Gamma-Ray Bursts as Relativitic Objects

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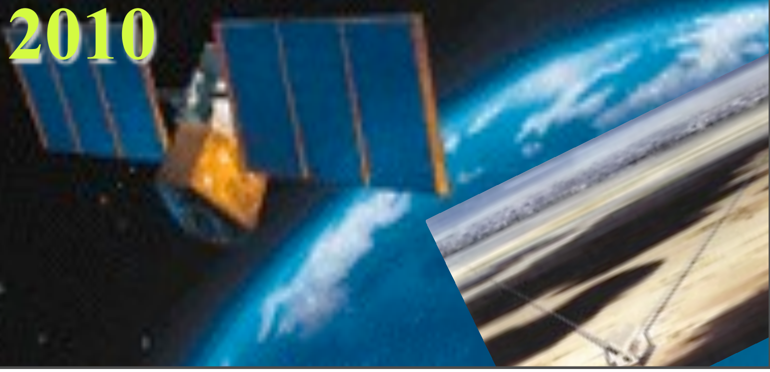
JGRG20 Kyoto 2010



Happy Birthday
Mazal Tov - מזל טוב

The Early Days of Numerical Relativity
Nakamura, Maeda, Miyama, Sasaki, 1981

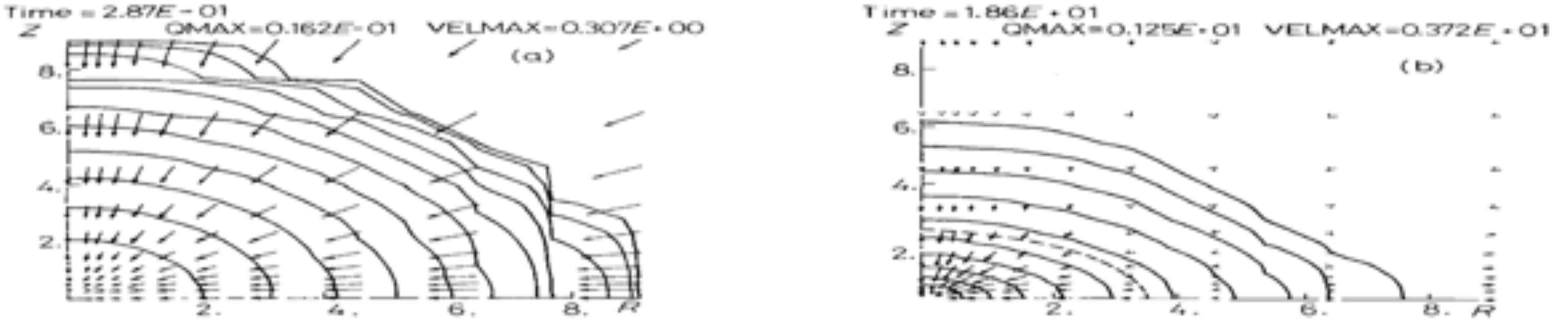


Fig. 2.(a) Contour lines of Q_b at $t=0.287$ for A50. The space integral of Q_b becomes M_B, that is, $2\pi\int_0^\infty\int_{-\infty}^{\infty} Q_b R\,dR\,dZ = M_B$. The precise definition of Q_b can be found in Paper I. Each line corresponds to $Q_b = \mathrm{QMAX}\cdot 10^{-n/2}$ for $n=1,2,\cdots,11$. QMAX is shown in the figure. Arrows show the vector $(J_R/Q_b, J_Z/Q_b)$. The maximum of this vector is shown in the figure as VELMAX.
(b) The contour lines of Q_b for A50 at $t=18.6$. The notations are the same as Fig. 2(a). The dashed line shows the apparent horizon.

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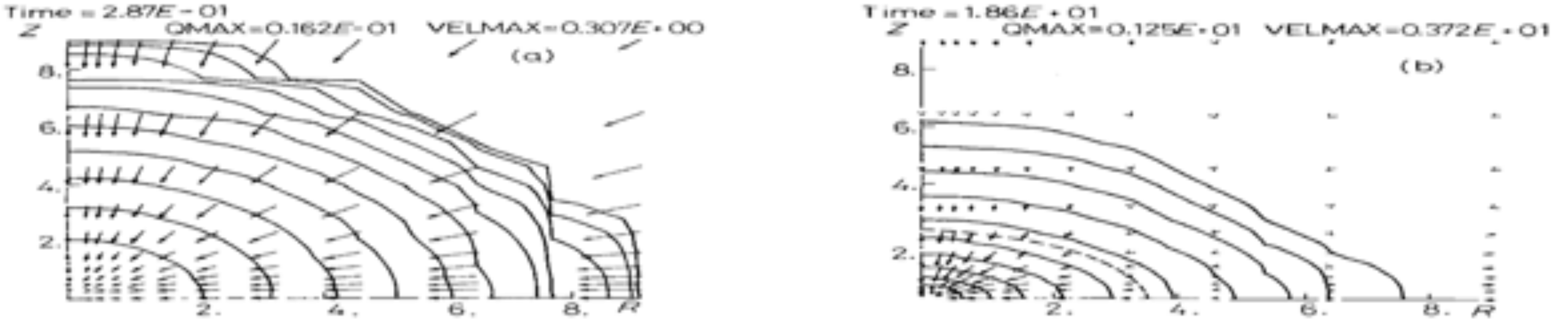

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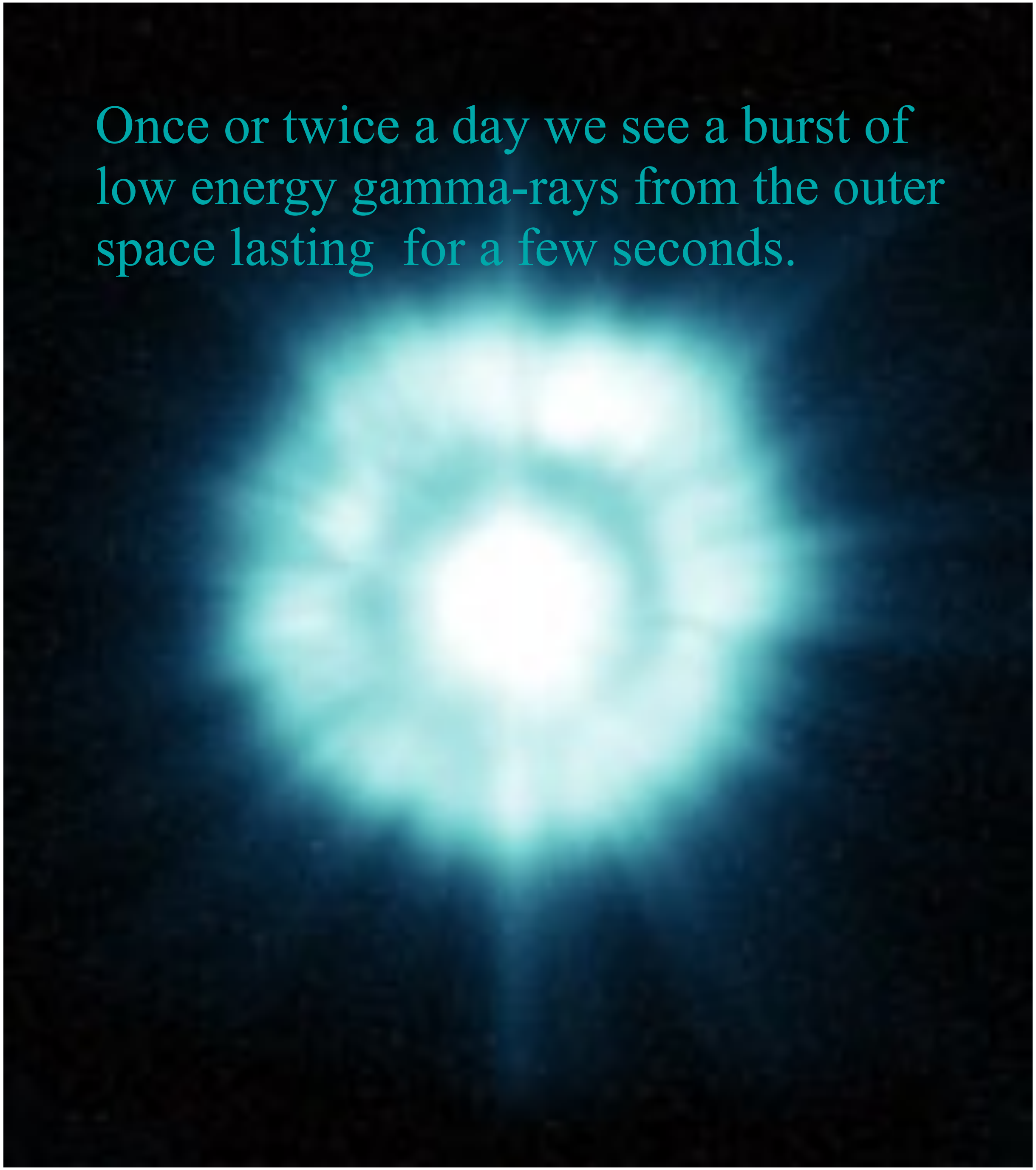
- Piran, Tsvi; Nakamura, T. Jets in supernova 1987A? 1987 Nature .330, 28
- Piran, T.; Nakamura, T. Current Detectors Detect Gravitational Radiation from Newborn Pulsars? 1988 PThPh..80, 18
- Nakamura, Takashi; Piran, Tsvi The origin of the planet around PSR 1829 - 10 1991 ApJ, 382L, 81

Paczynski 1991:
More than a decade ago observations of a ‘mystery spot’ near SN 1987A were reported by Karovska et al. (1987) and Matcher et al. (1987). Piran & Nakamura (1987) suggested that this might have been a jet generated by the supernova. Not knowing about SN 1987A Cen (1998) suggested that supernovae may create relativistic jets, which may give rise to gamma-ray bursts. This idea gained some support when the new analysis of SN 1987A data provided stronger evidence for the original ‘mystery spot’, and in addition provided evidence for a second spot on the opposite side of the supernova, suggesting relativistic jets (Nisenson & Papaliolios).

Once or twice a day we see a burst of low energy gamma-rays from the outer space lasting for a few seconds.



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The energy released during a burst (~10^{51} erg within a few seconds) is only a few orders of magnitude below the energy released by the rest of the Universe at the same time!

GRBs are the (electromagnetically) brightest objects in the Universe. Only ~8 orders of magnitude less then the theoretically maximal * luminosity (c^5/G)~10^{59} erg/sec .

$$\frac{Mc^2}{GM/c^3}$$

* Up to relativistic corrections.

GRBs are good for many thing:

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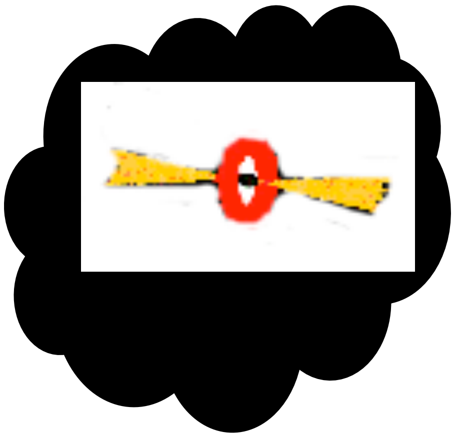

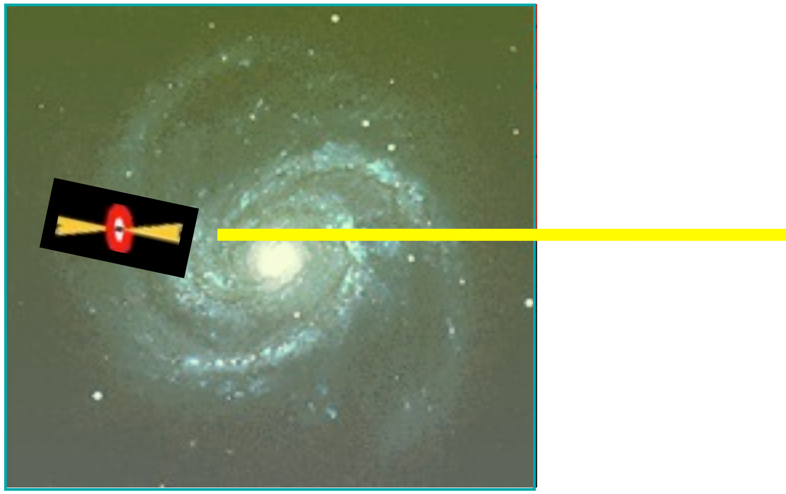

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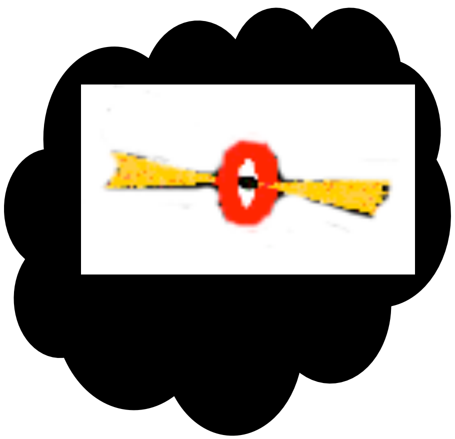

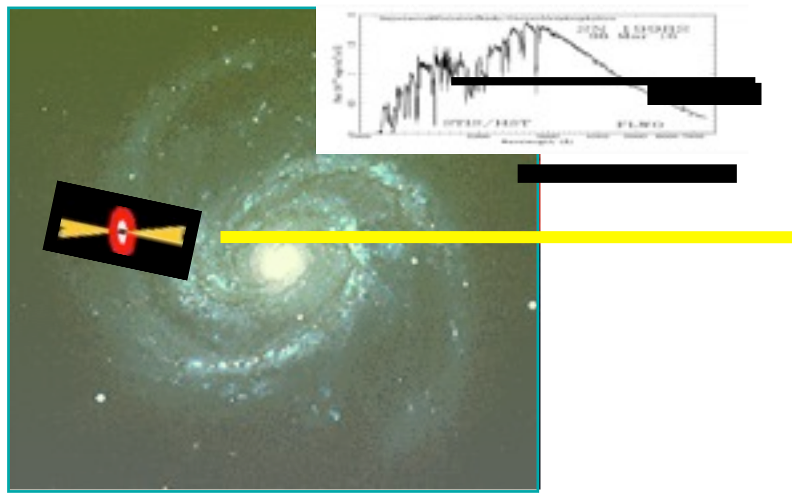

bad
GRBs are ~~good~~ for many thing:

- **Determining the high redshift history of the universe ?**
- **Destroy Life on Earth (mass extinction) ??**

GRBs are ~~good~~ bad for many thing:

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- Determining the high redshift history of the universe ?
- Destroy Life on Earth (mass extinction) ??
- Measuring quantum gravity effects

GRBs are good for many thing:

- Determining the high redshift history of the universe ?
- Destroy Life on Earth
extinction) ??
- Create Life on Earth
formation)?
- Measuring quantum gravity effects ?

- **Accompany sources of Gravitational Radiation (Kochanek & Piran, 1993).**

GRBs and Relativity

- **Observations**
- **Relativistic Motion**
- **The Fireball Model**
- ***Black Hole or Not Black Hole?***
- ***Gravitational Radiation from GRBs***
  - **Sources**
  - **Rates**
  - **Gravitational radiation from the inner engine**
- ***Lorentz violation with GRBs***
- **Conclusions and prospects**

THE DISCOVERY

- GRBs 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.

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An invited prediction (Sterling Colgate 1967) - GRBs as shock breakout from (galactic) supernovae

Properties

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- Duration 0.01-1000s

Prope

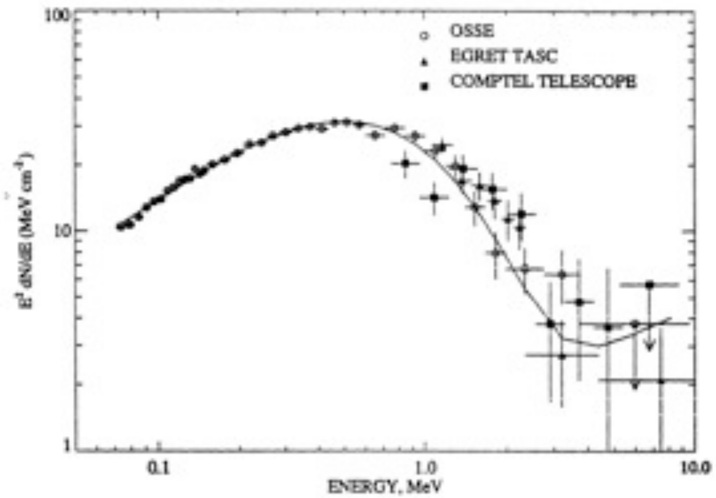

Figure 9 The spectrum of GB 910601 observed over a wide energy range, as measured by three experiments on *CGRO* (Share et al 1994). A typical broad spectrum with a peak power at about 600 keV is seen. (The fitted spectral up-turn above 4 MeV is not significant.)

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  Two populations (long and short)

- **~10-2000keV photons**

  (non thermal spectrum)

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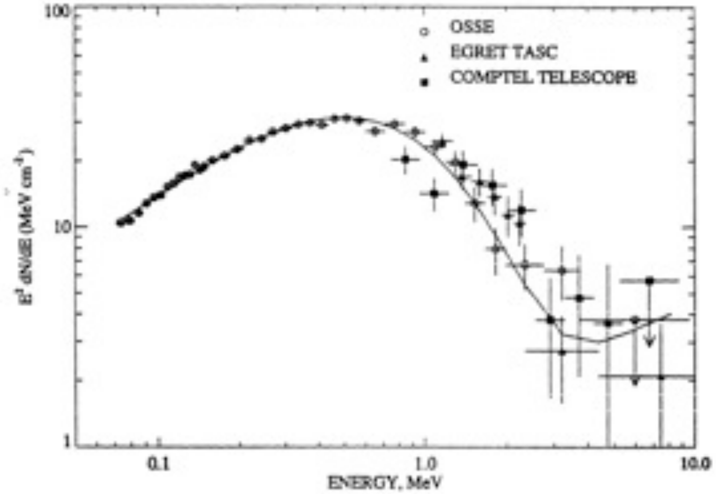
- Rapid variability



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Properties

- Duration 0.01-1000s

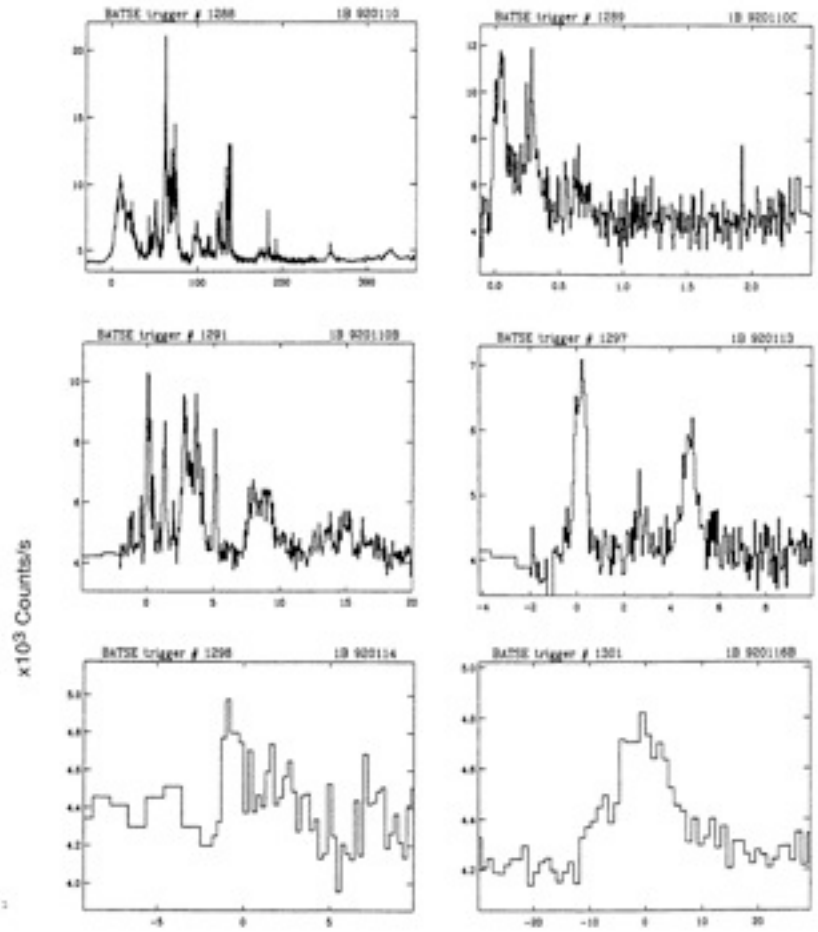
  Two populations (long and short)
- ~10-2000keV photons

  (non thermal spectrum)

  (very high energy tail,

  up to dozen GeV, 500GeV?)
- Rapid variability

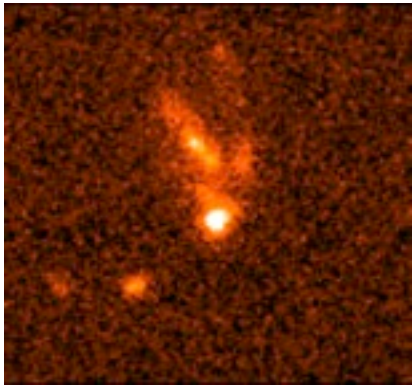
  (less than 10ms)



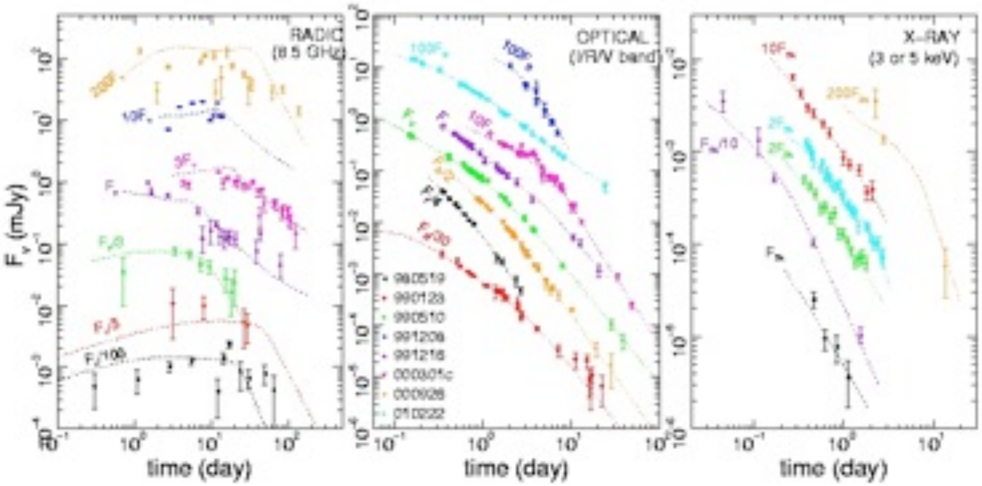
ATERGLOW

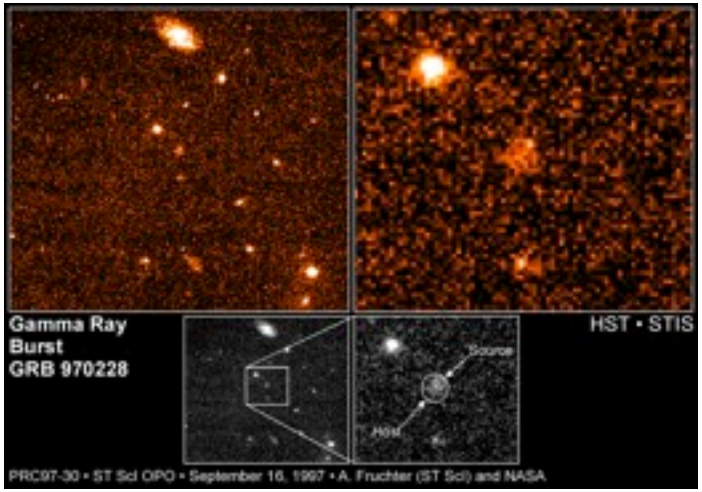
- The bursts are followed by

  multiwavelength afterglow: X-ray, radio, Optical

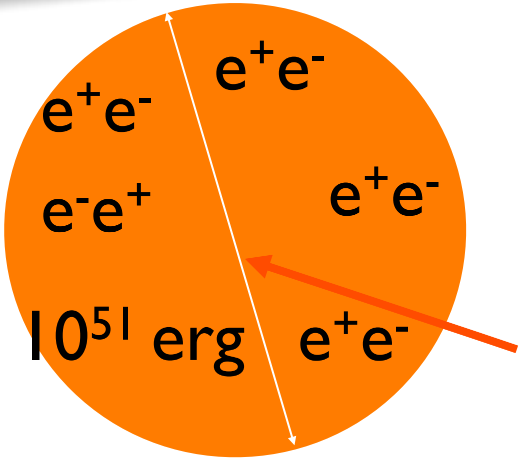


BeppoSAX





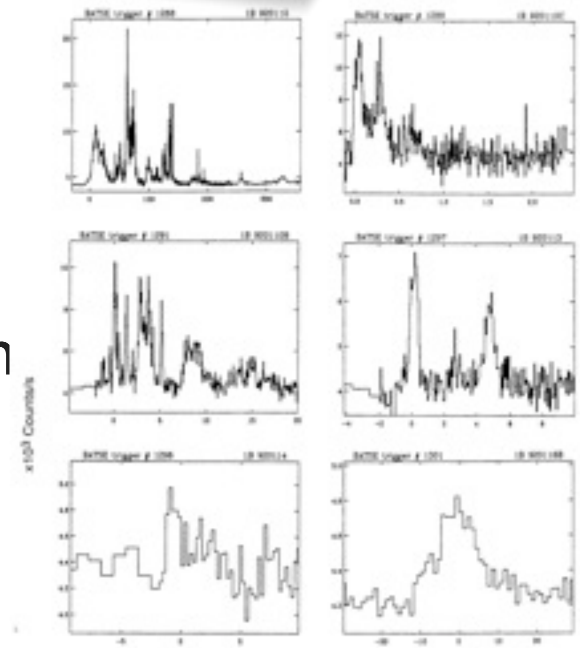
Relativistic Motion



0.1sec

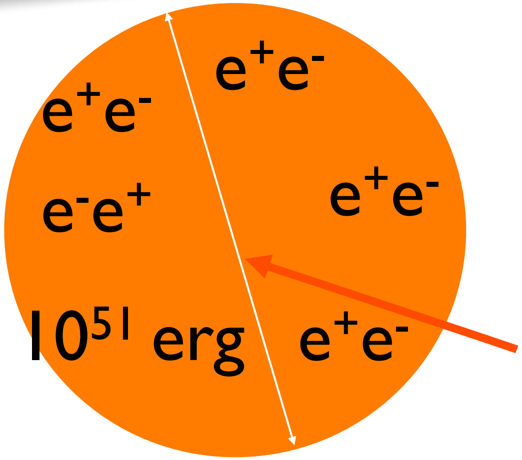
$\Downarrow$

$R<3\times10^{9}$cm



Relativistic Motion

$\gamma\gamma \rightarrow e^+e^-$



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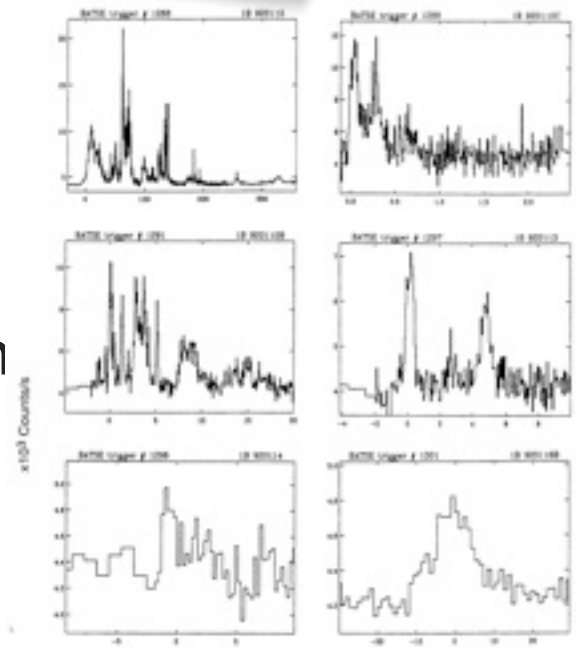

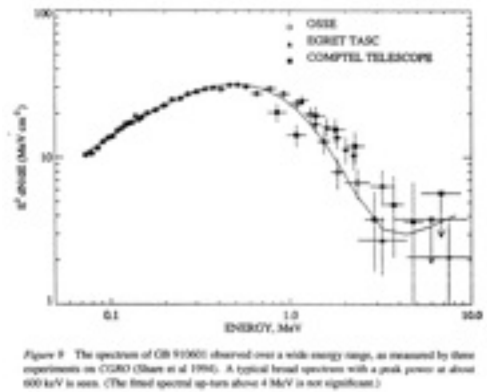

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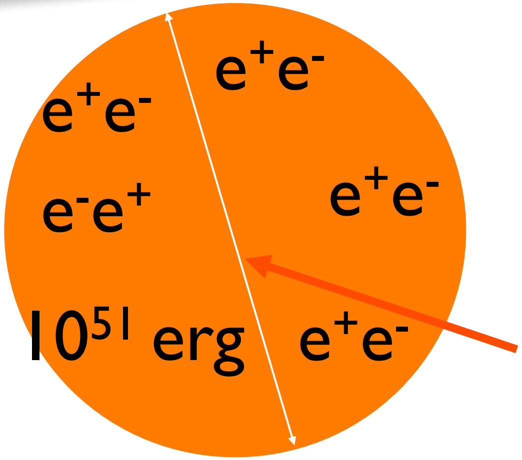
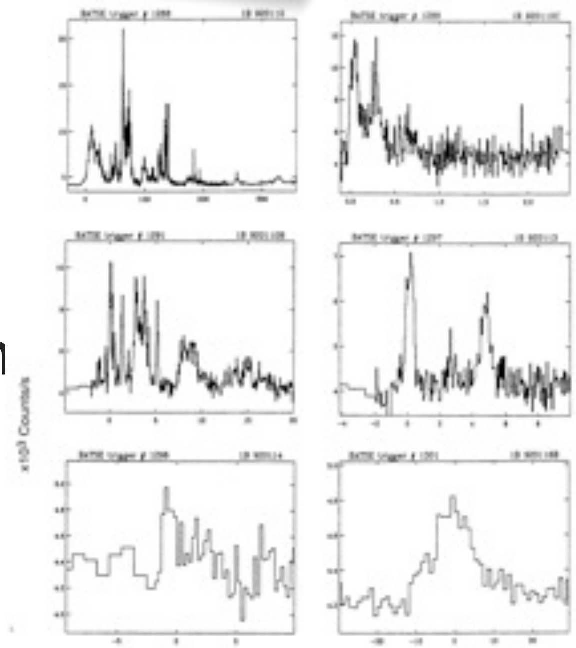


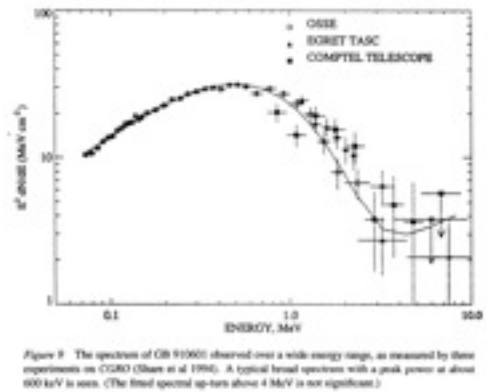
$\tau \sim 10^{15}$

0.1sec

$\Downarrow$

$R < 3 \times 10^{9}$cm





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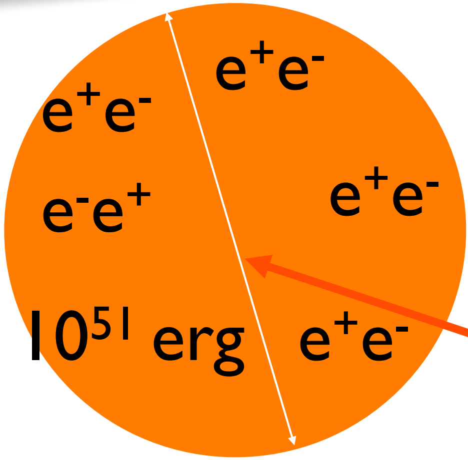
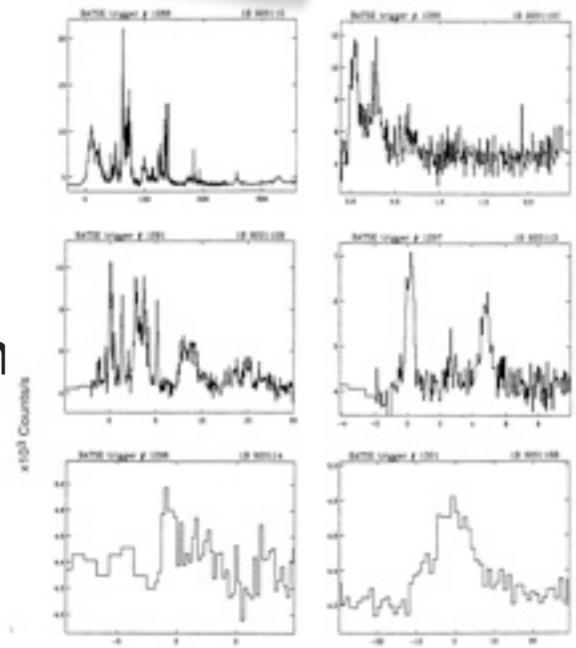
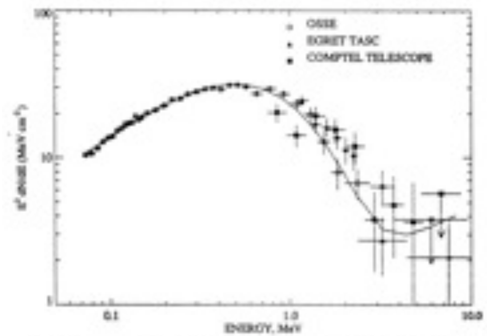


0.1sec

$\Downarrow$

~~$R<3\times10^9$cm~~



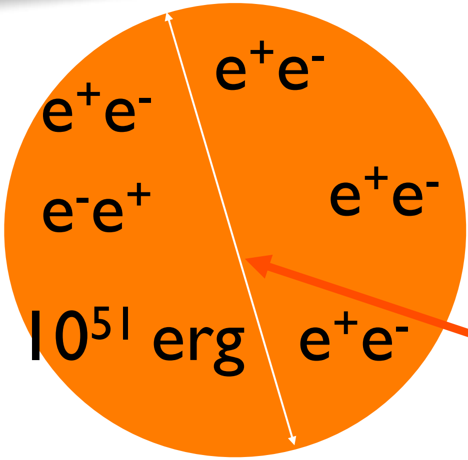


$\tau \sim 10^{15}$

$$\left.\begin{array}{l} h\nu \Rightarrow h\nu/\Gamma \\ \delta t \Rightarrow R/c\Gamma^2 \end{array}\right\} \tau \propto \Gamma^{-(4+\alpha)}$$

Relativistic Motion

$\gamma\gamma \rightarrow e^+e^-$



0.1sec

$\Downarrow$

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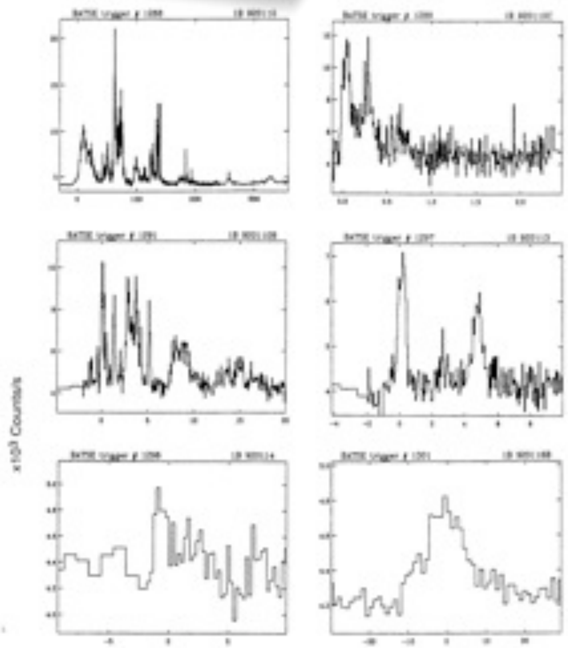

$\tau\sim10^{15}$

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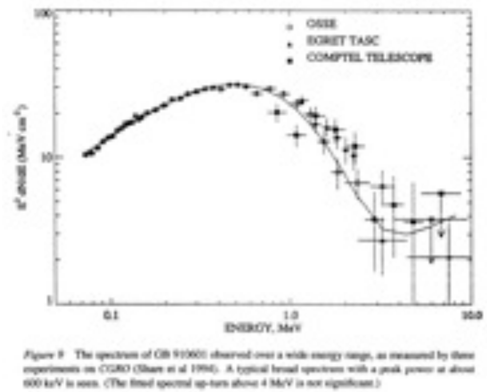
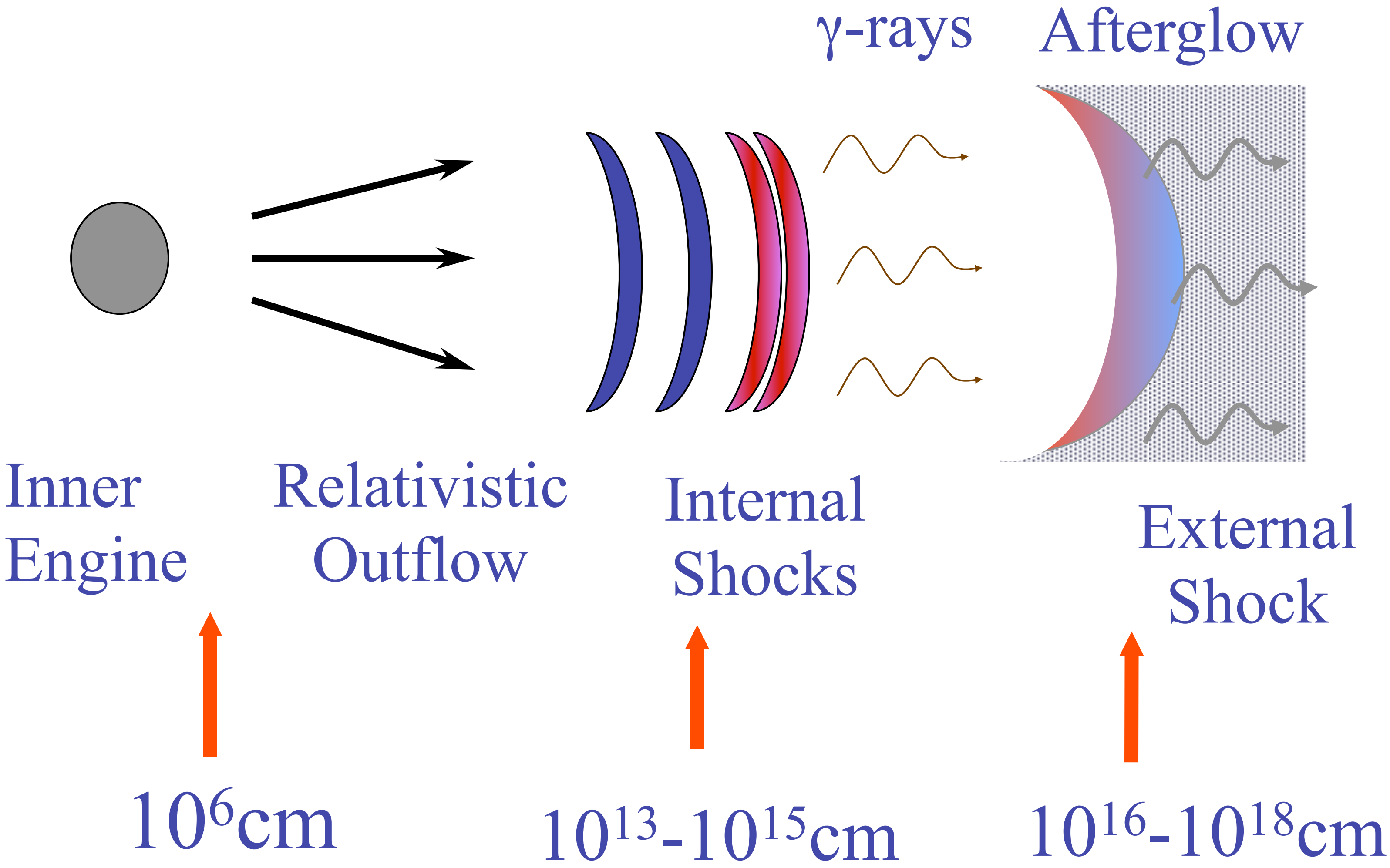


