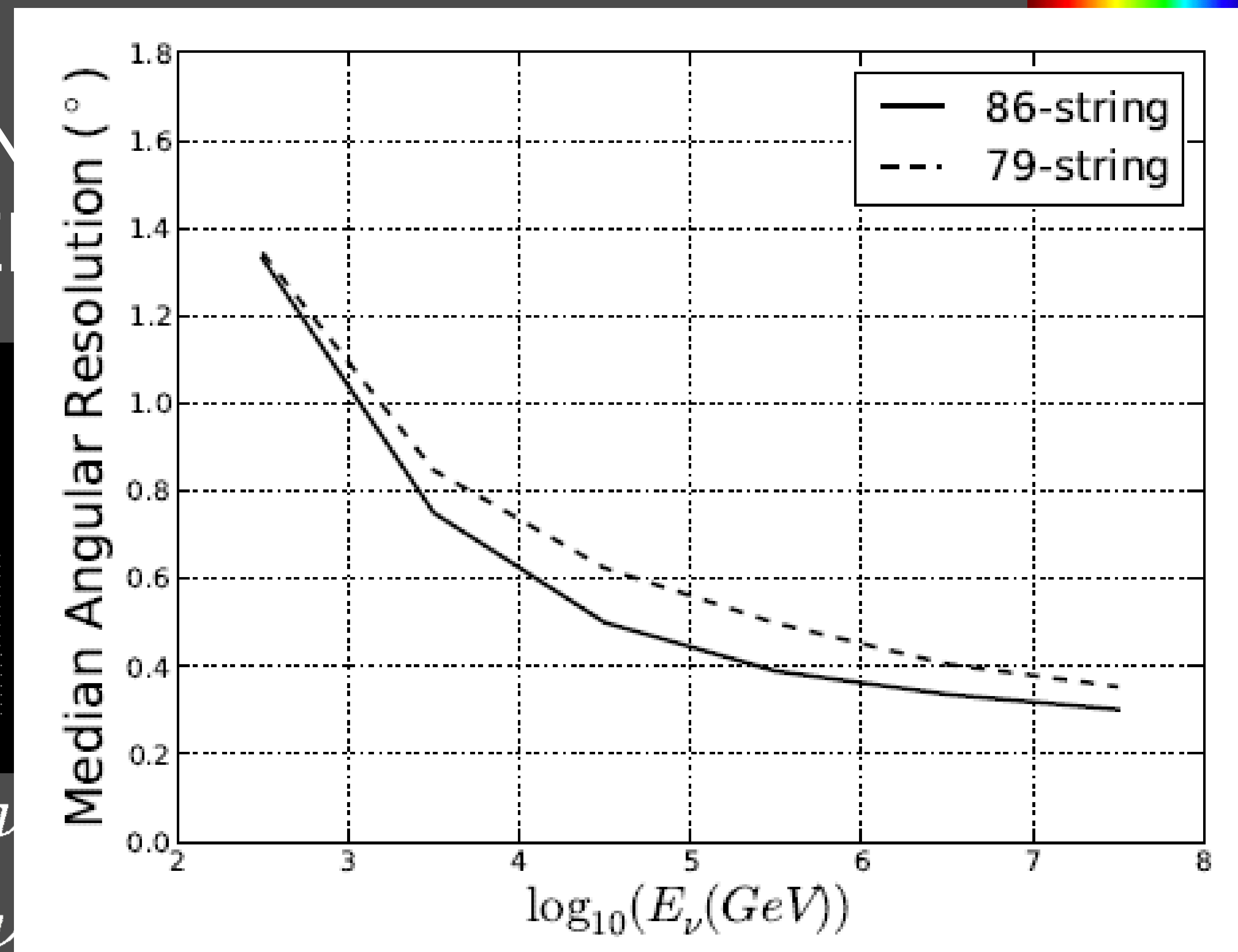
$\nu_\mu + N \rightarrow \mu + X$

N

/El

ν

ν

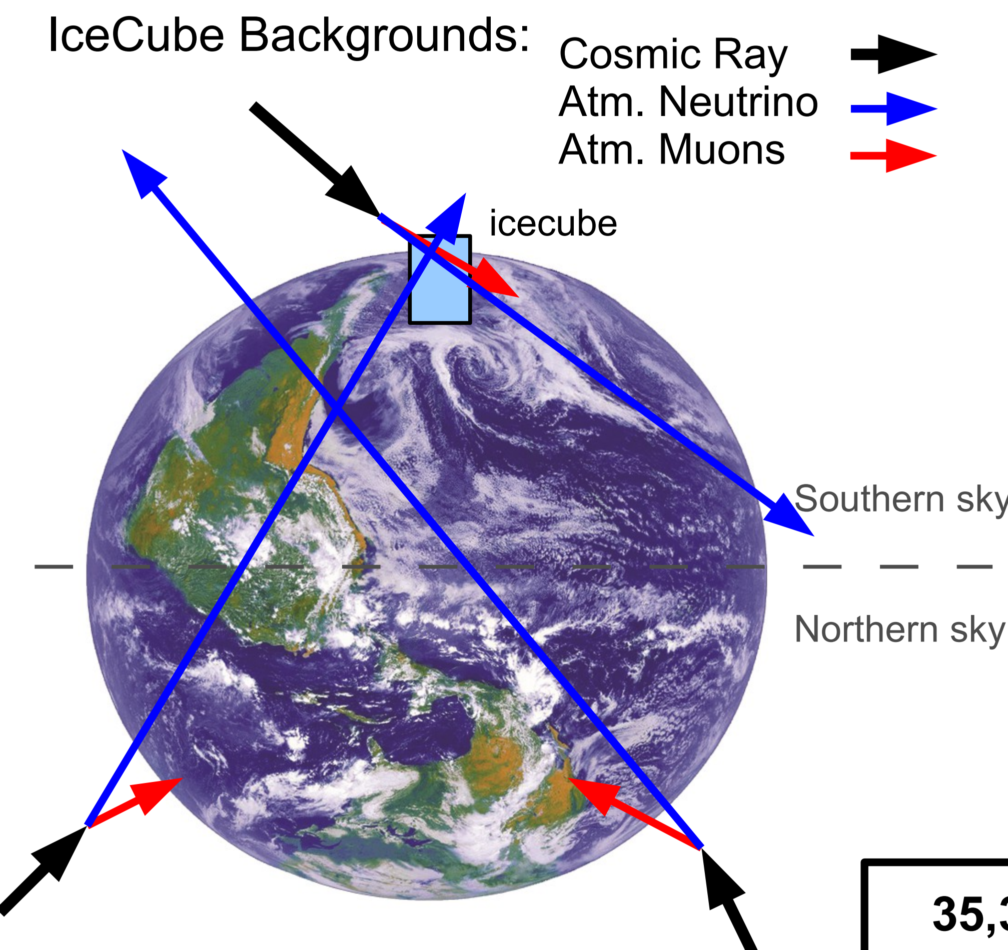


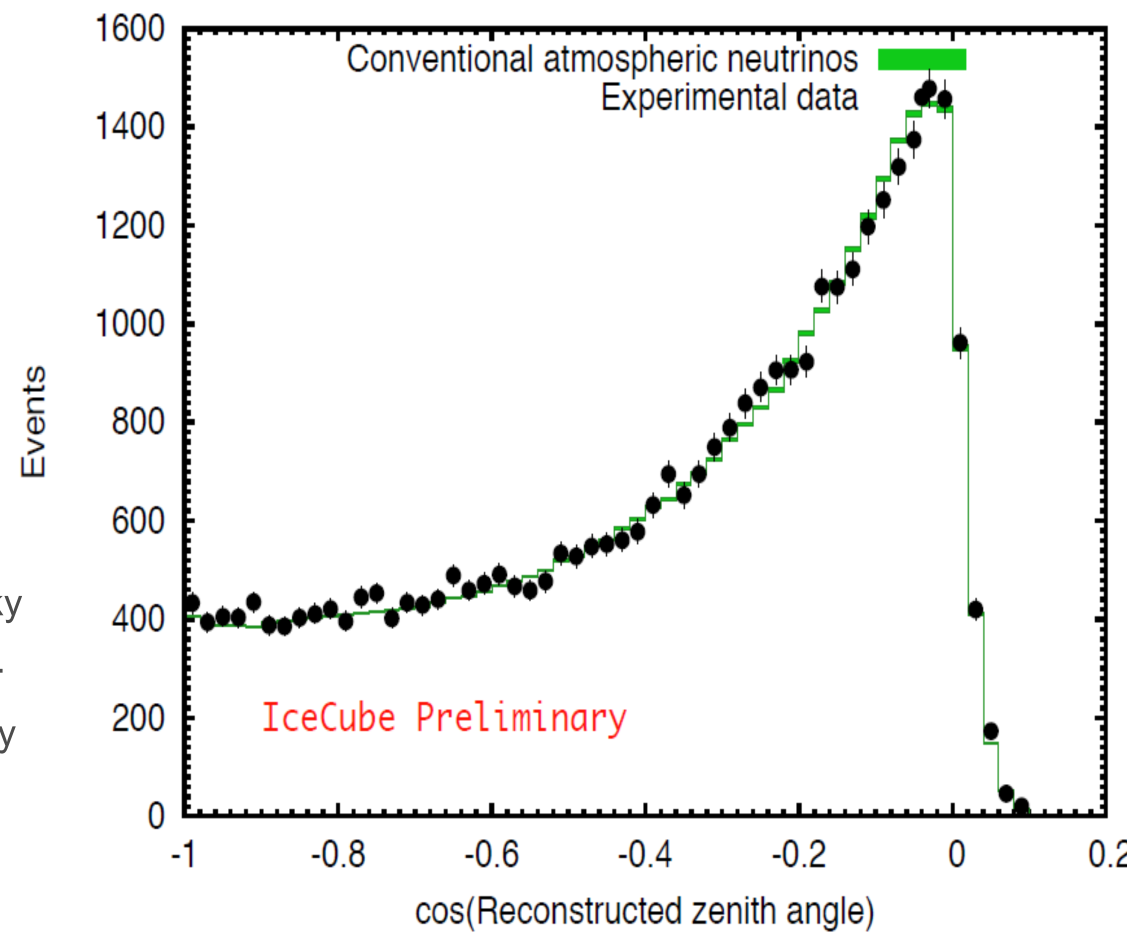
Track

Shower

Double-Shower (not observed yet)

