IceCube's neutrinos:
The beginning of extra-galactic neutrino astronomy

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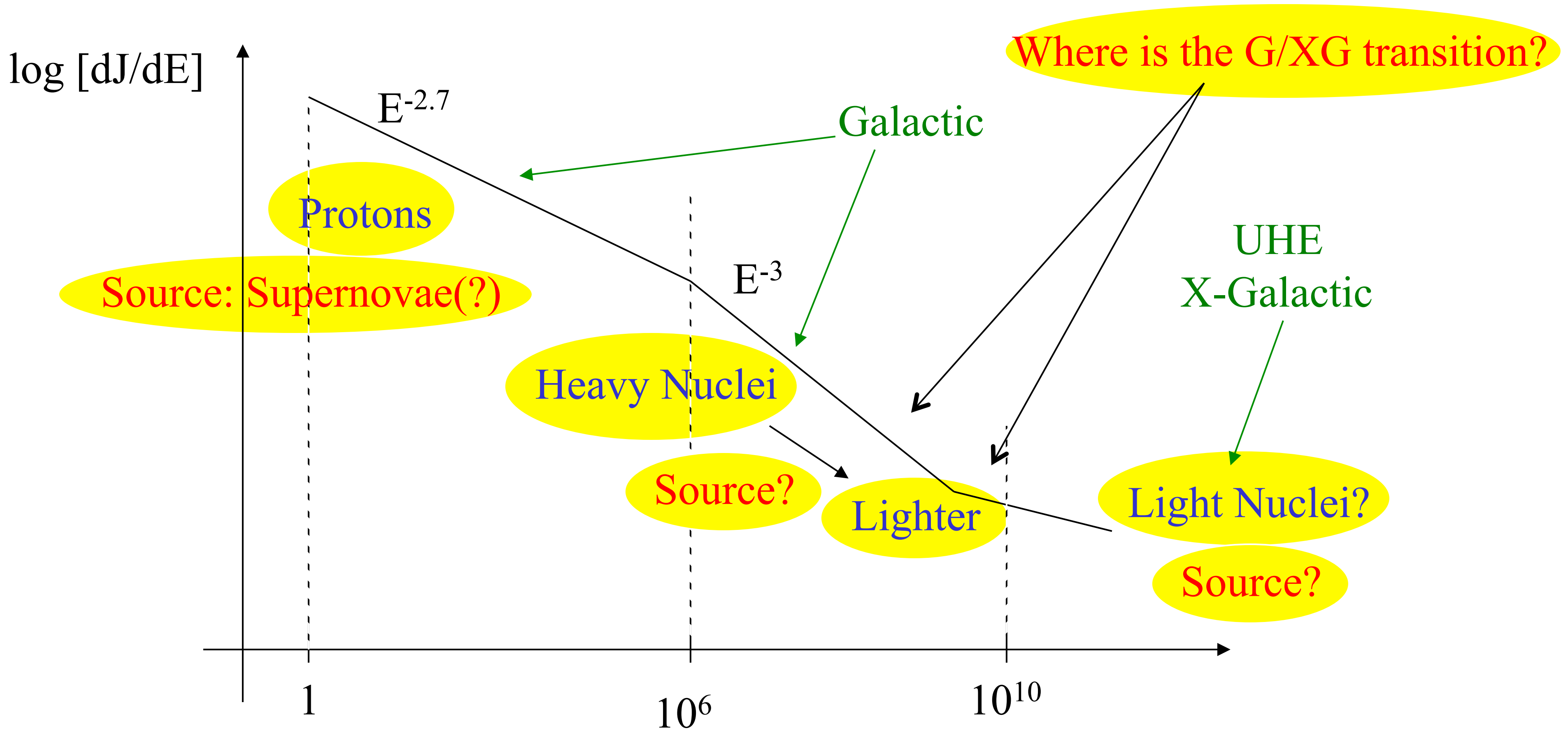
The main driver of HE ν astronomy: The origin of CRs



Cosmic-ray E [GeV]

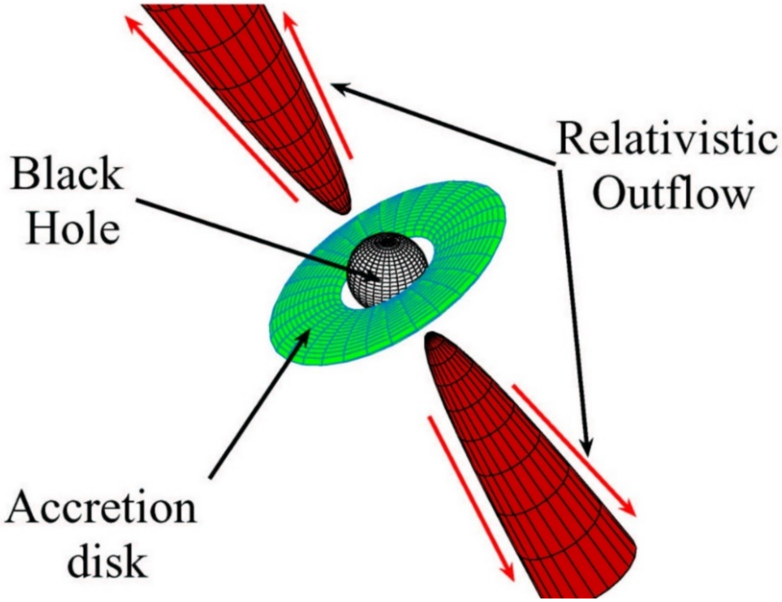
[Reviews: Helder, et al. 12; Lemoine 13]

The >10^{10}GeV challenge

- Electromagnetic acceleration in astrophysical sources requires
  $L > 10^{14} L_{Sun} (\Gamma^2/\beta) (\varepsilon/Z\ 10^{20}eV)^2$. [Lovelace 76; EW 95, 04; Norman et al. 95]

- Propagation limited due to interaction with radiation backgrounds
  (CMB, IR) to <0.5 Gyr → Must be transient.

- Leading "engines":
  Relativistic jets driven by rapid mass accretion onto black holes.
  - Newly formed solar mass BHs (GRBs) [EW 95] ,
  - Stellar disruption by massive BHs at galaxy centers [Gruzinov & Farrar 09].



- Many open Q's:
  Energy extraction, Jet acceleration and content (kinetic/Poynting),
  Particle acceleration, Radiation mechanisms.

High energy ν telescopes

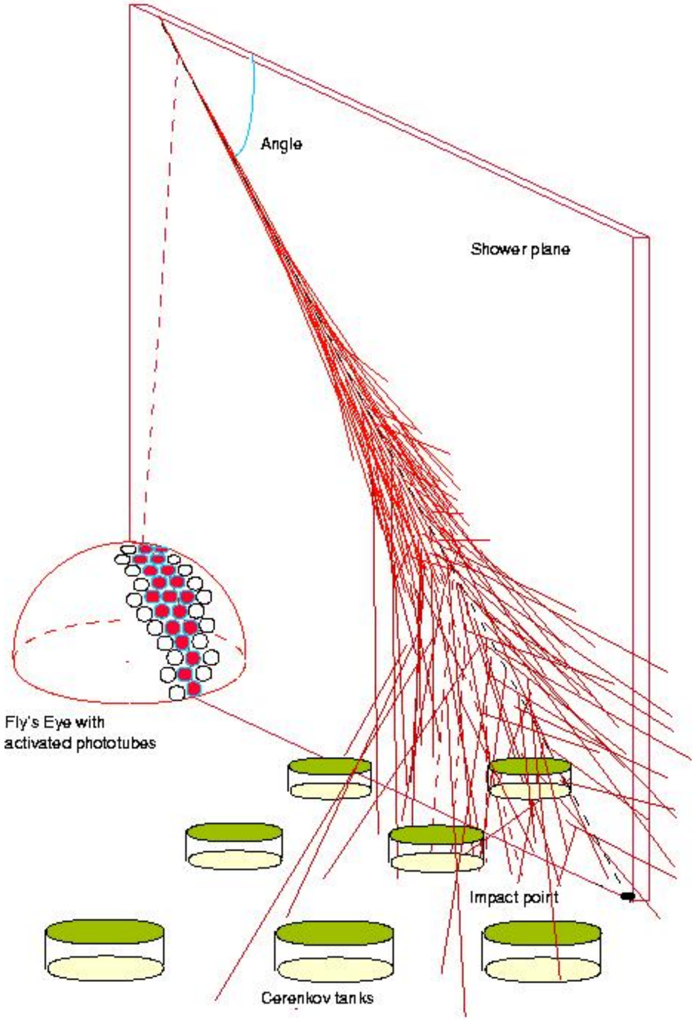
- Detect HE ν's from

  p)A)-p/p(A)-γ → charged pions → ν's

  $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu_\mu} + \nu_\mu$

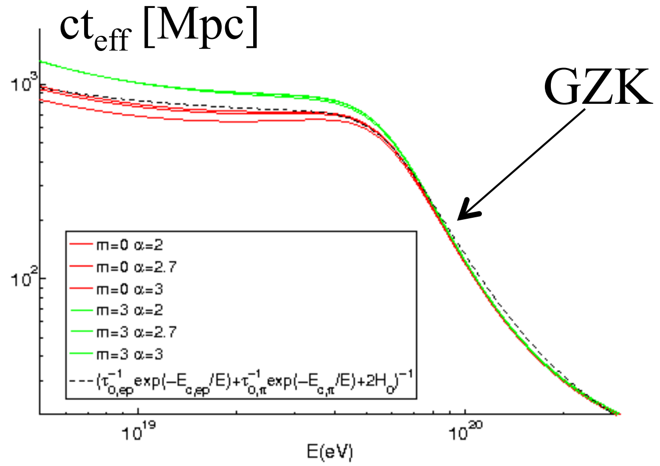
  $\varepsilon_\nu/(\varepsilon_A/A) \sim 0.05$

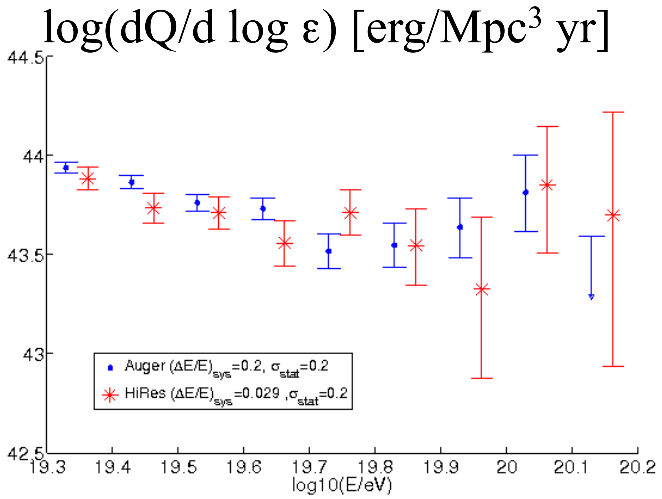
- Goals:
  - Identify the particles,
  - Identify the sources,
  - Study source/acceleration physics,
  - Study ν/fundamental physics.



>10^{10}GeV spectrum: hints for p's

4 π j= c Q t





- p + γ[CMB] → N + π
  limits p life time (propagation)
  above $10^{19.7}$eV

- Assuming p, obs. imply

$$dQ/d\log\varepsilon \equiv \varepsilon_p^2 d\dot{n}_p/d\varepsilon_p = Const.$$

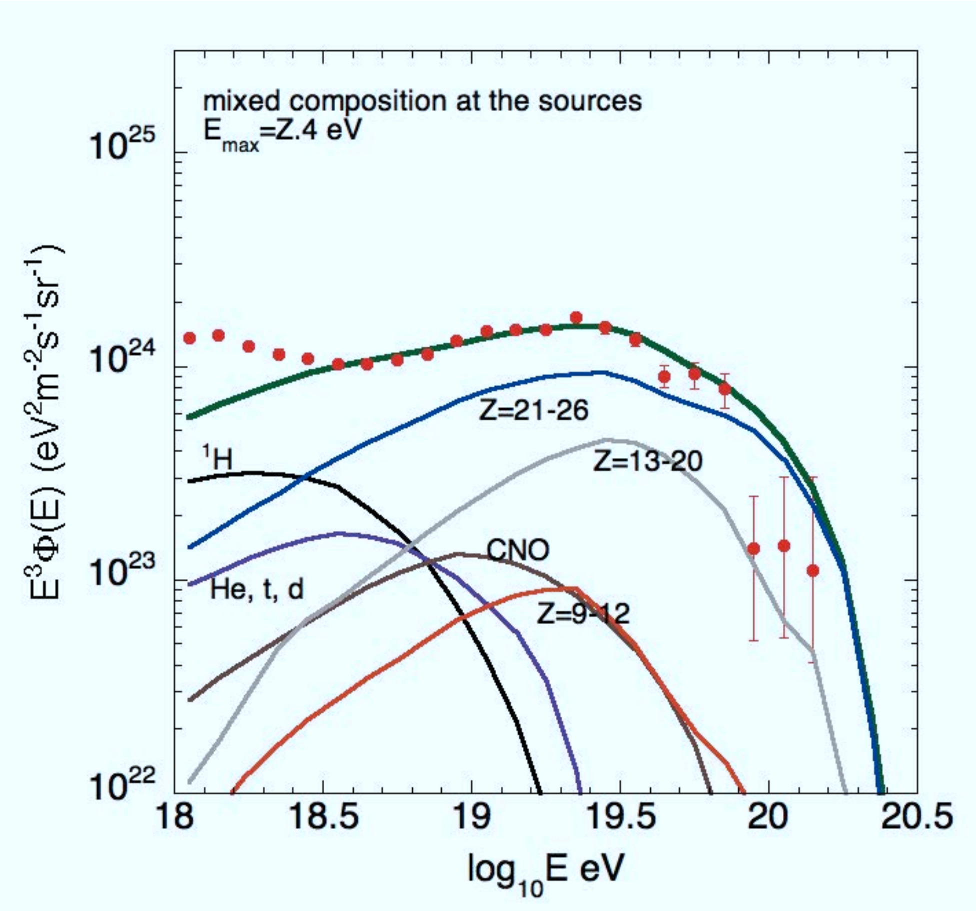
$$= (0.5 \pm 0.2)\times 10^{44}\,\mathrm{erg/Mpc^3yr}$$

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

- dQ/d log E =Const.:
  - Observed in a wide range of systems,
  - Obtained in collision-less shock acceleration (the only predictive model of particle acceleration).

[Krimsky 77; R. Blandford & Eichler 87; Axford 95; Keshset & EW 05; Sironi et al. 13 ...]

