The Role of Magnetars in Gamma-Ray Bursts

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with

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What is a GRB?

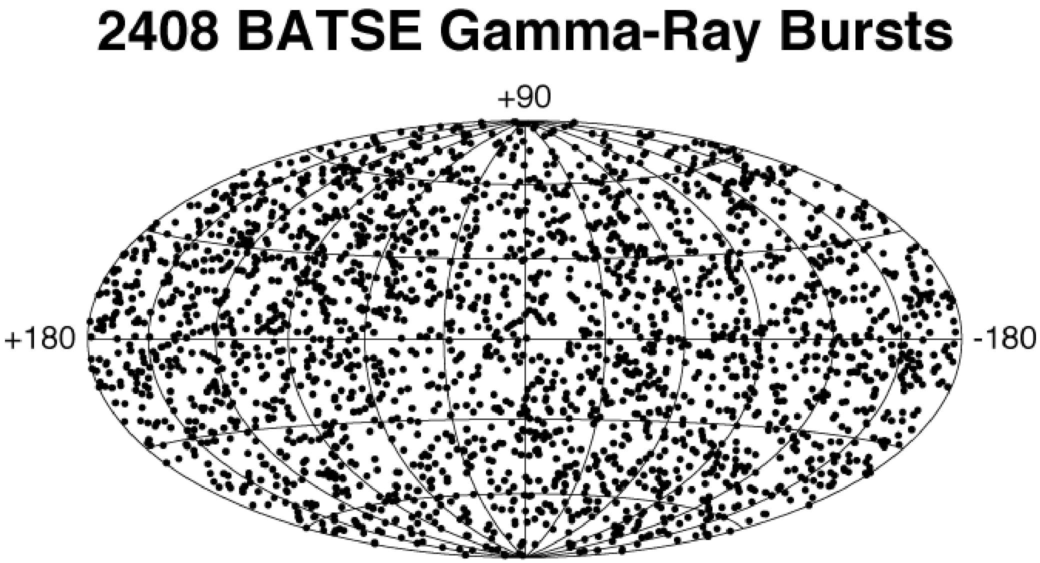
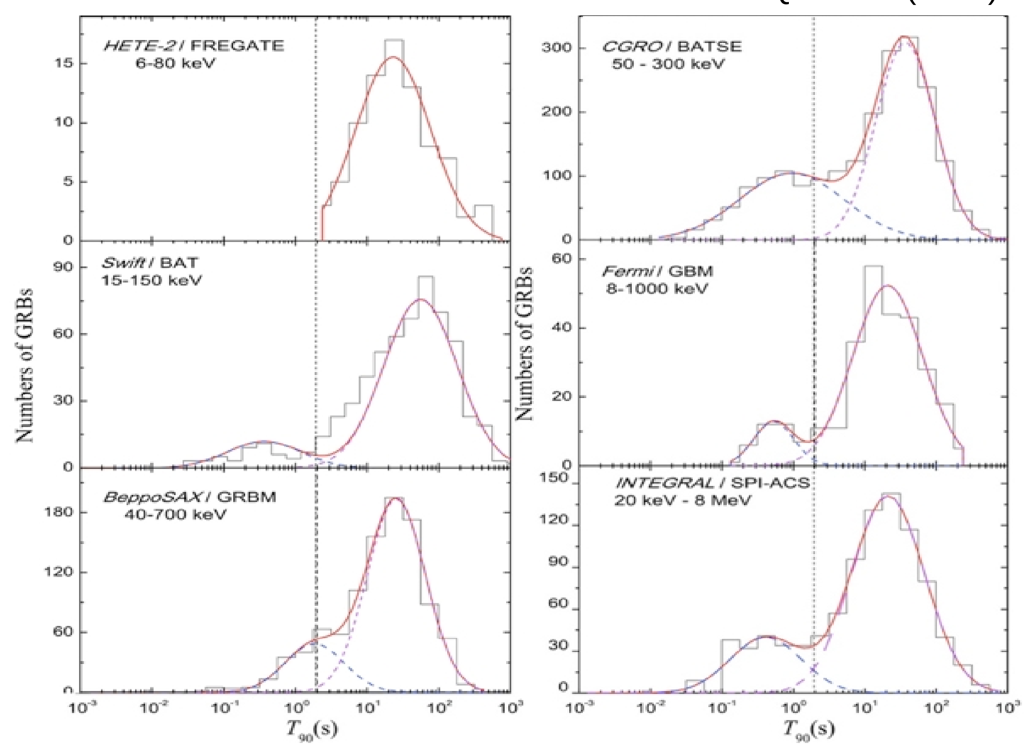


Image credit: NASA GSFC

- Short, intense bursts of EM radiation
- Isotropically distributed across the sky
- Cosmological distances
- Isotropic equivalent energy release up to the order of 10^{54} erg

- Two broad classes are apparent (Kouveliotou et al. 1993)
- Divided by duration (T_{90}) and spectral hardness
- Possible third class exists (Norris & Bonnell, 2006)
- Now perhaps even a fourth! (Levan et al. 2014)

Qin et al. (2013)

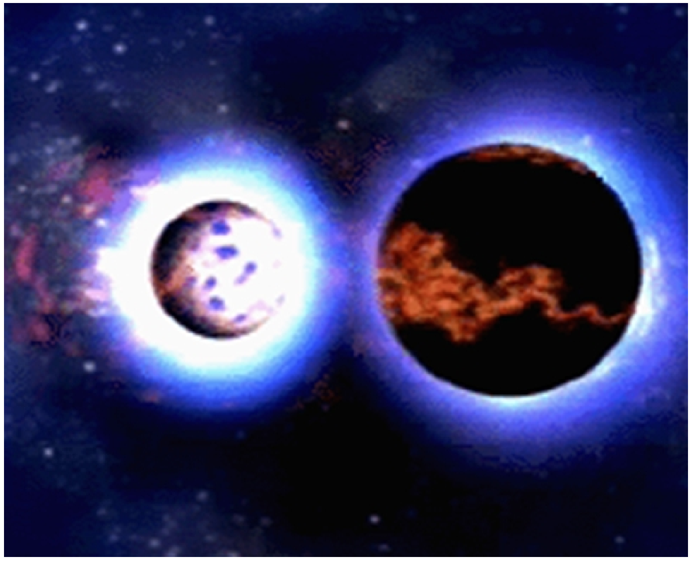


Two main classes

Short vs **Long**

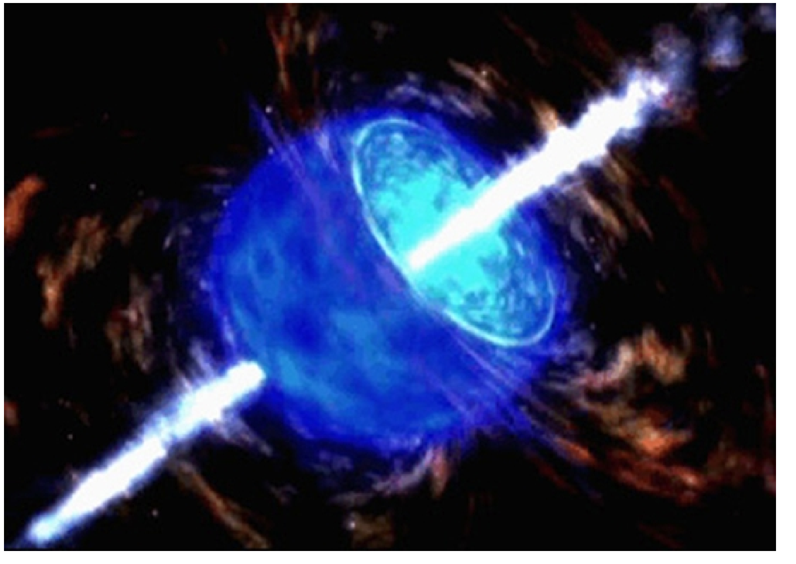
Short

- T_{90} < 2 seconds
- Less well understood (harder to follow up!)
- No SNe to deep limits (e.g. Fox et al. 2005)
- Found in both early and late-type hosts (e.g. Gehrels et al. 2005, D'Avanzo et al. 2009)
- Often found with large offsets from host galaxies (e.g. Berger 2010)
- `Kilonova' detected (Tanvir et al. 2013)
- **Compact binary merger progenitor**



Long

- T_{90} > 2 seconds
- Spectrally softer
- Actively star forming, moderately low metallicity host galaxies (e.g. Bloom et al. 1998, Fruchter et al. 1999)
- Found close to star forming regions (Fruchter et al. 2006)
- Always observed with type 1b/c SNe where possible (e.g. Hjorth et al. 2003)
- **Core collapse progenitor**



