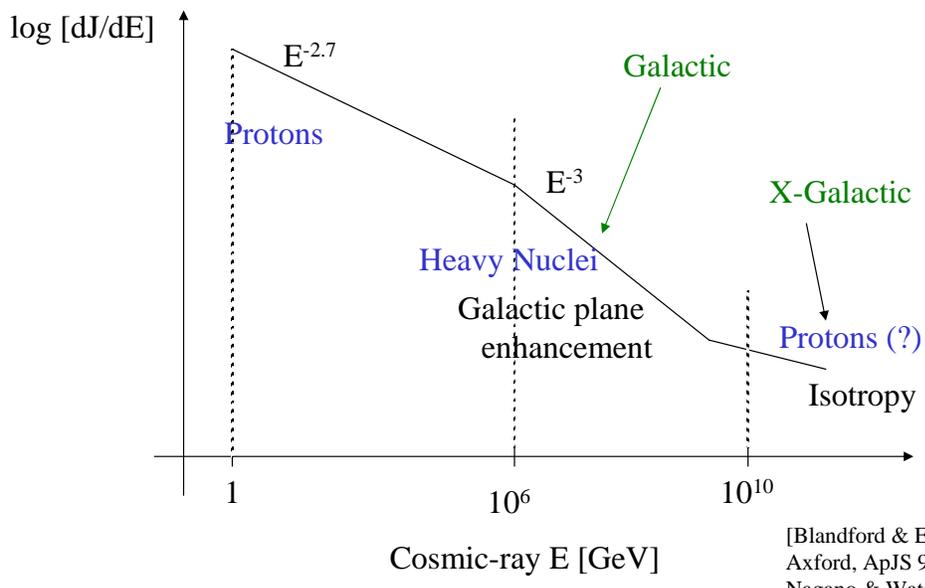


# GRBs, jets and high energy particles

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- Why (should you) bother with high energies?
- GRBs and jets (Clearing the fog)
- GRBs and high energy particles

Why (should you) bother with high  
energies?



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



## The UHECR challenge

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

$$L > 4\pi R^2 \Gamma^2 \frac{B^2}{8\pi} v > \frac{1}{2\beta} \left( \frac{\epsilon_p}{e} \right)^2 c \Gamma^2$$

$$L > 2 \frac{\Gamma^2}{\beta} \epsilon_{p,20}^2 \times 10^{45} \text{ erg/s}$$

[Hillas 1984; Waxman 04]

## The suspects

- AGN (steady):

$$\Gamma \sim \text{few} \longrightarrow L > 10^{47} \text{ erg/s}$$

Few, brightest AGN

[Lovelace 1976;  
Hillas, ARA&A (1984)]

- GRBs (transient):

$$\Gamma \sim 300 \longrightarrow L > 10^{51} \text{ erg/s}$$

Average  $L_{\gamma} \sim 10^{52} \text{ erg/s}$

[Waxman 95; Vietri 95; Milgrom & Usov 95]

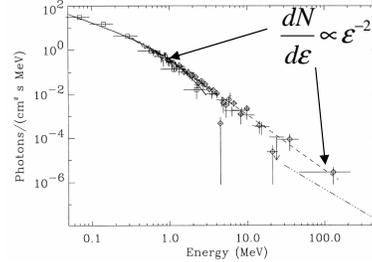
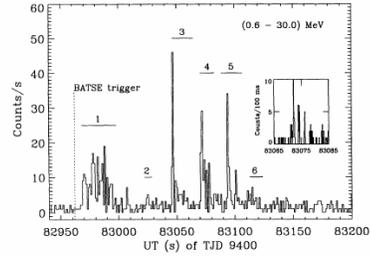
GRBs and jets (Clearing the fog)

[Fishman & Meegan 95]

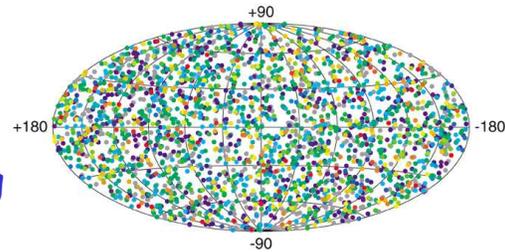
- $T \sim 0.01$  to  $100$  s  
Short:  $T \sim 0.2$  s, Long:  $T \sim 20$  s  
Variability:  $\Delta t \sim 1$  ms
- Non-thermal spectrum  
1--  $>100$  MeV  
Most E @  $\epsilon > 1$  MeV
- Isotropic sky distribution



