High energy neutrino astronomy: Where are we now, what did we learn?

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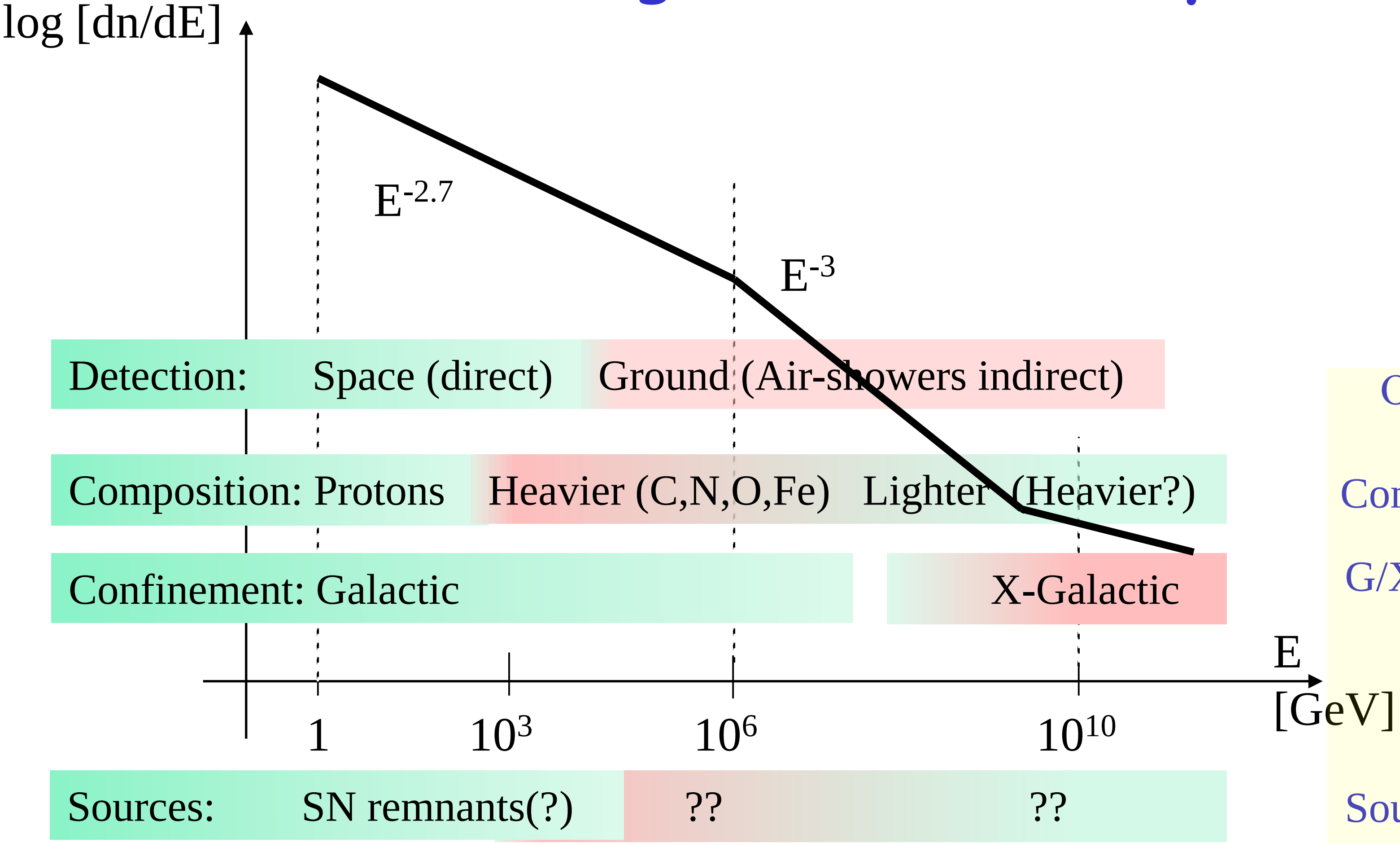
The main driver of HE ν astronomy: The origin of Cosmic Rays



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

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

Open Q's

Composition?

G/XG transition?

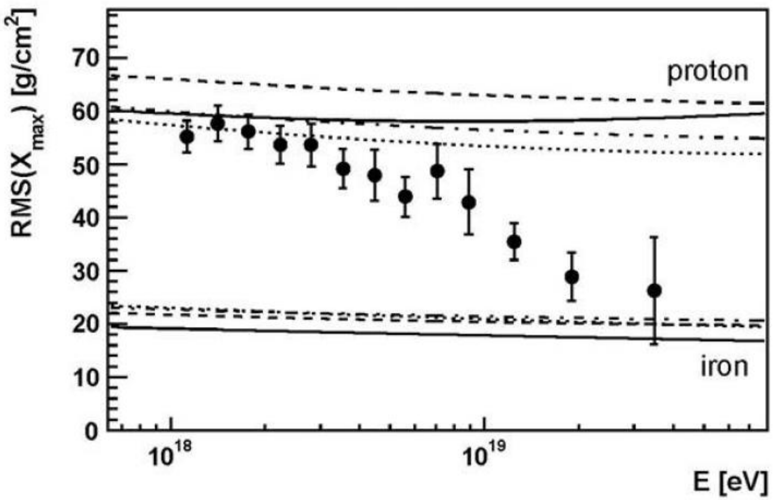
Sources?

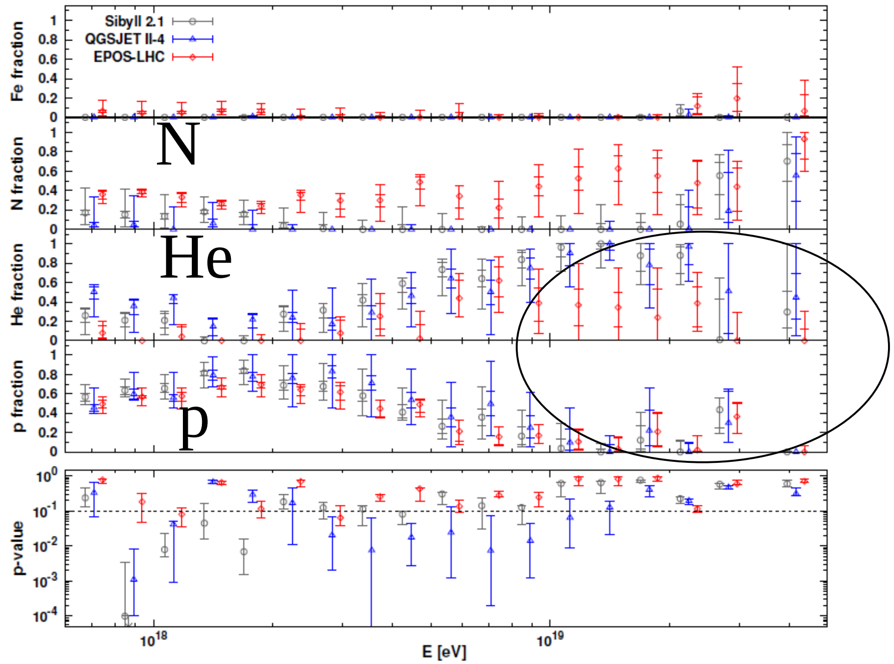
Acceleration?

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

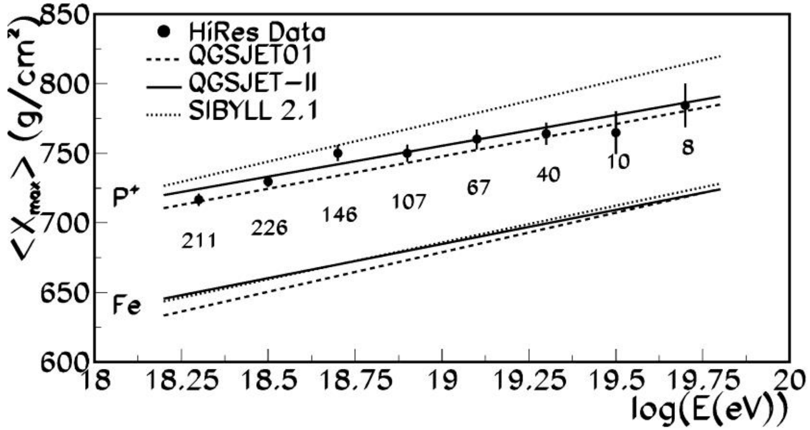
UHE: Air shower composition constraints

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





HiRes Stereo 2010 & TA Hybrid 2015



- A light component is required at UHE.
- Air-shower analyses inconclusive.
  - E_{CM}>100TeV,
  - Air-shower modelling & analysis.

>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

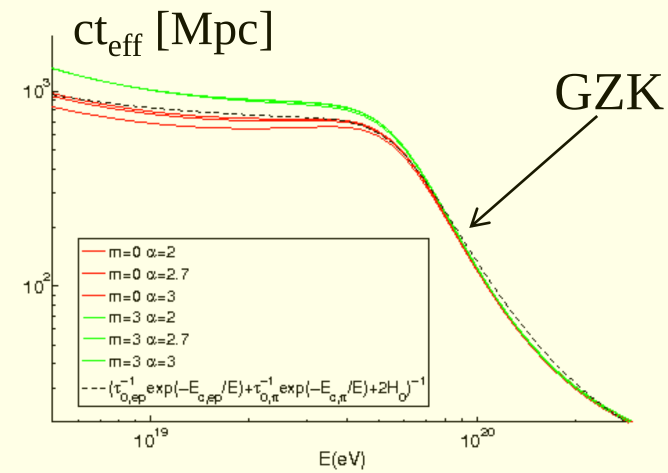
$$Q_E = E^2\frac{d\dot{n}}{dE} = Const.$$
$$= (0.5 \pm 0.2)10^{44}\,\frac{\text{erg}}{\text{Mpc}^3\text{yr}},$$

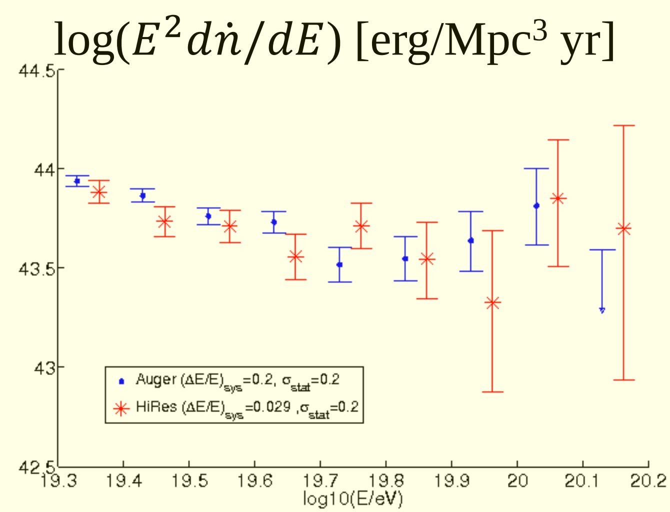
[EW 95, Bahcall & EW 03, Katz & EW 09]

  - 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).

$$\frac{dn}{dE} = \frac{d\dot{n}}{dE}t_{eff}(E)$$





Acceleration: Max E

- Astrophysical EM acceleration requires $L > 10^{14}\frac{\Gamma^2}{\beta}\left(\frac{E}{Z\,10^{20}\mathrm{eV}}\right)^2 L_{\rm sun}$.

  [Lovelace 76; EW 95, 04; Norman et al. 95]

- No $L > 10^{14} L_{\rm sun}$ sources to 300Mpc → Transient "bursting" sources.

  $\Delta t(p-\gamma)\sim 10^5\mathrm{yr} \gg$ Transient duration,

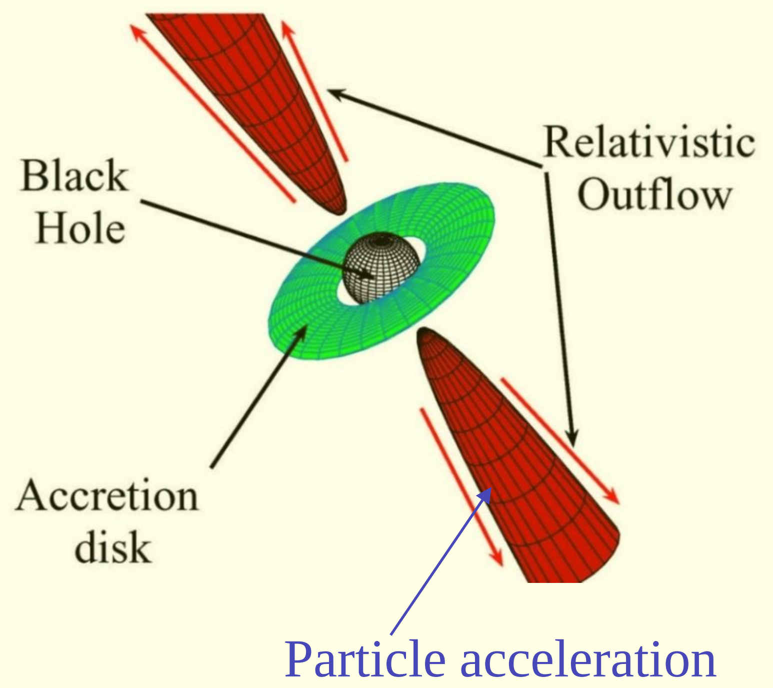
  No $p-\gamma$ association.

- Candidates- Relativistic jets driven by mass accretion onto BHs.
  - Gamma-ray bursts (GRB), newly formed solar mass BHs;
    [Vietri 95, Milgrom & Usov 95, EW 95]
  - Tidal disruption of stars (TDE) by massive BHs at galaxy centers.
    [Gruzinov & Farrar 09]

(- Young, ms, 10^{13}G Neutron Stars?

If they exist… [Arons 03,… Lemoine et al. 15].)