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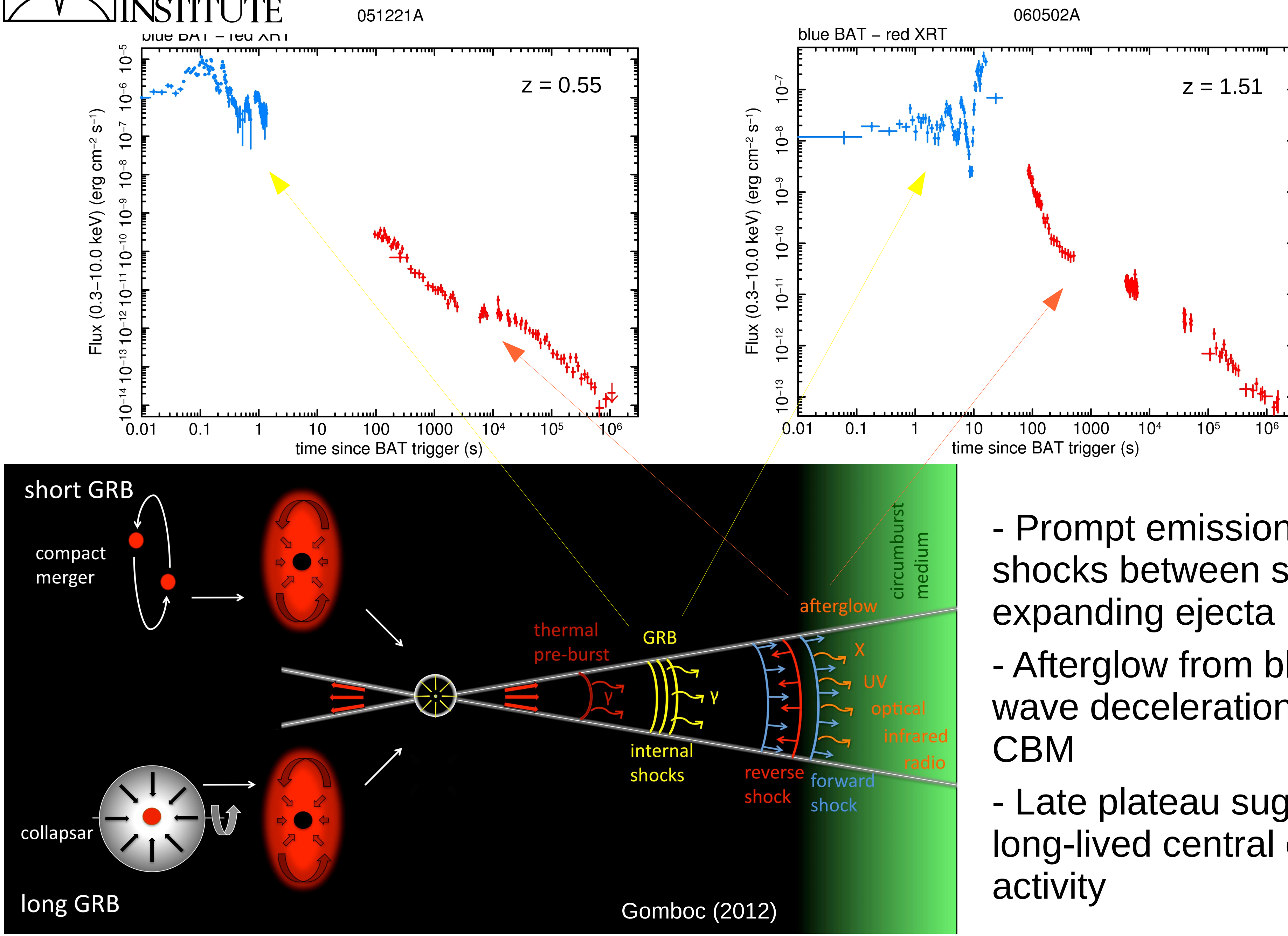
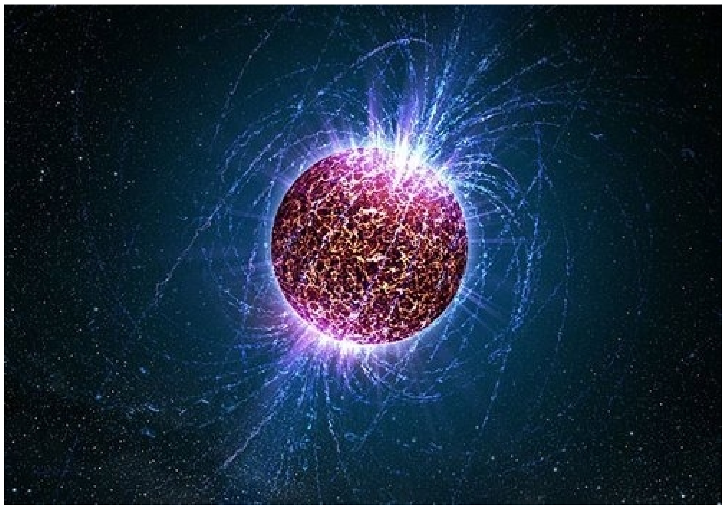
The decelerating fireball model

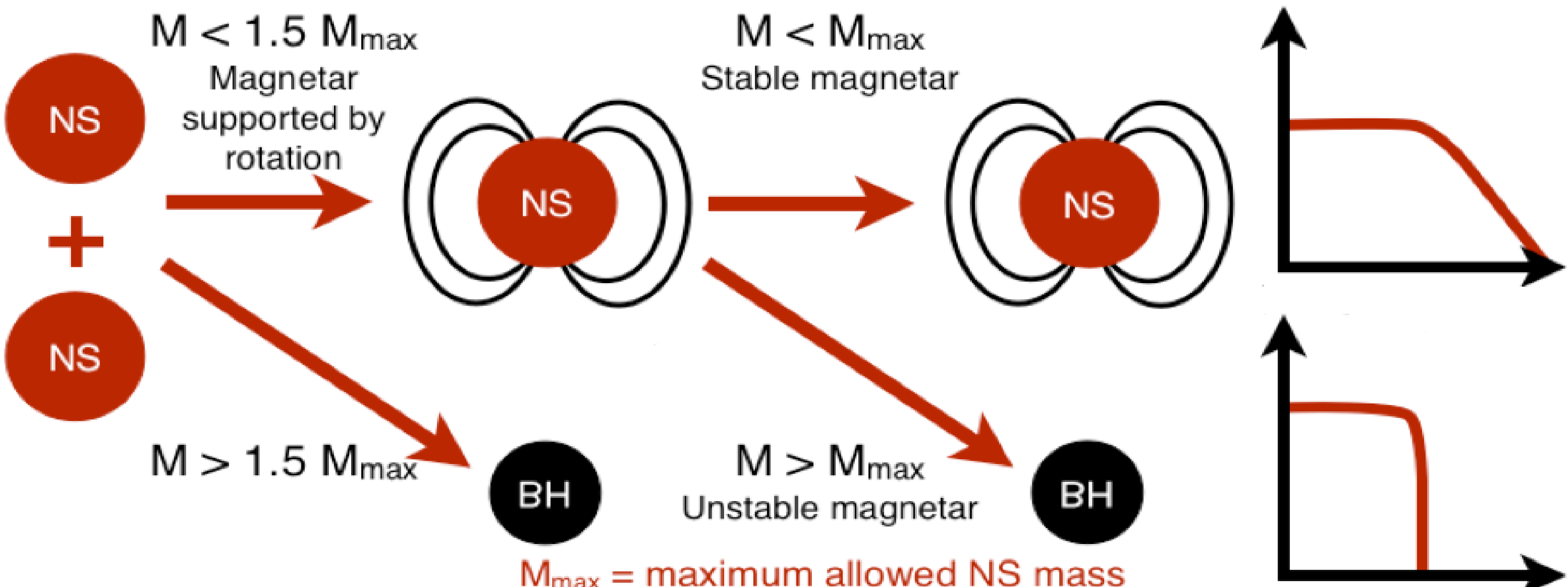


- Prompt emission from shocks between shells of expanding ejecta
- Afterglow from blast wave deceleration in CBM
- Late plateau suggests long-lived central engine activity

Magnetar central engine



- Post-merger massive NS with high B-field (~ 10^15 G) and rapid rotation (1ms)
- Loses energy to surroundings along open magnetic field lines (magnetic dipole radiation)
- Potential for delayed collapse to BH as rotational support is withdrawn
- Energy injection has characteristic spin-down timescale defined by the magnetar's B and P

