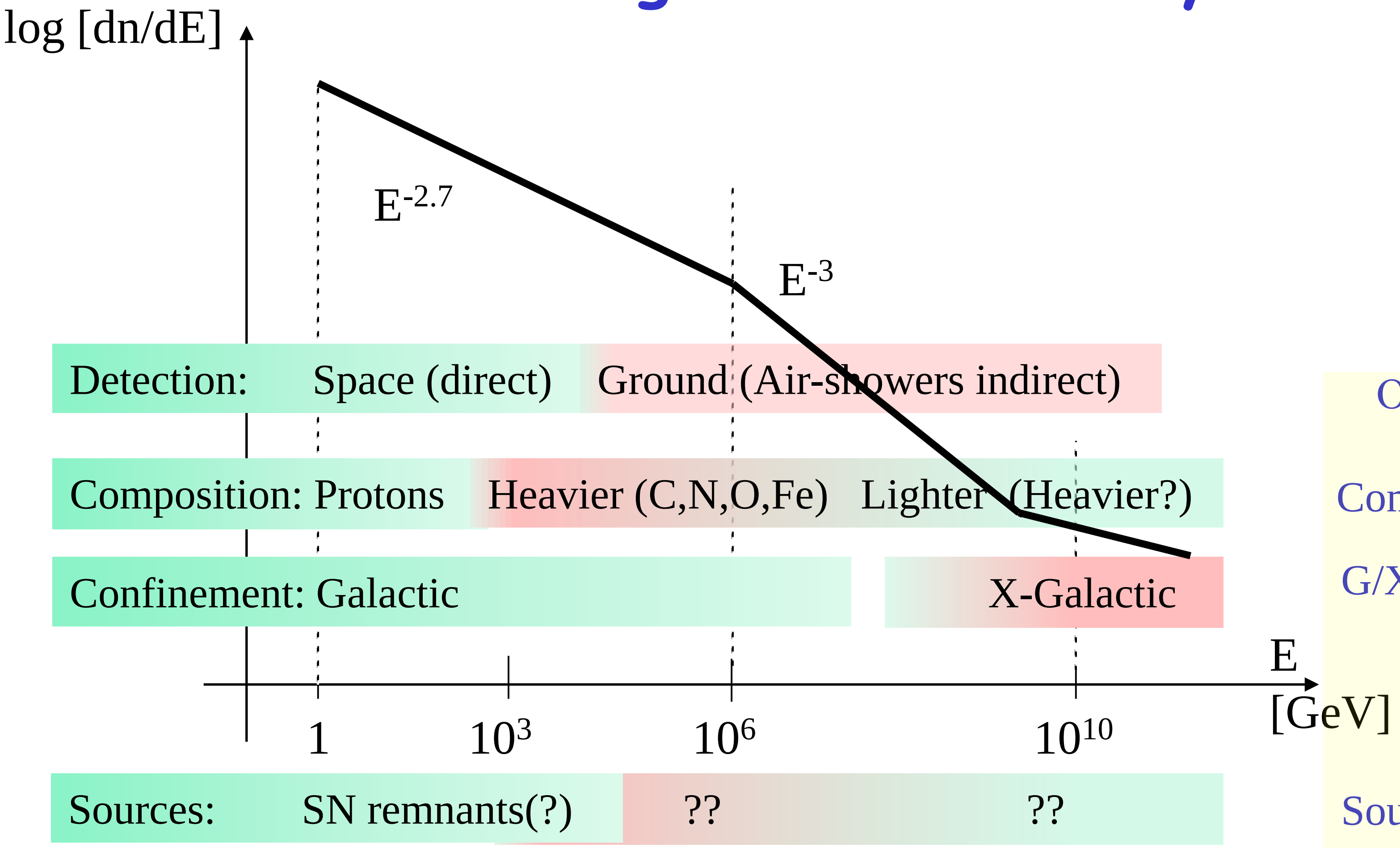
High energy neutrino astronomy: Where are we now, what did we learn?

E. Waxman
Weizmann Institute of Science

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



Detection: Space (direct) Ground (Air-showers indirect)

Composition: Protons Heavier (C,N,O,Fe) Lighter (Heavier?)

Confinement: Galactic X-Galactic

Sources: SN remnants(?) ?? ??

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

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

Open Q's

Composition?

G/XG transition?

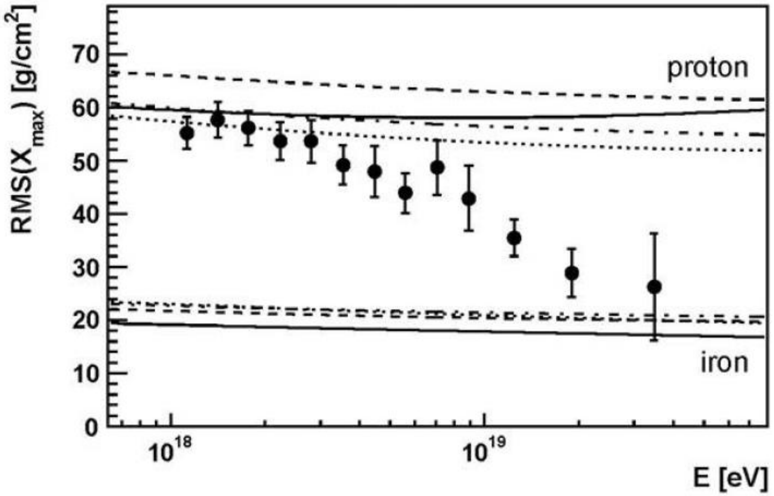
Sources?

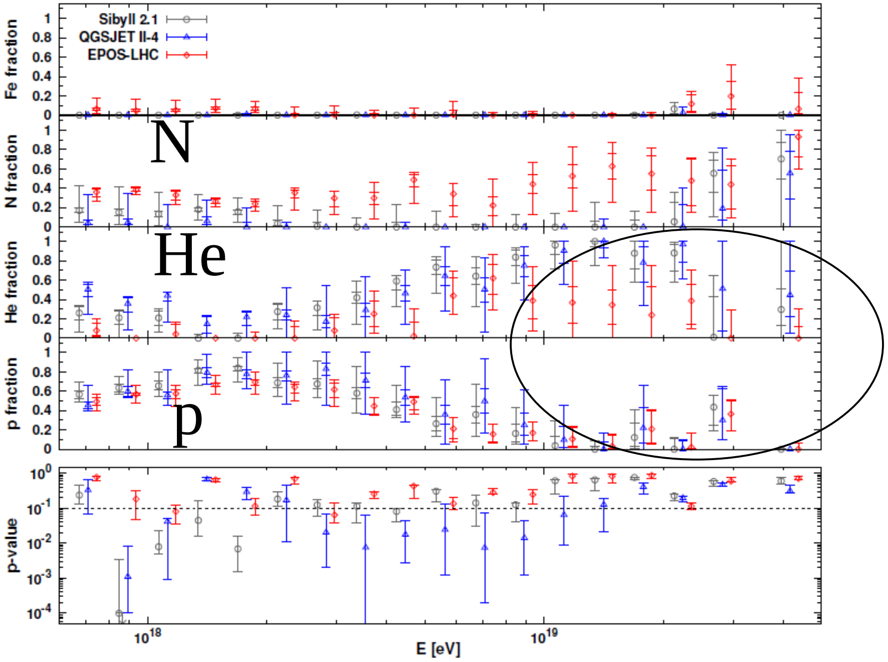
Acceleration?

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

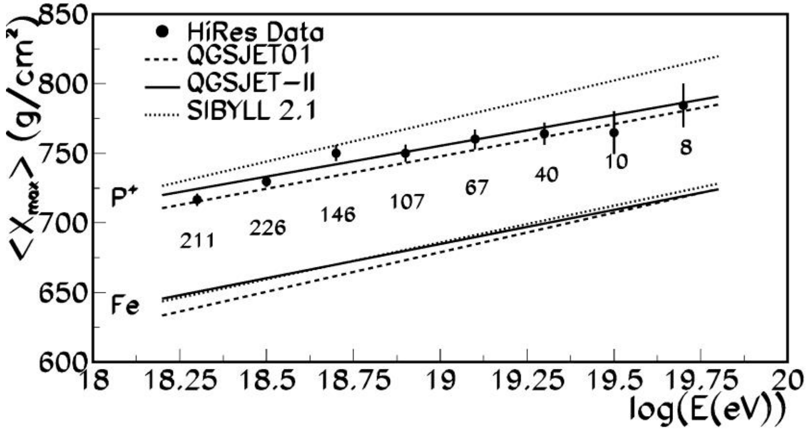
UHE: Air shower composition constraints

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.
  $t_{eff}<1$Gyr, d<300Mpc.

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

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

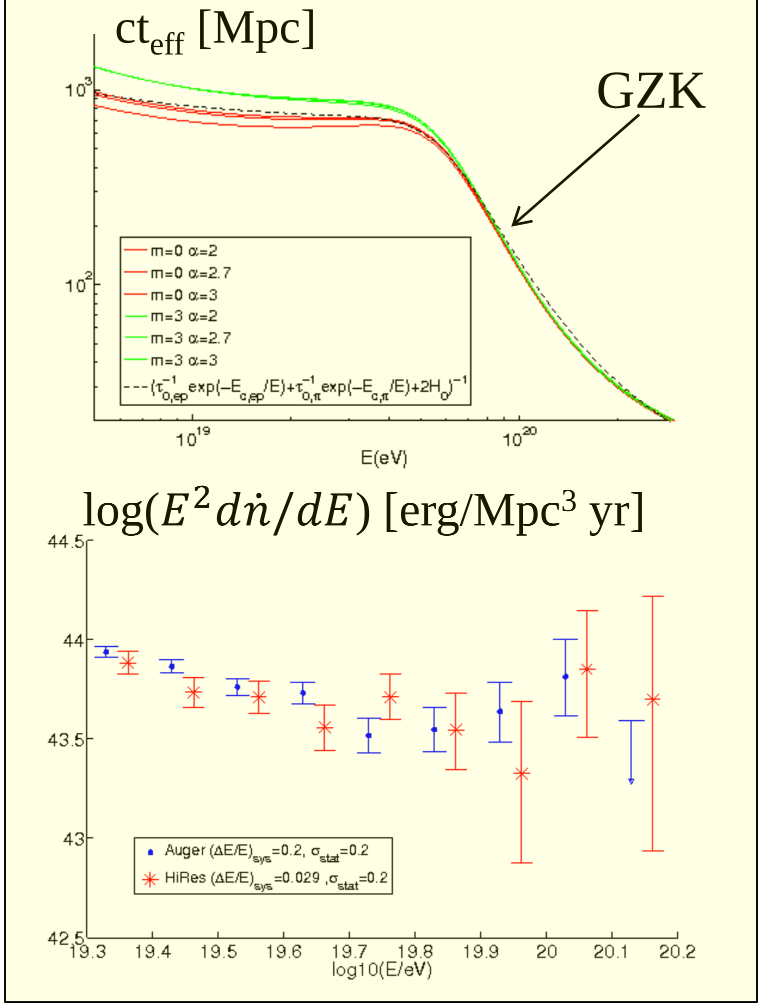
$$= (0.5 \pm 0.2)10^{44}\,\frac{\text{erg}}{\text{Mpc}^3\text{yr}},$$

[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).

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



Acceleration: Max E

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

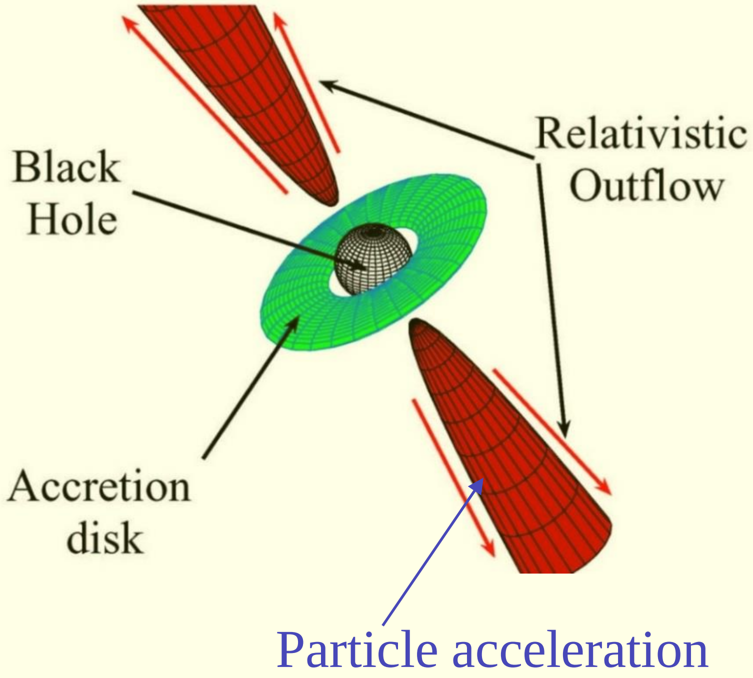
[Lovelace 76; EW 95, 04; Norman et al. 95]

- No $L > 10^{14} L_{\mathrm{sun}}$ 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):

$$E^2 \frac{dj_\nu}{dE} \leq E^2 \Phi_{\text{WB}} = \frac{3}{8} \frac{ct_H}{4\pi} \zeta \left(E^2 \frac{d\dot{n}}{dE} \right) = 10^{-8} \zeta \frac{\text{GeV}}{\text{cm}^2\text{s sr}},$$

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

[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.