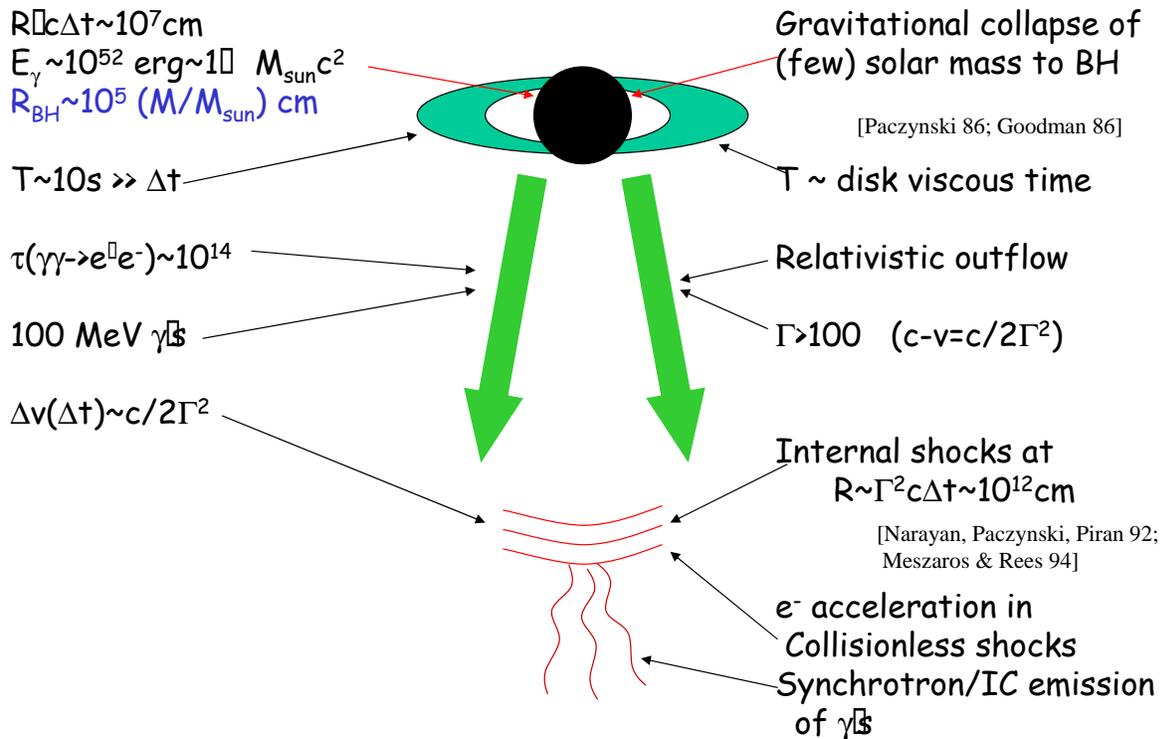
Cosmological origin  
 $d \sim 10^{28}$  cm  $\rightarrow E_\gamma(z \sim 1) = 10^{52}$  erg