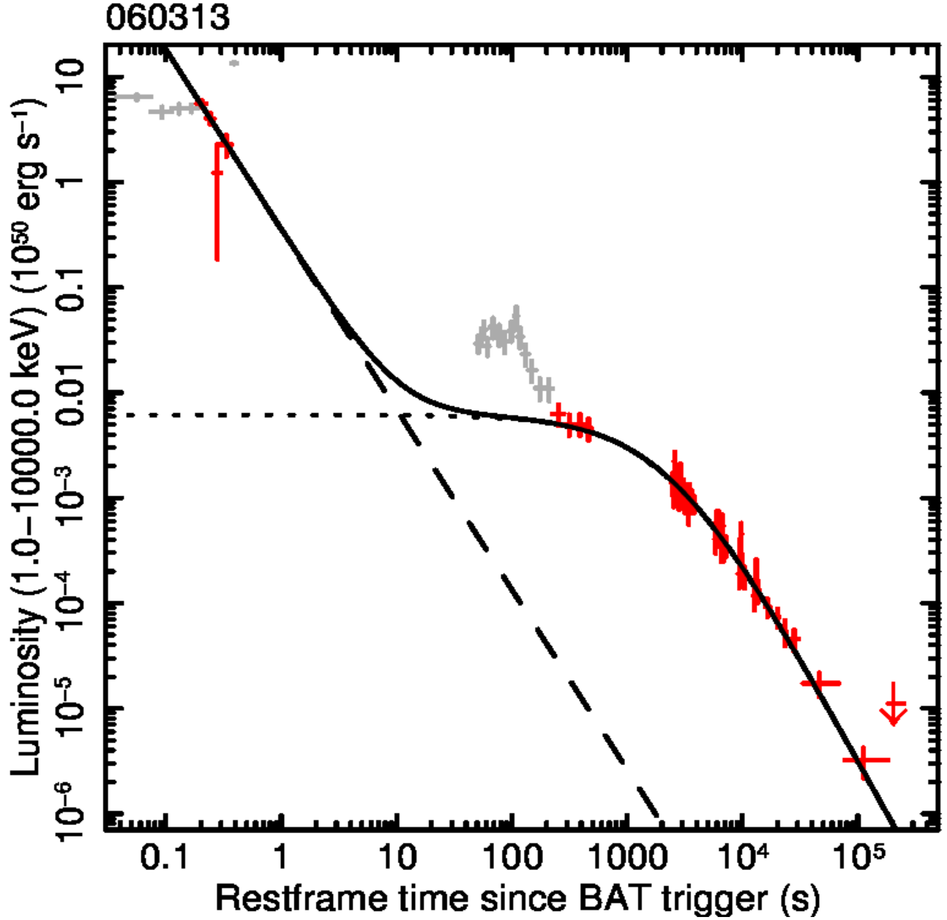


Magnetar central engine

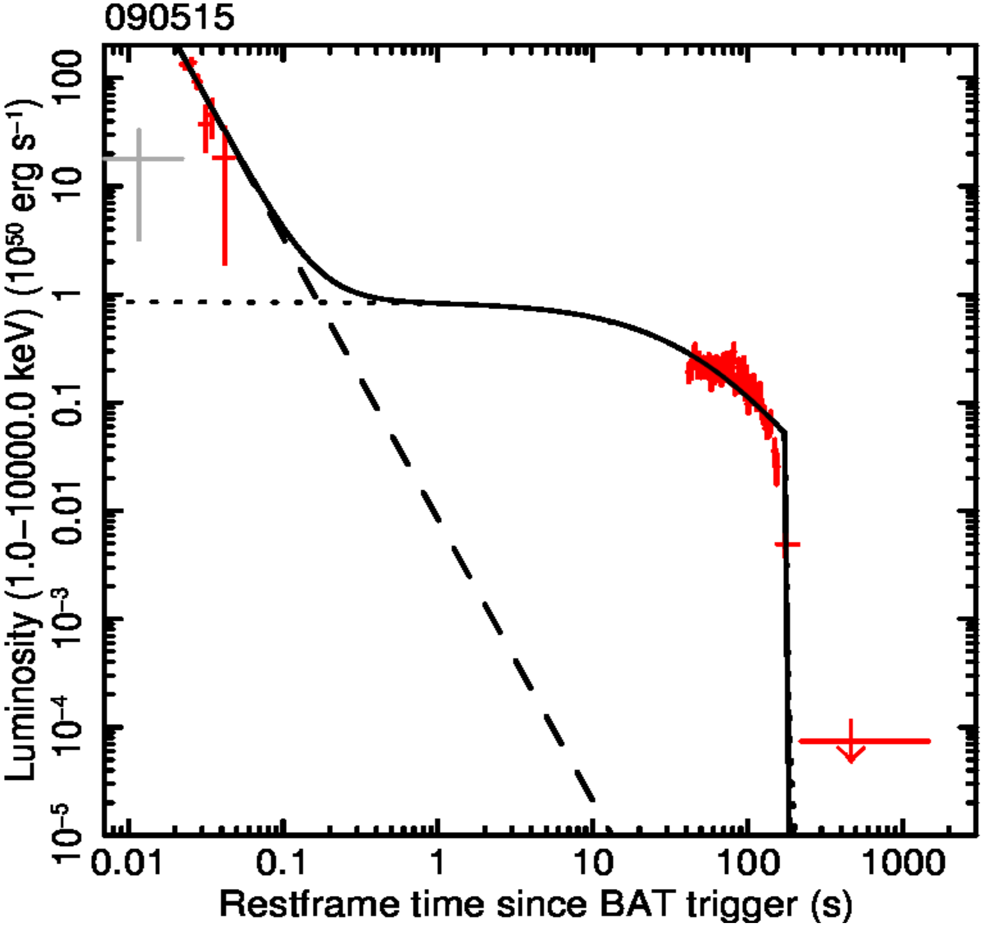
$$T_{em,3} = 2.05(I_{45} B_{p,15}^{-2} P_{0,-3}^{2} R_6^{-6})$$

$$L_{0,49} \sim (B_{p,15}^{2} P_{0,-3}^{-4} R_6^{6})$$

Zhang & Mészáros (2001)



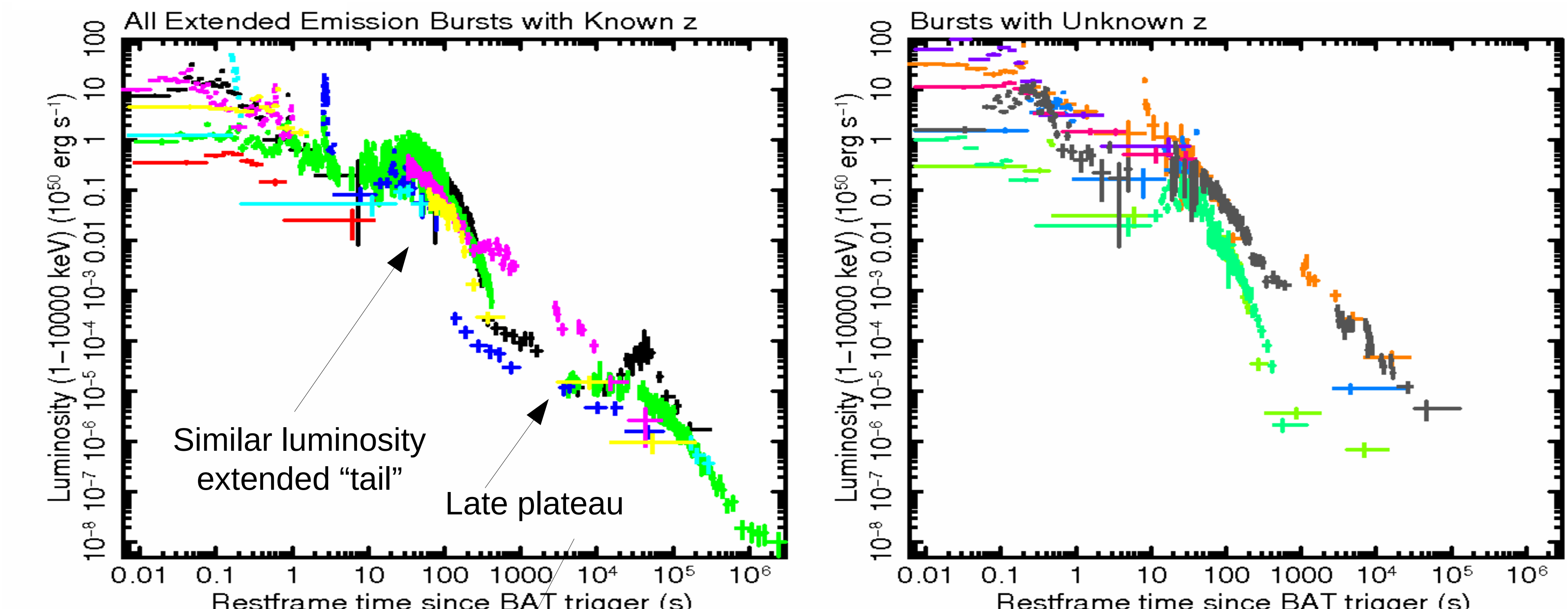
Stable

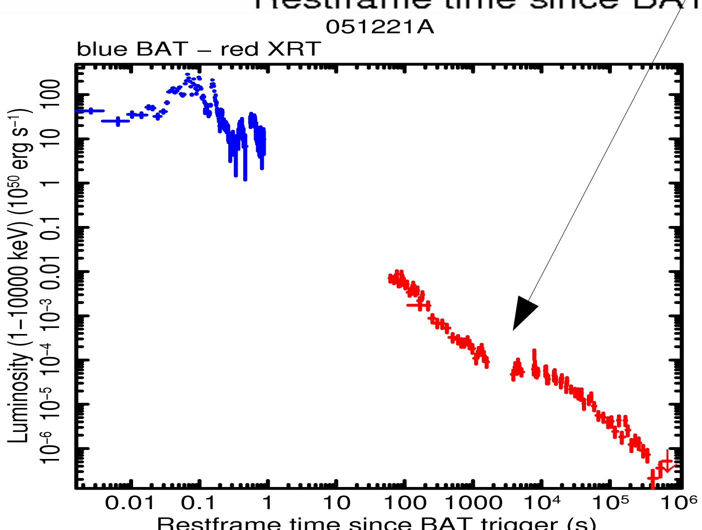


Unstable

Fits from Rowlinson et al. (2013)

Extended emission GRBs





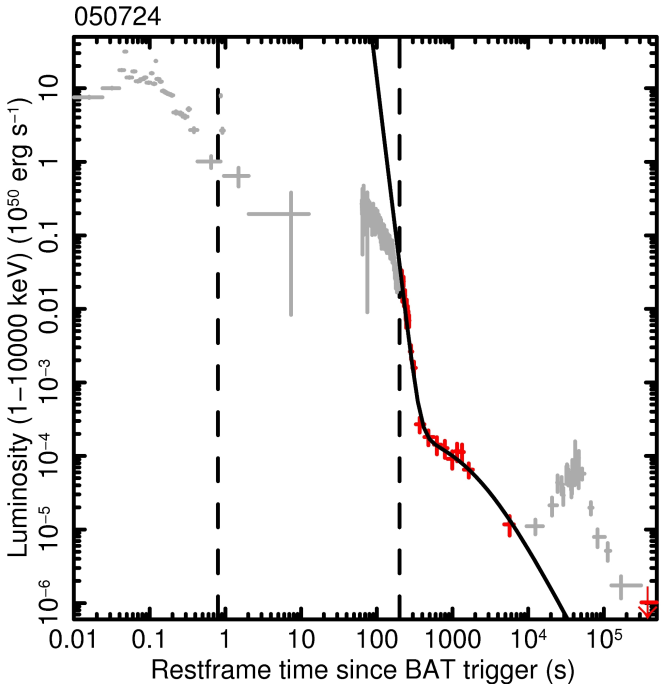
- High-energy rebrightening at around 10 seconds
- Seen in BAT (for *Swift* bursts)
- Typically lasts ~ 100 seconds
- Spectrally softer than prompt emission
- Remarkably uniform, suggestive of common central engine

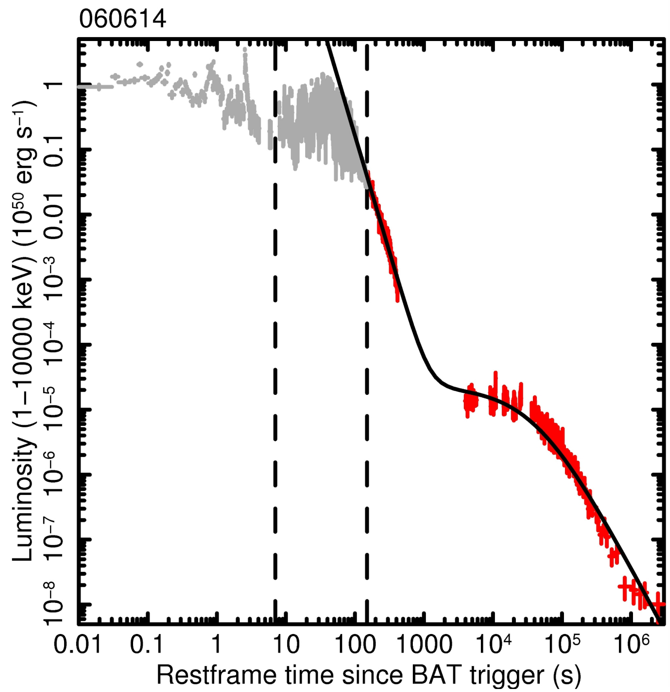
EE magnetar fits

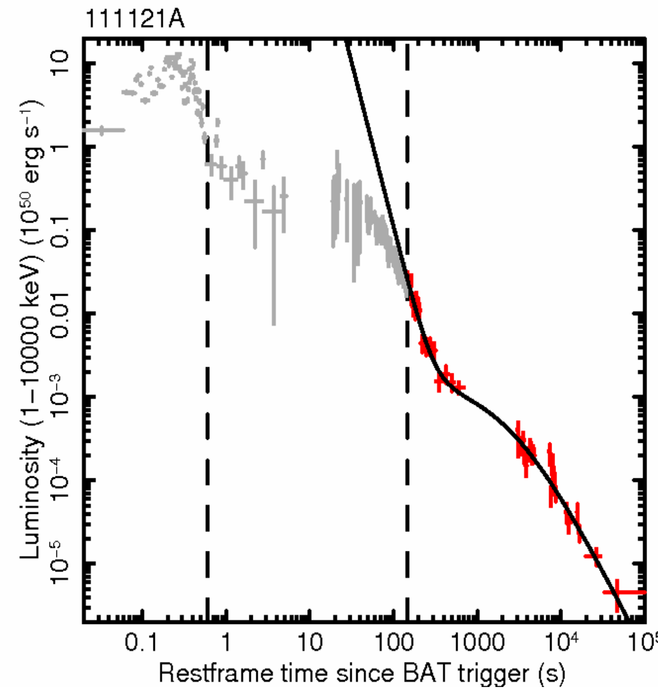
$$T_{em,3} = 2.05(I_{45} B_{p,15}^{-2} P_{0,-3}^{2} R_6^{-6})$$

$$L_{0,49} \sim (B_{p,15}^{2} P_{0,-3}^{-4} R_6^{6})$$

Zhang & Mészáros (2001)







