GRB Central Engine and Compact Star Connection

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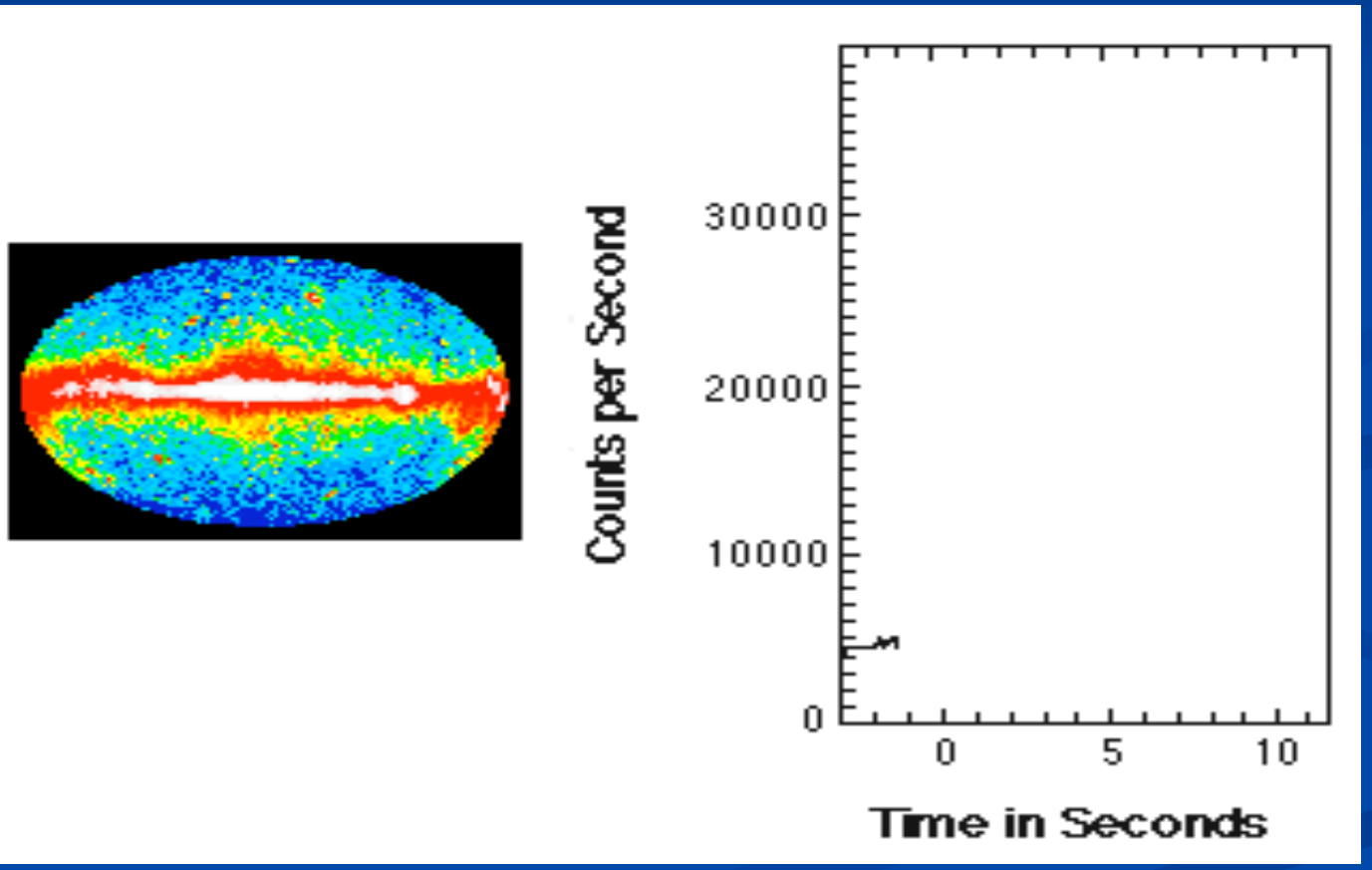
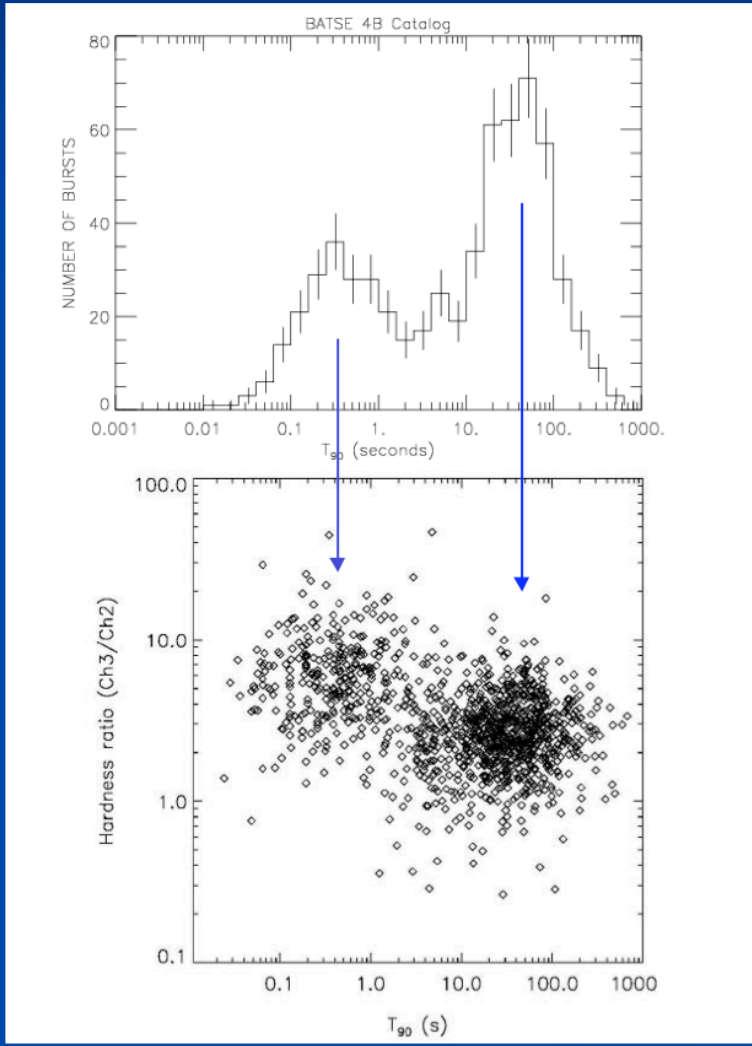
Plan of the talk

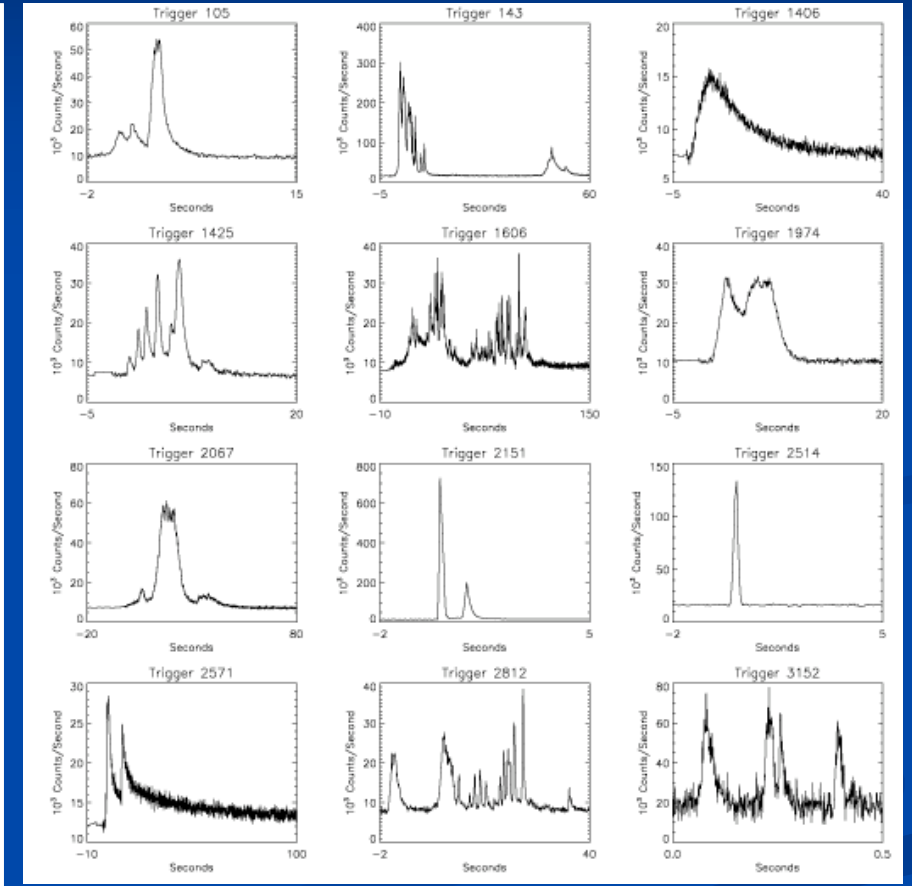
- To address a special audience: compact star and QCD community, who cares about the central engine (not the emission region) of GRBs
- Focus on the required GRB central engine properties based on observations
- Briefly comment on some proposed central engine models

GRBs: Bursts of Gamma-rays from Heaven



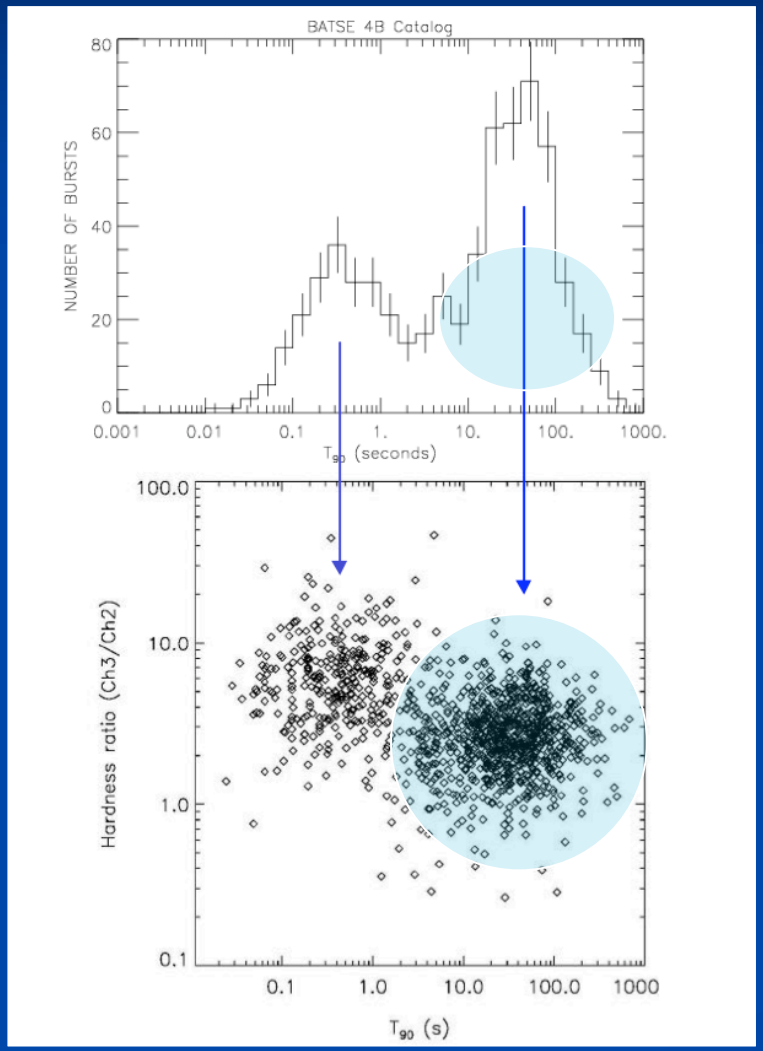
Short/Hard vs. Long/Soft

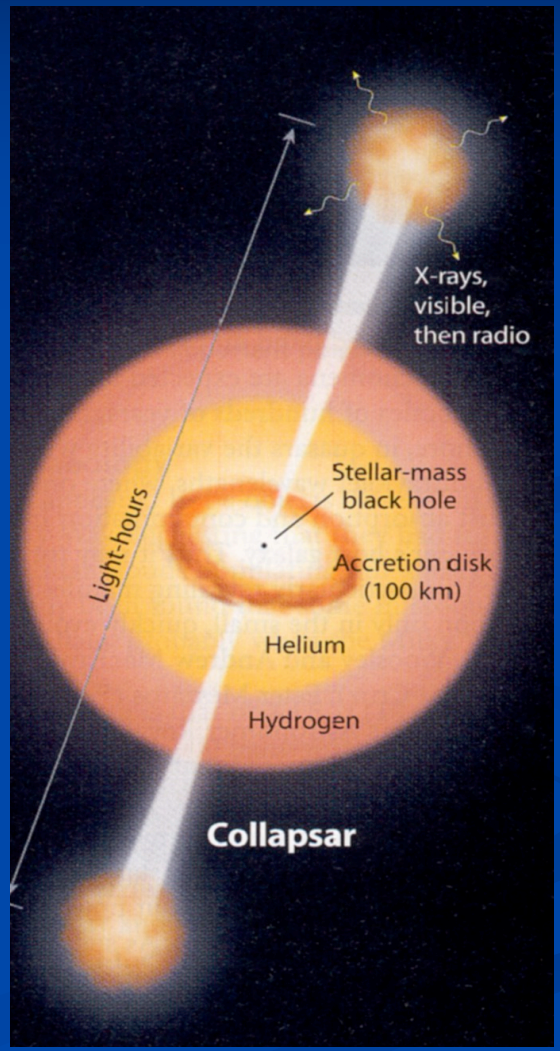




BATSE results (Kouveliotou et al. 1993)

