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

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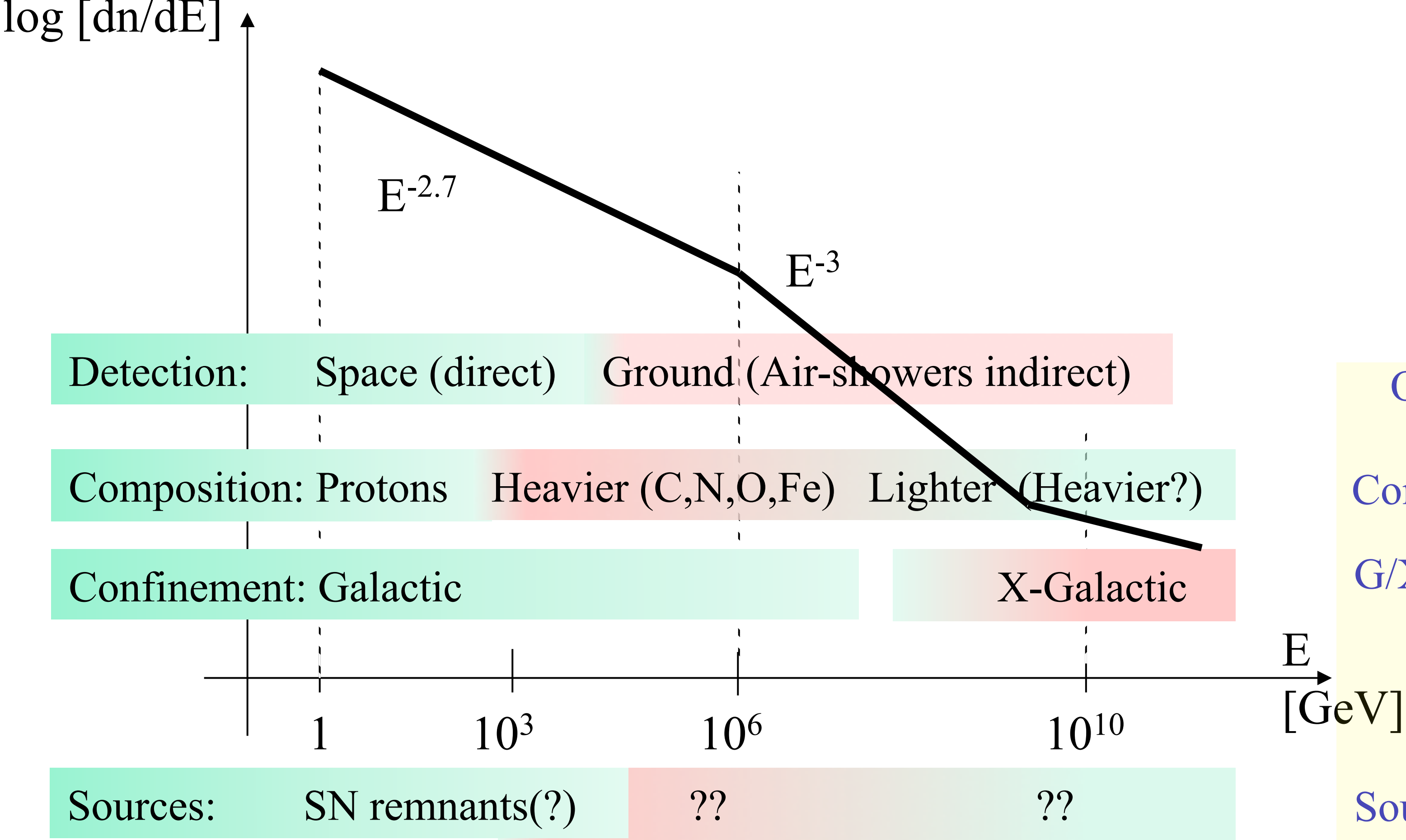
The main driver of HE ν astronomy: The origin of Cosmic Rays



$$dn/dE = dn/dE\ t_{conf.}(E)$$
$$\Rightarrow Q_E = E^2\ dn/dE$$

Open Q's

Composition?

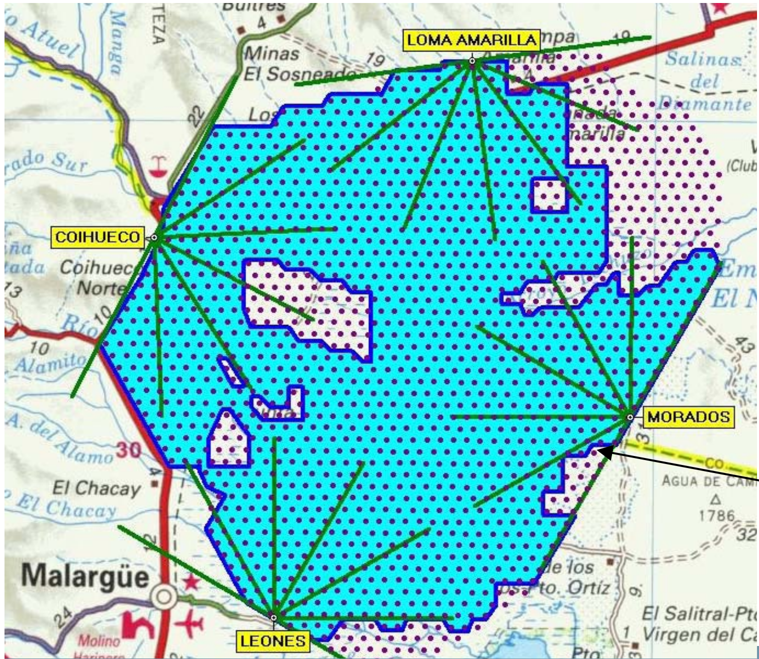
G/XG transition?

Sources?

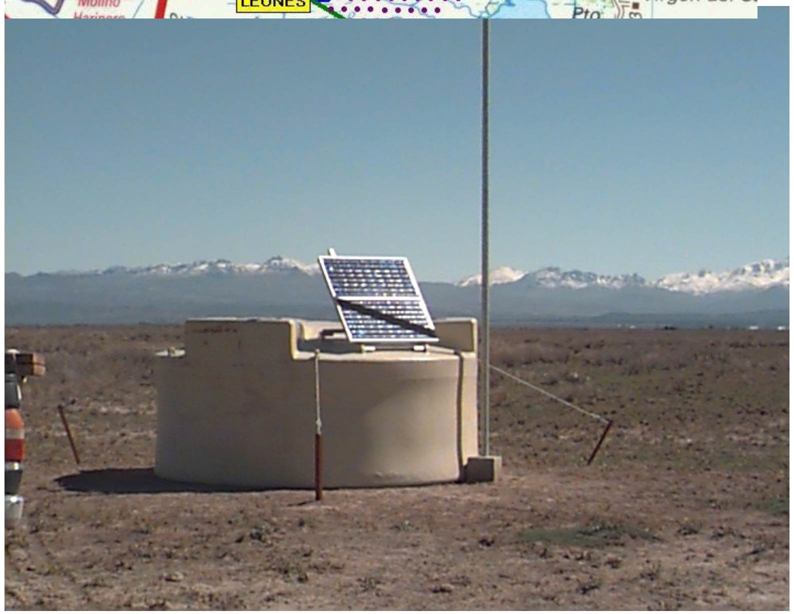
Acceleration?

