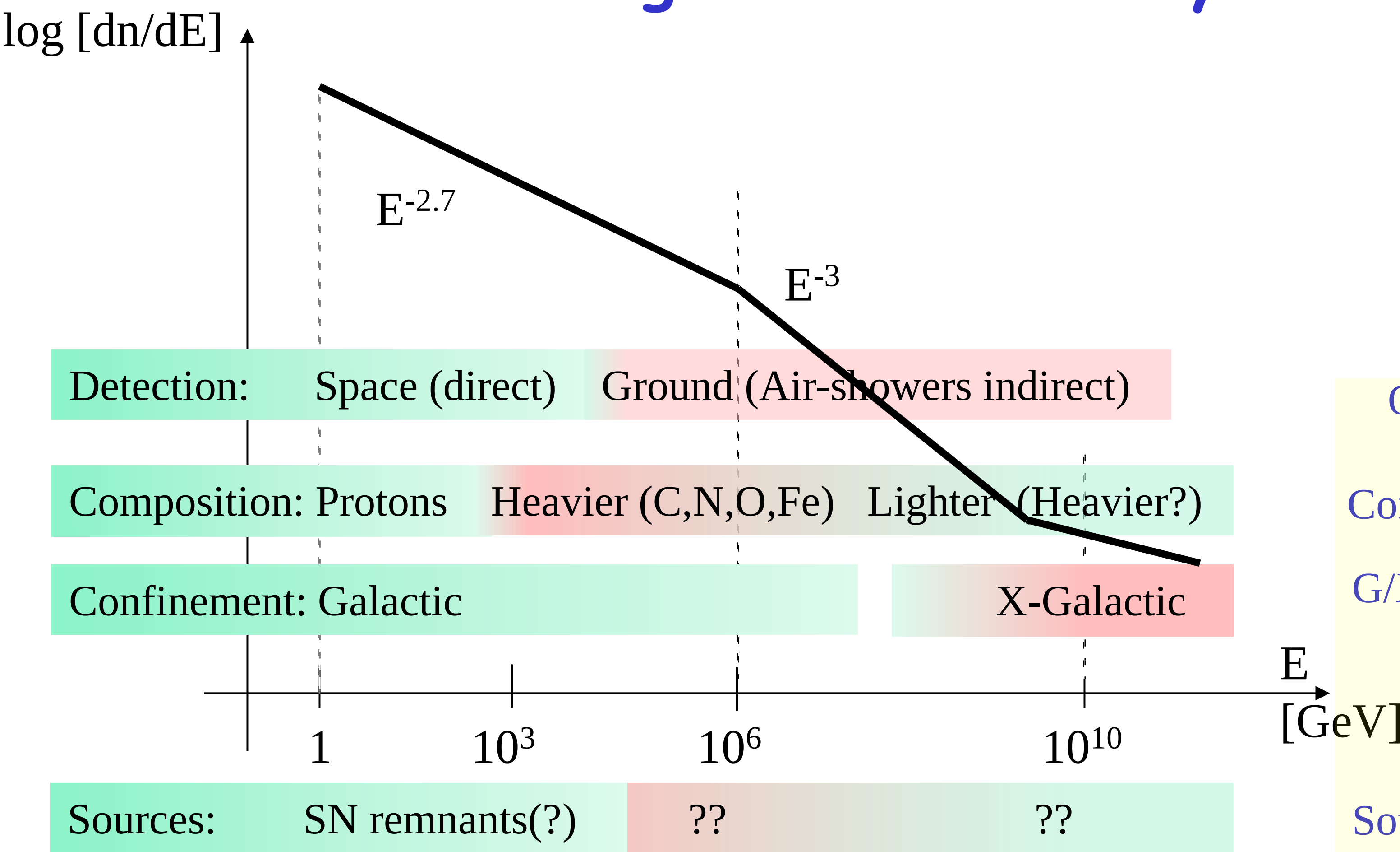
High energy neutrino astronomy
What we have learned and the way forward

Eli Waxman
Weizmann Institute of Science

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?

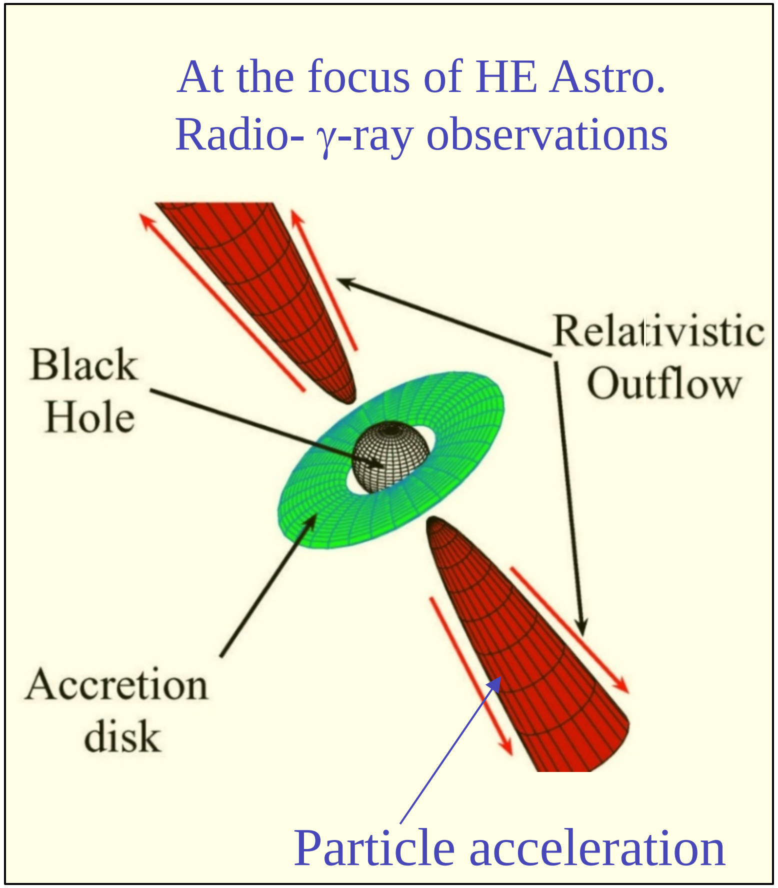
[Reviews: Helder, et al. 12; Lemoine 13]

The acceleration challenge

- EM acceleration: $L > 10^{12} \frac{\Gamma^2}{v/c} \left(\frac{E/Z}{10^{11}\mathrm{GeV}}\right)^2 L_{\mathrm{sun}}$.

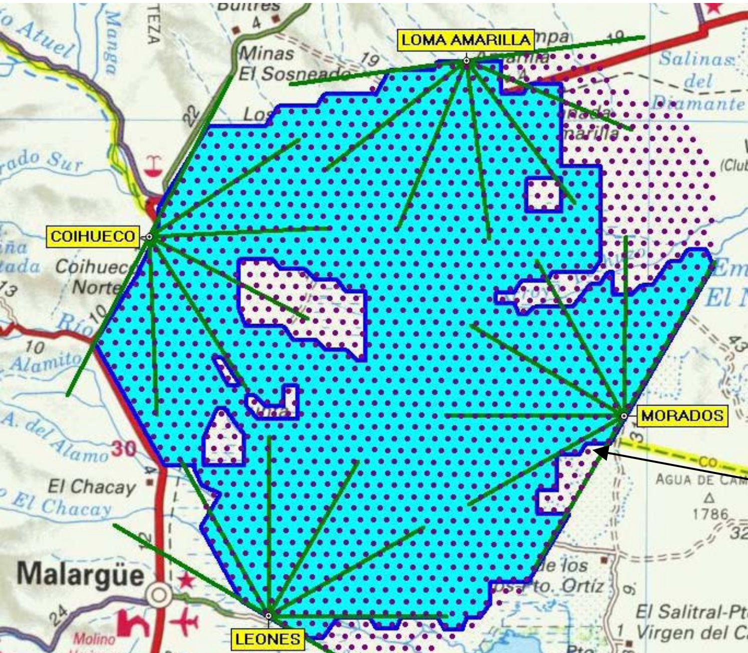
[Lovelace 76; EW 95; Norman et al. 95; Lemoine & EW 09]

- $Z > 10$ - Multiple candidates,
- P - Transient $L > 10^{12} L_{\mathrm{sun}}$ sources
  (No steady $L > 10^{12} L_{\mathrm{sun}}$ at d<300Mpc):
  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,
    may produce "GRB-like" jets.
    [Gruzinov & Farrar 09,Wang & Liu 16]



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

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

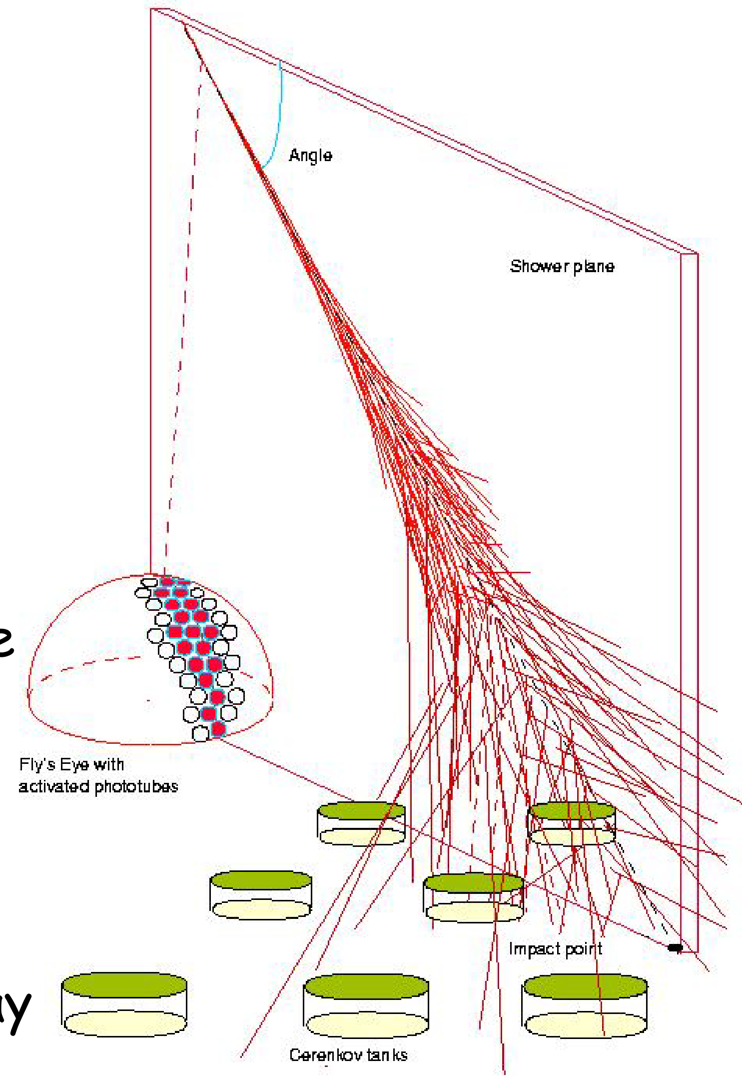


$J(>10^{11}\text{GeV}) \sim 1 / 100\ \text{km}^2\ \text{year}\ 2\pi\ \text{sr}$

Auger: 3000 km^2

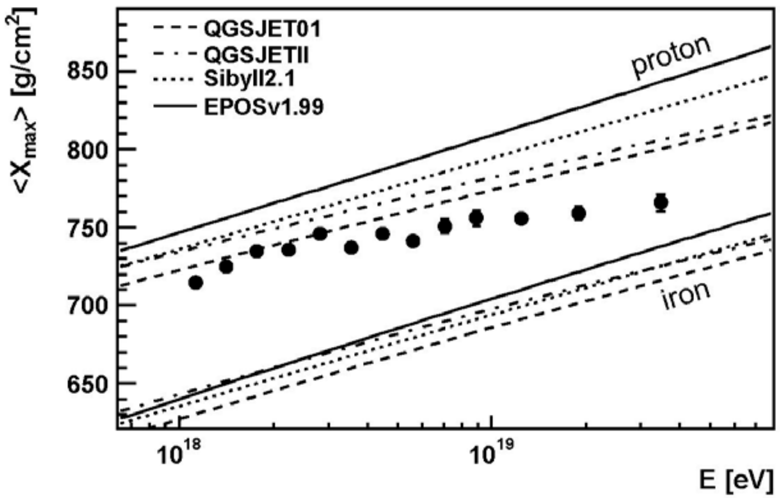
Fluorescence detector

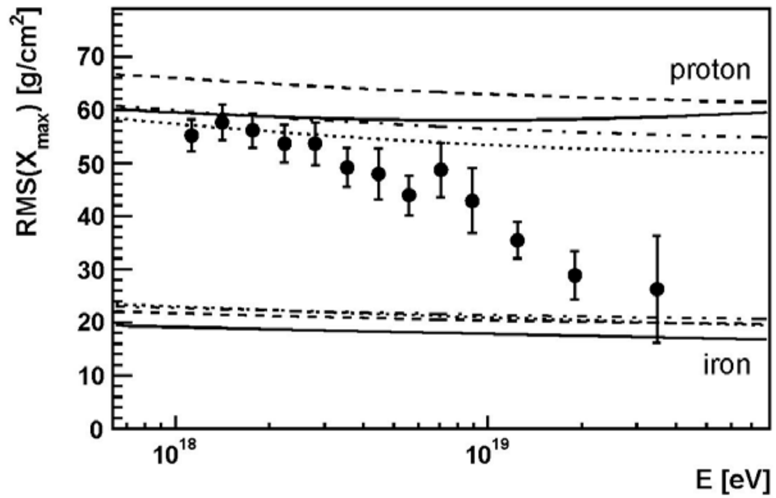
Ground array



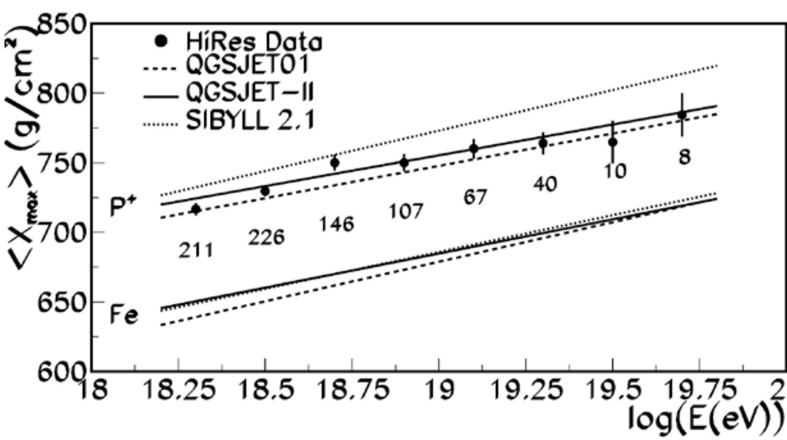
UHE: Air shower composition constraints

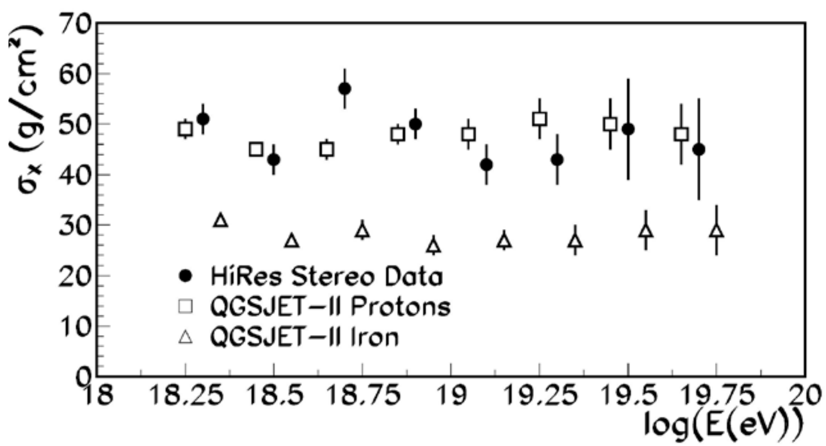
Auger 2010





HiRes Stereo 2010



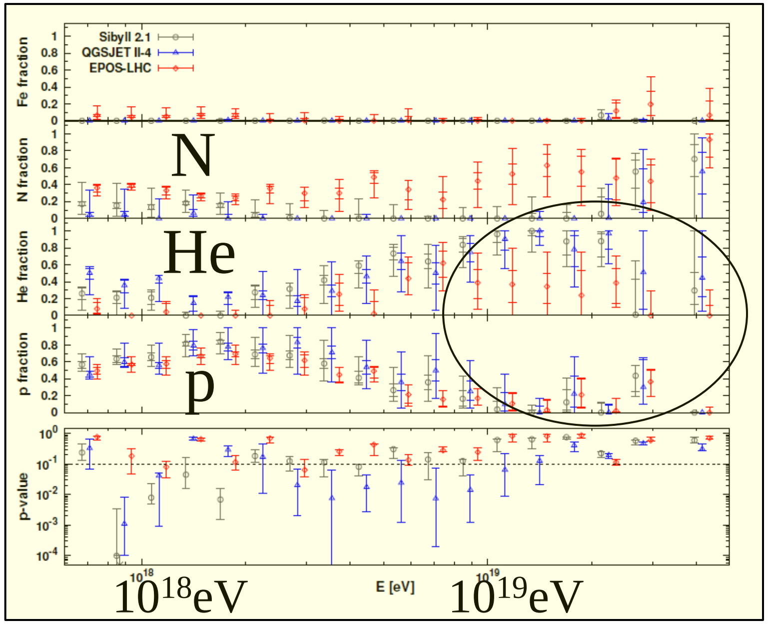


UHE: Air shower composition constraints

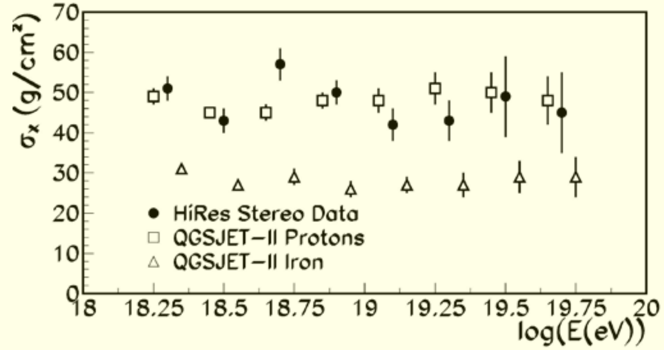
- Discrepancy between experiments.

- Air-shower analyses inconclusive:
  - Models inconsistent with data (X_{max} dist., muons);
  - Large uncertainties within used models;
  - ~25% uncertainty at E_{CM}>100TeV corresponds to N ←→ H.

