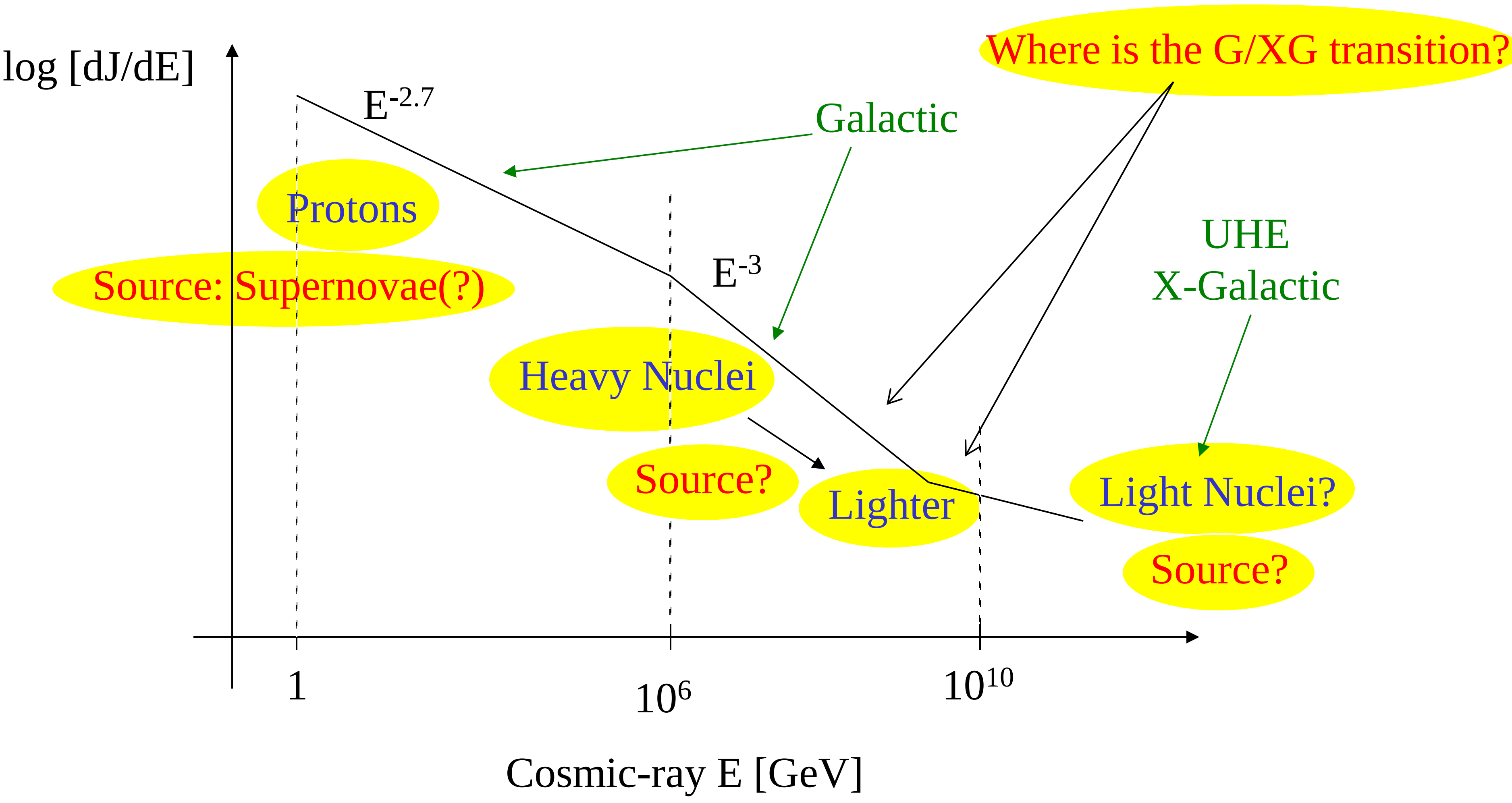
The origin of cosmic neutrinos and the high energy sky, a theoretical perspective

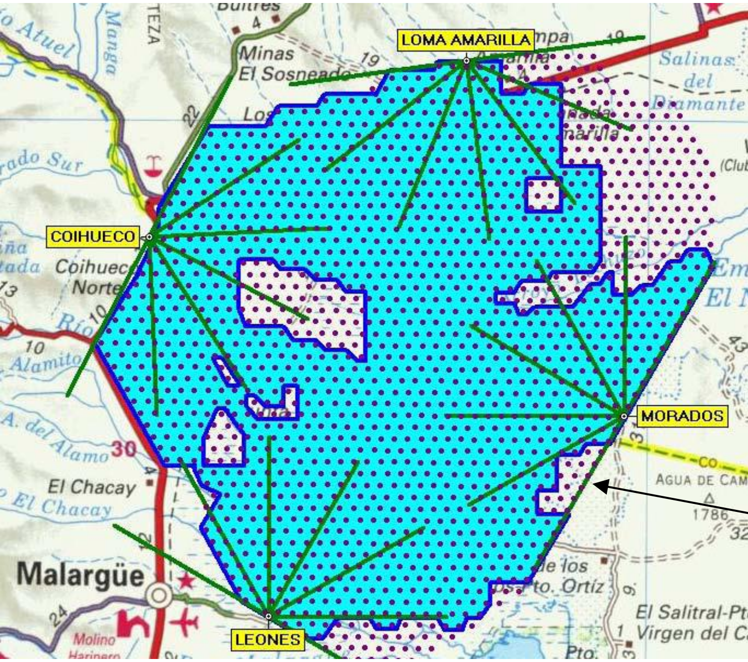
E. Waxman
Weizmann Institute

Solvay-Francqui Workshop on Neutrinos: from reactors to the cosmos
May 2015

The main driver of HE ν astronomy: The origin of CRs



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

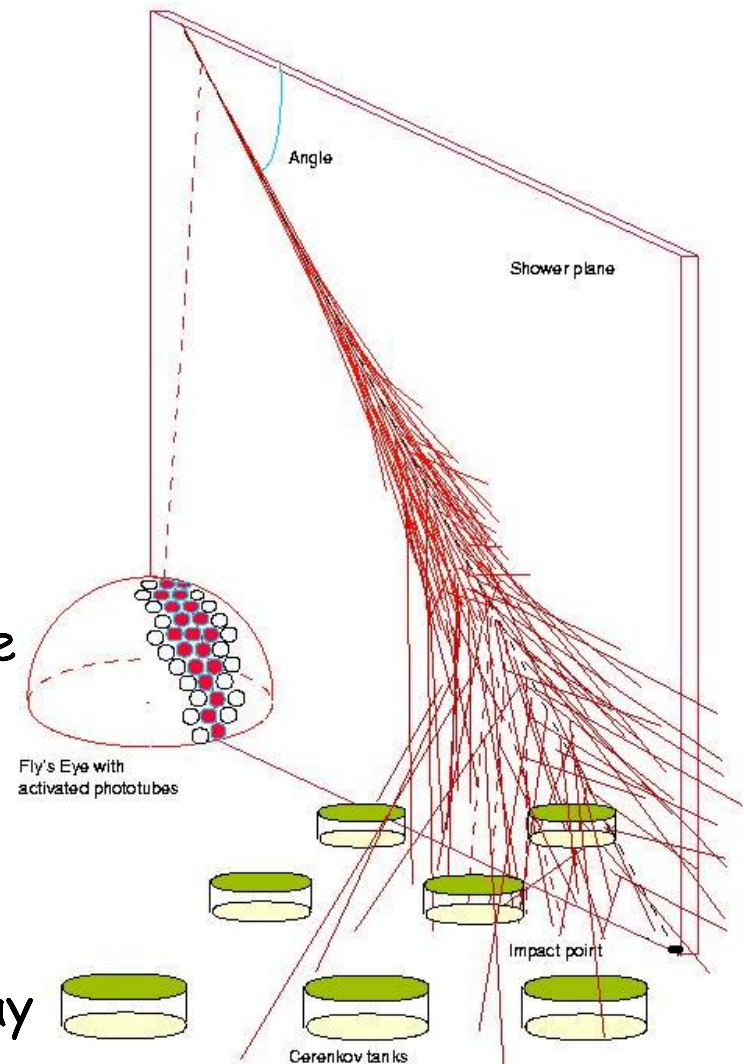


$J(>10^{11}\text{GeV}) \sim 1 \,/\, 100\ \text{km}^2\ \text{year}\ 2\pi\ \text{sr}$

Auger:
3000 km^2

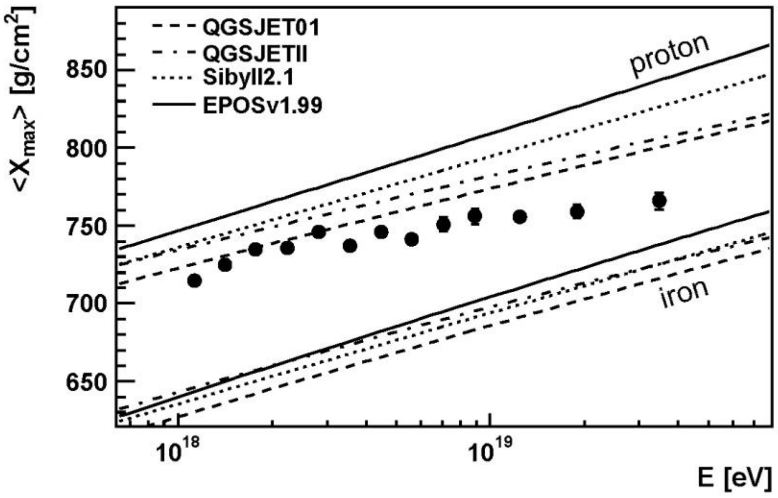
Fluorescence detector

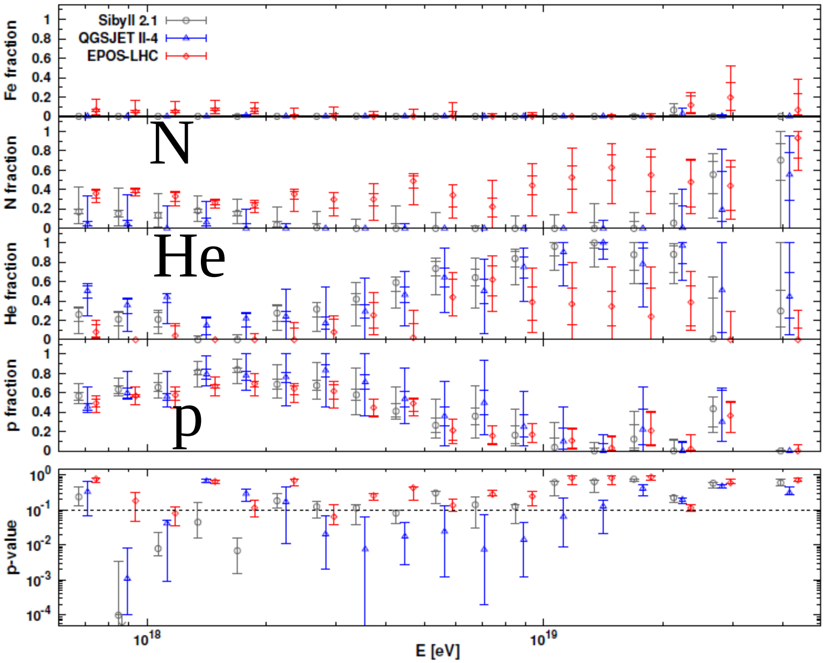
Ground array



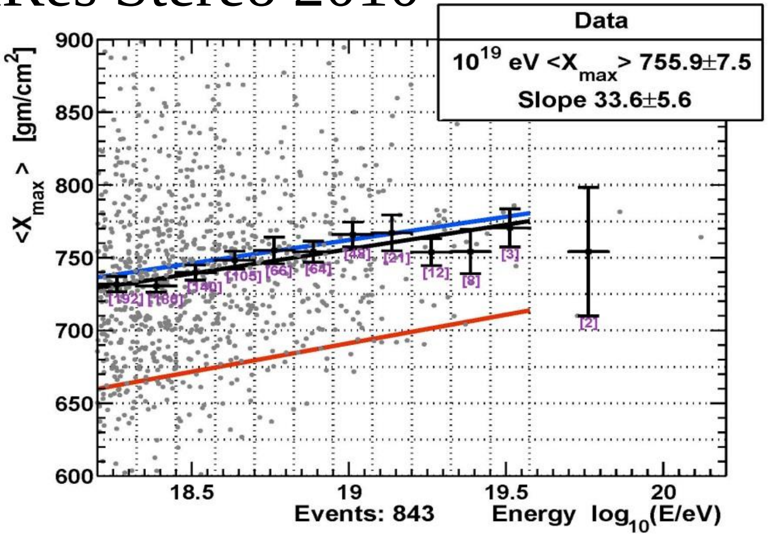
UHE: Composition

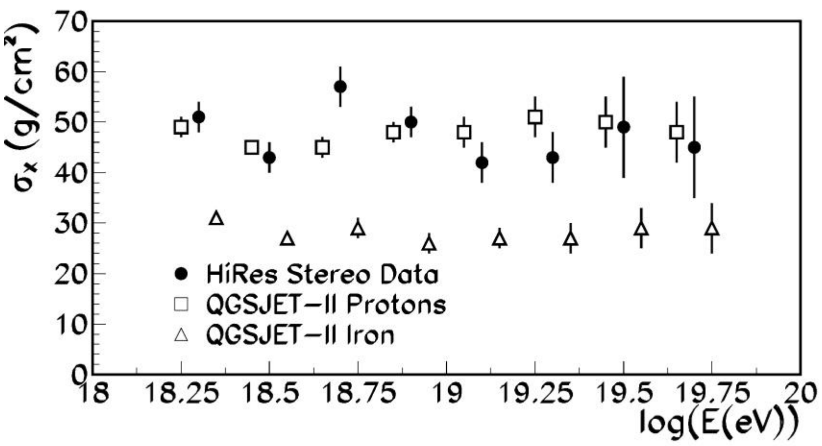
Auger 2010: Fe, 2015: He(??)





