GRBs and magnetars in the multi-messenger era

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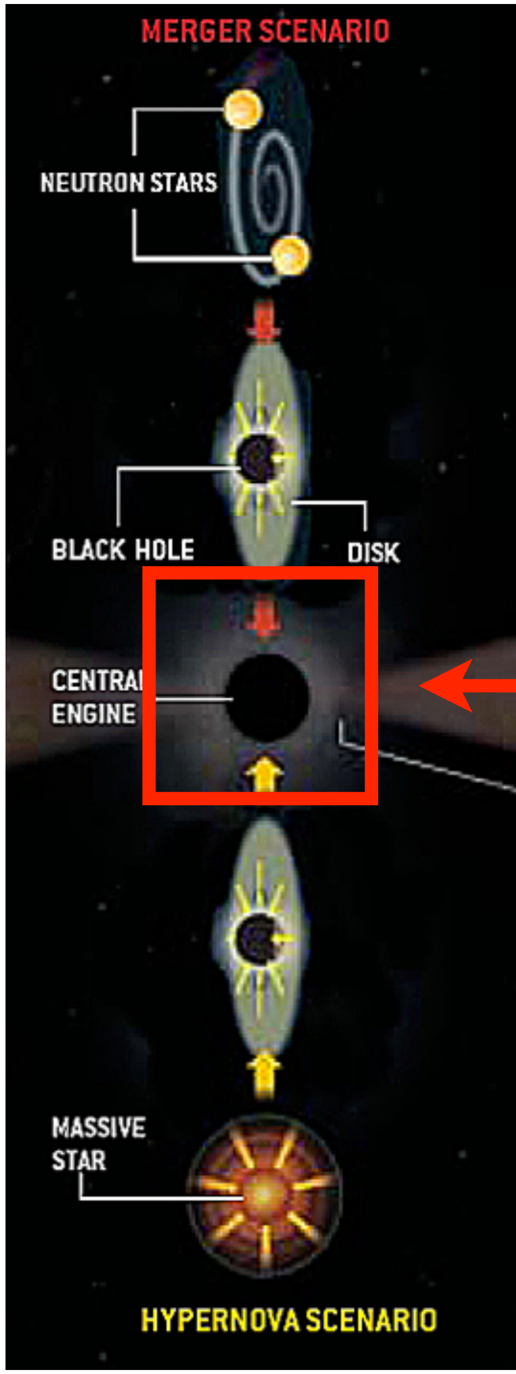
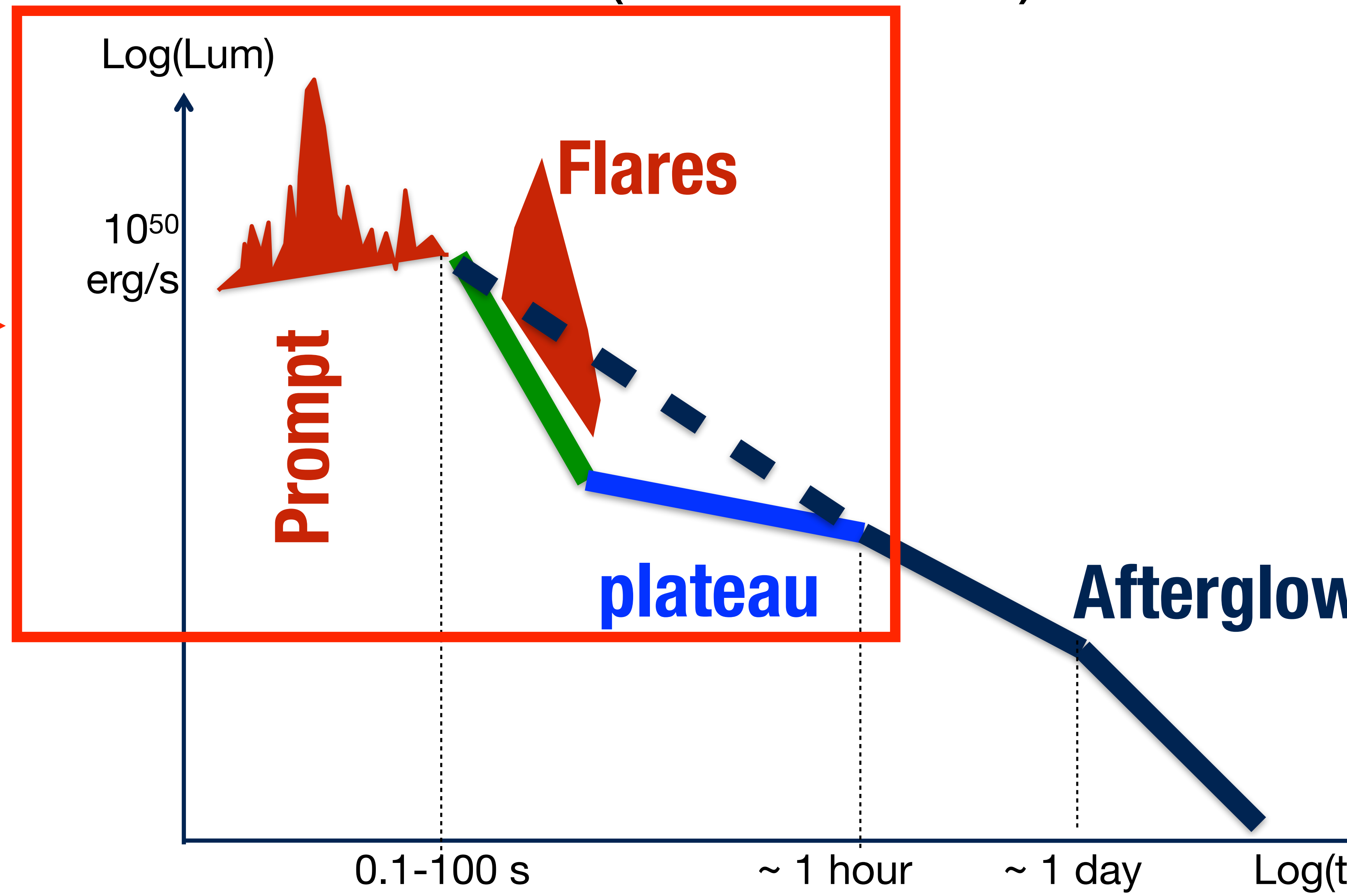
The central engine of GRBs

Short GRBs



Long GRBs

Magnetars: highly magnetised ($B \sim 10^{12-14}$ G) NSs

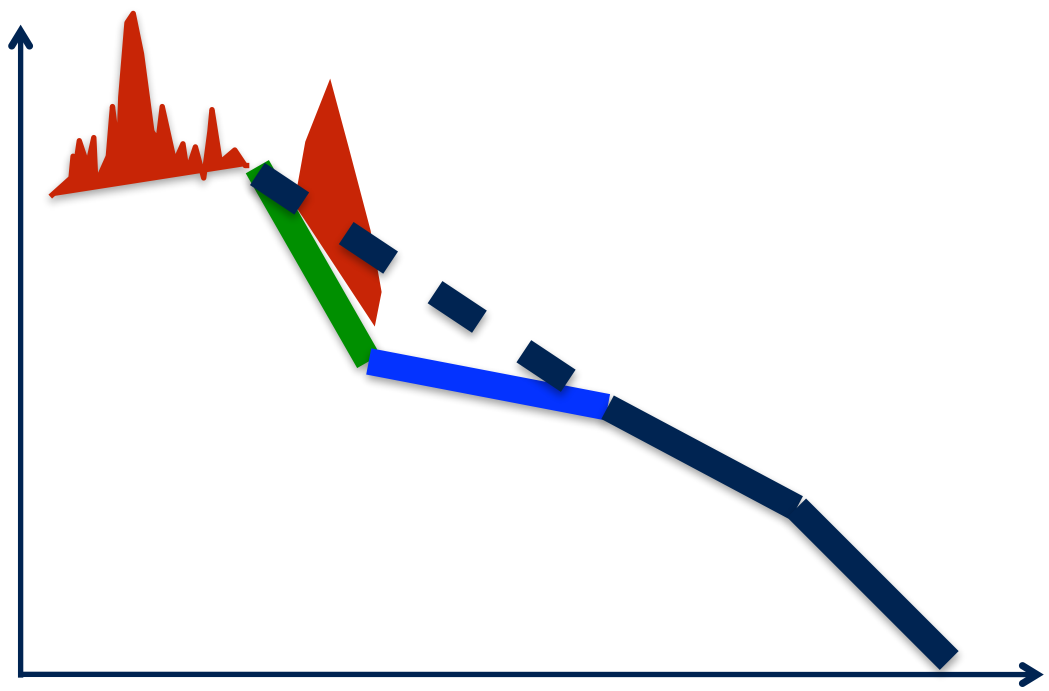


Magnetars are competing with BHs as source of GRB power

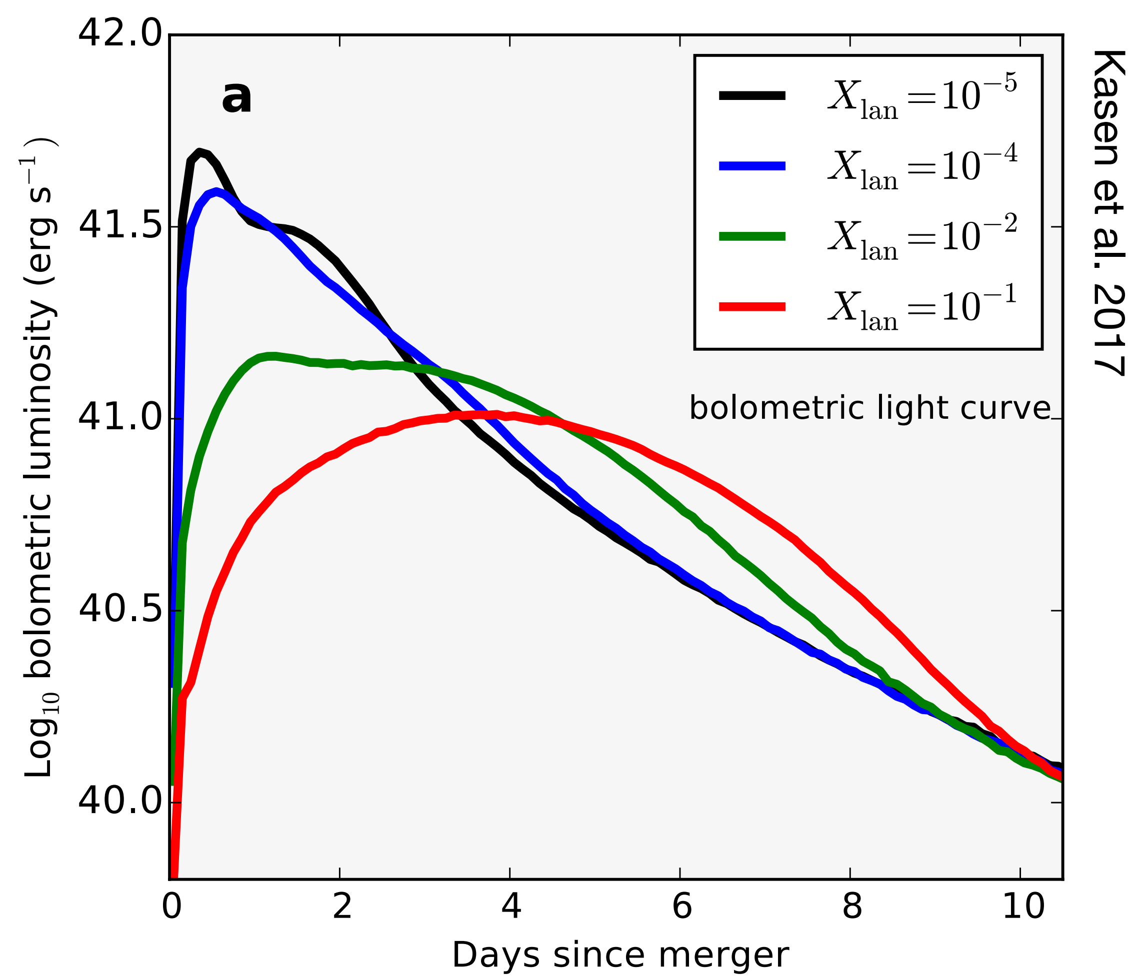
Usov 1992, Duncan & Thompson 1992, Dai & Lu 1998, Zhang & Meszaros 2001, Metzger et al. 2011, ….