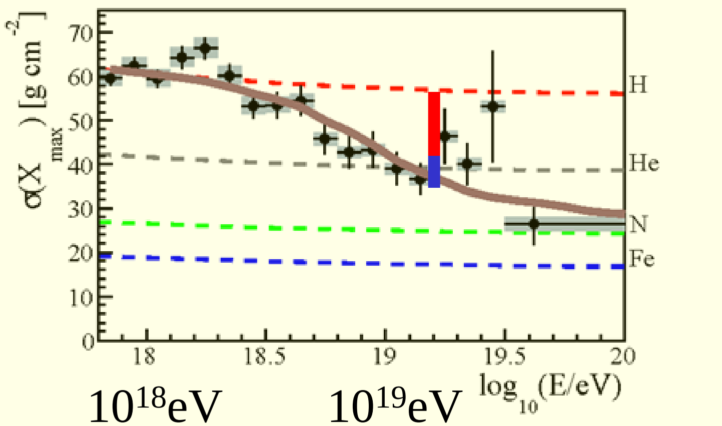
[e.g. Ulrich, Engel & Unger 11]



HiRes Stereo 2010: p



Auger 2015: p/He/N [??]



— 25% σ & elasticity uncertainty
— exp. sys. uncertainty

$>10^{10}$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

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

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

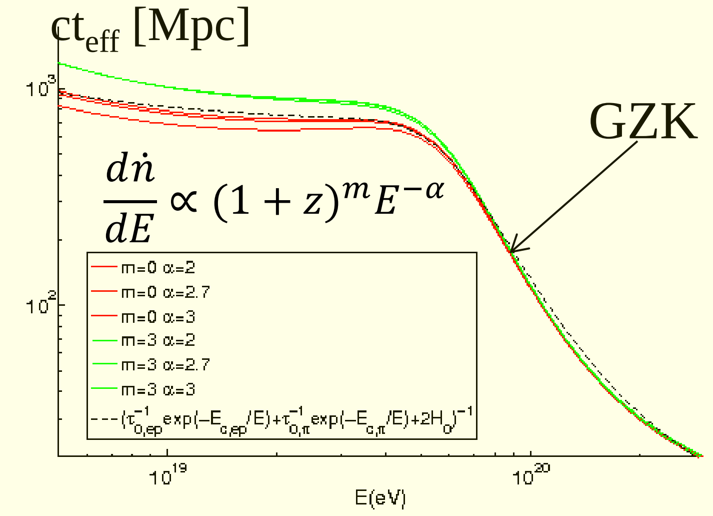
  - Modified by p-GZK suppression.

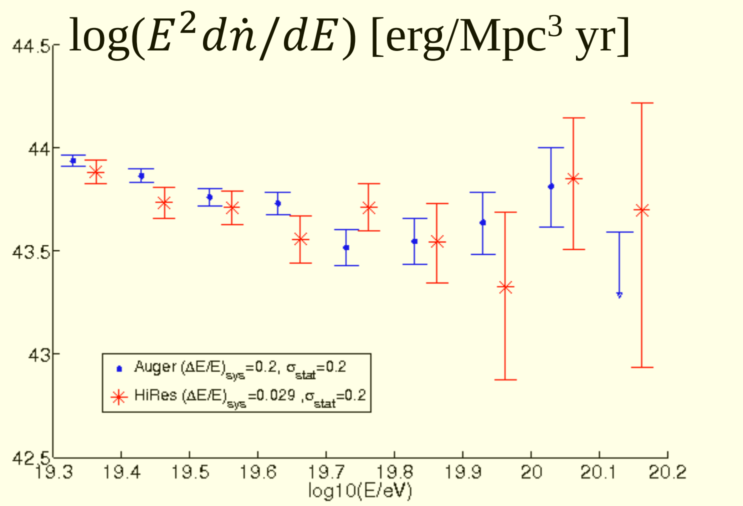
- G-XG transition @ ~10^{10}GeV.

- $1/E^2$ spectrum:
  - Observed in a wide range of systems,
  - Obtained in EM acceleration in collision-less shocks (the only predictive acceleration model).

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

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





UHE p-sources & GRB's

UHE p source requirements	GRBs' characteristics
Transient	1-100s long ✓
$L > 10^{12}\Gamma^2 L_{\text{Sun}}$	$\Gamma \sim 10^{2.5}$ & $L \sim 10^{19}\, L_{\text{Sun}}$ ✓
$E^2 \frac{d\dot{n}}{dE} = 5 \times 10^{43} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$	$Q(\text{MeV}\,\gamma, z = 0) = 10^{43.3\pm1} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$ ✓

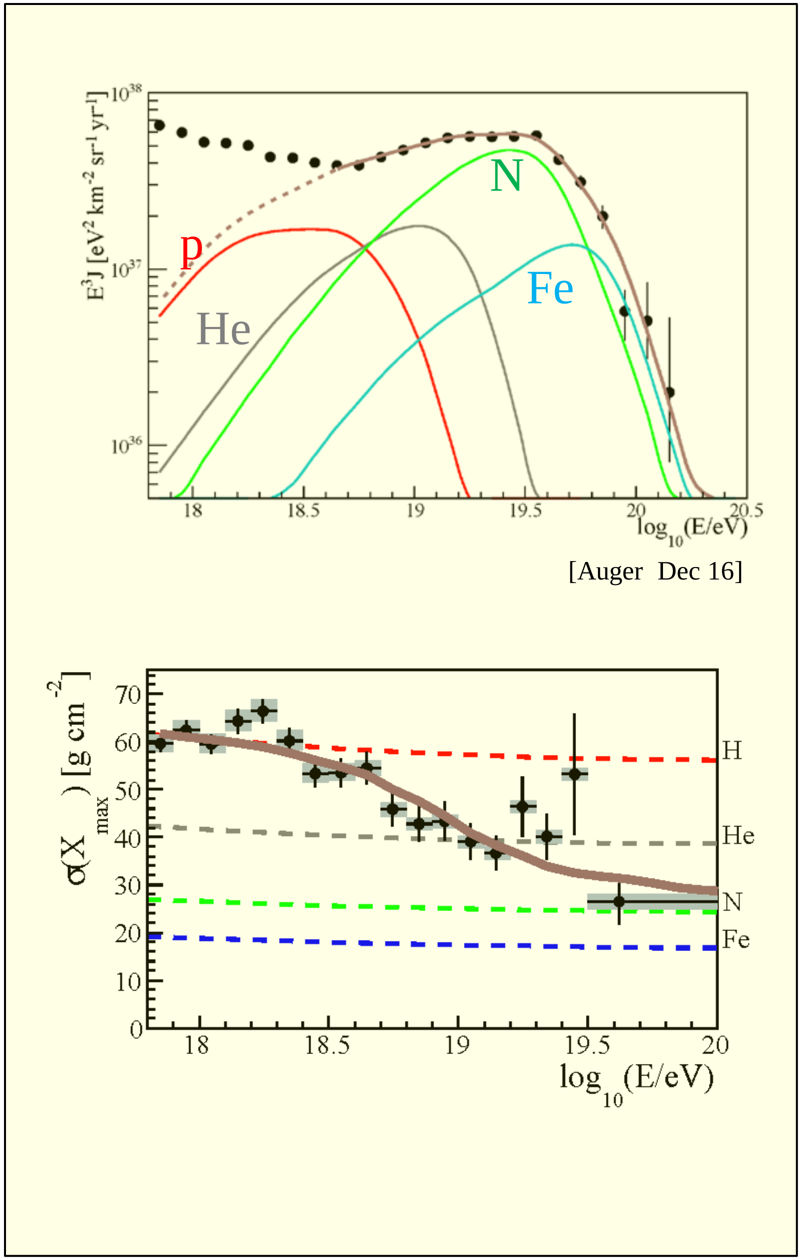
[EW 95]

A mixed composition?

- Model:
  - "Cutoff" @ $\frac{E}{Z/10} = 5 \times 10^{10}\mathrm{GeV}$,
  - Acceleration: $E^2 \frac{d\dot{n}}{dE} \propto E$,
  - Composition @ source:
    H : He : N = 10% : 60% : 30%.

- Challenges:
  - The suppression at $10^{19.5}$eV is due to the acceleration process, a coincidence with p-GZK.
  - Unknown acceleration process.
  - Unexpected plasma composition.

- But, cannot be ruled out.



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,

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

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

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

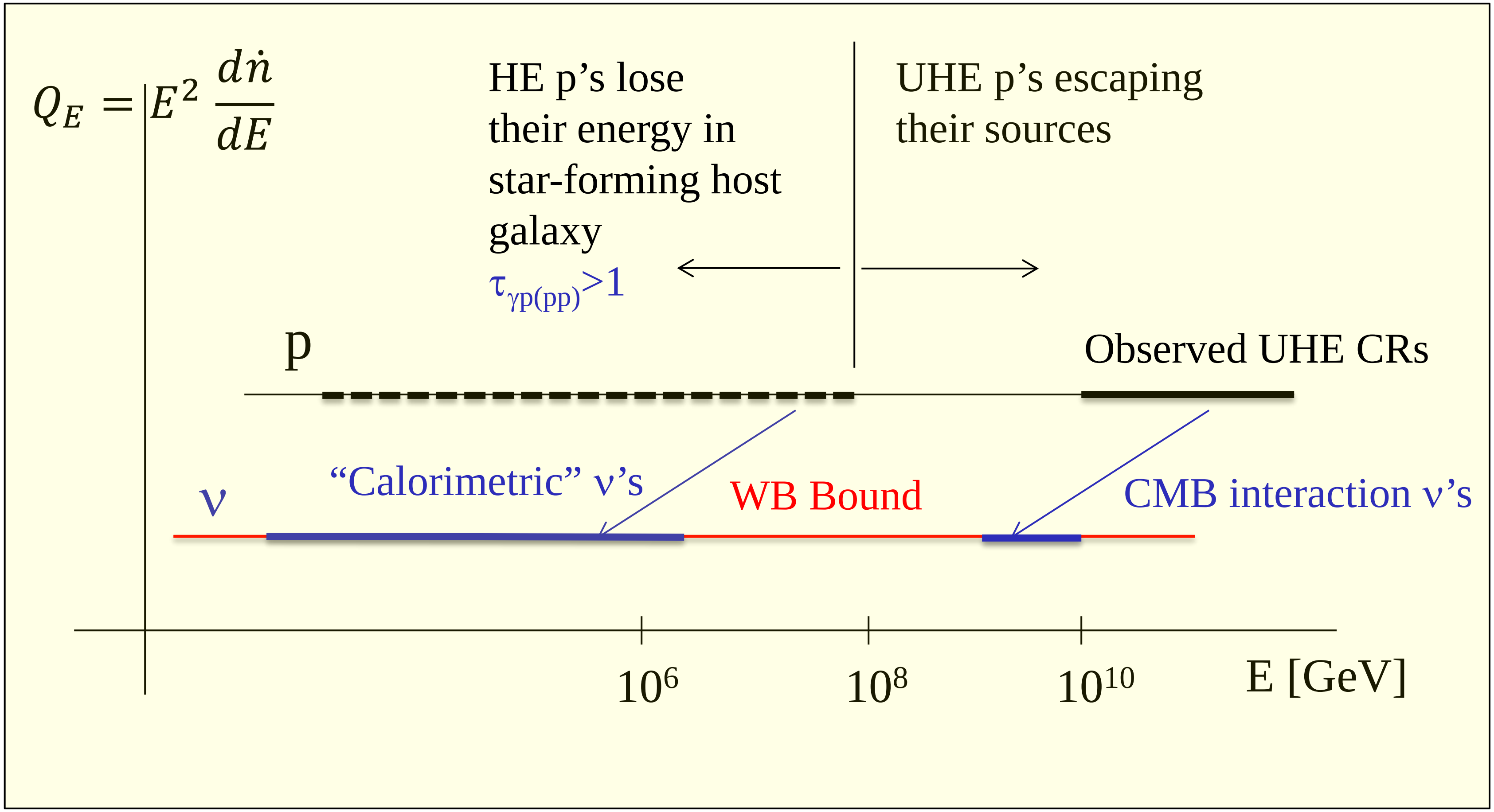
[EW & Bahcall 99; Bahcall & EW 01]

- 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.

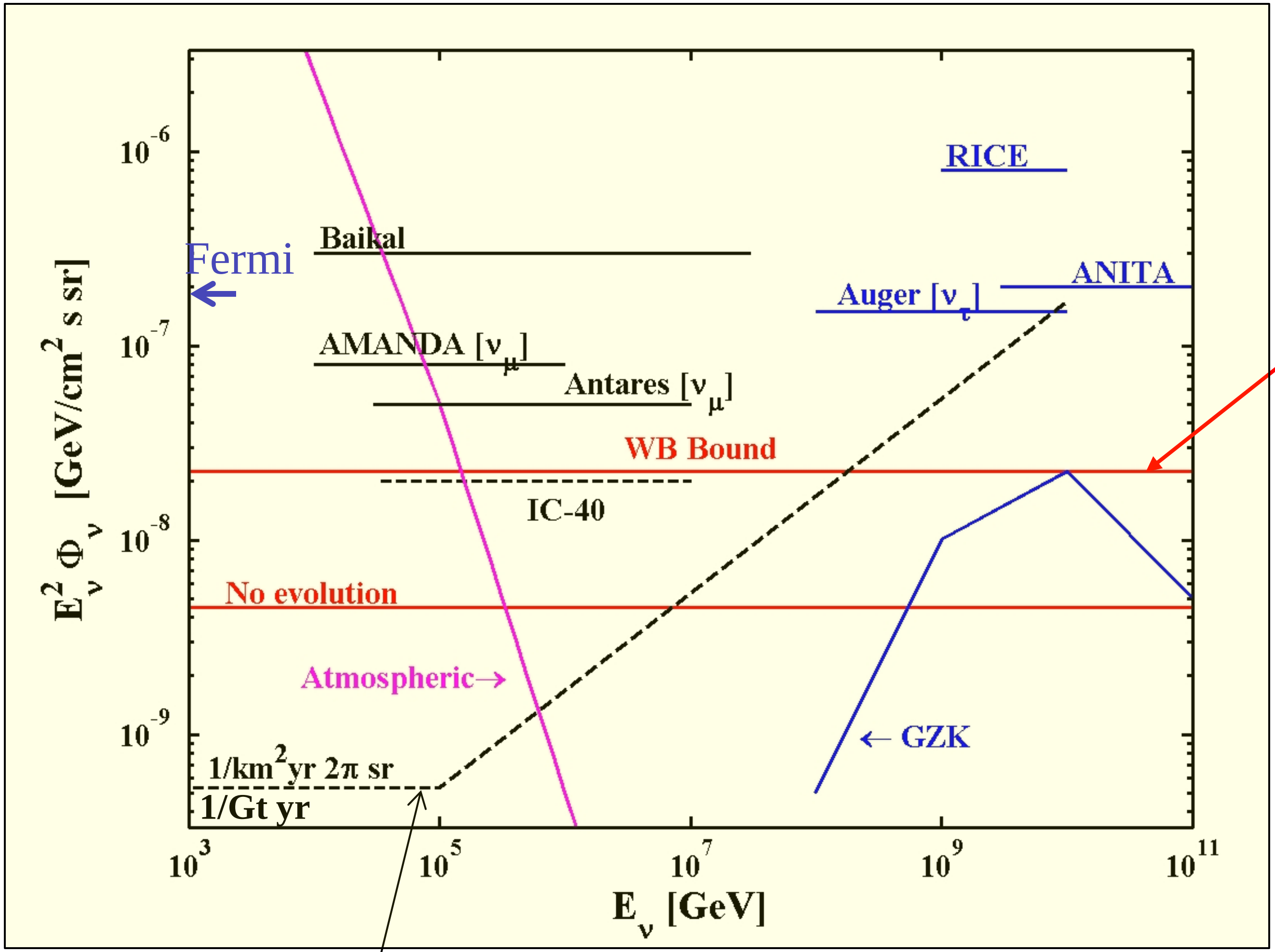
    Most stars formed in rapidly star-forming galaxies,
    which are p "calorimeters" for E_p<~10^6GeV,
    all p→π by pp in the inter-stellar gas, $t_{pp} < t_{\rm conf}(E < 10^6\,{\rm GeV})$.