Mixed composition



[Allard 12]

HE Neutrinos: predictions

For cosmological proton sources,

$$dQ/d\log\varepsilon \equiv \varepsilon_p^2 d\dot{n}_p/d\varepsilon_p = Const. = (0.5\pm 0.2)\times 10^{44}\,\mathrm{erg/Mpc^3yr} \quad .$$

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

$$\varepsilon_\nu^2\frac{dj_\nu}{d\varepsilon_\nu} \le \Phi_{\mathrm{WB}} \equiv \frac{3}{8}\frac{ct_H}{4\pi}\zeta\frac{dQ_p}{d\log\varepsilon} = 2.5\times 10^{-8}\,\zeta\left(\frac{dQ/d\log\varepsilon}{10^{44}\,\mathrm{erg/Mpc^3yr}}\right)\frac{\mathrm{GeV}}{\mathrm{cm^2s\,sr}},$$

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

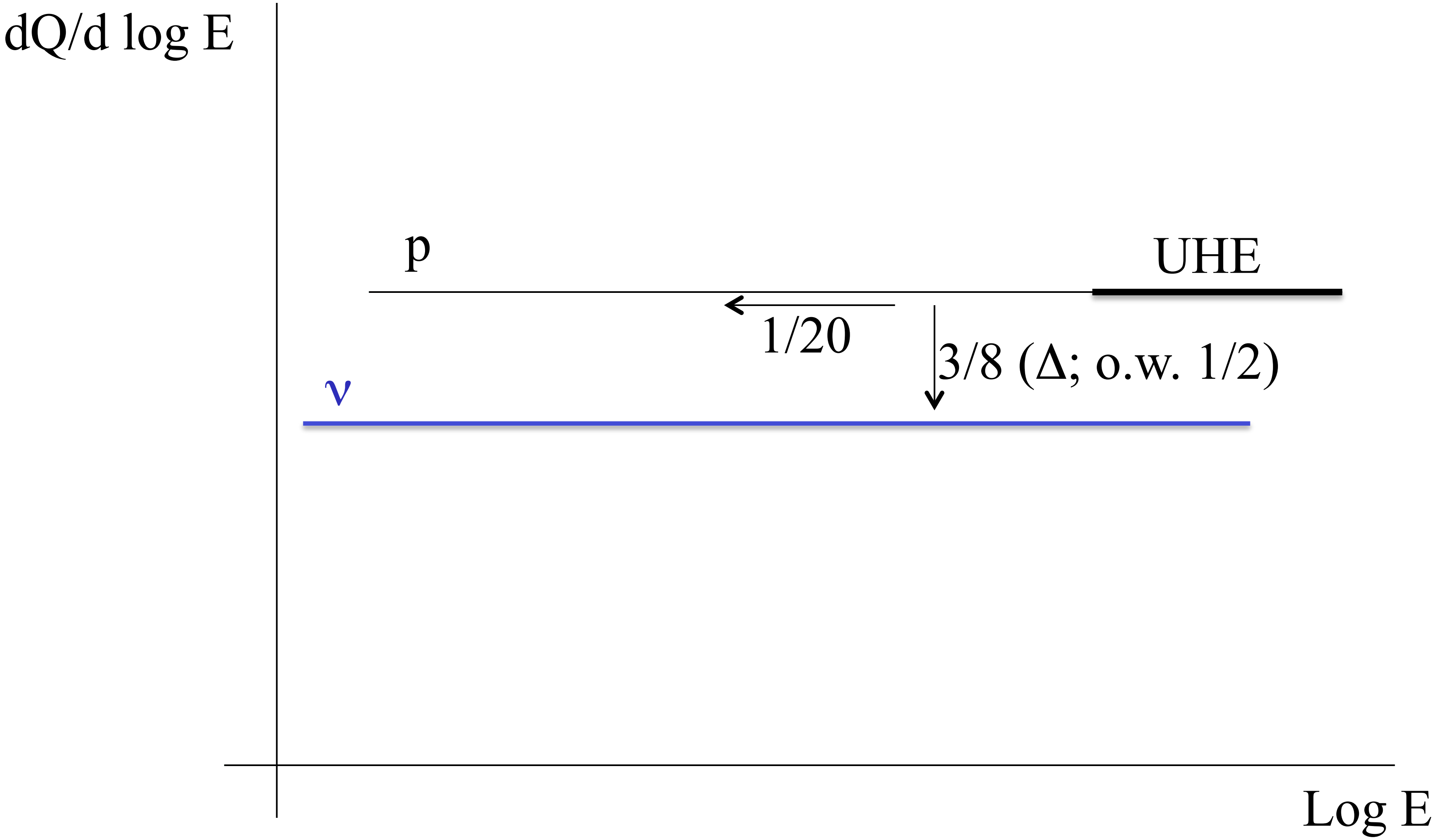
[EW & Bahcall 99;
Bahcall & EW 01]

- For example: $\Phi_{\mathrm{GRB}} \approx 0.1\,\Phi_{\mathrm{WB}}$ at 10^6GeV<E<10^8GeV,
  $\Phi_{\mathrm{GRB}} \approx 0.01\,\Phi_{\mathrm{WB}}$ at 10^5GeV.

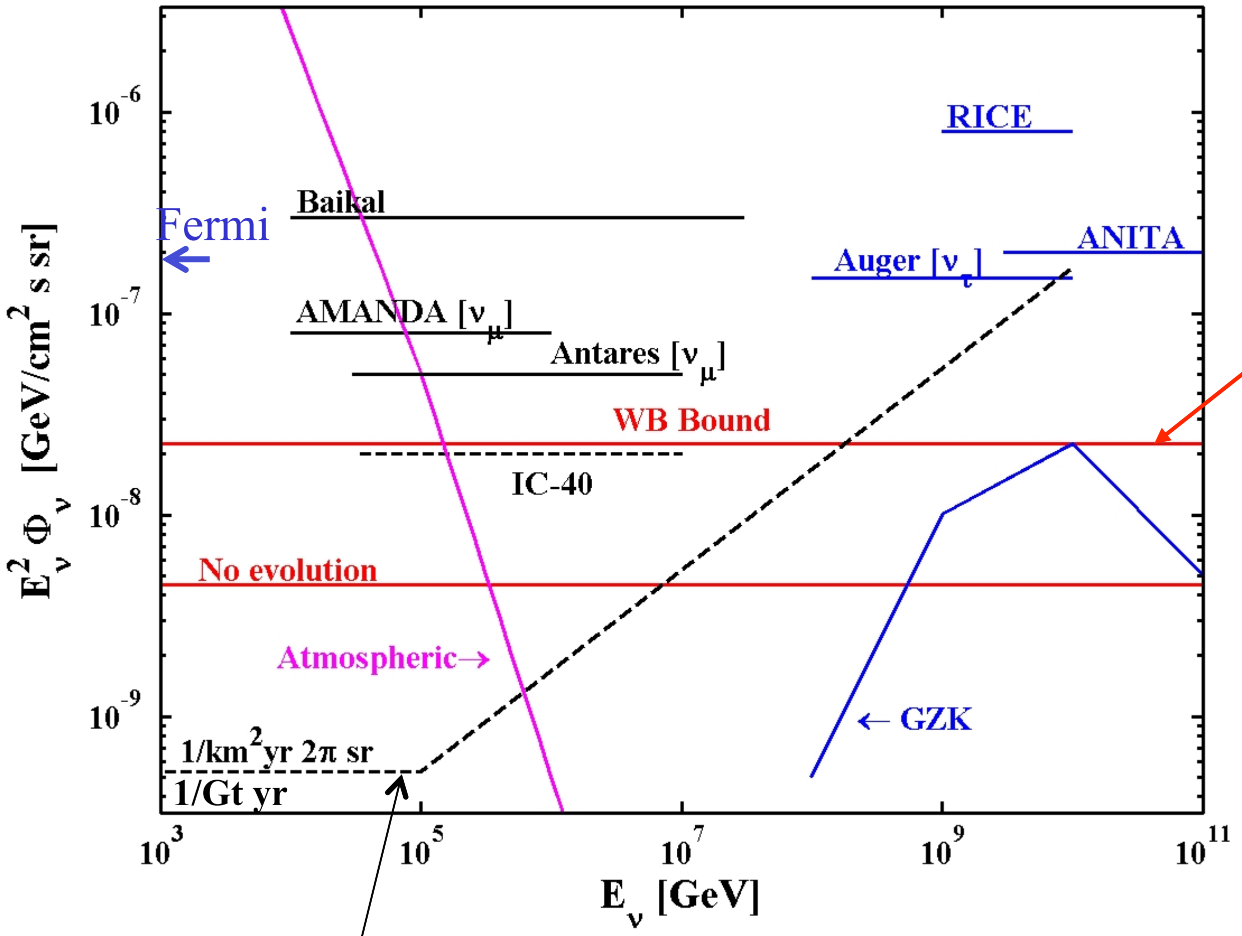
[EW & Bahcall 97]

- Saturation of the bound at
  - At ~10^{10}GeV (GZK), [Berezinsky & Zatsepin 69]
  - <~10^6GeV (If sources reside in star-forming galaxies). [Loeb & EW 06]

WB bound: p and ν production



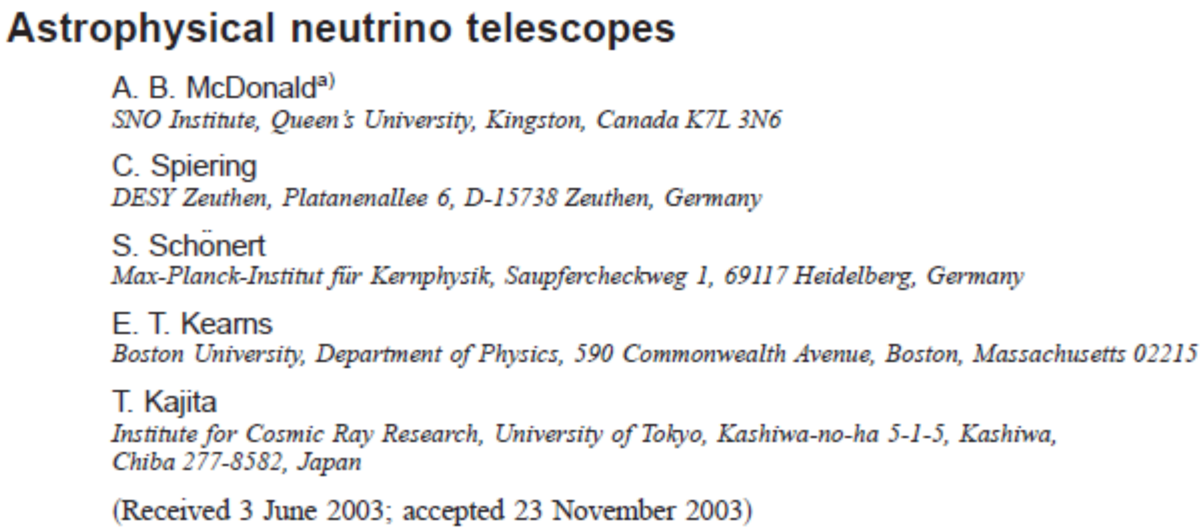
Bound implications: >1Gton detector (natural, transparent)



2 flavors,

$$\frac{dQ/d\log\varepsilon}{10^{44}\,\mathrm{erg/Mpc^3yr}} = 0.5$$

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



Astrophysical neutrino telescopes

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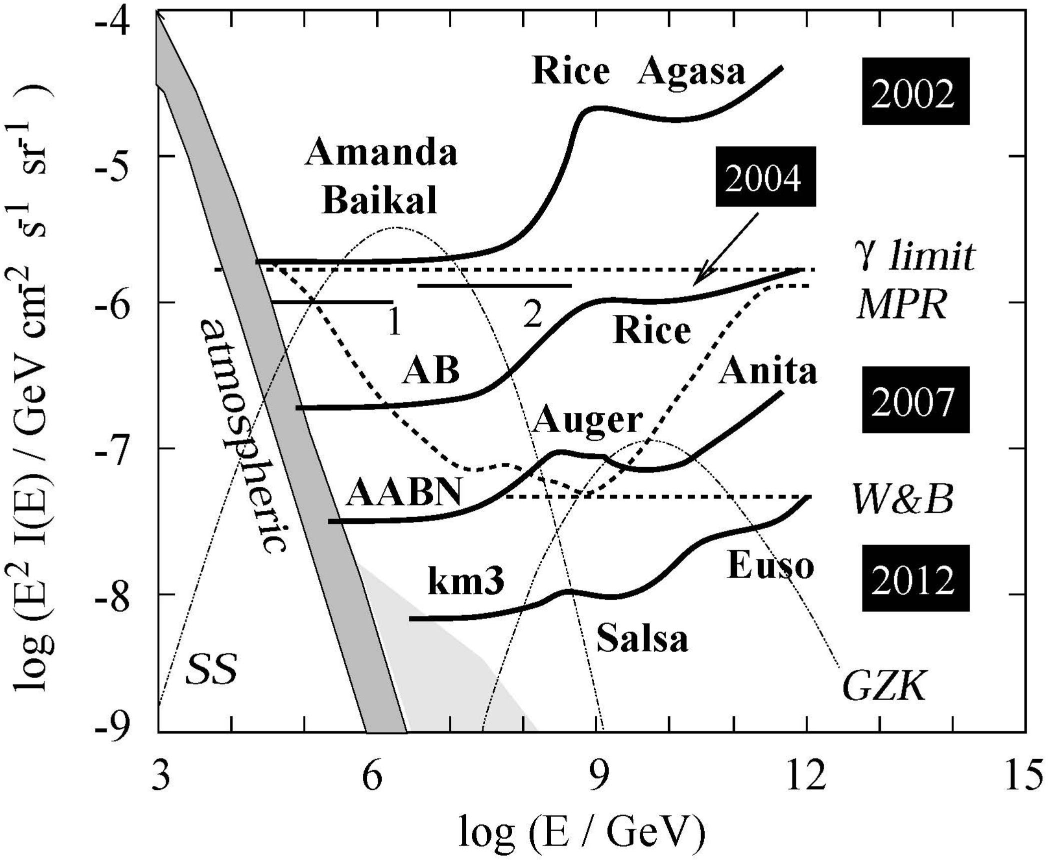
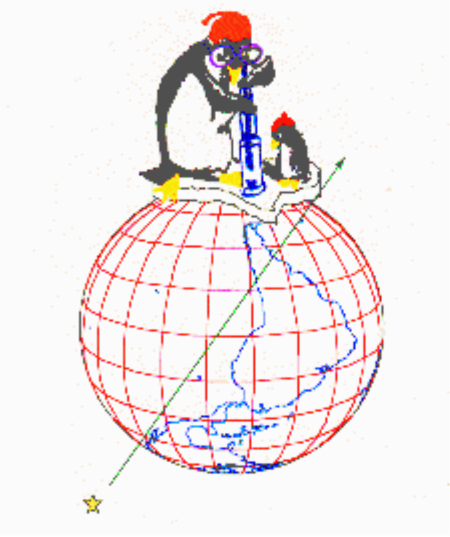
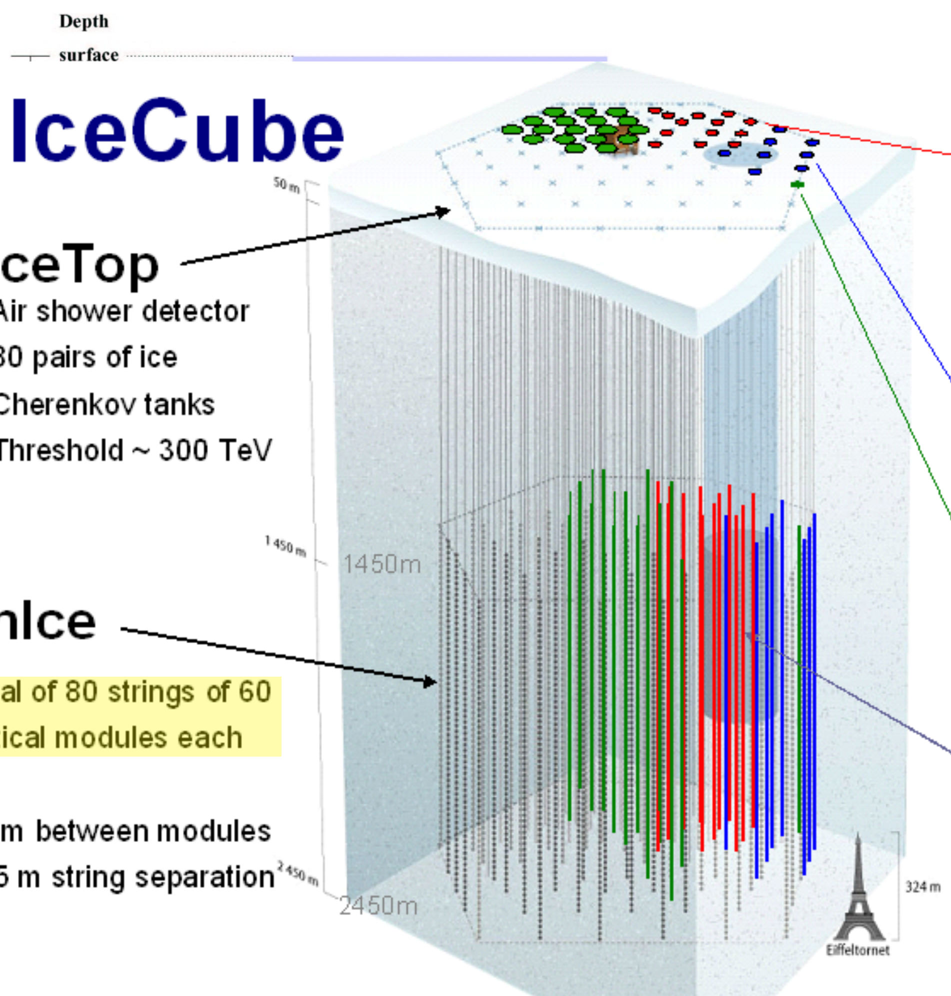
(Received 3 June 2003; accepted 23 November 2003)

