X-Ray Flares (and Plateaus) as Clues of the Central Engine

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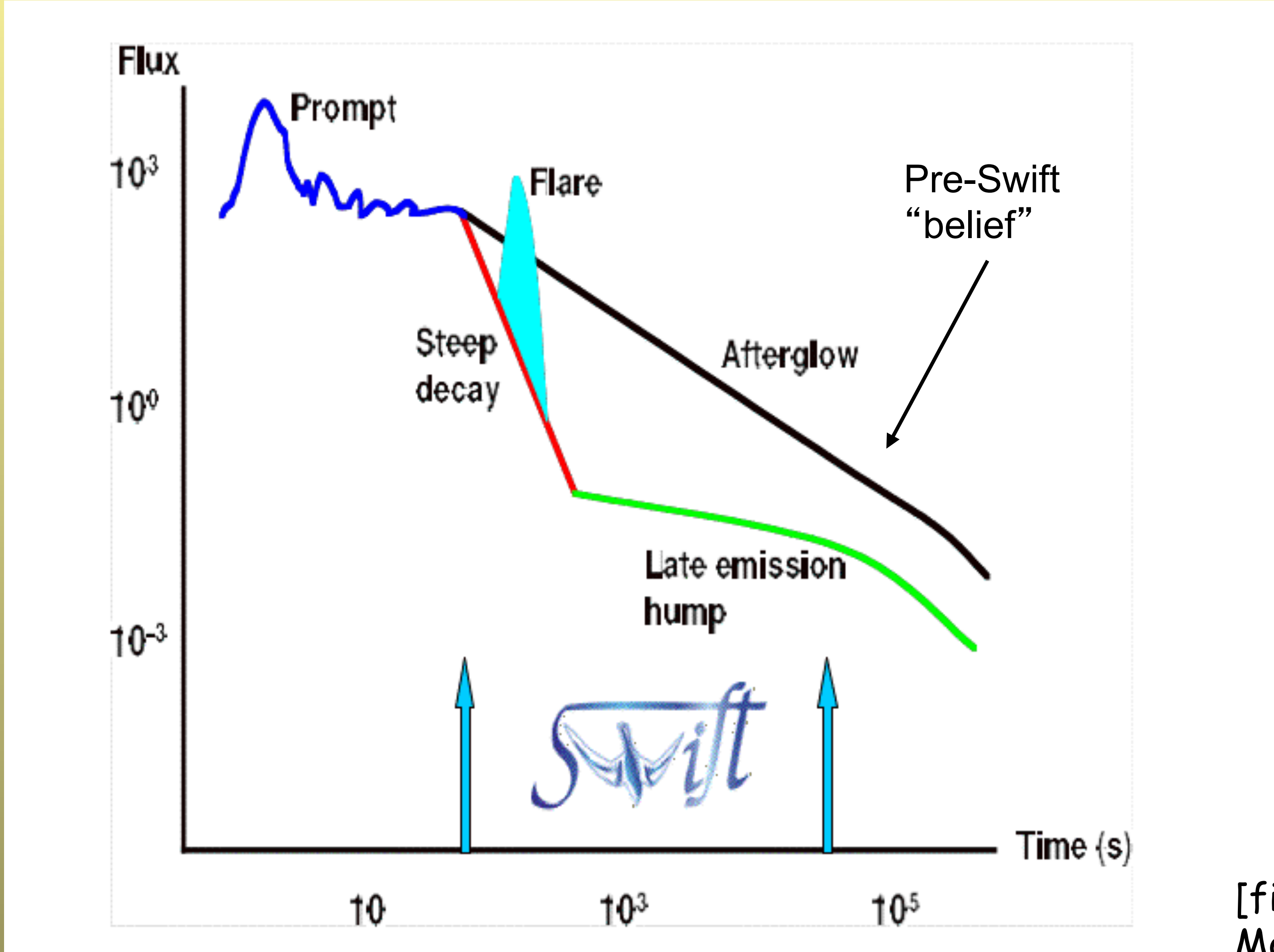
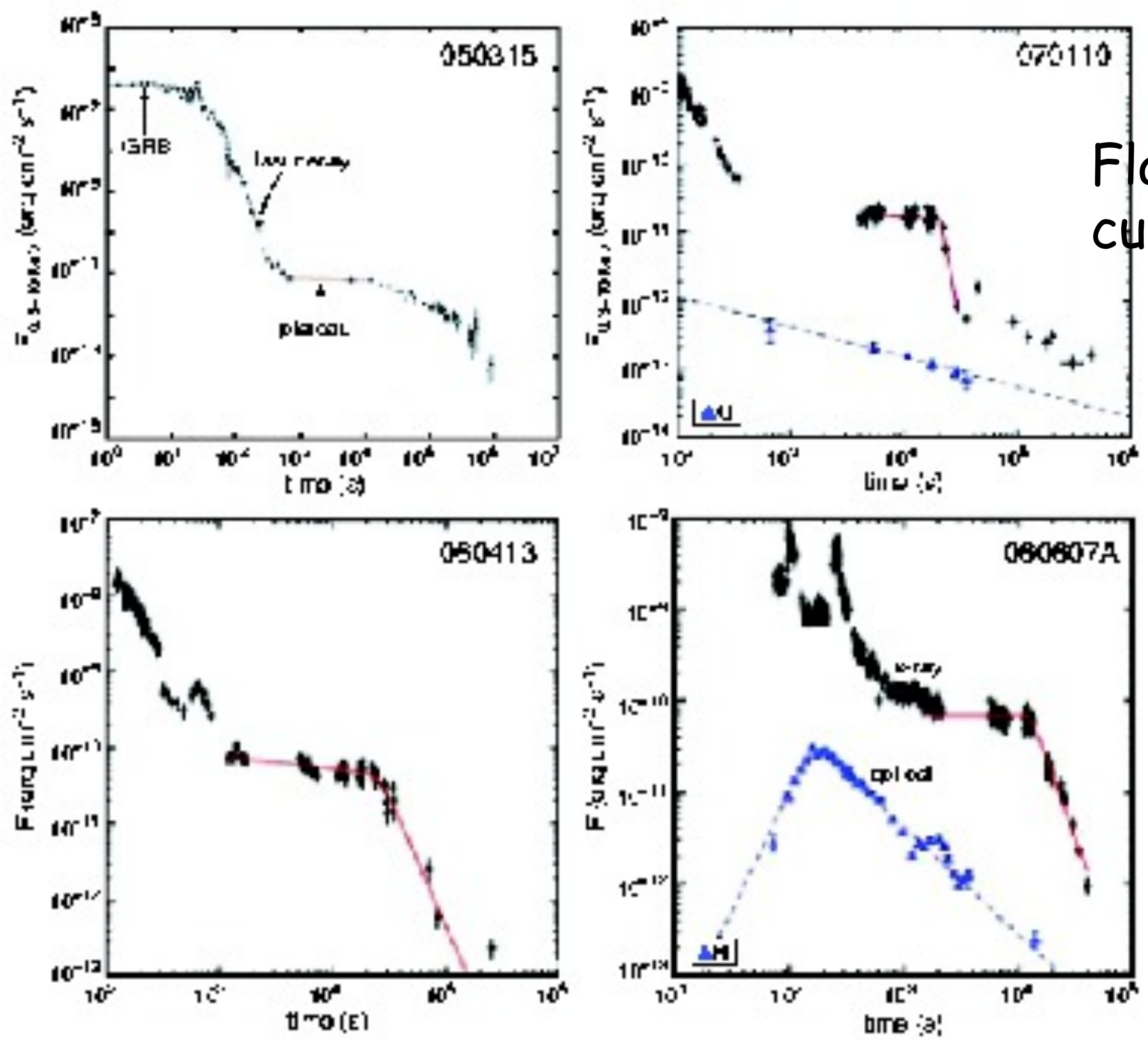
Swift observations opened a new window…



[figure courtesy of R. Mockovitch]