Observational imprints of the magnetar

- The **GRB** emission



- The **kilonova** emission associated to **SGRBs**



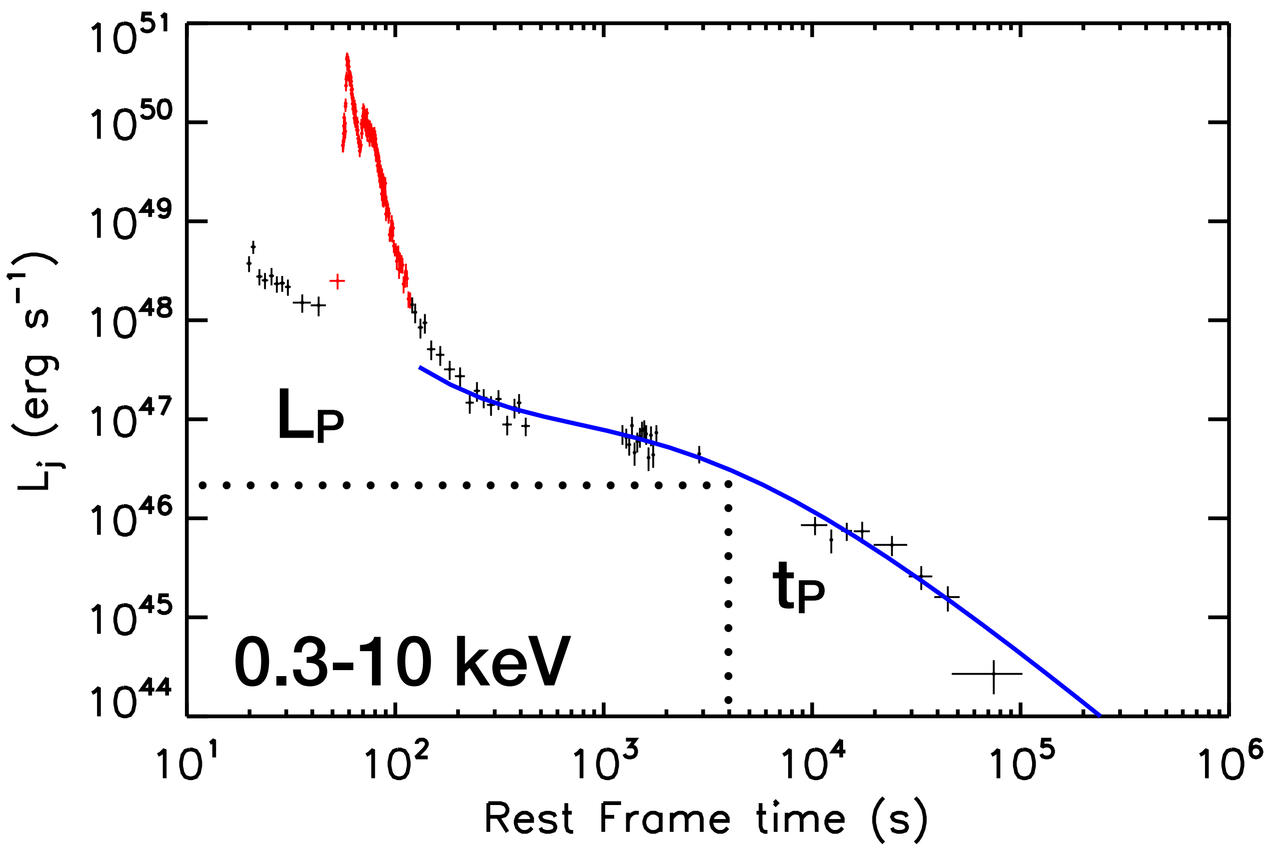
Observational imprints of the magnetar

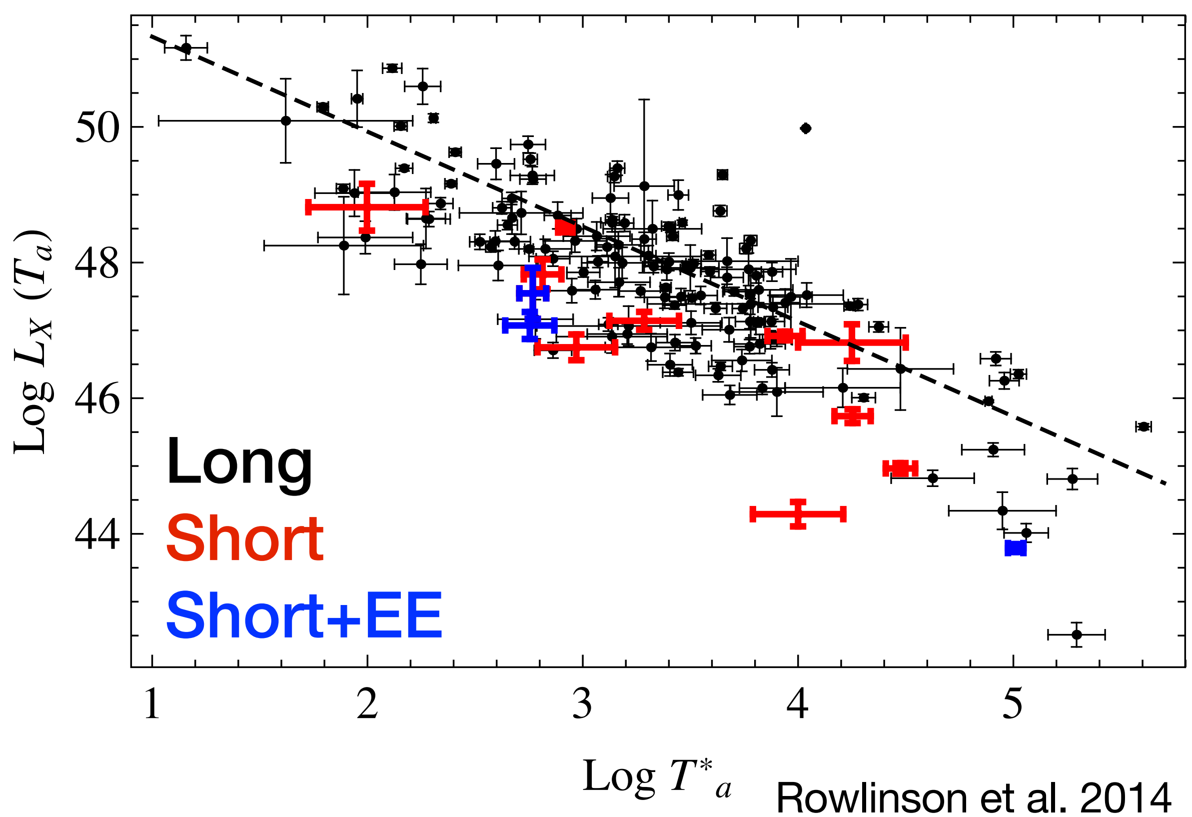
The GRB emission:

- **X-ray plateau**
- Extended emission in SGRBs
- Pre- and post-cursors in the prompt emission

The **kilonova** emission associated to **SGRBs**

First evidence for magnetars: the X-ray plateau





Rowlinson et al. 2014

- **Plateau** phase in the X-ray afterglow of LGRBs and SGRBs

➡ **Energy injection into the afterglow lasting ~ hours**

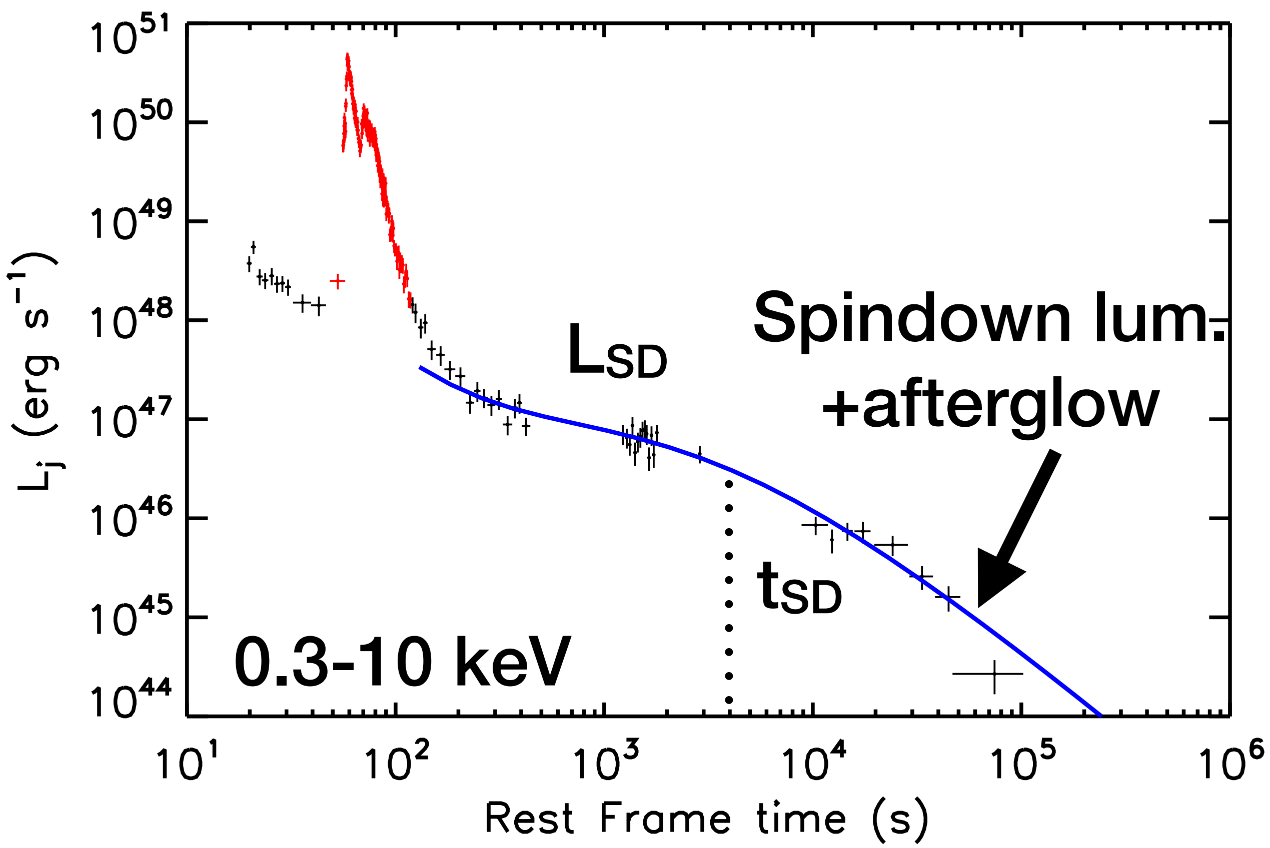
- Correlations between the **plateau** properties and the prompt emission (Dainotti et al. 2008, 2010, 2013, 2015)

Magnetar **spin-down power** provides a straightforward explanation of the features of the **plateau**

$$L_{sd}(t) = \frac{I\,K\omega_i^4}{(1+2K\omega_i^2 t)^2} = \frac{L_i}{(1+at)^2}$$

Dai & Lu 1998, Zhang & Meszaros 2001, Corsi & Meszaros 2009, Lyons et al. 2010, Dall'Osso et al. 2011, Metzger et al. 2011 Bernardini et al. 2012, 2013, Rowlinson et al. 2013, 2014, Lu & Zhang 2014, Lu et al. 2015, Stratta et al. 2018.