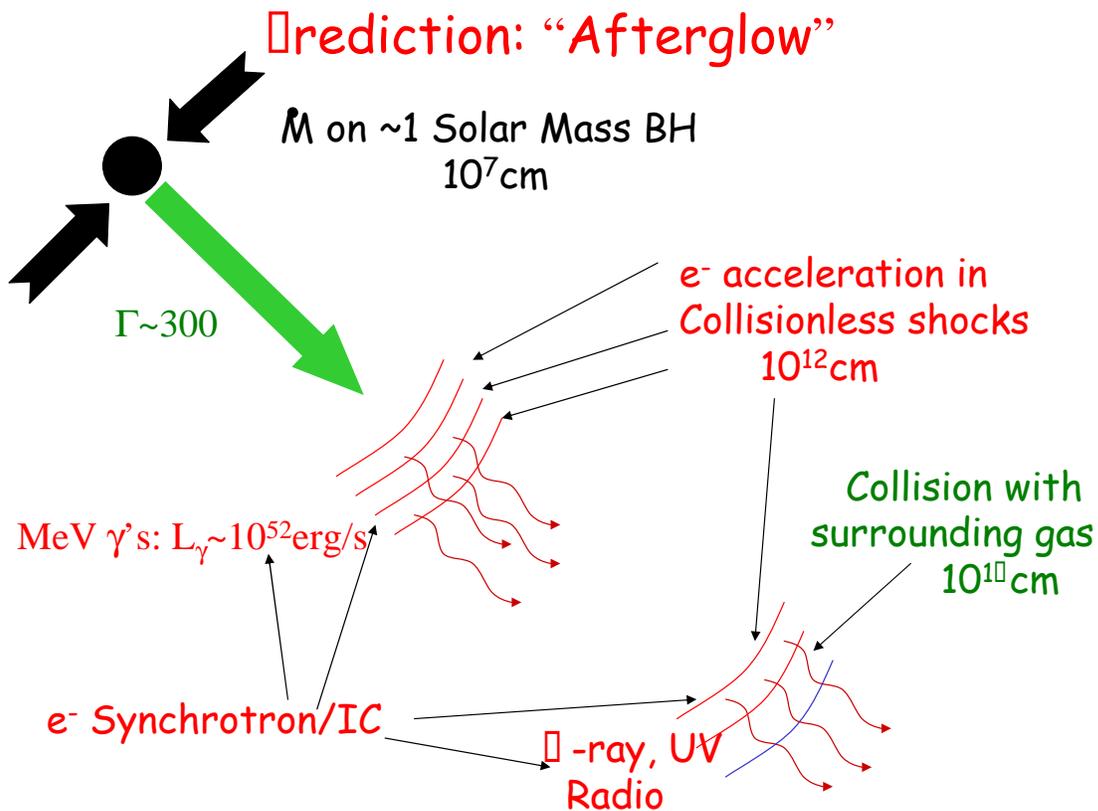


[Winkler et al. 95]

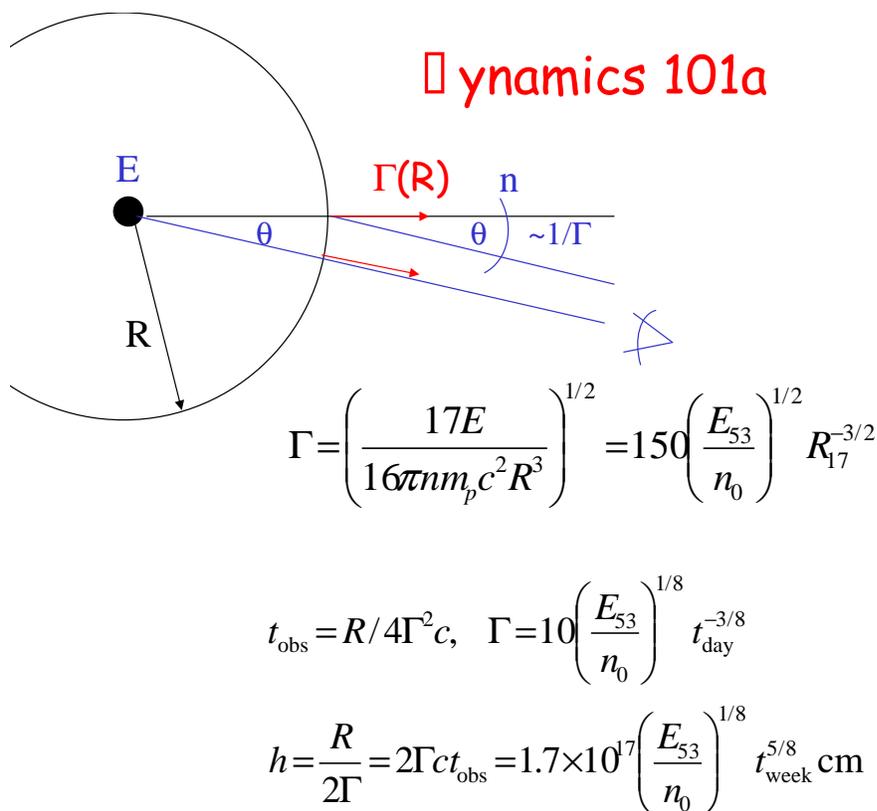


## The "fireball" model





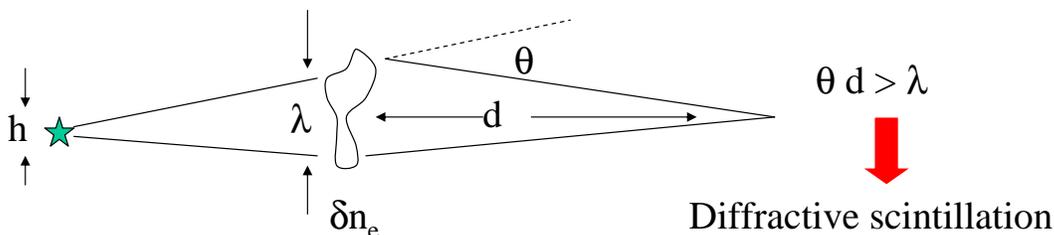
[Paczynski & Rhoads 93; Katz 94; Meszaros & Rees 97; Vietri 97; Waxman 97; Sari, Piran & Narayan 98]