$\tau<1 \rightarrow \Gamma>100$

The Internal-External Fireball Model



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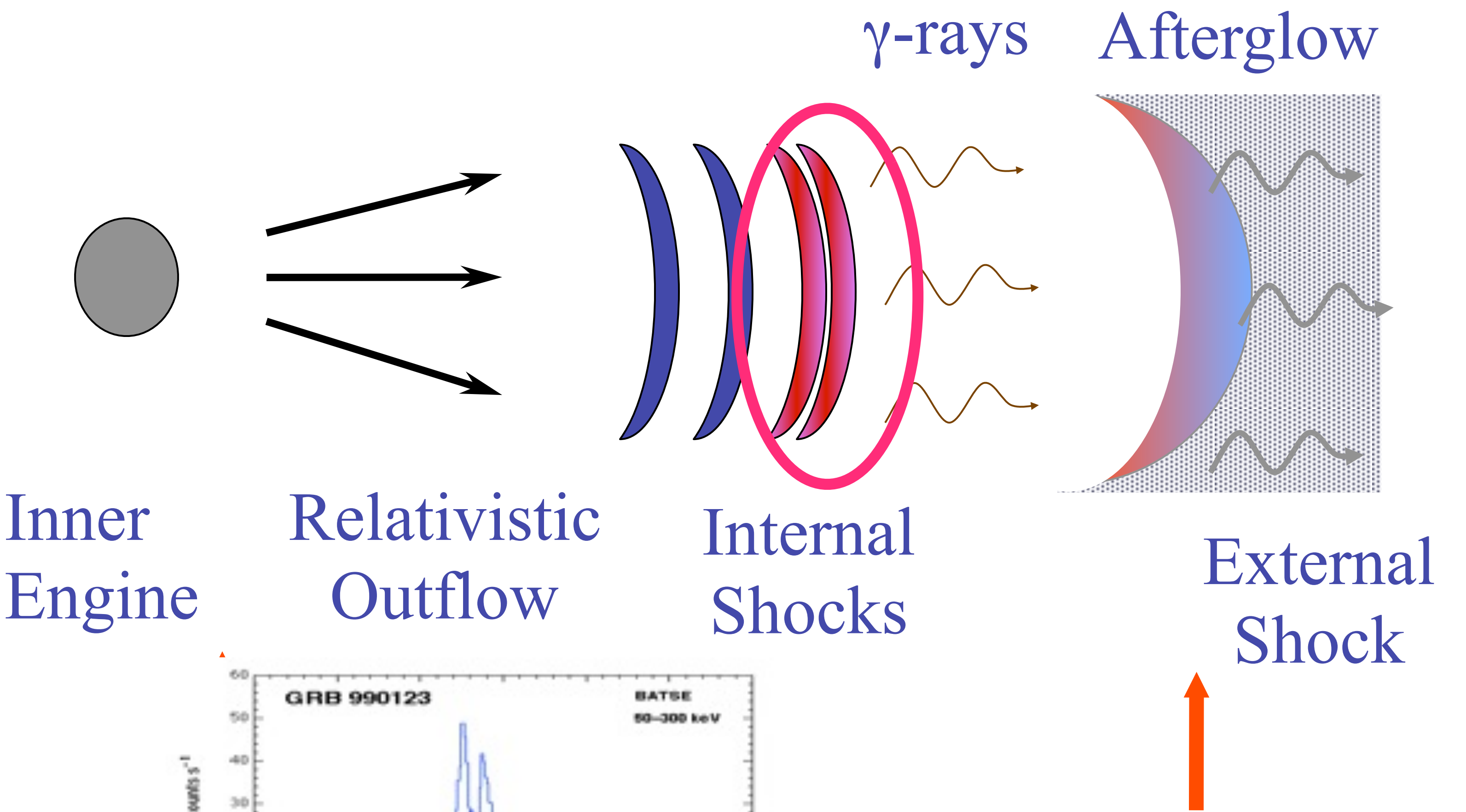
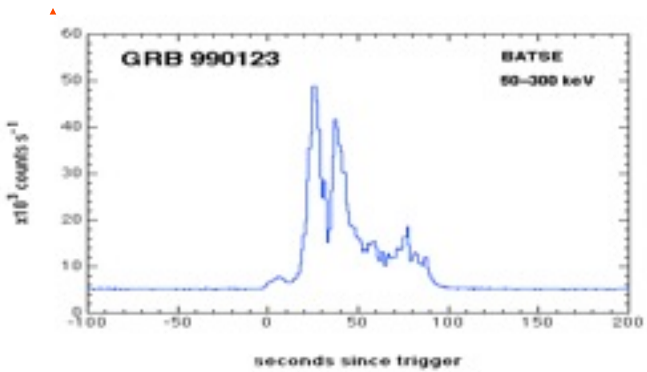
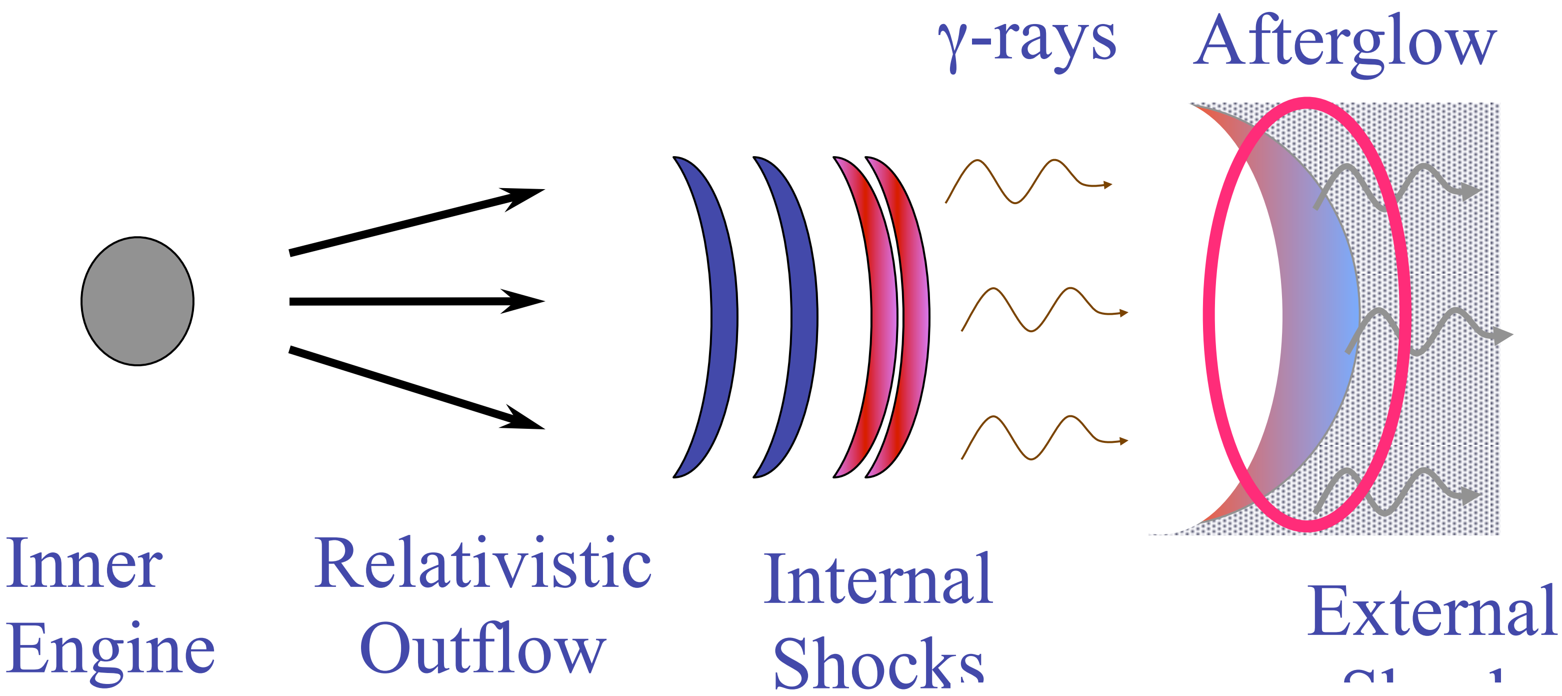




1)^{15}cm

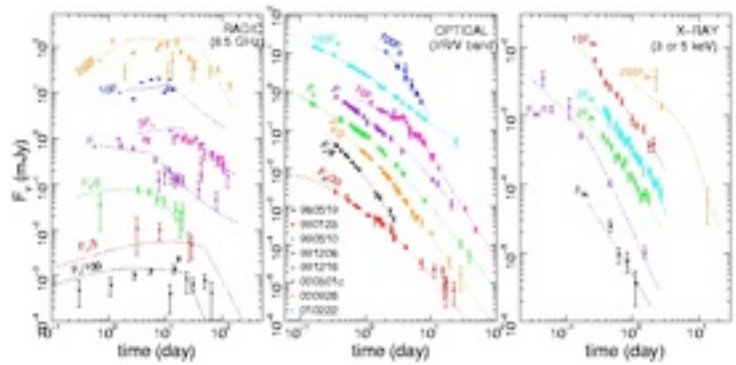
10^{16}-10^{18}cm

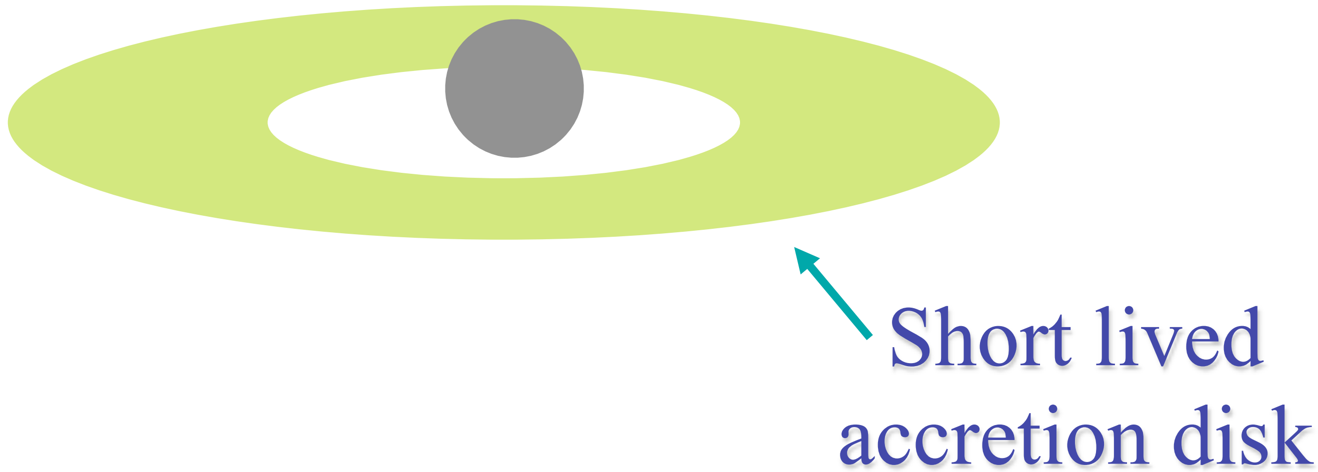
The Internal-External Fireball Model



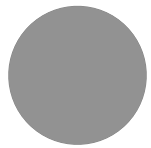
10^6cm

10^{13}-10^{15}c



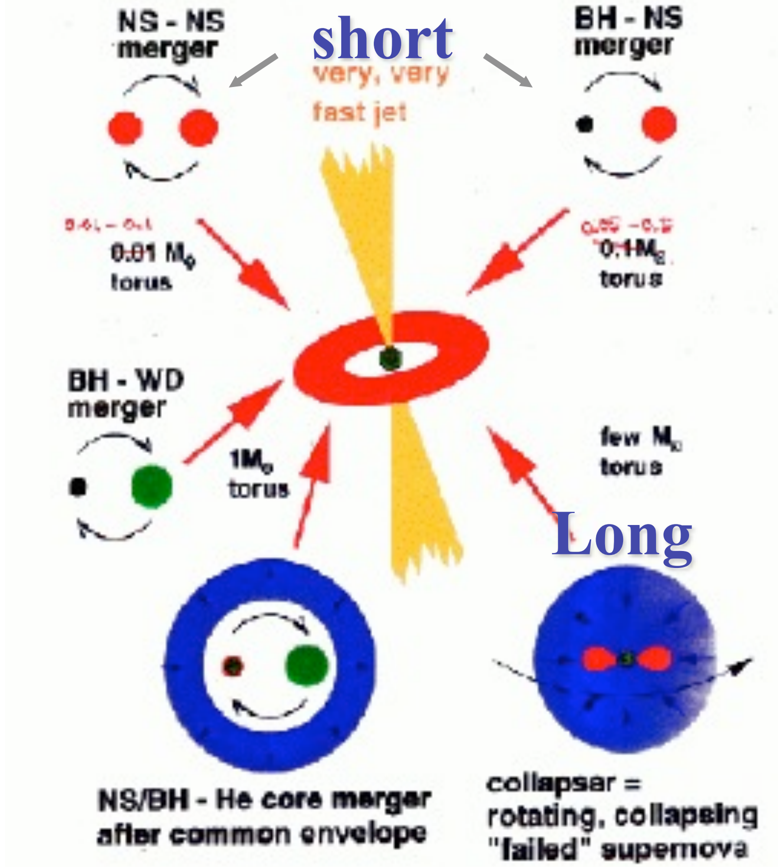

Short lived
accretion disk

Duration ~30 sec – accretion time scale.

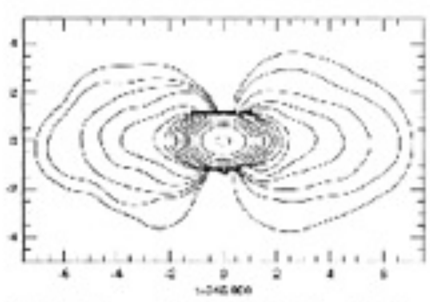


Variability $\leq$ 0.1 sec – fluctuation time scale.

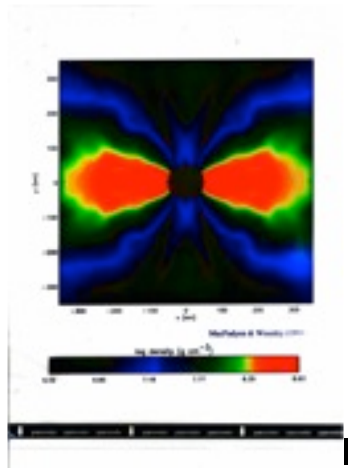
Routes to a BH-Disk-Jet



- NS/BH-NS merger
- BH-WD merger
- NS/BH-He core merger
- Collapsar

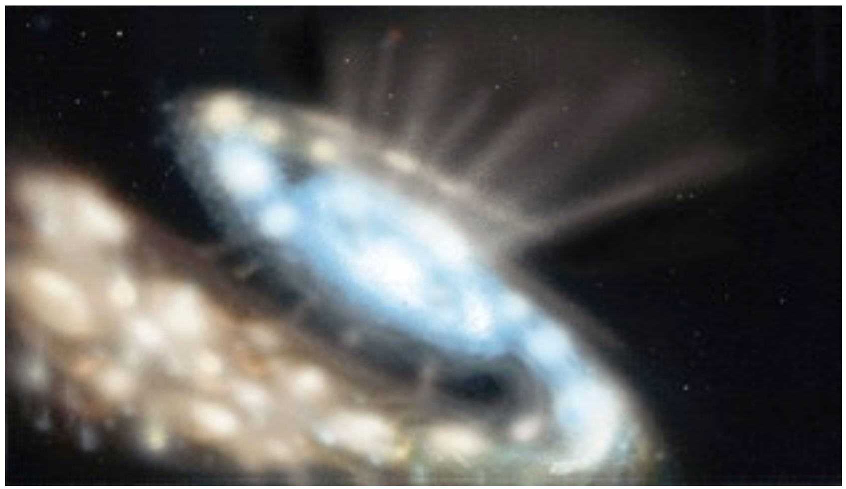


Davies et al , 94



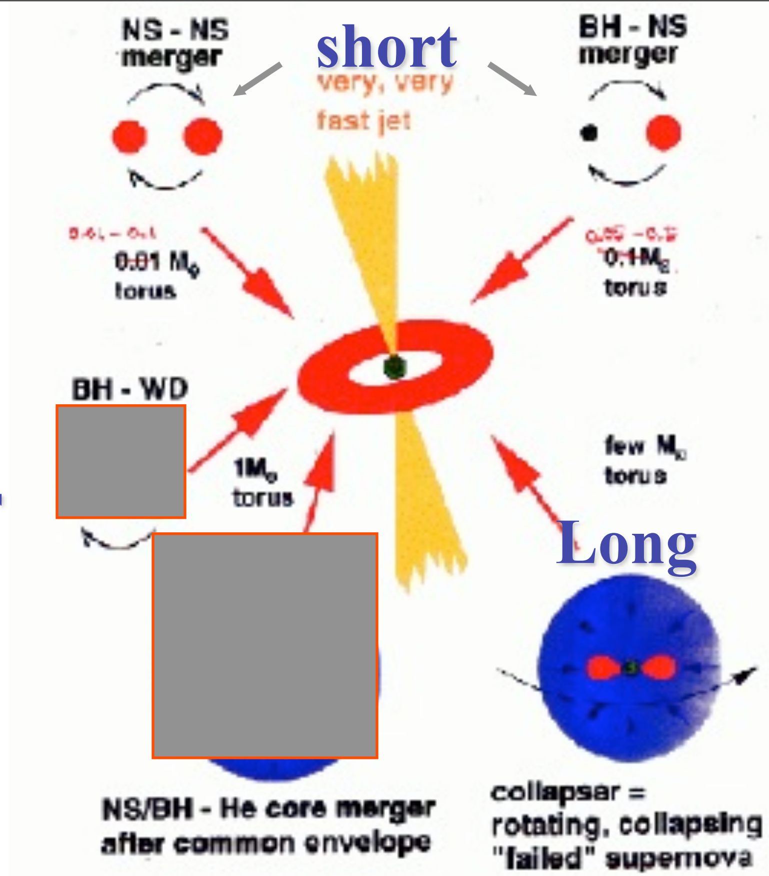
ISA

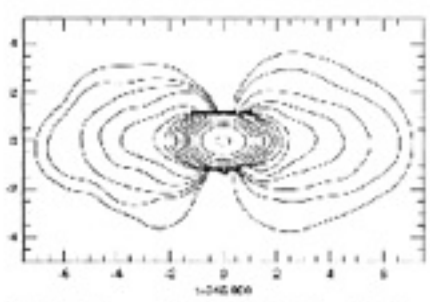
Woosley et al, 99



Routes to a BH-Disk-Jet

- NS/BH-NS merger - SHORT
- ~~BH-WD merger~~
- ~~NS/BH-He core merger~~
- Collapsar - LONG





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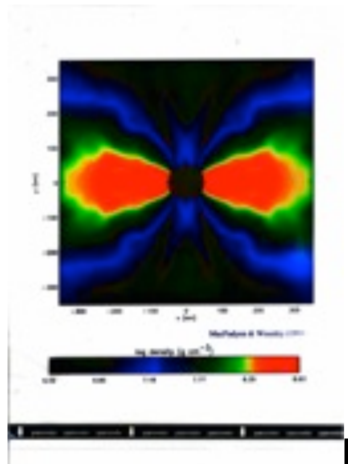

Woosley et al, 99

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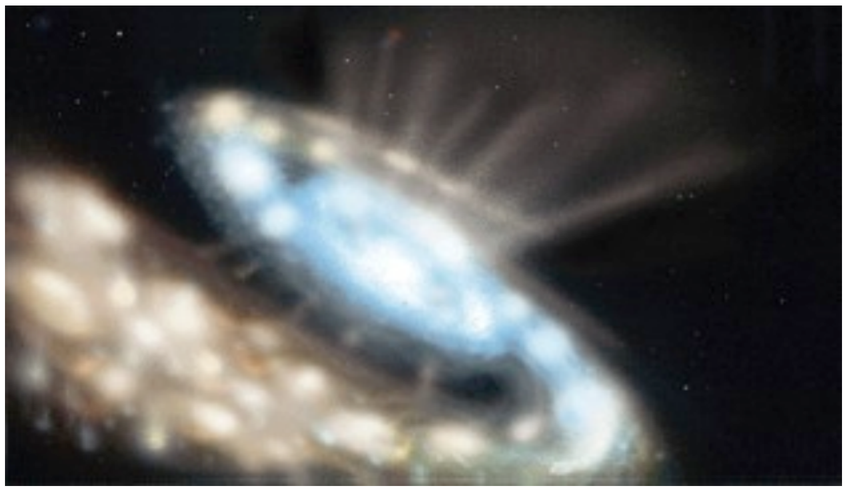

Jets and the Jet Break

(Rhoads 1999; Sari, Piran & Halpern 1999)

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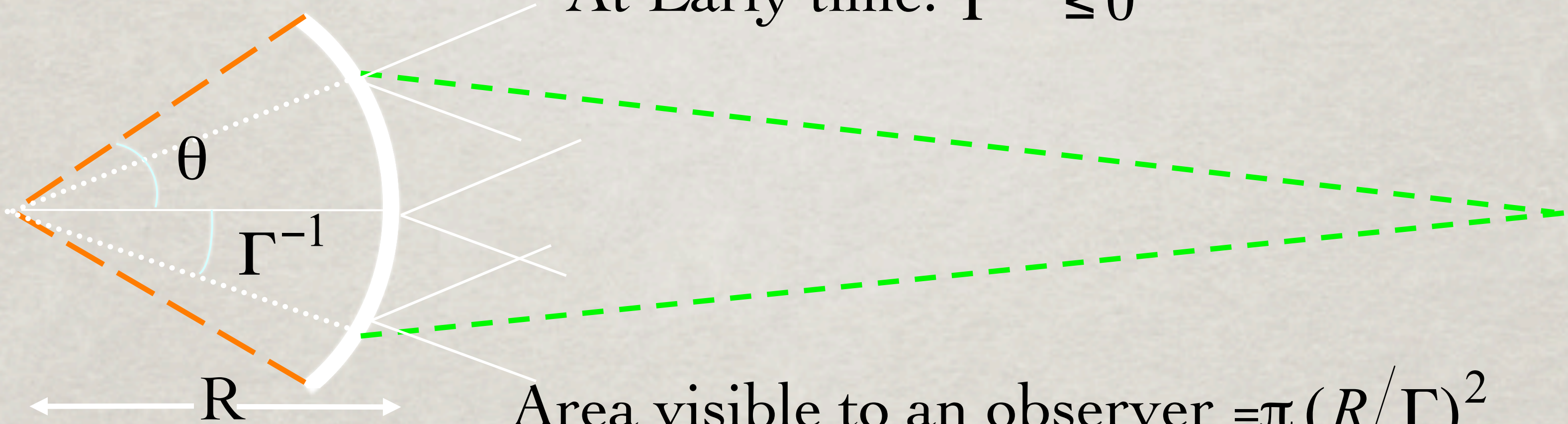
At Early time: $\Gamma^{-1} \leq \theta$

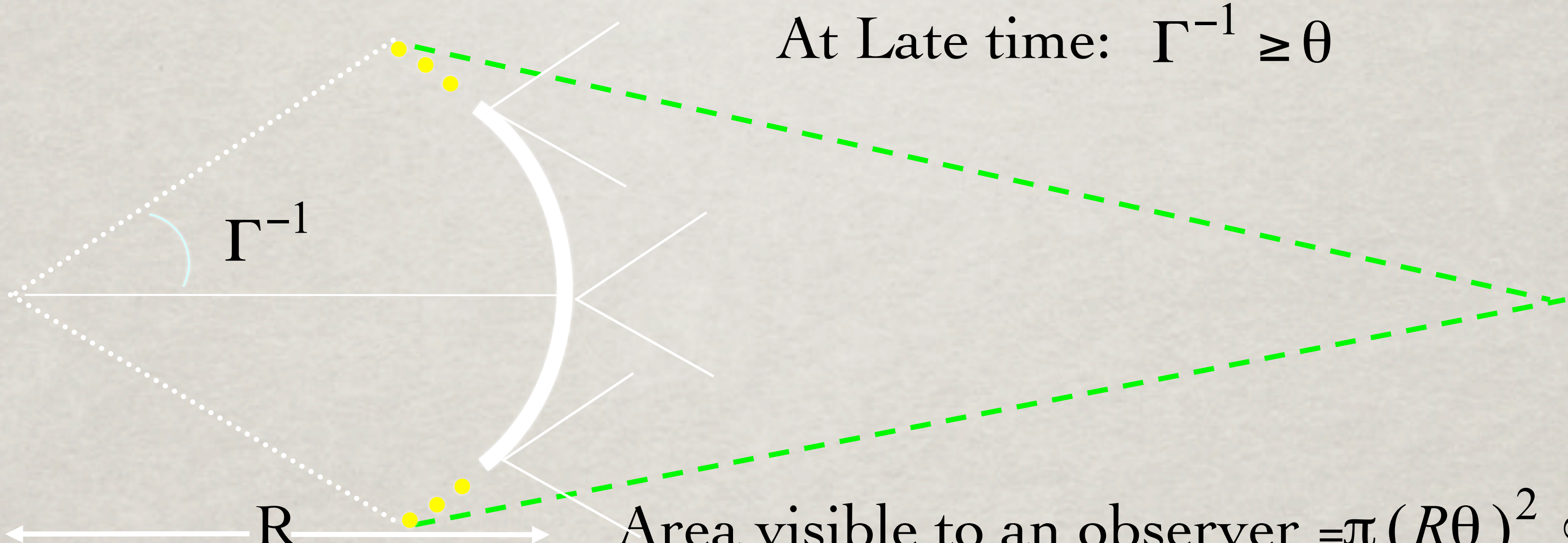


Area visible to an observer $= \pi (R/\Gamma)^2$

Jets and the Jet Break

(Rhoads 1999; Sari, Piran & Halpern 1999)

At Late time: $\Gamma^{-1} \geq \theta$



Area visible to an observer $= \pi (R\theta)^2 \propto$

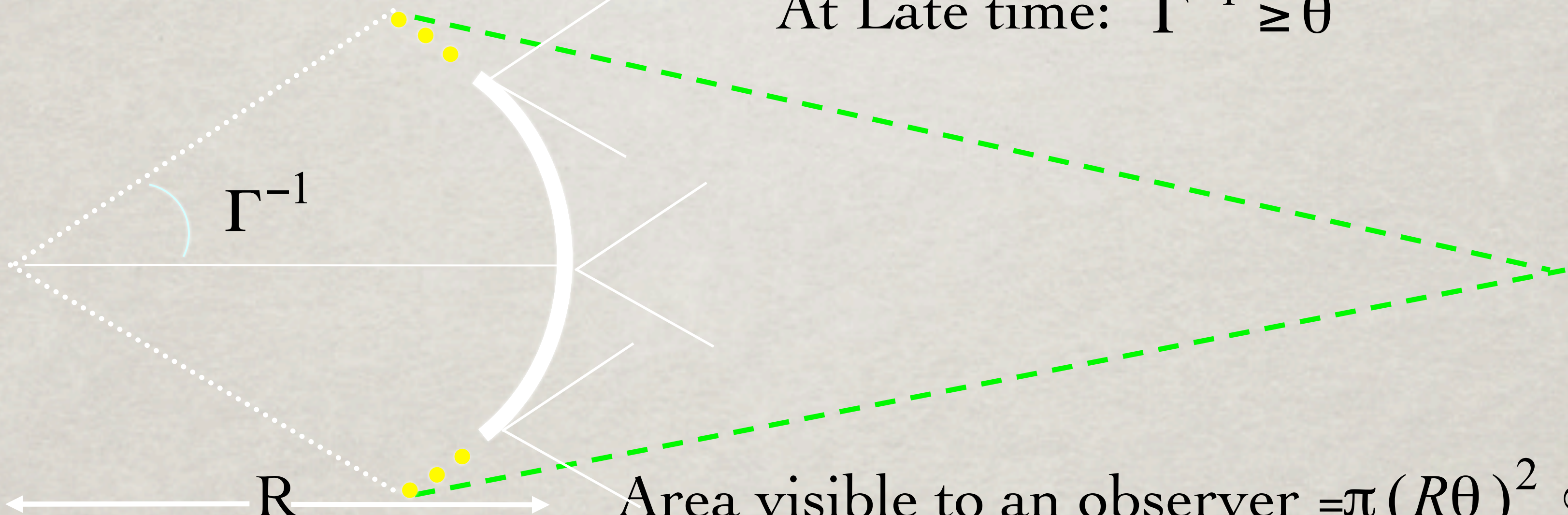
$(R/\Gamma)^2 (\theta\Gamma)^2 \propto (R/\Gamma)^2 t$

Jets and the Jet Break

(Rhoads 1999; Sari, Piran & Halpern 1999)

Jet break at $\Gamma = \theta^{-1}$: θ=0.16 (n/E)$^{1/8}$ (t/day)$^{3/8}$

At Late time: $\Gamma^{-1} \geq \theta$



Area visible to an observer $= \pi (R\theta)^2 \propto$

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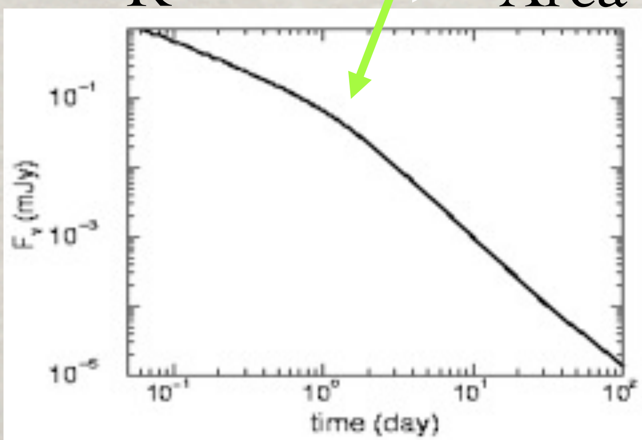
$$(R/\Gamma)^2 (\theta\Gamma)^2 \propto (R/\Gamma)^2\, t$$



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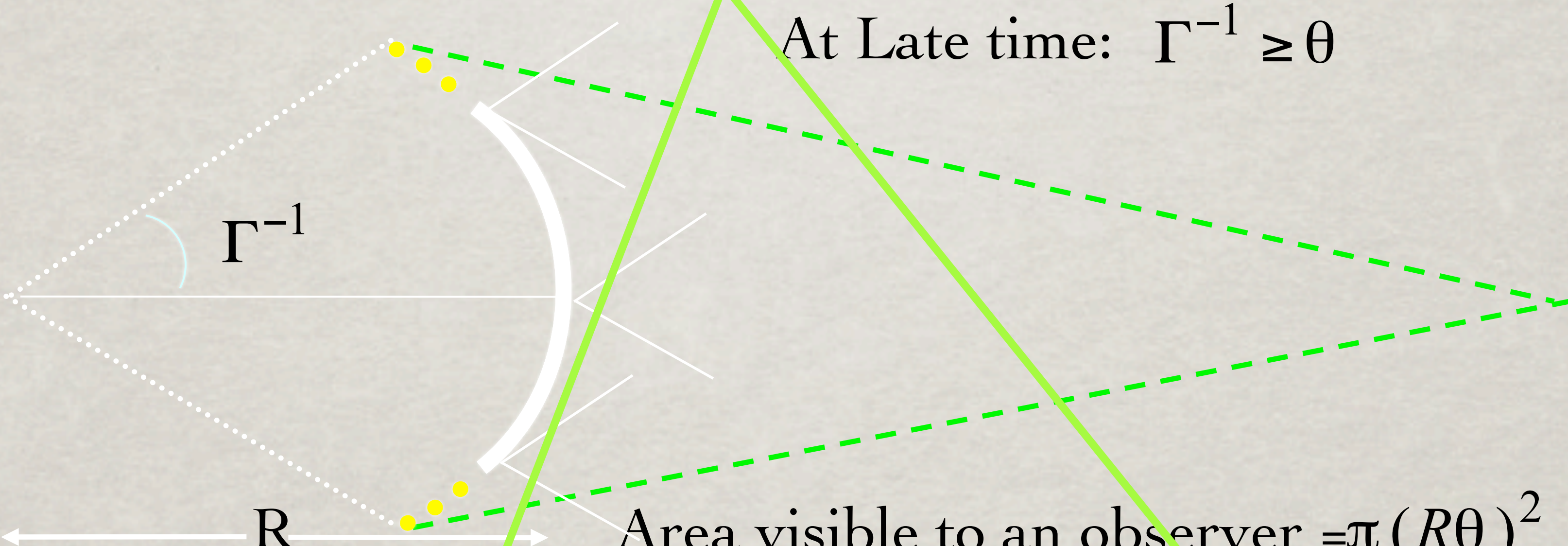
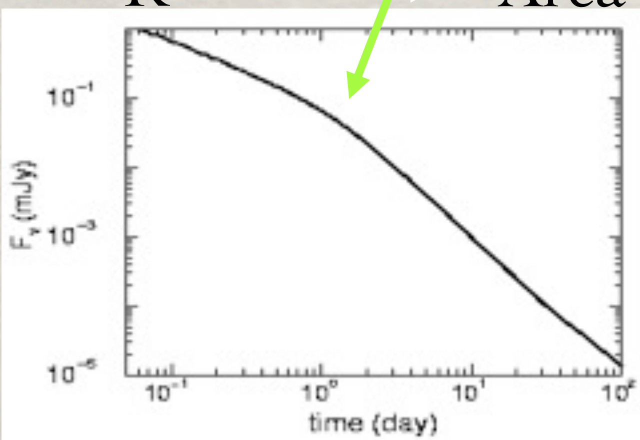
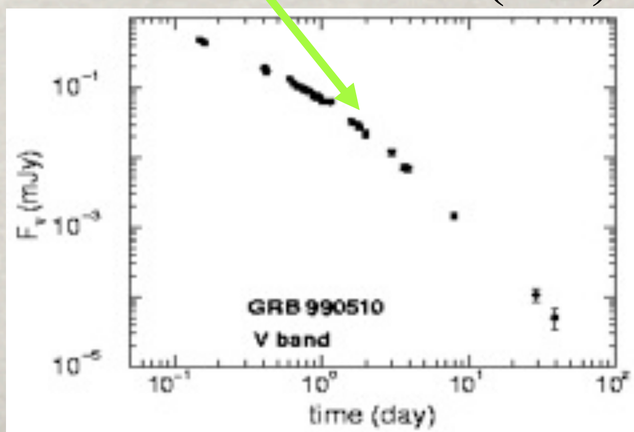
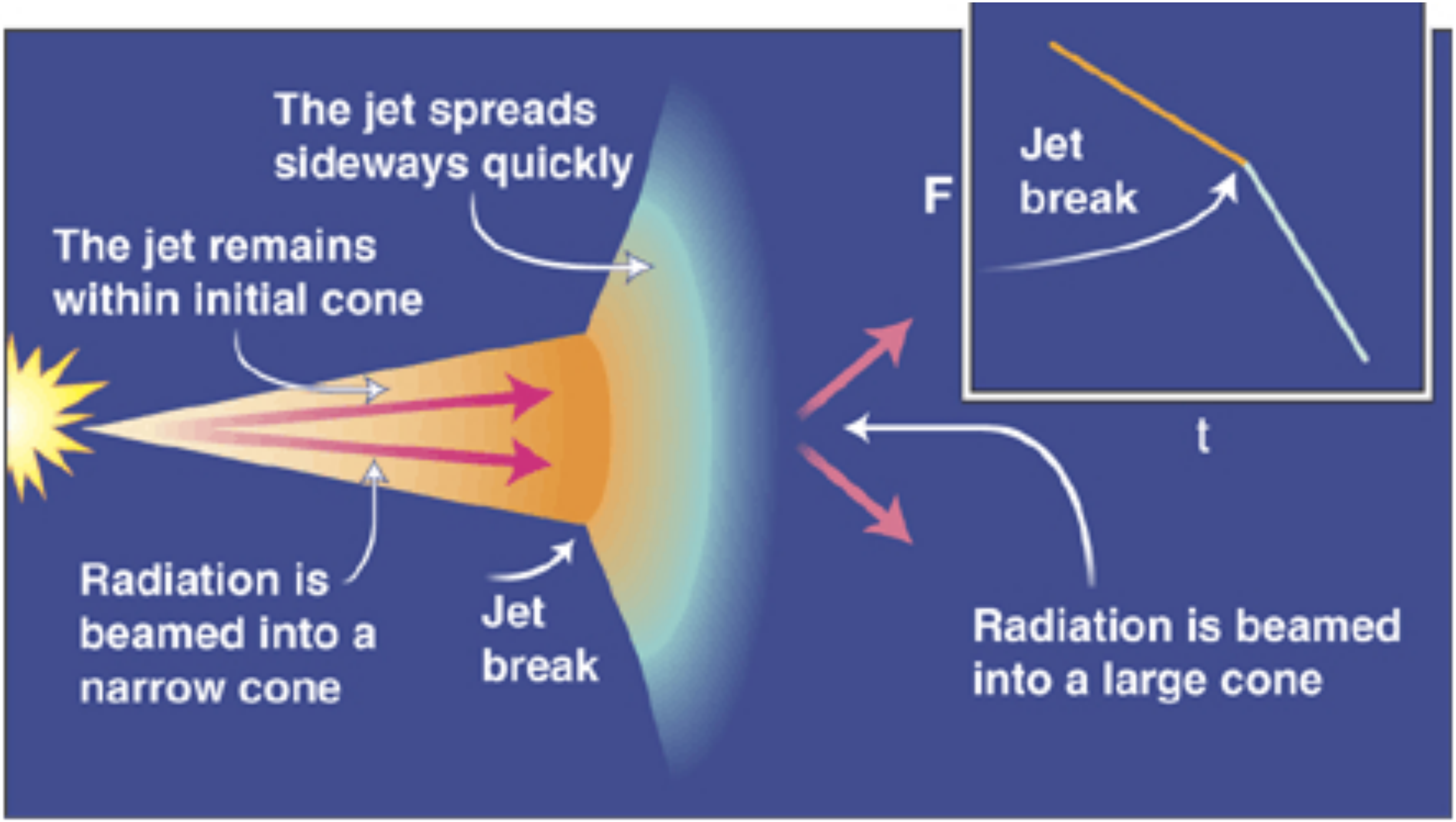


Area visible to an observer $= \pi (R\theta)^2 \propto$ … $\Gamma)^2\, t$



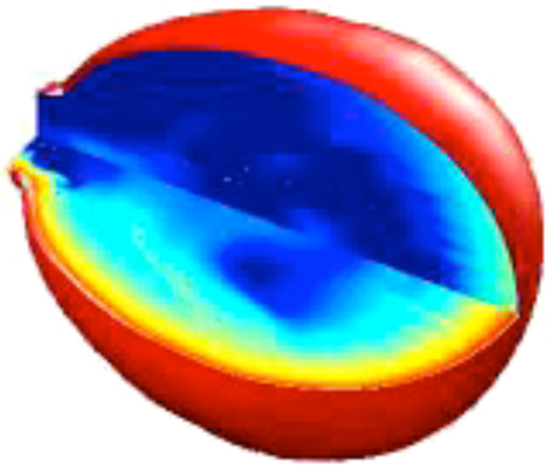



The jet spreads sideways quickly
The jet remains within initial cone
Radiation is beamed into a narrow cone
Jet break
Radiation is beamed into a large cone
F
Jet break
t

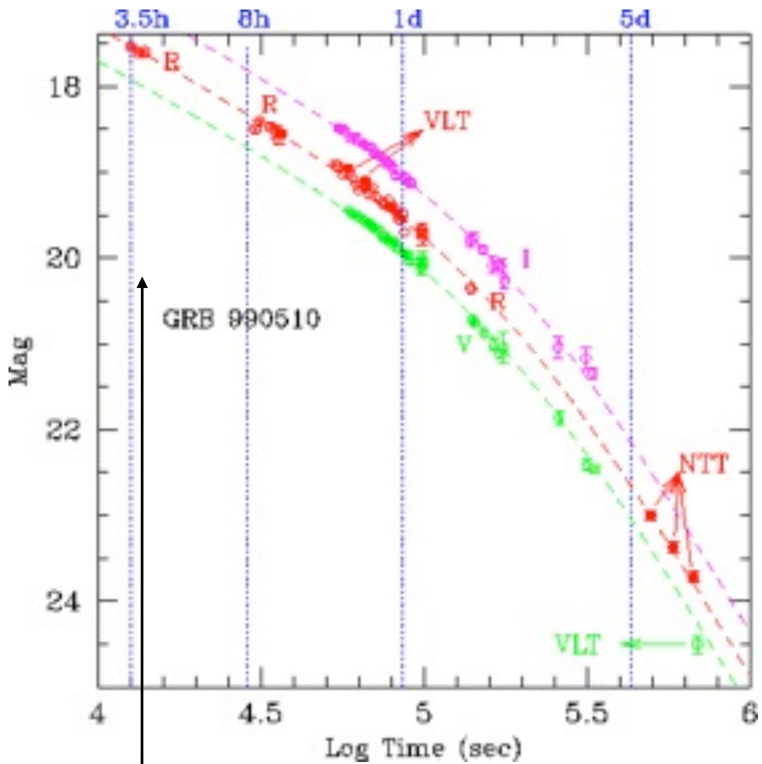
Hydrodynamic Simulation of a Relativistic Jet

