BOOSTED DARK MATTER AND FEATURES IN ICECUBE HESE DATA

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(Work with Atri Bhattacharya, Aritra Gupta and Satyanarayana Mukhopadhyay)

(based on JCAP 1503 (2015), 027 and JCAP 05 (2017) 002 [(arXiv 1407.3280) and arXiv 1612.02834)]

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Features in the 1347-day HESE data.........

- The data, to a high level of significance (about 5.7σ), indicate that above a few tens of TeV, the sources of the events are primarily non-atmospheric and extra-terrestrial in nature.

  - Single power-law fit to the flux underlying the observed events disfavors the expected spectral index from Fermi shock acceleration considerations, $\gamma = -2$, by more than 4σ. Present best fit value of γ is significantly steeper, being around $\gamma = -2.58$.

    One reason for the steeper fit is the non-observation of about 3 to 4 additional events, which are expected between 2 PeV and 10 PeV, largely due to the expected presence of the Glashow resonance.

    - Directional analyses of data , at present level of statistics, is compatible with an isotropic diffuse flux, although several studies indicate the presence of a small galactic bias.

      More data will be able to ascertain whether the galactic bias is real, in which case it would imply important (and possibly new) underlying physics.

Features in the 1347-day HESE data.........

- The three highest energy events, with the estimated (central value) of the deposited 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 cascade events between roughly 400 TeV and 1 PeV.

- At lower energies, in the approximate range of 50–100TeV, there appears to be an excess, with a bump-like feature. The maximum local significance of this excess is about 2.3σ.

- Finally, the data when interpreted as being due to a single astrophysical power-law neutrino flux, appears to require an unusually high normalization for this flux, which is at the level of the Waxman-Bahcall (WB) bound.

Premise…….

Study the implications of the premise that any new, relativistic, highly energetic neutral particle that interacts with quarks and gluons would create cascade-like events in the IceCube (IC) detector.

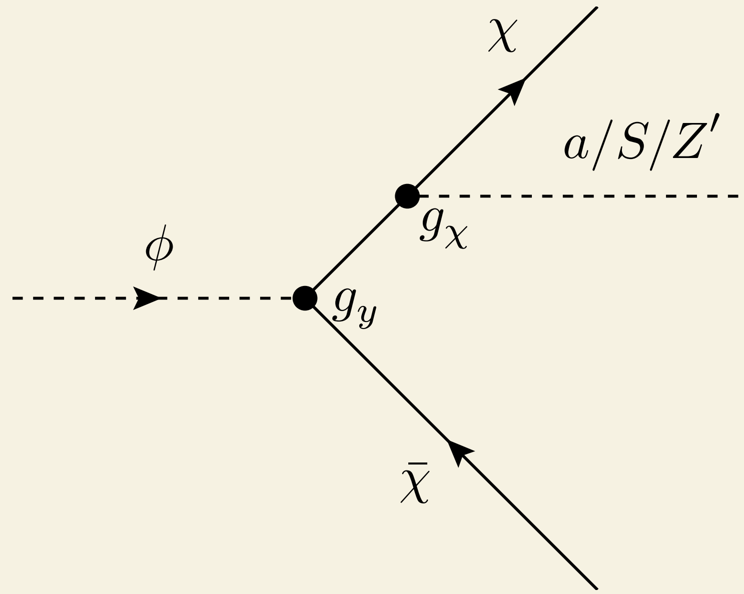
Such events would be observationally indistinguishable from neutral current deep-inelastic (DIS) scattering events due to neutrinos.

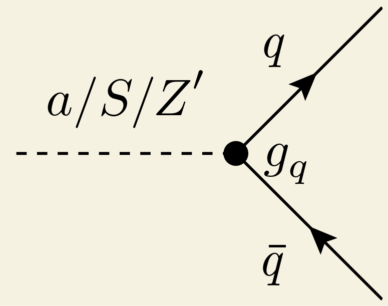
Consequently, one reason for deviations, breaks or excesses in the expected astrophysical power-law neutrino spectrum could be the flux of such a particle.

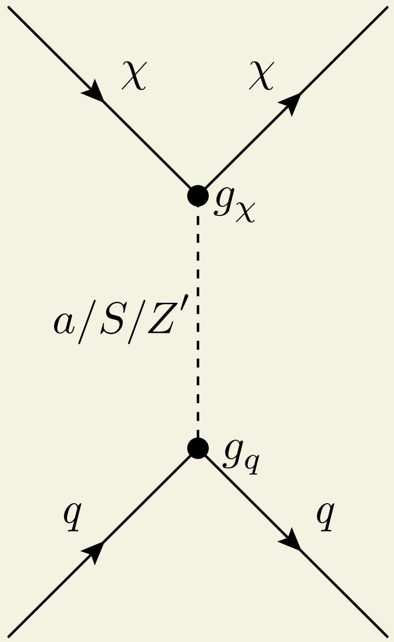
Bhattacharya, RG, Gupta JCAP 1503 (2015), 027 (1407.3280)

Explore its consequences…….

The relevant interactions and fluxes……..







1. **Flux-1:** An underlying power-law flux of astrophysical neutrinos, $\Phi_{Ast} = N_{Ast}E^{-\gamma}$, whose normalization ($N_{Ast}$) and index ($\gamma$) are left free.

2. **Flux-2:** A flux of boosted light dark matter (LDM) particles (χ), which results from the late-time decay of a heavy dark matter (HDM) particle (φ). When χ is much lighter than φ, its scattering in IC resembles the NC DIS scattering of an energetic neutrino, giving rise to cascade-like events.

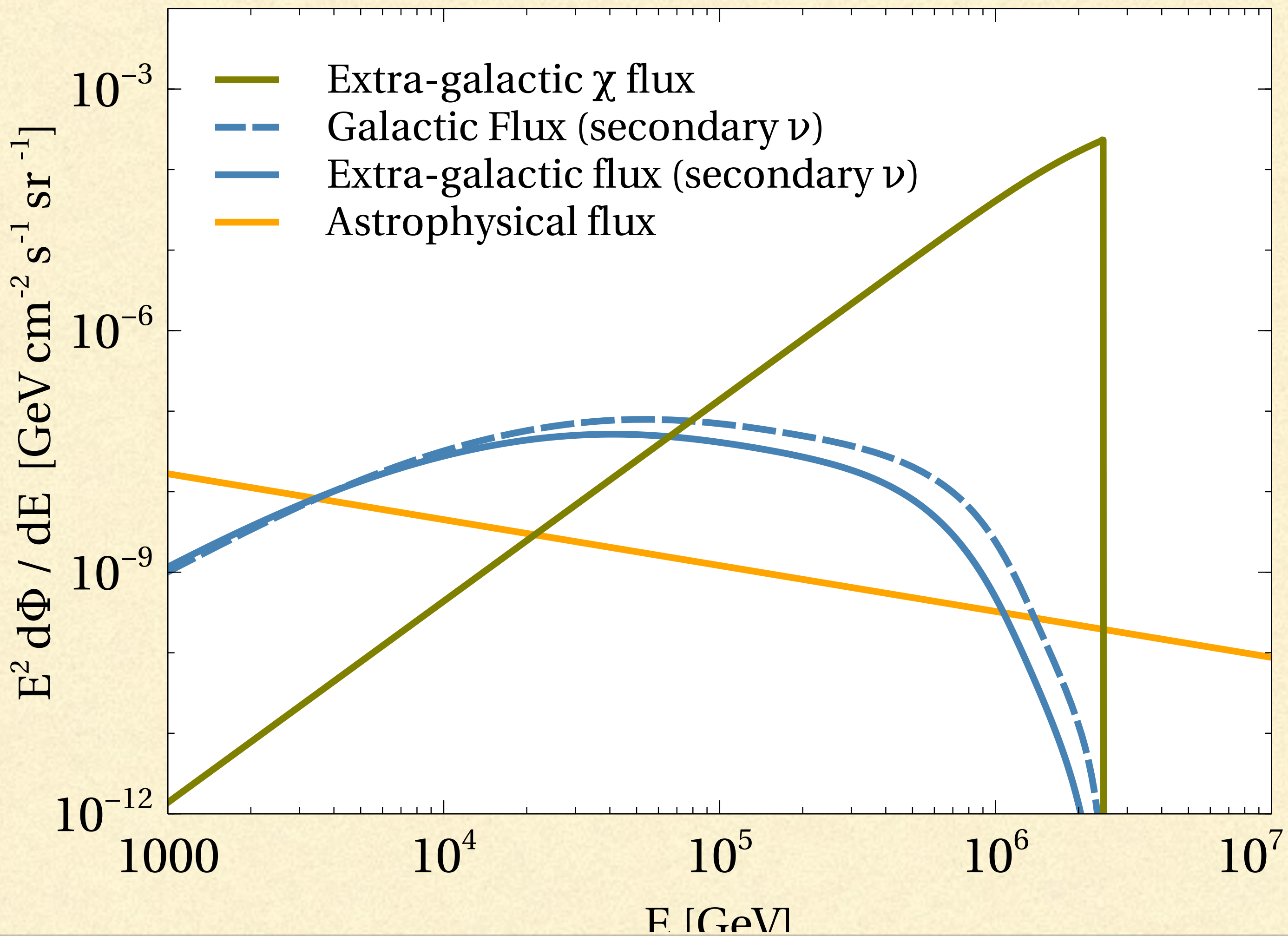
3. **Flux-3:** The flux of secondary neutrinos resulting from three-body decay of the HDM, where a mediator particle is radiated off a daughter LDM particle. The mediator then subsequently decays to SM particles, producing neutrinos down the decay chain. Since the NC DIS scattering that results from Flux-2 requires a mediator particle which couples to both the LDM and the SM quarks, such a secondary neutrino flux is always present.

Kopp, Liu and Wang, JHEP 1504 (2015) 105 , arXiv:1503.02669

4. **Flux-4:** The conventional, fixed, and well-understood, atmospheric neutrino and muon background flux, which is adapted from IC analyses.

Example case of pseudo scalar mediator.. ……..

In Scenario I, the three highest energy PeV events, which are cascades characterized by energy depositions (central values) of 1.04 PeV, 1.14 PeV and 2.0 PeV, are assumed to be due to Flux-2 above, requiring an HDM mass of O(5) PeV. Both Flux-1 and Flux-3 contribute to account for rest of the HESE events, including the small bump-like excess in the 30 – 100 TeV range. This scenario, in a natural manner, allows for the presence of a gap, or break in the spectrum between 400 TeV to 1 PeV.



Constraints and other considerations ……..

PeV events from DM scattering.. ……..

The IC event rate from LDM DIS scattering, for a given choice of mediator mass, is determined by the quantity $F = f_\varphi g_q^2 g_\chi^2/\tau_\varphi$.

Couplings should be perturbative, $g_{\chi,q} < 4\pi$.

$\tau_\varphi > 4.35 \times 10^{17}$ seconds (lifetime of Universe) and $f_\varphi < 1$

bound, $F < 5.7 \times 10^{-14}\ s^{-1}$.

If the value of F exceeds this maximum, the couplings will not be perturbative, or the HDM would have decayed too quickly to have an appreciable density in the present Universe.

Secondary flux………

Proportional to g_χ^2 (again, in the limit where the two-body decay width is much larger than the three-body width). It is also inversely proportional to the life-time of the HDM, τ_φ.

A typical value that occurs in the fits is, for instance, $F = 10^{-26}\ s^{-1}$, and using this leads to a lower bound $g_q g_\chi = 6.6 \times 10^{-5}$. Assuming, for simplicity, $g_q \sim g_\chi = g$, each coupling should thus be greater than about 8×10^{-3}.

Constraints and other considerations ....

The relic density of χ, $f_\chi = \Omega_\chi / \Omega_{DM}$, is not of direct relevance to our study, as long as it does not overclose the Universe

if f_χ is significant, the spin-independent direct detection bounds on the scalar and vector interactions are very strong, though not for pseudo-scalar.

It is possible to dilute the density by increasing g_χ, and restricting to values of $m_\chi > m_M$, such that the dominant annihilation mode of χ is to the mediator pair, which can then decay to the SM fermions even via a small g_q. ($F = f_\varphi g_q^2 g_\chi^2 / \tau_\varphi$.)

(The IC event rates do not depend upon m_χ as long as it is significantly smaller than the HDM mass)

Constraints and other considerations ……..

Collider constraints are sensitive to the interplay of several couplings and mass parameters relevant to our study, specifically, g_q, g_X, m_X and m_M .

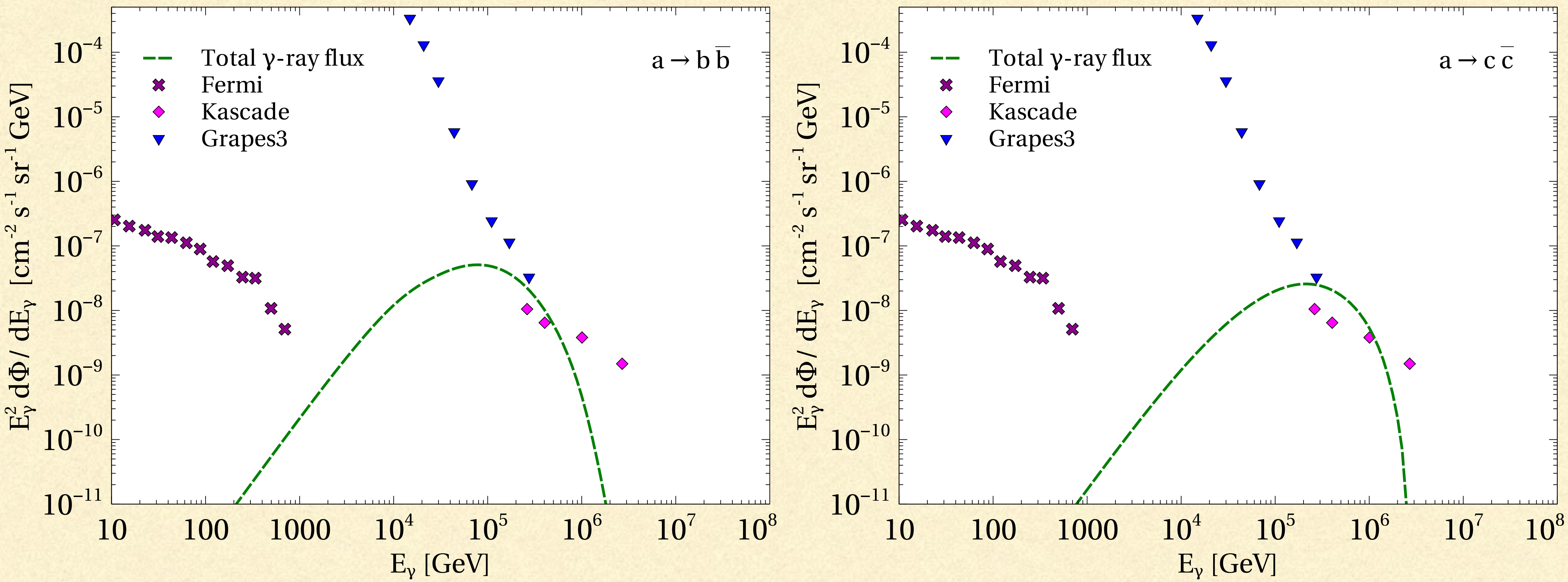
A scalar or pseudo-scalar mediator particle which dominantly couples to heavy fermions can be produced in association with one or two b-quarks (involving the parton level processes g b(b) $\rightarrow$ b(b) S/A and g g $\rightarrow$ b b S/A respectively) further to an LDM pair S/A $\rightarrow$ XX.

In case, $m_x > m_{S/A}$, the (pseudo-)scalar would decay back to the SM fermion pairs, thereby making the search considerably harder due to large SM backgrounds.

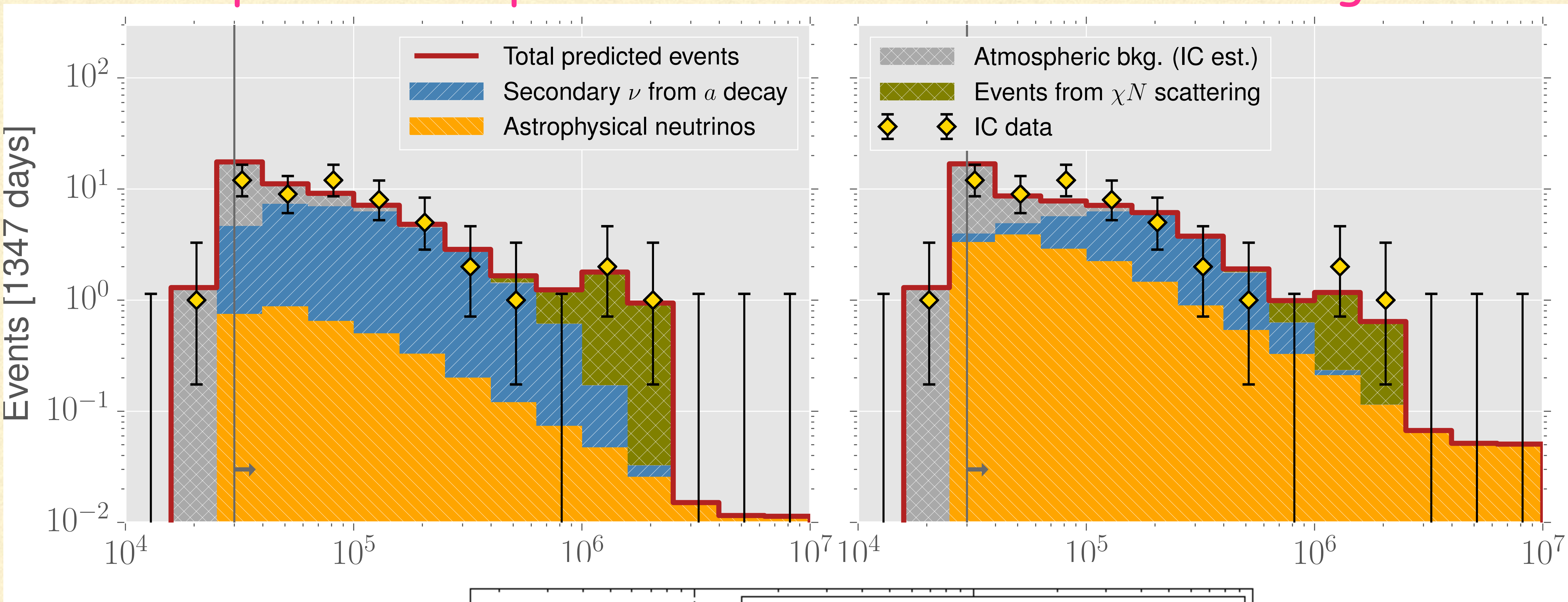
Respecting all collider constraints, require $g_q g_X < O(0.1)$, which is well satisfied in our work.

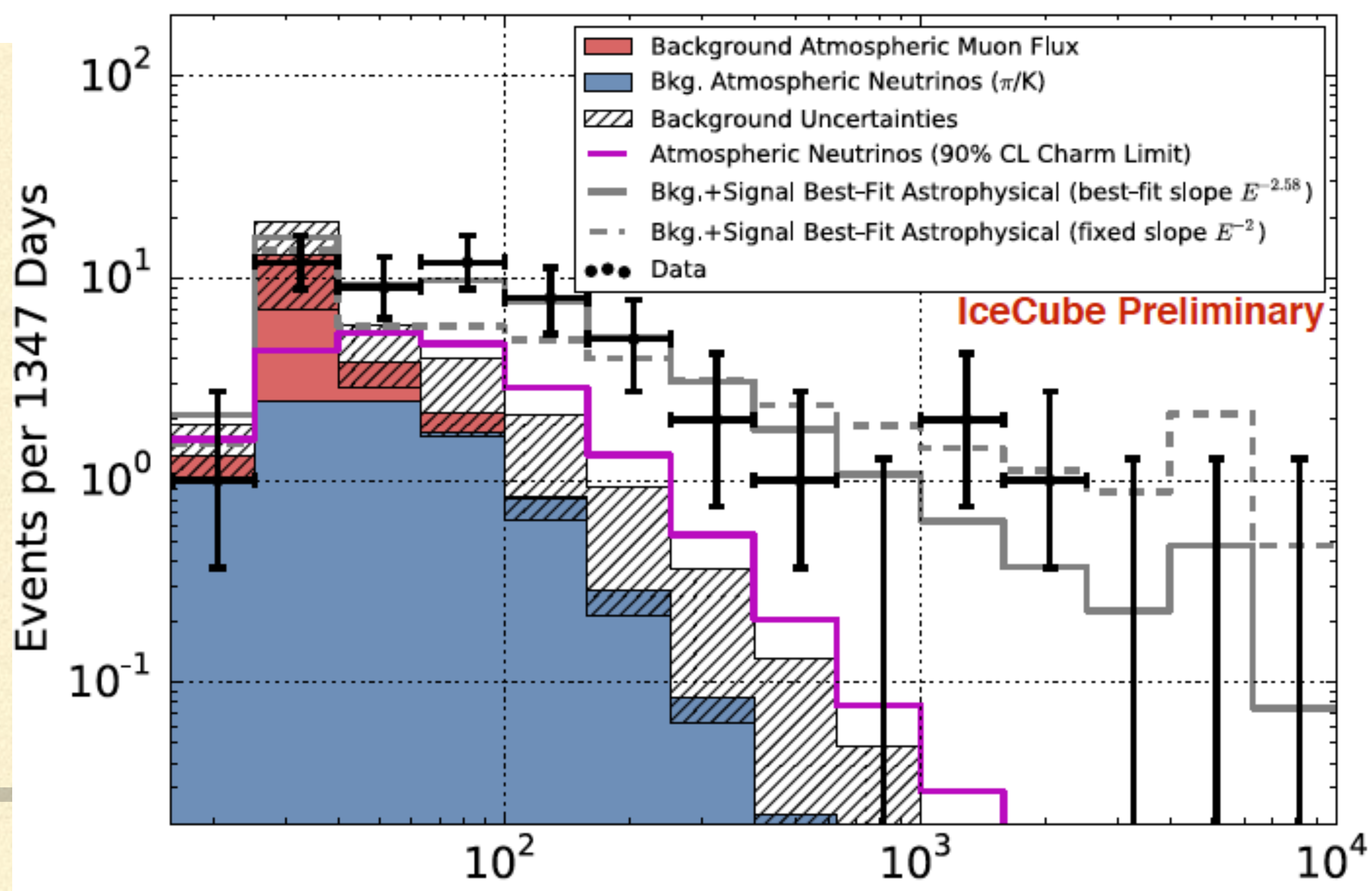
M. R. Buckley, D. Feld and D. Goncalves, *Scalar Simplified Models for Dark Matter*, *Phys. Rev.* **D91** (2015) 015017, [1410.6497].

Constraints and other considerations ....



Example case of pseudo scalar mediator.. ……..Fitting IC data



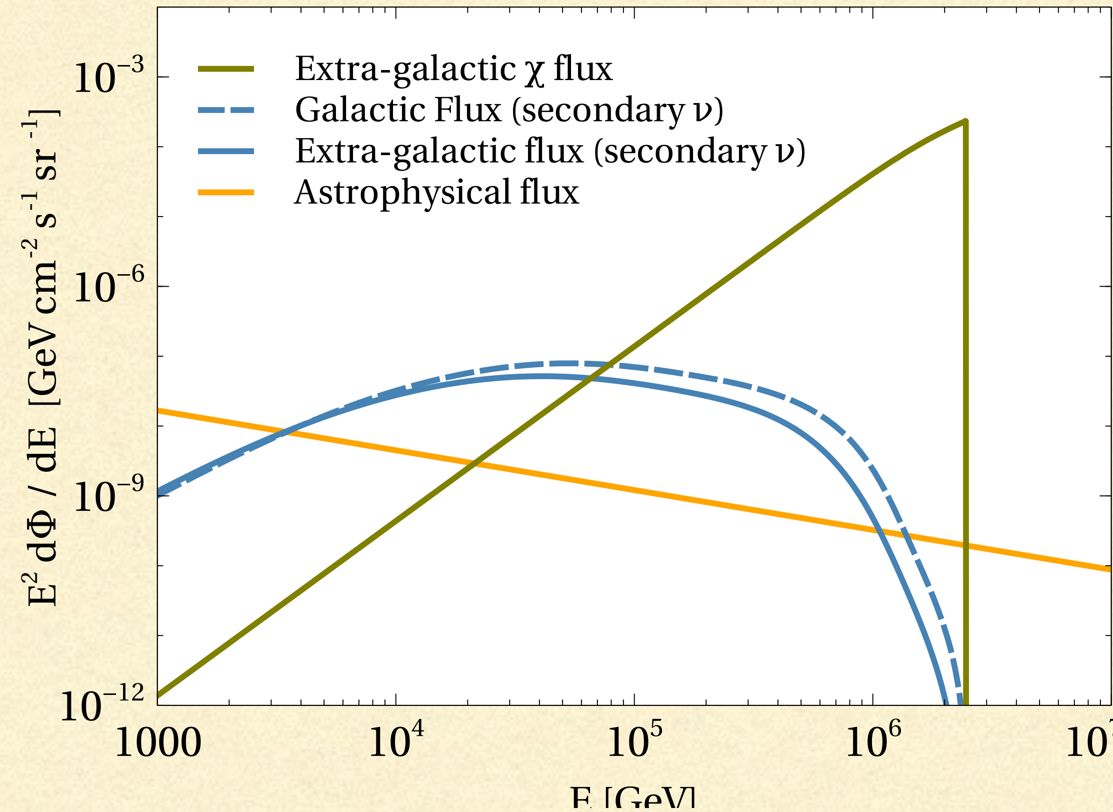


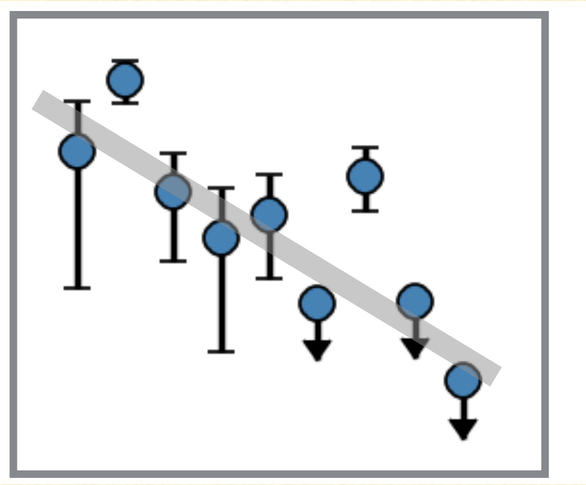
Features accounted for by Scenario I ....

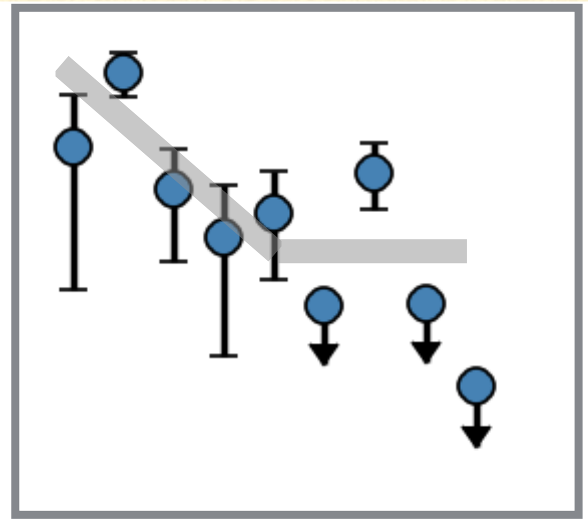
The secondary neutrino event spectrum has a shape that would allow it to naturally account for a 'bump', or excess, in the vicinity of 30-100 TeV.

The astrophysical neutrino contribution, especially in the $b\bar{b}$ case, is not a dominant component. Proximity to the WB bound is not an issue

A dip in the region 400-1000TeV occurs naturally due to the presence of fluxes of different origin in this region.

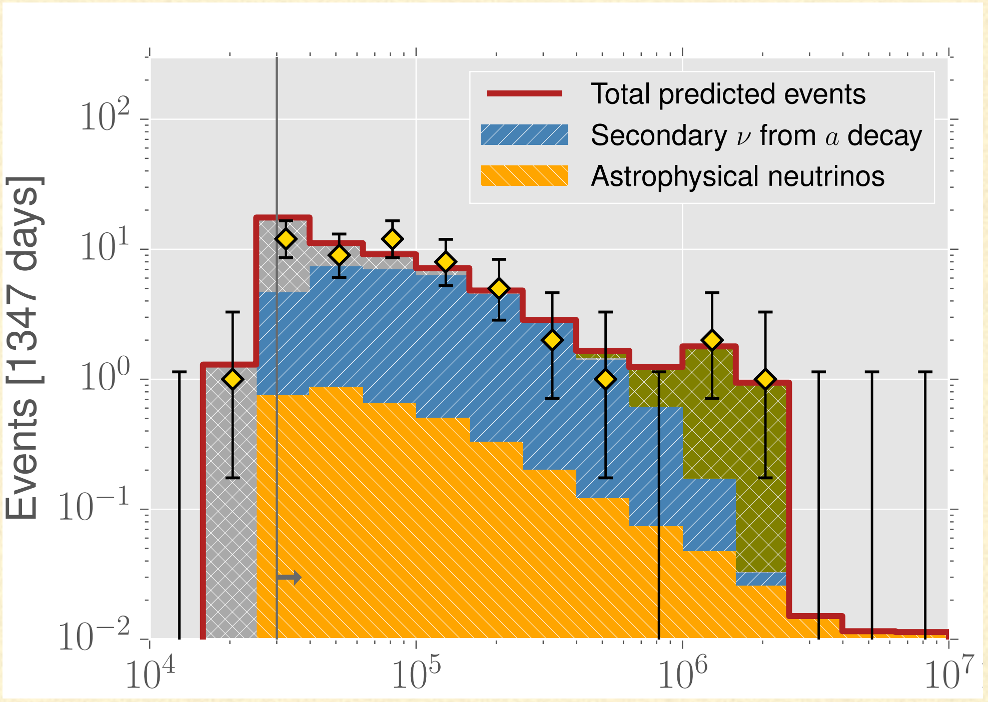






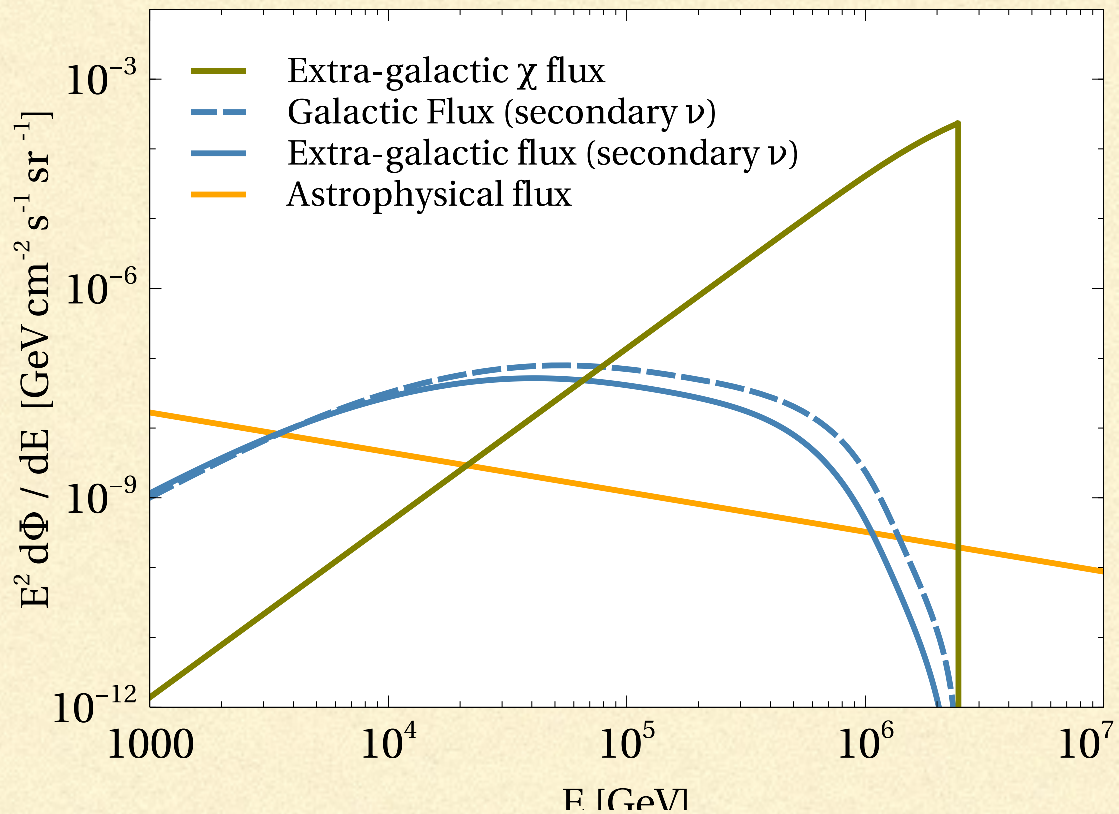
Are we seeing a break in the spectrum, anisotropy, multiple components,...?

T. DeYoung, IC talk, PASCOS 2016



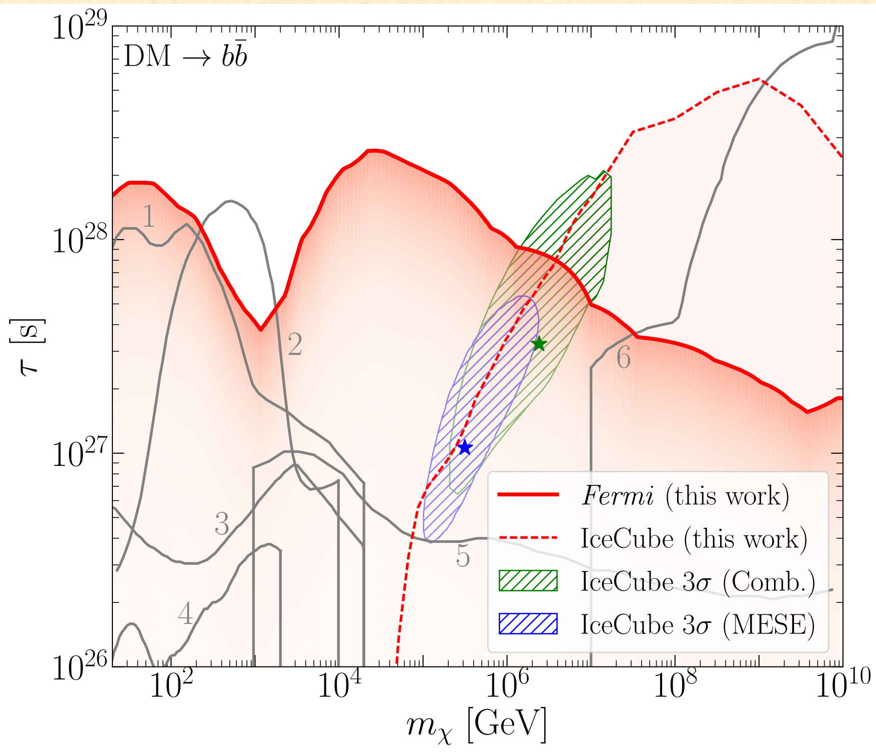
Features accounted for by Scenario I …….. (contd)

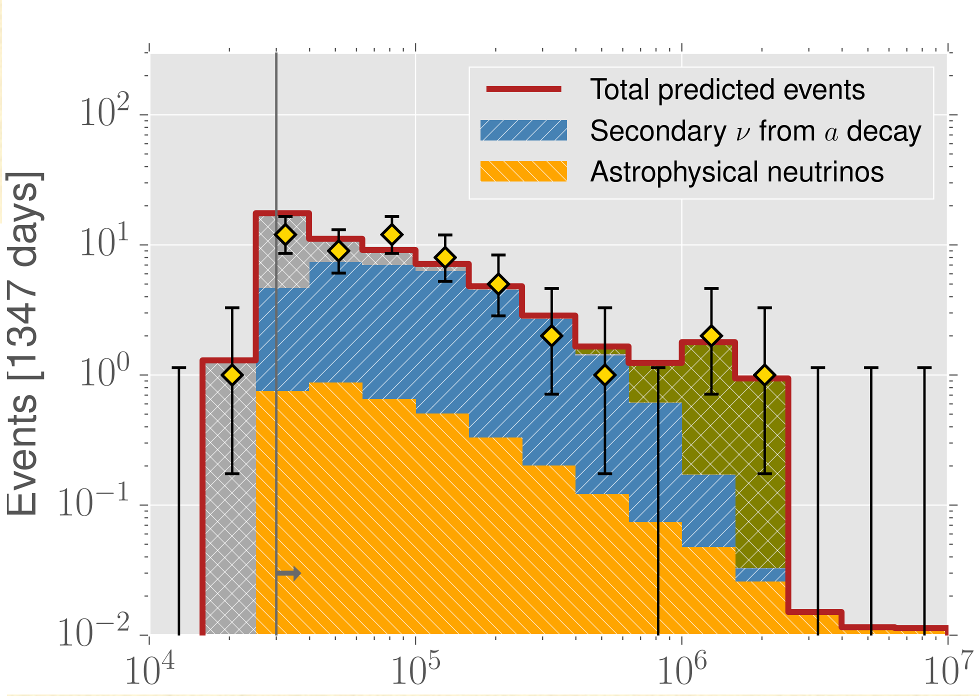
- Over the present exposure period, no HESE events are expected in the region beyond 2-3 PeV, since the only contributing flux here is the astrophysical flux, which is significantly lower in this scenario as opposed to the IC best-fits. With more exposure, some astrophysical events can be expected to show up in this region.



We also note that recent constraints on decaying DM for masses from ~400 MeV to ~10^7 GeV by performing an analysis of Fermi gamma-ray data from 200 MeV to 2 TeV are evaded because they apply to DM decaying to SM particles.

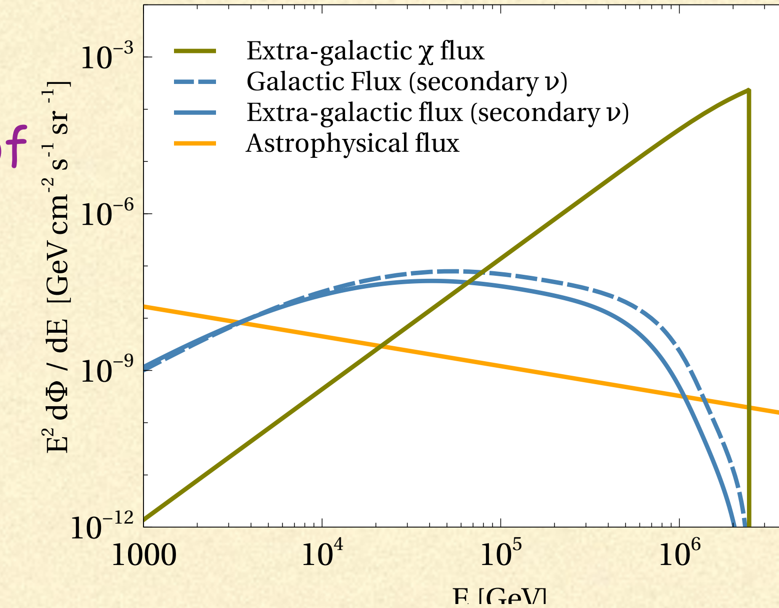
Cohen, Murase, Rodd, Safdi and Soreq, arXiv: 1612.05638





Testable Predictions from Scenario I ……..

Expect to see a gradual statistical improvement in the evidence for a dip-like structural feature around 400–800TeV, since this region marks the interface of fluxes of different origins.

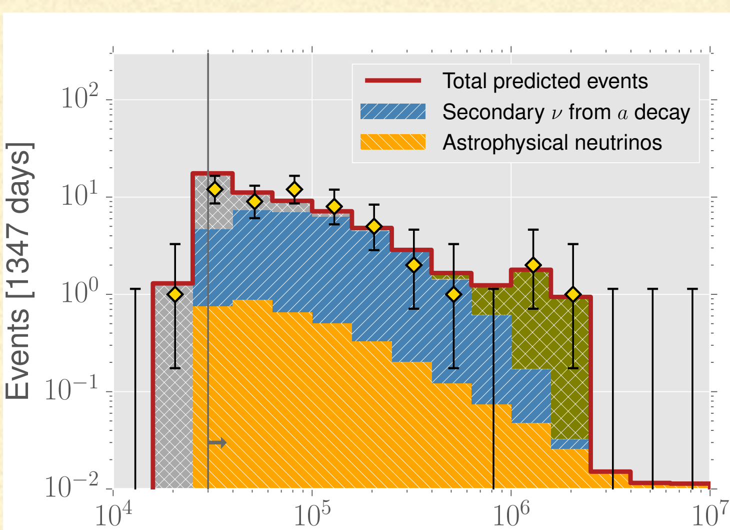


Improvement in statistics for bump like feature in the 30-100 TeV region.

Expect a paucity of events beyond 2.1 PeV, due to a significantly lower astrophysical flux compared to current IC predictions.

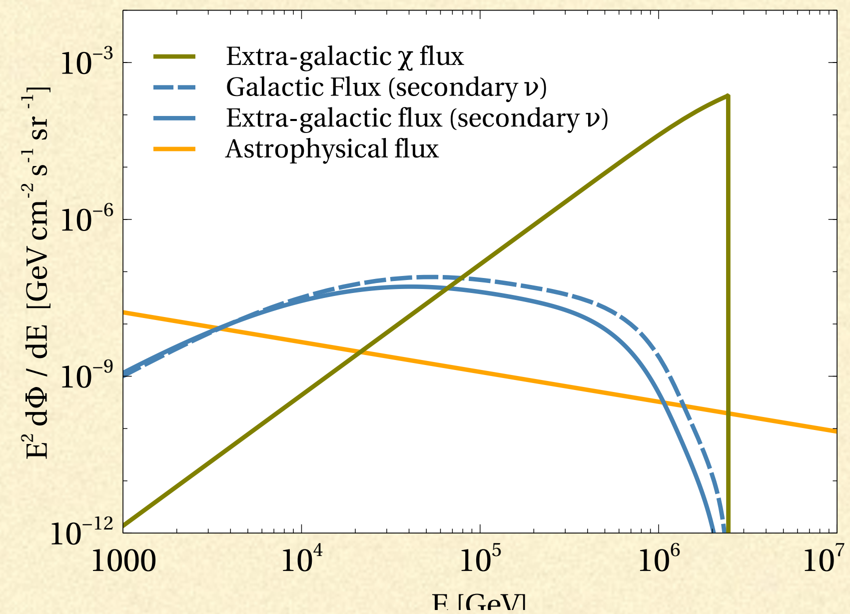
A PeV event spectrum predominantly from LDM scattering (due to HDM decay) predicts i) a significantly enhanced ratio of cascade-to-track events approximately in the (0.75–2.5 PeV) region,

ii) a build-up in the number of such cascade events in this region as the HDM decay and LDM scattering proceed, and



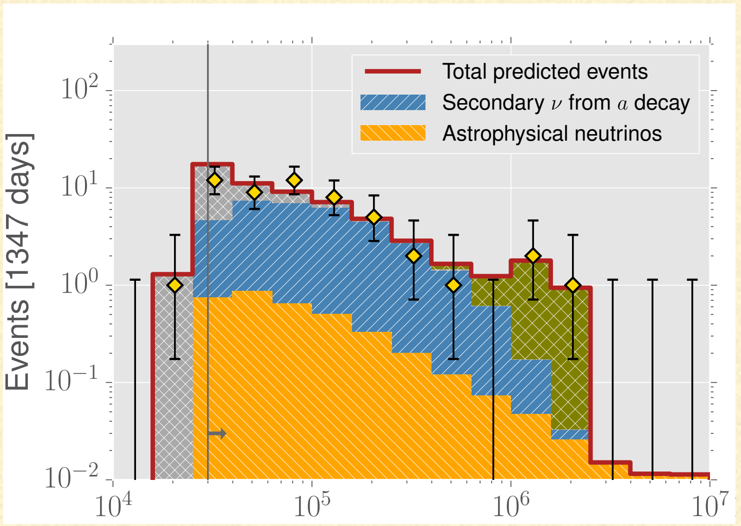
iii) a small but non-zero number of up-going cascades in this energy region over time from the northern hemisphere compared to the case where these events would have been due to a neutrino flux (because of the relatively lower χ-nucleon cross section and consequent reduced screening by the earth).

Testable Predictions from Scenario I ....



Finally, through-going muon track events beyond ~ 3 PeV are also expected to be lower in number in this scenario than what current IC power-law fit predictions suggest.

The overall signal would also exhibit a gradual galactic bias with more statistics, since generically, in DM scenarios, the contributions from our galaxy and from extra-galactic DM are roughly of the same order. Such a directional bias is not expected in a genuinely isotropic flux.



Thank you for your attention!

Backup Slides

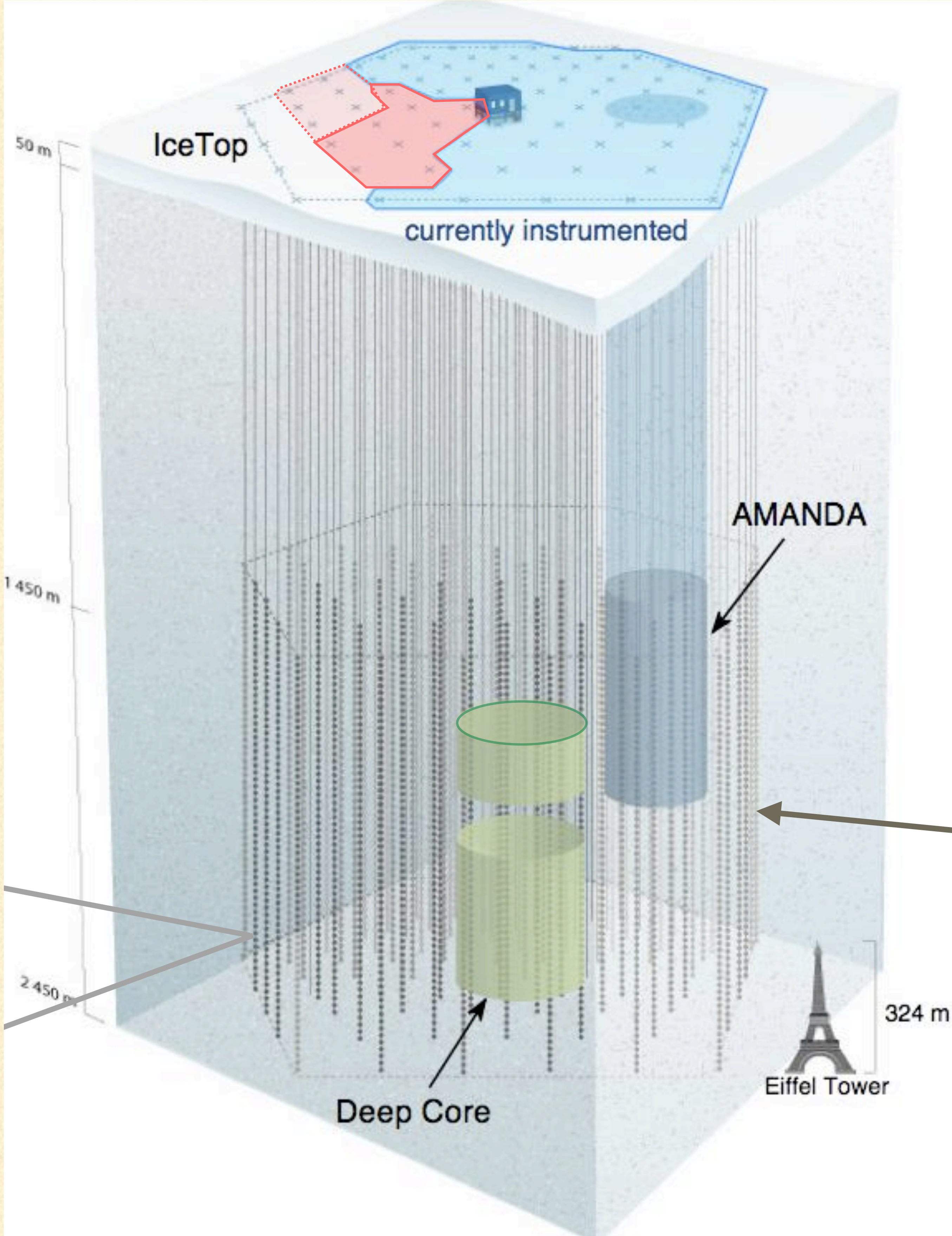
Conclusions ……..

Very good fits to 1347 day HESE data are obtainable assuming that some of the IC events, which characterize animals features are due to boosted DM.

Gap/break around 400- 1 PeV occurs naturally
Understanding why no events after ~ 2 PeV
Secondary flux naturally gives excess at 50-100 TeV
No puzzling proximity to WB bound

Constraints have been considered and are respected by our fits.

The IceCube Detector

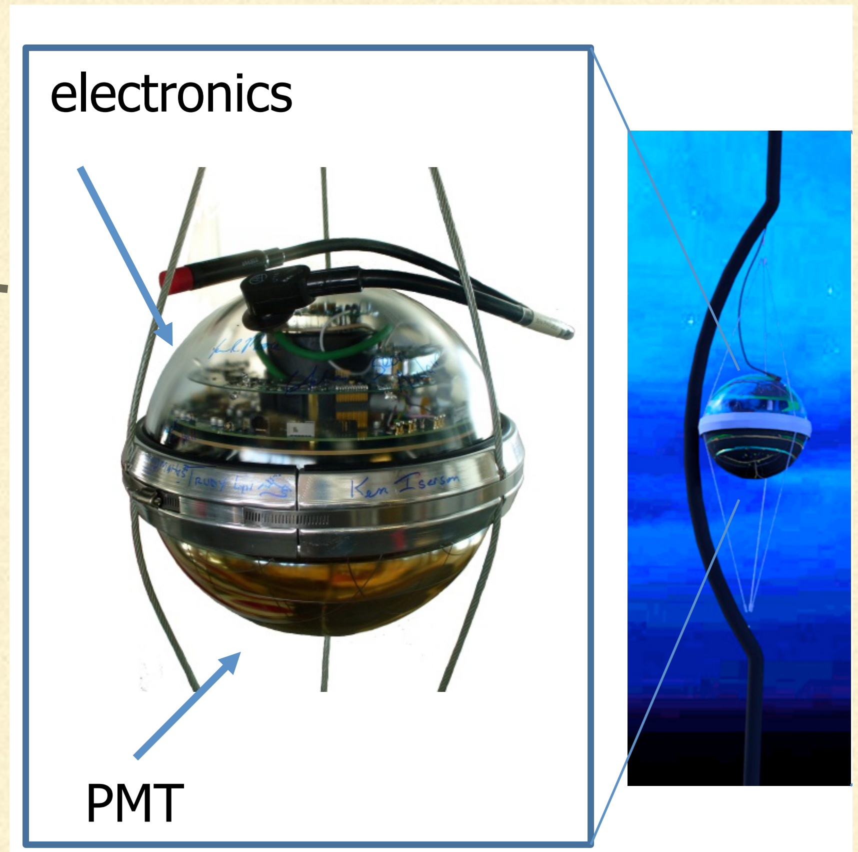


86 strings, 60 OM/string

17 m distance between 2 OM o
same string

125 m distance between 2
consecutive strings

1 km^3 instrumented volume



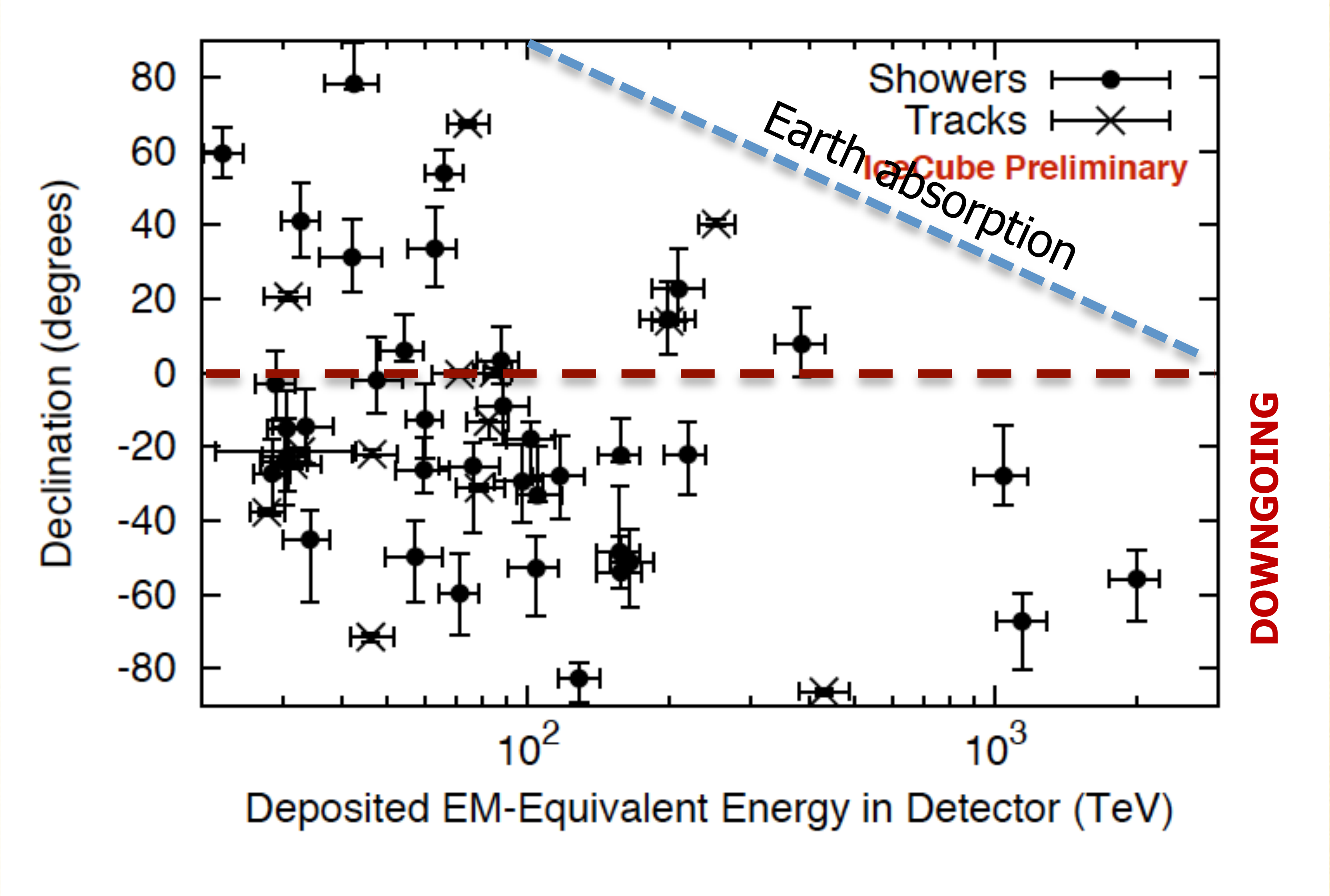
DIGITAL OPTICAL MODULE

IceCube Results………….