…. of surprises….with *PLATEAUS & FLARES*

PLATEAUS - long GRBs

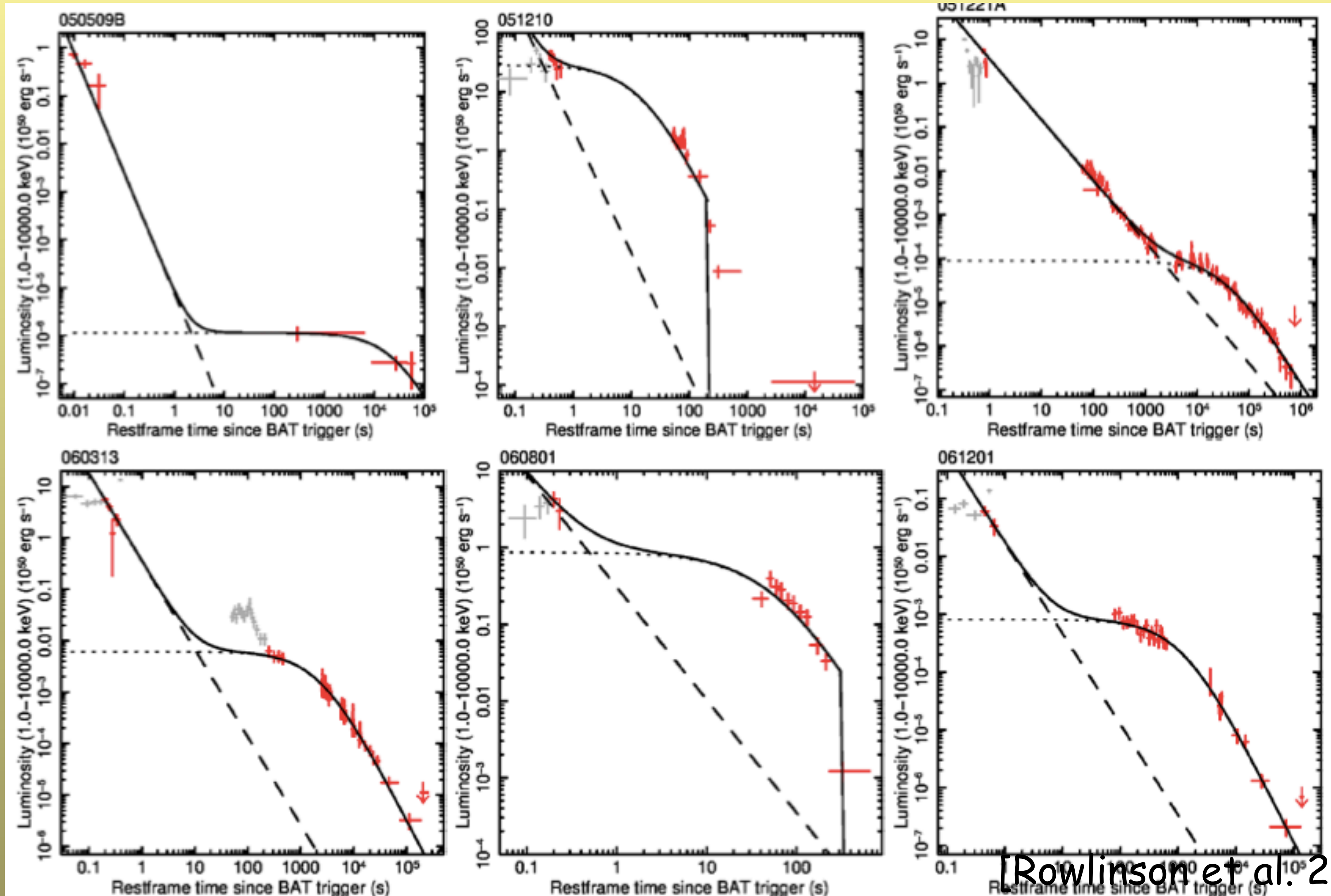


Flattening of light curves on timescales of 10^3 – 10^4 sec

Clearly seen in LONG GRBs

[from Kumar, Narayan & Johnson 2008]

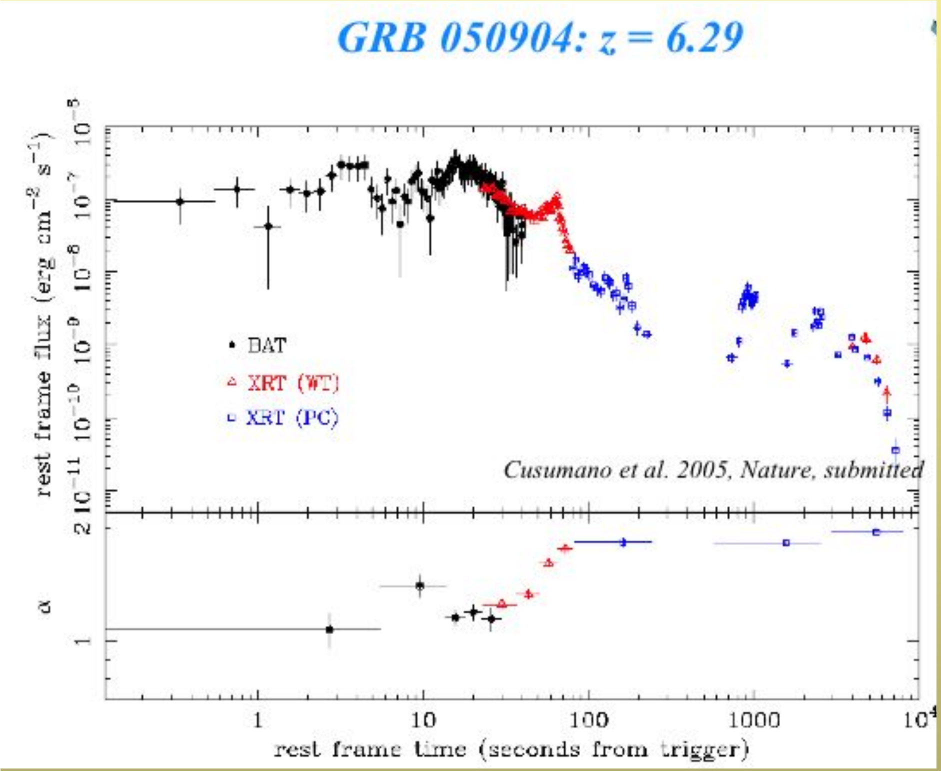
PLATEAUS - short GRBs



[Rowlinson et al. 2013]

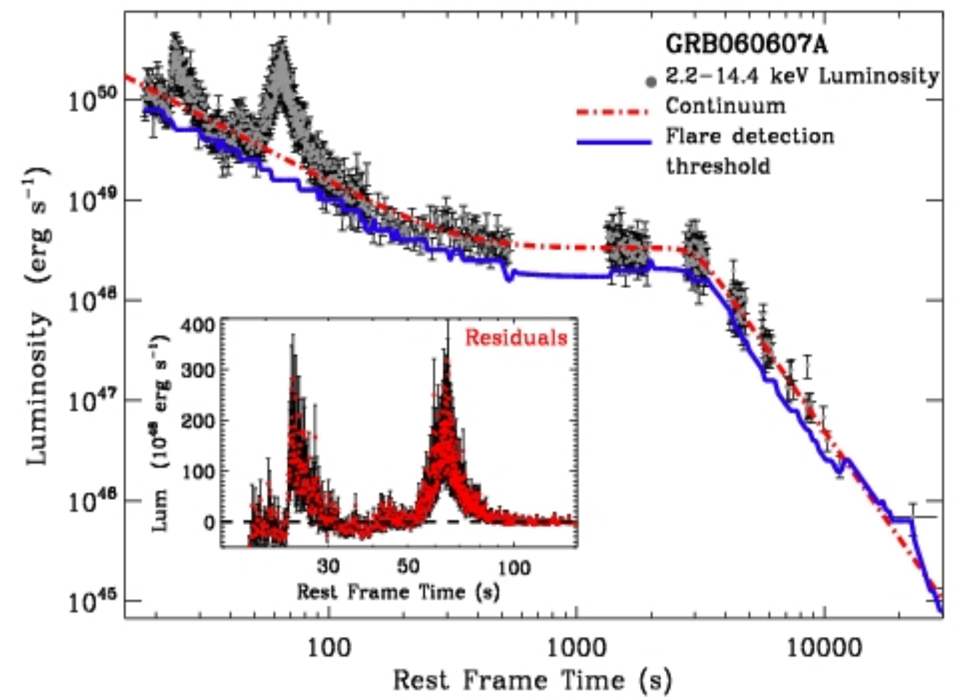
About half of all Swift detected SGRBs (as of May 2012) can be clearly fitted with a magnetar plateau phase [Rowlinson et al 2013]