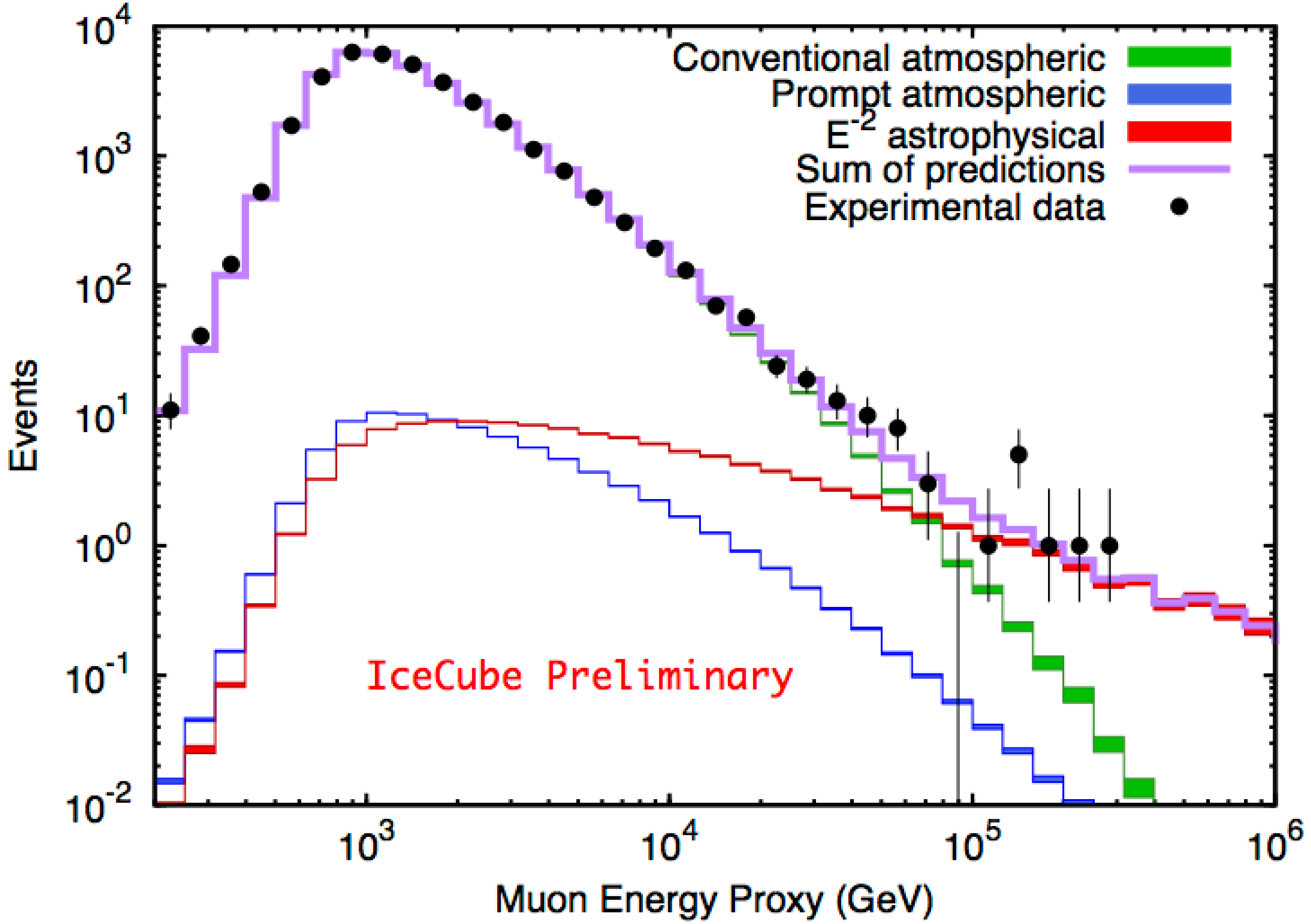
A way to get rid of the muon background
Only consider up-going events





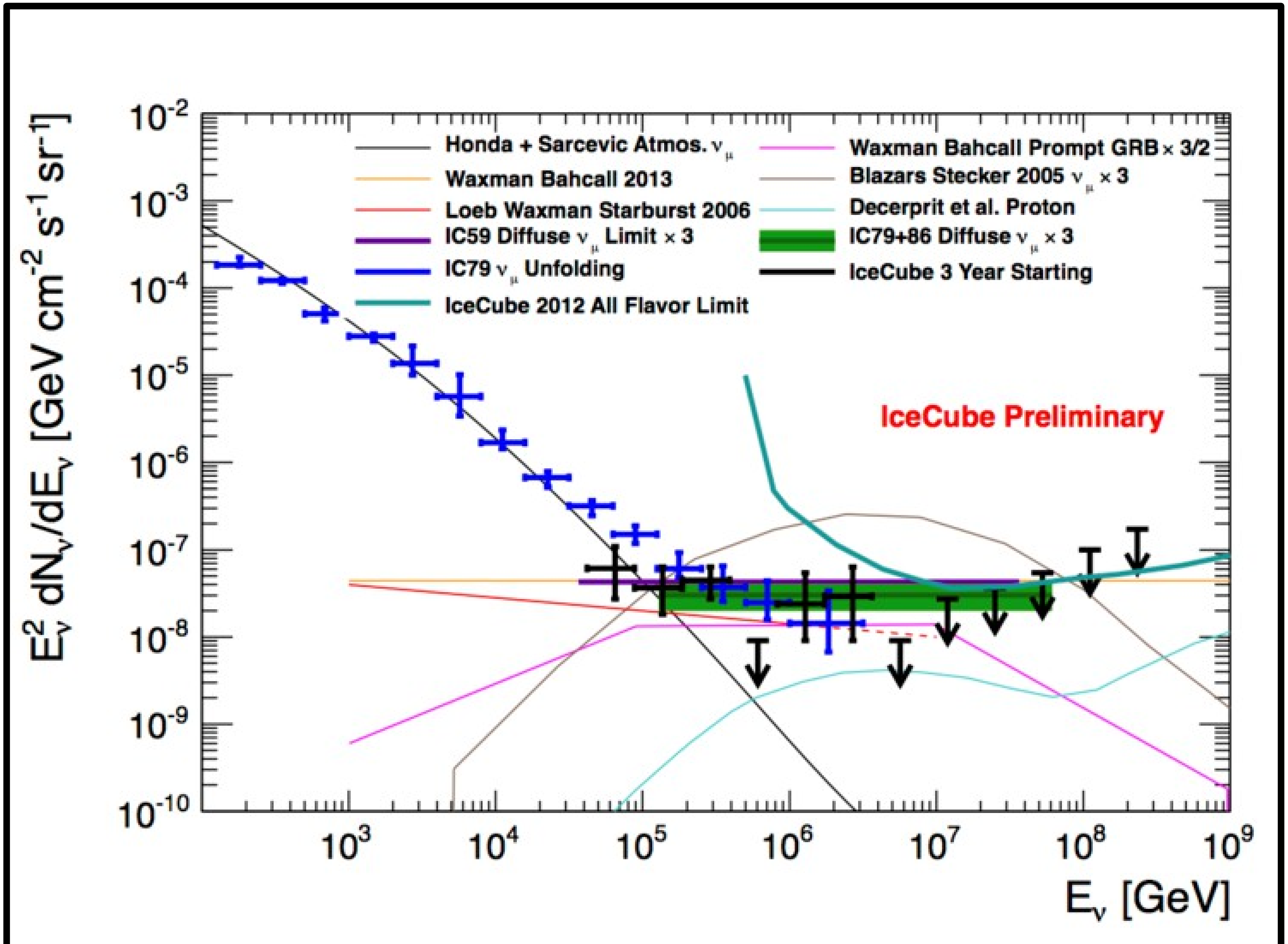
35,300 events
< 25.5 events from atmospheric muons

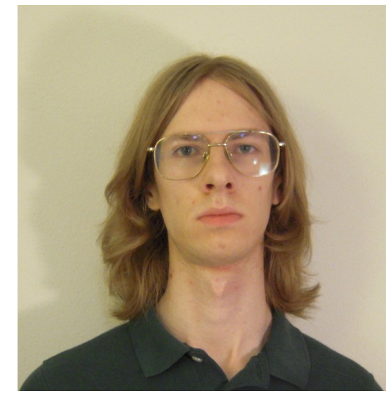
Cosmic Neutrinos Found!



Details of this analysis

Chris Weaver's talk: Next Session R8 (rm 202)