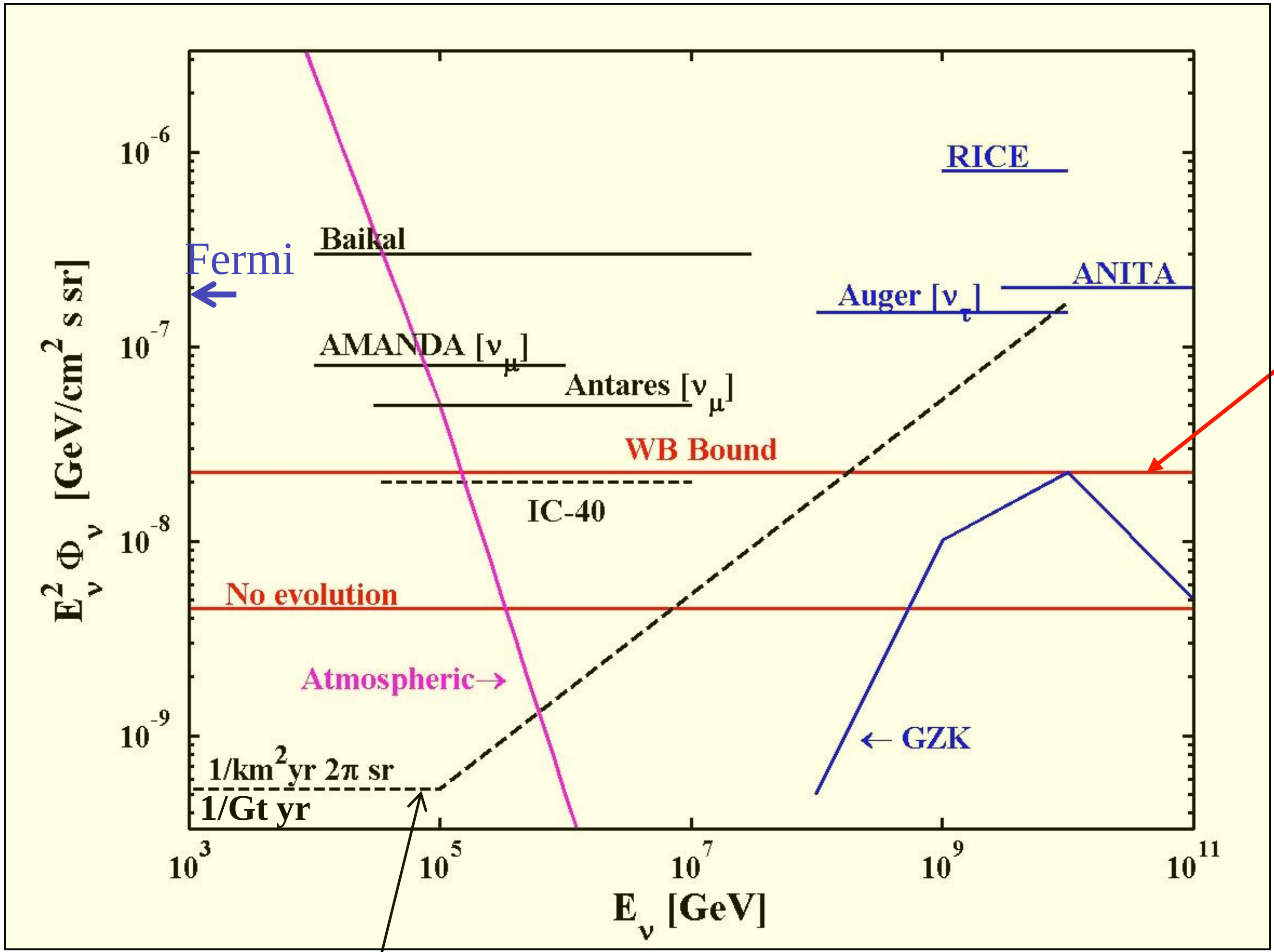
    Most stars formed in rapidly star-forming galaxies,
    which are p "calorimeters" for E_p<~10^6GeV,
    all p→π by pp in the inter-stellar gas, $t_{pp} < t_{\text{conf}}(E < 10^6\text{GeV})$.

[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)

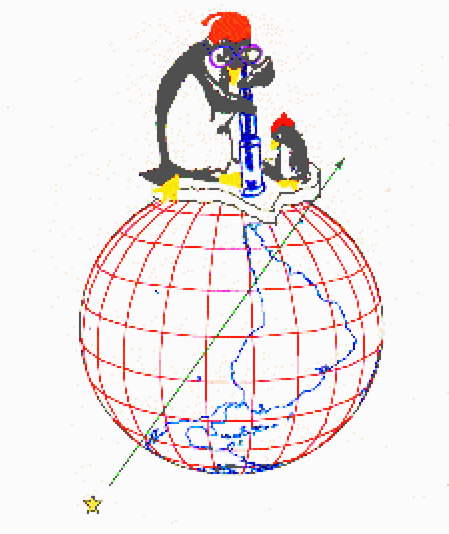


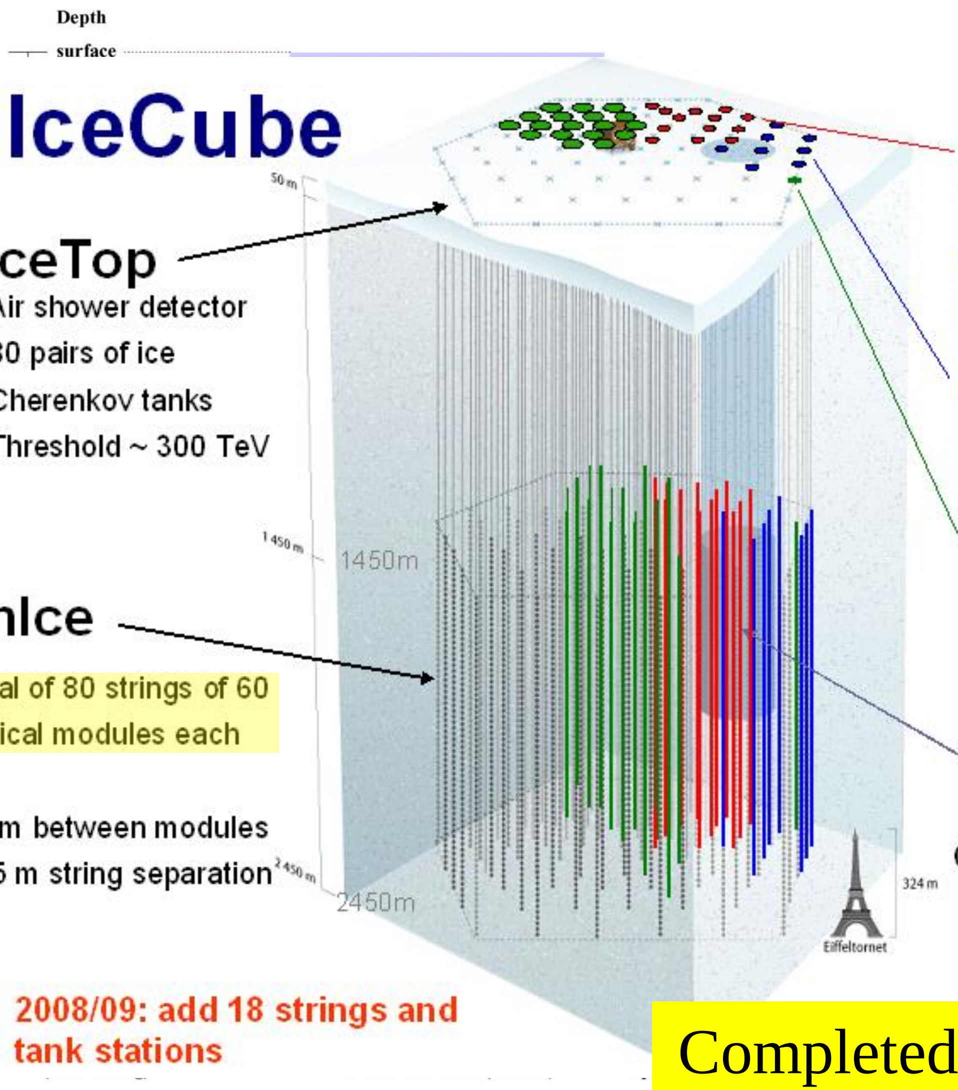
2 flavors,

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

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

AMANDA & 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

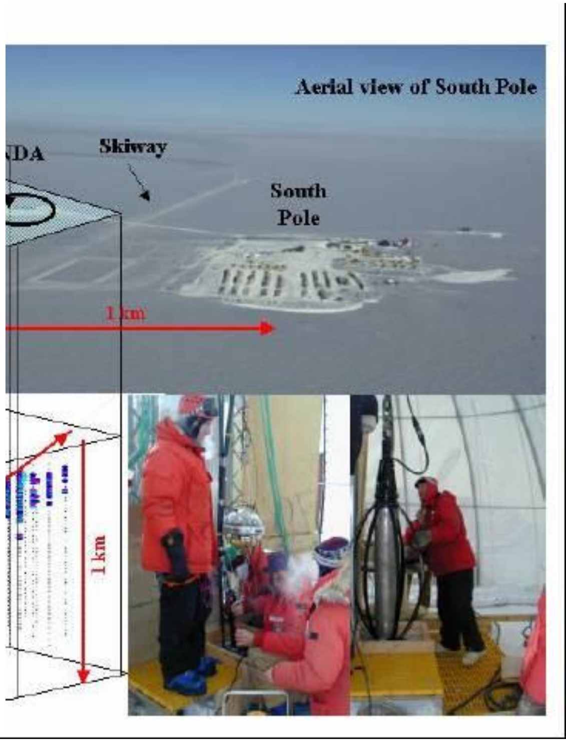
2004-2005 : 1 string

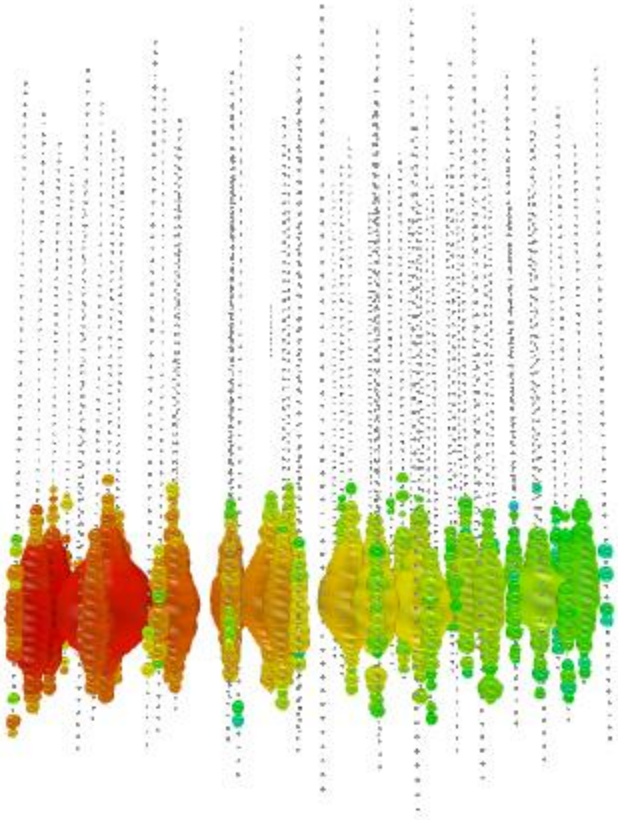
AMANDA-II
19 strings
677 modules

Current configuration:
40 strings,
40 IceTop stations
plus AMANDA

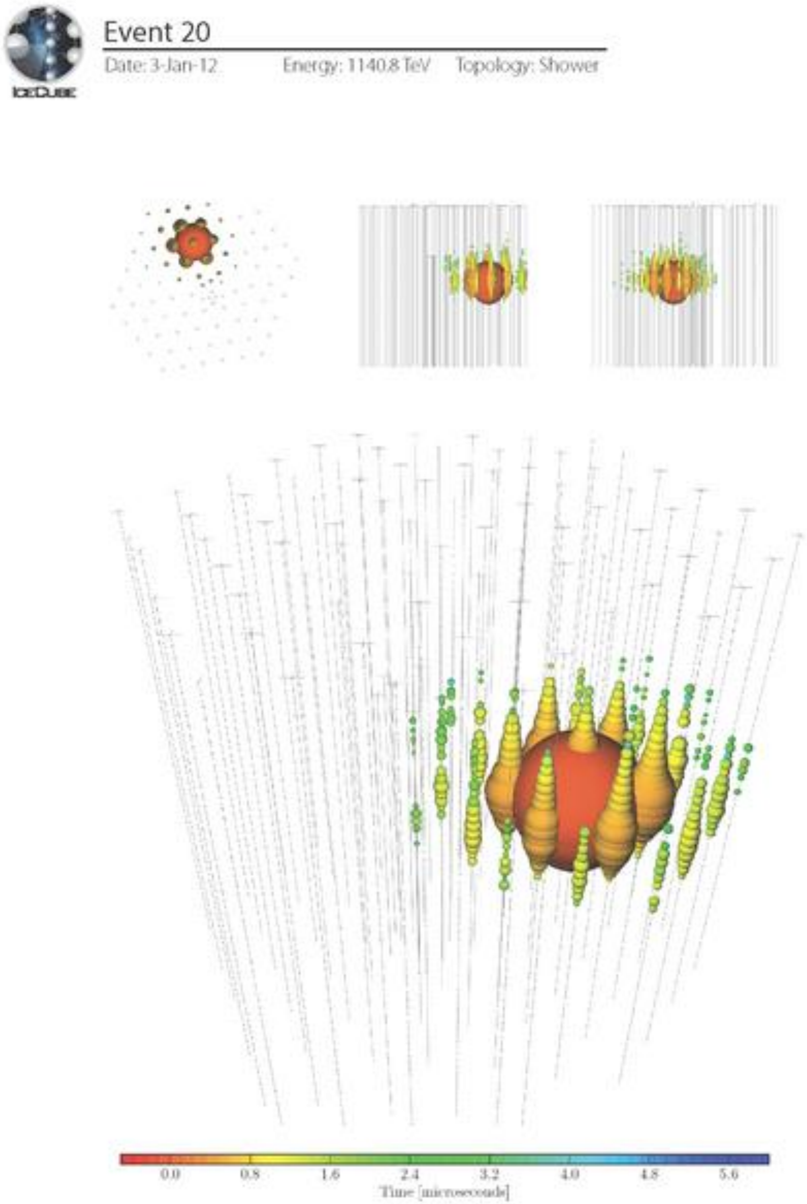
2008/09: add 18 strings and
tank stations

Completed Dec 2010





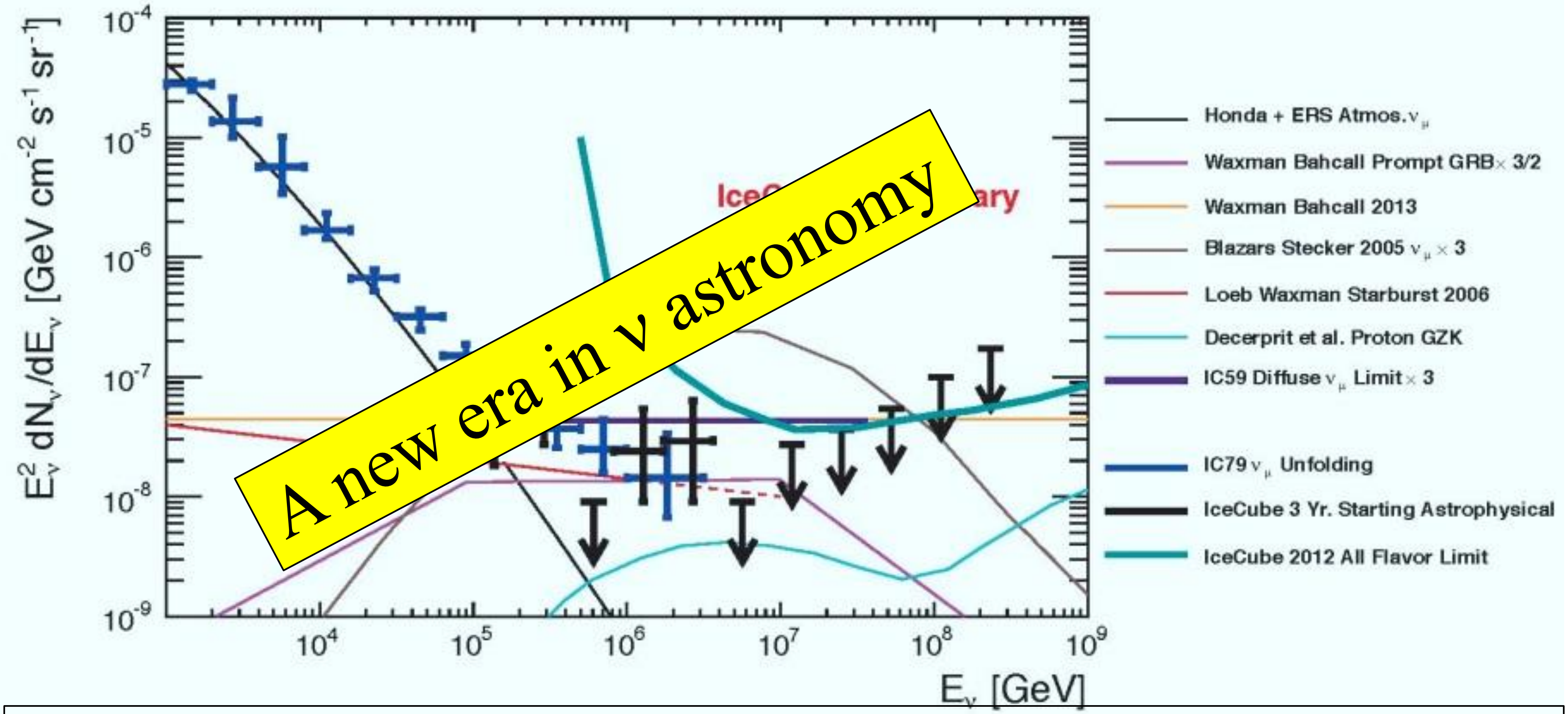
400TeV



1100TeV

IceCube: 37 events at 50Tev-2PeV

~6σ above atmo. bgnd. [02Sep14 PRL]



