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

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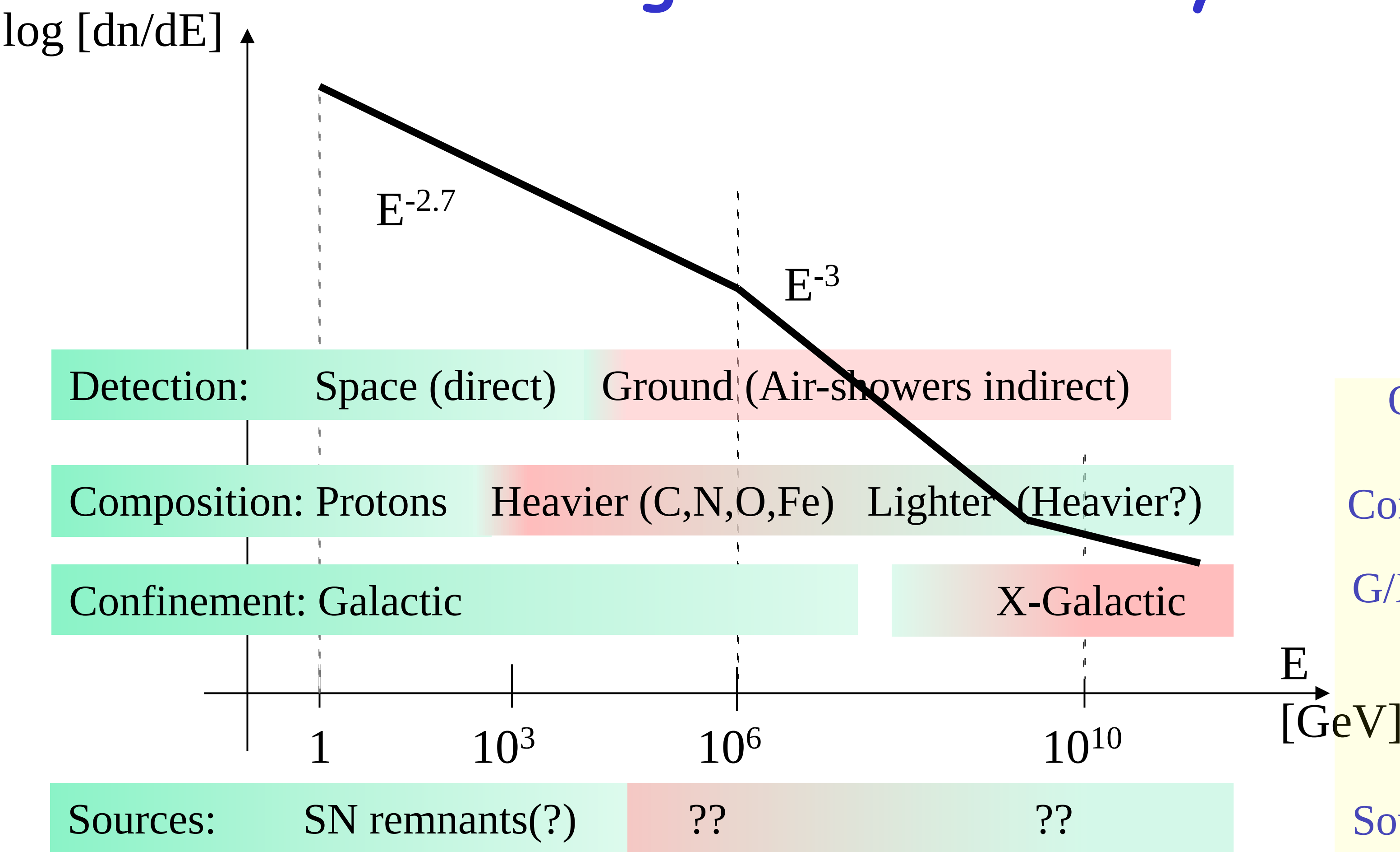
The main driver of HE ν astronomy: The origin of Cosmic Rays



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

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

Open Q's

Composition?

G/XG transition?

Sources?

Acceleration?

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

The acceleration challenge

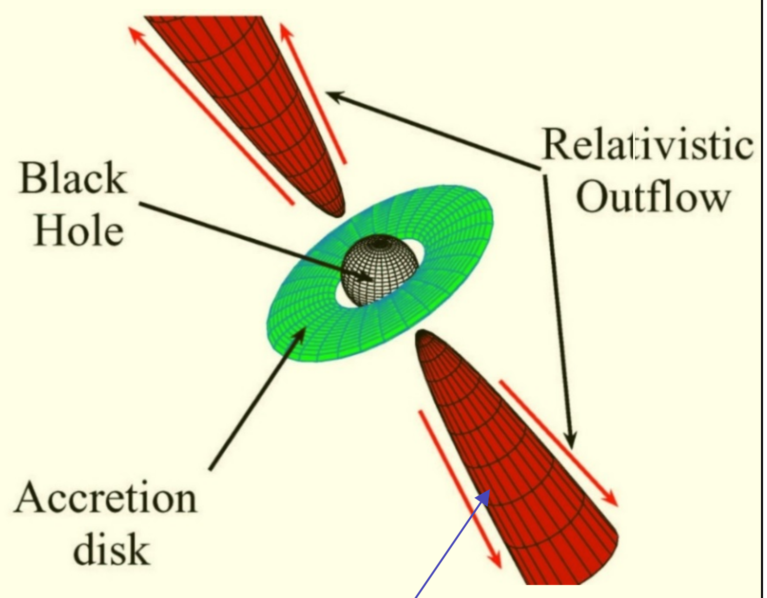
- EM acceleration: $L > 10^{12} \frac{\Gamma^2}{v/c} \left(\frac{E/Z}{10^{11}\mathrm{GeV}}\right)^2 L_{\mathrm{sun}}$.

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

- $Z > 10$ - Several candidates.

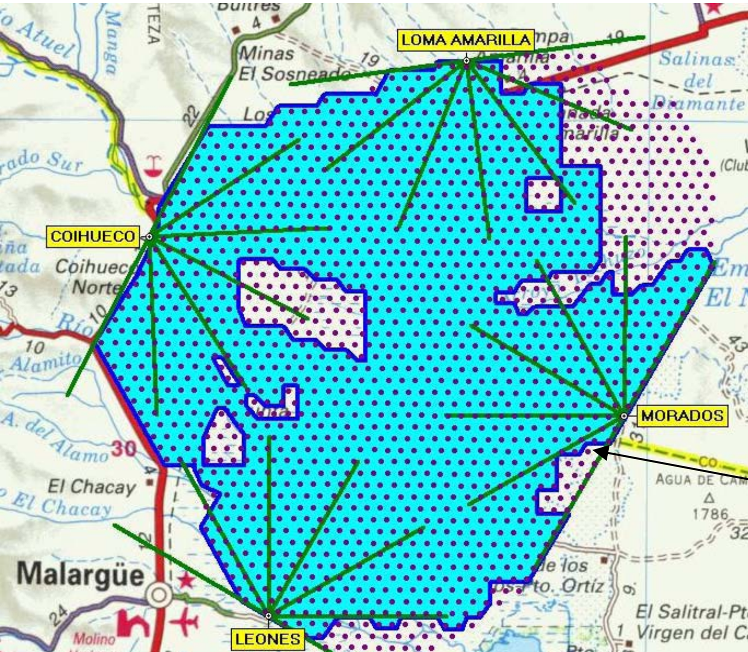
- p – 2 candidate transient sources,
  Rapid mass accretion onto BHs.
  - Gamma-ray bursts (GRB),
    newly formed solar mass BHs;
    [Vietri 95; Milgrom & Usov 95; EW 95]
  - Tidal disruption of stars (TDE) by
    massive BHs at galaxy centers,
    may produce "GRB-like" jets.
    [Gruzinov & Farrar 09; Wang & Liu 16]