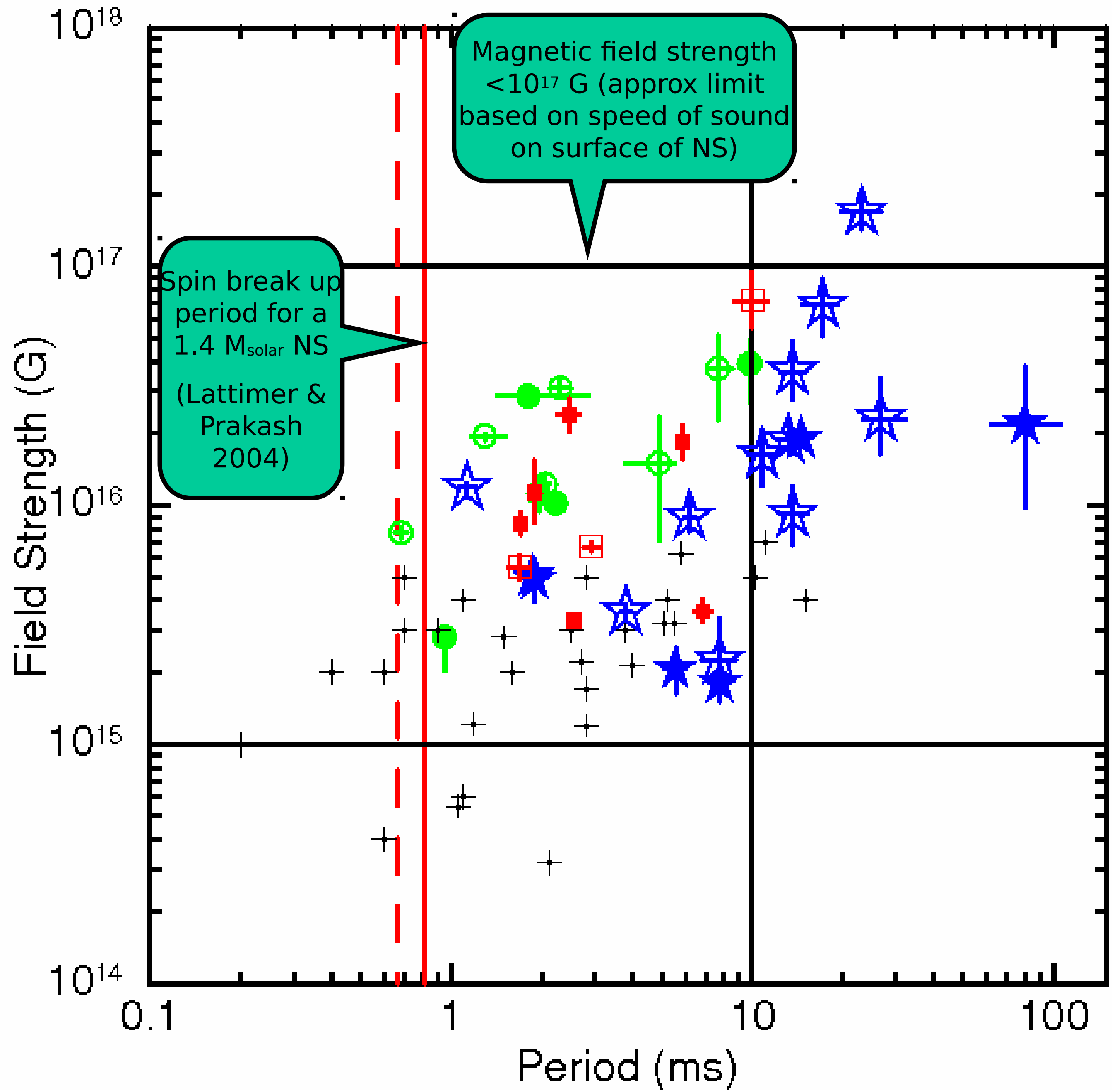
- Extended tail may affect spin period
- Assume EE draws entirely on rotational energy reservoir
- Assume constant dipole field

$$\Delta E = 2\pi^2 I (P_i^{-2} - P_0^{-2})$$

Wider GRB context

- Stable magnetars
- Unstable magnetars
- Long GRB candidates
- EE GRBs

- EE GRB light curves energetically compatible with a magnetar central engine
- Magnetar parameters in the EE sample indistinguishable from SGRB sample
- Difference in formation mechanism or environment?
- Unequal mass binary?
- Magnetic propeller?



Gompertz et al. 2013, MNRAS, 431, 1745

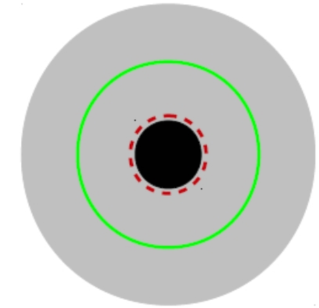
Magnetic propulsion

- Marginally bound material ejected by the merger can return to the central object on time scales of a few seconds (e.g. Lee et al. 2009)

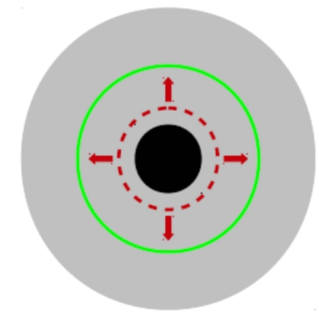
- Returning material encounters an extremely strong, rapidly rotating magnetic field

- Ejected material may emit through shocks, much like the prompt

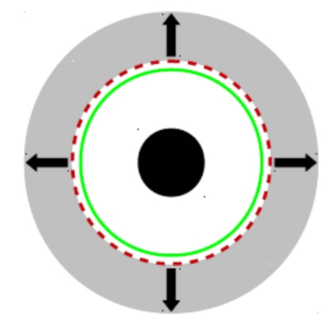
A) r_m is suppressed by a high accretion rate (and/or high P and/or low B). $r_c > r_m$ so material is orbiting faster than the field lines at the point of encounter. Interaction SLOWS material, spinning up the magnetar and allowing accretion onto the surface.



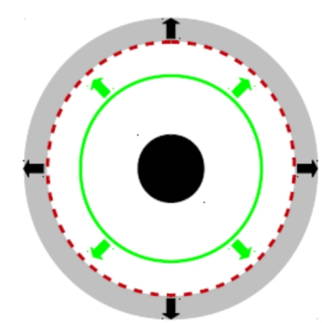
B) As accretion falls off, r_m expands.



C) When $r_m > r_c$ material is orbiting slower than the field lines when they encounter each other. Interaction ACCELERATES material, ejecting it from the system. This is the propeller regime.

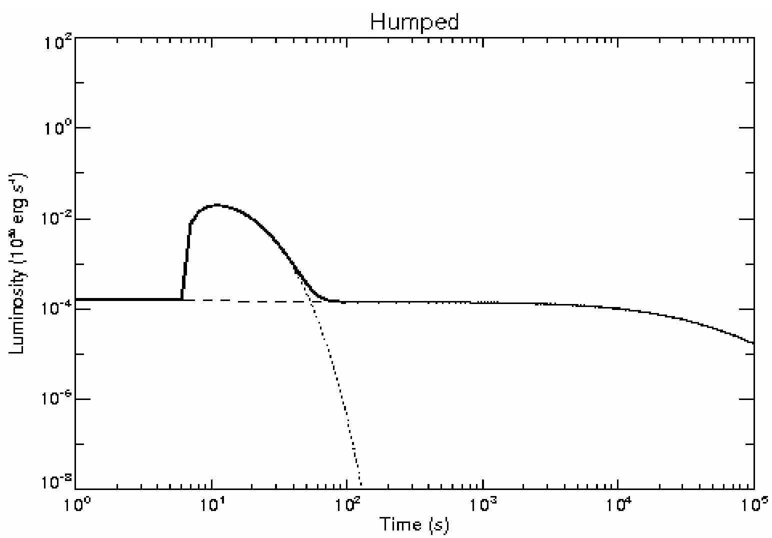


D) Loss of angular momentum to expelled material causes r_c to expand.



Synthetic light curves

540 synthetic light curves were created, using varying P, B, M_d, R_d and M_{NS}



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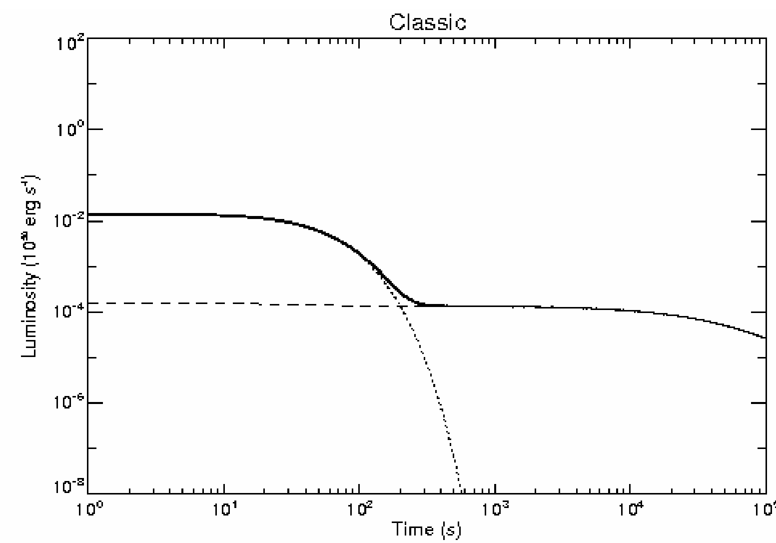

