Astrophysical Sources of High Energy ν's

Eli Waxman
Weizmann Institute, ISRAEL

High Energy (>1TeV) ν Telescopes

- Main Goal: Extend "ν Horizon"

  < 10^5 light yrs [Solar, SNe MeV ν's]

  → $\sim 10^{10}$ light yrs

  Unexplored energy, distance scale

- Cosmological Sources → Low Flux → High Energy

  MeV → TeV

  $\xrightarrow{\sigma}$

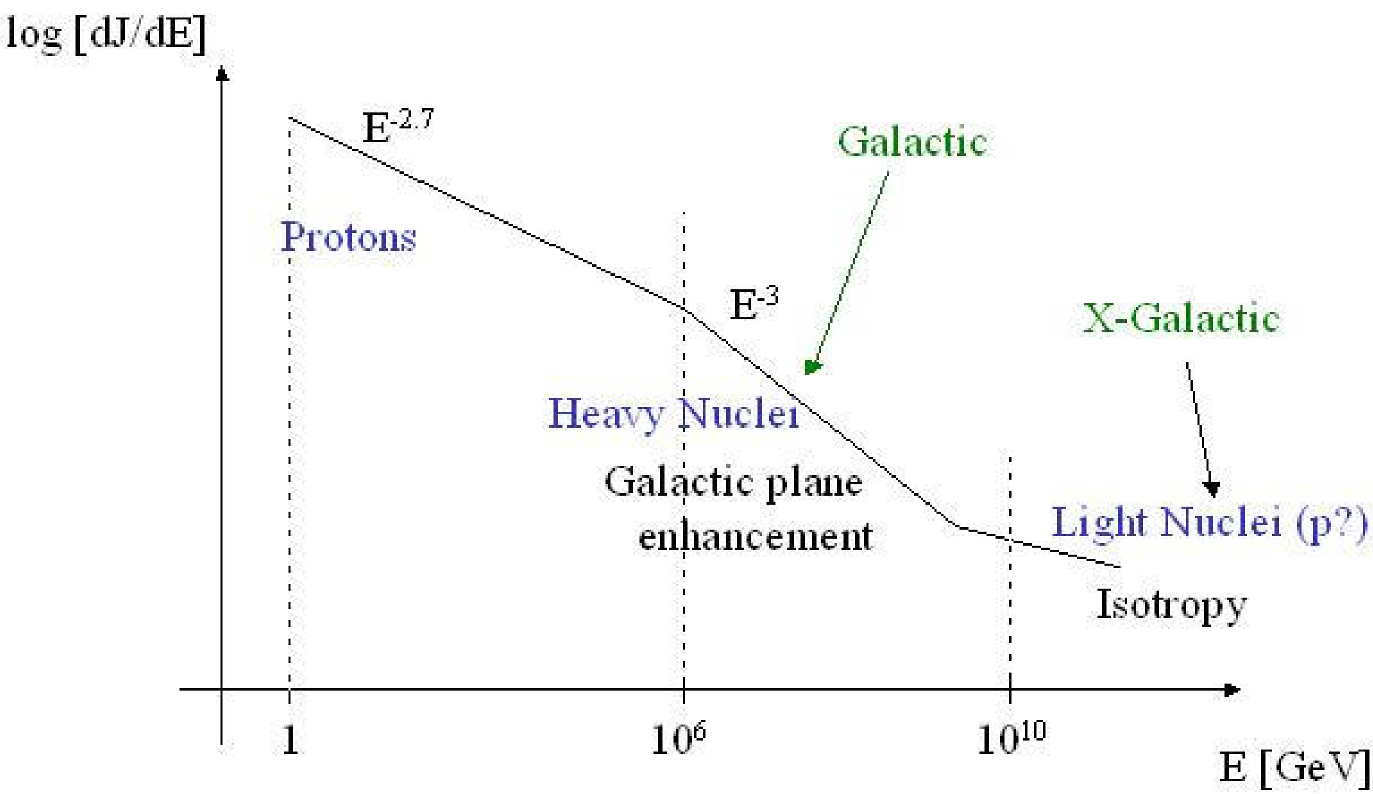
  1 kton → 1 Gton

- Gton detectors:

  Scale required (Model independent)

  Feasible (Baikal, AMANDA)

Cosmic ray flux and Composition



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

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

X-Galactic ν's

- At 10^{19} eV:

  Spectrum becomes harder

  Composition changes

  No anisotropy

⇨ X-Galactic sources of protons

- $p\gamma$ (pN) Interactions $\longrightarrow$ π's $\longrightarrow$ ν_e's, ν_μ's

⇨ X-Galactic, high energy ν's

Flux $\longleftrightarrow$ Detector size?