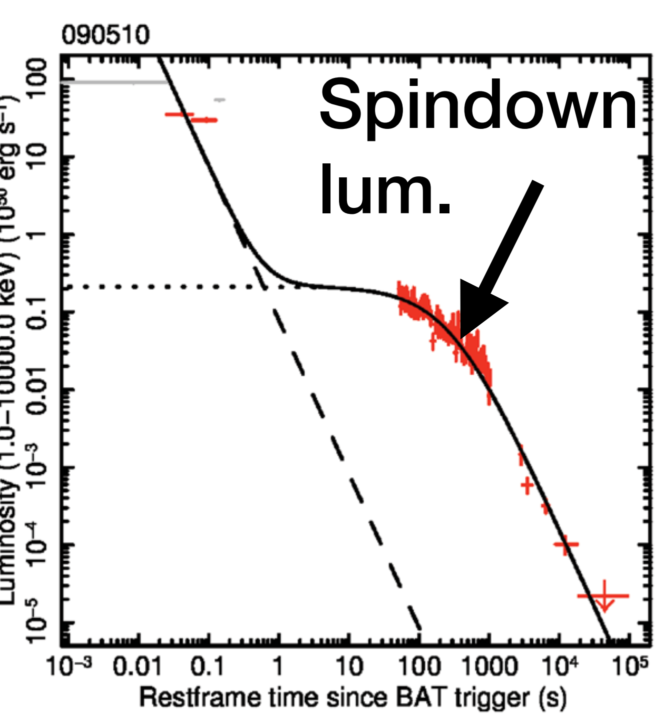
First evidence for magnetars: the X-ray plateau

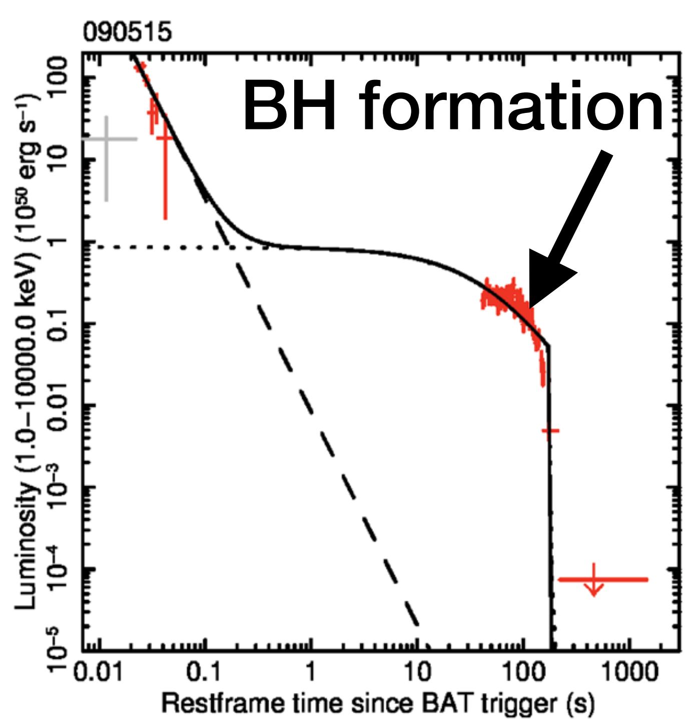


- **external** **plateau**: continuous energy injection into the forward shock

$$\frac{dE(t)}{dt} = L_{\rm sd}(t) - k'\frac{E(t)}{t} = \frac{L_i}{(1+at)^2} - k'\frac{E(t)}{t}$$

Dall'Osso et al. 2011



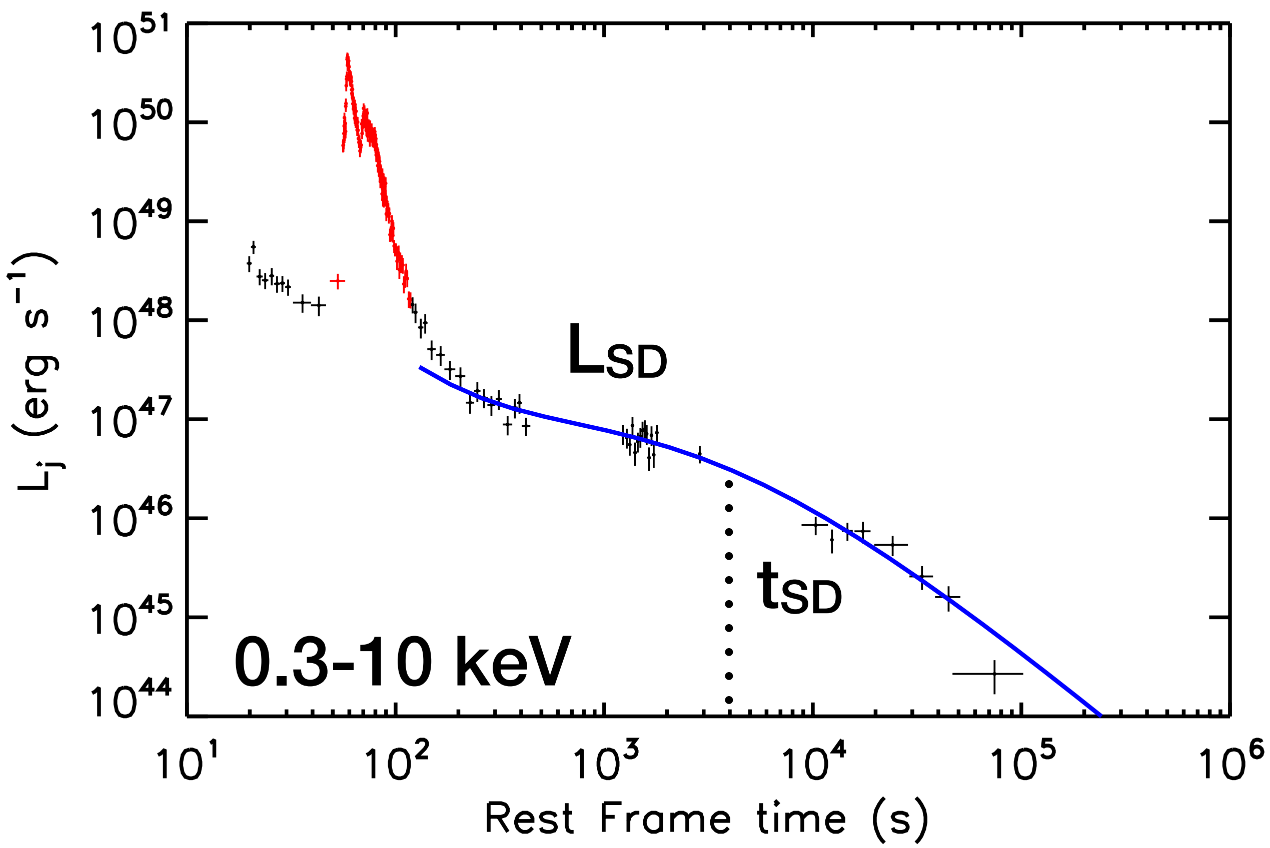


Rowlinson et al. 2013

- **internal** **plateau**: long-lived magnetar or collapse to BH

Dai & Lu 1998, Zhang & Meszaros 2001, Corsi & Meszaros 2009, Lyons et al. 2010, Dall'Osso et al. 2011, Metzger et al. 2011 Bernardini et al. 2012, 2013, Rowlinson et al. 2013, 2014, Lu & Zhang 2014, Lu et al. 2015, Stratta et al. 2018.

First evidence for magnetars: the X-ray plateau

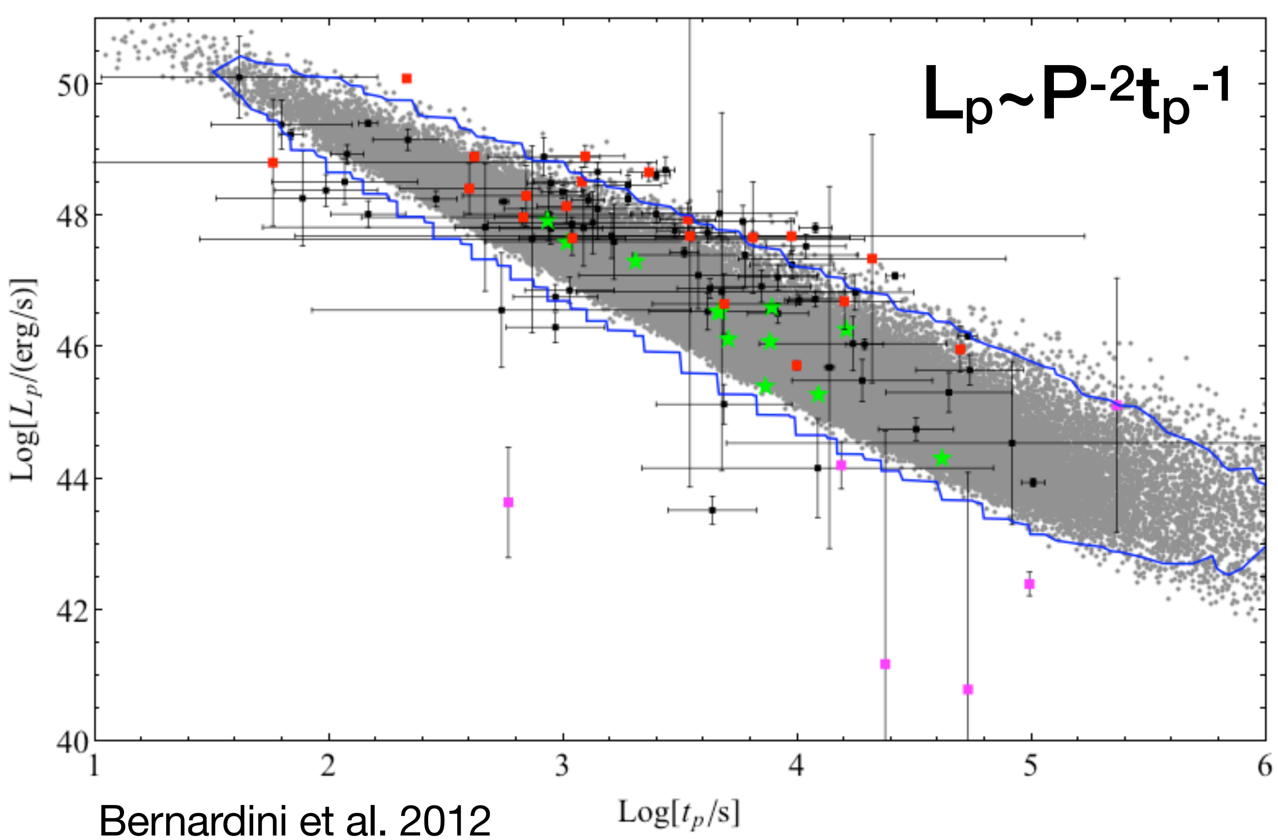


$$L_{\rm sd} = 10^{49} B_{15}^2\, P_{-3}^{-4}\, {\rm erg\,s^{-1}}$$

$$t_{\rm sd} = 3 \times 10^3 B_{15}^{-2}\, P_{-3}^2\, {\rm s}\,,$$

⇨ **$B \sim 10^{15}$ G**
P~1 ms

Direct estimates of **B** and **P** from X-ray data



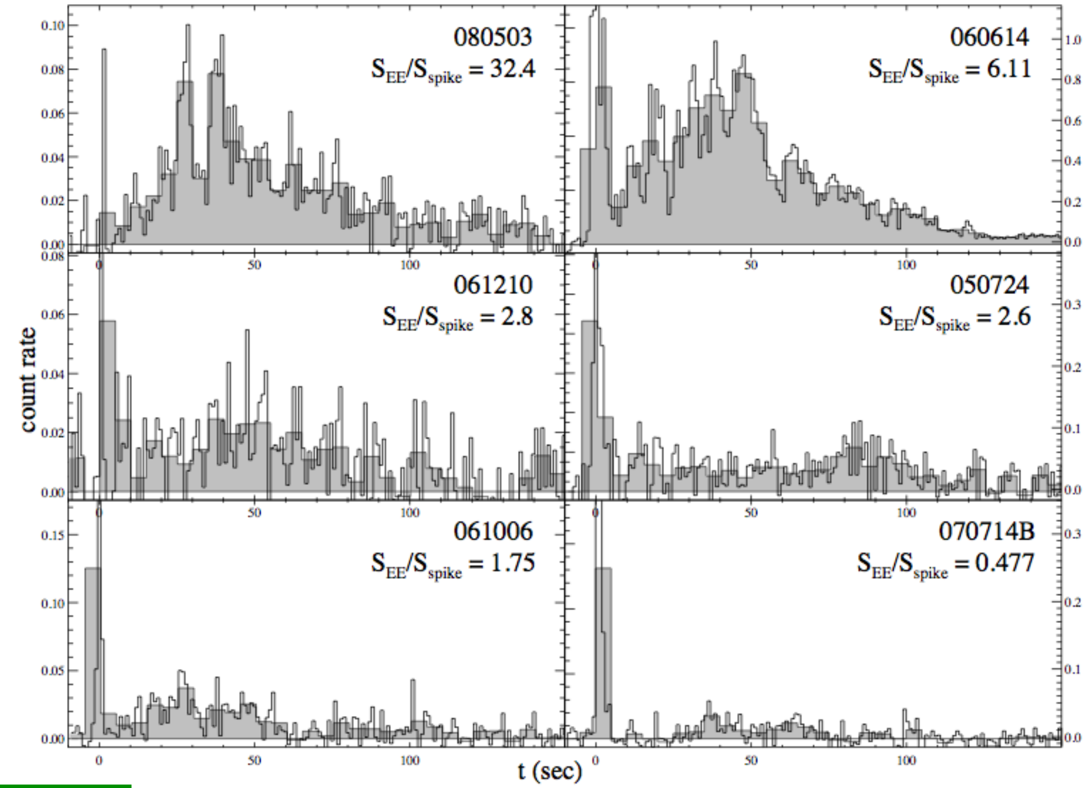
Bernardini et al. 2012

➡ **Luminosity-duration correlation implied by the model** (Bernardini et al. 2012, see also Rowlinson et al. 2014)

➡ **B-P relation** with SGRBs in the long-period region and the LGRBs in the opposite side (Stratta et al. 2018)

Dai & Lu 1998, Zhang & Meszaros 2001, Corsi & Meszaros 2009, Lyons et al. 2010, Dall'Osso et al. 2011, Metzger et al. 2011 Bernardini et al. 2012, 2013, Rowlinson et al. 2013, 2014, Lu & Zhang 2014, Lu et al. 2015, Stratta et al. 2018.