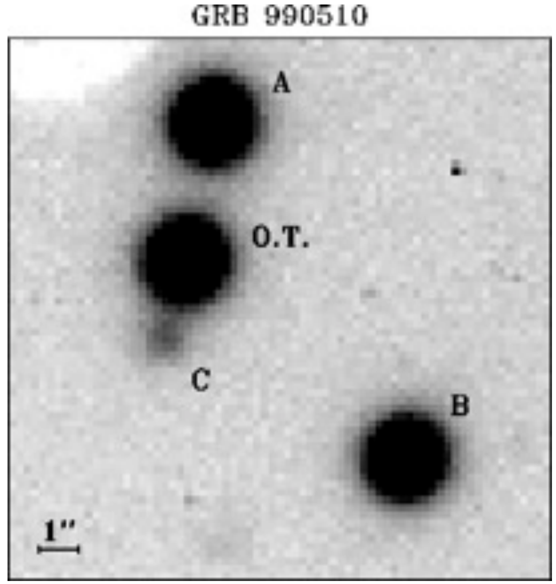
J. Granot, M. Miller, T. Piran, W. M. Suen

P. A. Hughes, 2001



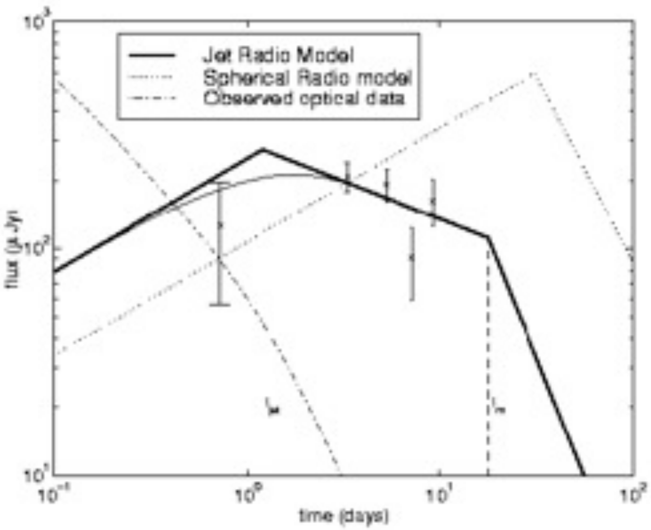
Movie by S. Ayal, J. Granot





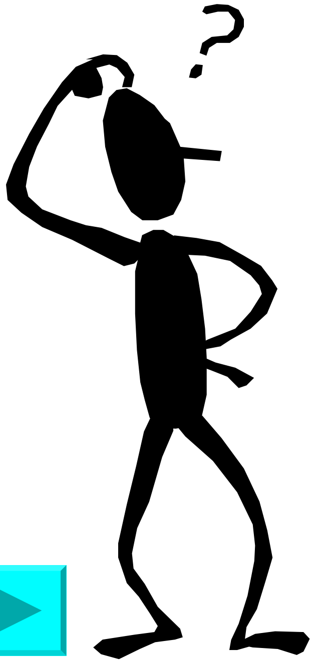
$\alpha_1 = 0.85$ $\alpha_2=2.18$

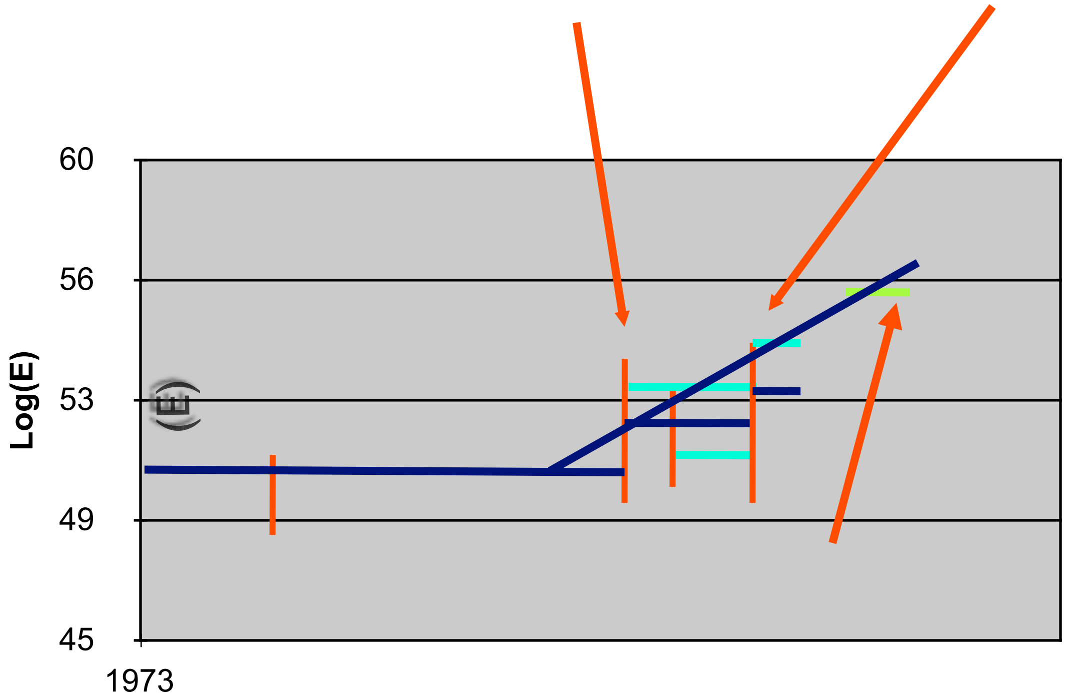
t_{break} = 1.2 days ⇒ jet angle = 4°



Harrison et al 1999

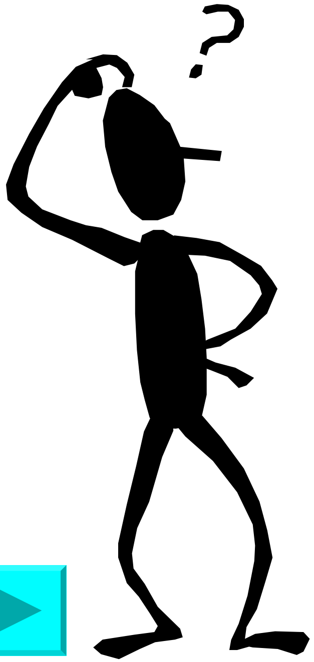
The Energy

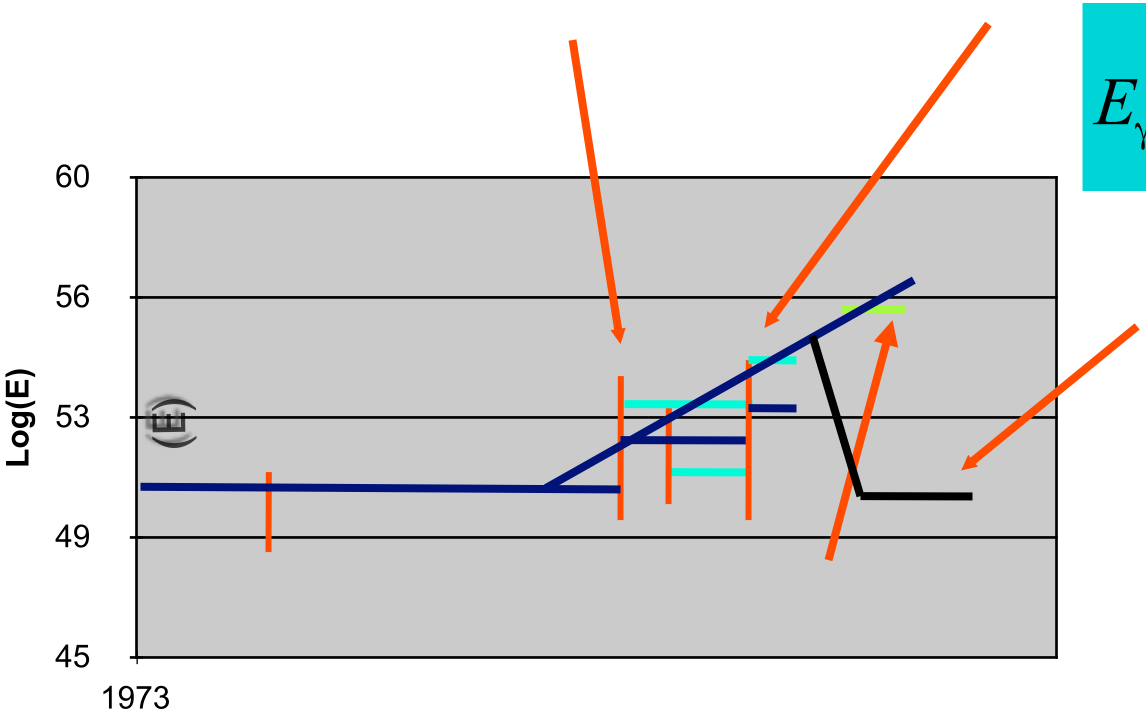




The Energy

$$E_\gamma = \frac{\theta^2}{2} E_{\gamma\, iso}$$

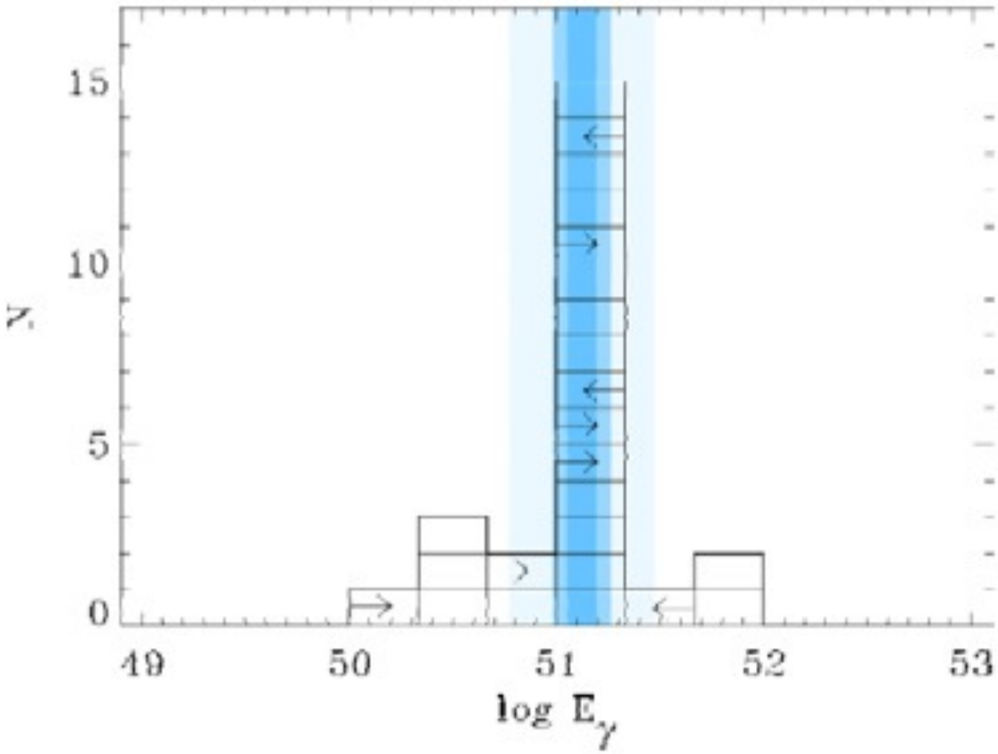




Jets

$$E_\gamma = \frac{\theta^2}{2} E_{\gamma\, iso}$$

From Bloom et al., 03



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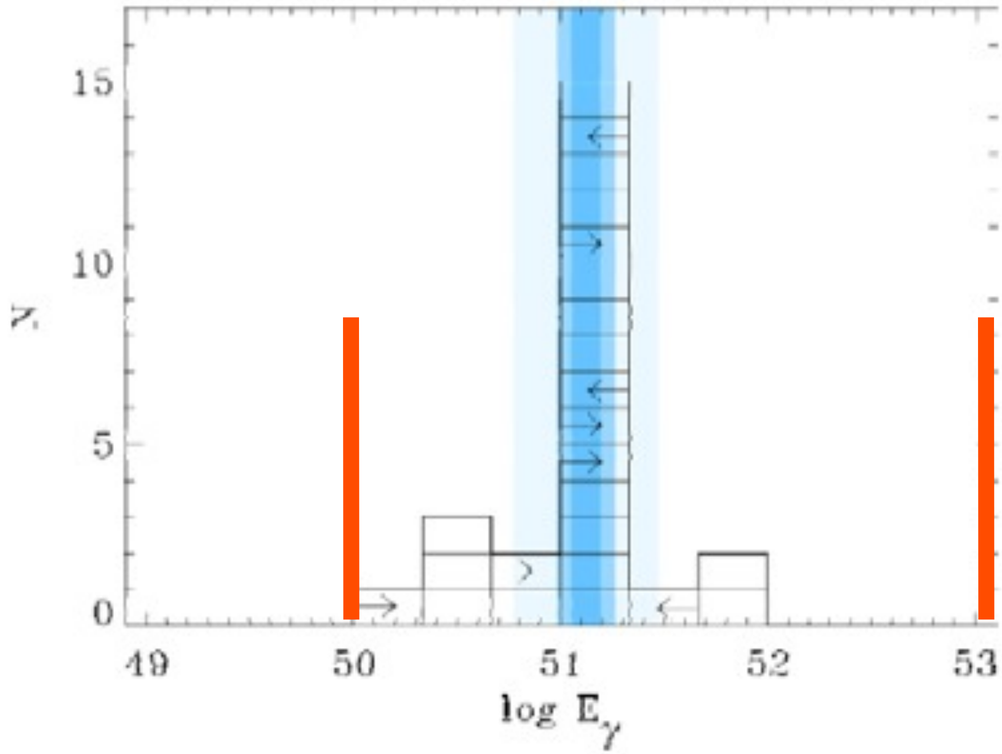

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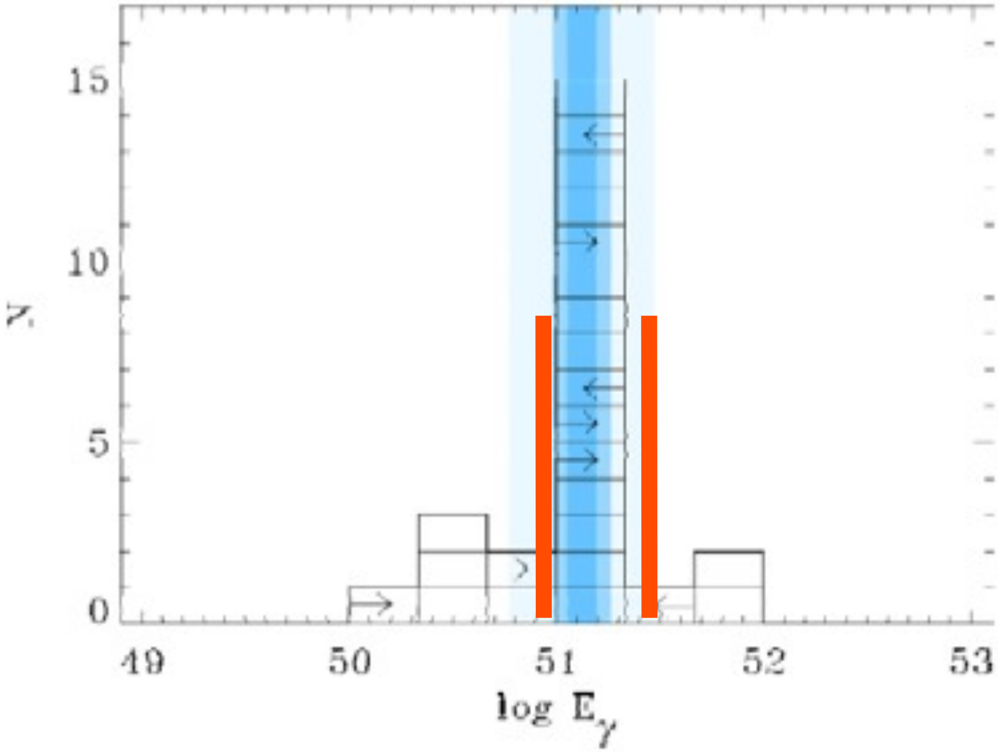

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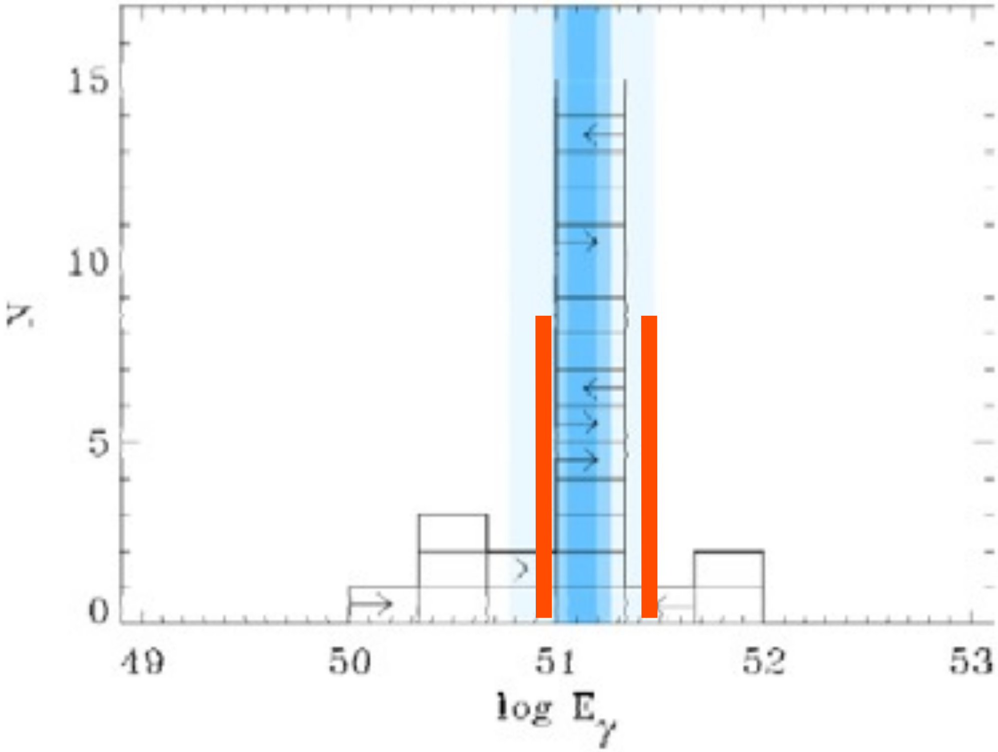
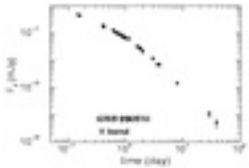
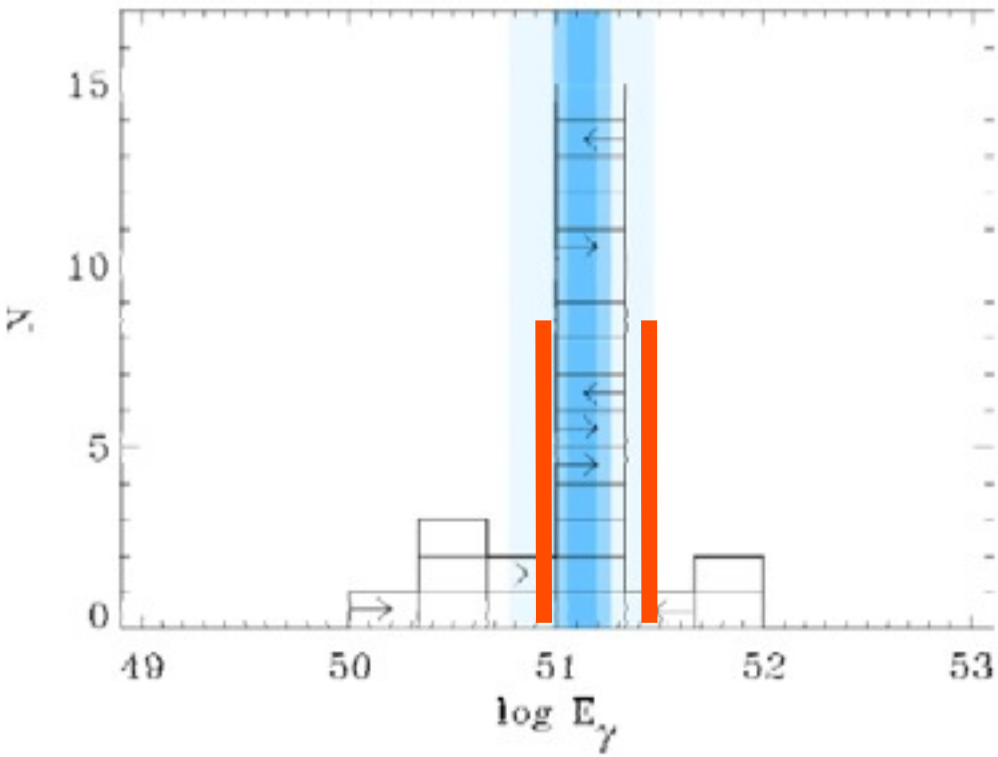


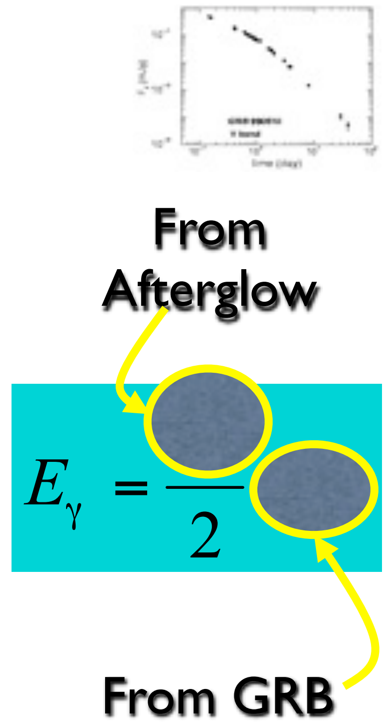


From Afterglow

$$E_\gamma = \frac{\quad}{2} E_{\gamma\ iso}$$

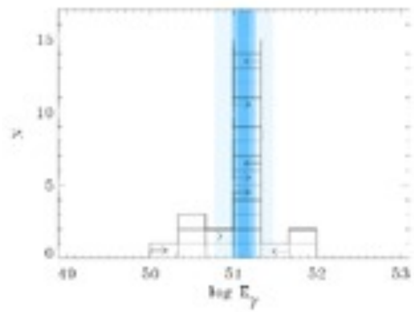
From Bloom et al., 03





From Bloom et al., 03

But :



Berger et al., Nature, 2003

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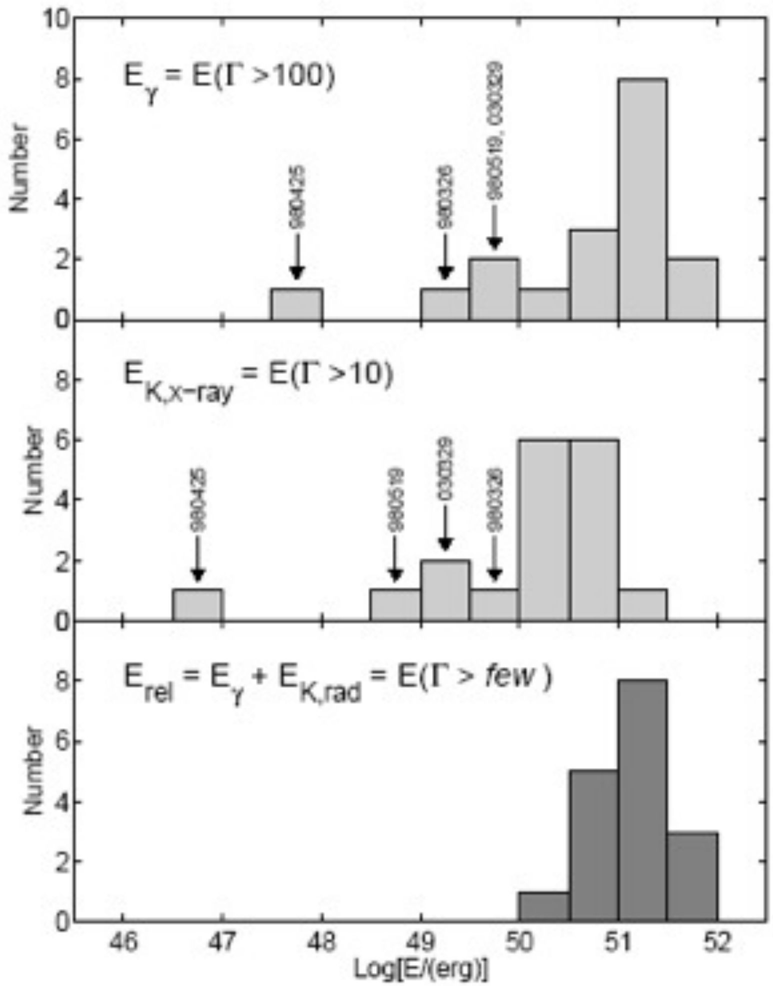

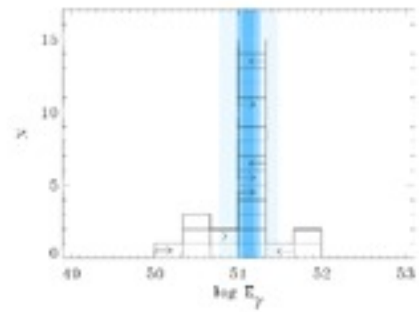

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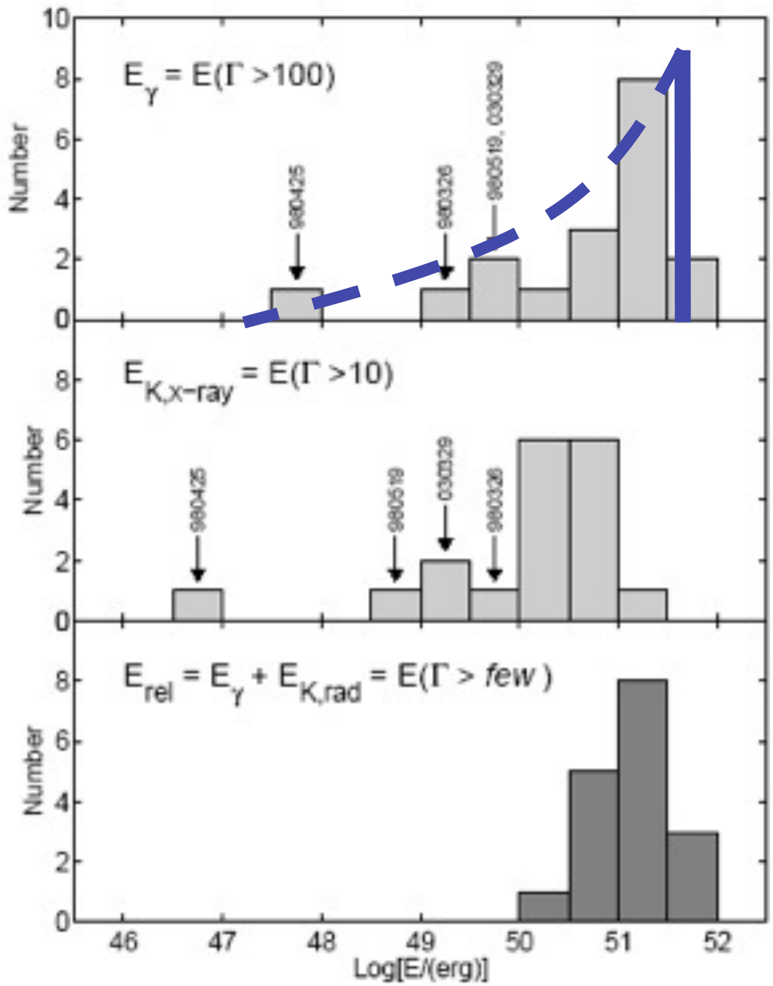
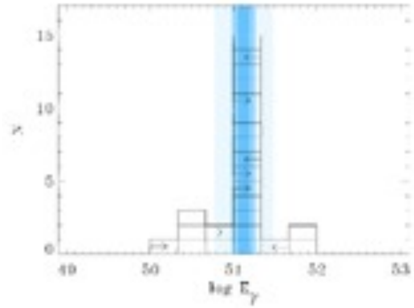


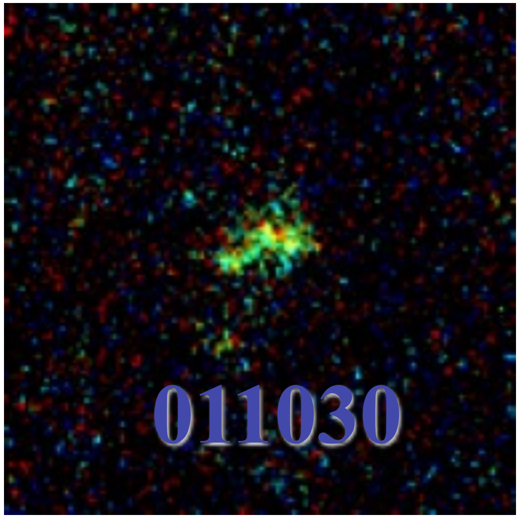


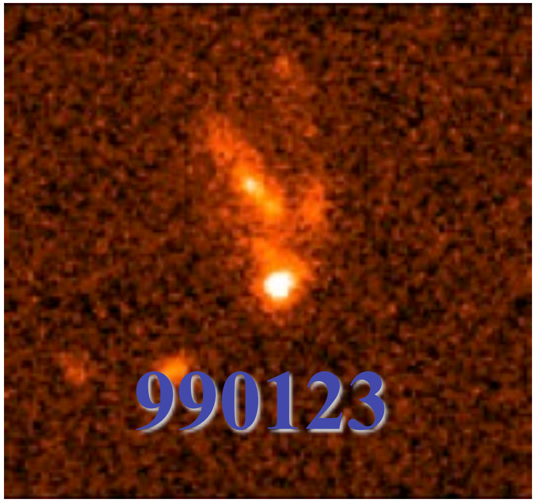
Berger et al., Nature, 2003

Black hole?

- Usov 1992 - Magnetar source
  - Need 10^{15} G at the source
  - Many be powered by rotation?
- Main problem is that energy budget is marginal, especially for very energetic bursts.
- Also need to channel the Magnetar energy to a narrow jet?

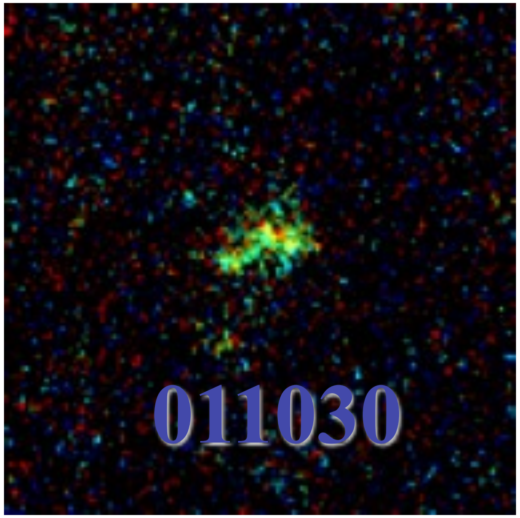
Long Duration GRBs: Massive Stars & Sne

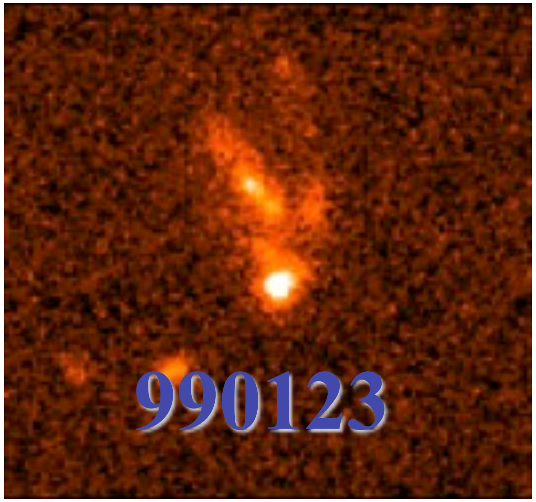




Long Duration GRBs: Massive Stars & Sne

- GRB host galaxies are star-forming galaxies
- High column density/ extincted bursts
- In regions of very high star formation (Fruchter).





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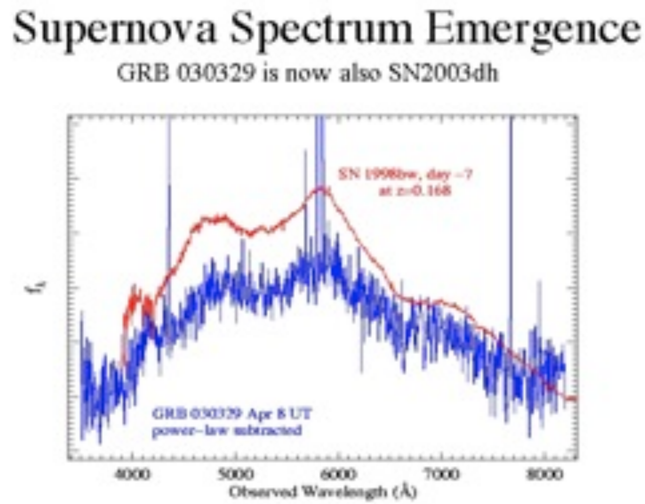
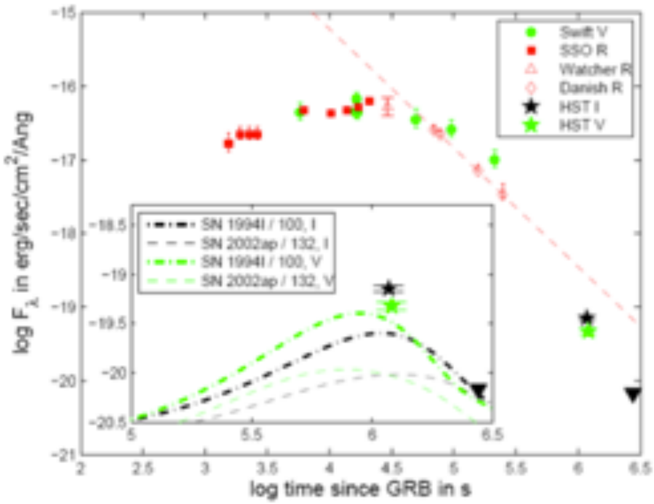


T. Matheson (CfA), GCN 2120

Long Duration GRBs: Massive Stars & Sne

- GRB host galaxies are star-forming galaxies
- High column density/ extincted bursts
- In regions of very high star formation (Fruchter).
- Association with type Ibc SNe
- But SNe are not seen in some GRBs?



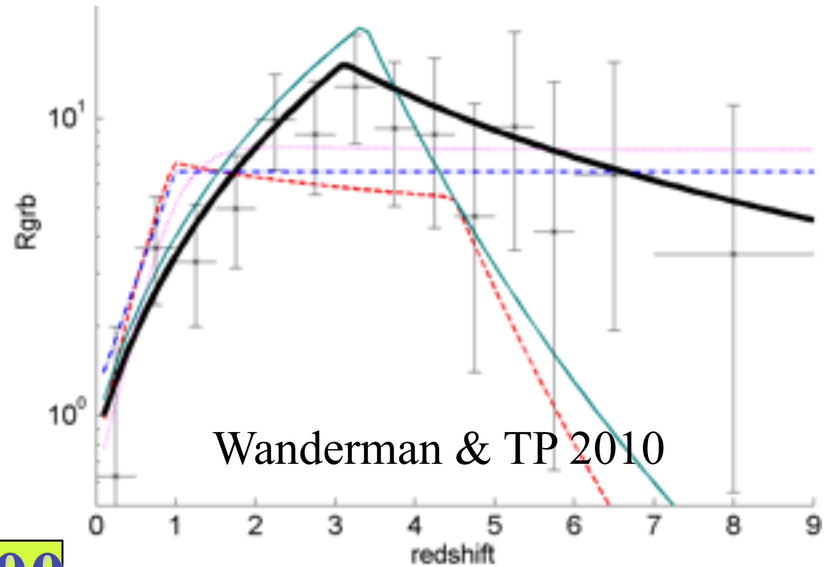
Rates of Long Bursts

Rates of Long Bursts

Rates of Long Bursts

- The observed rates of long GRBs is 1 per day by BATSE
- 1 GRB per Gpc^3/yr
- An observed burst per galaxy in 2×10^7 years
- 3×10^5 years/galaxy with a beaming correction of ~50
- This rate is a factor of >1000 below the rate of SNe.
- Does not follow the SFR –

<u>requires more distant bursts!</u>

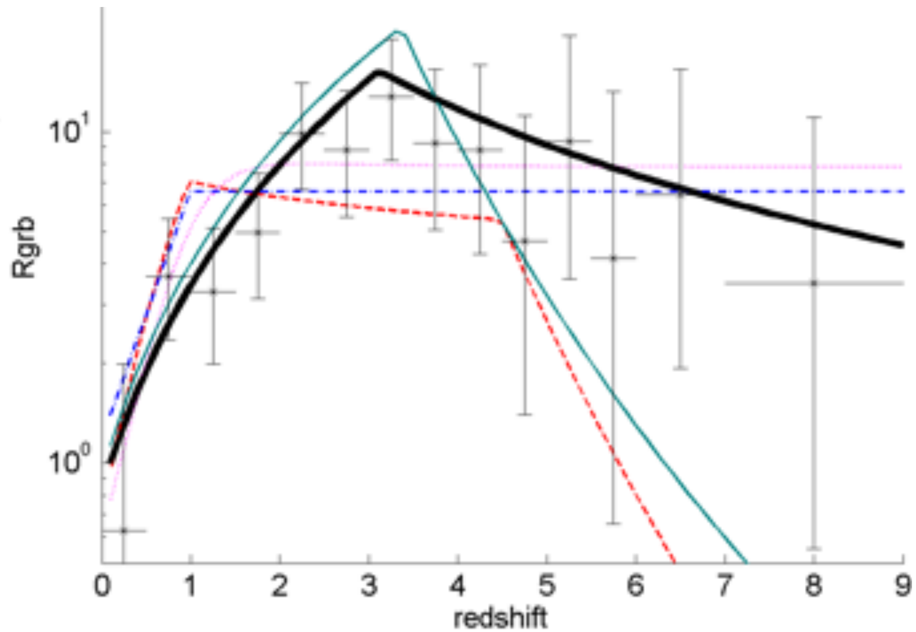


Rates of Long Bursts

Rates of Long Bursts

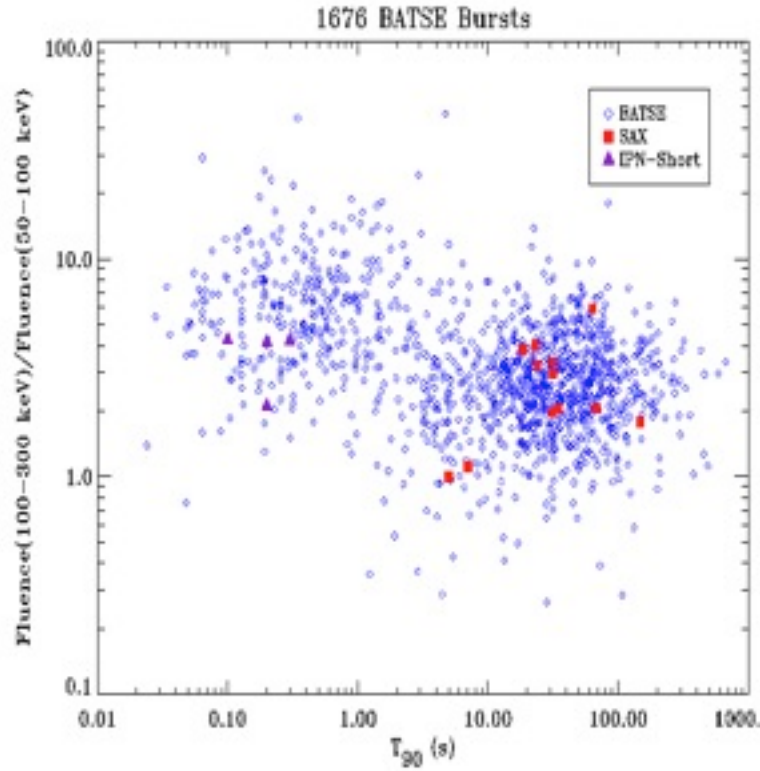
- The observed rates of long GRBs is 1 per day on BATSE
- The implied rate is about 1 Gpc^3/yr
- Or an observed burst per galaxy in 2×10^7 years
- 3×10^5 years/galaxy with a beaming correction of ~50
- This rate is a factor of >1000 below the rate of SNe.
- Does not follow the SFR –

<u>requires more distant bursts!</u>



Wanderman & TP 2010

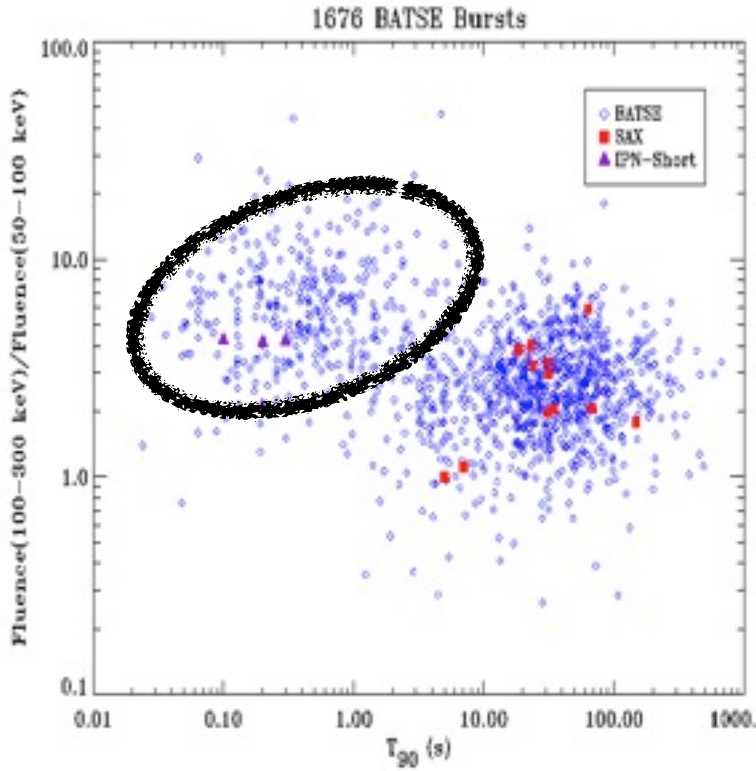
Short GRBs



1676 BATSE Bursts
BATSE
SAX
IPN-Short
Fluence(100−300 keV)/Fluence(50−100 keV)
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
T_{90} (s)

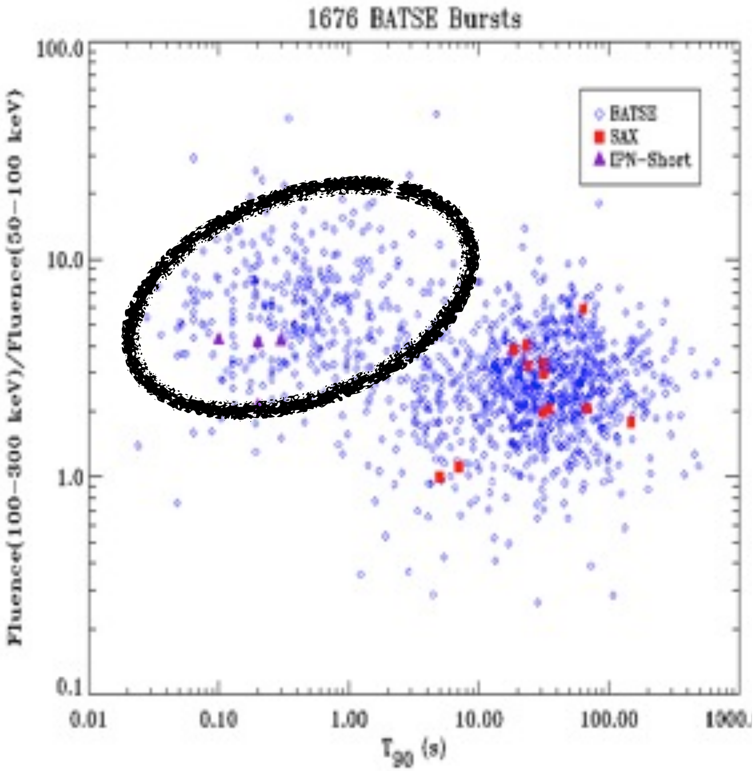
Short GRBs

- ~ 1/3 of BATSE long bursts.



