Gamma Ray Bursts a luminous candle?

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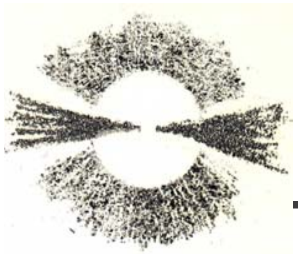
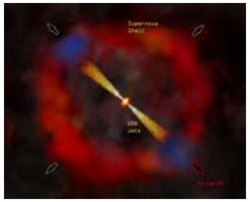
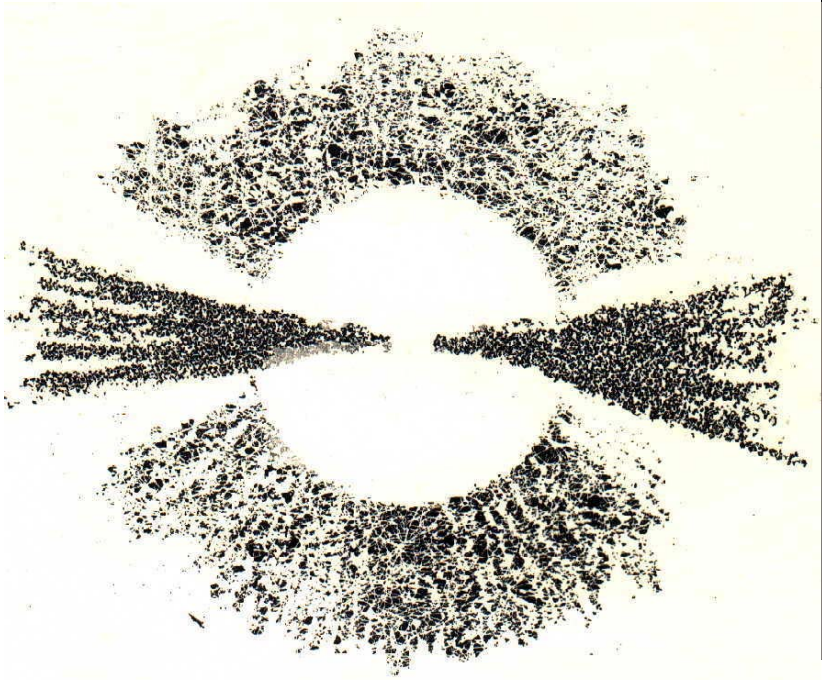


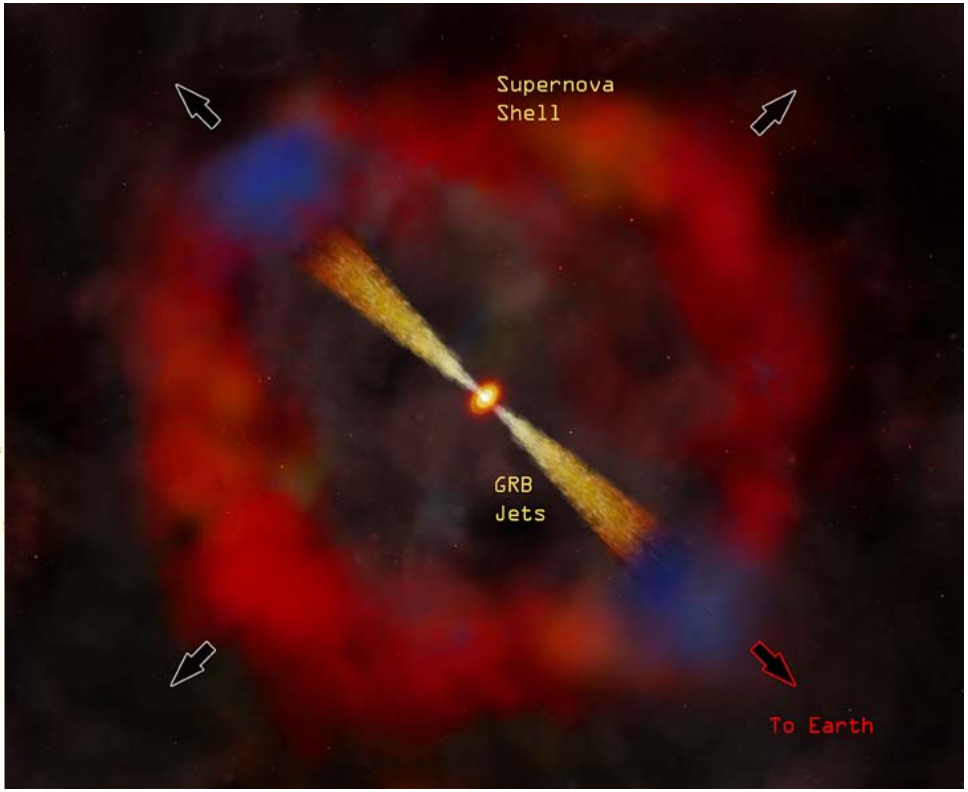
GRB a general introduction



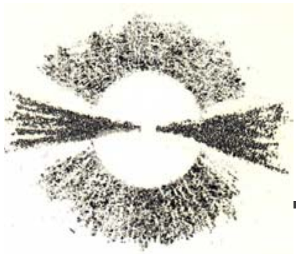
An artistic connection?

e^+e^- 1970's

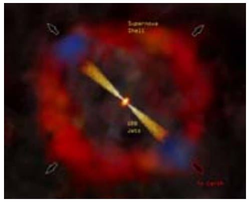




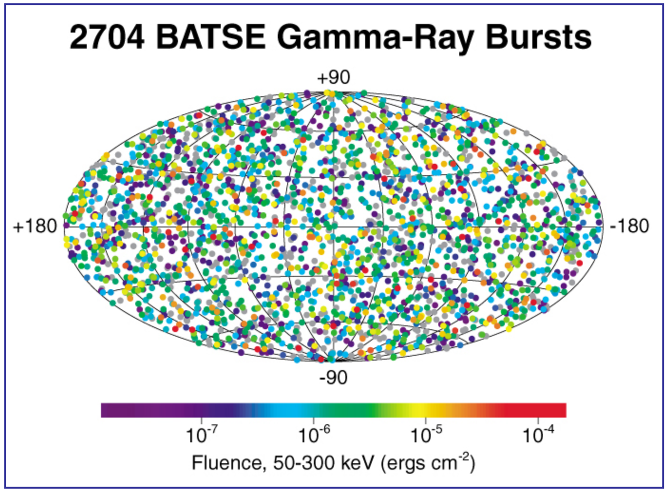
GRB 020813 (credits to CXO/NASA)

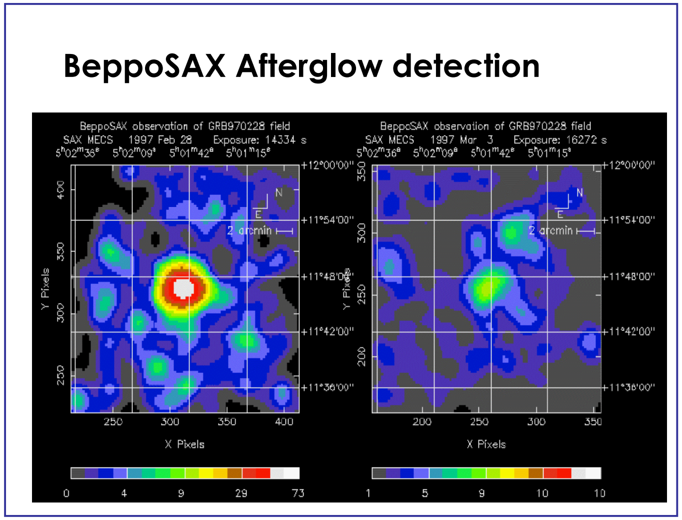


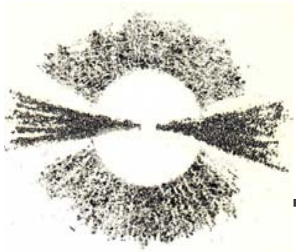
Outline



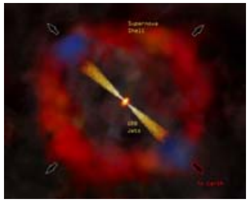
- Introduction
  - GRB as “tool”
- The “gamma” era
- The “afterglow” era
  - Jet emission
  - Std candles hints
  - X-ray lines
  - Hints on Progenitors
- SN & GRB connection
- A “Cosmological” era?
- The Compton tail
  - A new step towards “standardization”



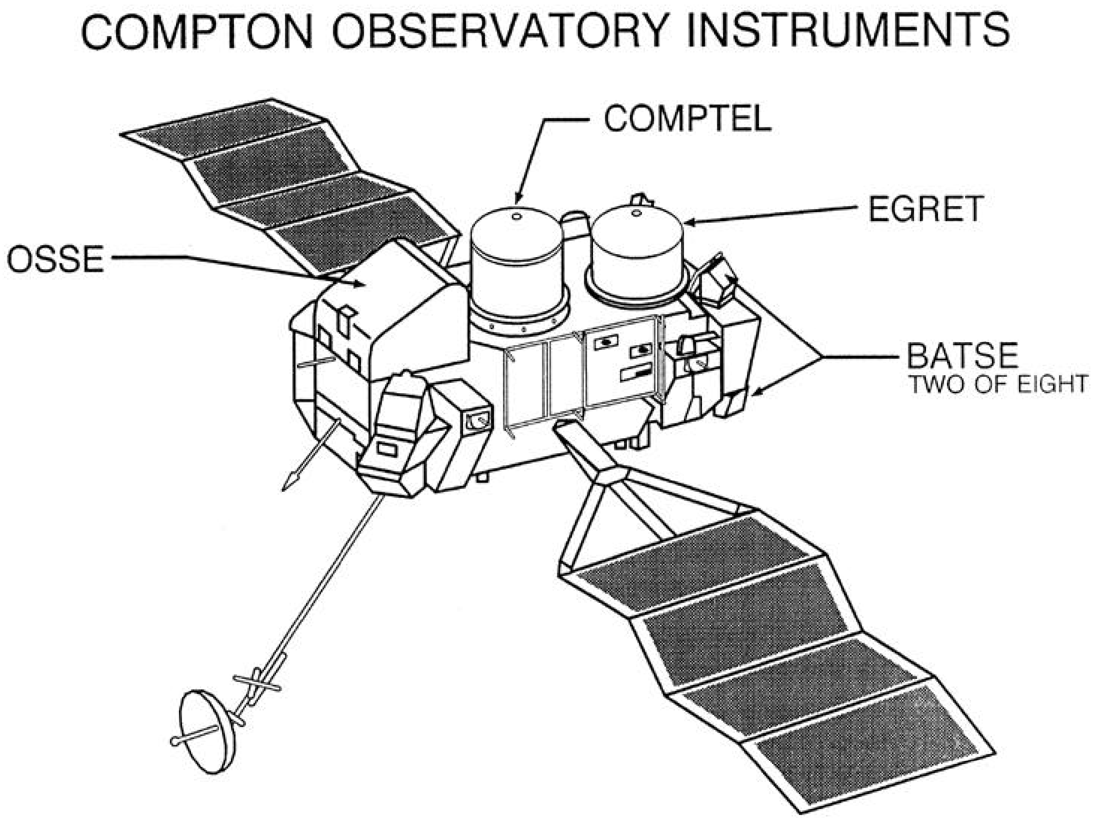




The “gamma” era

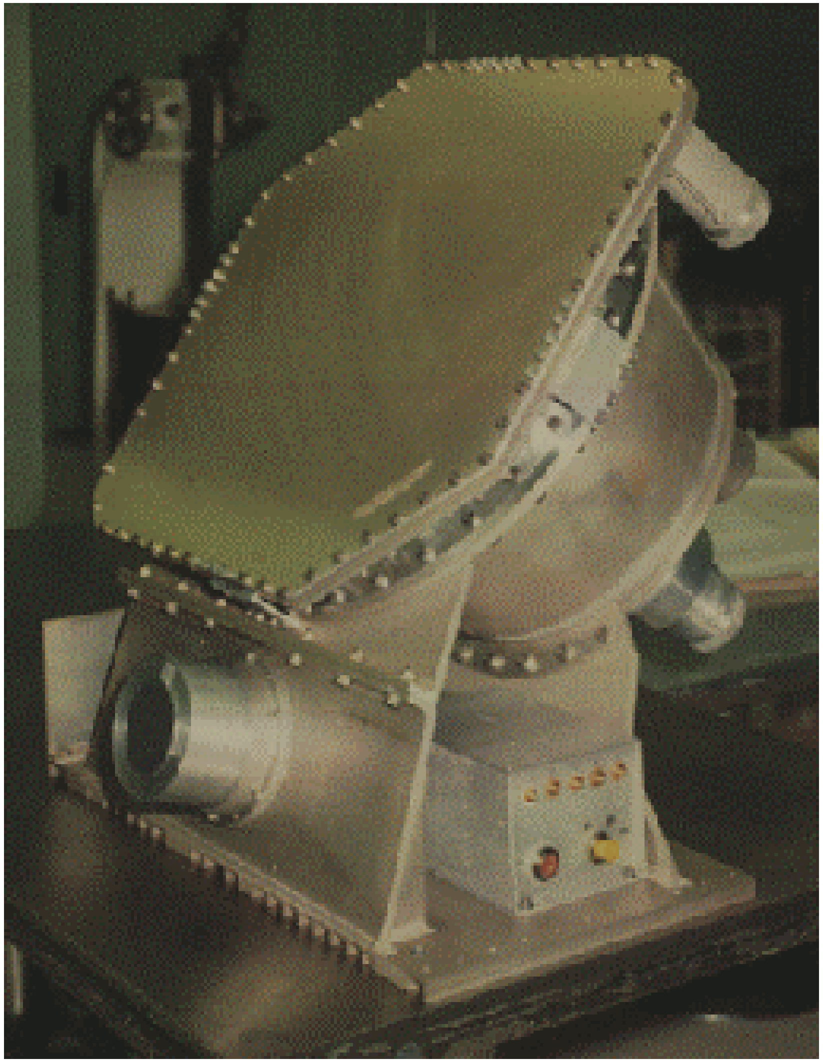


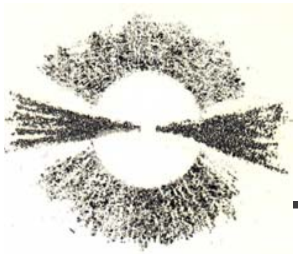
- Distribution of sources
- Cosmological or Galactic?
- No host problem
- NS binary?



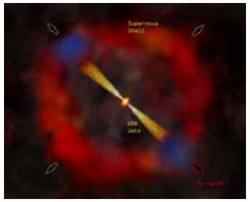
The BATSE instrument

- NaI scintillators
- 20 keV – 2 MeV
- FoV 4π

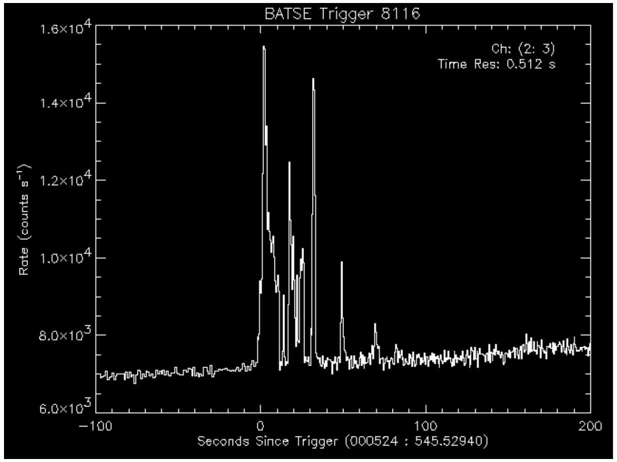




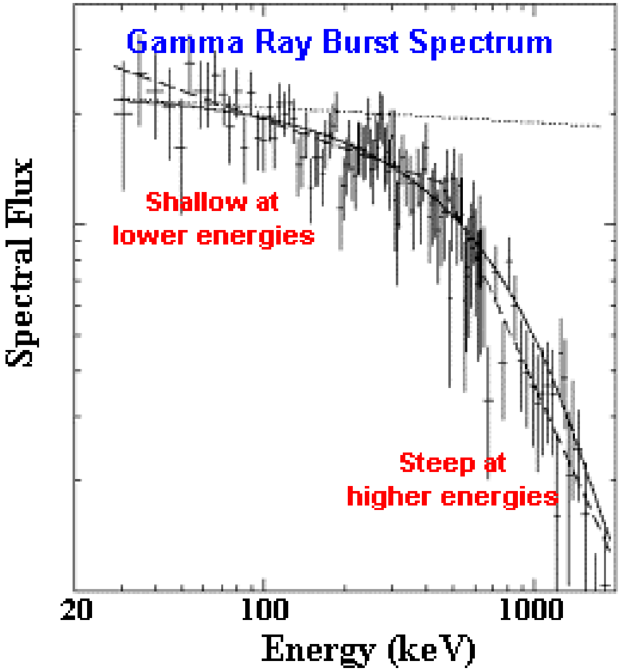
Gamma-Ray Bursts



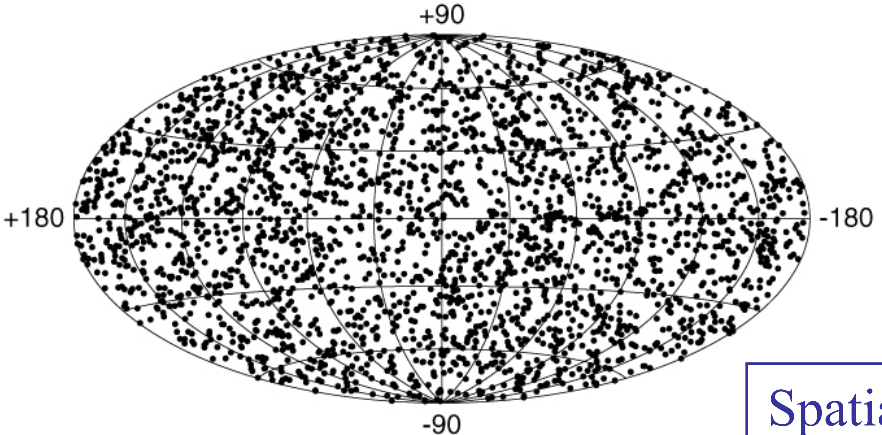
Temporal behaviour



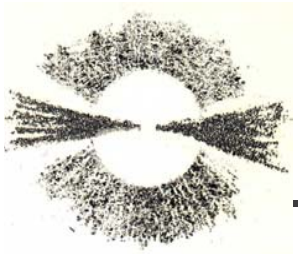
Spectral shape



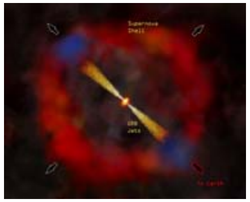
2704 BATSE Gamma-Ray Bursts



Spatial distribution



GRB: where are they?



The great debate (1995)

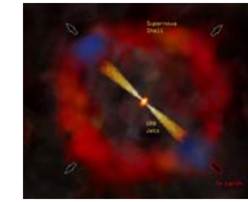
Fluence: 10^{-7} erg cm^{-2} s^{-1}
Distance: 1 Gpc
Energy: 10^{51} erg

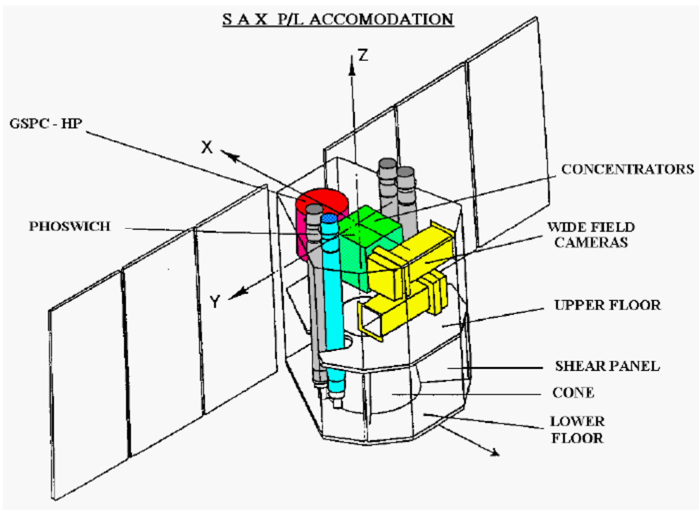
Distance: 100 kpc
Energy: 10^{43} erg

Cosmological - Galactic?