HiRes Stereo 2010 & TA Hybrid 2015

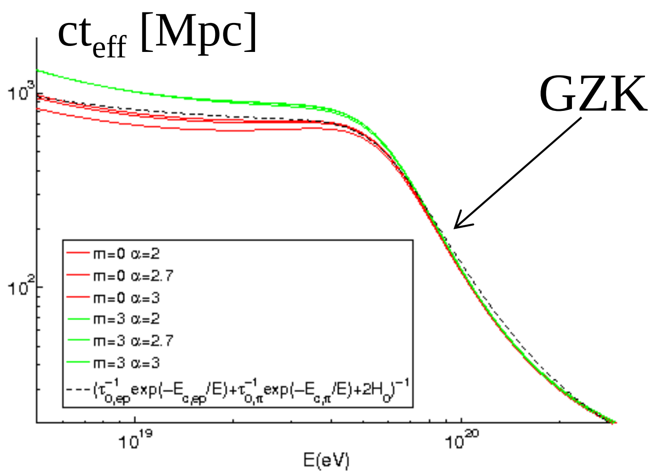


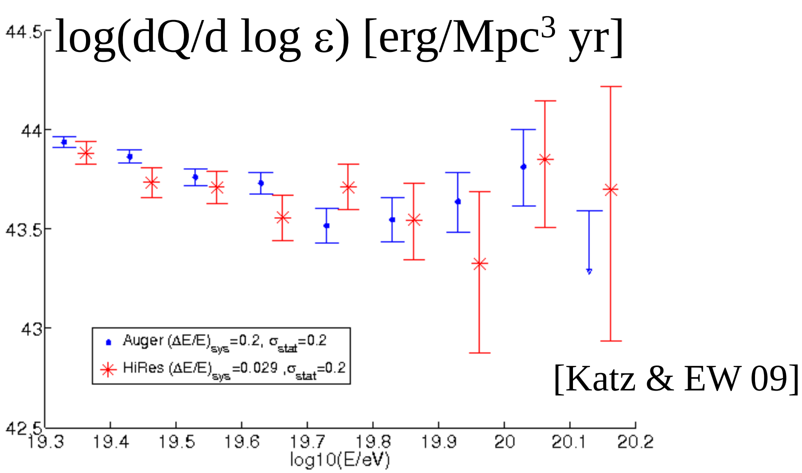


UHE: Energy production rate & spectrum

Protons

$4\pi j = c\,Q\,t$



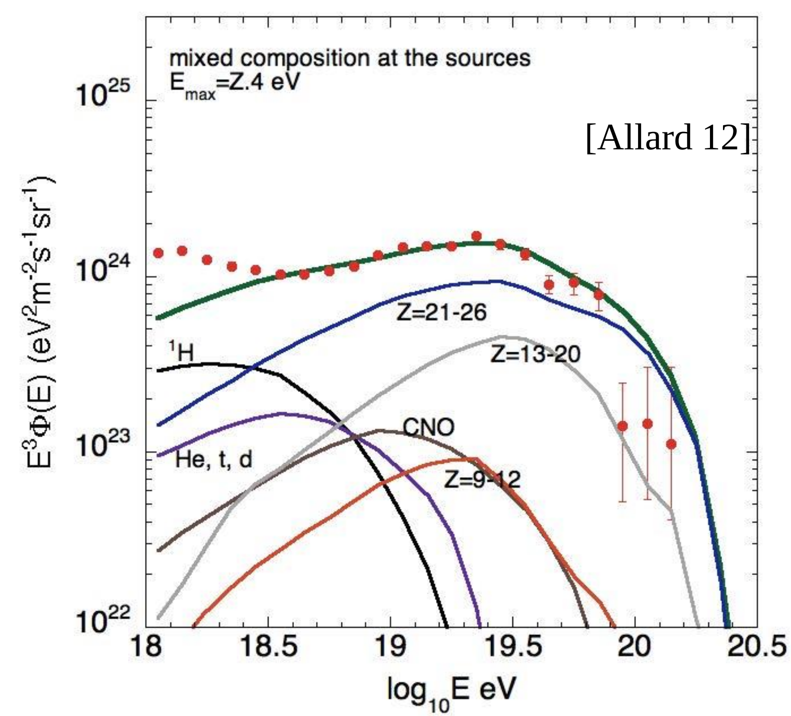


$$dQ/d\log\varepsilon \equiv \varepsilon_p^2 d\dot{n}_p/d\varepsilon_p = Const.$$

$$= (0.5 \pm 0.2)\times 10^{44}\,\mathrm{erg/Mpc^3 yr}$$

- dQ/d log E =Const.:
  - Observed in a wide range of systems,
  - Obtained in collision-less shock acceleration (the only predictive model of particle acceleration).

Mixed composition



Intermediate energy: Neutrinos

- p + γ → N + π
  $\pi^0 \to 2\gamma$; $\pi^+ \to e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$; $\varepsilon_\nu/\varepsilon_p \sim 0.05$

→ Identify UHECR sources,
  Study BH accretion/acceleration physics.

- For all known sources, $\tau_{\gamma p} <= 1$:

$$\varepsilon_\nu^2 \frac{dj_\nu}{d\varepsilon_\nu} \le \Phi_{\rm WB} \equiv \frac{3}{8}\frac{ct_H}{4\pi}\zeta\frac{dQ_p}{d\log\varepsilon} = 2.5\times10^{-8}\,\zeta\left(\frac{dQ/d\log\varepsilon}{10^{44}\,\rm erg/Mpc^3yr}\right)\frac{\rm GeV}{\rm cm^2 s\, sr}$$

$$\zeta = 0.6,\ 3 \quad \text{for} \quad f(z) = 1,\ (1+z)^3$$

[EW & Bahcall 99;
Bahcall & EW 01]

- If X-G p's: $\varepsilon_\nu^2 \frac{dj_\nu}{d\varepsilon_\nu}(10^{19}\,\rm eV) = \Phi_{\rm WB}$

[Berezinsky & Zatsepin 69]

→ Identify primaries, determine f(z)

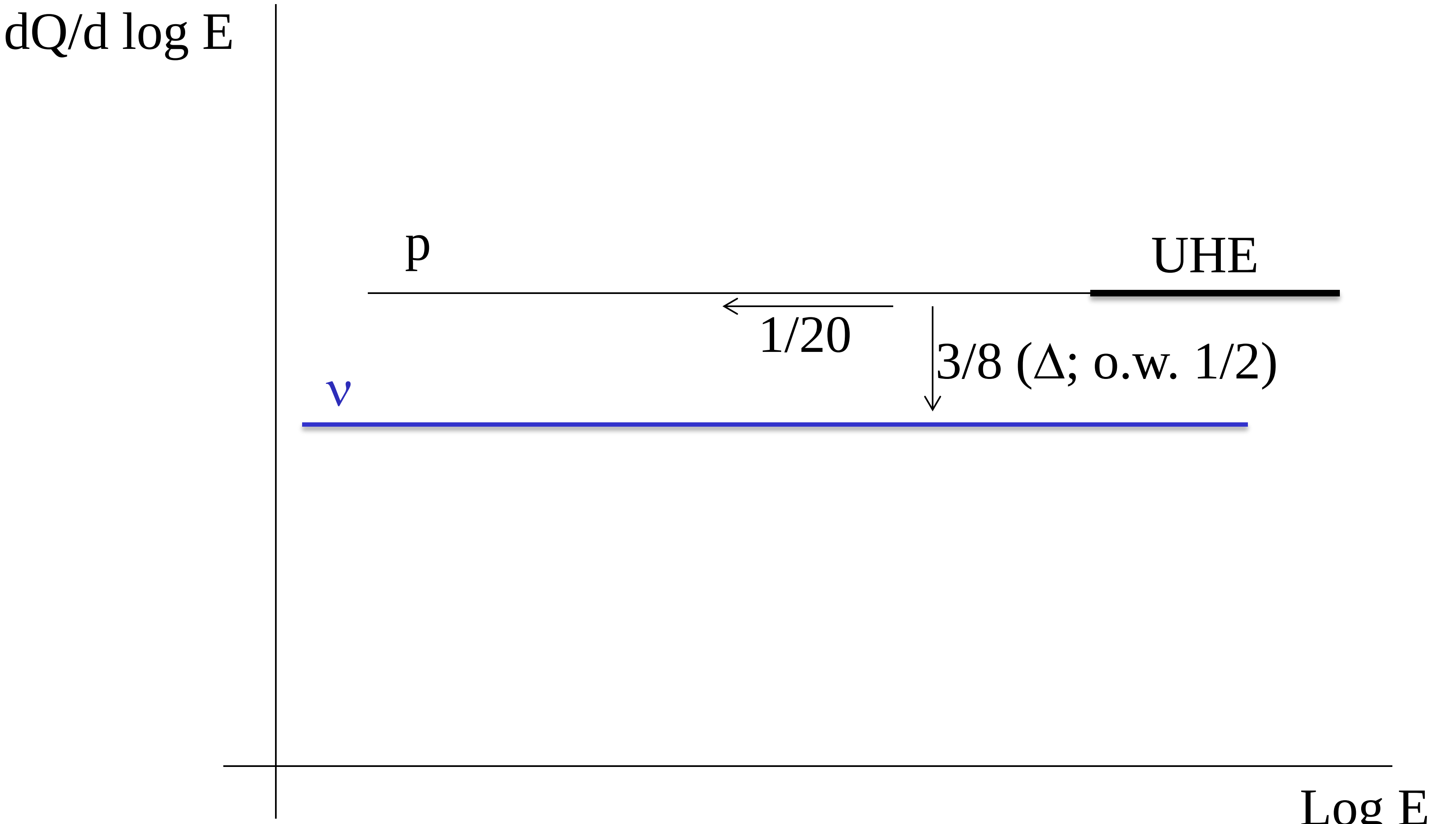
π production: p/A—p/γ

- π decay → $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 (propagation)→ $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1

- p(A)-p: $\varepsilon_\nu/\varepsilon_p$~1/(2x3x4)~0.04 ($\varepsilon_p \rightarrow \varepsilon_A/A$);
  - IR photo dissociation of A does not modify Γ;
  - Comparable particle/anti-particle content.

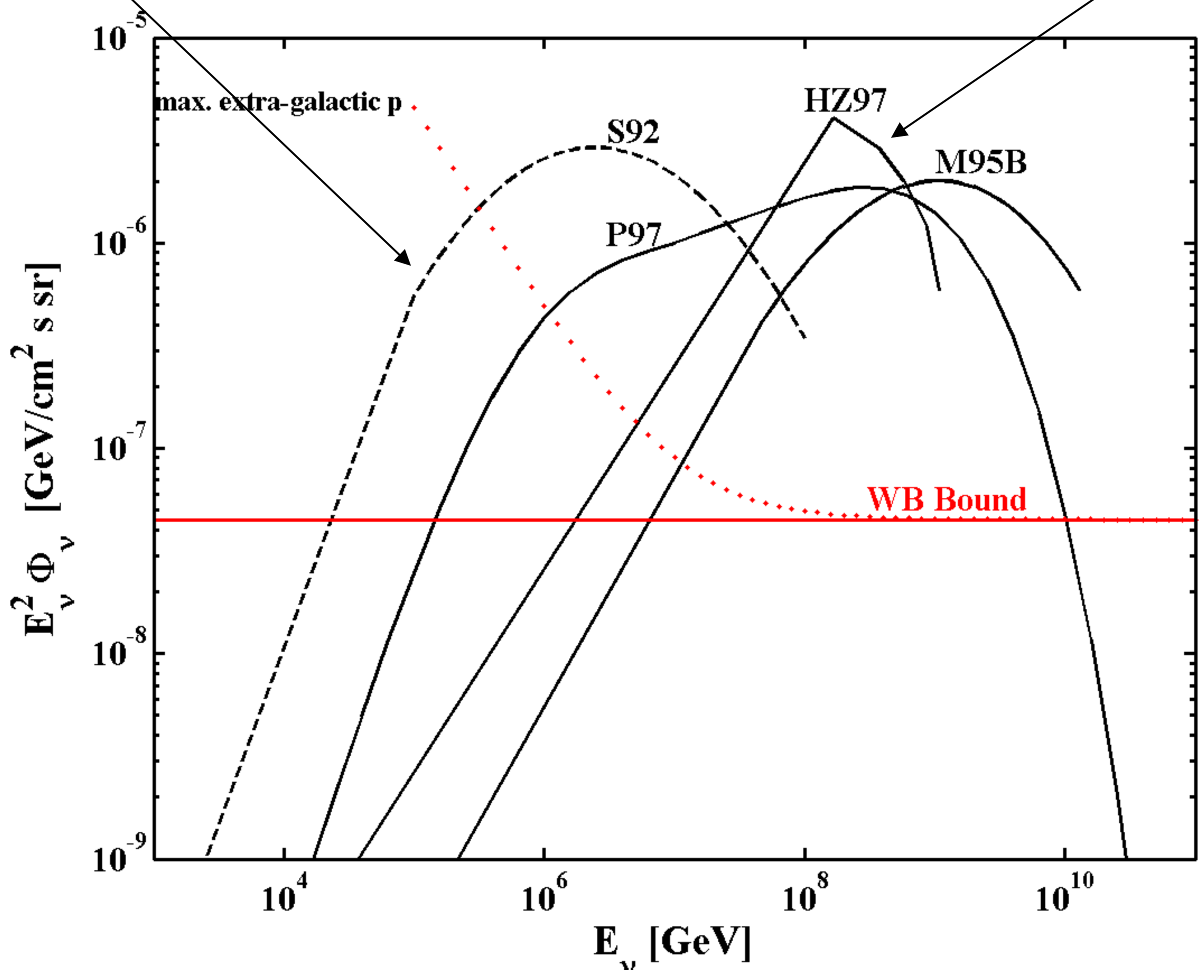
- p(A)-γ: $\varepsilon_\nu/\varepsilon_p$~ (0.1—0.5)x(1/4)~0.05;
  - Requires intense radiation at ε_γ>A keV;
  - Comparable particle/anti-particle content, ν_e excess if dominated by Δ resonance (dlog n_γ/dlog ε_γ<-1).

