GRB & Jet model

Kunihito IOKA (Osaka Univ.)

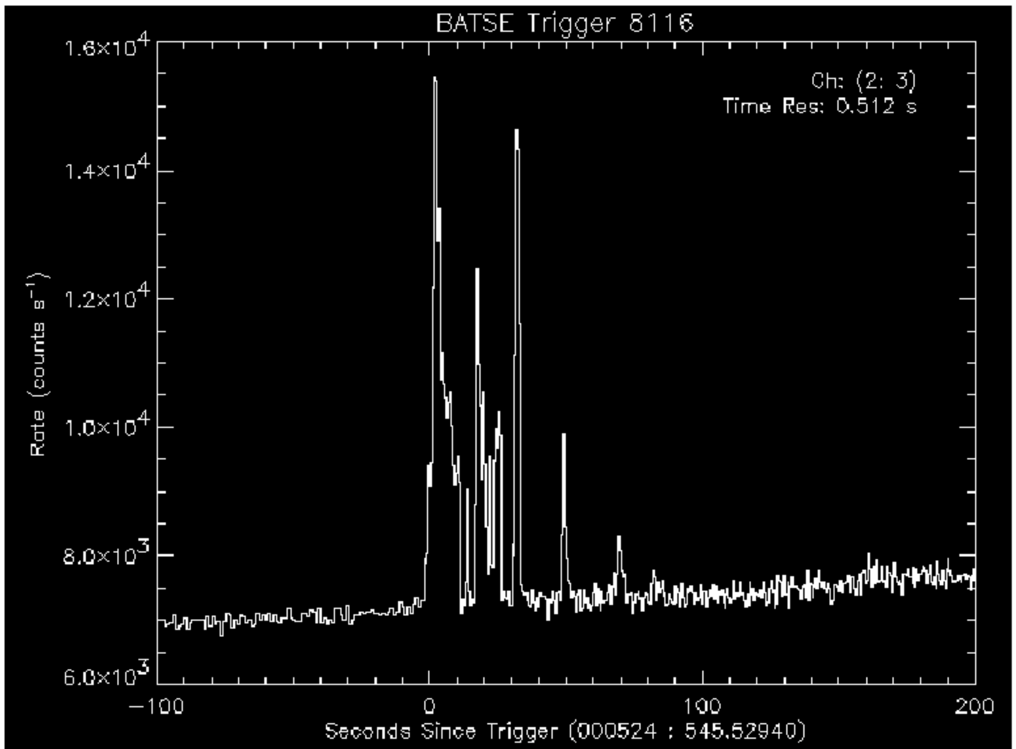
1. Observation
2. Fireball
3. Internal shock
4. Afterglow
5. Jet
6. Central engine
7. Links with other fields
8. Luminosity-lag
9. X-ray flash
10. Summary

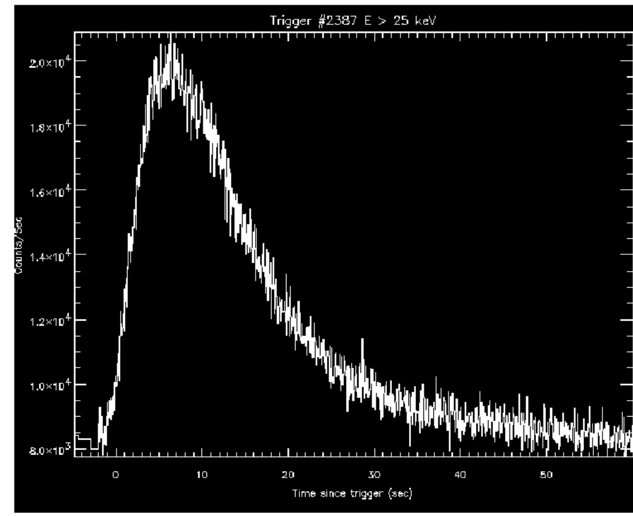
1. Observation

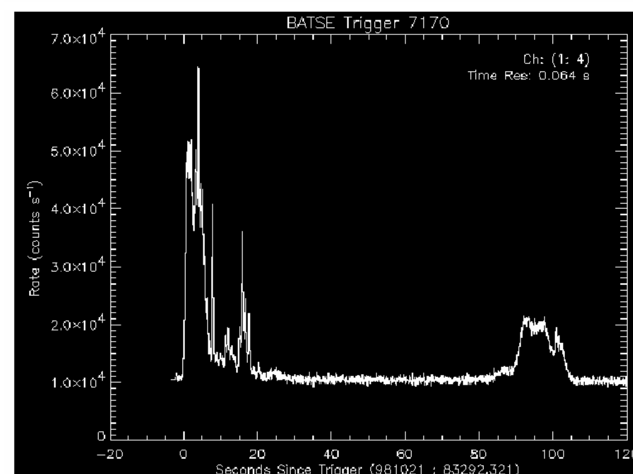
Gamma-Ray Burst

Vela satellites in 1967

Brightest object $\approx 10^{52}$ ergs s^{-1}



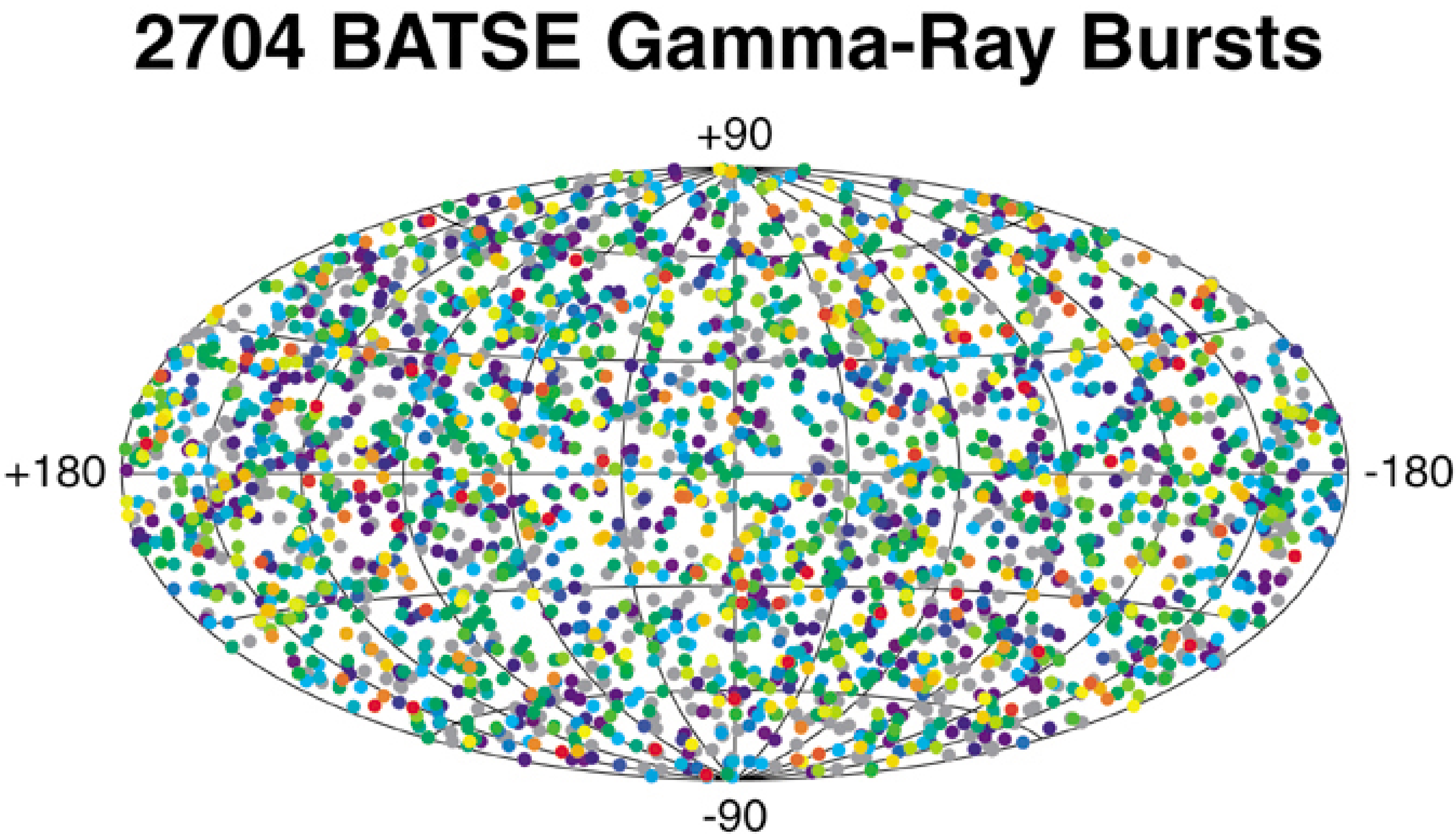




Origin has been a puzzle

Angular distribution

Isotropic



~1000 events/yr

Spatial distribution   Inhomogeneous

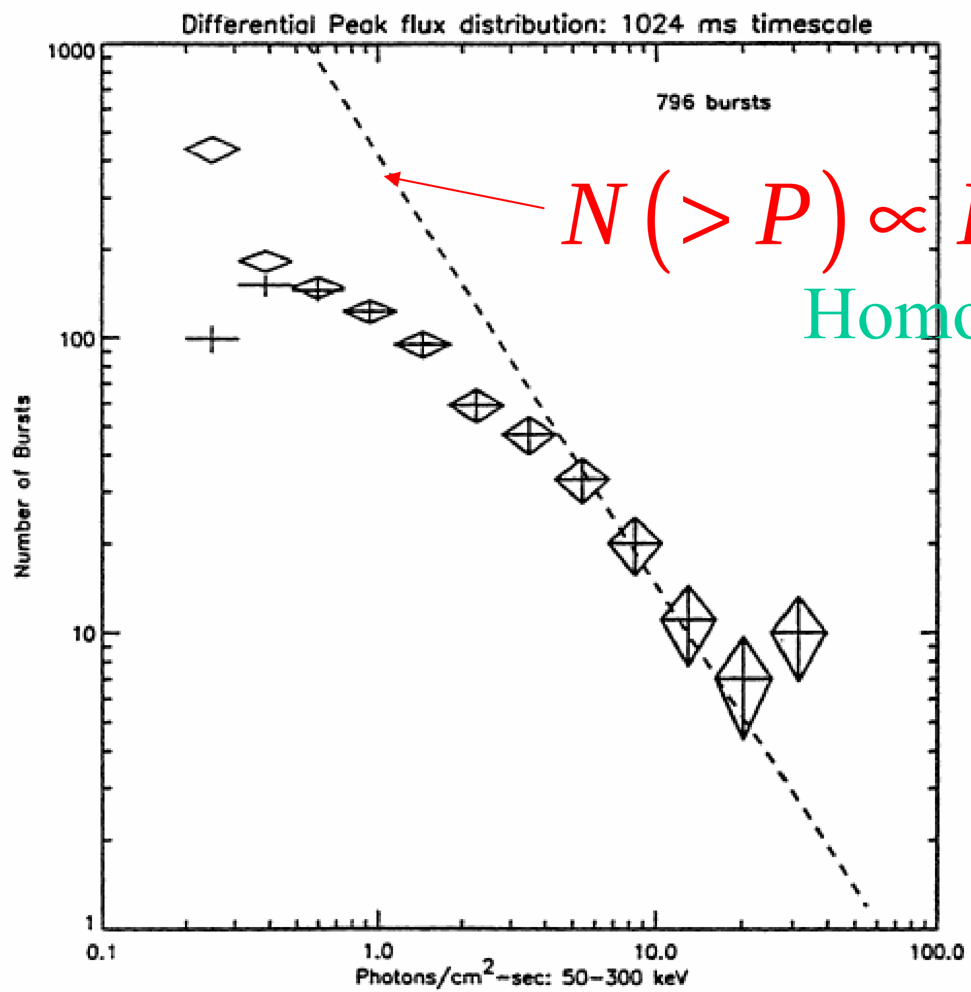


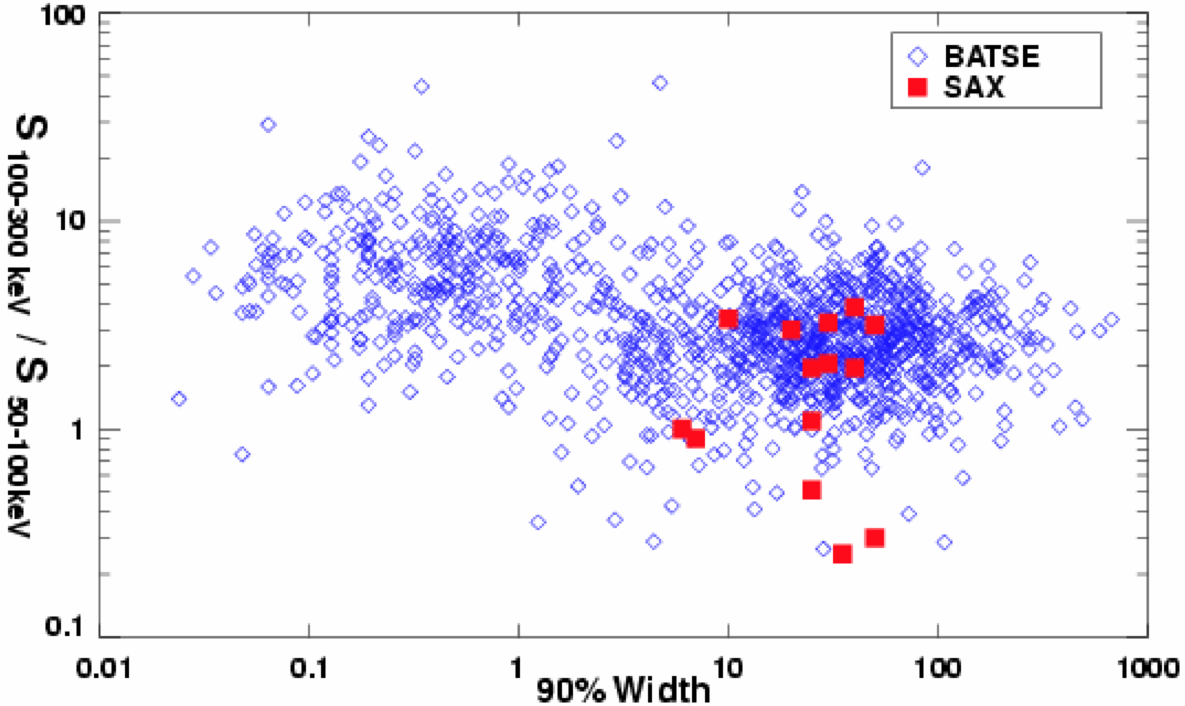
Figure 12 The peak flux distribution of 796 gamma-ray bursts observed by BATSE (Pendleton et al 1995). The flux is measured over the energy range 50–300 keV.