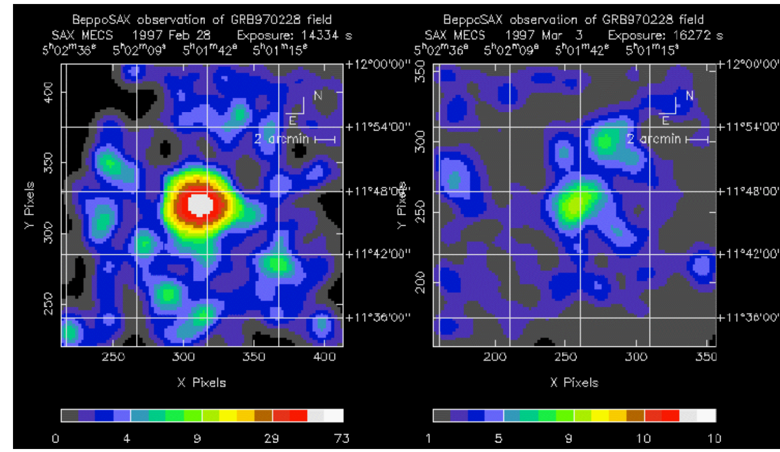
Need a new type of observation!

The Afterglow

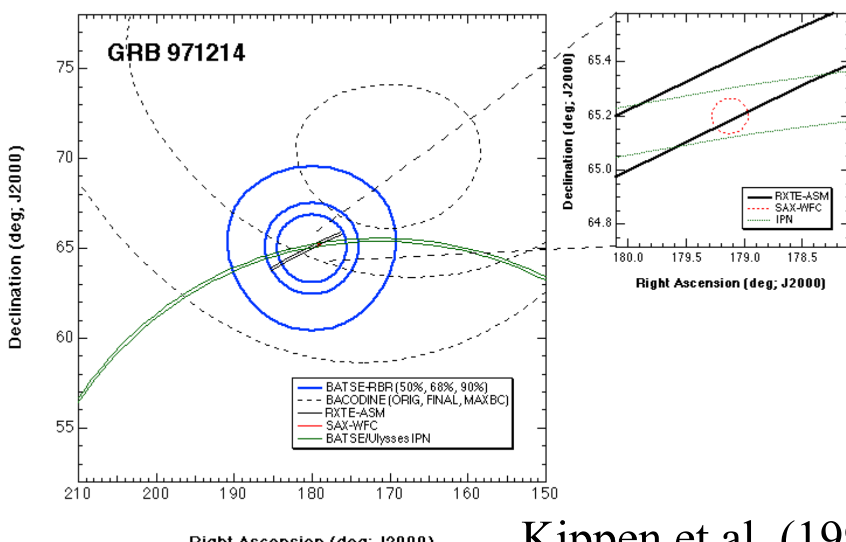




- Good Angular resolution (< arcmin)
- Observation of the X-Afterglow

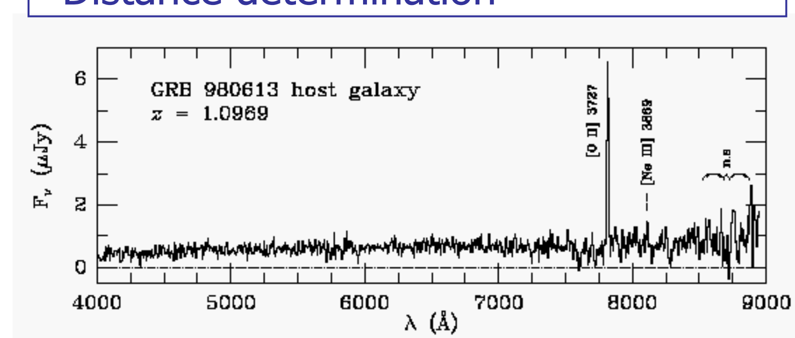


Costa et al. (1997)



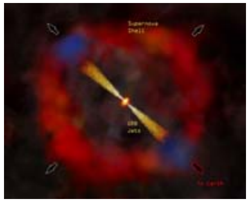
Kippen et al. (1998)

- Optical Afterglow (HST, Keck)
- Direct observation of the host galaxies
- Distance determination



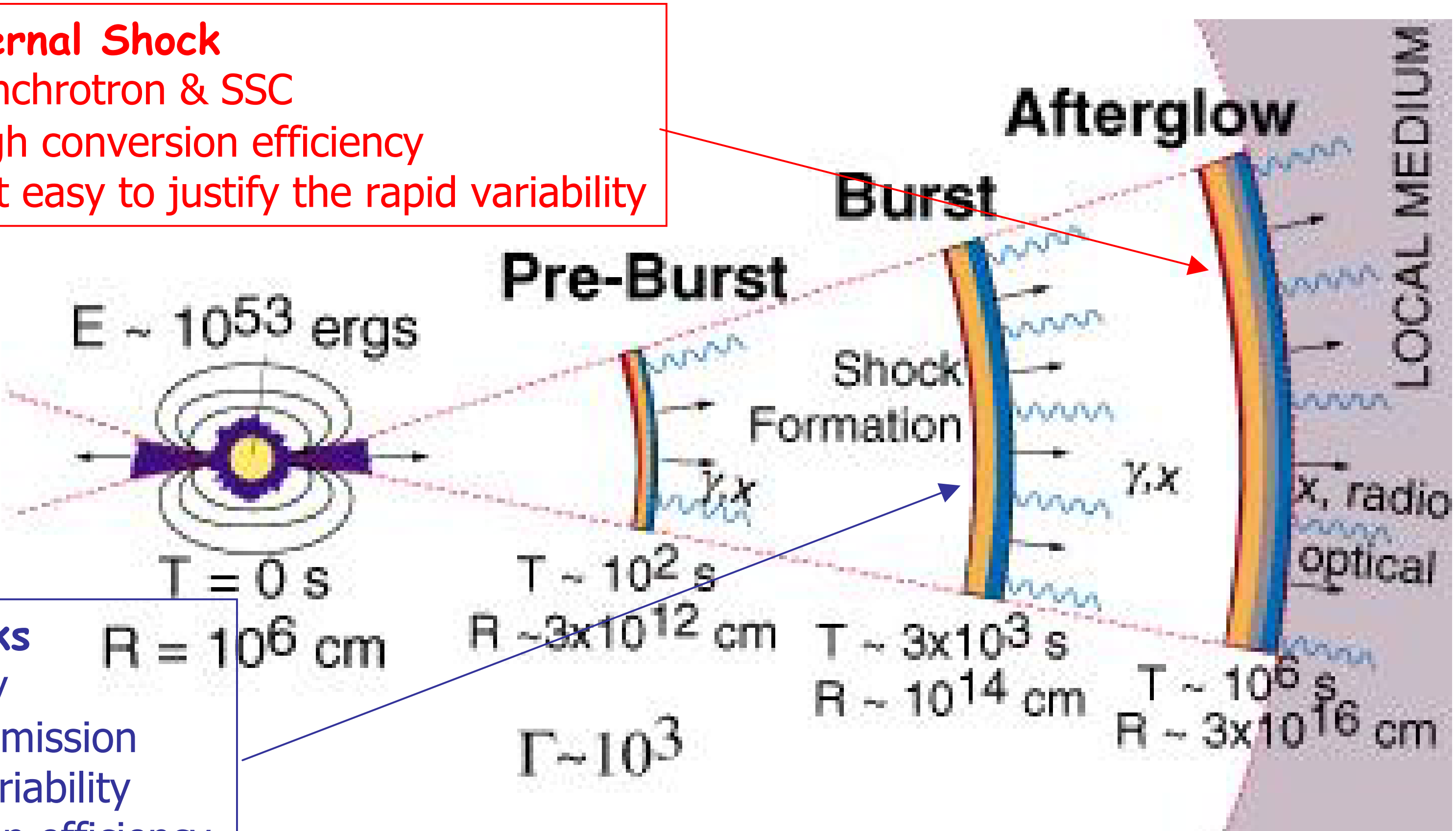
Djorgoski et al. (2000)

The Fireball "standard" model

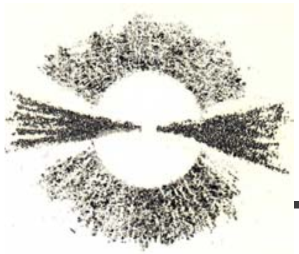


- Relativistic motion of the emitting region
- Shock mechanism converts the kinetic energy of the shells into radiation.
- Baryon Loading problem

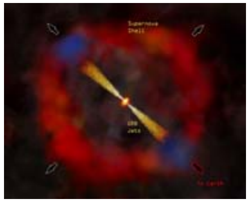
External Shock
- Synchrotron & SSC
- High conversion efficiency
- Not easy to justify the rapid variability

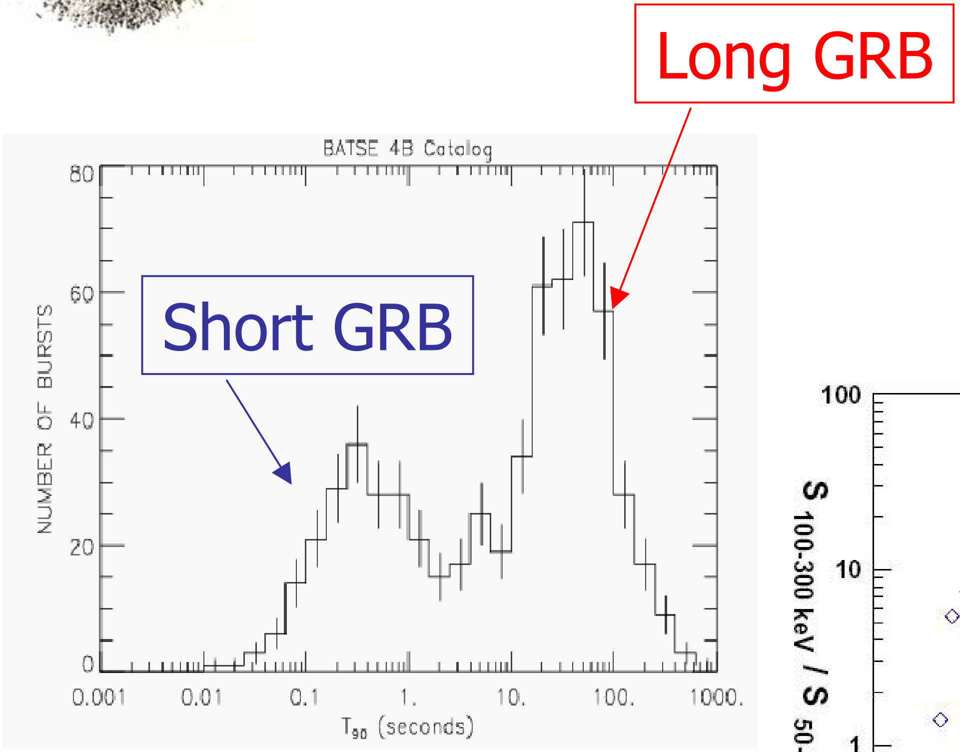


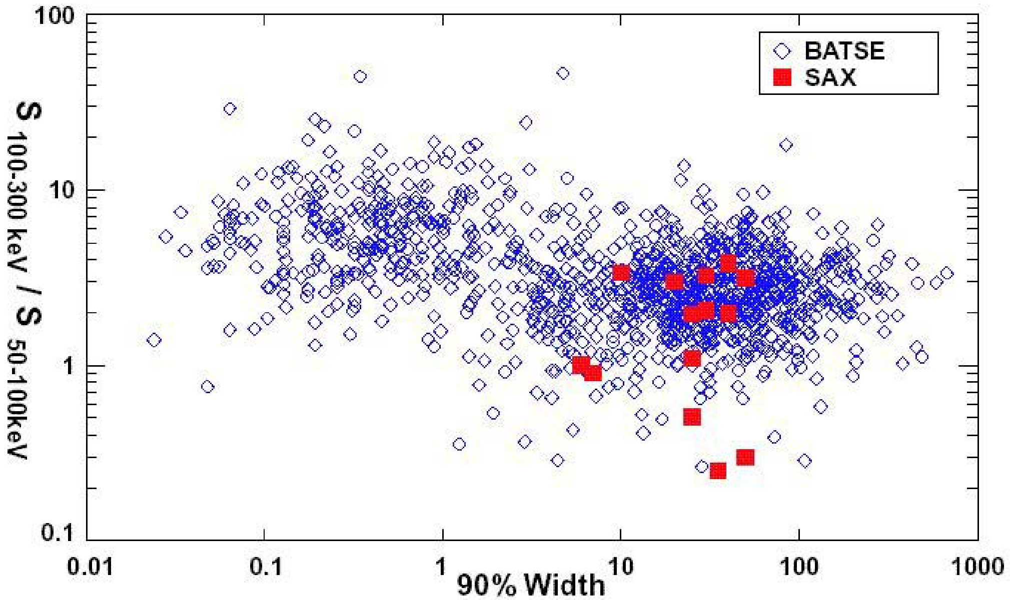
Internal Shocks
- Source activity
- Synchrotron Emission
- Rapid time Variability
- Low conversion efficiency

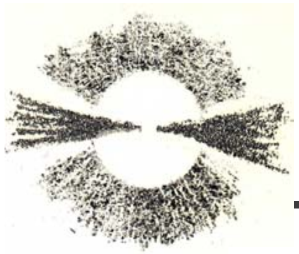


GRB Progenitors

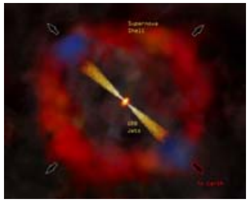


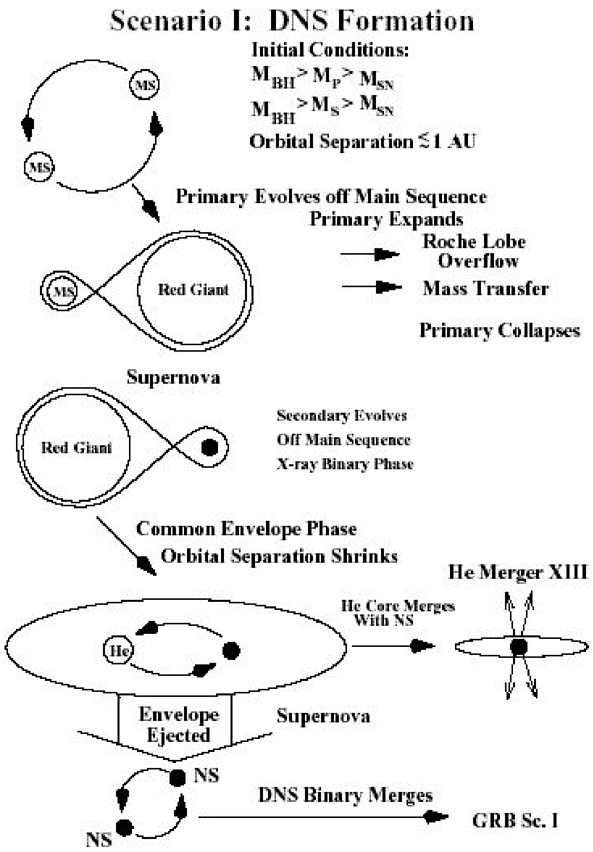


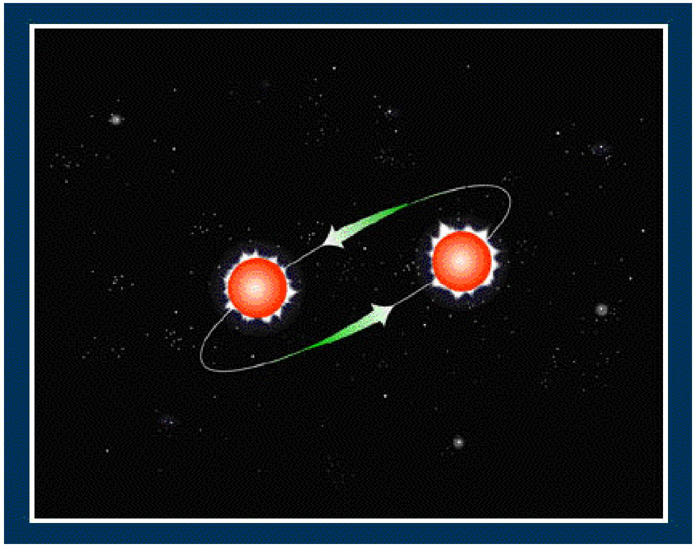


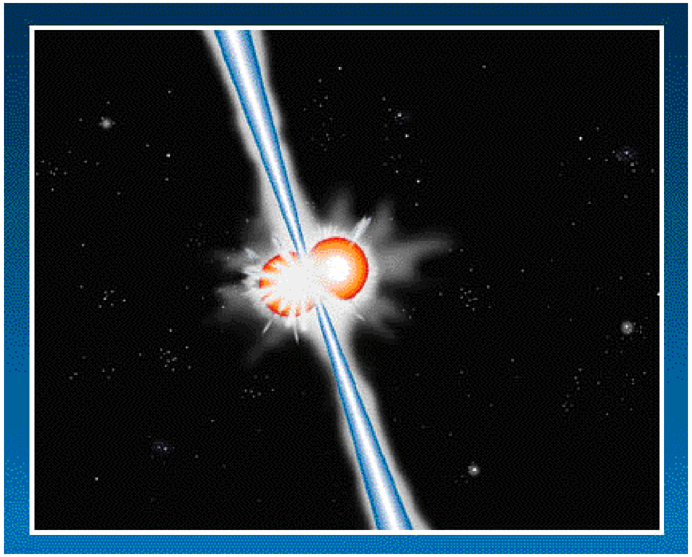


NS/BH Binary Mergers



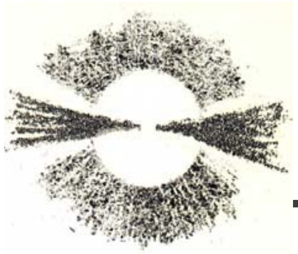




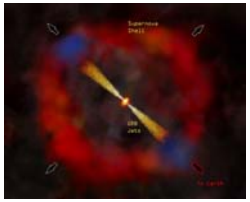


Merging of compact objects (NS-NS, NS-BH, BH-BH).
These objects are observed in our Galaxy.
The merging time is about 10^8 yr, via GW emission.