[Rev. Sci. Inst]



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

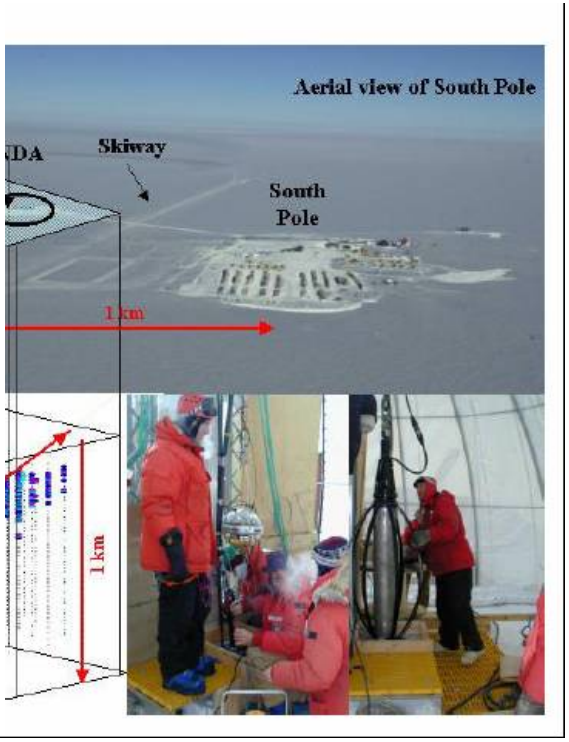
2004-2005 : 1 string

AMANDA-II
19 strings
677 modules

Current configuration:
40 strings,
40 IceTop stations
plus AMANDA

2008/09: add 18 strings and
tank stations

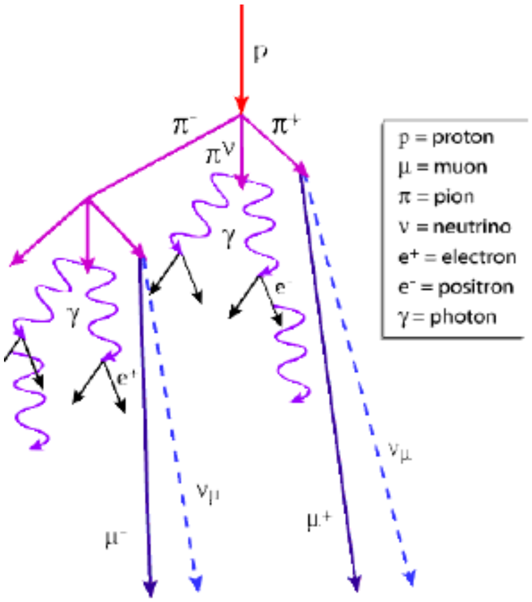
Completed Dec 2010

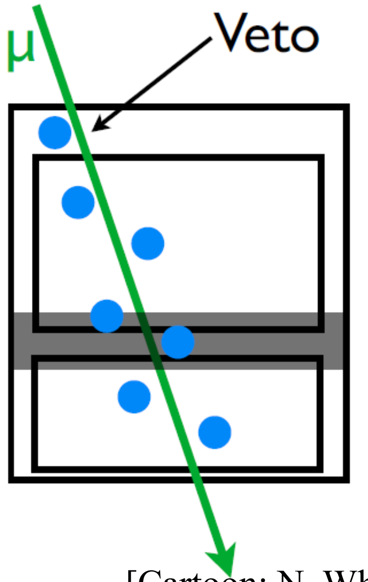


Looking up: Vetoing atmospheric neutrinos

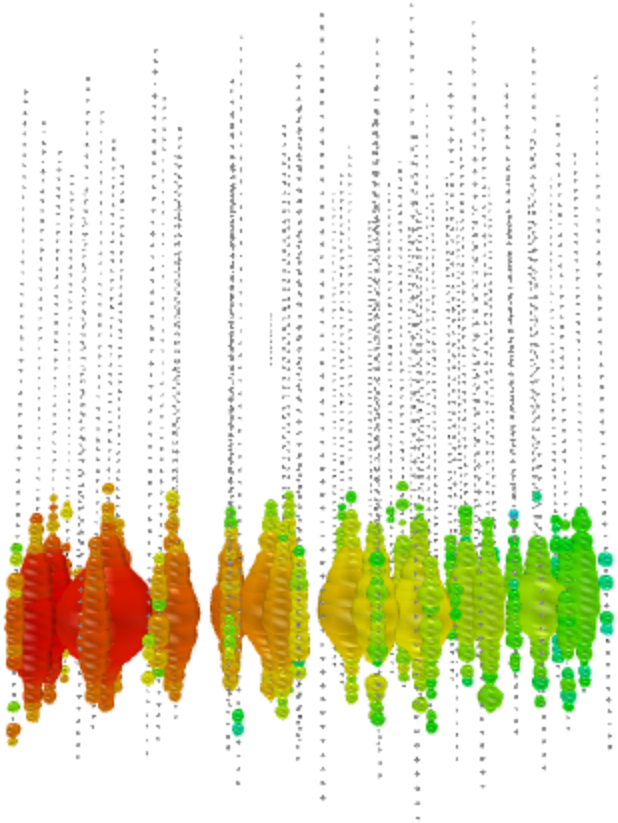
[Schoenert, Gaisser et. al 2009]

- 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).

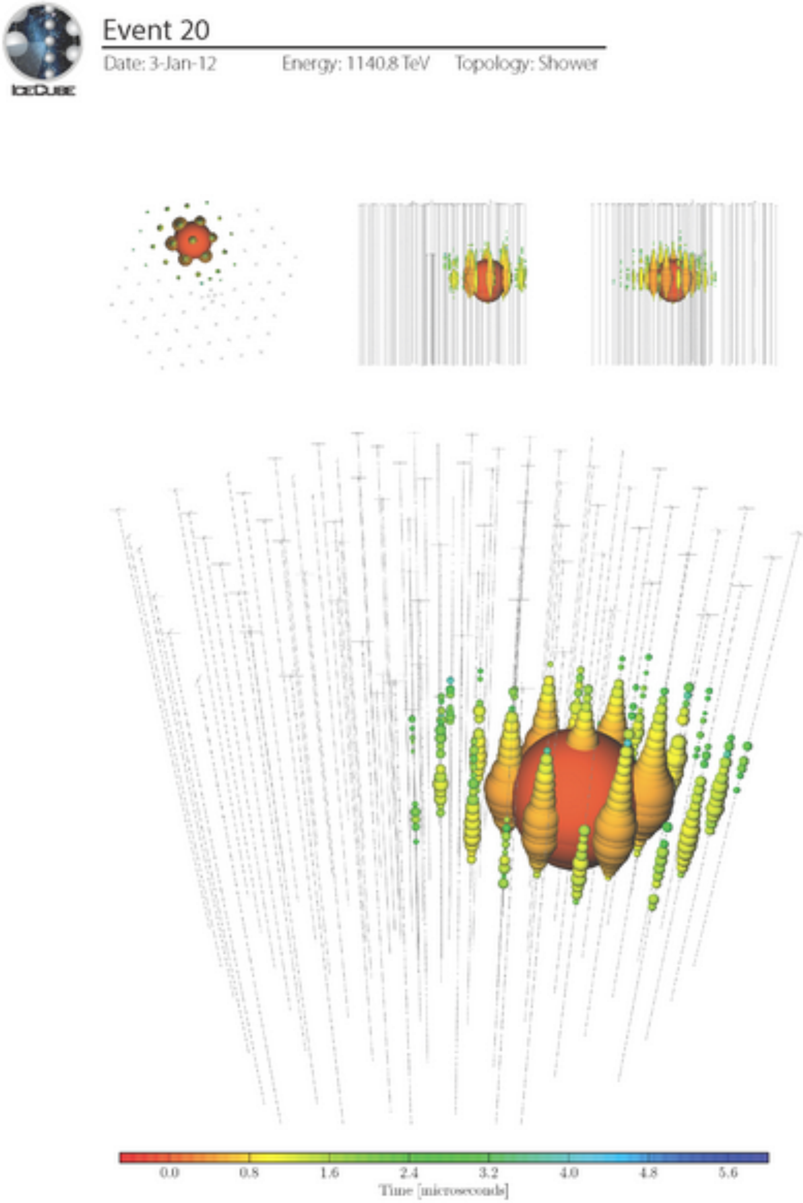




[Cartoon: N. Whitehorn]



400TeV

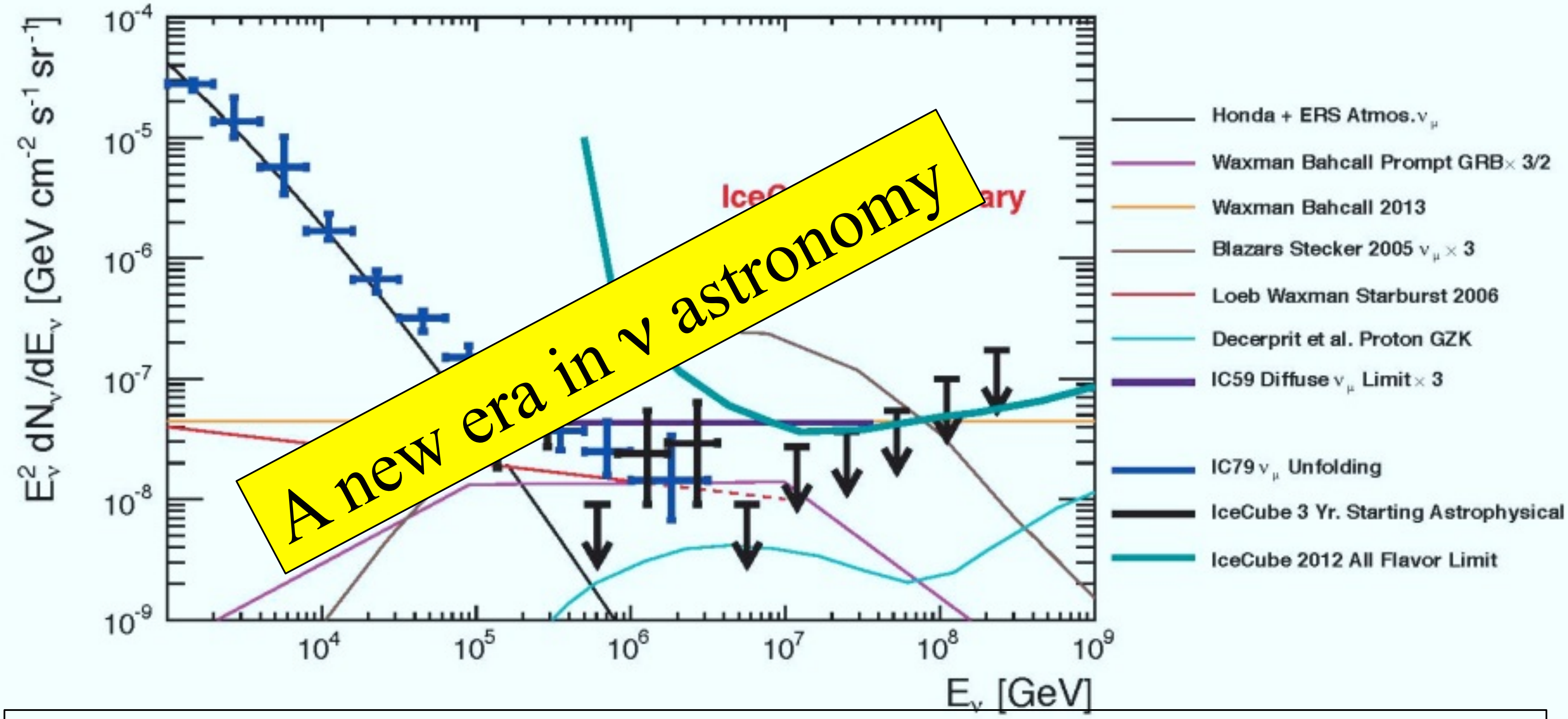


1100TeV

IceCube: 37 events at 50Tev-2PeV

~6σ above atmo. bgnd.

[02Sep14 PRL]



A new era in ν astronomy

$\varepsilon^2\Phi_\nu = (2.85+-0.9)\mathrm{x}10^{-8}\mathrm{GeV/cm^2sr\ s} = \varepsilon^2\Phi_{WB} = 3.4\mathrm{x}10^{-8}\mathrm{GeV/cm^2sr\ s}$ (2PeV cutoff?)
Consistent with Isotropy and
with $\nu_e{:}\nu_\mu{:}\nu_\tau = 1{:}1{:}1$ (π deacy + cosmological prop.).

Astrophysical neutrino telescopes

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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:

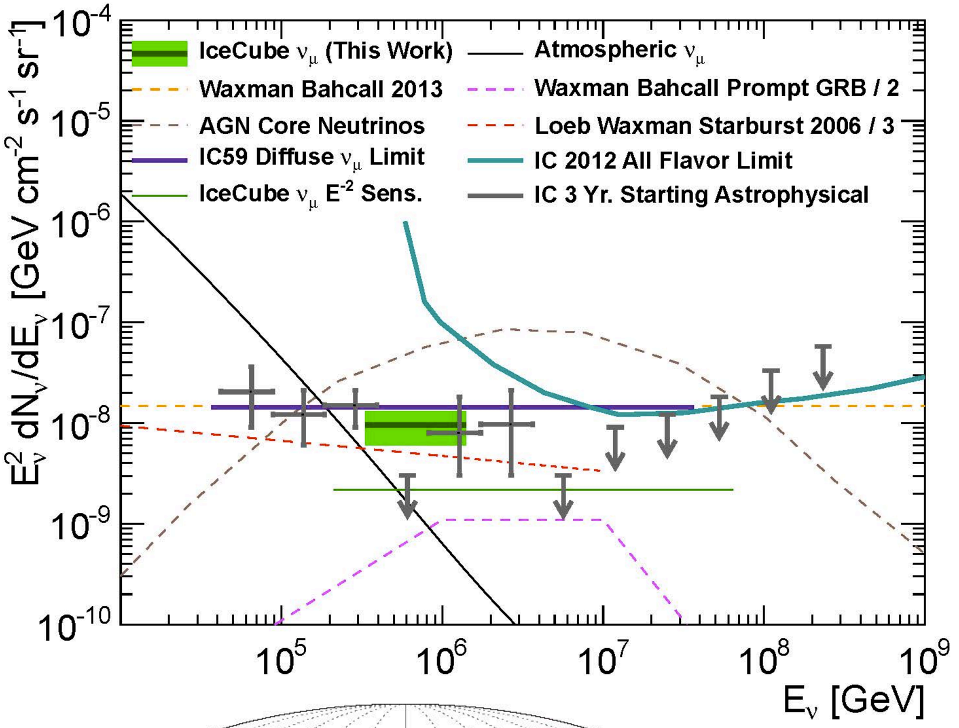
- 2002 Davis (Cl) & Koshiba (Kamiokande)

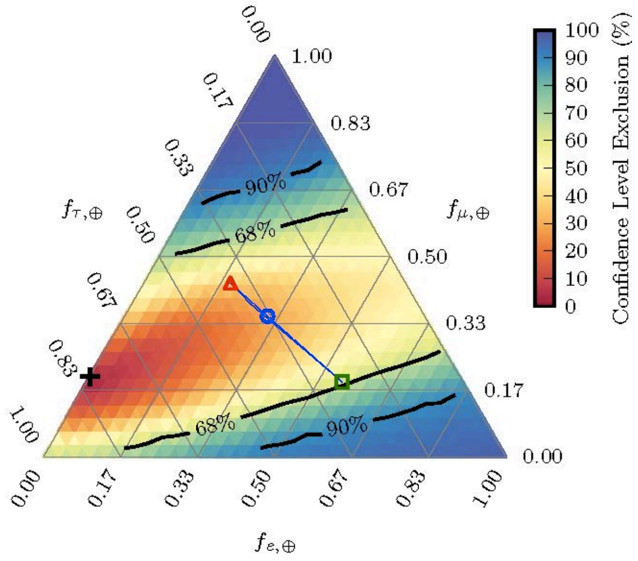
"*for pioneering contributions to … detection of cosmic ν's*";