$$N(>P) \propto P^{-3/2}$$

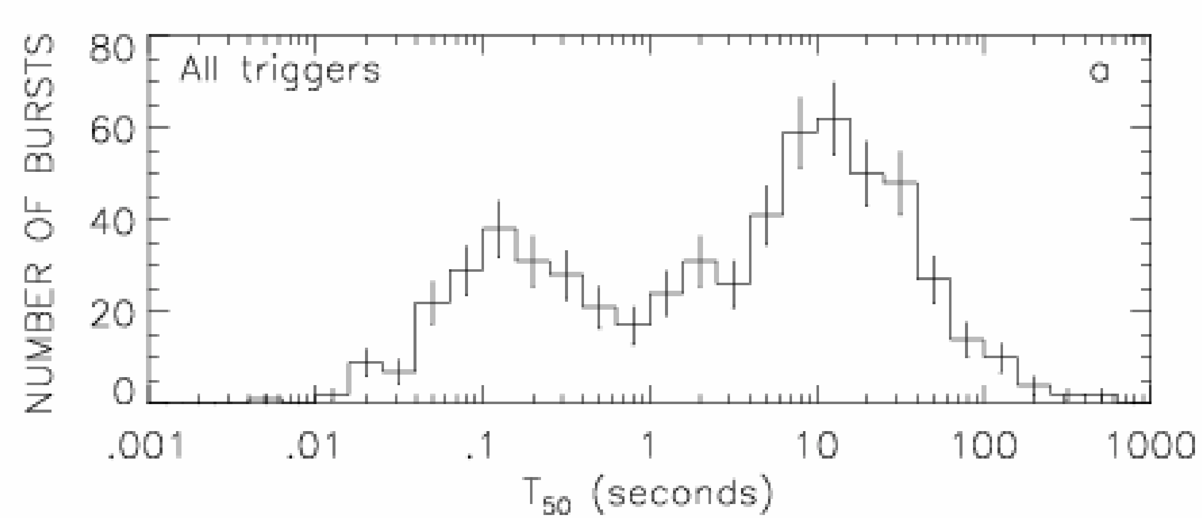
Homogeneous in Euclidean

$$\langle V/V_{\max} \rangle = 0.330 \pm 0.010$$

Duration



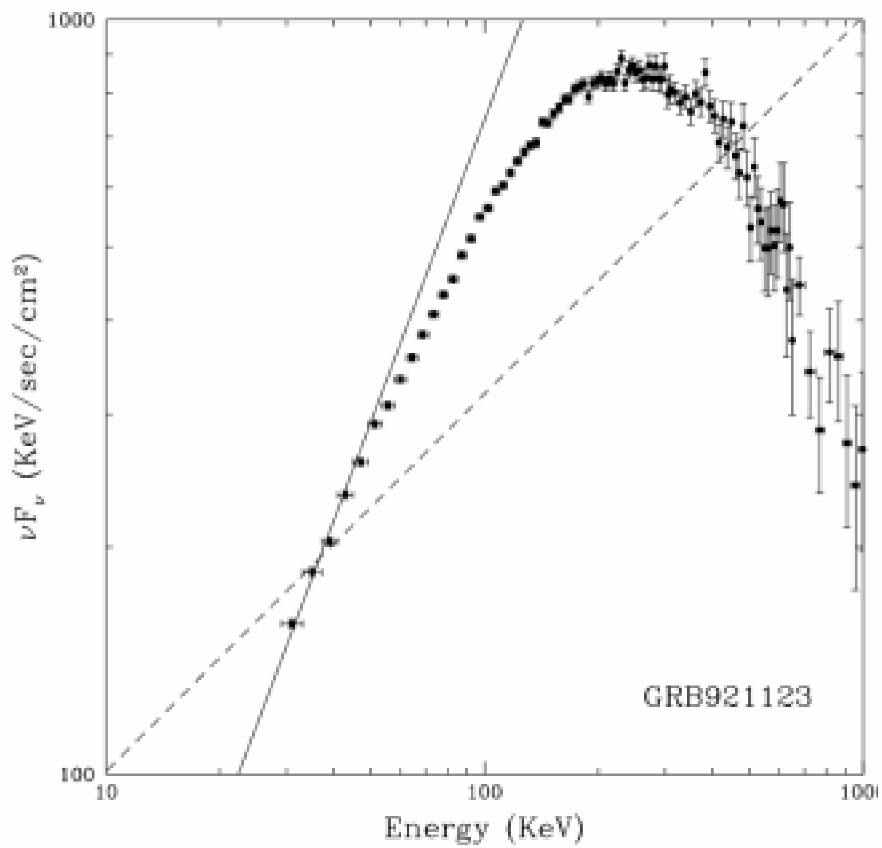
Long-soft
Short-hard

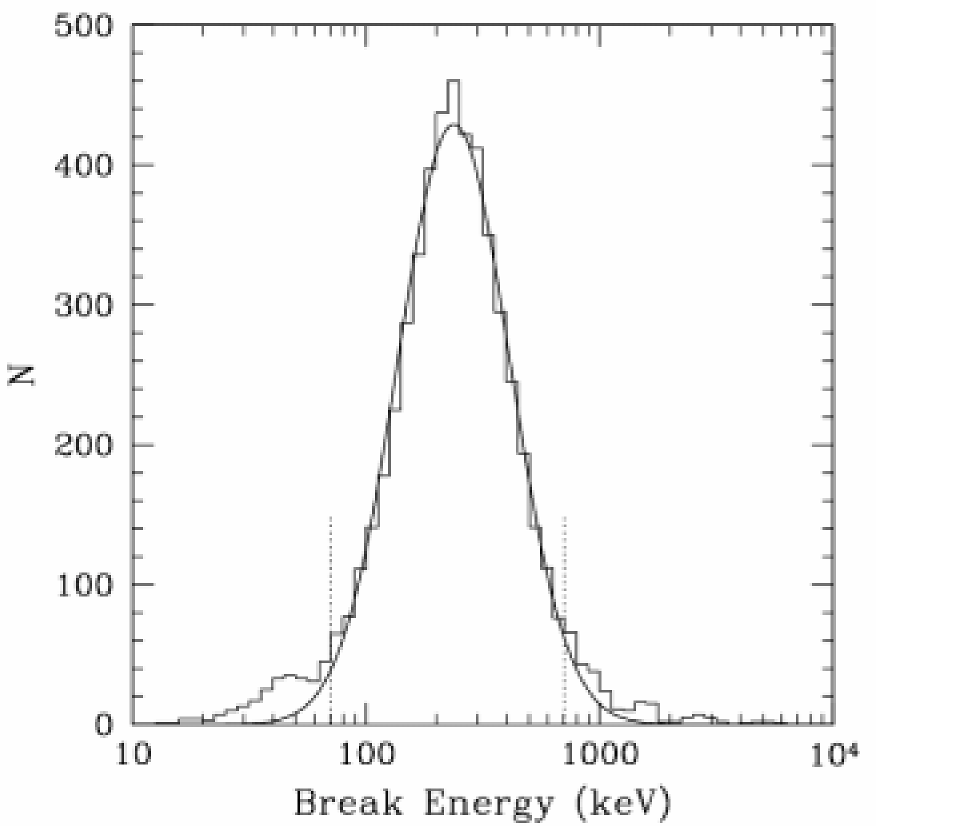


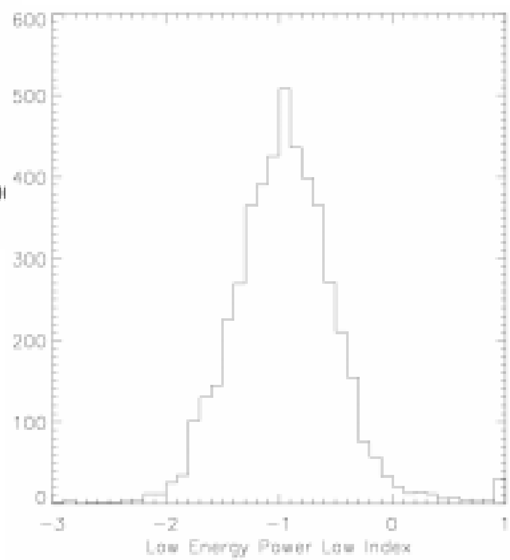
Long burst
Short burst

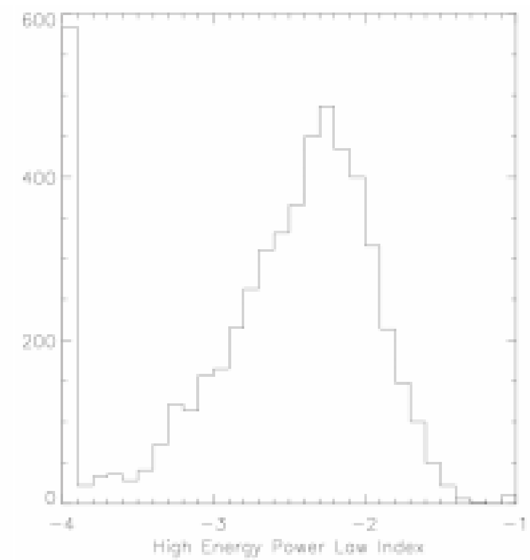
Spectrum

Band spectrum





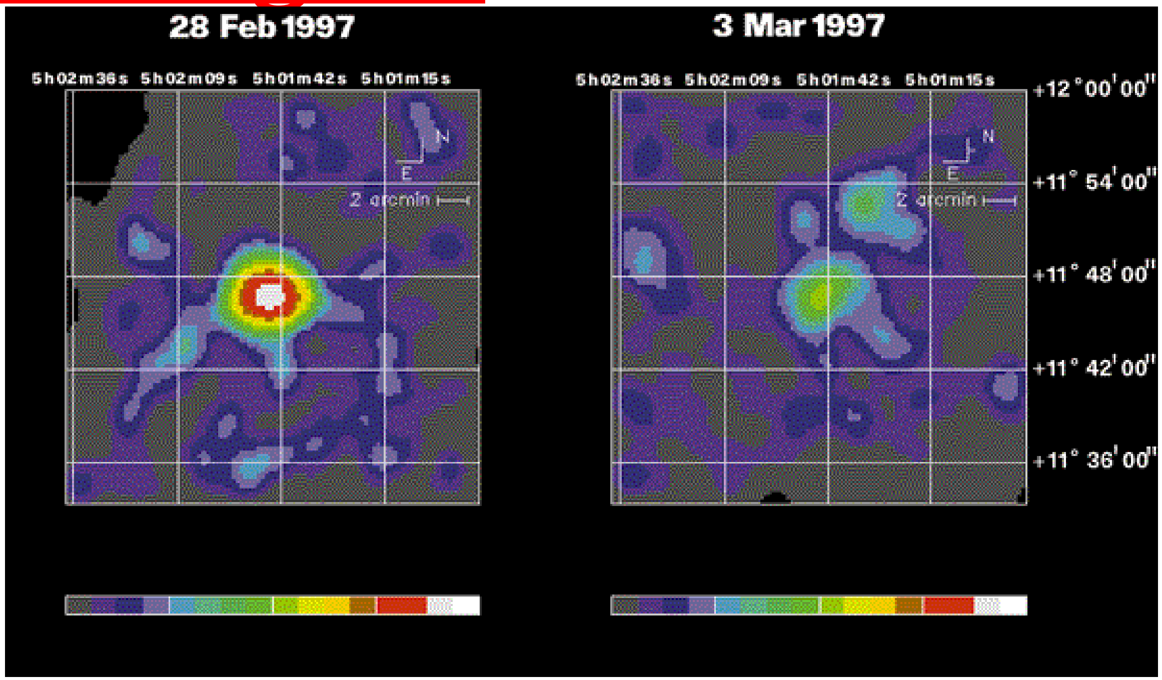




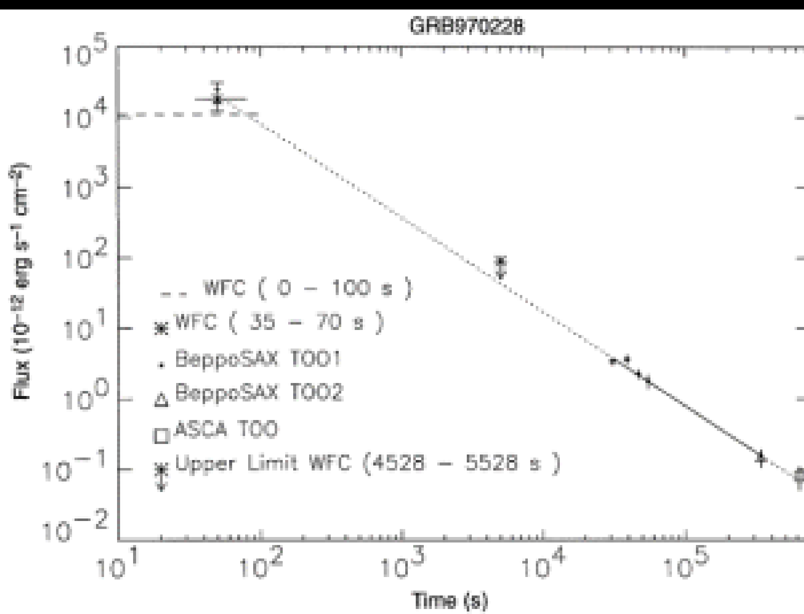
Non-thermal

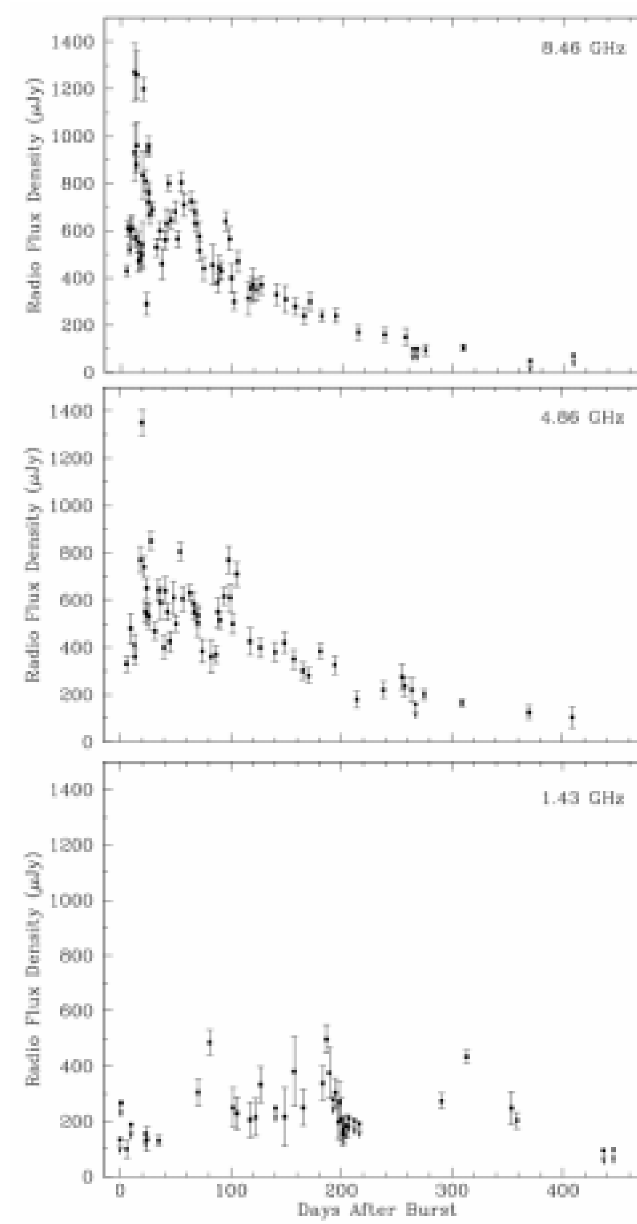
Afterglow

Beppo-SAX in 1997



X-ray

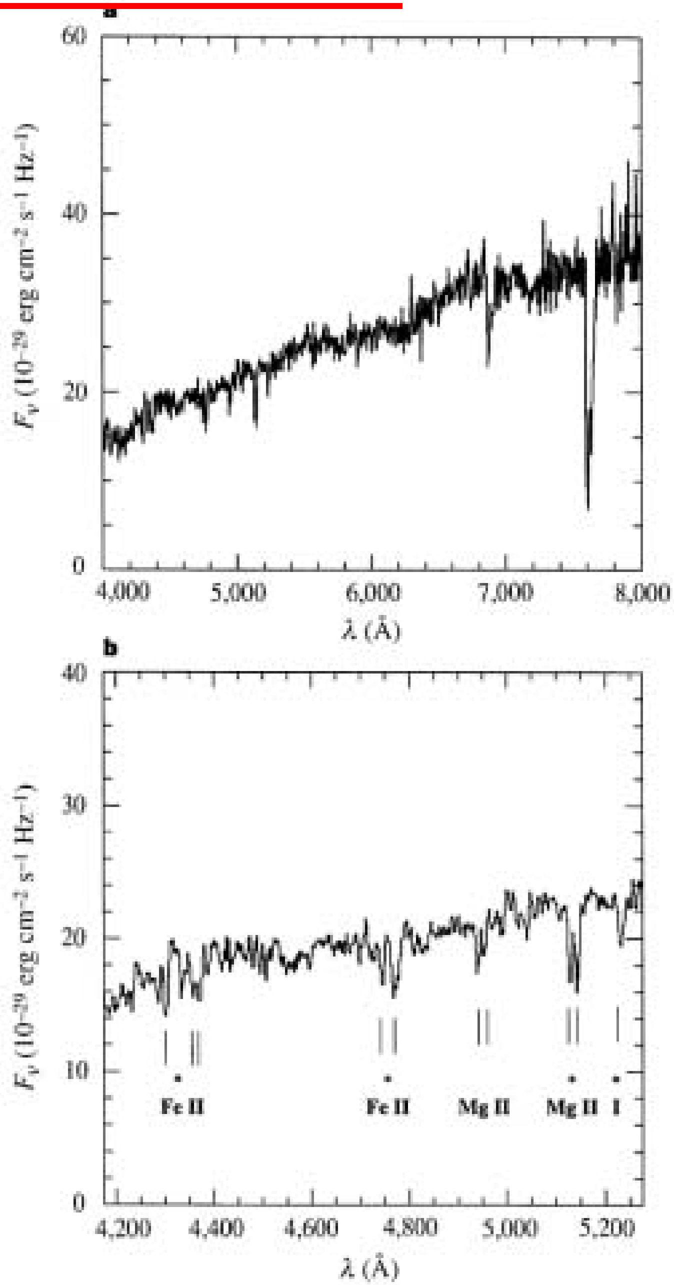


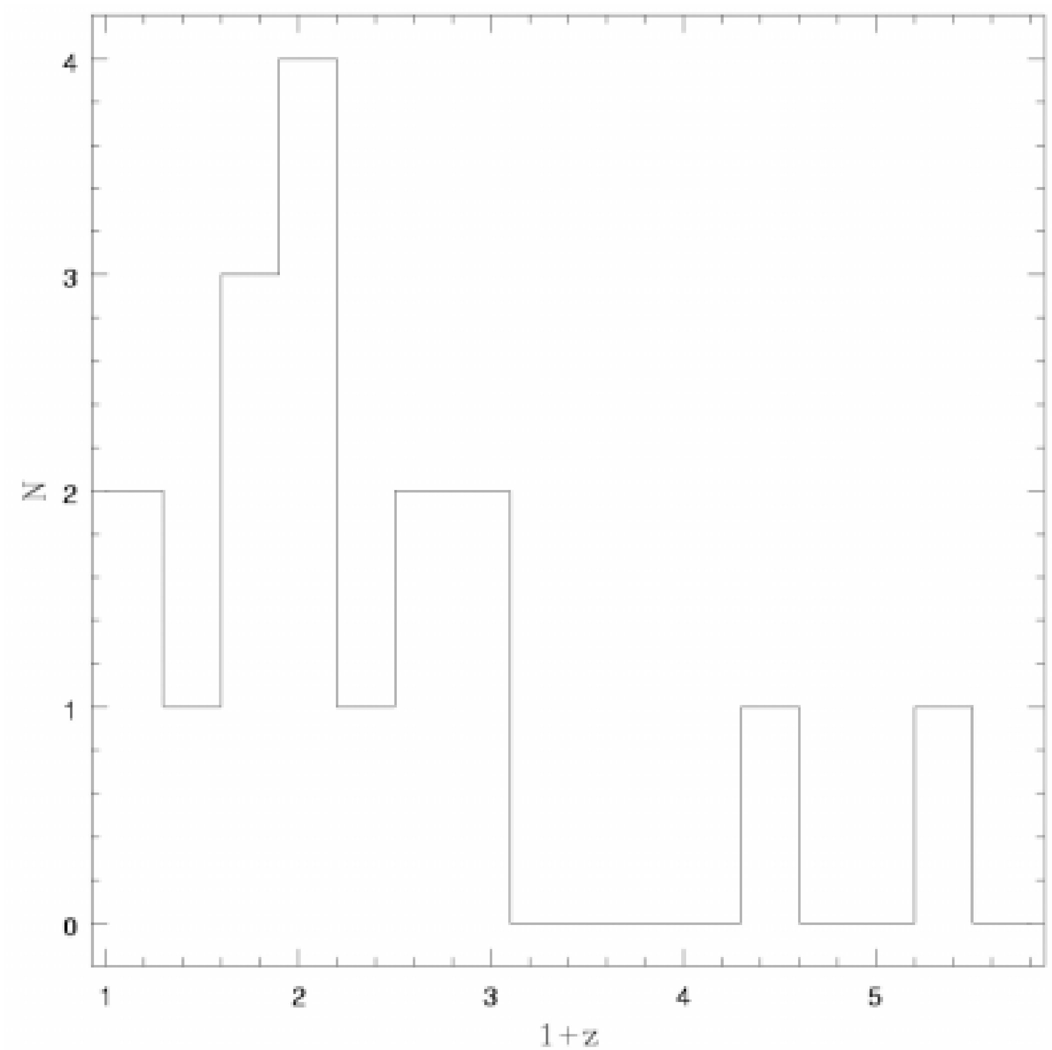


Radio

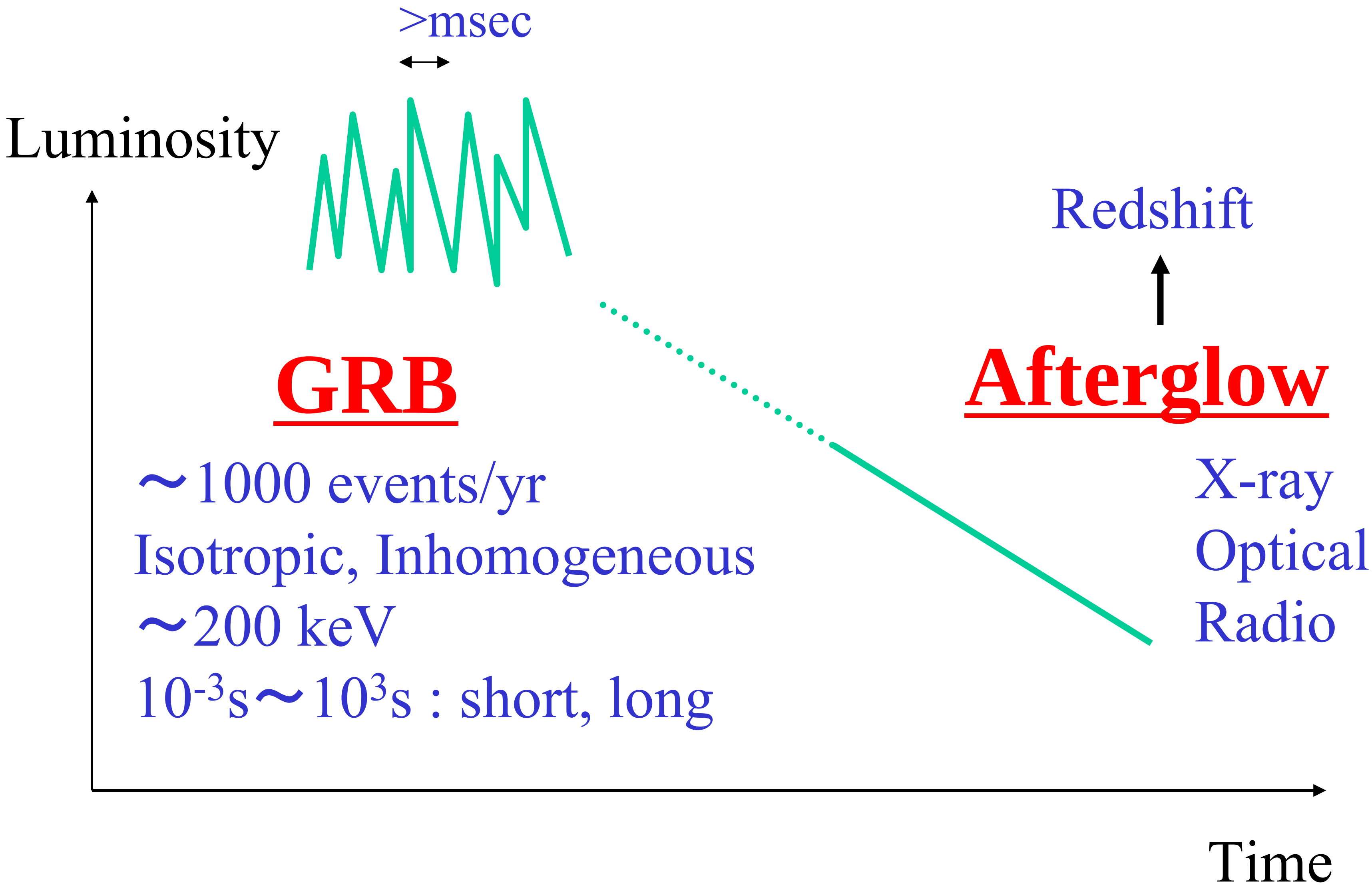
Redshift

Optical → Redshift





Summary of observation



2. Fireball

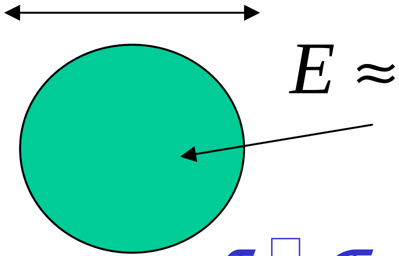
Compactness problem

$E_\gamma \geq \text{MeV}$

$$\gamma\gamma \to e^+ e^-$$

$$R \approx c\delta T \approx 10^8 \left(\delta T/10\text{ms}\right)\text{cm}$$

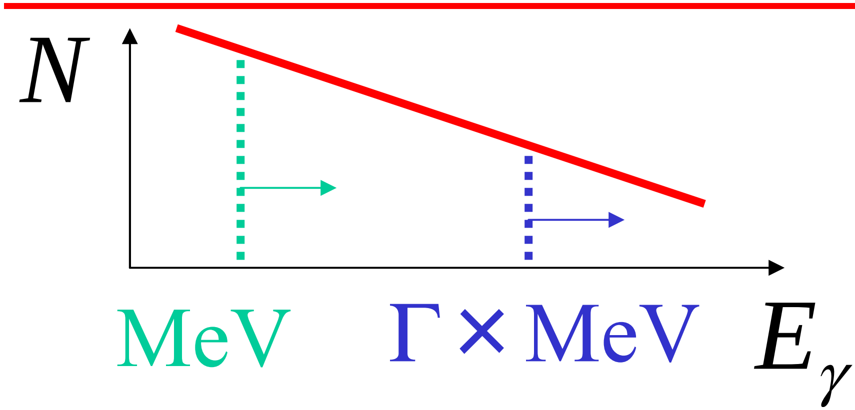
$$E \approx FD^2 \approx 10^{49} F_{-7} D_{28} \text{erg}$$