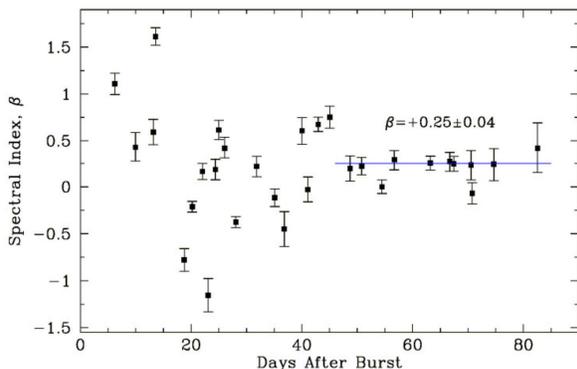
[Blandford & McKee 76]

[Waxman 97]

## Direct size measurement: I. Scintillation



- Finite size, cosmological source:  $h_{\text{crit.}} \sim \text{few} \times 10^{17} \text{ cm}$

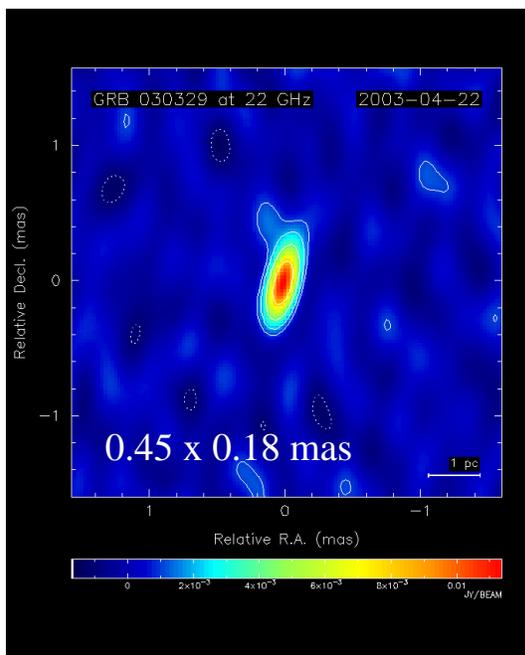


$$h = \frac{R}{2\Gamma} = 2\Gamma ct_{\text{obs}} = 10^{17} \left( \frac{E_{53}}{n_0} \right)^{1/8} t_{\text{week}}^{5/8} \text{ cm}$$

[Goodman 97;  
Waxman, Kulkarni & Frail 98]

## II. Resolved afterglow

[Taylor et al. 04]



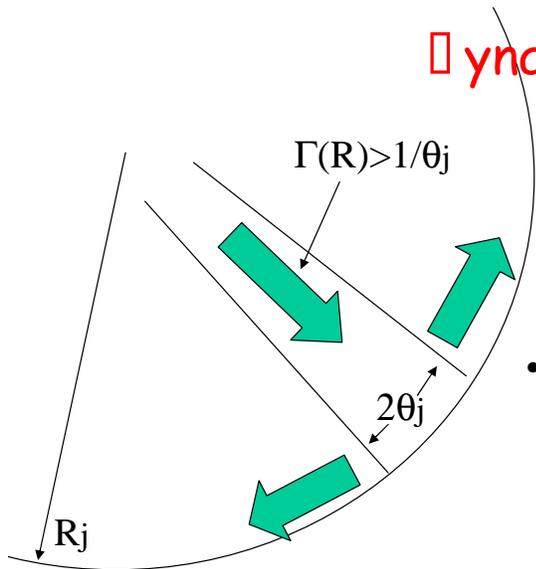
- GRB 030329, 24 days after the burst ( $z=0.17$ )
- VLBA+Bonnet at 22 GHz –
- Marginally resolved at 0.08 milliarcsec
- Superluminal expansion @  $5c$

$$h = 3.4 \times 10^{17} \text{ cm}$$

$$2\Gamma ct = 3.8 \left( \frac{E_{53}}{n_0} \right)^{1/8} t_{24\text{day}}^{5/8} \times 10^{17} \text{ cm}$$

[Frail et al. 04;  
Granot, Ramirez-Ruiz & Loeb 04]