3 yrs: 37 events in 988 days
bkg. 6.6+5.9 atm v,
5.7 sigma evidence for astrophysical neutrino signal

4 yrs: 54 events ~ 7 sigma evidence

Mostly ve CC and NC cascades



Zenith distribution consistent with isotropic astrophysical flux

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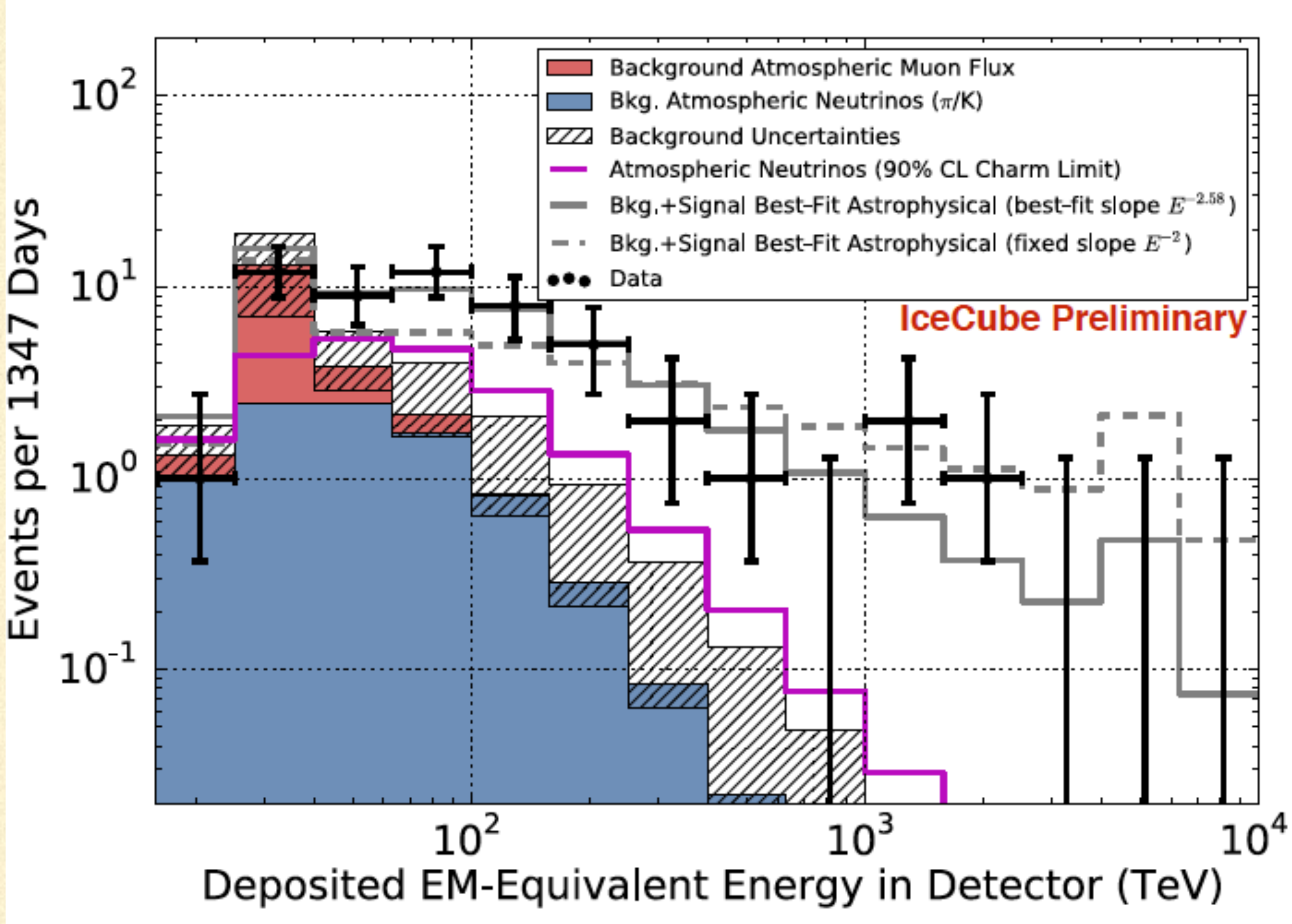
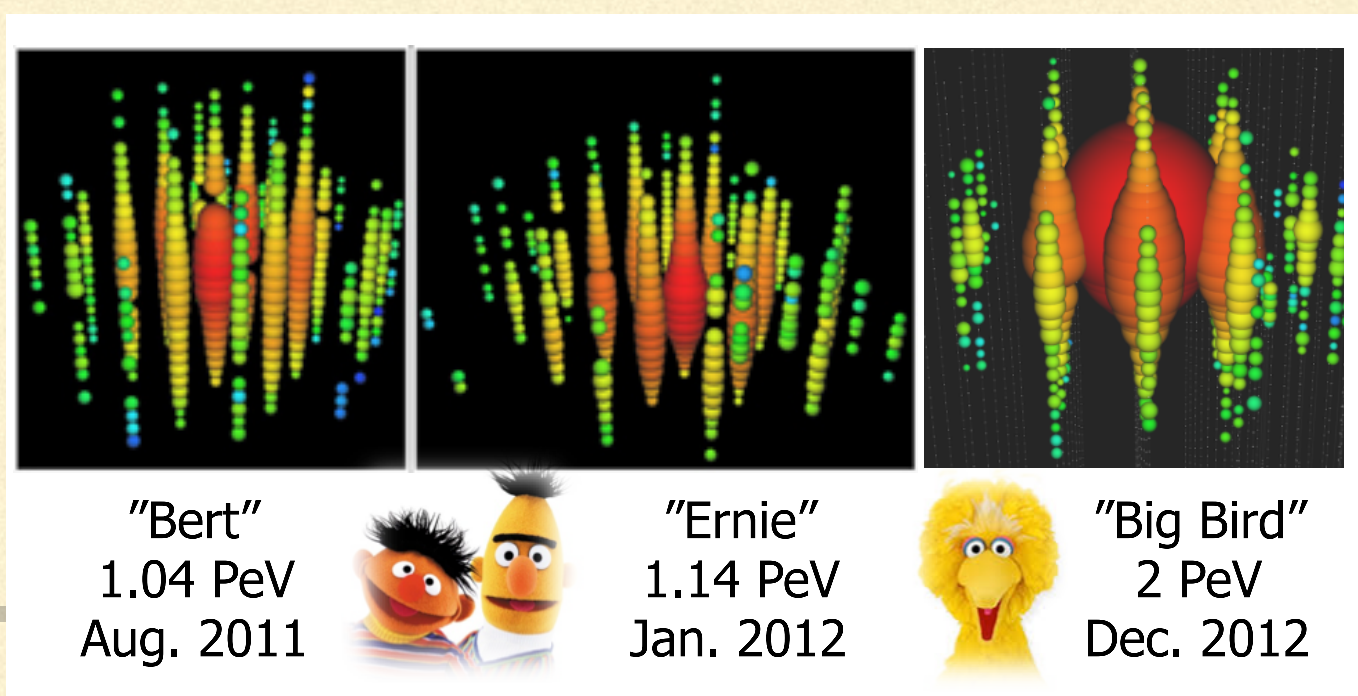
IceCube Results…………Some interesting features

Three cascade events in ~ 1-2 PeV region.

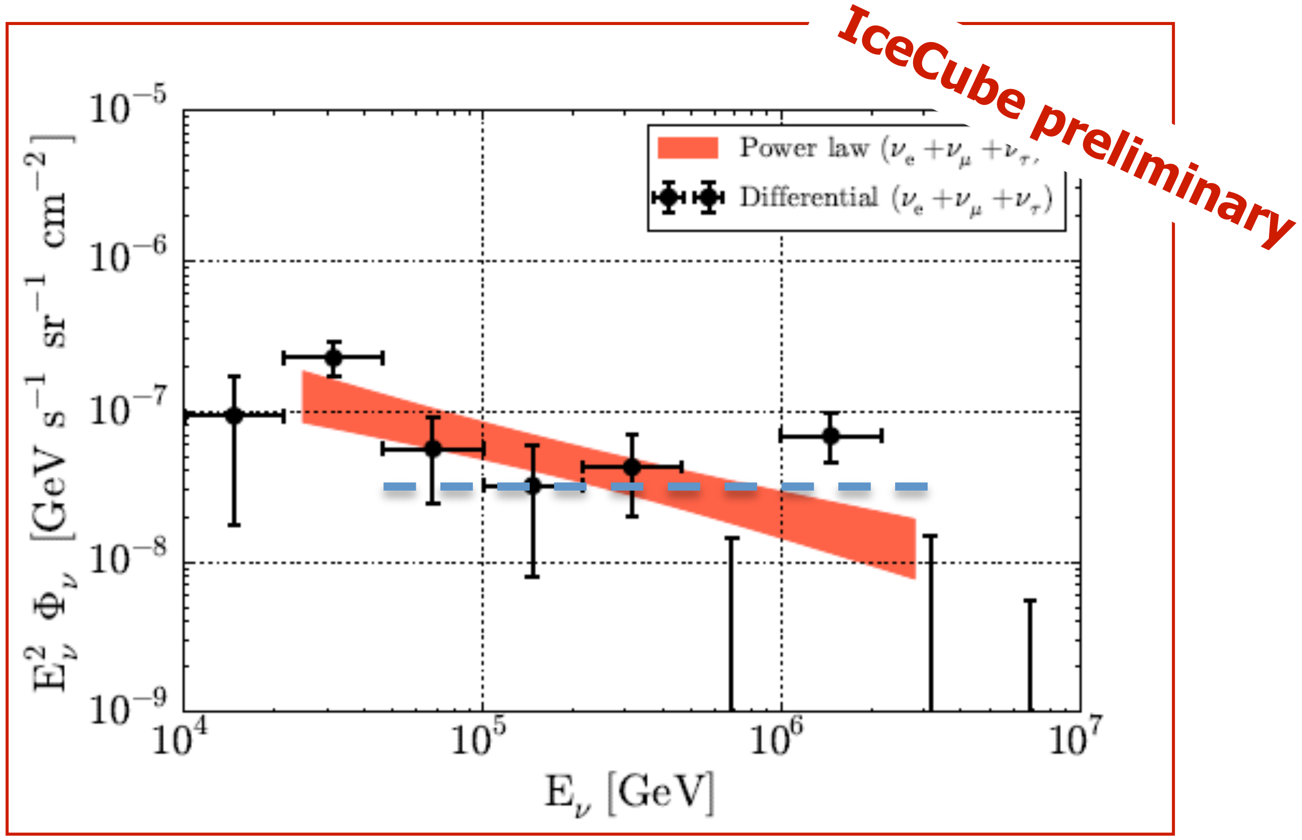
Temporally separated by months



IC has high sensitivity between 1-10 Pev, yet no cascade events beyond ~ 2PeV, although ~3-4 expected due to Glashow Resonance



No events between 400 TeV and 1 PeV



- 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!

- $$\Phi_\nu = \boxed{(7.0^{+1.0}_{-1.0}) \times 10^{-18}\,\mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{\boxed{-2.49\pm0.08}}$$
- E^{-2} excluded at $\boxed{4.6\,\sigma}$

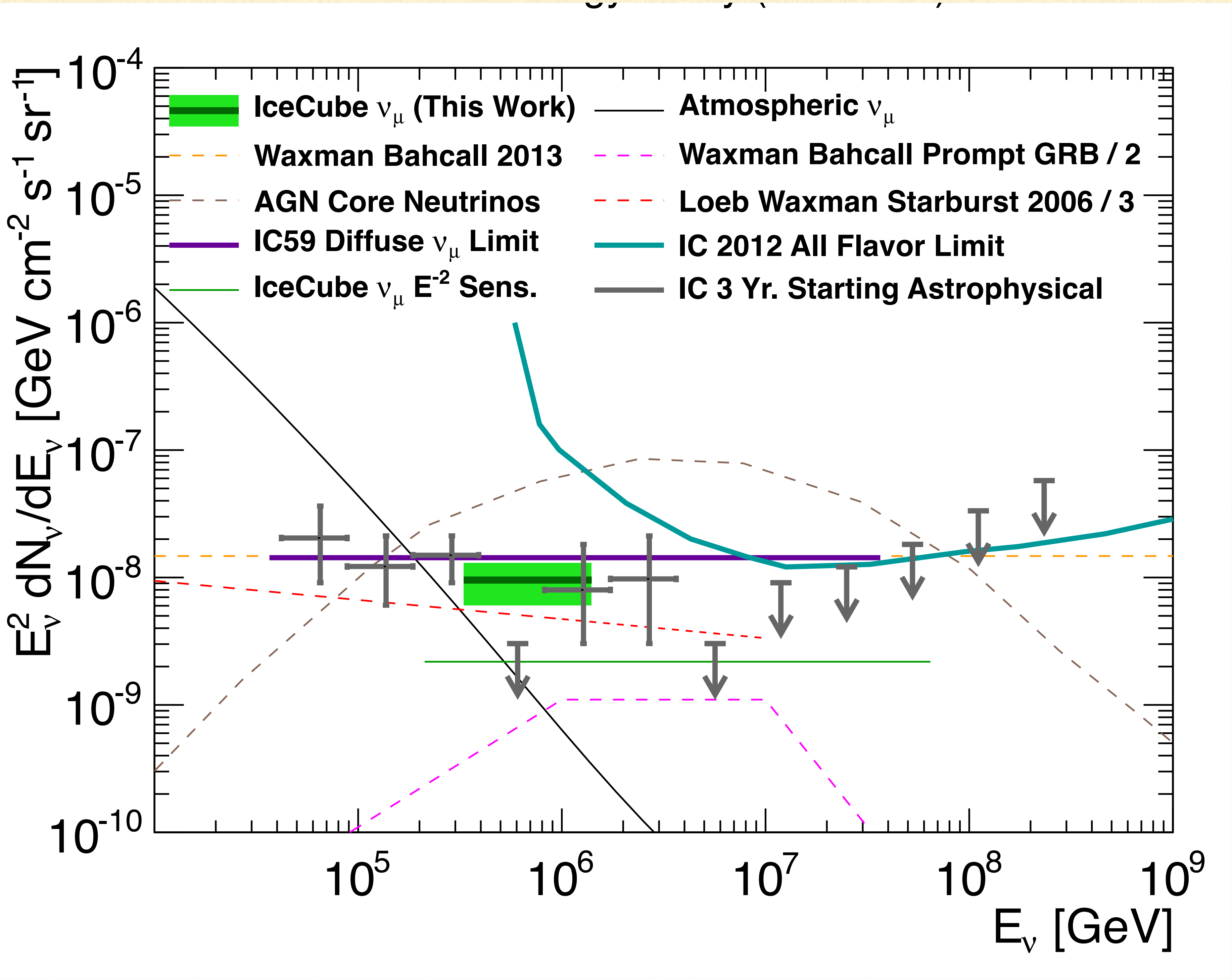
Best fit hypothesis B:

all-flavor!

- $$\Phi_\nu = \boxed{(8.0^{+1.3}_{-1.2}) \times 10^{-18}\,\mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{\boxed{-2.31\pm0.15}} \times \exp\left(-E/\boxed{(2.7^{+7.7}_{-1.4})\,\mathrm{PeV}}\right) .$$
- preferred over hypothesis A by $\boxed{1.2\,\sigma}$

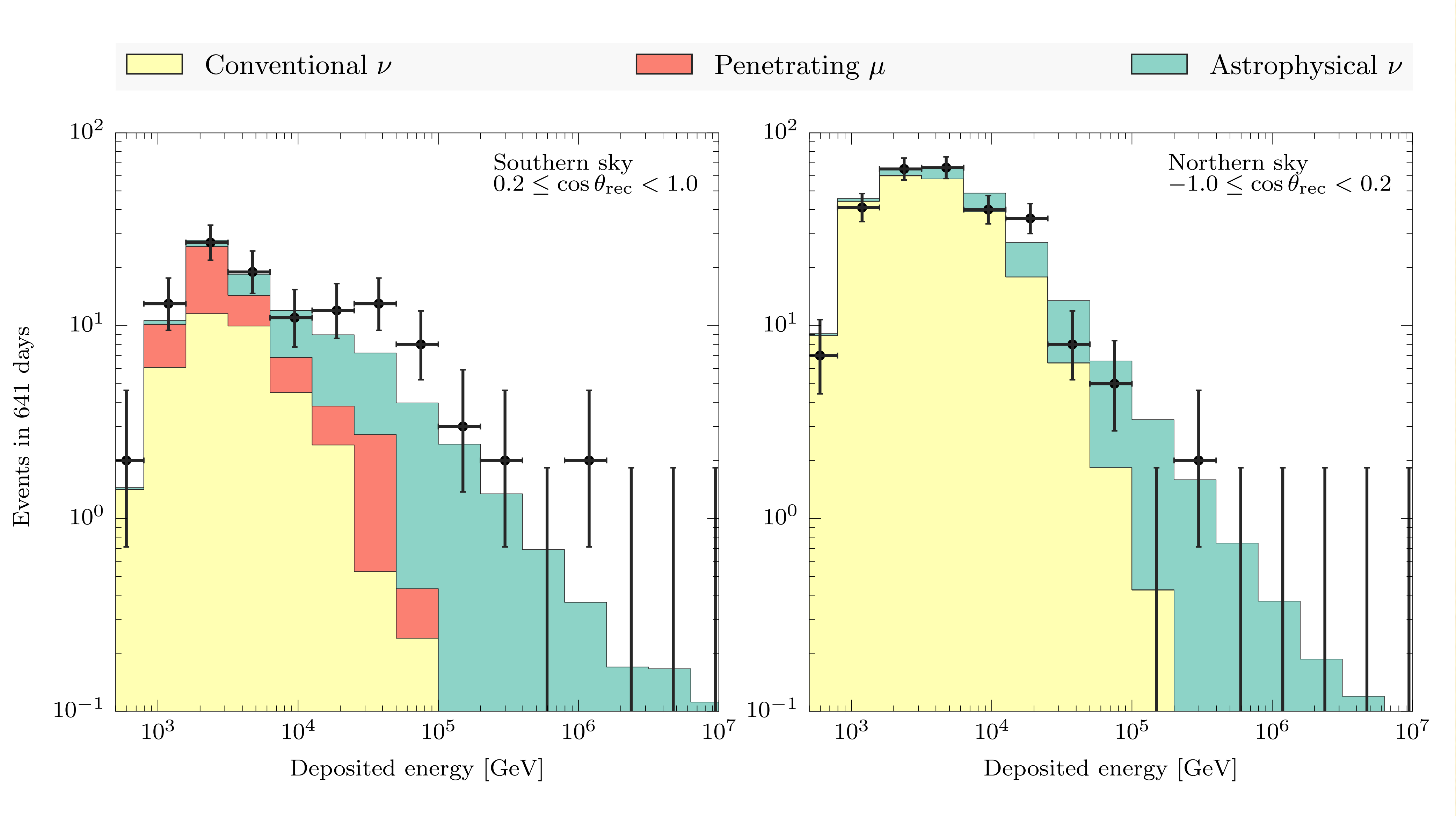
Features in IceCube data.....

Proximity to WB bound is puzzling and difficult to understand



Features in IceCube data.....

At lower energies, in the range of 50 – 100 TeV, there appears to be an excess, with a bump-like feature (compared to a simple power-law spectrum), which is primarily present in events from the southern hemisphere. The maximum local significance of this excess is about 2.3σ.

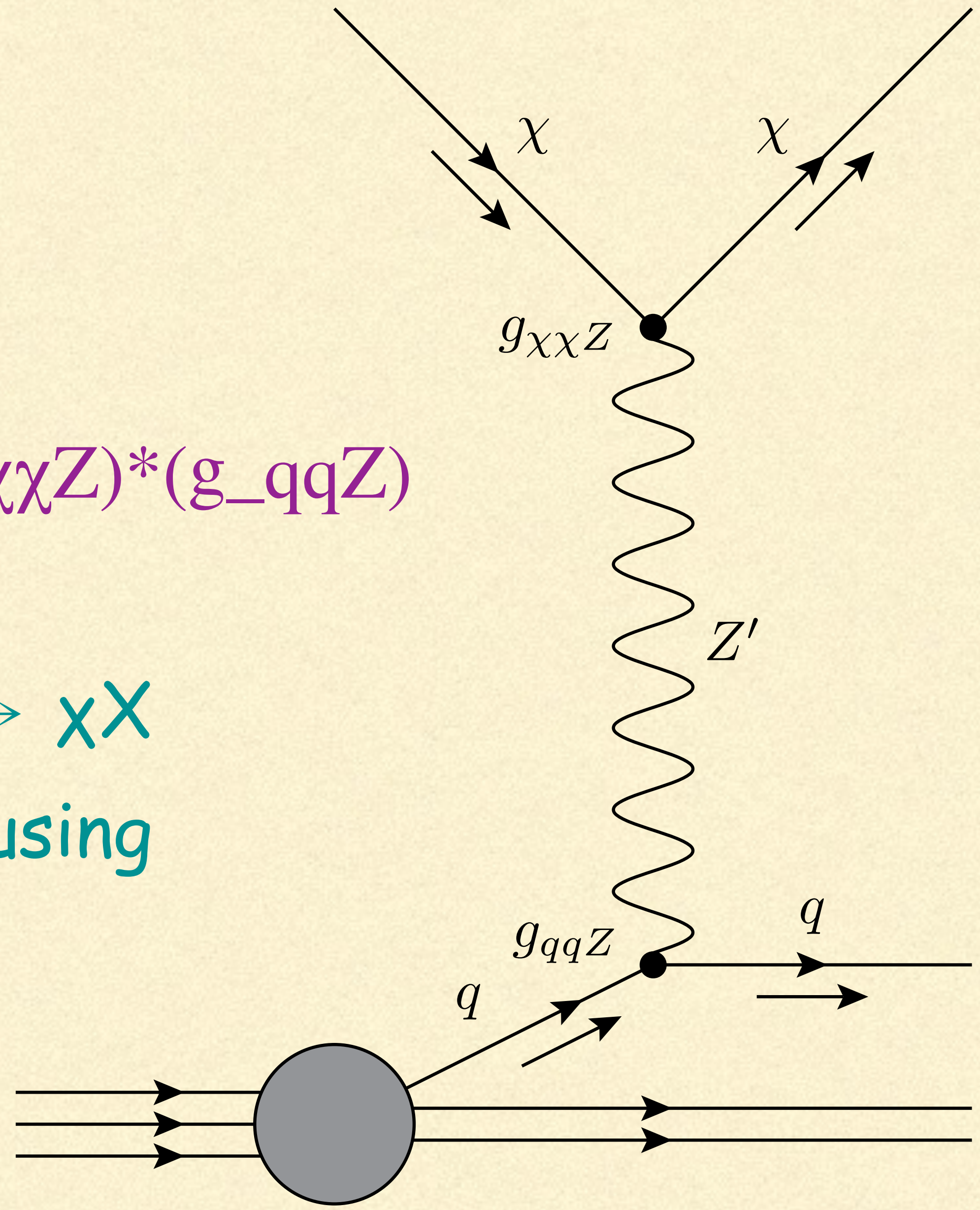


Understanding the features via a boosted DM scenario

Z' which connects SM and DM sectors

Vector-like couplings assumed

G = (g_χχZ)*(g_qqZ)

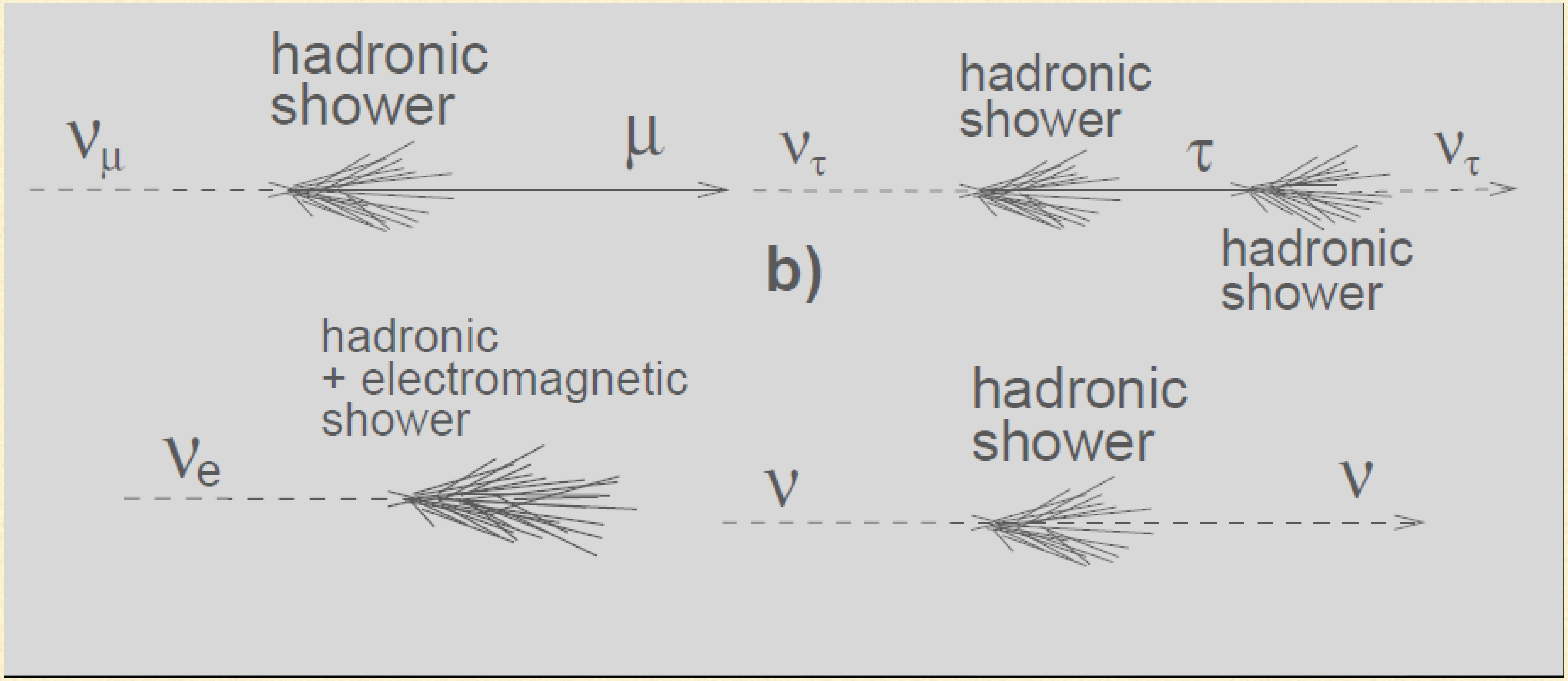


Compute the DIS cross-section for $\chi N \rightarrow \chi X$ in the lab-frame, 100 GeV ≤ E^{in} ≤ 10 PeV, using CT10 parton distribution functions.

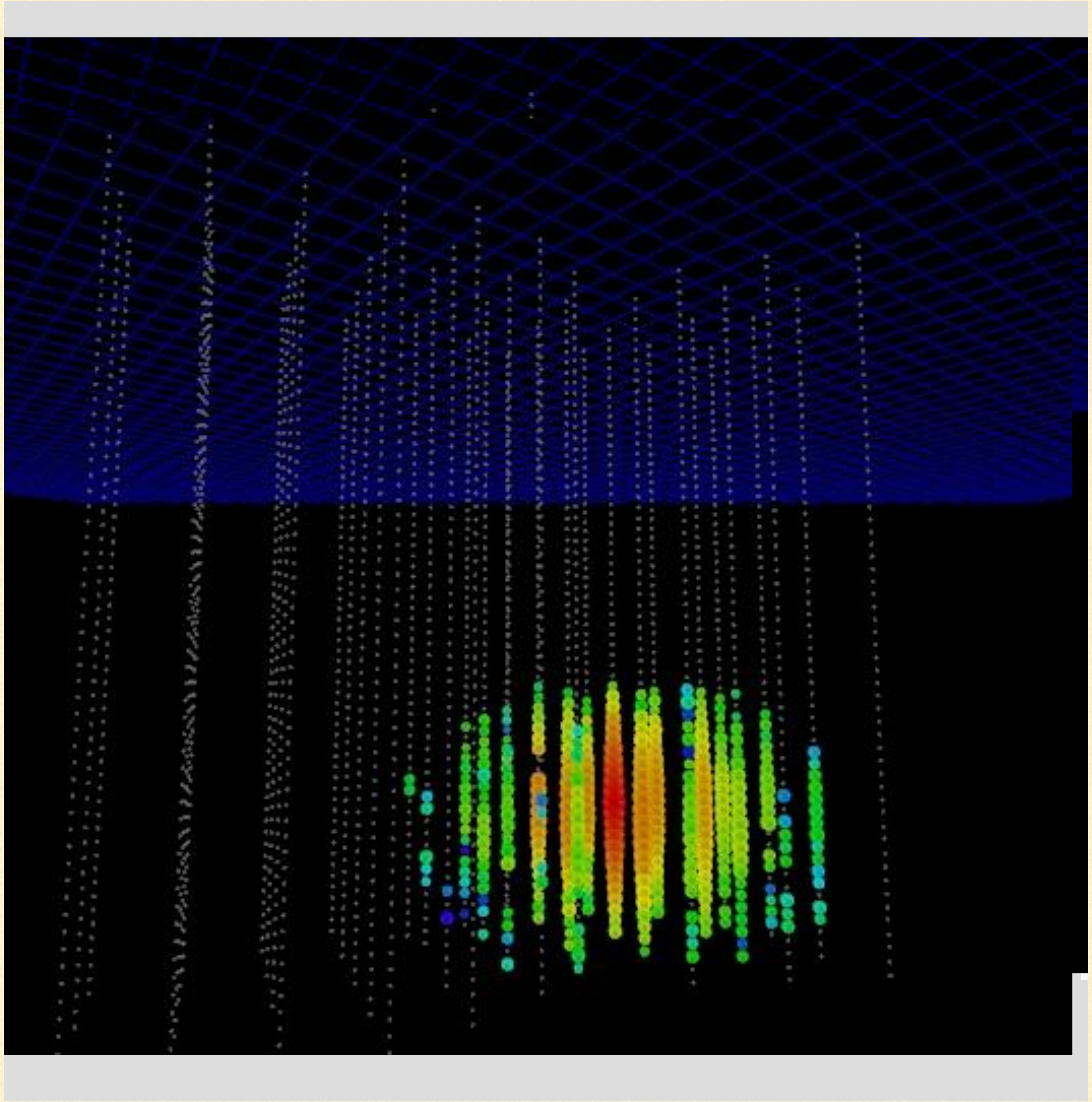
We set the Z' mass to be 5 TeV. (For Z' with mass > 2.9 TeV, the couplings $g_{\chi\chi Z}$ and g_{qqZ} are largely unconstrained by collider searches.)

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

What are the signals in IC and what do they loo like?



Typical Cascade event in Icecube.....

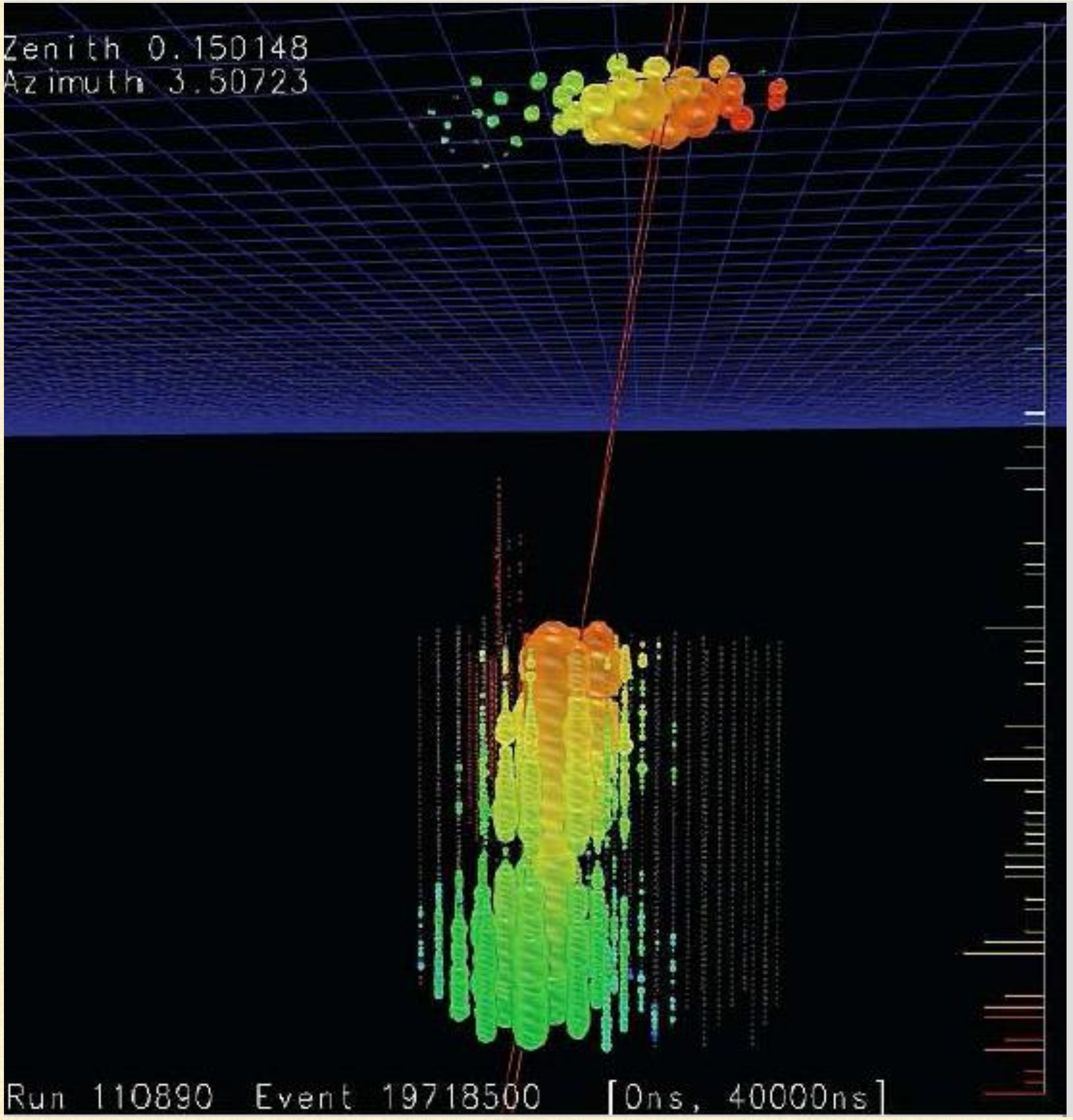


Signal is isotropic

Good Energy resolution, not so good directional resolution

Typical Track event in Icecube.....

Signal events will thus mainly be up going, i.e from northern hemisphere to avoid large atmospheric muon background

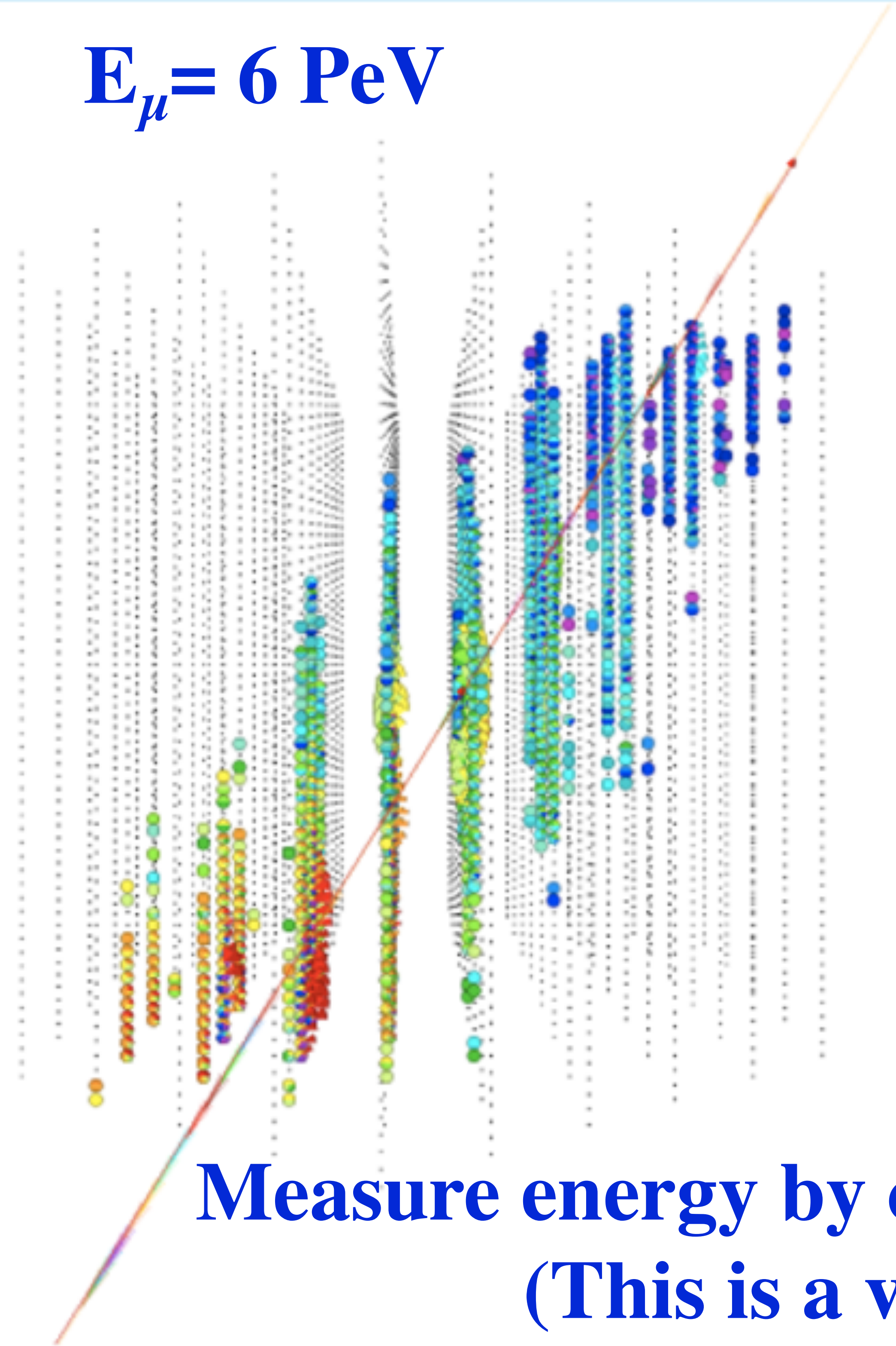


This particular event is a background event, which will be vetoed

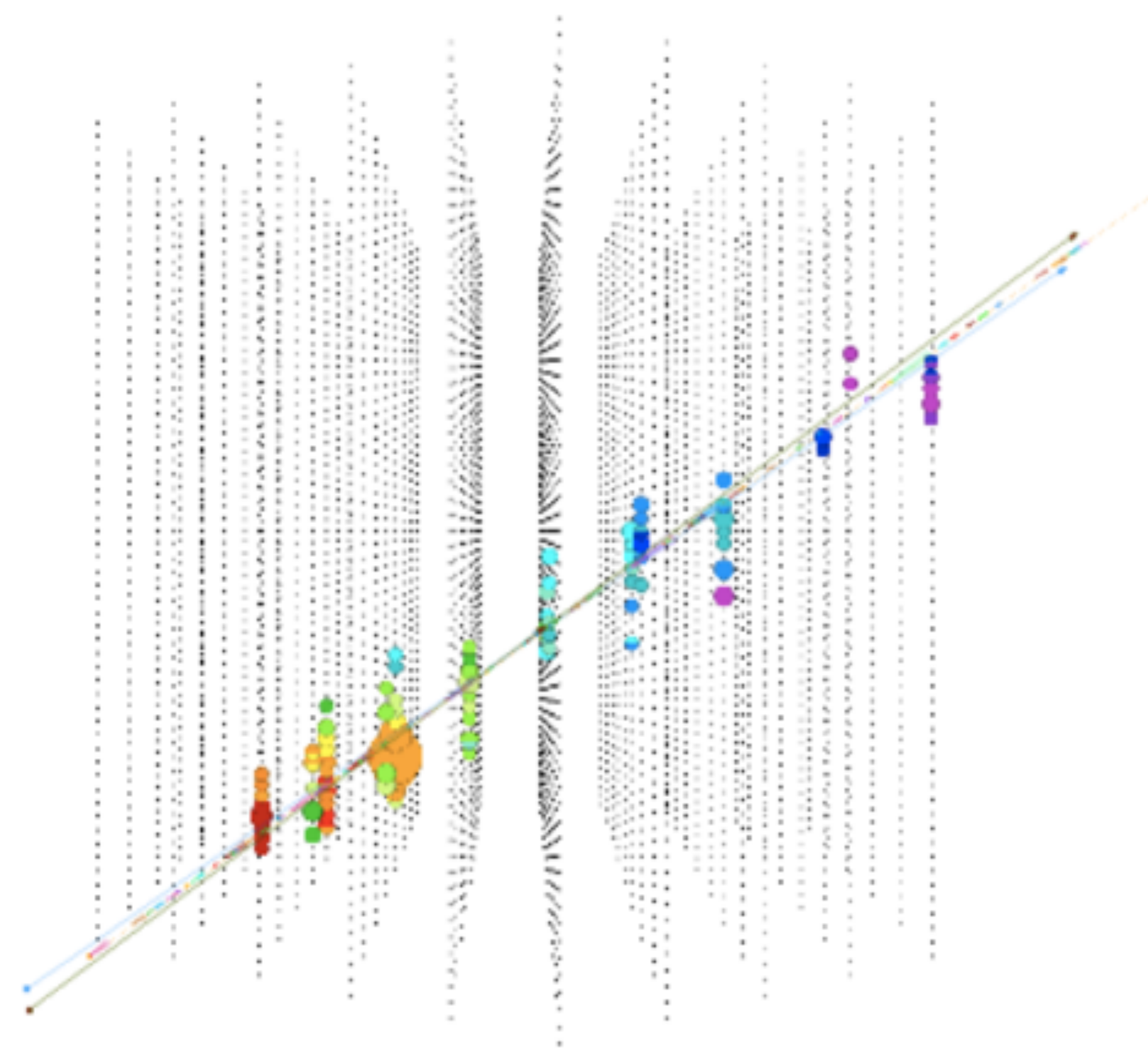
Good direction resolution, not so good energy resolution

Muon Events

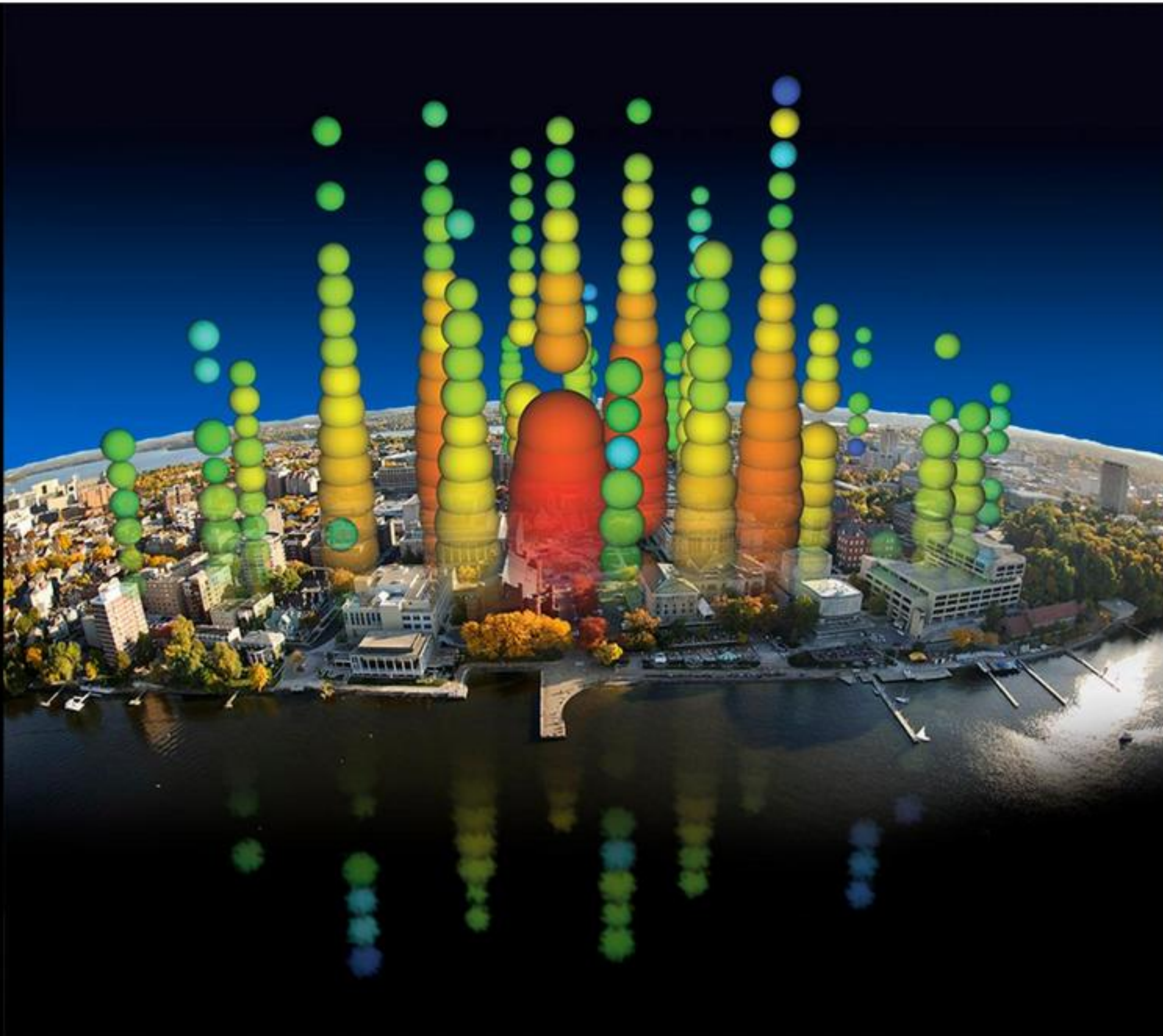
E_μ= 6 PeV



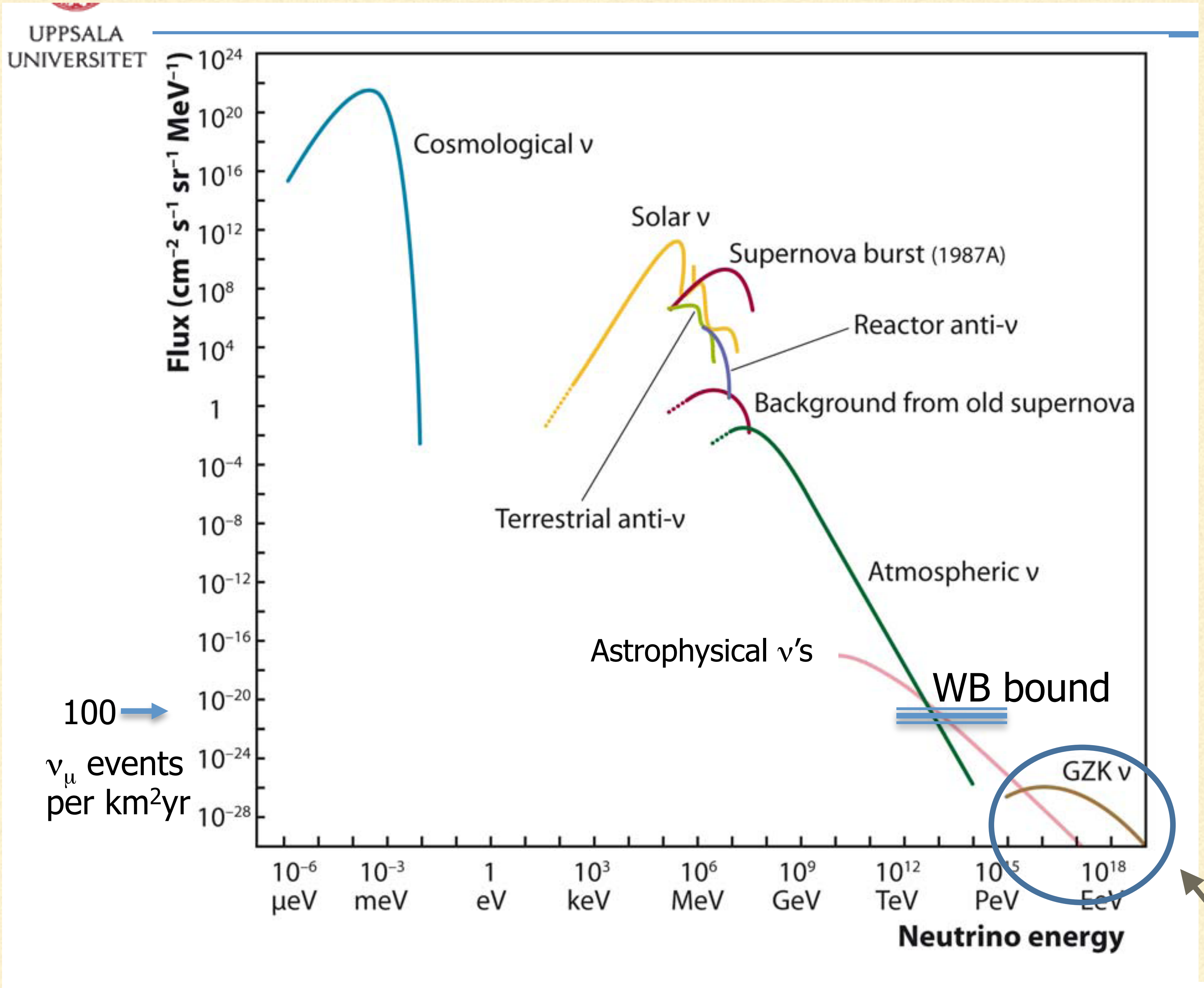
E_μ= 10 TeV



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

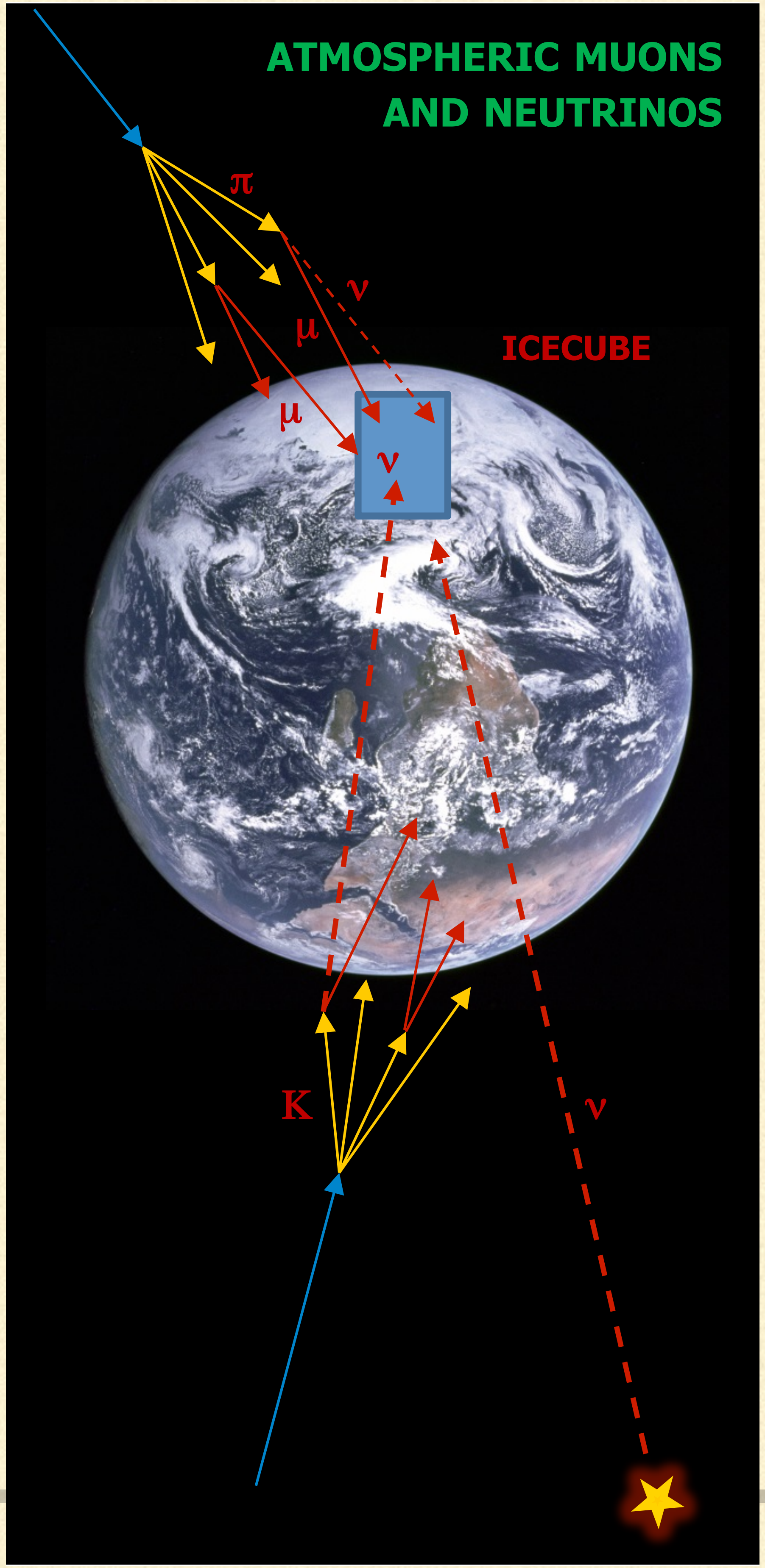


What signal are UHE neutrino detectors looking for?…….



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

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



- atmospheric μ rate ~ 10^3/sec (background, from above)
- atmospheric ν rate ~ 10^-3/sec (background, isotropic)
- ASTROPHYSICAL ν rate ~ 10^-6/sec (signal)

An important constraint on neutrino fluxes: The Waxman Bahcall bound

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

$$\begin{aligned} E_\nu^2\, \Phi_{\rm WB}^{\nu_{\rm all}} &\approx (3/8)\, \xi_z\, \epsilon_\pi\, \mathcal{T}\, \frac{c}{4\pi}\, E^2 \frac{d\dot{n}}{dE} \\ &\approx 2.3\times 10^{-8}\, \epsilon_\pi\, \xi_z\, \mathrm{GeV\, cm^{-2}\, s^{-1}\, sr^{-1}} \end{aligned}$$

[Waxman and Bahcall, Phys.Rev. D59 (1999) 023002;
Phys.Rev. D64 (2001) 023002

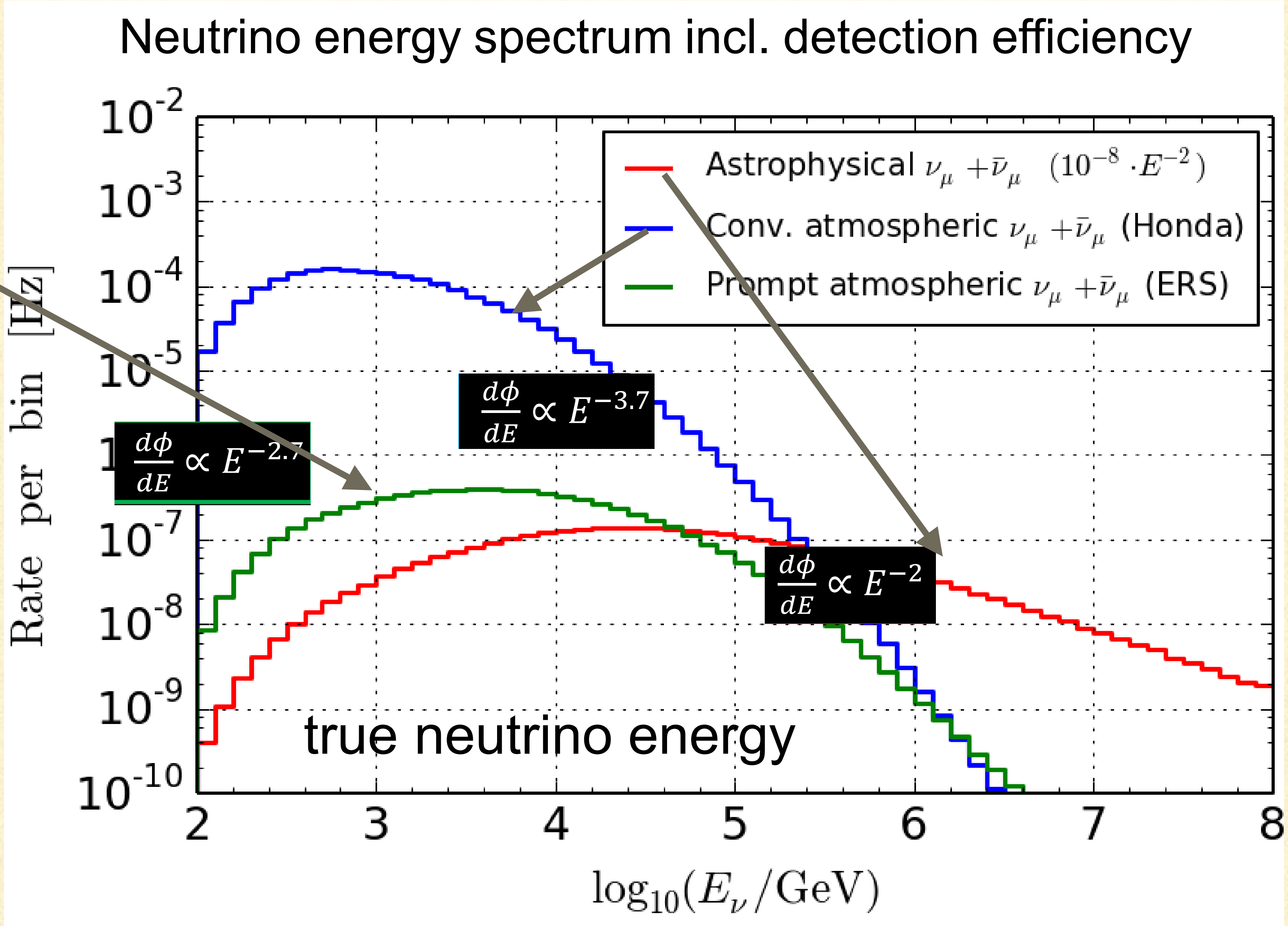
What are the sources for astrophysical neutrinos?.......

