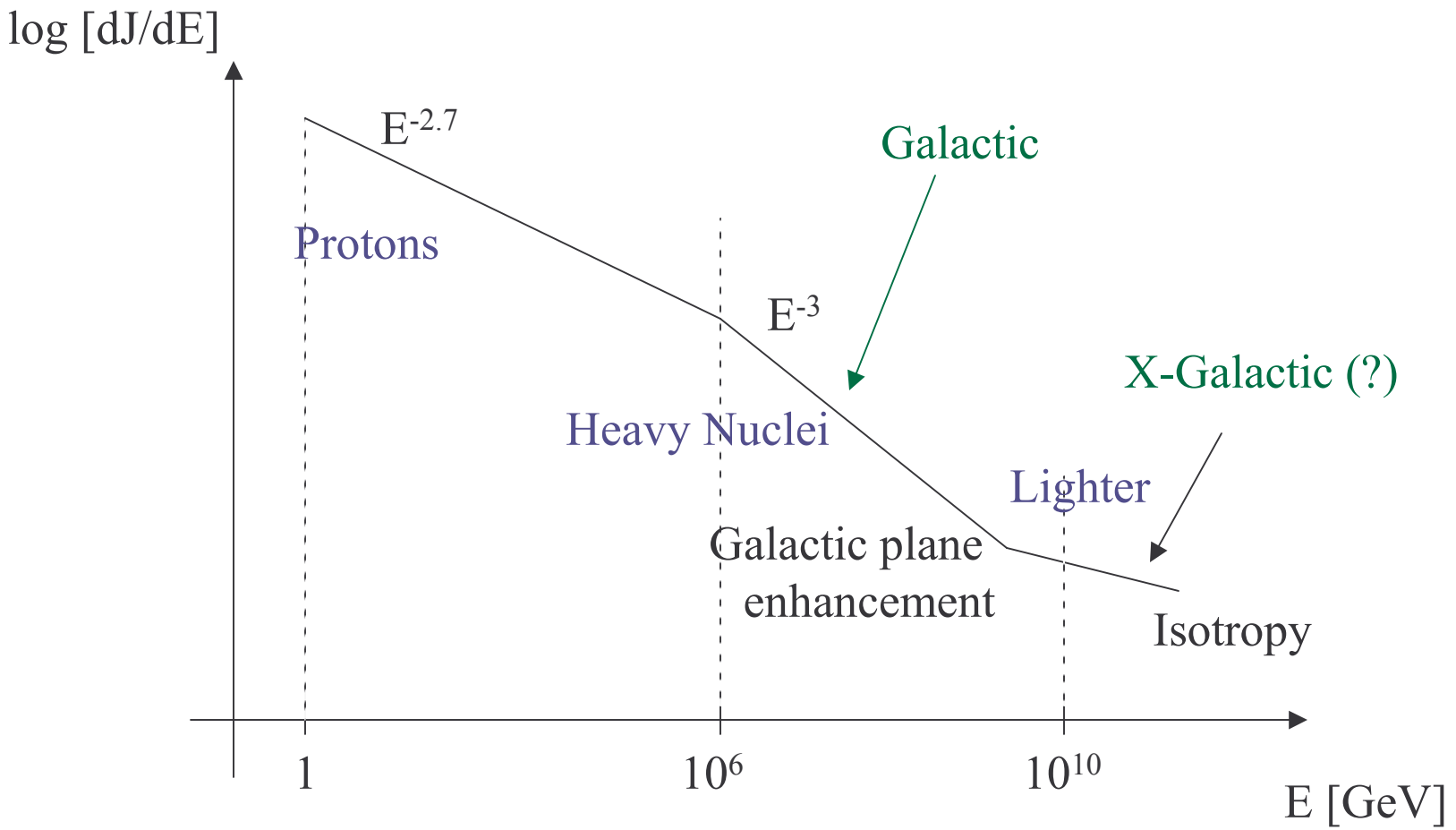
Has the GZK cutoff been observed?

