IceCube neutrinos and the origin of cosmic-rays

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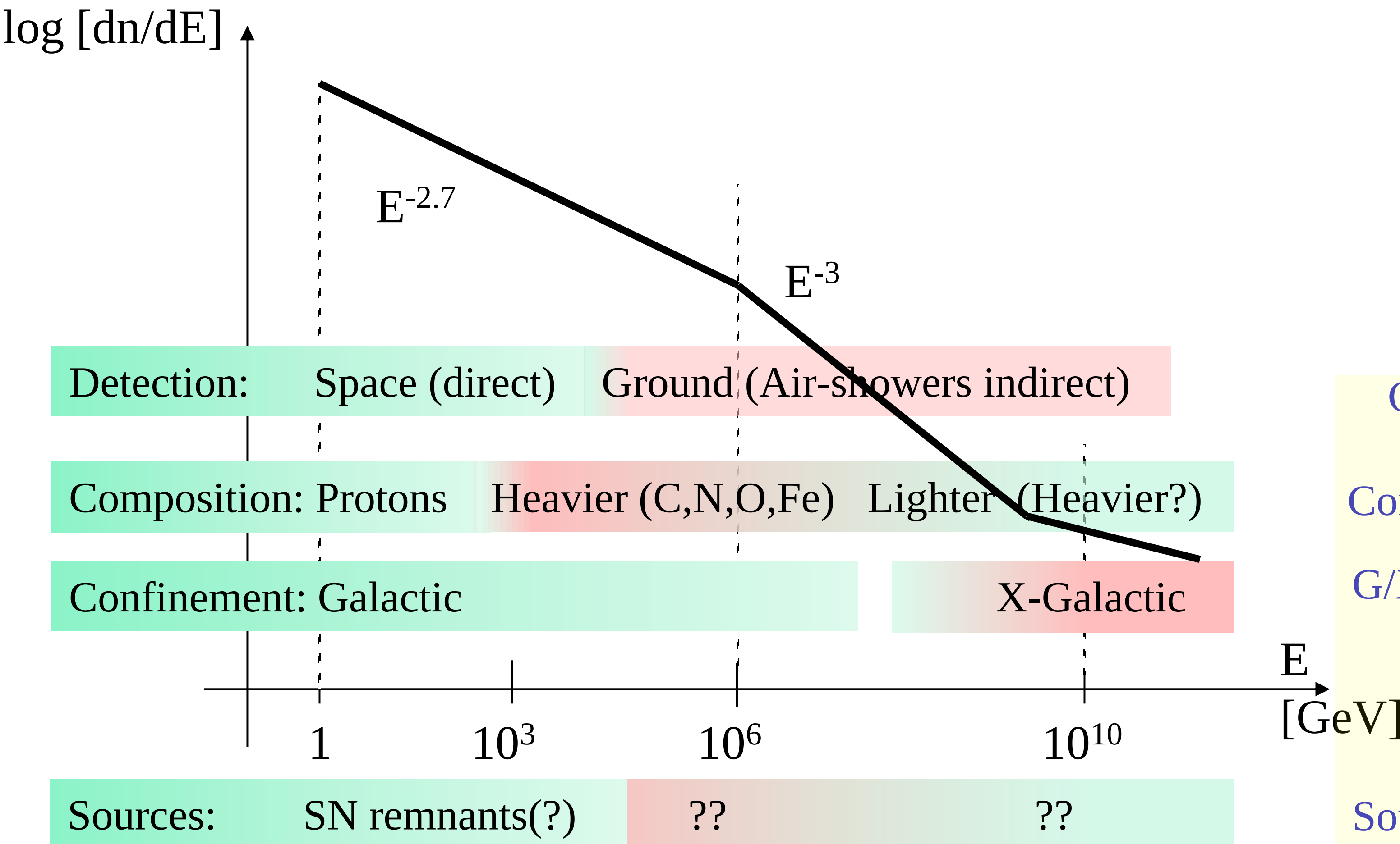
The origin of Cosmic Rays: Open Questions



$$\frac{dn}{dE} = \frac{d\dot{n}}{dE} t_{\text{conf.}}(E)$$

$$\Rightarrow Q_E = E^2 \frac{d\dot{n}}{dE} \approx Const.$$

Open Q's

Composition?

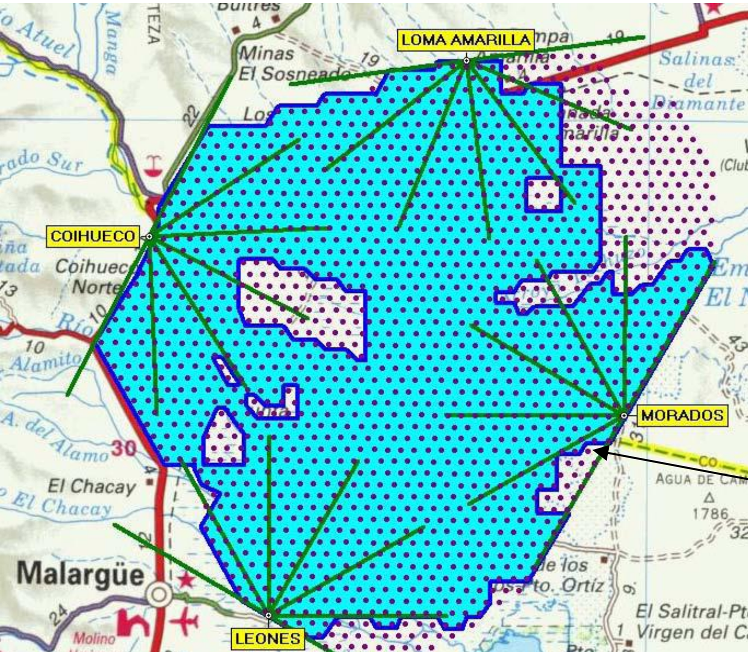
G/XG transition?

Sources?

Acceleration?

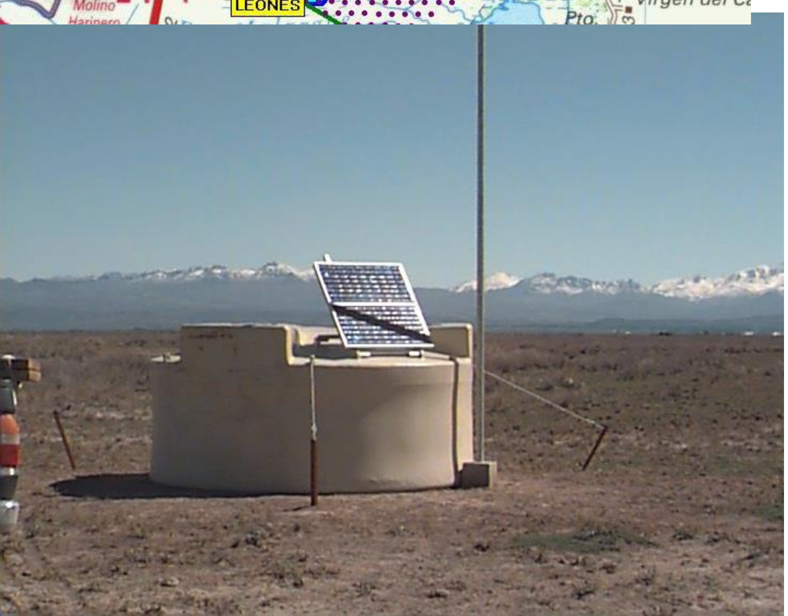
[Reviews: Helder, et al. 12; Lemoine 13]

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



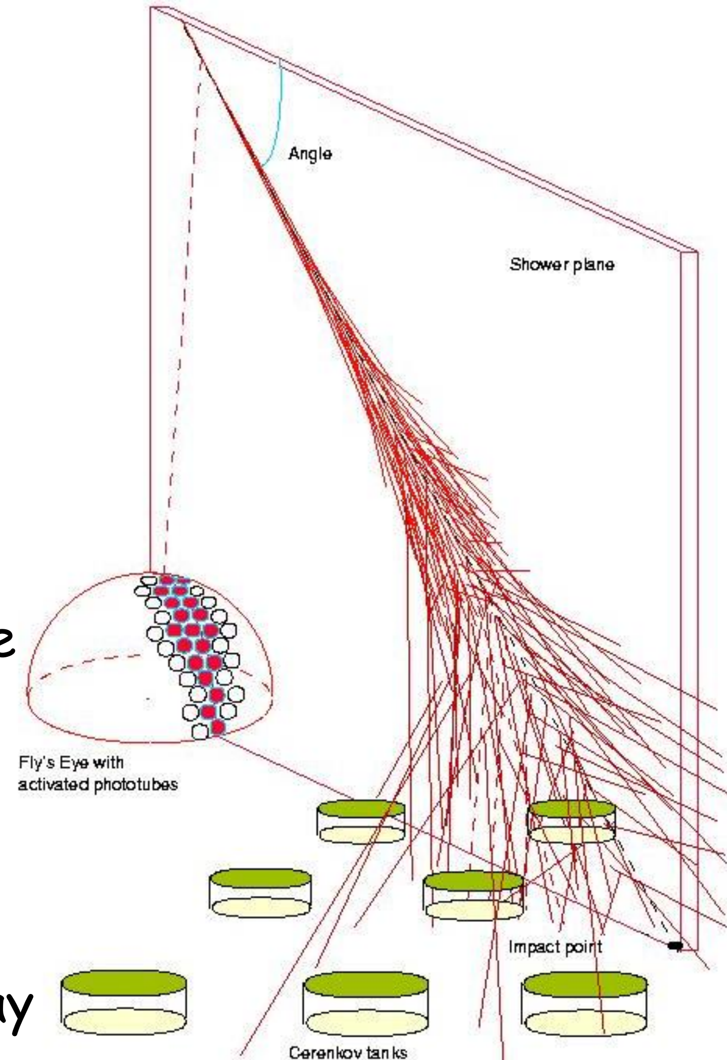
$J(>10^{11}\text{GeV}) \sim 1$ / 100 km^2 year 2π sr