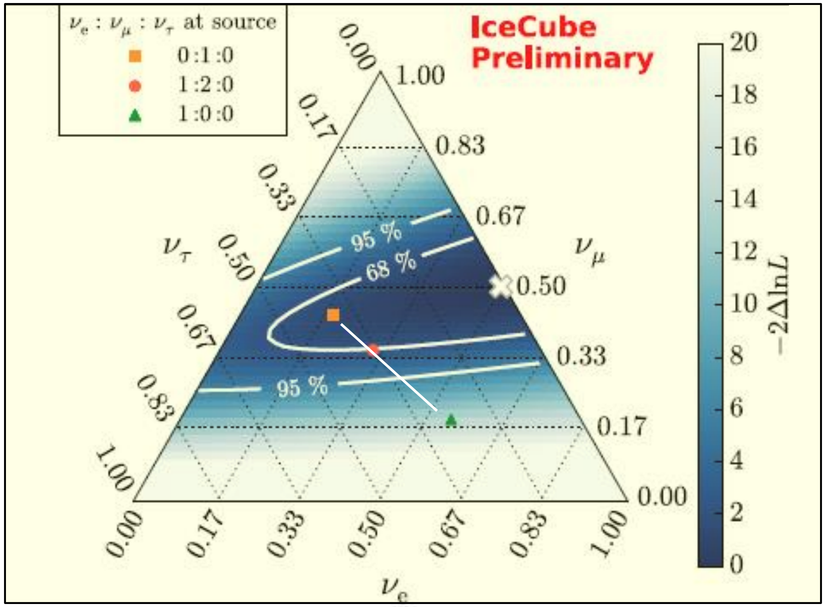
A new era in ν astronomy

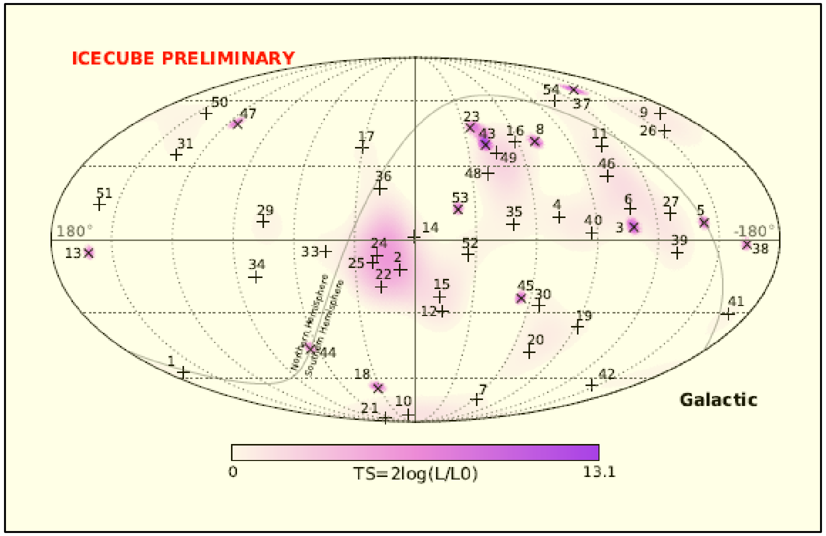
$E^2\Phi_\nu$ =(2.85+-0.9)x10^{-8}GeV/cm^{2}sr s =$E^2\Phi_{WB}$= 3.4x10^{-8}GeV/cm^{2}sr s (2PeV cutoff?).

Consistent with Isotropy,

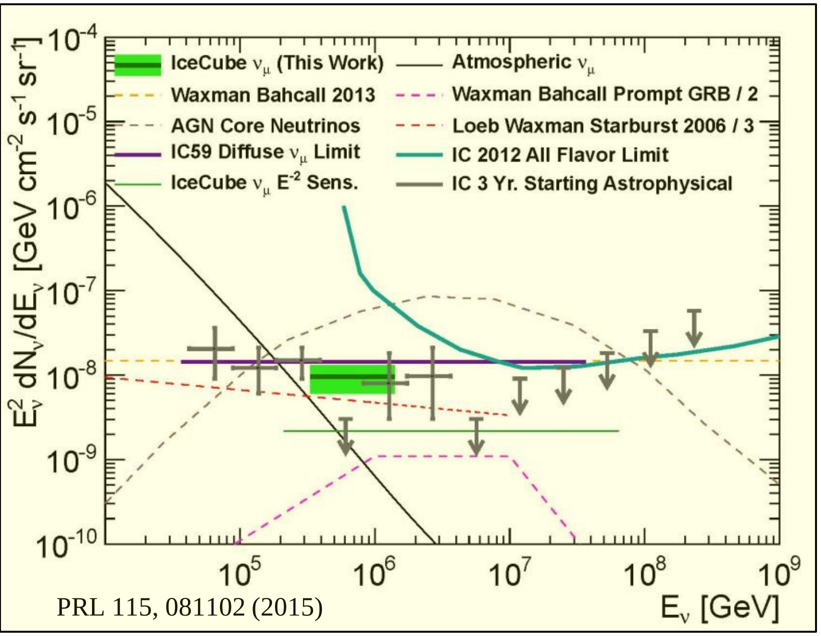
$\nu_e:\nu_\mu:\nu_\tau$=1:1:1 (π deacy + cosmological prop.).

Status: Isotropy, flavor ratio

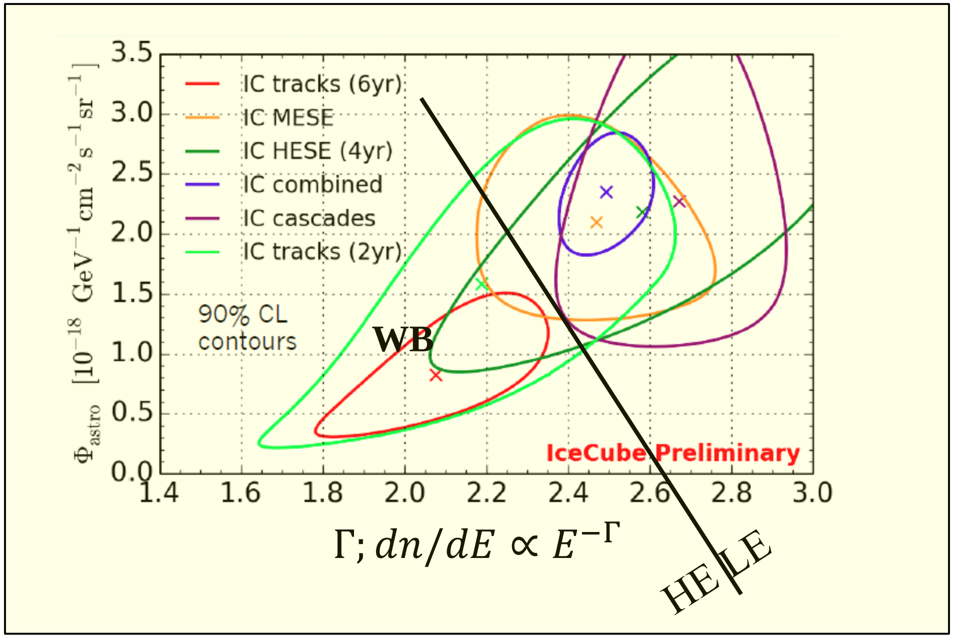


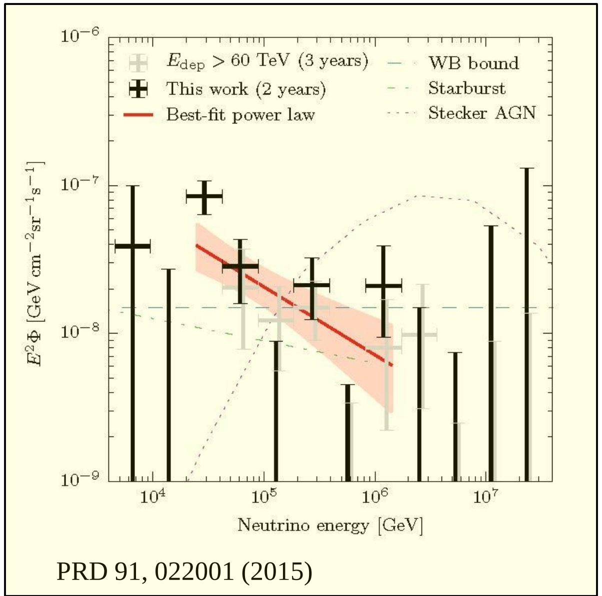


Status: Flux, spectrum



PRL 115, 081102 (2015)





PRD 91, 022001 (2015)

- Excess below ~50TeV→ A new component?
- Note: - $\Phi \sim 0.01\, \Phi_{\rm Atm.}$,

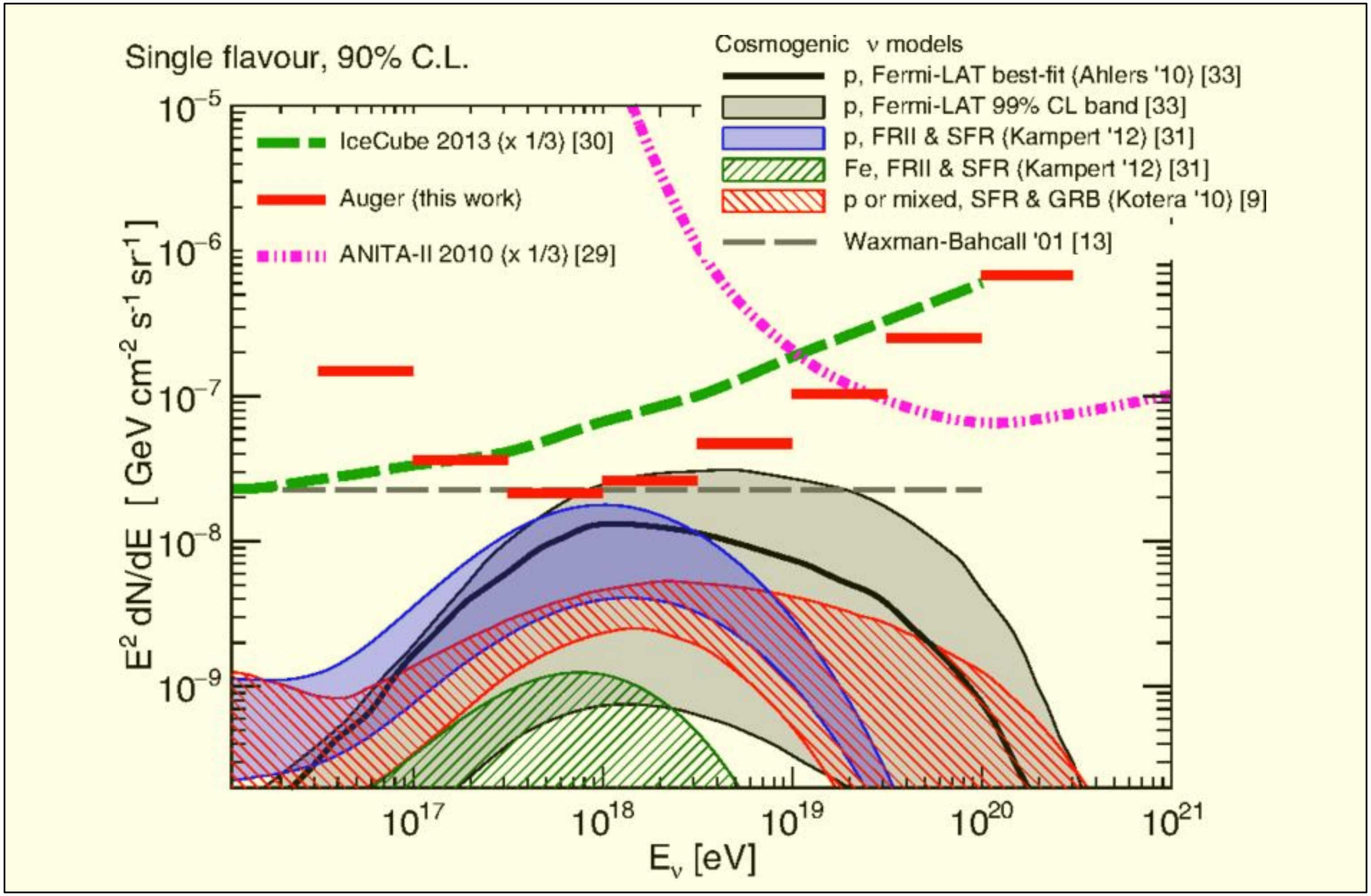
  - Varying veto efficiency.

- Fermi γ's @ ~0.1TeV

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

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

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.