At the focus of HE Astro.
Radio- γ-ray observations



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]
  - <~10^6GeV -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,

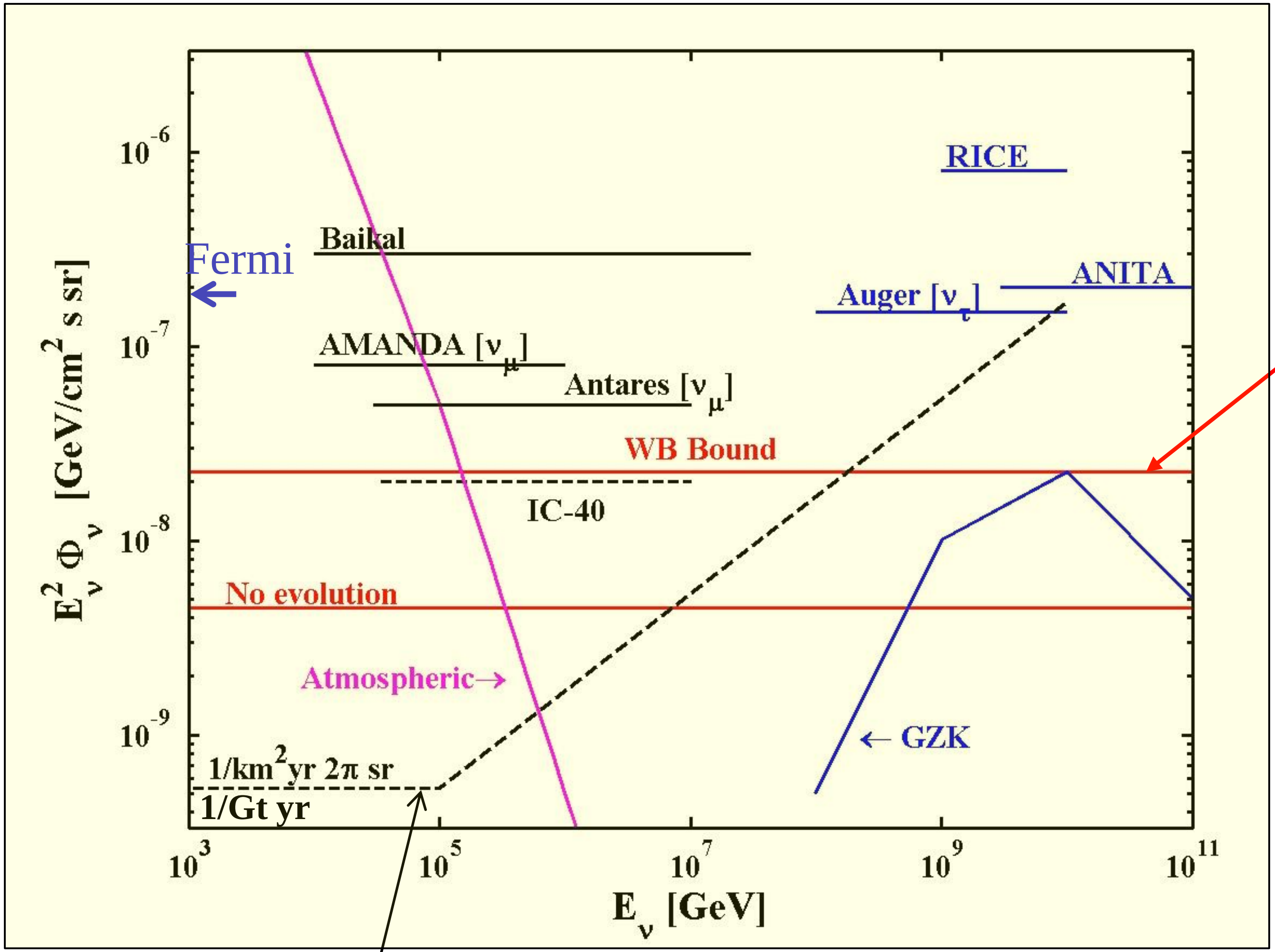
    all p→π by pp in the inter-stellar gas, $t_{pp} < t_{\text{conf}}(E < 10^6 \text{GeV})$.

[Loeb & EW 06]

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

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

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



2 flavors,

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

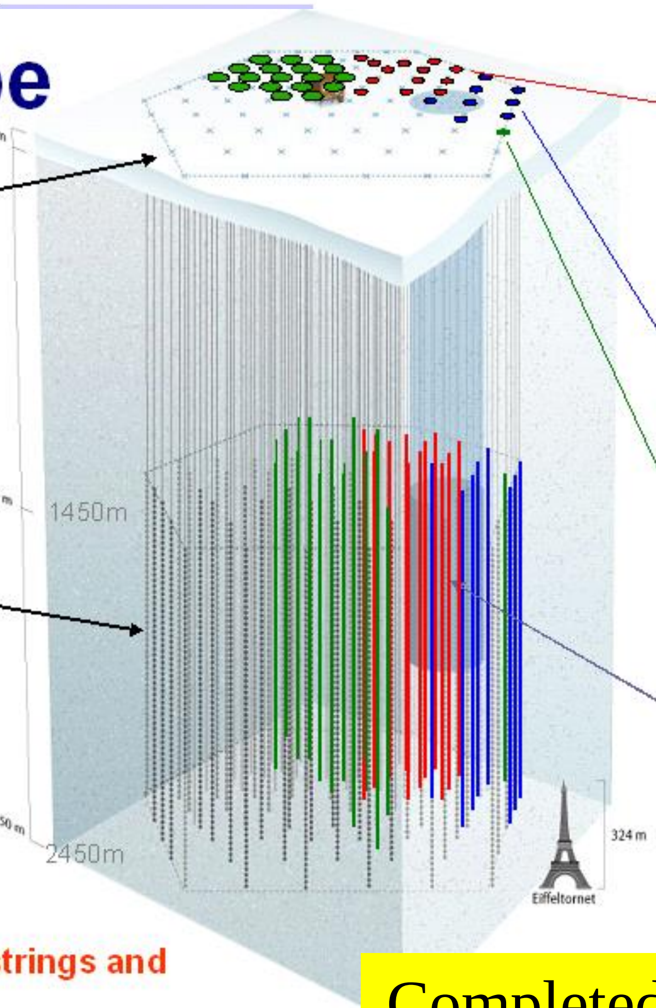
Rate ~ $(E\Phi)N_n\sigma(E)$, σ~E → Rate ~ $(E^2\Phi)M$

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

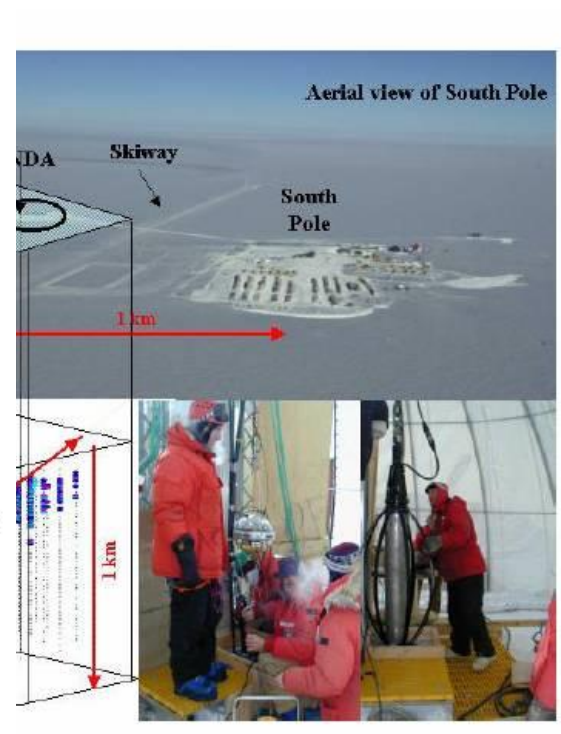
2006-2007:
13 strings deployed

2007-2008
18 strings deployed

2005-2006: 8 strings

2004-2005 : 1 string

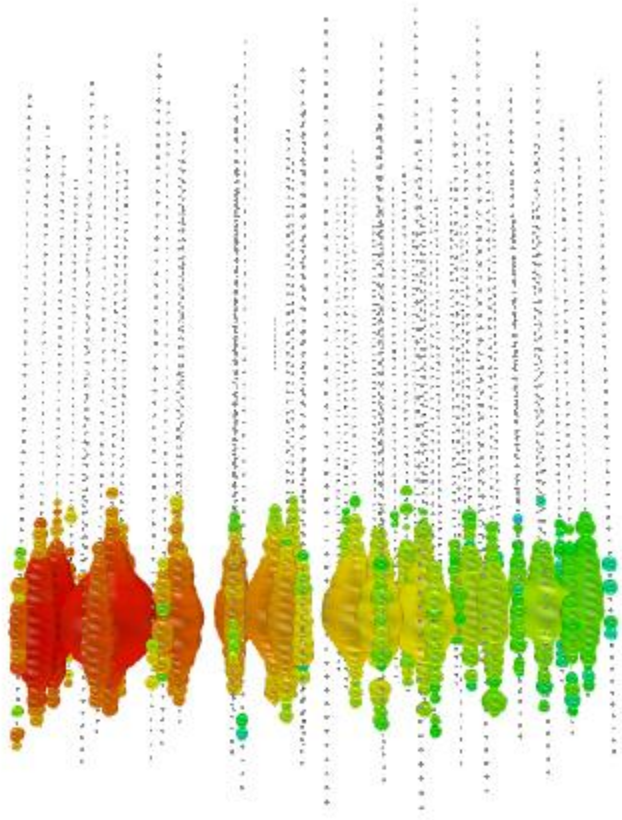
AMANDA-II
19 strings
677 modules



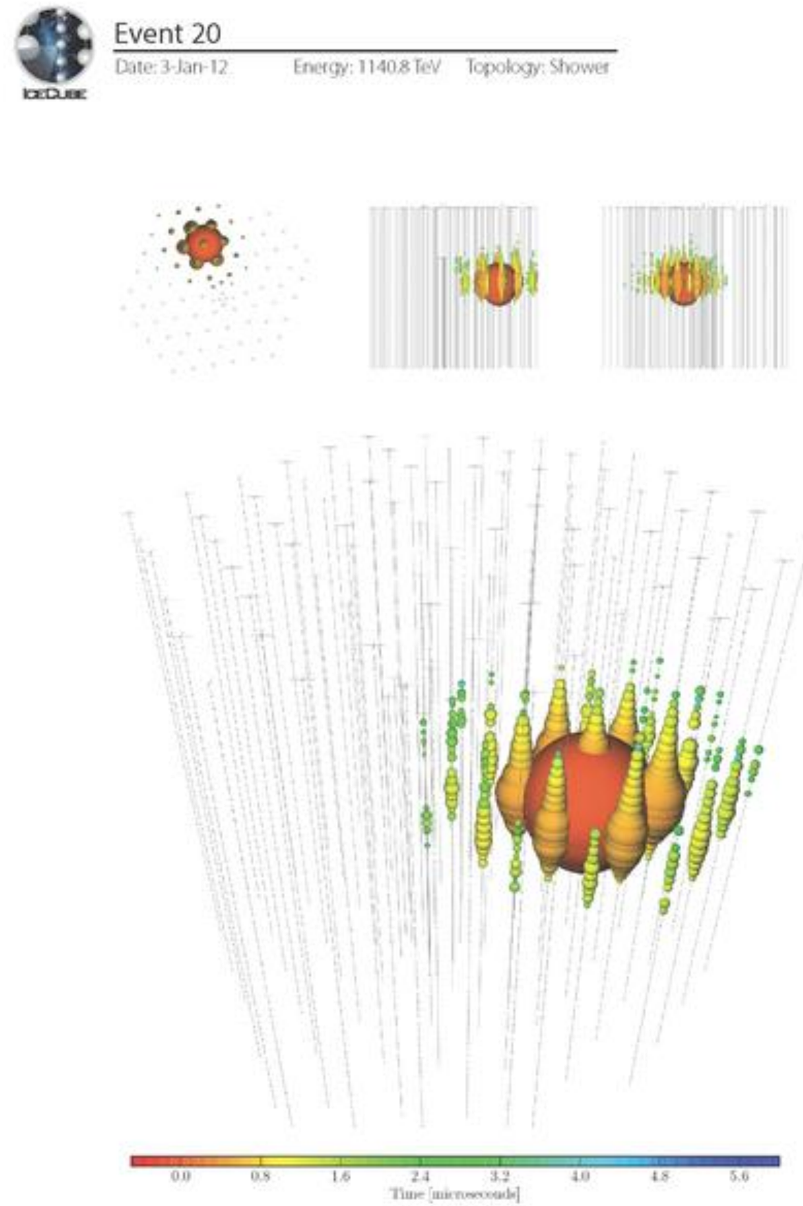
Current configuration:
40 strings,
40 IceTop stations
plus AMANDA

2008/09: add 18 strings and tank stations

Completed Dec 2010



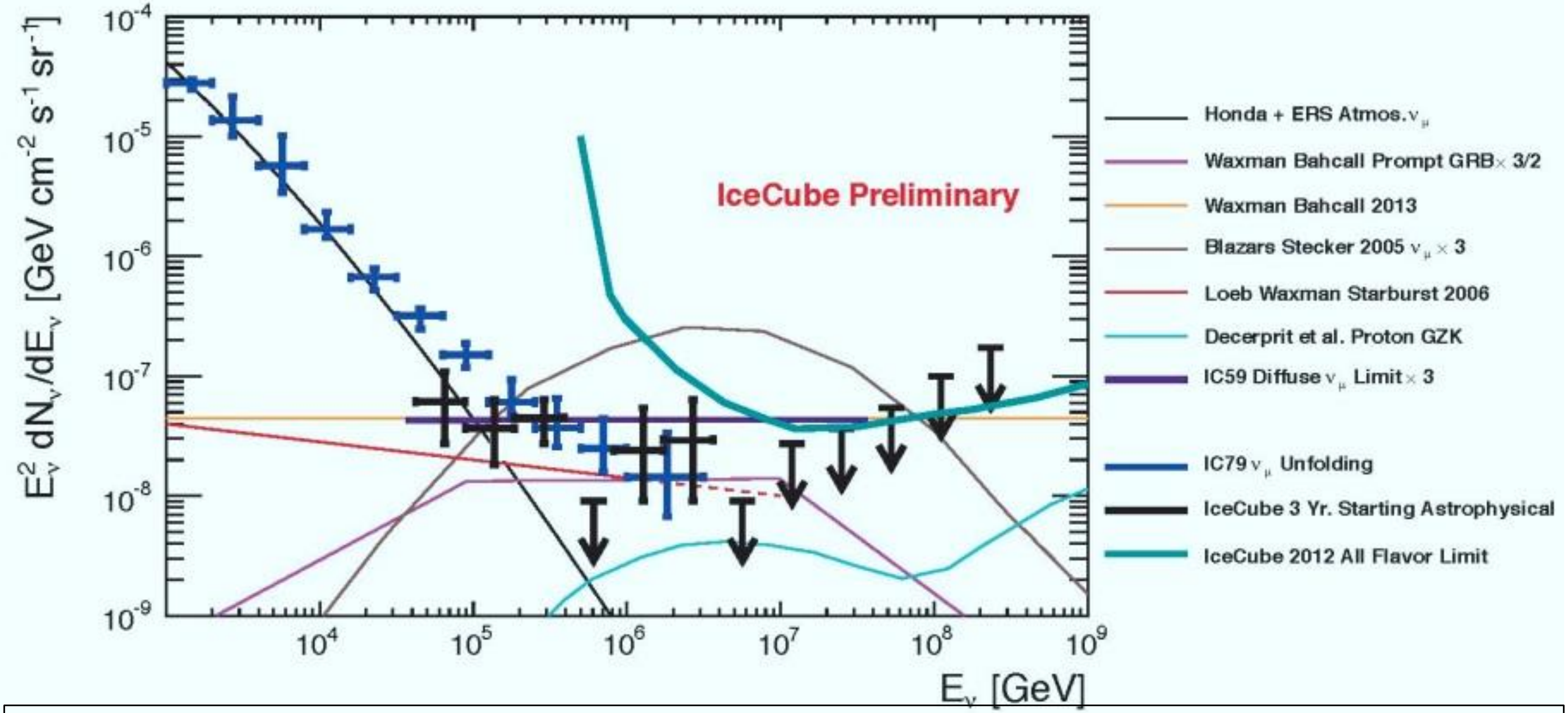
400TeV



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.).