- **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

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

$\rightarrow$ $\Phi_\nu \propto E^{-2}$

What does IceCube see so far?

Discussion of results, analysis and conjectures

IceCube Results……………Spectral and flavour fits

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

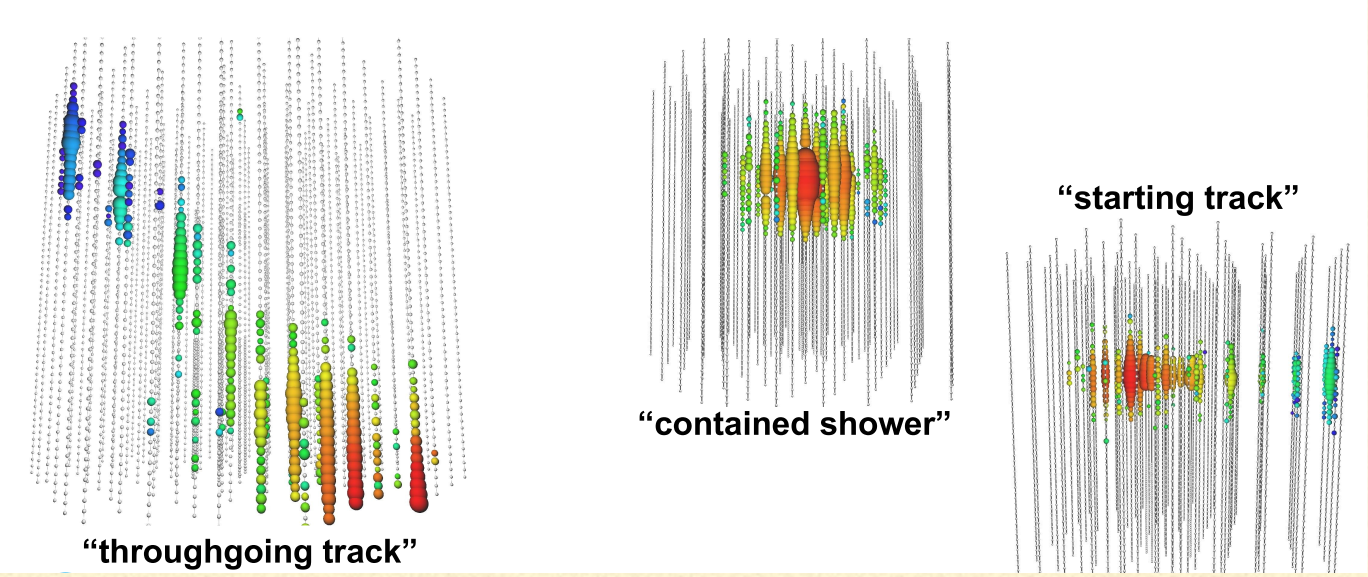
$\rightarrow$ $\Phi_\nu \propto E^{-2}$

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

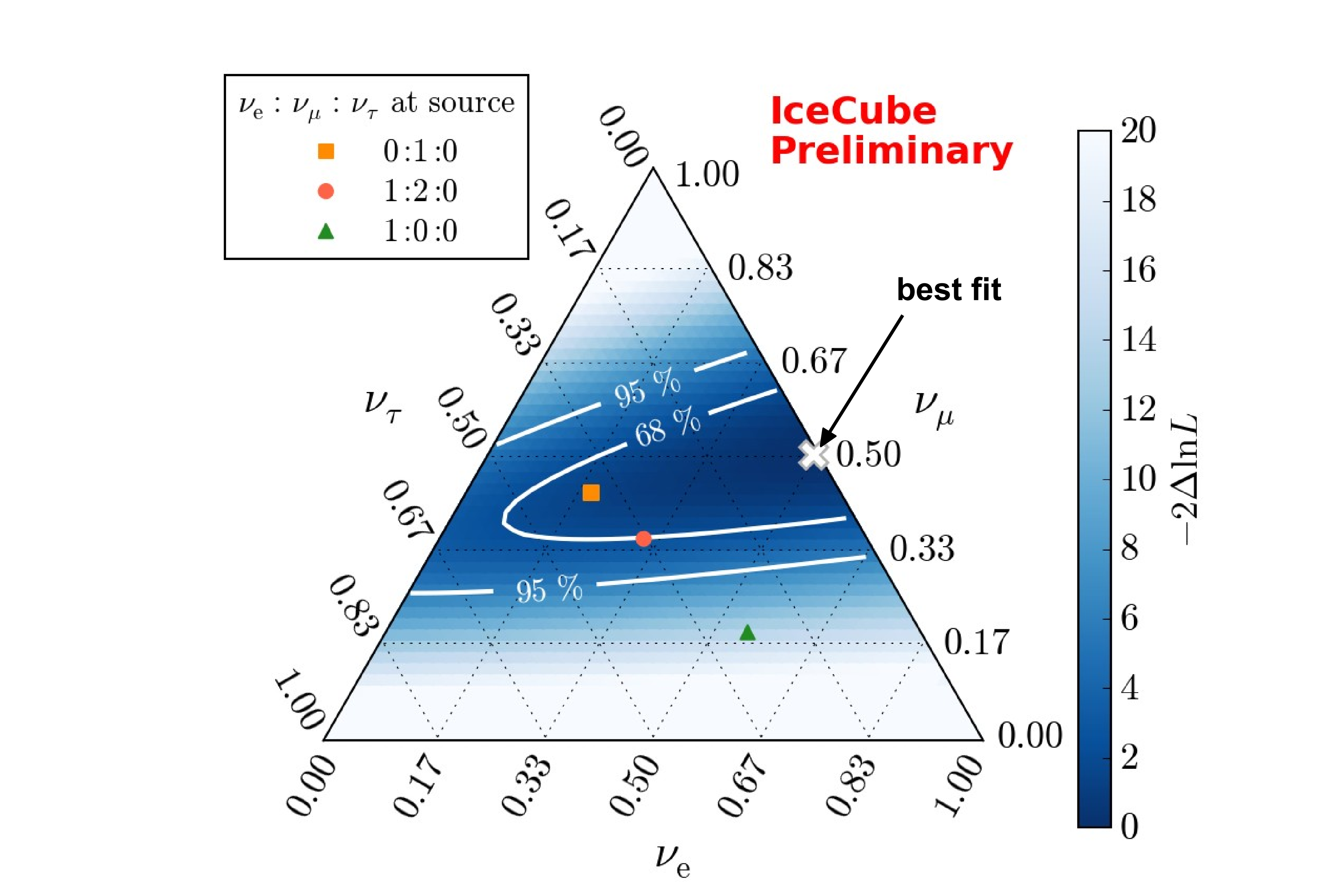


Pion-decay: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$

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

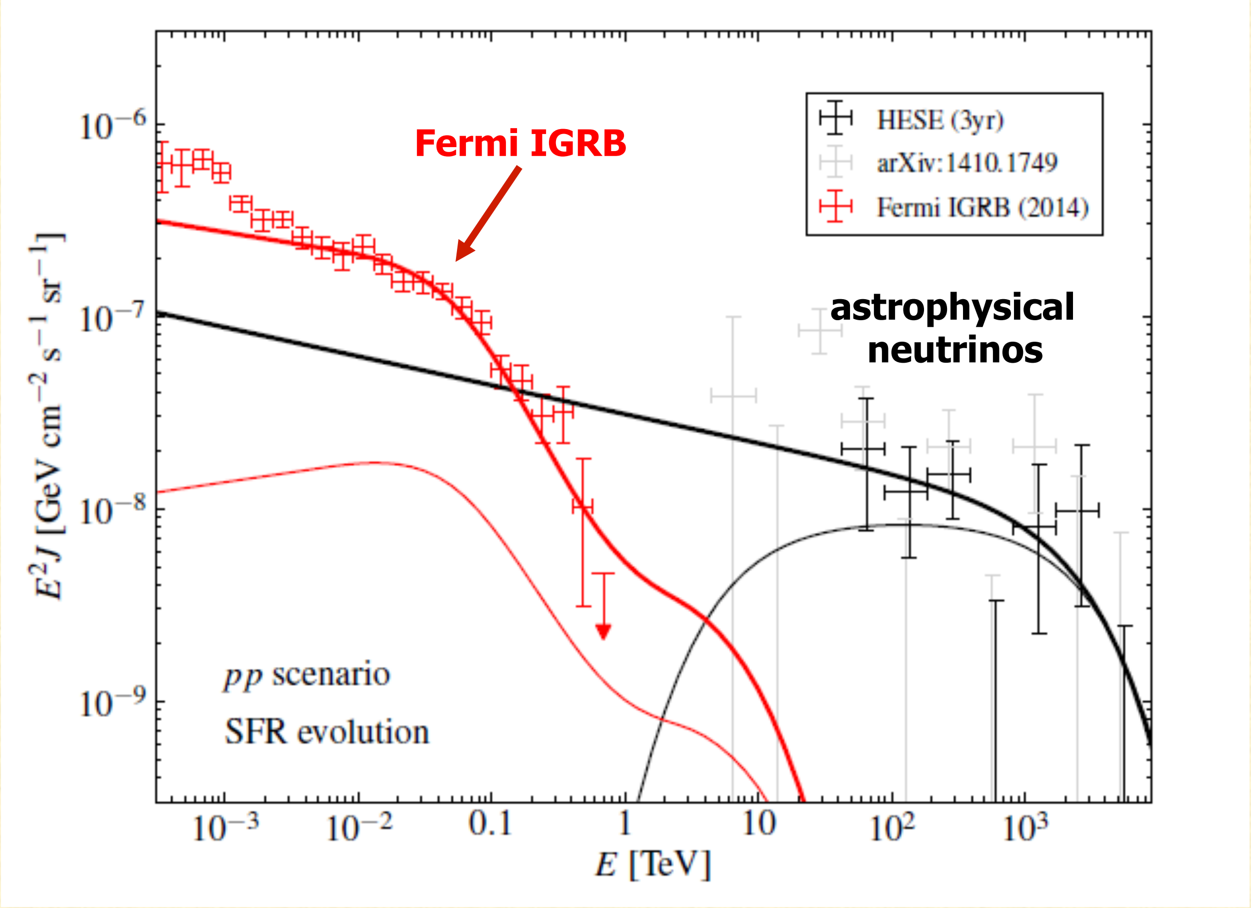
Neutron-decay: $\nu_e : \nu_\mu : \nu_\tau = 1:0:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 0.56:0.22:0.22$

IceCube Results……………Spectral and flavour fits



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

Additional conclusions from observations re nature of flux



The measured ν flux for E>60 TeV is $E^2\Phi \sim 10^{-8}$ GeVcm^{-2}s^{-1}sr^{-1} i.e. comparable to the Waxman-Bahcall bound.

This is unexpectedly high.

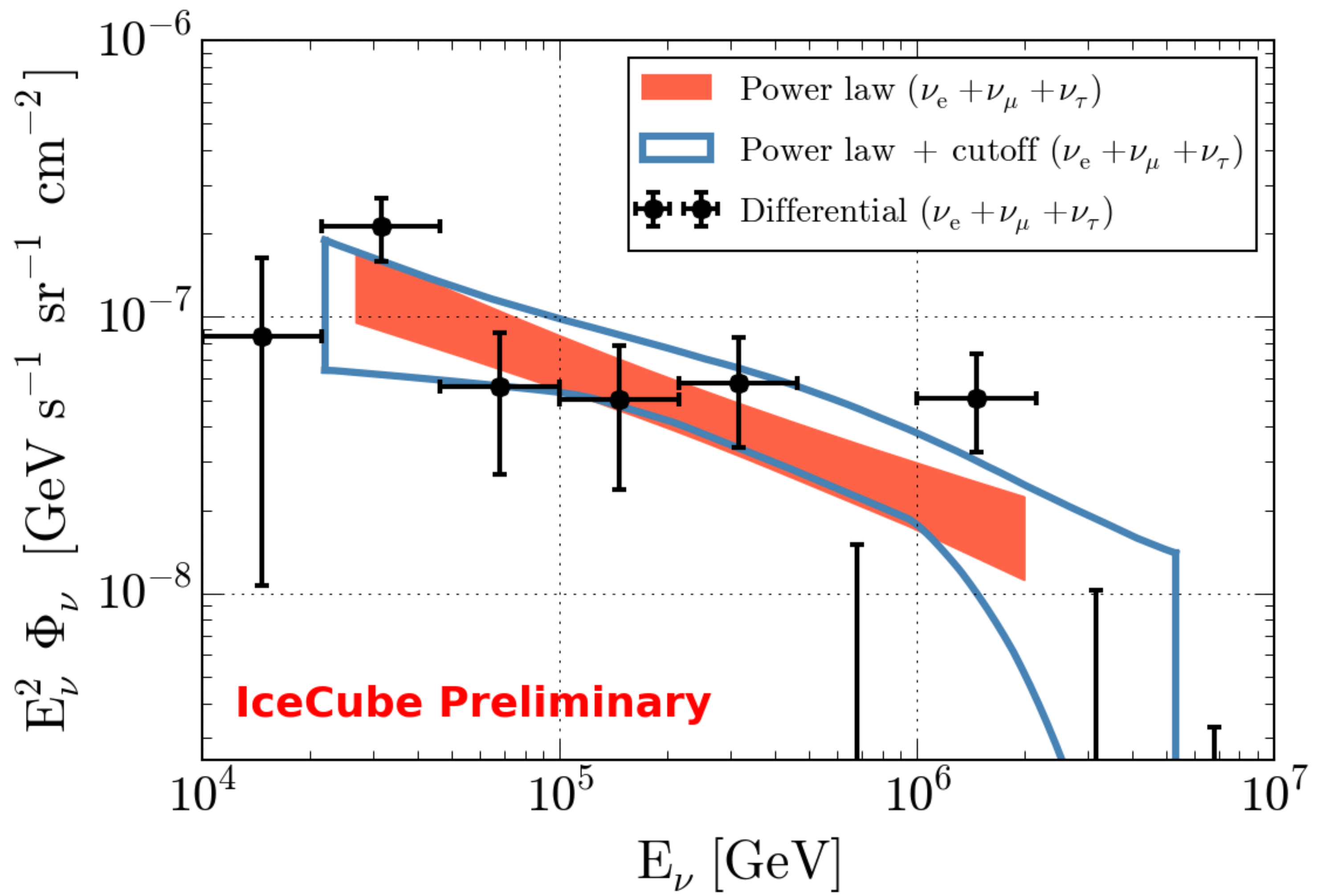
Observations compatible with the conjecture that cosmic accelerators are hadronic and radiate comparable energy in γ's and ν's

[M. Ahlers, arXiv:, arXiv:1412.5106]

Olga Botner talk at IPA, Mar 2015,

Recent: Excess at 30 TeV.....

> All-flavor neutrino energy spectrum



ICECUBE DESY

Lars Mohrmann — lars.mohrmann@desy.de — August 4, 2015

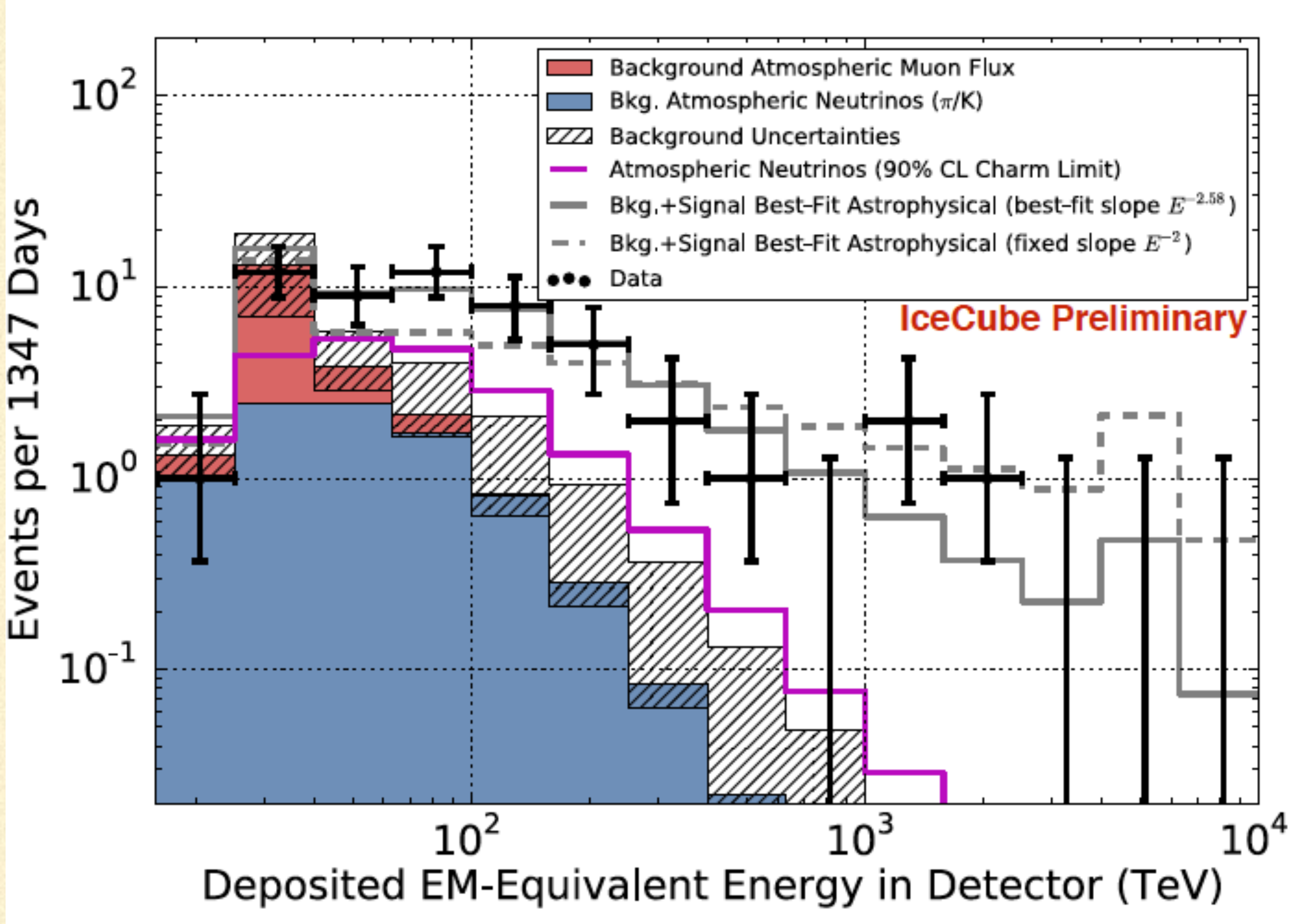
Excess at ~ 30 TeV. Could be a fluctuation, or new low energy component, or steeper spectrum overall than currently thought. ~2 sigma, more info from IC awaited before conclusions can be drawn.

IceCube events and Dark matter………….

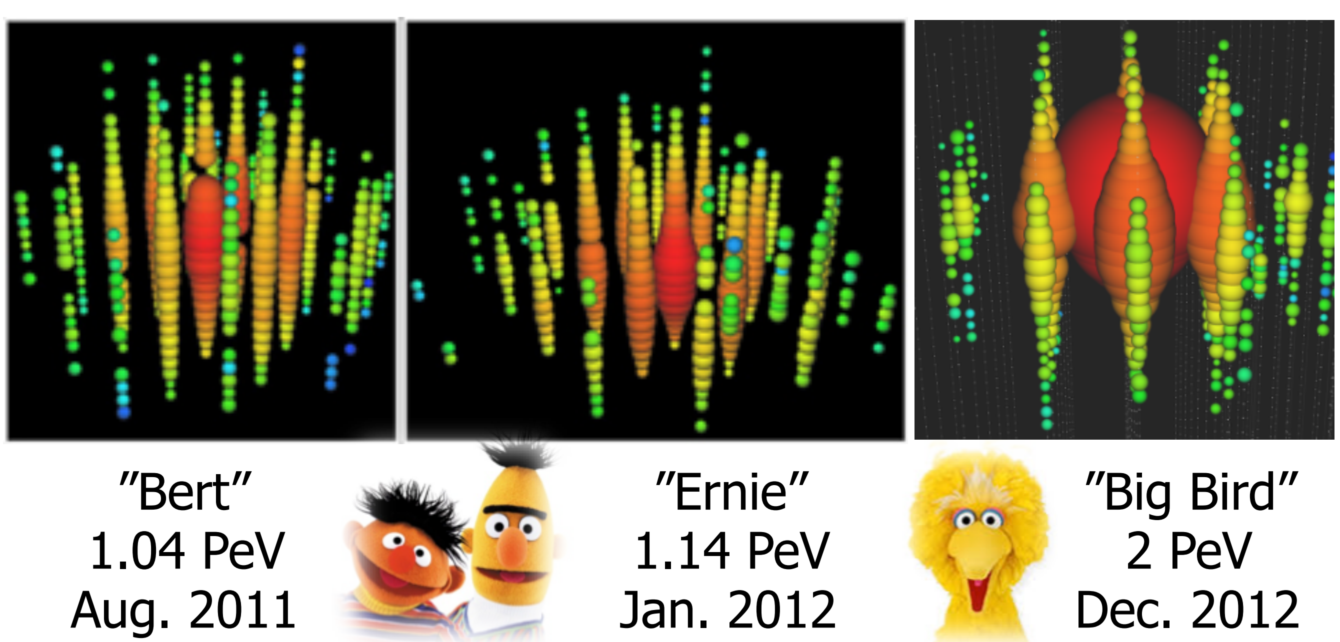
Return to some explanations of intriguing features of these events

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

Many attempts to explain these features. In particular, the cut-off has b
attributed to source astrophysics/class of source, dark matter and Loren
violation etc.

In the following, we discuss DM explanations of these features.

Motivations to go beyond WIMPS….

While theoretical preferences and aesthetics have guided the efforts towards DM model building and experiments, actual parameter space for allowed DM is vast.

Specifically, the DM mass can span the range 10^{-15}–10^{15} GeV, and its interaction cross-section with nucleons and annihilation cross-section into particles can lie in the range 10^{-76}–10^{-41} cm^2.

IceCube events and Dark matter…………..

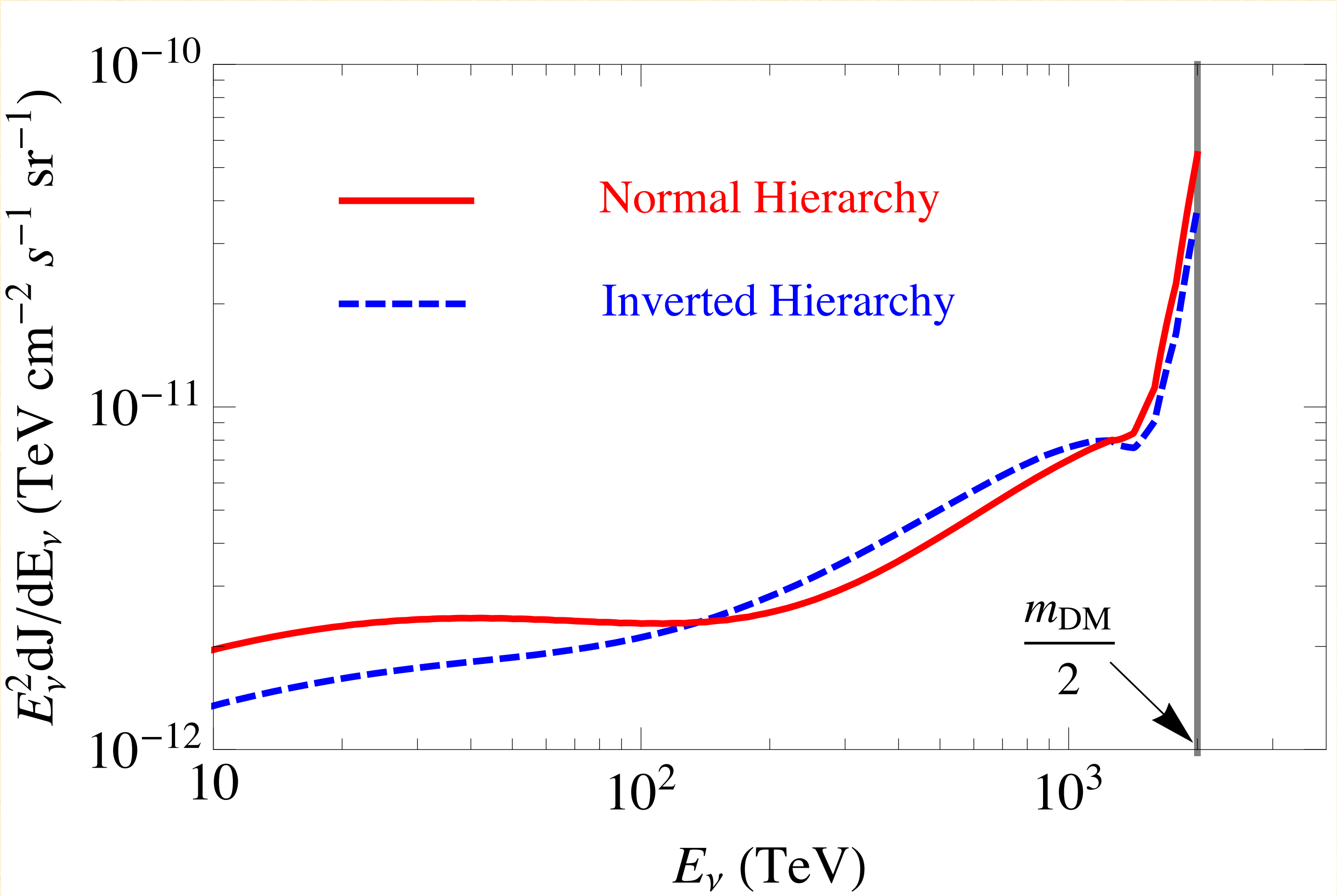


Figure 7. The energy spectrum of $(\nu_e + \nu_\mu + \nu_\tau)/3$ from decaying DM of the model proposed in [34], for NH and IH cases. For the mass of DM we assumed $m_{\rm DM} = 4$ PeV, and for lifetime: 7.3×10^{27} s for NH and 1.1×10^{28} s for IH.

PeV DM decays to neutrinos, giving the IC observed events.

Feldstein et al, Esmaili et al, Bai et al

Let us note a testable (with time) , generic feature of all DM decay scenarios which aim to explain all or a subset of IC events as being due to DM :

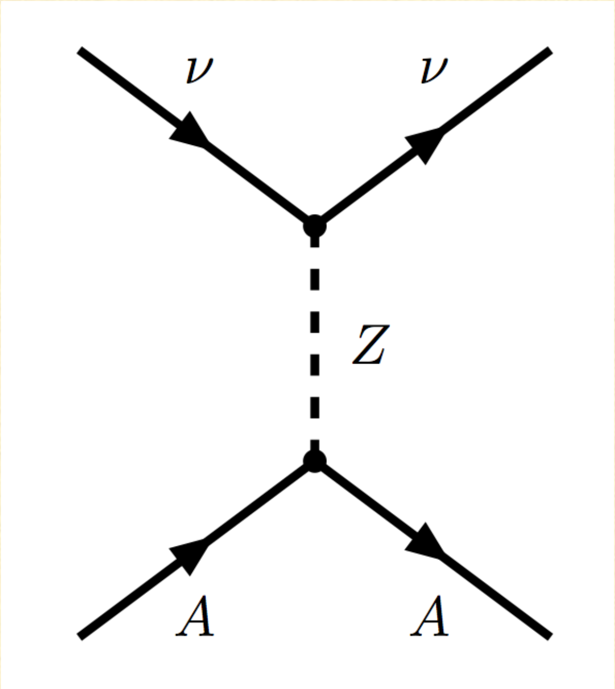
All events in IC which are DM induced must show an anisotropy which comprises of roughly equal galactic and extragalactic components

IceCube events and Dark matter………….

The direct detection of DM at UHE?

[A Bhattacharya, RG and A Gupta, JCAP 1503 (2015) 03, 027 (arXiv 1407.3280)]

Similarity between neutrino nucleus NC interaction and DM-nucleus interaction at low energies



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

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

Extrapolate this similarity to high energies, noting that DM, while primarily non-relativistic, may have a small, highly energetic and relativistic component that arises from the (slow) decay of the primary heavy particle.

We assume that the DM sector consists of at least two particle species with the following properties:

- A co-moving non-relativistic, non-thermal real scalar species φ, with a mass of O(10 PeV), which is unstable but decays with a very large lifetime (>> 10^17 secs) to χ, and does not have any decay channels to SM particles. It comprises the bulk of present-day DM.
- A lighter fermionic DM species (FDM), χ with mass $m_\chi \ll m_\varphi$, which we assume is produced in a monochromatic pair when the PDM decays, i.e., $\varphi \to \bar{\chi}\chi$, each with energies of $m_\varphi/2$.

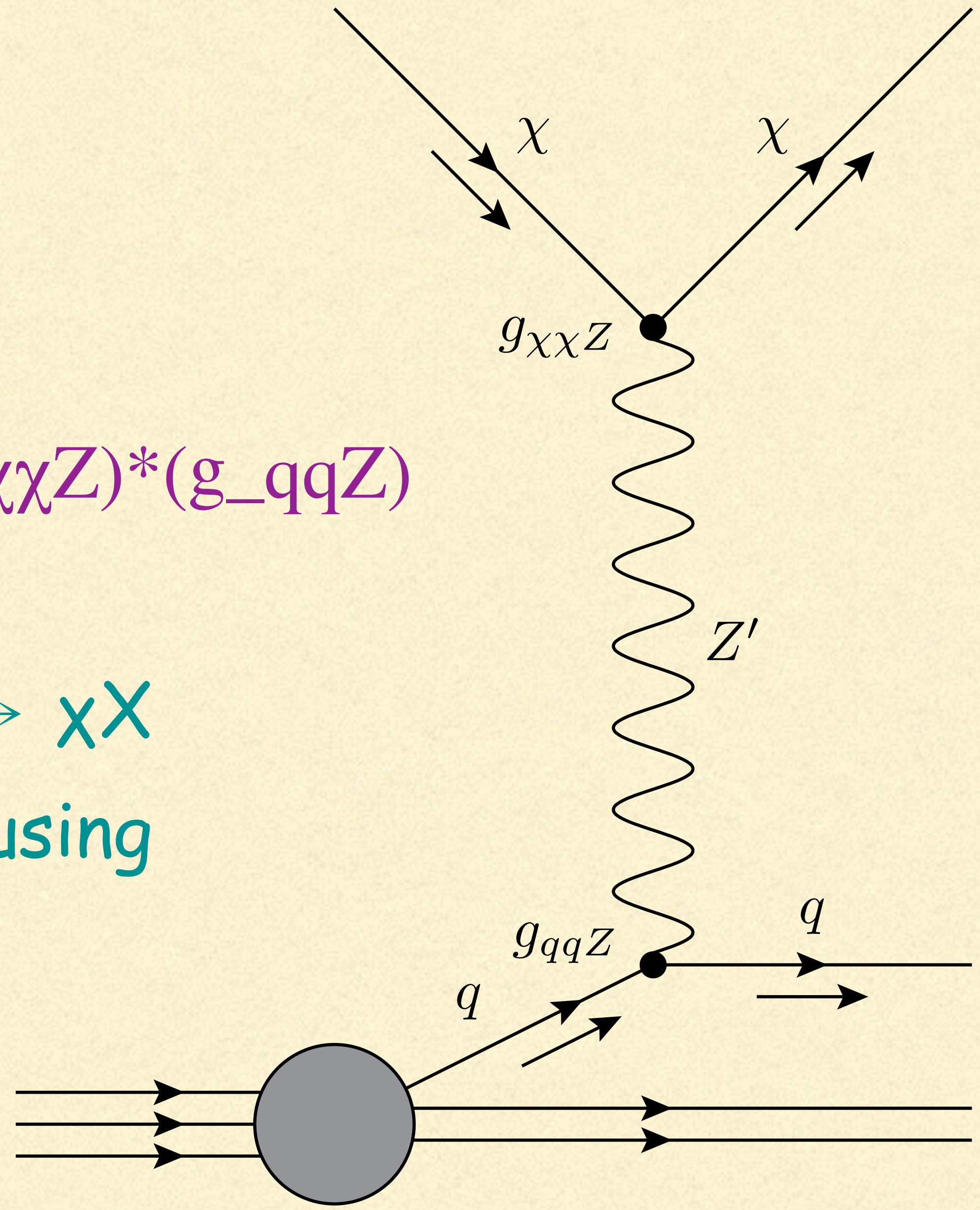
φ does not decay to SM particles, constraints relevant here are those based on a) CMB anisotropies , b) light nuclei abundances during Big-Bang Nucleosynthesis (BBN) and c) limits from structure formation,

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

Z′ which connects SM and DM sectors

Vector-like couplings assumed

G = (g_χχZ)*(g_qqZ)

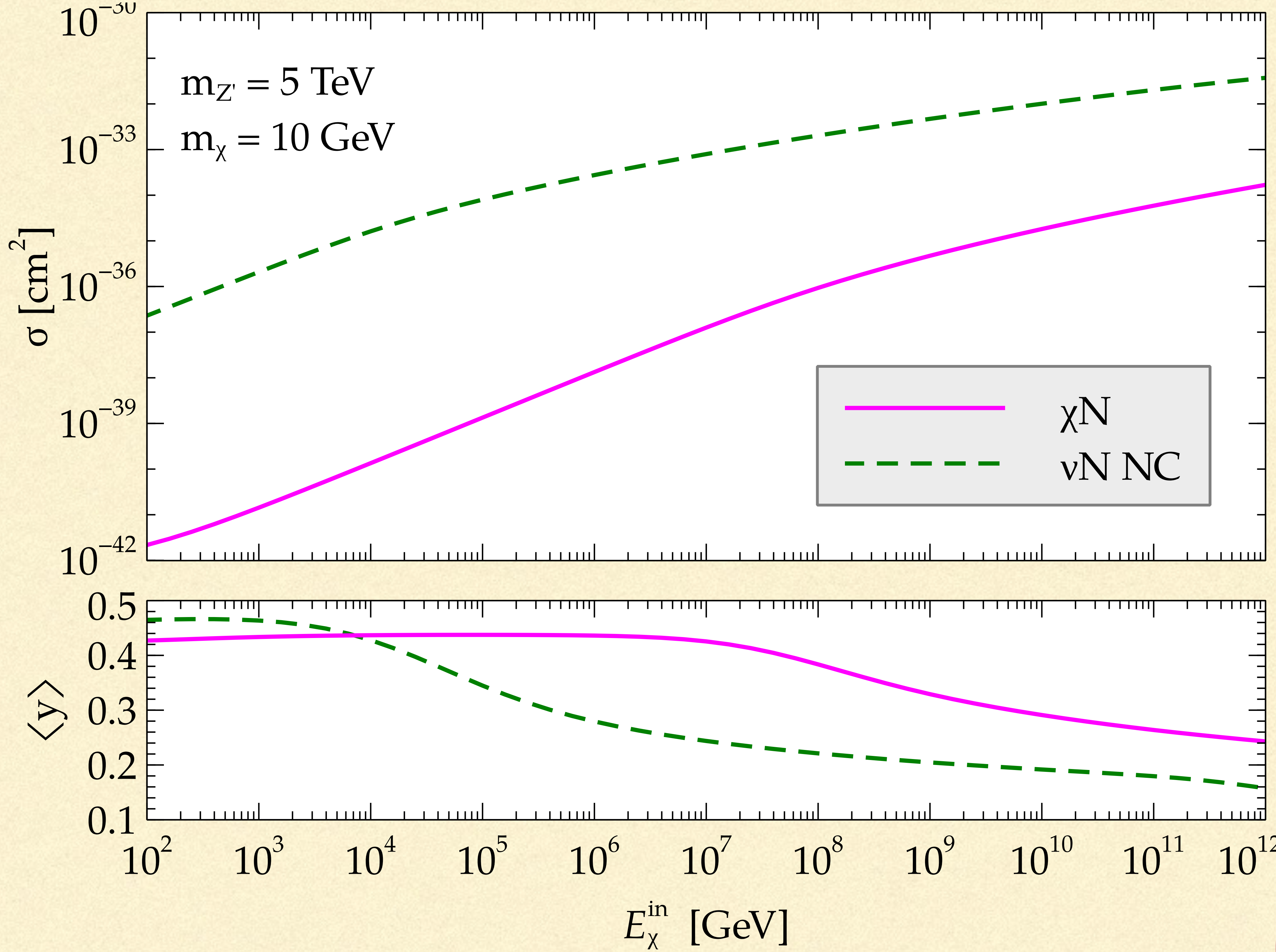


Compute the DIS cross-section for χN → χX in the lab-frame, 100 GeV ≤ E^in ≤ 10 PeV, using CT10 parton distribution functions.

We set the Z′ mass to be 5 TeV. (For Z′ with mass > 2.9 TeV, the couplings gχχZ and gqqZ are largely unconstrained by collider searches.)

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

χ-nucleon cross-section

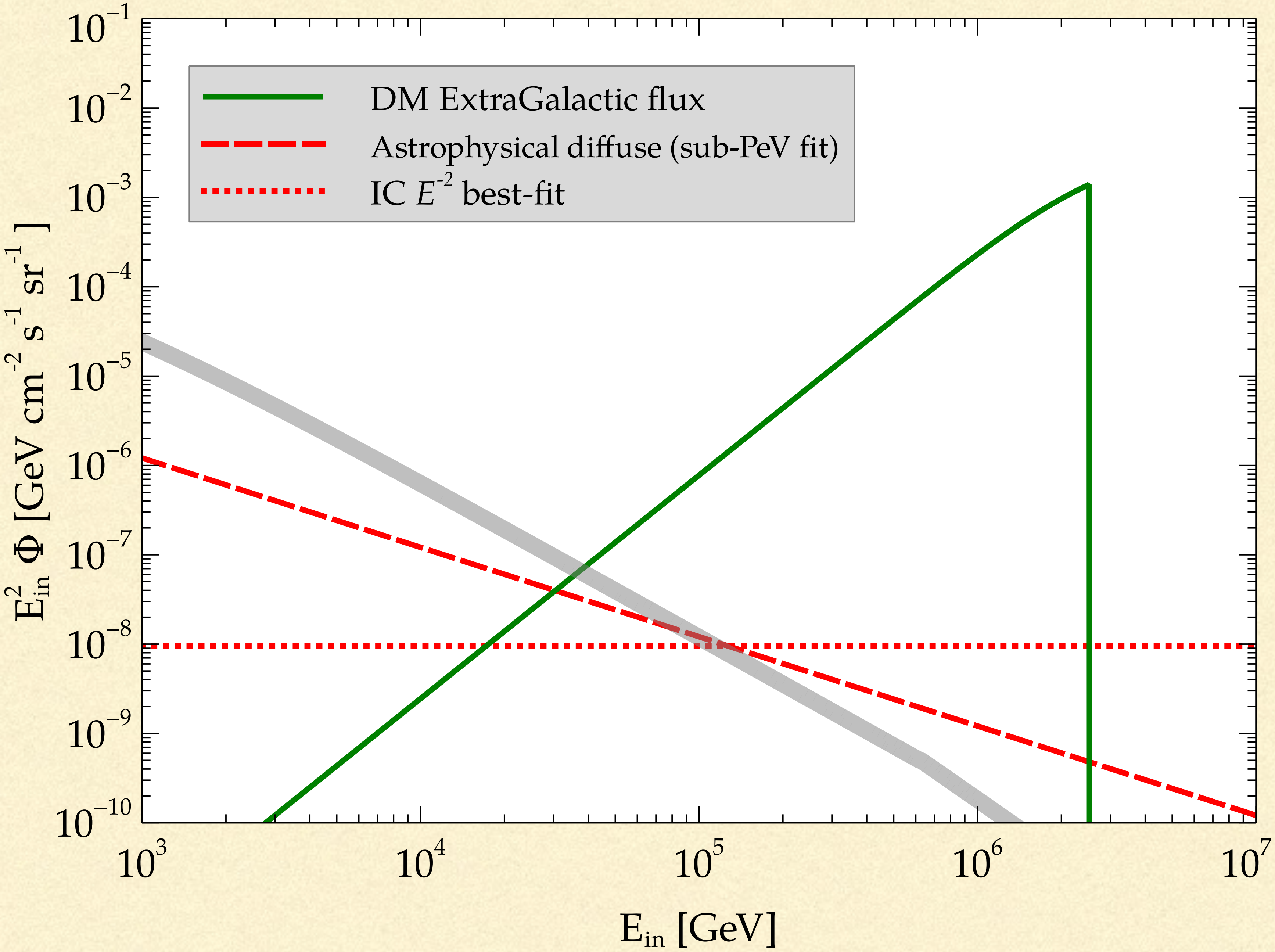


$$y = \frac{E_\chi^{\rm in} - E_\chi^{\rm out}}{E_\chi^{\rm in}} = \frac{E^{\rm dep}}{E_\chi^{\rm in}} \,.$$

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

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

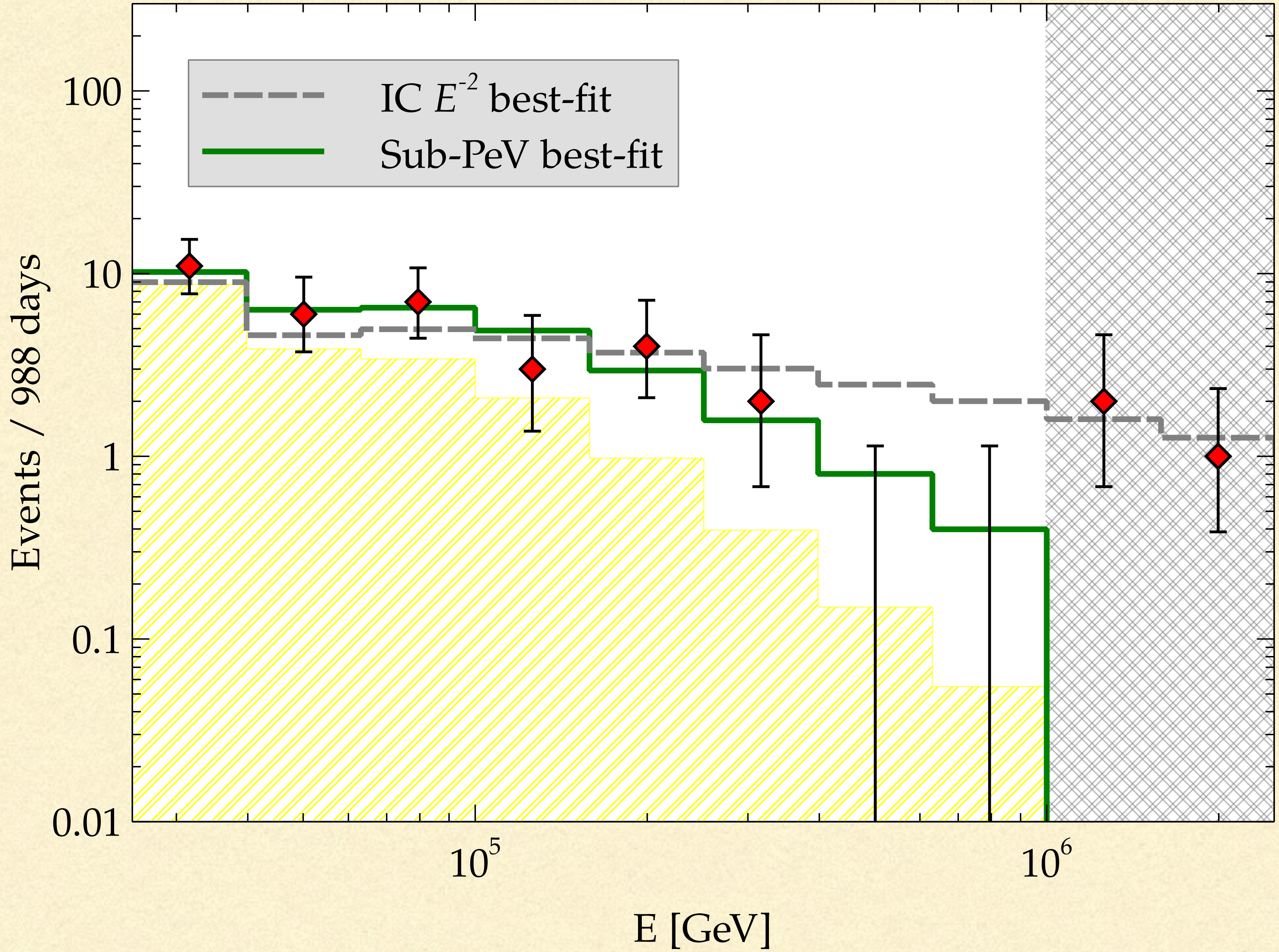
Flux of the χ………



Both galactic and extra-galactic (z dependant) fluxes contribute in almost equal measure.

[A Bhattacharya, RG and A Gupta, JCAP 1503 (2015) 03, 027 (arXiv 1407.3280)]

Fits………



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

(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

Also, in this scenario, in the 1-3 PeV range, one expects cascade events only.

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

With 4 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 > 4σ,
- there appears to be some tension between muon only track spectrum and the cascades (spectral index of 1.9 vs 2.5)
- there seems to be an excess at ~30 TeV in all flavor spectrum
- 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

Conclusions……

With 4 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.

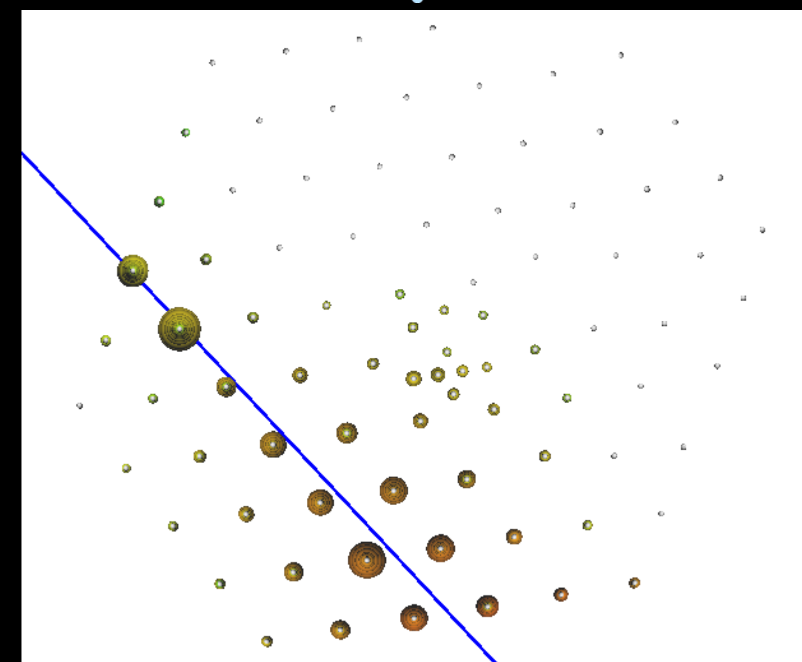
g questions that remain to be answered:

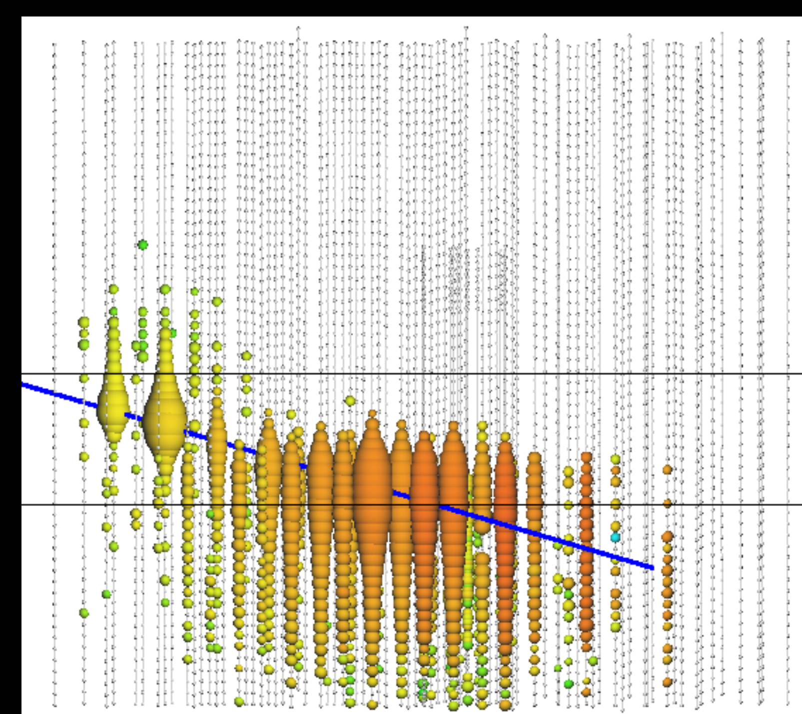
- Flux appears to cut-off ~ 2PeV (why are GR events not seen?)
- Why is flux so close to WB bound
- Will the gap (400 TeV to 1 PeV) survive?
- Do the PeV events have a different origin?
- Do any of the IC events have a DM origin?

Recent: The highest energy event is a track.....

Multi-PeV track event
Event information

- Date
  - → June 11th 2014 (56819.20444852863 MJD)
- Arrival direction
  - → Declination 11.48 deg
  - → Right Ascension 110.34 deg
  - → Angular resolution < 1 deg
- Energy loss inside the detector
  - → 2.6 ± 0.3 PeV
- Muon energy and neutrino energy are at least that
- Reference
  - → ATEL #7856





III. Physikalisches Institut

RWTH AACHEN IceCube

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A measurement of the diffuse astrophysical muon neutrino flux
Leif Rädel | ICRC 2015, The Hague | 04.08.2015

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)

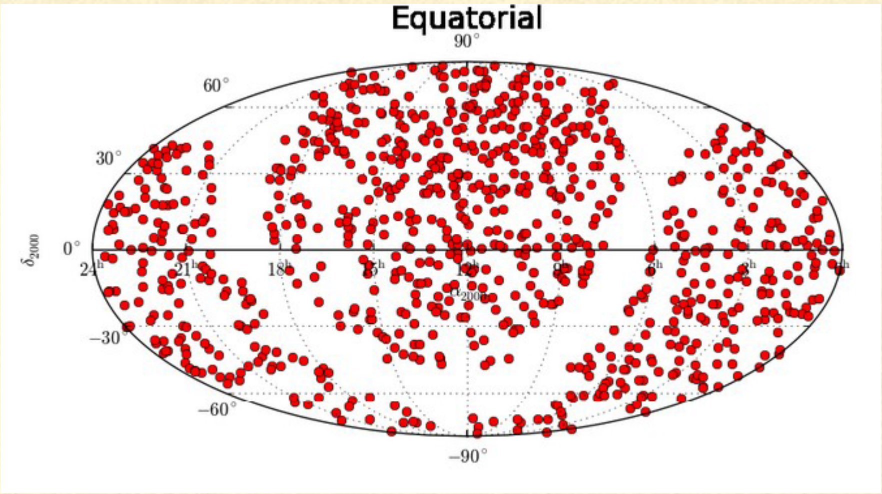
limits on the ν flux disfavor much of the parameter space for the latest GRB models

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

[IceCube, arXiv:1412.6510] IceCube present and future / Olga Botner

2015-05-03 34

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

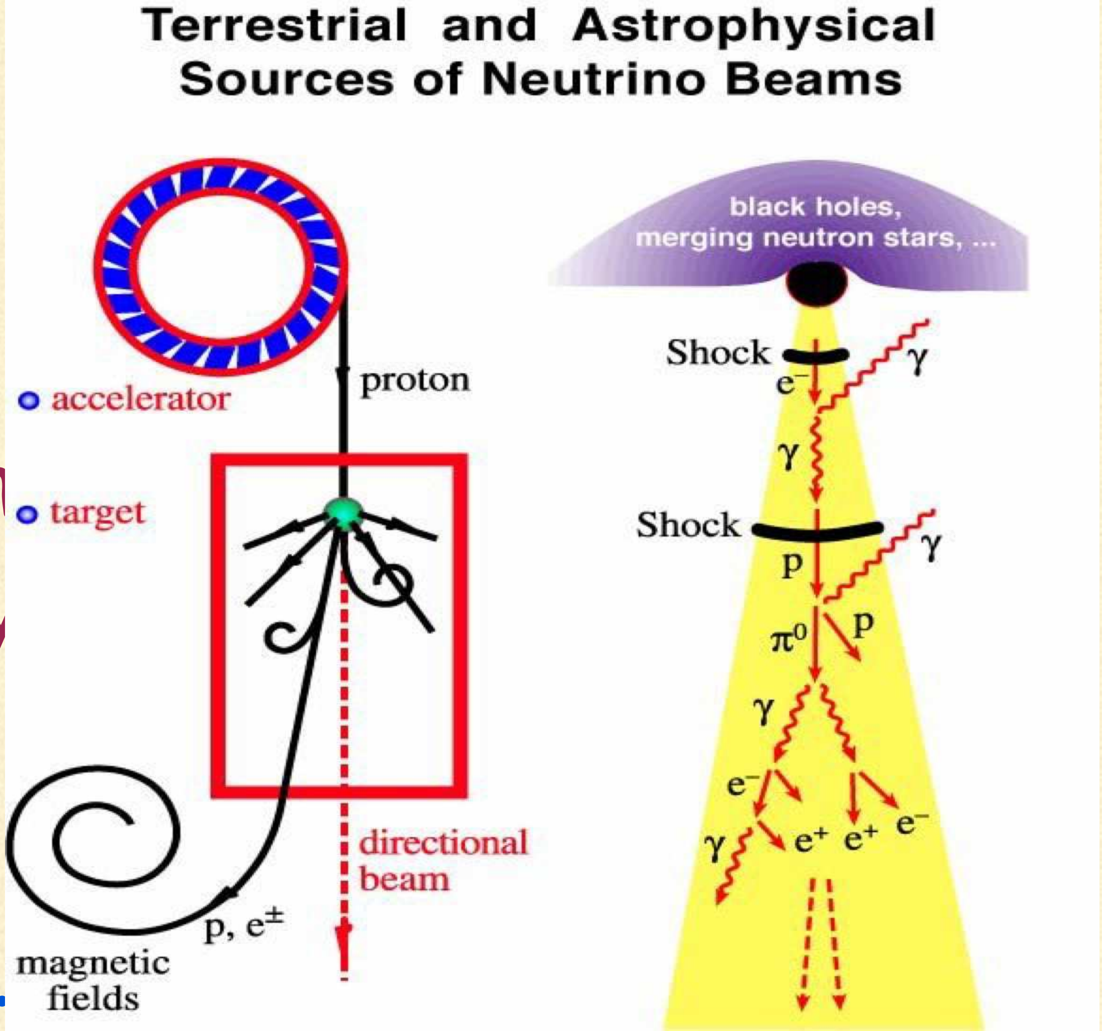
[T. Glüsenkamp, RICAP 2014, proceedings] 2015-05-03 35

Why are UHE neutrinos interesting?.......

The highest particle energies are believed to reside in dense astrophysical environments which have powerful natural particle accelerators and beam dumps.

