ICECUBE AND THE HIGHEST ENERGY NEUTRINOS: AN OVERVIEW

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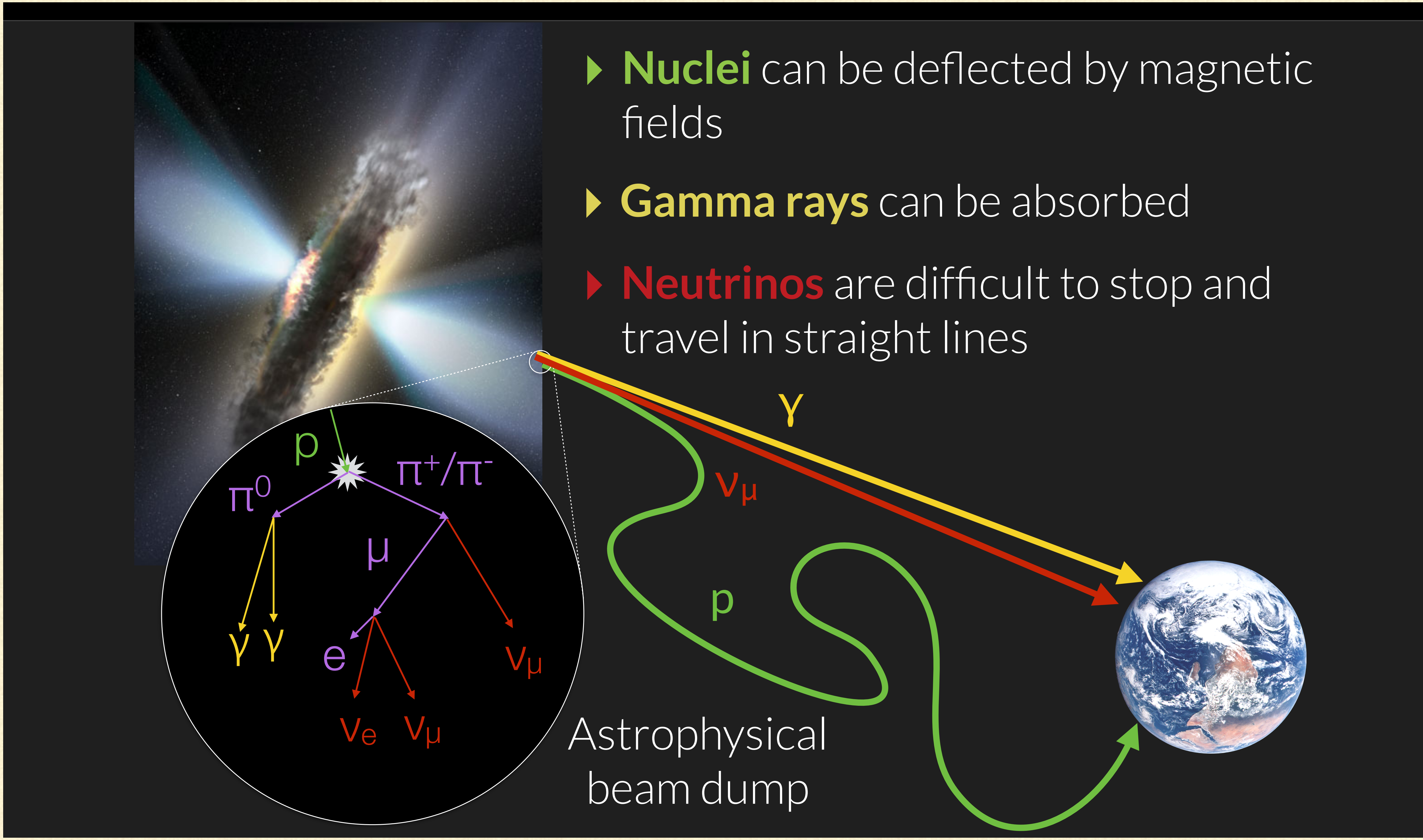
WHEPP, IISER Bhopal, Dec 17, 2017

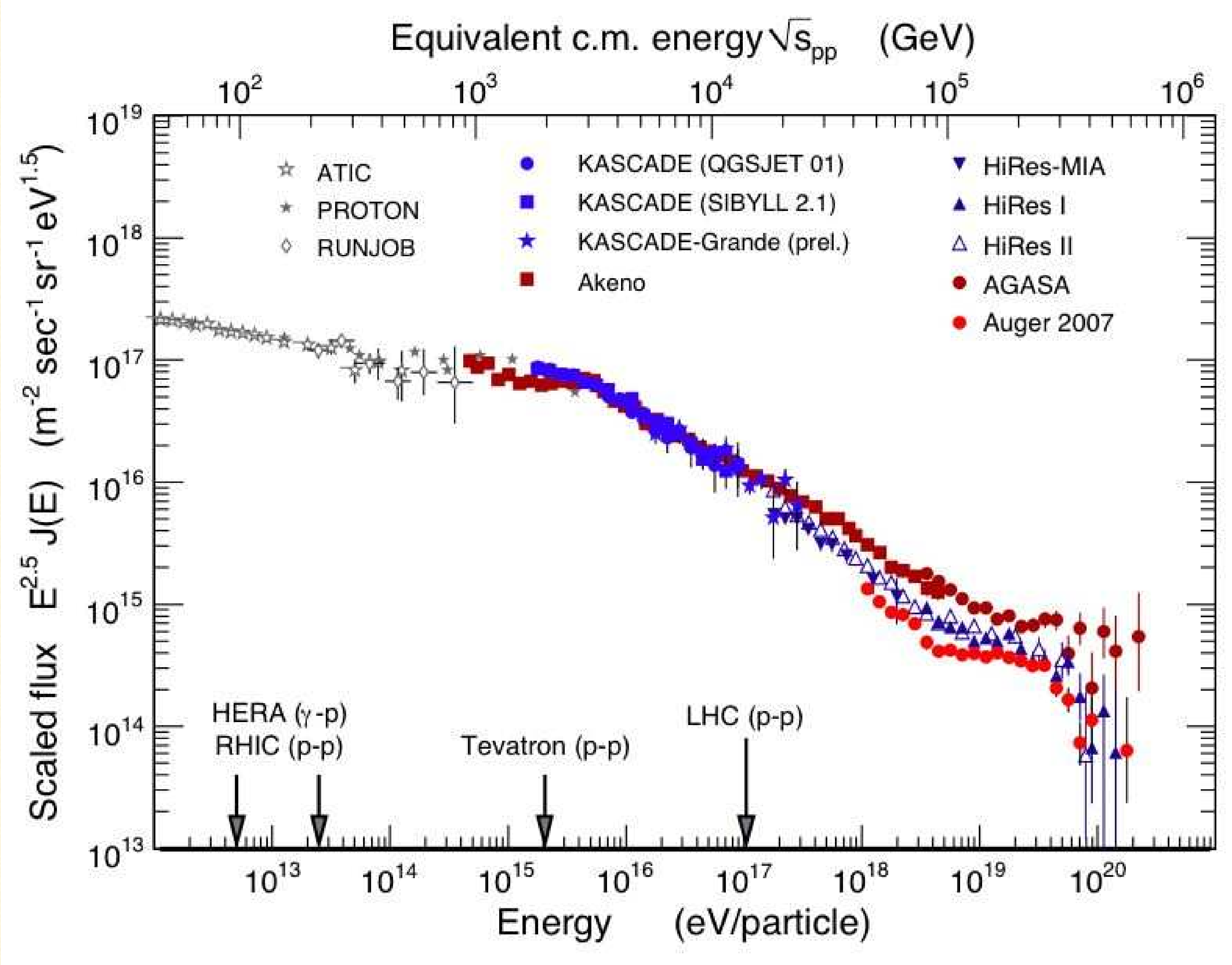
Typical source: charged particle acceleration via high magnetic fields, and a dense environment



It is widely believed that UHE neutrinos are produced in charged pion decays produced in pp and or pγ interactions in the source. Oscillations transform the original $\nu_e:\nu_\mu:\nu_\tau$ 1:2:0 flux to 1:1:1, hence tau flux is expected.

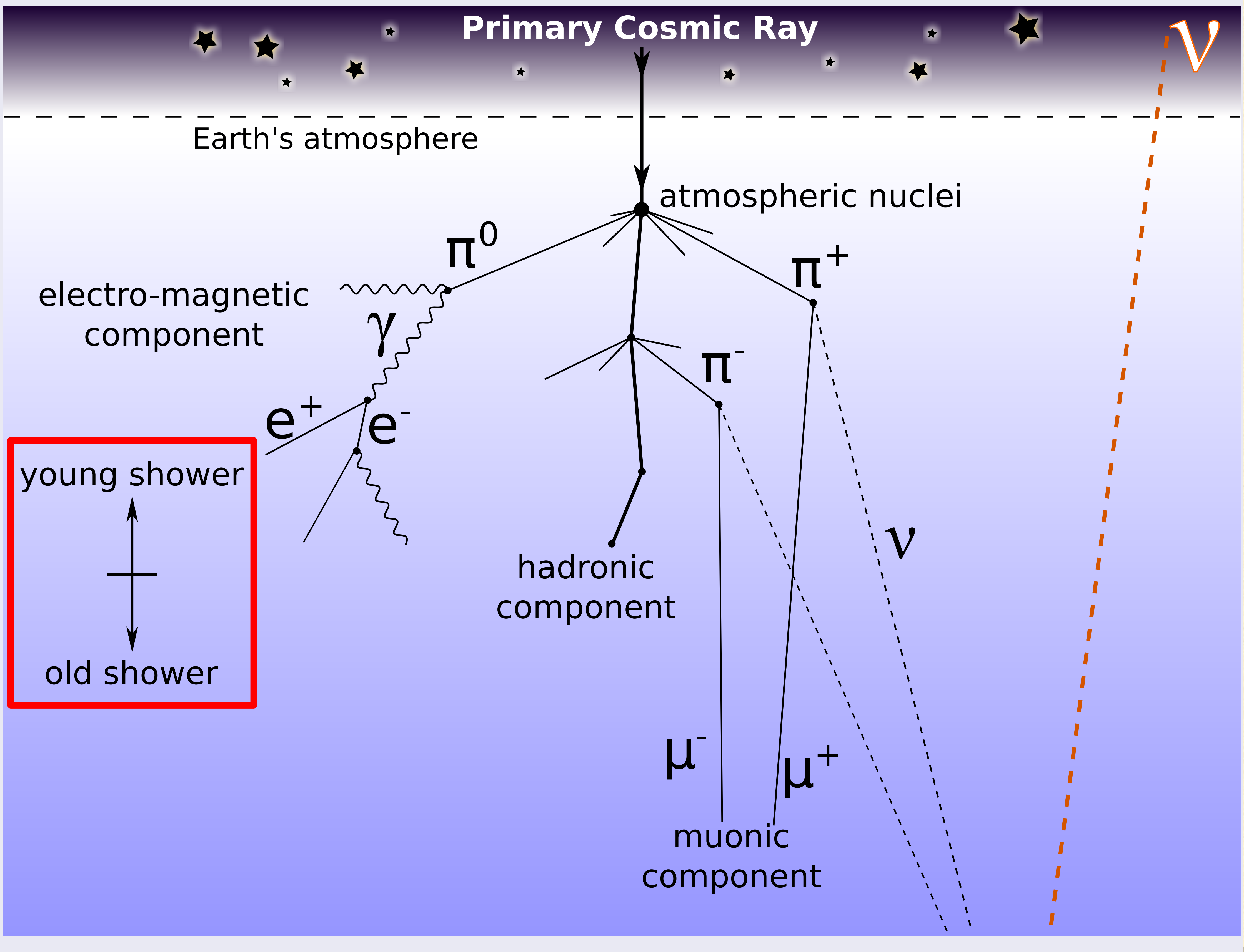
Slide from C Kopper, ICRC 2017

High Energy Cosmic Rays.....

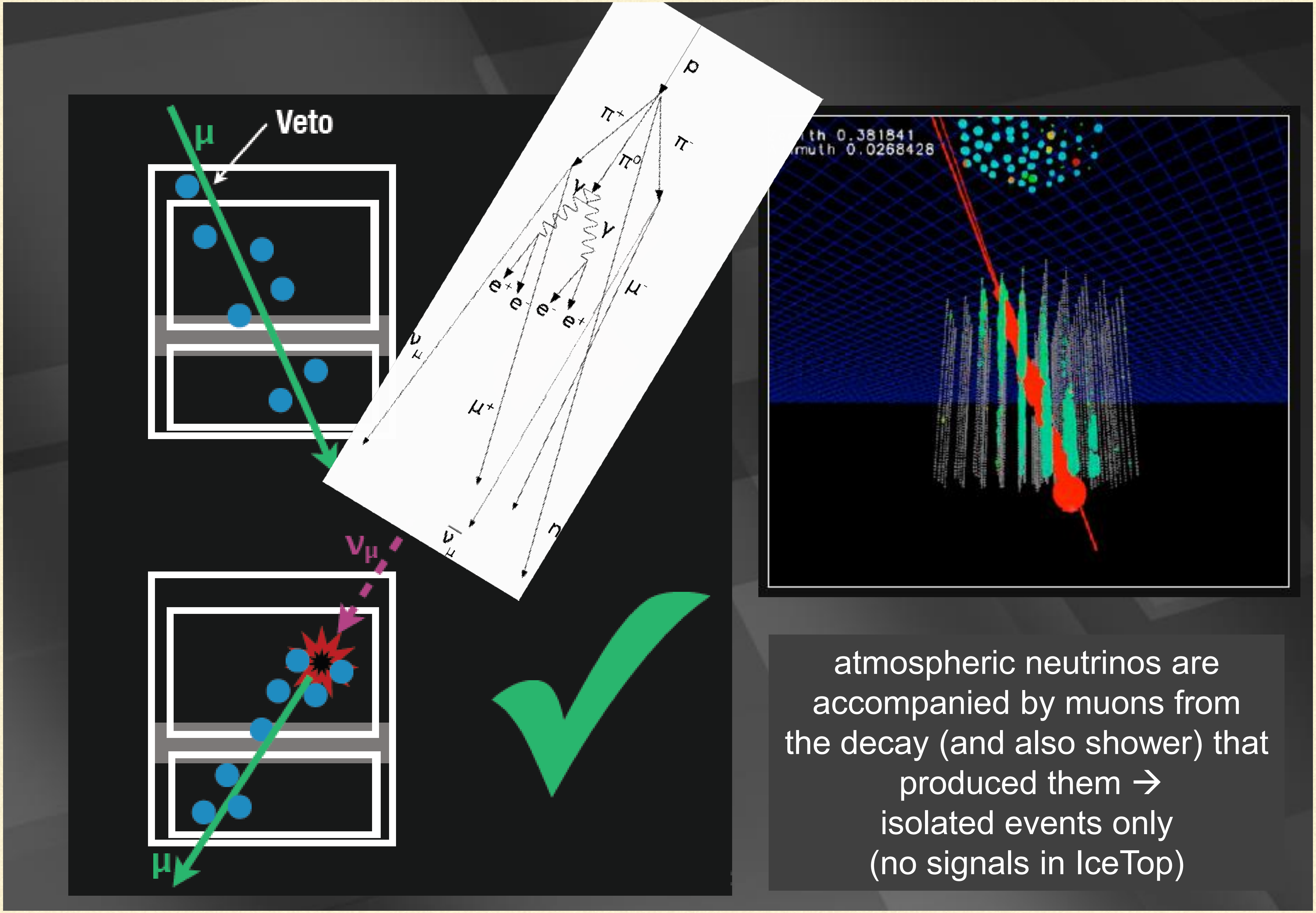


Comparing the UHECR to terrestial accelerators......

Atmospheric neutrinos..... a background

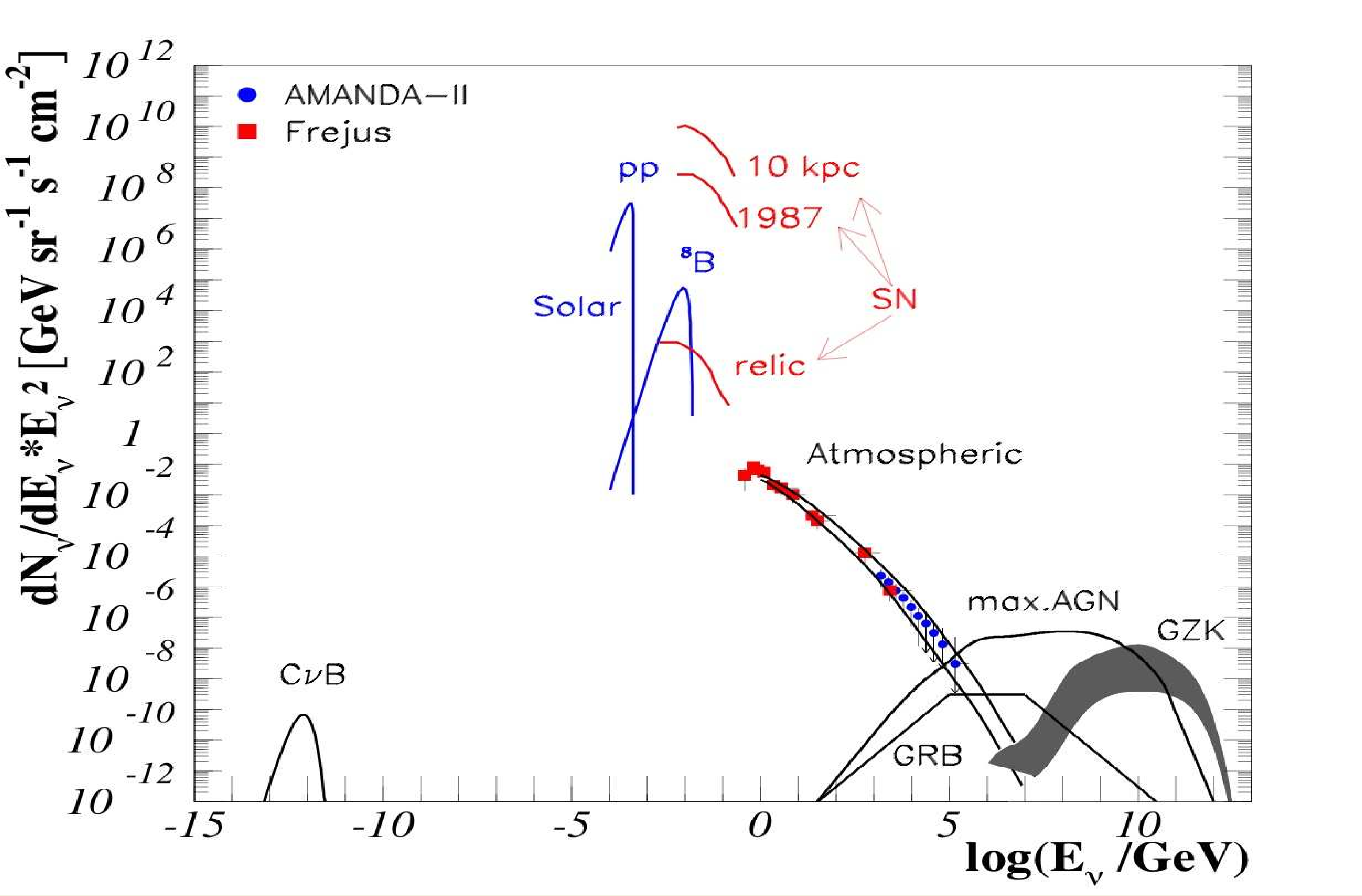


Differentiating signal (UHE ν) from background (atmos ν) ……

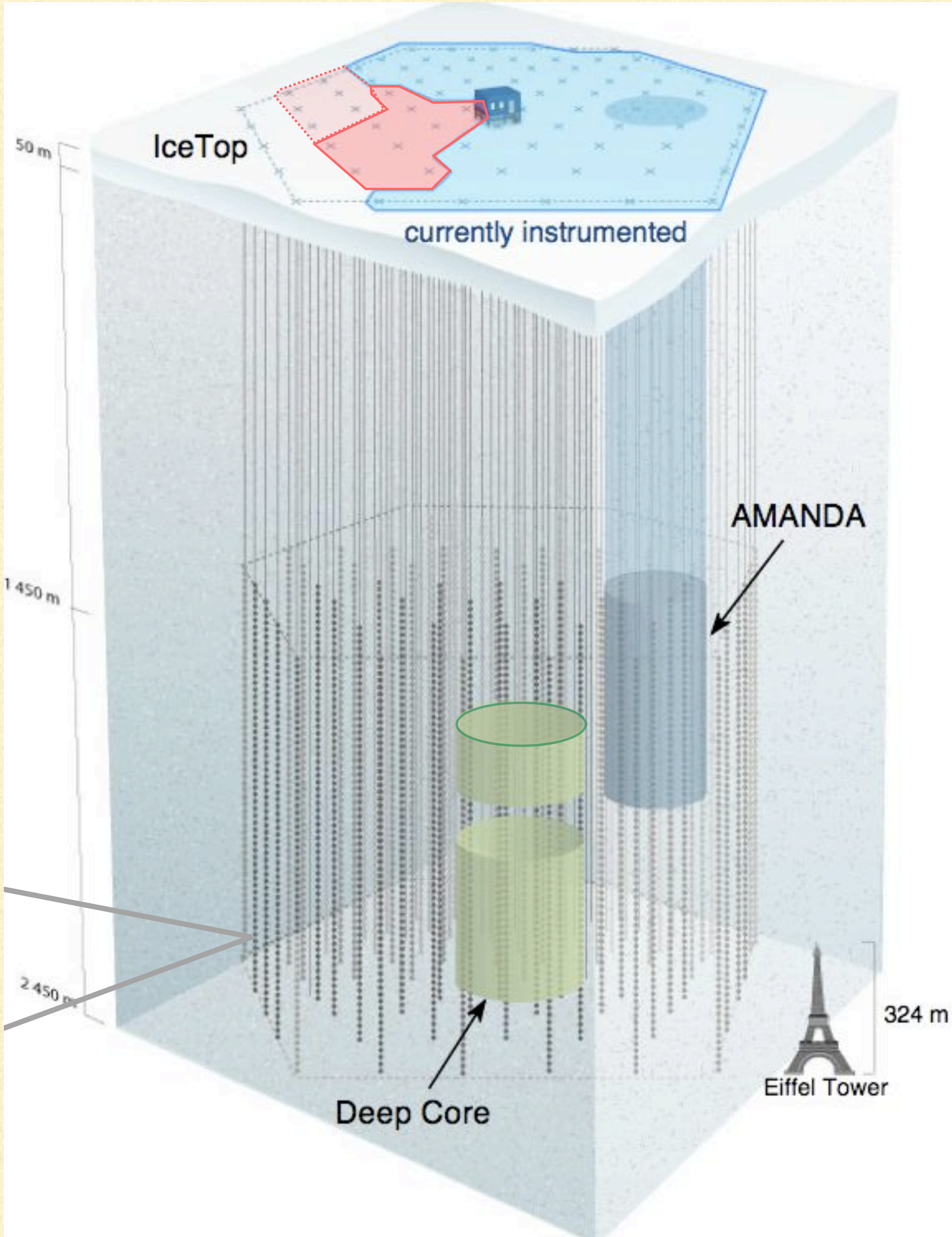


Slide from F Halzen, TeVPA 2017

The Sky in Neutrinos.....



The IceCube Detector



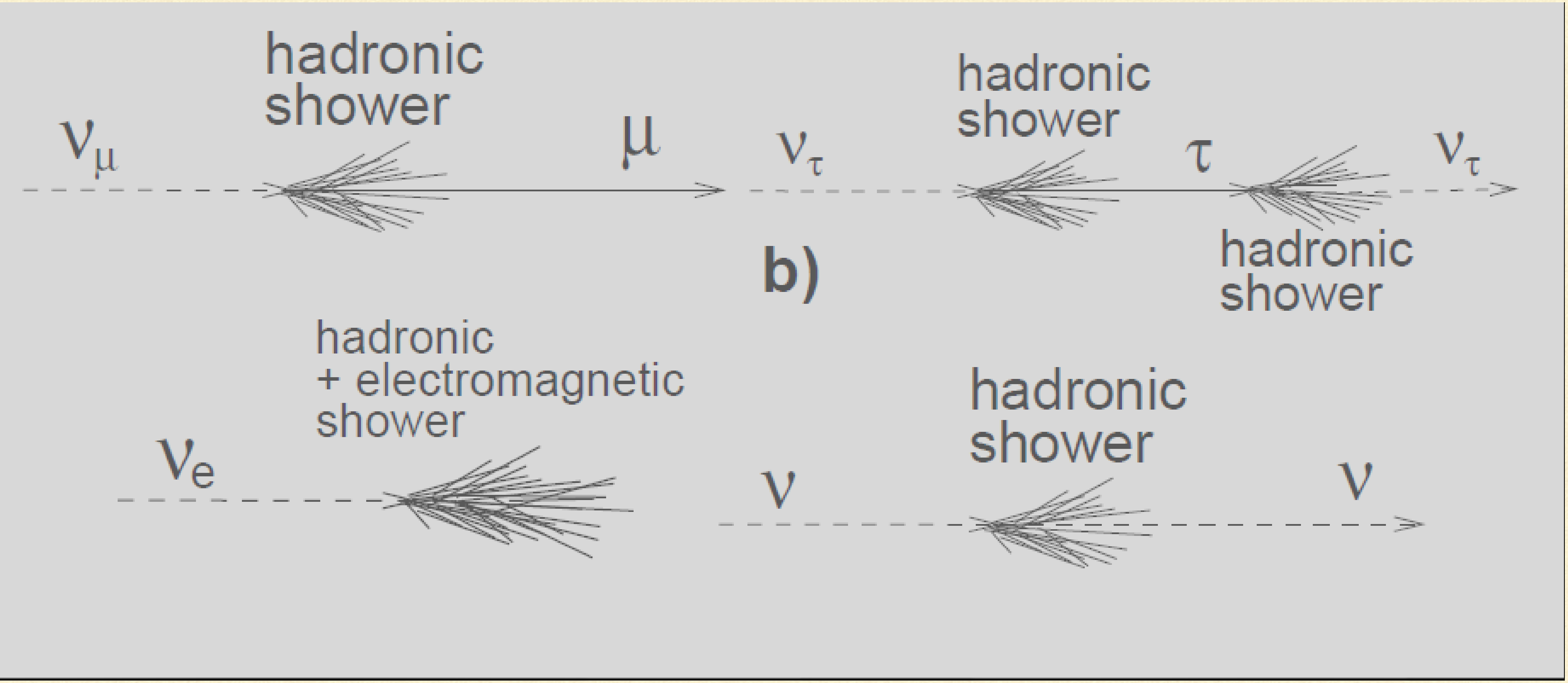
86 strings, 60 OM/string

17 m distance between 2 OM on same string

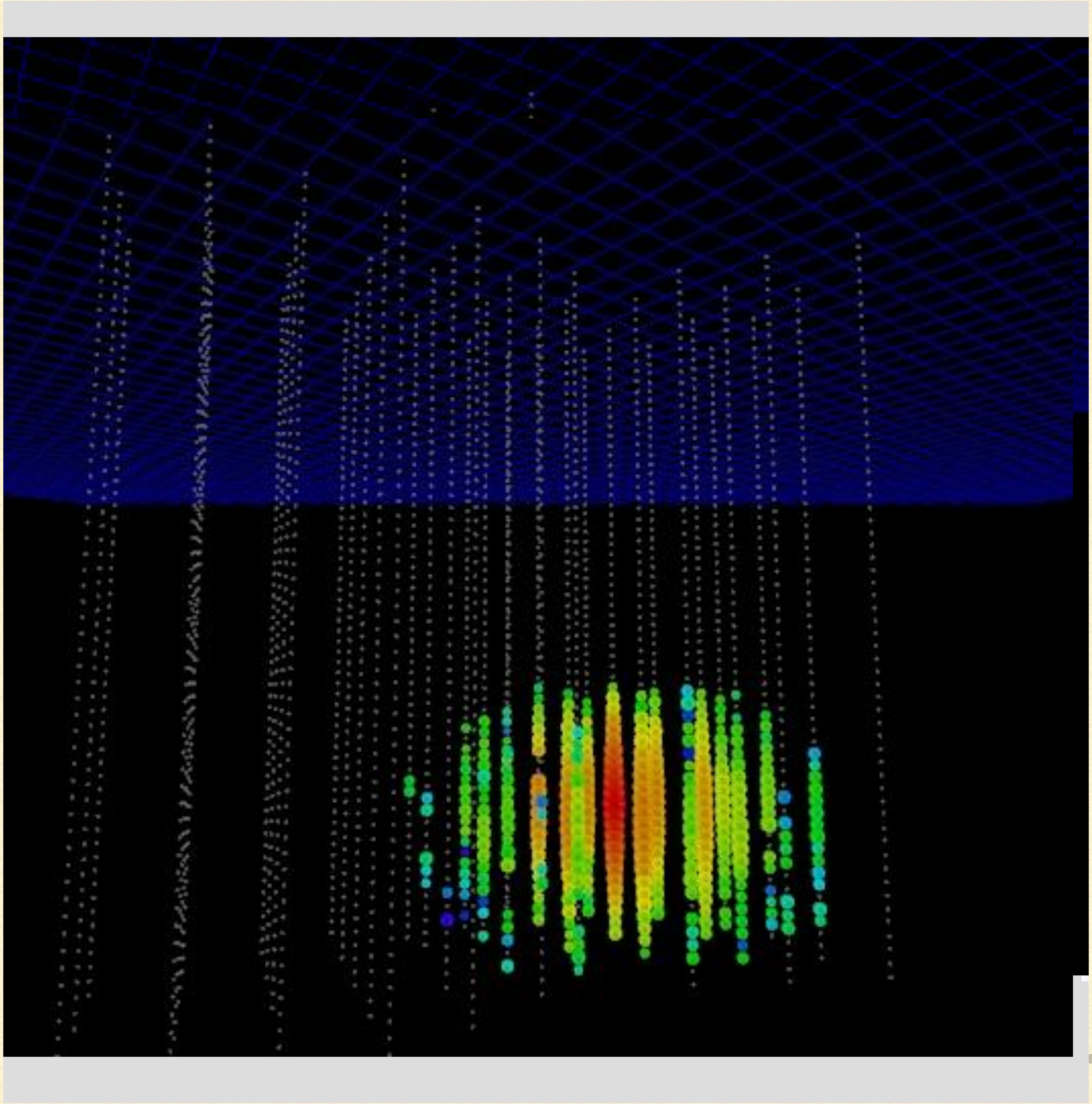
125 m distance between 2 consecutive strings

1 km^3 instrumented volume

Neutrino Signals in IceCube.....