WB bound: p and ν production



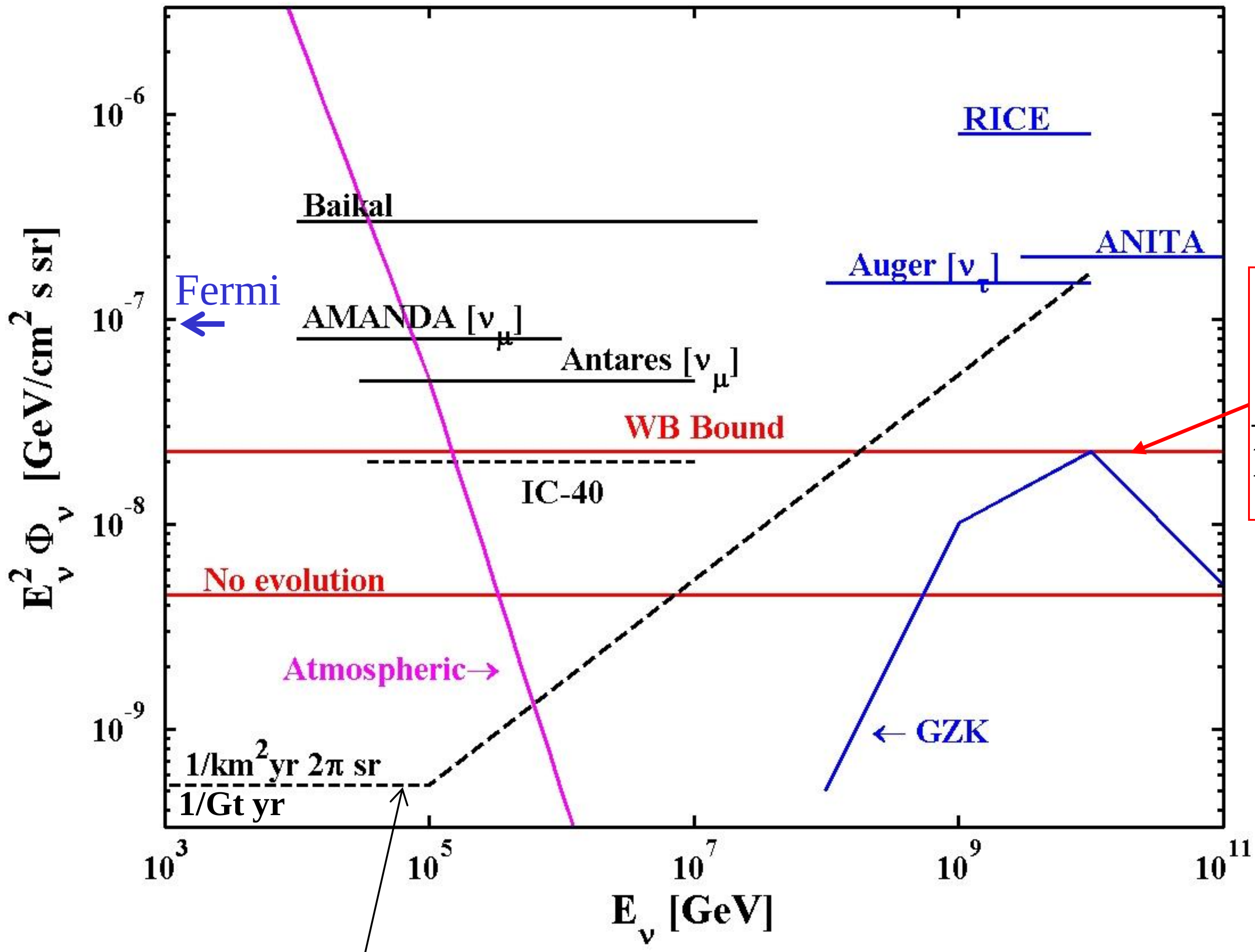
“Hidden” (ν only) sources

Violating UHECR bound



[M95: Mannheim 1995
P97: Protheroe 1997
HZ97: Halzen & Zas 1997]

Bound implications: >1Gton detector (natural, transparent)



2 flavors,

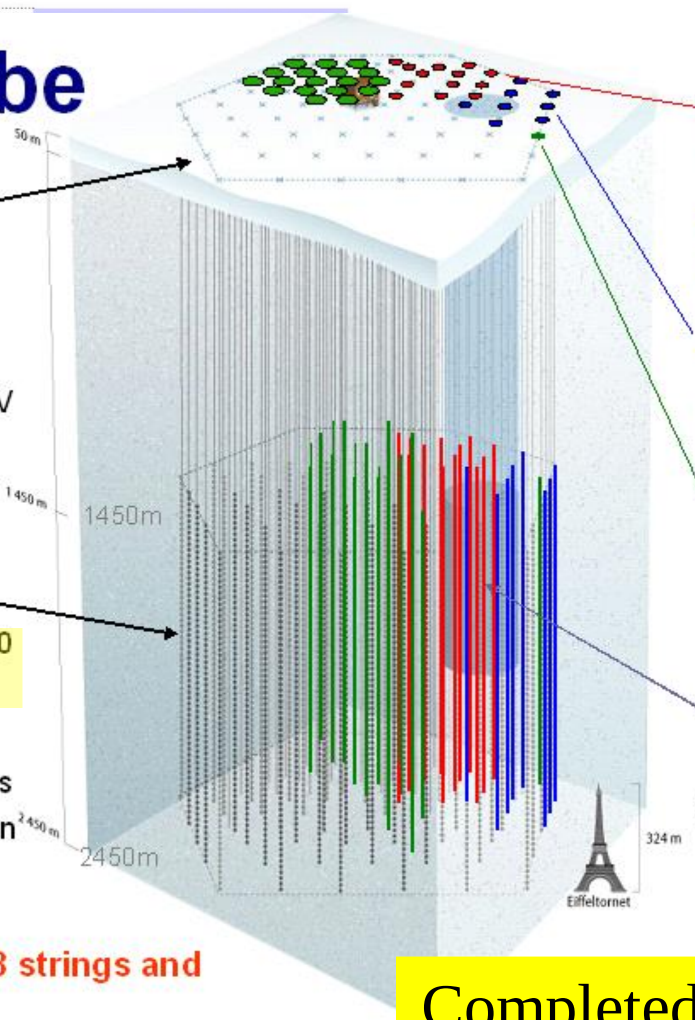
$$\frac{dQ/d\log\varepsilon}{10^{44}\,\mathrm{erg/Mpc^3yr}} = 0.5$$

Rate ~ (EΦ)N_nσ(E), σ~E → Rate ~ (E^2Φ)M

AMANDA & IceCube

Depth
surface

IceCube



IceTop
Air shower detector
80 pairs of ice
Cherenkov tanks
Threshold ~ 300 TeV

InIce
Goal of 80 strings of 60 optical modules each

17 m between modules
125 m string separation

2006-2007:
13 strings deployed

2007-2008
18 strings deployed

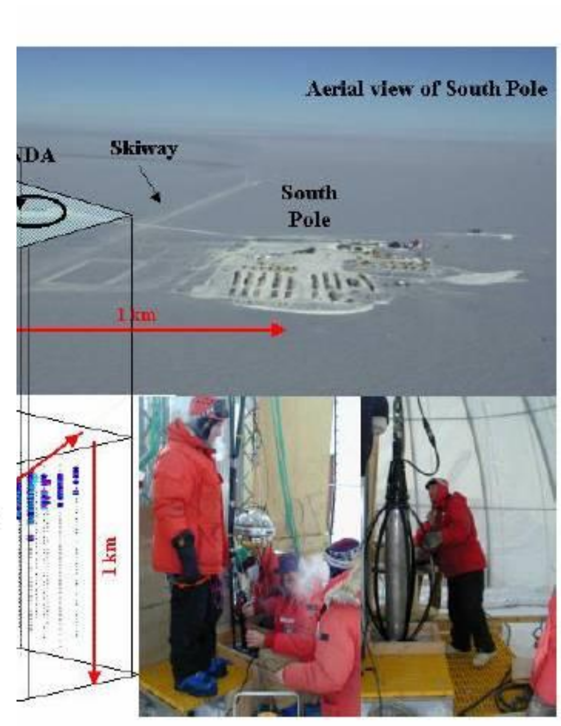
2005-2006: 8 strings

2004-2005 : 1 string

AMANDA-II
19 strings
677 modules

Current configuration:
40 strings,
40 IceTop stations
plus AMANDA

2008/09: add 18 strings and tank stations



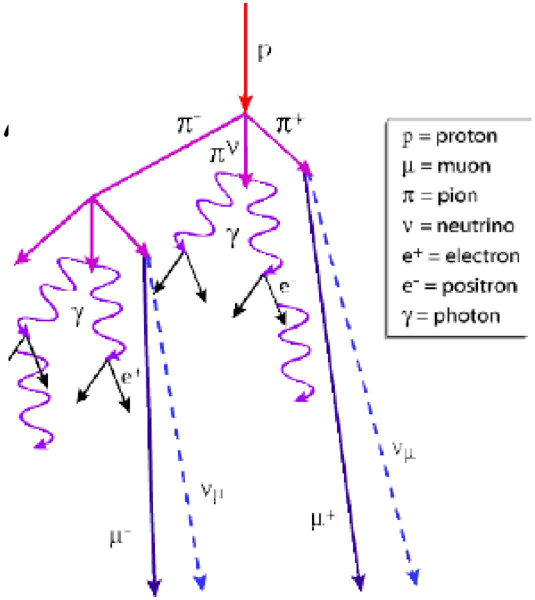
Completed Dec 2010

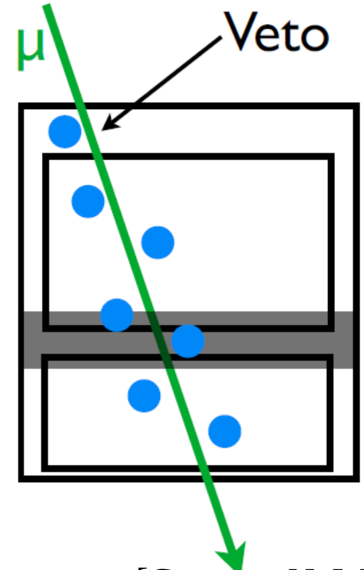
Looking up: Vetoing atmospheric neutrinos

[Schoenert, Gaisser et. al 2009]

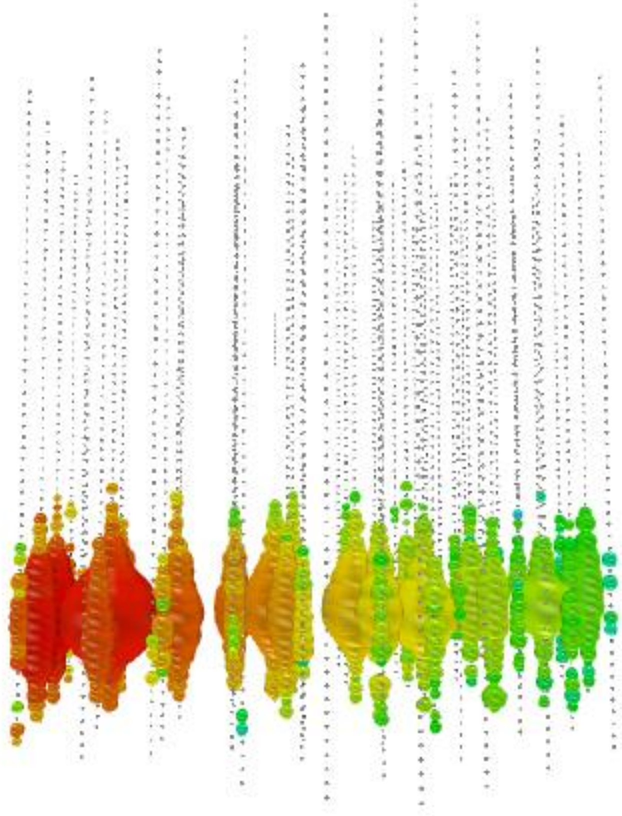
- Look for: Events starting within the detector, not accompanied by shower muons.
- Sensitive to all flavors (for 1:1:1 ν_μ induced μ~20%).
- Observe 4π.
- Rule out atmospheric charmed meson decay excess:

  Anisotropy due to downward events removal (vs isotropic astrophysical intensity).

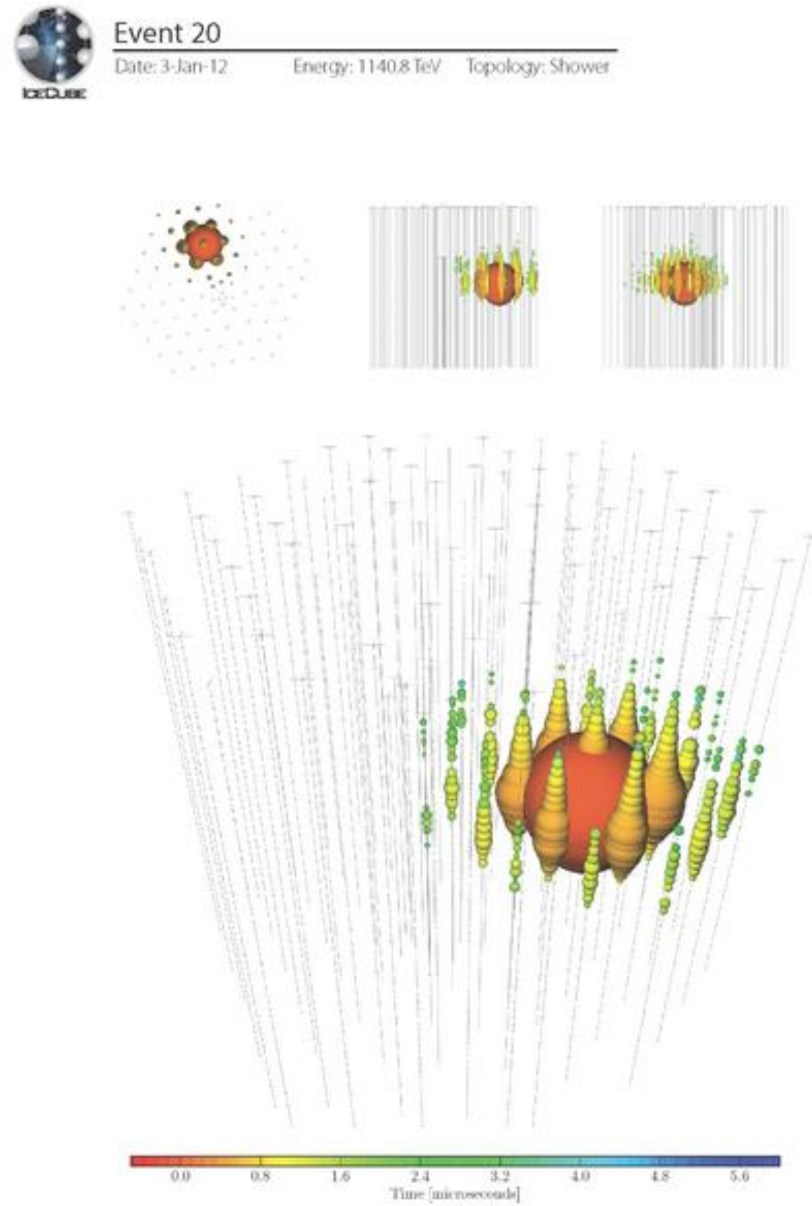




[Cartoon: N. Whitehorn]