Eli Waxman
Weizmann Institute, ISRAEL

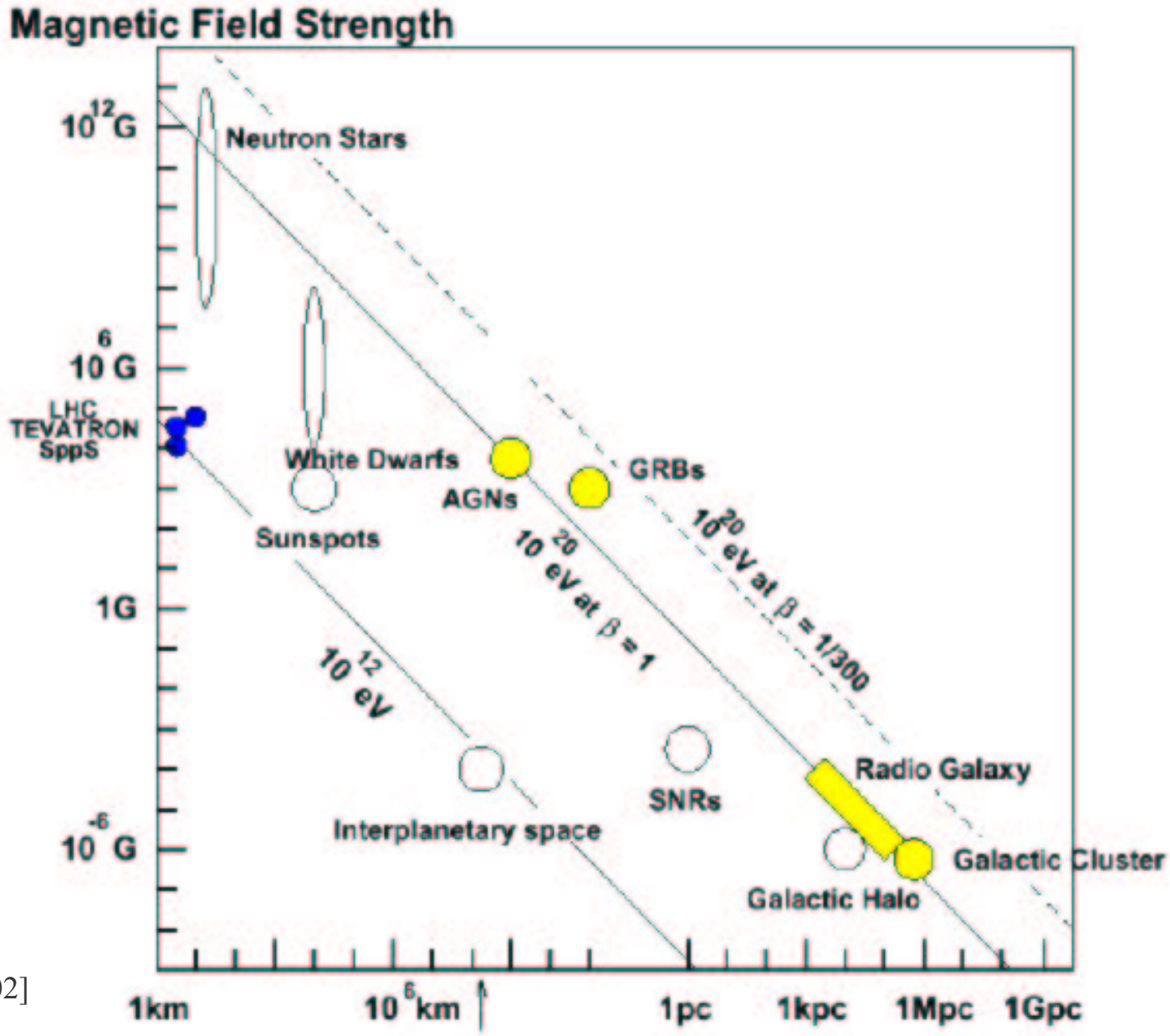
Cosmic ray flux and Composition



$U_{cr}(1GeV)=1\ eV/cm^3$

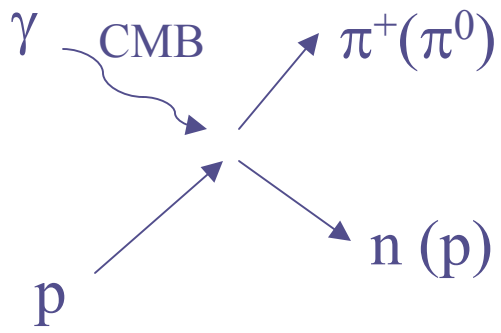
[Blandford & Eichler, Phys. Rep. 87; Axford, ApJS 94; Bird et al. 94; Nagano & Watson, Rev. Mod. Phys. 00; Abu-Zayyad et al. 01]

Challenge I: Acceleration Problem



[K. Arisaka 02]

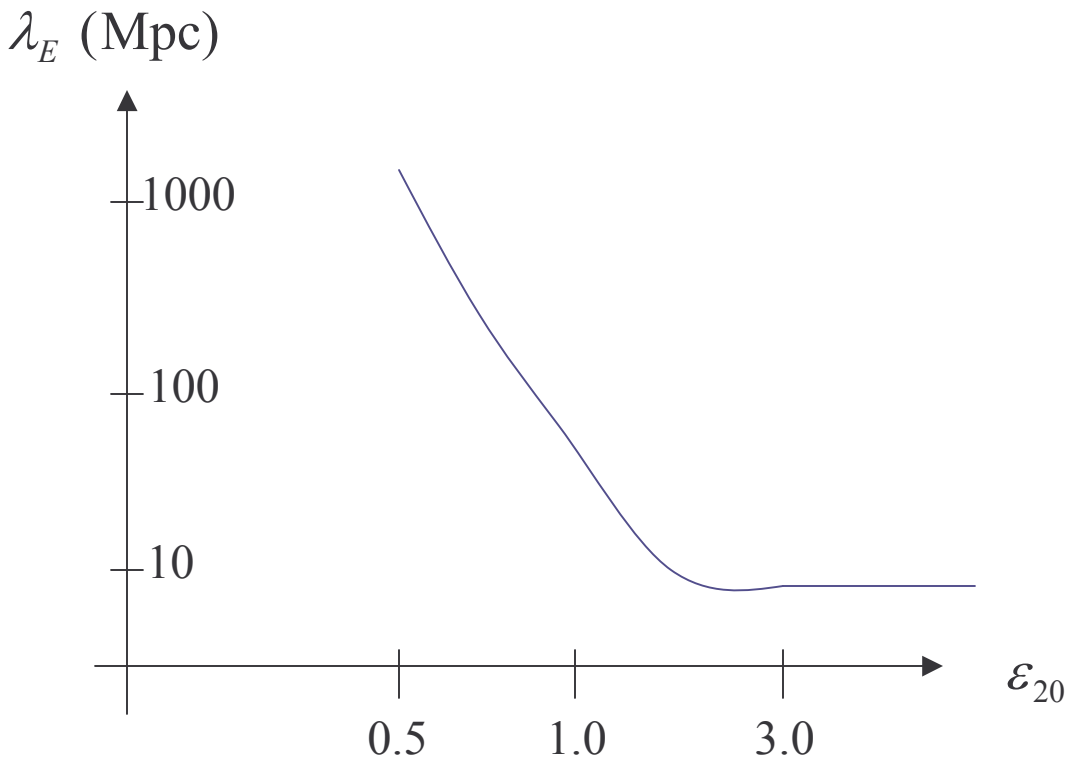
Challenge II: Propagation (GZK)



