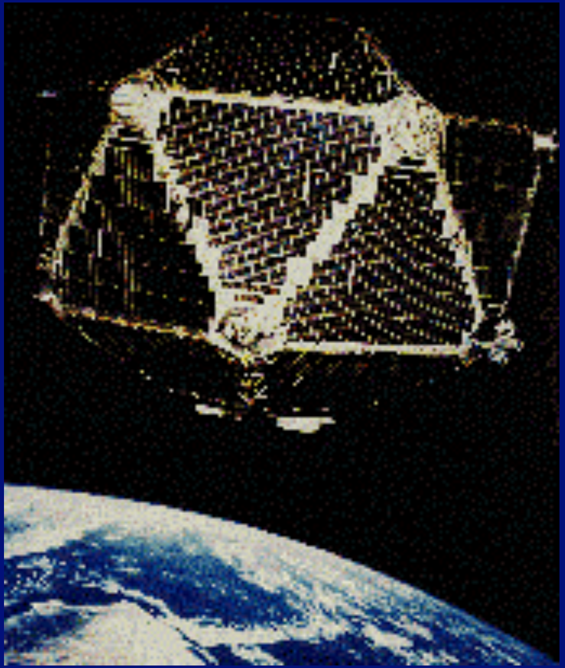
Gamma Ray Bursts

The Largest Bangs in the Universe, Since the Big One.

THE DISCOVERY

Gamma-Ray Bursts (GRBs) Short (few seconds) bursts of 100keV- few MeV were discovered accidentally by Klebesadal Strong and Olson in 1967 using the Vela satellites (defense satellites sent to monitor the outer space treaty).

- *The discovery was reported for the first time only in 1973.*

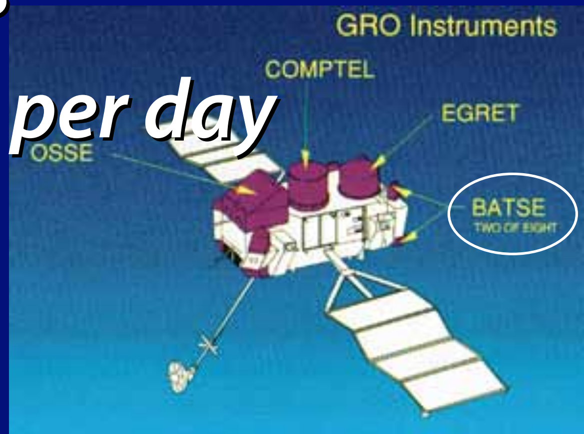


- There was an "invite prediction". S. Colgate was asked to predict GRBs as a scientific excuse for the launch of the Vela Satellites

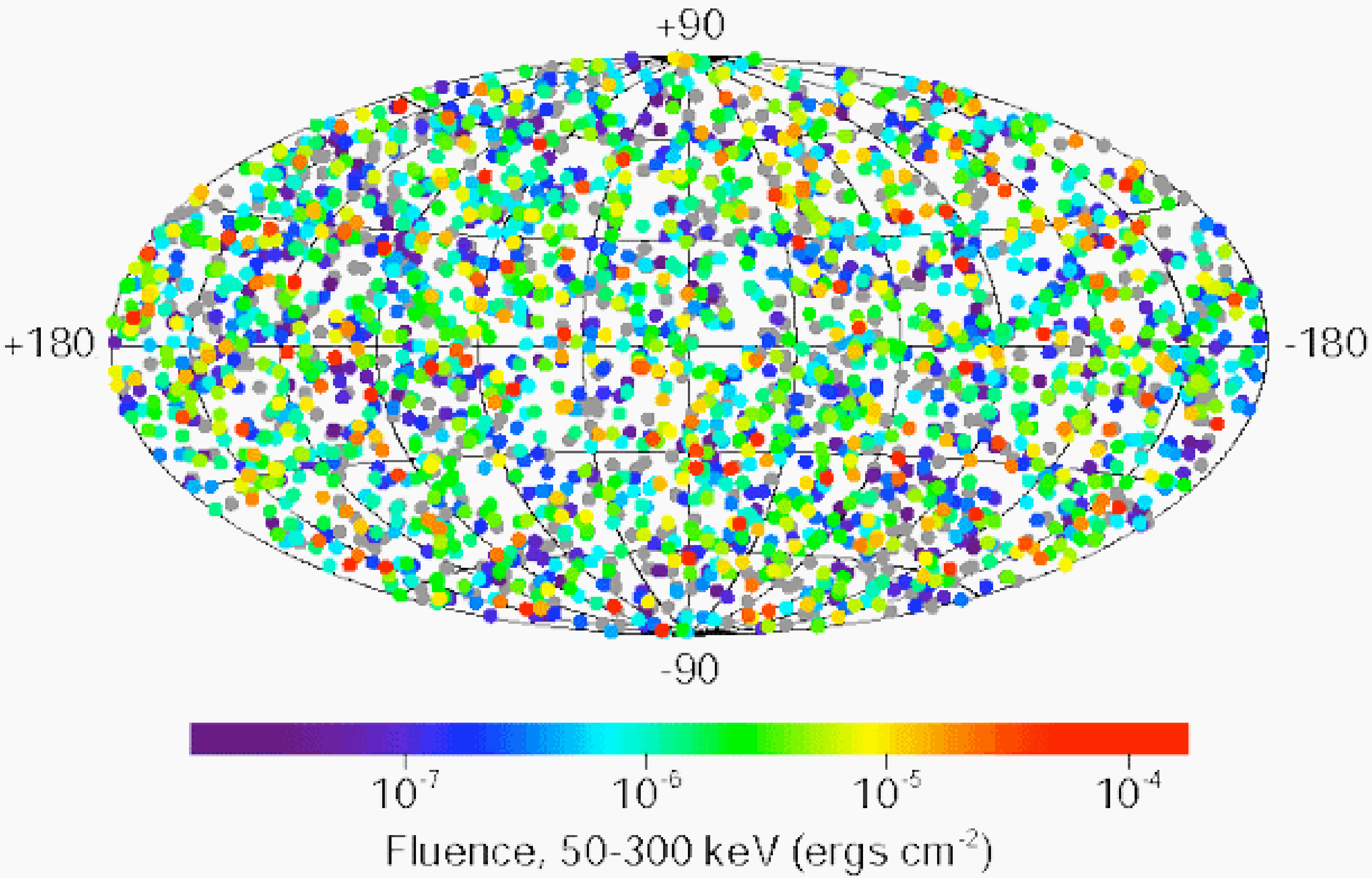
BATSE - Compton GRB

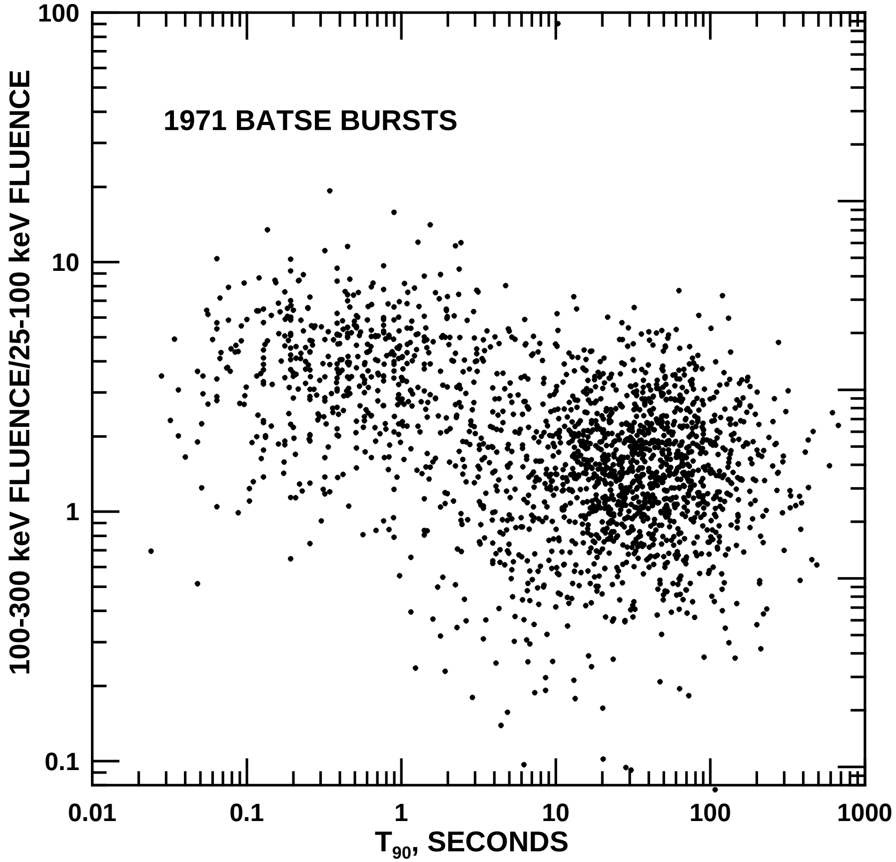
- *GRBs are Isotropic on the Sky*
- *GRBs divide into two classes*
- *GRBs happen about 3 times per day*

Compton-GRO

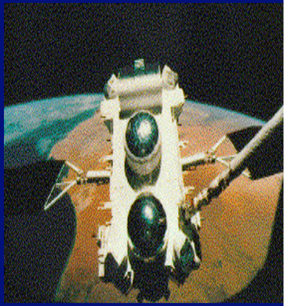


2704 BATSE Gamma-Ray Bursts




1971 BATSE BURSTS
100-300 keV FLUENCE/25-100 keV FLUENCE
100
10
1
0.1
0.01
0.1
1
10
100
1000
T90, SECONDS

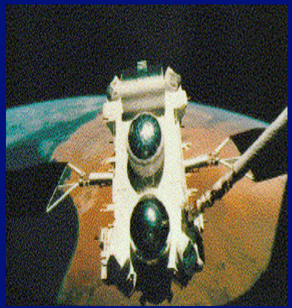
1991: BATSE –
The First Revolution



- *BATSE on Compton - GRO (Fishman et. al.) discovered that the distribution of GRBs is isotropic:*

GRBs are Cosmologic Distances or are they?

1991: GRBs are Cosmological



- ***BATSE on Compton - GRO (Fishman et. al.) discovered that the distribution of GRBs is isotropic:***

- The flux distribution (paucity of weak bursts) shows that the bursts cannot be very nearby in the disk:

⇒ **GRBs are Cosmological**

- By now there are redshift measurements for the afterglow of two dozen bursts.

GRBs and Relativity

GRBs are the brightest and most luminous objects known today.

GRBs involve the fastest macroscopic relativistic motion observed so far ($\Gamma>100$)

GRBs signal (most likely) the formation of newborn black holes.

Sources of GRBs (merging NS or Collapsars) are also sources of Gravitational radiation

GRBs are the brightest objects in the universe.

GRBs are the most relativistic objects known today.

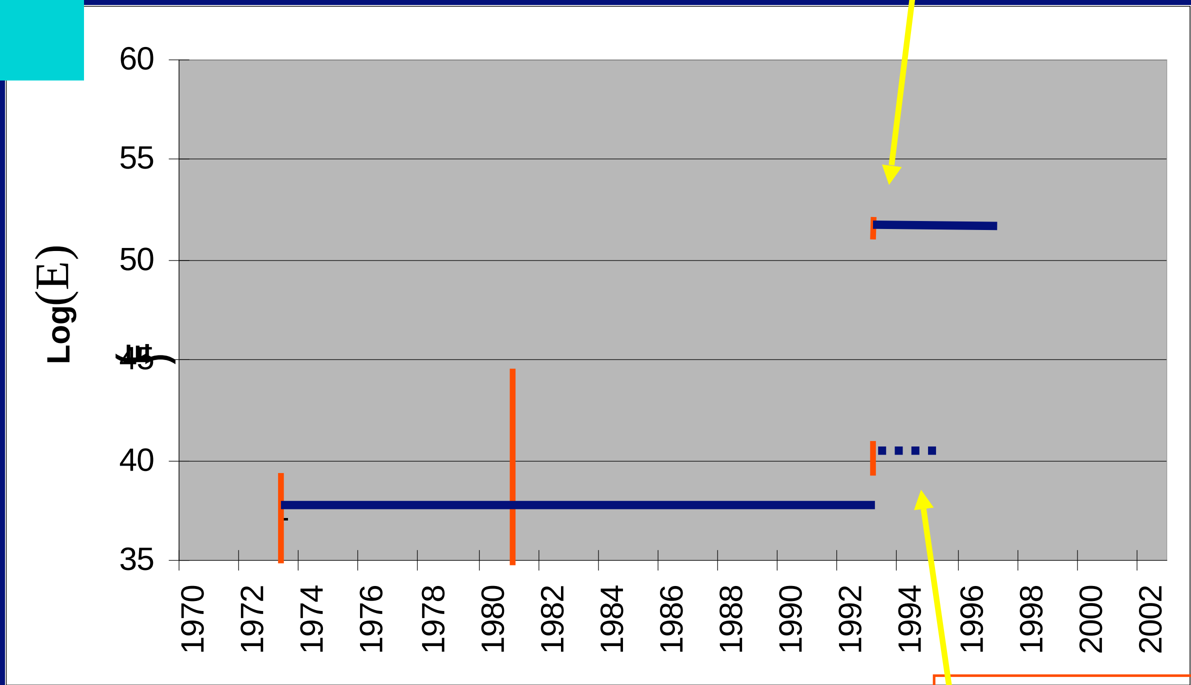
Revised Energy Estimates

The observed fluences are ~10^{-7} - 10^{-5} ergs/cm^2

$$F = \frac{E(1+z)}{4\pi d_L^2}$$

Cosmological corrections.

Cosmological

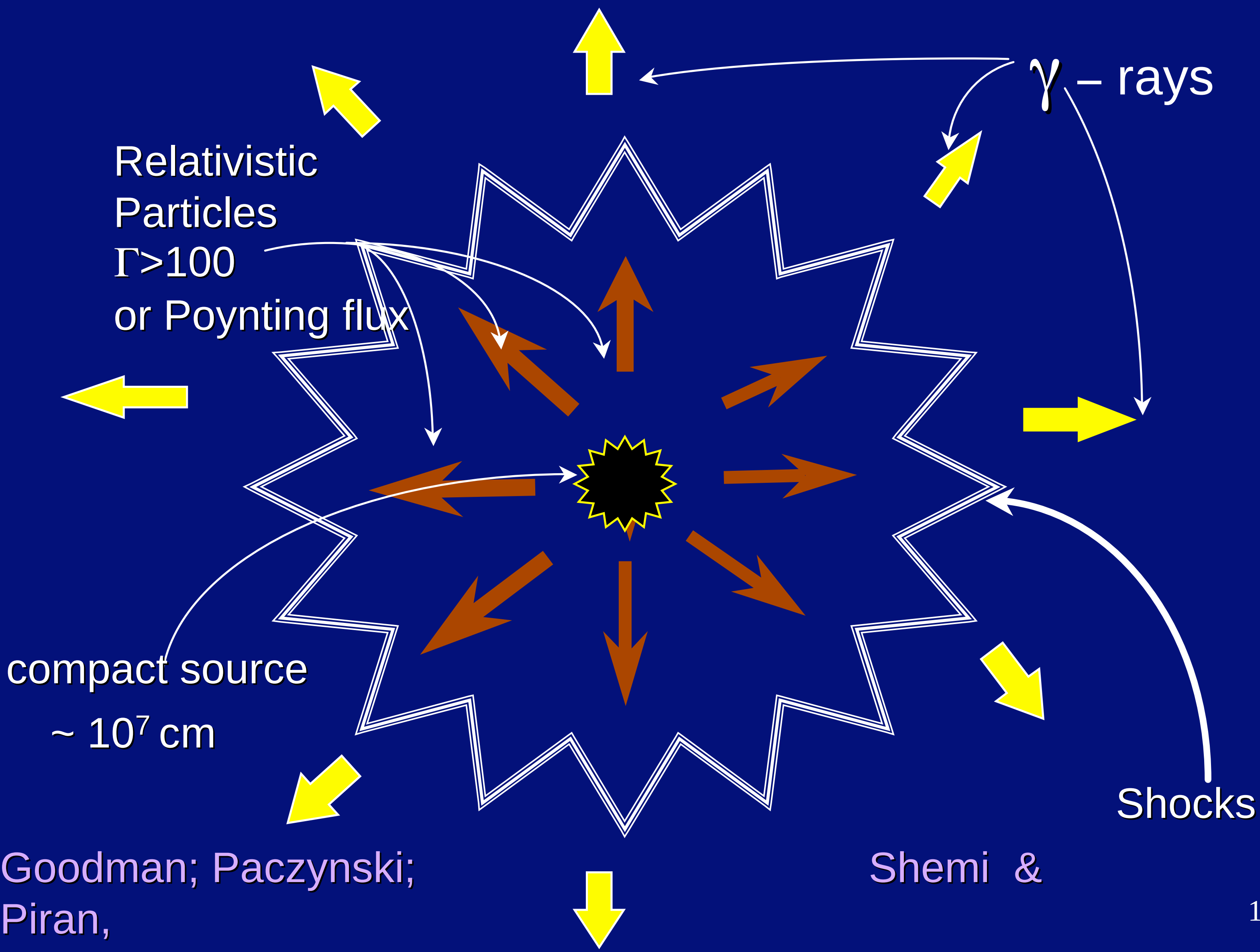


Galactic Halo models

- $z \sim 1 \Rightarrow E \sim 10^{52}$ergs $\Rightarrow$ **GRBs are the (electromagnetically) most luminous objects in the Universe.**
- **For a few second the luminosity of a GRB is comparable to the luminosity of the rest of the Universe.**

From Tsvi Piran

The Fireball Model



Goodman; Paczynski;
Piran,
Narayan, Paczynski & Piran;

Shemi &

Meszaros &

Implications of 10^{52}ergs

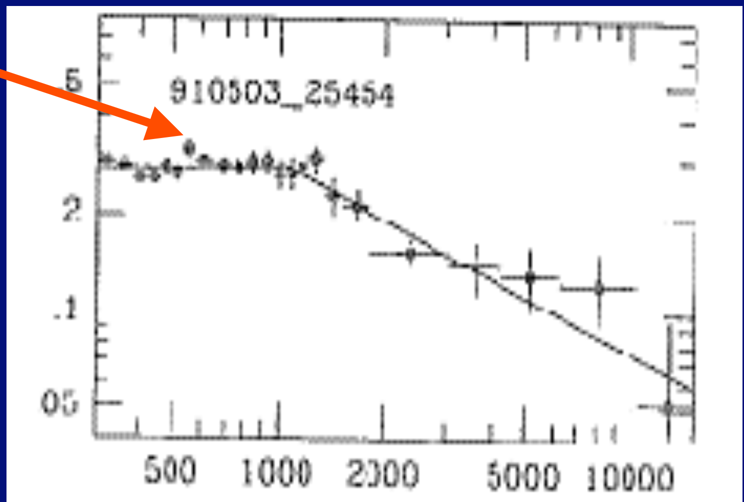
Implications of 10^{52} ergs -
The Compactness Problem: $\gamma\gamma \rightarrow e^+e^-$

- $\delta T \leq .1$ *sec* $\Rightarrow$ $R \leq c\delta T = 3\ 10^9$ *cm.*
- $E \cong 10^{52}$*ergs.*

$\Rightarrow \tau_{\gamma\gamma} = n_\gamma \sigma_T R \geq 10^{15}$

$\Rightarrow$ Expect No Photons above 500keV!