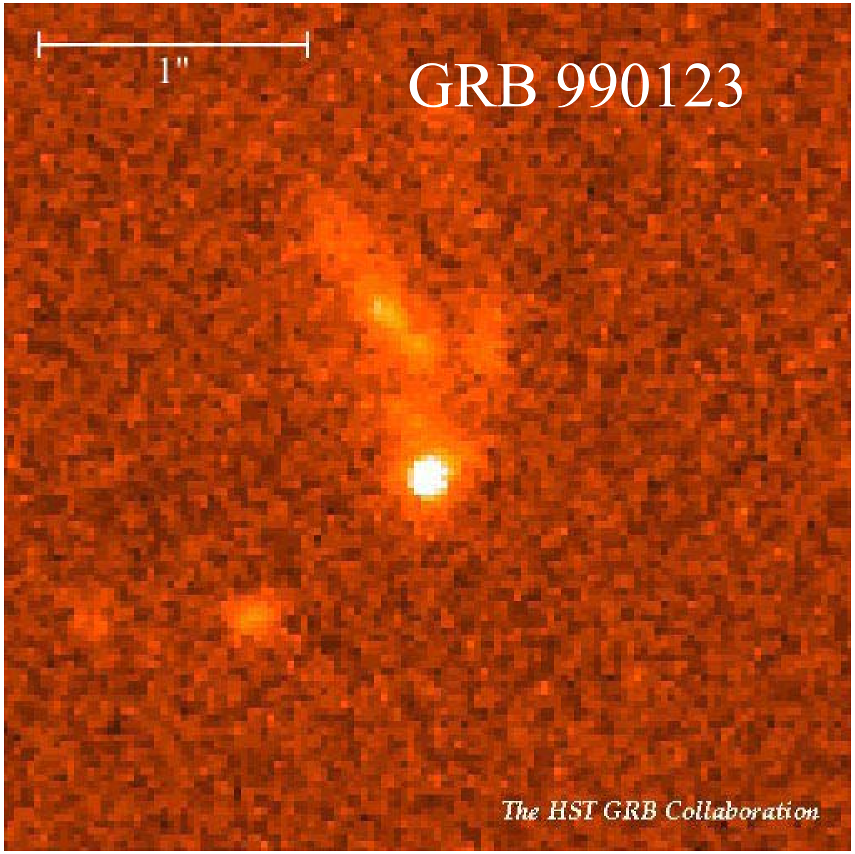
Eichler et. al. (1989)

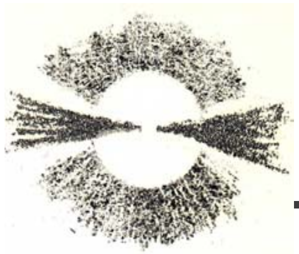


The “afterglow era”

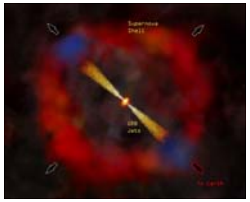


- Detection of Host Galaxies
- GRB beaming and energetics
- SN connection
- X-ray lines

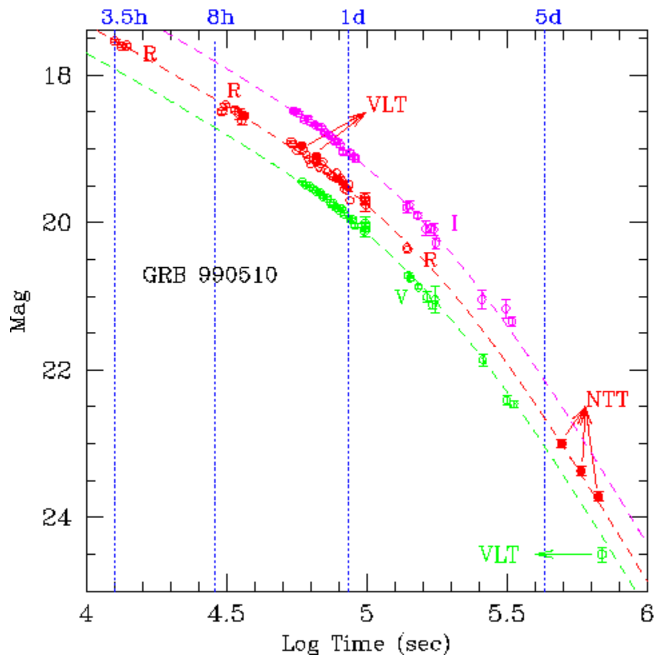




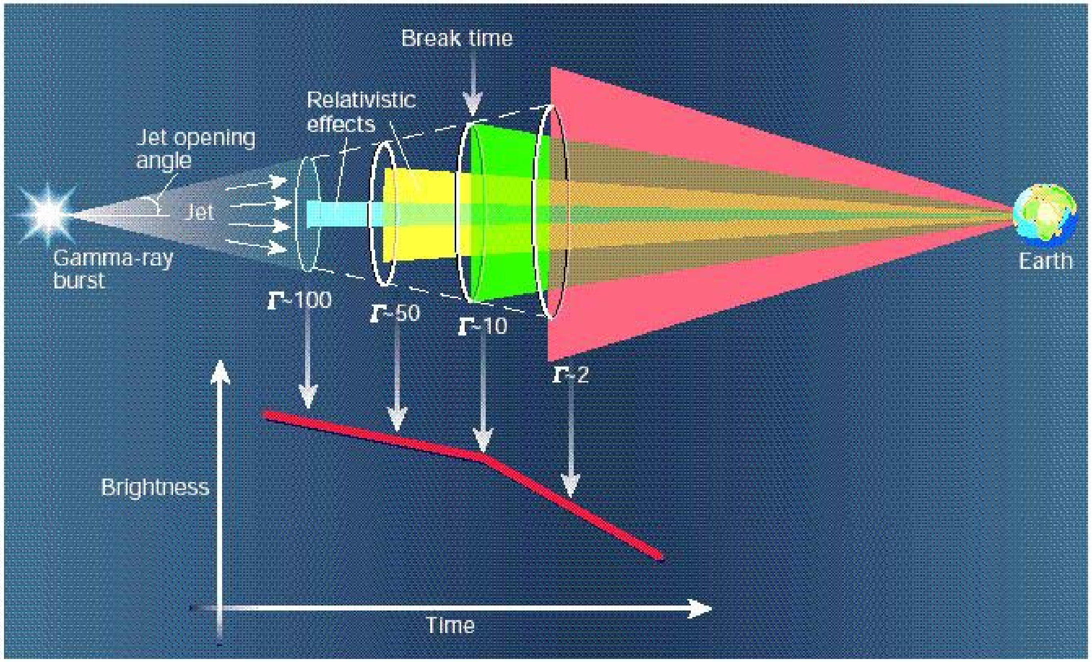
Jet Opening Angle



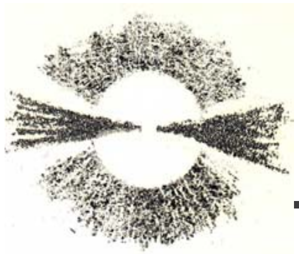
Harrison et al (1999)



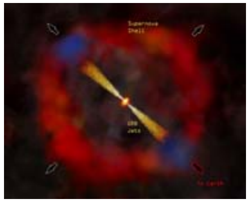
Achromatic Break

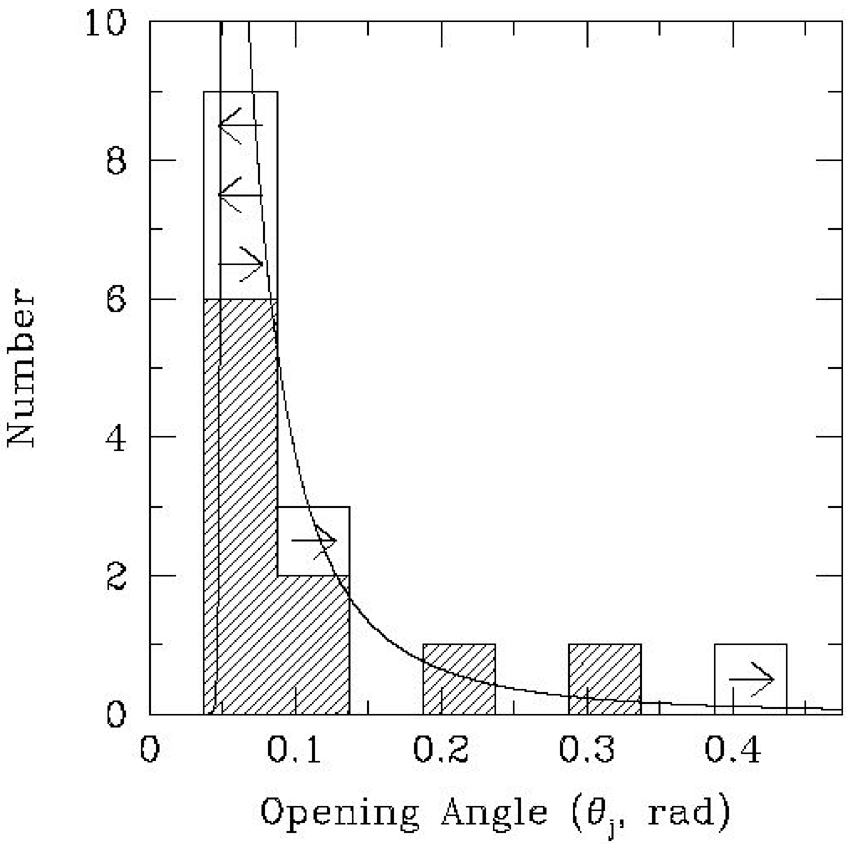


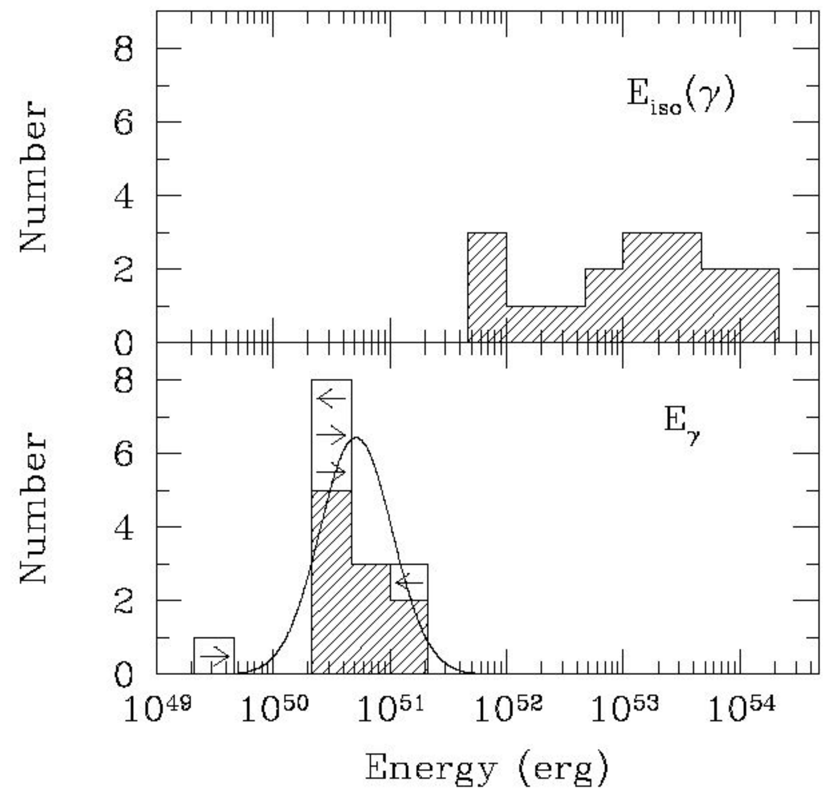
Woosley (2001)



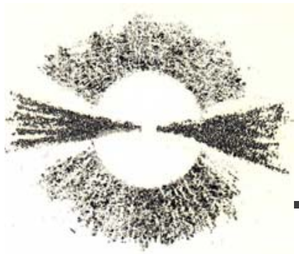
Jet and Energy Requirements



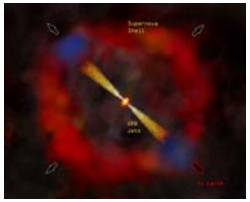


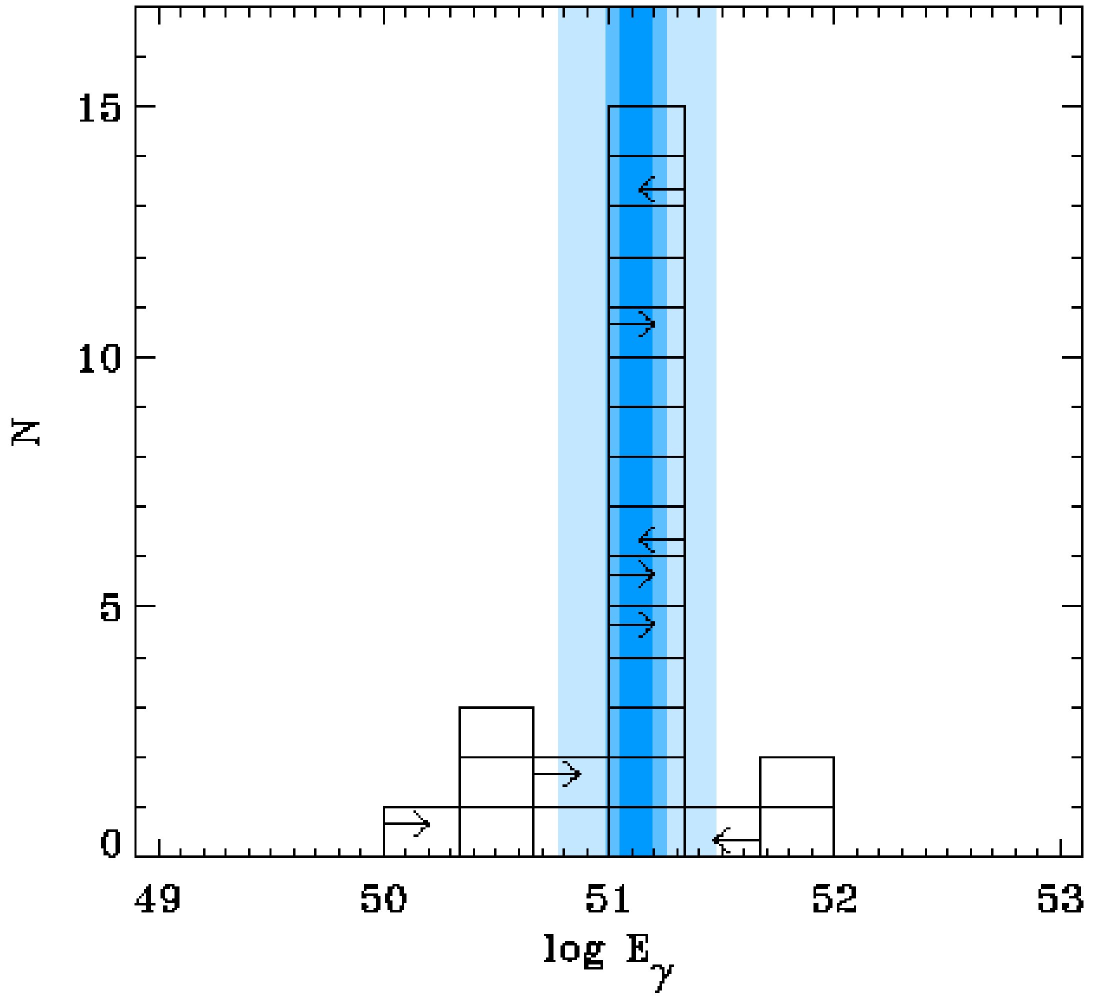


Frail et al. (2001)

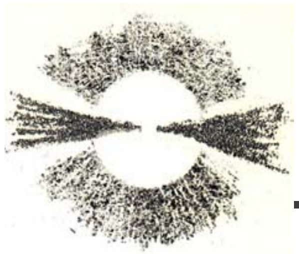


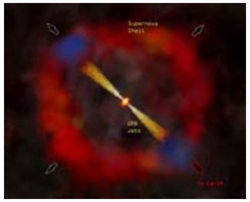
Jet and Energy Requirements





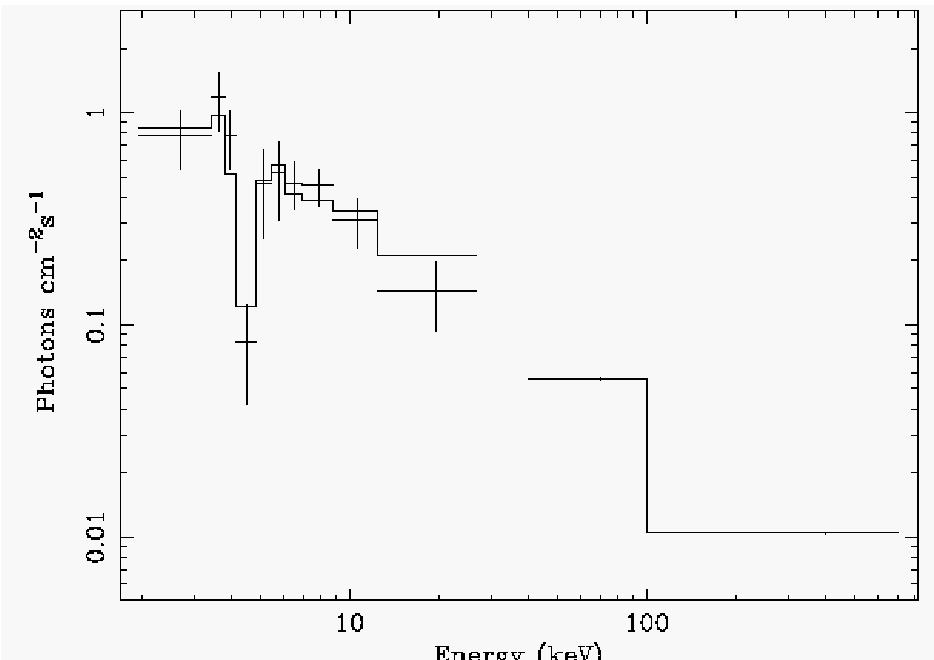
Bloom et al. (2003)





X-ray Lines

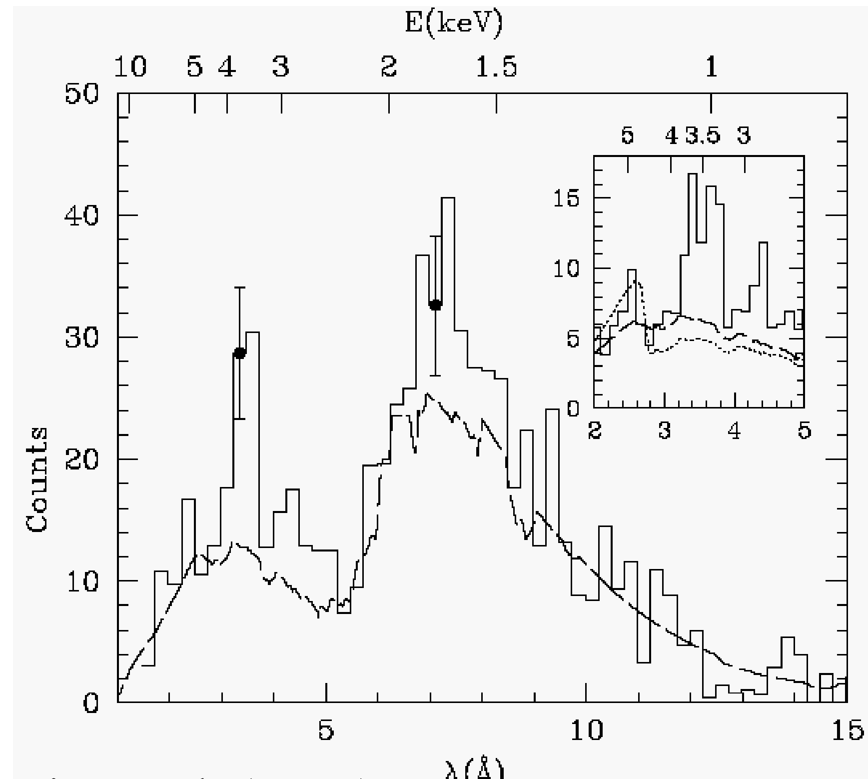
GRB 990705



Amati et al. (2000)