Point Sources

$$P_{\nu\mu} = \frac{\lambda_\mu}{\lambda_\nu} = 10^{-4}\left(\frac{\varepsilon_\nu}{100\text{TeV}}\right)^{\alpha} \quad , \alpha = \begin{cases} 1 \text{ for } \varepsilon_\nu < 100\text{Te}V, \\ 0.5 \text{ o.w.} \end{cases}$$

Signal: $$\mu \text{ event} \# \approx 1\left(\frac{f_\nu}{10^{-11}\text{erg/cm}^2\text{s}}\right)\left(\frac{\varepsilon_\nu}{100\text{TeV}}\right)^{\alpha-1}\left(\frac{AT}{1\text{km}^2\text{yr}}\right)$$

Background (atmos. ν's):

$$N_\sigma \approx 3\left(\frac{f_\nu}{10^{-12}\text{erg/cm}^2\text{s}}\right)\Theta_{\text{deg}}^{-1}\left(\frac{\varepsilon_\nu}{300\text{ TeV}}\right)^{0.8}\left(\frac{AT}{1\text{km}^2\text{yr}}\right)^{1/2}$$

⇨ For 10 -- 1000 TeV:

$$f_\nu \geq 10^{-11} A_{\text{km}^2}^{-1} \text{erg/cm}^2\text{s}$$

$$f_\nu\left(\Delta t / 100\text{s}\right) \geq 3 \times 10^{-5} A_{\text{km}^2}^{-1} \text{erg/cm}^2$$

Cosmological sources:

$$d = 10^{28}\,\mathrm{cm} \quad \Rightarrow \quad \begin{cases} L_\nu \geq 10^{46} A_{\mathrm{km}^2}^{-1}\,\mathrm{erg/s} \\ L_\nu (\Delta t / 100\ \mathrm{s}) \geq 10^{52.5} A_{\mathrm{km}^2}^{-1}\,\mathrm{erg} \end{cases}$$

Most Powerful Cosmological sources:

AGN (Steady) $\qquad f_\gamma \approx 10^{-11}\,\mathrm{erg/cm^2 s}$

GRBs (~100s transient) $\qquad F_\gamma \approx 10^{-5}\,\mathrm{erg/cm^2}$

⇓

~1km² detector

Diffuse background

Signal:

$$\mu \text{ event } \# \approx 1\left(\frac{\varepsilon_\nu^2\Phi_\nu}{10^{-9}\,\text{GeV/cm}^2\text{s sr}}\right)\left(\frac{\varepsilon_\nu}{100\,\text{TeV}}\right)^{\alpha-1}\left(\frac{AT}{1\text{km}^2\text{yr}}\right)$$

Background (atmos. ν's):

$$N_\sigma \approx 3\left(\frac{\varepsilon_\nu^2\Phi_\nu}{10^{-8}\,\text{GeV/cm}^2\text{s sr}}\right)\left(\frac{\varepsilon_\nu}{300\text{TeV}}\right)^{0.8}\left(\frac{AT}{1\text{km}^2\text{yr}}\right)^{1/2}$$