BUT:



The Solution

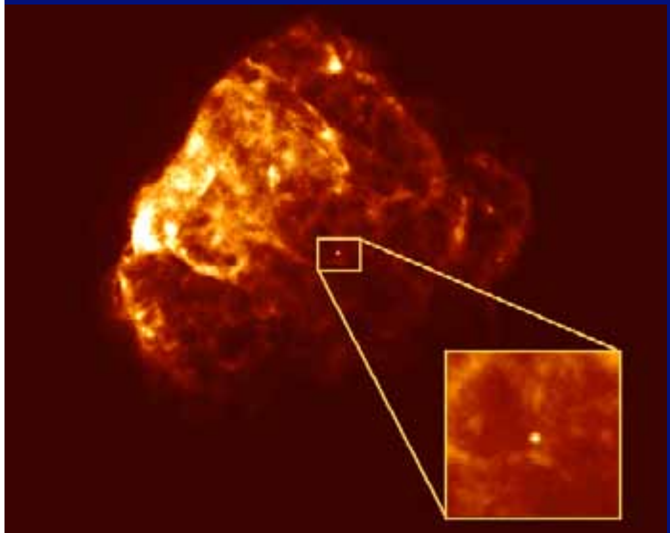
Relativistic Motion

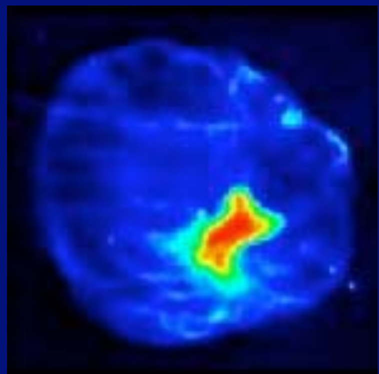
- $R \leq c\gamma^2 \delta T$
- $E_{ph}\,(obs) = \gamma\, E_{ph}\,(emitted)$

- $\tau_{\gamma\gamma} = \gamma^{-(2+2\alpha)}\, n_\gamma \sigma_T R \geq 10^{15}/\gamma^{(2+2\alpha)}$

$$\gamma \geq 100 \quad (\alpha \cong 2)$$

Supernova Remnants (SNRs) - the Newtonian Analogue





- *~ 10 solar masses are ejected at ~10,000 km/sec during a supernova explosion.*
- *The ejecta is slowed down by the interstellar medium (ISM) emitting x-ray and radio for ~10,000 years.*

Gamma-Ray Burst:
3 Stages

1) Compact Source, $E>10^{52}$erg

↓

2) Relativistic Kinetic Energy

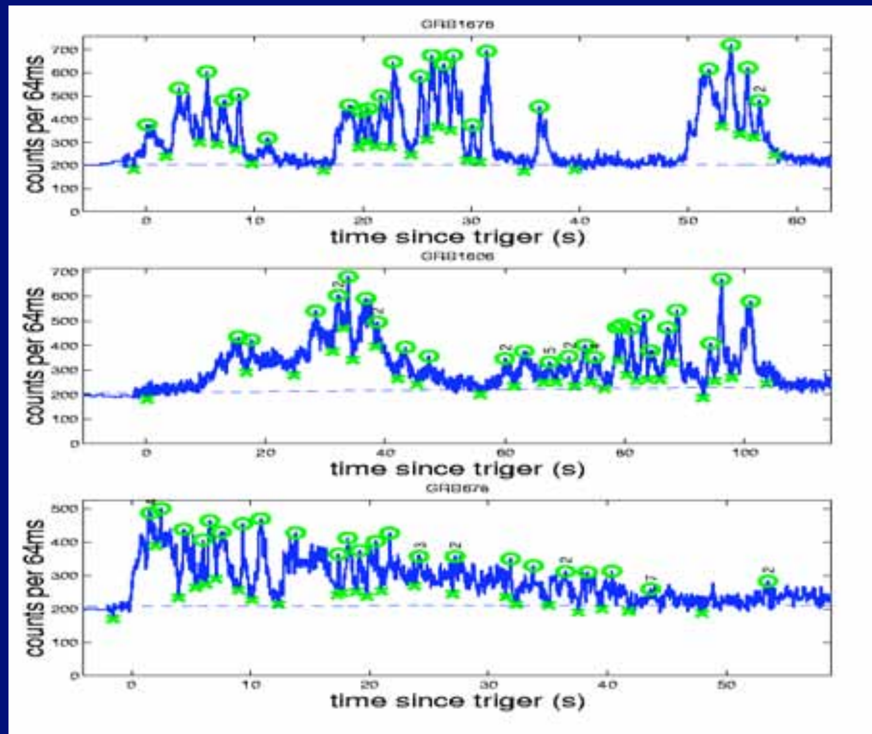
↓

3) Kinetic Energy to Internal Energy to Radiation=GRB

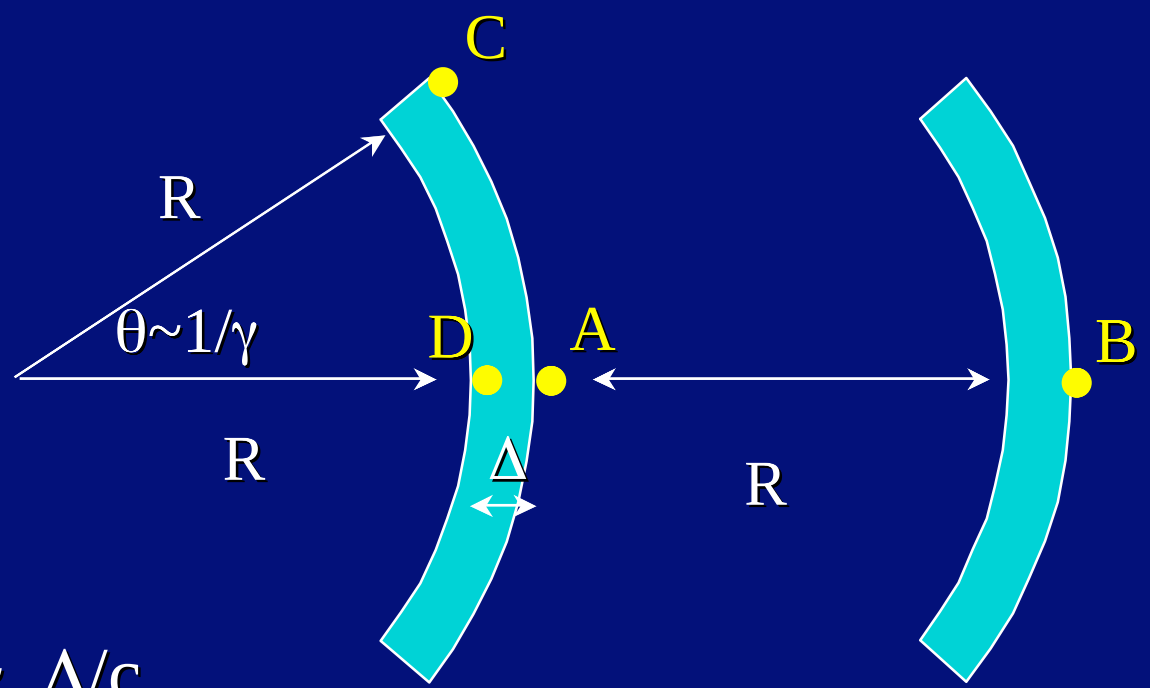
Temporal Variability- the Second Clue

$\delta T < 1\text{sec}, \quad T \sim 100 \quad \longrightarrow \quad N = T/\delta T > 100$

- ***External shocks cannot produce the observer variability in the light curves** (Sari & Piran, 97, Fenimore et al, 97).*



Relativistic Time Scales



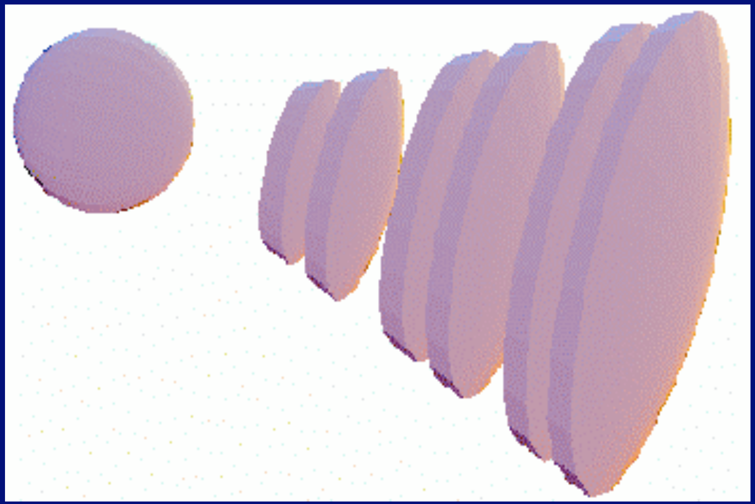
$t_D - t_A \sim \Delta/c$

$t_C - t_A \sim R(1-\cos\theta)/c \sim R/2\gamma^2 c$

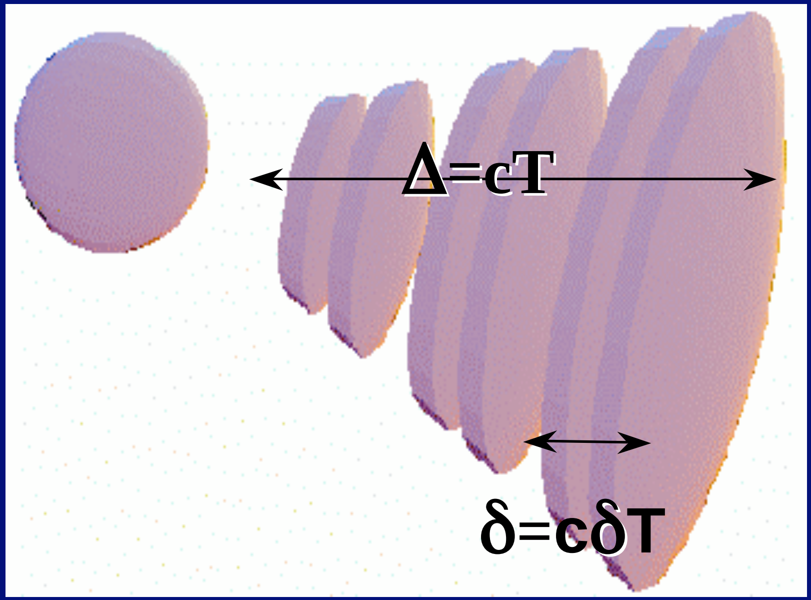
$t_B - t_A \sim R\,(1-\beta)\,/\,c \sim R/2\gamma^2 c$

External vs. Internal Shocks

- *External shocks are shocks between the relativistic ejecta and the ISM - just like in SNRs.*
- *Internal shocks occur between different shells within the relativistic ejecta.*

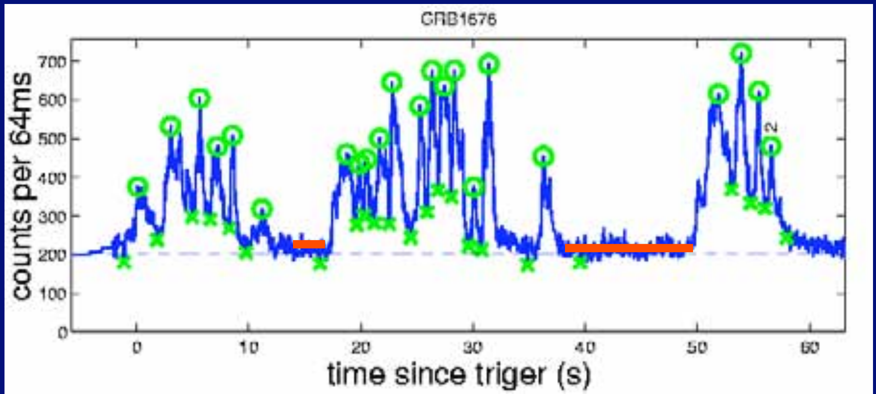


Internal Shocks



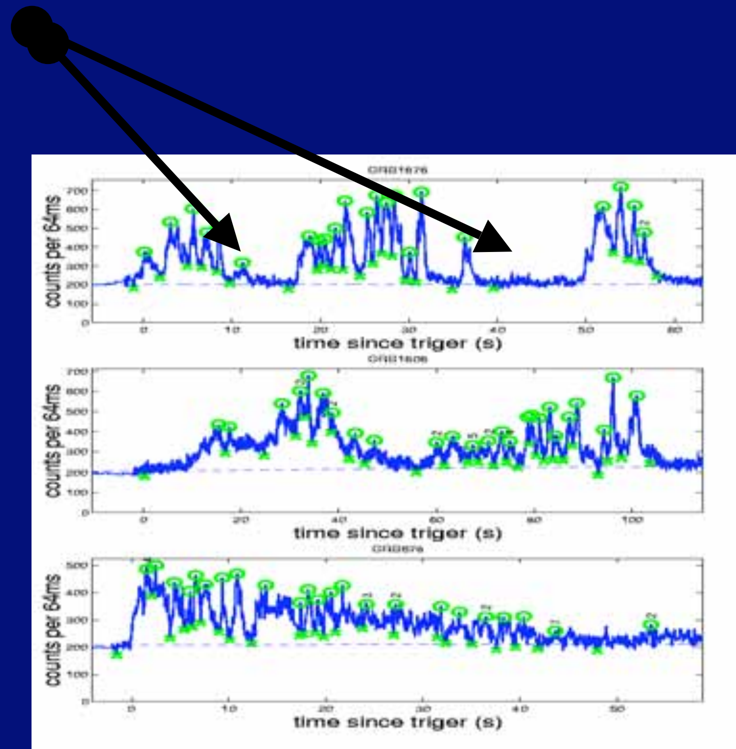
- δT = $R/c\gamma^2$ = $\delta/c \leq \Delta/c = T$
- ***The observed light curve reflects the activity of the "inner engine". Need TWO time scales.***
- ***Quiescent Periods within long bursts suggest that the source is inactive for of dozen seconds within long bursts***

(Nakar and Piran, 2000).

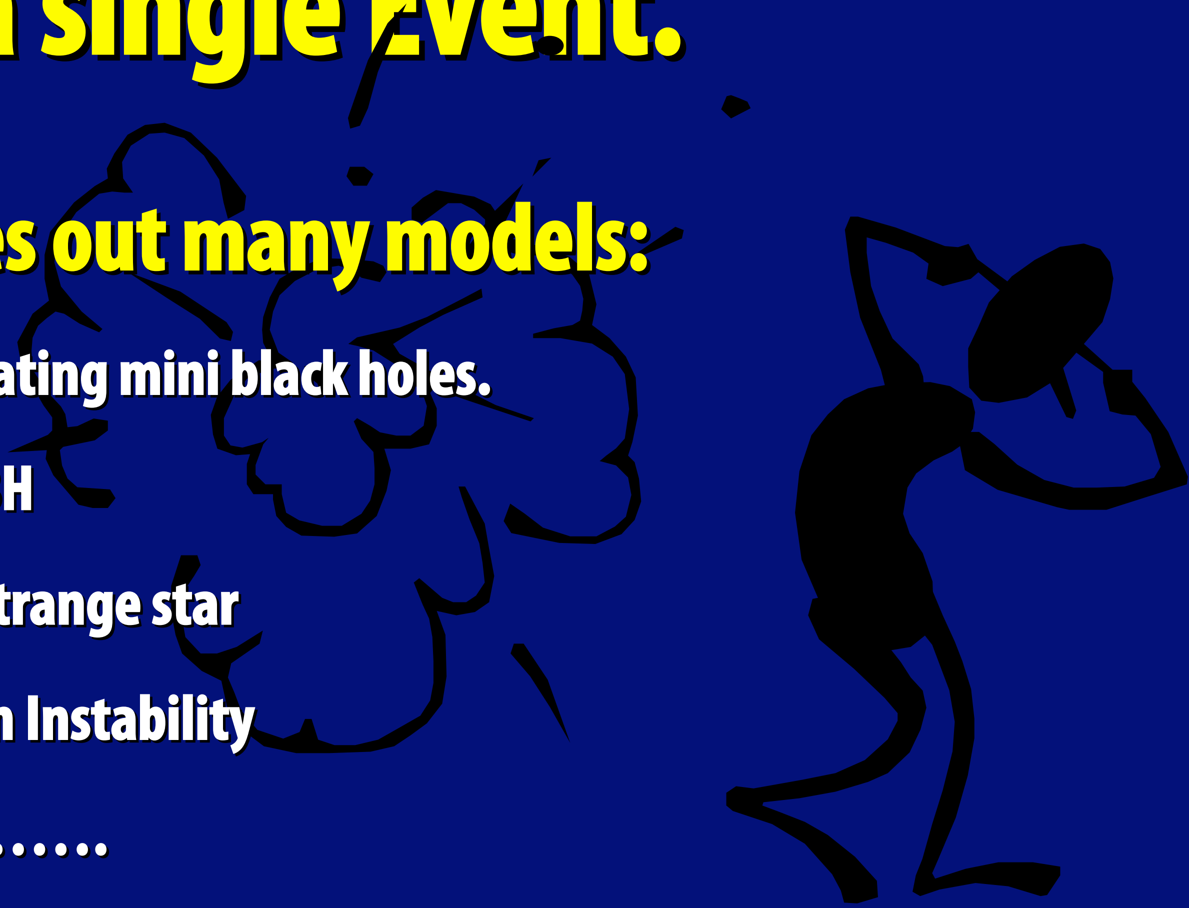


Quiescent Periods

- ***Quiescent Periods within long bursts suggest that the source in in active for periods of dozen seconds within long bursts** (Nakar and Piran, 2000).*



(most)* GRBs cannot originate from a single Event.