FLARES - long GRBs



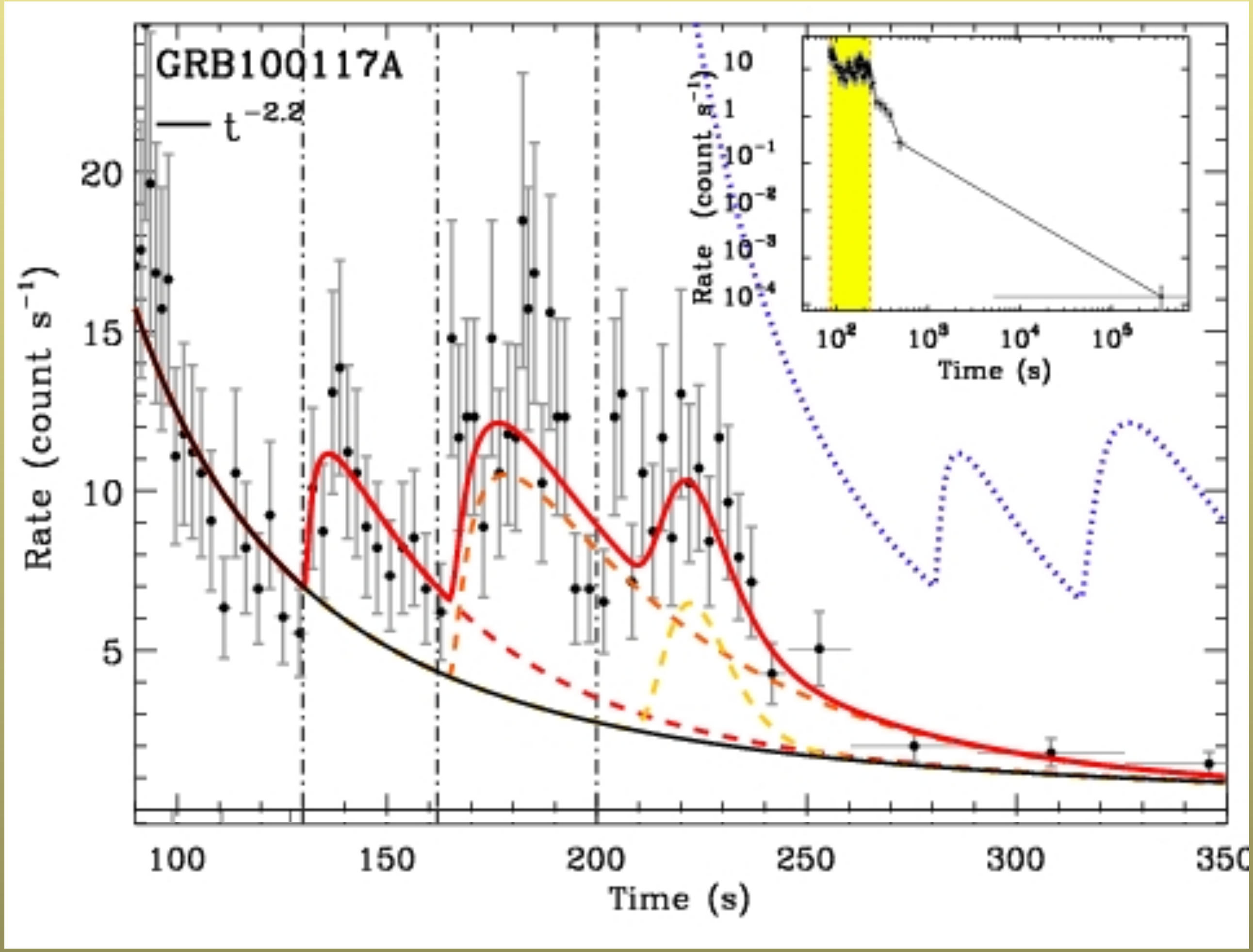
[Cusumano et al. 2005]

- Observed in over a third of the long GRBs
- Number of flares can vary from 1 to 6-7



[Margutti et al. 2010]

FLARES - short GRBs

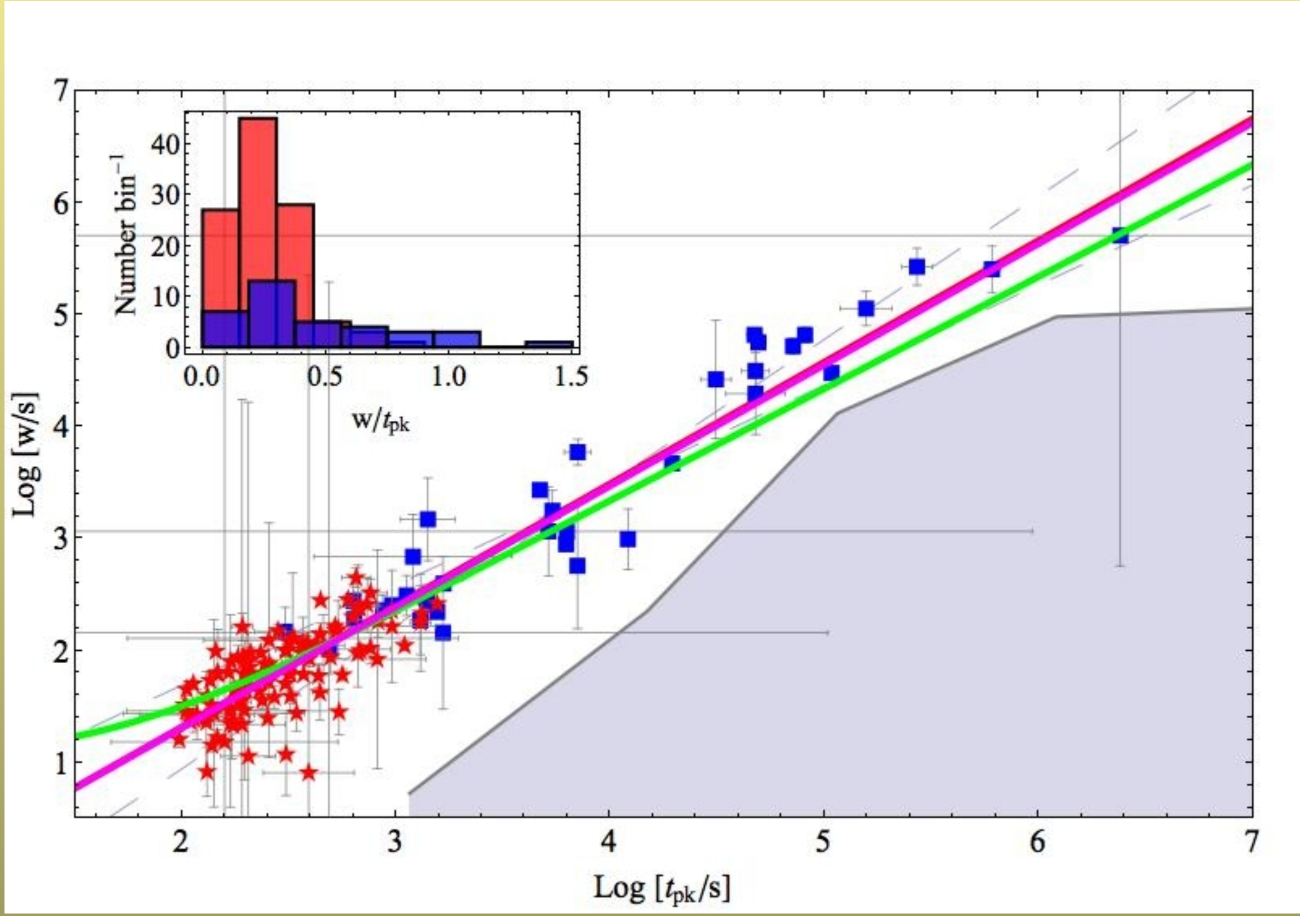


Displayed by a number of short GRBs as well

GRB 100117A

[Margutti et al. 2011]

FLARES: properties (long GRBs)



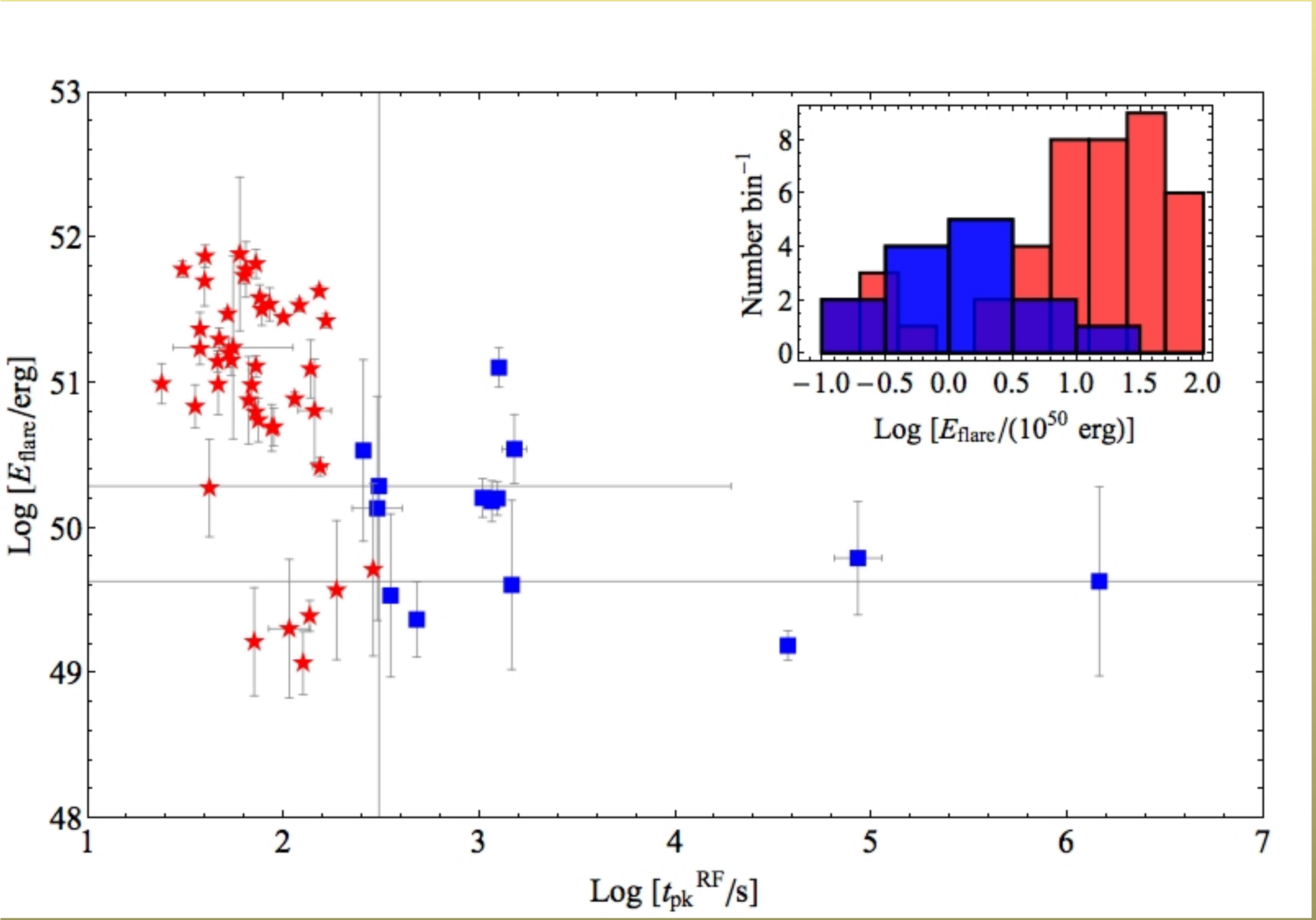
[Bernardini et al. 2011]