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

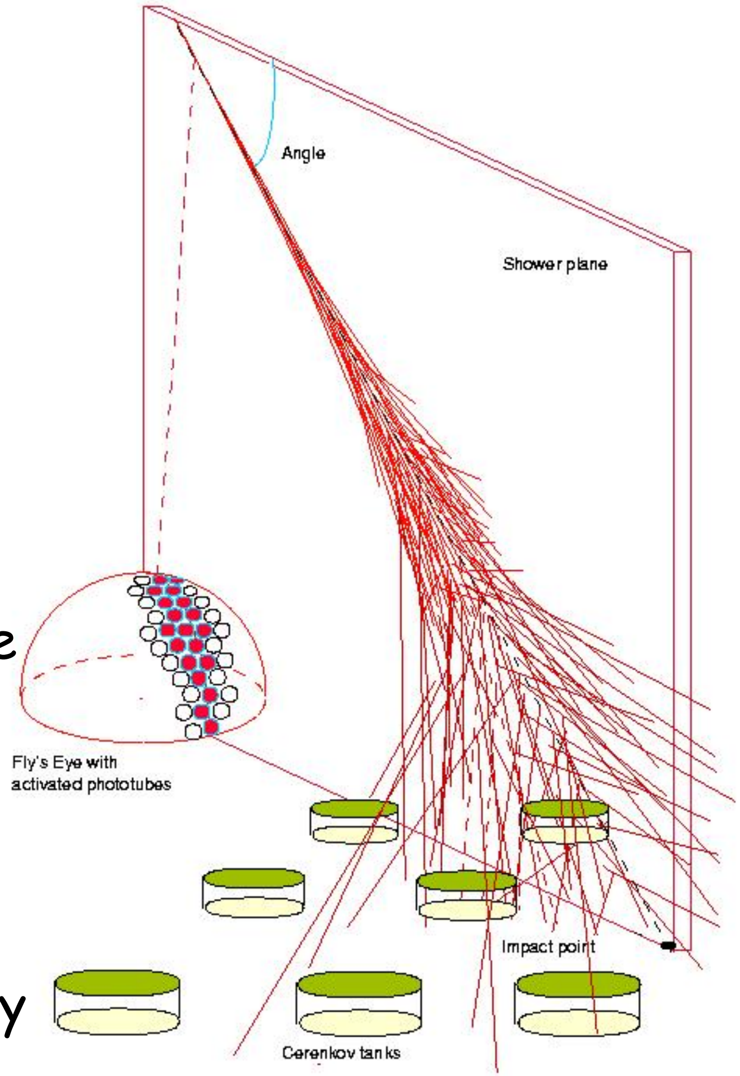
UHE, $>10^{10}$GeV, CRs



Auger:
3000 km^2



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

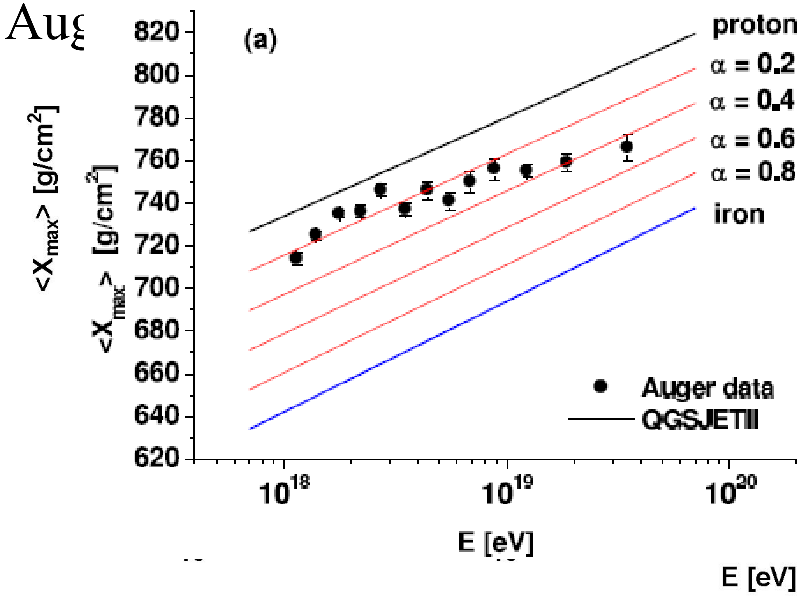


Fluorescence
detector

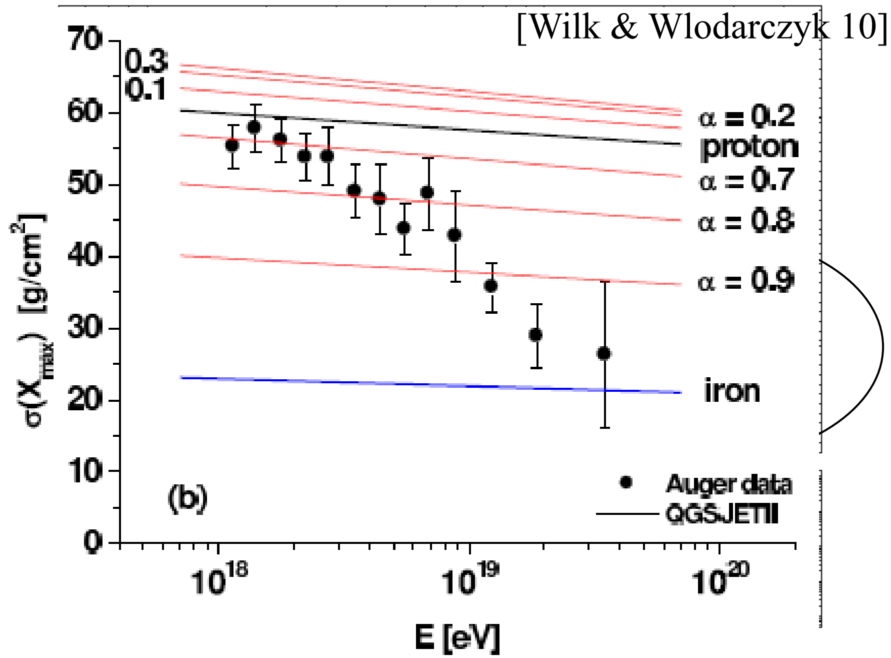
Ground array

UHE: Air shower composition constraints

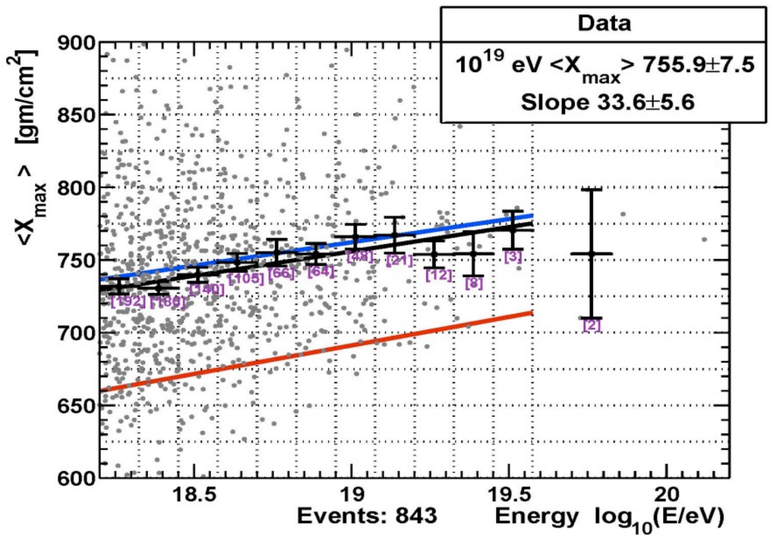
Aug

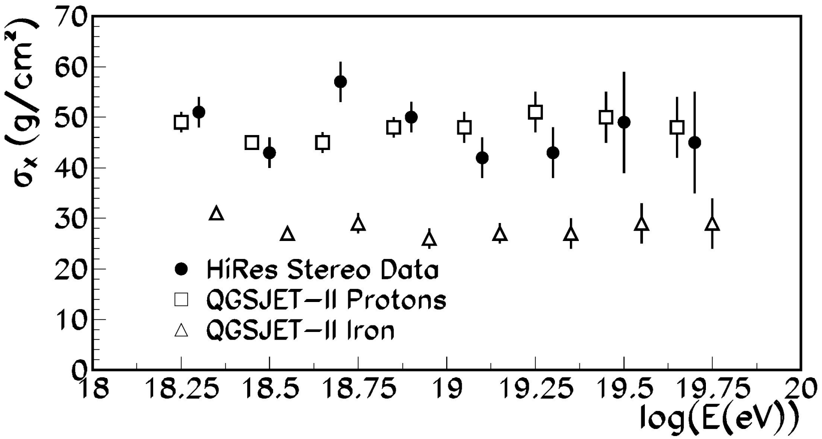


[Wilk & Wlodarczyk 10]



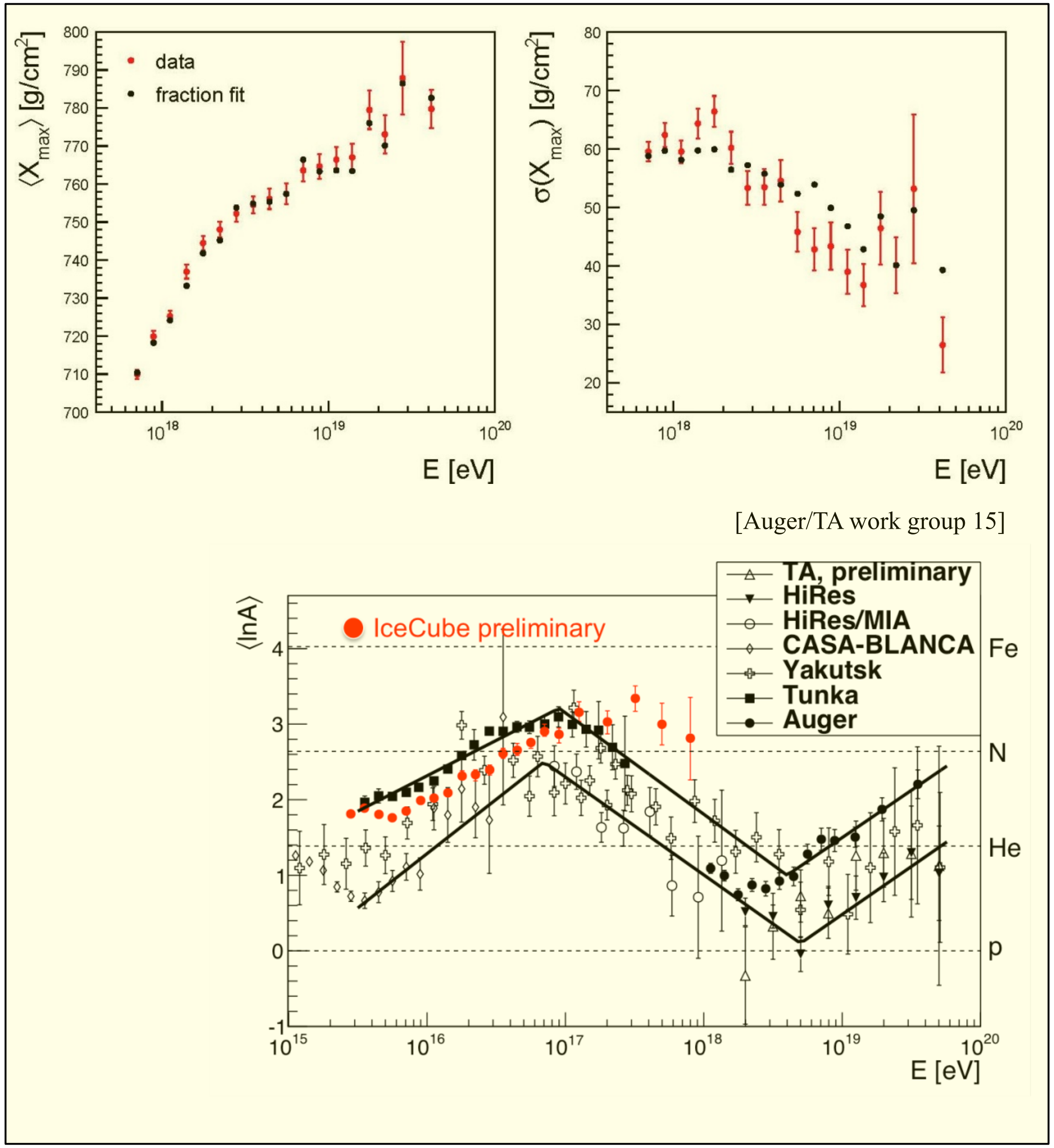
HiRes Stereo 2010 & TA Hybrid 2015





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

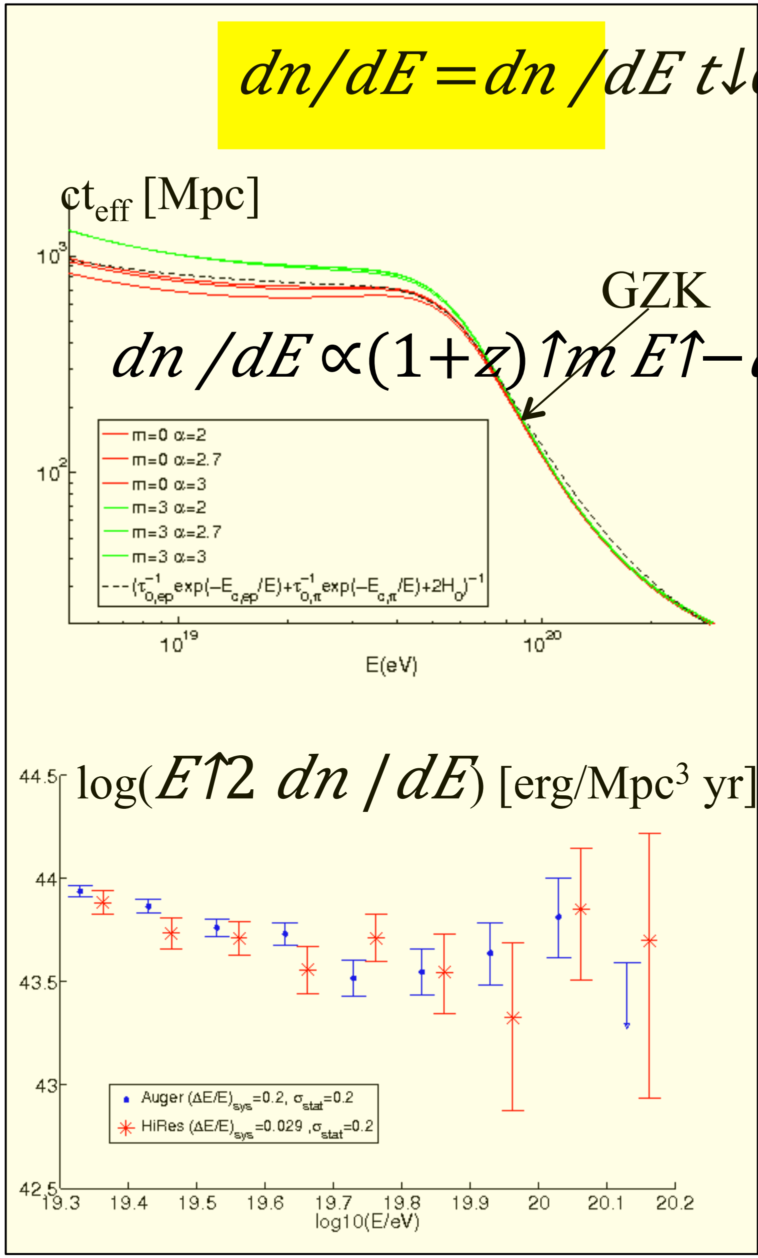
$$Q_E = E^2\, dn/dE = Const.$$

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

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

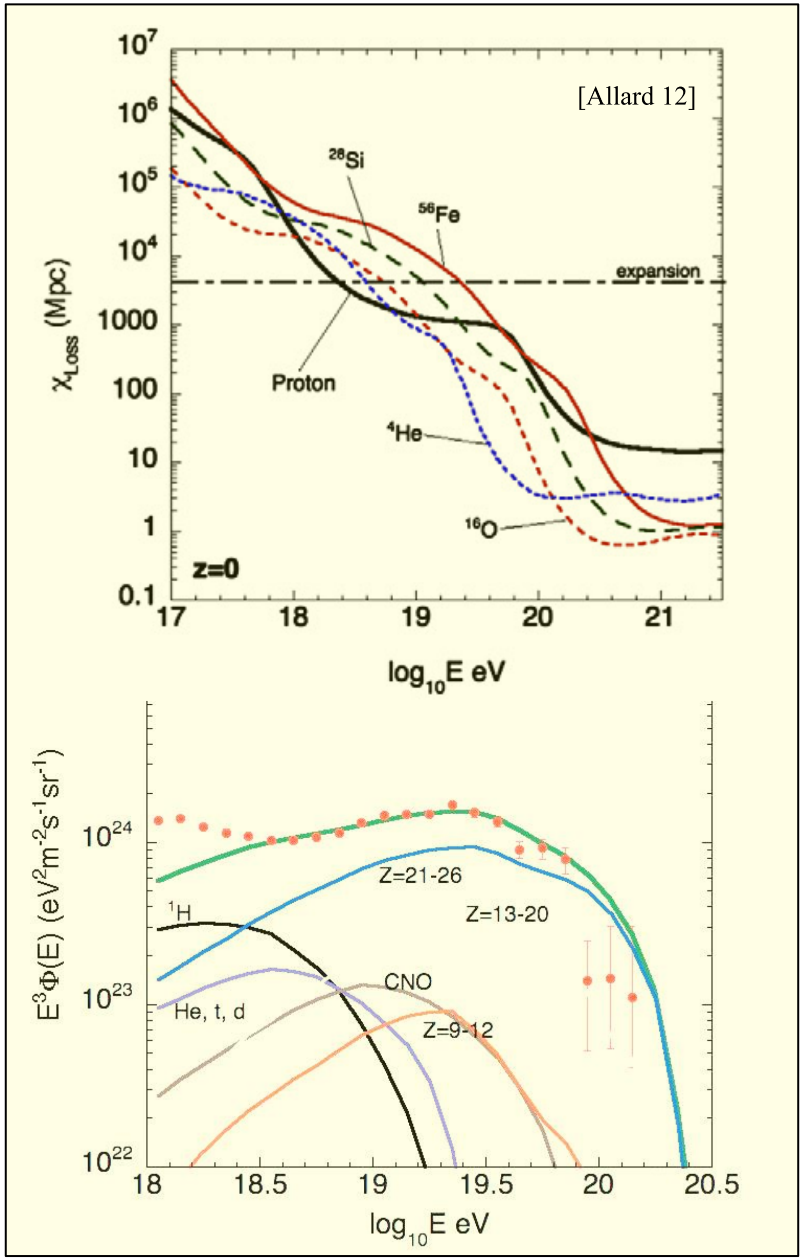
  - Modified by p-GZK suppression.

- 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.