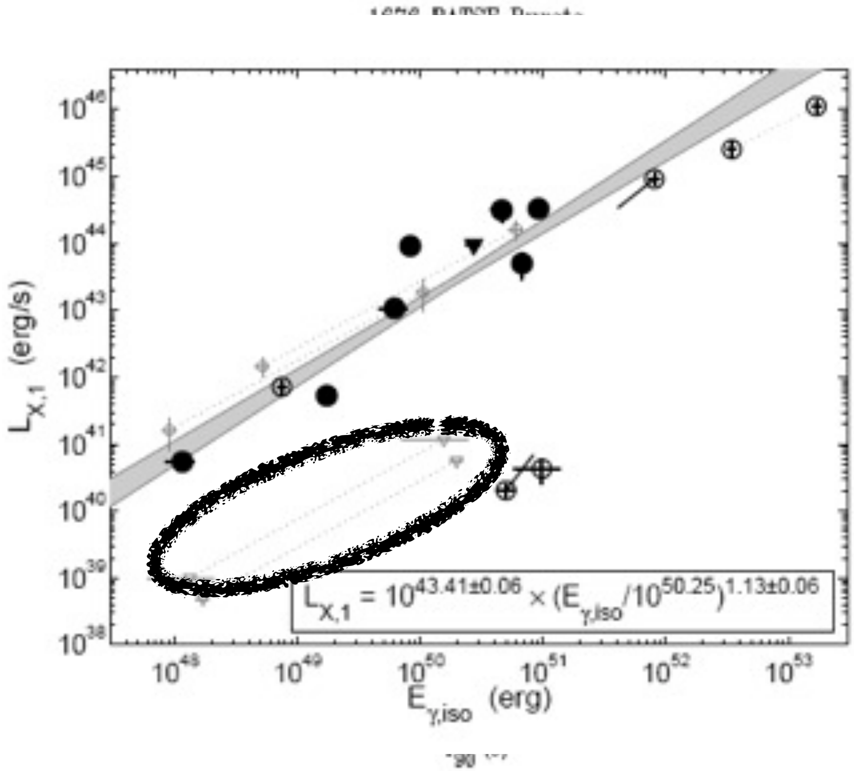
Short GRBs

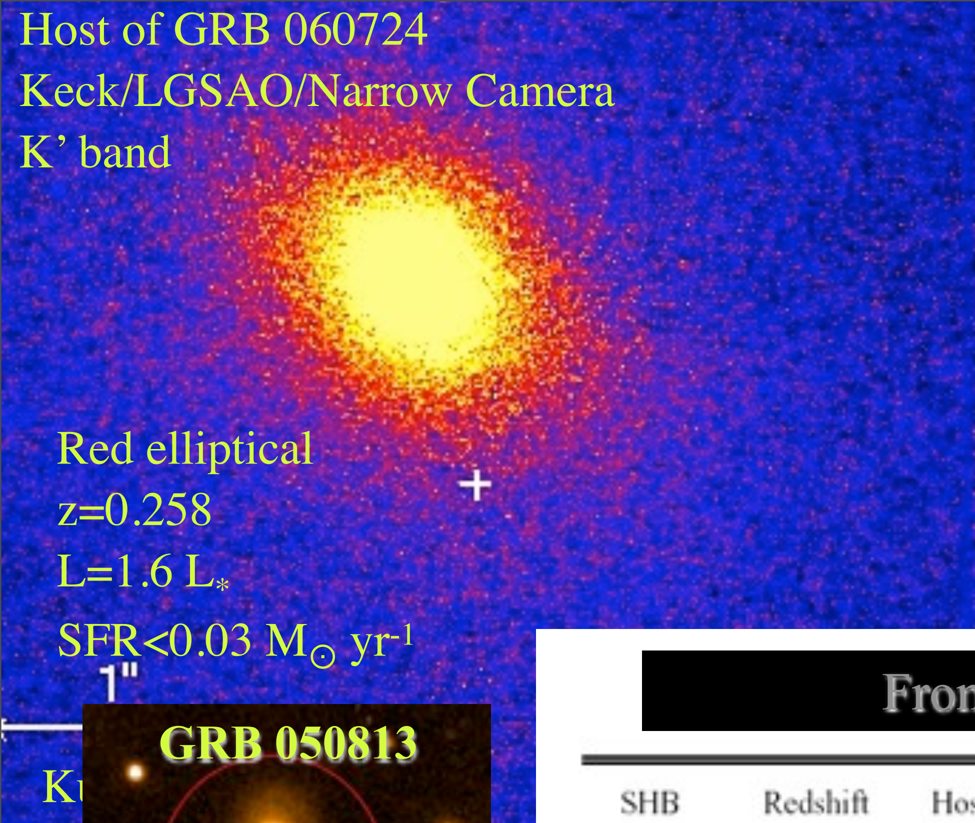
- ~ 1/3 of BATSE long bursts.
- ~1/10 of *Swift* long bursts.



Short GRBs

- ~ 1/3 of BATSE long bursts.
- ~1/10 of *Swift* long bursts.
- Lower total energy and weaker afterflows.





Evidence for an old population

From Nakar, Gal Yam & Fox 05

SHB	Redshift z	Host Galaxy Type	Association significance	Reference
790613	0.09	E/S0	$\sim 3\sigma$	Gal-Yam *et al.* 2005
000607	0.14	Sb	$\sim 2\sigma$	Gal-Yam *et al.* 2005
050509b	0.22	E/S0	$3-4\sigma$	Bloom *et al.* 2005; Kulkarni *et al.* 2005 Castro-Tirado *et al.* 2005; Gehrels 2005
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050813	0.72	E/S0	-	Gladders *et al.* 2005; Berger 2005
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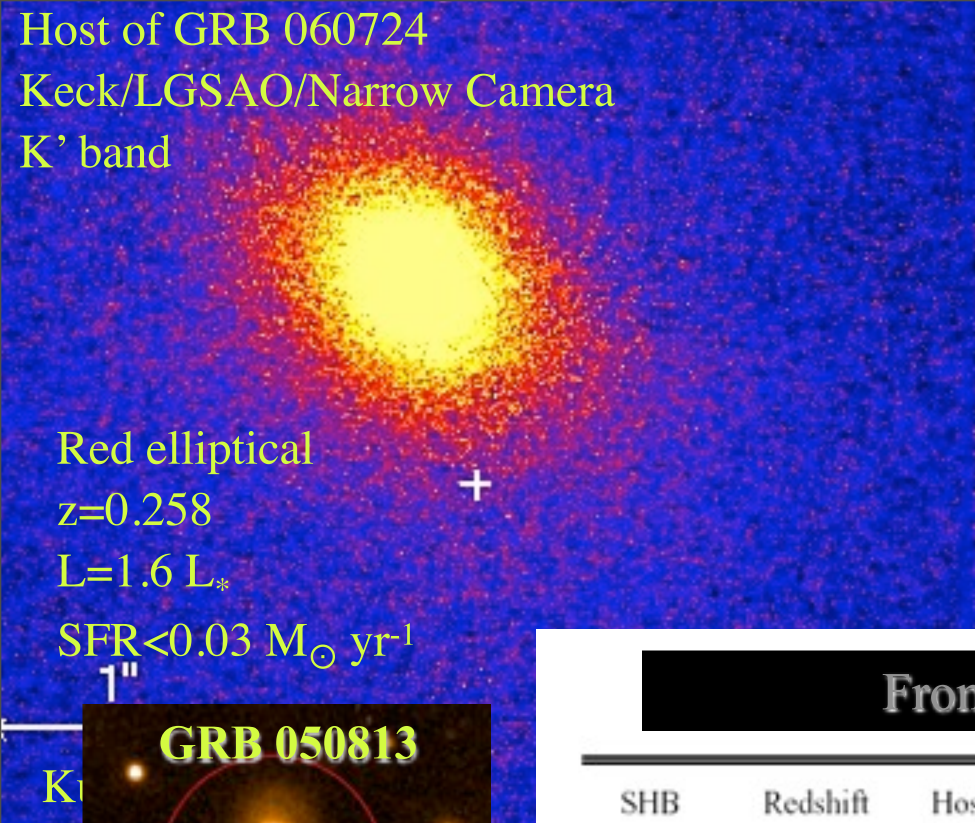

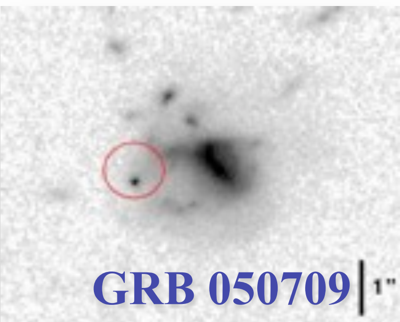

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letters to nature

Nature **340**, 126 - 128 (13 July 1989); doi:10.1038/340126a0

Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

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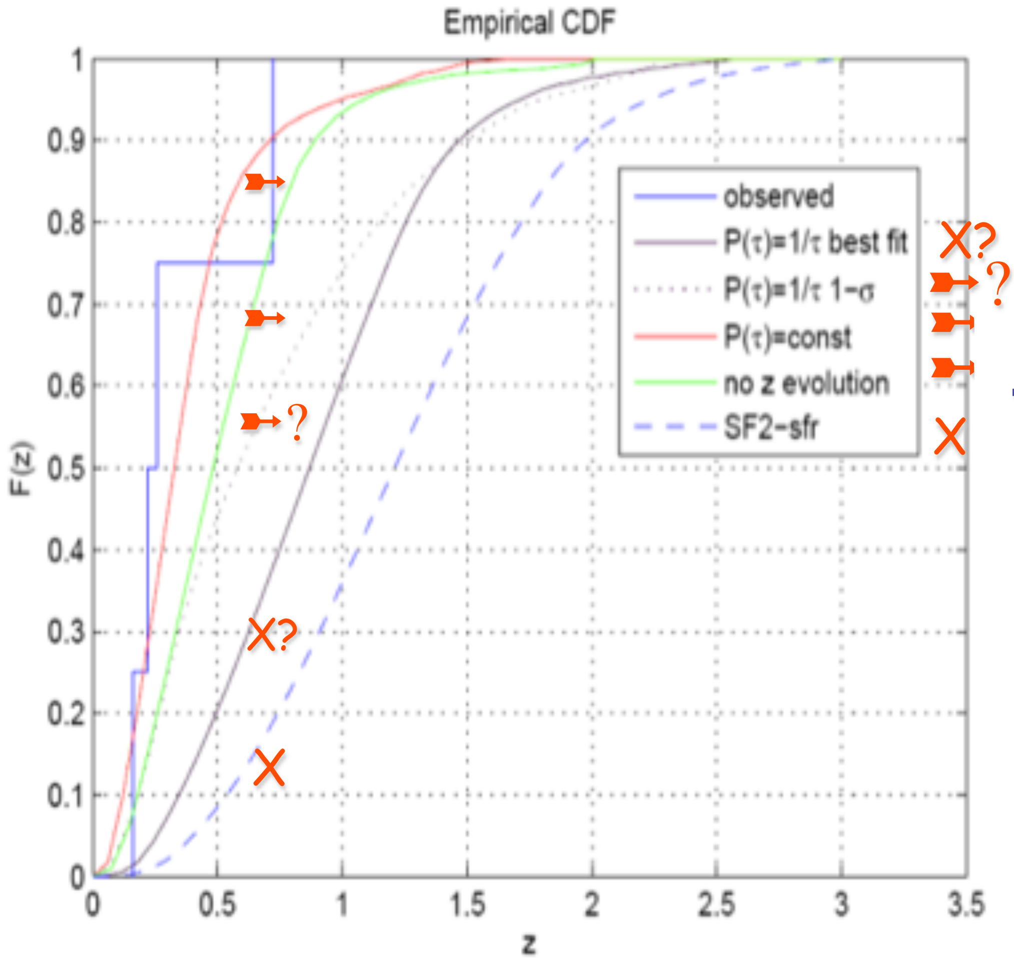
[*]Department of Physics, Ben Gurion University, Beer Sheva, Israel, and Astronomy Program, University of Maryland, College Park, Maryland 20742, USA
[†]Department of Physics, The Technion, Haifa, Israel
[‡]Racah Institute for Physics, Hebrew University, Jerusalem, Israel, and Princeton University Observatory, Princeton, New Jersey 08544, USA
[§]Departments of Physics and Astrophysics, University of Chicago, 5640 Ellis Avenue, Chicago, Illinois 60637, USA, and NASA/Fermilab Astrophysics Center, Batavia, Illinois 60510, USA

NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

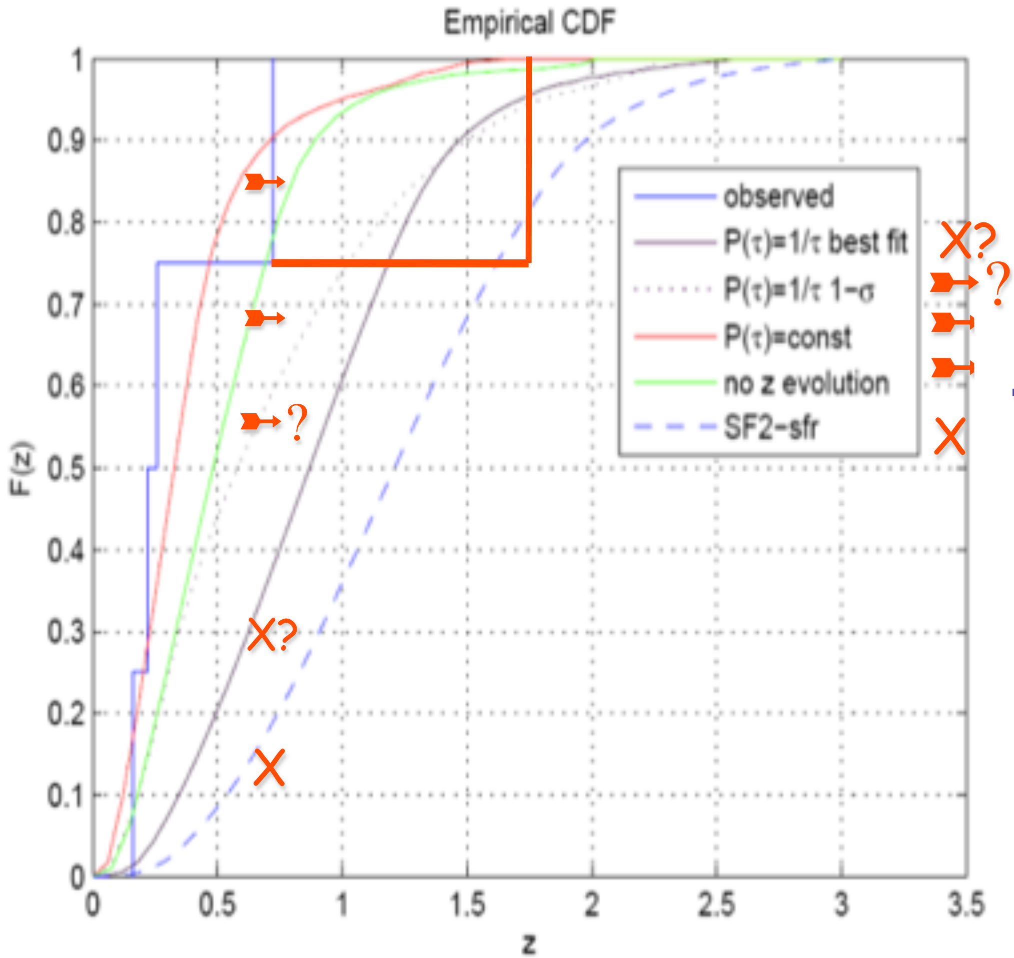
Short bursts (Guetta & Piran, 06)



GRB	050509b	050709	050724	0508132
z	0.22	0.16	0.257	0.722
$L_{\gamma,iso}/10^{51}$erg/sec	0.14	1.1	0.17	1.9

Table 1. The Swift/HETE II current sample of SHBs with a known redshift

Don't follow the SFR – There are more nearby (late) bursts – and time delay after SFR



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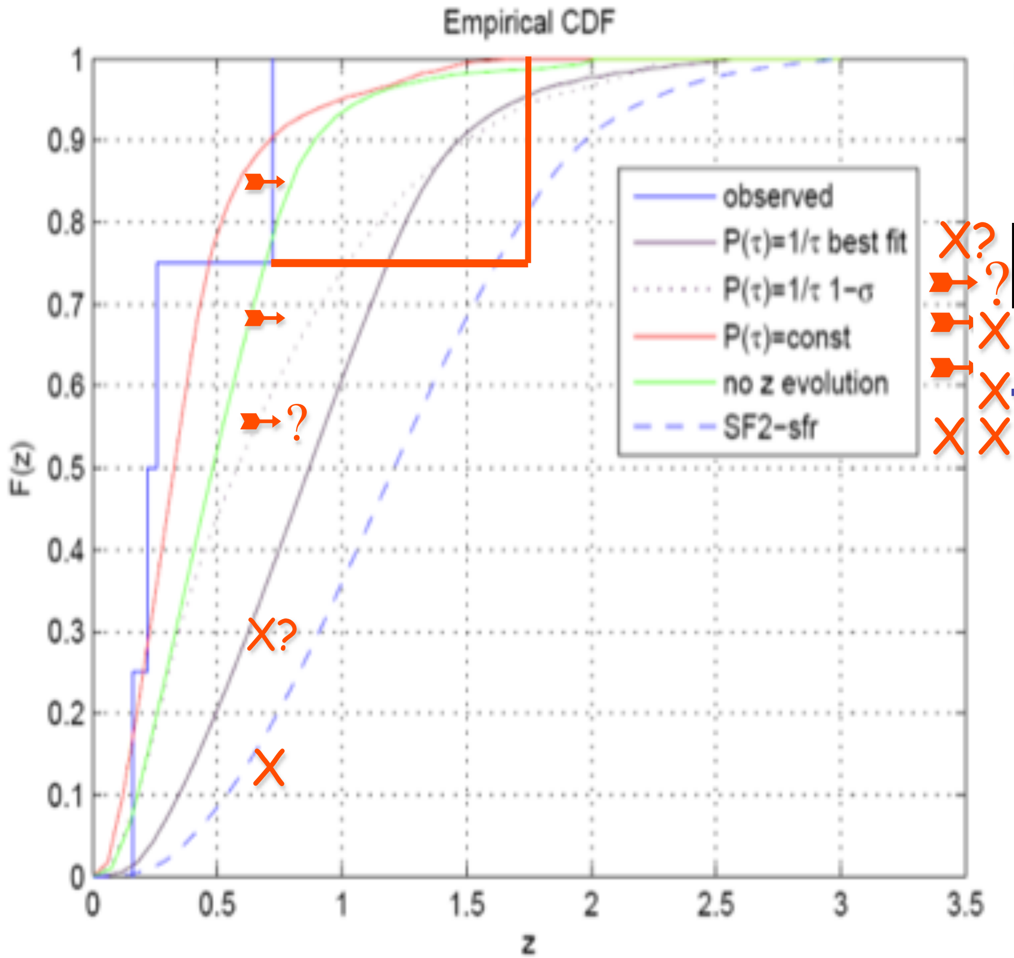

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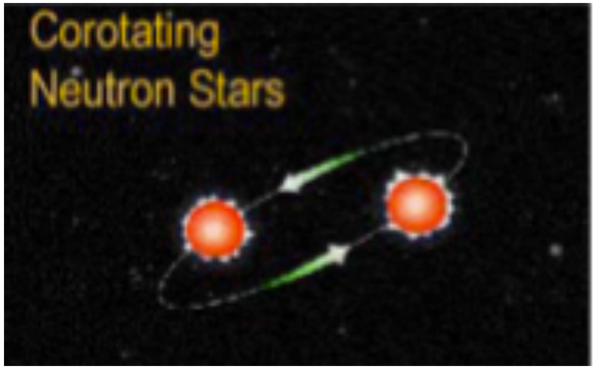
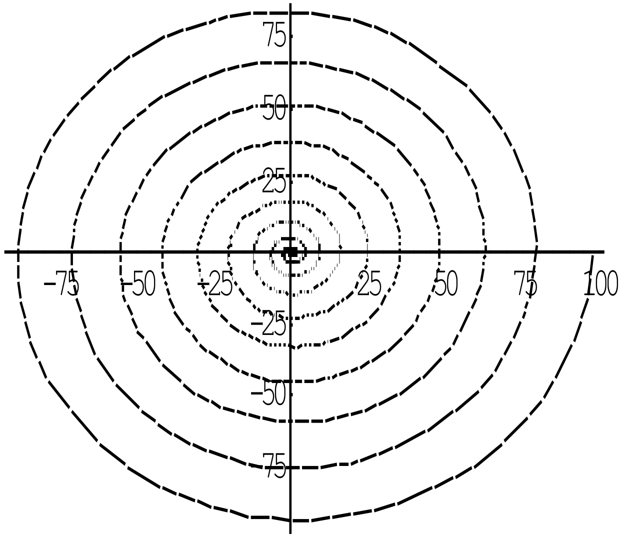
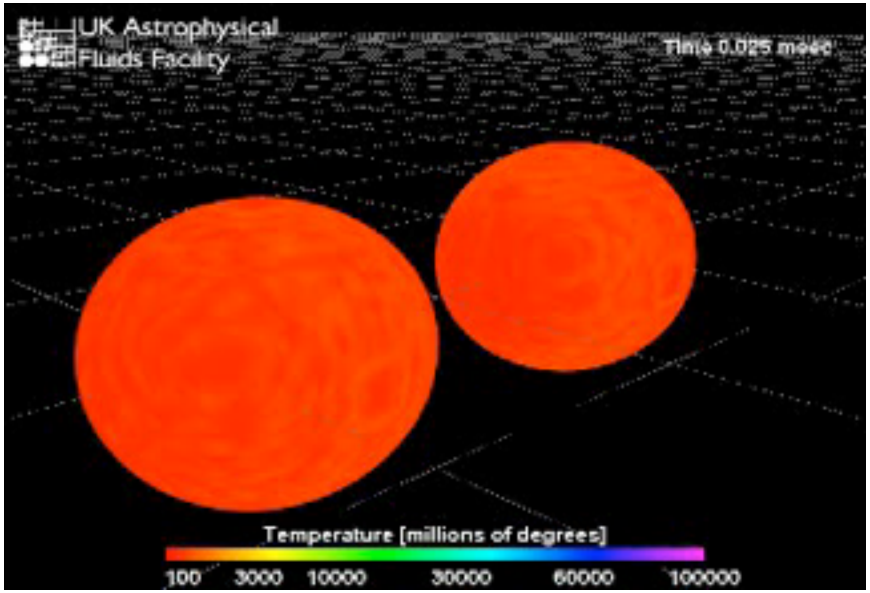


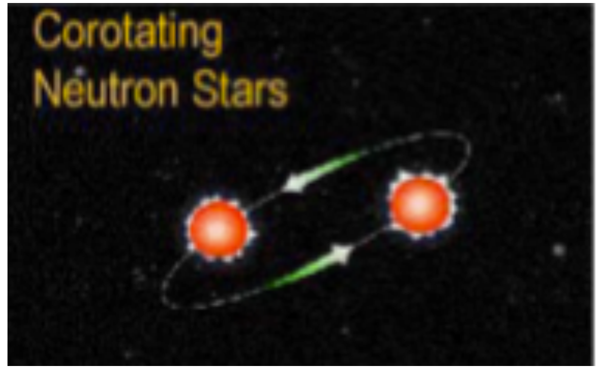


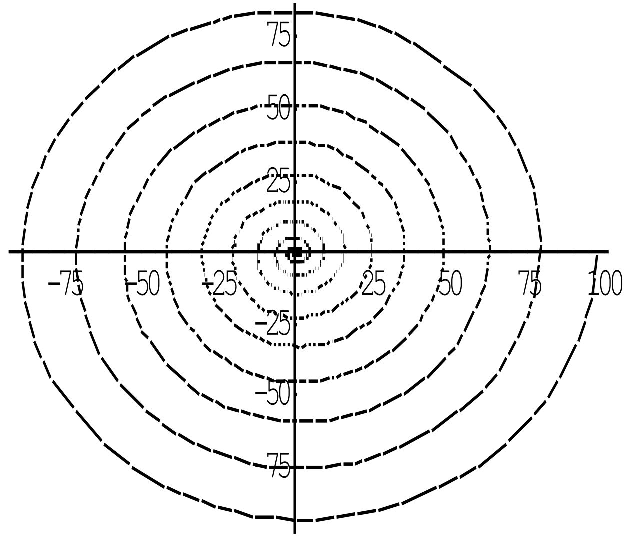
$$\tau \propto a^4$$

$$p(\tau)d\tau \propto p(a)da\frac{d\tau}{da} \propto \frac{1}{a}\frac{1}{a^3} \propto \frac{1}{\tau}$$

- **Within the context of NS mergers expect p(τ) ∝1/τ (TP 92)**







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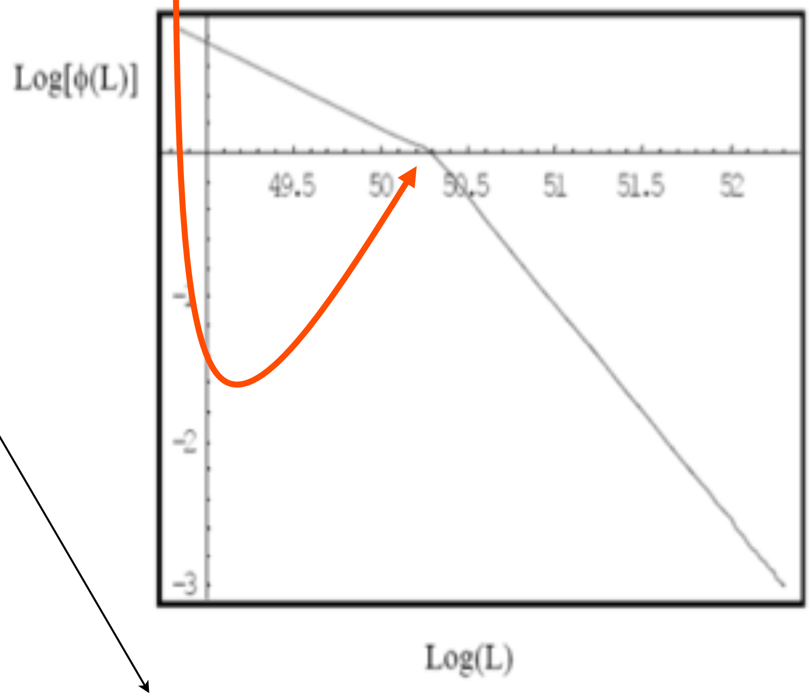
Luminosity function and Rates of short GRBs

~10 /Gpc^3/yr ⇔
80 mergers /Myr Galaxy*

*Assuming a beaming factor of 30

L*~2 10^{50}erg/sec



8×10^{-5} yr^{-1} MWG

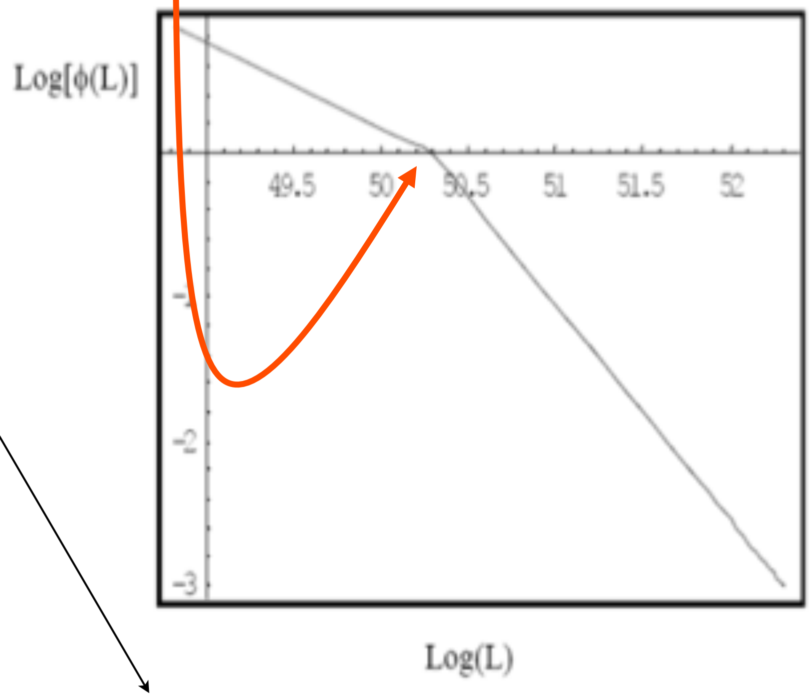
Luminosity function and Rates of short GRBs

~10 /Gpc^3/yr ⇔ 80 mergers /Myr Galaxy*

*Assuming a beaming factor of 30

Comparable to the estimated rate of mergers

$L^* \sim 2\ 10^{50}$ erg/sec

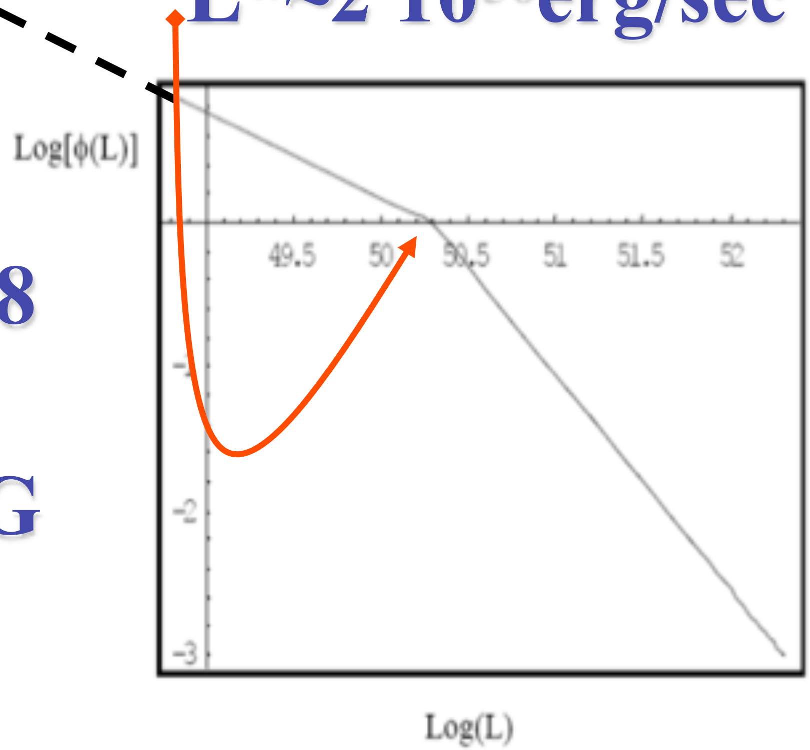


8×10^{-5} yr^{-1} MWG

Luminosity function and Rates

Weakly constrained by current detectors

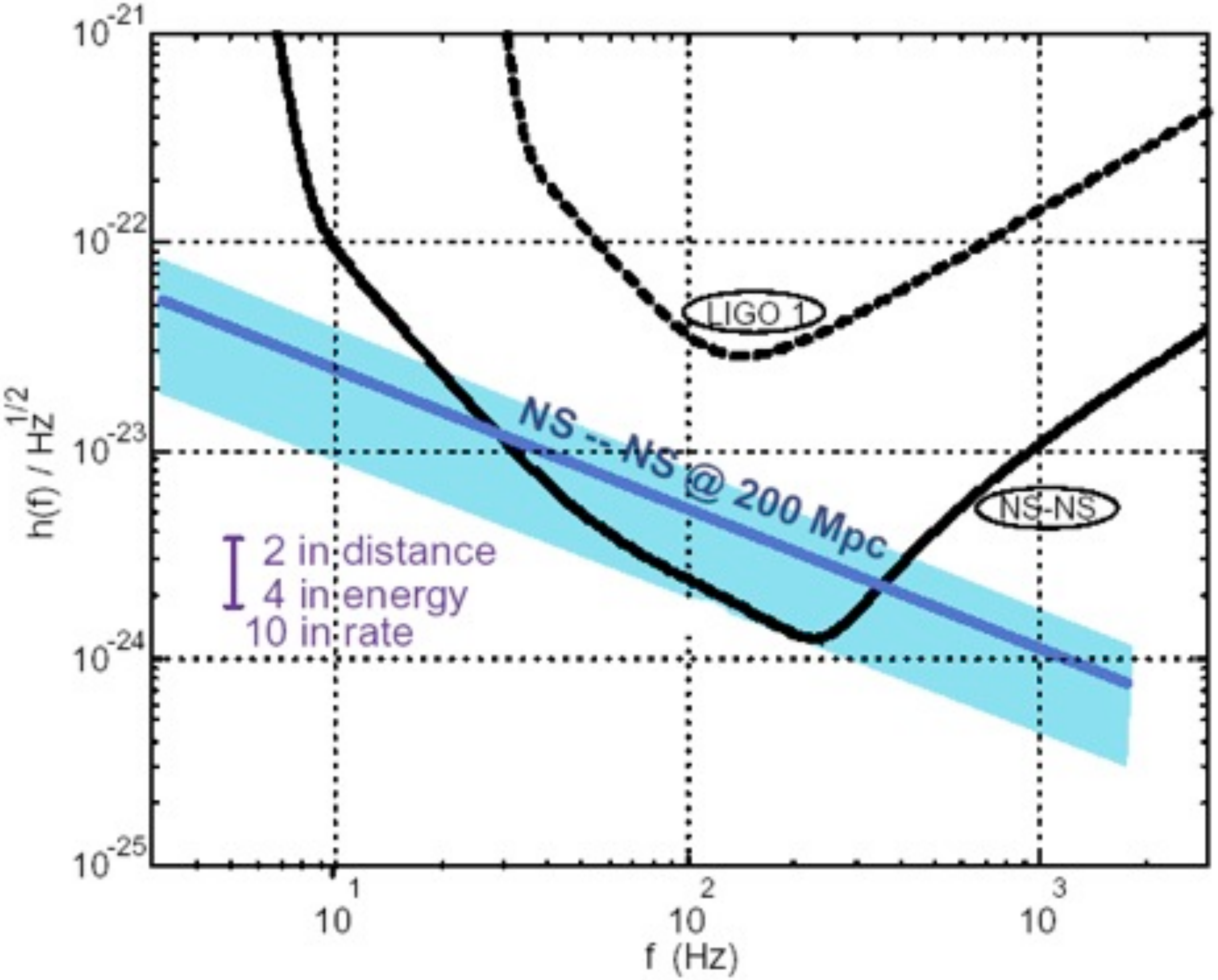
$L^* \sim 2\ 10^{50}$erg/sec



$\sim 10^4$ /Gpc^3/yr ⇔ 8 $\times 10^4$ mergers /Myr Galaxy 0.08 yr^{-1} MWG

Nakar, Gal-Yam, Fox 05,

See also Tanvir 05

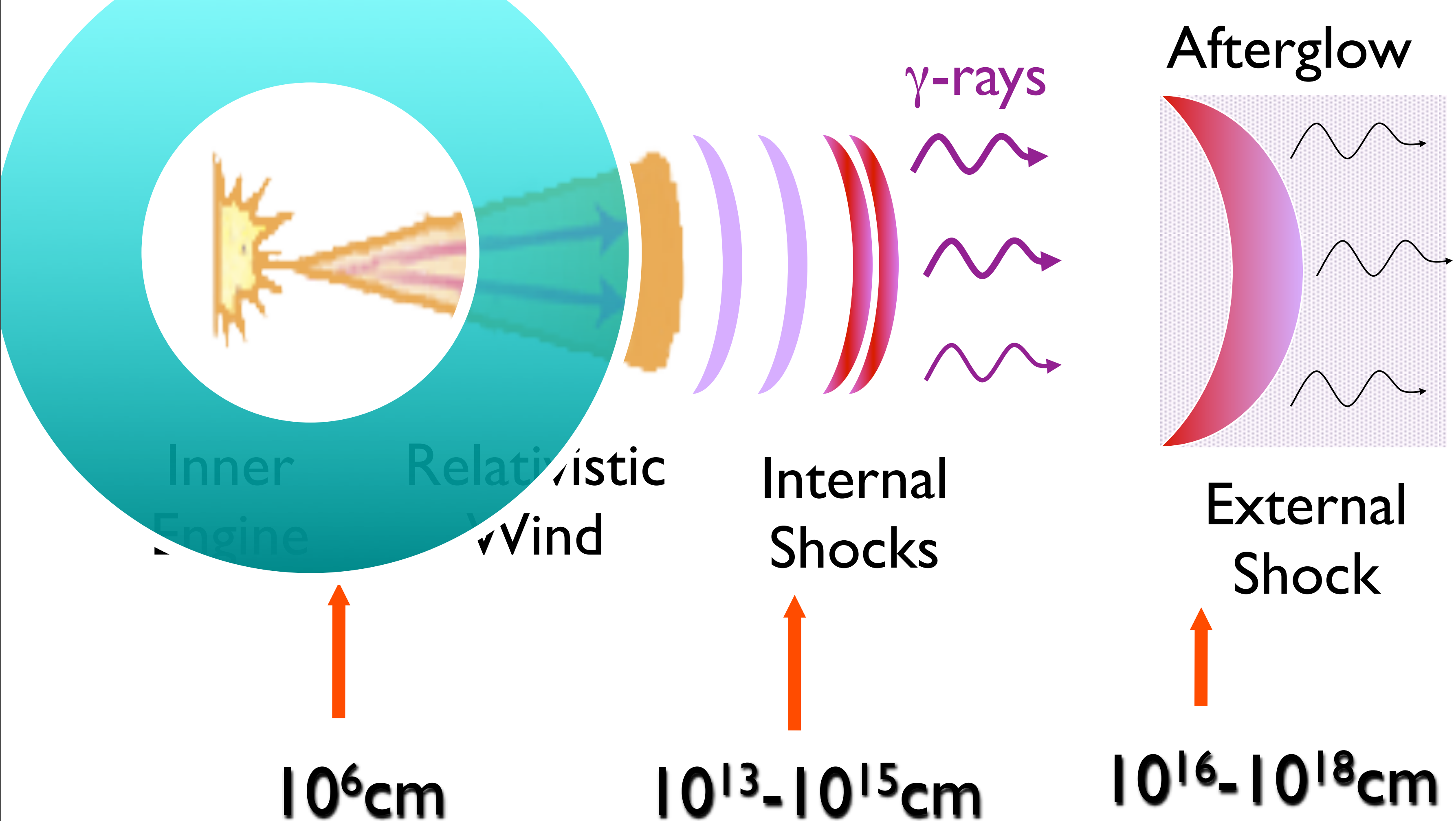


80 Myr/Galaxy ⇒20 (0.5) events/yr within 200Mpc

10^5 Myr/Galaxy ⇒20 (1) events/yr within 40Mpc

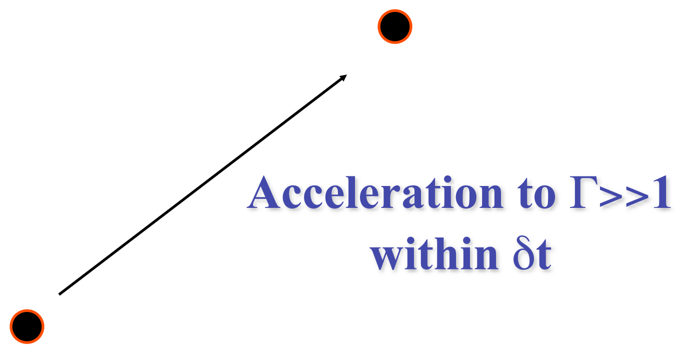
1 out of 30 in coincidence with a (short) GRB!

