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Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Extra-galactic sources of high energy neutrinos

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Extra-Galactic High Energy Neutrinos: Challenges & Prospects

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High energy ν's: A new window

MeV ν detectors:

- Solar & SN1987A ν's
- Stellar physics (Sun's core, SNe core collapse)
- ν physics

>0.1 TeV ν detectors:

- Extend ν horizon to extra-Galactic scale

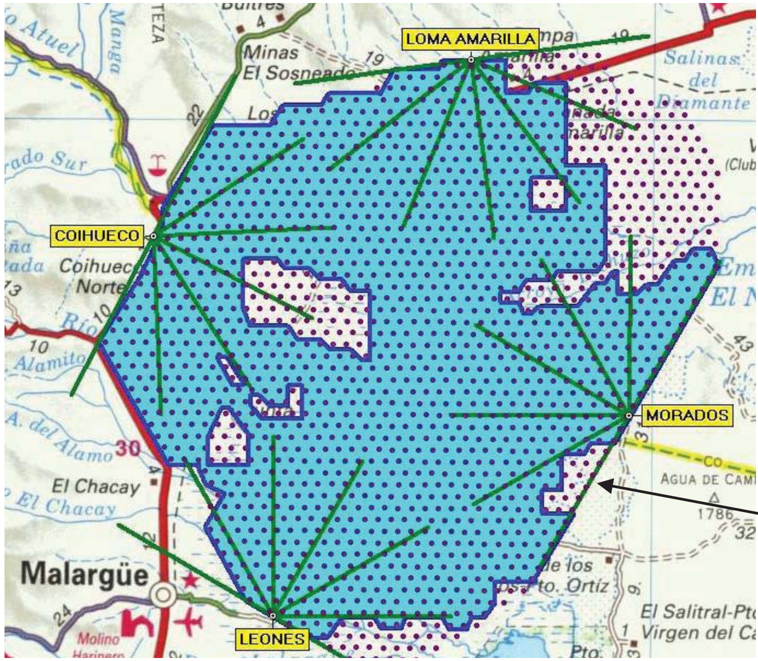
  MeV ν detectors limited to local (Galactic) sources

  [10kt @ 1MeV→1Gton @ TeV , $\sigma_{TeV}/\sigma_{MeV} \sim 10^6$]
- Study "Cosmic accelerators" [pγ, pp → π's → ν's]
- ν physics

Cosmic accelerator:

- Open questions → Prime scientific motivation
- Observed properties → Detector characteristics