Auger:
3000 km^2



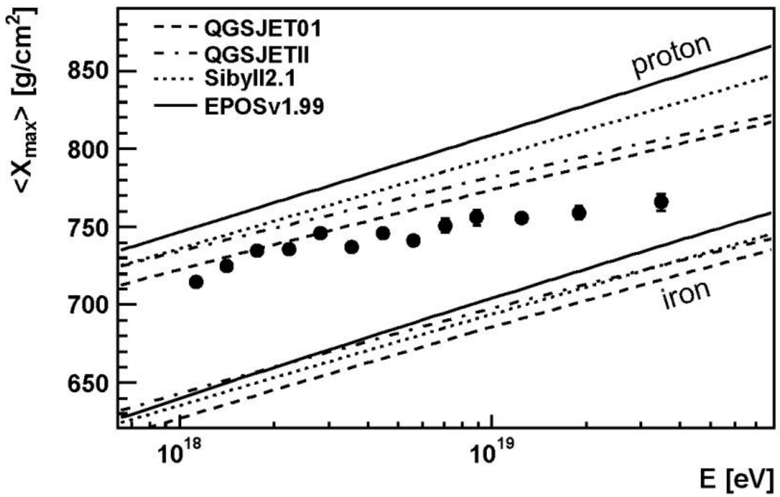
Fluorescence detector

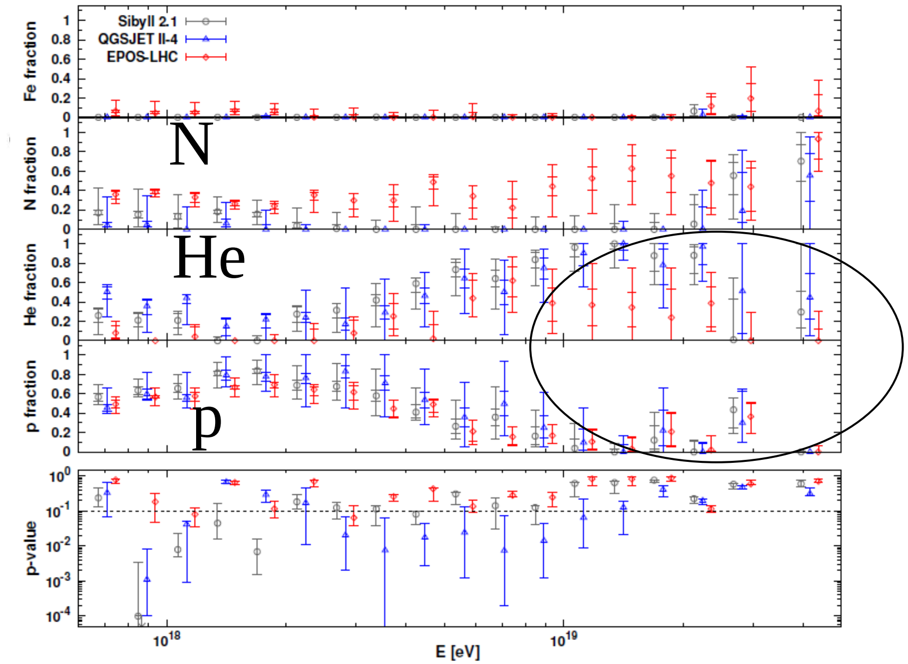
Ground array



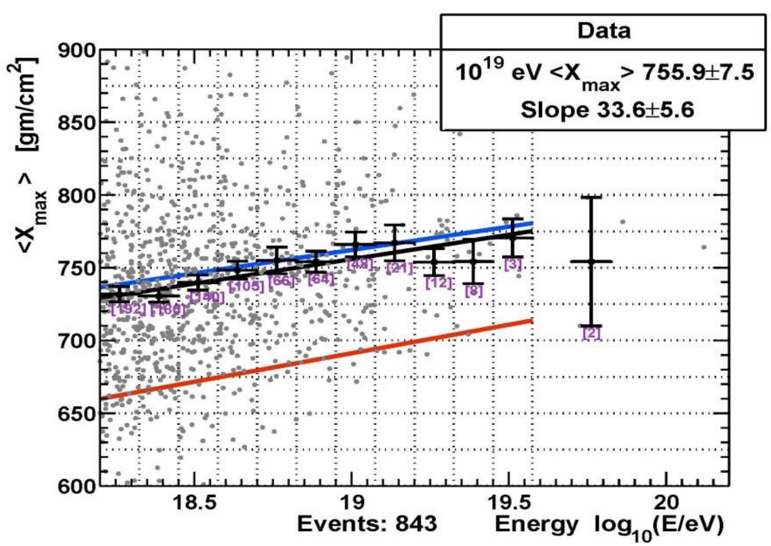
UHE: Air shower composition constraints

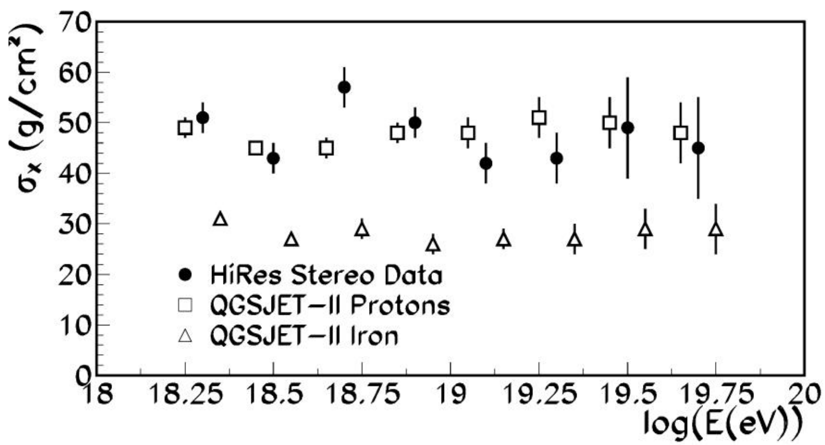
Auger 2010: Fe, 2015: p, He(??)





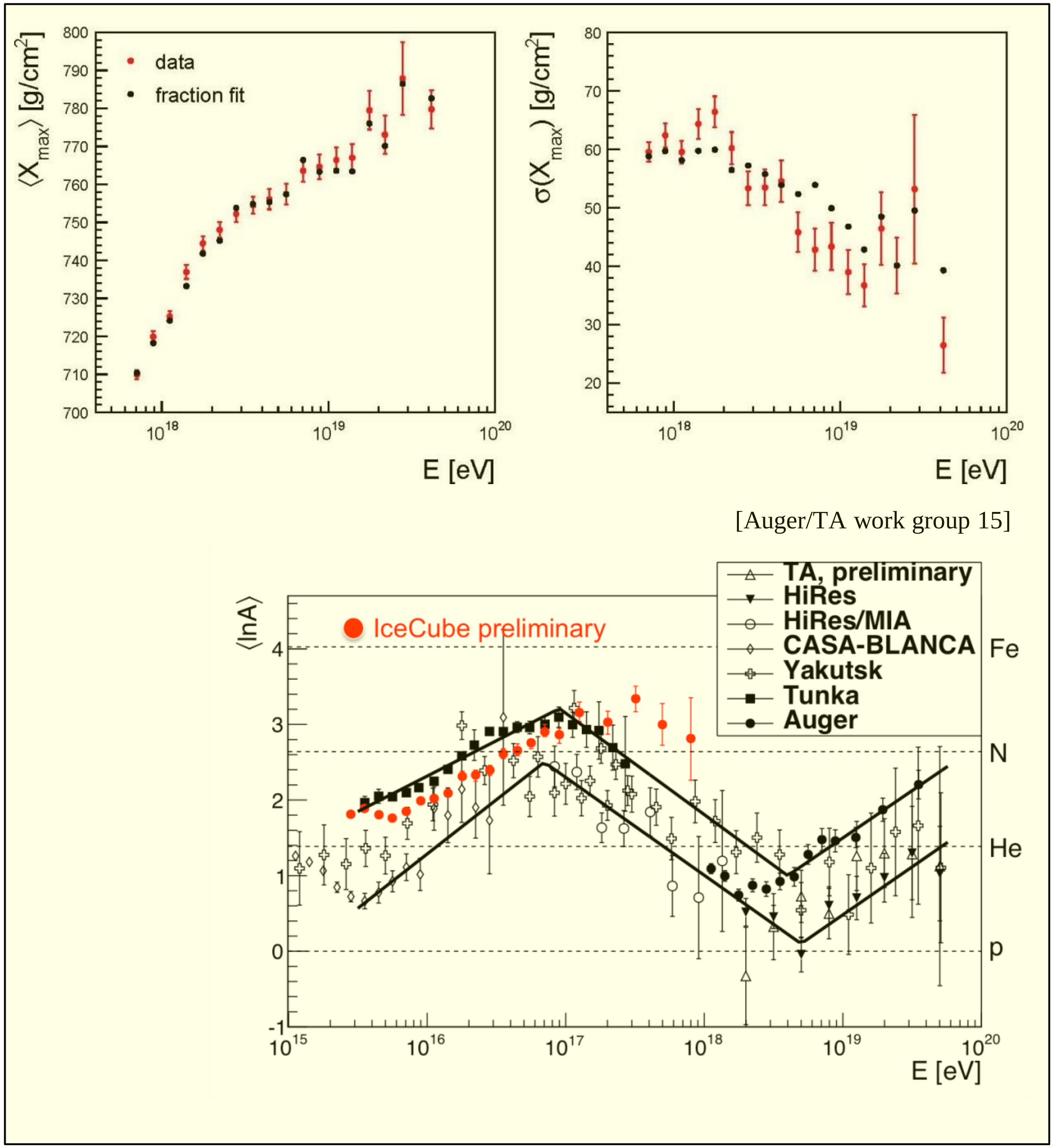
HiRes Stereo 2010 & TA Hybrid 2015





UHE: Air shower composition constraints

- Discrepant results of experimental analyses.
  Auger: {H,He,N};
  HiRes/TA: {H}.
- Discrepancies between shower models and data.
- Uncertainties in extrapolation to E_{CM}>100TeV not spanned by models used.
- Air shower analyses- Inconclusive.



$>10^{10}$GeV spectrum: a hint to p's

- p + γ[CMB] → N + π, above $10^{19.7}$eV. t_{eff}<1Gyr, d<300Mpc.

