Gamma Ray Bursts

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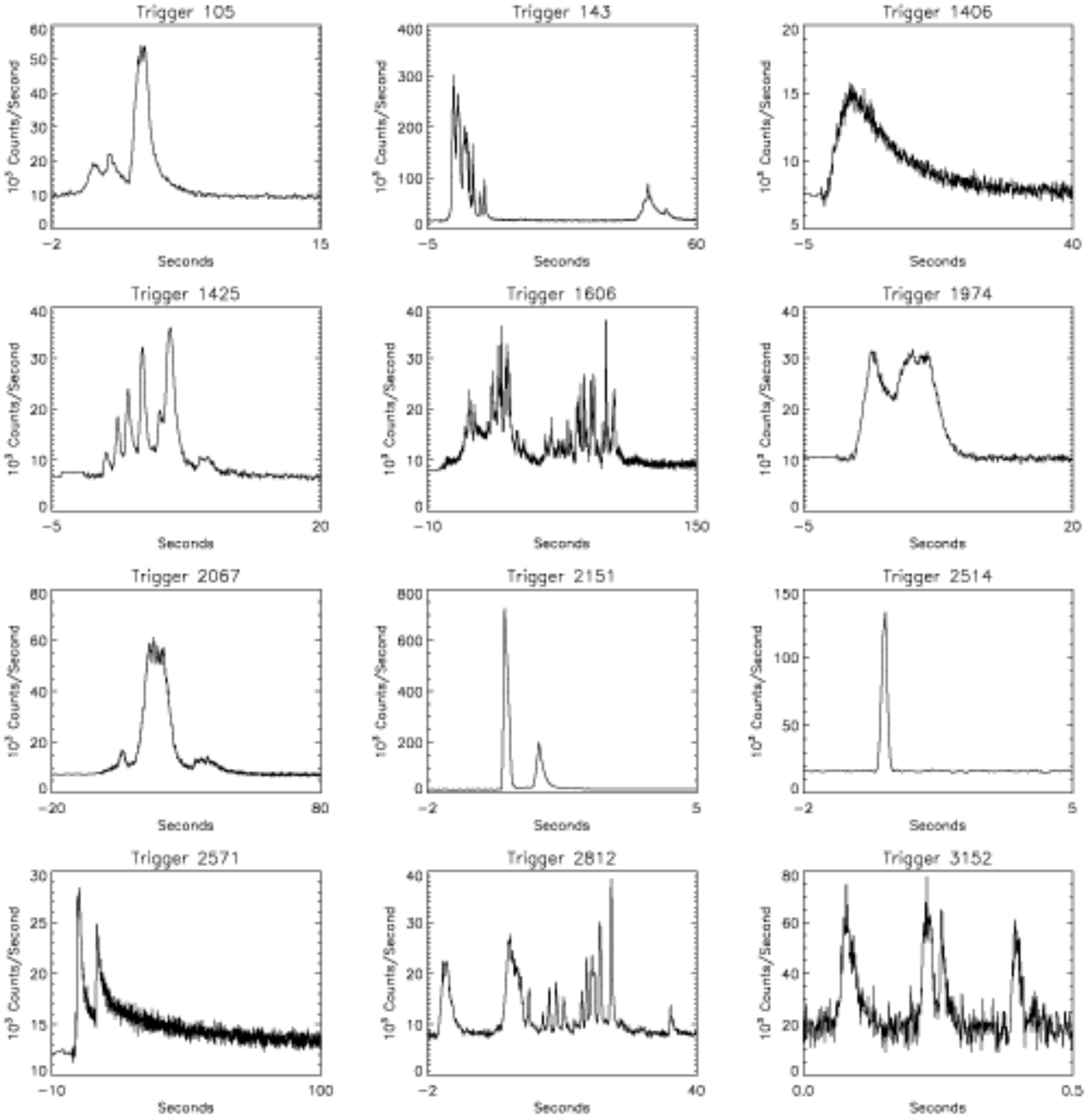
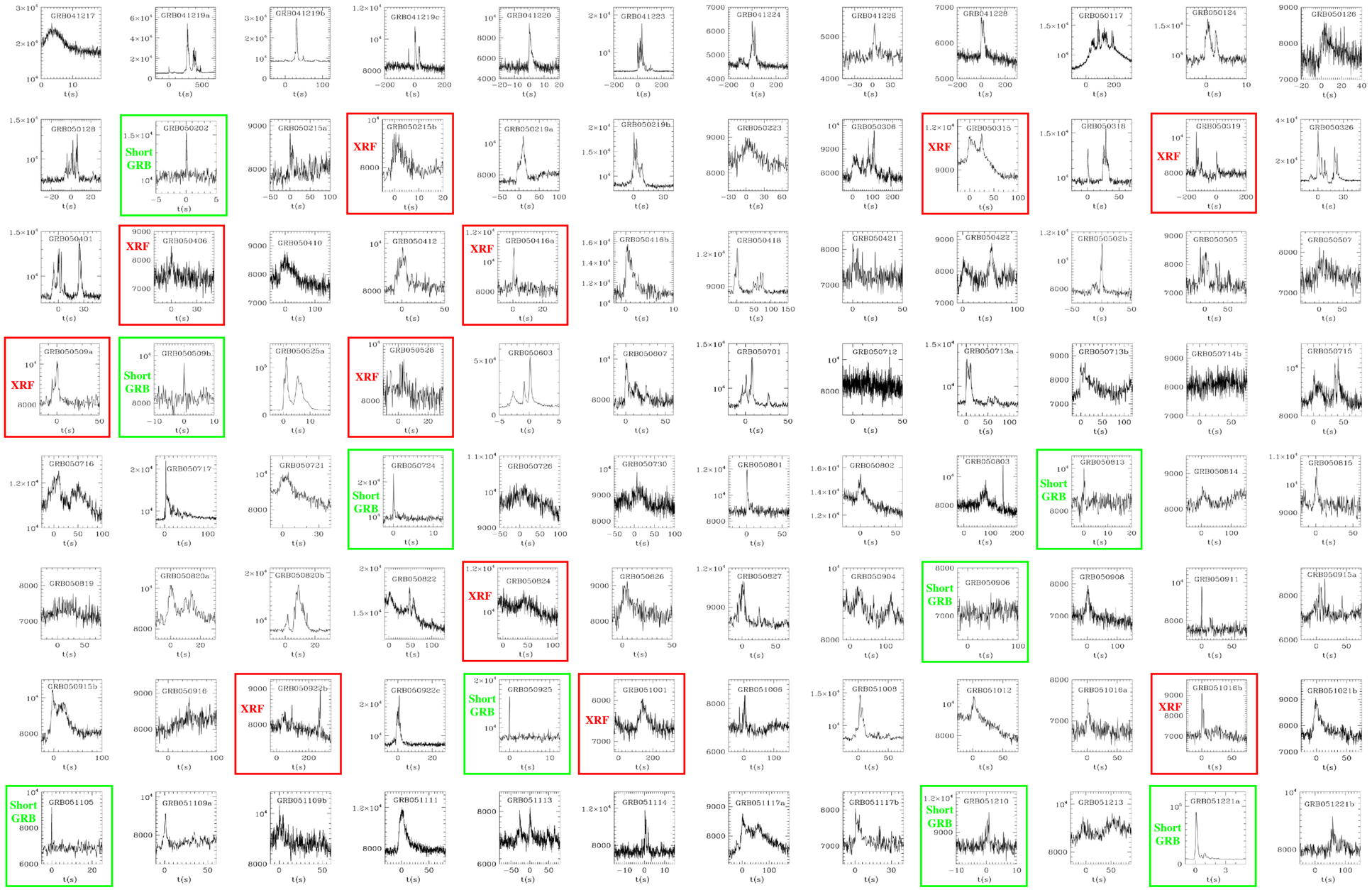
IFPU February 10 2023

GRB light curves



Swift GRBs


GRB041217
GRB041219a
GRB041219b
GRB041219c
GRB041220
GRB041223
GRB041224
GRB041226
GRB041228
GRB050117
GRB050124
GRB050126
GRB050128
Short GRB
GRB050202
GRB050215a
XRF
GRB050215b
GRB050219a
GRB050219b
GRB050223
GRB050306
XRF
GRB050315
GRB050318
XRF
GRB050319
GRB050326
GRB050401
XRF
GRB050406
GRB050410
GRB050412
XRF
GRB050416a
GRB050416b
GRB050418
GRB050421
GRB050422
GRB050502b
GRB050505
GRB050507
XRF
GRB050509a
Short GRB
GRB050509b
GRB050525a
XRF
GRB050526
GRB050603
GRB050607
GRB050701
GRB050712
GRB050713a
GRB050713b
GRB050714b
GRB050715
GRB050716
GRB050717
GRB050721
Short GRB
GRB050724
GRB050726
GRB050730
GRB050801
GRB050802
GRB050803
Short GRB
GRB050813
GRB050814
GRB050815
GRB050819
GRB050820a
GRB050820b
GRB050822
XRF
GRB050824
GRB050826
GRB050827
GRB050904
Short GRB
GRB050906
GRB050908
GRB050911
GRB050915a
GRB050915b
GRB050916
XRF
GRB050922b
GRB050922c
Short GRB
GRB050925
XRF
GRB051001
GRB051006
GRB051008
GRB051012
GRB051016a
XRF
GRB051016b
GRB051021b
Short GRB
GRB051105
GRB051109a
GRB051109b
GRB051111
GRB051113
GRB051114
GRB051117a
GRB051117b
Short GRB
GRB051210
GRB051213
Short GRB
GRB051221a
GRB051221b

The discovery of GRBs by the Vela satellites

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Constellation of 6+6 satellites carrying simple X-ray scintillators detectors. 10^5 km orbit.

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Detect γ-rays from nuclear explosions

The discovery of GRBs by the Vela satellites

Constellation of 6+6 satellites carrying simple X-ray scintillators detectors. 10^5 km orbit.

Detect γ-rays from nuclear explosions

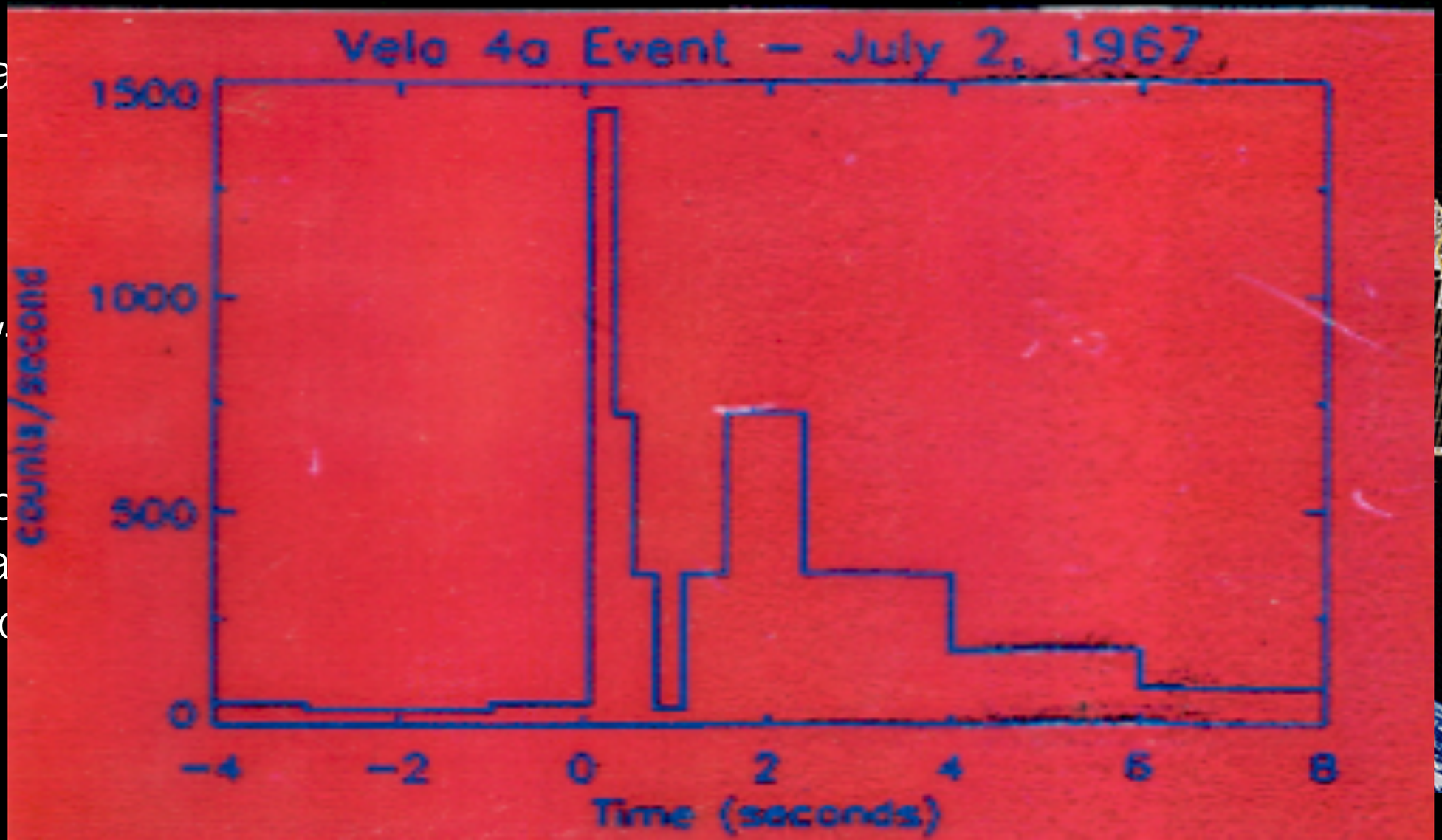
First launch 1963
Last Advanced Vela launch 1970
In operation till 1985

The discovery of GRBs by the Vela satellites

Constella
simple X-
orbit.

Detect γ-

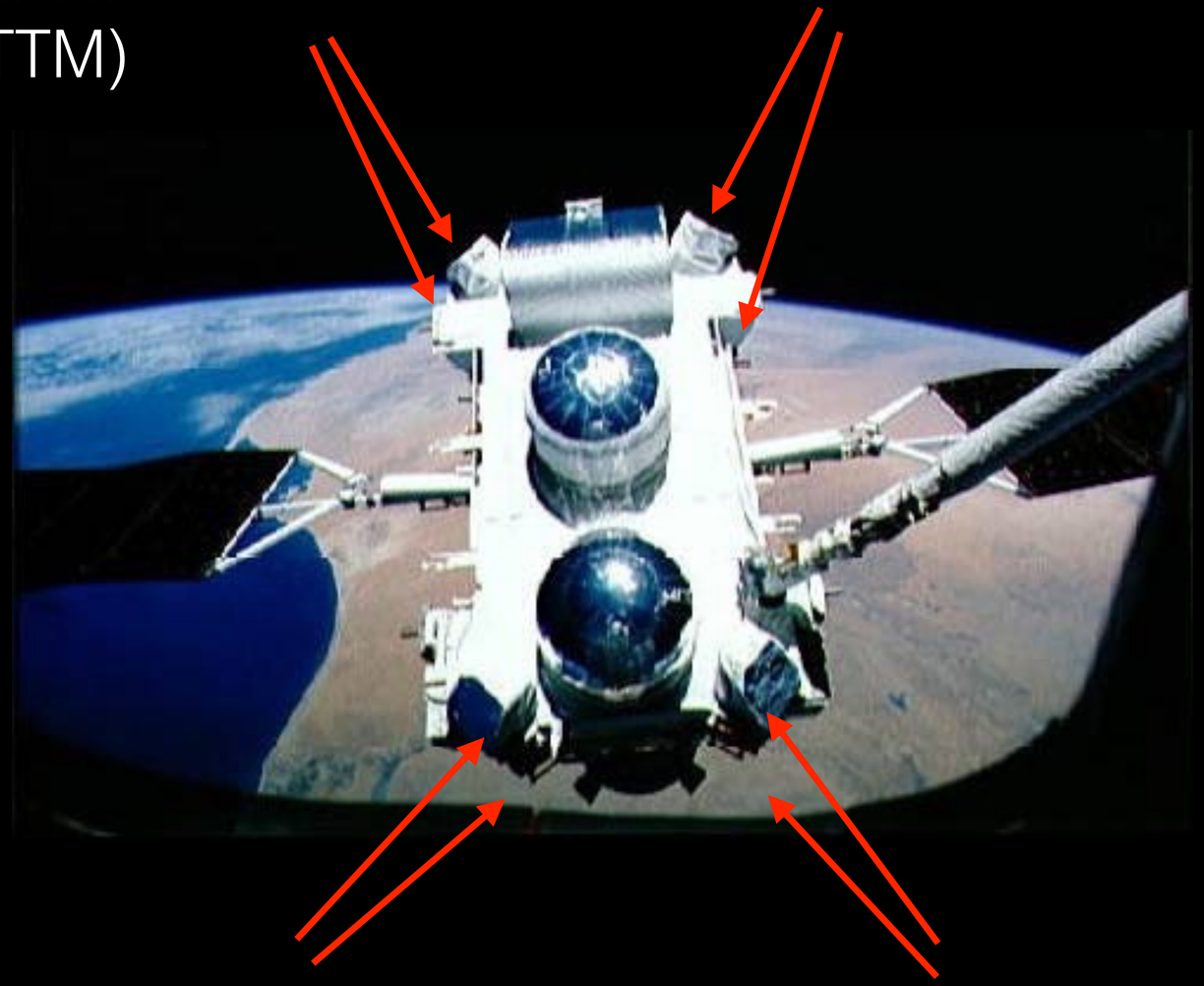
First launc
Last Adva
In operatio



CGRO/BATSE

CGRO/BATSE

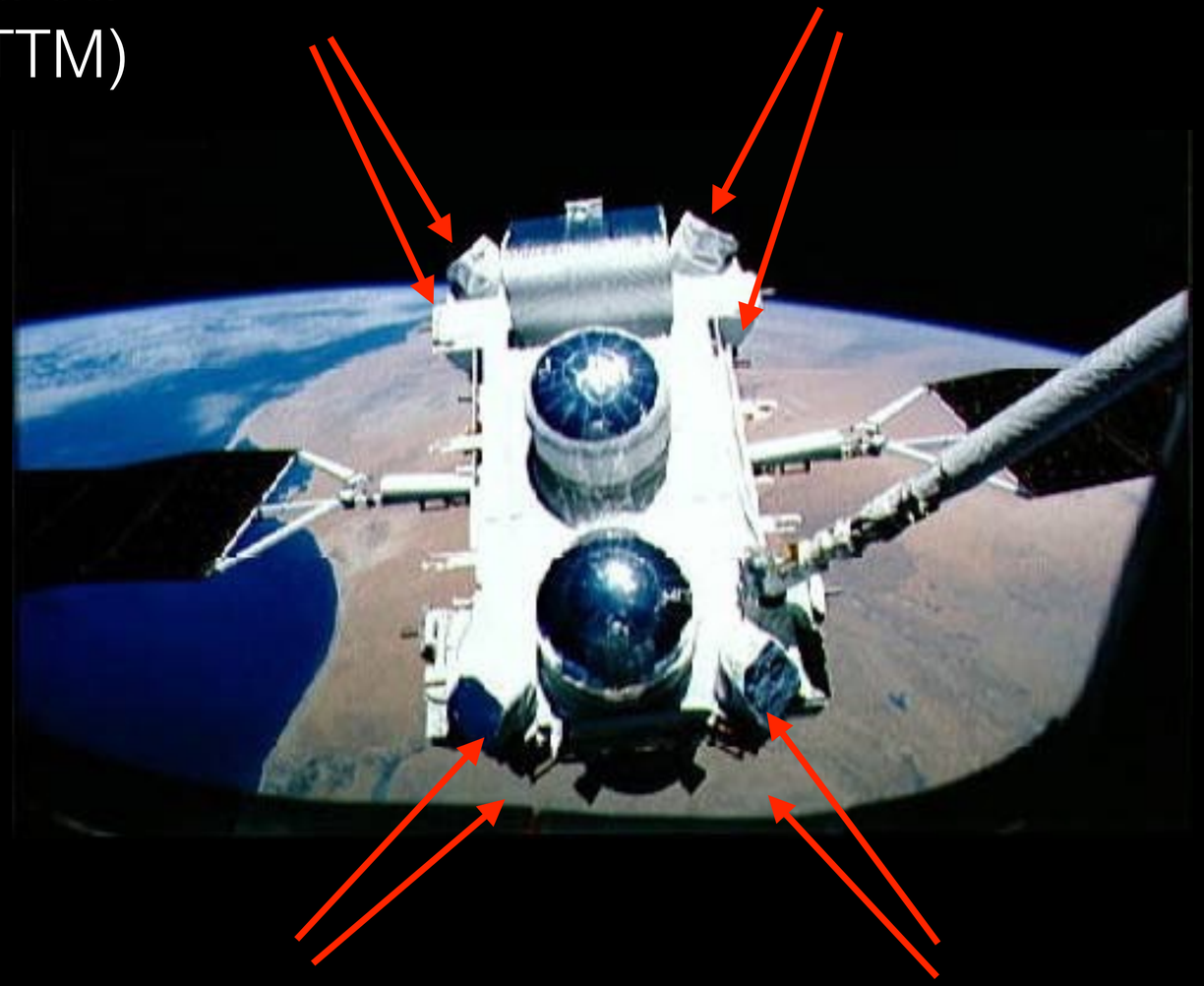
8 NaI(Tl) scintillators at the 8 corners of the spacecraft
each ~2000cm^2 collecting area
Best temp. resolution 2μs (TTM)



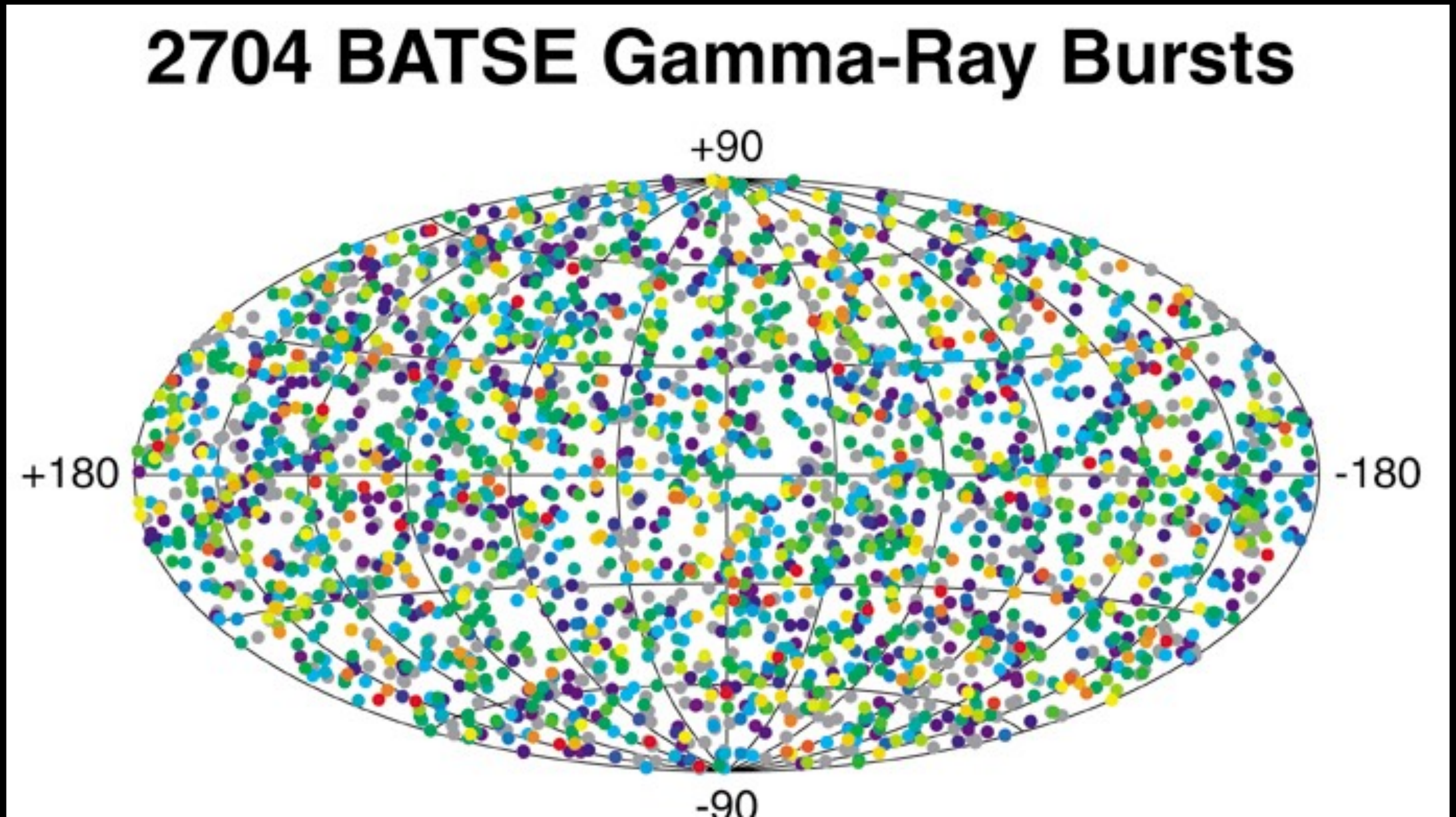
CGRO/BATSE

8 NaI(Tl) scintillators at the 8 corners of the spacecraft
each ~2000cm^2 collecting area
Best temp. resolution 2μs (TTM)