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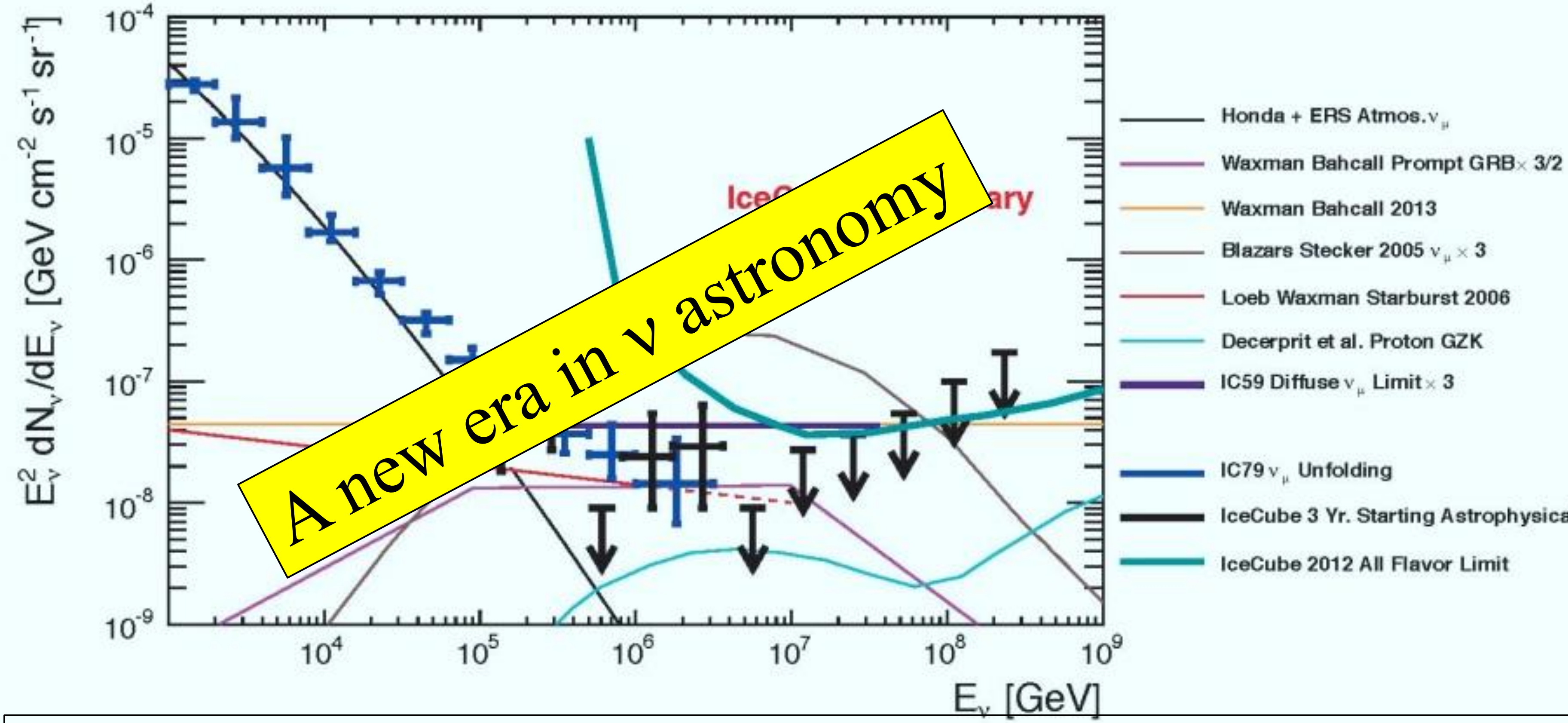

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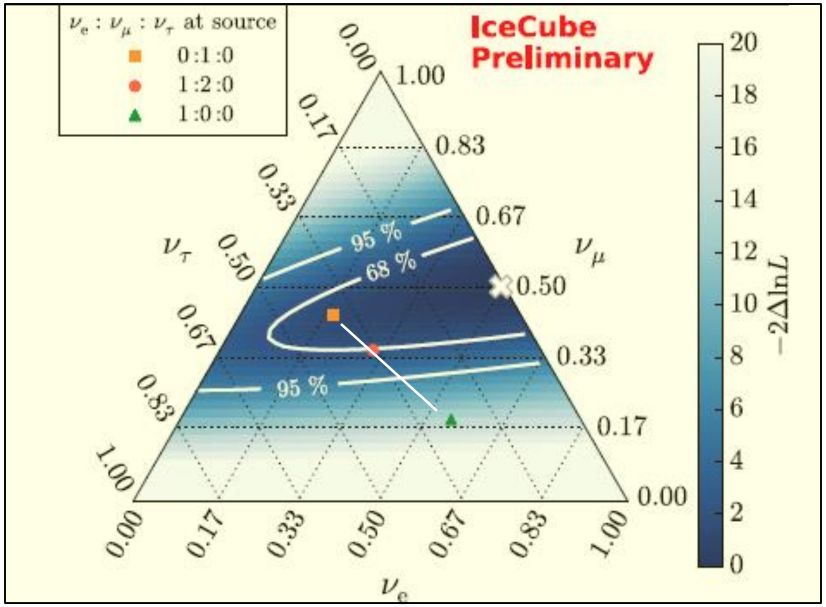
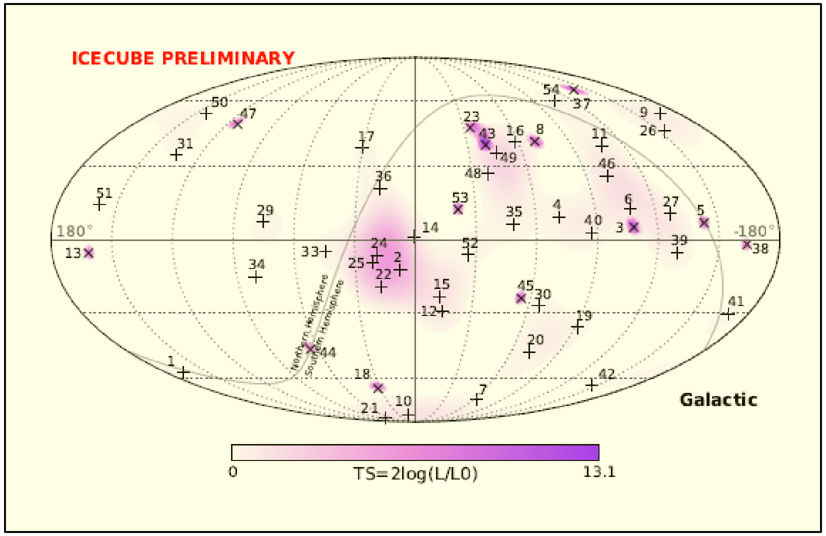
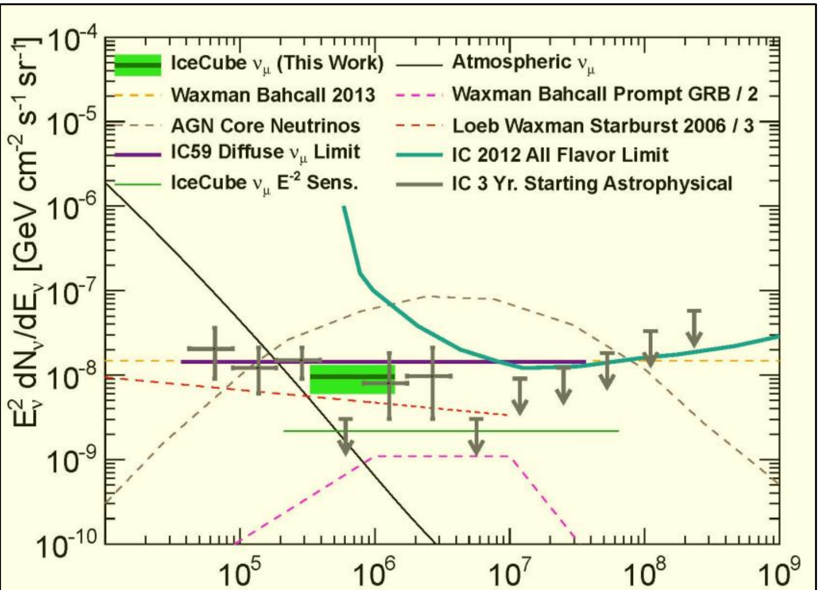
Consistent with Isotropy,
$\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ (π deacy + cosmological prop.).

Status: Isotropy, flavor ratio

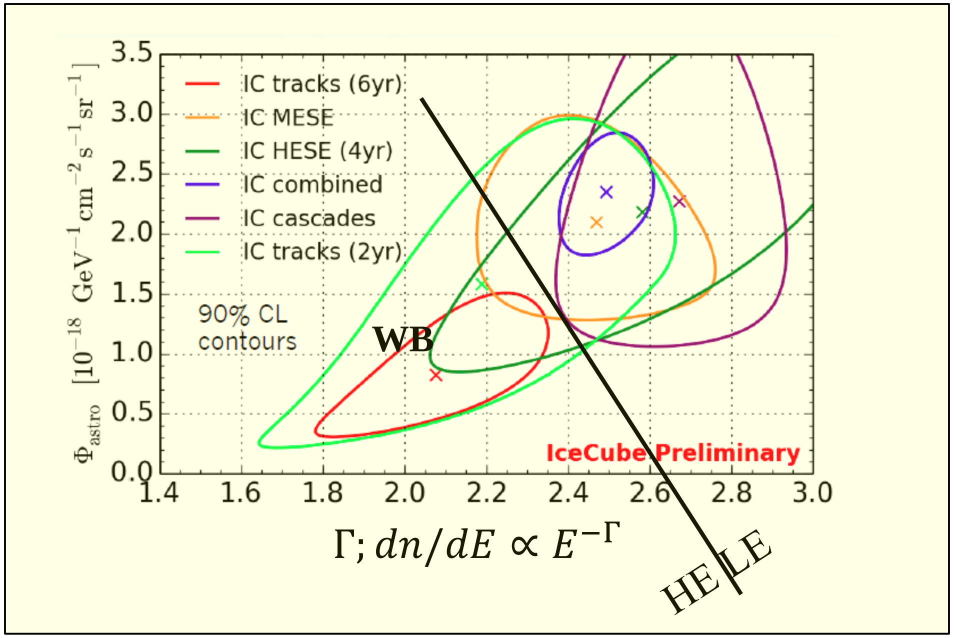


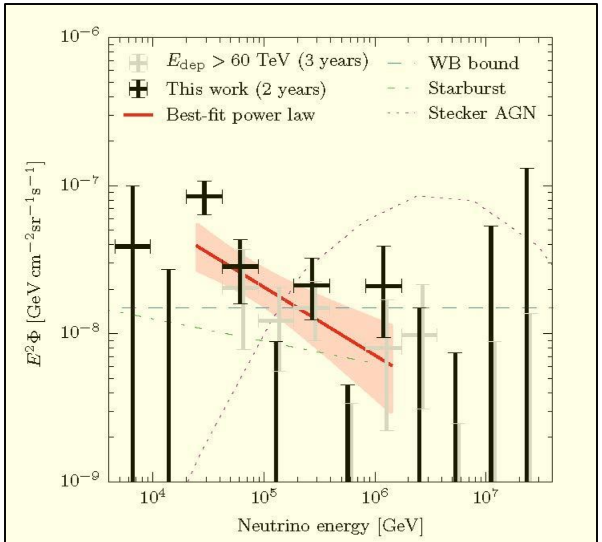


Status: Flux, spectrum



PRL 115, 081102 (2015)





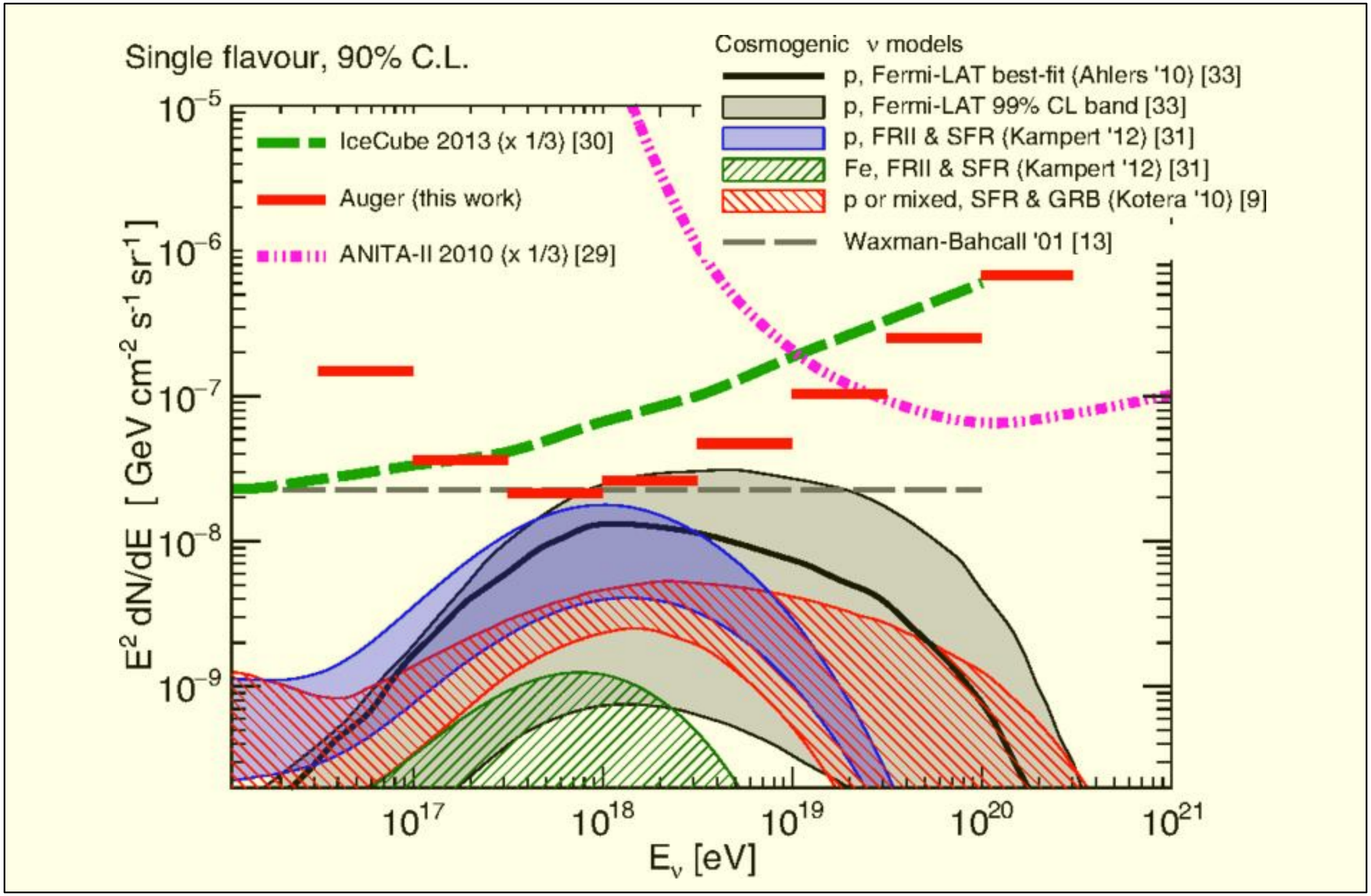
PRD 91, 022001 (2015)

- Excess below ~50TeV→ A new component?
- Note: - $\Phi \sim 0.01\, \Phi_{Atm.}$,
  - Varying veto efficiency.
- Fermi γ's @ ~0.1TeV

$$I_{\gamma,XG} \approx 10^{-7} \frac{\text{GeV}}{\text{cm}^2\text{s sr}} \rightarrow \Gamma_{XG} < 2.2\ ;$$

$$I_{\gamma,G\pi^0} \approx 2 \times 10^{-7} \frac{\text{GeV}}{\text{cm}^2\text{s sr}} \rightarrow \text{~30 TeV “bump”?}$$