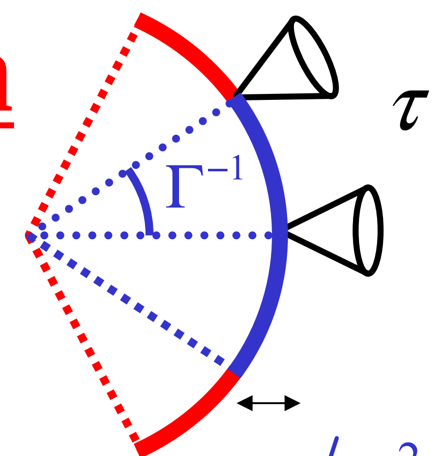


$$\tau \sim \sigma_T \frac{FD^2}{R^3 m_e c^2} R \sim 10^{13} \left(\frac{F}{10^{-7}\ \text{erg cm}^{-2}}\right)\left(\frac{D}{3\text{Gpc}}\right)^2 \left(\frac{\delta T}{10\text{ms}}\right)^{-2}$$

Optically thick $\Leftrightarrow$ Non-thermal

Relativistic motion



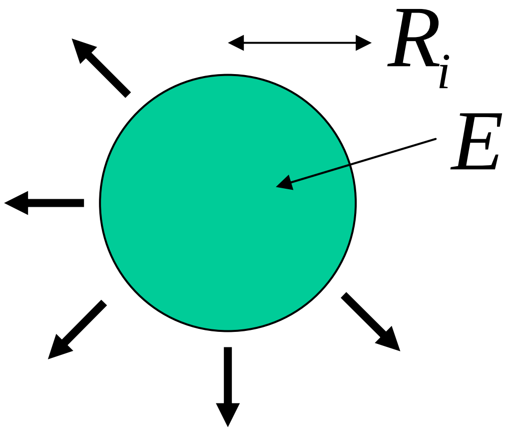


$$\tau \propto \Gamma^{-4+\beta_B} \sim \Gamma^{-6.5}$$

$$\Gamma \geq 10^2$$

Fireball

$$T_i \sim 10 E_{52}^{1/4} R_{i,7}^{-3/4} \mathrm{MeV}$$



$$\text{entropy const} \Rightarrow T^3 R^3 = \text{const}$$

$$n_{\pm} \propto \exp\left(-m_e c^2 / k_B T\right) \Rightarrow T_p \approx 20\text{keV:thin}$$

$$R_{\pm} = \left(T_i / T_p\right) R_i \approx 6 \times 10^9 E_{52}^{1/4} R_{i,7}^{1/4} \text{cm}$$

$$\text{energy const} \Rightarrow \gamma T^4 R^3 = \text{const} \Rightarrow \gamma \sim R / R_i \qquad T_{obs} \sim \gamma T \sim T_i$$

Thermal

+Baryon

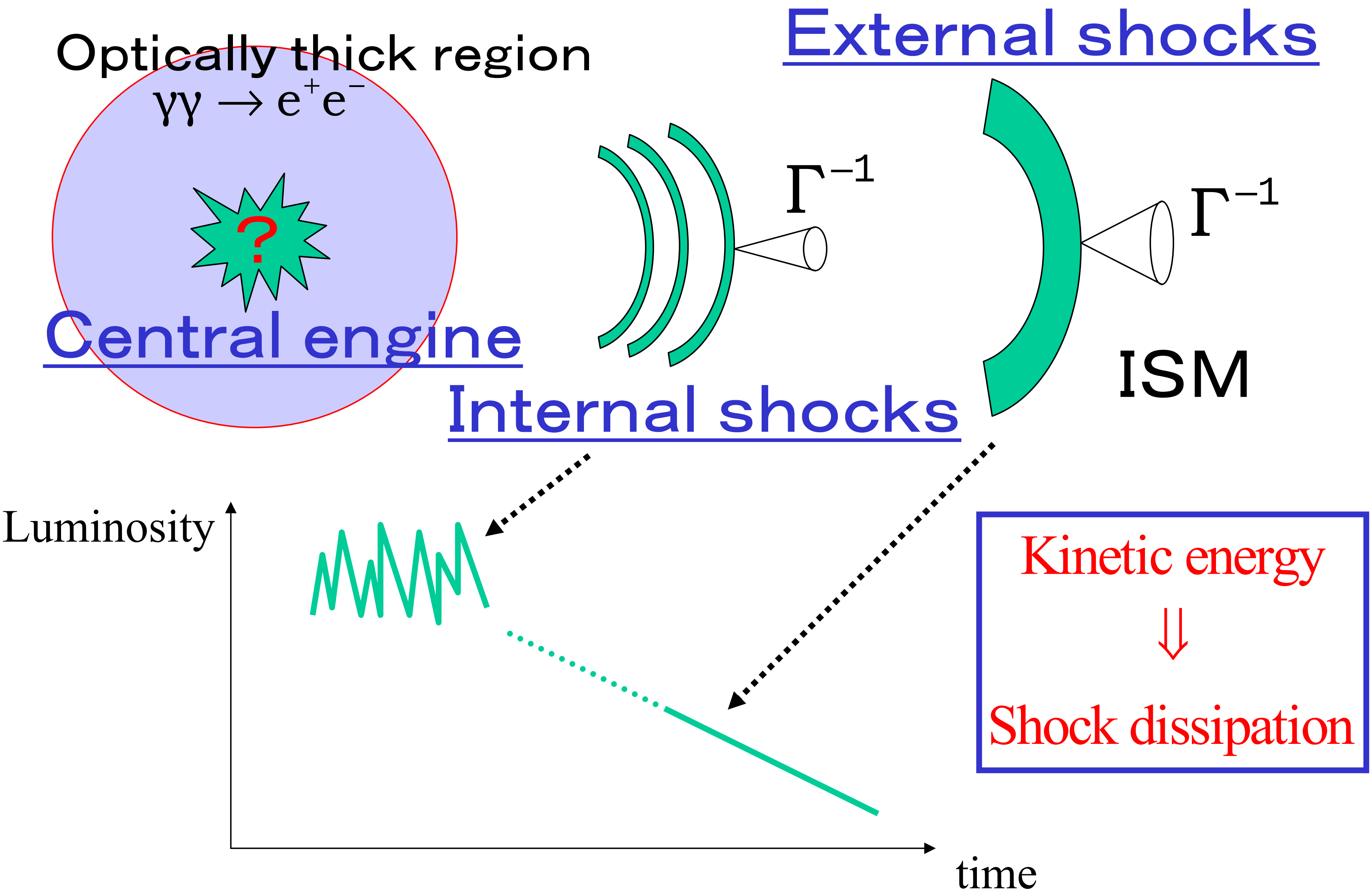
$$\eta = E / Mc^2$$

$$n_b \propto R^{-3} \qquad R_{thin} \sim 1 \times 10^{14} E_{52}^{1/2} \eta_2^{-1/2} \text{cm}$$

$$R_{matter} = \eta R_i = 1 \times 10^9 \eta_2 R_{i,7} \text{cm : Matter dominant} \quad E \sim \gamma M c^2$$

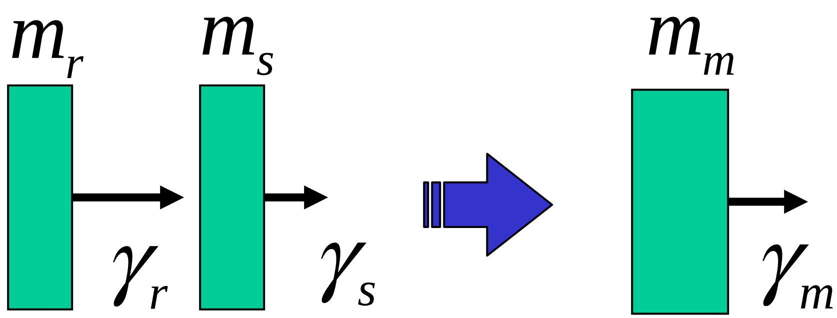
$10^{10} < \eta$: Pure radiation	$10^5 < \eta < 10^{10}$: Electron dominated
$1 < \eta < 10^5$: Relativistic baryon	$\eta < 1$: Newtonian

Internal-External shock model



3. Internal shock

Two shell collision



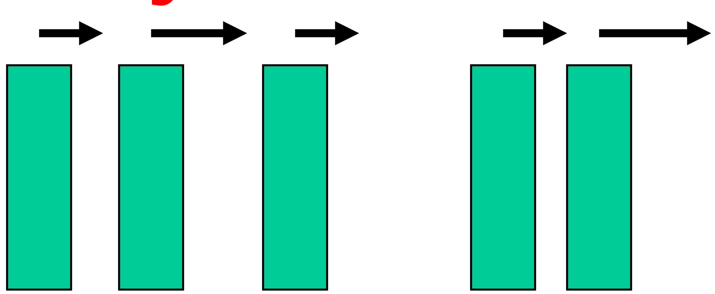
- $m_r\gamma_r + m_s\gamma_s = (m_r + m_s + E_m)\gamma_m$
- $m_r\sqrt{\gamma_r^2 - 1} + m_s\sqrt{\gamma_s^2 - 1}$

$$= (m_r + m_s + E_m)\sqrt{\gamma_m^2 - 1}$$

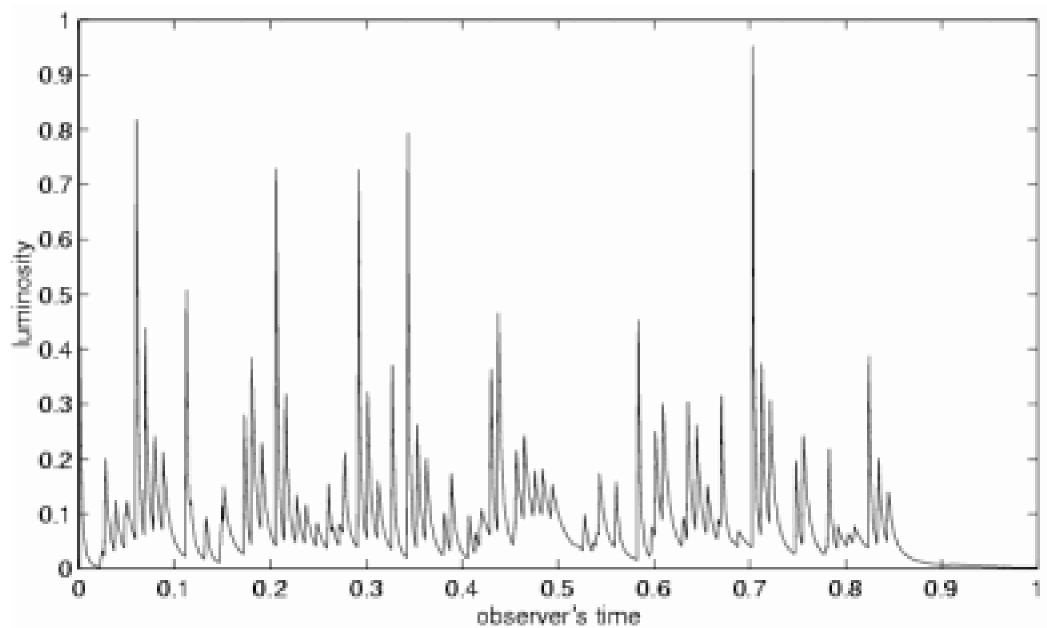
$$\text{efficiency} : \varepsilon = 1 - \frac{(m_r + m_s)\gamma_m}{m_r\gamma_r + m_s\gamma_s}$$

$$m_r = m_s : \varepsilon > 0.5 \text{ when } \gamma_r / \gamma_s > 13.9$$

Many shell

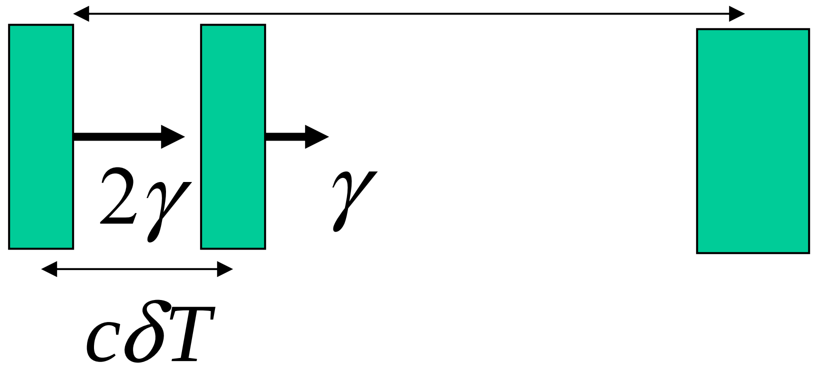


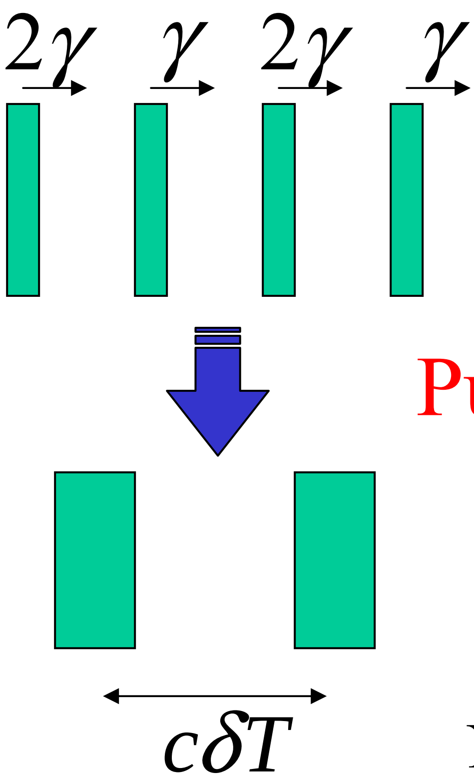
Kobayashi,Piran&Sari(97)

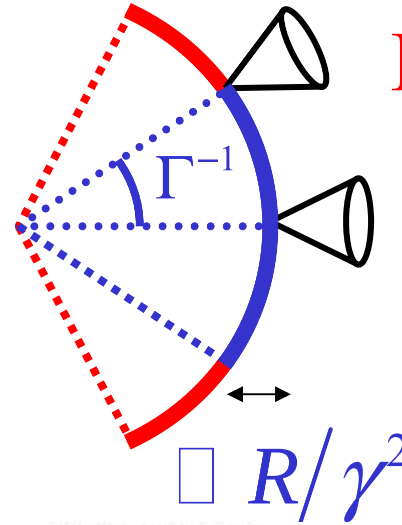


Time scale

$R \square\ \gamma^2 c\delta T \square\ 10^{13}\,\mathrm{cm}$





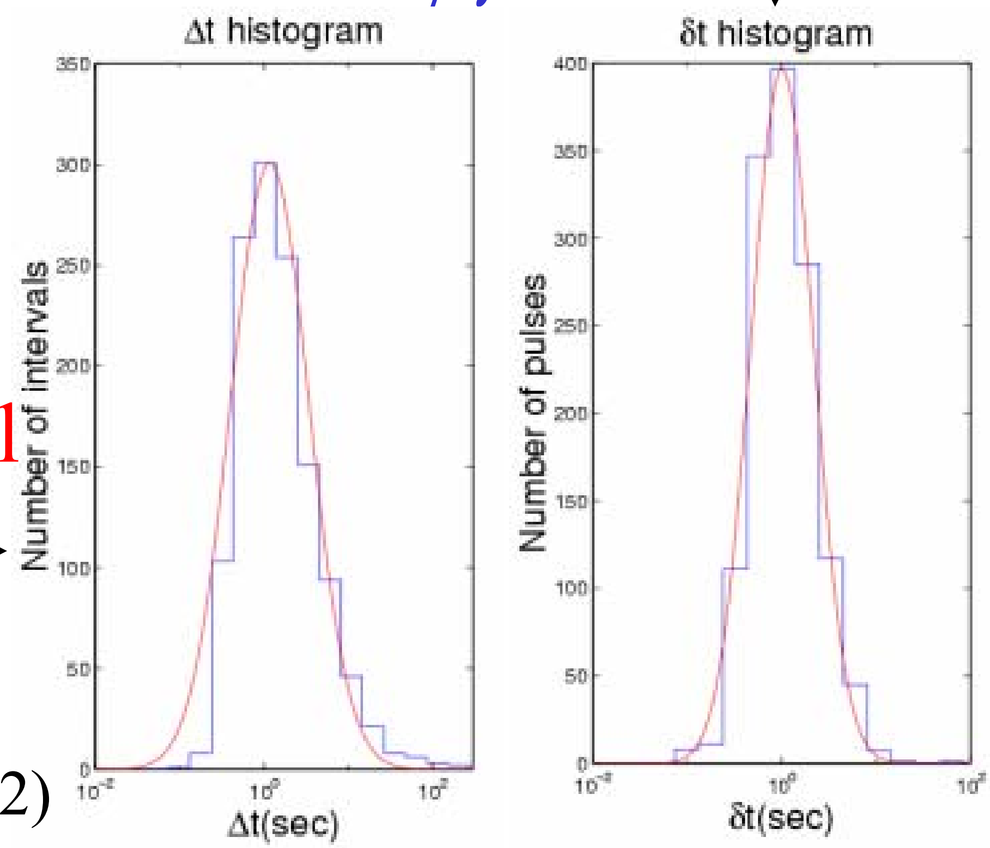


Pulse width

$$\frac{R}{c\gamma^2} \square\ \delta T$$

Pulse interval

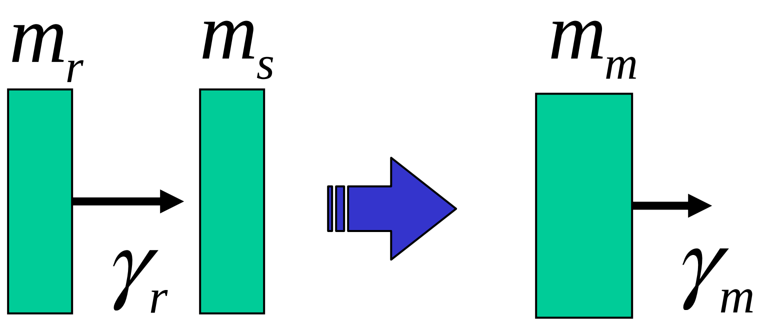
δT



Nakar&Piran(02)

4. Afterglow

External shock



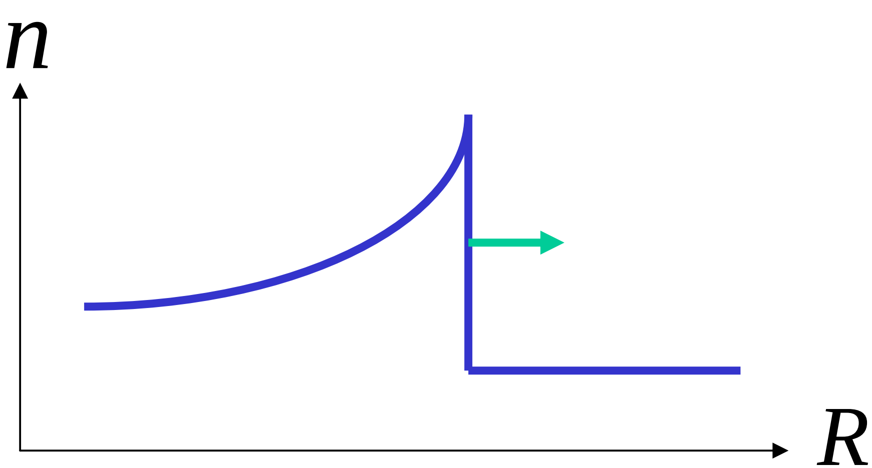
$$\gamma_m = \gamma_r / 2 \Rightarrow m_s \approx m_r / \gamma_r$$

$$m_s = \frac{4\pi}{3} R^3 n m_p$$

$$E = \gamma_r m_r c^2 = \frac{4\pi}{3} R^3 n m_p c^2 \gamma_r^2$$

$$R \sim 10^{16} E_{51}^{1/3} \gamma_2^{-2/3} n_0^{-1/3} \mathrm{cm}$$

Hydrodynamics

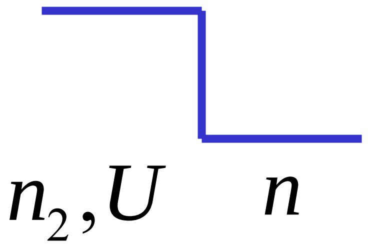


$$E \sim \frac{4\pi}{3} R^3 n m_p c^2 \gamma^2$$

$$T \sim R / \gamma^2$$

$$\gamma \propto T^{-3/8}$$

Relativistic shock



$$n_2 = (4\gamma + 3)n$$

$$U = (\gamma - 1) n m_p c^2$$

Jump condition

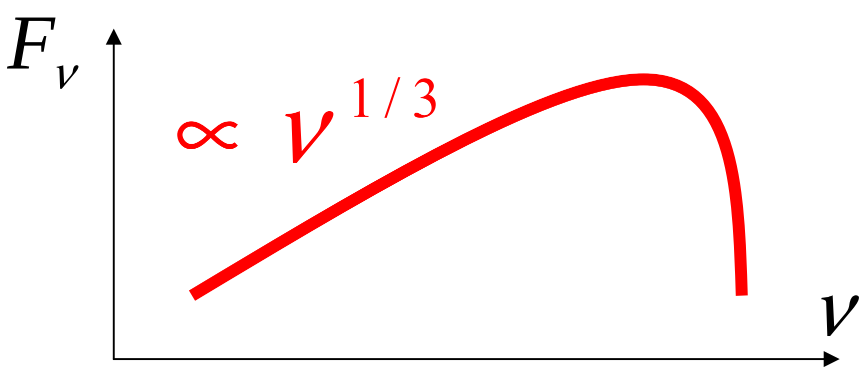
① Electron Fermi acceleration

$$\varepsilon_e = U_e / U \sim O(1), \quad N(\gamma_e) \propto \gamma_e^{-2.2} \text{ (Fermi acc.)}$$