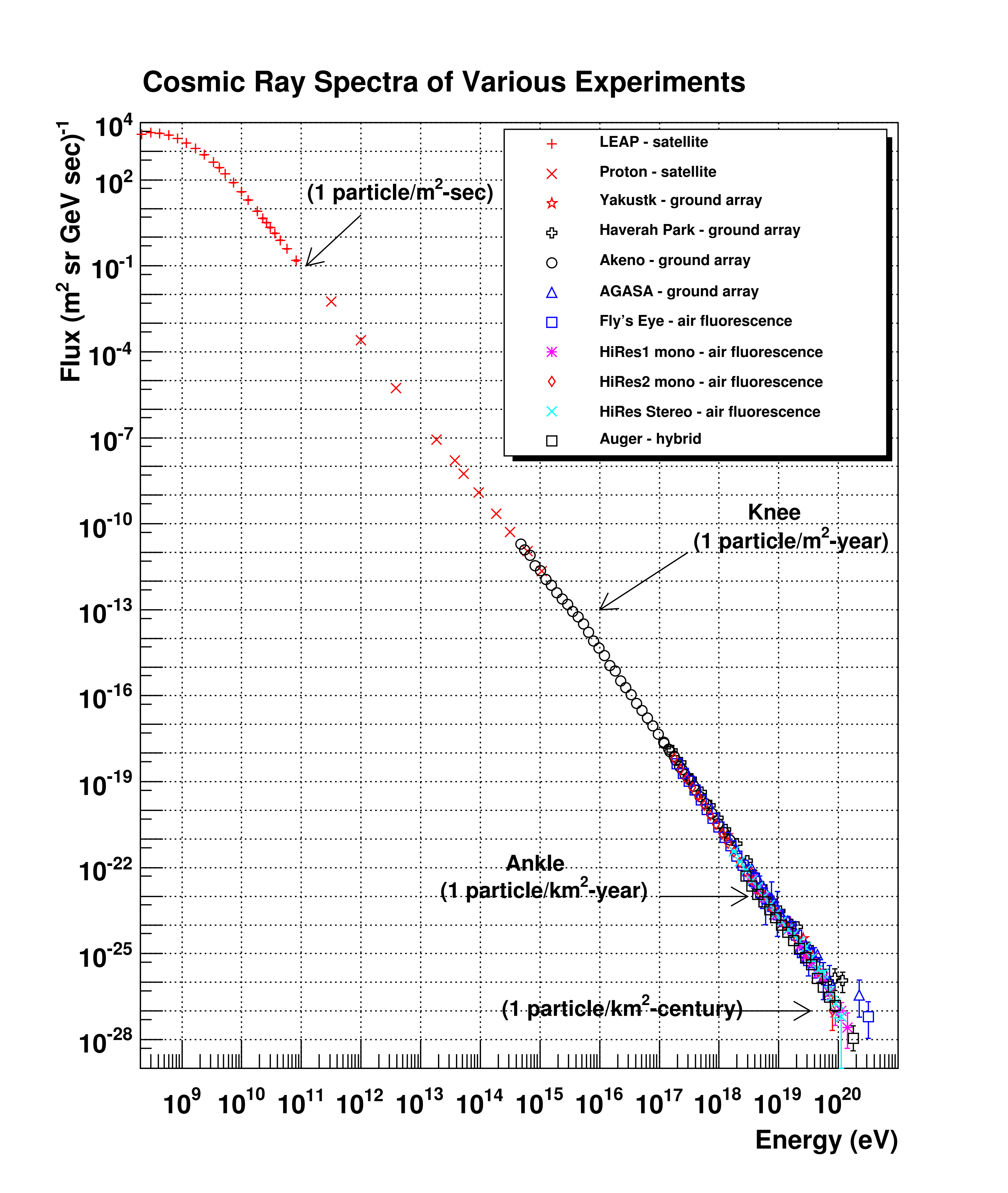
Charged particles, photons and neutrons produced in these accelerators are either deflected and/or interact and are degraded in energy or decay before detection on earth. Only neutrinos carry information of the source and survive the passage in a relatively unmodified form over cosmological distances

- UHE Particle Physics in general an Physics in particular, is intimately Rays.........
- We begin with a discussion of CR..



The study of UHE neutrinos produced in these environments is thus a window to fundamental physics at the highest energies, as well as to nature's most powerful accelerators.

Cosmic Rays.....



Different energy ranges open windows to different physics and sources....

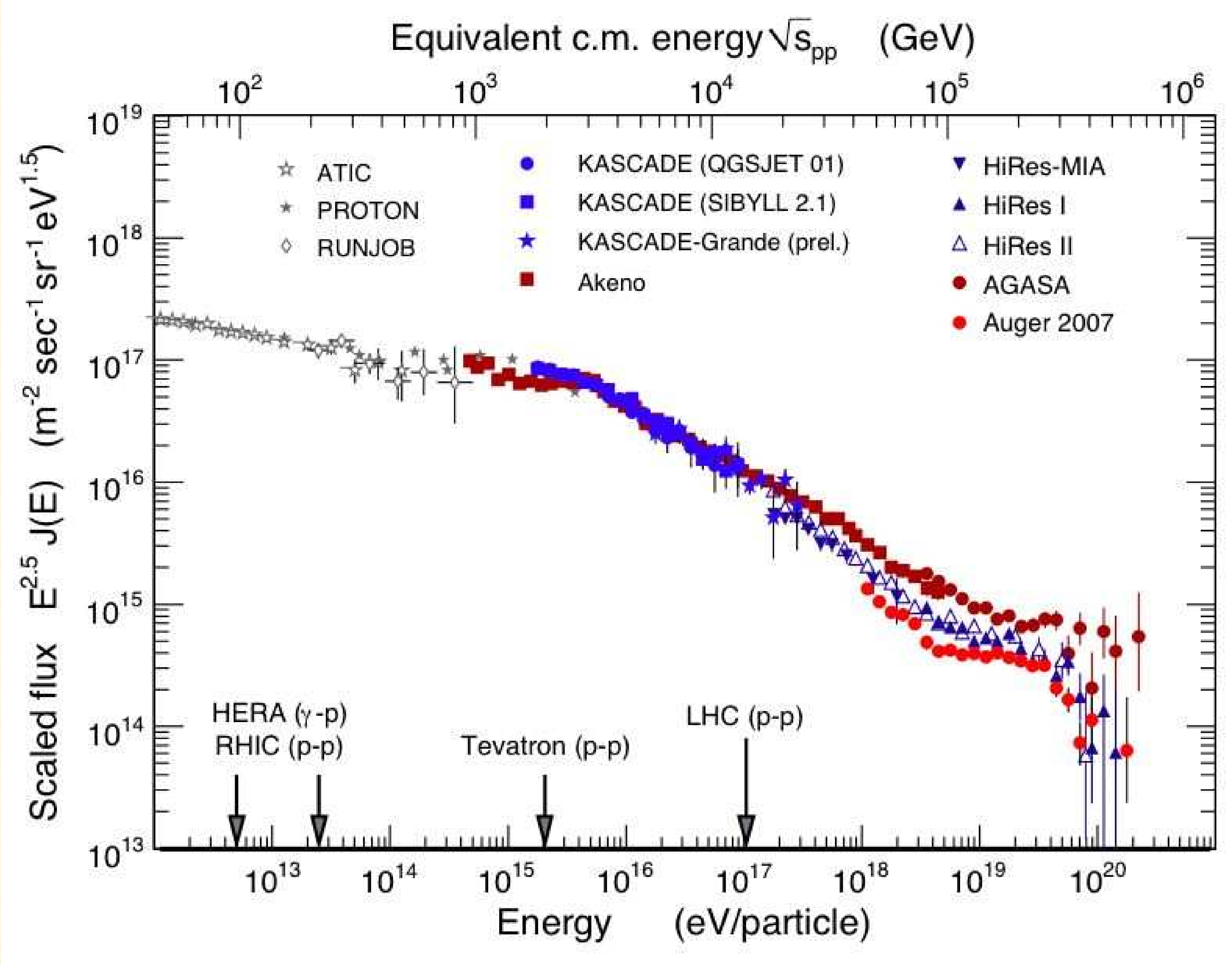
10^8 eV to 10^10 eV- Solar physics......

10^10-10^17 eV, Galactic sources and propagation....... (composition known up to these energies)

10^18 eV and beyond....??? (AGNs, GRBs....) neither origin nor composition known well

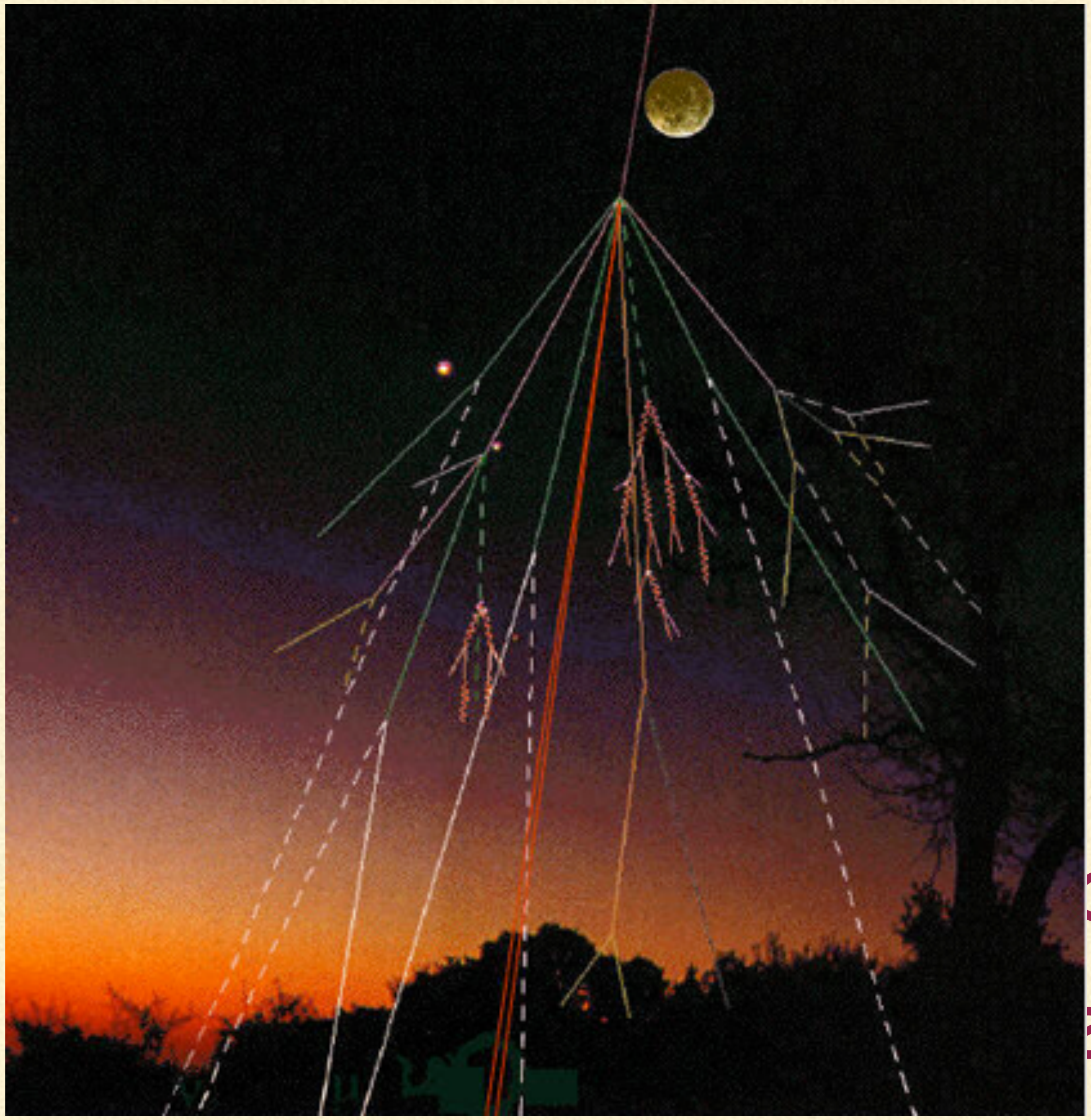
- Nonetheless, a huge number of particles: protons, light nuclei, (possibly) heavy nuclei, over a huge range of energies arrive from the cosmos to earth.
- UHE Particle Physics in general and UHE Neutrino Physics in particular, is intimately linked to UHE cosmic Rays because we have reasons to believe both have the same source.........
- We begin with a discussion of CR.........

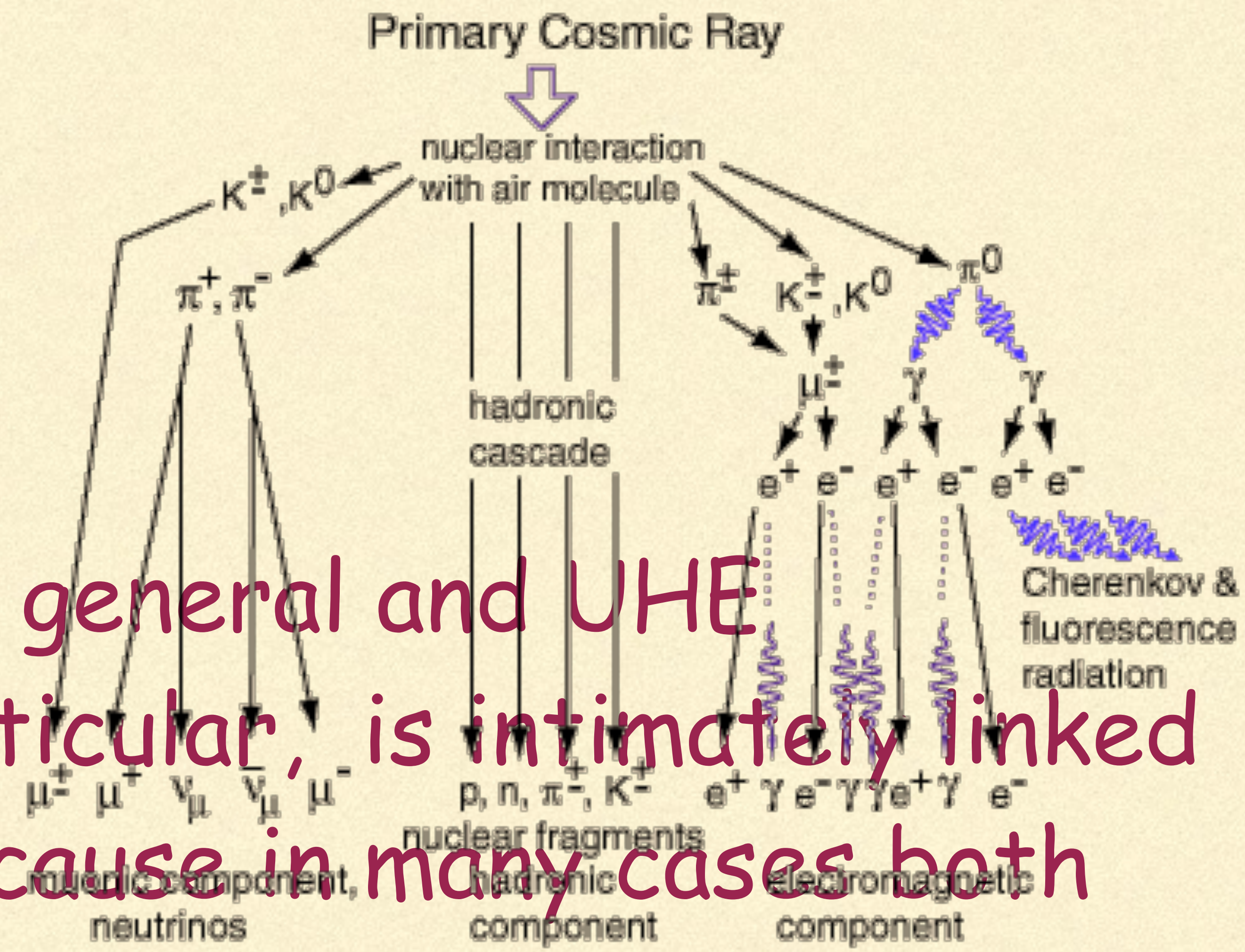
High Energy Cosmic Rays.....



Comparing the UHECR to terrestial accelerators....

Observing High Energy Cosmic Rays.......

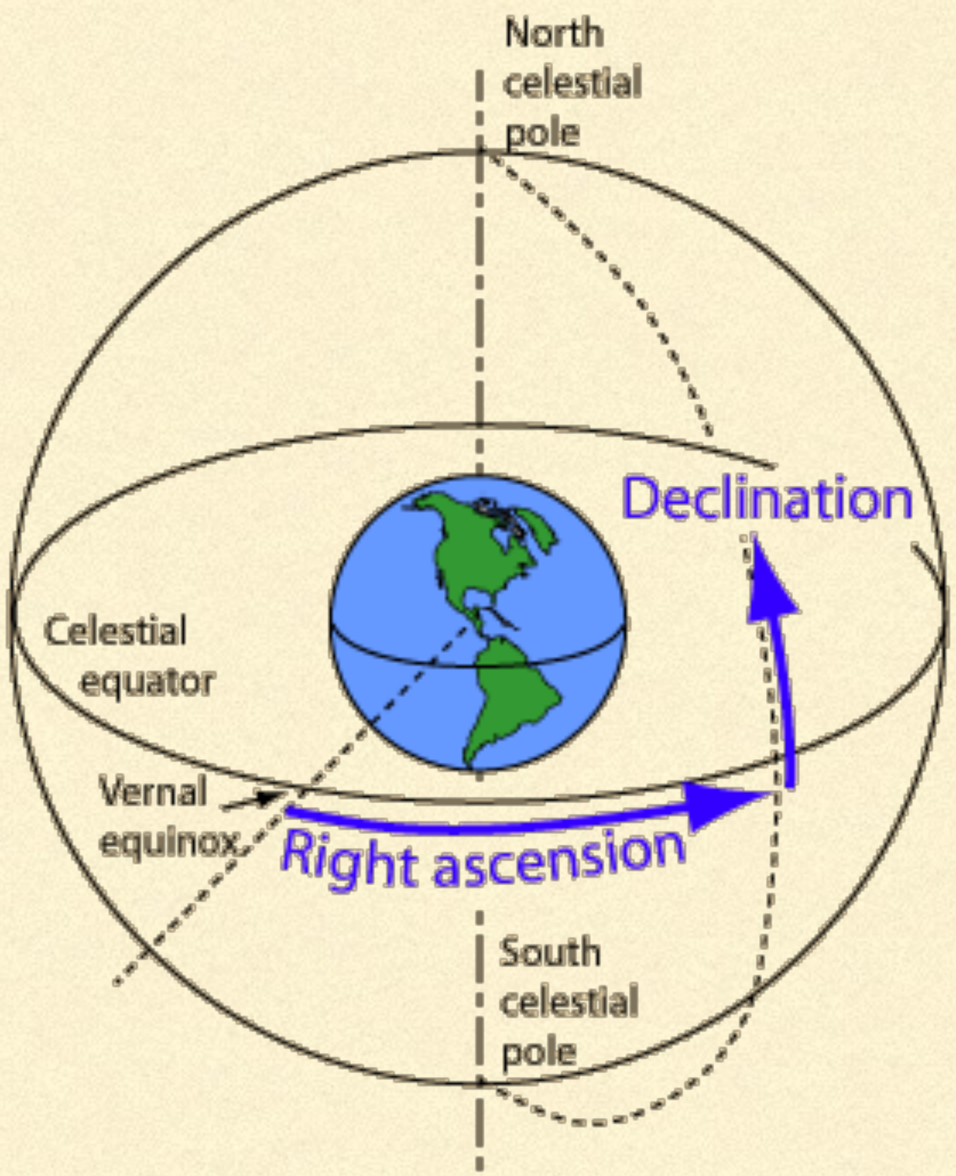




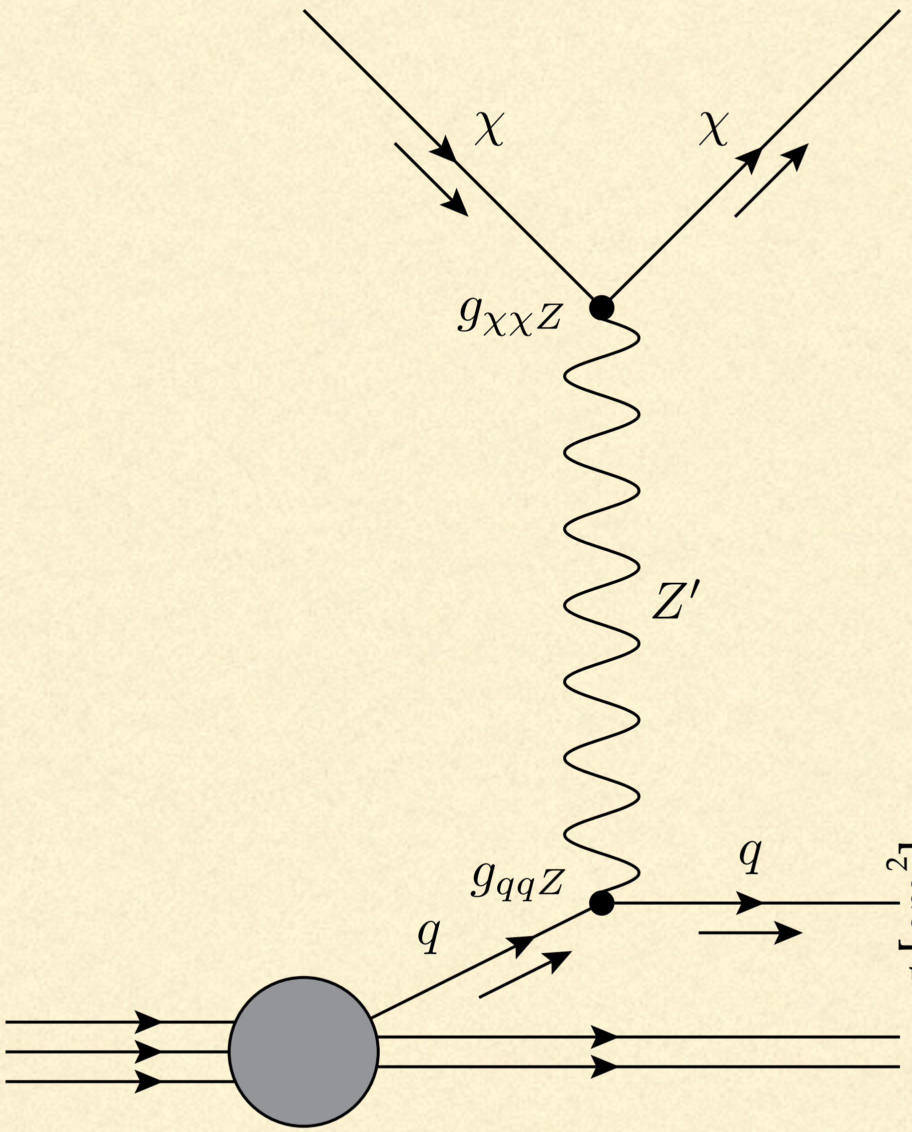
in general and UHE
articular, is intimately linked
because in many cases both
e.........

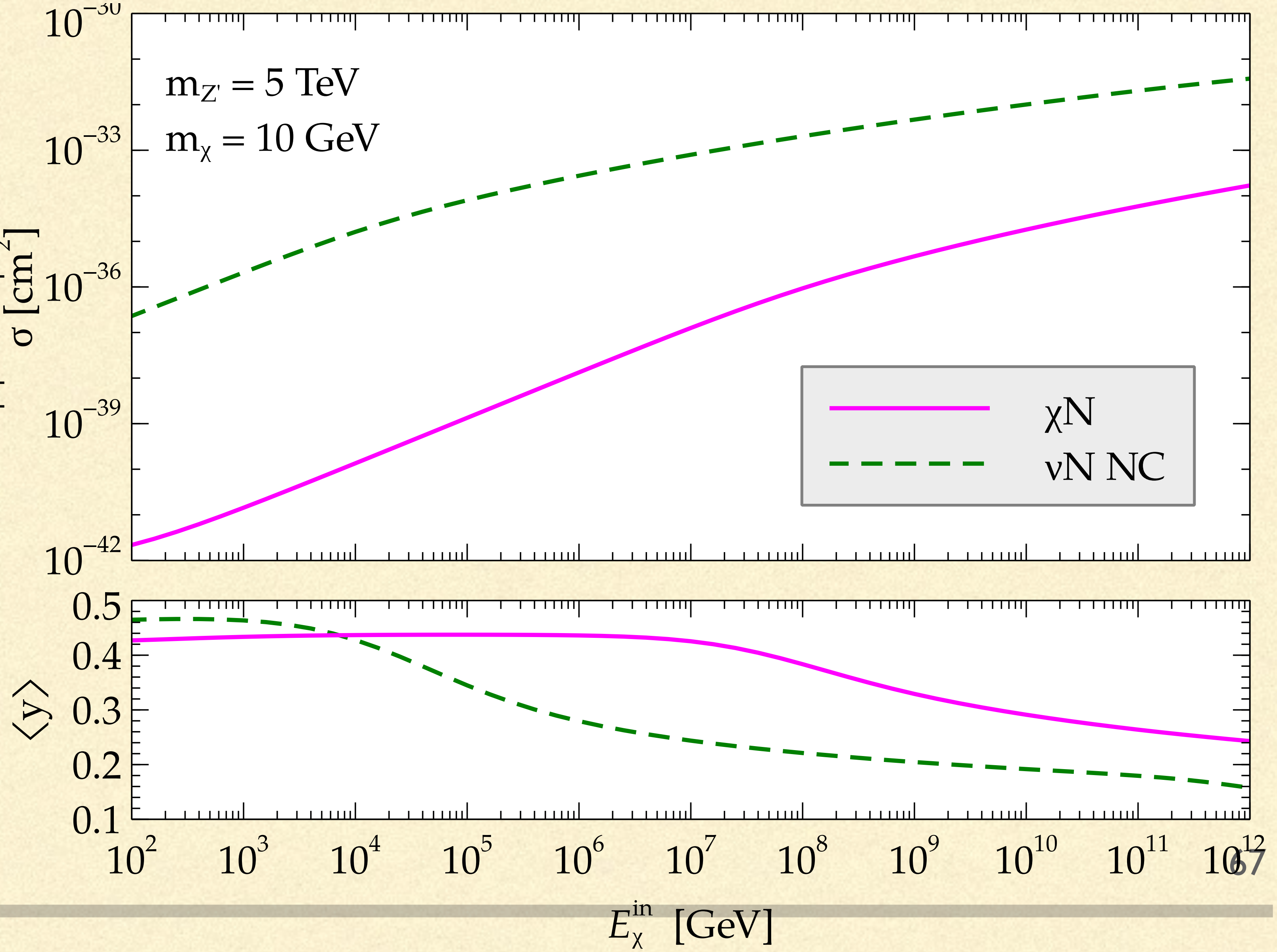
- We begin with a discussion of CR.........

Despite decades of experiment, we do not really understand the origin of the highest energy CR, since none of the models we have can account for such high energies convincingly. Since we believe that their production at source is also accompanied by UHE neutrinos, their detection would help us better understand the nature of the highest energy sources.


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

Interaction of a highly energetic DM particle in an IceCube-like detector.





The Glashow Resonance....

The Glashow Resonance (GR) refers to the Standard Model process which results in the resonant formation of an intermediate W^- in $\bar{\nu}_e e$ at E_nu = 6.3 PeV.

Glashow '60, Berezinsky and Gazizov, '77

- The final states could be to leptons or hadrons, giving both showers and muon or tau lepton tracks in UHE detectors.

- While usually dwarfed by the neutrino-nucleon cross-section, the anti-neutrino-electron cross-section at the GR is higher than the neutrino-nucleon cross-section at all energies upto 10^21 eV.

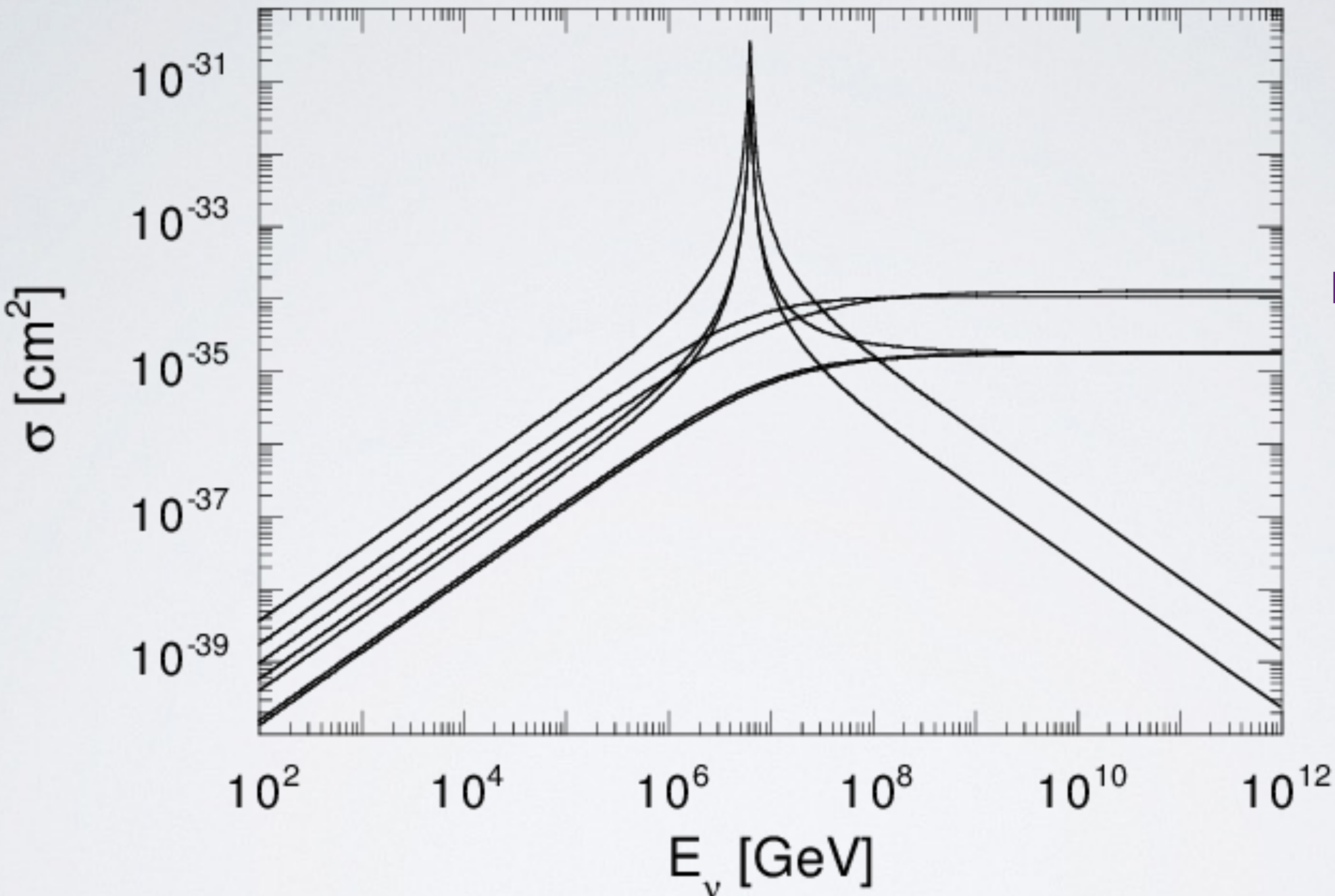
GR Xsecs.....

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

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

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

Neutrino Cross-sections at the Glashow Resonance



RG, Quigg, Reno and Sarcevic, 95

The cross-sections

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

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

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
JCAP 1110 (2011) 017
(arXiv:1108.3163)

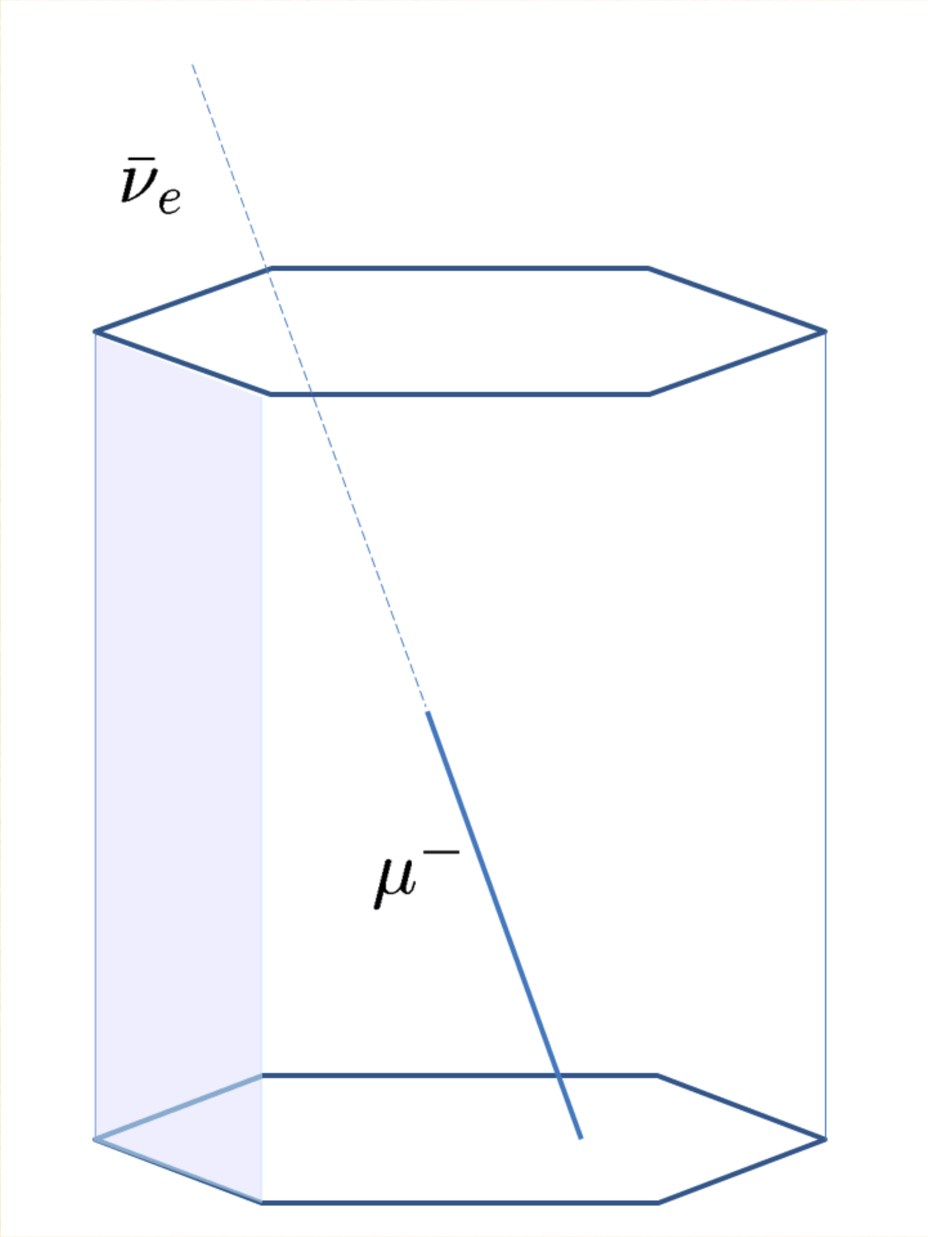


Figure 2: Pure muon

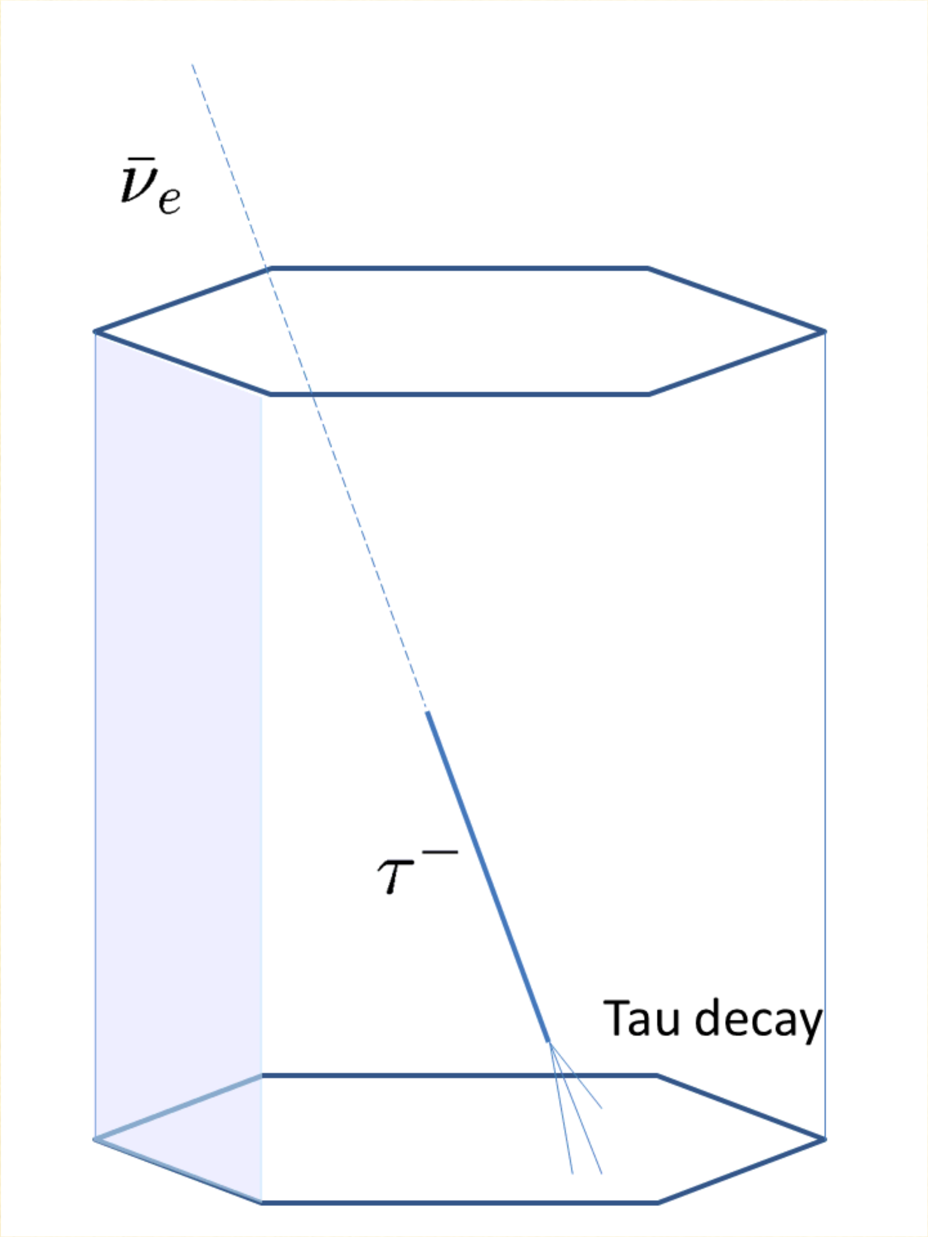


Figure 3: Contained lollipop

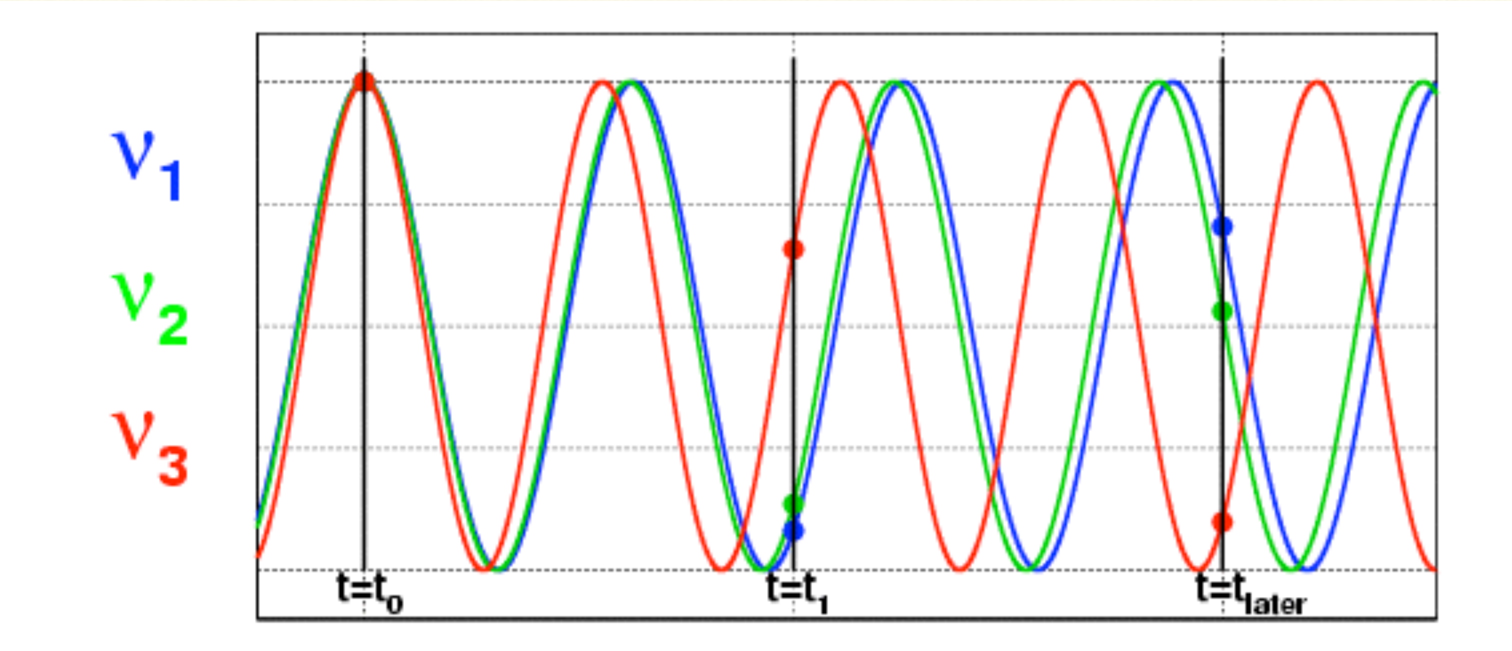
Bhattacharya, RG, Rodejohann and Watanabe
JCAP 1110 (2011) 017
(arXiv:1108.3163)

Neutrino properties…………

Neutrinos have tiny masses, about 10^-7 times (or less)the mass of the lightest charged particle (the electron).

Absolute mass values not exactly known.

Neutrinos oscillate, i.e change flavour, as they propagate



Produced neutrino flavour may thus be different from detected neutrino flavour

Neutrinos…………

Neutrinos barely interact, having a mean free path length of 1 light year even when passing thru lead

Thus very large volume detectors are necessary to observe them, especially when fluxes are small

But it also means they can do what no other particle can,

a) they can escape from dense UHE astrophysical environments

b) travel to us over cosmological distances (Mpc) without interacting in-between.

c) bring information which can be directly related to source

The Matter in our Universe is made up of quarks and leptons (fermions)

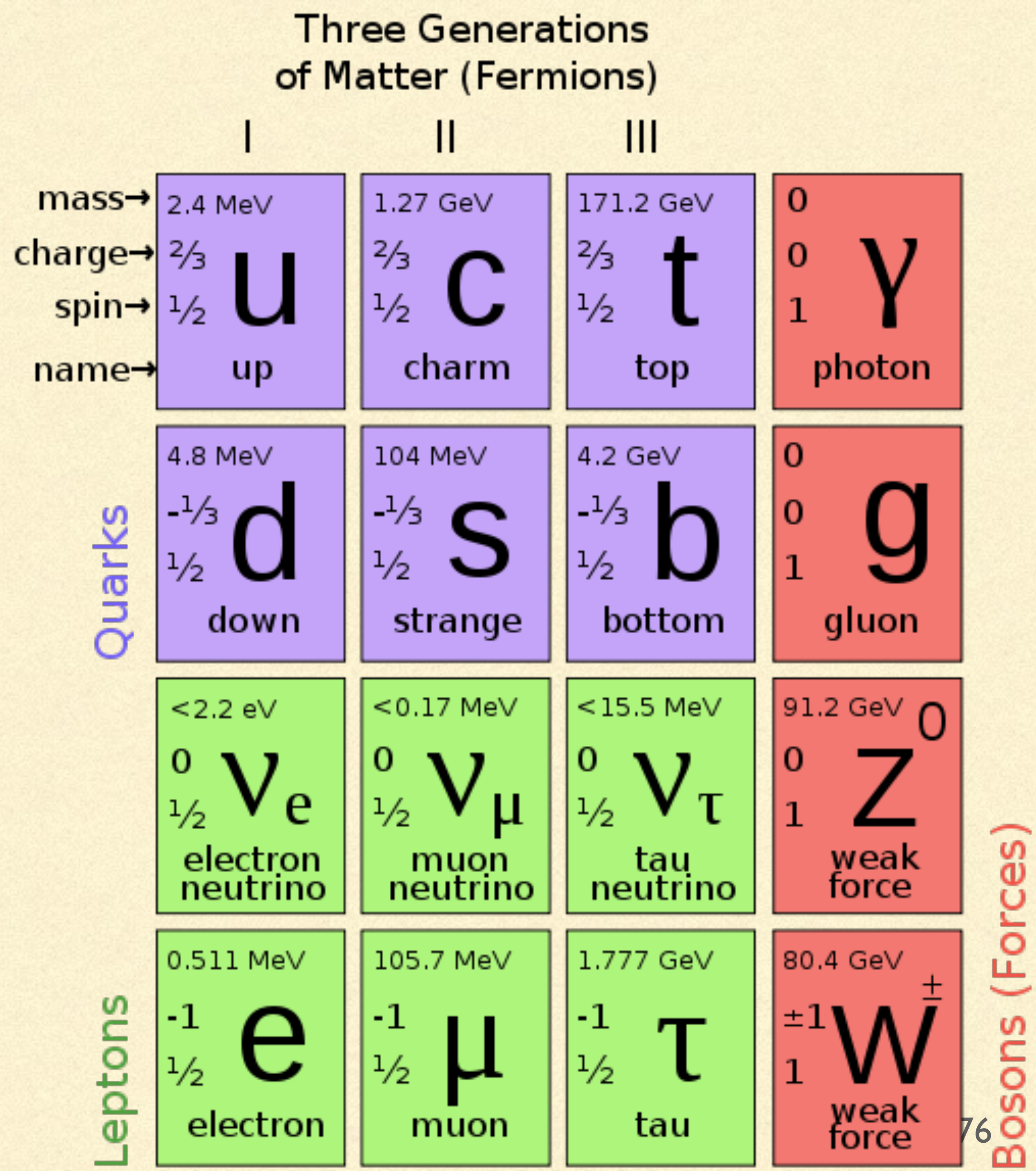
They exchange other particles called bosons when they interact with each other via the fundamental forces

Each particle is said to carry the “charge” of a force to which it is sensitive

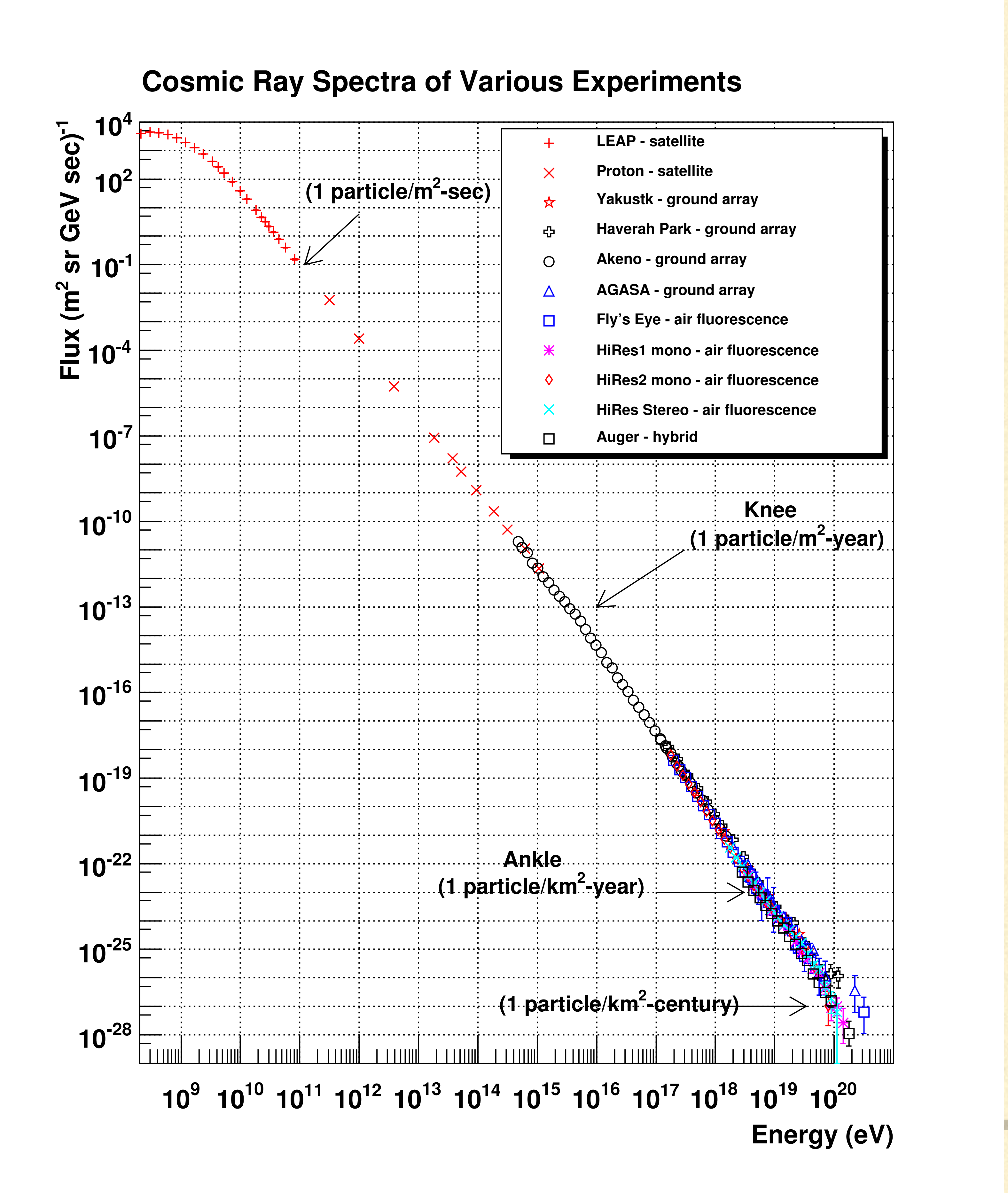
Quarks experience the strong, electromagnetic, weak and gravitational forces, and thus carry all 4 types of charges

The charged leptons (e, mu, tau) experience or couple to the electromagnetic, weak and gravitational forces

Neutrinos couple to the weak and gravitational forces



Cosmic Rays.....



Vast amount of Data which spans ..

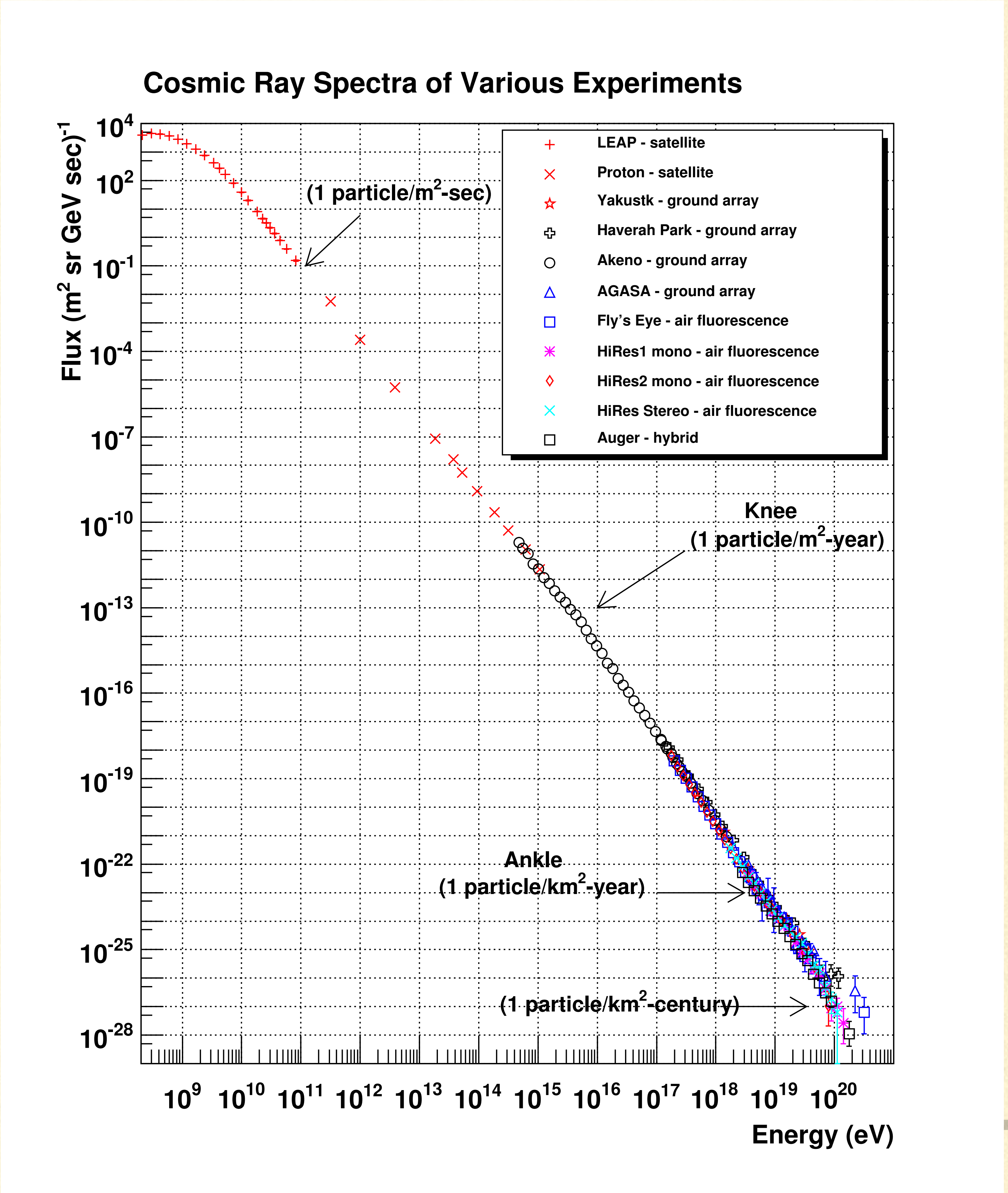
Over 30 orders of magnitude in flux

Over 10 orders of magnitude in energy

Approximate E^(-3) spectrum over entire range.

Composition at lower energies known, 89% protons, 10% alpha particles and 1% heavy nuclei, minute content of antiparticles

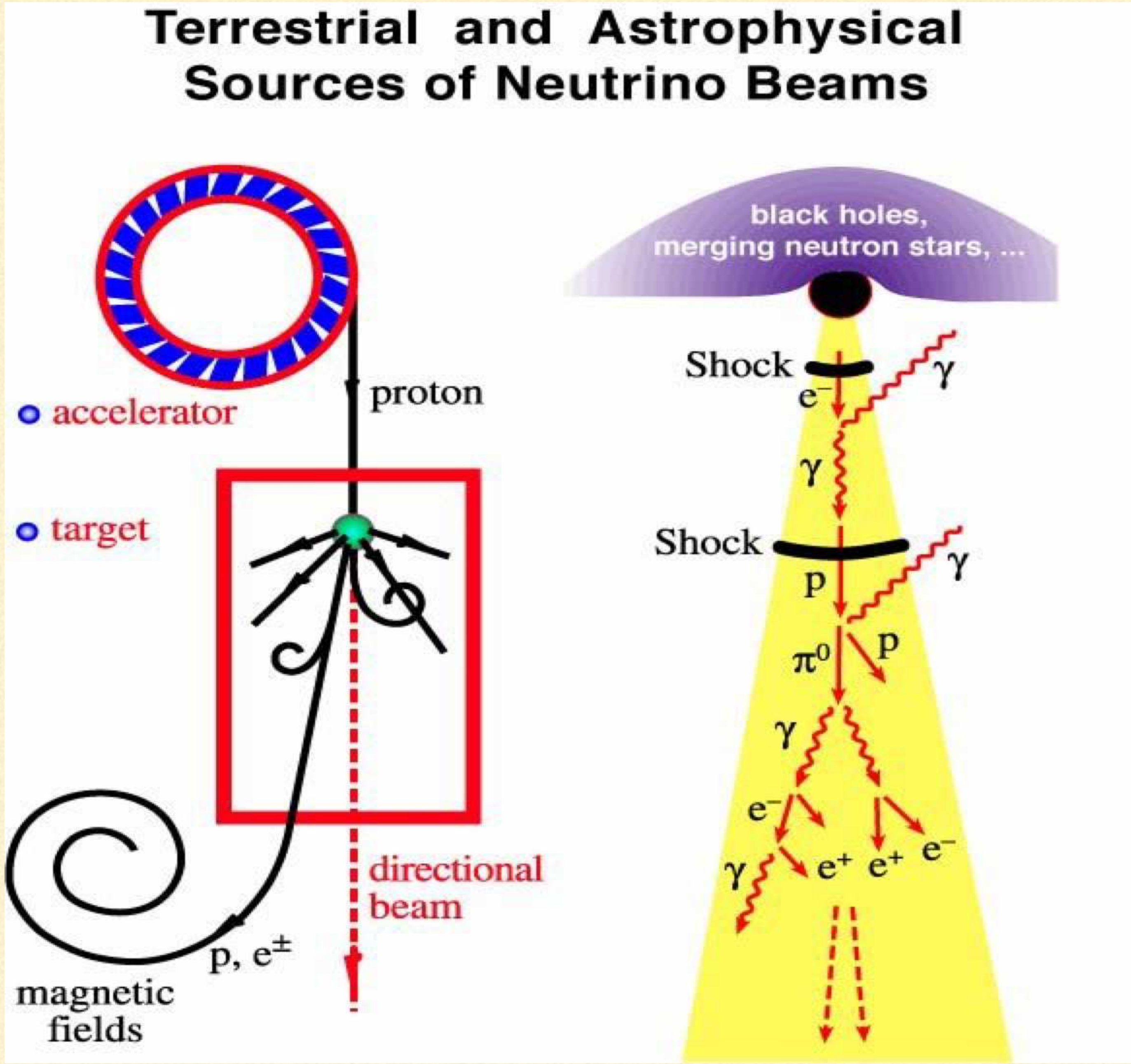
Cosmic Rays.....