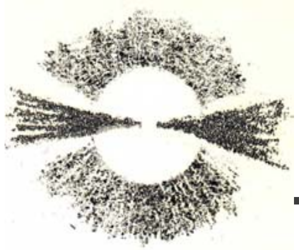
Transient Absorbtion Line

Emission Lines

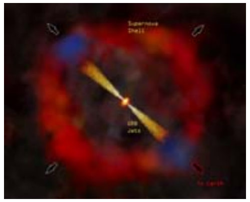


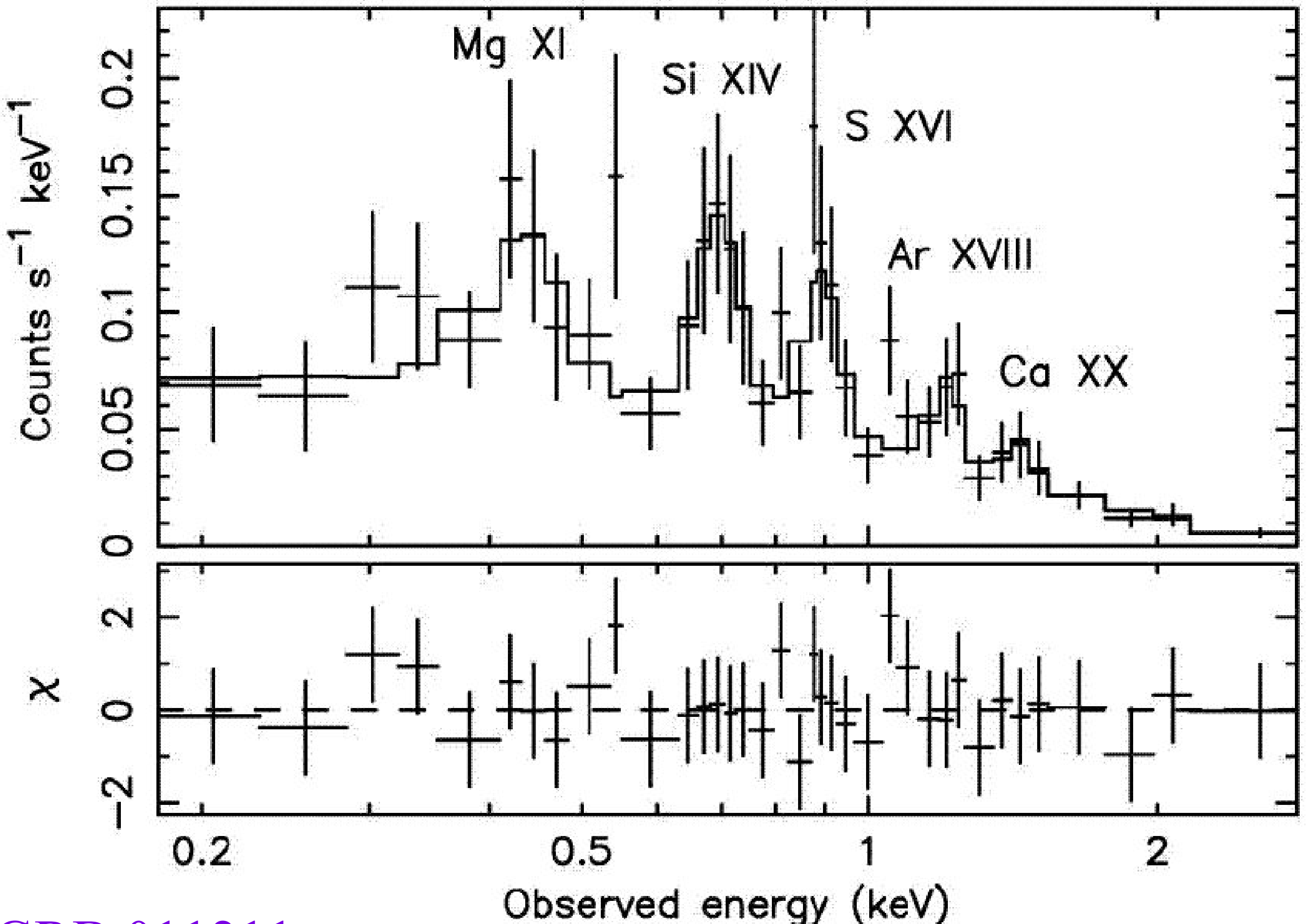
Piro et al. (2000)

GRB 991216



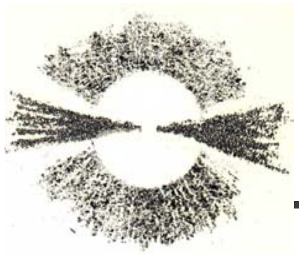
X-ray Lines

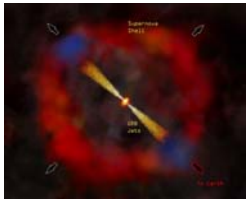




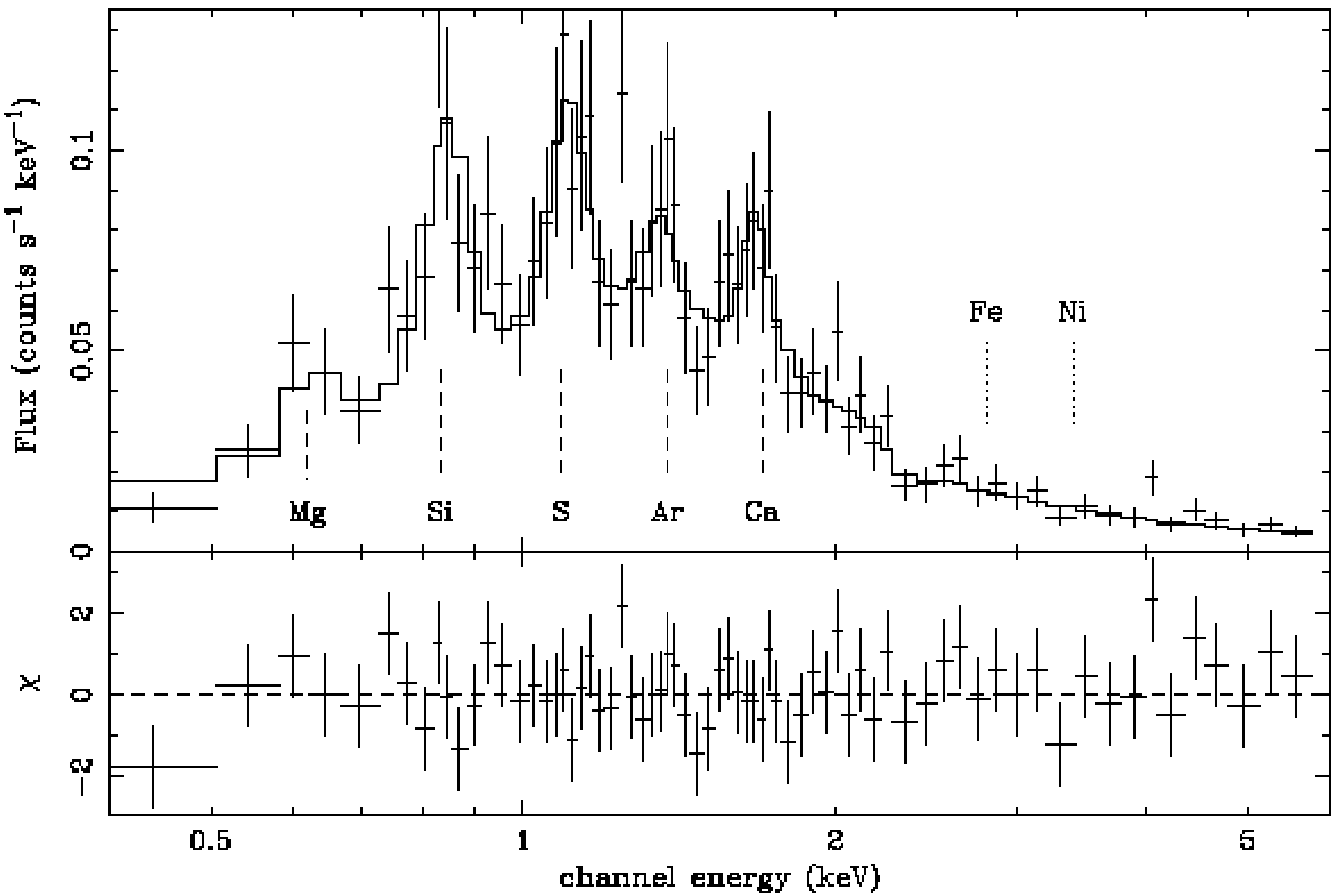
GRB 011211

Reeves et al. (2002)



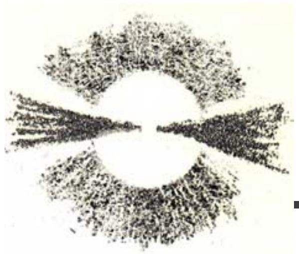


X-ray Lines

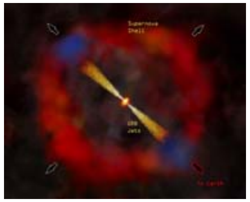


GRB 030227

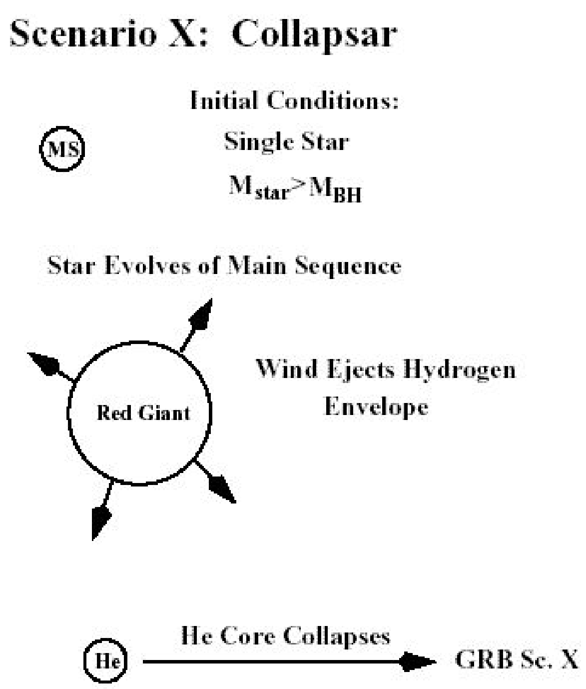
Watson et al. (2003)

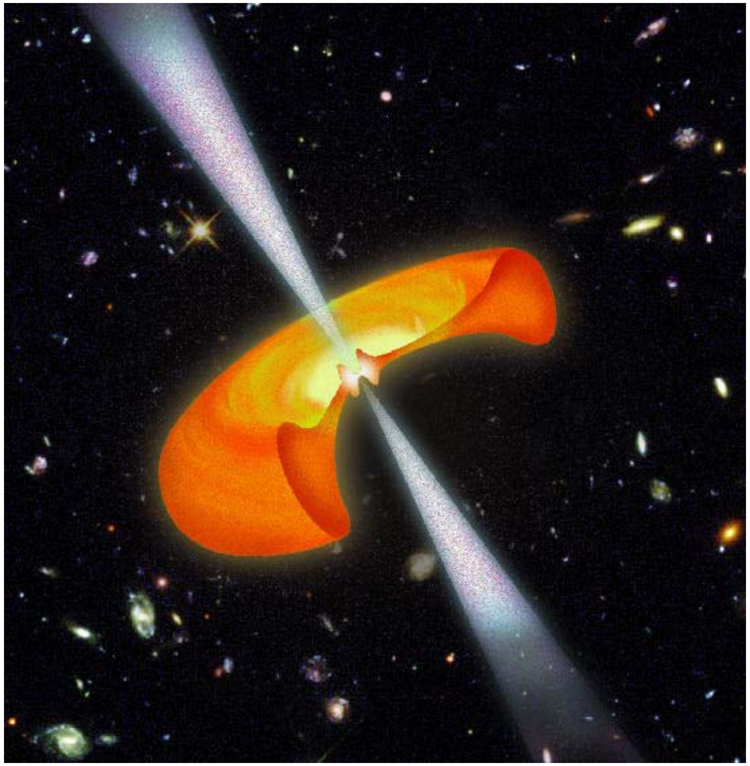


Collapsar model

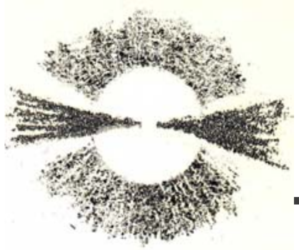


Woosley (1993)

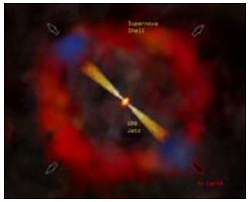




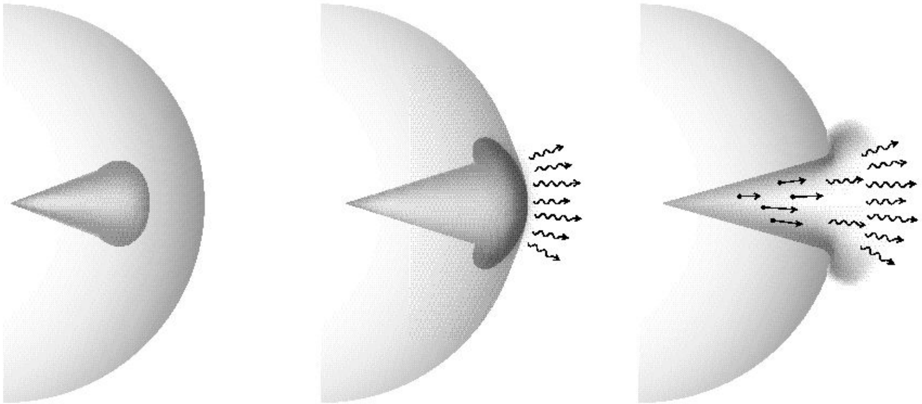
- Very massive star that collapses in a rapidly spinning BH.
- Identification with SN explosion.



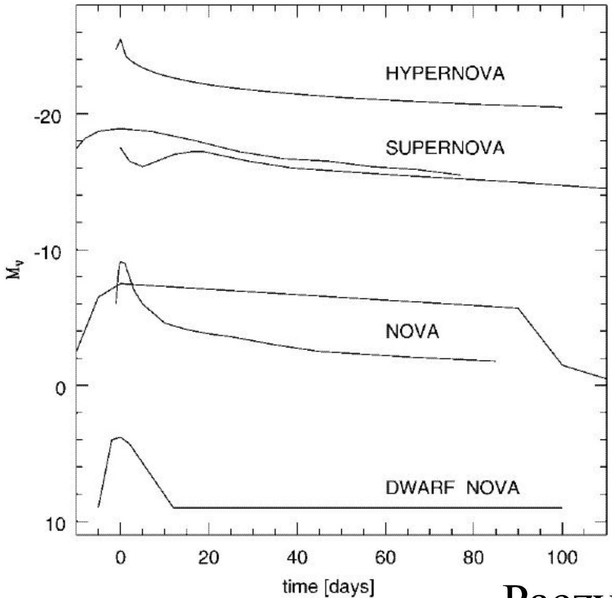
Collapsar Model



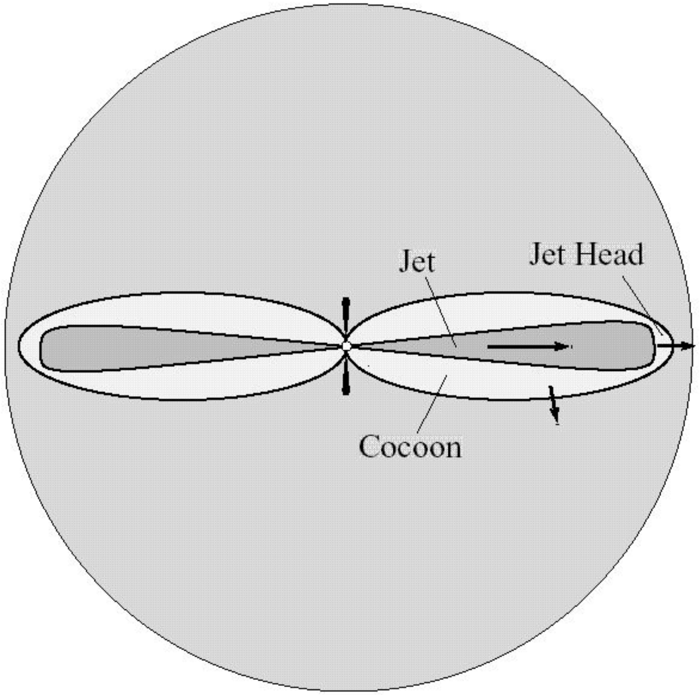
Ramirez Ruiz et al. (2002)

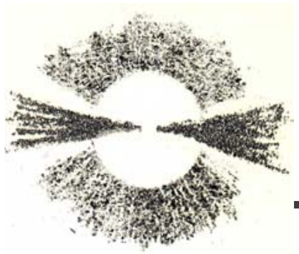


Jets out of the Envelope

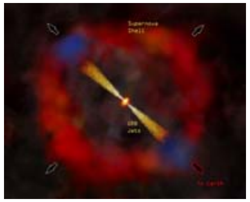


Paczynski (1998)

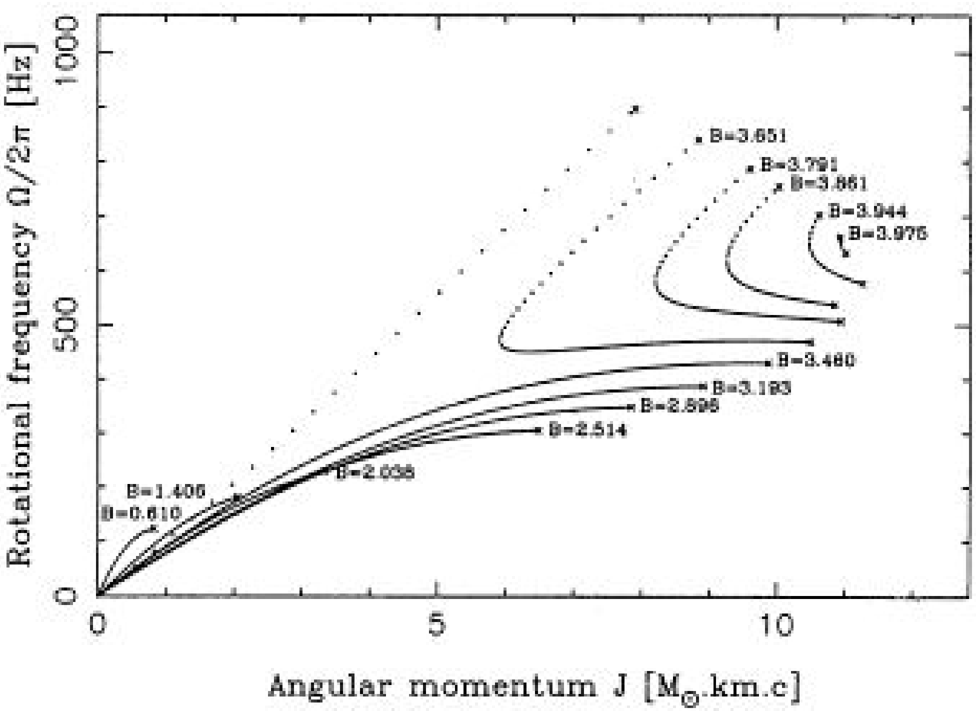


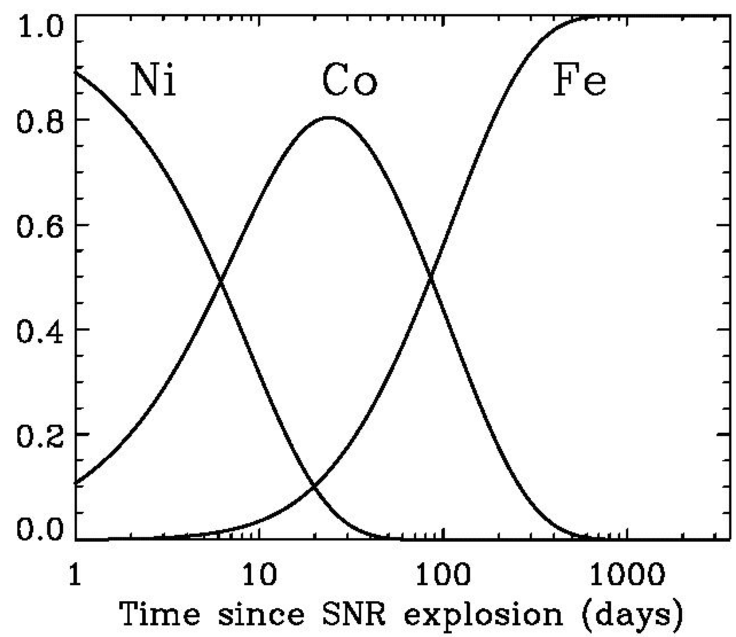


Supranova



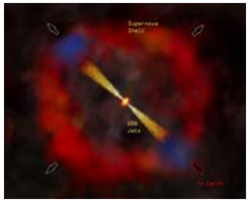
Salgado et. al. (1994)