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



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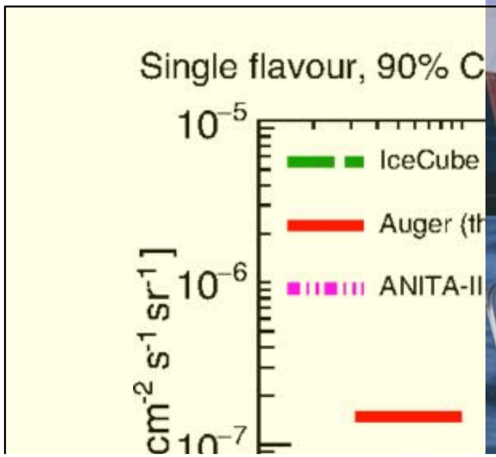
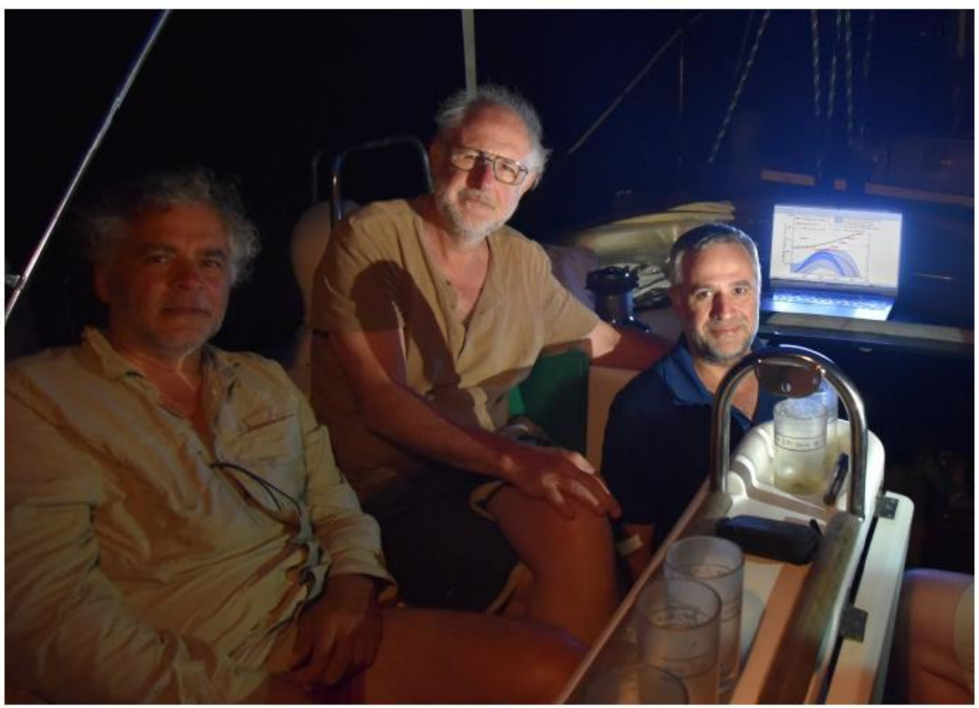




IceCube's (>50TeV) ν sources

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

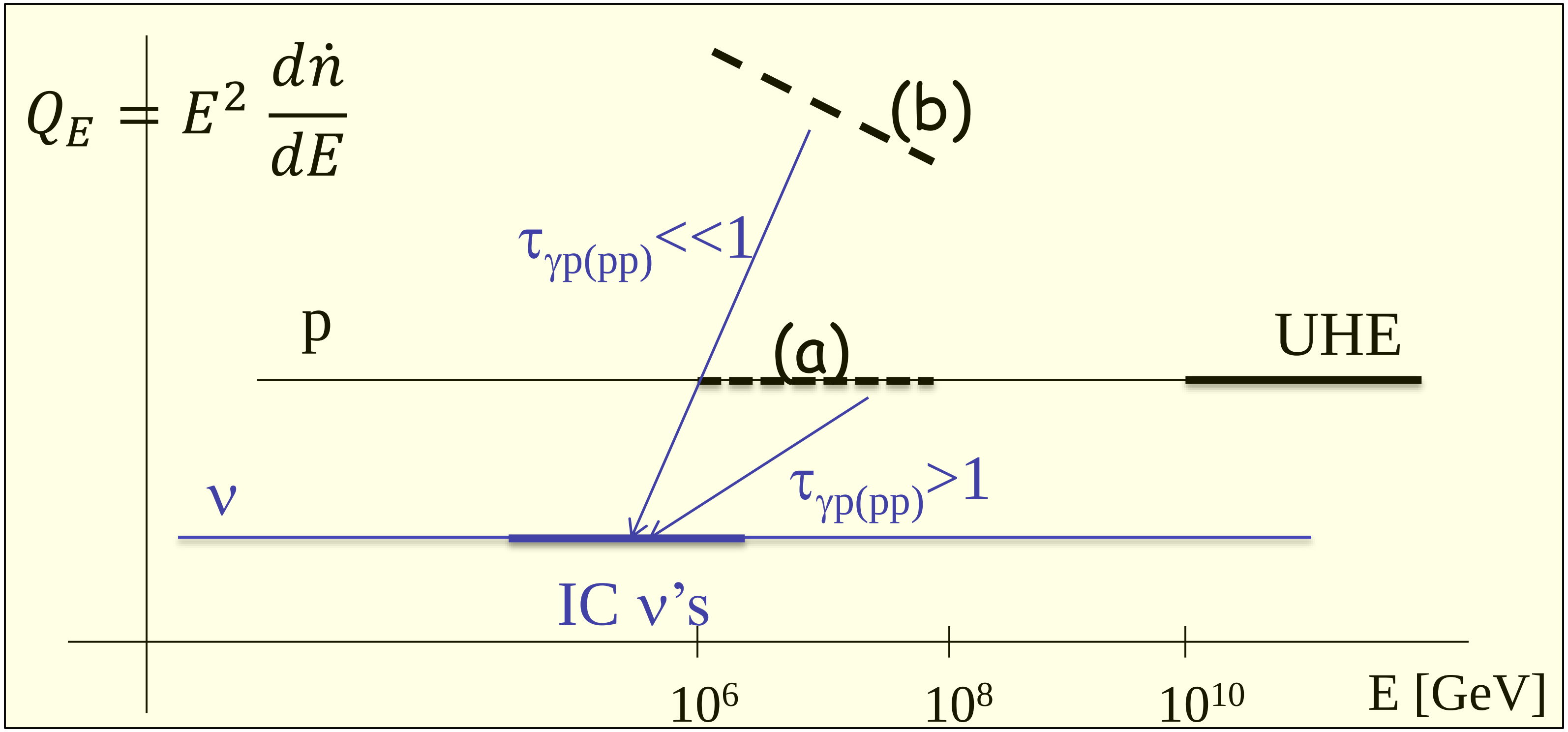
- Galactic?
  Unlikely- Isotropy.

→ 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 is (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.



Identifying the "calorimeters"

- No sources with multiple-ν_μ-events:

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

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

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

$$\Delta\Theta \approx 1 \deg,$$

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

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

Identifying the sources

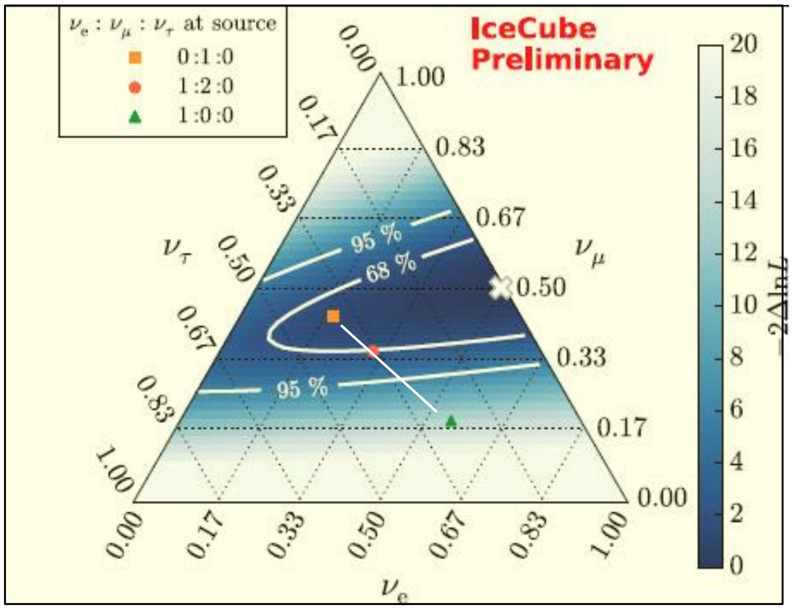
- IC's ν's are likely produced by the "calorimeters" surrounding the sources.
  Φ_ν(prompt) << Φ_ν(calorimeter) ~ Φ_{WB} [e.g. Φ_ν(GRB) <~0.1 Φ_{WB}].

- Detection of prompt ν's from transient CR sources,
  temporal $\nu-\gamma$ 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]

Future constraints from flavor ratios



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

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

E.g. (for π decay)

[Capozzi et al. 13]

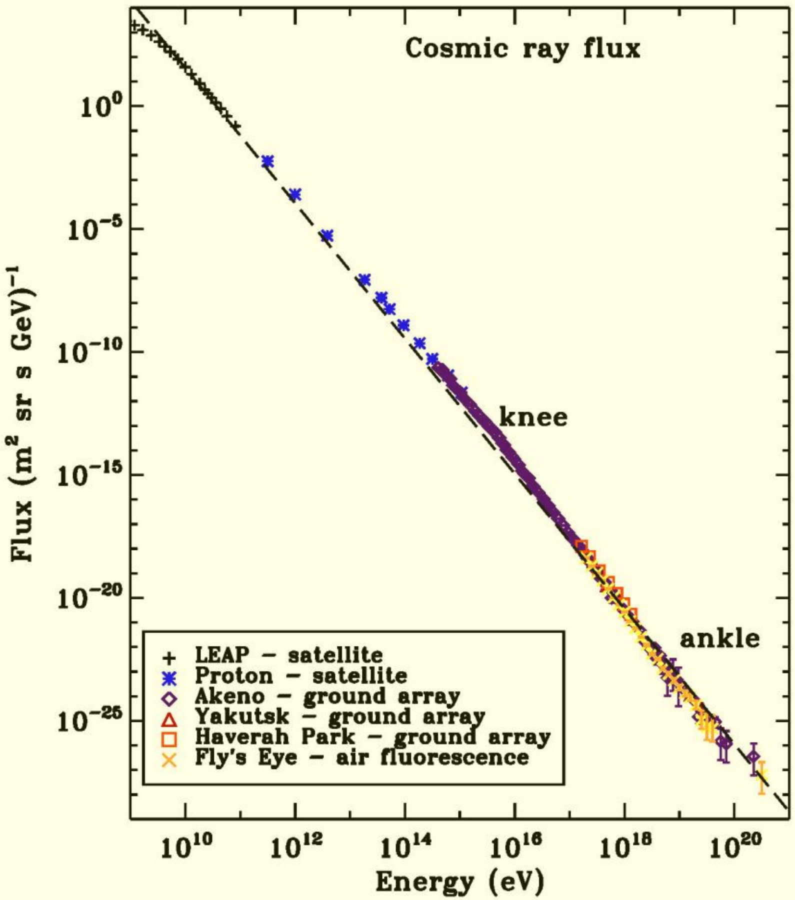
$\mu/(e+\tau) = 0.49\ (1-0.05 \cos \delta_{CP})$,

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

[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…]

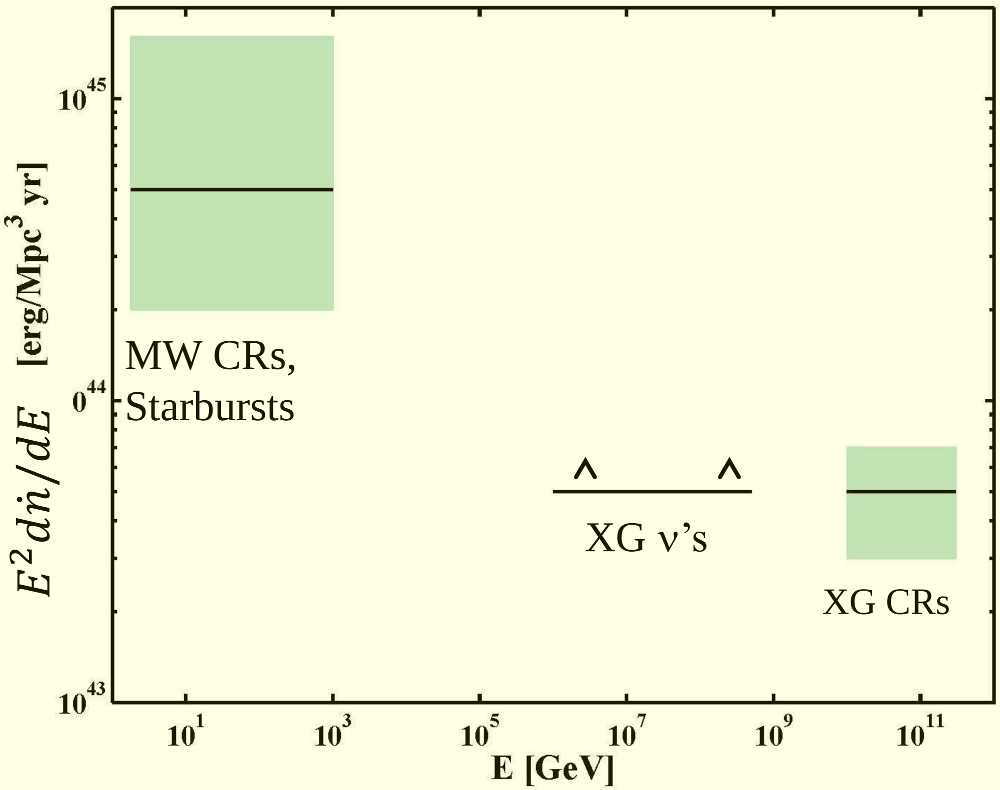
A single cosmic ray source across the spectrum?

Observed spectrum



[From Helder et al., SSR 12]

Generation spectrum



[Katz, EW, Thompson & Loeb 14]

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.

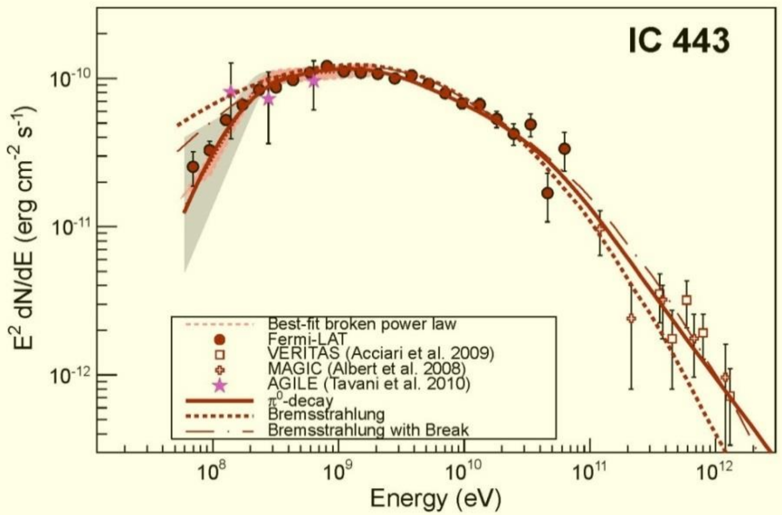
- Expansion of M_{eff} @ ~100TeV to ~10Gton (NG-IceCube, Km3Net):
  - Reduced uncertainties in ν flux, spectrum, isotropy, flavor ratio.
    [A different ν source at <50TeV? A cutoff >3PeV?]
  - Identification of CR/ν "calorimeters".
  - Likely identification of CR sources by temporal $\nu-\gamma$ association.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

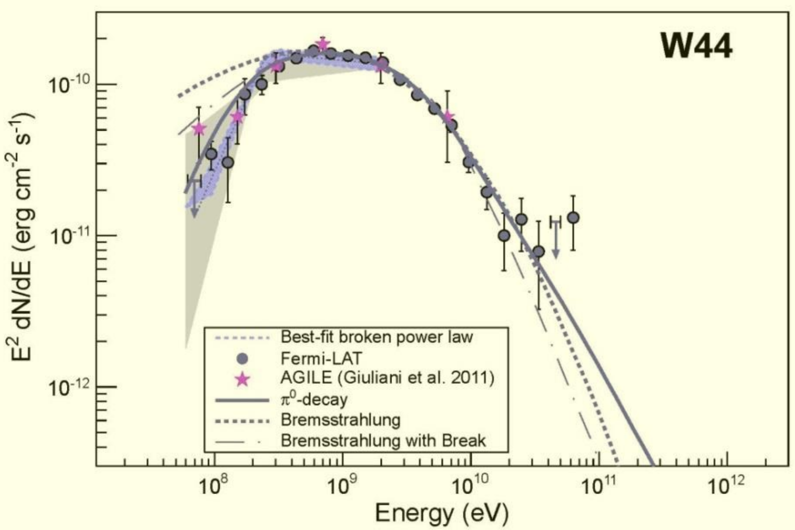
- Adequate sensitivity for ~10^{10}GeV GZK ν's (ARA, ARIANNA, [Auger data]).
  - Confirm (reject?): UHE CRs are p.