$$\varepsilon_\gamma > \frac{m_\pi m_p}{\varepsilon_p} \sim 10^{-3}\,\varepsilon_{20}^{-1}\ \text{eV} \Rightarrow \quad n_\gamma \sim \frac{400}{\text{cm}^3}\exp\left[1-\frac{3}{\varepsilon_{20}}\right]$$

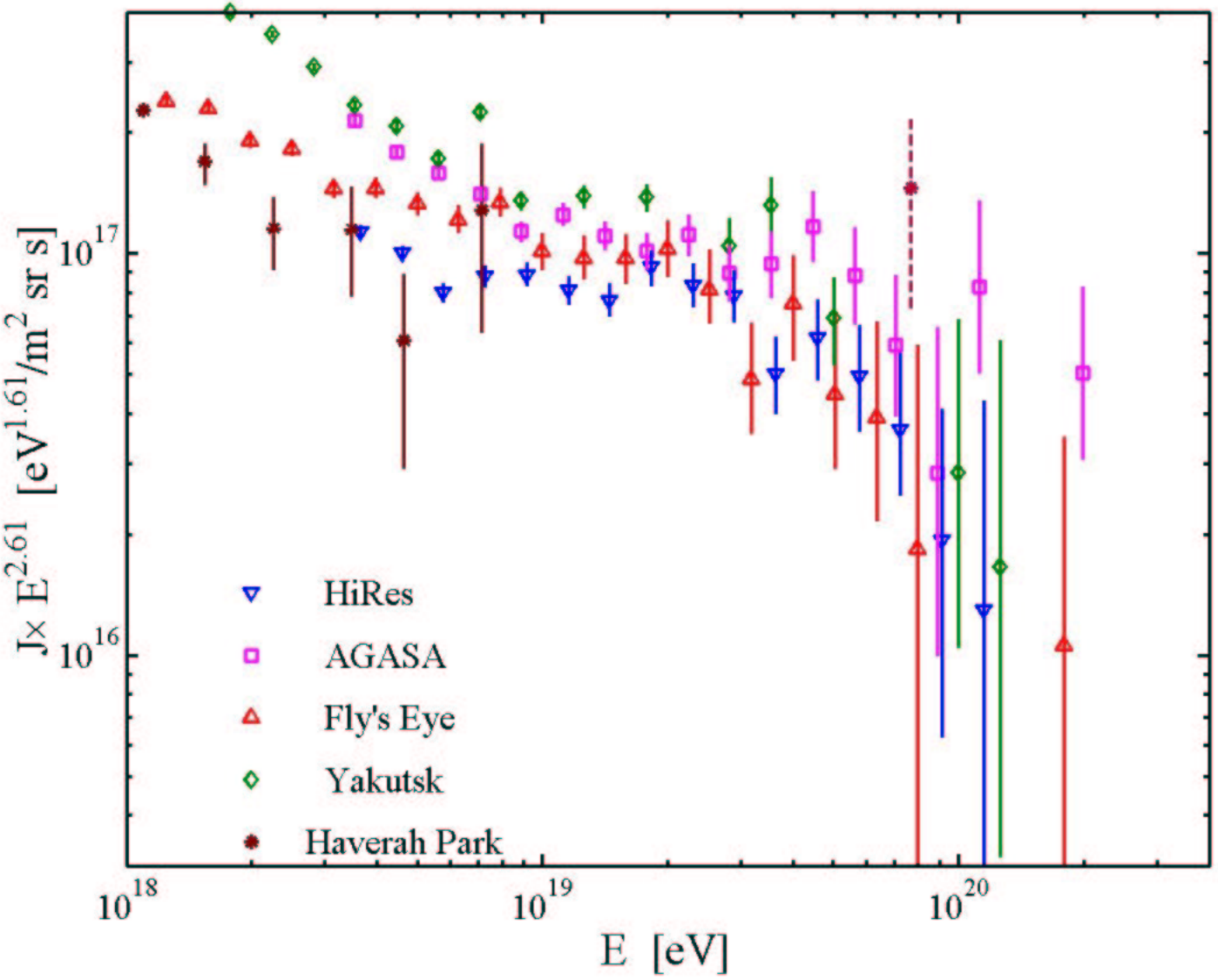
$$\lambda_E \sim \frac{m_p}{m_\pi}\frac{1}{n_\gamma \sigma_{\gamma p}}$$