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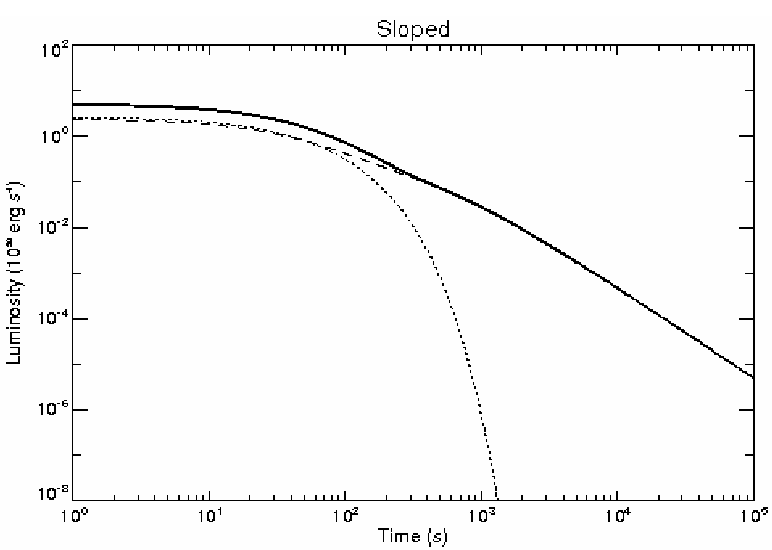

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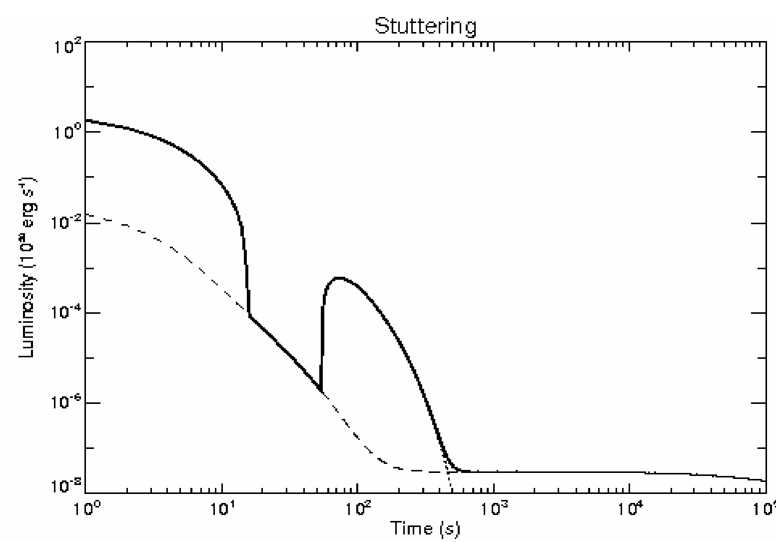

12%

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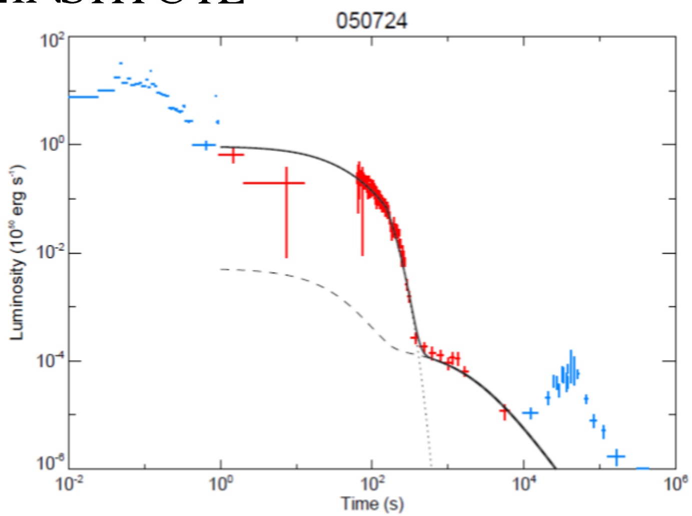
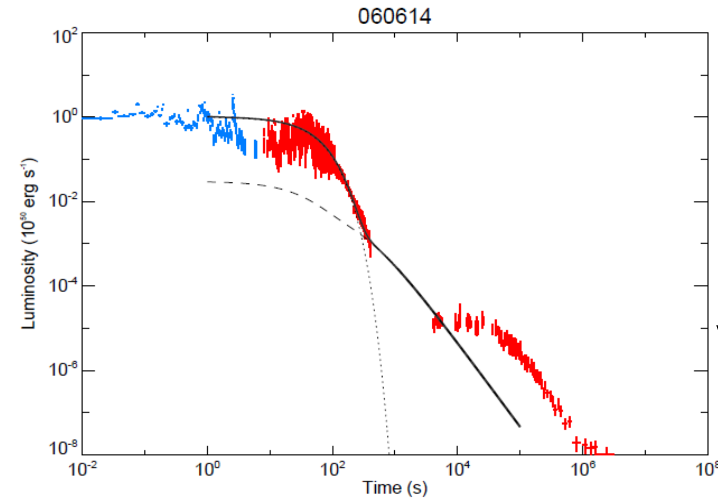
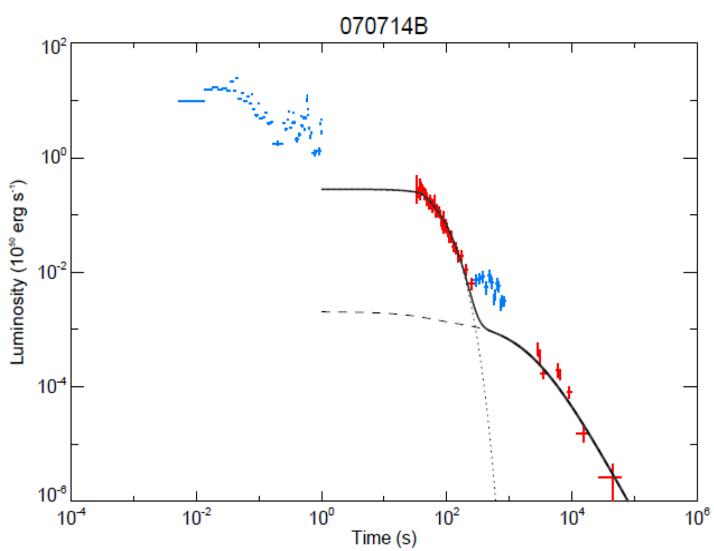
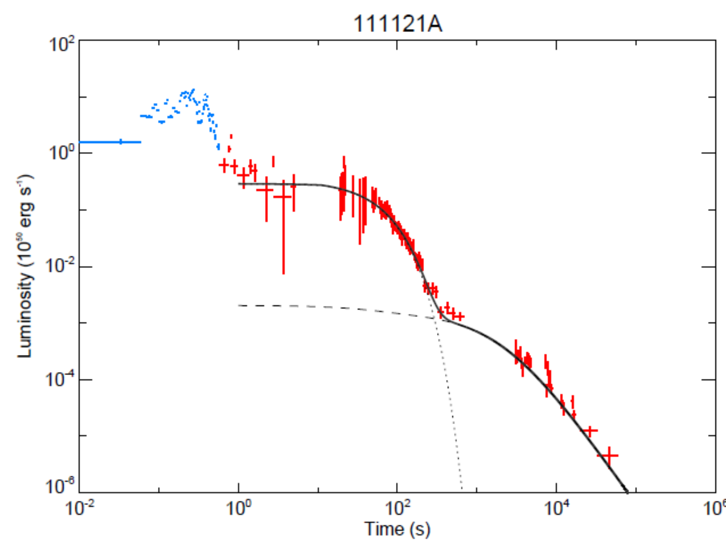
Fitting





Poor fit at late times; maybe B varies?





Assumed 40% KE to EM propeller efficiency; 5% for dipole; <0.9c ejection velocity

Gompertz, O'Brien & Wynn, 2014, MNRAS, 438, 240

Uses MPFIT (Markwardt 2009)

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Results

Gompertz et al. 2014, MNRAS, 438, 240

GRB	P (ms)	B ($10^{15} G$)	M_d ($M_\odot$)	R_d (km)
050724	0.93 ±0.04	0.88 ±0.04	$(2.63 \pm 0.13) \times 10^{-2}$	1217 ±4
051227	0.69 [L]	0.45 ±0.19	$(1.10 \pm 0.18) \times 10^{-2}$	695 ±41
060614	0.69 [L]	1.17 ±0.05	$(1.20 \pm 0.01) \times 10^{-2}$	1300 ±4
061006	1.51 ±0.21	1.48 ±0.07	$(2.01 \pm 0.37) \times 10^{-2}$	400 ±2
061210	0.69 [L]	0.18 ±0.05	$(3.20 \pm 2.88) \times 10^{-3}$	674 ±753
070714B	0.69 [L]	0.31 ±0.05	$(6.91 \pm 0.28) \times 10^{-3}$	1378 ±72
071227	1.54 ±0.12	0.57 ±0.08	$(7.63 \pm 1.02) \times 10^{-3}$	1131 ±17
080123	3.75 ±0.46	1.92 ±0.16	$(5.82 \pm 1.10) \times 10^{-3}$	742 ±6
111121A	0.69 [L]	0.31 ±0.03	$(4.80 \pm 0.10) \times 10^{-3}$	1538 ±43

- Derived disk masses between 3×10^{-3} to 3×10^{-2} solar masses.
- Outer disk radii between 400 – 1500 km.
- Consistent with theoretical predictions (e.g. Lee et al. 2009)
- P and B still lie in allowed parameter space.
- Best fits require an exponential accretion profile rather than a power law – as expected in the presence of strong outflows (Fernández & Metzger 2013).
- Propeller fits require efficient (> 10%) conversion of KE to EM.