Waxman-Bahcall bound

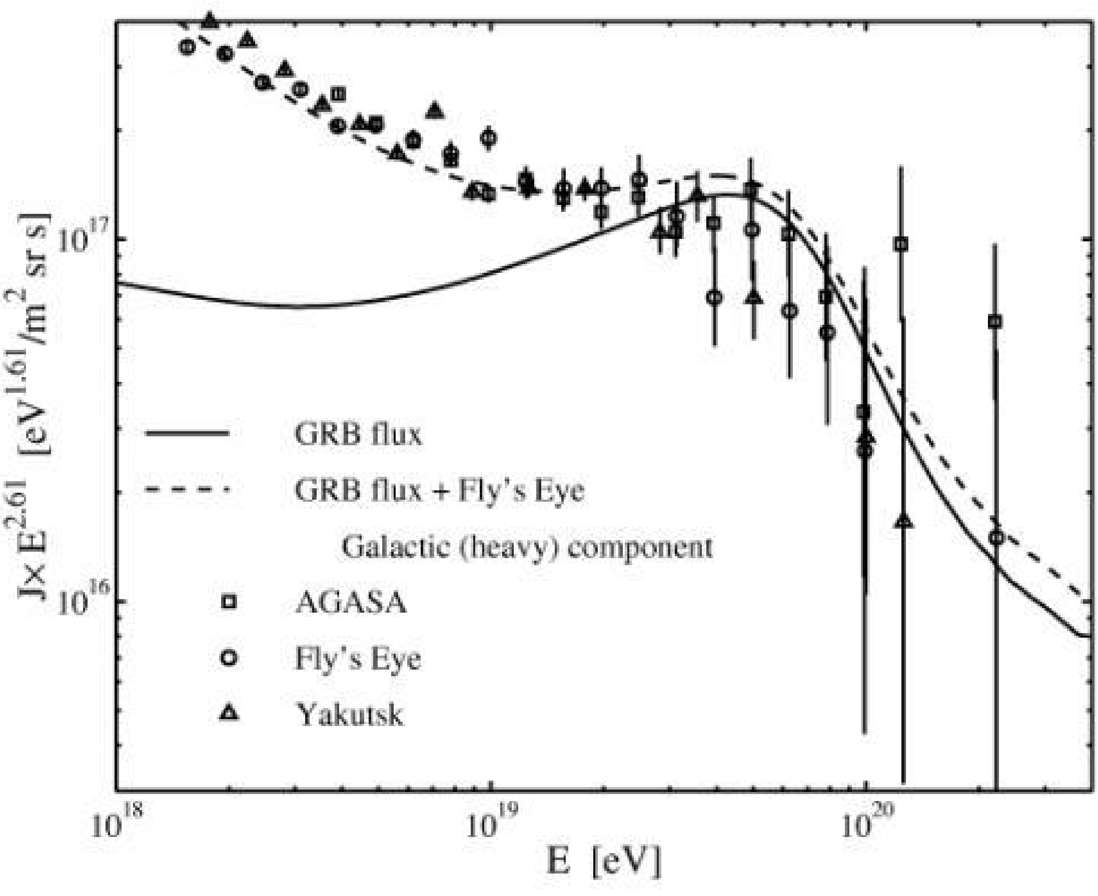
[EW & Bahcall 99, Bahcall & EW 01]