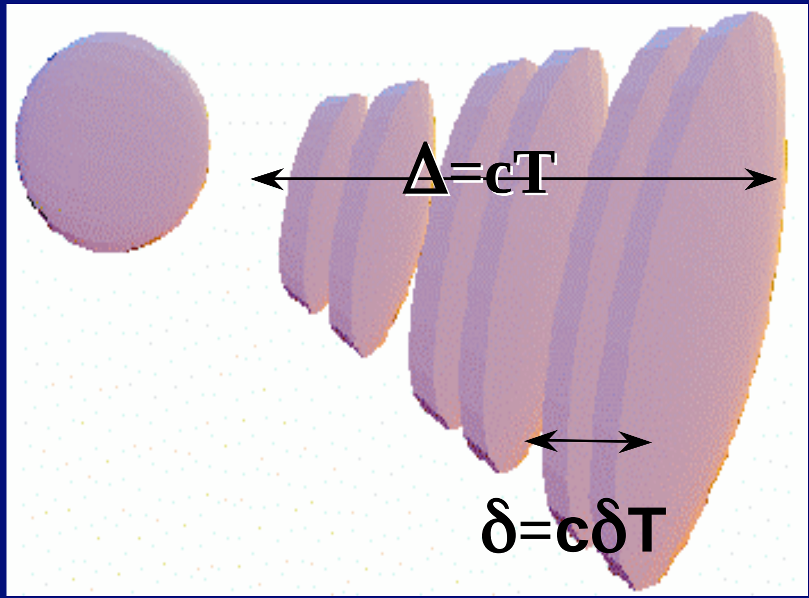


This rules out many models:

- Evaporating mini black holes.
- NS -> BH
- NS -> strange star
- Vacuum Instability
- ………….

*** Highly variable (there is a small group of smooth bursts which can be explosive)**

Internal Shocks ÞAfterglow



- **Internal shocks can convert only a fraction of the kinetic energy to radiation**

  (Sari and Piran 1997; Mochkovich et. al., 1997; Kobayashi, Piran & Sari 1997).

➢ **It should be followed by additional emission.**

Gamma-Ray Burst:
4 Stages

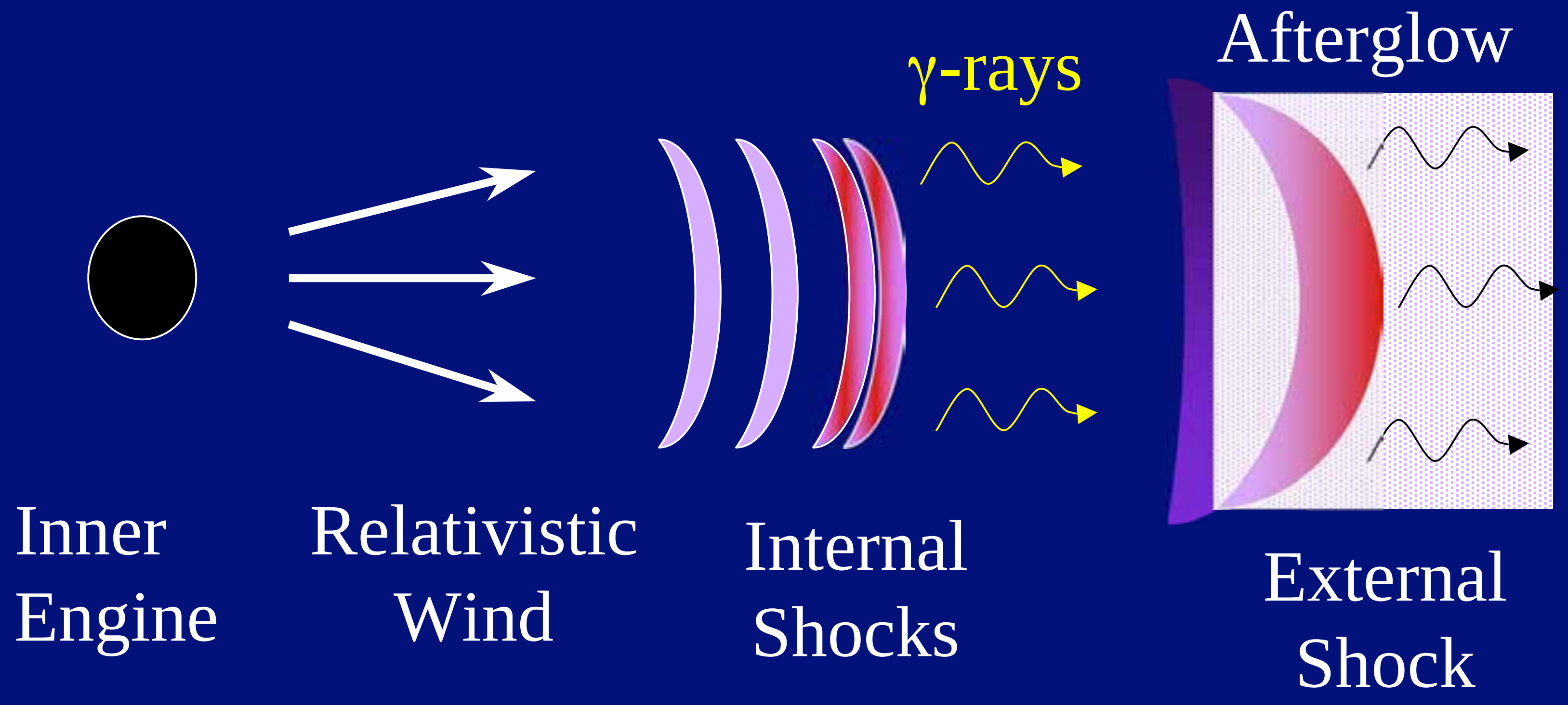
1) Compact Source, $E>10^{51}$erg

2) Relativistic Kinetic Energy

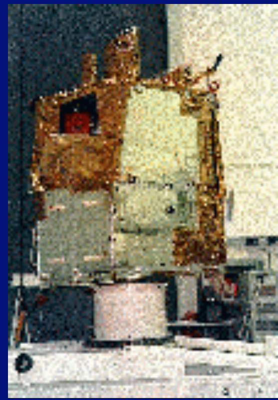
3) Radiation due to Internal shocks = GRBs

4) Afterglow by external shocks

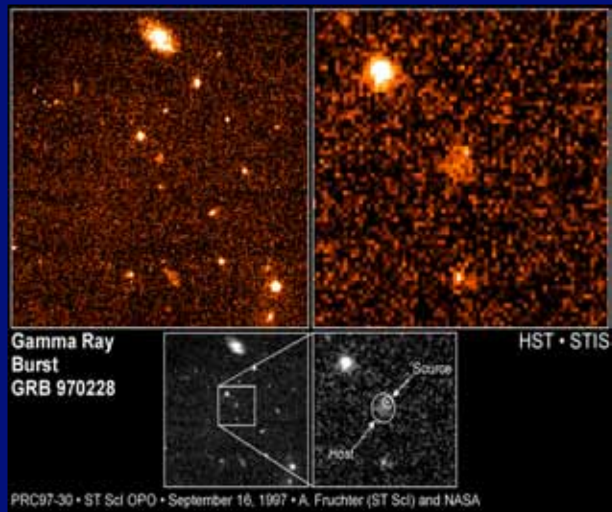
The Internal-External Fireball Model



Afterglow – The Second Revolution



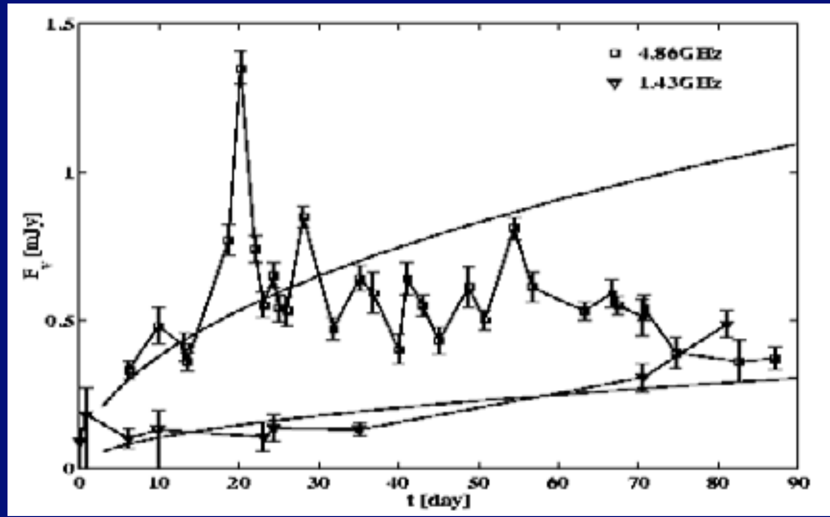
- *The Italian/Dutch satellite BeppoSAX discovered x-ray afterglow on 28 February 1997 (Costa et. al. 97).*



- *Immediate discovery of Optical afterglow (van Paradijs et. al 97).*

The Radio Afterglow of GRB970508

(Frail et. al, 97).

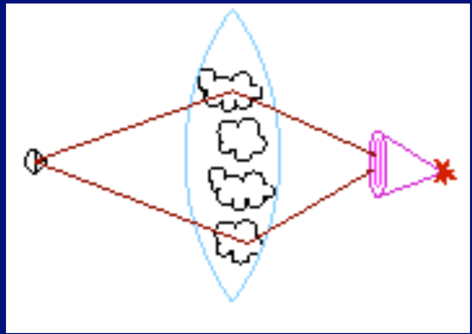


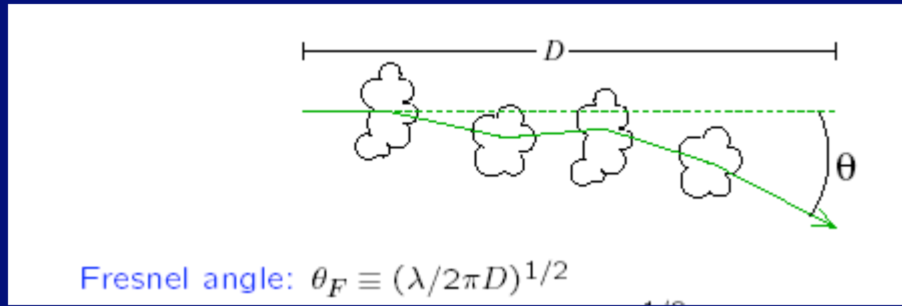
- *Variability:*
  - *Scintillations (Goodman, 97; Frail et al 97)*
  - → *Size after one month ≅10^{17}cm.*
- *Rising Spectrum at low frequencies:*
  - *Self absorption (Katz & Piran, 97; Frail et al 97)*

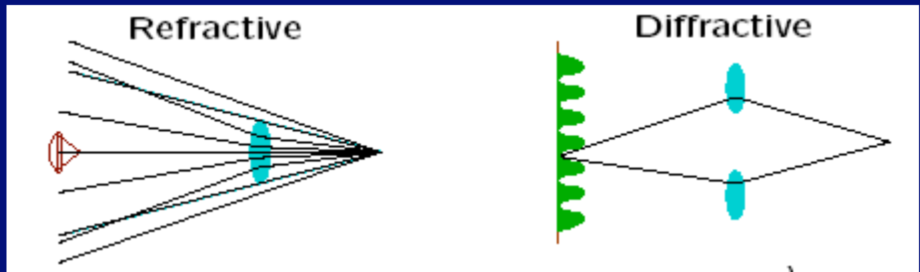
    → *Size after one month ≅ 10^{17}cm.*

➢ ***Relativistic Motion!!!*** *(but γ ≅ 2 since this is a long time after the explosion).*

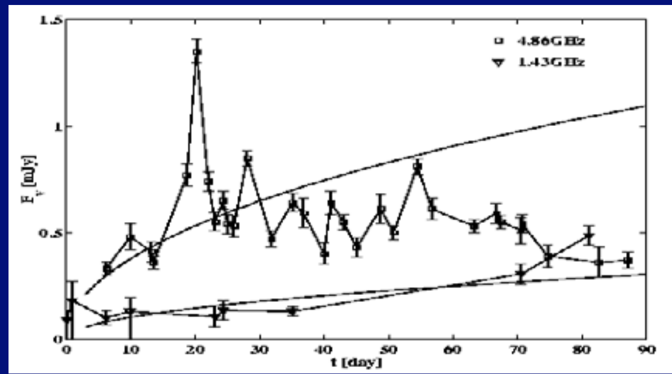
Scintillations







Strong scattering: $\theta_d \gg \theta_F$.
Weak scattering: $\theta_d \ll \theta_F$.



Scintillations determine the size of the source in a model independent way. The size (~10^{17}cm) is as expected (3e10 cm/s * 80 day* 86400 s/day)

Afterglow Theory

Hydrodynamics: *deceleration of the relativistic shell by collision with the surrounding medium*
(Blandford & McKee 1976)

(Meszaros & Rees 1997, Waxman 1997, Sari 1997, Cohen, Piran & Sari 1998)

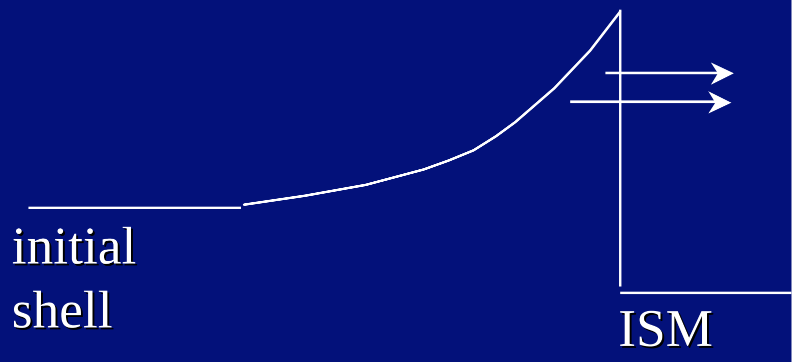
Radiation: *synchrotron + Inverse Compton Scattering*

(Sari, Piran & Narayan 98)

Clean, well defined problem.

Few parameters:

$E, n, p, \varepsilon_e, \varepsilon_B$



- ***Adiabaticity:*** $E_0 = Mc^2\gamma^2 = (4\pi/3)R^3c^2\gamma^2$

- ***Arrival time:*** $t_{obs} = R/2\gamma^2$

- ***Energy densities:*** $e_e = \varepsilon_e e = \varepsilon_e n_0 c^2\gamma^2$

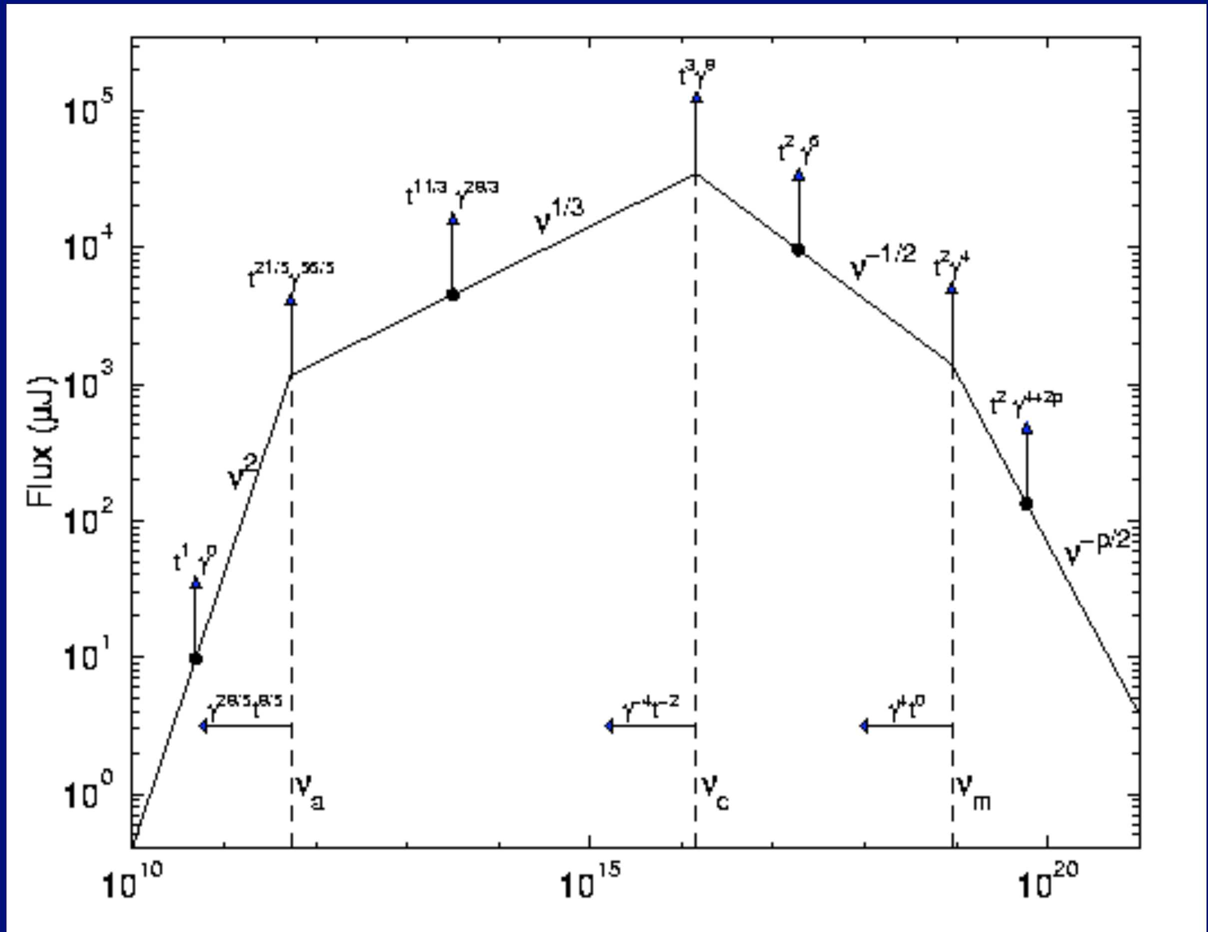
  $e_B = \varepsilon_B e = \varepsilon_B n_0 c^2\gamma^2$