$$\sim 11\exp\left[\frac{3}{\varepsilon_{20}}-1\right] \quad \text{Mpc}$$

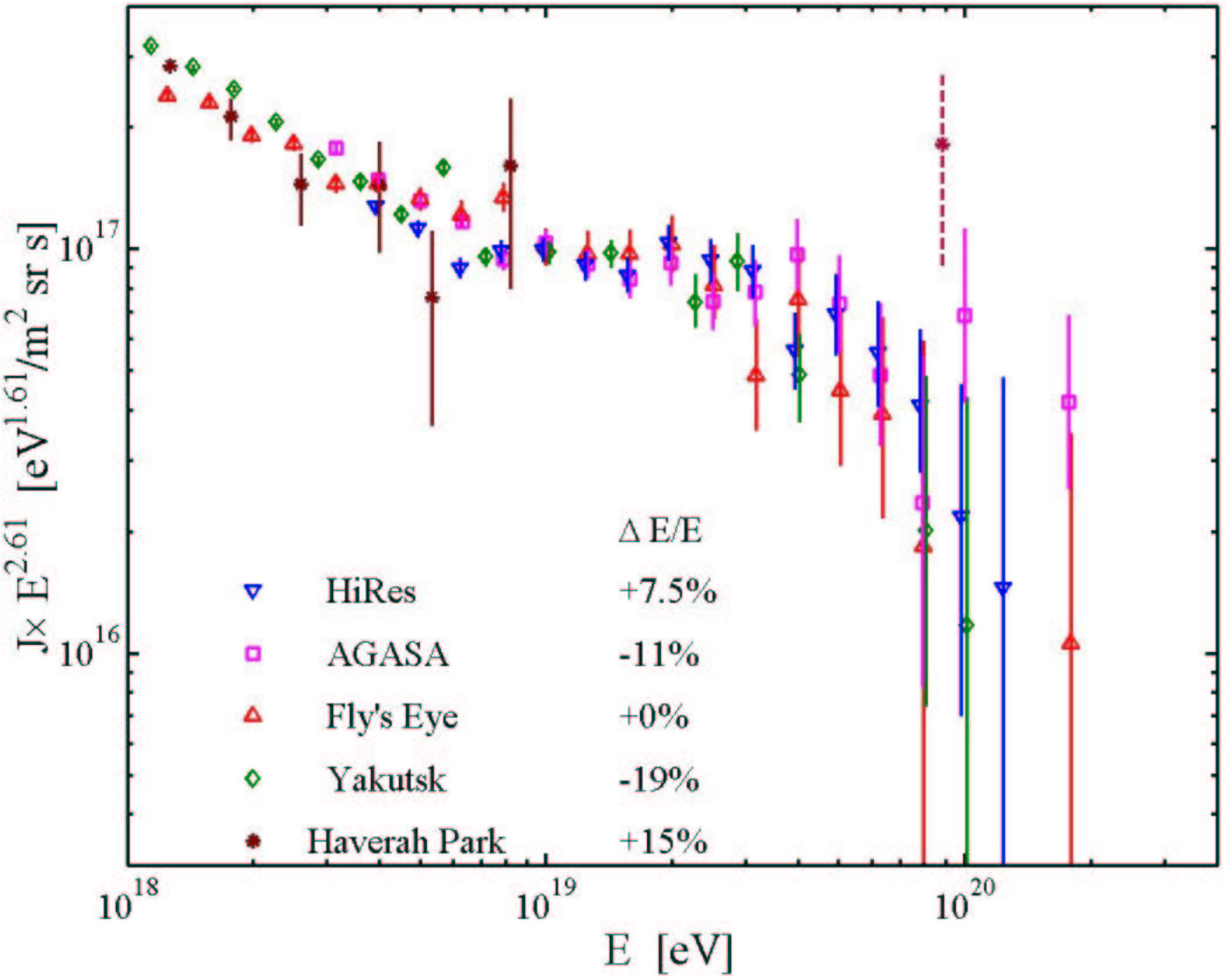


[Greisen 66;
Zatsepin & Kuzmin 66]

The Data


J× E^2.61 [eV^1.61/m^2 sr s]
10^17
10^16
HiRes
AGASA
Fly's Eye
Yakutsk
Haverah Park
10^18
10^19
10^20
E [eV]

Data- Calibrated at 10^{19}eV



Model

[EW 95]

- Fly's Eye fit for Galactic heavy (<10^{19}eV):

  $J_G \sim E^{-3.50}$

- X-Galactic protons:

  Generation spectrum (shock acceleration):

$$dn_p / d\varepsilon_p \propto \varepsilon_p^{-n} \quad , \quad n = 2;$$

  Generation rate (GRB motivated):