$$\varepsilon_\nu^2\Phi_\nu \le 4.5\times10^{-8}\,\text{GeV/cm}^2\text{s sr}$$

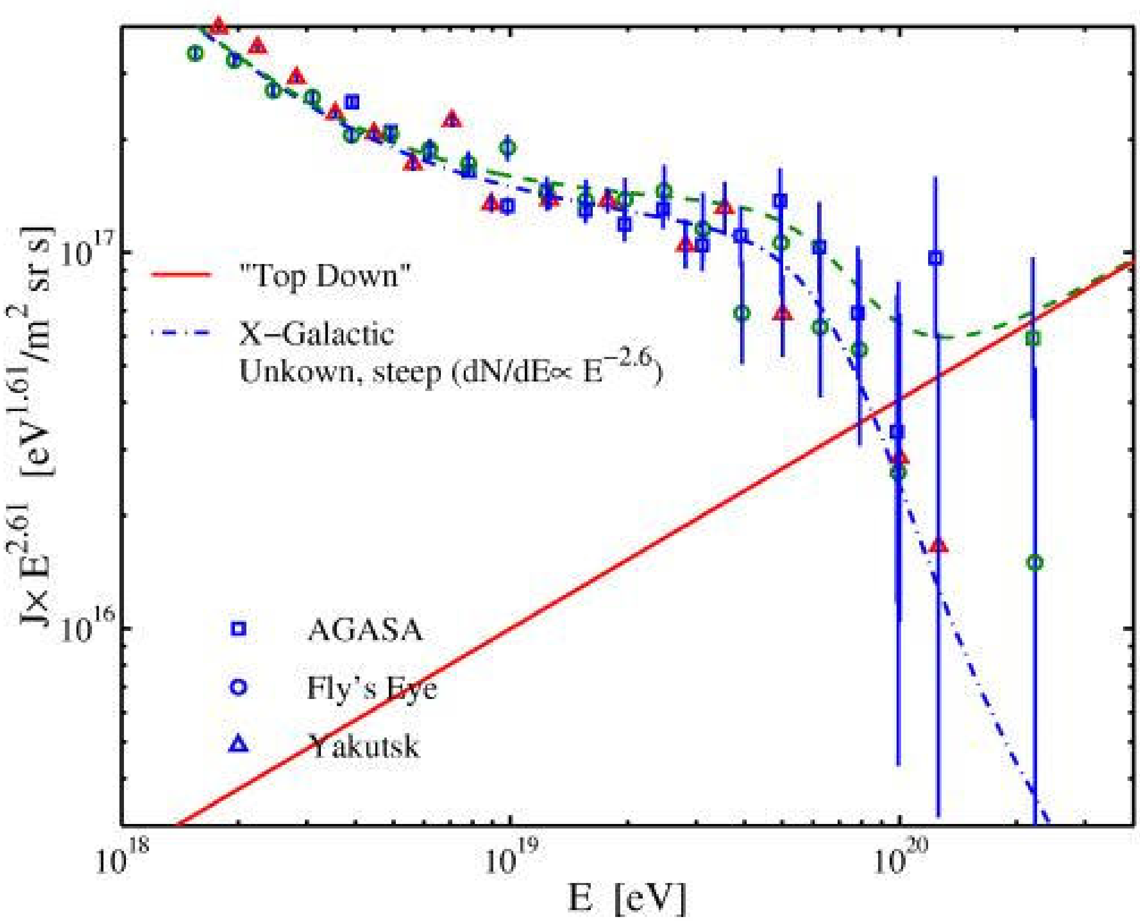
~1km² detector

X-Galactic proton generation rate

X-G Model: $\varepsilon_p^2 d\dot{n}_p / d\varepsilon_p = 0.8 \times 10^{44}\,\mathrm{erg/Mpc^3yr}$ [Model: EW 95]

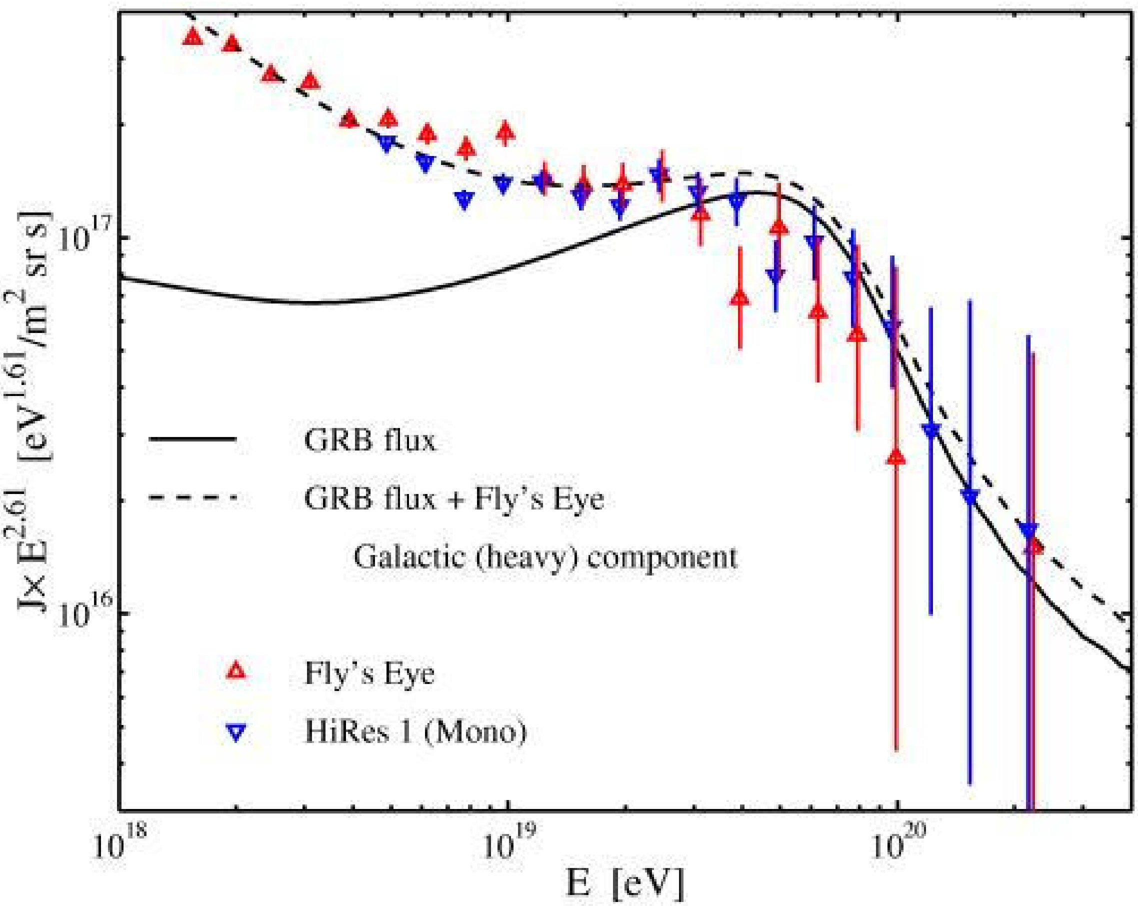


“Top Down” Contribution?