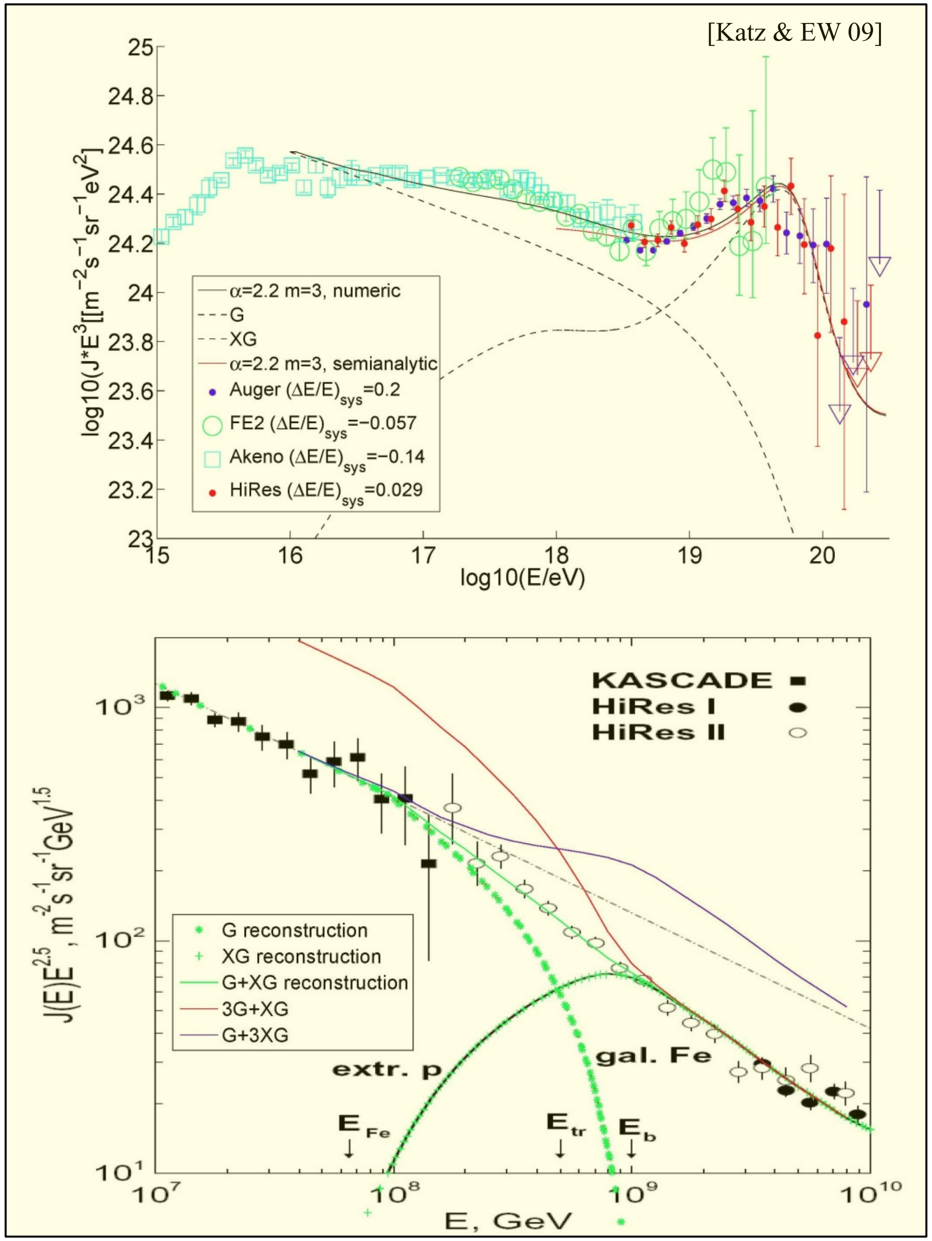
Where is the G-XG transition?

- A flat p generation spectrum,

  $Q_E = E^2\, dn/dE = Const.$

  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 $1/E^2$;
  - $Q^{XG} \gg Q(>10^{19}eV)$.



High energy ν telescopes

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

$$E^2\, dn/dE = Const. = (0.5\pm0.2)10^{44}\ erg/Mpc^3\ yr\ .$$

- An upper bound to the ν intensity (all $p\rightarrow\pi$):

$$E^2\, dj_\nu/dE \le E^2\, \Phi_{WB} = 3/8\ ct_H/4\pi\ \zeta (E^2\, dn/dE) = 10^{-8}\ \zeta GeV/cm^2\ s\ sr\ ,$$

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

[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,

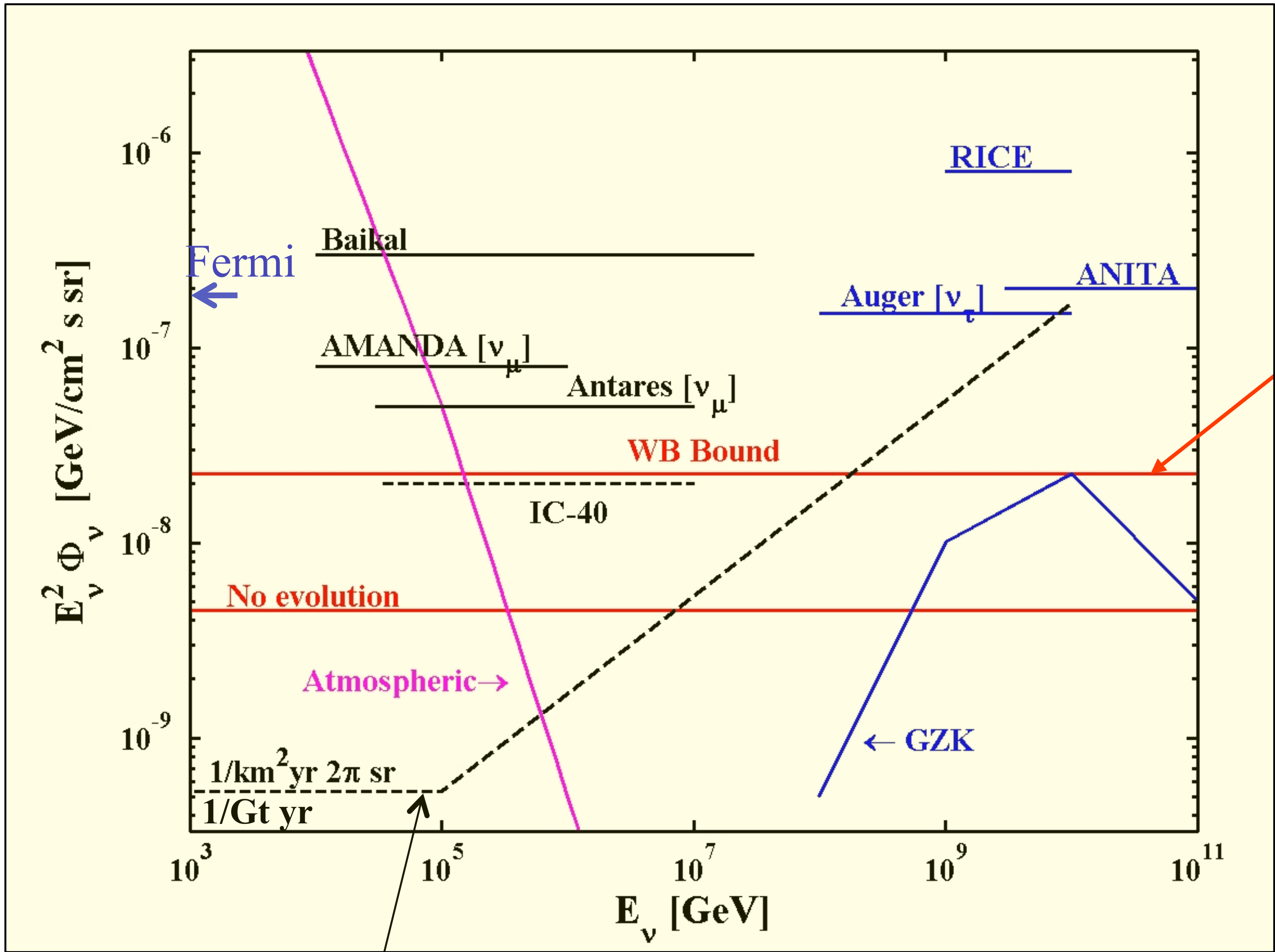
    which are p "calorimeters" for E_p<~10^6GeV,

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

[Loeb & EW 06]

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

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



2 flavors,

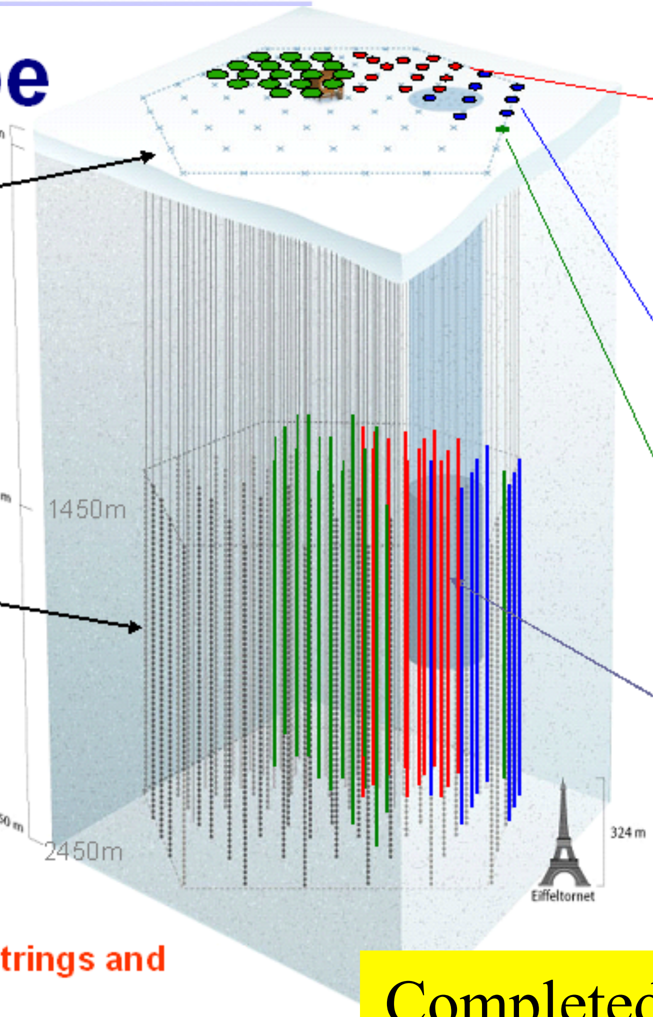
$$\frac{E^2 d\dot{n}/dE}{10^{44}\,\mathrm{erg/Mpc^3 yr}} = 0.5$$