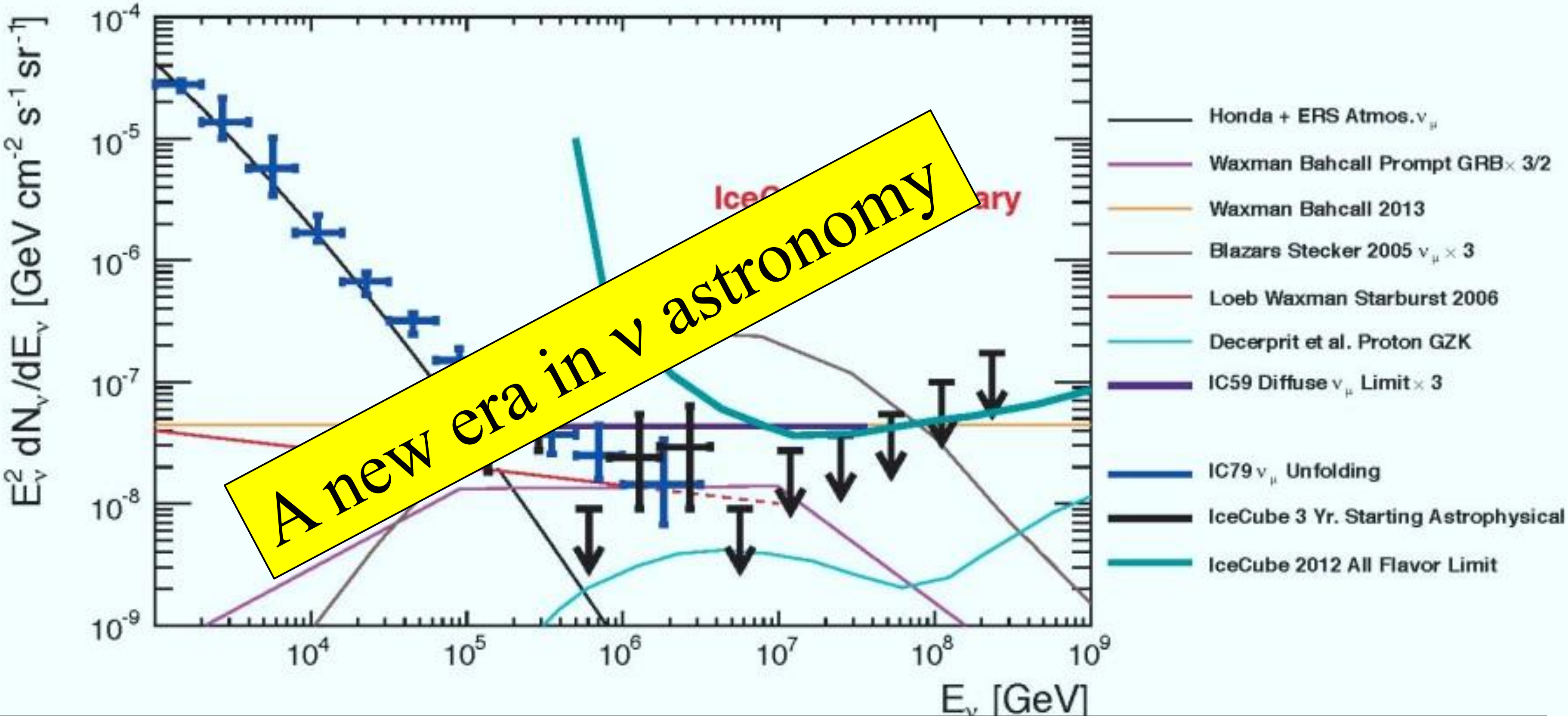
400TeV



1100TeV

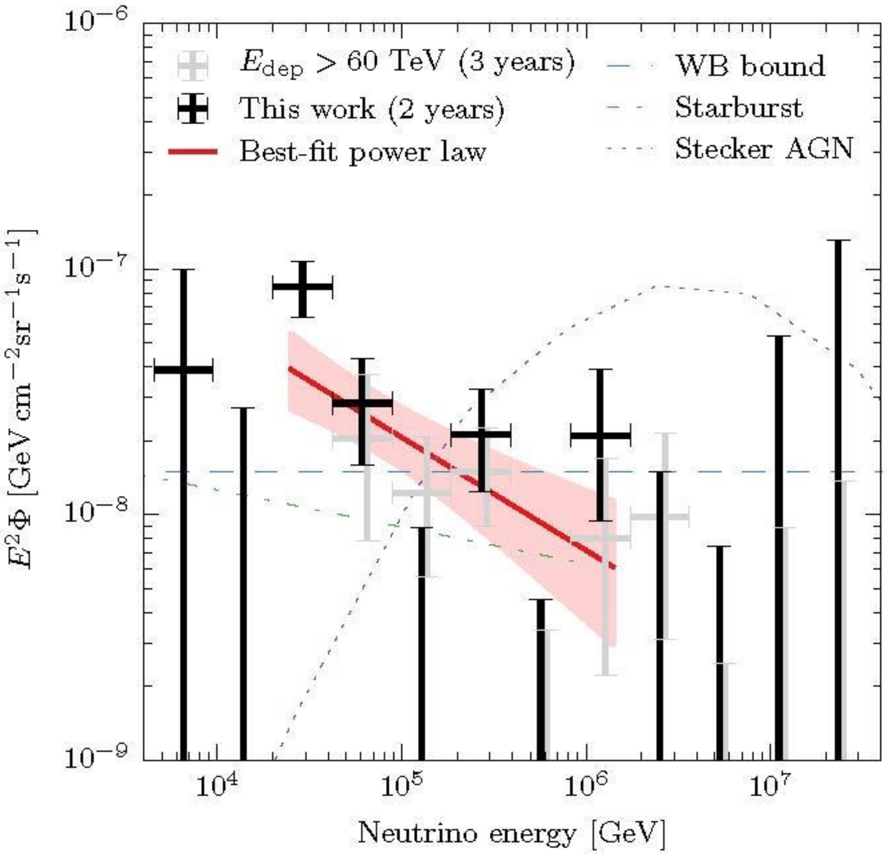
IceCube: 37 events at 50Tev-2PeV

~6σ above atmo. bgnd. [02Sep14 PRL]



$\varepsilon^2\Phi_\nu$ =(2.85+-0.9)x10^{-8}GeV/cm^{2}sr s =$\varepsilon^2\Phi_{WB}$= 3.4x10^{-8}GeV/cm^{2}sr s (2PeV cutoff?)
Consistent with Isotropy and
with ν_e:ν_μ:ν_τ=1:1:1 (π deacy + cosmological prop.).

Lower energy: a ~30 TeV 'excess'?



- Excess at ~30TeV point → d log n_ν/d log ε=-2.46+-0.12; softer than 2.2 at 90% cl.

- >50 TeV spectrum d log n_ν/d log ε=-2 (-1.9+-0.2)
- A new low E component?
- Note:
  - Binning,
  - Southern hemisphere only,
  - (- Fermi XG γ bgnd limit).

IceCube's detection: Implications

- DM decay?

  The coincidence of $50TeV<E<2PeV$ ν flux, spectrum (& flavor) with the WB bound is unlikely a chance coincidence.

- Unlikely Galactic: Isotropy,

  and $\varepsilon^2\Phi_\gamma \sim 10^{-7}(E_{0.1TeV})^{-0.7}$GeV/cm^{2}s sr [Fermi]

  $\rightarrow \varepsilon^2\Phi_\nu \sim 10^{-9}(E_{0.1PeV})^{-0.7}$GeV/cm^{2}s sr $\ll \Phi_{WB}$

  If Galactic: New, unknown sources; Chance coincidence with WB.

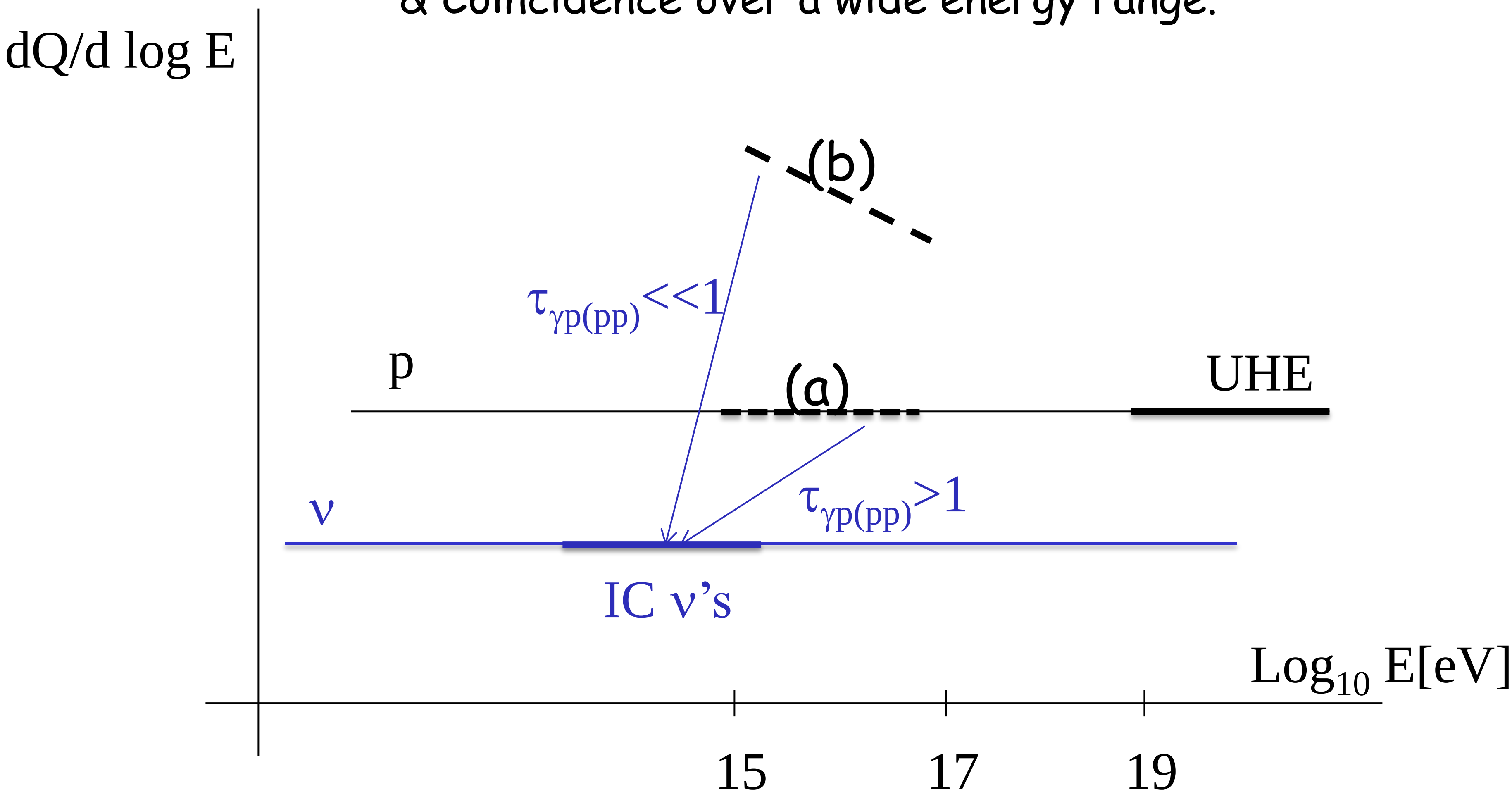
- $\rightarrow$ XG sources.
- Recall: known UHECR sources cannot account for IC's flux ($\tau_{\gamma p(pp)}<1$) [e.g. Murase et al. 2014].

IceCube's detection: XG CR pion production

(a) UHE CR sources reside in (<10^{17}eV) "Calorimeters",

or

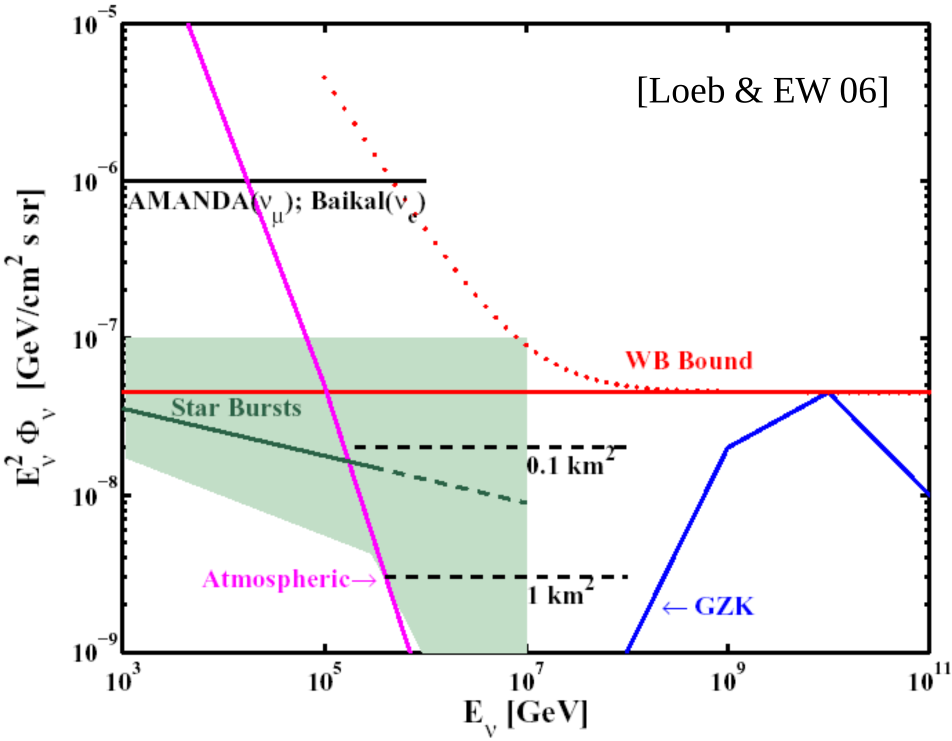
(b) $Q \gg Q_{UHE}$ sources (unknown) with $\tau_{\gamma p(pp)} \ll 1$ (ad-hoc)
& Coincidence over a wide energy range.



Candidate CR calorimeters: Starburst galaxies

- Radio, IR & γ-ray (GeV-TeV) observations
  → Starbursts are calorimeters for E/Z reaching (at least) 10PeV.
- Most of the stars in the universe were formed in Starbursts.

- If:
  CR sources reside in galaxies
  and
  Q~Star Formation Rate (SFR),
  Then:
  $\Phi_\nu(\varepsilon_\nu<1\mathrm{PeV}) \sim \Phi_{WB}$.