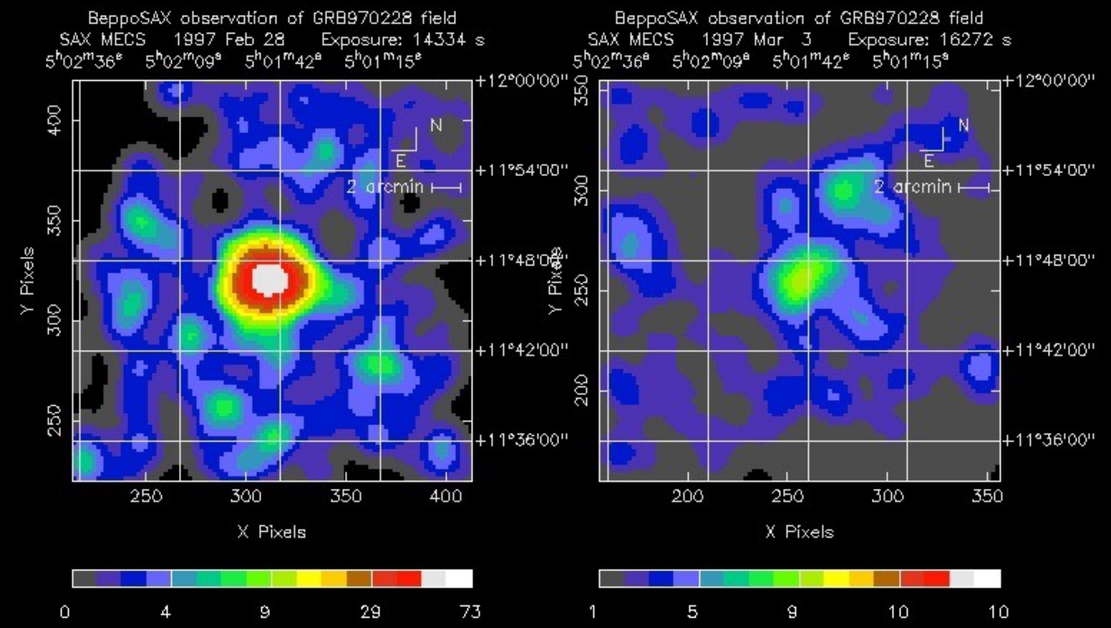
Position accuracy
a few-several deg

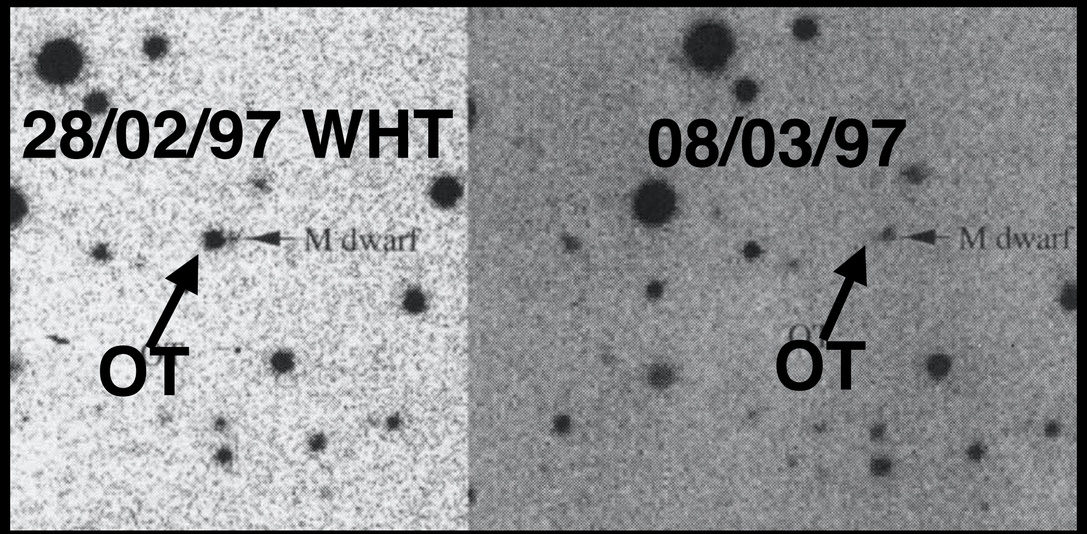


CGRO/BATSE



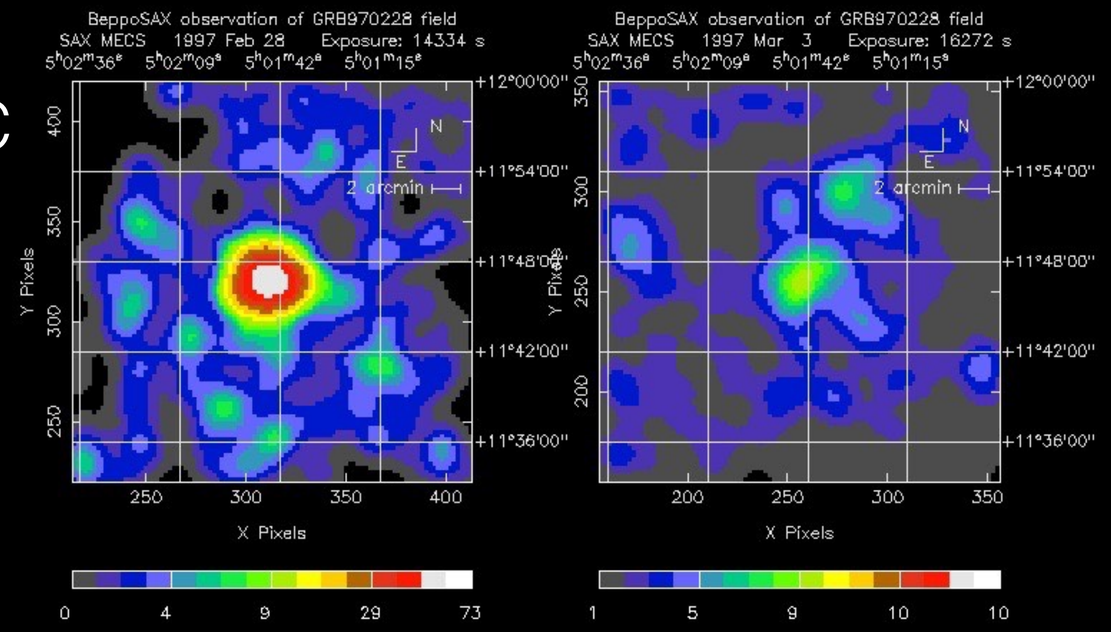
GRB970228

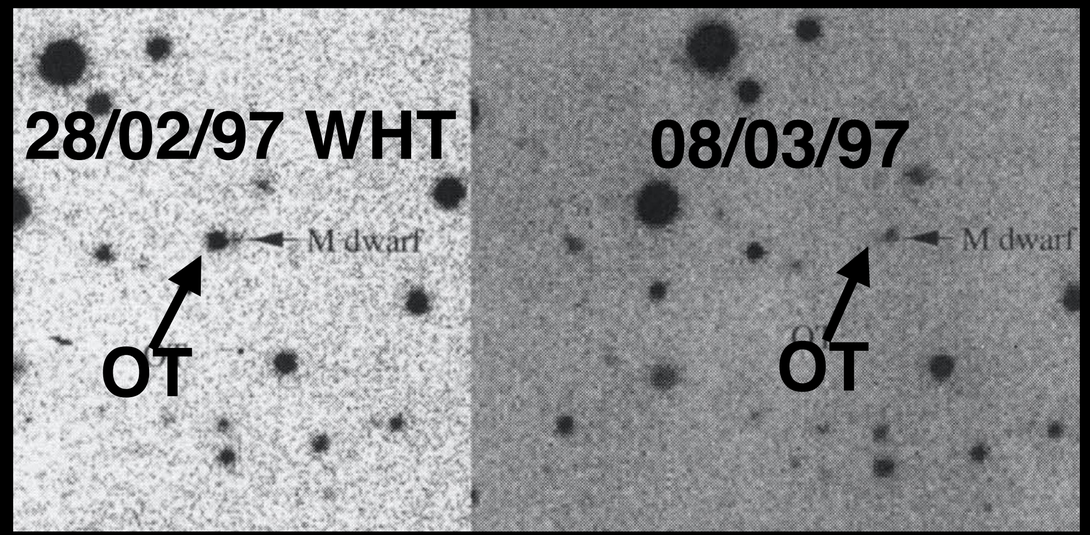

BeppoSAX observation of GRB970228 field
SAX MECS 1997 Feb 28 Exposure: 14334 s
5h02m36s 5h02m09s 5h01m42s 5h01m15s
+12°00'00"
+11°54'00"
+11°48'00"
+11°42'00"
+11°36'00"
N
E
2 arcmin
Y Pixels
X Pixels
250 300 350 400
0 4 9 29 73
BeppoSAX observation of GRB970228 field
SAX MECS 1997 Mar 3 Exposure: 16272 s
5h02m36s 5h02m09s 5h01m42s 5h01m15s
200 250 300 350
1 5 9 10 10


28/02/97 WHT
M dwarf
OT
08/03/97
M dwarf
OT

GRB970228

Detected and localised to a several arcmin by BSAX/WFC

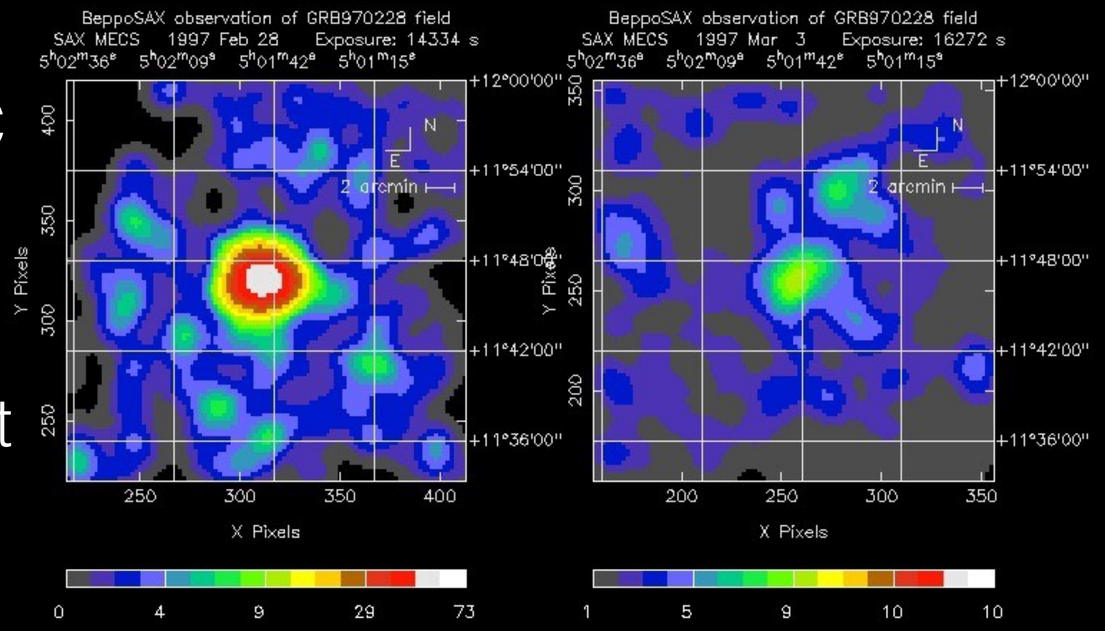


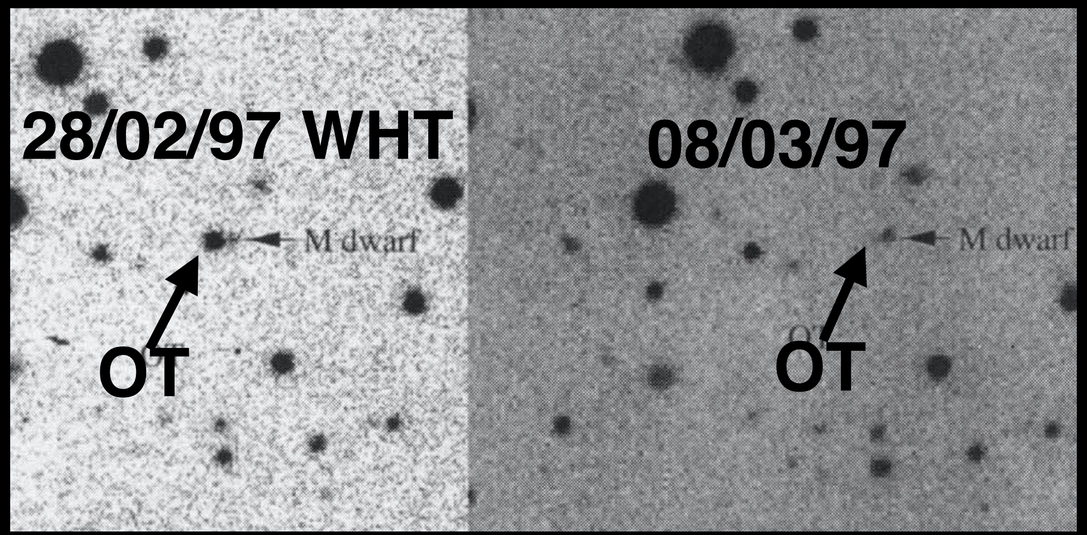


GRB970228

Detected and localised to a several arcmin by BSAX/WFC

Satellite repointed and field observed with X-ray telescopes 8hr after the event





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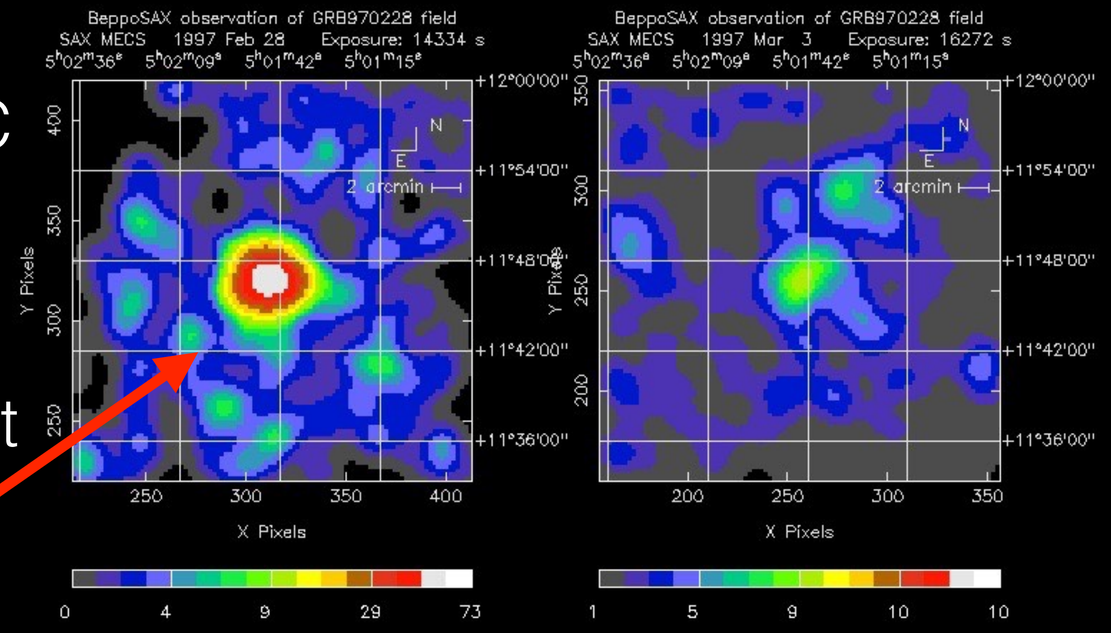
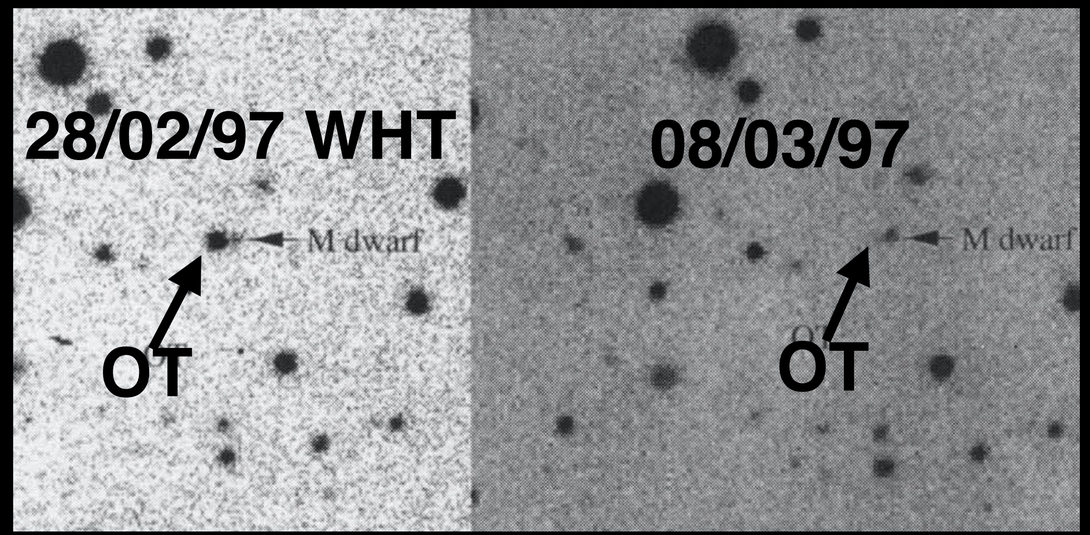
Discovery of first X-ray afterglow. <1arcmin position disseminated





GRB970228

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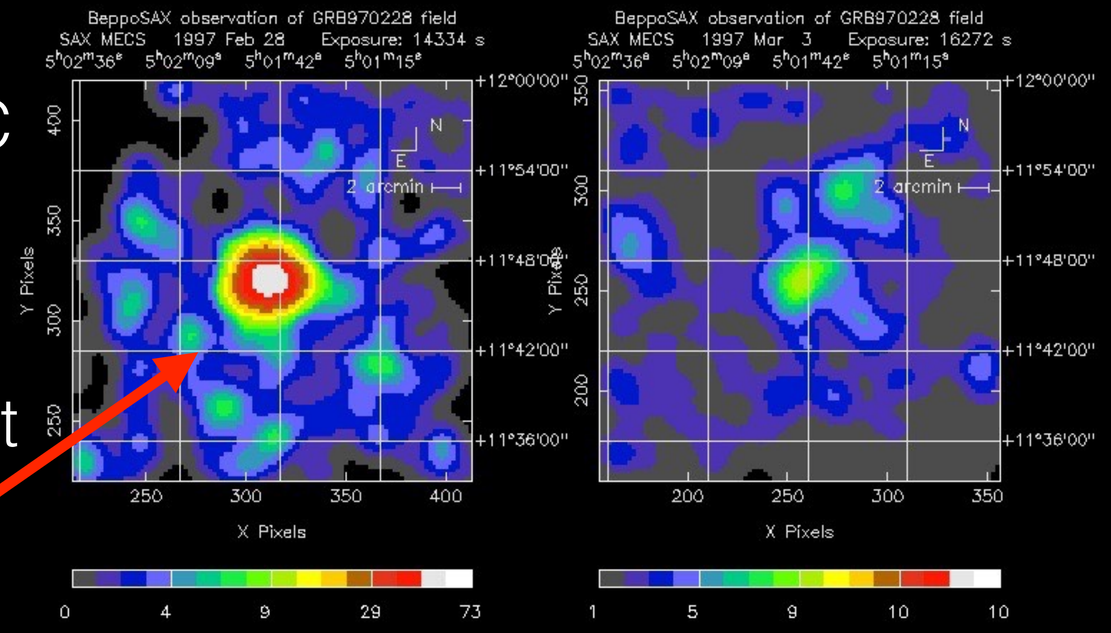
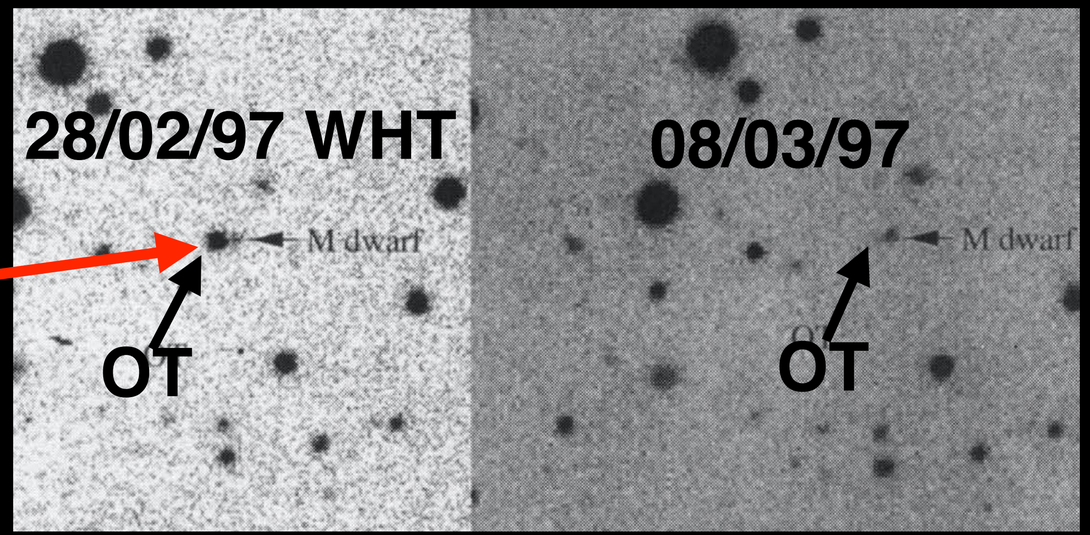
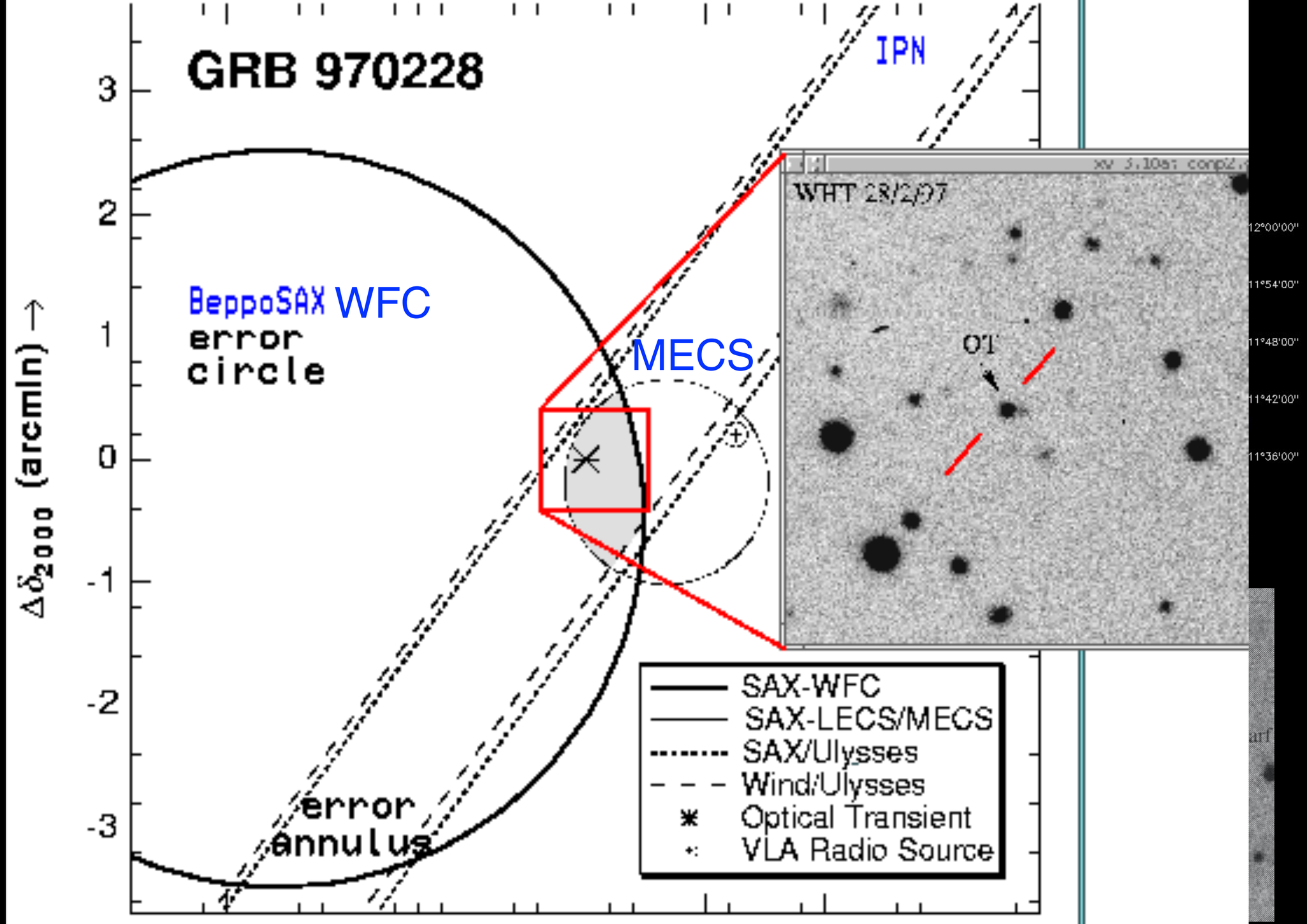
Satellite repointed and field observed with X-ray telescopes 8hr after the event

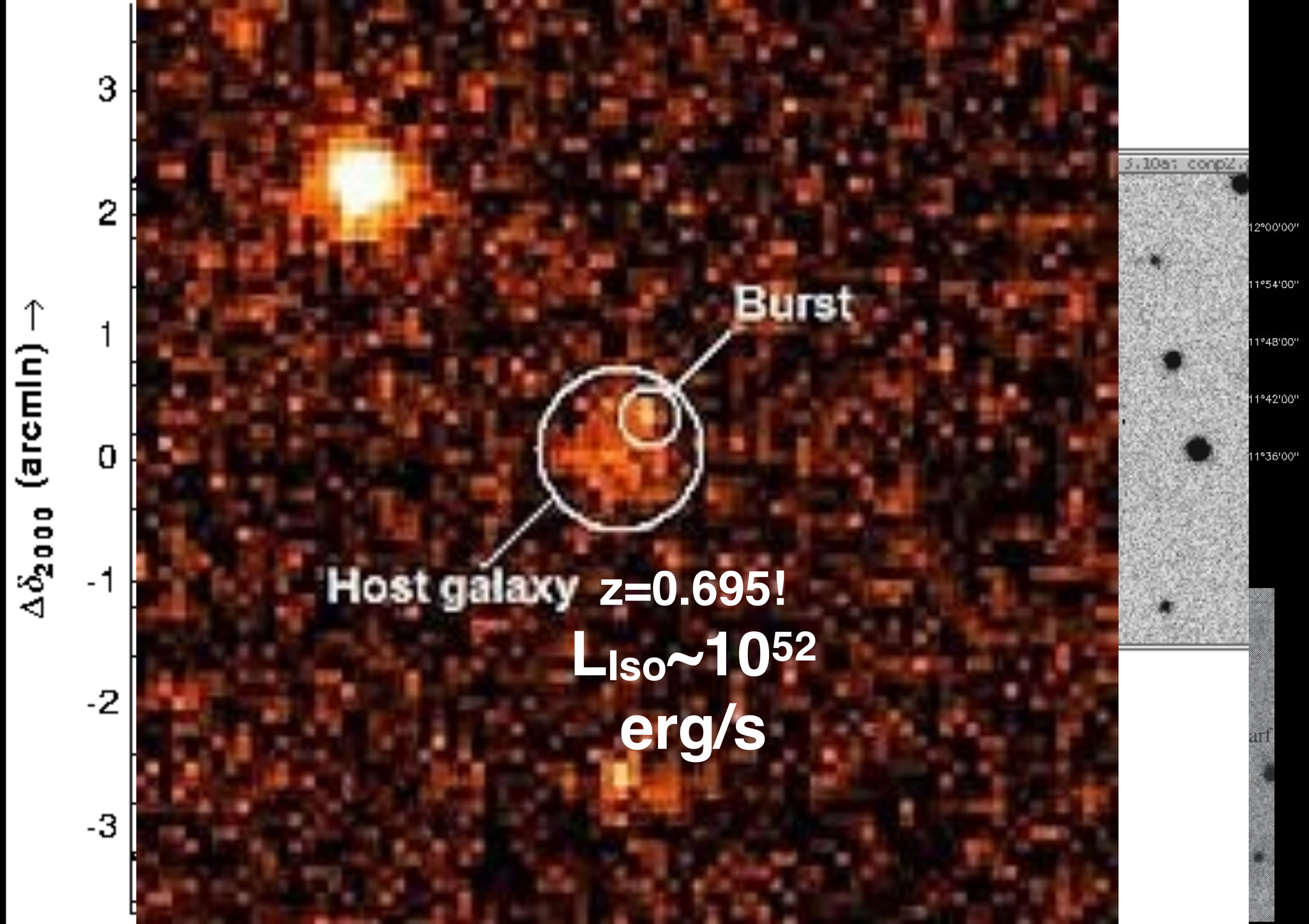
Discovery of first X-ray afterglow. <1arcmin position disseminated