- Observed spectrum consistent with
  - A flat generation spectrum of p's

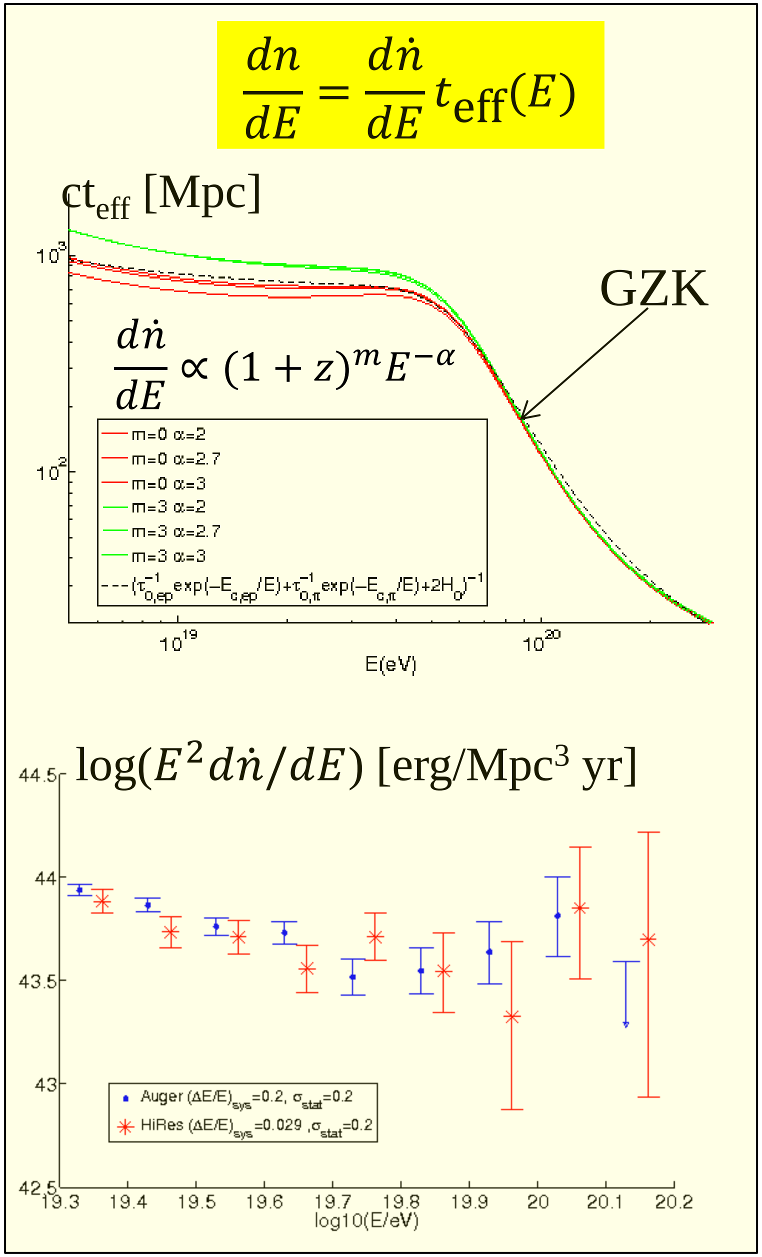
$$Q_E = E^2 \frac{d\dot{n}}{dE} = Const.$$

$$= (0.5 \pm 0.2) 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}},$$

[EW 95, Bahcall & EW 03, Katz & EW 09]

  - Modified by p-GZK suppression.

- Q_E=Const.:
  - Observed in a wide range of systems,
  - Obtained in EM acceleration in collision-less shocks (the only predictive acceleration model).

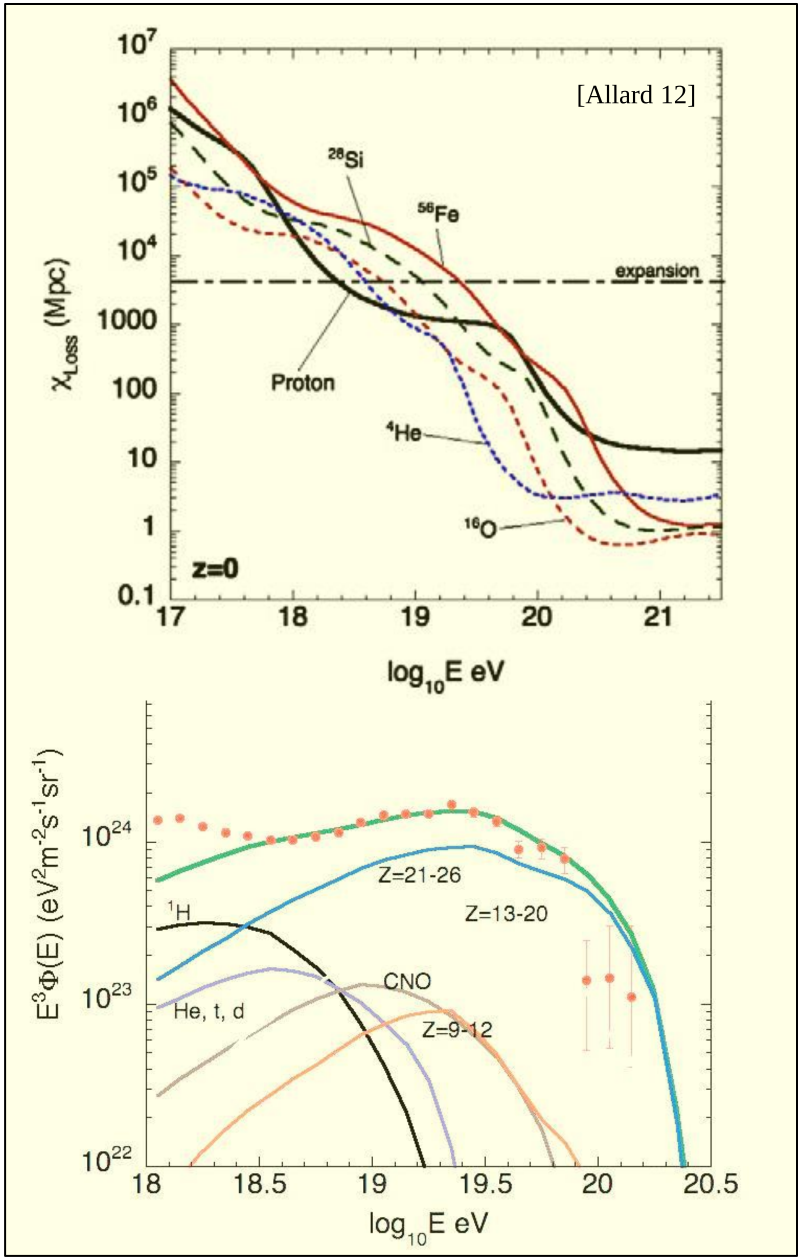


A mixed composition?

- The suppression at $10^{19.5}$eV is due to the acceleration process, just a coincidence with p-GZK.

- Large # of free parameters, yet- Auger $\sigma(X_{max})$ not explained.

- But, cannot be ruled out. E.g. talk by N. Globus.



Where is the G-XG transition?

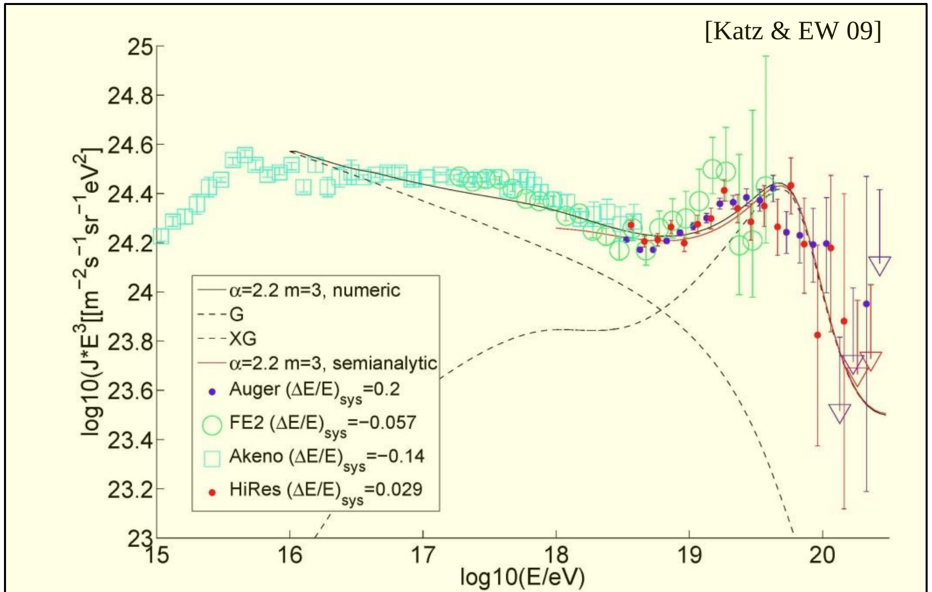
- A flat p generation spectrum,

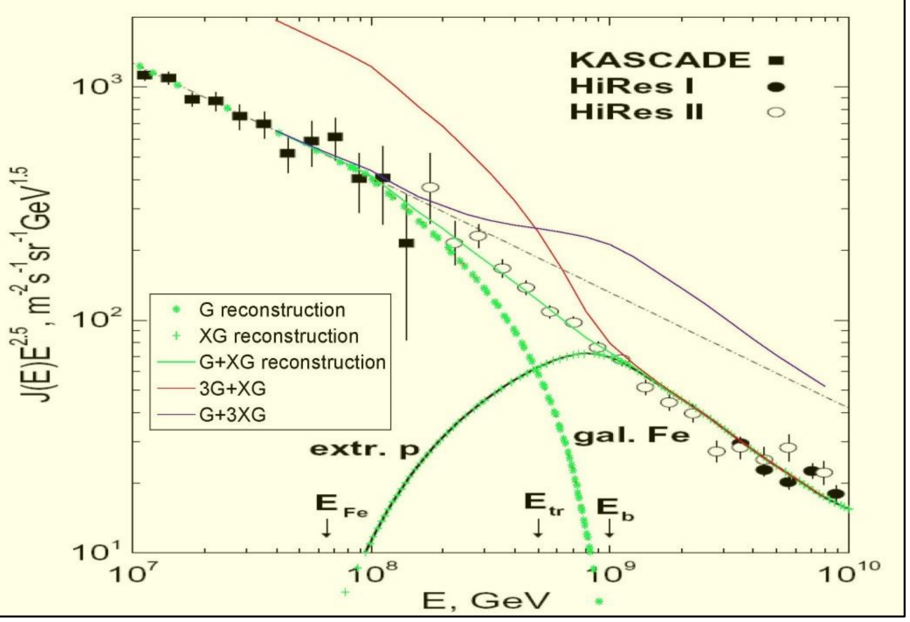
  $Q_E = E^2 \frac{d\dot{n}}{dE} = Const.$

  Implies:

  - Transition at ~ 10^{19}eV;
  - Small XG contribution at 10^{18}eV (no "dip" model").

- Transition at 10^{18}eV implies
  - Fine tuning of G/XG components;
  - Spectrum softer than $1/E^2$;
  - $Q^{XG} \gg Q(>10^{19}\text{eV})$.





High energy ν telescopes

- Detect HE ν's from
  p(A)-p/p(A)-γ → charged pions → ν's,
  $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu_\mu} + \nu_\mu$,
  $E_\nu/(E_A/A) \sim 0.05$.

- Goals:
  - Identify the sources (no delay or deflection with respect to EM),
  - Identify the particles,
  - Study source/acceleration physics,
  - Study ν/fundamental physics.