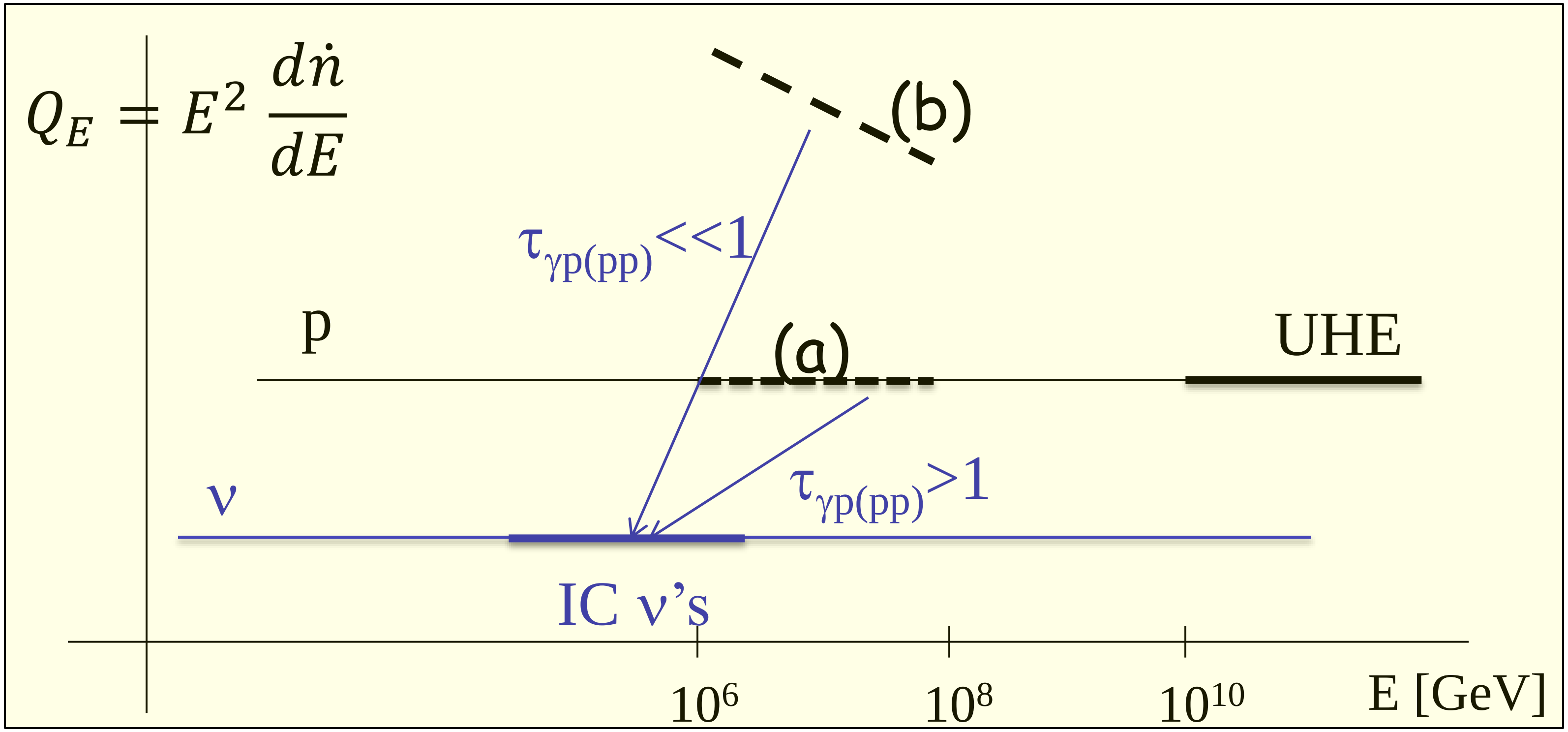
→ XG CR sources.
Coincidence with Φ_{WB} suggests a connection to the UHE sources.

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.


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

Identifying the "calorimeters"

- No sources with multiple-ν_μ-events:

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

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

- Rare bright sources: Ruled out (eg AGN, n~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 →A x 10 for n~10^{-5}/Mpc^3 (eg starbursts).

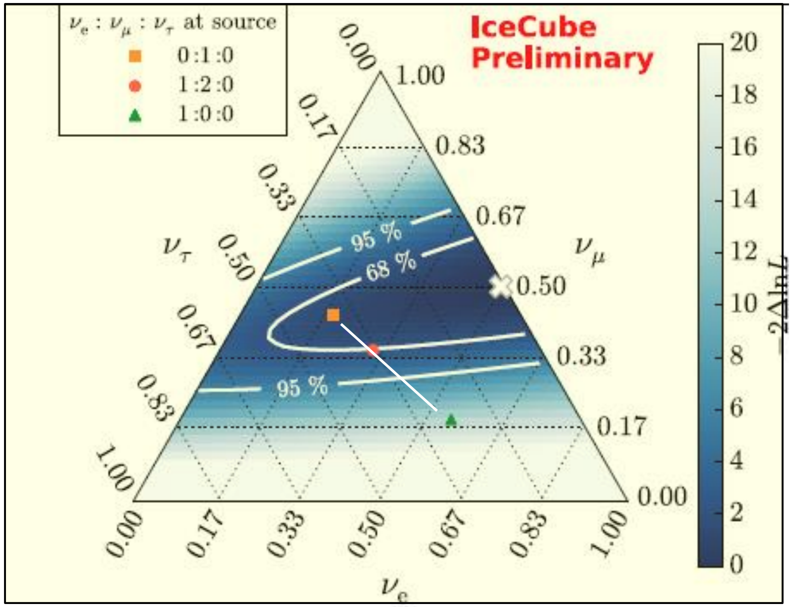
Identifying the sources

- 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}].
- 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]

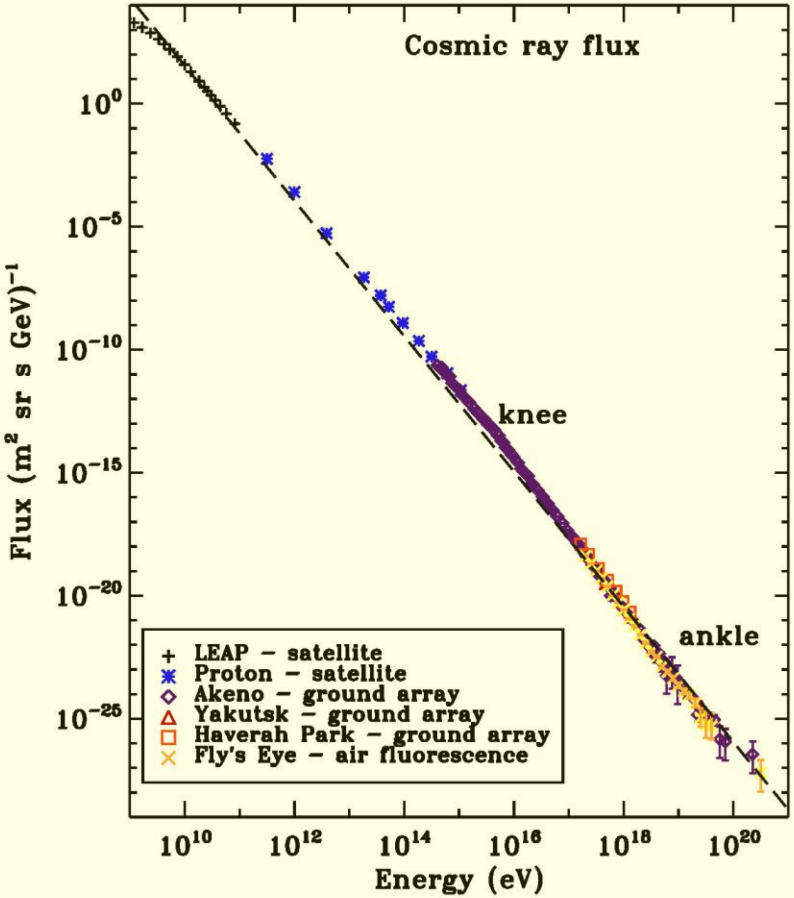
$\mu/(e+\tau) = 0.49\ (1-0.05\ \mathrm{Cos}\ \delta_{CP})$,

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

[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…]

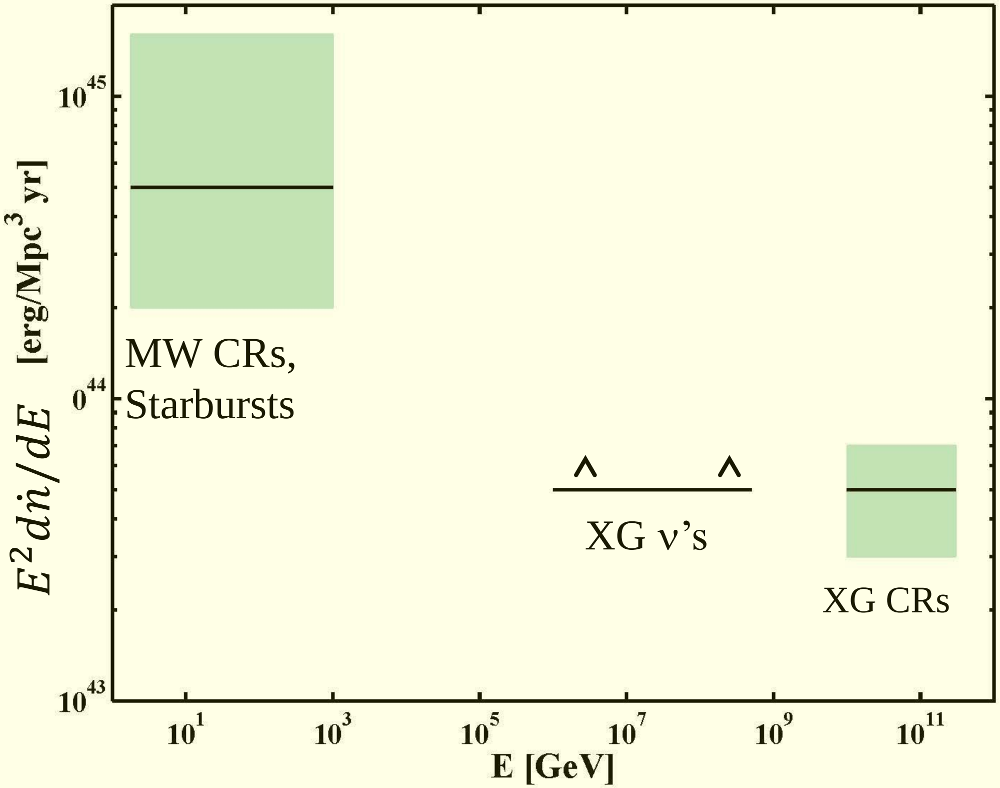
A single cosmic ray source across the spectrum?

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.

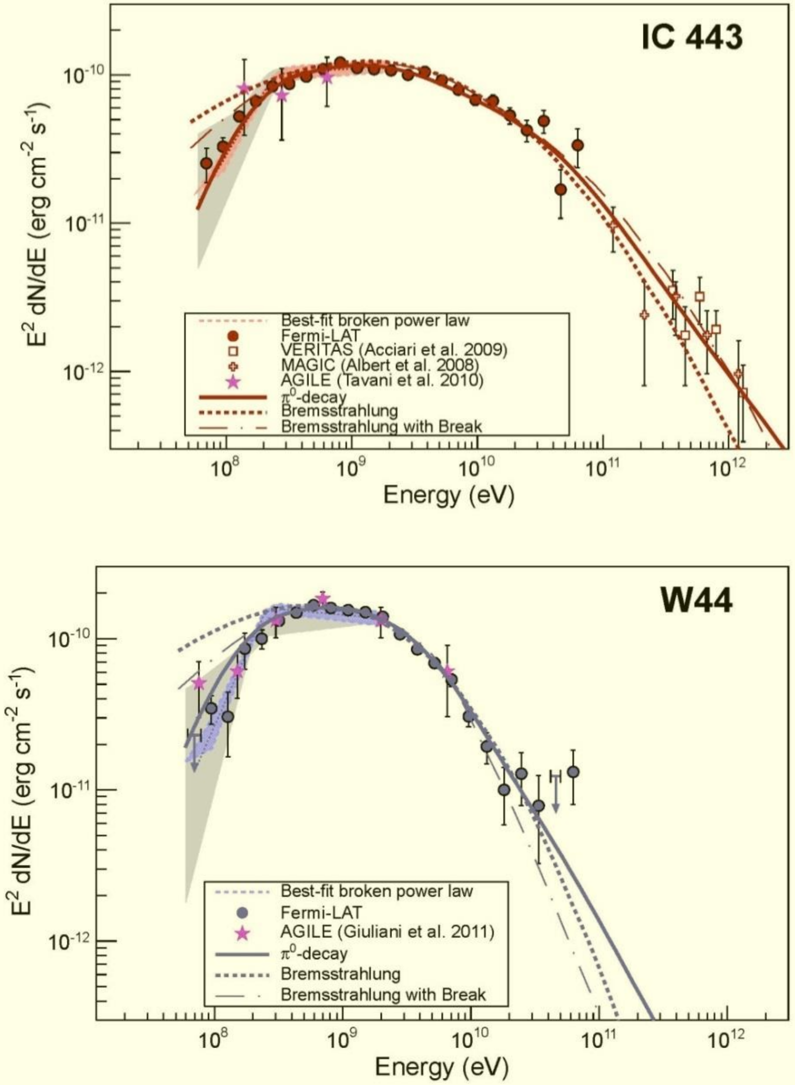
- Expansion of M_{eff} @ ~100TeV to ~10Gton (NG-IceCube, Km3Net):
  - Reduced uncertainties in ν flux, spectrum, isotropy, flavor ratio. [A different ν source at <50TeV? A cutoff >3PeV?]
  - Identification of CR/ν "calorimeters".
  - Likely identification of CR sources by temporal $\nu-\gamma$ association.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

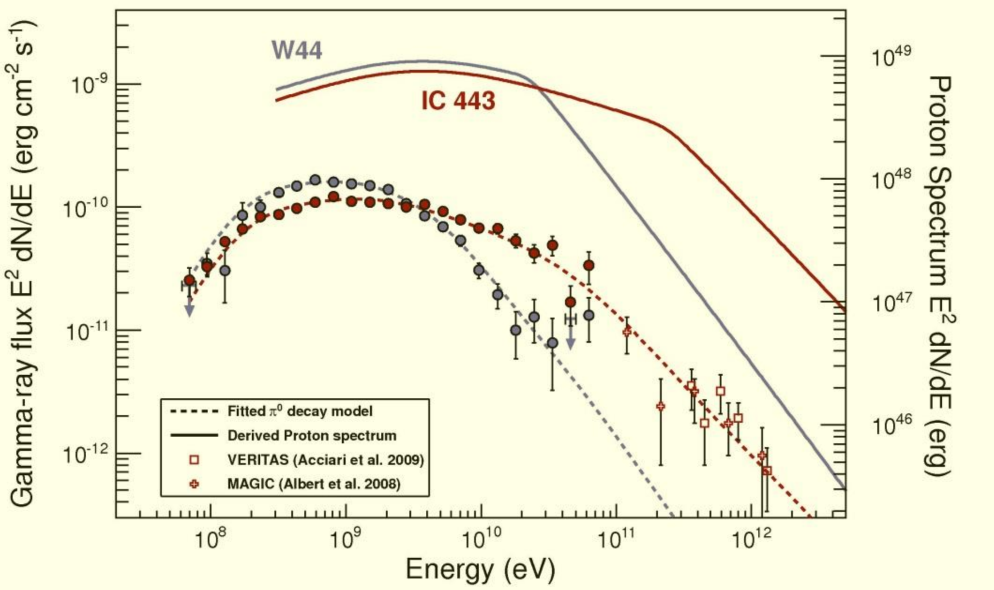
Backup Slides

Are SNRs the sources of E<1PeV CRs?