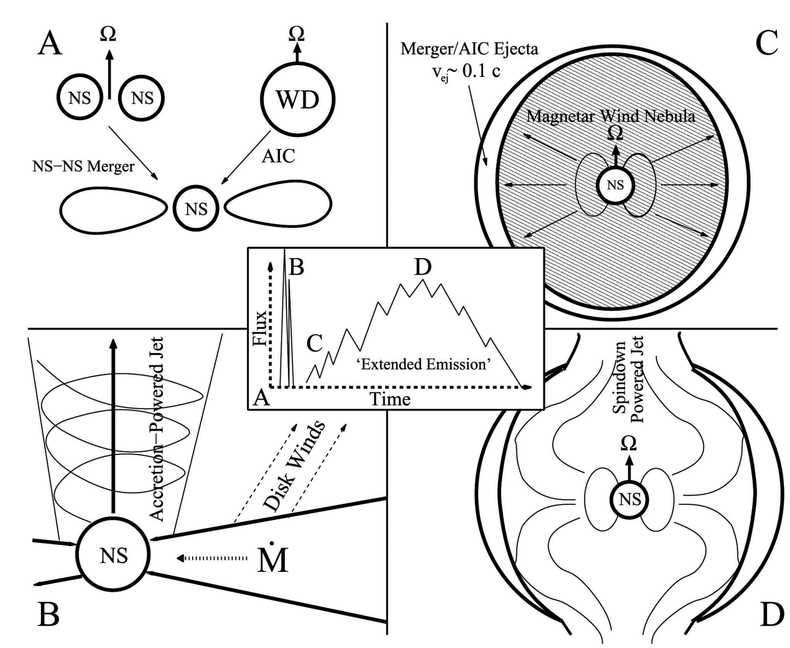
Extended Emission in SGRBs



~15% of SGRBs show an **extended emission (EE)** in the prompt phase
(Lazzati et al. 2001, Norris & Bonnell 2006)

Possible interpretations within the magnetar model:

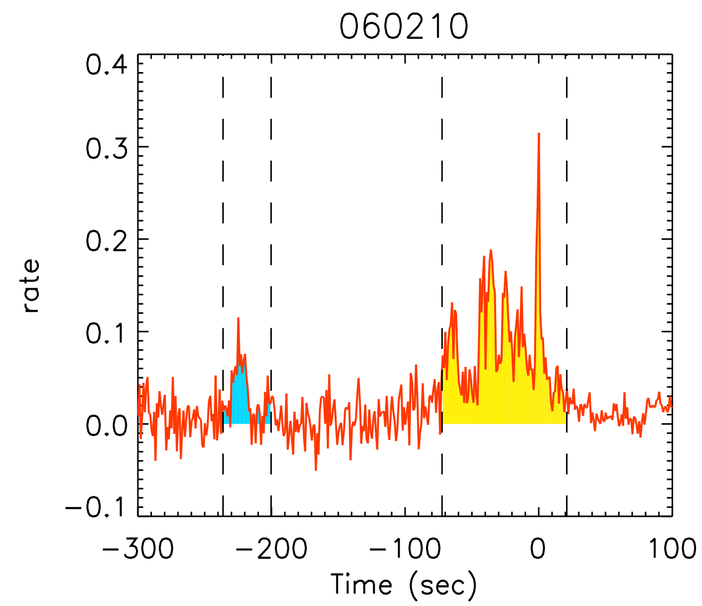
- **EE** + **X-ray plateau**: rotational powered wind (Metzger et al. 2008)
- **EE**: propeller mechanism (material ejected by centrifugal forces) + **X-ray plateau**: rotational powered wind (Gompertz et al. 2014)



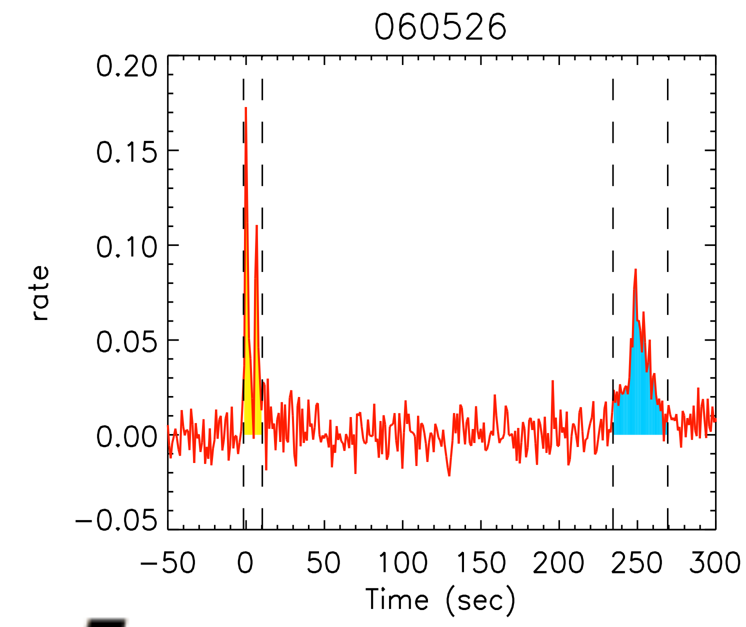
Gompertz et al. 2014

The GRB prompt emission activity

Precursors



Post-cursors



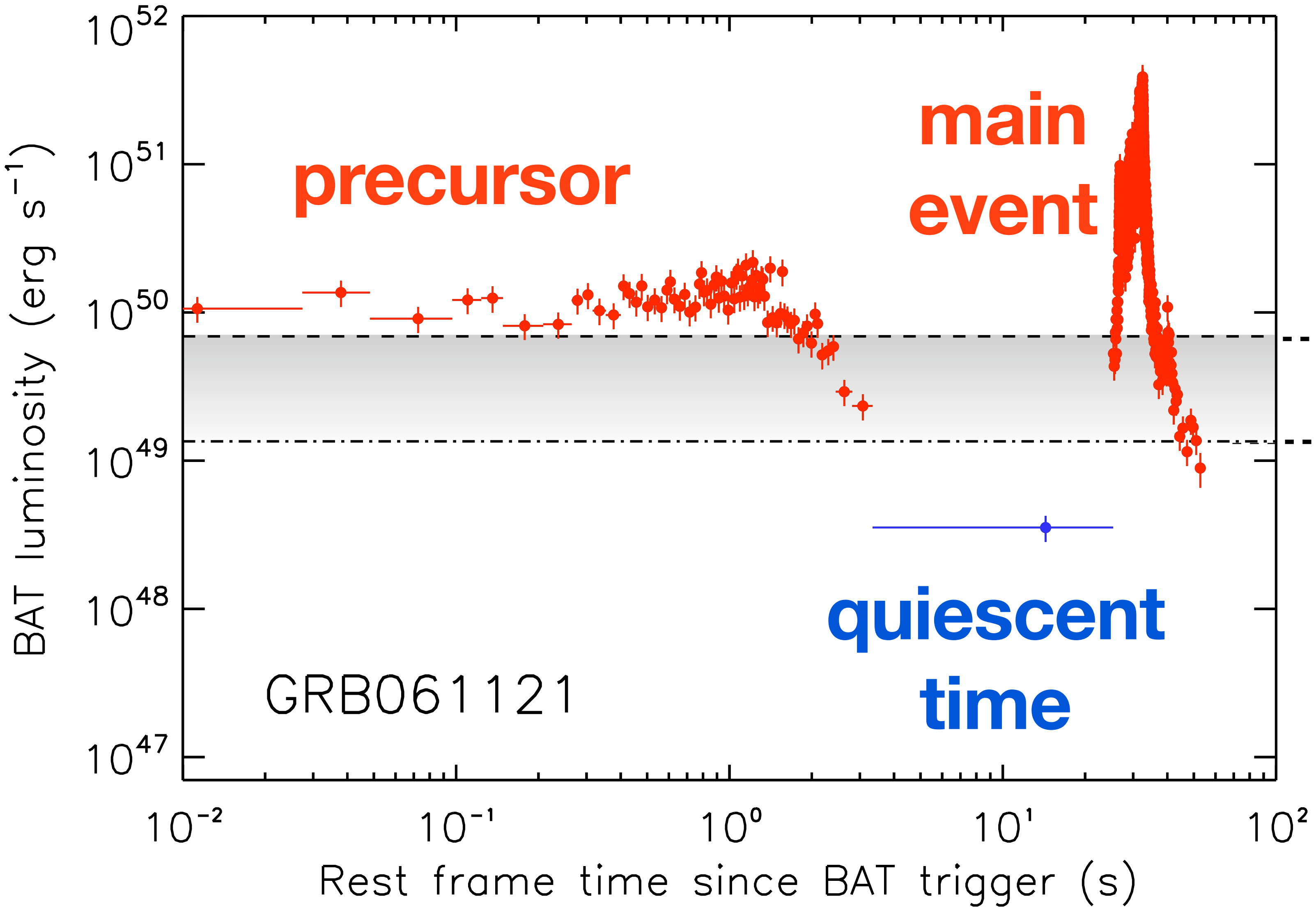
intermittent prompt emission activity

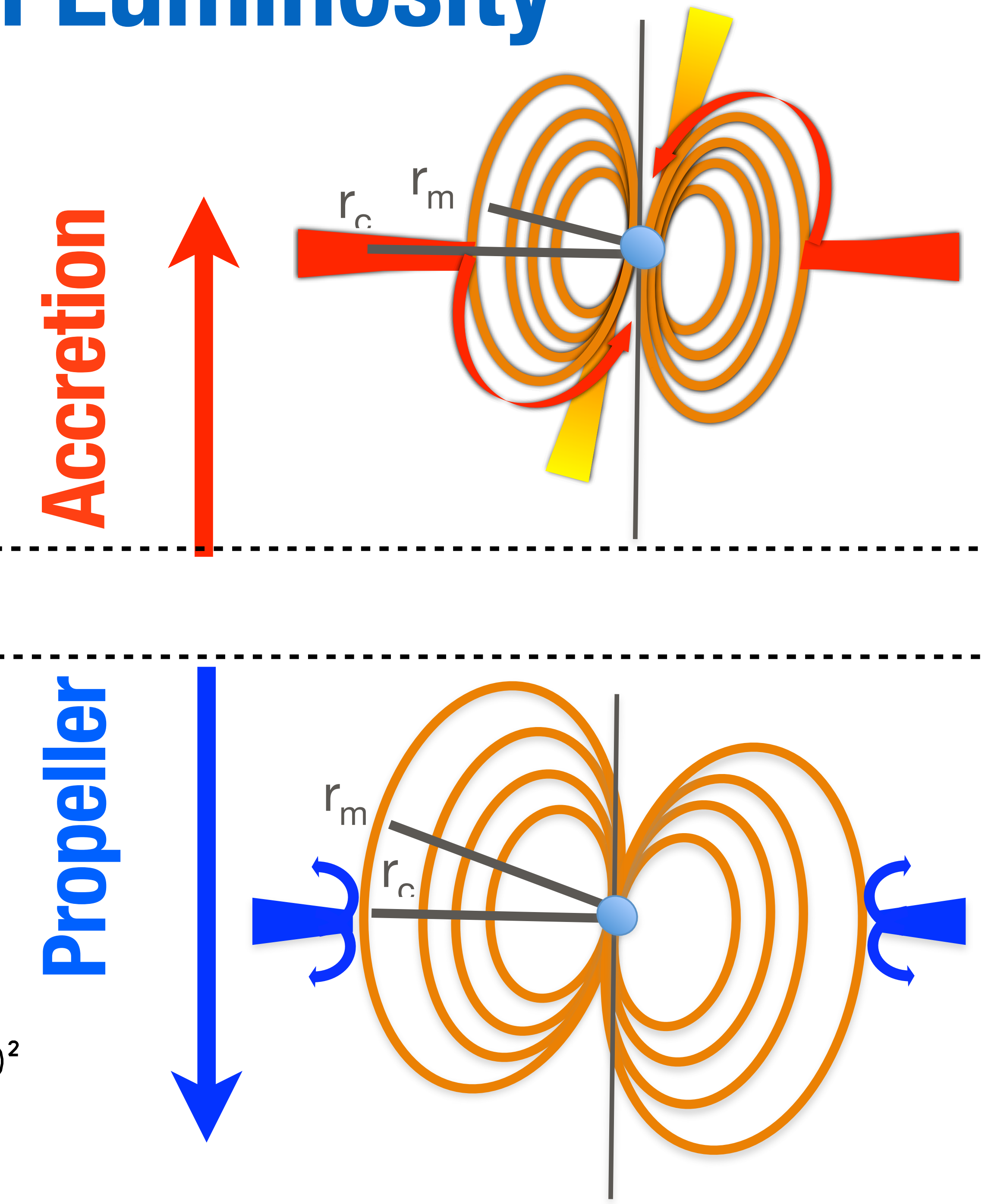
How to switch on and off a GRB?