Signals in Icecube..... Cascade (or Shower) event

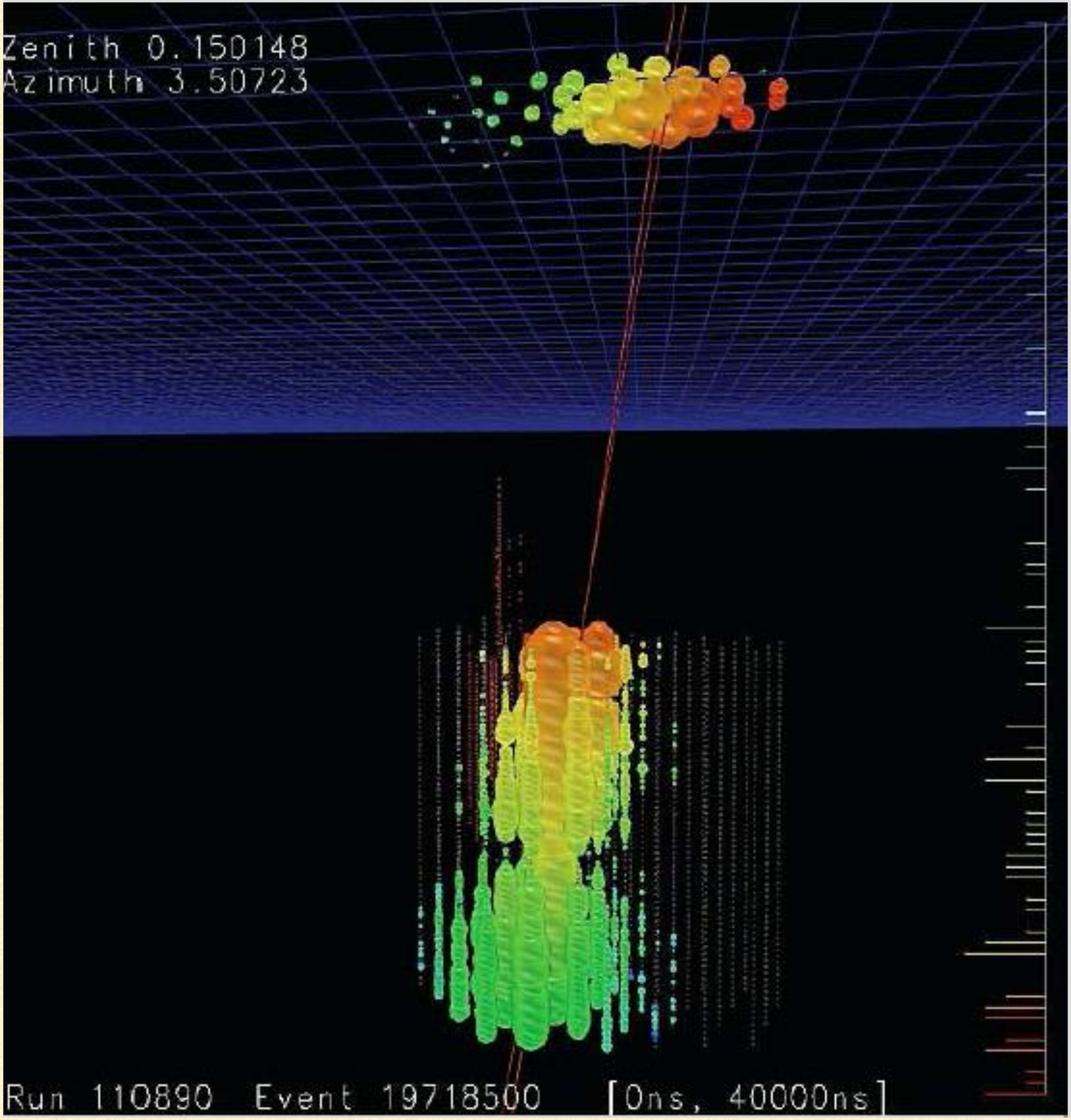


All NC, CC ν_e

15 % resolution on the deposited energy

10° angular resolution (above 100 TeV)

Signals in Icecube..... Track event (muons)



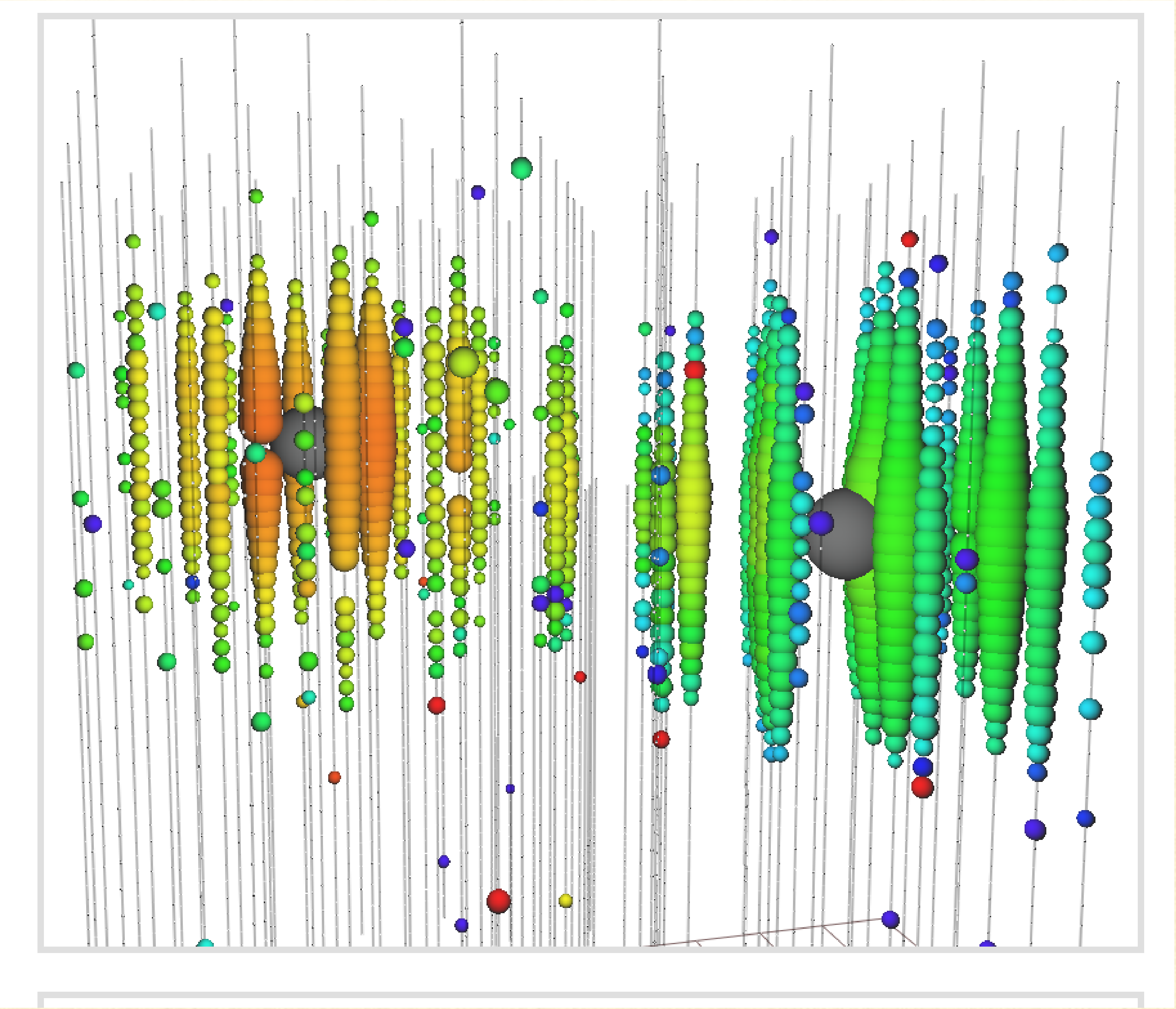
Charged current ν_μ

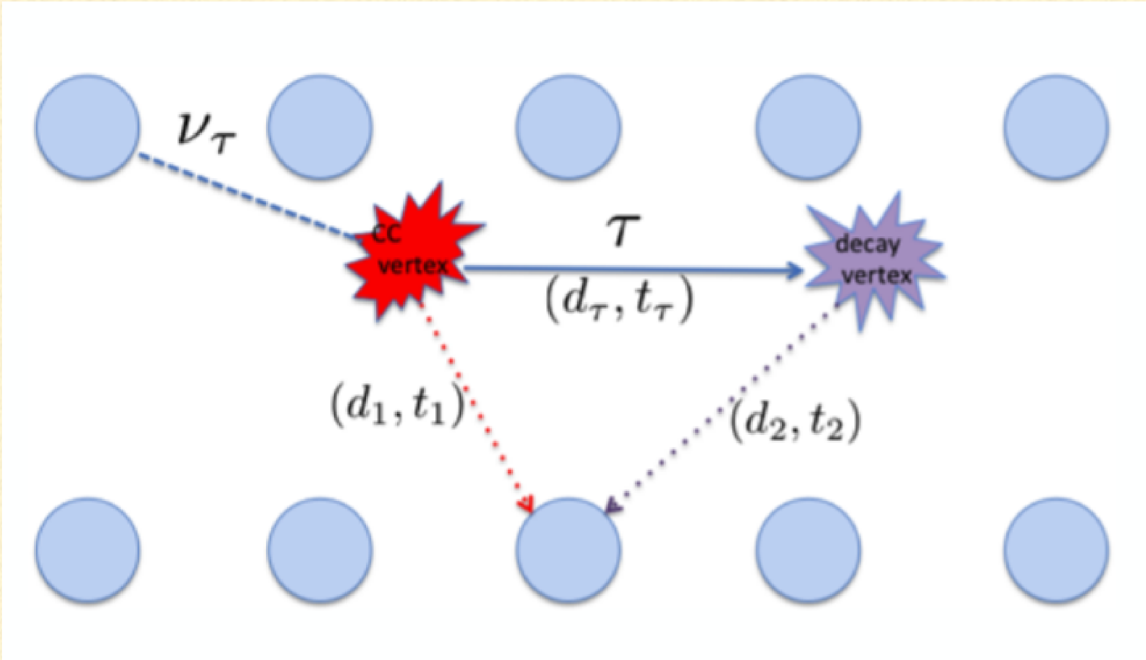
Factor ~2 energy resolution

<1° angular resolution

Signals in Icecube..... double bang event (taus)

(how do you see a tau?)

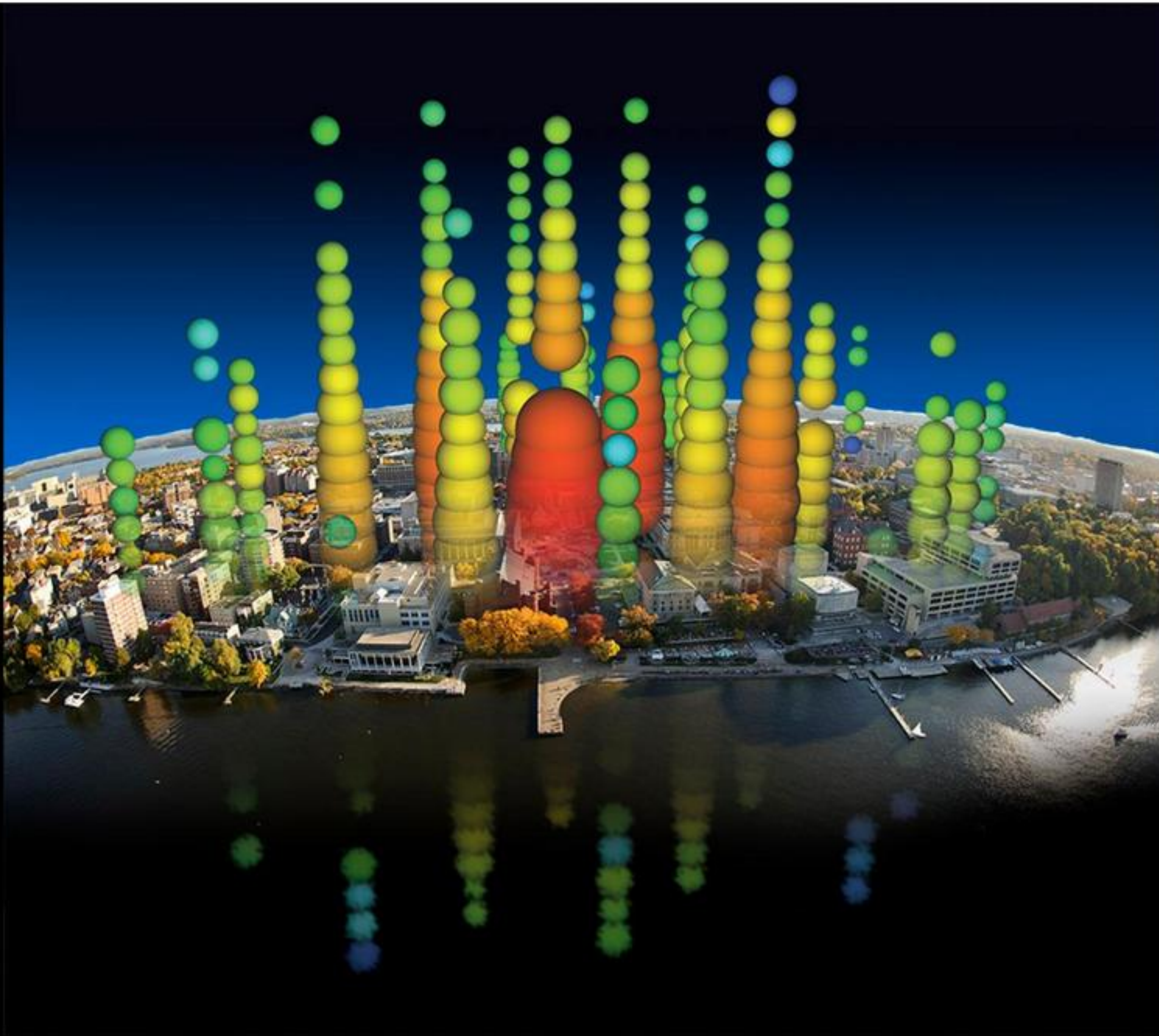




Double Bang ν_τ

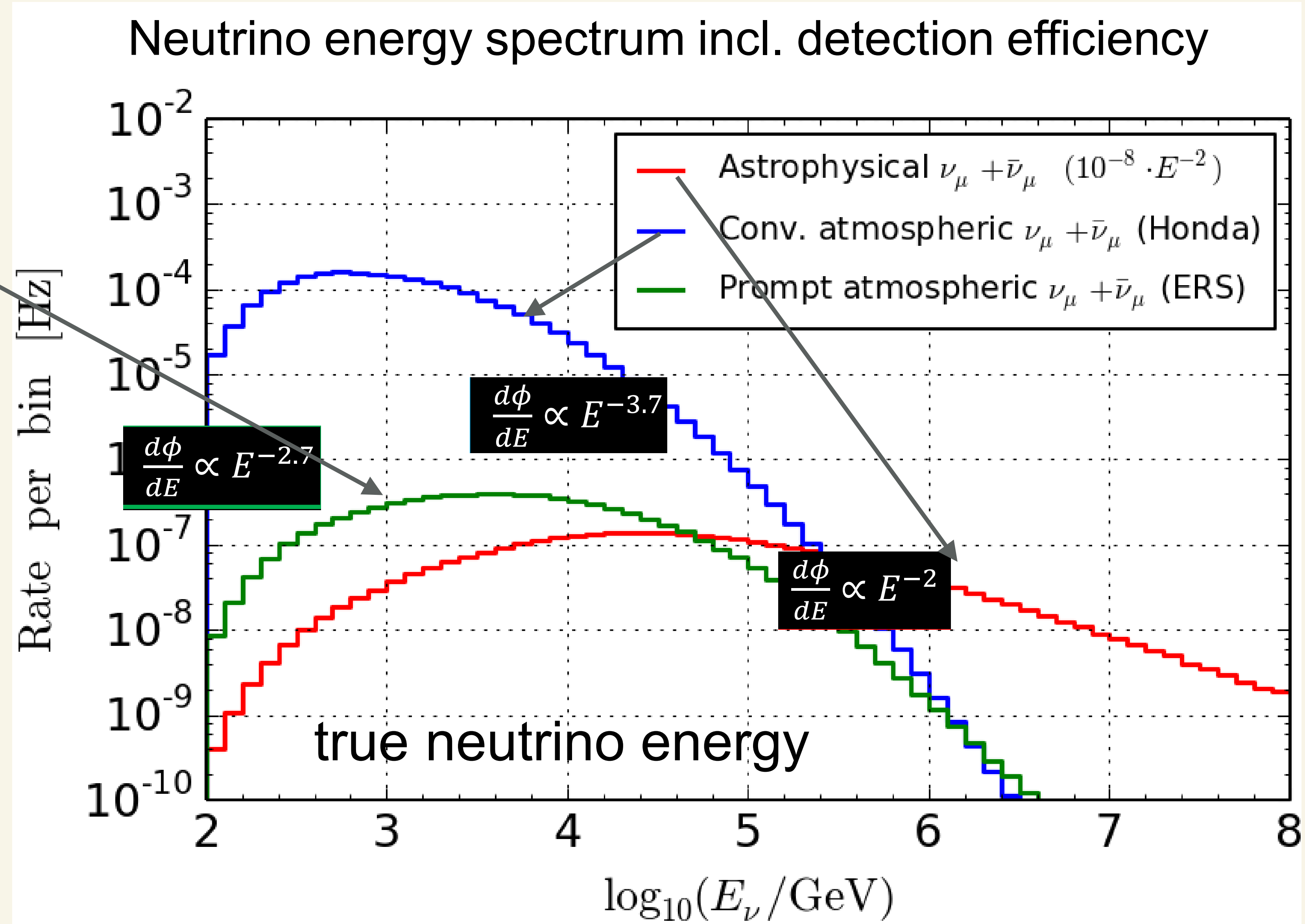
Vertex separation ~50m/PeV

Not yet observed



Expected fluxes.....

prompt atmospheric, from charm decay, not yet observed



Atmospheric neutrinos, from pion/kaon decay, background, dominates until ~ 100 TeV, rapidly falling

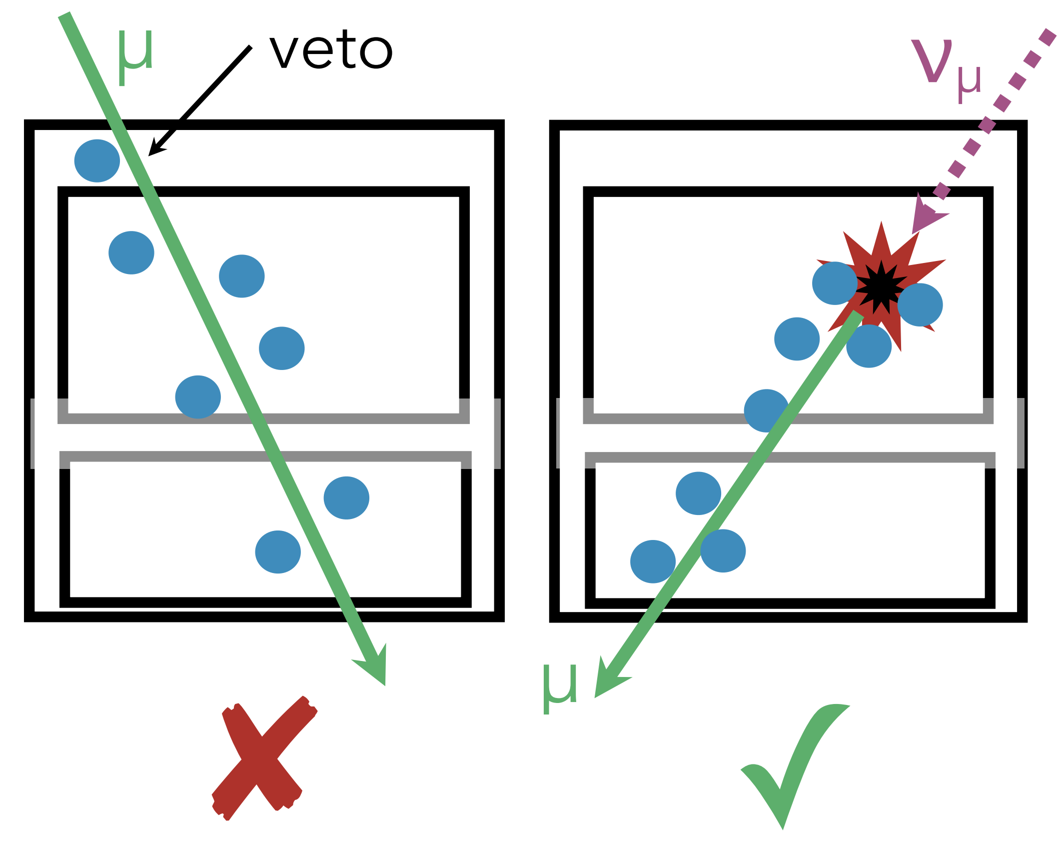
Astrophysical flux emerges ~ 100 TeV and above

Benchmark model: Fermi acceleration at shock fronts

→ $\Phi_\nu \propto E^{-2}$

What does IceCube actually see so far?

Starting events……..6 years data available now



IceCube, Science 342, 2013

37 events in 3 years

$\Phi(E) \sim 1.5 \cdot 10^{-8}\, E^{-2.3}$

IceCube, PRL 113, 2014

→

82 events in 6 years

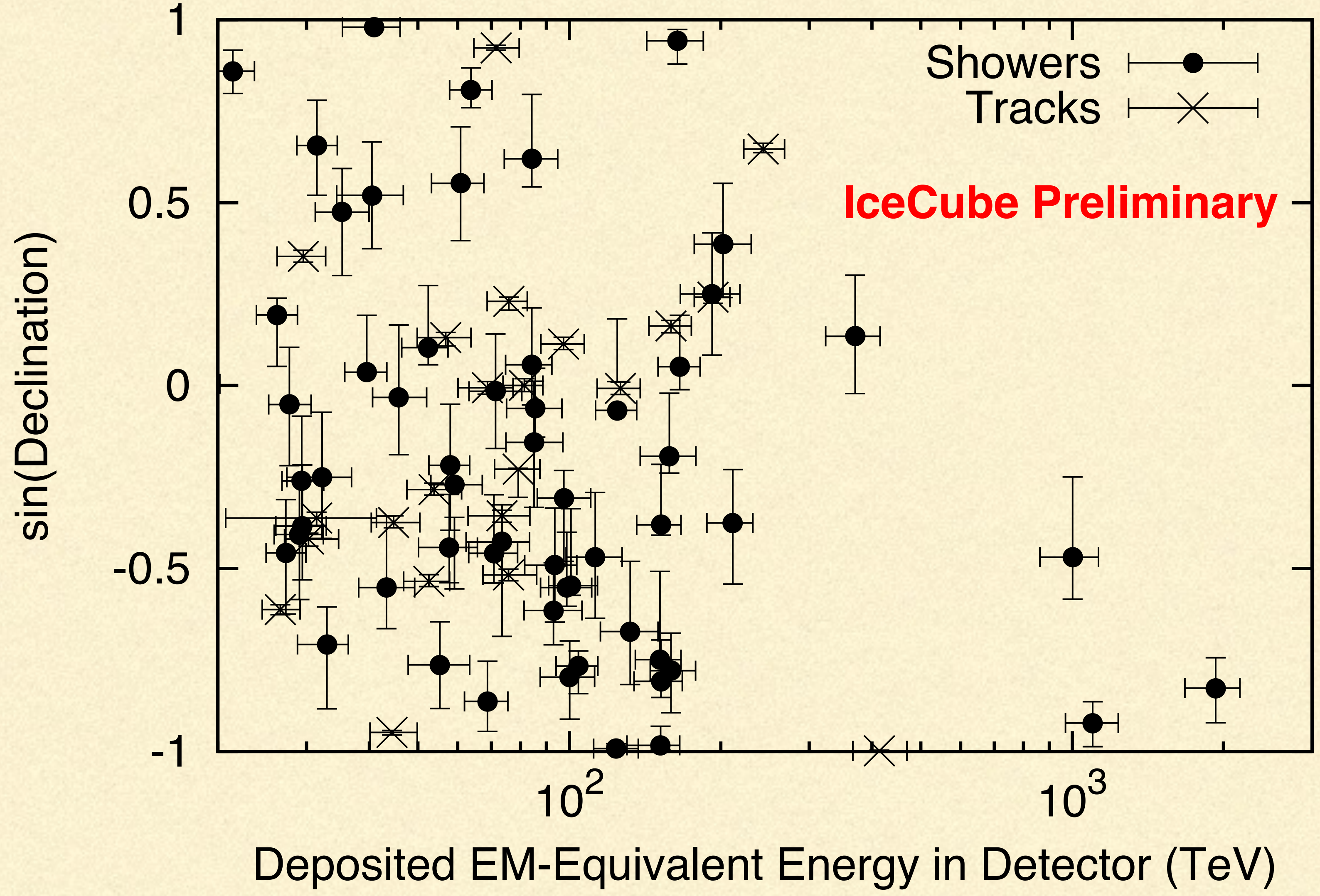
$\Phi(E) \sim 2.5 \cdot 10^{-8}\, E^{-2.9}$

IceCube, ICRC 2017, NU060

Starting events……..6 years

80 (+2) events observed, mix of track (muon) and cascades.