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



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

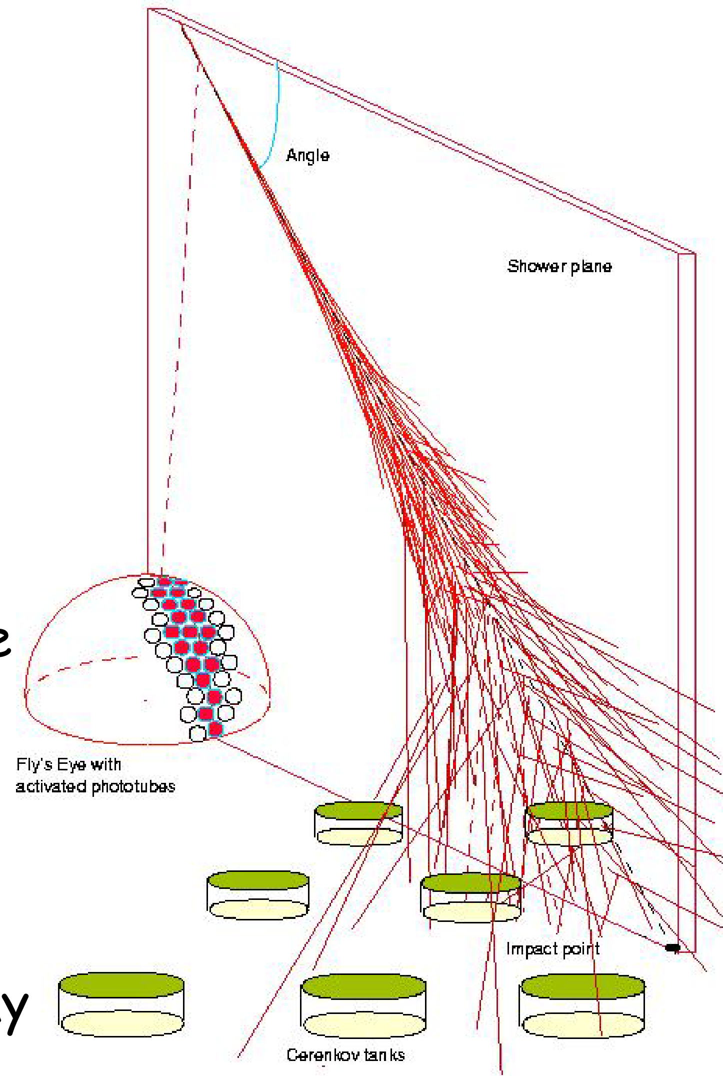
UHE, $>10^{10}$GeV, CRs



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

Auger:
3000 km^2

Fluorescence detector



Ground array

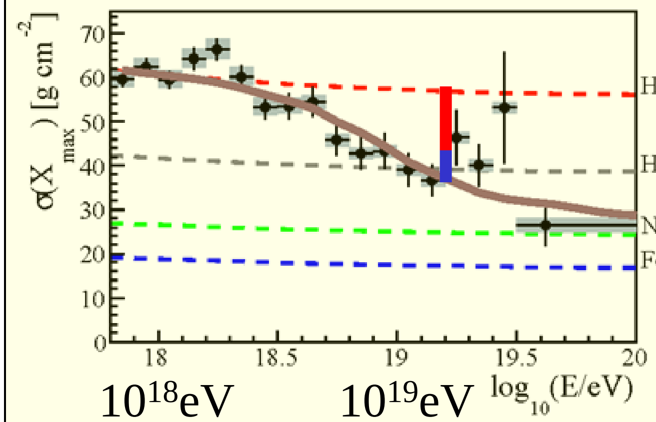
UHE: Air shower composition constraints

- 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.

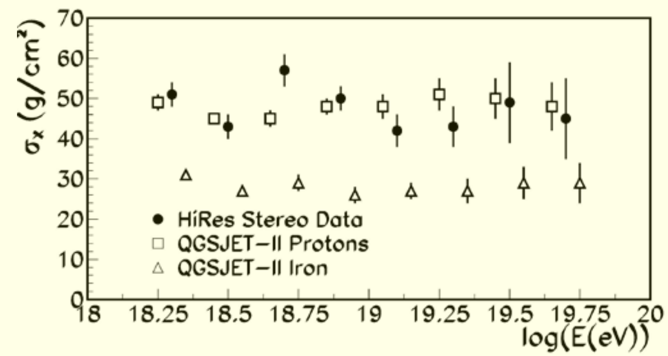
[e.g. Ulrich, Engel & Unger 11]

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



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

HiRes Stereo 2010: p



$>10^{10}$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

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

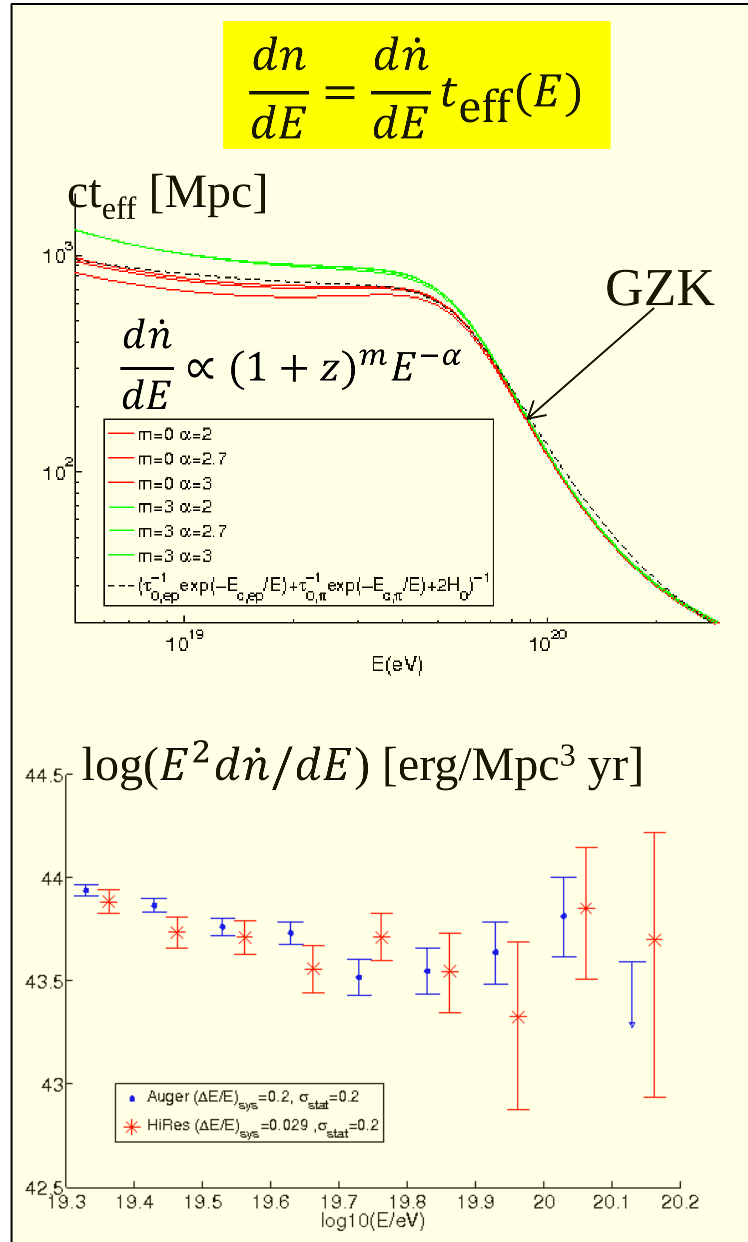
$$= (0.5 \pm 0.2)10^{44}\,\frac{\text{erg}}{\text{Mpc}^3\text{yr}},$$

[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]



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 $p \to \pi$):

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

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

[EW & Bahcall 99; Bahcall & EW 01]

- Saturation of the bound.
  - $\sim 10^{10}$GeV -If- Cosmological p's. [Berezinsky & Zatsepin 69]
  - $<\sim 10^6$GeV -If- Cosmological p's & CR ~ star-formation activity.

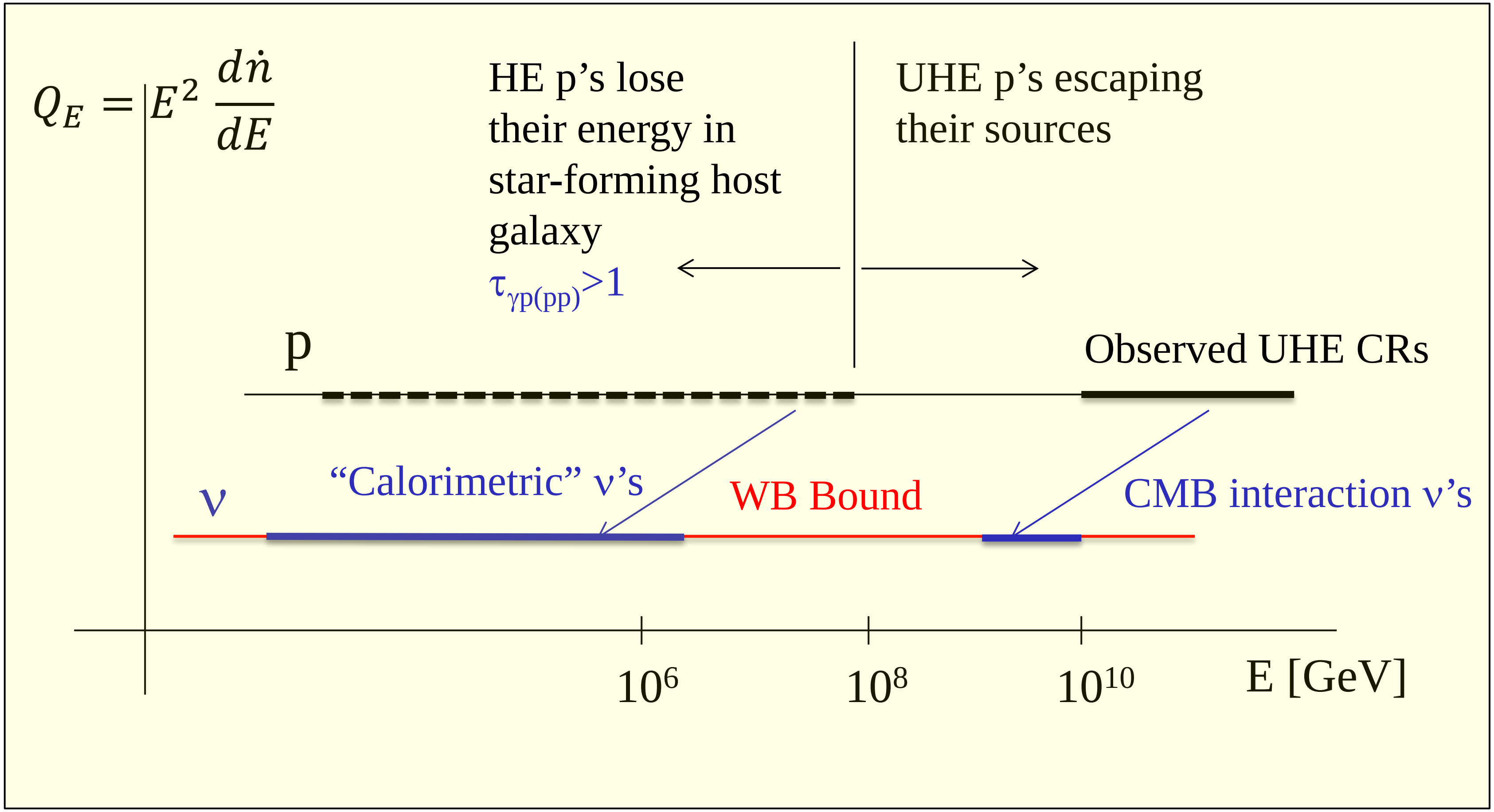
    Most stars formed in rapidly star-forming galaxies,