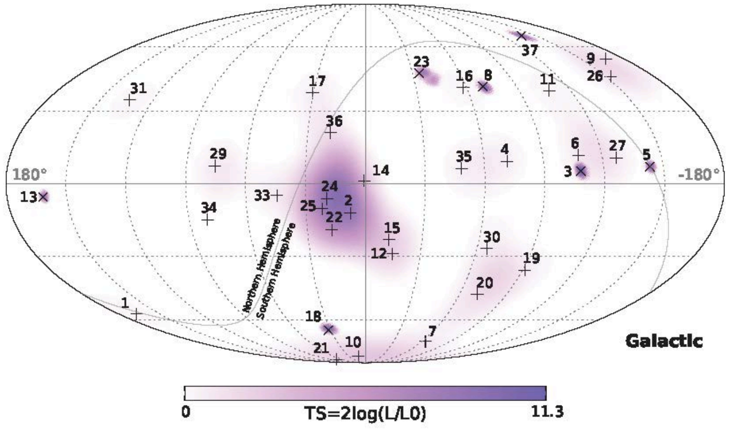
- 2015 McDonald (SNO) and Kajita (Super-K)

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

Flux, spectrum, isotropy & flavor ratio [July 15]

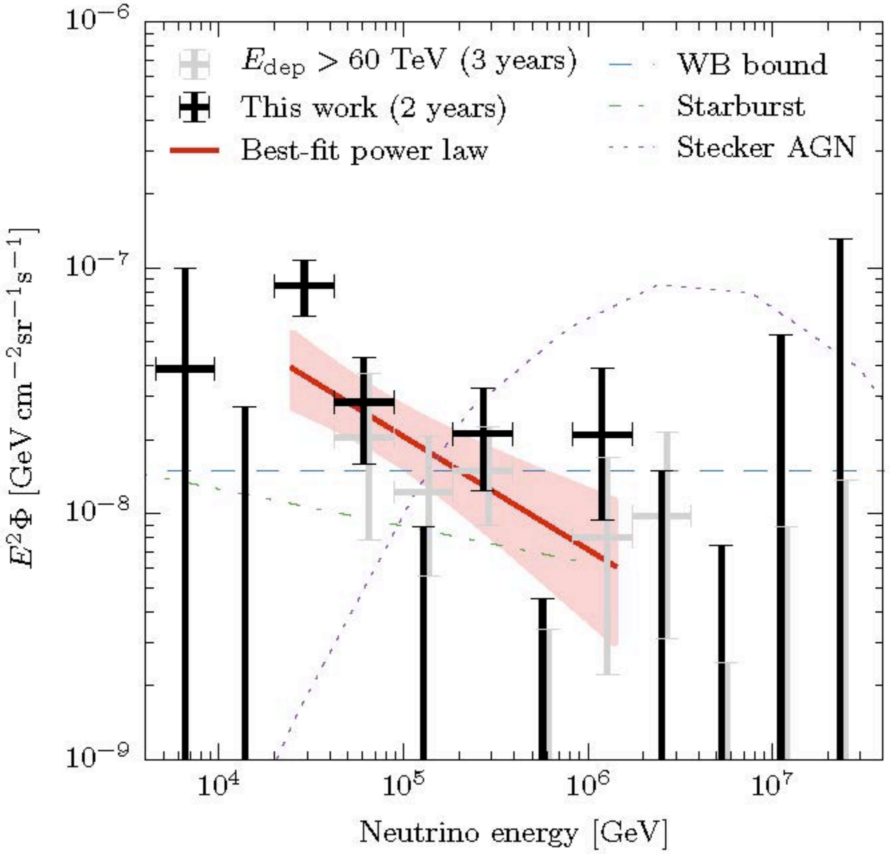






Without new physics,
Nearly single parameter
(~f_e @ source).

Lower energy: a ~30 TeV 'excess'?



- Excess at ~30TeV point → d log n_ν/d log ε=-2.46+-0.12; softer than 2.2 at 90% cl.

- >50 TeV spectrum d log n_ν/d log ε=-2 (-1.9+-0.2)
- A new low E component?
- Note:
  - Binning,
  - Southern hemisphere only,

  (- Fermi XG γ bgnd limit).

IceCube's detection: Implications

- DM decay?

  The coincidence of 50TeV<E<2PeV ν flux, spectrum (& flavor) with the WB bound is unlikely a chance coincidence.

- Unlikely Galactic: Isotropy,

  and $\varepsilon^2\Phi_\gamma \sim 10^{-7}(E_{0.1\mathrm{TeV}})^{-0.7}$ GeV/cm^{2}s sr [Fermi]

  → $\varepsilon^2\Phi_\nu \sim 10^{-9}(E_{0.1\mathrm{PeV}})^{-0.7}$ GeV/cm^{2}s sr $\ll \Phi_{WB}$.

  If Galactic: New, unknown sources; Chance coincidence with WB.

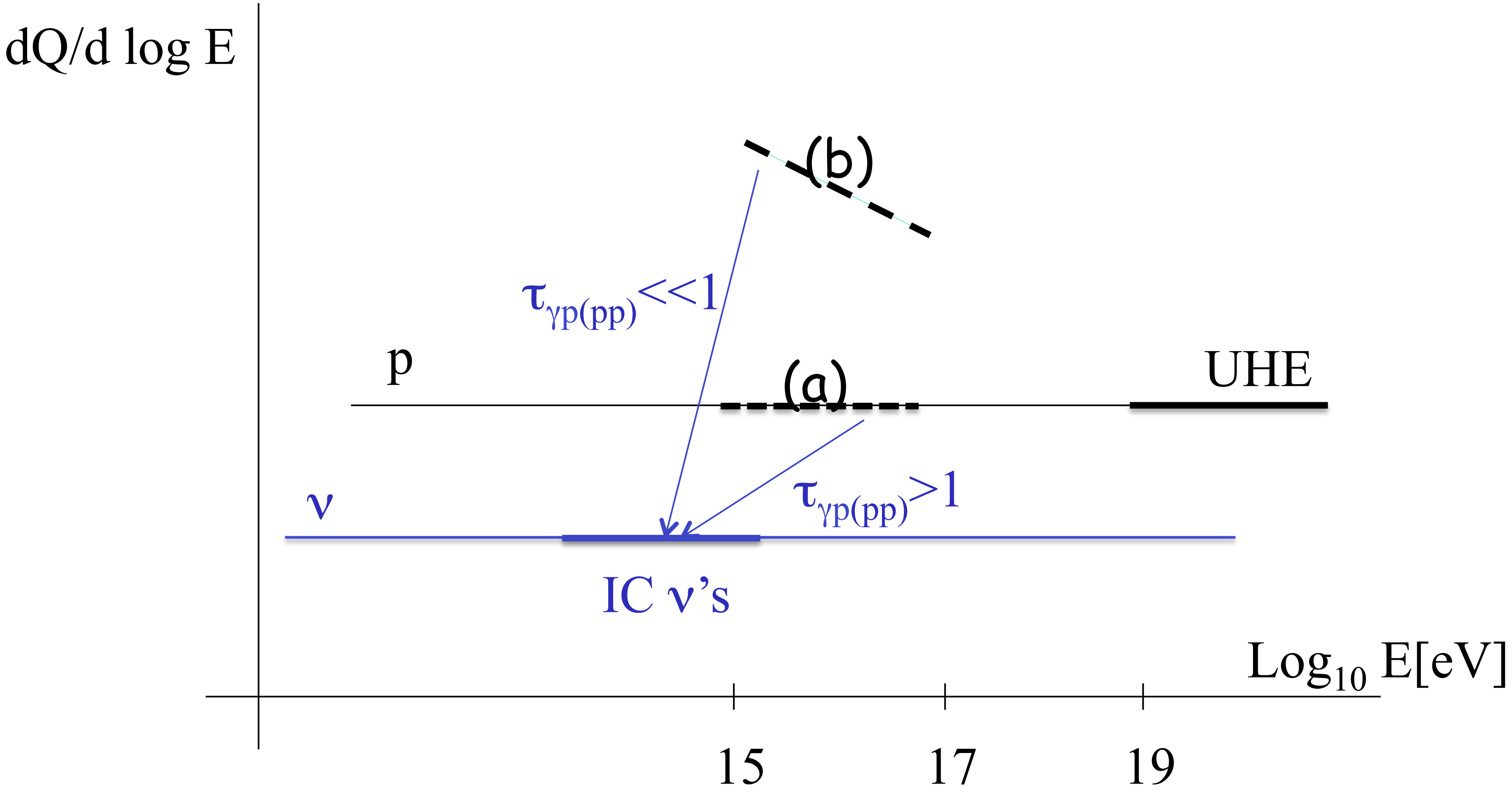
- → XG sources.
- Recall: known UHECR sources cannot account for IC's flux ($\tau_{\gamma p(pp)}<1$).

IceCube's detection: XG CR pion production

(a) UHE CR sources reside in ($<10^{17}$eV) "Calorimeters",

or

(b) $Q \gg Q_{UHE}$ sources (unknown) with $\tau_{\gamma p(pp)} \ll 1$ (ad-hoc)
& Coincidence over a wide energy range.



Star forming galaxies: candidate CR calorimeters

- Starbursts: $(n,B,SFR)/(n,B,SFR)_{MW} \sim 100\text{-}1000$; 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 $f(p \to \pi)$:
  - $t(p \to \pi) < t(\text{wind})$ → $\Sigma_{disk} > m_p v/\sigma_{pp} c = 0.03\, v/300\ \mathrm{km/s}\ \ \mathrm{g/cm}^2 \equiv$ "starburst".
  - $f(p \to \pi) = \min(1, 0.5\sigma_{pp}/m_p \Sigma_{diff}.)$, scaling from the MW→ f=1 to E> 1PeV.

- Most of the stars in the universe were formed in galaxies with high SFR.

  If $Q_{CR} \sim SFR$ Then $\Phi_\nu(\varepsilon_\nu < 1\mathrm{PeV}) \sim \Phi_{WB}$ [Loeb & EW 06] .

- 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]:

Fermi's XG γ-ray background [EGB]

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

- $Q_\gamma \sim (2/3)Q_\nu$ → For 'flat' generation spectrum, $d \log n_p/d \log \varepsilon_p = -2$, $\varepsilon^2\Phi_\gamma \sim (2/3)\varepsilon^2\Phi_\nu \sim 0.2\times10^{-7}$GeV/cm^{2}s sr.
- Interaction of >~1TeV photons with IR background gives $\varepsilon^2\Phi_\gamma([0.05,0.1,0.8]$ TeV ~ $[0.4, 0.2, 0.01]\times10^{-7}$GeV/cm^{2}s sr, i.e.: $\varepsilon^2\Phi_\gamma \sim 0.1$ EGB.

- Implications:
  - Flat generation spectrum, $d \log n_p/d \log \varepsilon_p > -2.2$ (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 ($d \log n_p/d \log \varepsilon_p = -2.5$).

Constraints on source density

$$n_s L_{\nu_\mu} \approx 0.6\times 10^{43}\left(\frac{\zeta}{3}\right)^{-1} \text{erg/Mpc}^3\ \text{yr} \quad\Rightarrow\quad L_{\nu_\mu} \approx 2\times 10^{42}\left(\frac{\zeta}{3}\,\frac{n_s}{10^{-7}\,\text{Mpc}^{-3}}\right)^{-1} \text{erg/s}\,,$$

$$f_{\lim} \approx \frac{E_\nu}{AtP_{\nu\mu}} \approx 10^{-12}\ \text{erg/cm}^2\text{s} \quad\Rightarrow\quad d_{\lim} \equiv \left(\frac{L_{\nu_\mu}}{4\pi f_{\lim}/2.4}\right)^{1/2} \approx 150\ \left(\frac{\zeta}{3}\,\frac{n_s}{10^{-7}\,\text{Mpc}^{-3}}\right)^{-1/2} \text{Mpc}\,,$$

$$N_s(\text{multiple}\quad \nu_\mu\quad \text{events}) = \frac{2\pi}{3} n_s d_{\lim}^3 \approx 1\left(\frac{\zeta}{3}\right)^{-3/2}\left(\frac{n_s}{10^{-7}\,\text{Mpc}^{-3}}\right)^{-1/2} \quad \propto A^{3/2}\,.$$

- The absence of multiple-ν_μ-event sources implies:

$$n_s > 10^{-7}(\zeta/3)^{-3}/\text{Mpc}^3\,,\quad N_s > 10^6,\quad \frac{N_s}{4\pi} > 30/\deg^2,\quad L_\nu < 3\times 10^{42}\,\text{erg/s}\,.$$

<u>Implications</u>:

- Identify sources by angular correlation with catalogs- unlikely:

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

- Bright AGN (FSRQ, BL Lac, n~10^{-11}(10^{-8})/Mpc^3)- Ruled out.
- Starbursts, n~10^{-5}/Mpc^3- a few should be detected with A X 10.

Identifying the CR sources

- IC's ν's are produced by the "calorimeters" surrounding the sources.
- $\Delta\Theta$~1deg → Identification by angular distribution impossible.

- Our only (realistic) hope:
  Identification of transient sources by temporal $\nu-\gamma$ association.

* UHE CR source must be transient:
  $L>10^{47}$erg/s, GRBs or bright (yet to be detected) AGN flares.

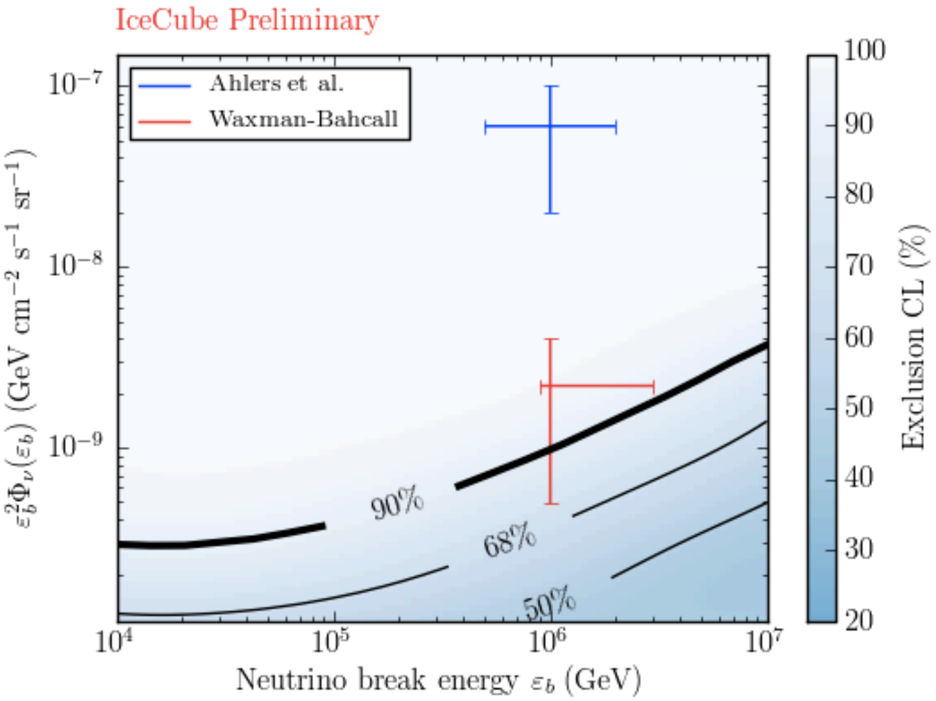
- Requires:
  Wide field EM monitoring,
  Real time alerts for follow-up of high E ν events,
  and
  Significant increase of the ν detector mass at ~100TeV
  [Φ_ν(source) may be « Φ_ν(calorimeter)~Φ_{WB} [e.g. Φ_ν(GRB) ~0.1 Φ_{WB}]].