Prompt emission powered by **accretion** onto the magnetar

Bernardini et al., 2013, 2015, see also Metzger et al., 2018

The Prompt Emission Luminosity





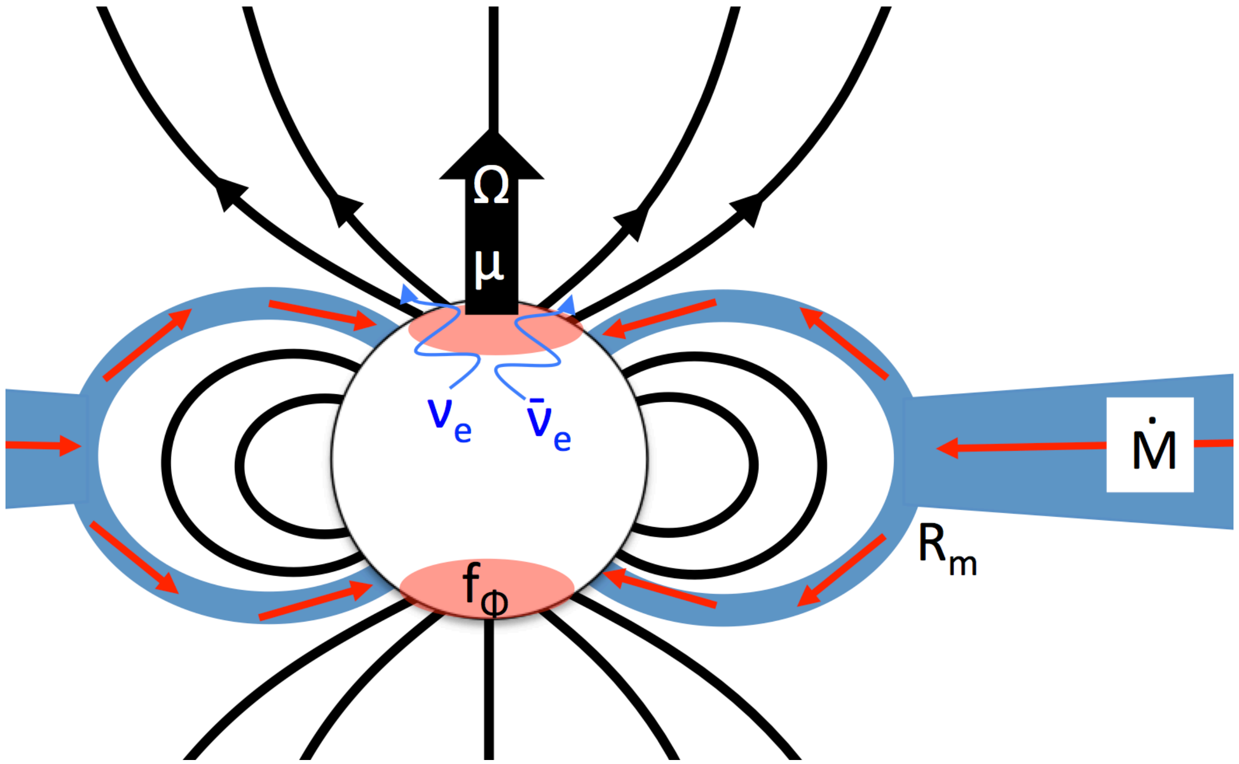
$$L_{\rm min} = 4\times10^{50} B_{15}^2\, P_{-3}^{-7/3}\,{\rm erg\,s^{-1}}$$

$$L(r_{\rm m}) = 2\times10^{50} B_{15}^2\, P_{-3}^{-3}\,{\rm erg\,s^{-1}}$$

⇦ **B~10^{15} G**
P~1 ms

Bernardini et al., 2013, 2015

Fall-back accretion onto magnetars



Metzger et al., 2018

- GRB powered only by the **magnetar rotational energy** through a wind heated by neutrinos driven by the proto-magnetar

  ➡ **magnetised ultra-relativistic outflow**

- accretion allows for more complex time evolution of the spin-down power, possibly also for **time gaps in the light curve**

Effects of accretion:

- additional source of energy
- modify the magnetar parameters at birth compared to the estimates from the late X-ray emission

Observational imprints of the magnetar

The GRB emission:

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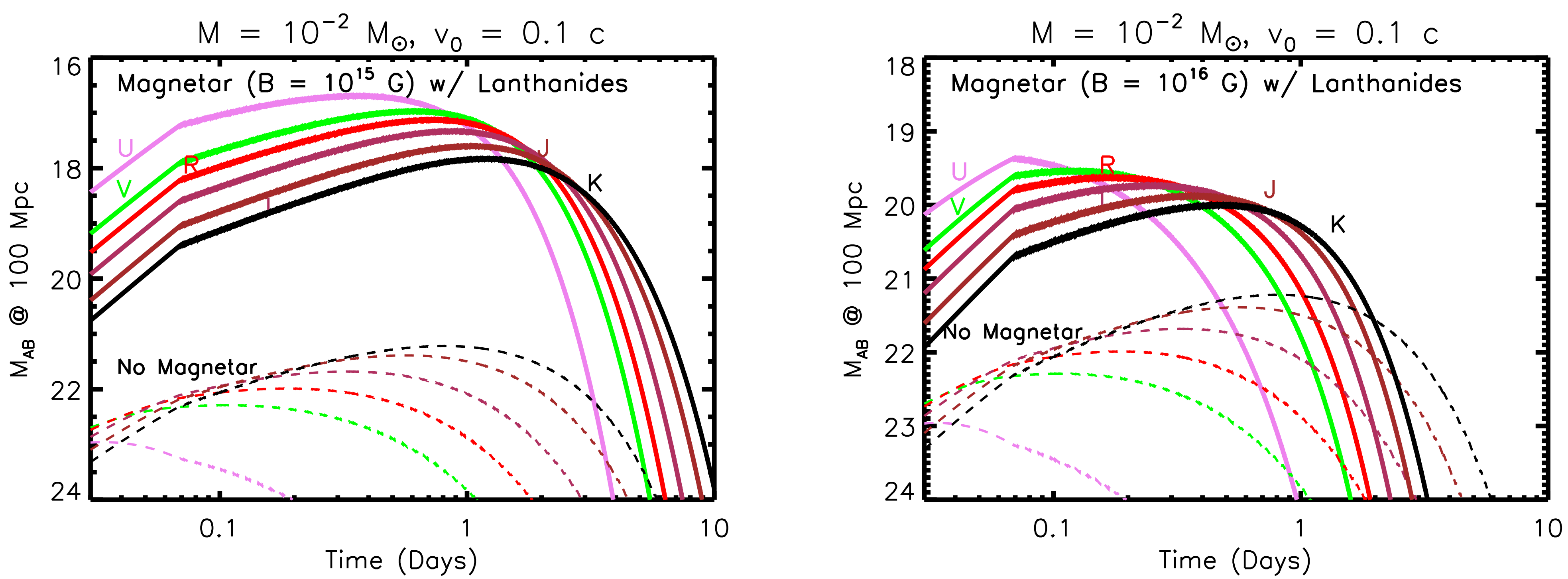
The kilonova emission associated to SGRBs