Expected background: 15.6 atmospheric, 25.2 atmos muons



Angular Distribution of events is isotropic, indicating that most events are extragalactic.

Information on type of source from the track/shower event discrimination........

Pion-decay:	$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \longrightarrow$	$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$
Muon-damped:	$\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0 \longrightarrow$	$\nu_e : \nu_\mu : \nu_\tau \sim 0.22 : 0.39 : 0.39$
Neutron-decay:	$\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0 \longrightarrow$	$\nu_e : \nu_\mu : \nu_\tau \sim 0.56 : 0.22 : 0.22$

Pion/muon decay sources and muon damped sources are compatible at present, neutron decay sources are not.

Additional conclusions from observations re source class….

Constraints on GRB's as sources of UHE nu

up going ν_μ track search – 506 bursts (4 years)

all-flavor cascade search – 257 bursts (1 year)

limits on the ν flux disfavor much of the parameter space for the latest GRB models

Conclusion: ONLY <1% OF THE ASTROPHYSICAL ν FLUX CAN COME FROM GRBs

[IceCube, arXiv:1412.6510]

Additional conclusions from observations re source class….

862 blazars from the 2nd Fermi AGN catalog

as few assumptions as possible

track analysis 2009 – 2011

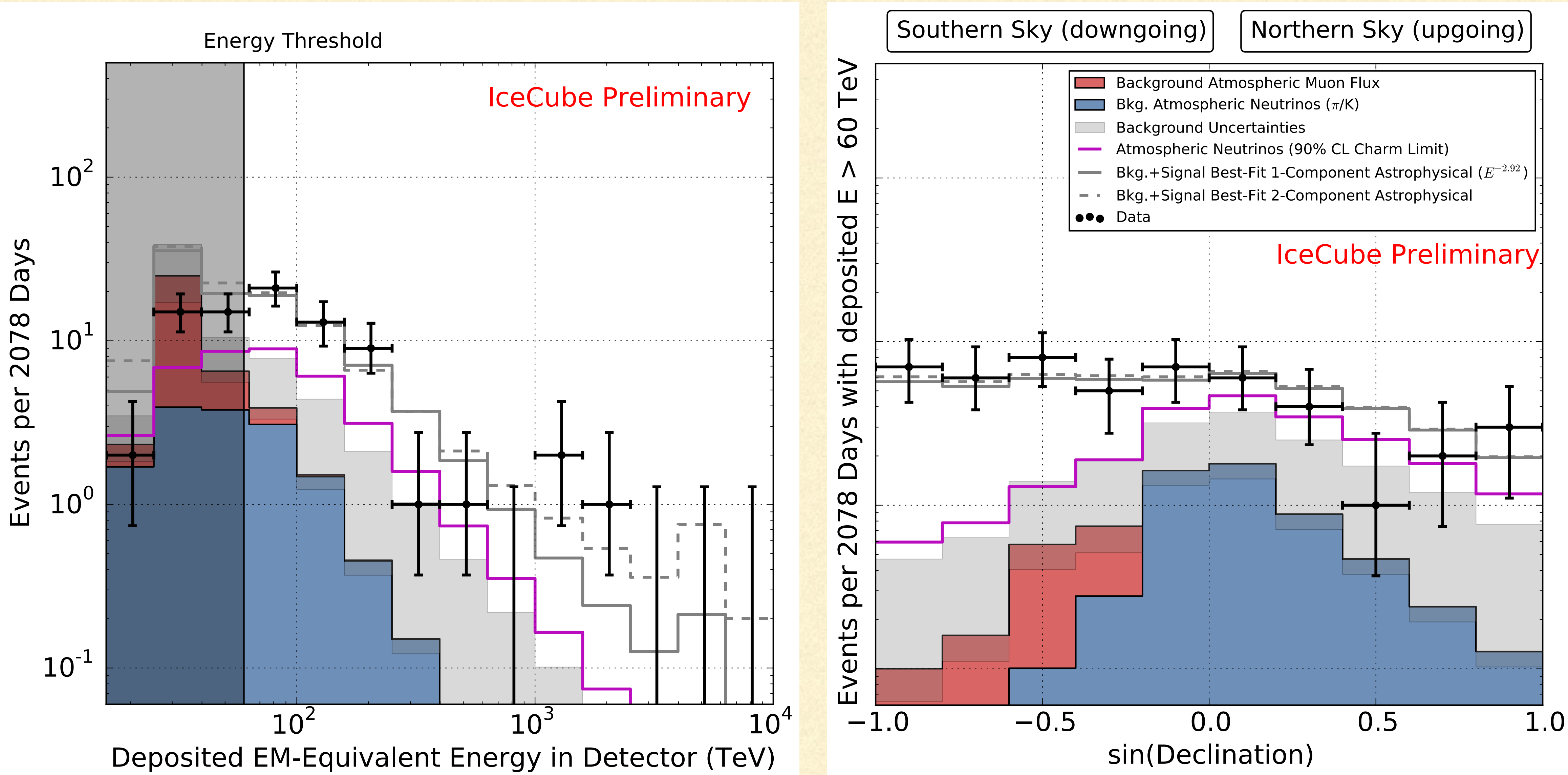
estimate of max. signal from the entire population

compare with $E^{-2.5}$ energy spectrum

Conclusion:ONLY <20% OF THE ASTROPHYSICAL ν FLUX CAN COME FROM BLAZARS

[T. Glüsenkamp, RICAP 2014, proceedings]

HESE events ……6 yr data available



(a) deposited energies

(b) arrival directions

37 events in 3 years

$\Phi(E) \sim 1.5 \cdot 10^{-8} E^{-2.3}$

IceCube, PRL 113, 2014

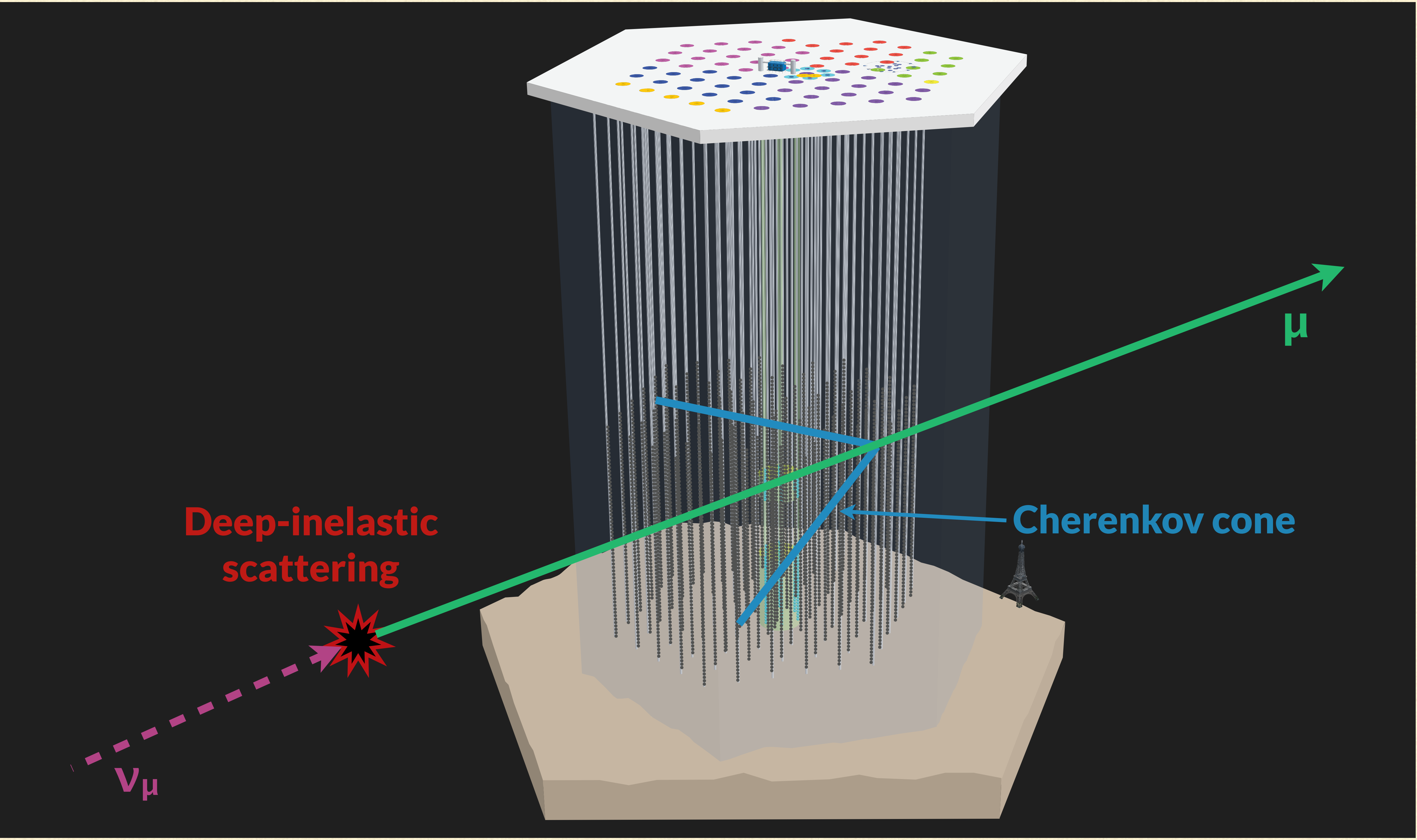
→

82 events in 6 years

$\Phi(E) \sim 2.5 \cdot 10^{-8} E^{-2.9}$

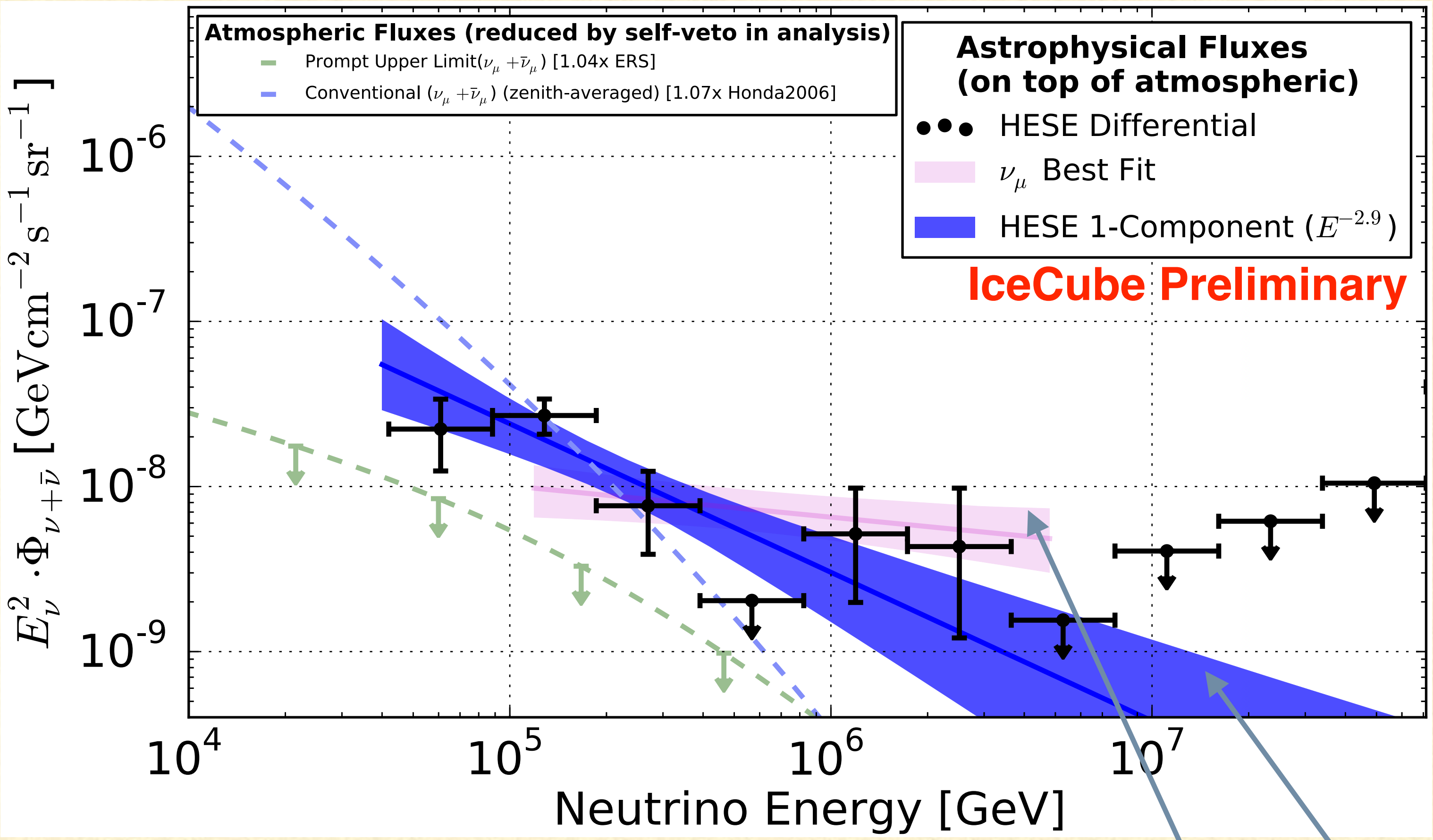
IceCube, ICRC 2017, NU060

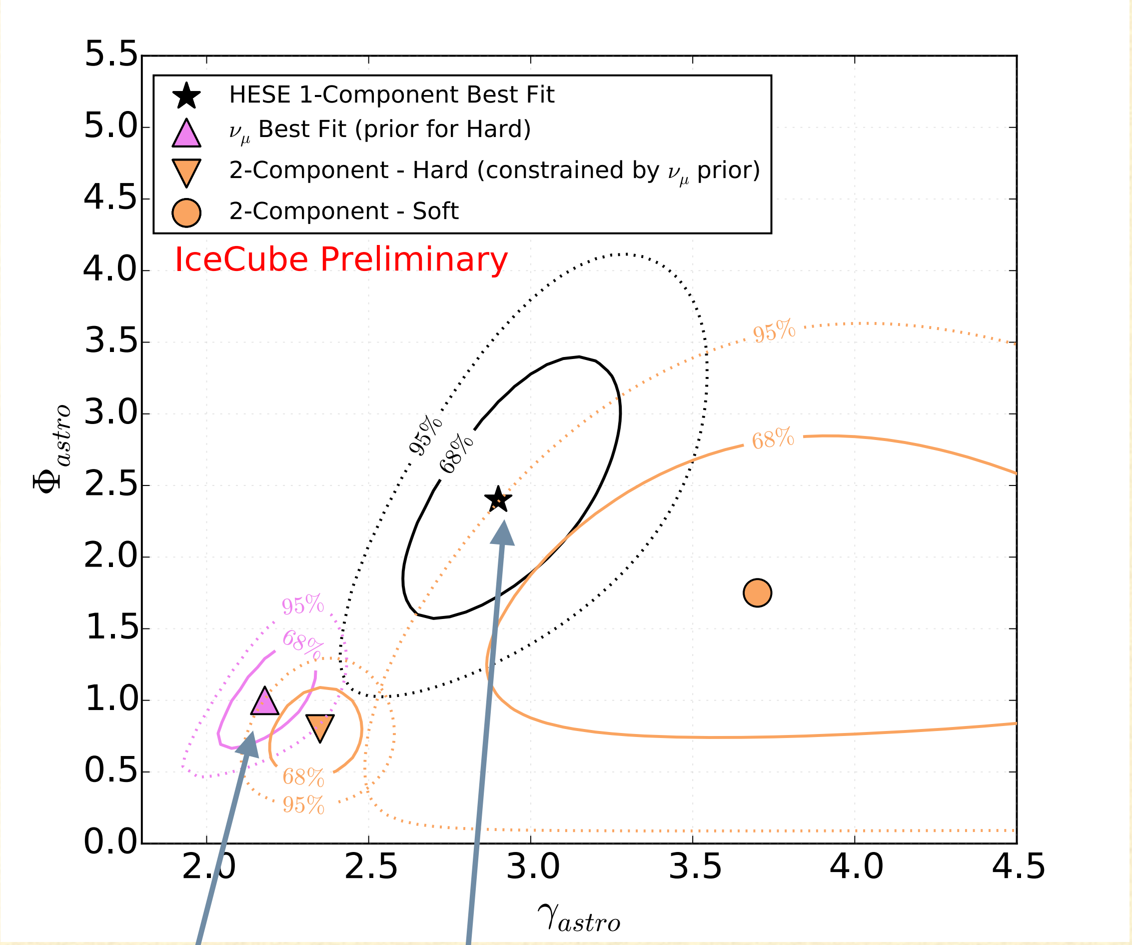
Through-Going VHE muon track events ……8 yr data available



Slide from C Kopper, ICRC 2017

Questions/Issues: Power-law behavior of observed neutrino fluxes…..



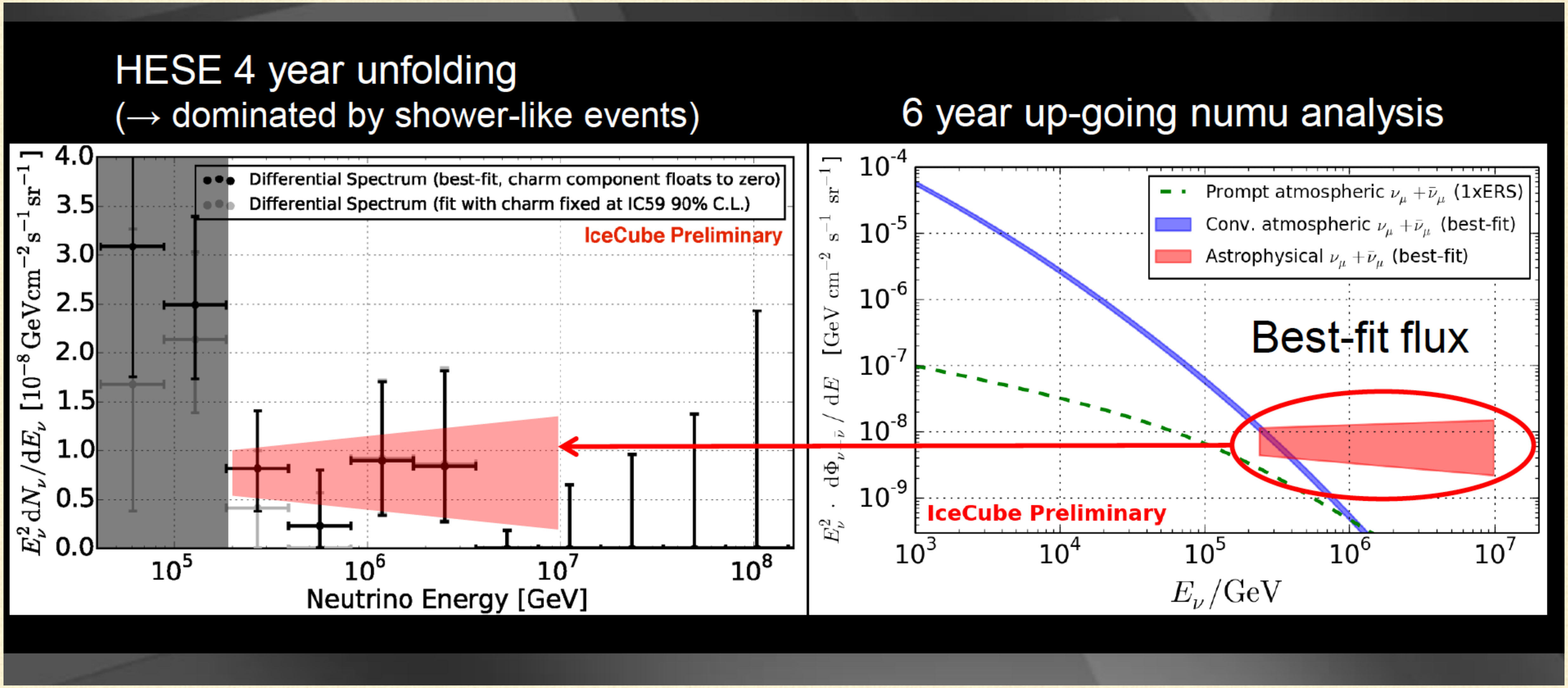


It is widely believed that UHE neutrinos are produced in charged pion decays produced in pp and or pγ interactions in the source. Such neutrinos are expected to follow a E^{-2} spectrum

However….

Power-law behavior (index) of 8 yr up-going muon data and HESE data significantly different.

Questions/Issues: Power-law behavior of observed neutrino fluxes…..



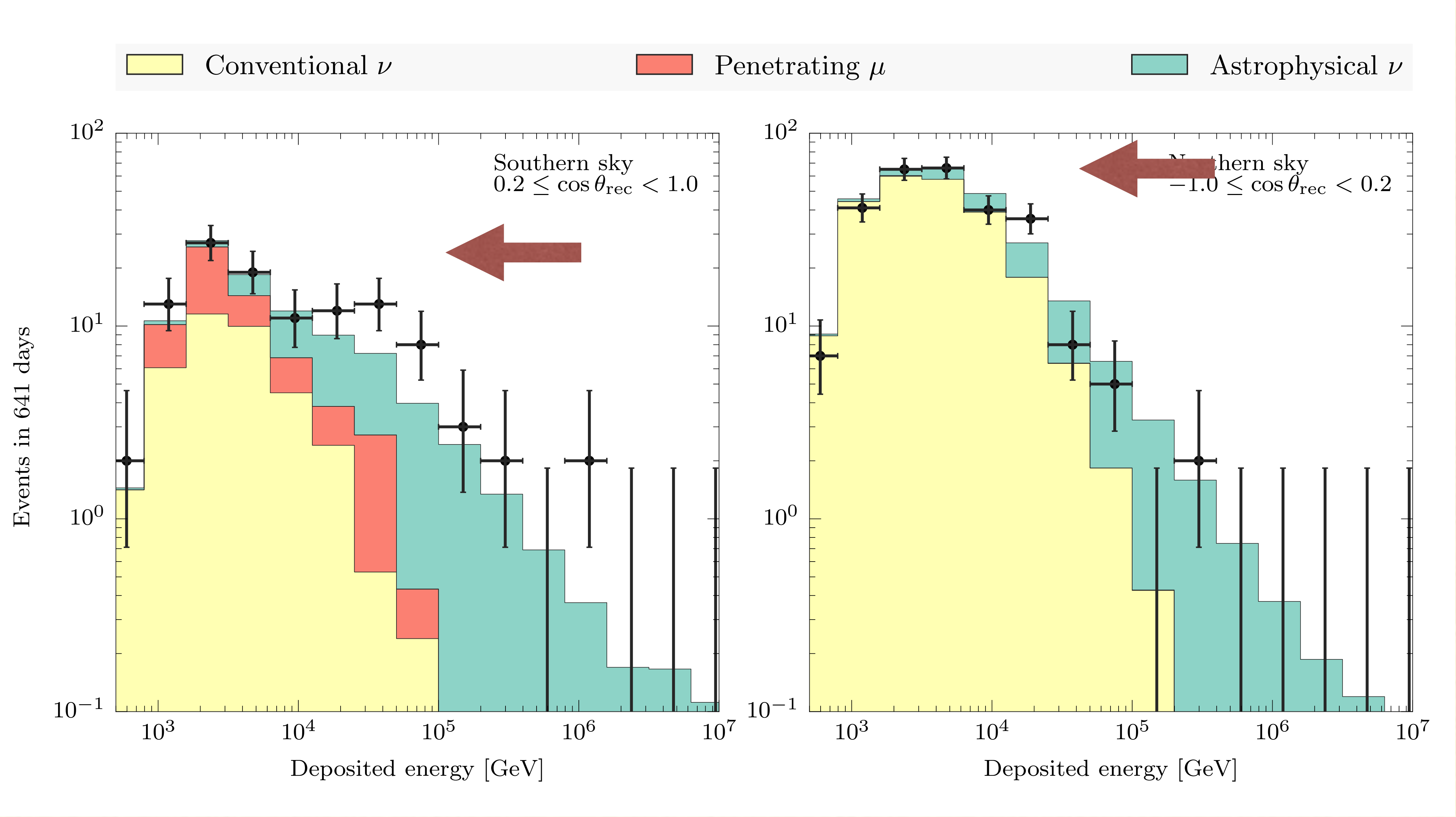
Power-laws of the HESE and thoroughgoing muon fluxes seem consistent with each other only above 100 TeV, and with Fermi shock acceleration.

Difficult, in this way of looking at the data, to understand the 30-100 TeV data (MESE), or use single power-law for all data.

New physics? (Talk by D Marfatia, this session)

Questions/Issues: Excess in 30-100 GeV region………

At lower energies, in the range of 30 – 100 TeV, there appears to be an excess, with a bump-like feature (compared to a simple power-law spectrum), which is prominently present in events from the southern hemisphere, but also visible in events from the northern hemisphere.The maximum local significance of this excess is about 2.3σ.