## Dynamics 101b



- “Ignorant” jet/observer

$$t_{\text{comoving}} = R/\Gamma c,$$

$$\Delta_{\text{comoving}} = R/\Gamma \approx \theta_j R : \Gamma > 1/\theta_j$$

- $\Gamma(R) = 1/\theta_j$ : Sideways expansion

$$\theta = 0.1 \left( \frac{E_{\text{Iso},53}}{n_0} \right)^{-1/8} t_{\text{j,day}}^{3/8}$$

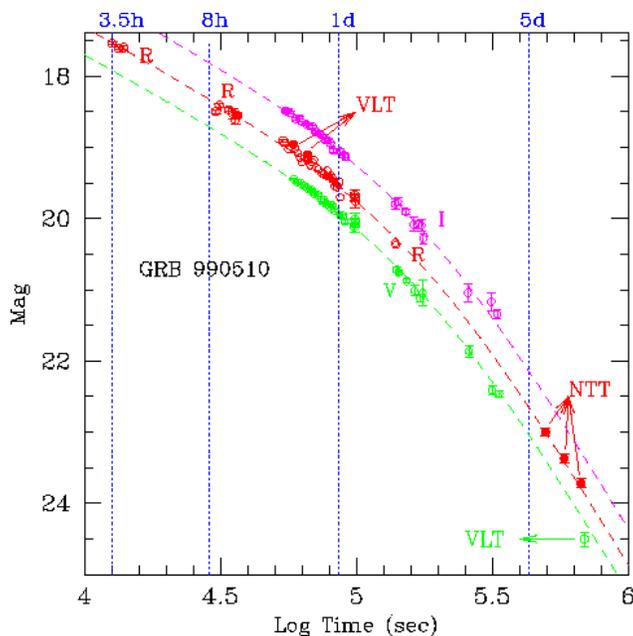
[Rhoads 97, 99]

$$t < t_j: h = 1.7 \times 10^{17} \left( \frac{E_{\text{Iso},53}}{n_0} \right)^{1/8} t_{\text{week}}^{5/8} \text{ cm}$$

$$t > t_j: t \propto R_j / \Gamma^2 c$$

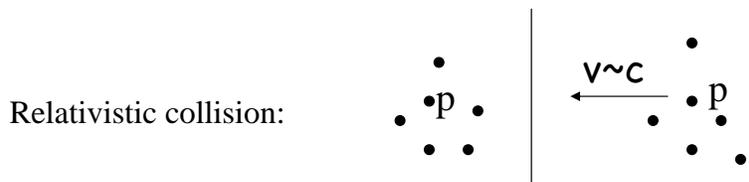
$$h \approx h(t_j) \left( \frac{t}{t_j} \right)^{1/2} = 1.6 \times 10^{17} \left( \frac{E_{51}}{n_0} \right)^{1/6} t_{\text{week}}^{1/2} \text{ cm}$$

## “Jet breaks”



[Staneck et al. 99; Harrison et al. 99]

# Collisionless shock 101



Coulomb:  $m_e c^2 = \frac{e^2}{d} \Rightarrow \lambda_{Coul.} \approx \frac{m_p}{m_e} \frac{1}{n \pi d^2} = 10^{28} n_0^{-1} \text{ cm}$

Nuclear:  $\lambda_{Nuc.} \approx \frac{1}{n \sigma_{pp}} = 10^{25} n_0^{-1} \text{ cm}$

Plasma:  $\omega_p = \sqrt{\frac{4 \pi n e^2}{m_p}} \Rightarrow \frac{c}{\omega_p} \approx 10^7 n_0^{-1/2} \text{ cm}$

• B build-up:  $B^2 / 8\pi = \epsilon_B u_{thermal}$

• Non-thermal  $e^-$ :  $\gamma_m \equiv \gamma_{e,thermal} = \epsilon_e \frac{m_p}{m_e} \Gamma$