Collected over decades, using many different types of detection techniques

Ground Arrays, Air Fluorescence, Balloons, Satellites, Cerenkov light detectors, Radio Detection.....

The assumed generic UHECR accelerator.....



The assumed generic UHECR accelerator.....

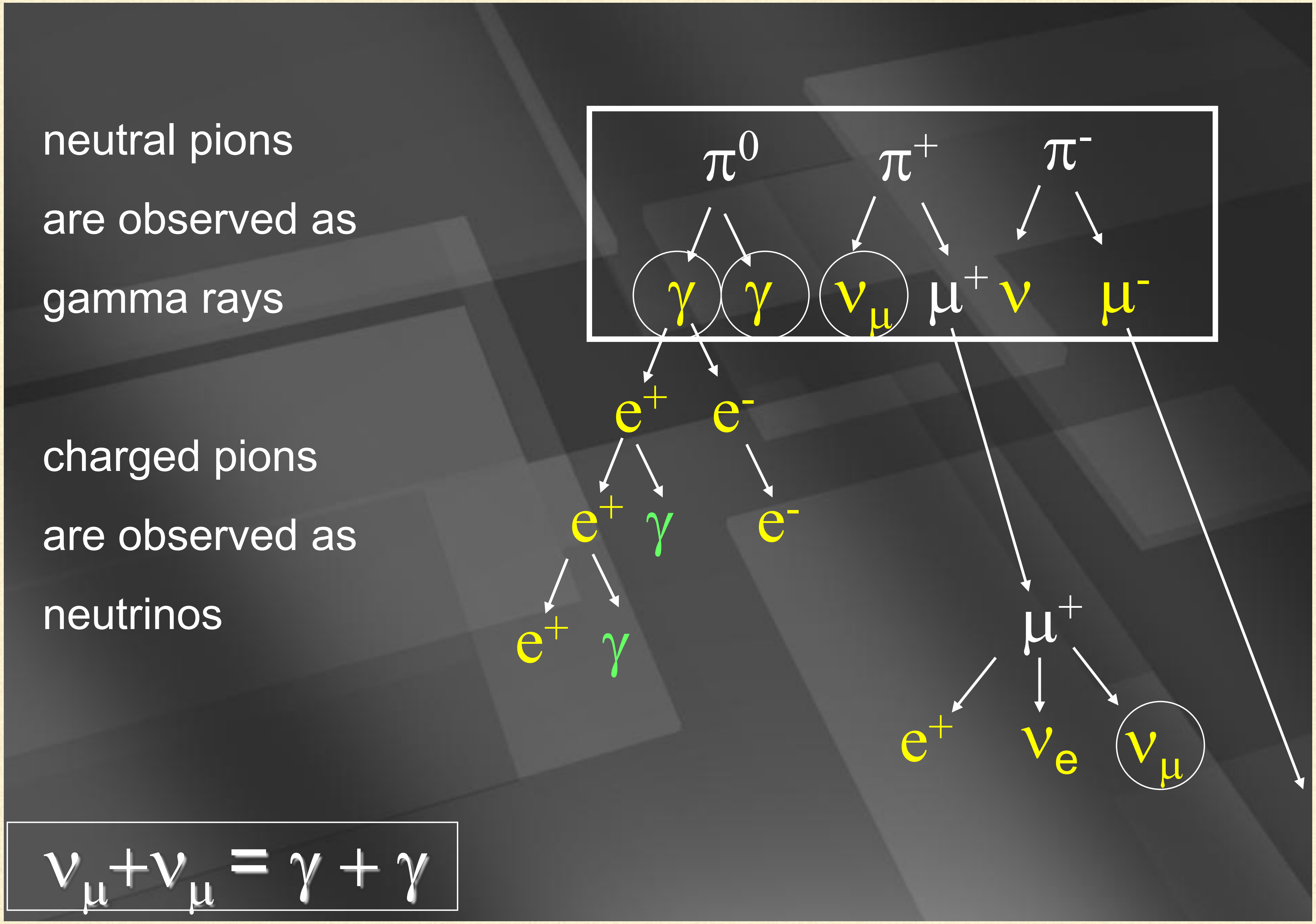
Charged particle ($e, p,$ions) acceleration acheived by confining them in its B field. Electrons quickly lose their energy via synchrotron radiation, and the photons created act as targets for the protons.

$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$ **and** $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$ **interactions. Pions decay to μ and ν, protons tend to stay confined, neutrons and neutrinos leave the accelerator, with the former later decaying to give protons.**

The branching ratios, all of $\sim O(1)$ are known from particle physics, giving comparable and co-related fluxes for CR, γ rays and ν .Observations of TeV γ rays and CR thus can put bounds on the UHE ν fluxes

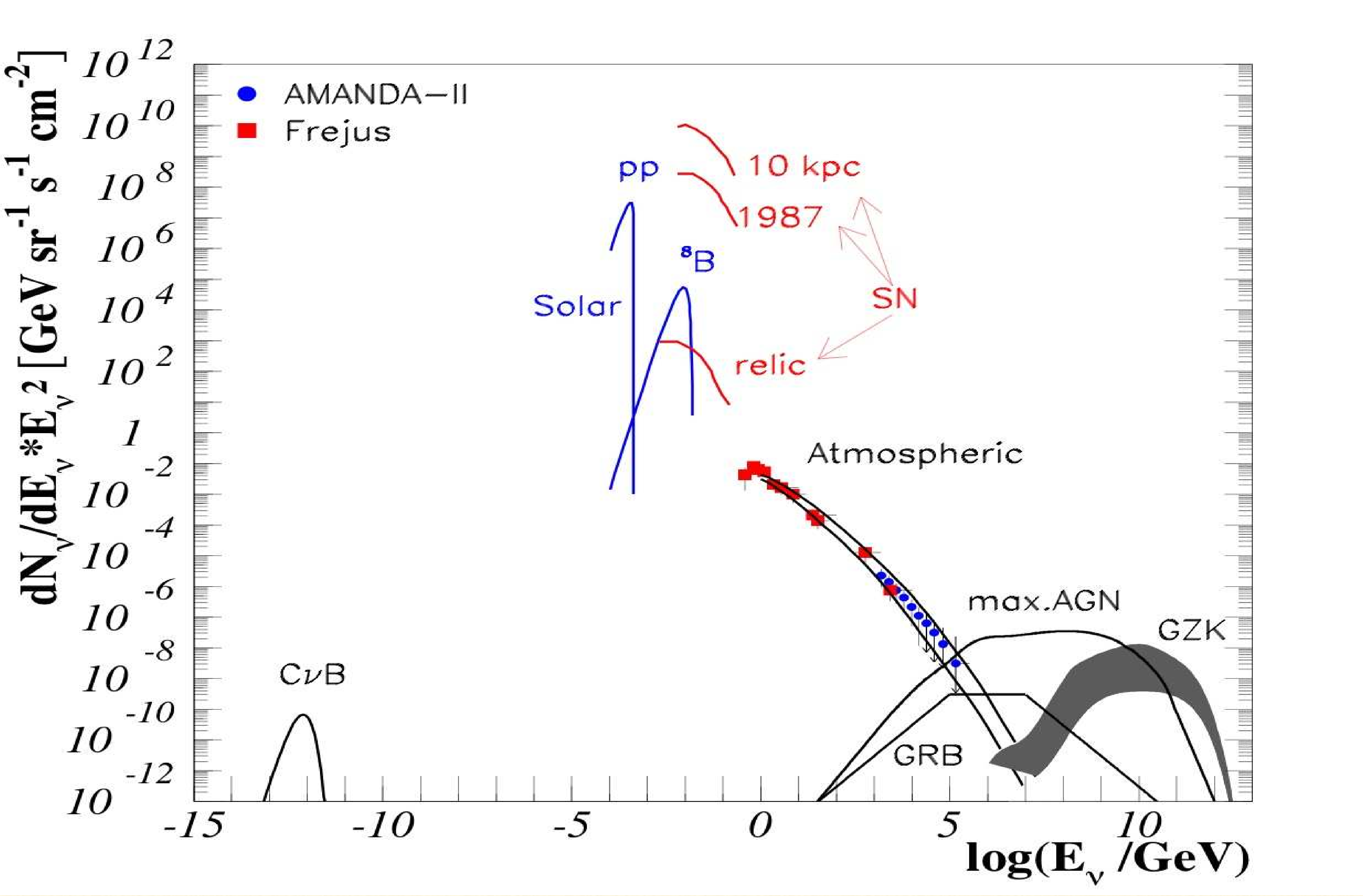
(Waxman and Bahcall; Mannheim, Protheroe and Rachen)

Fluxes from UHE astrophysical accelerators are co-related.....

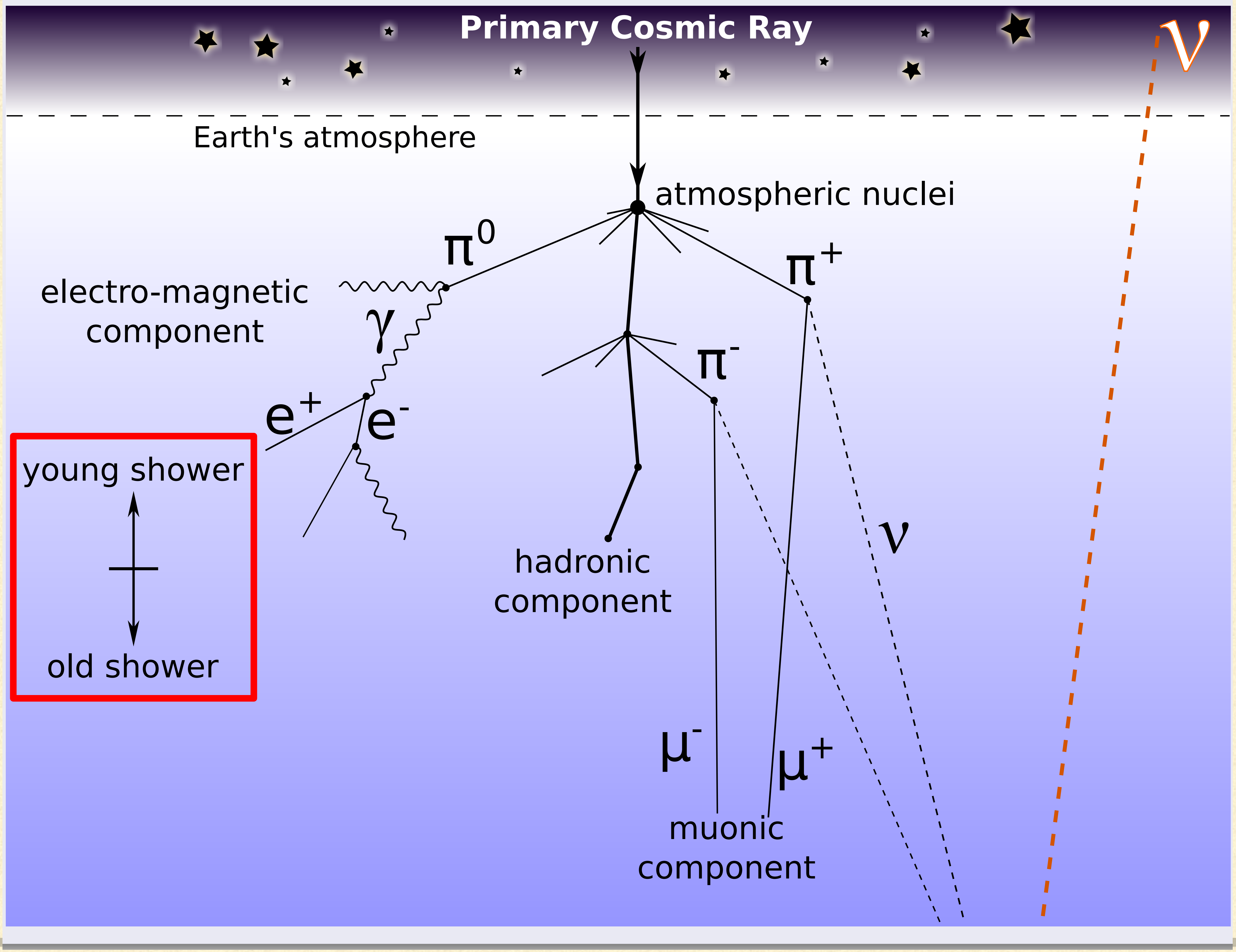


- Importantly, travel over cosmological distances and consequent oscillation brings these neutrinos to a flavour ratio of 1:1:1

The Sky in Neutrinos.....



Atmospheric UHE neutrinos.....



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

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

$$\hookrightarrow \mu^{+} + \nu_{\mu}$$

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

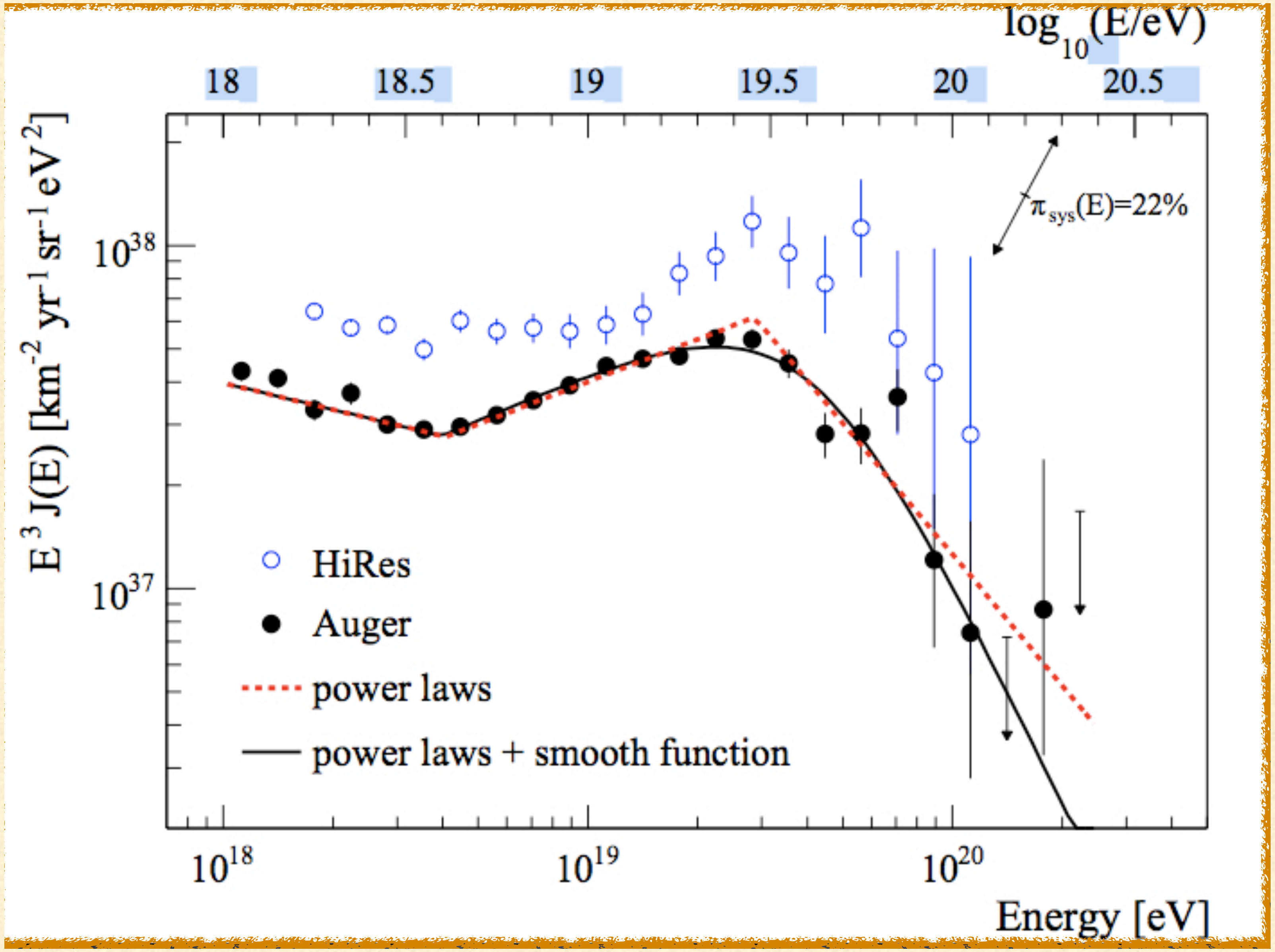
$$p + \gamma_{\rm bgr} \rightarrow \Delta(1232) \rightarrow \pi^{0} + p$$

$$\hookrightarrow \gamma + \gamma$$

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

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

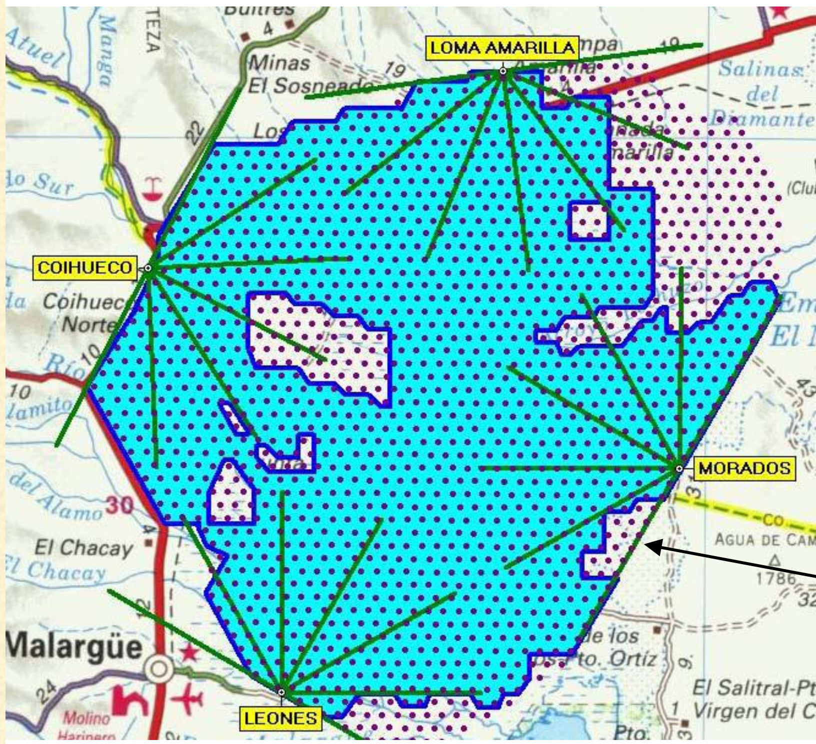
UHECR.....features at the highest energies



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

Pierre Auger Detector

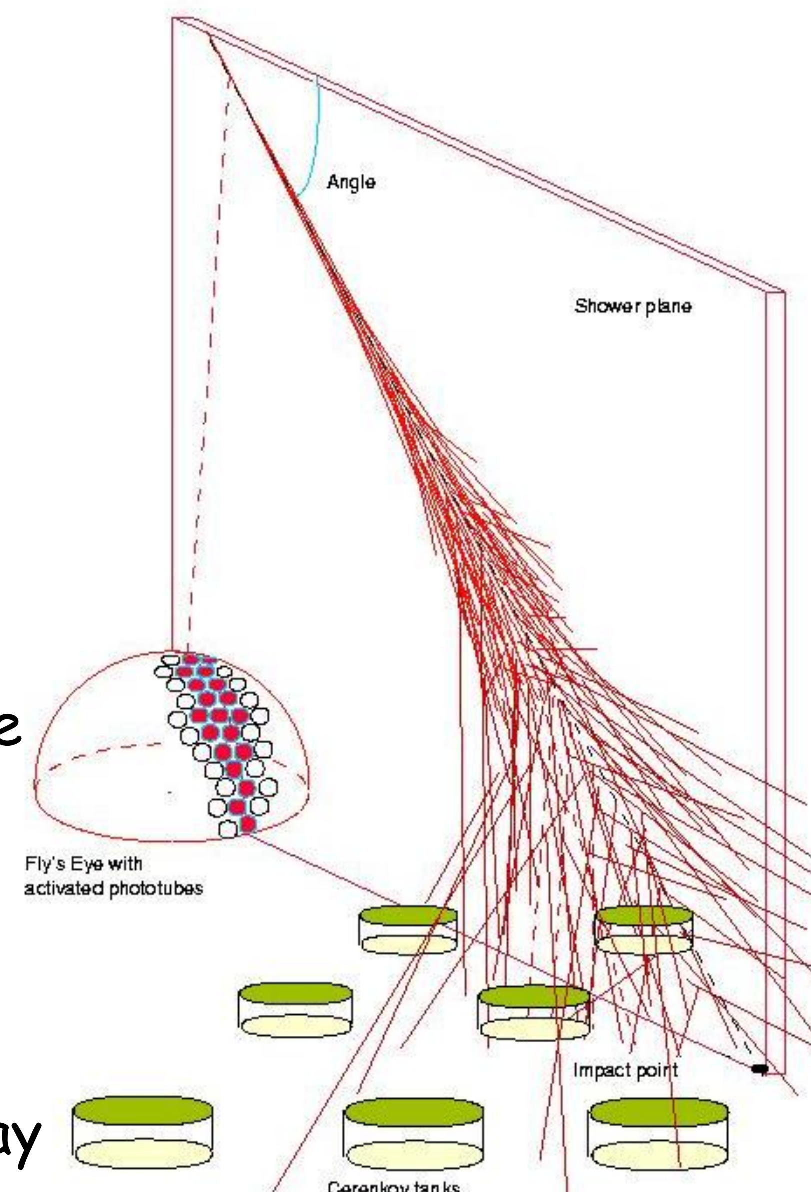
UHE, $>10^{10}$GeV, CRs



$J(>10^{11}\text{GeV}) \sim 1 \;/\; 100\ \text{km}^2\ \text{year}\ 2\pi\ \text{sr}$

Auger:
3000 km^2

Fluorescence detector

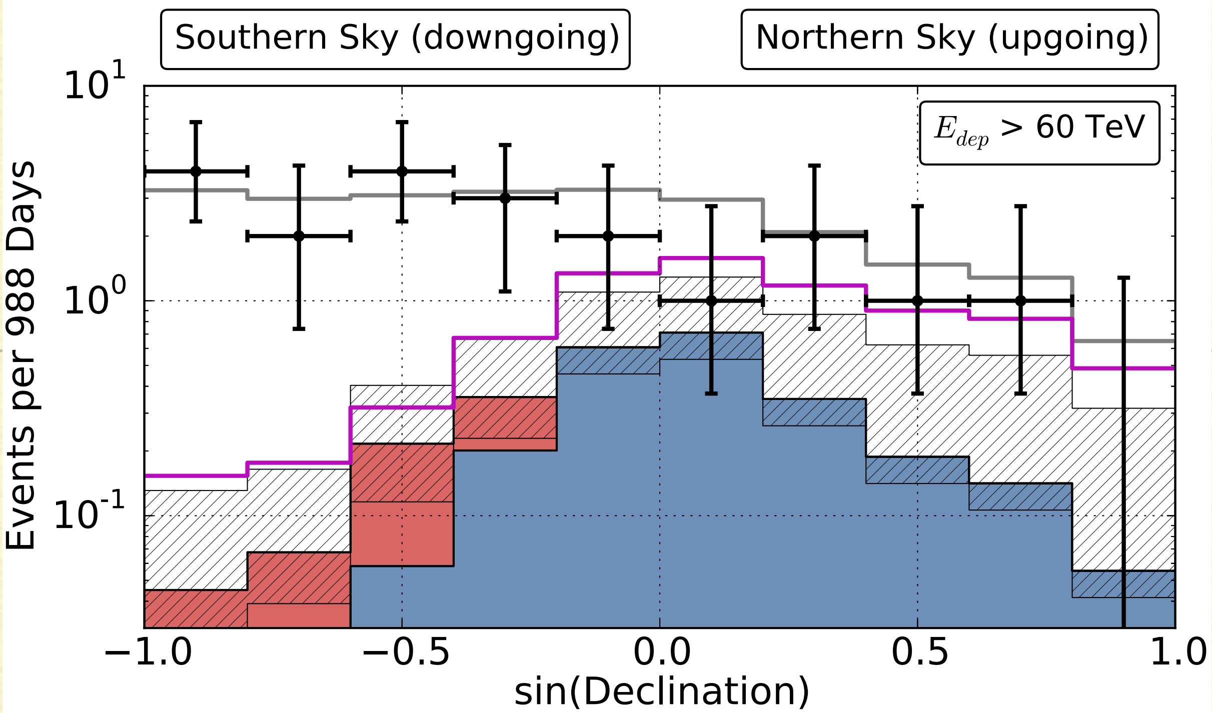


Ground array

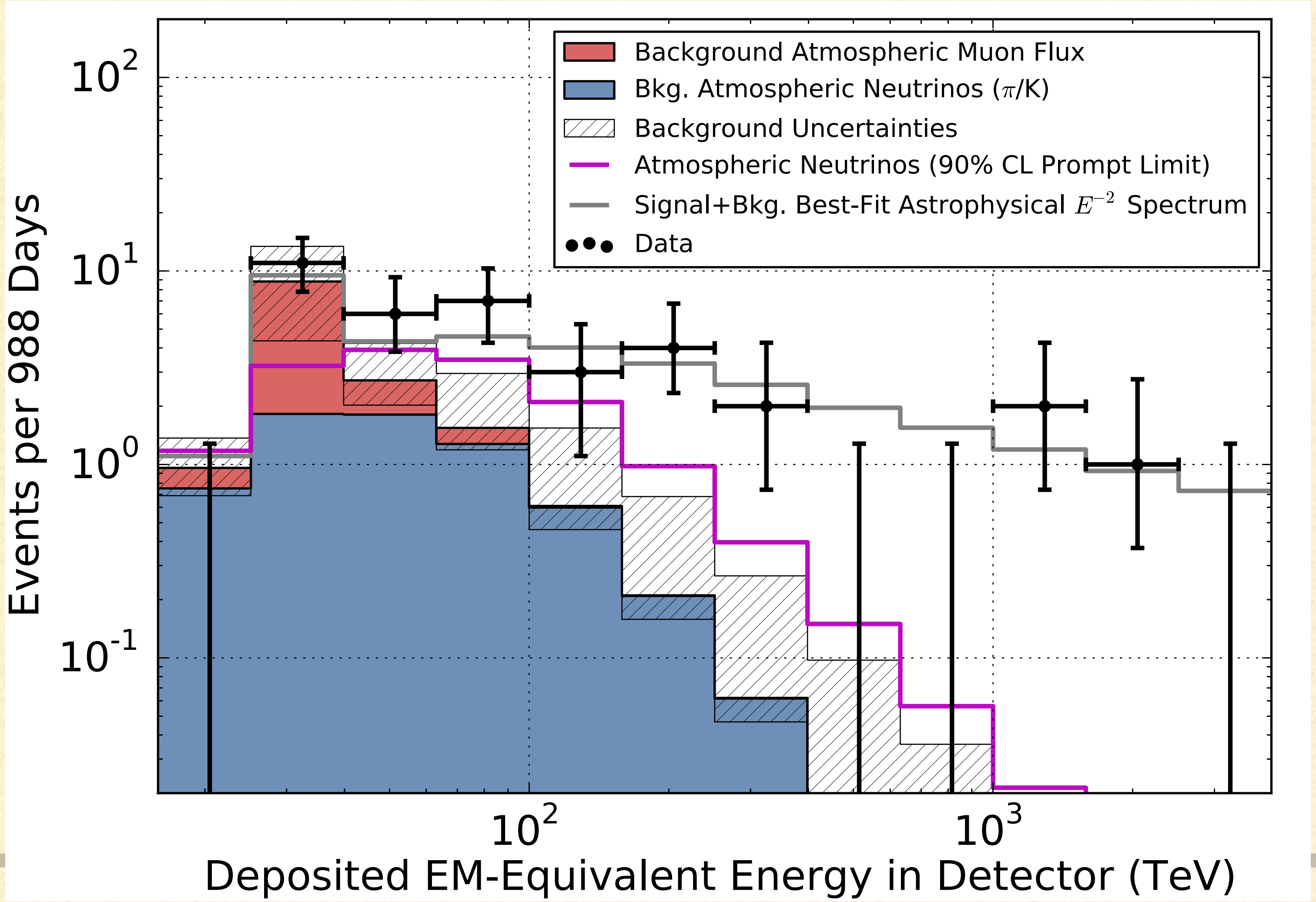

60 photomultipliers/string

Recent Observations at IceCube.......

- 37 events over a 3 year period which are non-atmospheric in origin and extra-terrestial. Atmospheric origin rejected at 5.7σ. (Expect 6.6 atmospheric events)
- Energies between 60 TeV and 2 PeV, the highest ever neutrino energies observed!
- Events appear to be isotropically distributed (no significant galactic bias, no point-source like signal)
- 9 track events, 28 cascade events, consistent with 1:1:1 flux ratio.



Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 60 TeV
Events per 988 Days
sin(Declination)



Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Uncertainties
Atmospheric Neutrinos (90% CL Prompt Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
Deposited EM-Equivalent Energy in Detector (TeV)

37 events with energies between 30 TeV and 2 PeV

21 cascade events, 7 muon track events

ID	Dep. Energy (TeV)	Observation Time (MJD)	Decl. (deg.)	R.A. (deg.)	Med. Angular Error (deg.)	Event Topology
1	$47.6^{+6.5}_{-5.4}$	55351.3222110	−1.8	35.2	16.3	Shower
2	117^{+15}_{-15}	55351.4659612	−28.0	282.6	25.4	Shower
3	$78.7^{+10.8}_{-8.7}$	55451.0707415	−31.2	127.9	$\lesssim 1.4$	Track
4	165^{+20}_{-15}	55477.3930911	−51.2	169.5	7.1	Shower
5	$71.4^{+9.0}_{-9.0}$	55512.5516214	−0.4	110.6	$\lesssim 1.2$	Track
6	$28.4^{+2.7}_{-2.5}$	55567.6388084	−27.2	133.9	9.8	Shower
7	$34.3^{+3.5}_{-4.3}$	55571.2585307	−45.1	15.6	24.1	Shower
8	$32.6^{+10.3}_{-11.1}$	55608.8201277	−21.2	182.4	$\lesssim 1.3$	Track
9	$63.2^{+7.1}_{-8.0}$	55685.6629638	33.6	151.3	16.5	Shower
10	$97.2^{+10.4}_{-12.4}$	55695.2730442	−29.4	5.0	8.1	Shower
11	$88.4^{+12.5}_{-10.7}$	55714.5909268	−8.9	155.3	16.7	Shower
12	104^{+13}_{-13}	55739.4411227	−52.8	296.1	9.8	Shower
13	253^{+26}_{-22}	55756.1129755	40.3	67.9	$\lesssim 1.2$	Track
14	1041^{+132}_{-144}	55782.5161816	−27.9	265.6	13.2	Shower
15	$57.5^{+8.3}_{-7.8}$	55783.1854172	−49.7	287.3	19.7	Shower
16	$30.6^{+3.6}_{-3.5}$	55798.6271191	−22.6	192.1	19.4	Shower
17	200^{+27}_{-27}	55800.3755444	14.5	247.4	11.6	Shower
18	$31.5^{+4.6}_{-3.3}$	55923.5318175	−24.8	345.6	$\lesssim 1.3$	Track
19	$71.5^{+7.0}_{-7.2}$	55925.7958570	−59.7	76.9	9.7	Shower
20	1141^{+143}_{-133}	55929.3986232	−67.2	38.3	10.7	Shower
21	$30.2^{+3.5}_{-3.3}$	55936.5416440	−24.0	9.0	20.9	Shower
22	220^{+21}_{-24}	55941.9757760	−22.1	293.7	12.1	Shower
23	$82.2^{+8.6}_{-8.4}$	55949.5693177	−13.2	208.7	$\lesssim 1.9$	Track
24	$30.5^{+3.2}_{-2.6}$	55950.8474887	−15.1	282.2	15.5	Shower
25	$33.5^{+4.9}_{-5.0}$	55966.7422457	−14.5	286.0	46.3	Shower
26	210^{+29}_{-26}	55979.2551738	22.7	143.4	11.8	Shower
27	$60.2^{+5.6}_{-5.6}$	56008.6845606	−12.6	121.7	6.6	Shower
28	$46.1^{+5.7}_{-4.4}$	56048.5704171	−71.5	164.8	$\lesssim 1.3$	Track
29	$32.7^{+3.2}_{-2.9}$	56108.2571970	41.0	298.1	7.4	Shower
30	129^{+14}_{-12}	56115.7283566	−82.7	103.2	8.0	Shower
31	$42.5^{+5.4}_{-5.7}$	56176.3914123	78.3	146.1	26.0	Shower
32	—	56211.7401165	—	—	—	Coincident
33	385^{+46}_{-49}	56221.3423965	7.8	292.5	13.5	Shower
34	$42.1^{+6.5}_{-6.3}$	56228.6055210	31.3	323.4	42.7	Shower
35	2004^{+236}_{-262}	56265.1338659	−55.8	208.4	15.9	Shower
36	$28.9^{+3.0}_{-2.6}$	56308.1642711	−3.0	257.7	11.7	Shower
37	$30.8^{+3.3}_{-3.5}$	56390.1887617	20.7	167.3	$\lesssim 1.2$	Track

PPL. TABLE I. Properties of the events. Tabular form of Fig. 1. Events 1-28 were previously published in [11] and are luded here, with no changes, for completeness. Events 28 and 32 have coincident hits in the IceTop surface array, implying t they are almost certainly produced in cosmic ray air showers.

3 events with PeV energy

Angular distribution consistent with isotropy

Flavour distribution consistent with 1:1:1

Ask certain questions and try to answer in best possible way in order to assess present situation.

Can the signal be explained by atmospheric neutrinos alone?

Answer: Very unlikely

Reasons:

- Observed events have much higher energy, and significantly higher spectrum (E^-2 as opposed to E^-3.7)
- 11 events with energy above 100 TeV (including 3 over 1 PeV), wherea atmospheric expectation is less than 2 events above 100 TeV
- Atmospheric origin would imply many more muon tracks compared to cascades, (2/3 vs the 1/4 which are observed).
- Adding even the most optimistic charm production models still gives softer spectrum and fewer events than seen.
- Any atmospheric origin will give excess muons, triggering muon veto, biasing events to Northern hemisphere. However, most events are from the south.
- $> 5.7\sigma$ significance for non-atmospheric origin.

Can the signal be explained by astrophysical (extraterrestial) neutrinos?

Answer: Yes

Reasons:

- Equal flavour flux would produce cascade event:track event ratio of 4:1. When superposed with atmospheric events , expect this to be approx 3:1, as is seen. (Atmospheric backgnd expected is 10.6 events)
- Since neutrinos in the relevant energy region suffer significant absorption in the earth, most events from isotropic extraterrestial flux will also be from south (as is seen).
- Data reasonably described by a E^-2 spectrum. However, one would expect 3-6 more events in 2 PeV to 10 PeV range, which are not seen

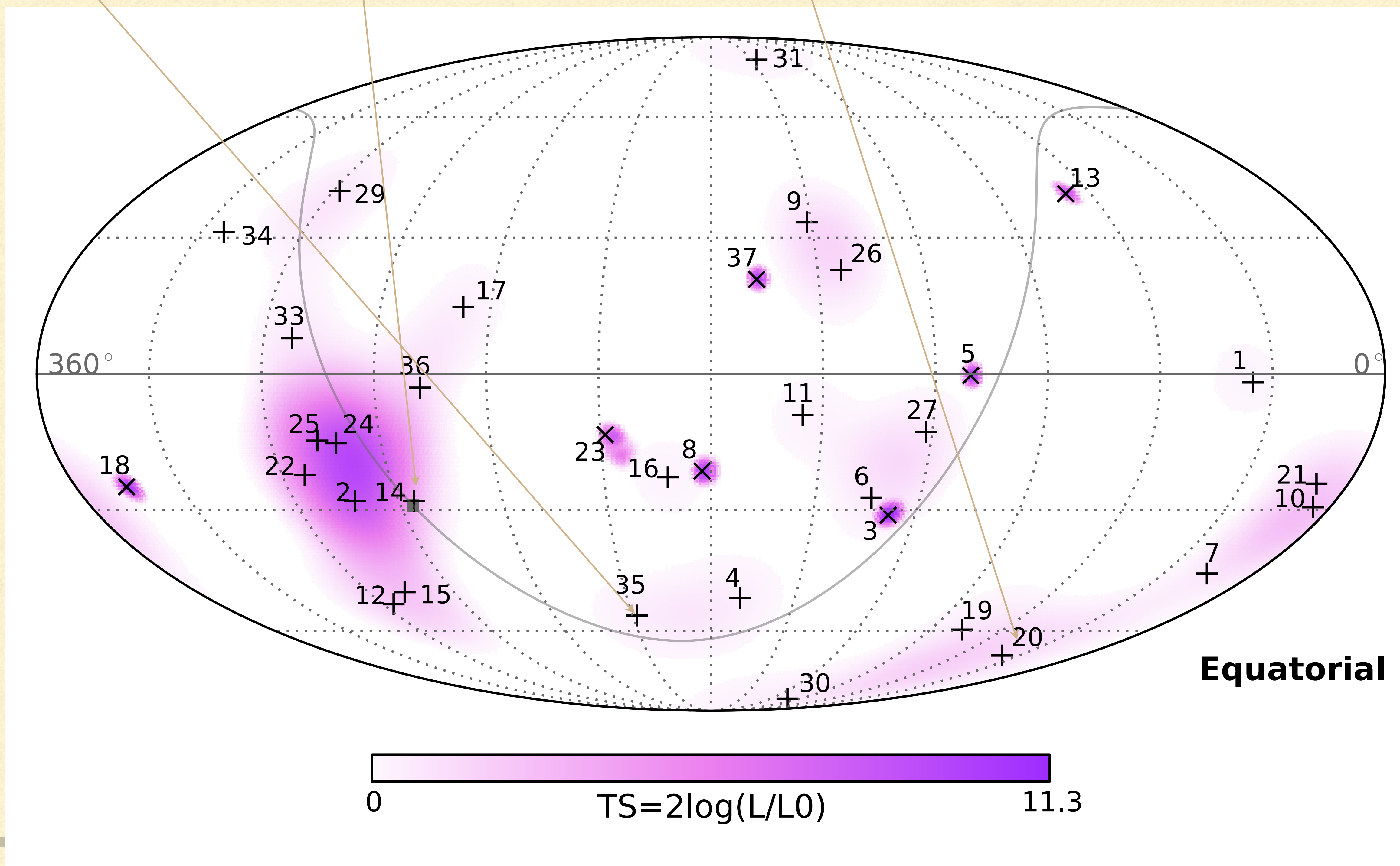
Important

1.04 PeV event

2 PeV event

1.2 PeV event

temporal separation
about 7 mos.



There is a gap in the data. Is it significant?

Answer according to IceCube: Probably not.

(What gap?)

(Answer: There are 34 events between 30 TeV and 400 TeV, none between 400 TeV and 1 PeV)

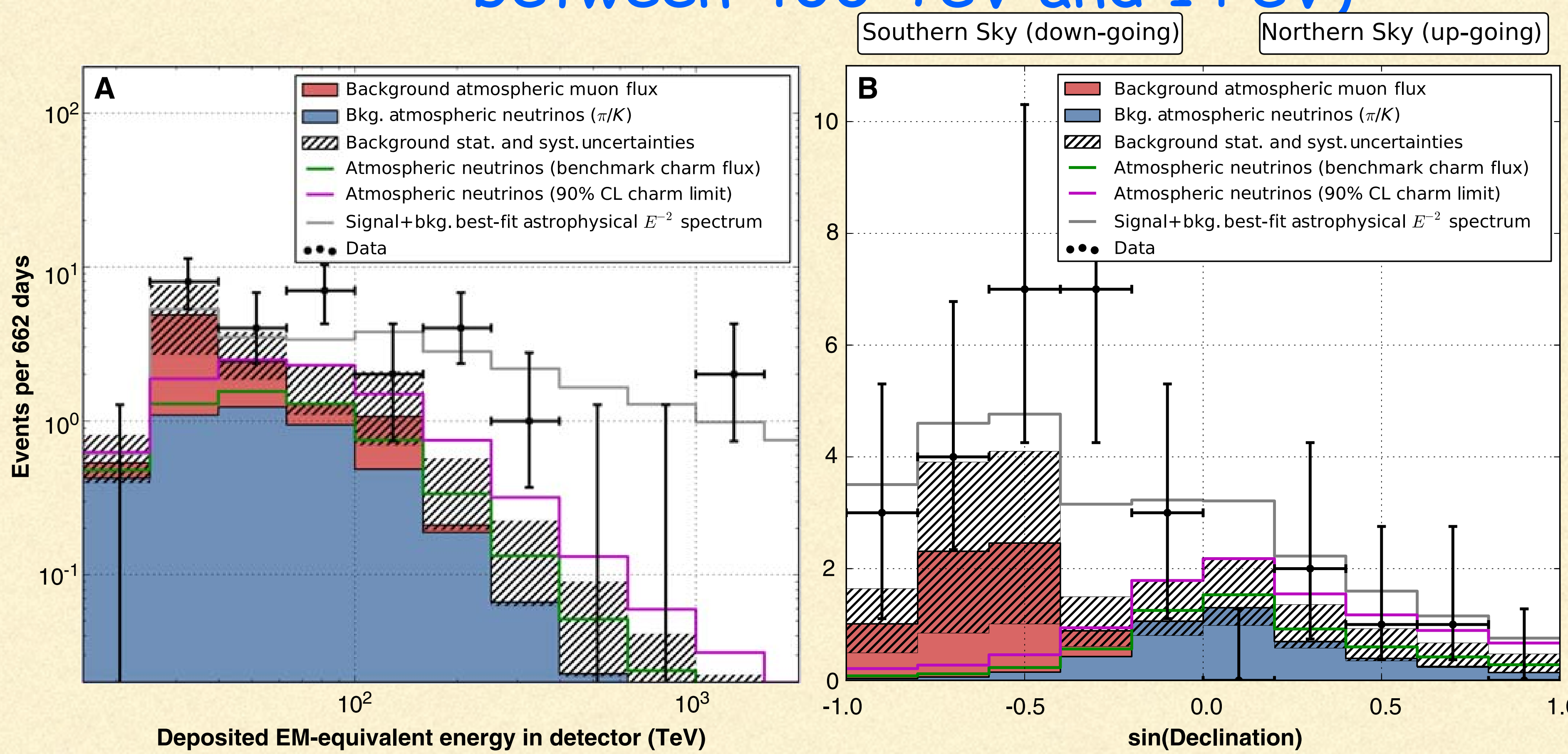


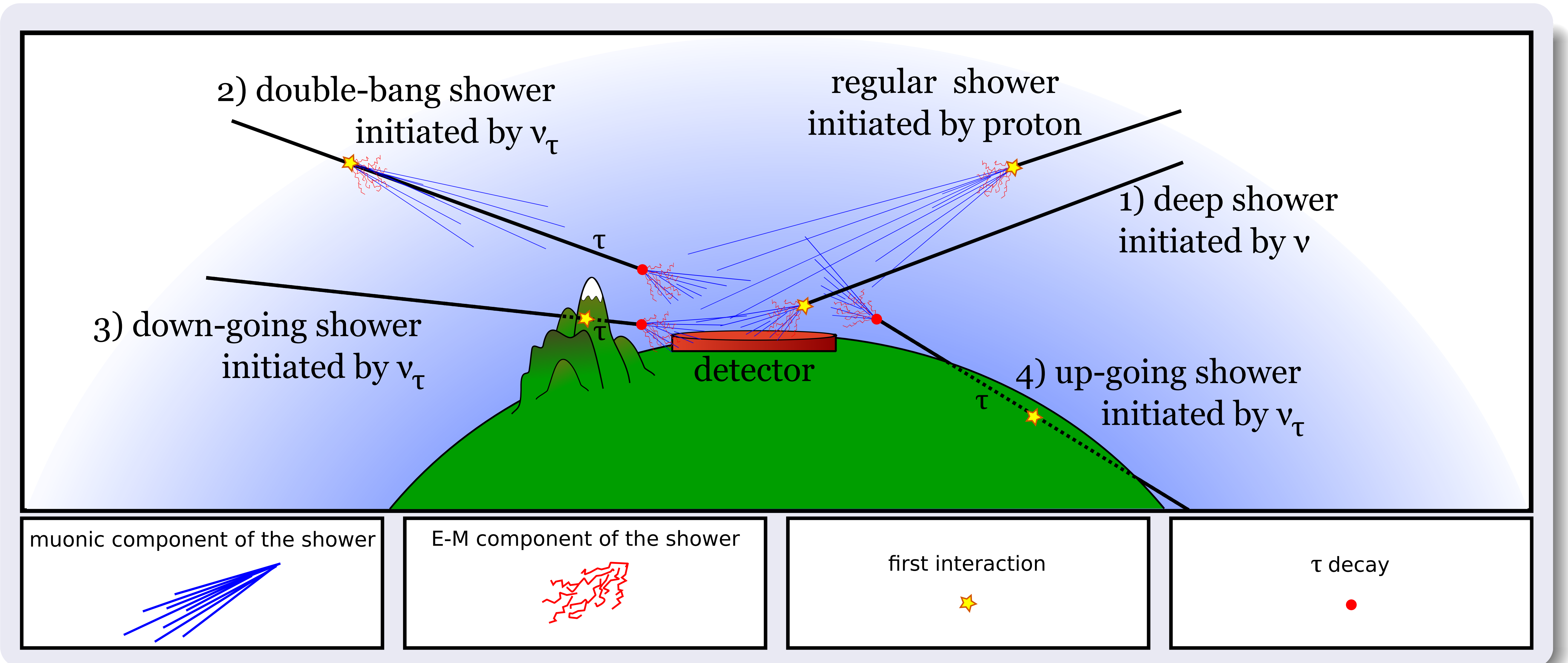
Fig. 4. Distributions of the deposited energies and declination angles of the observed events compared to model predictions. (**A** and **B**) Zenith angle entries for data (B) are the best-fit zenith position for each of the 28 events; a small number of events (Table 1) have zenith uncertainties larger than the bin widths in this figure. Energies plotted (A) are reconstructed in-detector visible energies, which are lower limits on the neutrino energy. Note that deposited energy spectra are always harder than the spectrum of the neutrinos that produced them because of the neutrino cross section increasing with energy. The expected rate of atmospheric neutrinos is shown in blue, with atmospheric muons in red. The green line shows our benchmark atmospheric neutrino flux (see the text), and the magenta line shows the experimental 90% bound. Because of a lack of statistics from data far above our cut threshold, the shape of the distributions from muons in this figure has been determined using Monte Carlo simulations with total rate normalized to the estimate obtained from our in-data control sample. Combined statistical and systematic uncertainties on the sum of backgrounds are indicated with a hatched area. The gray line shows the best-fit E^{-2} astrophysical spectrum with a per-flavor normalization (1:1:1) of $E^2\Phi_\nu(E) = 1.2 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}.

The 2 unexpected features are the gap between 350 TeV and 1 PeV, and the lack of events beyond a PeV. Also noticeable is the clustering of the 3 ~PeV events.

Situation is intriguing, with no single explanation being a perfect fit. However, extra-terrestial neutrinos from CR sources appear to be the favourite….. More data (coming soon) and new ideas would help………..

k you for your attention…….

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



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?

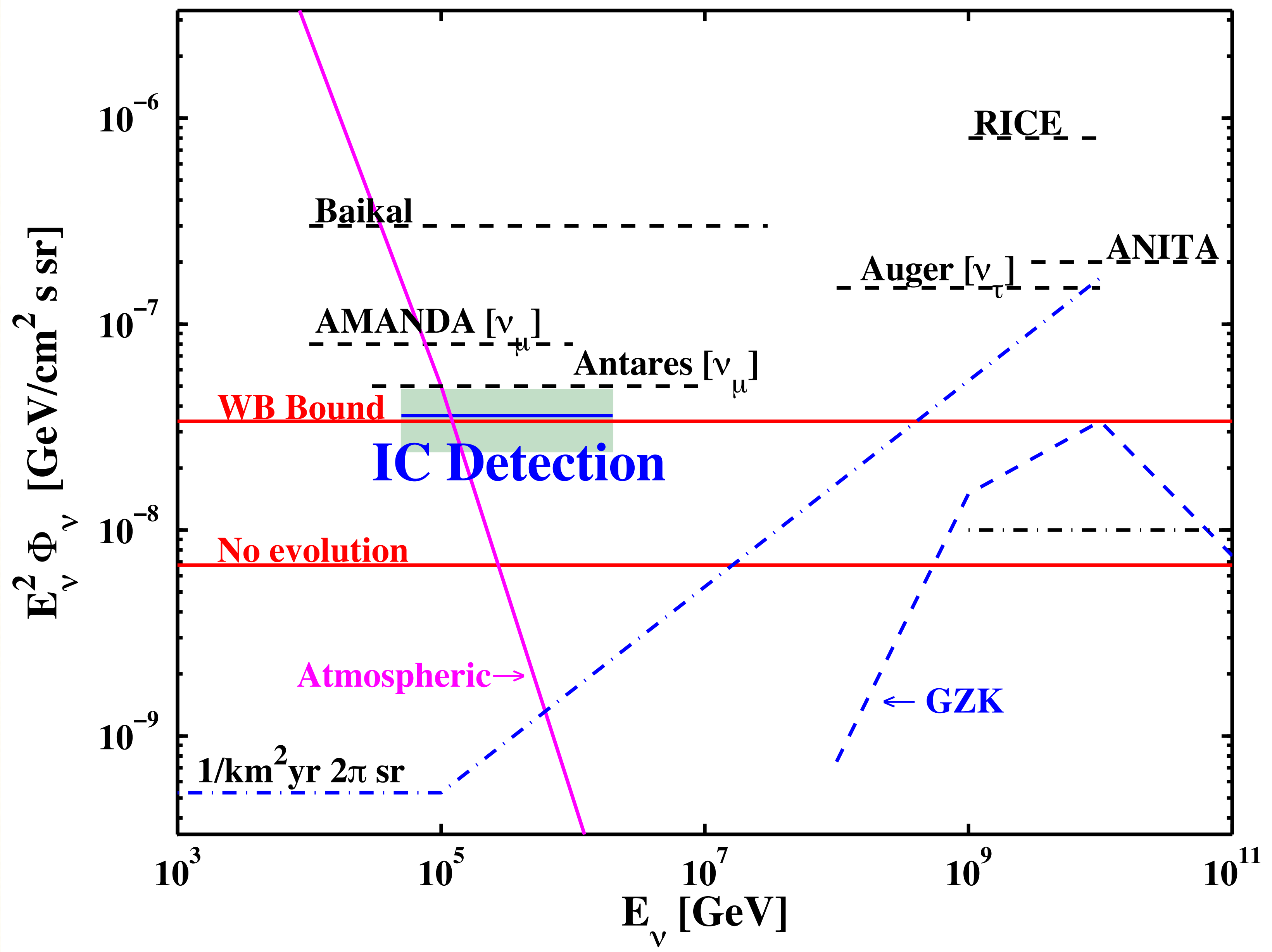
The 2 PeV events are a line signature from dark matter decay/annihilation (Feldstein et al, 1303.7320.) This also yields a continuum signal at lower energies, but this is model dependant, and usually below atmospheric.

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)

Where is the detected signal with respect to the WB bound?

Answer: It sits on it.



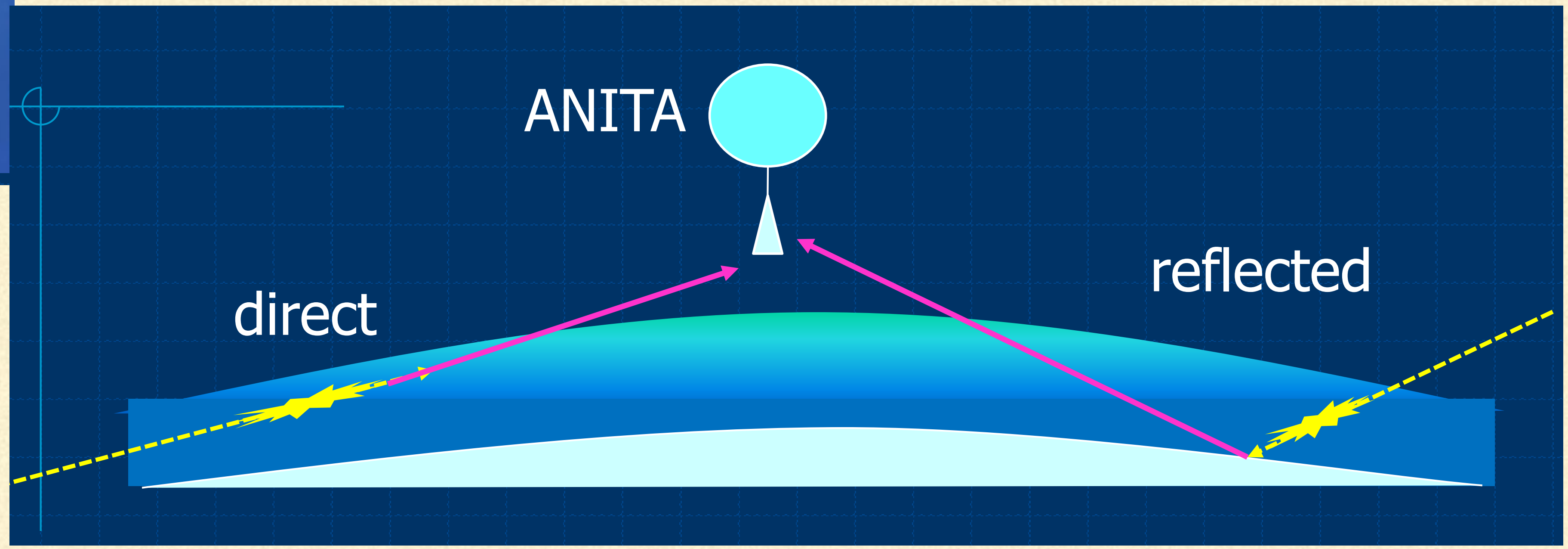
This strengthens somewhat the assumption that UHE CR and UHE neutrinos may have the same sources powered by accelerators like AGNs and GRBs.

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!



Auger results.....

After unblinding:

0

candidates for the search periods.

search periods

Down-going	:	Nov 07	to	May 10
Up-going	:	Jan 04	to	Feb 09

Both periods are equivalent to 2 yrs. full Auger

- The Pierre Auger Observatory is sensitive to UHE neutrinos:
  - down-going neutrinos ($\theta \in [75^\circ, 90^\circ]$): all flavours CC & NC.
  - up-going neutrinos ($\theta \in [90^\circ, 95^\circ]$): ν_τ CC.
- Signature: very inclined showers with significant E-M content.
- ZERO neutrino candidate events found in data.
- Maximum sensitivity at the most relevant range for GZK neutrinos (1 EeV).

Any other issue related to the WB bound?

Answer: Yes

The numerical value of the WB bound depends on an assumption as to the CR energy beyond which the CR flux is extragalactic. If the PeV and hundred TeV neutrinos are extragalactic, then CR flux above 100 PeV must be extragalactic, and not, as assumed by WB, above 1 EeV. This alters (increases) the level of the bound by a factor of 10.

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.