Collapsars: model for long GRBs



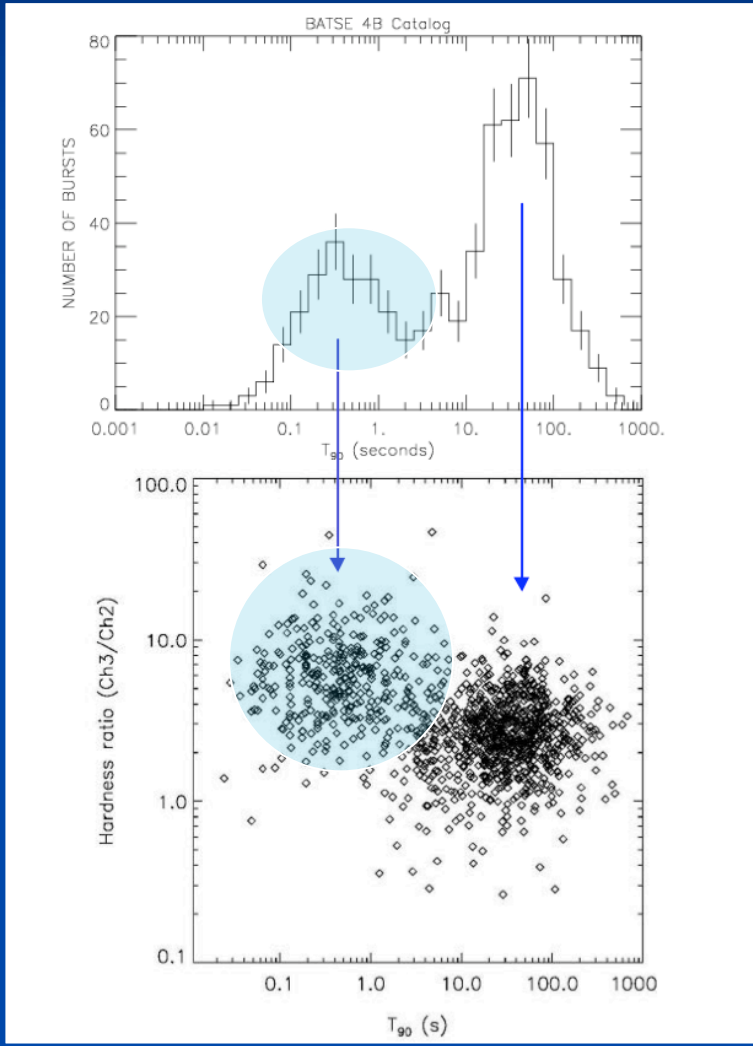


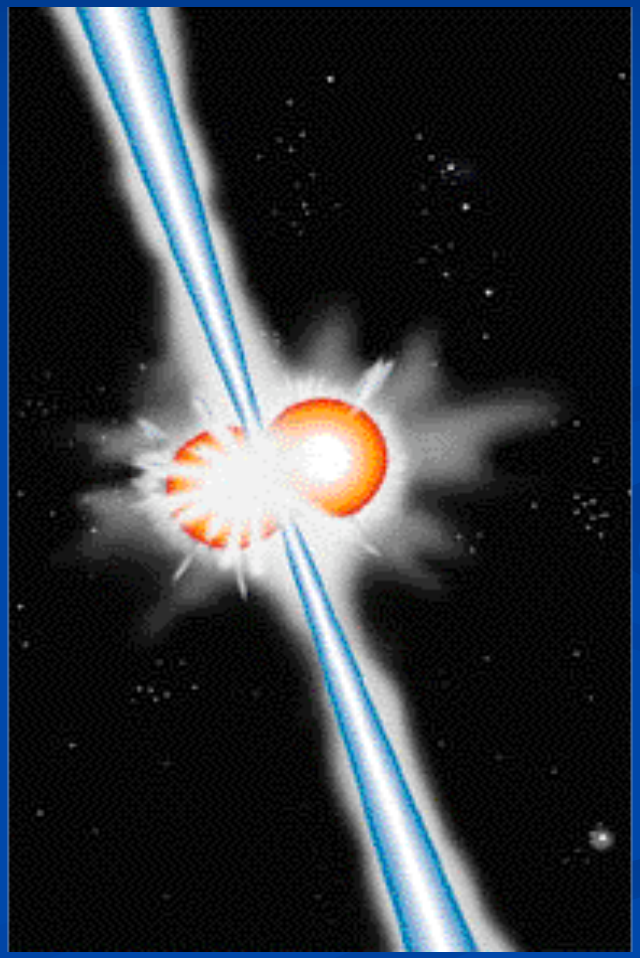
Beppo-SAX
HETE-2 era

Woosley 93

MacFadyen &
Woosley 99

Compact star mergers: model for short GRBs





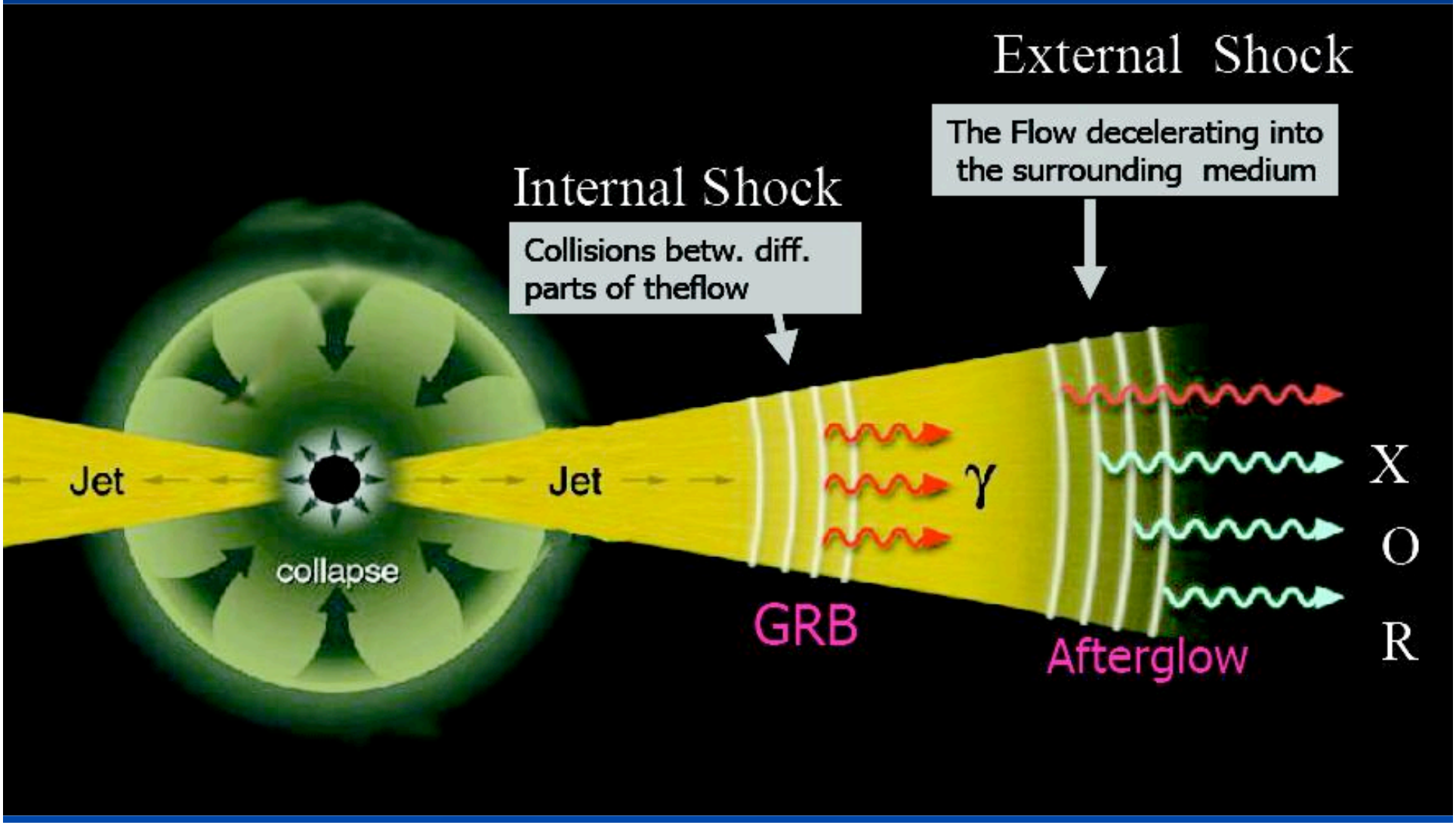
Swift era

Paczynski 86

Eicher et al. 89

"Generic" Fireball Shock Model

(Paczynski, Meszaros, Rees, Sari, Piran, …)



Pros & Cons of a generic emission model

- Pros:
  - Emission properties do not rely on progenitor and central engine, can be studied in a clean manner
- Cons:
  - No clue about the central engine at all!

Fortunately … (or unfortunately)

- The GRB observations suggest that a solely generic model does not interpret everything
  - Disappointment: the model is no longer "clean"
  - Hope: provide some clues to diagnose the central engine

GRB central engine requirements

- Energetic and luminous (E_{iso}~10^{49}-10^{55} erg, L_{iso}~10^{47}-10^{53} erg/s)
- Clean - relativistic ejecta
- Rapid variability, diverse temporal behavior
- Intermittent, delayed activity with reducing amplitudes
- A possible steady component (due to spindown)?
- A Poynting flux dominated ejecta?

Requirement 1:

Energetics & Luminosity

Distance and Energetics

Galactic halo:

$$L_\gamma(\mathrm{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{42}\,\mathrm{erg/s}\left(\frac{d}{30\mathrm{kpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\mathrm{erg/s/cm^2}}\right)$$

Cosmological:

$$L_\gamma(\mathrm{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{51}\,\mathrm{erg/s}\left(\frac{d}{1\mathrm{Gpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\mathrm{erg/s/cm^2}}\right)$$

For comparison:

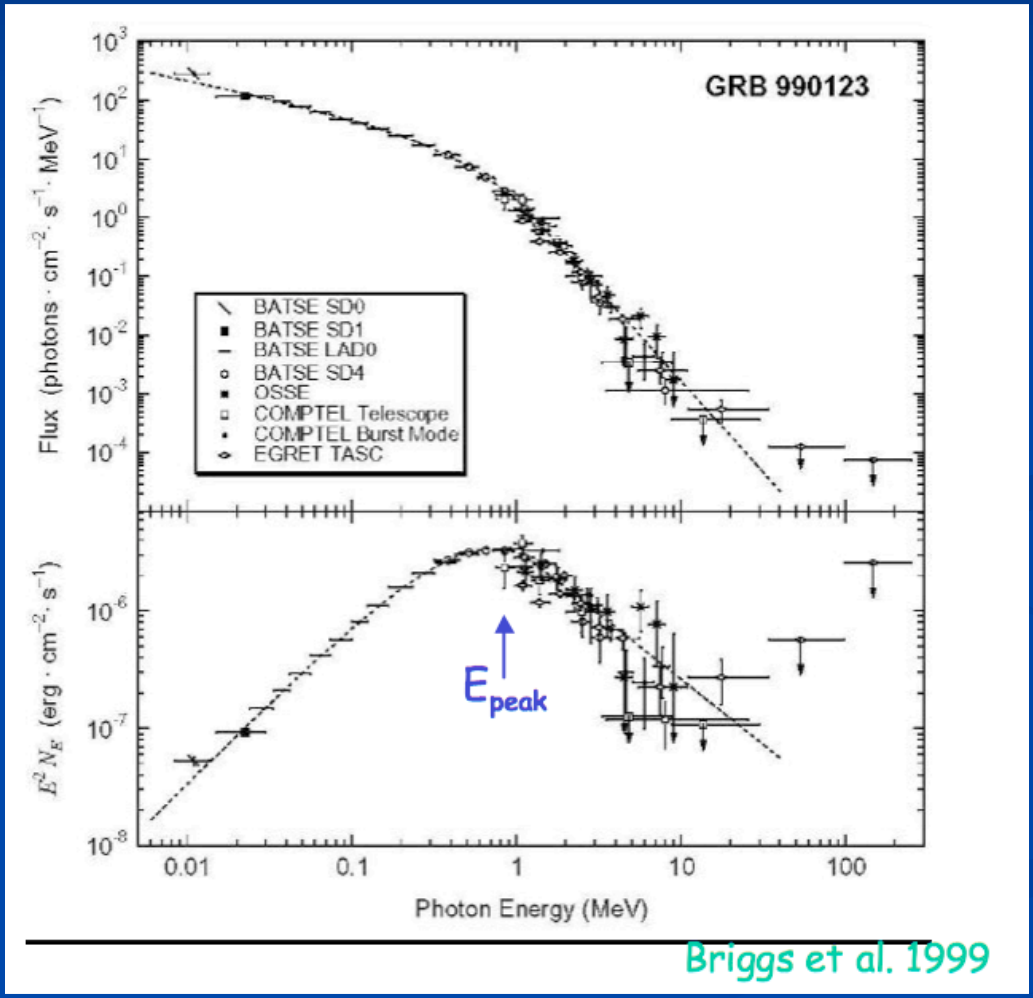
$$L_\odot \sim 10^{33}\,\mathrm{erg/s},\ L_{gal} \sim 10^{44}\,\mathrm{erg/s},\quad L_{\mathrm{AGN,M}} \sim 10^{48}\,\mathrm{erg/s}$$

Energy emitted by a GRB in one second is comparable to -
Energy of Sun emitted in the entire life time: $10^{33}\times3.15\times10^{7}\times10^{11}\sim3\times10^{51}$ erg

Requirement 2:

Low baryon loading

Non-thermal, smoothly joint broken power law spectrum



Photons with energy > 1 MeV observed

Electron rest mass: 0.511 MeV

Two photon production:

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

Relativity at Work

* The huge luminosity of GRBs raises the "Compactness Problem".
* The only solution is that the GRB ejecta is moving with a speed very close to speed of light!
* The central engine must be "clean" to allow very low mass loading

Compactness Problem

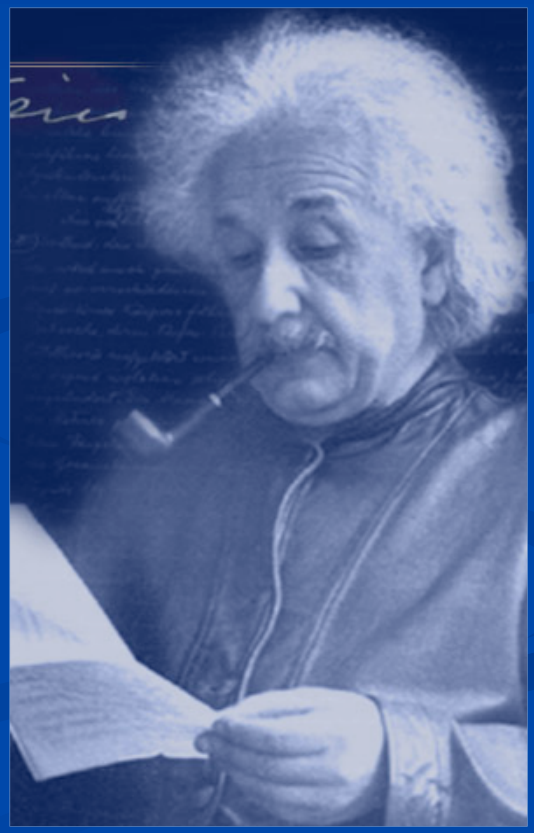
For isotropic emission, total radiated energy

$$E_0 = F(4\pi D^2)$$
$$\approx 10^{51}(F/(10^{-6}\mathrm{ergs/cm^2}))(D/(3\mathrm{Gpc}))^2.$$

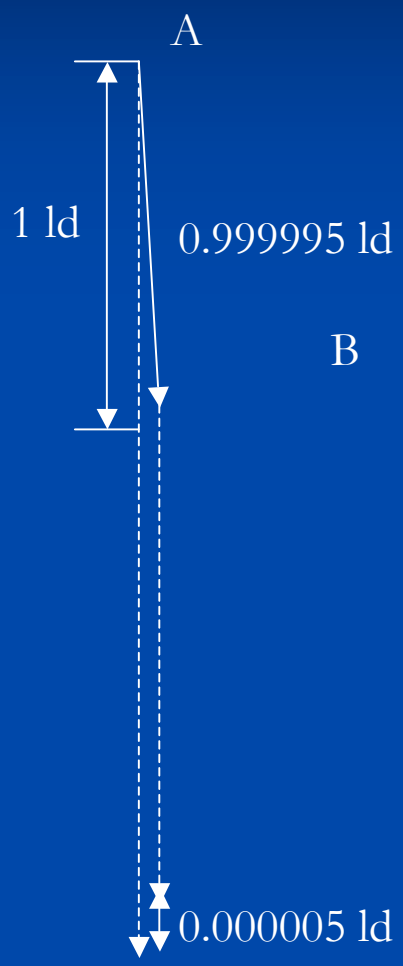
The source size $R_i = c\delta T \simeq 3 \times 10^7\ \mathrm{cm}\delta T_{-3}$. The optical depth for $\gamma\gamma \longrightarrow \mathrm{e^+e^-}$, $\tau_{\gamma\gamma}$, is very large:

$$\tau_{\gamma\gamma} = \frac{f_\mathrm{p}\sigma_\mathrm{T}FD^2}{R_i^2 m_\mathrm{e}c^2}$$
$$\sim 10^{17} f_\mathrm{p}\left(\frac{F}{10^{-6}\mathrm{ergs/cm^2}}\right)\left(\frac{D}{3\ \mathrm{Gpc}}\right)^2\left(\frac{\delta T}{1\ \mathrm{ms}}\right)^{-2},$$

where f_p denotes the fraction of photon pairs satisfying $\sqrt{E_1 E_2} > \mathrm{m_e\ c^2}$.



Relativity at Work



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The optical depth for
large:

$$\tau_{\gamma\gamma} =$$
$$\sim 10^{17} f_{\rm p}(\frac{F}{10^{-6}\mathrm{ergs/}}$$

where $f_{\rm p}$ denotes the
satisfying $\sqrt{E_1 E_2} >$n

Solution: relativistic fireball

The fireball has to be relativistic:

(1) The minimum size in the emission region is

$$R_{\rm s} = \gamma^2 c\delta T.$$

(2) Photons are blueshifted, so in the comoving frame, the factor $f_{\rm p}$ is lower by a factor of $\gamma^{2\alpha}$, where α is the spectral index.