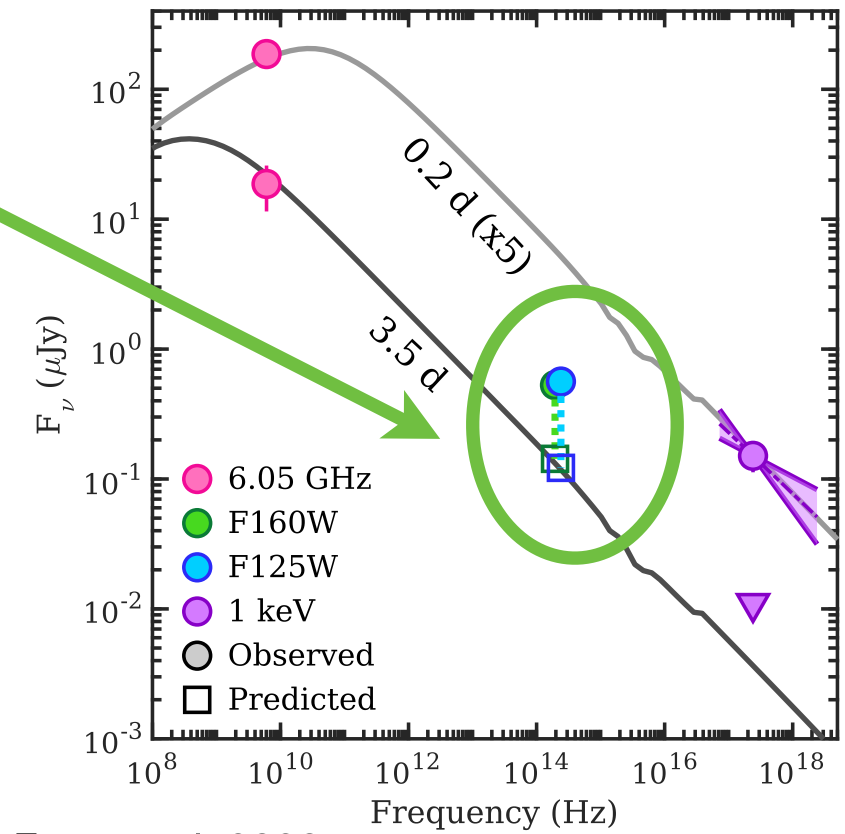


Metzger 2019

The magnetar-boosted Kilonova

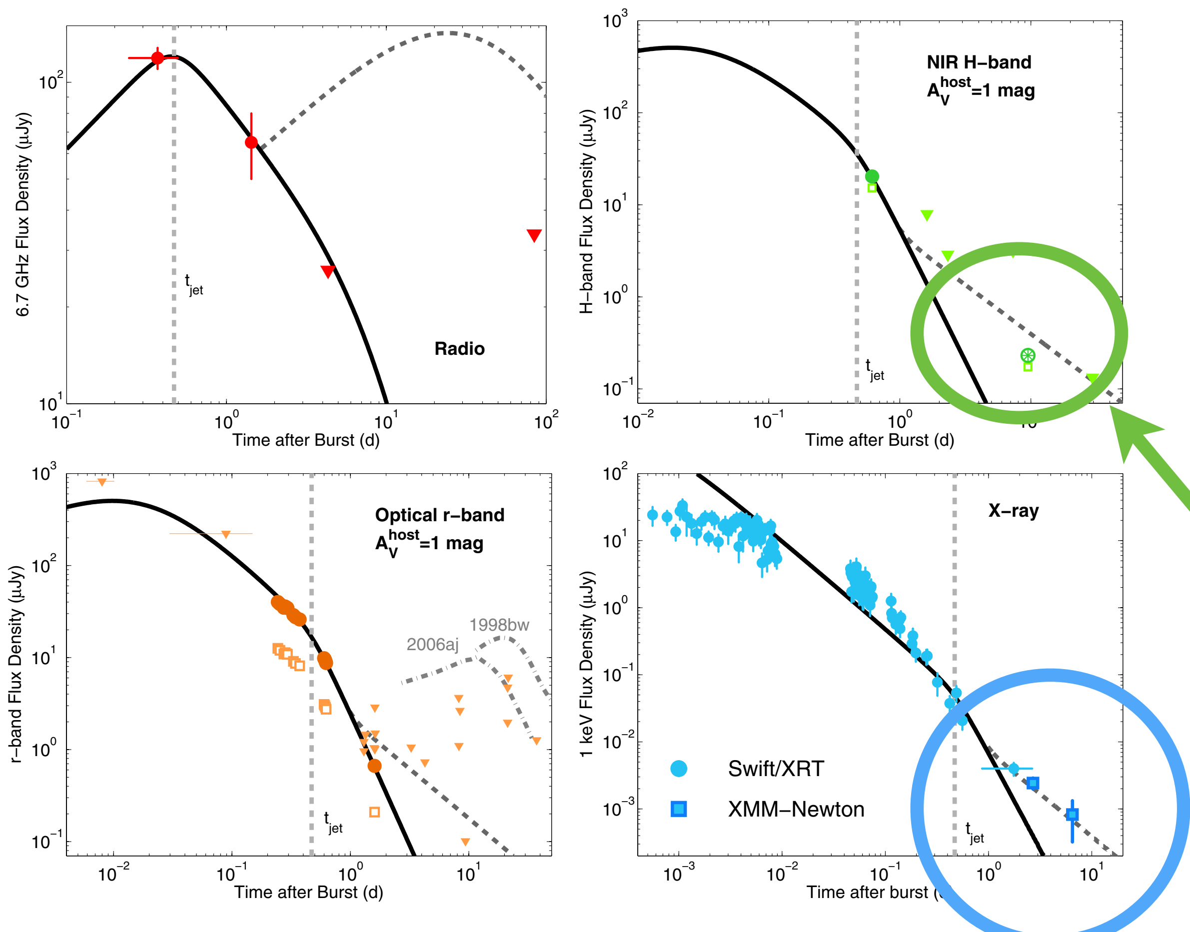
- The magnetar can provide an additional source of heating in the kilonova
- Magnetar boosting claimed in the **kilonova** associated to **GRB200522A** (Fong et al., 2020)
- Imprint of the magnetar in three other SGRBs and their associated kilonovae (Gao et al., 2017)

GRB200522A



Fong et al. 2020

GRB130603B



Fong et al. 2014

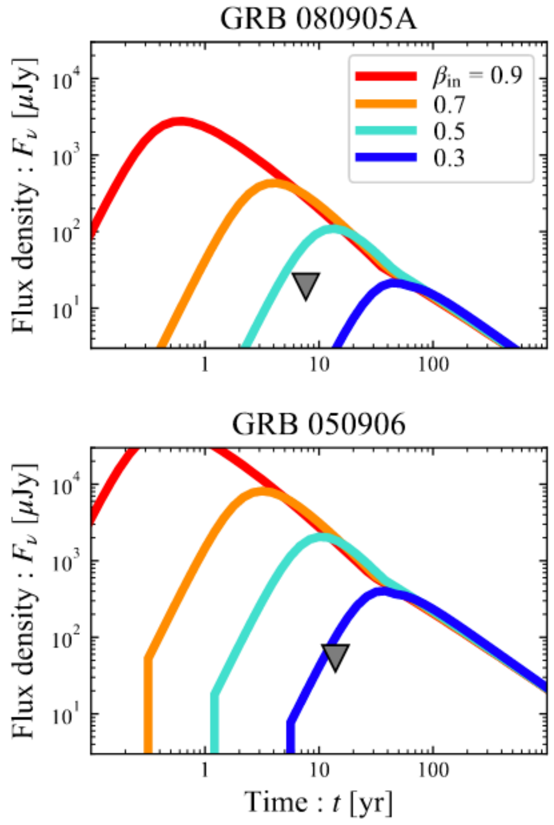
- Possible contribution from the magnetar in the X-ray emission also in another SGRB with **kilonova**, **GRB130603B** (Fong et al., 2014)

Can magnetars power all GRBs?

1. Magnetars have a **limited energy budget (a few x 10^{52} erg)**
   ➡ **LGRBs often above limit.** However:
   - **Accretion**: further energy supplier (~ 10^{53} erg, e.g. Dall'Osso et al.
   - True $E_\gamma < E_{iso}$ due to collimation
   - Sufficient to energise the accompanying SN (Mazzali et al., 2014)
   - Only a few LGRBs are shown to be too energetic

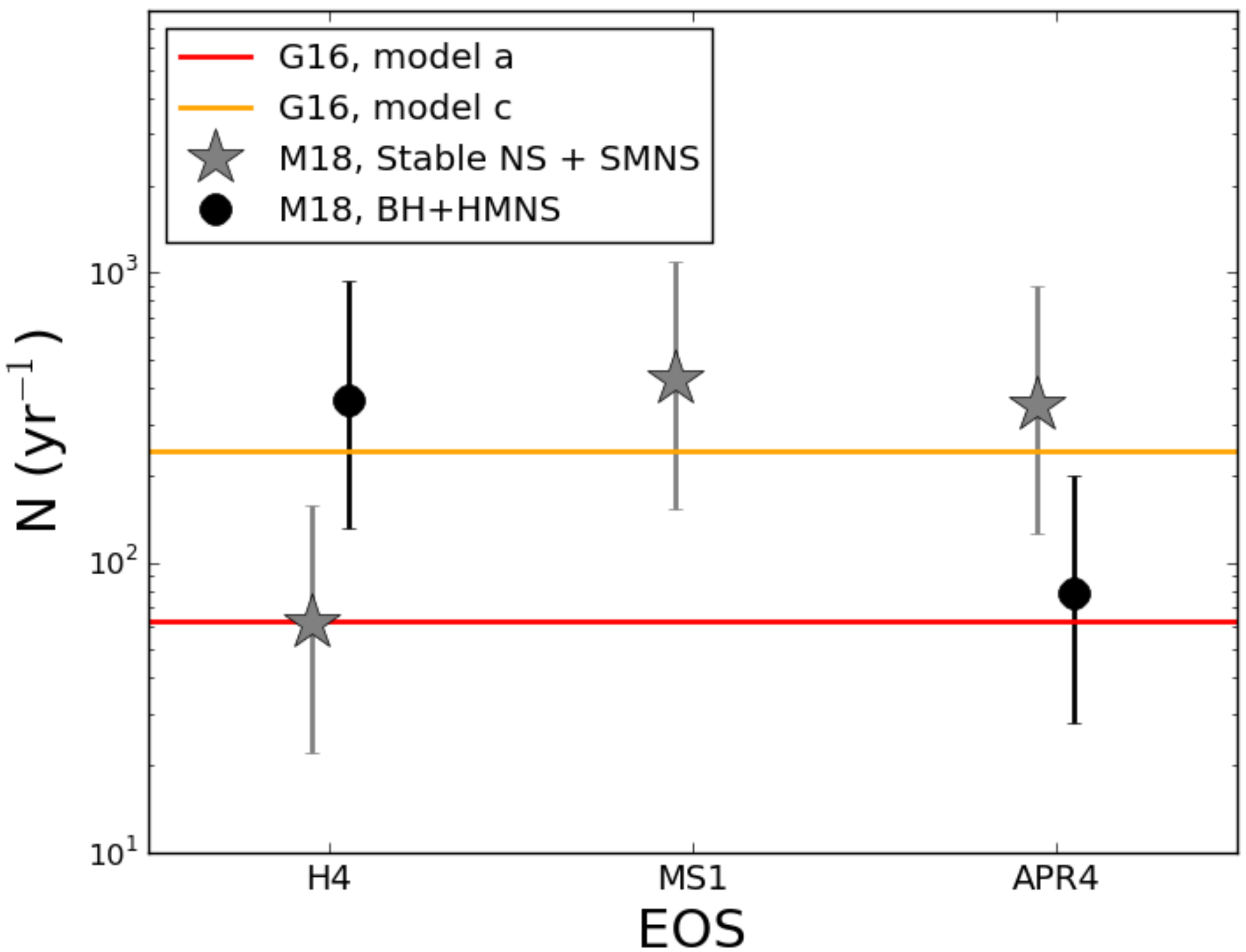
   ➡ **SGRBs often below limit**:
   - Radio upper limits in SGRBs rule out very energetic merger ejecta (Ricci et al., 2021)

Ricci et al. 2021



2. **Difficult for magnetars to launch ultra-relativistic jets** (e.g. Ciolfi, 2020, see however Uzdensky & MacFadyen 2007 for LGRBs)
3. **No periodicity found in the GRB prompt emission** (Dichiara et al. 2013, Guidorzi et al. 2016)
   - Temporal patterns related to the magnetar may be quenched by the fireball formation and dissipation processes
4. Galactic magnetar population is not compatible with being formed within the GRB scenario (Rea et al., 2016)
   ➡ **population of "super-magnetars" connected with GRBs having "special" progenitors, forming NSs with higher B at birth**

Constraints on the aftermath of BNS merger



Patricelli & Bernardini, 2020

- Catalog of BNS mergers by combining BNS merger rate and NS mass distribution inferred from measurements of Galactic BNSs
- Predict the number of BNS systems ending as magnetars (stable or Supramassive NS) or BHs (formed promptly or after the collapse of a hypermassive NS) for different EOSs (H4, MS1, APR4)
- Compare these outcomes with the observed rate of SGRBs

➡ for most EOSs **the rate of magnetars produced after BNS mergers is sufficient to power all the SGRBs** (Patricelli & Bernardini, 2020, see also Piro et al., 2017, Margalit & Metzger, 2019)

Timescale over which differential rotation is removed has key implication on the long-term stability of the remnant (Margalit et al. 2022)

The GRB central engine in the MM era

Lesson learned from GW 170817/GRB 170817A:

- The **merger remnant** (~2.7 $M_\odot$) can be either a hyper massive NS or a BH
- **Non-thermal emission:**
  - ➡ The X-ray flux is too low for a long-lived NS (e.g. Pooley+18, Hajela+19), and no sign for long-lived central engine activity. However, if the spin-down losses are dominated by GW emission, the contribution to the X-ray luminosity from the magnetar is negligible (e.g. Dall'Osso+15, Piro+19)
  - ➡ The "kilonova afterglow" might be also spin down emission from a magnetar with an unusually low magnetic field $B \sim 10^9$ G (Hajela et al. 2021)
- **Thermal emission:**
  - ➡ The blue component and the large mass of lanthanide-free ejecta with $E_{kin} \sim 10^{51}$ erg argue in favor of a HMNS collapsed to a BH in ~1s (Granot et al. 2017, Margalit & Metzger 2017, Shibata et al. 2017, Metzger et al. 2018, Rezzolla et al. 2018, Gill et al. 2019b, Ciolfi 2020, Murguia-Berthier et al. 2020)