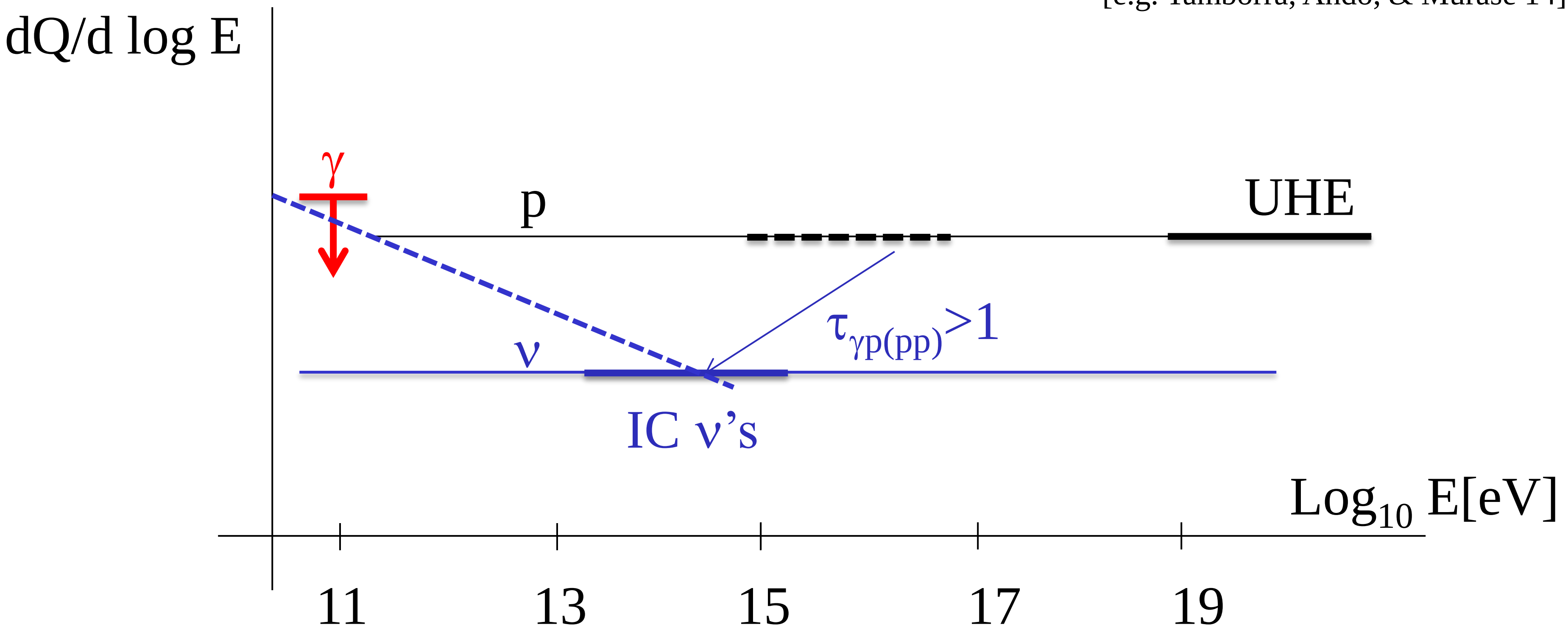
- (And also a significant fraction of the γ-bgnd).

A note on Fermi's XG diffuse γ-ray upper limit

- Fermi diffuse XG: $\varepsilon^2\Phi_\gamma$(0.1TeV) <~ 10^{-7} GeV/cm^{2}s sr.
- IceCube diffuse XG: $\varepsilon^2\Phi_\nu$ (100TeV)~0.3×10^{-7}GeV/cm^{2}s sr.

→ Flat proton generation spectrum, d log n/d log ε>-2.2, with significant contribution to the diffuse XG γ-bgnd.

[e.g. Tamborra, Ando, & Murase 14]



IceCube's detection: XG CR pion production

(a) UHE CR sources reside in (<10^{17}eV) "Calorimeters": Starbursts.
Implications:
G-XG transition @ 10^{19}eV;
The (G) >$10^{6.5}$eV flux is suppressed due to propagation.

or

(b) $Q \gg Q_{UHE}$ sources (unknown) with $\tau_{\gamma p(pp)} \ll 1$ (ad hoc, fine tuning)
& Coincidence over a wide energy range:
- AGN jets in Galaxy clusters,
  $dQ/d\log\varepsilon \sim 10^{47}$erg/Mpc^{3}yr, $\tau_{pp} \sim 10^{-2}$ [Murase, Inoue & Nagataki 2008]
- Low L GRBs;

.

.

.

Low Energy, ~10GeV

$$\frac{dQ}{d\log\varepsilon} \approx \frac{(dQ/d\log\varepsilon)_{\rm Galaxy}}{(SFR)_{\rm Galaxy}} \times < SFR/V >_{z=0}$$

- Our Galaxy- using "grammage", local SN rate

$$\frac{dQ}{d\log\varepsilon} \sim [3--15]\times 10^{44}\left(\frac{\varepsilon}{10Z\ \rm GeV}\right)^{-\delta} \rm erg/Mpc^3yr, \quad \delta \approx 0.1\text{-}0.2$$

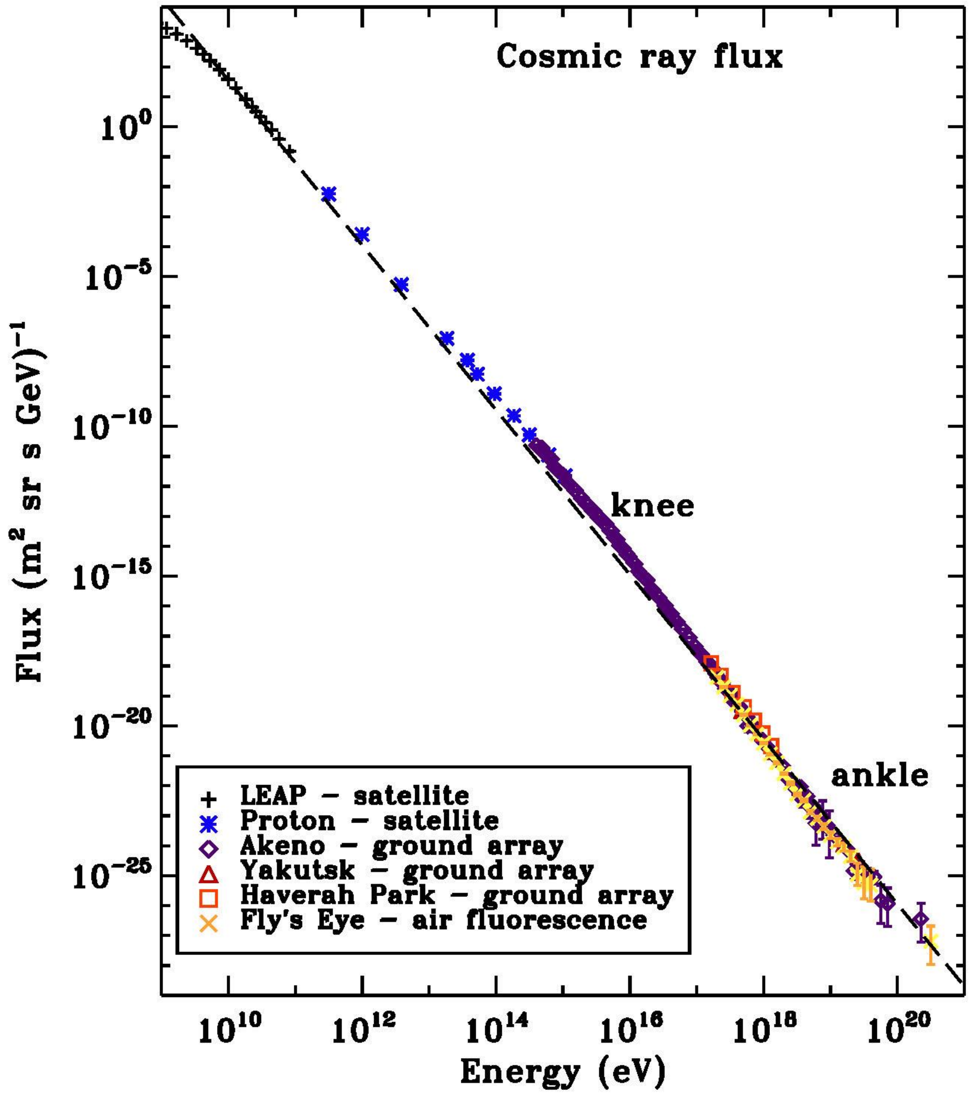
- Starbursts- using radio to γ observations

$$\frac{dQ}{d\log\varepsilon}(\varepsilon \sim 10\rm GeV, z=0) \approx 5\left(\frac{0.3}{f_{synch.}}\right)\times 10^{44}\,\rm erg/Mpc^3yr$$

→ Q/SFR similar for different galaxy types,
dQ/dlog ε ~Const. at all ε!

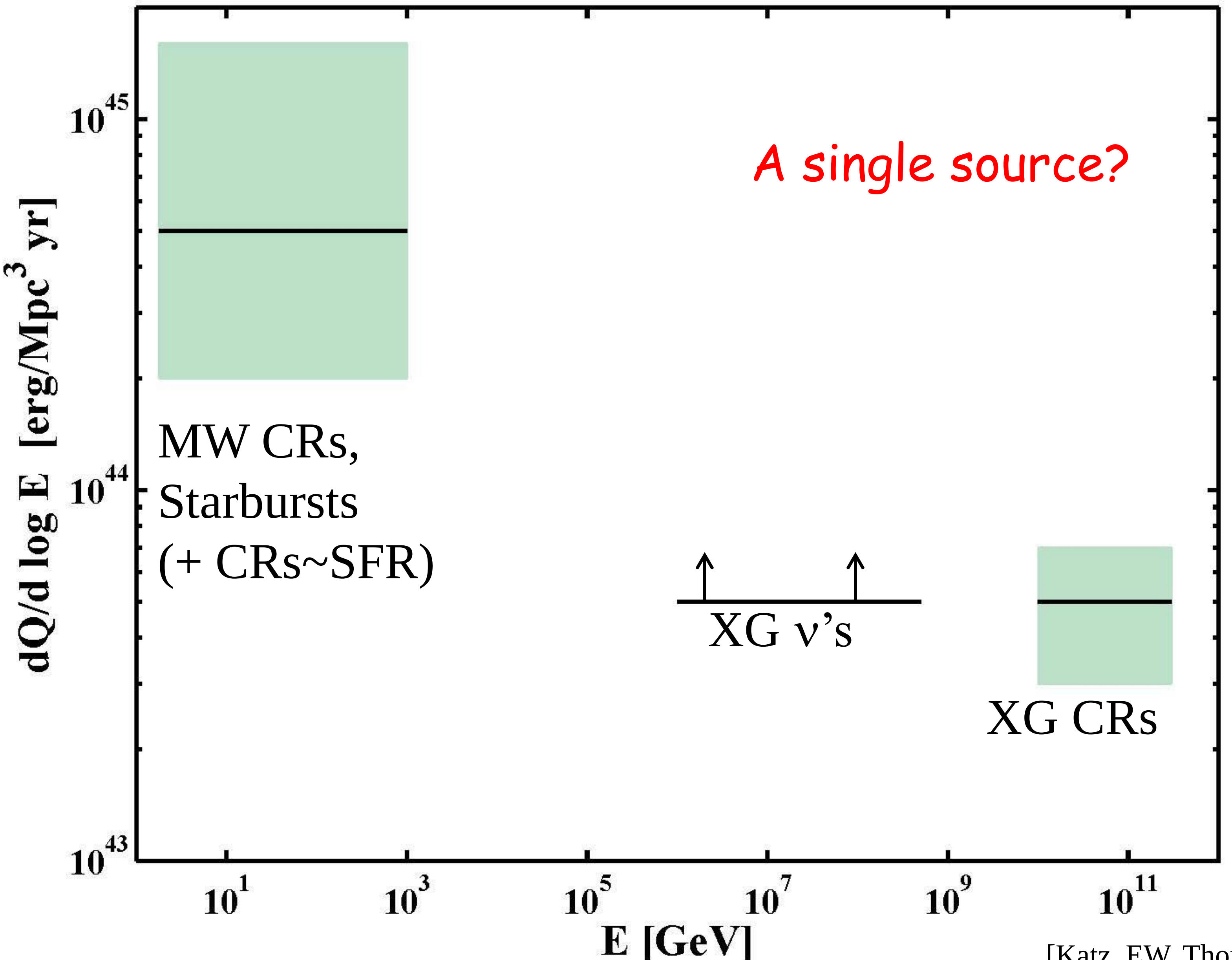
[Katz, EW, Thompson & Loeb 14]

The cosmic ray spectrum



[From Helder et al., SSR 12]

The cosmic ray generation spectrum



[Katz, EW, Thompson & Loeb 14]

Constraints on source density

$$n_s L_{\nu_\mu} \approx 0.6\times 10^{43}\left(\frac{\zeta}{3}\right)^{-1} \text{erg/Mpc}^3\ \text{yr} \quad \Rightarrow \quad L_{\nu_\mu} \approx 2\times 10^{42}\left(\frac{\zeta}{3}\frac{n_s}{10^{-7}\,\text{Mpc}^{-3}}\right)^{-1} \text{erg/s}$$

$$f_{\lim} \approx \frac{E_\nu}{AtP_{\nu\mu}} \approx 10^{-12}\ \text{erg/cm}^2\text{s} \quad \Rightarrow \quad d_{\lim} \equiv \left(\frac{L_{\nu_\mu}}{4\pi f_{\lim}/2.4}\right)^{1/2} \approx 150\left(\frac{\zeta}{3}\frac{n_s}{10^{-7}\,\text{Mpc}^{-3}}\right)^{-1/2} \text{Mpc}$$

$$N_s(\text{multiple}\quad \nu_\mu \quad \text{events}) = \frac{2\pi}{3} n_s d_{\lim}^3 \approx 1\left(\frac{\zeta}{3}\right)^{-3/2}\left(\frac{n_s}{10^{-7}\,\text{Mpc}^{-3}}\right)^{-1/2}$$

- The absence of multiple-ν_μ-event sources implies:

$$n_s > 10^{-7}(\zeta/3)^{-3}/\text{Mpc}^3, \quad N_s > 10^6, \quad \frac{N_s}{4\pi} > 30/\deg^2, \quad L_\nu < 3\times 10^{42}\,\text{erg/s}$$

Implications:

- Source identification by angular correlation unlikely ($d\Theta$~0.5deg, $N_\nu(z<0.1)/N_\nu$~1/20).
- Bright AGN (FSRQ, BL Lac, n~$10^{-11}(10^{-8})/\text{Mpc}^3$)- Ruled out.
- Starbursts, n~$10^{-5}/\text{Mpc}^3$- a few should be detected with A X 10.