Flares widths vs their peak time: *correlated*

Later flares last *longer*

Same correlation also obeyed by short GRBs [Margutti et al 2011]

FLARES: properties (long GRBs), cont.



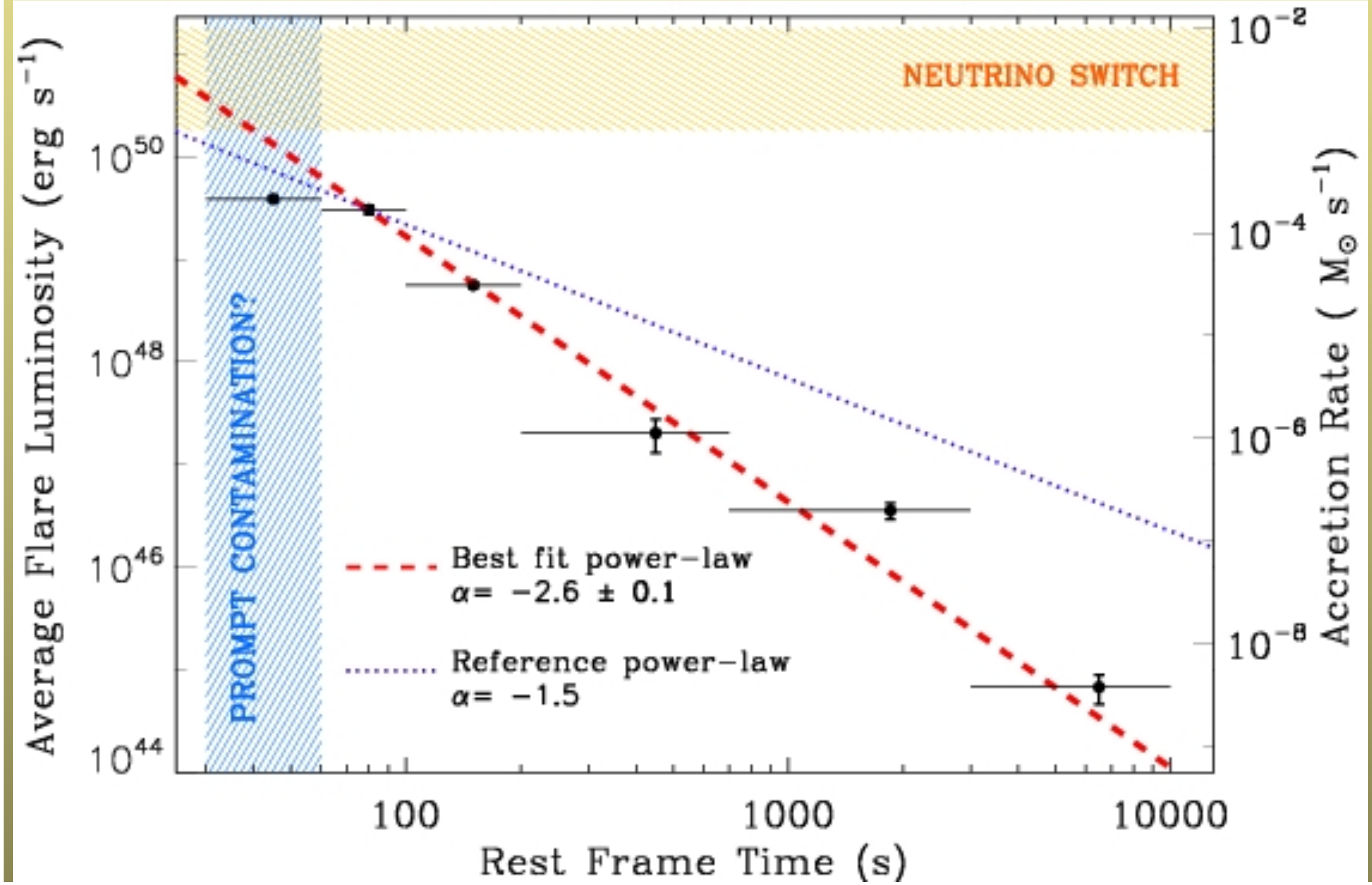
[Bernardini et al. 2011]

Early flares tend to be more energetic than later ones

Flare energies can be comparable to that of the prompt emission

FLARES: properties (long GRBs), cont.

Average flare luminosity declines as $L \propto T^{-2.6}$



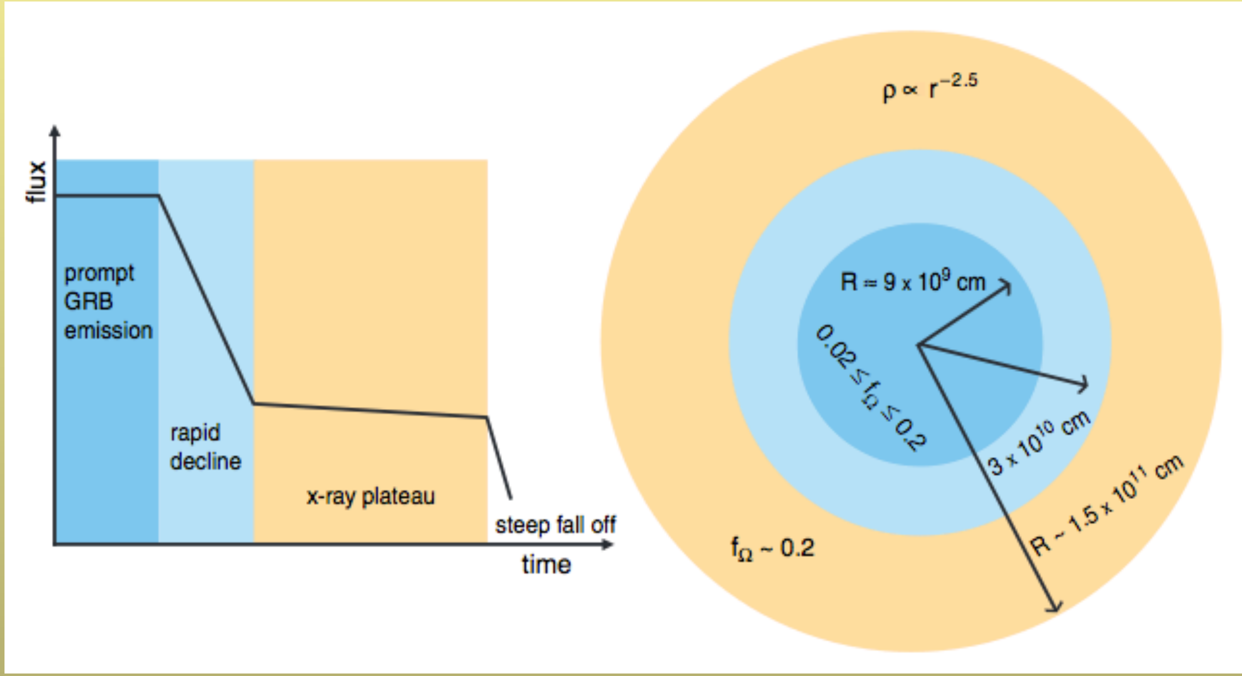
[Margutti et al. 2010; sample of 55 flares from 29 GRBs]

Theory:

Plateaus

Plateaus in long GRBs: Accretion Model

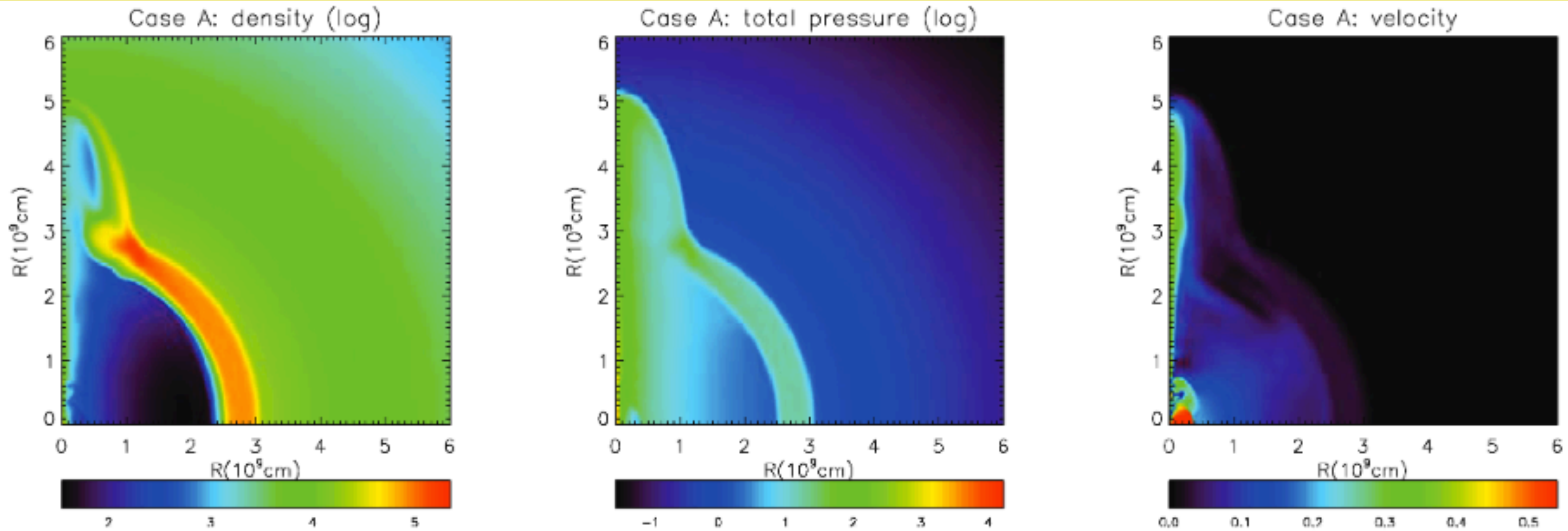
[Kumar, Narayan & Johnson 2008]



Different segments of the light curve reflect different accretion zones in the progenitor star

- Core $\longrightarrow$ prompt emission
- Core transition zone $\longrightarrow$ rapid decline
- Envelope ($\rho \propto r^{-2}$) $\longrightarrow$ plateau

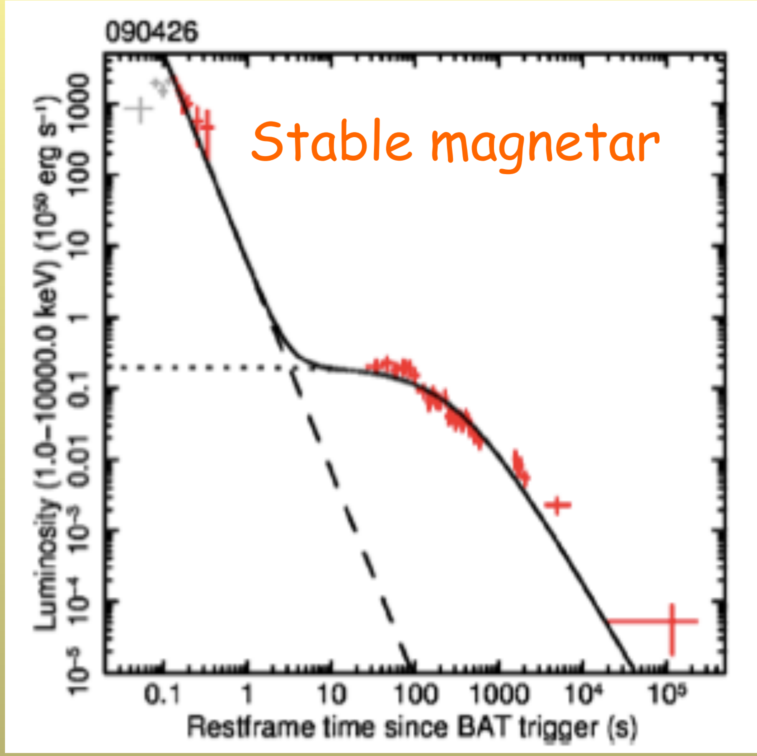
Plateaus in long GRBs: Magnetar Model

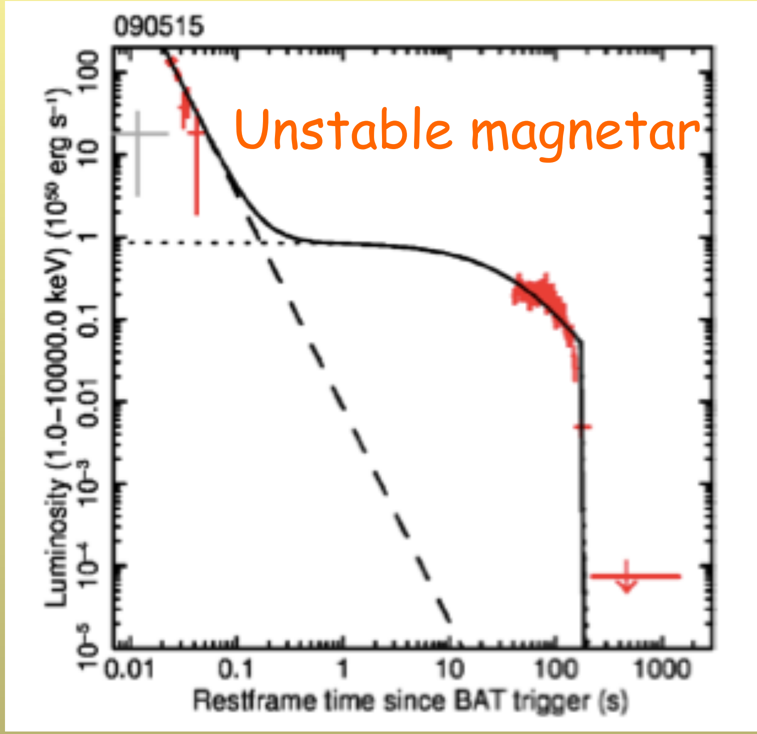


Bucciantini et al (2009): The production of a collimated relativistic jet that can escape the progenitor star is a robust consequence of the formation of a B~10^{15}G, P~ 1 ms neutron star during core-collapse SNe.
Magnetar model for long GRBs developed in detail by Metzger et al. (2011). Also Lyutikov (2010) [+ talk]

- Plateaus powered by late-time rotational energy loss

Plateaus in short GRBs

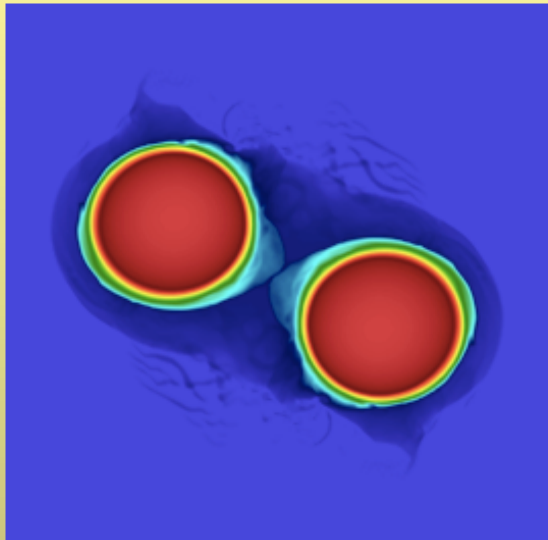




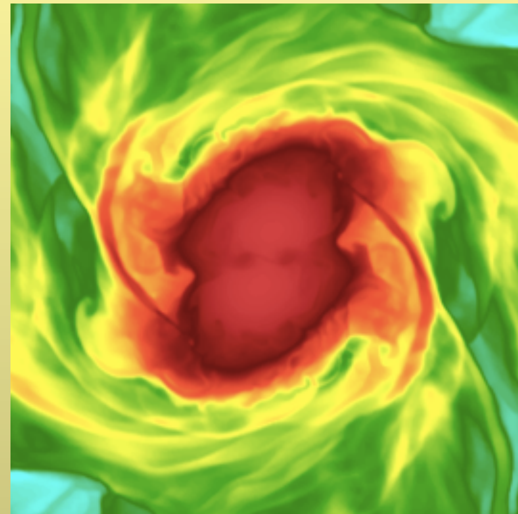
[Rowlinson, O' Brien, Metzger et al. 2013]

Energy powered by a (stable/unstable) magnetar provides a good fit to the light curves of a sizeable fraction of Swift SGRBs [Rowlinson et al. 2013]

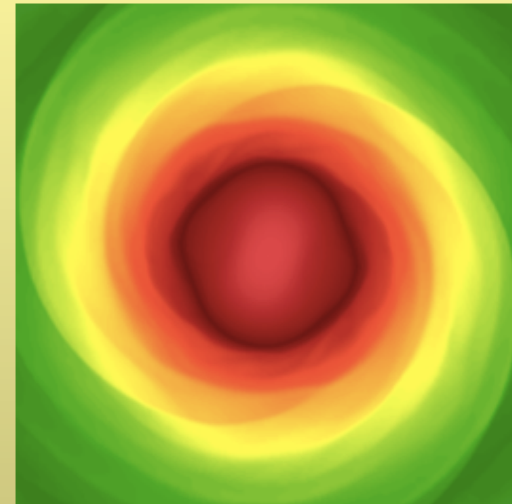
Magnetar formation via NS-NS mergers?