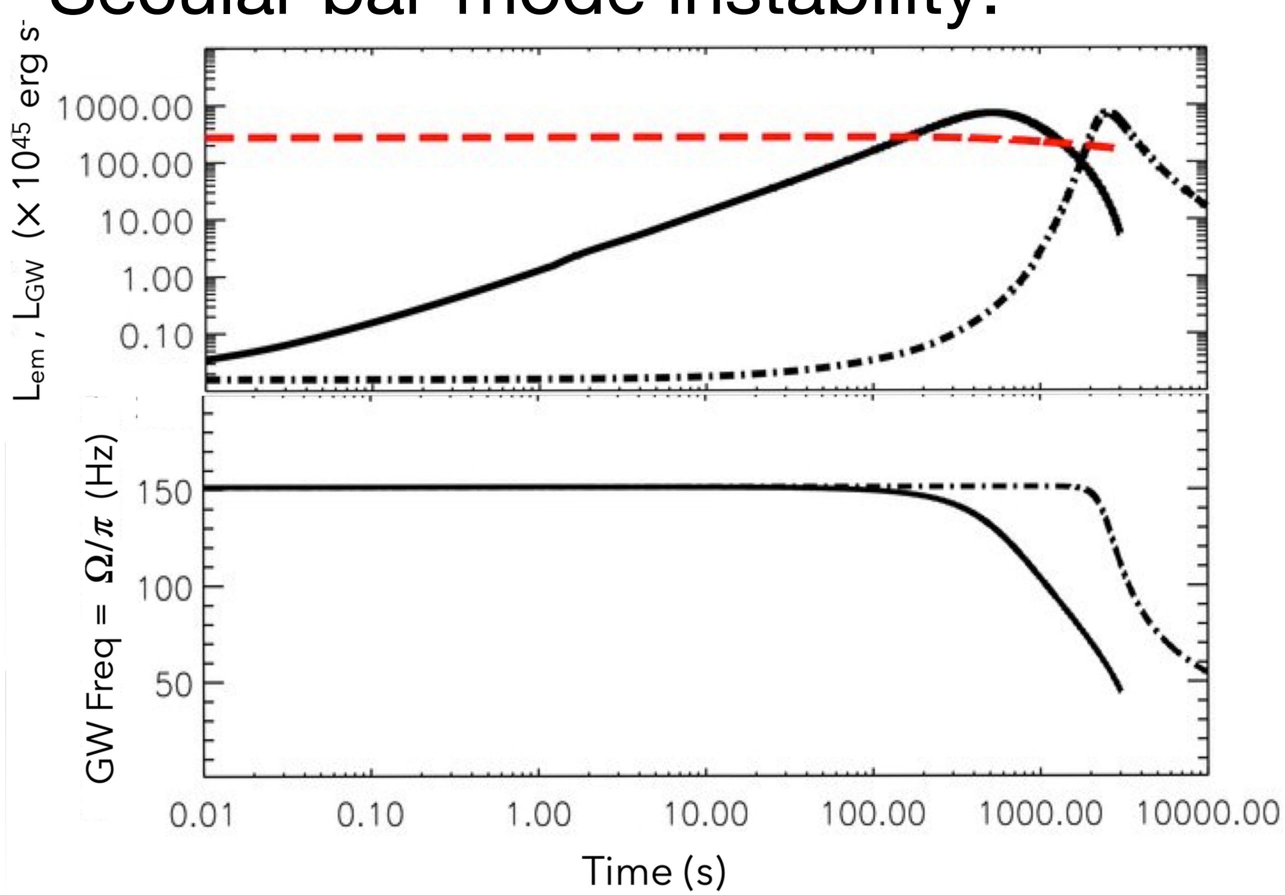
No final proof of the nature of the GRB central engine, however rapid collapse to a BH is the most probable scenario

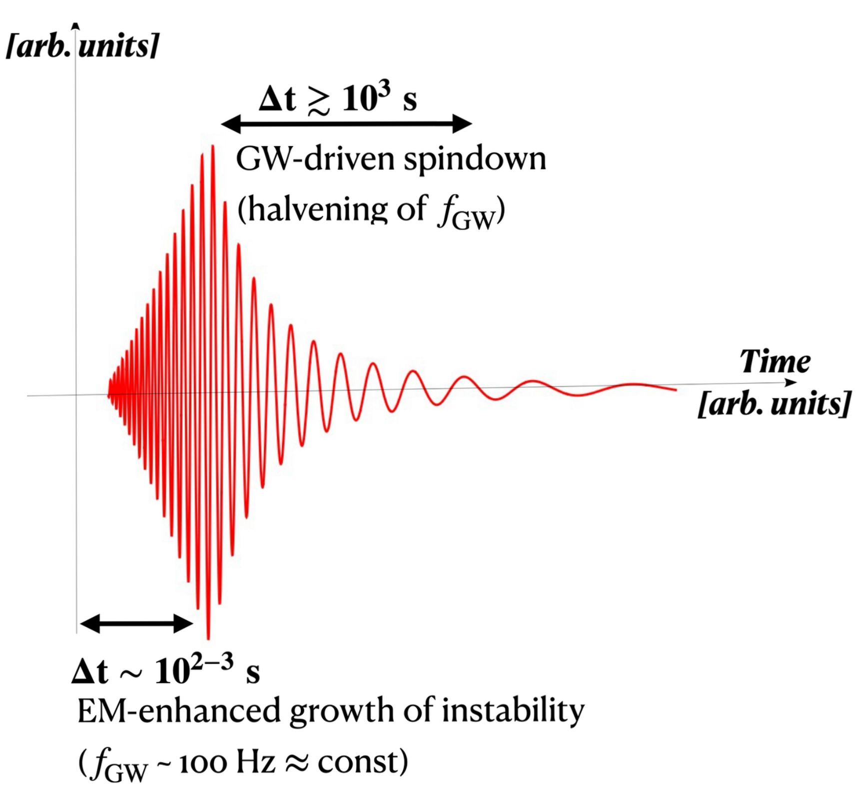
Direct detection of GWs from the magnetar

- Newly born proto-magnetars are source of GW if they spin fast enough to excite dynamical (ß>0.27) or secular bar-mode instabilities (ß>0.14)
- Onset of dynamical instabilities at magnetar birth more likely thanks to spin-up induced by accretion
- GW signal detectable over long timescales (~ hours) and in a much larger volume than any other isolated NS

See Dall'Osso & Stella 2021 for a general review

Secular bar-mode instability:



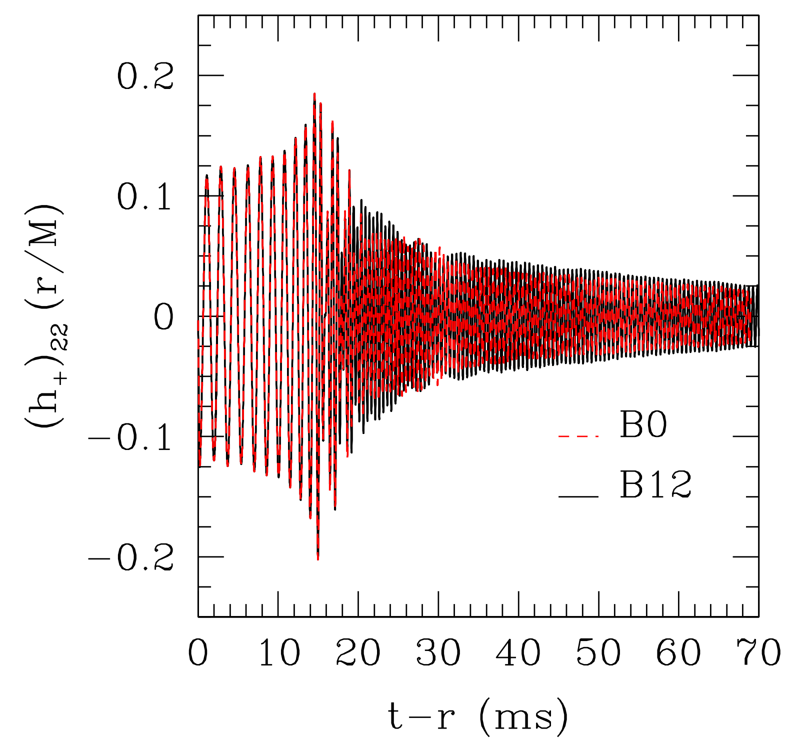


Dall'Osso & Stella 2021, adapted from Corsi & Meszaros, 2009

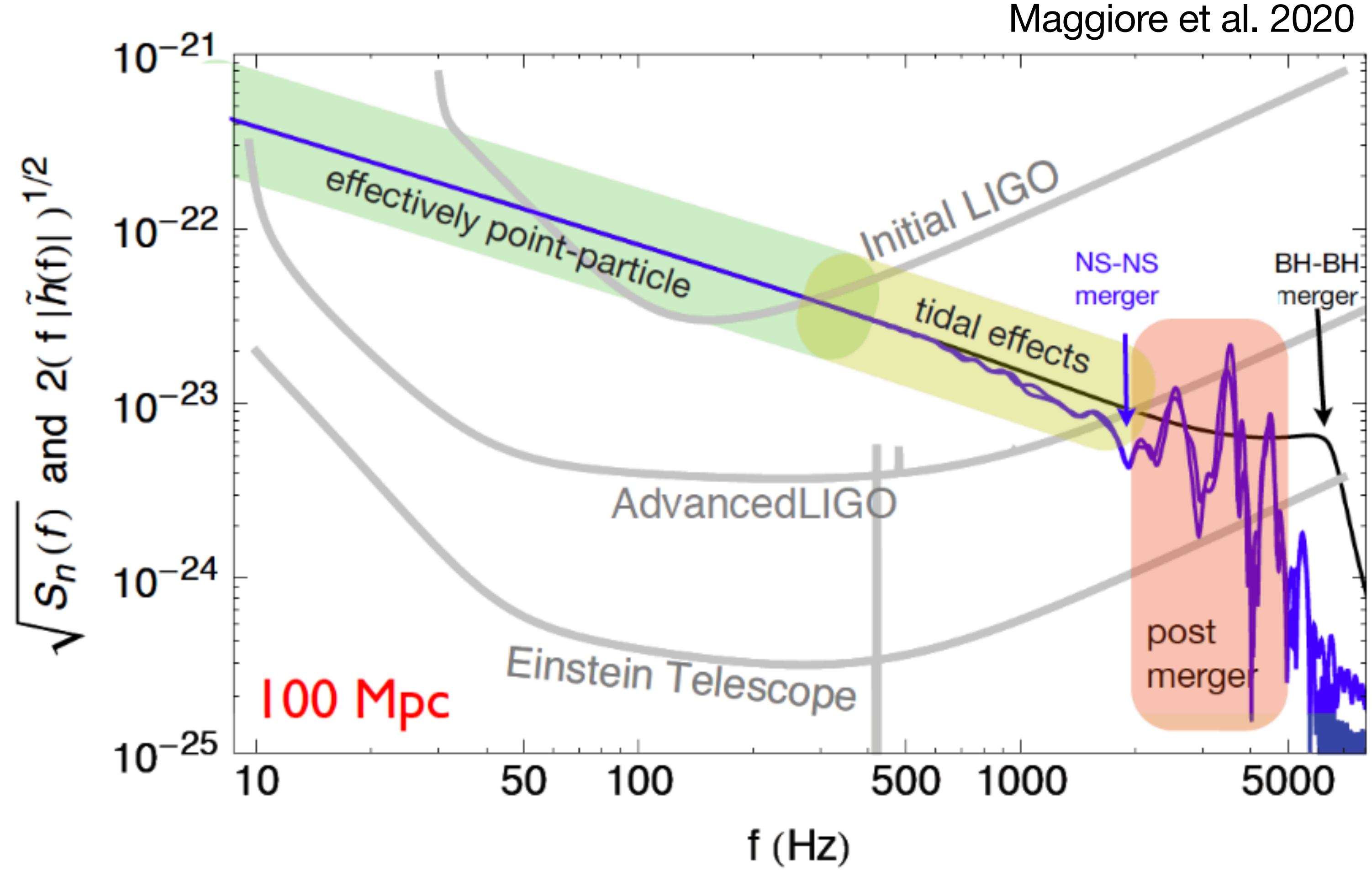
Direct detection of GWs from the magnetar

- Long-lasting post-merger signals are the best direct detection to distinguish between the formation of a magnetar or a BH (e.g. Giacomazzo & Perna 2012, 2013; Dall'Osso et al., 2015)
- Searches in the LIGO/Virgo data for short and intermediate duration signals in GW 170817/GRB 170817A not conclusive (Abbott et al. 2017, 2019; see however Van Putten & Della Valle 2018)
- Hard to get it any time soon, but **good prospects with 3rd generation of detectors, as the ET** (Maggiore et al. 2020)

Giacomazzo & Perna 2013



Maggiore et al. 2020



Conclusions

✓ Observations of GRB emission, in particular of their X-ray emission, point towards **magnetars as plausible candidates as GRB central engines**