[Murase & EW 15]

Identifying the CR sources

- IC's ν's are produced by the "calorimeters" surrounding the sources.
- $\Delta\Theta$~1deg → Identification by angular distribution impossible.

- Our only (realistic) hope:
  Identification of transient sources by temporal $\nu-\gamma$ association.

* UHE CR source must be transient:
  $L>10^{47}$erg/s, GRBs or bright (yet to be detected) AGN flares.

- Requires:
  Wide field EM monitoring,
  Real time alerts for follow-up of high E ν events,
  and
  Significant increase of the ν detector mass at ~100TeV
  [Φ_ν(source) may be << Φ_ν(calorimeter)~Φ_{WB} [e.g. Φ_ν(GRB) ~0.1 Φ_{WB}]].

Source candidates & physics challenges

- Electromagnetic acceleration in astrophysical sources requires

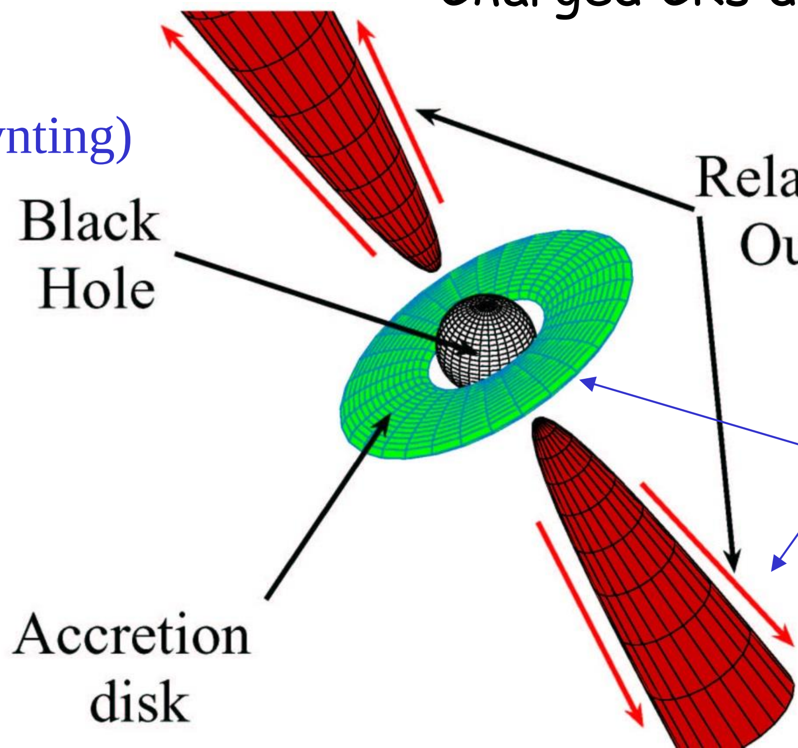
  $L > 10^{14} L_{Sun} (\Gamma^2/\beta) (\varepsilon/Z\ 10^{20} eV)^2$ [Lovelace 76; EW 95, 04; Norman et al. 95]

- GRB: $10^{19} L_{Sun}$, $M_{BH} \sim 1 M_{sun}$, $\dot{M} \sim 1 M_{sun}/s$, $\Gamma \sim 10^{2.5}$

  AGN: $10^{14} L_{Sun}$, $M_{BH} \sim 10^9 M_{sun}$, $\dot{M} \sim 1 M_{sun}/yr$, $\Gamma \sim 10^1$

- No steady sources at $d < d_{GZK}$ → Transient Sources (AGN flares?), Charged CRs delayed compared to γ's.

Energy extraction;
Jet acceleration and
content (kinetic/Poynting)



Particle acceleration,
Radiation mechanisms

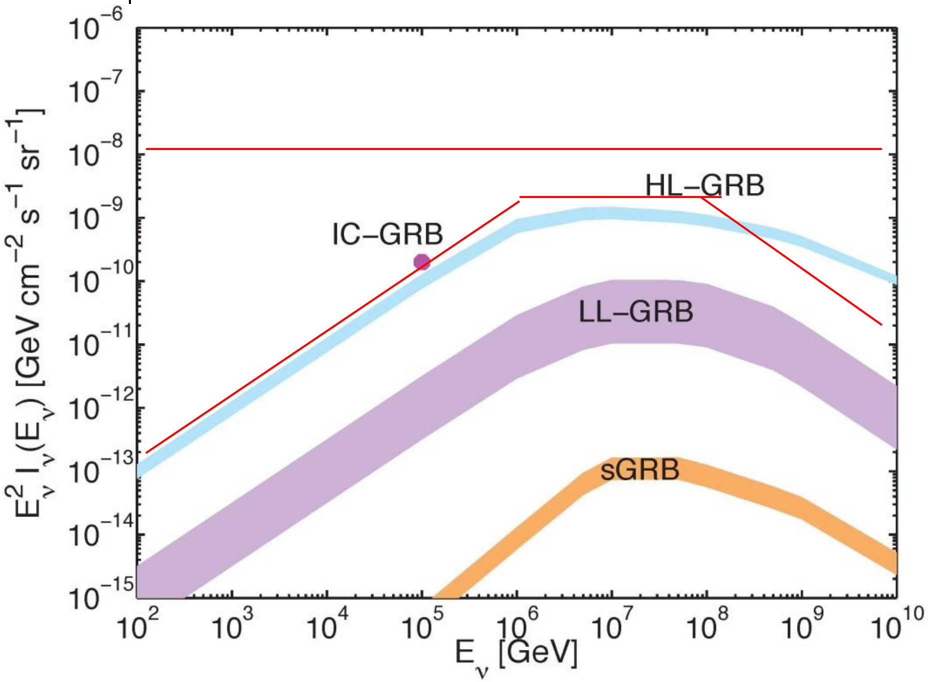
A note on GRBs

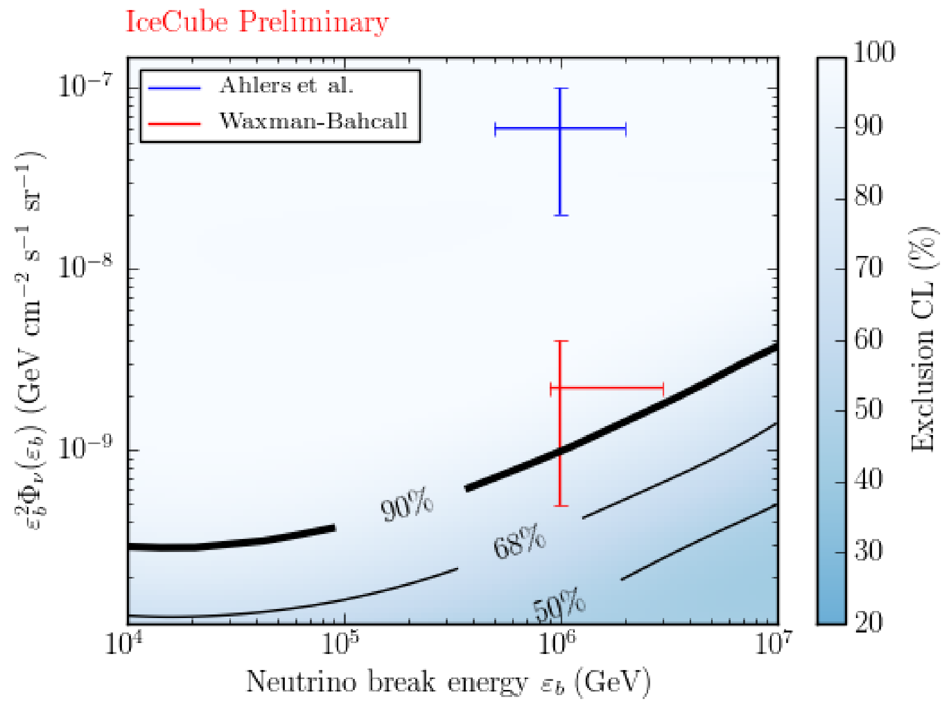
$$\varepsilon_{\nu,b} = 500\left(\frac{\varepsilon_{\gamma,b}}{1\mathrm{MeV}}\right)^{-1}\Gamma_{2.5}^{2}\,\mathrm{TeV} \approx 1\mathrm{PeV}$$

$$\Phi_{\mathrm{GRB}} \approx 0.2\Phi_{\mathrm{WB}} \times \min\left[\frac{\varepsilon_{\nu}}{\varepsilon_{\nu,b}}, 1\right]$$

[EW & Bahcall 97]

$E^2\Phi$





IC is achieving relevant sensitivity.

[Tamborra & Ando 15;

Hummer, Baerwald, and Winter 12; Li 12; He et al 12 …]

What will we learn from $\nu-\gamma$ associations?

- Identify the CR sources.
  Resolve key open Qs in the accelerators' physics
  (BH jets, particle acceleration, collisionless shocks).

- Study fundamental/ν physics:
  - π decay → $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 (Osc.)→ $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1
    → τ appearance,
    [Learned & Pakvasa 95; EW & Bahcall 97]
  - GRBs: ν-γ timing (10s over Hubble distance)
    → LI to 1:10^{16}; WEP to 1:10^6 .
    [EW & Bahcall 97; Amelino-Camelia,et al.98; Coleman &.Glashow 99; Jacob & Piran 07]

- Optimistically (>100's of ν's with flavor identification):
  Constrain δ_{CP}, new phys.
  [Blum, Nir & EW 05; Winter 10; Pakvasa 10; … Ng & Beacom 14; Ioka & Murase 14; Ibe & Kaneta 14; Blum, Hook & Murase 14]

Summary

- IceCube detects extra-Galactic ν's. $\Phi_\nu=\Phi_{WB}$ at 50TeV-2PeV.

* The flux is as high as could be hoped for.
* $\Phi_\nu=\Phi_{WB}$ implies a connection with UHECRs.
* Explained if UHECR sources reside in "calorimeters"- starbursts, implying a single transient source for all >1PeV (>1GeV?) CRs.
* Strongly suggests UHECRs are p, G/XG transition at 10^{19}eV.

→ Closing in on the origin of Cosmic-Rays.

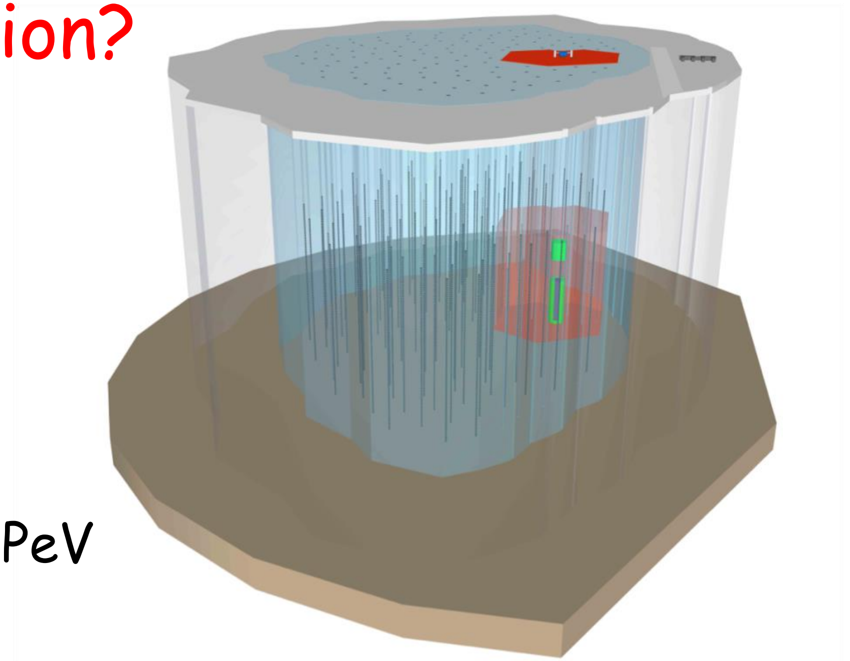
- Open Questions:

* Uncertainties in ν flux, spectrum, isotropy, flavor ratio.
* The CR/ν sources not identified [not unexpected].

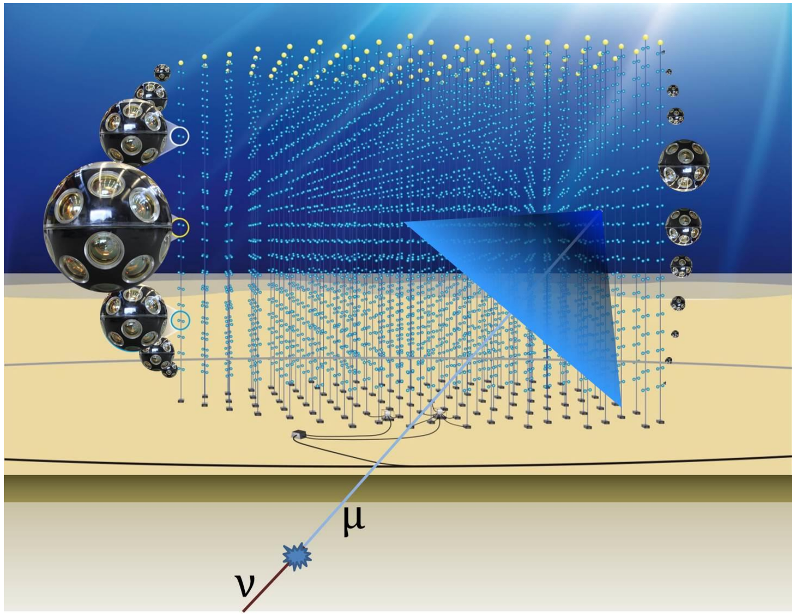
- Temporal ν–γ association is key to:

  CR sources identification, Cosmic accelerators' physics, Fundamental/ν physics.

What is required for the next stage of the ν astronomy revolution?



- IceCube's detection rate (~1/yr @ E>1 PeV, ~10/yr @ E>0.1PeV) insufficient for precision spectrum, flavor ratio and (an)isotropy, and for source identification.
  → Expansion of ν telescopes M_{eff} @ ~1PeV to ~10Gton (NG-IceCube, Km3Net).