- ***Electron distribution:***

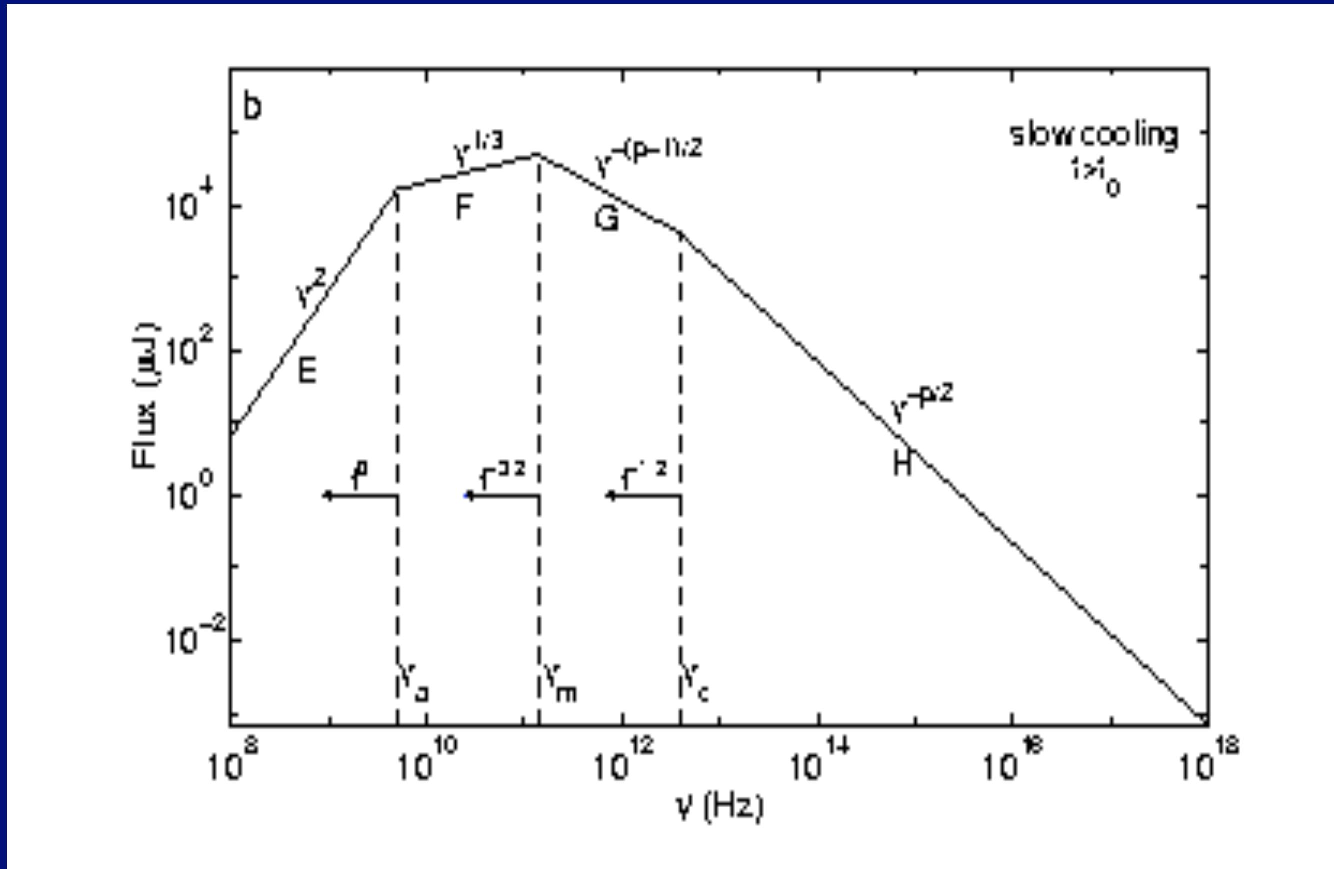
  $n(\gamma) \propto \gamma^{-p} \text{ for } \gamma > \gamma_{\min} \propto e_e$

The Simplest Synch Spectrum (I)

(Sari Piran & Narayan 1998)

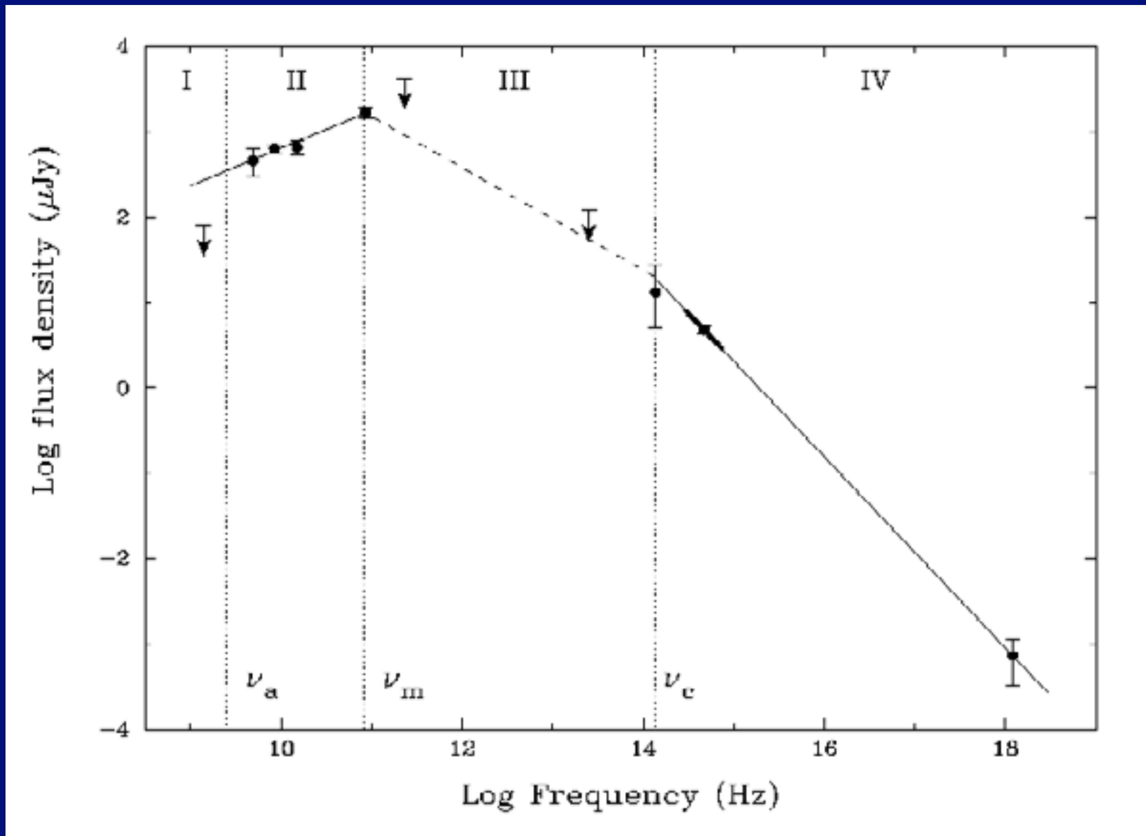


The Simplest Synch Spectrum (II)

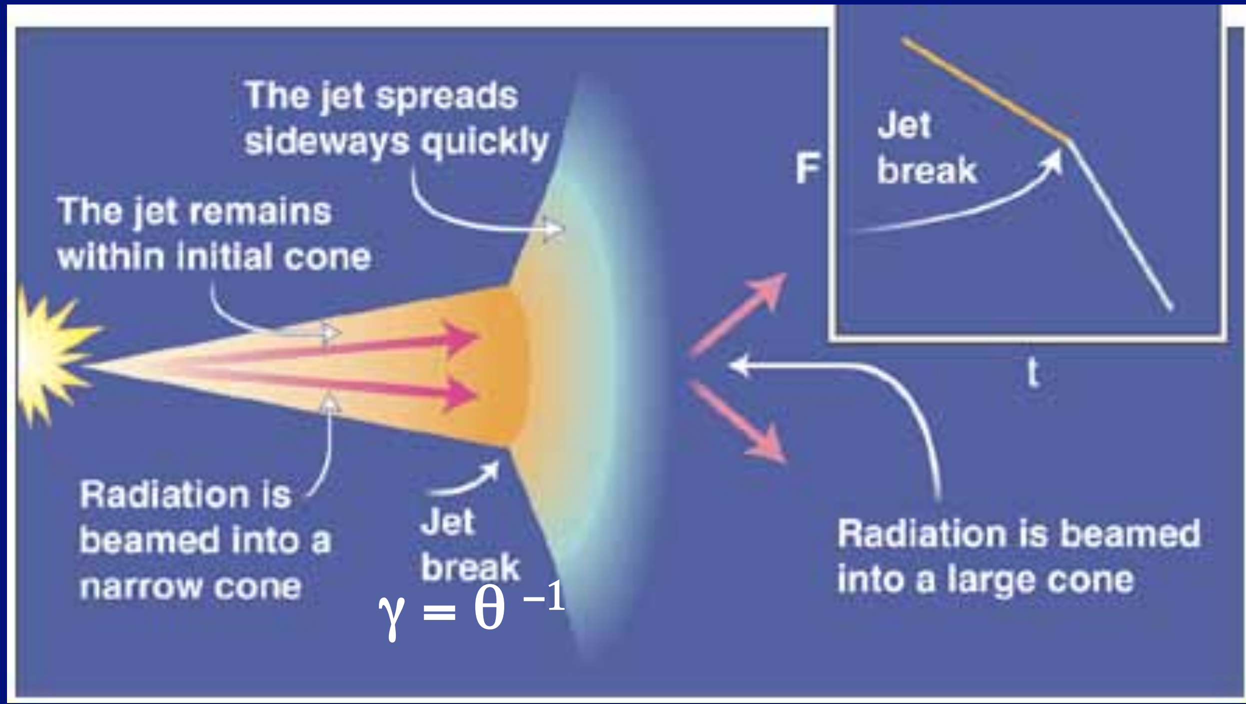


Comparison with Observations

(Sari, Piran & Narayan 98; Wijers & Galama 98; Granot, Piran & Sari 98)



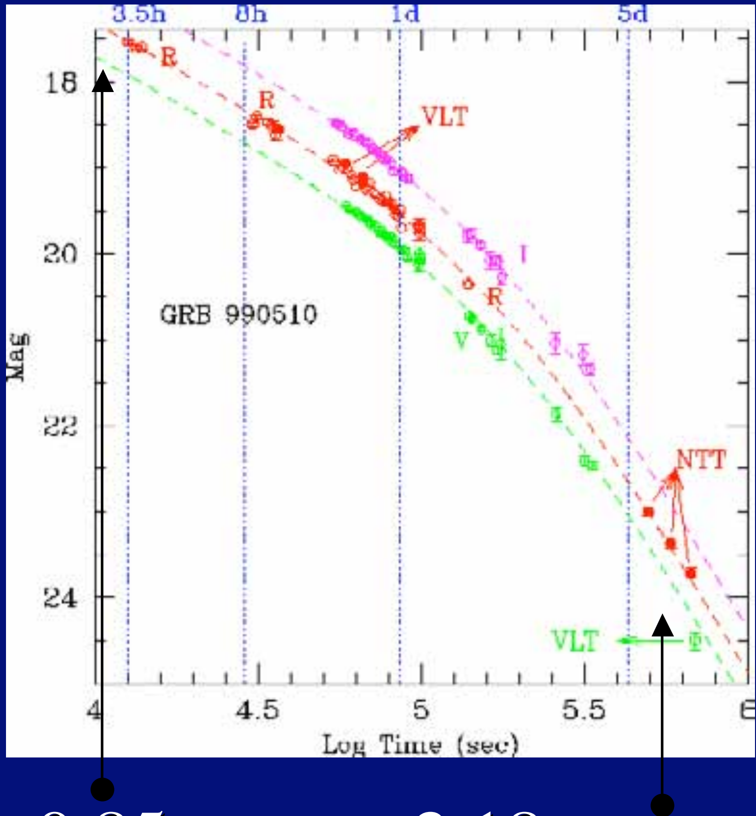
JETS and BEAMING

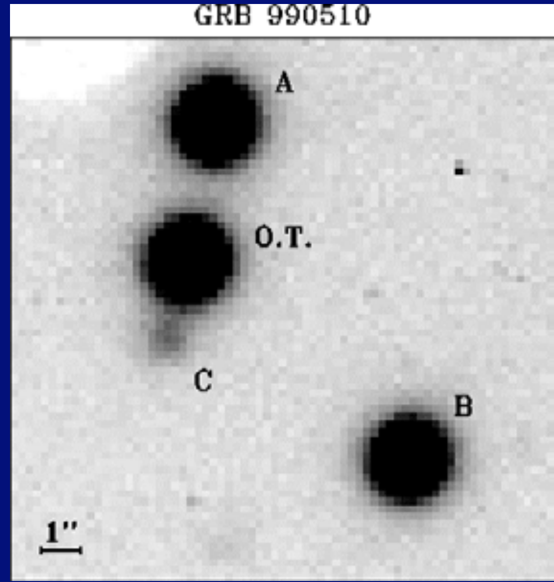


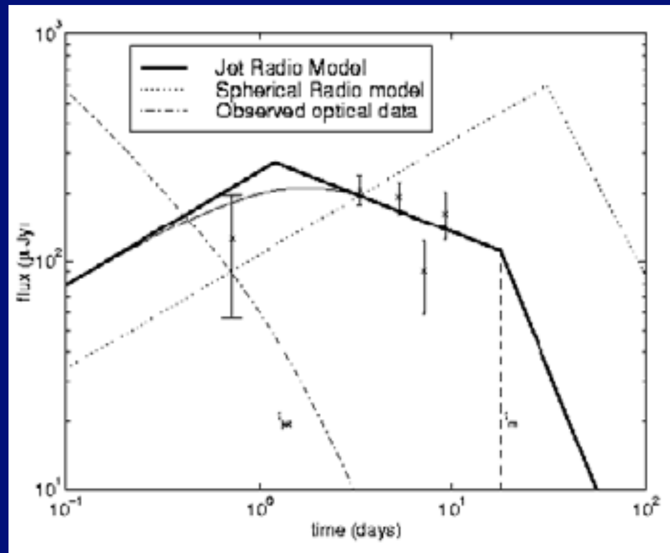
Jets with an opening angle q expand forwards until $g= q^{-1}$ and then expand sideways rapidly

lowering quickly the observed flux (Piran, 1995; Rhoads, 1997; Wijers et al, 1997; Panaitescu & Meszaros 1998).

GRB 990510 - A GREAT JET







$\alpha_1 = 0.85$ $\alpha_2 = 2.18$

$t_{break} = 1.2$ *days* $\Rightarrow$ *jet angle* $= 4^o$

From Harrison et al 1999

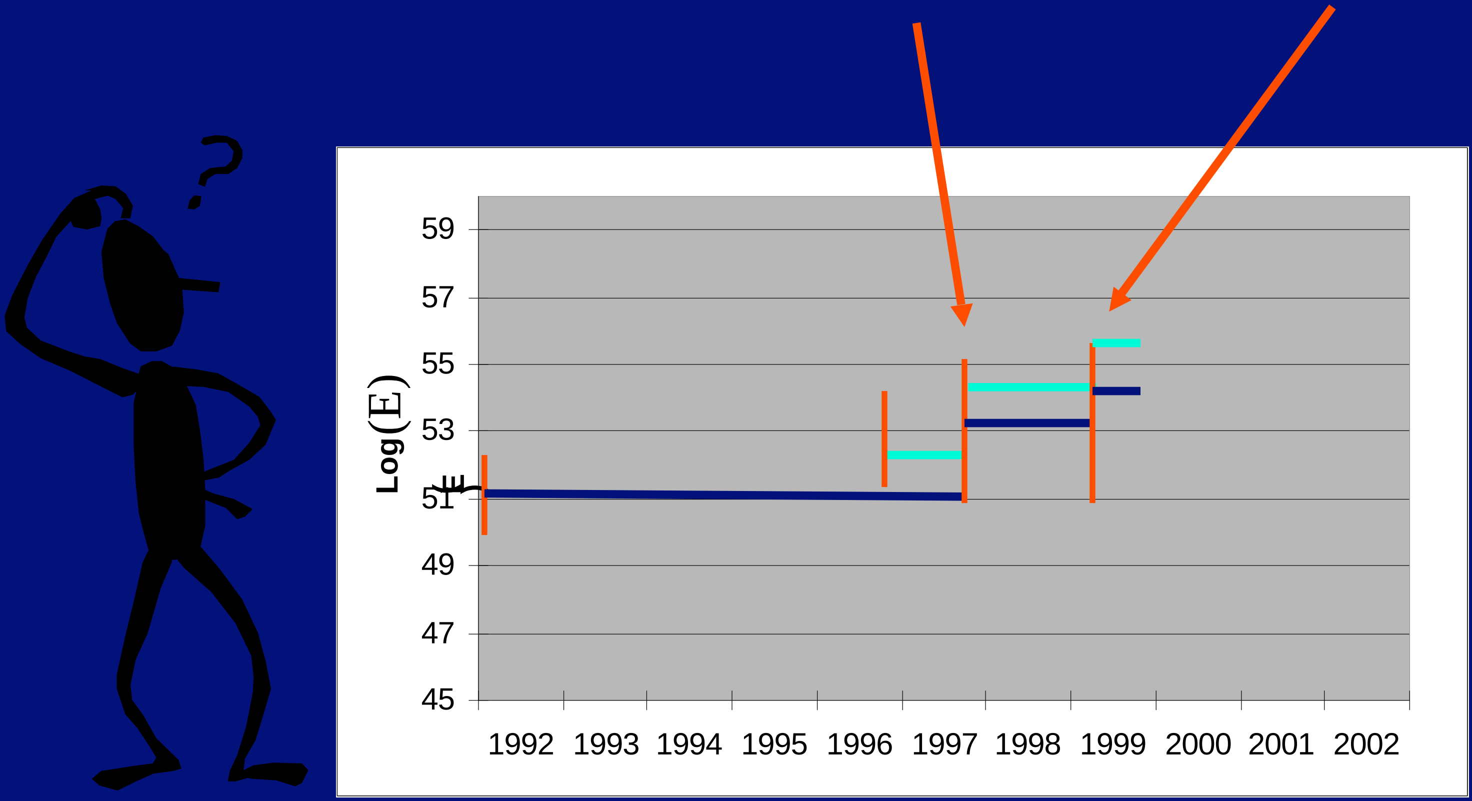
Redshift and Energy Determination

GRB	Z	E ($\times 10^{51}$)
970228	0.695	22.4
970508	0.835	5.46
970828	0.958	220
971214	3.412	211
980613	1.096	5.67
980703	0.967	60.1
990123	1.6	1440
990506	1.3	854
990510	1.619	178
990705	0.84	270
990712	0.433	5.27
991208	0.706	147
991216	1.02	535
000131	4.5	1160
000131c	2.034	46.4
000418	1.119	82.0
000926	2.037	297

The Energy Crisis?