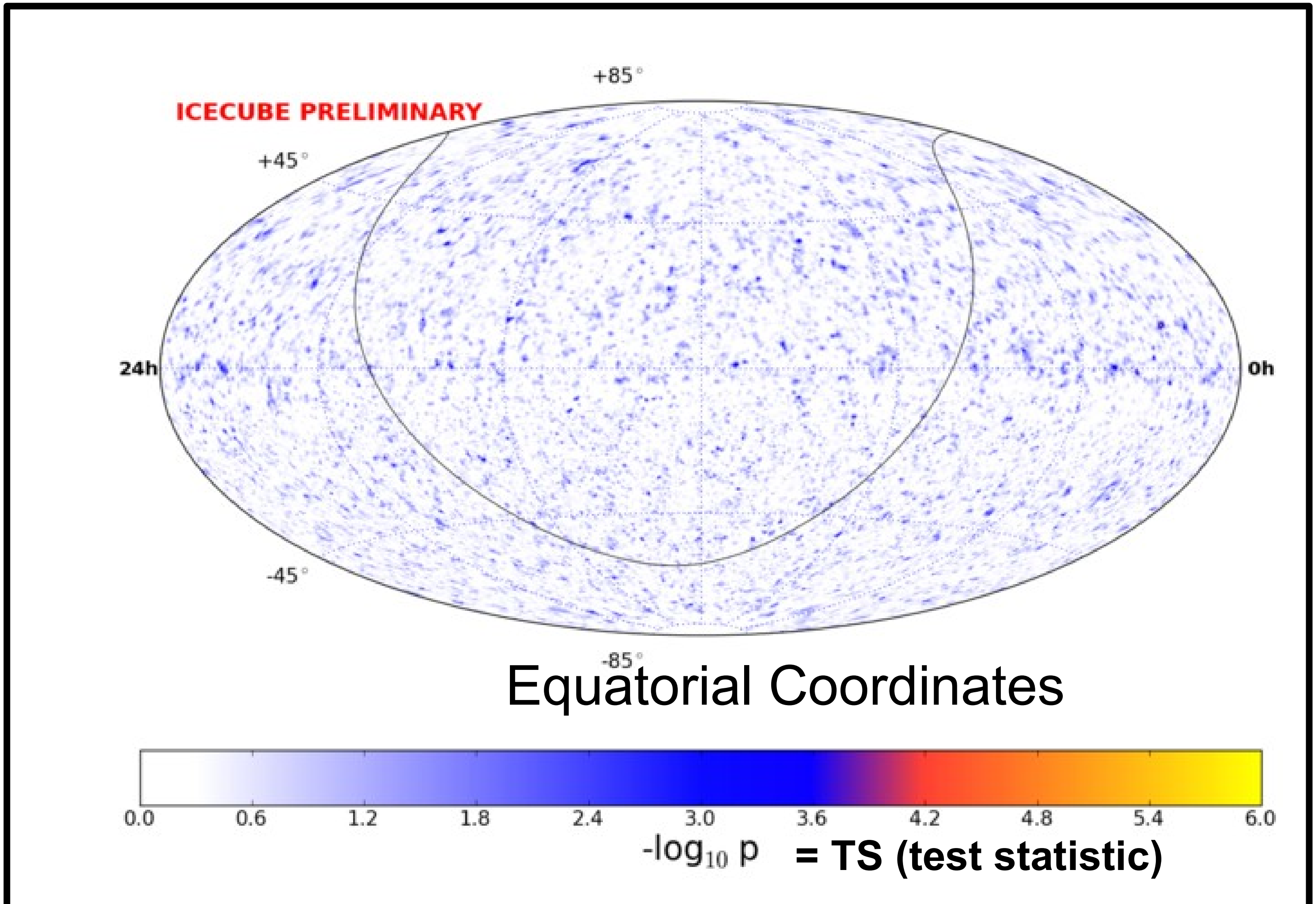


Neutrino Astrophysics:
We found a cosmic neutrino flux in up-going events!

Neutrino Astronomy:
So what are the source(s) of these events? Where do they come from?

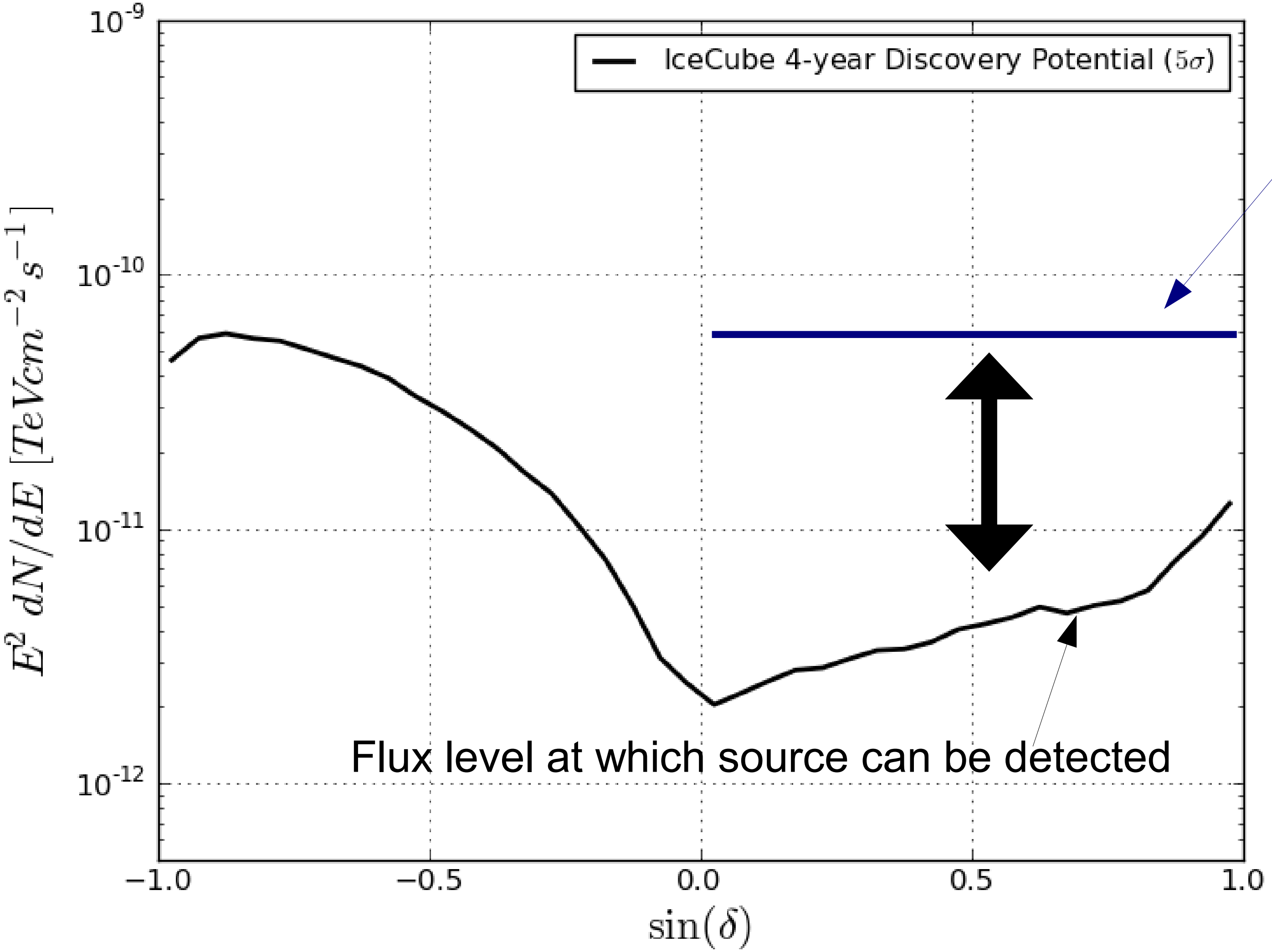
High Statistics High Background Astronomy Analysis

Jake Feintzeig's talk: Next Session R8 (rm 202)



Comparing source search to the measured diffuse flux
How many sources?

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



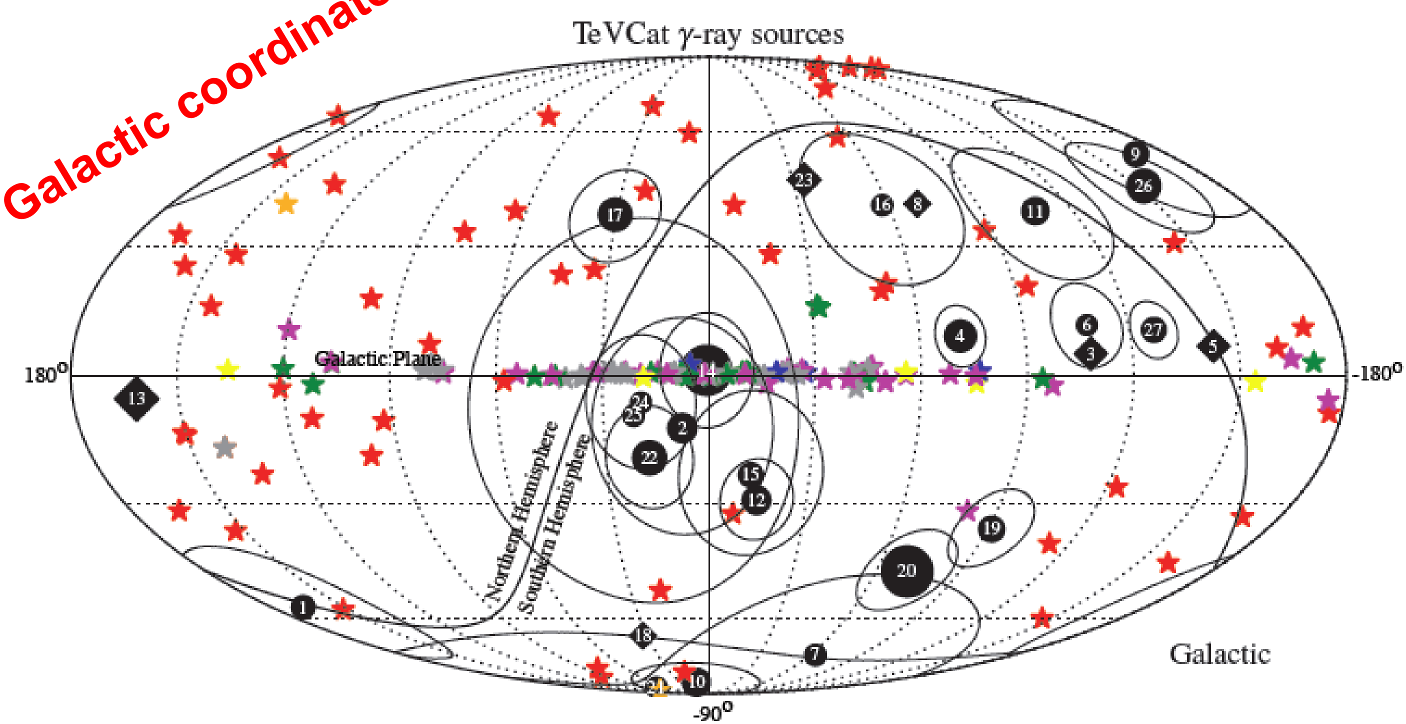
$N_{sources}$ ≥ ~15

Many ways around it
- extended sources
- much softer spectrum

Which sources are possible?
Markus Ahler's Talk: Saturday

Gamma-ray Astronomy Connection?

Galactic coordinates!



LBL, IBL, LBL, FRI, FSRQ Globular Cluster, Star Forming Region, Massive Star Cluster
Binary PWN Shell, SNR/Molec.Cloud, Composite SNR Starburst Others [TeVCat'14]

State of Cosmic Neutrino Observation

	Astrophysics	Astronomy
Low Statistics, Low Background	Diffuse flux seen at levels of $\sim 10^{-8} E^{-2}$[GeV/cm^2/s/str] !	No evidence clustering: • With each other • Along the galactic plane
High Statistics, High Background	New! This conference! Diffuse flux seen at levels of $\sim 10^{-8} E^{-2}$[GeV/cm^2/s/str] in the northern hemisphere!!!	No evidence clustering

Multiple sources distributed isotropically???