Solution:

$$\tau_{\gamma\gamma} = \frac{f_{\rm p}}{\gamma^{2\alpha}}\frac{\sigma_{\rm T} F D^2}{R_{\rm s}^2 m_{\rm e} c^2}$$
$$\approx \frac{10^{17}}{\gamma^{(4+2\alpha)}} f_{\rm p}(\frac{F}{10^{-6}\mathrm{ergs/cm^2}})(\frac{D}{3\ \mathrm{Gpc}})^2(\frac{\delta T}{1\ \mathrm{ms}})^{-2}.$$

$\tau_{\gamma\gamma} < 1$ requires $\gamma \geq 10^2$. Baryon loading should be small:

$$E_0/(c^2\gamma) \leq 10^{-5}\mathrm{M}_\odot(E_0/(2\times 10^{51}\mathrm{ergs})),$$

Typical speed: v ~ 0.999995 c, or Γ ~ 300

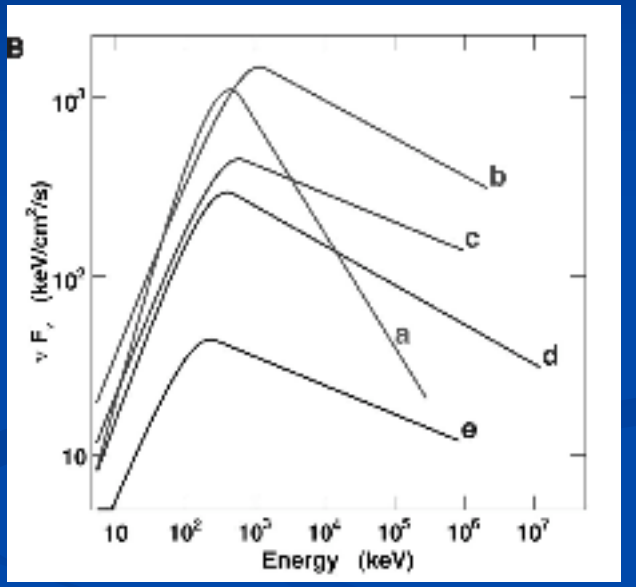
How large is Γ?
Method 1: pair opacity constraint

TABLE 3

LIMITS ON SELECTED BURSTS

GRB	f_1	α	$e_{max}/m_e c^2$	z	$\hat{\tau}$	Limit A	Limit B	Reference
Bursts with Very High Energy Photons								
910503	8.71	2.2	333	1	3.0×10^{12}	**340**	300	1
910601	0.5	2.8	9.8	1	1.8×10^{11}	72	**110**	2
910814	13.5	2.8	117	1	4.7×10^{12}	**200**	190	3
930131	1.95	2.0	1957	1	7.0×10^{11}	**420**	270	4
940217	0.36	2.5	6614	1	1.2×10^{11}	**340**	120	5
950425	1.62	1.93	235	1	6.0×10^{11}	**300**	280	6
990123	1.1	2.71	37	1.6	1.2×10^{12}	150	**180**	7
Bursts with Redshifts								
971214	0.35	2	1	3.42	2.6×10^{12}	192	**410**	8
	0.1	3	1	3.42	7.5×10^{11}	64	**160**	8
980703	0.08	2	1	0.966	2.7×10^{10}	69	**140**	8
	0.02	3	1	0.966	8.0×10^{9}	24	**56**	8
990510	0.1	2	1	1.62	1.2×10^{11}	98	**200**	8
	0.03	3	1	1.62	3.7×10^{10}	34	**79**	8
Unusual Bursts								
980425	0.04	2	1	0.0085	1.0×10^{4}	4.6	**6.4**	8
	0.01	3	1	0.0085	2.9×10^{3}	2.8	**3.8**	8
970417a.....	...	...	2×10^{6}	0.3	8.7×10^{8}	**170**[a]	...	8, 9

Lithwick & Sari (2001)



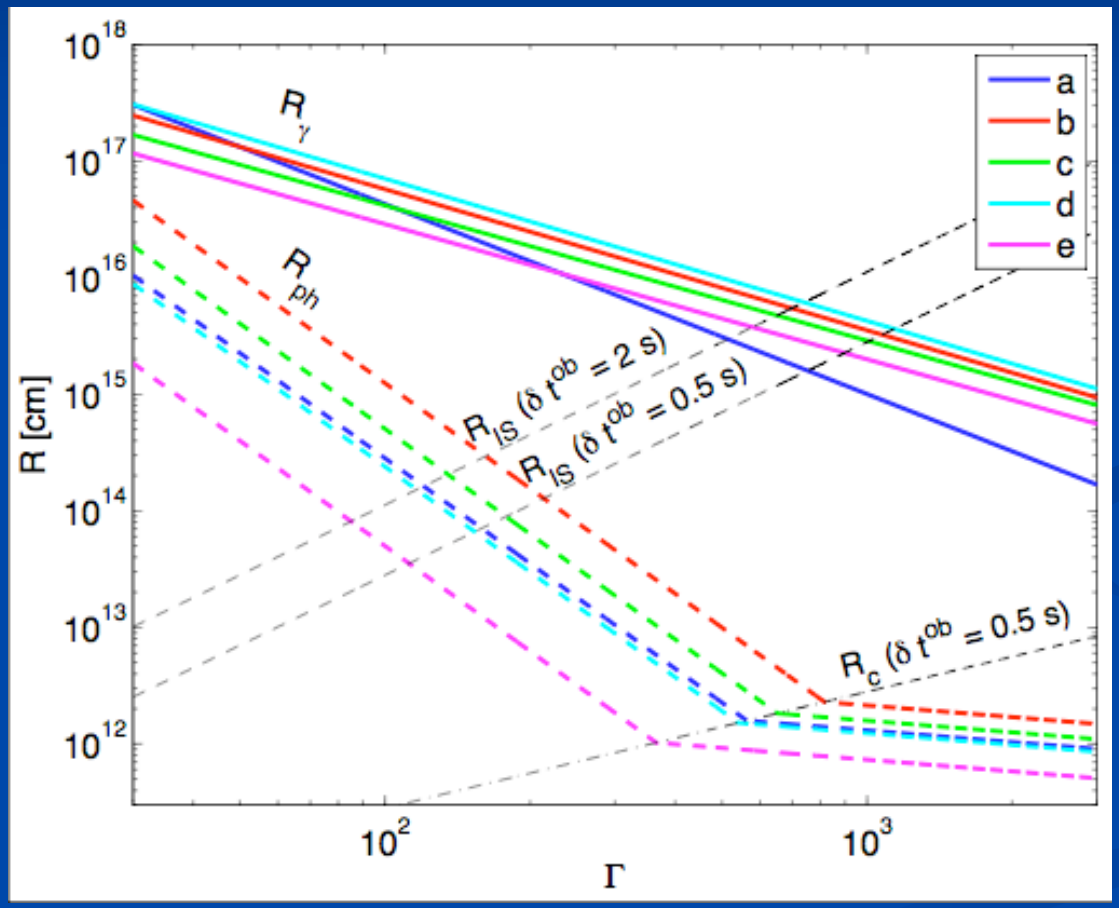
GRB 080916C

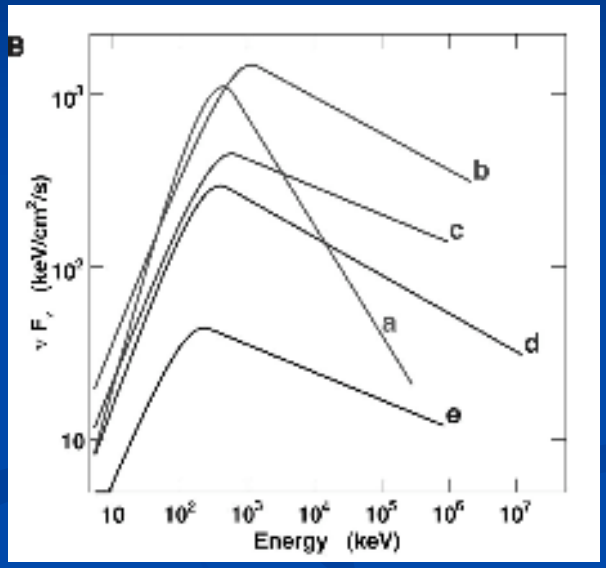
Γ > 800

(Abdo et al. 2009)

Radius-Γ constraints

(Zhang & Pe'er 09)



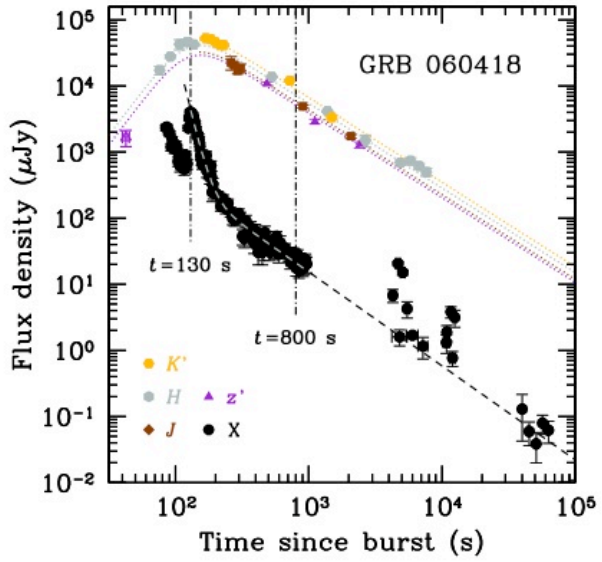


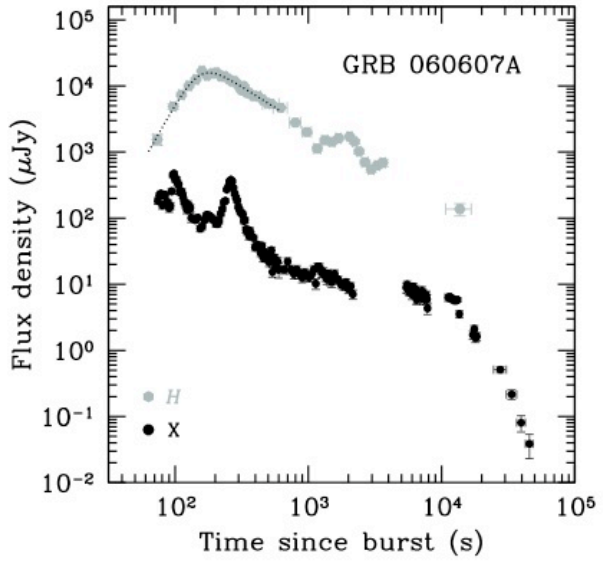
$$\tau_{\gamma\gamma}(E) = \frac{C(\beta)\sigma_T d_z^2 f_0}{-1-\beta}\left(\frac{E}{m_e^2c^4}\right)^{-1-\beta}\frac{1}{R_\gamma^2}\left(\frac{\Gamma}{1+z}\right)^{2+2\beta}$$

$$f_0 = A\cdot\Delta T\left[\frac{E_p(\alpha-\beta)}{(2+\alpha)}\right]^{\alpha-\beta}\exp(\beta-\alpha)(100\ \mathrm{keV})^{-\alpha}$$

How large is Γ?
Method 2: Deceleration time

$$\Gamma(t_{\rm peak}) = \left[\frac{3E_\gamma(1+z)^3}{32\pi n m_{\rm p} c^5 \eta t_{\rm peak}^3}\right]^{1/8} \approx 160 \left[\frac{E_{\gamma,53}(1+z)^3}{\eta_{0.2} n_0 t_{\rm peak,2}^3}\right]^{1/8}, \qquad (1)$$





For both bursts: $\Gamma \sim 400\ (\eta\ n)^{-1/8}$

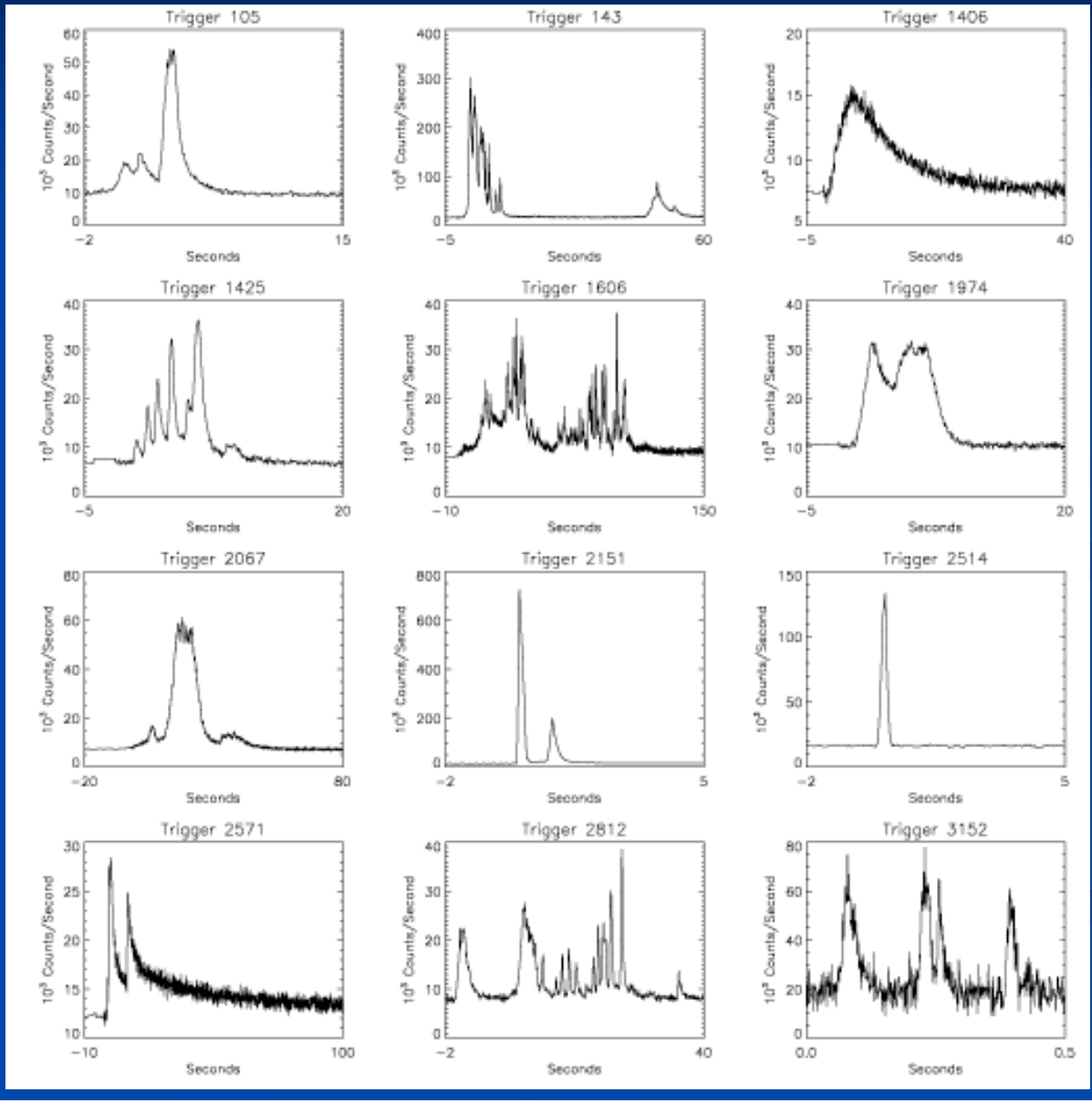
How large is Γ? A Summary

- For normal GRBs Γ is probably between ~30 and ~1000. Typical value is Γ~(300-400)
- Cannot be too low (compactness problem)
- Cannot be too high
  - Γ ~ 400 has been measured in GRB 060418 and GRB 060607A
  - For fireball acceleration, it is hard to accelerate to very high Γ even if the dimensionless entropy is high
  - For magnetic acceleration, σ cannot be extremely high (massive star envelope naturally gives baryon loading to reduce the σ parameter)
- Low-luminosity GRBs and X-Ray Flashes: Γ can be as low as several

Requirement 3:

