IceCube's neutrinos: What we have learned

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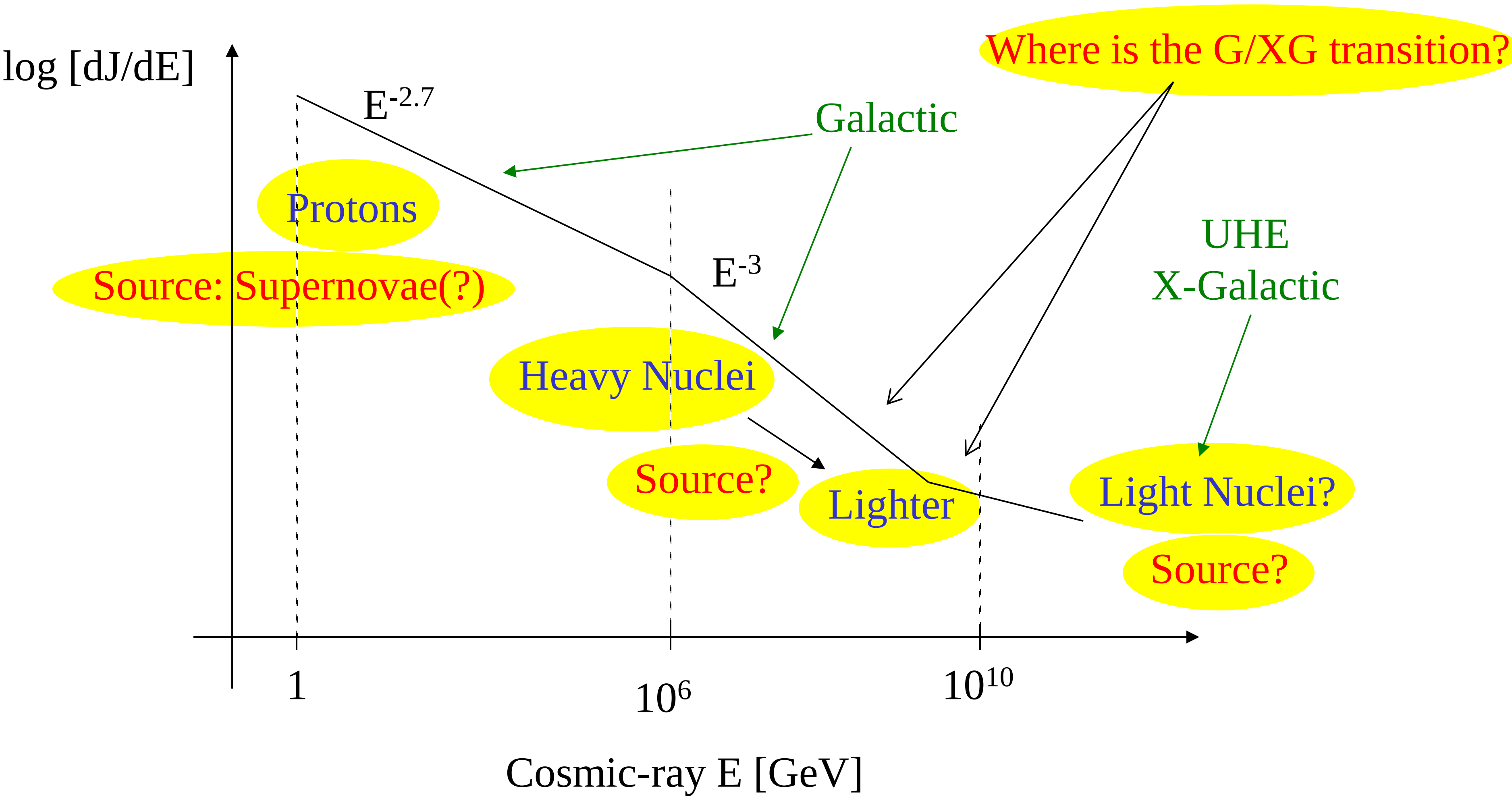
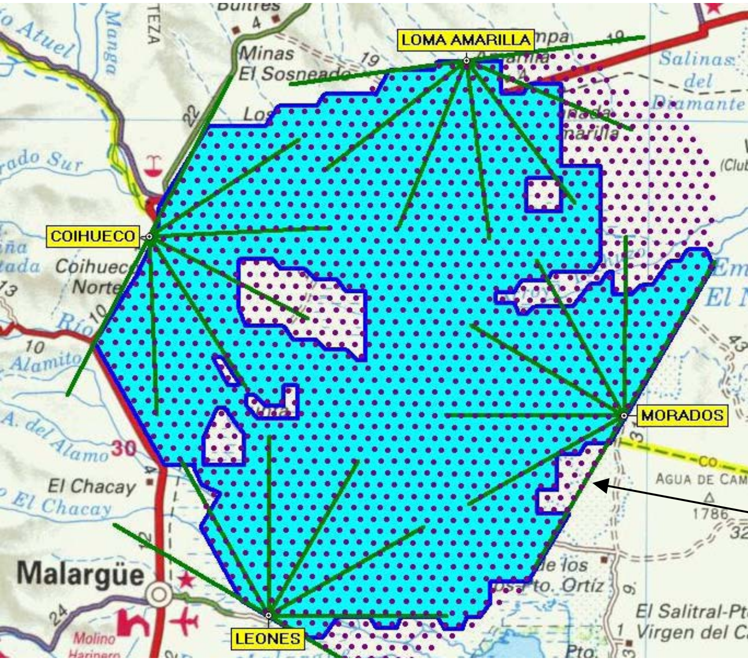
The main driver of HE ν astronomy: The origin of CRs