$\gamma > \gamma_m : \frac{dn}{d\gamma} \propto \gamma^{-p} ; p \approx 2$

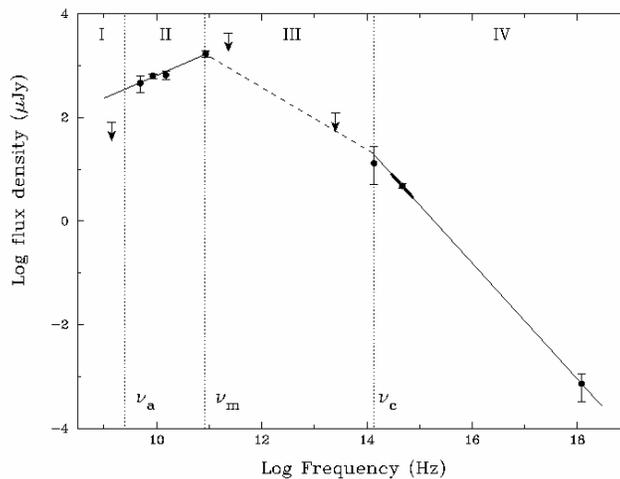
## Observations: Synchrotron spectrum

- Parameters:  $E, n, \epsilon_e, \epsilon_B, (\theta_j, p)$

- Observations:  $f_m, v_m, v_c, v_a$



$E \sim 10^{52} \text{ erg}, n \sim 1/\text{cm}^3,$   
 $\epsilon_e \sim \epsilon_B \sim 10^{-0.5}$   
 $p = 2.2 \pm 0.1$



[Wijers & Galama 99]

- Not too many examples Note, e.g.  $f_m \sim (n \epsilon_B)^{1/2} E$   
 $n \sim v_a^{25}$

## Fireball “calorimetry”

- Sub-relativistic @ 1yr,  
Isotropic radio emission.

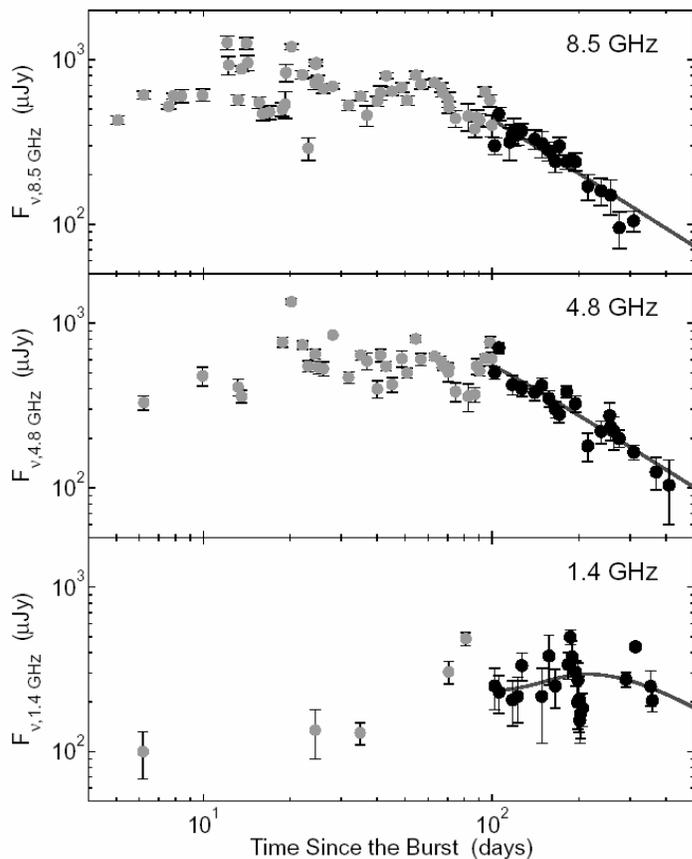
$$R_{NR} = 10^8 (E_{51}/n_0)^{1/3} \text{ cm}$$

$$t_{NR} = 1 (E_{51}/n_0)^{1/3} \text{ yr}$$

$$L_\nu [t_{NR}, 10 \text{ GHz}] \sim 10^{31} n_0^{3/4} E_{51} \text{ erg/sHz}$$

[Frail, Waxman & Kulkarni 00;  
Livio & Waxman 01]

- Long term radio observations  
→ determine total fireball E



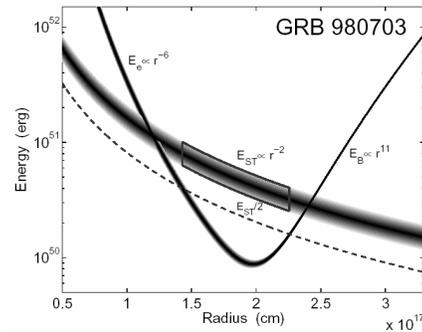
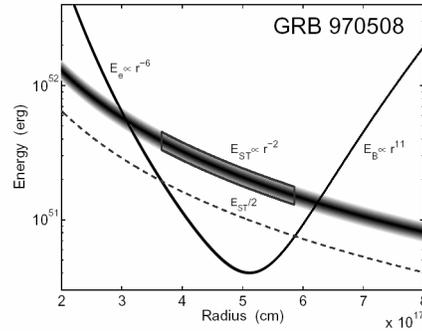
GRB 70508