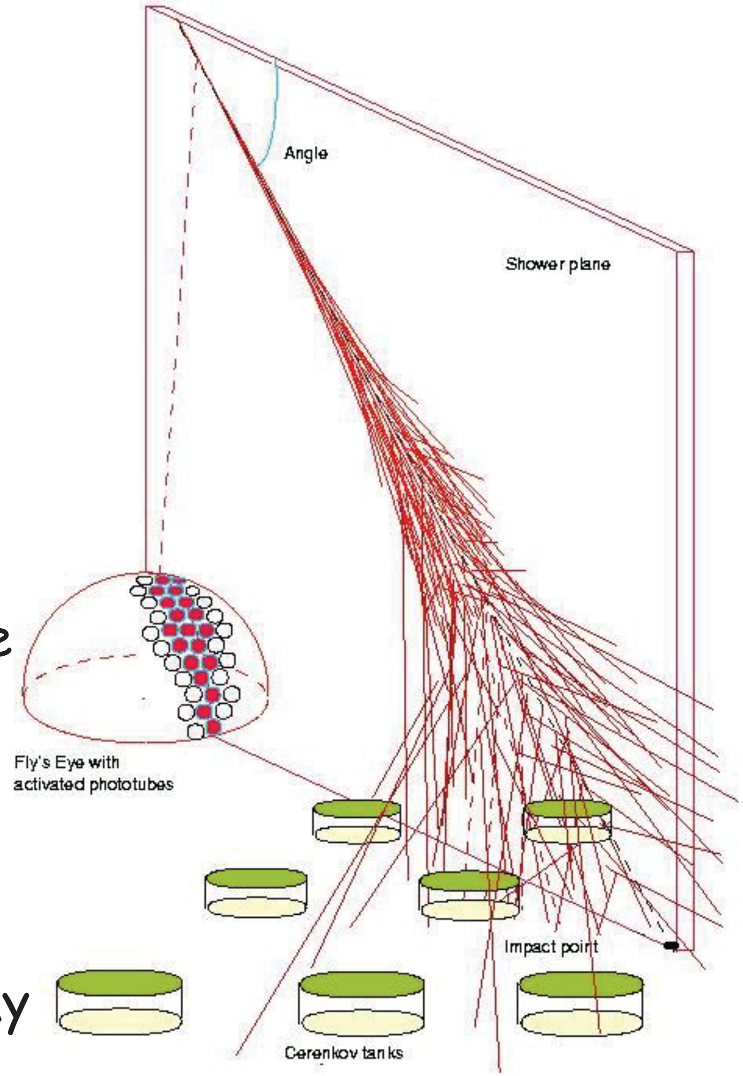
UHE, >10^{10}GeV, CRs



J(>10^{11}GeV)~1 / 100 km^2 year 2π sr

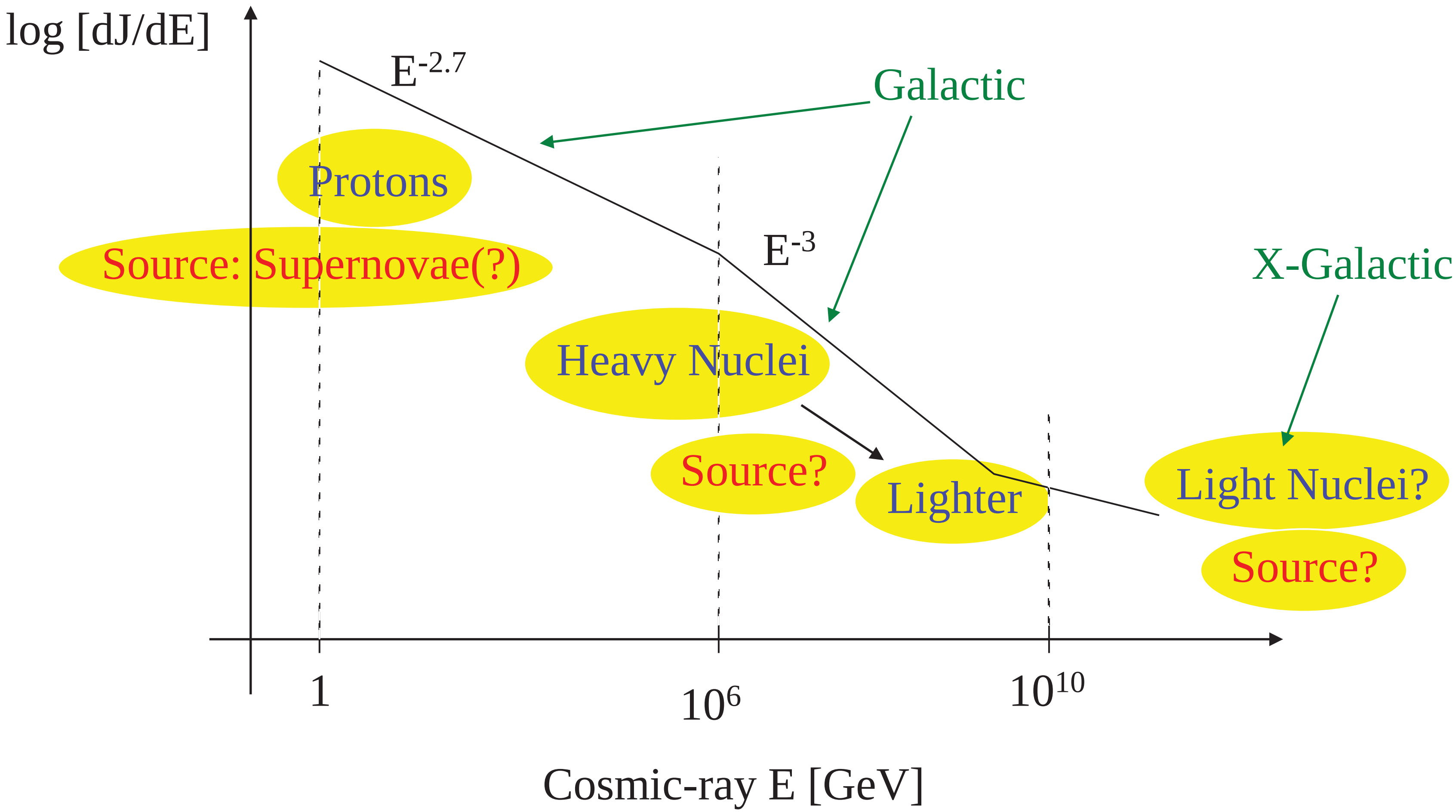
Auger:
3000 km^2

Fluorescence detector



Ground array

Cosmic accelerators

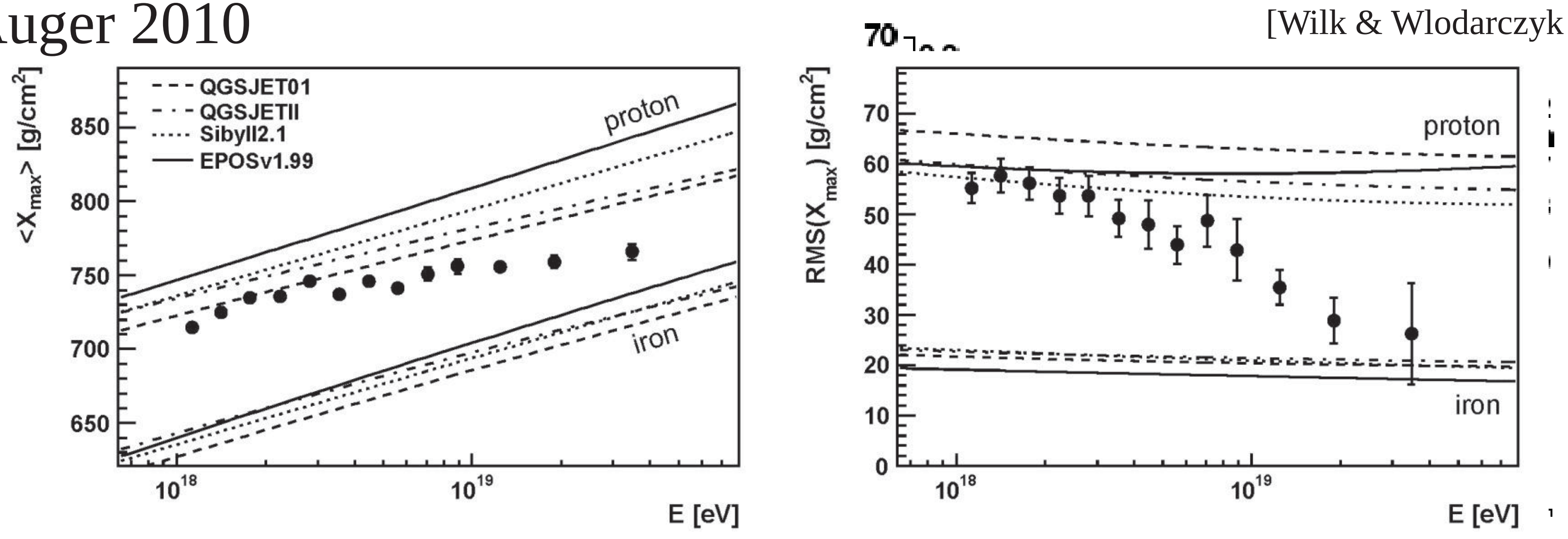


[Blandford & Eichler, Phys. Rep. 87;
Axford, ApJS 94;
Nagano & Watson, Rev. Mod. Phys. 00]

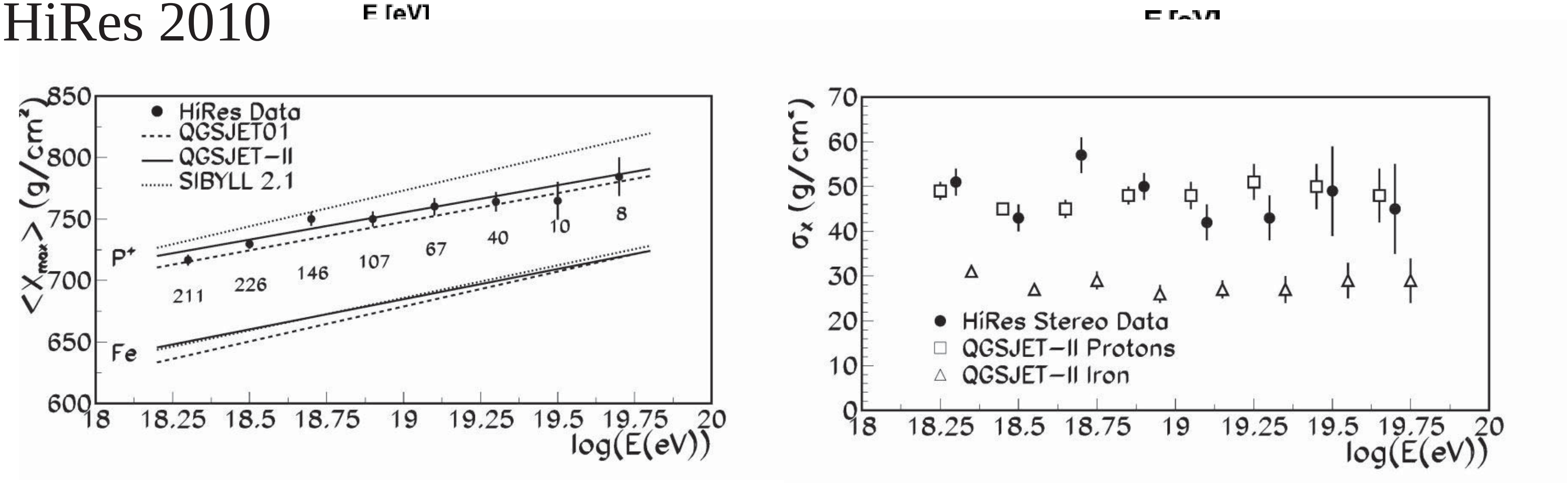
Composition

Auger 2010

[Wilk & Wlodarczyk 10]



