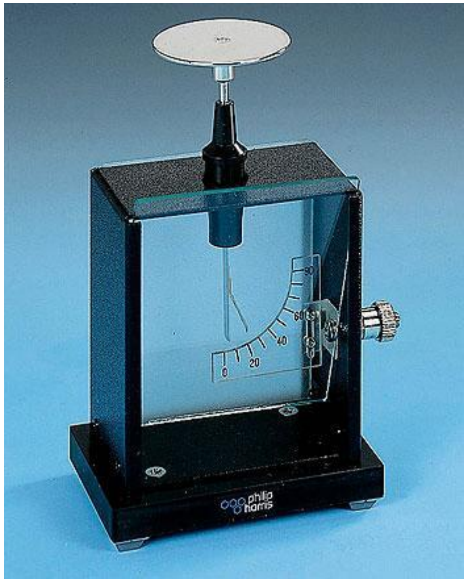
From Hess to HESE:

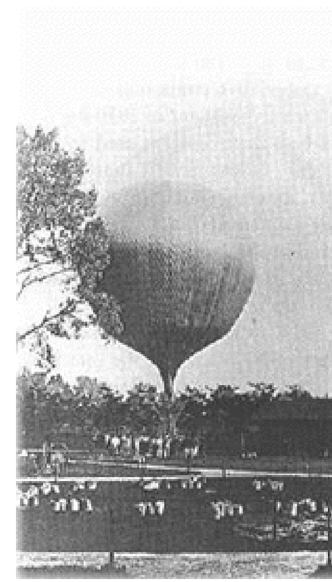
Intro to IceCube Astrophysical Neutrino Analysis

Jim Braun

2014 Madison Bootcamp

Cosmic Rays: 1912





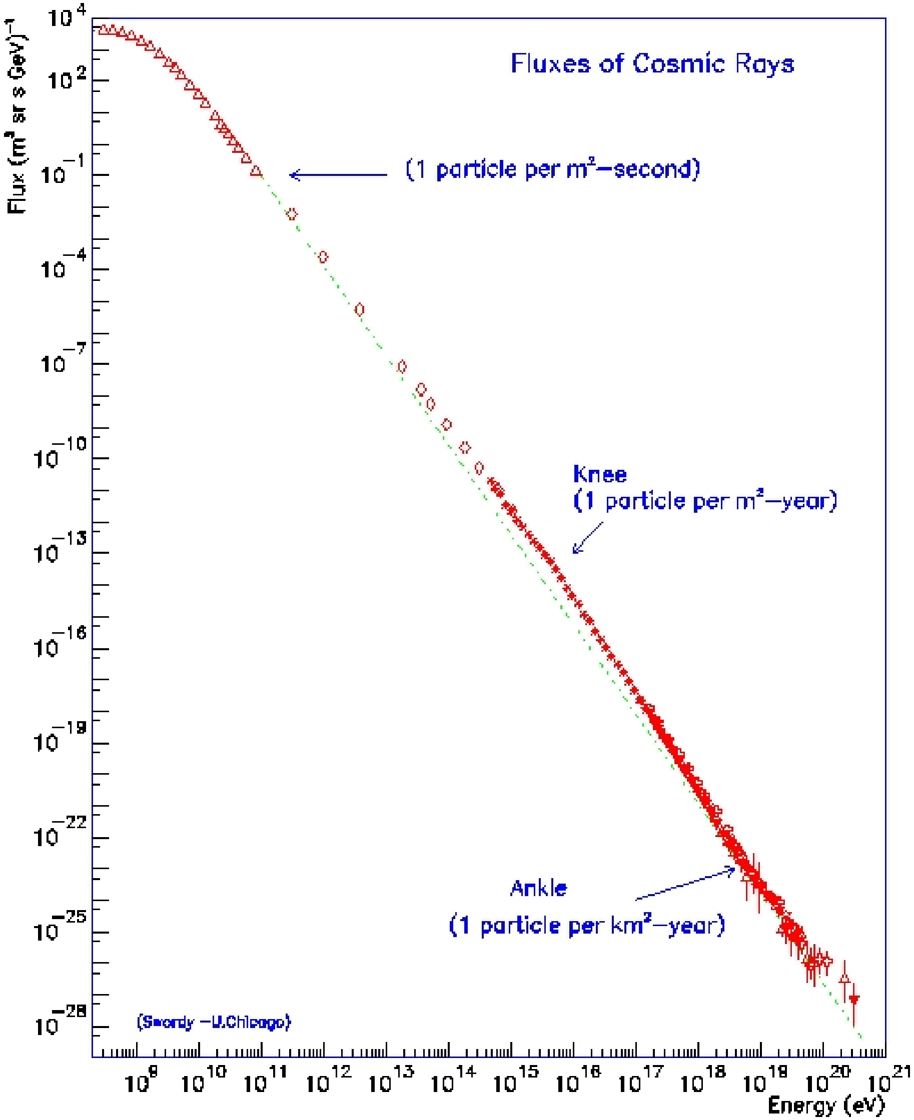
Elevation	Rate
Ground	12
1km	10
2 km	12
3.5 km	15
5 km	27

"The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above."

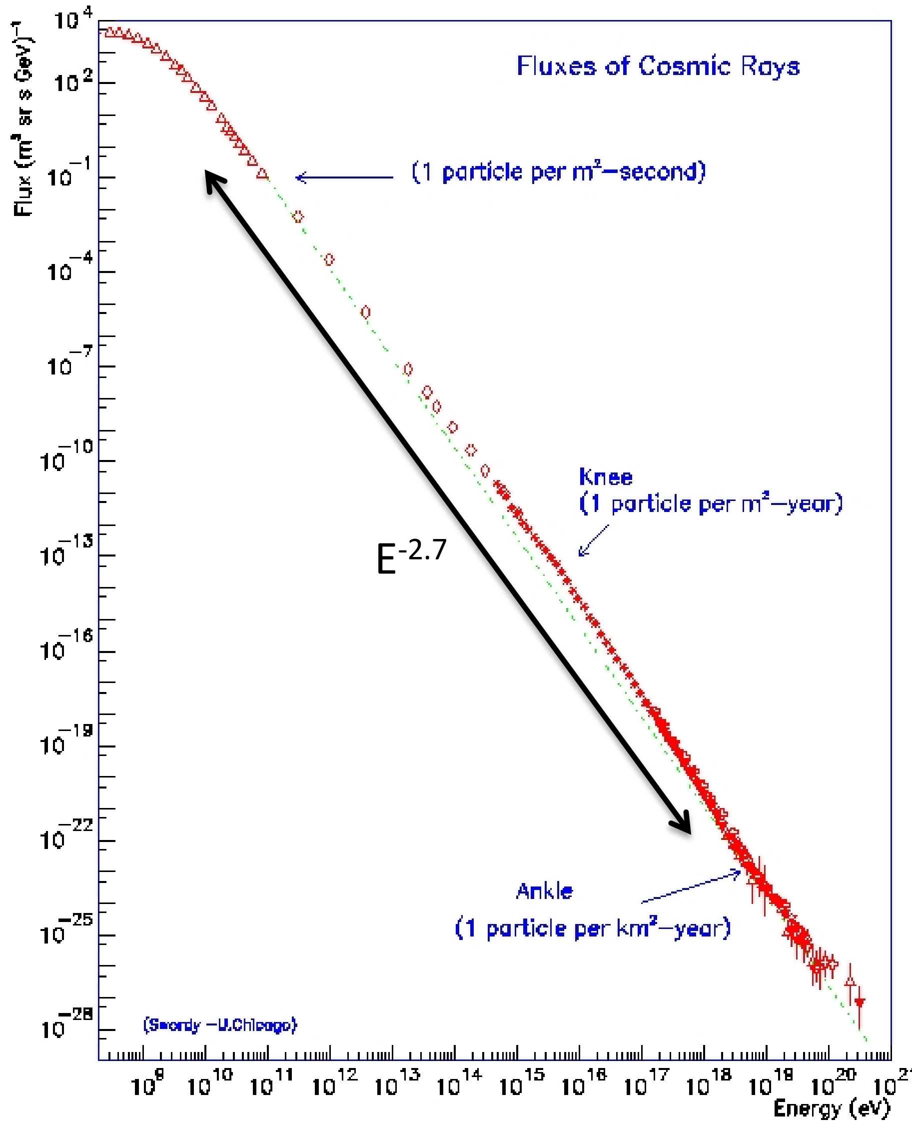
Victor F. Hess, Nobel Laureate

Physikalische Zeitschrift, 13:1084-1091, November 1912.

Cosmic Rays: 2012



Cosmic Rays: 2012



Cosmic Rays: 2012

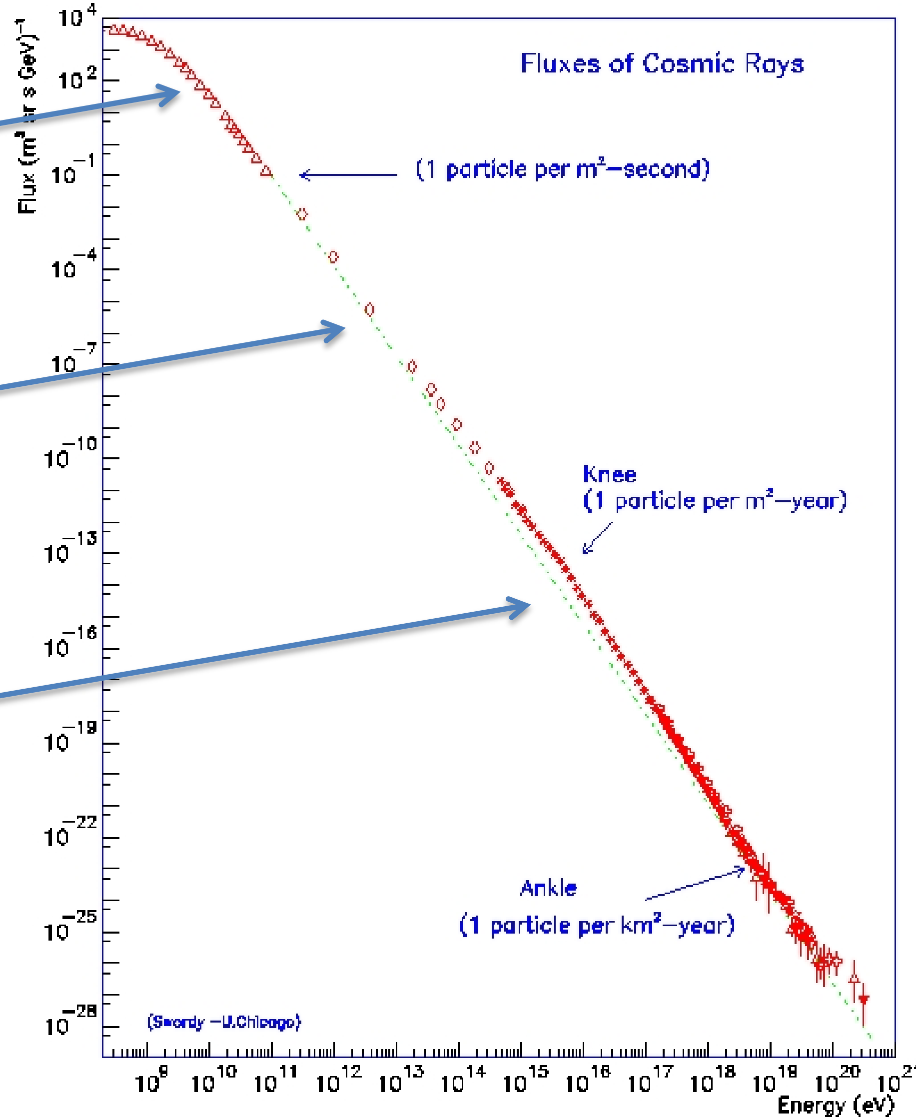
Small
Detector area

Satellites

Balloon-Borne
Detectors

Air Shower
Detectors

Large
Detector area



Cosmic Rays: 2012

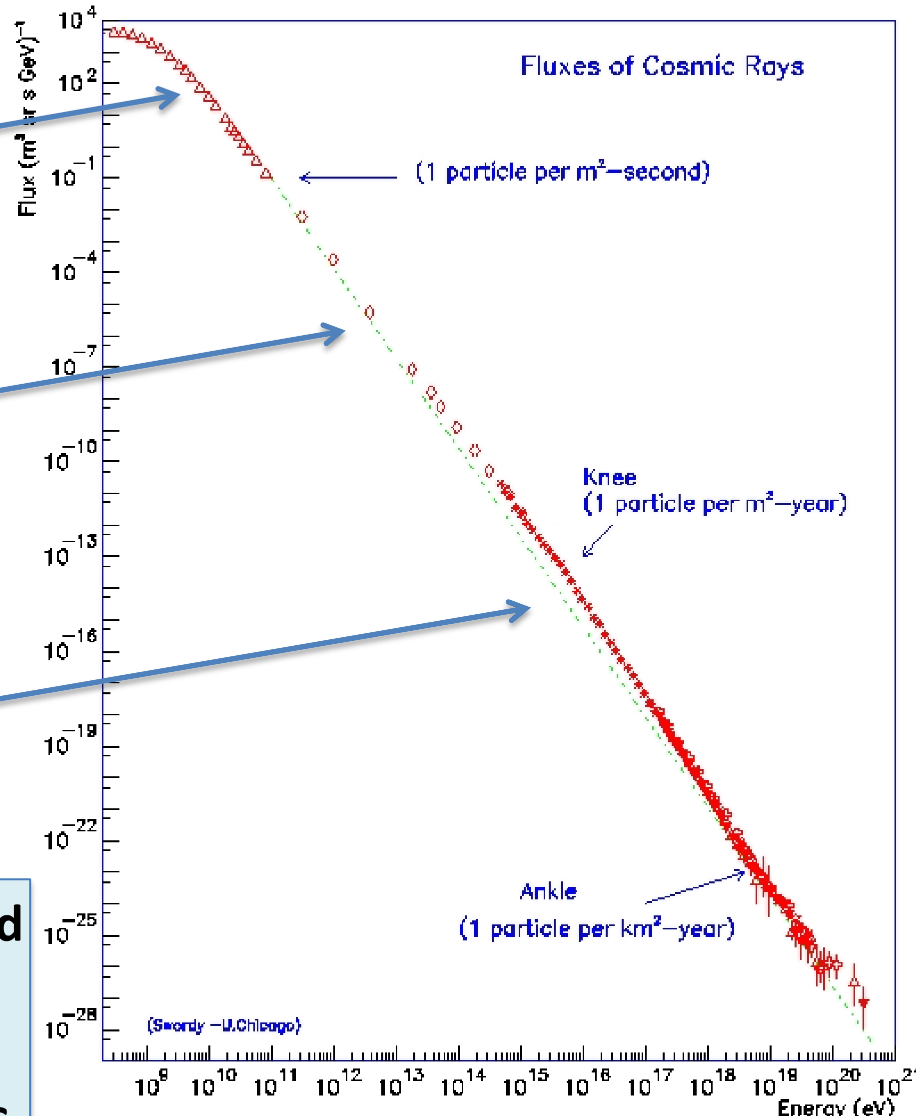
Small
Detector area

Large
Detector area

Satellites

Balloon-Borne Detectors

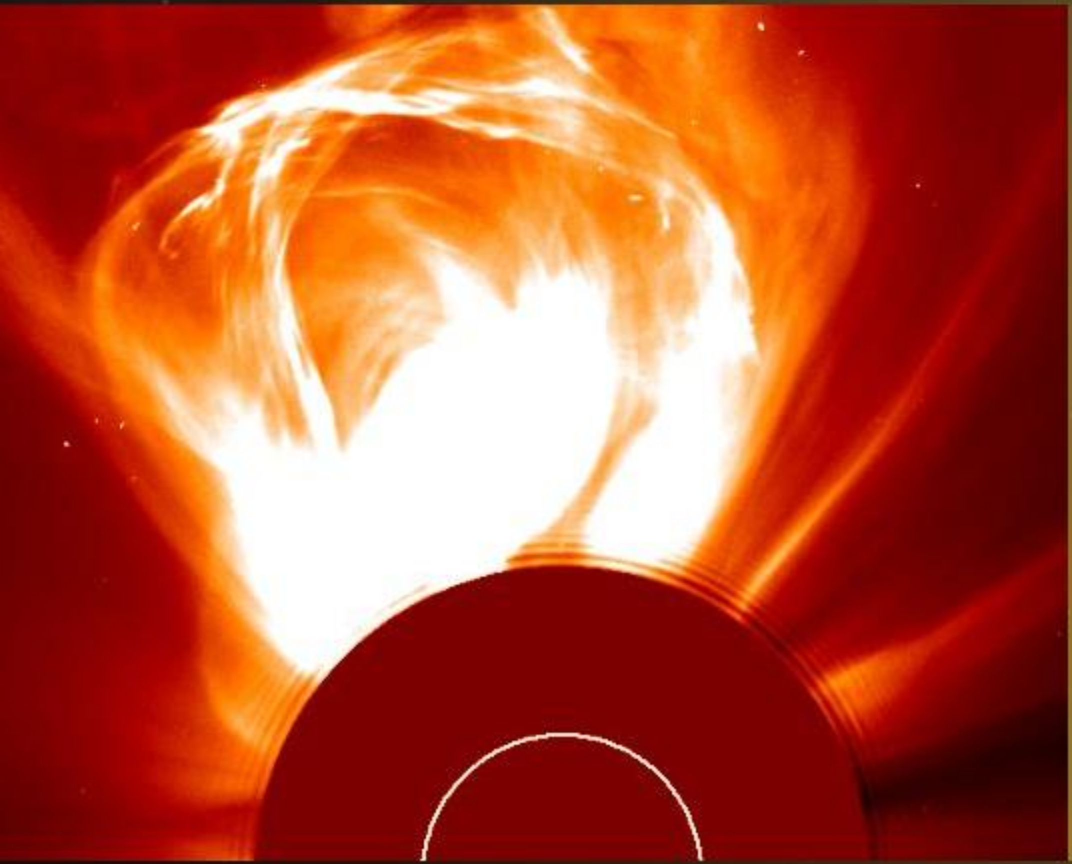
Air Shower Detectors



Where do cosmic rays come from and how are they created?

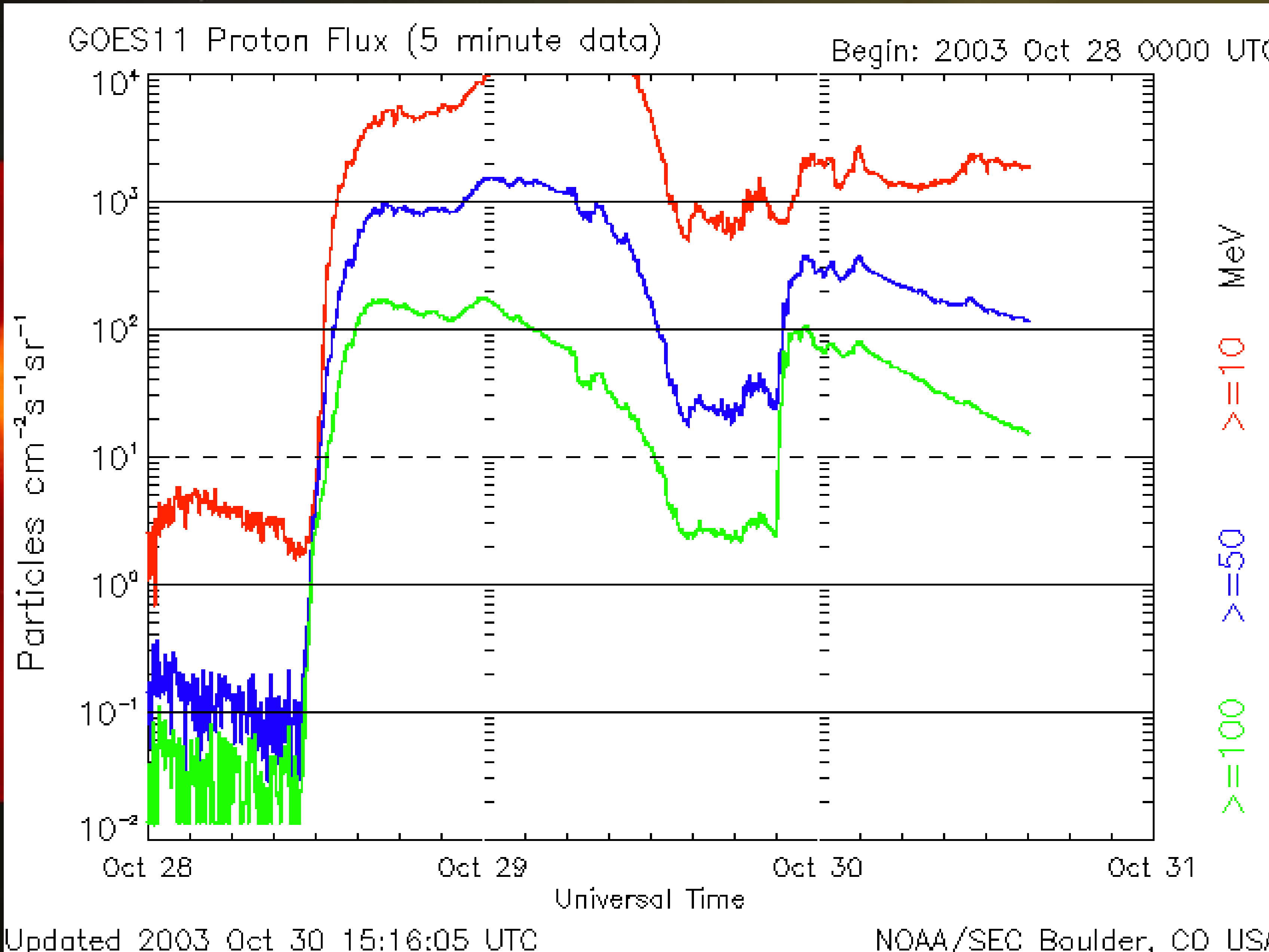
What is the composition of energetic particles reaching the Earth?