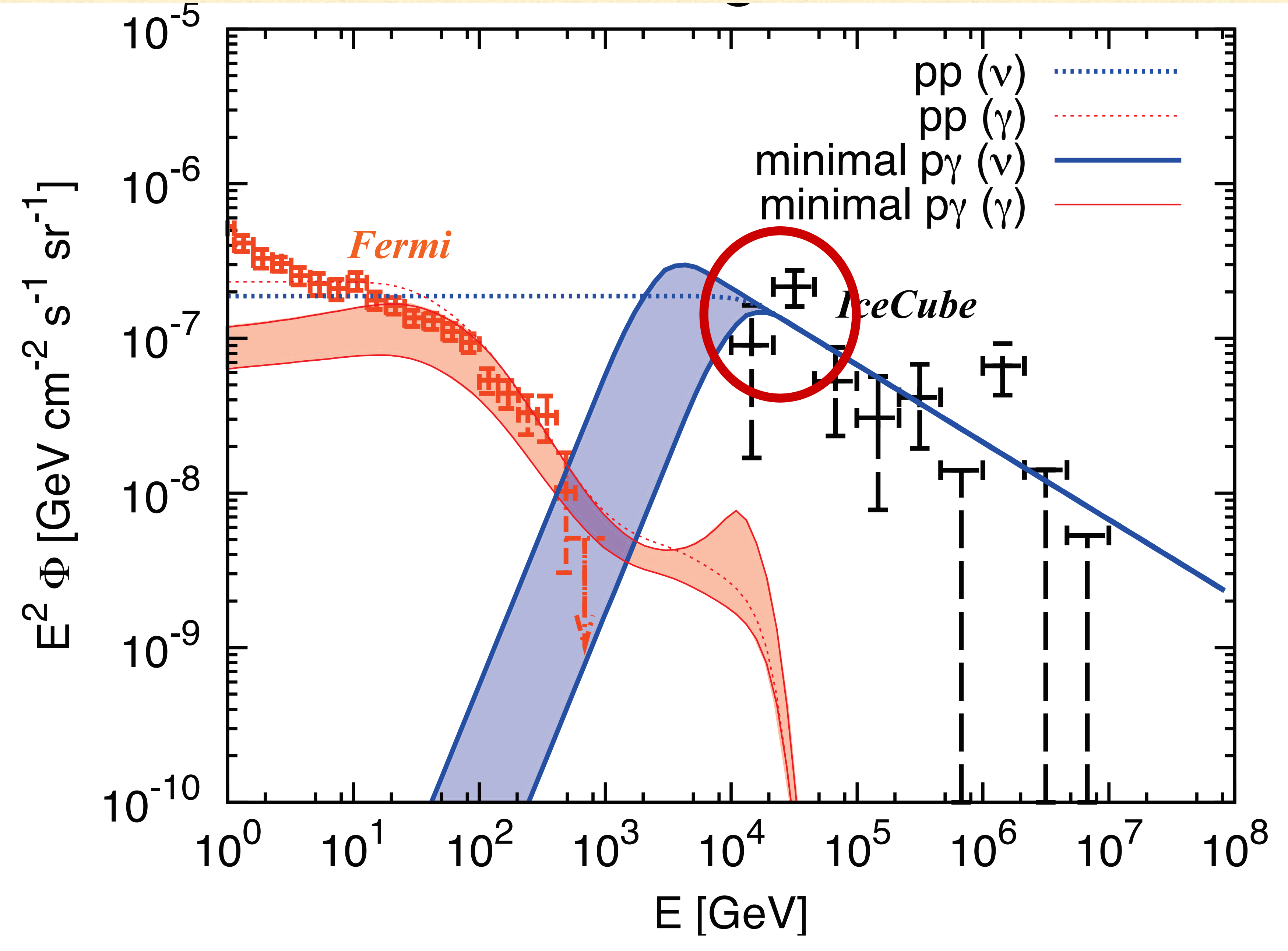


Fermi Gamma-ray data in tension with IC neutrino data in >30 TeV range………

For any source, the same processes that produce charged pions which decay to give you the UHE neutrino flux also produce neutral pions which decay to HE photons.

This leads to a natural co-relation

between the ν and the γ fluxes.



For both pp and pγ sources, the observed neutrino flux in IC in the 30-100 TeV region exhibits strong tension with Fermi gamma ray (IRGB) data in GeV region.

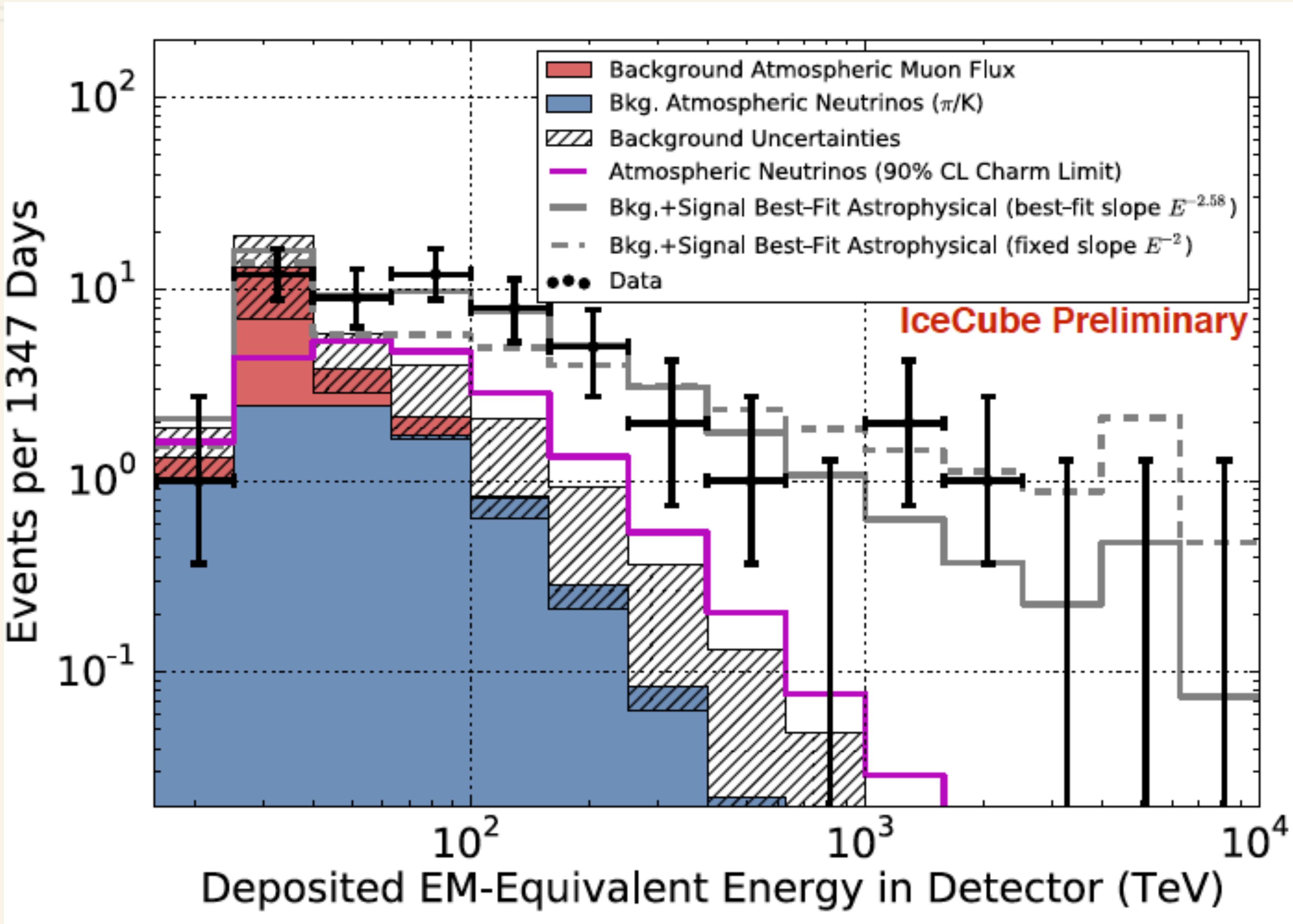
This implies either "dark" or opaque sources, or new physics.

(Talk by Aritra Gupta today in WG3 +WG5 session)

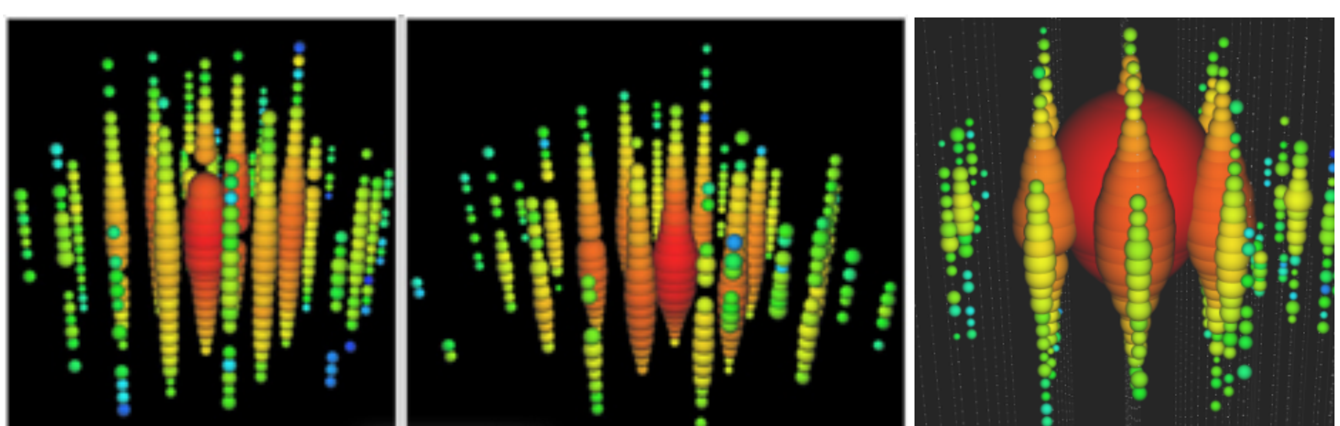
IceCube Results…………Some interesting features

Three cascade events in ~ 1-2 PeV region.

Temporally separated by months



IC has high sensitivity between 1-10 Pev, yet no events beyond ~ 2PeV, although ~2-3 expected due to Glashow Resonance



"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

No events between 400 TeV and 1 PeV

Conclusions……

With 6 years of data on astrophysical neutrinos, IceCube is already making interesting physics statements re UHE neutrino spectra, fluxes and sources. This will continue to strengthen with more data.

- At present the data tell us that
- expected E^-2 spectrum is disfavored at very high significance, if single power-law fit attempted. there appears to be tension between muon only track spectrum and the cascades (spectral index of -2.1 vs -2.92)
- There seems to be an excess at ~30-100 TeV in all flavor spectrum. PeV events seem isolated from fit.
- the neutrinos cannot come from neutron decay sources

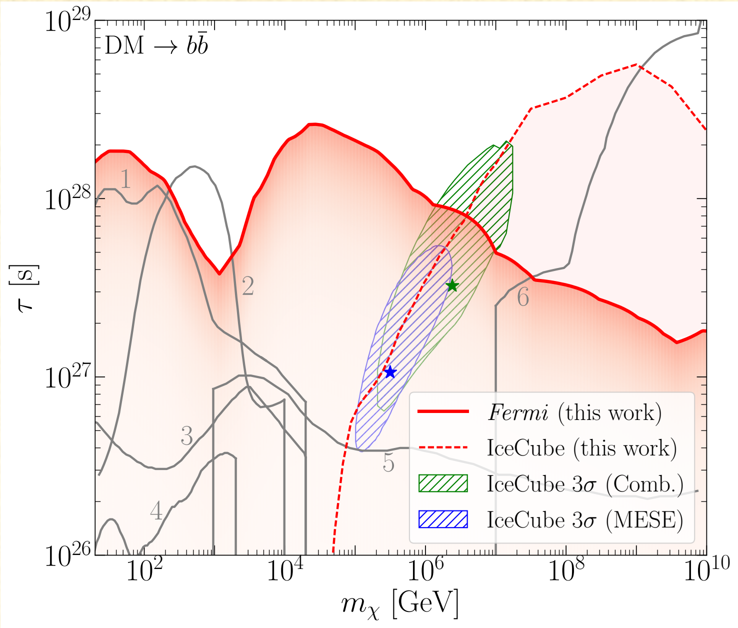
  that GRBs, once considered important sources, cannot account for more than 1% of the astrophysical flux, nor can blazars account for more than 20% of the flux
- Source/sources remain unknown.

What more may be gleaned from the data so far?.....

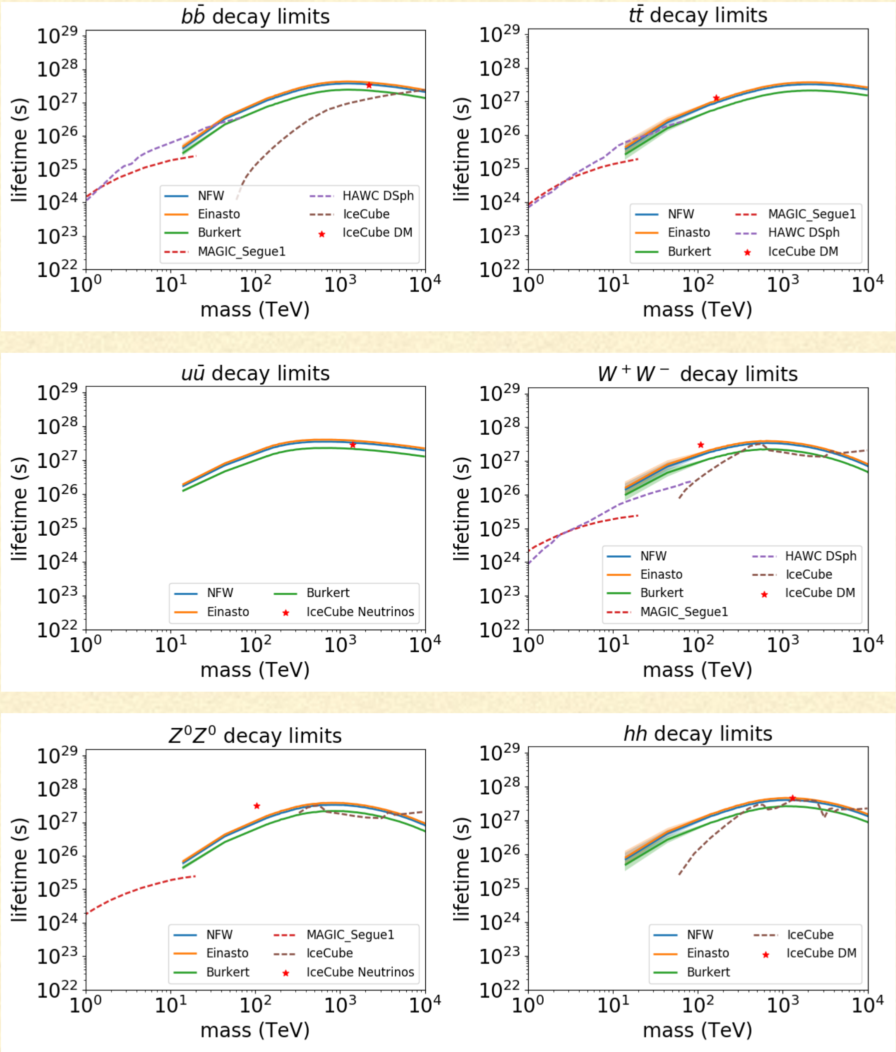
It is possible that the power-law fit incompatibilities and the excesses are pointing to the presence of more than one component.

Much work has gone into interpreting the spectrum and excesses as also coming from DM decay into neutrinos.

These interpretations are also subject to and tightly constrained by gamma-ray observations.



Constraints from FERMI



Constraints from HAWC

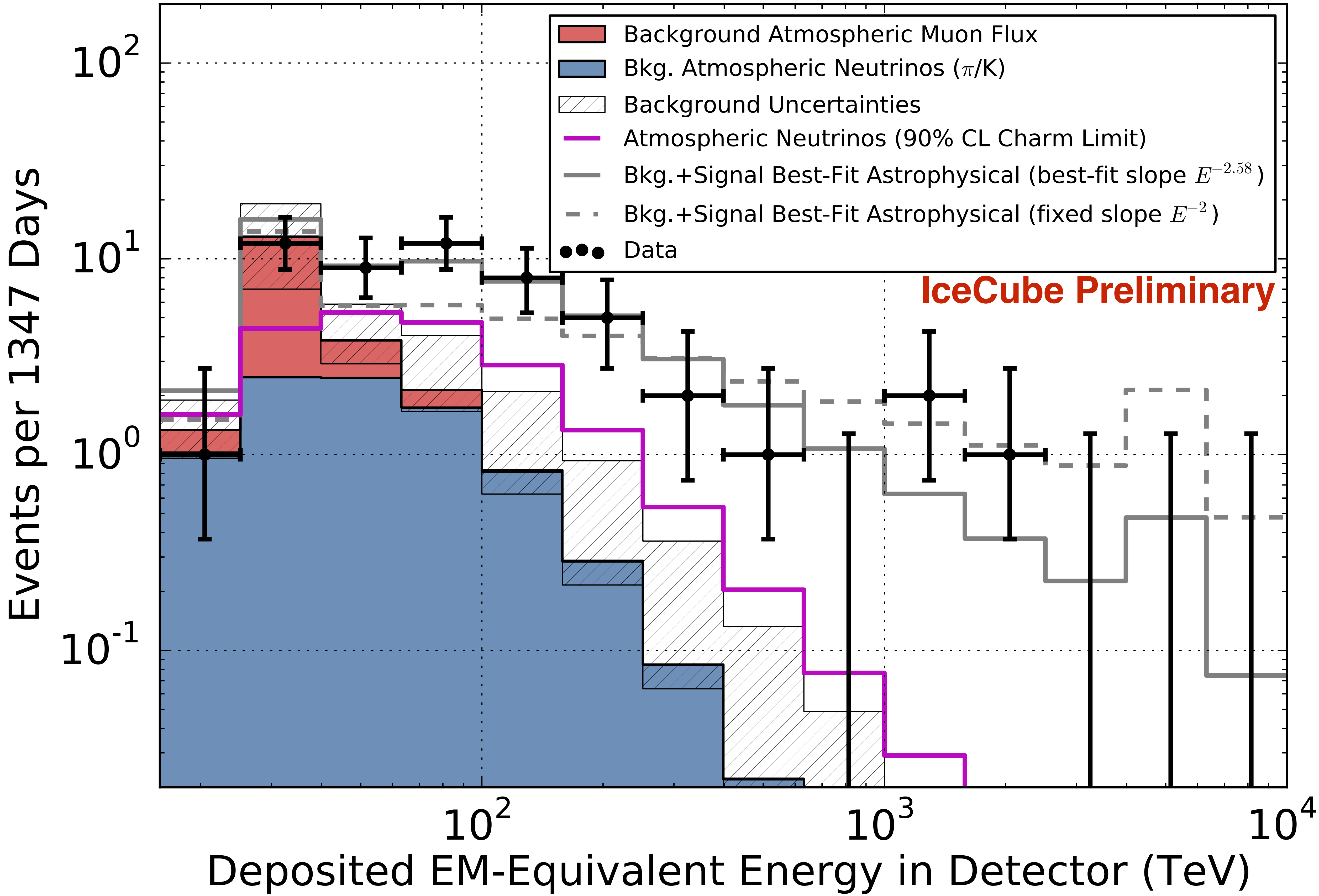
More on this in WG session.......

The important question that will be addressed with more data is :

Is IceCube pointing to important new physics, or will more stats show conformity with standard astrophysical origins of UHE neutrinos?

(More on this in today's WG3 +WG5 session)

Thank you for your attention!



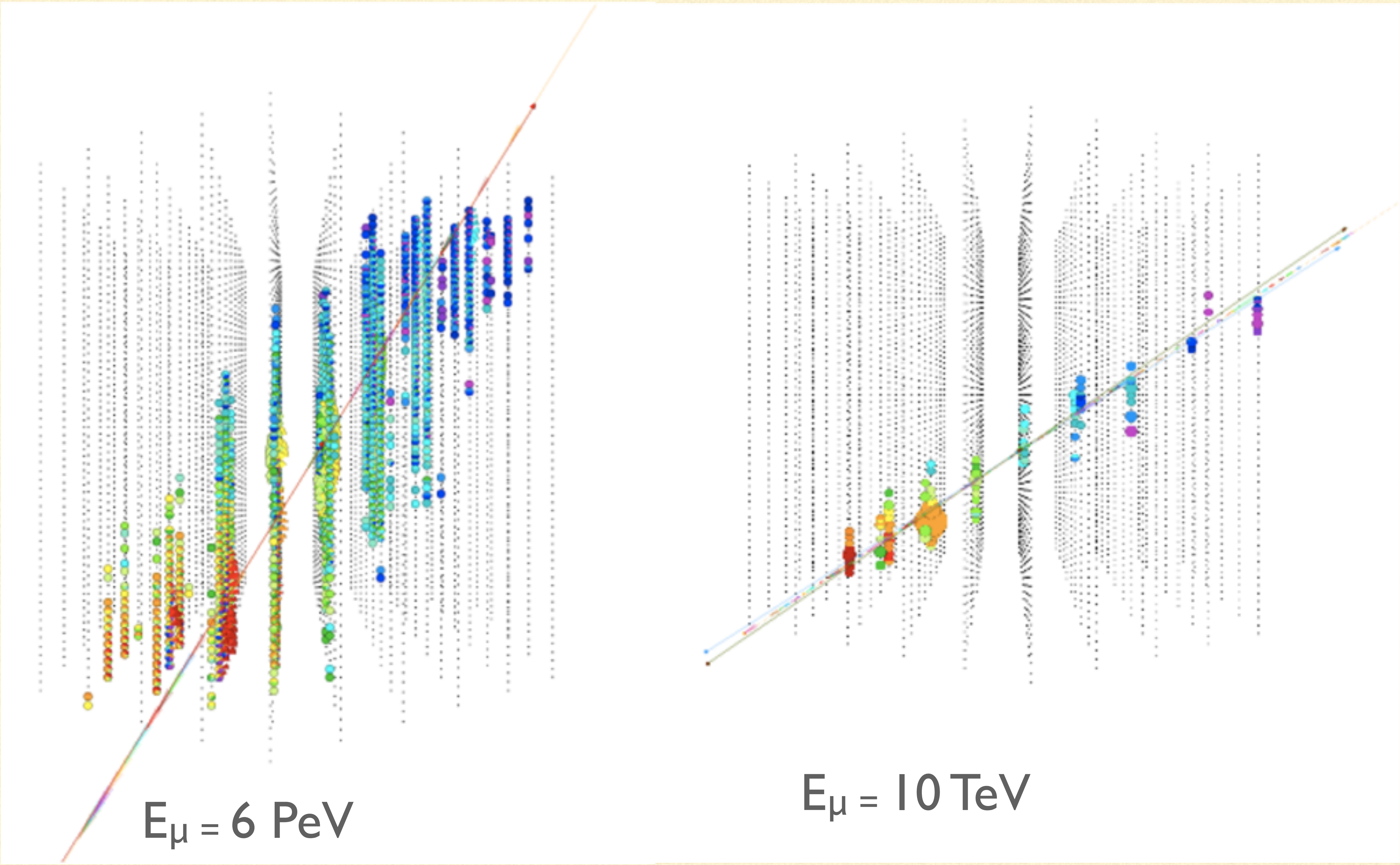
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
Bkg.+Signal Best-Fit Astrophysical (fixed slope E^{-2})
Data
IceCube Preliminary
Events per 1347 Days
Deposited EM-Equivalent Energy in Detector (TeV)

Why are they interesting?.......

The highest energies in Nature are believed to reside in dense astrophysical environments.

The study of UHE neutrinos produced in these environments is a window to fundamental physics at the highest energies.

Signals in Icecube….. Muon energy measurement



Measure energy by counting the number of fired PMT.
(This is a very simple but robust method)

While gamma-rays, neutrinos & cosmic rays inject similar energies into the universe, common sources are still to be discovered.

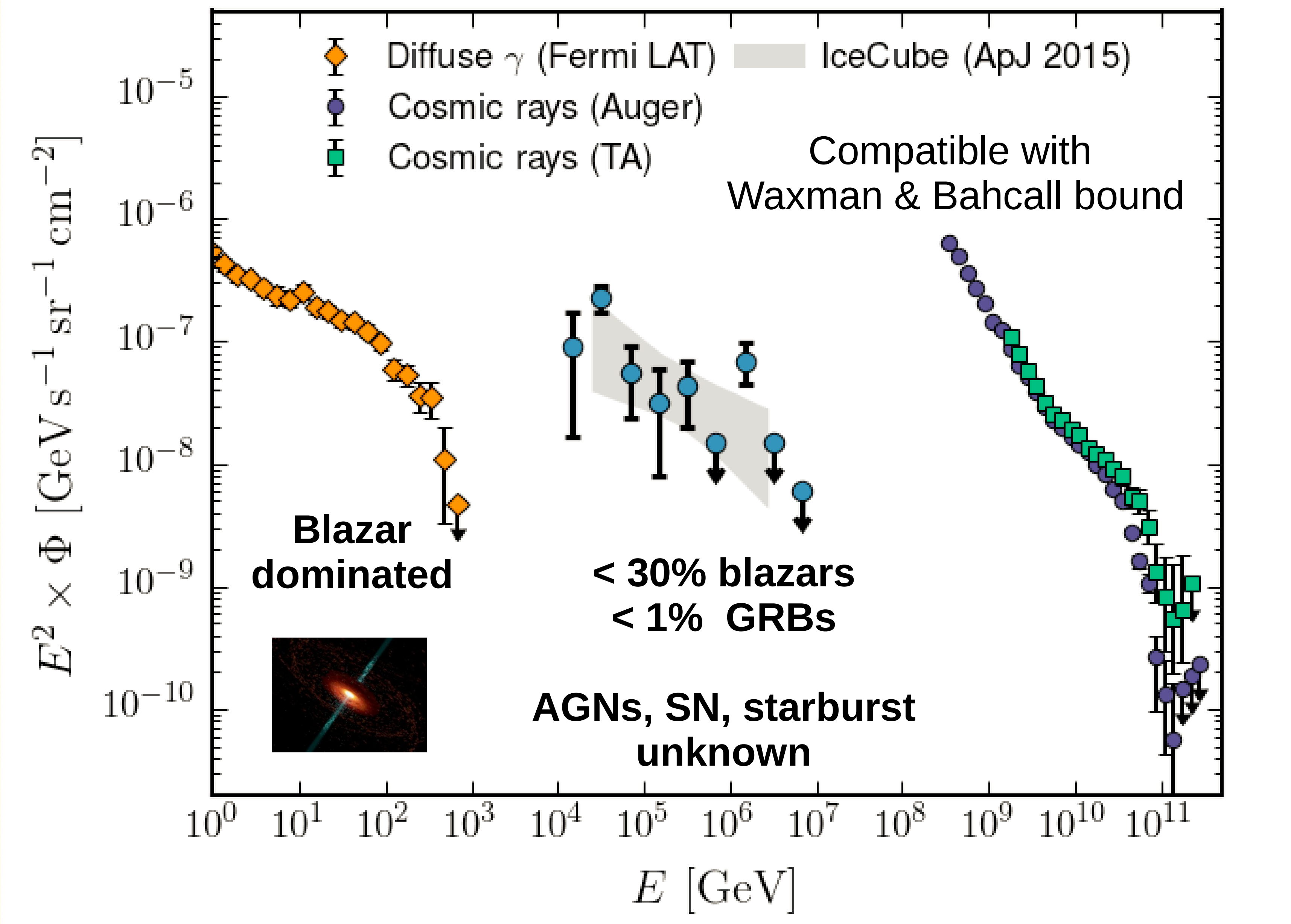


Fig. adapted from L. Mohrmann

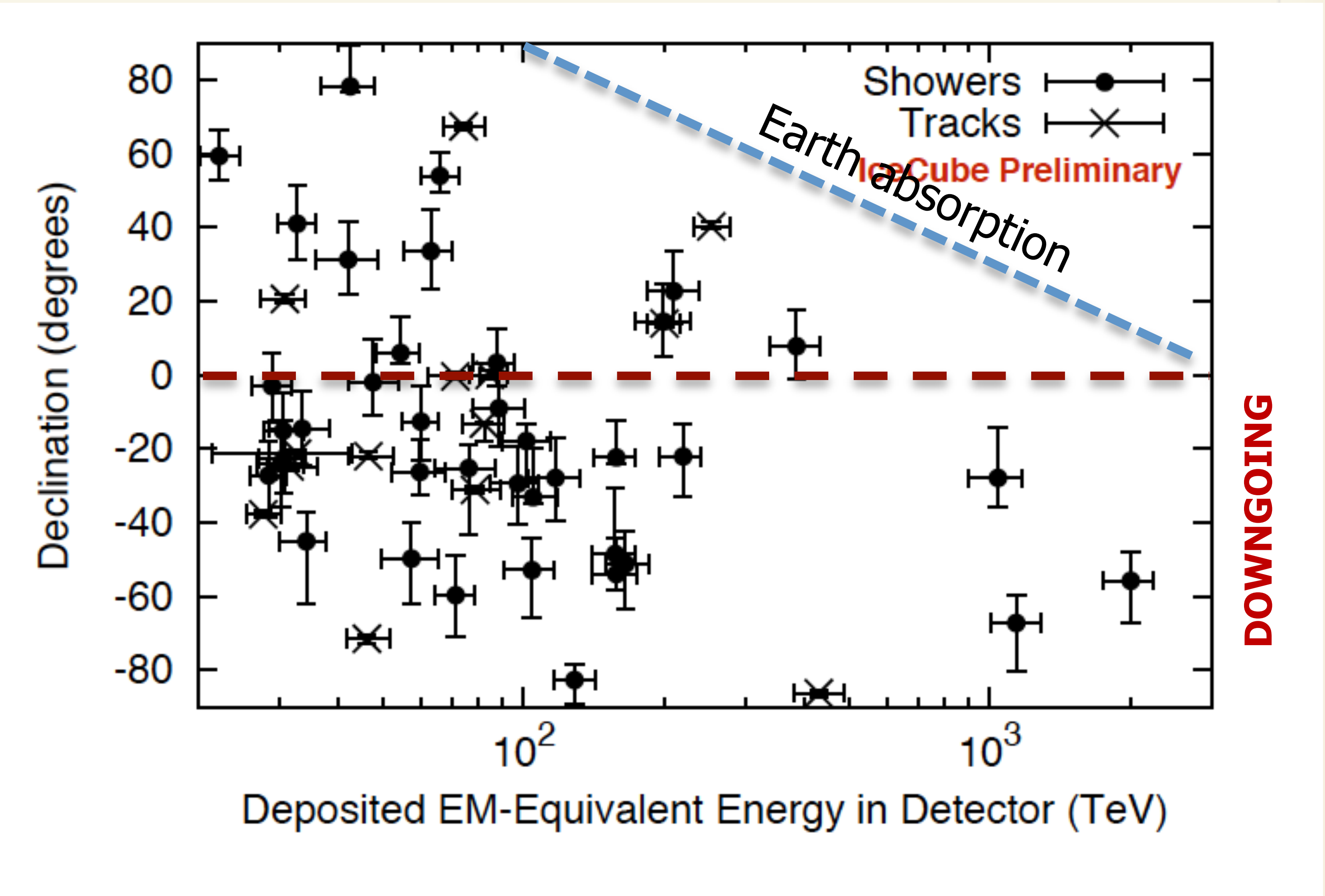
IceCube Results...............

