What do we learn from the recent cosmic-ray positron measurements?

K. Blum*, B. Katz*, E. Waxman
Weizmann Institute

*currently at IAS, Princeton

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PAMELA 09

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Letter

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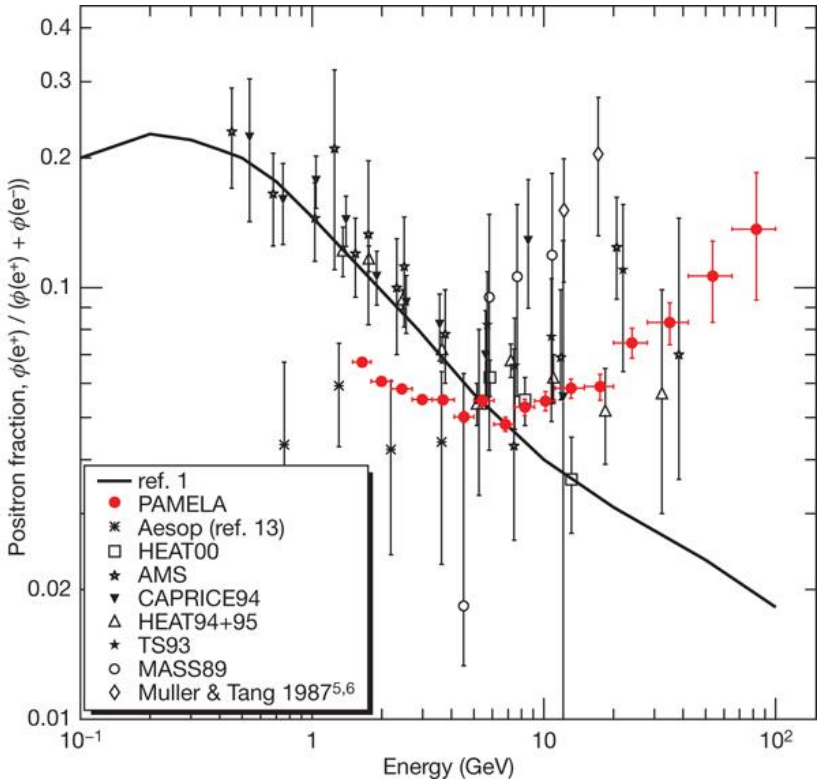
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

…Our results clearly show an increase in the positron abundance at high energy that cannot be understood by standard models describing the secondary production of cosmic-rays.



The positron "anomaly"

- A common argument:

$$\frac{n_+(E)}{n_e(E)} = \frac{\dot{n}_+ \tau_{+,\text{conf.}} f_{+,\text{rad}}}{\dot{n}_e \tau_{e,\text{conf.}} f_{e,\text{rad}}} \propto \frac{n_p \tau_{+,\text{conf.}} f_{+,\text{rad}}}{\dot{n}_e \tau_{e,\text{conf.}} f_{e,\text{rad}}} = \frac{\dot{n}_p \tau_{p,\text{conf.}} \tau_{+,\text{conf.}} f_{+,\text{rad}}}{\dot{n}_e \tau_{e,\text{conf.}} f_{e,\text{rad}}}$$

$$= \frac{\dot{n}_p}{\dot{n}_e} \frac{\tau_{+,\text{conf.}}}{\tau_{e,\text{conf.}}} \frac{f_{+,\text{rad}}}{f_{e,\text{rad}}} \tau_{p,\text{conf.}} \quad \propto \quad \tau_{p,\text{conf.}} \propto E^{-0.5}$$

- Unsubstantiated assumptions:

$$\dot{n}_p \propto \dot{n}_e, \qquad \frac{\tau_{+,\text{conf.}}}{\tau_{e,\text{conf.}}} = 1, \qquad \frac{f_{+,\text{rad}}}{f_{e,\text{rad}}} = 1$$

- The "anomaly" implies that (some of) these assumptions, which are not based on theory or observations, are not valid.

What is the e^+ excess claim based on?

- On assumptions not supported by data/theory

* primary e^- & p produced with the same spectrum,
and e^- and e^+ suffer same f_{rad}
→ $e^+/e^- \sim \Sigma_{sec} \sim \varepsilon^{-0.5}$

Or

* detailed assumptions RE CR propagation,
e.g. isotropic diffusion, $D \sim \varepsilon^{\delta}$,
within an ε-independent box
→ $f_{rad} \sim \varepsilon^{(\delta-1)/2}$

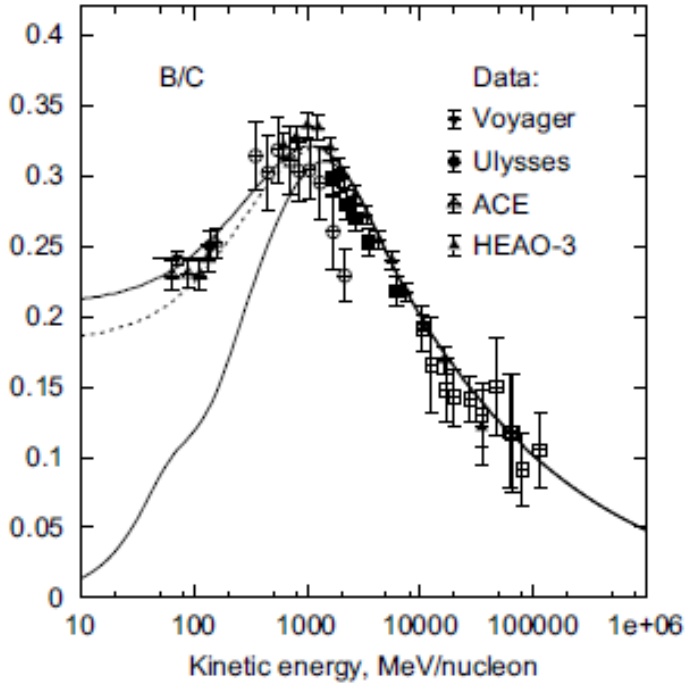
- If PAMELA/AMS correct, these assumptions are wrong

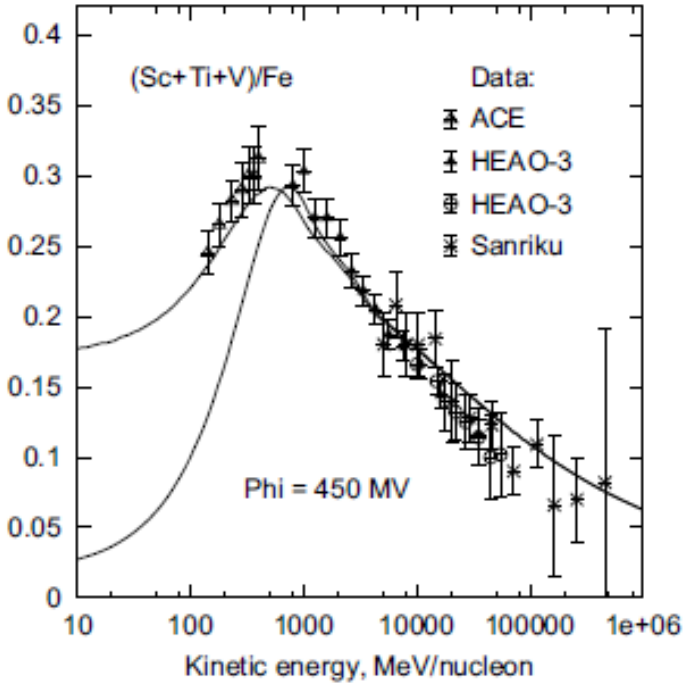
What we really know

- For all secondary nuclei (e.g. C → B, Be; …):