971214

990123



From Tsvi Piran

The Resolution of the Energy Crisis

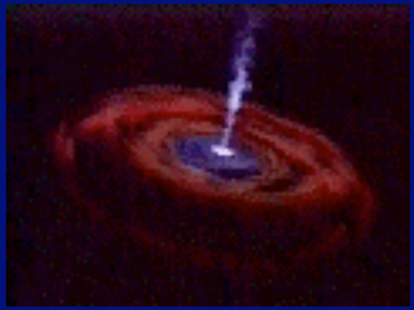
- *E_{tot} - The total energy*
- *$E_{\gamma\ iso}$ - Observed (iostropic) γ–ray energy*

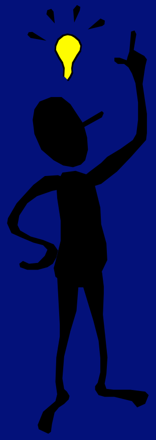
Beaming:

~~$$E_{tot} = \varepsilon_\gamma^{-1} E_{\gamma\ iso}$$~~

- E_γ - Actual γ–ray energy

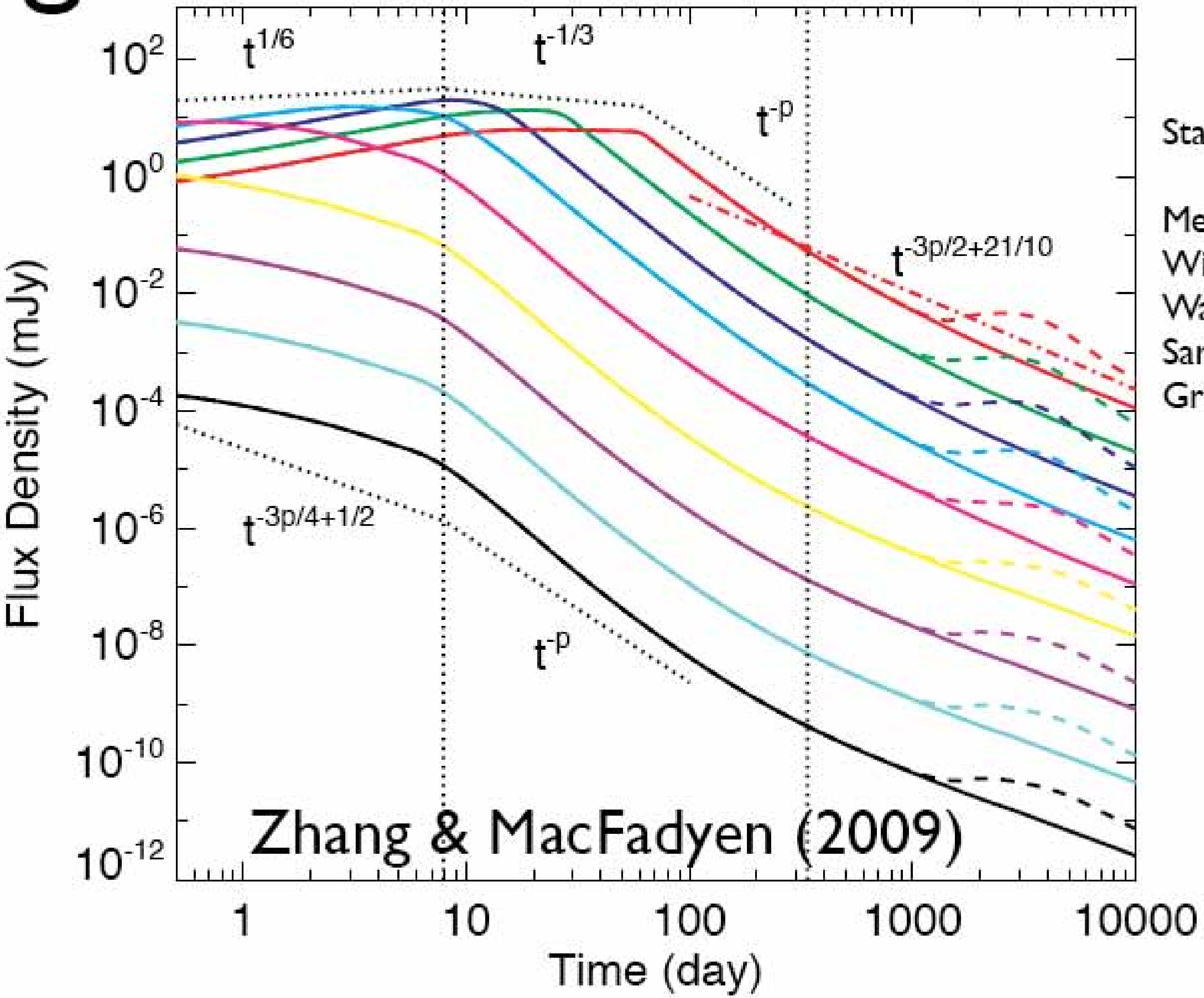
$$E_{tot} = \varepsilon_\gamma^{-1} E_\gamma = \varepsilon_\gamma^{-1} \frac{\theta^2}{2} E_{\gamma\ iso}$$





The two most powerful BeppoSAX bursts are jets (Sari, Piran & Halpern; 1999).

Light Curves Radio-X-Ray

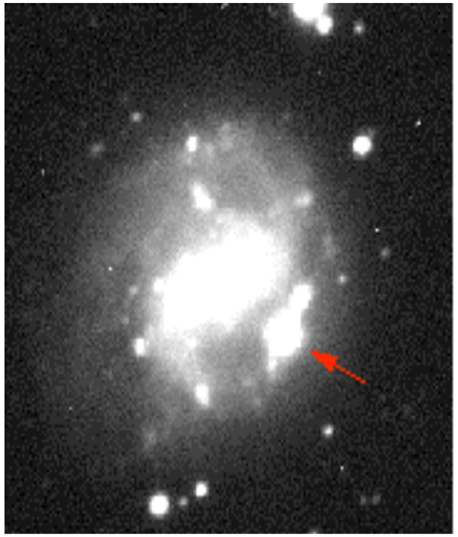


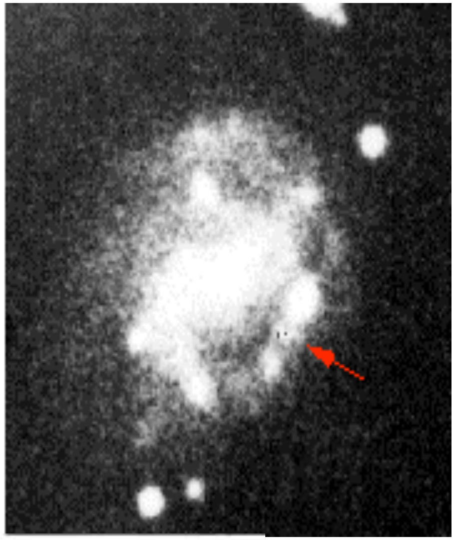
Standard AG model:

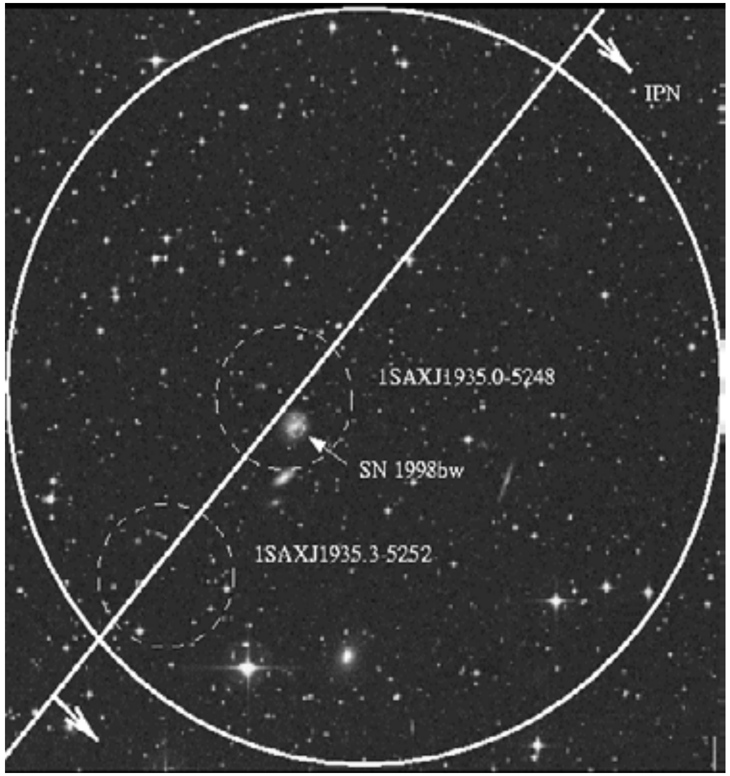
Meszaros & Rees(1997),
Wijers et al (1997),
Waxman(1997),
Sari et al(1998),
Granot et al (1999)

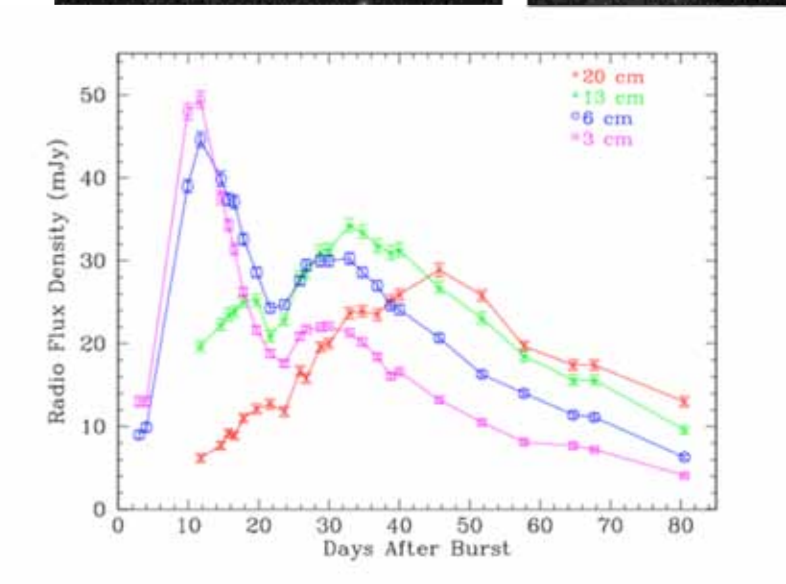
SN 1998bw was discovered in Gamma Rays

Beppo-Sax

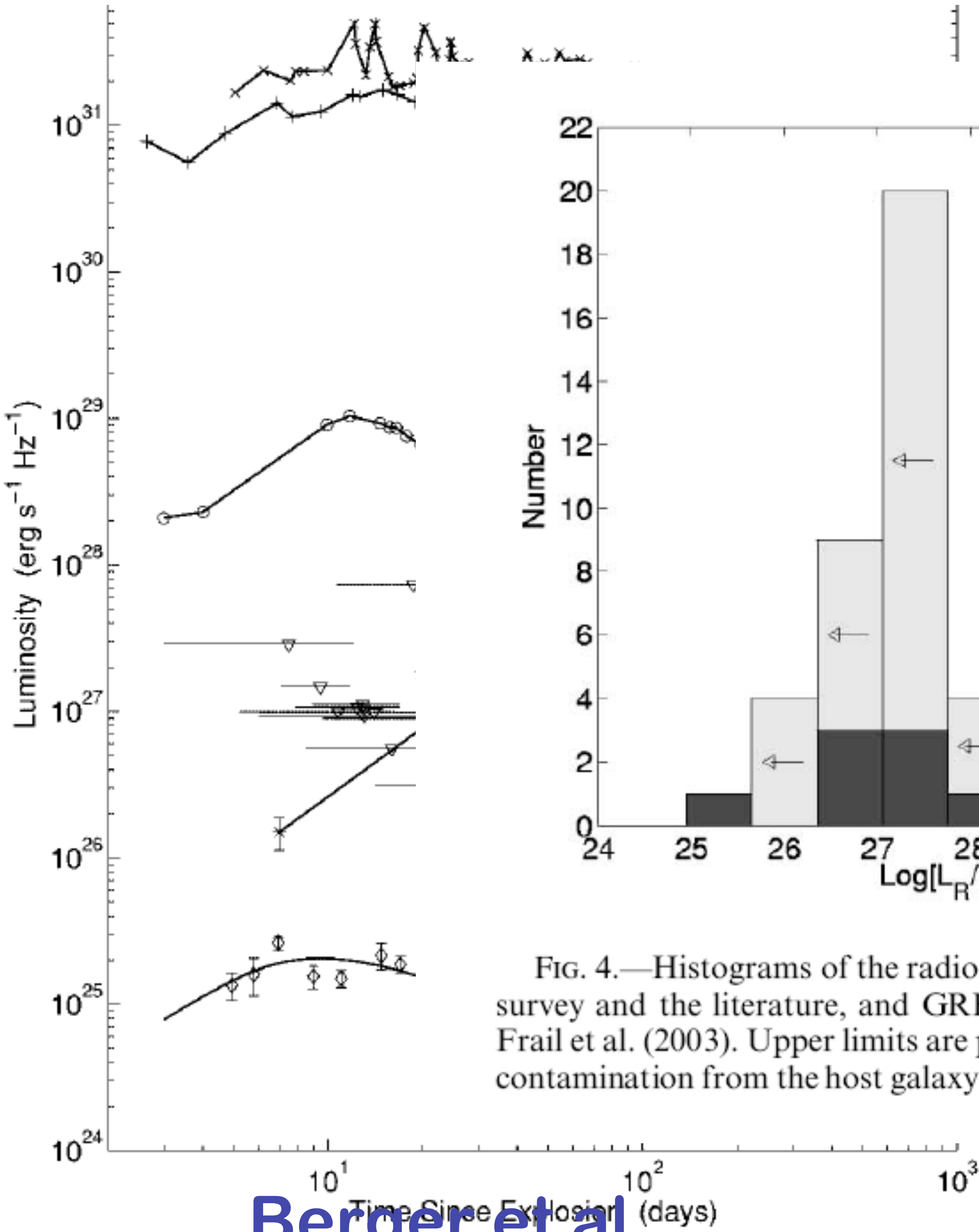








Brightest Radio SN ever –
Measurement indicate relativistic
Eject… funny very high velocity
Spectrum … within a day of GRB



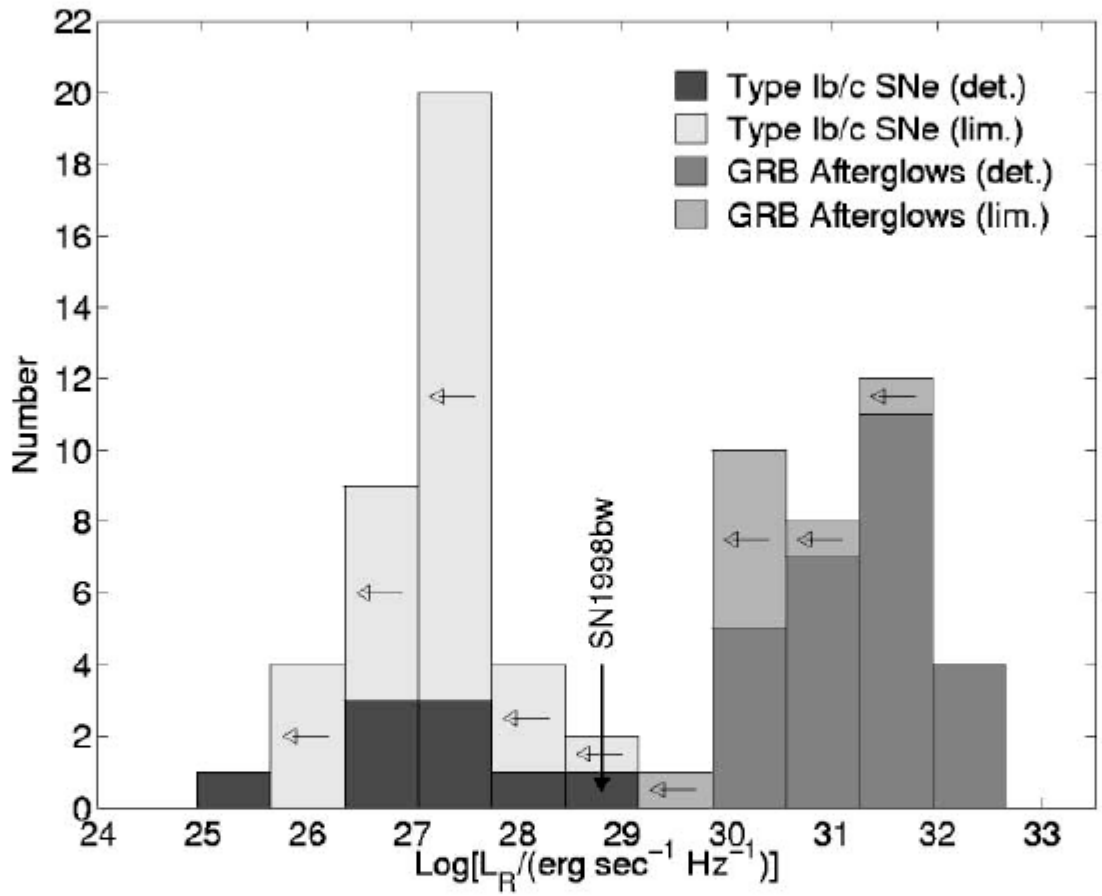
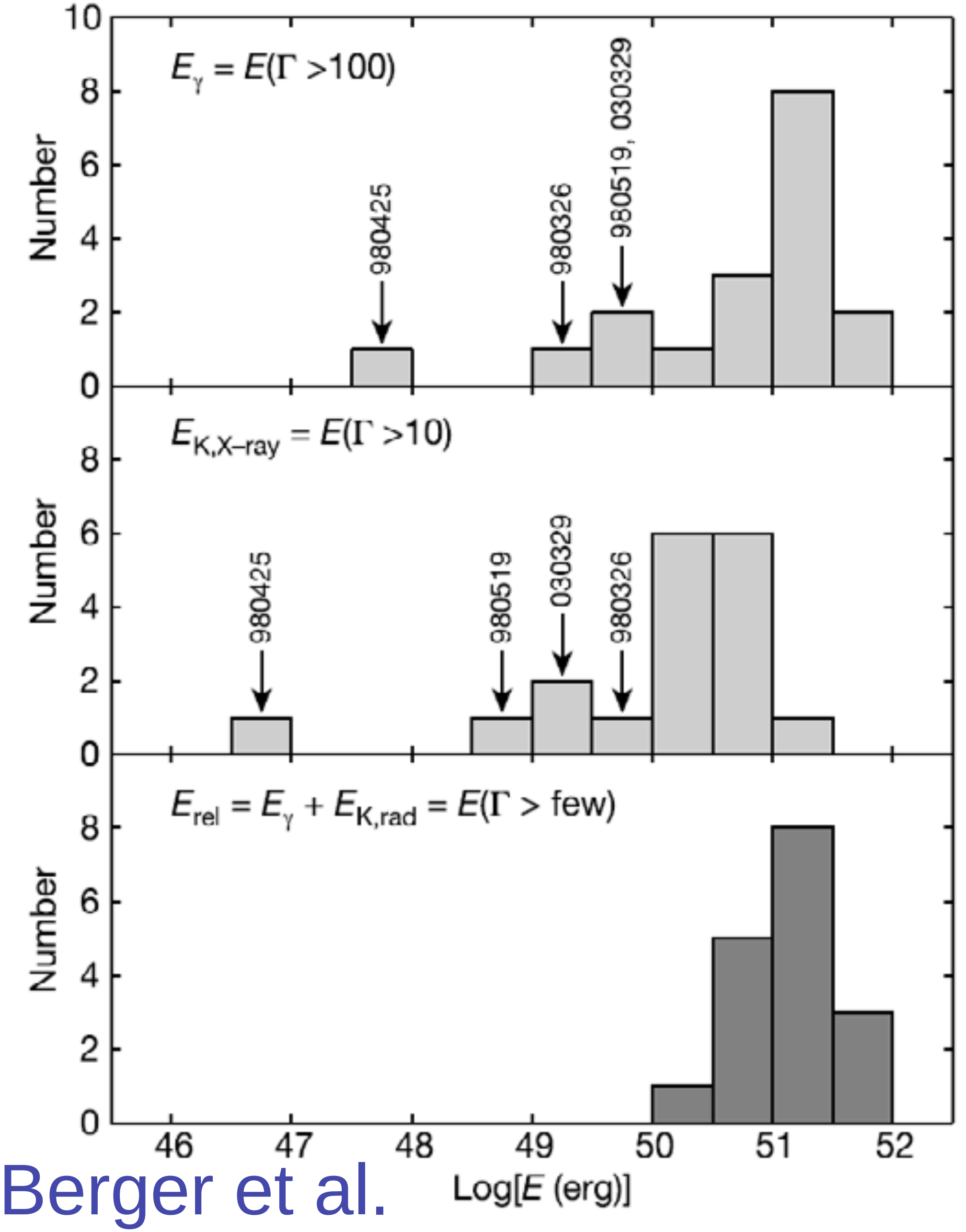


FIG. 4.—Histograms of the radio luminosity of Type Ib/c SNe from this survey and the literature, and GRB radio afterglows from the sample of Frail et al. (2003). Upper limits are plotted as 3 σ, unless there is significant contamination from the host galaxy (see Table 1).