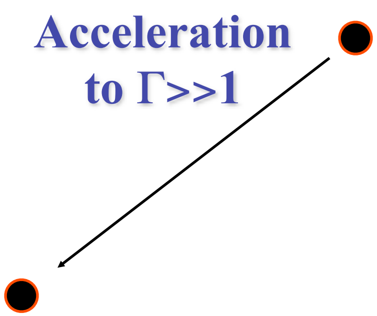
Internal - External Shocks



Gravitational Radiation from jet acceleration?

Regardless of the nature of the "inner engine" the fireball model predicts gravitational radiation from the acceleration of ~10^{51}ergs to relativistic velocity (Piran, 00, Segalis & Ori, 2001; Sago, Ioka, Nakamura, Yamazaki, 2004).





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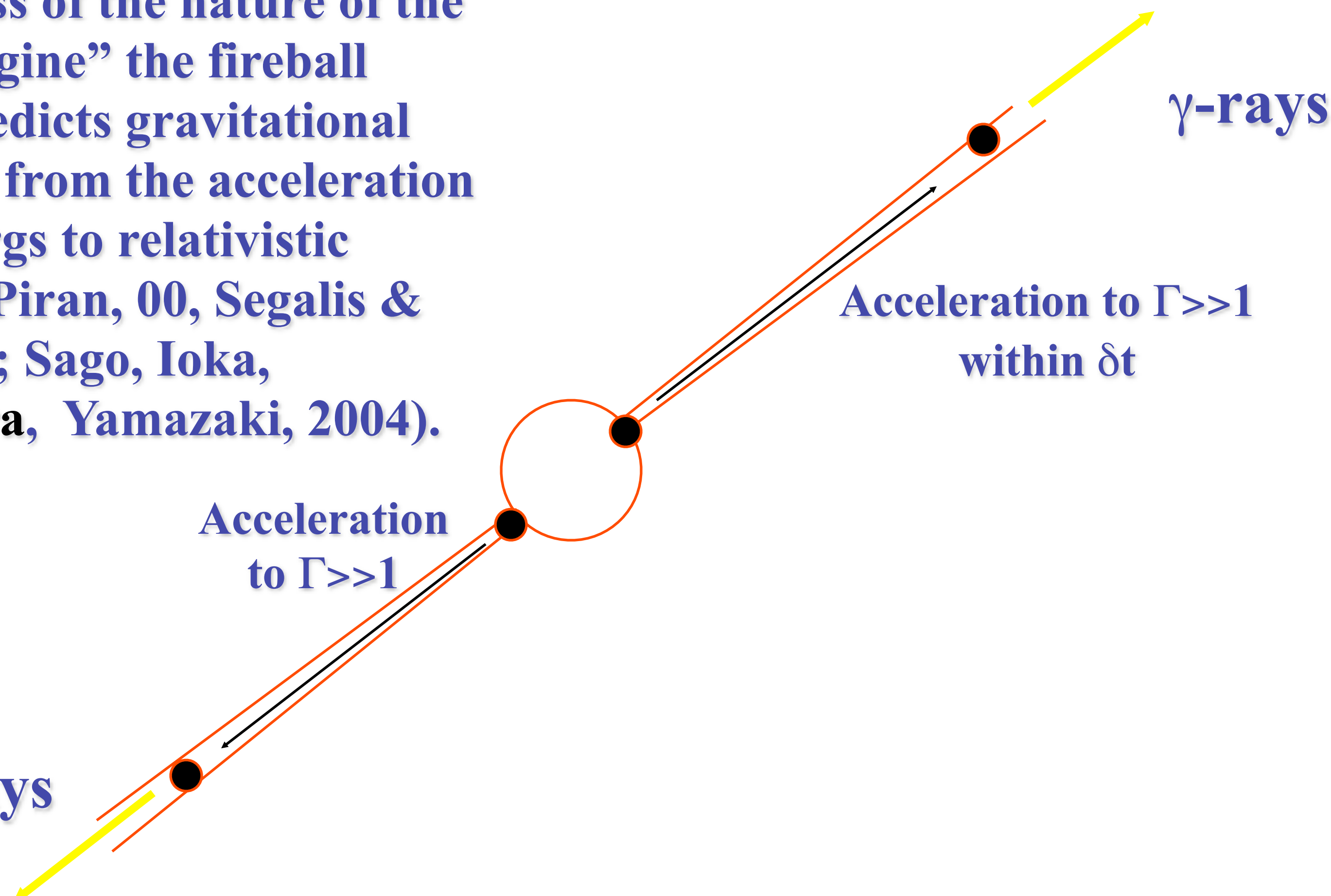
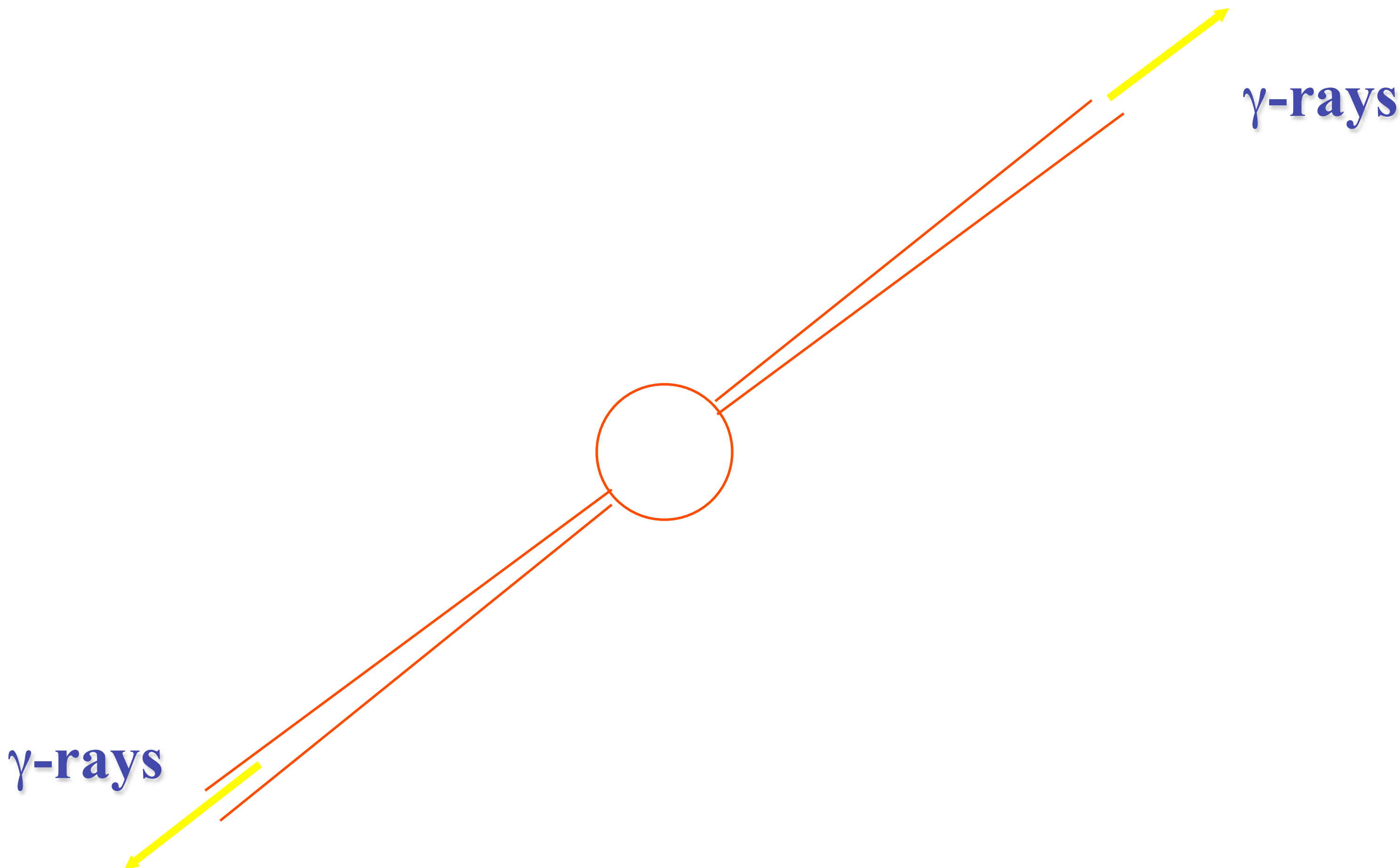
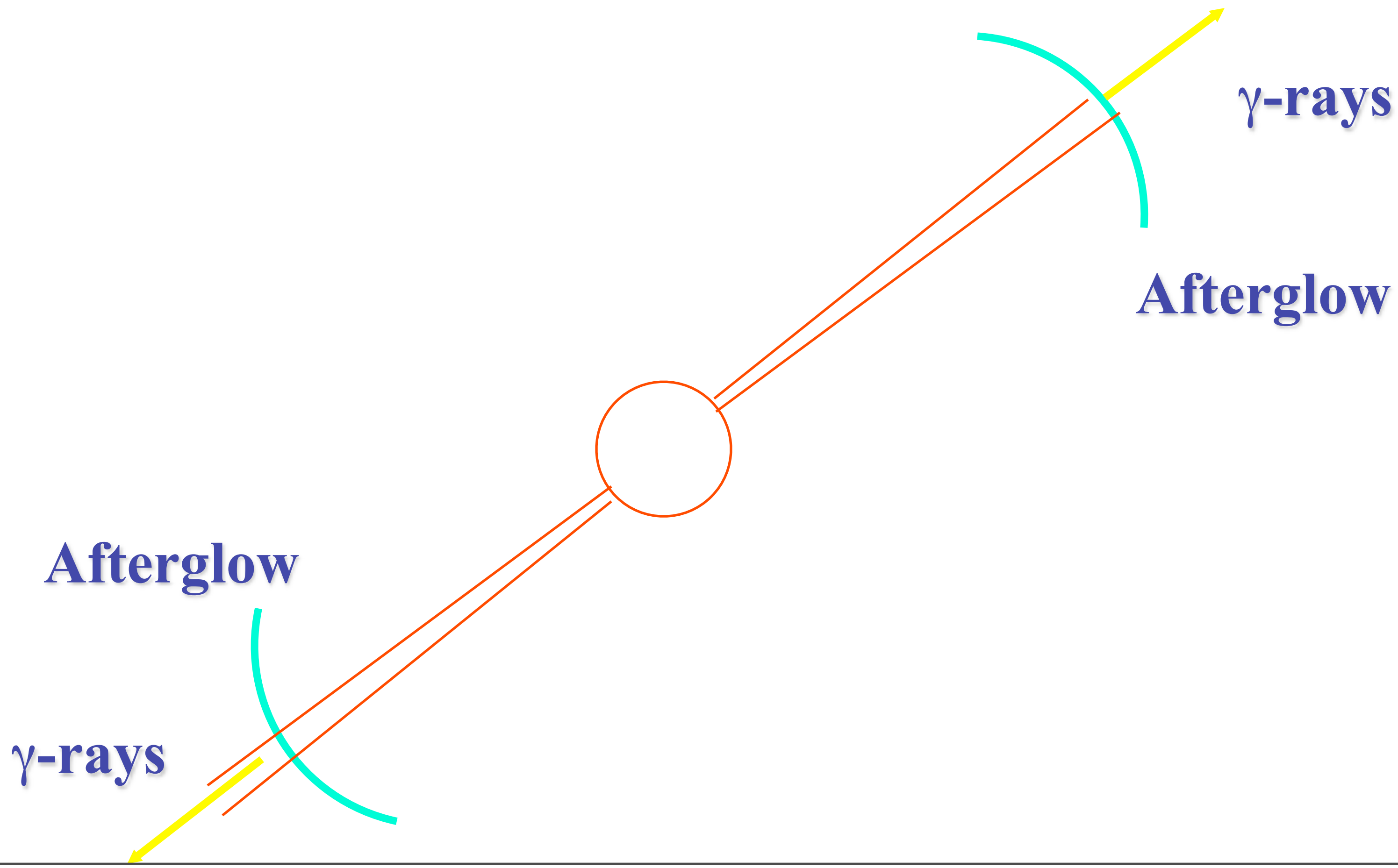
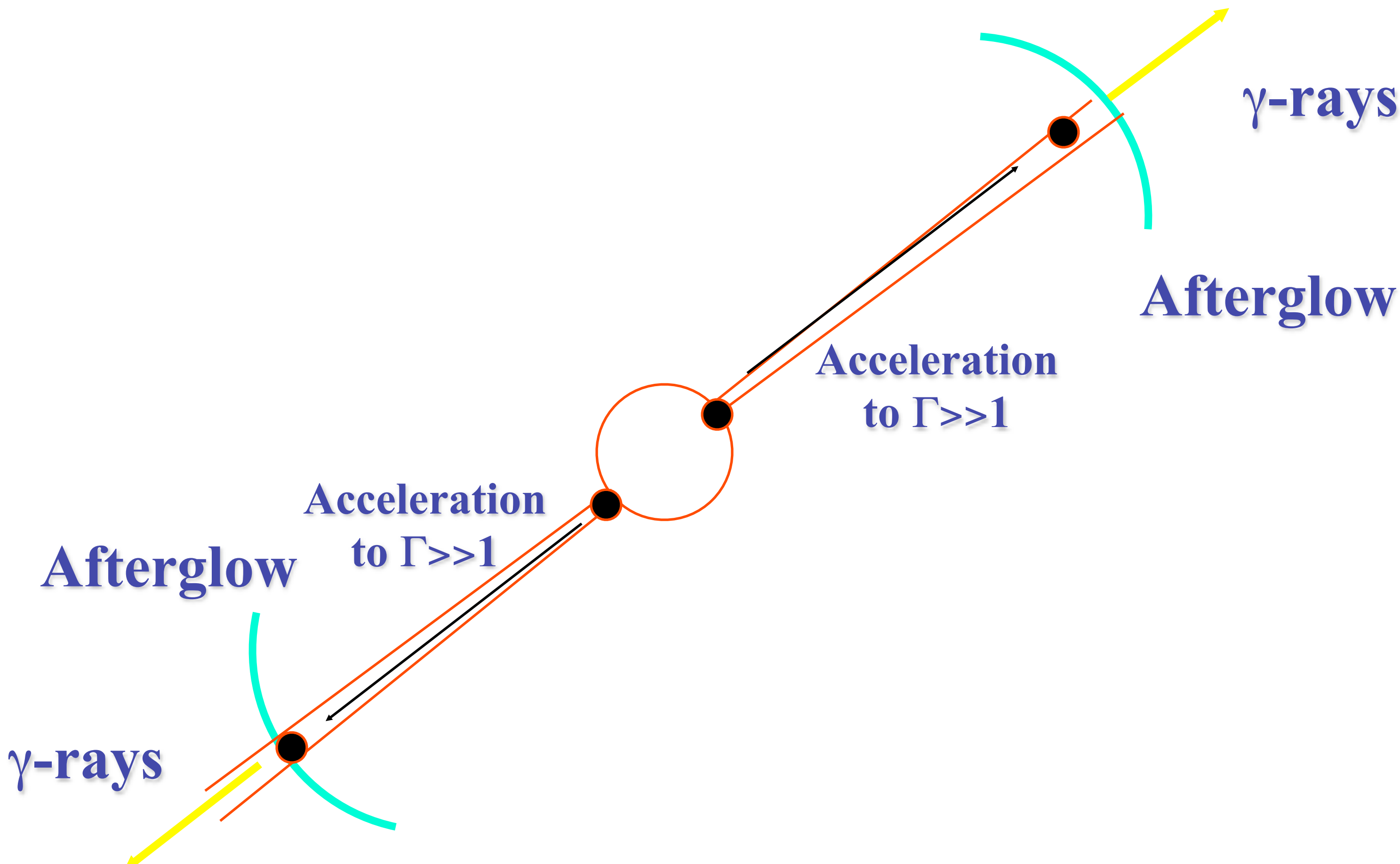
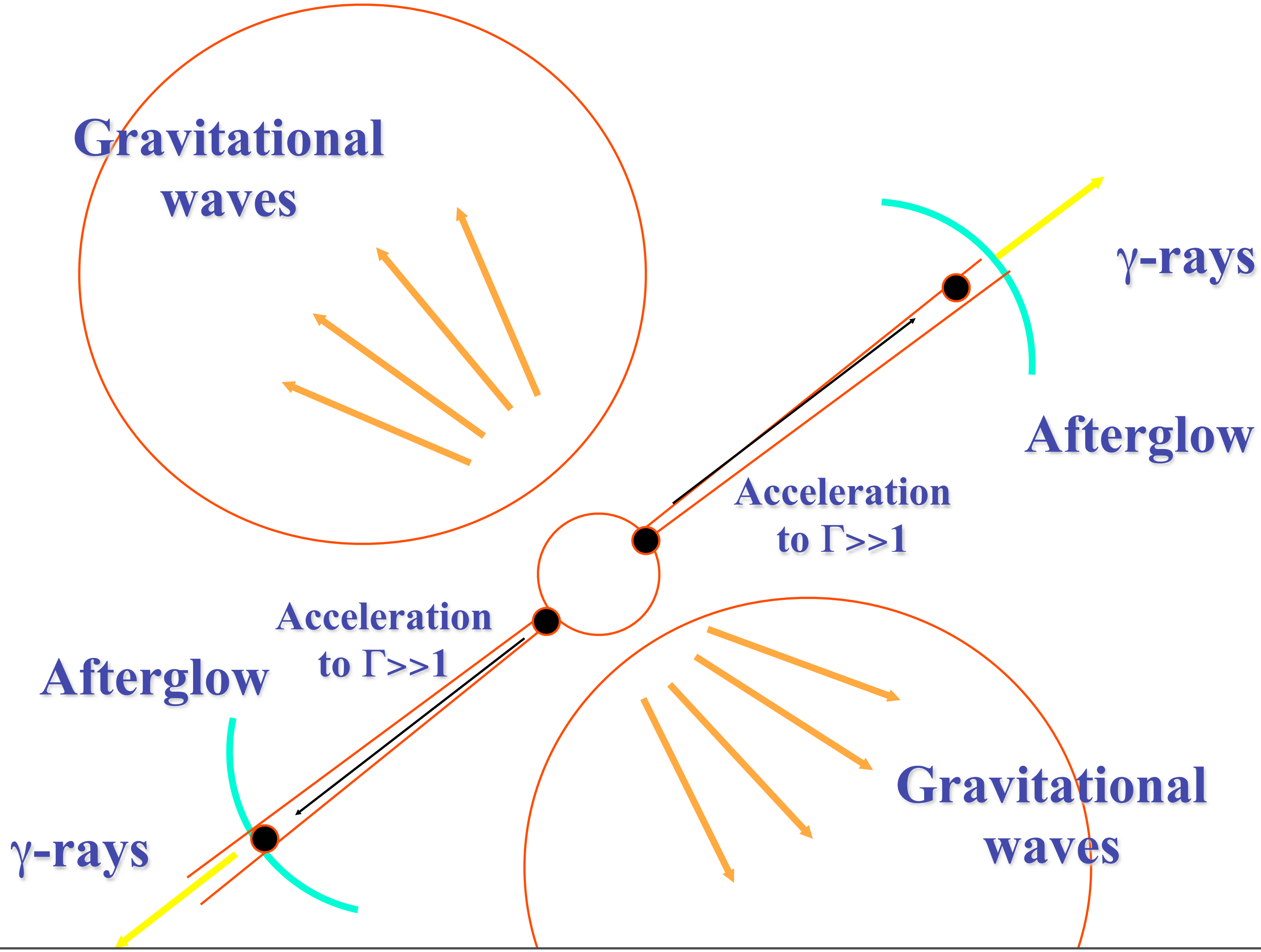


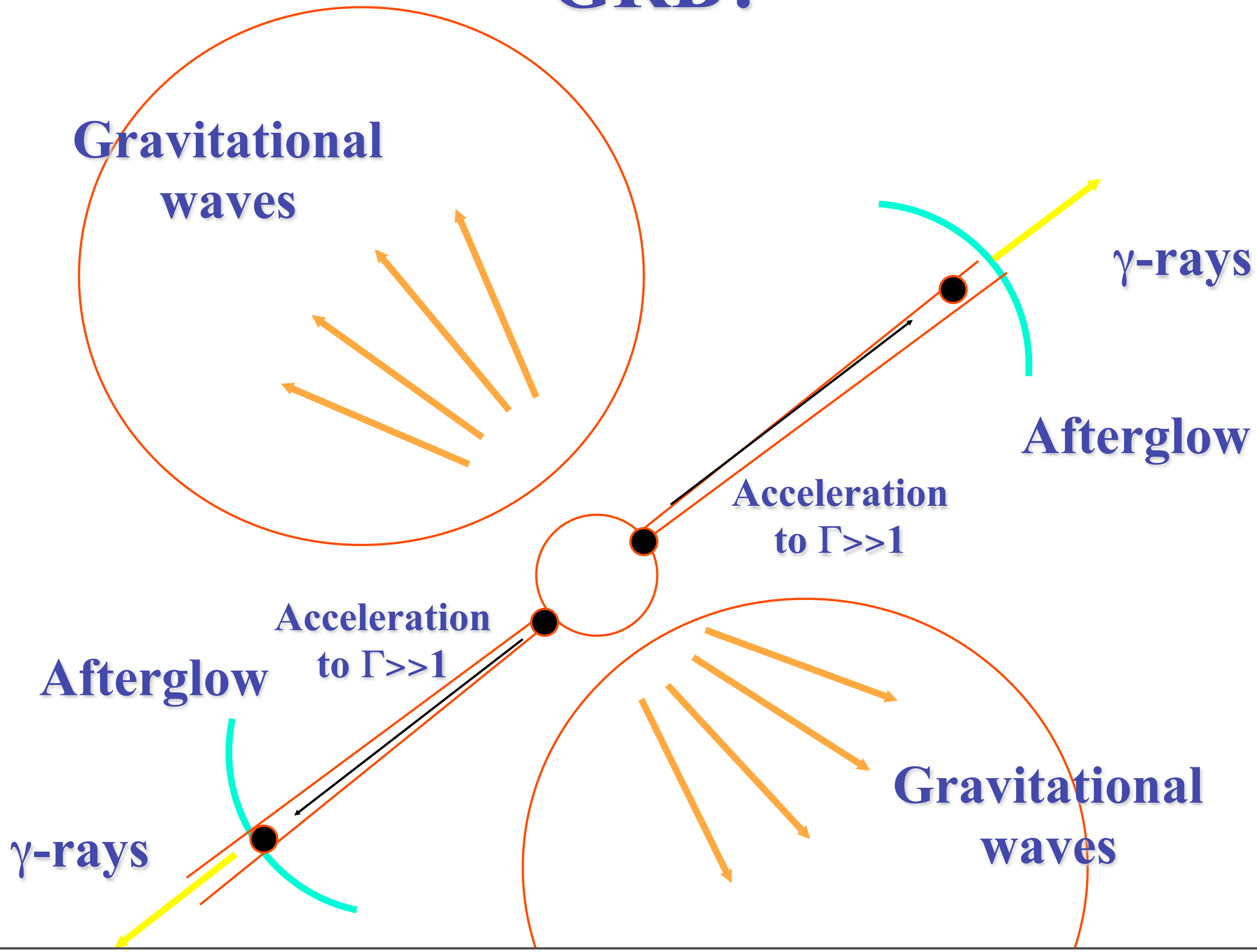

γ-rays
γ-rays


γ-rays
Afterglow
Afterglow
γ-rays

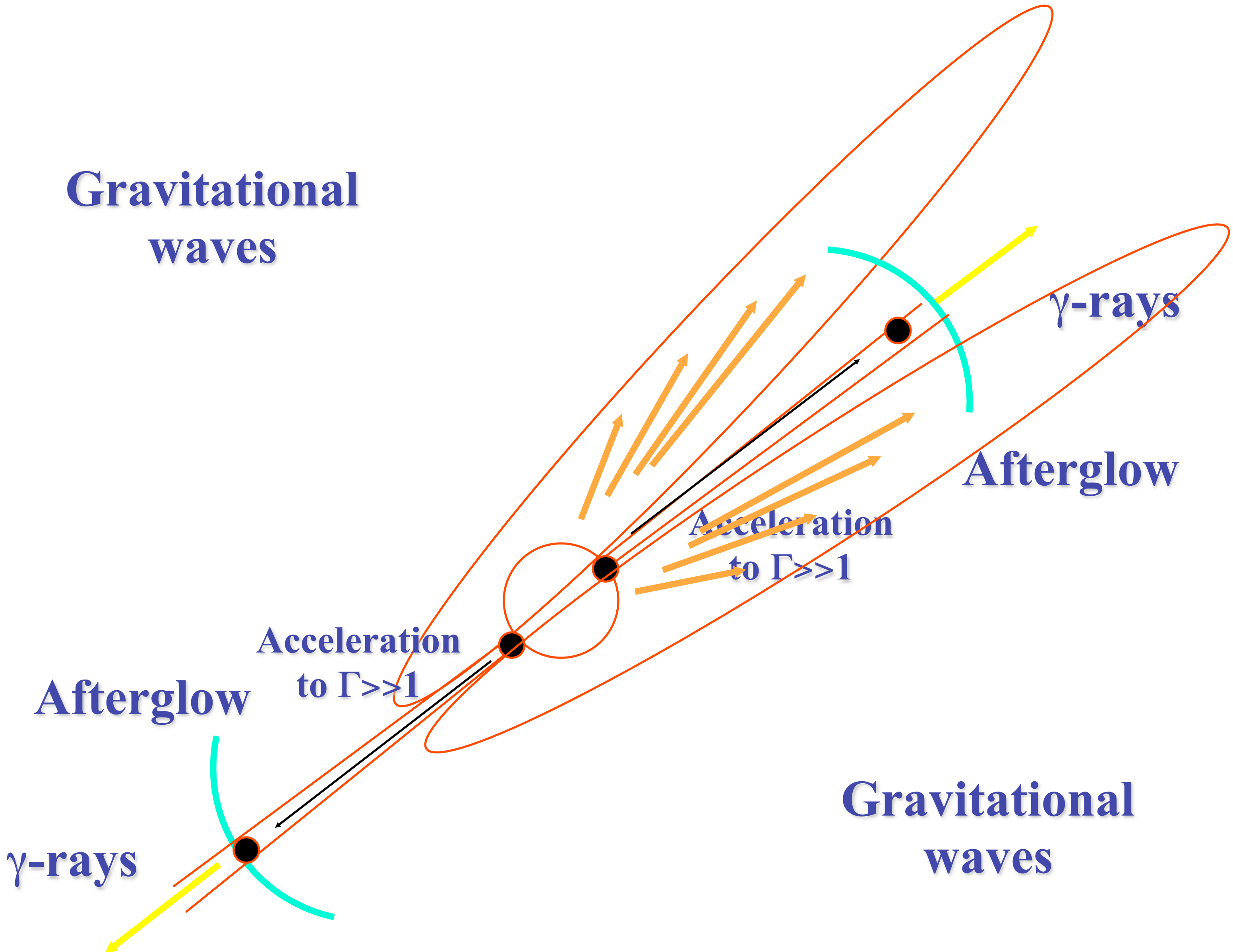

γ-rays
Afterglow
Acceleration
to Γ>>1
Acceleration
to Γ>>1
Afterglow
γ-rays


Gravitational
waves
γ-rays
Afterglow
Acceleration
to Γ>>1
Acceleration
to Γ>>1
Afterglow
γ-rays
Gravitational
waves

No Coincidence between this Gravitational Radiation and the GRB?



Slightly better



Beaming & Anti-Beaming

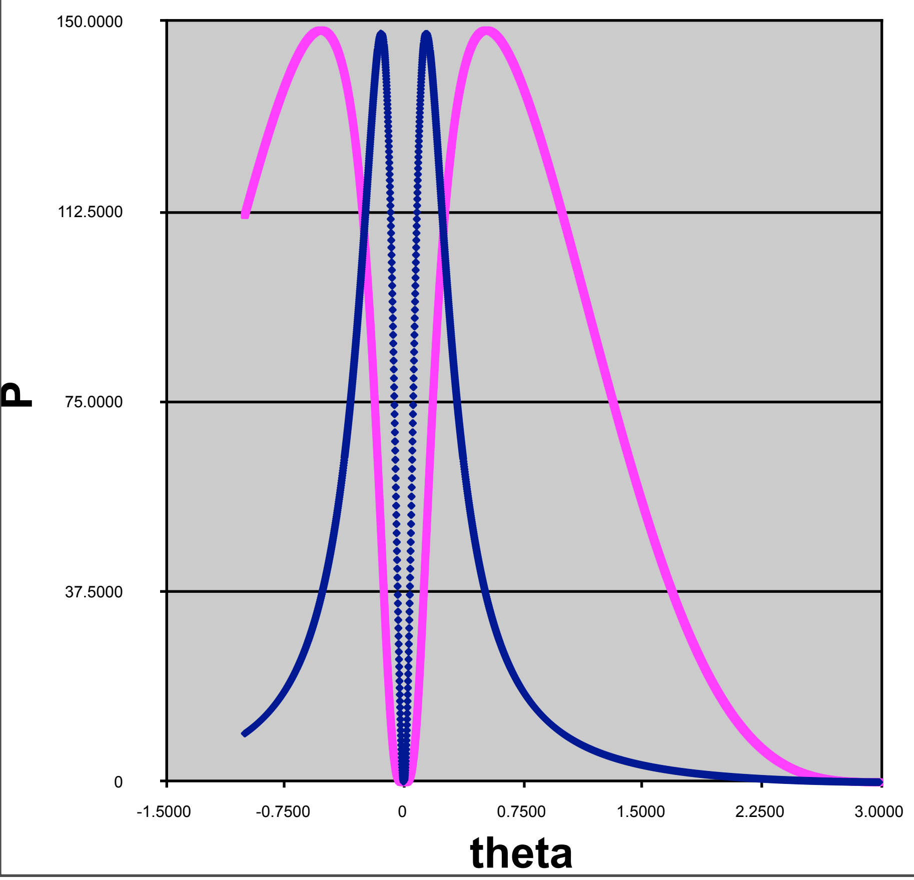
- The angular distribution of radiation from an accelerating source is set by two effects:
  - In the source's rest-frame, emission is perpendicular to the acceleration direction –no radiation in the forward direction
  - Passing from the CMRF to an observer frame, the emission is relativistically Lorentz contracted in the forward direction, by a factor of Γ

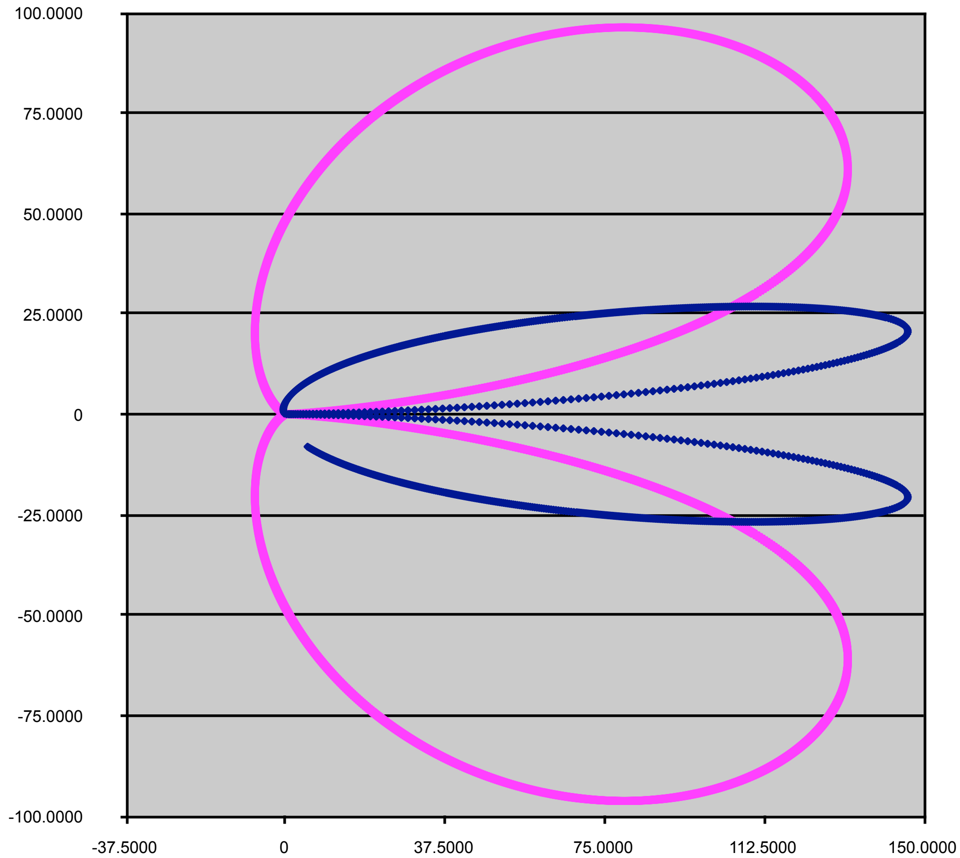
Credit: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

- These two effects are competing:
  - For EM dipole radiation ($\sim \sin^2\theta$), the result is "Beaming" into a solid angle $\theta \sim \Gamma^{-1}$ of width $\sim \Gamma^{-1}$, forward
  - For GW quadropole radiation ($\sim \sin^4\theta$), the result is "Anti-Beaming": almost uniform distribution except for a beam of width $\theta \sim \Gamma^{-1/2}$ forward (Maggiore, 2007)
- This suggests looking for regions of joint detectability

Beaming (EM) & Anti-Beaming (GW) A Region of Joint-Detectability

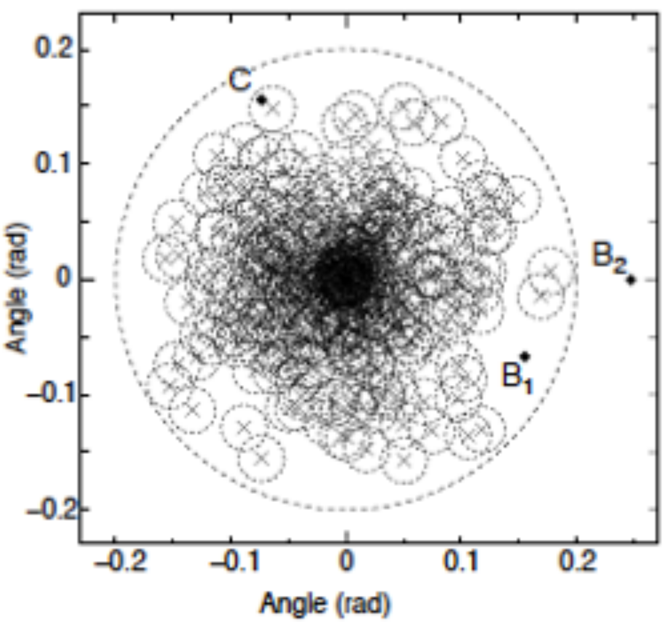
- **Electromagnetic Radiation**
- **Gravitational Radiation**