② Magnetic field

$$\varepsilon_B = U_B / U \sim O(1)$$

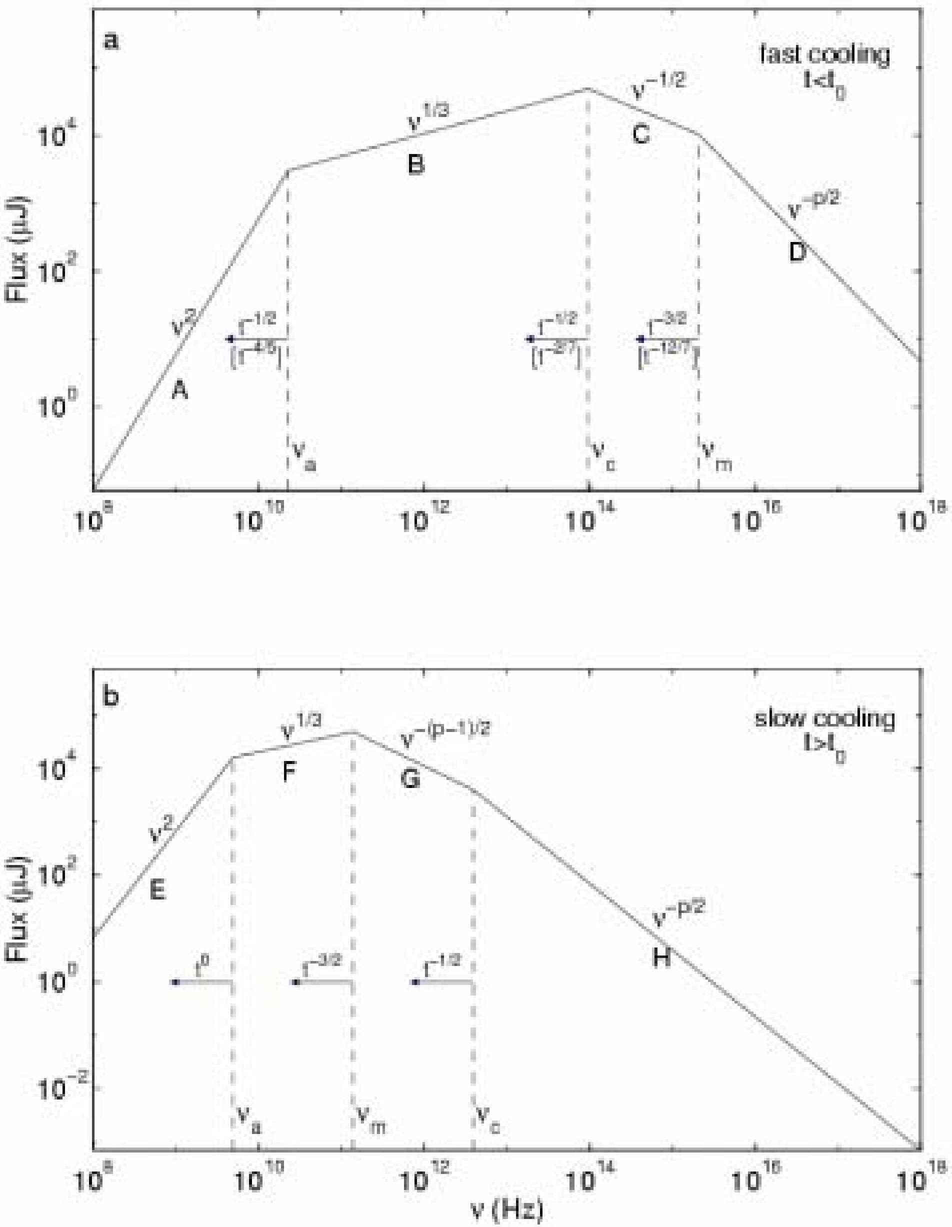
Electron synchrotron emission



$$\nu F_\nu(\gamma_e) = \frac{4}{3} \sigma_T c \gamma^2 \gamma_e^2 \frac{B^2}{8\pi}$$

$$\nu(\gamma_e) = \gamma_2 \gamma_e^2 \frac{qB}{m_e c}$$

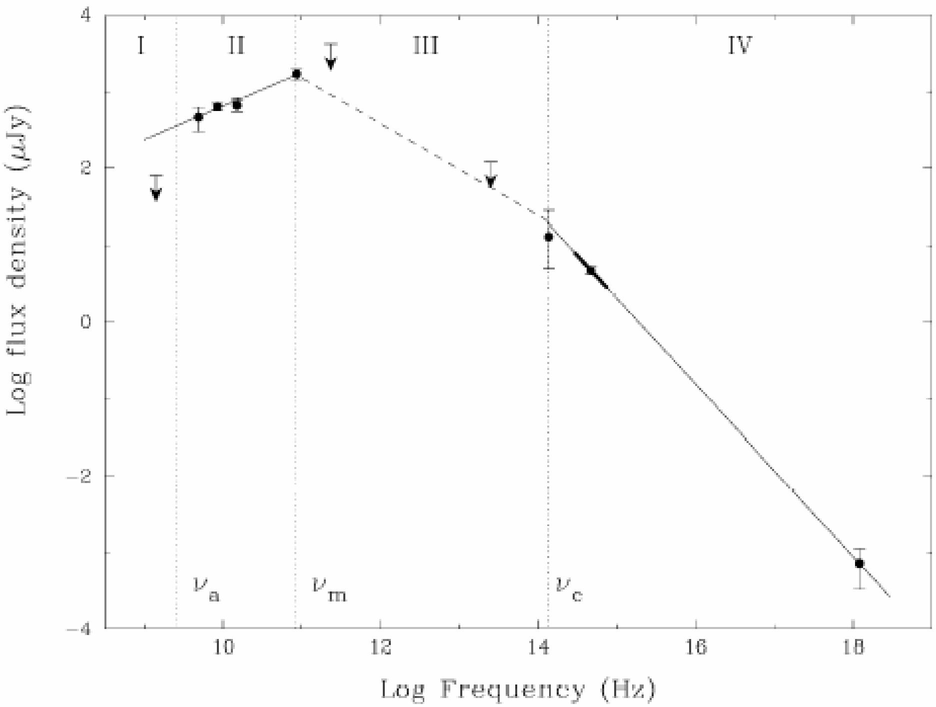
Spectrum

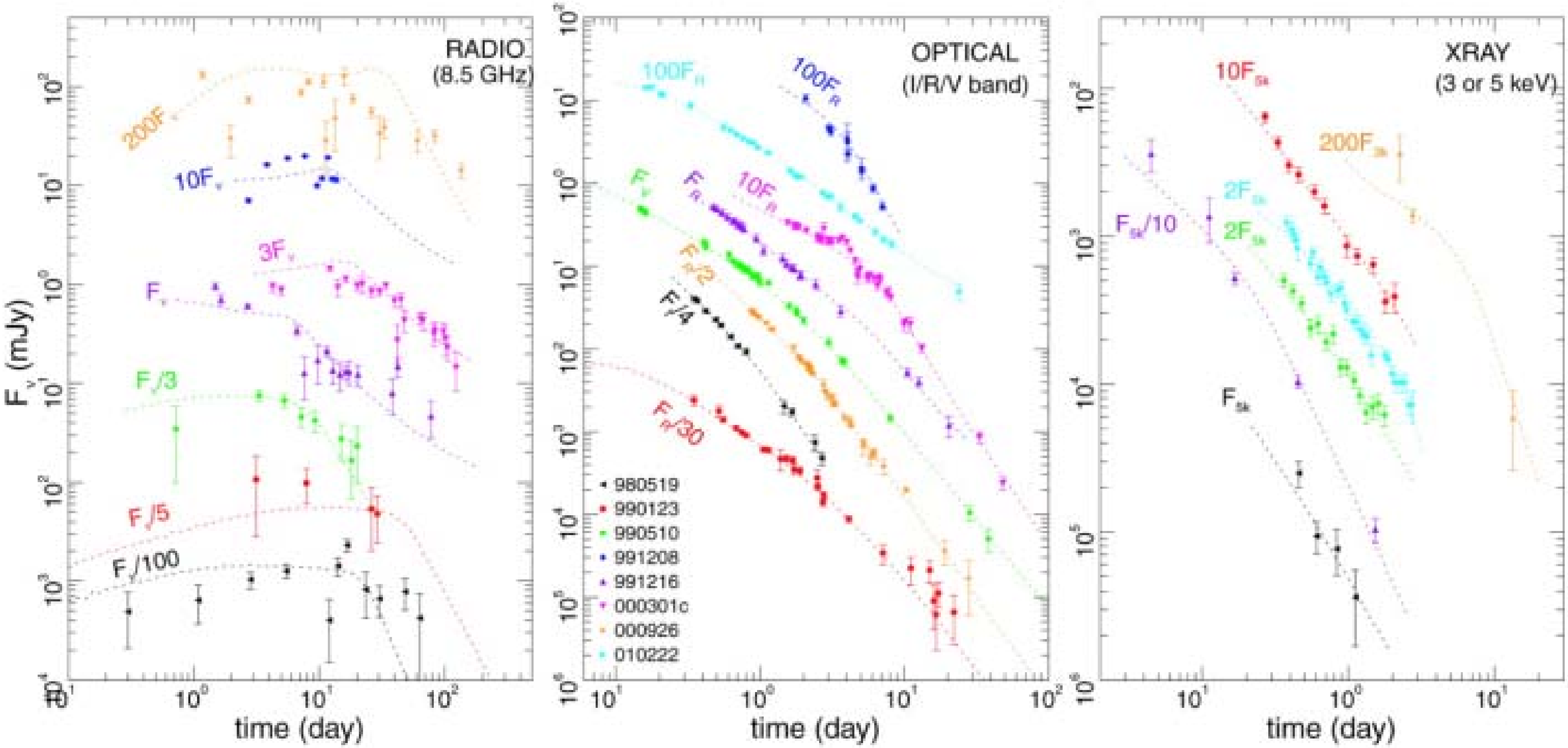


$$\{E, n, \varepsilon_e, \varepsilon_B\}$$

$$\Updownarrow$$

$$\{F_{\nu,\max}, \nu_a, \nu_m, \nu_c\}$$





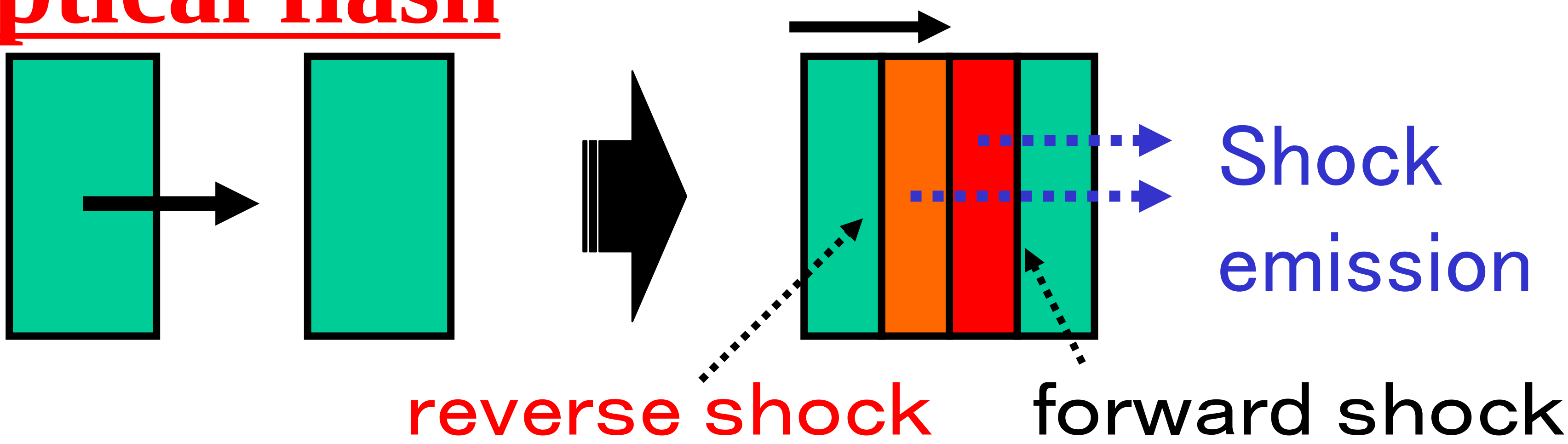
$E \sim 10^{52}\,\mathrm{erg}$

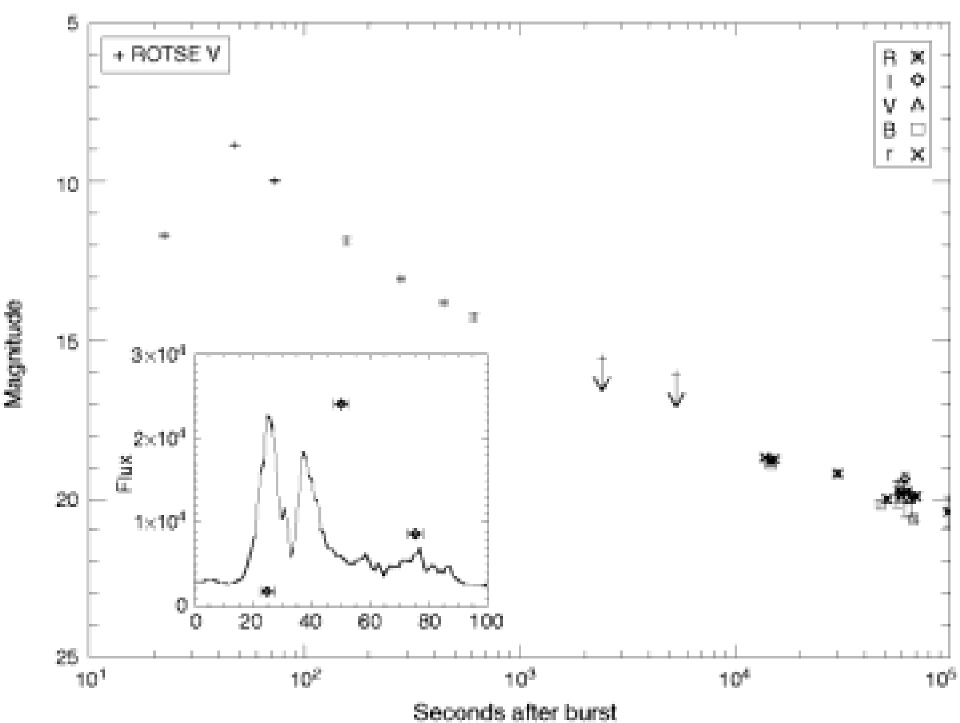
$n \sim 0.1 - 50\,\mathrm{cm}^{-3}$ ⟷ Collapsar, Hypernova

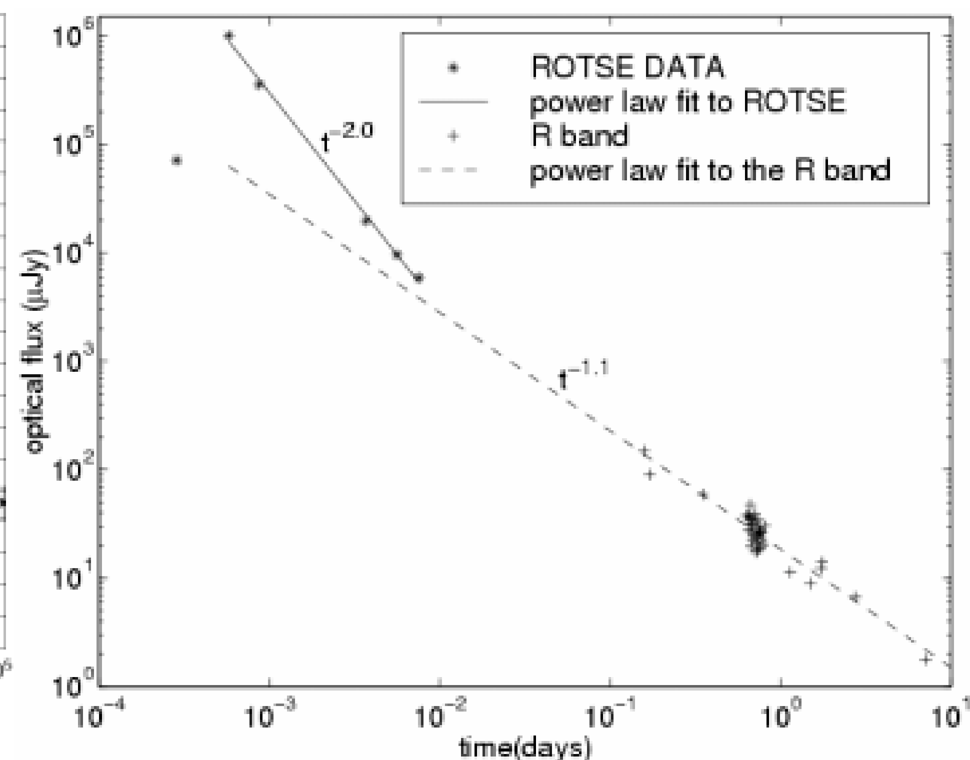
$\varepsilon_e \sim 0.1$

$\varepsilon_B \sim 0.01$

Optical flash



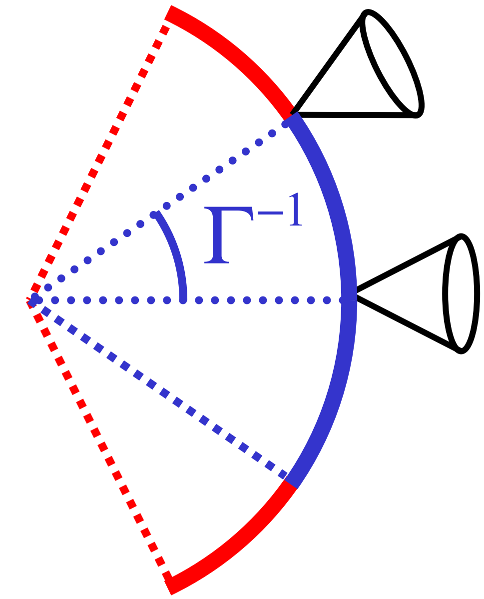




5. Jet

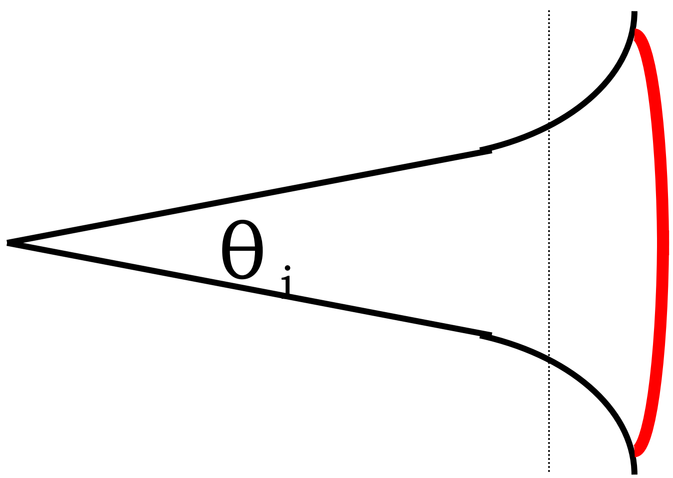
Jet & Relativistic beaming

- Relativistic beaming $\approx \Gamma^{-1}$
- Jet　　Energy, Event rate, Model



Jet in afterglow

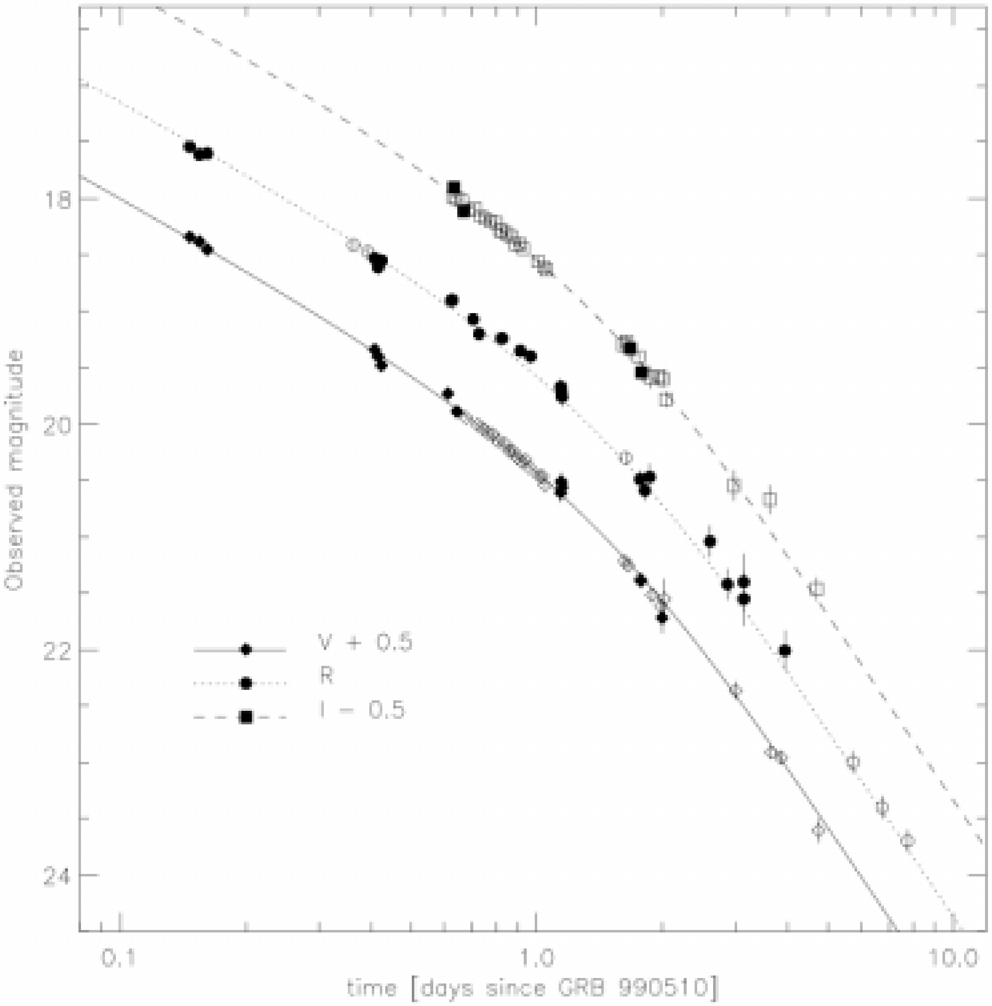
$\theta \approx \theta_i + \Gamma^{-1} \Rightarrow \theta_i \leq \Gamma^{-1}$: sideways expansion