A note on GRBs

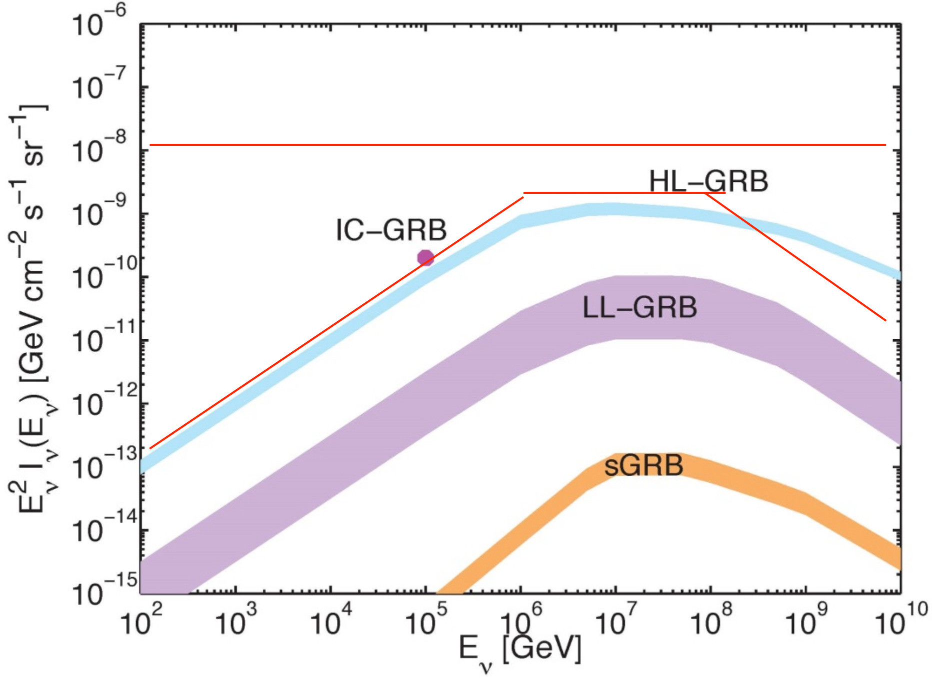
$$\varepsilon_{\nu,b} = 500\left(\frac{\varepsilon_{\gamma,b}}{1\text{MeV}}\right)^{-1}\Gamma_{2.5}^{2}\,\text{TeV} \approx 1\text{PeV}$$

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

[EW & Bahcall 97]



$E^2\Phi$



IC is achieving relevant sensitivity.

[Tamborra & Ando 15;

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

What will we learn from $\nu-\gamma$ associations?

- Identify the CR sources.
  Resolve key open Qs in the accelerators' physics
  (BH jets, particle acceleration, collisionless shocks).

- Study fundamental/ν physics:
  - π decay → $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 (Osc.)→ $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1
    ◊ τ appearance,
    [Learned & Pakvasa 95; EW & Bahcall 97]
  - 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]

- Optimistically (>100's of ν's with flavor identification):
  Constrain δ_{CP}, new phys.

[Blum, Nir & EW 05; Winter 10; Pakvasa 10;
… Ng & Beacom 14; Ioka & Murase 14;
Ibe & Kaneta 14; Blum, Hook & Murase 14;
Marfatia, McKay & Weiler 15;]

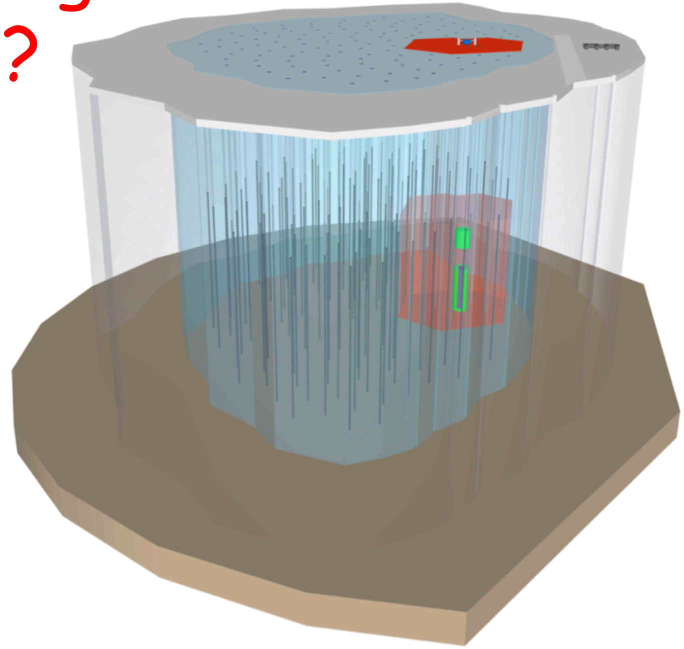
Summary

- IceCube detects extra-Galactic ν's. $\Phi_\nu=\Phi_{WB}$ at 50TeV-2PeV.
  - * The flux is as high as could be hoped for.
  - * $\Phi_\nu=\Phi_{WB}$ implies a connection with UHECRs,
  - * Explained if UHECR sources reside in "calorimeters"-
    star forming galaxies,
    implying a single transient source for all >1PeV (>1GeV?) CRs.
  - * Strongly suggests UHECRs are p, G/XG transition at 10^{19}eV.
  - → Closing in on the origin of Cosmic-Rays.

- Open Questions:
  - * Uncertainties in ν flux, spectrum, isotropy, flavor ratio.
  - * The CR/ν sources not identified [not unexpected].

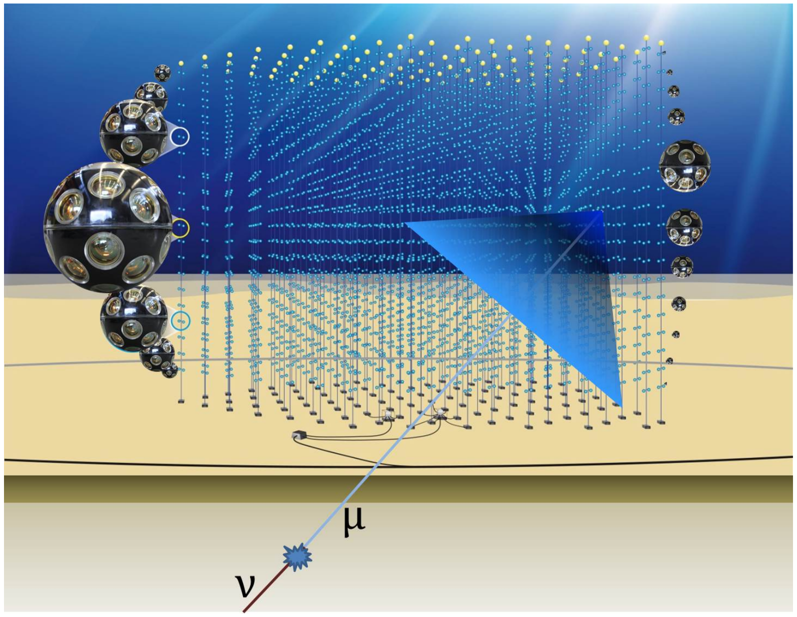
- Temporal $\nu-\gamma$ association is key to:
  CR sources identification, Cosmic accelerators' physics,
  Fundamental/ν physics.

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).

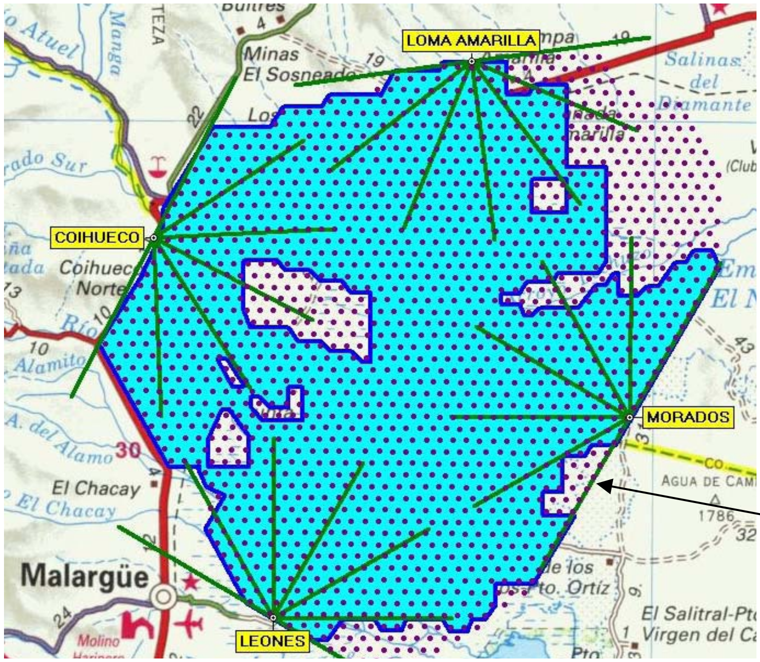
- Wide field EM monitoring.



- Adequate sensitivity for detecting the ~10^{10}GeV GZK ν's.
- HE γ-ray telescopes play a key role.

Backup Slides

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

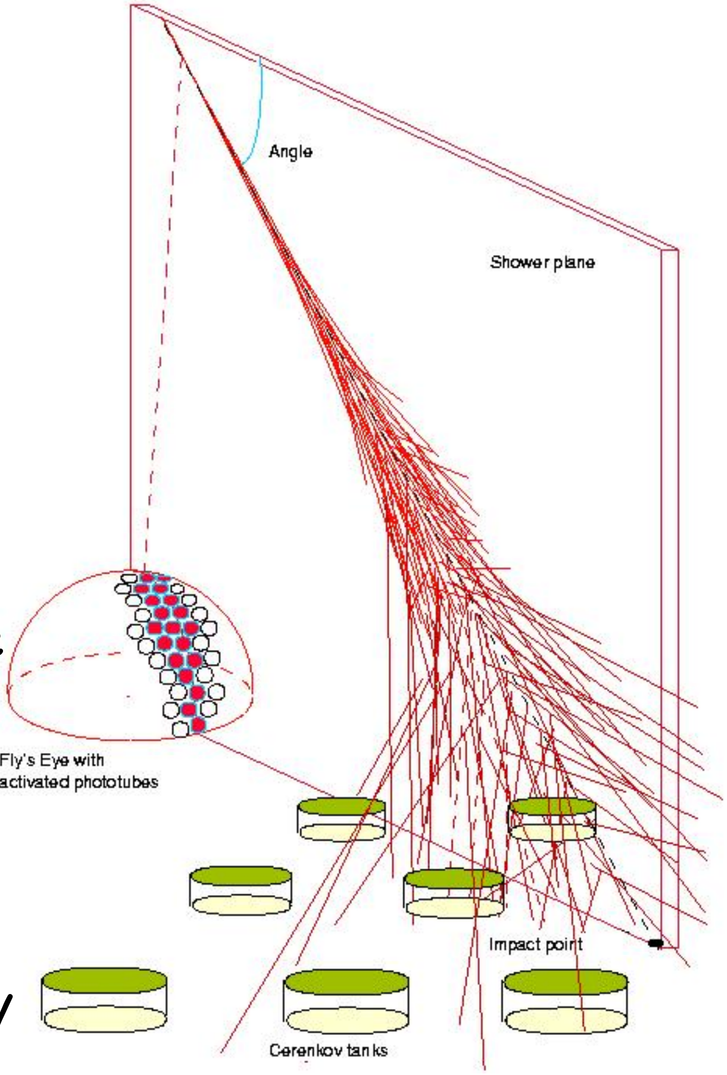


$J(>10^{11}\text{GeV}) \sim 1\ /\ 100\ \text{km}^2\ \text{year}\ 2\pi\ \text{sr}$

Auger:
3000 km^2

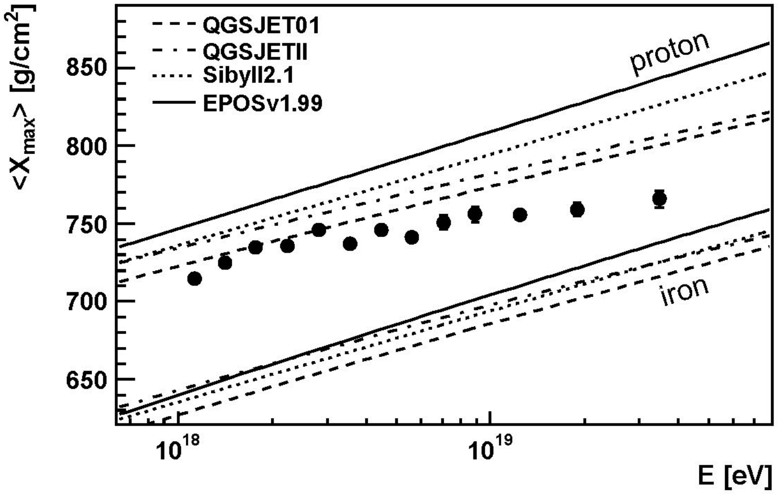
Fluorescence detector

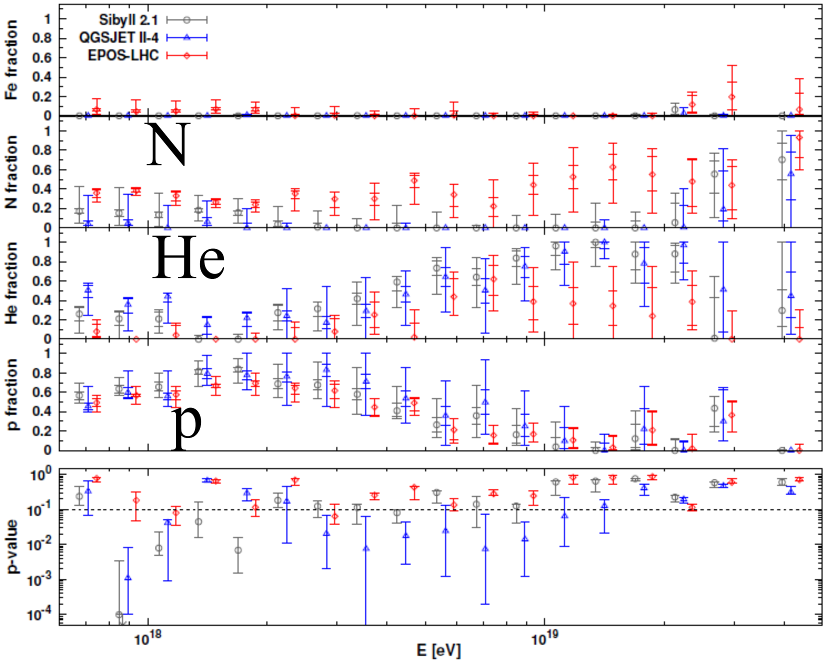
Ground array



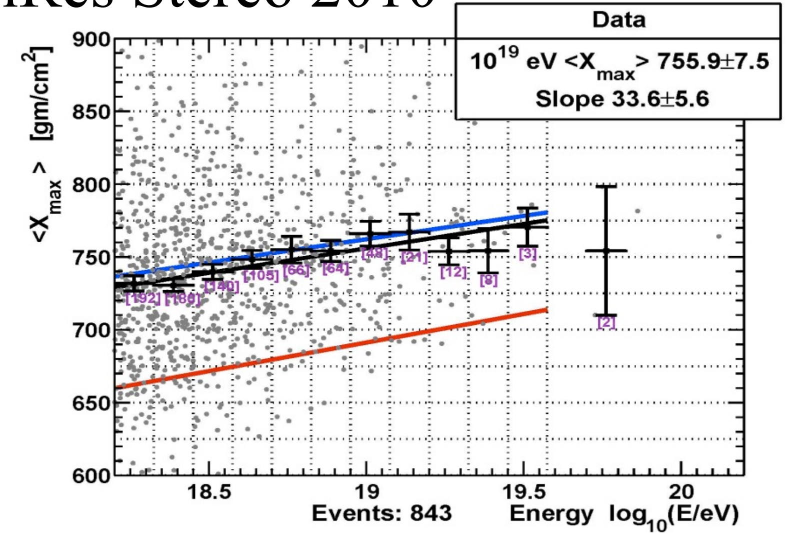
UHE: Composition

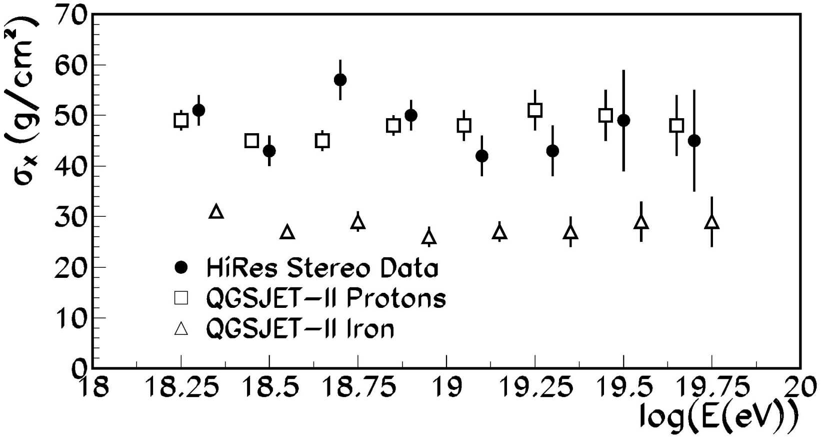
Auger 2010: Fe, 2015: He(??)