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

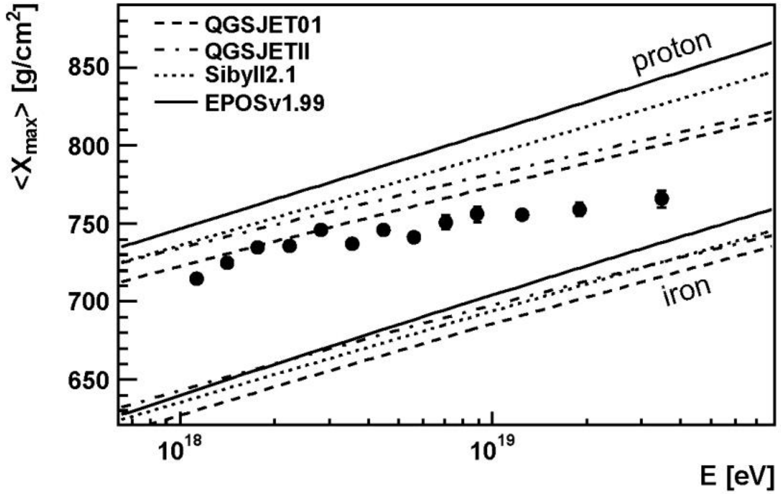


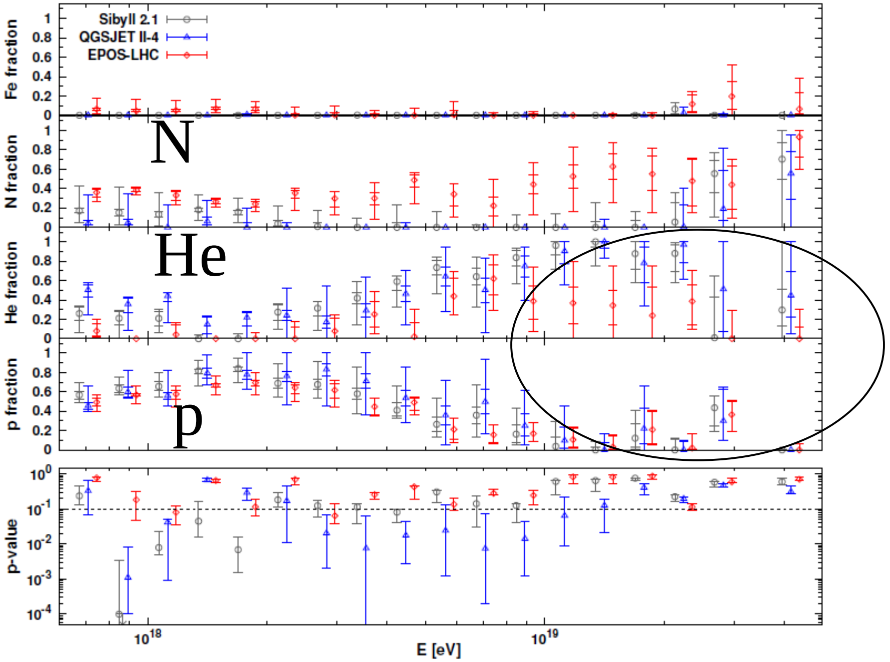
- So far, no direct evidence.
- EM observations- ambiguous.
- Modelling complex (interaction with molecular clouds).
- π^0 interpretation → E_p<100 GeV.



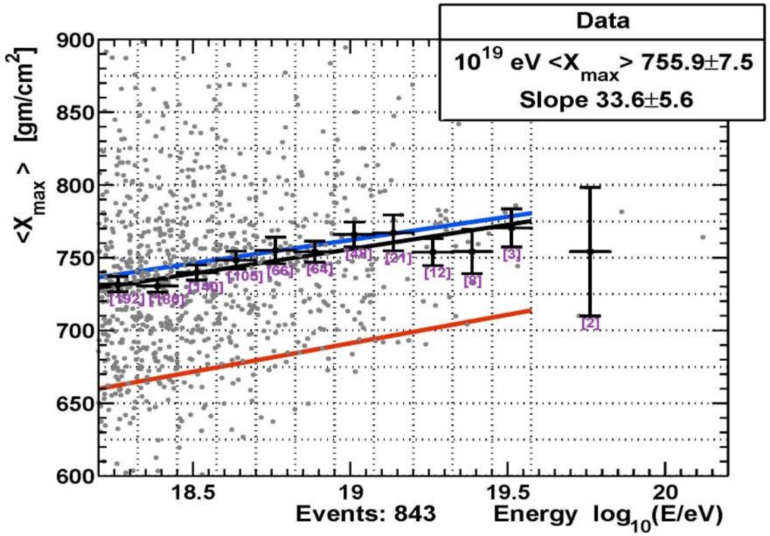
UHE: Air shower composition constraints

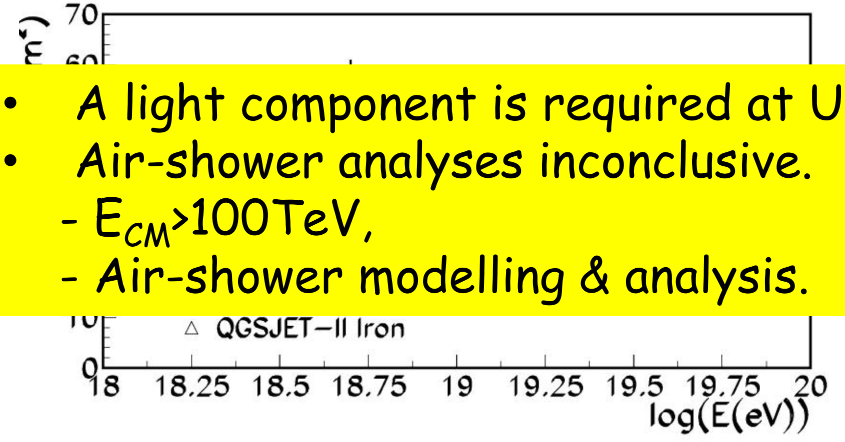
Auger 2010: Fe, 2015: p, He(??)





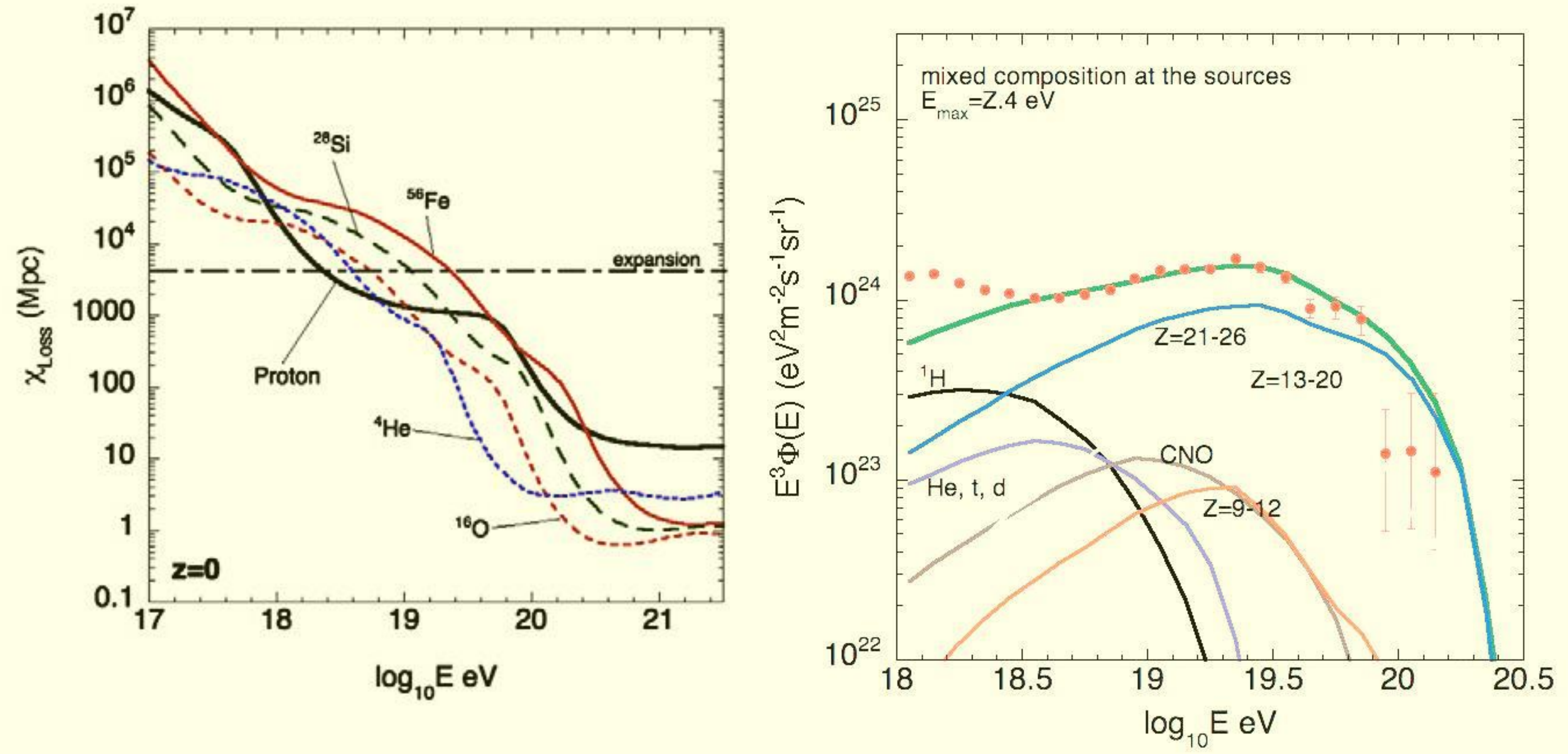
HiRes Stereo 2010 & TA Hybrid 2015





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

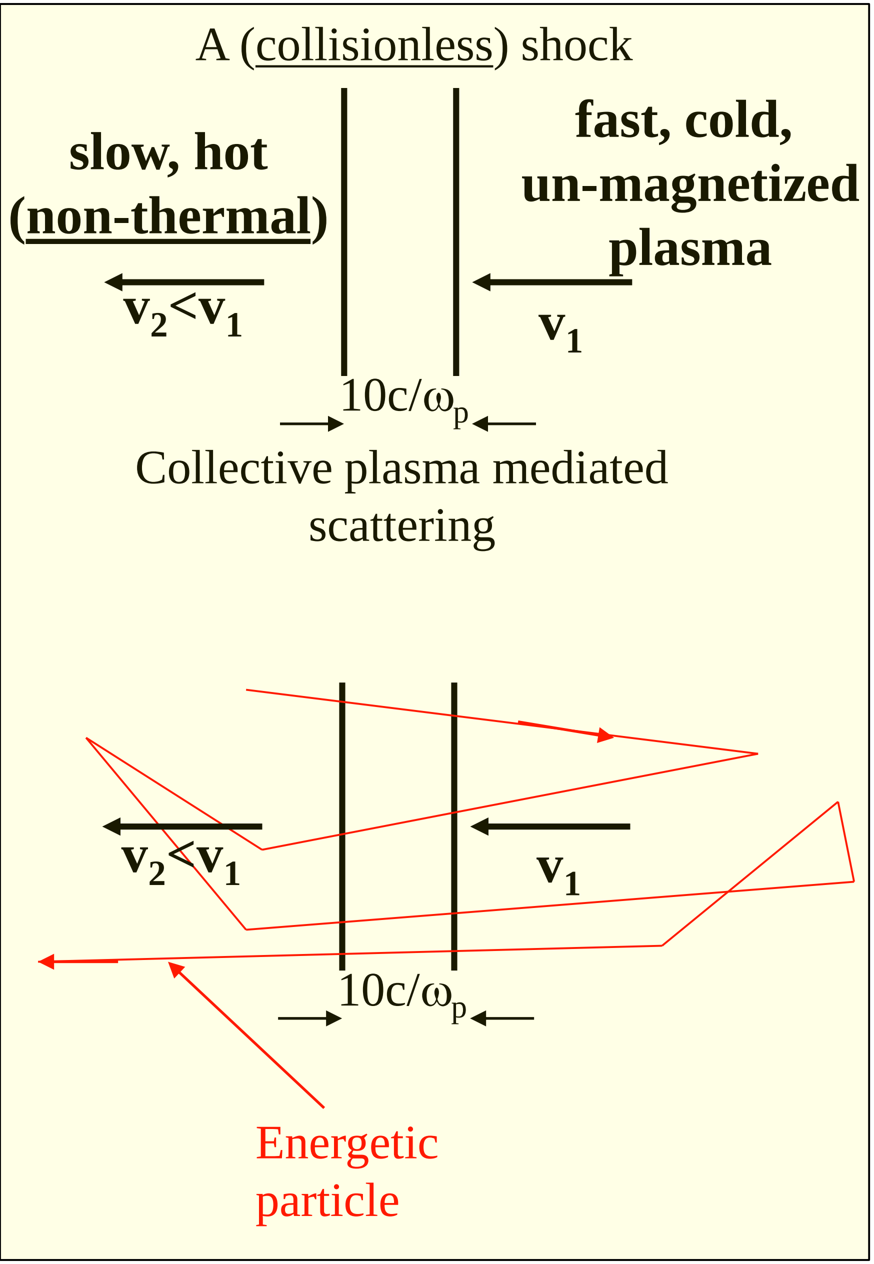
A mixed composition



[Allard 12]

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

Acceleration: Collisionless shocks



A (collisionless) shock

slow, hot (non-thermal)

fast, cold, un-magnetized plasma

Collective plasma mediated scattering

Energetic particle

- 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^-).

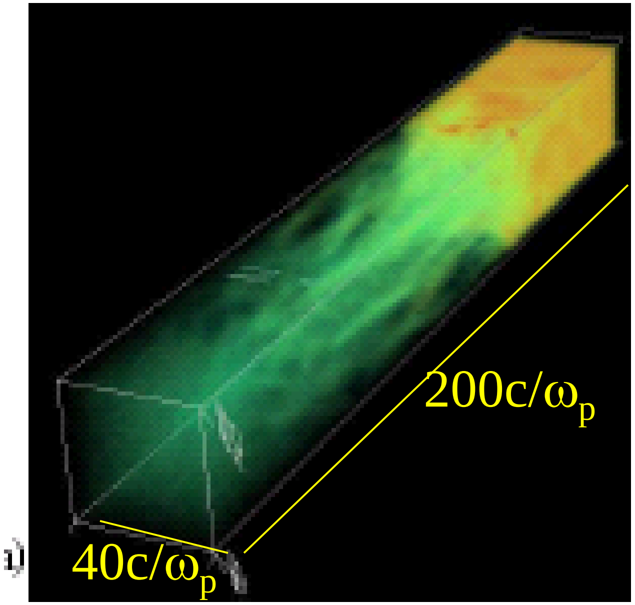
- Supported by basic principles plasma simulations.

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

- [The only predictive model.]