[Loeb & EW 06]

HE ν: predictions



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

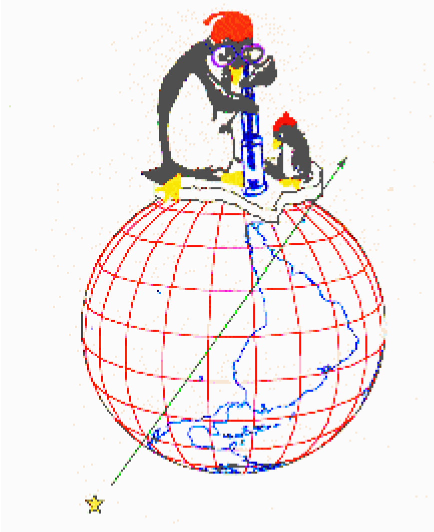


2 flavors,

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

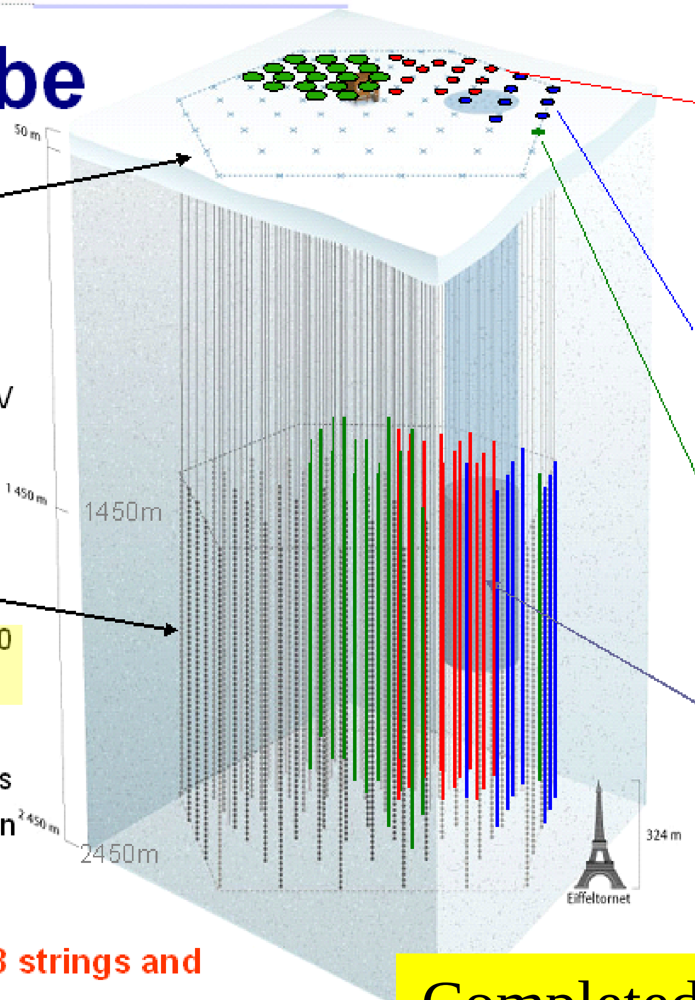
Rate ~ (EΦ)N_nσ(E), σ~E → Rate ~ (E^2Φ)M

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

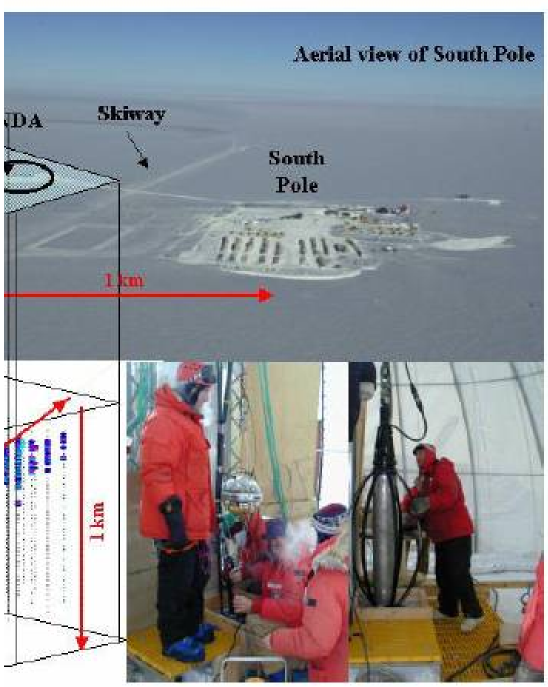
2007-2008
18 strings deployed

2005-2006: 8 strings

2004-2005 : 1 string

AMANDA-II
19 strings
677 modules

Current configuration:
40 strings,
40 IceTop stations
plus AMANDA



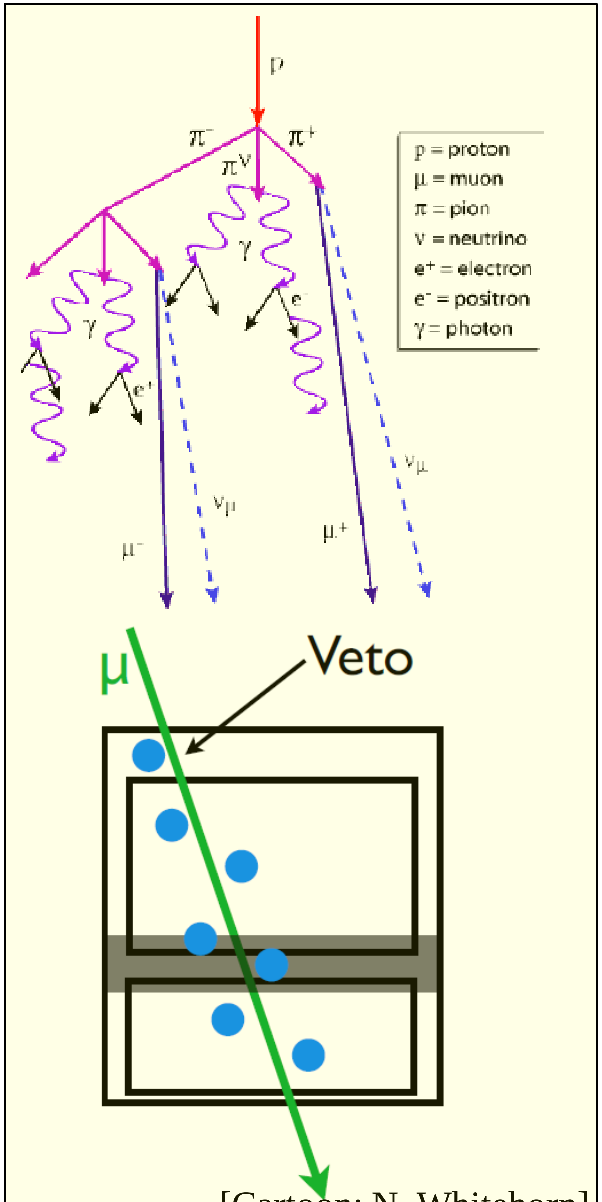
2008/09: add 18 strings and tank stations

Completed Dec 2010

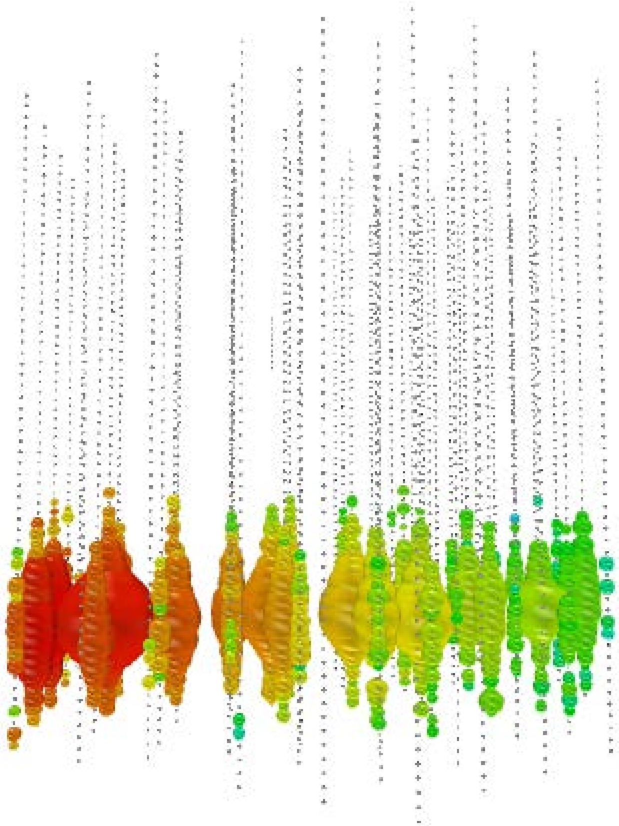
Looking up: Vetoing atmospheric neutrinos

[Schoenert, Gaisser et. al 2009]

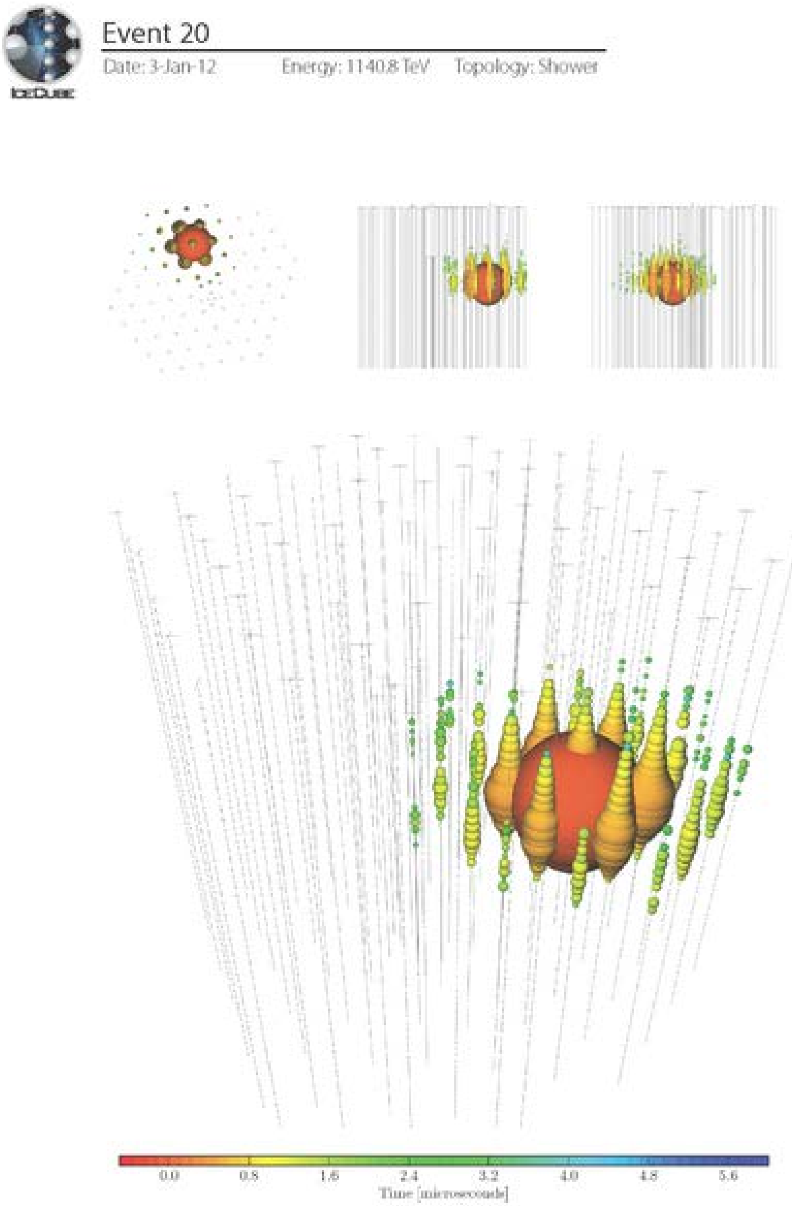
- Look for: Events starting within the detector, not accompanied by shower muons.
- Sensitive to all flavors
  (for 1:1:1, ν_μ induced μ~20%).
- Observe 4π.
- Rule out atmospheric charmed meson decay excess:
  Anisotropy due to downward events removal (vs isotropic astrophysical intensity).



[Cartoon: N. Whitehorn]



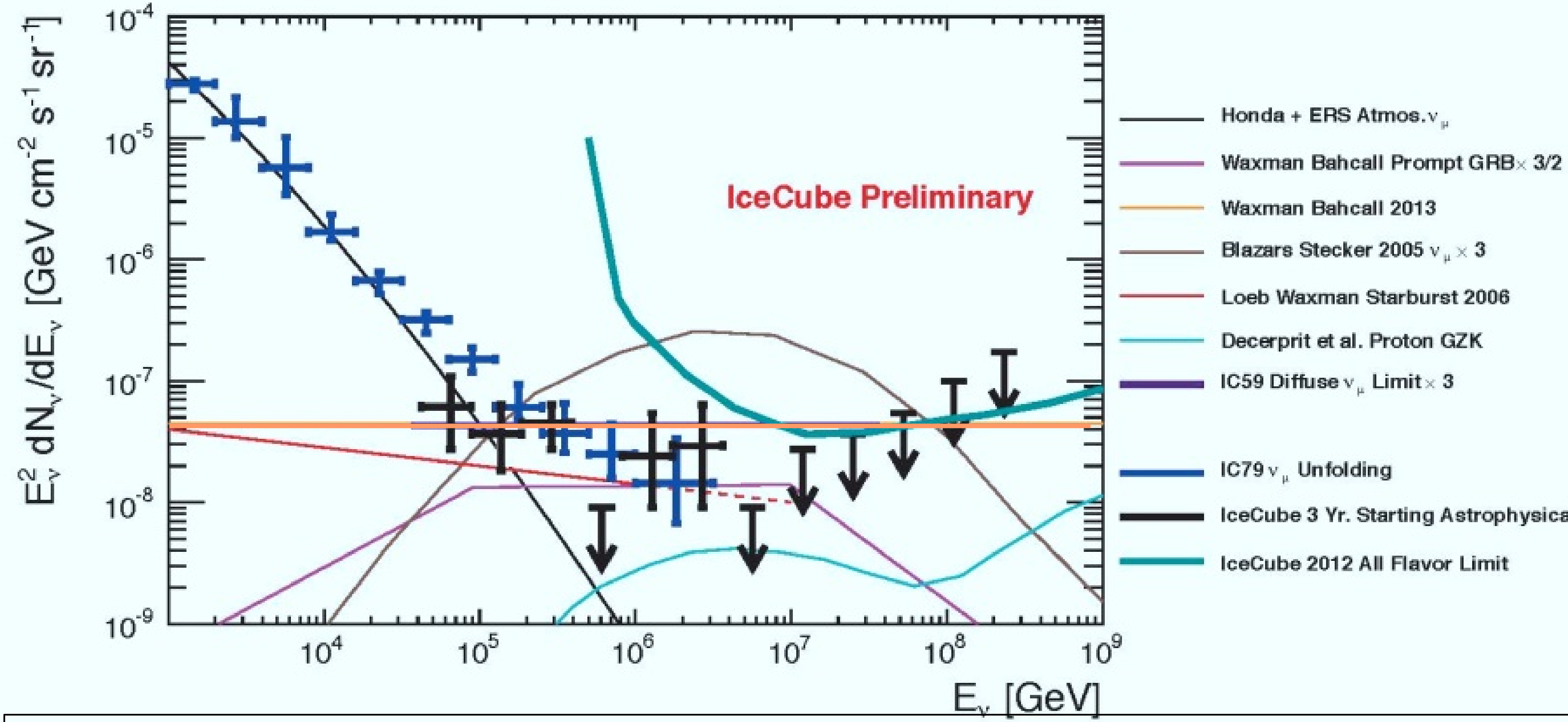
400TeV



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,

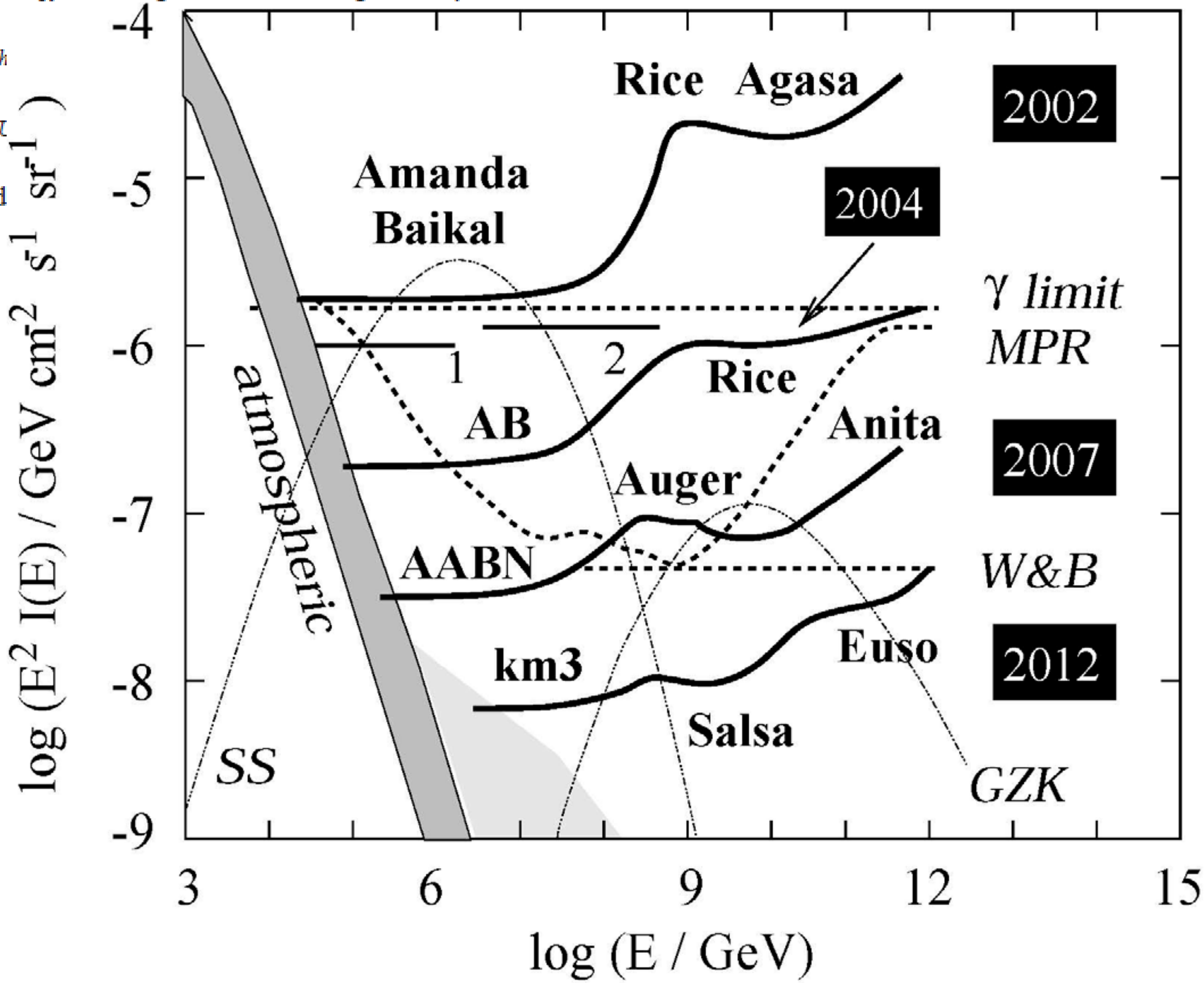
$\nu_e:\nu_\mu:\nu_\tau$=1:1:1 (π deacy + cosmological prop.).

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 Ph
T. Kajita
Institute for Cosmic Ray Research, U
Chiba 277-8582, Japan

(Received 3 June 2003; accepted

[Rev. Sci. Inst.]