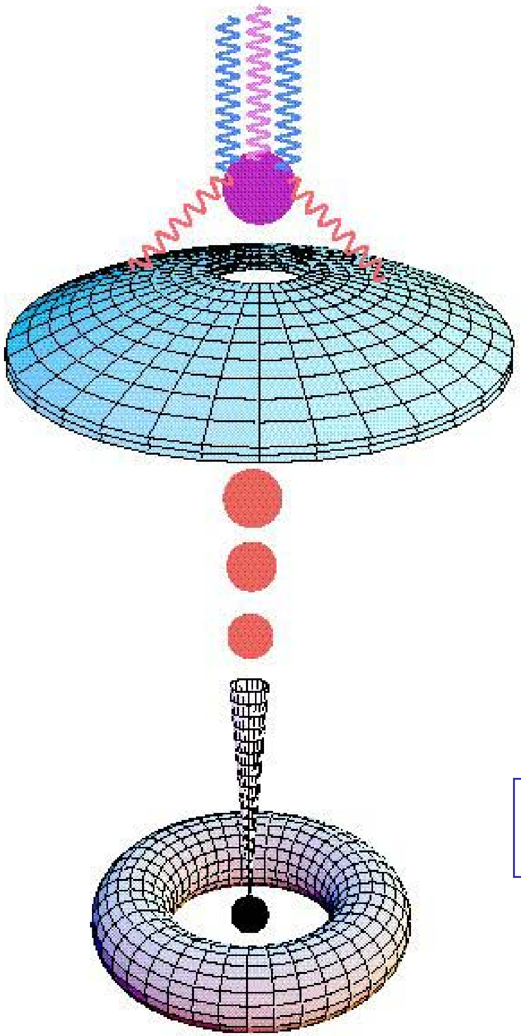


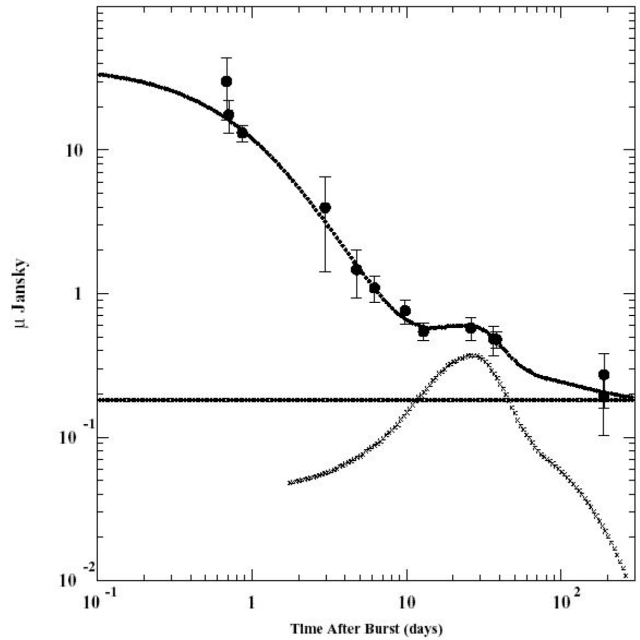
Vietri & Stella (1998)

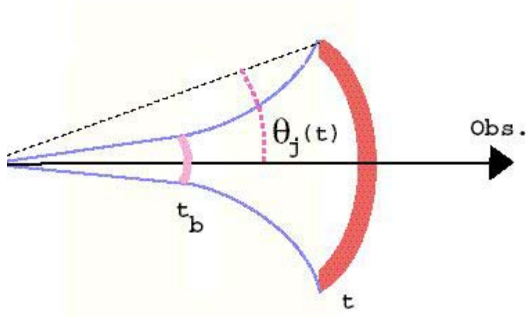
SupraMassive NS
Baryon Clean Environment



Cannonball

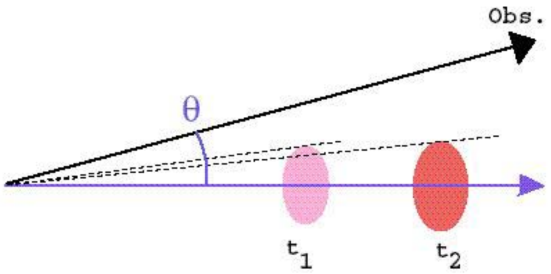






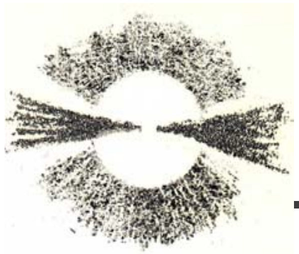
(a) FIRETRUMPET

Two stage mechanism

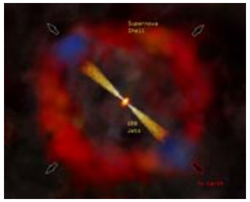


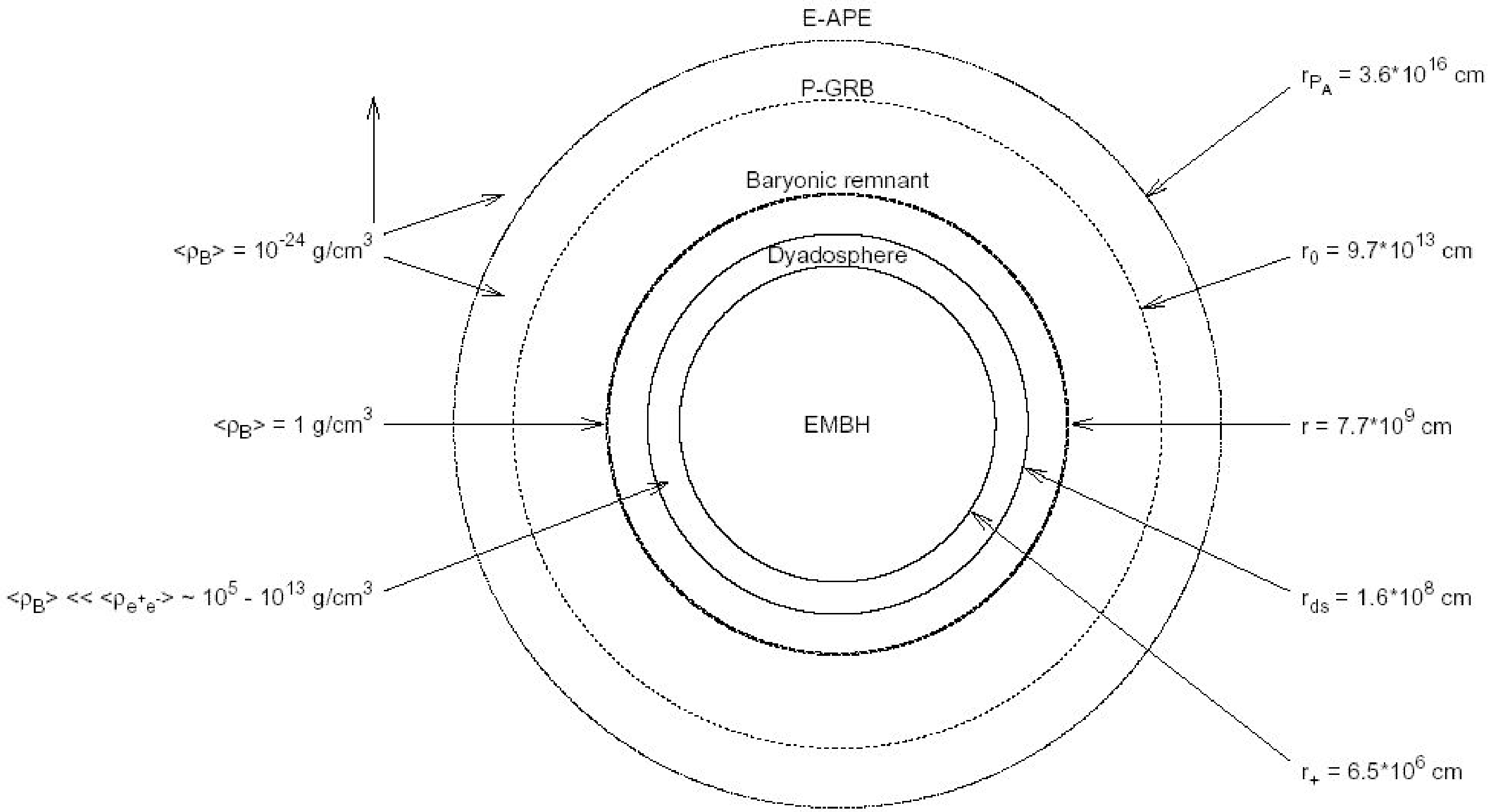
(b) CANNONBALL

Dar & De Rujula (2000)



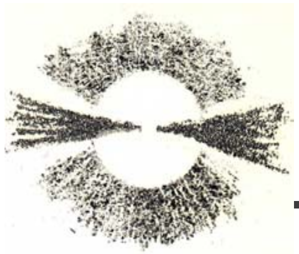
EMBH and Vacuum Breakdown



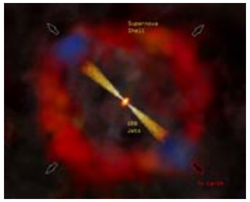


Ruffini et al. (2003)

Charged BH

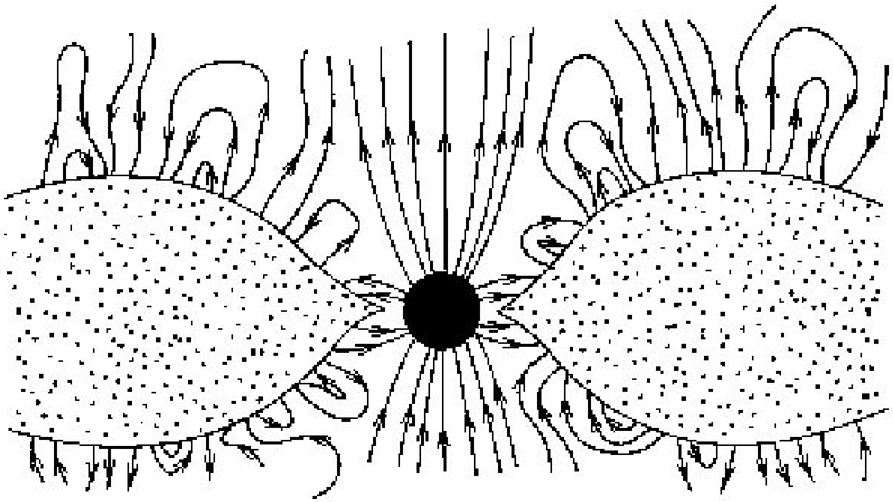


The Fireworks model



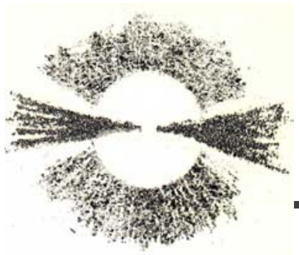
The energetics of the long duration GRB phenomenum is compared with models of a rotating Black Hole (BH) in a strong magnetic field generated by an accreting torus.

- Blandford-Znajek mechanism for GRB
- $$E_{BZ} = 0.3 \cdot 10^{54} \left(\frac{M_{bh}}{M_{\odot}} \right)$$

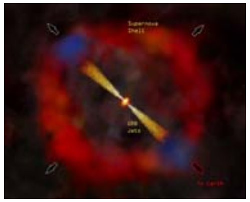


Blandford & Znajek (1977)
Brown et al. (2000)
Barbiellini & Longo (2001)
Barbiellini, Celotti & Longo (2003)

Figure from McDonald, Price and Thorne (1986)



Available Energy



A rough estimate of the energy extracted from a rotating BH is evaluated with a very simple assumption an inelastic collision between the rotating BH and the torus.

- Inelastic collision between a rotating BH (10 $M_\odot$)and a massive torus (0.1 $M_\odot$) that falls down onto the BH from the last stable orbit
- Conservation of angular momentum: $\boxed{I_{bh}\Omega_{bh} + I_t\Omega_t = I\Omega}$
- Available rotational energy:

$$\Delta E_{rot} \approx \frac{1}{2} I_{bh}\Omega^2_{bh}\left(1 - \frac{I_{bh}}{I}\right) = 2M^3_{bh}\Omega^2_{bh}\left(1 - \frac{M^3_{bh}}{M^3}\right)$$

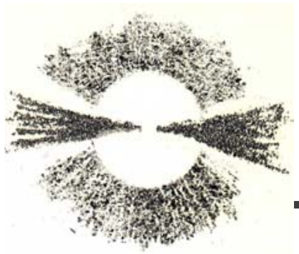
$$\Delta E_{rot} \approx 2M^3_{bh}\Omega^2_{bh}\left(3\frac{M_t}{M_{bh}}\right) \approx 3E_{rot,bh}\frac{M_t}{M_{bh}} \approx \frac{3}{8}M_t c^2$$

- Available gravitational energy:

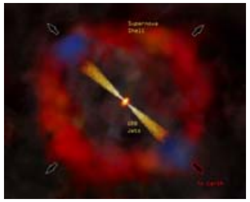
$$\Delta E_{grav} = \frac{GM_t M_{bh}}{R_{bh}} - \frac{GM_t M_{bh}}{3R_{bh}} \approx \frac{1}{3}M_t c^2$$

- Total available energy:

$$\boxed{\Delta E = \Delta E_{rot} + \Delta E_{grav} \cong 10^{53}\ \text{erg}}$$



Vacuum Breakdown



The GRB energy emission is attributed to an high magnetic field that breaks down the vacuum around the BH and gives origin to a $e^{\pm}$ fireball.

Polar cap BH vacuum breakdown

Pair production rate

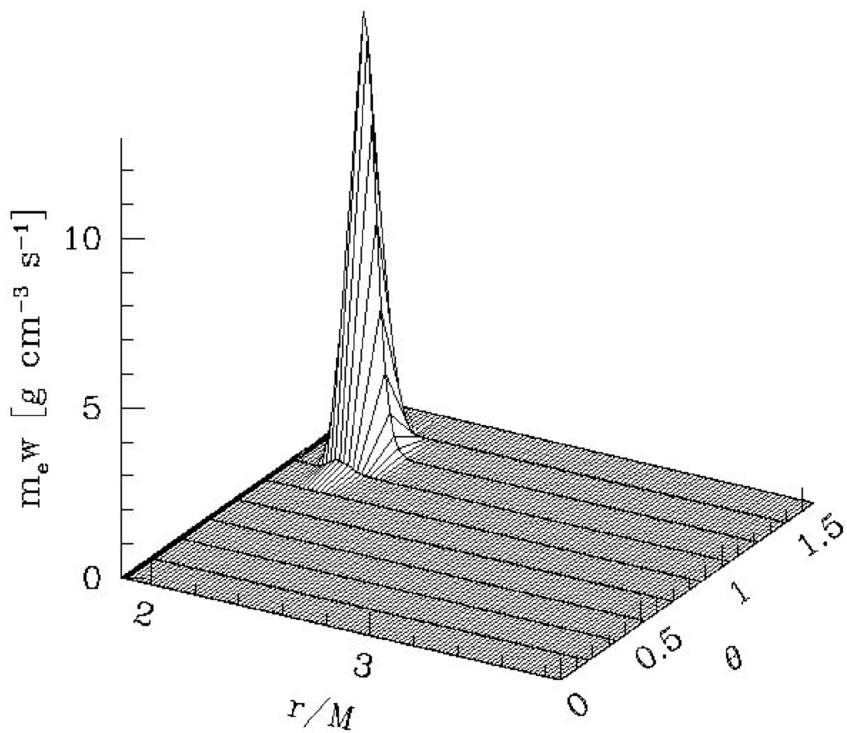
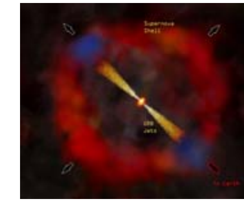
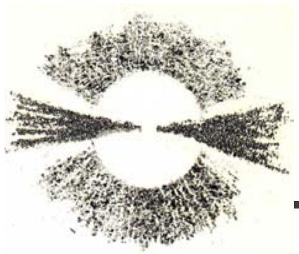


Figure from Heyl 2001

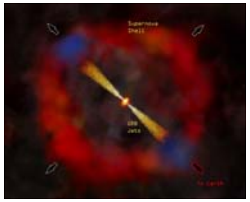
Vacuum Breakdown



- Critical magnetic field: $\boxed{B_c = 4.5 \cdot 10^{13}\ \text{Gauss}}$
- Charge acquired by a BH rotating in an external magnetic field (Wald 1974) $\boxed{Q = 2BJ \approx 2 \cdot 10^{16}\ \text{C}}$
- Electric field: $\boxed{E \approx 2 \cdot 10^{15}\ \text{V/cm}}$
- Pair volume: $\boxed{V_c \approx R_{bh}^3}$

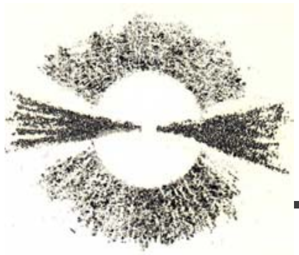


The formation of the fireball

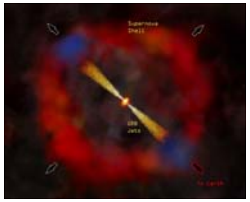


The energy released in the inelastic collision is available to create a series of plasmoids made of the pairs created and accelerated close to the BH.

- Pair density (e.g. Fermi 1966): $\boxed{n_{e^{\pm}} = 8 \cdot 10^{29}\ \mathrm{cm}^{-3}}$
- Magnetic field density: $\boxed{U_B = 8 \cdot 10^{25}\ \mathrm{erg\ cm}^{-3}}$
- Energy per particle: $\boxed{\varepsilon_0 \approx \eta_{acc} 10^{-4}\ \mathrm{erg}}$
- Energy in plasmoid: $\boxed{E_{plasmoid} = V_c U_B \approx 10^{45}\ \mathrm{erg}}$
- Number of plasmoids: $\boxed{N_{plasmoid} = \eta_B \frac{\Delta E}{E_{plasmoid}} \approx \eta_B 10^{8}}$



The formation of the fireball



After the formation of the plasmoid the particles undergo three processes.