    which are p "calorimeters" for $E_p <\sim 10^6$GeV,

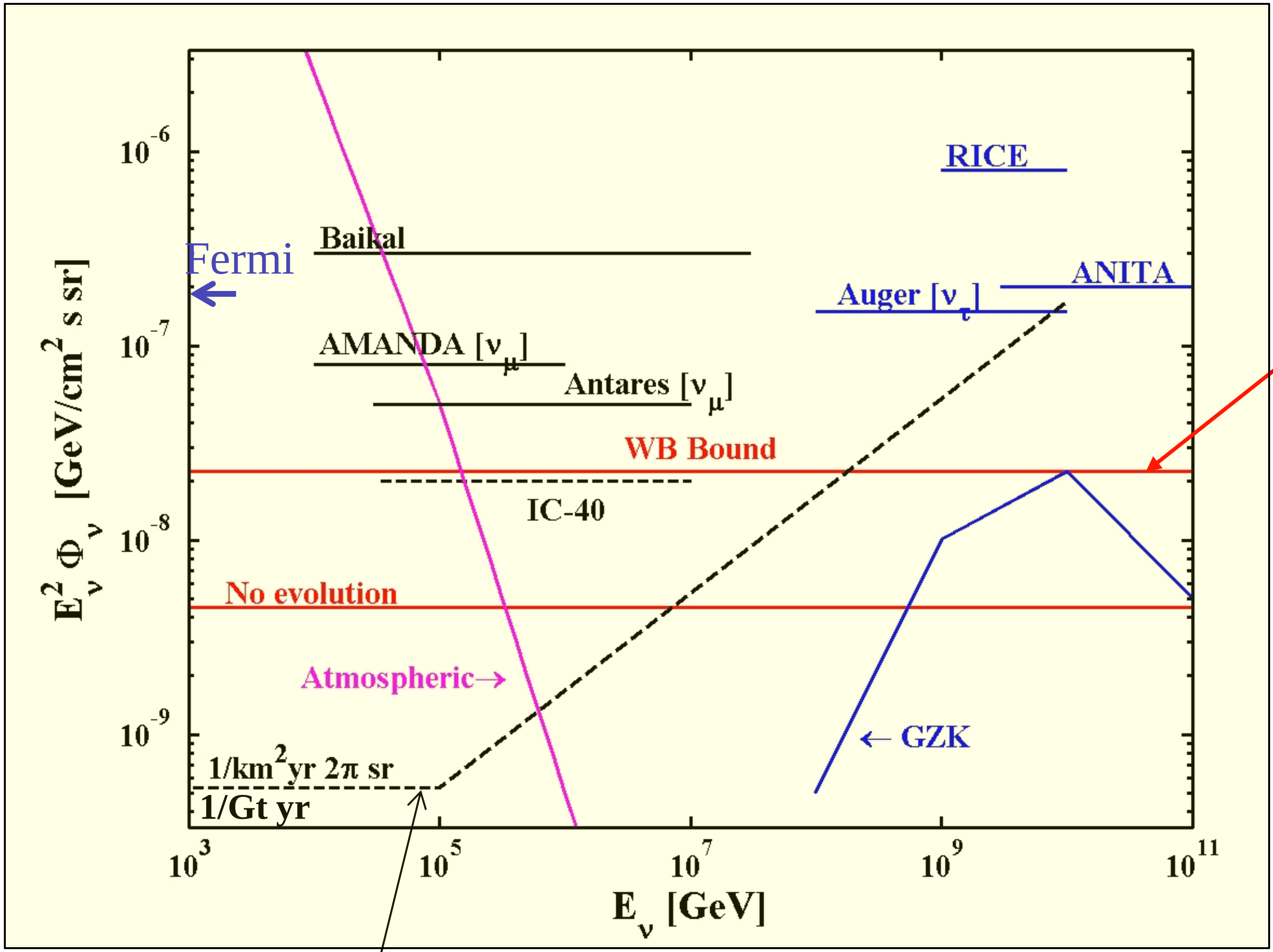
    all $p \to \pi$ by pp in the inter-stellar gas, $t_{pp} < t_{\text{conf}}(E < 10^6 \text{GeV})$.

[Loeb & EW 06]

HE ν: predictions



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

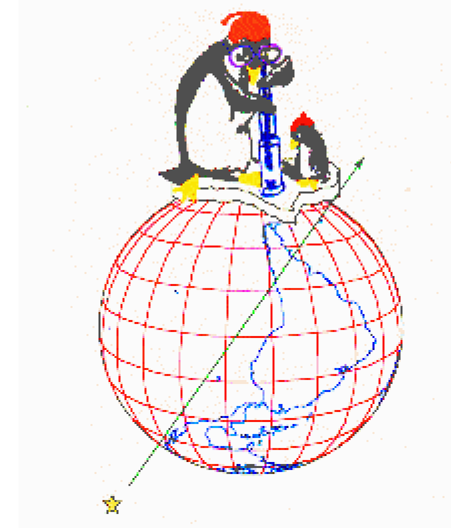


2 flavors,

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

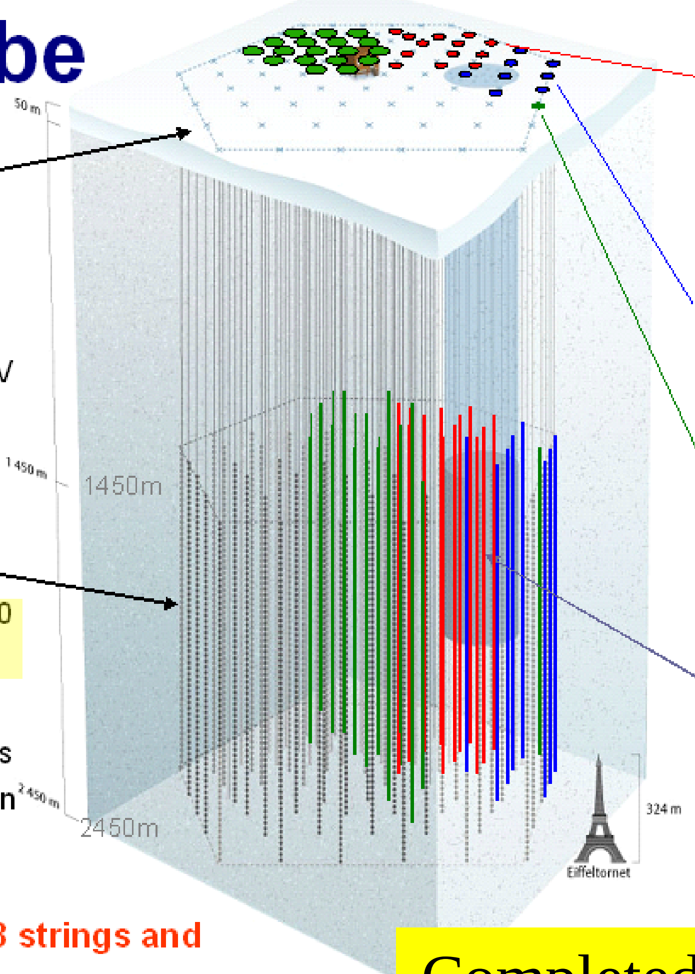
Rate ~ (EΦ)N_nσ(E), σ~E → Rate ~ (E^2Φ)M