Discovery of first optical afterglow






GRB 970228
IPN
BeppoSAX WFC
error
circle
MECS
error
annulus
WHT 28/2/97
OT
SAX-WFC
SAX-LECS/MECS
SAX/Ulysses
Wind/Ulysses
Optical Transient
VLA Radio Source
$\Delta\delta_{2000}$ (arcmin) →
3
2
1
0
-1
-2
-3
12°00'00"
11°54'00"
11°48'00"
11°42'00"
11°36'00"


3
2
1
0
-1
-2
-3
$\Delta\delta_{2000}$ (arcmin) →
Burst
Host galaxy
z=0.695!
L_{Iso}~10^{52}
erg/s
12°00'00"
11°54'00"
11°48'00"
11°42'00"
11°36'00"

Host Galaxy Detected for GRB970508

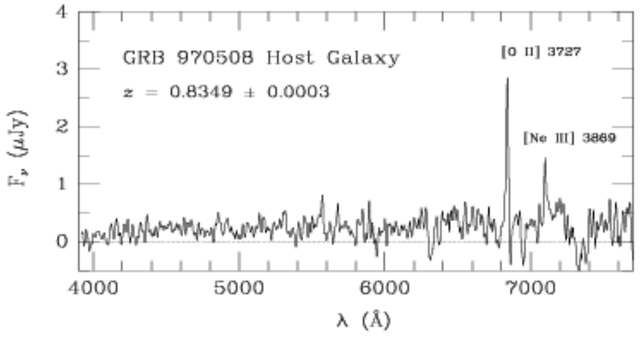
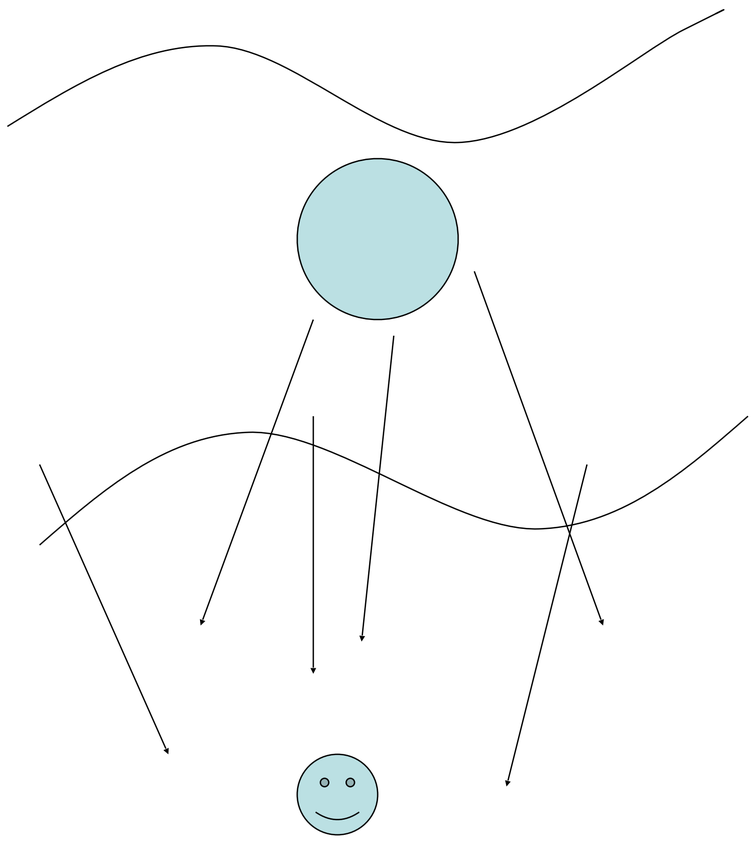
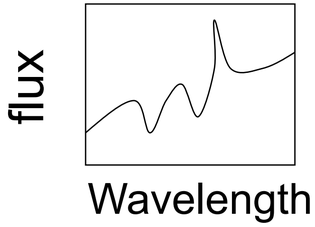


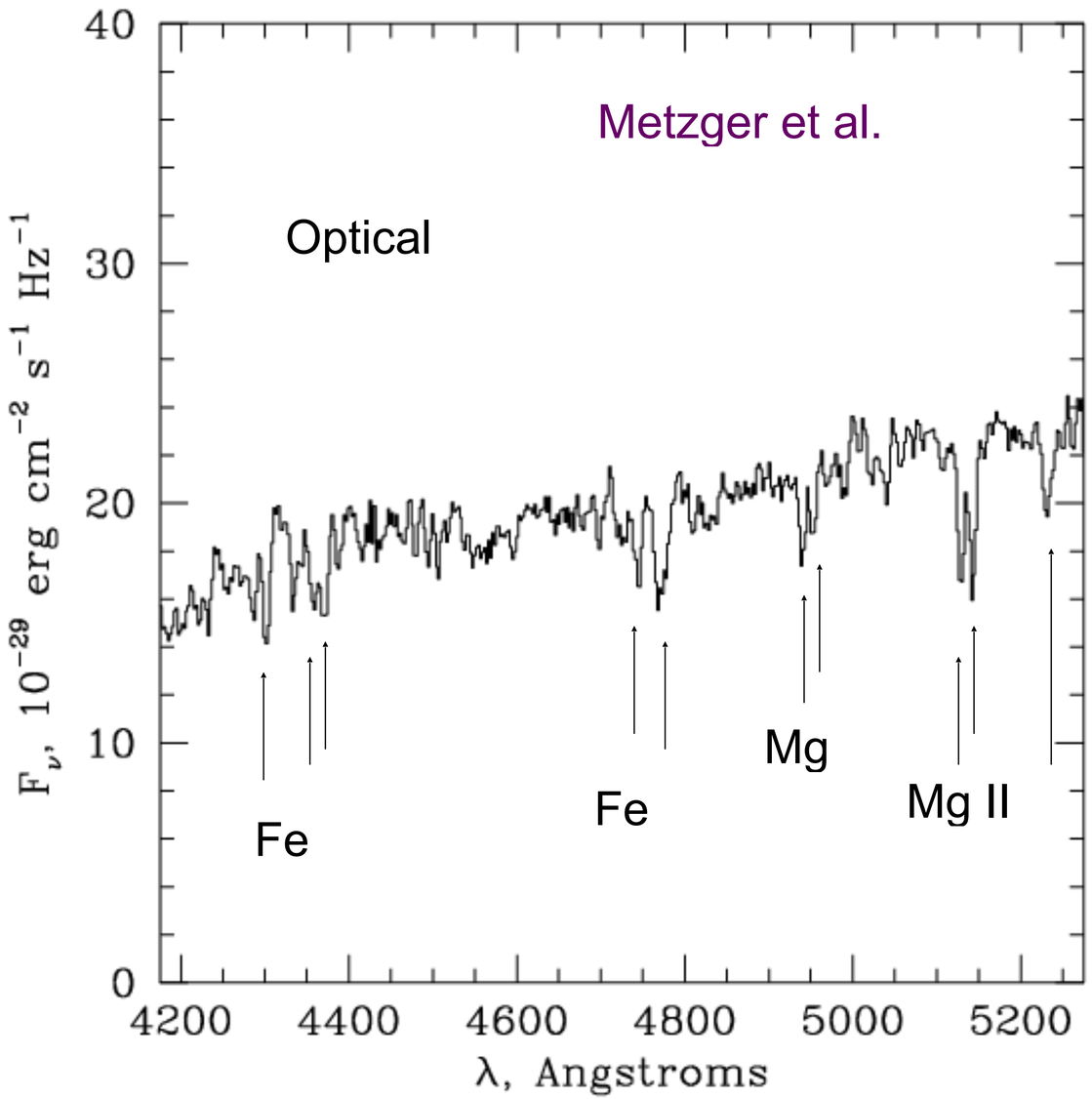
FIG. 2.— The weighted average spectrum of the host galaxy of GRB 970508, obtained at the Keck telescope. The spectra were smoothed with a Gaussian with a $\sigma = 5$ Å, roughly corresponding to the instrumental resolution. Prominent emission lines are labeled.

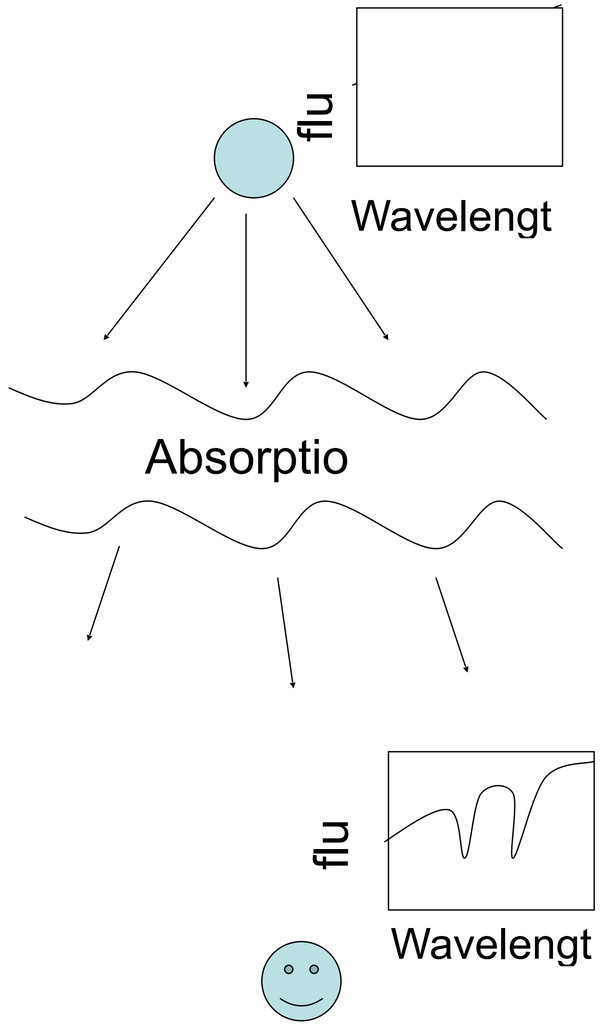
Z=0.835





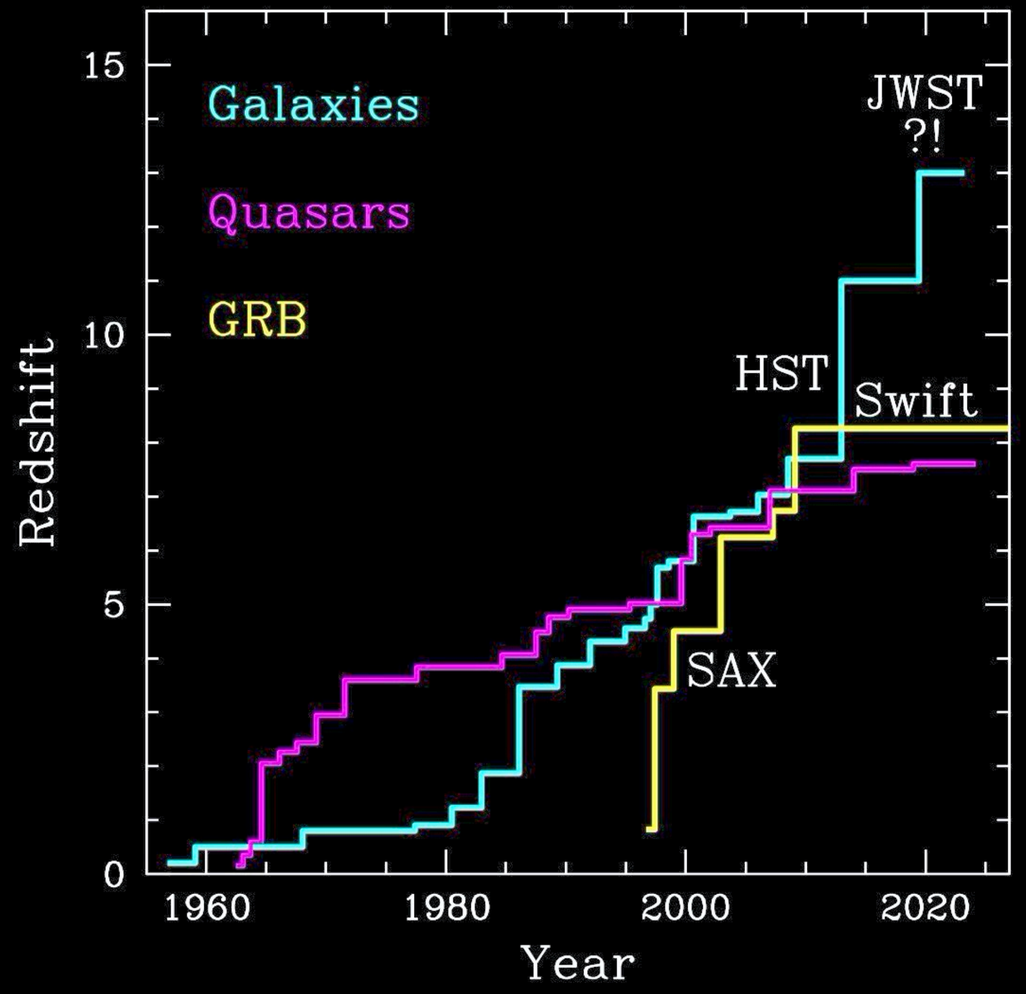
GRB970508 – Absorption Lines: z=0.835

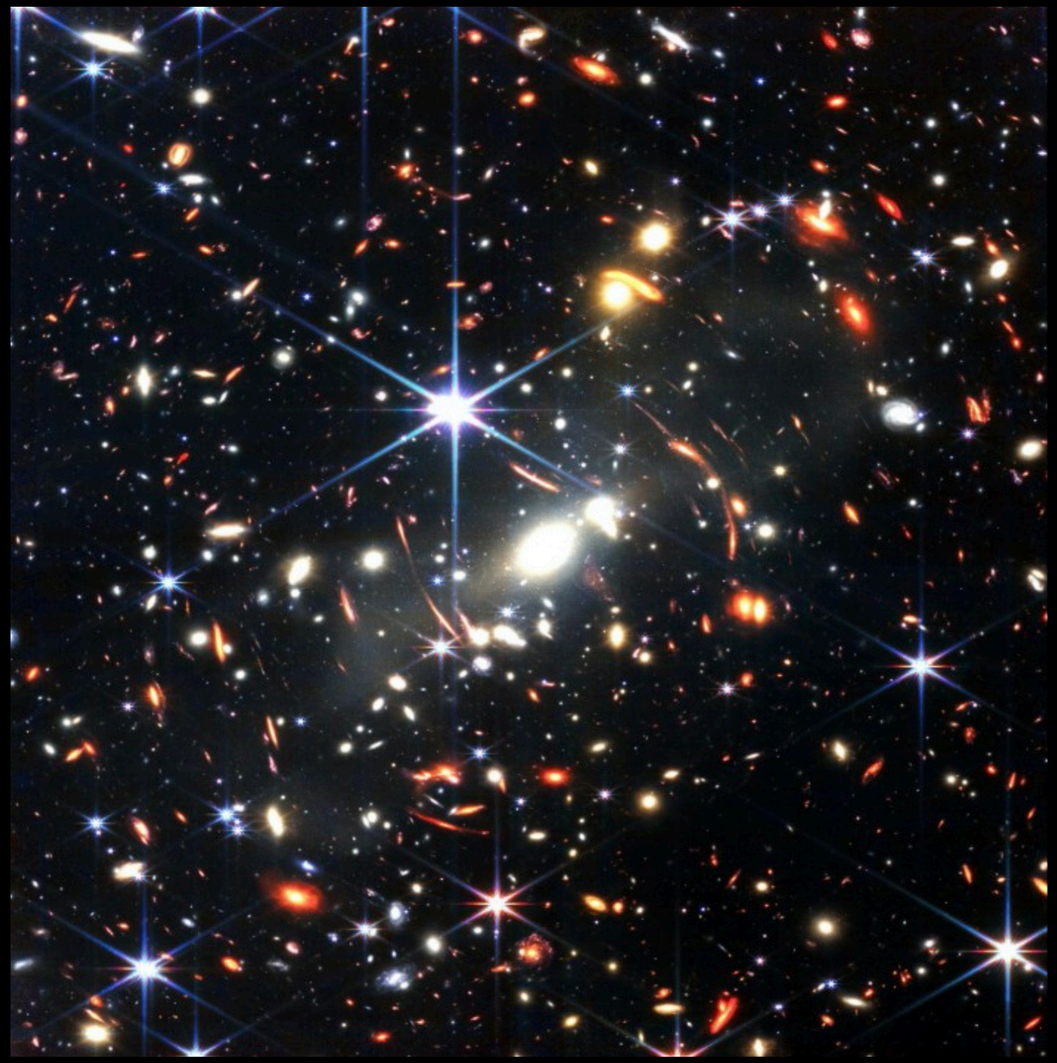




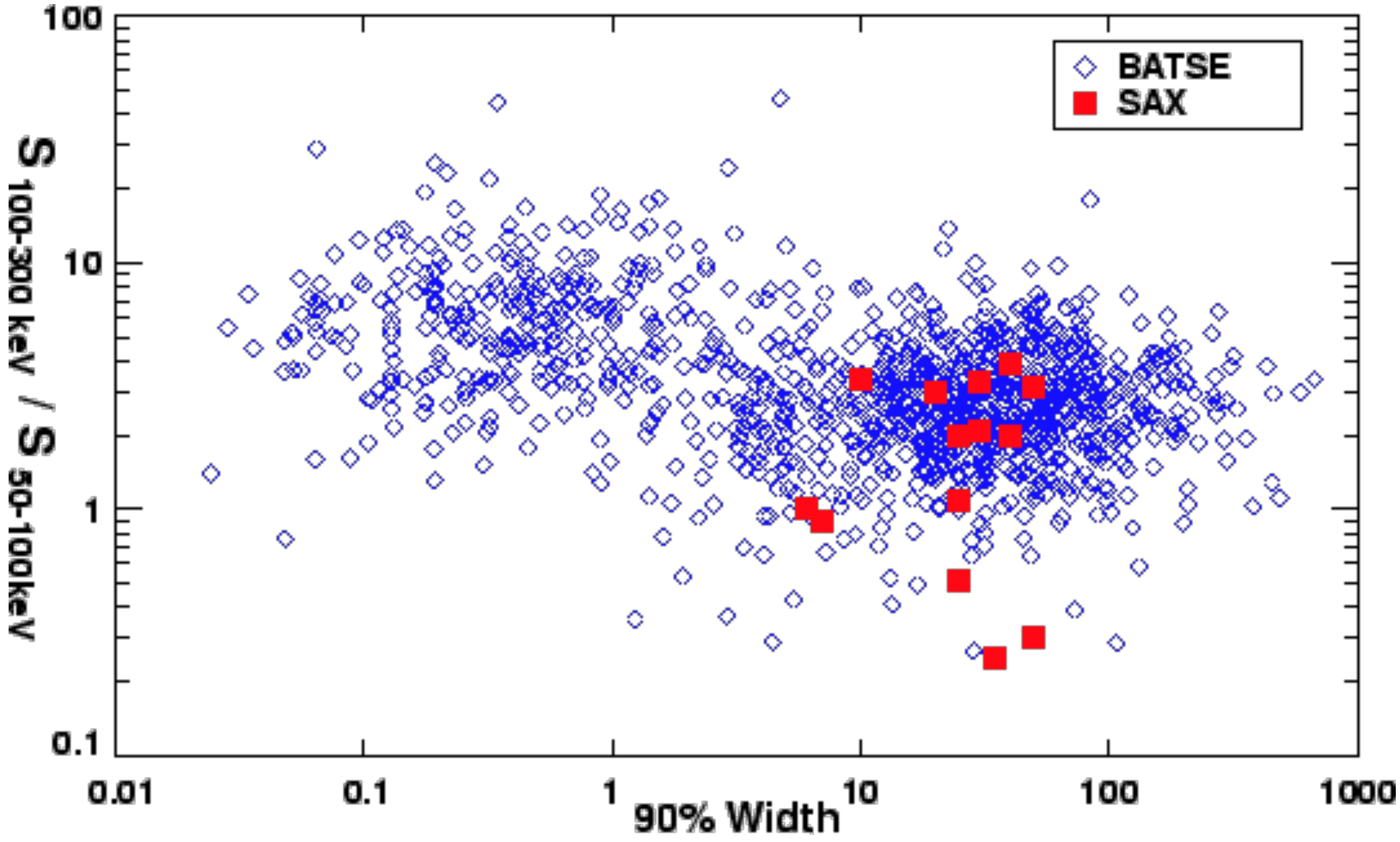
A flash in the dark: GRB and high-z galaxies

cosmic blasts spotting distant galaxies

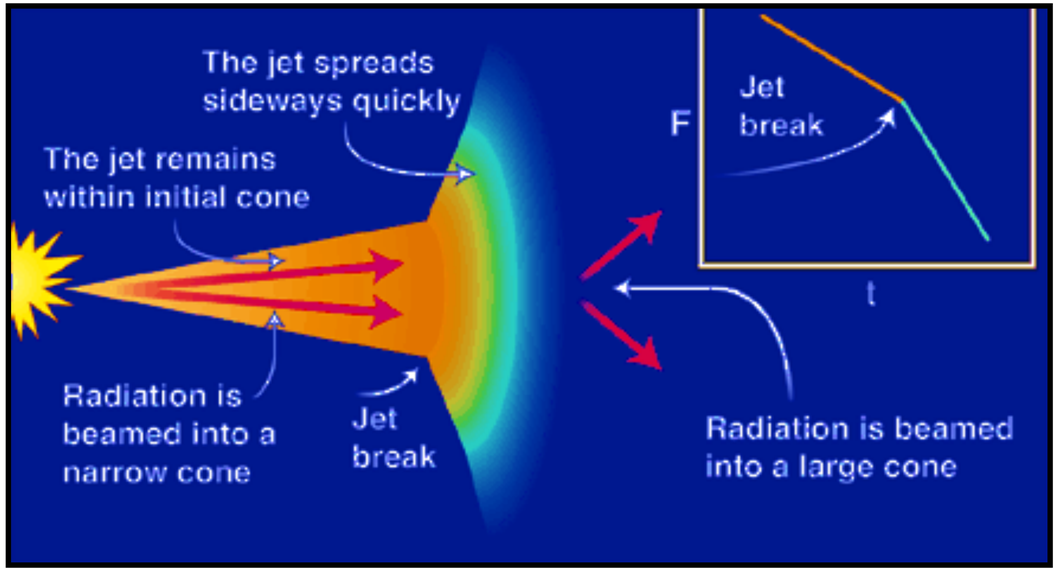




Gamma-Ray Burst Duration vs. Energy Spectrum



Jet Signatures

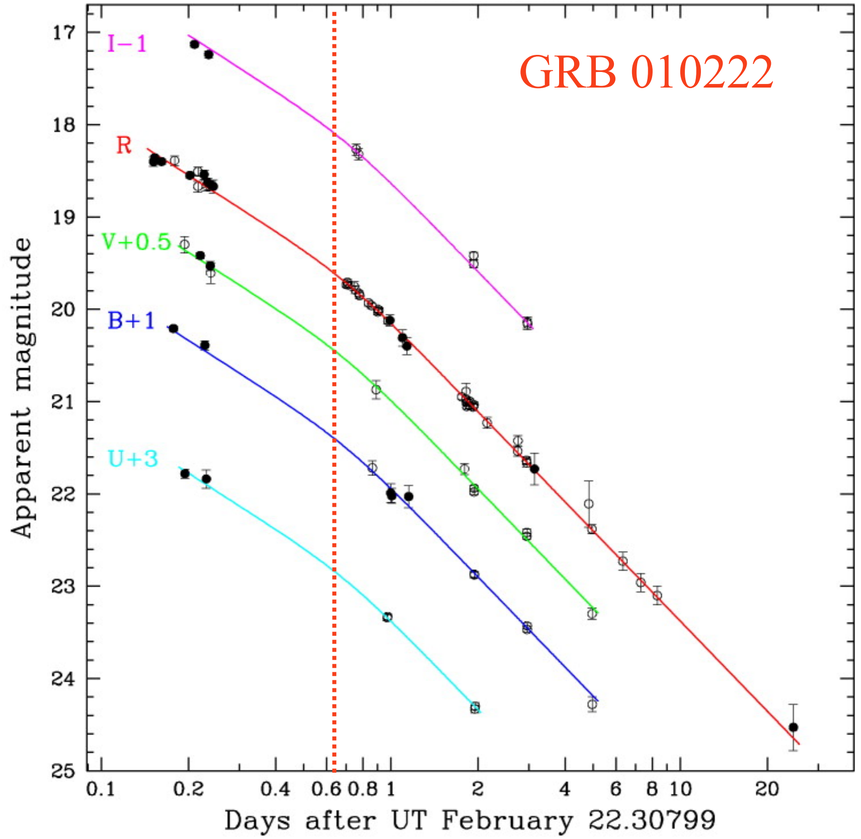


Piran, *Science,* 08 Feb 2002

$$E_\gamma = (1-\cos\theta_b)E_{\gamma,\mathrm{iso}}$$

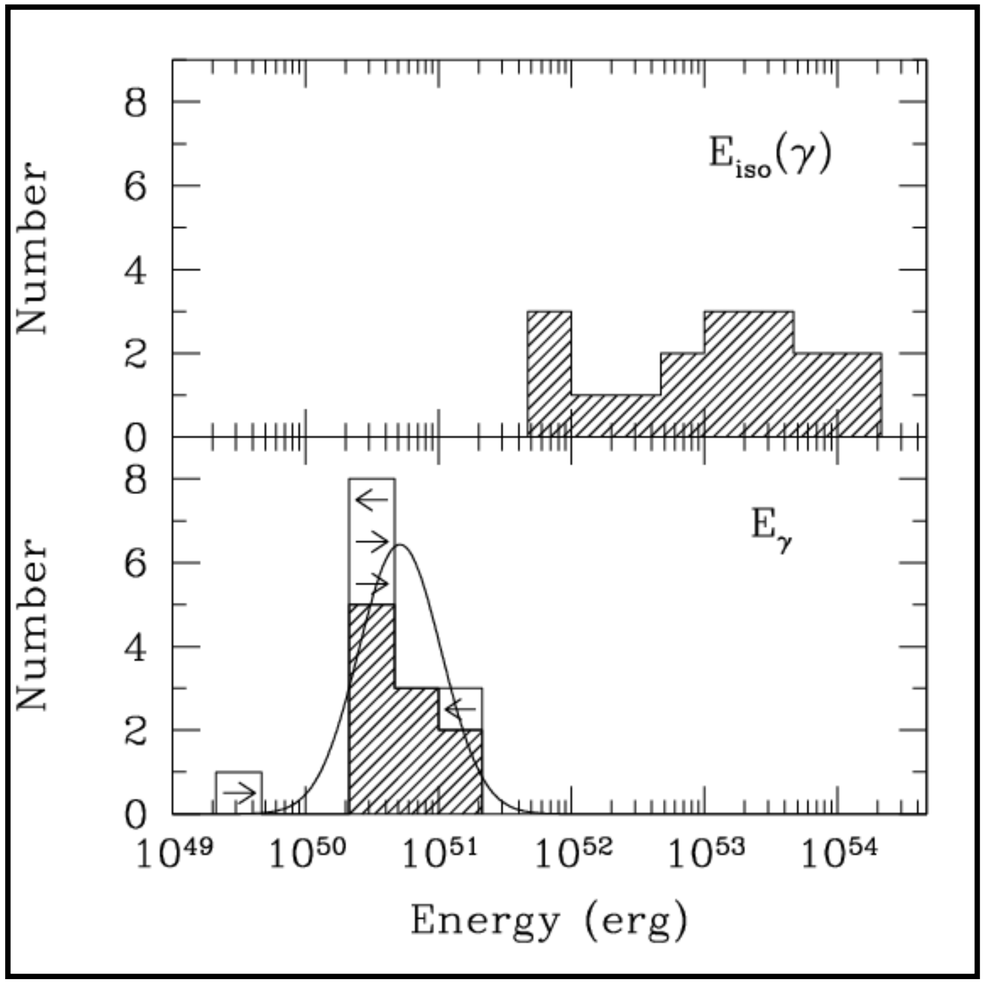
$$f_b = (1-\cos\theta_b) \approx \theta_b^{\,2}/2$$

$$\theta_b \propto \left[\frac{n_o \eta_\gamma}{E_{\gamma,\mathrm{iso}}}\right]^{1/8} \left[\frac{t_{\mathrm{break}}}{1+z}\right]^{3/8}$$