$$n_{\rm sec}(\varepsilon) = n_{\rm prim.} \times \sigma_{\rm eff.} \times n_{p,\rm ISM} c t_{\rm conf.} = n_{\rm prim.} \times \sigma_{\rm eff.} \times \frac{\Sigma_{\rm sec}(\varepsilon / Z)}{m_p}$$

$$\Sigma_{\rm sec} \approx 8.7 \left(\frac{\varepsilon}{10Z \text{ GeV}} \right)^{-0.5} \text{ g/cm}^2 ; \qquad \frac{n_{i,\rm sec}}{n_{j,\rm sec}} = \frac{\tilde{\sigma}_i}{\tilde{\sigma}_j}$$





Why does it work?

- We have no basic principles model for CR propagation.
- In general

$$\frac{dn_{i,\mathrm{sec},0}}{dE} = \sum_{j\neq i}\int d^3x \int dE' \frac{dn_j(x,E')}{dE'} n(x) \frac{d\sigma_{j\to i}(E',E)}{dE} cG(x,E/Z)$$

- If: The CR composition (n_j/n_p) is independent of x,
  The CR spectrum is independent of x
  (or: E/Z the same for prim. & sec.),

Then:

$$\frac{dn_{i,\mathrm{sec},0}}{dE} = n_{p,0}\frac{d\sigma_i}{dE}\frac{\Sigma_{\mathrm{sec}}}{m_p}, \quad \text{where}$$

$$\frac{d\sigma_i}{dE} \equiv \sum_{j\neq i}\frac{n_j}{n_p}\int dE' n_j^{-1}\frac{dn_j(E')}{dE'}\frac{d\sigma_{j\to i}(E',E)}{dE}$$

$$t_{\mathrm{sec}}(E/Z) \equiv \int d^3x \frac{n_p}{n_{p,0}}\frac{n(x)}{n_0}G(x,E/Z), \qquad \Sigma_{\mathrm{sec}}(E/Z) \equiv n_0 m_p c t_{\mathrm{sec}}(E/Z)$$

What we really know: application to e^+

- Positron secondaries:

$$n_{i,\mathrm{sec}}(E) = \left[\sum_{j\neq i} n_j \frac{\sigma_{j\to i}}{m_p} - \frac{n_i \sigma_i}{m_p}\right] \Sigma_{\mathrm{sec}}(E/Z)$$

$$\frac{n_{i,\mathrm{sec}}}{n_{j,\mathrm{sec}}} = \frac{\tilde{\sigma}_i}{\tilde{\sigma}_j} \quad \Rightarrow \quad n_+ = n_p \tilde{\sigma}_+ \frac{\Sigma_{\mathrm{sec}}(E/Z)}{m_p} \times f_{+,\mathrm{rad}}$$

Known from Lab

Measured from CR sec.

Suppression due to synchrotron
And inverse Compton energy loss

- A robust, model independent, upper limit:

$$n_+ \leq n_p \tilde{\sigma}_+ \Sigma_{\mathrm{sec}}(E/Z)/m_p$$

- Estimate f_{rad} at 20GeV from ^{10}Be (10^7yr): ~0.3
  (CMB and starlight ~1eV/cm^3, e^+ lifetime ~10^7yr).

Some cautionary notes

- t_{sec} is not the residence time

$$t_{\rm res}(E/Z) \equiv \int d^3x \frac{\dot{n}(x)}{<\dot{n}>} \int \frac{d^3x'}{V} G(x, E/Z; x')$$

- If G(x,x′) is independent of x′ then

$$t_{\rm res} = \frac{\dot{n}_0}{<\dot{n}>} t_{\rm sec}\,, \qquad \text{and} \qquad n_{i,0}(E) = \dot{n}_0 t_{\rm sec} = <\dot{n}> t_{\rm res}$$

- For particles with life time τ, f_{sec} depends on model assumptions. It may, e.g., attain the values τ/t_{res} or $V(t_{prop}<\tau)/V_G$ under different model assumptions.

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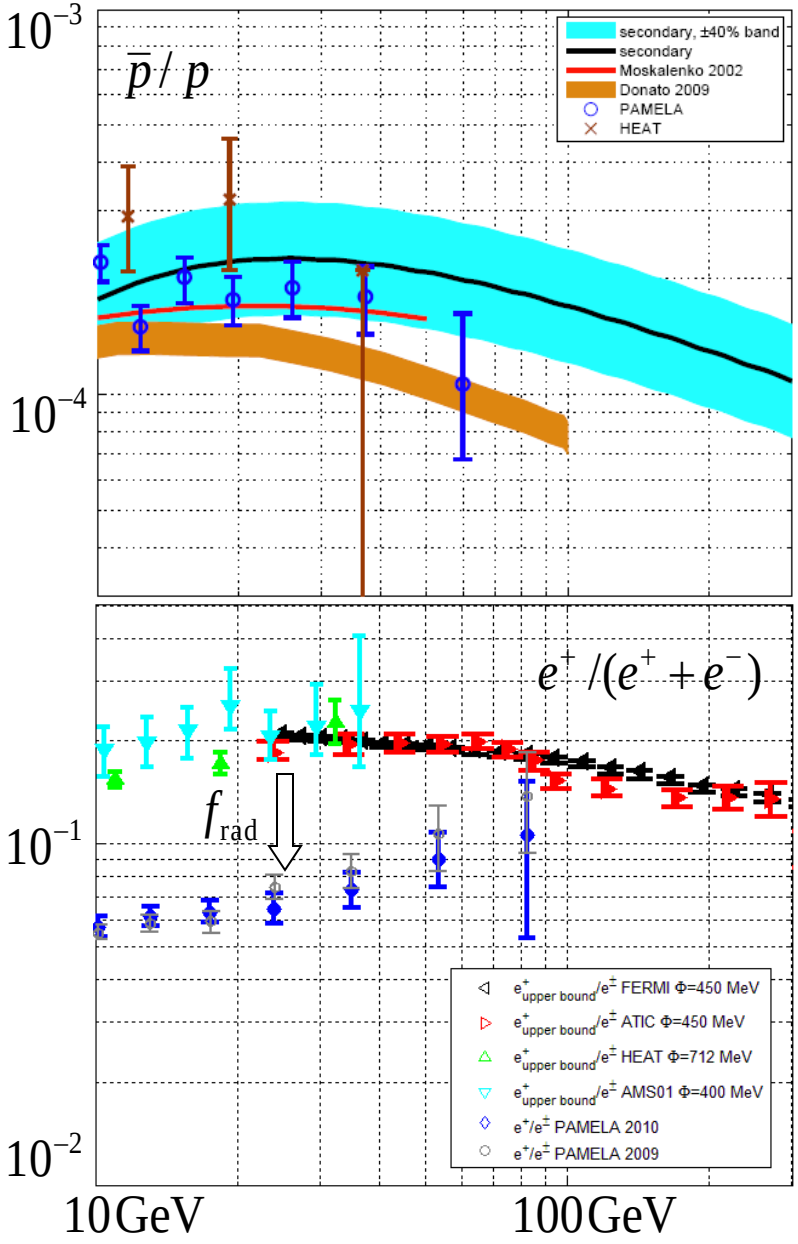