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

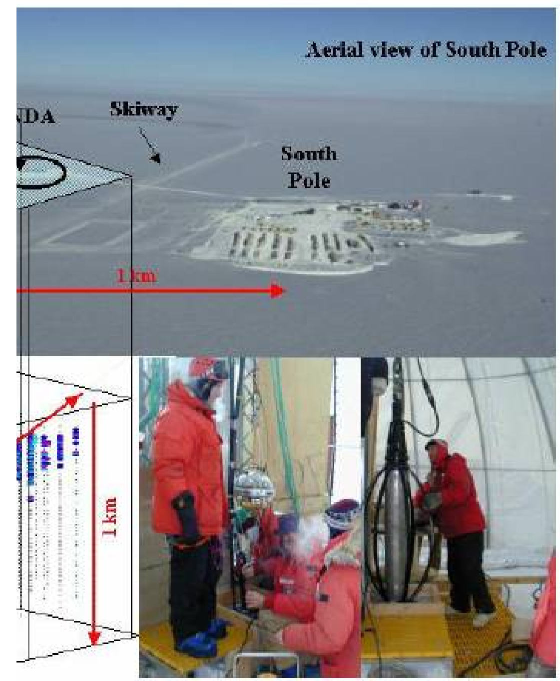
2007-2008
18 strings deployed

2005-2006: 8 strings

2004-2005 : 1 string

AMANDA-II
19 strings
677 modules

Current configuration:
40 strings,
40 IceTop stations
plus AMANDA

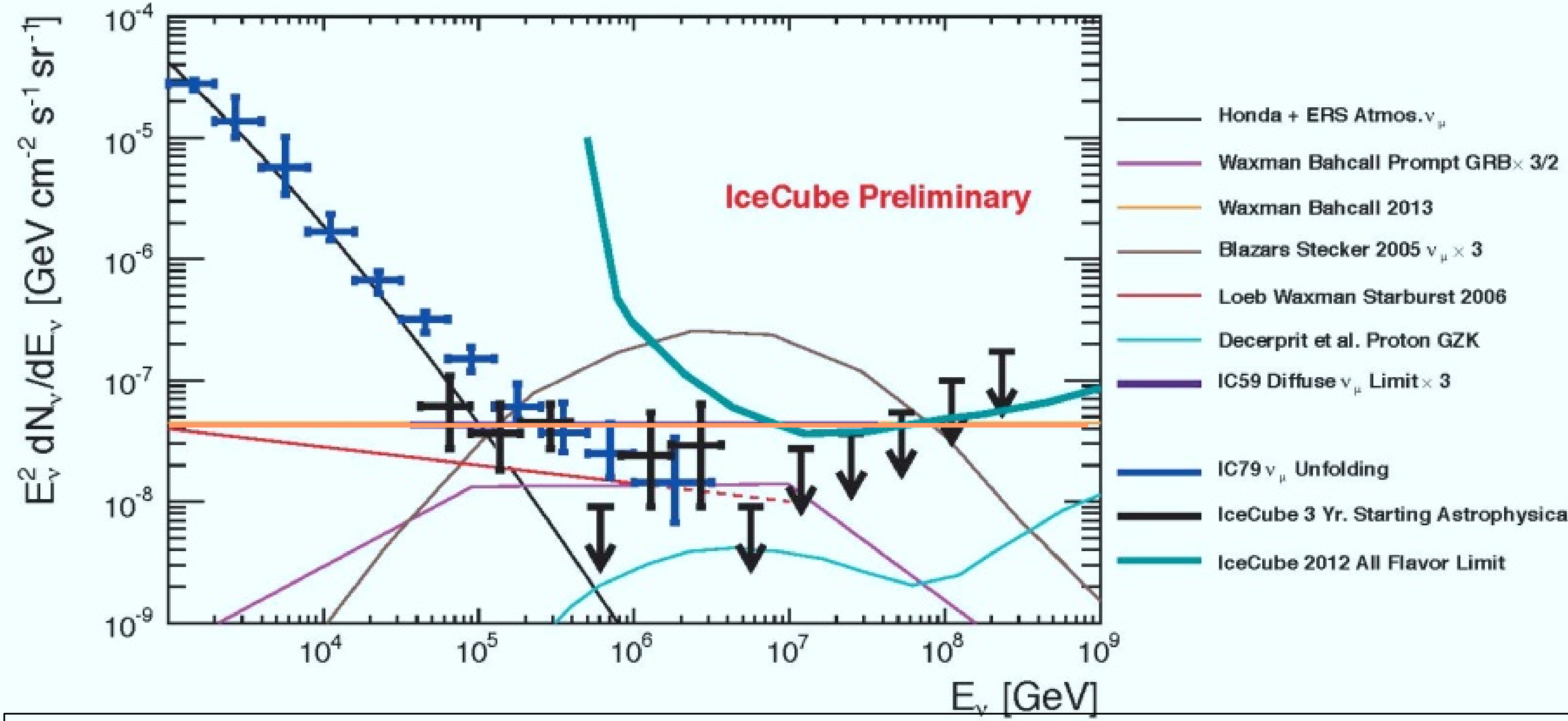


2008/09: add 18 strings and tank stations

Completed Dec 2010

IceCube: 37 events at 50Tev-2PeV

~6σ above atmo. bgnd. [02Sep14 PRL]



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

Consistent with Isotropy,

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

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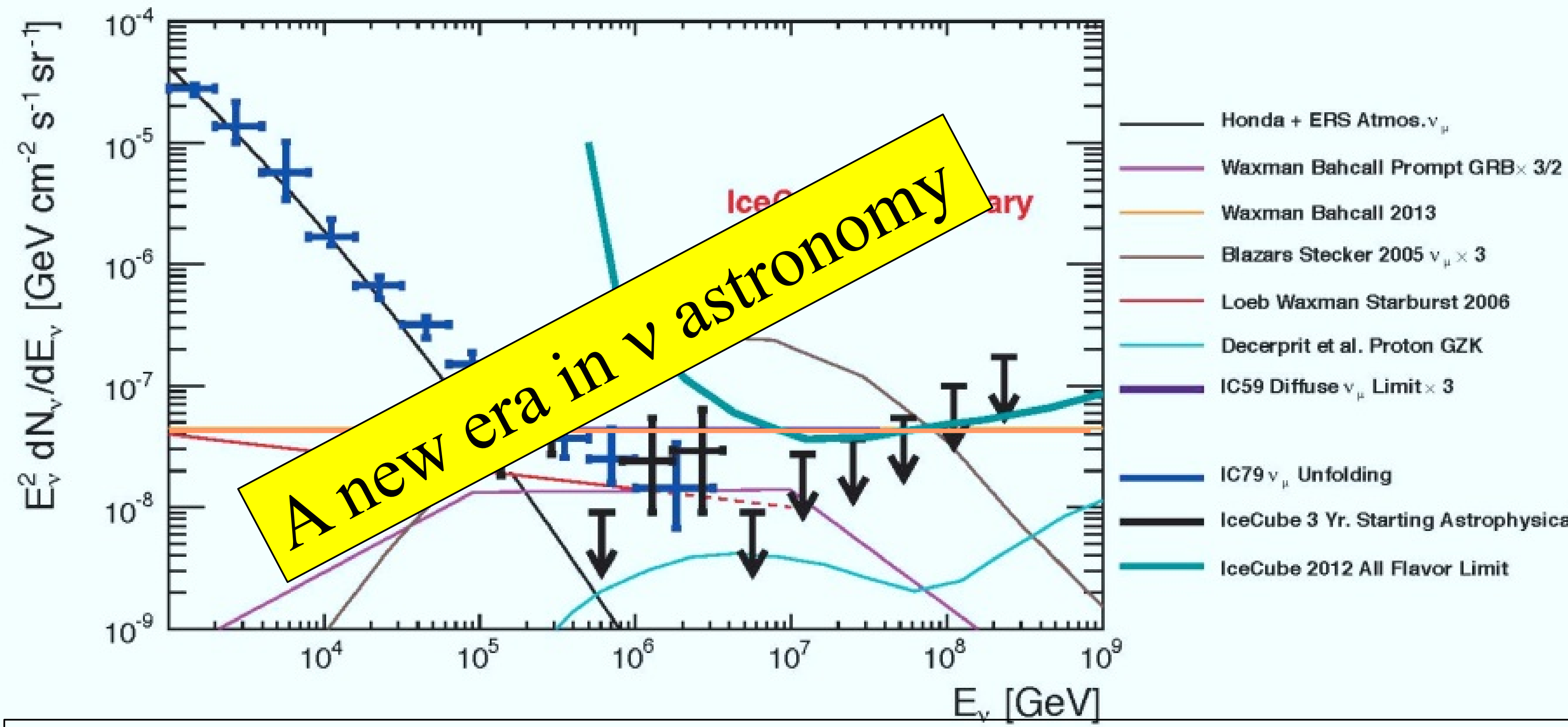

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Astrophysical neutrino telescopes