Collisionless shocks: Plasma simulations

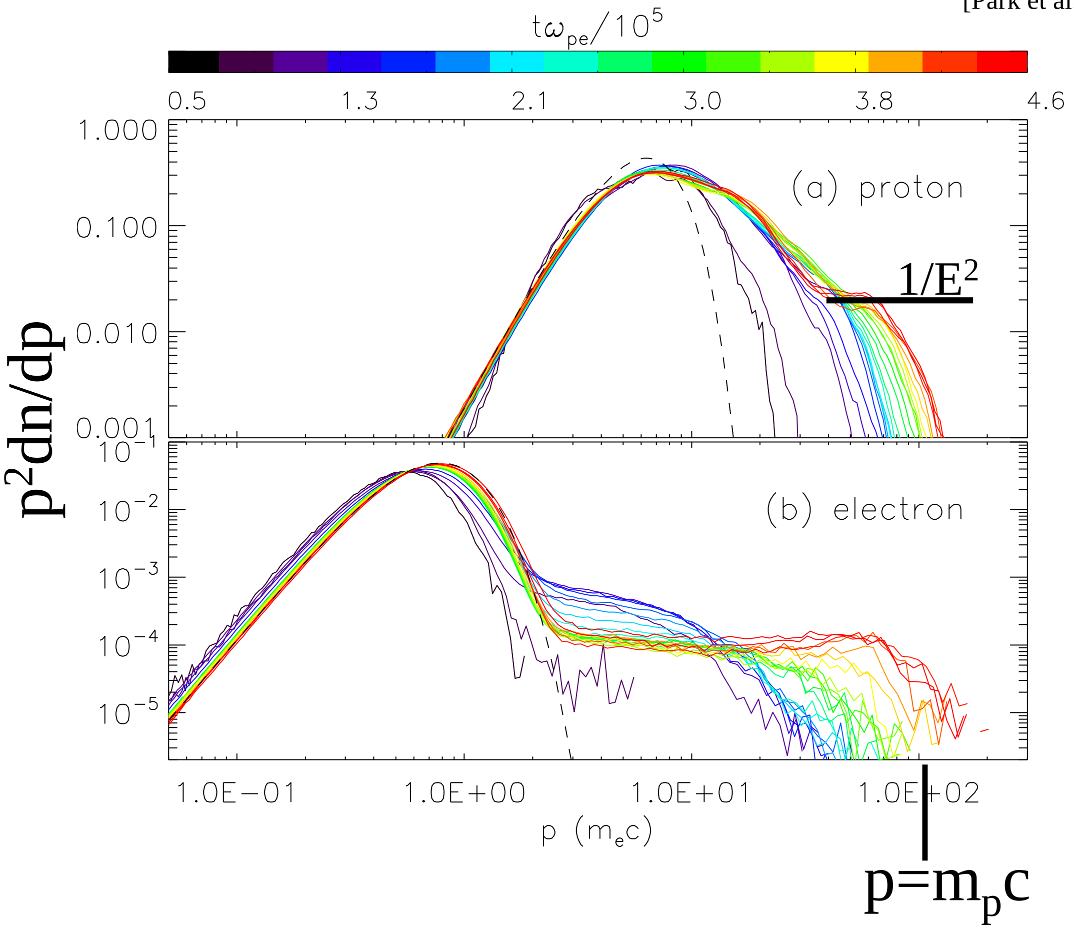
3D, $m_p/m_e=1$



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

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

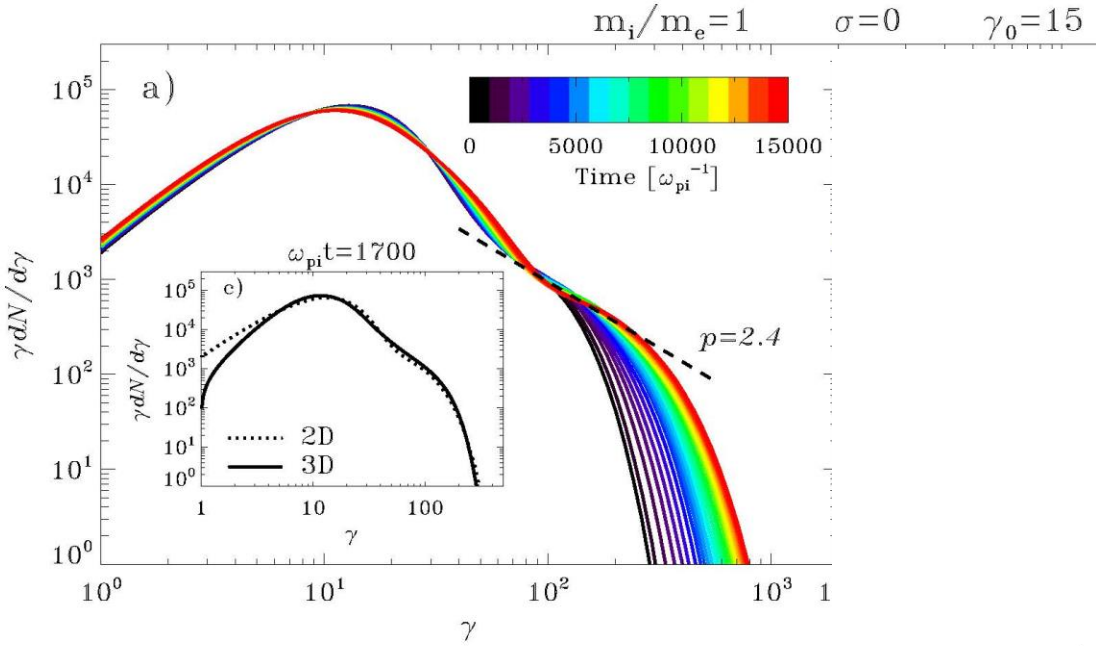
[Park et al. 15]

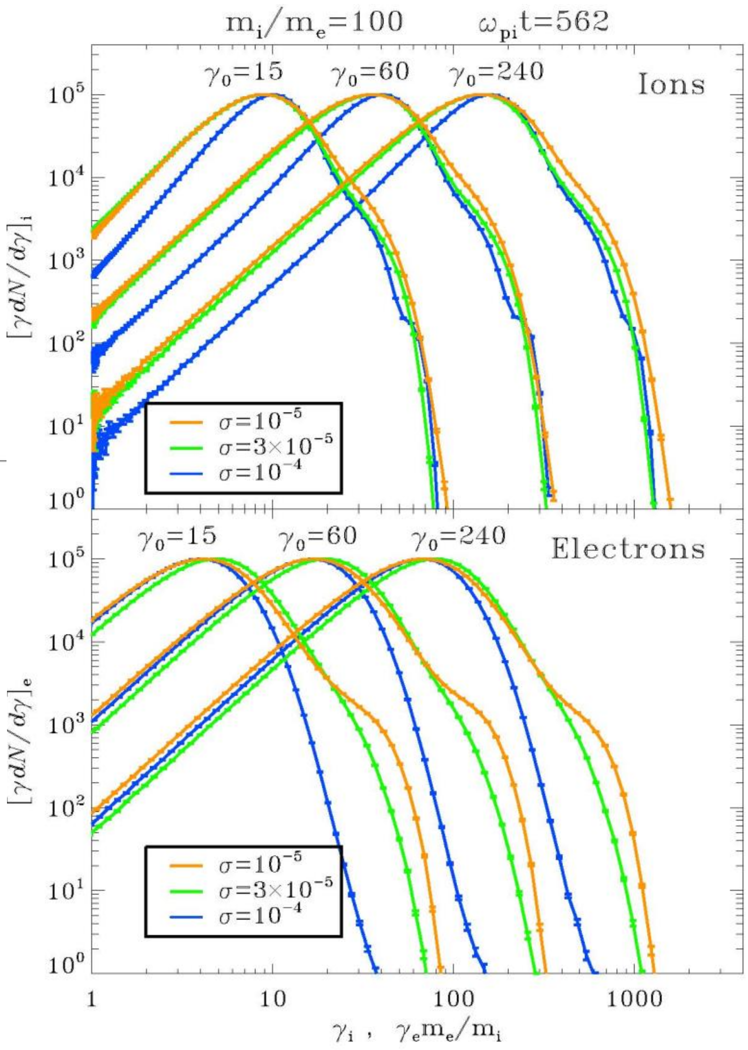


Particle acceleration in collisionless shocks

- No basic principles theory.
- Challenges:

  Self-consistent particle/B,
  Non linear with a wide range of
  temporal/physical scales.





[Sironi, Spitkovsky & Arons 13]

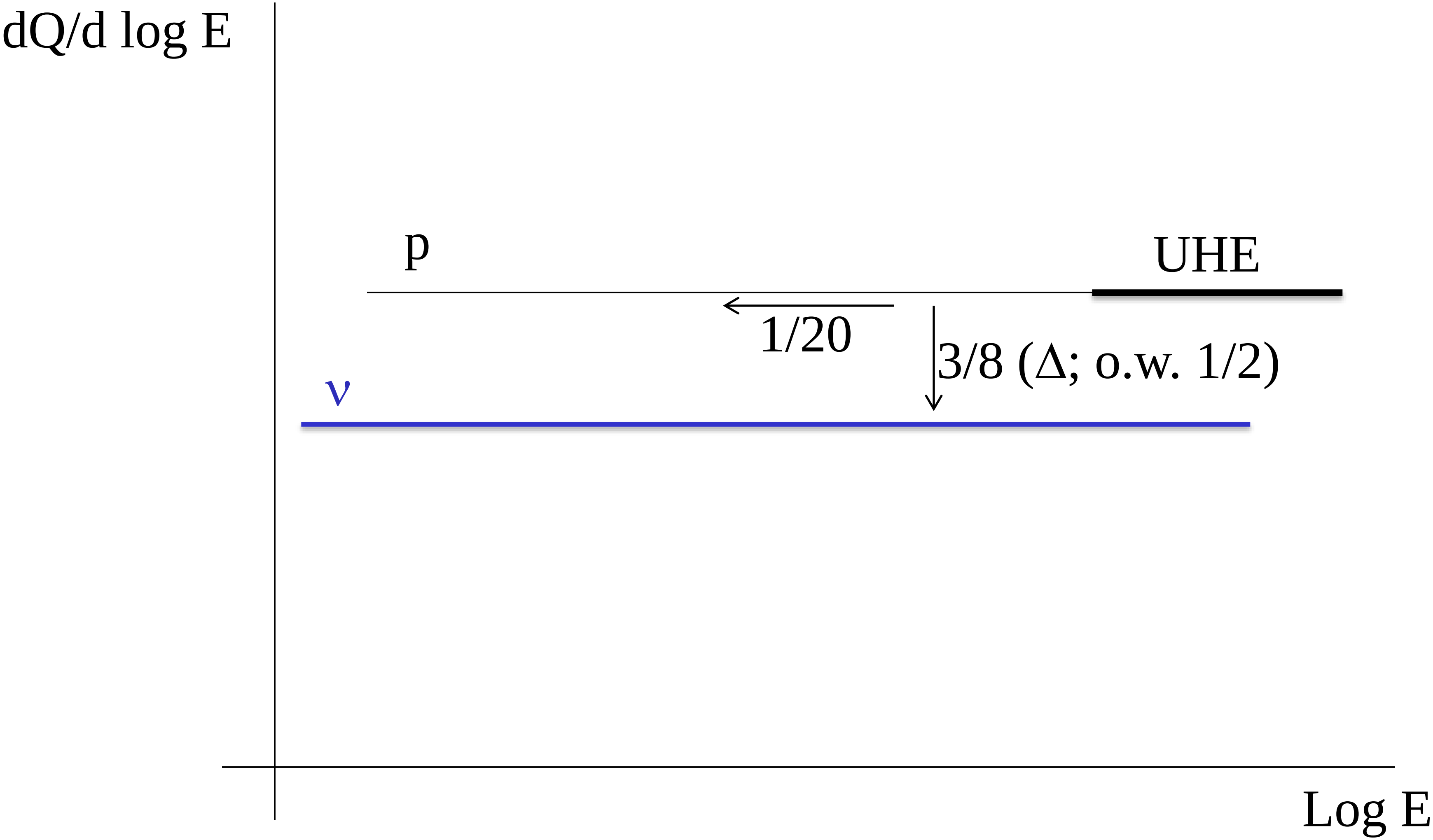
π production: p/A—p/γ

- 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



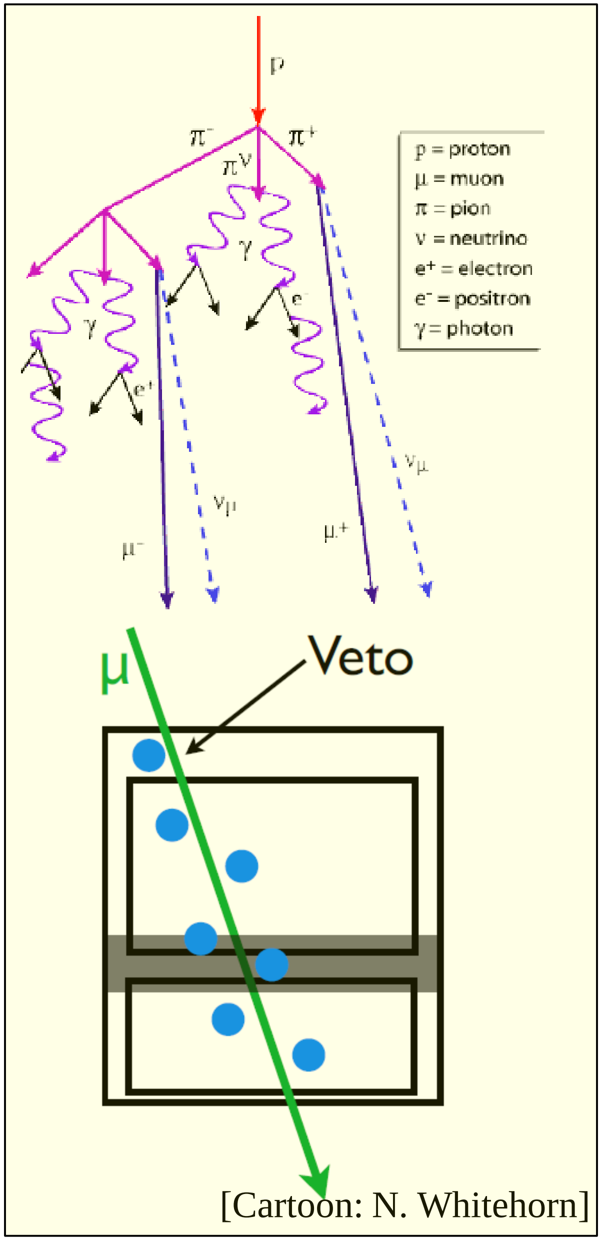
Looking up: Vetoing atmospheric neutrinos

[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).