- For all secondaries (e.g. anti-p)

$$n_i(\varepsilon) = \left[\sum_{j\neq i} n_j \frac{\sigma_{j\to i}}{m_p} - \frac{n_i\sigma_i}{m_p}\right]\Sigma_{sec}(\varepsilon/Z)$$

$$\Sigma_{sec} \approx 8.7\left(\frac{\varepsilon}{10Z\ \mathrm{GeV}}\right)^{-0.5}\ \mathrm{g/cm^2}$$

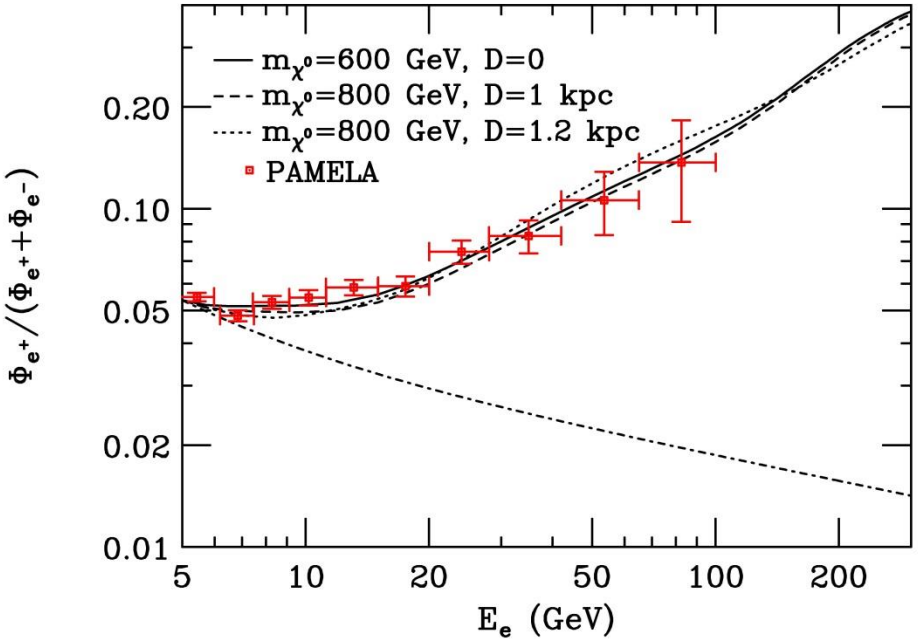
- Radiative e^+ losses- depend on propagation in Galaxy (poorly understood)

$$n_+(\varepsilon) = n_p\tilde{\sigma}_+\frac{\Sigma_{sec}(\varepsilon/Z)}{m_p}f_{rad}$$

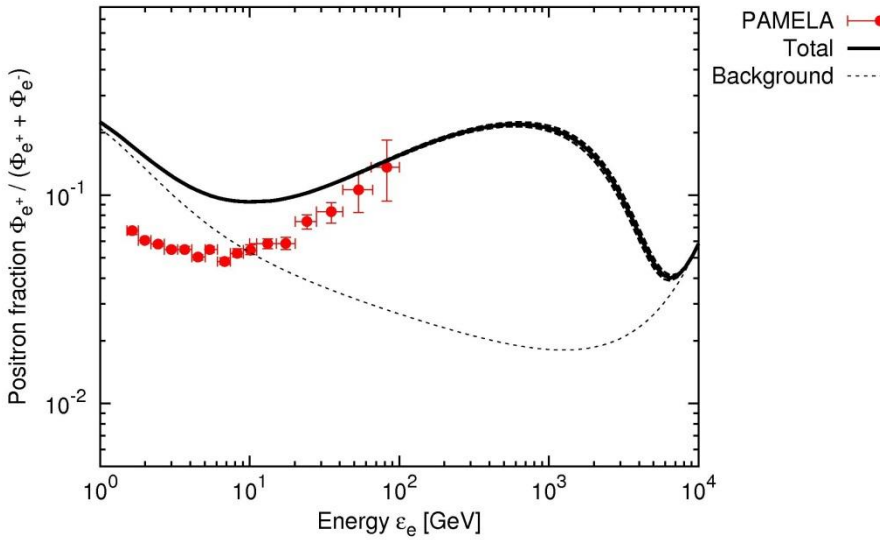
* At ~20GeV: f_{rad}~0.3~$f_{^{10}Be}$
  → e^+ consistent with 2ndary origin
* Above 20GeV:
  If PAMELA correct
  → energy independent $f_{rad}(\varepsilon)$

[Katz, Blum, Morag & EW 10]