Rapid Variability, Diverse Temporal Properties

Irregular light Curves



Temporal constraints

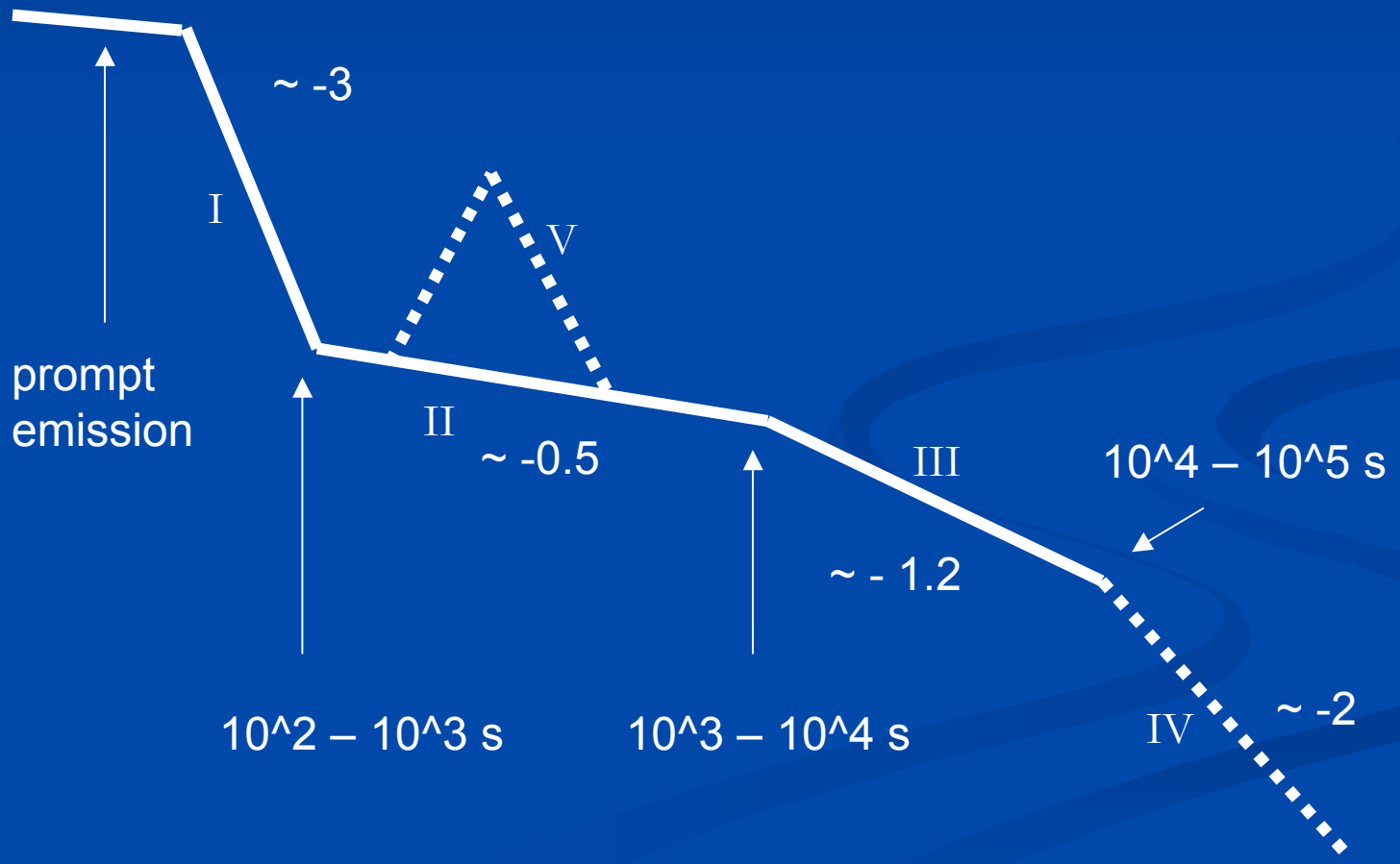
- The shortest variability time scale is sub-millisecond. The size of the central engine should be smaller than 10^7 cm, suggesting a compact star, either a black hole - torus system, or a pulsar-like objects (NS, QS, etc)
- Some bursts are very smooth. The observed variability can be modulated by the stellar envelope, and therefore longer than that of the central engine

Requirement 4:

Delayed Intermittent Activity

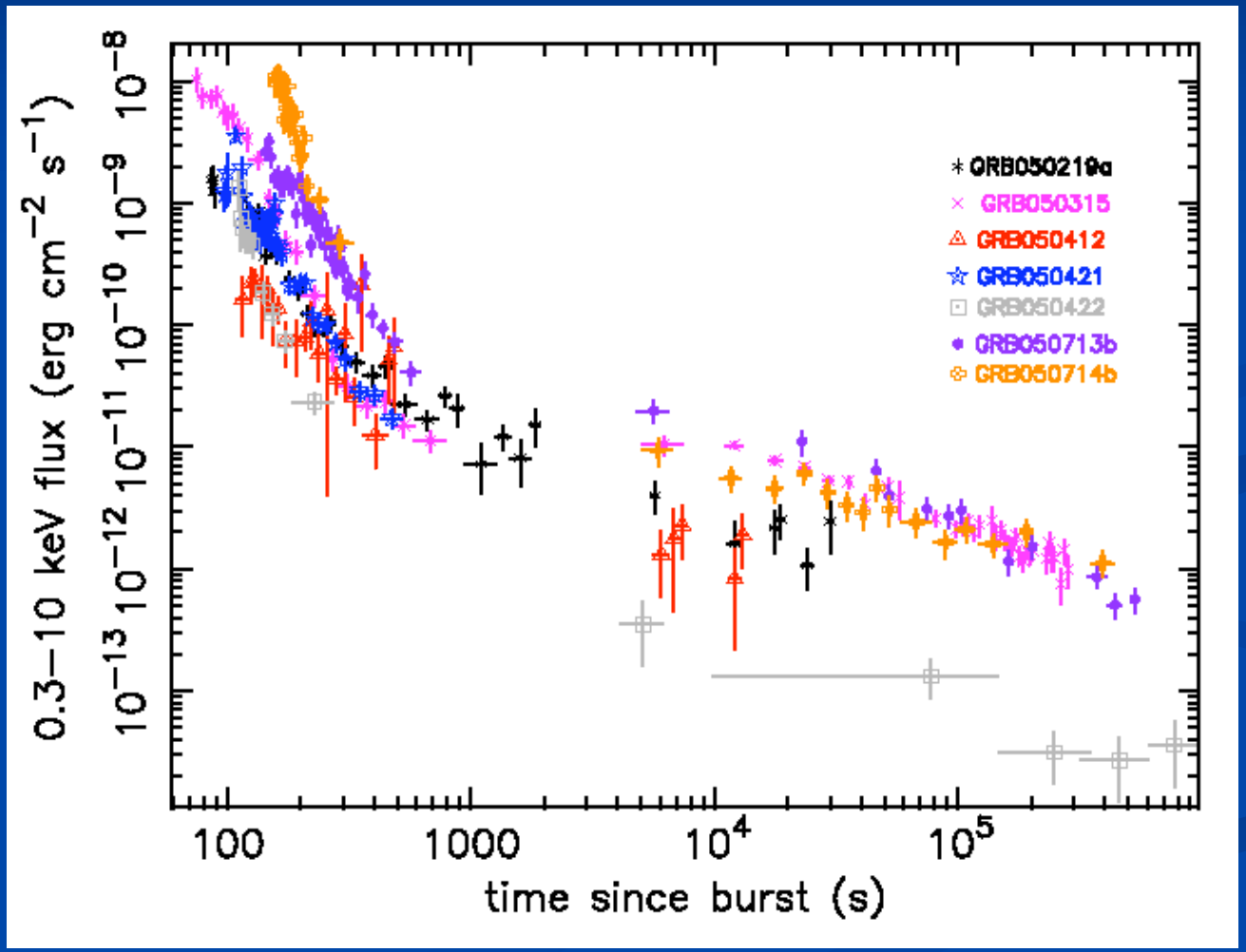
A Canonical X-ray Lightcurve

(Zhang et al. 2006; Nousek et al. 2006; O'Brien et al. 2006)



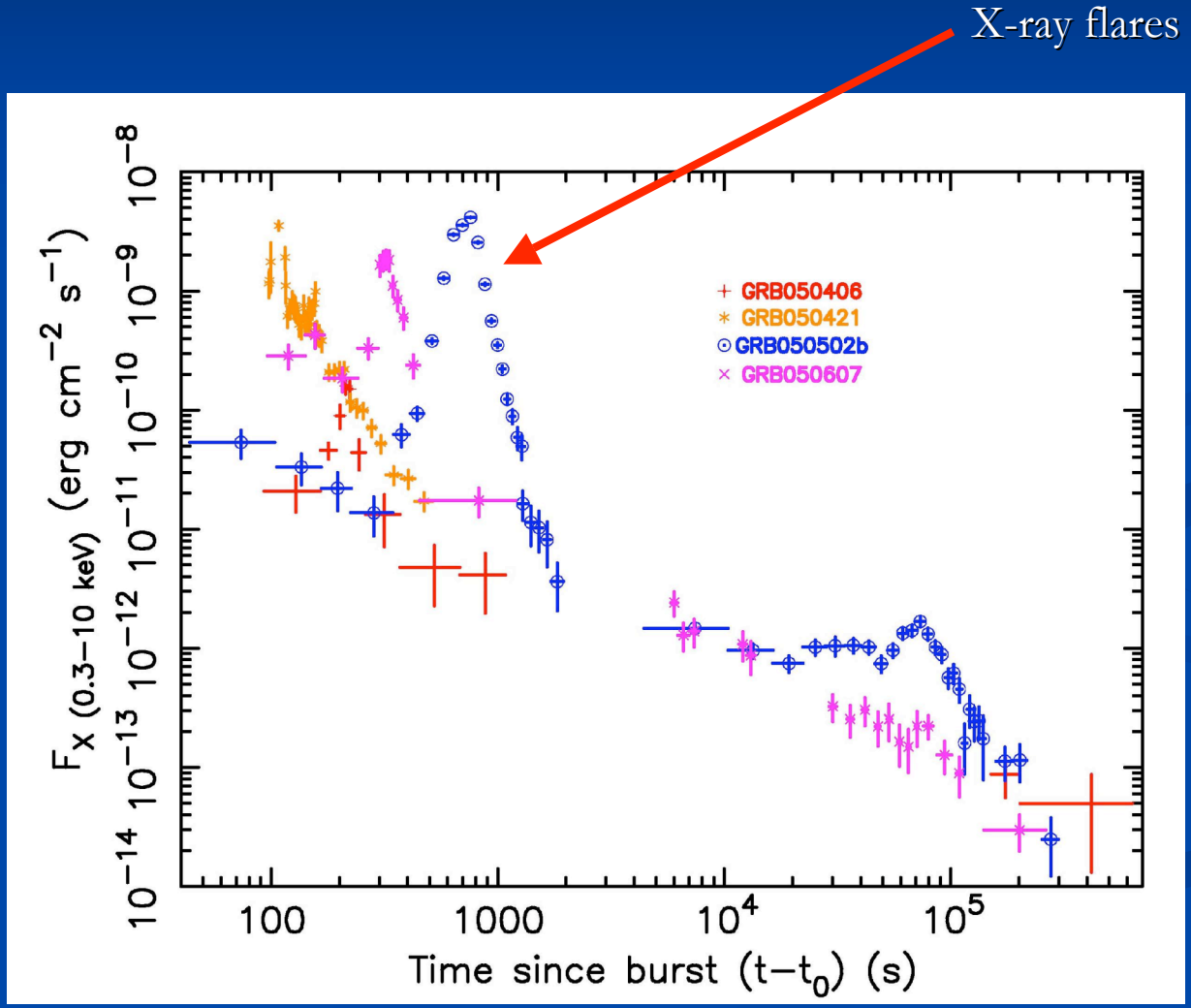
Early XRT afterglow (1)

(Nousek et al. 2006; O'Brien et al., 2006)



Early XRT afterglow (2)

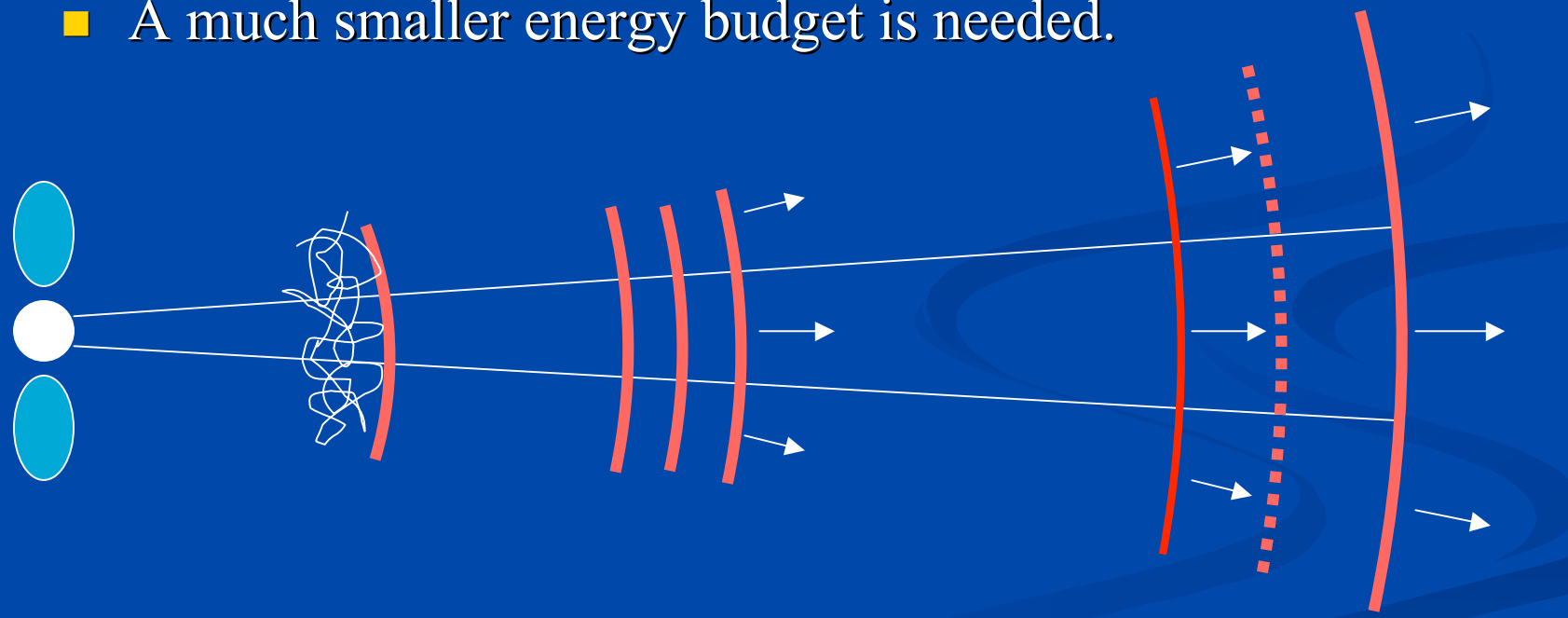
(Nousek et al. 2006; O'Brien et al., 2006)



X-Ray Flares: Late central engine activity

(Burrows et al. 2005; Zhang et al. 2006; Fan & Wei 2005)

- Can naturally interpret rapid rise and rapid fall of the lightcurves.
- A much smaller energy budget is needed.