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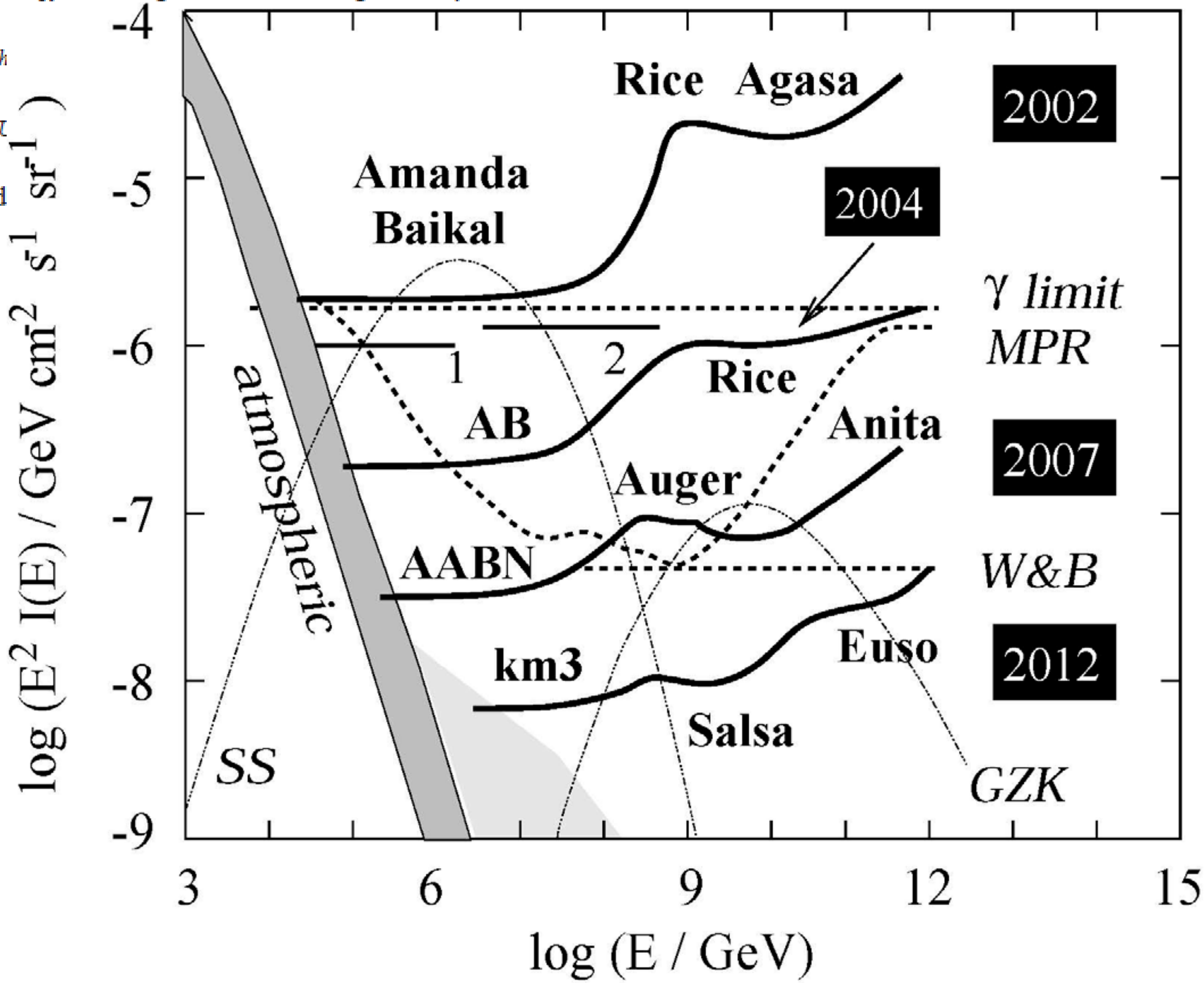
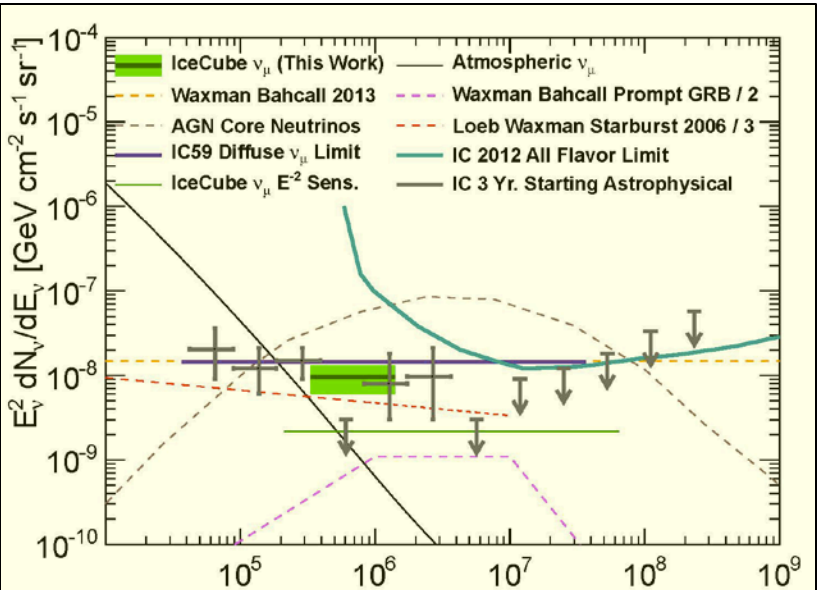
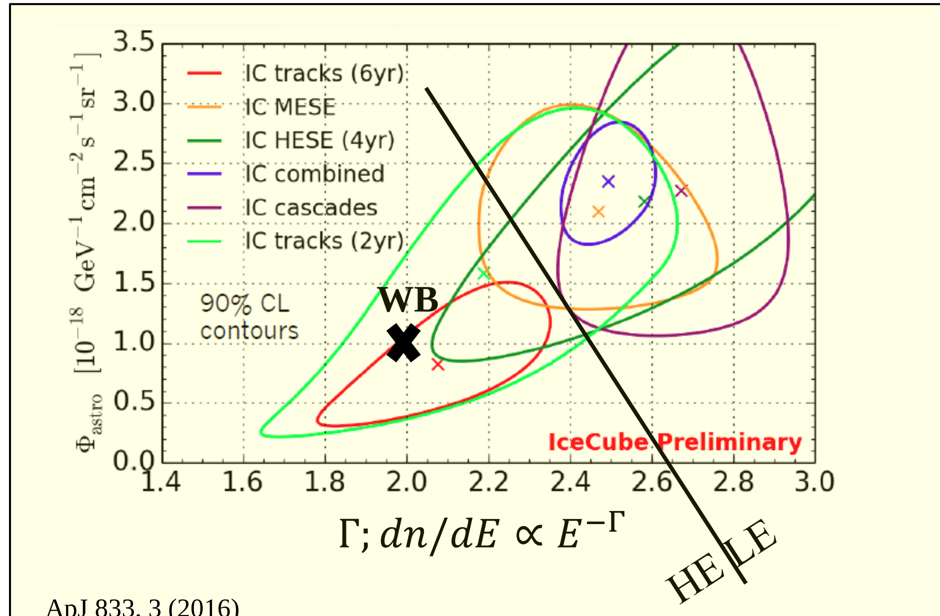
[Rev. Sci. Inst.]



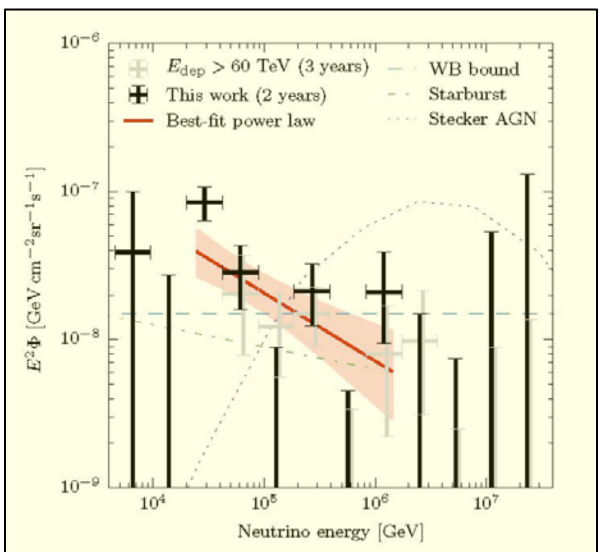
Status: Flux, spectrum



PRL 115, 081102 (2015)



ApJ 833, 3 (2016)



PRD 91, 022001 (2015)