Backup Slides

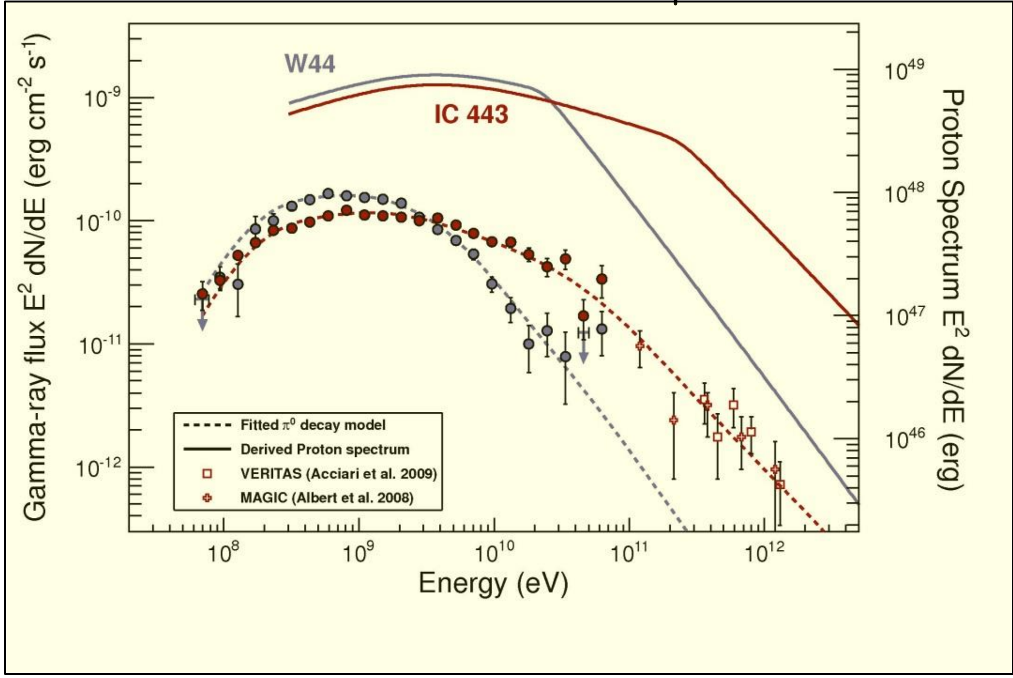
Are SNRs the sources of E<1PeV CRs?

π^0 decay signature [Ackermann et al. 13].



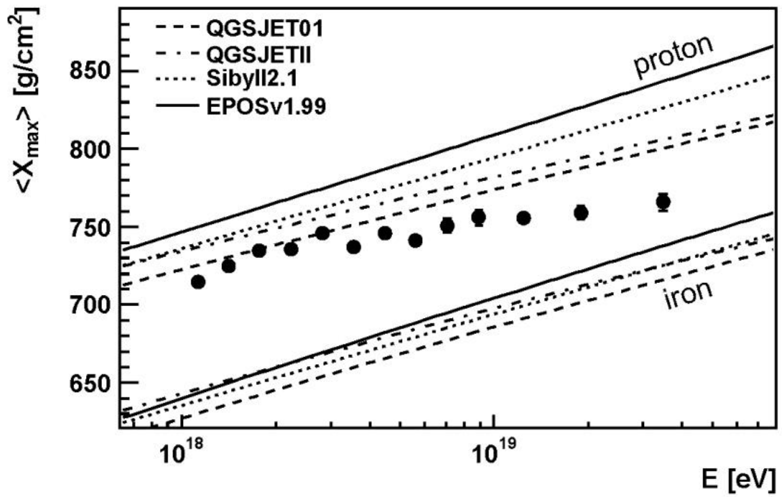


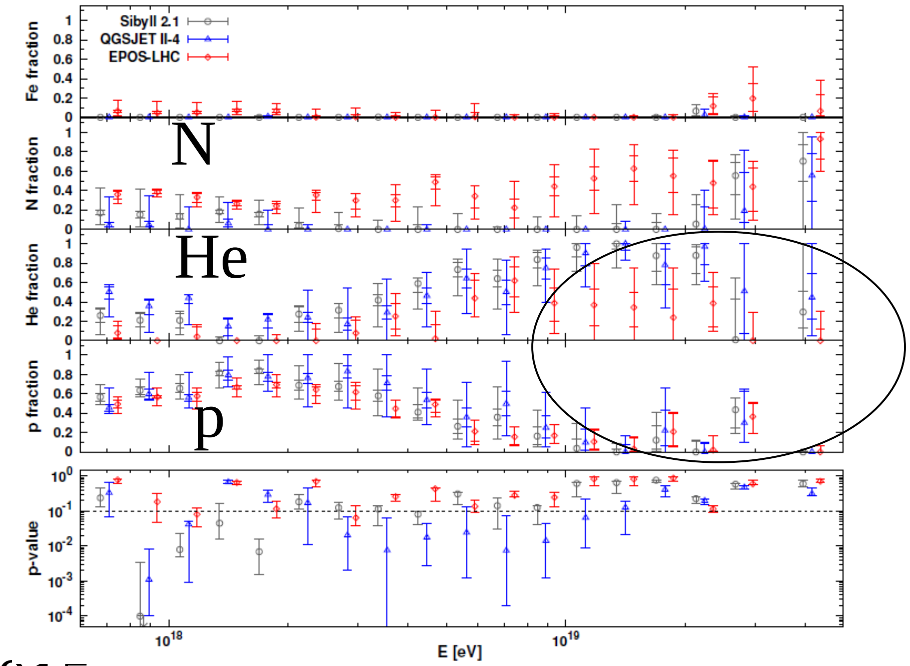
- So far, no direct evidence.
- EM observations- ambiguous.
- Modelling complex (interaction with molecular clouds).
- π^0 interpretation → E_p<100 GeV.



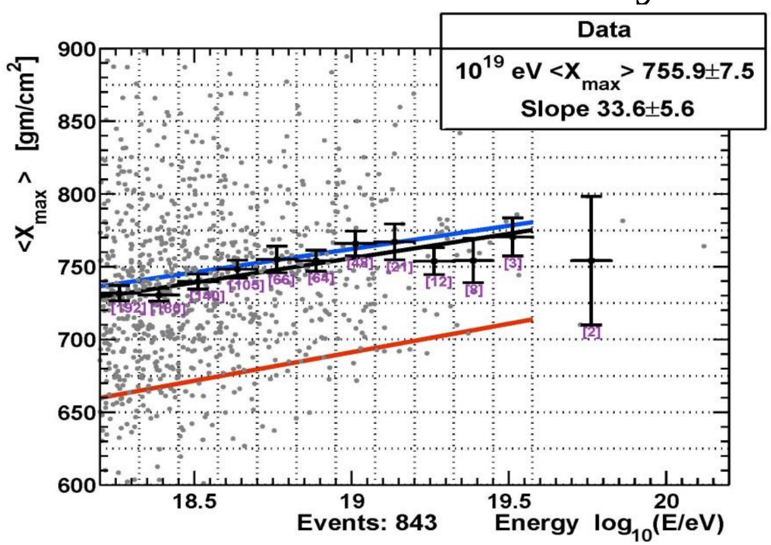
UHE: Air shower composition constraints

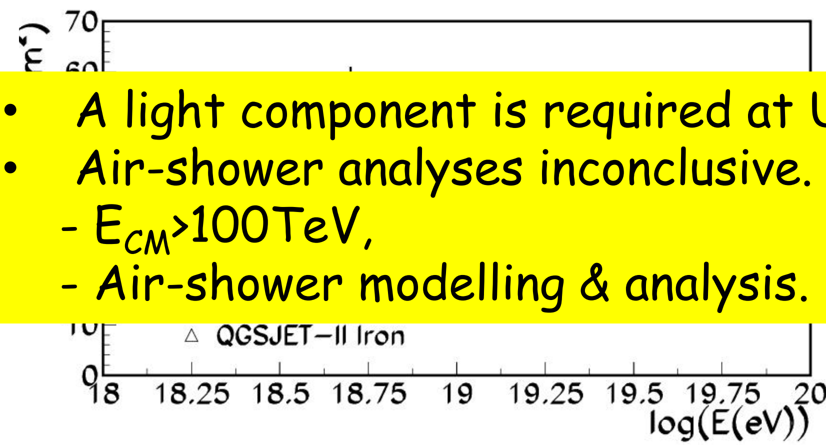
Auger 2010: Fe, 2015: p, He(??)





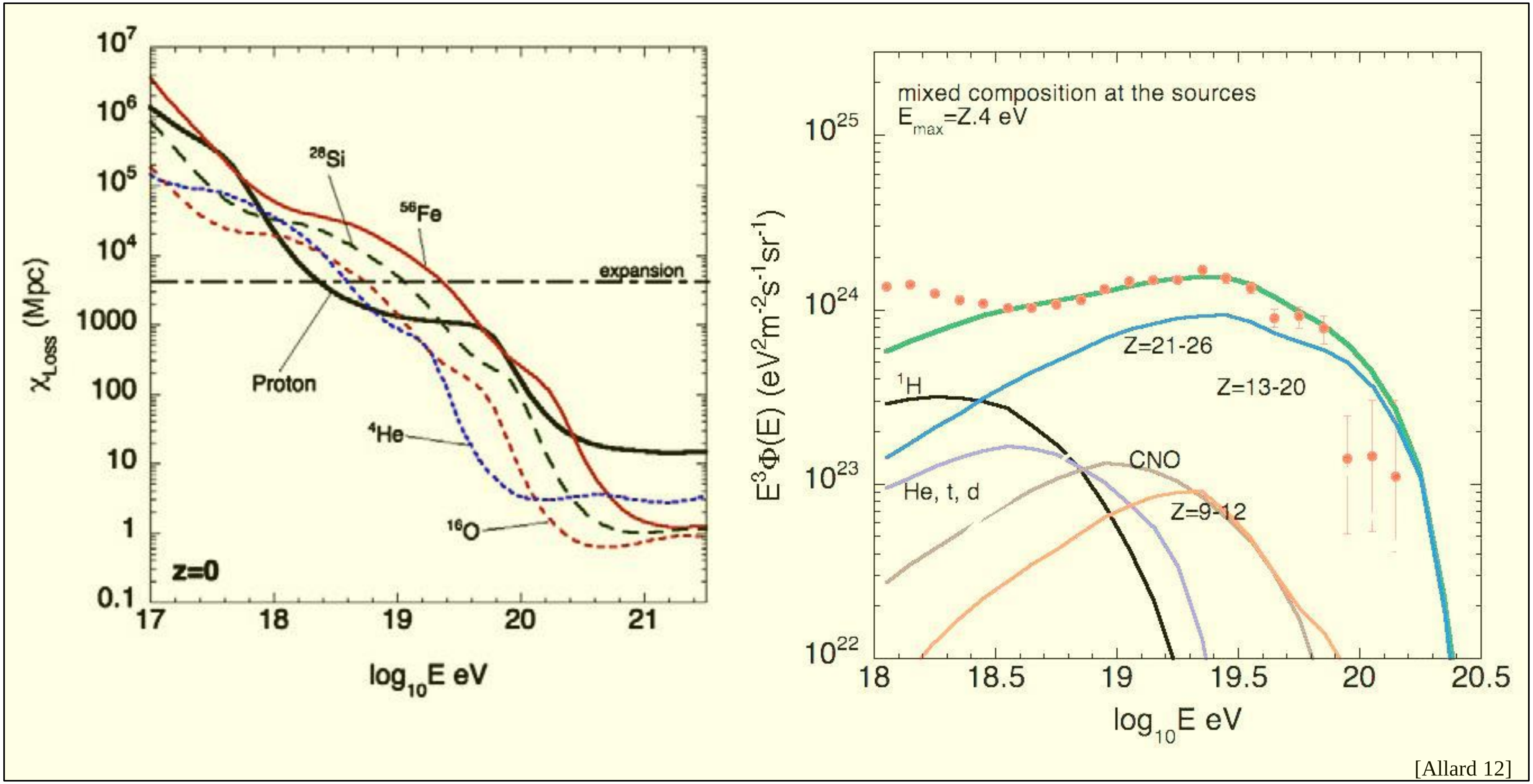
HiRes Stereo 2010 & TA Hybrid 2015





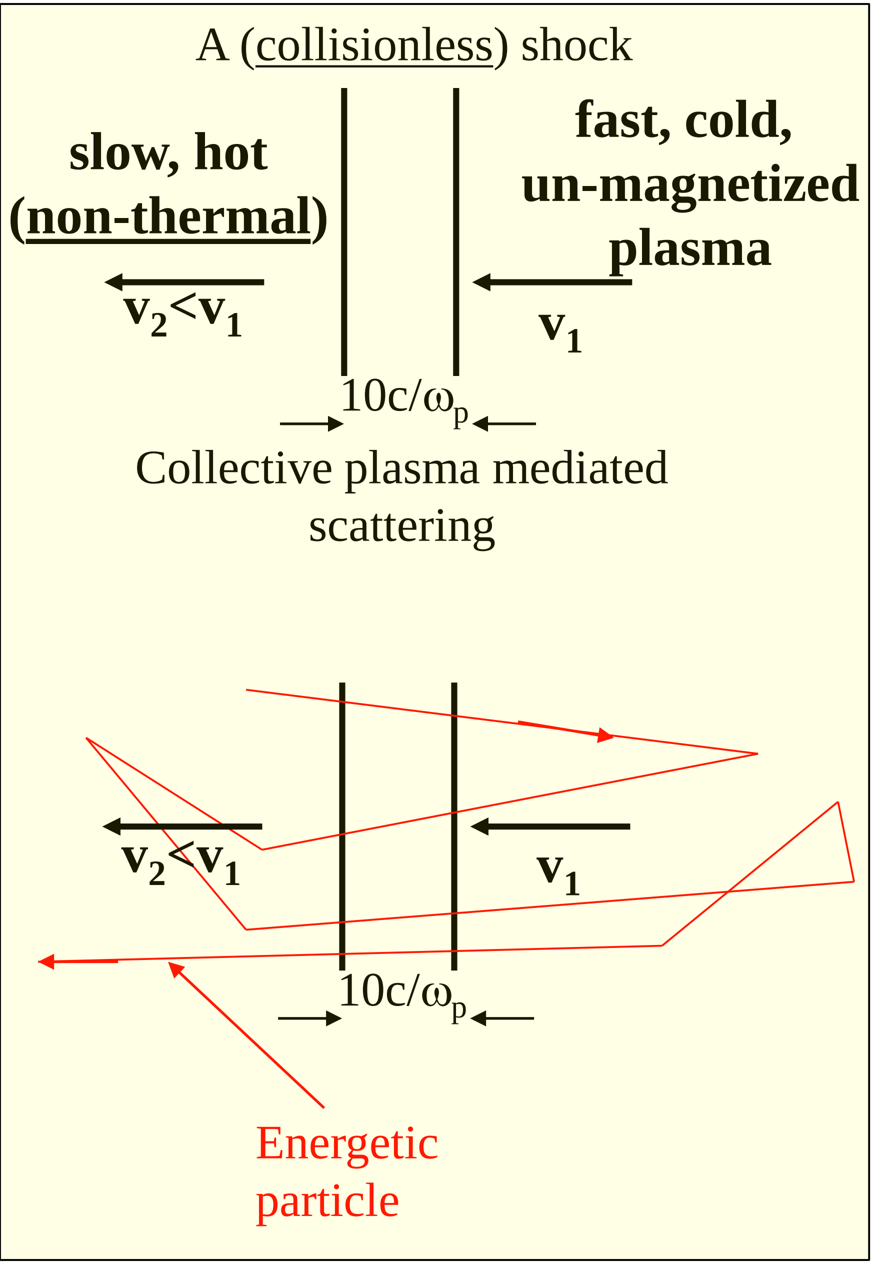
- A light component is required at UHE.
- Air-shower analyses inconclusive.
  - E_{CM}>100TeV,
  - Air-shower modelling & analysis.