- Acceleration time scale in E field: $$t_{acc} \approx \frac{10^2 \eta_{acc} m_e c^2}{eEc} \approx 10^{-19} \eta_{acc} \mathrm{s}$$

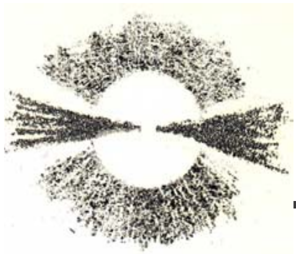
- Particle collimation by B field: $$t_{coll} \approx \frac{\rho}{c \sin\lambda} \approx \frac{\eta_{acc}}{\sin\lambda} 10^{-19} \mathrm{s}$$

Curvature radius: $$\rho = 3 \cdot 10^6 \frac{E(\mathrm{GeV})}{B(\mathrm{Gauss})} \mathrm{cm}$$

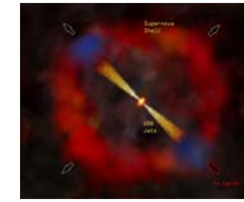
- Randomisation time scale by Compton Scattering in radiation field with temperature T_0:

$$t_{rand} \approx 10^{-16} \eta_{acc} \mathrm{s}$$

$$\mathrm{T}_0 = \left(\frac{B^2}{8\pi} \cdot \frac{1}{a} \right)^{1/4} \approx 10^{10} \mathrm{K}$$

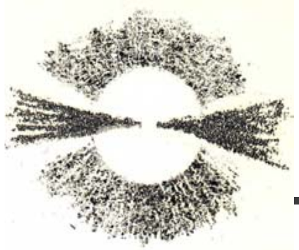


Two phase expansion

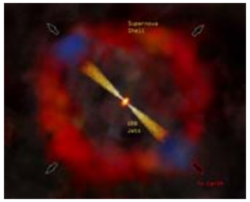


The first phase of the evolution occurs close to the engine and is responsible of energizing and collimating the shells. It ends when the external magnetic field cannot balance the radiation pressure.

- Phase 1 (acceleration and collimation) ends when: $\boxed{t_{rand} = t_{coll}}$
- Assuming a dependence of the B field: $\boxed{B \propto R^{-3}}$
  this happens at $\boxed{R_1 \approx 10^8 \, \mathrm{cm}}$
- Parallel stream with $\boxed{\Gamma_1 = 30\eta_{acc}}$
- Internal "temperature" $\boxed{\Gamma_1^{'} \approx 1}$

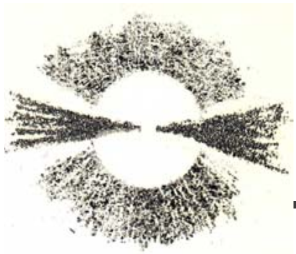


Two phase expansion

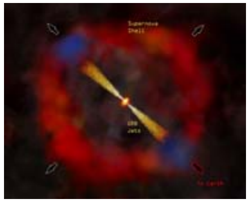


The second phase of the evolution is a radiation dominated expansion.

- Phase 2 (adiabatic expansion) ends at the smaller of the 2 radii:
  - Fireball matter dominated: $$R_\eta = R_0 \frac{E}{Mc^2}$$
  - Fireball optically thin to pairs: $$R_{pair} = R_0 \left(\frac{3E}{4\pi R_0^3 T_p^4} \right)^{1/4}$$
- R_2 estimation $$\boxed{R_2 = 50 R_0}$$
- Fireball adiabatic expansion $$\boxed{\frac{\Gamma_2'}{\Gamma_1'} = \frac{R_2}{R_0}}$$



Jet Angle estimation



The fireball evolution is hypothized in analogy with the in-flight decay of an elementary particle.

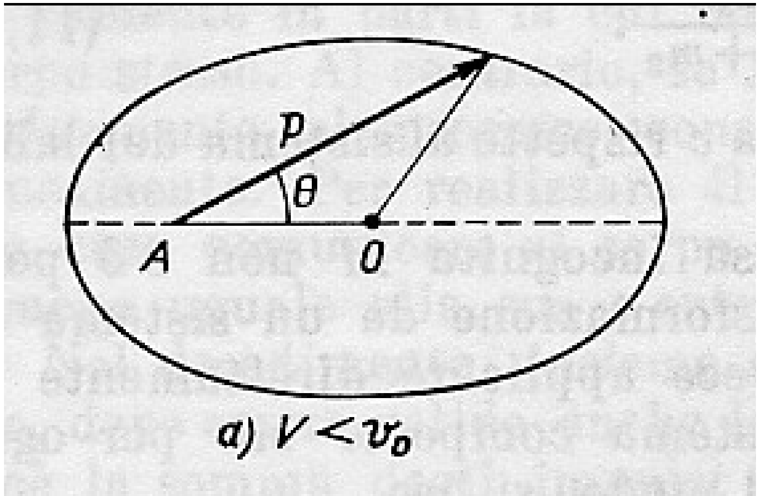


Figure from Landau-Lifšits (1976)

- Lorentz factors

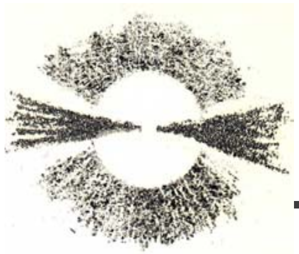
$$\Gamma_{||} = 2\Gamma_1\Gamma_2^{'} \qquad \Gamma_{\perp} = \Gamma_2^{'}$$

- Opening angle

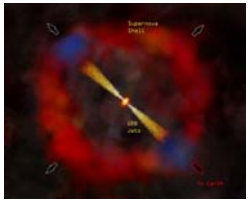
$$\theta_c \sim \tan\theta_c = \frac{\Gamma_\perp}{\Gamma_1\Gamma_2^{'}} = \frac{\Gamma_2^{'}}{\Gamma_1\Gamma_2^{'}} = \frac{1}{\Gamma_1}$$

- Result:

$$\boxed{\theta_c \sim \frac{1}{\Gamma_1} \sim 2 \times 10^{-1}}$$



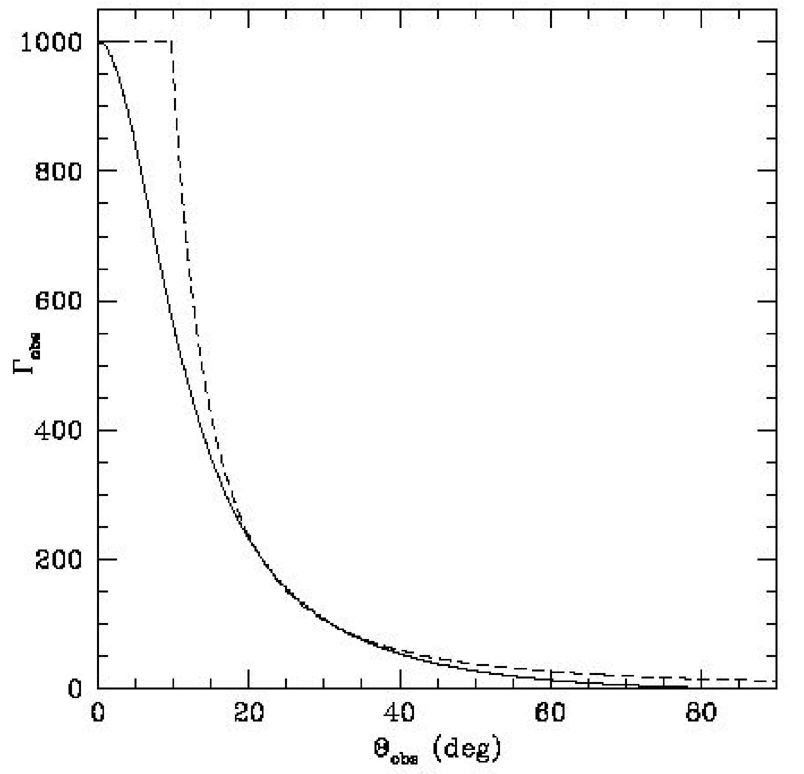
Energy Angle relationship



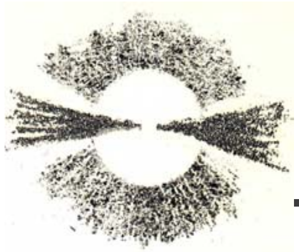
The observed angular distribution of the fireball Lorentz factor is expected to be anisotropic.

$$E(\theta') \propto \Gamma_1 \Gamma_2' (1 + \beta_2' \cos\theta')$$

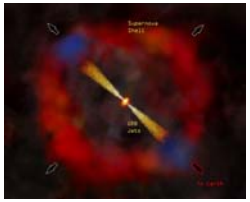
$$\tan(\theta) = \frac{\sin\theta'}{\Gamma_1(\beta_1 + \cos\theta')}$$

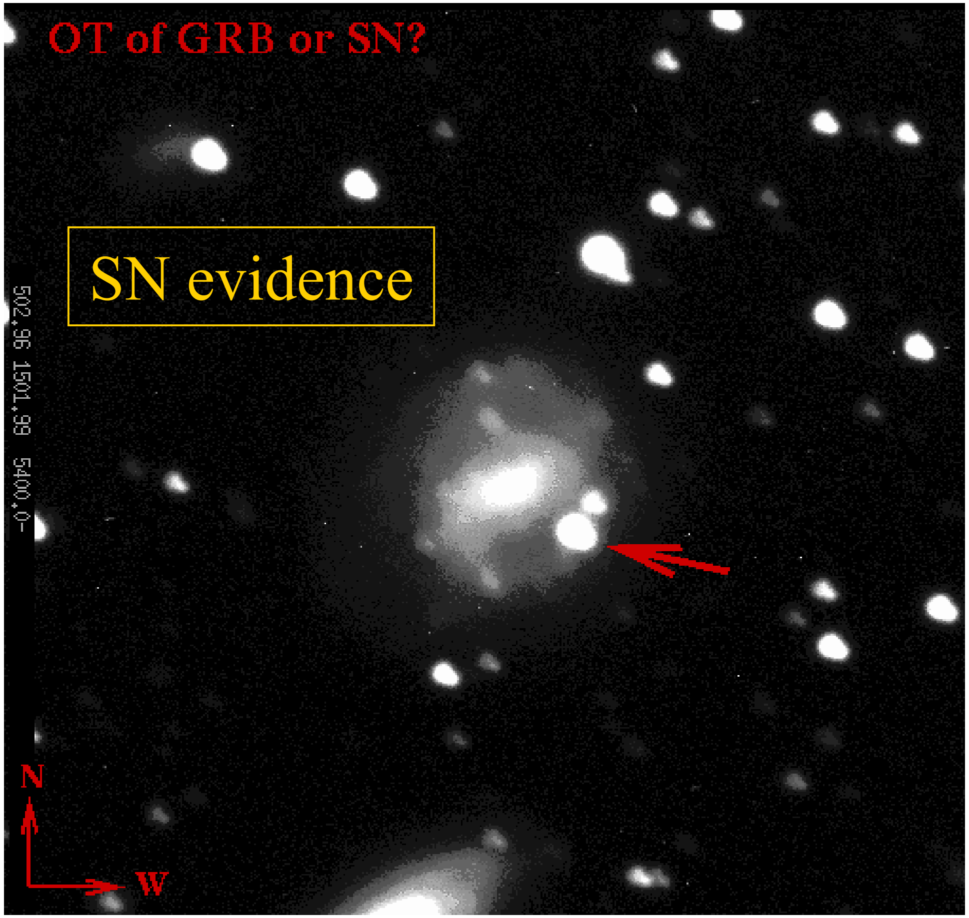


Predicted Energy-Angle relation



SN- GRB connection



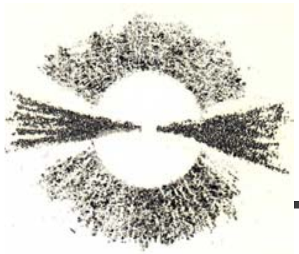


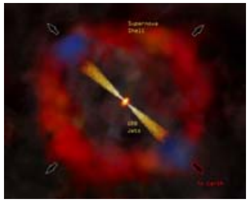
SN 1998bw - GRB 980425

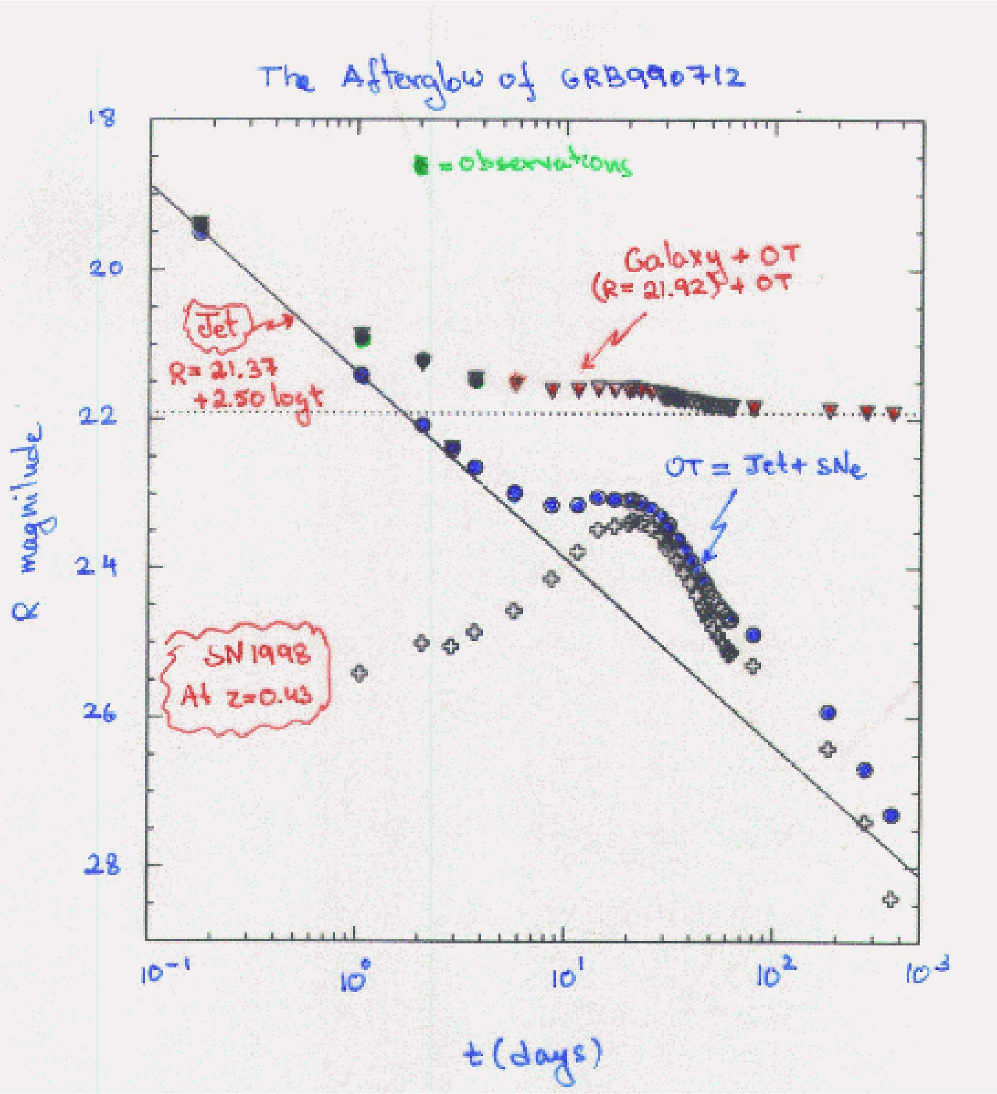
chance coincidence $O(10^{-4})$

(Galama et al. 98)

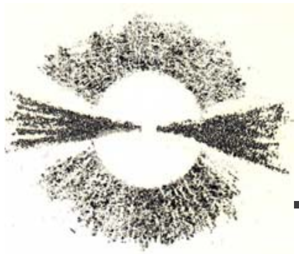
GRB & SN first predictions



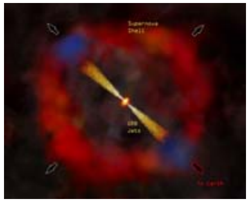


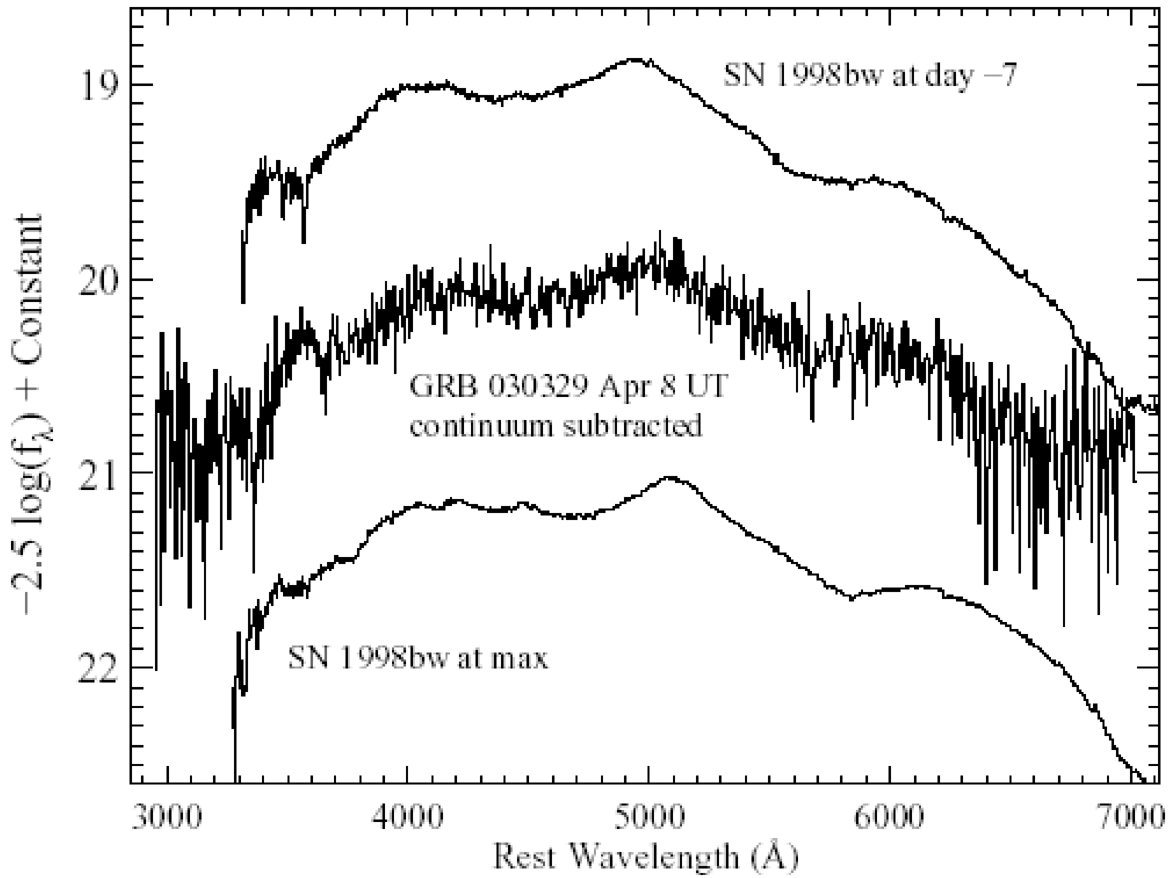


Hjorth, Fynbo, Dar & Courbin (1999)



GRB 030329: the “smoking gun”?