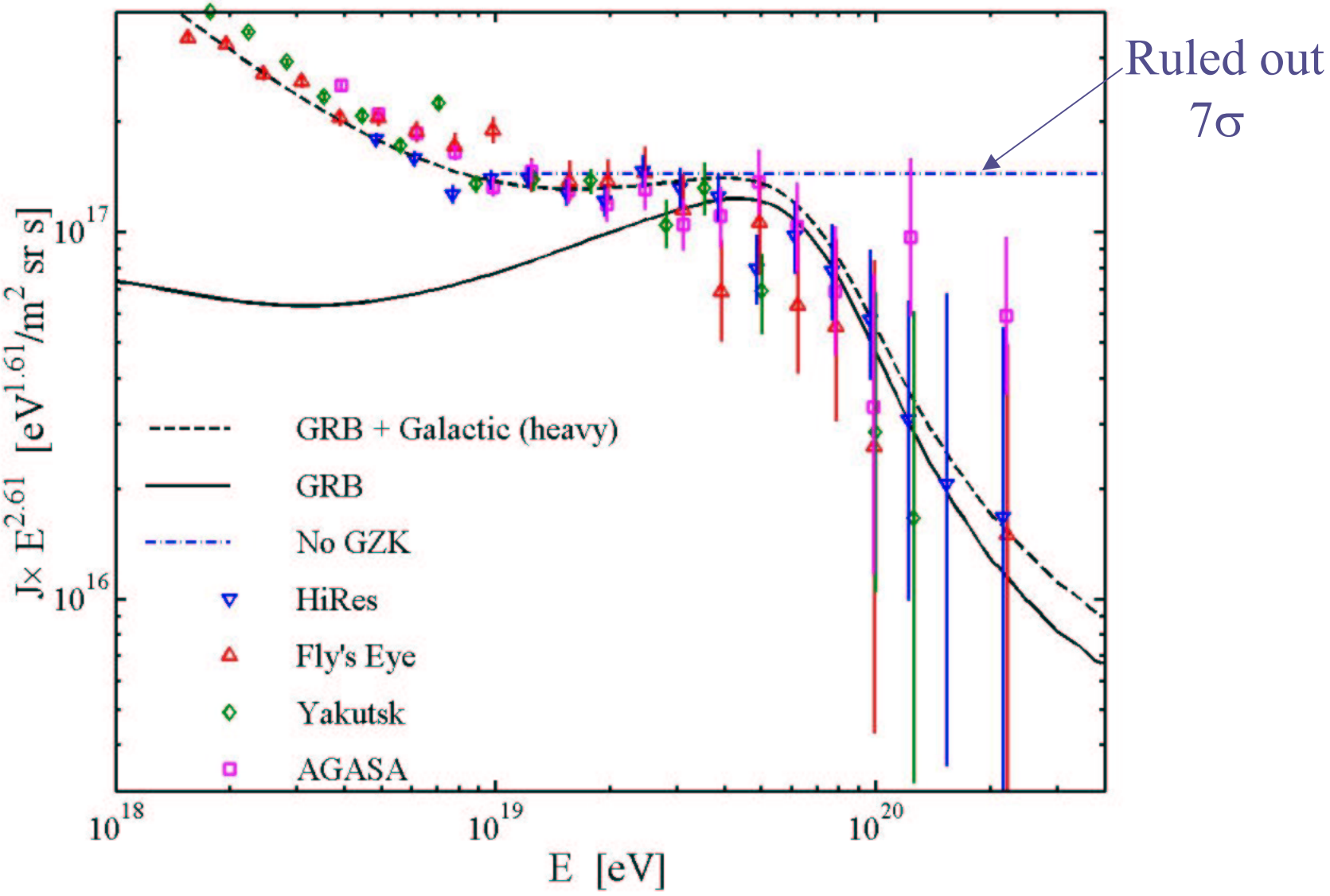
$$\mathbf{R} \equiv \left(\int_{10^{19}\,\mathrm{eV}}^{10^{21}\,\mathrm{eV}} d\varepsilon_p \; \varepsilon_p \frac{d\dot{n}_p}{d\varepsilon_p} \right)_{z=0} \approx 3 \cdot 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3\,\mathrm{yr}} ;$$

  Redshift evolution ~ SFR (GRB motivated).

[Bahcall & EW 02]