A Local Accelerator: Solar Flare



coronal
mass
ejection
→
10 GeV
particles

flows of charged particles result in large B-fields


GOES11 Proton Flux (5 minute data)
Begin: 2003 Oct 28 0000 UTC
Particles cm⁻²s⁻¹sr⁻¹
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Oct 28
Oct 29
Oct 30
Oct 31
Universal Time
>=10 MeV
>=50
>=100
Updated 2003 Oct 30 15:16:05 UTC
NOAA/SEC Boulder, CO USA

fl

s

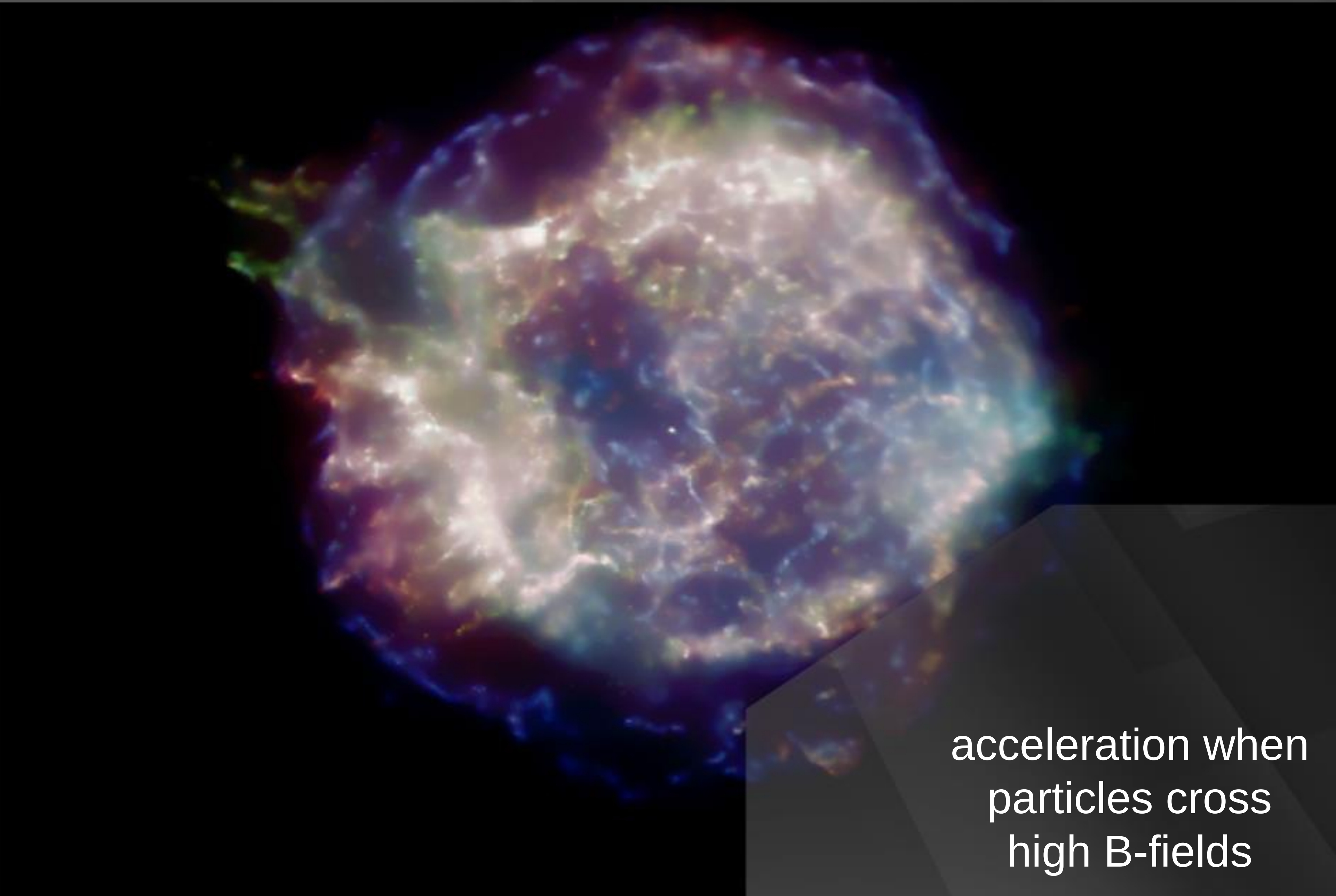
Hillas formula :

- accelerator must contain the particles

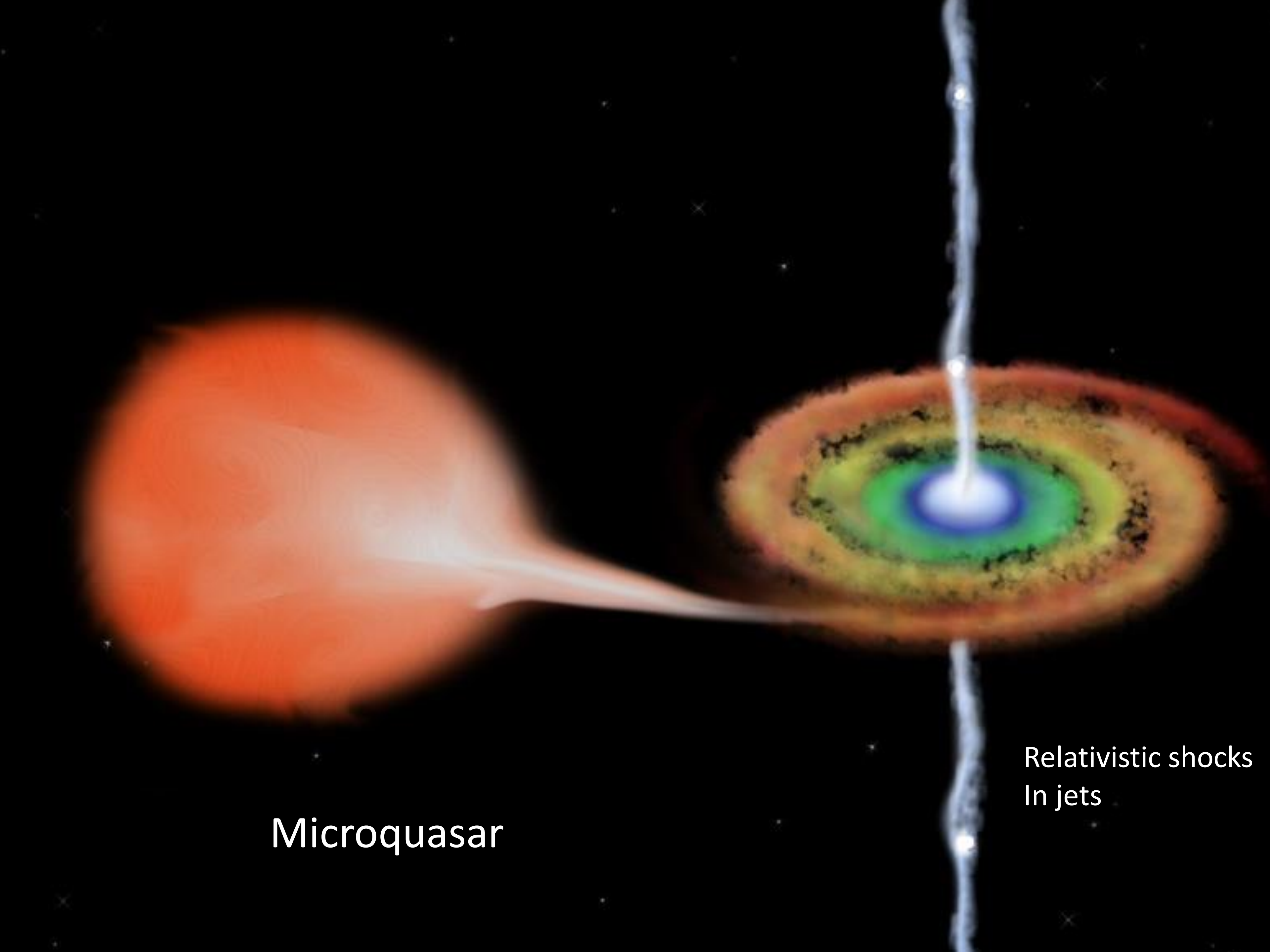
$$R_{gyro} \left(= \frac{E}{\mathrm{v}qB}\right) \leq R$$

$$E \leq \mathrm{v}\, qBR$$

cassiopeia A supernova remnant in X-rays



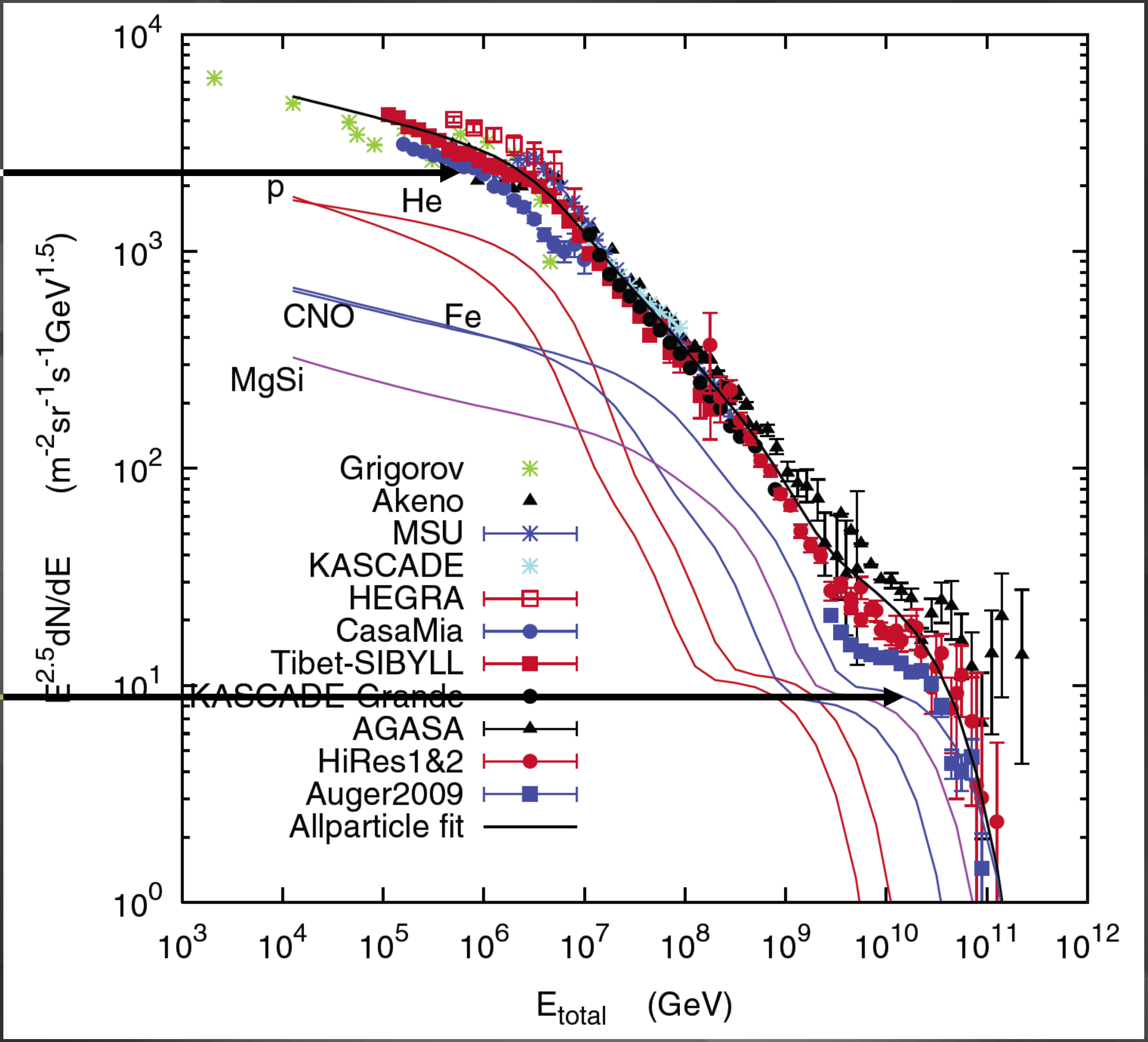
acceleration when
particles cross
high B-fields


Relativistic shocks
In jets
Microquasar

sources accommodating the observed energy budget

Galactic:

extragalactic:

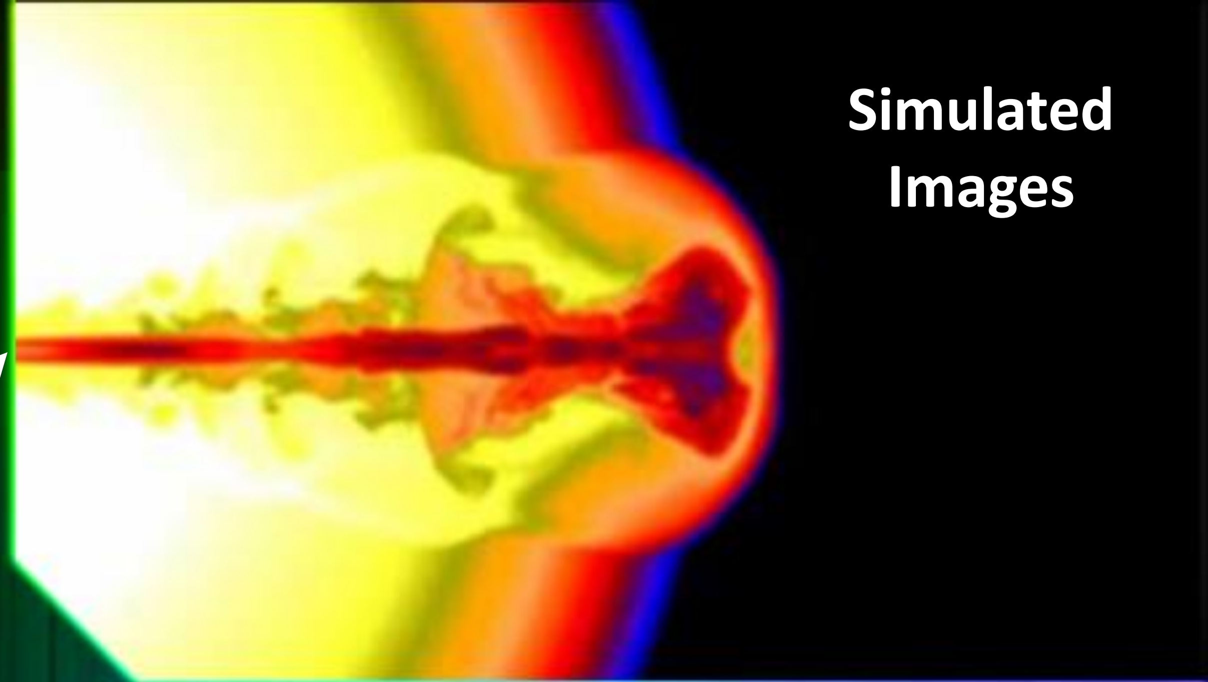


active galaxy

supermassive
black hole

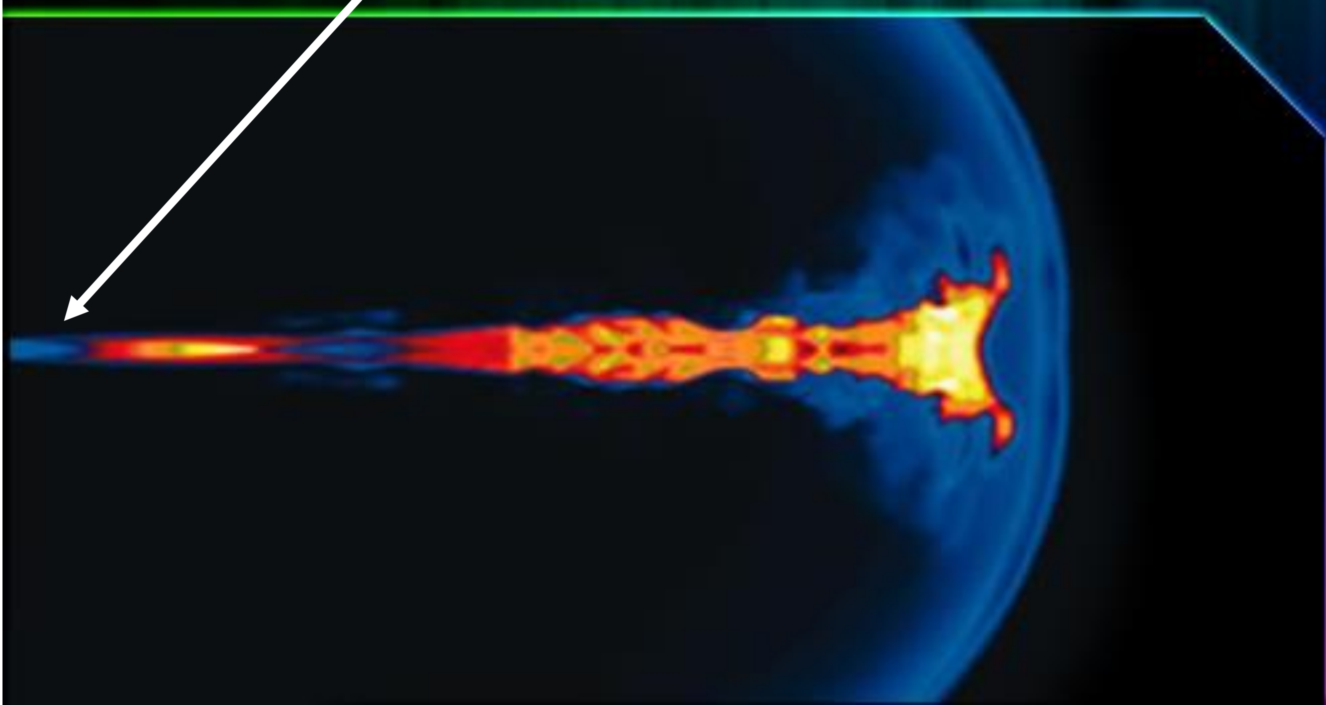
collapse of massive star produces a

gamma ray burst



Simulated Images

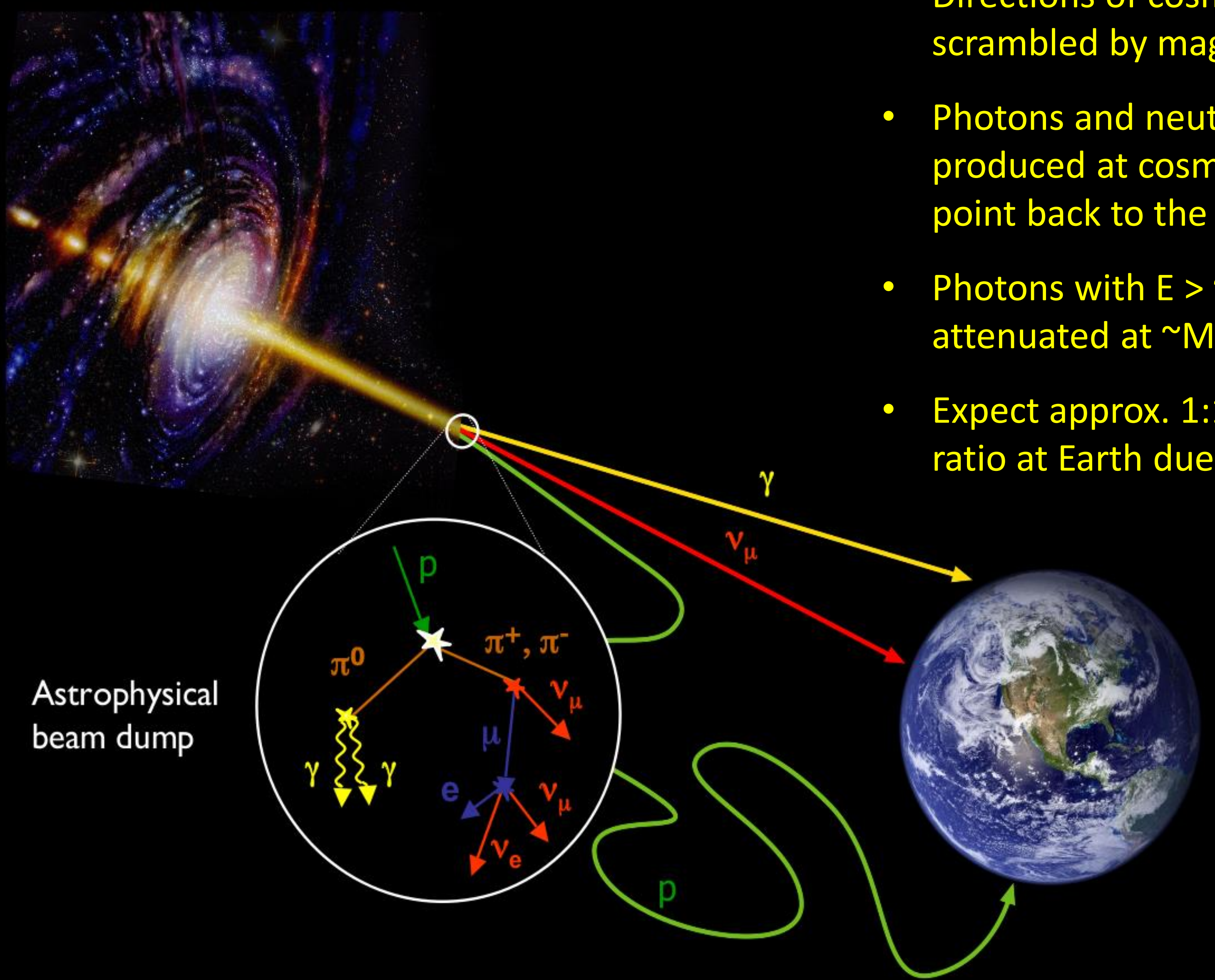
spinning black hole



neutrinos are produced in the interactions of fireball protons (cosmic rays) with synchrotron photons

Cosmic Messengers

- Directions of cosmic rays are scrambled by magnetic fields
- Photons and neutrinos are produced at cosmic ray sources and point back to the source
- Photons with E > ~10 TeV are attenuated at ~Mpc distances
- Expect approx. 1:1:1 neutrino flavor ratio at Earth due to oscillations