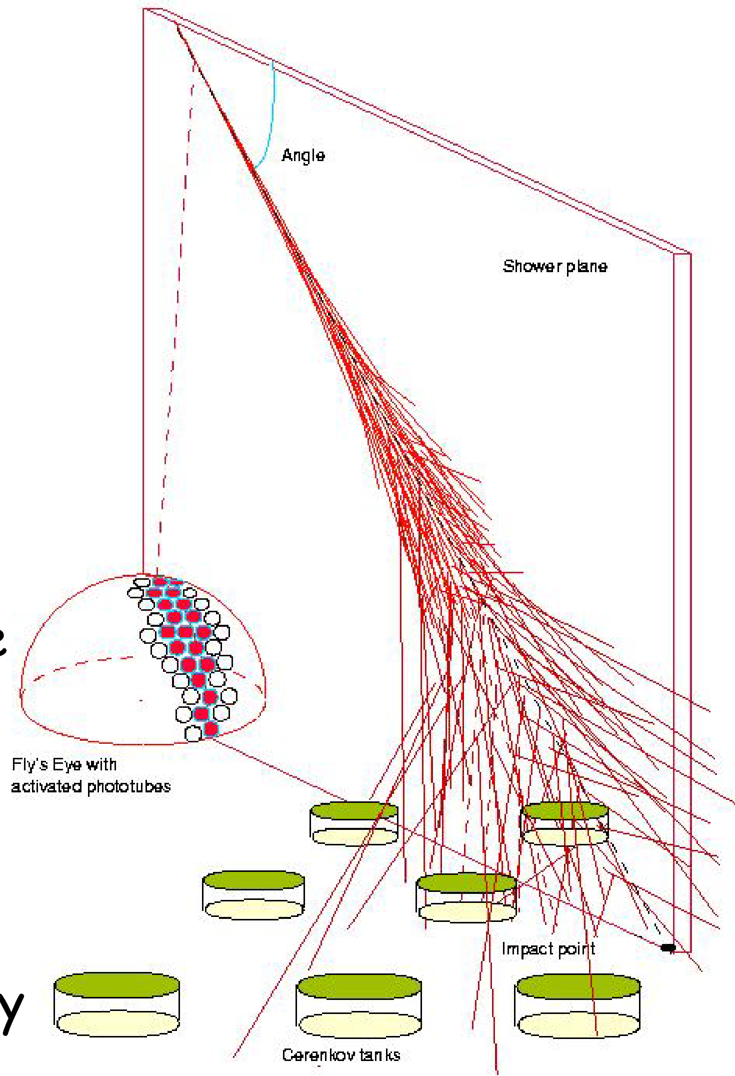
UHE, >10^{10}GeV, CRs



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

Auger:
3000 km^2

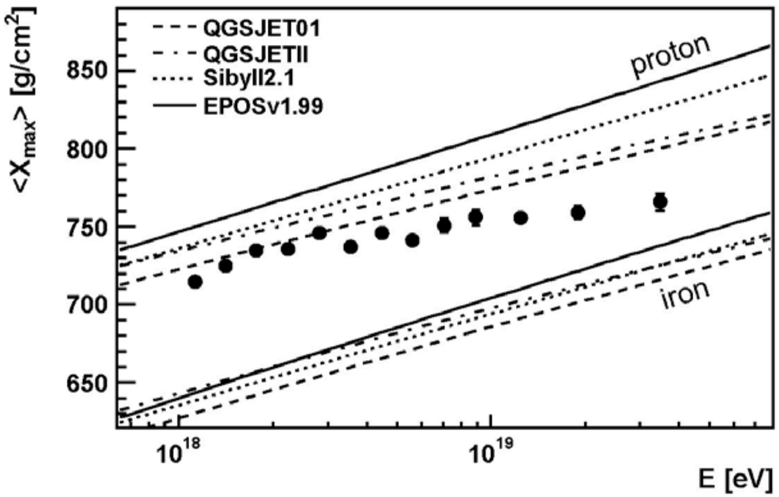
Fluorescence detector

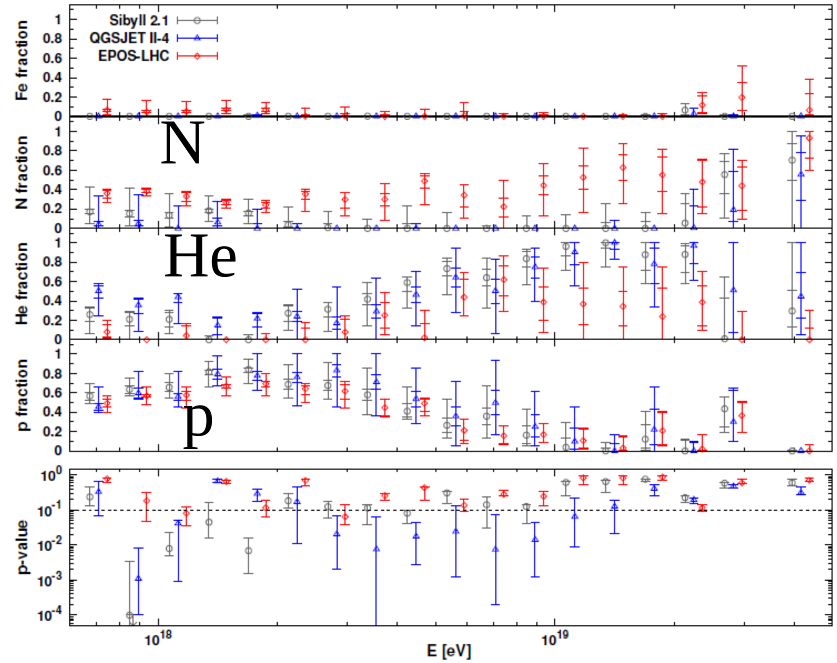


Ground array

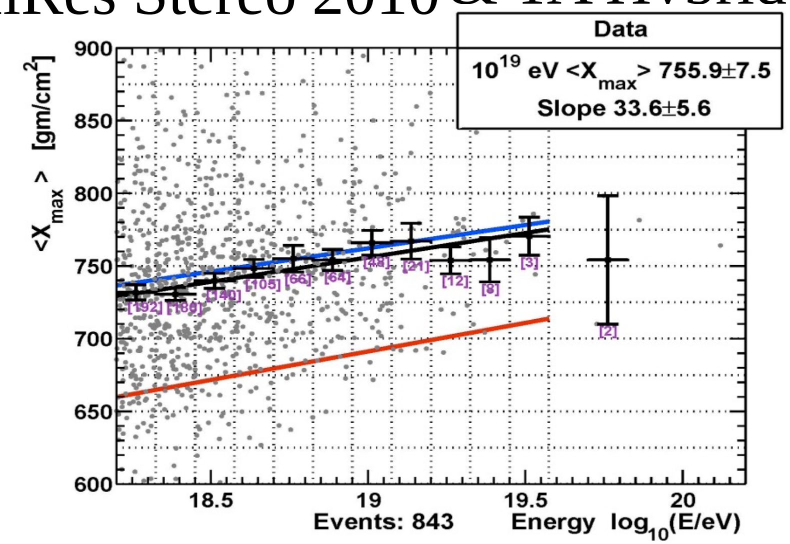
UHE: Composition

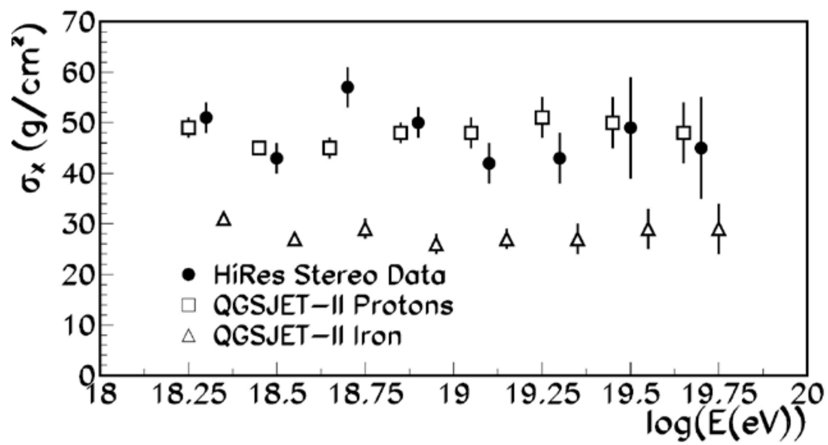
Auger 2010: Fe, 2015: He(??)