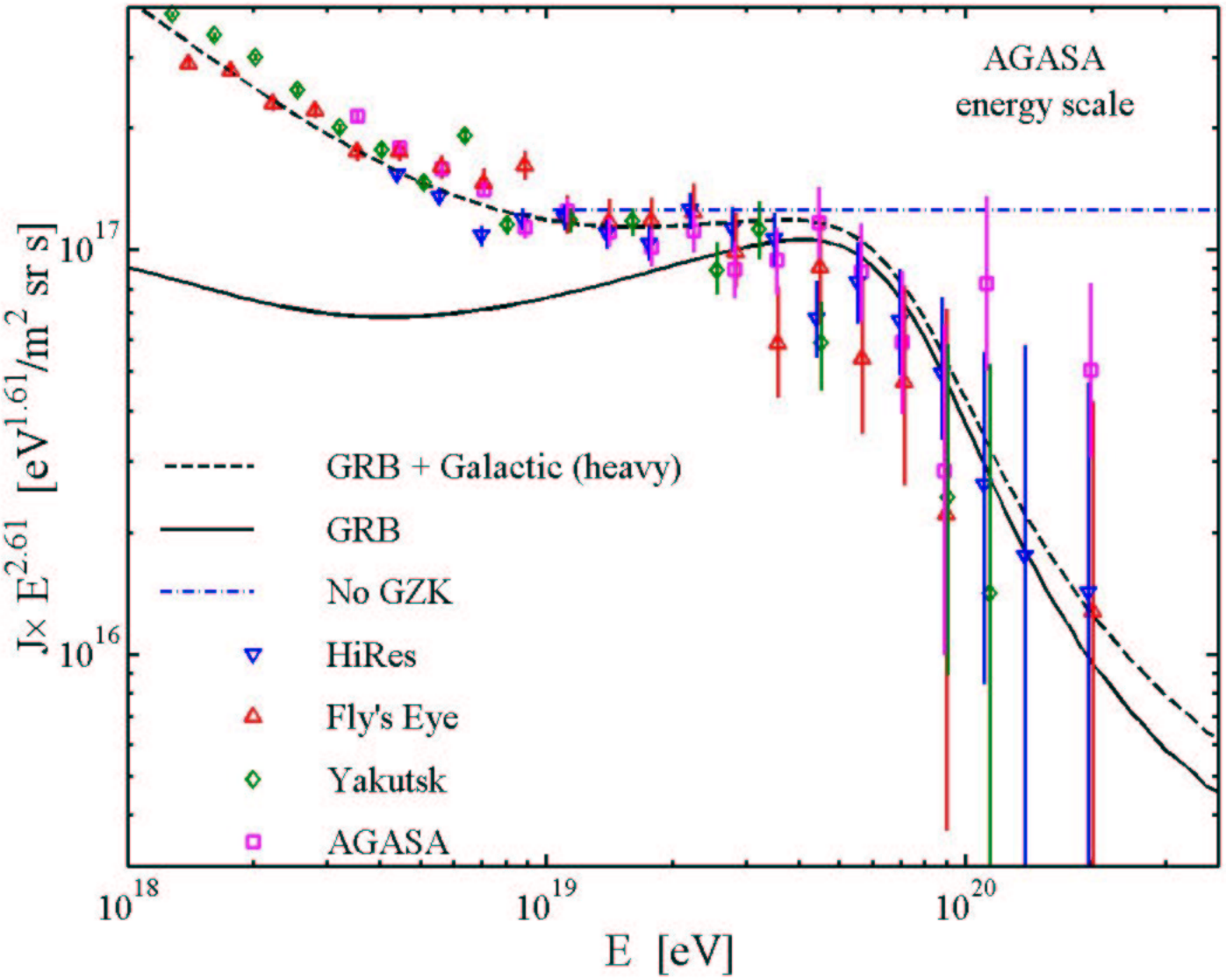
Model vs. Data

X-G Model: $\mathbf{R} = 3.5 \times 10^{44}\,\mathrm{erg/Mpc^3 yr};\ n = 2$



Conclusions are Robust

$$\mathbf{R} = 3.0 \times 10^{44}\,\mathrm{erg/Mpc^3 yr};\ \mathrm{n} = 2.1$$



Data/Model consistency

$$s^2_{HR} \equiv N^{-1} \sum_{i,j} \frac{\left(n_{ij} - n_{ij,HR}\right)^2}{n_{ij,HR}}; \quad s^2_{Model} \equiv \widetilde{N}^{-1} \sum_{i,j} \frac{\left(n_{ij} - n_{ij,Model}\right)^2}{n_{ij,Model}}$$

- 10^{19}eV to 10^{20}eV:

$$s^2_{HR} = 1.06,\ N = 26; \quad s^2_{Model} = 1.20,\ \widetilde{N} = 36$$

- Yakutsk, Fly's Eye, HiRes: Consistent with

XG protons: $\varepsilon_p^2 \frac{d\dot{n}_p}{d\varepsilon_p} \approx 0.8 \cdot 10^{44} \frac{\text{erg}}{\text{Mpc}^3\,\text{yr}}$ + GZK

- AGASA (25% of total exposure):

  Consistent below 10^{20}eV

  Excess above 10^{20}eV: 2.2+/-0.8 ⟷ 8 observed

Implications for HE ν Telescopes

- Observed $J_{CR}(>10^{19}\text{eV})$

$$\longrightarrow \varepsilon^2 \left.\frac{d\dot{n}_{cr}}{d\varepsilon}\right|_{z=0} \approx 10^{44}\ \text{erg/Mpc}^3\text{yr}$$