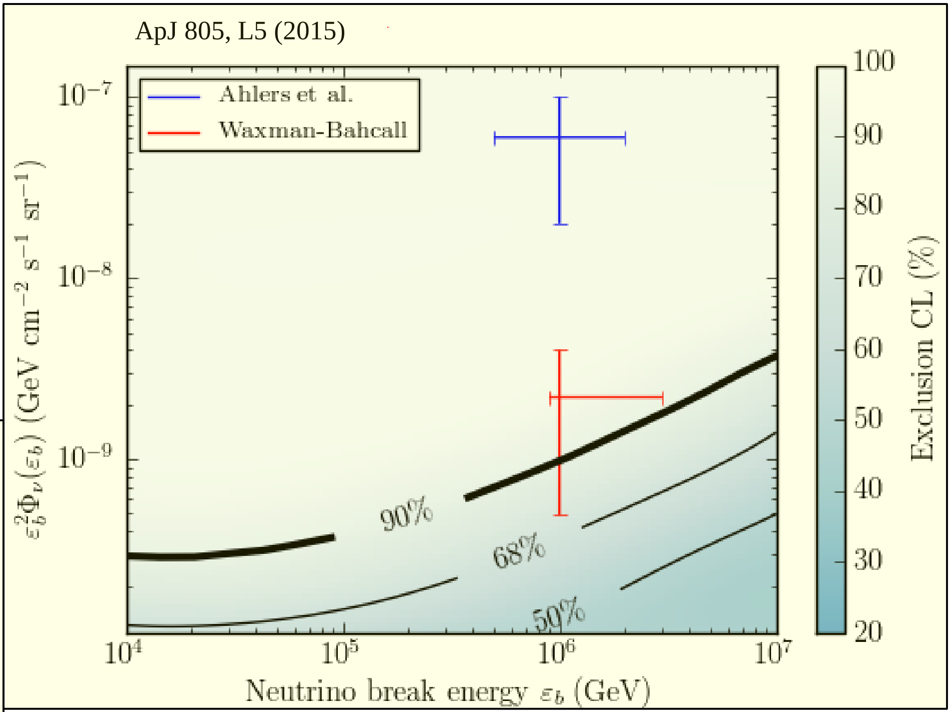
[Cartoon: N. Whitehorn]

A note on prompt GRB ν's

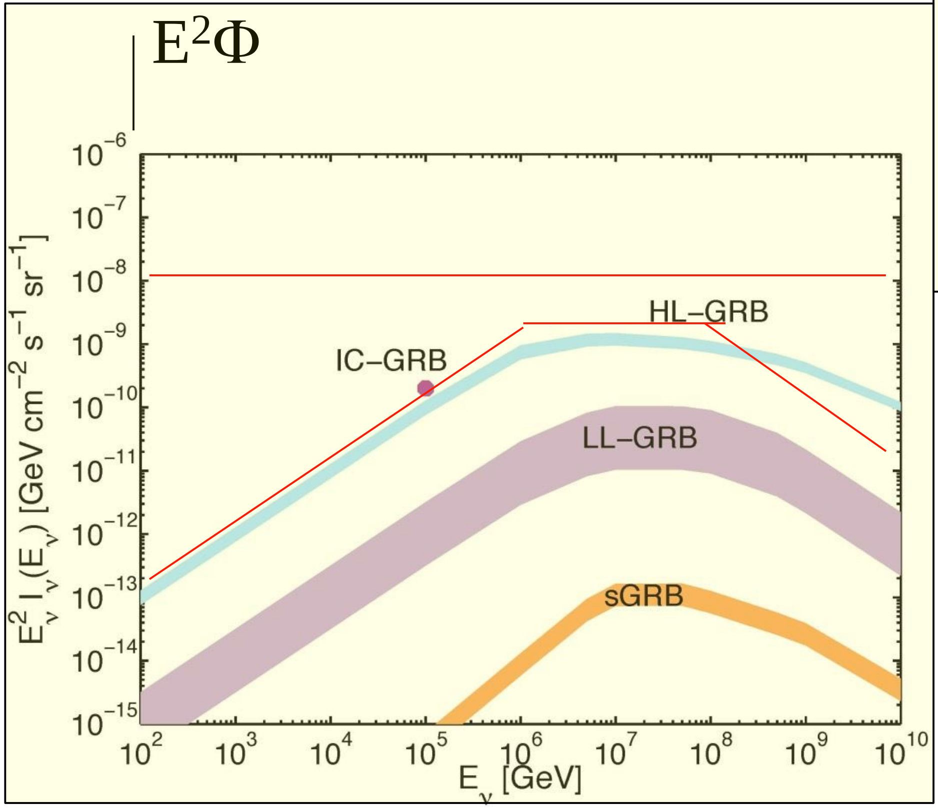
$$\varepsilon_{\nu,b} = 500\left(\frac{\varepsilon_{\gamma,b}}{1\mathrm{MeV}}\right)^{-1}\Gamma^2_{2.5}\,\mathrm{TeV} \approx 1\mathrm{PeV}$$

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

[EW & Bahcall 97]



ApJ 805, L5 (2015)



- 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]

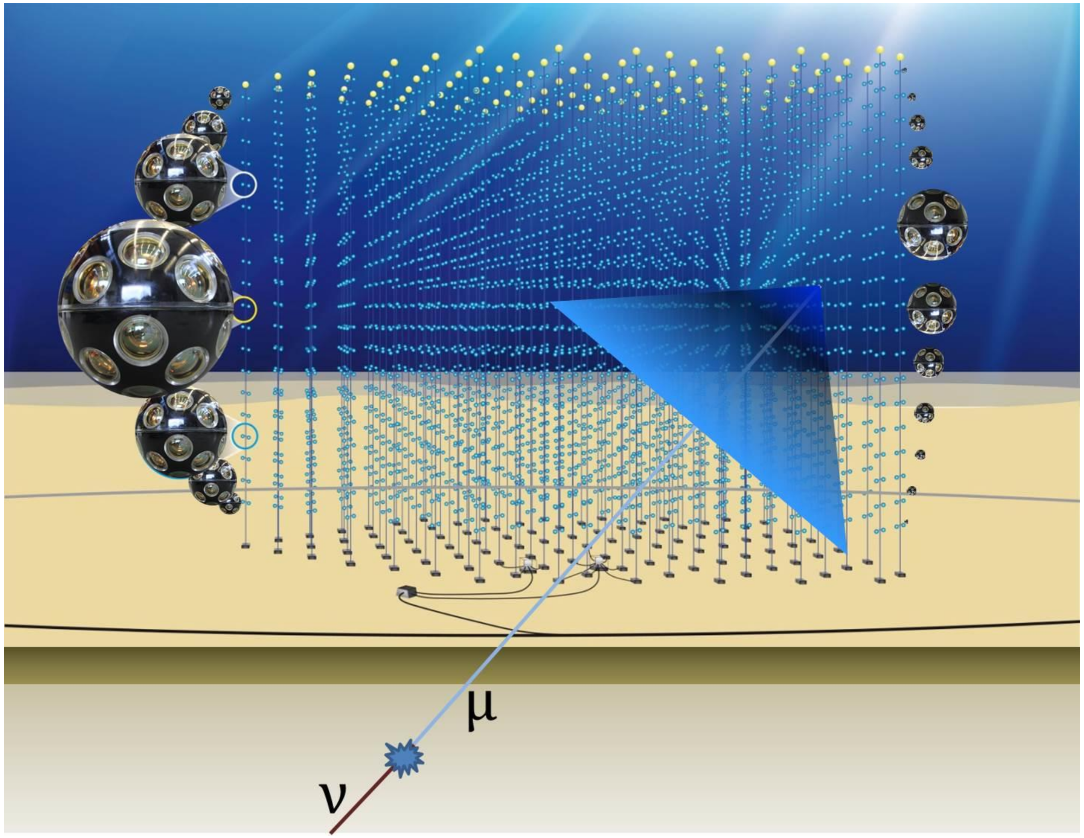
- EGB: $E^2\Phi_\gamma$([0.05,0.1,0.8] TeV) ~ [3,1,0.2]x 10^{-7} GeV/cm^{2}s sr.
- IceCube: $E^2\Phi_\nu$ (100 TeV) ~ 0.3x10^{-7}GeV/cm^{2}s sr.

- 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.

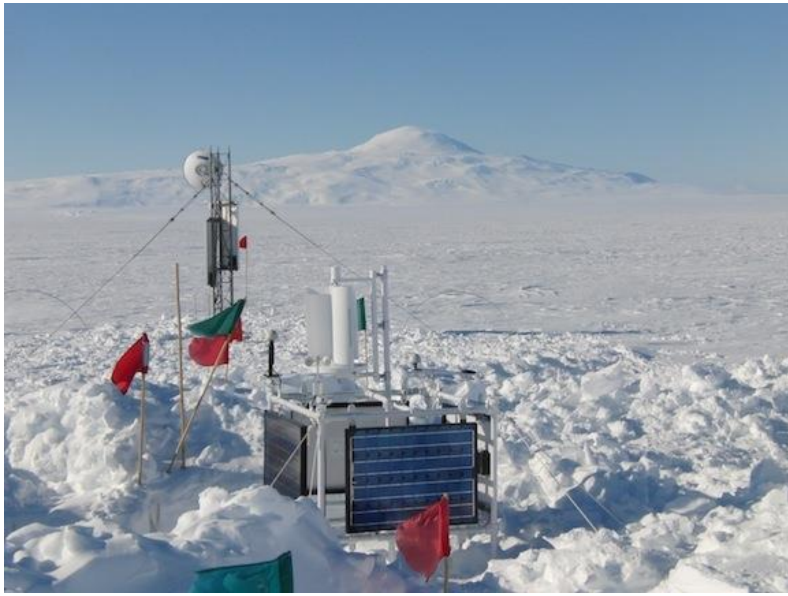
- Implications:
  - Flat generation spectrum, d log n/d log E >-2.2 (steeper- exceed EGB, e.g. [e.g. Tamborra, Ando, & Murase 14]).
  - Resolving ~90% of the EGB will constrain ν sources.
  - "Strong tension with EGB" [e.g. Bechtol et al. 15] due to assuming a steep spectrum (d log n/d log E =-2.5).

Future experimental developments

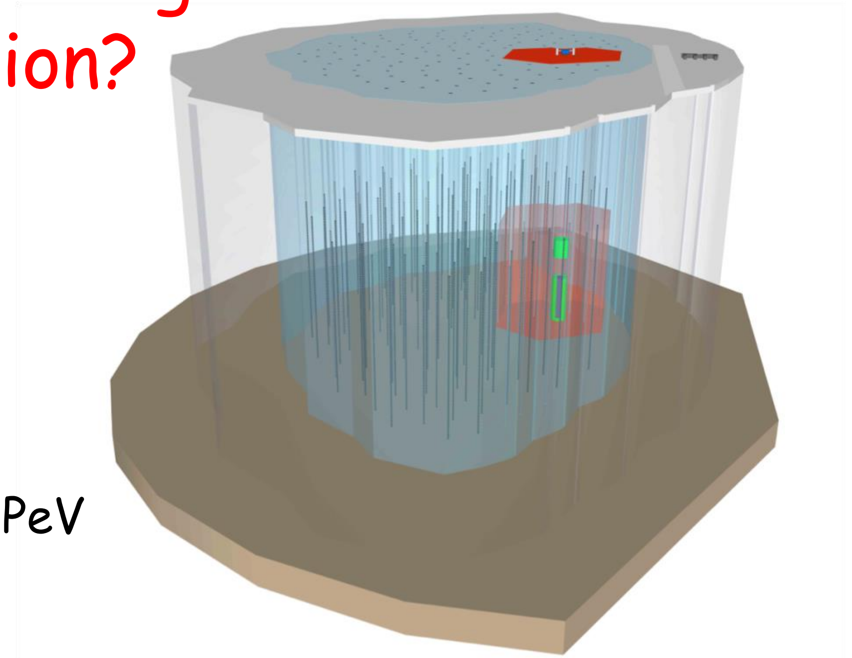
- IC extension
- Mediterranean
  Km3Net (~5x IC)



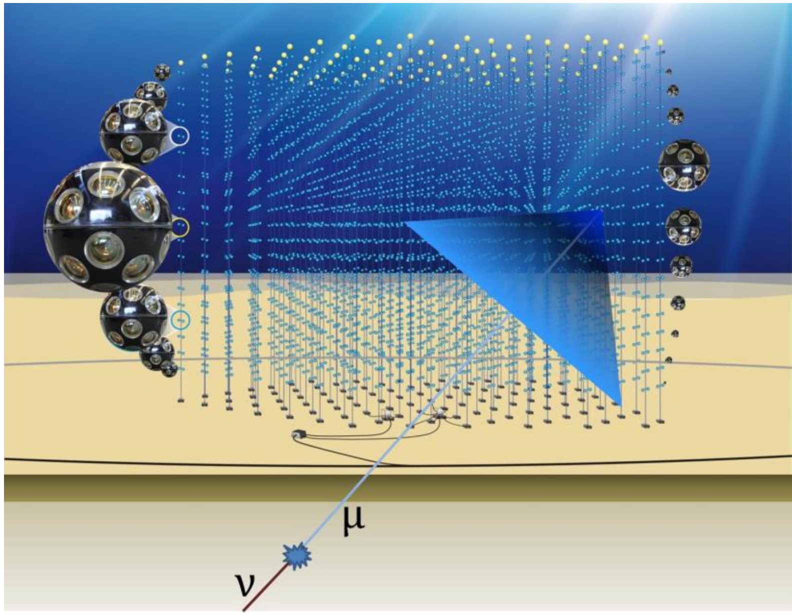
ARA & ARIANNA:
Coherent radio Cerenkov,
10^8 to 10^{10} GeV



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 $\Phi_\nu(\varepsilon_\nu<1\mathrm{PeV})\sim\Phi_{WB}$ [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

A. B. McDonald[a)]
SNO Institute, Queen's University, Kingston, Canada K7L 3N6

C. Spiering
DESY Zeuthen, Platanenallee 6, D-15738 Zeuthen, Germany

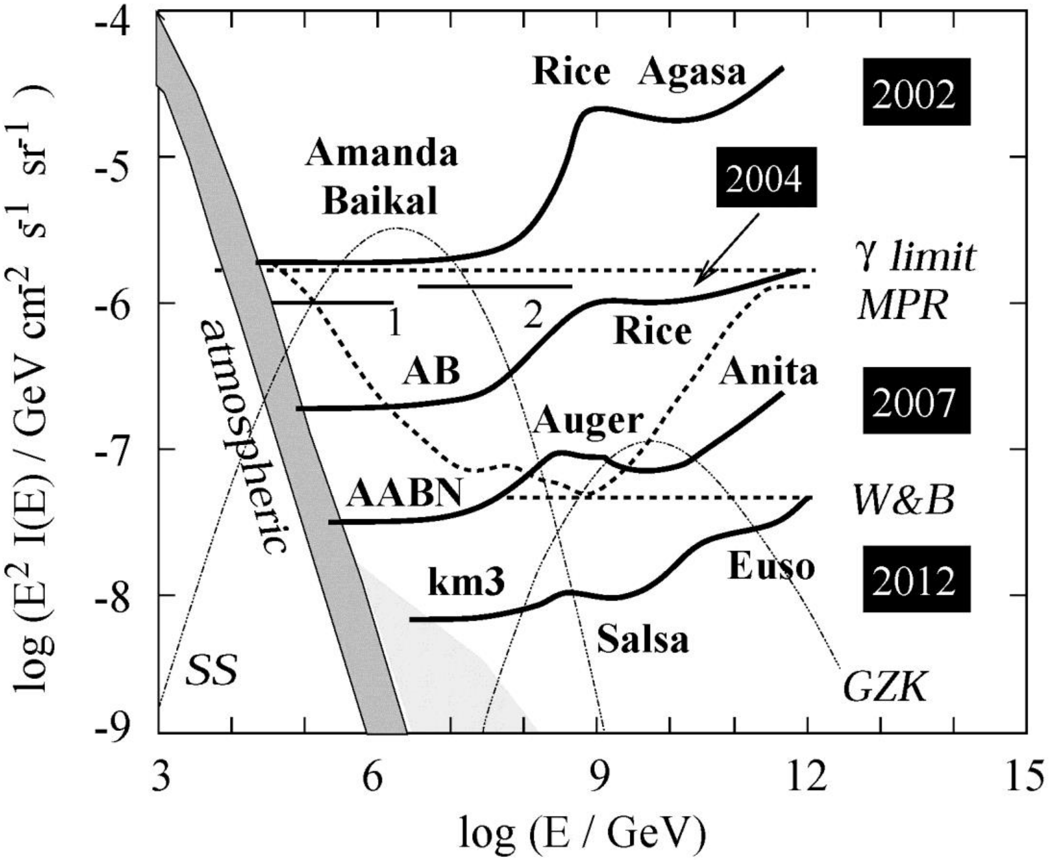
S. Schönert
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