Stanek et al. (2001)

Energy and Beaming Corrections



Frail et al. (2001)

The dispersion in isotropic GRG energies results from a variation in the opening (or viewing) angle

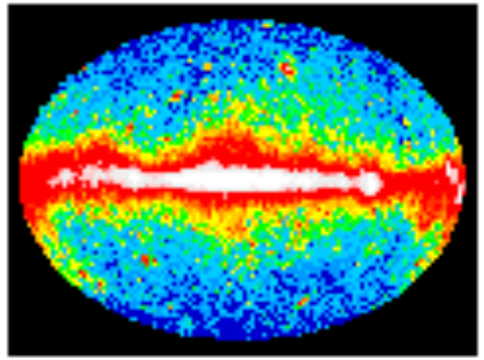
- The mean opening angle is about 4 degrees (i.e. $\langle f_b^{-1} \rangle \sim 500$)
- Geometry-corrected energies are narrowly clustered (1σ=2x)

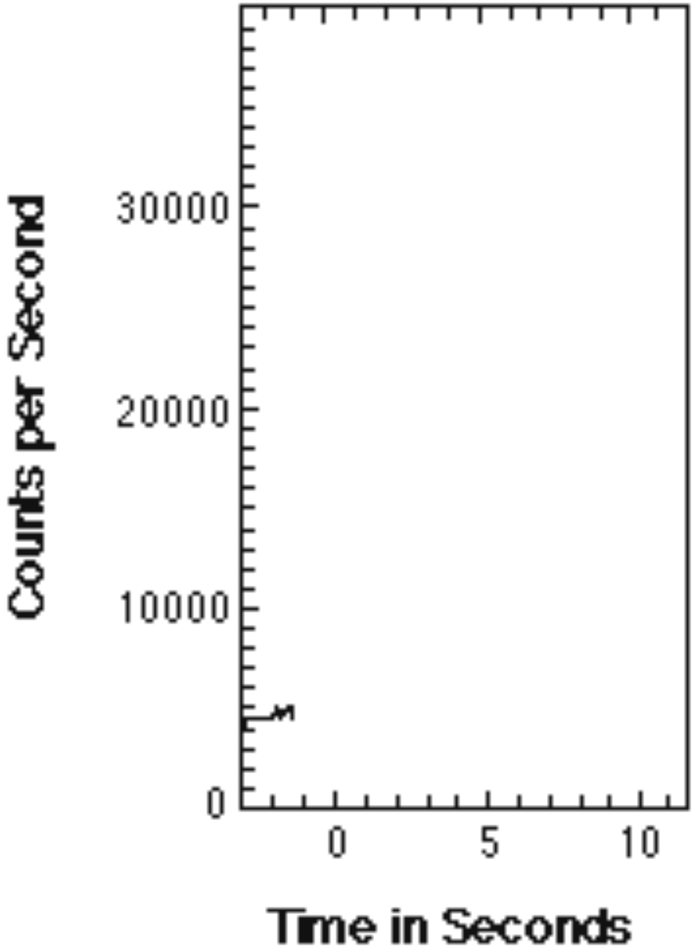
$$\langle E_\gamma \rangle = 5 \times 10^{50} \text{ erg}$$

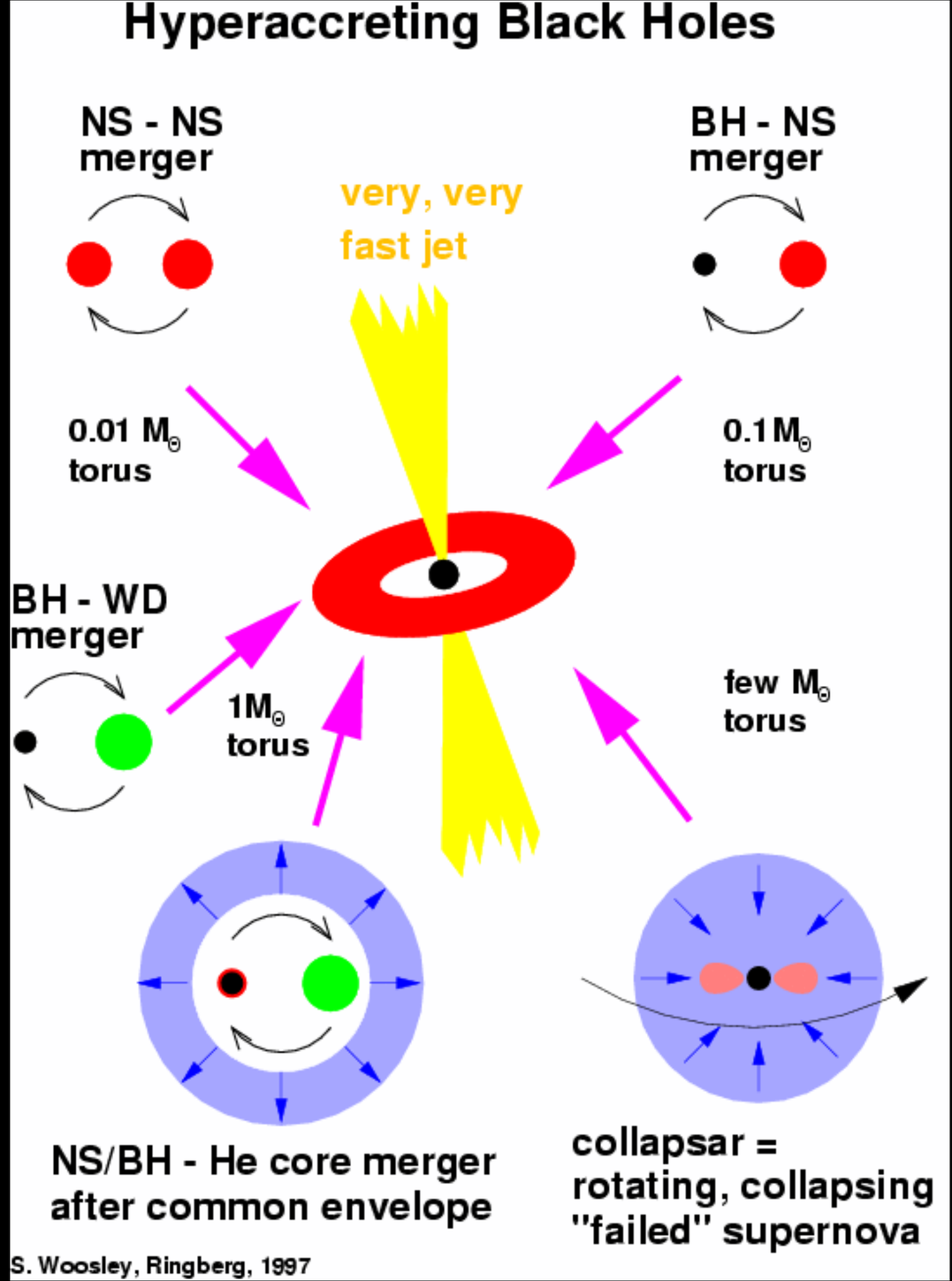
(for $n_o = 0.1\,\text{cm}^{-3}$ assumed)

GRBs in a nutshell

Sudden bursts of soft γ-rays
up to 10^{-3} ergs/s/cm^2 (μW/m^2)







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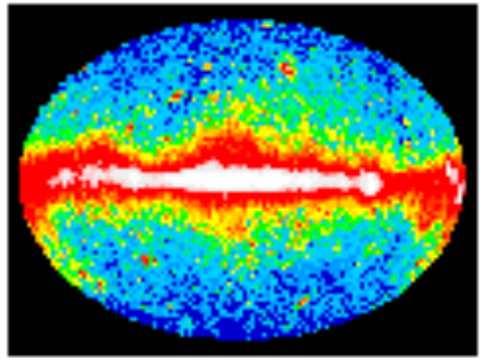

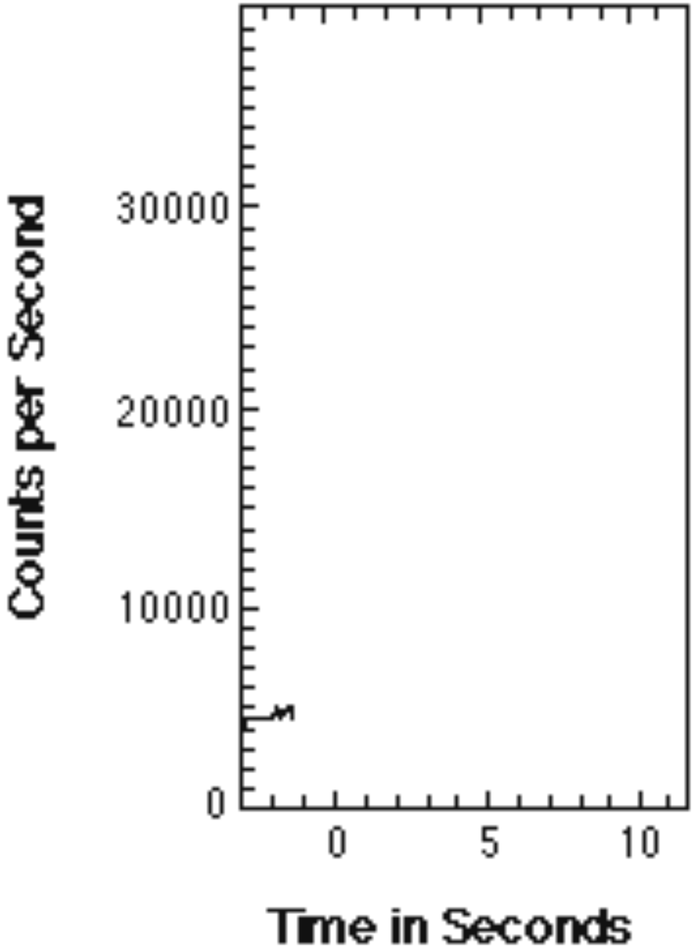

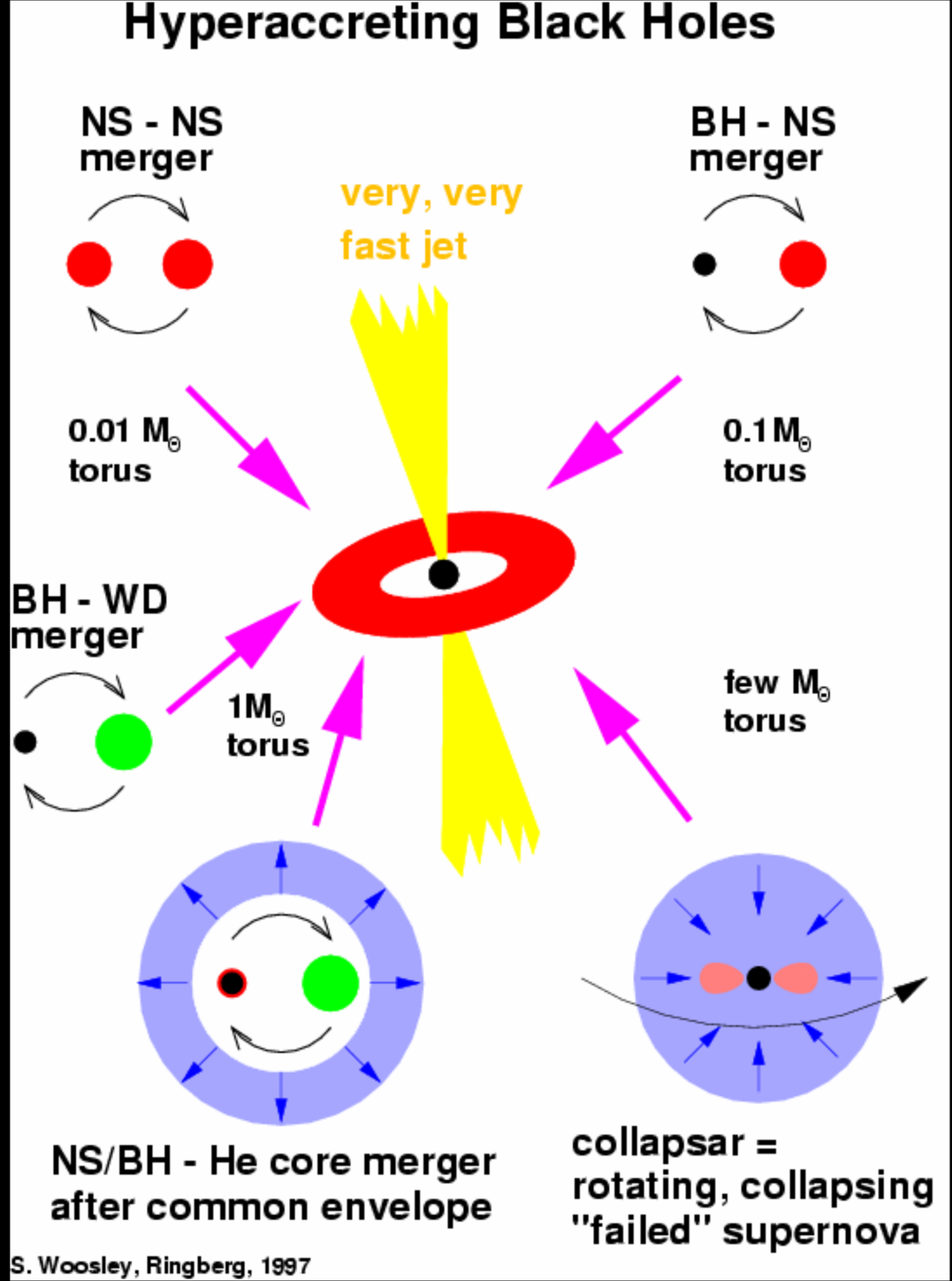

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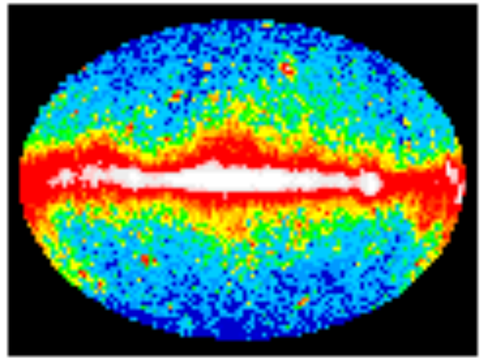

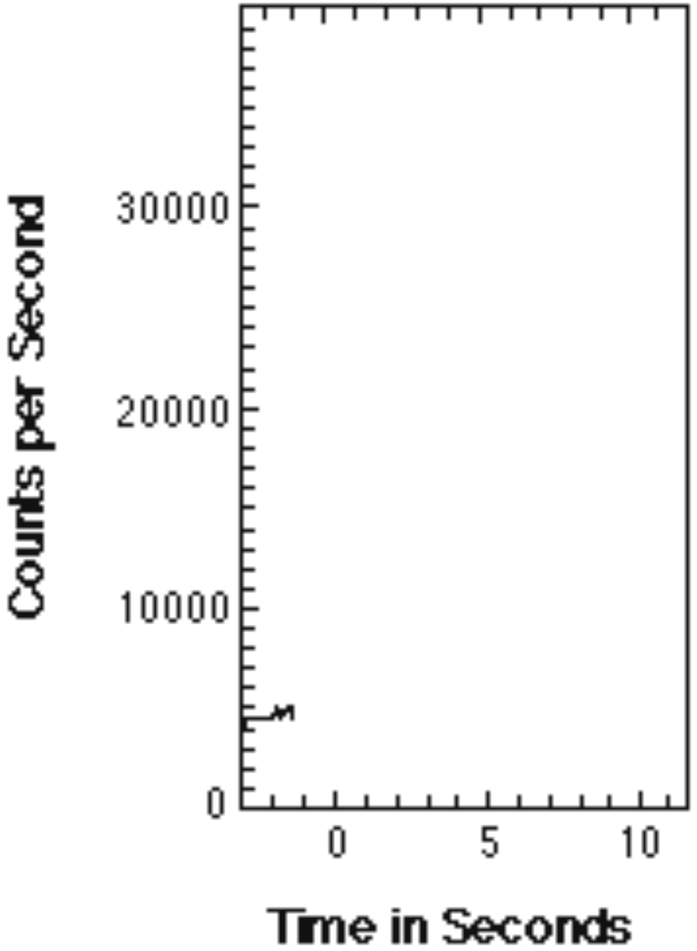

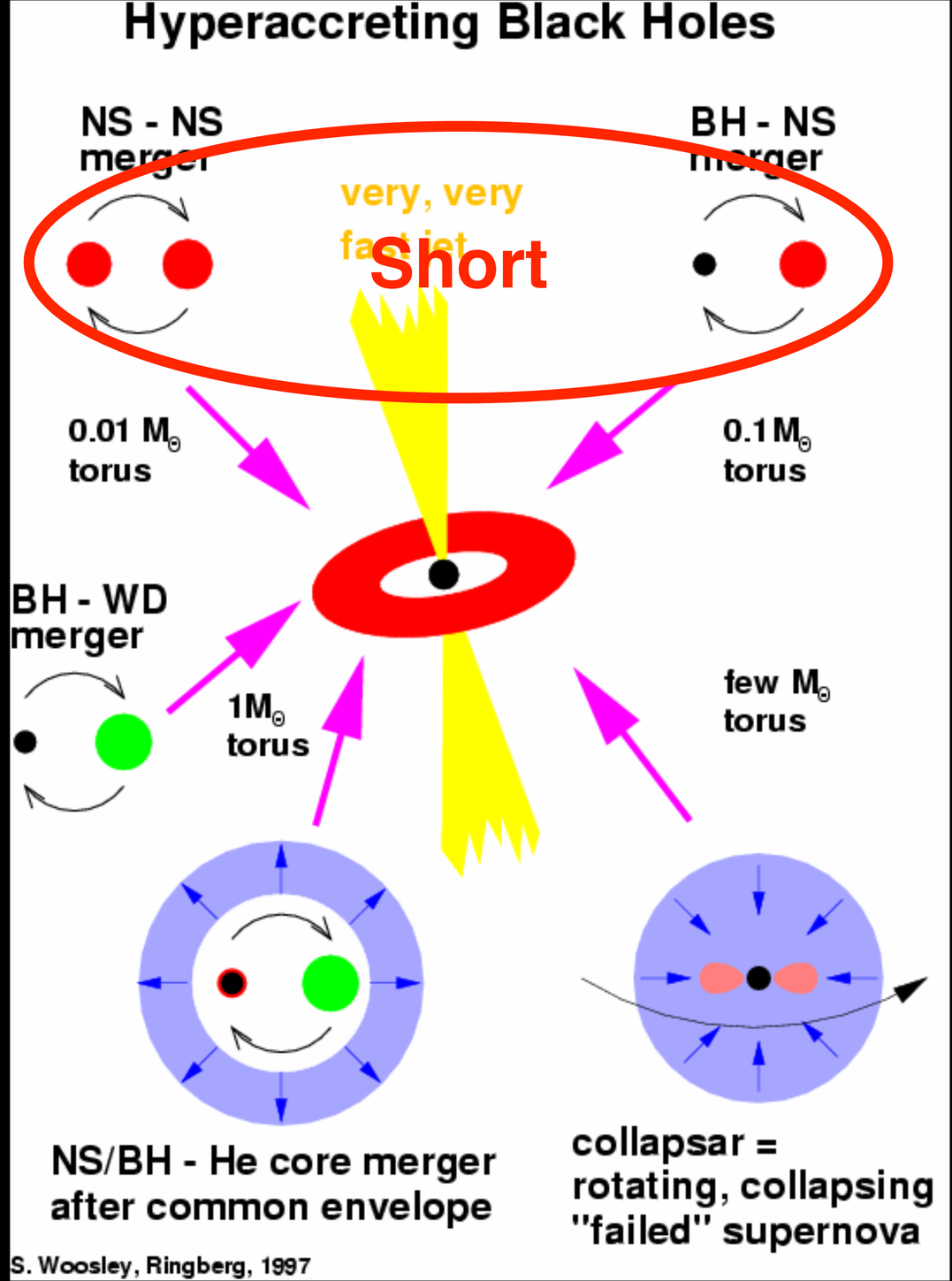

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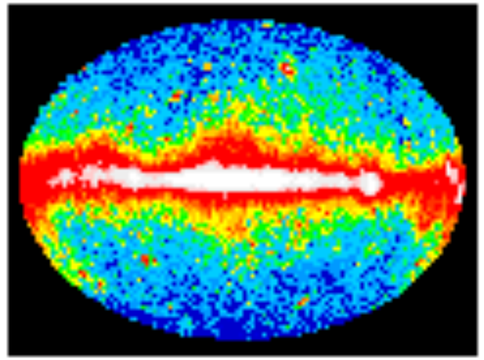
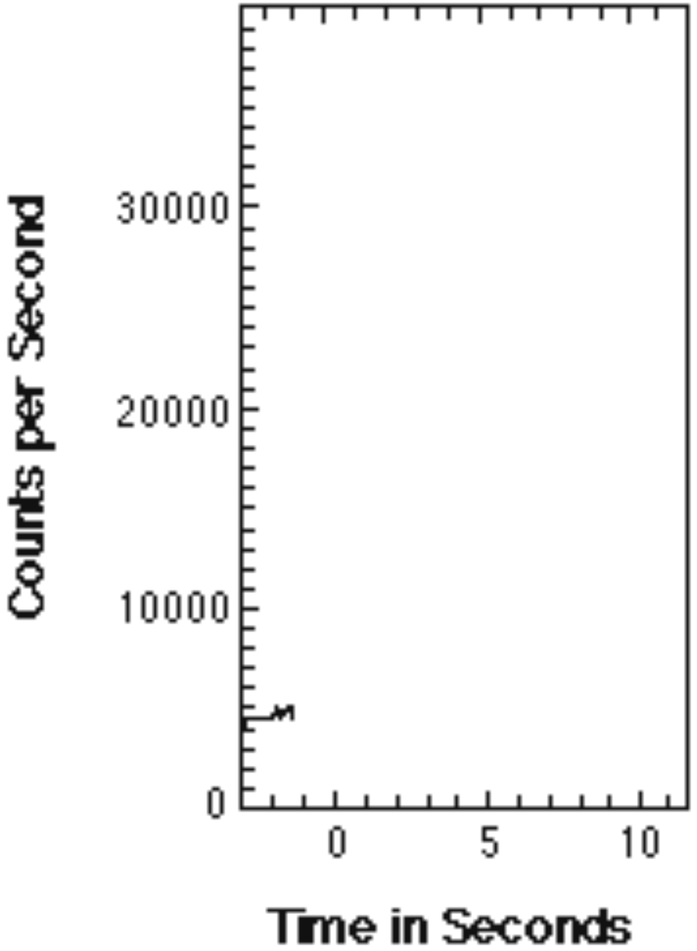
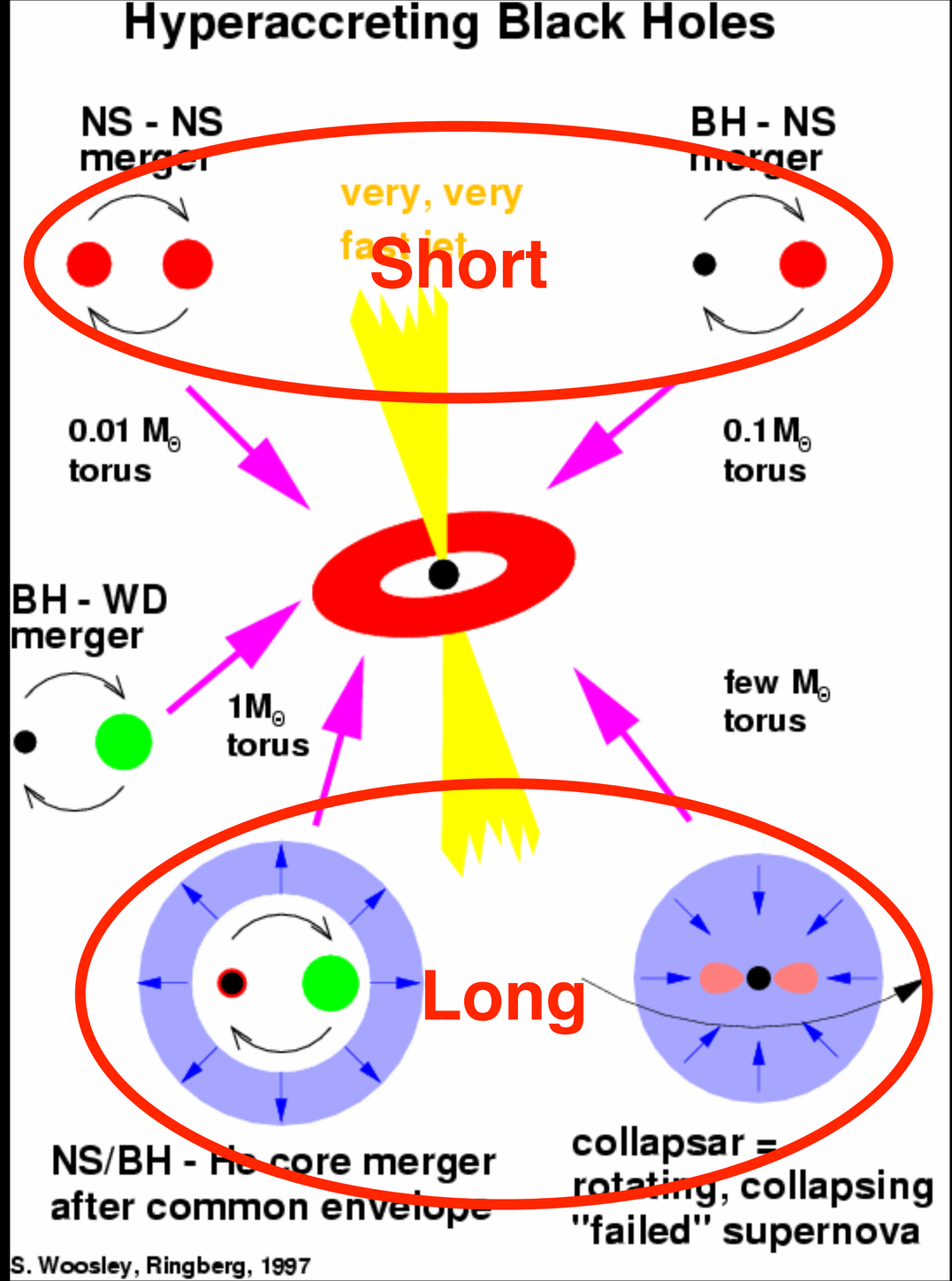