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The magnetar model in SGRBs

+ Naturally long-lived central engine
+ Energetically consistent with magnetar limitations
+ Produces afterglow fits with good fit statistics
+ Fits fall within allowed B and P parameter space
+ Can account for bursts with/without late plateaux and EE GRBs within a single model
+ Only model capable of explaining sudden & severe drops in flux (e.g. Troja et al. 2007)

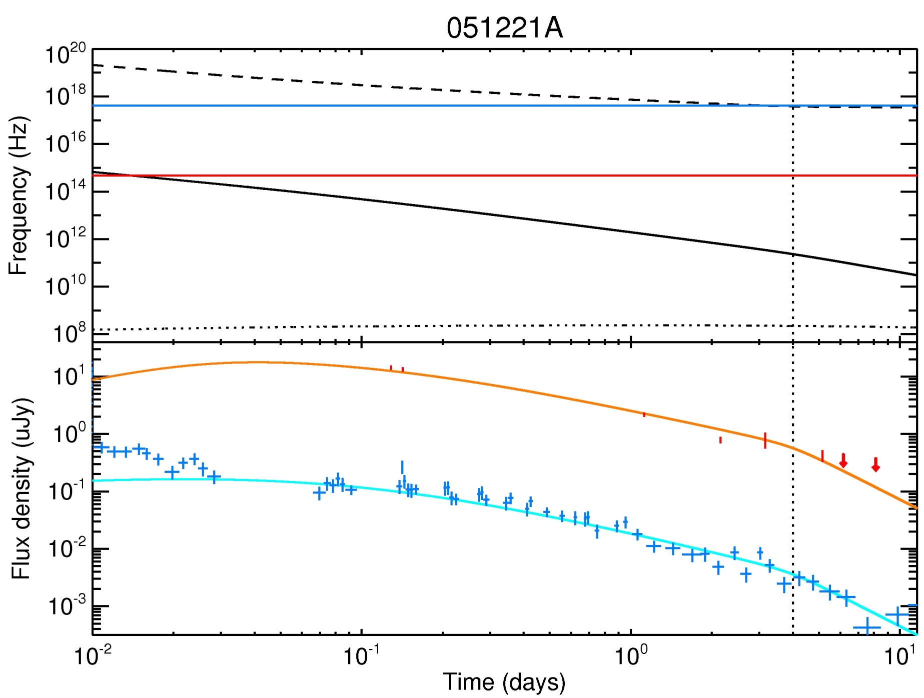
- Too simplistic; energy reprocessed in shock with assumed efficiency
- No spectral information
- Serious concerns over whether a jet with requisite Lorentz factor can be launched (e.g. Drenkhahn & Spruit, 2002; Dessart et al. 2007)
- Can a magnetar be formed through merger? (Massive NSs e.g. 2.01 Msol, Antoniadis et al. 2013, suggest yes)
- Where is the radio emission? (Metzger & Bower, 2014; Horesh et al. 2016)

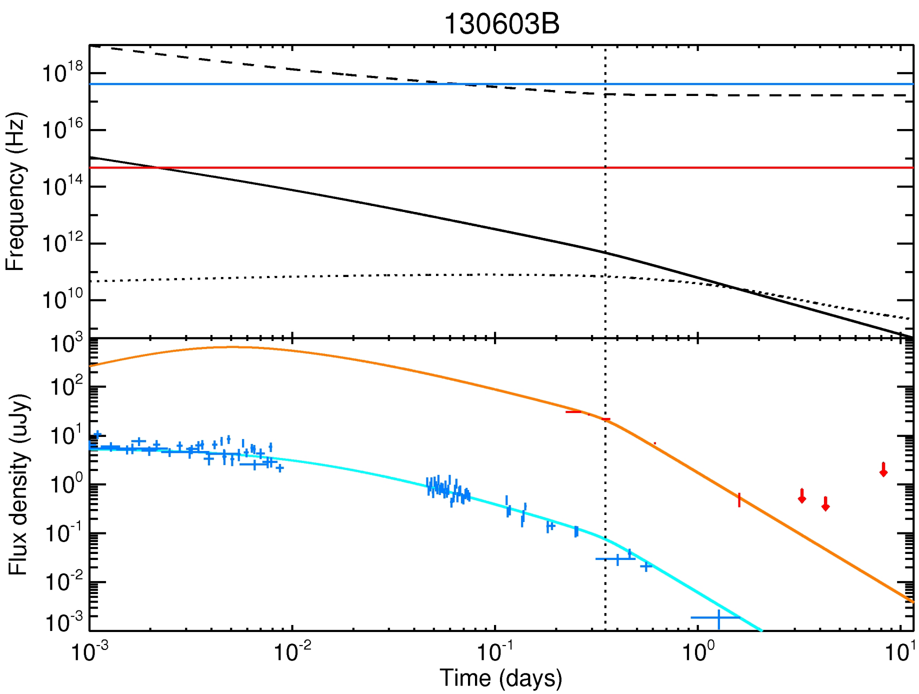
Other models for late plateaux:

- Fallback accretion (e.g. Rosswog 2007)
- Top heavy jet with prolonged coasting phase (Duffell & MacFadyen, 2015)
- Interactions with walls of a pulsar-excavated cavity (Holcomb et al. 2014)

Where is the radio signal?

- Standard dipole fitting assumes certain conversion efficiency from X-ray light curves.
- Gives no information on emission at longer wavelengths.
- Perform broadband modelling of forward shock emission with dipole (and EE) profile as time-varying energy injection.
- Available data is not constraining to self-absorption break (very few radio observations, even fewer detections) or cooling break (if above X-ray frequency).
- Many combinations of physical parameters can match available data.





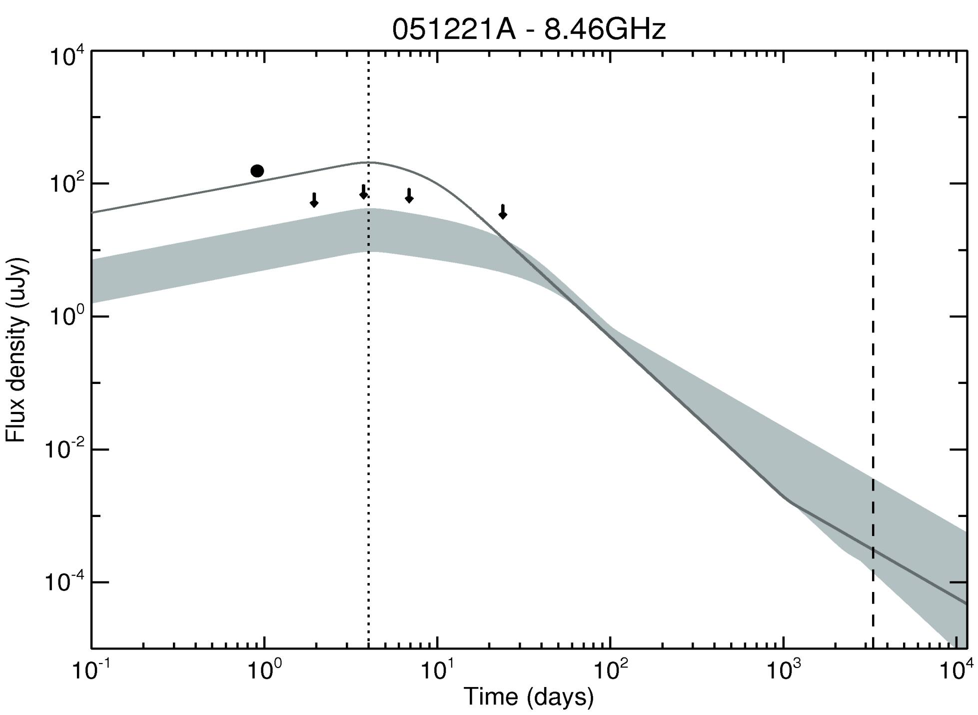
Radio signature

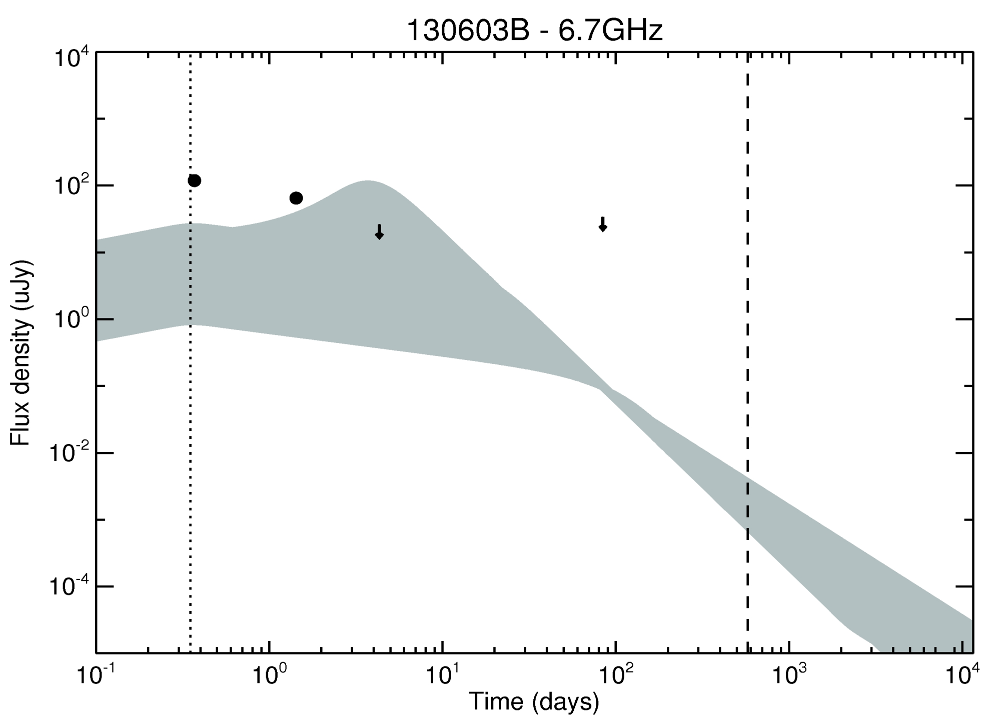
- Order of magnitude parameter space search for 3 physical parameters (ε_e, ε_B and n) and 3 energy terms (prompt, EE and dipole contributions).

- Each successful match provides a family of parameters that are self-consistent within the magnetar model.

- Can be used to create the expected radio signature for a magnetar injecting energy into a forward shock.

- Difficult to reproduce early-time radio observations with forward shock alone. Evidence for reverse shock?