[Berger et al. 04]

- Explosion energy:  
 $E \sim 10^{51-0.5} \text{ erg}$

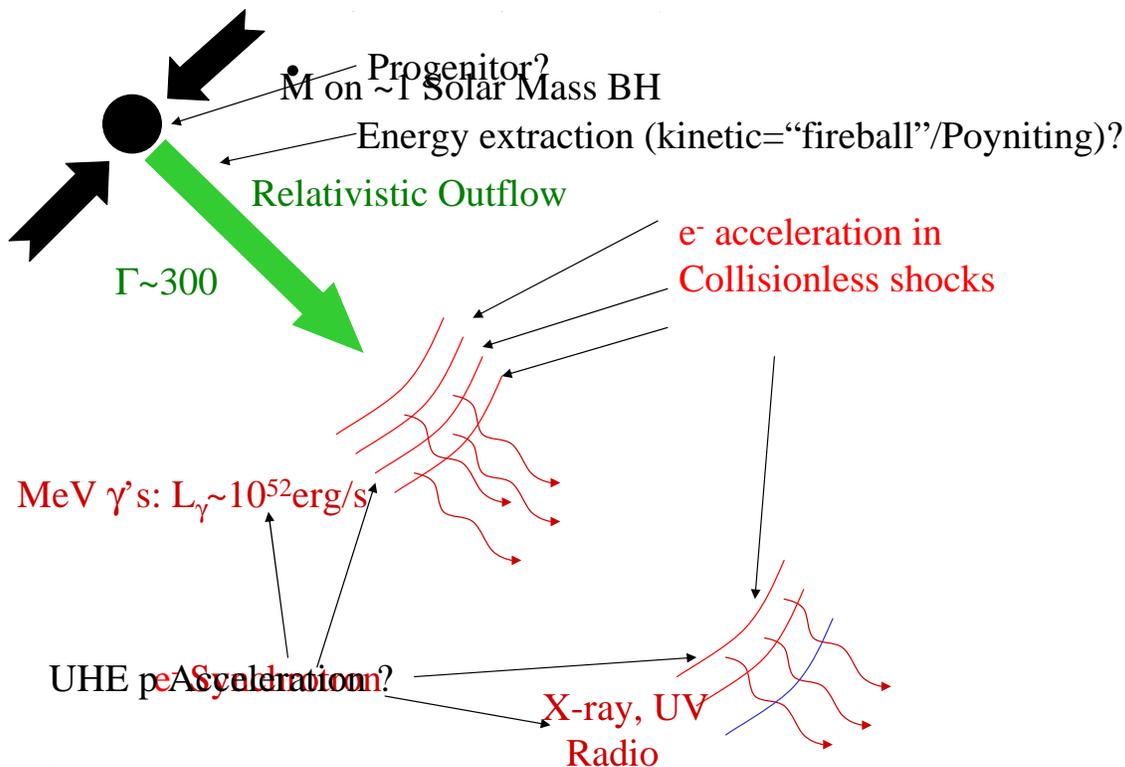
- Radius:  $R \sim 10^{17.5} \text{ cm}$

- Consistent with relativistic evolution:  $E, R, \theta_j$



[Frail, Waxman & Kulkarni 00; Berger et al. 04]

## GRBs and high energy particles



[Piran, Phys. Rep. 99; Meszaros, ARA&A 02; Waxman, Lec. Notes Phys. 598 (2003).]