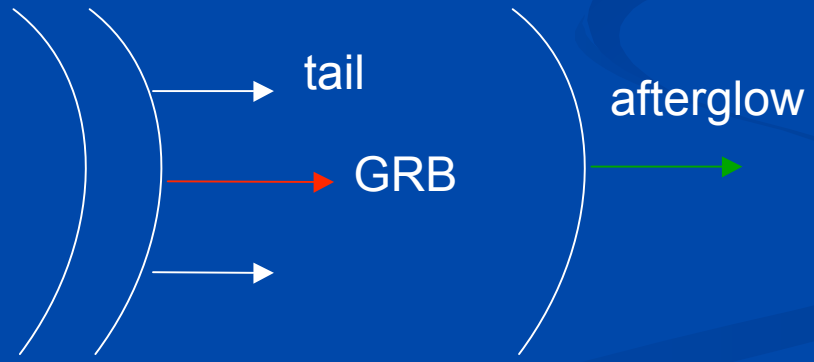


Clue: rapid decay

- Rapid decays are following both prompt emission and X-ray flares
- Very likely it is due to high-latitude emission upon sudden cessation of emission – curvature effect

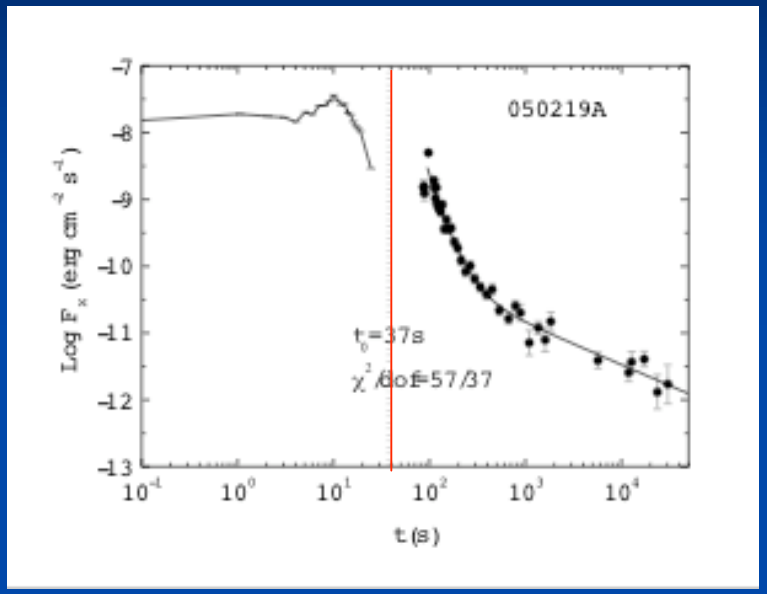
  (Kumar & Panaitescu 2000; Dermer 2004; Zhang et al. 2006; Dyks et al. 2005)

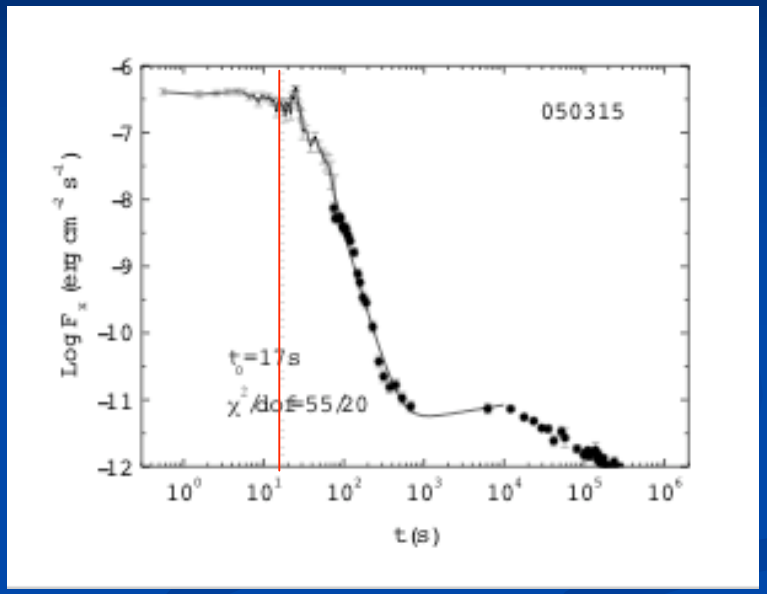
$$\alpha = \beta + 2, \qquad F_\nu = t^{-\alpha}\, \nu^{-\beta}$$

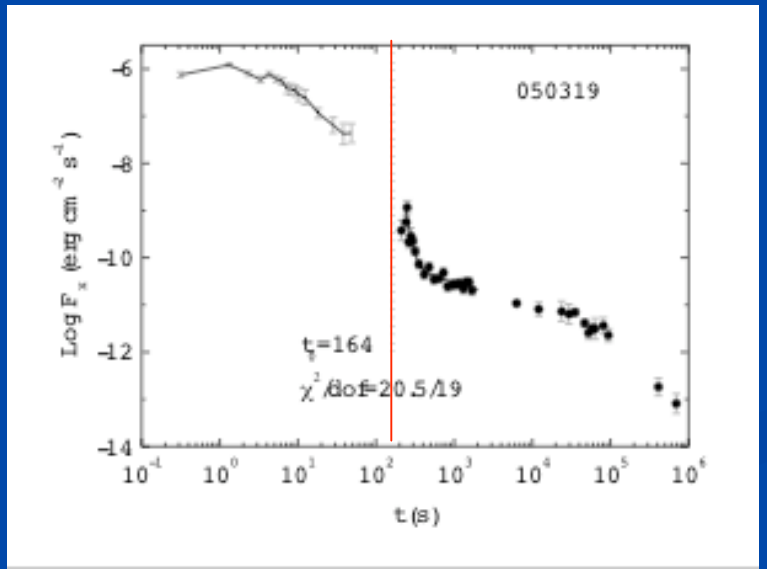


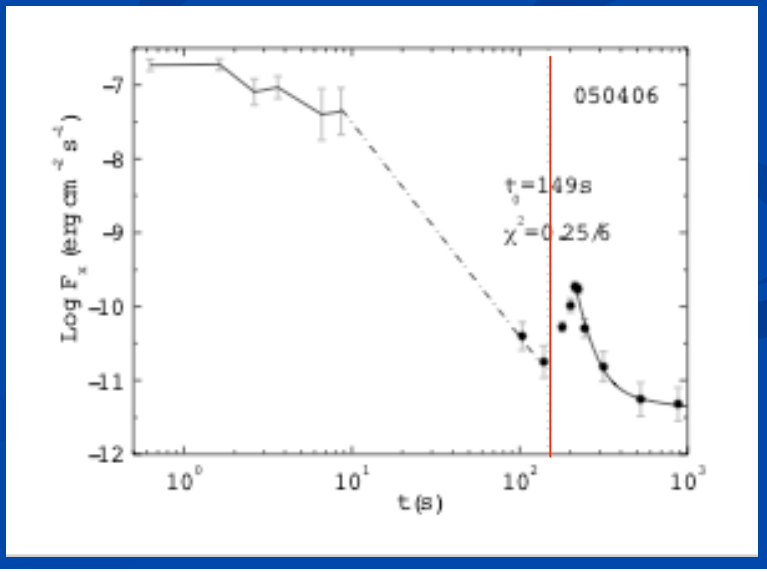
Testing curvature effect interpretation

Liang et al. (2006)









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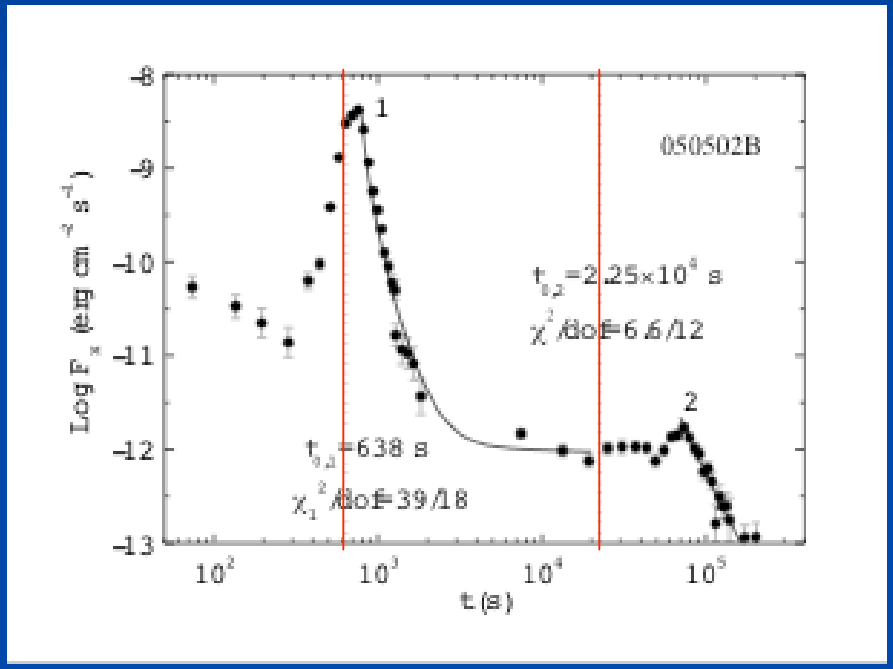
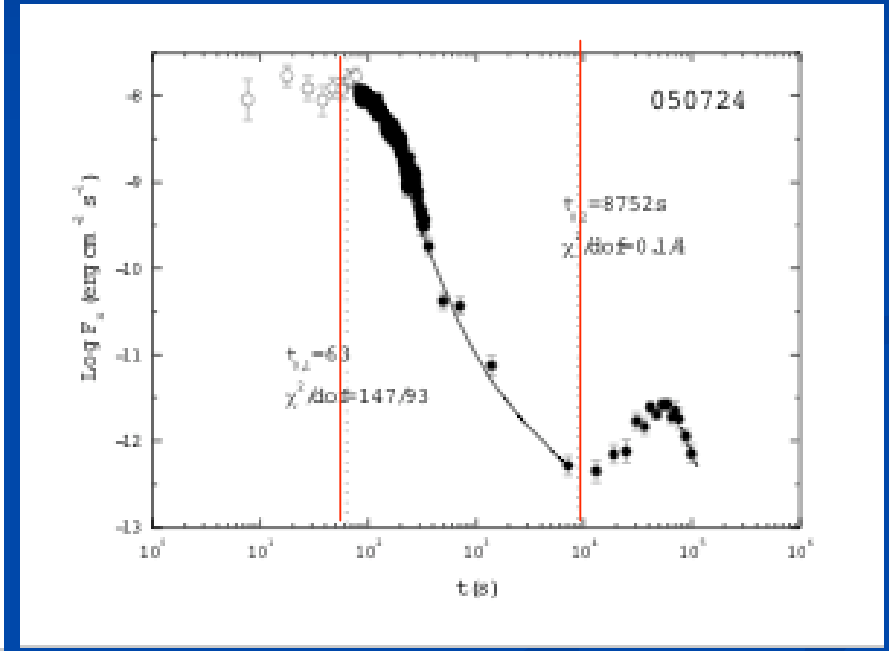




The long GRB 050502B and the short GRB 050724 have similar observational properties!

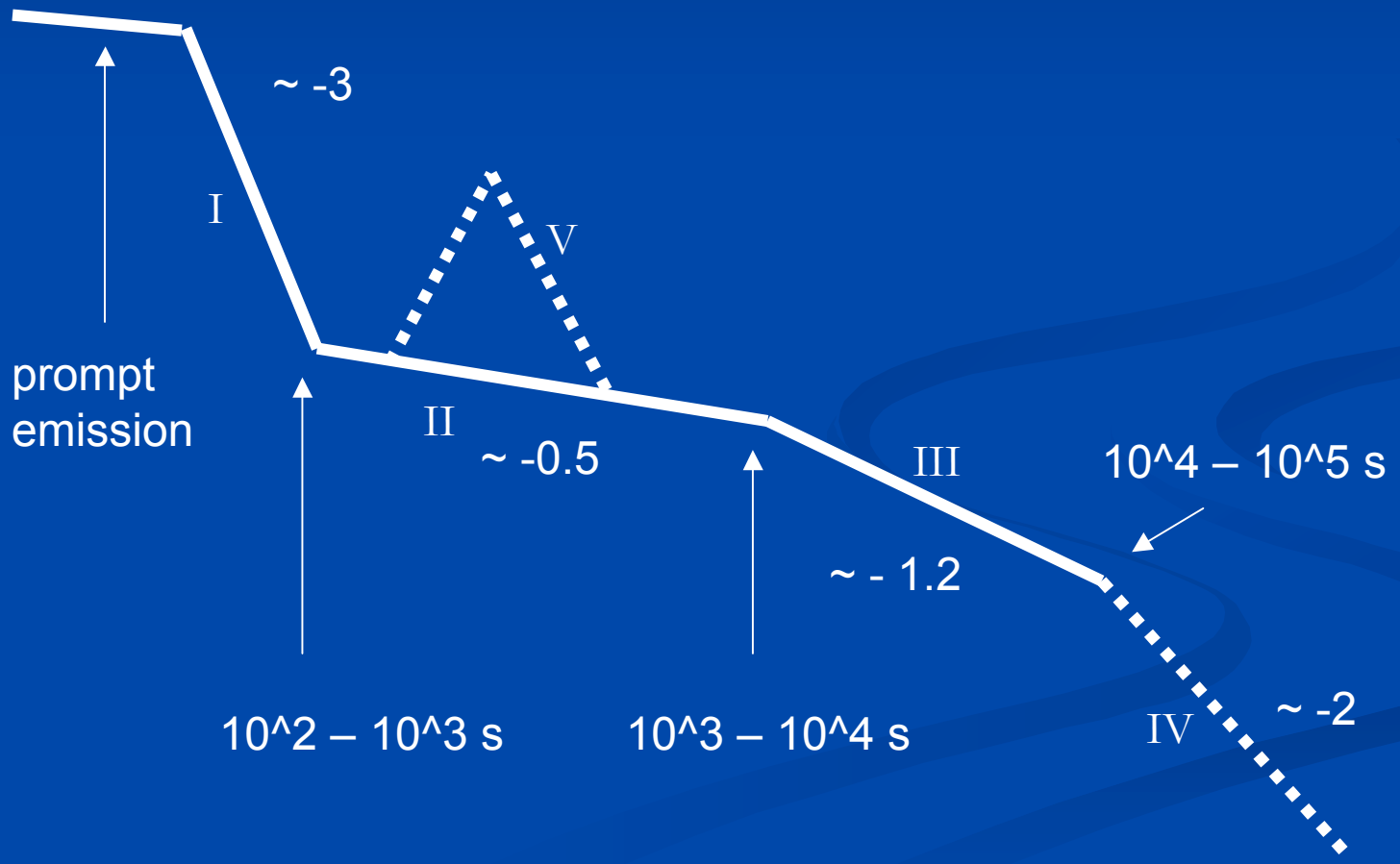
X-ray Flares

Requirement 5:

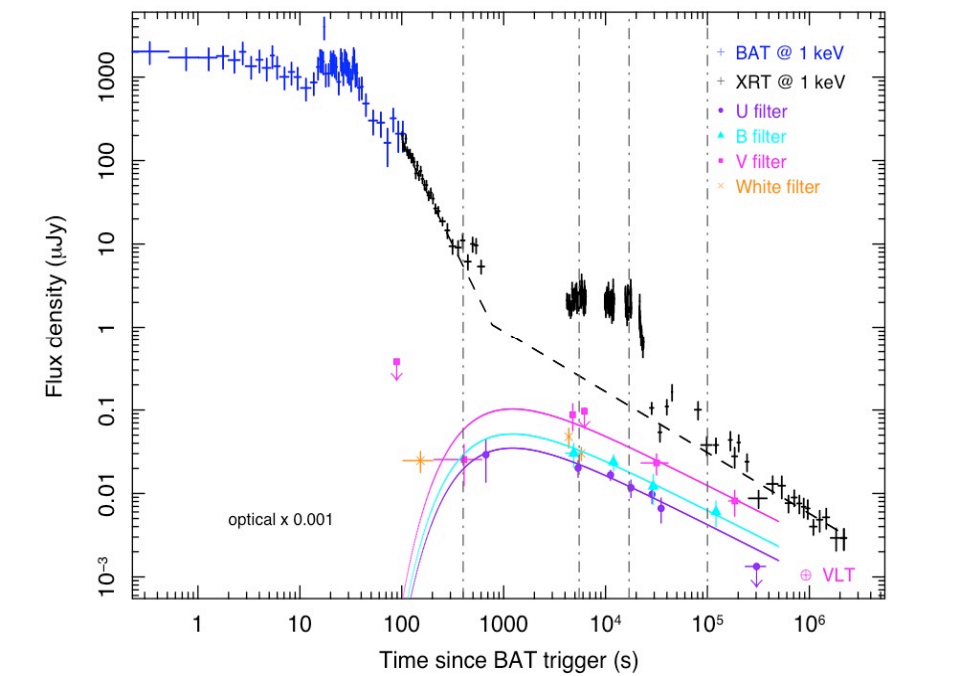
Occasionally a Steady Internal Emission Component?