Primary e+ sources

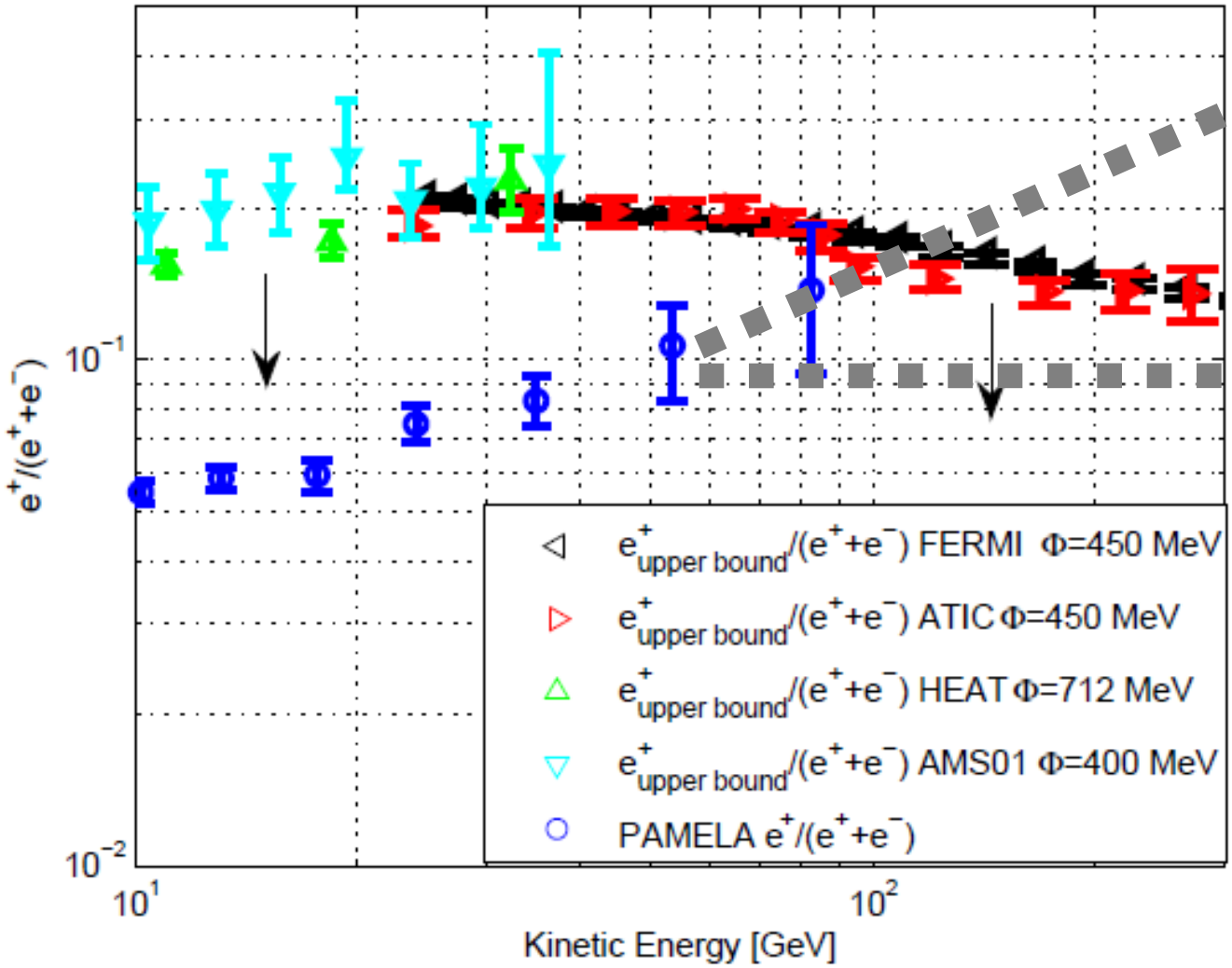


DM annihilation [Hooper et al. 09]



Pulsars [Kashiyama et al. 11]

New primary sources



?

Secondary origin

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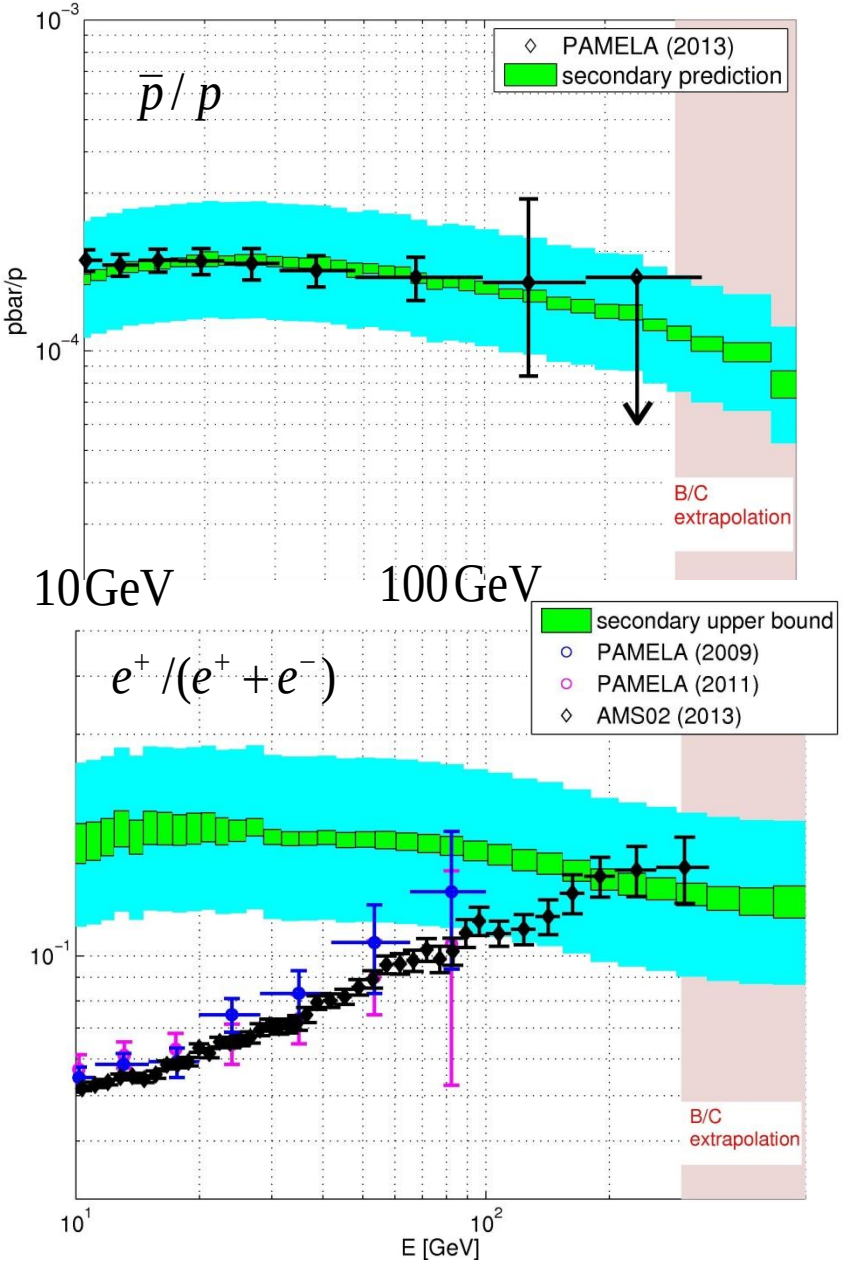


- Anti-p consistent with prediction.
- e^+ flux saturates at the secondary upper bound.
- The ABSOLUTE e^+ flux matches the secondary bound.
- In all primary e+ models (DM, pulsars…) there is no intrinsic scale that would explain why the ABSOLUTE observed flux lies near the data-driven secondary bound.

[Blum Katz & EW 13]

Conclusions

- Anti-p and e^+ measurements are in excellent agreement with secondary production model predictions.
- The saturation of the ABSOLUTE e^+ flux at the predicted secondary upper bound is a strong indication for a secondary origin, and is not expected in primary production models.
- Upcoming measurements at yet higher energy will further test the validity of the model.
- The main constraints that may be derived from the e^+ measurements are on models of Galactic CR propagation.
- In particular, the measurements constrain $f_{rad}(e^+)$.

Implications of $f_{sec}(e^+)$~0.3- an example

Under some model assumptions

$f_{sec}(e^+) \sim t_{cool}/t_{res}$

which would imply

$t_{res}(E/Z=10GeV) > 30Myr$, $t_{res}(E/Z=200GeV) < 1Myr$

and using Σ_{sec}

$\langle n_{ISM} \rangle (E/Z=10GeV) < 0.2 g/cc$,

$\langle n_{ISM} \rangle (E/Z=200GeV) > 0.6 g/cc$,

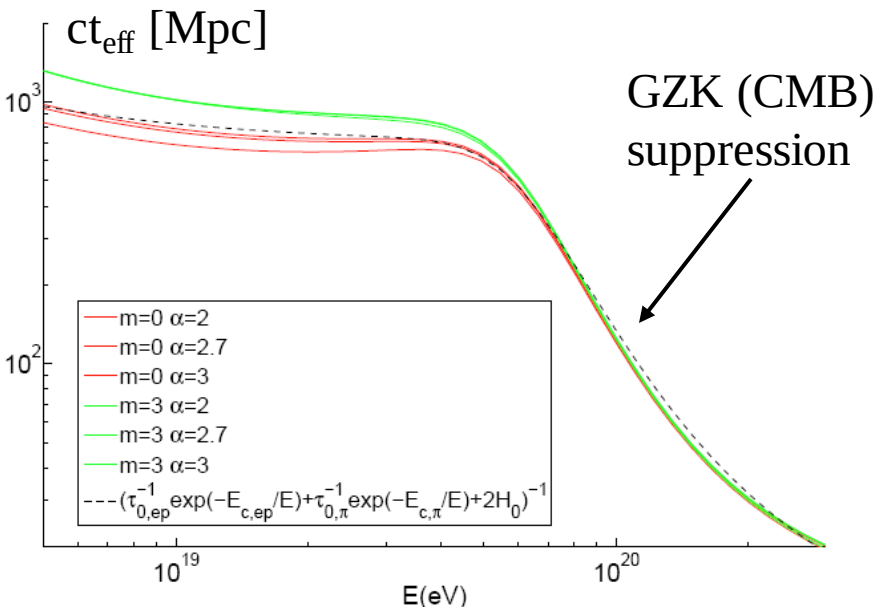
which in turn implies that the CR halo scale height decreases with E.