HiRes Data

[Matthews, Martens
For Hires, 11/01]



ν Flux Bound

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

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

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

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

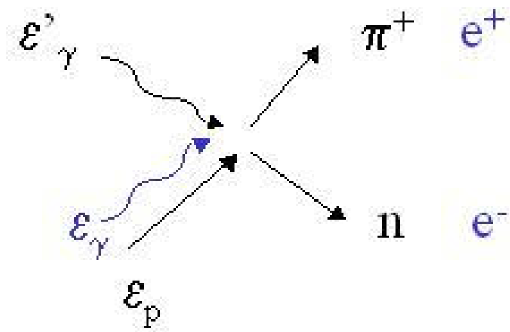
$$\varepsilon^2\Phi_\nu < \frac{c}{4\pi}\cdot\frac{1}{4}\varepsilon^2\frac{d\dot{n}_{cr}}{d\varepsilon}\cdot\zeta_z t_{\text{H}} = 1.5\times10^{-8}\zeta_z\frac{\text{GeV}}{\text{cm}^2\text{s sr}}$$

- 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]

$\tau_{\gamma p}$ for known sources

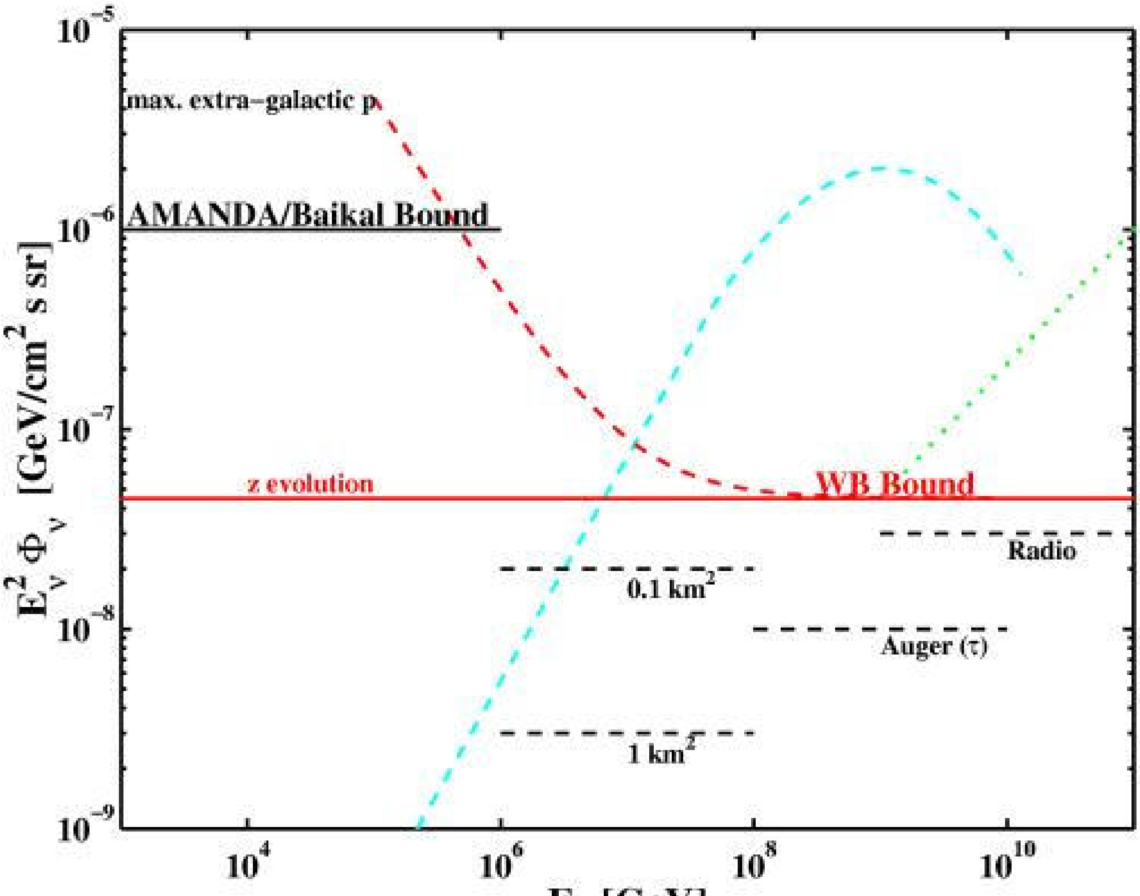


$$\left.\begin{array}{r} \varepsilon_p \varepsilon'_\gamma \geq m_p m_\pi \\ \varepsilon_\gamma \varepsilon'_\gamma \geq 2m_e^2 \end{array}\right\} \Rightarrow \quad \frac{\varepsilon_\gamma}{\varepsilon_p} = \frac{2m_e^2}{m_p m_\pi} = 4 \times 10^{-6}$$

$$\Rightarrow \quad \tau_{\gamma\gamma}\left(\varepsilon_\gamma = 1\,\mathrm{TeV}\right) \approx 2 \times 10^3 \, \tau_{\gamma p}\left(\varepsilon_p = 2 \times 10^{17}\,\mathrm{eV}\right)$$

AGN models vs. WB bound

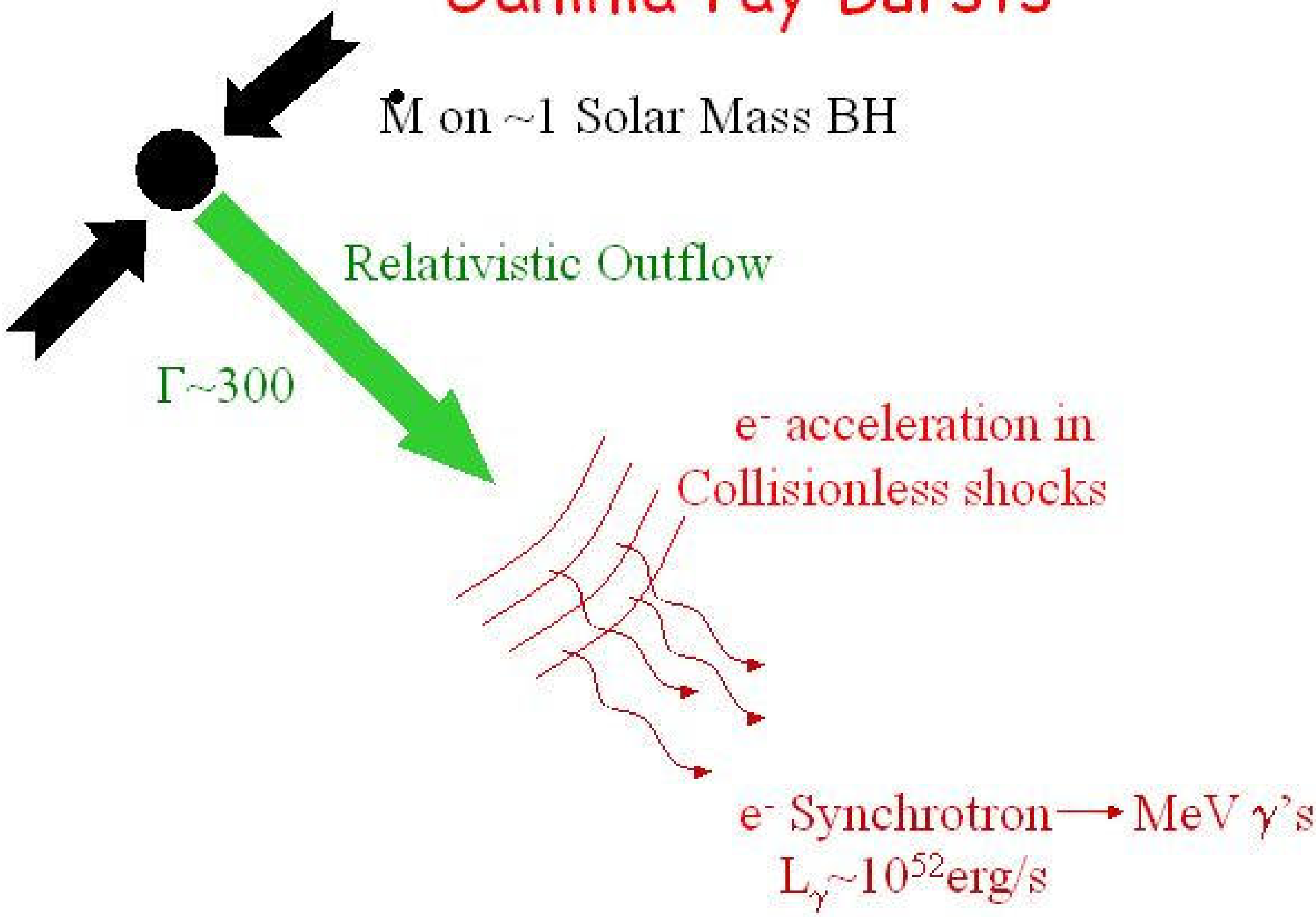
[EW & Bahcall 99, Bahcall & EW 01]