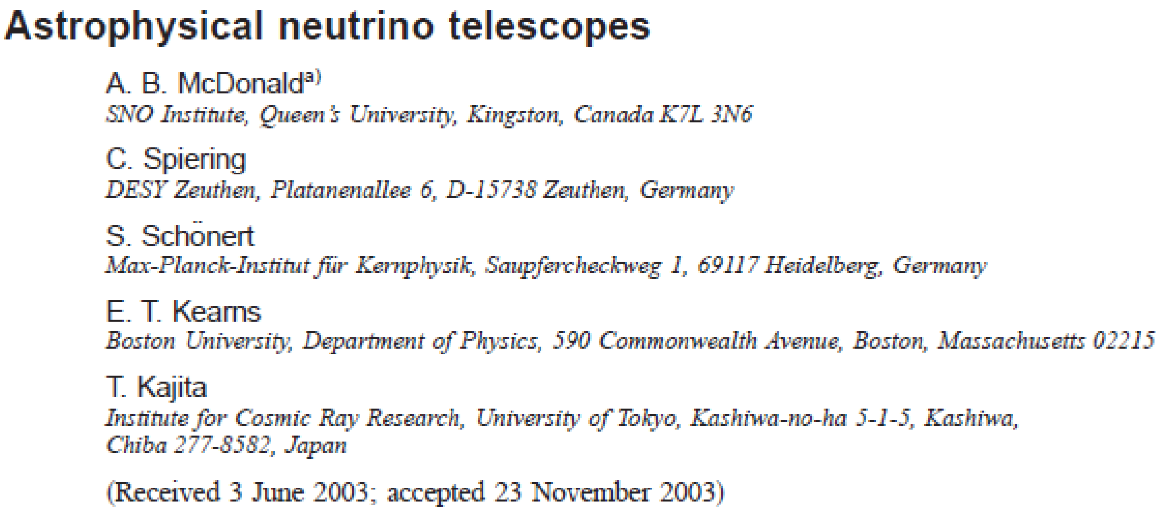
E. T. Kearns
Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, Massachusetts 02215

T. Kajita
Institute for Cosmic Ray Research, University of Tokyo, Kashiwa-no-ha 5-1-5, Kashiwa,
Chiba 277-8582, Japan

(Received 3 June 2003; accepted 23 November 2003)

[Rev. Sci. Inst.]





Astrophysical neutrino telescopes

A. B. McDonald[a)]
SNO Institute, Queen's University, Kingston, Canada K7L 3N6

C. Spiering
DESY Zeuthen, Platanenallee 6, D-15738 Zeuthen, Germany

S. Schönert
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

E. T. Kearns
Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, Massachusetts 02215

T. Kajita
Institute for Cosmic Ray Research, University of Tokyo, Kashiwa-no-ha 5-1-5, Kashiwa,
Chiba 277-8582, Japan

(Received 3 June 2003; accepted 23 November 2003)

MeV- GeV Achievements:

Detection of solar and SN ν's,
Tests of stellar structure and explosion models,
ν mass and oscillations.

>100 TeV Achievements:

Detection of extra-Galactic ν's.
More to come…

Nobel prizes:

- 2002 Davis (Cl) & Koshiba (Kamiokande)

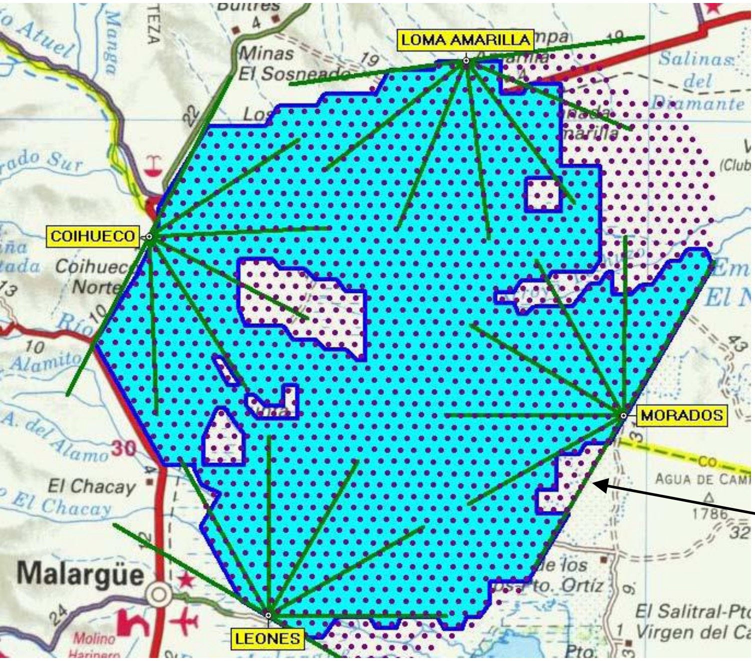
"*for pioneering contributions to … detection of cosmic ν's*";

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

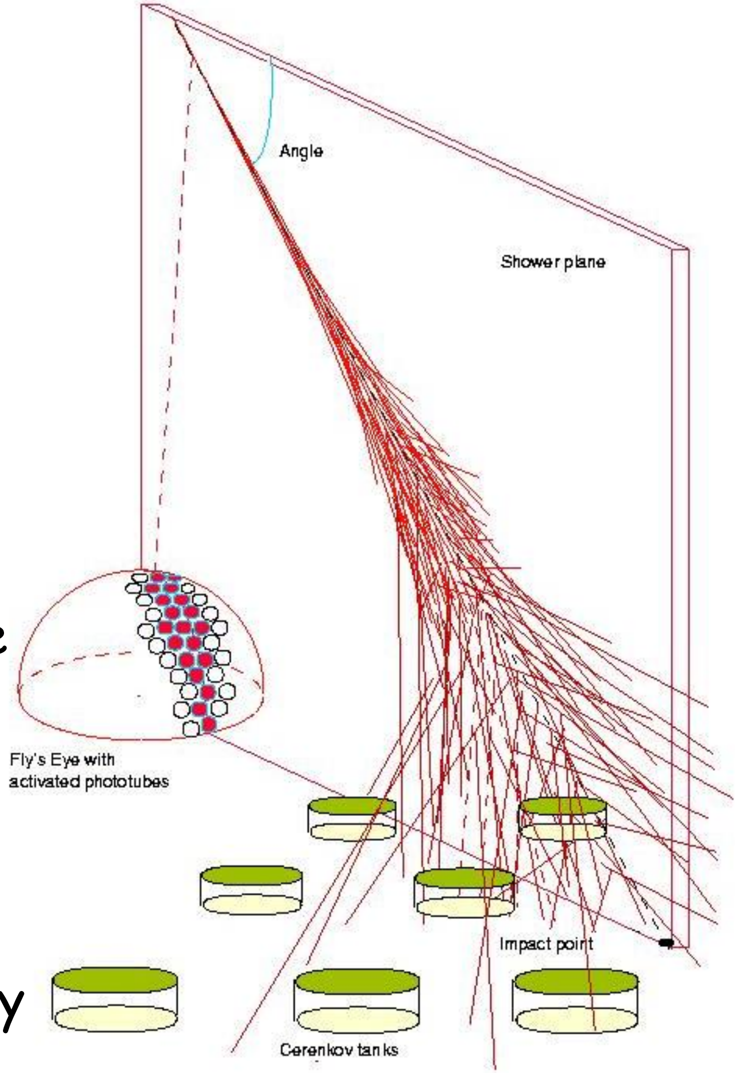
"*for the discovery of ν oscillations, which shows that ν's have mass*".

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

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



Auger:
3000 km^2



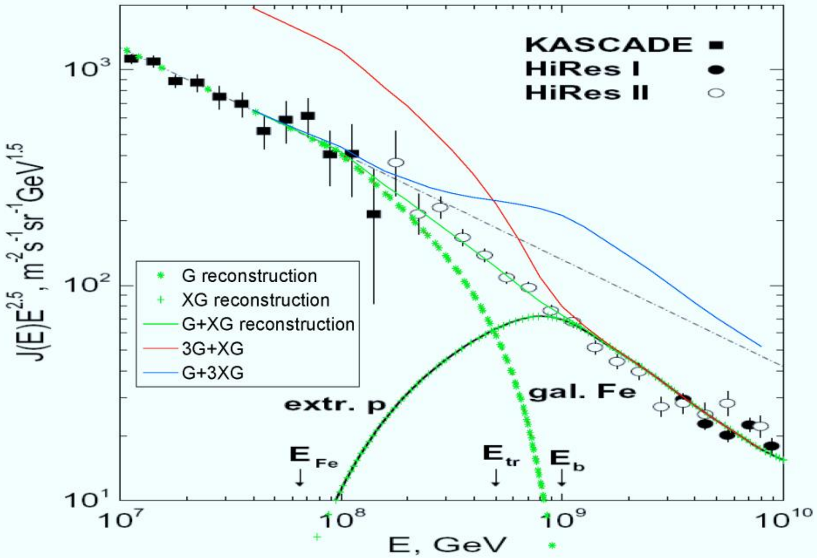
Fluorescence detector

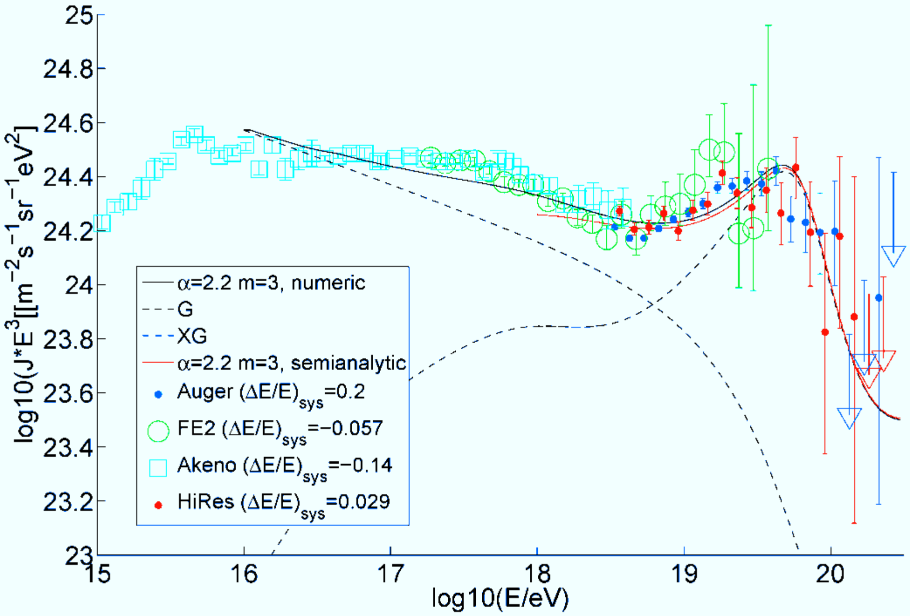
Ground array

Where is the G-XG transition?

@ $E<10^{18}$eV ?

dQ/dlog ε =Const → @ $E\sim10^{19}$eV





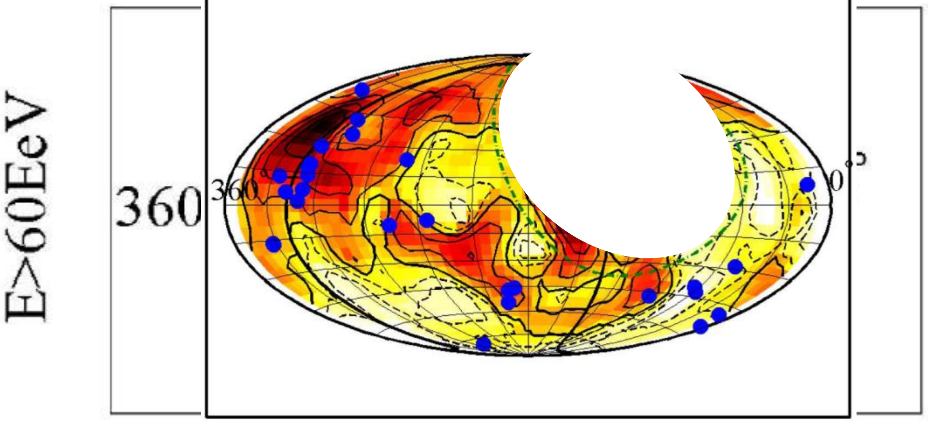
[Katz & EW 09]

- Fine tuning

UHE: Do we learn from (an)isotropy?

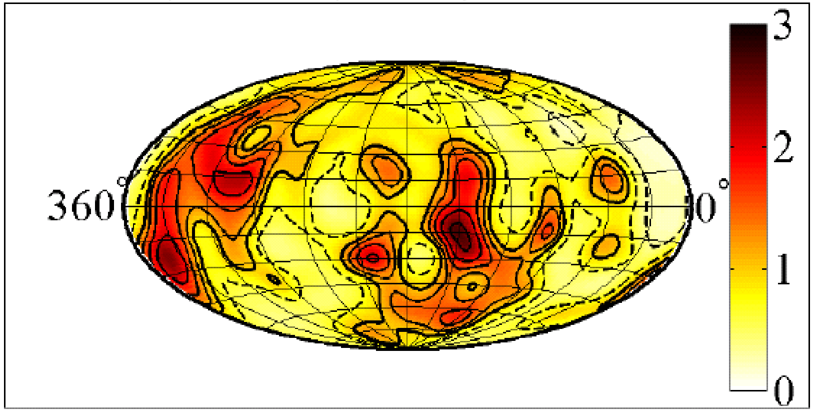
Biased ($\rho_{source} \sim \rho_{gal}$ for $\rho_{gal} > \overline{\rho_{gal}}$)

CR intensity map ($\rho_{source} \sim \rho_{gal}$)



[Kashti & EW 08]

Galaxy density integrated to 75Mpc



[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

.

.

.

Low Energy, ~10GeV

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

- 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]