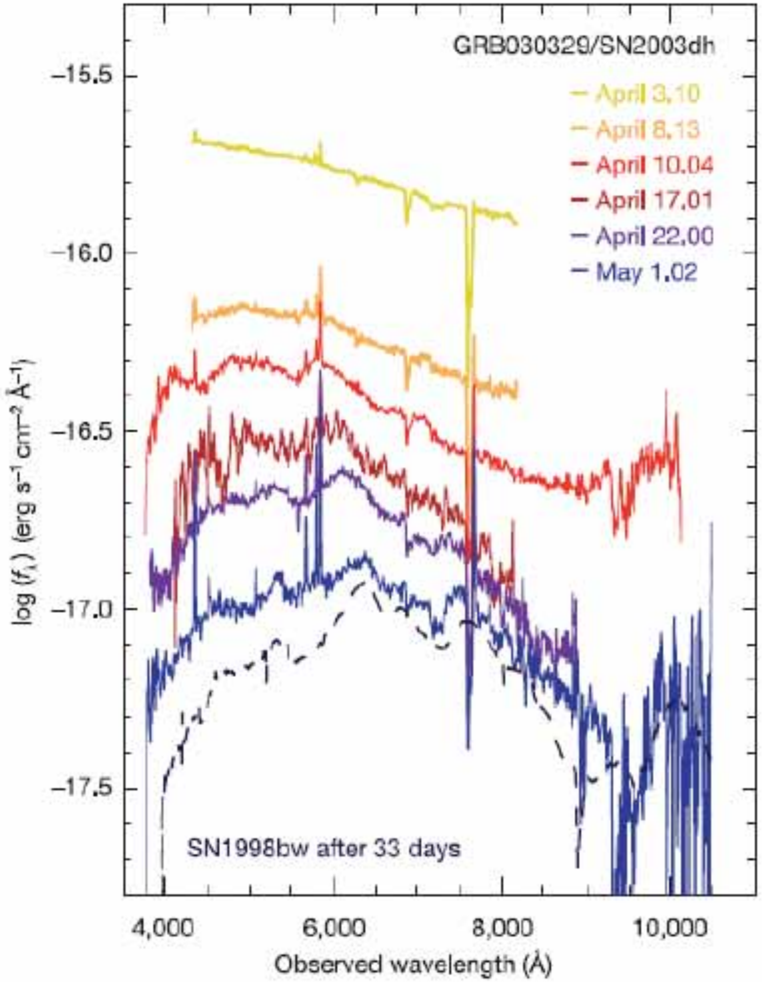
Berger et al.

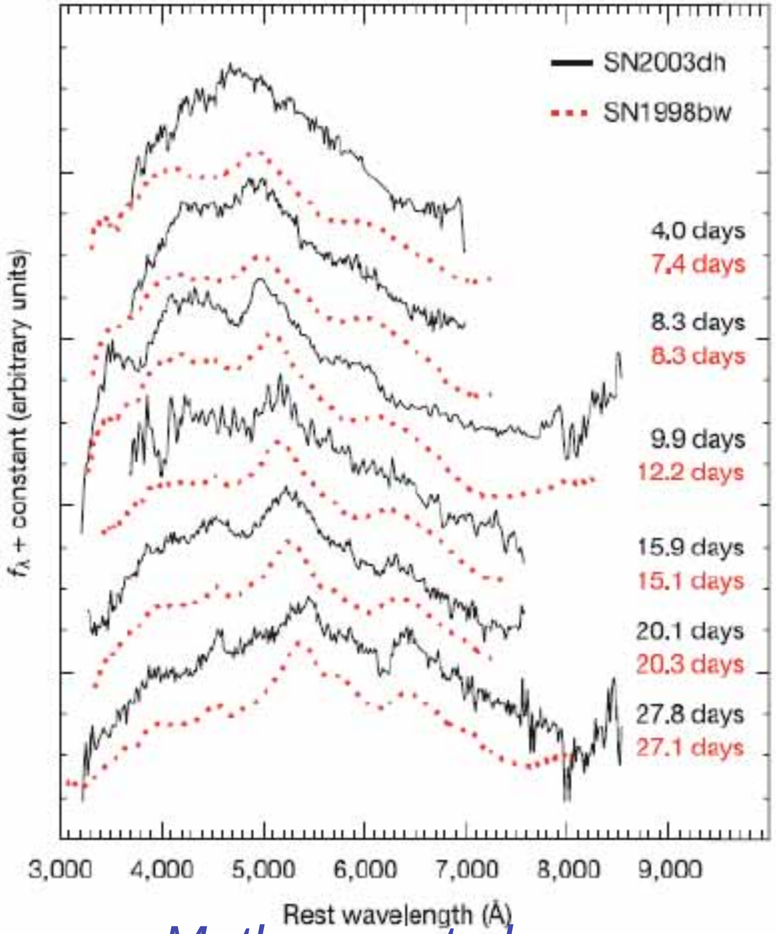


10
8
6
4
2
0
Number
$E_\gamma = E(\Gamma > 100)$
980425
980326
980519, 030329
$E_{K,X-ray} = E(\Gamma > 10)$
980425
980519
030329
980326
$E_{rel} = E_\gamma + E_{K,rad} = E(\Gamma > few)$
46
47
48
49
50
51
52
Log[E (erg)]

Berger et al.

SN 2003dh was also discovered in Gamma Rays, and it was more normal





Matheson et al.

Hjorth et al (2003)

Clues on the Inner Engine

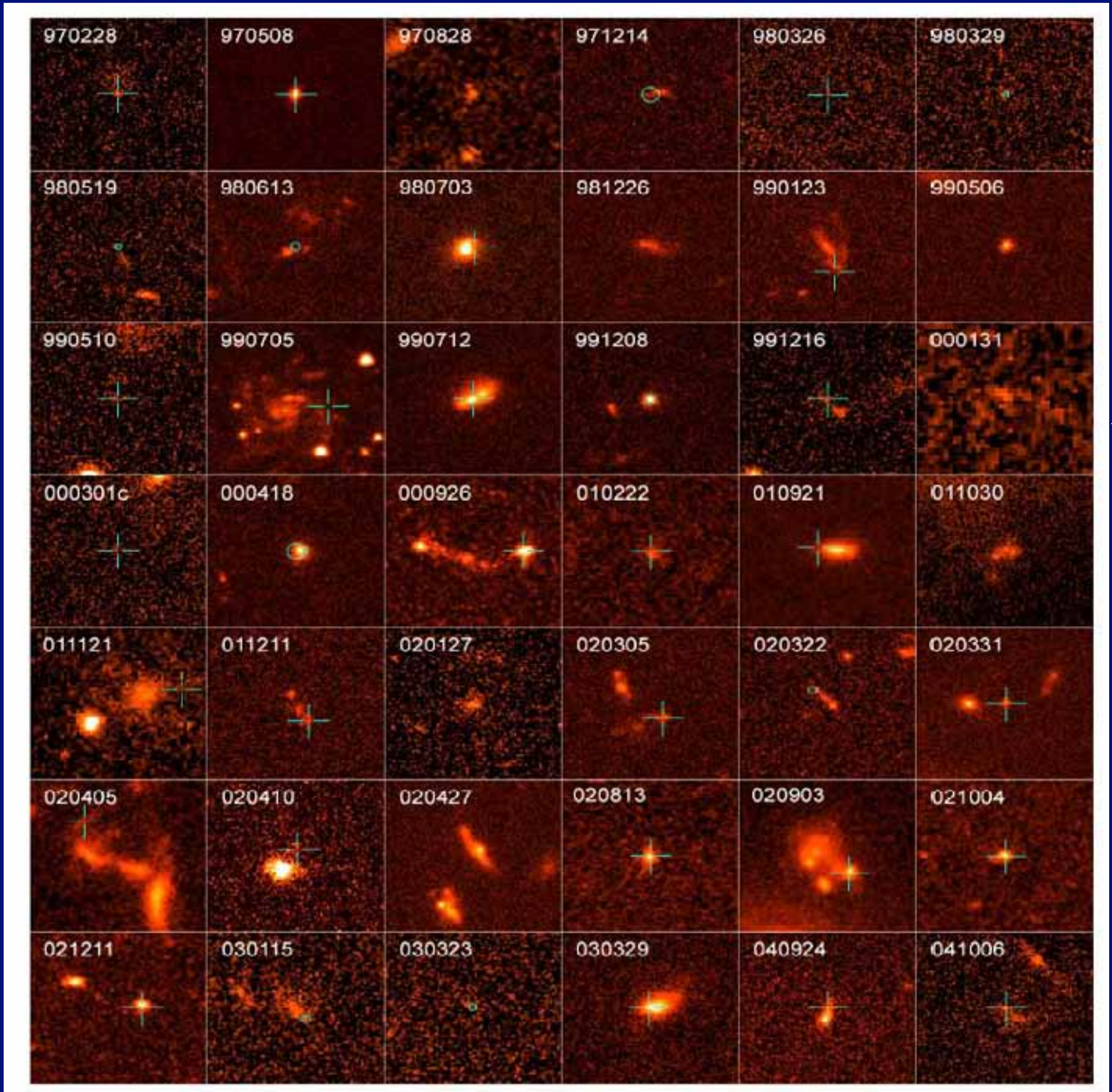
The inner source is hidden. The observations reflect only the conditions at the fireball.

- *E_{tot} ~ 10^{51} ergs*
- *$\delta\tau < 10^{-2}$ sec*
- *T ~ 30 sec*
- *γ ~ 200*
- *Jets ~ 2^o - 5^o*
- *Rate 10^{-5} /yr/galaxy*

- *A compact Object*
- *A compact Object*
- *Prolonged activity: an accretion disk ?*
- *Lower energy, higher rates, orphan afterglows*
- *A rare phenomenon*

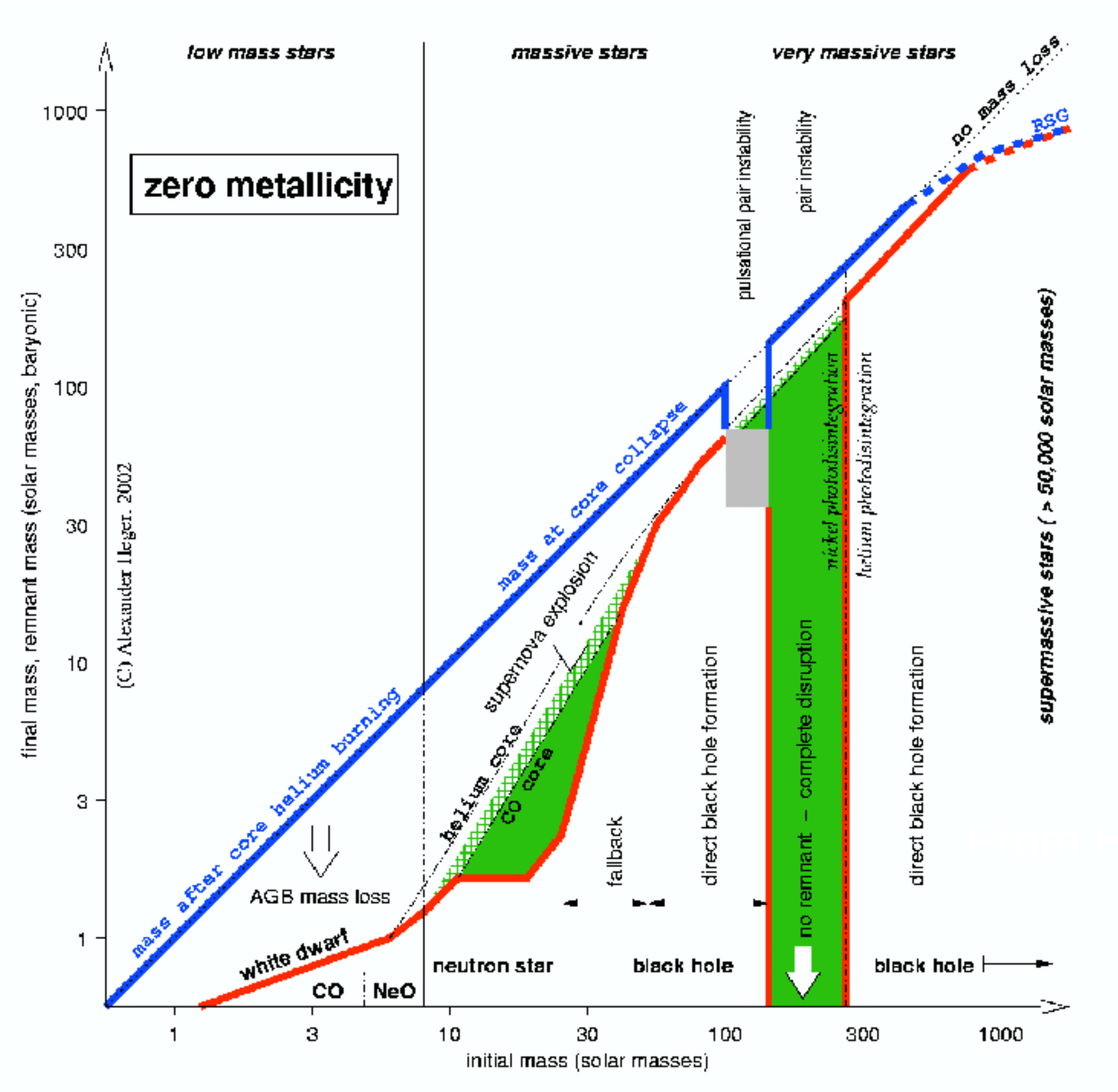
Most likely powered by accretion onto a newborn black hole

From Piran



Fruchter et al. (2006)

LSGRBs are found in star-forming galaxies. Their location within those galaxies is assoc-iated with the light with a tighter correlation than even Type Iip supernovae (but maybe not Type Ic).

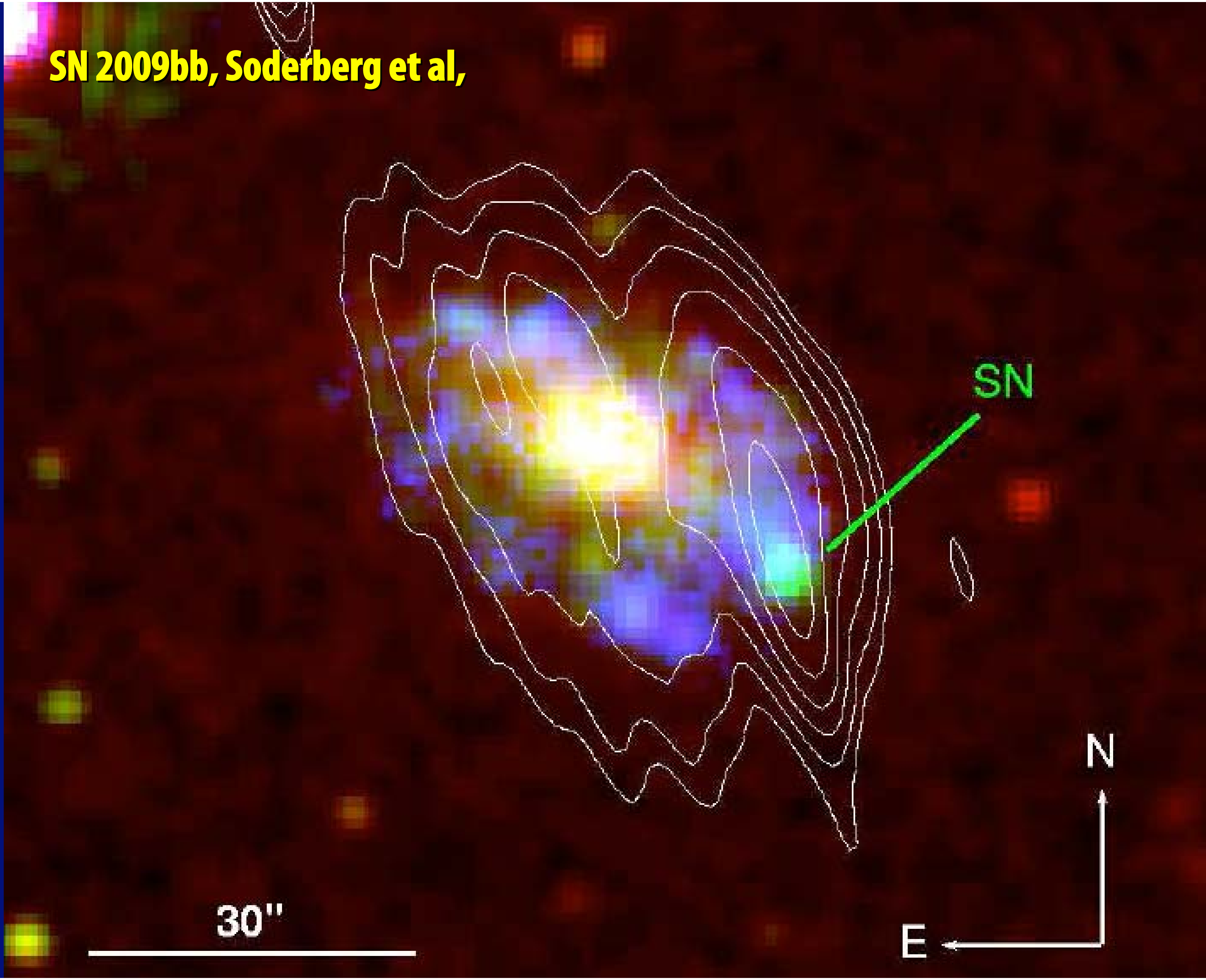

low mass stars
massive stars
very massive stars
zero metallicity
(C) Alexander Heger, 2002
final mass, remnant mass (solar masses, baryonic)
1000
300
100
30
10
3
1
mass after core helium burning
mass at core collapse
no mass loss
RSG
pulsational pair instability
pair instability
nickel photodisintegration
helium photodisintegration
supermassive stars (> 50,000 solar masses)
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
fallback
direct black hole formation
no remnant – complete disruption
direct black hole formation
neutron star
black hole
black hole
1
3
10
30
100
300
1000
initial mass (solar masses)

Heger

Rates and Distances

- *One long GRBs per $10^4 (\theta/0.1)^{-2}$ years per galaxy.*
  Beaming factor
- *One observable long burst per year at D~600 Mpc.*
- *One mis-directed burst per year at D~135 $(\theta/0.1)^{2/3}$ Mpc.*

SN 2009bb, Soderberg et al,



The rate at which massive stars die in the universe is very high and GRBs are a small fraction of that death rate.