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

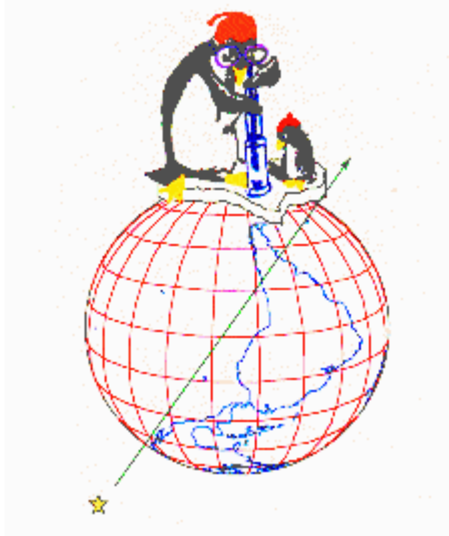
2004-2005 : 1 string

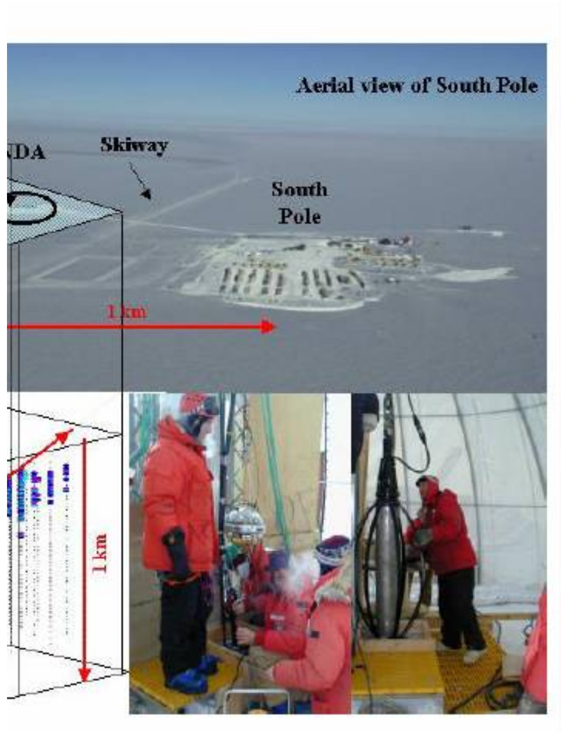
AMANDA-II
19 strings
677 modules

Current configuration:
40 strings,
40 IceTop stations
plus AMANDA

2008/09: add 18 strings and tank stations

Completed Dec 2010



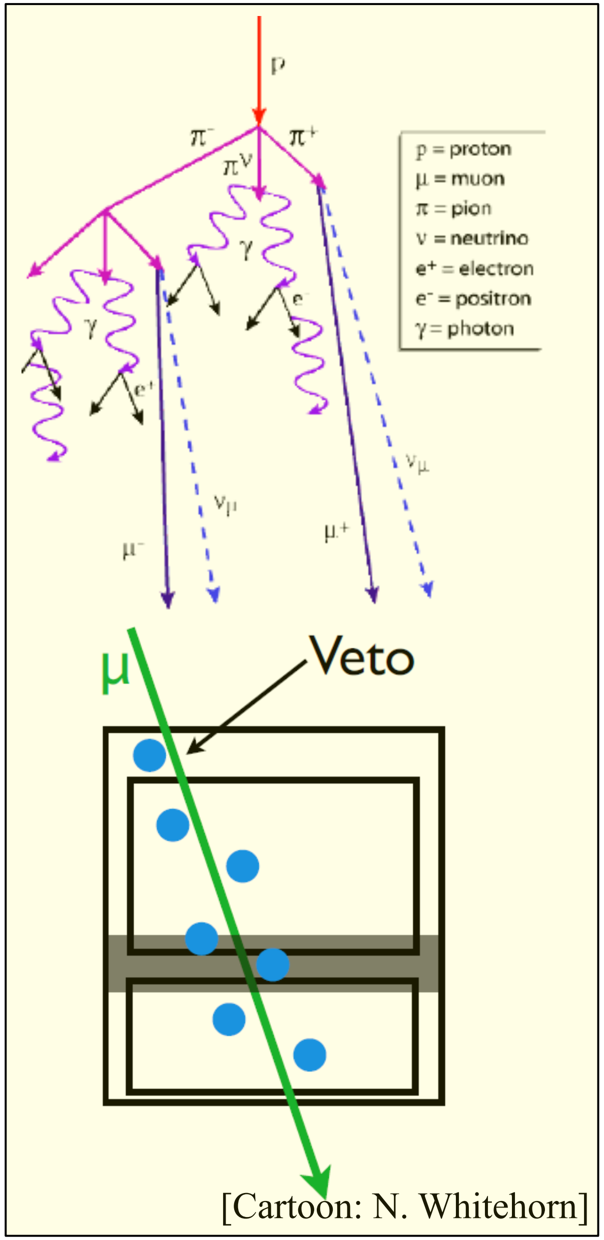


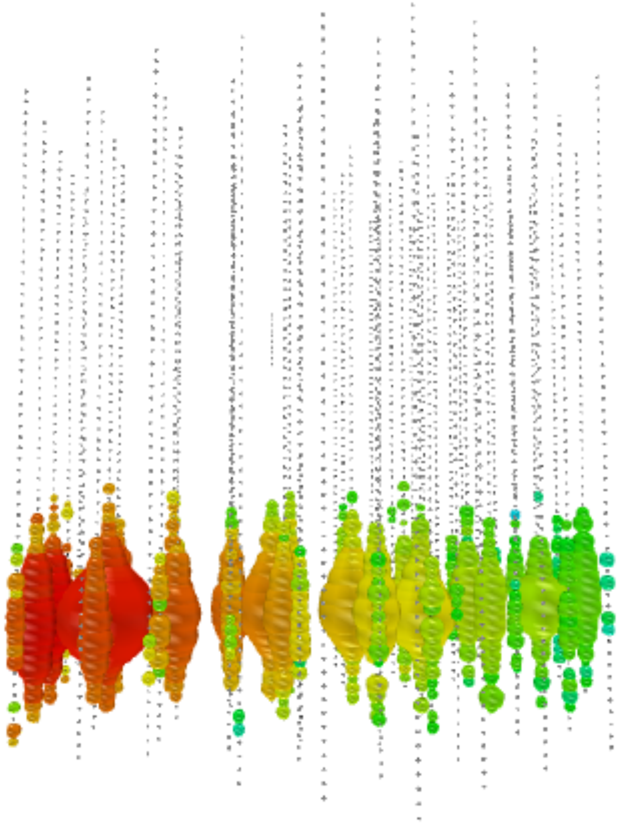
Looking up: Vetoing atmospheric neutrinos

[Schoenert, Gaisser et. al 2009]

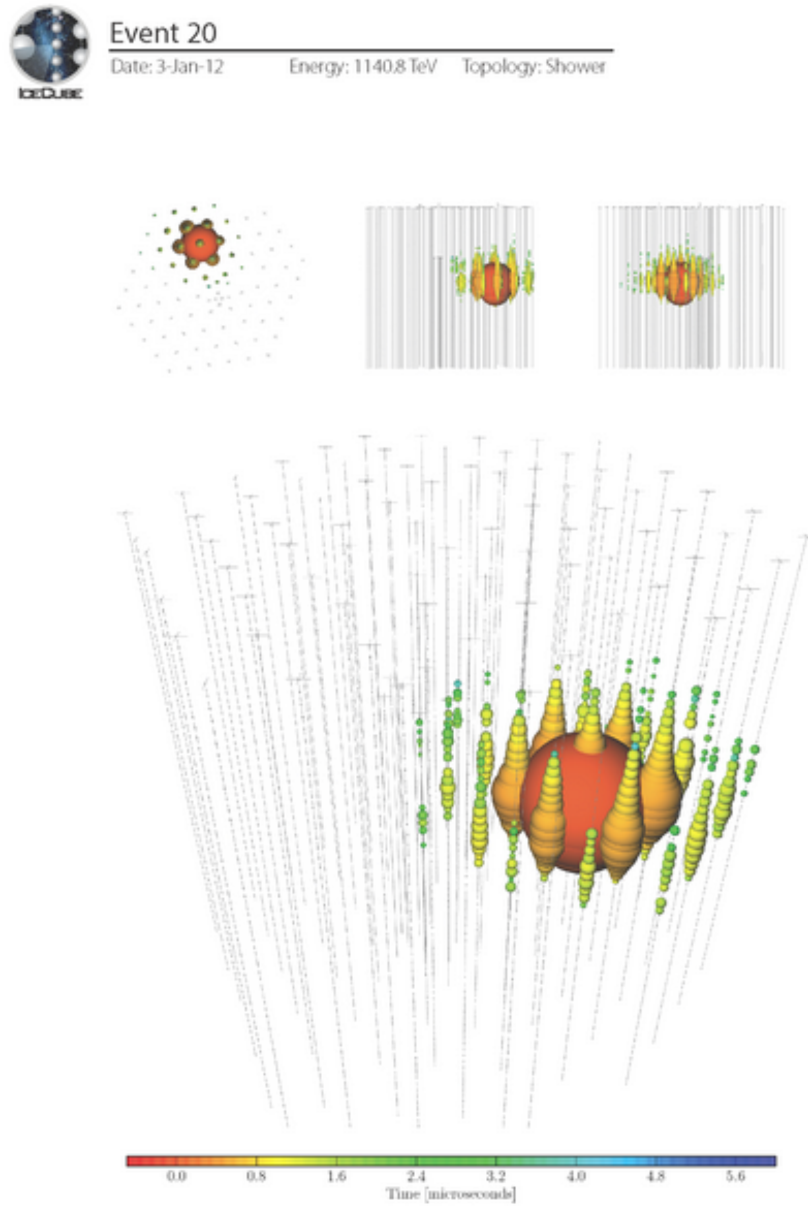
- Look for: Events starting within the detector, not accompanied by shower muons.

- 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).





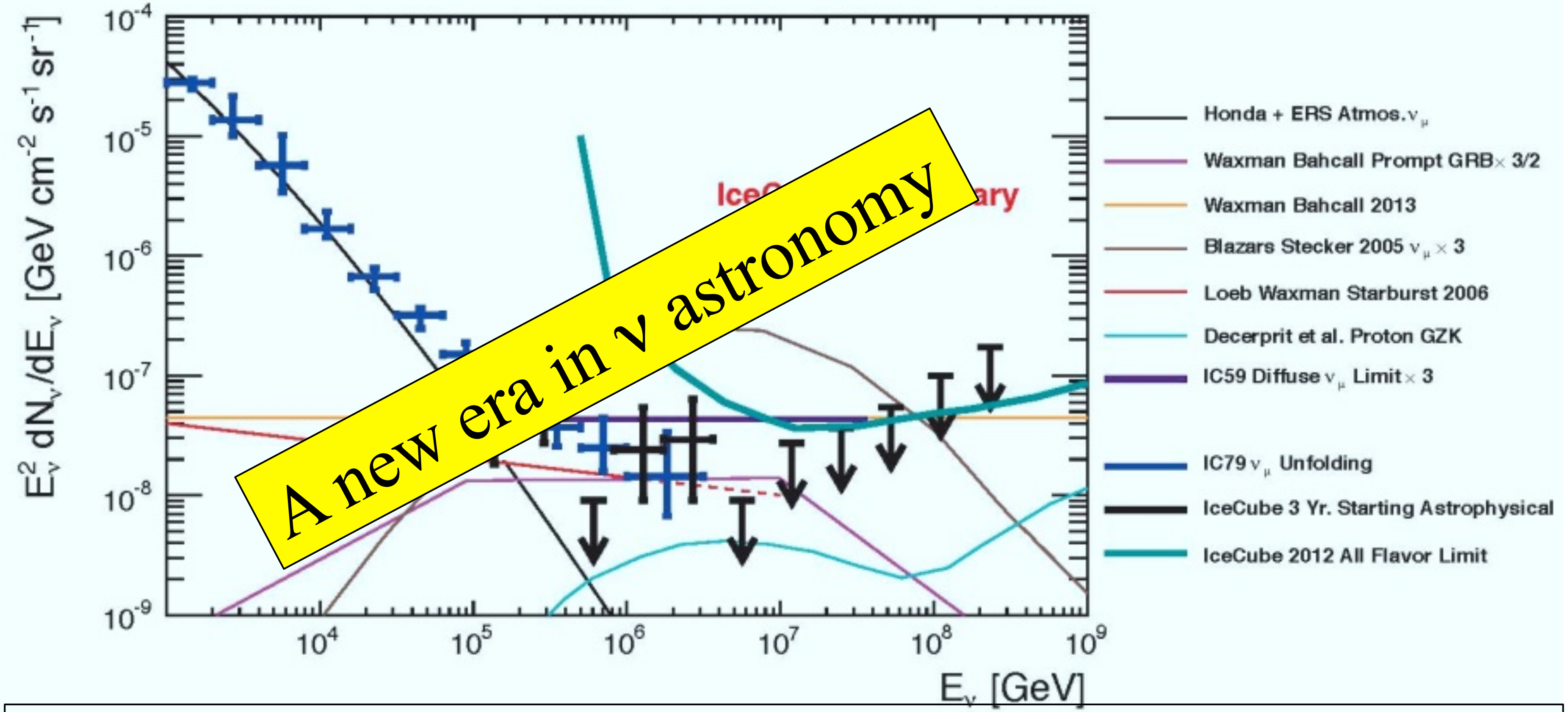
400TeV



1100TeV

IceCube: 37 events at 50Tev-2PeV

~6σ above atmo. bgnd. [02Sep14 PRL]

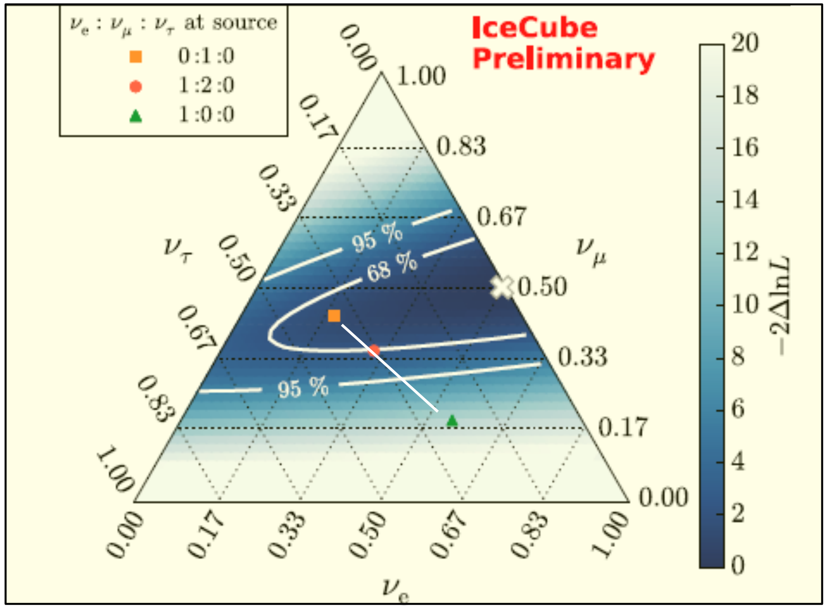


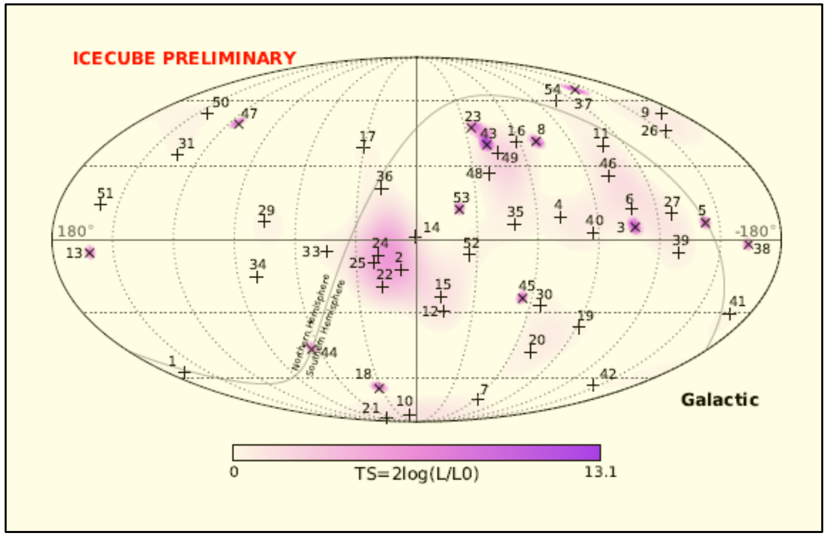
$E^2\Phi_\nu$ =(2.85+-0.9)x10^{-8}GeV/cm^{2}sr s =$E^2\Phi_{WB}$= 3.4x10^{-8}GeV/cm^{2}sr s (2PeV cutoff?).

Consistent with Isotropy,

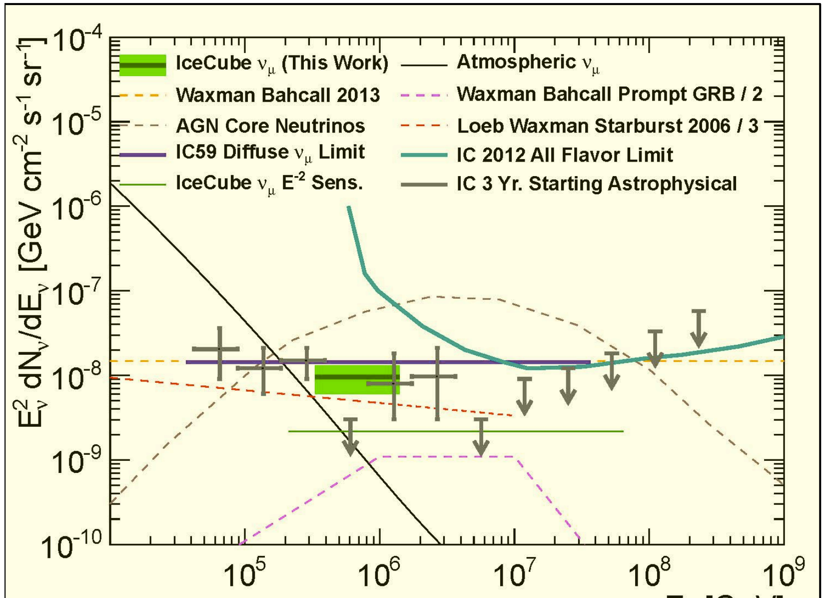
$\nu_e:\nu_\mu:\nu_\tau$=1:1:1 (π deacy + cosmological prop.).