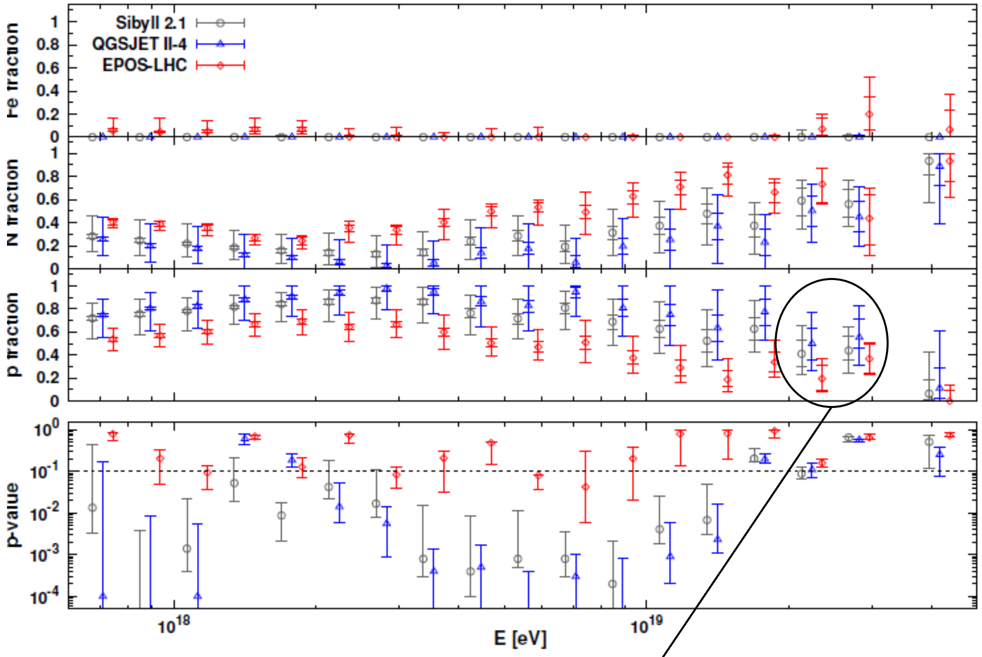
HiRes Stereo 2010 & TA Hybrid 2015





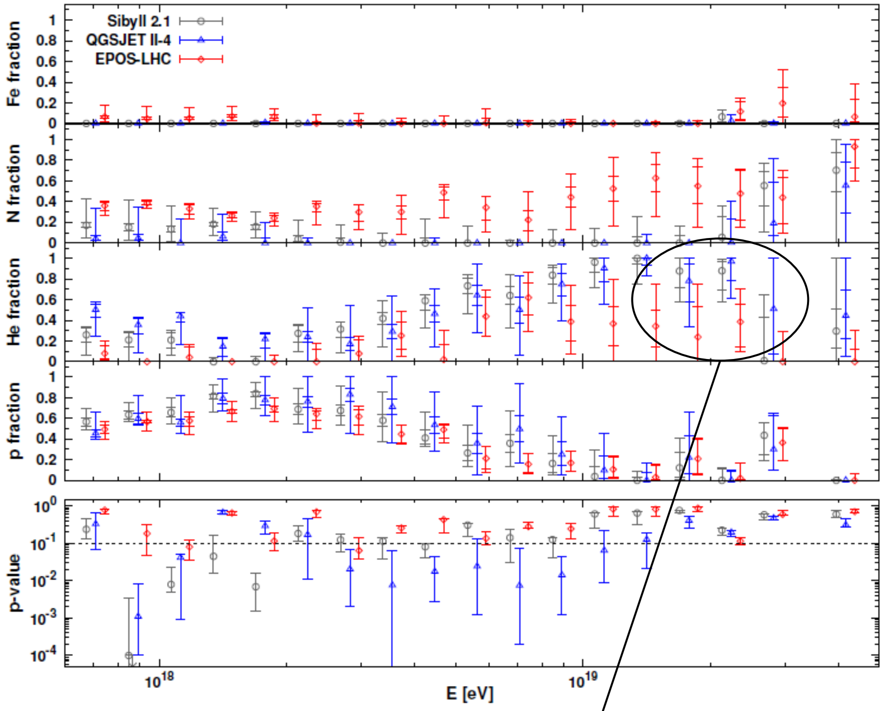
Auger 2014: Fe out, He in

p+N



10%<p frac.<90%

p+He+N

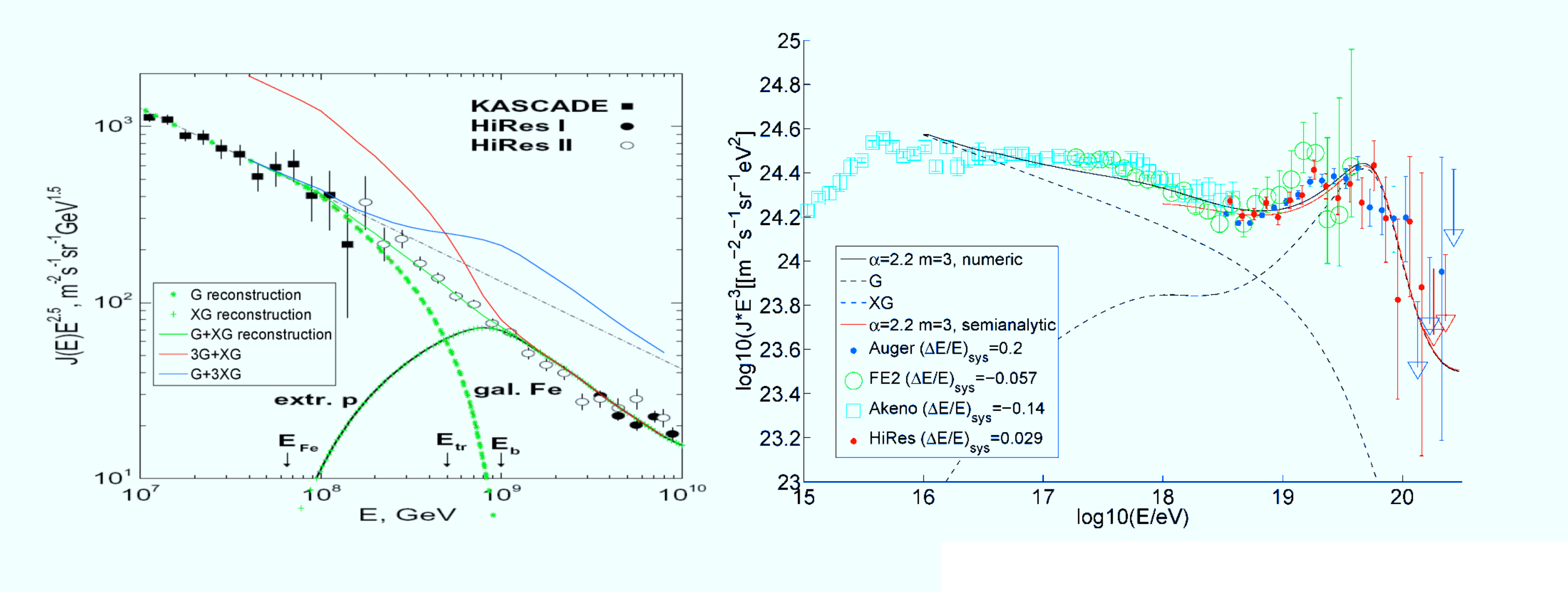


0%<He frac.<100%

Where is the G-XG transition?

@ E<10^{18}eV ?

dQ/dlog ε =Const → @ E~10^{19}eV



[Katz & EW 09]

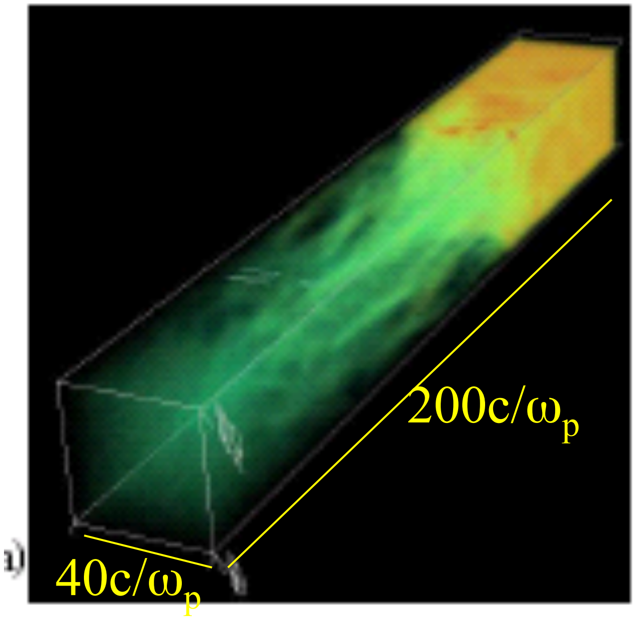
- Fine tuning

Collisionless shock acceleration

- The only predictive model.

- No complete basic principles theory, but
  - Test particle + elastic scattering assumptions give
    - $v/c \ll 1$: $dQ/d\log\varepsilon = \text{Const.}$, [Krimsky 77]
    - $v/c \sim 1$: $dQ/d\log\varepsilon = \text{Const.} \times \varepsilon^{-2/9}$ ($\Gamma \gg 1$, isotropic scattering). [Keshet & EW 05]
  - Supported by basic principles plasma simulations,

    [Spitkovsky 06, Sironi & Spitkovsky 09, Keshet et al. 09, …, Sironi, Spitkovsky & Arons 13]
  - $dQ/d\log\varepsilon = \text{Const}$ Observed in a wide range of sources (lower energy p's in the Galaxy, radiation emission from accelerated e^-).



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

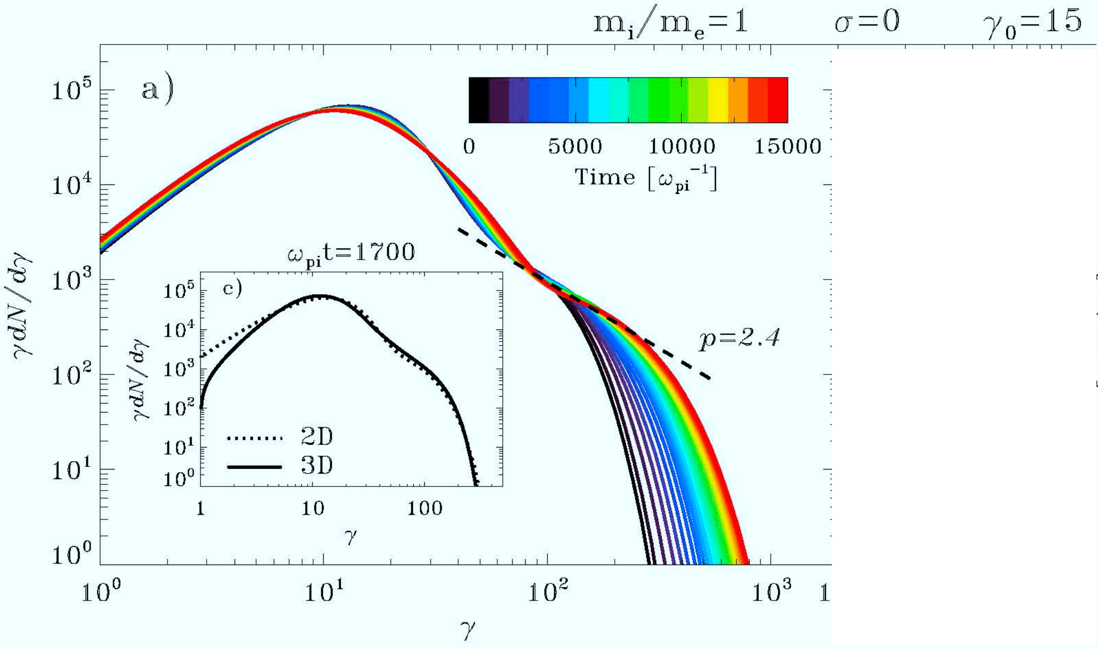
Particle acceleration in collisionless shocks

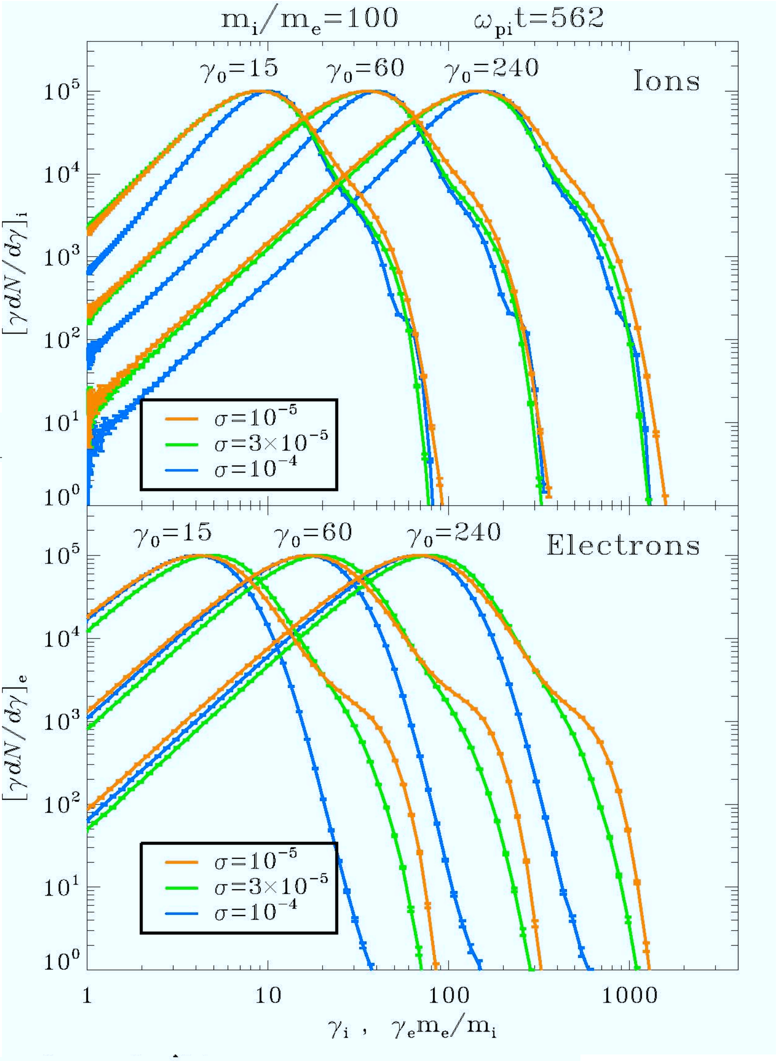
- No basic principles theory.
- Challenges:

  Self-consistent particle/B,

  Non linear with a wide range of

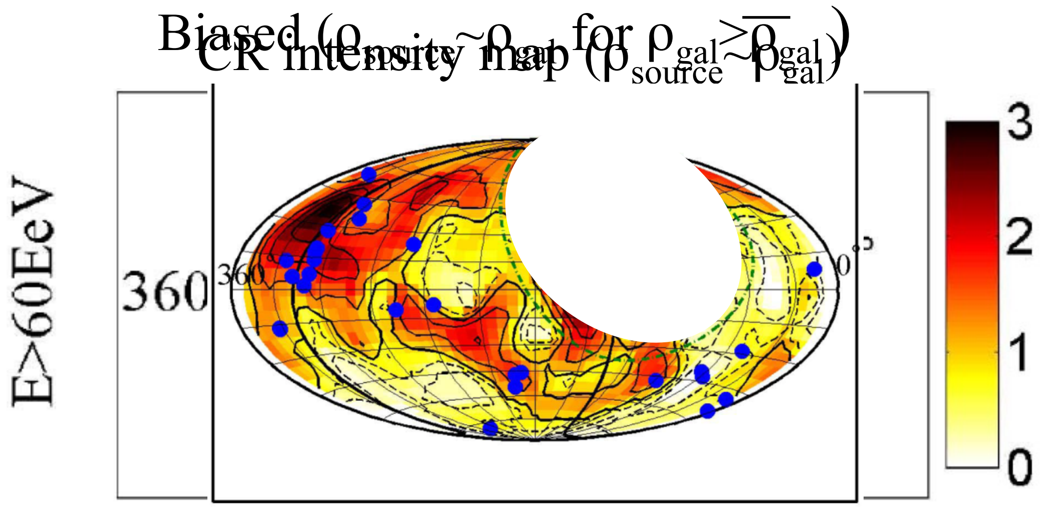
  temporal/physical scales.