HE ν: predictions

For cosmological proton sources,

$$E^2 \frac{d\dot{n}}{dE} = Const. = (0.5 \pm 0.2) 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}} .$$

- An upper bound to the ν intensity (all p→π):

$$E^2 \frac{dj_\nu}{dE} \le E^2 \Phi_{\text{WB}} = \frac{3}{8} \frac{ct_H}{4\pi} \zeta \left(E^2 \frac{d\dot{n}}{dE} \right) = 10^{-8} \zeta \frac{\text{GeV}}{\text{cm}^2\text{s sr}},$$
$$\zeta = 0.6{,}3 \text{ for } f(z) = 1, (1+z)^3.$$

[EW & Bahcall 99; Bahcall & EW 01]

- Saturation of the bound.
  - ~10^{10}GeV -If- Cosmological p's. [Berezinsky & Zatsepin 69]
  - <~10^{6}GeV -If- Cosmological p's & CR ~ star-formation activity.

    Most stars formed in rapidly star-forming galaxies,

    which are p "calorimeters" for E_p<~10^6GeV,

    all p→π by pp in the inter-stellar gas, $t_{pp} < t_{\text{conf}}(E < 10^6\text{GeV})$.

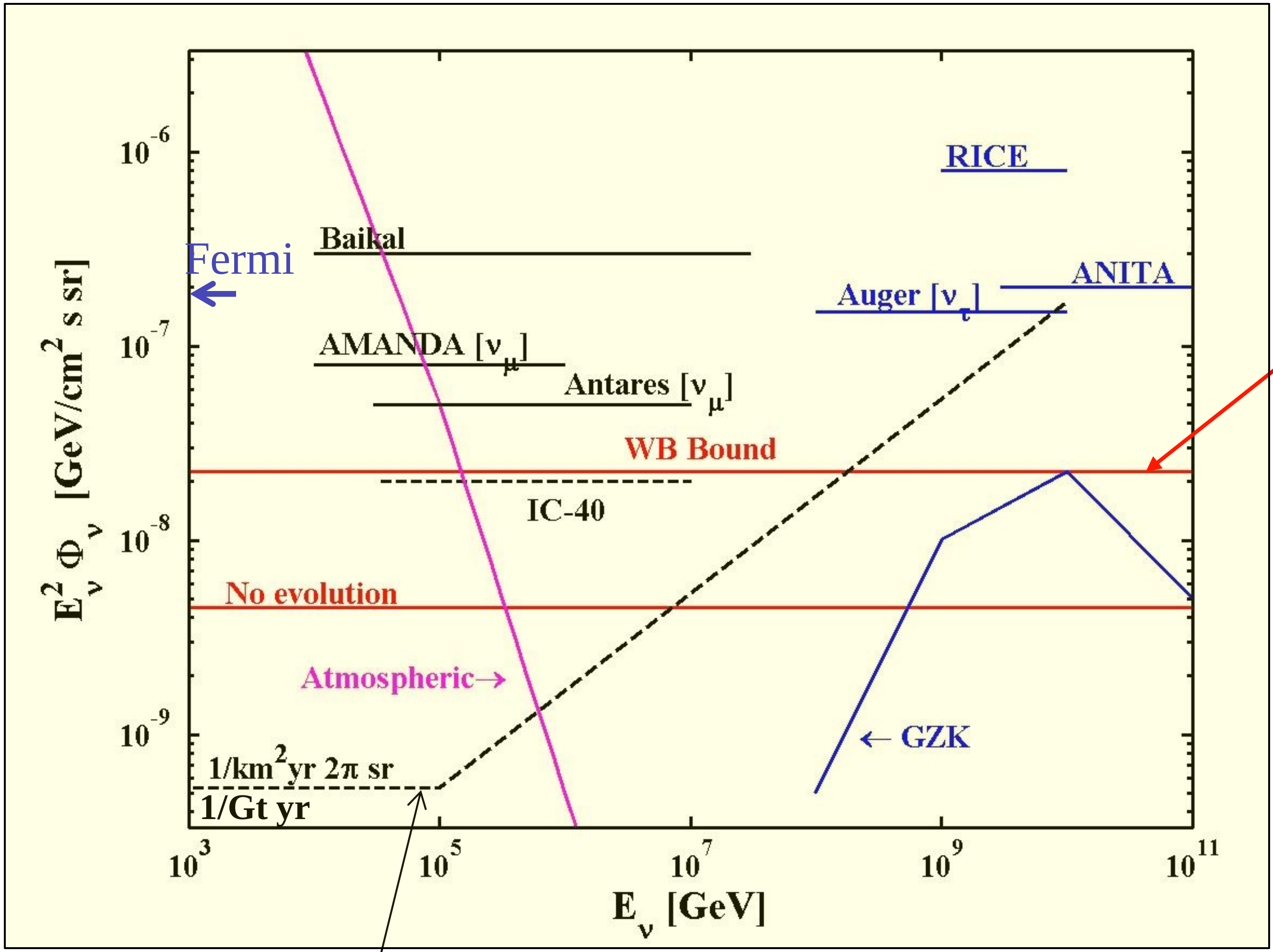
[Loeb & EW 06]

- Prompt emission from the source, $\Phi \ll \Phi_{\text{WB}}$.

  E.g. "classical GRB" $\Phi_{\text{grb}} \approx 10^{-2}(10^{-1})\Phi_{\text{WB}}$ at 10^5GeV (10^6GeV), [EW & Bahcall 97]

  (For LL/Choked GRBs- see talk by Peter Mészáros).