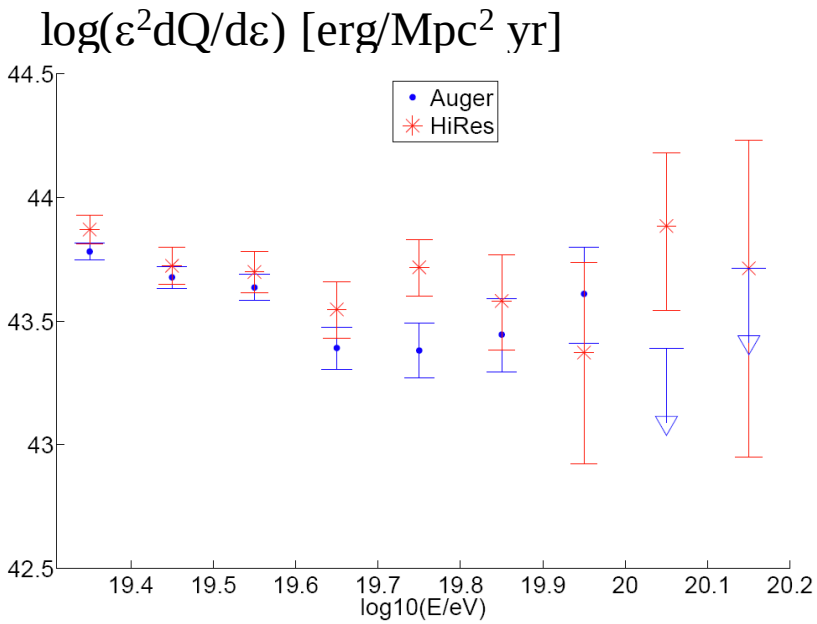
A note on the IceCube detection

UHE: Flux & Generation Spectrum

- $\varepsilon^2(dN/d\varepsilon)_{Observed}=\varepsilon^2(dQ/d\varepsilon)\, t_{eff.}$ ($t_{eff.}$: $p + \gamma_{CMB} \rightarrow N + \pi$)

  Assume: p, $dQ/d\varepsilon \sim (1+z)^m \varepsilon^{-\alpha}$





[Katz & EW 09]

- $>10^{19.3}$eV: consistent with protons, $\varepsilon^2(dQ/d\varepsilon) = 0.5(+-0.2) \times 10^{44}$ erg/Mpc^3 yr + GZK

[EW 1995; Bahcall & EW 03]

HE ν: UHECR bound

- $p + \gamma \rightarrow N + \pi$

  $\pi^0 \rightarrow 2\gamma$; $\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$

→ Identify UHECR sources

Study BH accretion/acceleration physics

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

$$\varepsilon_\nu^2 \frac{dj_\nu}{d\varepsilon_\nu} \leq \Phi_{\rm WB} \equiv 10^{-8}\ \zeta \left(\frac{\varepsilon^2 dQ/d\varepsilon}{10^{44}\,{\rm erg/Mpc^3 yr}} \right) \frac{\rm GeV}{\rm cm^2 s\ sr}$$

[EW & Bahcall 99; Bahcall & EW 01]

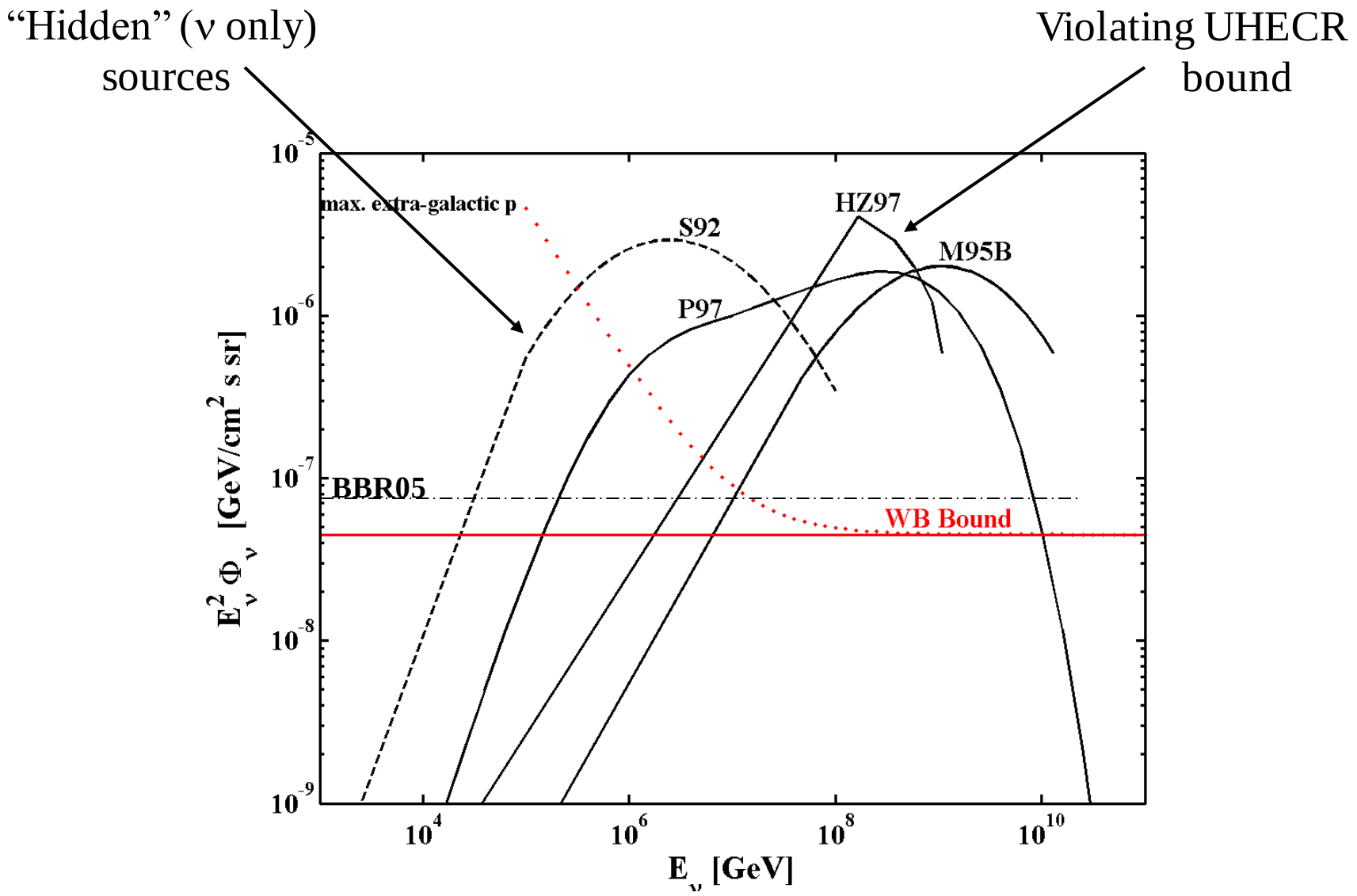
$$\zeta = 1, 5 \quad \text{for} \quad f(z) = 1, (1+z)^3$$