A Canonical X-ray Lightcurve

(Zhang et al. 2006; Nousek et al. 2006; O'Brien et al. 2006)

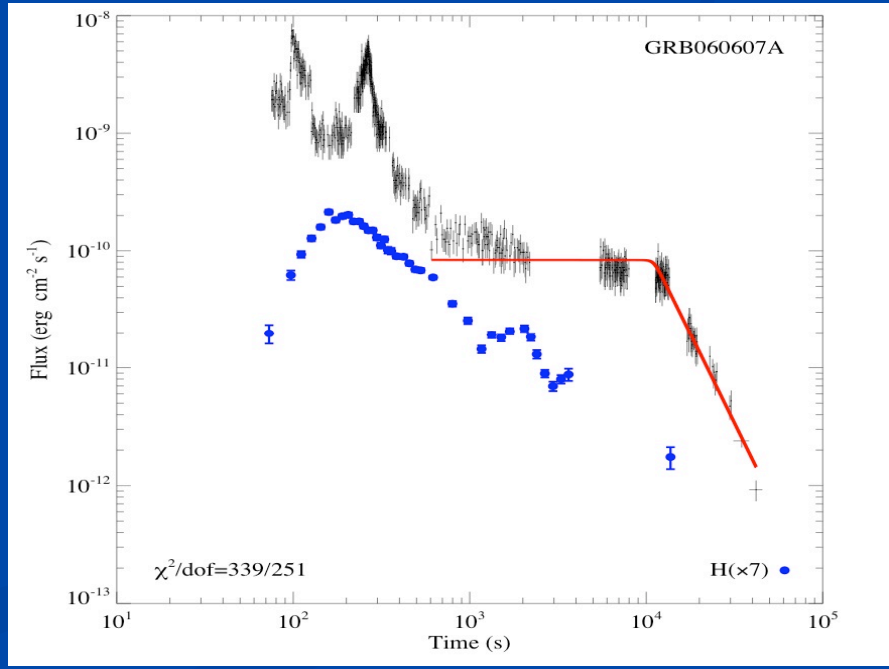


Internal Plateaus?

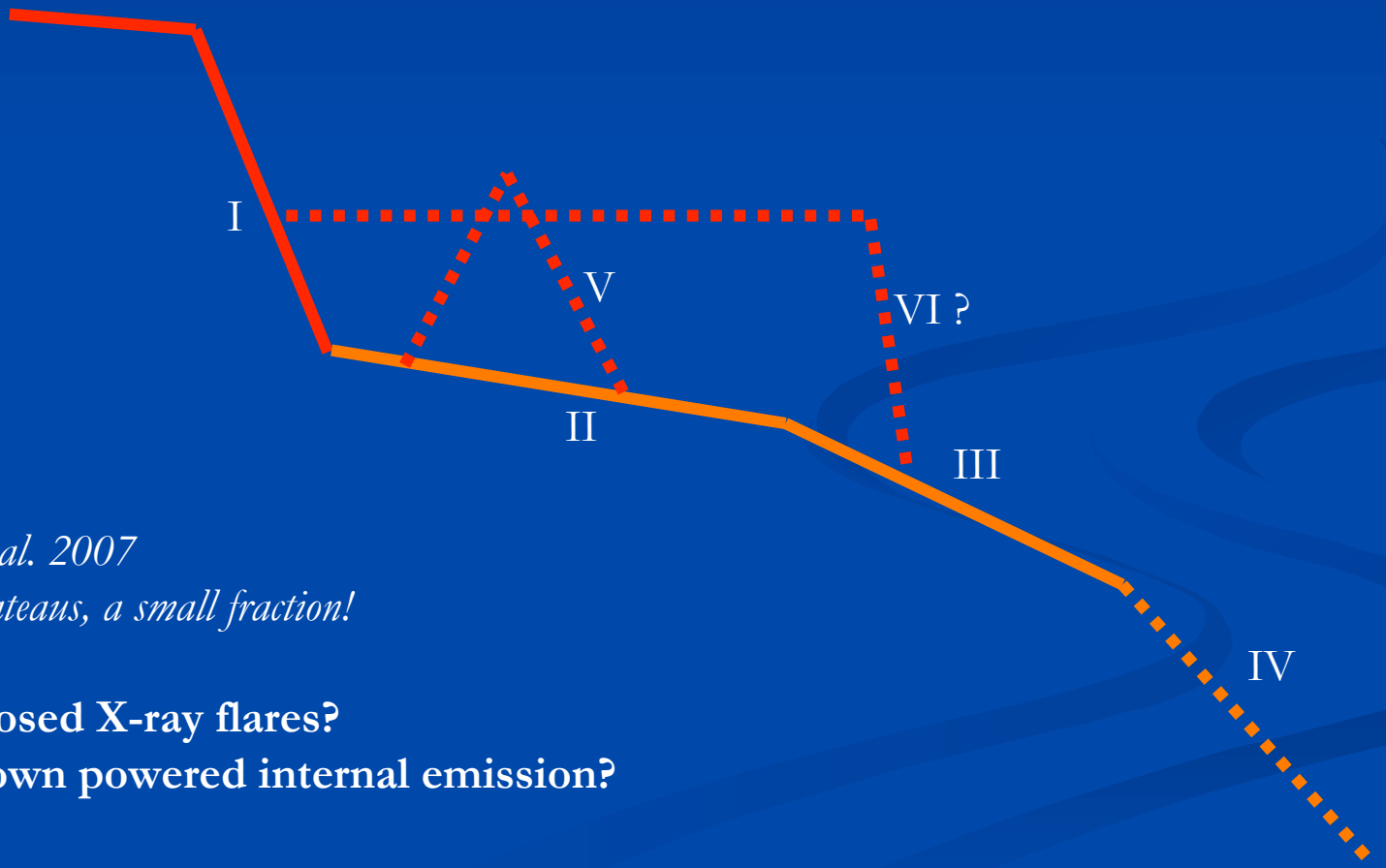


GRB 070110
Troja et al. 2007

GRB 060607A
Liang et al. 2007



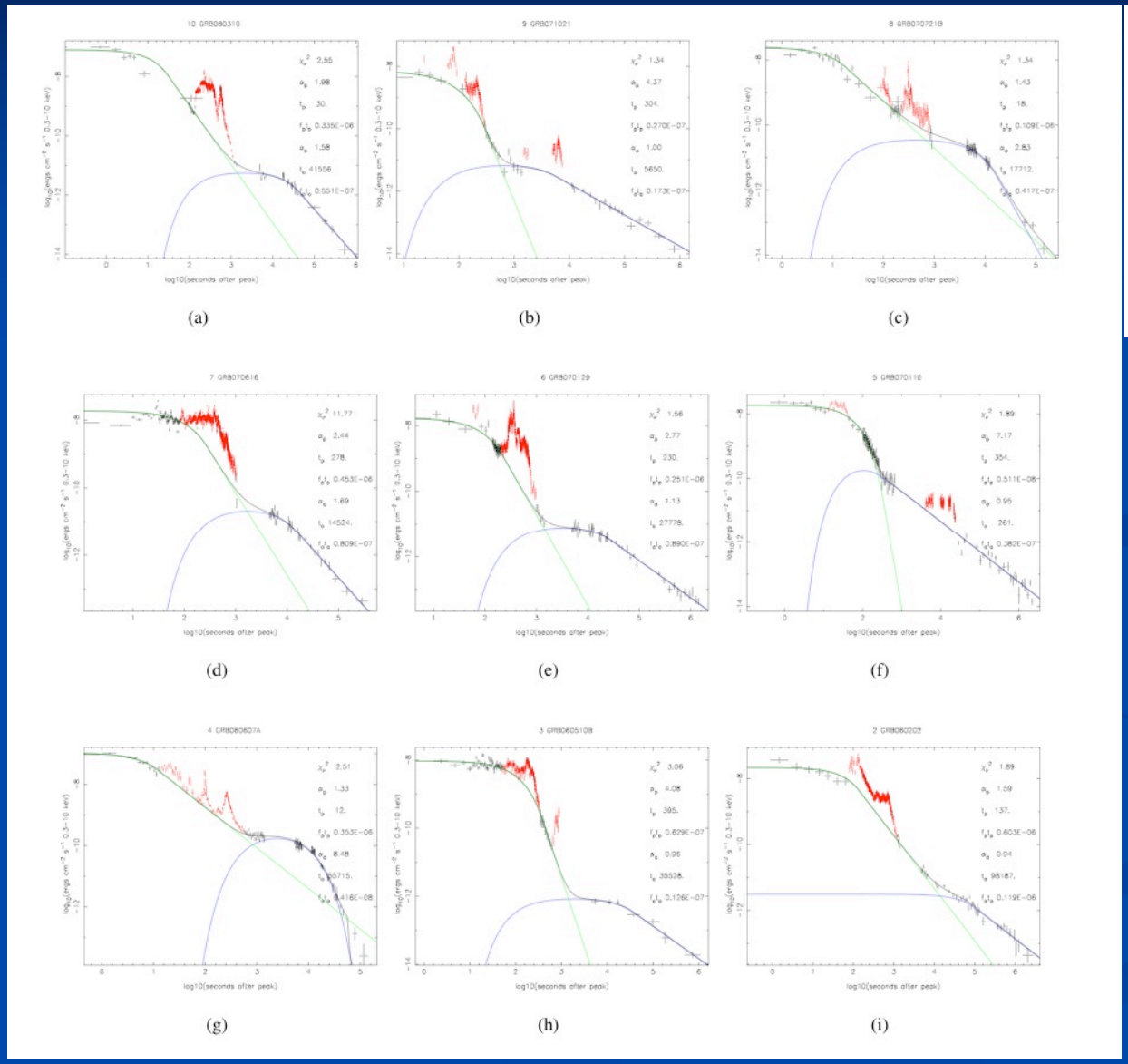
A New Component?

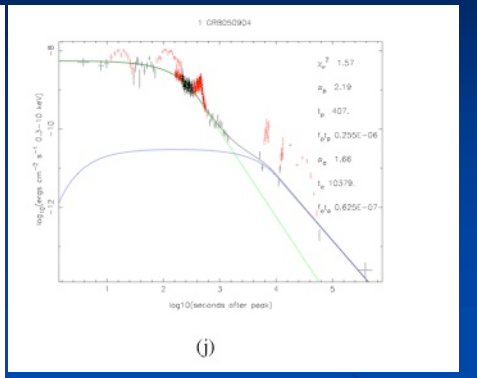


Liang et al. 2007
4/53 plateaus, a small fraction!

Superposed X-ray flares?
Spin-down powered internal emission?

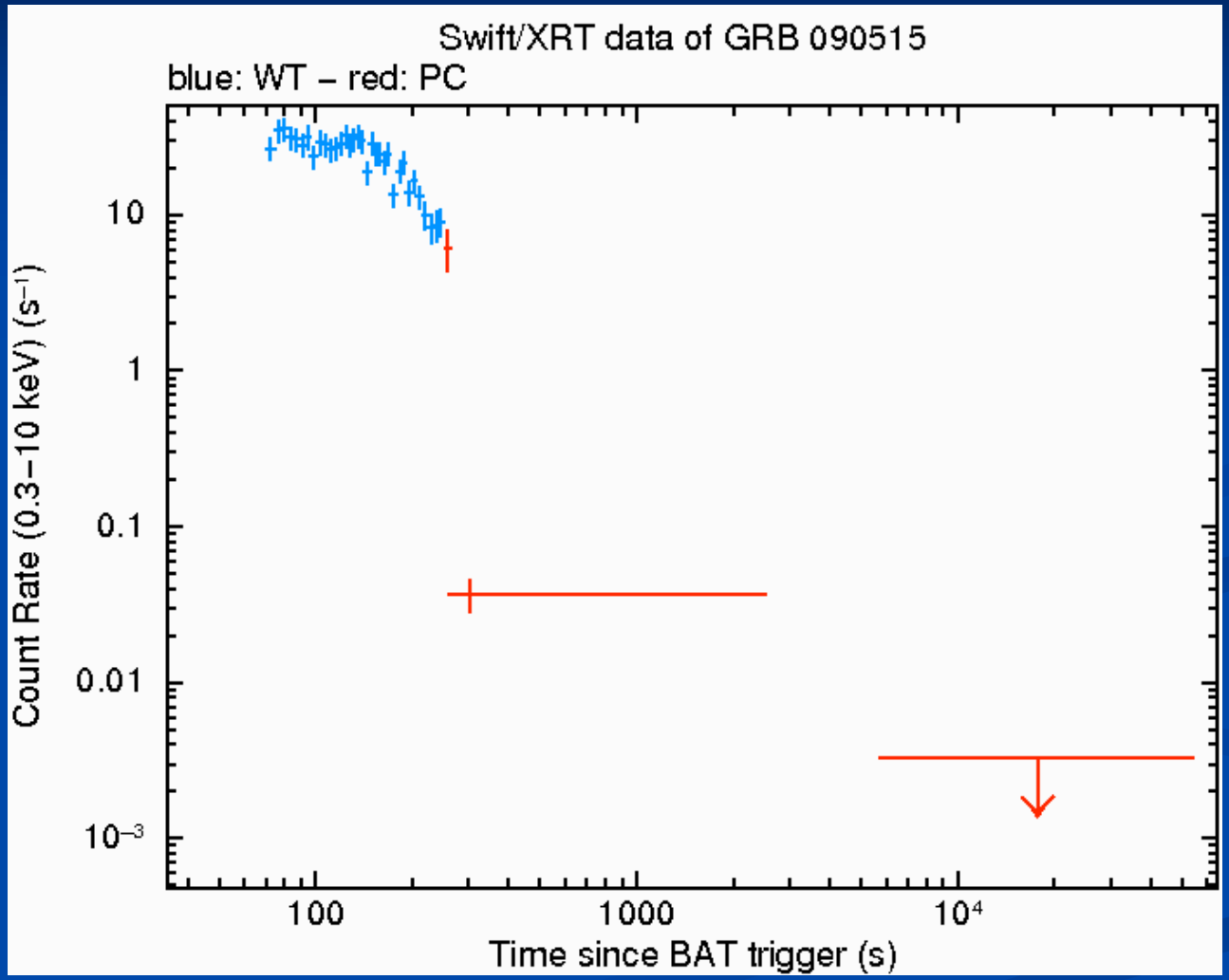
More examples





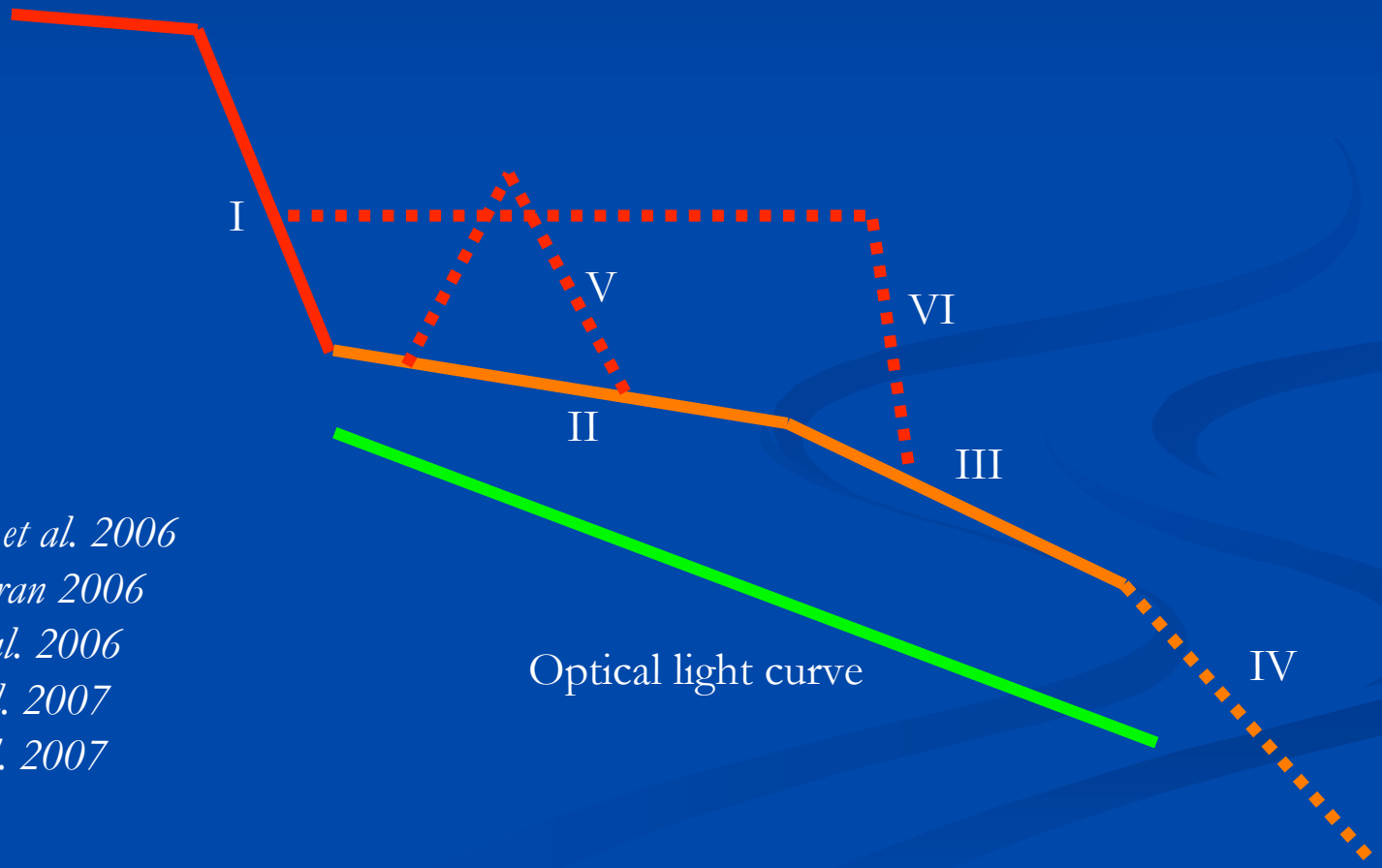
Lyons et al. 2009

GRB 090515



A short GRB followed by an internal plateau - NS-NS merger with a massive NS leftover