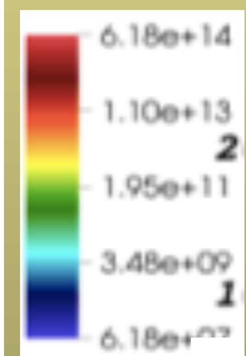
t = 8.34 ms



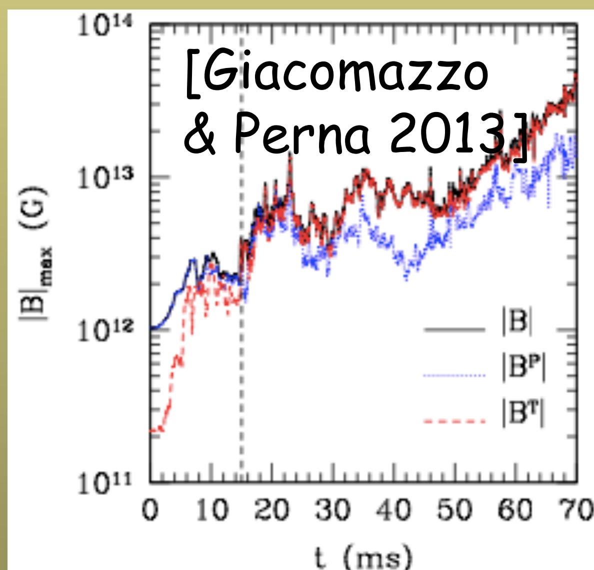
t = 18.9 ms



t = 66 ms



B ampl. also seen in local simulations by by Zrake & MacFadyen (2012)



GR MHD simulations of the merger of two 'small' NSs showed that a stable NS *can* be formed, and the B field is amplified during the merger

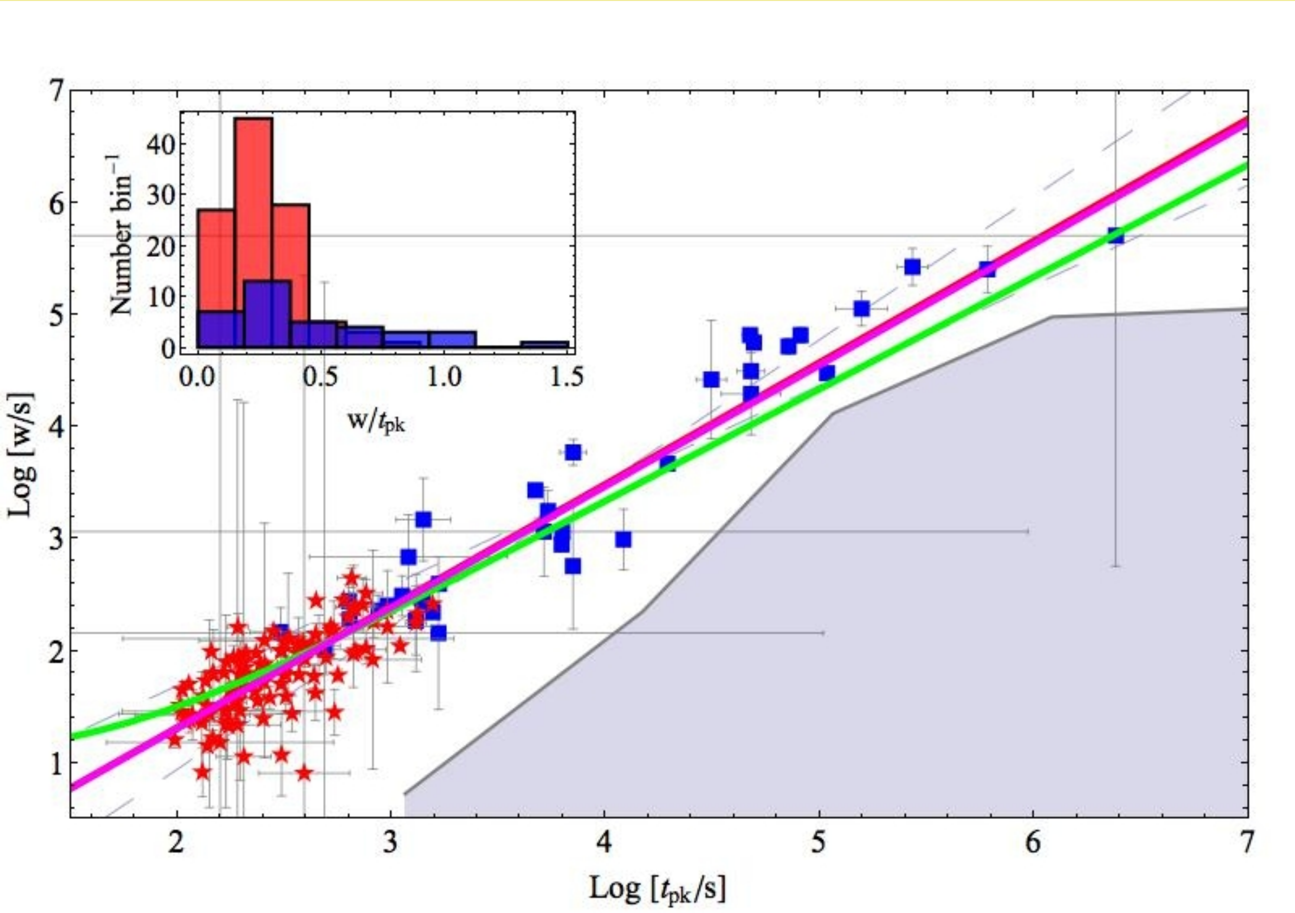
→ Magnetar formation may result from NS-NS merger

Or BH 'acting' as a millisecond magnetar? [Lyutikov]

Theory:

Flares

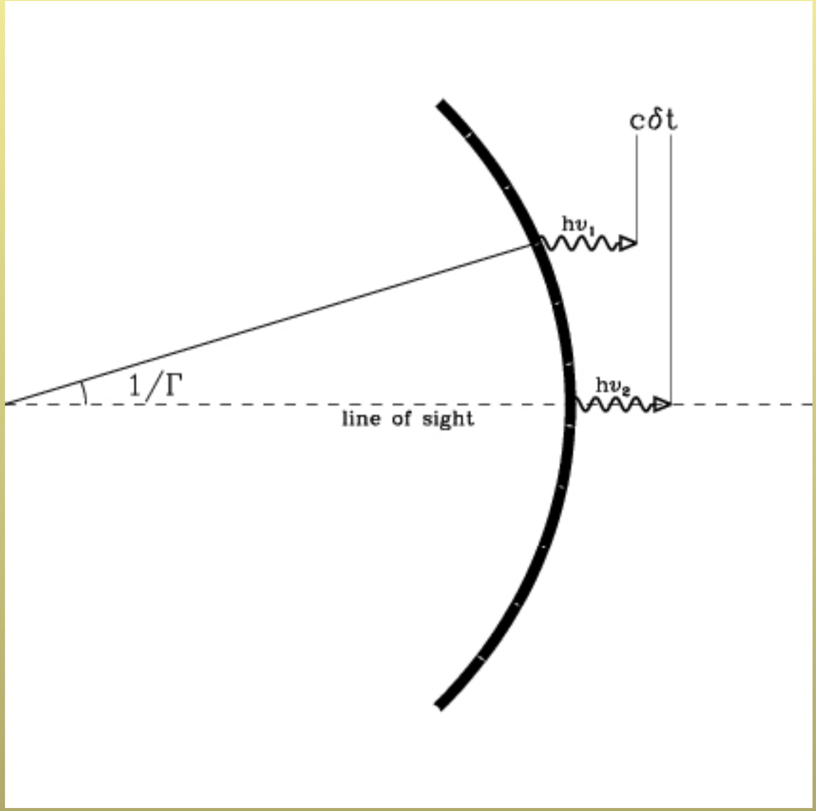
OBSERVATIONS PROVIDE *CLUES*....