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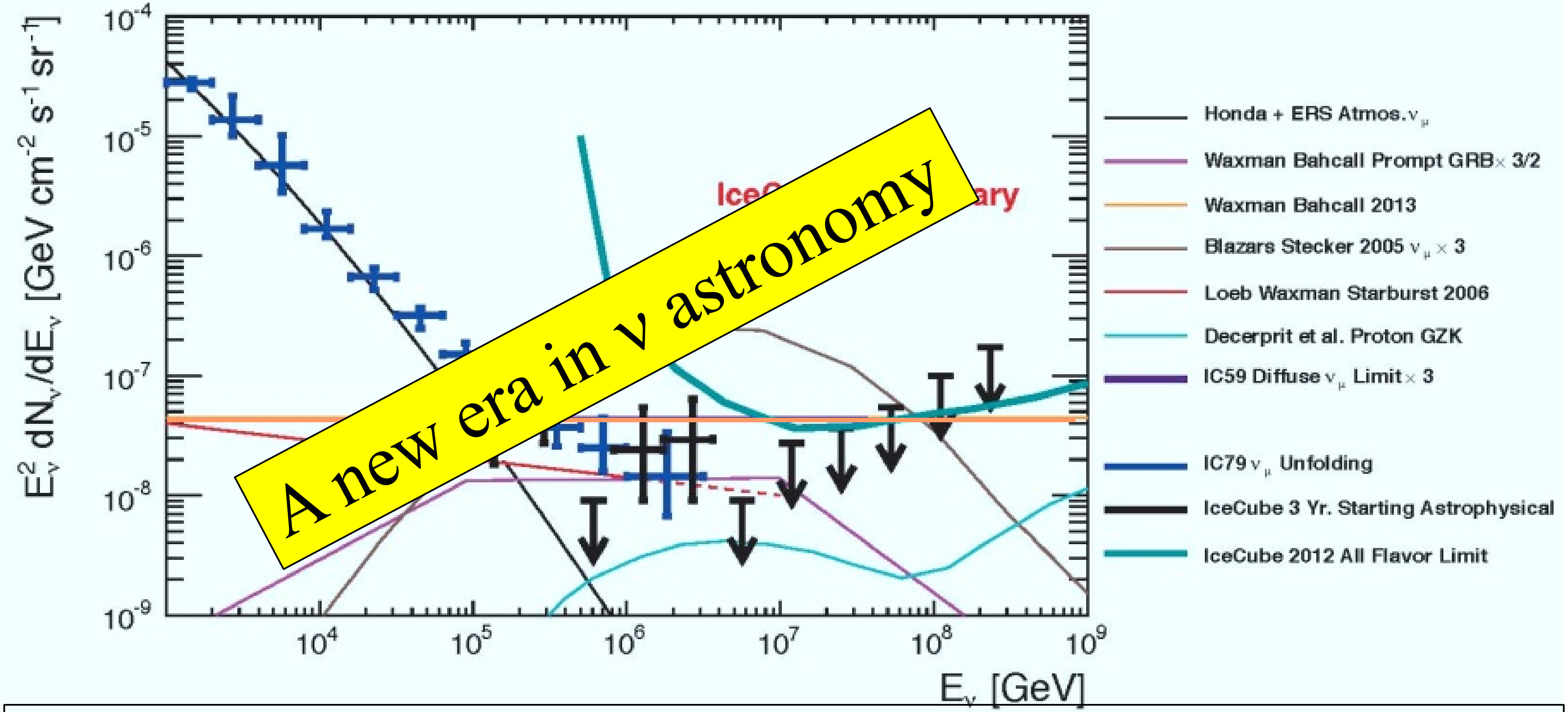

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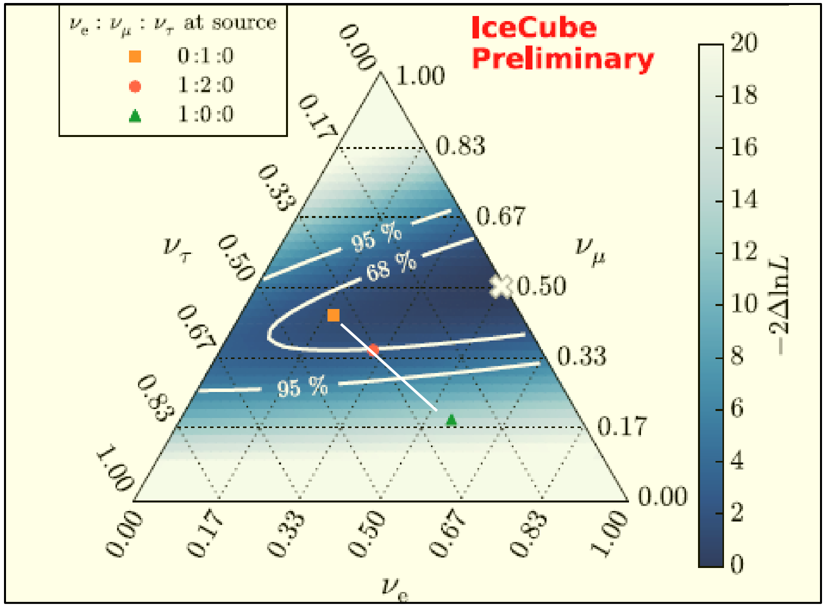
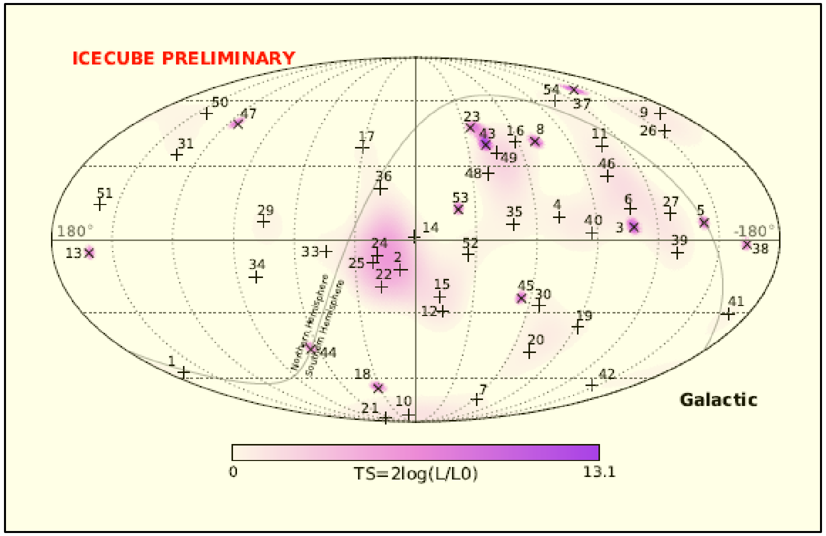
Consistent with Isotropy,

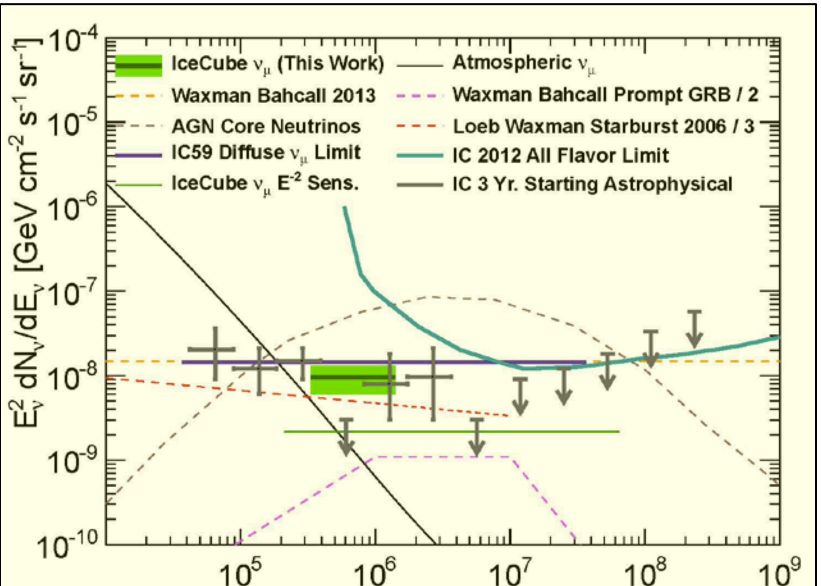
$\nu_e:\nu_\mu:\nu_\tau$=1:1:1 (π deacy + cosmological prop.).

Status: Isotropy, flavor ratio

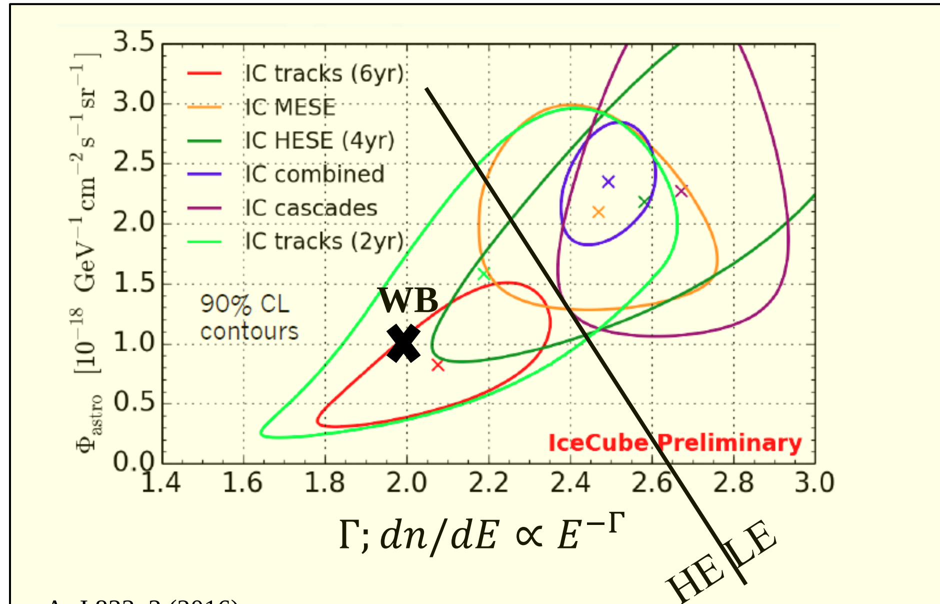




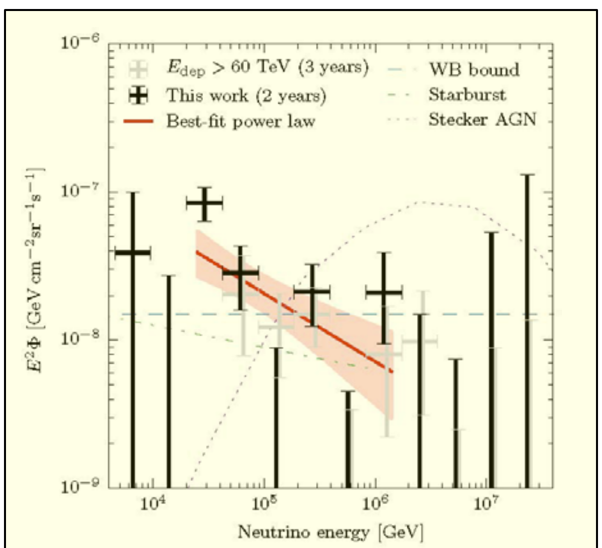
Status: Flux, spectrum



PRL 115, 081102 (2015)



ApJ 833, 3 (2016)



PRD 91, 022001 (2015)

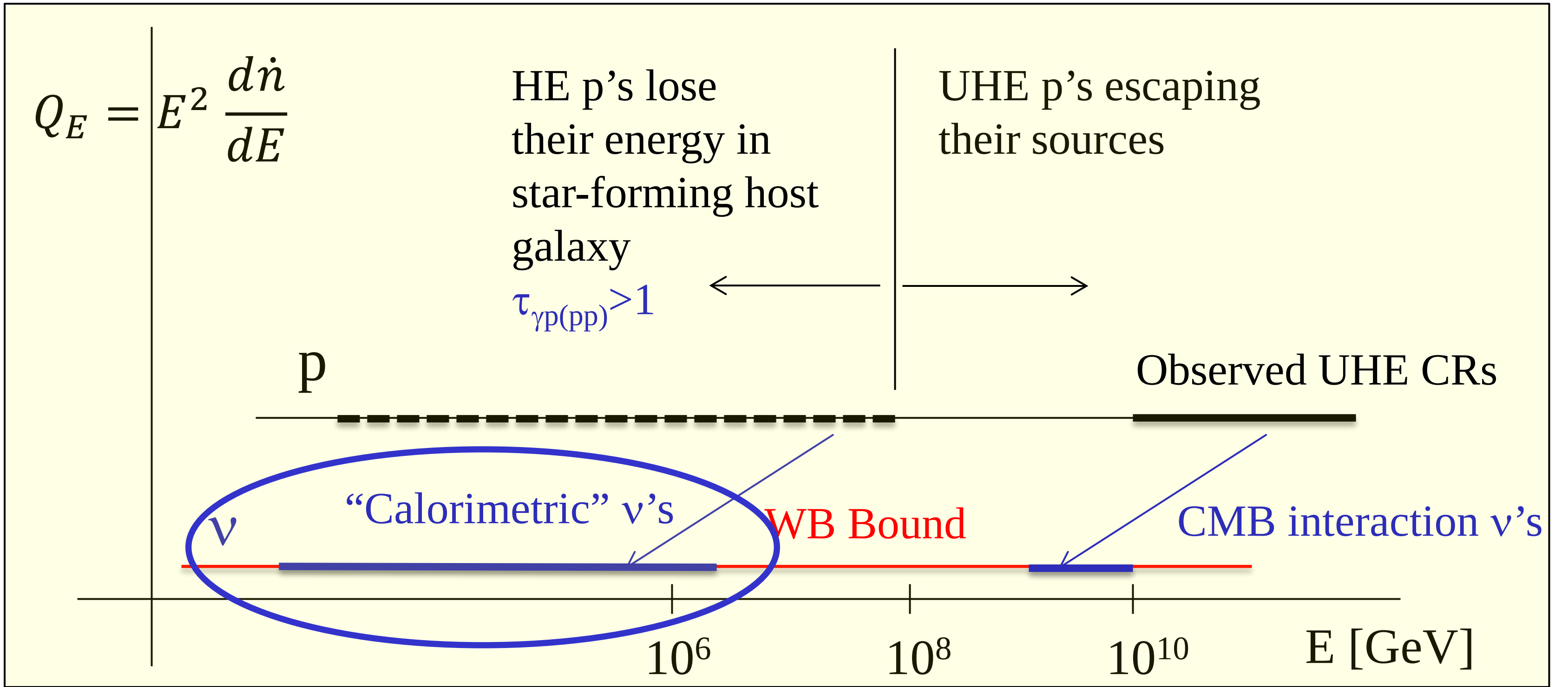
- Excess below ~50TeV.
  If real, likely a new low E component (rather than a soft Γ=2.5 spectrum).

[e.g. Palladino & Vissani 16]

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

IceCube's (>50TeV) ν sources

- DM decay? Unlikely- chance coincidence with Φ_{WB}.
- Galactic? Unlikely - Isotropy.
- A natural explanation
  (= no free parameters, no ad-hoc new sources postulated):
  XG UHE p sources, Q_E=Const., residing in (starburst) "calorimeters".
  Main open question: properties of star-forming galaxies at z~1.



IceCube's (>50TeV) ν sources

(a) Most natural (and predicted):

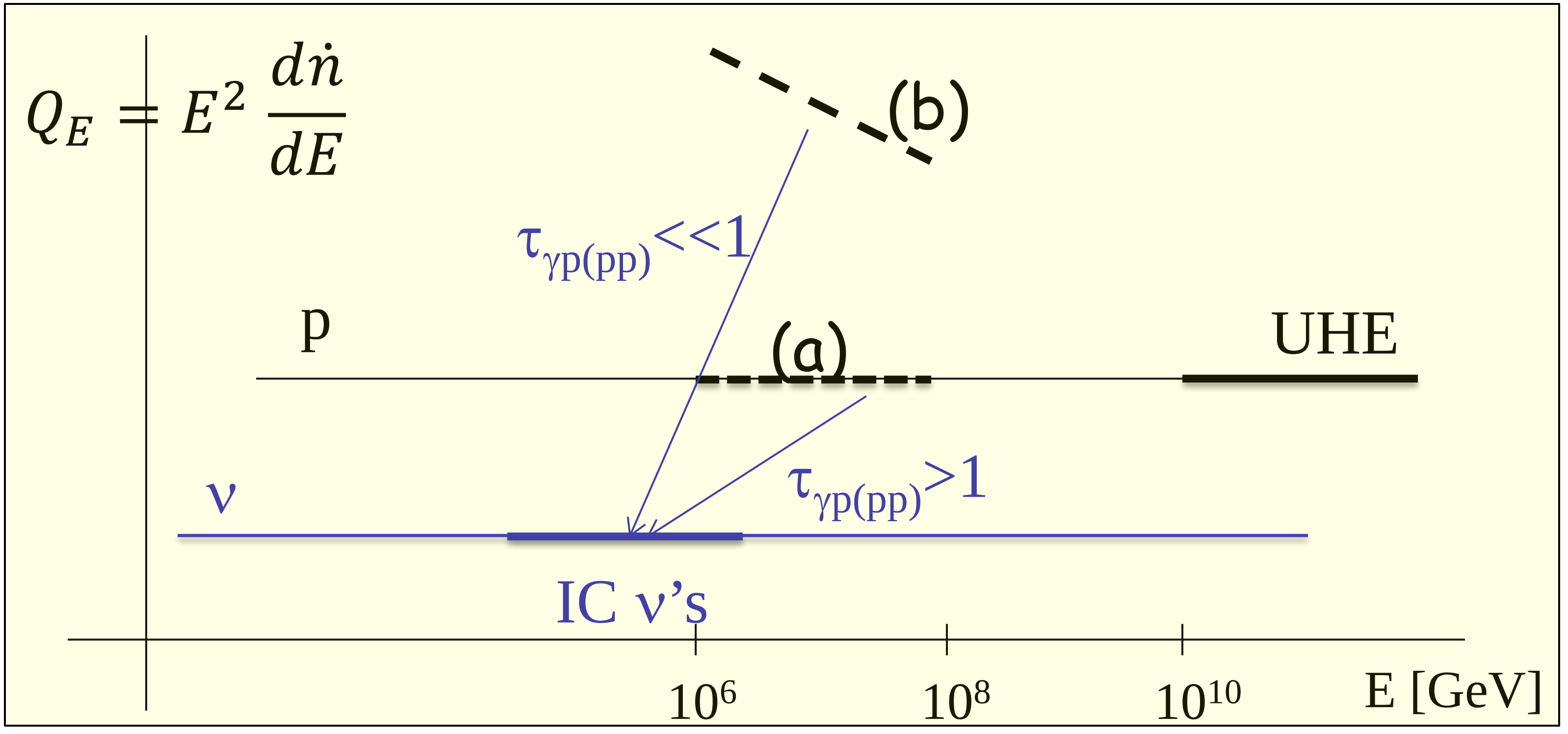
XG UHE p sources, Q_E=Const., residing in (starburst) "calorimeters".

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.



Have we already seen the "calorimeters"?

In γ's: $L_\gamma \sim (2/3) L_\nu$

- Predicted γ-flux from nearby starbursts (M82, NGC253)

$$E^2\phi_\gamma \approx 10^{-9.5}\mathrm{GeV/cm^2 s}$$ Below 10^4GeV.

- Detected by Fermi, HESS, VERITAS @ 10^{1-3}GeV.

[Lacki et al 11, Peng, Wang et al. 16]

In ν's: No sources with multiple-ν_μ-events

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

$$\Rightarrow n_s > \frac{10^{-7}}{\mathrm{Mpc}^3}\left(\frac{A}{1\mathrm{km}^2}\right)^3, \qquad N(\text{all sky}) > 10^6$$

$$, \qquad L_\nu < 10^{42.5}\mathrm{erg/s} = 10^9 L_{\mathrm{Sun}}.$$

[Kowalski 14, Ahlers & Halzen 14, Murase & EW 16]

- Rare bright sources: Ruled out (eg "blazars", $n<10^{-8.5}/\mathrm{Mpc}^3$).
- Detection of multiple events from few nearby sources requires A →A x 5 for $n\sim10^{-5}/\mathrm{Mpc}^3$ (eg starbursts).