Outline

- The Case for Neutrino Astrophysics
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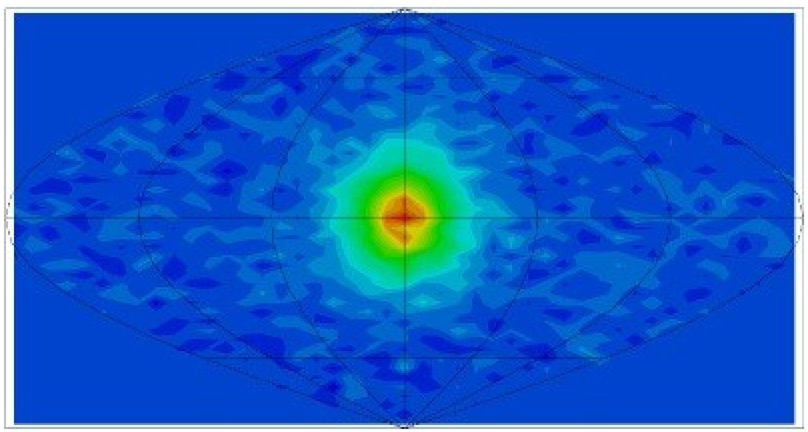
The Neutrino Astronomy Catalog

The Sun

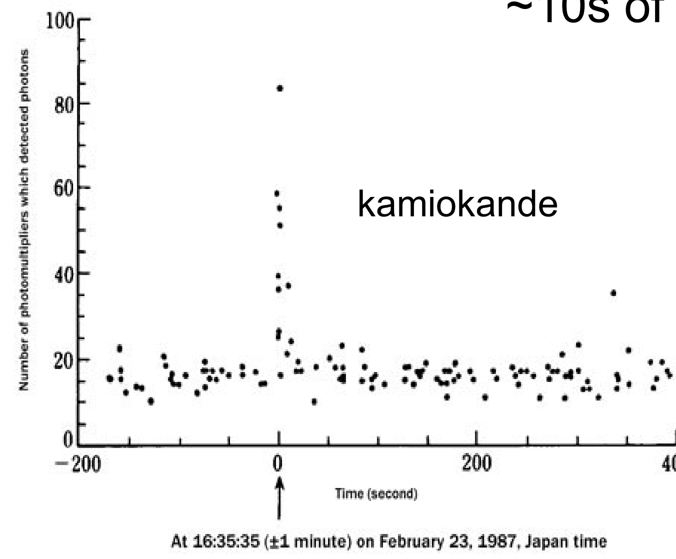
~10 MeV



super-kamiokande

Supernova 1987A

~10s of MeV



VERY close by source

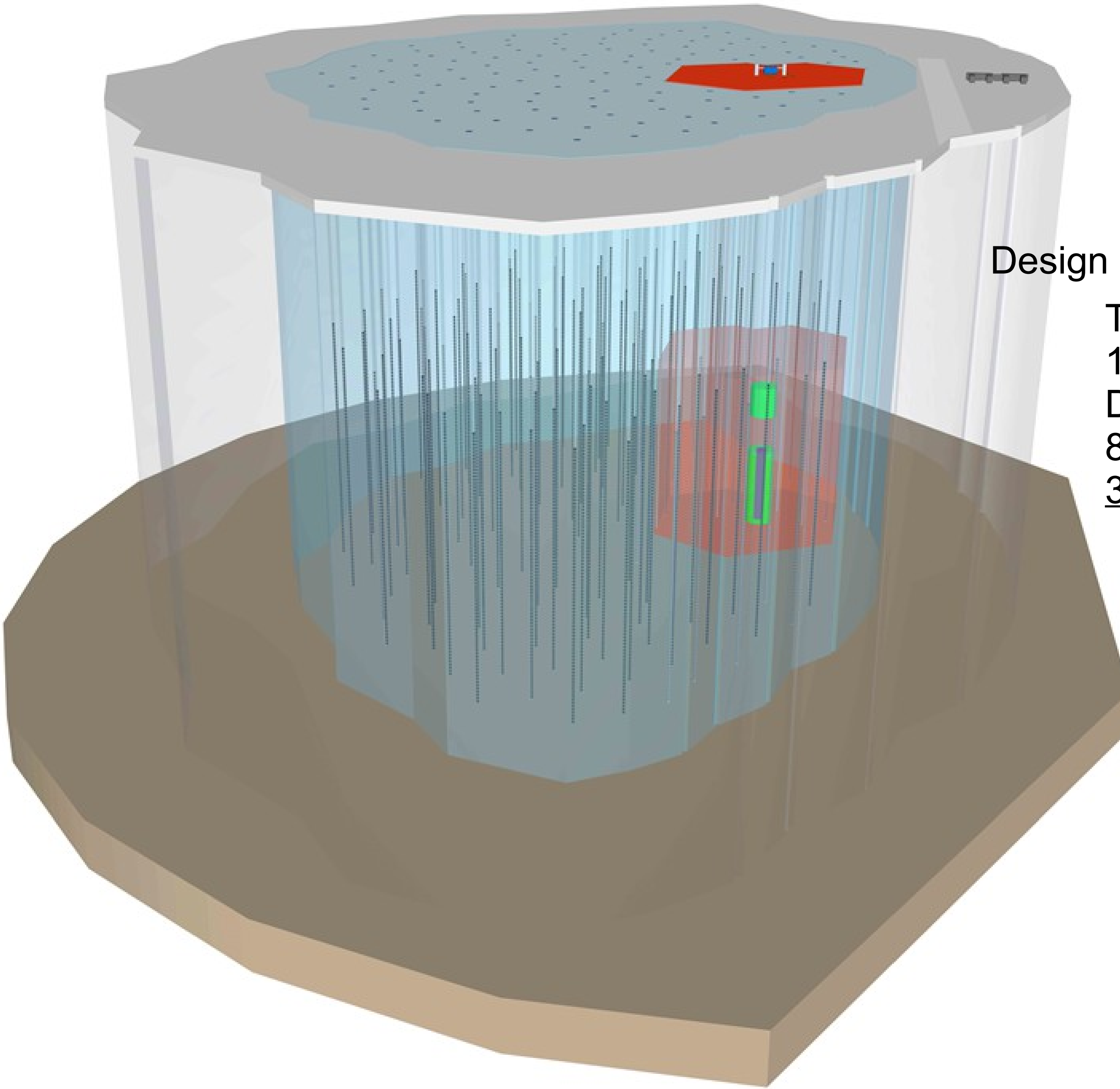
No direction, just timing

High statistics of events crucial!

- Only first 3 years of IceCube data, IceCube will run a lot longer
  → we will have many more events!

- Future: Maybe a bigger IceCube?
  → target high energy, detector can be sparser!

Next Generation IceCube



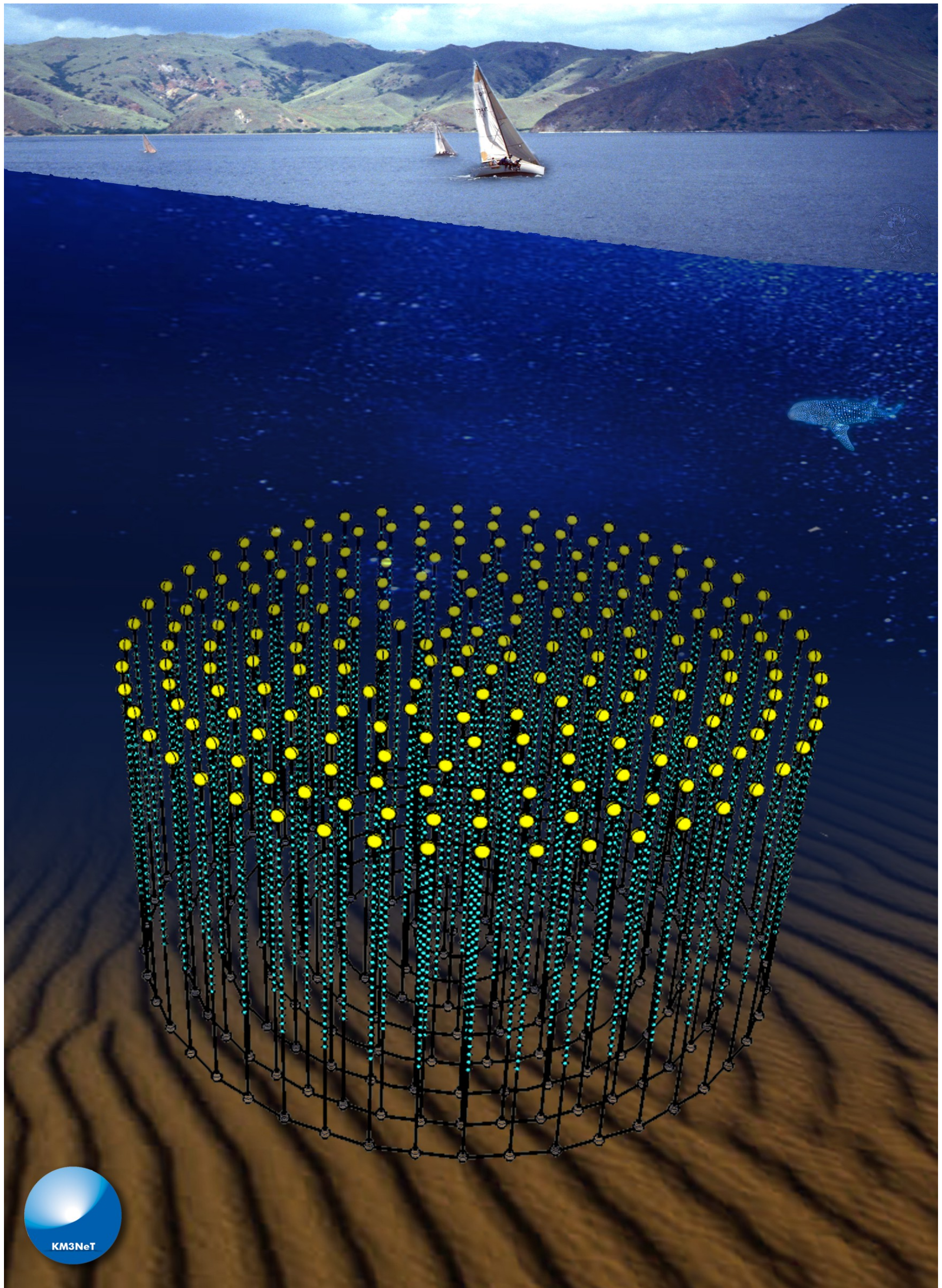
Design studies under way!