HiRes Stereo 2010 & TA Hybrid 2015

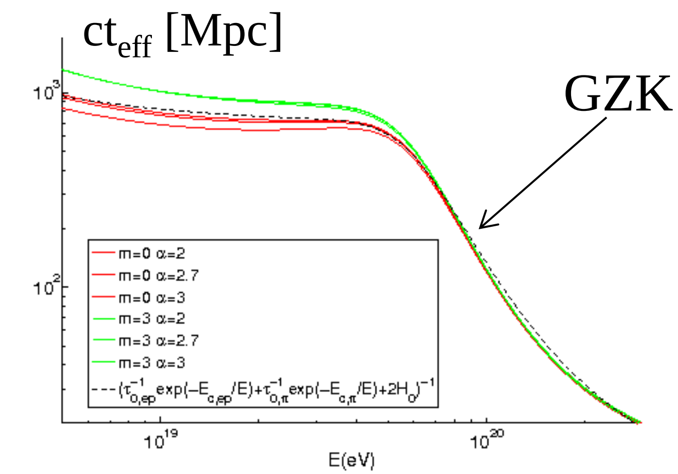


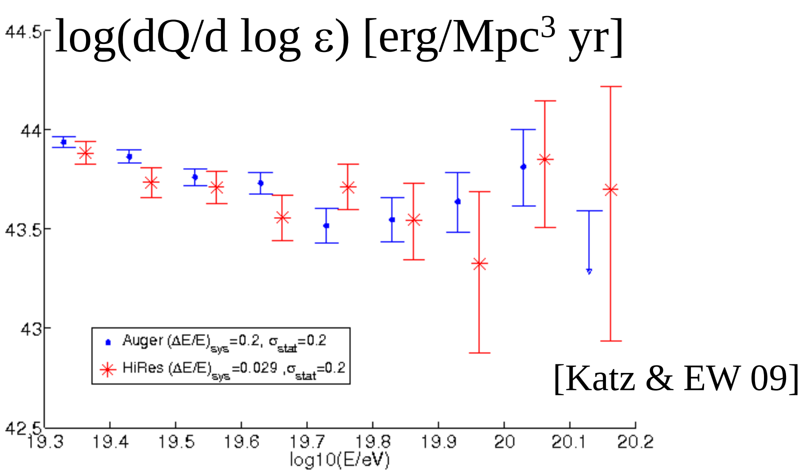


UHE: Energy production rate & spectrum

Protons

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

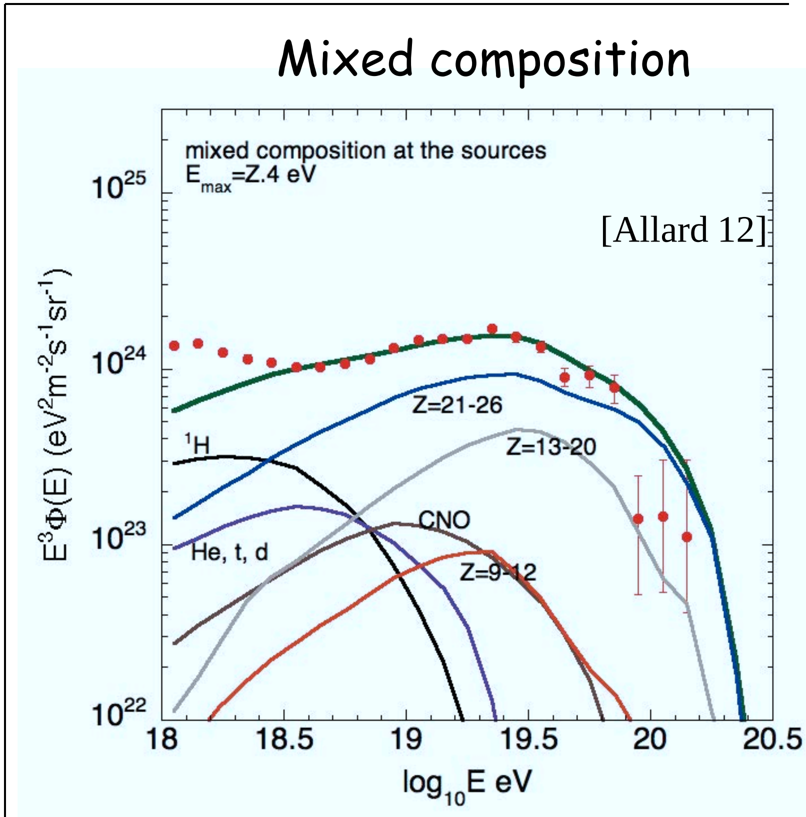




$$dQ/d\log\varepsilon \equiv \varepsilon_p^2 d\dot{n}_p/d\varepsilon_p = Const.$$

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

- 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).