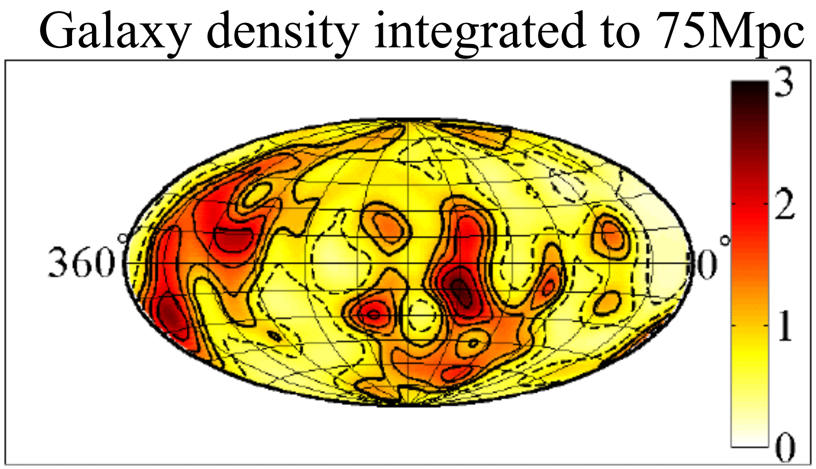


[Sironi, Spitkovsky & Arons 13]

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

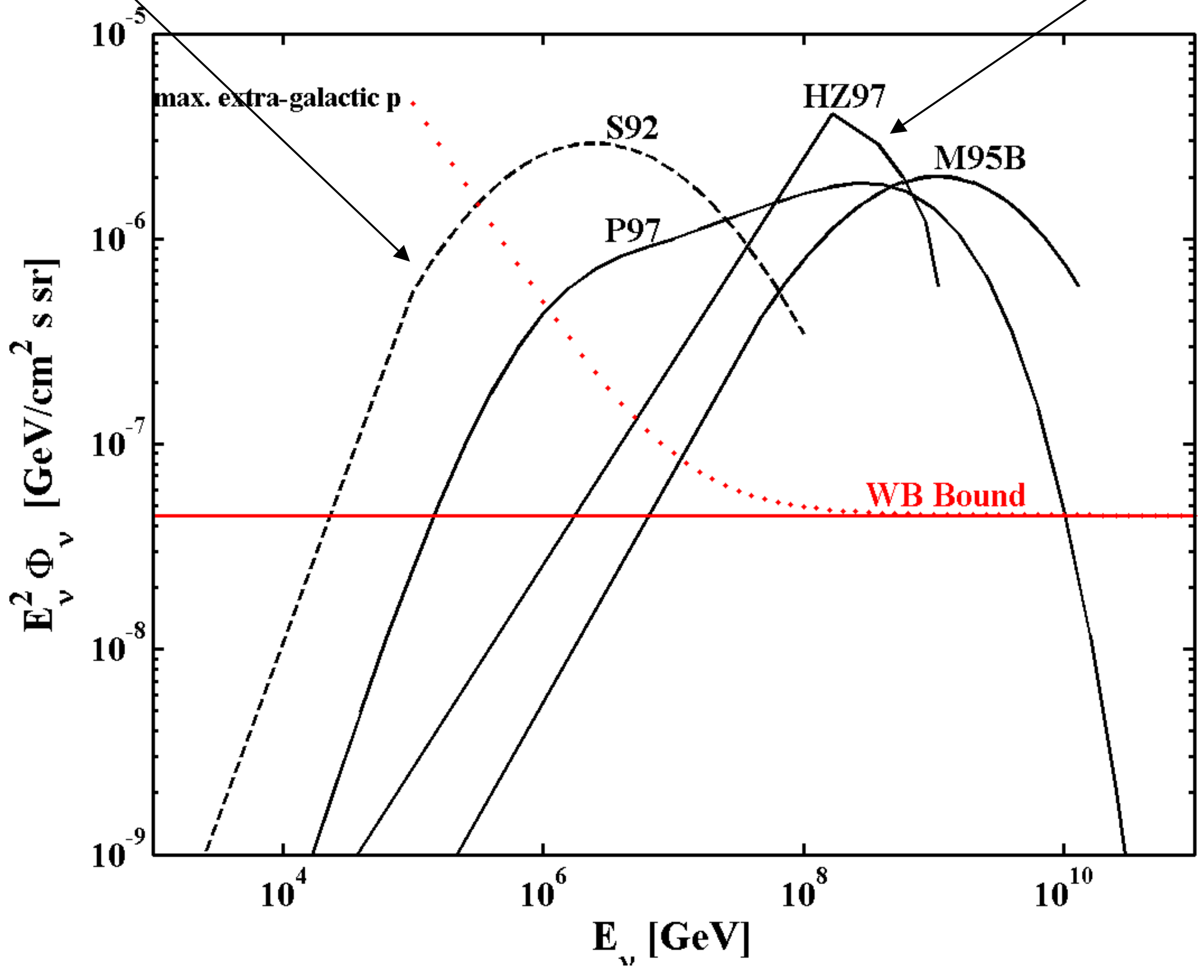
- π decay → $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 (propagation)→ $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1

- 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).

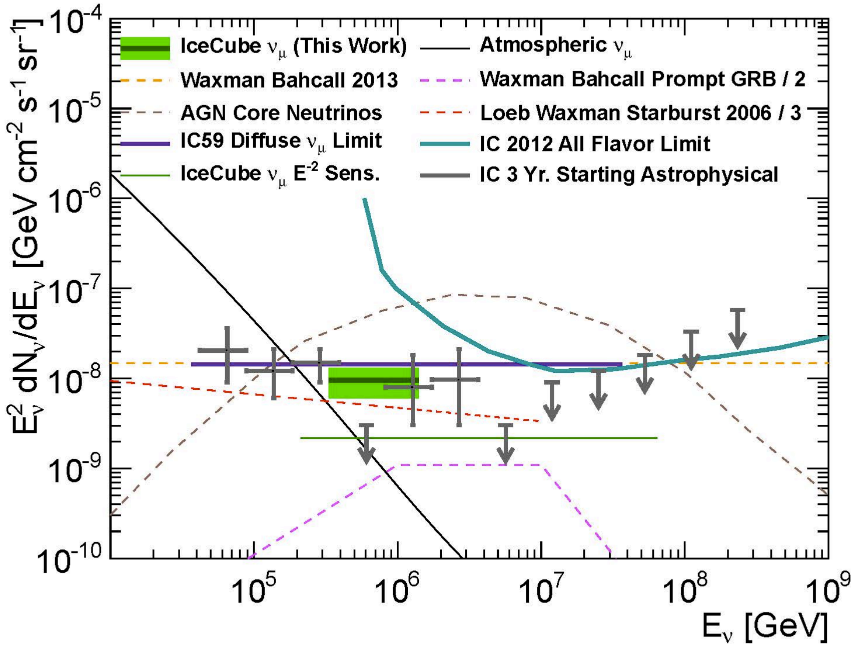
“Hidden” (ν only)
sources

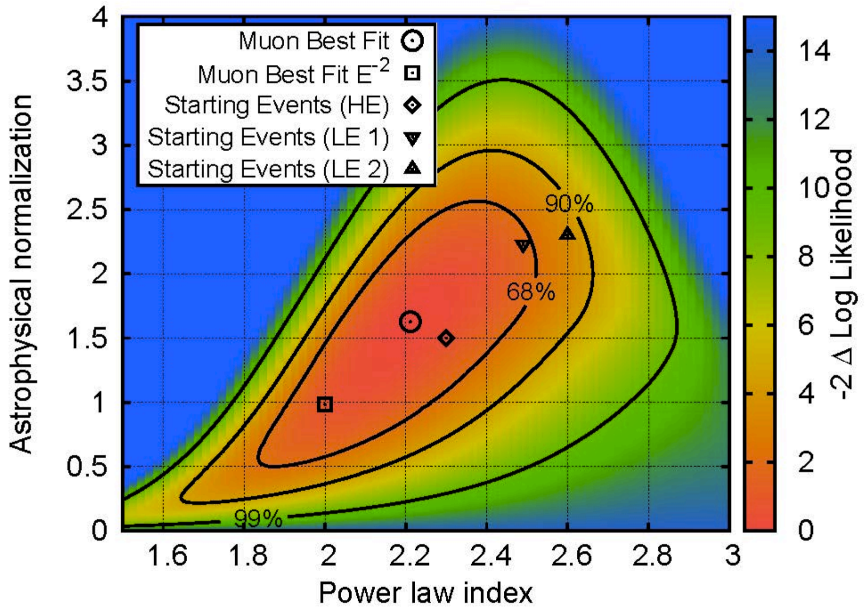
Violating UHECR
bound



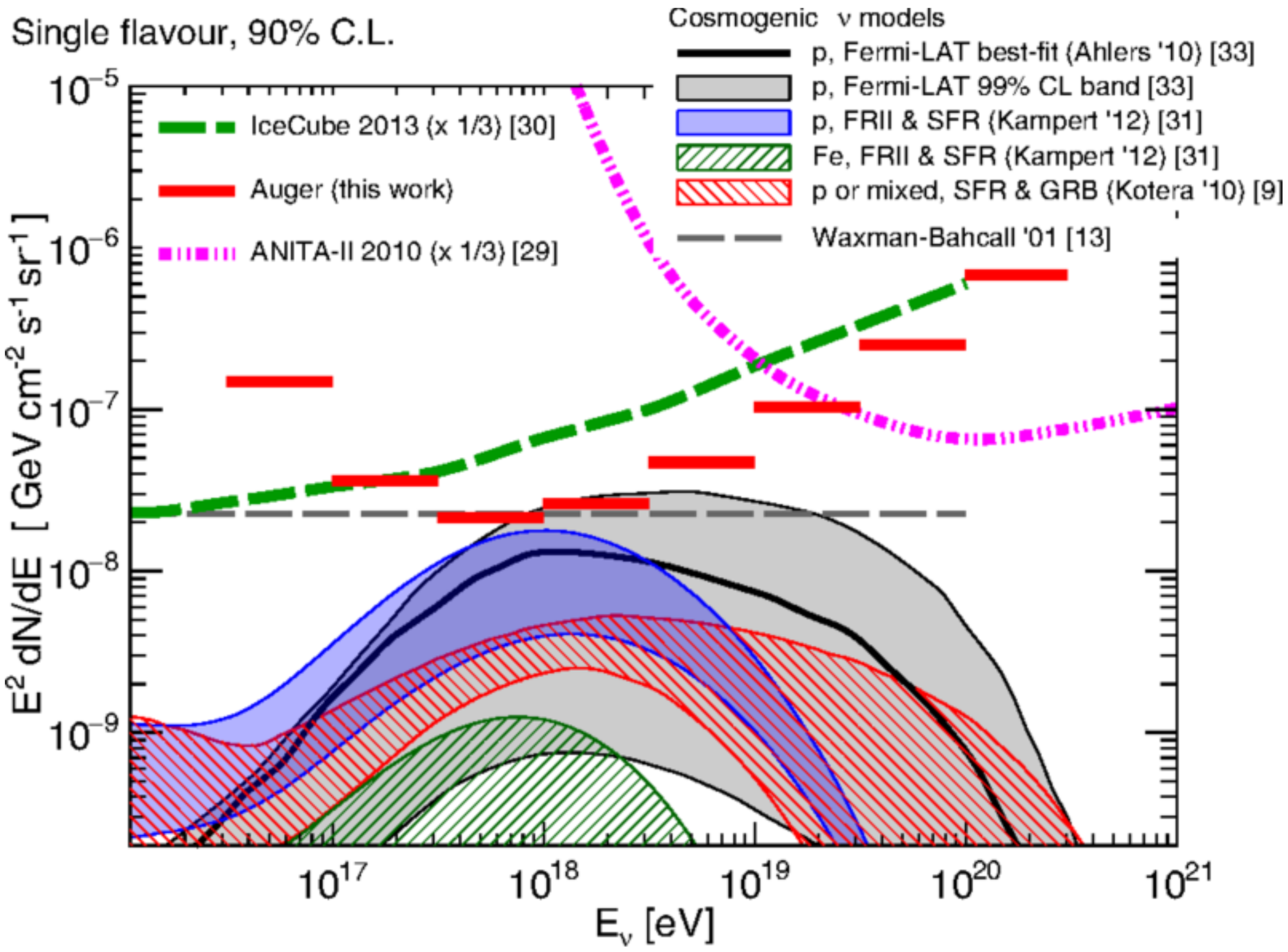
[M95: Mannheim 1995
P97: Protheroe 1997
HZ97: Halzen & Zas 1997]

IceCube North sky muons [July 15]





Auger's UHE limit [May 15]