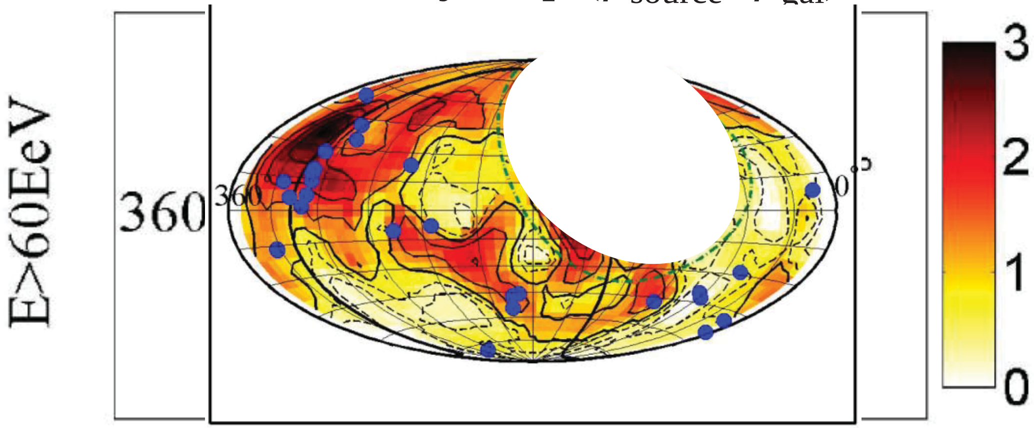
HiRes 2010



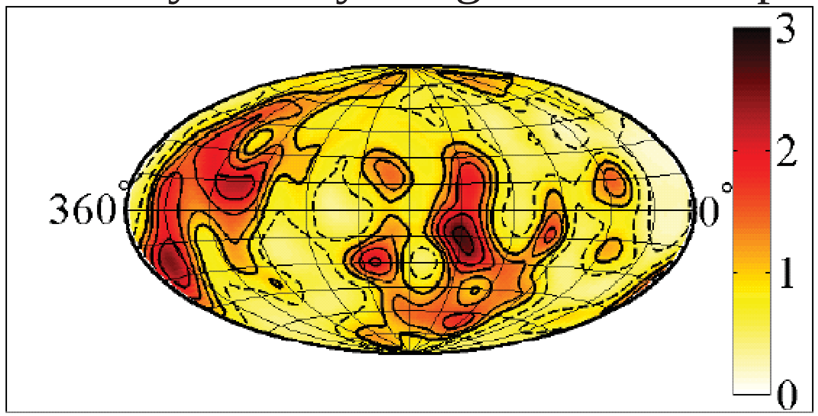
Anisotropy

Biased (ρ_{source}~ρ_{gal} for ρ_{gal}>$\overline{\rho}_{gal}$)

CR intensity map (ρ_{source}~ρ_{gal})



Galaxy density integrated to 75Mpc



[Kashti & EW 08]

[EW, Fisher & Piran 97]

- Cross-correlation signal:
  Anisotropy @ 98% CL; Consistent with LSS
  Repeater absence → N_s>N^2 → n>10^{-4}/Mpc^3
- Larger (27->69) sample: Aniso. @ 98.5% CL [Foteini et al. 11]

- Correlation with AGN?
  - Signal gone
  - Even if there = LSS

[Auger coll. 08]

Composition-Anisotropy connection

- p(E/Z) propagation = Z(E) propagation

\+ Plausible assumptions:

Acceleration of Z(>>1) to E ~ Acceleration of p to E/Z

Protons are (at least) equally abundant as Z at the source

→ Anisotropy of Z at $10^{19.7}$eV implies

Stronger aniso. signal (due to p) at $(10^{19.7}/Z)$ eV

[Lemoine & EW 09]

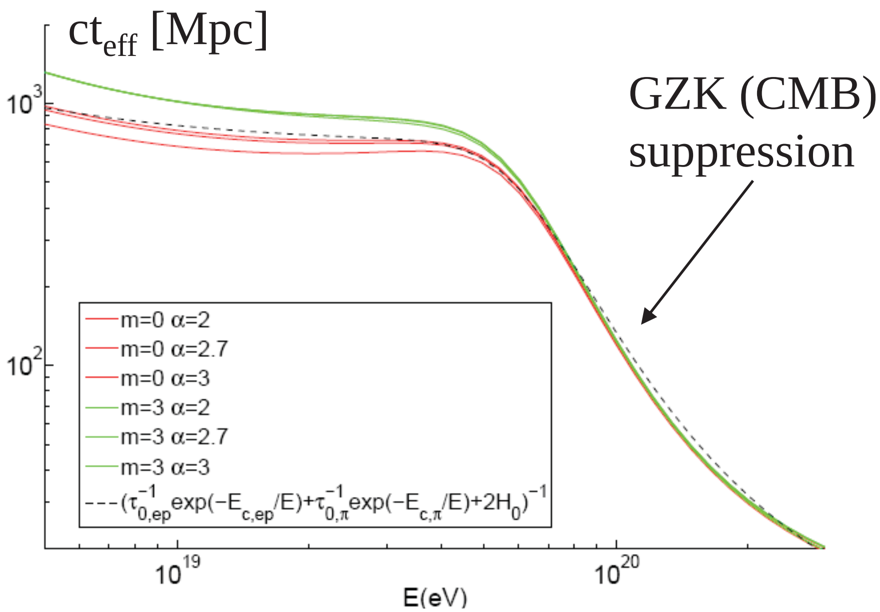
- Not observed → No high Z at $10^{19.7}$eV.

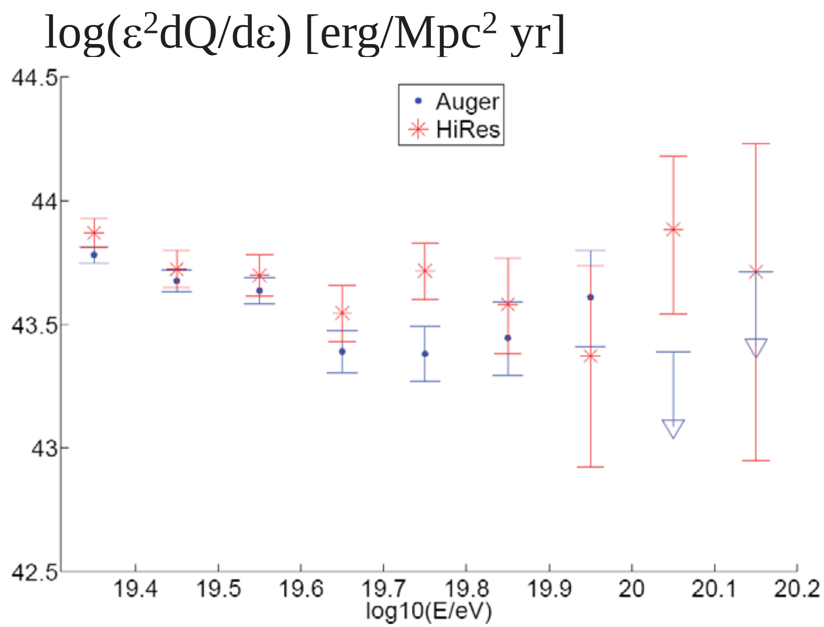
[→ No protons in the source [Auger coll. 11]]