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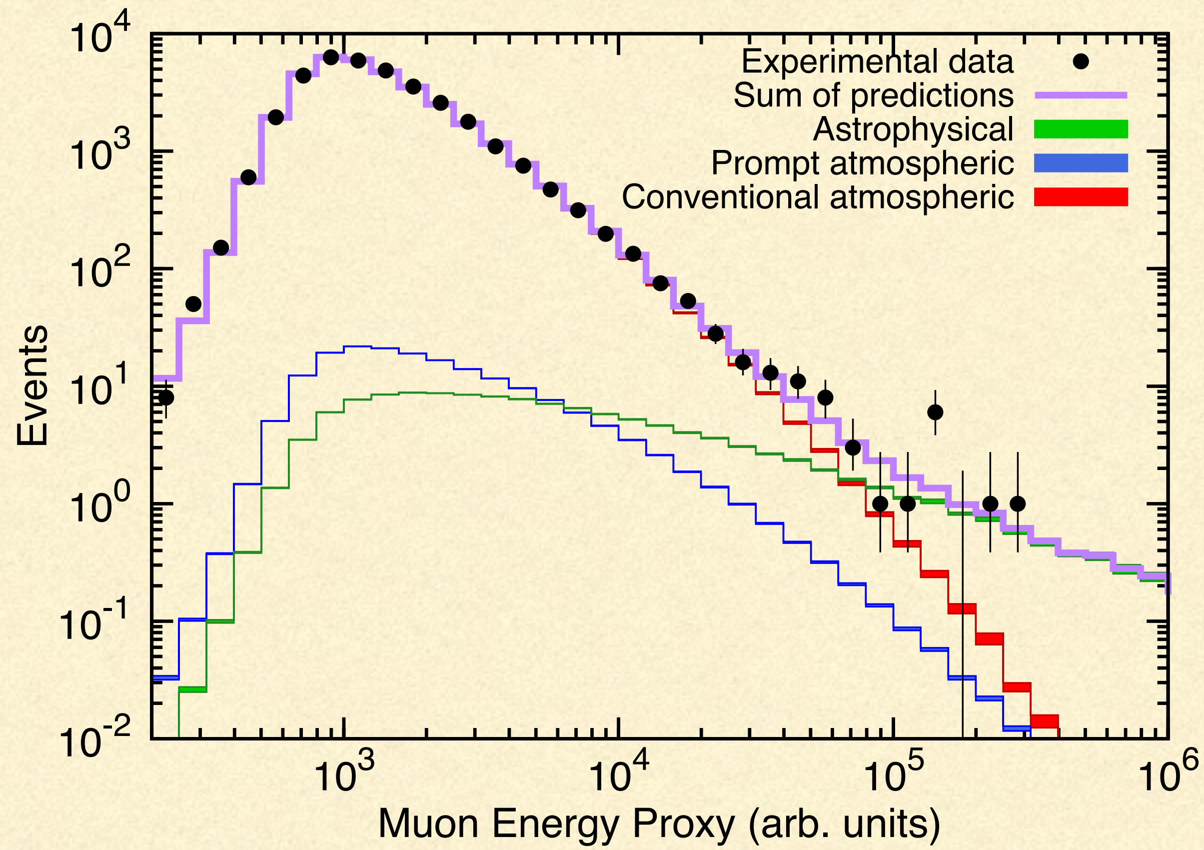
s channel enhancement of nu-quark scattering due to 0.6 TeV leptoquark (Barger and Keung, 1305.6907)



IC Muon analysis, 1507.04005

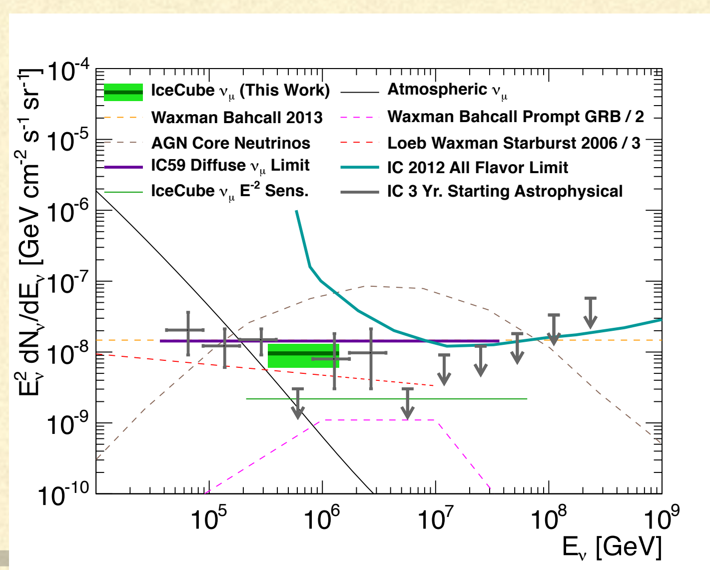
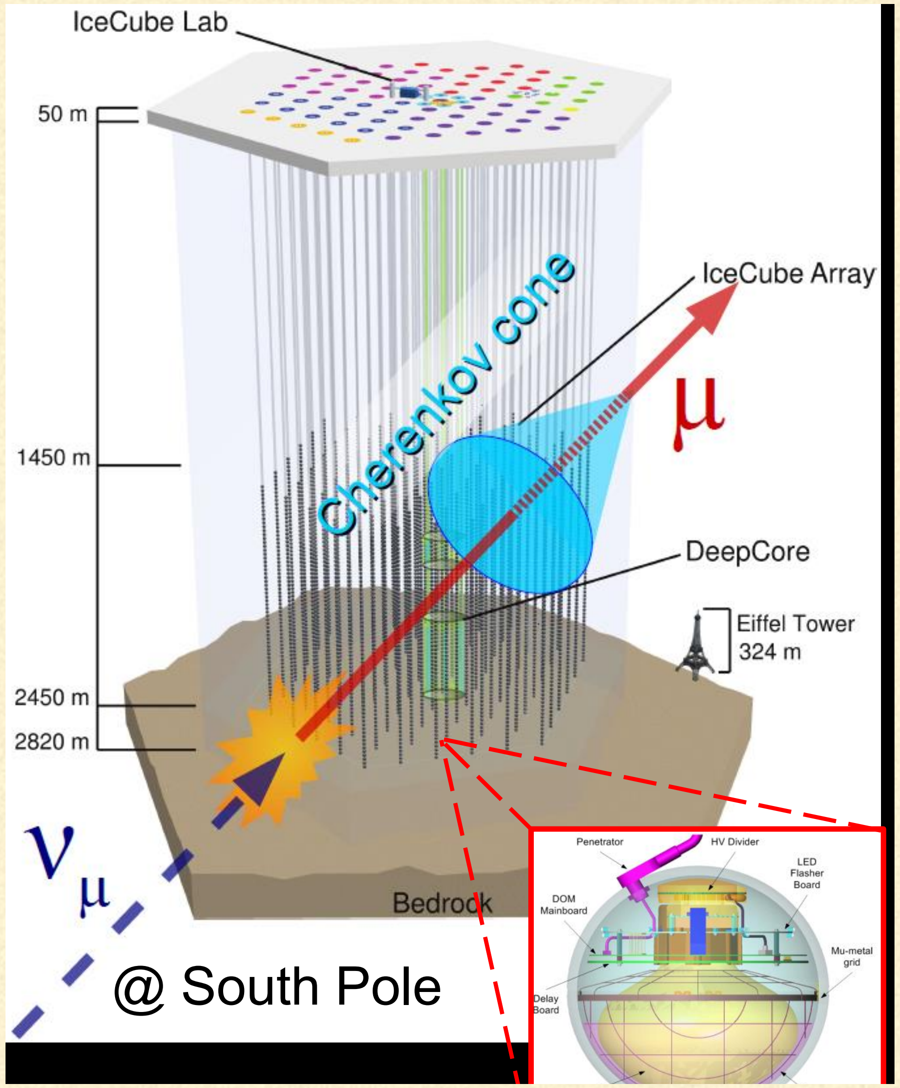


FIG. 4. Comparison of the best fit per-flavor astrophysical flux spectrum of E^{-2} from this work, assuming a flavor ratio of 1:1:1, (shown in dark green with the 68% error range in lighter green) to other selected IceCube measurements (heavy lines) [4, 12] and theoretical model predictions (thin, dashed lines) [5–7, 17, 20, 28]. The sensitivity of this analysis is also shown as the thin, green line.


IceCube Lab
50 m
1450 m
2450 m
2820 m
IceCube Array
Cherenkov cone
μ
DeepCore
Eiffel Tower
324 m
Bedrock
ν_μ
@ South Pole
Penetrator
HV Divider
LED Flasher Board
DOM Mainboard
Mu-metal grid
Delay Board

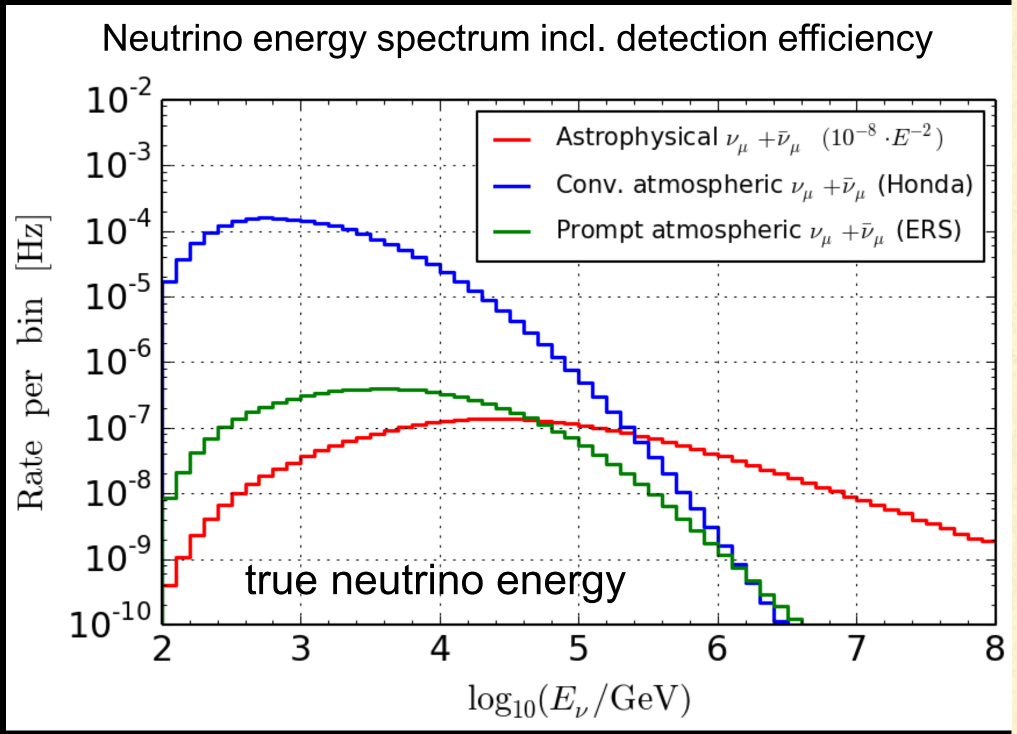
- Atmospheric neutrino background

Conventional atmospheric neutrinos

- From pion and kaon decays produced by cosmic ray interactions with the atmosphere
- Energy spectrum: $\boxed{\frac{d\phi}{dE} \propto E^{-3.7}}$

Prompt atmospheric neutrinos

- From heavy meson decays produced by cosmic ray interactions with the atmosphere (not measured yet)
- Energy spectrum: $\boxed{\frac{d\phi}{dE} \propto E^{-2.7}}$

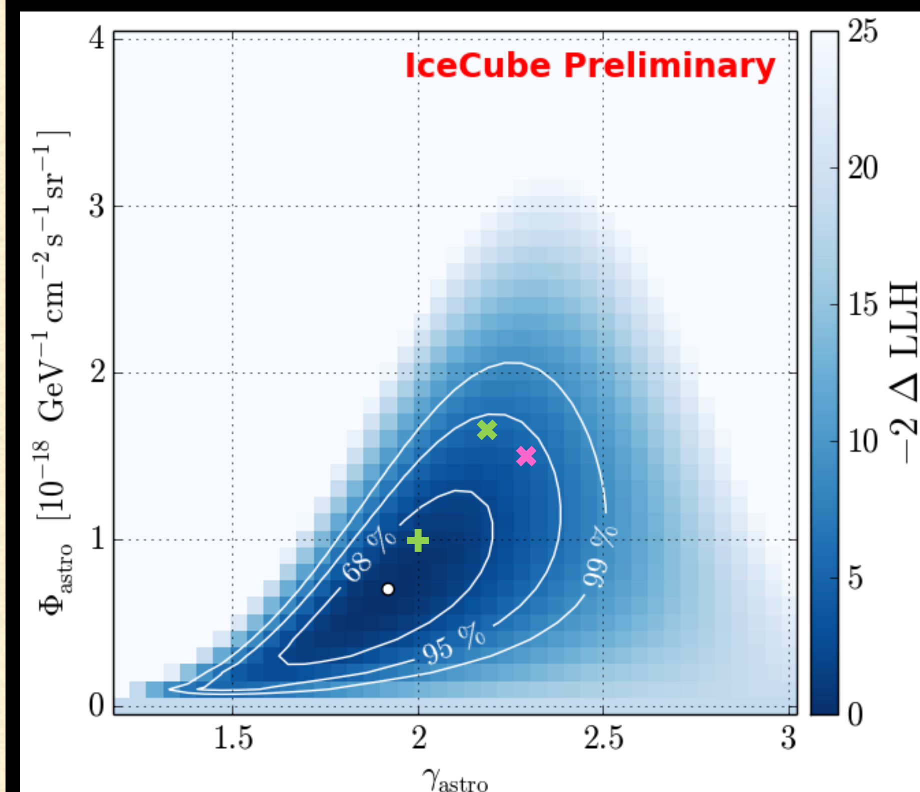


- Astrophysical neutrino signal
  - Energy spectrum: $\boxed{\frac{d\phi}{dE} \propto E^{-2}}$

4

A measurement of the diffuse astrophysical muon neutrino flux
Leif Rädel | ICRC 2015, The Hague | 04.08.2015

Honda: Honda et al., Phys. Rev. D 75 (Feb, 2007)
ERS: Enberg et al., Phys. Rev. D 78 (Aug, 2008)



- Correlation between astrophysical normalization @100TeV and the spectral index
- Best-fit astrophysical normalization:

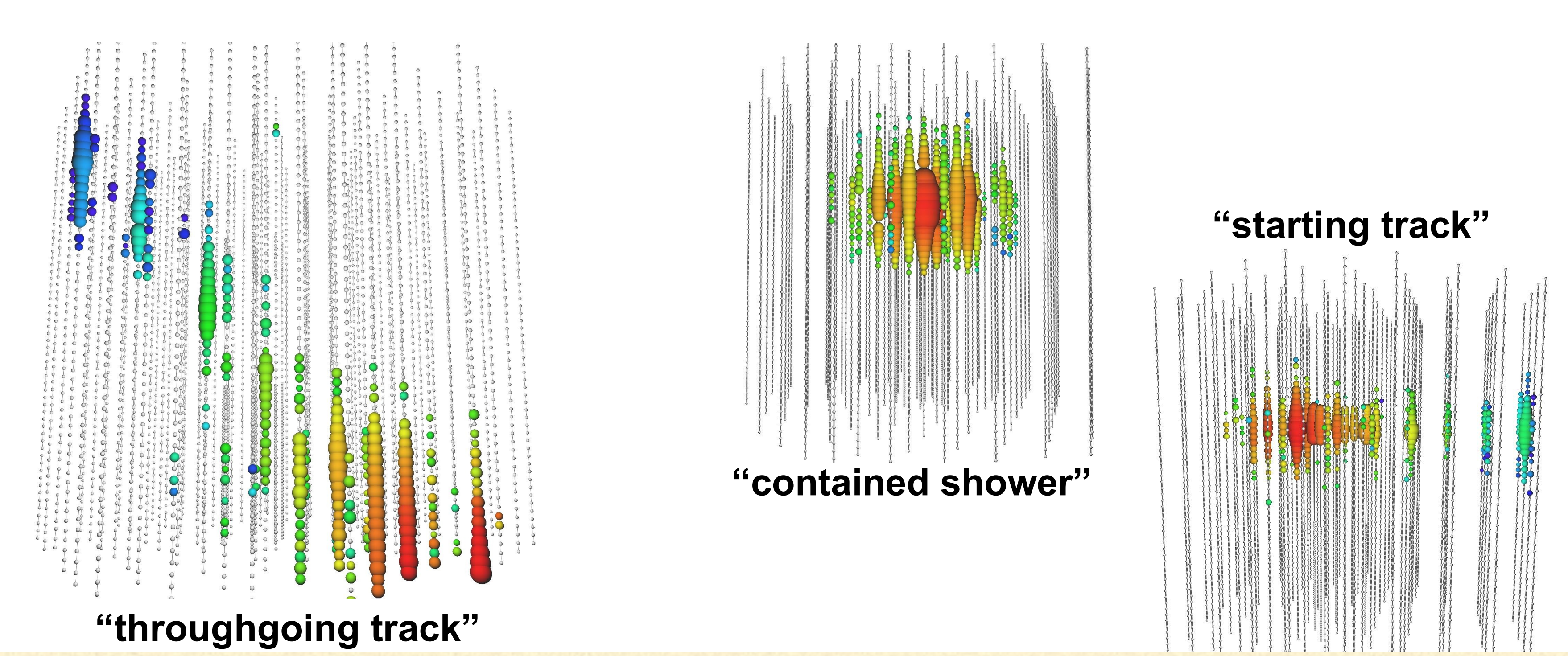
$$(0.66^{+0.40}_{-0.30}) \times 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$$

- Best-fit spectral index:

$$\gamma_{\mathrm{astro}} = 1.91 \pm 0.20$$

- Atmospheric-only hypothesis excluded by 4.3σ
- Compatible with the best-fit of high-energy starting event analysis (Phys. Rev. Lett. 113, 101101 (2014))
- Compatible with best-fit result of the current up-going muon neutrino analysis (accepted in Phys. Rev. Lett. arXiv:1507.04005)

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



Energy spectrum

- **Benchmark model:** Fermi acceleration at shock fronts
  $\rightarrow \quad \Phi_\nu \propto E^{-2}$
- Actual spectrum depends on source class
- **Hypothesis A:** $\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$
- **Hypothesis B:** $\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma} \times \exp(-E/E_{\mathrm{cut}})$

Flavor composition

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

Fit: allow any composition

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

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

Best fit hypothesis A:

all-flavor!

- $\Phi_\nu = \boxed{\left(7.0^{+1.0}_{-1.0}\right) \times 10^{-18}\,\mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{\boxed{-2.49\pm0.08}}$
- E^{-2} excluded at $\boxed{4.6\,\sigma}$

Best fit hypothesis B:

all-flavor!

- $\Phi_\nu = \boxed{\left(8.0^{+1.3}_{-1.2}\right) \times 10^{-18}\,\mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{\boxed{-2.31\pm0.15}}$

$$\times \exp\left(-E/\boxed{\left(2.7^{+7.7}_{-1.4}\right)\,\mathrm{PeV}}\right).$$

- preferred over hypothesis A by $\boxed{1.2\,\sigma}$

Both models describe the data well

TABLE I. Expected numbers of cascade events in the two energy bins, obtained by integrating the curves in the right panel (the realistic approach using the effective area) of Fig. 3. These numbers are typically a factor of ~ 5 below those for the left panel (the ideal case or "theorist's approach").

Possible Source	N(1 − 2 PeV)	N(2 − 10 PeV)
Atm. Conv. [45, 46]	0.0004	0.0003
Cosmogenic–Takami [48]	0.01	0.2
Cosmogenic–Ahlers [49]	0.002	0.06
Atm. Prompt [47]	0.02	0.03
Astrophysical E^{-2}	0.2	1
Astrophysical $E^{-2.5}$	0.08	0.3
Astrophysical E^{-3}	0.03	0.06

Cosmogenic neutrinos [63–72] have been invoked as the source of the PeV events, in part because the EHE search was designed to detect them, albeit at much higher en- ergies. Example spectra [48, 49] are shown in Fig. 1.

The $\nu_e + \bar{\nu}_e$ cascade spectra are shown in Fig. 3 and the numbers of events are given in Table I. Two problems are obvious. First, the expected numbers of events are very small because the spectrum normalization is low. Second, the predicted distribution of events emphasizes high, not low, energies.

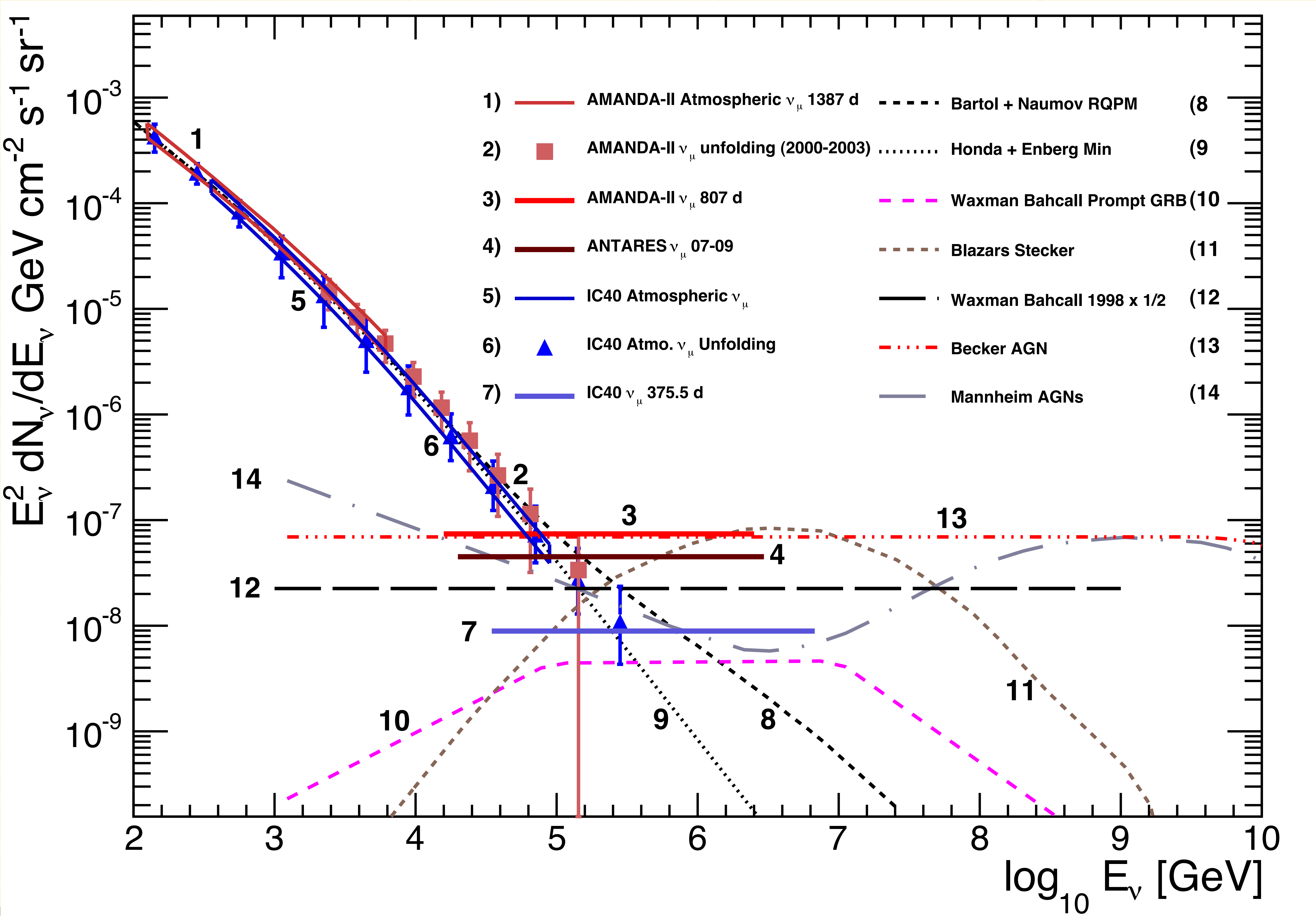
Beacom et al 1306.2309

An important constraint on neutrino fluxes: The Waxman Bahcall bound

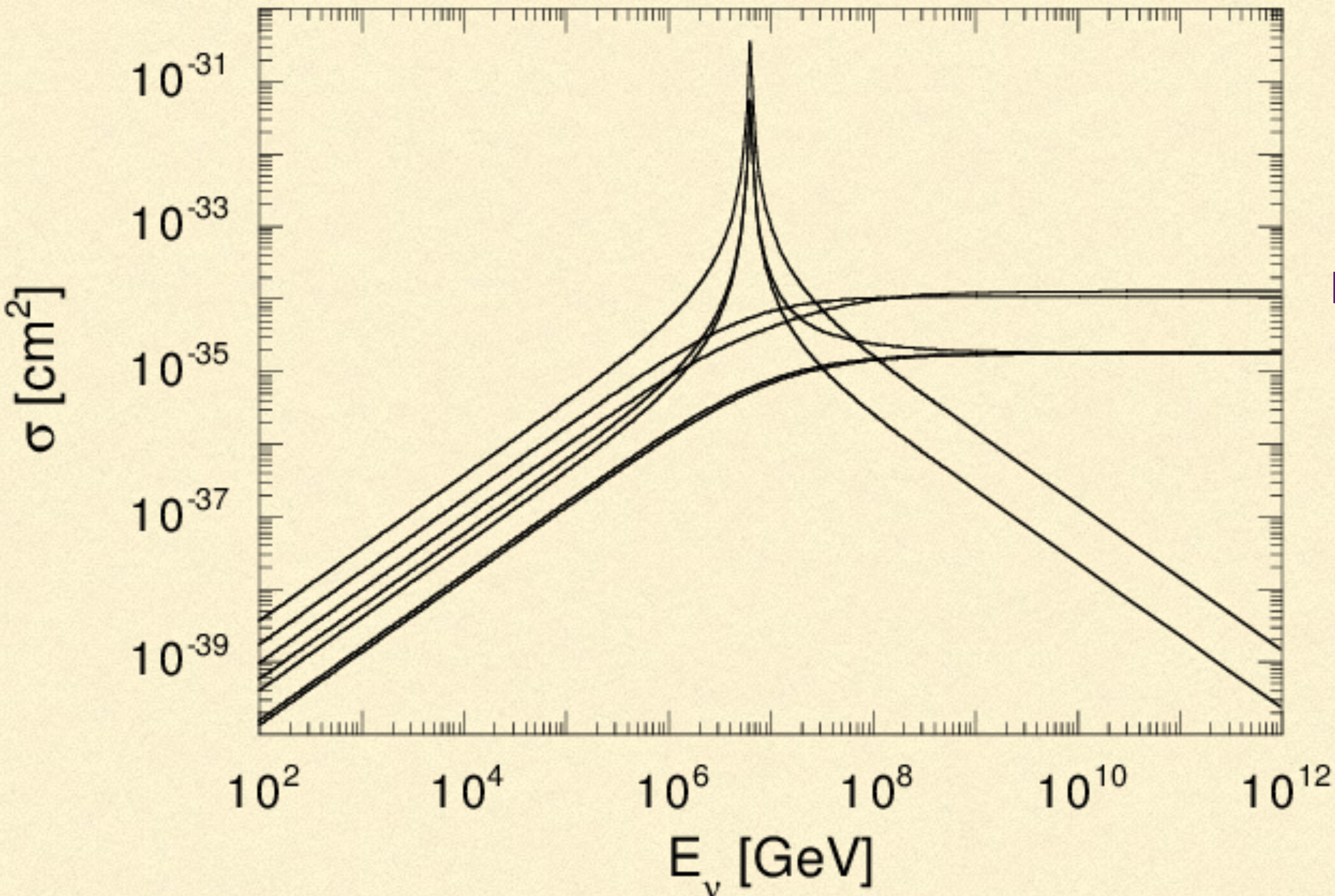
We know that the production of CR via p-p and p-gamma interactions is linked to that of neutrinos. Thus the flux of UHE neutrinos is bounded by the observed CR flux. This leads to the WB upper bound

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

Present IceCube bounds.....



Neutrino Cross-sections at the Glashow Resonance

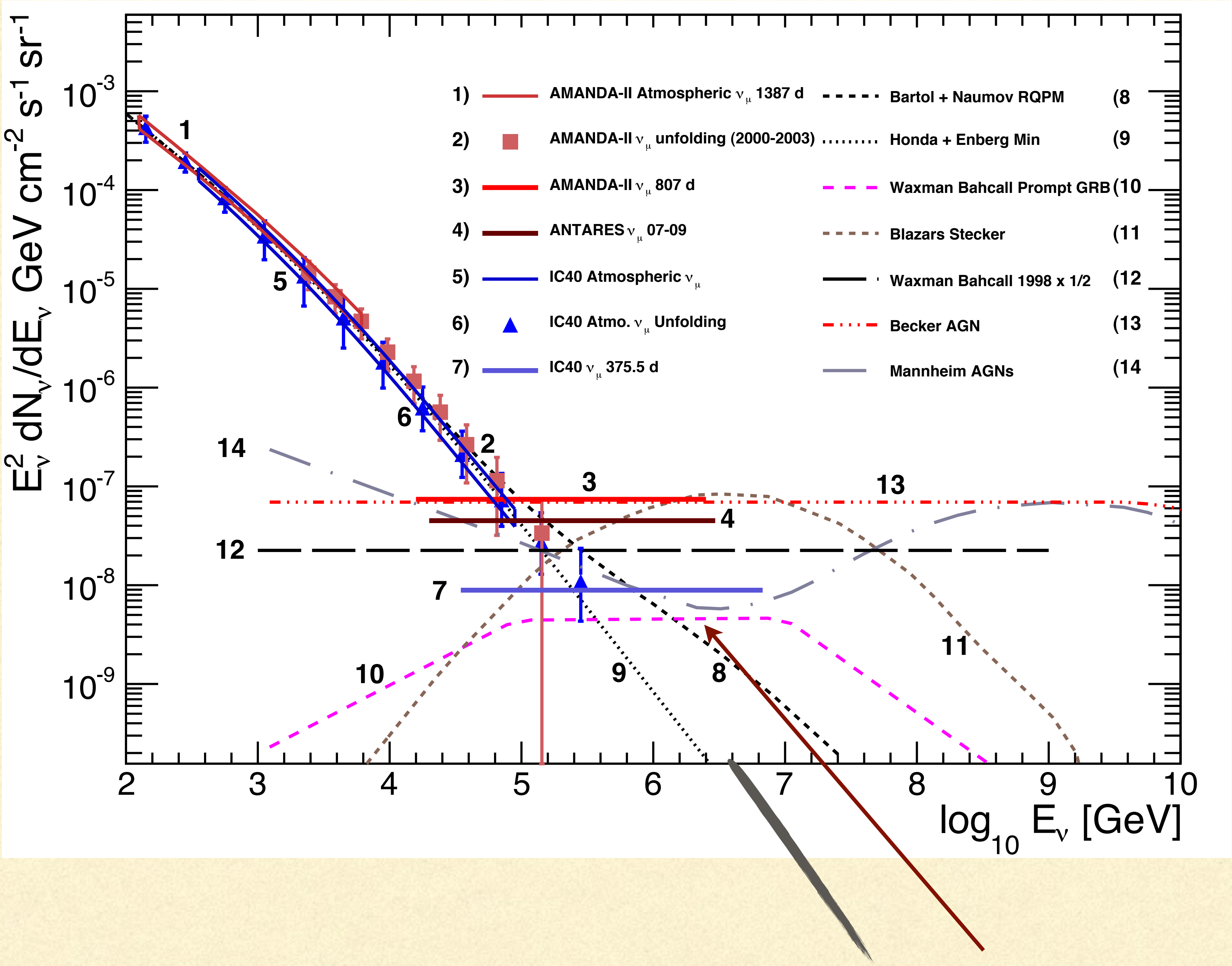


RG, Quigg, Reno and Sarcevic

The cross-sections

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

The Glashow Resonance....why it could be important



Icecube
arXiv:1104.5187

The region where an extra-galactic UHE flux emerges above the atmospheric background but stays below current IC bounds is in the neighbourhood of the GR

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)

Results........

Add conventional shower, resonant shower, pure muon and contained vertex lollipop to compute total signal

x	(Conventionalshower)	GR	Total
0.0	0.21	0.65	0.86
0.5	0.4	2.1	2.5
1.0	0.5	3.6	4.1

20, 12 and 4 events in Icecube in 5 years required to see signal from resonance depending on the relative abundance of p-gamma and p-p sources.

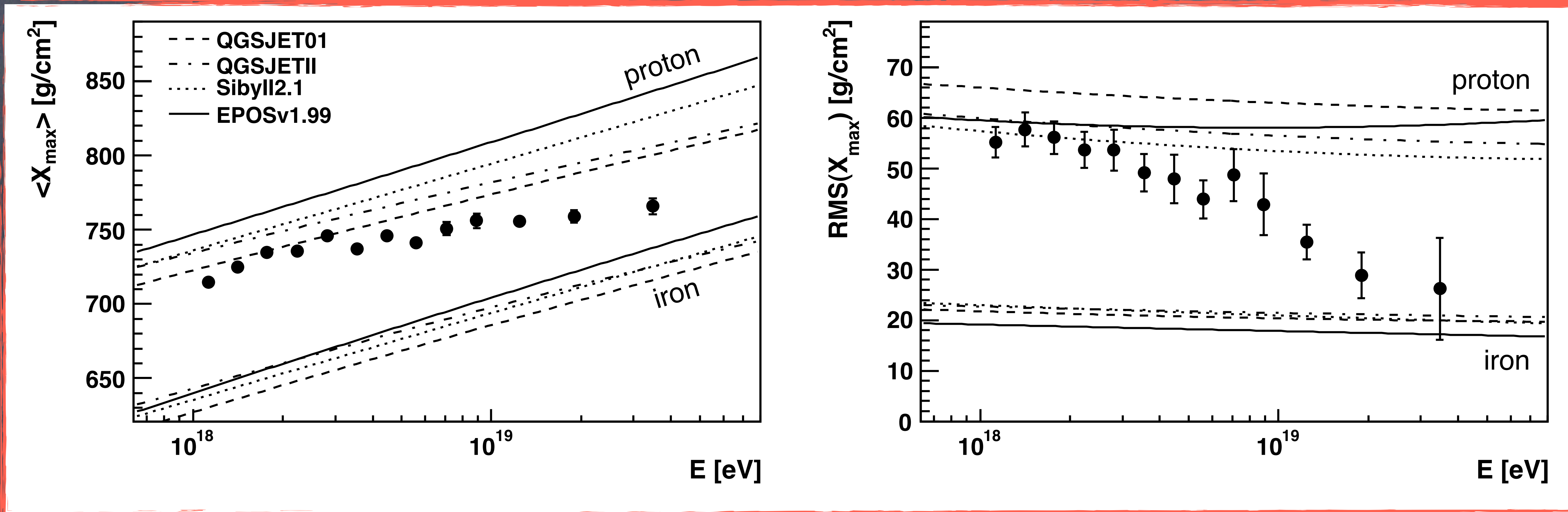
(Bhattacharya, RG, Rodejohann and Watanabe 2011)

Possible reasons for no signals so far........

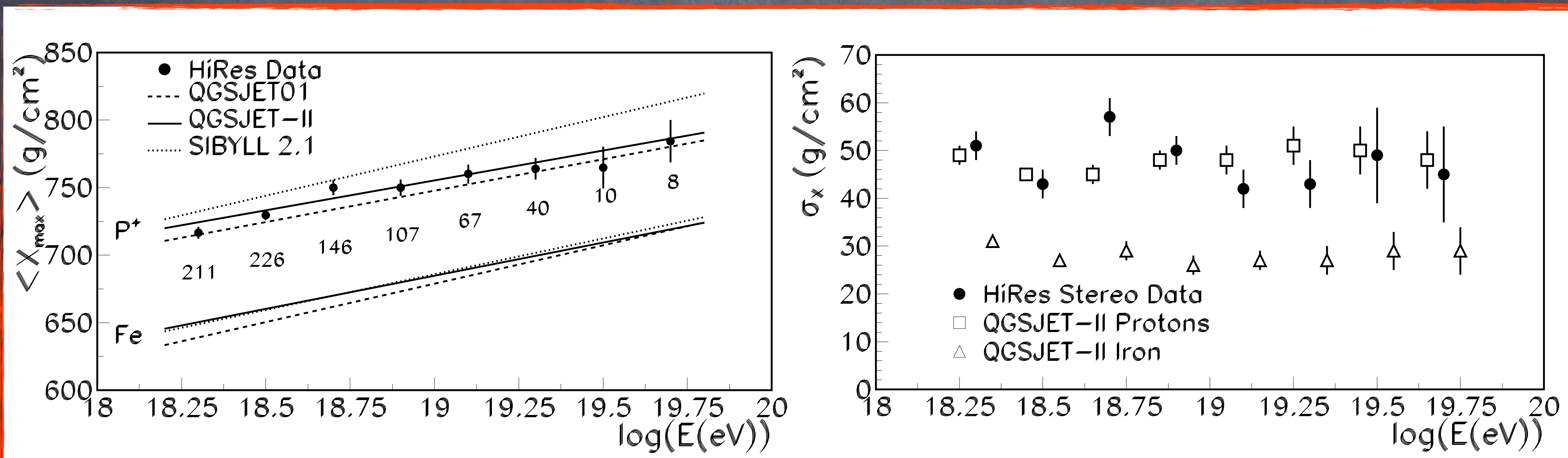
It is quite possible that the nature of astrophysical sources accelerating UHECRs is quite different from what we have envisaged and modeled.

If UHECR are composed of heavy nuclei, this could reduce the UHE neutrino flux. There is incomplete evidence to support this.

$\langle X_{\max} \rangle$ and $\mathrm{RMS}(\langle X_{\max} \rangle)$

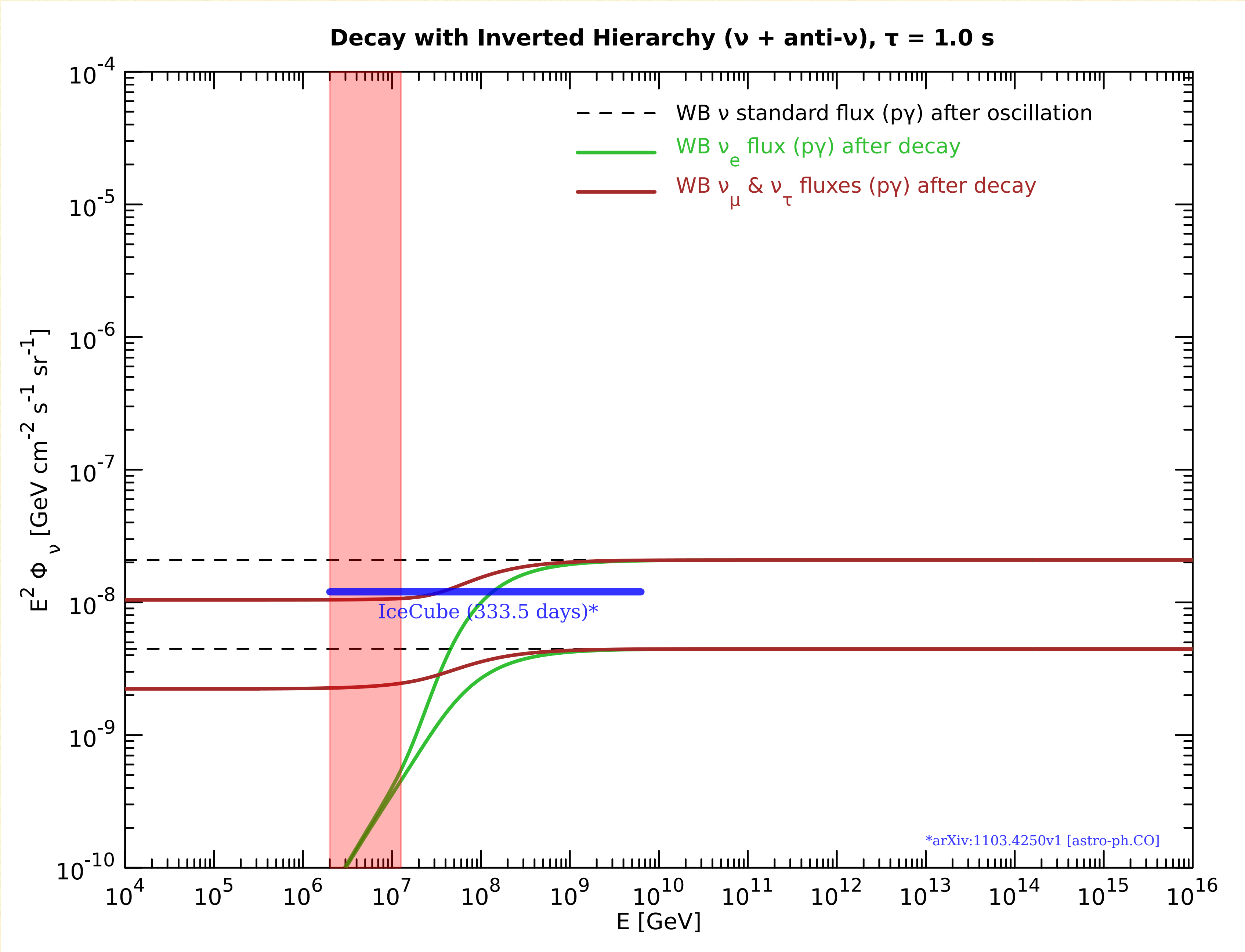


[Pierre Auger Collaboration, Phys. Rev. Lett. 104 (2010) 091101]

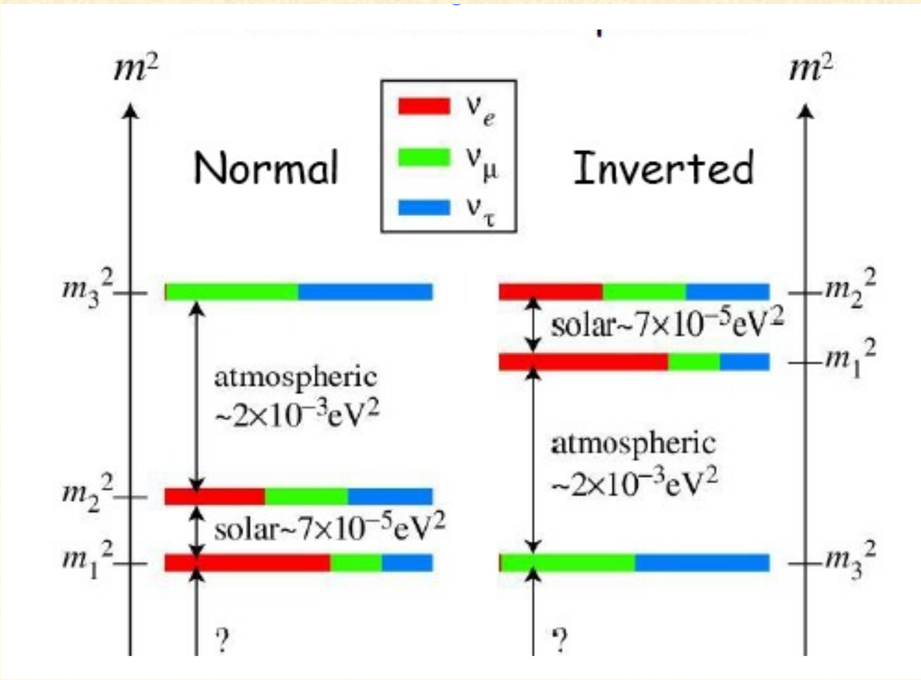


[HiRes Collaboration, Phys. Rev. Lett. 104 (2010) 161101]

Simple Decay Scenario with Inverted Hierarchy, changes in WB bound.......

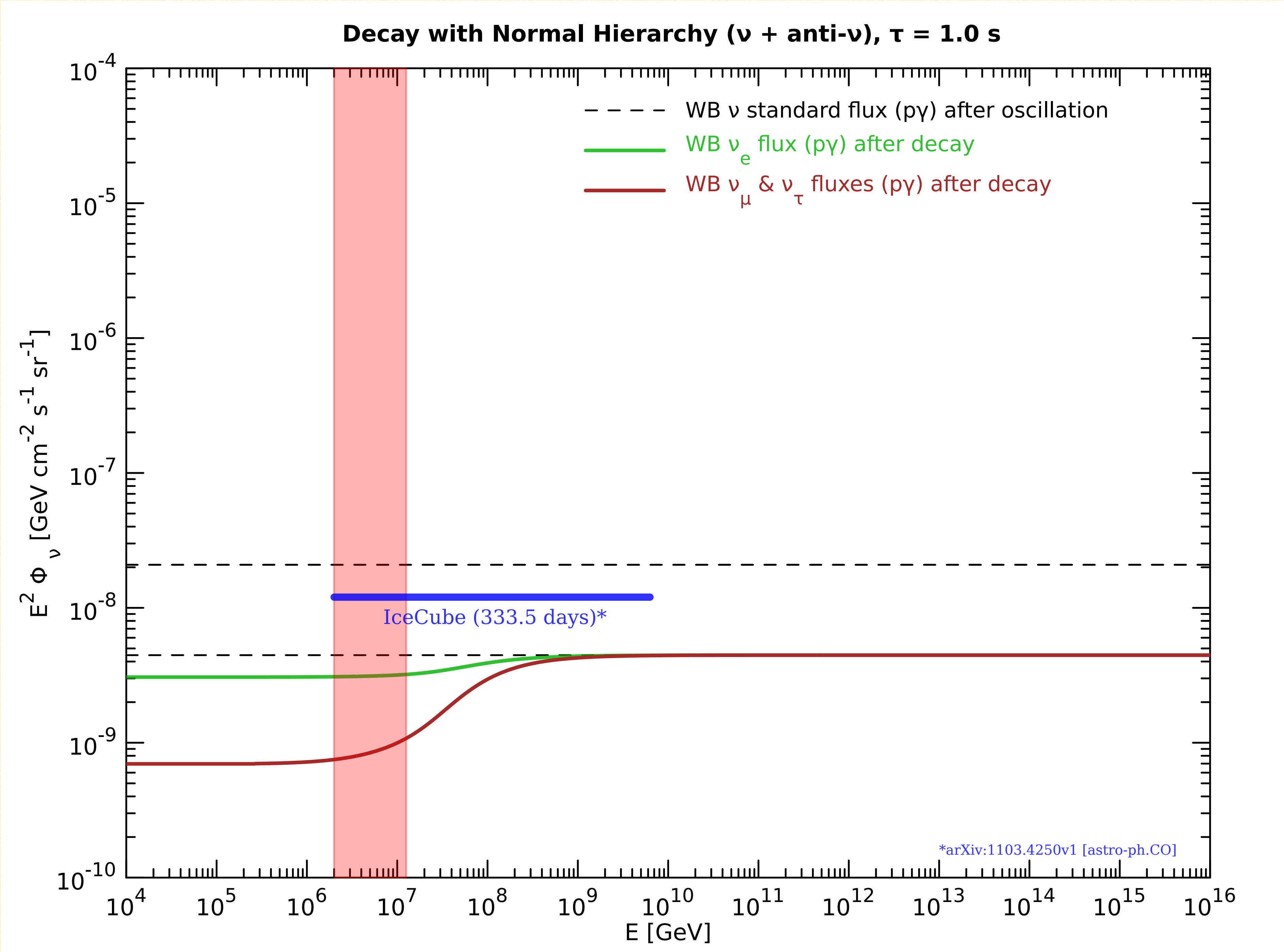


Bhattacharya, RG, Watanabe, 2010



Effects (events, ratios etc) depend on hierarchy

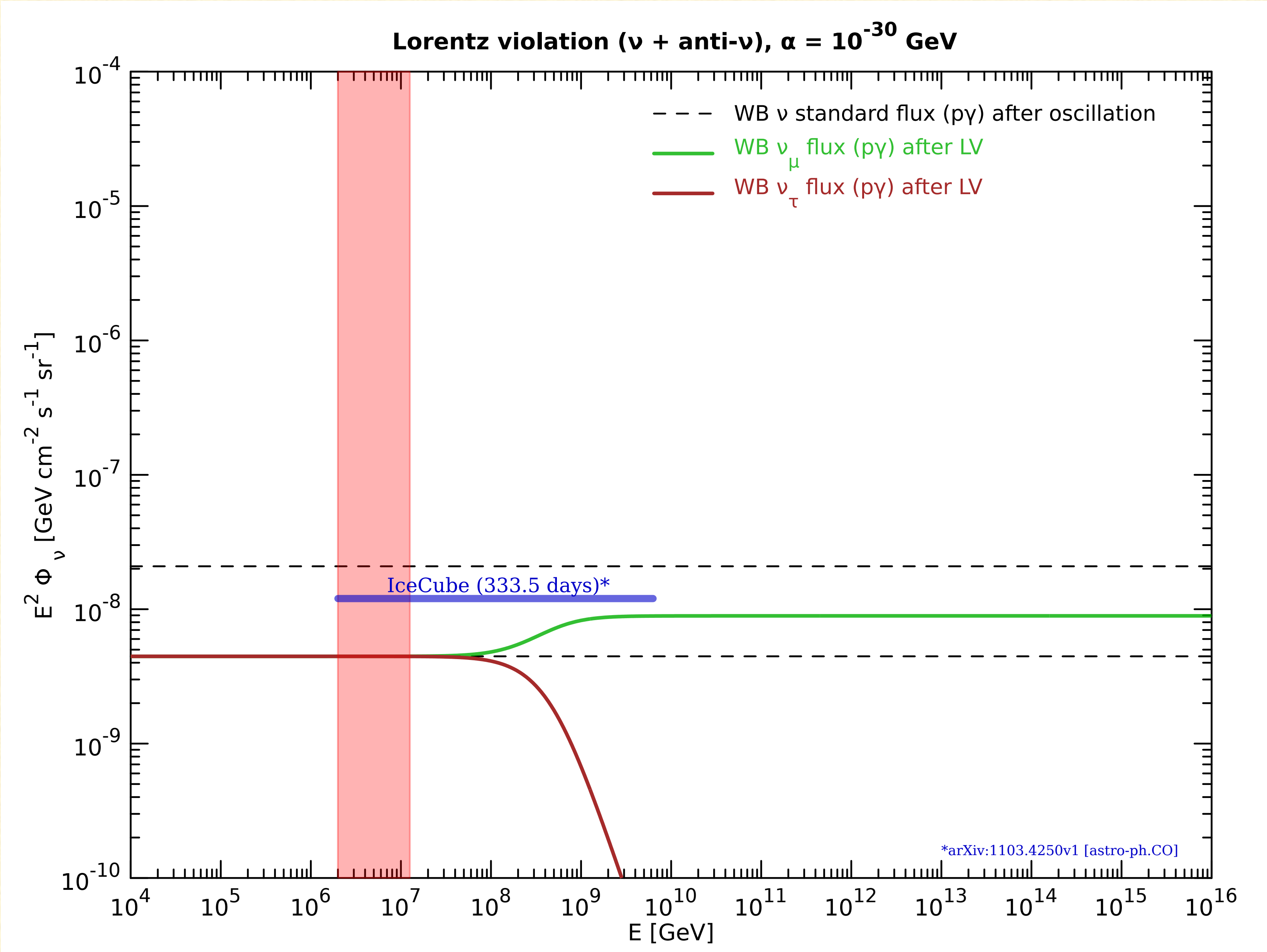
Simple Decay Scenario with Normal Hierarchy, changes in WB bound.......



Bhattacharya, RG, Watanabe, 2010

Depletion of nu_mu and nu_e fluxes with subsequent rise

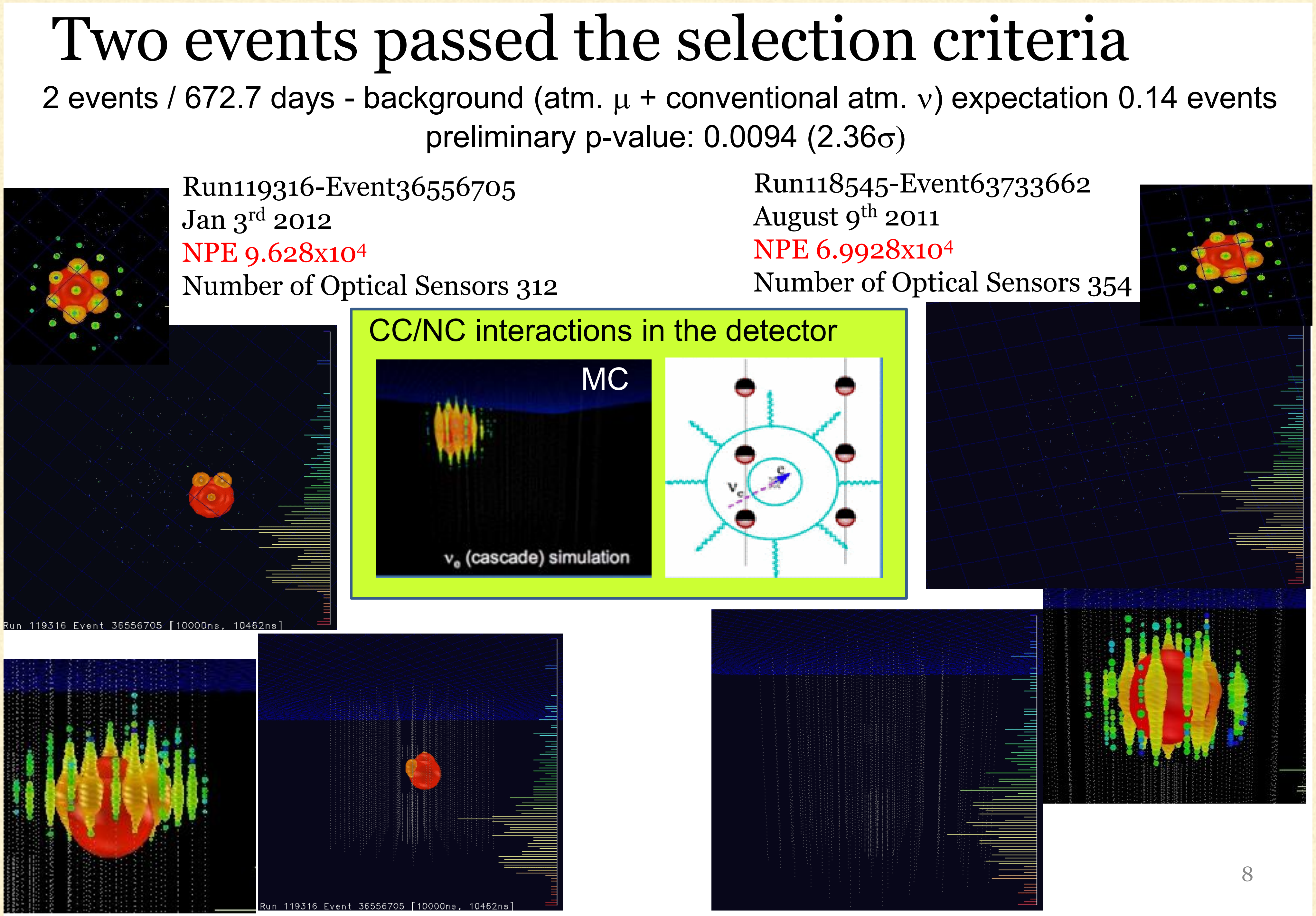
Changes in the WB bound for mu and tau flavours due to Lorentz Violation........



Bhattacharya, RG, Watanabe, 2010

Total disappearance of tau neutrinos above a certain energy.