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

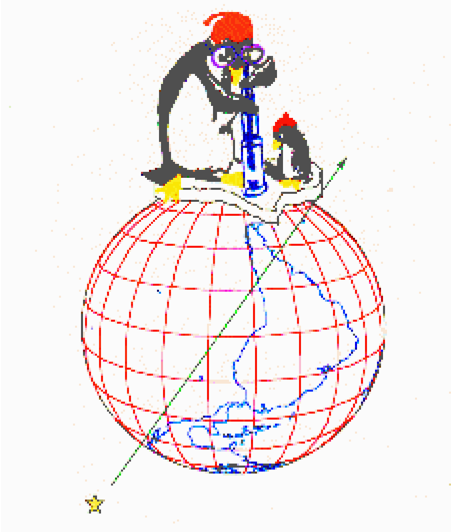


2 flavors,

$$\frac{E^2 d\dot{n}/dE}{10^{44}\,\mathrm{erg/Mpc^3 yr}} = 0.5$$

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

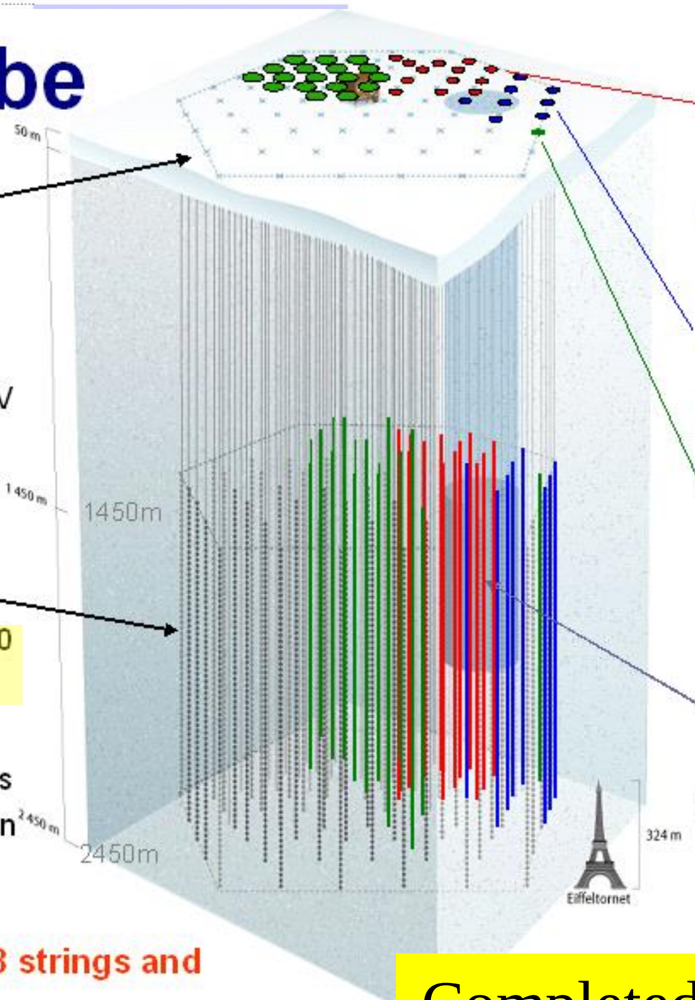
AMANDA & IceCube



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

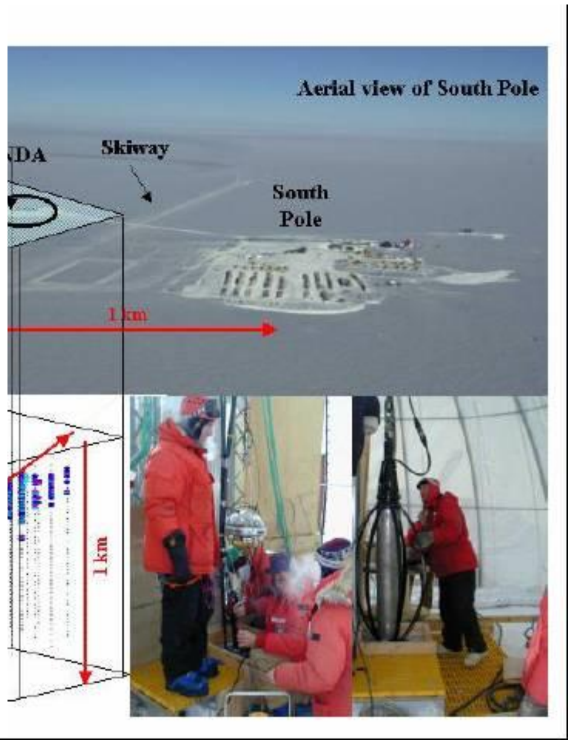
2005-2006: 8 strings

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

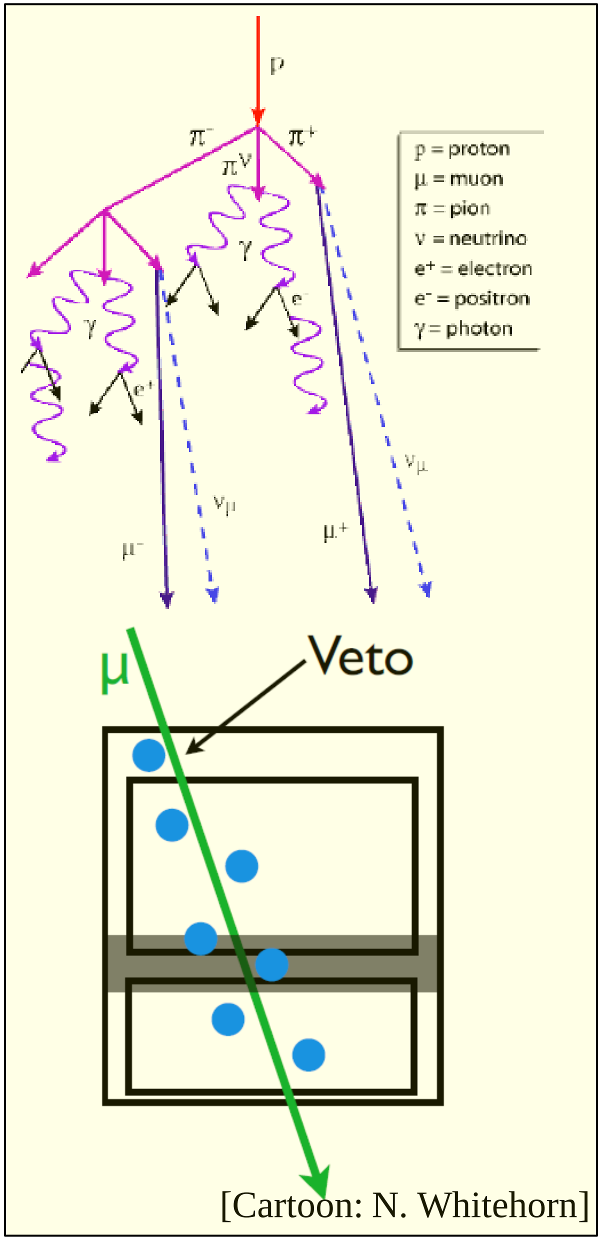


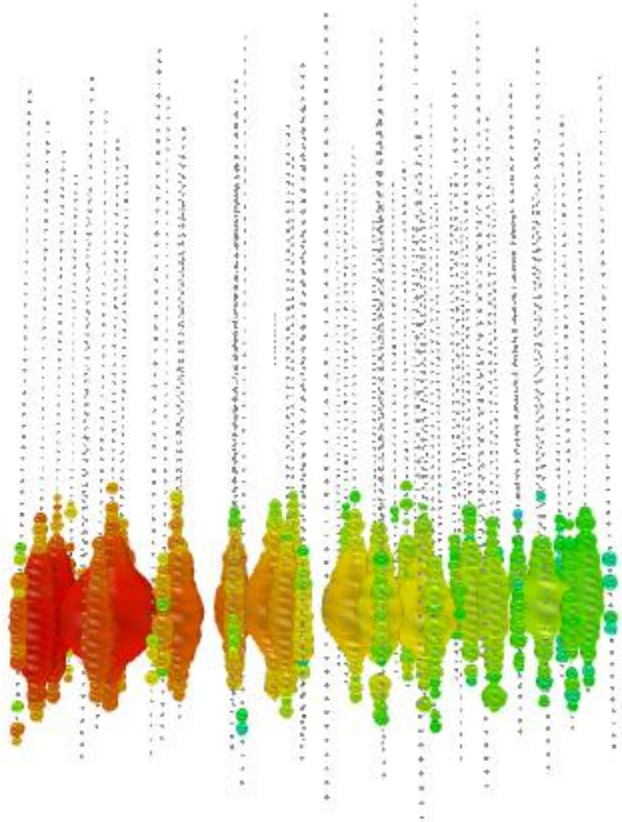
Completed Dec 2010

Looking up: Vetoing atmospheric neutrinos

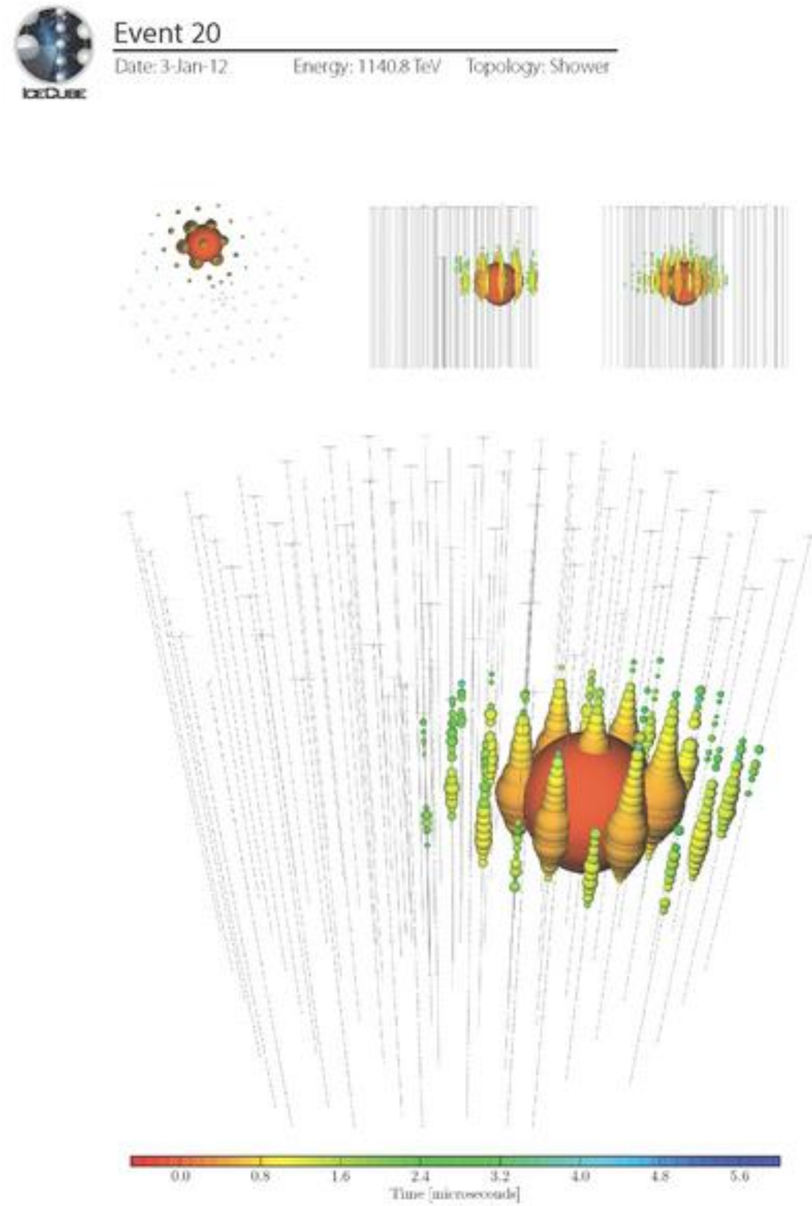
[Schoenert, Gaisser et. al 2009]

- 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).





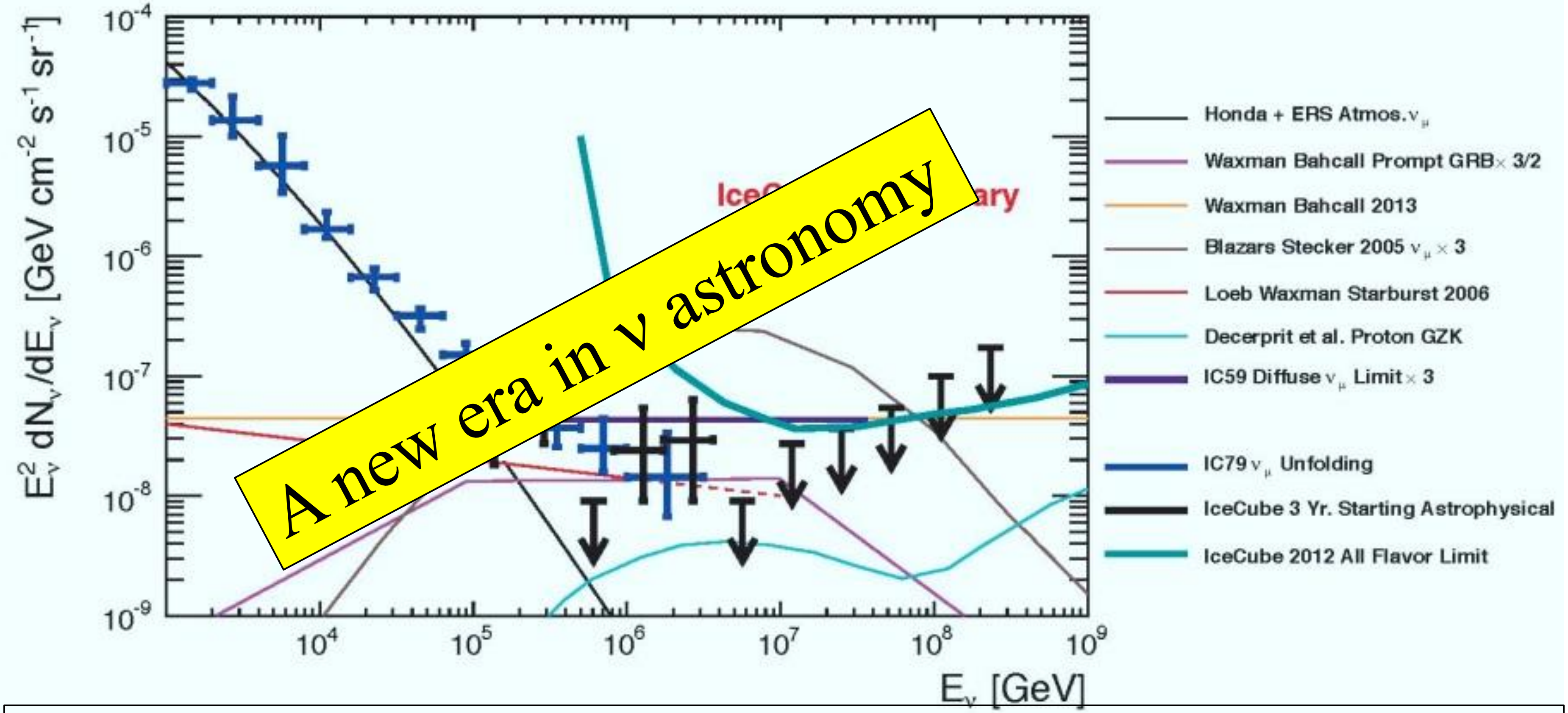
400TeV



1100TeV

IceCube: 37 events at 50Tev-2PeV

~6σ above atmo. bgnd. [02Sep14 PRL]