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

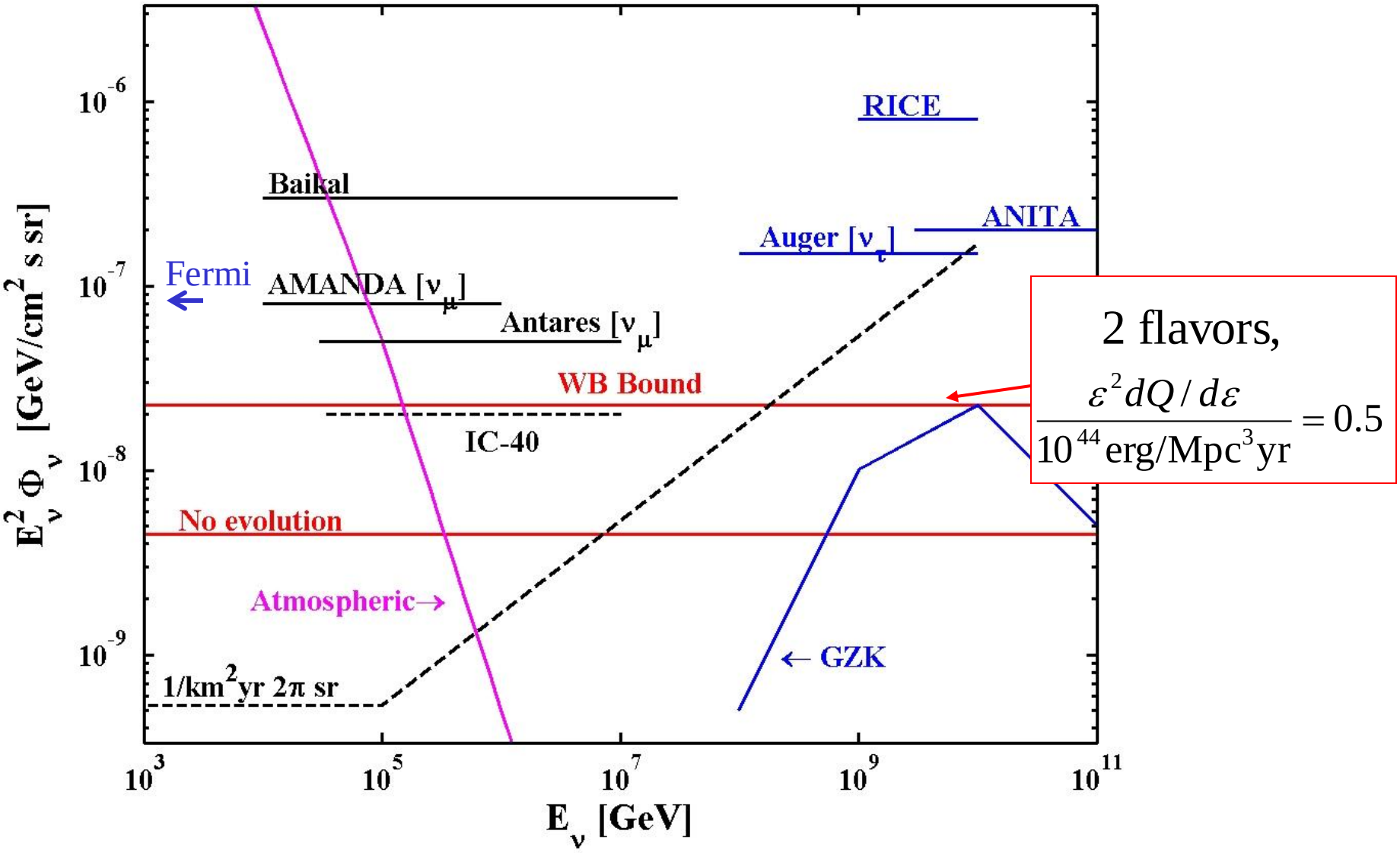
[Berezinsky & Zatsepin 69]

→ Identify primaries, determine f(z)

Bound implications: I. AGN ν models



Bound implications: ν experiments



2 flavors,

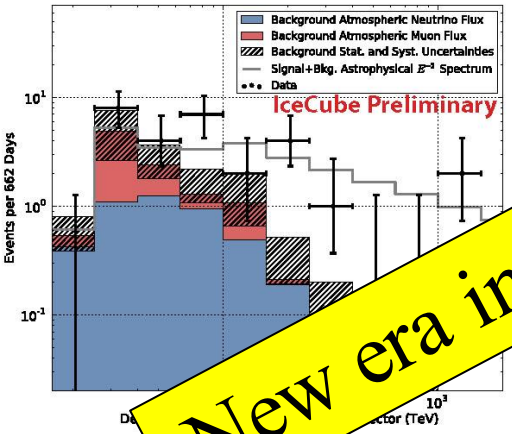
$$\frac{\varepsilon^2 dQ/d\varepsilon}{10^{44}\,\mathrm{erg/Mpc^3 yr}} = 0.5$$

IceCube (preliminary) detection

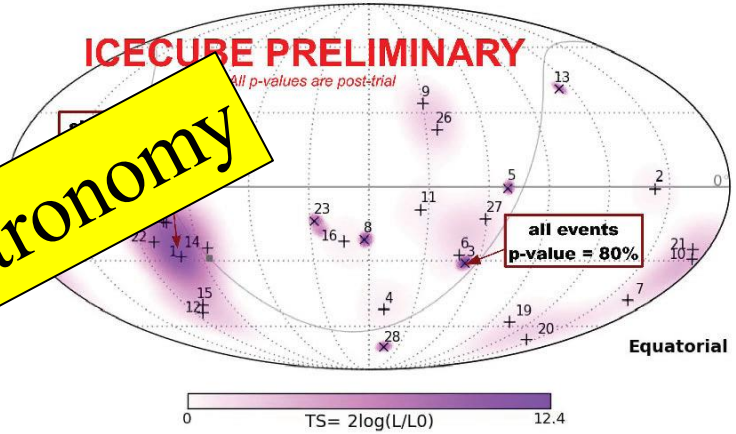
- 28 events, compared to 12 expected, above 50TeV; ~4σ (cutoff at 2PeV?)
- $1/E^2$ spectrum, $4x10^{-8}$GeV/cm^{2}s sr
- Consistent with $\nu_e:\nu_\mu:\nu_\tau=1:1:1$
- Consistent with isotropy