Intermediate energy: Neutrinos

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

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

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

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

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

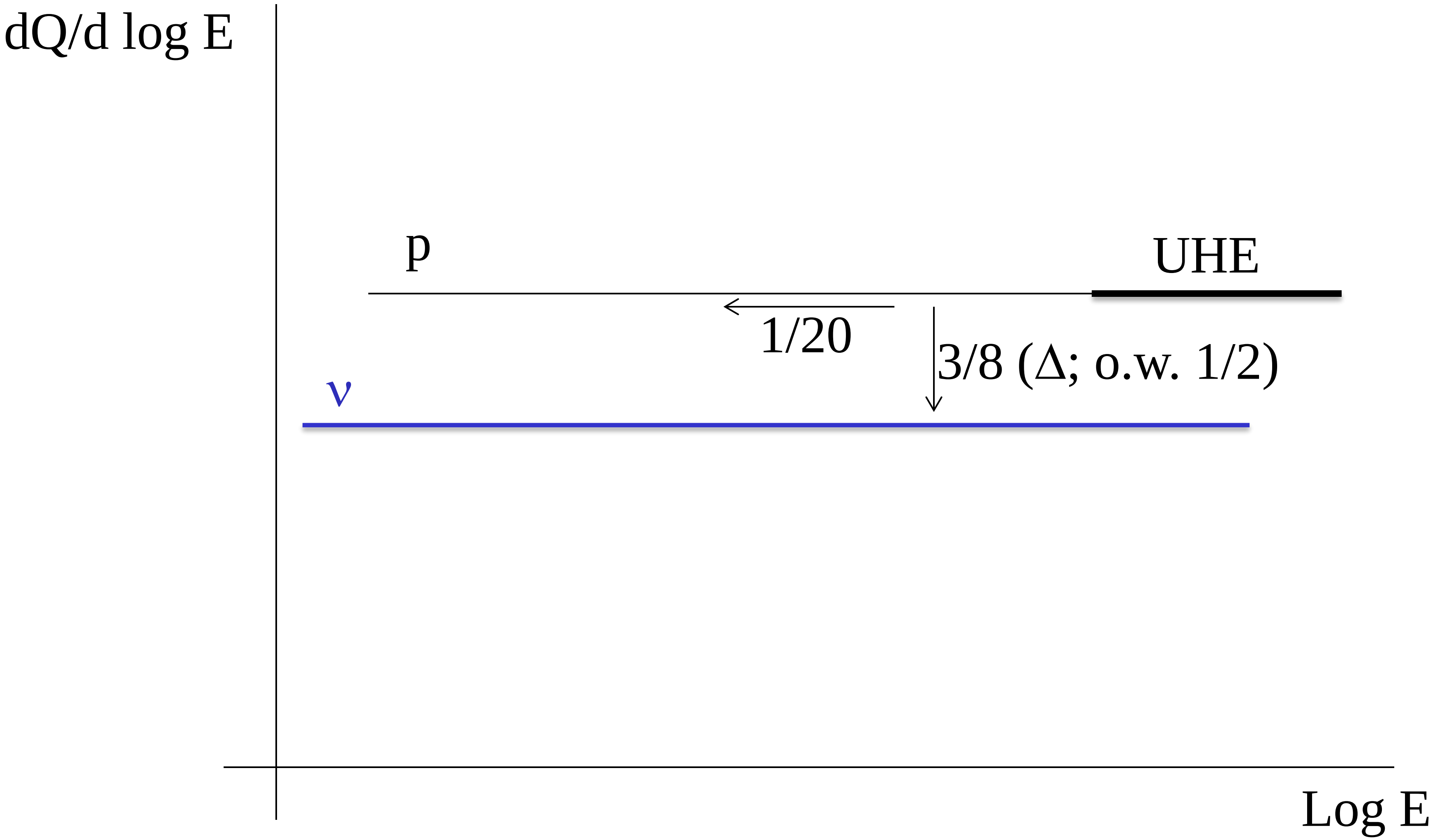
[EW & Bahcall 99;
Bahcall & EW 01]

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

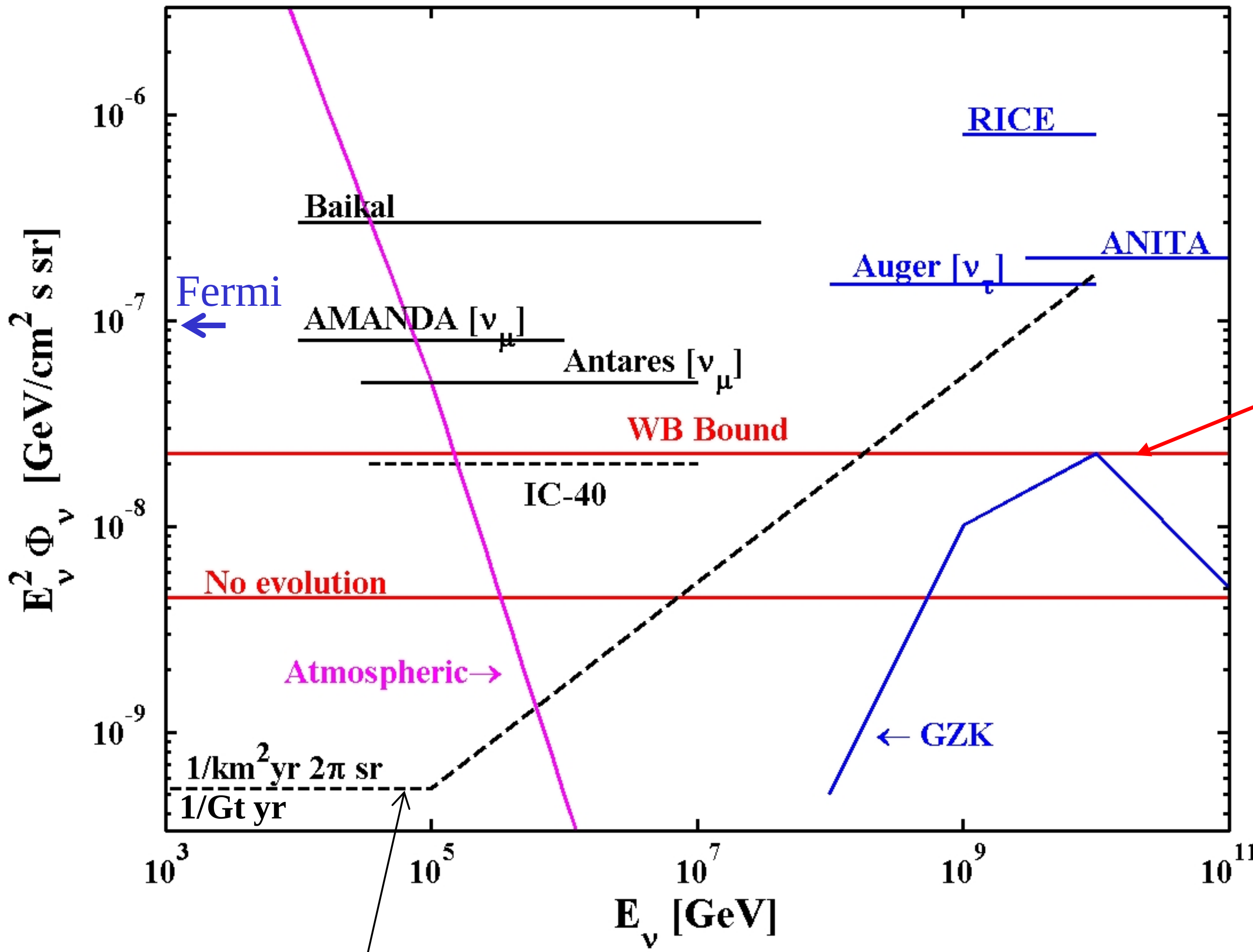
[Berezinsky & Zatsepin 69]

→ Identify primaries, determine f(z)