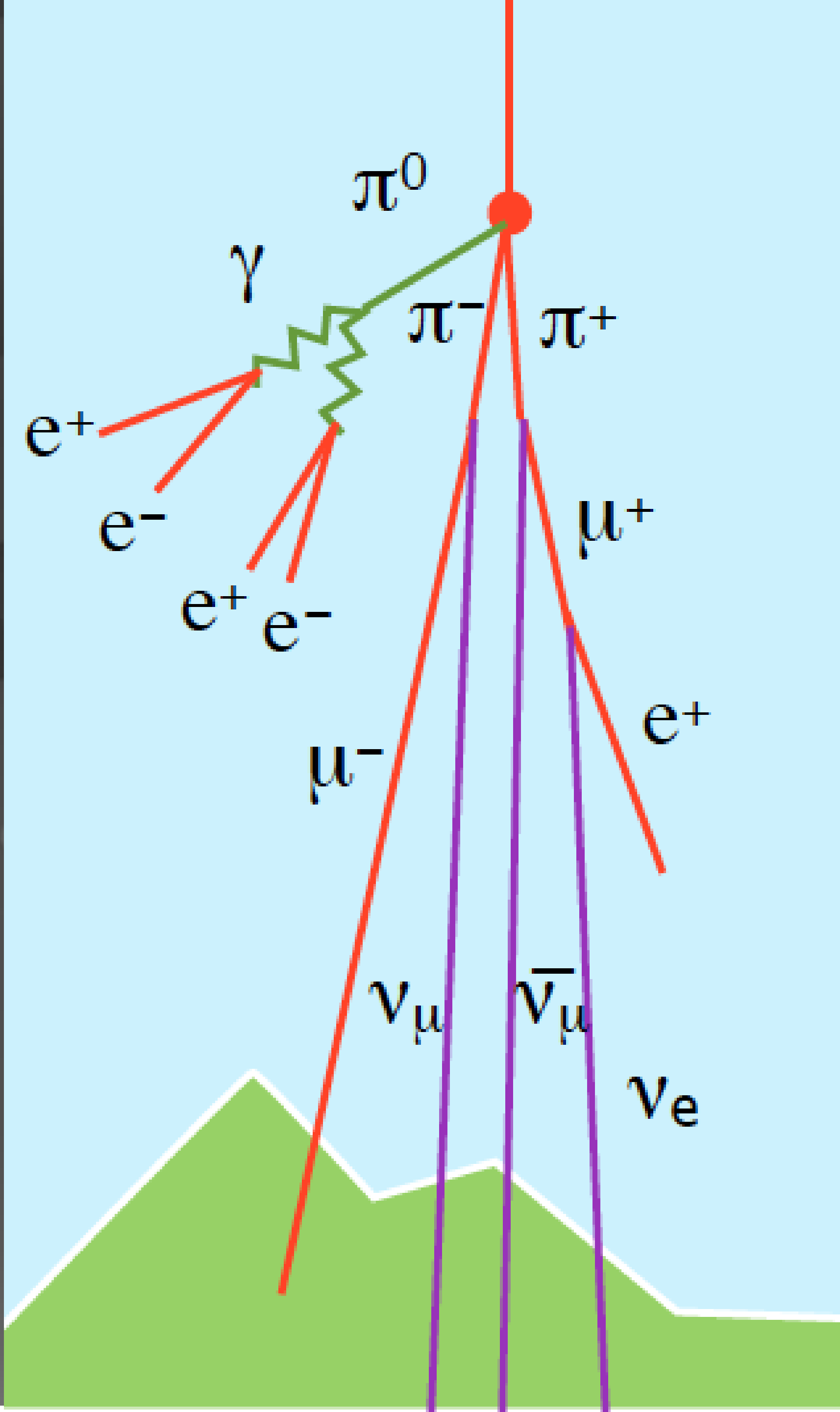
Air Showers

Interaction of cosmic ray in the atmosphere produces a shower of particles

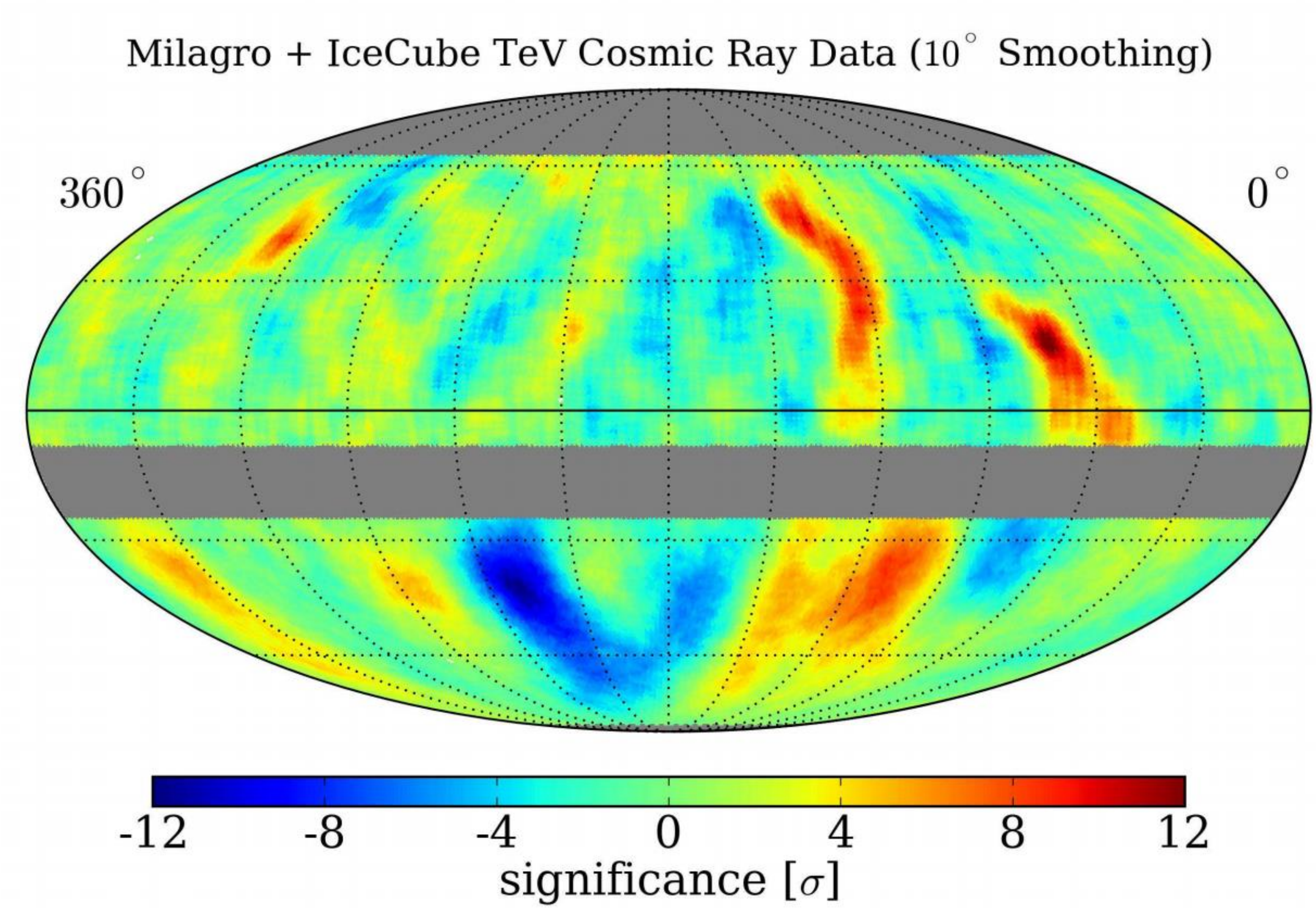
Charged particles produce Cherenkov/Fluorescence light in the atmosphere and in surface detectors

Charged pions from cosmic ray showers produce highly penetrating muons and neutrinos

Photons produce an electron/ photon (electromagnetic) cascade



Cosmic Ray Anisotropy

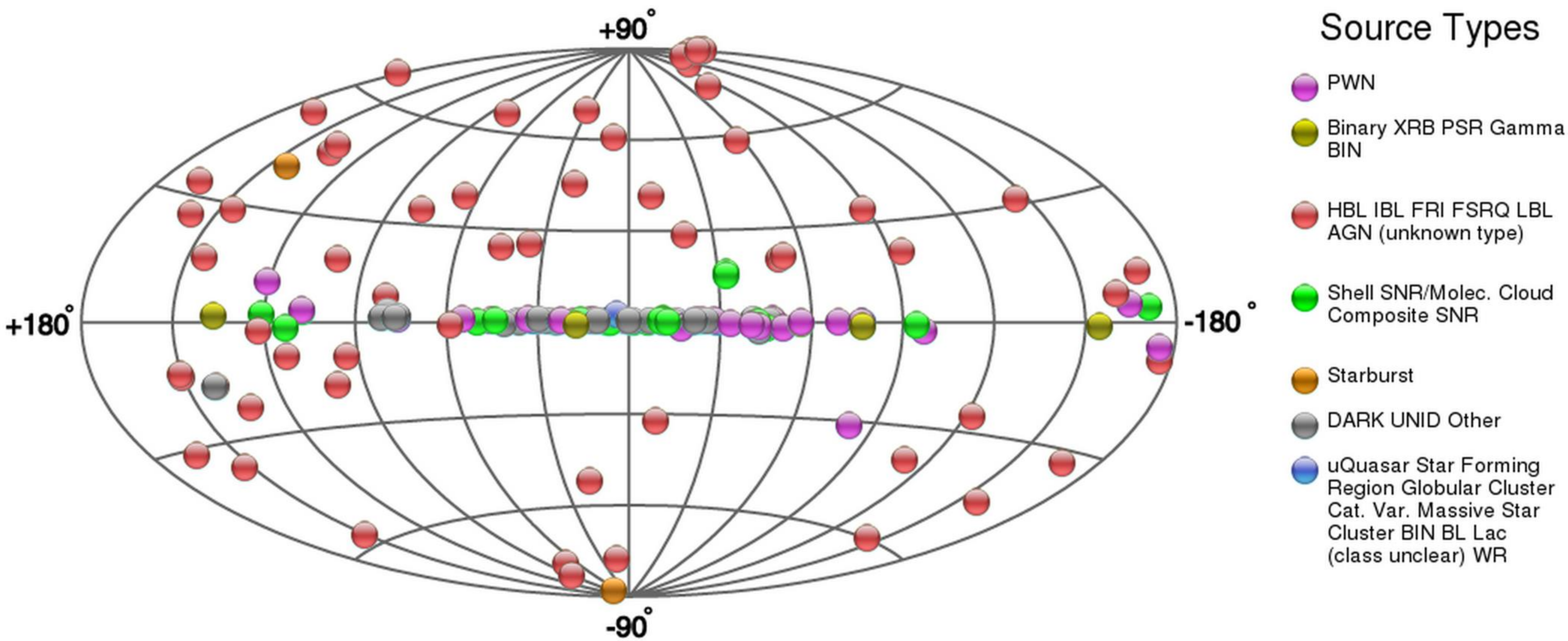


Anisotropy in cosmic ray arrival directions at ~TeV energies

Not yet understood

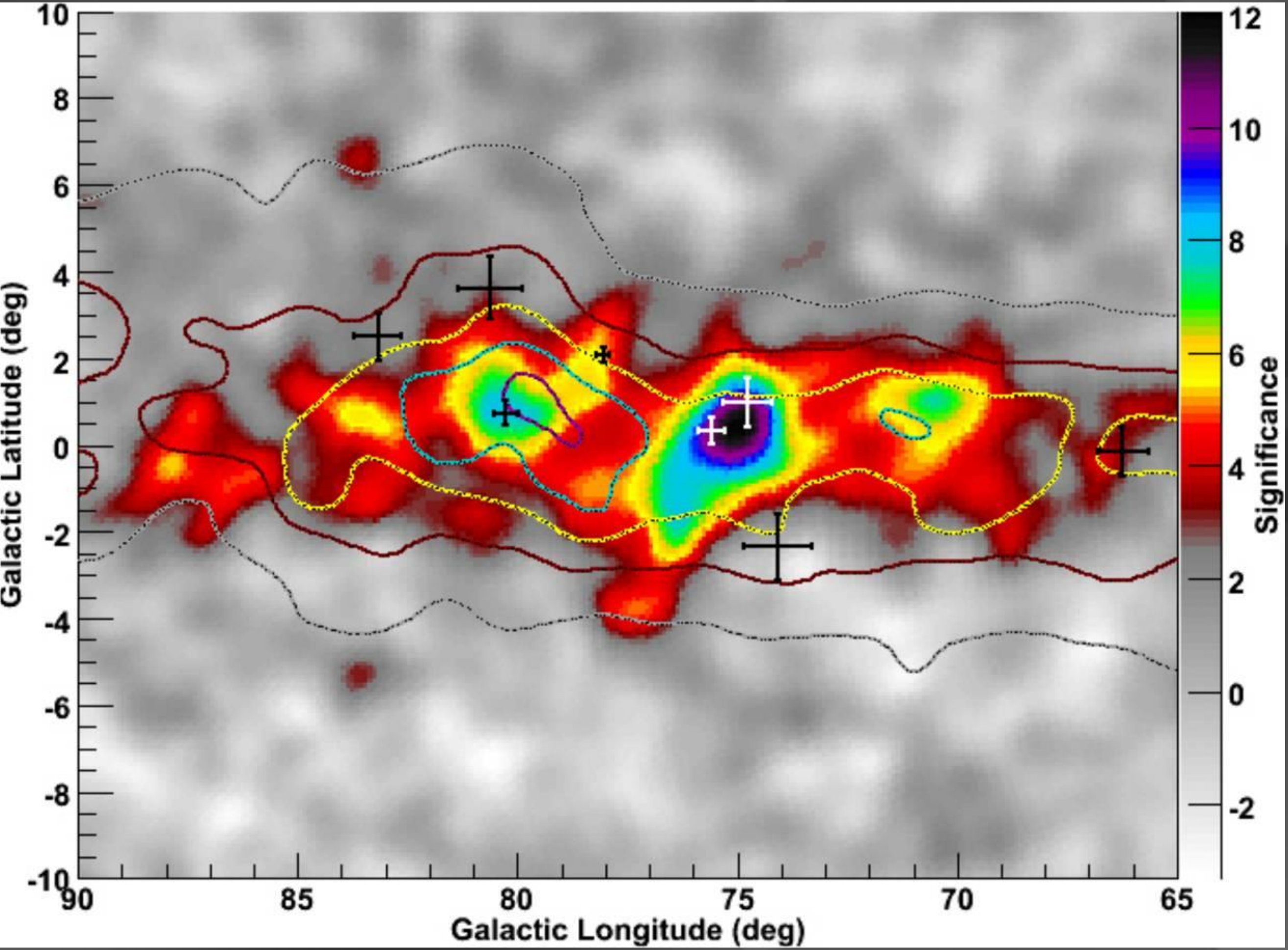
TeV Photon Astronomy

TeV Photon Astronomy



TeVCat: 148 Cataloged TeV photon sources

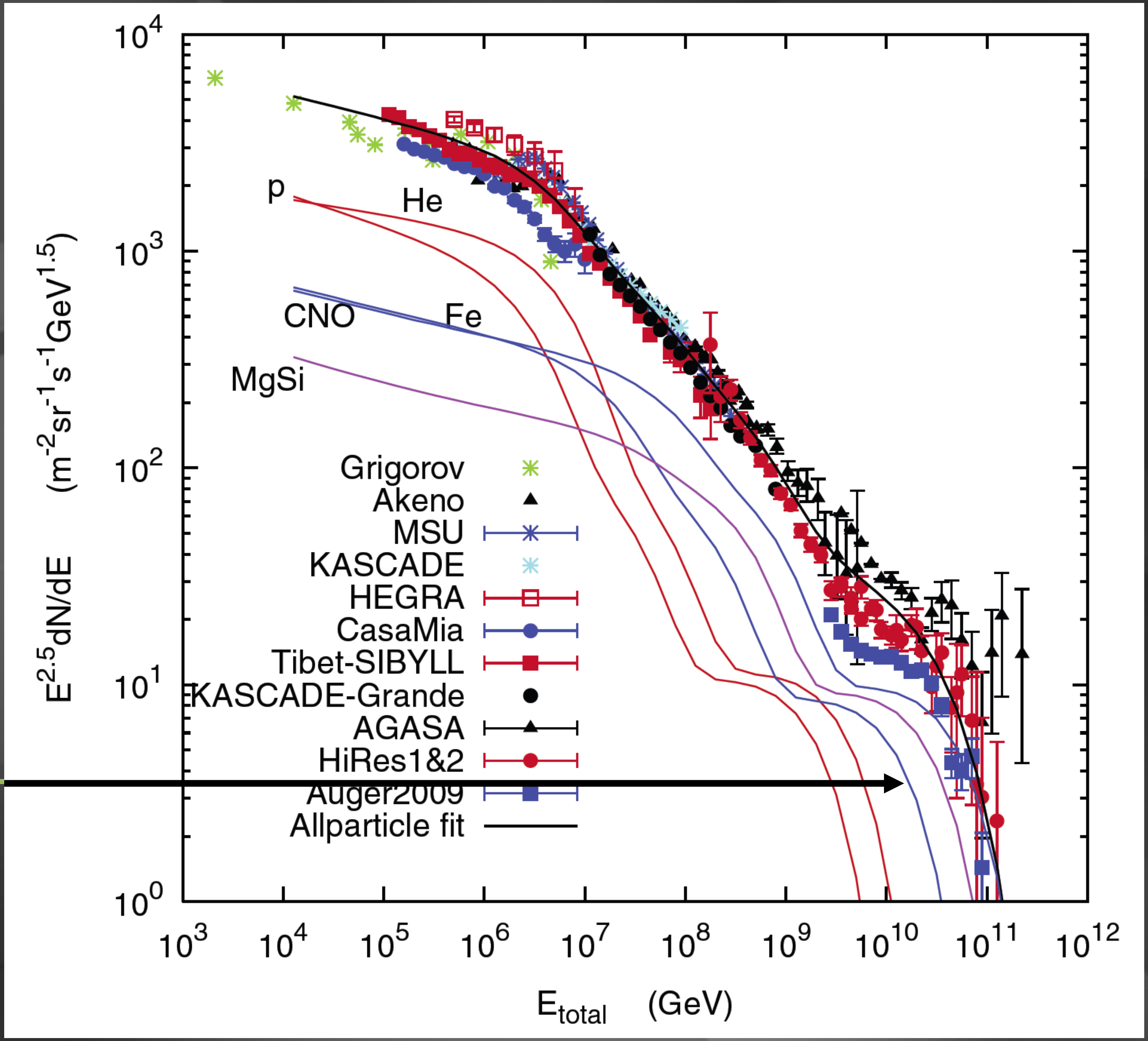
Cygnus region : Milagro



translation of
TeV gamma rays
into
TeV neutrinos :

3 ± 1 ν per year in IceCube per source

Galactic and extragalactic cosmic rays



GZK feature

cosmic rays interact with the microwave background

$$p+\gamma \rightarrow n+\pi^{+} \ and \ p+\pi^{0}$$

cosmic rays disappear, neutrinos appear

$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

...but it points at its source

Neutrino Astronomy

Observe neutrinos via weak interactions:

Neutral Current (NC): Z exchange

Hadronic cascade

Charged Current (CC): W exchange

Energetic cascade + lepton track

W production:

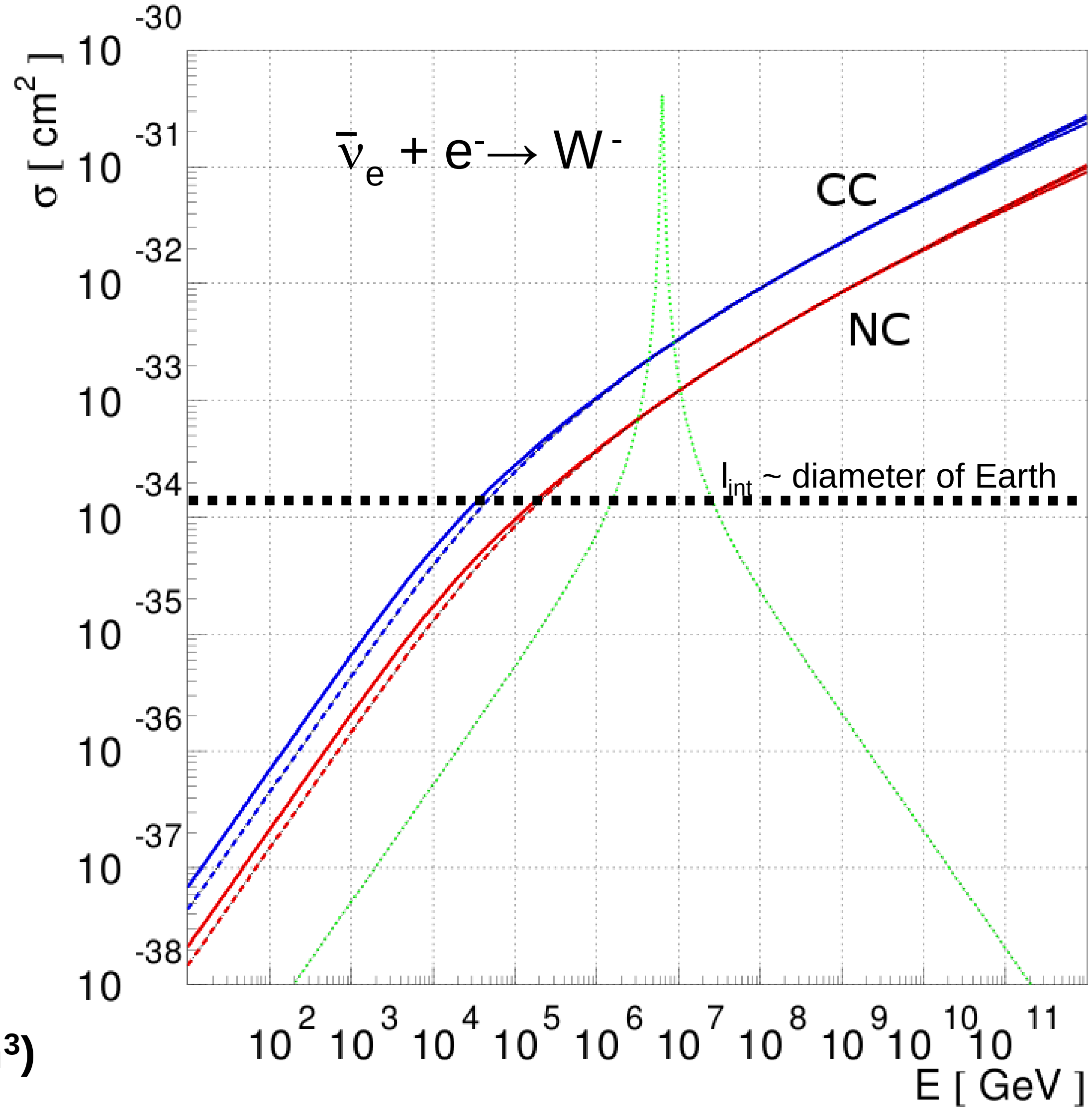
Cascades from electron antineutrinos

Glashow resonance at ~6.3 PeV

Interaction cross sections are tiny, but increase with energy

Observe cascades and tracks via Cherenkov emission

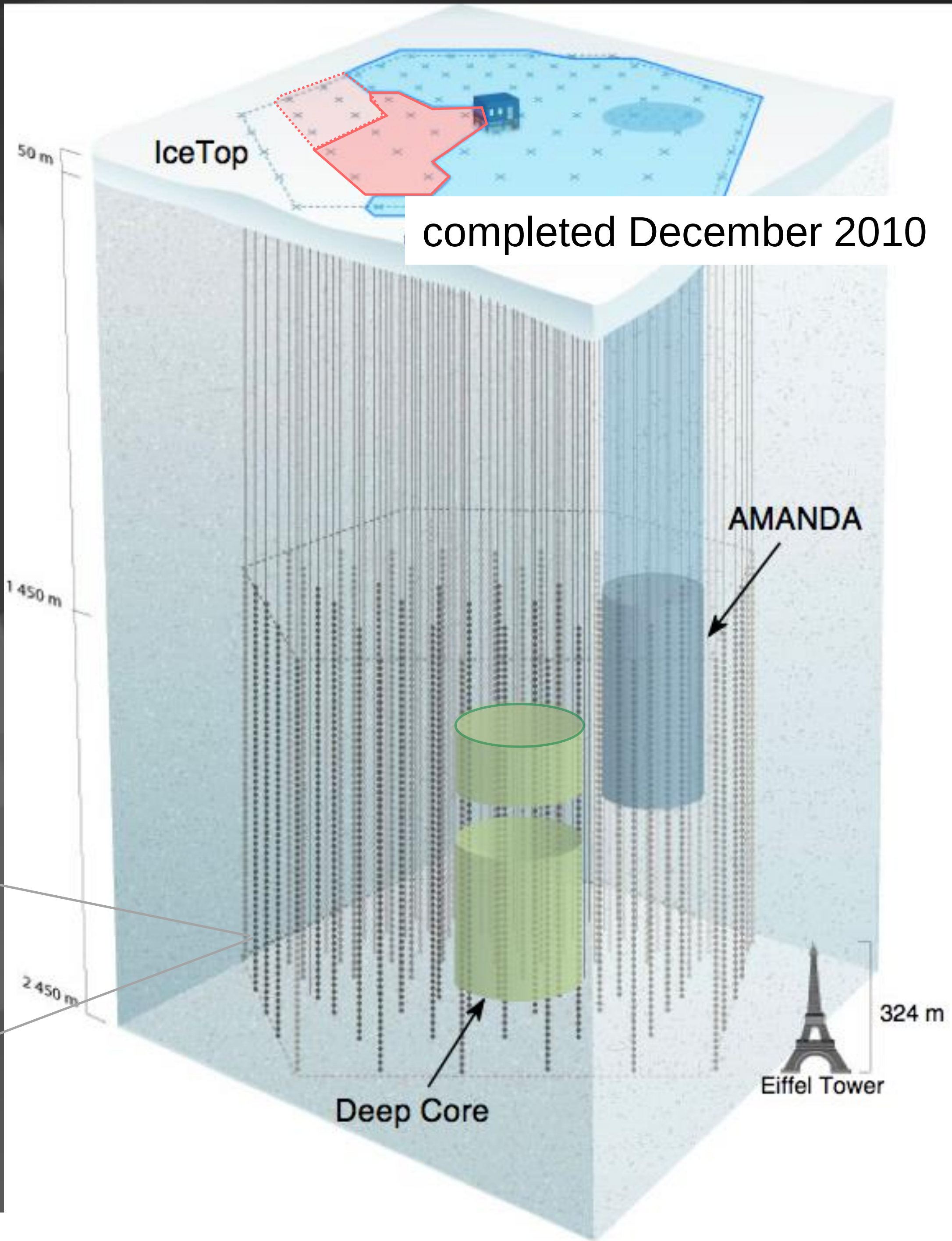
→ **Need large volume ~O(km³) of transparent medium**