$$E \sim \frac{4\pi}{3} R^3 n m_p c^2 \gamma^2 \underline{\theta^2}$$

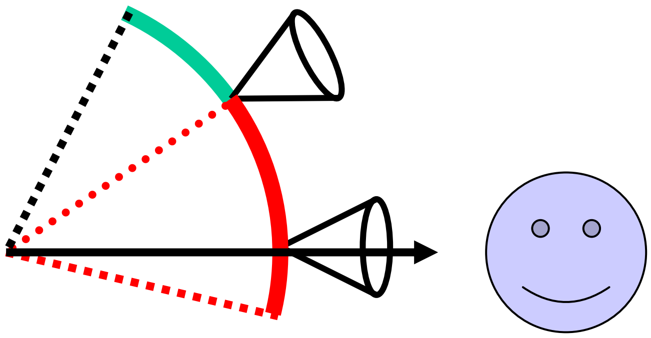
$$T \sim R/\gamma^2 \sim \gamma^{-2}$$

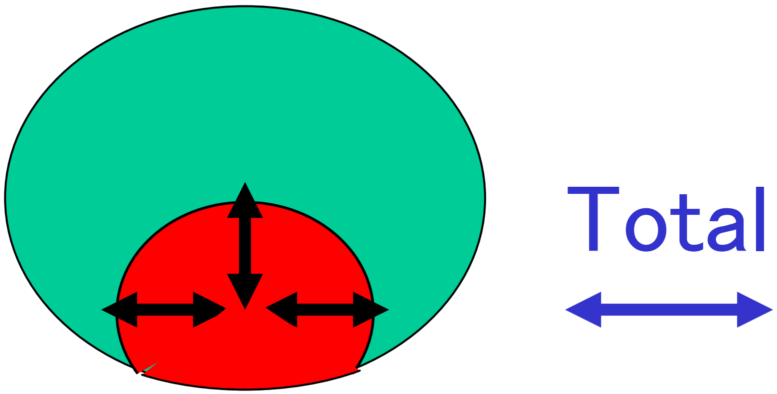
Break in afterglow



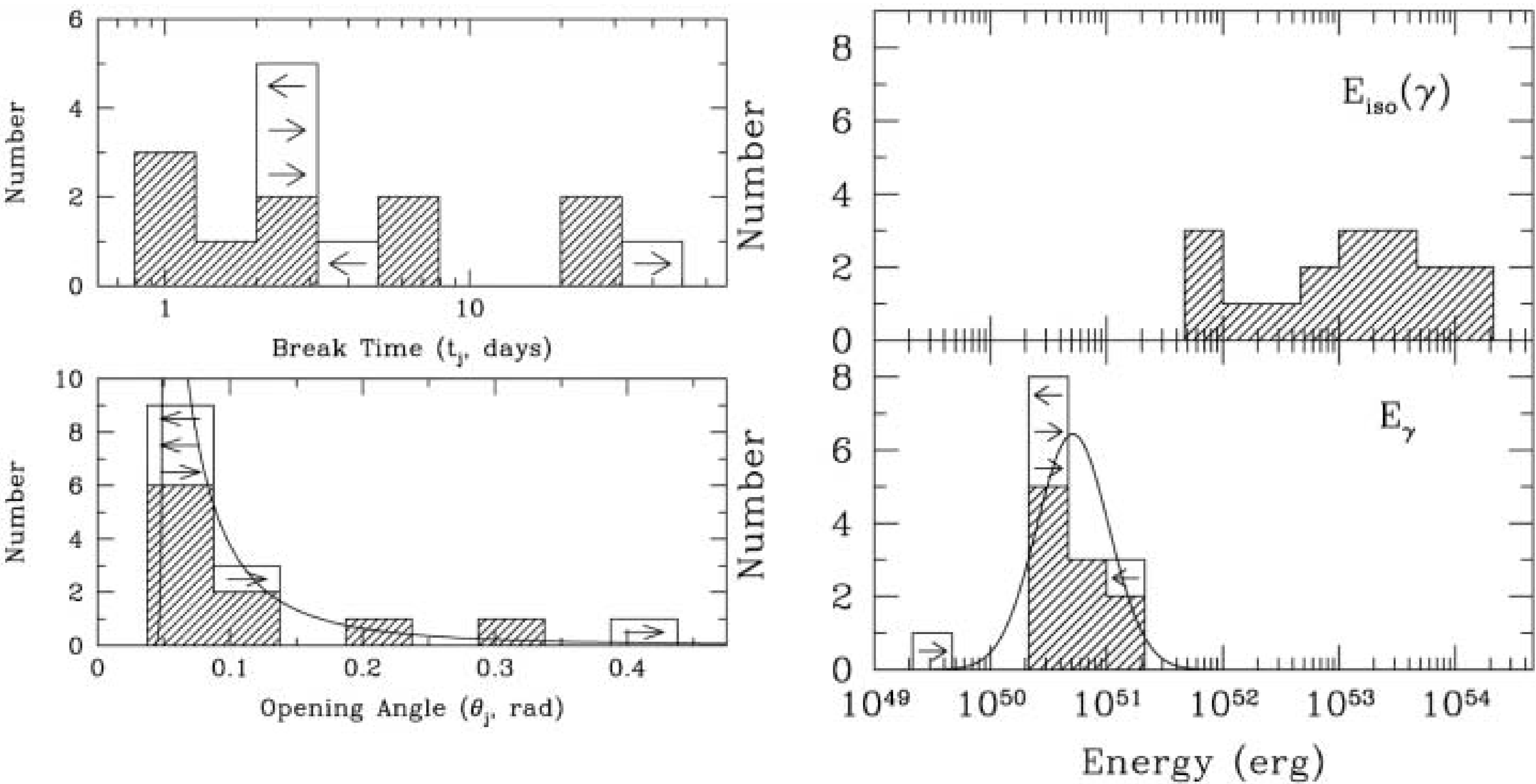
Polarization

A few %





Total energy



$$E \approx 10^{51}\,\mathrm{erg}$$

6. Central engine

Collapsar, Hypernova

① Collapse of massive star

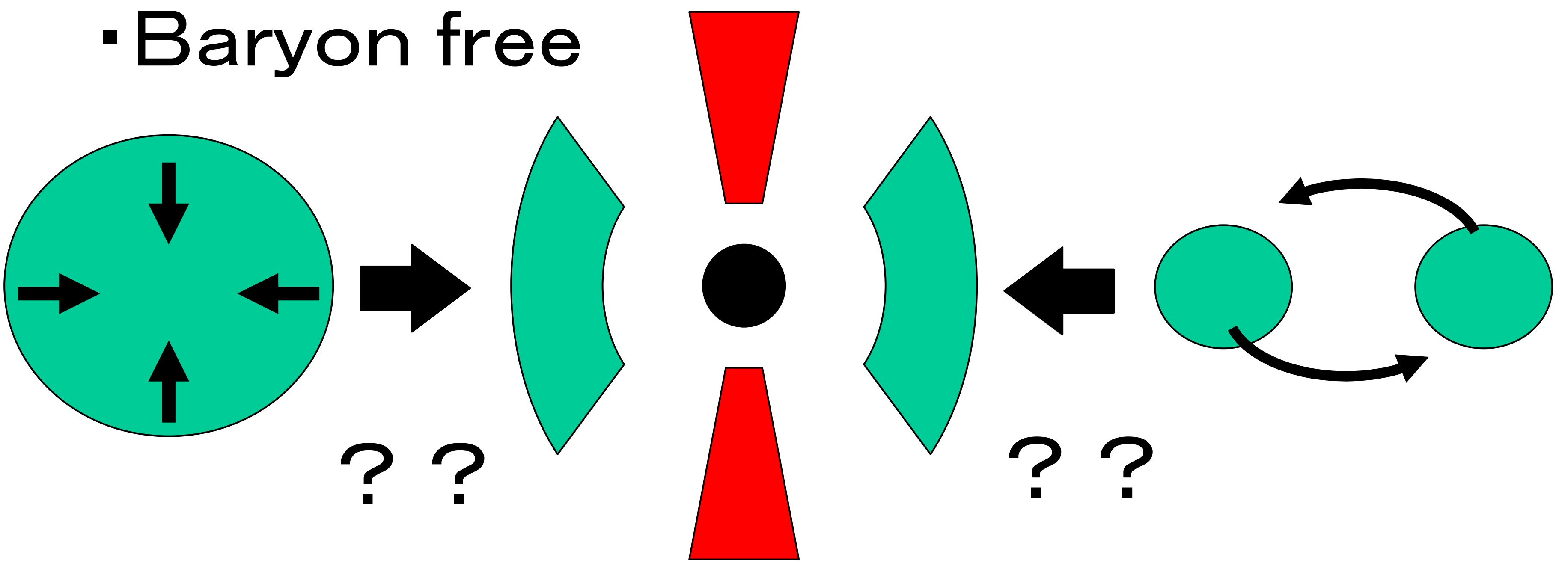
・Location within host galaxies

・GRB-Supernova (e.g., SN1998bw)

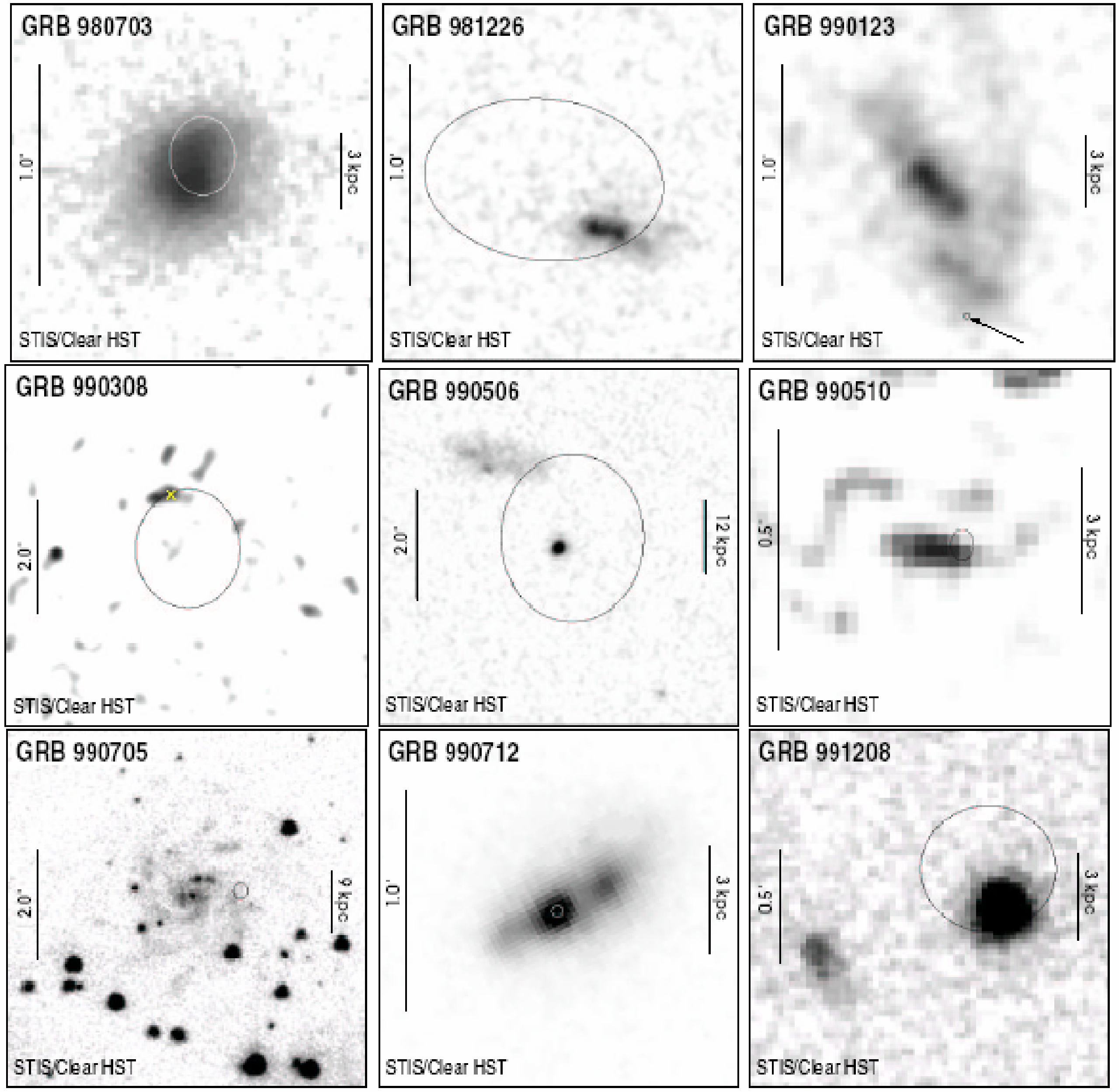
? High ambient gas density

② Mergers of compact objects

・Baryon free



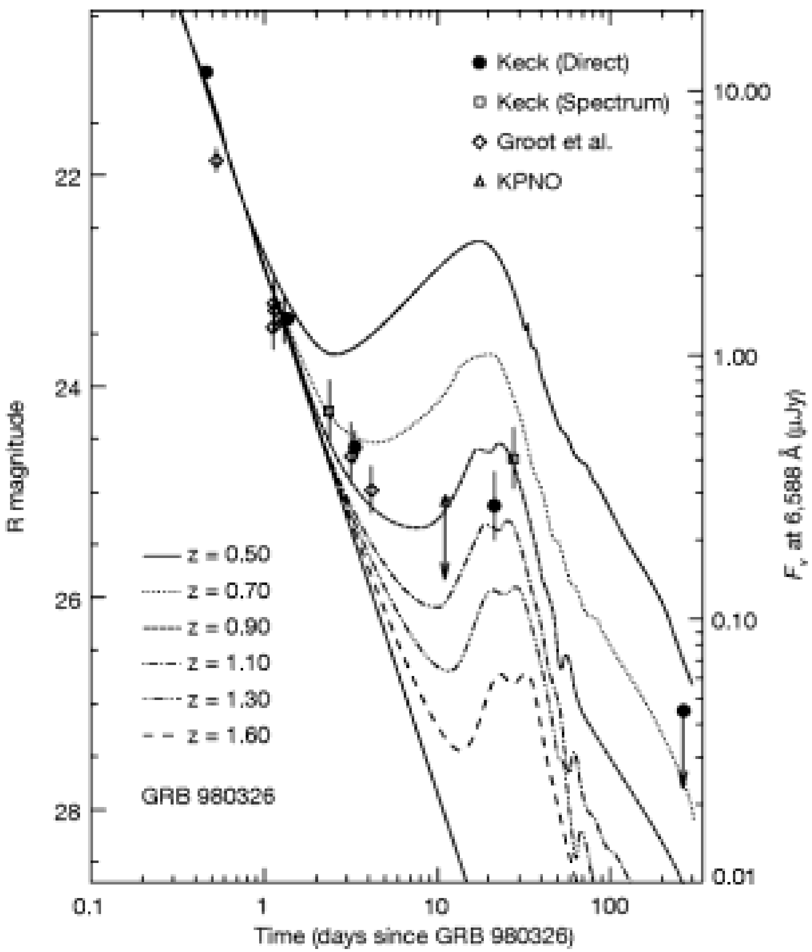
Host galaxy


GRB 980703
1.0"
3 kpc
STIS/Clear HST
GRB 981226
1.0"
STIS/Clear HST
GRB 990123
1.0"
3 kpc
STIS/Clear HST
GRB 990308
2.0"
STIS/Clear HST
GRB 990506
2.0"
12 kpc
STIS/Clear HST
GRB 990510
0.5"
3 kpc
STIS/Clear HST
GRB 990705
2.0"
6 kpc
STIS/Clear HST
GRB 990712
1.0"
3 kpc
STIS/Clear HST
GRB 991208
0.5"
3 kpc
STIS/Clear HST

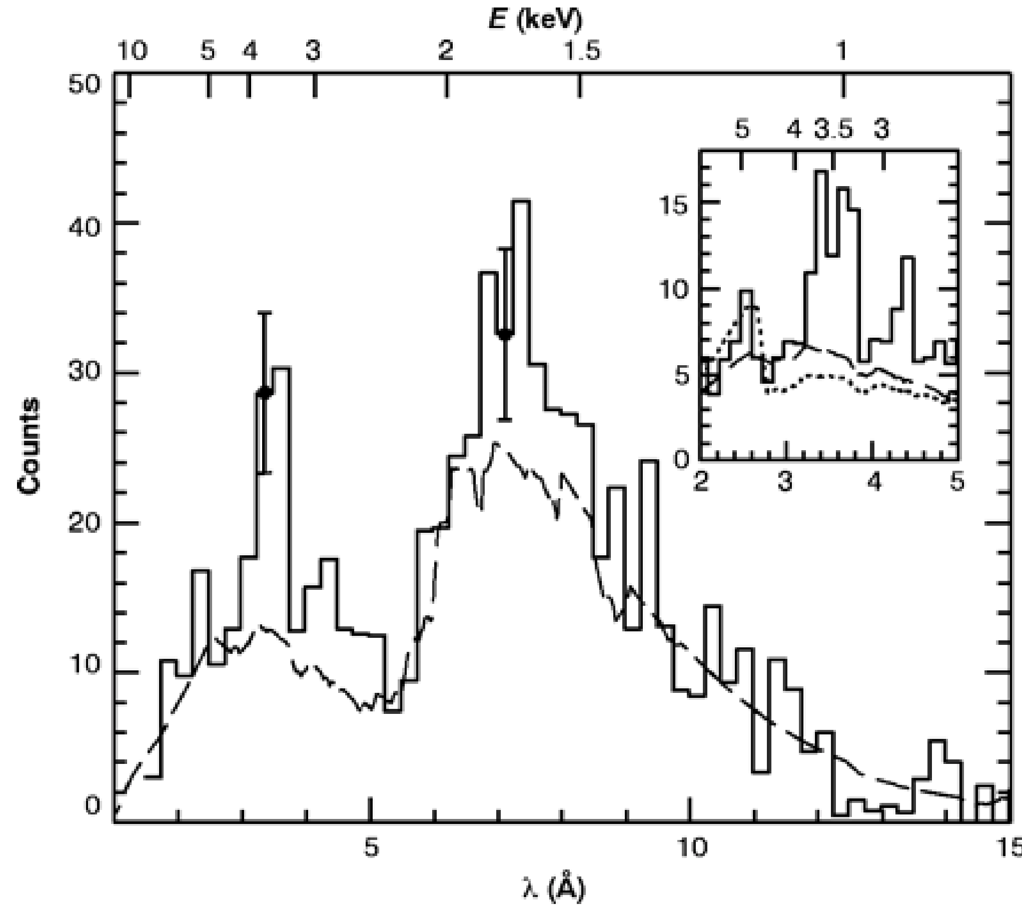
SN1998bw-GRB980425

$$L_\gamma \square (5.5 \pm 0.7) \times 10^{46}\,\text{erg/s}: \quad \square\, 10^{-6}\,\text{dim}$$