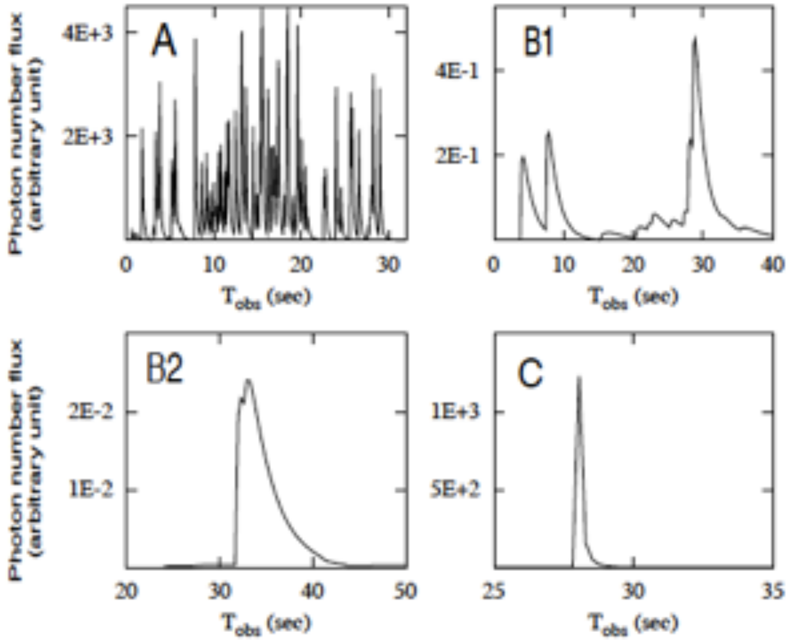


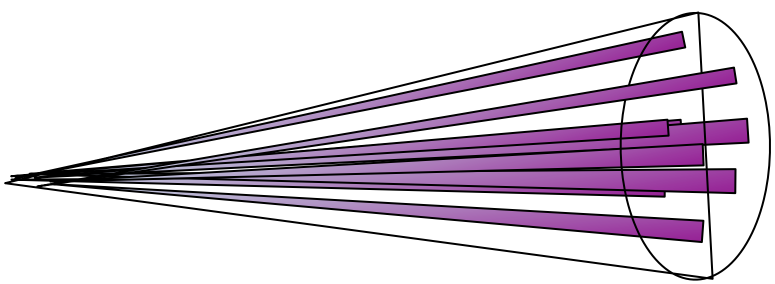


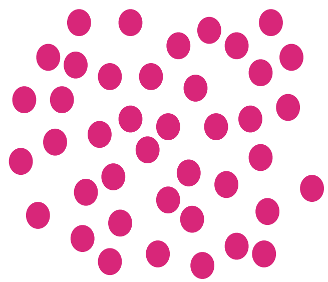
The sub jet model

Nakamura, 2000, Yamazaki, Ioka, Nakamura, 2002



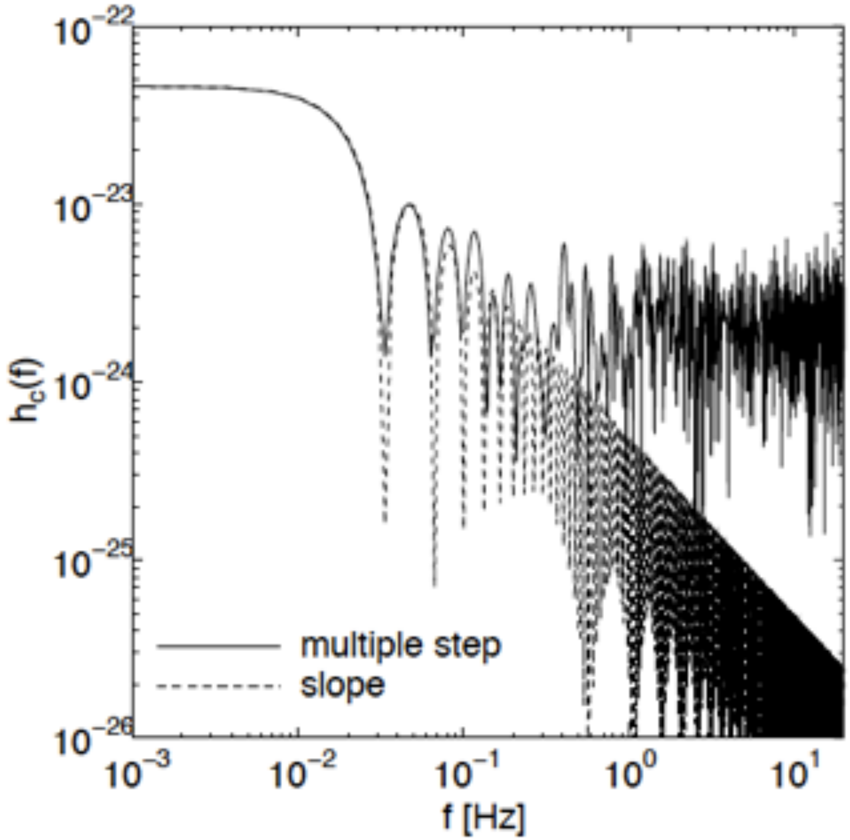




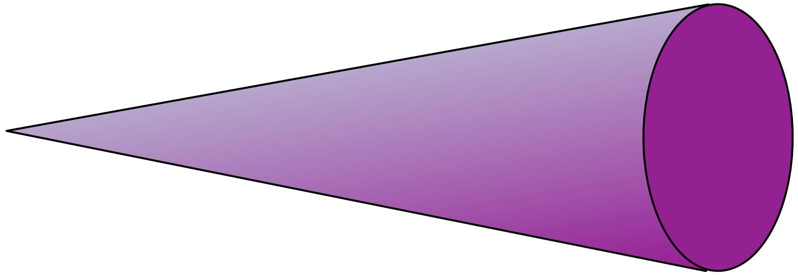


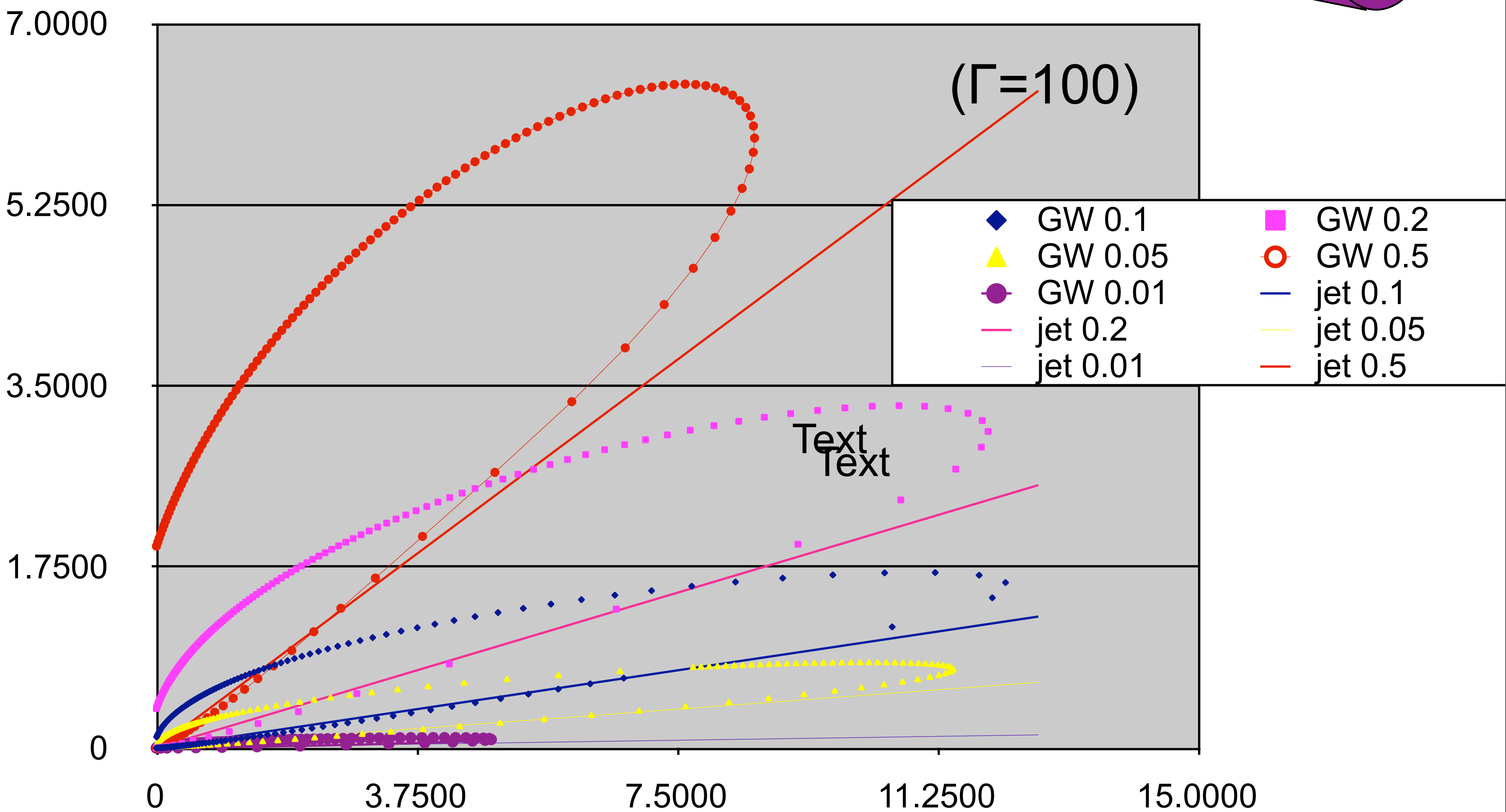
Gravitational Radiation emission in the subjet model

Sago, Ioka, Nakamura, Yamazaki, 2004

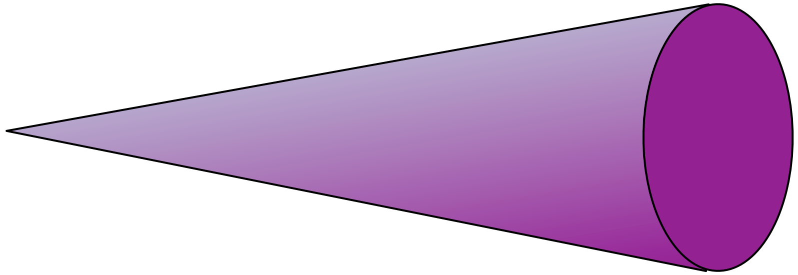


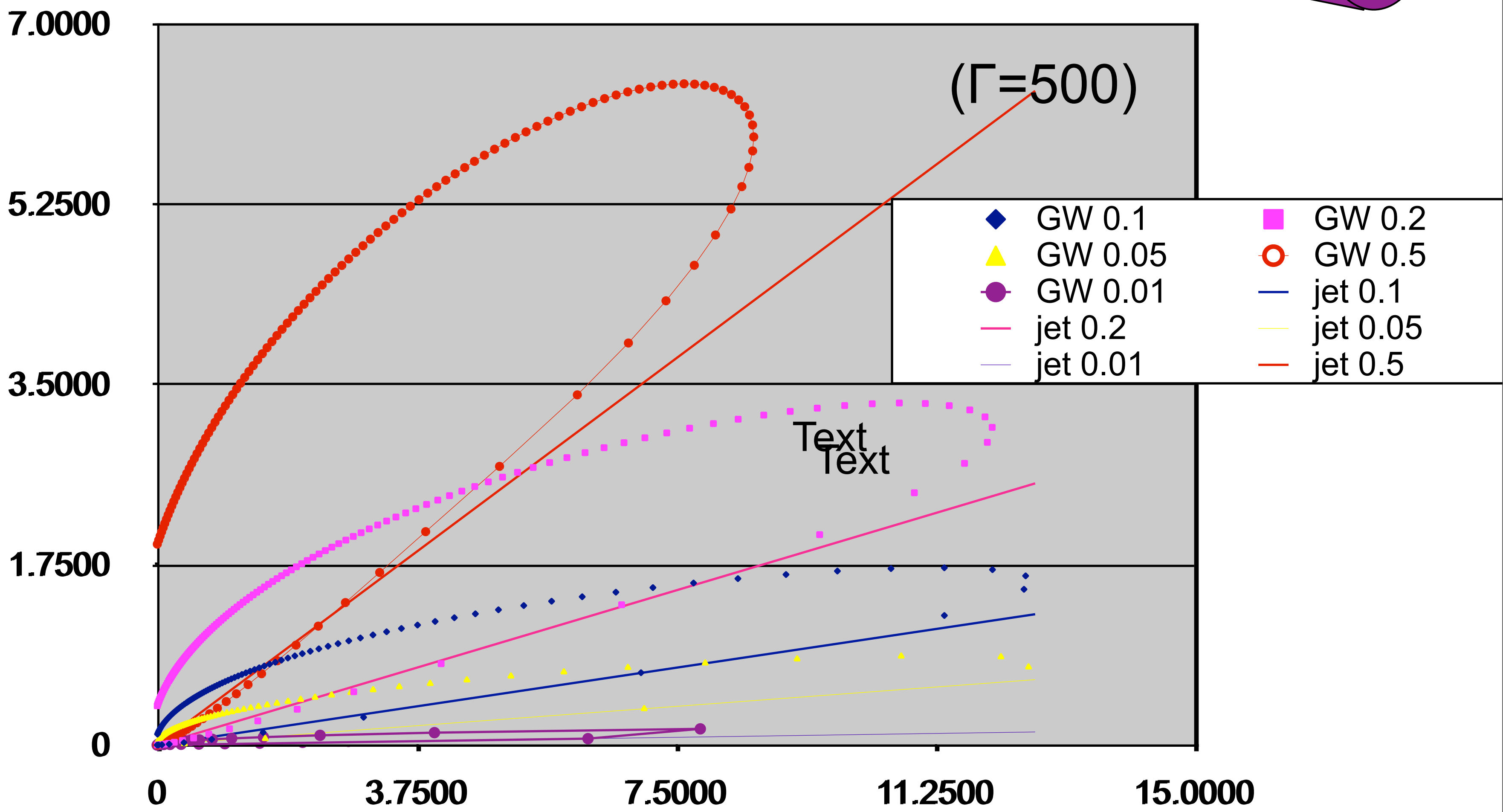
Uniform Jets



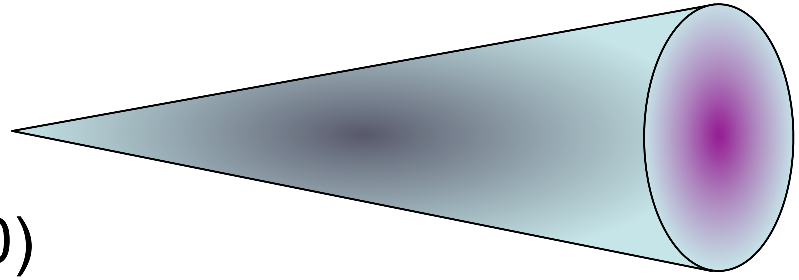


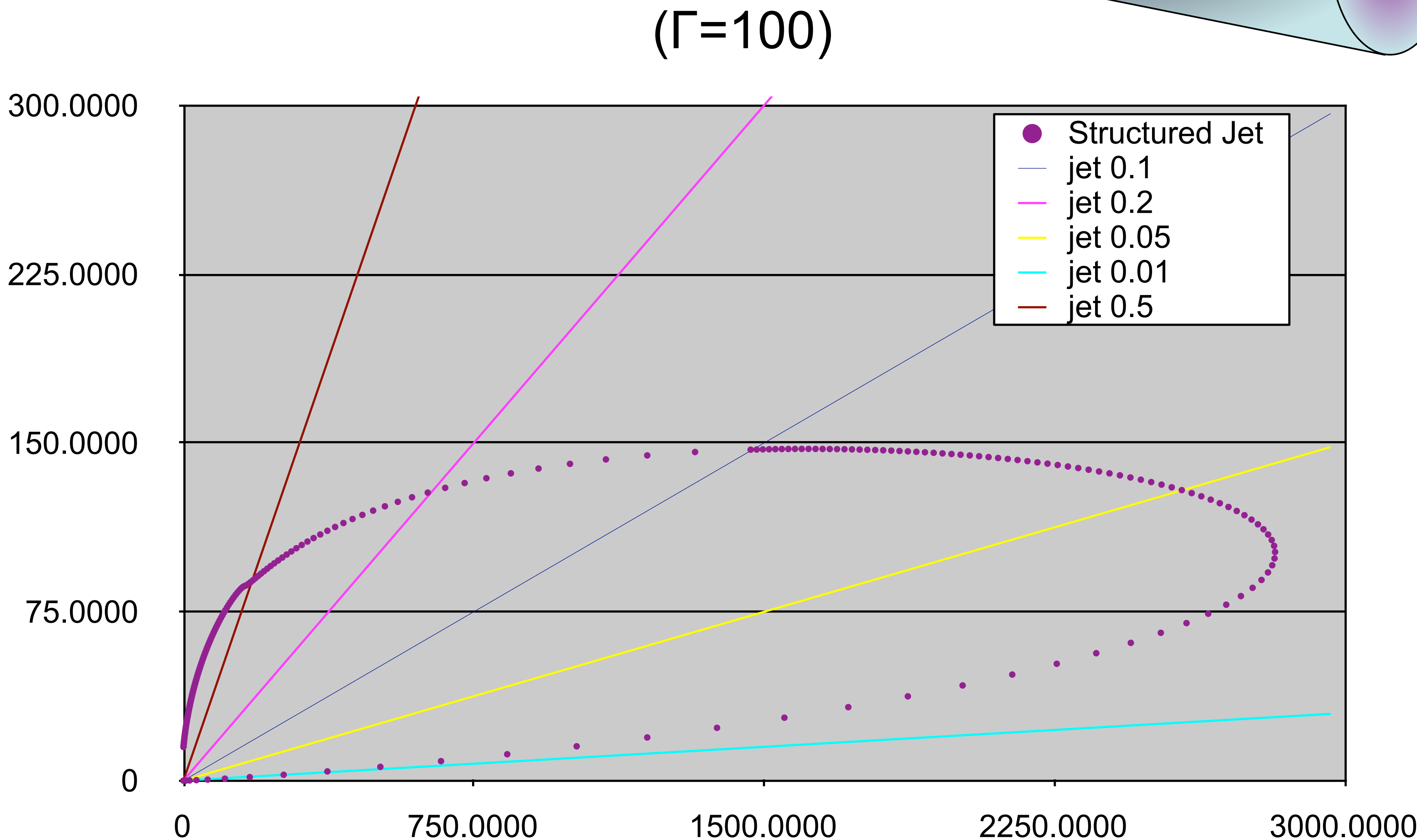
Uniform Jets





Structured Jets

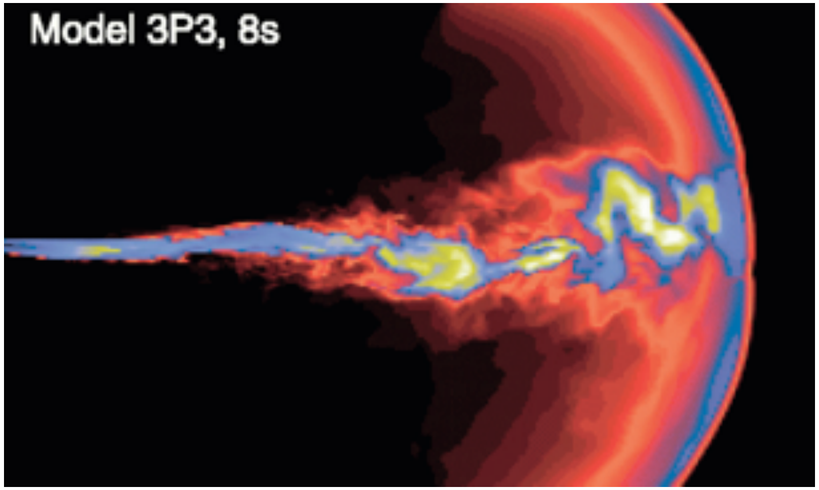


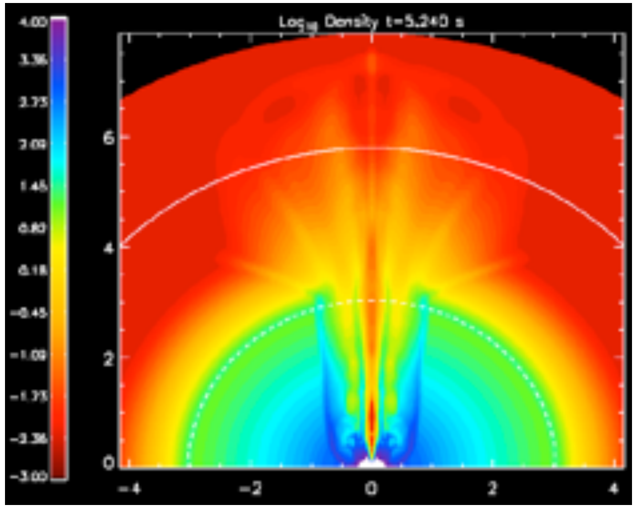


Structured Jet

- "Anti-Beaming" arises from the $\sin^2\theta$ term in the signal amplitude due to its quadrupole type ($\sin^4\theta$ in energy)
- But at low θ the structured jet's intensity $\propto\theta^{-2}$ and these terms cancel.
- $\Rightarrow$Lorentz beaming along the central jet axis.
- The peak is effectively determined by the cutoff core angle, Γ^{-1} the GW can be detected all the way down to $O(\Gamma^{-1})$ of the central axis.
- $E=2\pi/\delta t*(G/4c\pi^2)*(m^2\gamma^2\beta^4)*\int(\Delta h^{jet}(\theta^{obs}))^2=(G/c\delta t)(m^2\gamma^2\beta^4)\int d\cos\theta(\Delta h^j(\theta))^2$ **$\sim 8*10^{41}(1*10^{42})$ erg**
- **The peak signal amplitude at r=500Mpc away is $h\sim 2Gm\gamma\beta^2/c^2r*\Delta h^j(max)\sim 10^{-25}$**

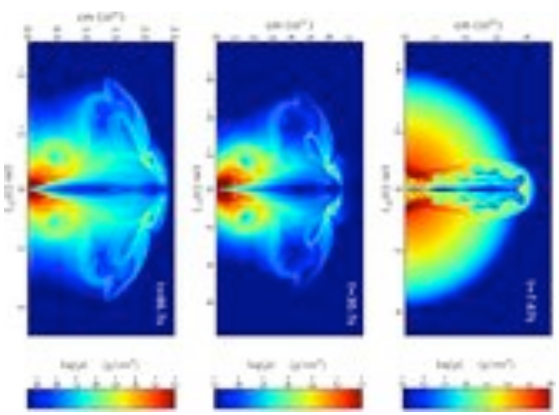
Jets and the Star

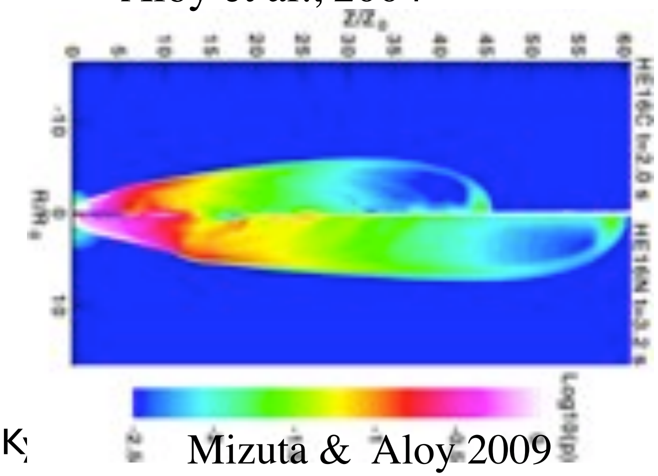




Zhang, Woosley & Heger, 2004; Zhang & MacFadyen 2008

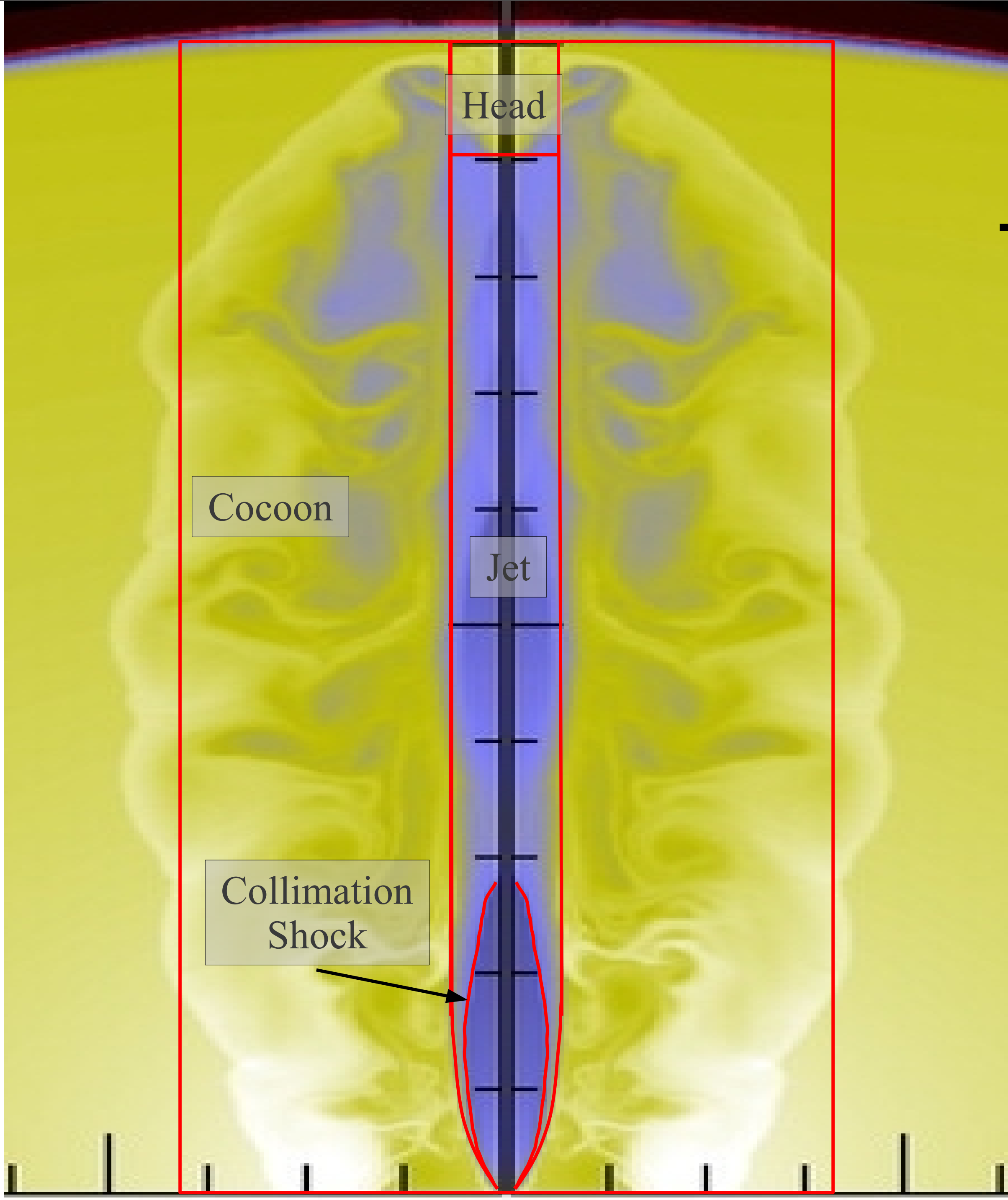
Aloy et al., 2004





Lazzati, Morsony & Begelman 2009

Mizuta & Aloy 2009



The Jet Envelope Interaction - How Jets Penetrate the Stellar Envelope

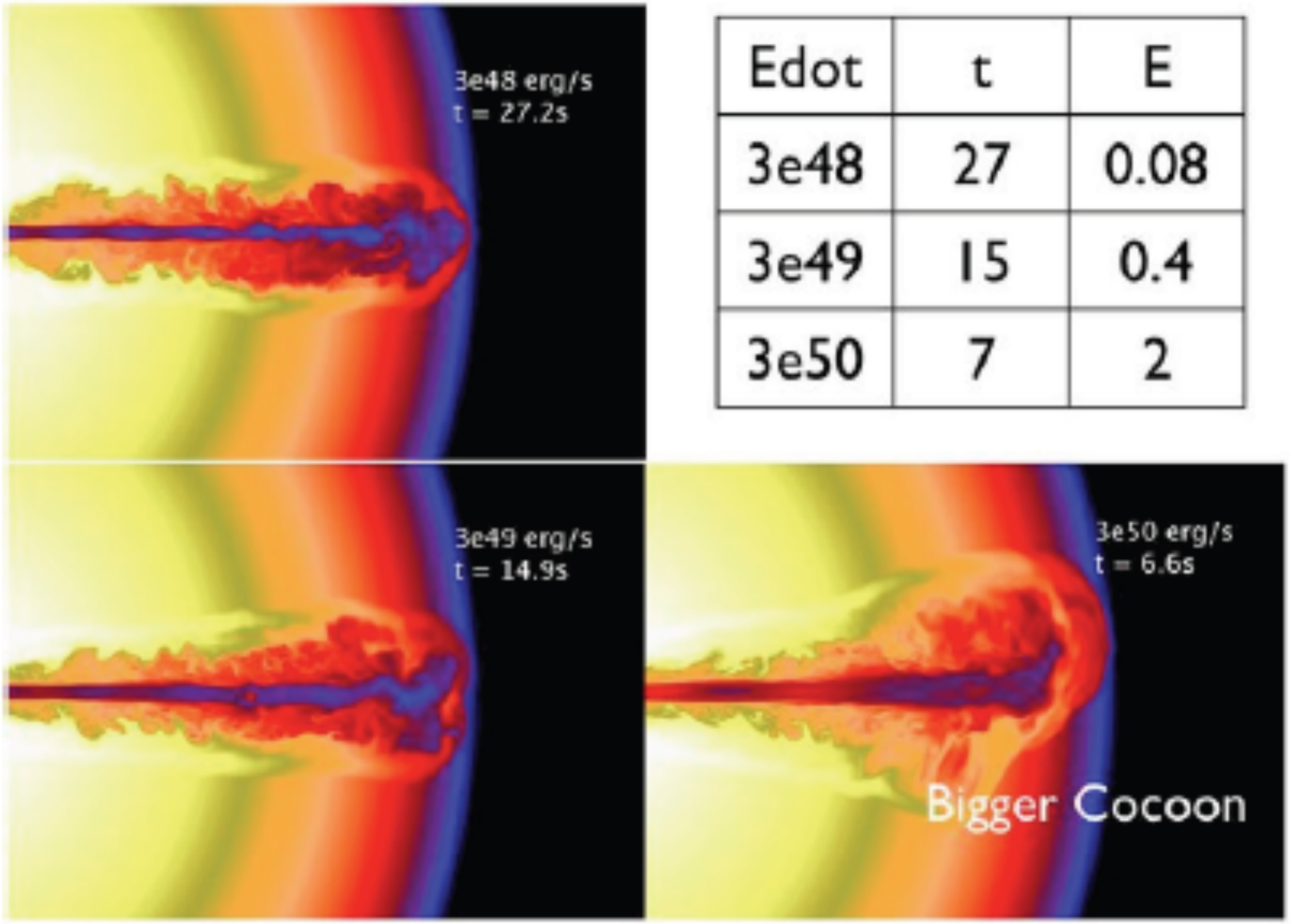
Omer Bromberg, Ehud Nakar, Re'em Sari, TP

Conditions when the Jet Escapes

$$
\begin{aligned}
t_b &= 28\ sec \cdot M_{15}^{1/3} R_{11}^{2/3} L_{47}^{-1/3} \theta_1^{4/3}, \\
\beta_h(t_b) &= 0.16 \cdot M_{15}^{-1/3} R_{11}^{1/3} L_{47}^{1/3} \theta_1^{-4/3}, \\
\beta_c(t_b) &= 5.7 \times 10^{-3} \cdot M_{15}^{-1/3} R_{11}^{1/3} L_{47}^{1/3} \theta_1^{-1/3}, \\
\theta_j(t_b) &= 0.13^\circ \cdot M_{15}^{-1/6} R_{11}^{7/6} L_{47}^{1/6} \theta_1^{4/3}, \\
\theta_c(t_b) &= 2.2^\circ \cdot \theta_1, \\
T_c(t_b) &= 7.8\ KeV \cdot M_{15}^{1/12} R_{11}^{-7/12} L_{47}^{1/6} \theta_1^{-1/6} \\
\Gamma_j(t_b) &\simeq 5.7 \cdot \theta_1^{-1},
\end{aligned}
$$

Energy needed for the Jet to Escape

From W. Zhang 2006



Edot	t	E
3e48	27	0.08
3e49	15	0.4
3e50	7	2

$E = 2.8 \times 10^{48}$ergs $(t/30sec)^{-2}$ (M/15 M_sun) $(R/10^{11}cm)^{4/3}$ $(\theta/10^{o})^{8/3}$

Energy needed for the Jet to Escape

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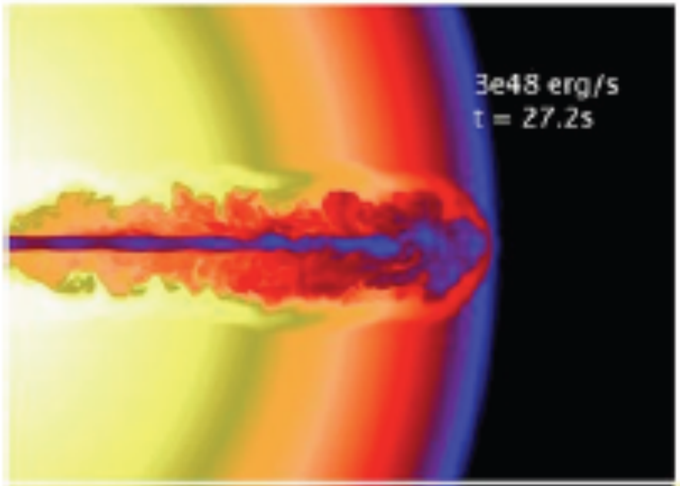

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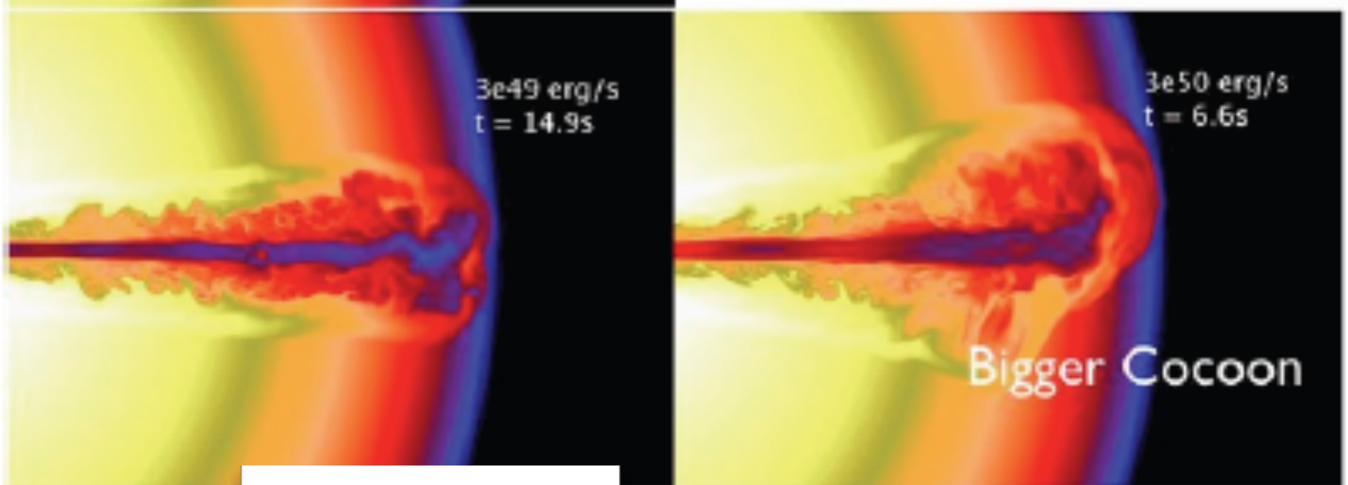
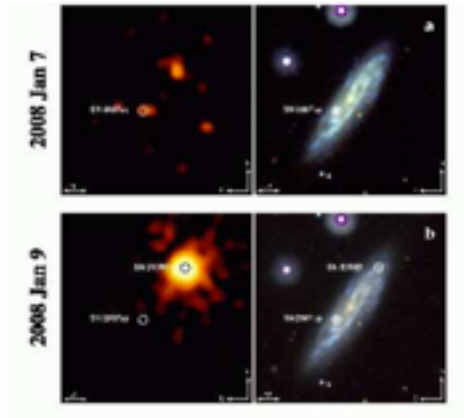
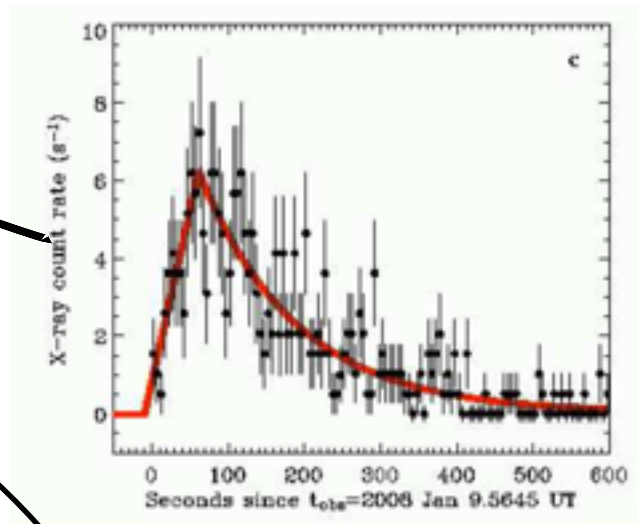


$E = 2.8 \times 10^{48}$ erg $(t/30sec)^{-2}$ M/15 M_sun) $(R/10^{11} cm)^{4/3}$ $(\theta/10^{o})^{8/3}$

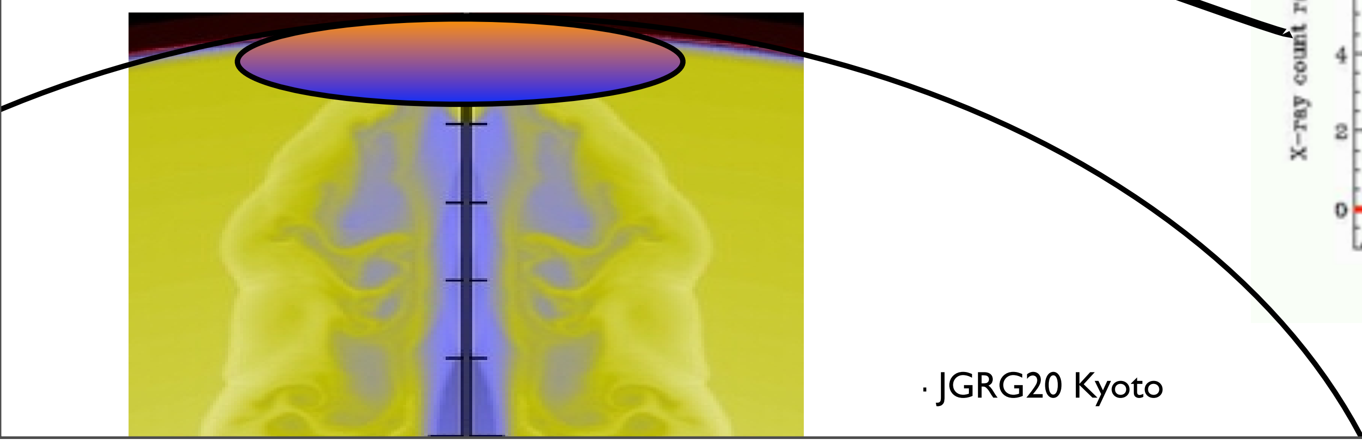
A “failed GRB”

- A weak jet (“failed GRB”) leads to a hot spot on the stellar envelope.
- This could have been SN 2008D (Mazzali et al., 2008) which is usually interpreted as a “shock break out”..
- The rate implies a (failed) jet in almost every SN Ib,c.



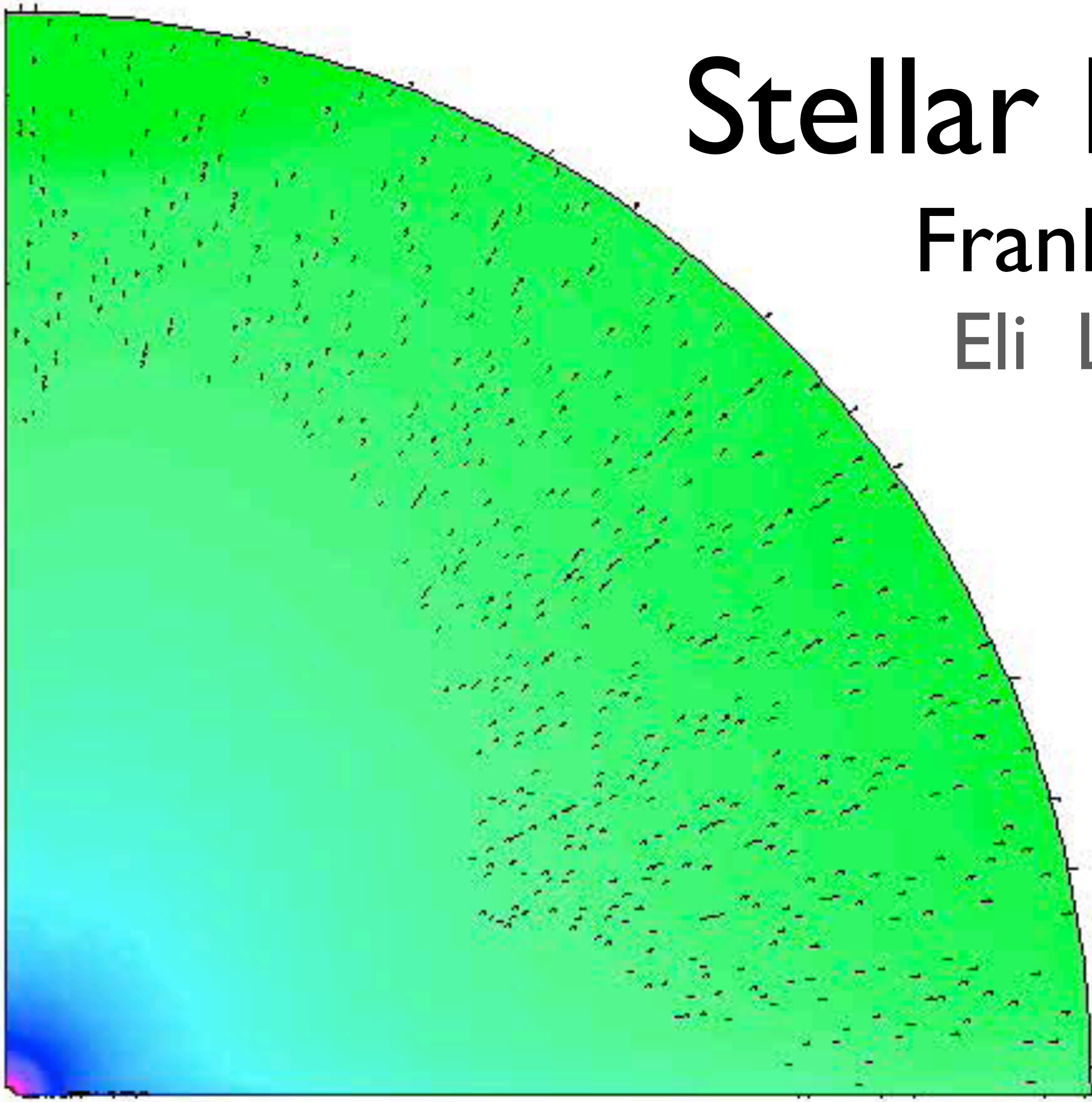


A few keV



The Fate of the Stellar Envelope?