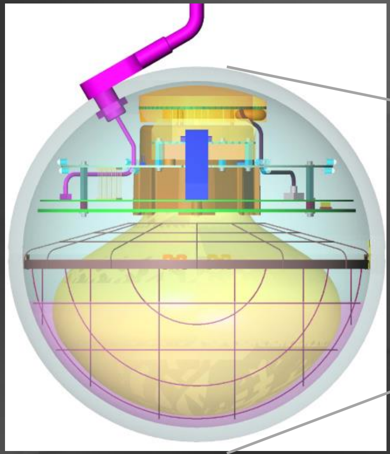


D. Chirkin, arXiv:hep-ph/0407075

IceCube / Deep Core

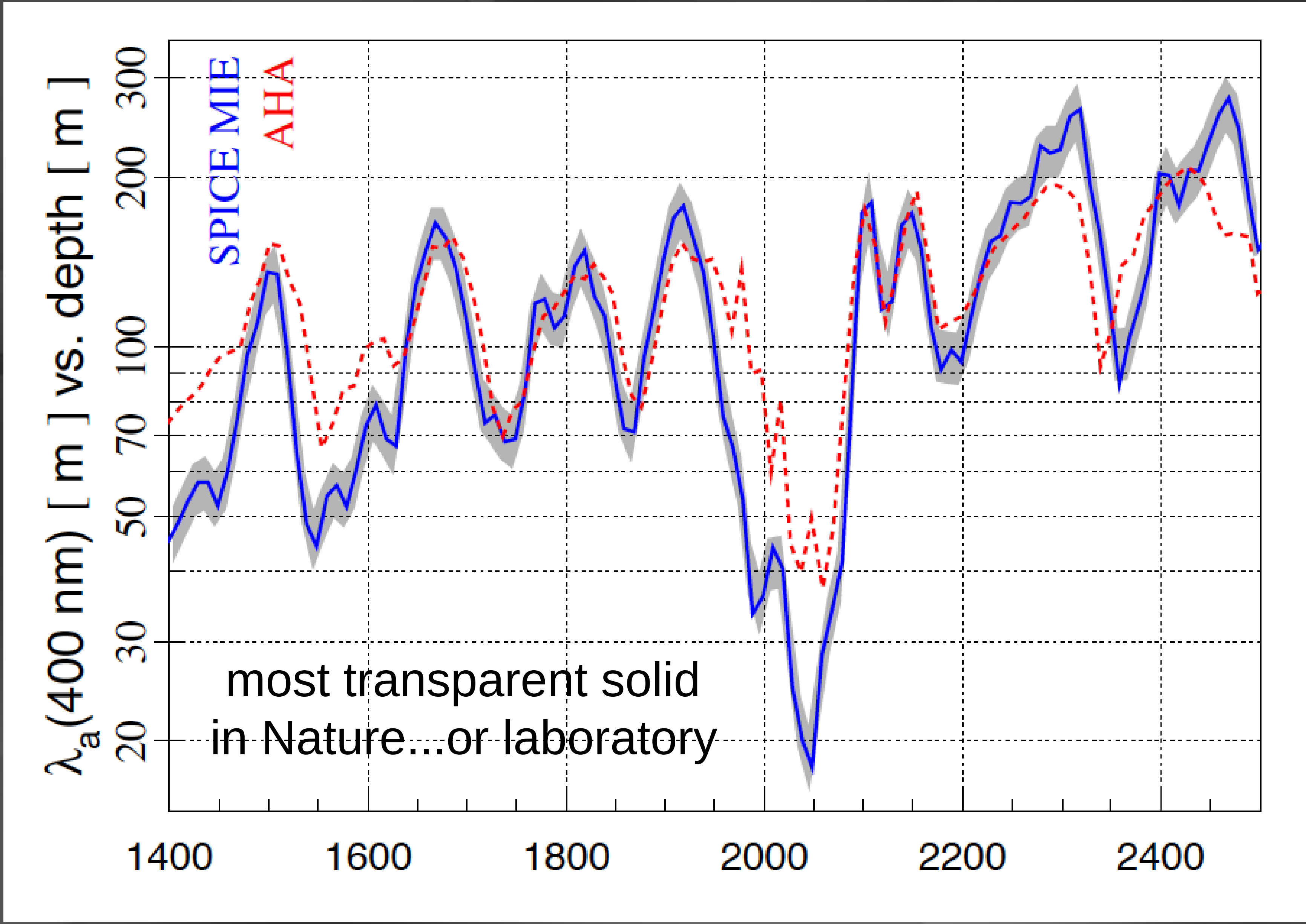
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity



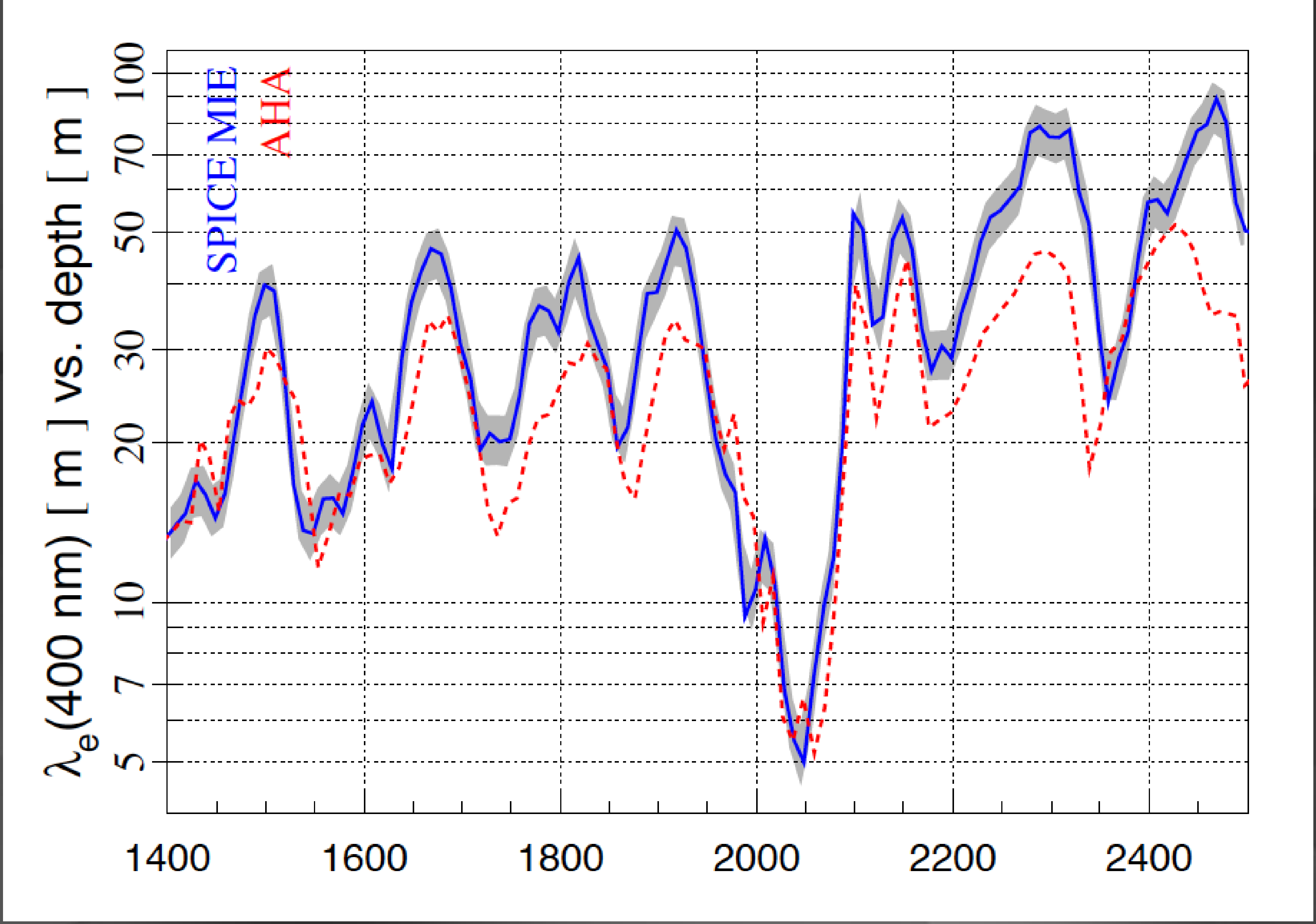


Digital Optical Module (DOM)

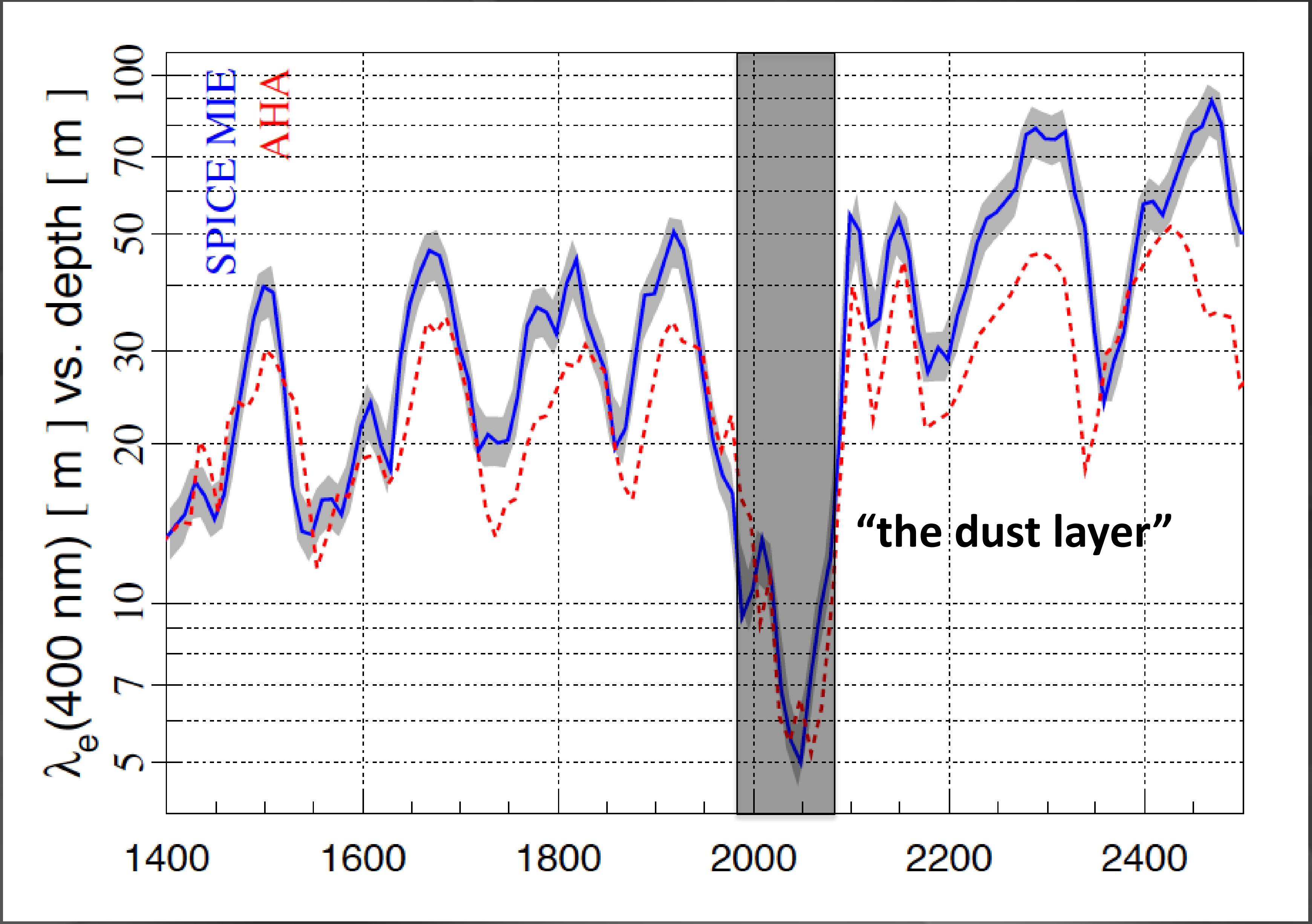
absorption length



scattering length

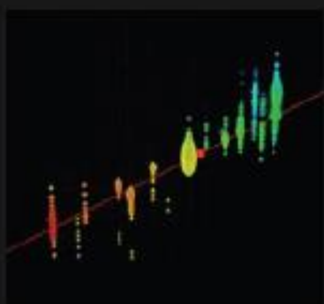


scattering length



Neutrino event signatures

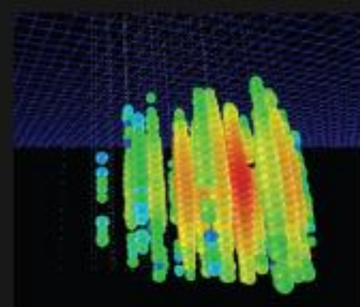
CC Muon Neutrino



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

track (data)

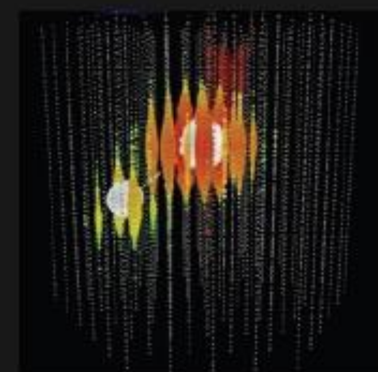
Neutral Current / Electron Neutrino



$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$
$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

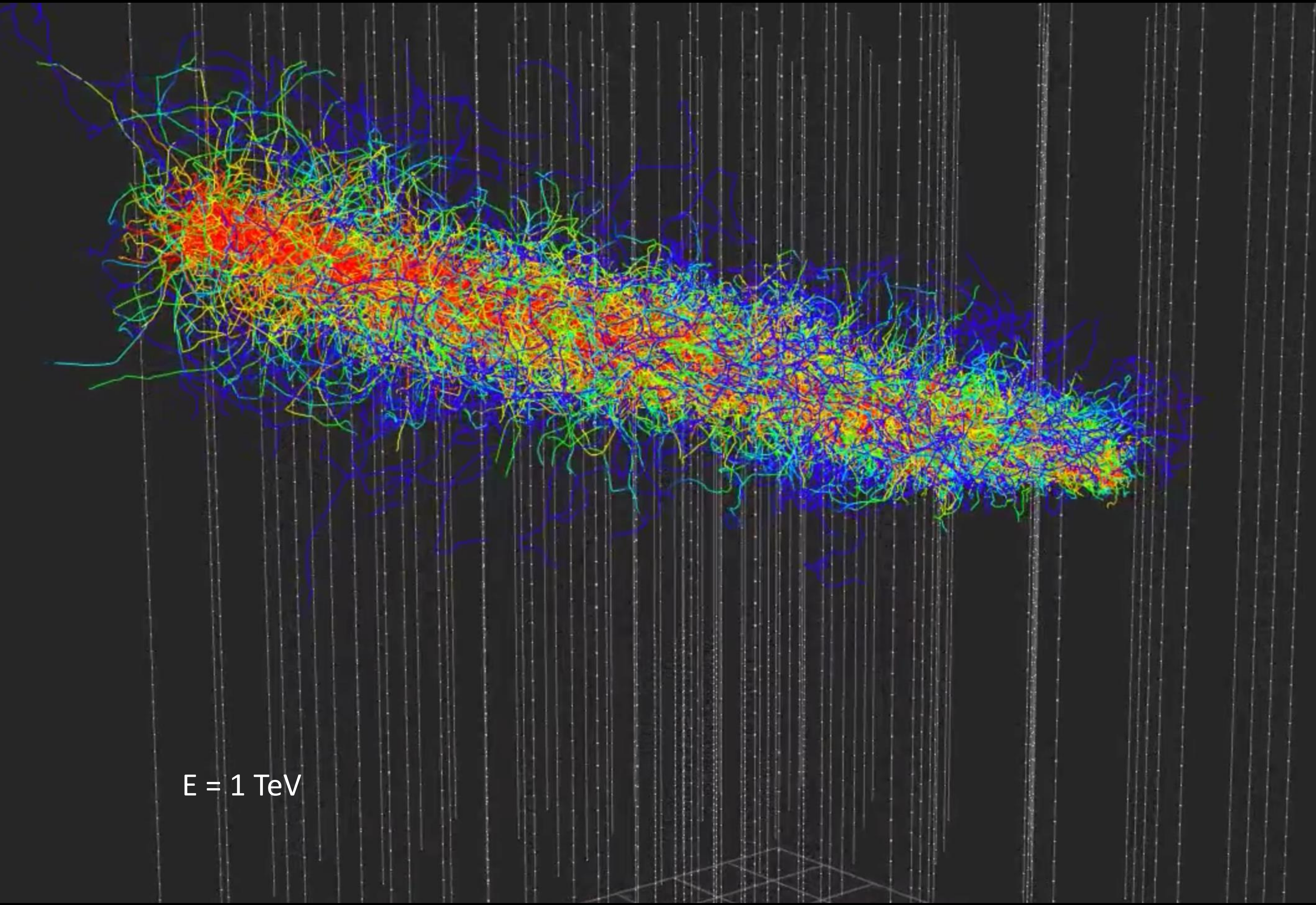
CC Tau Neutrino

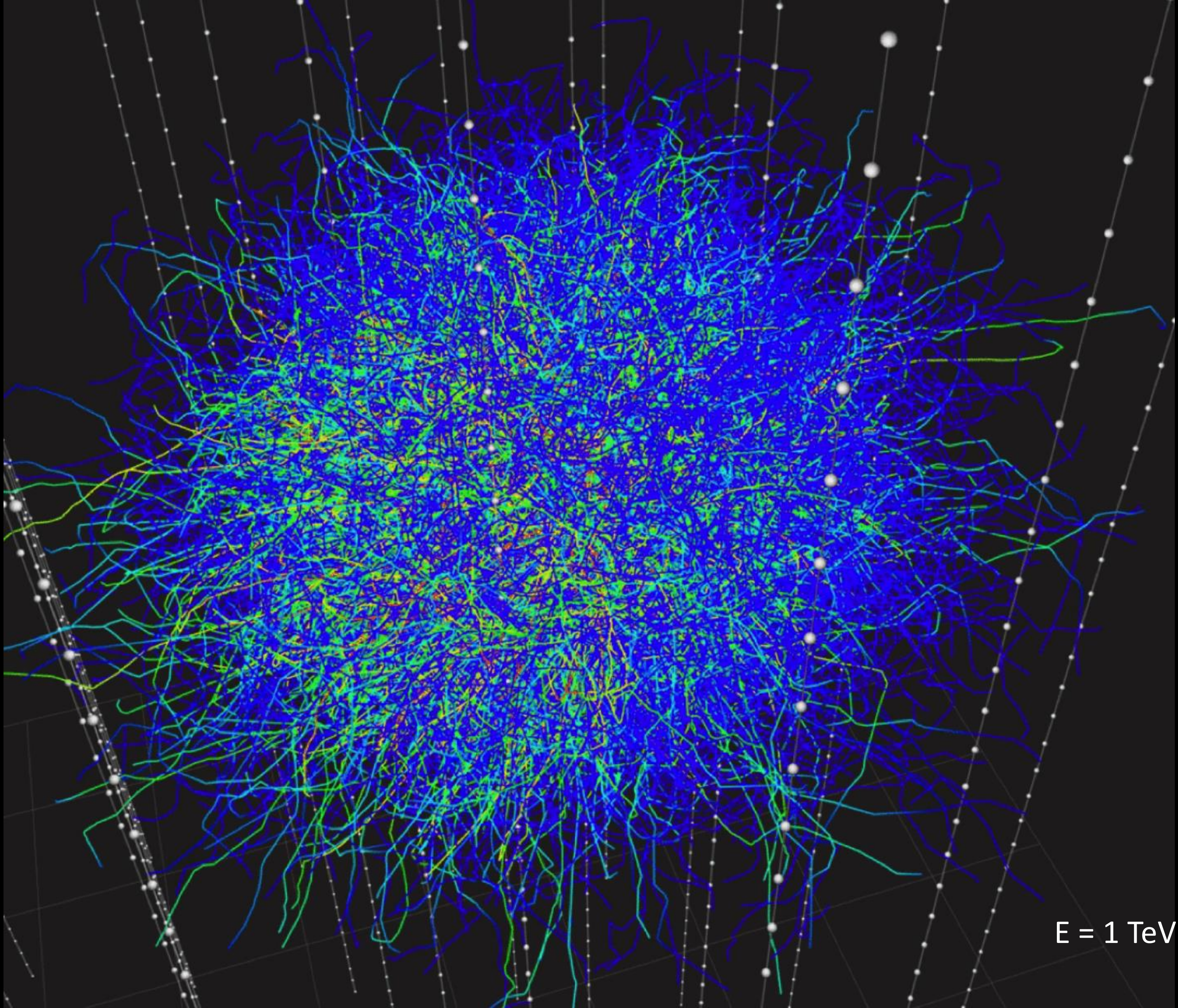


$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

PeV+; Not yet observed


E = 1 TeV


E = 1 TeV

Event Reconstruction

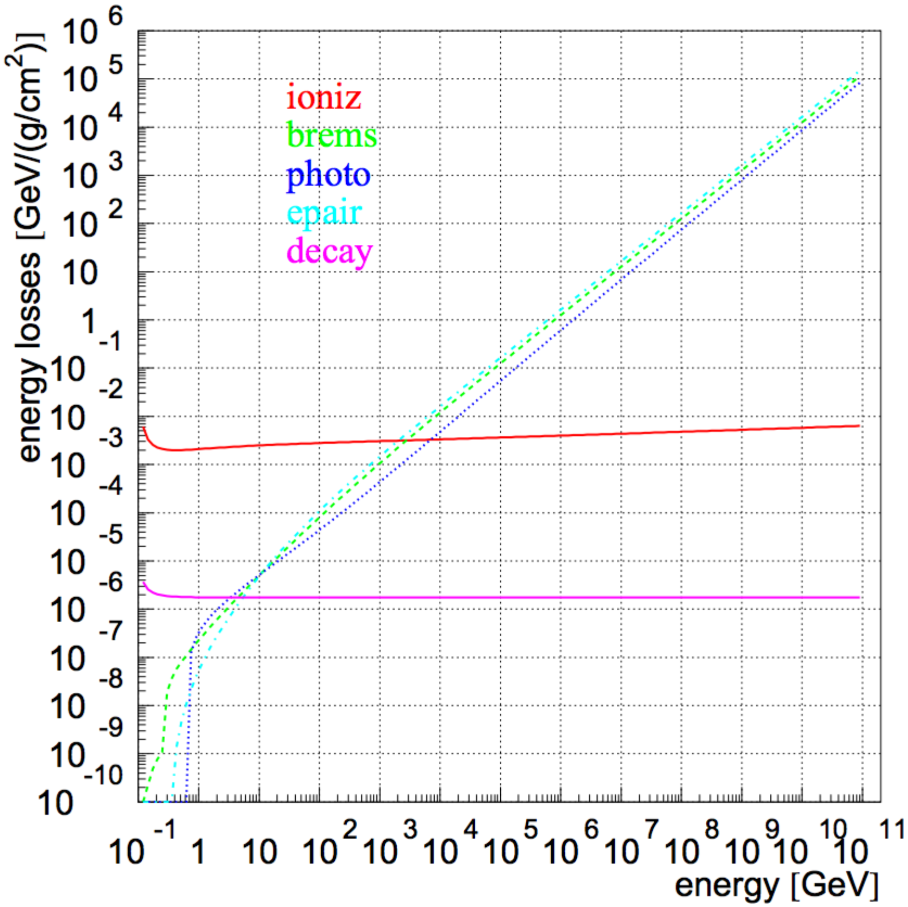
- **Angle reconstruction**: Fit photon arrival times to best track. Long tracks provide lever arm!
- **Energy Reconstruction**: Fit number and pattern of detected photons to best energy loss

Much more from Claudio on Thursday

Tracks	Cascades
Angle: 0.5˚ - 1˚	**Angle**: 15˚+
Energy: Factor of ~2	**Energy**: ~15%

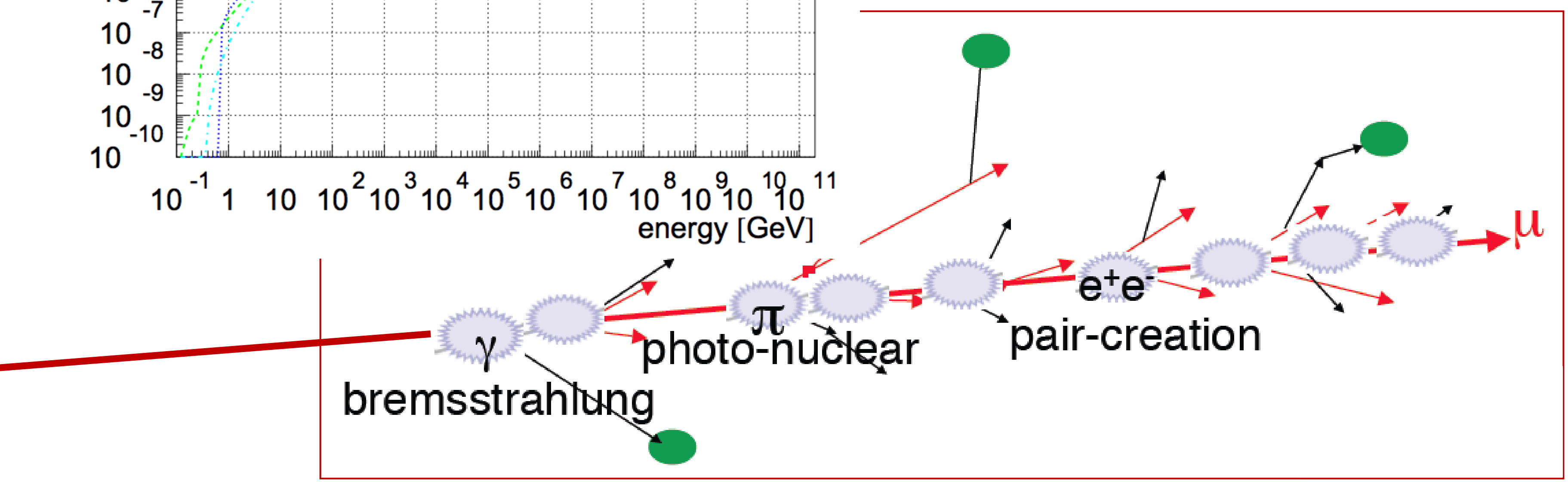
These analysis channels have very different characteristics!