Lightcurve



Fe line

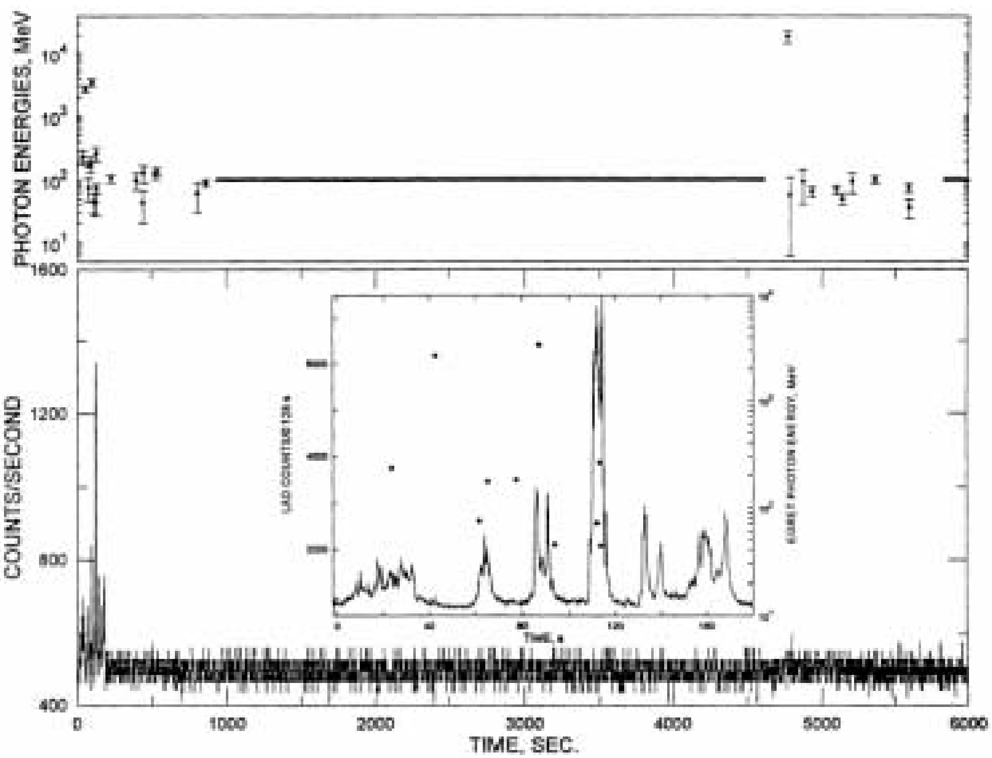


7. Links with other fields

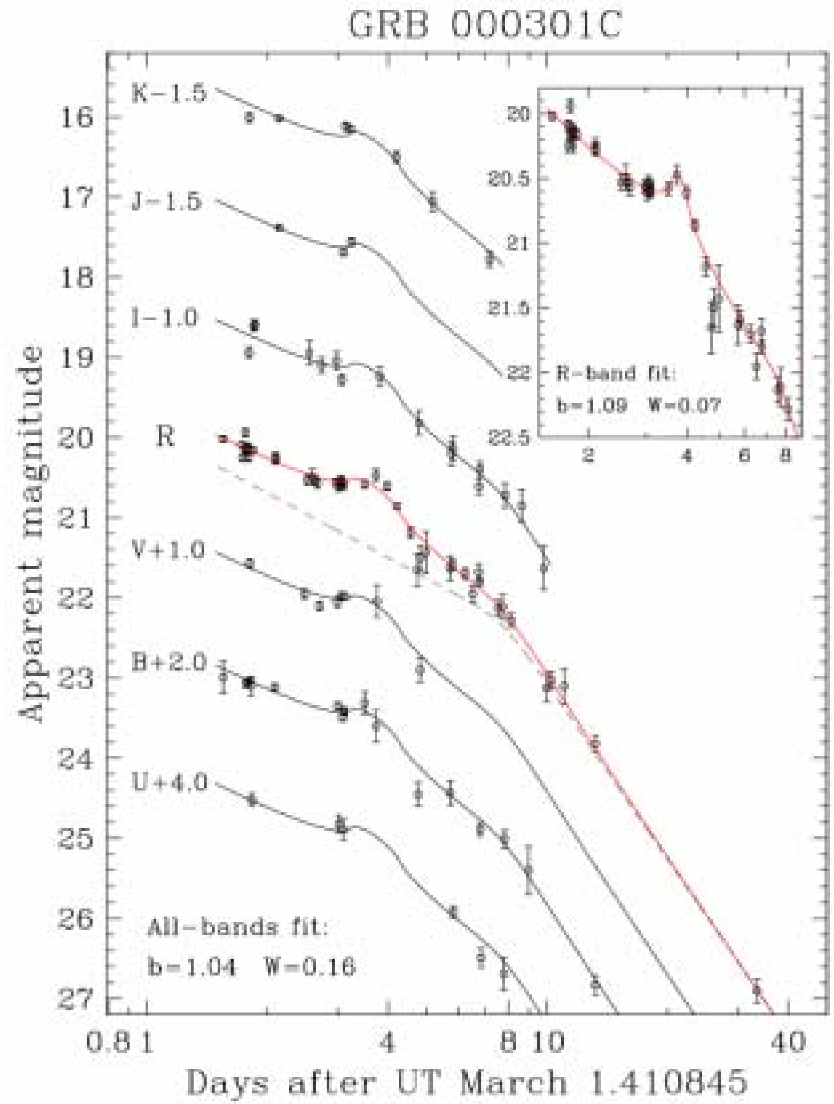
CR, HEν, HEγ

$\approx 10^{44}$ erg/Mpc^3/yr

$\approx$ UHECR (10^{19} - 10^{21} eV)

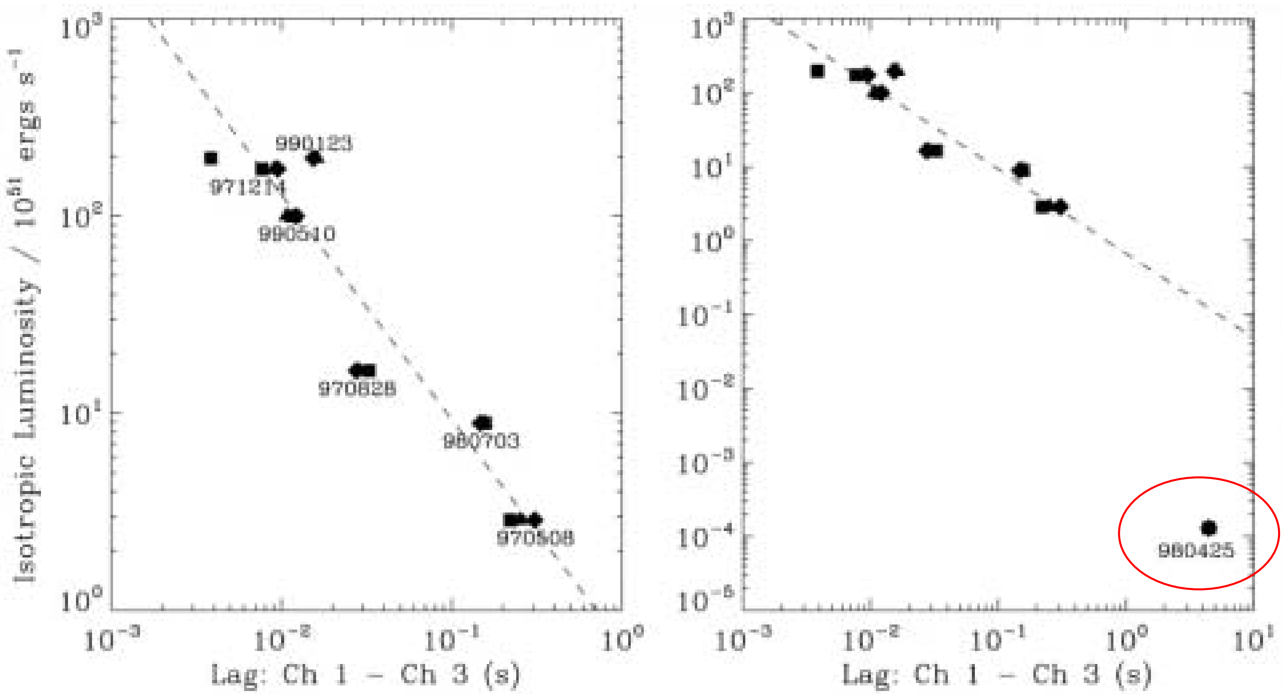


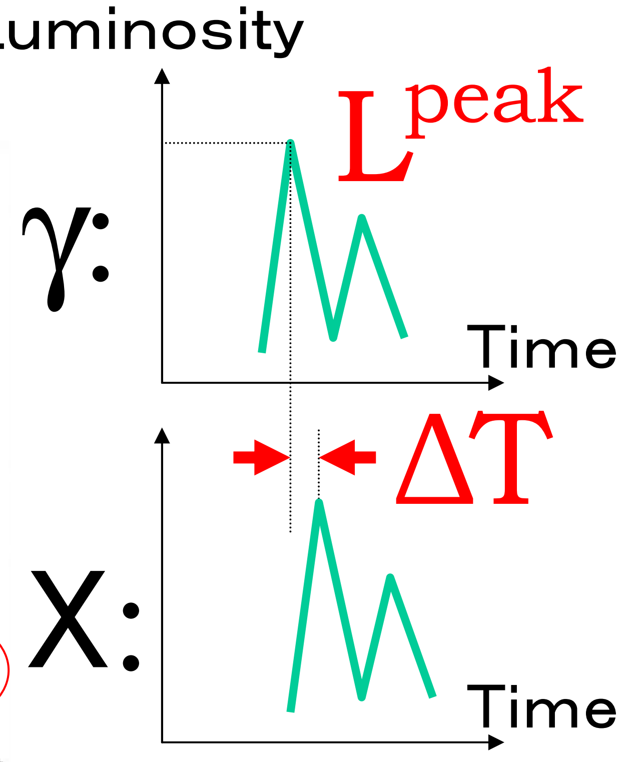
Cosmology



8. Luminosity-lag

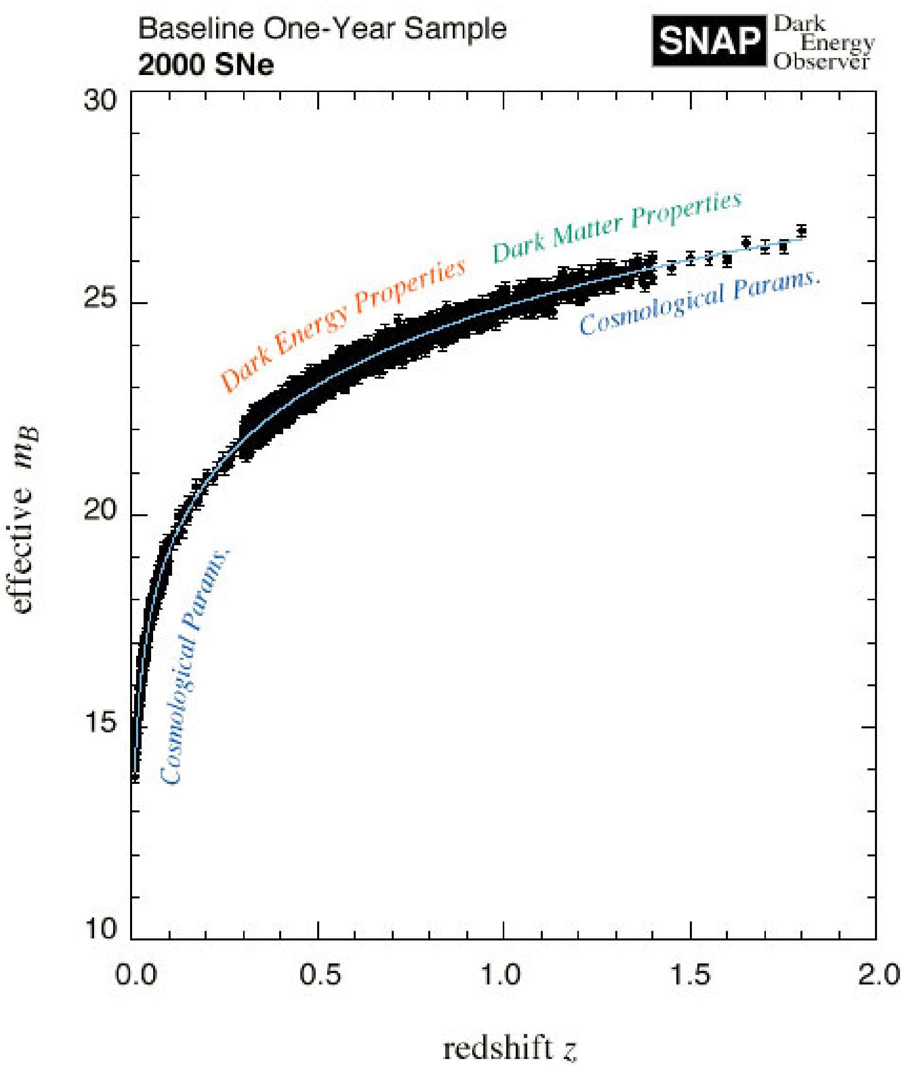
ApJ,554,L163(01)

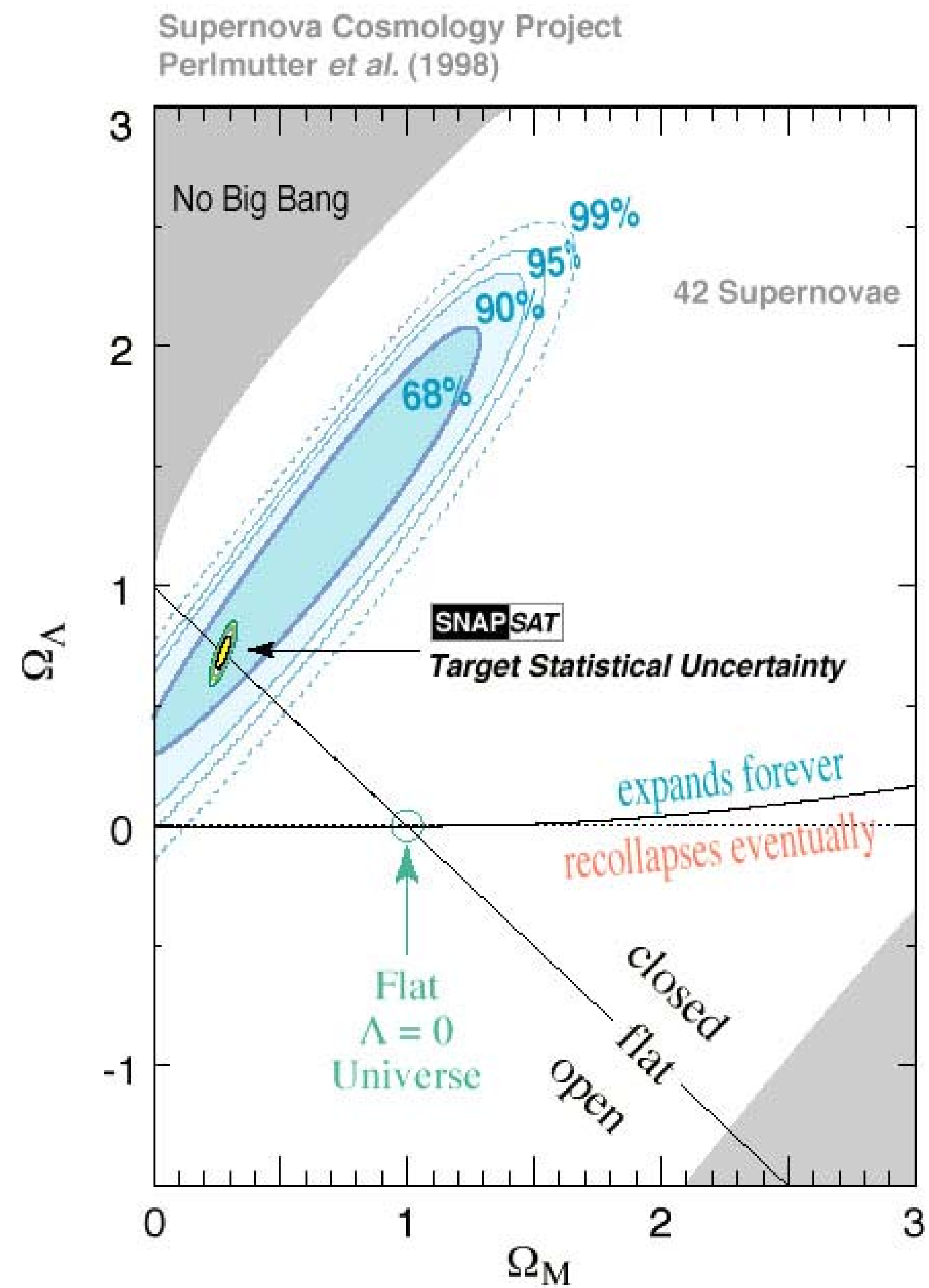




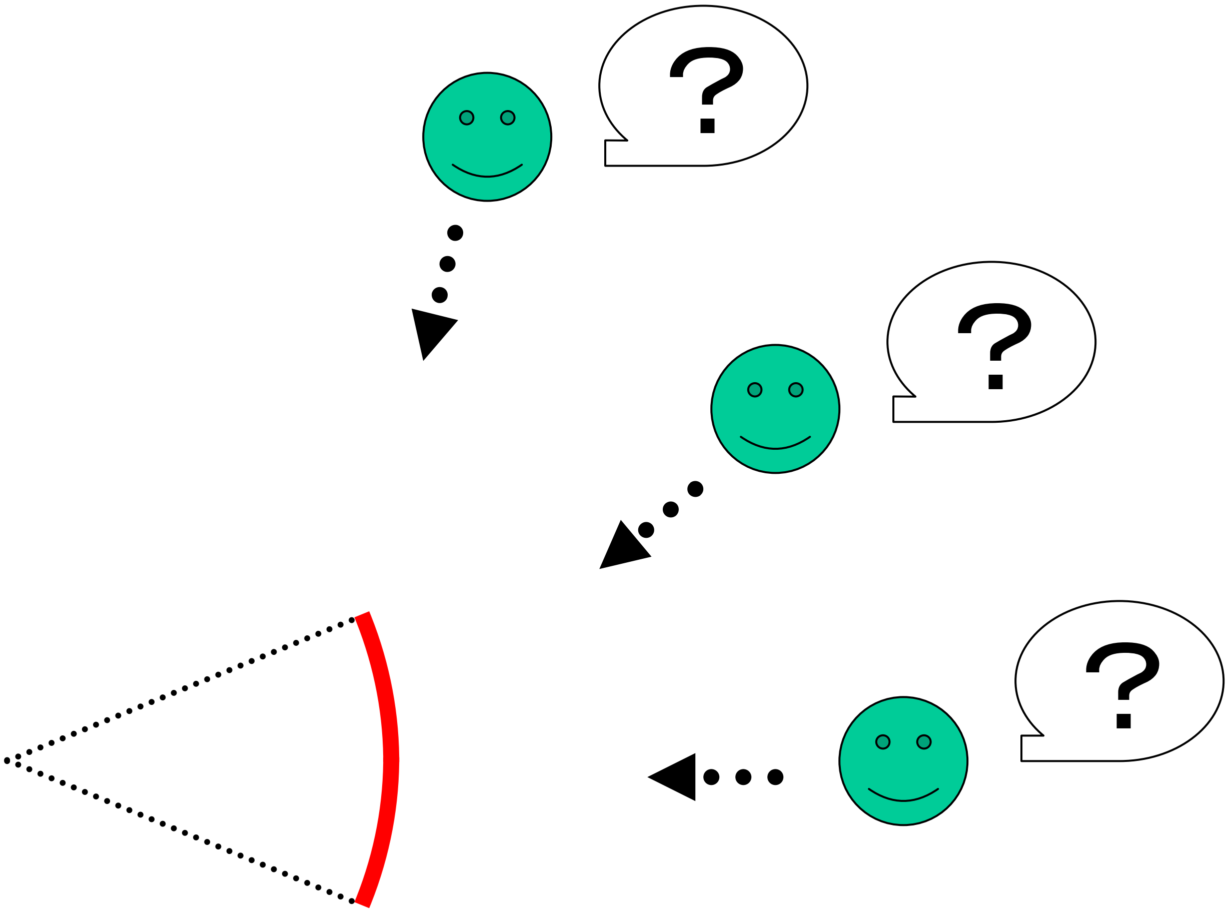
$L^{peak} \uparrow \Leftrightarrow \Delta T \downarrow$

- Standard candle ?
- Brighter than SNe Ia
- Less extinction


Baseline One-Year Sample
2000 SNe
SNAP
Dark Energy Observer
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.
effective m_B
redshift z
30
25
20
15
10
0.0
0.5
1.0
1.5
2.0


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAPSAT
Target Statistical Uncertainty
expands forever
recollapses eventually
Flat
$\Lambda = 0$
Universe
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

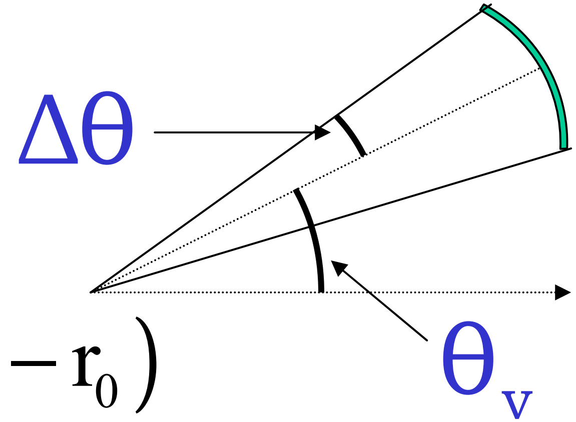
Viewing angle of a single jet



⇒Luminosity-lag relation ？

Thin jet

Emissivity



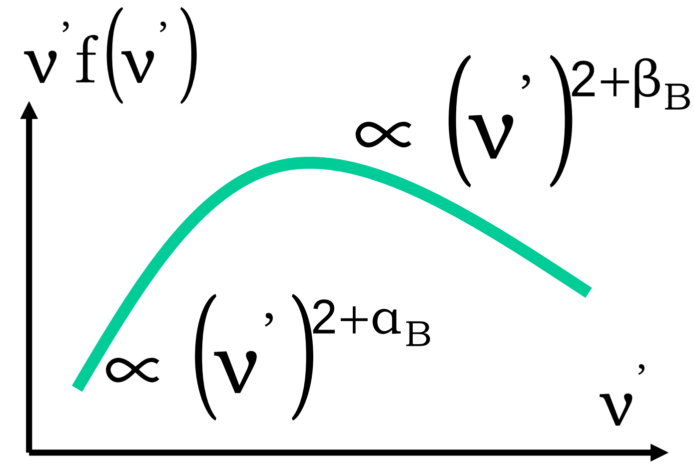
$$j'_{\nu'}(r,t) = A_0 f(\nu')\ \delta(t-t_0)\ \delta(r-r_0)$$

$$\times H(\Delta\theta - |\theta-\theta_v|)\, H\left[\cos\phi - \left(\frac{\cos\Delta\theta - \cos\theta_v\cos\theta}{\sin\theta_v\sin\theta}\right)\right]$$