AGN- Mannheim 95

Mannheim, Protheroe, Rachen 01

Gamma-ray Bursts



[Meszaros, ARA&A 02]

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

[EW 95]

- 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 ⟶

$$\varepsilon_e^2 \frac{d\dot{n}_e}{d\varepsilon_e} = \frac{30}{\text{Gpc}^3\text{yr}} \times 10^{51}\text{erg} = 0.3 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$$

Afterglow ⟶ z distribution

[Frail et al. 01
Schmidt 01]

$$L_\gamma \approx 10^{51}\,\text{erg/s} \quad \rightarrow \quad 10^{52}\,\text{erg/s}$$

$$\varepsilon_e^2 \frac{dn_e}{d\varepsilon_e} = \frac{0.5}{\text{Gpc}^3\text{yr}} \times 500 \times 0.5 \cdot 10^{51}\,\text{erg} = 1.3 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$$

GRB ν's

[EW & Bahcall 97, 99]

- $$\gamma + p \rightarrow n + \pi^+ ; \quad \pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$
$$\frac{\varepsilon_p}{\Gamma} \frac{\varepsilon_\gamma}{\Gamma} \geq 0.3 \, \mathrm{GeV}^2$$

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

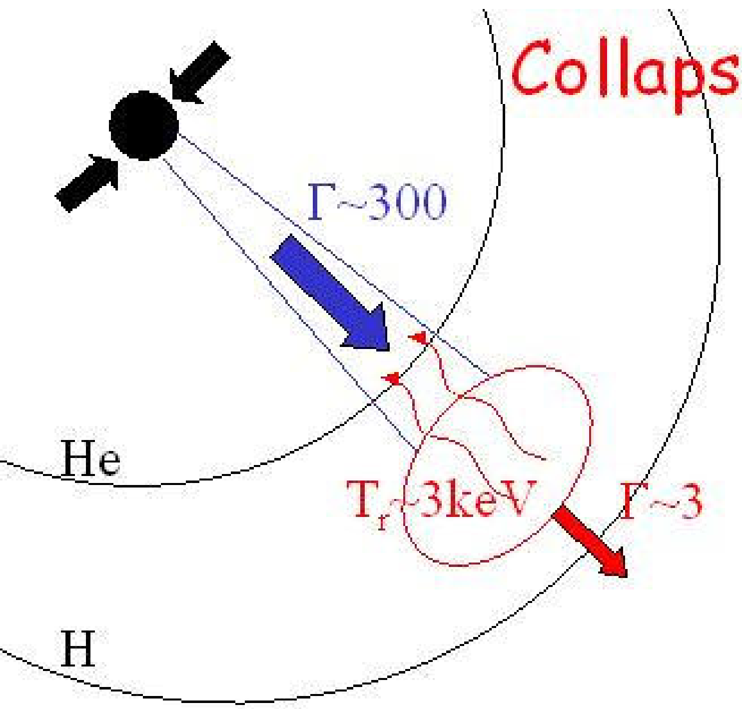
- $f_{p \rightarrow \pi} \approx 0.2$
  Weak dependence on model parameters