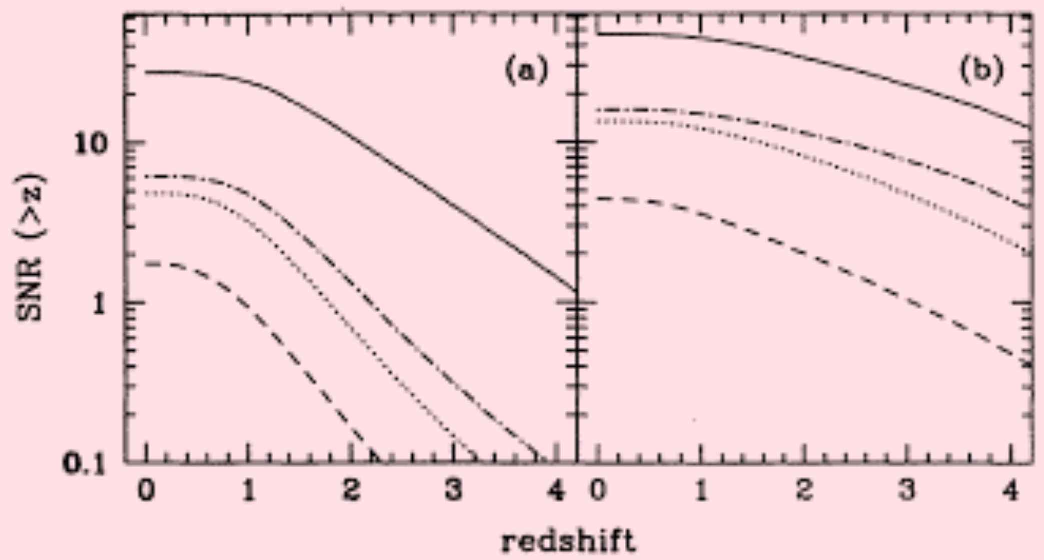


Figure 3. Predicted cumulative number of Type Ia and II(+b/c) SNe above a given redshift z in a 4×4 arcmin^2 field. Solid line: Type II SNe. Dashed-dotted line: Type Ia SNe with $\tau = 0.3$ Gyr. Dotted line: Type Ia SNe with $\tau = 1$ Gyr. Dashed line: Type Ia SNe with $\tau = 3$ Gyr. The effect of dust extinction on the detectability of SNe is negligible in these models. (a) Model predictions of the 'merging' scenario of Fig. 1a. (b) Same for the 'monolithic collapse' scenario of Fig. 1b.

Madau, della Valle, & Panagia, MNRAS, 1998

Supernova rate per 16 arc min squared per year ~20

This corresponds to an all sky supernova rate of

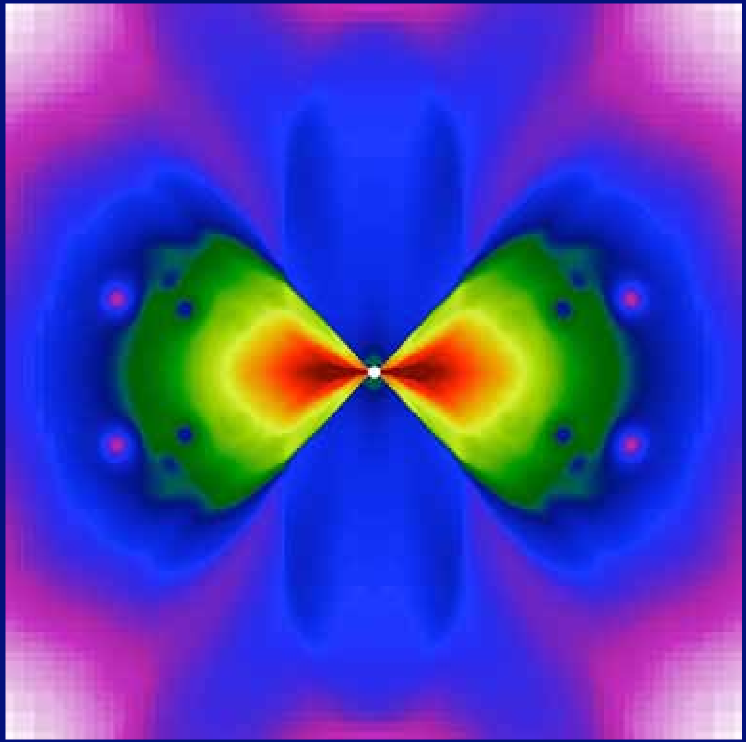
6 SN/sec

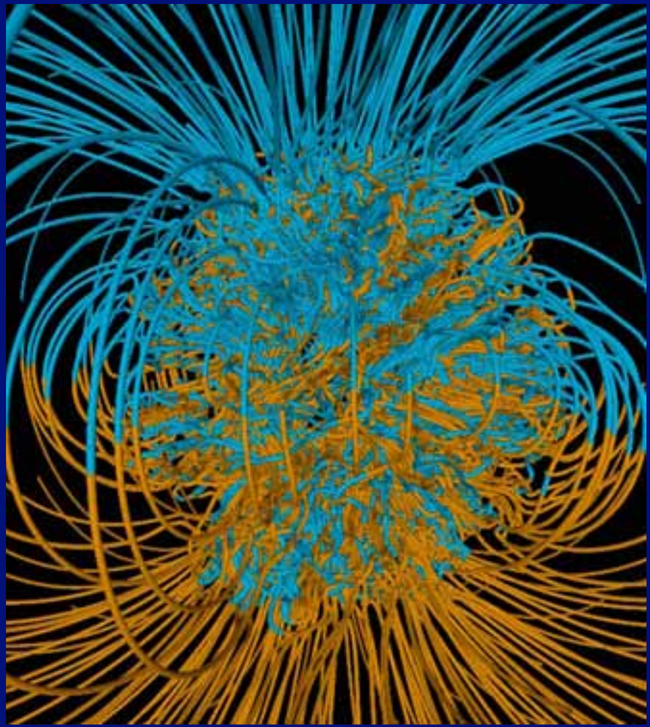
*For comparison the universal GRB rate is about 3 /day * 300 for beaming or*

~ 0.02 GRB/sec

Today, there are two principal models being discussed for GRBs of the "long-soft" variety:

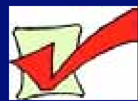
- The collapsar model
- The millisecond magnetar





The ultimate source of energy in both is rotation.

"Predictions" of both the collapsar and magnetar models*

- Relativistic jets 
- Occur in star forming regions 
- Occur in hydrogen-stripped stars and are often accompanied by SN Ibc 
- Are a small fraction of SN Ibc  ~0.3% of all SN
- Are favored by low metallicity (and rapid rotation) 
- Occur in CSM with density proportional to r^{-2} ?

* Predicted by collapsar model but probably consistent with magnetar model

Proto-magnetars

Magnetars have fields ~ $10^{14\text{-}15}$ G
They might be born as fast rotators
Efficient dynamo implies $P \sim t_{conv} \sim$ ms

Millisecond magnetar have the correct energy

$$E_{Rot} \approx 2 \times 10^{52} \left(\frac{P}{1\ \mathrm{ms}} \right)^{-2} \mathrm{ergs}$$

Pro

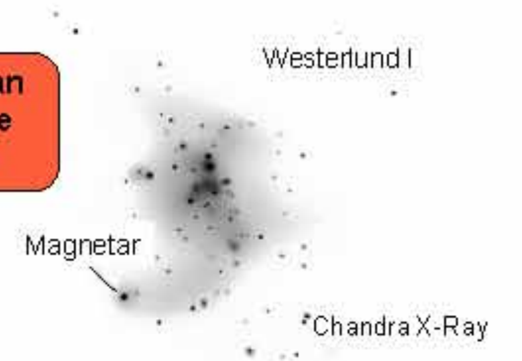
NS are naturally associated to core collapse SN
Less angular momentum required than BH-AD
NS population can explain transition from asymmetric SNe to XRFs to GRBs

Typical spin-down times are ~ 100-1000 sec

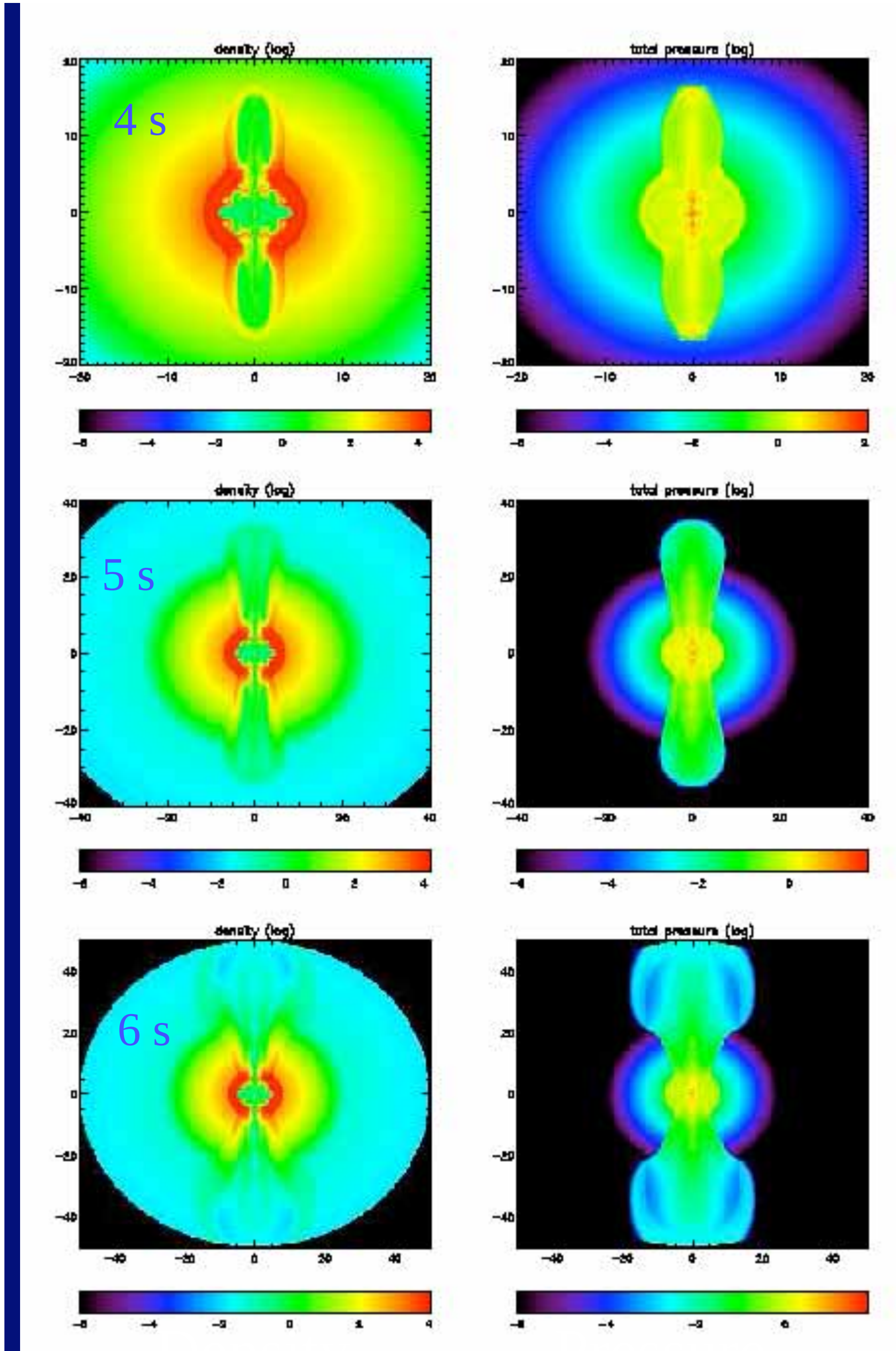
$$\dot{E} \approx 10^{49} \left(\frac{P}{1\ \mathrm{ms}} \right)^{-4} \left(\frac{B_{Dip}}{10^{15}\ \mathrm{G}} \right)^{2} \mathrm{ergs\ s^{-1}}$$

Pulsars have relativistic winds

Magnetars can have massive progenitors



Faintest Cluster Members are O7 (Muno 2006)



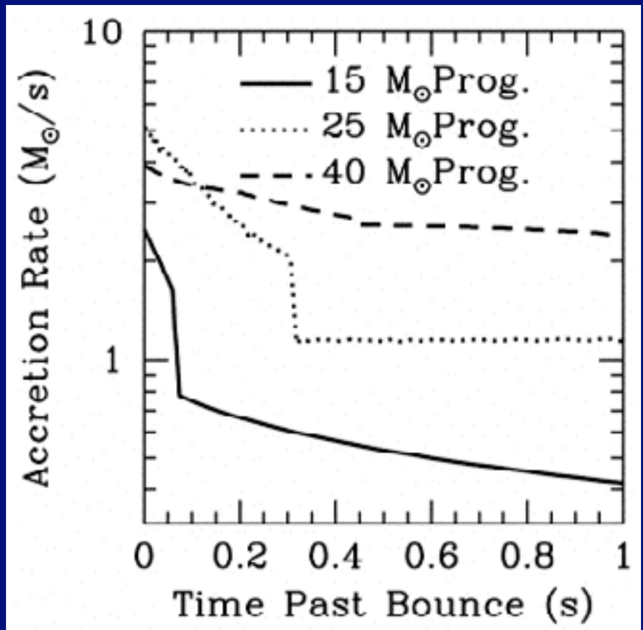
Density Pressure

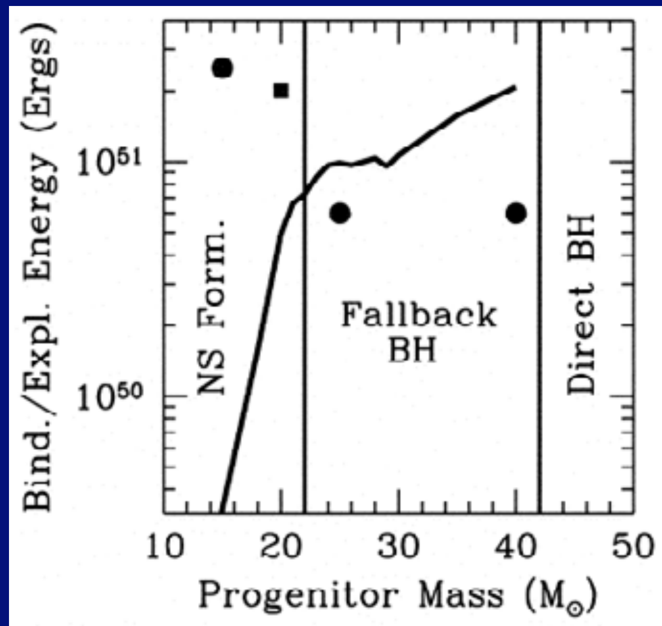
Bucciantini, Quataert, Arons, Metzger and Thompson (MNRAS; 2007) and refs therein, see also Komissarov et al (2008)