Flux & Spectrum

- $\varepsilon^2(dN/d\varepsilon)_{Observed} = \varepsilon^2(dQ/d\varepsilon)\, t_{eff.}$ $\quad$ $(t_{eff.} : p + \gamma_{CMB} \rightarrow N + \pi)$

  Assume: p, $dQ/d\varepsilon \sim (1+z)^m \varepsilon^{-\alpha}$





[Katz & EW 09]

- $>10^{19.3}$eV: consistent with
  protons, $\varepsilon^2(dQ/d\varepsilon) = 0.5(+-0.2) \times 10^{44}$ erg/Mpc^3 yr + GZK

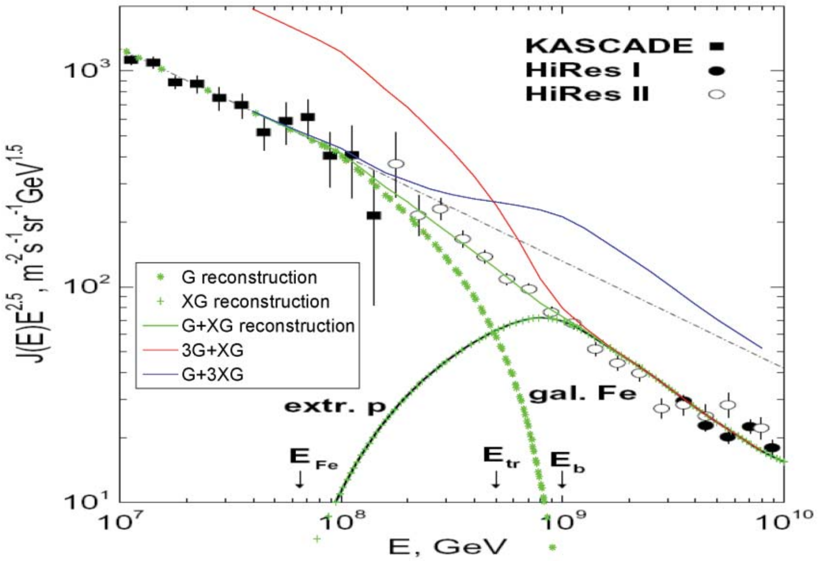
[EW 1995; Bahcall & EW 03]

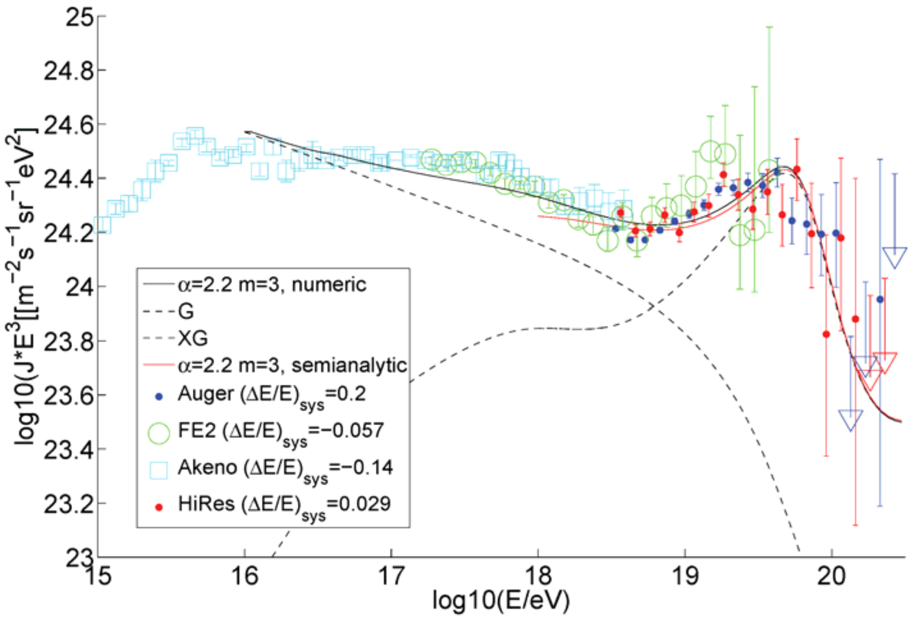
- $\varepsilon^2(dQ/d\varepsilon)$ ~Const.: Consistent with shock acceleration

[Reviews: Blandford & Eichler 87; EW 06

cf. Lemoine & Revenu 06]

G-XG Transition at ~10^{18}eV?



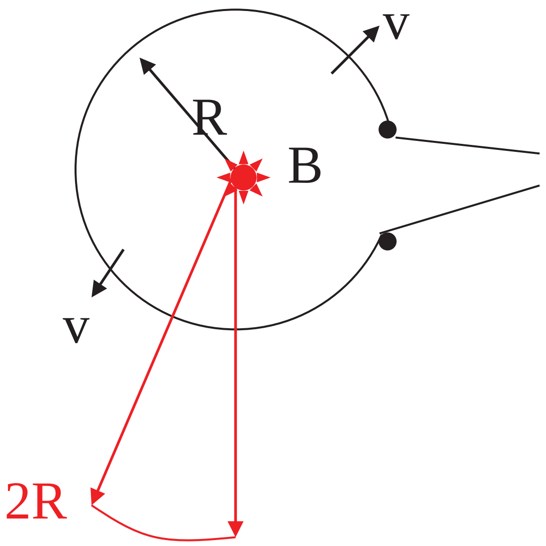


@ 10^{18}eV: Fine tuning

G cutoff @ 10^{19}eV
Inconsistent spectrum

[Katz & EW 09]

The 10^{20}eV challenge



$l = R/\Gamma$

$(\delta t_{RF} = R/\Gamma c)$

$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/\mathrm{v}} = \frac{\mathrm{v}}{\mathrm{c}}BR \quad \Rightarrow \quad \varepsilon_p < \frac{\mathrm{v}}{\mathrm{c}} eBR/\Gamma$$

$$L > 4\pi R^2 \Gamma^2 \frac{B^2}{8\pi}\mathrm{v} > \frac{1}{2\mathrm{v}/c}\left(\frac{\varepsilon_p}{e}\right)^2 c\,\Gamma^2$$