Energy Reconstruction of Muons



Amount of light recorded is proportional to dE/dx

dE/dx proportional to E for E > ~TeV



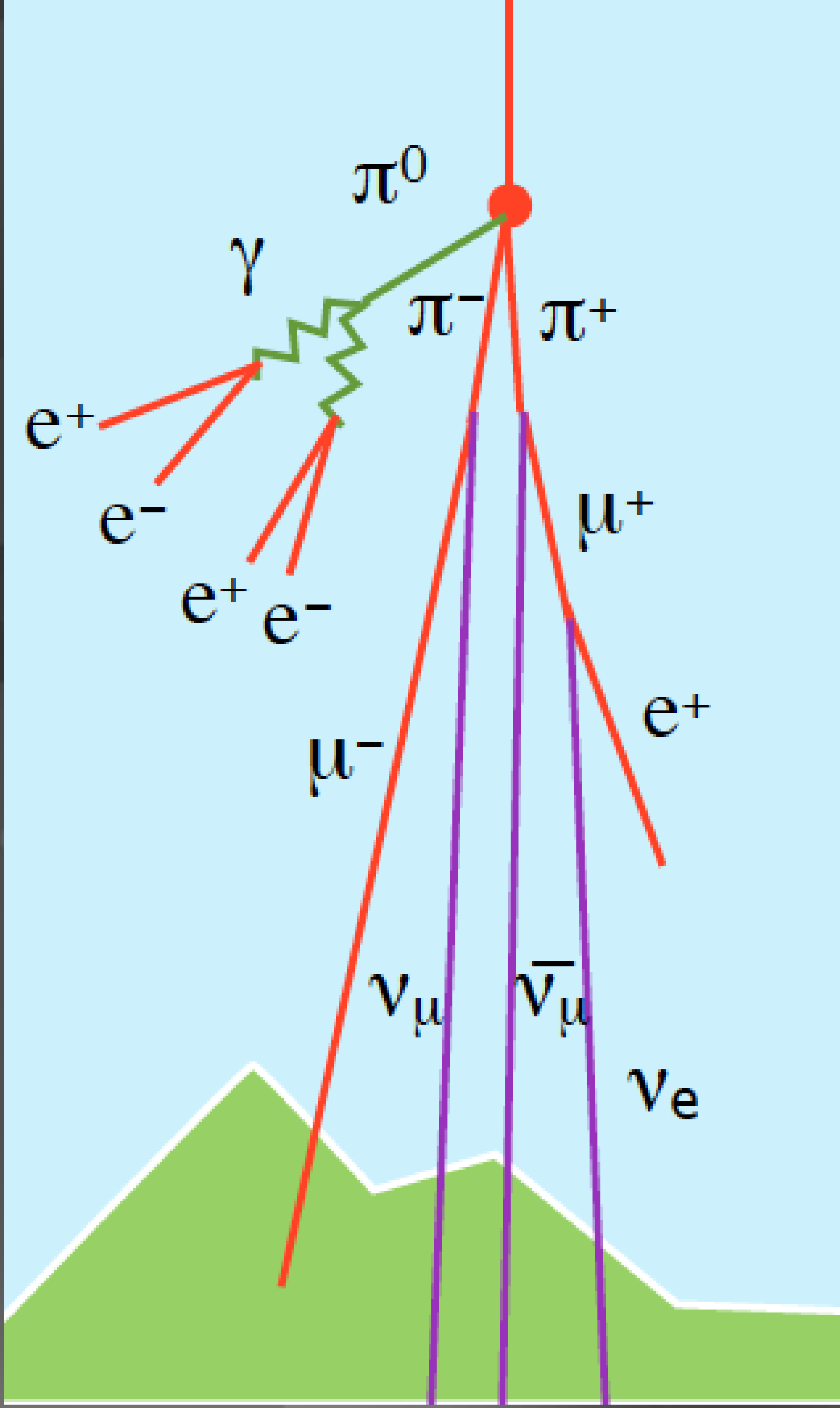
IceCube Events

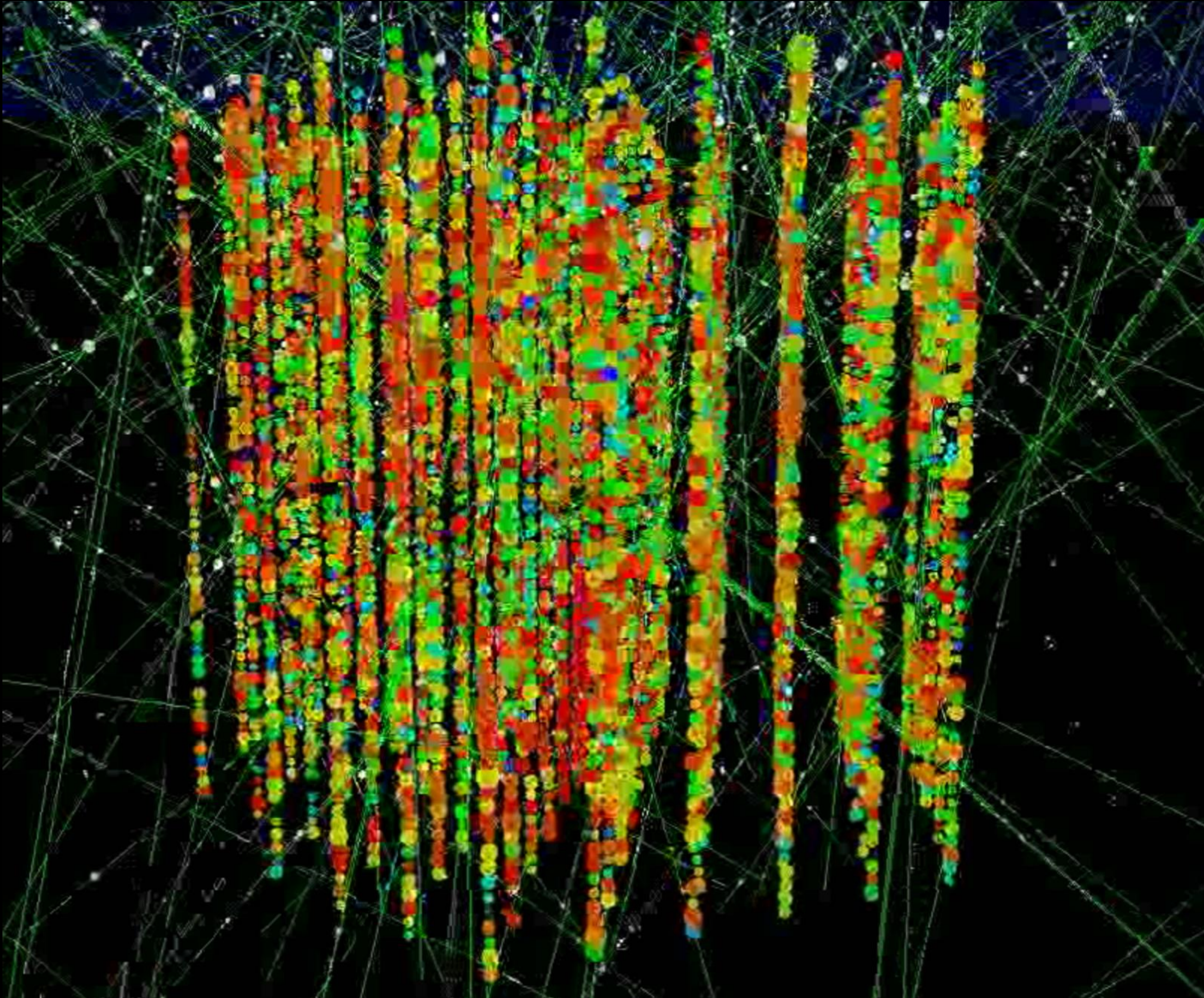
Most events are downgoing muons from cosmic ray air showers: 2.5 kHz

~few in 10^{-6} are muons from atmospheric neutrinos

~few in 10^{-10} are neutrinos from astrophysical sources

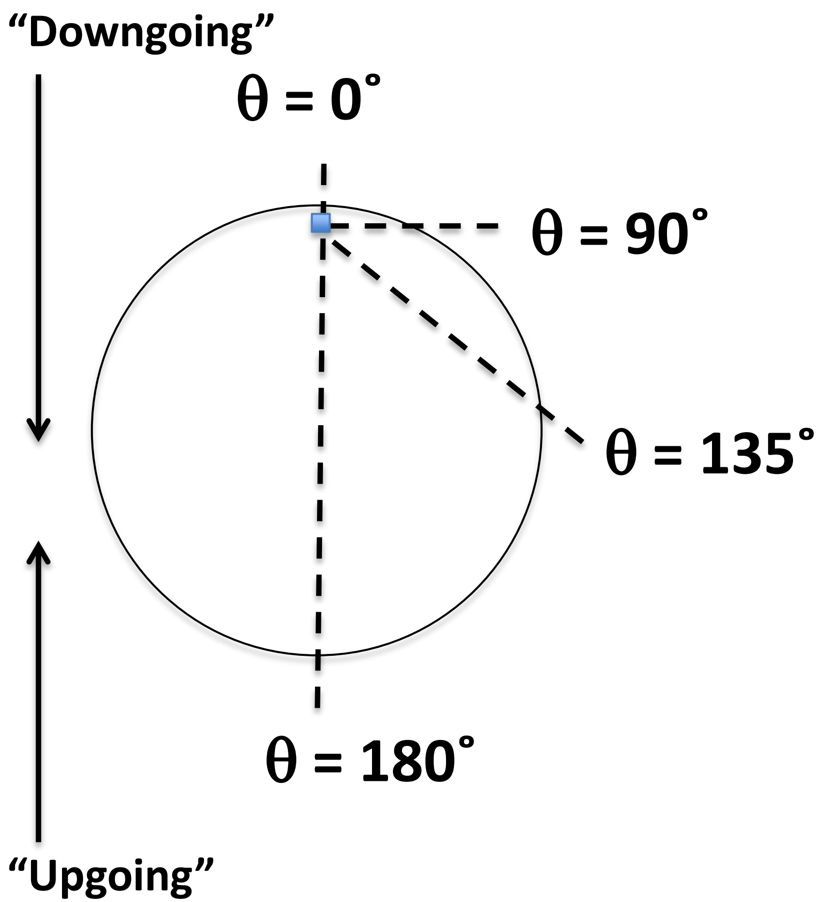
Goal: Isolate events from astrophysical sources

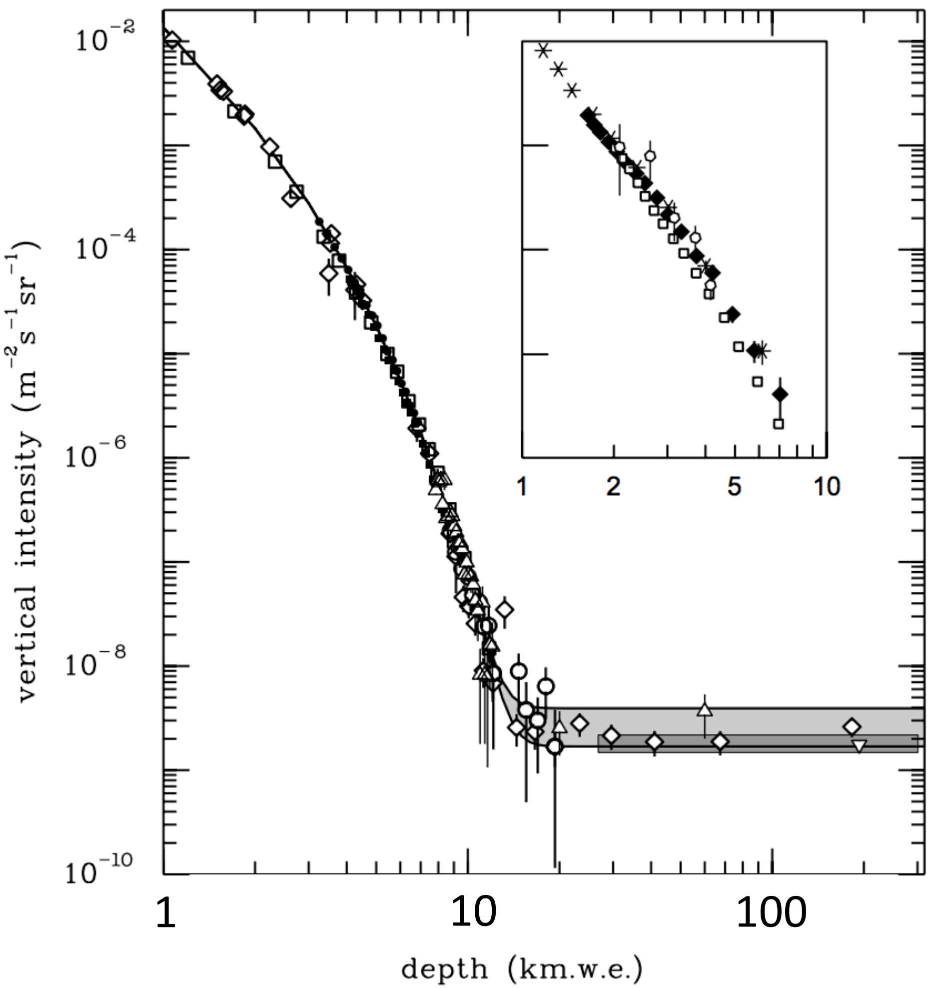




Earth Absorption

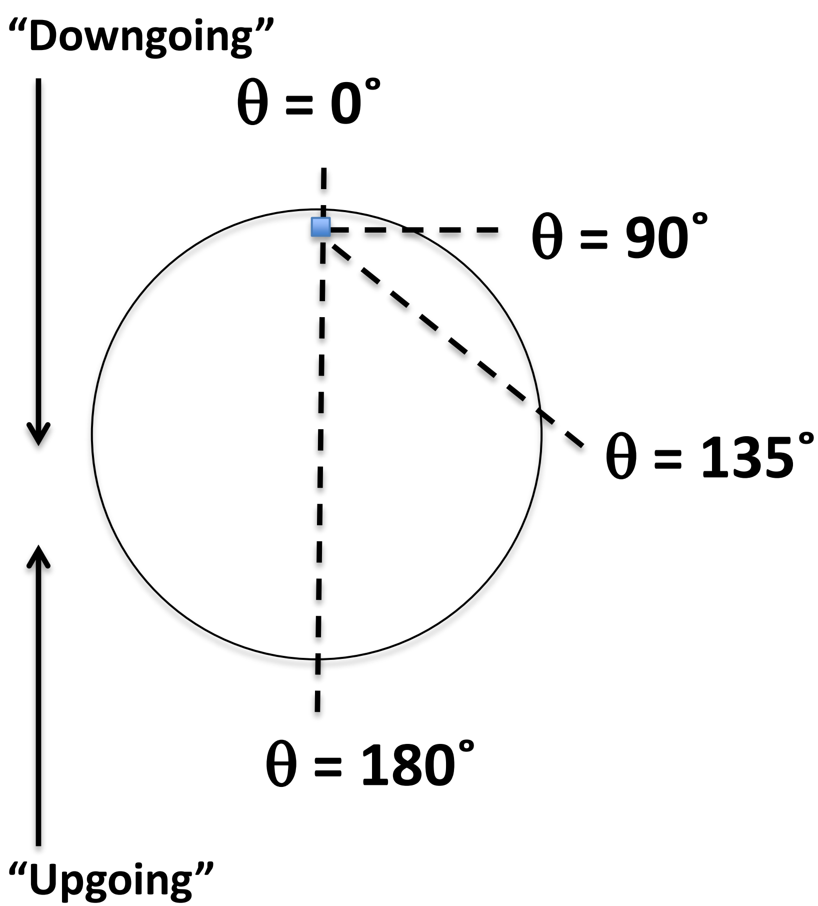
- **Cosmic ray muons only penetrate ~10 km and are absorbed for θ > 85˚**

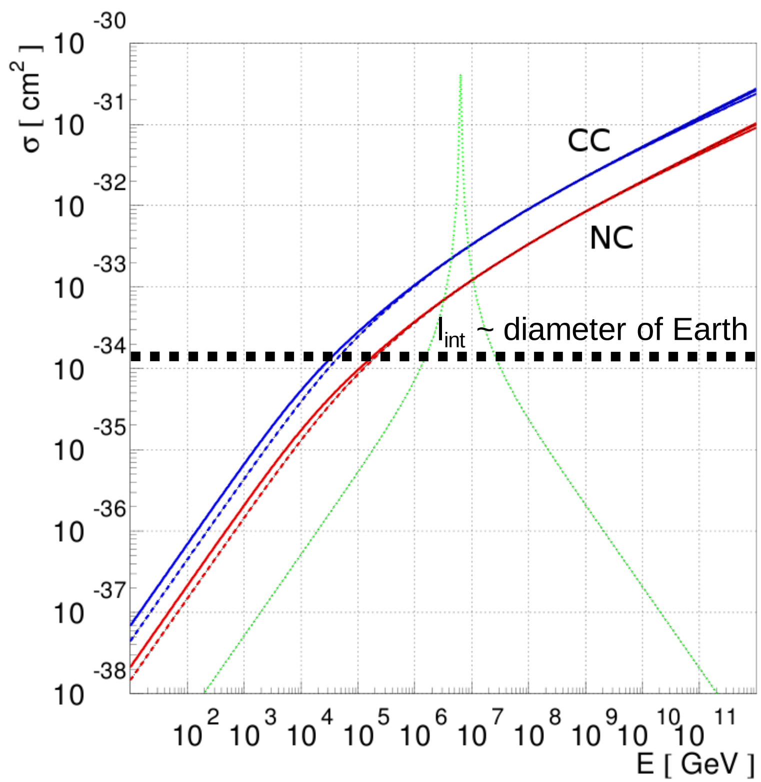




Earth Absorption

- **Cosmic ray muons only penetrate ~10 km and are absorbed for θ > 85˚**





- **PeV neutrinos are absorbed for θ > ~135˚**
- **Attenuation energy for θ = 180˚ is ~30 TeV**

Reducing the Cosmic Muon Background

- **Zenith angle (θ):** Cosmic ray muons cannot reach IceCube for $\theta > 85^\circ$
  - Tails of point-spread function (PSF) are large
  - Quality cuts required to eliminate misreconstructed upgoing events

- **Topology:** Cascades or muons that start inside the detector must be from neutrinos
  - Requires implementation of a veto/filter to exclude throughgoing events

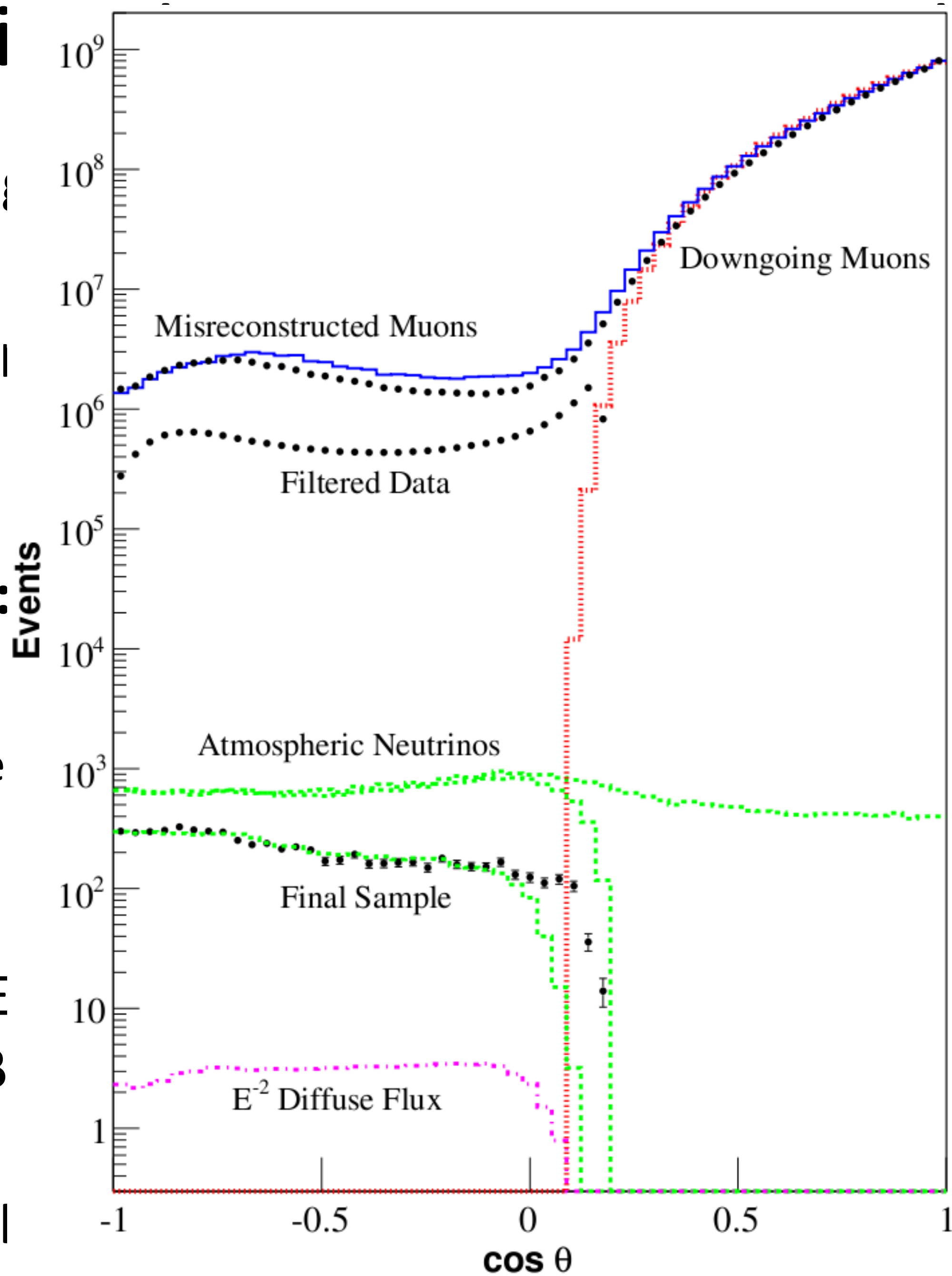
- **Energy:** Expect $E^{-2} – E^{-2.6}$ for astrophysical neutrinos
  Backgrounds fall much more sharply ($\sim E^{-3.7}$)