Status: Isotropy, flavor ratio

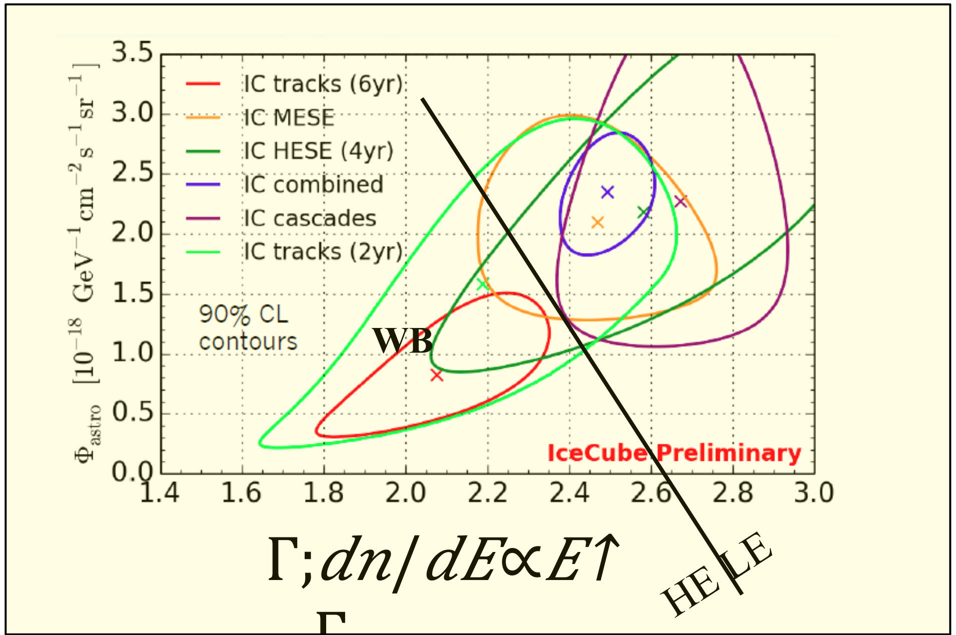




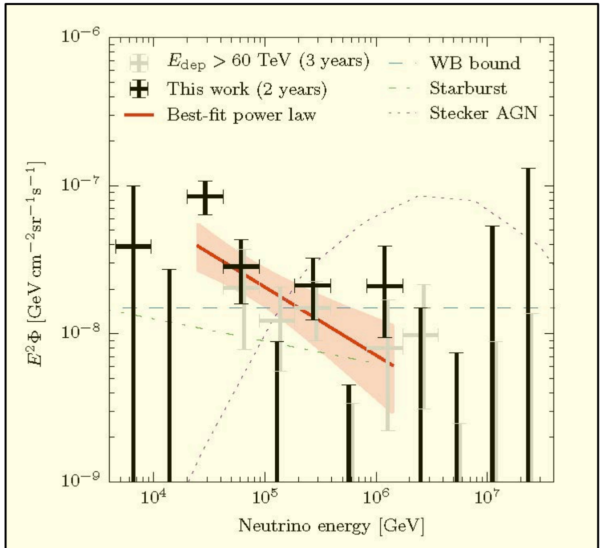
Status: Flux, spectrum



PRL 115, 081102 (2015)



$\Gamma; dn/dE \propto E^{-\Gamma}$

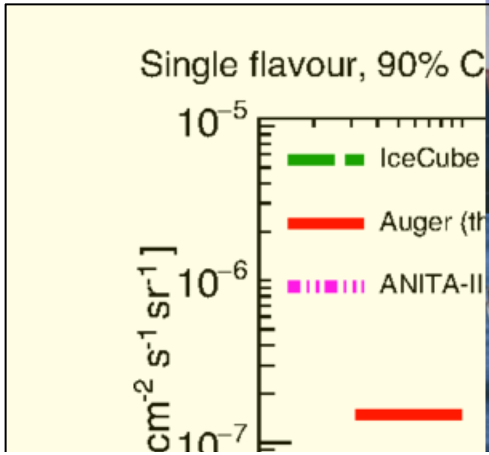


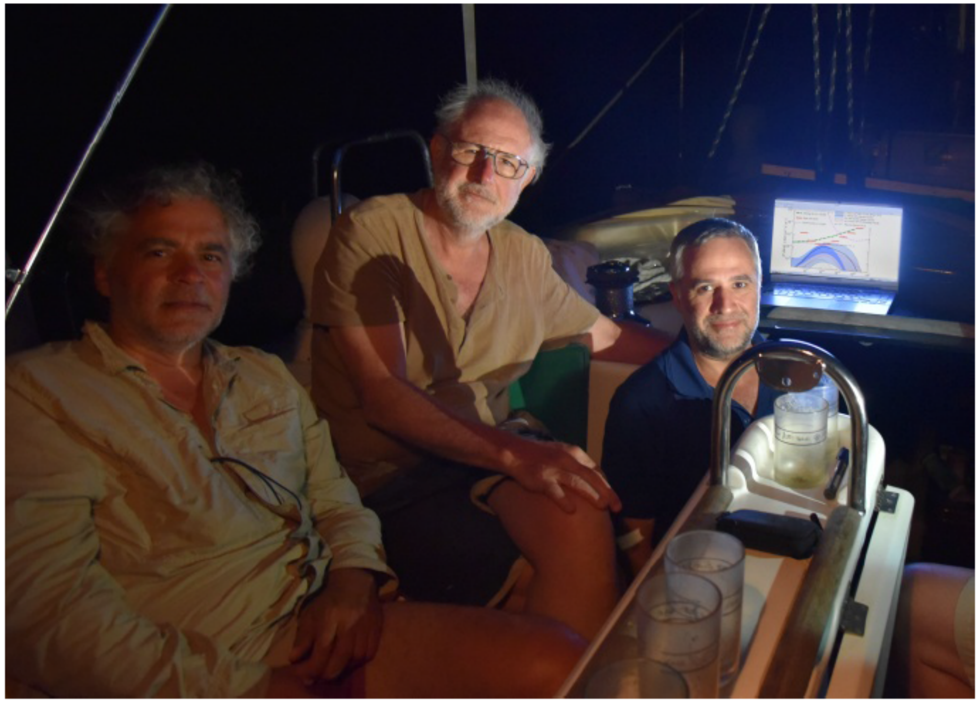
PRD 91, 022001 (2015)

- 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 γ-ray DGE intensity (all sky average) at 1-100GeV
    $E^2\Phi_\gamma \sim 2\times10^{-7}(E_{0.1TeV})^{-0.7}$GeV/cm^{2}s sr,
    extrapolated to IceCube's energy
    $E^2\Phi_\nu \sim 2\times10^{-9}(E_{0.1PeV})^{-0.7}$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):

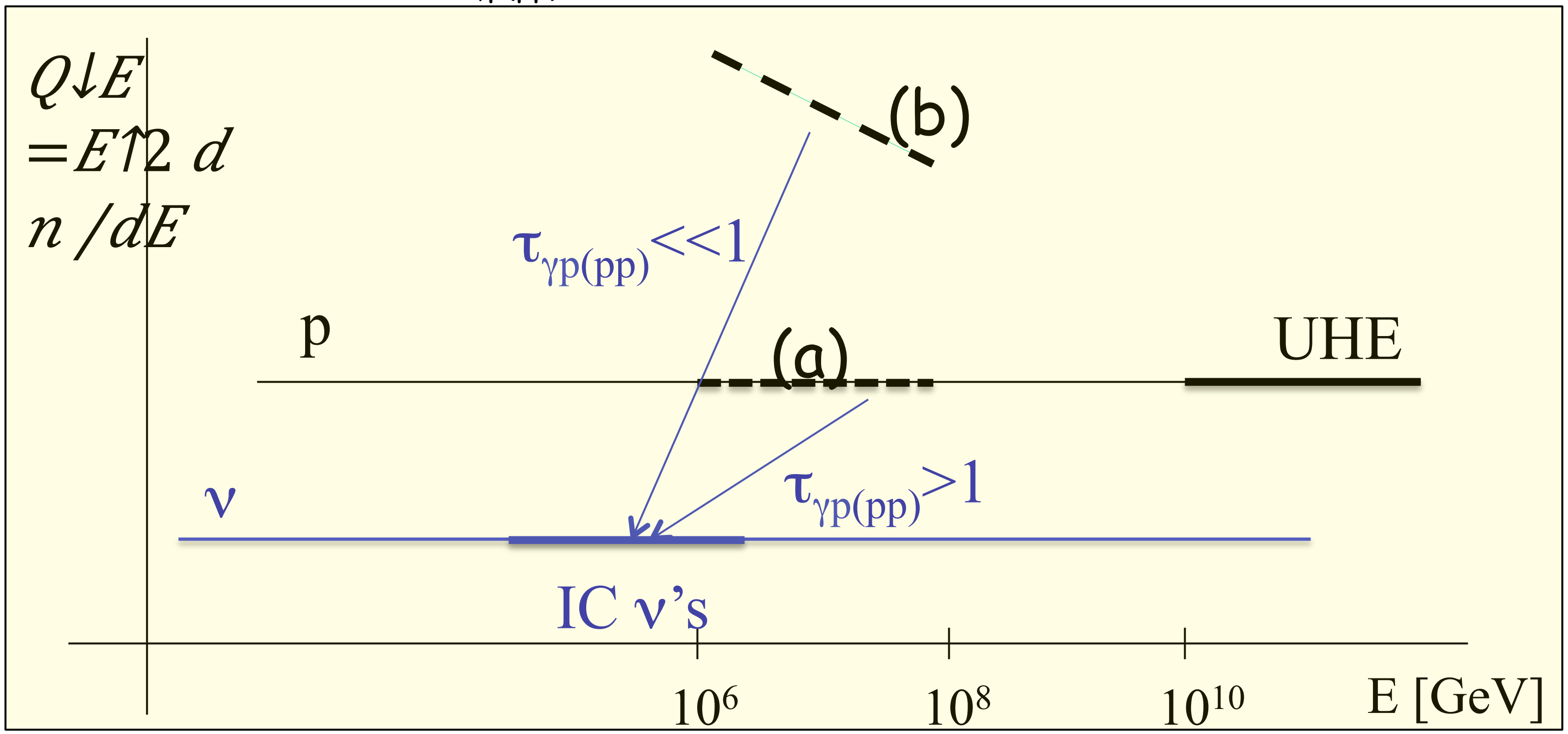
XG UHE p sources, Q_E=Const., residing in (starburst) "calorimeters".

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

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

(b) Q>>Q_{UHE} sources with $\tau_{\gamma p(pp)}$<<1, ad-hoc Q/Q_{UHE}>>1 & $\tau_{\gamma p(pp)}$<<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, $d\log n / d\log E > -2.2$

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

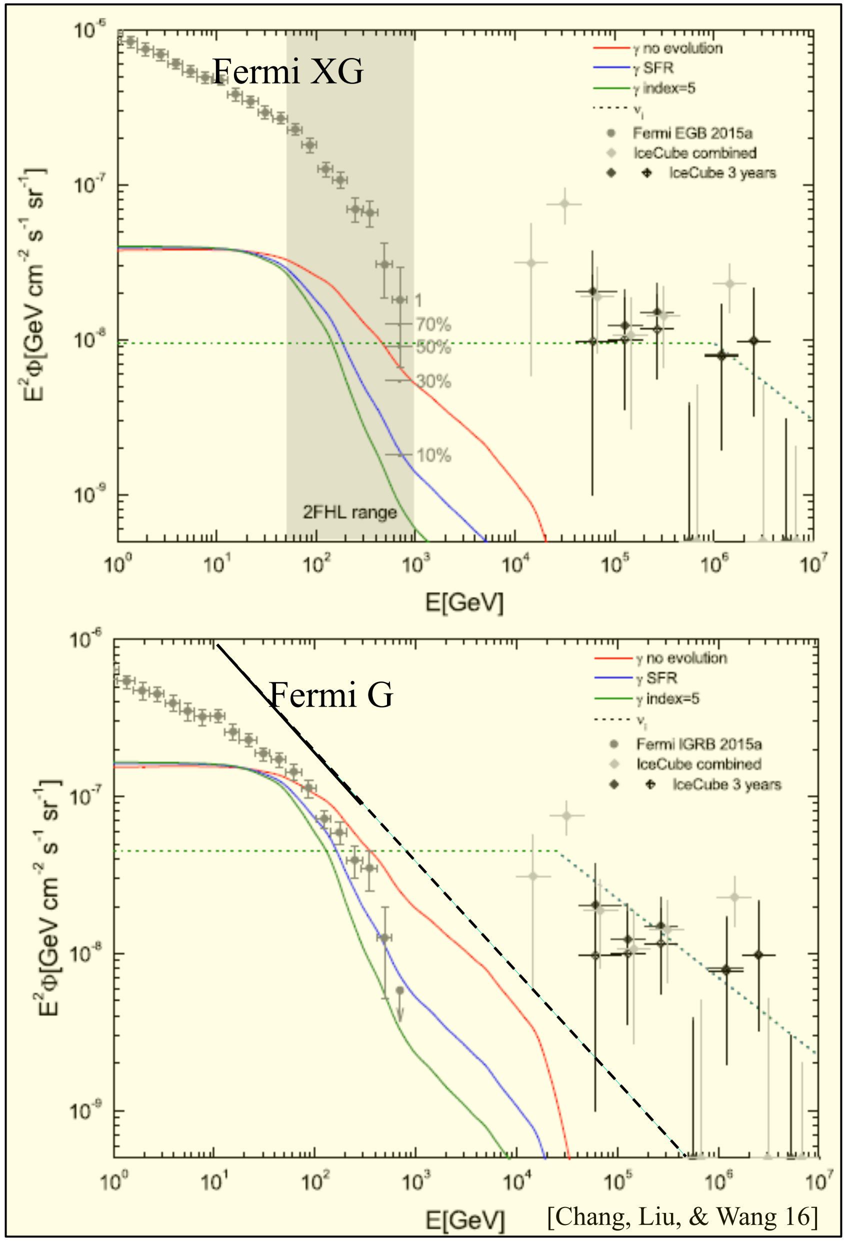
  SFR (or faster) z evolution

  [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].