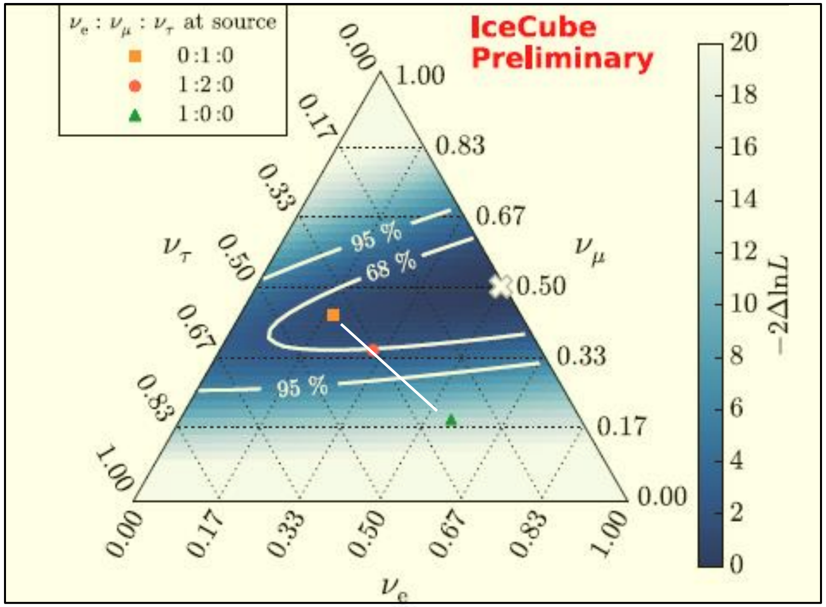


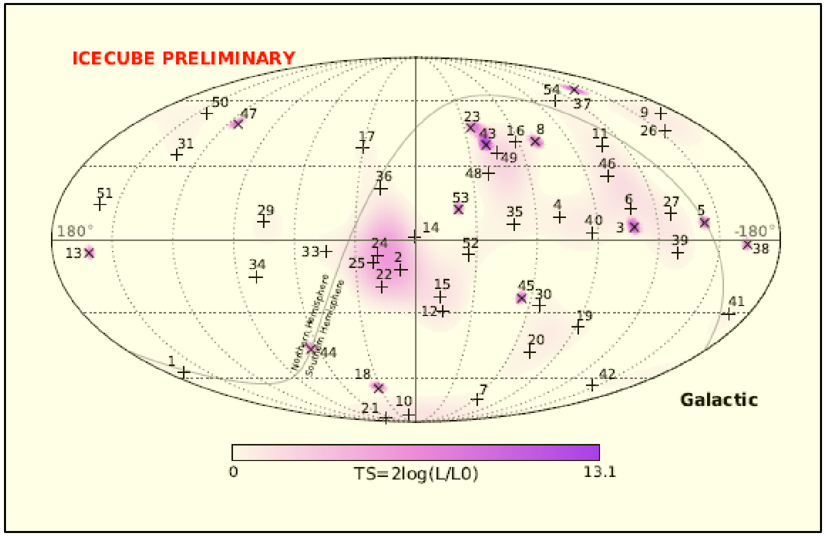
$E^2\Phi_\nu$ =(2.85+-0.9)x10^{-8}GeV/cm^{2}sr s =$E^2\Phi_{WB}$= 3.4x10^{-8}GeV/cm^{2}sr s (2PeV cutoff?).

Consistent with Isotropy,

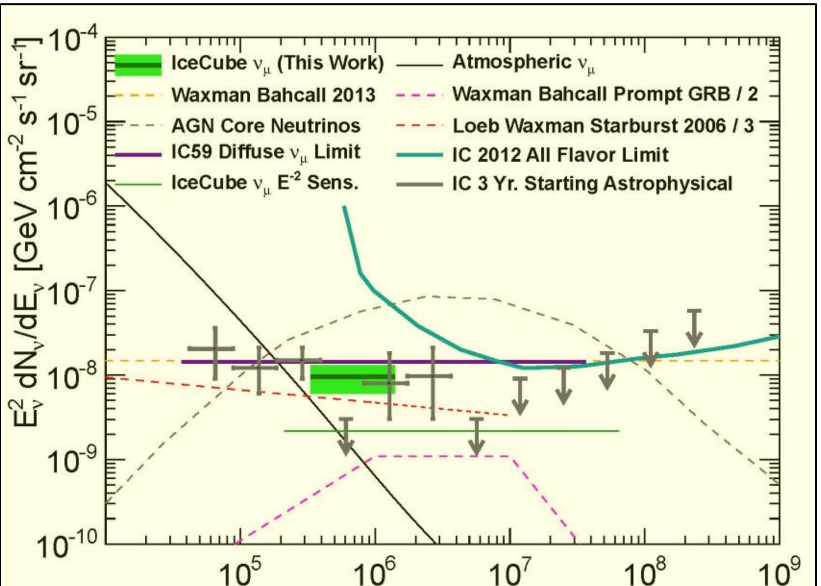
$\nu_e:\nu_\mu:\nu_\tau$=1:1:1 (π deacy + cosmological prop.).

Status: Isotropy, flavor ratio

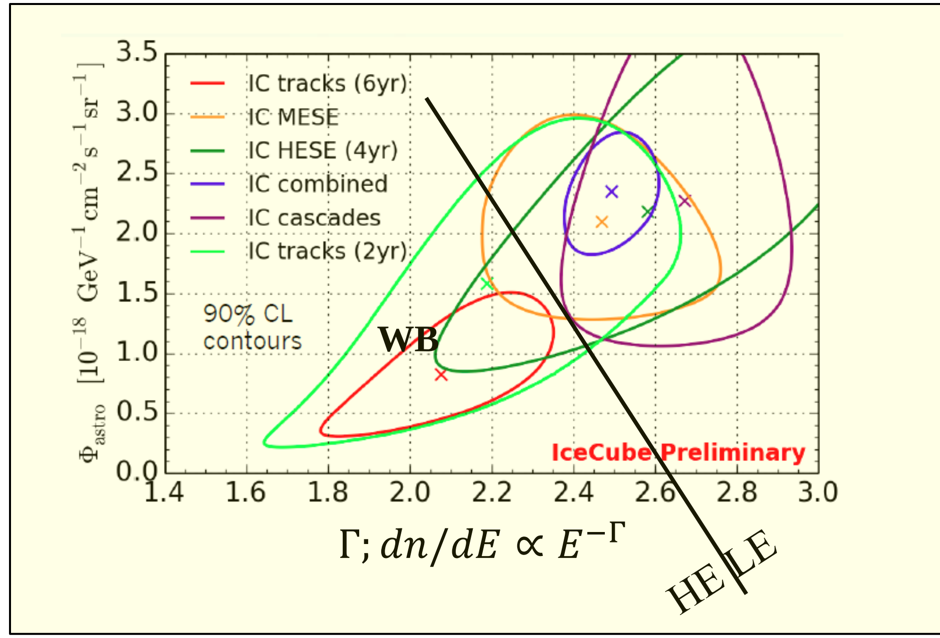


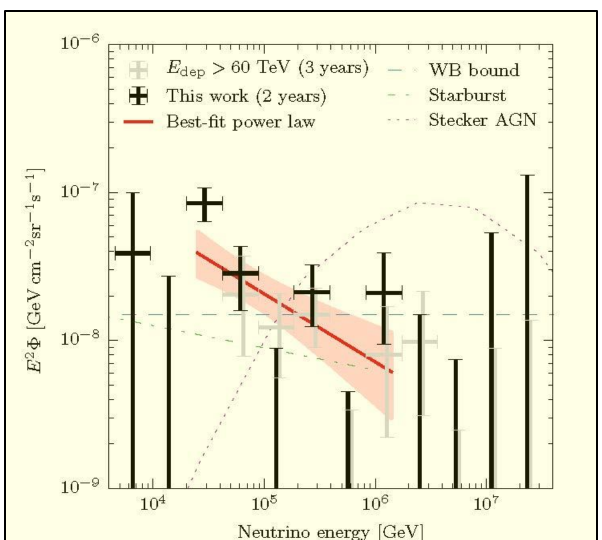


Status: Flux, spectrum



PRL 115, 081102 (2015)





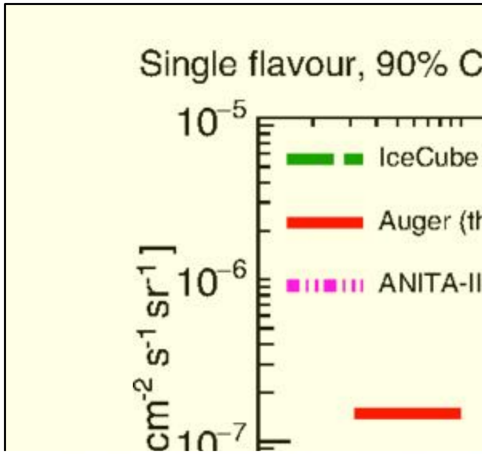
PRD 91, 022001 (2015)

- Excess below ~50TeV.
  If real, likely a new low E component
  (rather than a soft Γ=2.5 spectrum).

[e.g. Palladino & Vissani 16]

- However, note:
  - $\Phi \sim 0.01\, \Phi_{Atm.}$ at low E,
  - Veto efficiency decreasing at low E,
  - Tension with Fermi data.

Auger's UHE limit [May 15, <2013/6 data]



IceCube's (>50TeV) ν sources

- DM decay?
  Unlikely- chance coincidence with Φ_{WB}.

- Galactic? Unlikely.
  - Isotropy.
  - Fermi's (total) γ-ray intensity at 0.1-1TeV

    $$E^2\Phi_\gamma \sim 3\times10^{-7}(E_{0.1TeV})^{-0.7} GeV/cm^2 s\ sr$$

    extrapolated to IceCube's energy

    $$E^2\Phi_\nu \sim 3\times10^{-9}(E_{0.1PeV})^{-0.7} GeV/cm^2 s\ sr \ll \Phi_{WB}$$

→ XG CR sources.
Coincidence with Φ_{WB} suggests a connection to the UHE sources.