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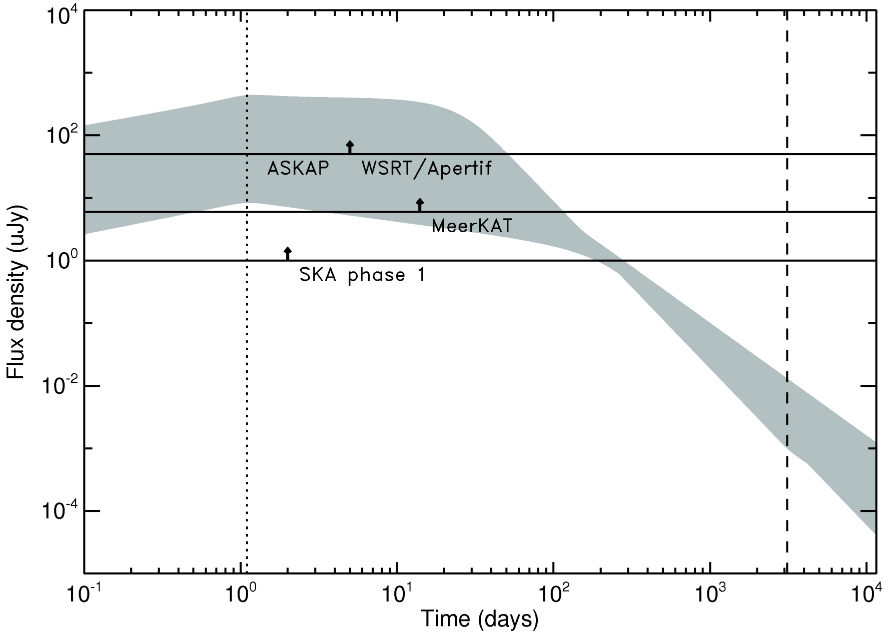
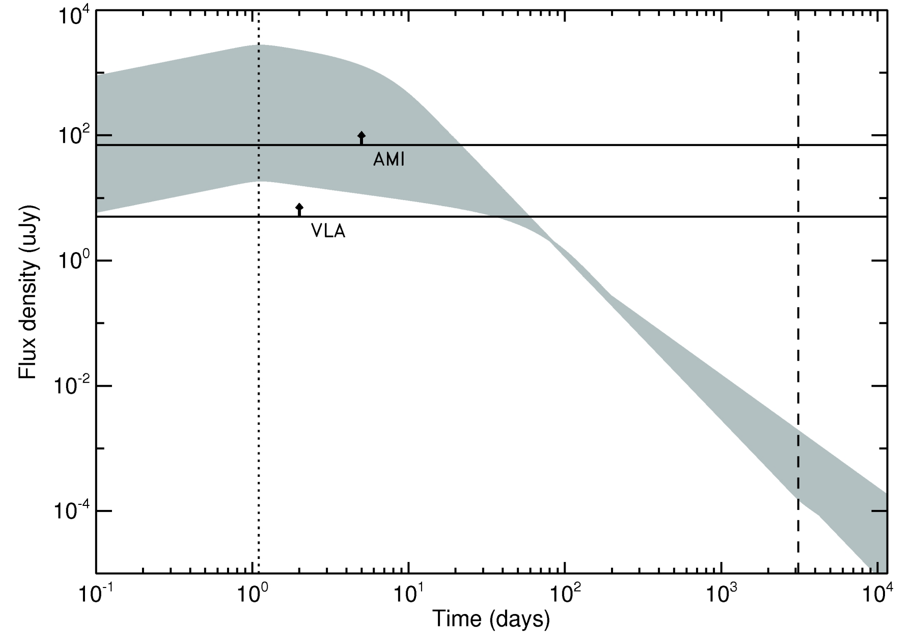
Gompertz et al. 2015, MNRAS 448, 629

Detectability

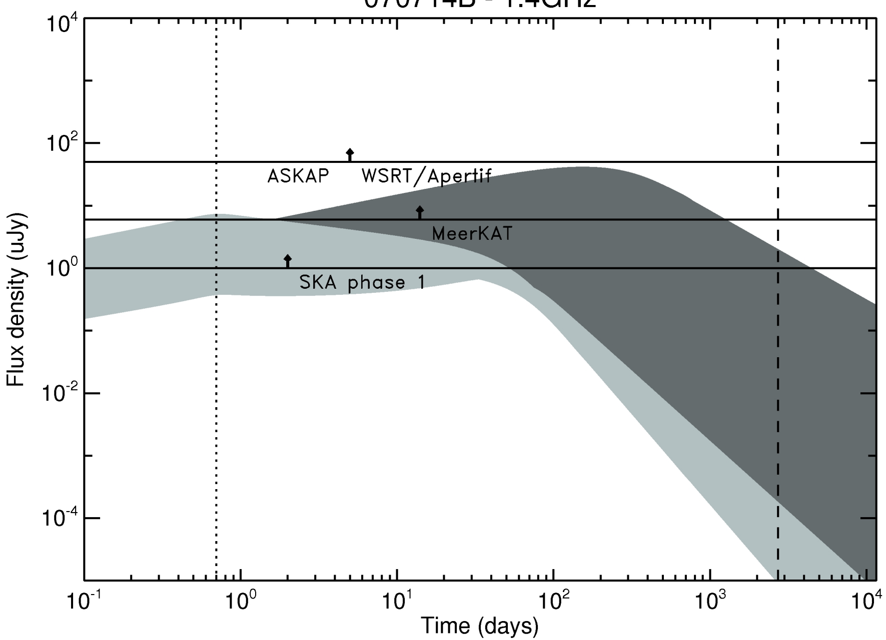
060614 - 1.4GHz



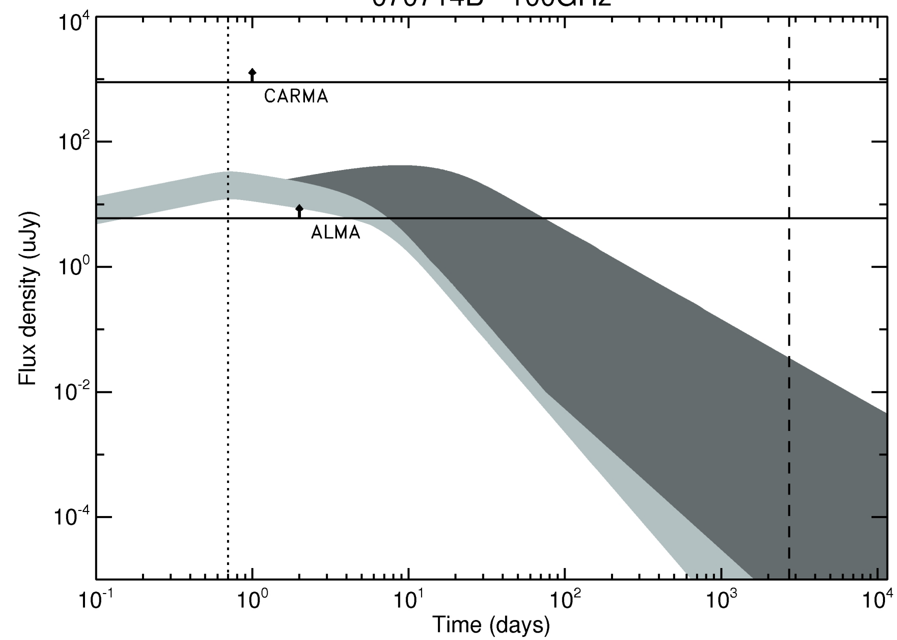
060614 - 15GHz



070714B - 1.4GHz



070714B - 100GHz



SGRB summary

- Short and EE GRB light curves are both consistent with energy injection from a magnetar central engine

- Magnetar properties appear to be identical in both classes; difference may be down to formation or environment

- The quasi-stable population of magnetars may be very useful in constraining the NS equation of state

- A 'hot spot' is expected at the magnetic poles. Candidate for timing analysis?

- A magnetic propeller provides a possible source of EE, since it is predicated on the presence of a fall-back disc, regardless of magnetar properties

- Broadband observations are consistent with forward shock energy injection, but reverse shocks required at early times

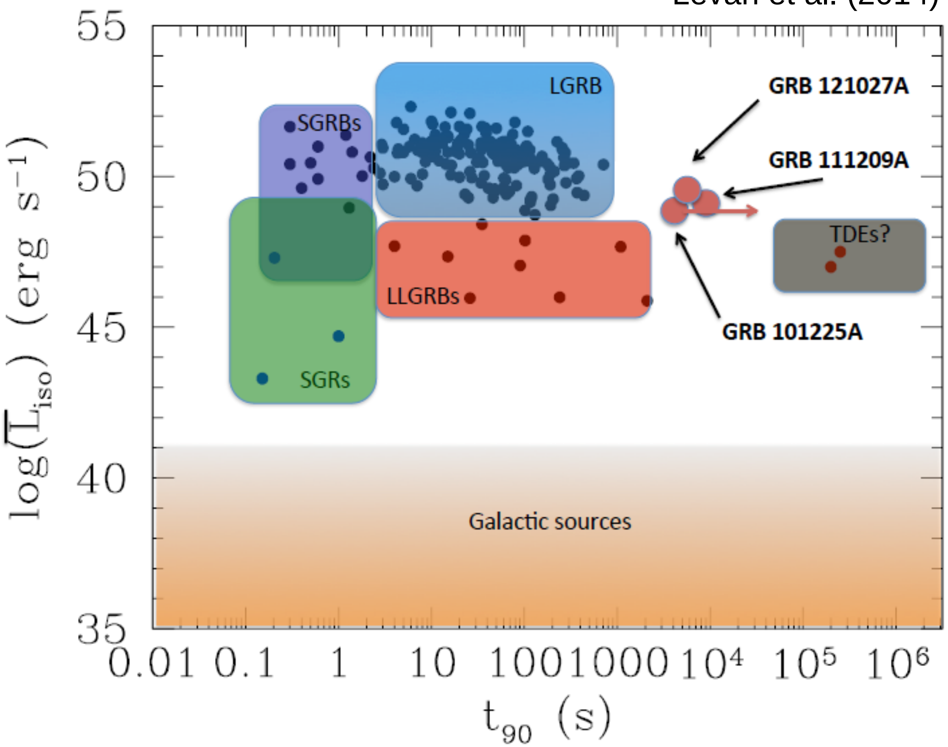
- Previous radio observations provide some constraints to parameter space, but have not yet fully probed the model. Detections are likely to be from reverse shocks.