3 yrs: 37 events in 988 days

bkg. 6.6+5.9 atm ν, 5.7 sigma evidence for astrophysical neutrino signal

4 yrs: 54 events ~ 7 sigma evidence

Mostly νe CC and NC cascades



Zenith distribution consistent with isotropic astrophysical flux

•

What are the sources for astrophysical neutrinos?…….

No correlation with any source class established so far…….

- **Galactic:** (full or partial contribution)
  - diffuse or unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [MA & Murase'13; Neronov, Semikoz & Tchernin'13;Neronov & Semikoz'14; Guo, Hu & Tian'14]
  - extended Galactic emission [Su, Slatjer & Finkbeiner'11; Crocker & Aharonian'11] [Lunardini & Razzaque'12;MA & Murase'13; Razzaque'13; Lunardini *et al.*'13] [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein *et al.*'13; Esmaili & Serpico '13; Bai, Lu & Salvado'13]
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13] [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - active galactic nuclei (AGN) [Stecker'91,'13;Kalashev, Kusenko & Essey'13] [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14;Kalashev, Semikoz & Tkachev'14]
  - gamma-ray bursts (GRB) [Murase & Ioka'13]
  - starburst galaxies [Loeb & Waxman'06; He *et al.*'13;Yoast-Hull, Gallagher, Zweibel & Everett'13] [Murase, MA & Lacki'13; Anchordoqui *et al.*'14; Chang & Wang'14]
  - hypernovae in star-forming galaxies [Liu *et al.*'13]
  - galaxy clusters/groups [Murase, MA & Lacki'13;Zandanel *et al.*'14]
  - . . .

Slide from M. Ahlers, NeuTel 2015

Energy spectrum and flavor composition in a joint fit

M. G. Aartsen et al. (IceCube Collaboration) arXiv: 1507.03991

Assume isotropic flux

Benchmark model: Fermi acceleration at shock fronts

→ $\Phi_\nu \propto E^{-2}$

$$\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$$ Hypothesis A

$$\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma} \times \exp(-E/E_{\mathrm{cut}})$$ Hypothesis B

Combine results from **8 different searches**

ID	Signatures	Observables	Period
T1	throughgoing tracks	energy, zenith	2009–2010
T2	throughgoing tracks	energy, zenith	2010–2012
S1	cont. showers	energy	2008–2009
S2	cont. showers	energy	2009–2010
H1*	cont. showers, starting tracks	energy, zenith	2010–2014
H2	cont. showers, starting tracks	energy, zenith, signature	2010–2012
DP*	double pulse waveform	signature	2011–2014
PS*	part. cont. showers	energy	2010–2012

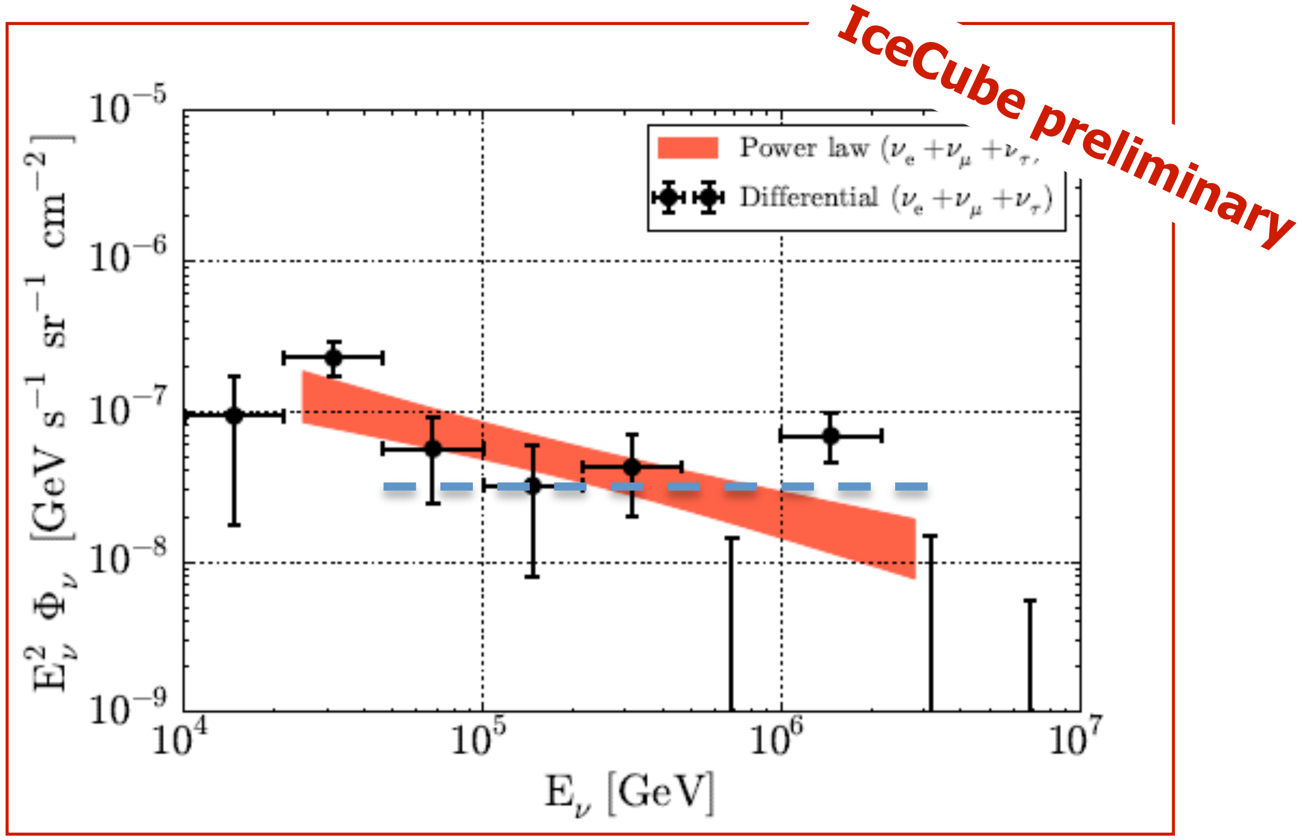
Pion-decay: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$

Muon-damped: $\nu_e : \nu_\mu : \nu_\tau = 0:1:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 0.22:0.39:0.39$

Neutron-decay: $\nu_e : \nu_\mu : \nu_\tau = 1:0:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 0.56:0.22:0.22$

Pion/muon decay flux and muon damped fluxes are compatible at present, neutron decay is not.

IceCube Results……………Spectral and flavour fits



- E^{-2}, **no cut-off**
  $\Updownarrow$ $4.6\,\sigma$
- $E^{-2.49}$ **, no cut-off**
  $\Updownarrow$ $1.2\,\sigma$
- $E^{-2.31}$ **, cut-off at** $2.7\,\mathrm{PeV}$

Assume isotropic flux and $\nu_e:\nu_\mu:\nu_\tau=1:1:1$

Best fit hypothesis A:

all-flavor!

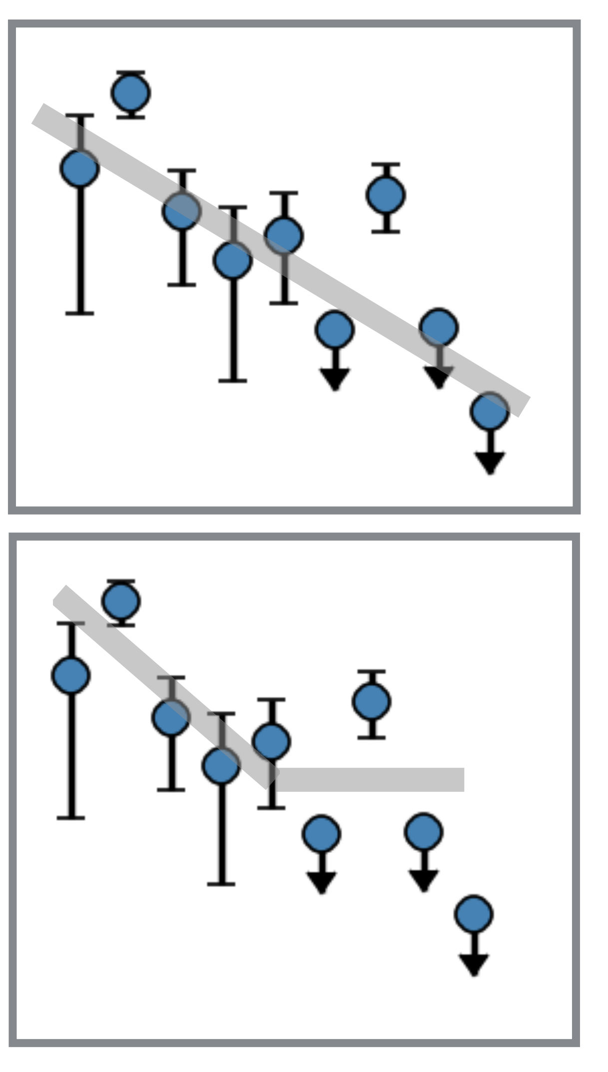
- $$\Phi_\nu=\left(7.0^{+1.0}_{-1.0}\right)\times10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}\times\left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.49\pm0.08}$$
- E^{-2} excluded at $4.6\,\sigma$

Best fit hypothesis B:

all-flavor!

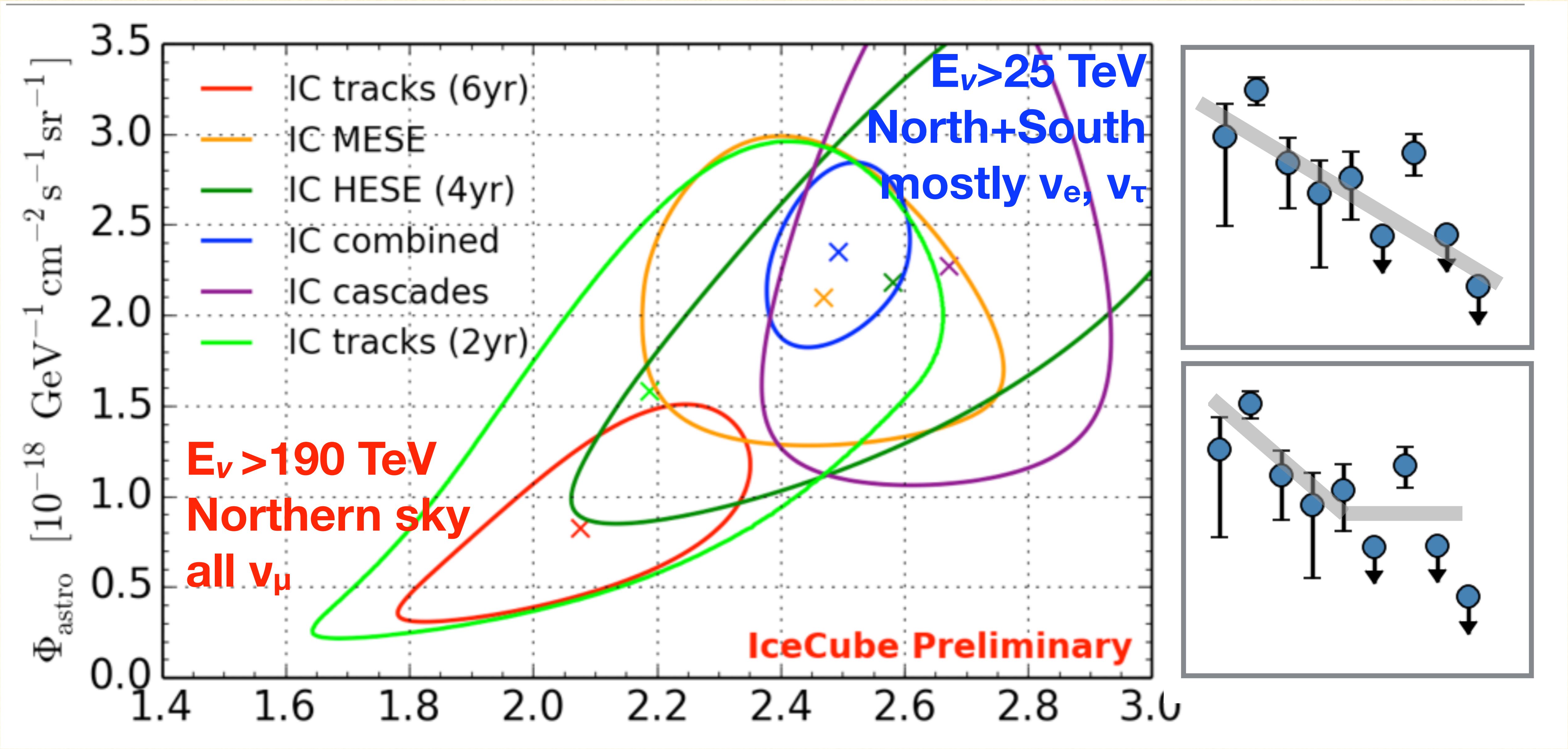
- $$\Phi_\nu=\left(8.0^{+1.3}_{-1.2}\right)\times10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}\times\left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.31\pm0.15}\times\exp\left(-E/\left(2.7^{+7.7}_{-1.4}\right)\,\mathrm{PeV}\right).$$
- preferred over hypothesis A by $1.2\,\sigma$

Features in IceCube data.....



Below 1 PeV, there appears to be a dip in the spectrum, with no events between roughly 400 TeV and 1 PeV.[4]

Features in IceCube data.....More than one flux?



An important constraint on neutrino fluxes: The Waxman Bahcall bound

hep-ph/9807282, hep-ph/9902383

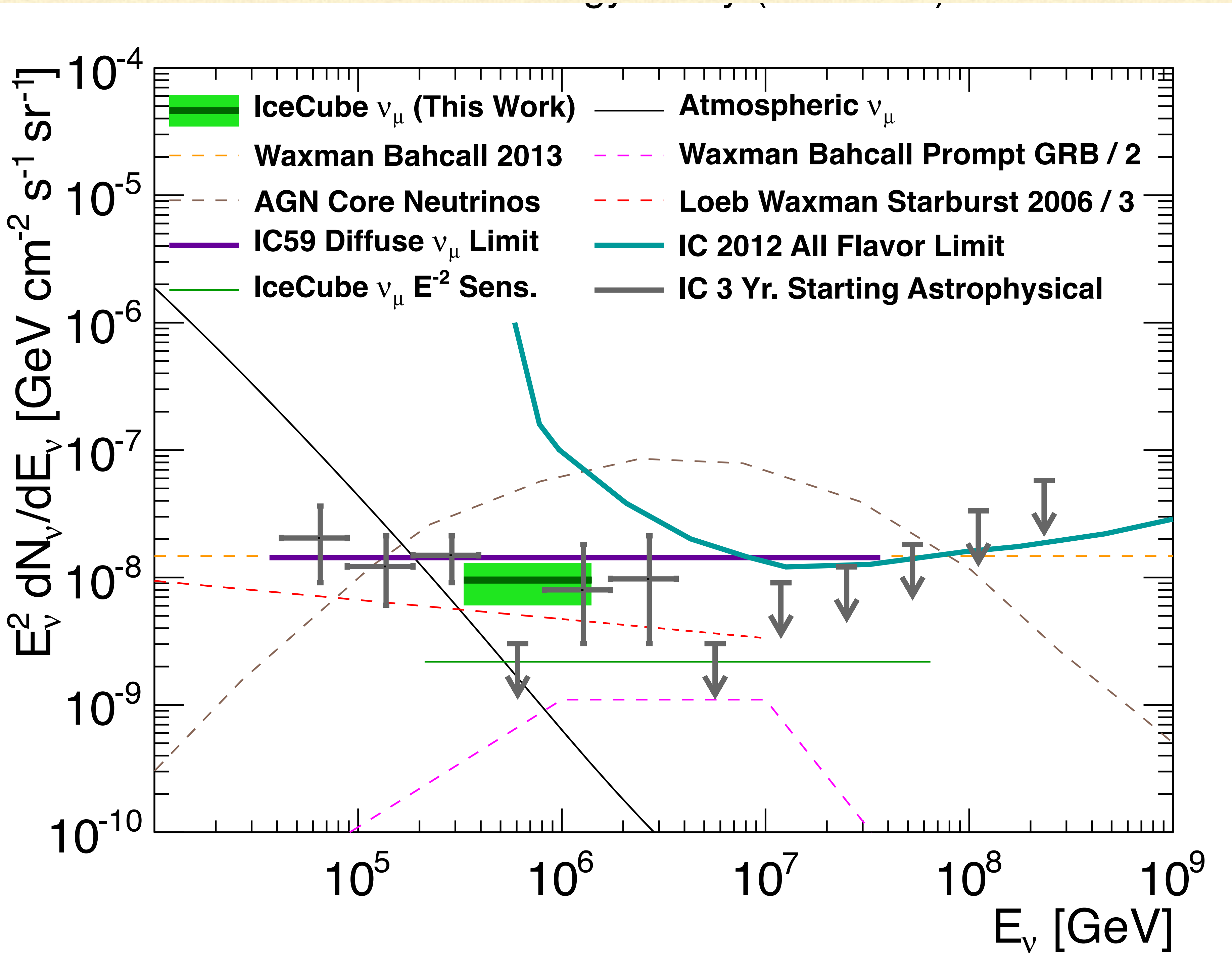
Assuming that the production of CR via p-p and p-gamma interactions is linked to that of neutrinos, the flux of UHE neutrinos is bounded by the observed CR flux. This leads to the WB upper bound

The WB bound is valid for sources which are optically thin to proton photo-meson and proton-nucleon interactions, from which protons can escape. Such sources are characterized by an optical depth τ which is typically less than one. The bound is conservative by a factor of ~ 5/τ.

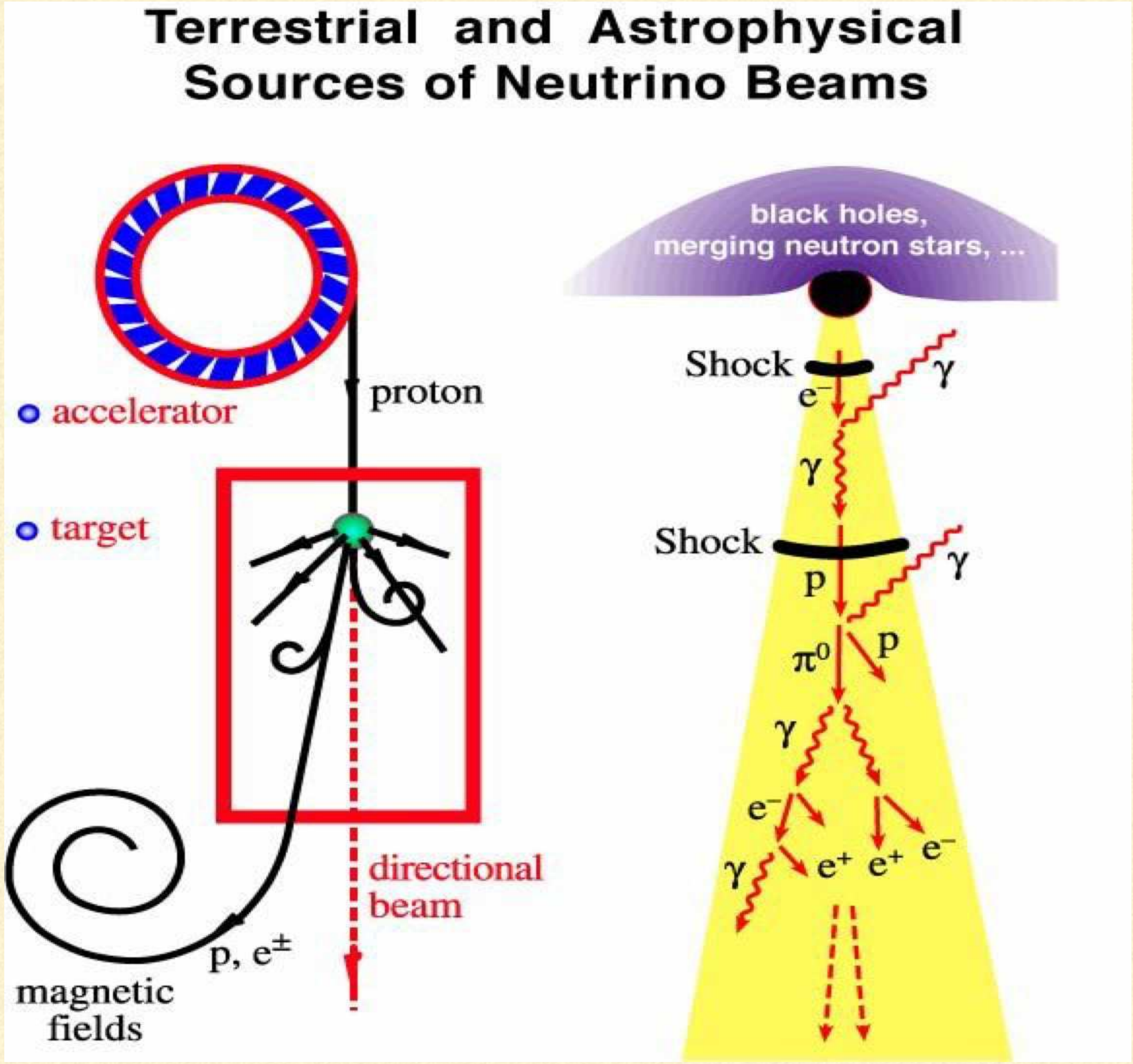
$$\begin{aligned} E_\nu^2\,\Phi_{\rm WB}^{\nu_{\rm all}} &\approx (3/8)\,\xi_z\,\epsilon_\pi\,\mathcal{T}\,\frac{c}{4\pi}\,E^2\,\frac{d\dot{n}}{dE} \\ &\approx 2.3\times10^{-8}\,\epsilon_\pi\,\xi_z\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \end{aligned}$$

Features in IceCube data.....

Proximity to WB bound is puzzling and difficult to understand



The assumed generic UHECR accelerator.....