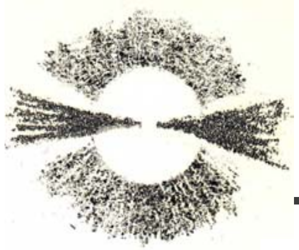




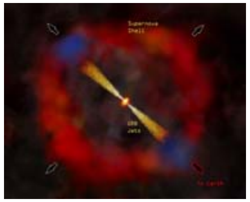
(Matheson et al. 2003)

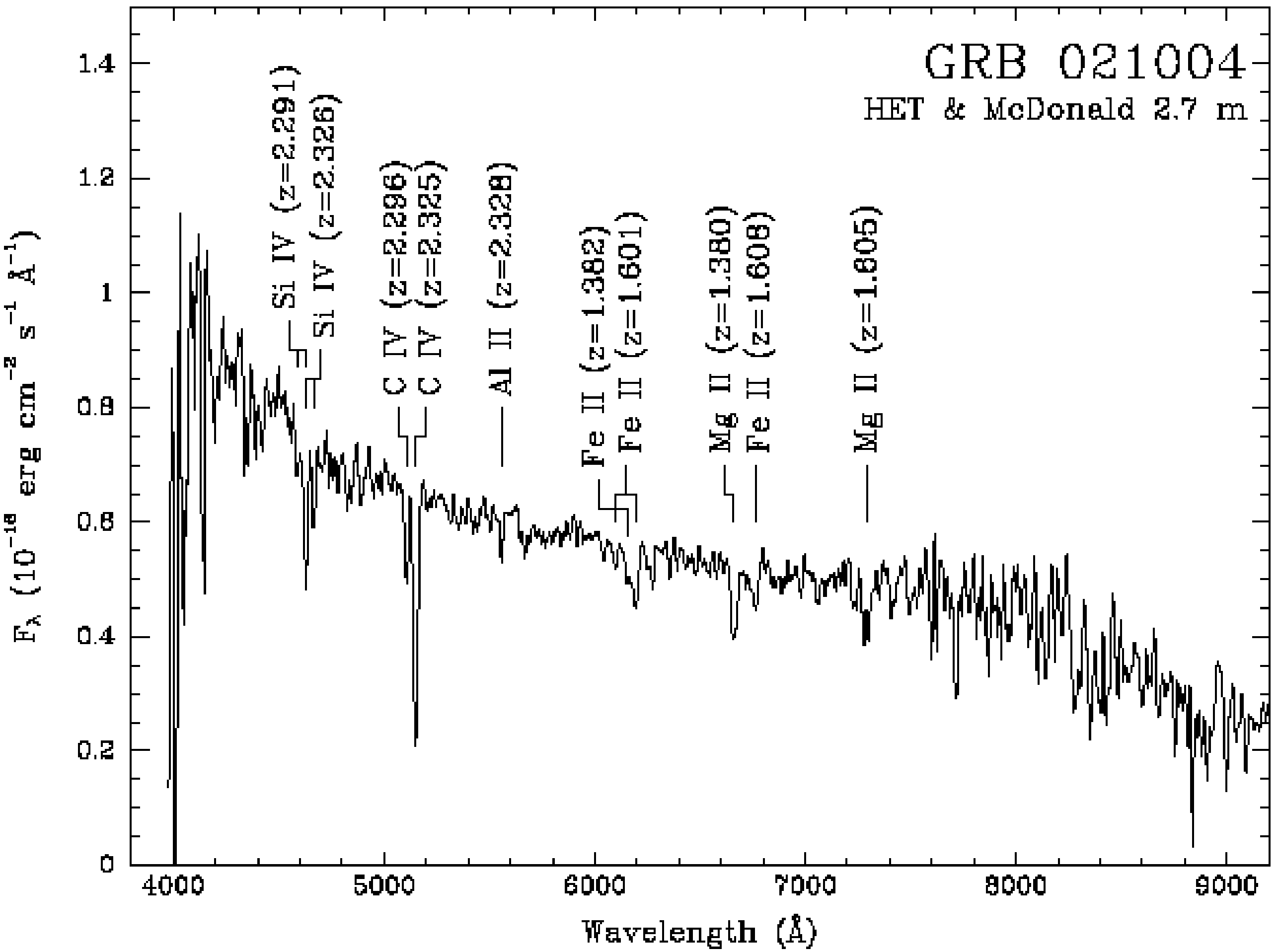
A “Cosmological” era?

- GRB cosmology
- First Stars



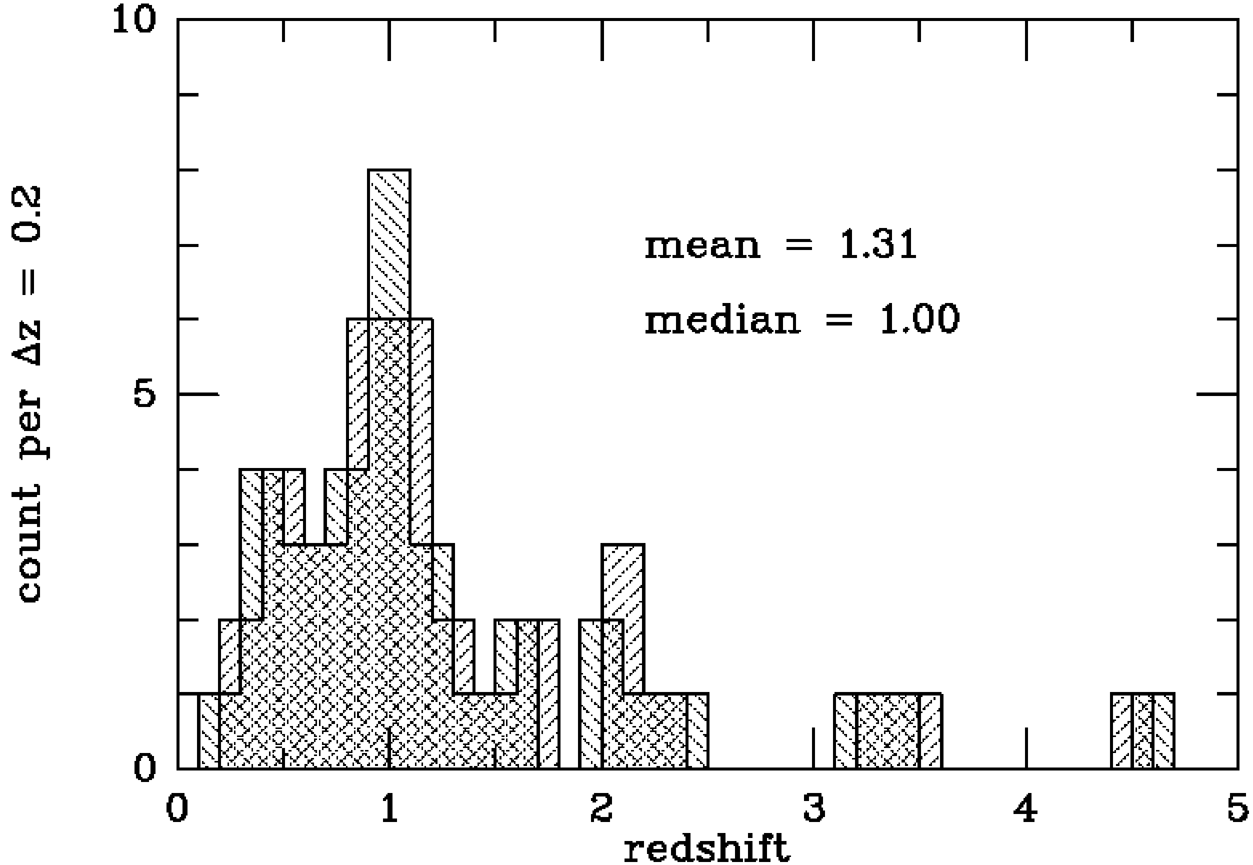
High precision radiography of ISM from z=2.3





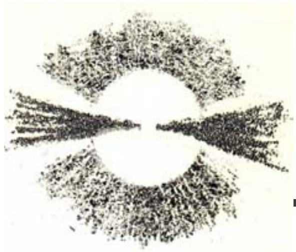
Schaefer et al. 2002

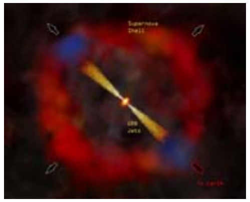
GRB and Cosmology

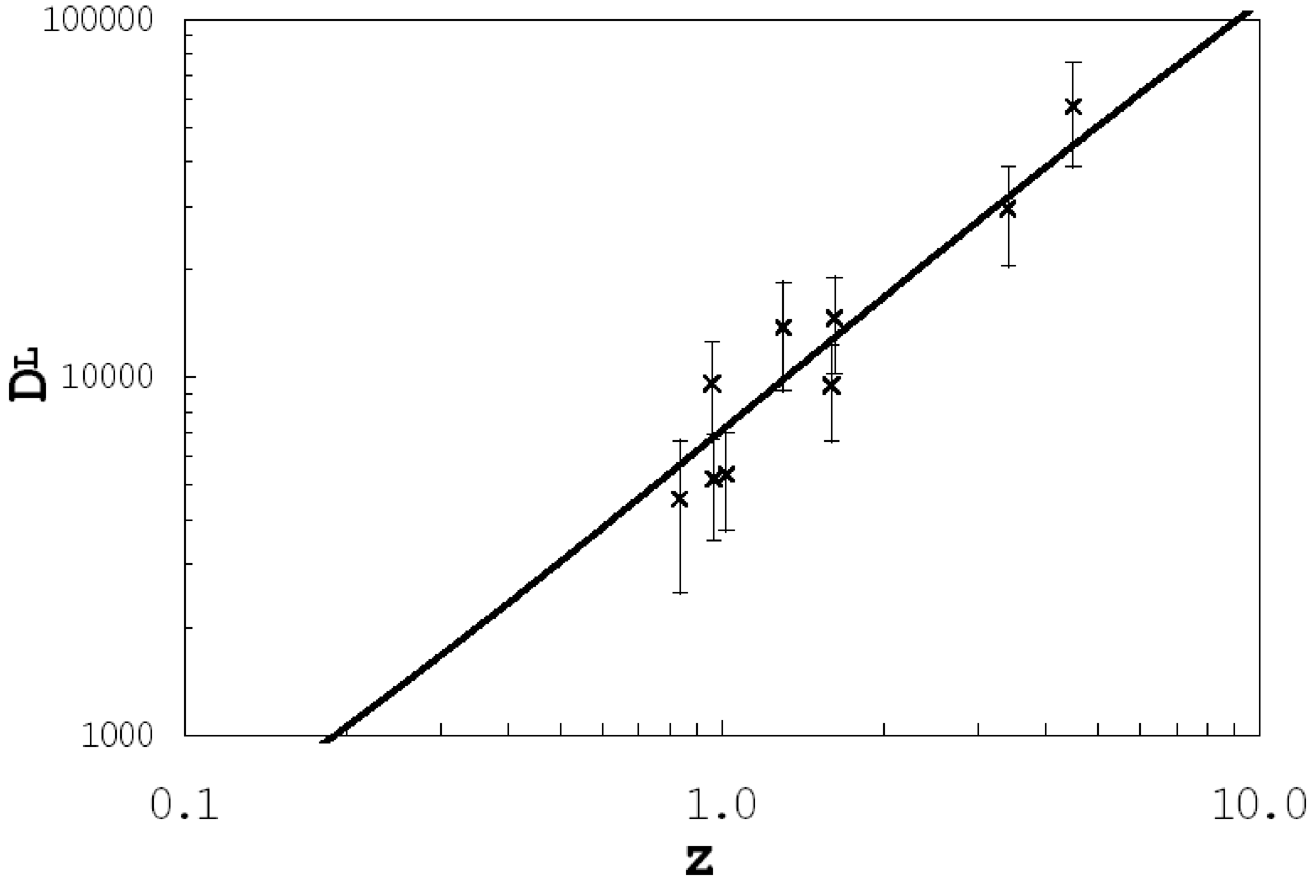


Djorgovski et al. 2003

GRB and Cosmology

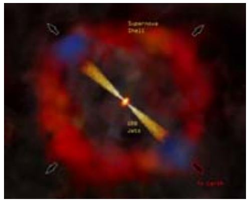






Schaefer (2003)

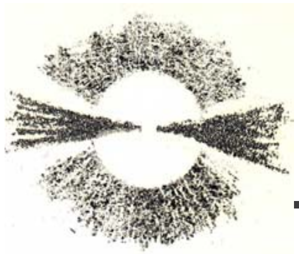
GRB and Cosmology



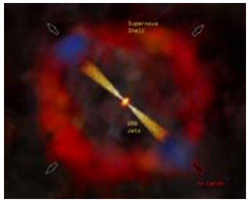
- Meszaros & Rees (2003) astro-ph/0305115
- GRB afterglow detection in the range (z = 10 – 30)

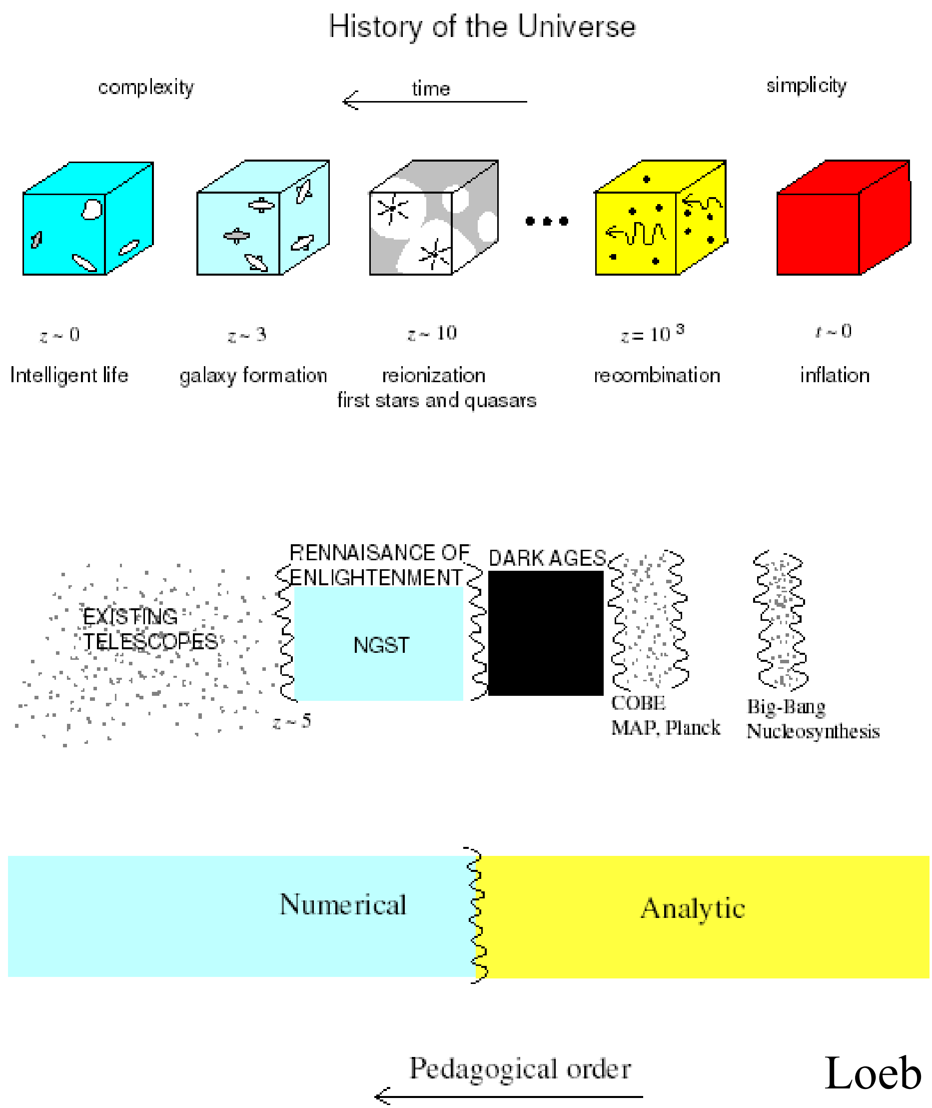
z	$\frac{\lambda_{Ly\alpha,H}}{\mu m}$	$\frac{E_t}{keV}$	$\frac{E_{Fe,K\alpha}}{keV}$	$F_E(10s)$	$F_E(10^2s)$	$F_E(10^3s)$	$F_E(10^4s)$	$F_E(10^5s)$
3	0.486	0.22	1.675	1.9^{-9}	6.8^{-10}	5.4^{-11}	4.3^{-12}	3.4^{-13}
6.5	0.912	0.22	0.893	6.1^{-10}	4.4^{-10}	3.5^{-11}	2.8^{-12}	2.2^{-13}
9.0	1.216	0.22	0.670	4.1^{-10}	4.1^{-10}	3.3^{-11}	2.6^{-12}	2.1^{-13}
12	1.581	0.22	0.515	3.0^{-10}	3.0^{-10}	3.2^{-11}	2.5^{-12}	2.0^{-13}
18	2.310	0.22	0.353	2.0^{-10}	2.0^{-10}	3.2^{-11}	2.6^{-12}	2.1^{-13}
30	3.770	0.22	0.216	1.3^{-10}	1.3^{-10}	3.5^{-11}	2.8^{-12}	2.2^{-13}

- X-ray flashes (E_{peak}, Rate ½ GRB, Isotropic) (Heise 2003) structured jets off-axis GRBs or high Z GRBs?