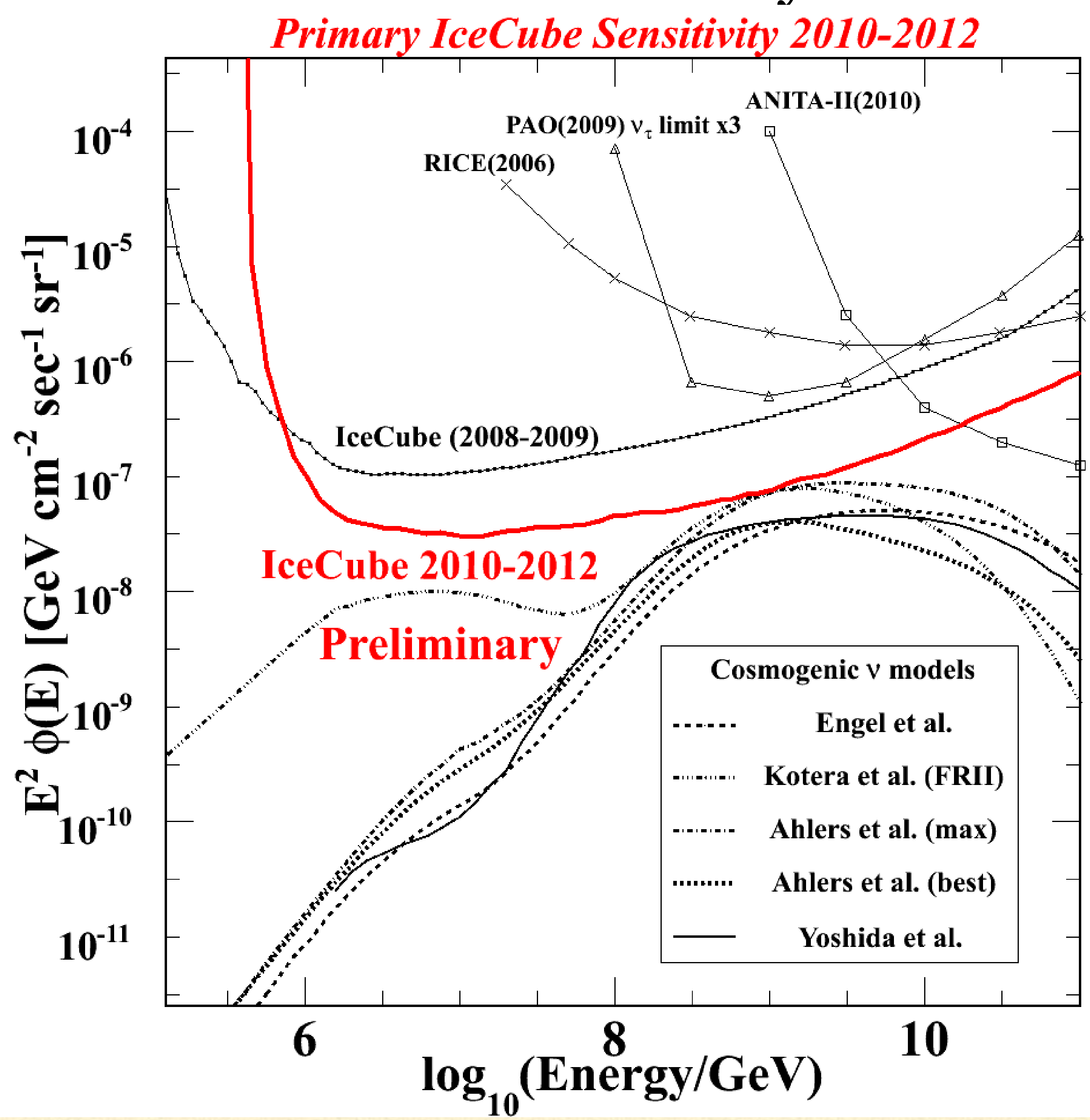
The latest from ICECUBE......an observation of 2 events!



A. Ishihara, Neutrino 2012 Icecube talk

The latest from ICECUBE......more stringent bounds.......

IceCube UHE Sensitivity 2010-2012



- Significantly improved from the previous IceCube results
- The world's best sensitivity!
- Will constrain (or detect) the neutrino fluxes down to mid-strong cosmological evolution models

13

A. Ishihara, Neutrino 2012 Icecube talk

the origin of these two events is at present not clear, and is currently under study

CONCLUSIONS

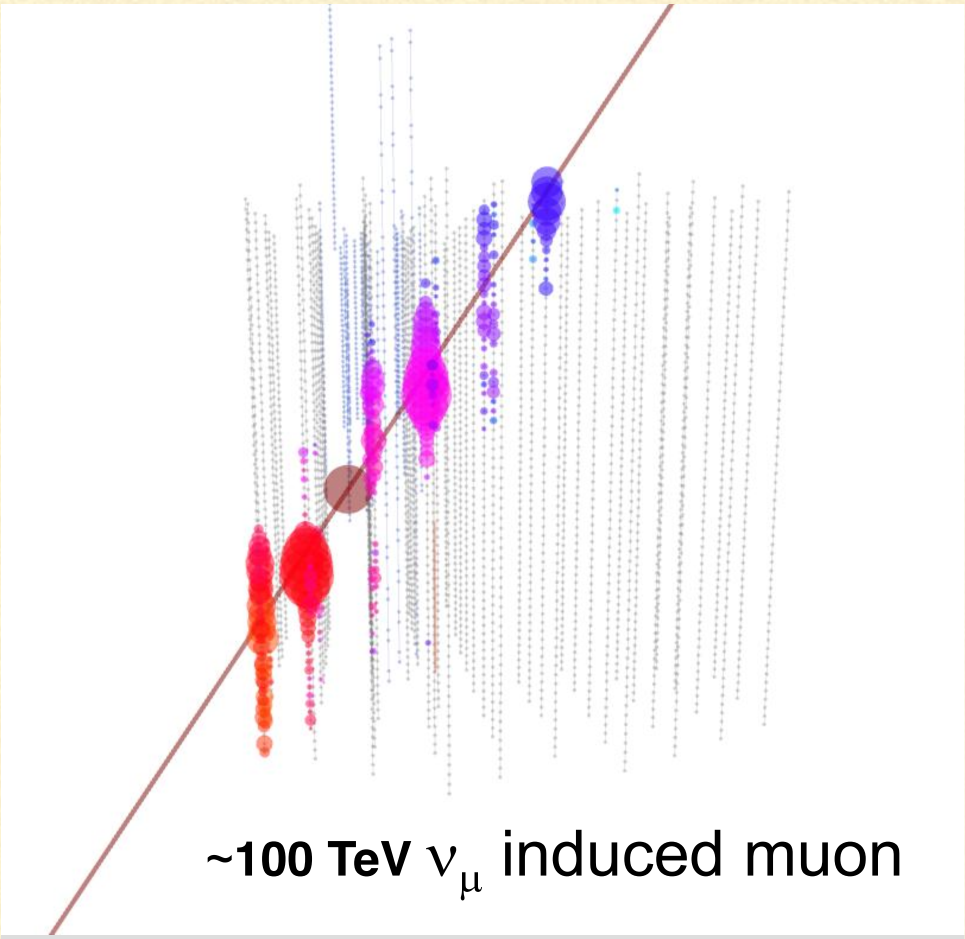
The study and detection of UHE neutrinos opens important frontiers in energy and detection techniques.

The detection of UHEnus would confirm that our basic understanding of Nature's most powerful accelerators is correct.

Similarly, not detecting anything (soon!) may require radical revision of current ideas about UHECR origin and acceleration

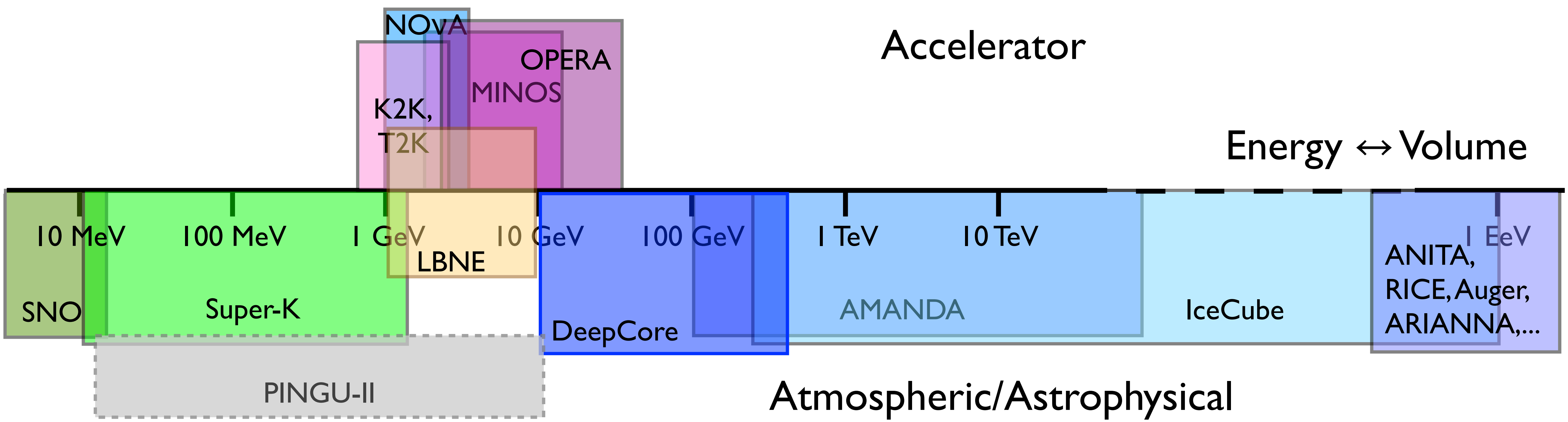
On the other hand, it could also be due to effects during propagation, due to fundamental effects originating in particle physics rather than astrophysics.

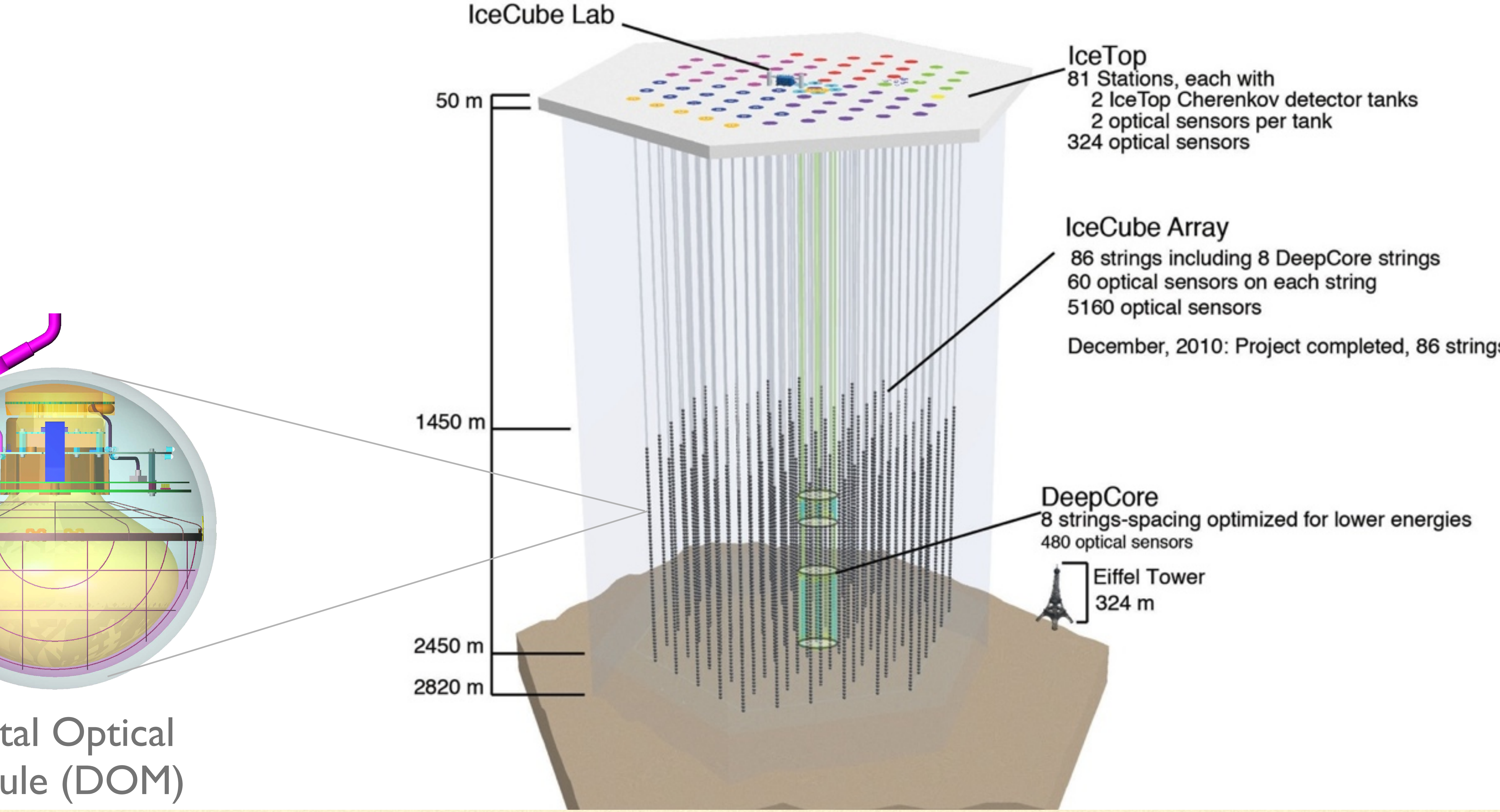
Intriguing new signal announced a few weeks ago has added to the mystery.....


~100 TeV ν_μ induced muon

- Rate = Neutrino flux
  x Absorption in Earth
  x Neutrino cross section
  x Size of detector
  x Range of muon (for ν_μ)
- Range favors ν_μ
  - ~4 to 15 km.w.e. for $E_\nu \sim$ 10 to 1000 TeV

- Pushing below Waxman-Bahcall "limit" in 100 TeV – 10 PeV range disfavors proton dominance in 1 – 100 PeV range


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



tal Optical
ule (DOM)

An important constraint on neutrino fluxes: The Waxman Bahcall bound

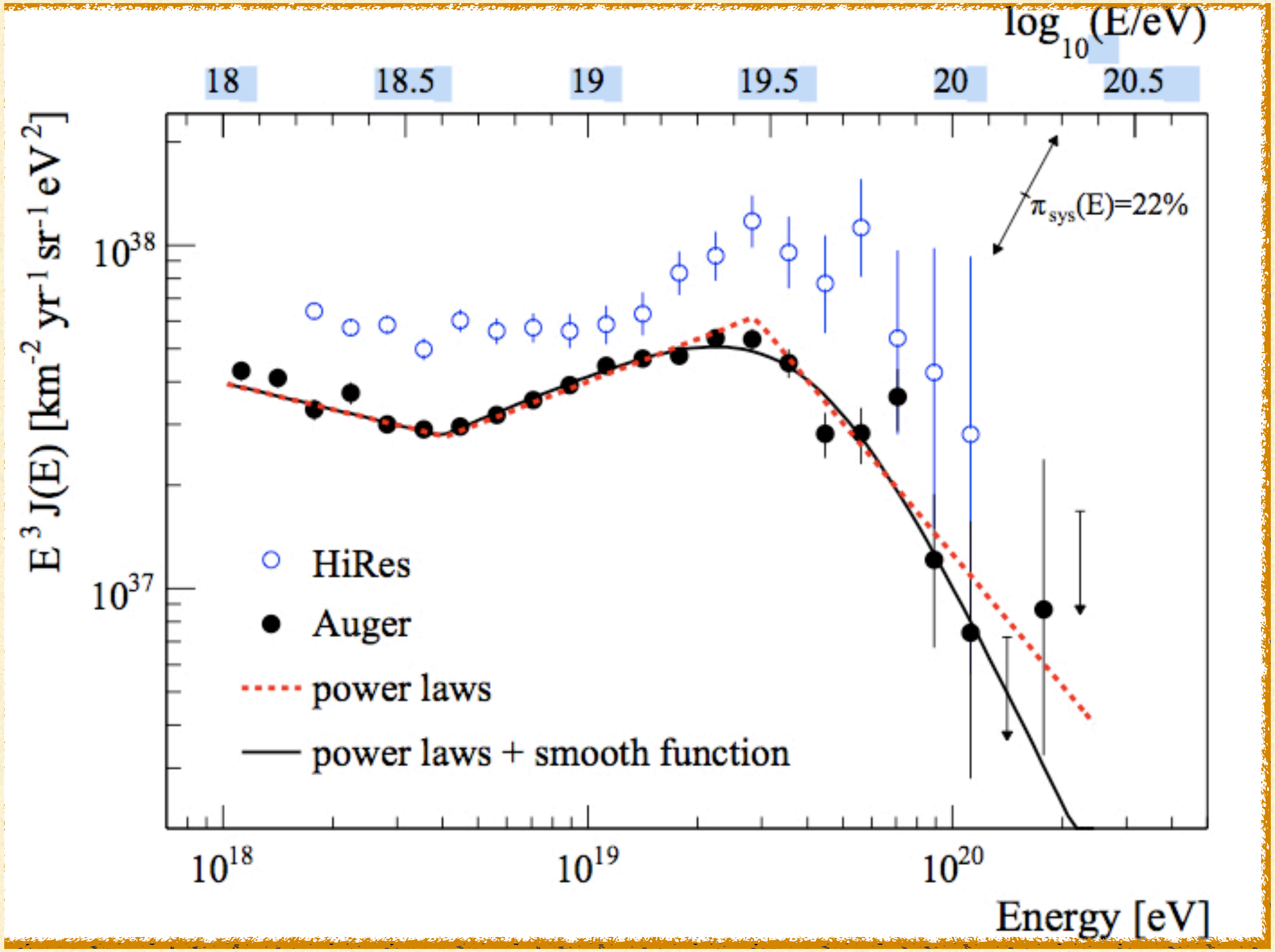
We know from observations that the flux above the ankle is one 3 x 10^19 eV particle per year per km^2 per sr

$$
\begin{aligned}
E\left\{EJ_{\mathrm{CR}}\right\} &= \frac{3\times 10^{10}\,\mathrm{GeV}}{(10^{10}\,\mathrm{cm}^2)(3\times 10^{7}\,\mathrm{s})\,\mathrm{sr}} \\
&= 10^{-7}\,\mathrm{GeV}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}
\end{aligned}
$$

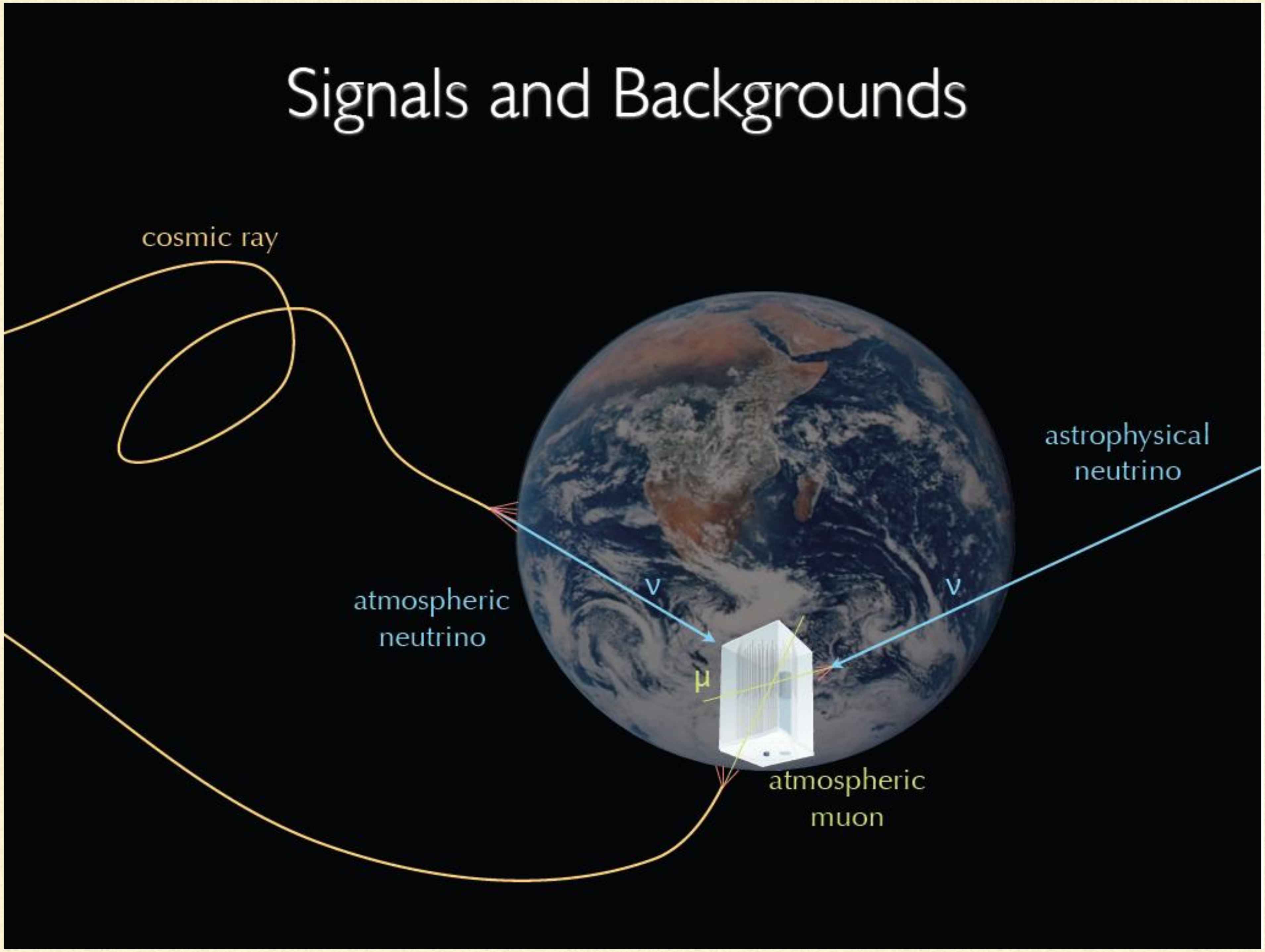
Converting this to energy/volume

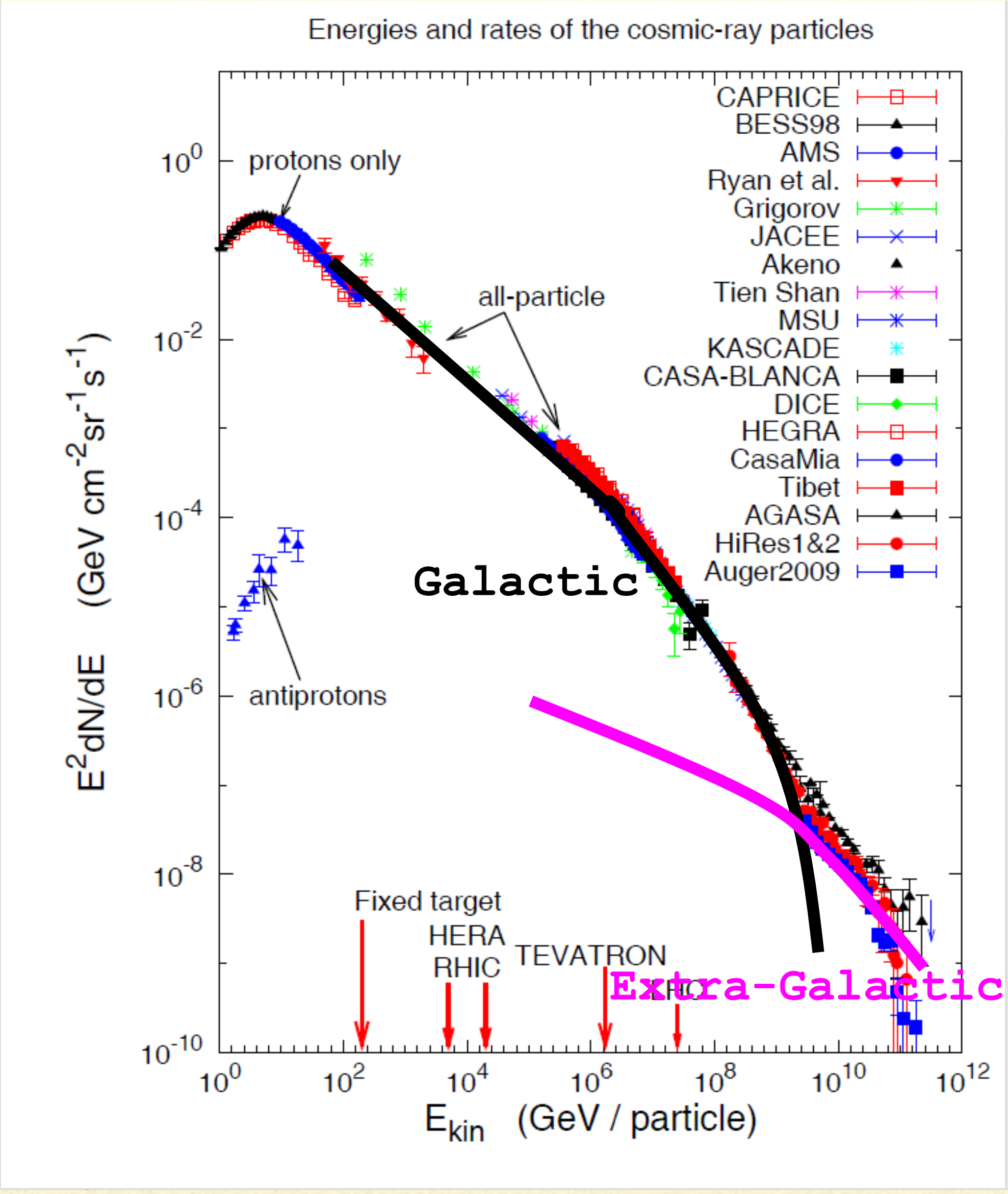
$$
\epsilon_{\mathrm{CR}} = \frac{4\pi}{c}\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \frac{10^{-7}}{E}dE\,\frac{\mathrm{GeV}}{\mathrm{cm}^2\,\mathrm{s}} \simeq 10^{-19}\,\mathrm{TeV}\,\mathrm{cm}^{-3}
$$

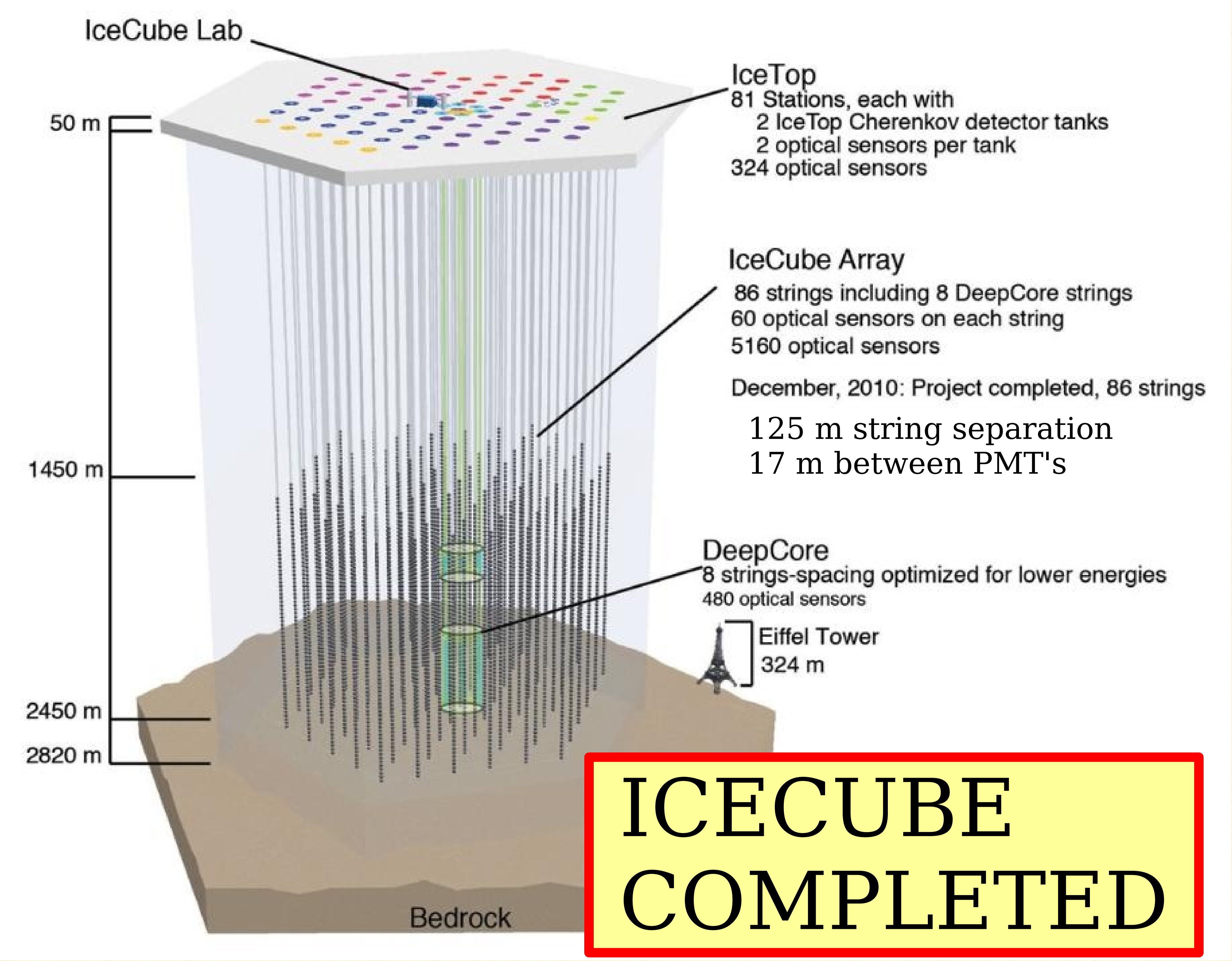
Assume this energy injection occurs over a Hubble time, 10^10 yr, calculate power injection by CR



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
πsys(E)=22%
HiRes
Auger
power laws
power laws + smooth function
10^18
10^19
10^20
Energy [eV]

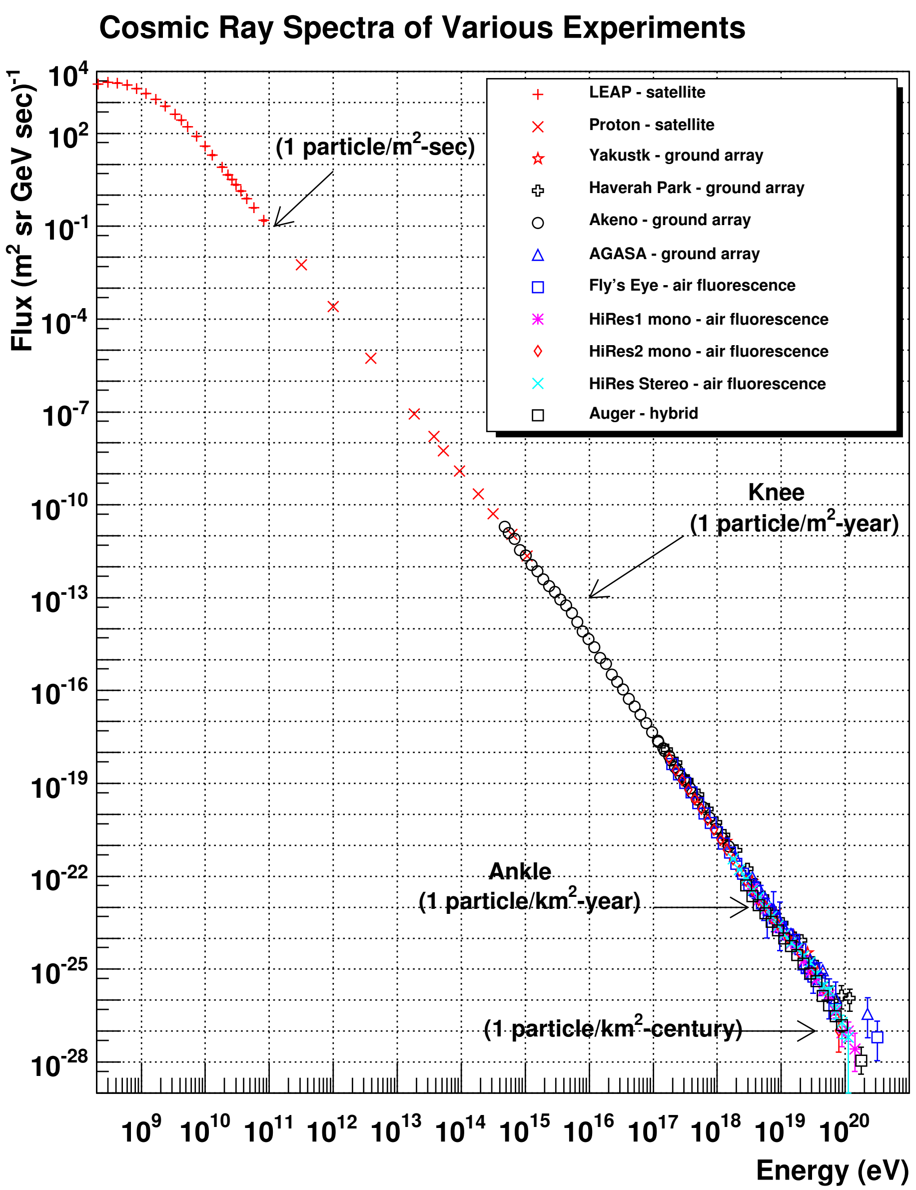

Signals and Backgrounds
cosmic ray
astrophysical neutrino
atmospheric neutrino
ν
ν
μ
atmospheric muon


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)



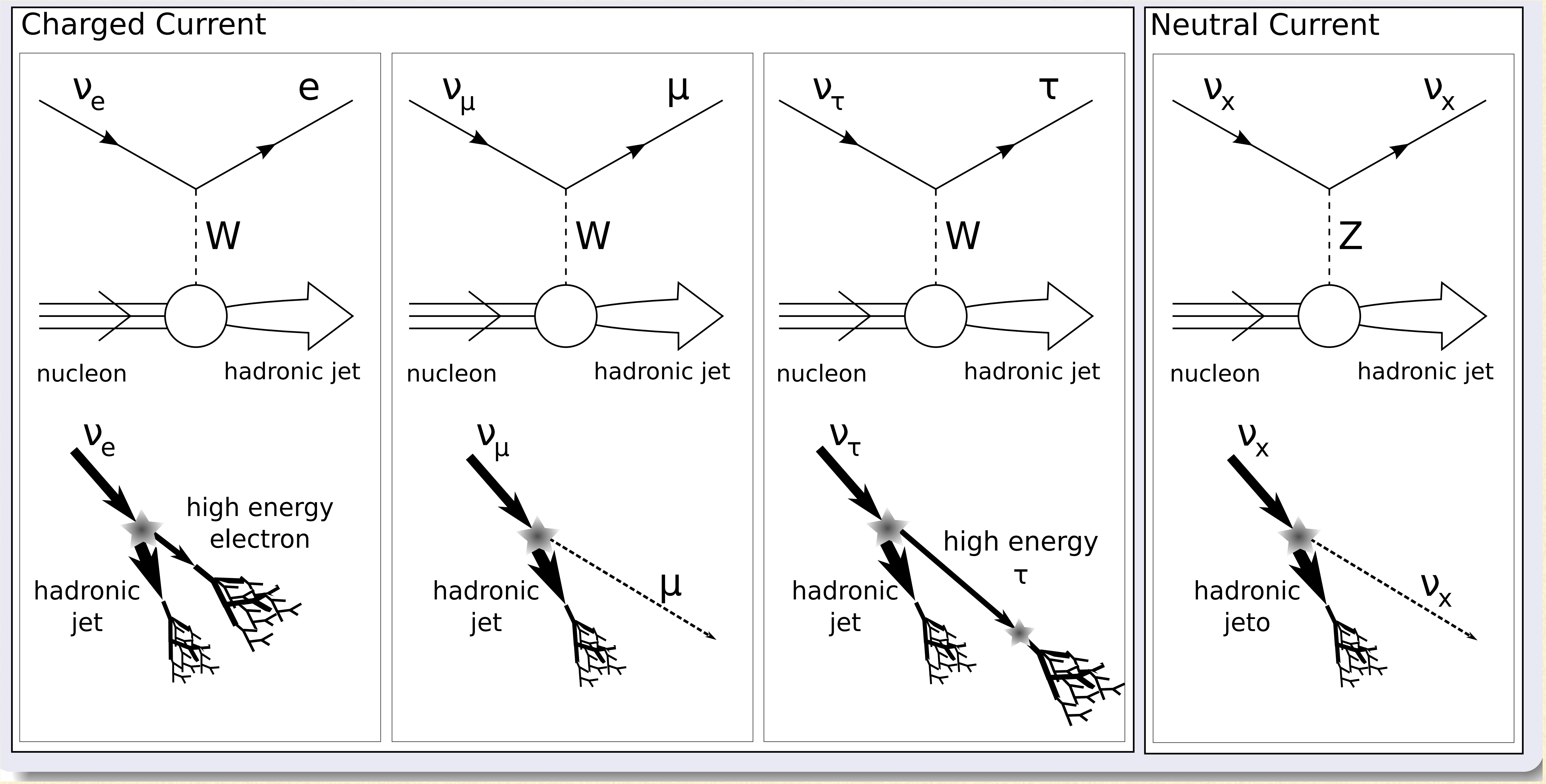
125 m string separation
17 m between PMT's

ICECUBE COMPLETED



CM energy

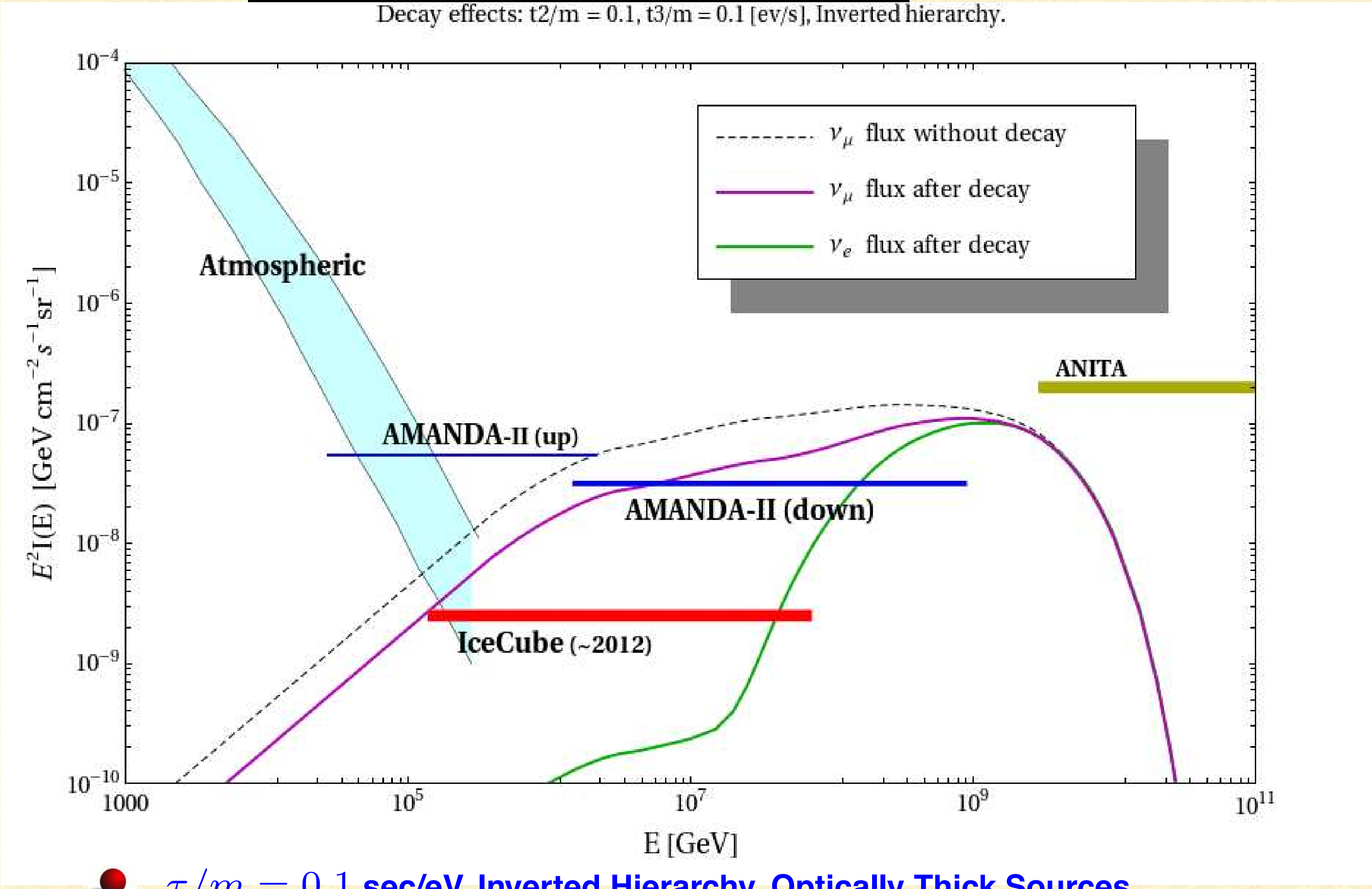
E_{lab}[eV]	E_{CM}[TeV]	Exp
10^{14}	0.8	SPS
10^{15}	2	Tevatr.
10^{16}	7	LHC
10^{17}	14	LHC?


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

In the standard scenario, neutrinos from pion decay have the flavour content $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. With $L_{osc} = \frac{4\pi E_\nu}{\Delta m^2} \sim 2.5 \times 10^{-24} \frac{E}{1eV}$ Mpc, oscillations over cosmological length scales average out and give a flavour content at Earth $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

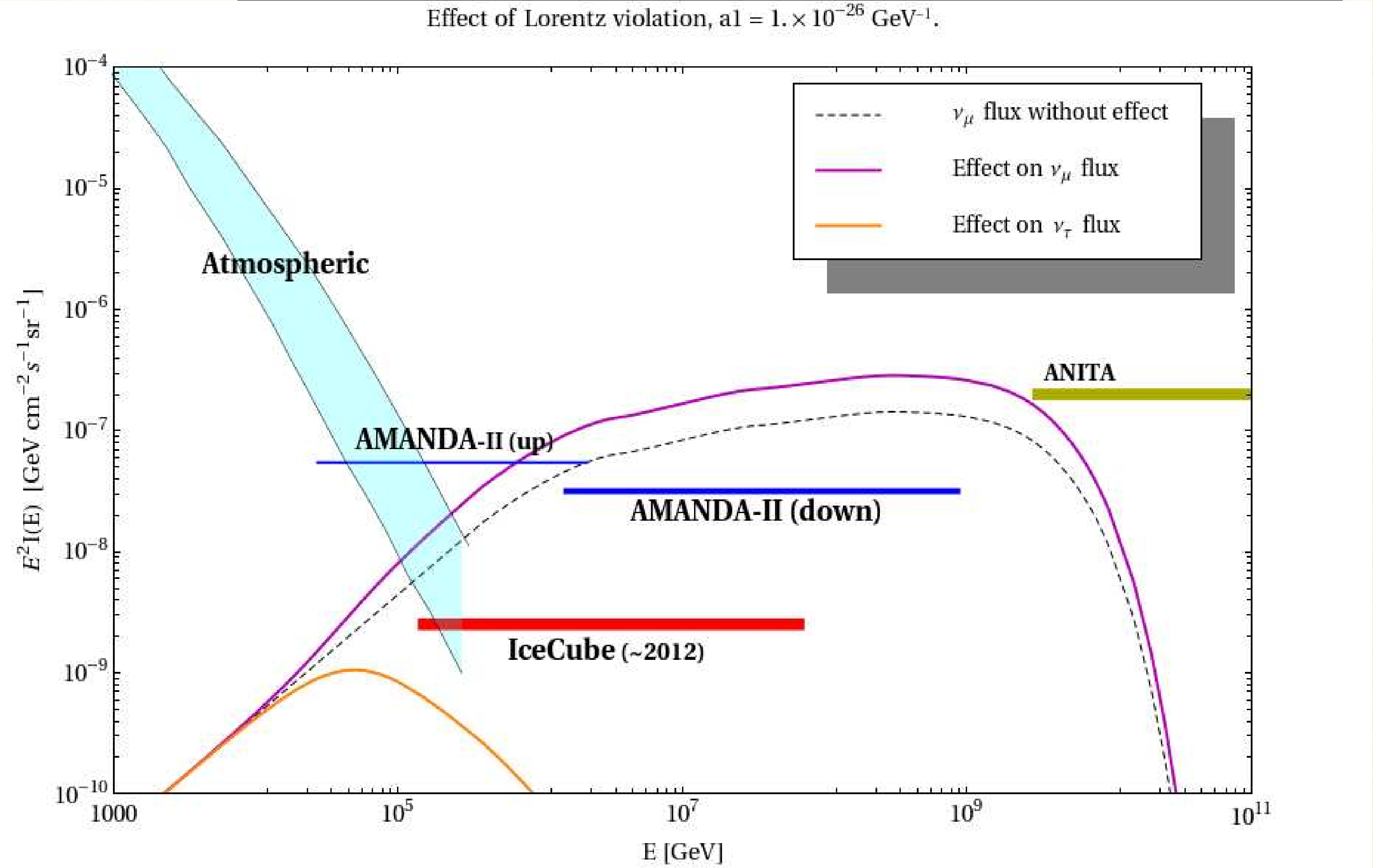
These standard ratios can be altered by physics beyond the Standard Model (Beacom, Bell, Hooper, Pakvasa and Weiler)

Diffuse Fluxes . . . Decay...



- $\tau/m = 0.1$ sec/eV, Inverted Hierarchy, Optically Thick Sources
- Shower Events undetectably below Muon events for energy $< 10^7$ GeV and rising between $10^7 - 10^8$ GeV, become equal thereafter. Spectral shapes distinguishably altered
- Sensitivity in the range $10^3 \geq \tau/m \geq 10^{-3}$ sec/eV

Lorentz Violation induced Flux changes . . ...



- τ **events completely suppressed, Optically Thick Sources**
- **AUGER, ICECUBE would record deficit of double-bang, lolipop and earth-skimming events**

Waxman-Bahcall bound

CR flux above ankle often summarized as
"one 3×10^{10} GeV particle per km square per yr per sr"
translated into energy flux

$$\begin{aligned} E\,\{E J_{\rm CR}\} &= \frac{3 \times 10^{10}\,{\rm GeV}}{(10^{10}\,{\rm cm}^2)(3 \times 10^7\,{\rm s})\,{\rm sr}} \\ &= 10^{-7}\,{\rm GeV\ cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1} \end{aligned}$$

Derive energy density in UHECRs using flux = velocity $\times$ density

$$4\pi \int dE\,\{E J_{\rm CR}\} = c\epsilon_{\rm CR}$$

taking $E_{\rm min} \simeq 10^{10}$ GeV and $E_{\rm max} = 10^{12}$ GeV

$$\epsilon_{\rm CR} = \frac{4\pi}{c} \int_{E_{\rm min}}^{E_{\rm max}} \frac{10^{-7}}{E} dE\, \frac{\rm GeV}{{\rm cm}^2\,{\rm s}} \simeq 10^{-19}\,{\rm TeV\,cm}^{-3}$$

Power required to generate this energy density over Hubble time

$$\mathcal{T} \approx 10^{10}\ {\rm yr}$$

Waxman-Bahcall bound (cont'd)

$$\dot{\epsilon}_{\rm CR}^{[10^{10},10^{12}]} \sim 5 \times 10^{44}\ {\rm TeV\,Mpc^{-3}\,yr^{-1}} \simeq 3 \times 10^{37}\ {\rm erg\,Mpc^{-3}\,s^{-1}}$$

Energy-dependent generation rate of CRs is therefore

$$E^2 \frac{d\dot{n}}{dE} = \frac{\dot{\epsilon}_{\rm CR}^{[10^{10},10^{12}]}}{\ln(10^{12}/10^{10})} \approx 10^{44}\,{\rm erg\,Mpc^{-3}yr^{-1}}$$

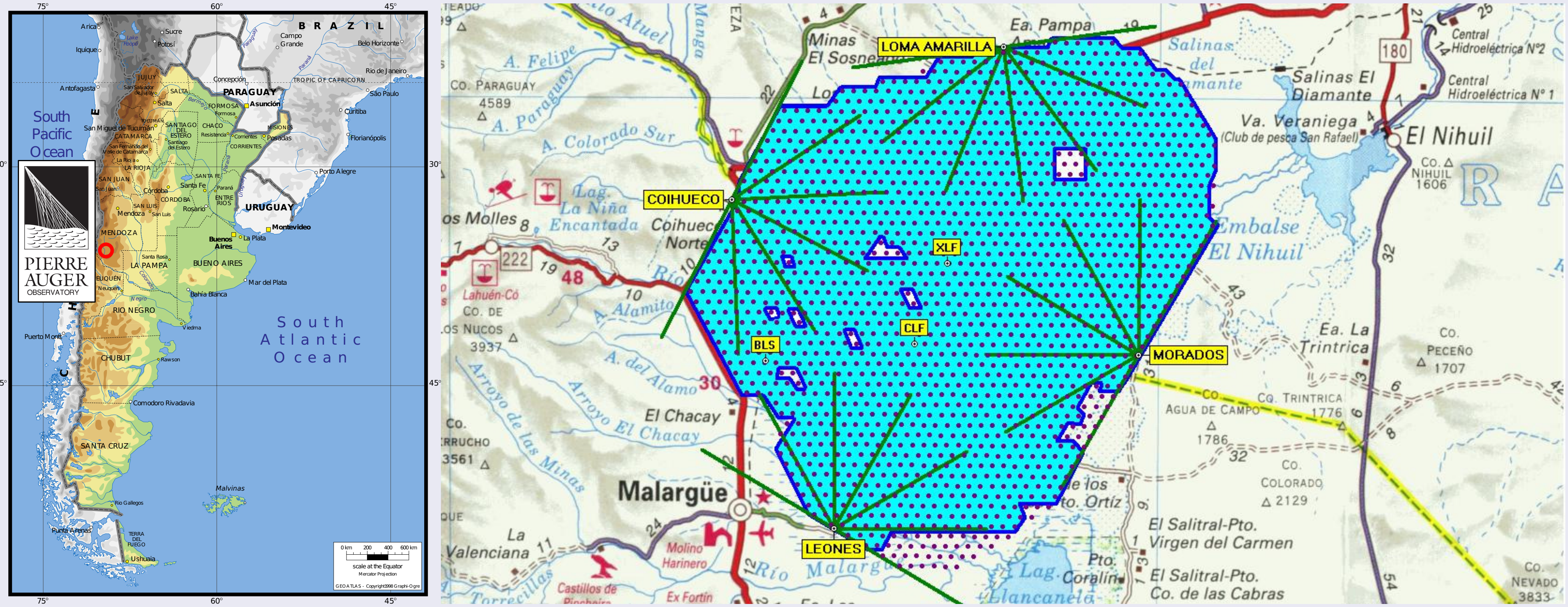
Energy density of neutrinos ☛ $E_\nu^2 \frac{dn_\nu}{dE_\nu} \approx \frac{3}{8}\epsilon_\pi\, \mathcal{T}\, E^2 \frac{d\dot{n}}{dE}$

"Waxman-Bahcall bound" is defined by condition $\epsilon_\pi = 1$

$$E_\nu^2\, \Phi_{\rm WB}^{\nu_{\rm all}} \approx (3/8)\, \xi_z\, \epsilon_\pi\, \mathcal{T}\, \frac{c}{4\pi}\, E^2 \frac{d\dot{n}}{dE} \approx 2.3 \times 10^{-8}\, \epsilon_\pi\, \xi_z\, {\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

$\xi_z \sim 3$ accounts for effects of source evolution with redshift

Pierre Auger Detector



- hybrid detector.
  - Surface Detector (SD): $\sim$1600 stations over 3000 km^2.
  - Fluorescence Detector (FD): 4 eyes, 24 telescopes.
- construction completed in June 2008.

The Glashow Resonance....

The Glashow Resonance (GR) refers to the Standard Model process which results in the resonant formation of an intermediate W^- in $\bar{\nu}_e e$ at E_nu = 6.3 PeV.

Glashow '60, Berezinsky and Gazizov, '77

- The final states could be to leptons or hadrons, giving both showers and muon or tau lepton tracks in UHE detectors.

- While usually dwarfed by the neutrino-nucleon cross-section, the anti-neutrino-electron cross-section at the GR is higher than the neutrino-nucleon cross-section at all energies upto 10^21 eV.

Due to these reasons, it could be useful to look carefully at this small but important region.

Additionally, it could be useful to identify events with unique signatures and low backgrounds in its neighbourhood.

Could it be used as a tool to see X-galactic diffuse neutrino signals?

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

Detecting the GR...........

- Earlier studies have focussed on its detection via shower events and on how the GR can be used as a discriminator of the relative abundance of pp vs p-gamma sources

Learned and Pakvasa '95, Anchordoqui, Goldberg, Halzen and Weiler '05, Bhattacharjee and Gupta '05, Maltoni and Winter '08, Hummer, Maltoni, Winter and Yaguna '10, Xing and Zhou '11

We study here its potential as a discovery channel for UHE neutrinos, using both showers and lepton tracks

The Generalized UHE Neutrino Flux...........