Backup Slides

GZK (Cosmogenic) Neutrinos.... (Griesen, Zatsepin, Kuzmin, 1966)

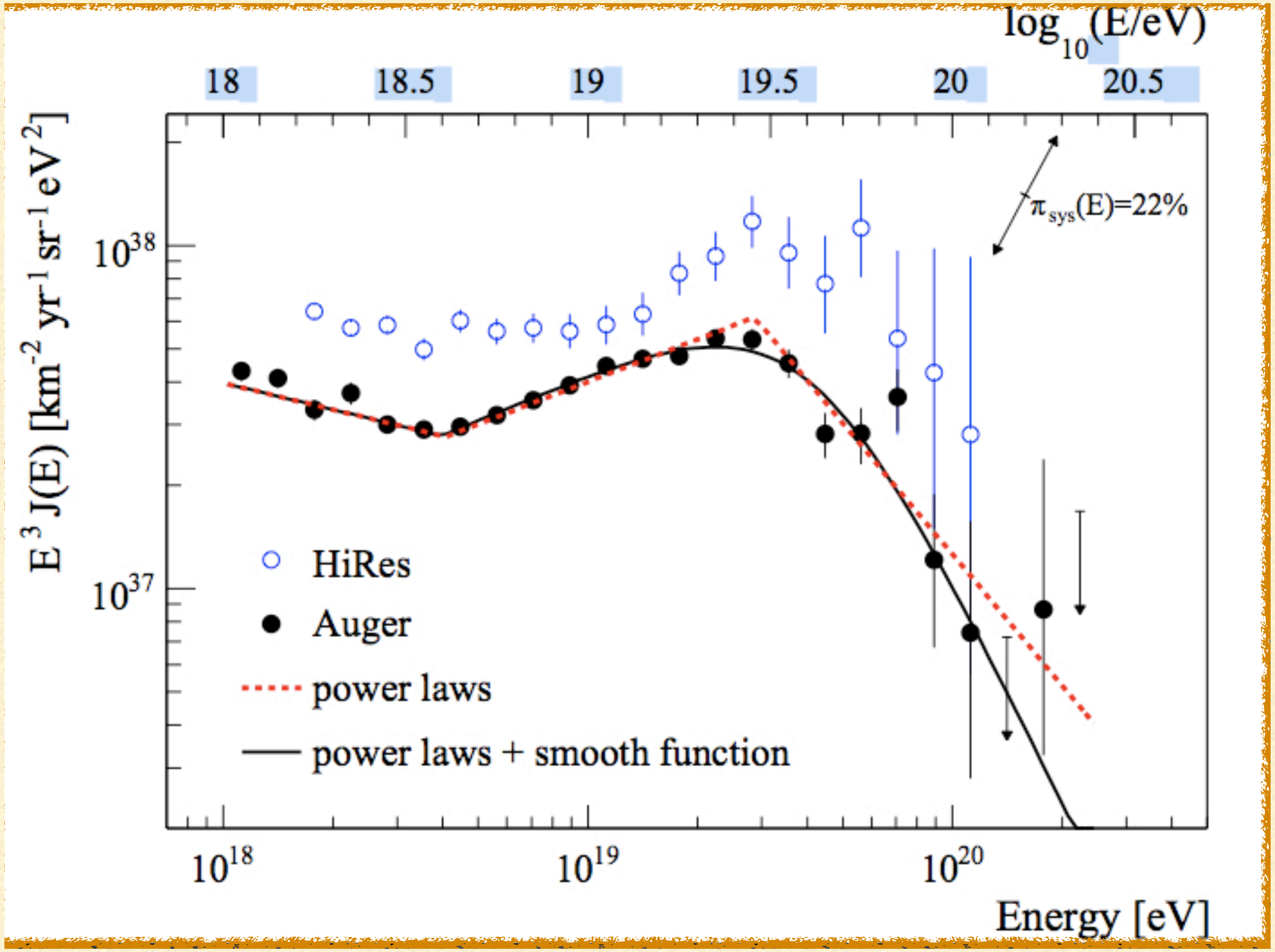
$$p + \gamma_{\rm bgr} \rightarrow \Delta(1232) \rightarrow \pi^+ + n$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$p + \gamma_{\rm bgr} \rightarrow \Delta(1232) \rightarrow \pi^0 + p$$
$$\hookrightarrow \gamma + \gamma$$

$$E^{\rm th}_{p\gamma_{\rm CMB}} = \frac{m_\pi\,(m_p + m_\pi/2)}{\omega_{\rm CMB}} \approx 6.8 \times 10^{10} \left(\frac{\omega_{\rm CMB}}{10^{-3}\ {\rm eV}}\right)^{-1}\ {\rm GeV}$$

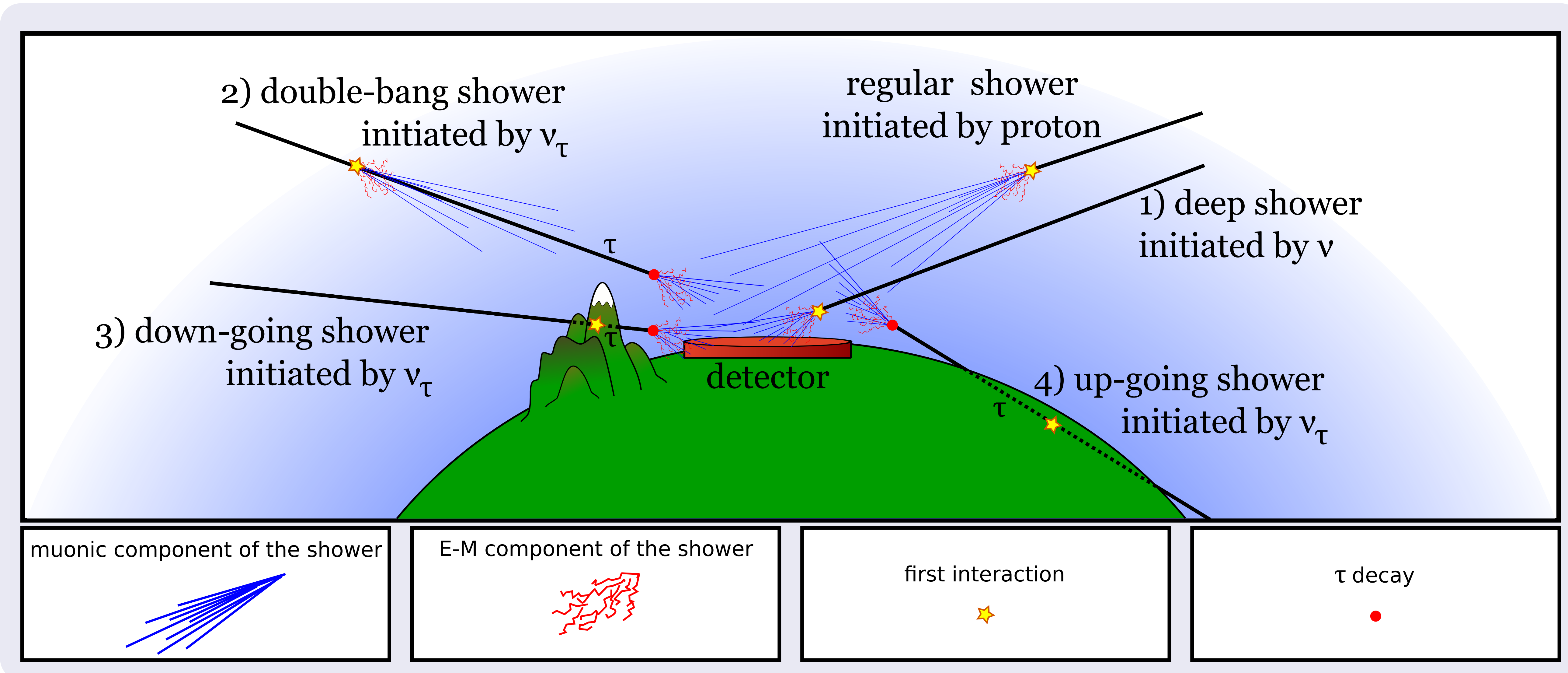
Let us note here that the neutron in the chain above will decay and give a anti-electron neutrino (useful later)

UHECR.....features at the highest energies



What Kind of Detectors are needed to see UHECR and/or UHE Neutrinos?

Signals in a surface detector.....(Auger)

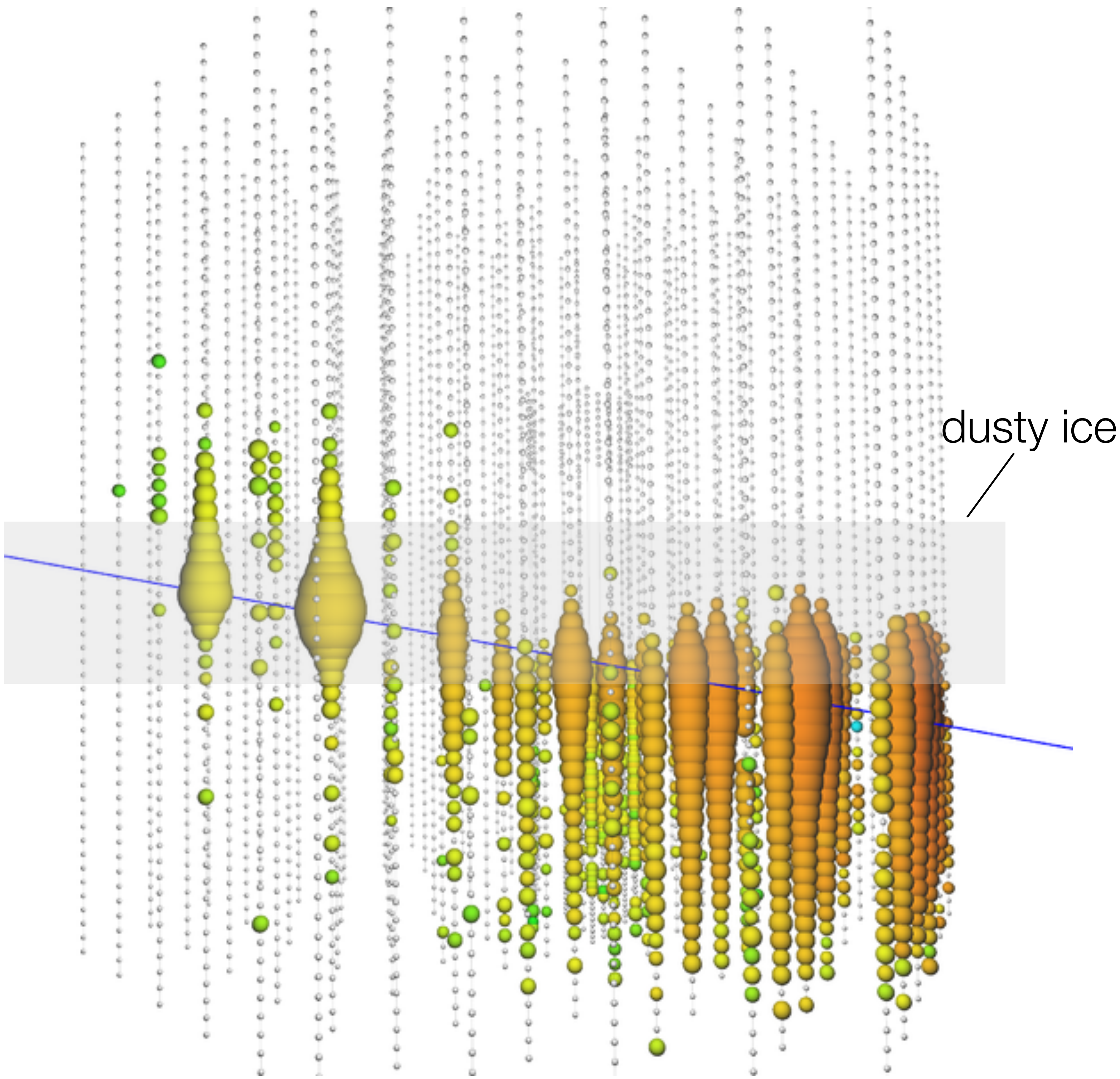


Upward-Going Muon Neutrinos

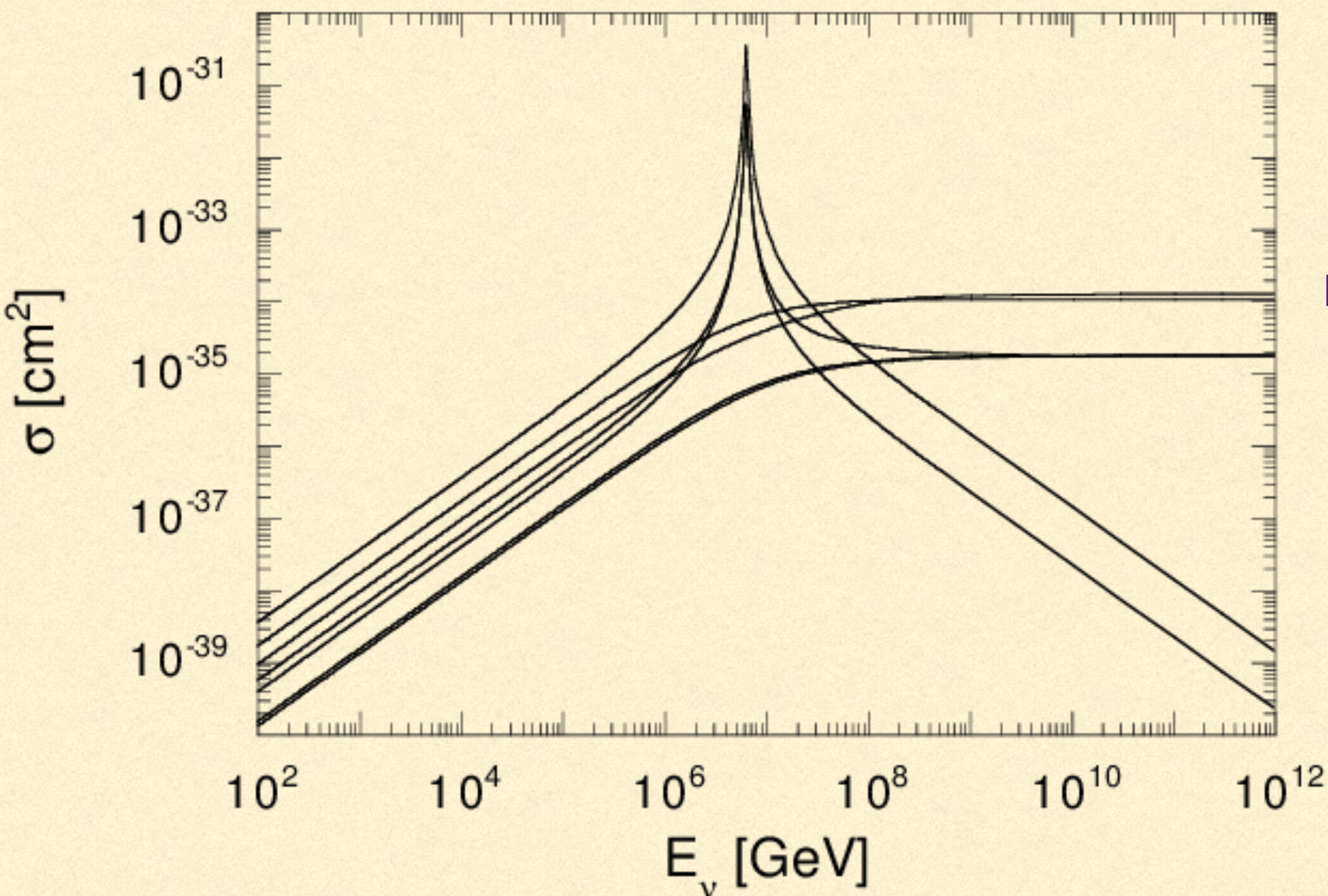
- Also observe 5.6σ excess in high-energy ν_μ passing through the Earth – completely independent observation channel

- Highest energy neutrino yet: 2.6 ± 0.3 PeV deposited in detector
  - *Lower limit on* E_ν

- Up-going track (ν_μ)
  - Declination 11.5°, 11/6/14



Neutrino Cross-sections at the Glashow Resonance



RG, Quigg, Reno and Sarcevic

The cross-sections

$\bar{\nu}_e e \rightarrow$hadrons , $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$, $\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu$, $\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau$ are resonant

We note that, at the GR........

$$\frac{\bar{\nu}_e e \to anything}{\nu_\mu + N \to \mu + anything} \approx 360$$

standard CC process total

$$\frac{\bar{\nu}_e e \to hadrons}{\nu_\mu + N \to \mu + anything} \approx 240$$

pure muon track, unique if contained initial vertex

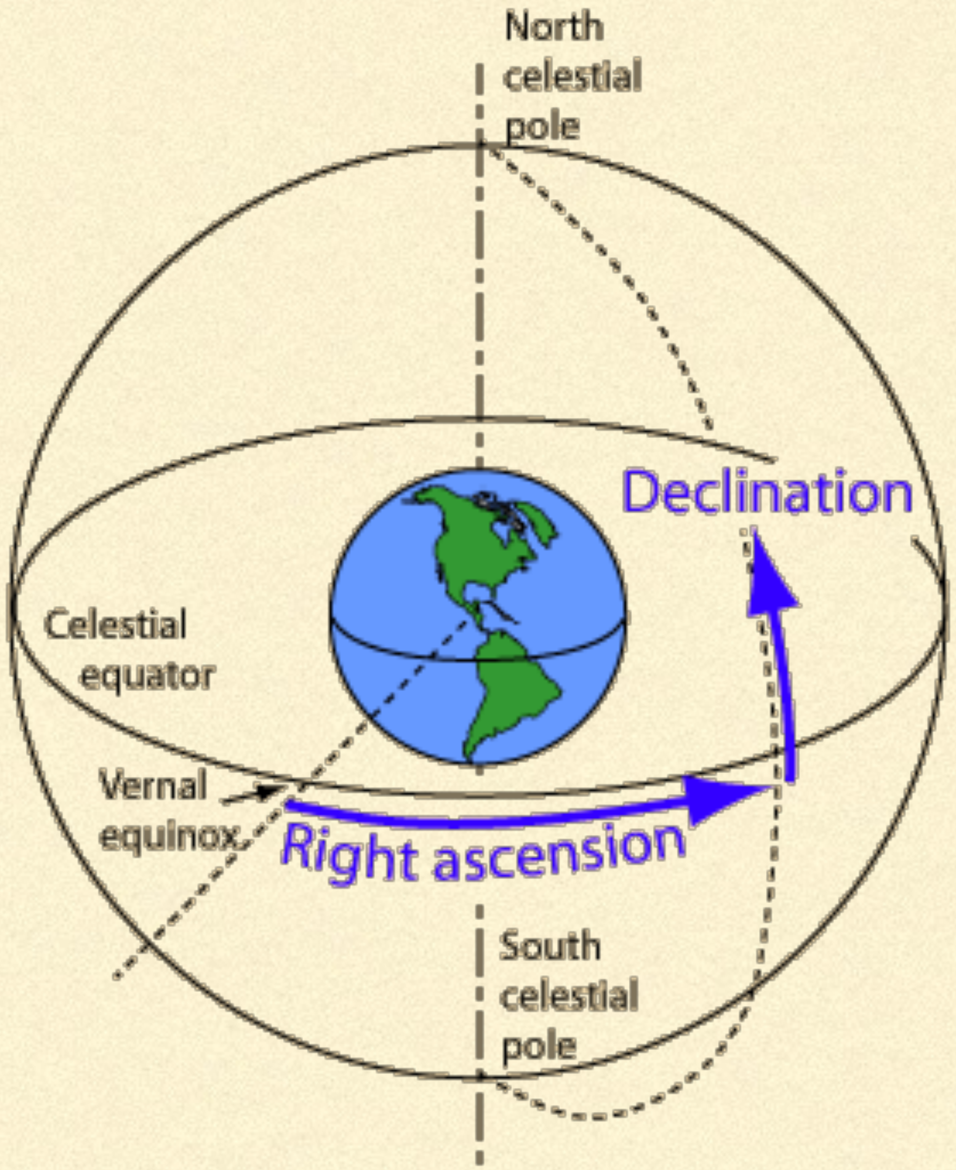
$$\frac{\bar{\nu}_e e \to \bar{\nu}_\mu \mu}{\nu_\mu + N \to \mu + anything} \approx 40$$

pure tau track, unique if contained lollipop

$$\frac{\bar{\nu}_e + e \to \bar{\nu}_\mu + \mu}{\nu_\mu + e \to \mu + \nu_e} \approx 1000$$

background to pure muon with contained initial vertex

(Bhattacharya, RG, Rodejohann and Watanabe 2011)


North
celestial
pole
Declination
Celestial
equator
Vernal
equinox
Right ascension
South
celestial
pole

- The data, when subjected to directional analyses , at its present level of statistics, is compatible with an isotropic diffuse flux, although several studies among the ones cited above indicate the presence of a small galactic bias. The accumulation of more data will be able to ascertain whether the galactic bias is real, in which case it would imply important underlying physics.

The three highest energy events [1], with the estimated (central value) of the de- posited energies of 1.04 PeV, 1.14 PeV and 2.0 PeV are all cascade events from the southern hemisphere. At these energies, *i.e.* E_ν 1 PeV, the earth becomes opaque to neutrinos, thus filtering out neutrinos coming from the northern hemisphere.

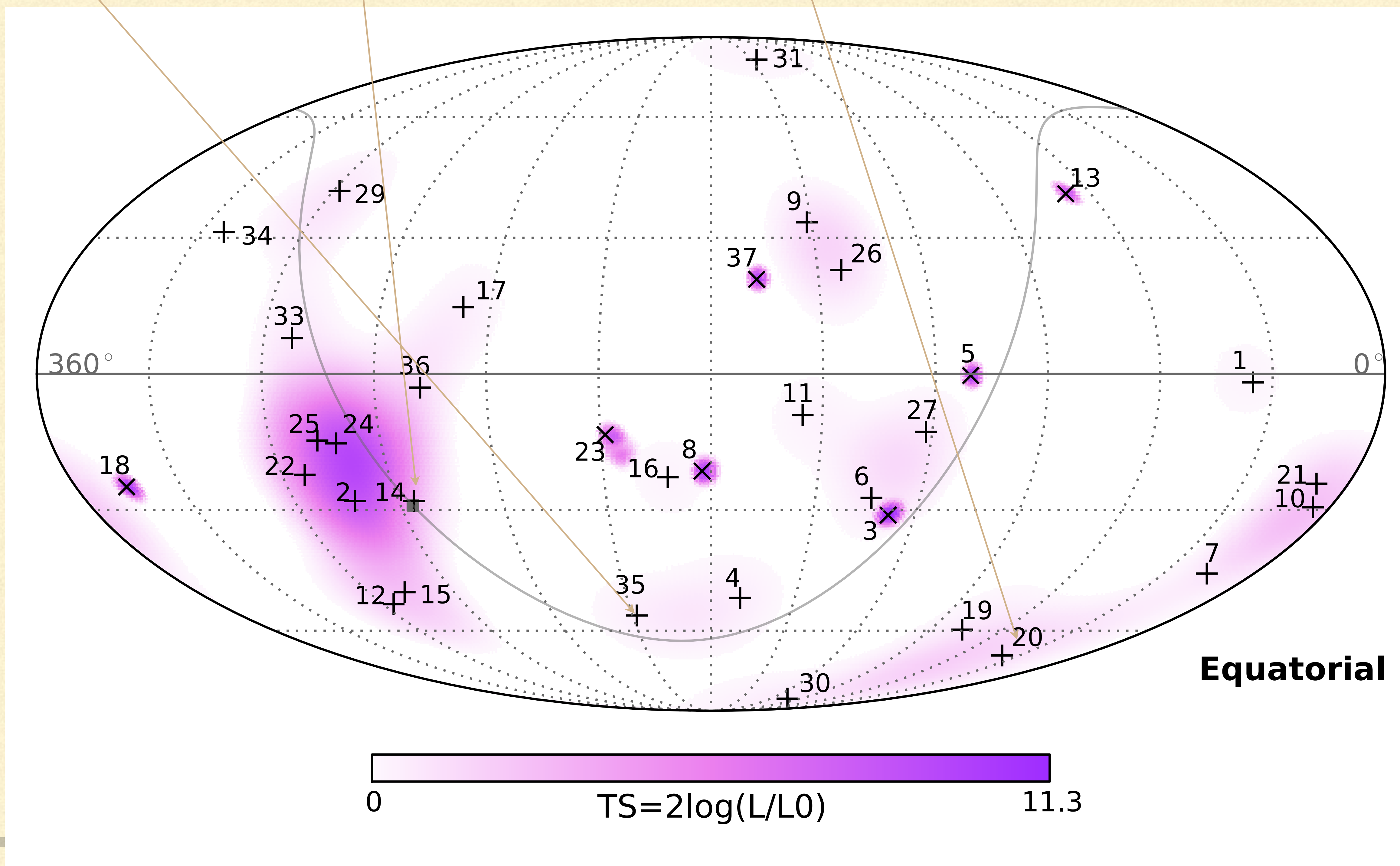
Below 1 PeV, there appears to be a dip in the spectrum, with no events between roughly 400 TeV and 1 PeV.[4]

1.04 PeV event

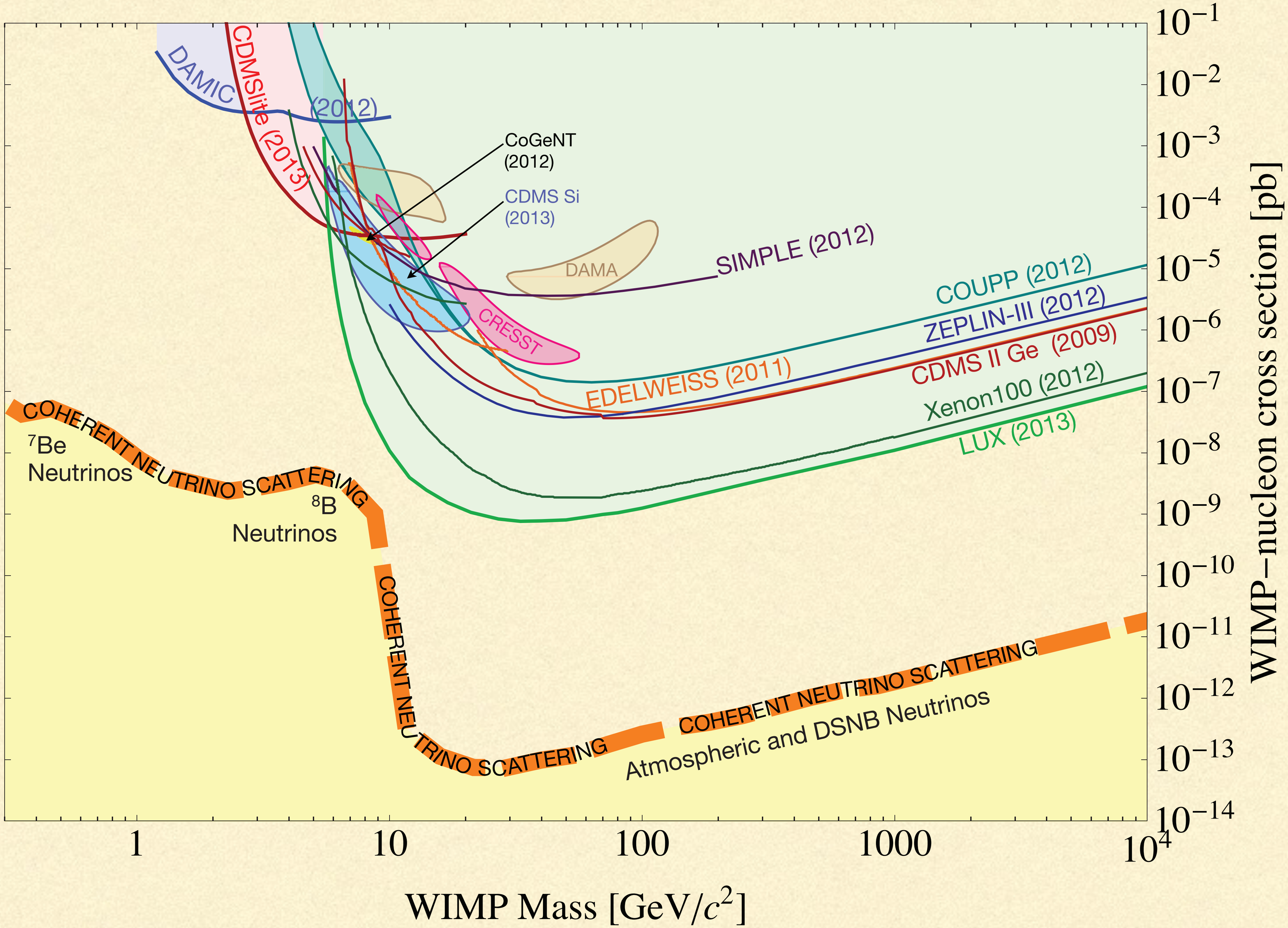
2 PeV event

1.2 PeV event

temporal separation
about 7 mos.