Fermi's XG γ-ray background [EGB]

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

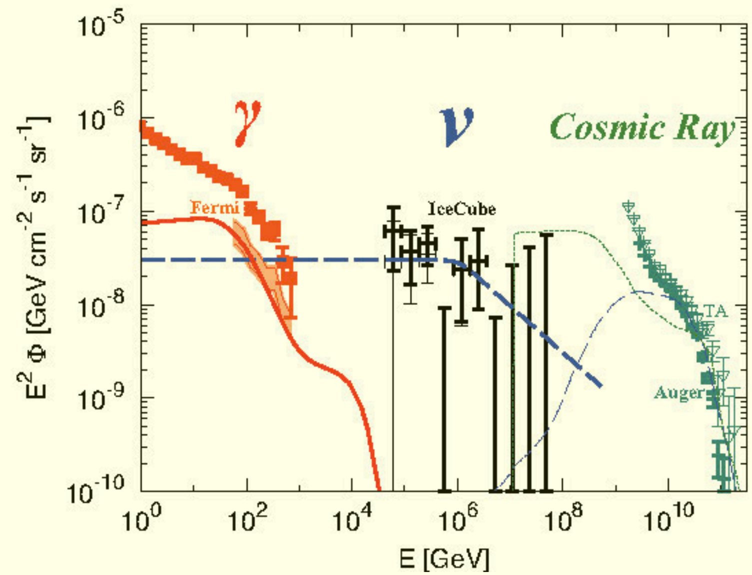
- The ν sources (starbursts?) produce a significant fraction of the unresolved γ–background.

  [Thompson, Quataert & EW 06]

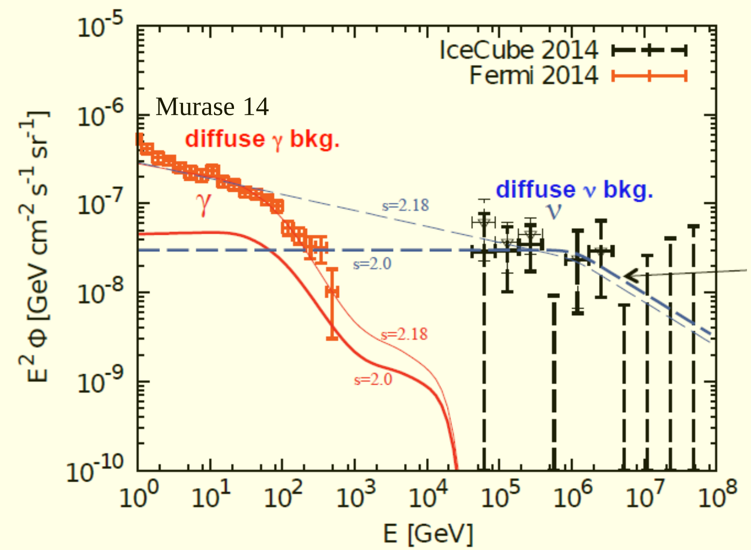
- $\frac{d \log n}{d \log E} > -2.2$

- The ~50TeV neutrino "excess" is in tension with Fermi's EGB.

  If real: "hidden" sources?



Based on [Murase & EW 16] ([Chang, Liu & Wang 16])



Model predictions vs. observations

Model: UHE CR flux dominated by shock accelerated p's,

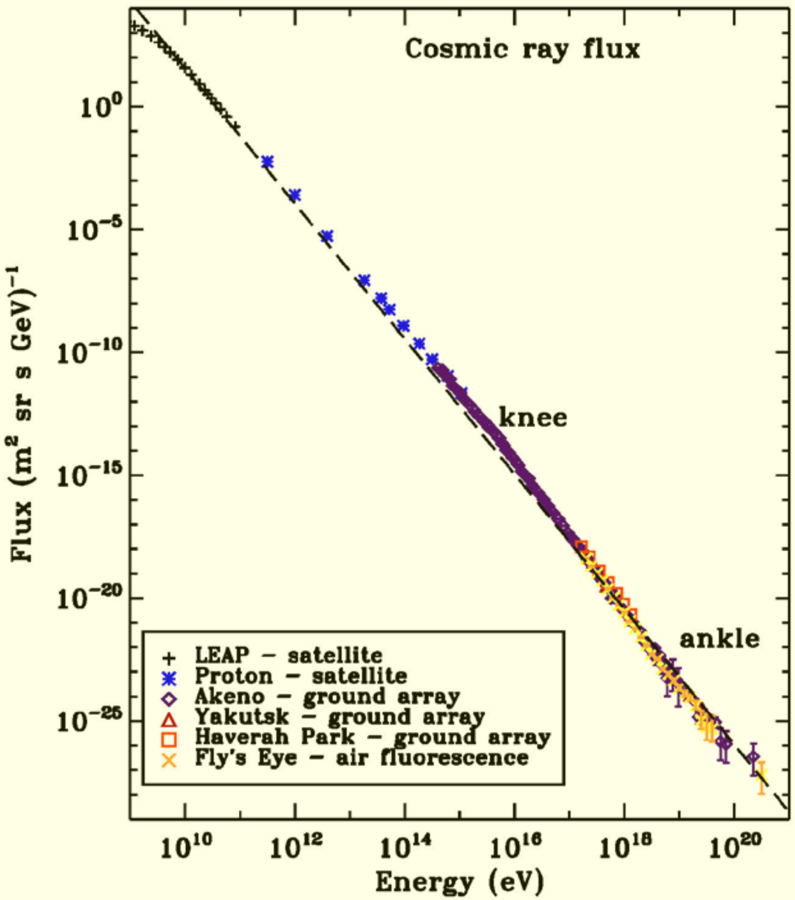
$+ L_{CR} \propto$ SFR.

Single parameter: $E^2 \frac{d\dot{n}}{dE} \approx Const. = Q = 0.5 \times 10^{44} \mathrm{erg/Mpc^3yr}$

UHE (>10^9GeV)		VHE		Galactic	
Prediction	Obs.	Prediction	Obs.	Prediction	Obs.
CR suppression above $10^{19.7}$eV	✓	$\phi_\nu = \phi_{WB}$ Below $10^6\mathrm{GeV}$	$\phi_\nu = \phi_{WB}$ @ $10^{5-6.5}\mathrm{GeV}$ ✓	G-XG transition at $10^{10}\mathrm{GeV}$	?
$\frac{d\log n}{d\log E} \approx -2$	✓	ϕ_ν suppressed above $10^6\mathrm{GeV}$	(low statistical significance) ✓ (dashed)	10 GeV CR production $\geq Q$	10 GeV CR production $Q \sim 10Q$ ✓
$\phi_\nu \approx \phi_{WB}$ @ $10^9\mathrm{GeV}$	? $\phi_\nu \leq \phi_{WB}$ (90% CL)	XG $\phi_\gamma \approx \phi_\nu \approx \phi_{WB}$ @ $10^2\mathrm{GeV}$	(source subtraction uncertainty) ✓ (dashed)		
(weak) LSS anisotropy	?	Nearby star-bursts (M82, NGC253) $\phi_\gamma \approx \phi_\nu$ $\approx 10^{-9.5}\mathrm{GeV/cm^2s}$ Below $10^4\mathrm{GeV}$	γ @ $10^{1-3}\mathrm{GeV}$ ✓ $\gamma \sim 10^4\mathrm{GeV}$? ν ?		

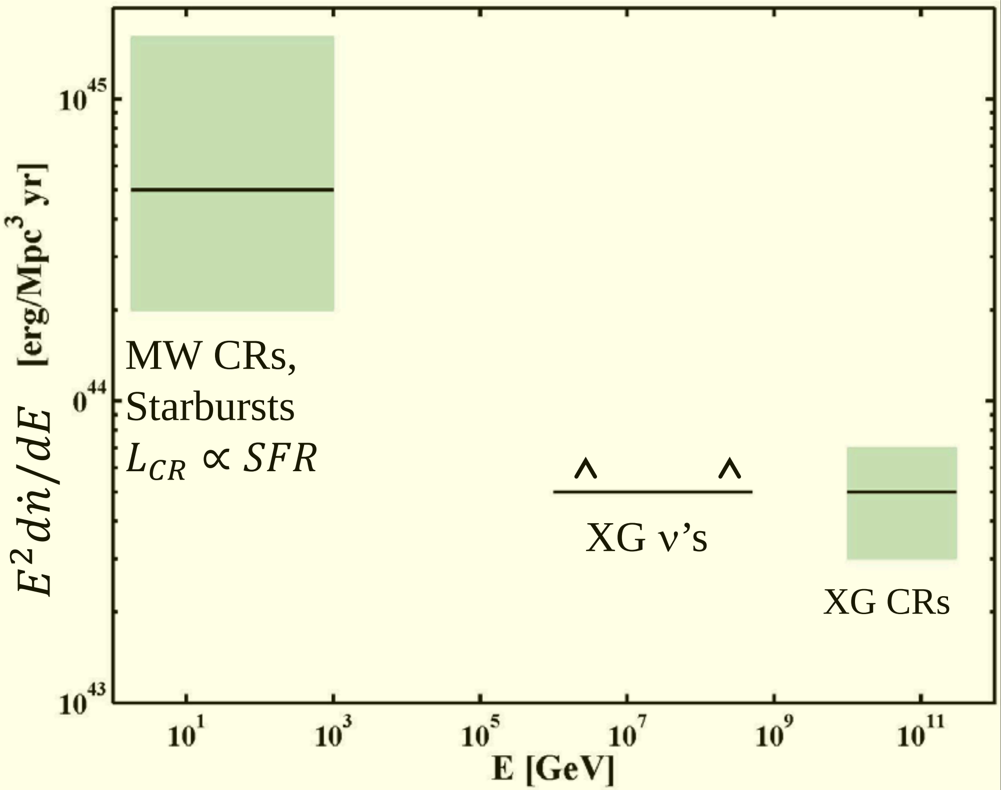
A single cosmic ray source across the spectrum?

Observed spectrum



[From Helder et al., SSR 12]

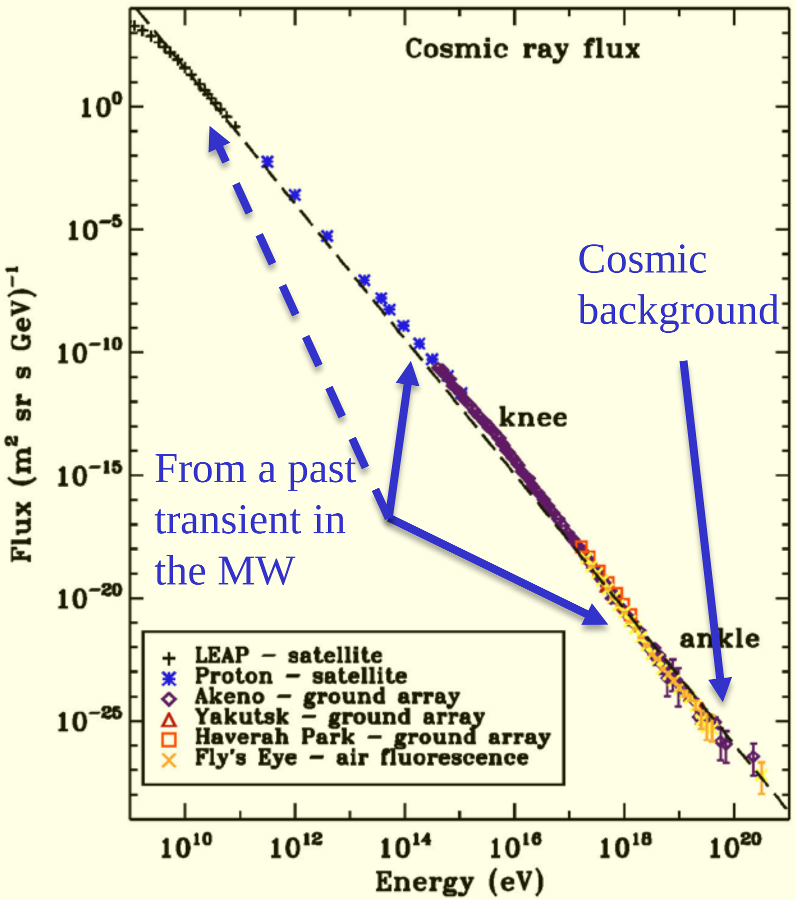
Generation spectrum



[Katz, EW, Thompson & Loeb 14]

A single cosmic ray source across the spectrum?

Observed spectrum



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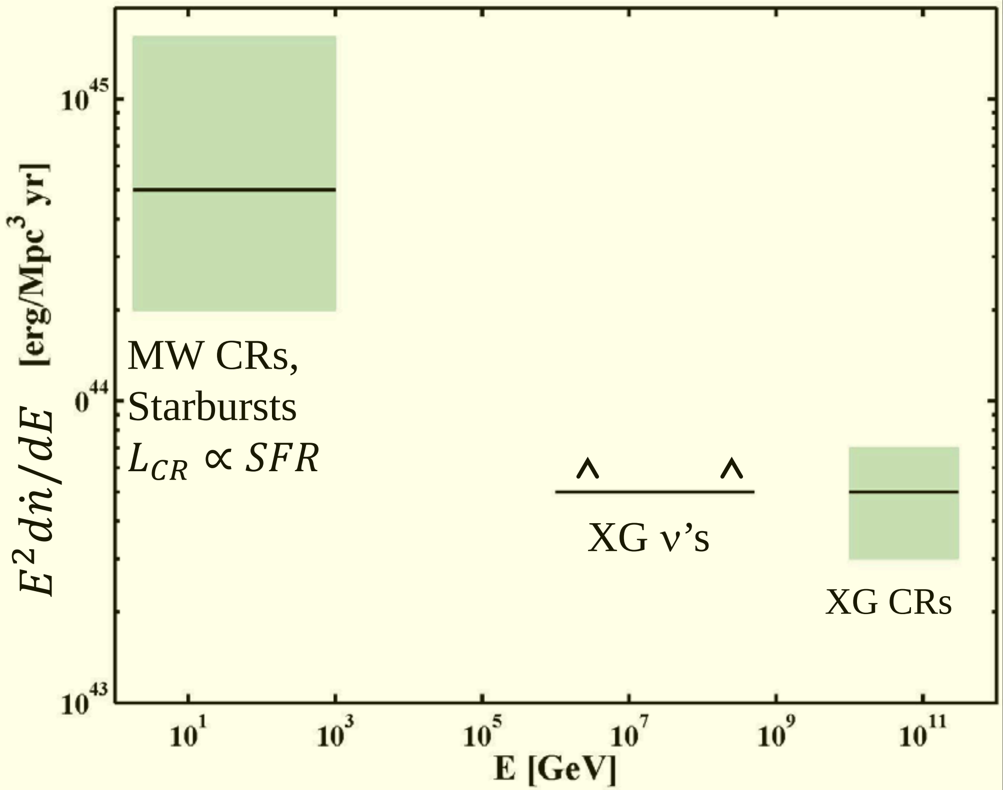


[Katz, EW, Thompson & Loeb 14]

Identifying the sources

- IC's ν's are likely produced by the "calorimeters" surrounding the sources.
  Prompt emission from the source, $\Phi \ll \Phi_{WB}$.
  E.g. "classical GRB" $\Phi_{grb} \approx 10^{-2}(10^{-1})\Phi_{WB}$ at 10^5GeV (10^6GeV). [EW & Bahcall 97]

- UHECRs are likely produced by transient "bursting" sources.

- 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 $1:10^6$.

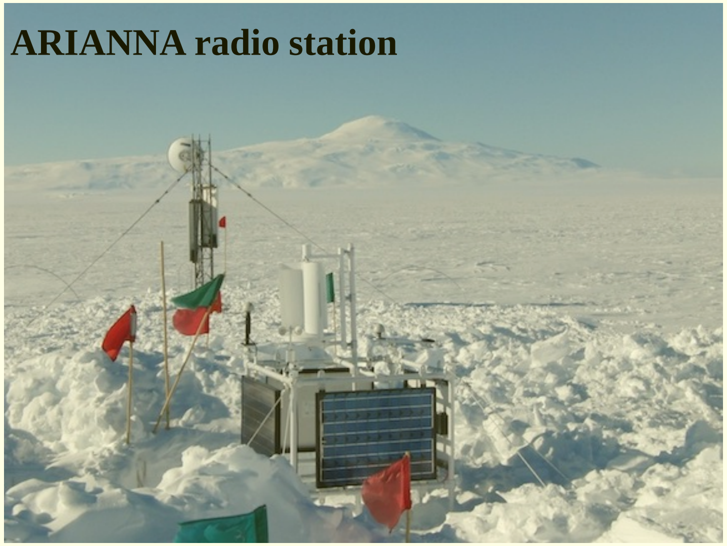
[EW & Bahcall 97; Amelino-Camelia,et al.98;
Coleman &.Glashow 99; Jacob & Piran 07, Wei et al 16]

The way forward: I. GZK ν's

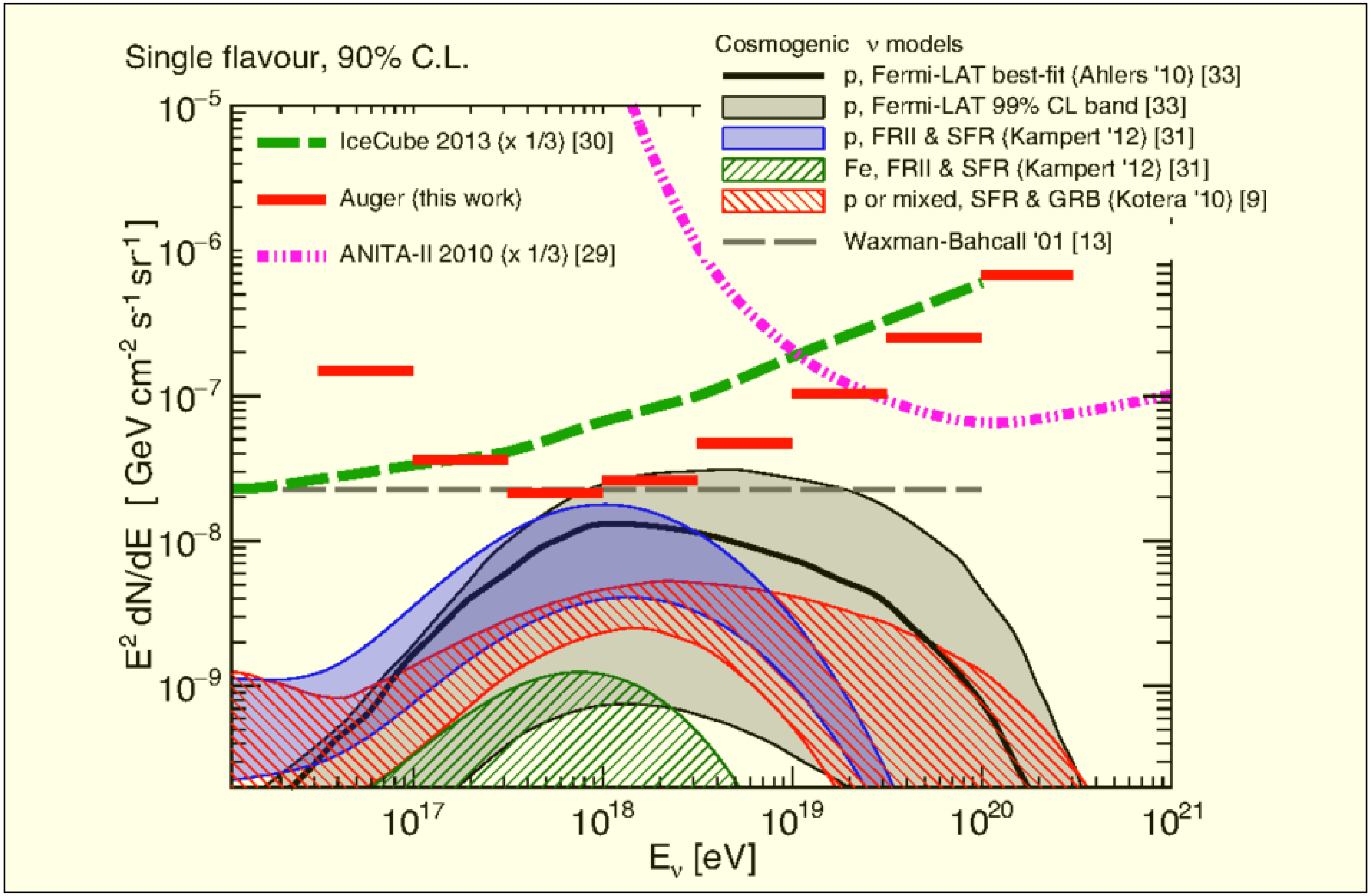
- Significant p fraction @ $10^{10.7}\mathrm{GeV}$
  → $\phi_\nu(10^9\mathrm{GeV}) \approx 10^{-8}\mathrm{GeV/cm^2s\ sr}$

- Detector with
  $10^{-9}\mathrm{GeV/cm^2s\ sr}$ @ $10^8 - 10^{10}\mathrm{GeV}$
  Will test p @ GZK,
  Measure p fraction down to 10%.