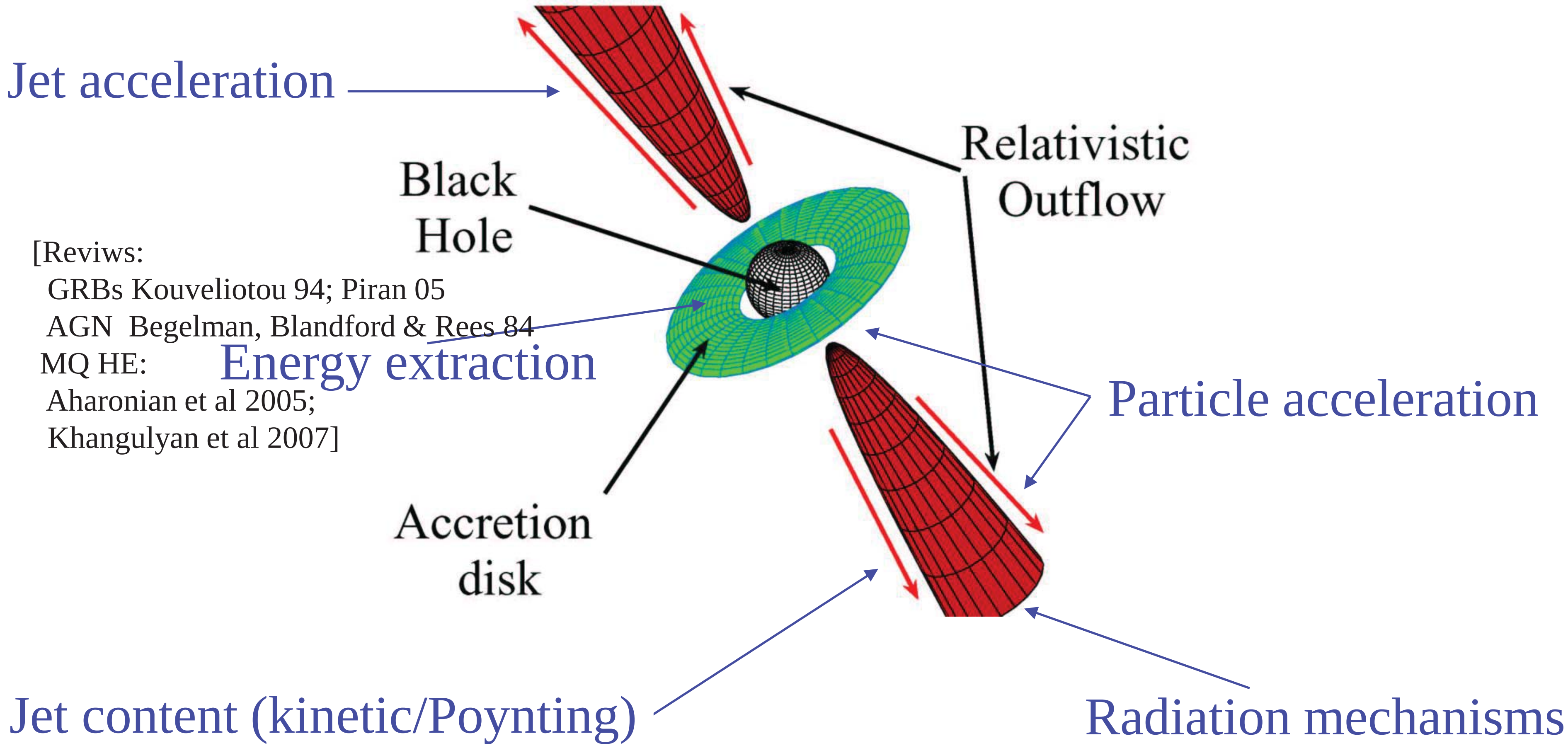
$$L > \frac{\Gamma^2}{\mathrm{v}/c}\left(\frac{\varepsilon_p}{10^{20}\,\mathrm{eV}}\right)^2 \times 10^{46}\ \mathrm{erg/s}$$

$$= \frac{\Gamma^2}{\beta}\varepsilon_{p,20}^2 \times 10^{12}\ \mathrm{L_{sun}}$$

[EW 95, 04,
Norman et al. 95]

Source physics challenges

- GRB: $10^{19} L_{Sun}$, $M_{BH} \sim 1 M_{sun}$, $\dot{M} \sim 1 M_{sun}/s$, $\Gamma \sim 10^{2.5}$
- AGN: $10^{14} L_{Sun}$, $M_{BH} \sim 10^{9} M_{sun}$, $\dot{M} \sim 1 M_{sun}/yr$, $\Gamma \sim 10^{1}$
- MQ: $10^{5} L_{Sun}$, $M_{BH} \sim 1 M_{sun}$, $\dot{M} \sim 10^{-8} M_{sun}/yr$, $\Gamma \sim 10^{0.5}$



[Reviws:
GRBs Kouveliotou 94; Piran 05
AGN Begelman, Blandford & Rees 84
MQ HE:
Aharonian et al 2005;
Khangulyan et al 2007]

What do we know about $>10^{19}$eV CRs?

- $J(>10^{11}\text{GeV})\sim 1$ / 100 km^2 year 2π sr
- Most likely X-Galactic ($R_L=\varepsilon/eB=40\varepsilon_{p,20}$kpc)
- (An)isotropy: 2σ, consistent with LSS
- Composition?

HiRes- p, Auger- becoming heavier(?), Anisotropy suggests p

- Production rate & spectrum:
  protons, $\varepsilon^2(dQ/d\varepsilon)\sim 0.5(+-)0.2\times 10^{44}$ erg/Mpc^3 yr + GZK
- No "repeaters": $N_{source}>N_{CR}^2$ → $n(@\ 10^{19.7}\text{eV}) > 10^{-4}/\text{Mpc}^3$

- Acceleration (expanding flow):

Confinement→ $L>L_B>10^{12}\,(\Gamma^2/\beta)\,(\varepsilon/Z\ 10^{20}\text{eV})^2\,L_{sun}$

Synch. losses→ $\Gamma > 10^{2.5}\,(L_{52})^{1/10}\,(\delta t/10\text{ms})^{-1/5}$

!! No $L>10^{12}\,L_{sun}$ at $d<d_{GZK}$ → Transient Sources

UHECR sources: Suspects

- Constraints: - $L > 10^{12} (\Gamma^2/\beta) L_{sun}$, $\Gamma > 10^{2.5} (L_{52})^{1/10} (\delta t/10ms)^{-1/5}$
  - $\varepsilon^2(dQ/d\varepsilon) \sim 10^{43.7}$ erg/Mpc^3 yr
  - $d(10^{20}eV) < d_{GZK} \sim 100$Mpc

  !! No $L > 10^{12} L_{sun}$ at $d < d_{GZK}$ → Transient Sources

- Gamma-ray Bursts (GRBs)

  √ $L_\gamma \sim 10^{19} L_{Sun} > 10^{12} (\Gamma^2/\beta) L_{sun} = 10^{17} (\Gamma/ 10^{2.5})^2 L_{sun}$ [EW 95, Vietri 95, Milgrom & Usov 95]

  √ $\Gamma \sim 10^{2.5} (L_{52})^{1/10} (\delta t/10ms)^{-1/5}$

  √ $\varepsilon^2(dQ/d\varepsilon)_\gamma \sim 10^{53}erg*10^{-9.5}$/Mpc^3 yr = $10^{43.5}$ erg/Mpc^3 yr

  √ Transient: $\Delta T_\gamma \sim 10$s << $\Delta T_{p\gamma} \sim 10^5$ yr [EW 95]

- Active Galactic Nuclei (AGN, Steady):

  $\Gamma \sim 10^1$ → $L > 10^{14} L_{Sun}$= few brightest [Blandford 76; Lovelace 76]

  !! Non at $d < d_{GZK}$ → Invoke:

  * "Hidden" (proton only) AGN [Boldt & Loewenstein 00]
  * $L \sim 10^{14} L_{Sun}$, $\Delta t \sim 1$month flares [Farrar & Gruzinov 08]

    If e^- accelerated: X/γ observations → rare $L > 10^{17} L_{sun}$ [EW & Loeb 09]