IceCube's (>50TeV) ν sources

(a) Most natural (and predicted):

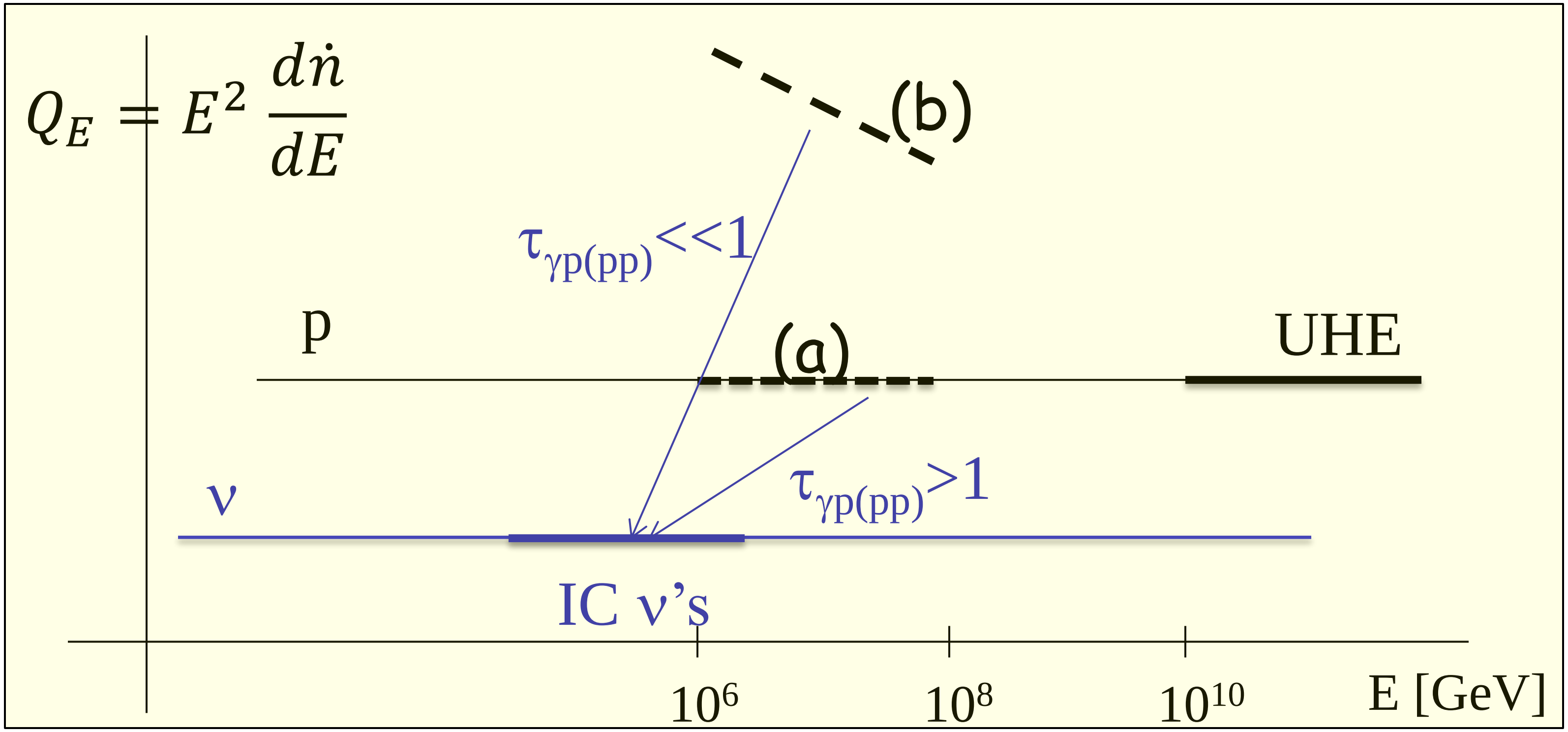
XG UHE p sources, Q_E=Const., residing in (starburst) "calorimeters".

Sources & calorimeters known to exit, no free model parameters.

Main open question: properties of star-forming galaxies at z~1.

(b) $Q \gg Q_{UHE}$ sources with $\tau_{\gamma p(pp)} \ll 1$, ad-hoc $Q/Q_{UHE} \gg 1$ & $\tau_{\gamma p(pp)} \ll 1$,

to give $(Q/Q_{UHE}) * \tau_{\gamma p(pp)} = 1$ over a wide energy range.



Fermi's XG γ-ray background [EGB]

- $Q_\gamma \sim (2/3) Q_\nu$.

- If ~90% of the EGB is resolved, then

  Flat generation spectrum, $\frac{d\log n}{d\log E} > -2.2$

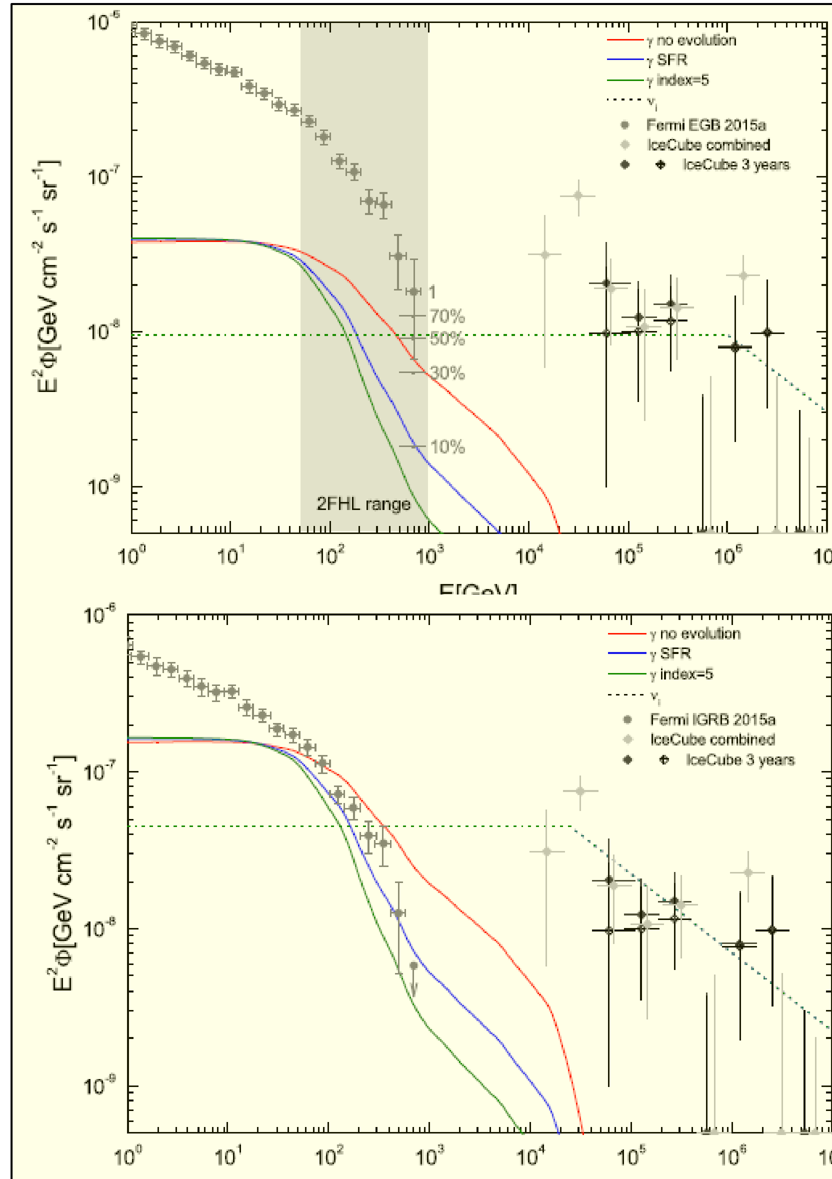
  [e.g. Tamborra, Ando, & Murase 14] ,

  SFR (or faster) z evolution

  [Chang, Liu & Wang 16].

- The <50TeV neutrino "excess" is in tension with Fermi's EGB:

  It's sources would saturate Fermi's EGB [Senno et al. 15].



[Chang, Liu, & Wang 16]

Identifying the "calorimeters"

- No sources with multiple-ν_μ-events:

$$N(\text{multiple } \nu_\mu \text{ events}) = 1 \left(\frac{\zeta}{3}\right)^{-\frac{3}{2}} \left(\frac{n_s}{10^{-7}\text{Mpc}^{-3}}\right)^{-\frac{1}{2}} \left(\frac{A}{1\text{km}^2}\right)^{\frac{3}{2}}$$

$$\Rightarrow n_s > \frac{10^{-7}}{\text{Mpc}^3}, \qquad N(\text{all sky}) > 10^6, \qquad L_\nu < 3 \times 10^{42}\text{erg/s}.$$

[Murase & Waxman 16]

- Rare bright sources: Ruled out (eg AGN, $n \sim 10^{-11}$--10^{-8}/Mpc^3).
- Angular correlation with catalogs of EM sources? Unlikely at present.

$$\Delta\Theta \approx 1\,\text{deg},$$

$$N_\nu(\mu-\text{tracks},\ z<0.1\,\text{sources}) = \frac{N_\nu(\text{tracks})}{N_\nu(\text{all})} \frac{N_\nu(z<0.1)}{N_\nu} N_\nu \approx \frac{1}{5}\frac{1}{20} N_\nu < 1.$$

- Detection of multiple events from few nearby sources Requires $A \to A \times 10$ for $n \sim 10^{-5}$/Mpc^3 (eg starbursts).

Identifying the sources

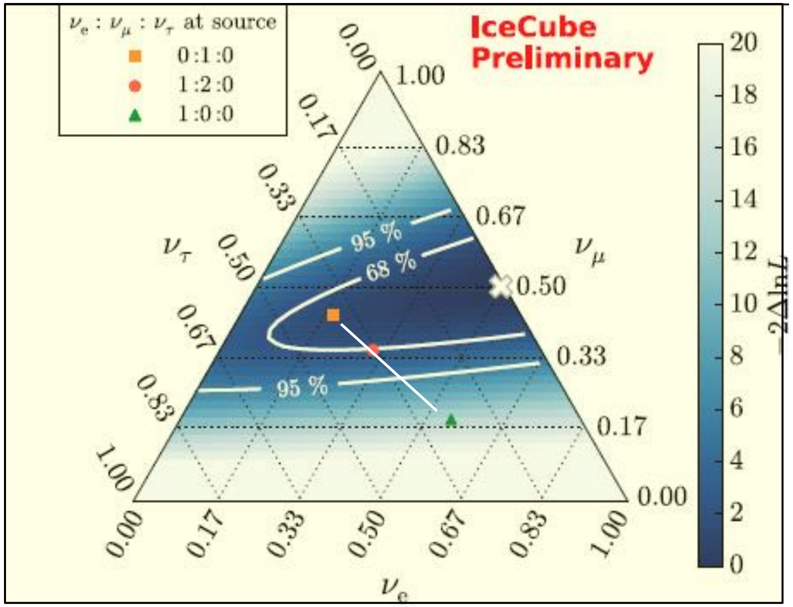
- IC's ν's are likely produced by the "calorimeters" surrounding the sources.
  Φ_ν(prompt) << Φ_ν(calorimeter) ~ Φ_{WB} [e.g. Φ_ν(GRB) <~0.1 Φ_{WB}].

- No $L > 10^{14} L_{\rm sun}$ sources to 300Mpc →
  UHECRs are likely produced by transient "bursting" sources.
- Detection of prompt ν's from transient CR sources,
  temporal ν–γ association, requires:
  Wide field EM monitoring,
  Real time alerts for follow-up of high E ν events,
  and
  Significant [x10] increase of the ν detector mass at ~100TeV.

- 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, Wei et al 16]

Future constraints from flavor ratios



- Without "new physics", nearly single parameter (~f_e @ source).
- Few % flavor ratio accuracy [requires x10 M_{eff} @ ~100 TeV]

→ Relevant ν physics constraints [even with current mixing uncertainties].

[Capozzi et al. 13]

E.g. (for π decay)

$\mu/(e+\tau) = 0.49\ (1-0.05\ \cos\delta_{CP})$,

$e/\tau = 1.04\ \ (1+0.08\ \cos\delta_{CP})$.