This figure:
120 strings
Depth <u>1.35 to 2.7 </u>km
80 DOMs/string
<u>300</u> m spacing

↓

Larger spacing probes higher energies

Future plans for a Mediterranean several cubic km telescope



KM3NeT

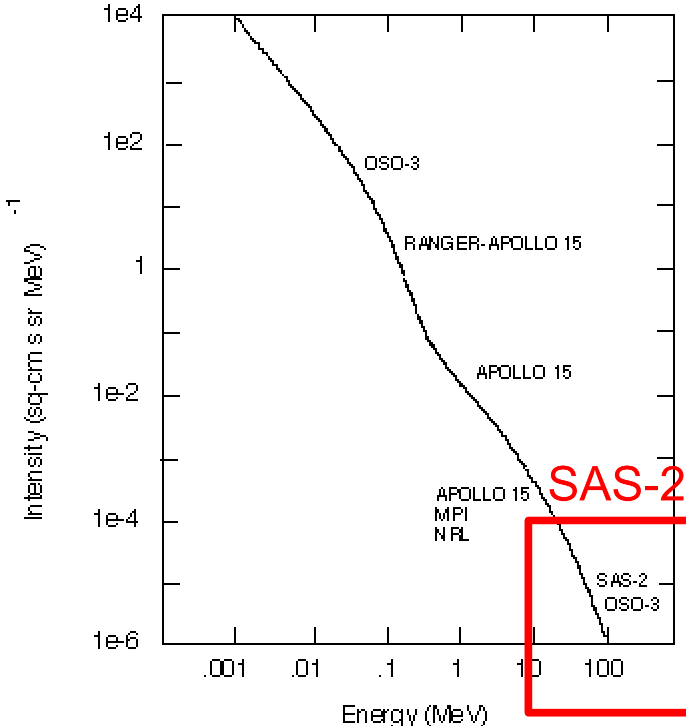
The future Mediterranean neutrino telescope

History is on our side!

Gamma-ray Astronomy

Diffuse signal → first source → catalog!

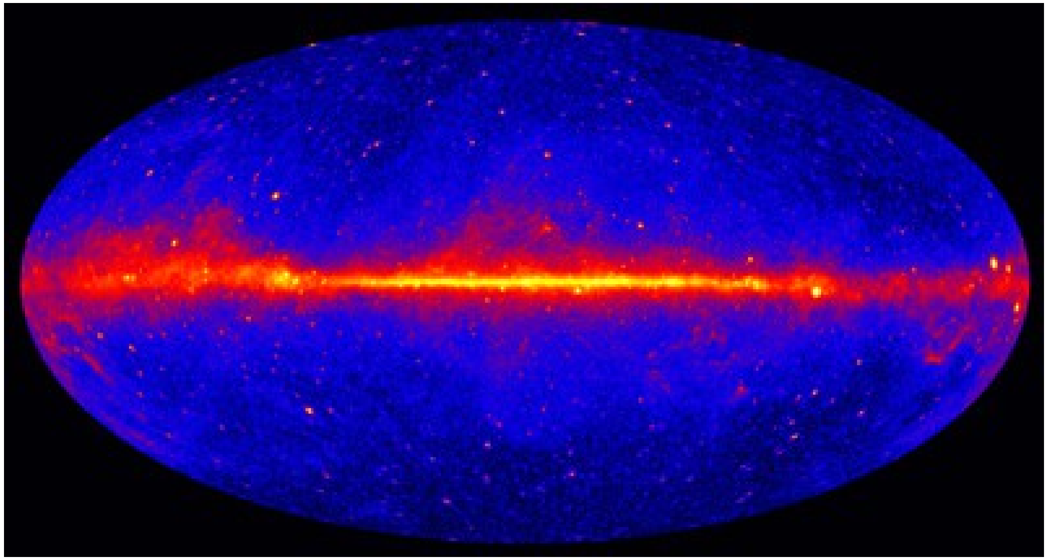
1970's



SAS-2

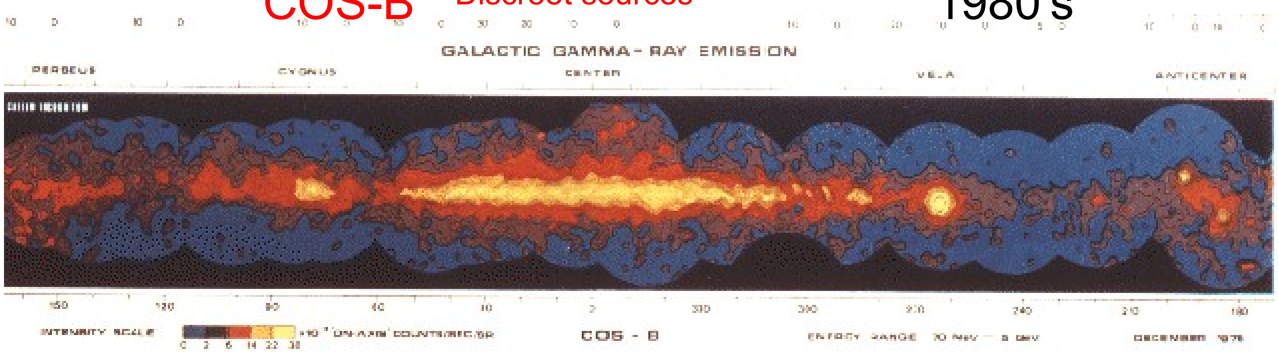
Diffuse celestial radiation

NOW Fermi 5-year data



GSFC nasa.gov

COS-B Discreet sources 1980's



GSFC nasa.gov

X-ray Astronomy

Diffuse signal → first source → catalog

(Sun detected in x-rays 1940's)

Diffuse emission and Scorpius X-1 1960's

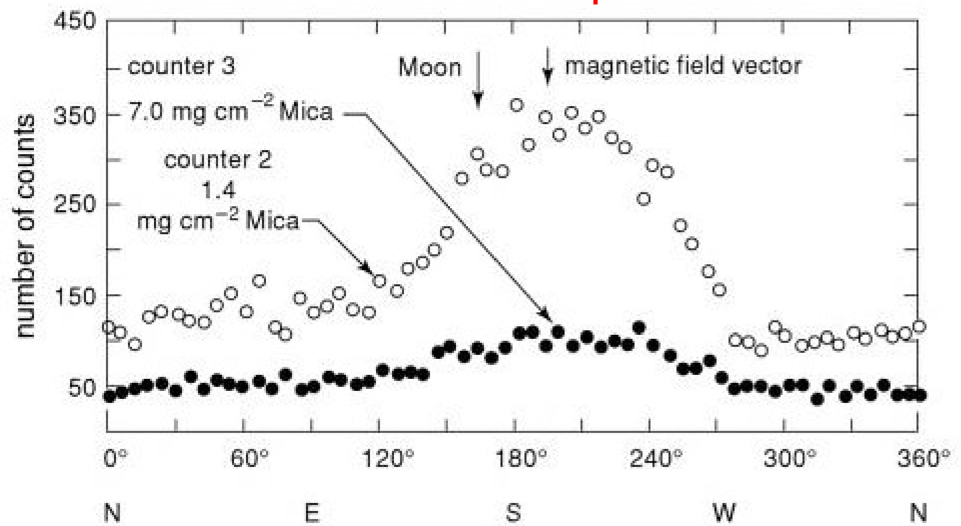
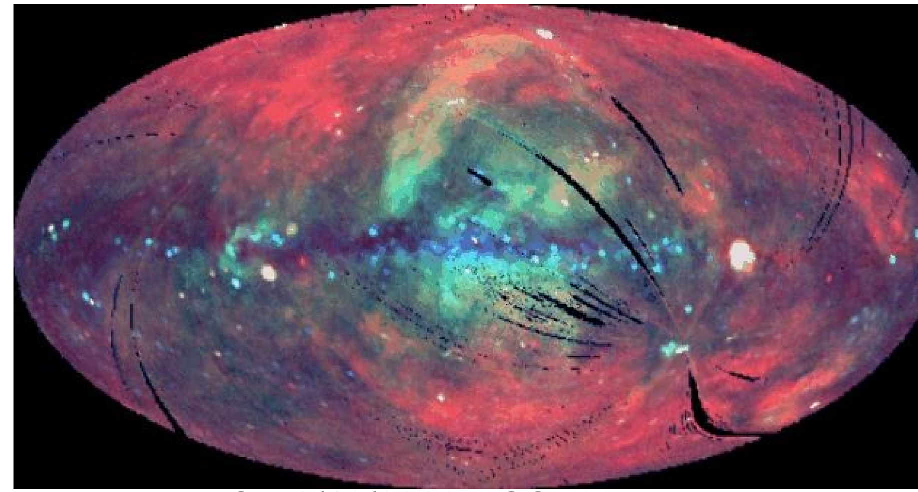
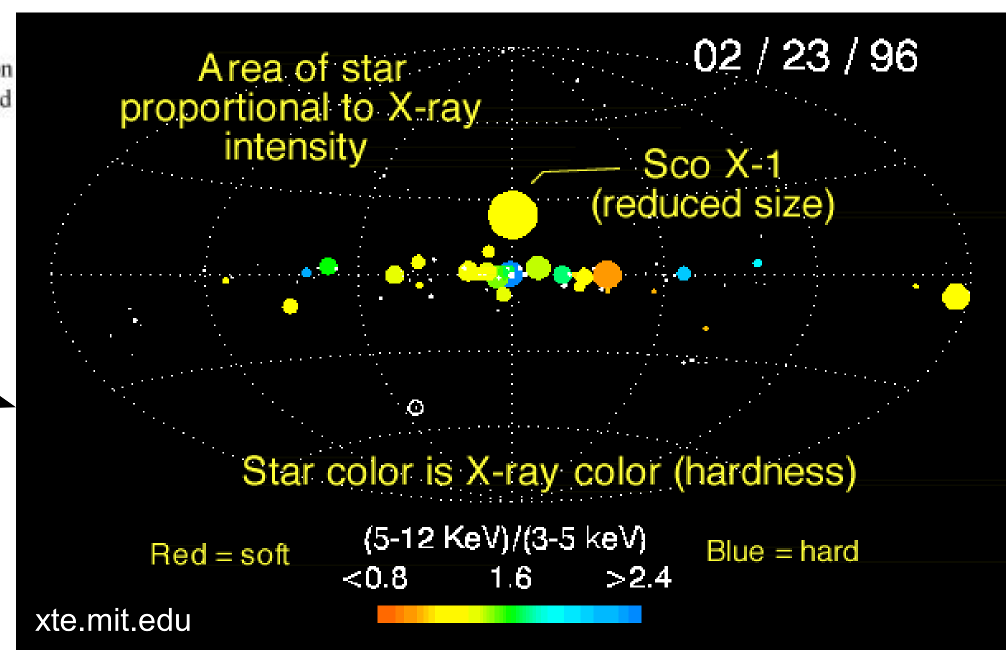


Figure 7.7: The discovery record of the X-ray source Sco X-1 and the X-ray background emission Giacconi and his colleagues in a rocket flight of June 1962. The prominent source was observed both detectors, as was the diffuse background emission (Giacconi *et al*., 1962).