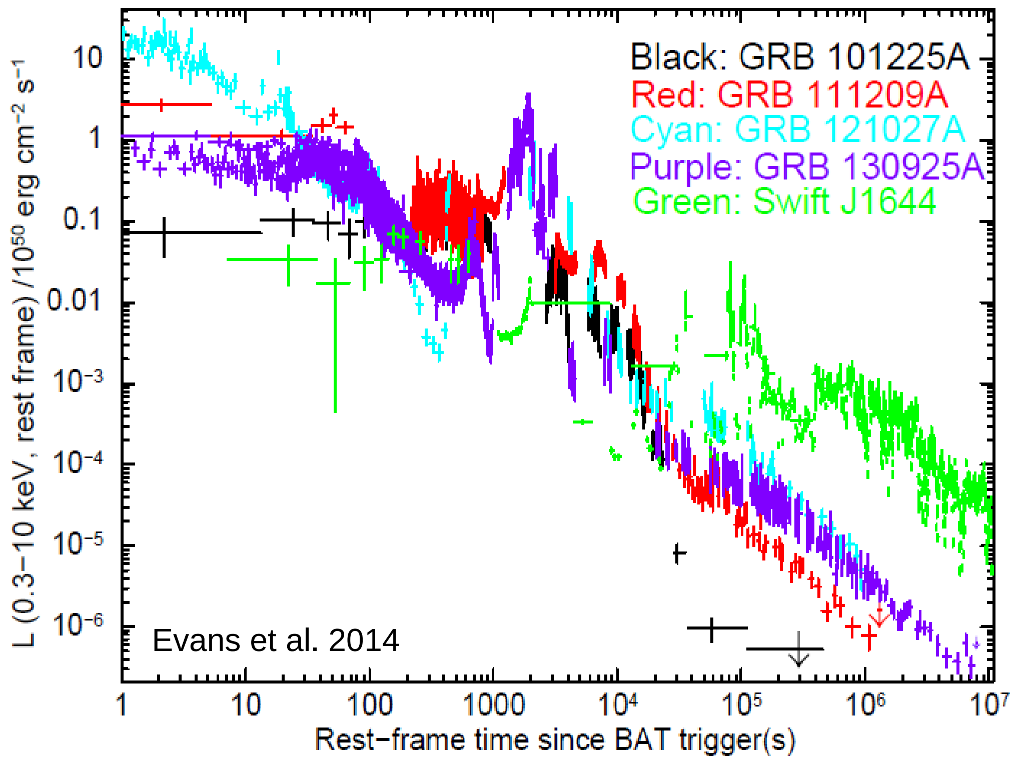
- New observatories, in particular ALMA and the upgraded VLA, are now able to fully probe the radio signature if on target within ~ 2 weeks

- SKA (phase 2) will be able to go deeper than our lowest prediction for around a year after trigger!

Ultra-long GRBs

Levan et al. (2014)





Swift has found a small number of "ultra long" transients/GRBs, with T_{90} >2000s

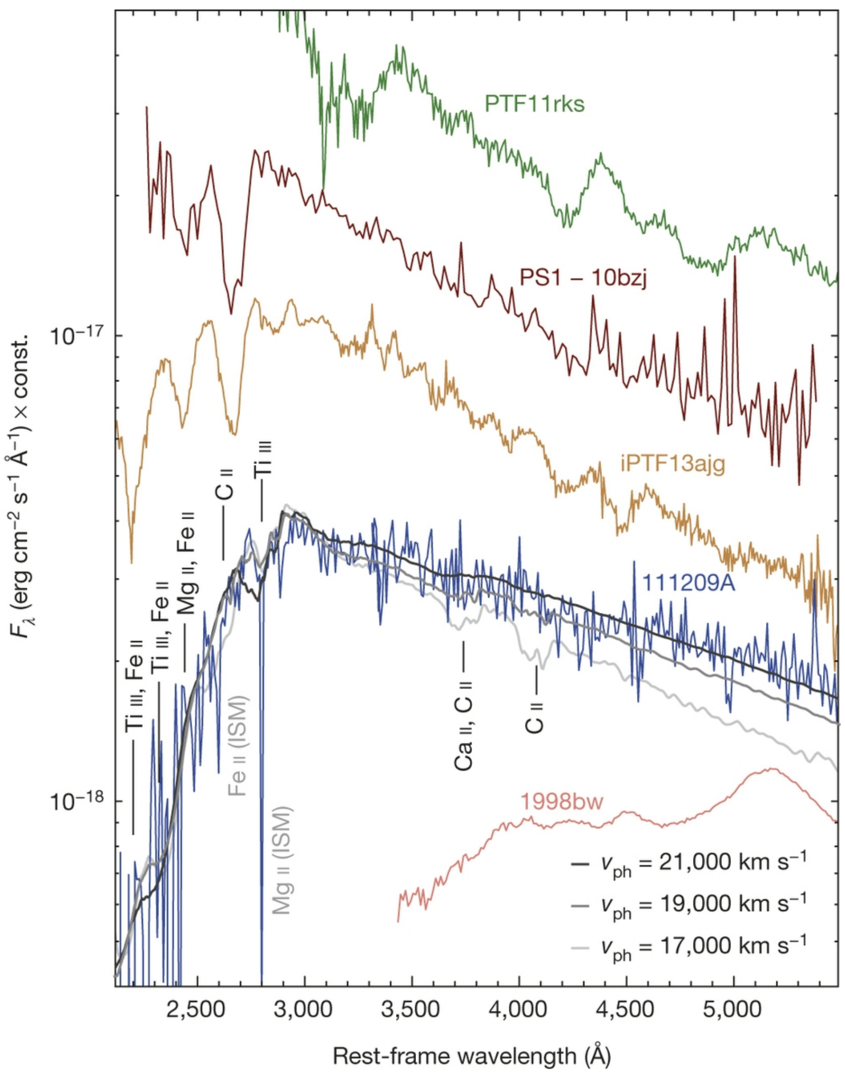
Durations are statistically distinct from LGRBs (Boer et al. 2015, Levan et al. 2015)

Brighter at late times than average GRB. Fainter at late times than Swift J1644+57

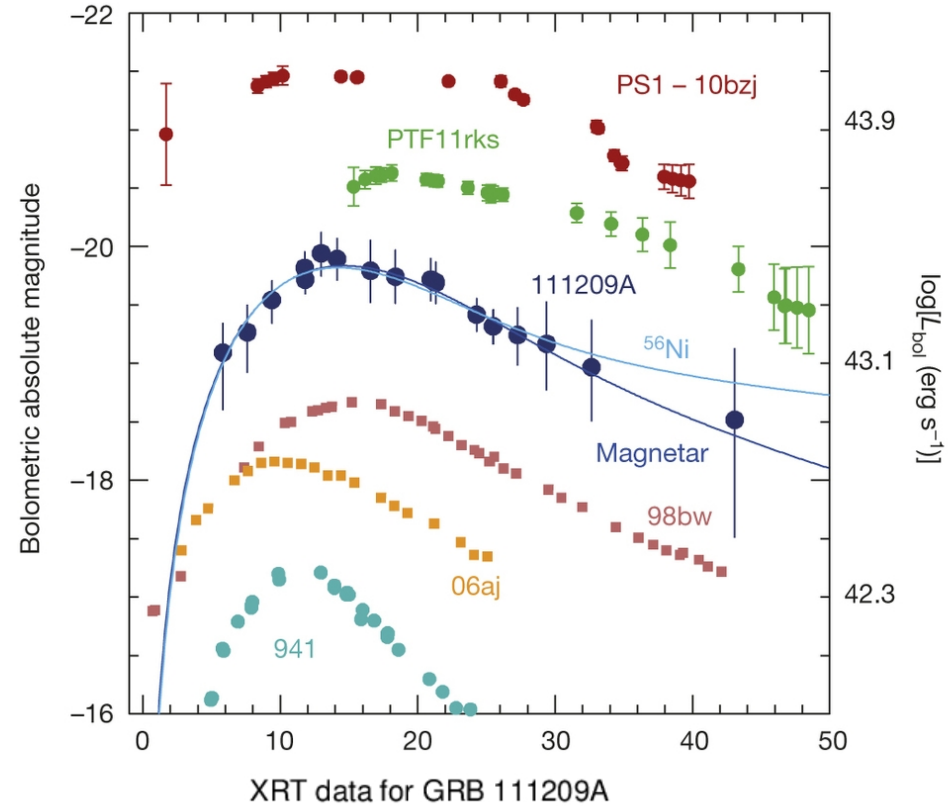
For GRB 130925 only detect a dust-scattered X-ray afterglow. Others have weak afterglows relative to the prompt emission

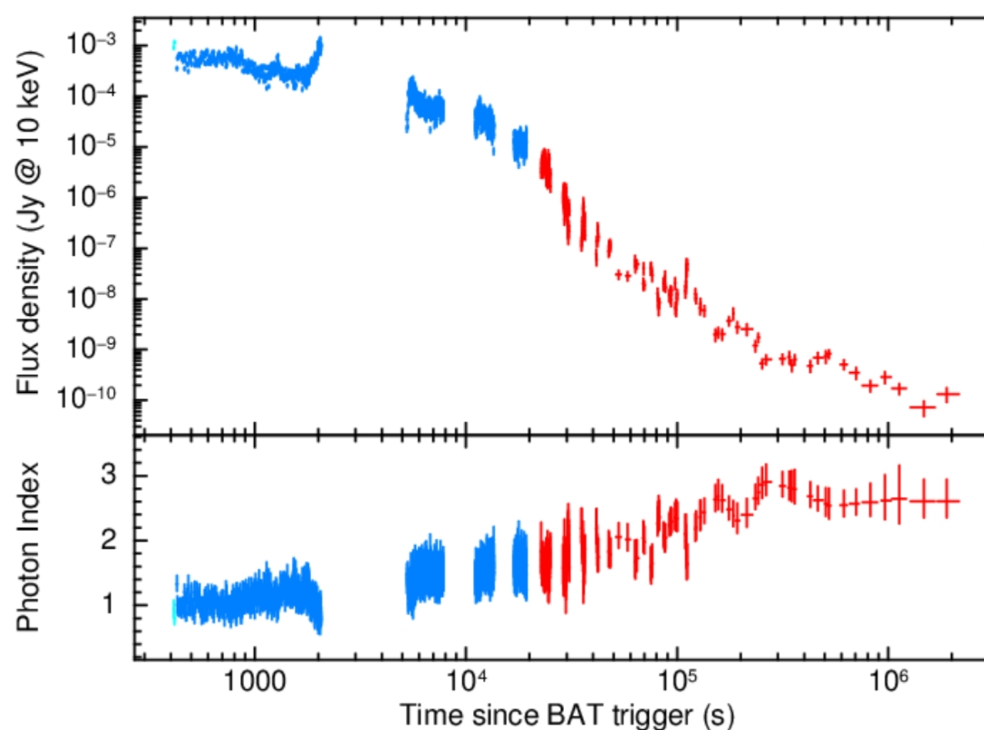
Hard to reconcile with afterglow (GRB) or fallback (TDE) models

GRB 111209A



Greiner et al. 2015





Energy budget

Required:

- Konus-Wind observed isotropic energy (5.7 +/- 0.7) x 10^53 erg over ~ 10ks
- 3 Msol moving at 20,000 km/s (photospheric velocity) requires at least ~ 3E51 erg (assuming maximum asphericity, cf. Maeda 2002)
- Integrated SN luminosity ~ 1E51 erg

Available:

- ~ 1-2E51 from core collapse/early accretion
- Maximum ~ 3E52 from a 1ms magnetar
- Thermal energy from radioactive decay at late times (at least 0.08Msol, Bersten et al. 2016)

Magnetar energy reservoir goes as 3E52 P^(-2) – at least a 3ms NS is required for the supernova alone

Beaming angle is extremely tight for anything but a 1ms magnetar. No break apparent in the X-ray light curve out until 21 days

Other ULGRBs