- Feasible (~5 yr) using the coherent radio Cerenkov technique,
  ARA & ARIANNA
  (unite at south pole).



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

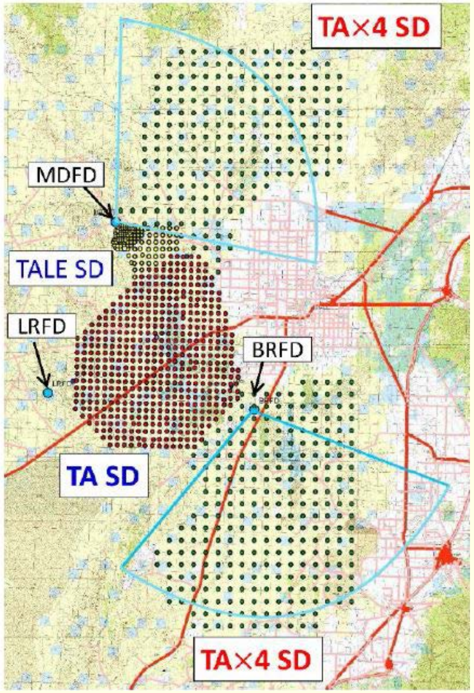


The way forward: UHE CR experiments

- Telescope-Array x 4
  (hybrid, ~Auger at the North).

- Auger' :
  Add scintillators for e/μ to
  Identify primary mass for all
  events (not only hybrid),
  Use p fraction for "astronomy"
  (anisotropy, sources).

- Complete deployment by 2020.



The way forward: II. VHE ν's

- M_{eff}~10 Gton @ $10^5 - 10^8$GeV

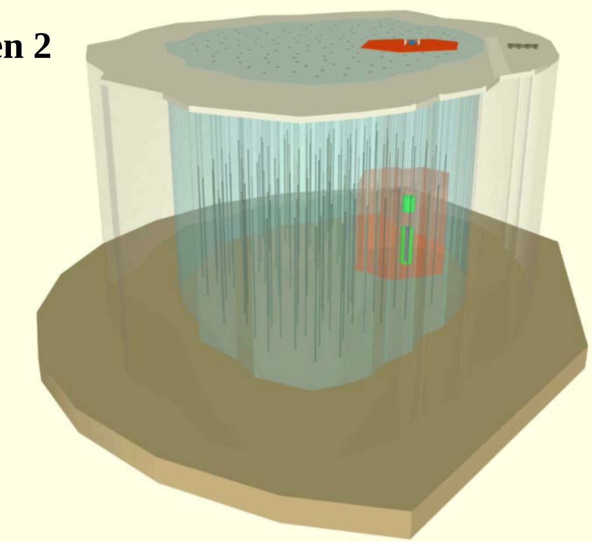
  - Reduce uncertainties in ν flux, spectrum, isotropy, flavor ratio. [A different ν source at <50TeV? A cutoff >3PeV?]

  - Detect the nearest CR/ν "calorimeters".

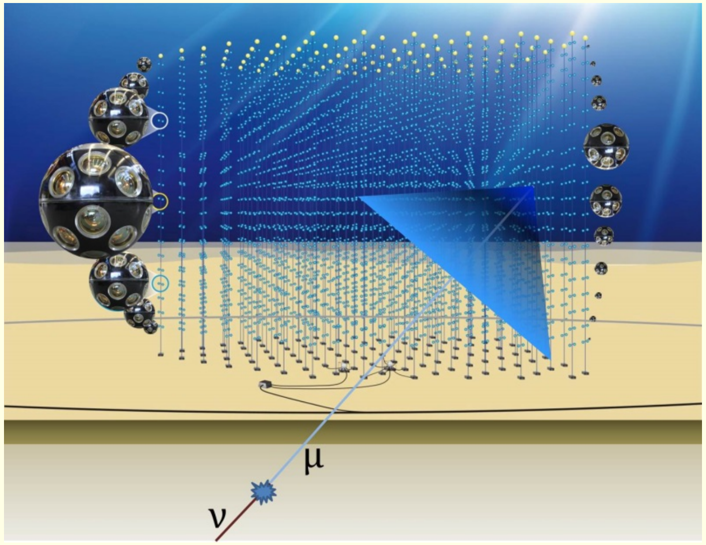
  - Possible identification of the CR sources by temporal ν–γ association (Φ_ν~0.1 Φ_{WB}). [Requires: Wide field EM monitoring, real time alerts, X/γ telescopes.]

- Feasible with IceCube Gen 2, KM3NeT (< 10yr).

IC Gen 2



KM3NeT



The way forward: III. HE ν's

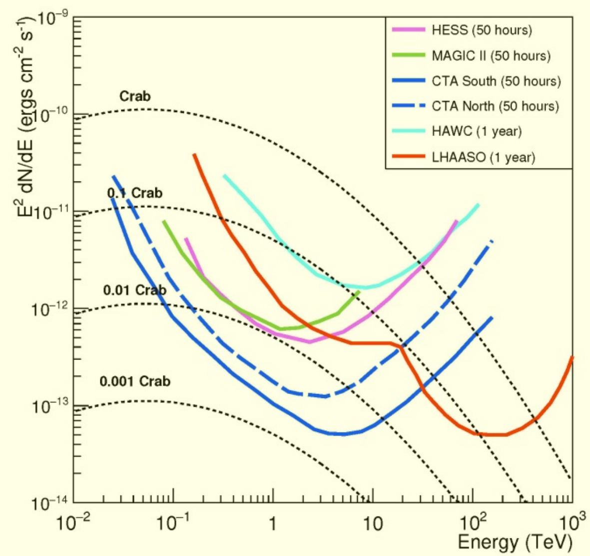
- M_{eff}~10 Gton @ $10^4 - 10^5$GeV
  - Point source sensitivity ~ advance γ-ray telescopes = CTA's (construction starts 2017).
  - "Multi-messenger" γ-ν astronomy, γ-ray detection of ν sources (L_γ~L_ν).
  - Search for Steady Galactic "Pevatrons".

10 Gton ν detector point source sensitivity

Ψ_{med} (°)	$E_{\mu,min}$ (TeV) 0.1	1	10	100
	Flux (10^{-13} TeV cm^{-2} s^{-1})			
0.1	1.11	1.12	1.25	2.03
0.2	1.66	1.67	1.78	2.63
0.3	2.13	2.13	2.24	3.13
0.5	2.95	2.96	3.06	4.02
1.0	4.76	4.76	4.87	5.94

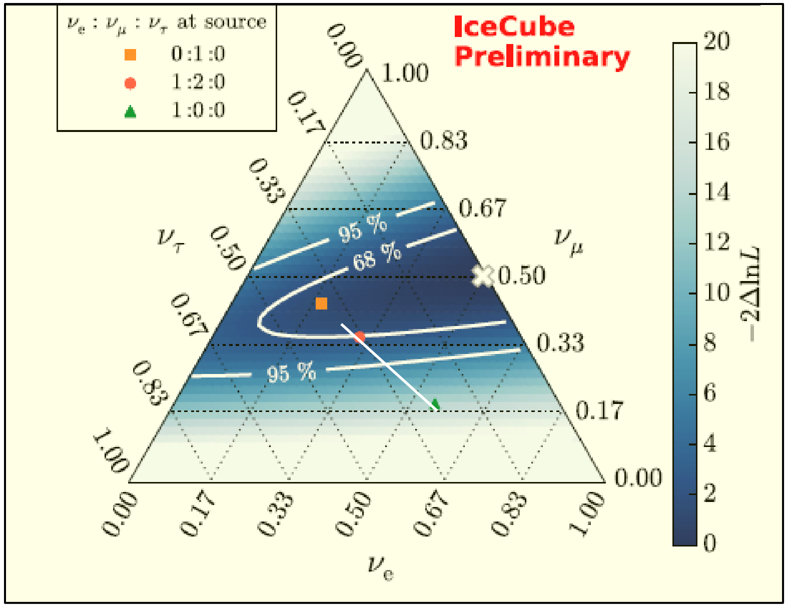
[van Santen 2017]

γ ray telescopes' sensitivity



[Di Sciascio et al. 2016]

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)

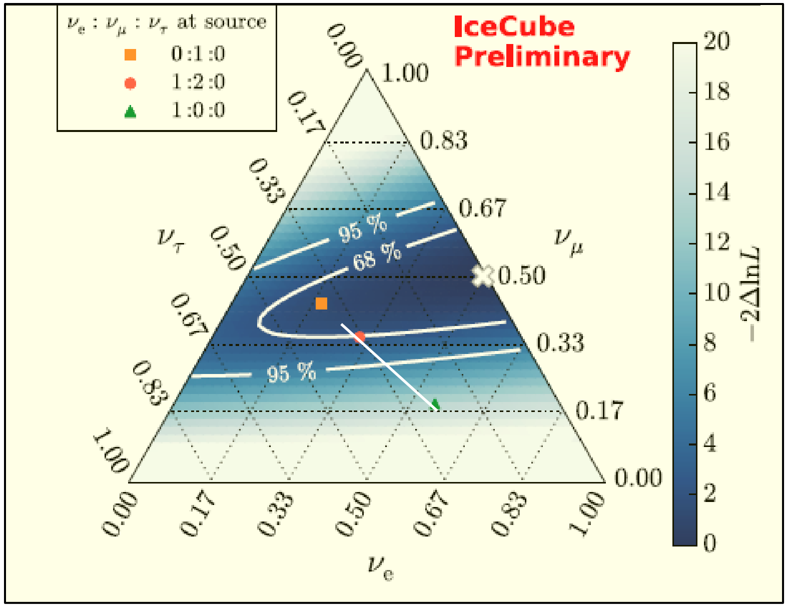
[Capozzi et al. 13]

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

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

[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…]

Future constraints from flavor ratios



ν's have done it before!

- 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]

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Short GRBs: multi-messenger prospects

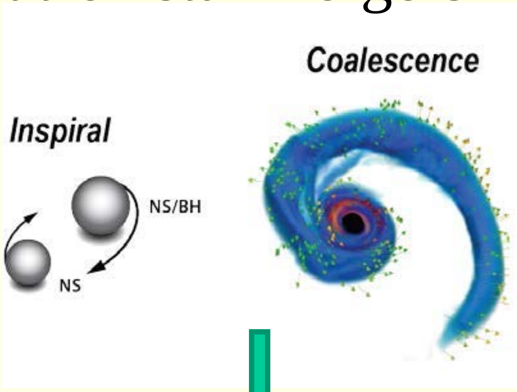
- The jets of short GRBs are believed to be driven by Neutron star mergers.

- Prospects for detection in
  Gravitational waves,
  Photons,
  Neutrinos.

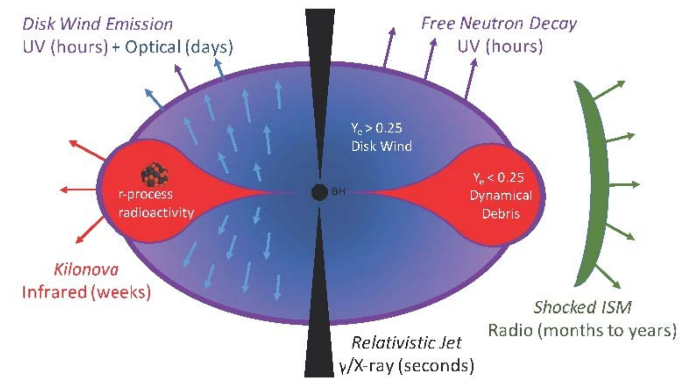
[Bartos et al. 11, 13; Bartos, Brady & Marka 13]

- Study
  Nuclear density matter,
  Jet "engines",
  Particle acceleration.

Neutron star mergers



Radio to gamma-ray "Afterglow"



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 from

  Transient XG p sources, $E^2 \frac{d\dot{n}}{dE} \approx Const.$, $L_{CR} \propto$ SFR;

  >1PeV (>1GeV?) Galactic CRs – from a past transient.

  Consistent with XG γ-background & nearby starburst γ emission.

- What is missing?
  - Reliable measurement of the p-fraction at UHE.
  - Identification of the PeV ν "calorimeters".
  - Identification of the (transient) CR sources.

- Can be addressed by next generation ν telescopes.
  - $10^{-9}\mathrm{GeV/cm^2 s\ sr}$ @ $10^8 - 10^{10}\mathrm{GeV}$ (ARA, ARIANNA, [Auger data]).
  - M_{eff}~10 Gton @ $10^5 - 10^8\mathrm{GeV}$ (IceCube Gen 2, KM3NeT).

  Wide field EM monitoring, real time alerts.

  "Multi-messenger": point source sensitivity ~ future γ telescopes (CTA, LHAASO).

Backup Slides

10^{11}GeV: The acceleration challenge

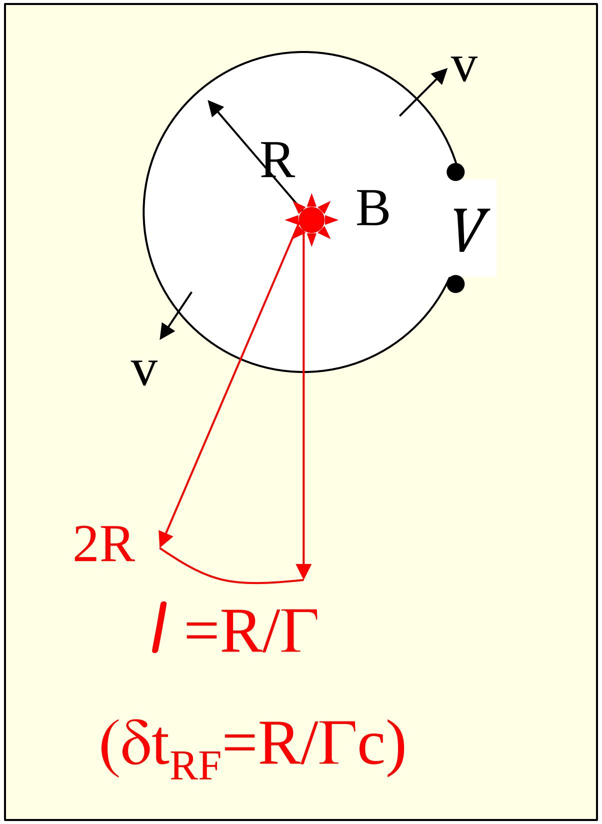
- Many accelerators suggested,
  none evades the simple constraint:

$$V=\frac{1}{c}\dot{\Phi}\approx\frac{1}{c}\frac{BR^2}{\frac{R}{v}}=\frac{v}{c}BR \;\Rightarrow\; E<\frac{\beta ZeBR}{\Gamma},$$

$$L>4\pi R^2\Gamma^2\frac{B^2}{8\pi}\beta c>\frac{\Gamma^2}{\beta}\left(\frac{E/Z}{10^{11}\mathrm{GeV}}\right)^2 10^{12}L_{\mathrm{Sun}}.$$

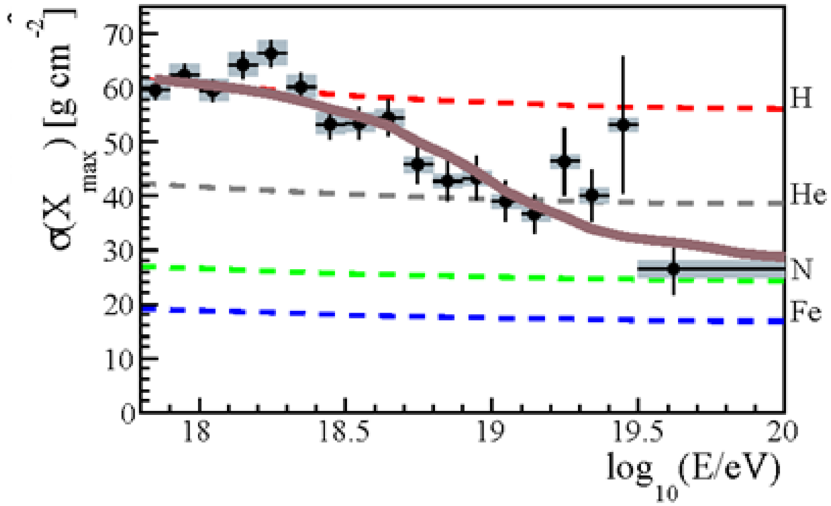
[Lovelace 76; EW 95; Norman et al. 95; Lemoine & EW 09]

- If UHE CR are p's- few candidate sources,
  if Z>10- many candidates.