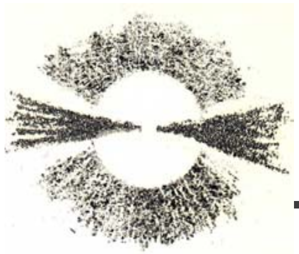


GRB Cosmology

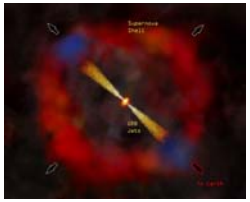


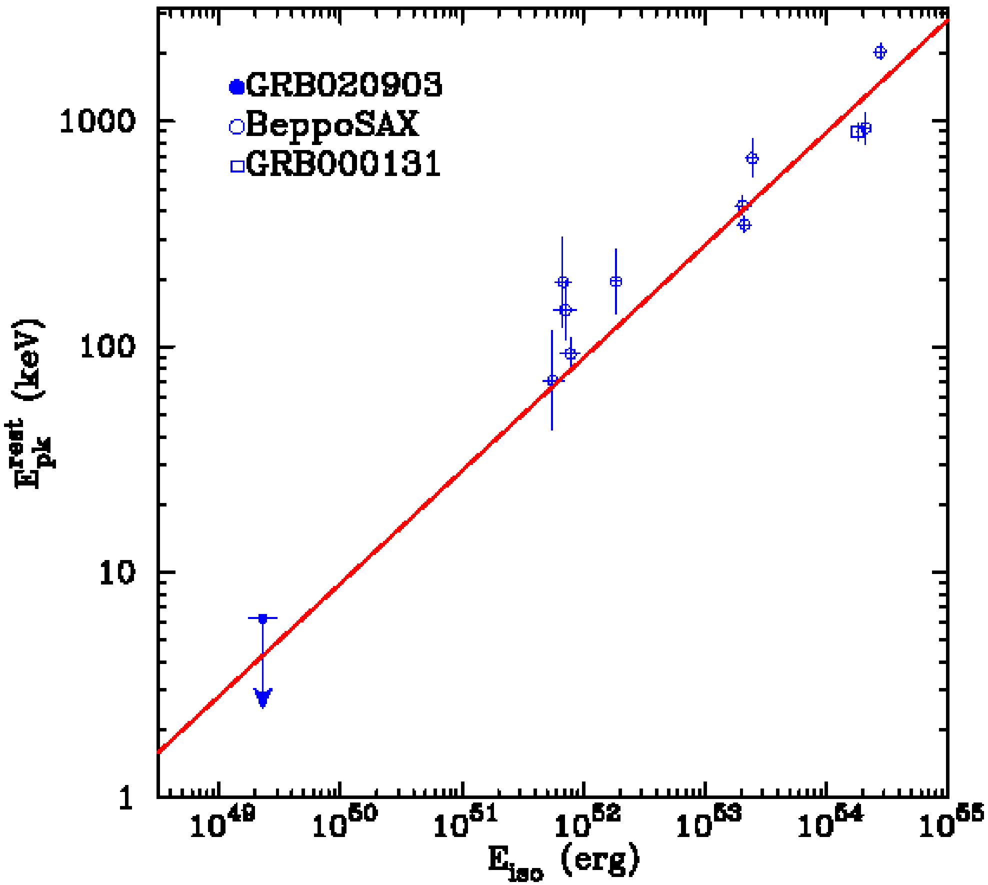


Loeb and Barkana (2000)



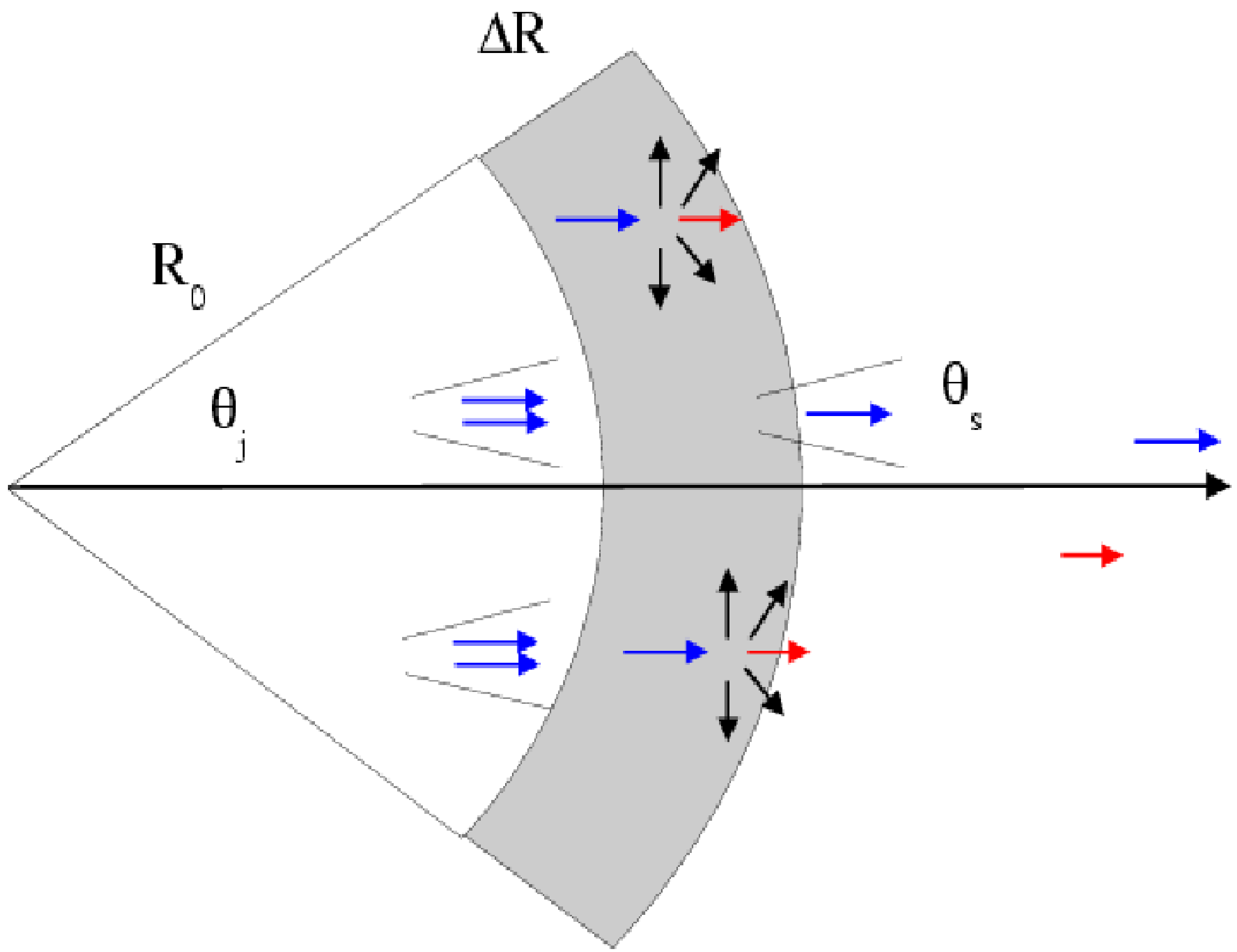
Peak Energy – Isotropic Energy



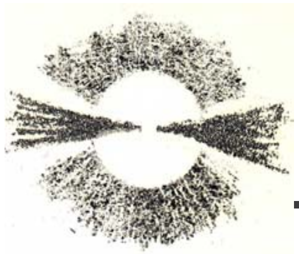


Sakamoto et al. (2003)

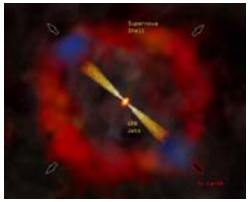
The Compton Tail



Barbiellini et al. (2004) in press



The Compton tail



- "Prompt" luminosity

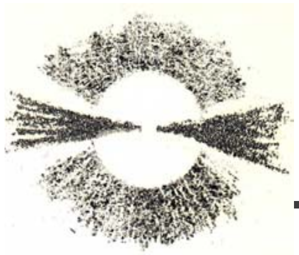
$$\langle L_{\rm s} \rangle = \langle \frac{dn_{\rm s}}{d\Omega\ dt} \rangle \simeq \frac{n_{\rm p}\ e^{-\tau}}{\pi\theta_{\rm s}^2\ t_{\rm grb}} \cdot \frac{\theta_{\rm s}^2}{\theta_{\rm j}^2}$$

- Compton "Reprocessed" luminosity

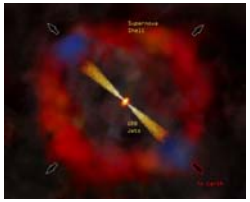
$$\langle L_{\rm c} \rangle = \frac{n_{\rm p}\ (1 - e^{-\tau})}{2\pi\ t_{\rm geom}} \qquad t_{\rm geom} \sim \frac{(R_0 + \Delta R)\theta_{\rm j}^2}{c}$$

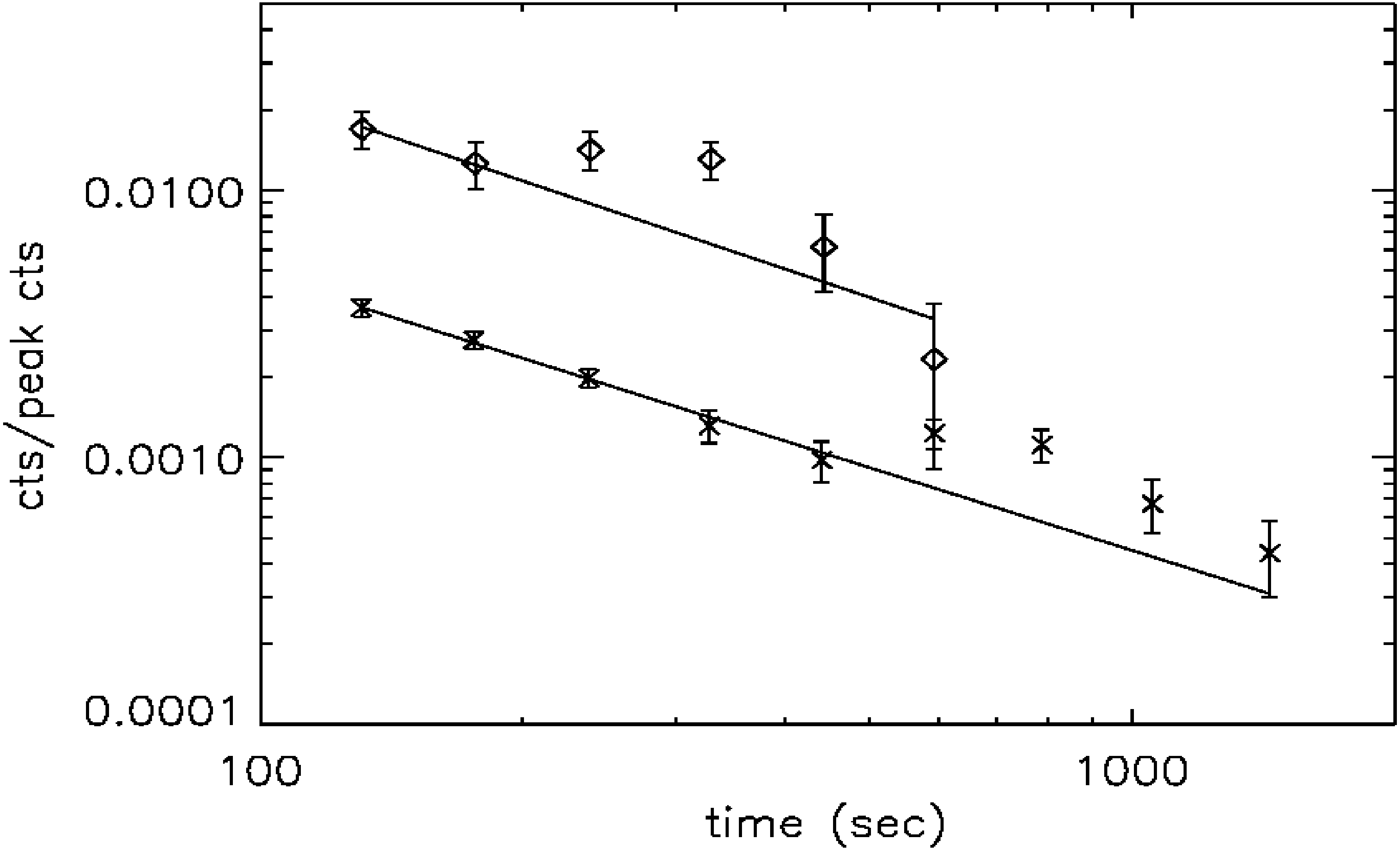
- "Q" ratio

$$\boxed{Q = \frac{\langle L_{\rm c} \rangle}{\langle L_{\rm s} \rangle} = (e^{\tau} - 1) \cdot \frac{c\ t_{\rm grb}}{(R_0 + \Delta R)}}$$

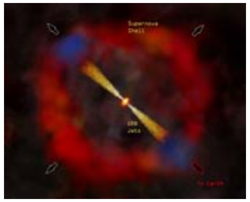


Bright and Dim GRB

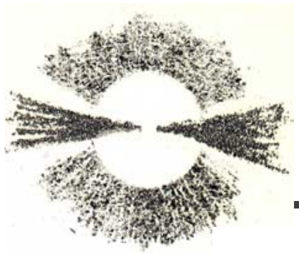




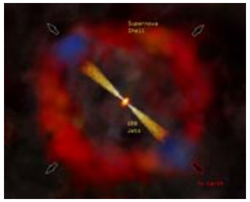
Bright and Dim Bursts



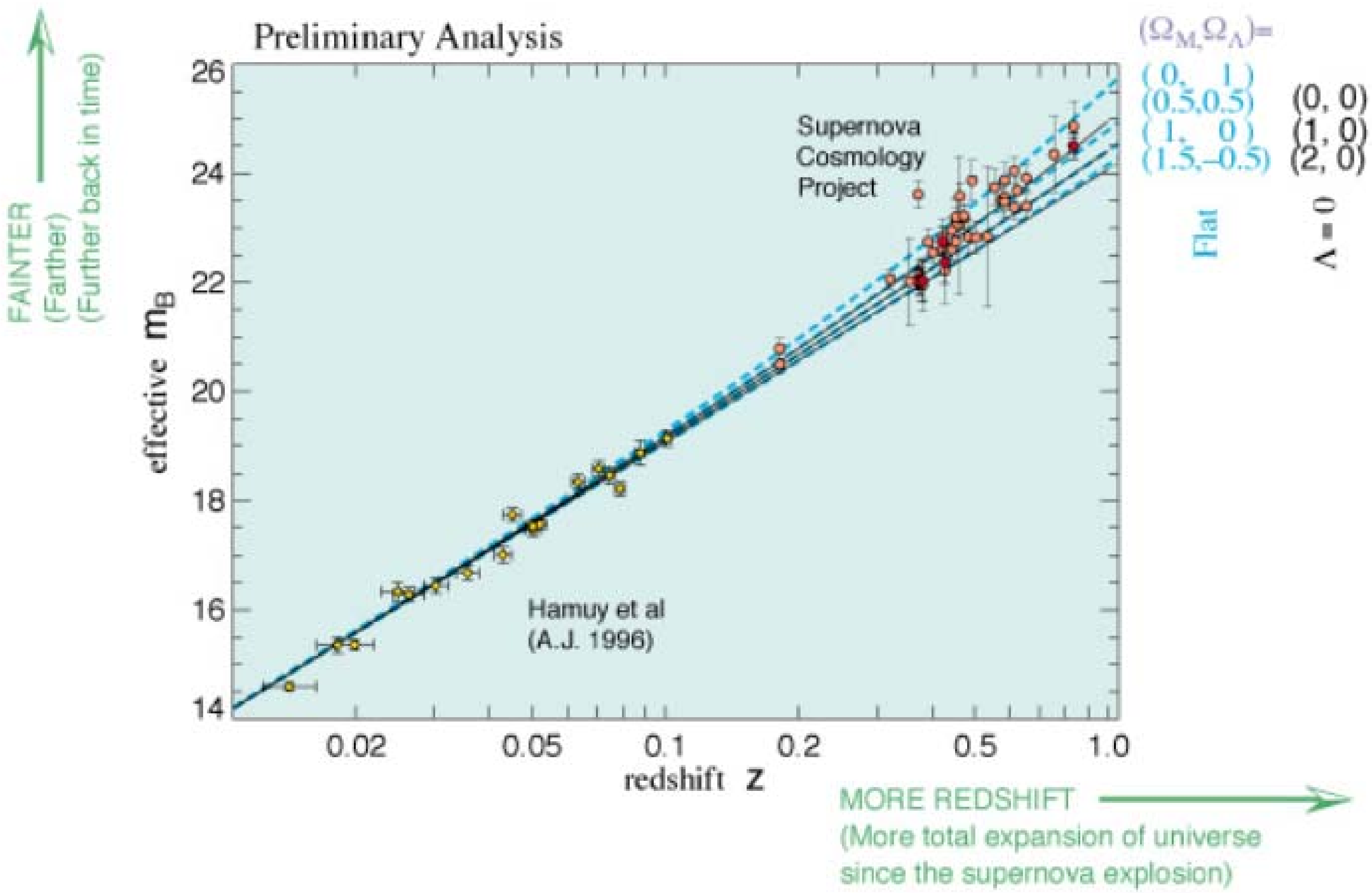
- Bright bursts (peak counts >1.5 $cm^{-2}\ s^{-1}$)
  - $Q = 4.0 \pm 0.8\ 10^{-4}$ (5 σ)
  - $\tau = 1.3$
- Dim bursts (peak counts < 0.75 $cm^{-2}\ s^{-1}$)
  - $Q = 5.6 \pm 1.4\ 10^{-3}$ (4 σ)
  - $\tau = 2.8$
- Mean fluence ratio = 11
- "Compton" correction $\boxed{E = e^{\tau} E_{\mathrm{obs}}}$
- Corrected fluence ratio = 2.8
- A cosmological effect?

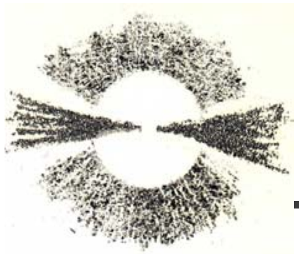


The SNIa "cosmology"

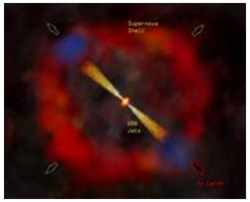


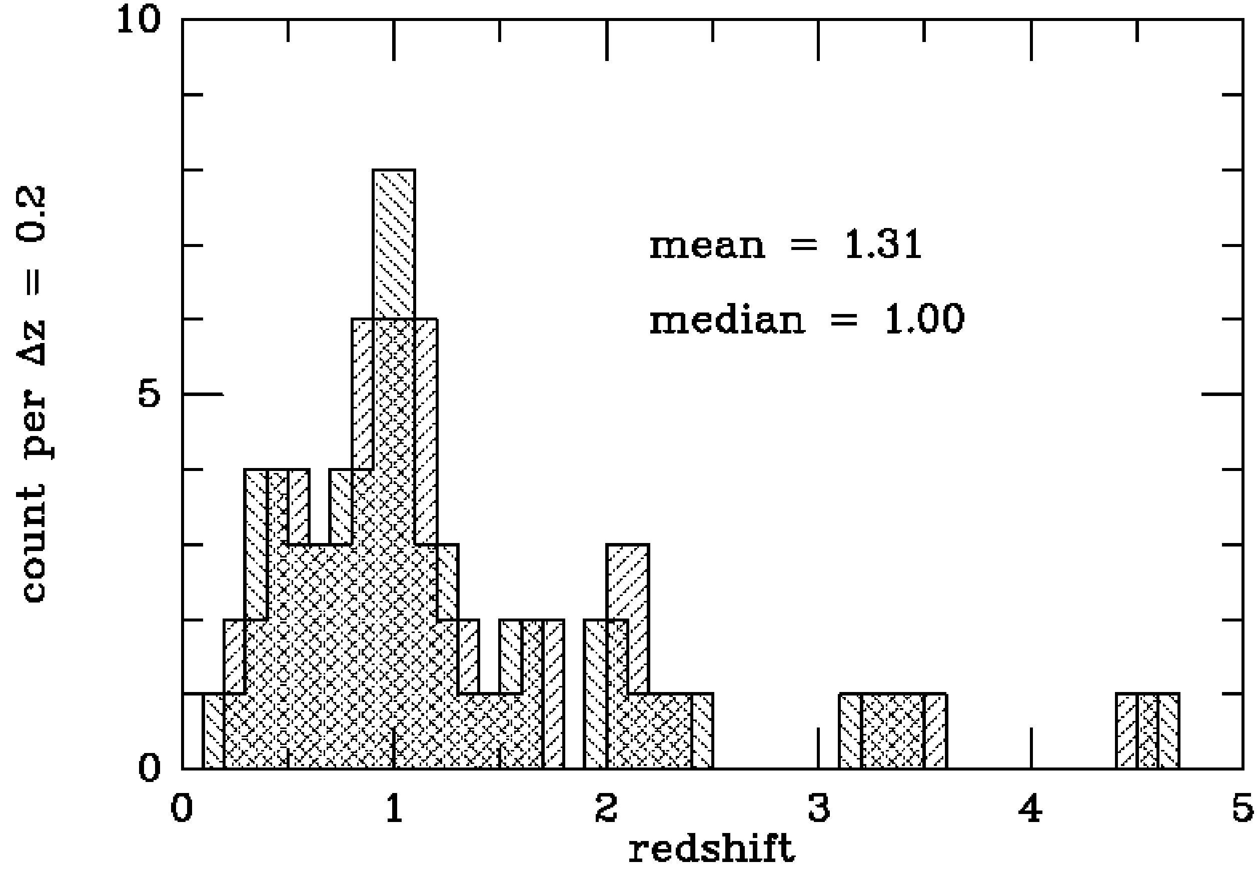
Hubble Plots



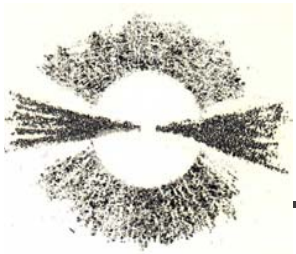


GRB and Cosmology

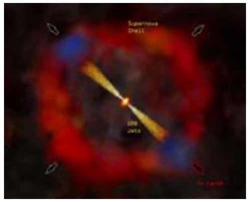




Djorgovski et al. 2003



Conclusions



- GRB and Cosmology: a long story
- Study of first galaxies and first stars
- Look into the Dark Ages
- Spectroscopy of high-Z Universe
- GRB as standard candle?
- GRB as cosmological probe