Collapsar Progenitors

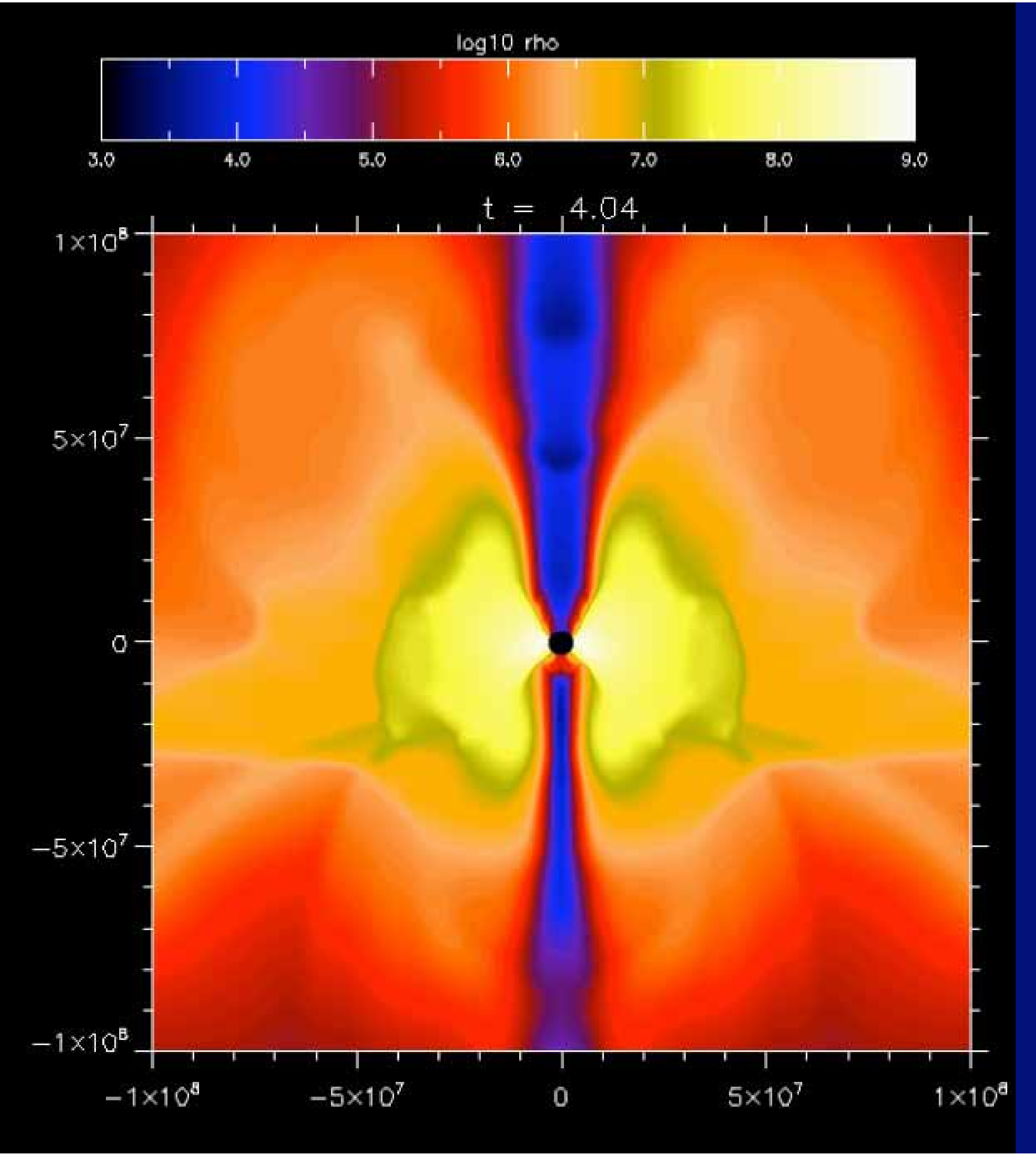
- ***Some Core collapse SN produce a black hole - either promptly or very shortly thereafter.***

- ***Sufficient angular momentum exists to form a disk outside the black hole)***



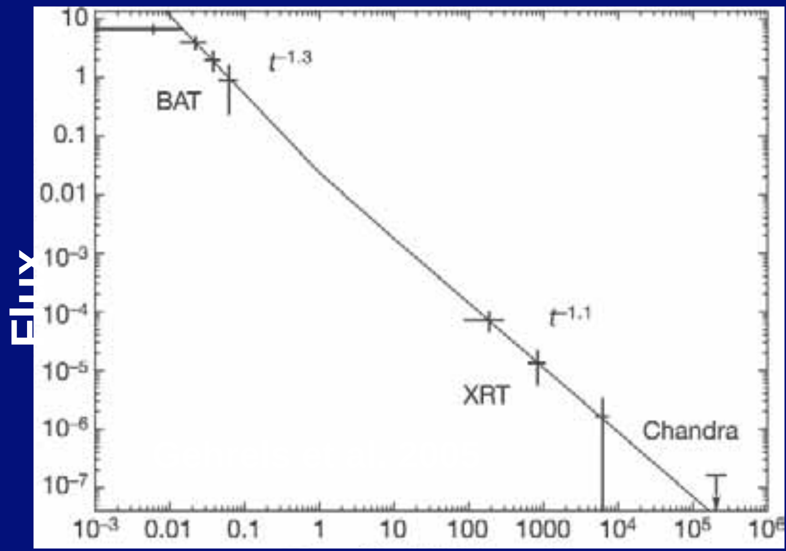


Fryer, ApJ, 522, 413, (1999)

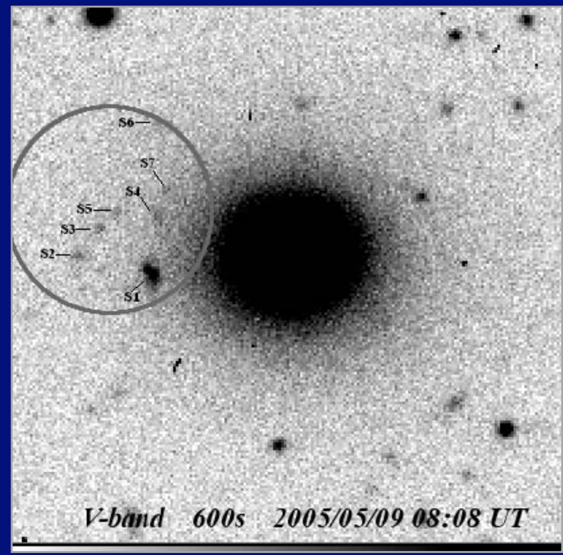

log10 rho
3.0
4.0
5.0
6.0
7.0
8.0
9.0
t = 4.04
1×10^8
5×10^7
0
−5×10^7
−1×10^8
−1×10^8
−5×10^7
0
5×10^7
1×10^8

Afterglow of Short Bursts

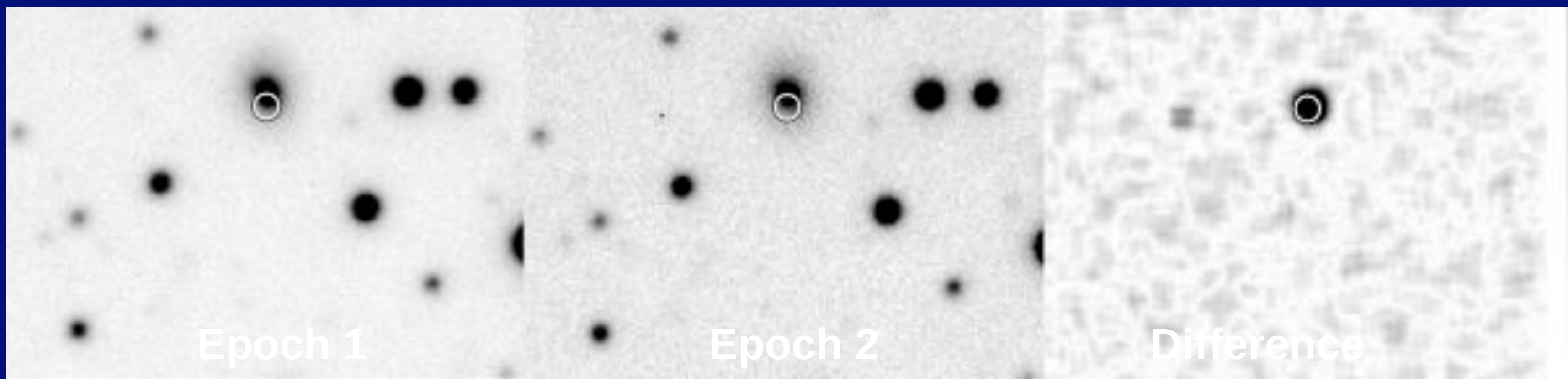
GRB 050509B
first short
GRB X-ray
afterglow
very faint!



Time since GRB (s)



GRB 050724 – the bright one: optical + X-ray – $z = 0.258$



Short Hard Bursts

In 2005 - 2006, several short hard bursts were localized by SWIFT and HETE-2 and coordinated searches for counterparts were carried ou The bursts were GRB 050509b (z = 0.2248, elliptical galaxy), 050709 (z = 0.161) and 050724 (z = 0.258)

The bursts were either on the outskirts of galaxies or in old galaxies with low star formation rate

There was no accompanying supernova

The redshifts were much lower than for the long soft bursts and thus the total energy was about two orders of magnitude less (because they are shorter as well as closer).

All this is consistent with the merging neutron star (or merging black hole neutron star) paradigm.

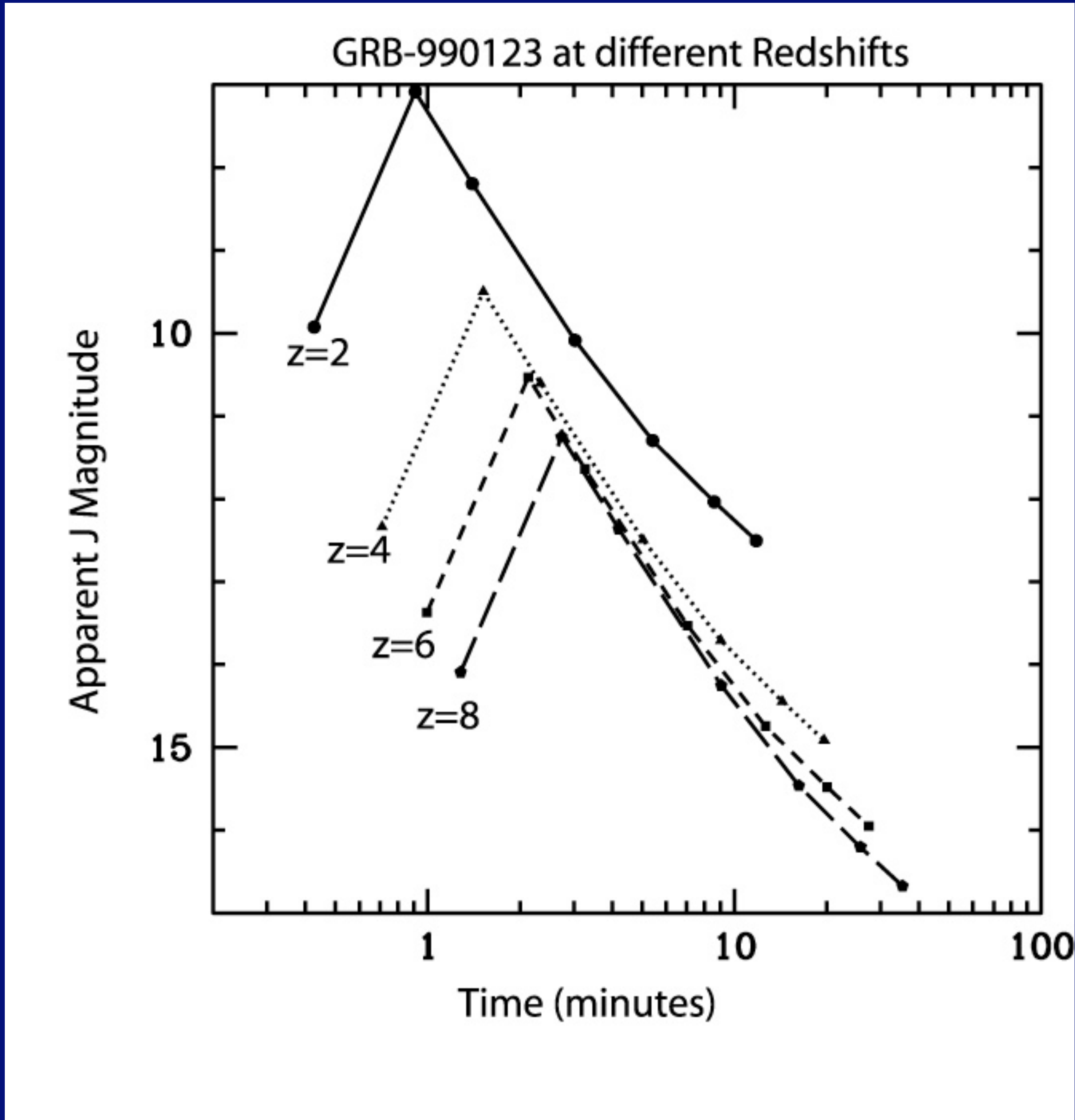
But Life is not so simple

- ***Since then, many Short GRBs have been found at high redshift, with the same energy as Long GRBs*** ***(Maybe two things make Short GRBs)***
- ***And emission several hours was seen in Gamma Rays, which violates predictions of Neutron Star merger (which take a few seconds)...This now maybe explained from debris taking a long time to fall onto the merged Blackhole..***

GRBs as Beacons for the Universe

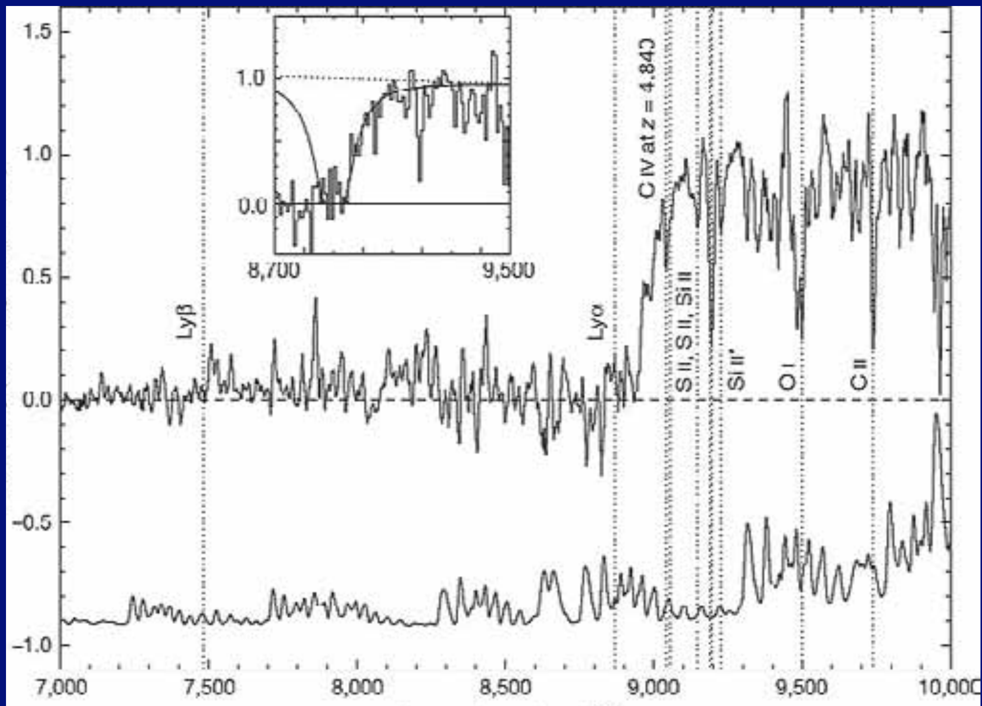
- *GRBs follow the star formation rate.*
- *GRBs and their afterglow can be detected even from Z~10.*
- *10-25% of GRBs are from Z>5?*
- *GRBs are ideal beacons to explore the early universe – at the time of "first light".*

How-b


GRB-990123 at different Redshifts
Apparent J Magnitude
Time (minutes)
10
15
1
10
100
z=2
z=4
z=6
z=8

A distant Explosion

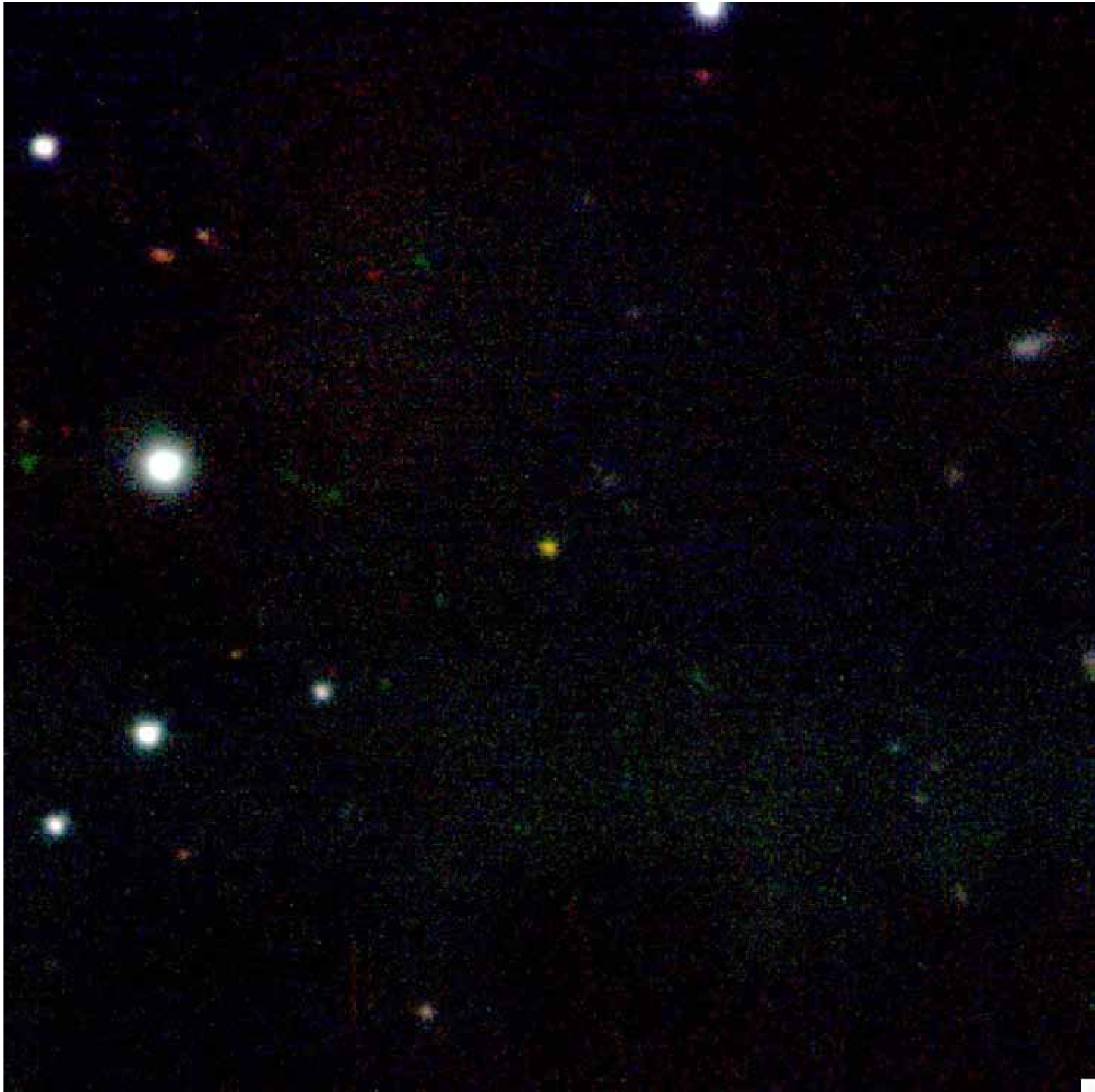
A record for a star: ***z* = 6.29**



Flux (erg cm^{-2} s^{-1} Å^{-1})

Rest wavelenght (Å)

Kawai et al. 2006



The Most Distant Object yet detected by Humankind.

600 Million Years Post Big Bang…

Very Little info on this object because its spectrum wasn't taken for 15 hours when it had faded by a factor of 1000…