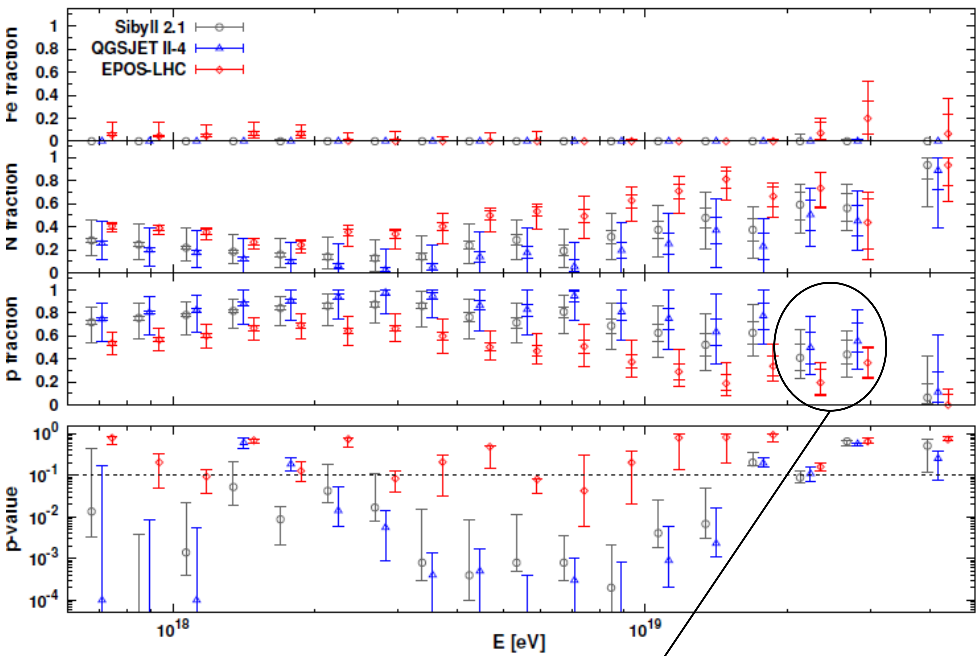


- Wide field EM monitoring.
- Adequate sensitivity for detecting the ~10^{10}GeV GZK ν's.
- HE γ-ray telescopes will play a key role

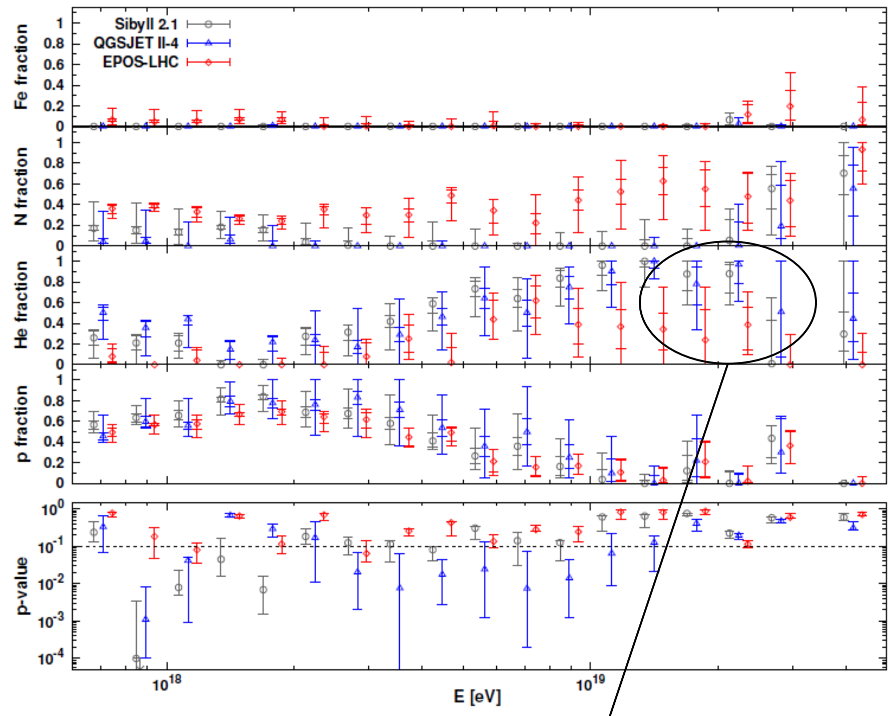
Backup Slides

Auger 2014: Fe out, He in

p+N



p+He+N



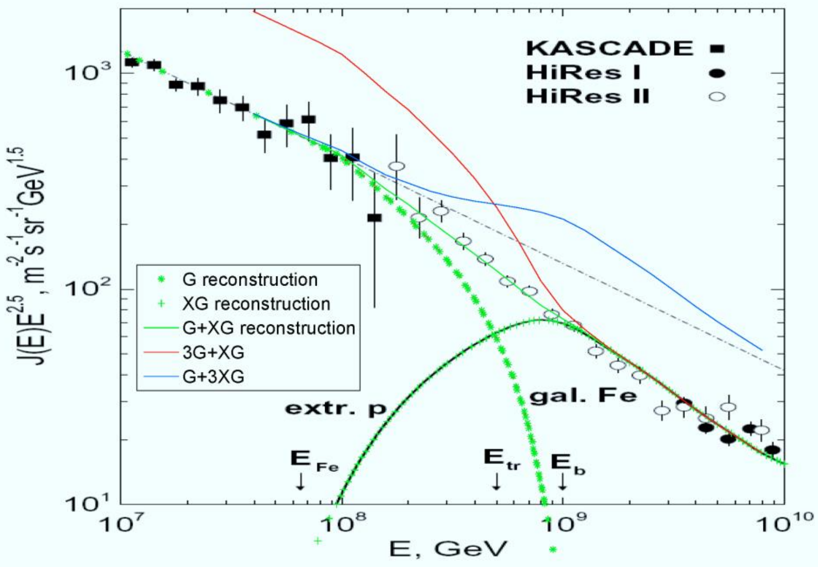
10%<p frac.<90%

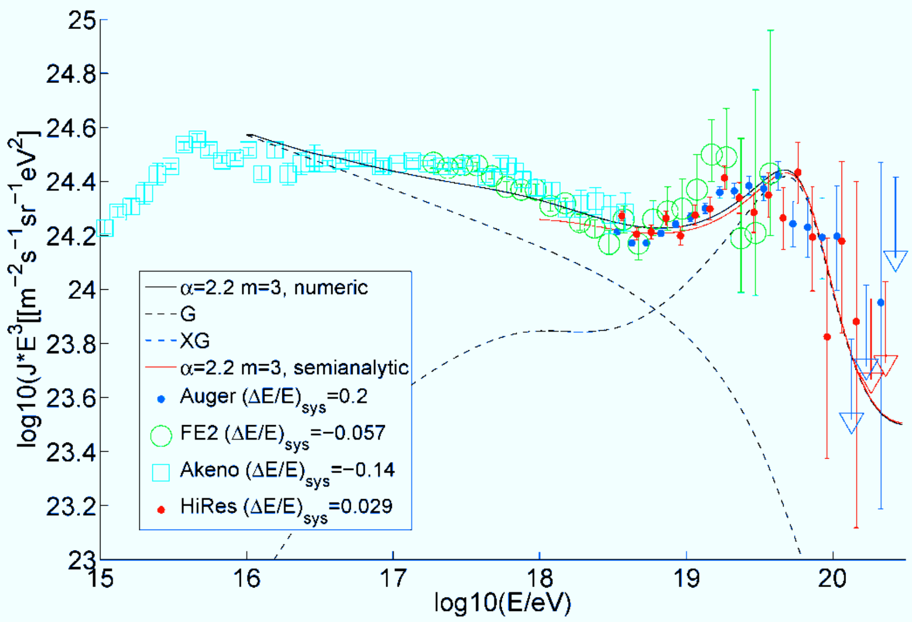
0%<He frac.<100%

Where is the G-XG transition?

@ E<10^{18}eV ?

dQ/dlog ε =Const → @ E~10^{19}eV





[Katz & EW 09]

- Fine tuning

Collisionless shock acceleration

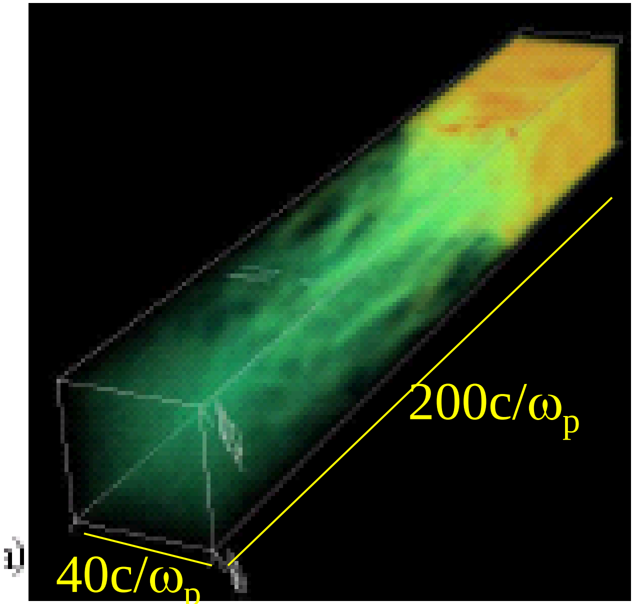
- The only predictive model.

- No complete basic principles theory, but
  - Test particle + elastic scattering assumptions give
    v/c<<1: dQ/d log ε=Const., [Krimsky 77]
    v/c~1: dQ/d log ε=Const.x$\varepsilon^{-2/9}$ (Γ>>1, isotropic scattering). [Keshet & EW 05]

  - Supported by basic principles plasma simulations,

    [Spitkovsky 06, Sironi & Spitkovsky 09, Keshet et al. 09, …, Sironi, Spitkovsky & Arons 13]

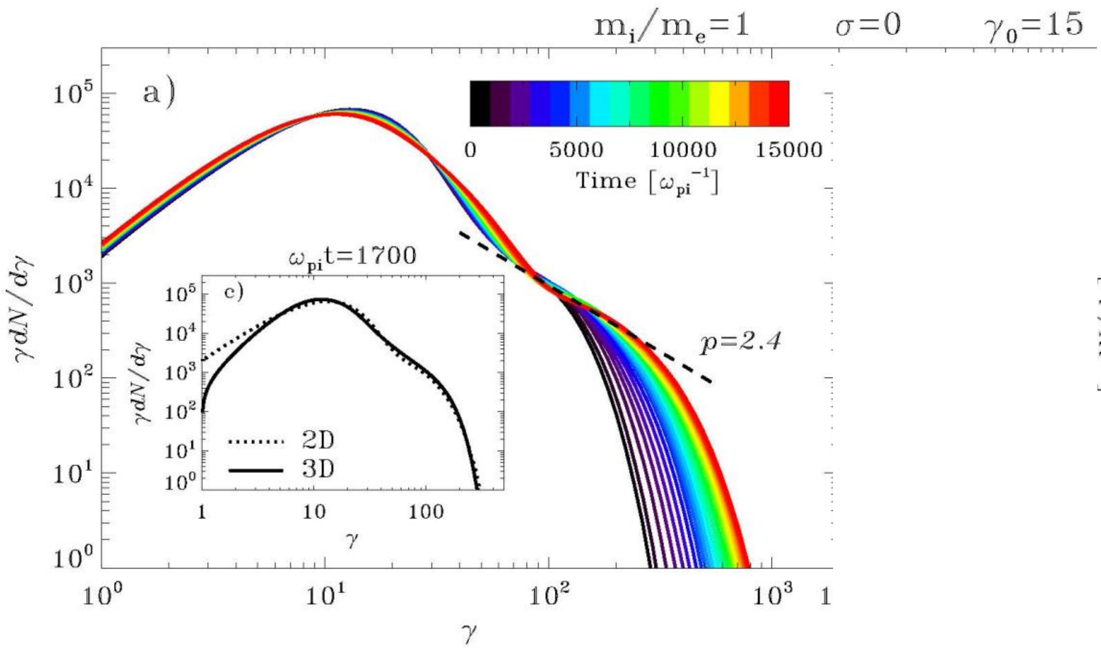
  - dQ/d log ε=Const Observed in a wide range of sources (lower energy p's in the Galaxy, radiation emission from accelerated e^-).

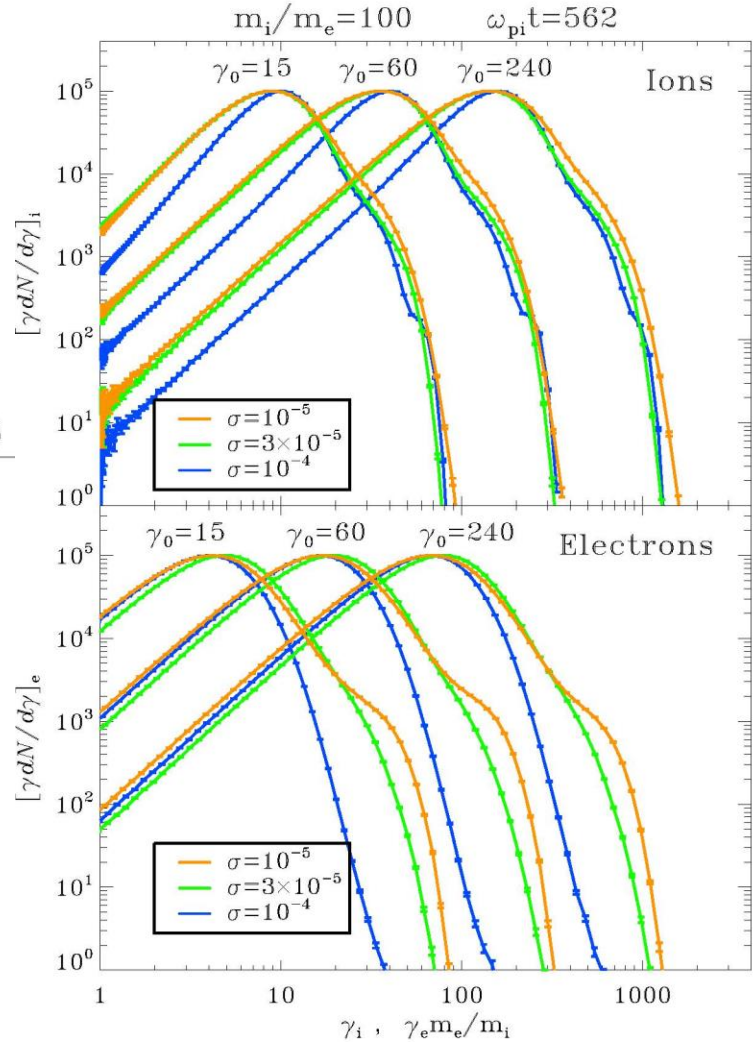


$$R_L(\varepsilon = \varepsilon_{thermal}) \approx \frac{c}{\omega_p}, \quad R_L \propto \varepsilon$$

Particle acceleration in collisionless shocks

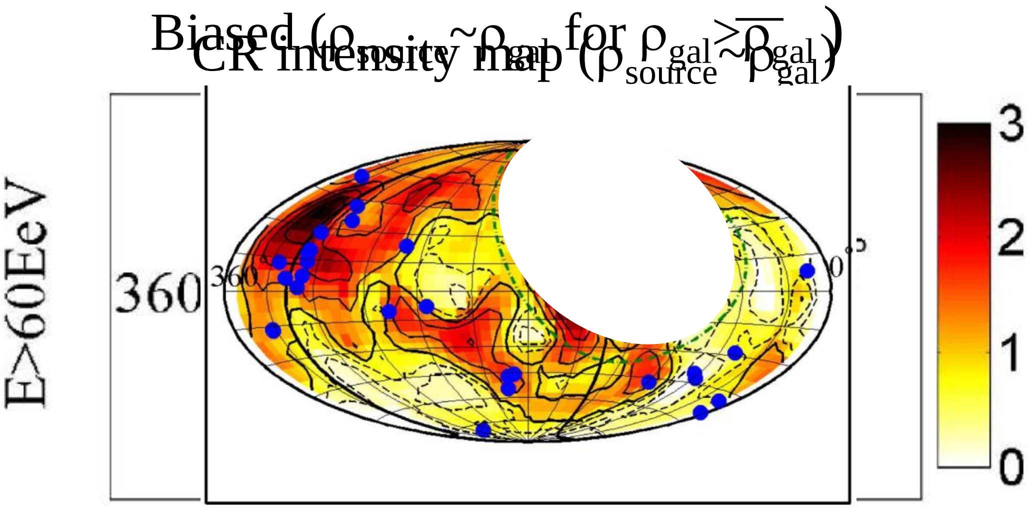
- No basic principles theory.
- Challenges:
  Self-consistent particle/B,
  Non linear with a wide range of temporal/physical scales.