[Blum et al. 05; Seprico & Kachelriess 05; Lipari et al . 07; Winter 10; Pakvasa 10; Meloni & Ohlsson 12; Ng & Beacom 14; Ioka & Murase 14; Ibe & Kaneta 14; Blum et al. 14; Marfatia et al. 15; Bustamante et al. 15…]

Low Energy, ~10GeV

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

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

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

- Starbursts- using radio to γ observations

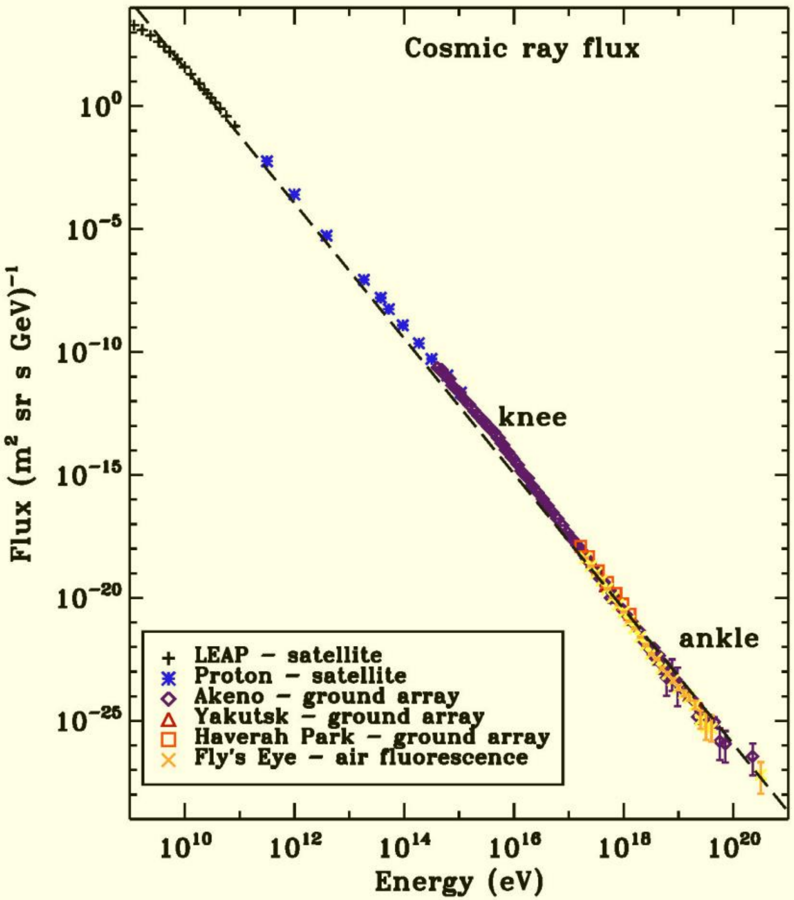
$$Q_E(E \sim 10\text{GeV}, z=0) \approx 5 \left(\frac{0.3}{f_{synch.}} \right) \times 10^{44} \text{erg}/\text{Mpc}^3\text{yr}$$

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

[Katz, EW, Thompson & Loeb 14]

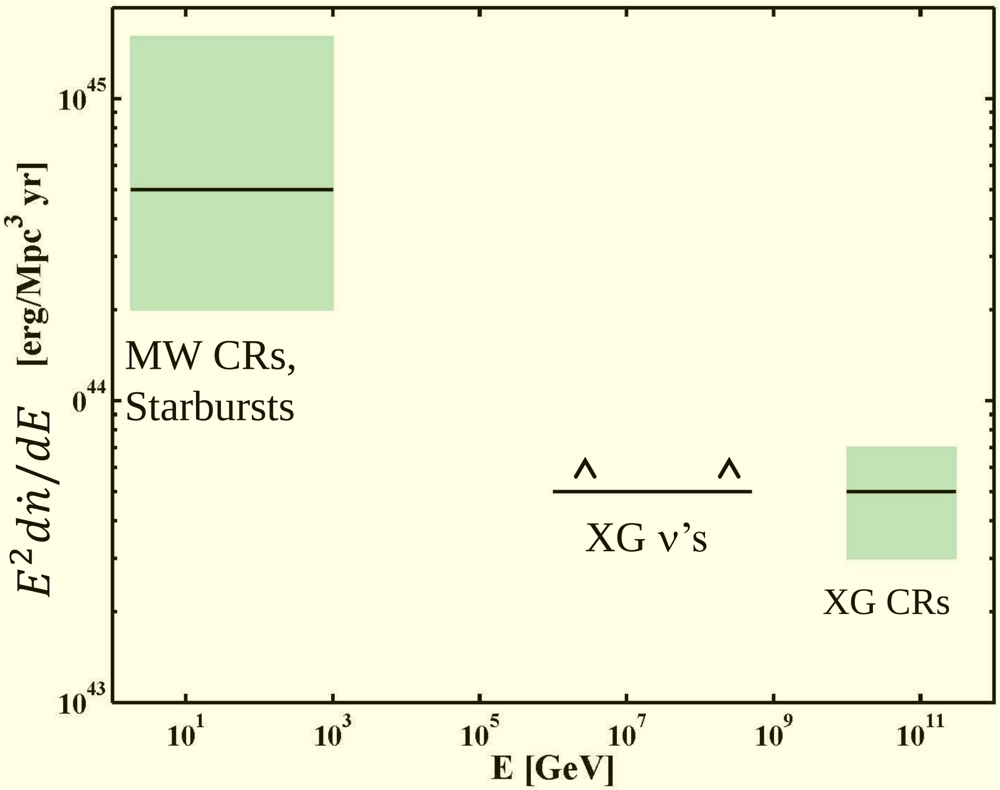
A single cosmic ray source across the spectrum?

Observed spectrum



[From Helder et al., SSR 12]

Generation spectrum



[Katz, EW, Thompson & Loeb 14]

A note on prompt GRB ν's

- "Classical" long GRBs:

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

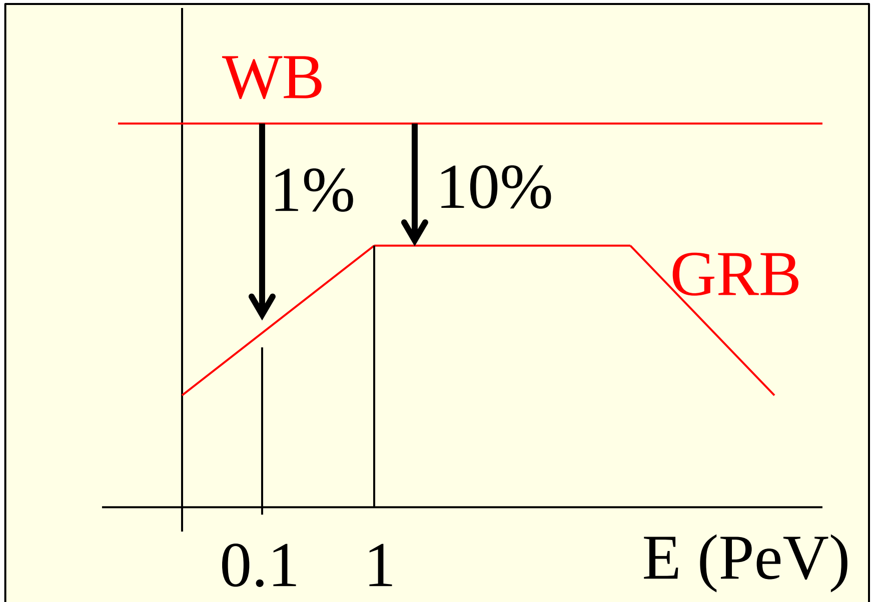
$$\Phi_{\mathrm{GRB}} \approx 0.2\Phi_{\mathrm{WB}} \times \min\left[\frac{\varepsilon_{\nu}}{\varepsilon_{\nu,b}}, 1\right]$$

[EW & Bahcall 97; Hummer, Baerwald, and Winter 12; Li 12; He et al 12 …Tamborra & Ando 15]

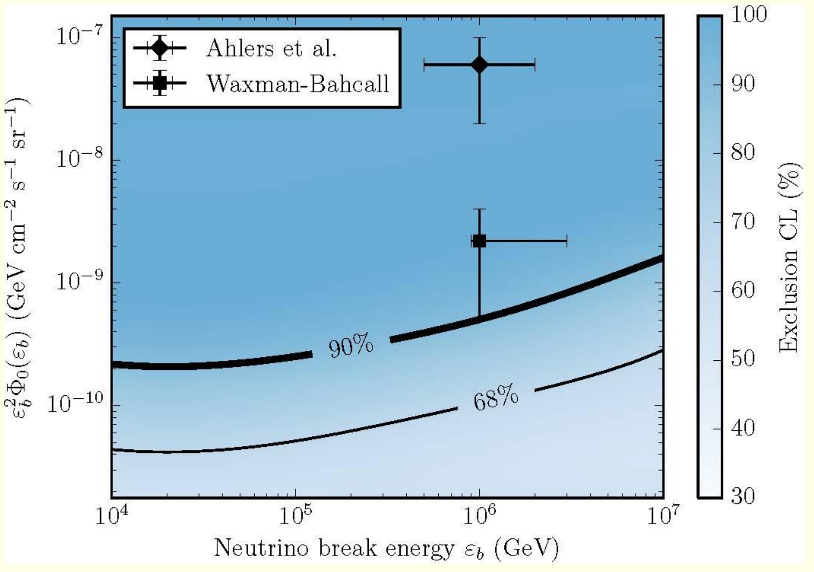
- IC has achieved relevant sensitivity: constraining model parameters.

- LLGRBs/Chocked GRBs have been suggested to dominate IceCube's signal [e.g. Senno, Murase, and Mészáros 16].

  Talk by Peter Mészáros.



[IceCube 16]



Summary

- IceCube detects extra-Galactic ν's: The beginning of XG ν astronomy.
  * The flux is as high as could be hoped for.
  * $\Phi_\nu \sim \Phi_{WB}$ suggests a connection with UHECRs:
  >10^{19}eV CRs and PeV ν's: XG p sources, $E^2 \frac{d\dot{n}}{dE} \approx Const.$, related to SFR.
  All >~1PeV (>1GeV?) CRs are produced by the same sources.

- Expansion of M_{eff} @ ~100TeV to ~10Gton (NG-IceCube, Km3Net):
  - Reduced uncertainties in ν flux, spectrum, isotropy, flavor ratio.
    [A different ν source at <50TeV? A cutoff >3PeV?]
  - Identification of CR/ν "calorimeters".
  - Likely identification of CR sources by temporal ν–γ association.
    [Wide field EM monitoring, real time alerts, γ telescopes.]
    Key to Accelerators' physics, Fundamental/ν physics.

- Adequate sensitivity for ~10^{10}GeV GZK ν's (ARA, ARIANNA, [Auger data]).
  - Confirm (reject?): UHE CRs are p.