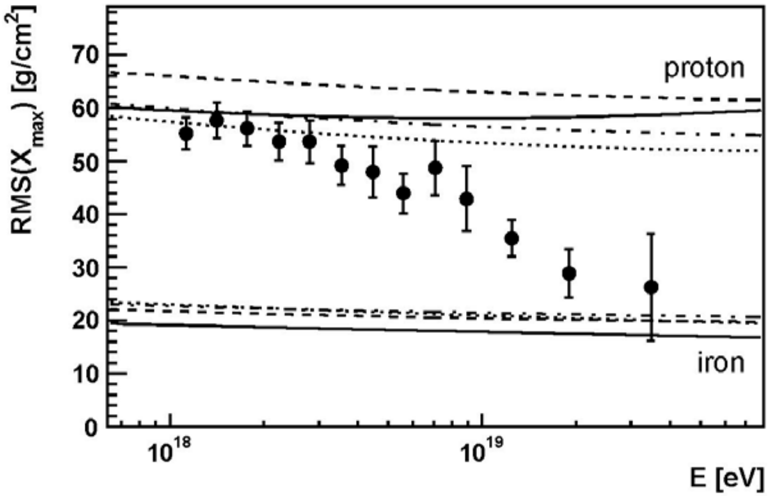


UHE: Air shower composition constraints

Auger 2015



Auger 2010



UHE: Air shower composition constraints Inconclusive

- Auger/HiRes discrepancy.

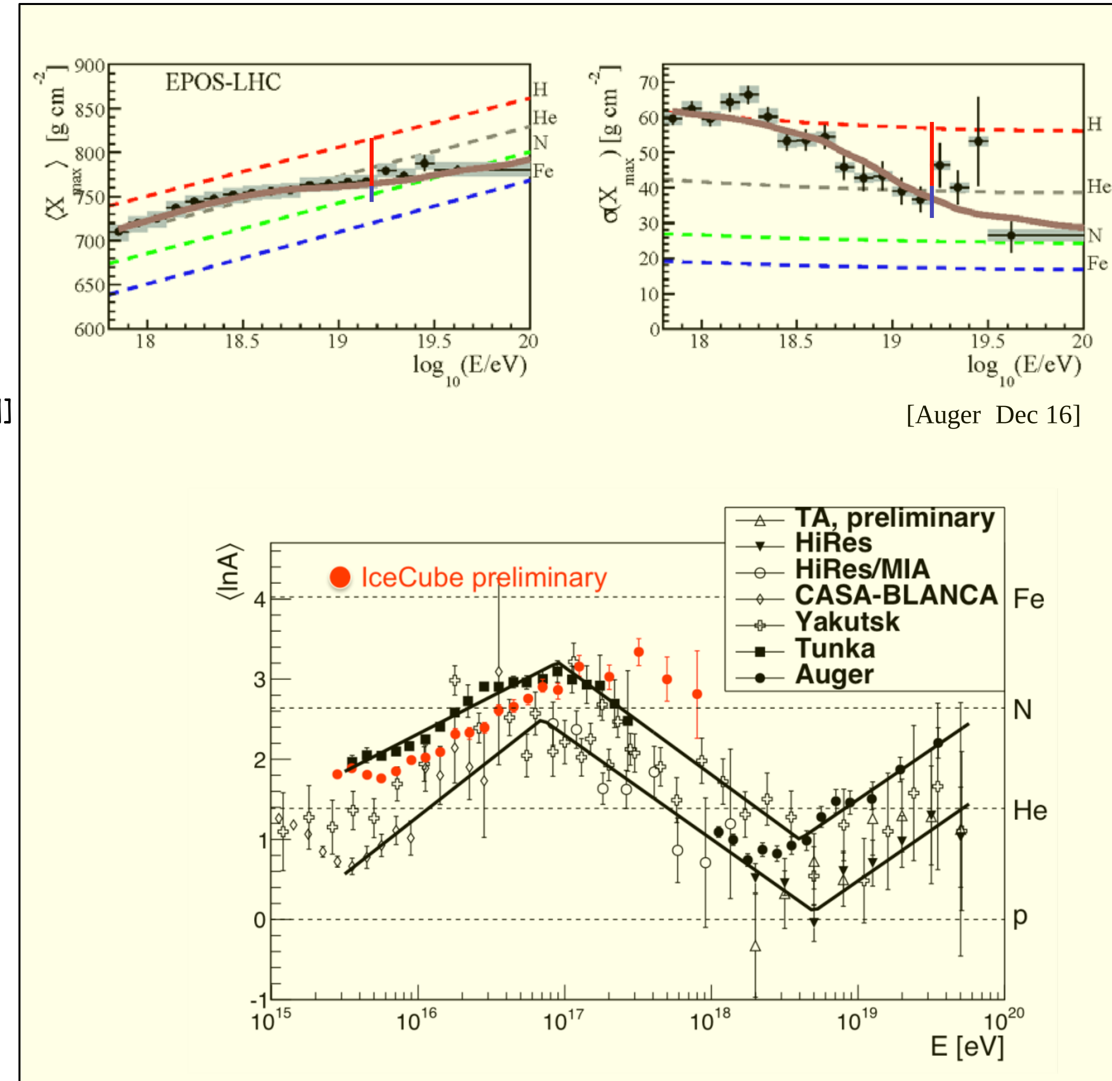
- Uncertainties in extrapolation to E_{CM}>100TeV
  (not spanned by models),

— 25% cross-section & elasticity
[Ulrich, Engel & Unger 11]]

— Exp. sys. uncertainty.

- Primary mass & Extrapolation to >100TeV effects are degenerate.

- Discrepancies between shower models and data.



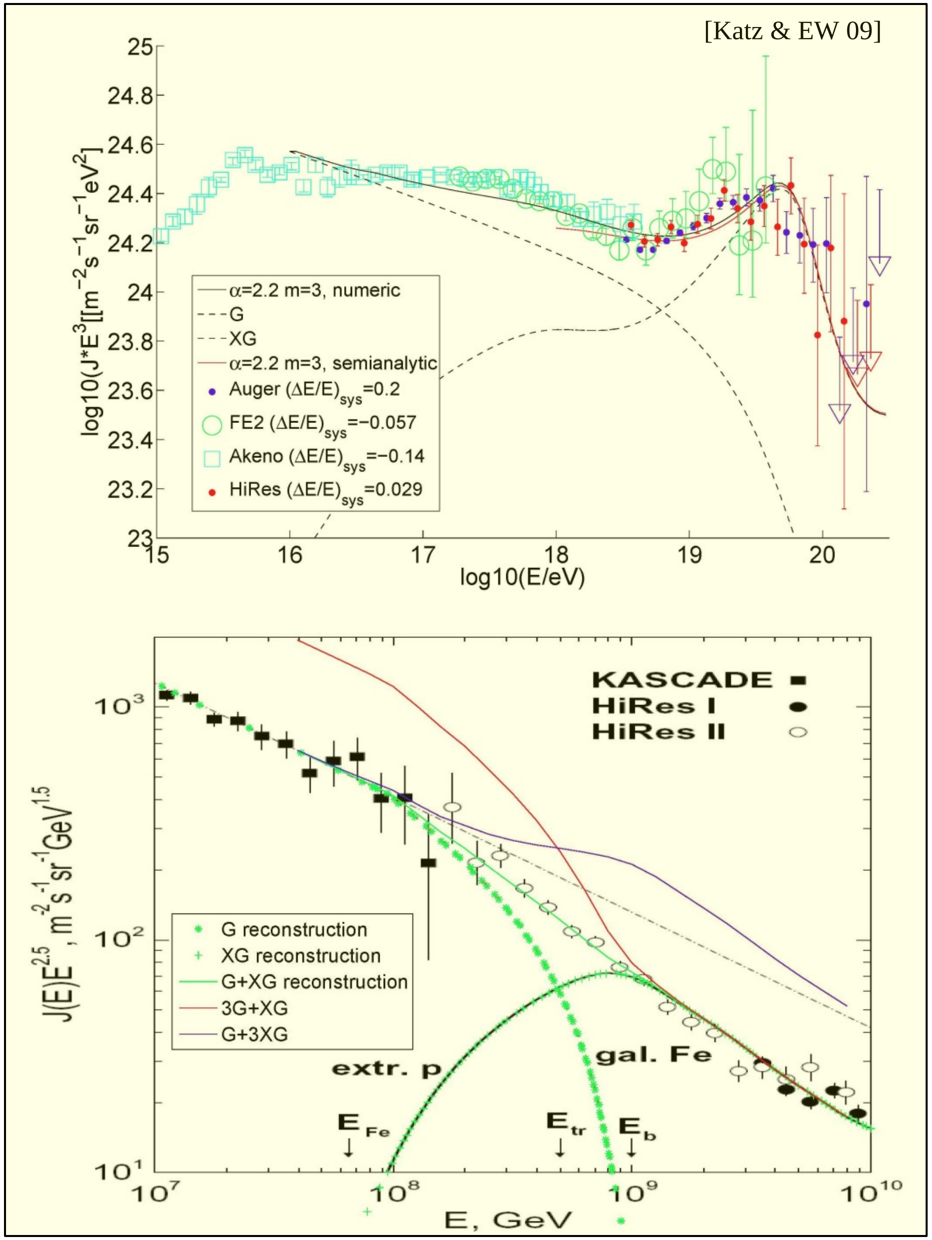
Where is the G-XG transition?

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

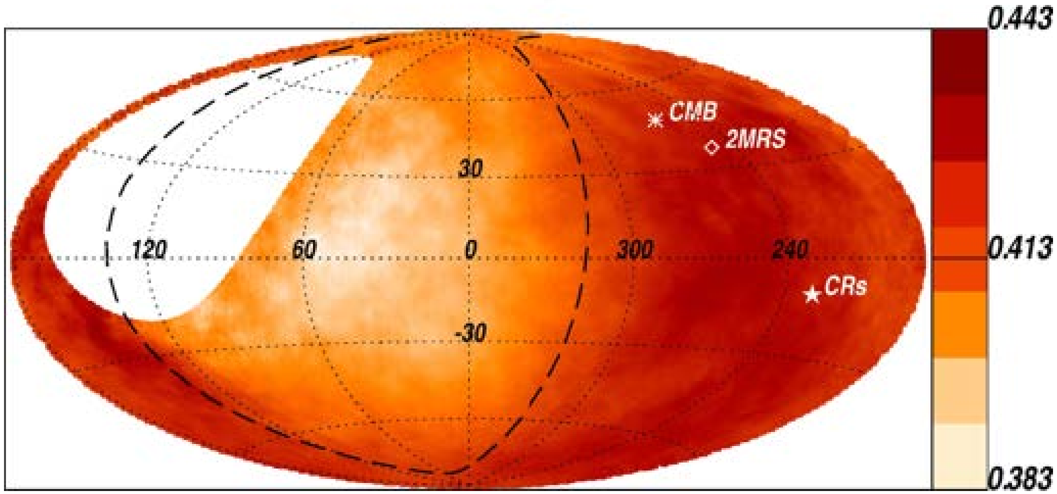


UHE: Do we learn from (an)isotropy?

- No significant anisotropy $>4\times10^{10}$GeV.
  Not a significant result:
  P(reject isotropy @ 95% CL with 600 events)=50%.

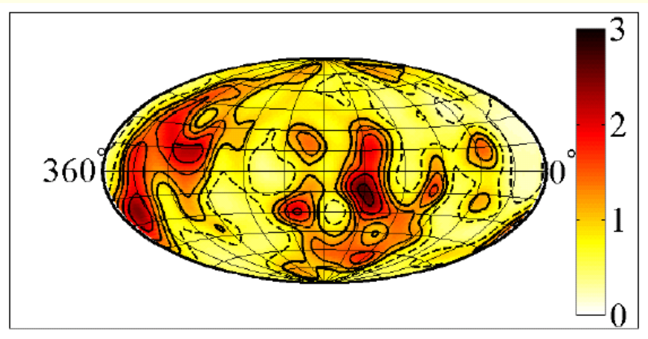
[Kashti & EW 08]

- Significant strong dipole at $\sim 8\times10^{9}$GeV.
  Near the Galactic plane.

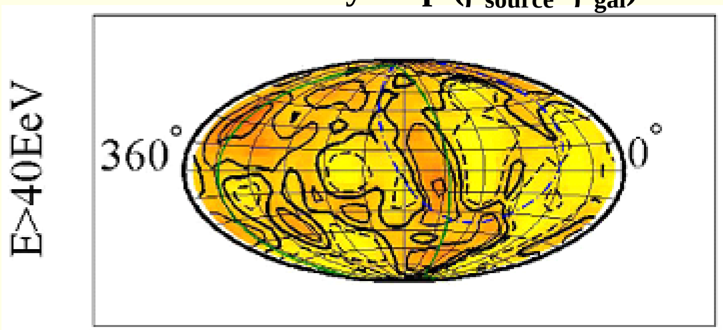


[Auger, Kampert 17]

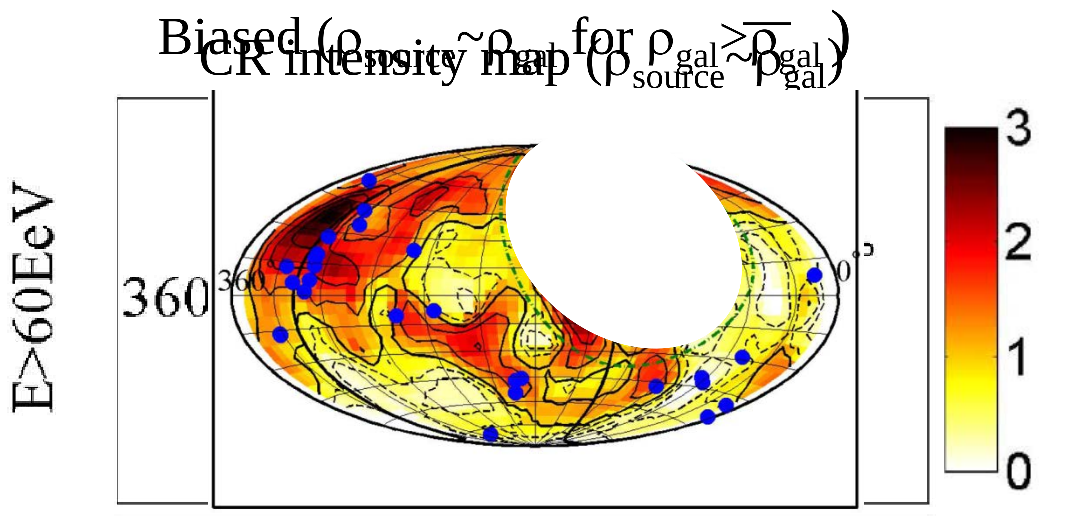
Galaxy density integrated to 75Mpc



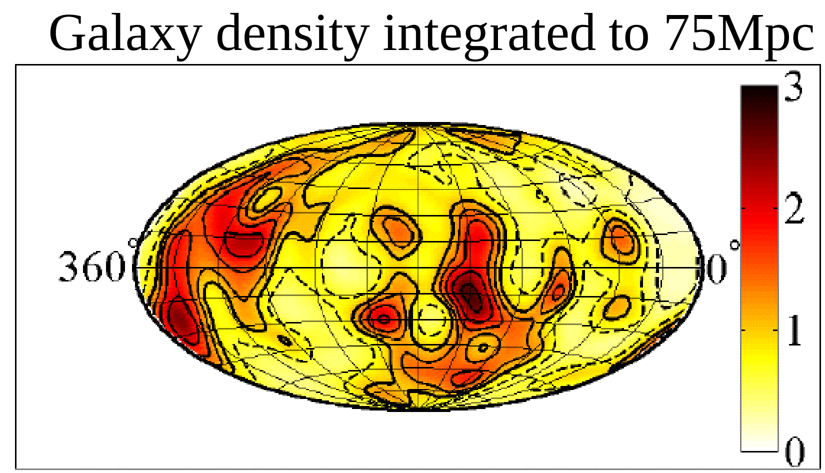
CR intensity map ($\rho_{source}\sim\rho_{gal}$)



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]

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).

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.

A note on prompt GRB ν's

- $Q_\gamma(z=0)$ by long GRBs ~ Q(UHE p):

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

- $UHE\ p\!:\ E^2\frac{d\dot{n}}{dE} = 10^{43.7\pm0.2}\frac{\text{erg}}{\text{Mpc}^3\text{yr}}$

$\rightarrow \frac{Q(\text{CR}-\text{p})}{Q(\text{GRB}-\text{e})} \sim 2.5\frac{\#\ \text{p decades}}{\#\ \text{e decades}} \sim \frac{20}{\#\ \text{e decades}}$

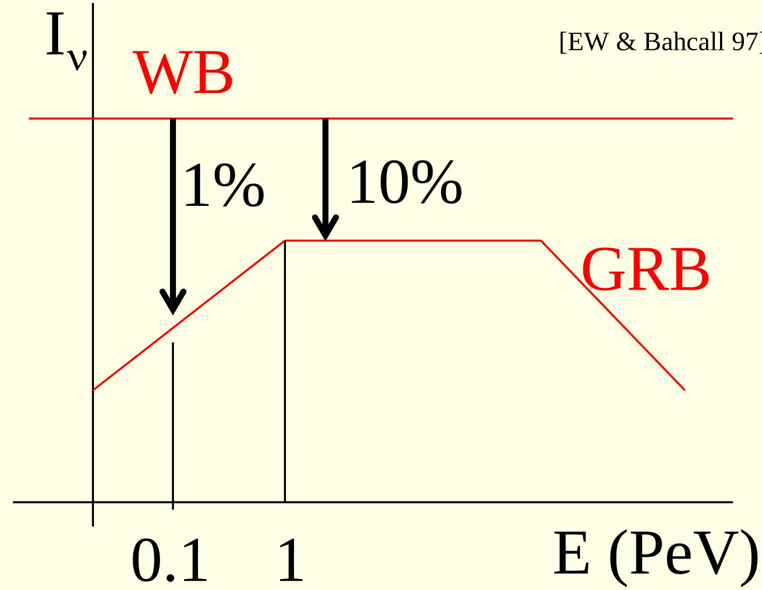
[EW 95] .

- Prompt ν: 0.01—0.1 Φ_{WB}.