Parametrize the flux at source as

$$\Phi_{\rm source} = x\Phi^{pp}_{\rm source} + (1-x)\Phi^{p\gamma}_{\rm source}.$$

- Standard oscillations with tribimaximal mixing give

$$\Phi^{pp}_{\rm earth} \propto \underbrace{\begin{pmatrix}1\\1\\1\end{pmatrix}}_{\nu} + \underbrace{\begin{pmatrix}1\\1\\1\end{pmatrix}}_{\bar\nu},$$

$$\Phi^{p\gamma}_{\rm earth} \propto \underbrace{\begin{pmatrix}0.78\\0.61\\0.61\end{pmatrix}}_{\nu} + \underbrace{\begin{pmatrix}0.22\\0.39\\0.39\end{pmatrix}}_{\bar\nu}.$$

Using the IC Apr 2011 bound as a benchmark flux, we have, for the sum of all species,

$$E_\nu^2 \Phi_{\nu+\bar\nu} \;=\; 2\times 10^{-8} \epsilon_\pi \xi_z \quad (\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}),$$

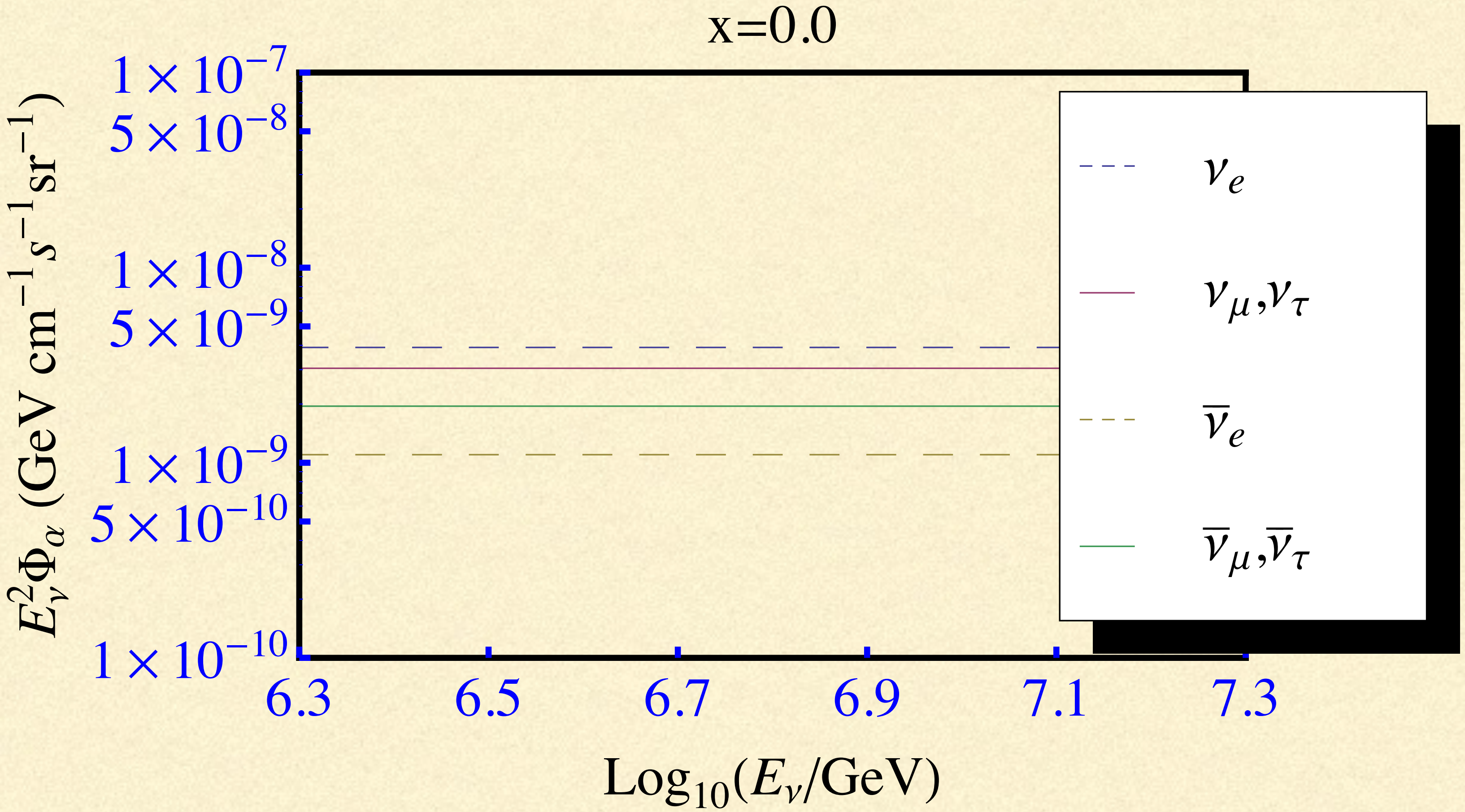
with

$$\Phi_{\nu_e} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.78}{3}\cdot 0.25\right]\frac{1}{E_\nu^2},$$

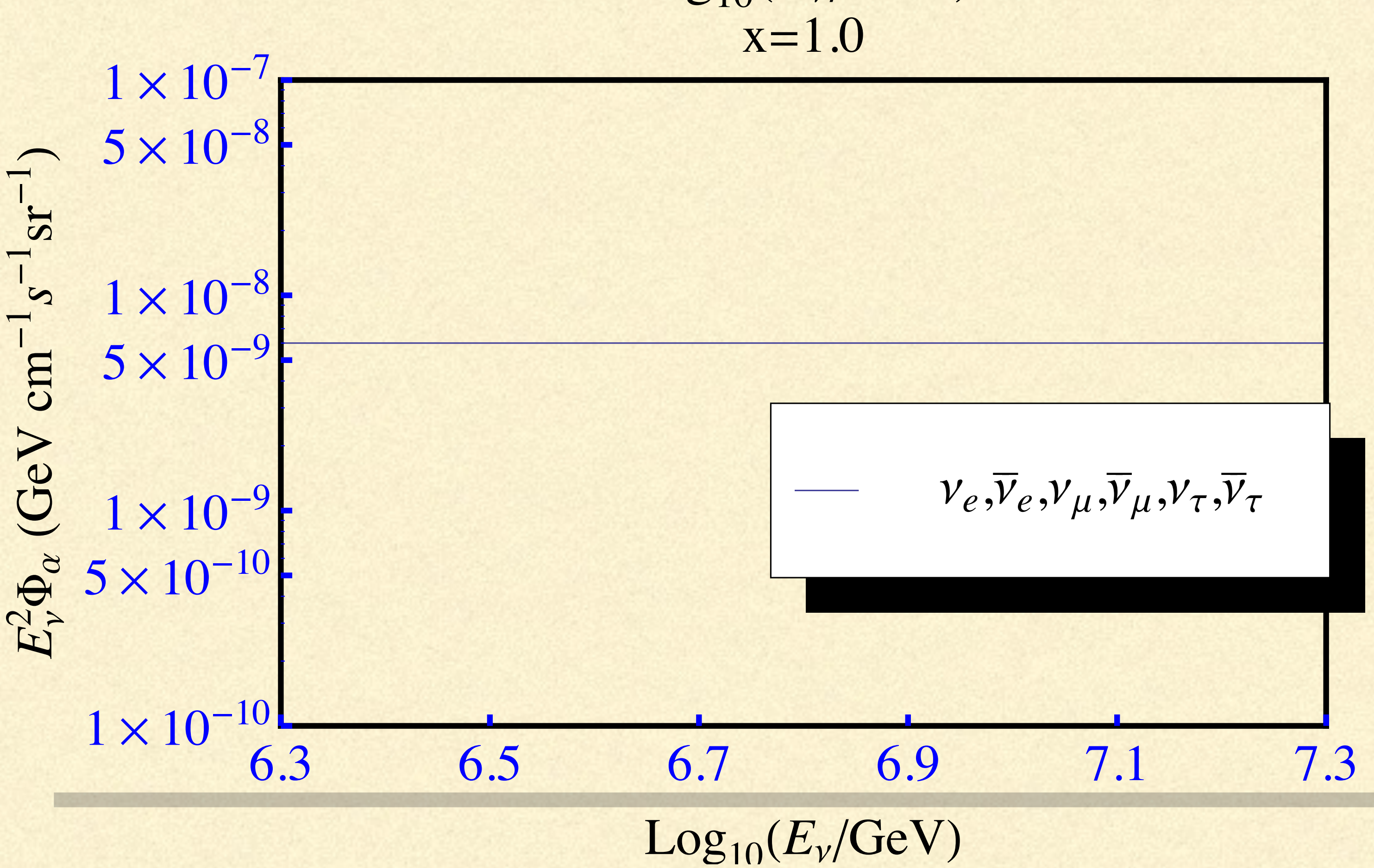
$$\Phi_{\nu_\mu} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.61}{3}\cdot 0.25\right]\frac{1}{E_\nu^2} = \Phi_{\nu_\tau},$$

$$\Phi_{\bar\nu_e} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.22}{3}\cdot 0.25\right]\frac{1}{E_\nu^2},$$

$$\Phi_{\bar\nu_\mu} = 6\times 10^{-8}\left[x\,\frac{1}{6}\cdot 0.6 + (1-x)\,\frac{0.39}{3}\cdot 0.25\right]\frac{1}{E_\nu^2} = \Phi_{\bar\nu_\tau}.$$



Fluxes hierarchical for p-gamma, democratic for pp sources



Mu and tau fluxes always equal for both neutrinos and anti-neutrinos irrespective of x for tribimaximal mixing

Shower events in the neighbourhood of the GR...

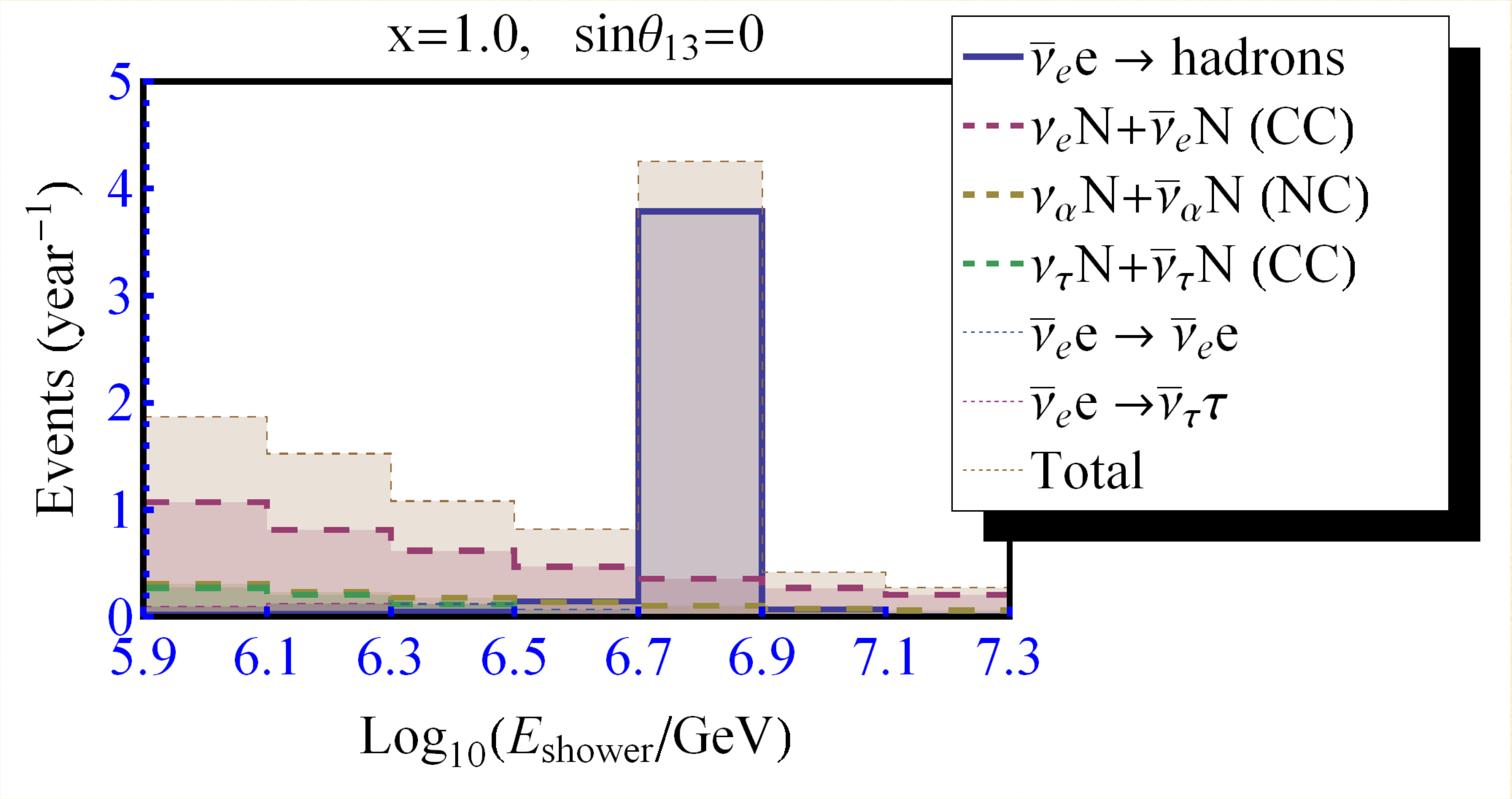
Resonant Events....

- $\bar{\nu}_e e \to \text{hadrons}$
- $\bar{\nu}_e e \to \bar{\nu}_e e$
- $\bar{\nu}_e e \to \bar{\nu}_\tau \tau$

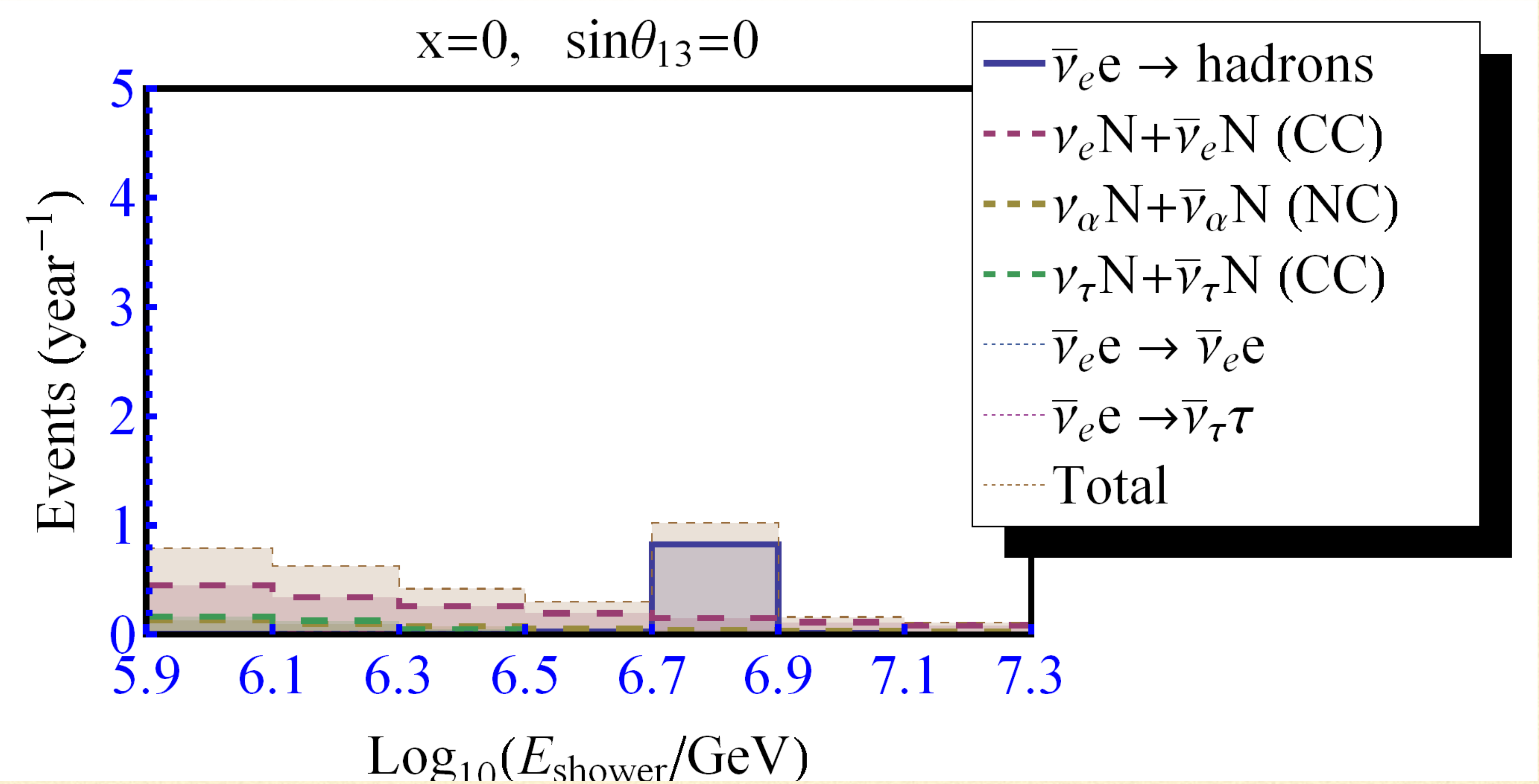
Non-Resonant Events....

- $\nu_e N + \bar{\nu}_e N \ (\text{CC})$
- $\nu_\tau N + \bar{\nu}_\tau N \ (\text{CC})$
- $\nu_\alpha N + \bar{\nu}_\alpha N \ (\text{NC})$

Shower and GR events for pp sources.....



Shower and GR events for p-gamma sources.....



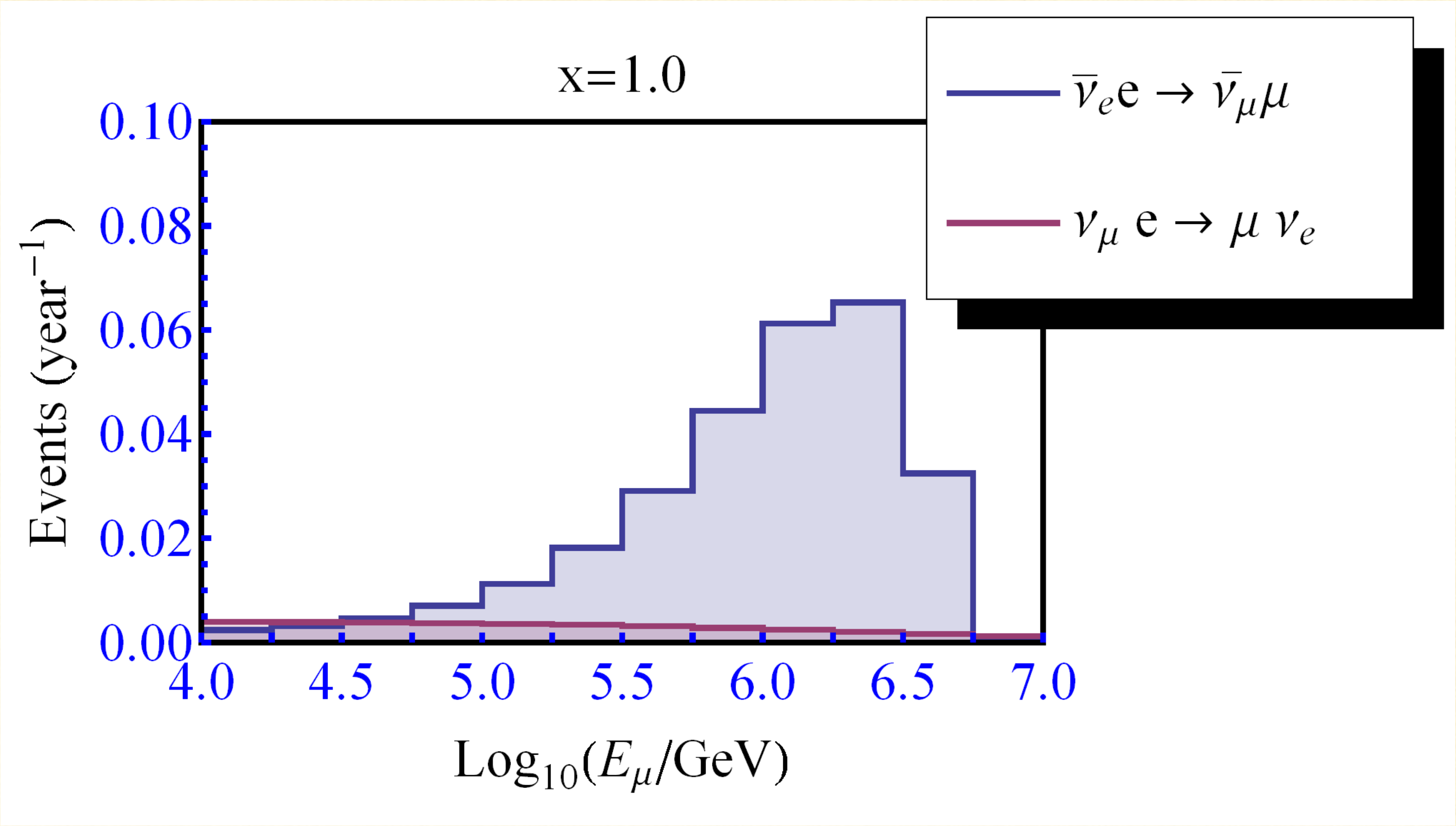
Pure Lepton Tracks at the GR.............

In addition to showers, the following processes are resonant and also have distinctive signatures

- $\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu$ pure muon track with contained vertex and nothing else
- $\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau$ lollipop with contained vertex

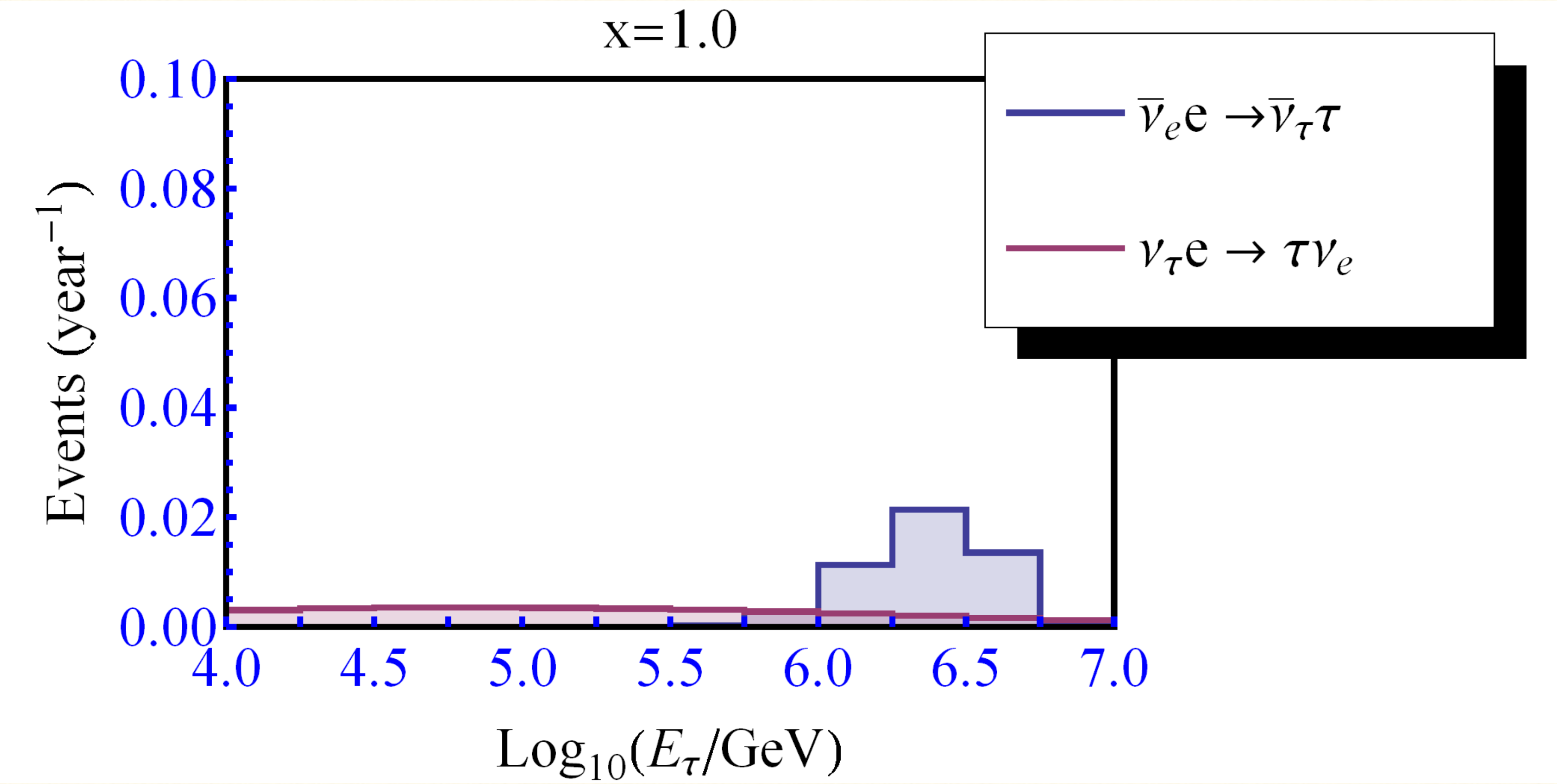
Add them to signal calculation for GR

Pure muons at the GR..............



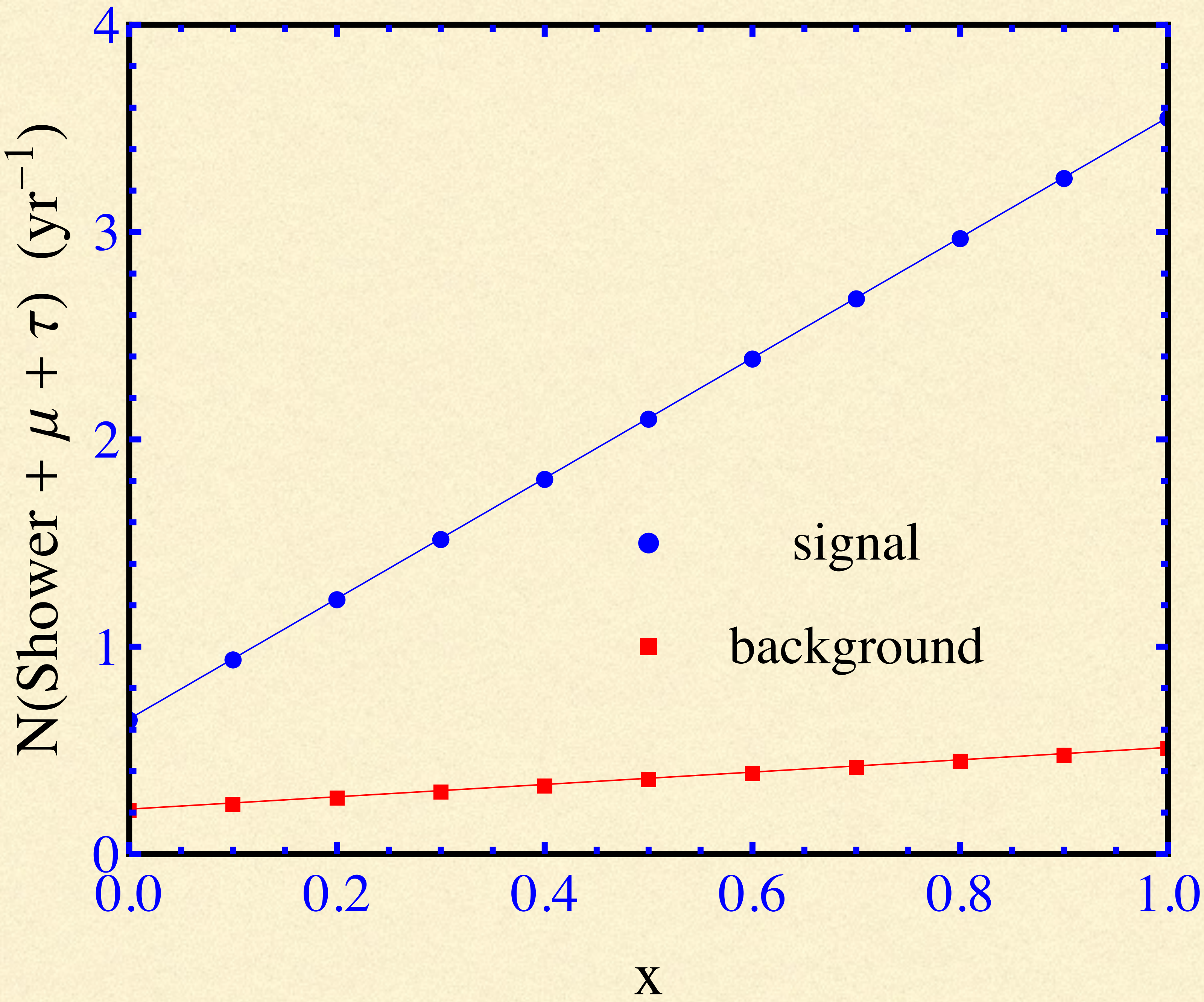
Pileup of muons in bins below GR energy , dictated by rapidity distribution...........

Contained Lollipops at the GR............



Once tau decay is put in, number of events is small, but have a distinctive topology and negligible background.

Signal (GR) to Background (non-resonant) comparison...........



S/B rises from 3 at x=0 to 7 at x=1

The GR and Physics beyond the SM

Due to its sensitivity to electron-antineutrinos, can the GR can provide a testing ground for some scenarios of BSM physics

Consider neutrino decay with normal hierarchy, where nu_3 and nu_2 are unstable and decay to nu_1

Then, a neutrino produced say, via a $W^\mu \overline{\nu}_i \gamma_\mu l_\beta$ vertex has a spectral flux

$$F_{\nu_i}^{\beta} = |U_{\beta i}|^2 A E^{-2},$$

Detection occurs via production of a charged lepton of flavour alpha, leading to

$$F^{\beta}_{\nu_\alpha} = |U_{\alpha 1}|^2 |U_{\beta 1}|^2 A E^{-2}$$

In the decay scenario under consideration, the full flavour spectrum for a given species is

$$F_{\nu_\alpha} = \sum_\beta \phi_\beta \, |U_{\alpha 1}|^2 |U_{\beta 1}|^2 A E^{-2}.$$

where

$\phi_\beta = (1, 2, 0)$ for pp sources, for instance

Thus $F_{\nu_e}/F_{\nu_\mu} = |U_{e1}|^2/|U_{\mu 1}|^2 \simeq 4.$

Beacom, Bell, Hooper, Pakvasa & Weiler

which is significantly different from the expected value of 1 independent of ϕ_β

For the generalized flux for decay,one may write

Here ν_2 and ν_3 are unstable; $\nu_{3,2} \to \nu_1 X$ and $m_1 \ll m_2, m_3$,

$$
\begin{aligned}
E^2 F_{\nu_e}(\text{earth}) &= 6\times 10^{-8}|U_{e1}|^2\left[x\,C^{\nu_e}_{pp}\frac{0.6}{6} + (1-x)C^{\nu_e}_{p\gamma}\frac{0.25}{3}\right],\\
C^{\nu_e}_{pp} &= |U_{e1}|^2 + 2|U_{\mu1}|^2 + \frac{1}{2}B_{2\to1}(|U_{e2}|^2 + 2|U_{\mu2}|^2) + \frac{1}{2}B_{3\to1}(|U_{e3}|^2 + 2|U_{\mu3}|^2),\\
C^{\nu_e}_{p\gamma} &= |U_{e1}|^2 + |U_{\mu1}|^2 + \frac{1}{2}B_{2\to1}(|U_{e2}|^2 + |U_{\mu2}|^2) + \frac{1}{2}B_{3\to1}(|U_{e3}|^2 + |U_{\mu3}|^2), \qquad \text{(A.1)}
\end{aligned}
$$

$$
\begin{aligned}
E^2 F_{\bar\nu_e}(\text{earth}) &= 6\times 10^{-8}|U_{e1}|^2\left[x\,C^{\bar\nu_e}_{pp}\frac{0.6}{6} + (1-x)C^{\bar\nu_e}_{p\gamma}\frac{0.25}{3}\right],\\
C^{\bar\nu_e}_{pp} &= C^{\nu_e}_{pp},\\
C^{\bar\nu_e}_{p\gamma} &= |U_{\mu1}|^2 + \frac{1}{2}B_{2\to1}|U_{\mu2}|^2 + \frac{1}{2}B_{3\to1}|U_{\mu3}|^2, \qquad \text{(A.2)}
\end{aligned}
$$

The generalized fluxes for other flavours of nu and antinu are then related to the electron flavour by

$$F_{\nu_\mu}(\text{earth}) = \frac{|U_{\mu 1}|^2}{|U_{e1}|^2} F_{\nu_e}(\text{earth}),$$

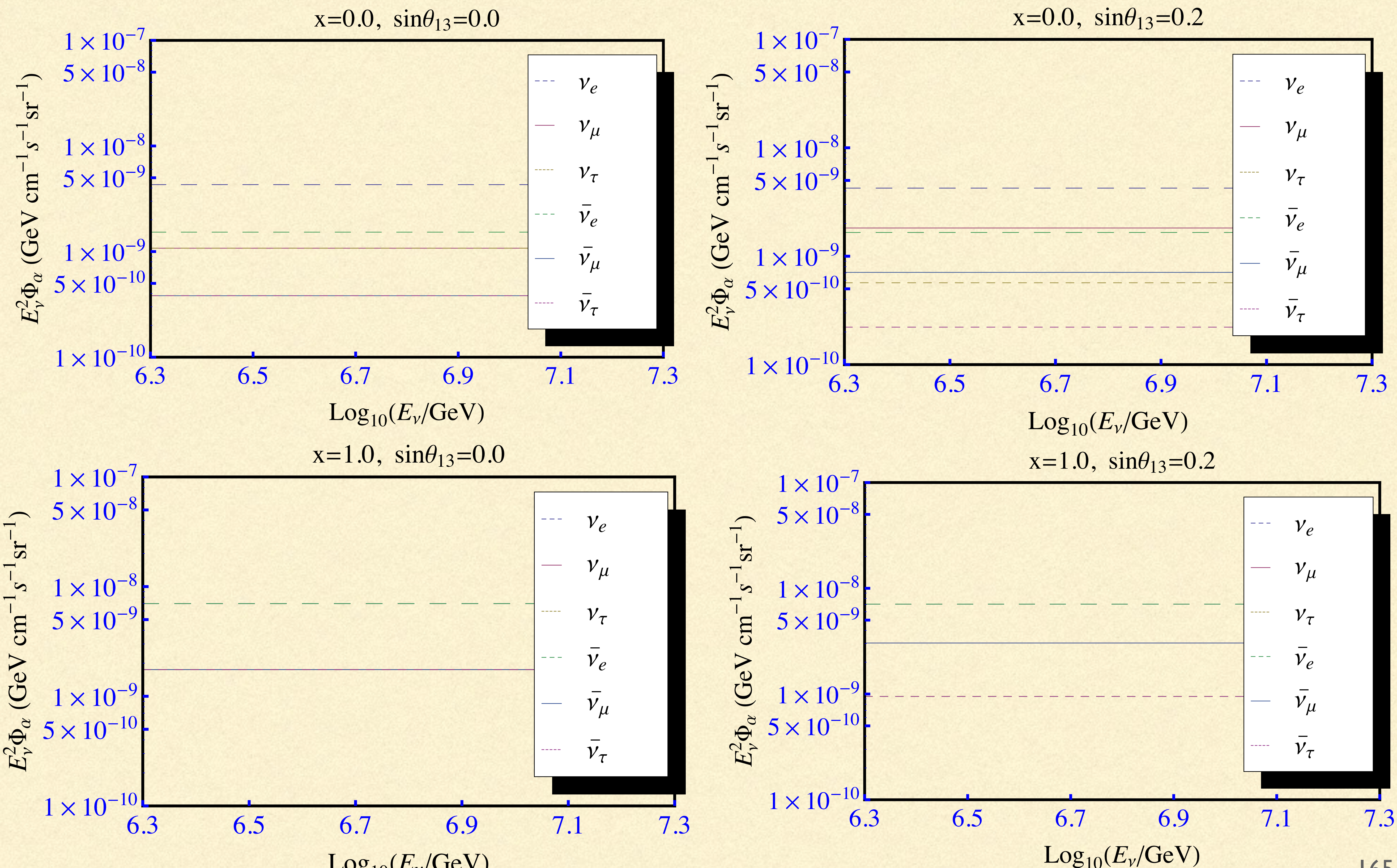
$$F_{\bar{\nu}_\mu}(\text{earth}) = \frac{|U_{\mu 1}|^2}{|U_{e1}|^2} F_{\bar{\nu}_e}(\text{earth}),$$

$$F_{\nu_\tau}(\text{earth}) = \frac{|U_{\tau 1}|^2}{|U_{e1}|^2} F_{\nu_e}(\text{earth}),$$

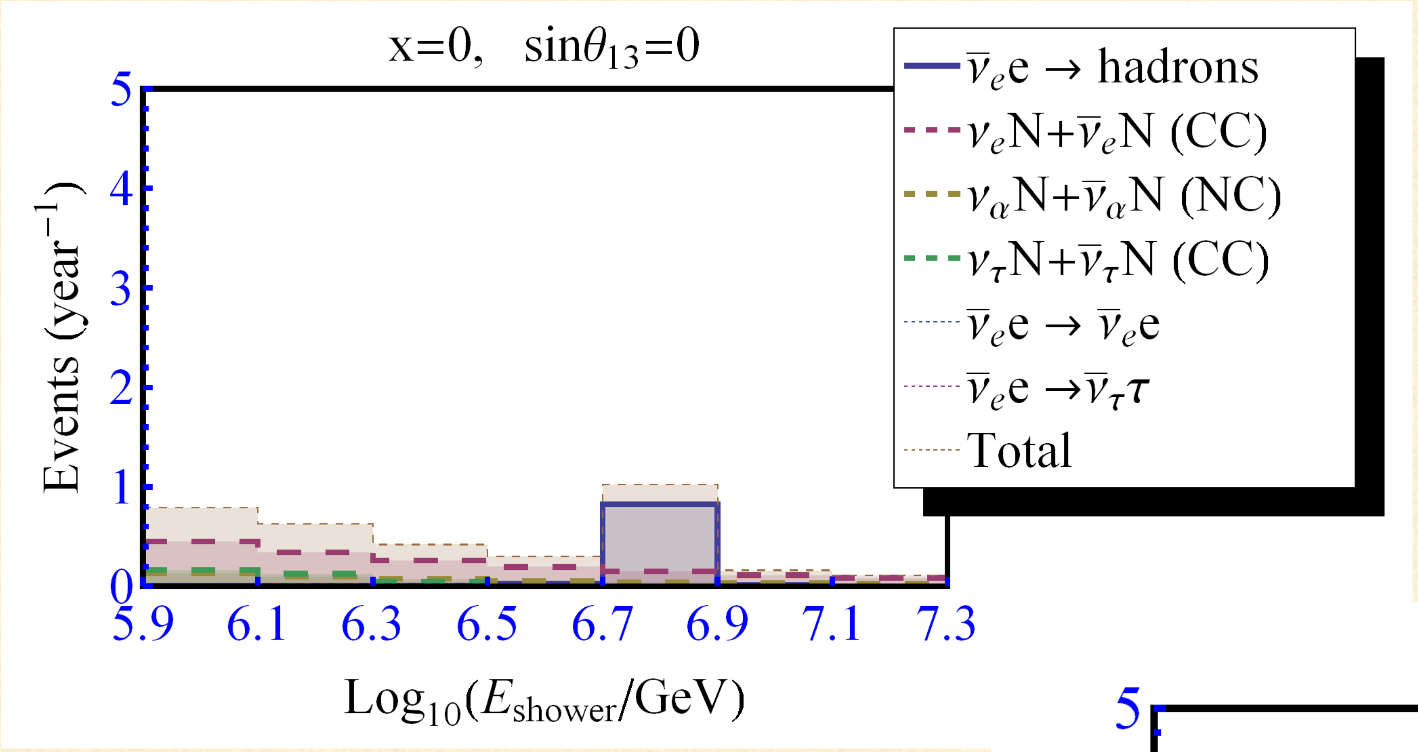
$$F_{\bar{\nu}_\tau}(\text{earth}) = \frac{|U_{\tau 1}|^2}{|U_{e1}|^2} F_{\bar{\nu}_e}(\text{earth}).$$

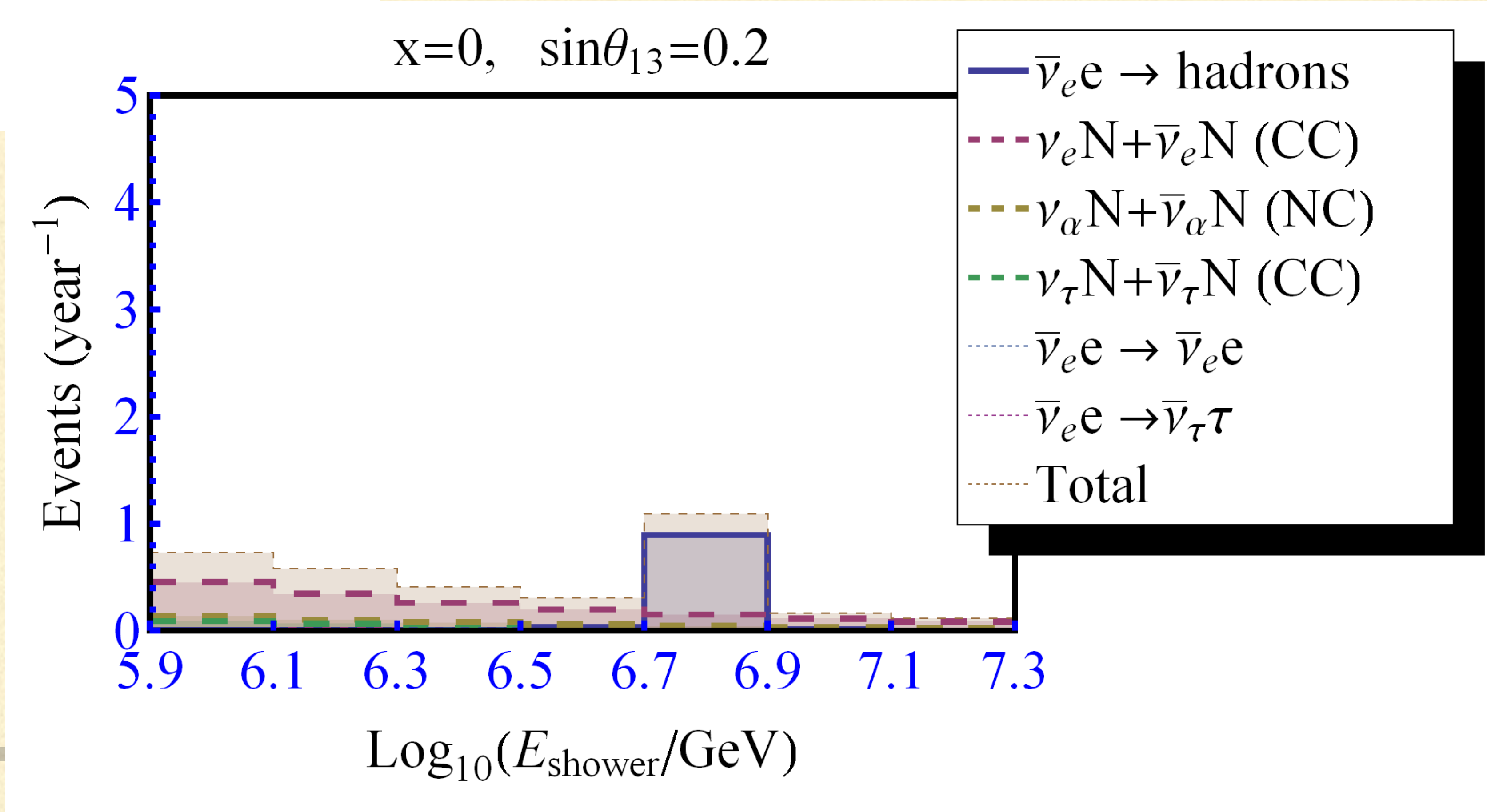
We note that the flavour ratios are independent of both x and decay branching ratios B

Decay fluxes......

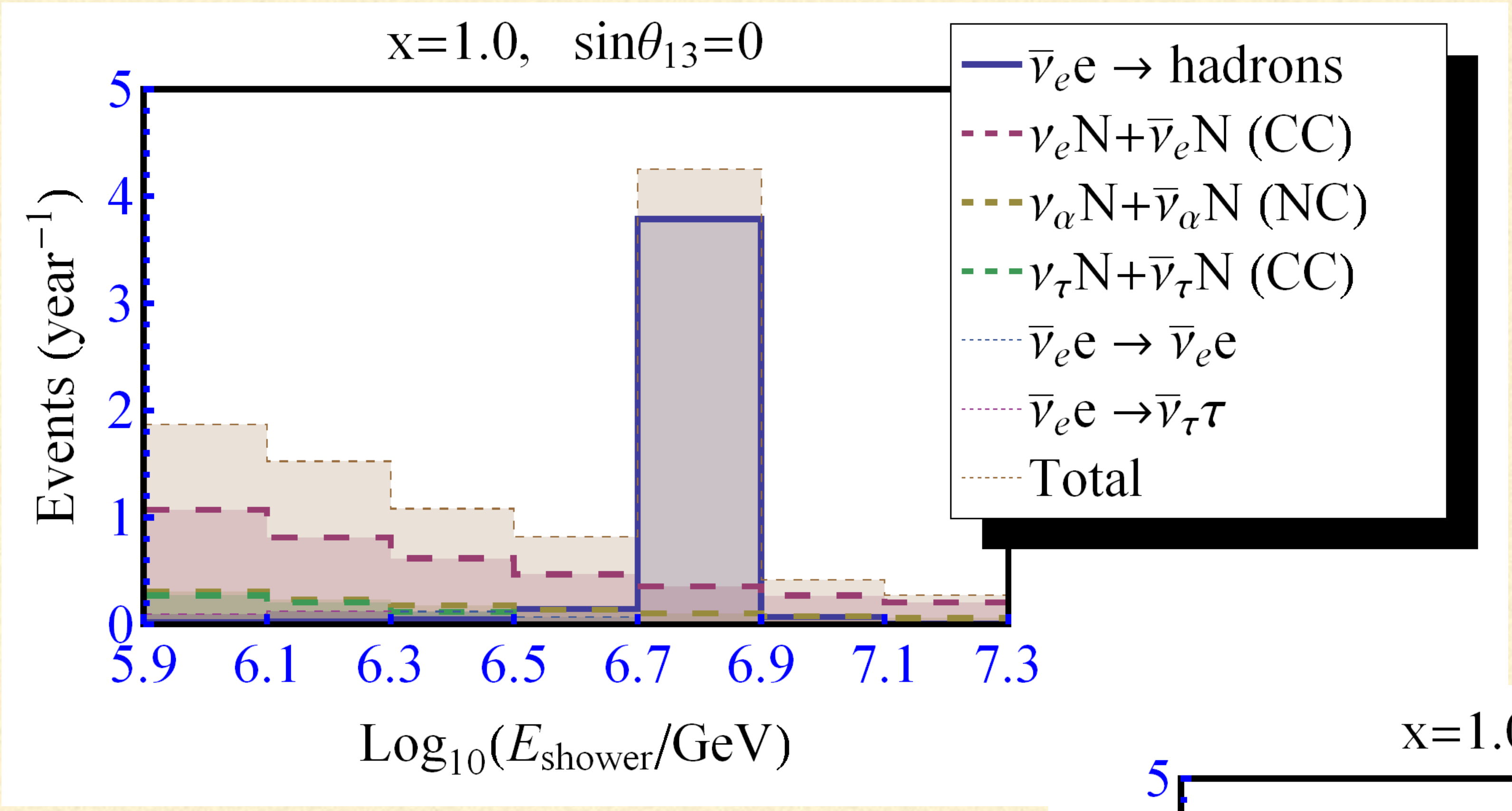


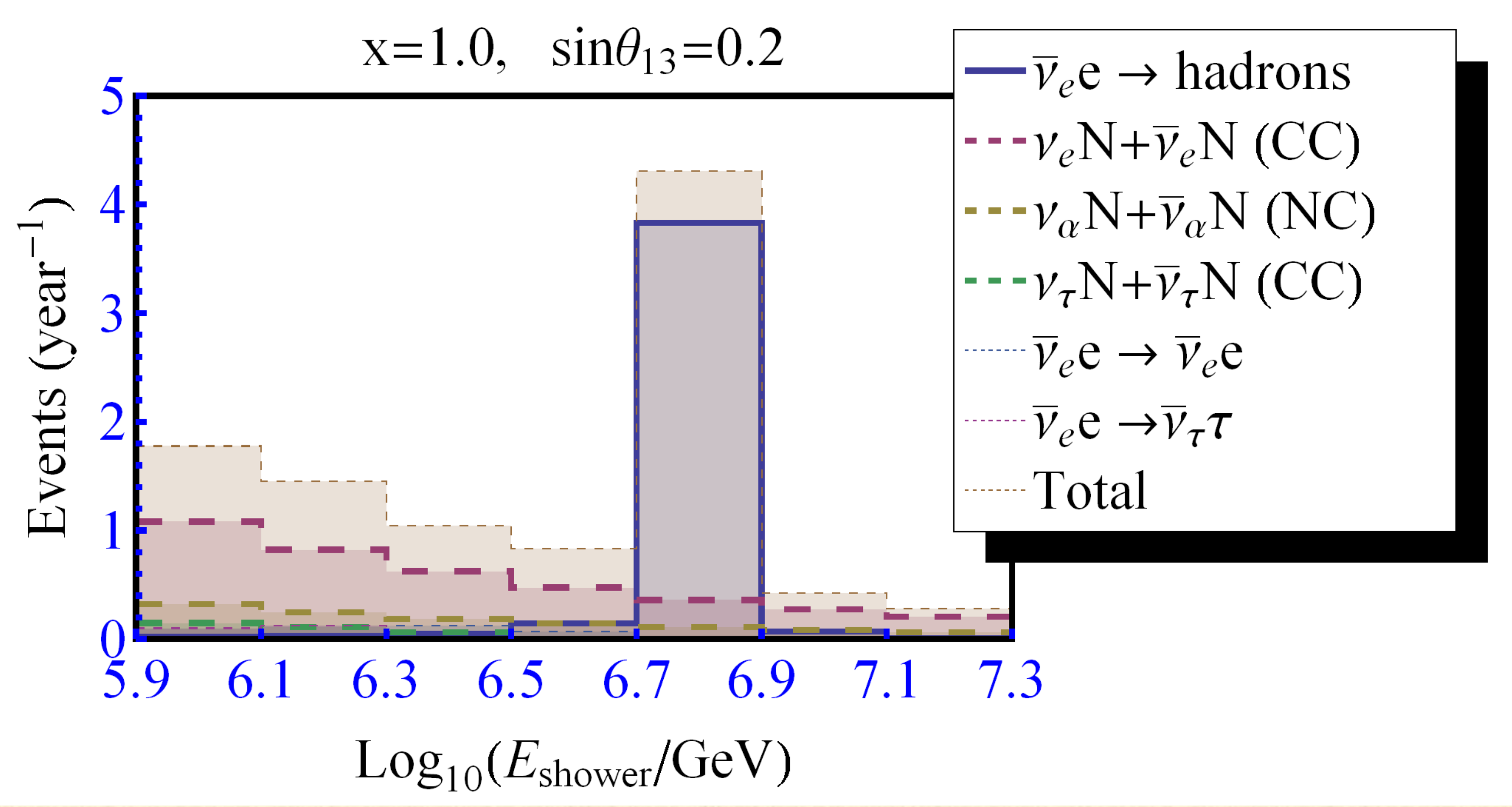
NH Decay Event Rates in the GR neighbourhood



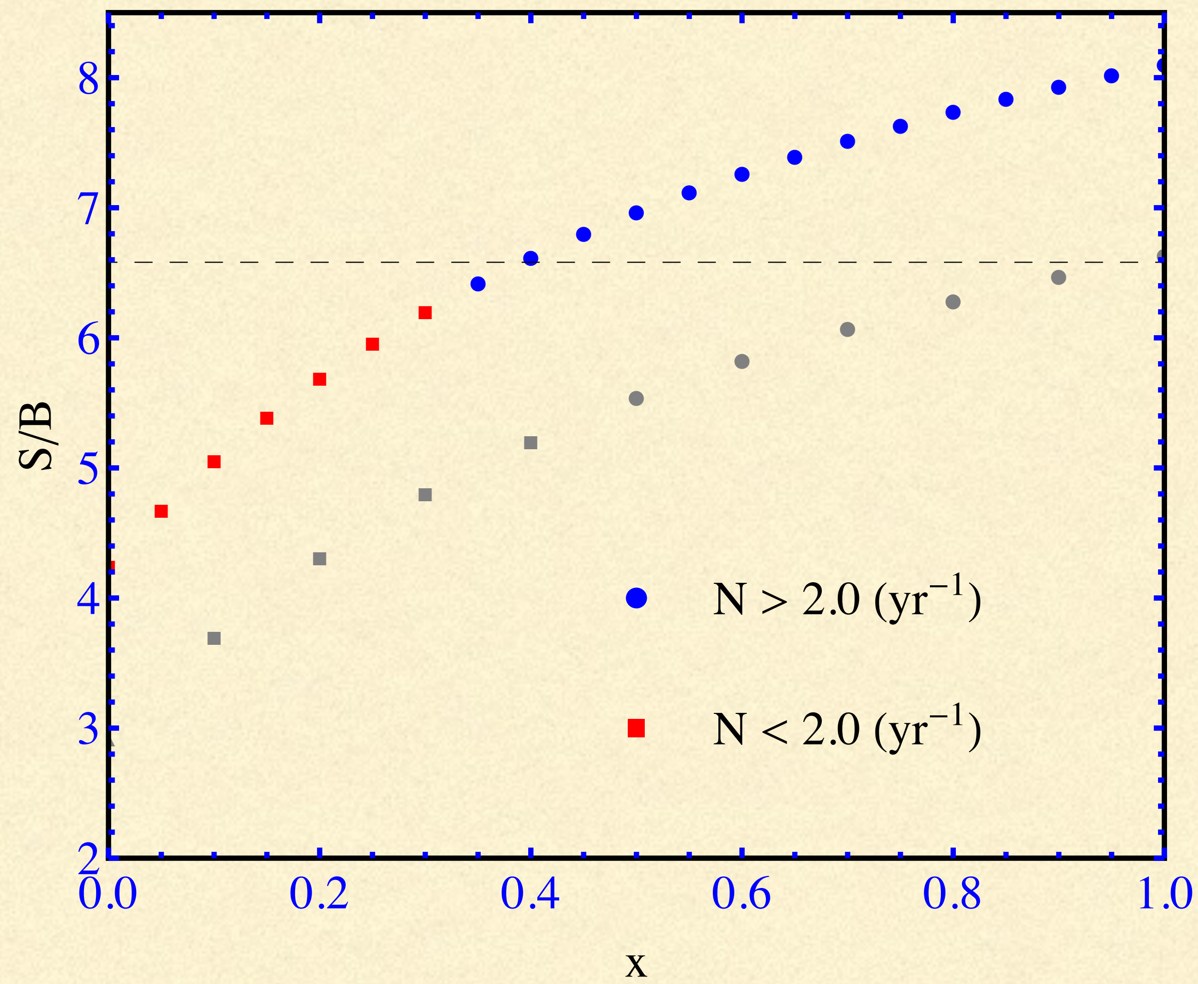


NH Decay Event Rates in the GR neighbourhood





S/B ratio for the decay scenario.........



Decay S/B depends on x but not on Branching ratios

(Not Seeing) UHE Neutrino Fluxes and Physics beyond the SM............

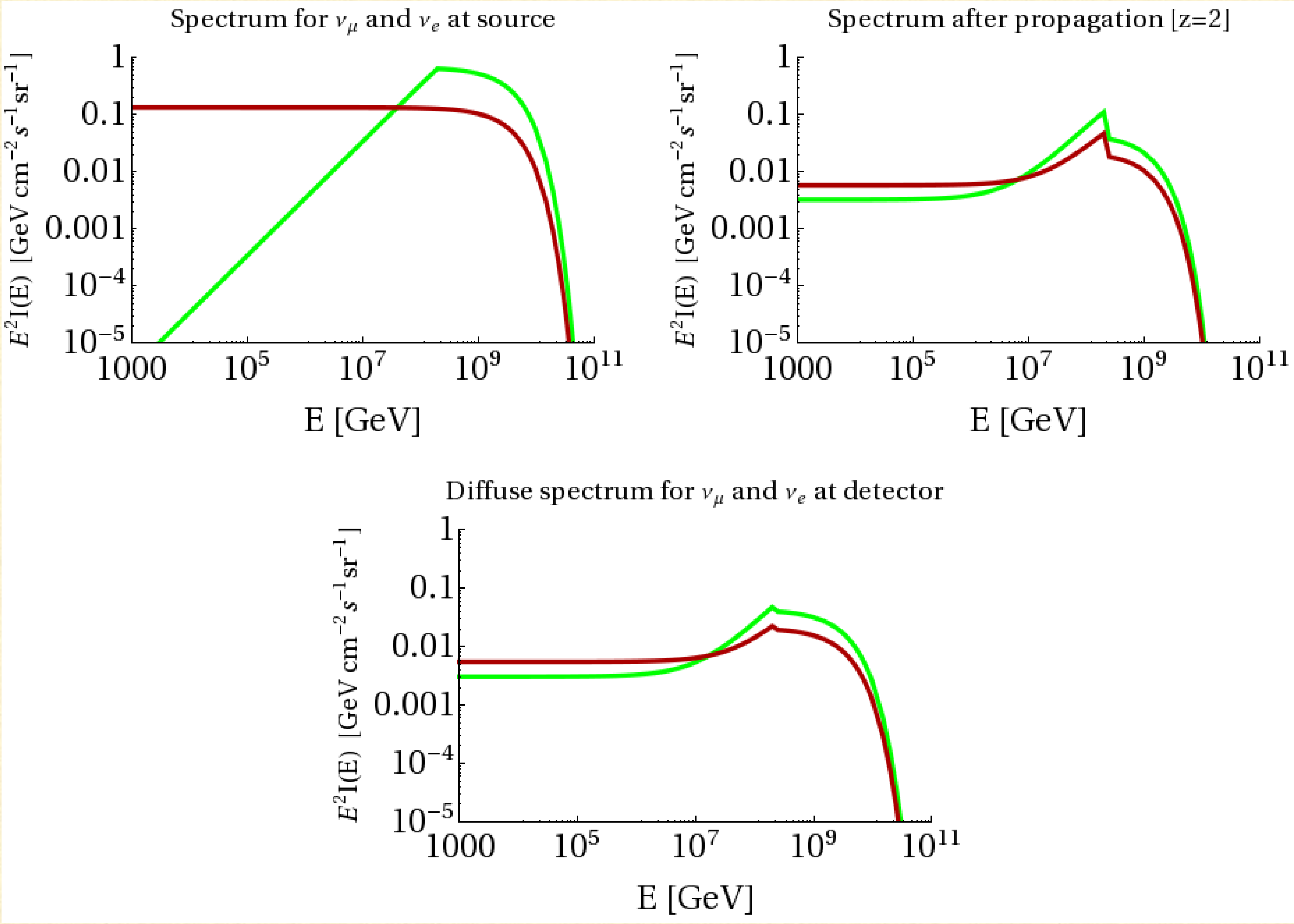
Our predictions of UHE fluxes at Earth depend, among other things, on oscillation probabilities based on SM physics.

Non-standard physics which affects the oscillation probabilities at propagation distances and energies relevant to UHE neutrinos will alter the fluxes we expect to observe.

This will alter the flavour ratios and event rates, sometimes very significantly.

The WB bound for each flavour can be used to study such changes

Spectra at source versus spectra at Earth.............



Oscillations wash out spectral differences at source

Conclusions....

Icecube limits on X-Galactic UHE neutrinos have grown progressively more stringent and have made neutrino astronomy a game of very small numbers.

The Glashow resonance is a small but potentially important region which should be explored as a discovery tool for these fluxes. It seems positioned in the right energy regime given the present situation.

While the quest to understand the nature of astrophysical sources via neutrino detection is the paramount goal, it should be kept in mind that non-standard physics during propagation may affect event ratios and flavour ratios non-trivially even though sources may be "standard".