Optimize selection using simulated data

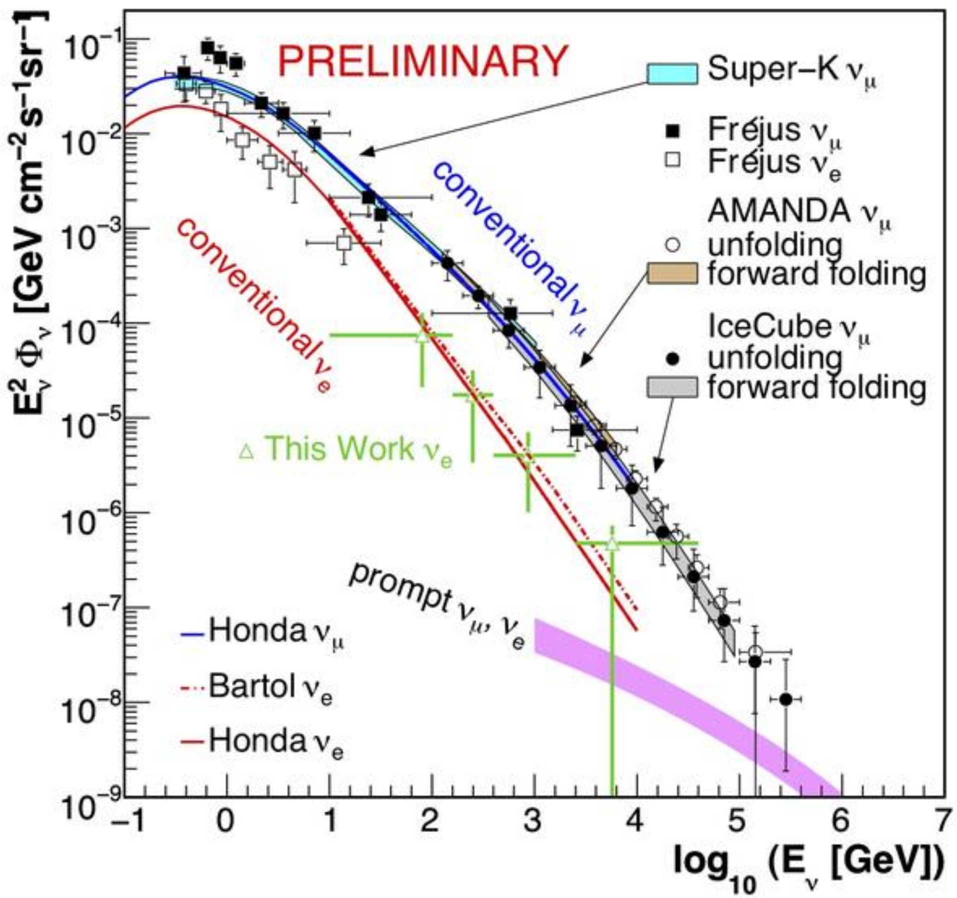
Reduci kground

- **Zenith an** ach IceCube
  - Tails of ı
  - Quality ed events
- **Topology:** the detector
  - Require roughgoing events
- **Energy:** E nos. B $^{-3.7}$)

O|



Atmospheric Neutrinos

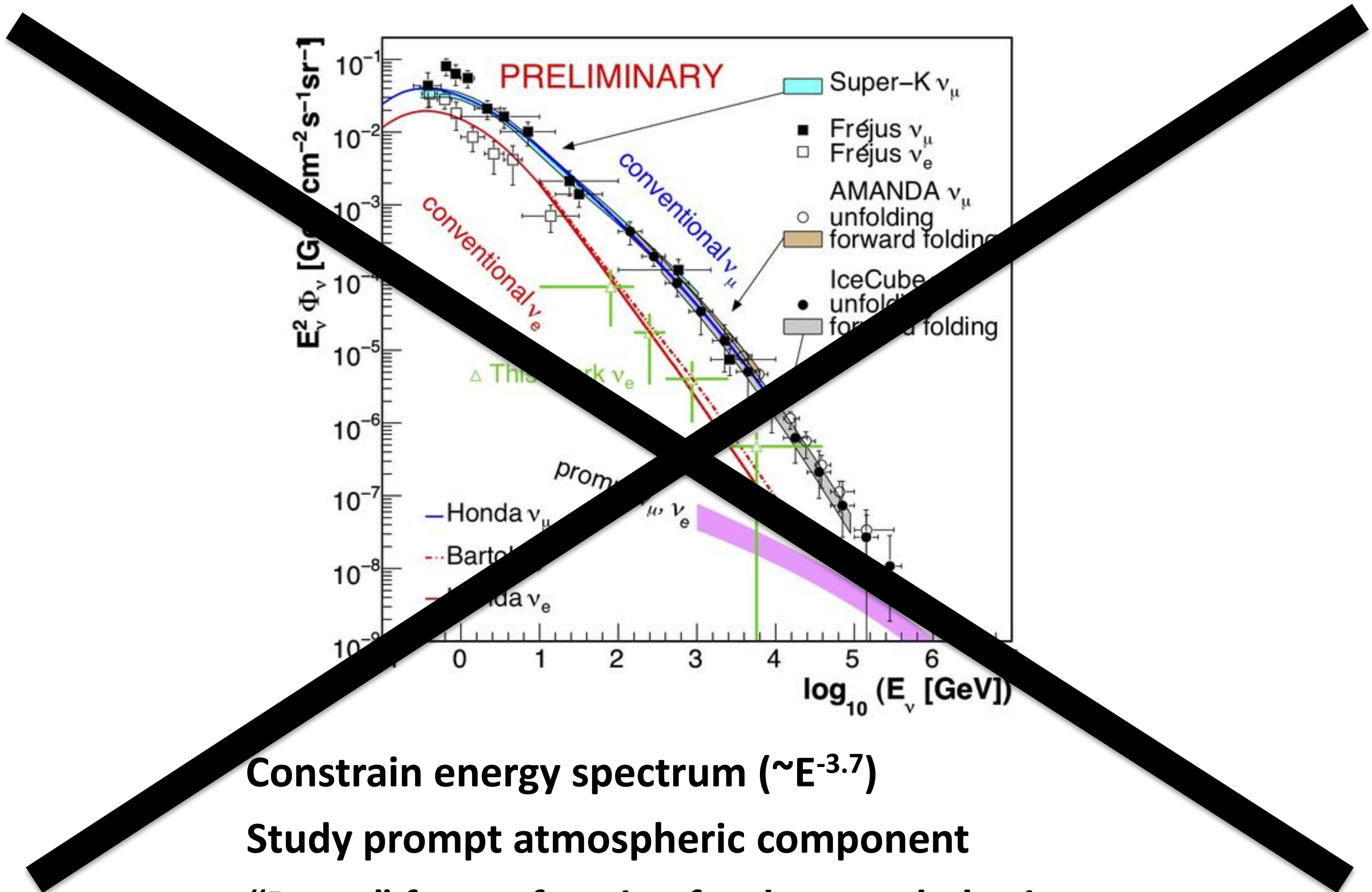


Constrain energy spectrum (~$E^{-3.7}$)

Study prompt atmospheric component

“Beam” for performing fundamental physics

Atmospheric Neutrinos



Constrain energy spectrum (~$E^{-3.7}$)

Study prompt atmospheric component

“Beam” for performing fundamental physics

Further Reduction of Background Events

- **Energy:** Expect $E^{-2} – E^{-2.6}$ for astrophysical neutrinos. Backgrounds fall much more sharply ($\sim E^{-3.7}$)
- **Space Angle:** Expect astrophysical neutrinos to cluster around source direction according to the detector PSF
- **Time:** In the case of a burst or flare, expect time dependence in neutrinos produced by the source

Analysis Type	Energy	Space Angle	Time
Diffuse	**X**		
Point Source	**X**	**X**	
Time-dep. point source	**X**	**X**	**X**

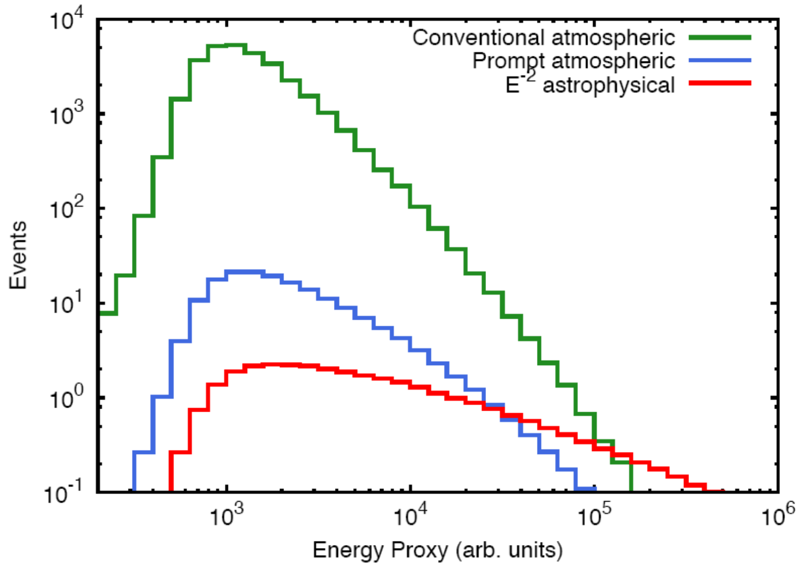
Diffuse Analysis

- Search for an astrophysical neutrino flux
  - Do not care where the neutrinos come from
  - Use various techniques to reduce the background:
    - Upgoing muons, cascades, high energy starting events (HESE)
- Isolate astrophysical component using event energy:
  - Events more closely matching an ~E^{-2} spectrum are more likely to be from the source

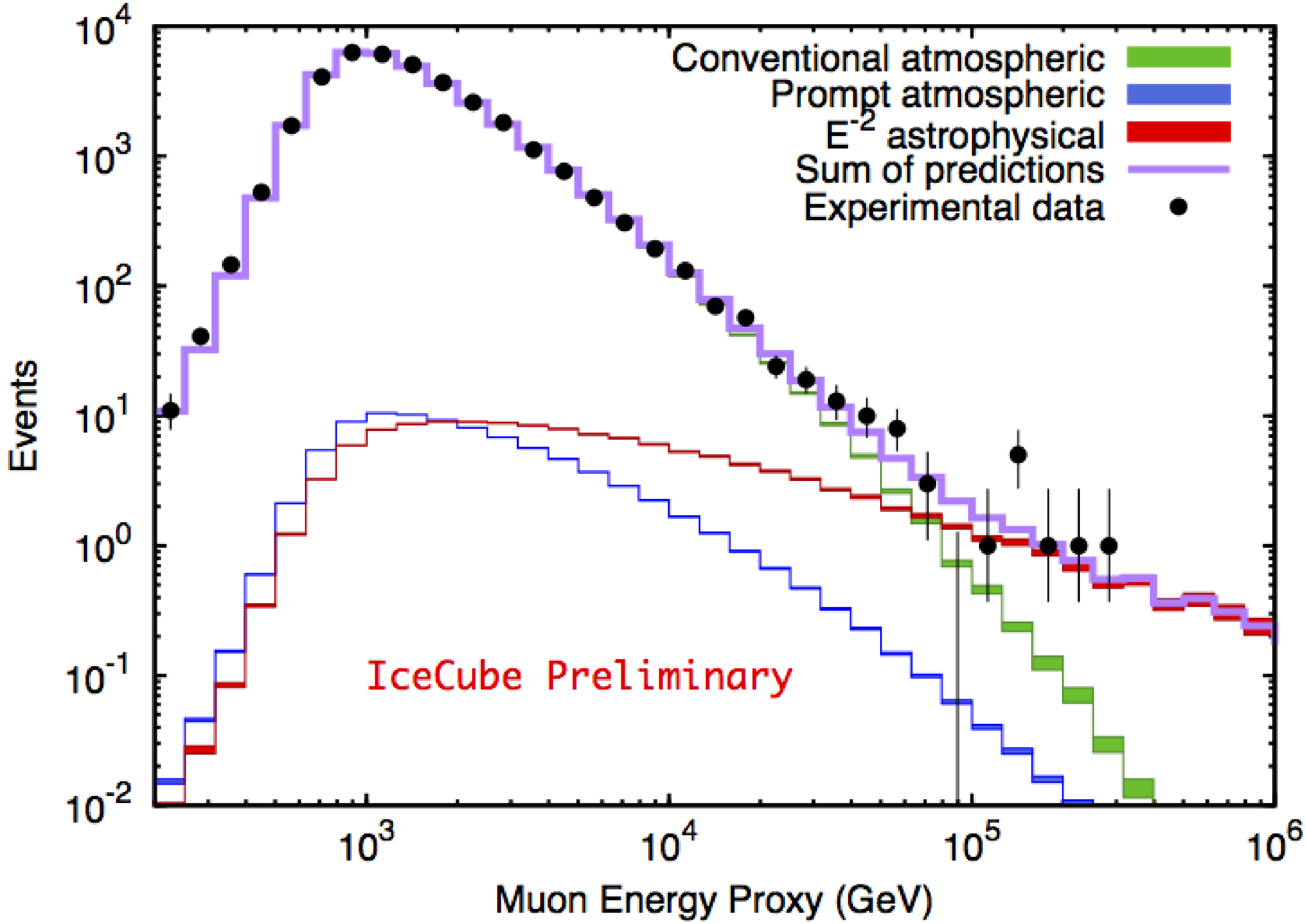
Fit data set to atmospheric + E^{-2} to determine the astrophysical flux

Compare to fit with no E^{-2} component to determine significance

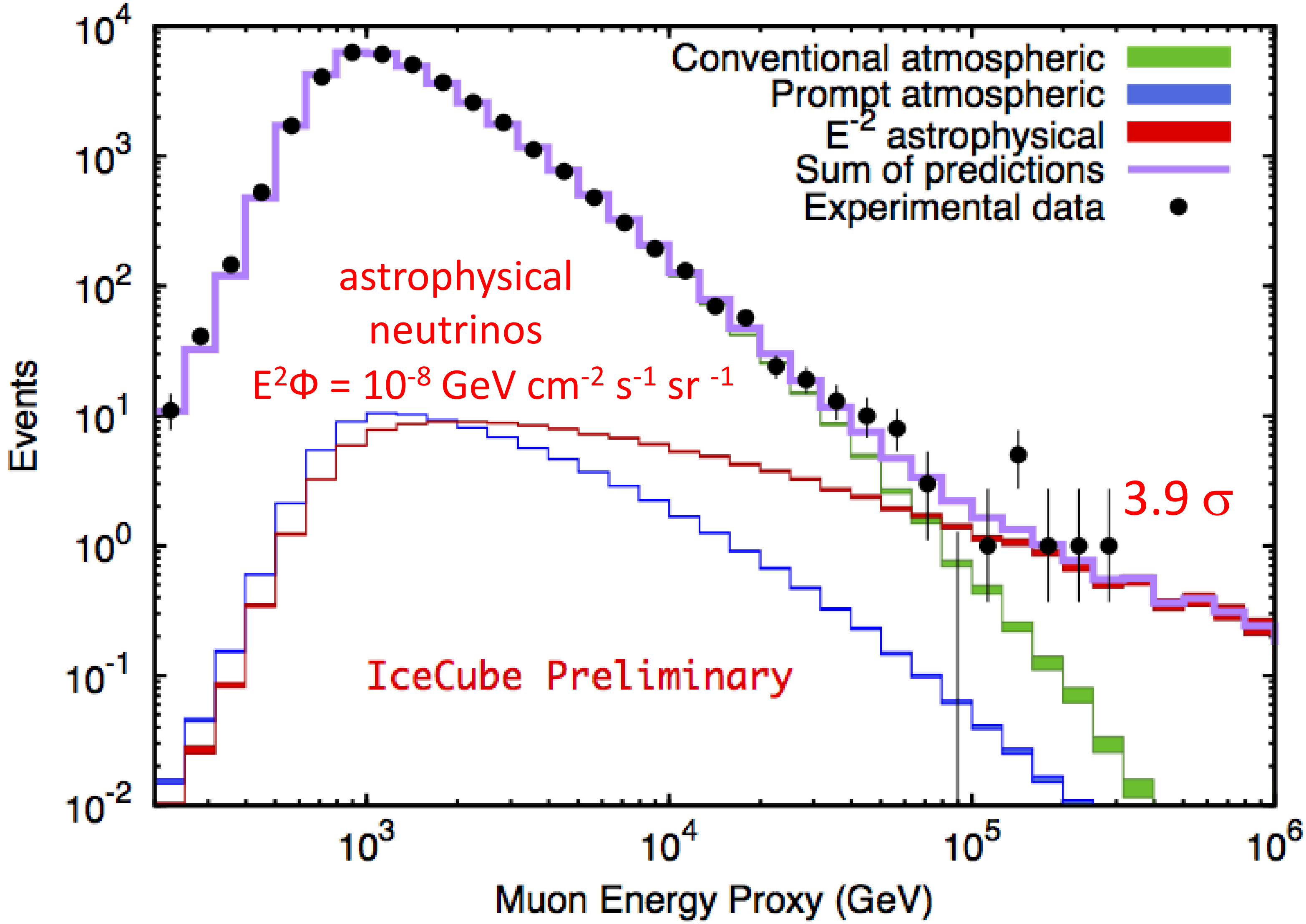
Dependent on simulated data and sensitive to systematics