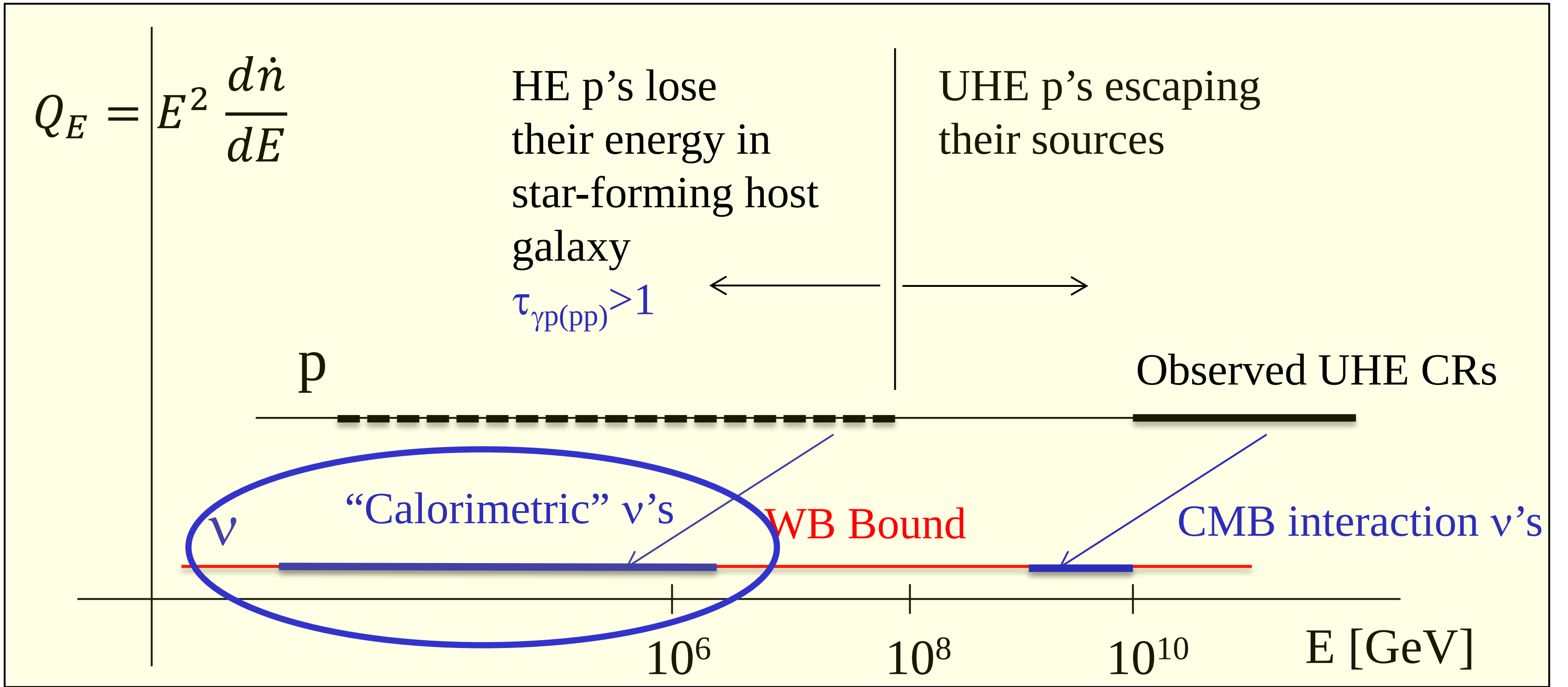
- Excess below ~50TeV.
  If real, likely a new low E component
  (rather than a soft Γ=2.5 spectrum).

[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.



Have we already seen the "calorimeters"?

In γ's: $L_\gamma \sim (2/3) L_\nu$

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

  $E^2\phi_\gamma \approx 10^{-9.5}\text{GeV/cm}^2\text{s}$ Below 10^4GeV.
- Detected by Fermi, HESS, VERITAS @ 10^{1-3}GeV.

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

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

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

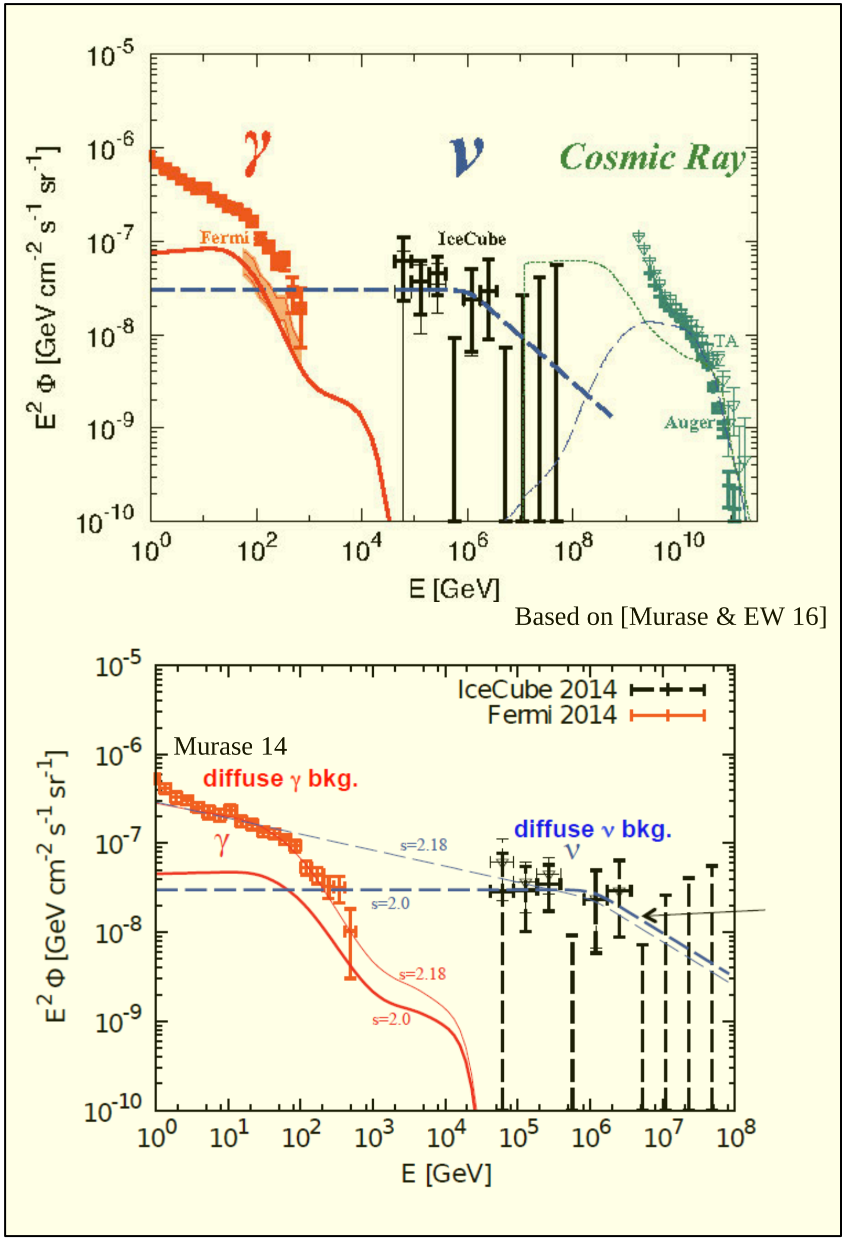
$$, \qquad L_\nu < 10^{42.5}\text{erg/s} = 10^9 L_{\text{Sun}}.$$

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

- Rare bright sources: Ruled out (eg "blazars", $n < 10^{-8.5}/\text{Mpc}^3$).
- Detection of multiple events from few nearby sources requires $A \rightarrow A \times 5$ for $n \sim 10^{-5}/\text{Mpc}^3$ (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?



Model predictions vs. observations

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

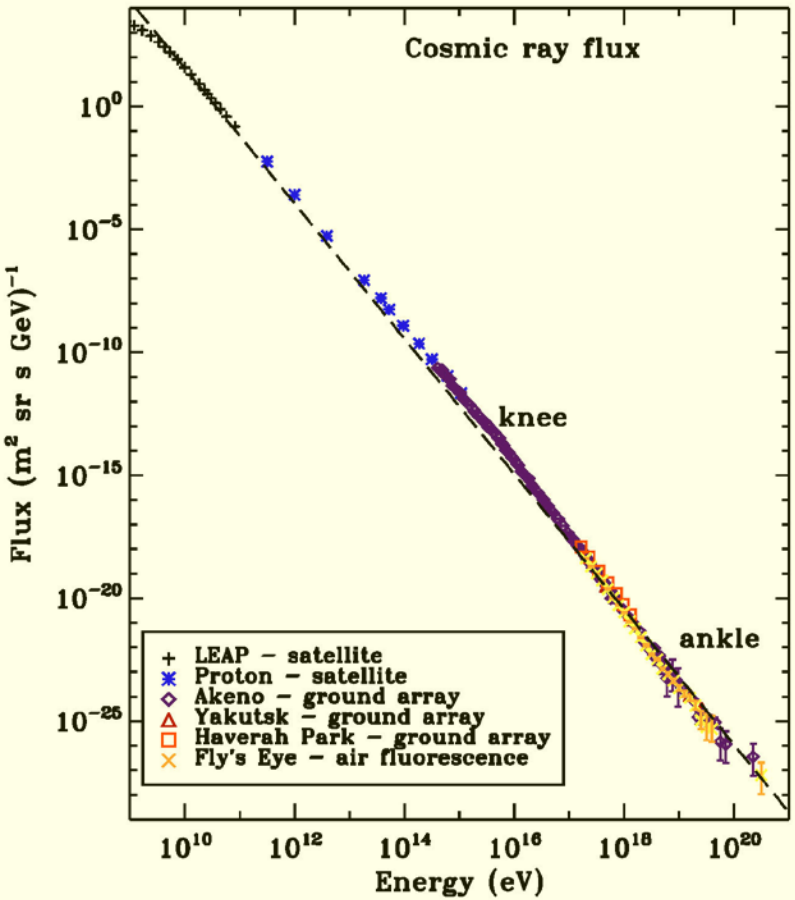
$+ L_{CR} \propto$ SFR.