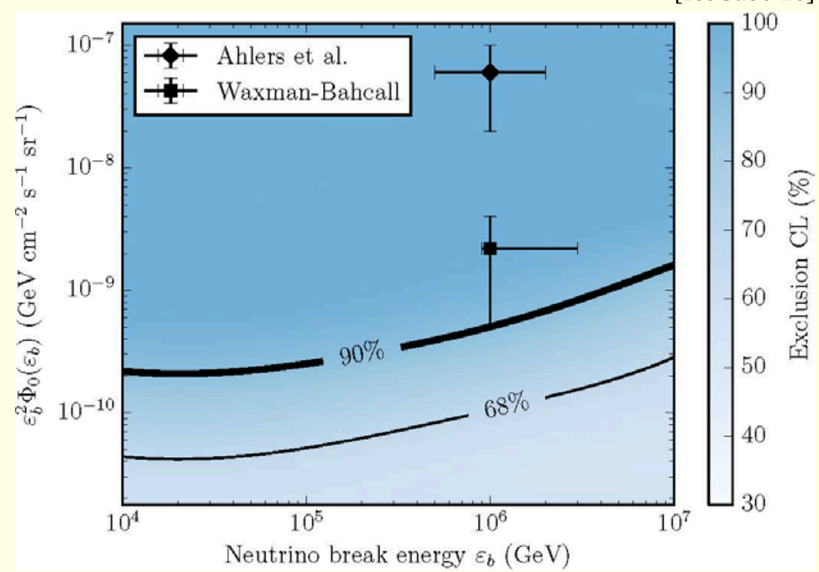
  [EW & Bahcall 97; Hummer, Baerwald, and Winter 12; Li 12; He et al 12 …Tamborra & Ando 15]

- IC has achieved relevant sensitivity: constraining model parameters.

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



[IceCube 16]



Low Energy, ~10GeV

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

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

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

- Starbursts- using radio to γ observations

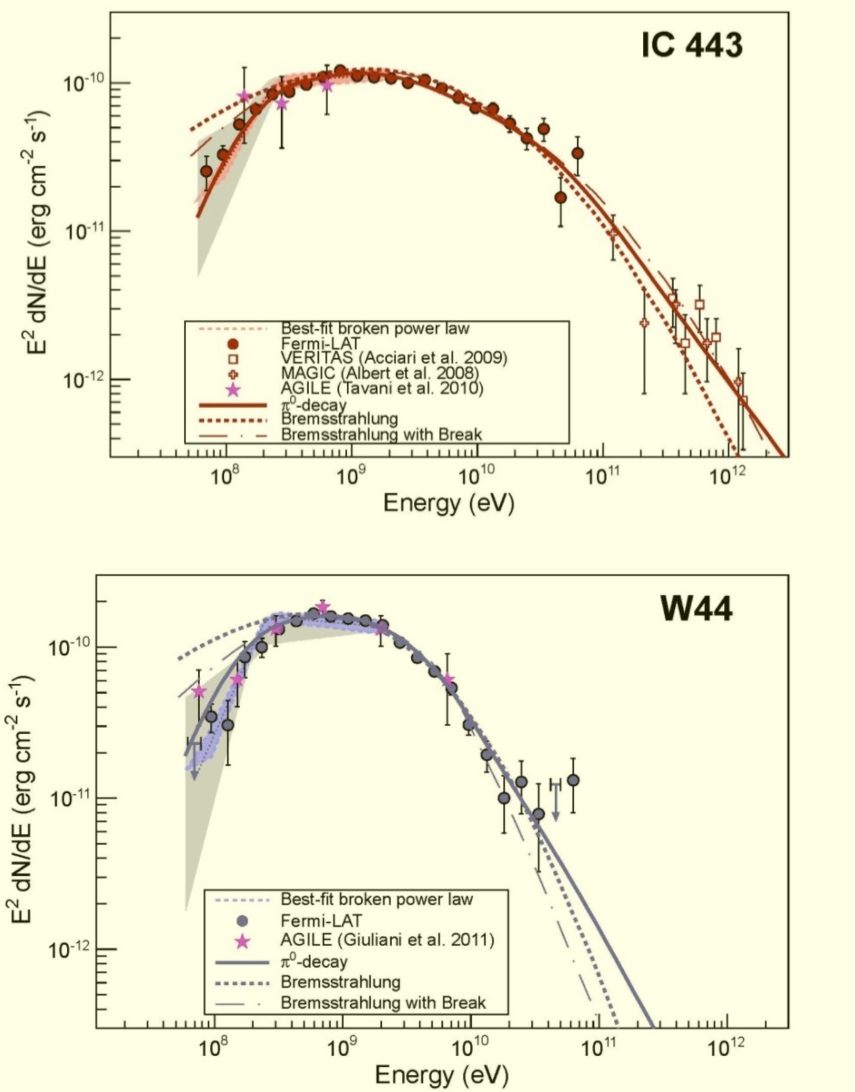
$$Q_E(E \sim 10\text{GeV}, z=0) \approx 5\left(\frac{0.3}{f_{synch.}}\right)\times 10^{44}\,\text{erg}/\text{Mpc}^3\text{yr}$$

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

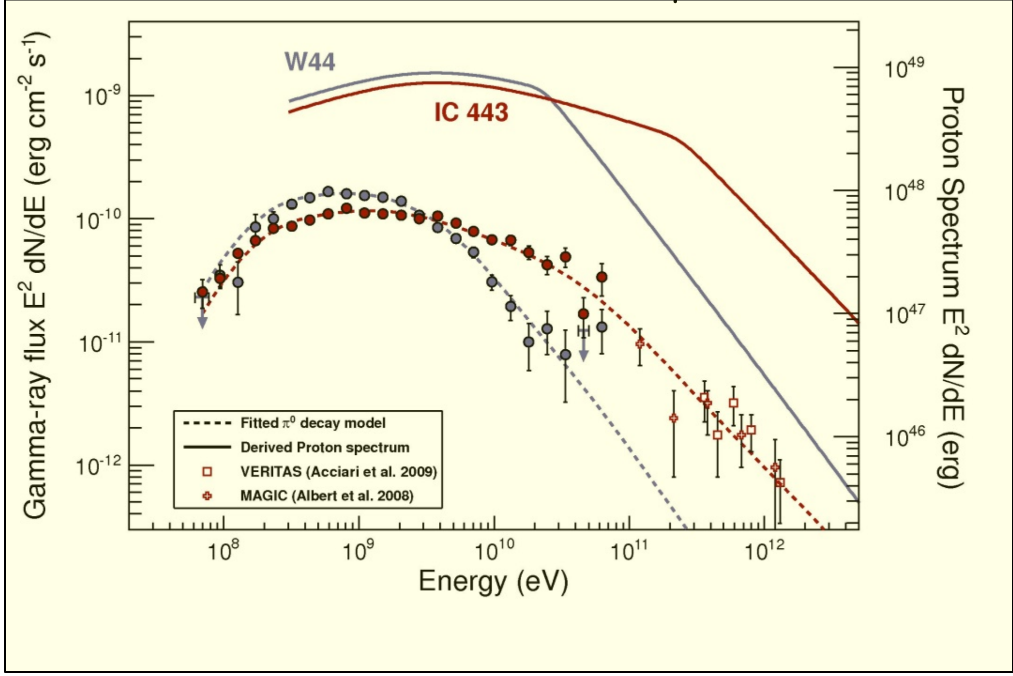
[Katz, EW, Thompson & Loeb 14]

Are SNRs the sources of E<1PeV CRs?

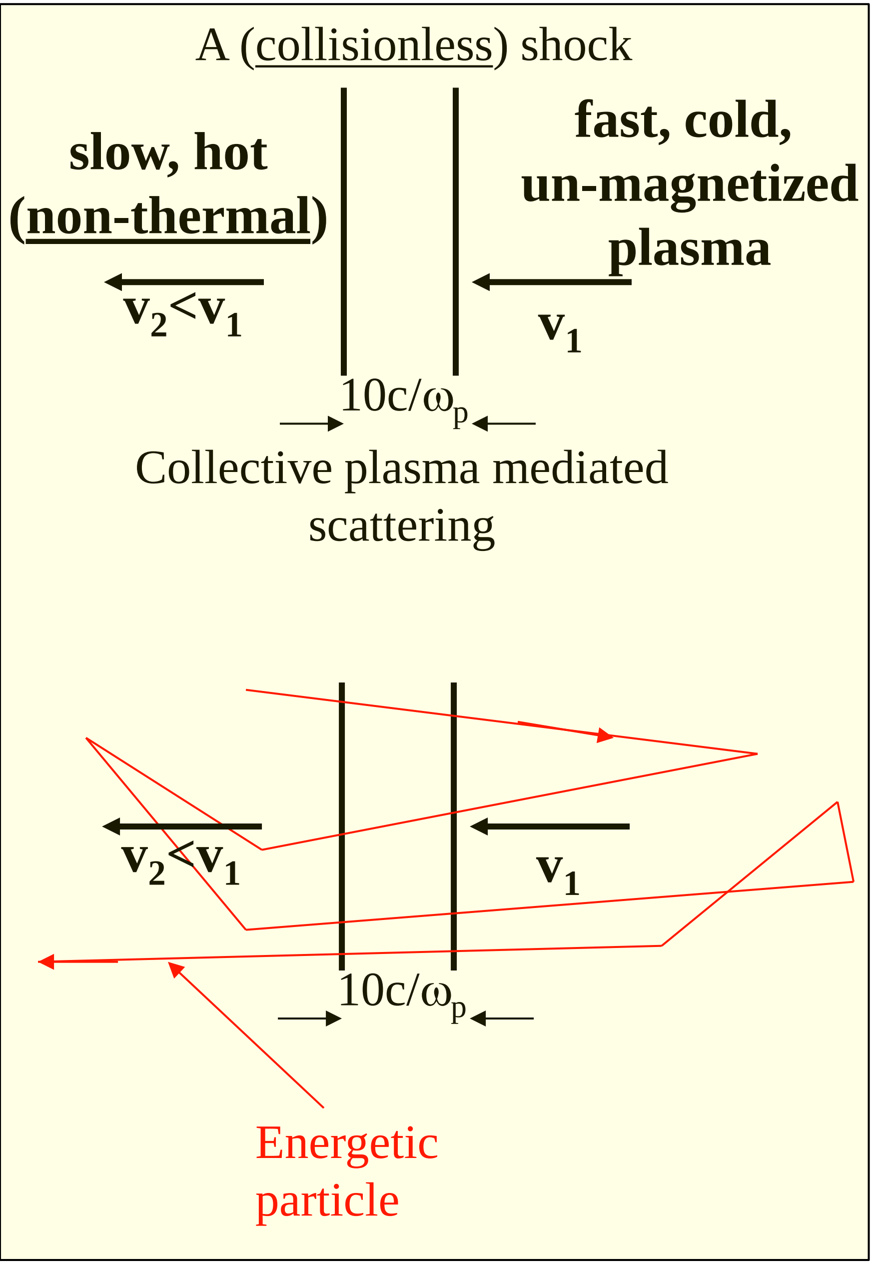
π^0 decay signature [Ackermann et al. 13].



- 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

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

[Krymsky 77; Kehset & EW 05]

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

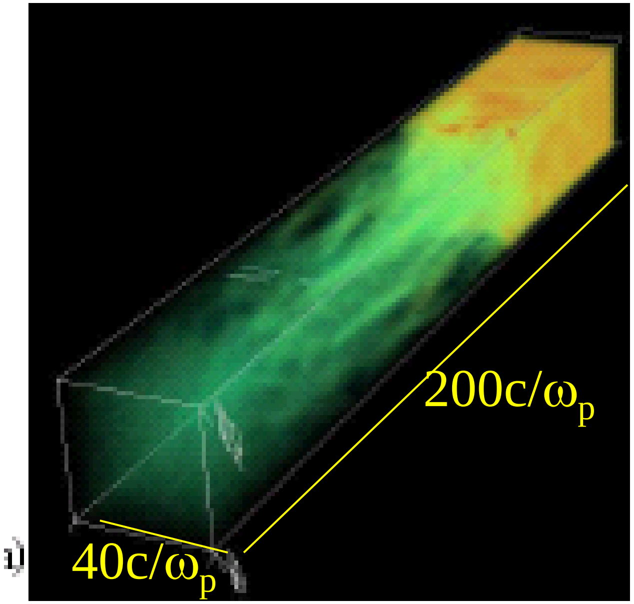
- Supported by basic principles plasma simulations.

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

- [The only predictive model.]

Collisionless shocks: Plasma simulations

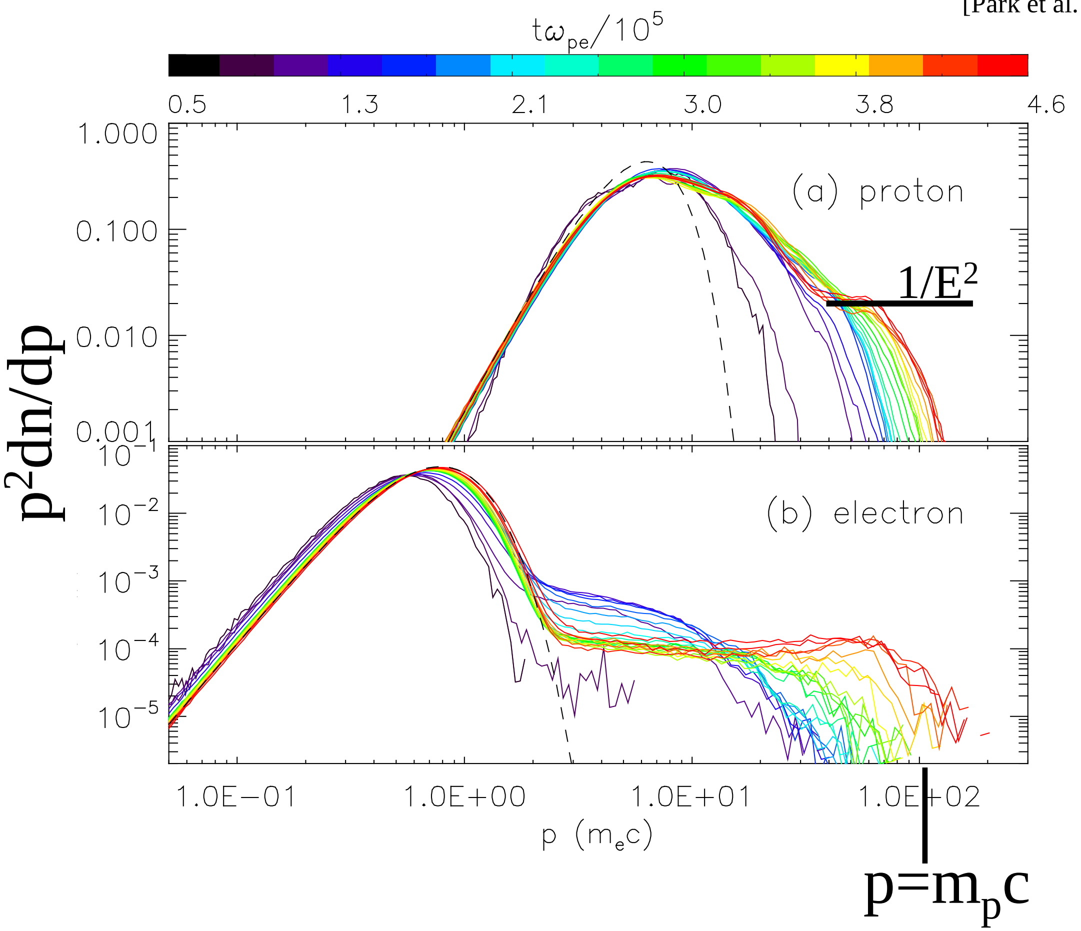
3D, $m_p/m_e=1$



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

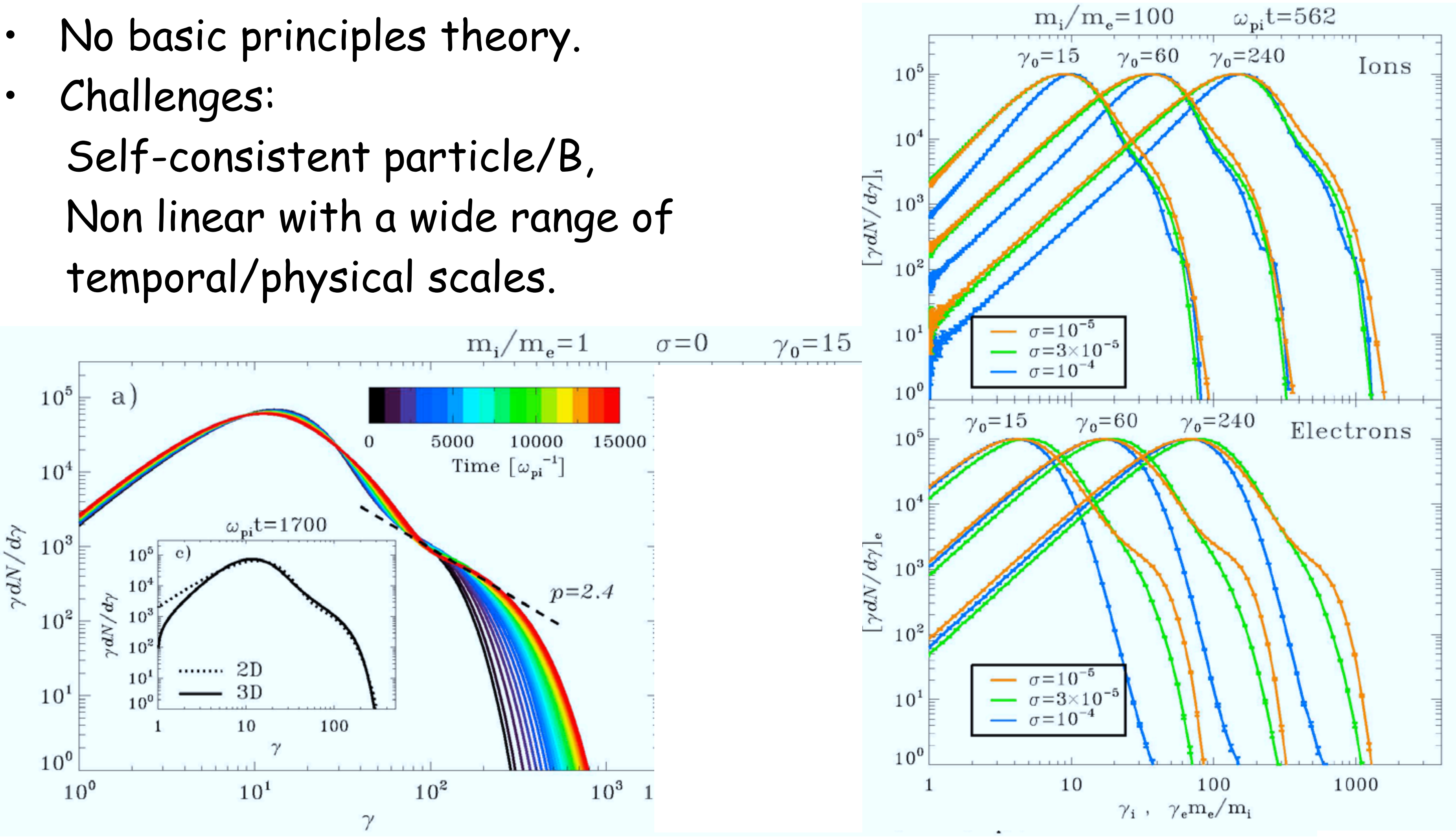
1D, $m_p/m_e=100$, $L=10^3 c/\omega_p$

[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]

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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