  If real: new unknown Galactic sources.



[Chang, Liu, & Wang 16]

Identifying the "calorimeters"

- No sources with multiple-ν_μ-events:

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

$$\Longrightarrow n_s > 10^{-7}/\text{Mpc}^3,\quad N(\text{all sky}) > 10^6,\quad L_\nu < 3\times10^{42}\,\text{erg/s}.$$

[Murase & Waxman 16]

- 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}].

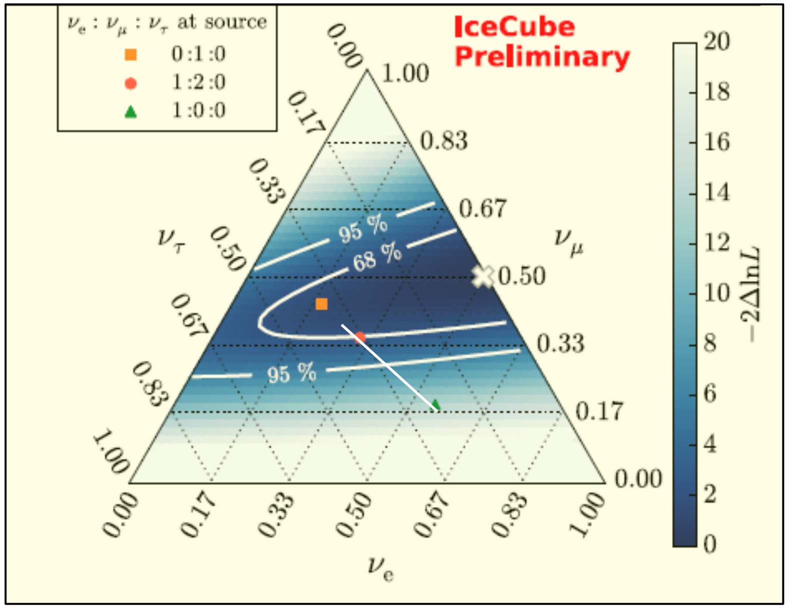
- No $L>10^{14} L_{sun}$ sources to 300Mpc →
  UHECRs are likely produced by transient "bursting" sources.
- Detection of prompt ν's from transient CR sources,
  temporal ν–γ association, requires:
  - Wide field EM monitoring,
  - Real time alerts for follow-up of high E ν events,

  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].

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…]

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

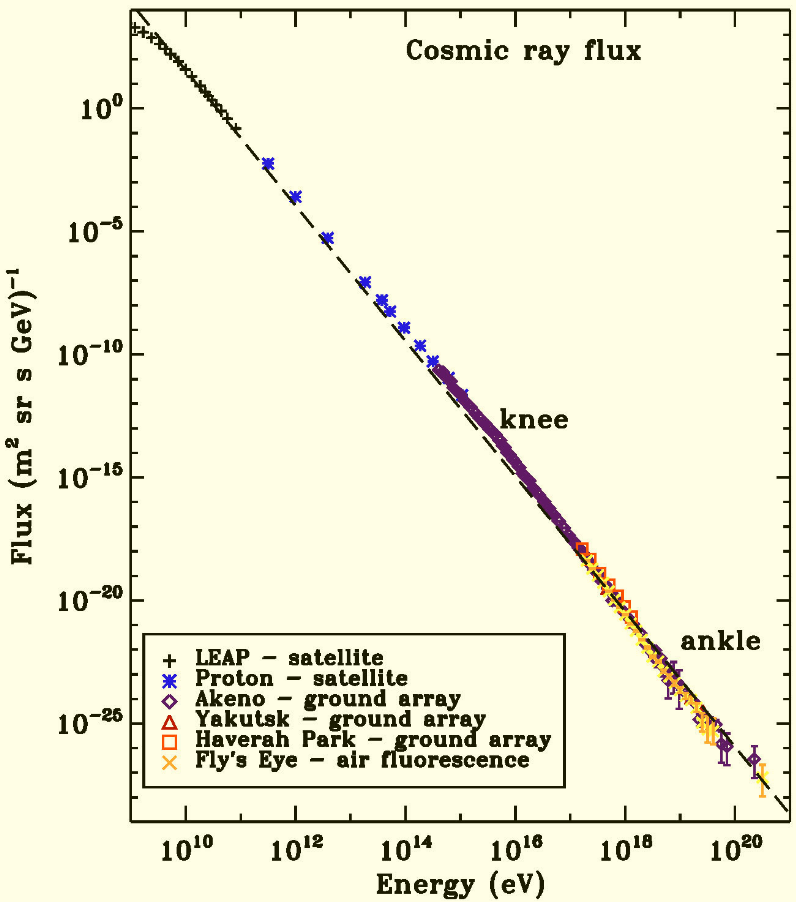
$$Q_E(E \sim 10\text{GeV}, z=0) \approx 5 \left(\frac{0.3}{f_{synch.}} \right) \times 10^{44} \text{erg}/\text{Mpc}^3\text{yr}$$

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

[Katz, EW, Thompson & Loeb 14]

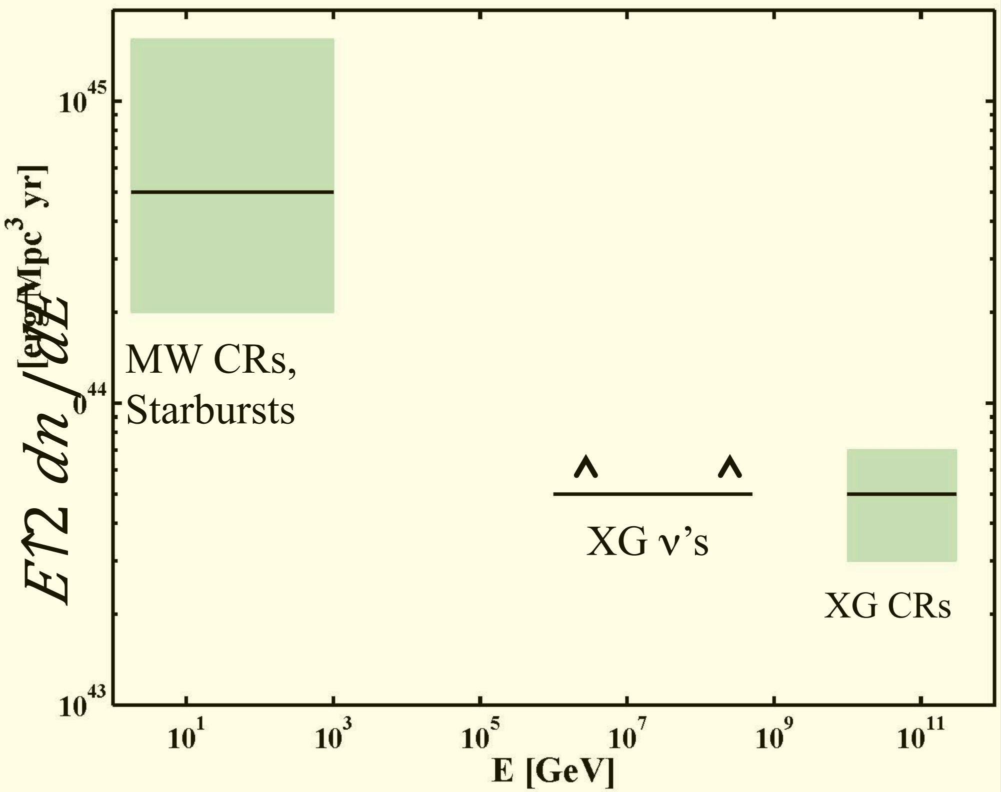
A single cosmic ray source across the spectrum?

Observed spectrum



[From Helder et al., SSR 12]

Generation spectrum



[Katz, EW, Thompson & Loeb 14]

A note on prompt GRB ν's

- Q_γ(z=0) by long GRBs ~ Q(UHE p):

- $R_{z=0} E_\gamma = 10^{52.3\pm0.7}$ $erg/{\sim}1Gpc^3\ yr = 10^{43.3\pm1}$ $erg/Mpc^3\ yr$

- $UHE\ p$: $E^2\ dn/dE = 10^{43.7\pm0.2}\ erg/Mpc^3\ yr$

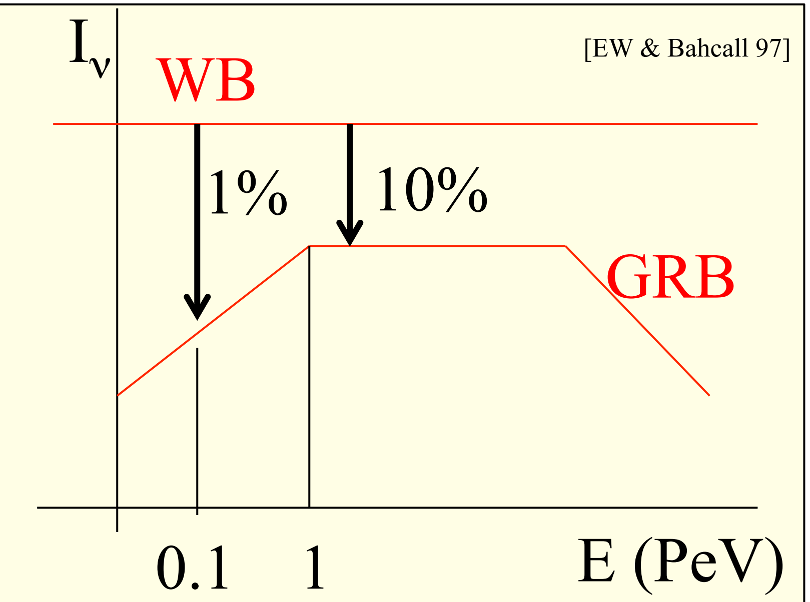
→ $Q(CR-p)/Q(GRB-e) \sim 2.5 \#\ p\ decades/\#\ e\ decades \sim 20/\#\ e\ decades$

[EW 95] .

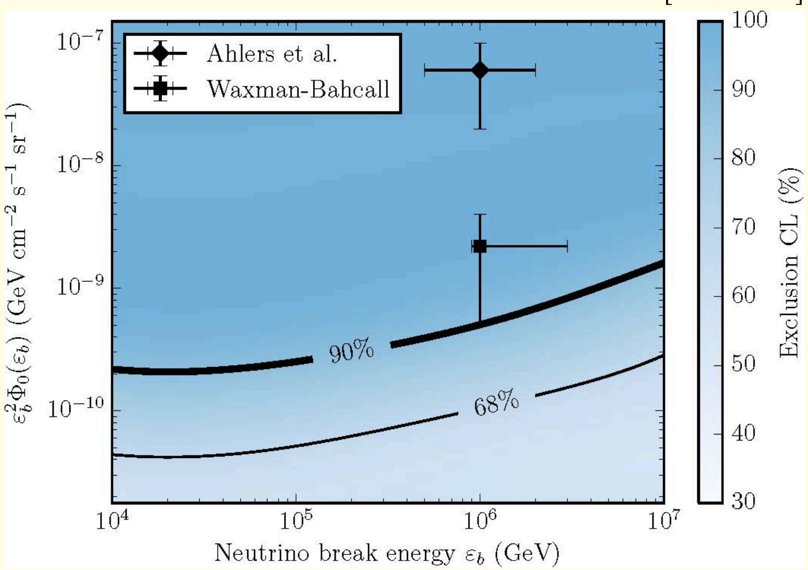
- Prompt ν: 0.01–0.1 Φ_{WB} .

[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



[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, $E^2\, dn/dE \approx Const.$, 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

Acceleration: Max E

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

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

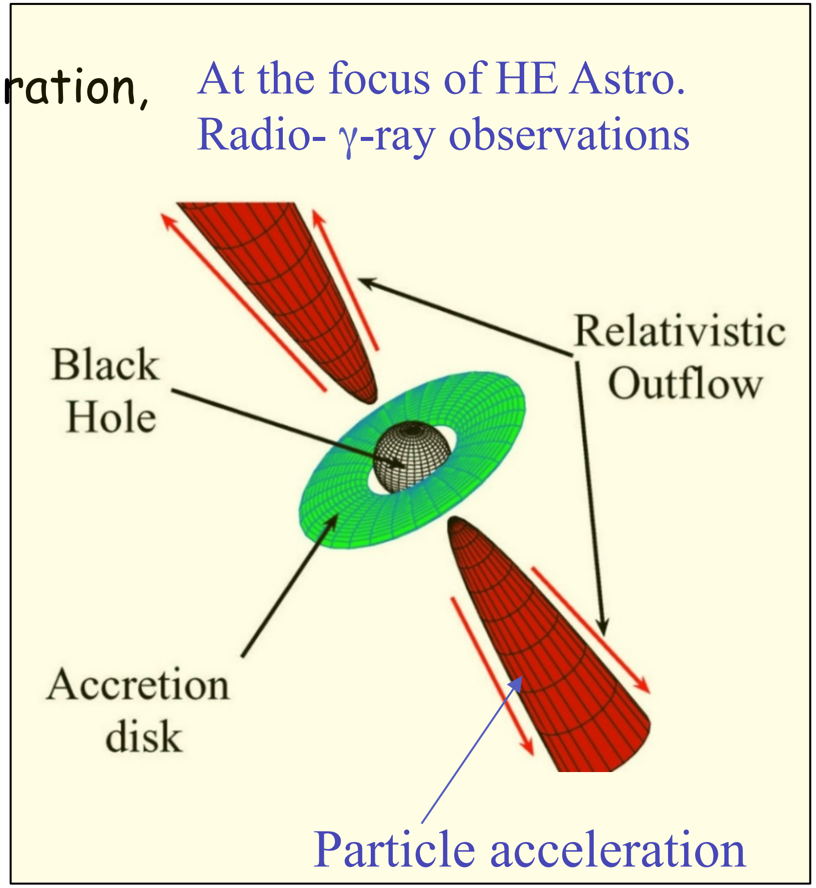
- No $L > 10^{14}\,L_{sun}$ sources to 300Mpc → Transient "bursting" sources.