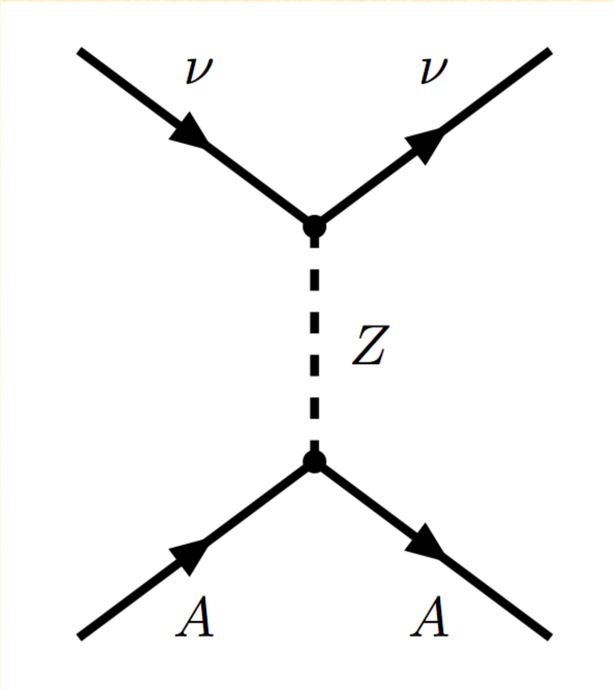


WIMPS….DM direct detection constraints



Gradual squeezing of allowed WIMP space by several expts with differing techniques

and DM-nucleon interaction at low energies



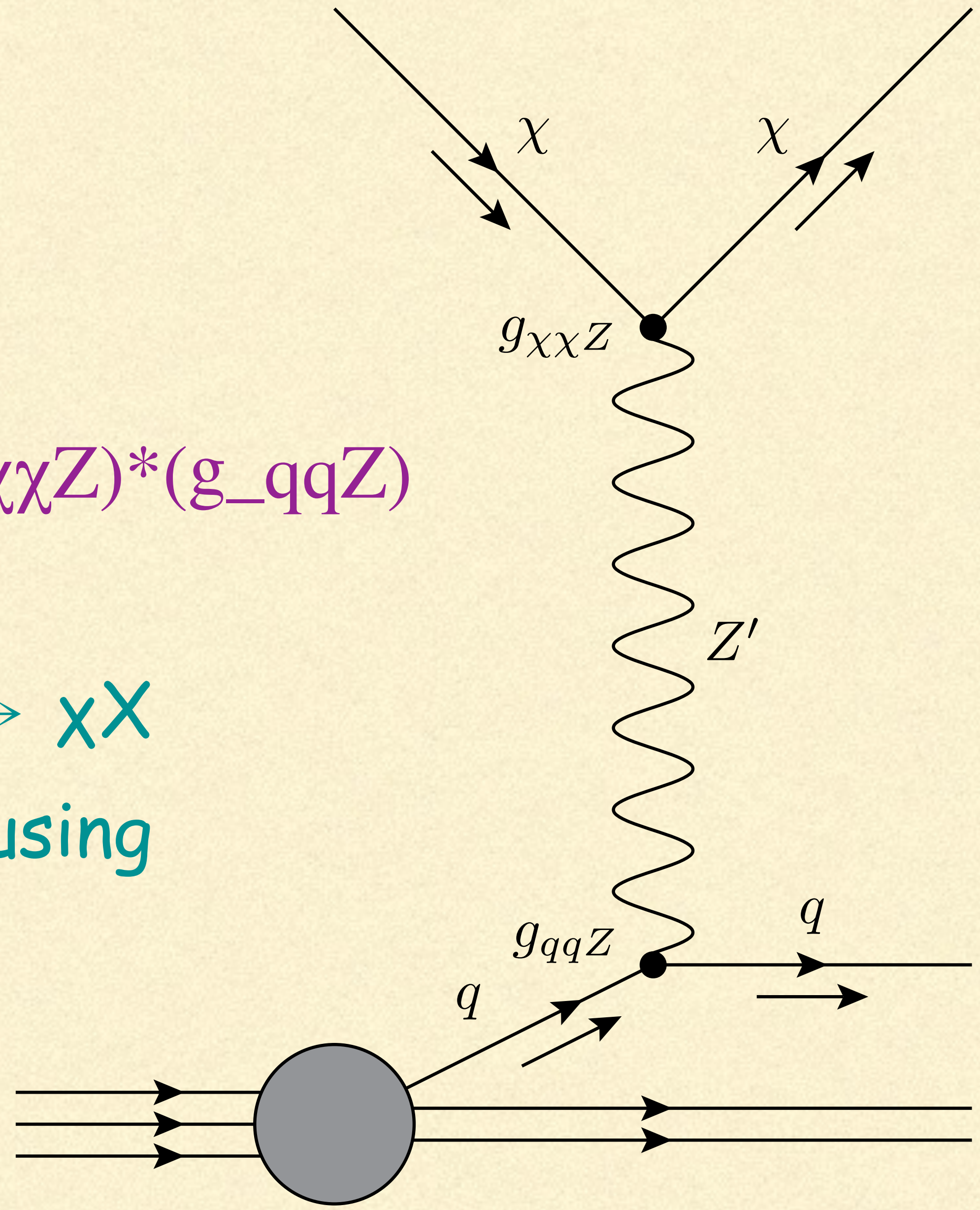
$$\sigma_{\nu A} \simeq \frac{4}{\pi} E_\nu^2 [Z w_p + (A - Z) w_n]^2,$$

$$\sigma_{\chi A} \simeq \frac{4}{\pi} \mu_{\chi A}^2 \left[Z f_p + (A - Z) f_n\right]^2,$$

Interactions of the χ.........

Z′ which connects SM and DM sectors

Vector-like couplings assumed



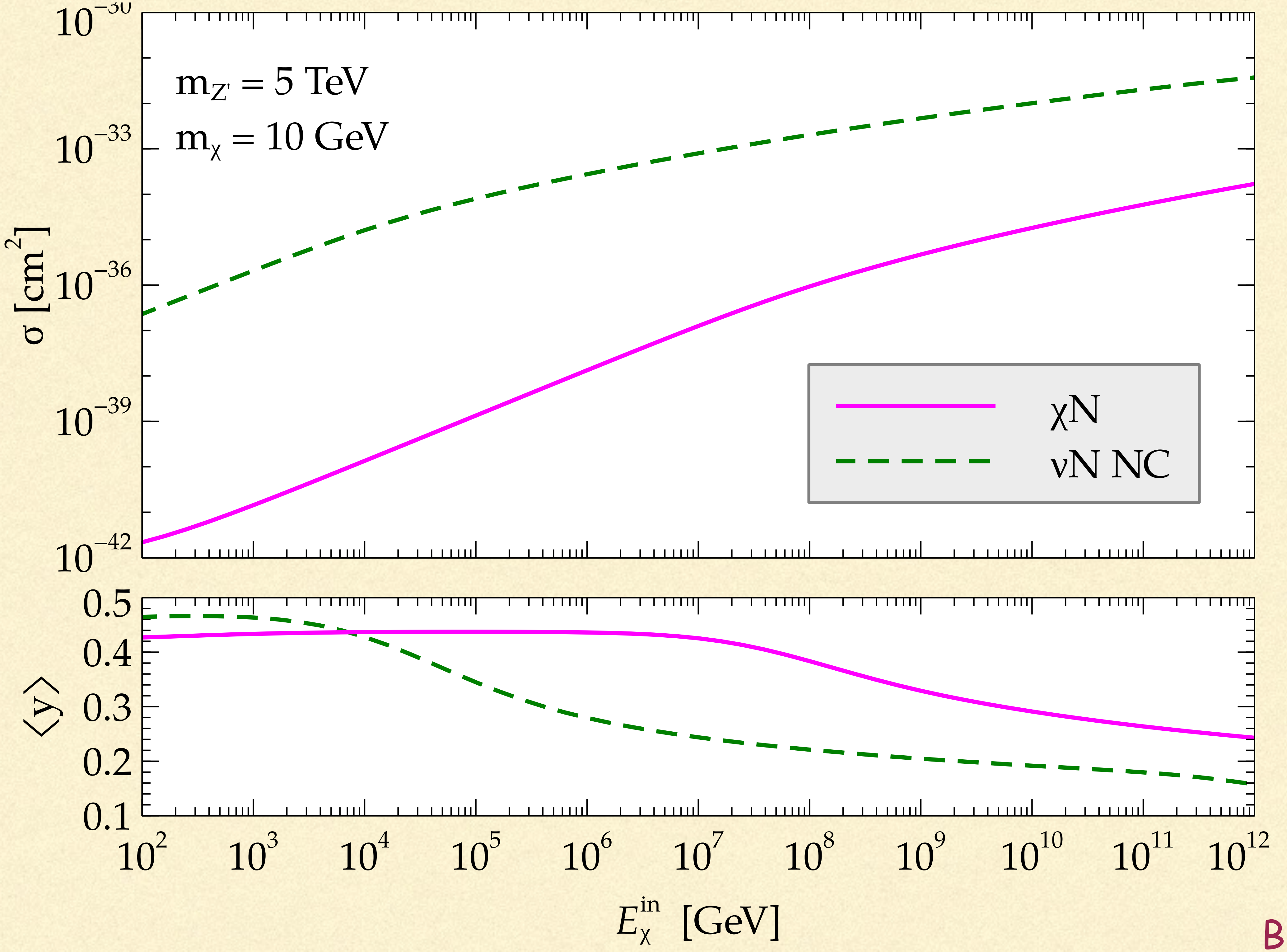
G = (g_χχZ)*(g_qqZ)

Compute the DIS cross-section for $\chi N \to \chi X$ in the lab-frame, 100 GeV ≤ E^{in} ≤ 10 PeV, using CT10 parton distribution functions.

We set the Z' mass to be 5 TeV. (For Z' with mass > 2.9 TeV, the couplings $g_{\chi\chi Z}$ and g_{qqZ} are largely unconstrained by collider searches.)

(Atri Bhattacharya, RG and Aritra Gupta, arXiv 1407.3280)

χ-nucleon cross-section

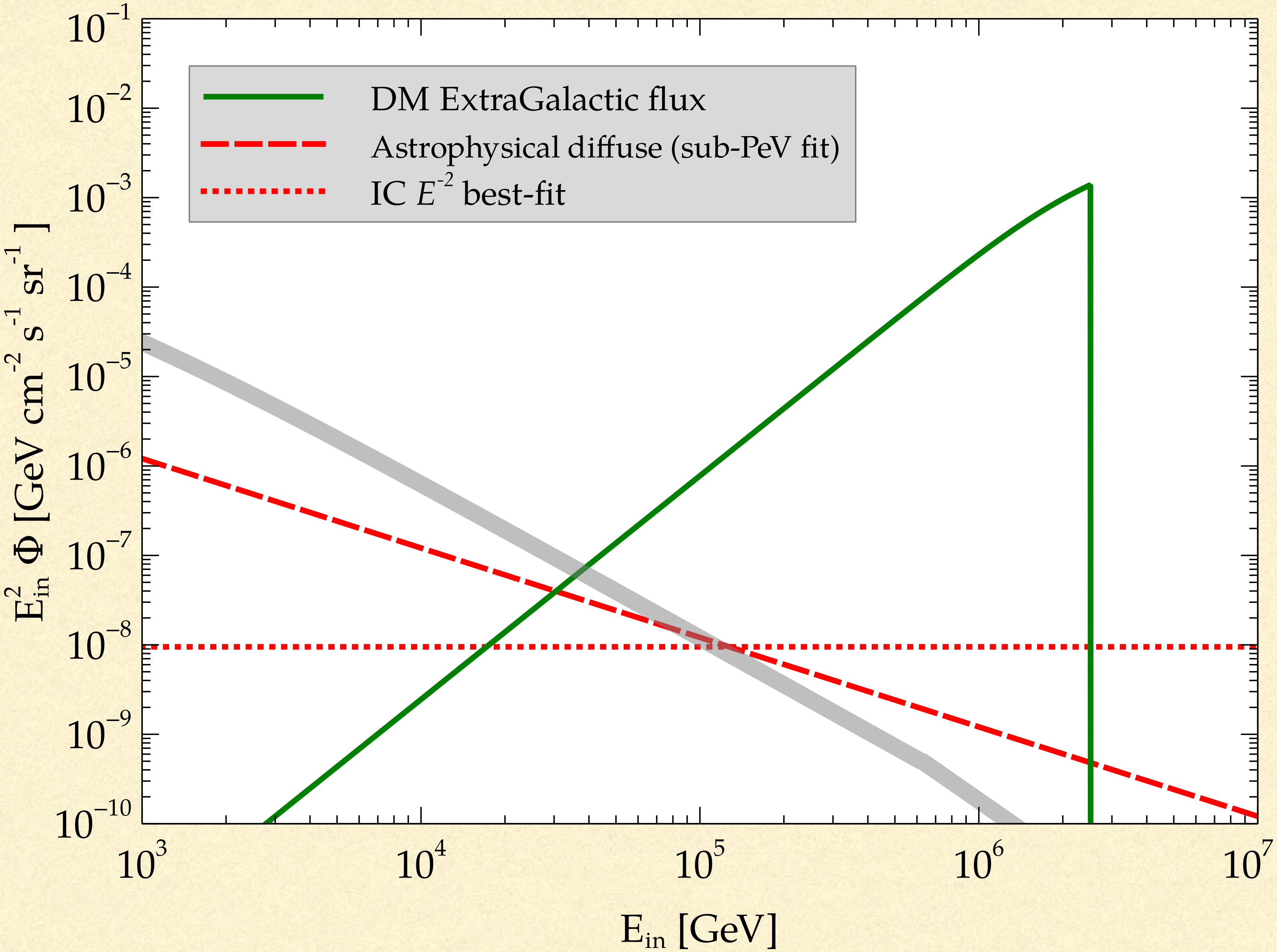


$$y = \frac{E_\chi^{\rm in} - E_\chi^{\rm out}}{E_\chi^{\rm in}} = \frac{E^{\rm dep}}{E_\chi^{\rm in}}\,.$$

$$\langle y(E)\rangle = \frac{1}{\sigma(E)}\int_0^1 {\rm d}y\, y \frac{{\rm d}\sigma(E,y)}{{\rm d}y}\,,$$

(Atri Bhattacharya, RG and Aritra Gupta, arXiv 1407.3280)

Flux of the χ………

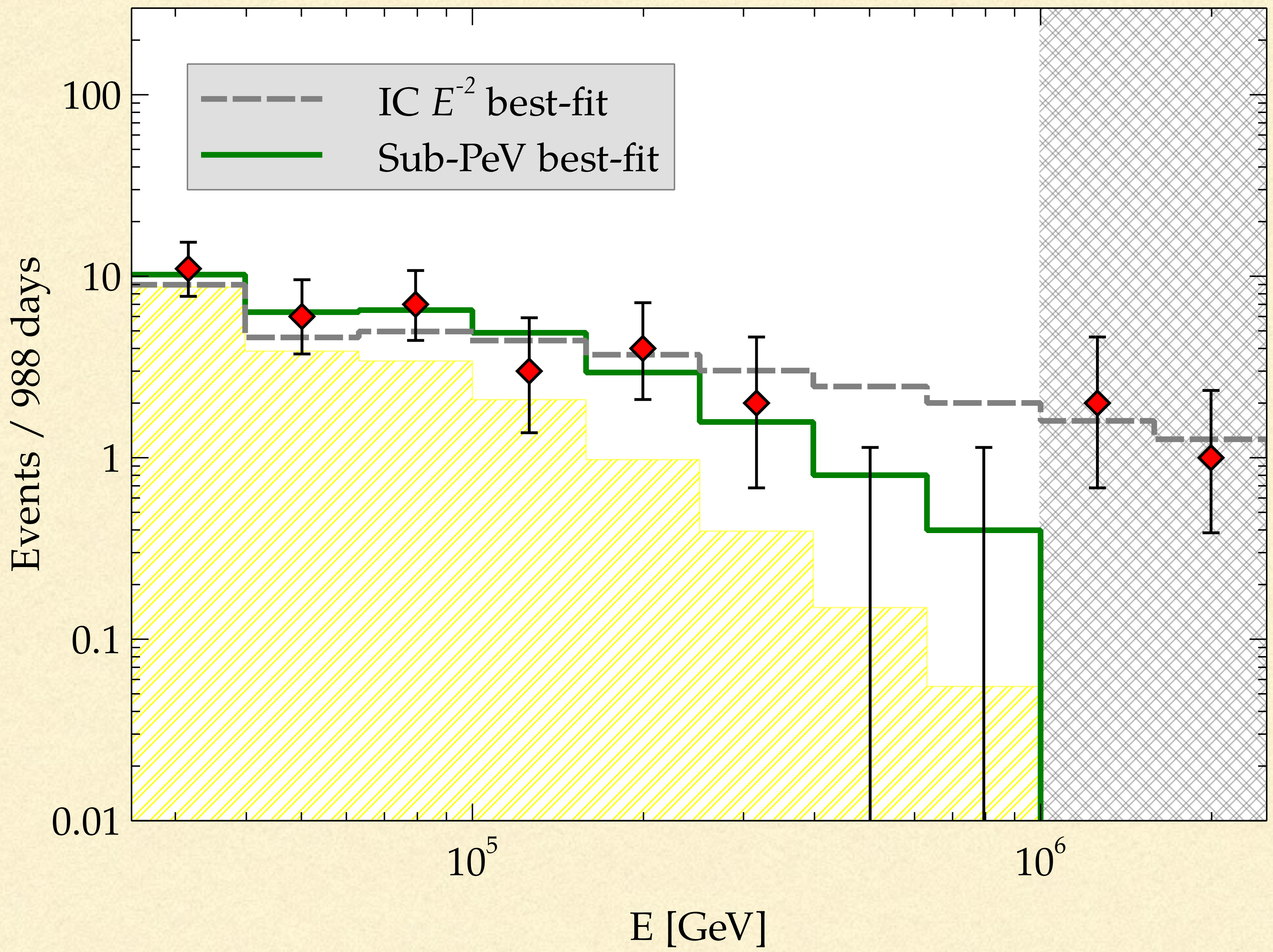


Galactic flux is a delta function and is not shown here.

EG flux does not contribute to sub-PeV events

(Atri Bhattacharya, RG and Aritra Gupta, arXiv 1407.3280)

Fits………



$$\Phi_{\rm astro} = 1.21 \times 10^{-3} E^{-3.0}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}.$$

(Atri Bhattacharya, RG and Aritra Gupta, arXiv 1407.3280)

Discriminators.........

How does one discriminate this scenario from other proposals?

Like some proposals,

(Feldstein et al, Esmaili et al, Ema et al, Anchordoqui et al, Ng et al, Stecker et al, Learned et al)

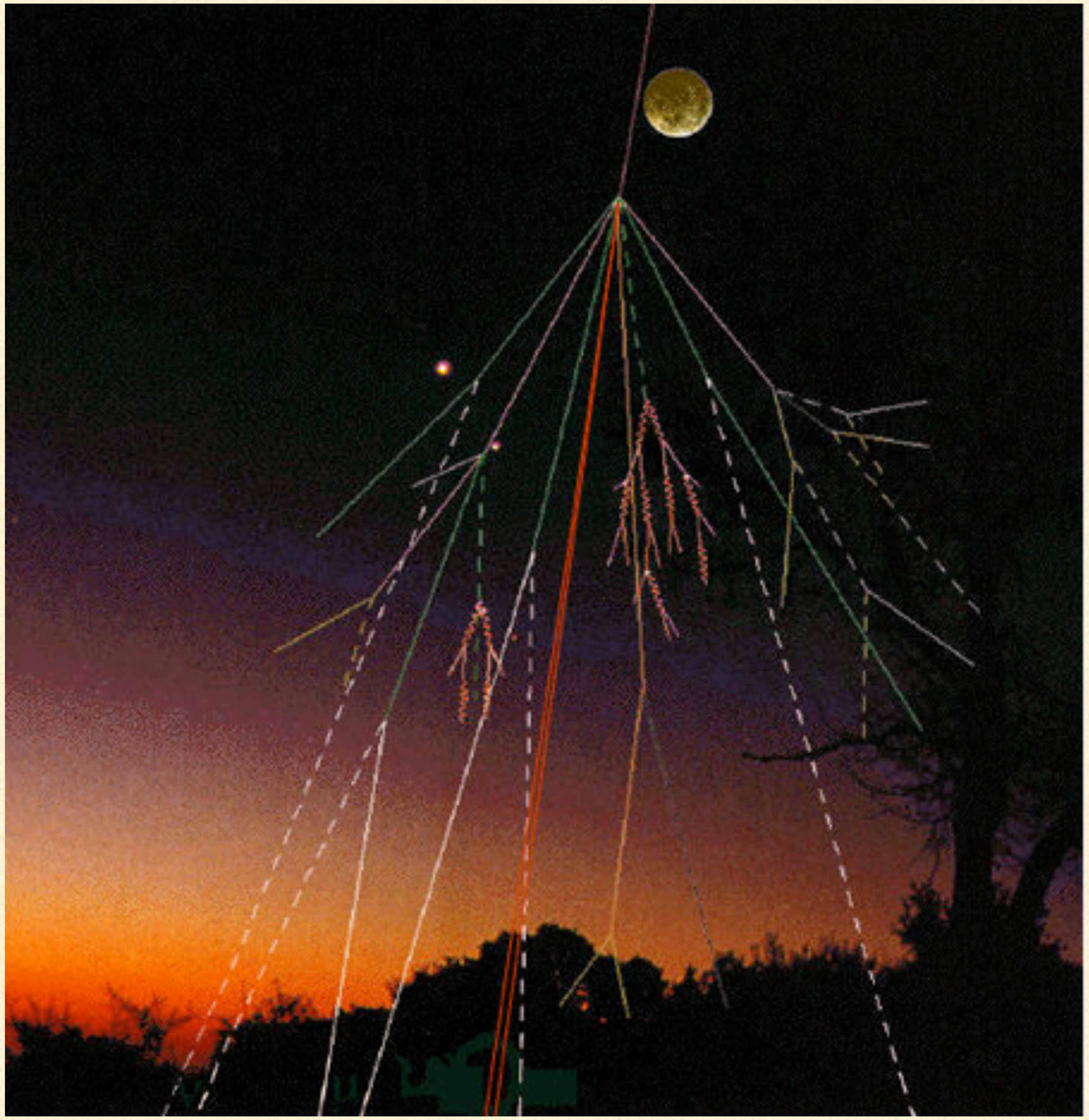
this explains the absence of events beyond 2.1 PeV.

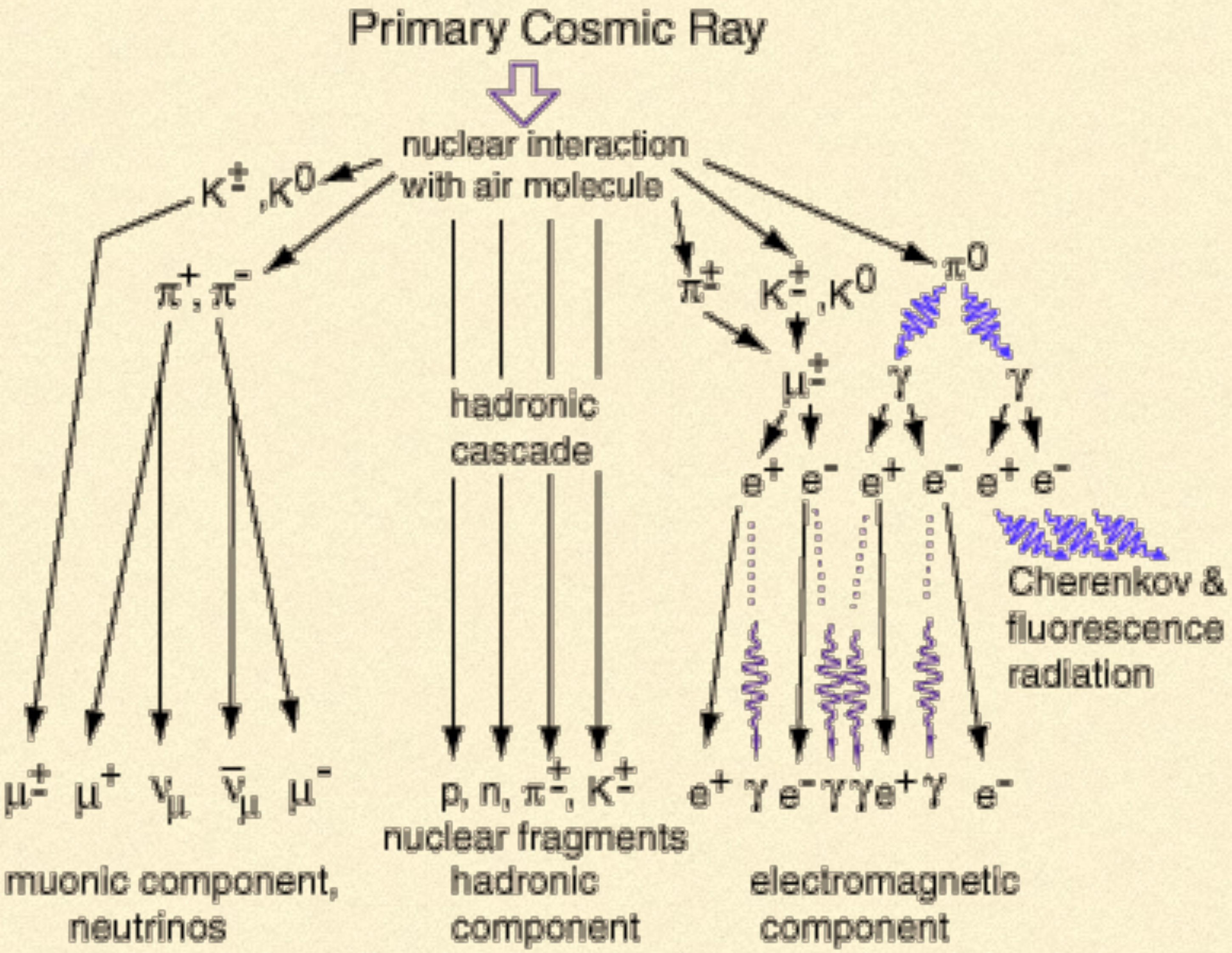
Like some other decaying DM proposals, this explains the clustering of events in the 1-3 PeV range

In this scenario, the gap between 400 TeV and 1 PeV is physical, because it reflects a break between 2 fluxes of different origins

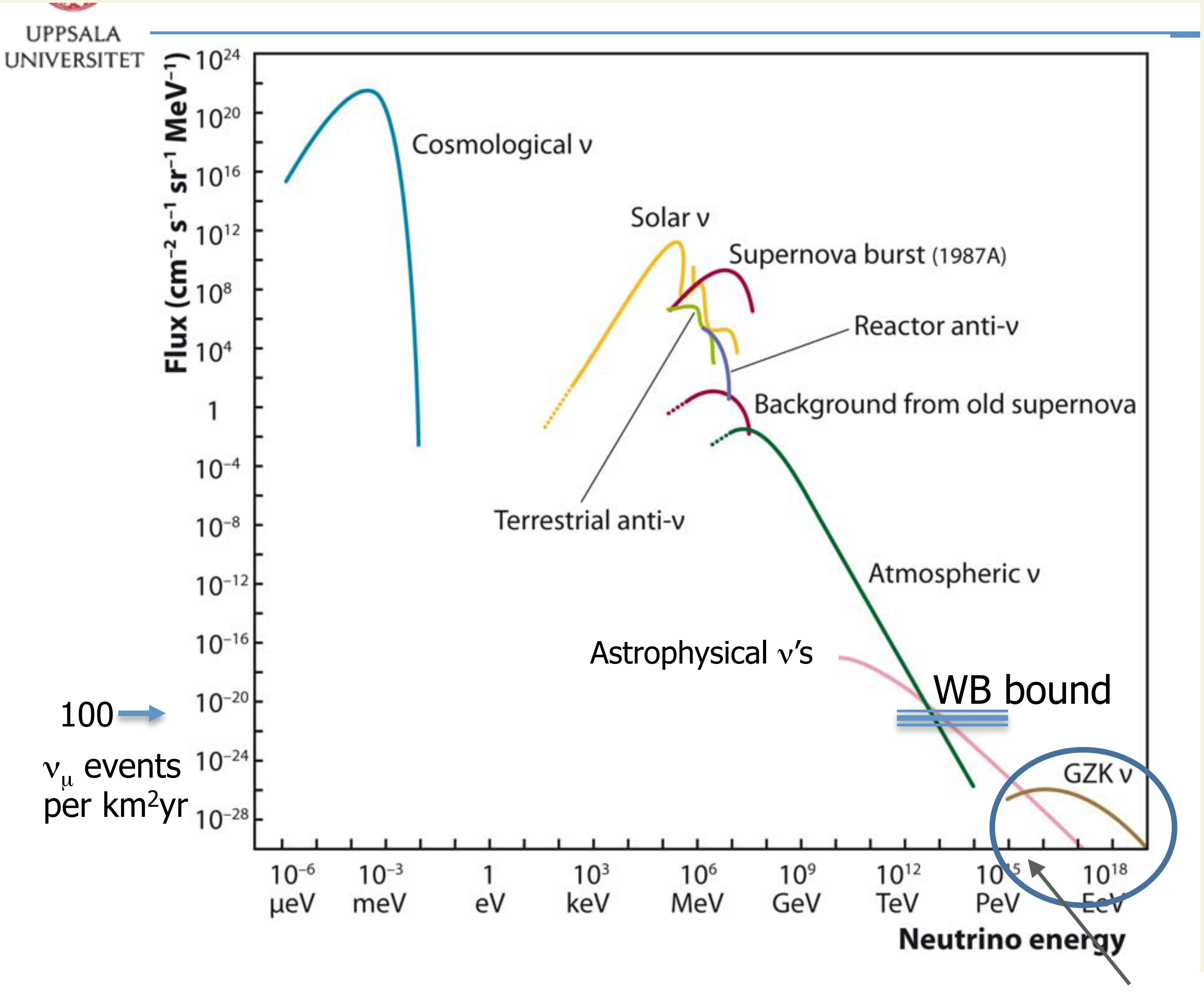
(Atri Bhattacharya, RG and Aritra Gupta, arXiv 1407.3280)

High Energy Cosmic Rays.......