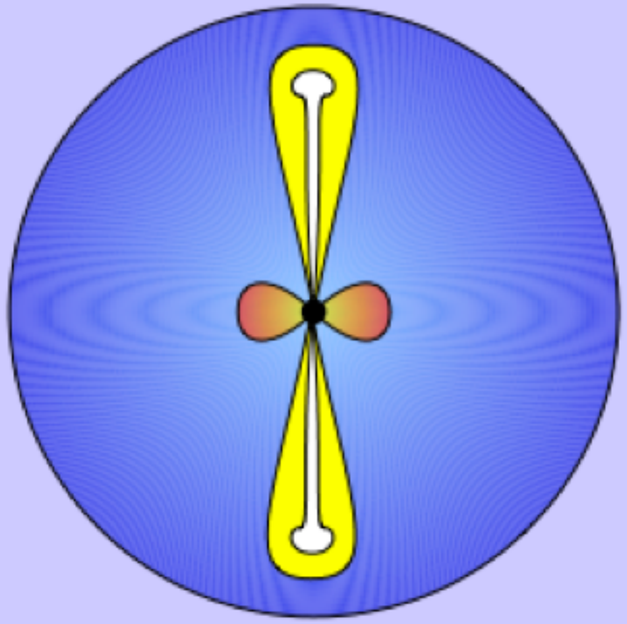




Progenitor Long GRBs: Collapsar model M>30 M◉

Very rough overview

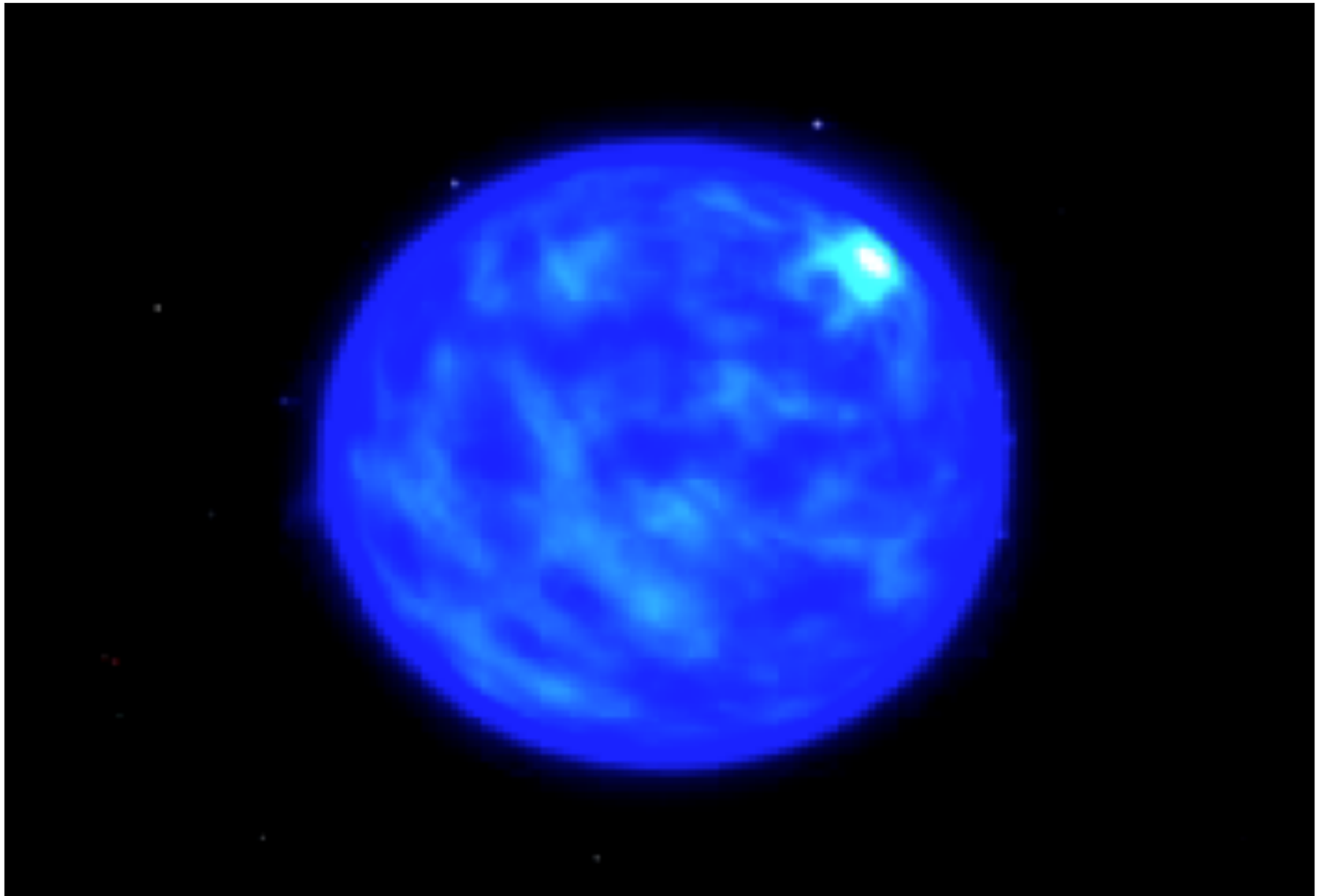
- The core of a rotating massive star collapses to a black hole.
- Material far from the axis does not fall straight in, but forms an accretion disk first.
- Dissipative effects in the disk convert kinetic energy into heat.
- Energy deposited over the poles of the disk powers jets.



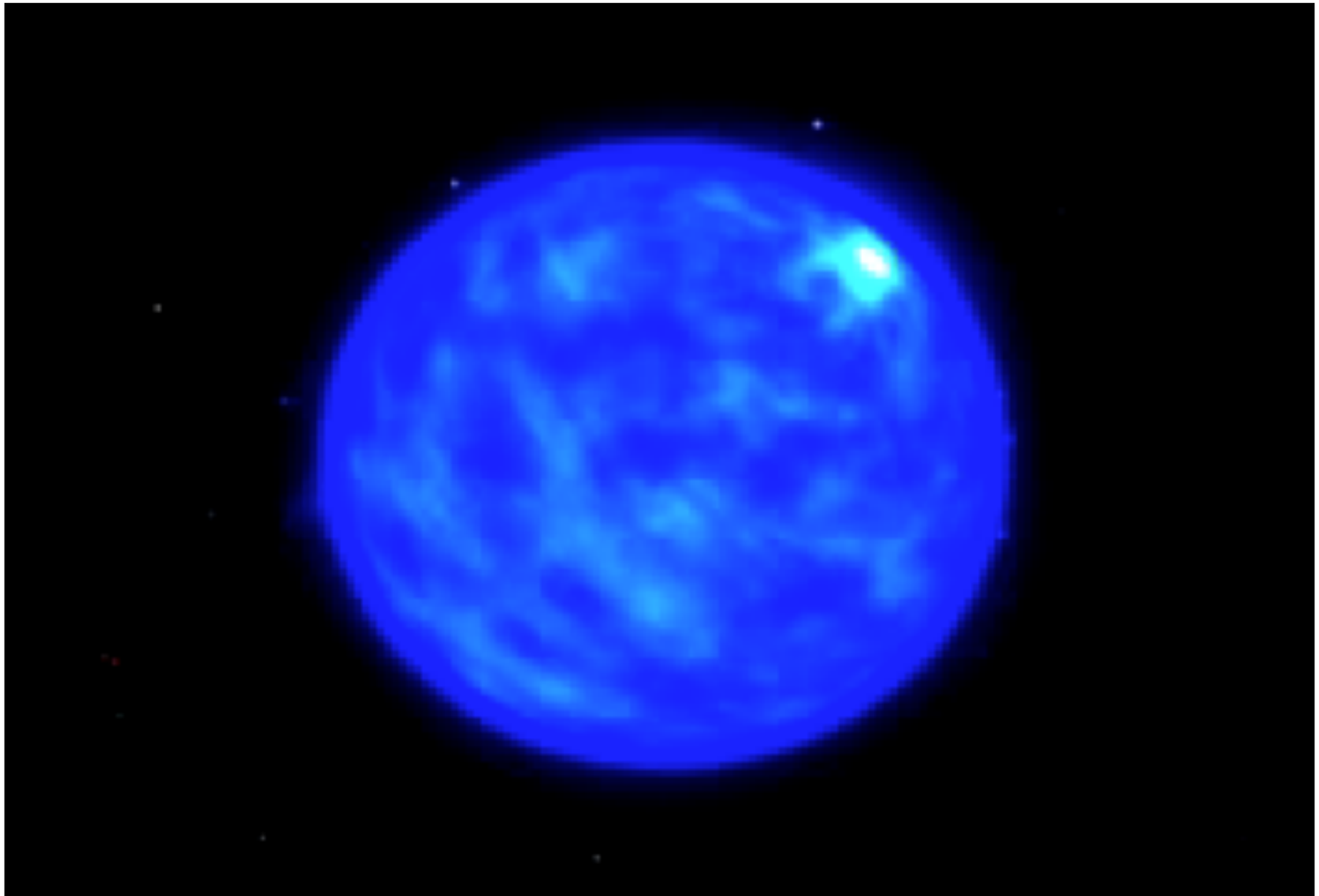
The progenitor star

- Mass: > 30 $M_\odot$
  - Lifetime: 4 – 7 million years
  - It will lose its hydrogen envelope through stellar winds, forming a Wolf-Rayet star, ≈ 300000 km in radius
  - Helium core > 12 $M_\odot$
  - Iron core > 2 $M_\odot$
- Rapidly rotating, ≈ 200 km/s at the surface

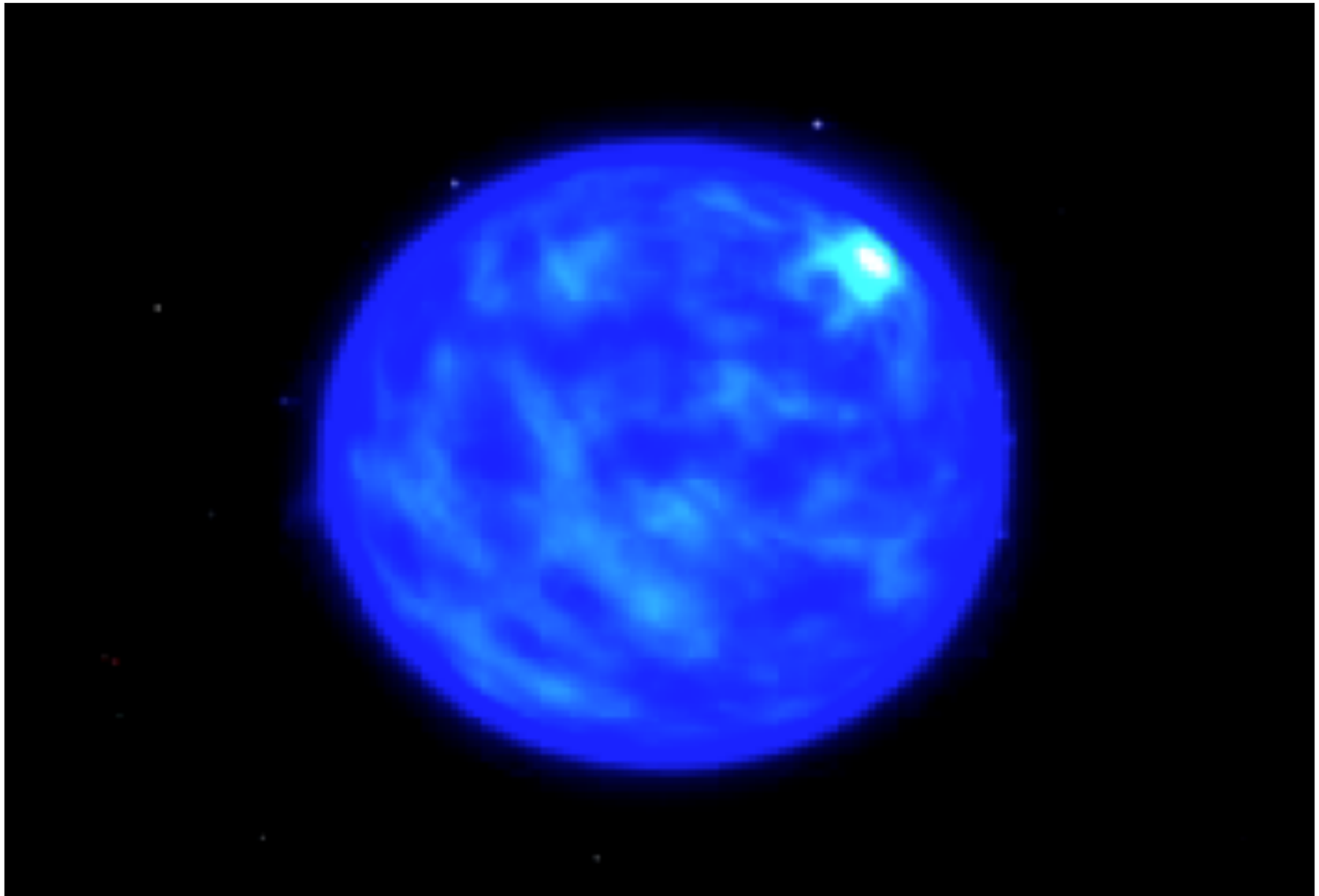
Modelli per un GRB



Modelli per un GRB



Modelli per un GRB



The compactness problem

- $Dt \sim 1\text{-}10$ ms → Compact sources $R_0 \sim c\,Dt \sim 3\ 10^7$ cm

- Cosmological sources (D~3 Gpc) → $L_g \sim fD^2 \sim 10^{52}$ erg/s

R of our galaxy ~ 30 kpc: extragalactic objects

$$\mathbf{e_{g1}\ e_{g2} \geq (m_e c^2)^2} \qquad \gamma\gamma \rightarrow e^+e^-$$

$$t_{gg} \sim \zeta_p R_0 n_g \sigma_T \sim \sigma_T L_g / 4\pi R_0 c\, \mathbf{e_g} \sim 10^{15}$$

ζ_p fraction of photons above the thereshold of pair production

$\sigma_T = 6.25 \times 10^{-25} cm^2$

$\mathbf{e_g}$ ~ 1 MeV

Optical depth t_{gg} ($\gamma\gamma \rightarrow e^+e^-$) >>1

Beaming hypothesis

$$l_\gamma = \frac{L\sigma_T}{Rm_e c^3} \geq 1000$$

but.. if $l_\gamma \geq 60$ γ - ray cannot excape, because they interact with X - ray photons to make $e^+ e^-$ couples

Doppler boosting

$$\delta = 1/\gamma\,(1 - \beta\cos\theta)$$

- $\Delta t_{obs} = \Delta t/\delta$
- light aberration $\nu_{obs} = \delta\,\nu$

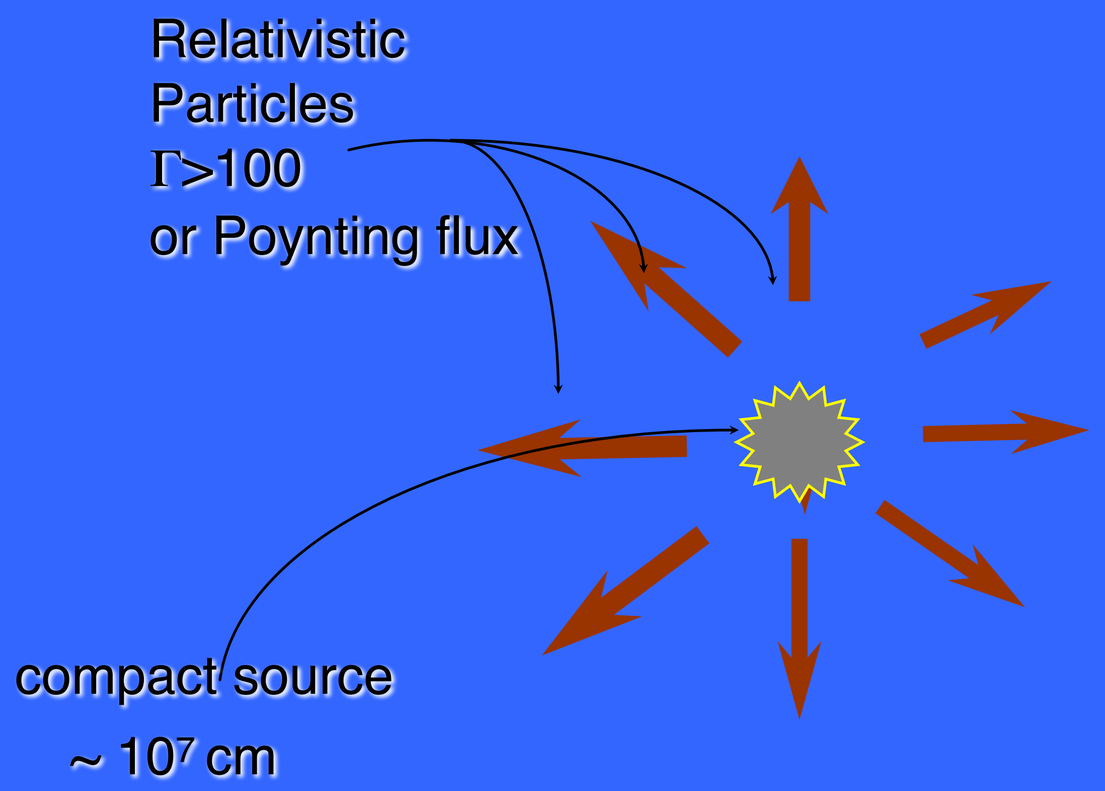
I_ν/ν^3 is relativistic invariant $I_{\nu obs} = \delta^3 I_\nu$

$$F_{\nu\,obs} = F_\nu\,\delta^{3+\alpha} \qquad F_{bol\,obs} = F_{bol}\delta^4$$

$$\frac{\Delta F_{obs}}{\Delta t_{obs}} = \delta^5 \frac{\Delta F}{\Delta t}$$

$$l = \frac{L_x\sigma_T}{Rm_e c^3} \qquad R \sim \delta c \Delta t \qquad l = \delta^{-5}\frac{L_{obs}}{\Delta t_{obs}}\frac{\sigma_T}{m_e c^4}$$

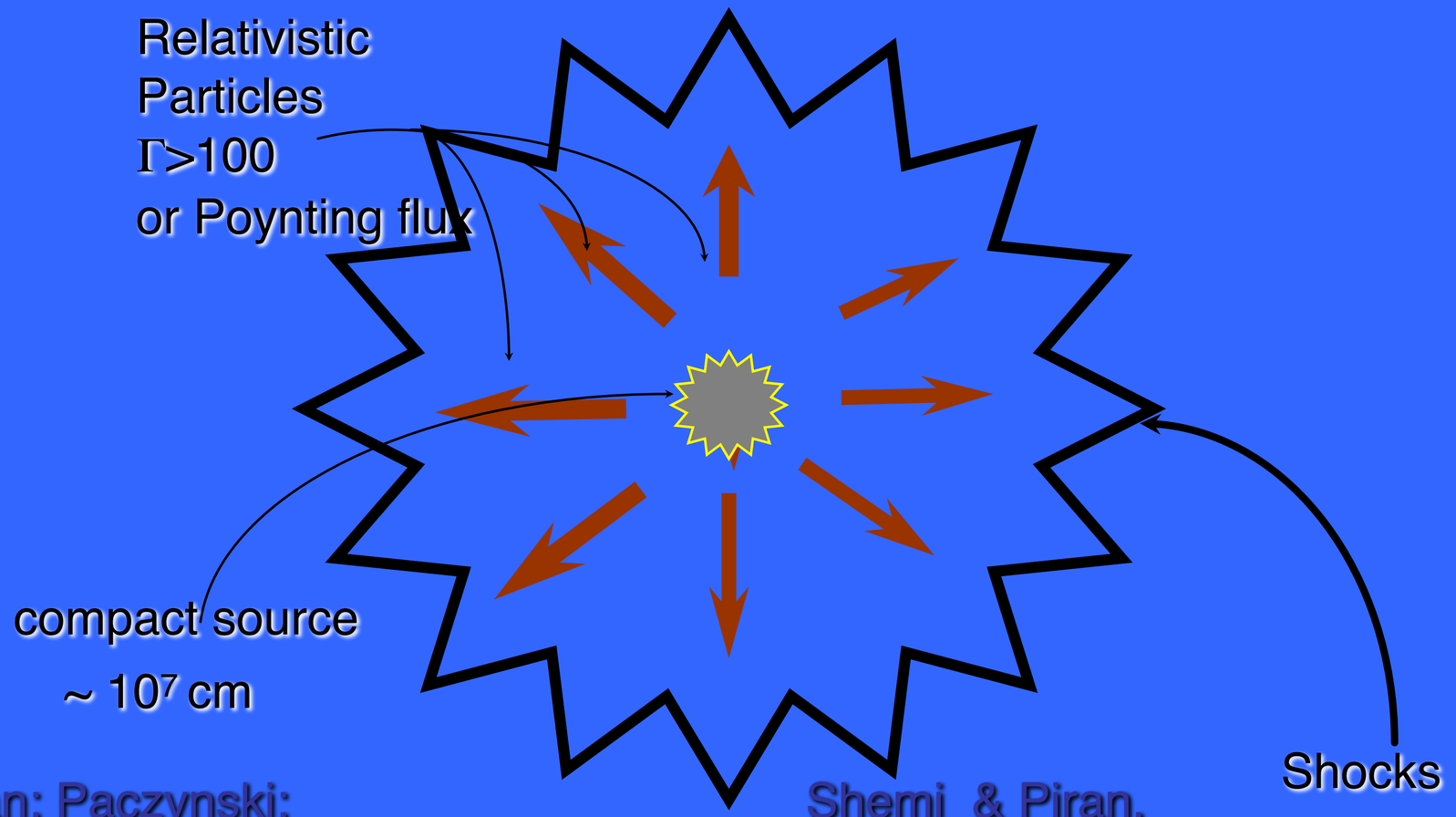
The Fireball Model



Goodman; Paczynski;
Narayan, Paczynski & Piran;

Shemi & Piran,
Meszaros & Rees

The Fireball Model



Goodman; Paczynski;
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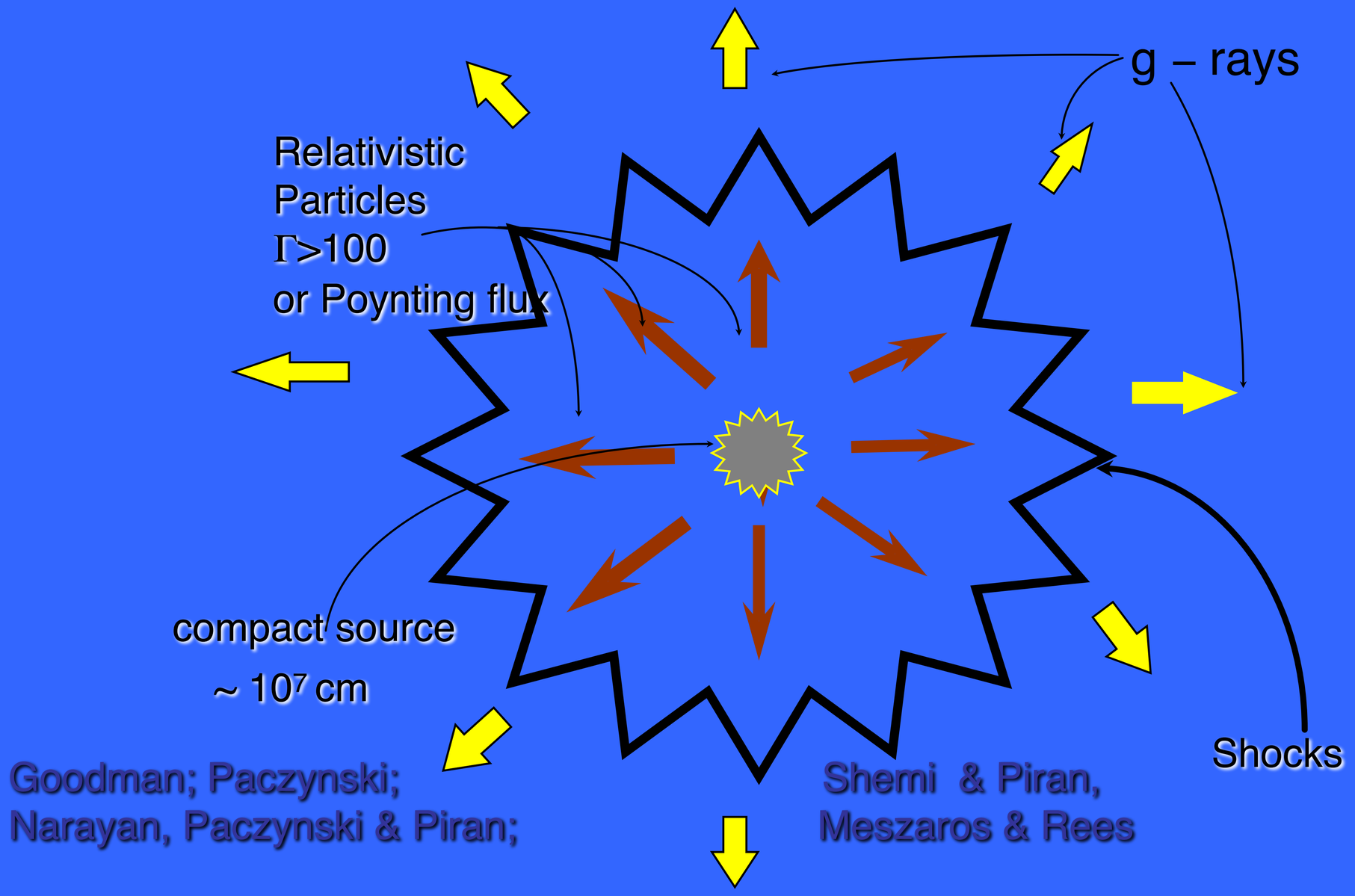
The Fireball Model