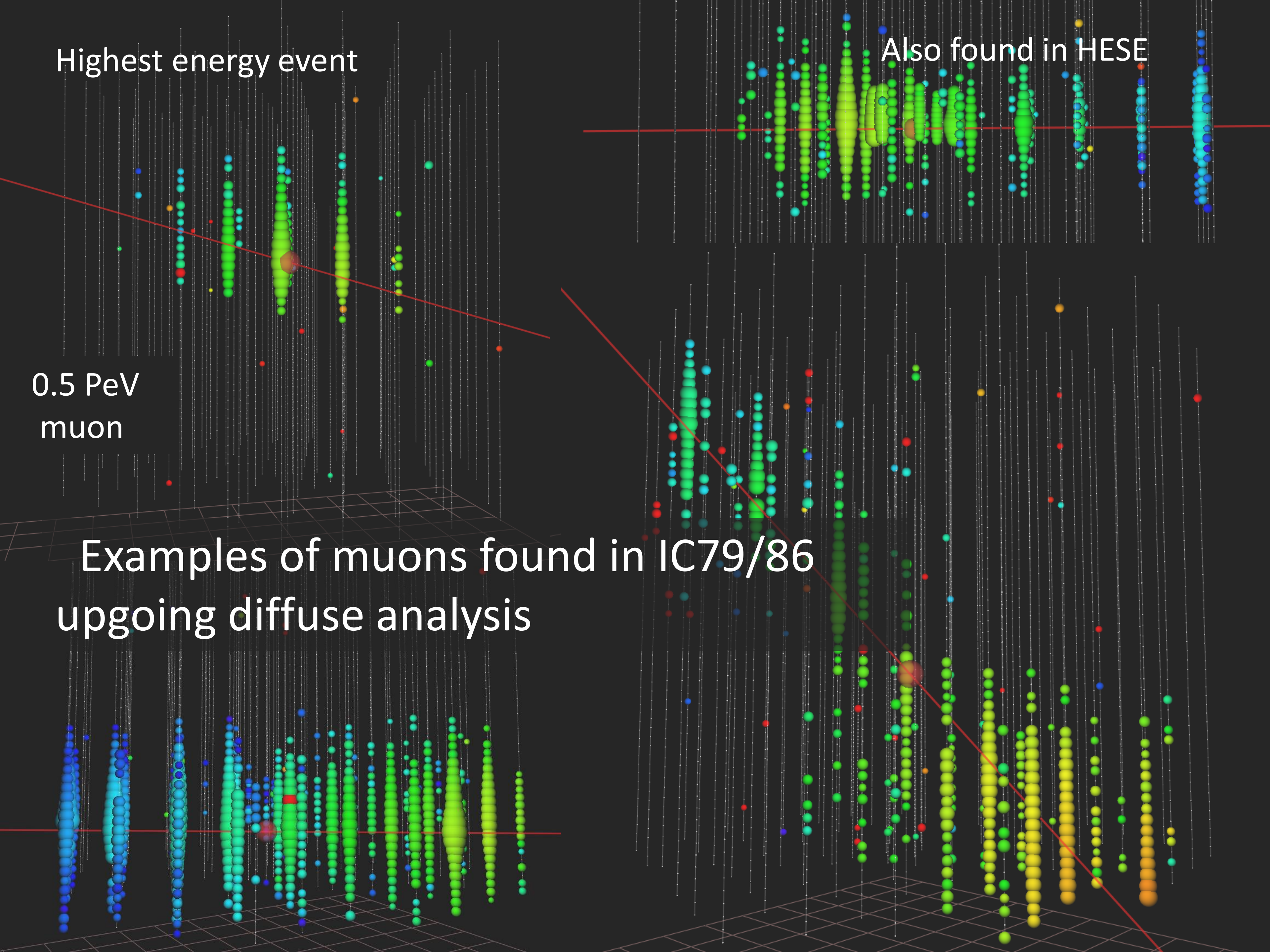
Upgoing Muon Analysis



Upgoing Muon Analysis

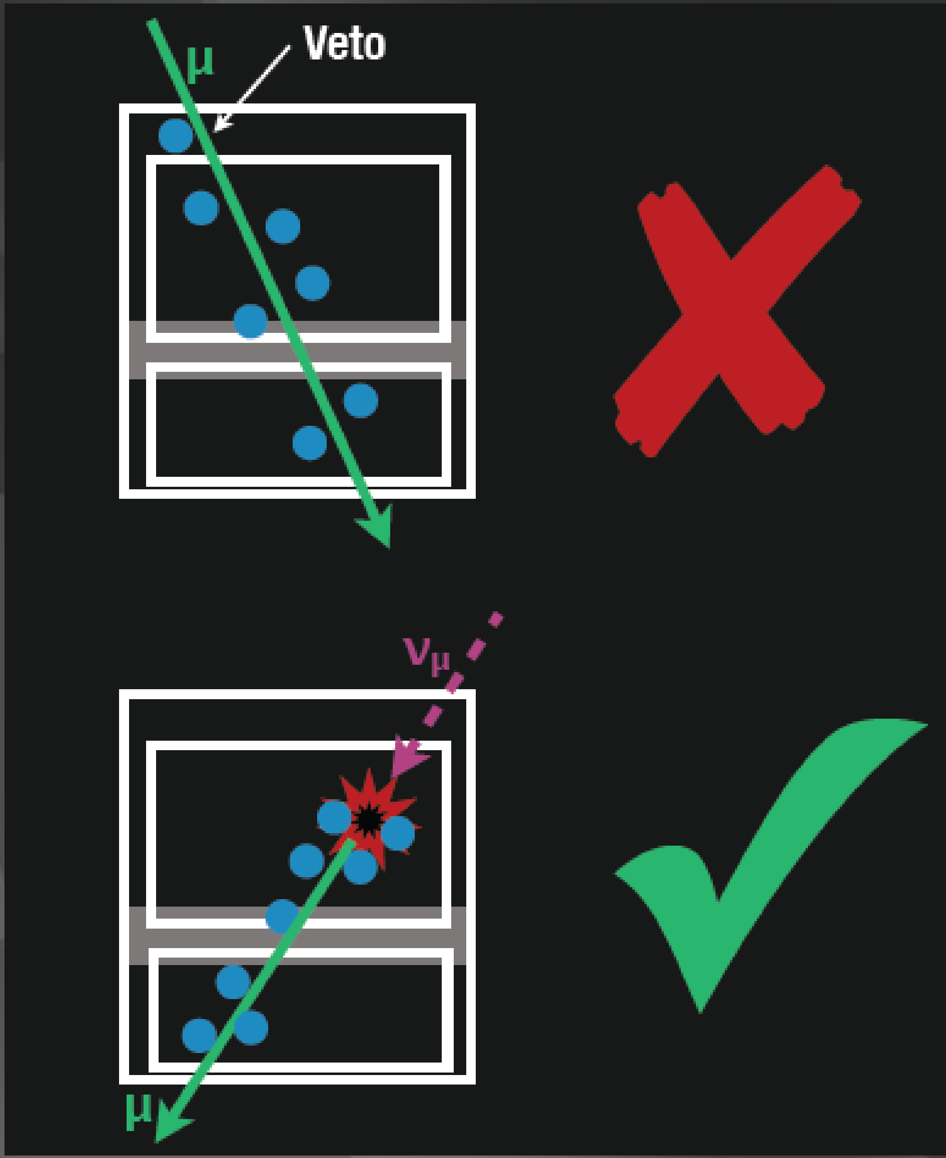


Examples of muons found in IC79/86 upgoing diffuse analysis

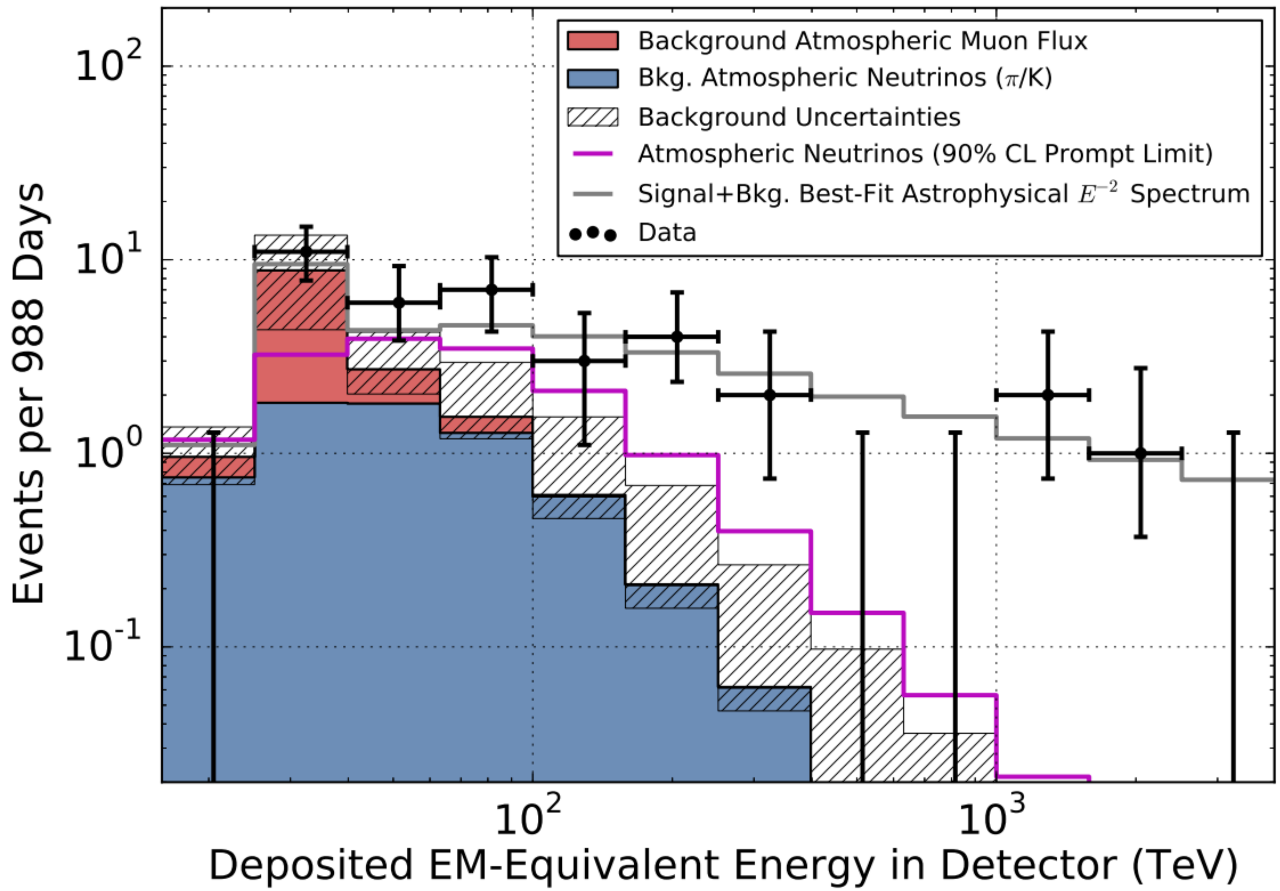


HESE: High-energy starting events

- Complete sky coverage
- Flavor determined
- Some will be muon neutrinos with good angular resolution



3-Year HESE Results: IC-79 + IC-86

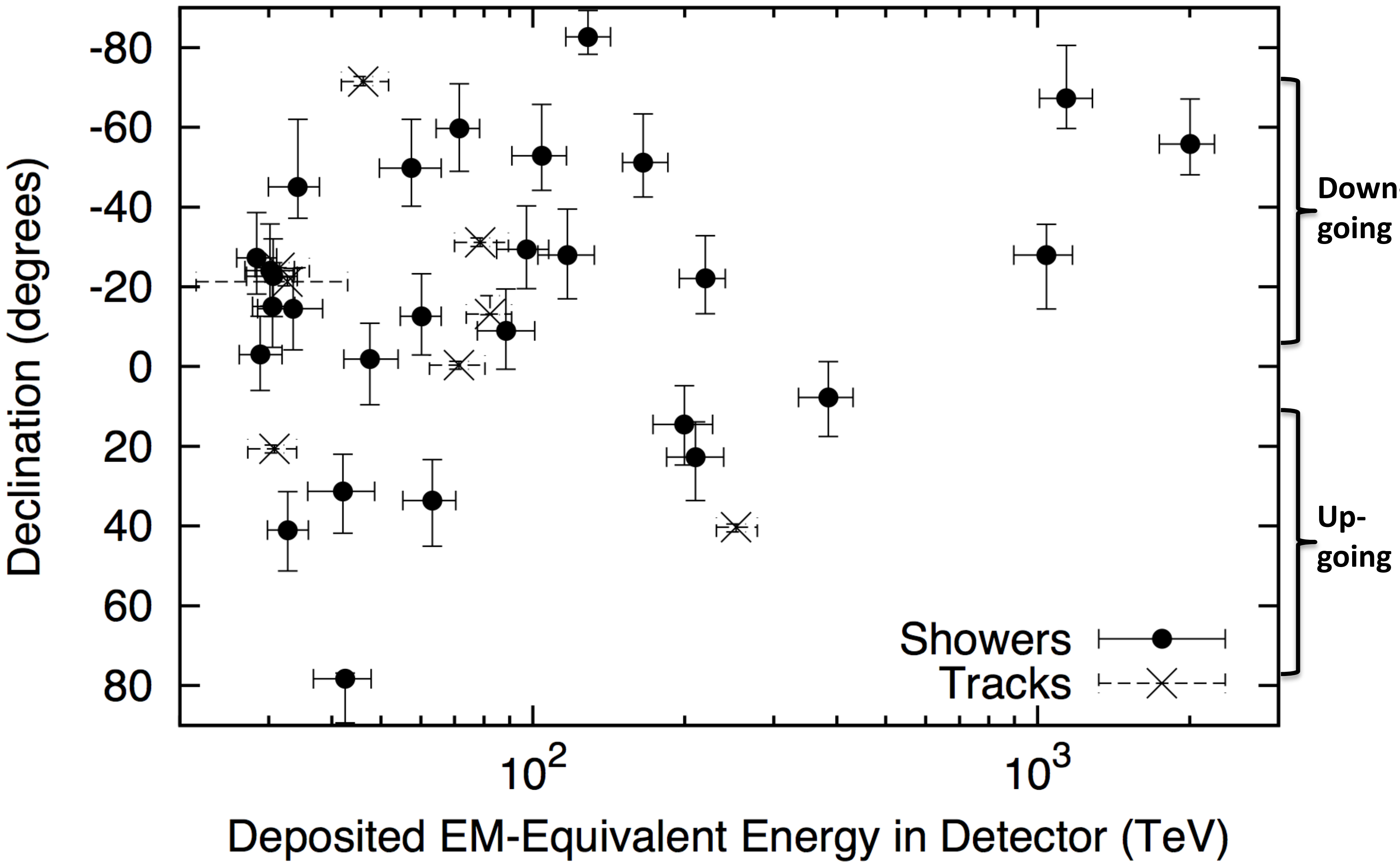


arXiv:1405.5303

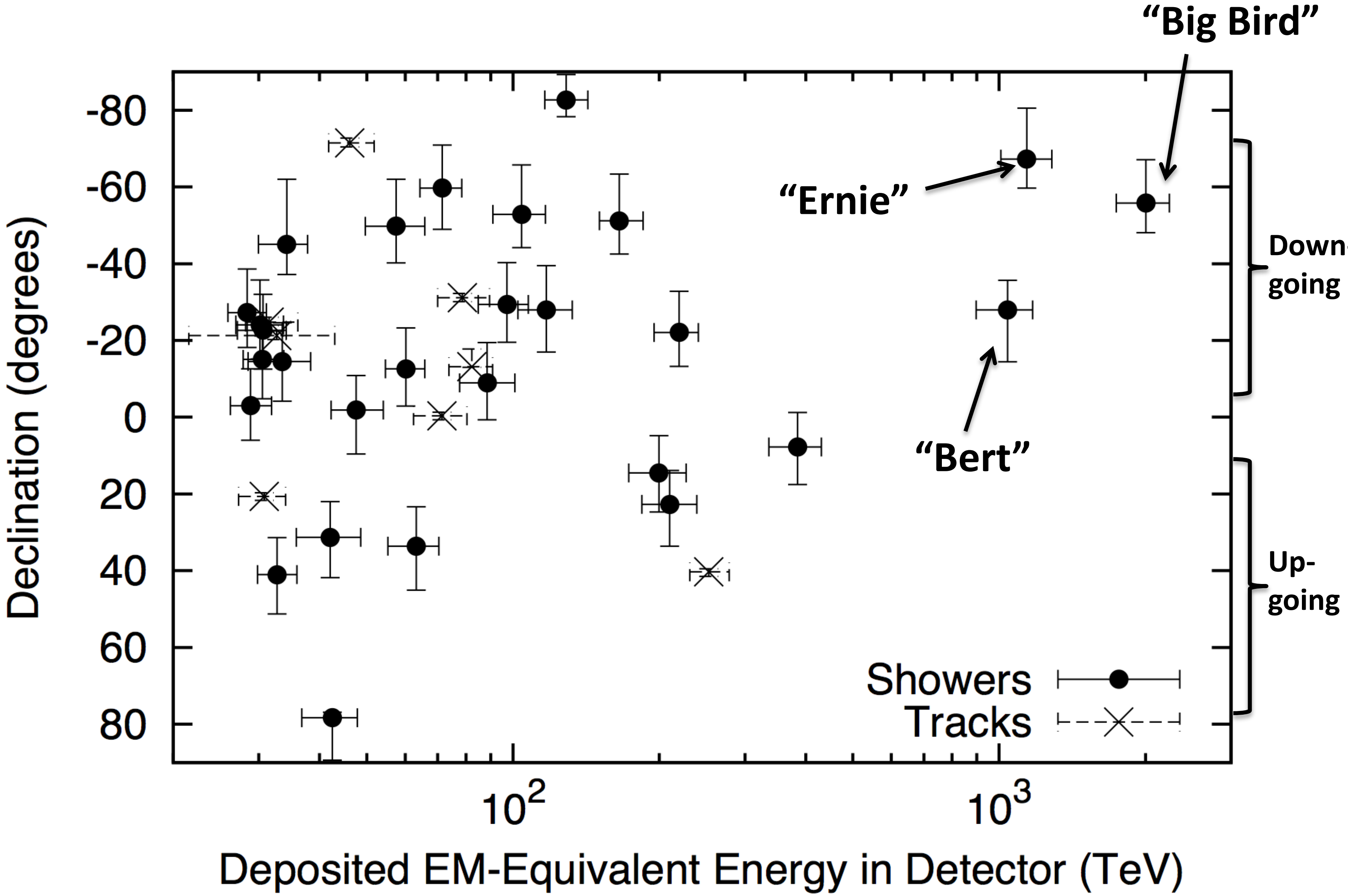
Total: 37 events

Expected background: 15 events

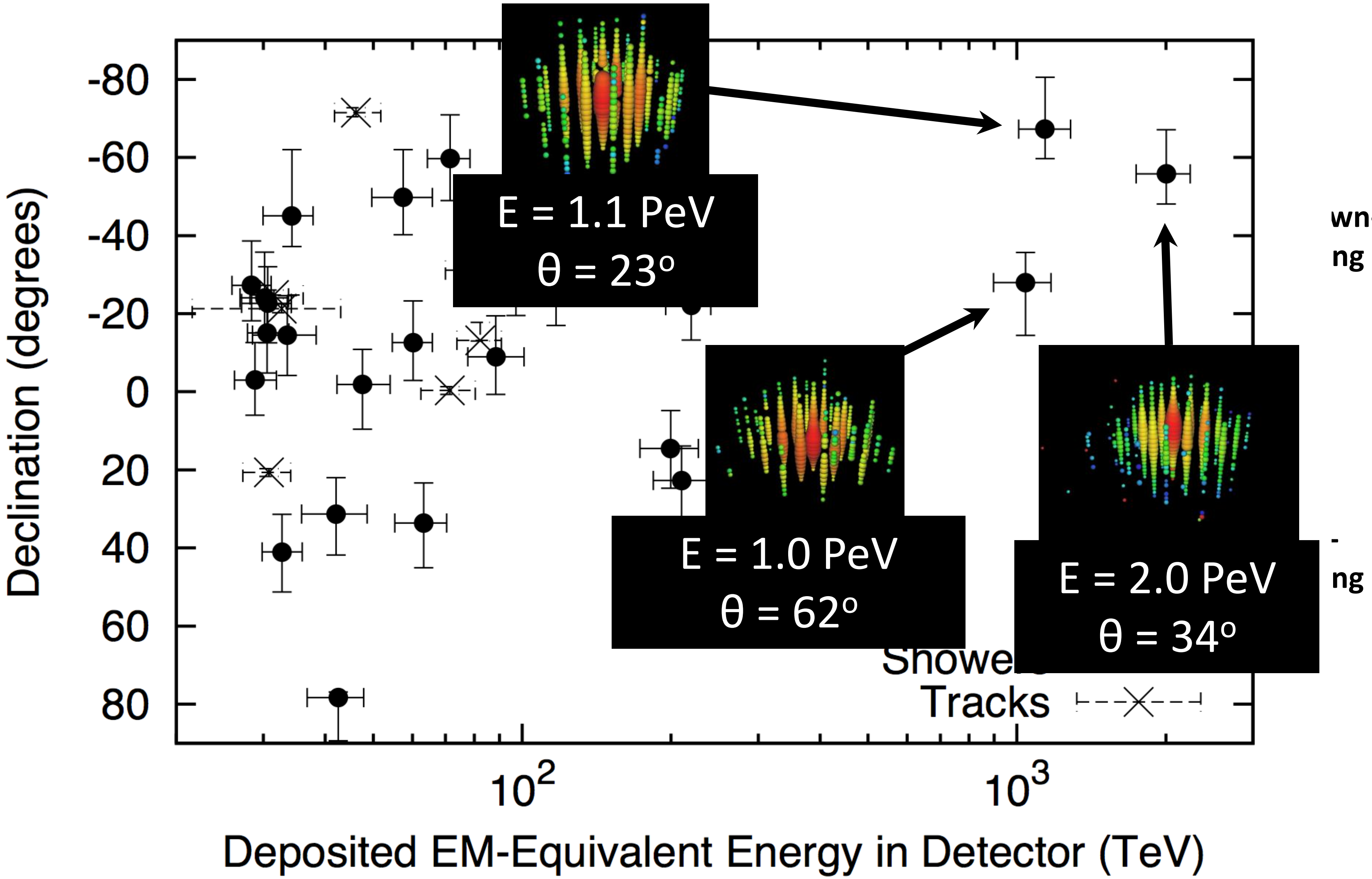
3-Year HESE Results: IC-79 + IC-86

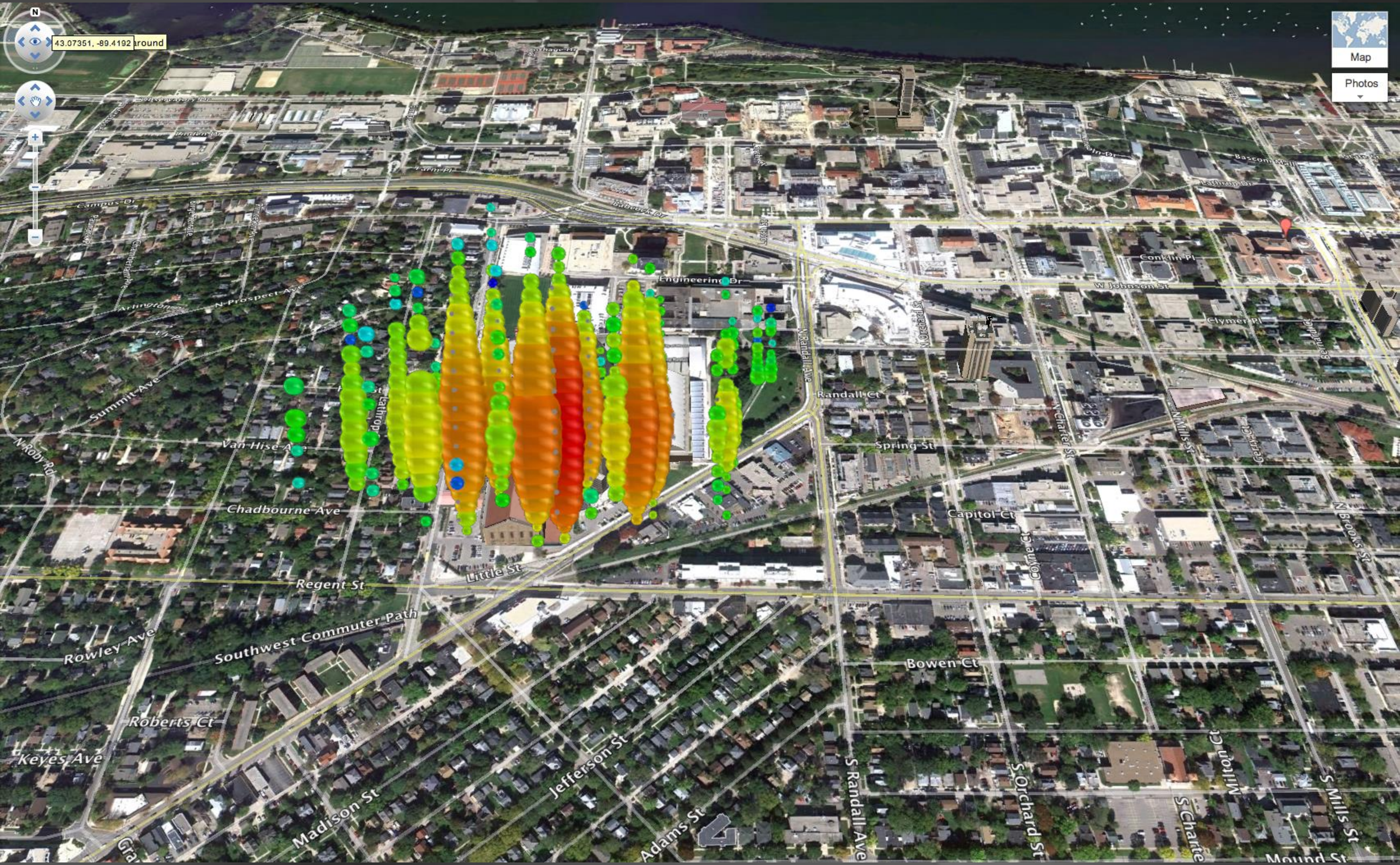


3-Year HESE Results: IC-79 + IC-86



3-Year HESE Results: IC-79 + IC-86



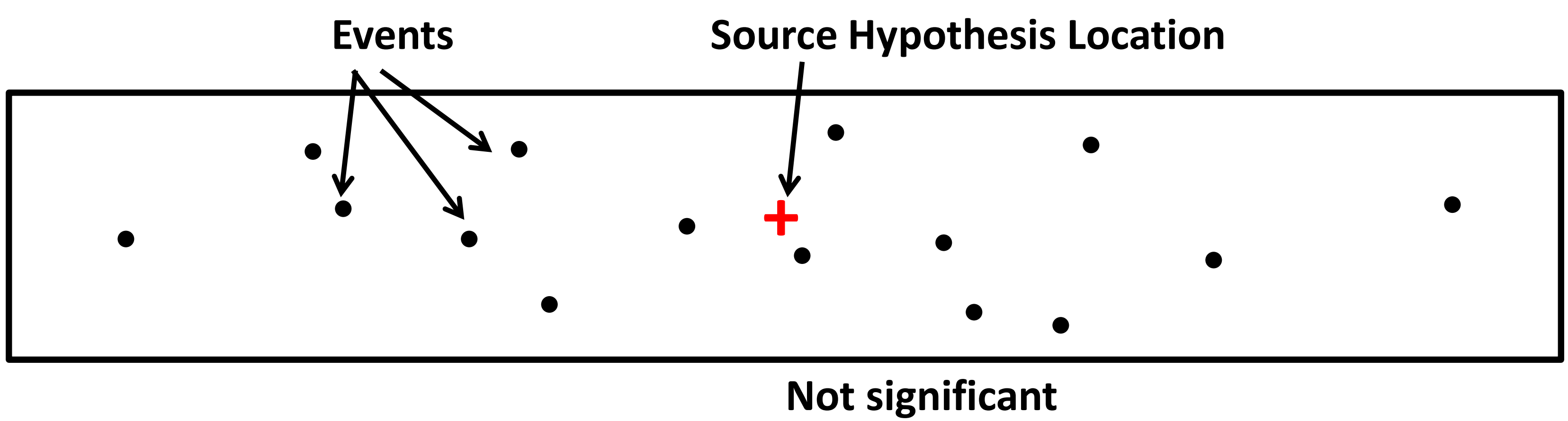


N
43.07351, -89.4192
around
Map
Photos
Campus Dr
Engineering Dr
W Johnson St
Conklin Pl
Clymer Pl
Bascom Mall
N Randall Ave
Randall Ct
Spring St
Capitol Ct
N Brooks St
Summit Ave
Van Hise Ave
Chadbourne Ave
Little St
Regent St
Southwest Commuter Path
Rowley Ave
Bowen Ct
Roberts Ct
Keyes Ave
Madison St
Jefferson St
Adams St
S Randall Ave
S Orchard St
Milton Ct
S Mills St
Mound St

Point Sources

- **Search for a localized astrophysical neutrino excess**
  - Assume a source location hypothesis (e.g. the Crab nebula)
  - Events close to the source location (relative to the angular resolution) are more likely to be from the source
  - Events more closely matching an ~E^{-2} spectrum are more likely to be from the source (similar to the diffuse analysis)