Spectrum

$$f(\nu') = \left(\frac{\nu'}{\nu'_0}\right)^{1+\alpha_B}\left[1+\left(\frac{\nu'}{\nu'_0}\right)^{s}\right]^{(\beta_B-\alpha_B)/s}$$

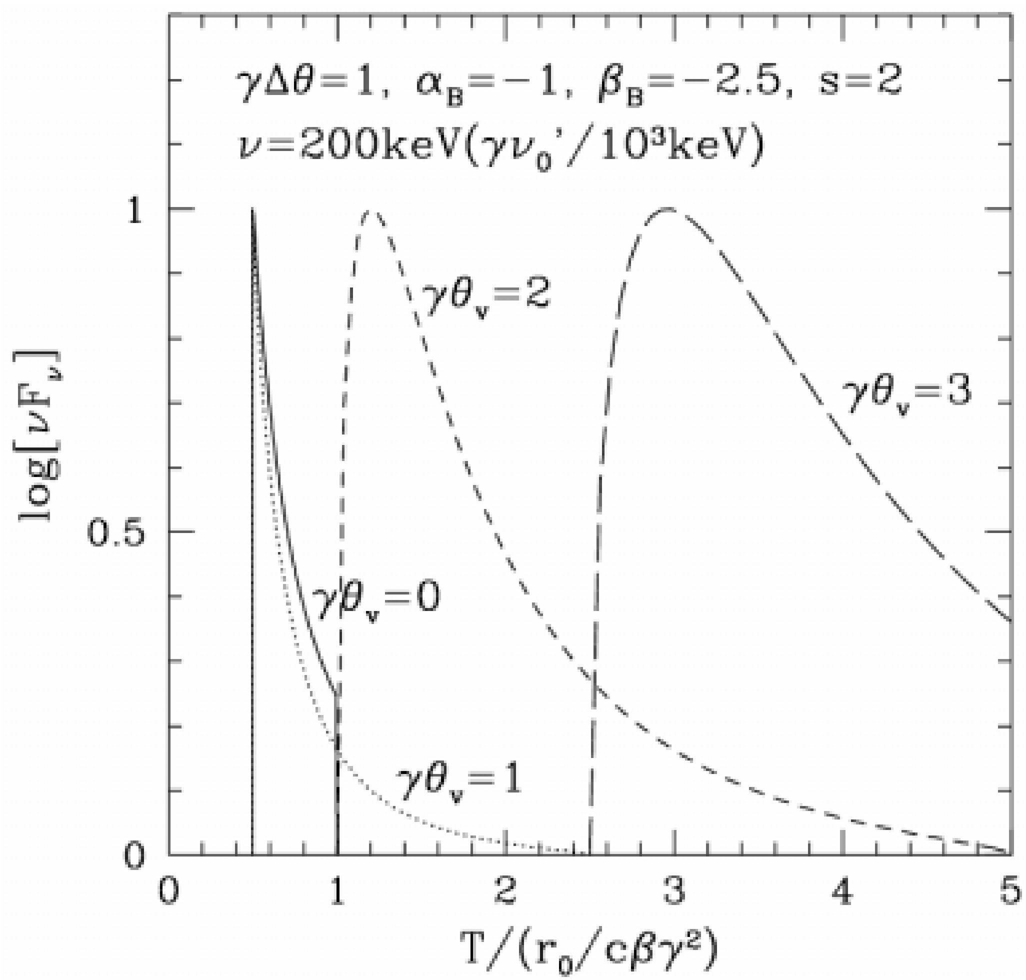
～Band spectrum



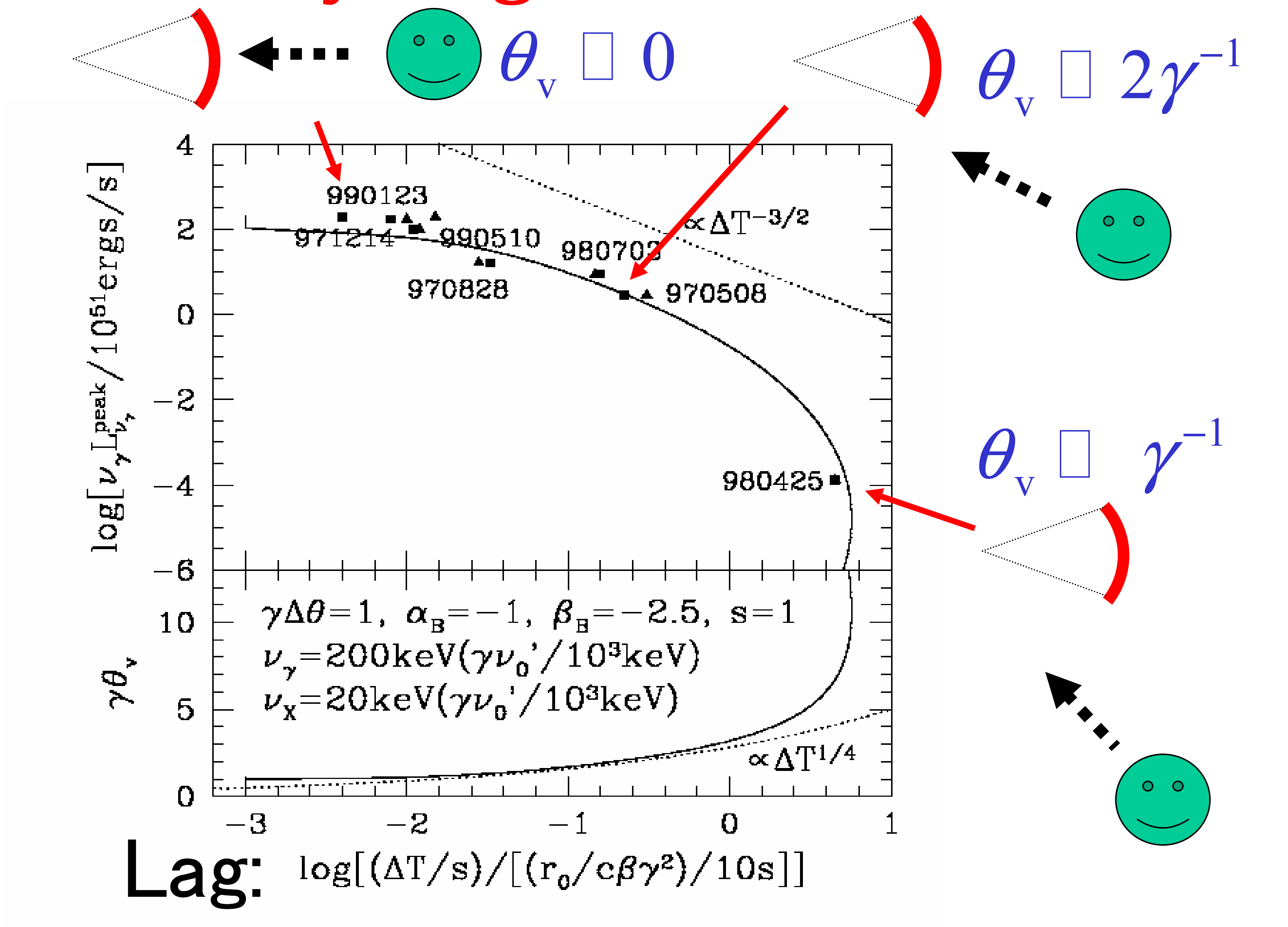
$$\gamma\Delta\theta = 1,\quad \alpha_B = -1,\quad \beta_B = -2.5,\quad s = 1$$

$$F_\nu(T) = \frac{2cA_0 r_0 \gamma^2}{D^2} \frac{\Delta\phi(T)}{\left[\gamma^2\left(1-\beta\cos\theta(T)\right)\right]^2} f\left[\nu\gamma\left(1-\beta\cos\theta(T)\right)\right]$$

where $1-\beta\cos\theta(T) = \frac{c\beta}{r_0}(T-T_0)$

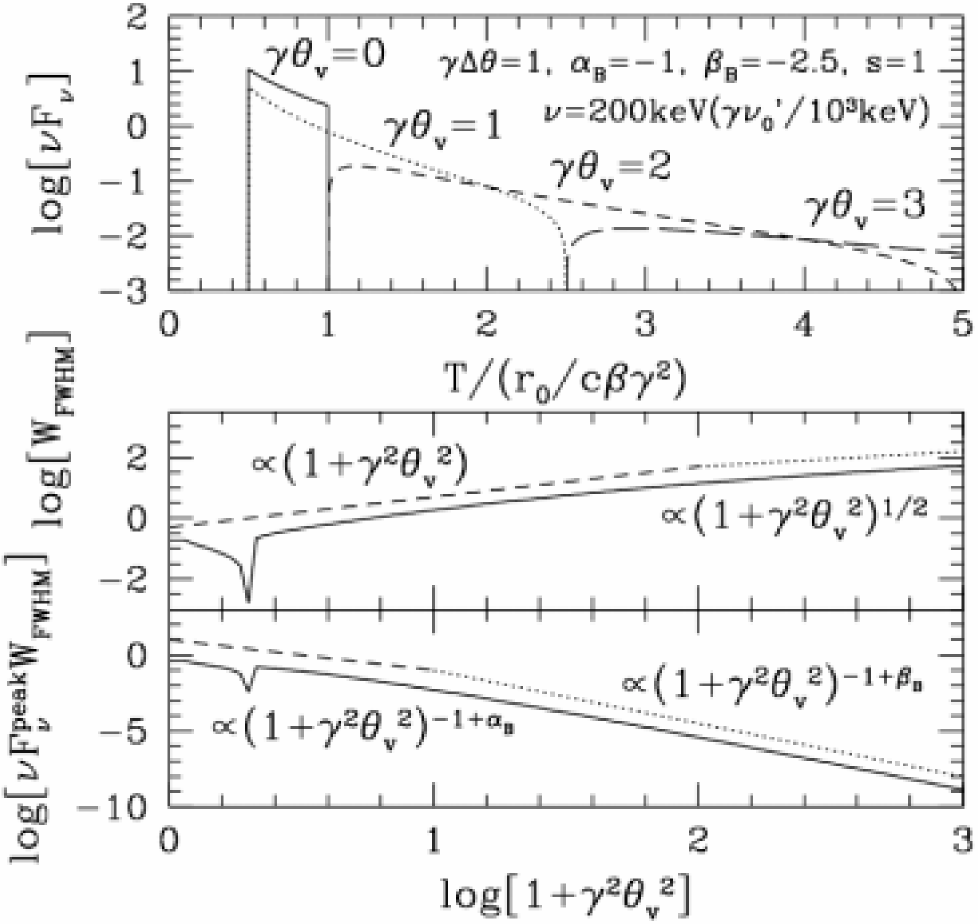


Luminosity-Lag Relation

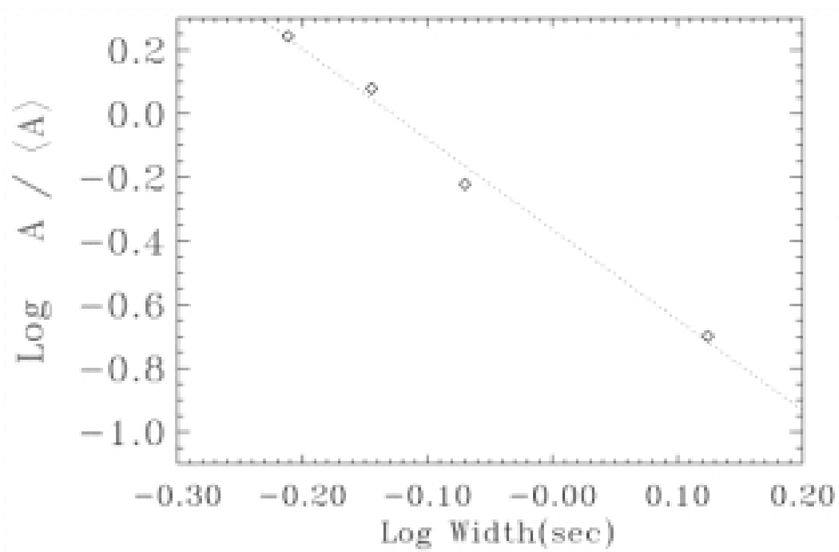


Pulse profile

FRED (Fast Rise Exponential Decay)



Luminosity-width



$$\nu F_\nu^{peak} \propto W_{FWHM}^{\kappa} \text{ where } \kappa = -2 + \alpha_B \approx -3$$

$$\Leftrightarrow \text{observation}: \kappa_{obs} \cong -2.8$$

Viewing angle

① Peak luminosity-spectral lag relation

② Peak luminosity-variability relation

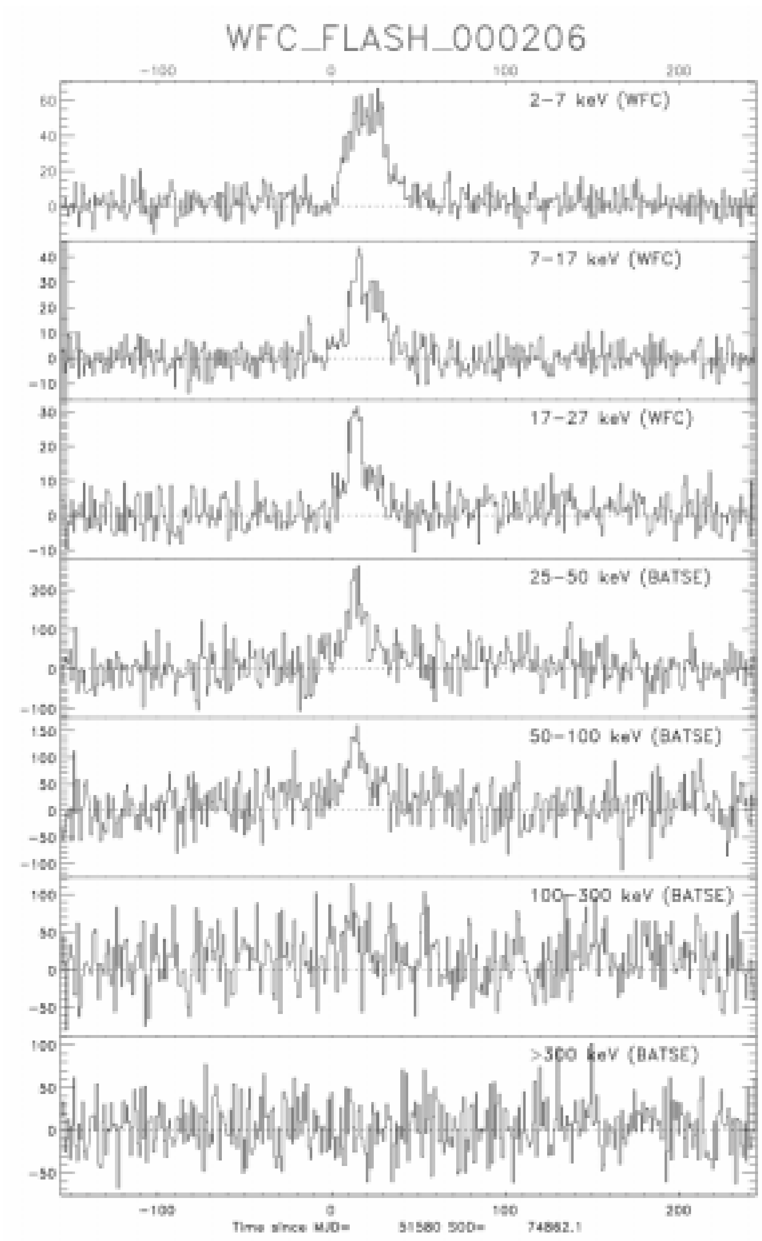
③ Luminosity-width relation

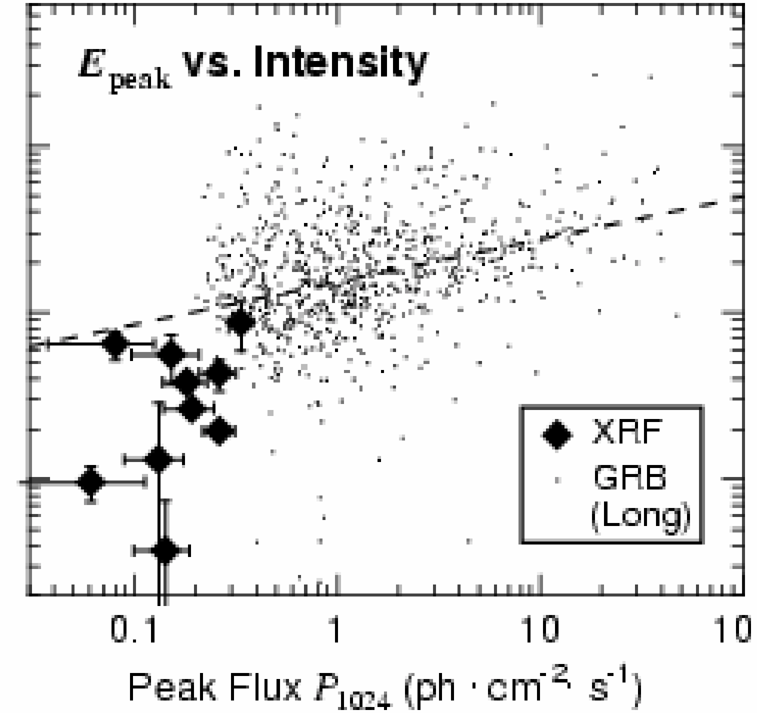
GRB980425

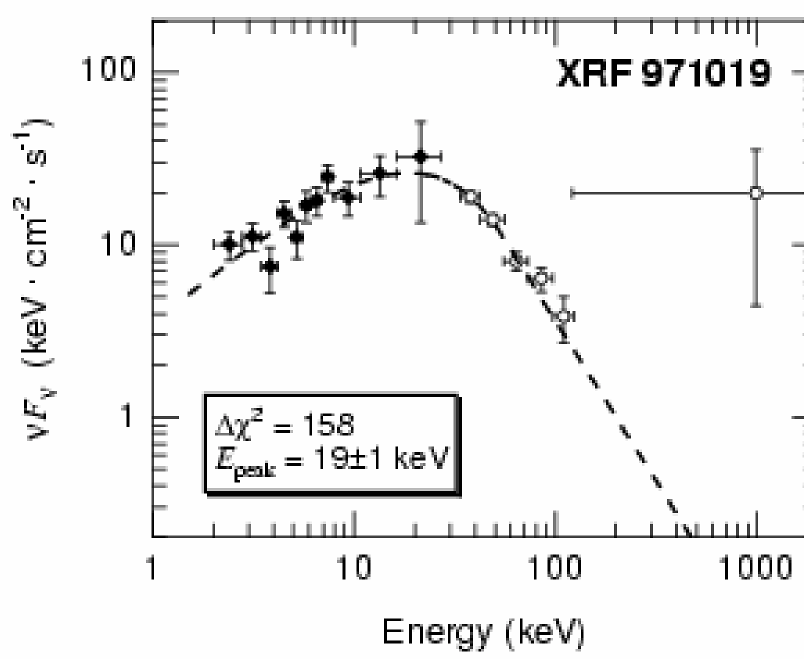
A typical GRB

⇒Association of GRBs with SNe

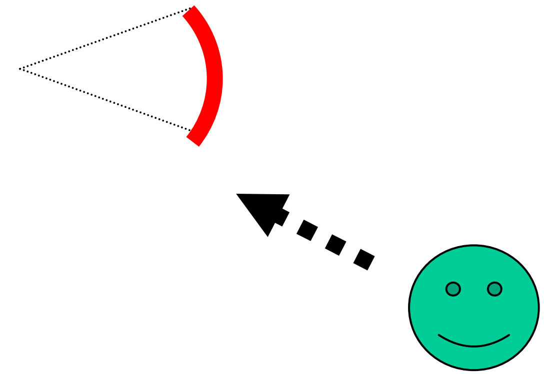
9. X-ray flash

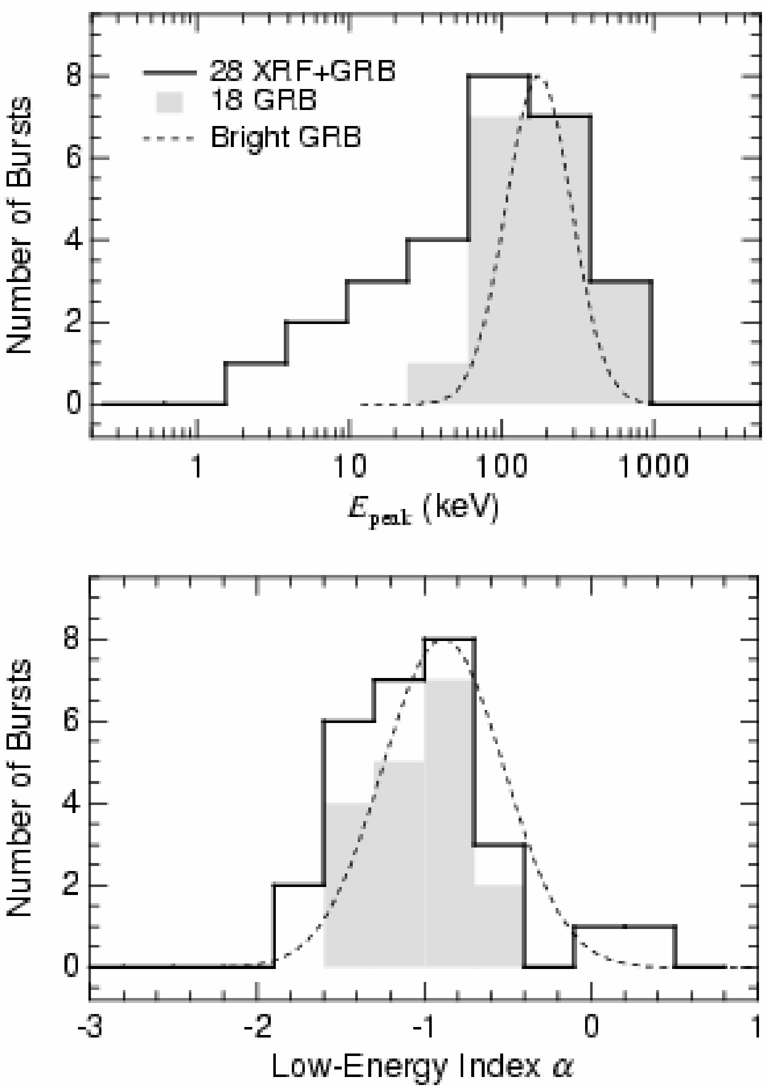

WFC_FLASH_000206
2-7 keV (WFC)
7-17 keV (WFC)
17-27 keV (WFC)
25-50 keV (BATSE)
50-100 keV (BATSE)
100-300 keV (BATSE)
>300 keV (BATSE)
Time since MJD= 51580 SOD= 74862.1