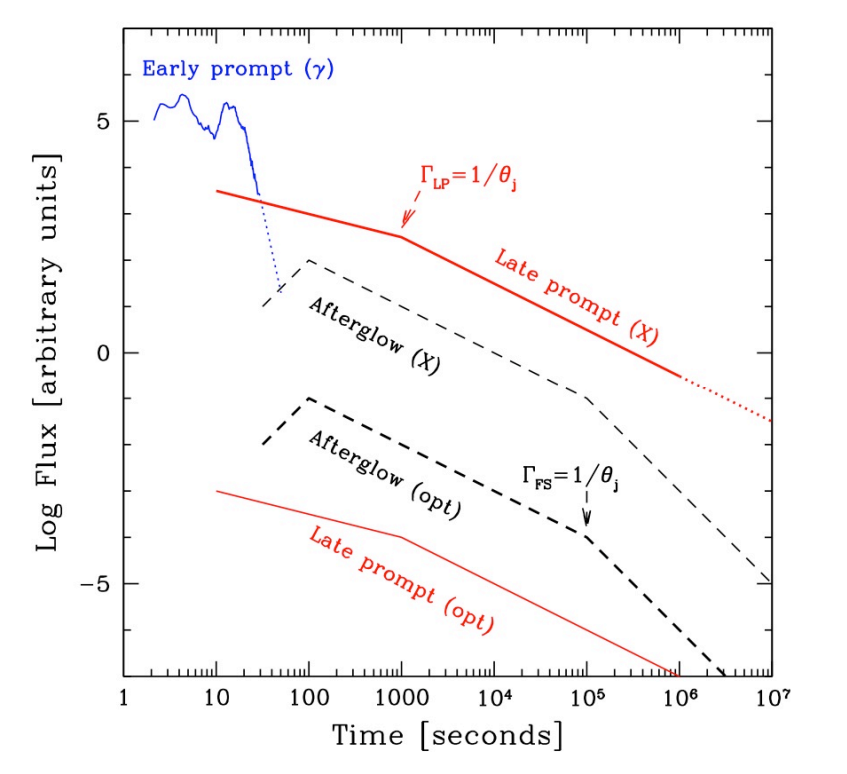
More puzzling: Some "normal" plateaus are chromatic!

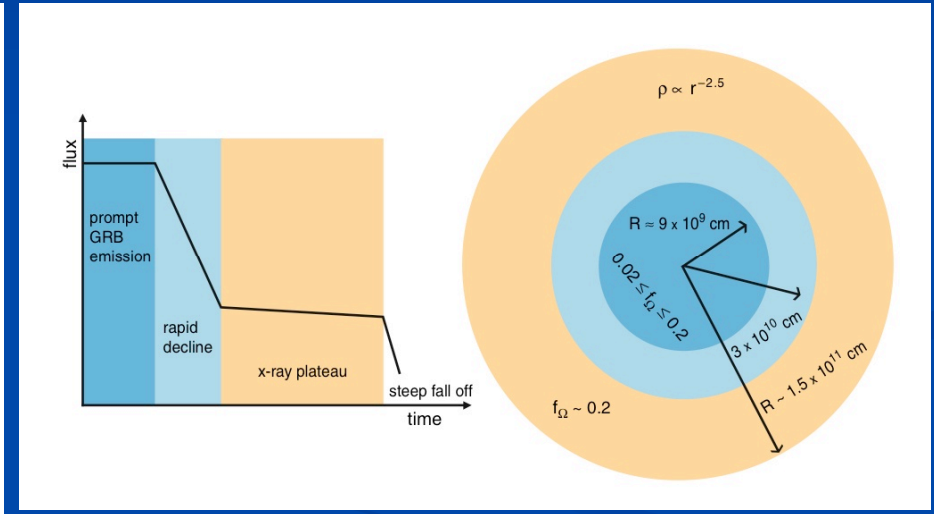


Panaitescu et al. 2006
Fan & Piran 2006
Huang et al. 2006
Urata et al. 2007
Liang et al. 2007

Central-Engine Powered X-Ray Afterglow?

(Ghisellini et al. 2007; Kumar et al. 2008)





Case not conclusive: not a requirement yet

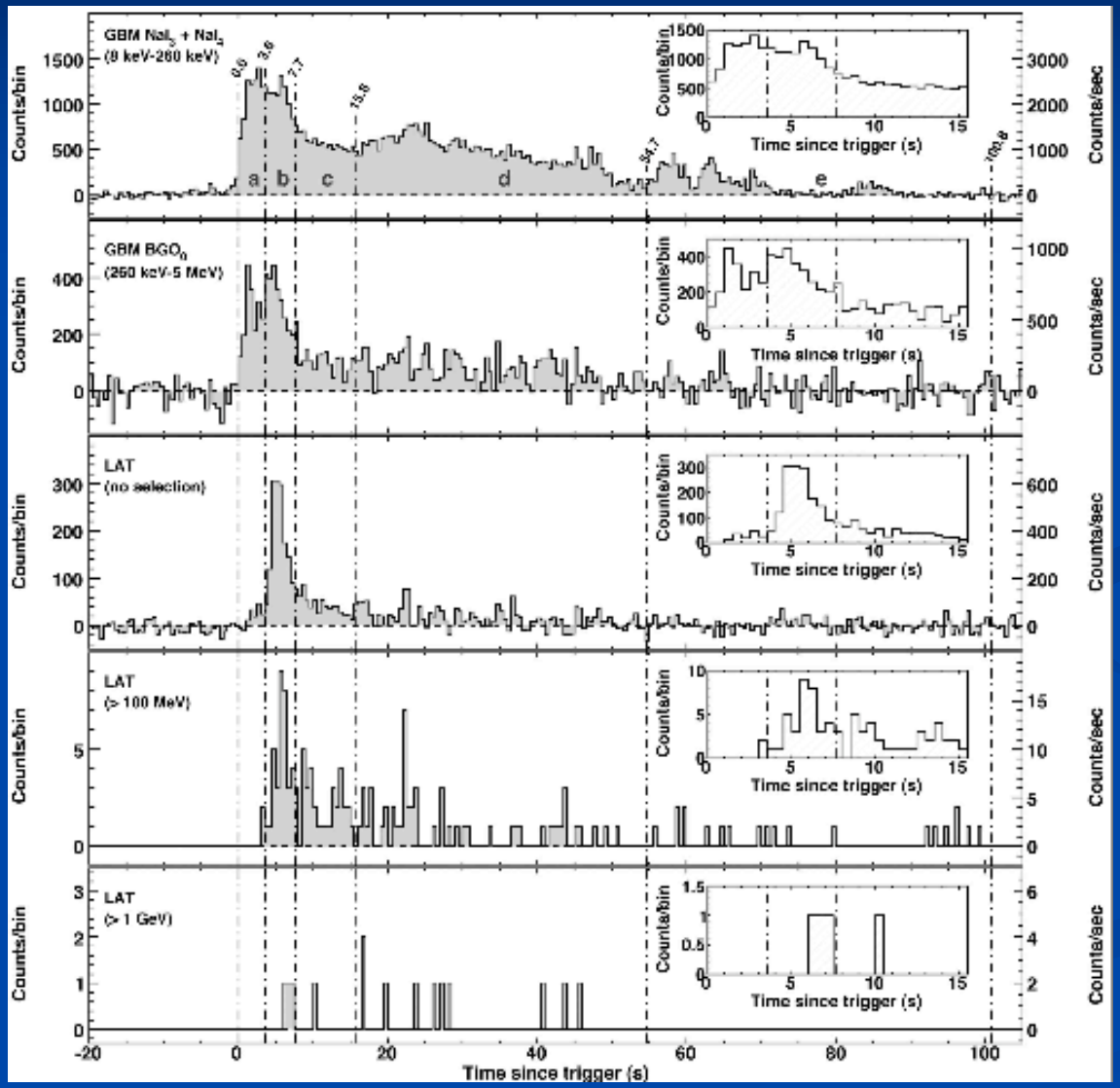
Requirement 6(?):

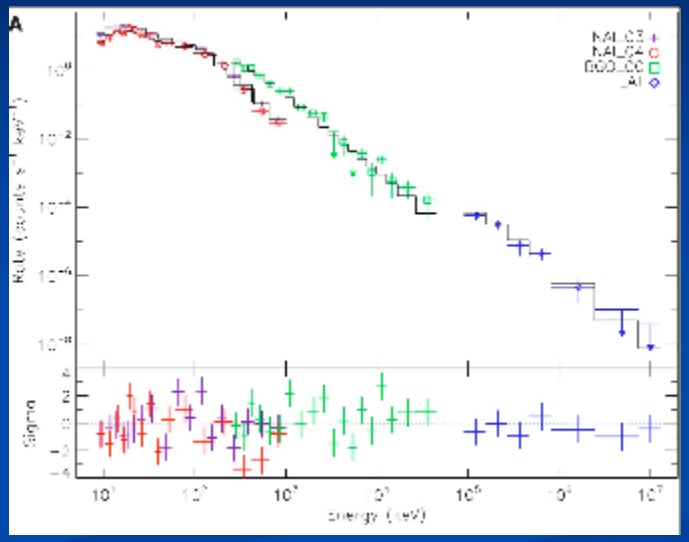
Launching a Poynting Flux Dominated Flow

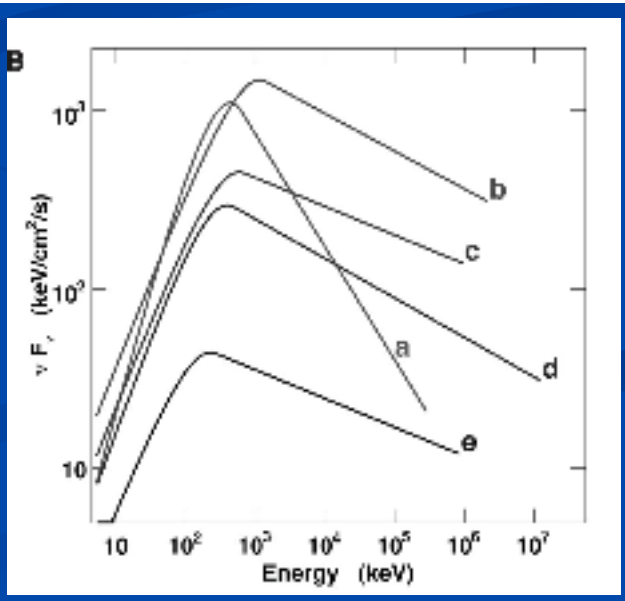
GRB 080916C

(Abdo et al. 2009, Science)

$z = 4.35 \pm 0.15$

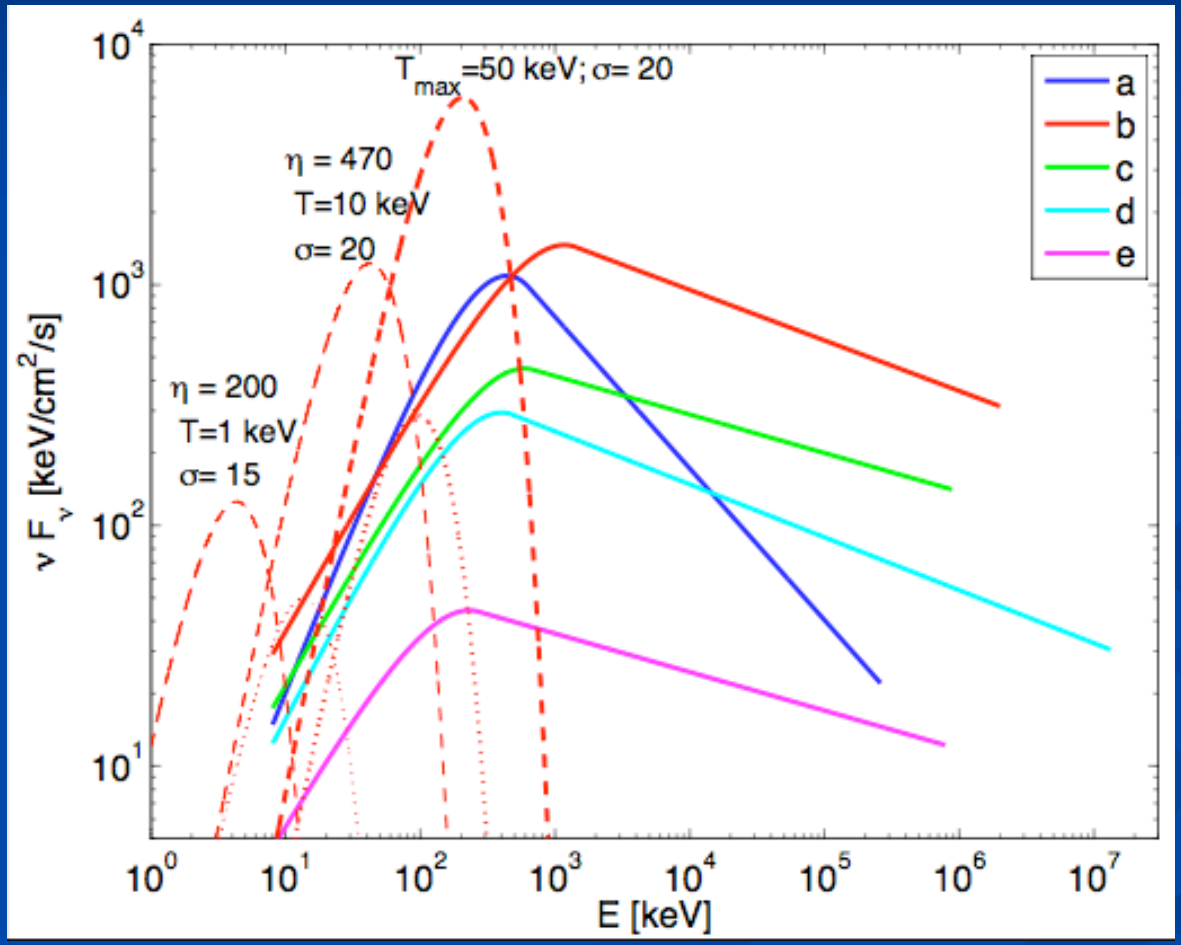






GRBs may not be fireballs!