Frank Genet,
Eli Livne, TP

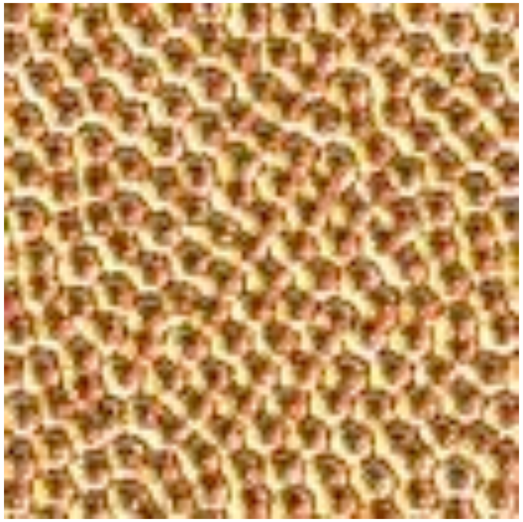


Lorentz Invariance with GRBs

(Amelino-Camelia et al., 98, Norris et al., 99, Ellis et al., 00,06, Amelino-Camelia and Piran, 02)

- Lorentz Violation (or deformation) appears in various Quantum Gravity Theories.

➢ Energy dependent dispersion and speed of light.



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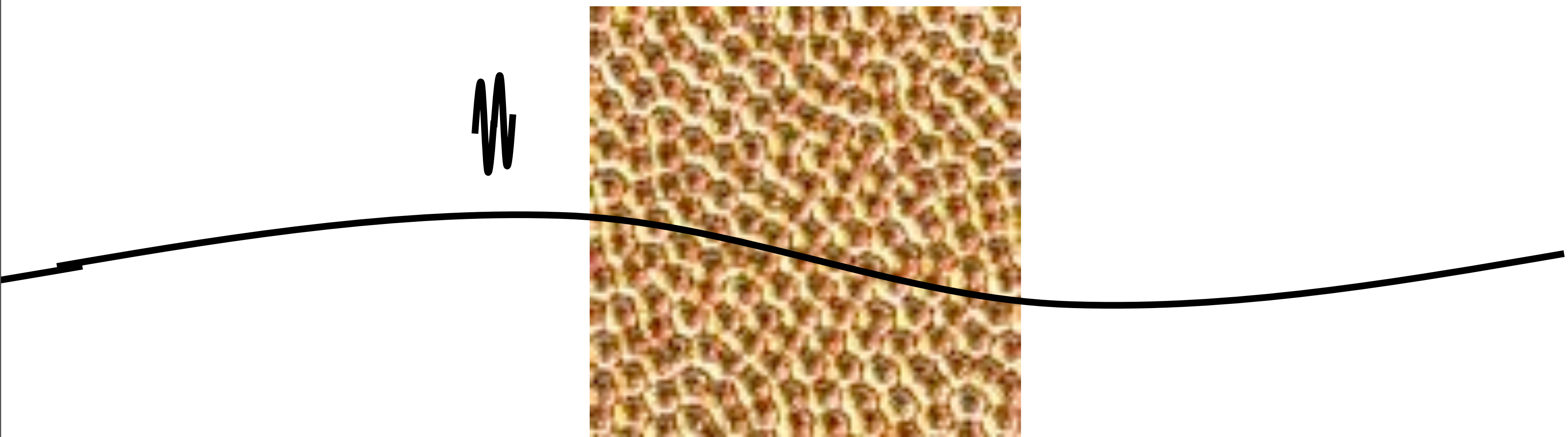

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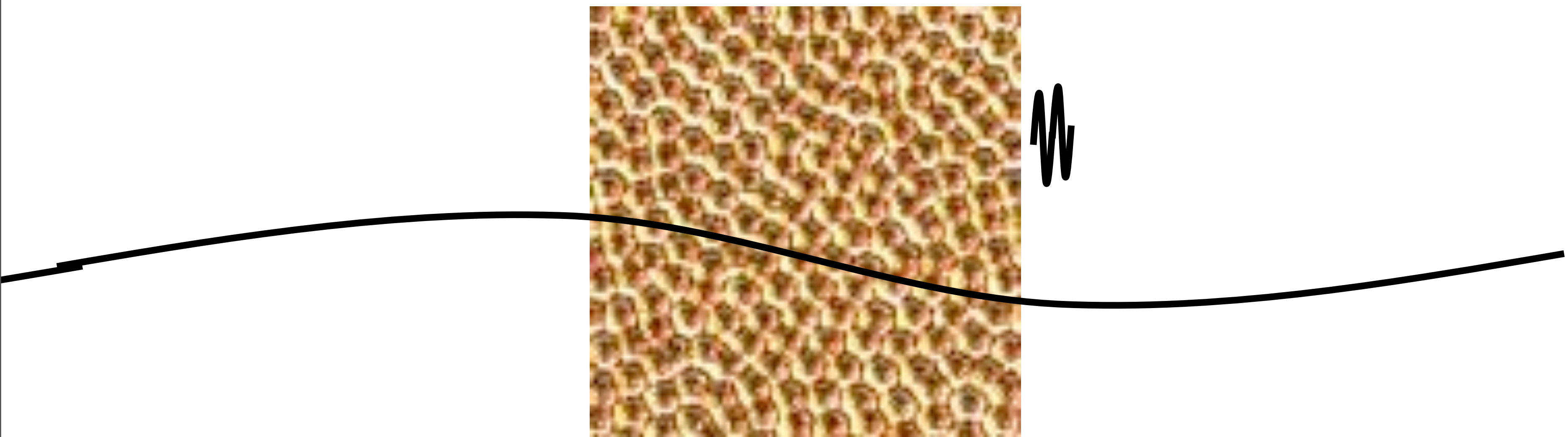

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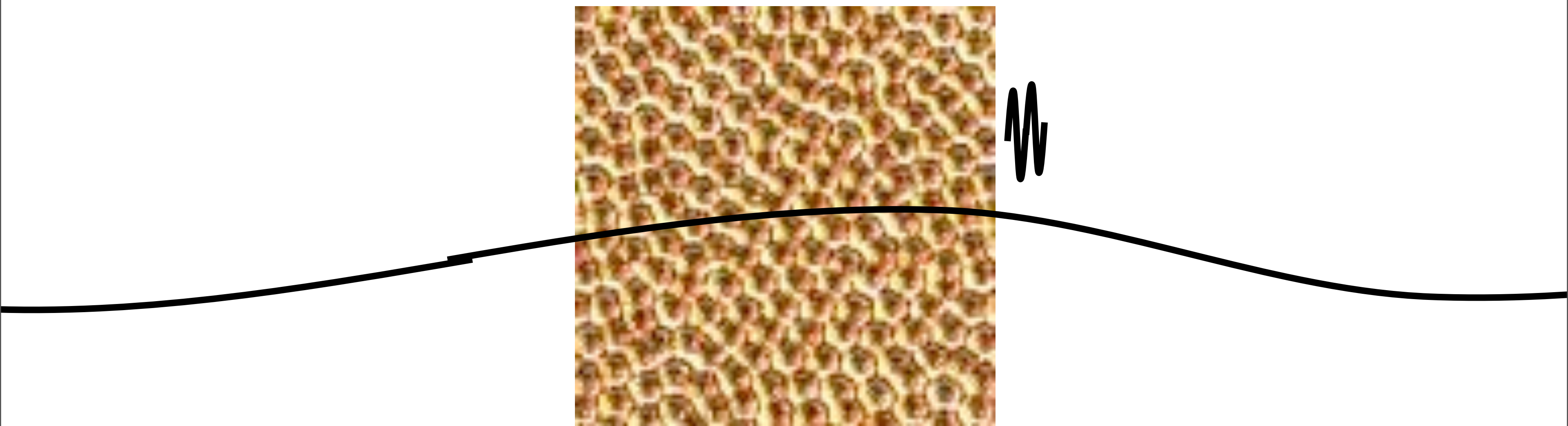


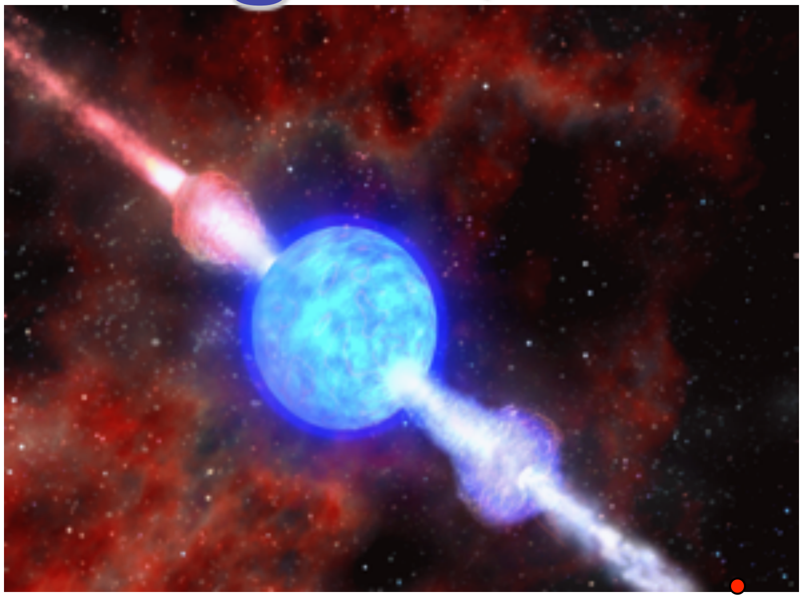
A phenomenological approach

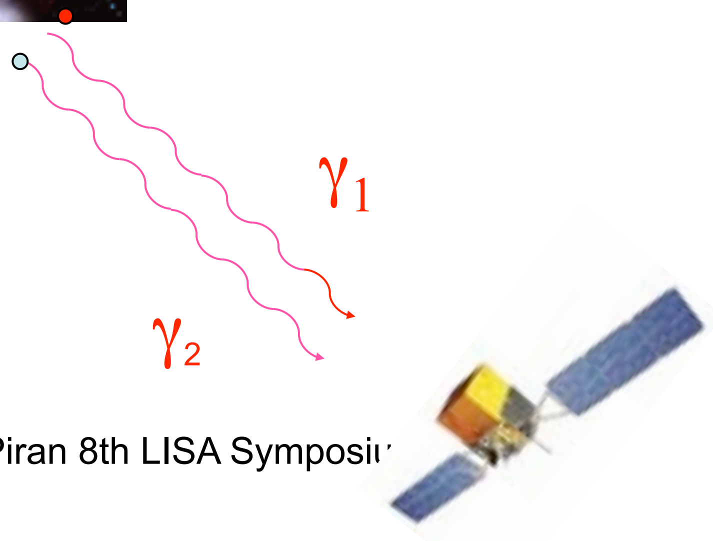
- The simplest leading order low-energy approximation of any theory that breaks Lorentz Invariance at a very high energy scale: ξE_{pl}, for the deformed dispersion relation is:

$$E^2 - p^2 - m^2 \approx \pm \left(\frac{E}{\xi_n m_{pl}} \right)^n E^2$$

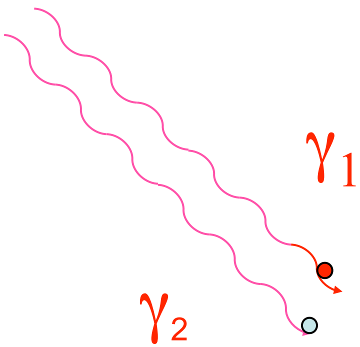
$$v \approx c \left[1 \pm \frac{(1+n)}{2} \left(\frac{E}{\xi m_{pl}} \right)^n \right]$$

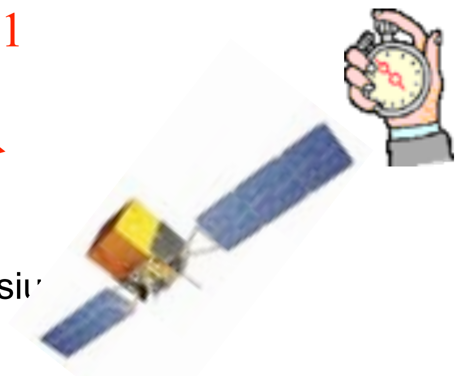
Energy dependent time of flight (Amelino-Camelia et al., 1998)



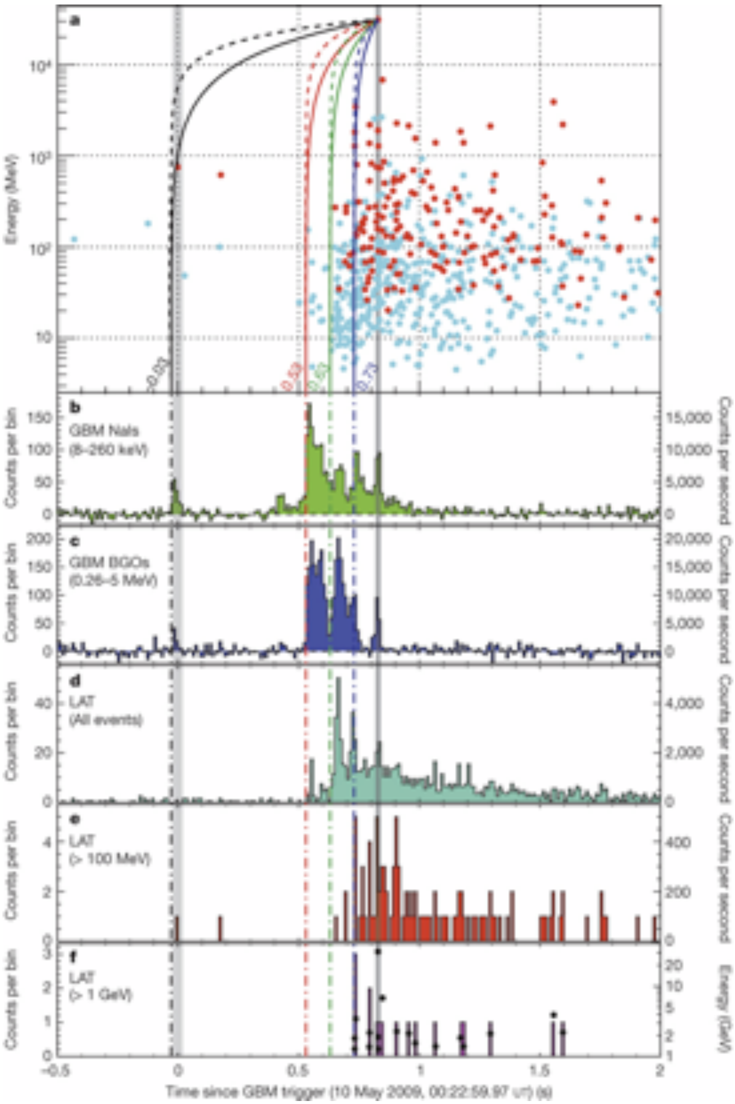


Energy dependent time of flight (Amelino-Camelia et al., 1998)





Fermi's observations of GRB 050910

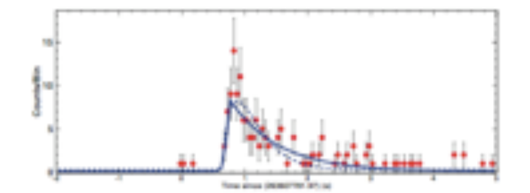


Z=0.903

$\Delta t_{0.1MeV\text{-}30GeV} < 0.9sec$

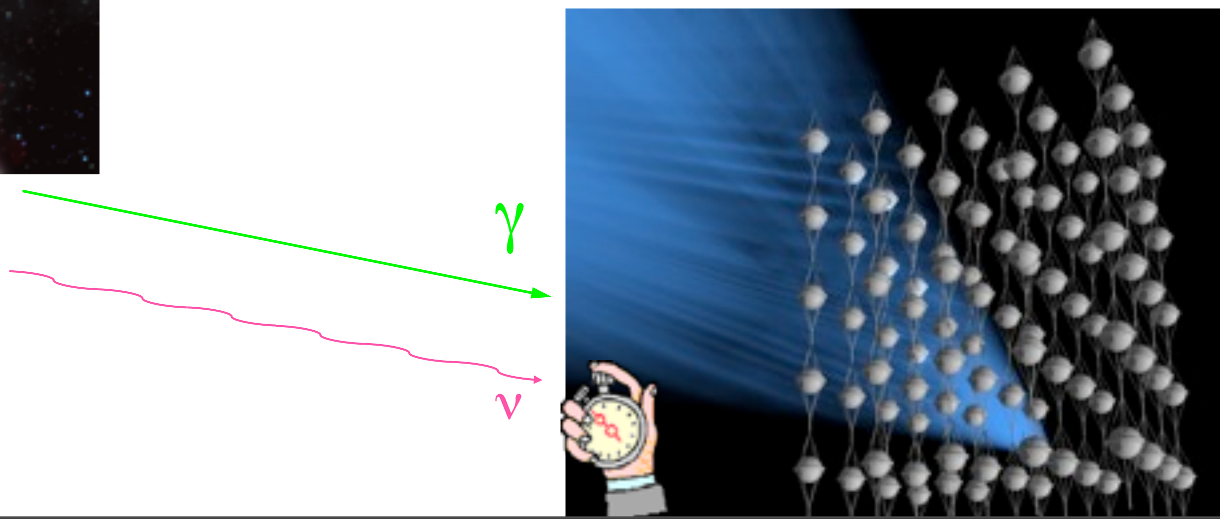
$\Rightarrow E^{(1)}_{LV} > 1.2 \cdot 10^{19}$ GeV

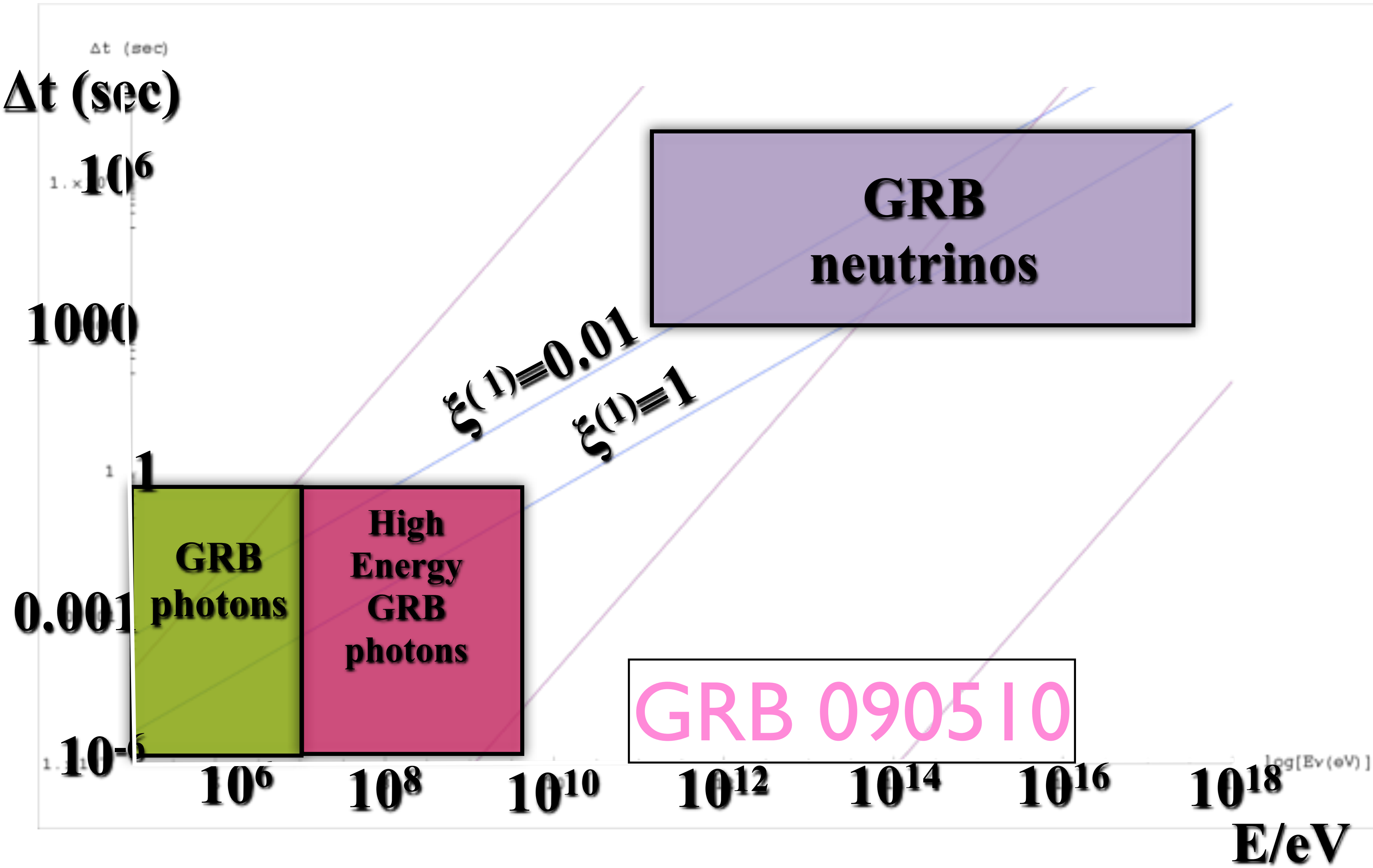
$= 1.2\ M_{pl}$



t_{start} (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of t_{start} or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{QG,1}/M_{Planck}$	limit on $M_{QG,2}$ in 10^{10} GeV/c^2
−30	< 859	start of any observed emission	0.1	1	> **1.19**	> 2.99
530	< 299	start of main < 1 MeV emission	0.1	1	> **3.42**	> 5.06
630	< 199	start of > 100 MeV emission	100	1	> **5.12**	> 6.20
730	< 99	start of > 1 GeV emission	1000	1	> **10.0**	> 8.79
—	< 10	association with < 1 MeV spike	0.1	±1	> **102**	> 27.7
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	−1	> **1.33**	> 0.54
$\lvert\Delta t/\Delta E\rvert$ < 30 ms/GeV		lag analysis of all LAT events	—	±1	> **1.22**	—

GRB ν's - An Opportunity For Observing Lorentz Invariance Deformation

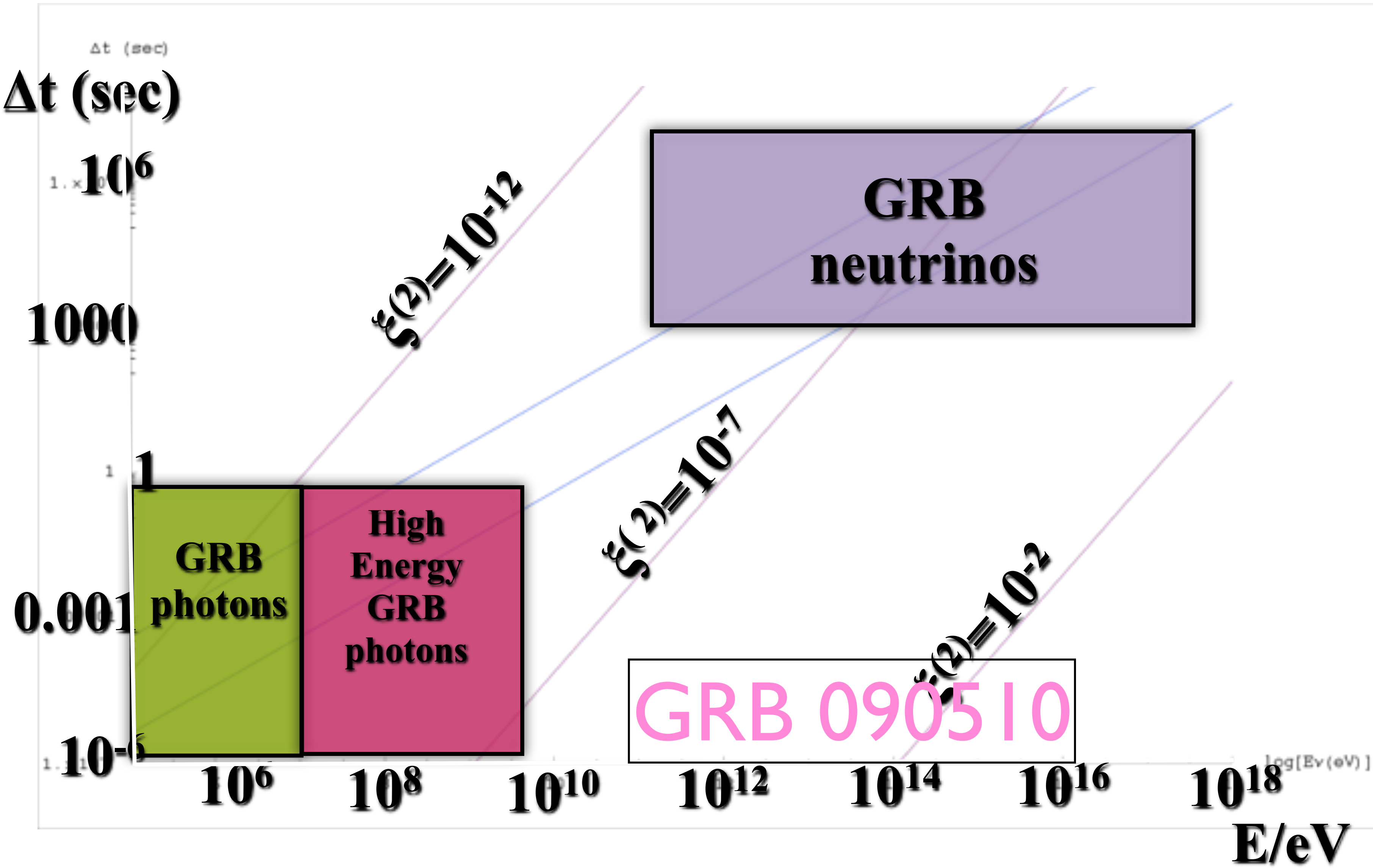




GRB 090510

$\xi^{(1,2)}=E_{LIV}/M_{Pl}$

JACOB & TP, 2007



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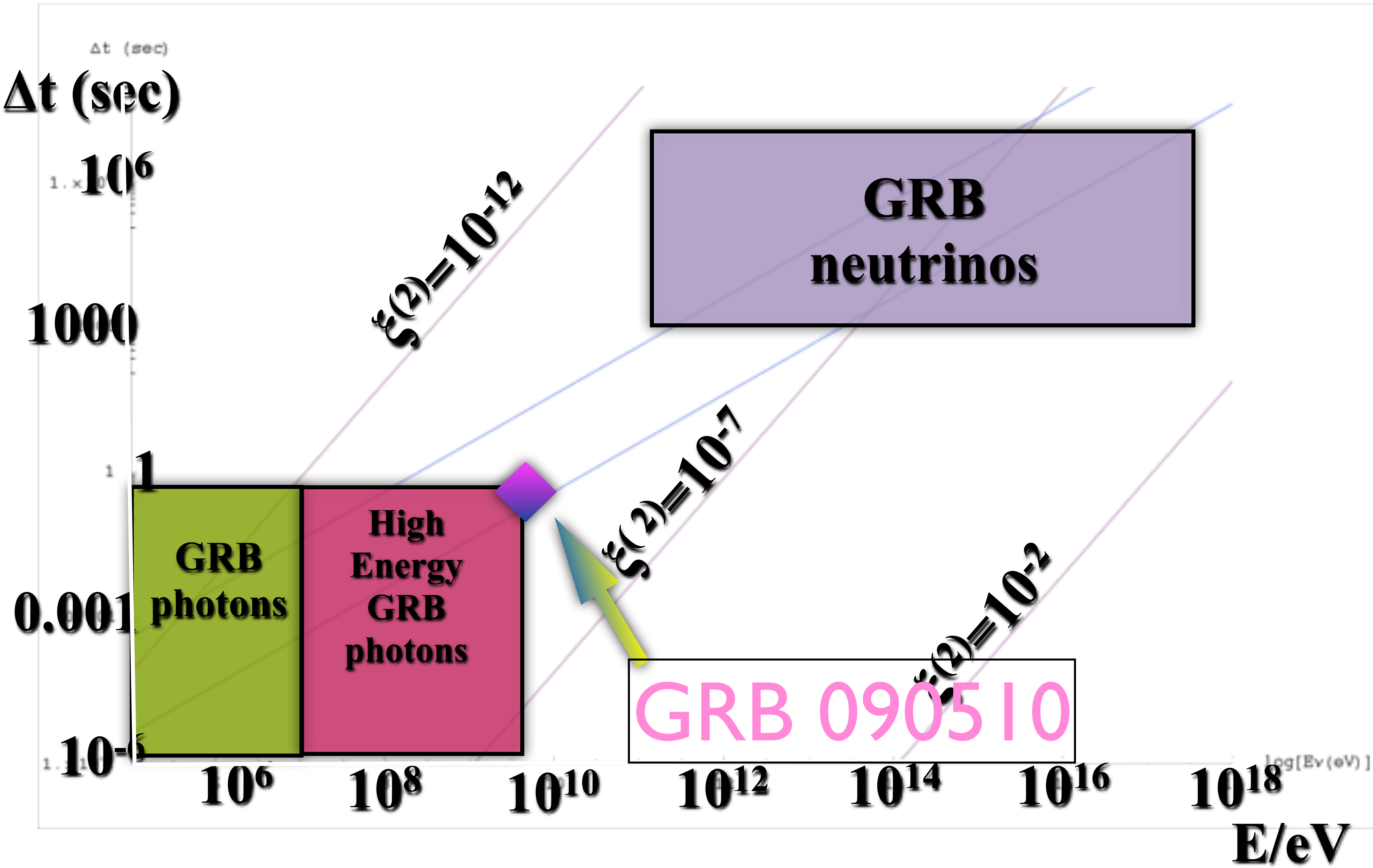

$\xi^{(1,2)}=E_{LIV}/M_{Pl}$ JACOB & TP, 2007

- Many Happy Years of Creative Ideas, Research and Funding for your Ambitious program

Summary

- GRBs involve macroscopic relativistic motion with Lorentz factors of > 100.
- GRBs involve most likely the formation of black holes (but for weak bursts rotating Magnetars cannot be ruled out yet).
- Long GRBs are related to Star formation but don’ necessarily track the SFR.
- Short GRBs most likely arise from NS-Mergers. GIving an independent estimate of rates (but depending on opening angles).
- Jets are an essential part of all GRB models.
- The acceleration of the jet is a source of gravitational radiation - but problems with beaming make it difficult to detect.
- Jets in Failed GRBs may show up as asymmetric SN (87A)?
- Jets may play an inportant role in the SN explosion.
- GRBs set the strongest limit on Lorentz invariance violation. Setting the scale of such violation to > M_{pl}

The End

Summary

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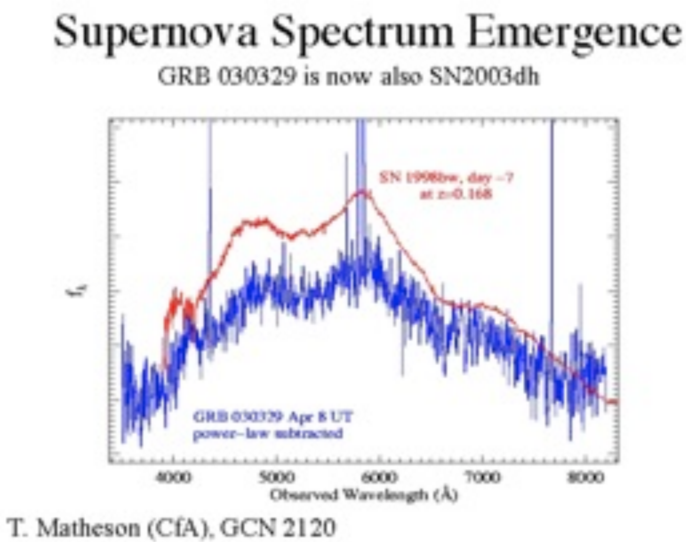

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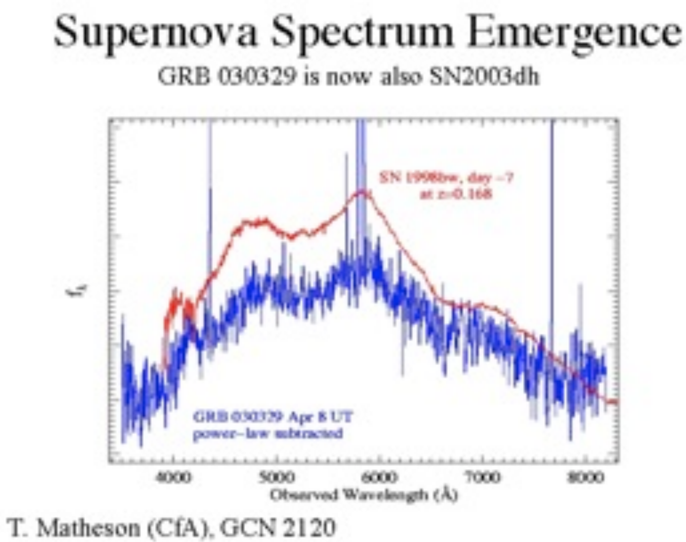

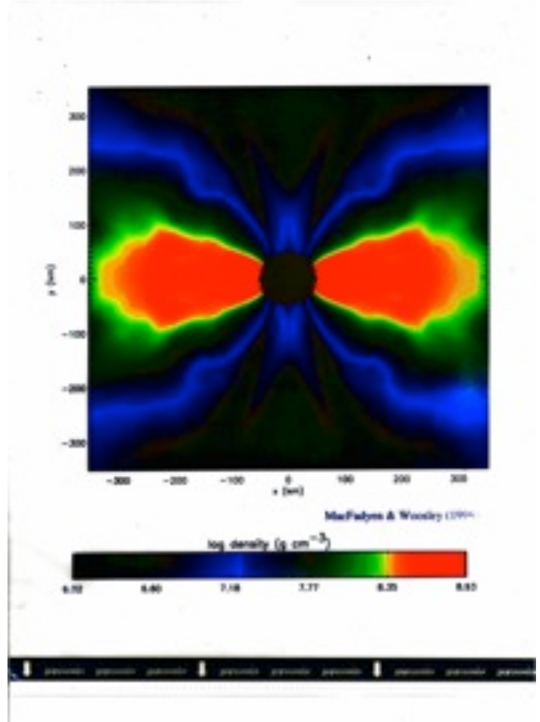

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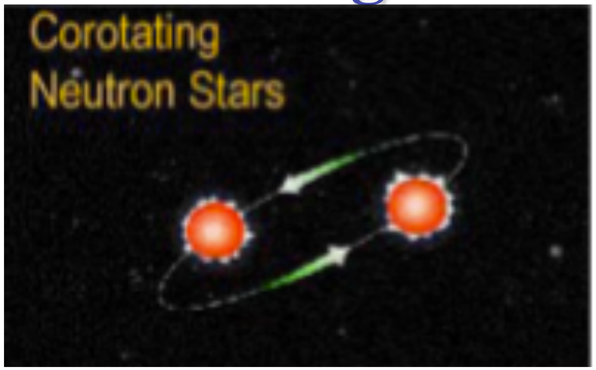

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- GRB coincidences enhance the significance of GW detection - but only 1 in 30 events.

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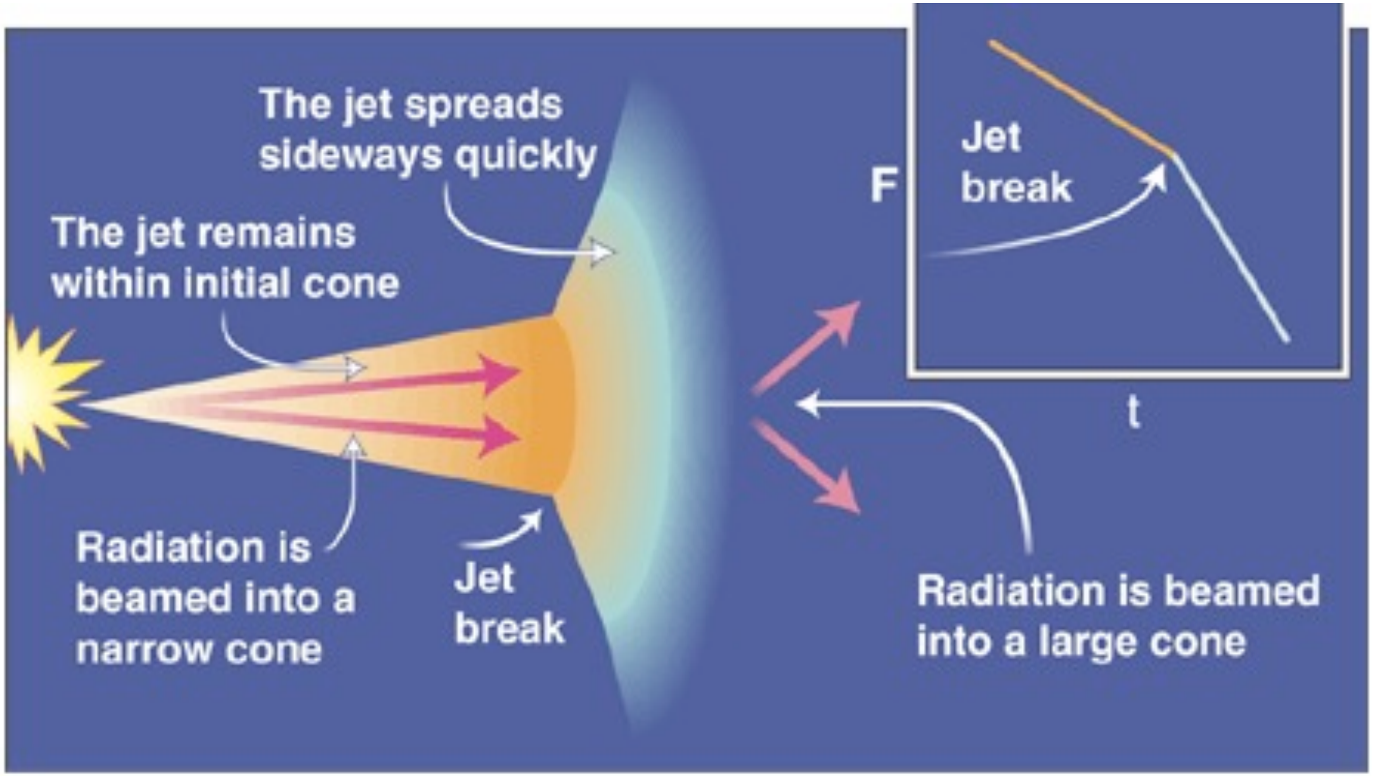
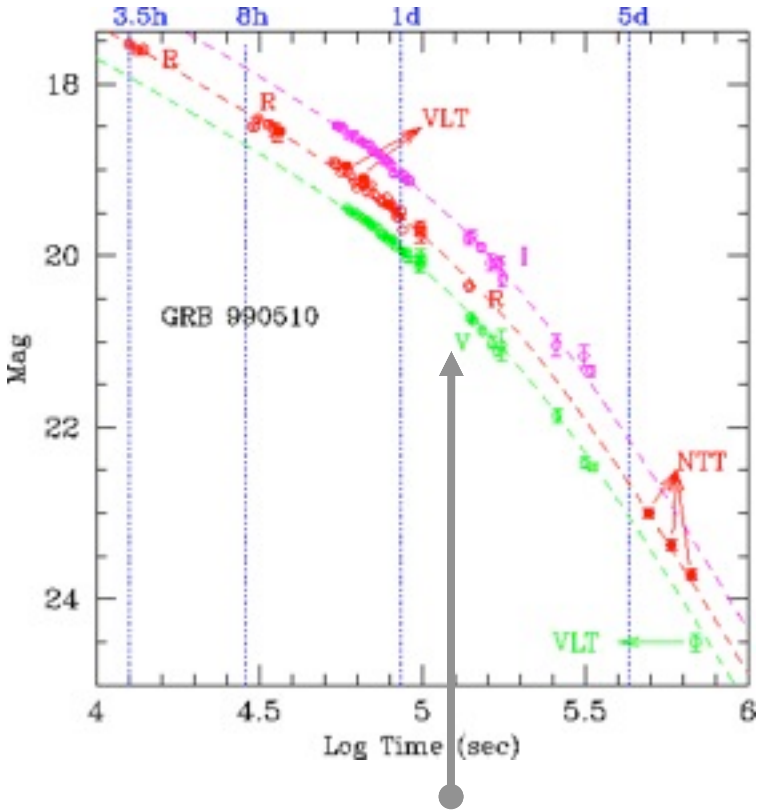
- $Rate_{GRB}$ > a few events/year up to 500 Mpc