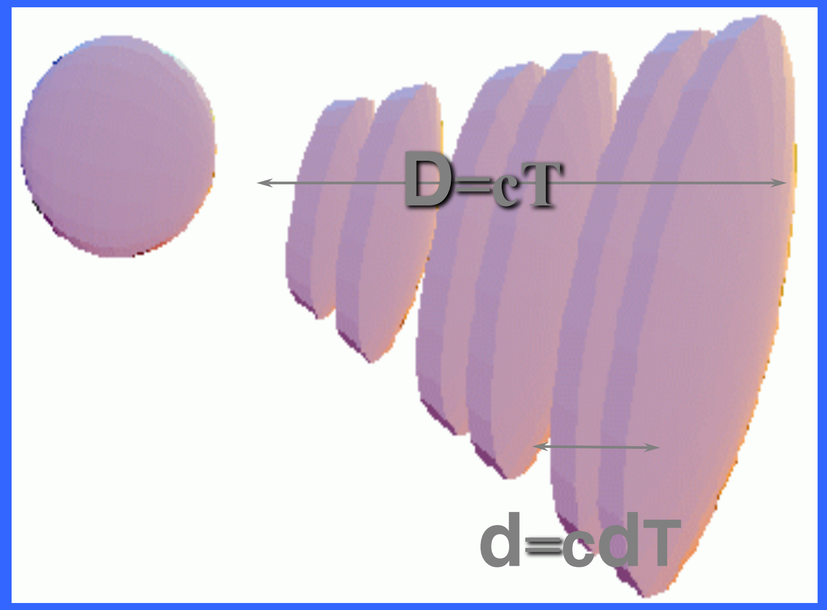
The Lorentz factor

The Lorentz factor

- As the fireball shell expands, the baryons will be accelerated by radiation pressure.
- The fireball bulk Lorentz factor increases linearly with radius.
- $\Gamma_0 \sim \eta \equiv E/M_0c^2$, M_0 total baryon mass of the fireball

Internal Shocks

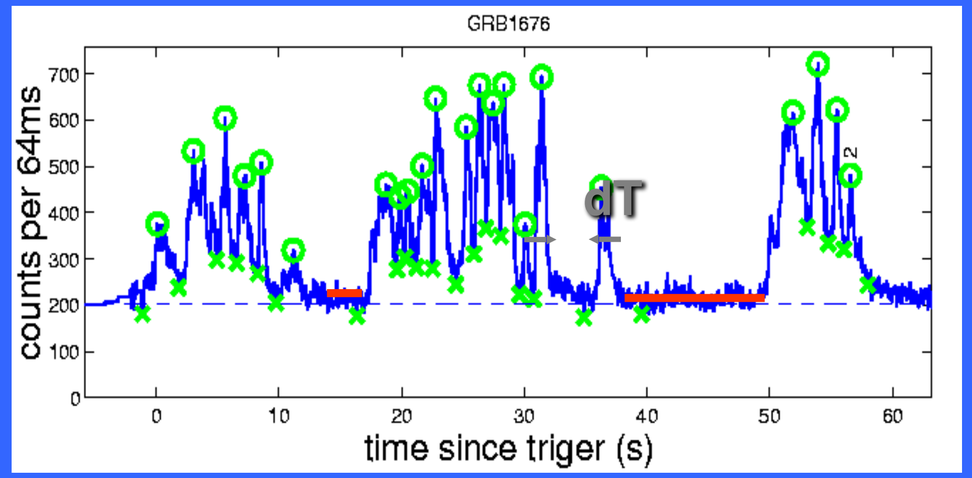
Shocks between different shells of the ejected relativistic matter



- $dT = R/cg^2 = d/c \sim$

$\sim D/c = T$

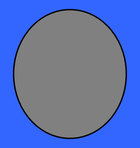
- The observed light curve reflects the activity of the "inner engine". → <u>Need TWO time scales.</u>
- To produce internal shocks the source must be active and highly variable over a "long" period.



T

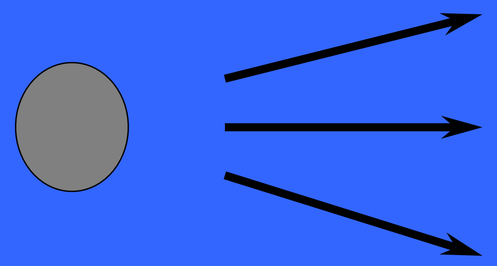
The Internal-External Fireball Model

The Internal-External Fireball Model



Inner
Engine

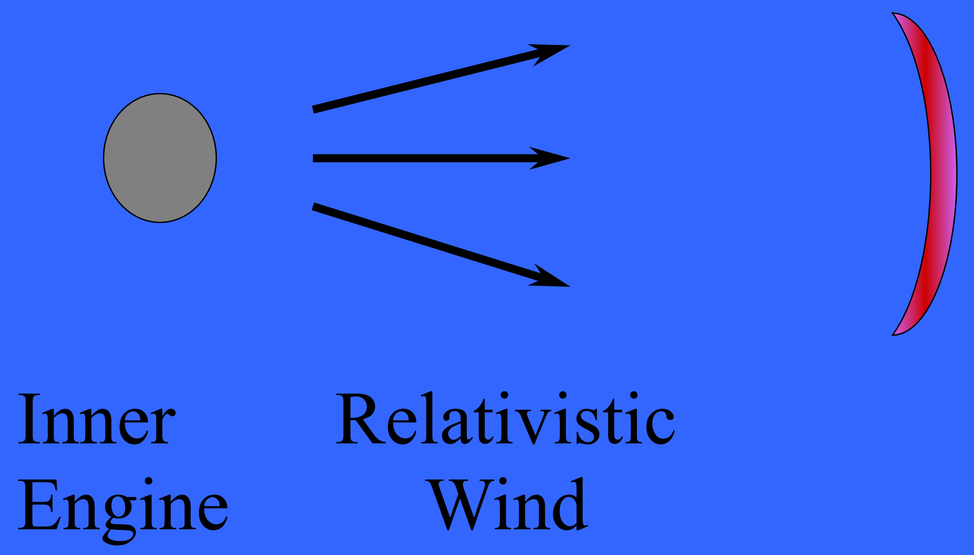
The Internal-External Fireball Model



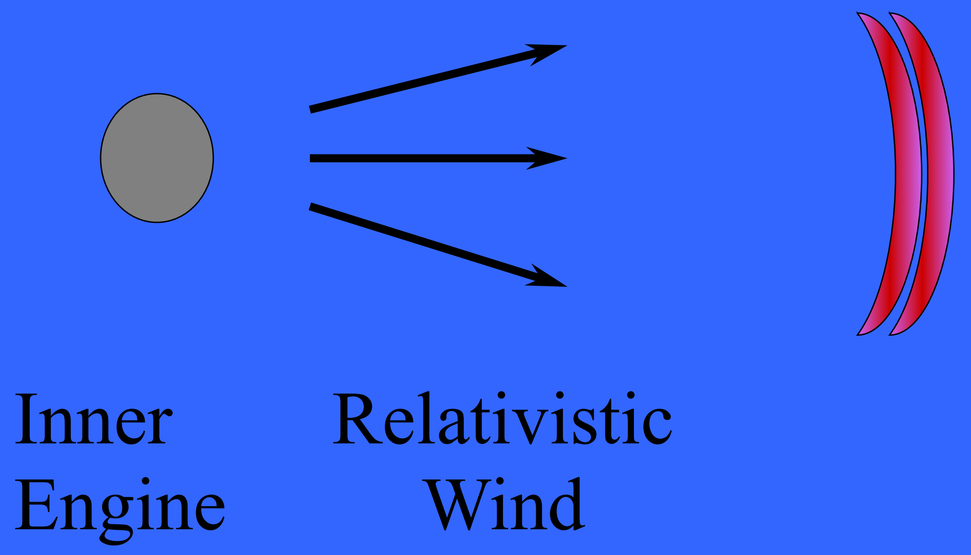
Inner Engine

Relativistic Wind

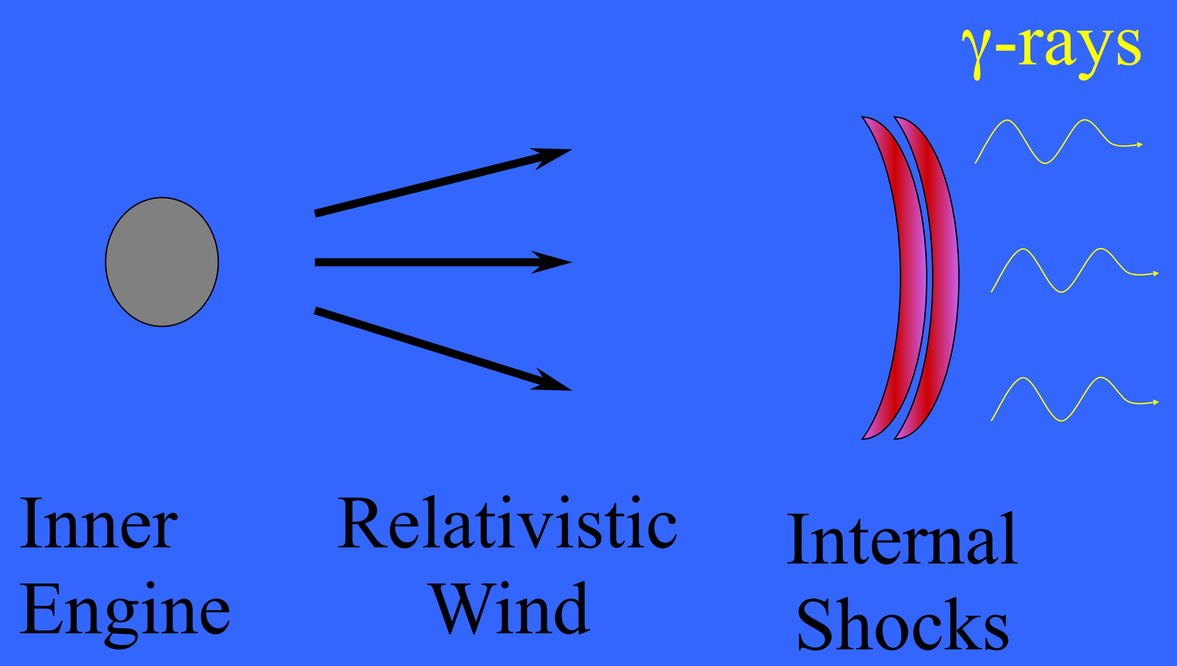
The Internal-External Fireball Model



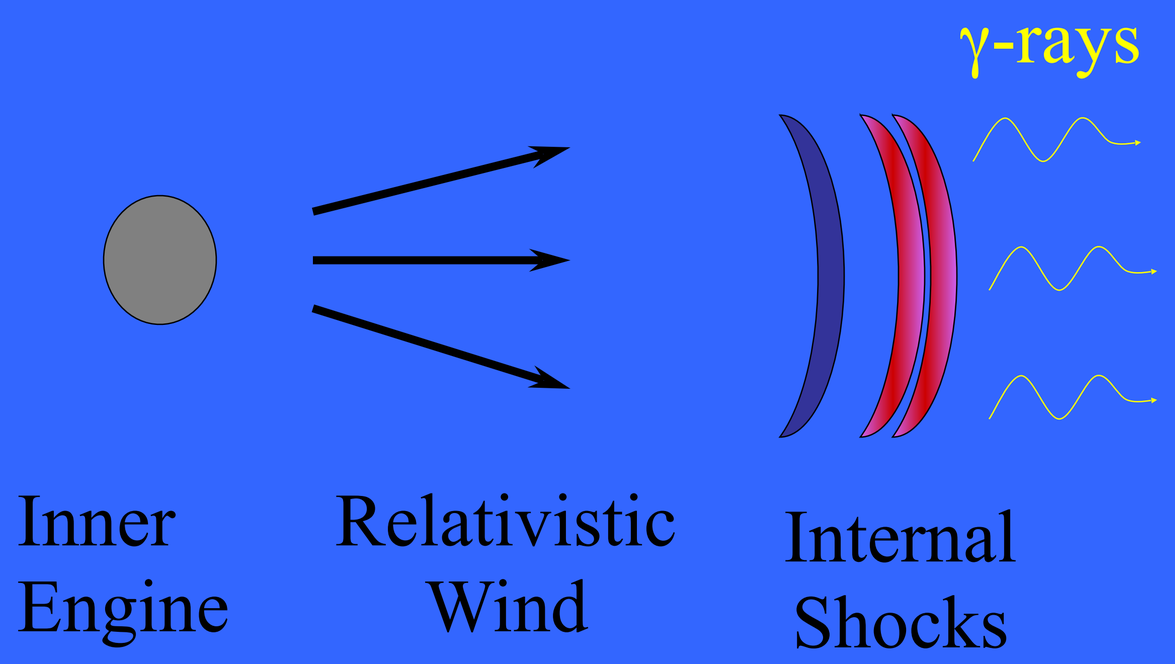
The Internal-External Fireball Model



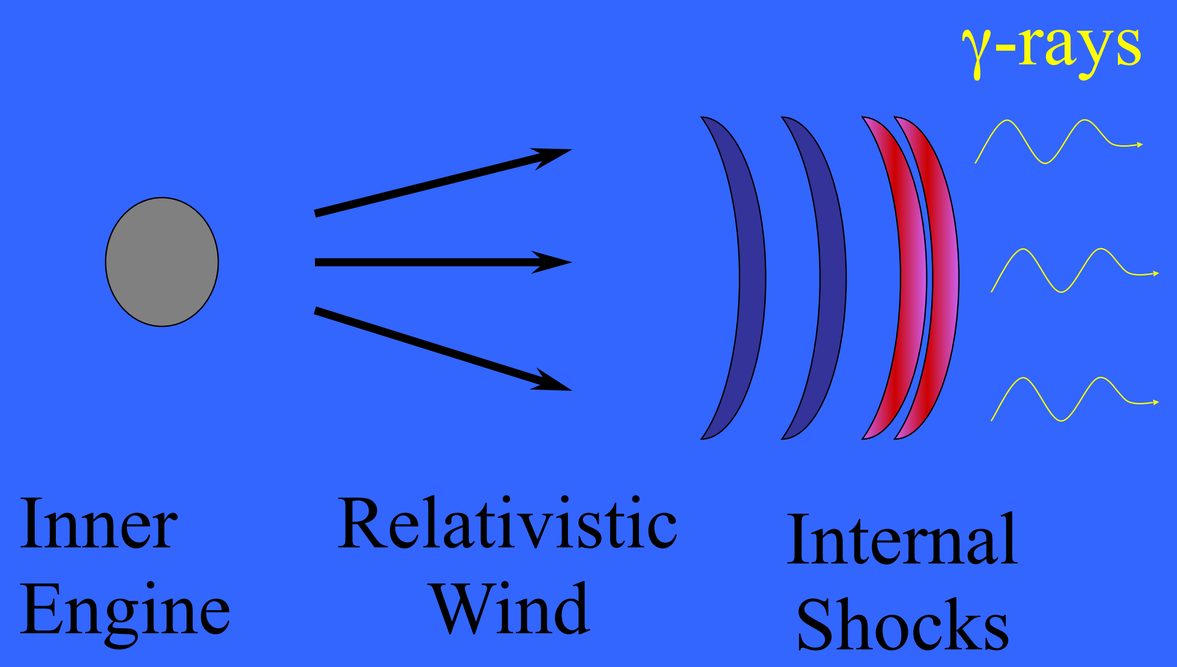
The Internal-External Fireball Model



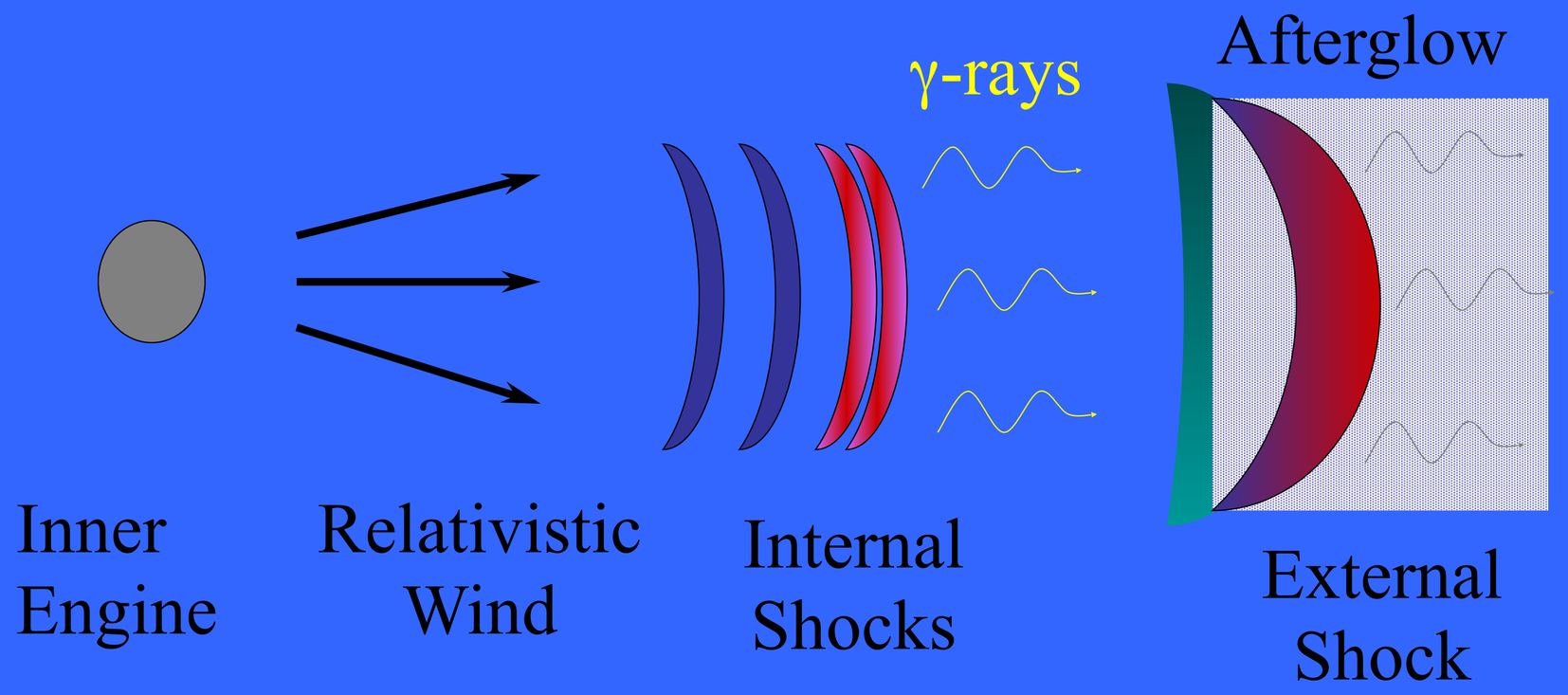
The Internal-External Fireball Model



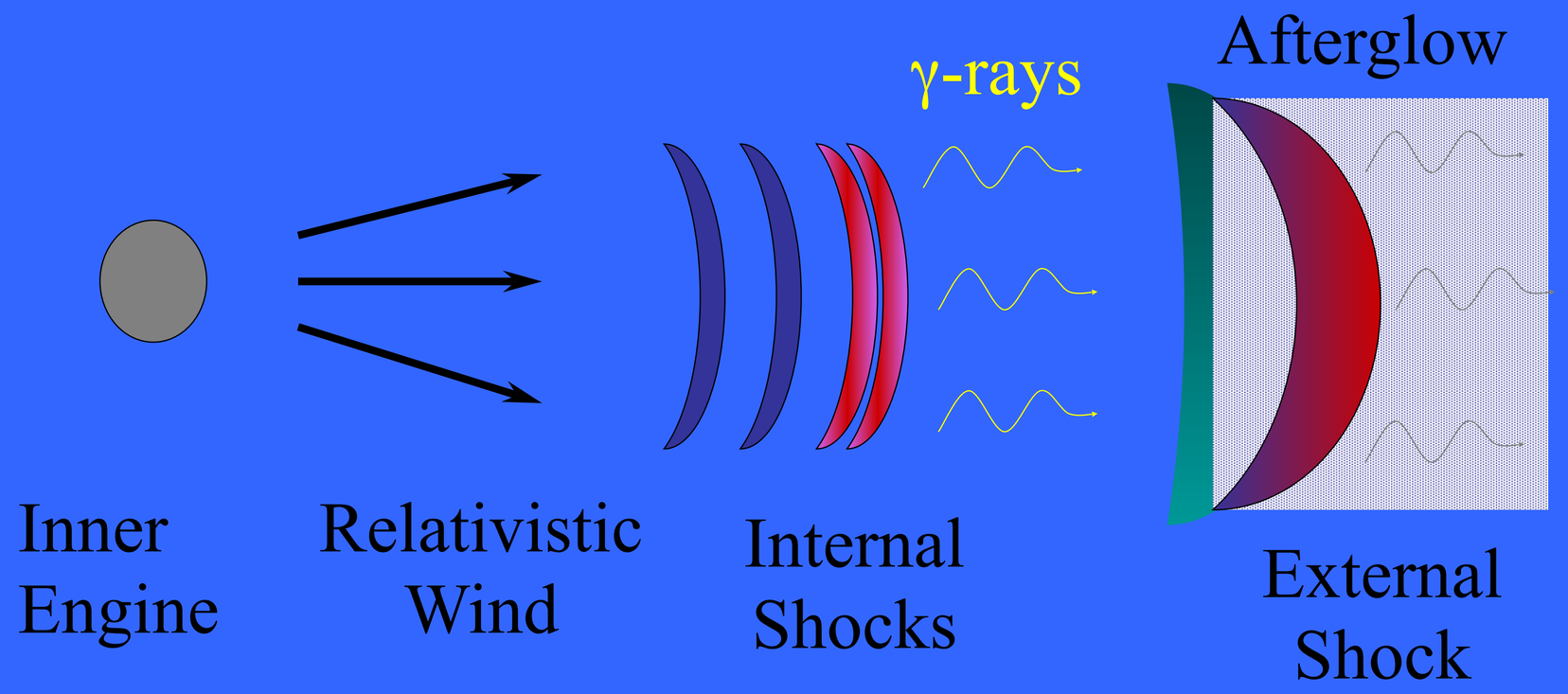
The Internal-External Fireball Model



The Internal-External Fireball Model



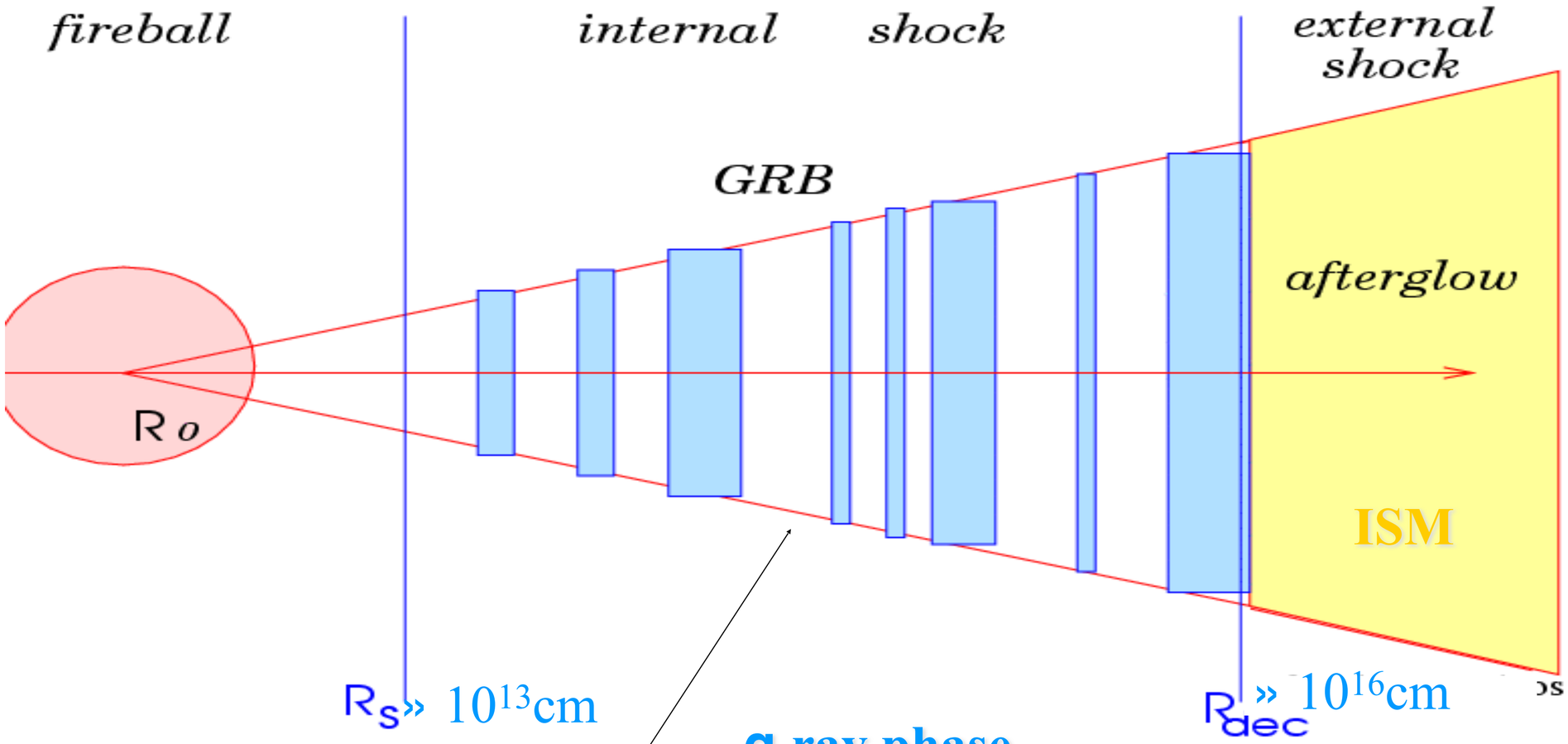
The Internal-External Fireball Model



There are no direct observations of the inner engine. The γ-rays light curve contains the best evidence on the inner engine's activity.