What signal are UHE neutrino detectors looking for?…….



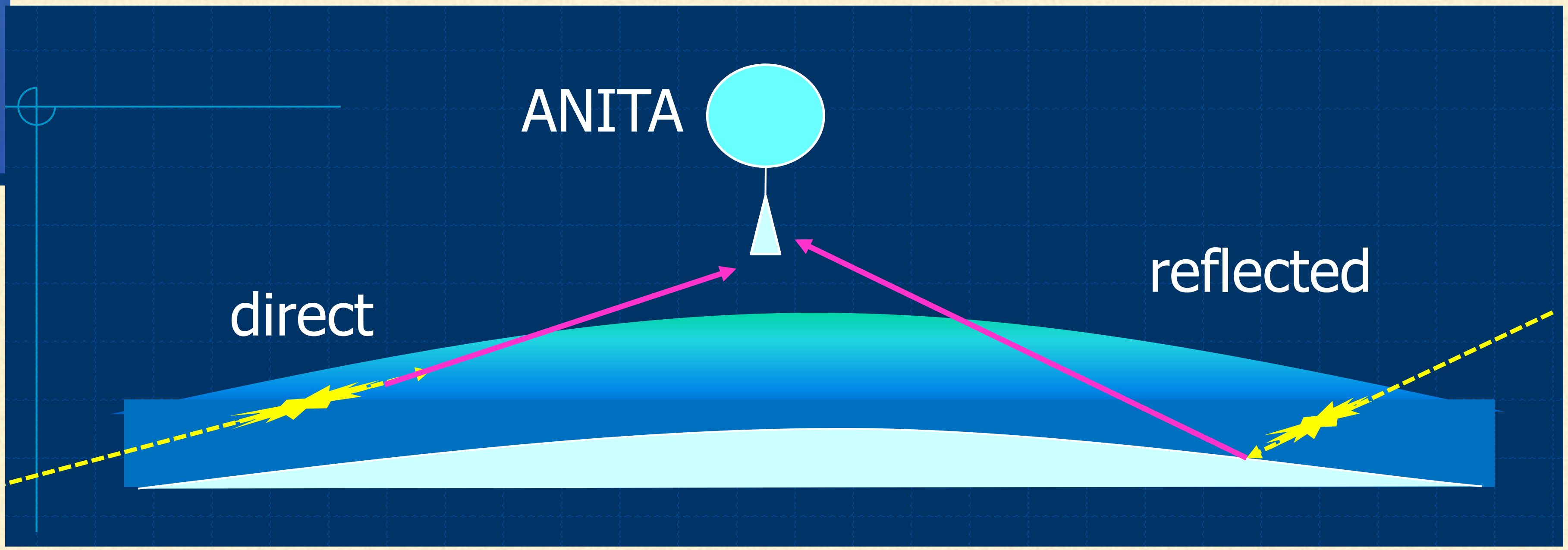
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{array}{l} n\pi^+ \rightarrow n\mu\nu \\ p\pi^0 \rightarrow \gamma\gamma \end{array}$$

ANITA Detector

Balloon experiment, using Askaryan effect

Ice is transparent to Cerenkov emission due to EM shower in radio range

Threshold 10^18 eV, but target volume is 1 million cubic km of ice!



From the spectral fits, the flavour mix, and the proximity to the WB bound, the data on the face of it seems to be astrophysical neutrinos originating in the same sources as UHE CR.

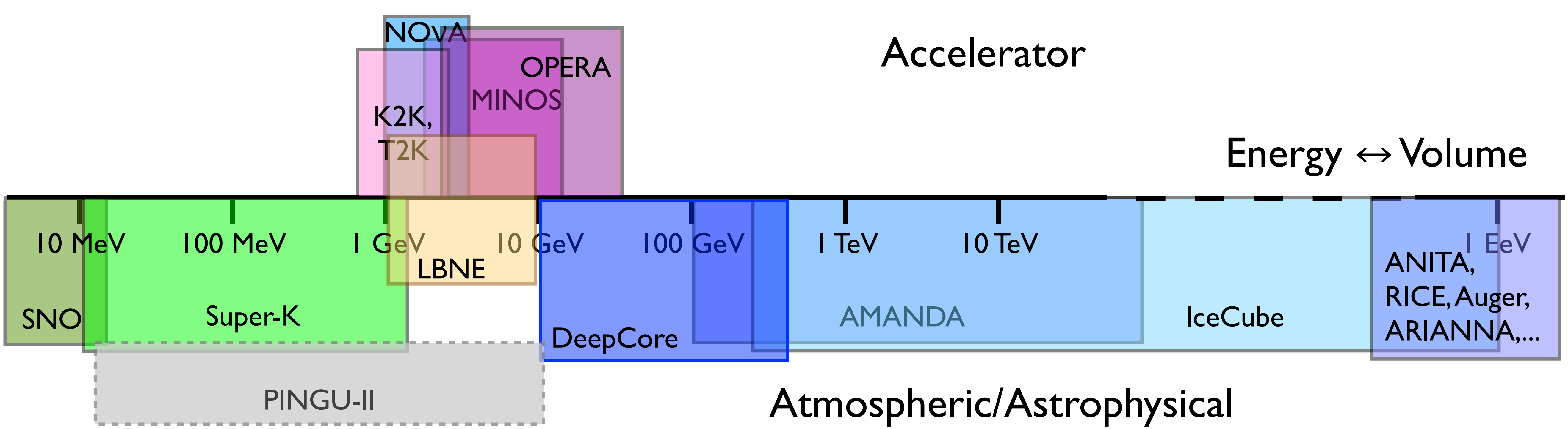
The 3 unexpected features are the gap between 250 TeV and 1 PeV, and the lack of events beyond a PeV, and the saturation of the bound.

What are some of the other possible explanations being proposed?

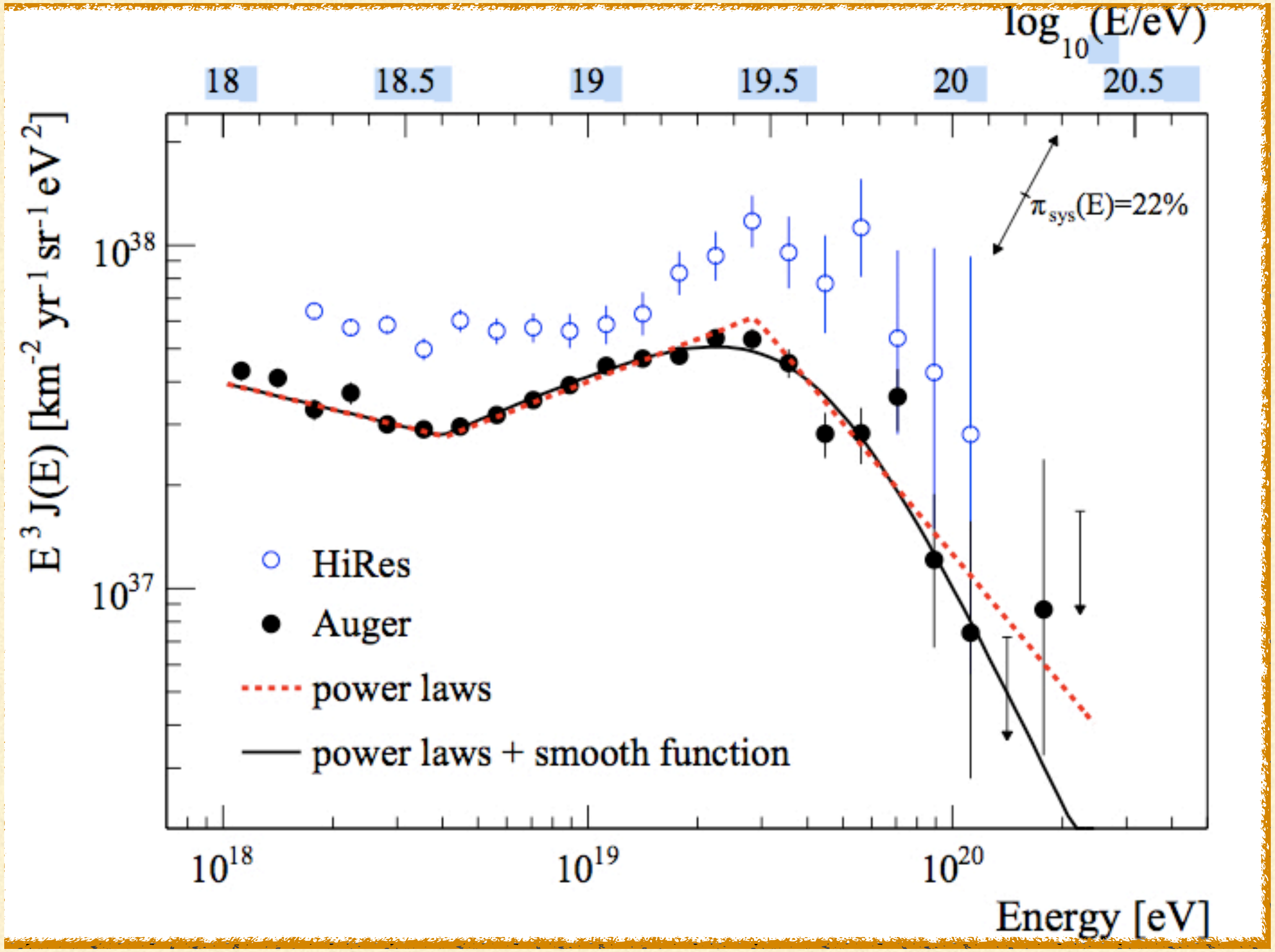
The 2 PeV events are a line signature from dark matter decay/annihilation (Feldstein et al, 1303.7320.) This also yields a continuum signal at lower energies, but this is model dependant, and usually below atmospheric.

Similar idea proposed by Esmaili et al, 1308.1105, but they have fit spectrum at < PeV

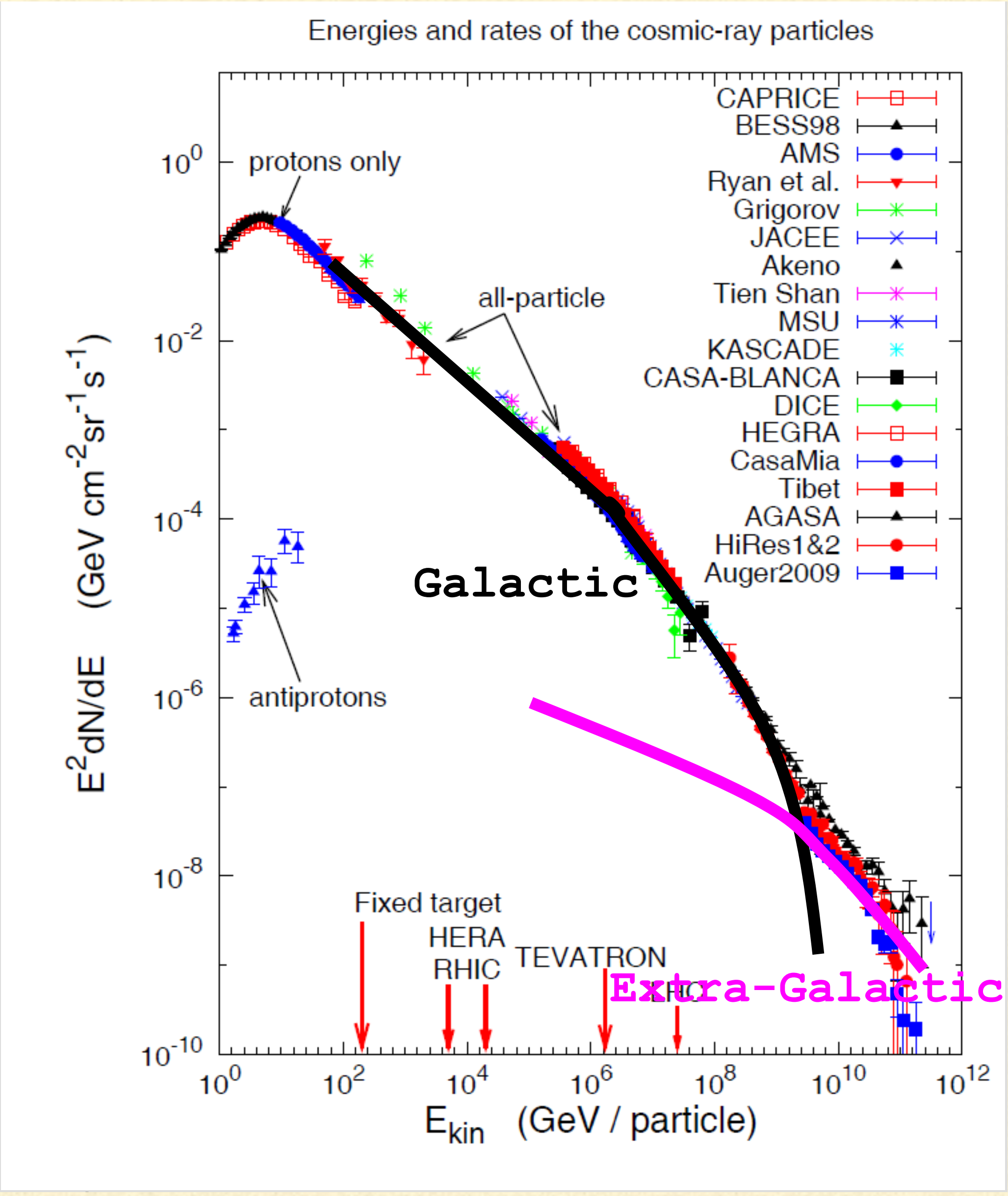
s channel enhancement of nu-quark scattering due to 0.6 TeV leptoquark (Barger and Keung, 1305.6907)



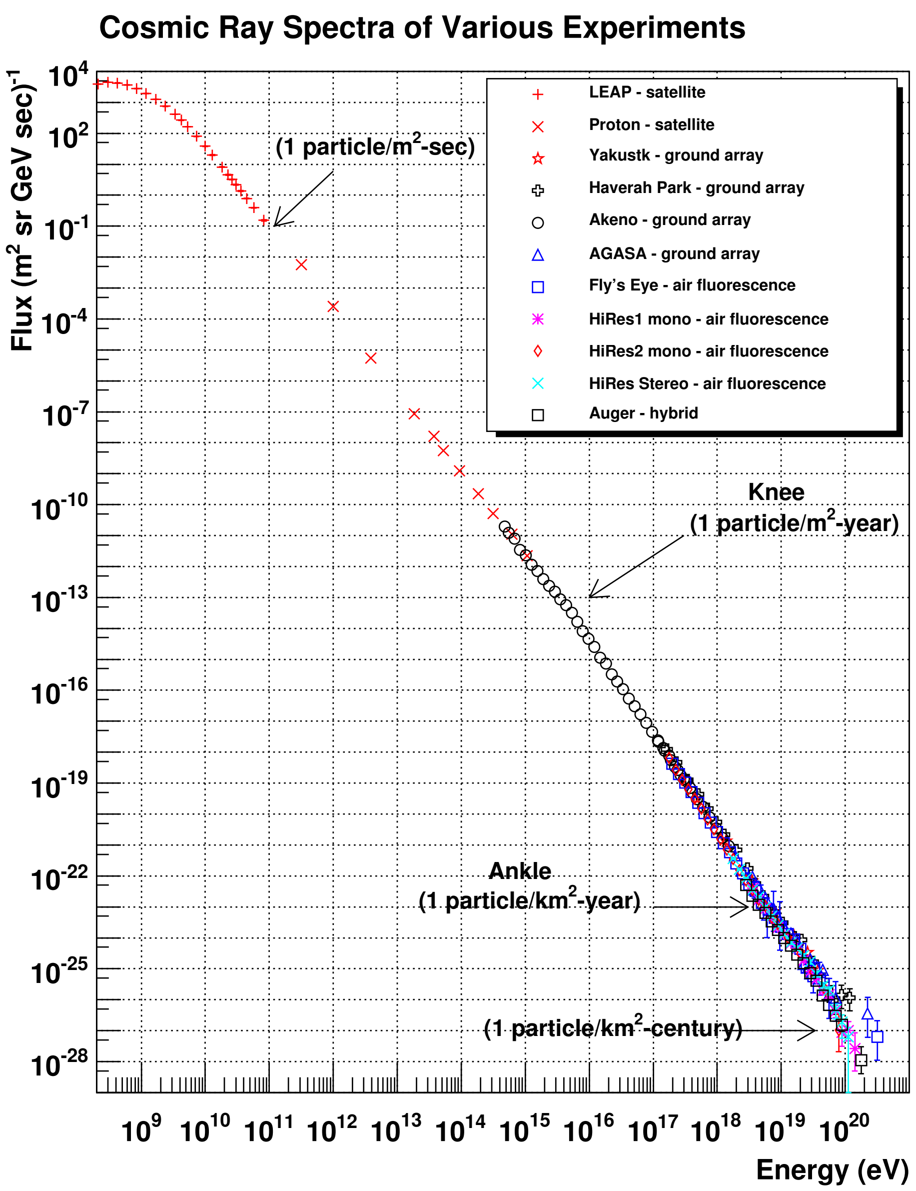
NOvA
OPERA
MINOS
K2K,
T2K
Accelerator
Energy ↔ Volume
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
1 EeV
LBNE
SNO
Super-K
DeepCore
AMANDA
IceCube
ANITA,
RICE, Auger,
ARIANNA,...
PINGU-II
Atmospheric/Astrophysical



log10(E/eV)
18
18.5
19
19.5
20
20.5
E^3 J(E) [km^-2 yr^-1 sr^-1 eV^2]
10^38
10^37
π_sys(E)=22%
HiRes
Auger
power laws
power laws + smooth function
10^18
10^19
10^20
Energy [eV]

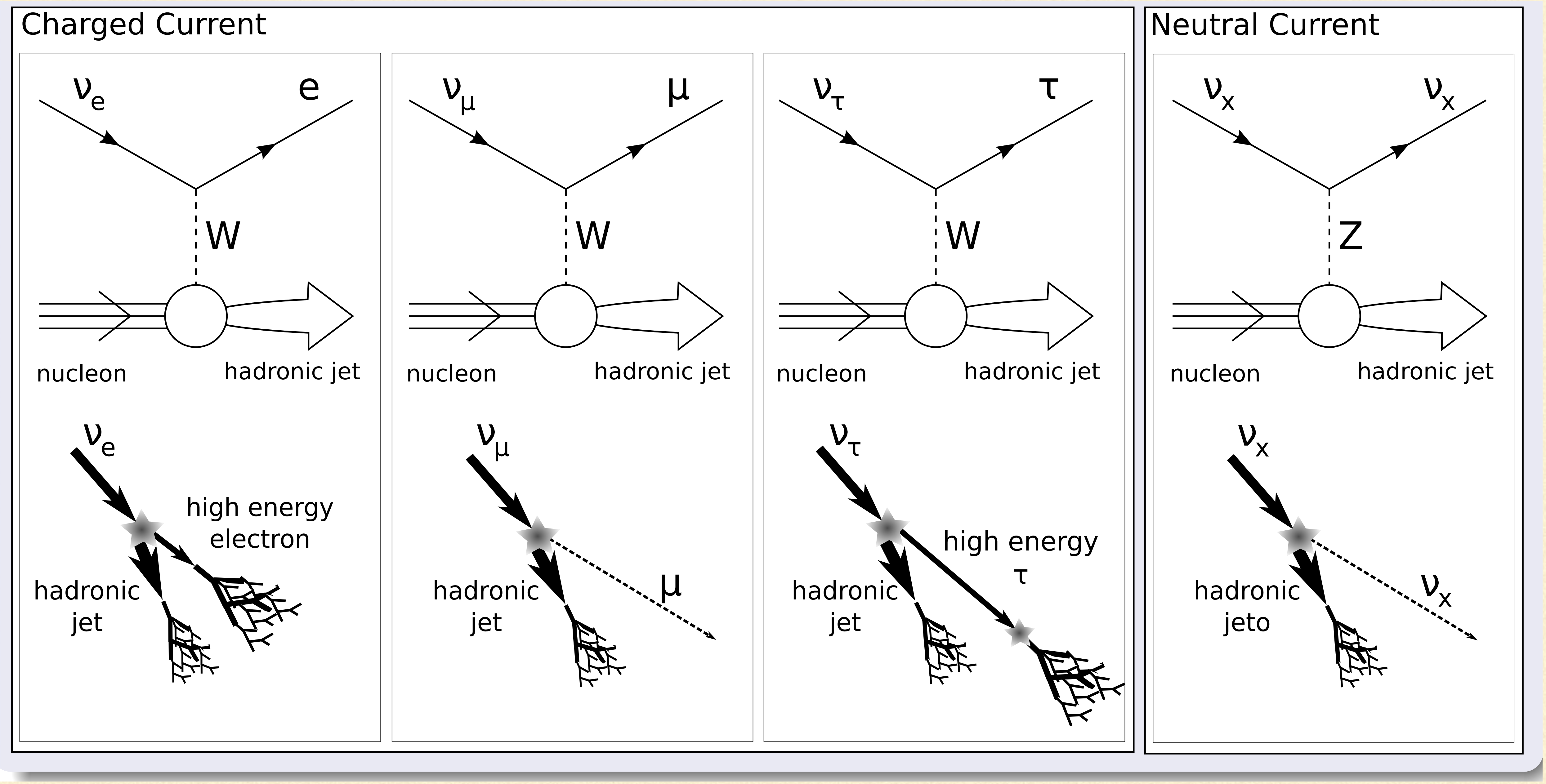


Energies and rates of the cosmic-ray particles
protons only
all-particle
antiprotons
Galactic
Extra-Galactic
Fixed target
HERA
RHIC
TEVATRON
LHC
CAPRICE
BESS98
AMS
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
AGASA
HiRes1&2
Auger2009
E^2dN/dE (GeV $cm^{-2}sr^{-1}s^{-1}$)
E_{kin} (GeV / particle)



CM energy

E_{lab}[eV]	E_{CM}[TeV]	Exp
10^{14}	0.8	SPS
10^{15}	2	Tevatr.
10^{16}	7	LHC
10^{17}	14	LHC?



Charged Current
Neutral Current
ν_e
e
W
nucleon
hadronic jet
ν_e
high energy electron
hadronic jet
ν_μ
μ
W
nucleon
hadronic jet
ν_μ
hadronic jet
μ
ν_τ
τ
W
nucleon
hadronic jet
ν_τ
high energy τ
hadronic jet
ν_x
ν_x
Z
nucleon
hadronic jet
ν_x
hadronic jeto
ν_x

GR Xsecs.....

$$\frac{d\sigma(\bar{\nu}_e e \to \bar{\nu}_\mu \mu)}{dy} = \frac{G_F^2 m E_\nu}{2\pi} \frac{4(1-y)^2[1-(\mu^2-m^2)/2mE_\nu]^2}{(1-2mE_\nu/M_W^2)^2 + \Gamma_W^2/M_W^2}$$

$$\frac{d\sigma(\bar{\nu}_e e \to \text{ hadrons})}{dy} = \frac{d\sigma(\bar{\nu}_e e \to \bar{\nu}_\mu \mu)}{dy} \cdot \frac{\Gamma(W \to \text{ hadrons})}{\Gamma(W \to \mu \bar{\nu}_\mu)}$$

Lab frame, m= electron mass, y= E_mu/E_nu

The Glashow Resonance.......Relevant Cross-sections

Reaction	σ [cm^2]
$\nu_\mu e \to \nu_\mu e$	5.86×10^{-36}
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	5.16×10^{-36}
$\nu_\mu e \to \mu \nu_e$	5.42×10^{-35}
$\nu_e e \to \nu_e e$	3.10×10^{-35}
$\bar{\nu}_e e \to \bar{\nu}_e e$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\mu \mu$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\tau \tau$	5.38×10^{-32}
$\bar{\nu}_e e \to$ hadrons	3.41×10^{-31}
$\bar{\nu}_e e \to$ anything	5.02×10^{-31}
$\nu_\mu N \to \mu^- +$ anything	1.43×10^{-33}
$\nu_\mu N \to \nu_\mu +$ anything	6.04×10^{-34}
$\bar{\nu}_\mu N \to \mu^+ +$ anything	1.41×10^{-33}
$\bar{\nu}_\mu N \to \bar{\nu}_\mu +$ anything	5.98×10^{-34}

RG, Quigg, Reno and Sarcevic '95