A mixed composition



- # free parameters >> # constraints, but cannot be ruled out.

Acceleration: Collisionless shocks



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

- Analytic (test-particle) approx. yields

  $$E^2 \frac{d\dot{n}}{dE} \approx Const.\ ,$$

  [Krymsky 77; Kehset & EW 05]

  as observed in a wide range of sources (lower energy p's in the Galaxy, radiation from accelerated e^-).

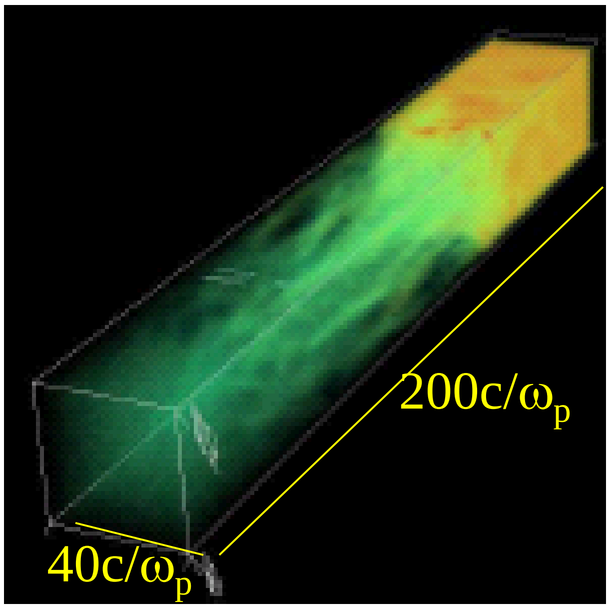
- Supported by basic principles plasma simulations.

  [Sironi et al 15, Park et al. 15]

- [The only predictive model.]

Collisionless shocks: Plasma simulations

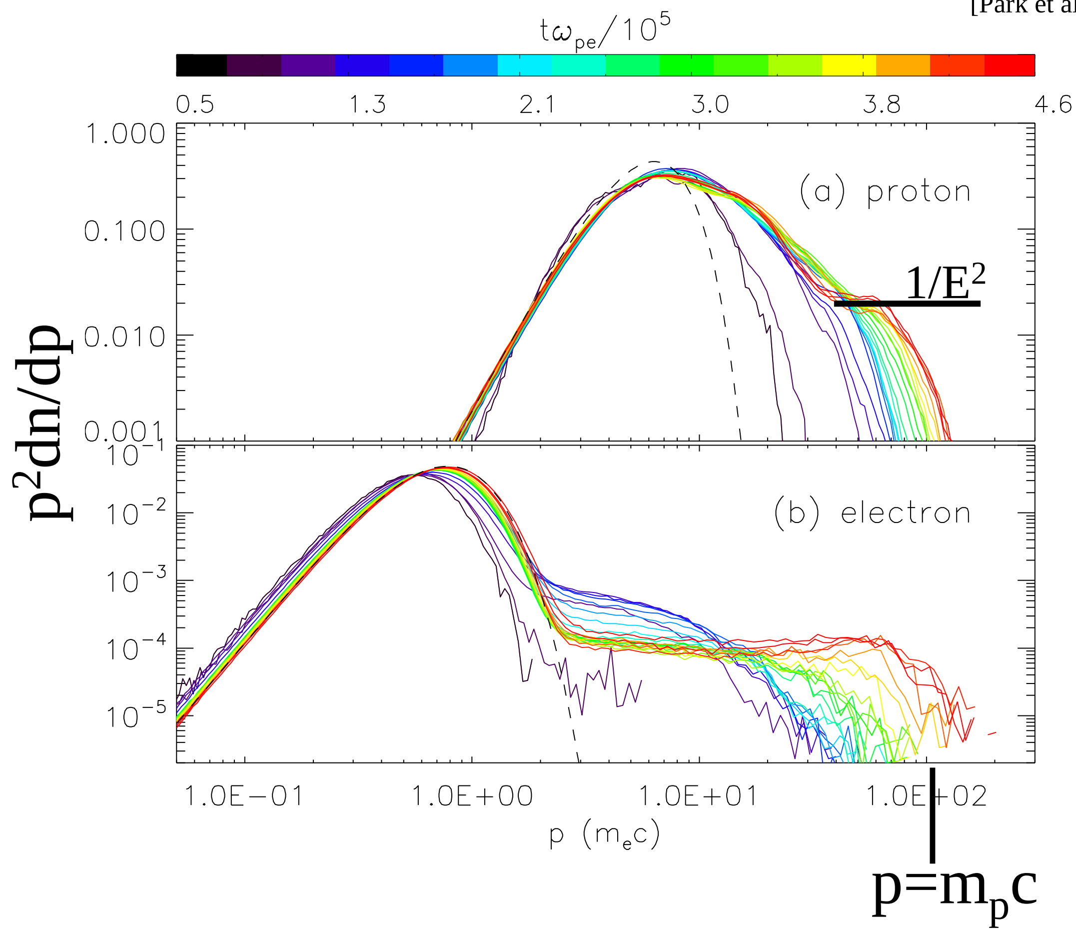
3D, $m_p/m_e=1$



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

1D, $m_p/m_e=100$, $L=10^3c/\omega_p$

[Park et al. 15]



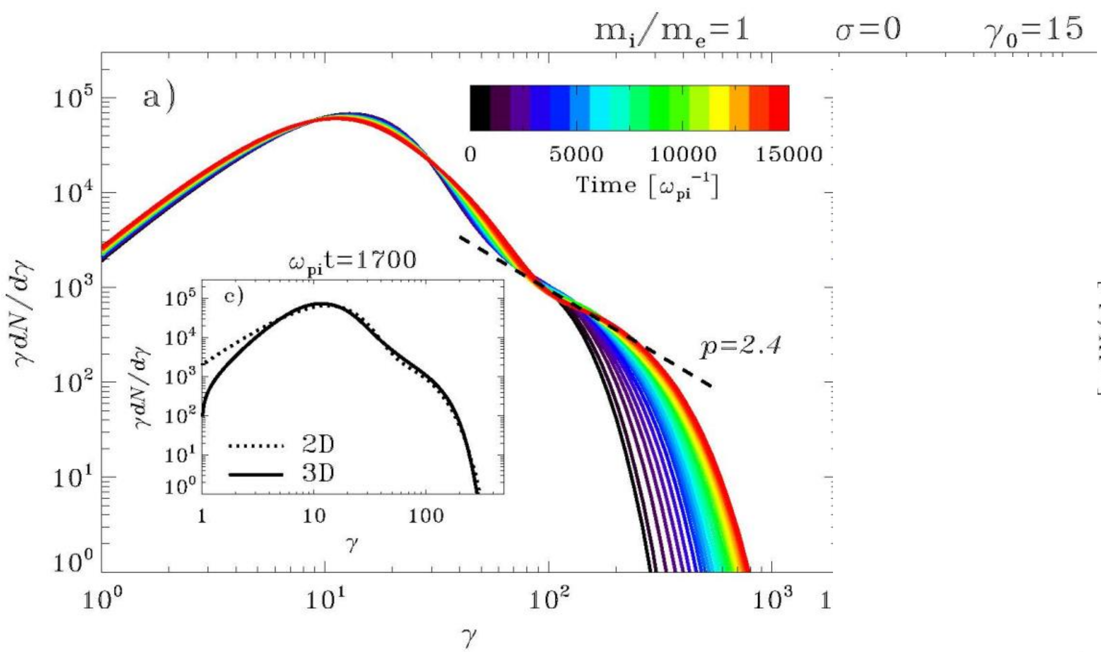
Particle acceleration in collisionless shocks

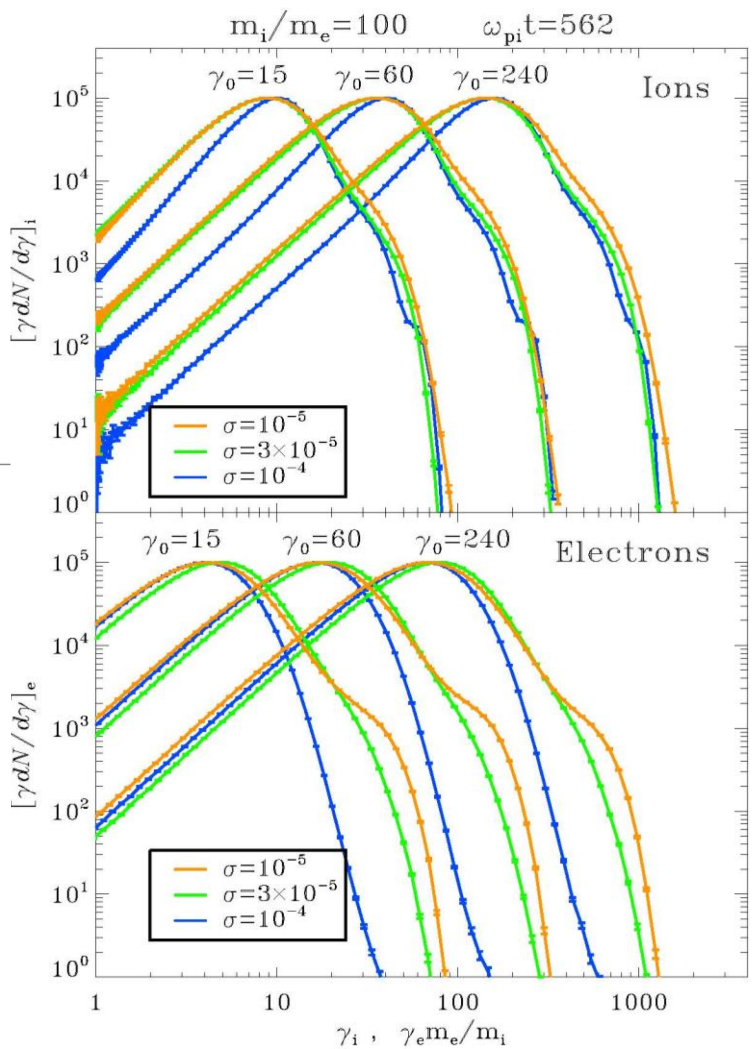
- No basic principles theory.
- Challenges:

  Self-consistent particle/B,

  Non linear with a wide range of

  temporal/physical scales.



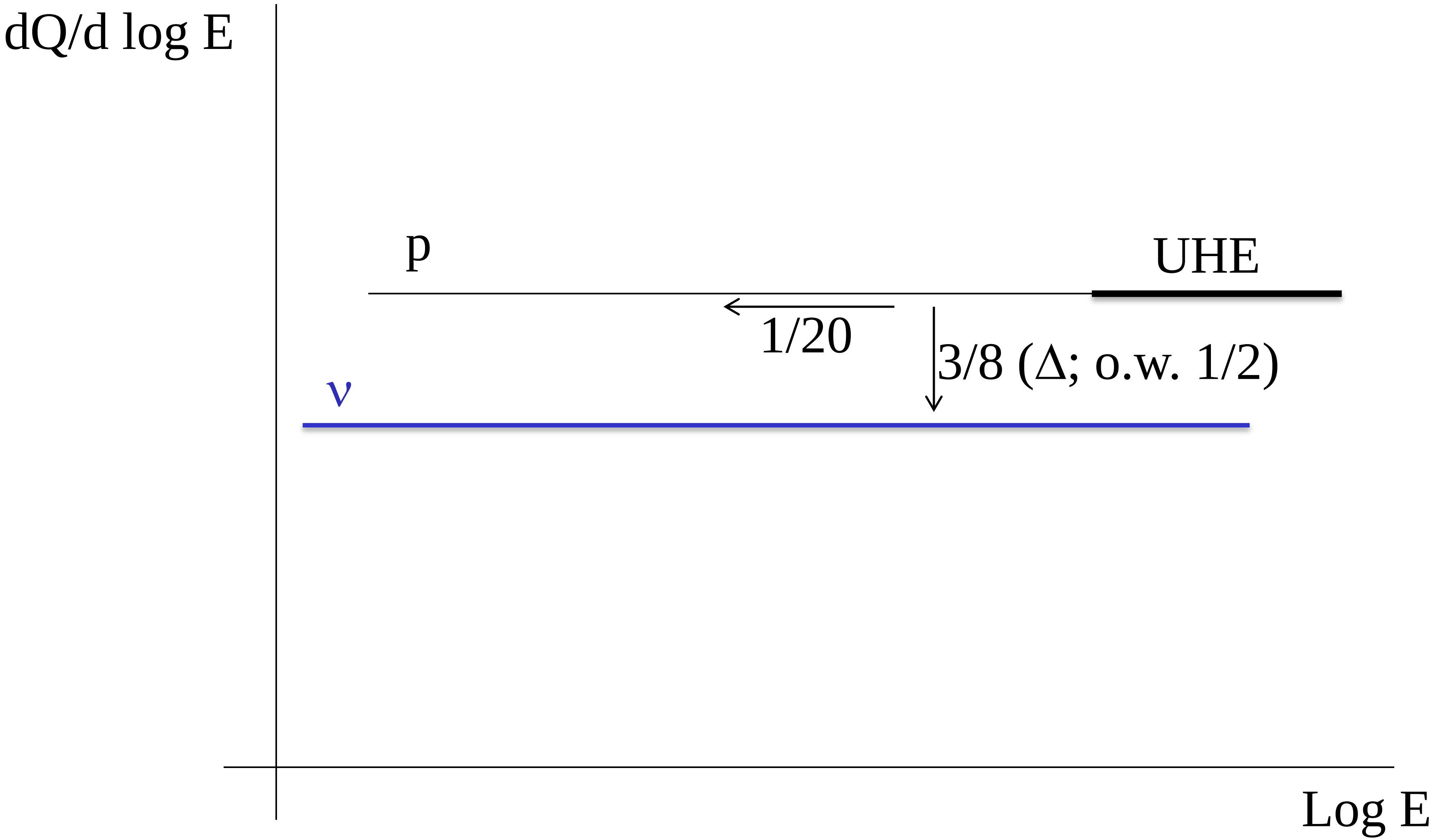


[Sironi, Spitkovsky & Arons 13]

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).