$p\gamma$ losses on CMB $\longrightarrow$ $z<0.25$

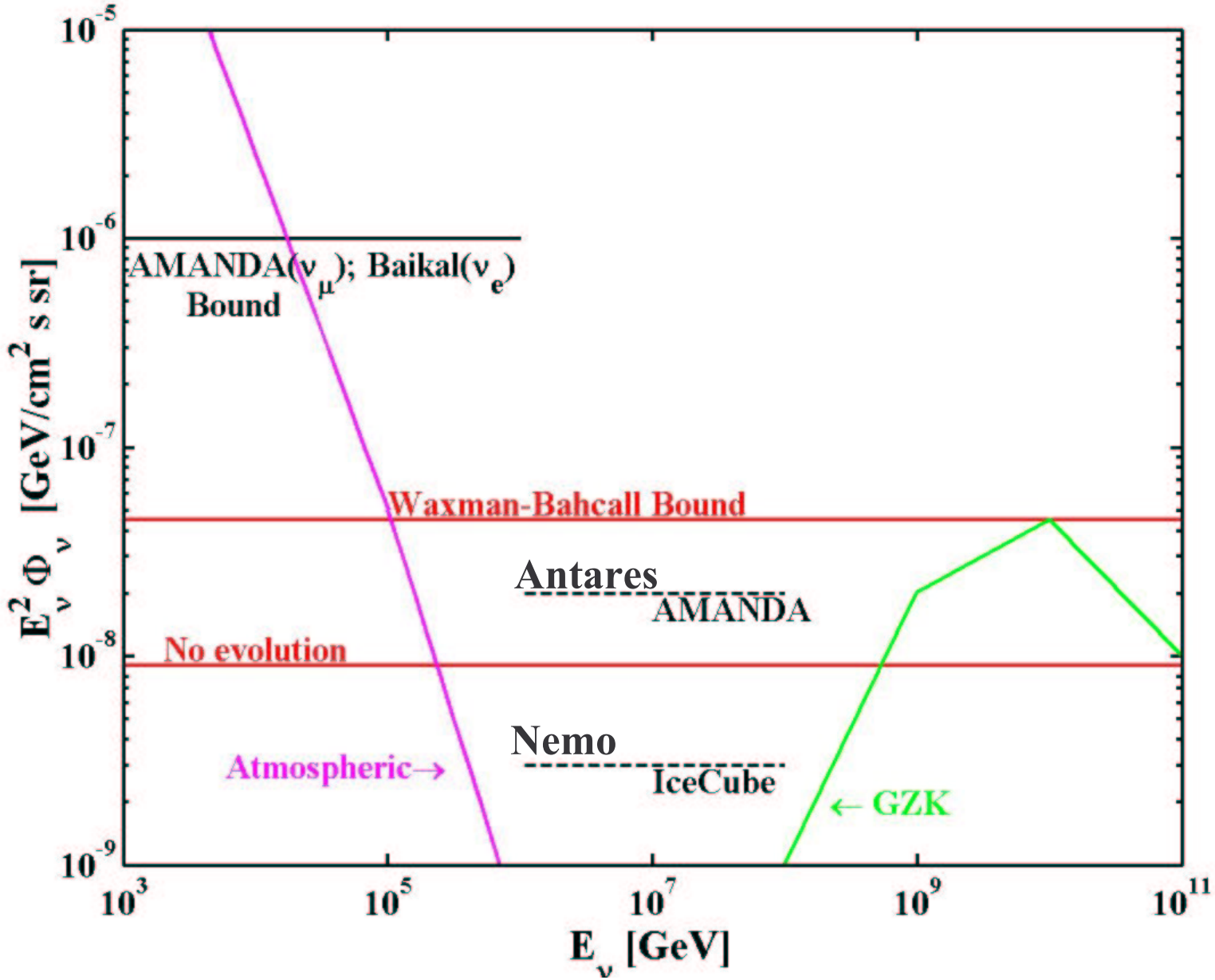
- For Sources with $\tau_{\gamma p}<1$:

$$\varepsilon^2\Phi_\nu < \frac{c}{4\pi}\cdot\frac{1}{4}\varepsilon^2\frac{d\dot{n}_{cr}}{d\varepsilon}\cdot\zeta_z t_{\text{H}} = 1.5\times10^{-8}\zeta_z\,\frac{\text{GeV}}{\text{cm}^2\text{s sr}}$$