WB bound: p and ν production



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



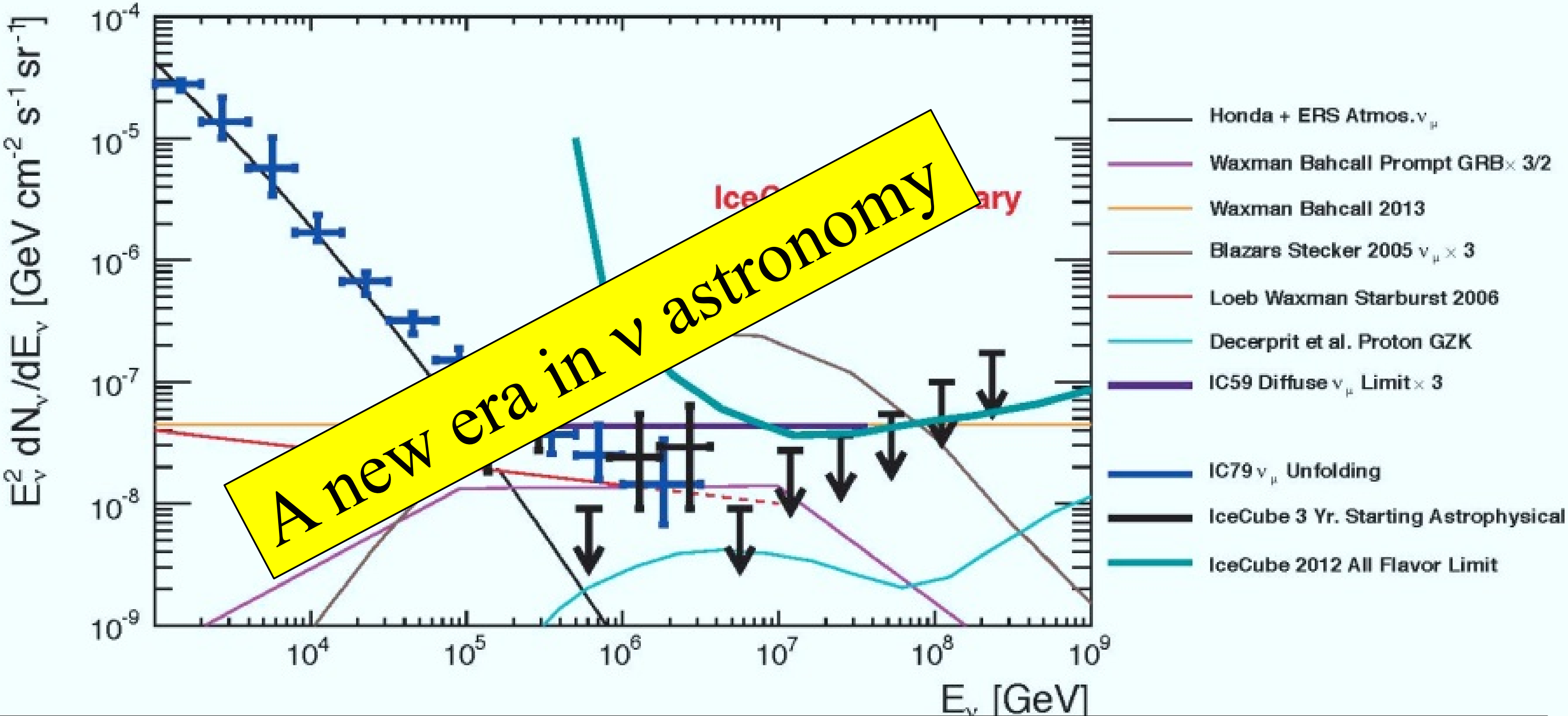
2 flavors,

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

Rate ~ $(E\Phi)N_n\sigma(E)$, σ~E → Rate ~ $(E^2\Phi)M$

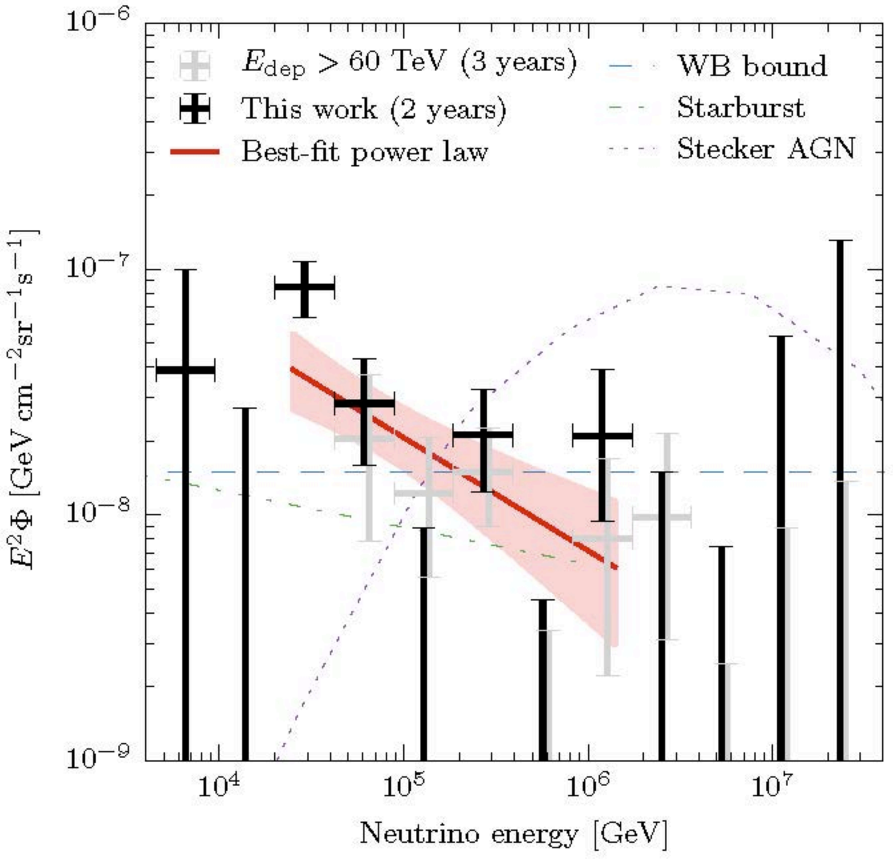
IceCube: 37 events at 50Tev-2PeV

~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]

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

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

- → XG sources.
- Recall: known UHECR sources cannot account for IC's flux ($\tau_{\gamma p(pp)}$<1)