The internal/external shock scenario

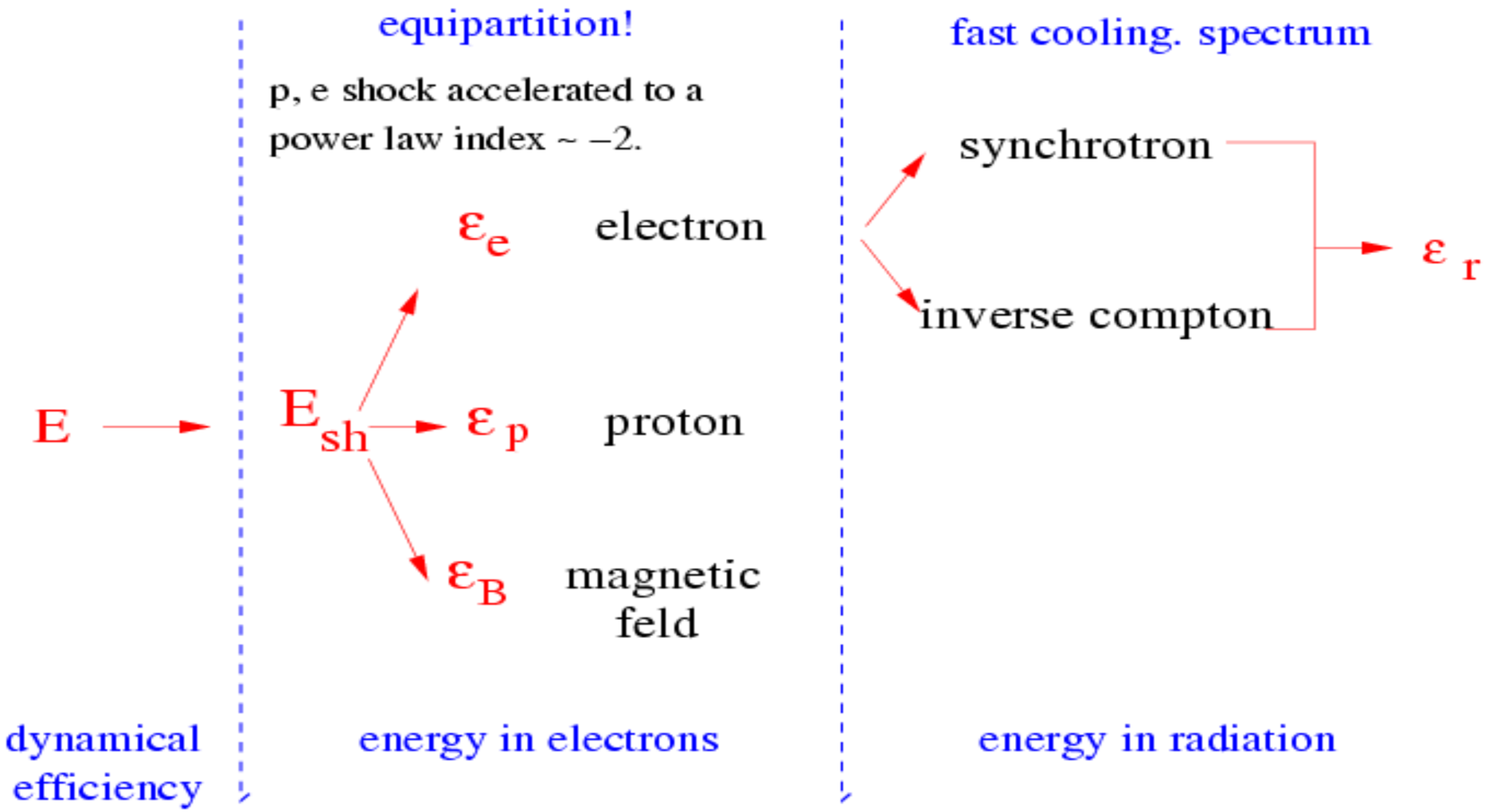
[Rees & Meszaros 1992, '94]



Efficient! [Guetta Spada & Waxman 2001]

The radiation mechanisms

For each collision:



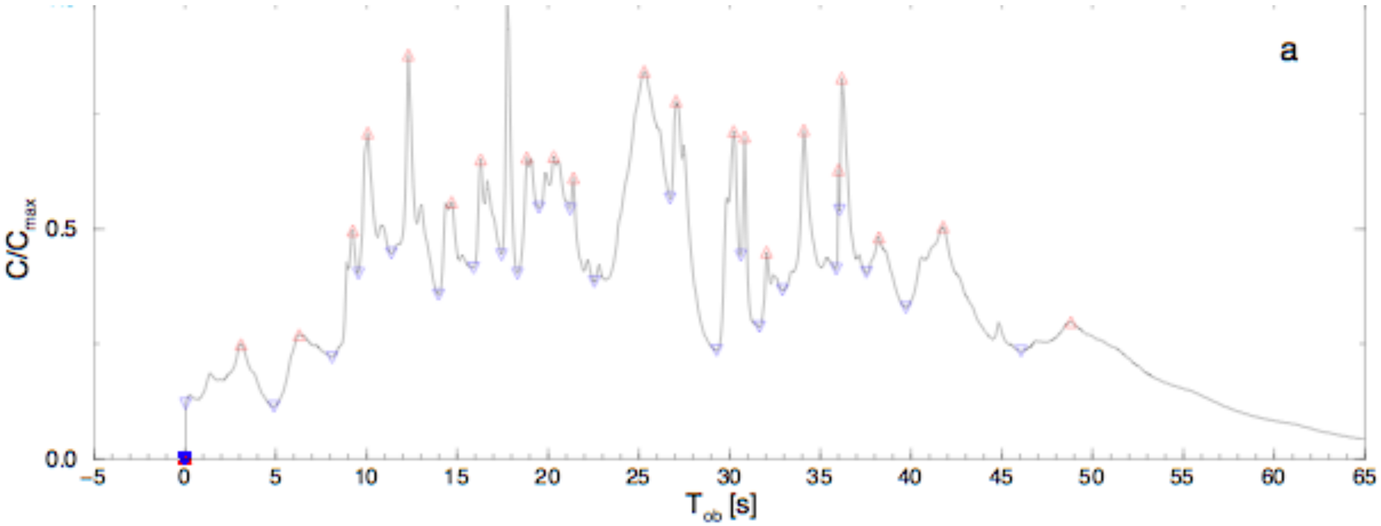
Light curves from internal shocks

Rapid variability and complexity of GRB lightcurves result of emission from multiple shocks in a relativistic wind

Δt (interval between ejected shells) determines the pulse duration and separation:

IS reproduce the observed correlation between the duration of the pulse (t_p) and the subsequent interval (Δt_p)

Numerical simulations reproduce the observed light curves



(Spada et al. 2000)

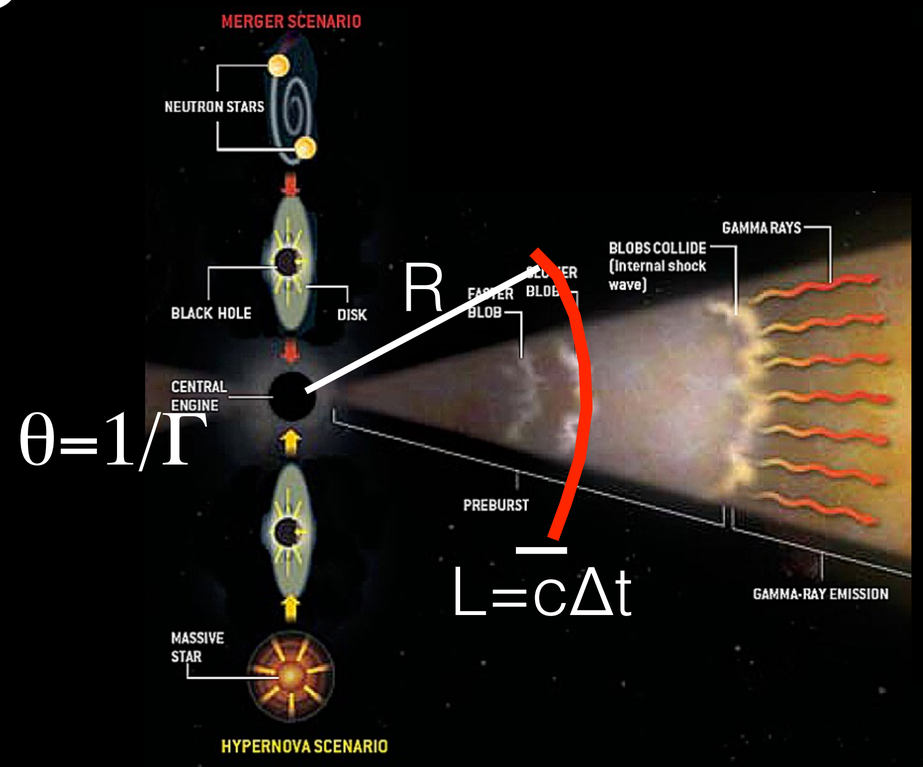
GRB inner engine

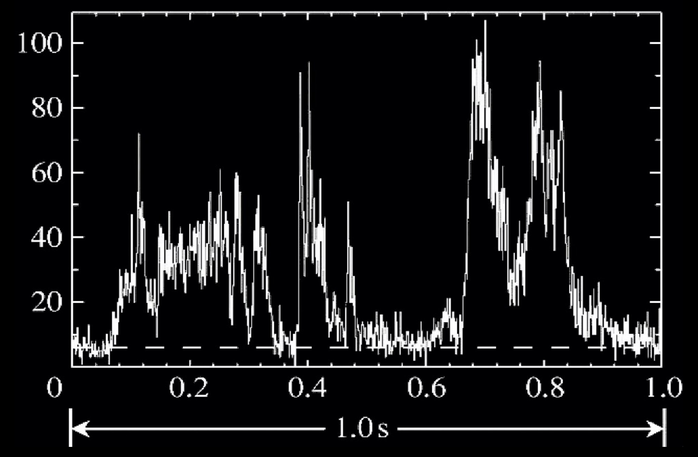
2 shells ejected at t_1, t_2 , speed Γ_1, $\Gamma_2=a\Gamma_1$ will collide at $R\sim2\Gamma^2L$

$\Delta t\sim L/c\sim R/2c\Gamma^2$ $R\sim2\Gamma^2c\Delta t$ $R\sim(\Gamma/100)(\Delta t/1ms)\ 6\times10^{11}cm$

γ-rays from collision reach observer at the same time of hypothetical γ-rays emitted at t_2

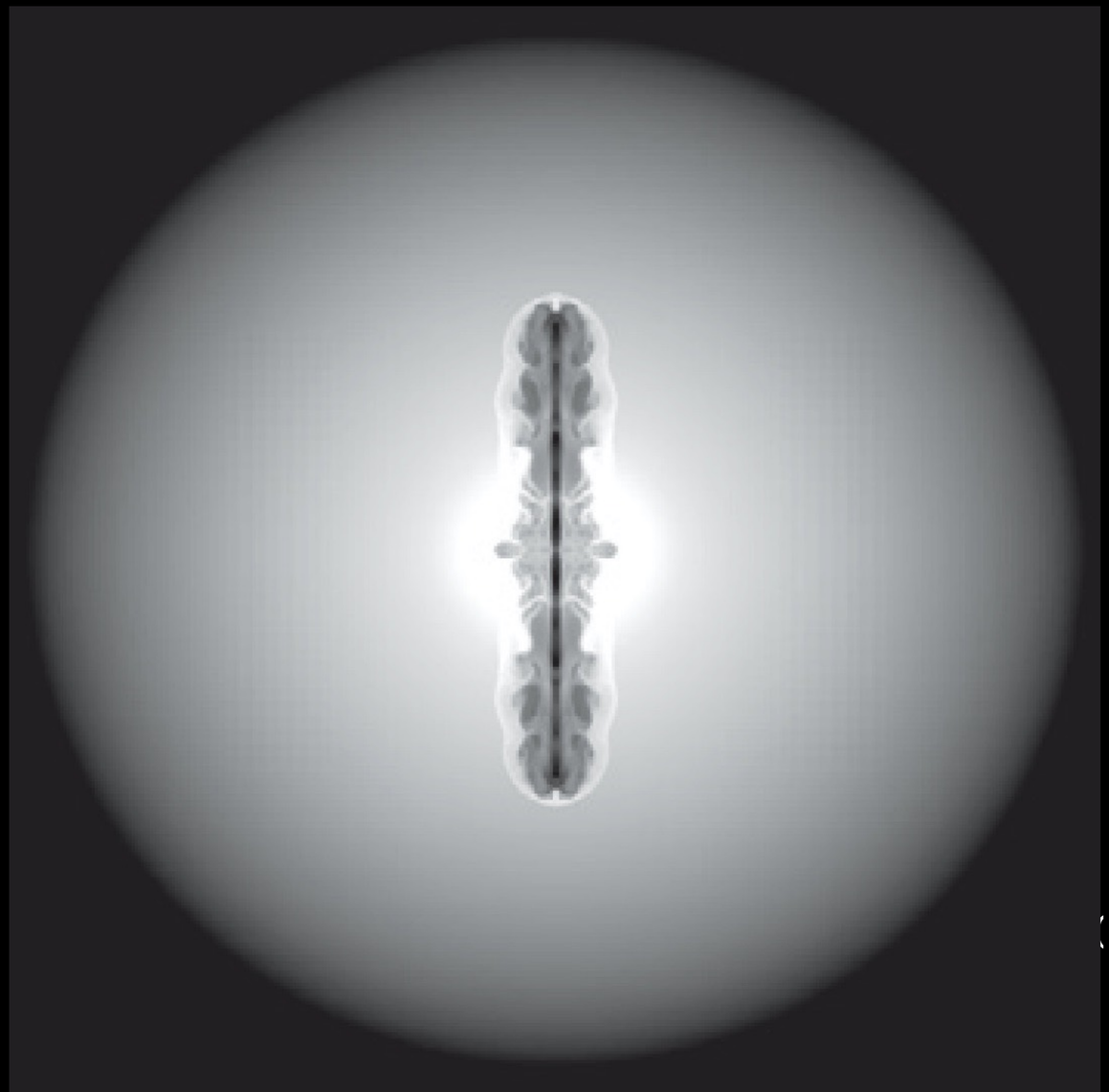
Observed light curves reproduce activity of inner engine (Nakar-Piran 2002)