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

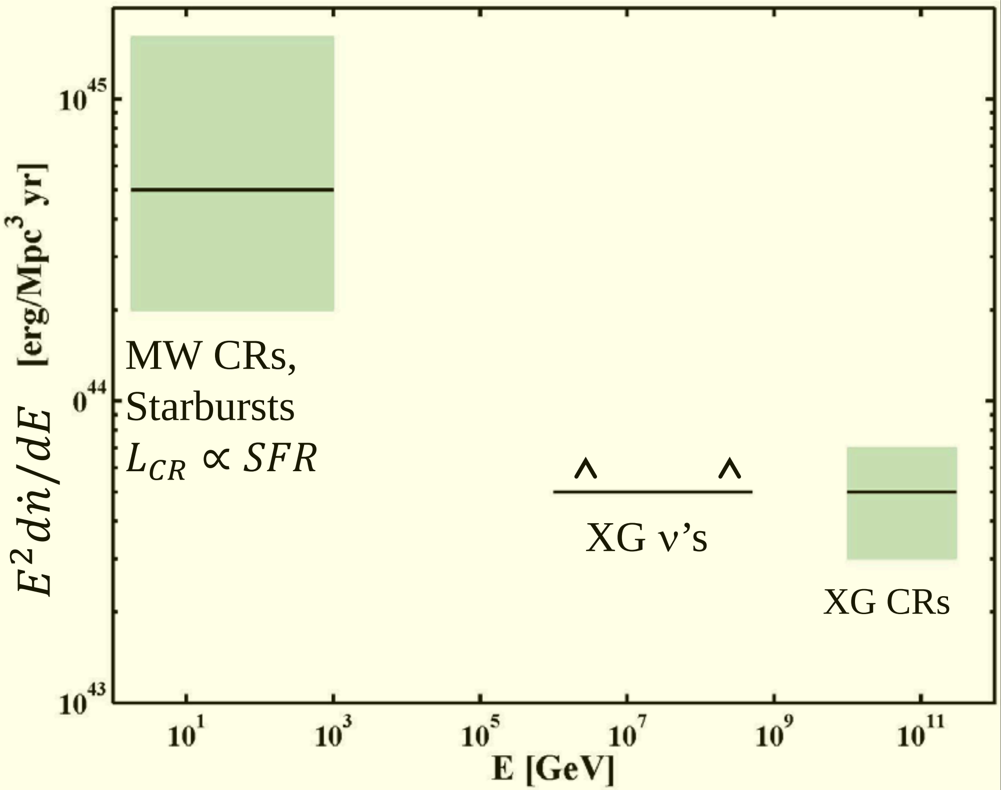
A single cosmic ray source across the spectrum?

Observed spectrum



[From Helder et al., SSR 12]

Generation spectrum



[Katz, EW, Thompson & Loeb 14]

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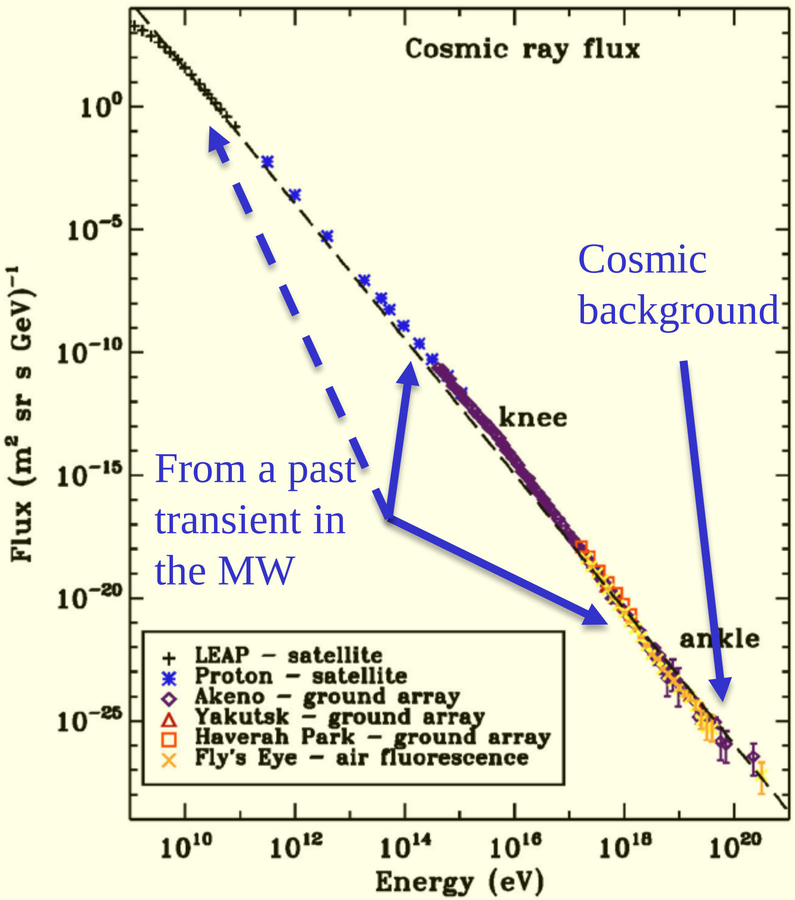

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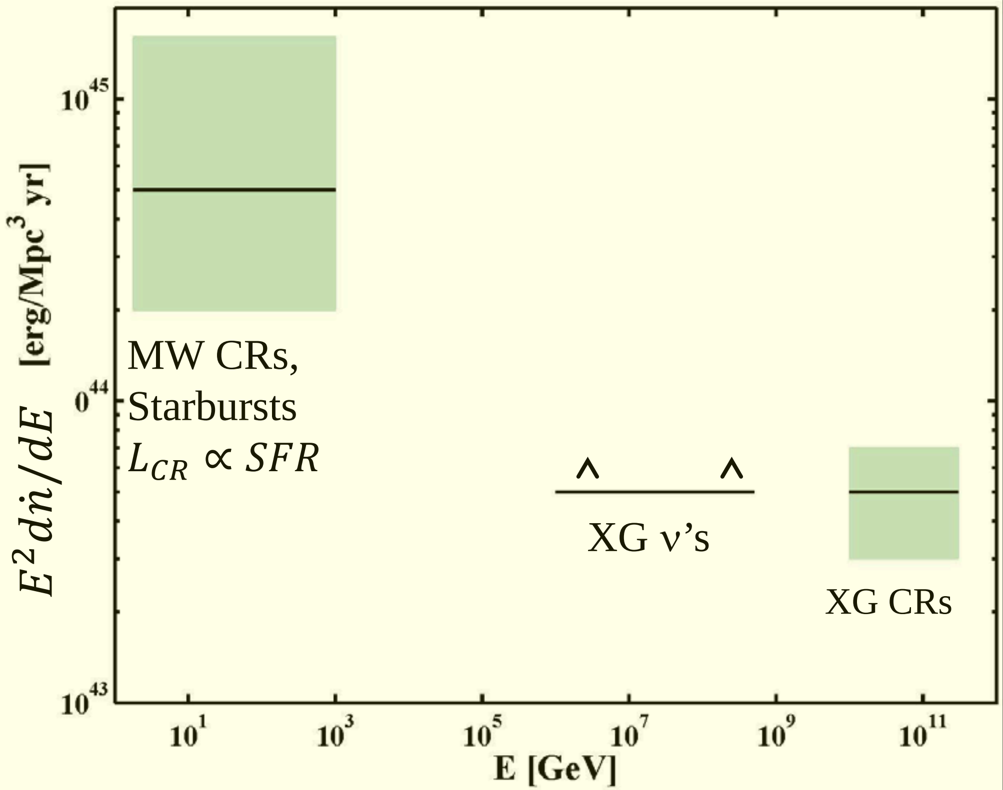


[Katz, EW, Thompson & Loeb 14]

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 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 .

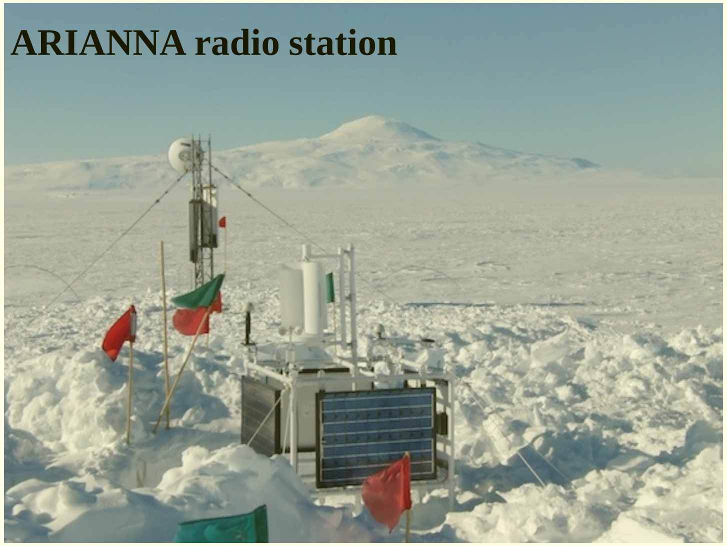
[EW & Bahcall 97; Amelino-Camelia,et al.98;
Coleman &.Glashow 99; Jacob & Piran 07, Wei et al 16]

The way forward: I. GZK ν's

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

- Detector with
  $10^{-9}\mathrm{GeV/cm^2 s\ sr}$ @ $10^8 - 10^{10}\mathrm{GeV}$
  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).