“The Cosmic Century” M. S. Longair



APOD 8/19/2000 ROSAT



Cosmic Neutrinos in IceCube

- The Case for Neutrino Astrophysics
  → is convincing
- IceCube Neutrino Observatory
  → is finally complete
- Observation of Astrophysical Neutrinos
  → has happened

  We see cosmic neutrinos all-sky in all flavors!

  NEW: we <u>also</u> see them in the northern sky with muon-neutrinos in an independent analysis!!
- Looking Forward
  → The hunt for sources is on!

IceCube Talks at the April Meeting

Session C4 Saturday 1:30pm

- Markus Ahlers “Theoretical Implications of IceCube Neutrinos”

Session E2 Saturday 3:30pm

- Carsten Rott "Indirect Detection Searches for WIMPs with Neutrinos”

Session E9 Saturday 3:30pm

- Frank McNally "Cosmic-ray anisotropy studies with IceCube"

Session K12 Sunday 1:30pm

- Laura Gladstone “The IceCube DeepCore Detector”
- Ty DeYoung "Determination of the neutrino mass hierarchy with PINGU"

Session R8 Monday 10:45pm (Next session!)

- Christopher Weaver "IceCube Results for Diffuse Muon Neutrinos"
- Jake Feintzeig “Searches for Point Sources of Astrophysical Neutrinos”
- Mariola Lesiak-Bzdak "Search for diffuse extraterrestrial contained neutrino-induced cascades"
- Bakhtiyar Ruzybayev "Measurement of the cosmic ray energy spectrum with IceCube"

Session U4 Monday 3:30pm

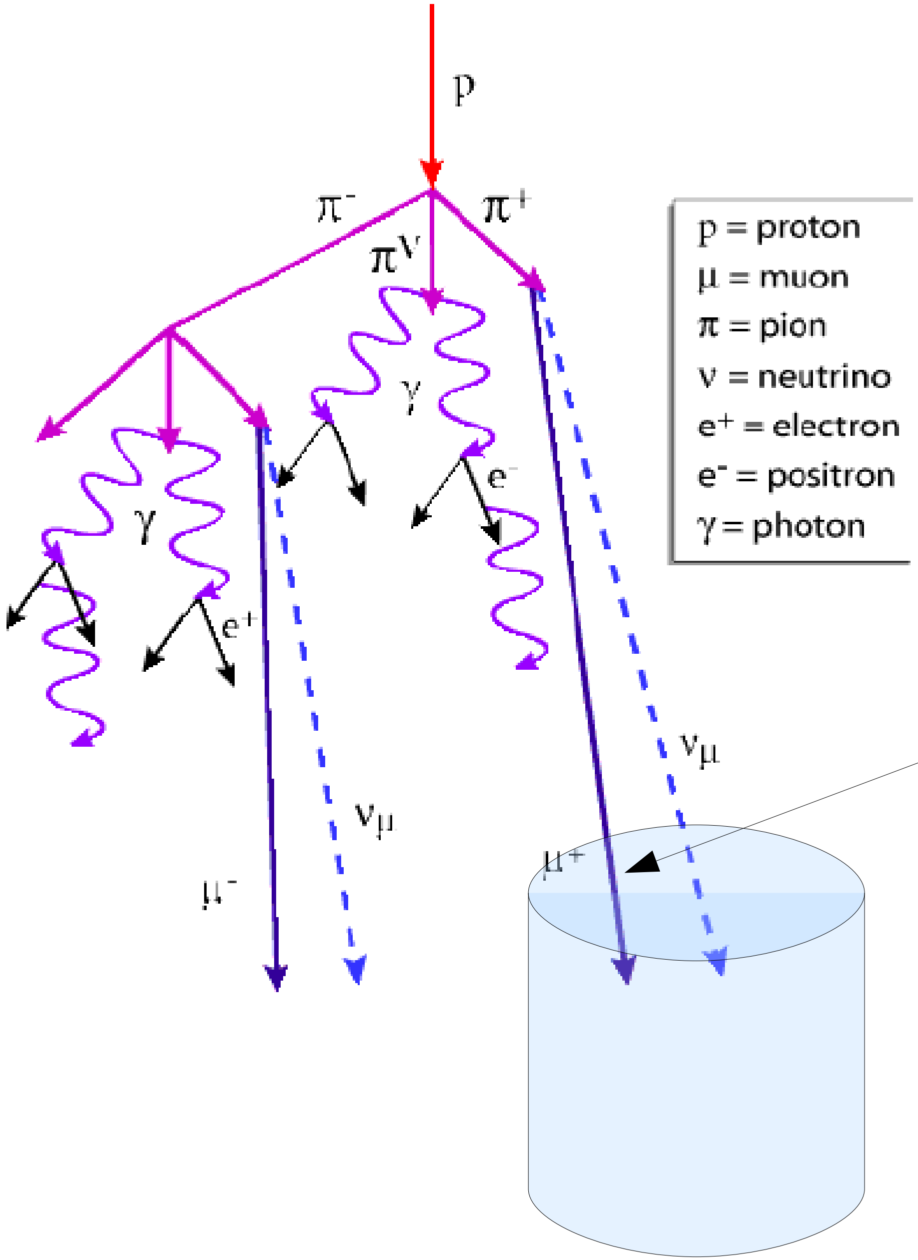
- Nathan Whitehorn “What PeV neutrinos teach us about Cosmic Rays”

Session Y8 Tuesday 1:30pm

- James Casey "Search For Correlation Between Known GRBs and Astrophysical Neutrinos"

Backups

Tagging atmospheric neutrinos

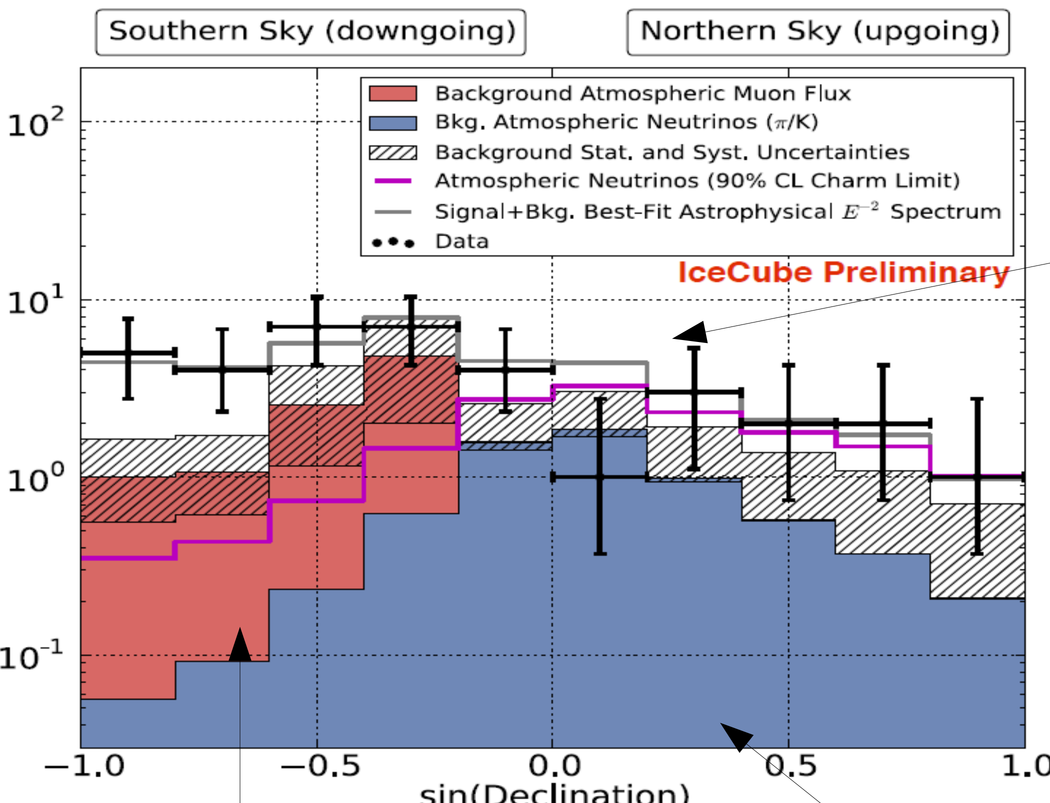


The accompanying muon trips the veto!

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

Declination Distribution of Events

= zenith



Diffuse signal

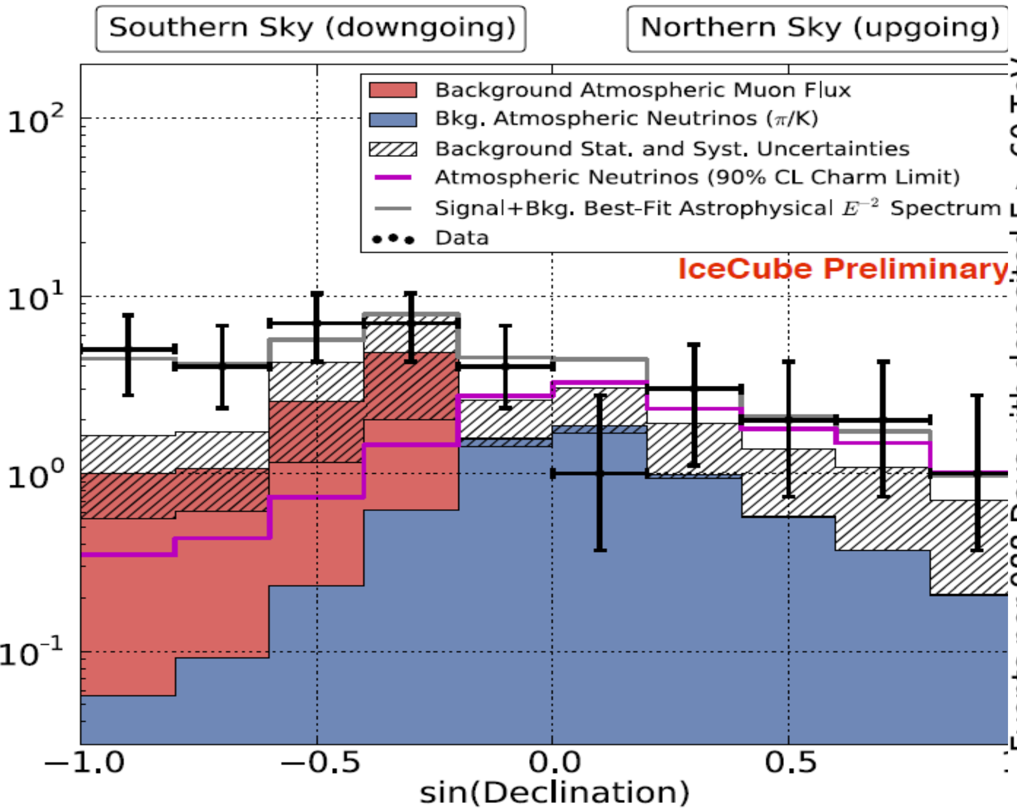
Muon background only in the southern sky