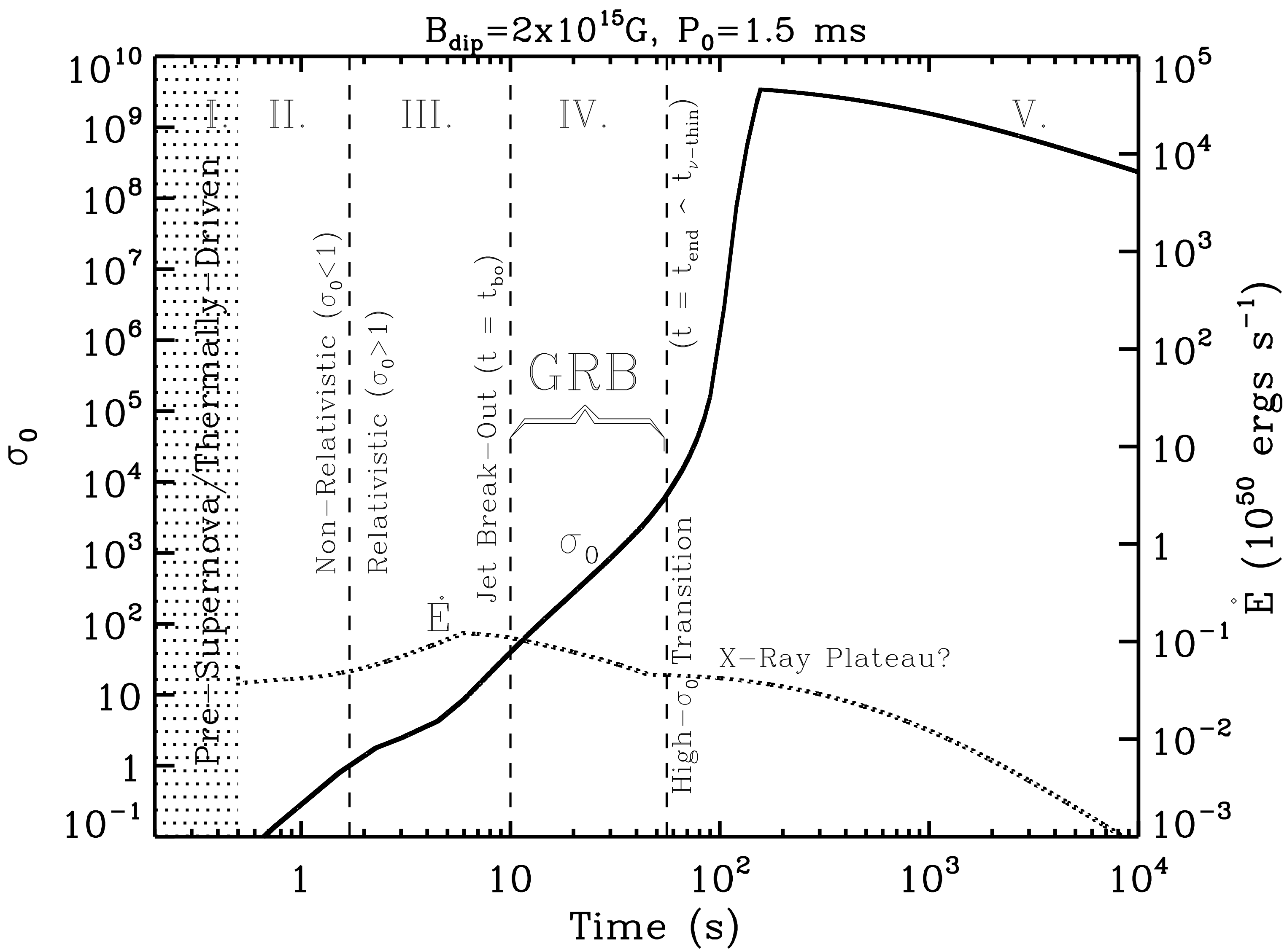
✓ Are all GRBs powered by magnetars?

- ➡ There are enough magnetars to power all SGRBs
- ➡ Not likely (at least not in the case of GRB 170817A!), but still the **majority are consistent with being powered by magnetars** (or more in general, by a long-lived central engine)

✓ Indirect evidences from GRB observations. **Direct proof possible from joint GW and EM detection of SGRBs**:

- ➡ clues from GW 170817/GRB 170817A: from EM observations only, still inconclusive
- ➡ definitive answer from **direct detection of GW signal from the remnant:** one of the expected breakthrough, but hardly achievable with the current generation detectors
- ➡ **much better prospects with the 3rd generation detectors (ET, CE)**

What about the prompt emission?



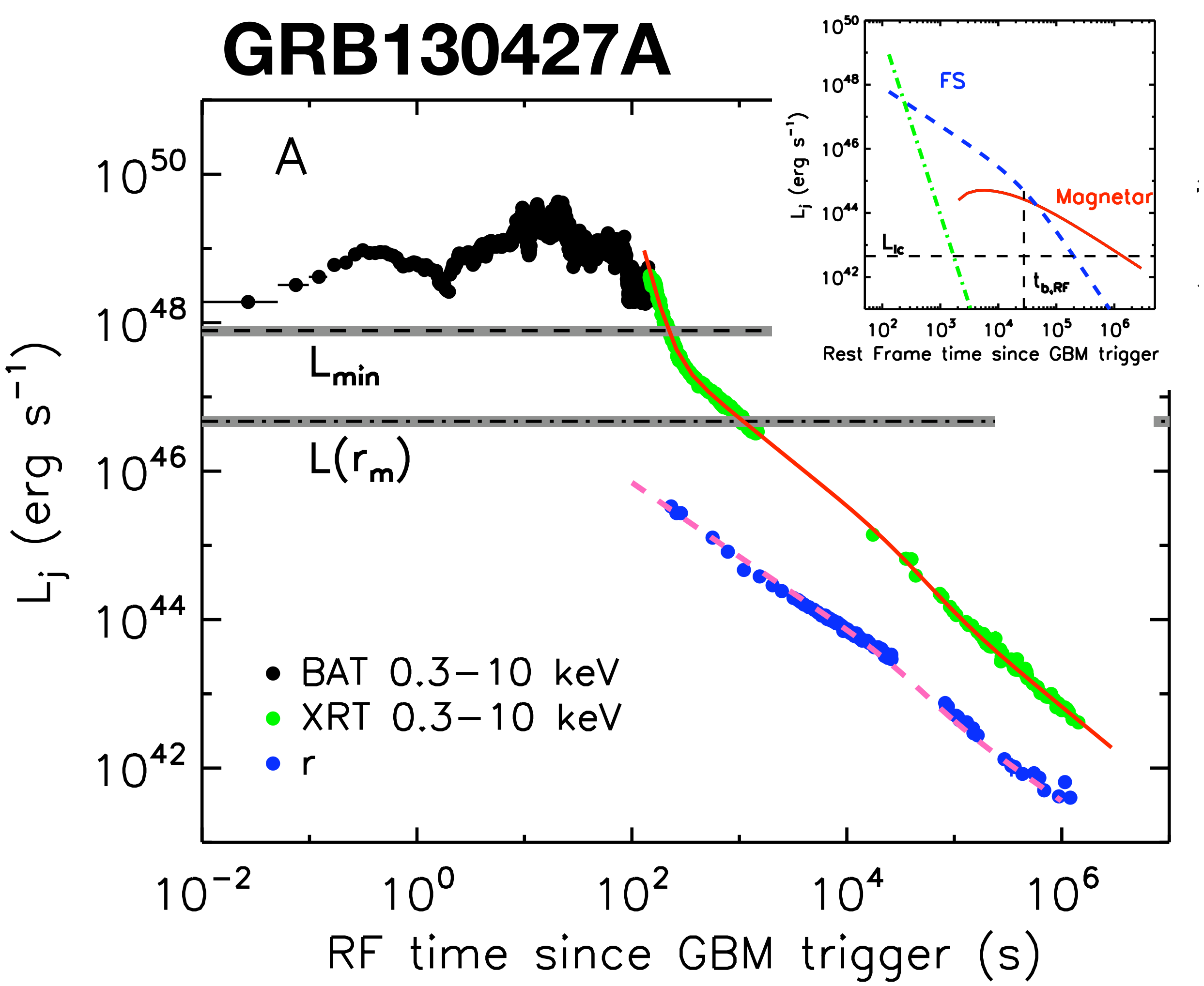
Metzger et al. 2011

- GRB powered only by the **magnetar rotational energy** through a wind heated by neutrinos driven by the proto-magnetar

➡ **magnetised ultra-relativistic outflow**

- **prompt**: internal shocks or magnetic reconnection
- dissipation inefficient at late times: **interaction with ISM + spindown power**

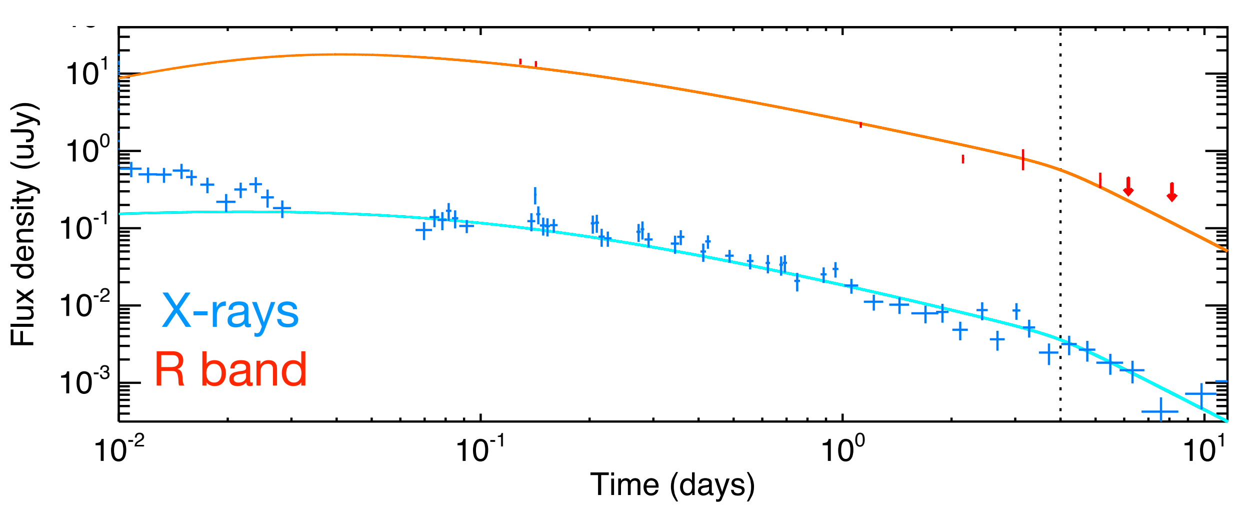
First evidence for magnetars: the GRB plateau

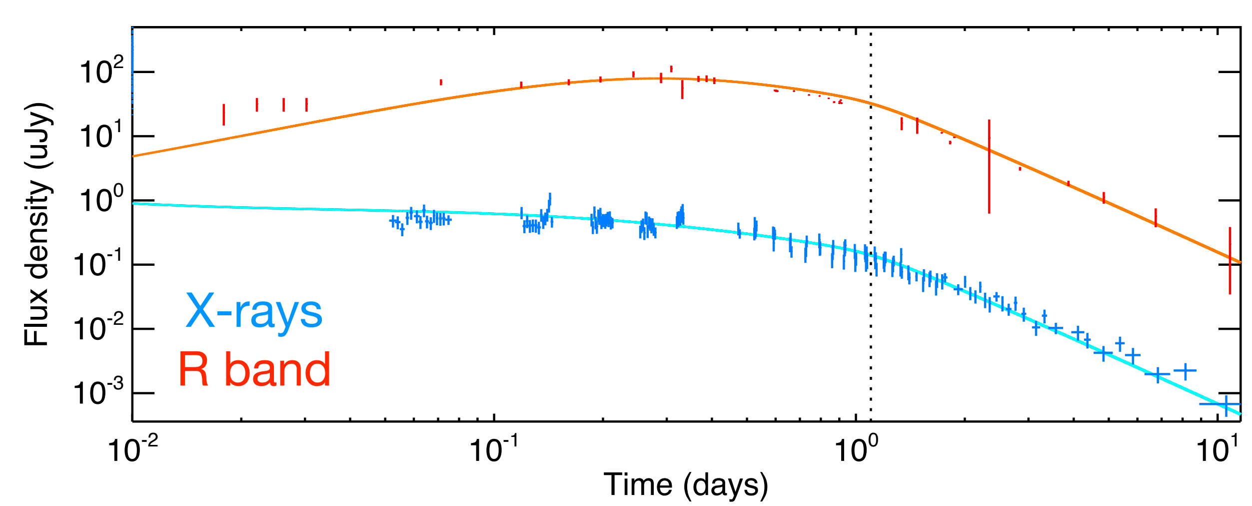


Bernardini et al. 2014

Why is the magnetar contribution chromatic?

- attempts to model the contribution in optical (and predictions for the radio)
- cases of prominent contribution observed only in X-rays





Gompertz et al. 2014