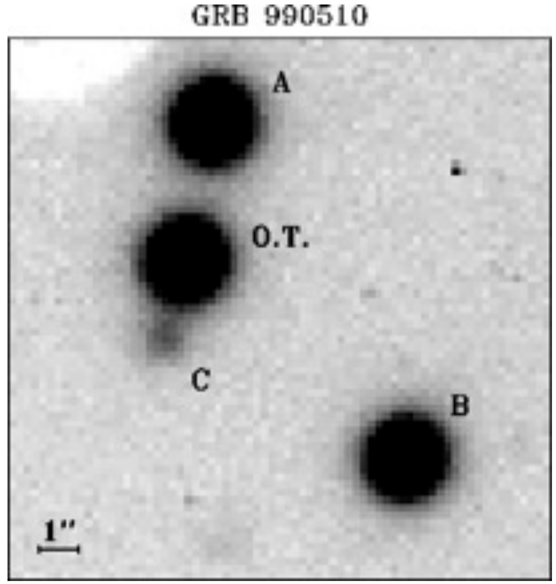
The Jet Break

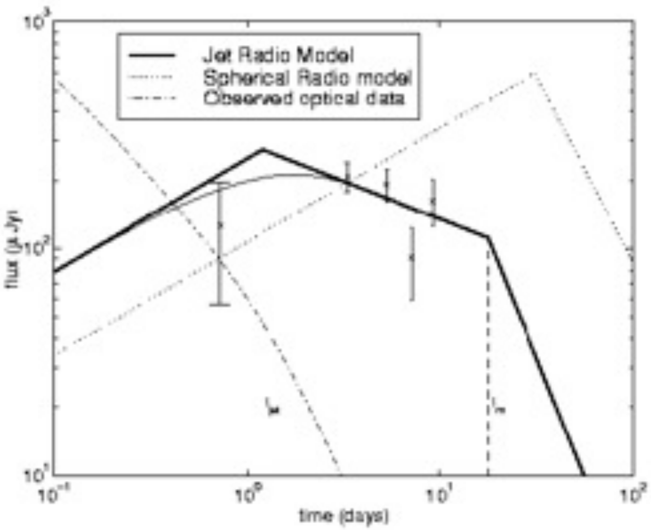


Jets with an opening angle θ expand forwards until $\gamma=\theta^{-1}$ and then expand sideways rapidly lowering quickly the observed flux (Piran, 1995; Rhoads, 1999; Sari, Piran, Halpern, 1999)

GRB 990510 – The Best Jet







t_{break} = 1.2 days → jet angle = 4

From Harrison et al 1999

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But - Short GRB afterglows are weak

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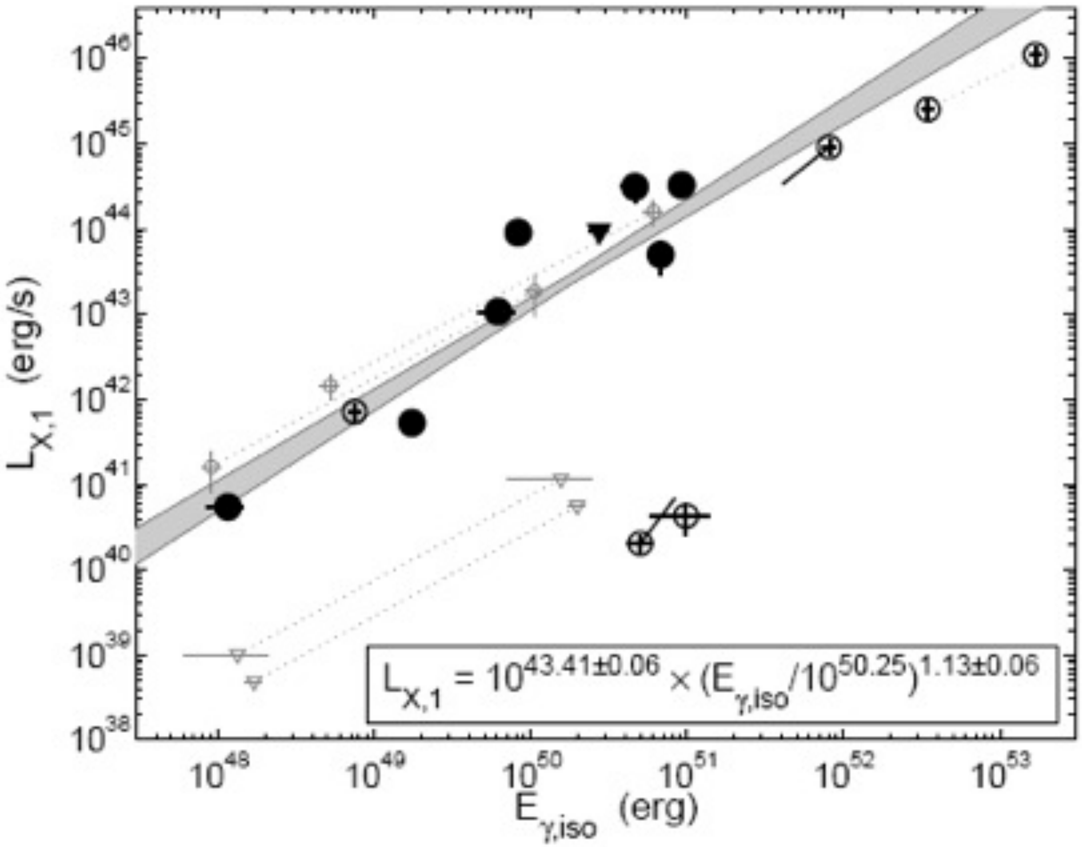
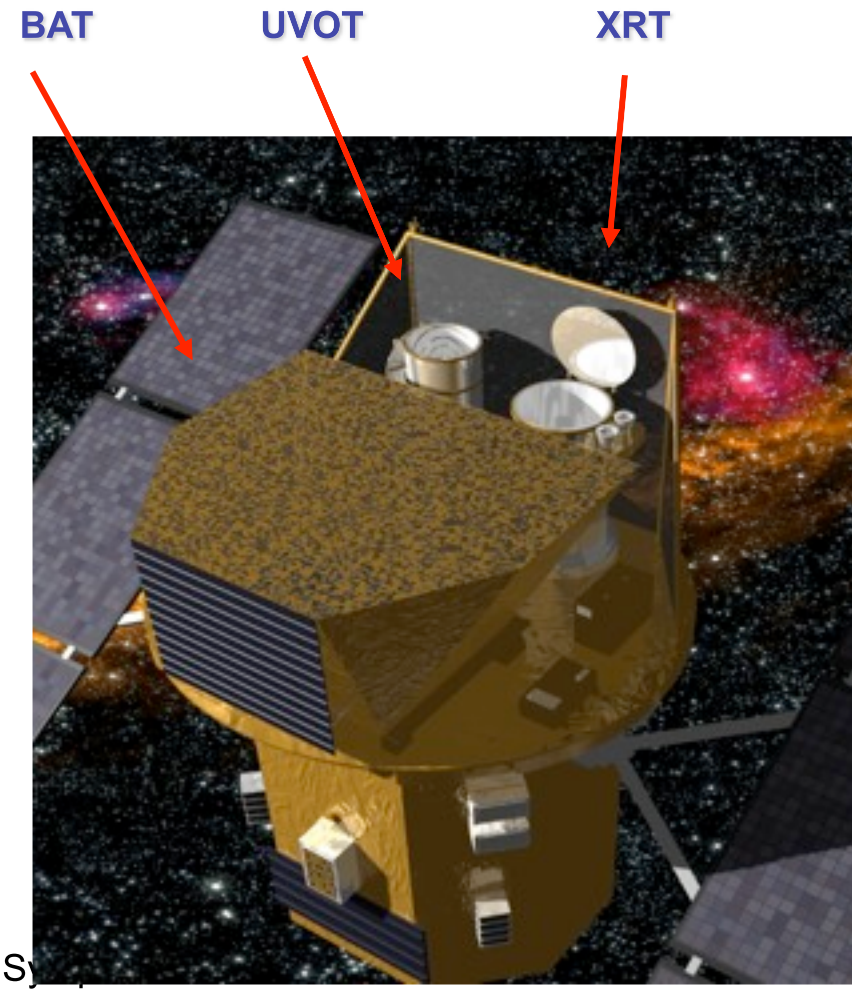


Swift

- **92 GRBs detected (~100 per year)**
- **72 XRT detections out of 79 observed**
- **20 UVOT detections out of 68 observed**

(42 detections ground-based + UVOT)



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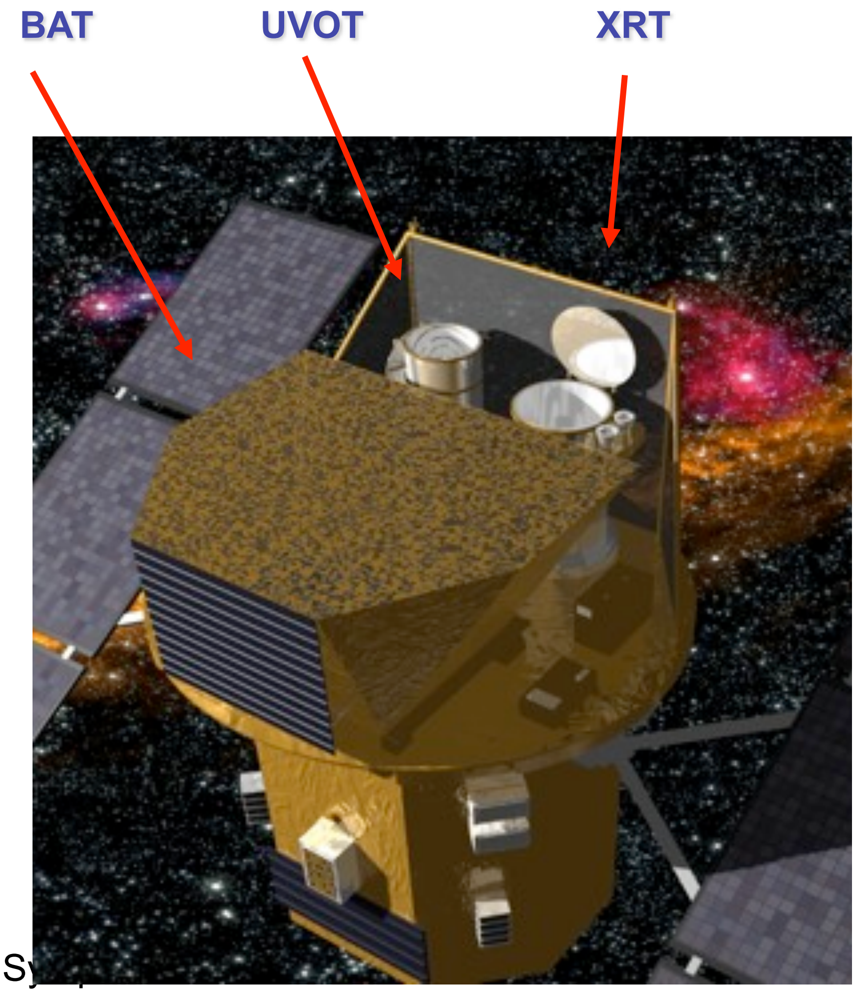
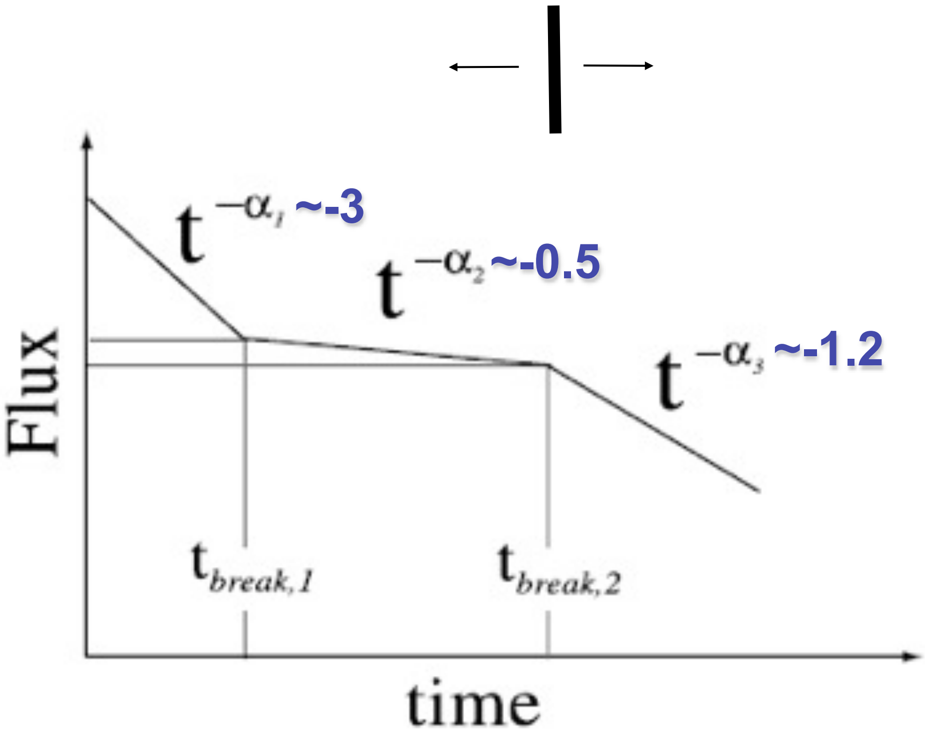


Swift – Schematic Afterglow light curve



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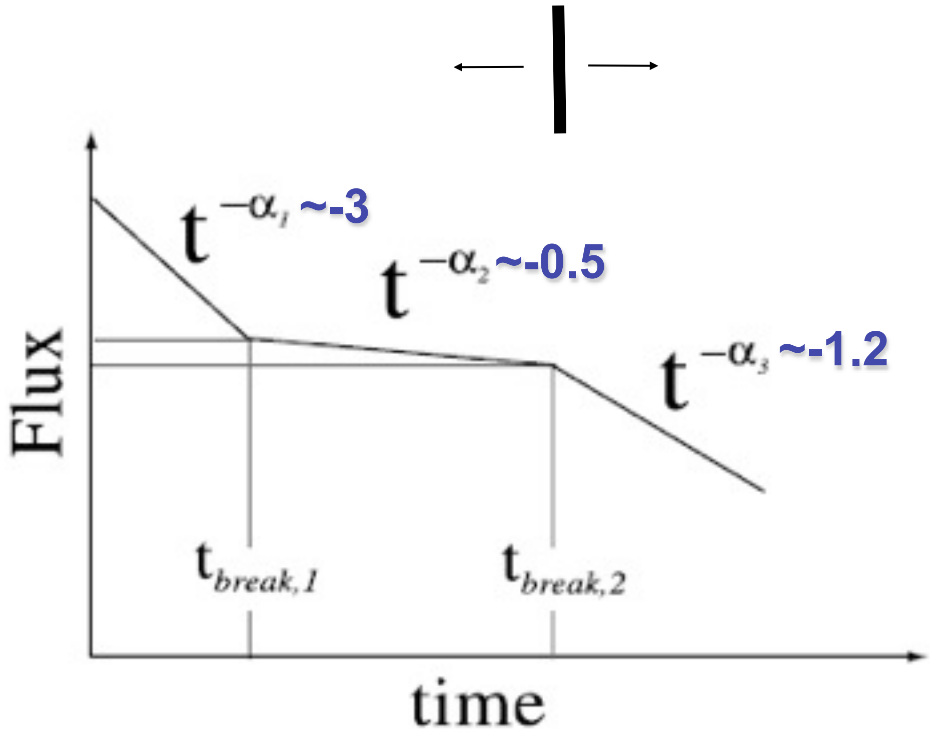
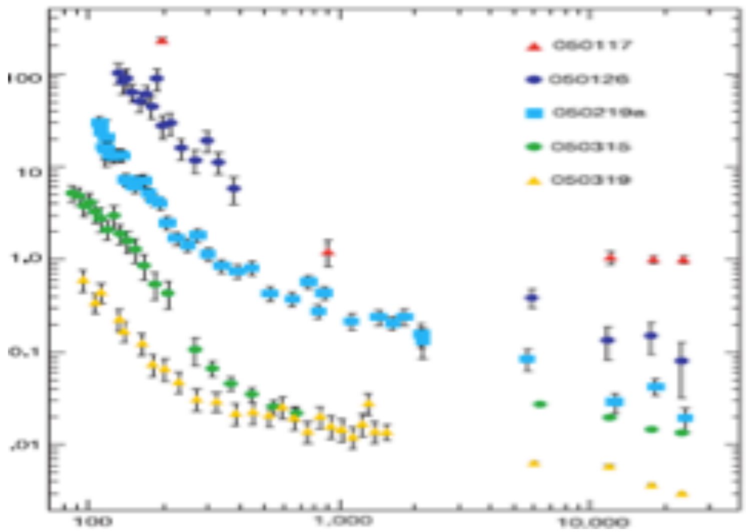


Steep initial decline



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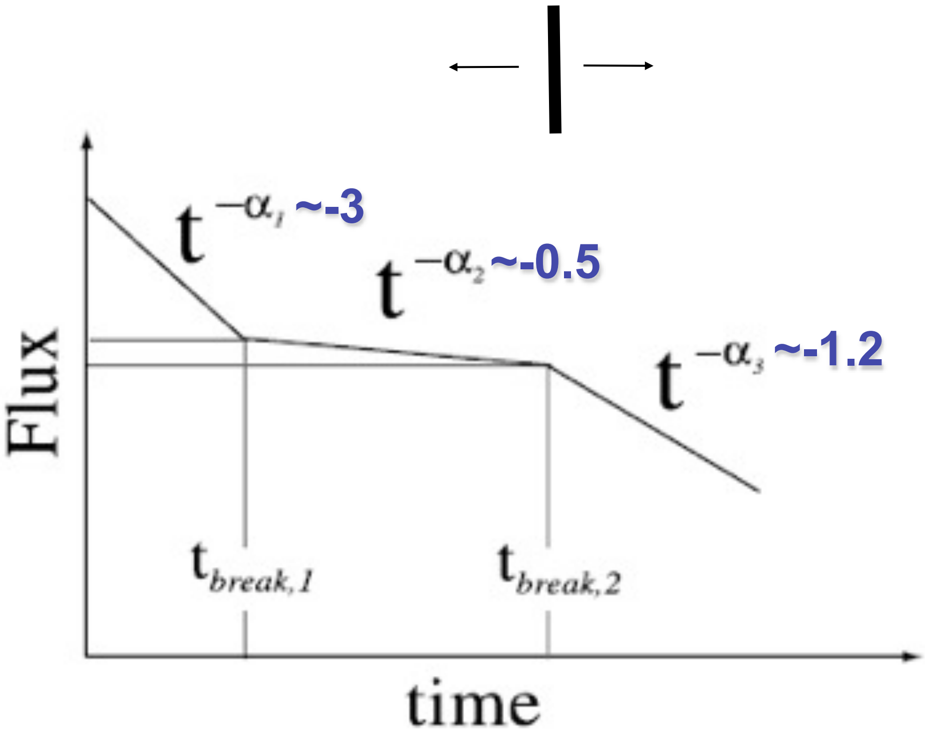

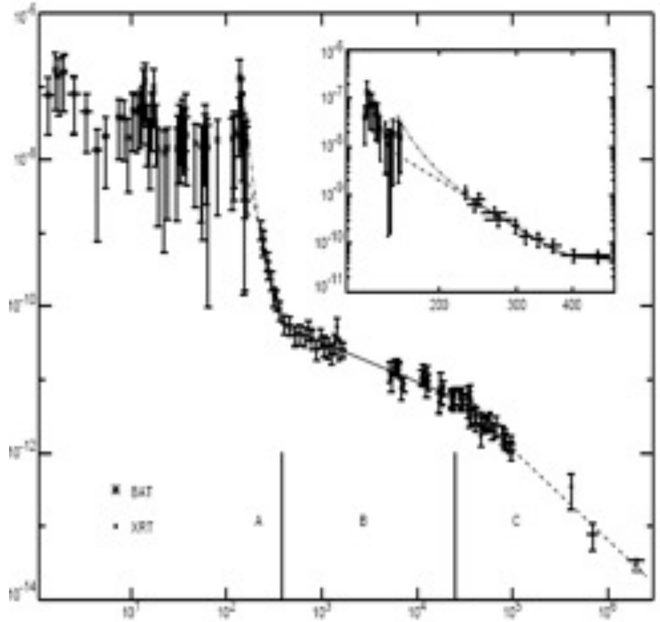

Shallow decline

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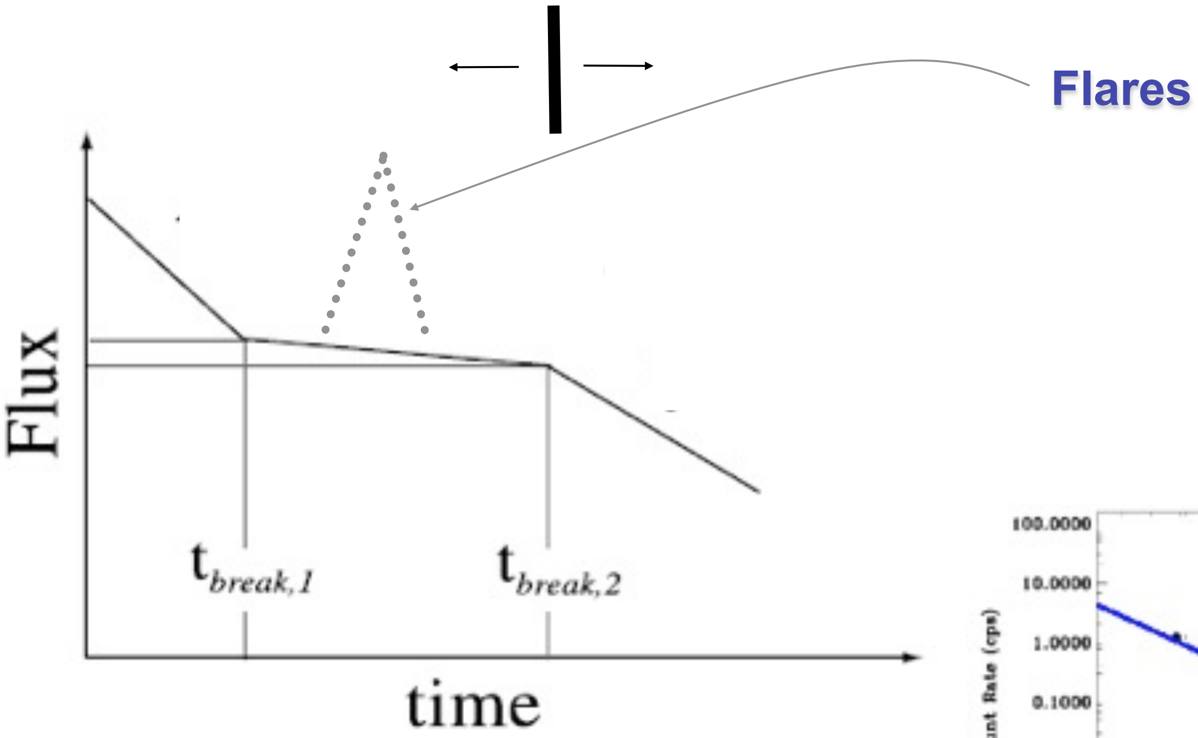

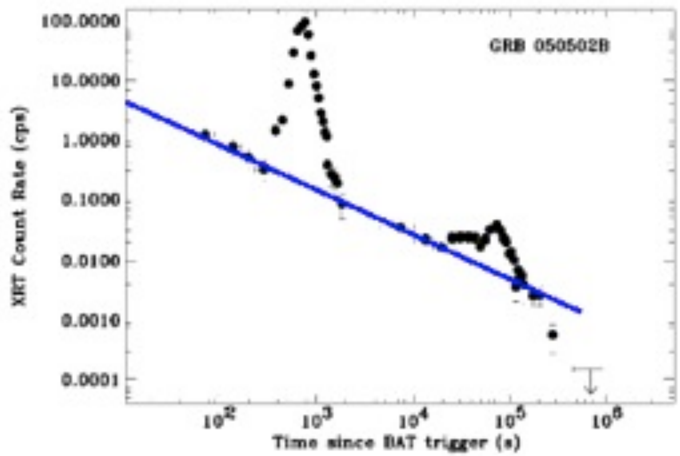

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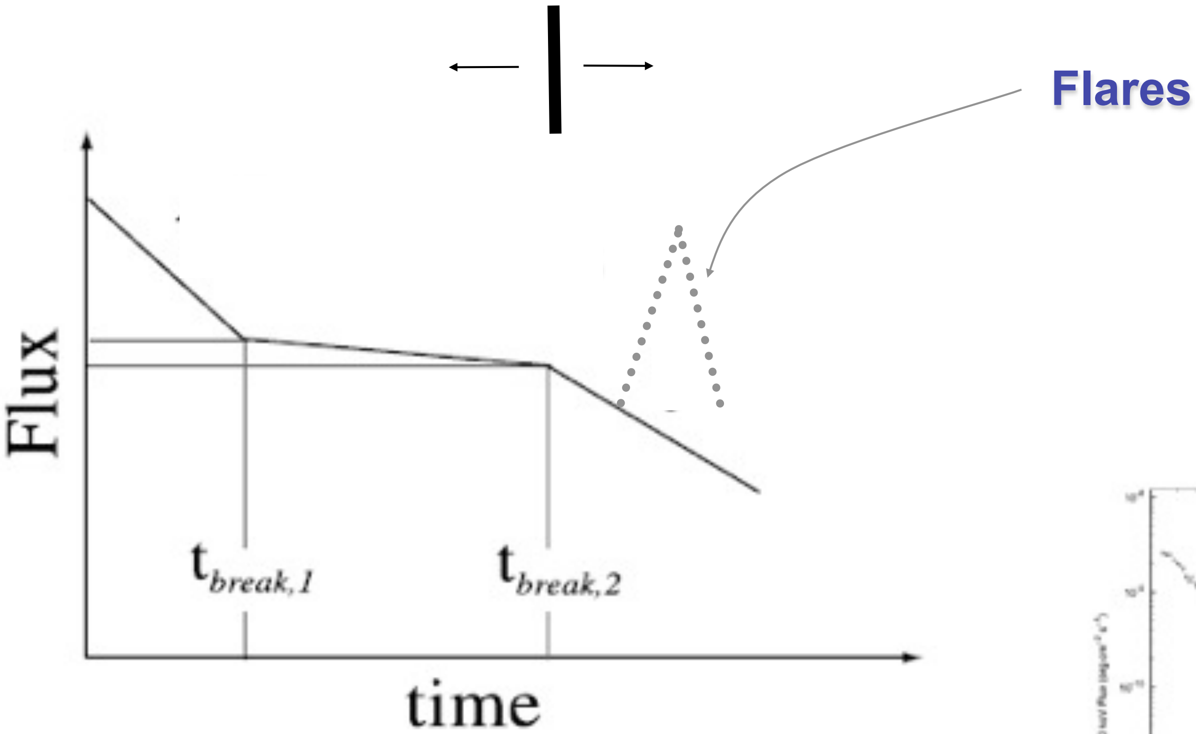

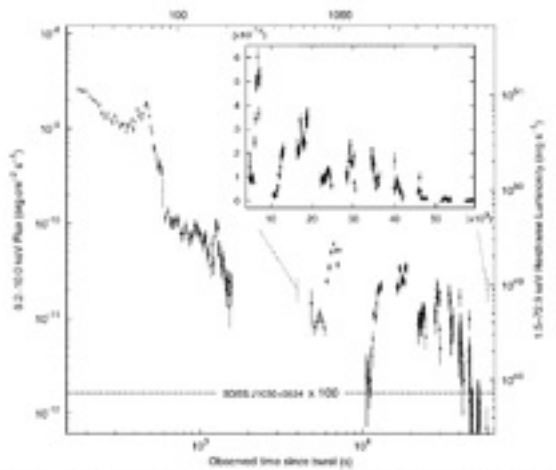

FIG. 1.—*Swift* XRT 0.2–10.0 keV light curve of GRB 050904 (~1.5–72.9 keV in the rest frame). The equivalent isotropic luminosity at $z = 6.29$ is plotted

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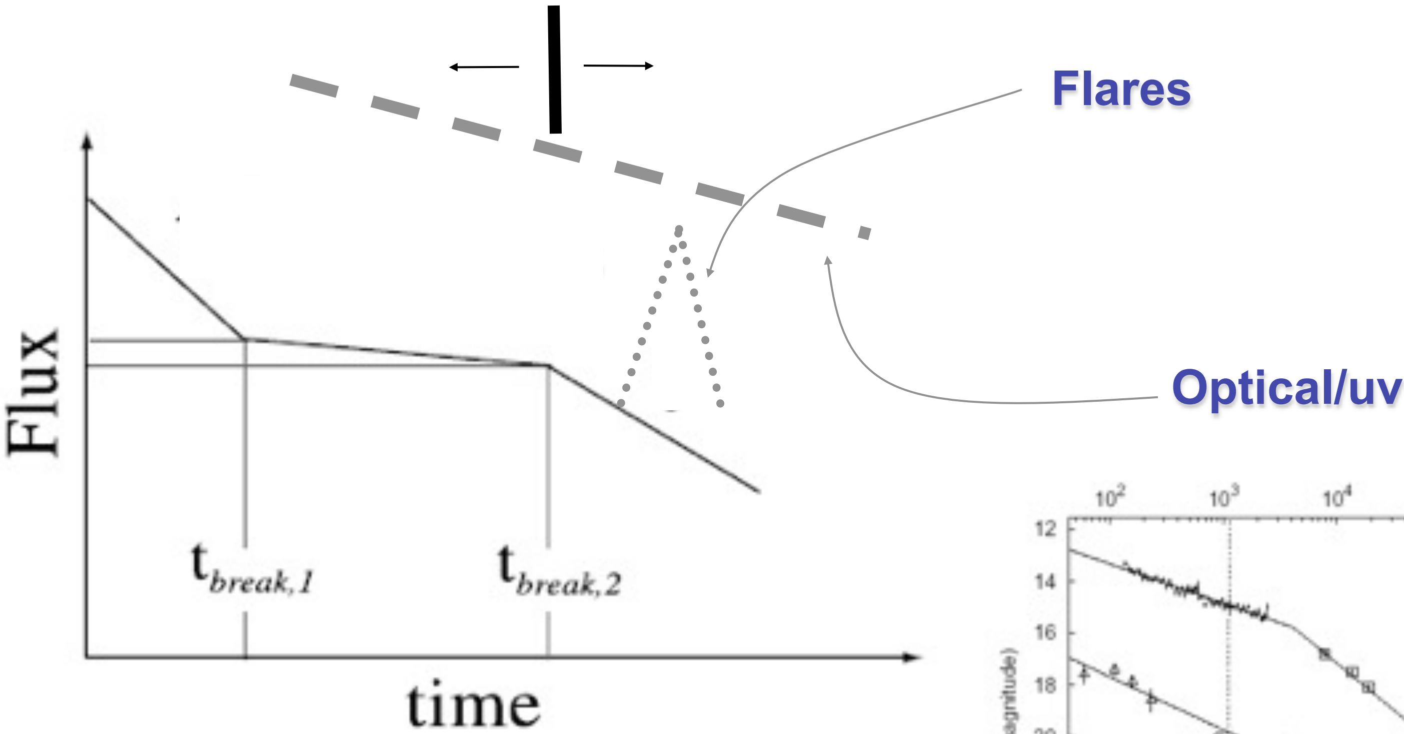


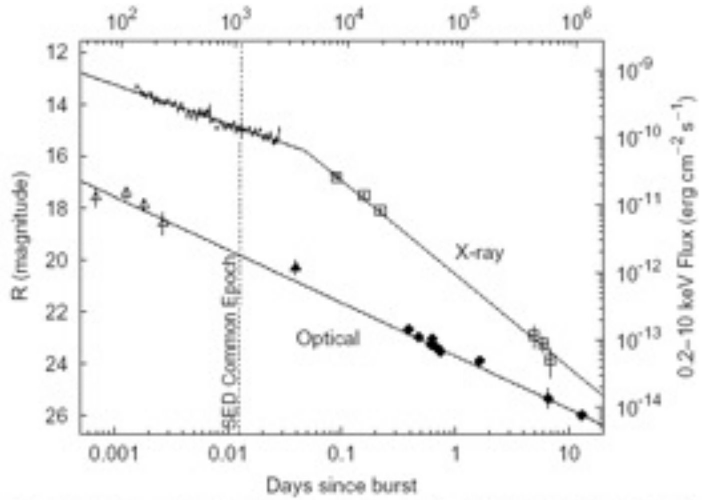
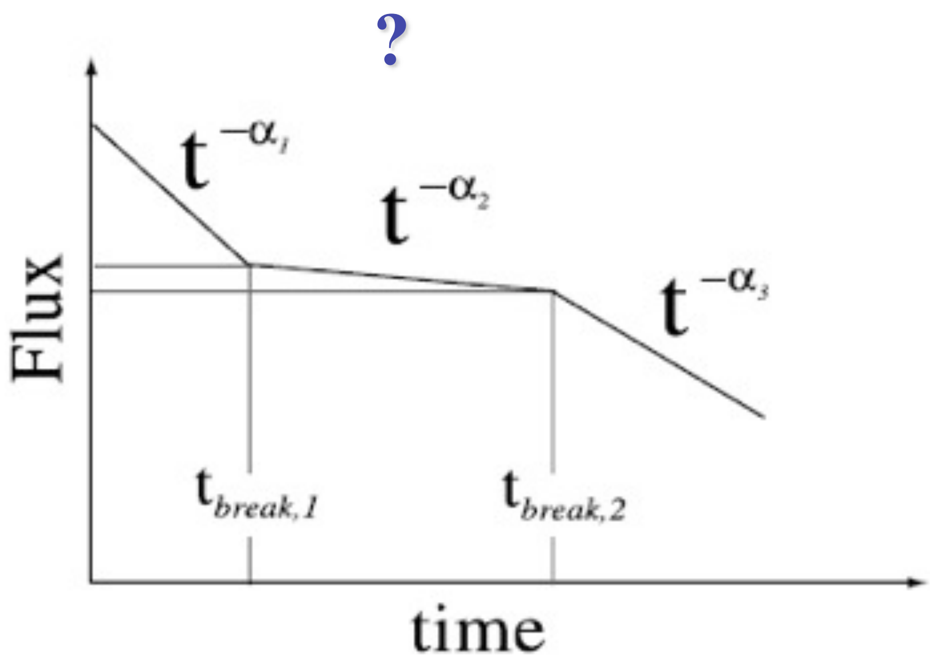


Fig. 3.— X-ray and optical lightcurves of the afterglow of GRB050401. The R-band

Some (pre-Swift) theoretical predictions

- Continued activity (Katz & TP, 97; Katz, TP & Sari 97)
- Refreshed shocks (Rees & Meszaros, 98; Kumar & TP, 00)
- Energy injection (Cohen & TP, 99; Sari & Meszaros, 00)
- Lorentz factor distribution (Rees & Meszaros, 98)
- High latitude emission (Kumar & Panaitescu, 00)

Swift early X-ray light curves



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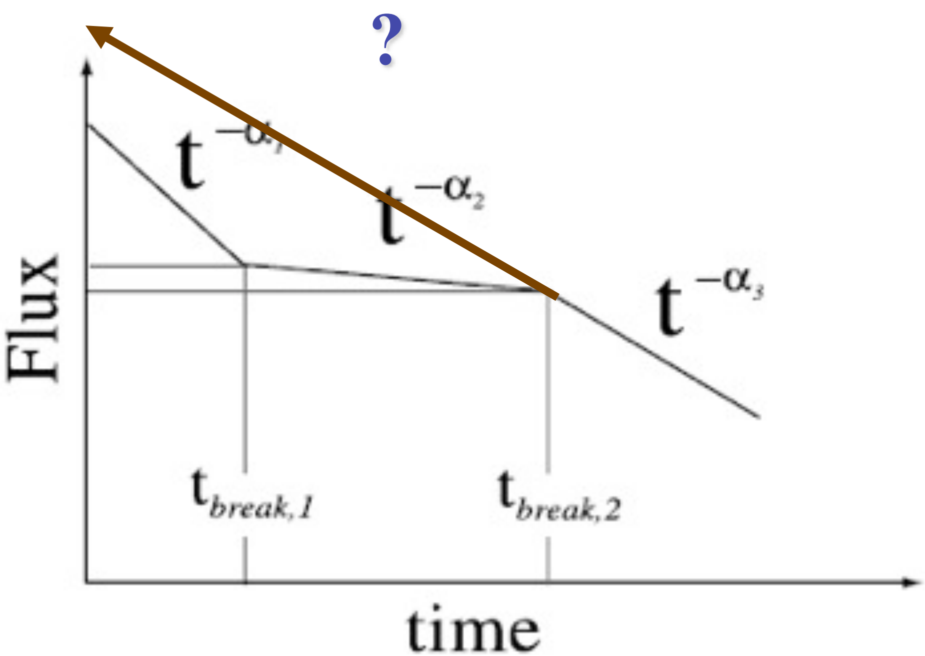

$$\kappa \equiv \frac{E^{obs}_{\gamma,iso}}{E_{k,iso,10h}} \approx 1$$

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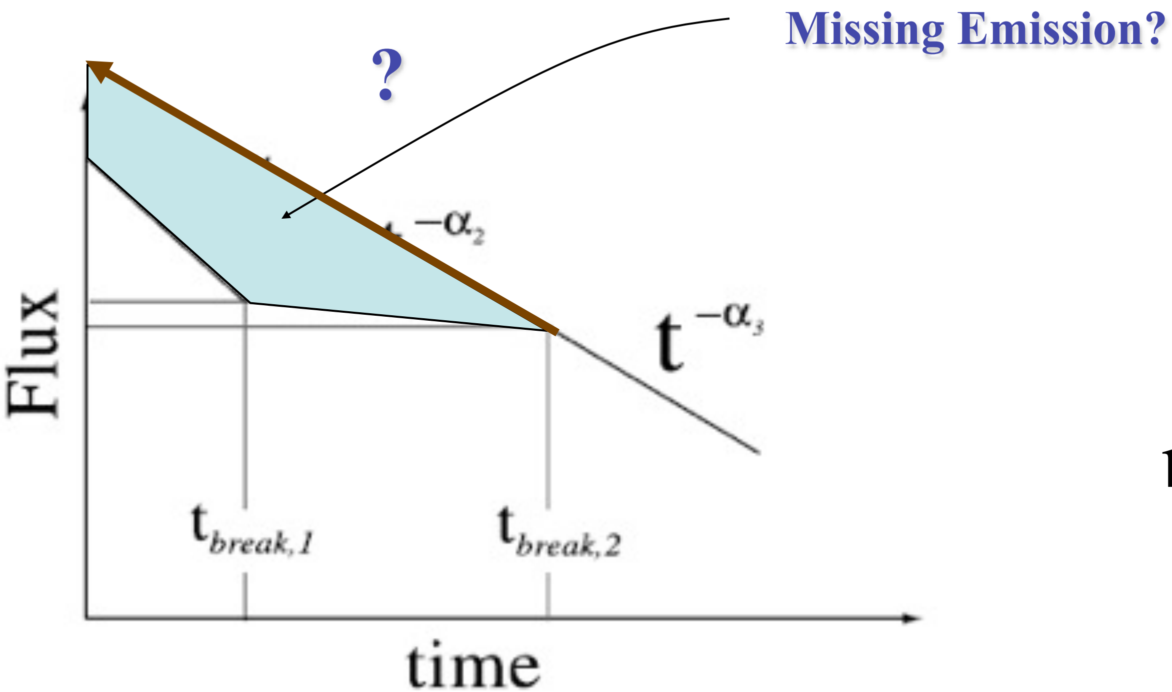

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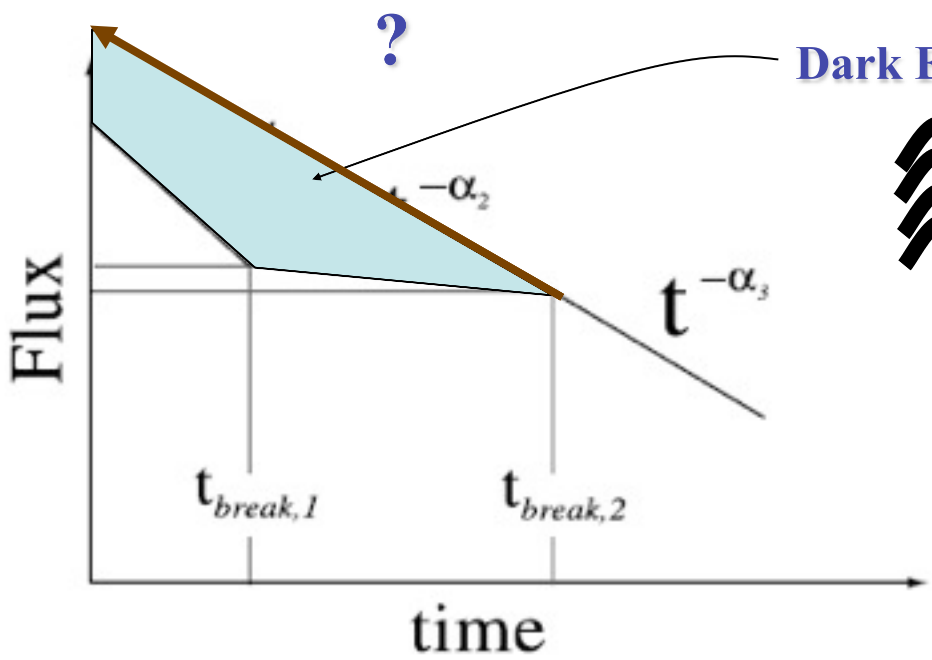

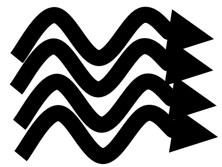

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