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

  No $p-\gamma$ association.

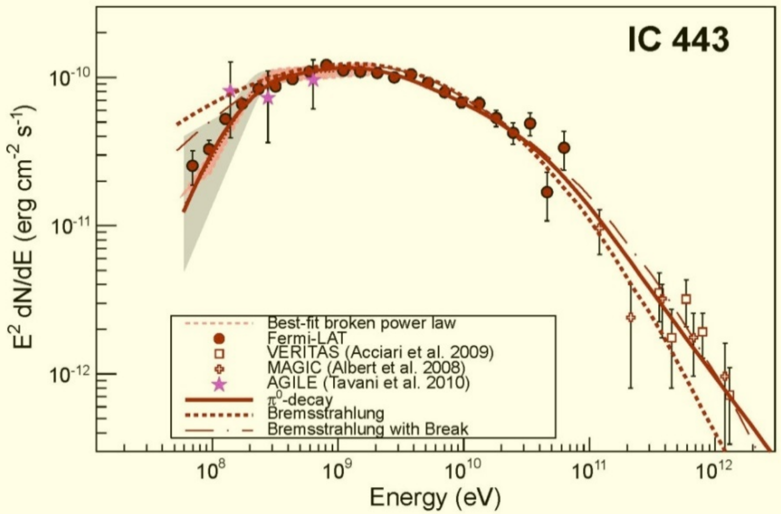
- Candidates- Relativistic jets driven by mass accretion onto BHs.
  - Gamma-ray bursts (GRB), newly formed solar mass BHs;
    [Vietri 95, Milgrom & Usov 95, EW 95]
  - Tidal disruption of stars (TDE) by massive BHs at galaxy centers.
    [Gruzinov & Farrar 09]

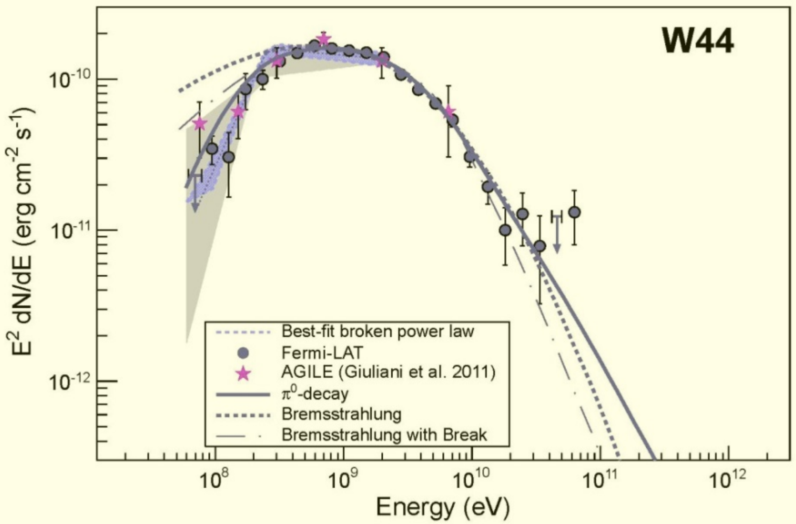
(- Young, ms, 10^{13}G Neutron Stars?
If they exist [Arons 03, Lemoine et al. 15])



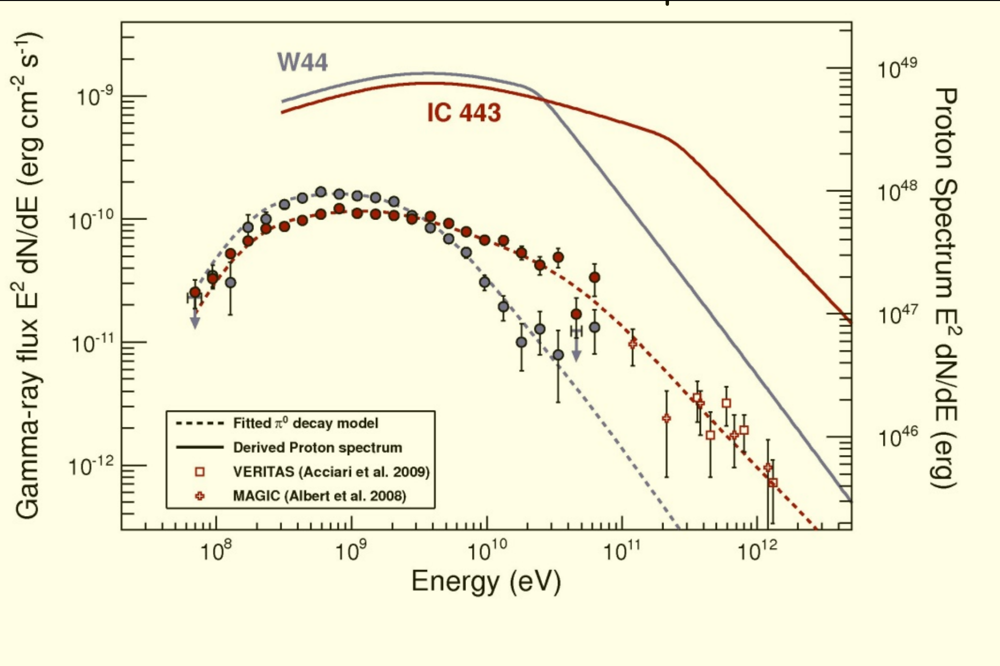
Are SNRs the sources of E<1PeV CRs?

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

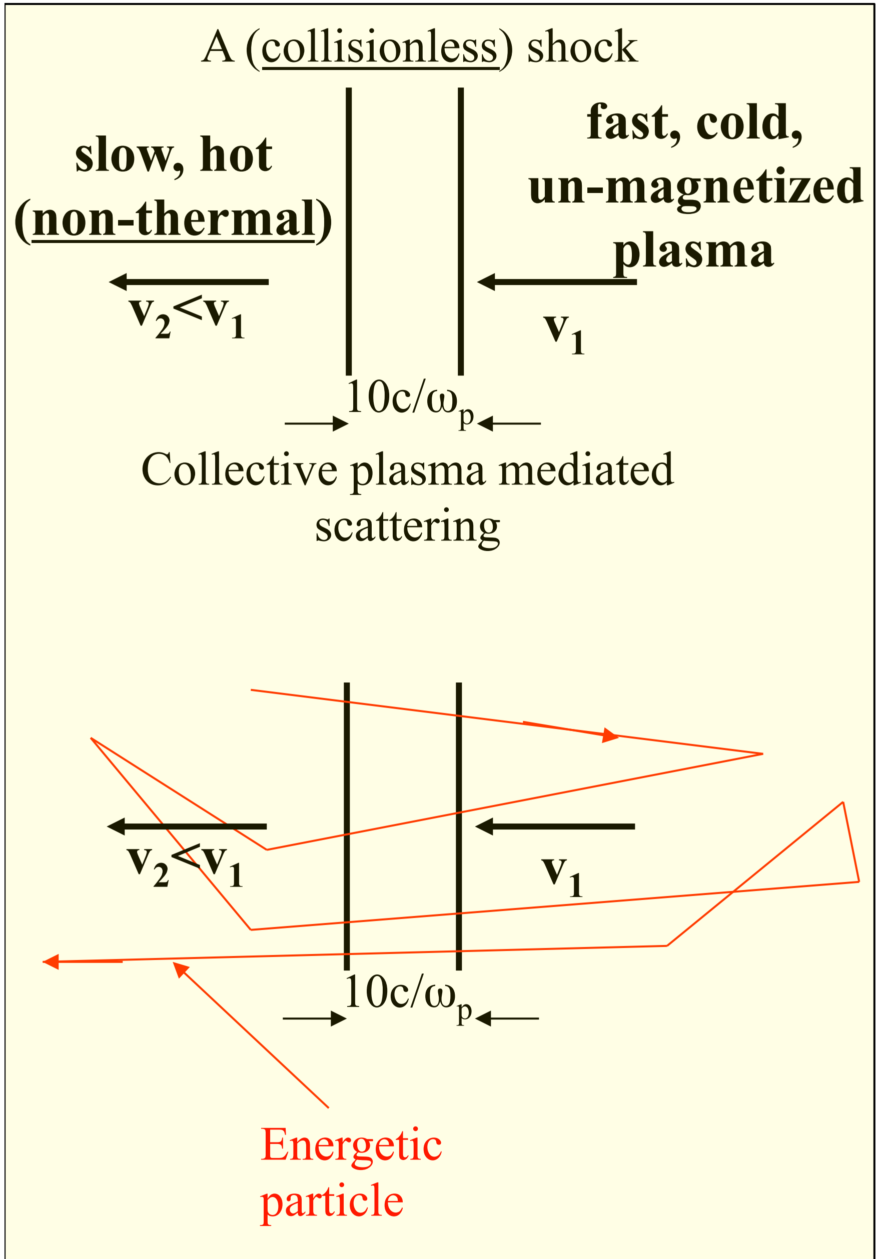




- So far, no direct evidence.
- EM observations- ambiguous.
- Modelling complex (interaction with molecular clouds).
- π^0 interpretation → E_p<100 GeV.



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

$$E^2\, dn/dE \approx Const.,$$

[Krymsky 77; Kehset & EW 05]

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

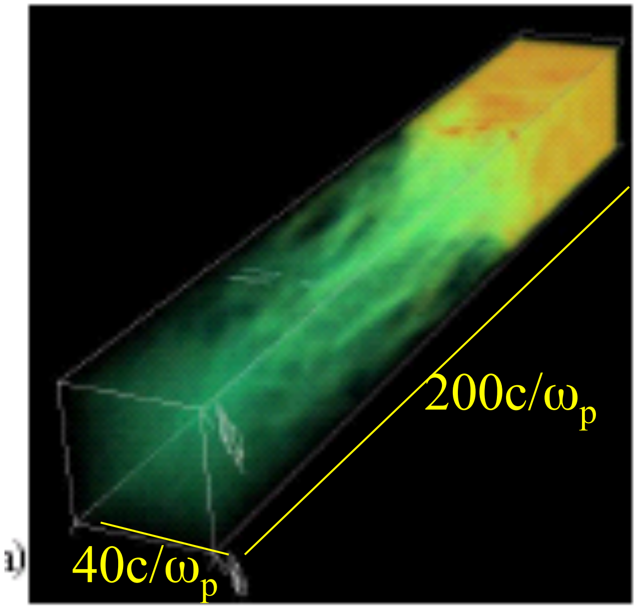
- Supported by basic principles plasma simulations.

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

- [The only predictive model.]