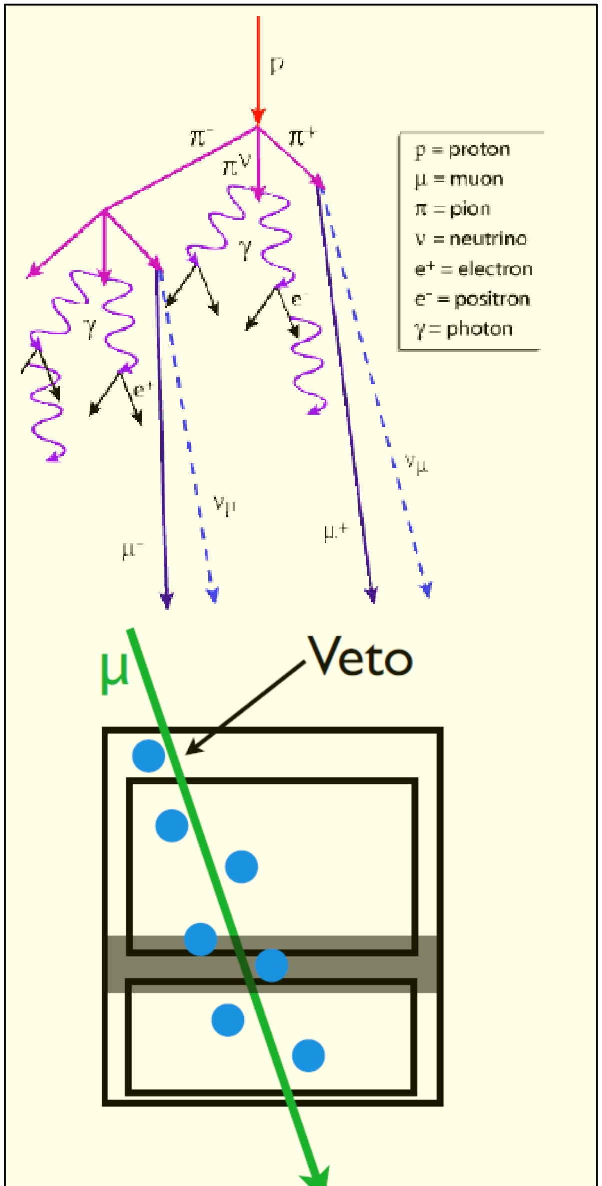
WB bound: p and ν production



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).



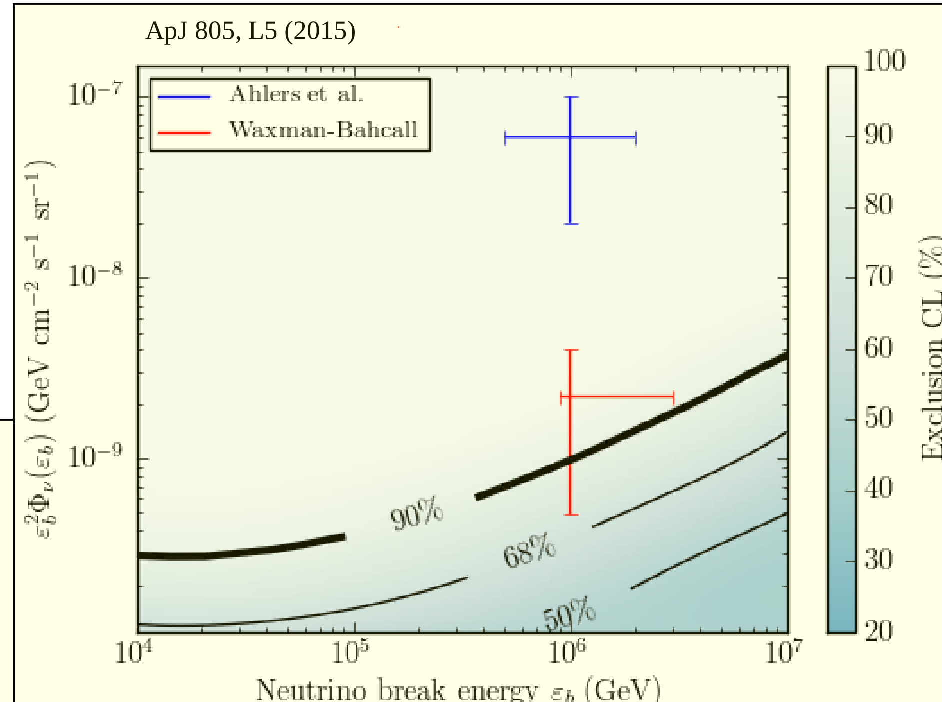
[Cartoon: N. Whitehorn]

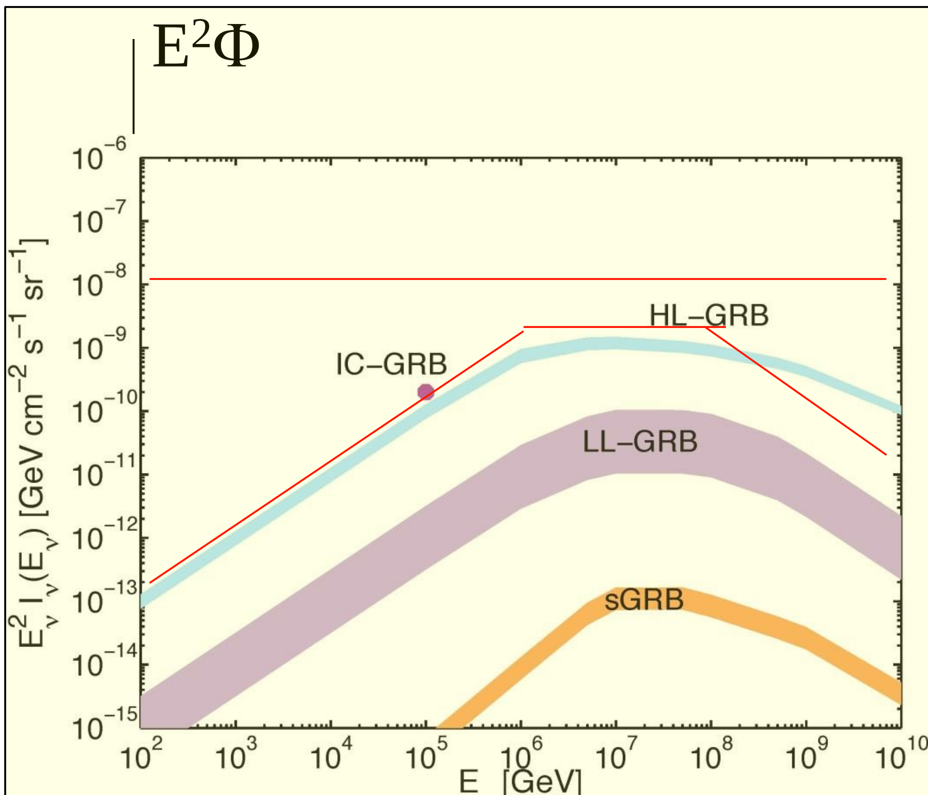
A note on prompt GRB ν's

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

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

[EW & Bahcall 97]





- IC is achieving relevant sensitivity.

[Tamborra & Ando 15;

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

Fermi's XG γ-ray background [EGB]

- EGB: $E^2\Phi_\gamma$([0.05,0.1,0.8] TeV) ~ [3,1,0.2]x 10^{-7} GeV/cm^{2}s sr.
- IceCube: $E^2\Phi_\nu$ (100 TeV) ~ 0.3x10^{-7}GeV/cm^{2}s sr.

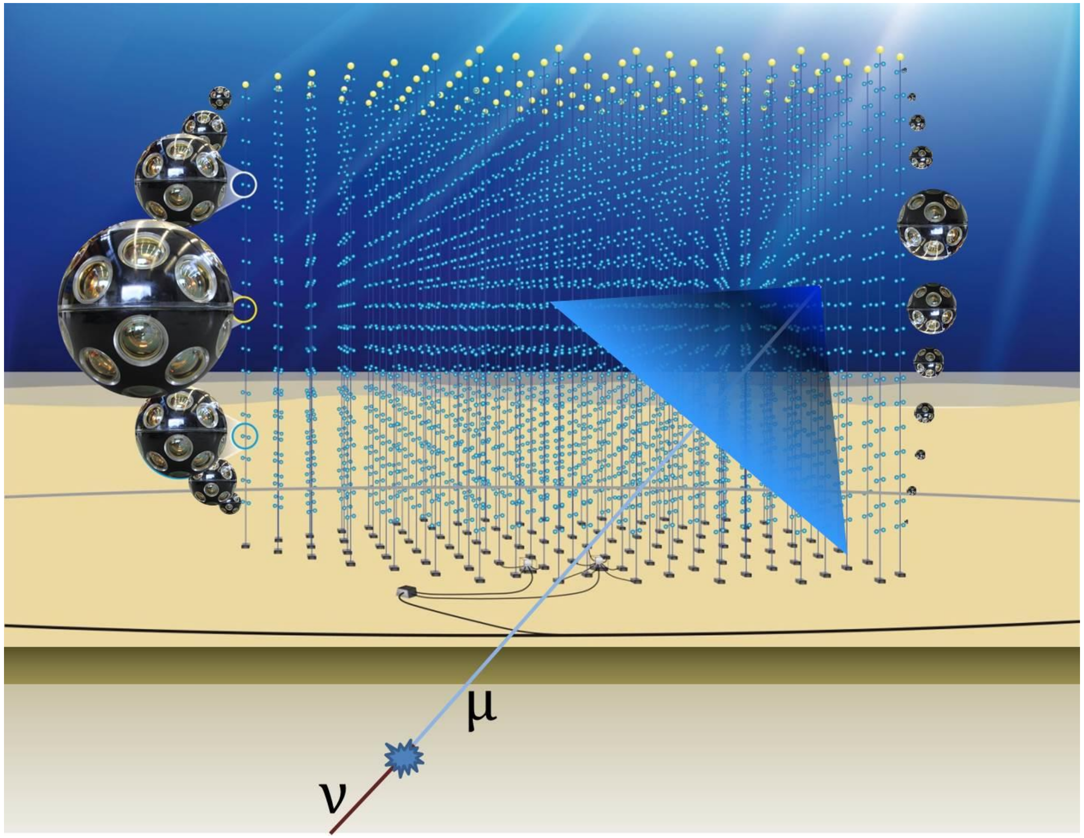
- Q_γ~(2/3)Q_ν → For 'flat' generation spectrum, d log n/d log E =-2, $E^2\Phi_\gamma$ ~ (2/3)$E^2\Phi_\nu$ ~ 0.2x10^{-7}GeV/cm^{2}s sr.
- Interaction of >~1TeV photons with IR background gives $E^2\Phi_\gamma$([0.05,0.1,0.8] TeV ~ [0.4, 0.2, 0.01]x10^{-7}GeV/cm^{2}s sr, i.e.: $E^2\Phi_\gamma$ ~ 0.1 EGB.

- Implications:
  - Flat generation spectrum, d log n/d log E >-2.2 (steeper- exceed EGB, e.g. [e.g. Tamborra, Ando, & Murase 14]).
  - Resolving ~90% of the EGB will constrain ν sources.
  - "Strong tension with EGB" [e.g. Bechtol et al. 15] due to assuming a steep spectrum (d log n/d log E =-2.5).

Future experimental developments

- IC extension
- Mediterranean

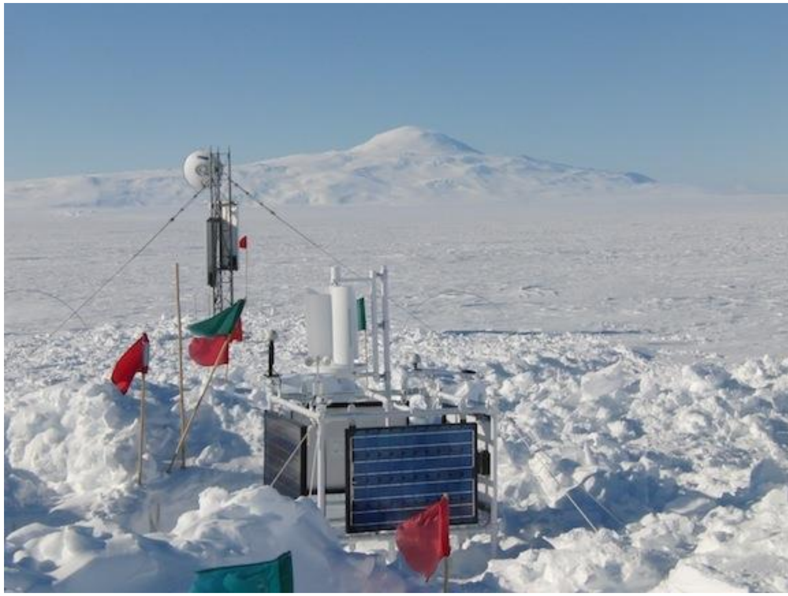
  Km3Net (~5x IC)



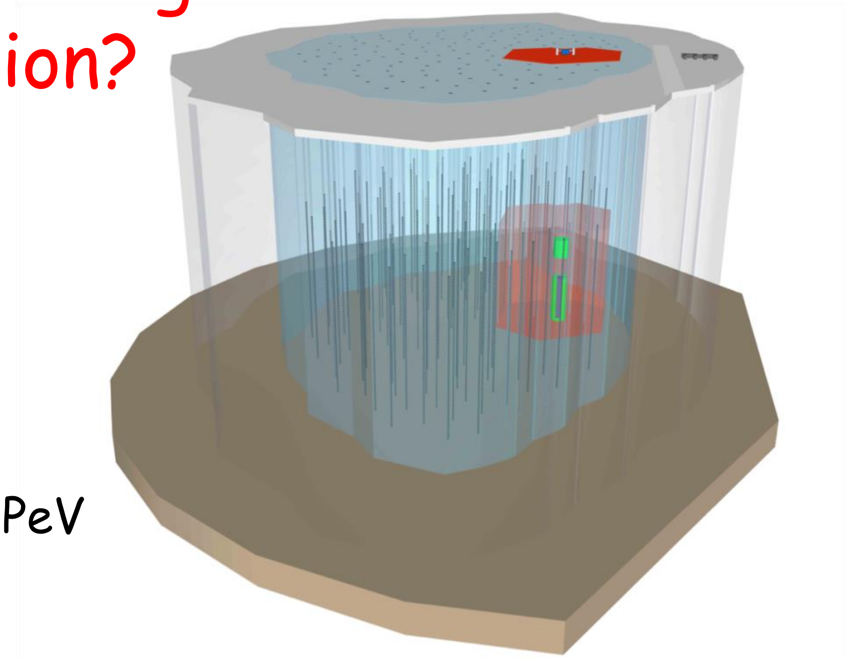
ARA & ARIANNA:

Coherent radio Cerenkov,

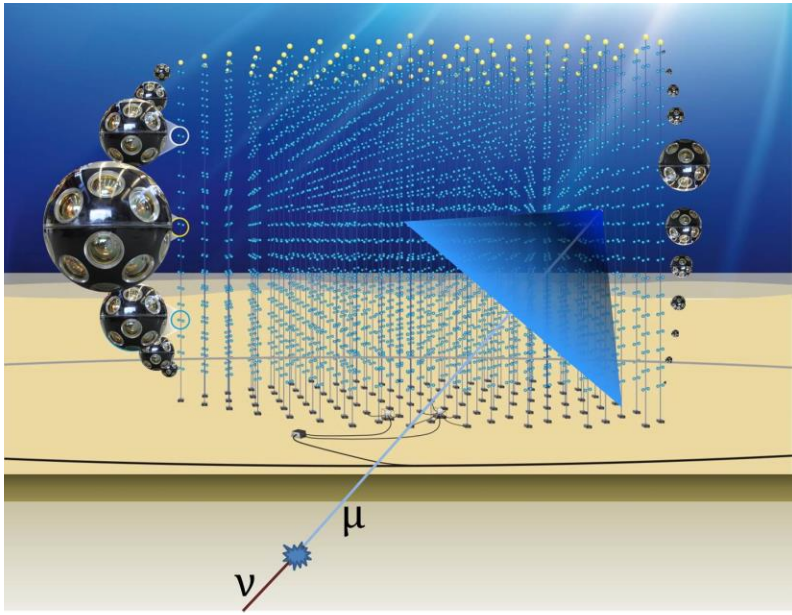
10^8 to 10^{10} GeV



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.