[Rachen & Meszaros 98; Guetta, Spada & EW 01]

$$\Rightarrow \quad \varepsilon^2 \Phi_\nu \approx 0.2 \varepsilon^2 \Phi_\nu^{WB} = 10^{-8} \frac{\mathrm{GeV}}{\mathrm{cm^2 s \, sr}} \quad , \quad \varepsilon_\nu \geq 10^{14.5} \, \mathrm{eV}$$

$$J_{\nu \rightarrow \mu} \approx 20 / \mathrm{km^2 yr}$$

Collapsar GRB ν's



$$\frac{\varepsilon_p}{\Gamma}\Gamma\varepsilon_\gamma \geq 0.3\,\mathrm{GeV}^2$$

$$\Rightarrow \quad \varepsilon_p \geq 100\,\mathrm{TeV}$$

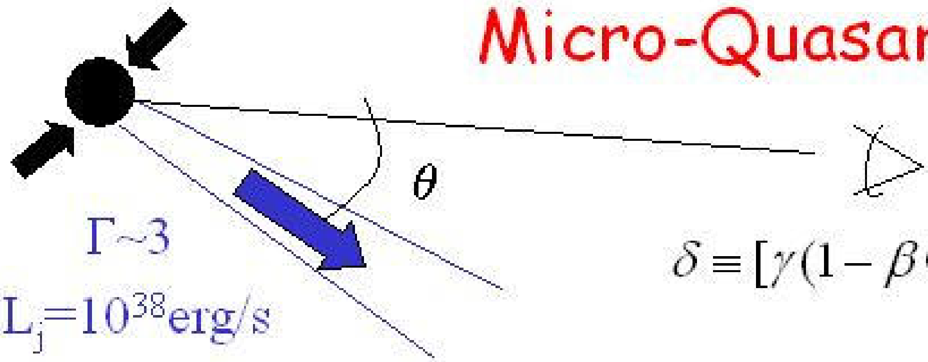
- $\varepsilon_\nu \geq 10^{12.5}$ eV

  $N_{\nu\to\mu} \approx 0.2/\mathrm{km}^2/\mathrm{Collapse}$ (10^3 GRBs/yr)

- Both "Chocked" and "successful" jets

[Meszaros & EW 01]

Micro-Quasars



$$\delta \equiv [\gamma(1-\beta\,\mathrm{Cos}\,\theta)]^{-1}$$

- $$N_\mu \approx 0.2\frac{\delta^3}{\gamma}\left(\frac{E}{10^{43}\mathrm{erg}}\right)\left(\frac{d}{3\mathrm{kpc}}\right)^{-2} \quad /\mathrm{km}^2$$
  $1\,\mathrm{TeV} \le \varepsilon_\nu \le 100\,\mathrm{TeV}$

- Provided: e-p jet

- SS433: 1/km² day

[Levinson & EW 01
diStefano et al. 02]

SNII Shock Break-out

- Radiative shock ⟶ (τ~1) Collisional

$$M = 4\pi R^2 \left(m_p / \sigma_T\right)\tau = 10^{-5} R_{13.5}^2 \tau \ M_{\rm Sun}$$

- EM Instabilities:

$$\omega_{EM} \cong \sqrt{0.1\frac{m_e}{m_p}}\,\frac{v}{c}\,\omega_{pi} = 10^6\,\frac{v}{10^9\,\rm cm/s}\,\rm s^{-1} >> \omega_{Coll.}$$

- Collisionless shock → p acceleration to ~10TeV

- p+p→p+N+π:

$$f_\gamma \approx f_\nu \approx 10^{-4}\tau\xi_p d_{10\rm kpc}^{-2}\ \rm erg/cm^2 s$$

$$T \approx 1\ \rm hr \quad , \quad \Delta T\left(\rm MeV\ \nu' s\right) \approx 10\ \rm hr$$

$$\varepsilon_\nu \le 1\tau^{2/5}\ \rm TeV \quad , \quad 0.1\ \rm GeV \le \varepsilon_\gamma \le 10\ \rm GeV$$

- N_μ=100$\xi_p\tau$ / km^2

[EW & Loeb 01]

Summary

- >1TeV ν produced in astrophysical sources
- WB (model independent) bound

  → ~1 km^3(=1Gton) detectors required

  >>100TeV ⇒ >>1 km^3 [radio,…]
- Baikal, AMANDA → 1 km^3 feasible

  Construction: IceCube, Antares, Nemo, Nestor

  Auger
- Astrophysics:

  Ultra-high energy cosmic-ray puzzle

  GRB progenitors

  GRB, Micro-Quasar models

  SNII models

  ?? ["Hidden" sources]

ν Physics

- $\nu_\mu \leftrightarrow \nu_\tau \longrightarrow \tau$ appearance
- GRBs: < 10s $\gamma \leftrightarrow \nu$ Timing:

Lorentz invariance (1-v/c) to $1:10^{16}$

Weak equivalence principle ($\Phi L/c^3$) to $1:10^6$

[EW & Bahcall 99, Bahcall & EW 01]