The way forward: II. VHE ν's

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

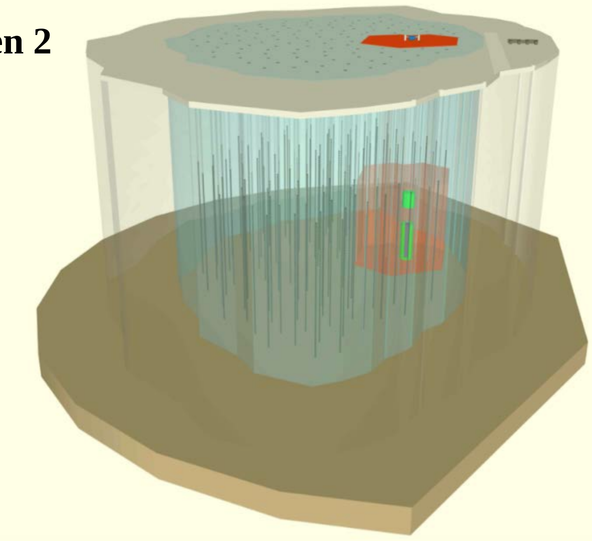
  - Reduce uncertainties in ν flux, spectrum, isotropy, flavor ratio. [A different ν source at <50TeV? A cutoff >3PeV?]

  - Detect the nearest CR/ν "calorimeters".

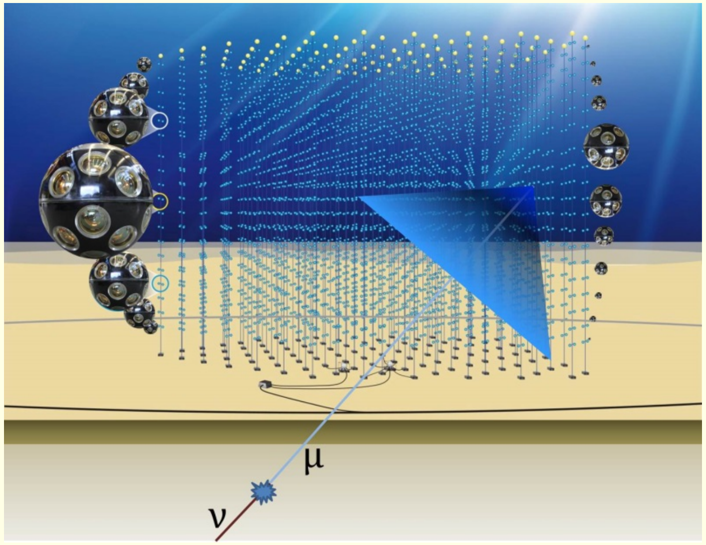
  - Possible identification of the CR sources by temporal ν–γ association (Φ_ν~0.1 Φ_{WB}). [Requires: Wide field EM monitoring, real time alerts, X/γ telescopes.]

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

IC Gen 2



KM3NeT



The way forward: III. HE ν's

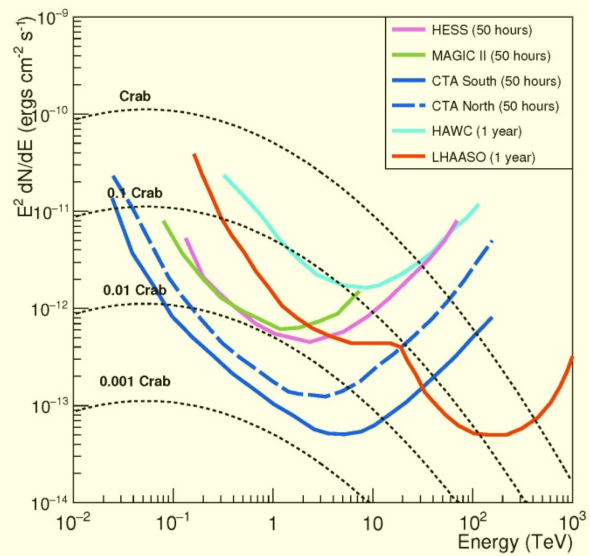
- M_{eff}~10 Gton @ $10^4 - 10^5$GeV
  - Point source sensitivity ~ advance γ-ray telescopes = CTA's (construction starts 2017).
  - "Multi-messenger" γ-ν astronomy, γ-ray detection of ν sources (L_γ~L_ν).
  - Search for Steady Galactic "Pevatrons".

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

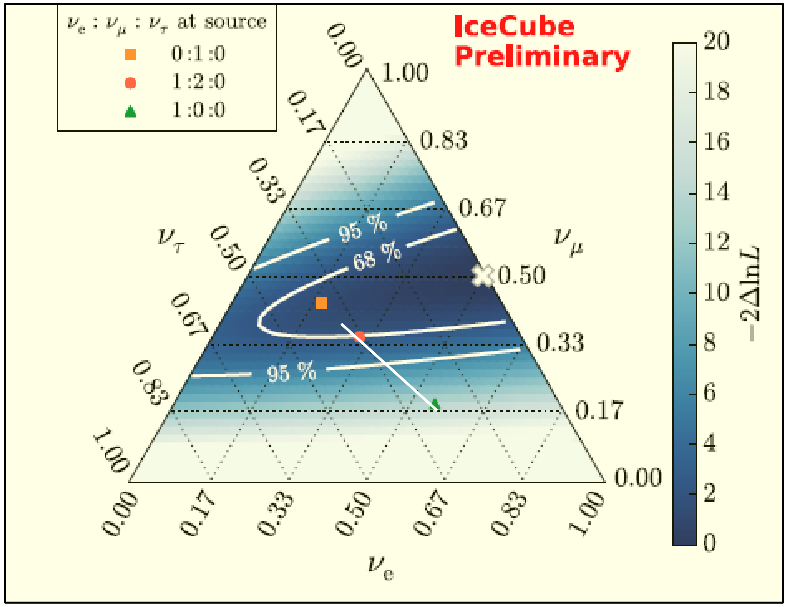
[van Santen 2017]

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)

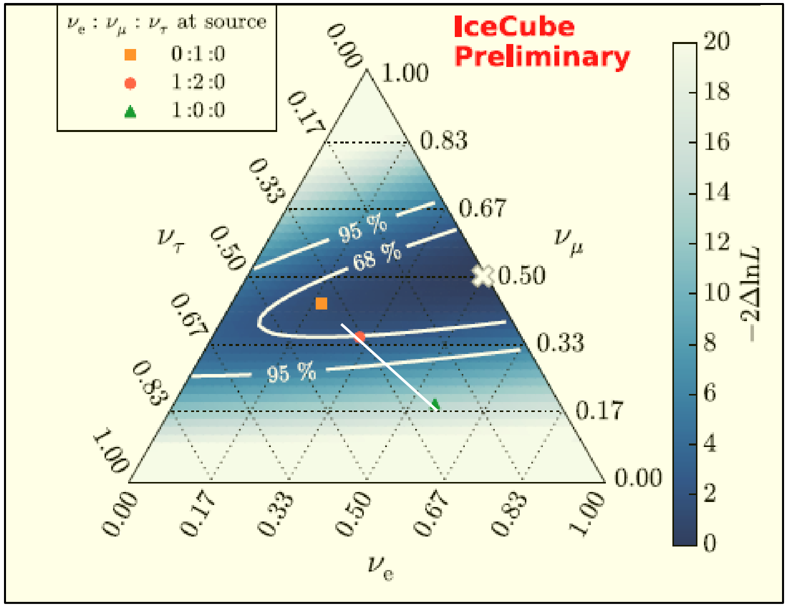
[Capozzi et al. 13]

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

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

[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).
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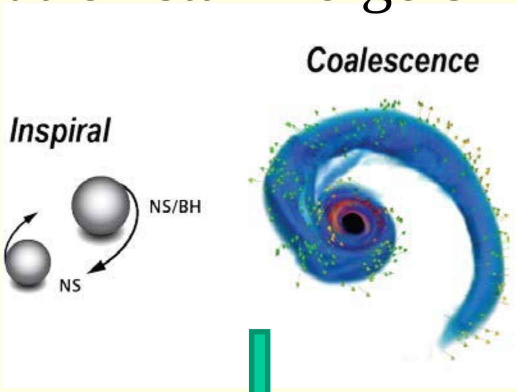
Short GRBs: multi-messenger prospects

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

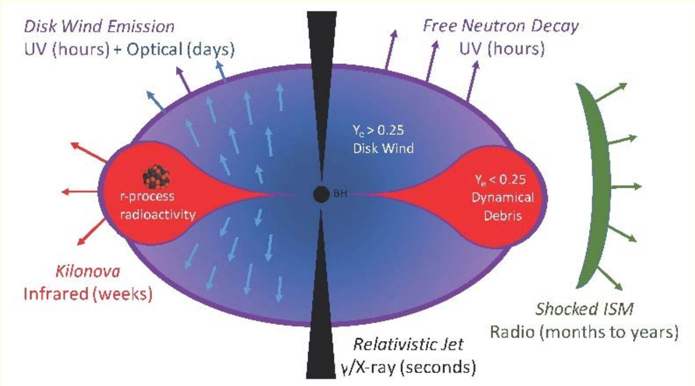
- Prospects for detection in
  Gravitational waves,
  Photons,
  Neutrinos.

- 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]).
  - $M_{eff} \sim 10$ Gton @ $10^5 - 10^8\mathrm{GeV}$ (IceCube Gen 2, KM3NeT).
  Wide field EM monitoring, real time alerts.
  "Multi-messenger": point source sensitivity ~ advanced γ telescopes (CTA).