HE ν's: UHECR bound

- $p + \gamma \rightarrow N + \pi$

  $\pi^0 \rightarrow 2\gamma$; $\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$

→ Identify UHECR sources

   Study BH accretion/acceleration physics

- For all known sources, $\tau_{\gamma p}<1$:

$$\varepsilon_\nu^2 \frac{dj_\nu}{d\varepsilon_\nu} \le \Phi_{\rm WB} \equiv 10^{-8}\,\zeta \left(\frac{\varepsilon^2 dQ/d\varepsilon}{10^{44}\,{\rm erg/Mpc^3 yr}}\right) \frac{\rm GeV}{\rm cm^2 s\, sr}$$

$$\zeta = 1, 5 \quad \text{for} \quad f(z) = 1, (1+z)^3$$

[EW & Bahcall 99; Bahcall & EW 01]

- If X-G p's: $$\varepsilon_\nu^2 \frac{dj_\nu}{d\varepsilon_\nu}(10^{19}\,{\rm eV}) = \Phi_{\rm WB}$$

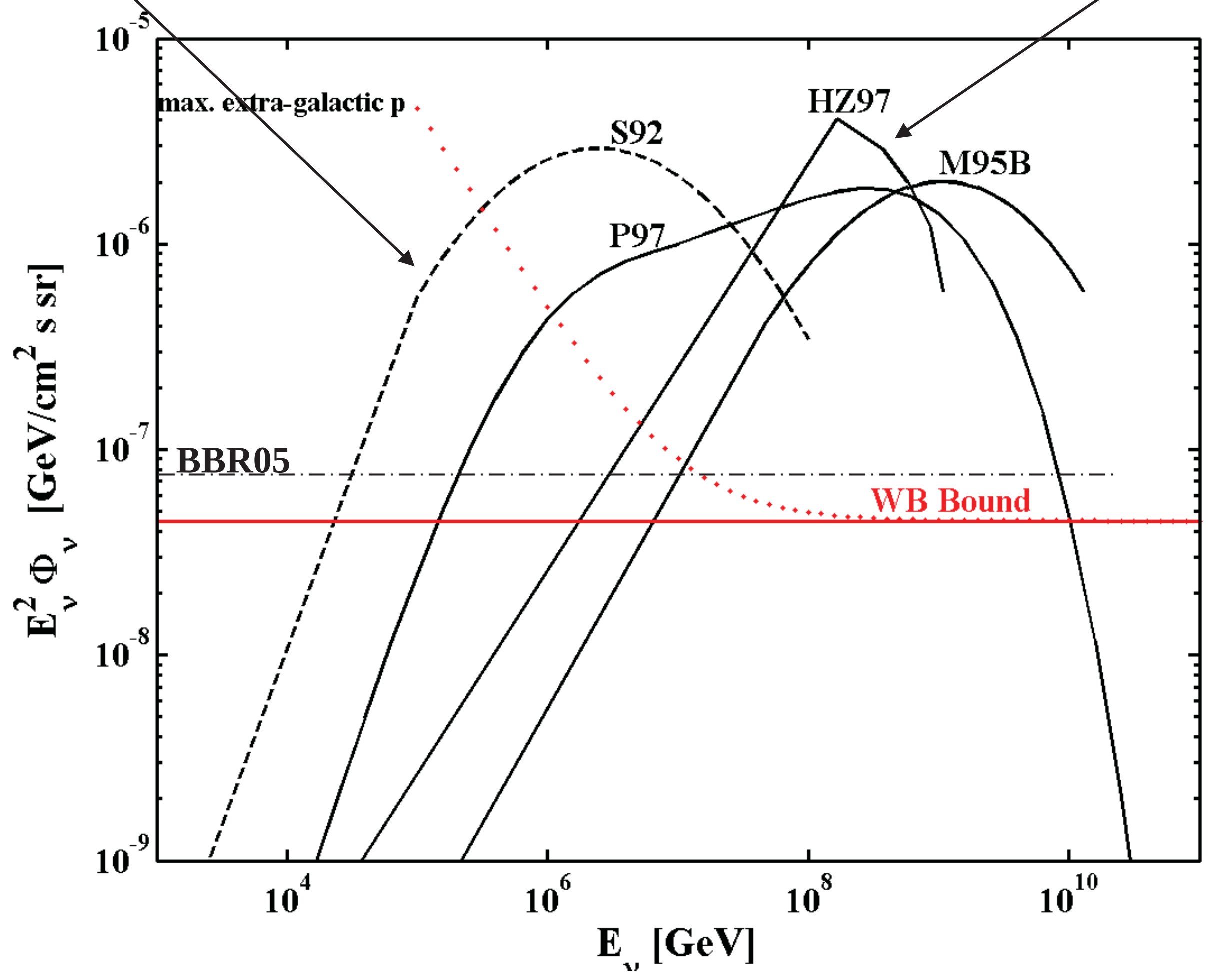
[Berezinsky & Zatsepin 69]

→ Identify primaries, determine f(z)