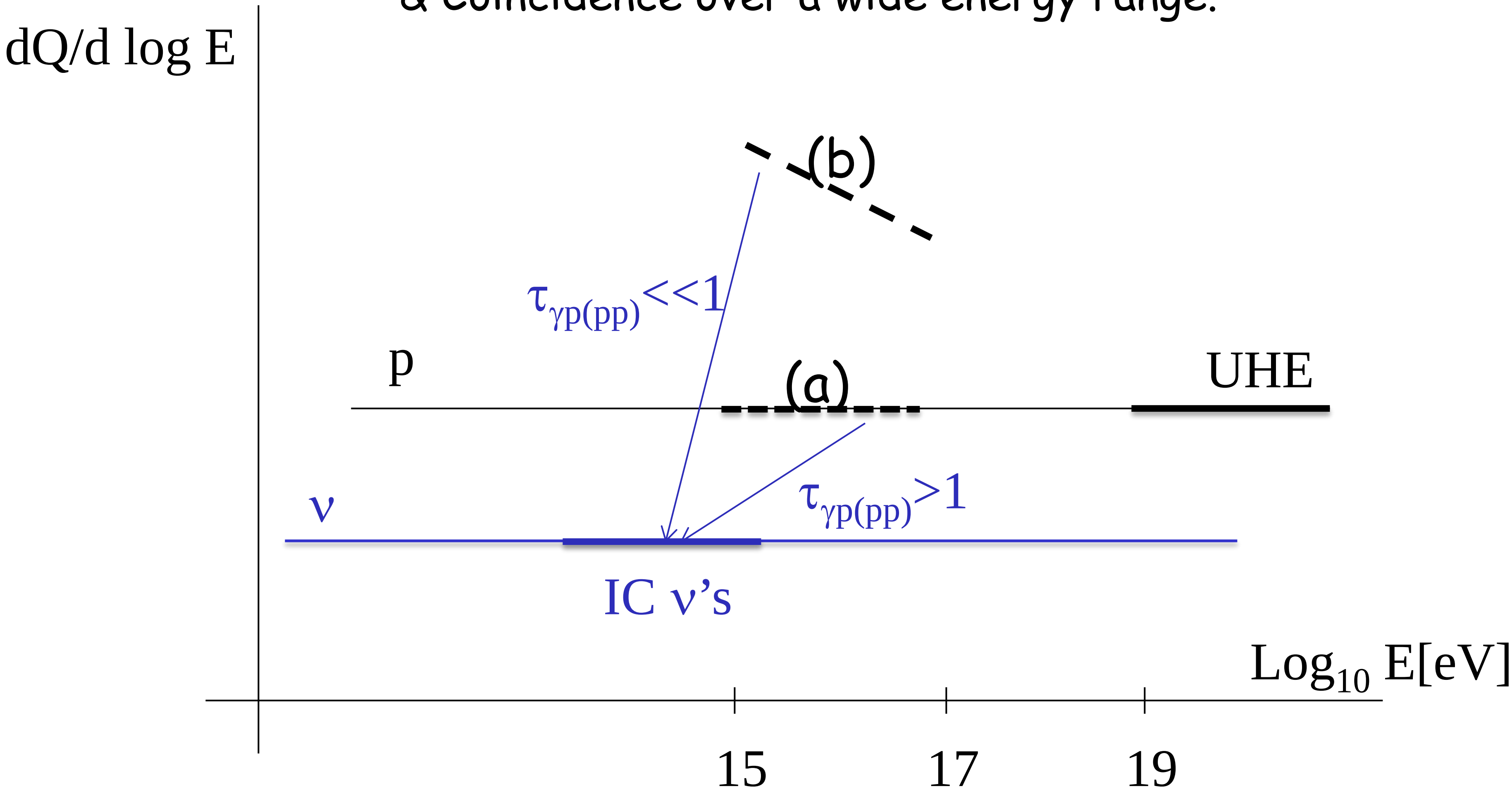
[e.g. Murase et al. 2014].

IceCube's detection: XG CR pion production

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

or

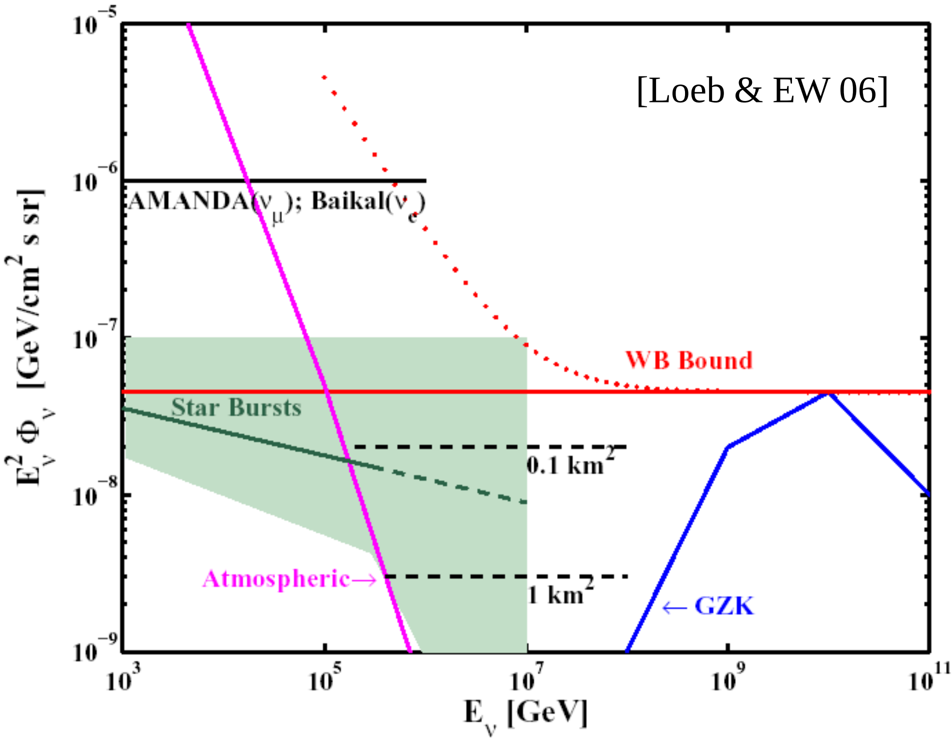
(b) $Q \gg Q_{UHE}$ sources (unknown) with $\tau_{\gamma p(pp)} \ll 1$ (ad-hoc) & Coincidence over a wide energy range.



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:
  $\Phi_\nu(\varepsilon_\nu<1\text{PeV}) \sim \Phi_{WB}$.