Energy Spectrum

- Harder than any expected atmospheric background
- Merges well into expected backgrounds at low energies
- Potential cutoff at $1.6^{+1.5}_{-0.4}$ PeV



Skymap: No Significant Clustering

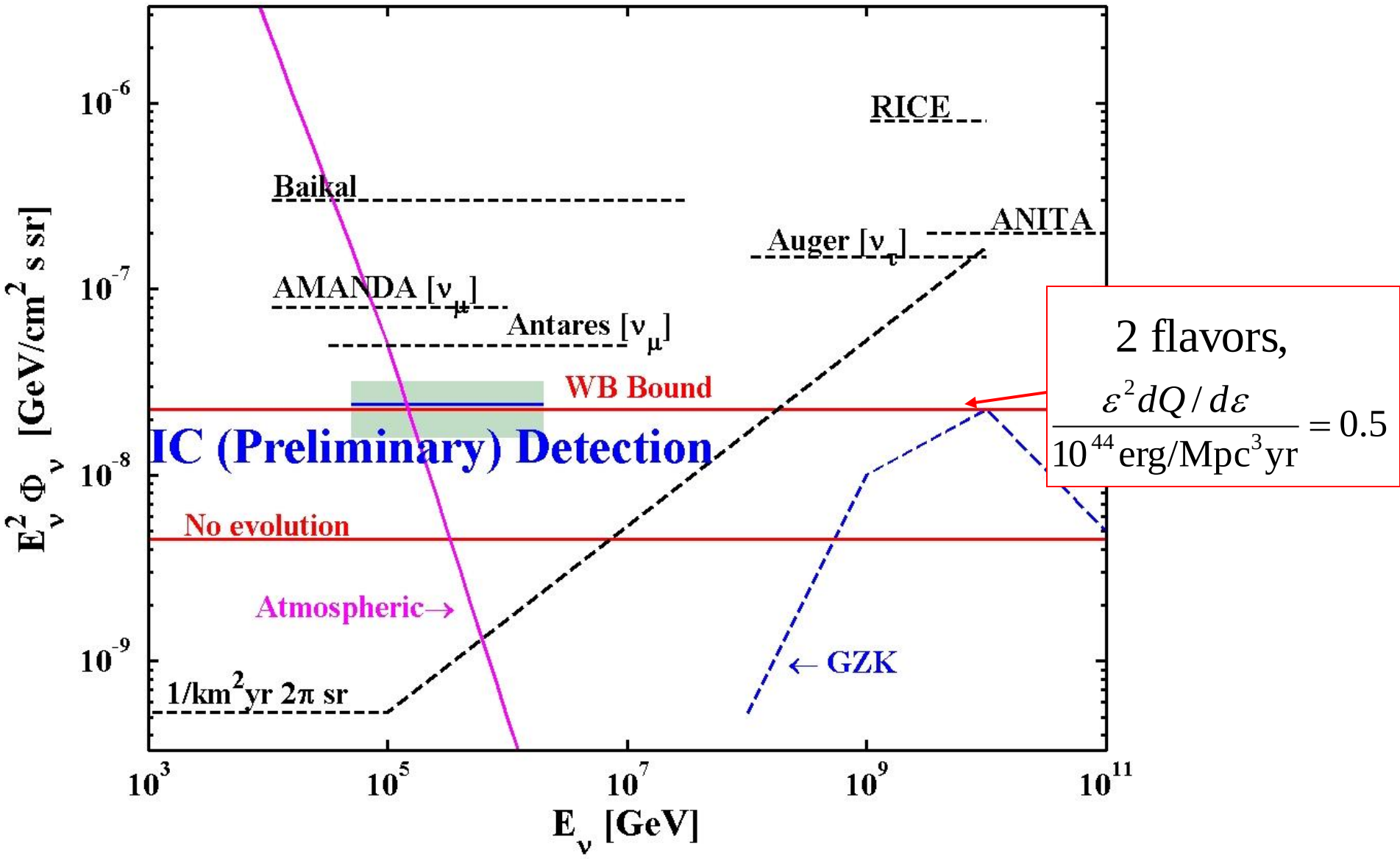


New era in ν astronomy

See: talk by Naoko Kurahashi Neilson

[N. Whitehorn, IC collaboration, IPA 2013]

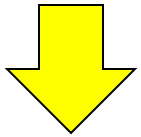
IceCube (preliminary) detection



IceCube's detection: Some implications

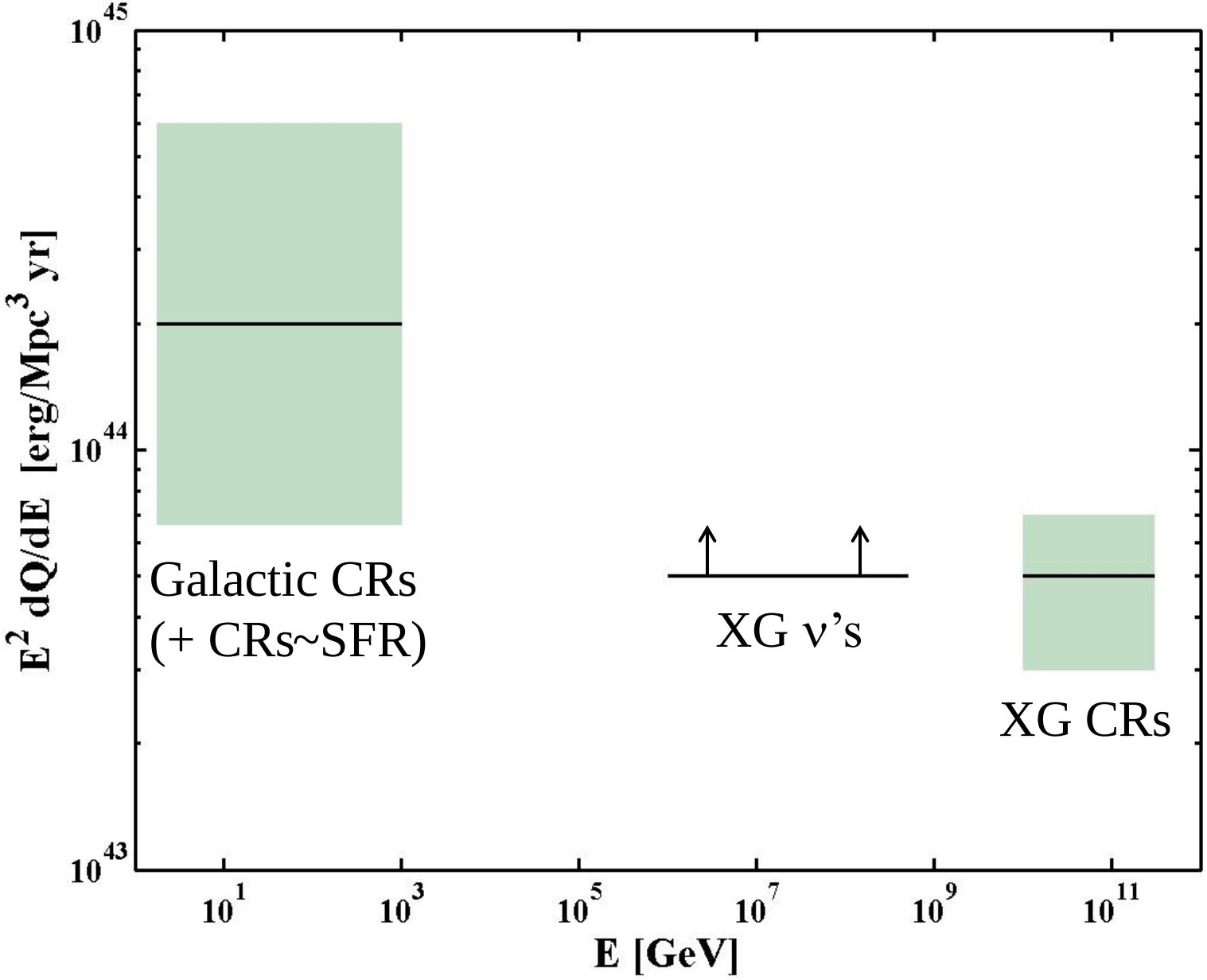
The coincidence of 50TeV<E<2PeV ν flux, spectrum (& flavor) with the WB bound is unlikely a chance coincidence.