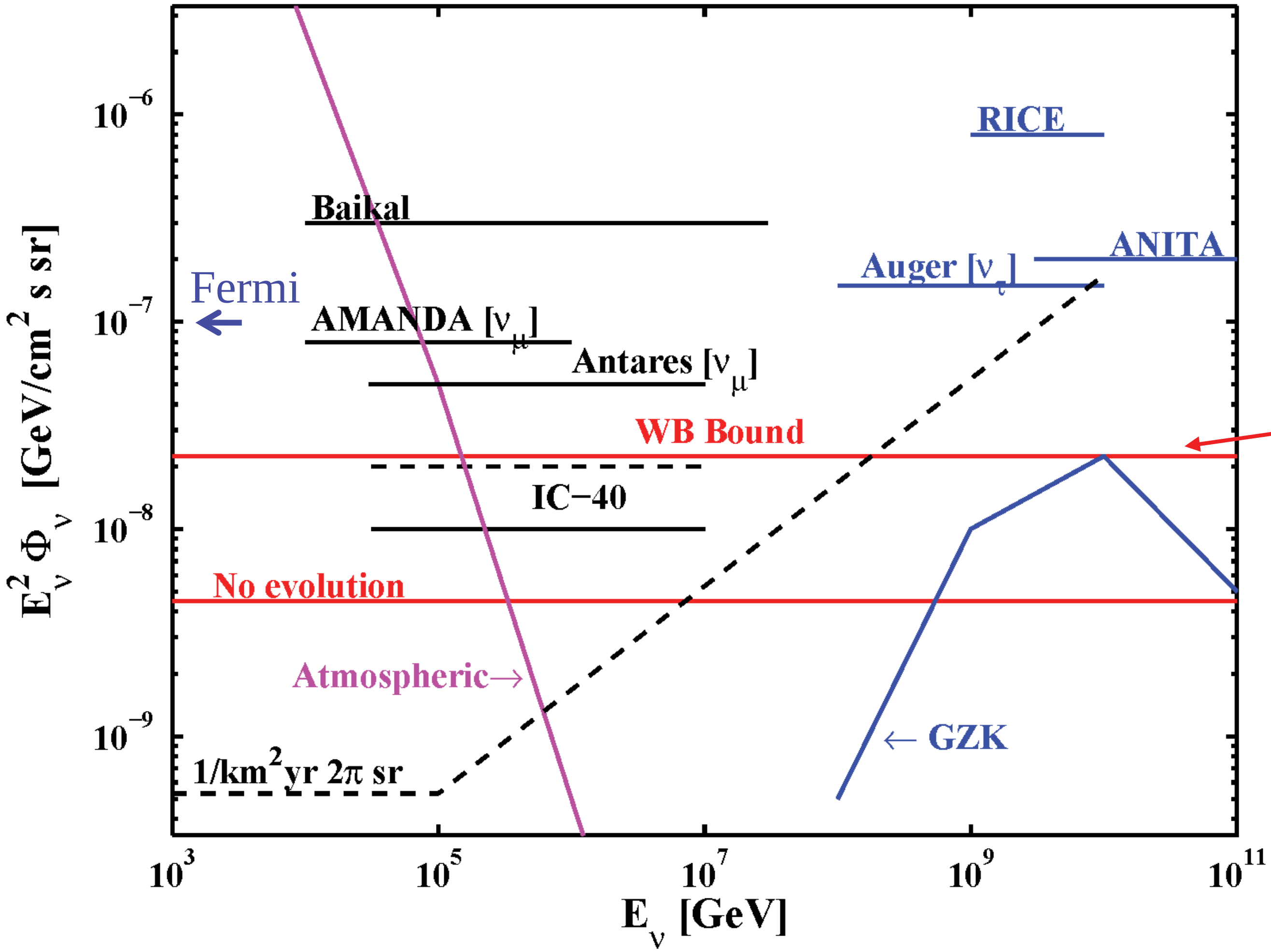
Bound implications: I. AGN ν models

“Hidden” (ν only) sources

Violating UHECR bound



Bound implications: II. ν experiments



No oscillations,

$$\frac{\varepsilon^2 dQ/d\varepsilon}{10^{44}\text{erg/Mpc}^3\text{yr}} = 0.5$$

No "hidden" sources!

Are steady UHECR sources likely to be detected?

- $1 \times 6 \times 10^{19}$eV /3000 km^2 = 2×10^4TeV/km^2
  $\times P_{\nu\mu}$(1TeV)~10^{-6} → 0.02 μ/km^2
  No repeaters → <10^{-3} μ/km^2

→ Steady UHECR source detection Unlikely
(unless L_ν>100 L_{CR},
i.e. "Hidden sources" which do not exist)

Transient sources: GRB ν's

- **If: Baryonic jet**

$$(\varepsilon_p/\Gamma)(\varepsilon_\gamma/\Gamma) \geq 0.3\,\mathrm{GeV}^2$$

$$\varepsilon_\gamma = 1\,\mathrm{MeV}, \Gamma = 10^{2.5} \Rightarrow \quad \varepsilon_p \geq 10^{16}\,\mathrm{eV}\,,\ 10^{14.5}\,\mathrm{eV} \leq \varepsilon_\nu (\leq 10^{16}\,\mathrm{eV})$$

$$f_{p\to\pi} \approx 0.2$$

$$\varepsilon^2\Phi_\nu \approx 0.2\Phi_\nu^{WB} \quad , \quad \varepsilon_\nu \geq 10^{14.5}\,\mathrm{eV}$$

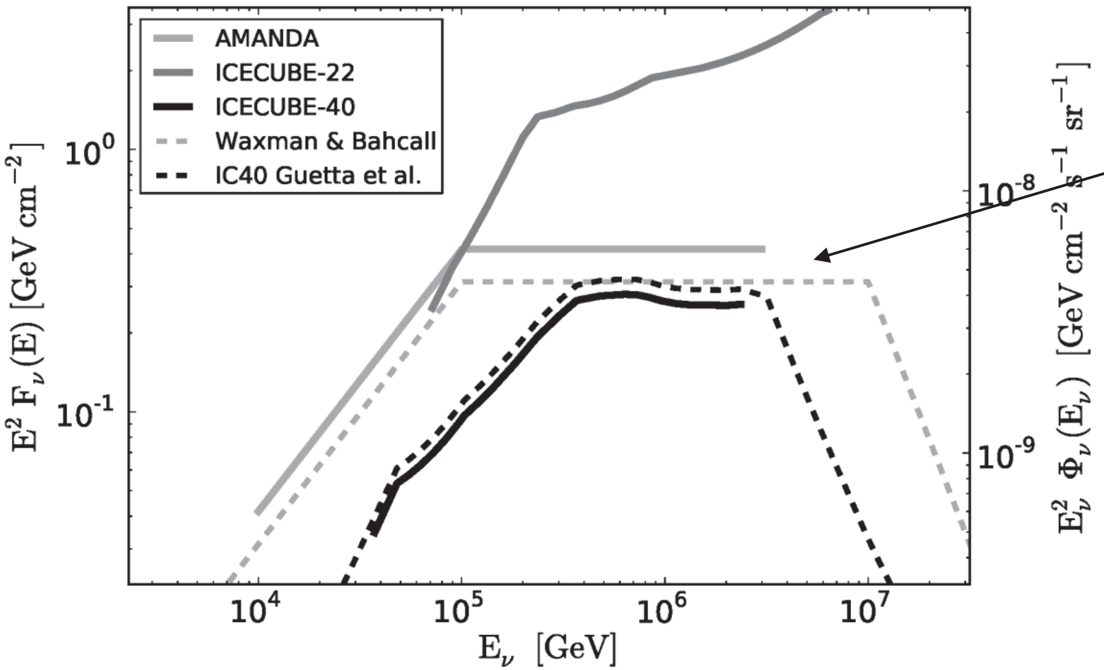
$$J_{\nu\to\mu} \approx 10\left(\frac{\varsigma}{5}\right)\left(\frac{f_\pi}{0.2}\right)\left(\frac{\varepsilon_{\nu,\mathrm{b}}}{10^{14.5}\mathrm{eV}}\right)^{-1/2}\left(\frac{\varepsilon^2 dQ/d\varepsilon}{0.5\times10^{44}\mathrm{erg/Mpc^3yr}}\right)/\,\mathrm{km^2yr}, \quad \sim 1\nu\ /100\ \mathrm{GRB}$$

[EW & Bahcall 97, 99; Rachen & Meszaros 98; Guetta et al. 01; Murase & Nagataki 06]

- **Background free:**

$$J^A_{\nu\to\mu} \sim 10^{-10}\left(\frac{\Delta\Theta}{0.5^o}\right)^2\left(\frac{E}{100\mathrm{TeV}}\right)^{-\beta}/\,\mathrm{km^2s}\,; \qquad \beta = \begin{cases}1.7 & E < 100\mathrm{TeV}\\ 2.5 & E > 100\mathrm{TeV}\end{cases}$$

GRB ν's: IC40 constraints



$$\frac{\varepsilon^2 dQ/d\varepsilon}{10^{44}\mathrm{erg/Mpc^3yr}} = 1$$

- No ν's for 117 GRBs (~1 expected, at 90%CL <2)
- IC is achieving relevant sensitivity
  [see also W. Winter's talk]

What will we learn?