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

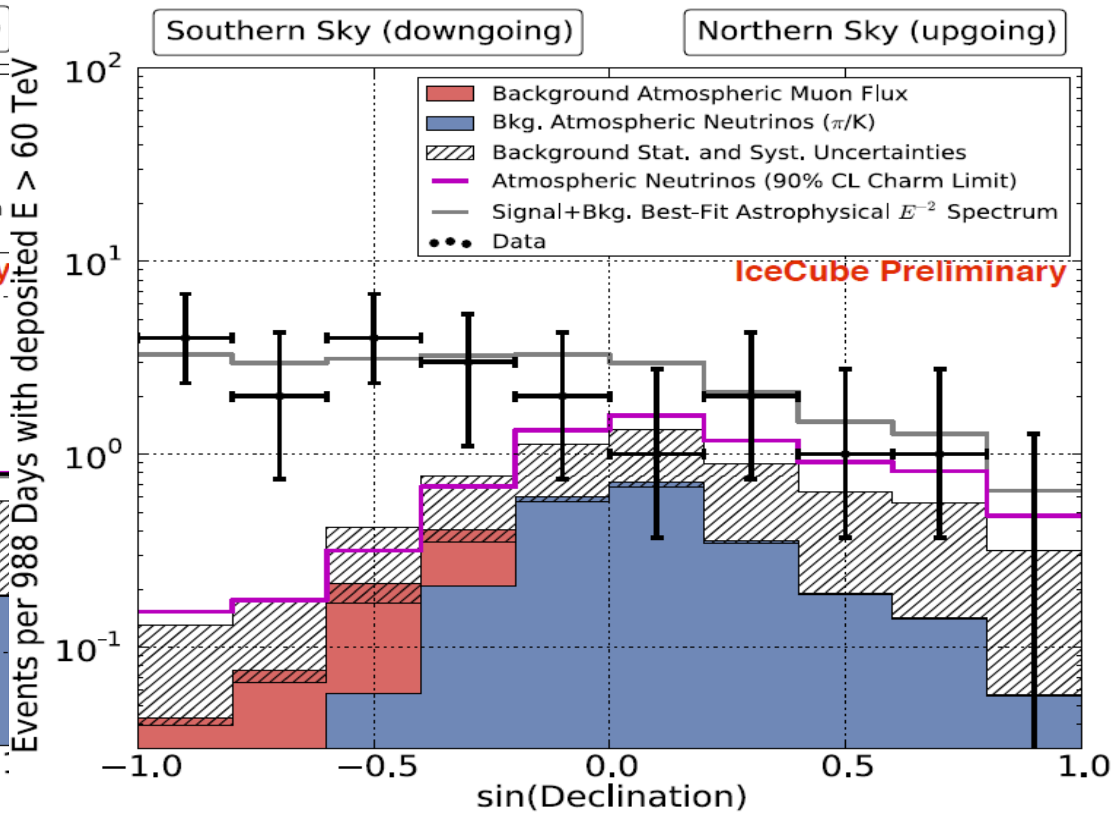
Declination Distribution of Events

= zenith

ALL EVENTS



EVENTS > 60 TeV



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

Maximize the likelihood L assuming a source at point x with energy spectrum $E^{-\gamma}$

Total # of events

\# of events from source
Varied to maximize L

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

Probability density that event i comes from a source at position x

×

Probability density that event i comes form a source with spectrum γ

Probability density that event i is from backgrounds expected at position x

×

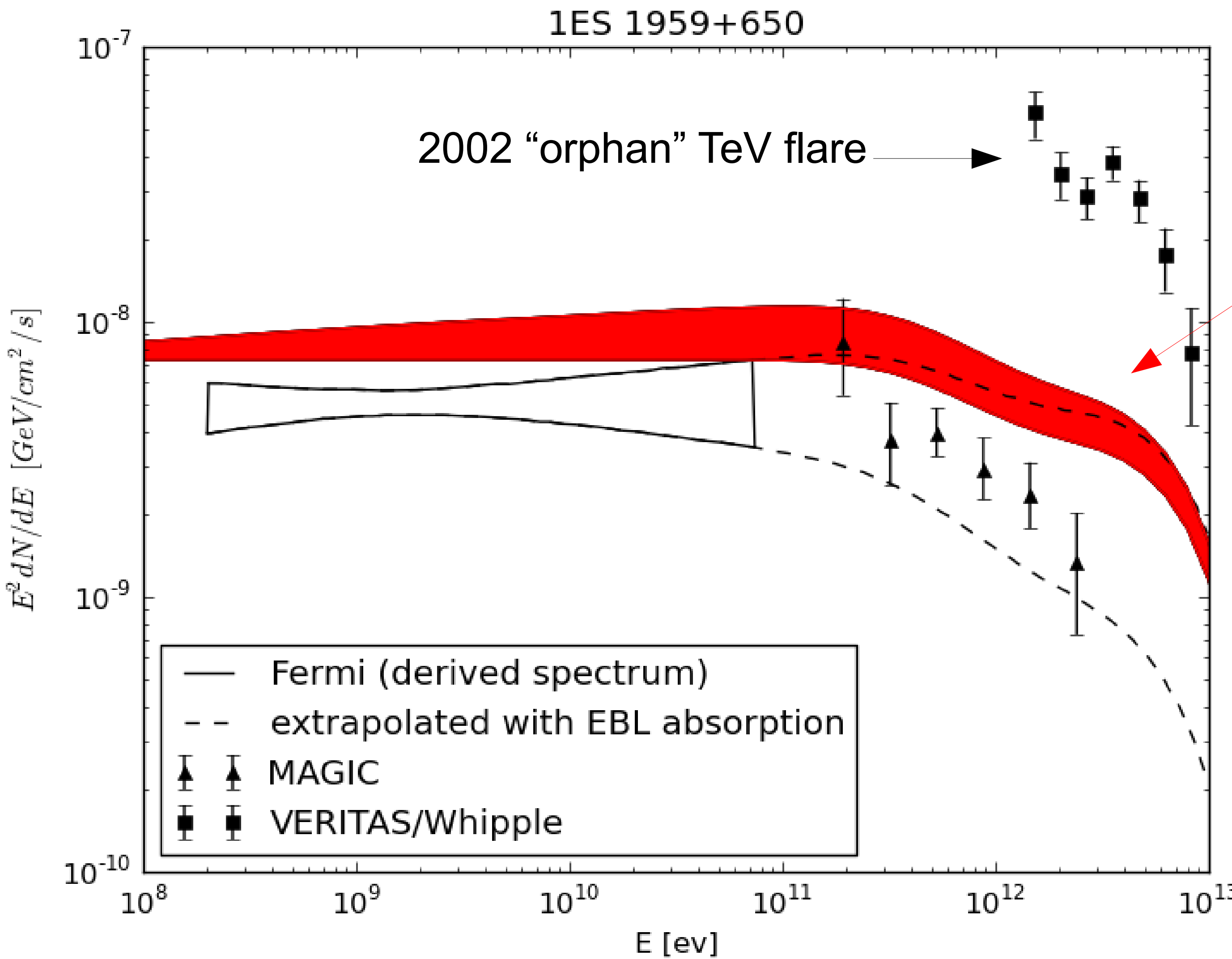
Probability density that event i comes form a known background energy spectrum

TS is calculated for every point in the sky x

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

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

Limits for sources: Blazar 1ES 1959+650



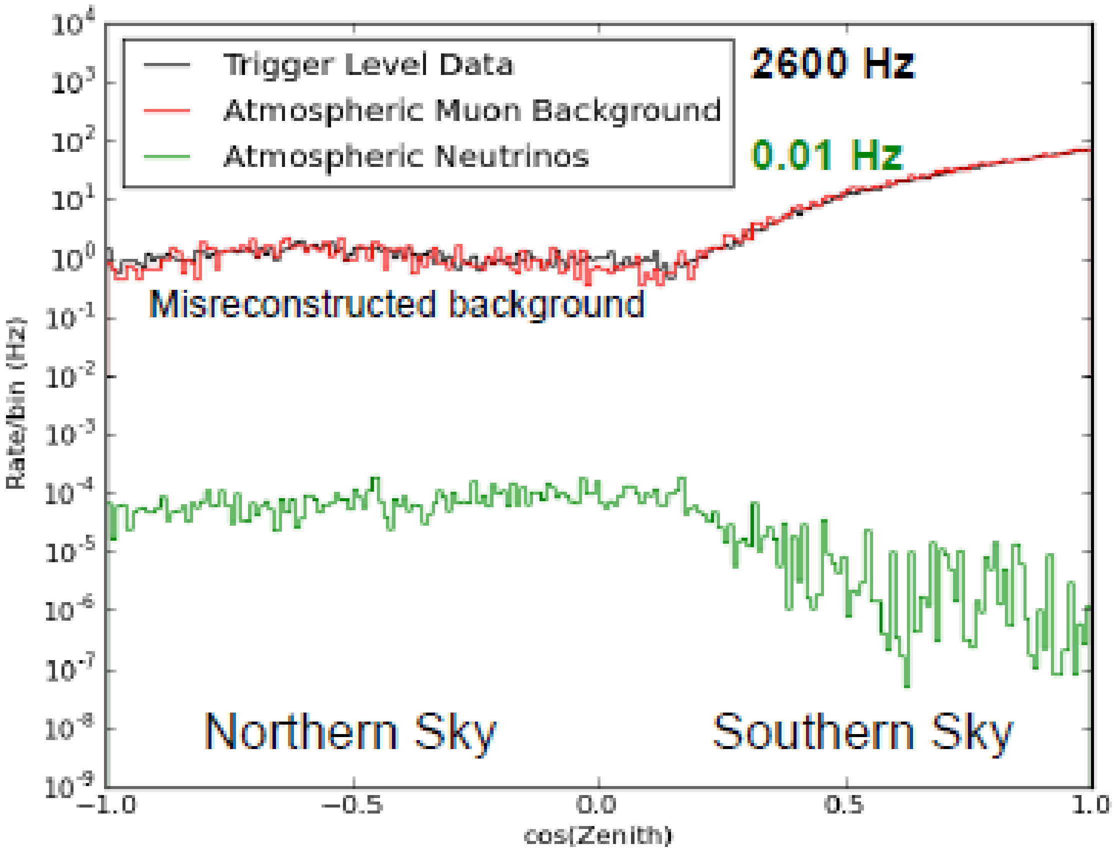
Neutrino Limit translated to γ limit assuming 1:1 ratio of π^0 to $\pi^{+/-}$ with γ flux attenuated due to interactions with EBL