- Unlikely Galactic: $\varepsilon^2\Phi_\gamma \sim 10^{-7}(E_{0.1TeV})^{-0.7}$ GeV/cm^{2}s sr [Fermi]
  → $\sim 10^{-9}(E_{0.1PeV})^{-0.7}$ GeV/cm^{2}s sr



- XG distribution of sources,
  p, $\varepsilon^2(dQ/d\varepsilon)_{PeV\text{-}EeV} \sim \varepsilon^2(dQ/d\varepsilon)_{>10EeV}$, $\tau_{\gamma p(pp)} > \sim 1$
  Or:
  $\varepsilon^2(dQ/d\varepsilon)_{PeV\text{-}EeV} >> \varepsilon^2(dQ/d\varepsilon)_{>10EeV}$, $\tau_{\gamma p(pp)} << 1$
  & Coincidence (over a wide energy range)

The cosmic ray generation spectrum



ν's from Star Bursts

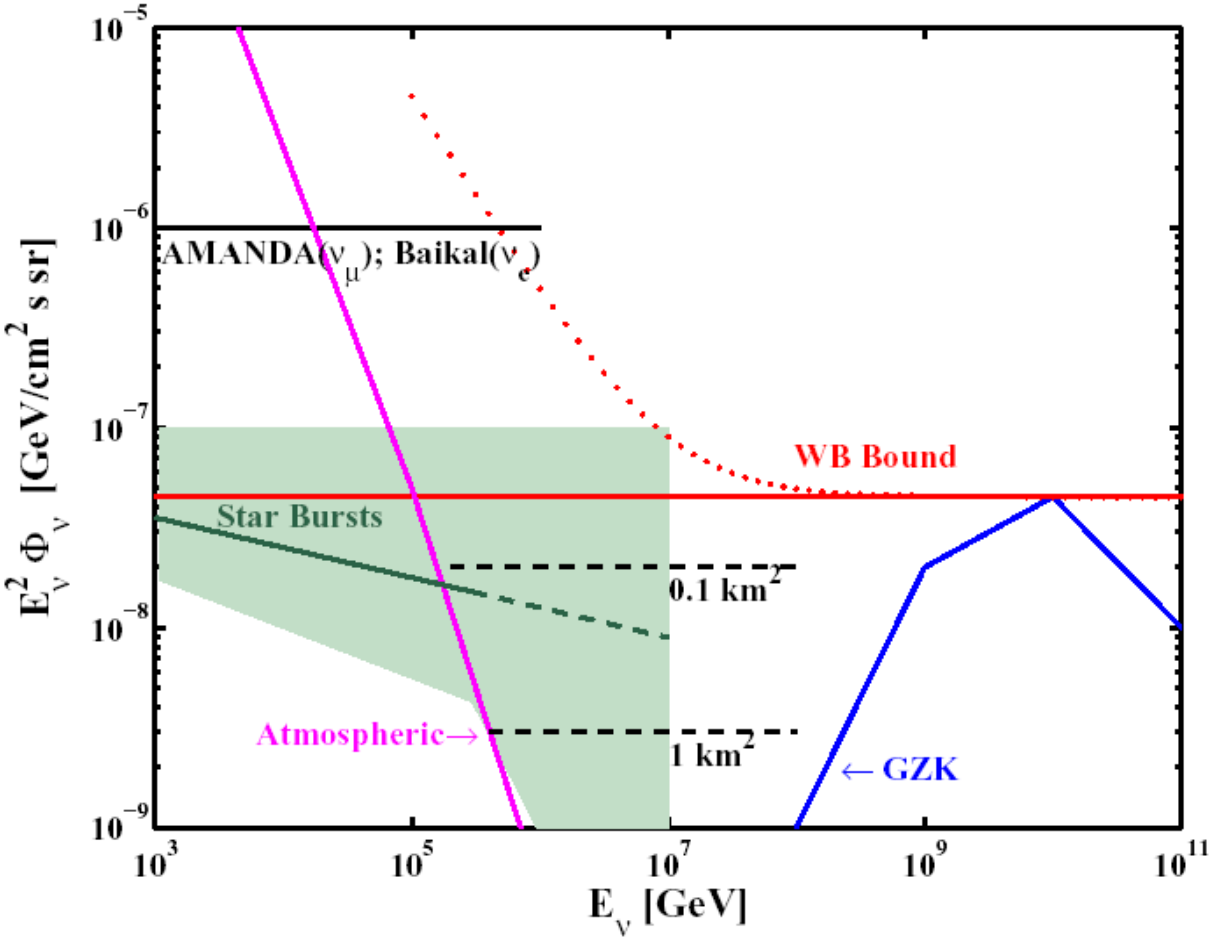
- Starburst galaxies
  - {Star formation rate, density, B} ~ 10^3x Milky way.
    Most stars formed in z>1.5 star bursts. [Quataert et al. 06]

- CR e's lose all energy to synchrotron radiation,
- ε<10PeV p's likely lose all energy to π production,
  at higher e may escape.

[Loeb & EW 06]

$\varepsilon^2(dQ/d\varepsilon) \sim 10^{44}$ erg/Mpc^3 yr $\rightarrow$ $\Phi_\nu \sim \Phi_{WB}$

Starburst galaxies: predicted ν emission



[Loeb & EW 06]

IceCube's detection: Some implications

- The identity of the CR source(s) is still debated.
- Open Q's RE candidate source(s) physics [accreting BHs].

- $\varepsilon^2(dQ/d\varepsilon) \sim 10^{44}$erg/Mpc^{3}yr at all energies (10—10^{10} GeV).
  Suggests: CRs of all E produced in galaxies @ a rate ~ SFR,
  by transients releasing ~$10^{50.5+-1.5}$erg.

- IceCube's detection: new era in ν astro.
  Next: spectrum, flavor, >1PeV, GZK,
  EM association- Bright transients are the prime targets.
- Coordinated wide field EM transient monitoring- crucial.
- EM Association may resolve outstanding puzzles:
  - Identify CR (UHE & G-CR) sources,
  - Resolve open "cosmic-accelerator" physics Q's
    (related to BH-jet systems, particle acc., rad. mechanisms),
  - Constrain ν physics, LI, WEP.