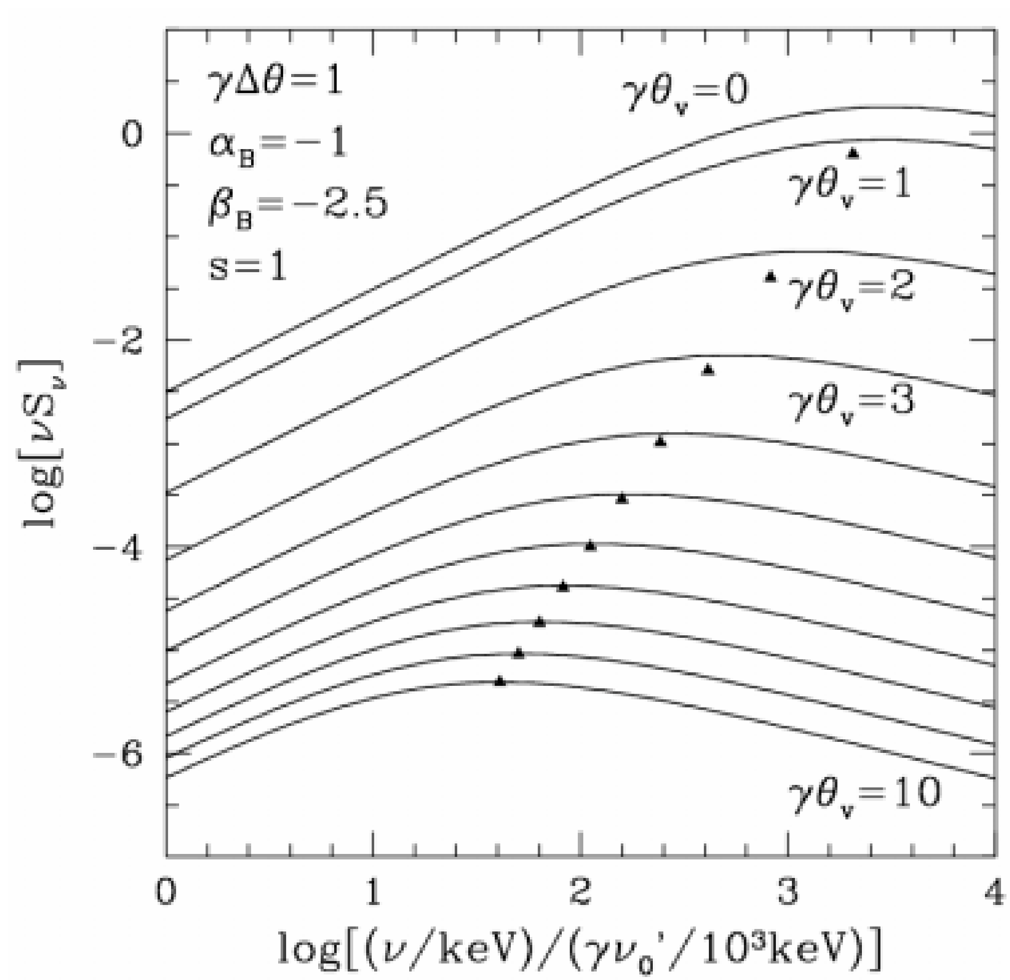

E_peak vs. Intensity
XRF
GRB (Long)
0.1
1
10
100
Peak Flux P_1024 (ph · cm^-2 s^-1)


XRF 971019
νF_ν (keV · cm^-2 · s^-1)
100
10
1
Δχ^2 = 158
E_peak = 19±1 keV
1
10
100
1000
Energy (keV)

Off-axis GRB

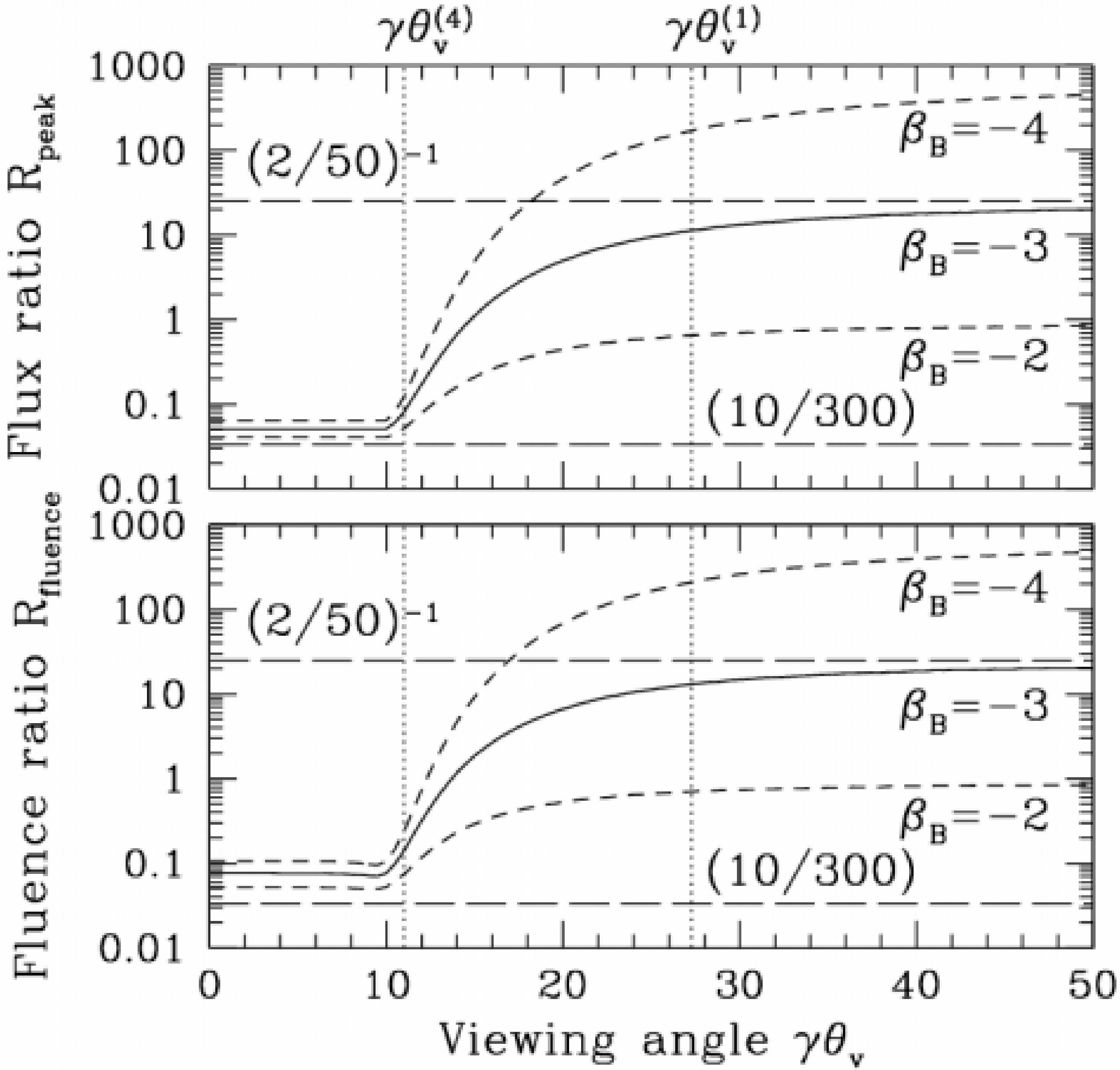


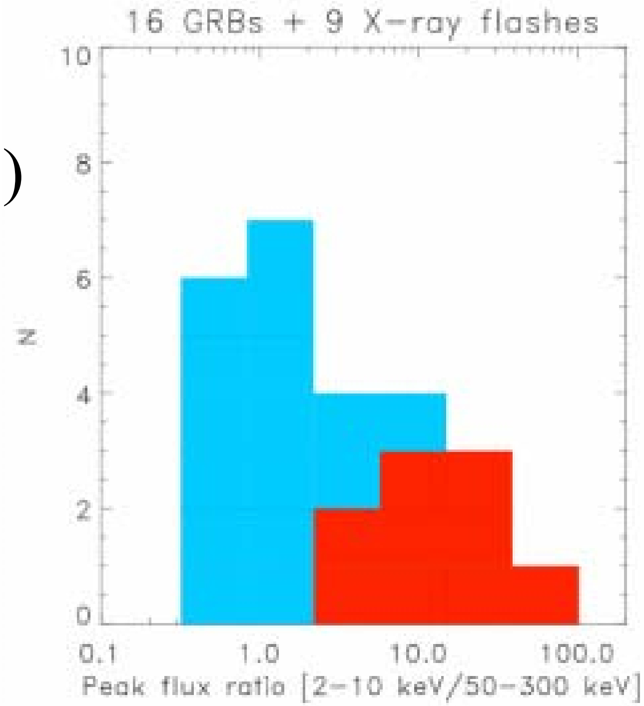

28 XRF+GRB
18 GRB
Bright GRB
Number of Bursts
0
2
4
6
8
1
10
100
1000
E_{peak} (keV)
Number of Bursts
-3
-2
-1
0
1
Low-Energy Index α

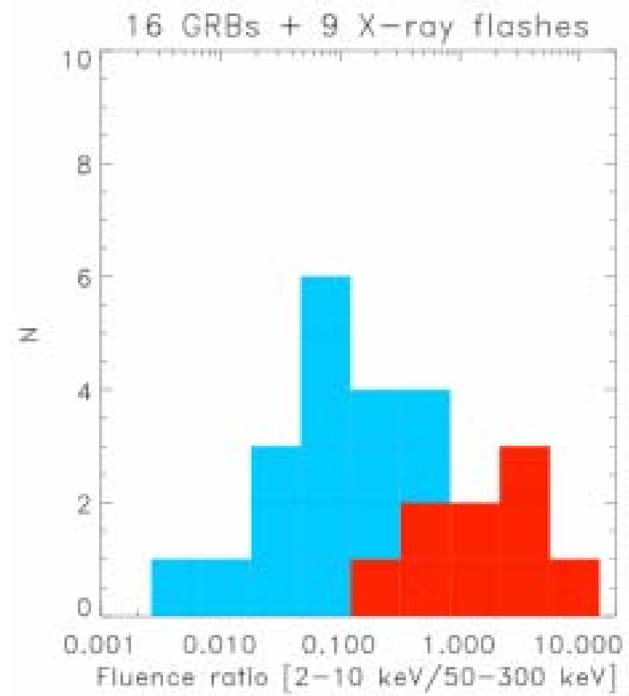

$\gamma\Delta\theta=1$
$\alpha_B=-1$
$\beta_B=-2.5$
s=1
$\gamma\theta_v=0$
$\gamma\theta_v=1$
$\gamma\theta_v=2$
$\gamma\theta_v=3$
$\gamma\theta_v=10$
$\log[\nu S_\nu]$
0
-2
-4
-6
1
2
3
4
$\log[(\nu/\mathrm{keV})/(\gamma\nu_0'/10^3\mathrm{keV})]$

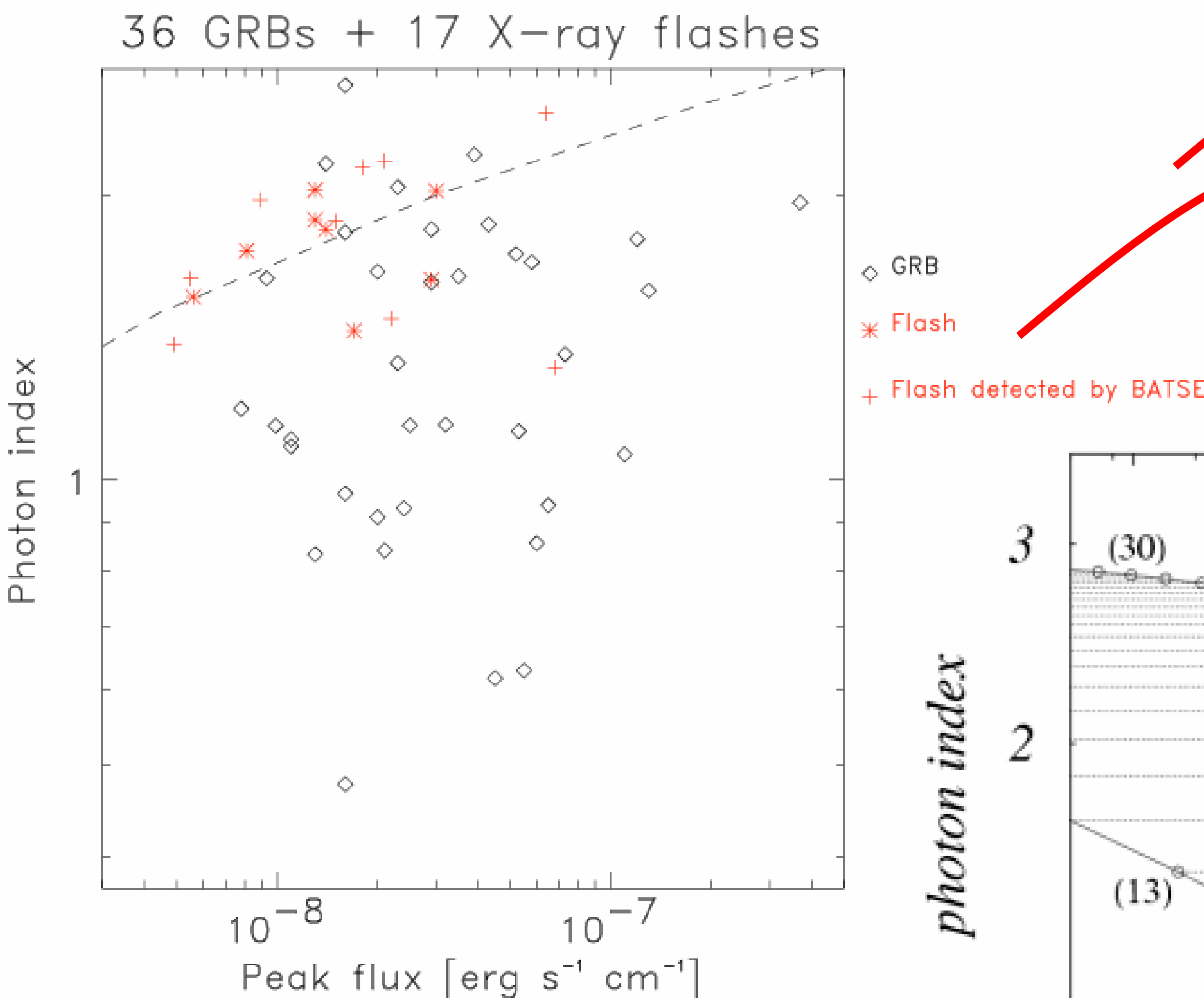
Flux/Fluence Ratio

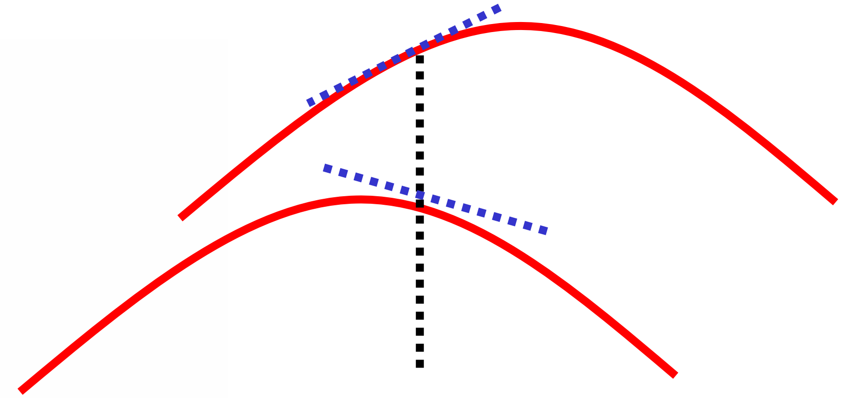
ApJ,571,L31(02)

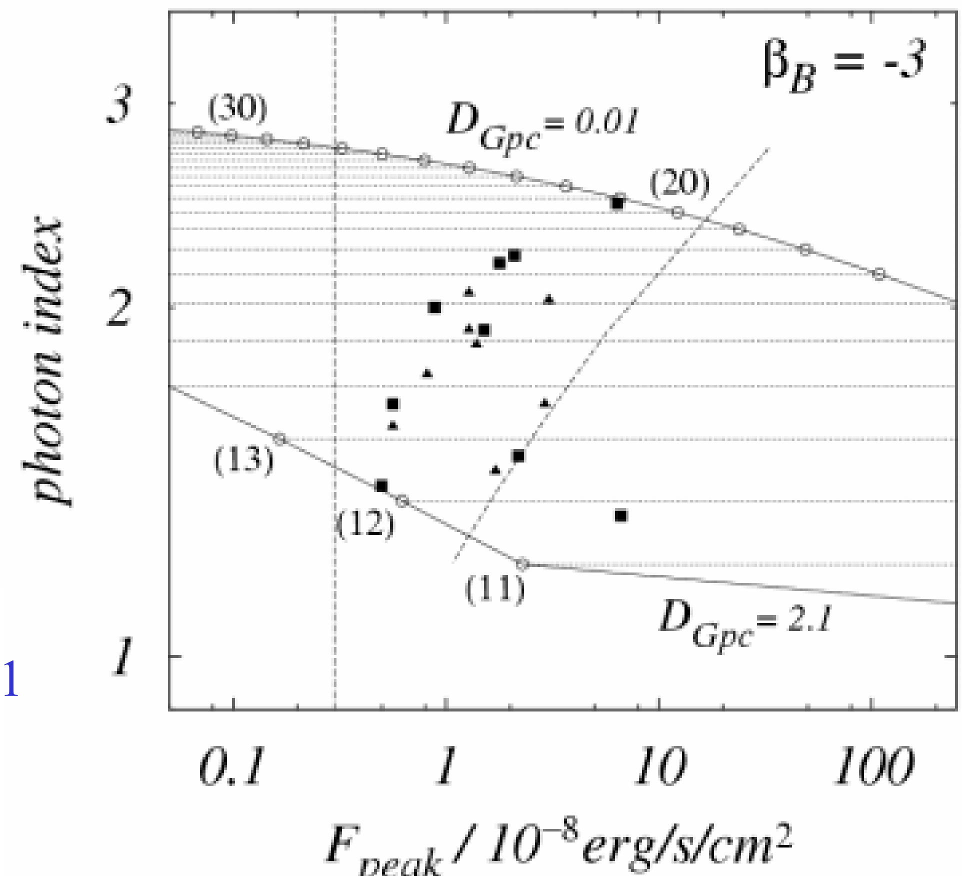












$$10^3\,\mathrm{yr}^{-1} \times \underline{5^{-3}} \times \underline{3^2} \approx 10^2\,\mathrm{yr}^{-1}$$

Volume   Viewing angle

10. Summary

GRB : Internal shock

Afterglow : External shock

Jet

Viewing angle

Various relations, X-ray flash

Central engine ???

Collapsar? Merger?

CR, HEν, HEγ, GW, Cosmology