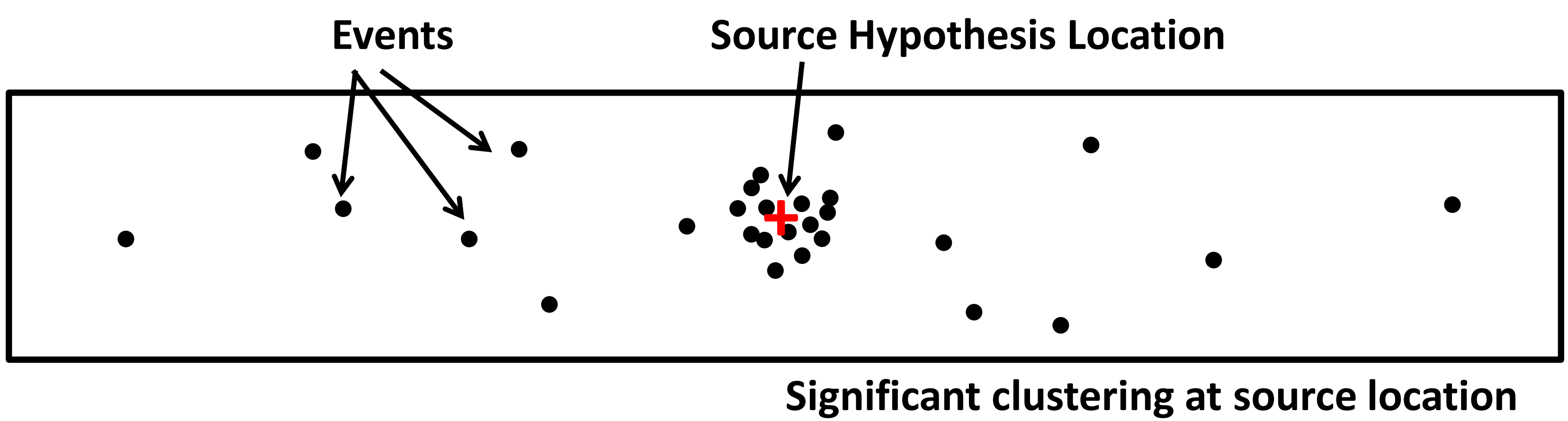
- **Example swath of sky:**



Point Sources

- **Search for a localized astrophysical neutrino excess**
  - Assume a source location hypothesis (e.g. the Crab nebula)
  - Events close to the source location (relative to the angular resolution) are more likely to be from the source
  - Events more closely matching an ~E^{-2} spectrum are more likely to be from the source (similar to the diffuse analysis)

- **Example swath of sky:**



- Key: **We can generally evaluate significance from the data itself**

Point Sources: Likelihood Approach

- Source hypothesis spatial location: $\mathbf{x_s}$; location of event i: $\mathbf{x_i}$

  → Space angle difference: $|\mathbf{x_i} - \mathbf{x_s}|$
- Source likelihood: $$\mathcal{S}_i = \frac{1}{2\pi \cdot \sigma_i^2} exp(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2})$$

  Gaussian probability Event angular resolution
- Events with better angular resolution produce a sharper likelihood

  → Prefer tracks over cascades
- Background likelihood: $\mathcal{B}_i = F(\vec{x}_i)$
- Treat N data events as mixture of source + background:

$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

- Maximize likelihood w.r.t. n_s; compare to likelihood without source:

$$\lambda = -2 \cdot log \left[\frac{\mathcal{L}(\vec{x}_s, n_s = 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s)} \right]$$

- Large λ favors source hypothesis

Point Sources: Likelihood Approach

- Source hypothesis spatial location: $\mathbf{x_s}$; location of event i: $\mathbf{x_i}$
  → Space angle difference: $|\mathbf{x_i} - \mathbf{x_s}|$
- Source likelihood: $$\mathcal{S}_i = \frac{1}{2\pi \cdot \sigma_i^2} exp\left(- \frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right) \cdot P(E_i|\gamma = 2)$$

  Gaussian probability   Event angular resolution

- Events with better angular resolution produce a sharper likelihood
  → Prefer tracks over cascades
- Background likelihood: $\mathcal{B}_i = F(\vec{x}_i) \cdot P(E_i|Background)$
- Treat N data events as mixture of source + background:

$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

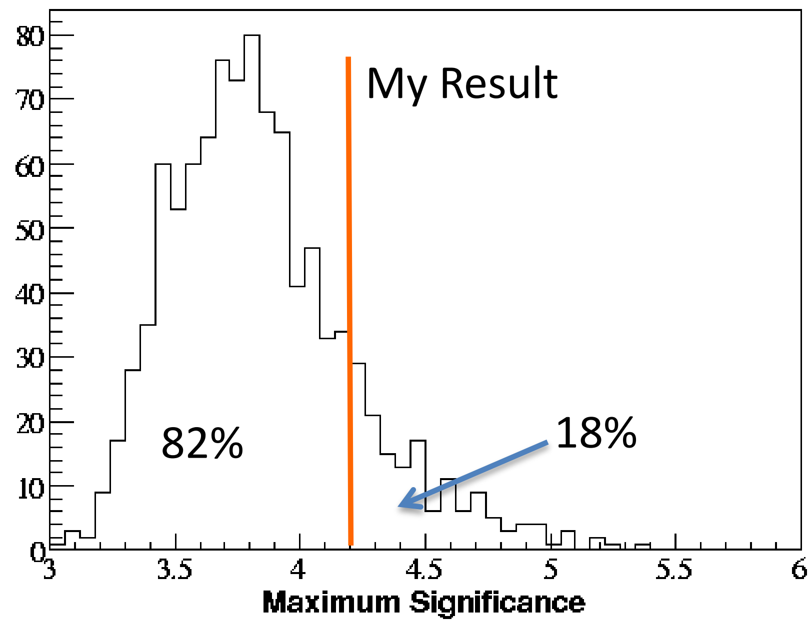
- Maximize likelihood w.r.t. n_s; compare to likelihood without source:

$$\lambda = -2 \cdot log \left[\frac{\mathcal{L}(\vec{x}_s, n_s = 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s)} \right]$$

- Large λ favors source hypothesis
- Can include energy information

What if we do not know where to look?

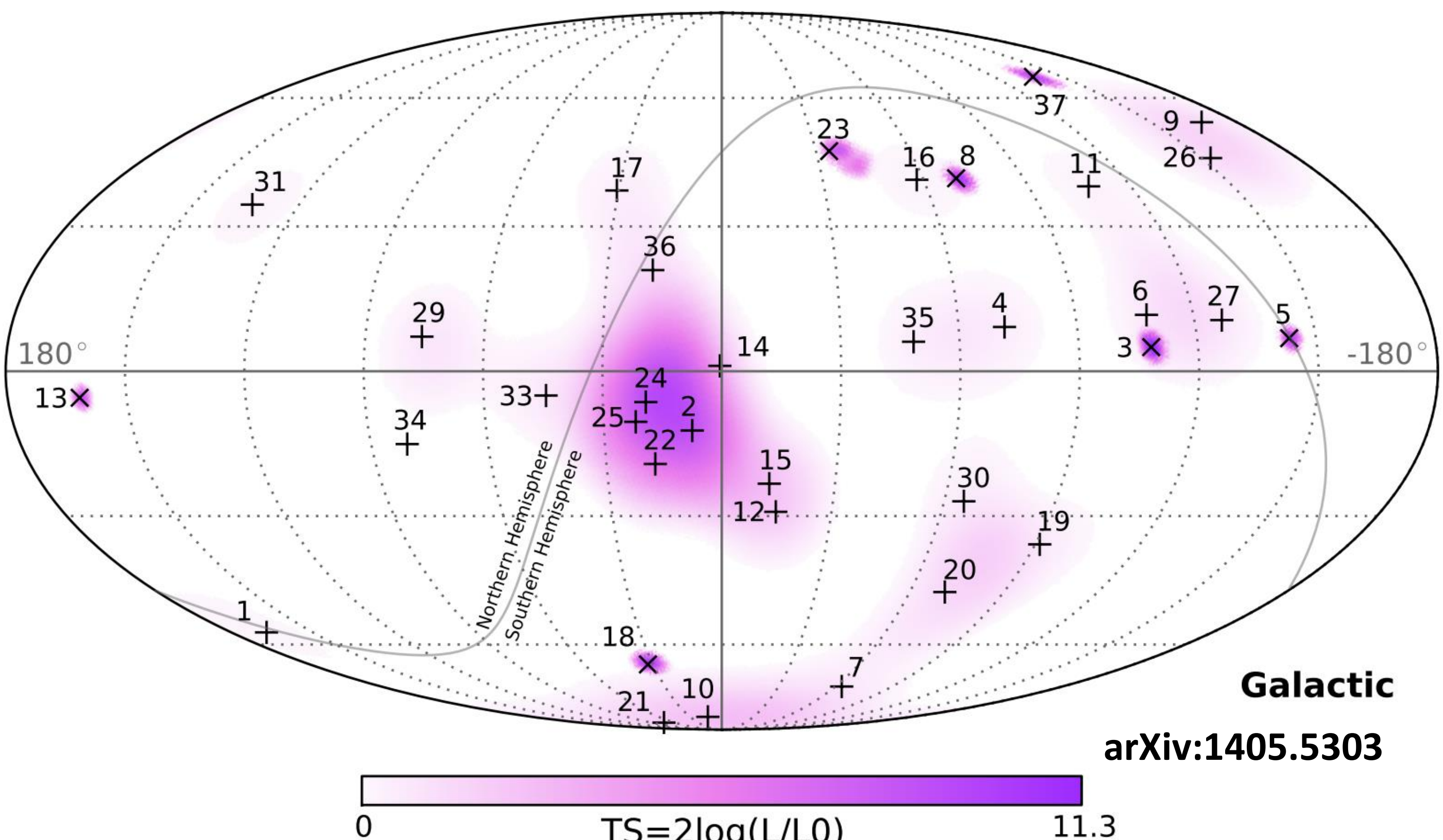
- **Look everywhere!**
  - Perform analysis on a fine grid of source locations
  - Grid feature spacing much smaller than angular resolution
  - Most likely source location is the highest obtained significance
  - Compare highest significance with that of datasets randomized in time to compute the significance



→ p = 0.18

- **Why not look everywhere?**
  - Trials factor
  - Typical analysis: all-sky search + list of sources

3-Year HESE Sky Map

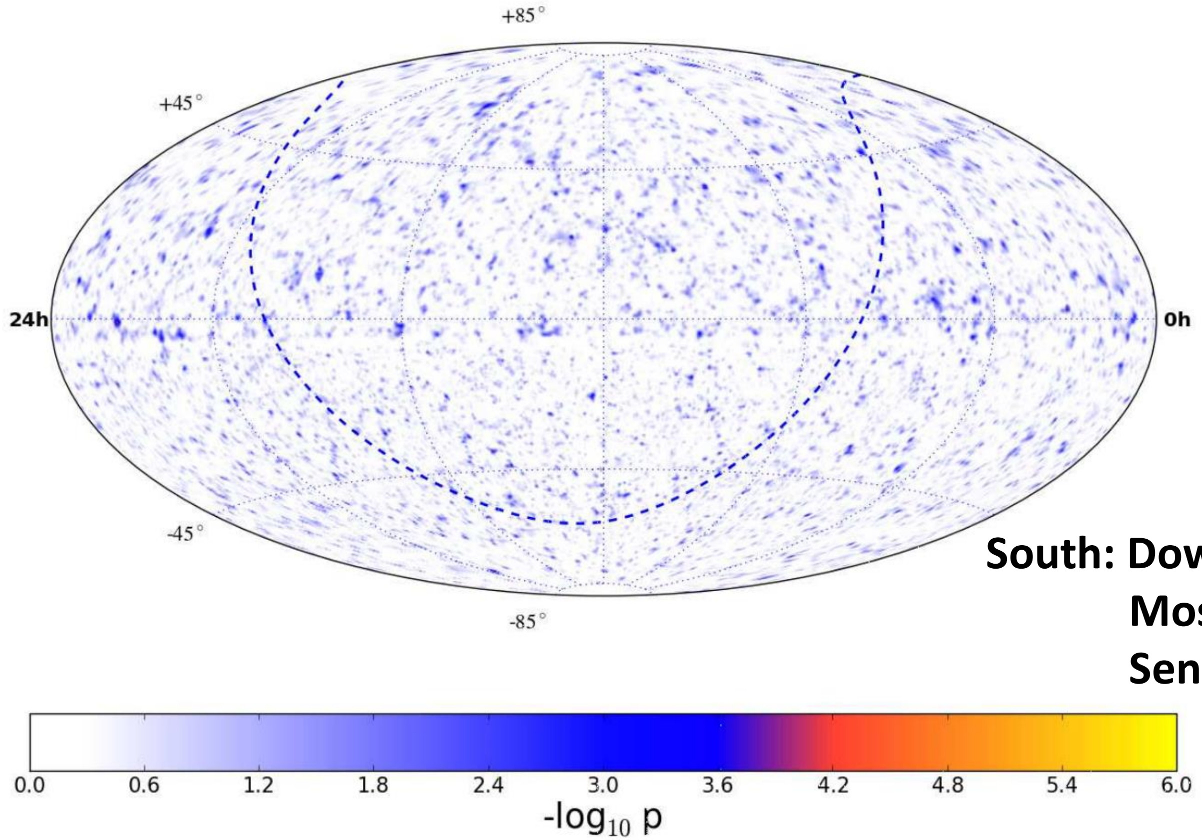


No significant clustering found

Point Sources: IC-40 + IC-59 + IC-79

North: Upgoing muons
Mostly atomspheric neutrinos

ApJ 779:132 **(2013)**



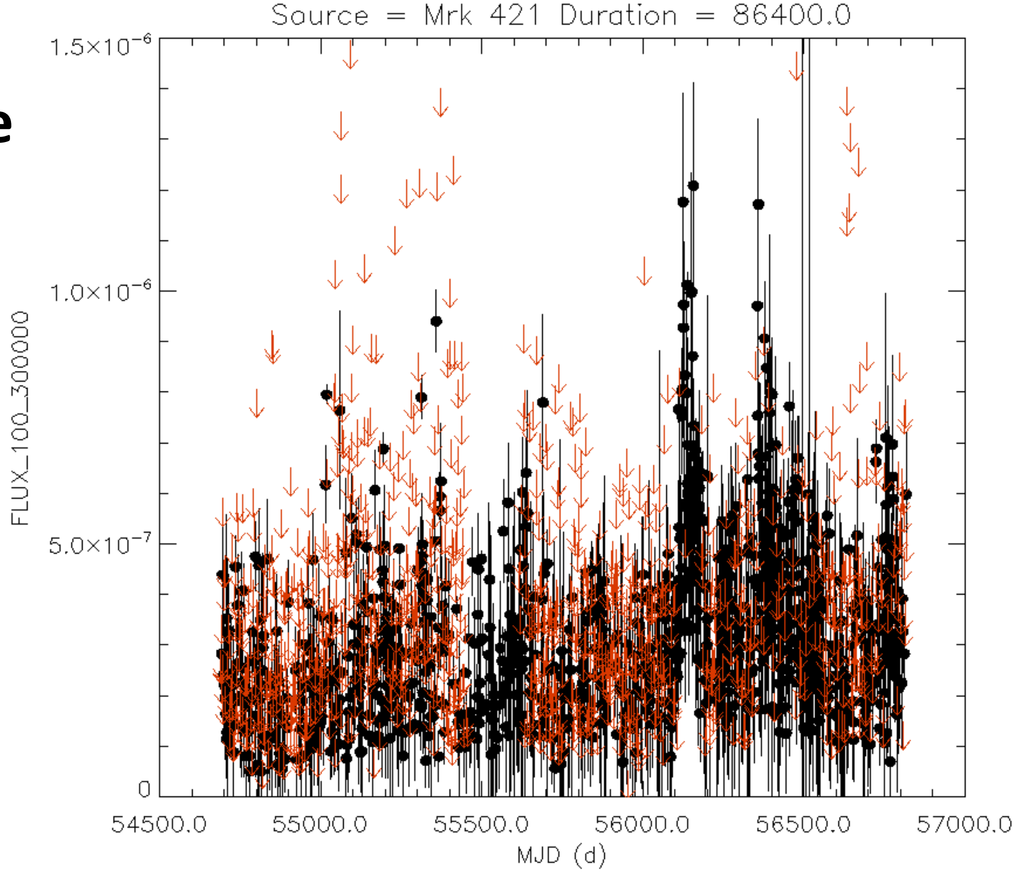
South: Downgoing muons
Mostly cosmic ray muons
Sensitive at ~PeV energies

No significant source discovered

Time Dependent Point Source Analysis

Objects flare

Mrk 421

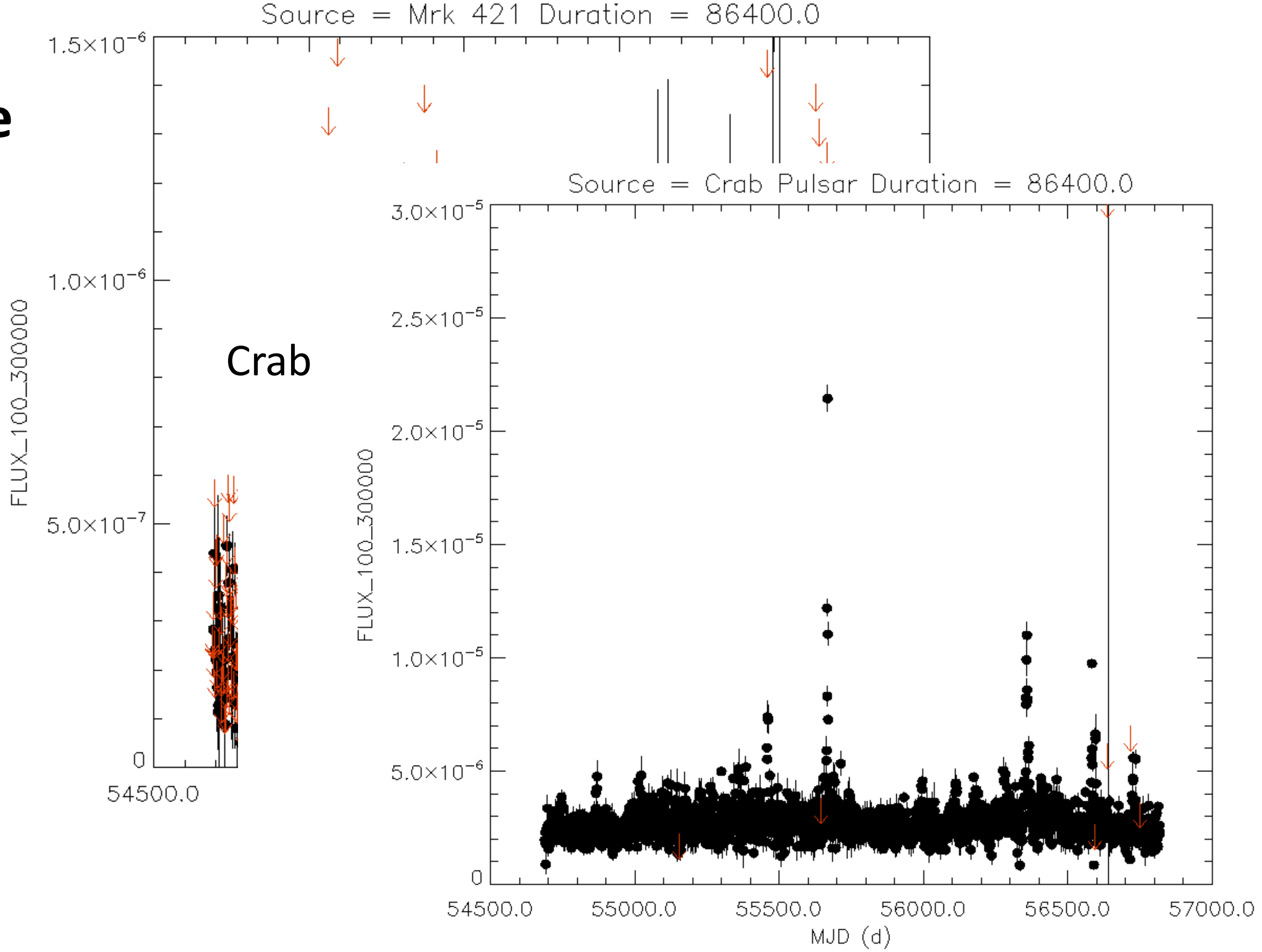


Time Dependent Point Source Analysis

Objects flare

Mrk 421

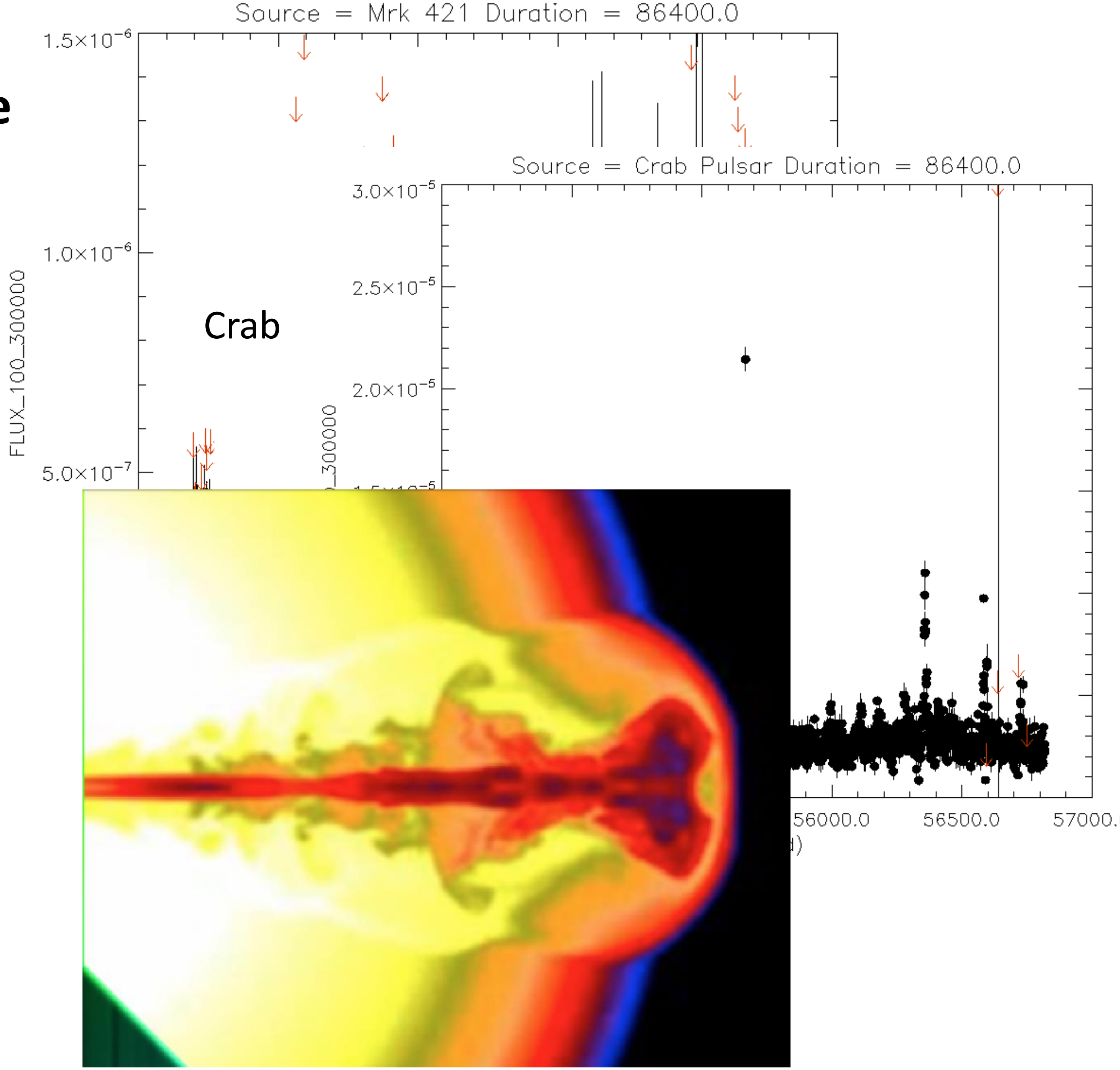
Crab



Time Dependent Point Source Analysis

Objects flare

Mrk 421



Or explode

Time Dependent Point Source Analysis

- Suppose neutrino emission is time-dependent:
  - Reduce background by only looking at (or weighting toward) select times
- Two types of searches:
  - **Triggered**: We already have a hypothesis for the emission time structure
  - **Untriggered**: Search in time for a flare/burst at a specific location
- Triggered searches are more sensitive
- GRBs: Burst duration of <1 second – 1000 seconds
  - IceCube is constraining GRBs cosmic ray models: **Nature 484, 351-354 (2012)**
- **Other IceCube published time-dependent (non-GRB) searches:**
  - Crab flare: **ApJ 745:45 (2012)**
  - Periodic sources: **ApJ 748:118 (2012)**
  - All-sky untriggered scan**: ApJ 744:1 (2012)**