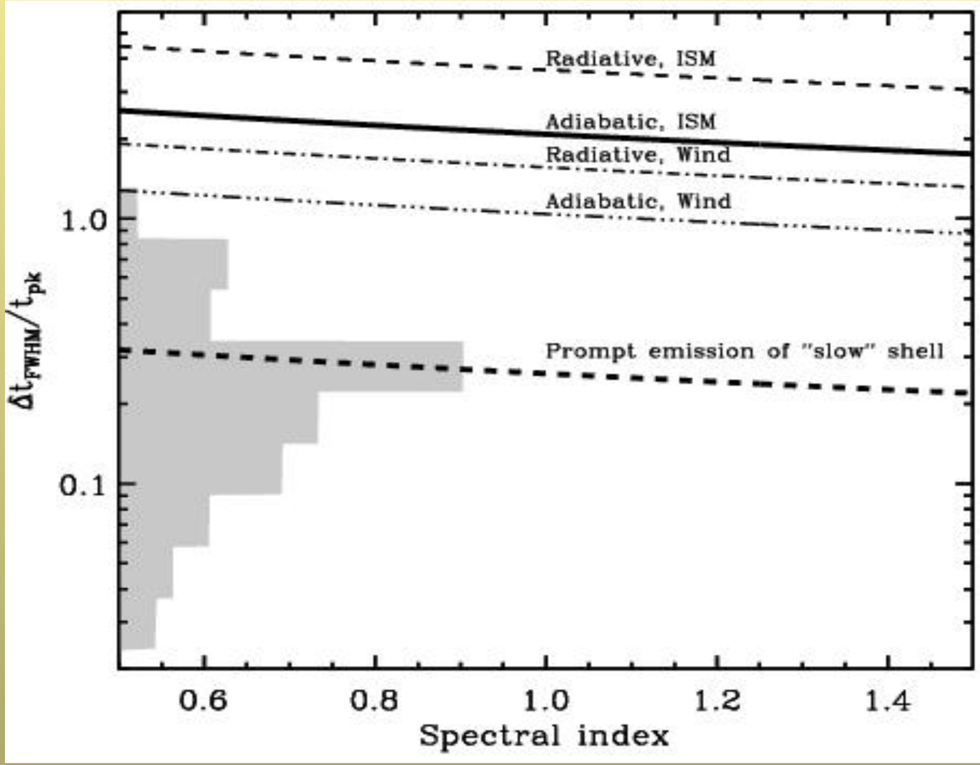


[E.g. Kocevski et al 2007; Chincarini et al. 2007; Bernardini et al. 2011]

Correlation between durations and times from trigger could be reflecting collisions between shocks at increasingly larger radii *or* an intrinsic property of the GRB engine.

Magnitudes of flare durations however rule out late shells at least in a fraction of bursts



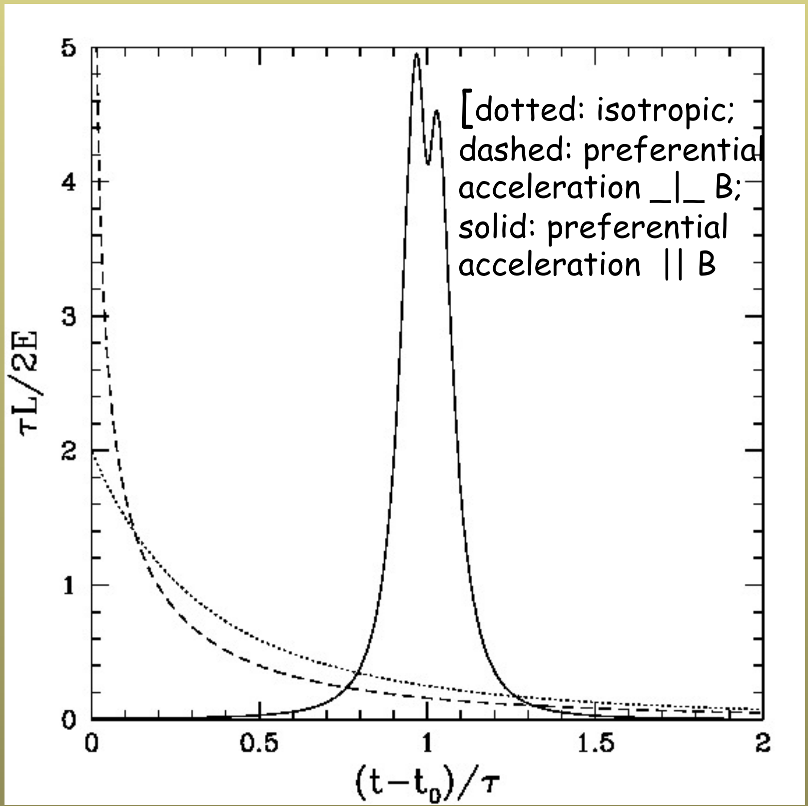


[Lazzati & Perna 2007]

•Similar conclusions reached by Chincarini et al. 2007: 10/69 of the flares analysed can *only* be explained by **prolonged activity of the central engine** (for comoving isotropic emission)

IMPORTANT *CAVEAT* [Beloborodov et al. 2011]

Previous considerations based on the assumption of intrinsic *isotropic* emission.



Intrinsic anisotropic emission can produce variability in the light curve on shorter timescales than it would for isotropic emission

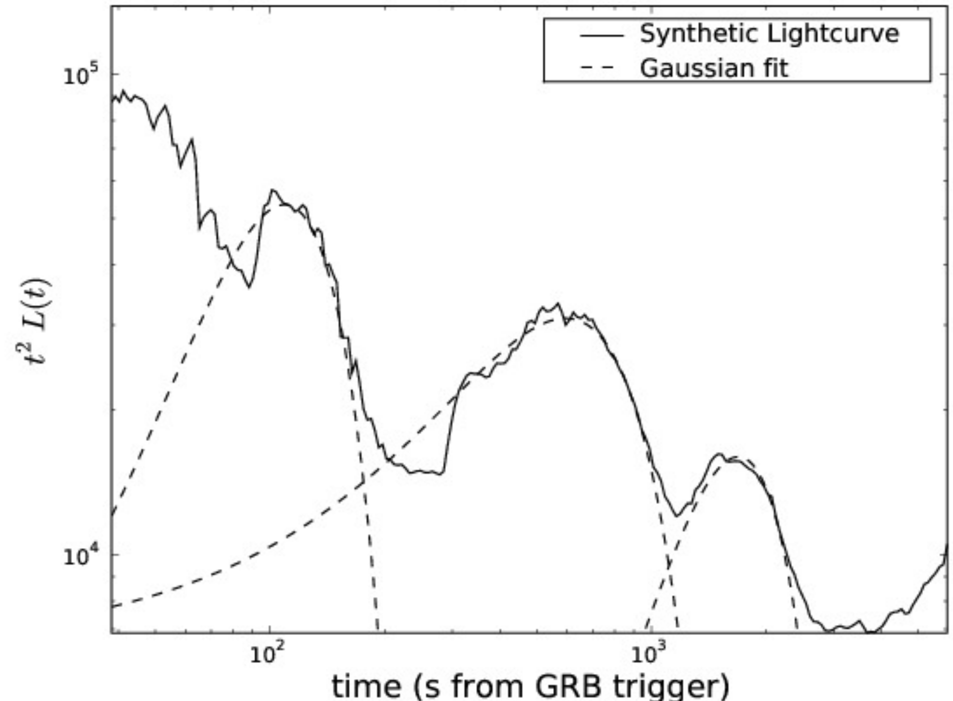
[Beloborodov et al. 2011]

HOW TO PRODUCE A "LONG-LIVED", "INTERMITTENT", GRB ENGINE?

- Collapsar-type models
- Compact merger-type models
- Progenitor-independent models

Collapsar-type models

- Core fragmentation followed by accretion [King et al. 2005]
- Propagation instabilities in jet within collapsing WR star [Lazzati et al. 2011]



- As the jet propagates inside the collapsing star, the varying pressure of both the jet and the star will cause the jet opening angle to vary

- A varying opening angle causes the jet luminosity per unit solid angle to vary

- Light curve flares are observed as a result of

q) Varying jet luminosity (for any los)
b) Varying angle for los close to the jet edge

- Typical flare duration $\delta t / t \sim 0.1$
- Flares with flux contrast larger than about one order of magnitude cannot be reproduced

Merger-type models

[Dai et al. 2006, also Metzger et al. 2011; Lyutikov and collab.]