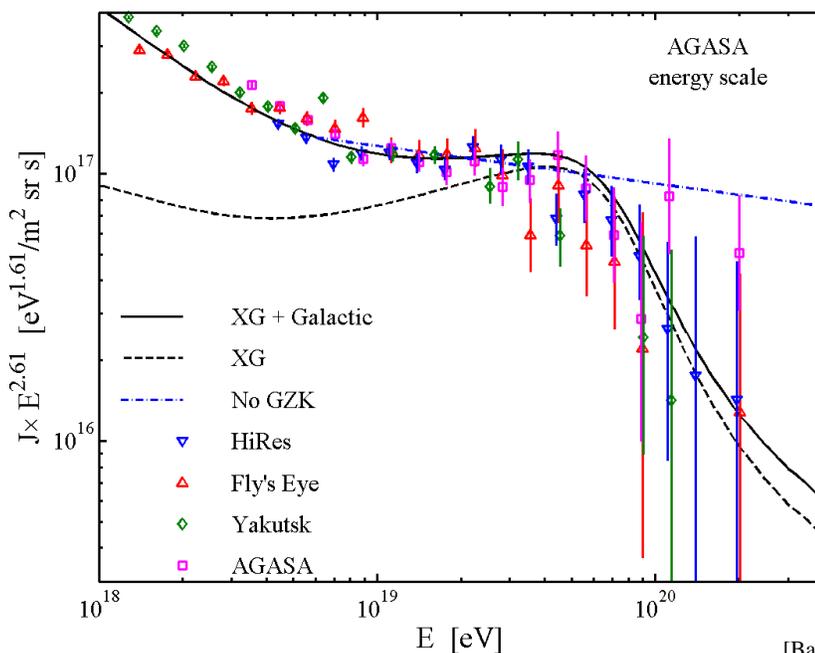
## Proton/electron acceleration

Protons	Electrons	Afterglow
<ul style="list-style-type: none"> <li>Acceleration/expansion: <math>u_B / u_e &gt; 0.2</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\text{MeV } \gamma\text{'s}</math>: <math>u_B / u_e &gt; 0.1</math></li> </ul>	$u_B / u_e \sim 1$
<ul style="list-style-type: none"> <li>Synchrotron losses: <math>\Gamma &gt; 10^2</math></li> </ul>	<ul style="list-style-type: none"> <li>Optical depth: <math>\Gamma &gt; 10^{2.5}</math></li> </ul>	$\Gamma > 10^{2.5}$
<ul style="list-style-type: none"> <li>Particle spectrum: <math>dn_p / d\varepsilon_p \propto \varepsilon_p^{-2}</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\gamma</math> spectrum: <math>dn_e / d\varepsilon_e \propto \varepsilon_e^{-2}</math></li> </ul>	
<ul style="list-style-type: none"> <li>p energy production: <math>\varepsilon_p^2 \frac{d\dot{n}_p}{d\varepsilon_p} \approx 10^{44} \frac{\text{erg}}{\text{Mpc}^3 \text{yr}}</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\gamma</math> energy production <math>\varepsilon_e^2 \frac{d\dot{n}_e}{d\varepsilon_e} \sim \frac{10}{\text{Gpc}^3 \text{yr}} \times 10^{52} \text{ erg} = 10^{44} \frac{\text{erg}}{\text{Mpc}^3 \text{yr}}</math></li> </ul>	$\cong \frac{0.5}{\text{Gpc}^3 \text{yr}} \times 10^{53.5} \text{ erg} = 10^{44} \frac{\text{erg}}{\text{Mpc}^3 \text{yr}}$

[Waxman 95]  
[Waxman 04]

## Rate calibration

$$R = 3.0 \times 10^{44} \text{ erg/Mpc}^3 \text{ yr}$$



[Bahcall & Waxman 03]

## “Generic” GRB fireball $\nu$ 's

- $\gamma + p \rightarrow n + \pi^+$  ;  $\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$   
 $(\epsilon_p / \Gamma)(\epsilon_\gamma / \Gamma) \geq 0.3 \text{ GeV}^2$
- $\epsilon_\gamma = 1 \text{ MeV}, \Gamma = 10^{2.5} \Rightarrow \epsilon_p \geq 10^{16} \text{ eV}, \epsilon_\nu \geq 10^{14.5} \text{ eV}$
- $f_{p \rightarrow \pi} \approx 0.2$

Weak dependence on model parameters

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

$$J_{\nu \rightarrow \mu} \approx 20 / \text{km}^2 \text{ yr} \quad (\text{bgnd free})$$

[Waxman & Bahcall 97, 99; Rachen & Meszaros 98; Guetta, Spada & Waxman 01;

Alvarez-Muniz & F. Halzen 99; Guetta, Hooper, Alvarez-Muniz, Halzen & E. Reuveni 04;

Dermer & Atoyan 04]

## Summary

- Long duration, cosmological GRBs:  
 $\Gamma > 100$ ,  $\theta_j \sim 0.1$ ,  $E \sim 10^{51-0.5}$  erg explosions  
Likely: (few)  $M_{\text{sun}}$  BH formation
- Likely sources of high energy particles  
May account for observed  $> 10^{10}$  eV particles  
predictions: to be tested by **Auger**  
  
>1 TeV Neutrinos: **km<sup>3</sup> neutrino telescopes**  
Detection: Identify UHE CR sources  
Unique probes on GRB jet physics  
Unique probe of neutrino physics