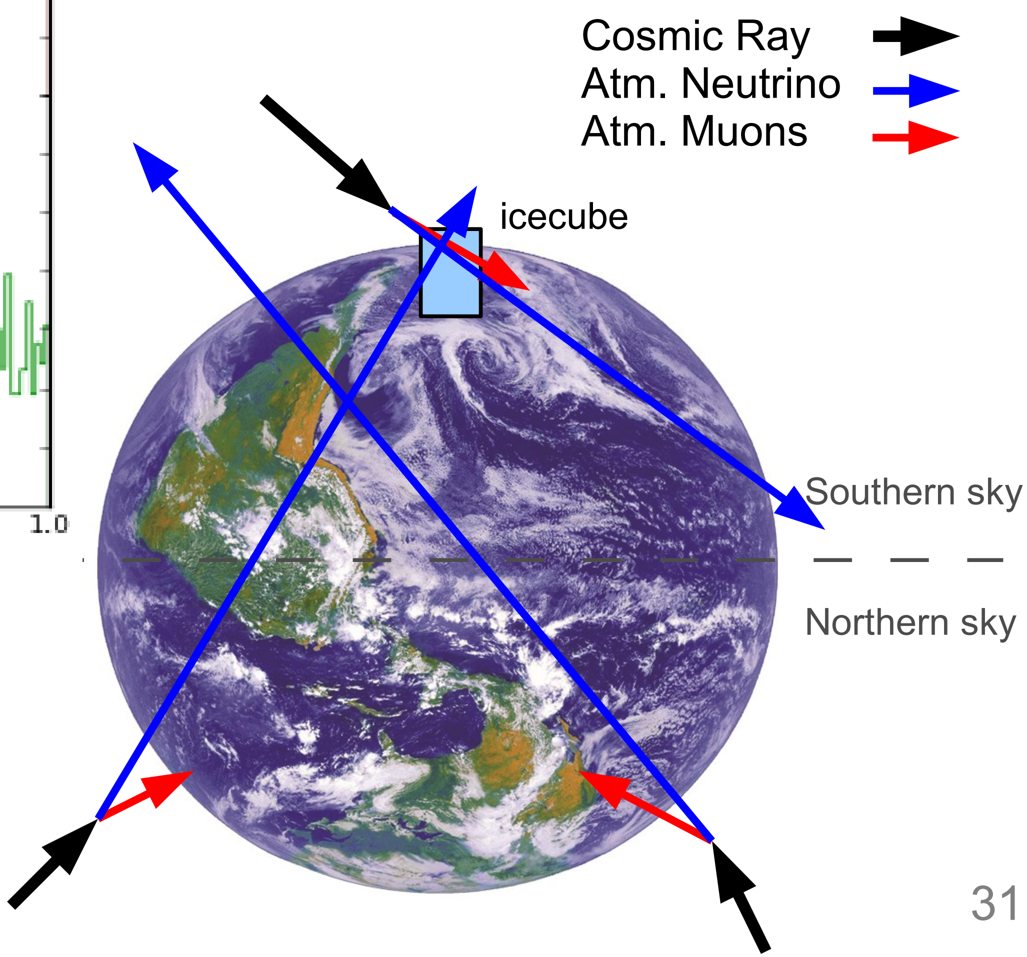
Width from secondary γs created by e^+/e^-

EBL model: A. Franceschini et al., Astron.Astrophys.487 (2008)

A. A. Abdo et al, Astrophys. J. (2009)

What does IceCube see?



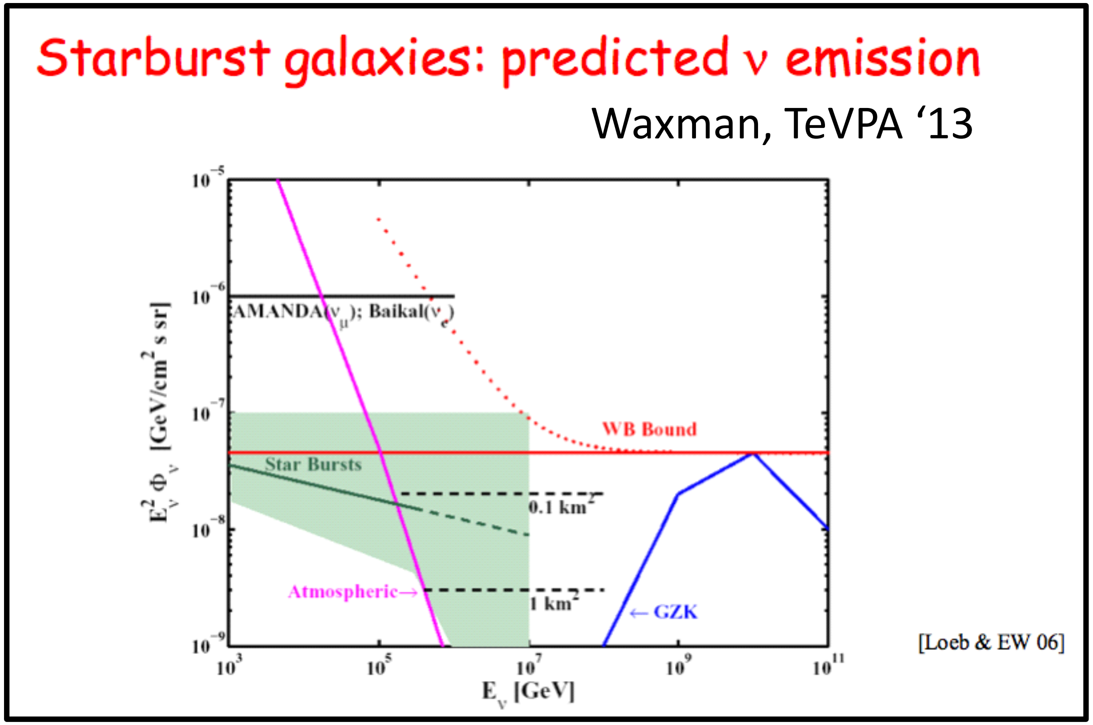


Could it be Starburst Galaxies?

IceCube does a stacking analysis on close-by starburst galaxies using the traditional muon data set 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



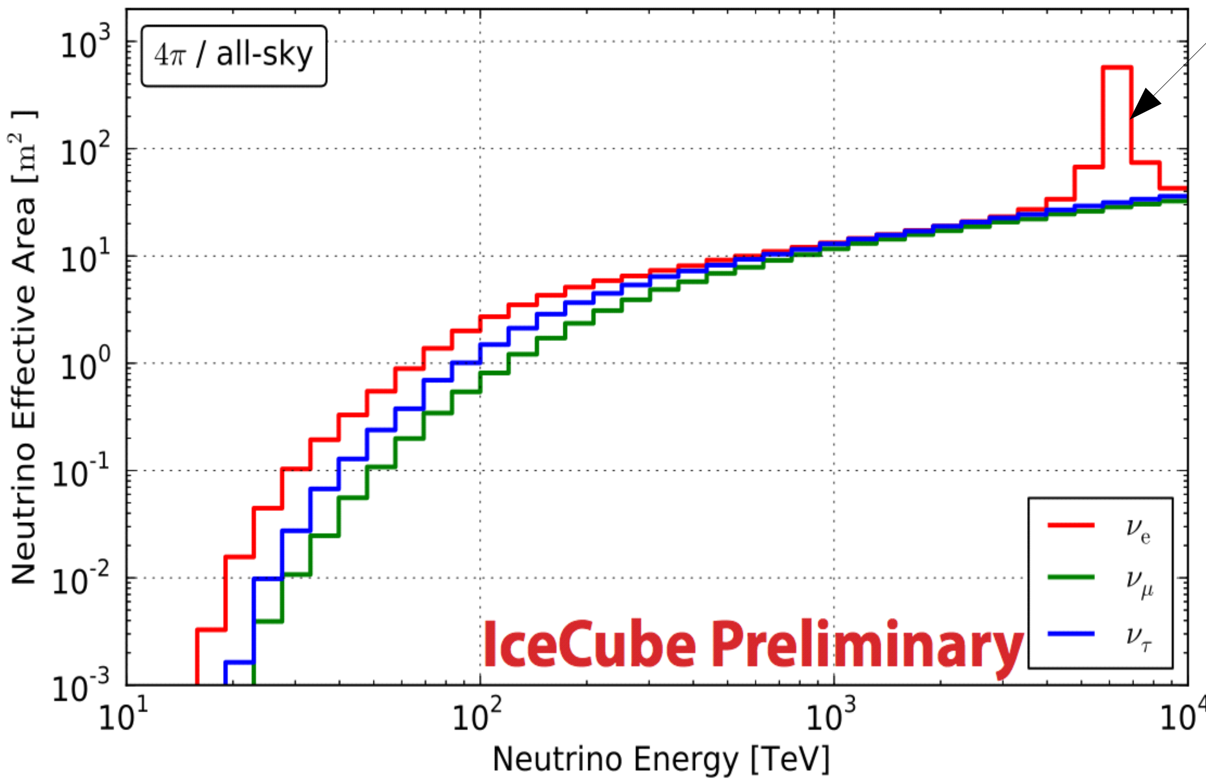
Unbroken E^{-2} flux limit: 7 x 10^{-10} E^2 GeV $cm^{-2}s^{-1}sr^{-1}$

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

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



Developed cascade direction reconstruction!