(Zhang & Pe'er 09)



$\sigma = L_p/L_b$

$\sigma > 20, 15$

The thermal residual emission from the fireball (like CMB) is TOO bright to be consistent with the data - **The flow has to be Poynting-flux dominated!**

GRB Central Engines

- BH - torus system
- Millisecond magnetars
- (Strange) Quark stars

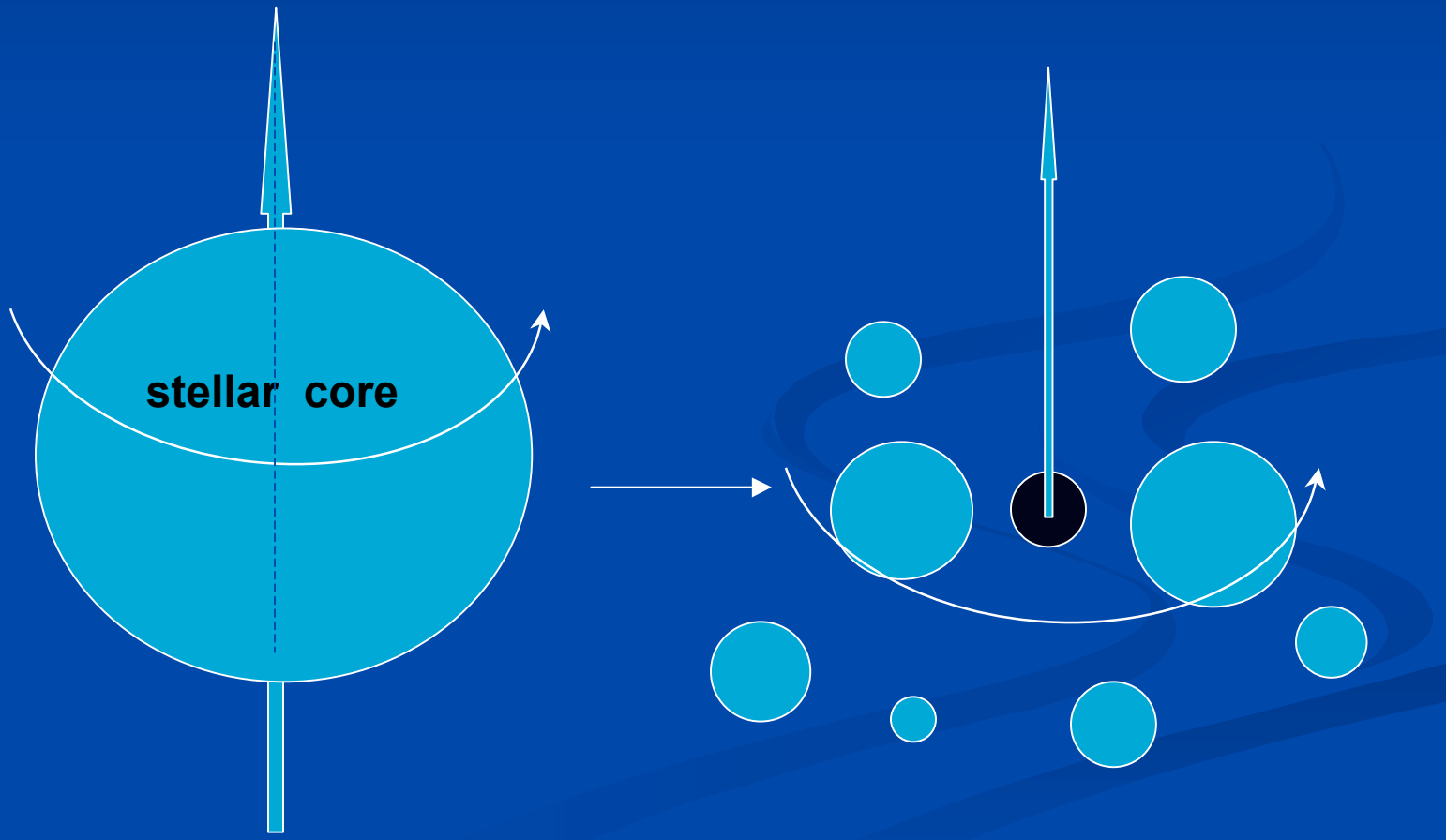
BH - Torus System

MacFadyen & Woosley; W. Zhang, Aloy, Proga …

- Natural outcome of a massive star core collapse
- GRB luminosity depends on accretion rate
- GRB energetics depends on mass of torus
- GRB jet launching mechanism
  - Neutrino annihilation
  - Magnetic mechanism (more favored)
- Mechanisms for late X-ray flares
- Issue: BH spindown (BZ mechanism) - not easy to power a constant luminosity

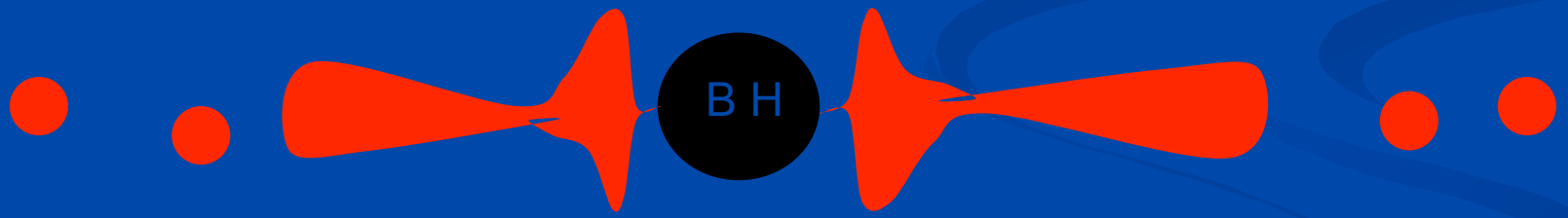
X-Ray flare Idea 1: Fragmentation of the Star

(King et al. 2005)



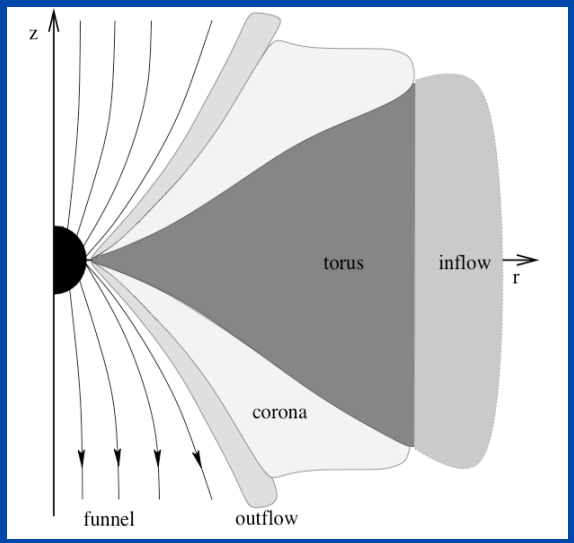
X-Ray Flare Idea 2: Fragmentation of the Disk

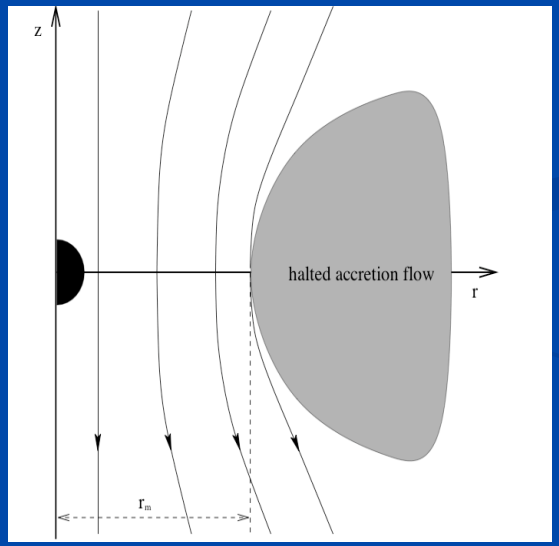
(Perna, Armitage & Zhang, 2006)

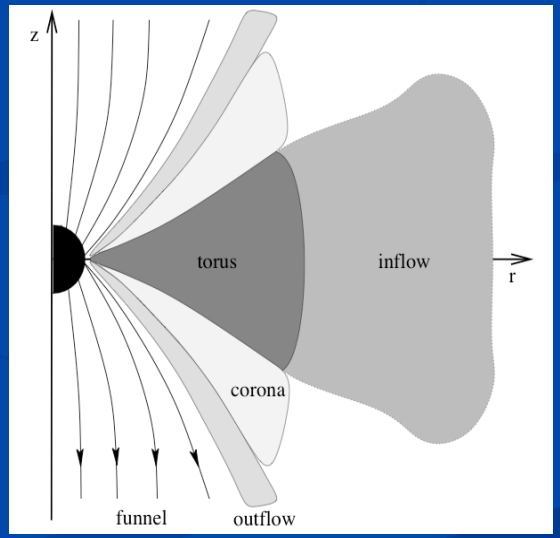


X-Ray Flare Idea 3: Magnetic barrier modulated accretion flow

(Proga & Zhang, 2006)







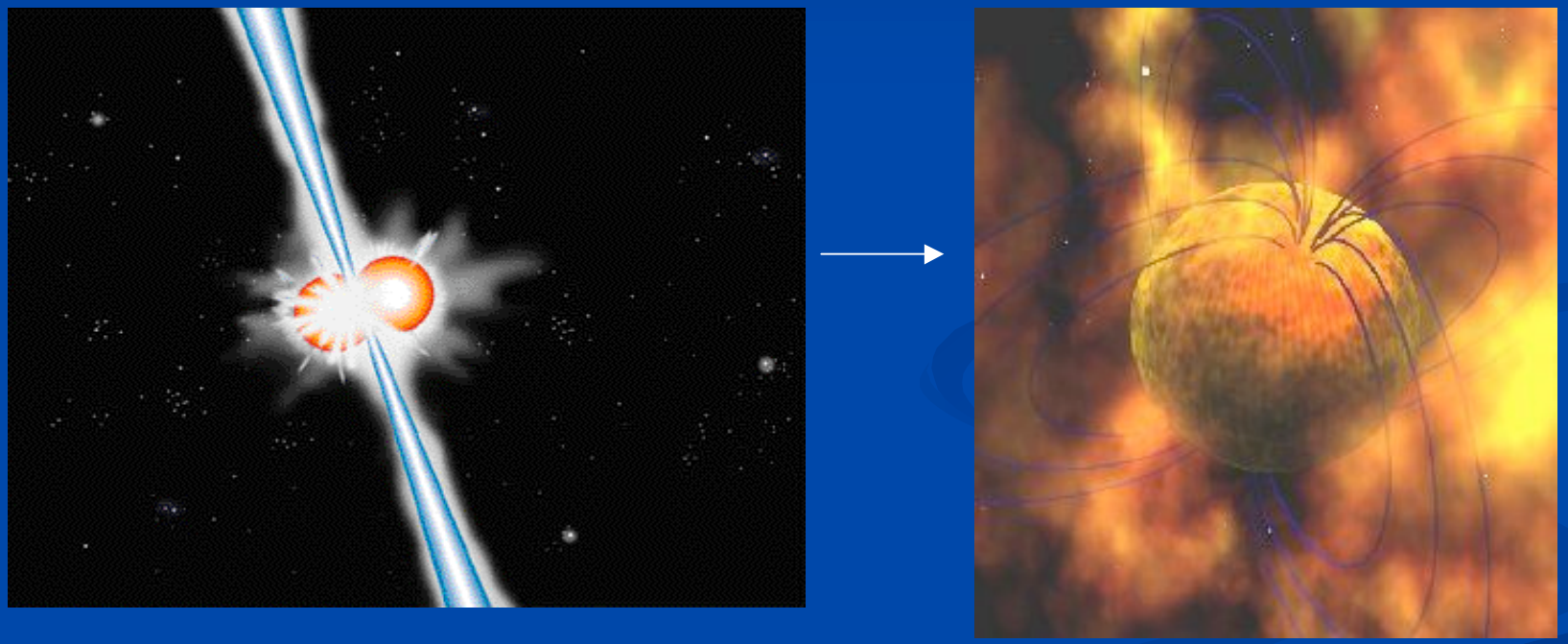
Millisecond Magnetar Central Engine

Usov, C. Thompson, Kluzniak, Ruderman, Wheeler
Blackman, Lyutikov, Dai, Lu, Zhang, Meszaros,
Quataert, T. Thompson, Metzger & Bucciantini …

- Happens if the progenitor star is not massive enough
- GRB luminosity depends on accretion rate/spindown rate
- GRB energetics depends on mass of torus & spin energy
- Naturally magnetized
- Mechanisms for late X-ray flares: postmerger massive NS, dynamo
- Natural spindown component - flat internal plateau
- Issue: how to launch a relativistic wind (NS too "dirty"), magnetic?

X-Ray Flare Idea 4: Post-merger millisecond pulsar

(Dai et al, 2006, Science)



Strange Quark Star Engine

Cheng, Dai, Lu, Ouyed, Staff, Xu, Paczynski, Haensel …

- Merits:
  - Additional energy power: 2-flavor quark state to 3-flavor quark state phase transition (Cheng & Dai); Solid quark star quakes (Xu & Liang); accretion power is also needed
  - Membrane, clean fireball (Cheng, Dai, Ouyed, Xu, Paczynski, Haensel)
  - Naturally spin down
- Issue:
  - Do they exist at all? Can they coexist with NS?
- Key:
  - Identify phenomena that can only be interpreted by QSs, but not by any other engines - difficult.

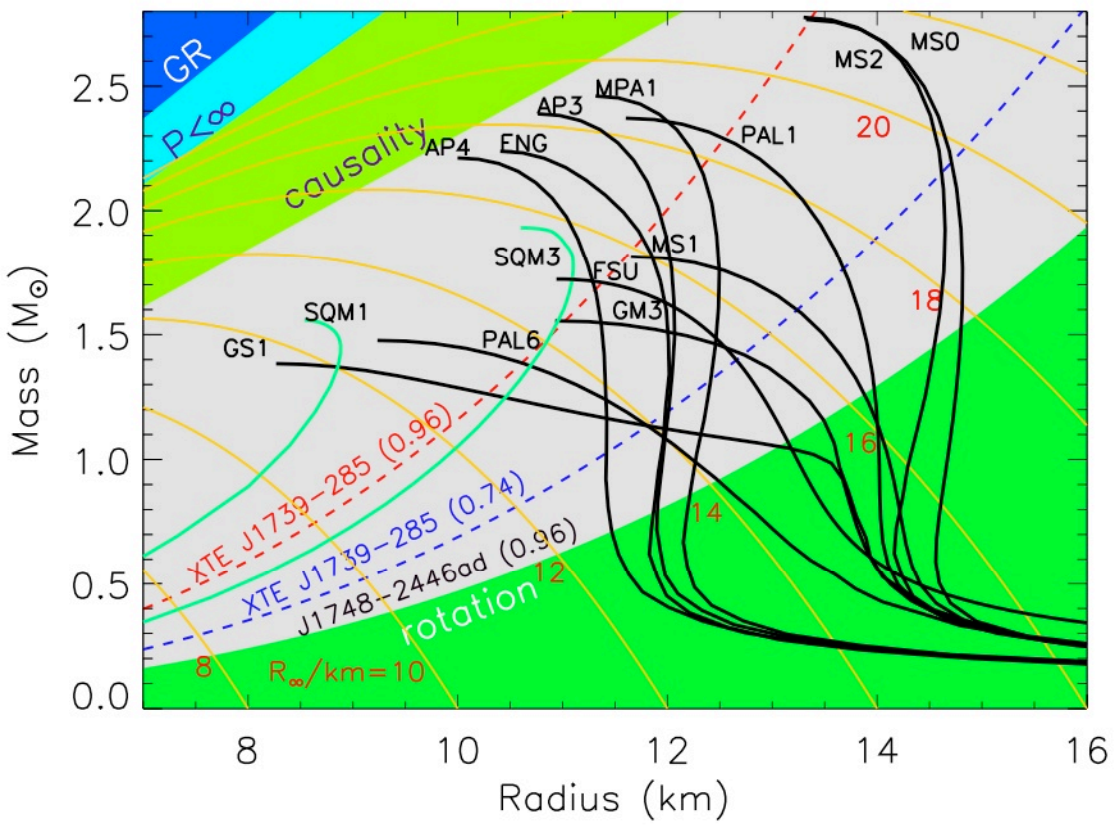


FIG. 2: Mass-radius trajectories for typical EOSs (see [6] for notation) are shown as black curves. Green curves (SQM1, SQM3) are self-bound quark stars. Orange lines are contours of radiation radius, $R_\infty = R/\sqrt{1-2GM/Rc^2}$. The dark blue region is excluded by the GR constraint $R > 2GM/c^2$, the light blue region is excluded by the finite pressure constraint $R > (9/4)GM/c^2$, and the green region is excluded by causality, $R > 2.9GM/c^2$. The light green region shows the region $R > R_{max}$ excluded by the 716 Hz pulsar J1748-2446ad [22] using Eq. (12). The upper red dashed curve is the corresponding rotational limit for the 1122 Hz X-ray source XTE J1739-285 [23]; the lower blue dashed curve is the rogorous causal limit using the coefficient 0.74 ms in Eq. (12).

Lattimer & Prakash (2007)

Conclusions

- A list of criteria have been set up based on GRB observations, which are the basic requirements for any reasonable central engine models.
- Right now no definite clue is available to pin down the GRB central engine. Several (three) types of central engine have been proposed.
- It is possible and even likely that more than one type of central engine are at work (e.g. intermittent vs. steady - accretion vs. spindown).