- Detection: highly informative
  - Identify CR source
  - Strong support: Baryonic jets, p acceleration,
    dissipation by collisionless shocks
  - Fundamental/ν physics

- Non-detection: ambiguous
  - $10/\mathrm{km}^2\mathrm{yr}$ is an order of mag. (proportional to $\zeta \times dQ/dE \times f_\pi$)
  - Significant non-detection ($\ll 10/\mathrm{km}^2\mathrm{yr}$, $\ll 1\nu/100\mathrm{GRB}$)

    Poynting jet (no p)

    or

    Dissipation mechanism (eg no p acceleration to relevant E)

    or

    Radiation mechanism ($\rightarrow f_\pi \ll 0.2$)

Non-UHE X-Galactic sources

- SNe
- Starbursts

(multi-)TeV SN ν's

- Radiation-to-collisionless mediated shocks
  Jet driven SNe
  → p acceleration & dense target → ν's

[- Razzaque et al. 04; Ando & Beacom 05;
- Gaisser and T. Stanev 87; Murase et al. 09;
- Wang et al. 2007; Murase et al. 08;
- EW & Loeb 01; Murase et al. 10]

- $E_{opt/UV}$~10^{51}erg SNe- wind breakouts?
  Wind breakouts must form collisionless shocks
  → E_γ(1MeV)~E_ν(1TeV)~E_{soft}
  10^{51}erg in 1TeV ν @ 100Mpc → 5μ/km²
  [Bgnd (1TeV) ~ 0.03/km²day]

[Katz, Sapir & EW 11]

M82

Mark Westmoquette (University College London),
Jay Gallagher (University of Wisconsin-Madison),
Linda Smith (University College London),
WIYN//NSF, NASA/ESA

M81

Robert Gendler

Starburst Galaxies

$$pp \to pn\pi^+, \quad \pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

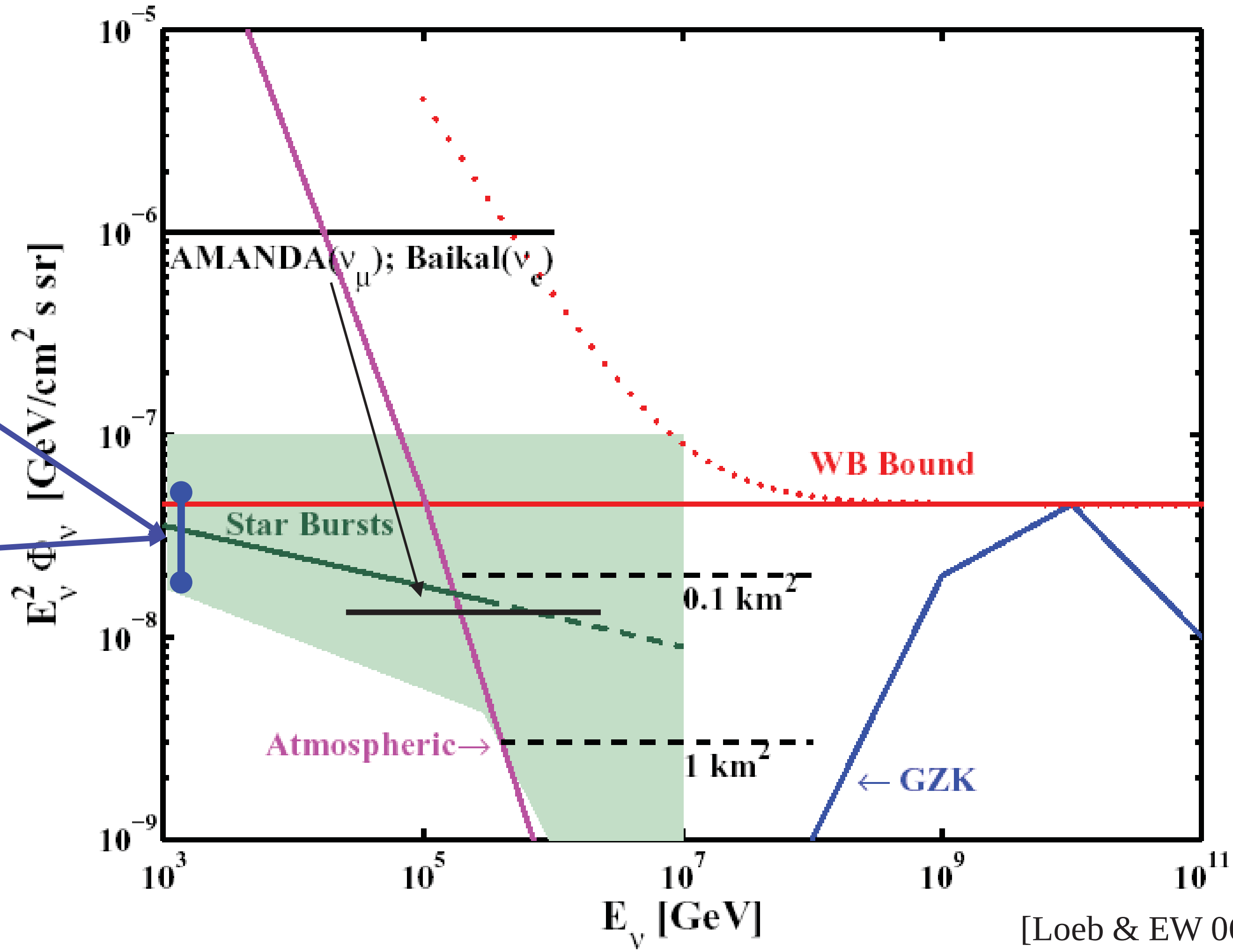
Synchrotron radio (~1GeV) → calibration → Φ_ν

$\pi^0 \to \gamma\gamma$, $\Phi_\nu \sim \Phi_\gamma$

M82, NGC253:
TeV
Hess, VERITAS 09

10GeV
Fermi 09→
dN/dE~1/E^p, p<~2.2

[Lacki et al. 11]



[Loeb & EW 06]

ν- physics & astro-physics

- π decay → $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 (Osc.)→ $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1
  τ appearance experiment
  [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]
- EM energy loss of μ's (and π's)
  $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 ($E>E_0$)→ 1:2:2
  GRBs: $E_0 \sim 10^{15}$eV
  [Rachen & Meszaros 98; Kashti & EW 05]
- Optimistic (>100 ν's): Combining $E<E_0$, $E>E_0$ flavor measurements may constrain flavor mixing
  [CPV, $\sin\Theta_{13}\cos\delta$]
  [Blum, Nir & EW 05; **Winter 10**]

Summary

- IceCube's sensitivity meets minimum requirements for detection of XG sources
- No HE XG ν's expected(detected) for(with) current exposure
  1st conclusion: No hidden sources
- Transients are the prime targets
- XG ν detection rate limited (<~10/yr)
- Detection of a handful of ν's may resolve outstanding puzzles:
  - Identify UHECR (& G-CR) sources
  - Resolve open "cosmic-accelerator" physics Q's
    (related to BH-jet systems, particle acc., rad. mechanisms)
  - High energy astro Q's (starbursts, SN breakouts…)
  - Constrain ν physics, LI, WEP
  - Unexpected?
- Coordinated wide field EM transient monitoring crucial
  - Enhance ν detection sensitivity
  - Identify sources, Physics output

- Time to go for >>1km scale detectors