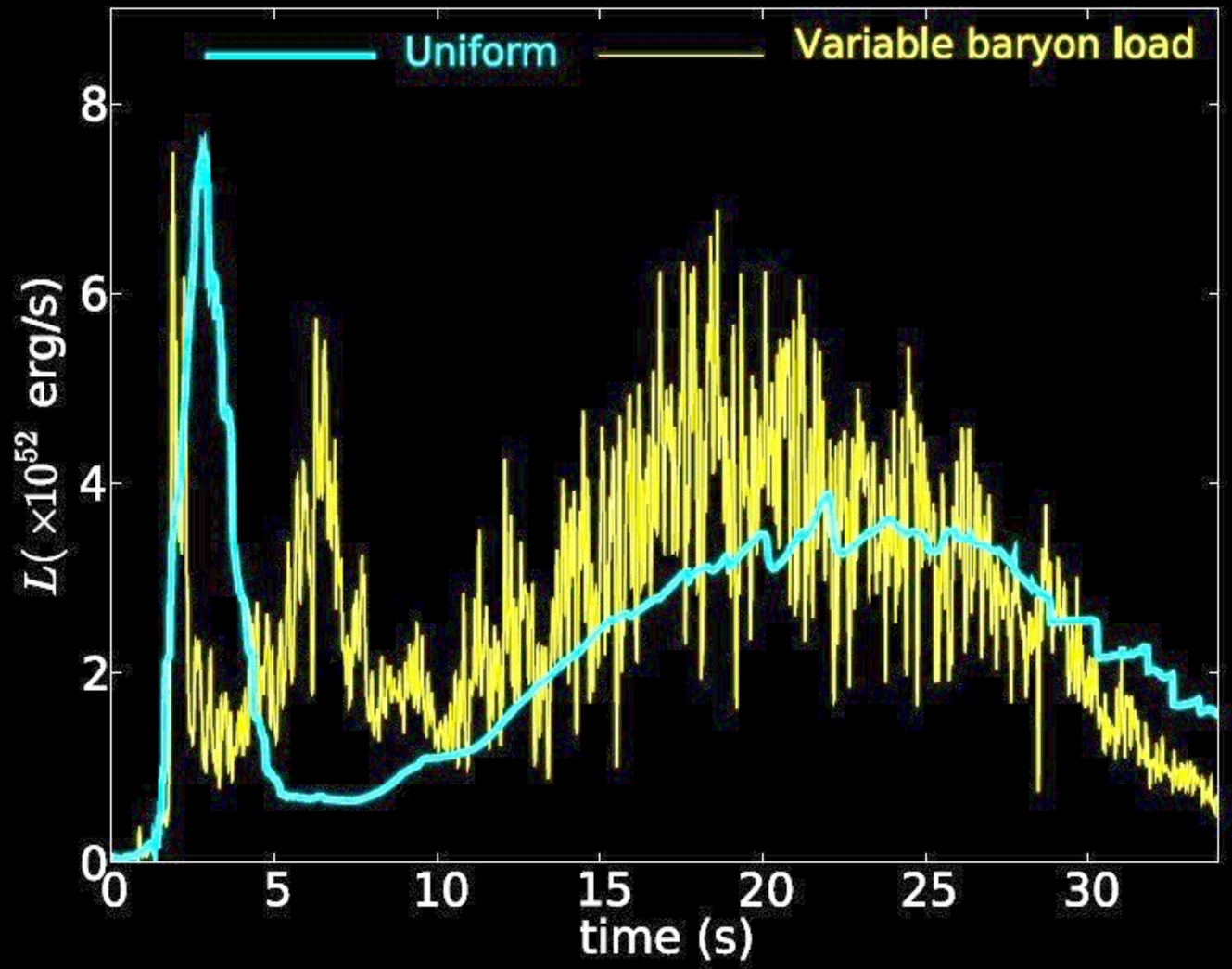




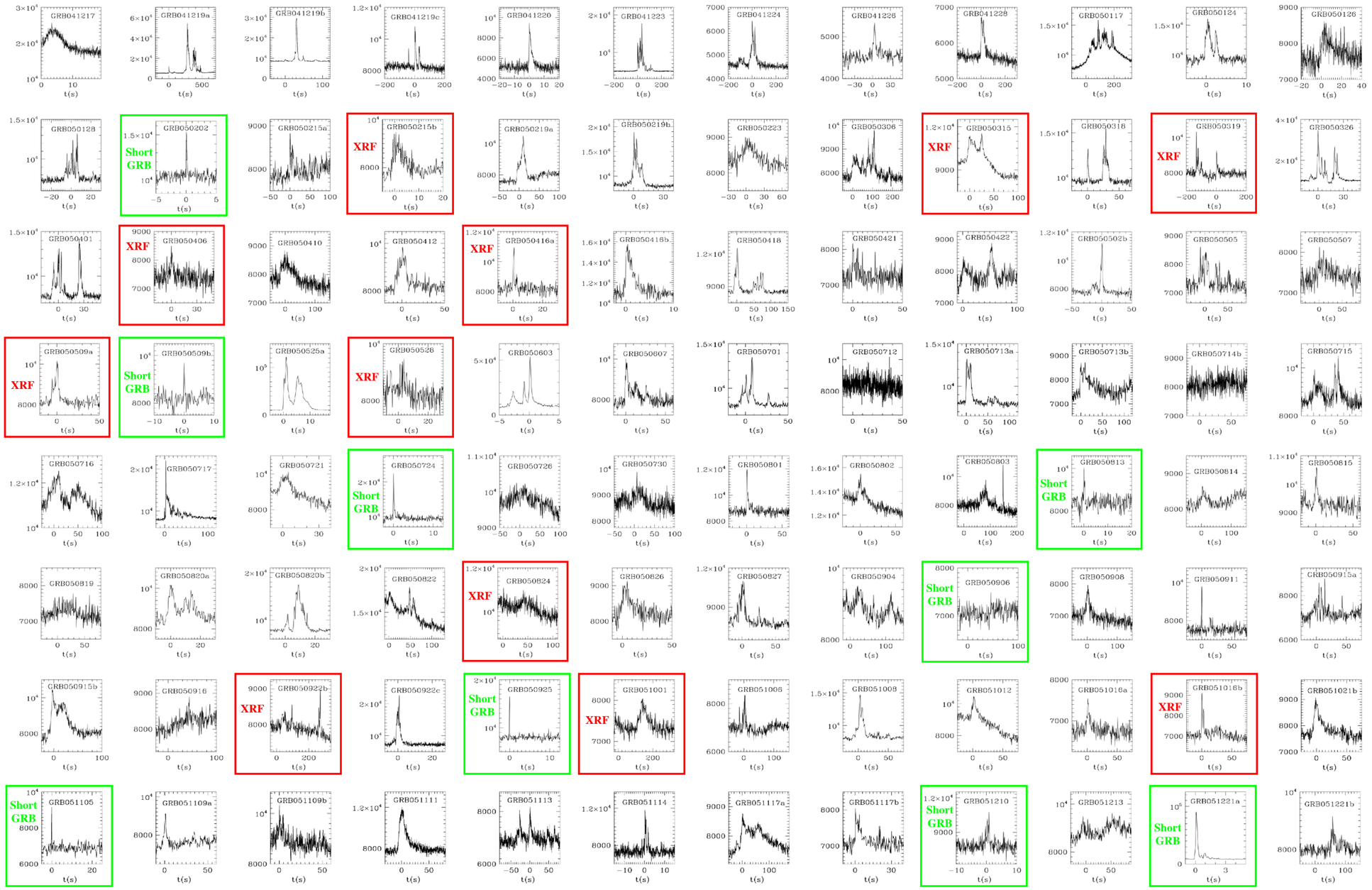
GRB inner engine

MERGER SCENARIO





Swift GRBs


GRB041217
GRB041219a
GRB041219b
GRB041219c
GRB041220
GRB041223
GRB041224
GRB041226
GRB041228
GRB050117
GRB050124
GRB050126
GRB050128
Short GRB
GRB050202
GRB050215a
XRF
GRB050215b
GRB050219a
GRB050219b
GRB050223
GRB050306
XRF
GRB050315
GRB050318
XRF
GRB050319
GRB050326
GRB050401
XRF
GRB050406
GRB050410
GRB050412
XRF
GRB050416a
GRB050416b
GRB050418
GRB050421
GRB050422
GRB050502b
GRB050505
GRB050507
XRF
GRB050509a
Short GRB
GRB050509b
GRB050525a
XRF
GRB050526
GRB050603
GRB050607
GRB050701
GRB050712
GRB050713a
GRB050713b
GRB050714b
GRB050715
GRB050716
GRB050717
GRB050721
Short GRB
GRB050724
GRB050726
GRB050730
GRB050801
GRB050802
GRB050803
Short GRB
GRB050813
GRB050814
GRB050815
GRB050819
GRB050820a
GRB050820b
GRB050822
XRF
GRB050824
GRB050826
GRB050827
GRB050904
Short GRB
GRB050906
GRB050908
GRB050911
GRB050915a
GRB050915b
GRB050916
XRF
GRB050922b
GRB050922c
Short GRB
GRB050925
XRF
GRB051001
GRB051006
GRB051008
GRB051012
GRB051016a
XRF
GRB051016b
GRB051021b
Short GRB
GRB051105
GRB051109a
GRB051109b
GRB051111
GRB051113
GRB051114
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Short GRB
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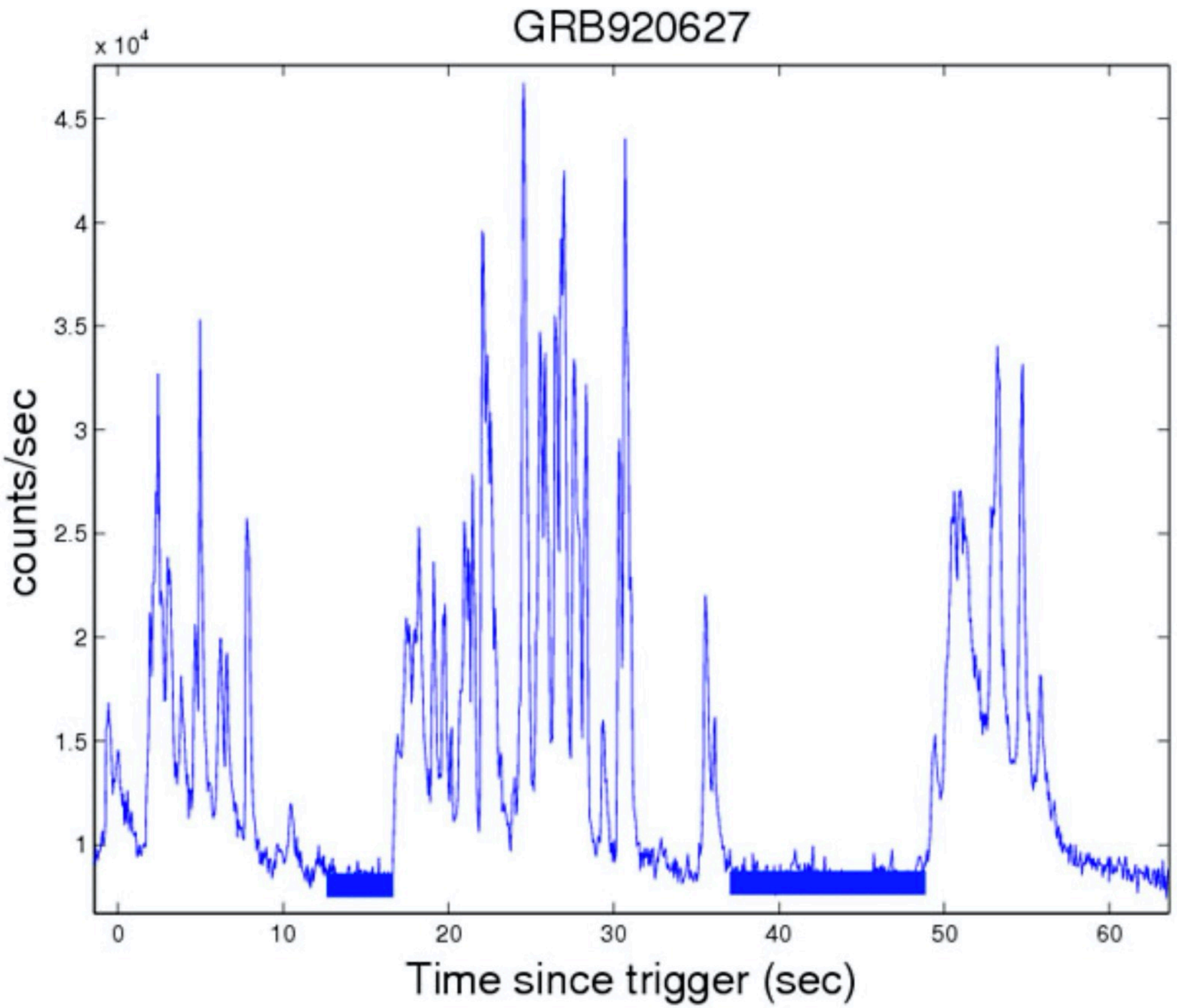
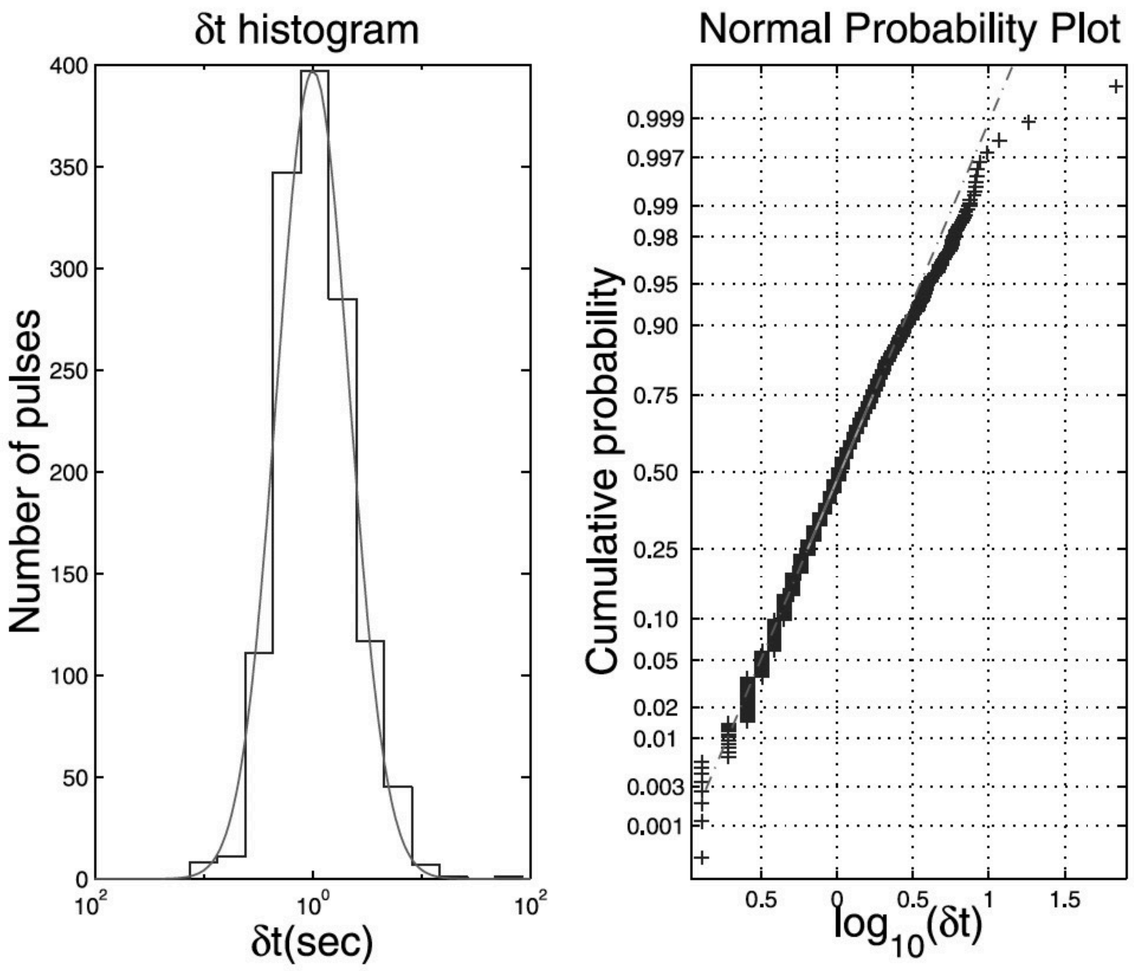
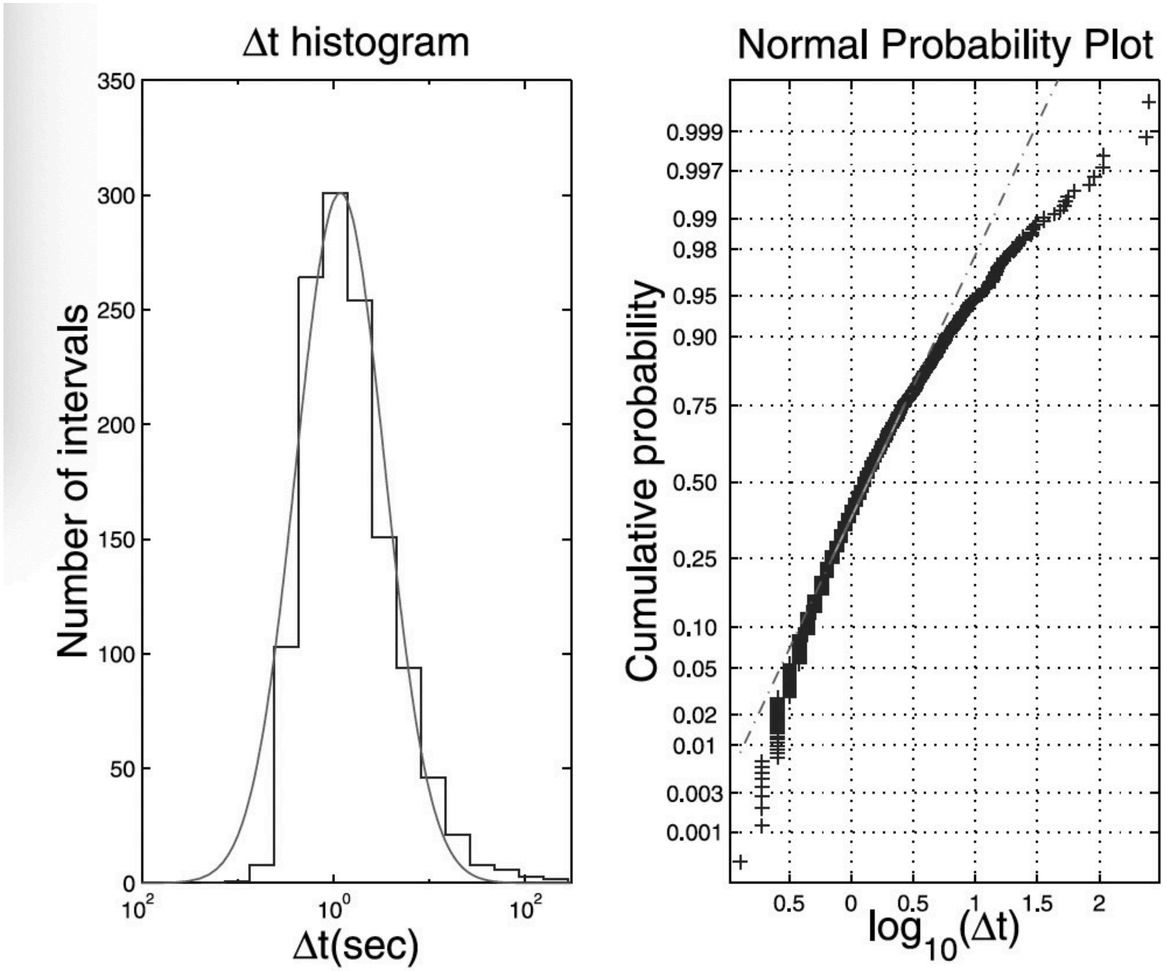
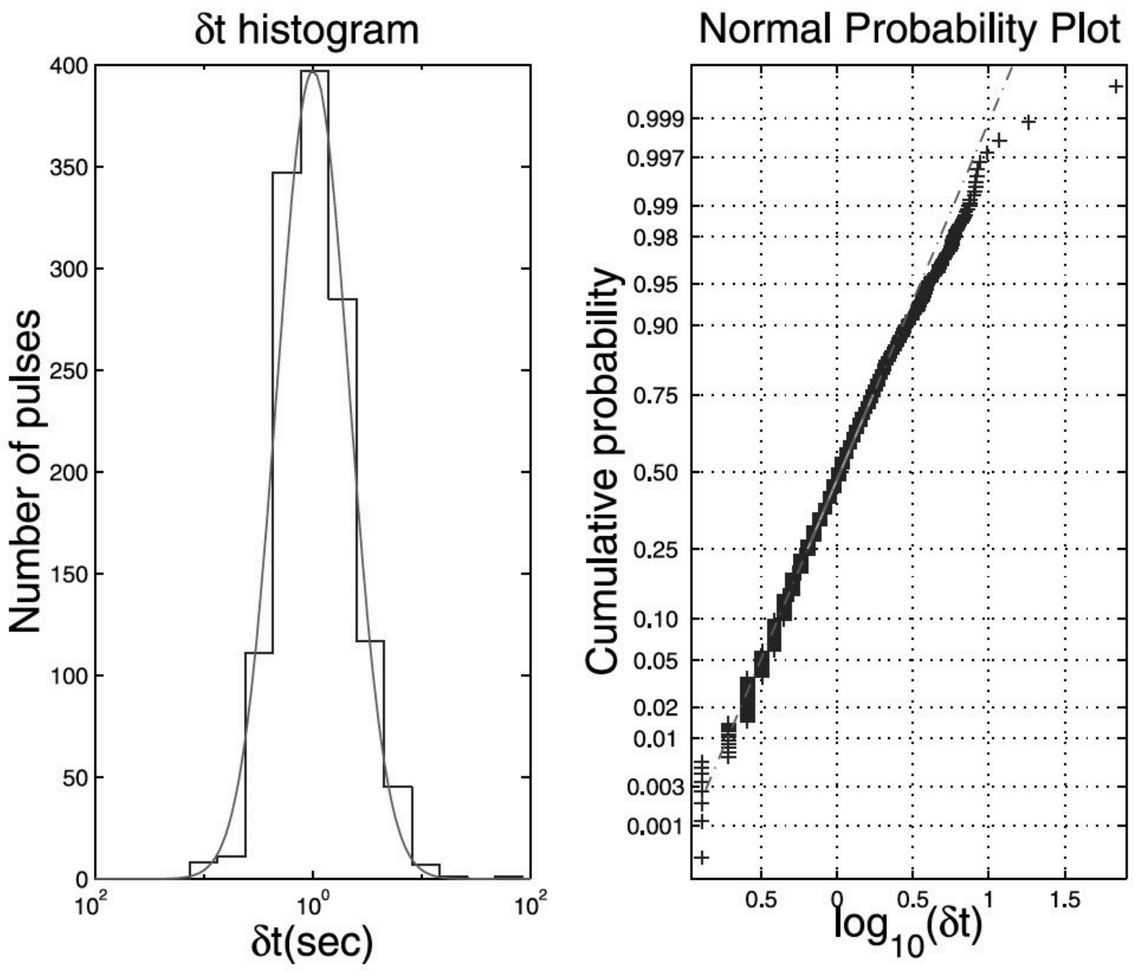
GRB051221b

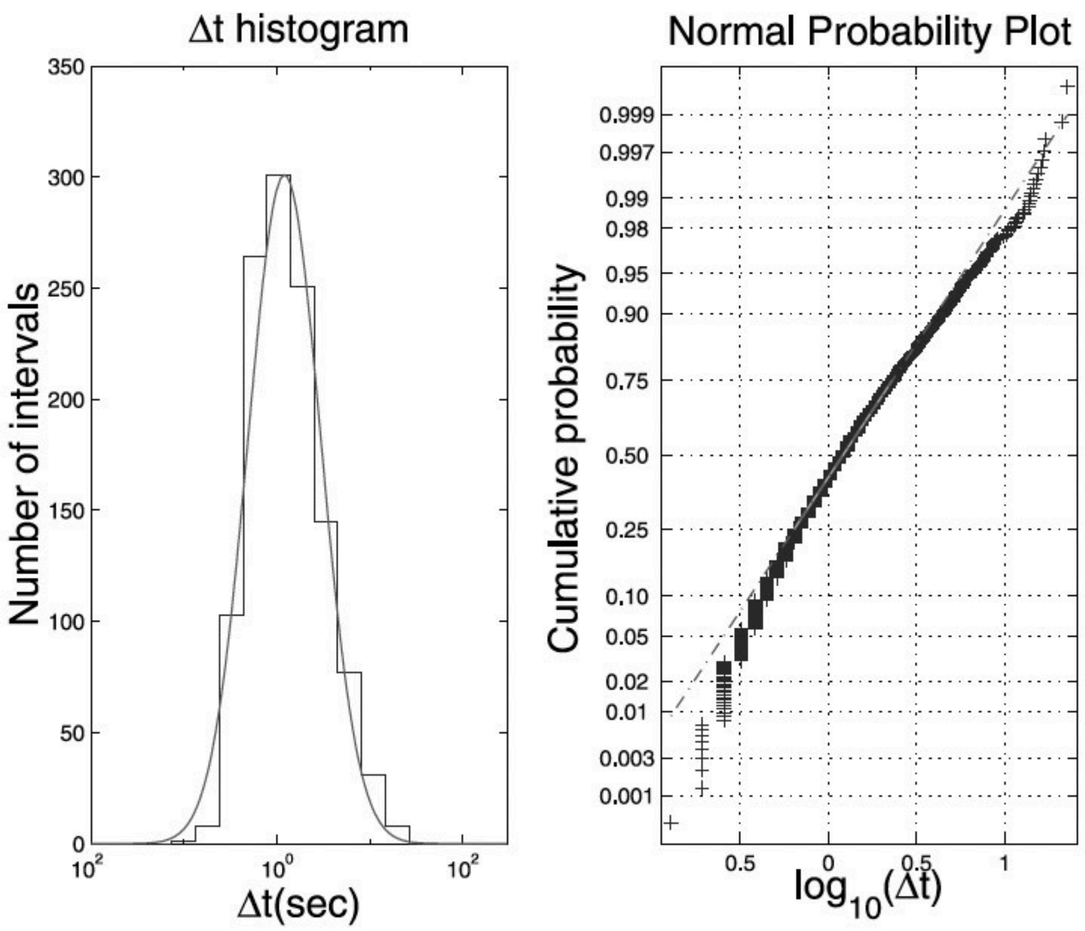

GRB920627
x 10^4
4.5
4
3.5
3
2.5
2
1.5
1
counts/sec
0
10
20
30
40
50
60
Time since trigger (sec)



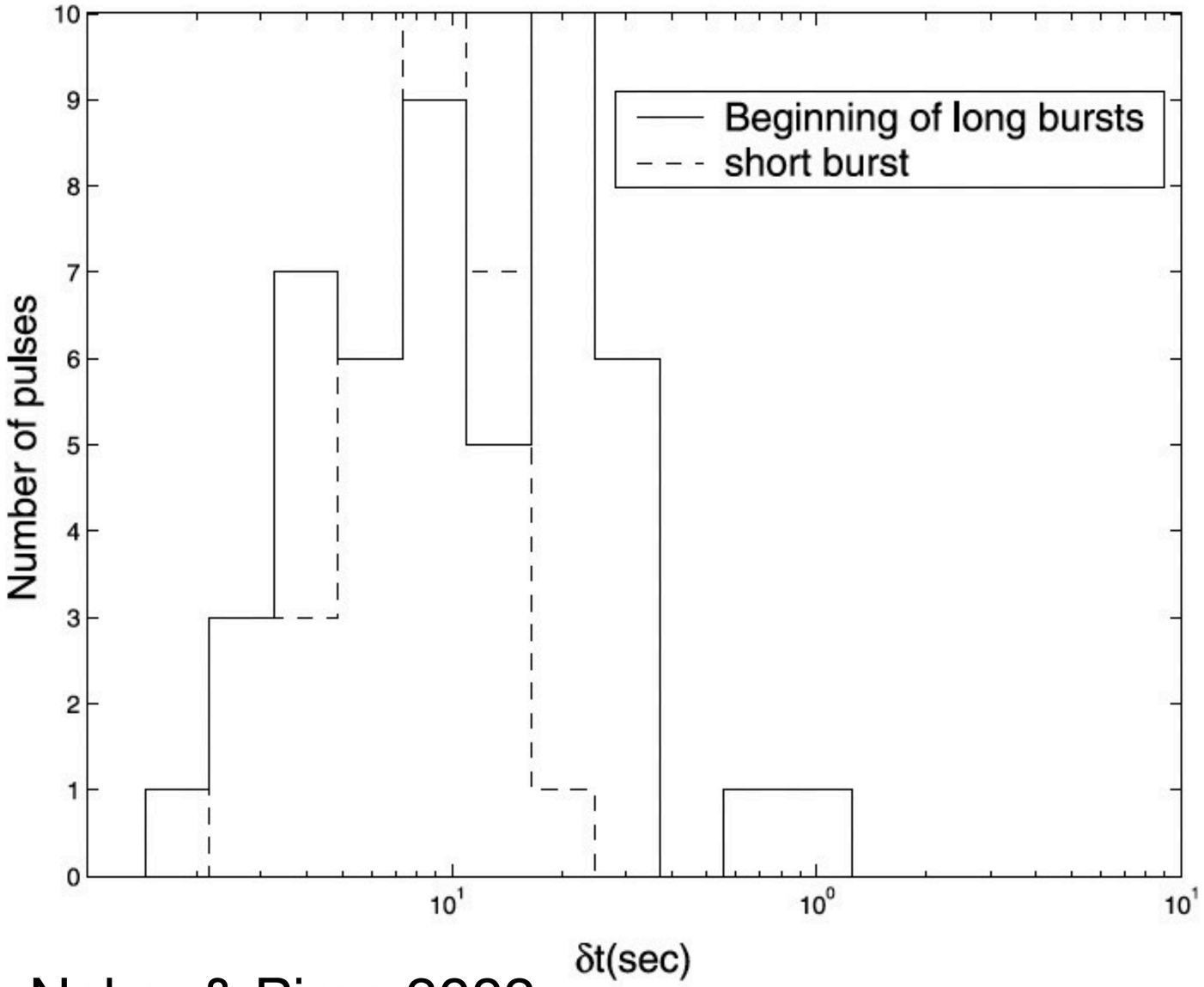


Nakar & Piran 2002

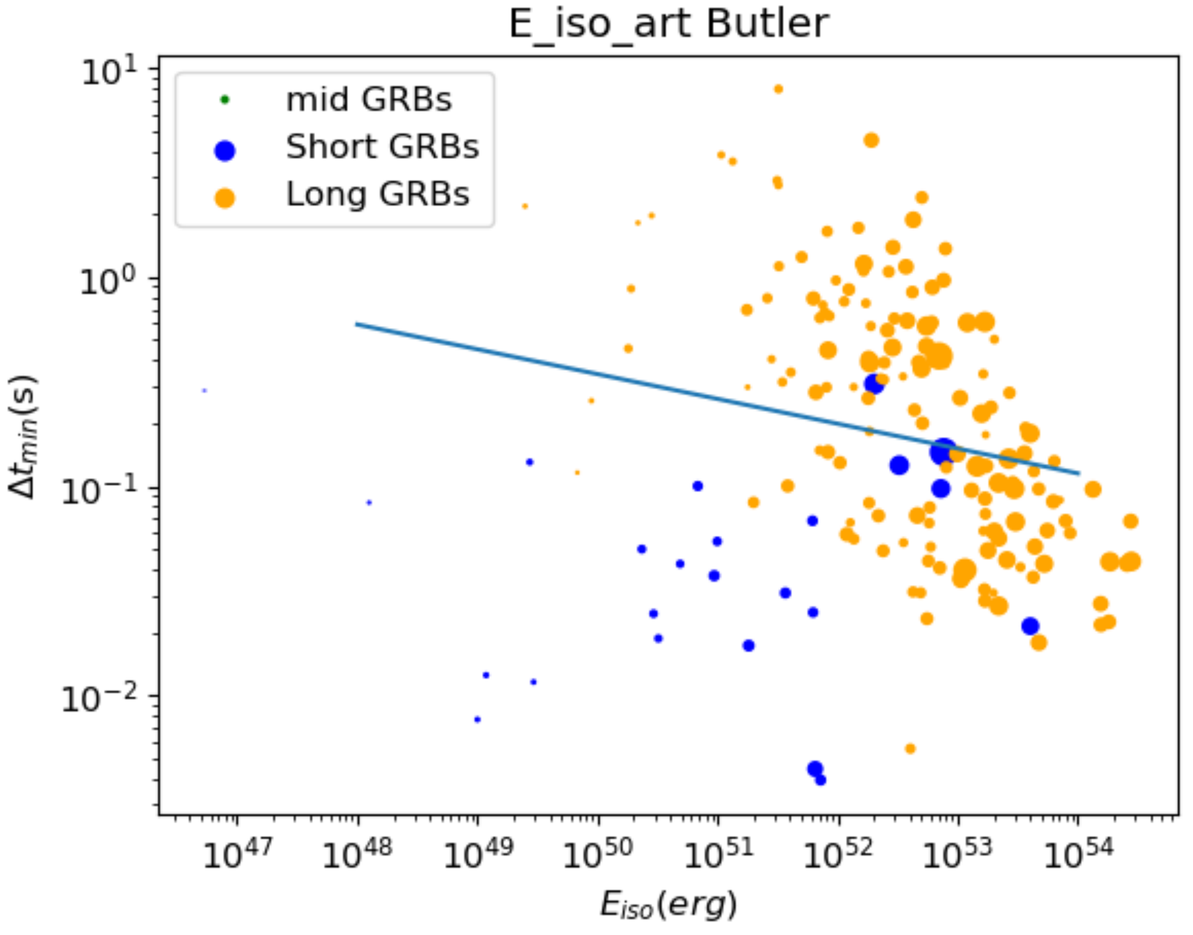


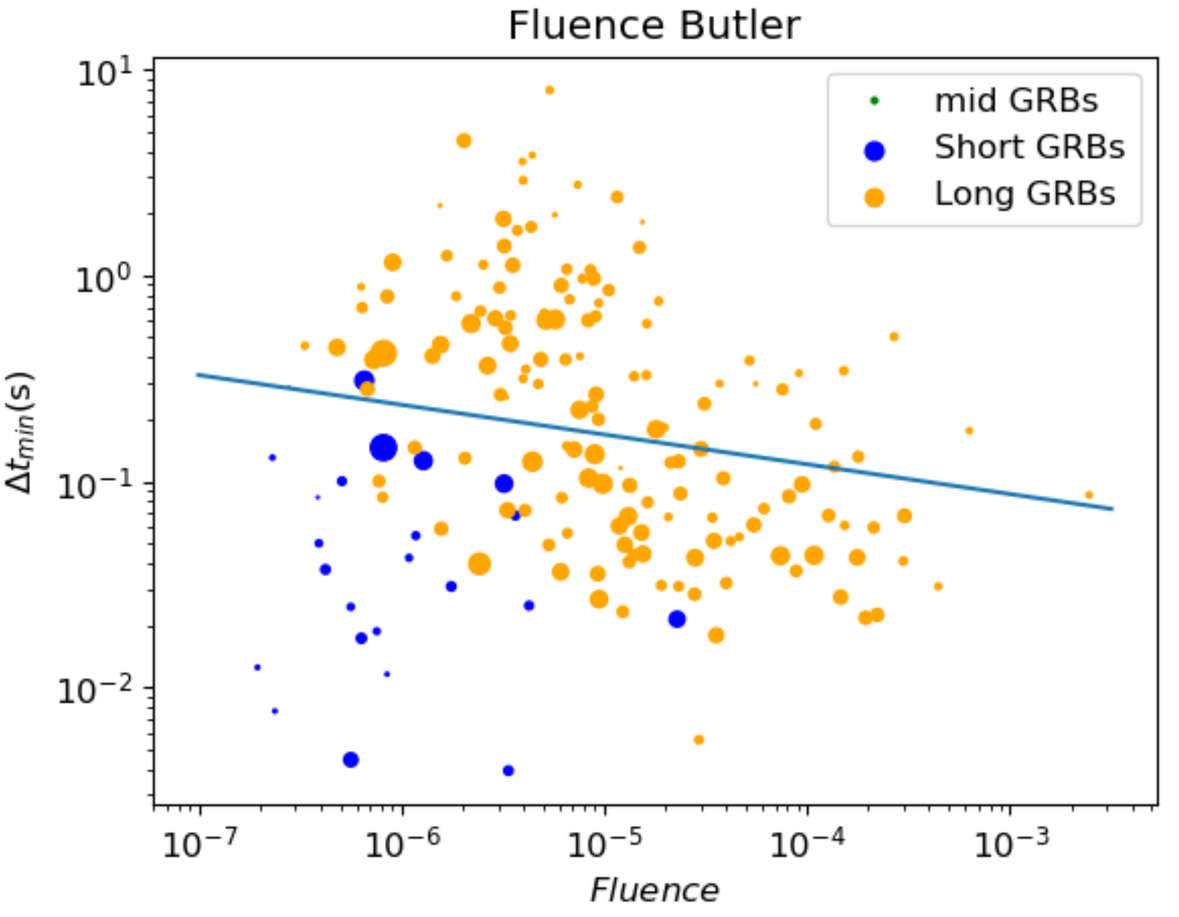


Nakar & Piran 2002



Nakar & Piran 2002


E_iso_art Butler
mid GRBs
Short GRBs
Long GRBs
Δt_{min}(s)
$E_{iso}(erg)$


Fluence Butler
mid GRBs
Short GRBs
Long GRBs
Δt_{min}(s)
Fluence