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

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;

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Low Energy, ~10GeV

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

- Our Galaxy- using “grammage”, local SN rate

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

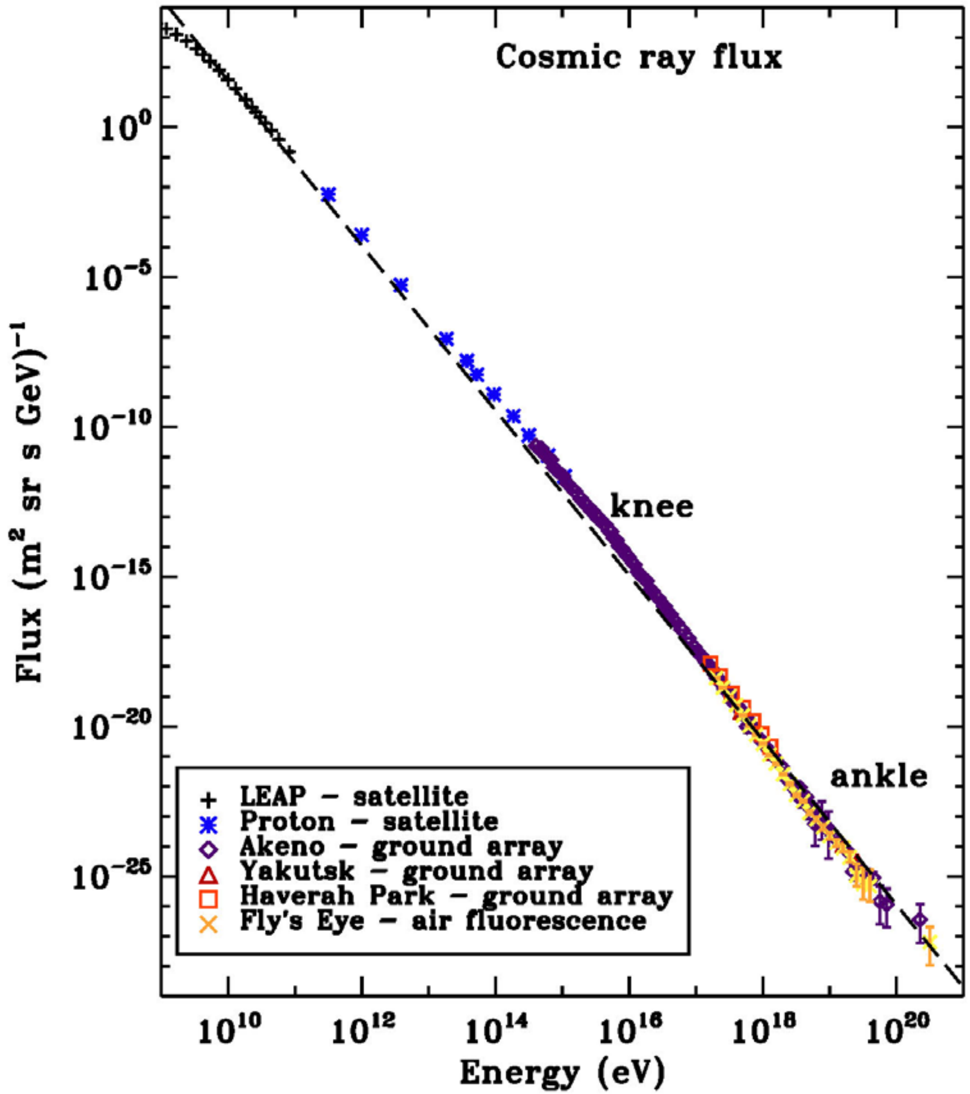
- Starbursts- using radio to γ observations

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

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

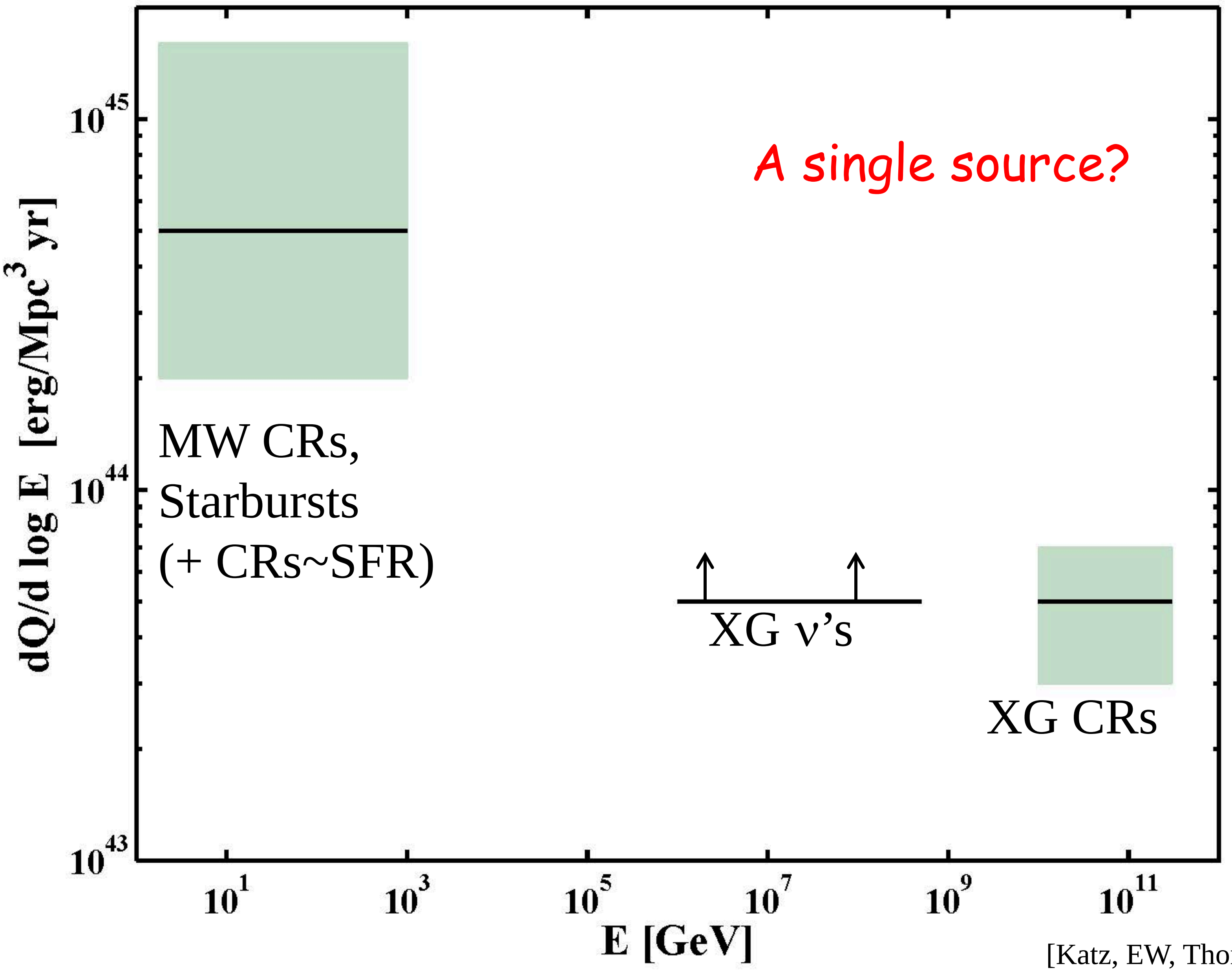
[Katz, EW, Thompson & Loeb 14]

The cosmic ray spectrum



[From Helder et al., SSR 12]

The cosmic ray generation spectrum



[Katz, EW, Thompson & Loeb 14]

Constraints on source density

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

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

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

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

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

Implications:

- Source identification by angular correlation unlikely (dΘ~0.5deg).
- Bright AGN (FSRQ, BL Lac, n~10^{-11}(10^{-8})/Mpc^3)- Ruled out.
- Starbursts, n~10^{-5}/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.