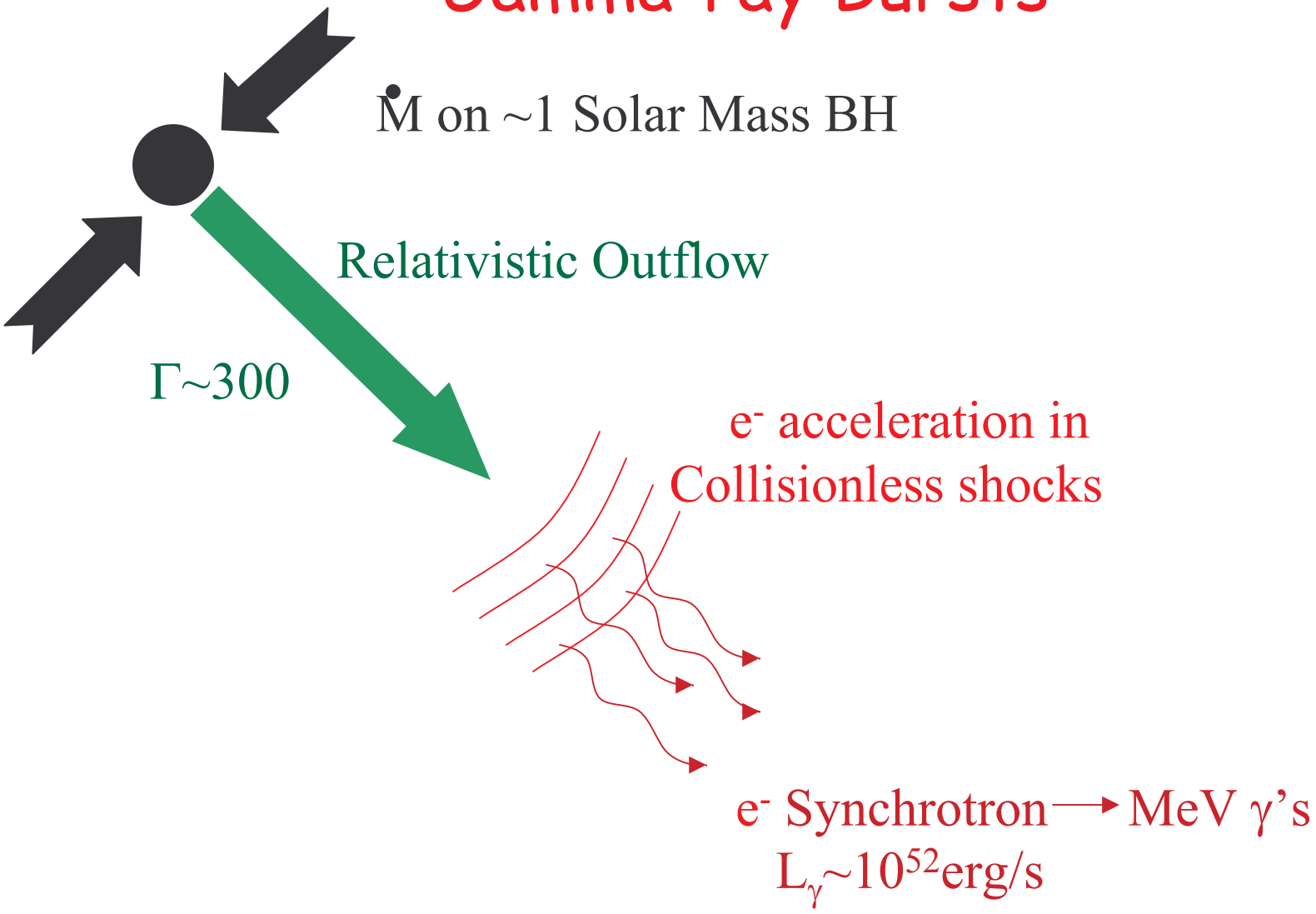
- Strongest know z evolution (QSO, SFR):

$$\dot{n}_{cr} \propto (1+z)^3 \quad \Rightarrow \quad \zeta_Z \approx 3$$

[EW & Bahcall 99, Bahcall & EW 01]


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$E_\nu^2 \Phi_\nu$ [GeV/cm^2 s sr]
AMANDA(ν_μ); Baikal(ν_e)
Bound
Waxman-Bahcall Bound
Antares
AMANDA
No evolution
Nemo
IceCube
Atmospheric→
← GZK
10^3
10^5
10^7
10^9
10^{11}
E_ν [GeV]

Gamma-ray Bursts



[Meszaros, ARA&A 02]

A note on GRBs

[EW 95]

Protons

- Acceleration:

$$u_B / u_e > 0.2\, \varepsilon_{p,20}^2 L_{\gamma,51}^{-1}$$

$$\Gamma > 10^2\, \varepsilon_{p,20}^{3/4}$$

- Particle spectrum:

$$dn_p / d\varepsilon_p \propto \varepsilon_p^{-2}$$

- p energy production:

$$\varepsilon_p^2 \frac{d\dot{n}_p}{d\varepsilon_p} = 0.8 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3 \text{yr}}$$

Electrons

- MeV γ's:

$$u_B / u_e \approx u_e / u_{\text{Internal}} > 0.1$$

$$\Gamma > 10^{2.5}$$

- γ spectrum

$$dn_e / d\varepsilon_e \propto \varepsilon_e^{-2}$$

- γ energy production

[Frail et al. 01
Schmidt 01]

$$\varepsilon_e^2 \frac{d\dot{n}_e}{d\varepsilon_e} \cong \frac{0.5}{\text{Gpc}^3 \text{yr}} \times 10^{53.5} \text{erg} = 1.3 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3 \text{yr}}$$

See: EW, Lec. Notes Phys. review (astro-ph/0103186)

Summary

- Yakutsk, Fly's Eye, HiRes: Consistent with

XG protons: $\varepsilon_p^2 \frac{d\dot{n}_p}{d\varepsilon_p} \approx 0.8 \cdot 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \mathrm{yr}}$ + GZK

(Robust; Consistent with GRB model predictions)

- AGASA (25% of total exposure):

  Consistent below 10^{20}eV

  Excess above 10^{20}eV: 2.2+/-0.8 ⟷ 8 observed

  New source/ New physics/ Local inhomogeneity ?? 25% energy over-estimate

- Need: Hybrid 10^{18}eV to 10^{20}eV observations (Auger)

Implications for ν telescopes

- X-Galactic sources of high energy ν's are out there

- UHE p flux constrains expected ν flux
  (Waxman-Bahcall Bound)
  ~ 1 km^3 scale required at 1 to 10^3 TeV energies
  (Ice, Water Cerenkov)
  >> 1 km^3 required at >>10^3 TeV
  (Radio)