Collisionless shocks: Plasma simulations

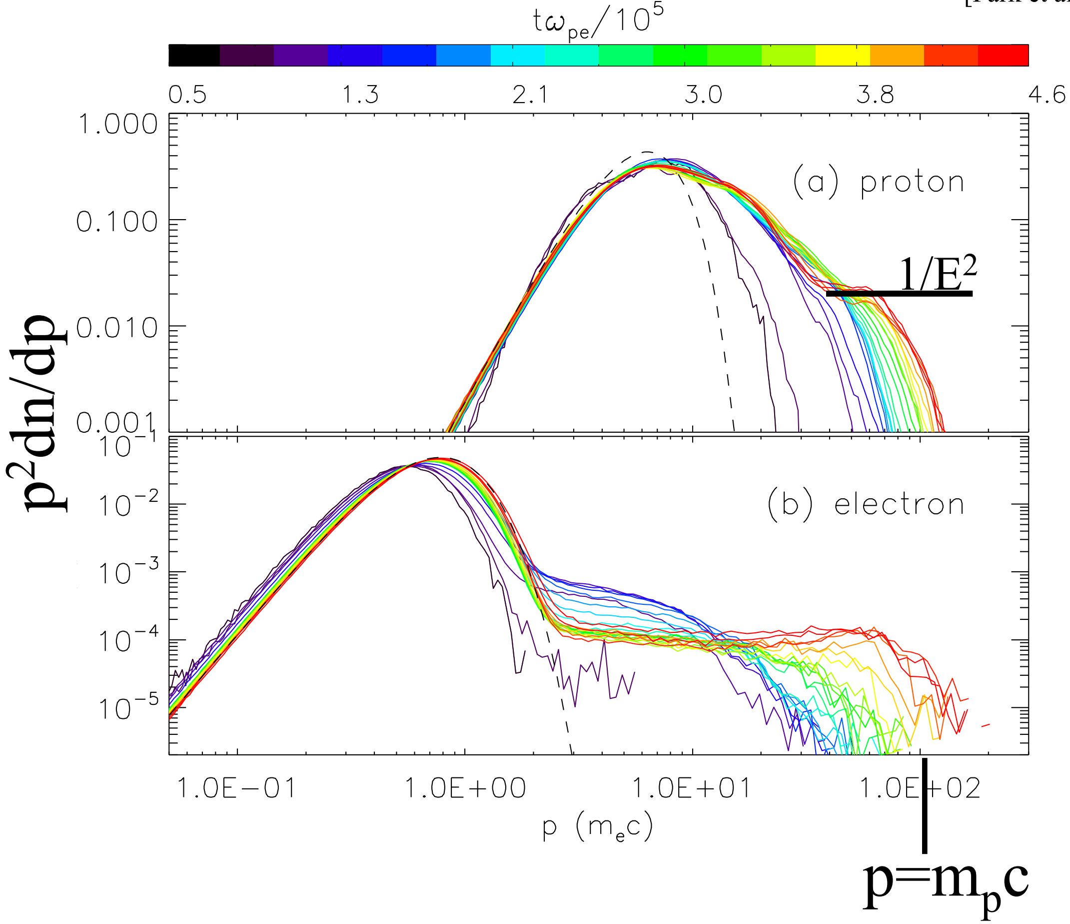
3D, $m_p/m_e=1$



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

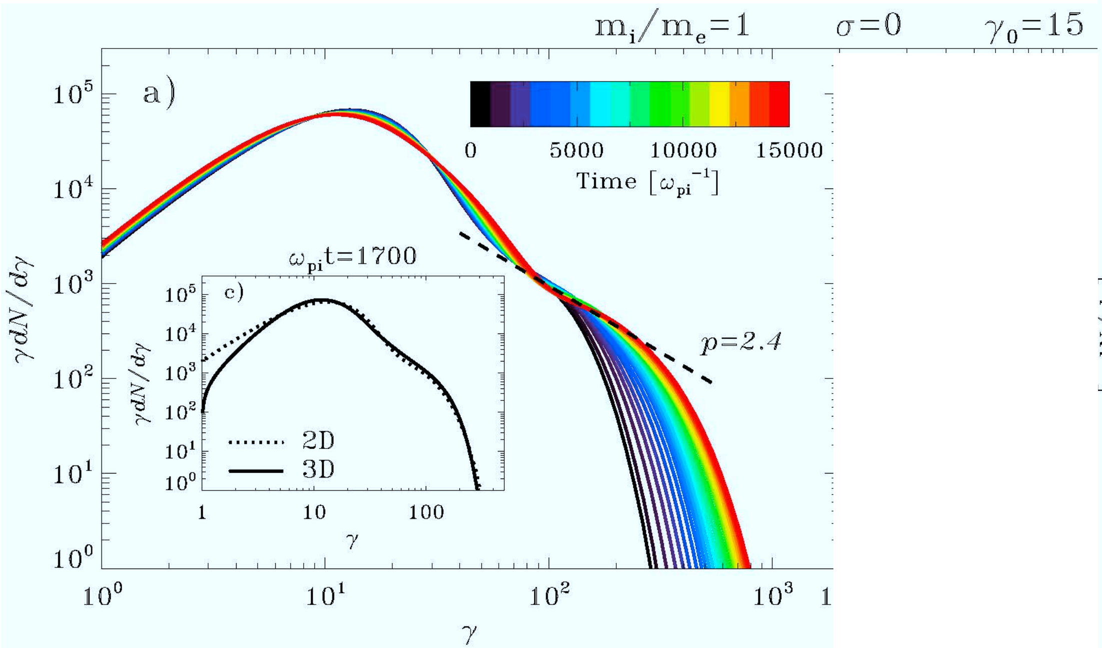
1D, $m_p/m_e=100$, $L=10^3 c/\omega_p$

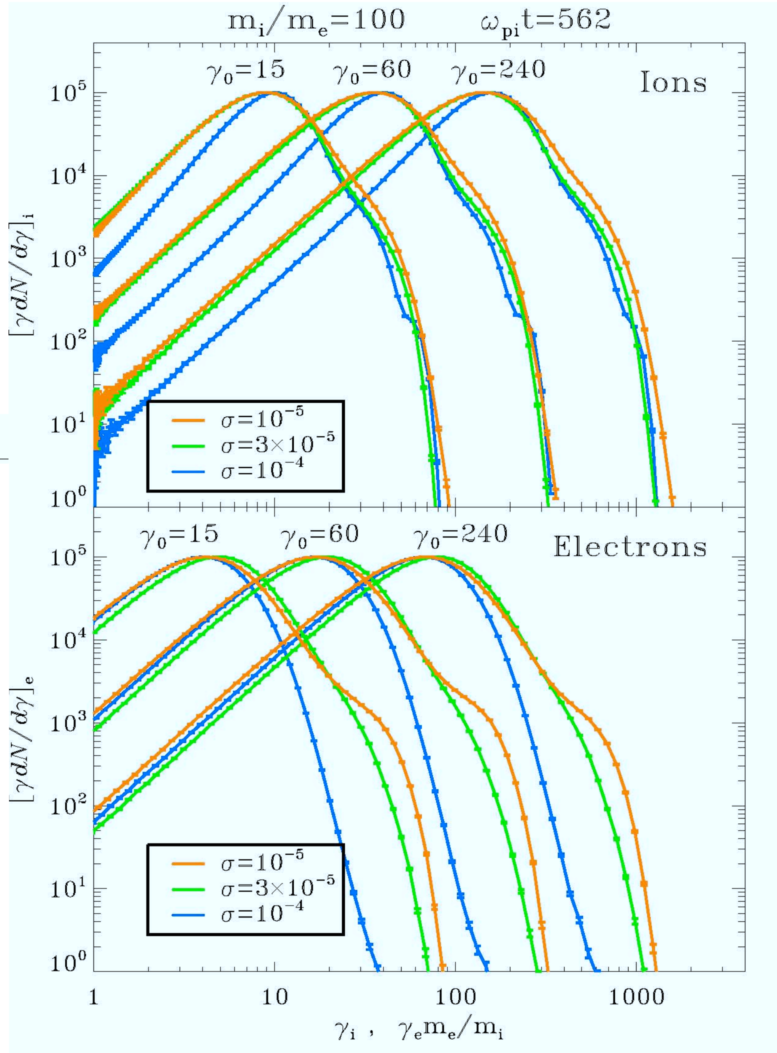
[Park et al. 15]



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

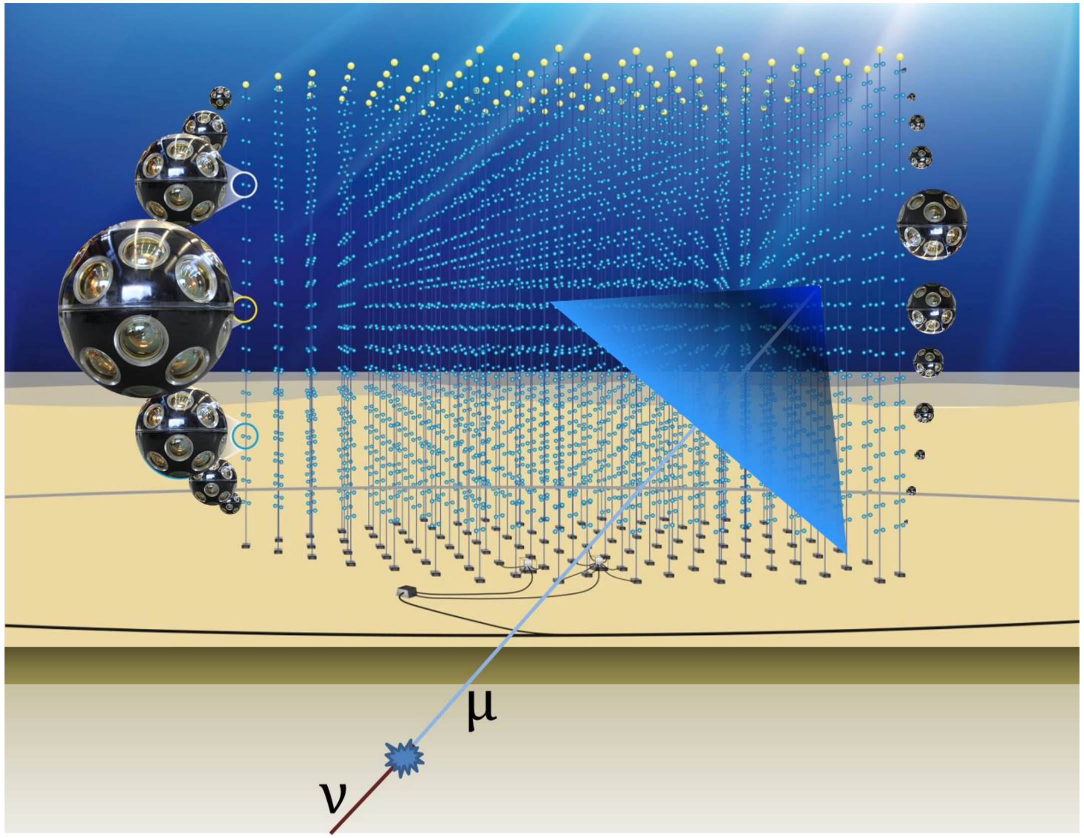
- π decay → ν_e:ν_μ:ν_τ = 1:2:0 (propagation)→ ν_e:ν_μ:ν_τ = 1:1:1

- 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.

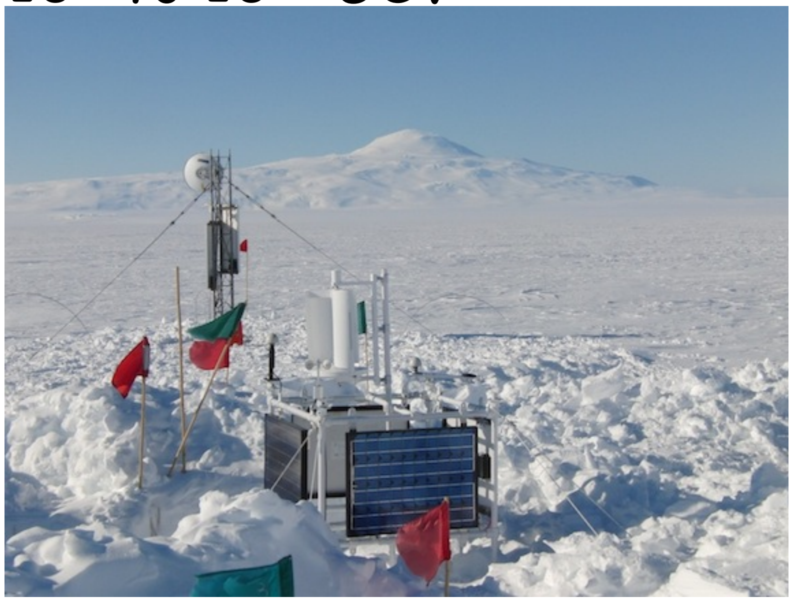
- p(A)-γ: $\varepsilon_\nu/\varepsilon_p$~ (0.1—0.5)x(1/4)~0.05;
  - Requires intense radiation at ε_γ>A keV;
  - Comparable particle/anti-particle content,
    ν_e excess if dominated by Δ resonance (dlog n_γ/dlog ε_γ<-1).

Future experimental developments

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



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



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 $\Sigma\downarrow disk > 0.03\ g/cm\uparrow 2$ $\equiv$ *"starburst".*

- Most of the stars in the universe were formed in galaxies with high SFR.
  If Q_{CR}~SFR Then $\Phi_\nu(\varepsilon_\nu<1PeV) \sim \Phi_{WB}$ [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

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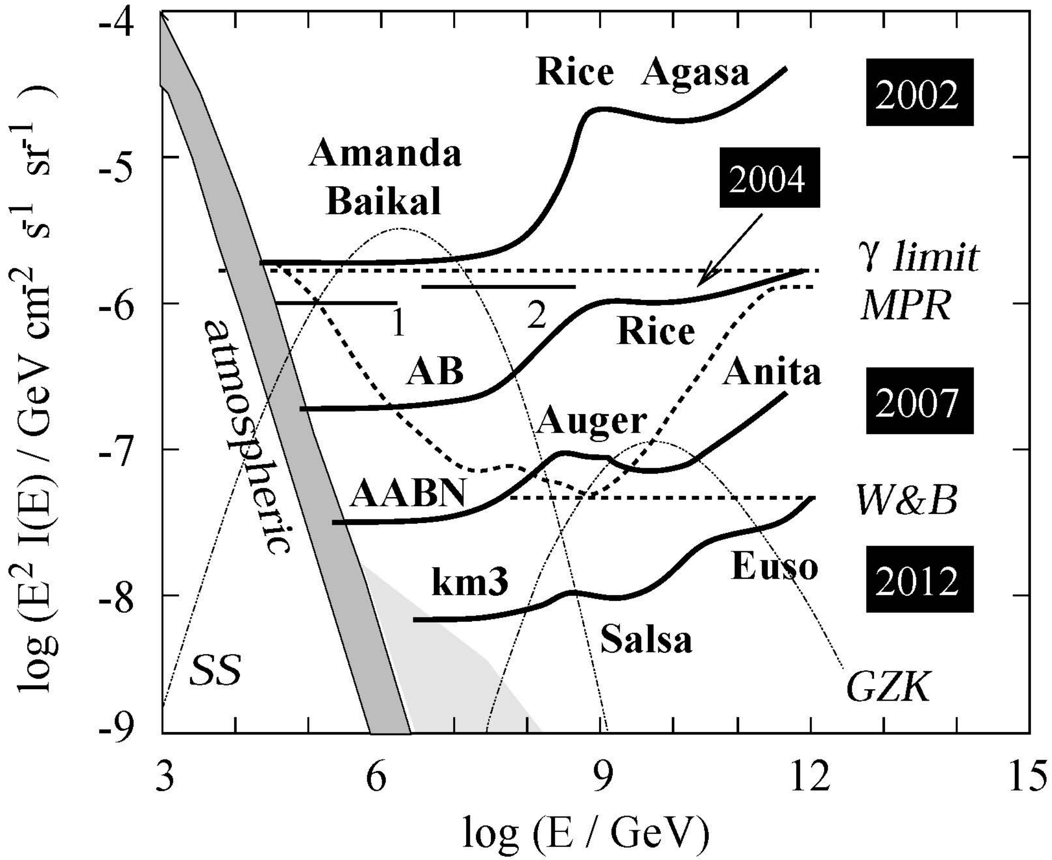

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MeV- GeV Achievements:

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*".