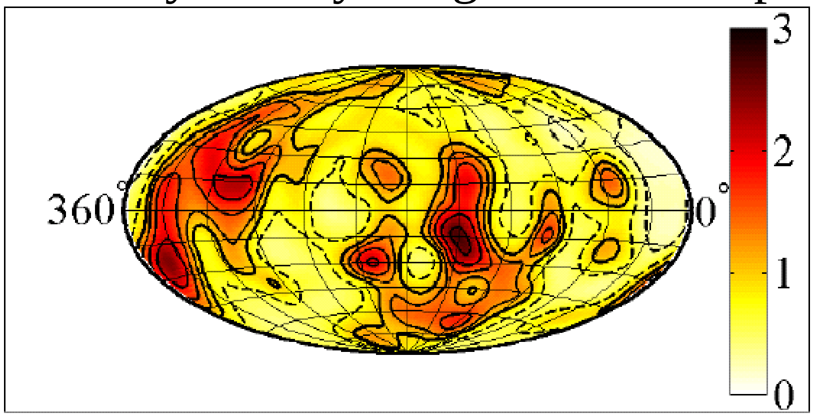


[Sironi, Spitkovsky & Arons 13]

UHE: Do we learn from (an)isotropy?



[Kashti & EW 08]



[EW, Fisher & Piran 97]

- Anisotropy @ 98% CL; Consistent with LSS

  [Kotera & Lemoine 08; Abraham et al. 08… Oikonomou et al. 13]

- TA 3(?)σ 20-degree "hotspot"? [Abbasi et al. 14]

- Anisotropy of Z at $10^{19.7}$eV implies

  Stronger aniso. signal due to p at $(10^{19.7}/Z)$ eV, since acceleration & propagation of p(E/Z)= Z(E).

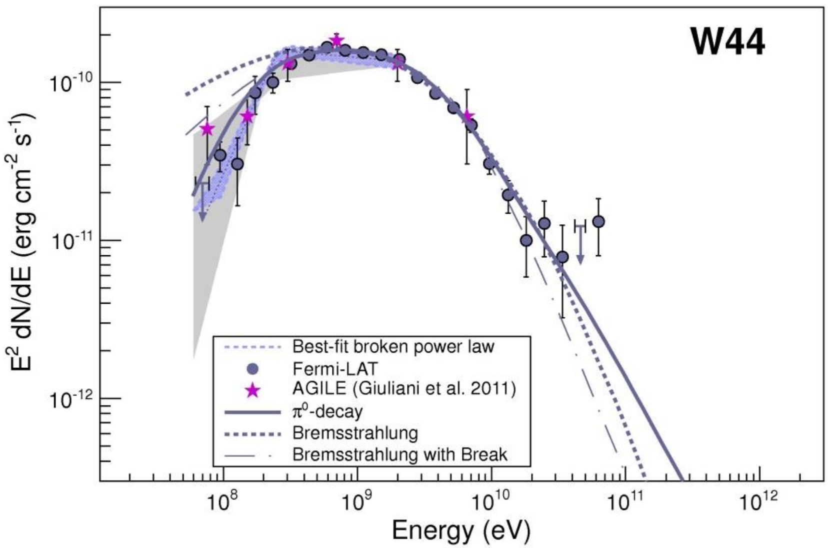
Not observed → No high Z at $10^{19.7}$eV

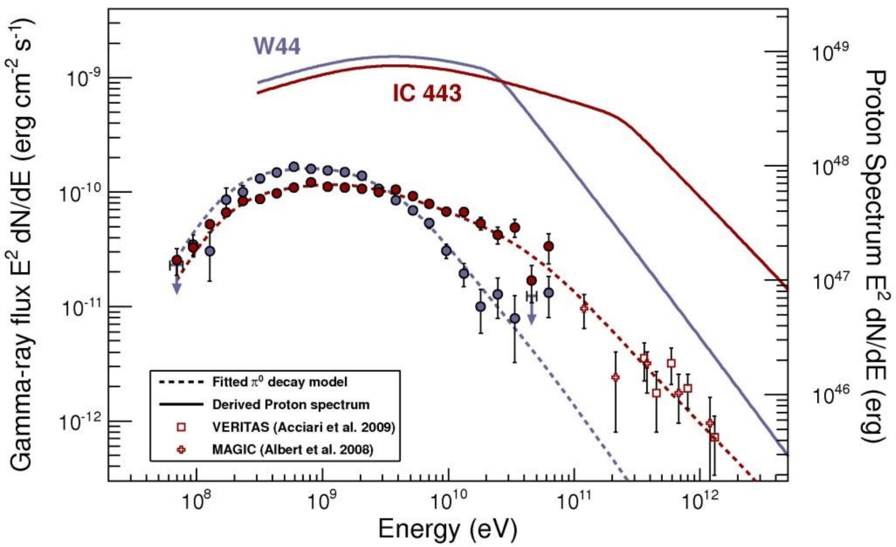
[Lemoine & EW 09]

Are SNRs the low E CR sources?

- So far, no clear evidence.
  Electromagnetic observations- ambiguous.

E.g.: “π decay signature” [Ackermann et al. 13]:



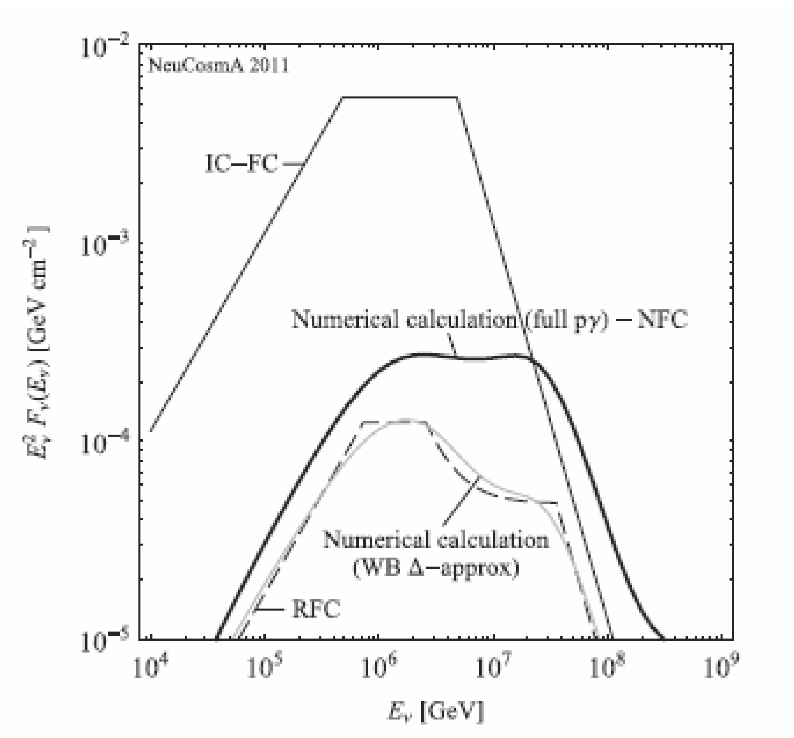


IceCube's GRB limits

- No ν's associated with ~200 GRBs (~2 expected).
- IC analyses overestimate GRB flux predictions, and ignore model uncertainties.
- IC is achieving relevant sensitivity.

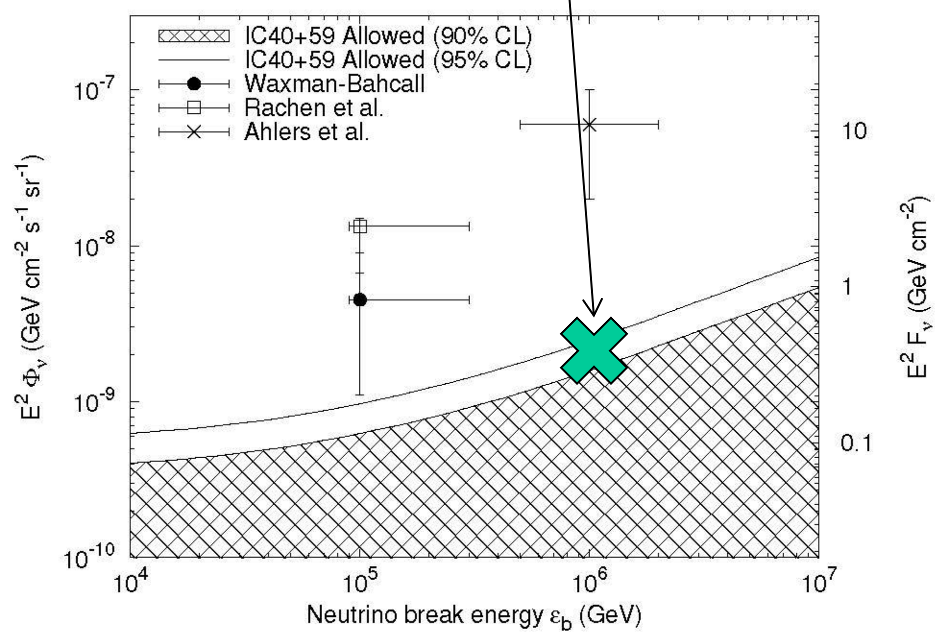
$$\varepsilon_{\nu,b} = 500\left(\frac{\varepsilon_{\gamma,b}}{1\mathrm{MeV}}\right)^{-1}\Gamma_{2.5}^{2}\,\mathrm{TeV} \approx 1\mathrm{PeV}$$

$$\Phi_{\mathrm{GRB}} \approx 0.2\Phi_{\mathrm{WB}}$$ [EW & Bahcall 97]



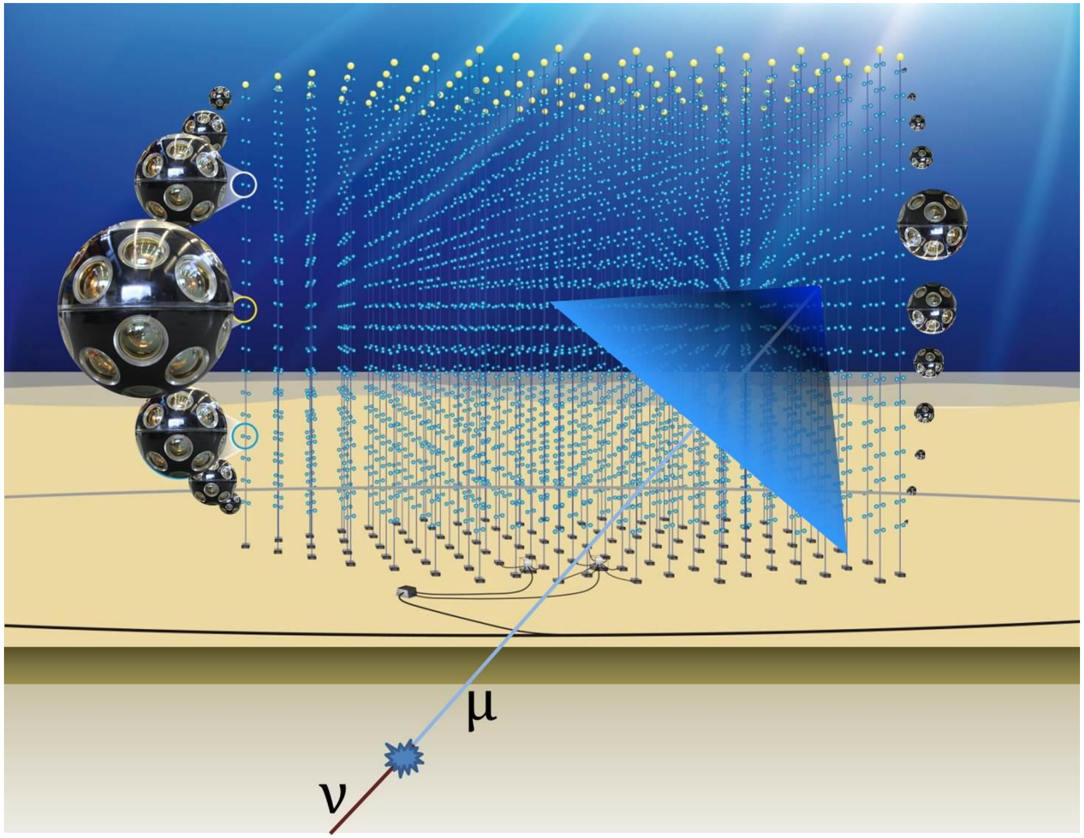
[Hummer, Baerwald, and Winter 12;

see also Li 12; He et al 12]



Future experimental developments

- IC extension
- Mediterranean
  Km3Net (~5x IC)



ARA & ARIANNA:
Coherent radio Cerenkov,
10^8 to 10^{10} GeV