Instabilities in msec pulsar formed after merger

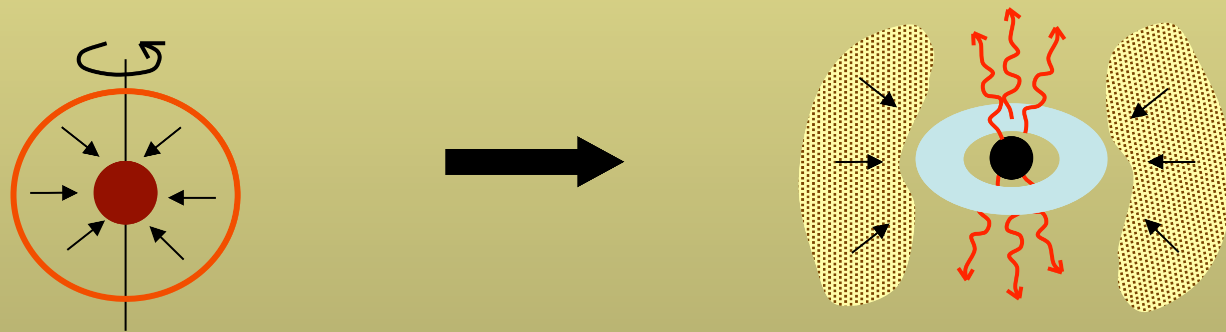
- Differentially rotating, msec pulsar formed after the merger of the neutron stars
- Differential rotation leads to windup of interior poloidal magnetic field
- Toroidal field becomes unstable due to buoyancy; rises and breaks through star surface
- Field reconnects yielding flare-like episodes

Progenitor-independent models (disk/jet)

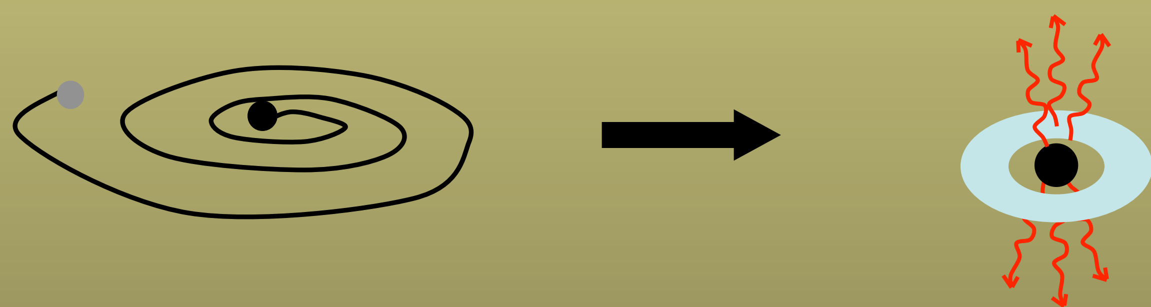
Flares observed in both long and short bursts, with similar properties

What is in common between them?

Long GRBs



Short GRBs



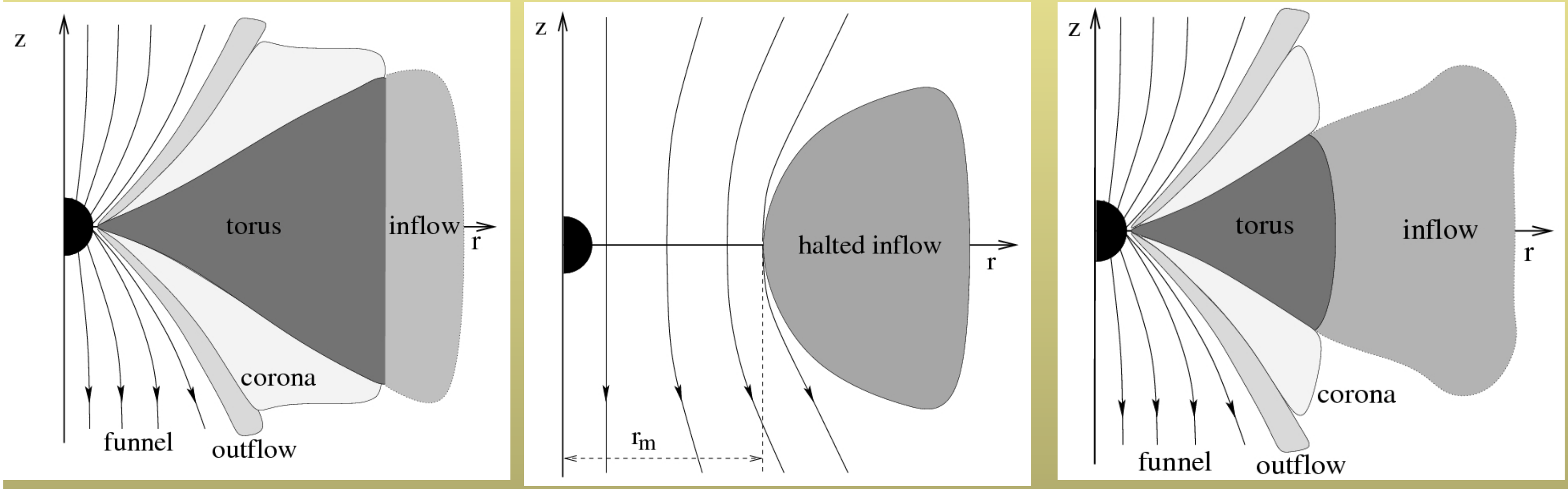
Common element: **ACCRETION DISK/JET**

Progenitor-independent models (disk/jet)

Magnetically driven models (disk)

[Proga & Zhang 2006]

Model driven by their numerical simulations



- Hyperaccretion causes poloidal B field to accumulate near the inner boundary;
- Accretion rate drops and magnetic pressure supports gas – accretion halts
- Gas accumulates and squashes B field inside again – accretion resumes

Estimated flare luminosity at least one or two order of magnitude lower than prompt gamma-ray emission

Progenitor-independent models (disk/jet)

Magnetically driven models (jet) [Giannios 2006]

This model does not require reviving the GRB engine

- Deceleration of the flow (and/or crossing of the reverse shock) revives MHD instabilities that lead to dissipation of magnetic energy through reconnection of magnetic field lines at different locations in the flow;
- A large fraction of the reconnected energy can be radiated away in the X-rays through synchrotron emission;
- Flare duration depends on the characteristic lengths of the reconnecting regions, as well as on how fast reconnection proceeds

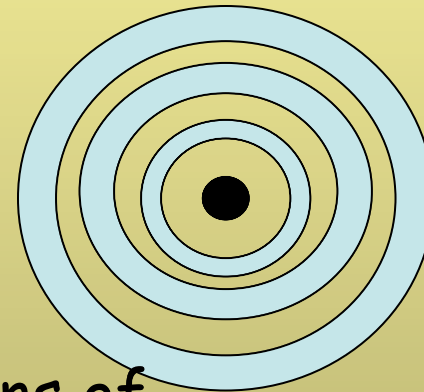
Important model prediction: flare energy is a fraction $\propto (\delta t_f / t_f)^3$ of the prompt GRB emission $\Rightarrow$

Fast evolving flares less energetic than smoother ones

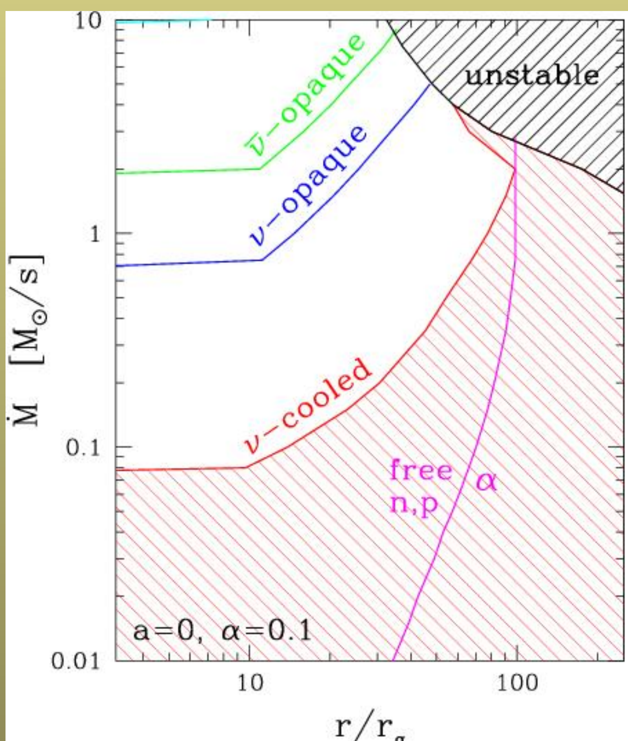
Progenitor-independent models (disk/jet)

Gravitationally driven models

[Perna, Armitage & Zhang 2006]



Observed correlation between δt_f and t_f suggestive of **viscous accretion** of material in clumps/ rings



[Chen & Beloborodov 2007]

Semianalytical calculations of hyperaccreting disks show that the outer parts of the disk become gravitationally unstable [e.g. Di Matteo, Perna & Narayan 2002; Chen & Beloborodov 2007; Piro & Pfhal]

Conditions for fragmentations present in outer disk [Perna et al. 2006]

Summary

- Early observations with Swift have shown the presence of plateaus and flares superimposed on the afterglow

- Ideas not lacking for explaining both plateaus and flares

What's next?

- As larger statistical samples allow better characterization of the properties of the long term emission, the various models will have to confront them *quantitatively.*

- Similarities between flares in long and short GRBs will need to be accounted for.

- Look for *independent* diagnostics: e.g. polarization in flares of magnetic origin (Fan et al. 2005); GW emission in disk fragmentation (Piro & Pfhal 2007).