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

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

- Our Galaxy- using “grammage”, local SN rate

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

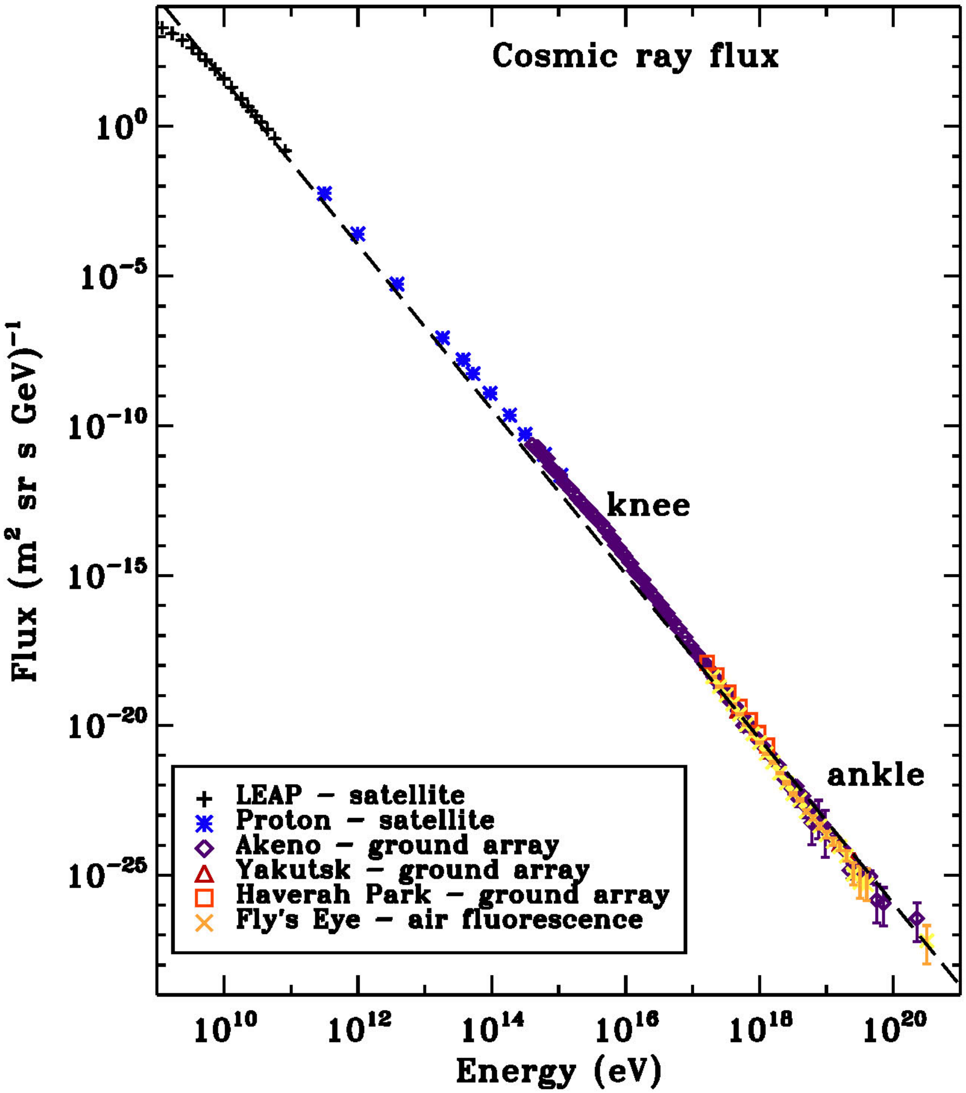
- Starbursts- using radio to γ observations

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

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

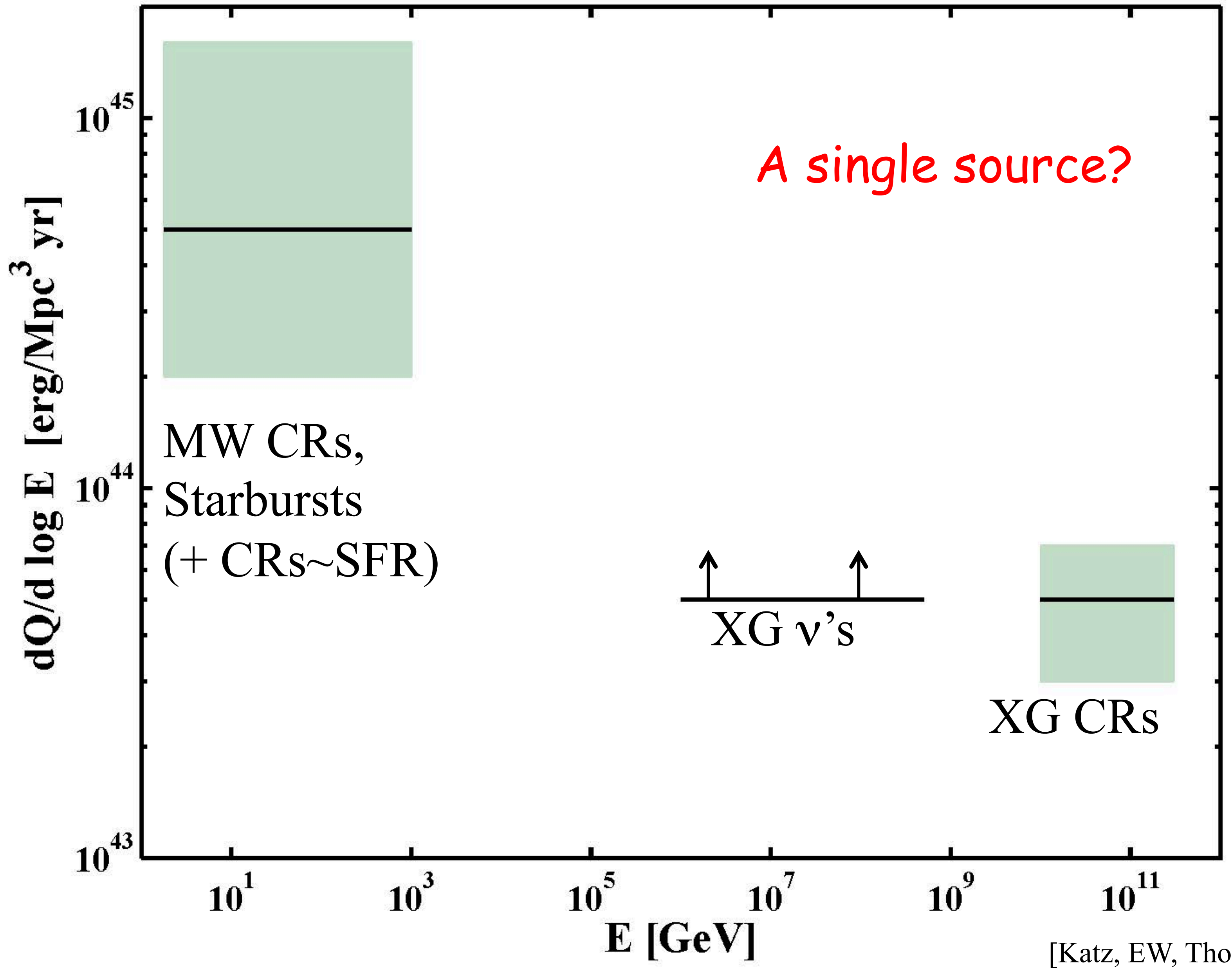
[Katz, EW, Thompson & Loeb 14]

The cosmic ray spectrum



[From Helder et al., SSR 12]

The cosmic ray generation spectrum

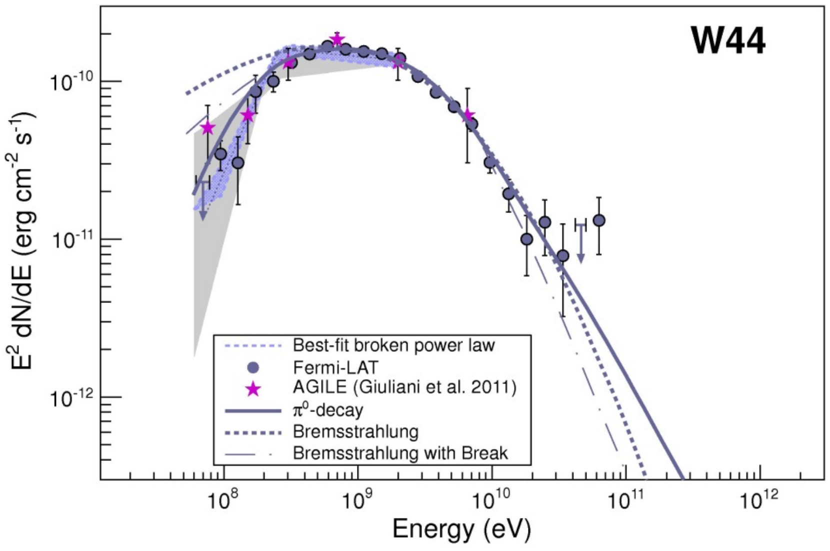


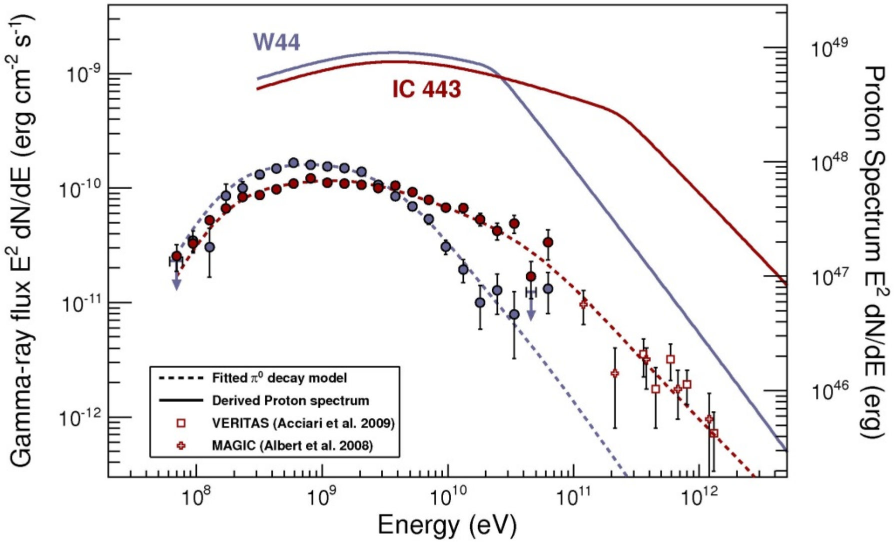
[Katz, EW, Thompson & Loeb 14]

Are SNRs the low E CR sources?

- So far, no clear evidence.
  Electromagnetic observations- ambiguous.

  E.g.: "π decay signature" [Ackermann et al. 13]:





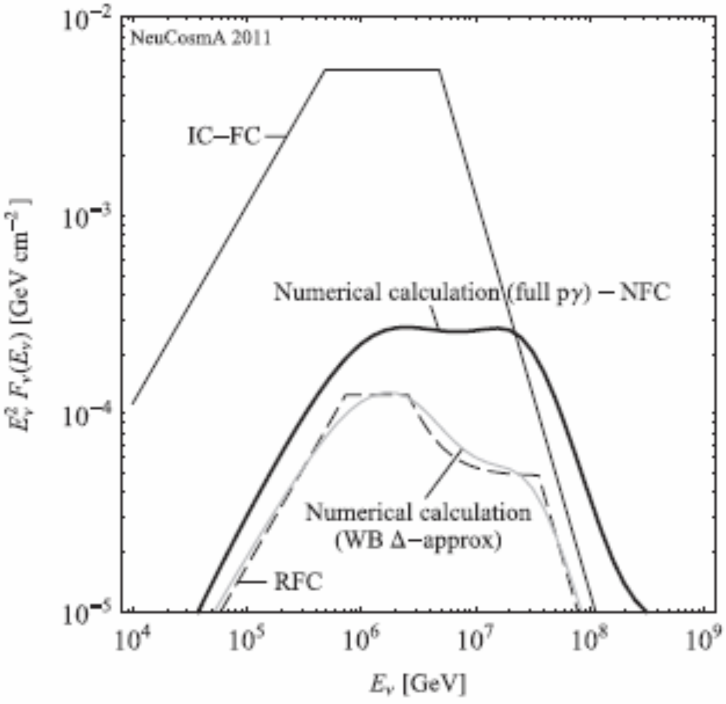
IceCube's GRB limits

- No ν's associated with ~200 GRBs (~2 expected).
- IC analyses overestimate GRB flux predictions, and ignore model uncertainties.
- IC is achieving relevant sensitivity.

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

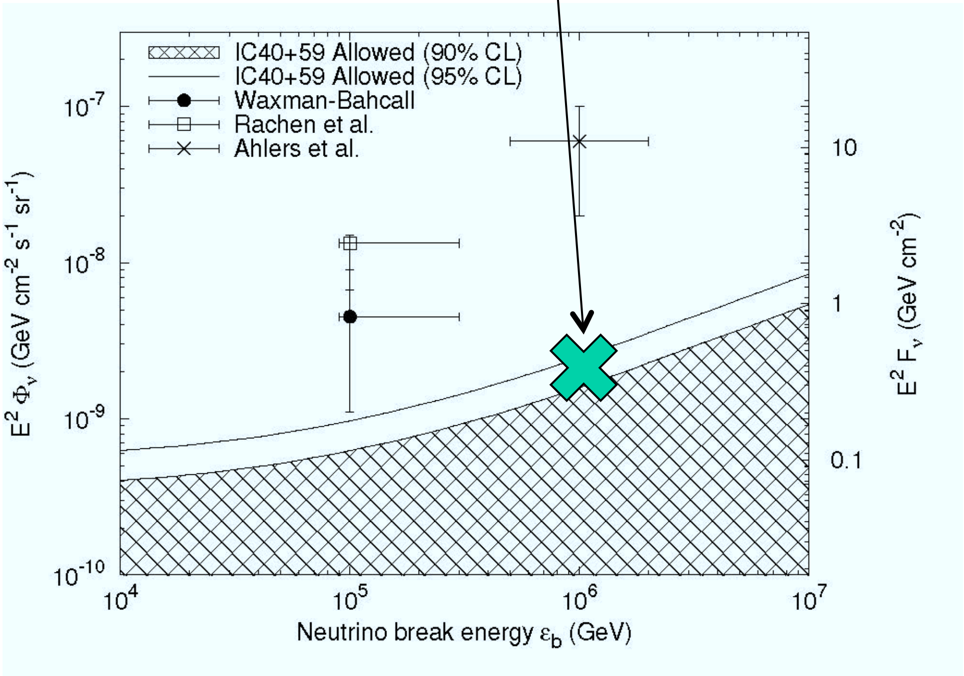
$$\Phi_{\mathrm{GRB}} \approx 0.2\Phi_{\mathrm{WB}}$$

[EW & Bahcall 97]



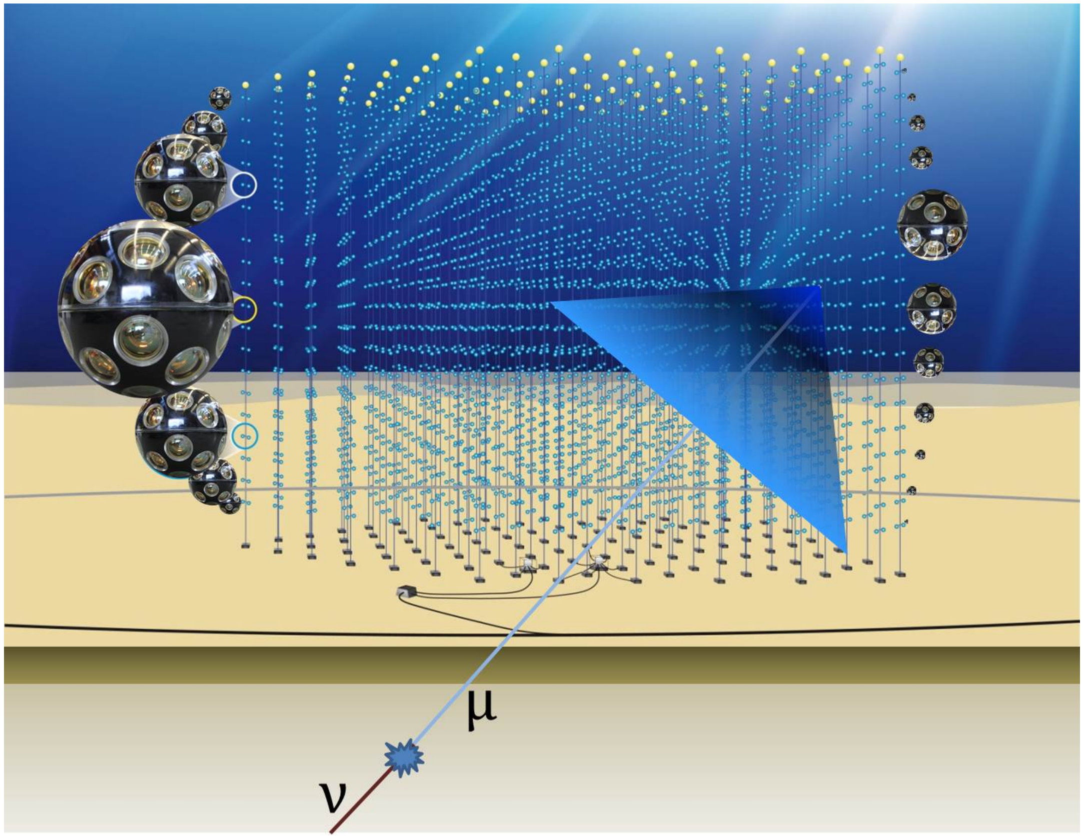
[Hummer, Baerwald, and Winter 12;

see also Li 12; He et al 12]



Future experimental developments

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



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