Star forming galaxies: candidate CR calorimeters

- Starbursts: $(n,B,SFR)/(n,B,SFR)_{MW}$ ~ 100-1000; SFR ~100 M_{sun}/yr.
- Radio, IR & γ-ray (GeV-TeV) observations
  → Starbursts are calorimeters for E/Z reaching (at least) 10TeV.
- Theoretical estimates of $f(p\rightarrow\pi)$:
  Scaling from the MW→ f=1 to E> 1PeV for $\Sigma_{disk} > 0.03\ \mathrm{g/cm^2} \equiv$ "starburst".

- Most of the stars in the universe were formed in galaxies with high SFR.
  If Q_{CR}~SFR Then $\Phi_\nu(\varepsilon_\nu$<1PeV)~Φ_{WB} [Loeb & EW 06; He 13; Liu 14; Senno et al. 15] .

- Main contribution: z=1--2 star-forming galaxies.
  Main Uncertainty: Fraction of stars formed in calorimetric environments.
  CO observations of z=1.5 'average' galaxies [e.g. Daddi et al 10]:
  SFR~ 100 M_{sun}/yr, molecular disks with Σ~0.1 g/cm^2,
  supportive but with large uncertainties.

Astrophysical neutrino telescopes

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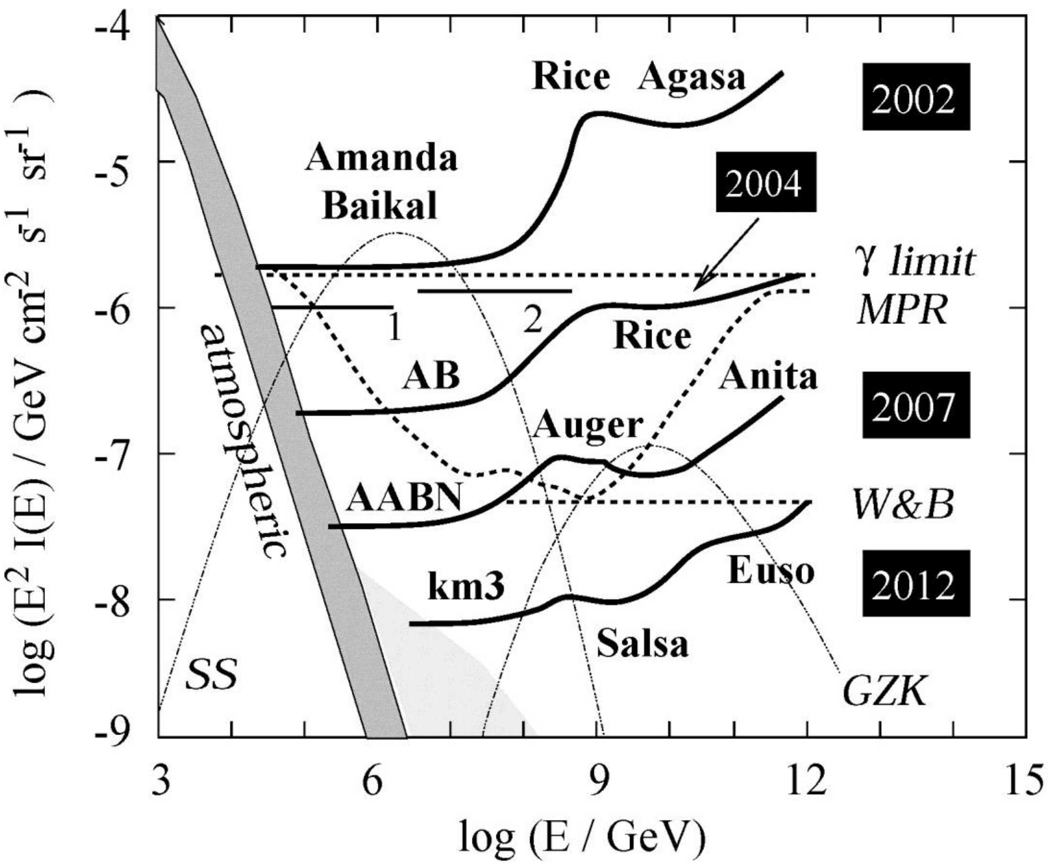
(Received 3 June 2003; accepted 23 November 2003)

[Rev. Sci. Inst.]



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<u>MeV- GeV Achievements</u>:

Detection of solar and SN ν's,

Tests of stellar structure and explosion models,

ν mass and oscillations.

<u>>100 TeV Achievements</u>:

Detection of extra-Galactic ν's.

More to come…

<u>Nobel prizes</u>:

- 2002 Davis (Cl) & Koshiba (Kamiokande)

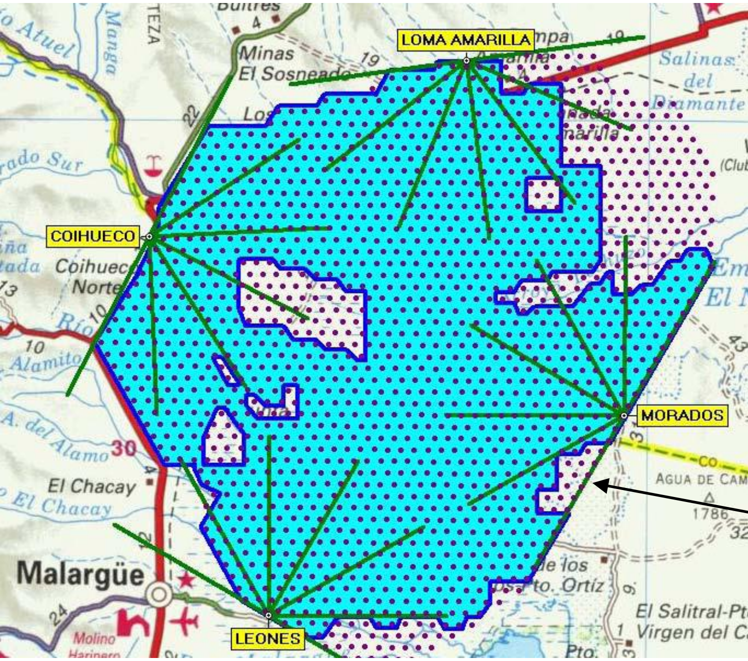
"*for pioneering contributions to … detection of cosmic ν's*";

- 2015 McDonald (SNO) and Kajita (Super-K)

"*for the discovery of ν oscillations, which shows that ν's have mass*".

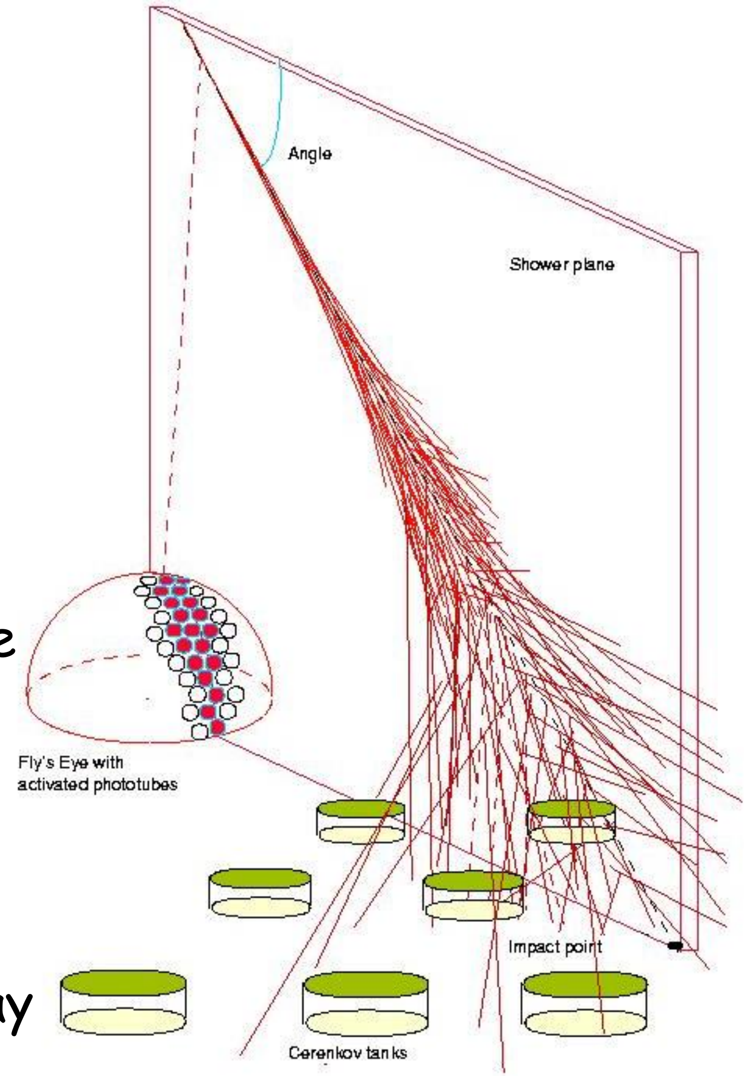
UHE, >10^{10}GeV, CRs

J(>10^{11}GeV)~1 / 100 km^2 year 2π sr



Auger:
3000 km^2

Fluorescence detector

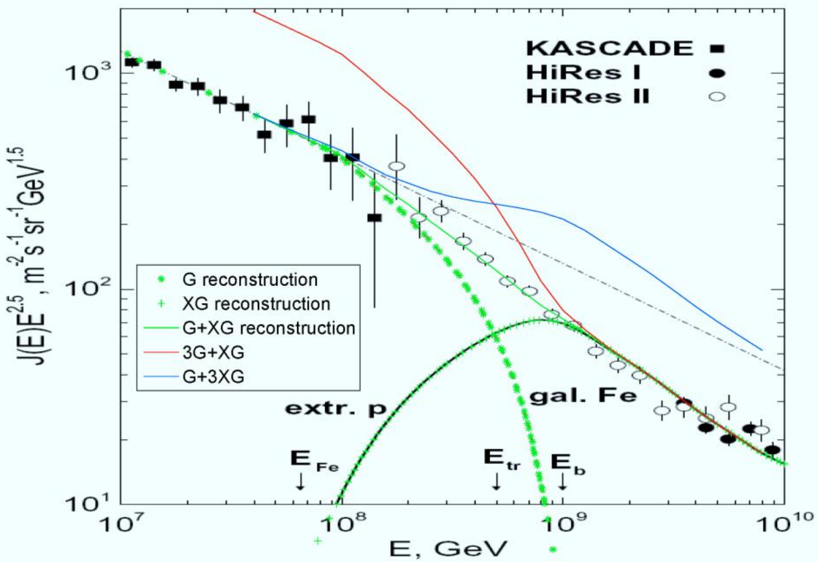


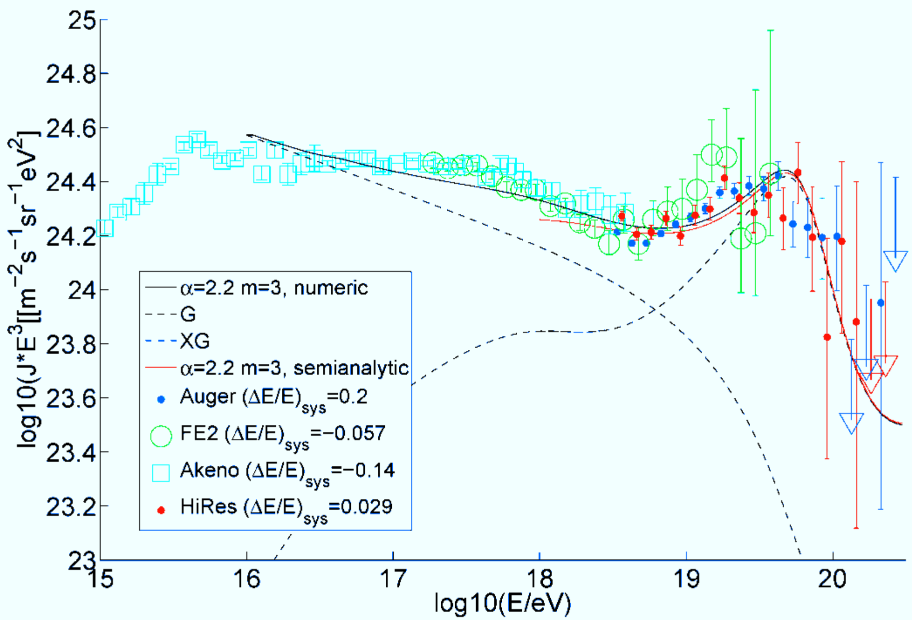
Ground array

Where is the G-XG transition?

@ E<10^{18}eV ?

dQ/dlog ε =Const → @ E~10^{19}eV

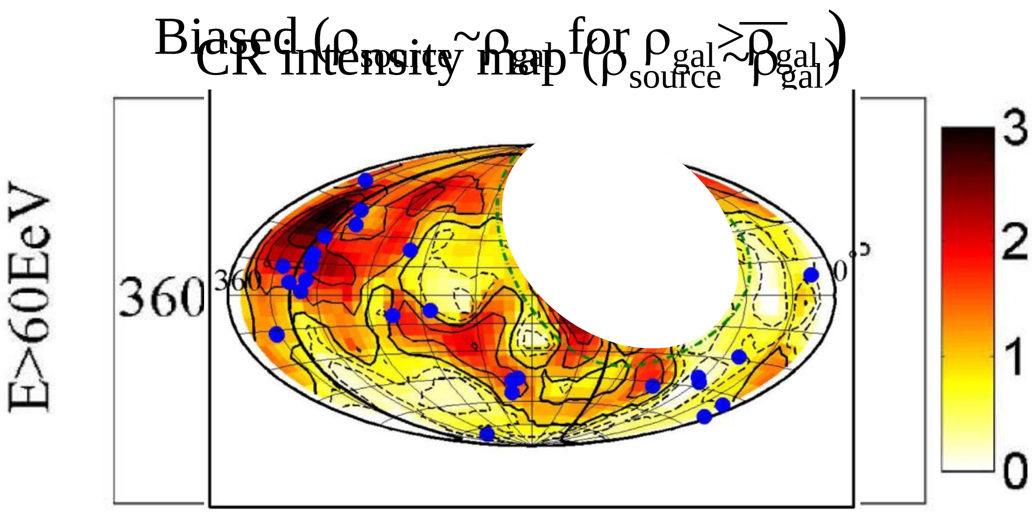




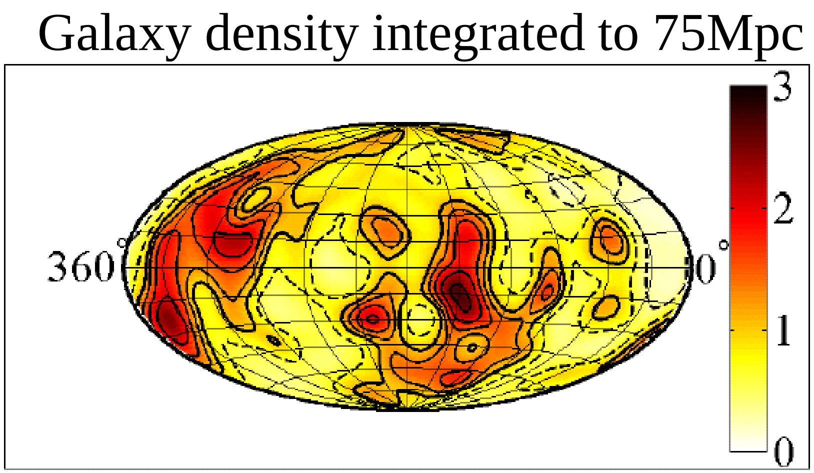
[Katz & EW 09]

- Fine tuning

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]

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]
- BL Lacs ["obtained through a fine-tuning with the data", Tavecchio & Ghisellini 2015]
- Low L GRBs

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Low Energy, ~10GeV

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

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

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

- Starbursts- using radio to γ observations

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

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

[Katz, EW, Thompson & Loeb 14]