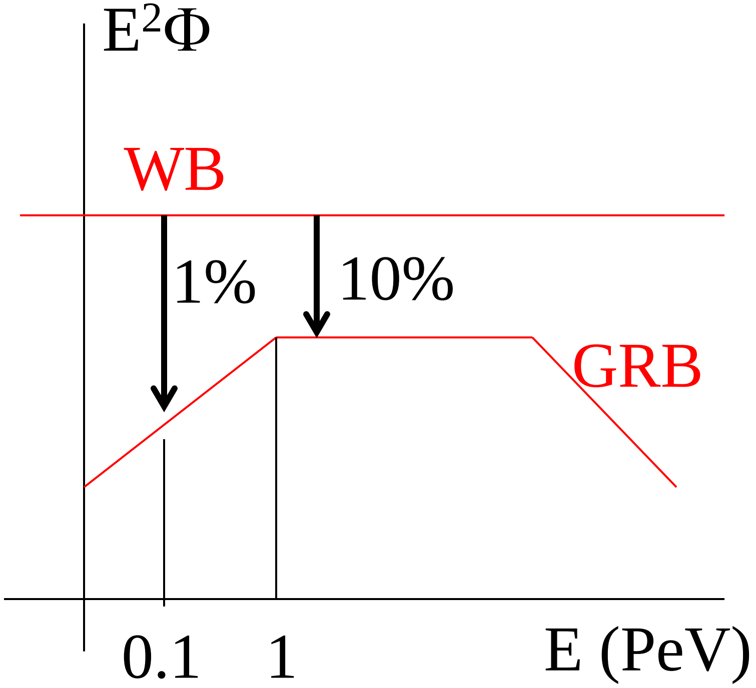
- Requires:
  Wide field EM monitoring,
  Real time alerts for follow-up of high E ν events,
  and
  Significant increase of the ν detector mass at ~100TeV
  [Φ_ν(source) may be << Φ_ν(calorimeter)~Φ_{WB} [e.g. Φ_ν(GRB) ~0.1 Φ_{WB}]].

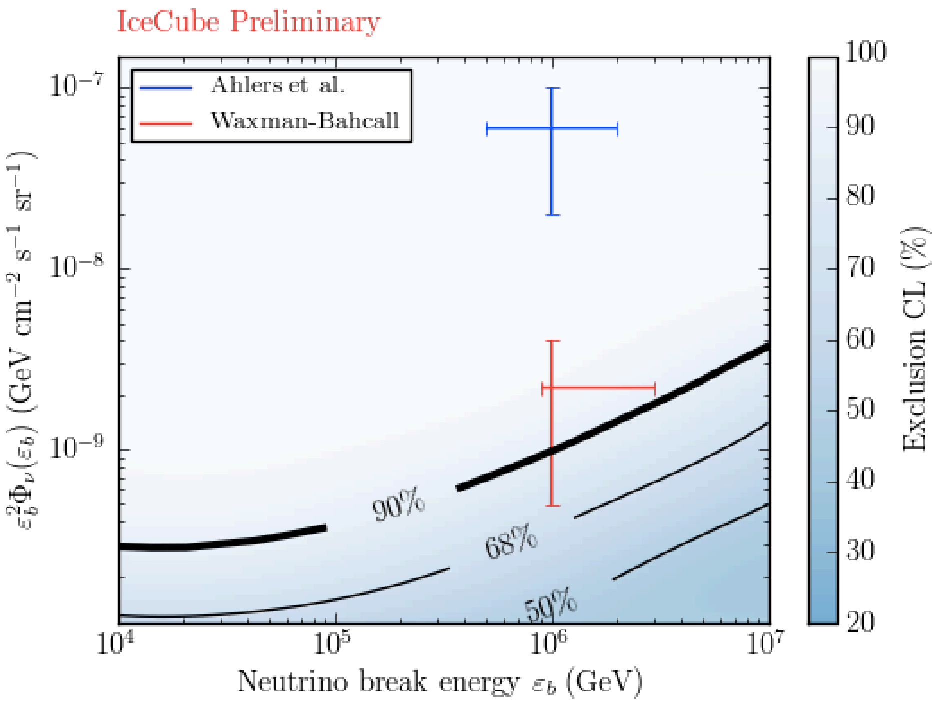
A note on GRBs

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

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

[EW & Bahcall 97]





- IC is achieving relevant sensitivity.

[For recebnt numerical calculations see, e.g. Hummer, Baerwald, and Winter 12; Li 12; He et al 12 … Tamborra & Ando 15]

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.

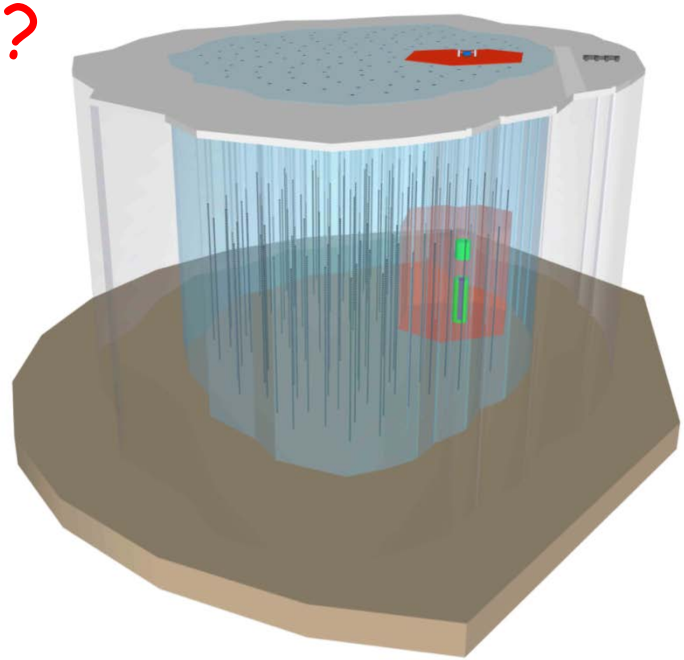
* The CR/ν sources not identified [not unexpected].

* Sensitivity close to enabling detection of GRB transients.

- Temporal $\nu-\gamma$ 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.