
Credits: Luís Calçada

GRBs and magnetars in the multi-messenger era

MARIA GRAZIA BERNARDINI

INAF - Osservatorio Astronomico di Brera

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INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

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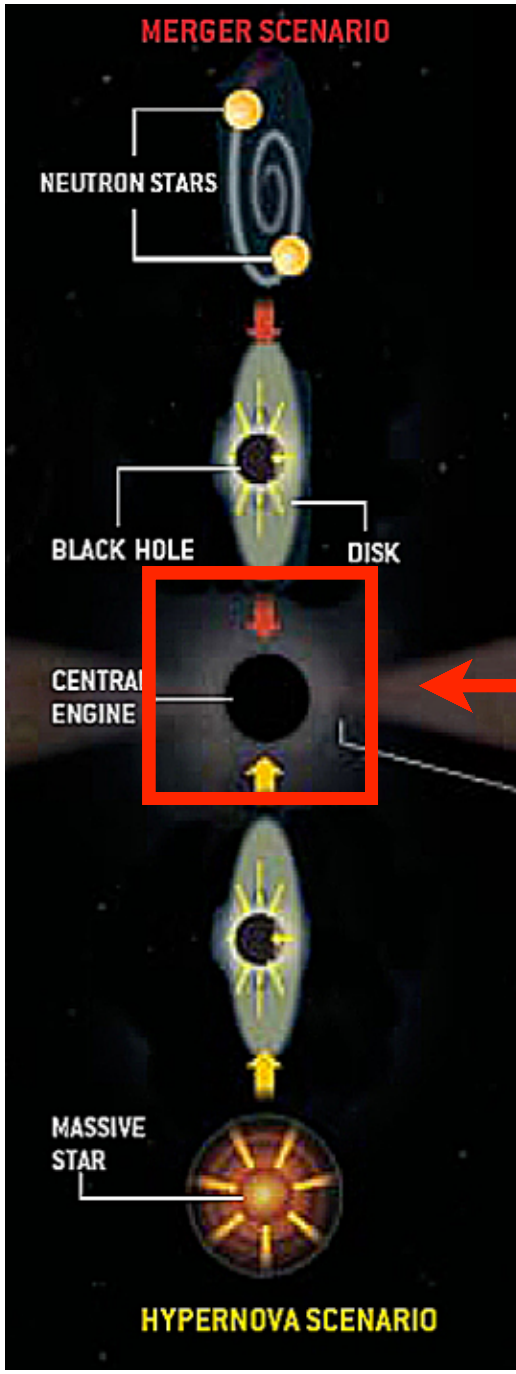
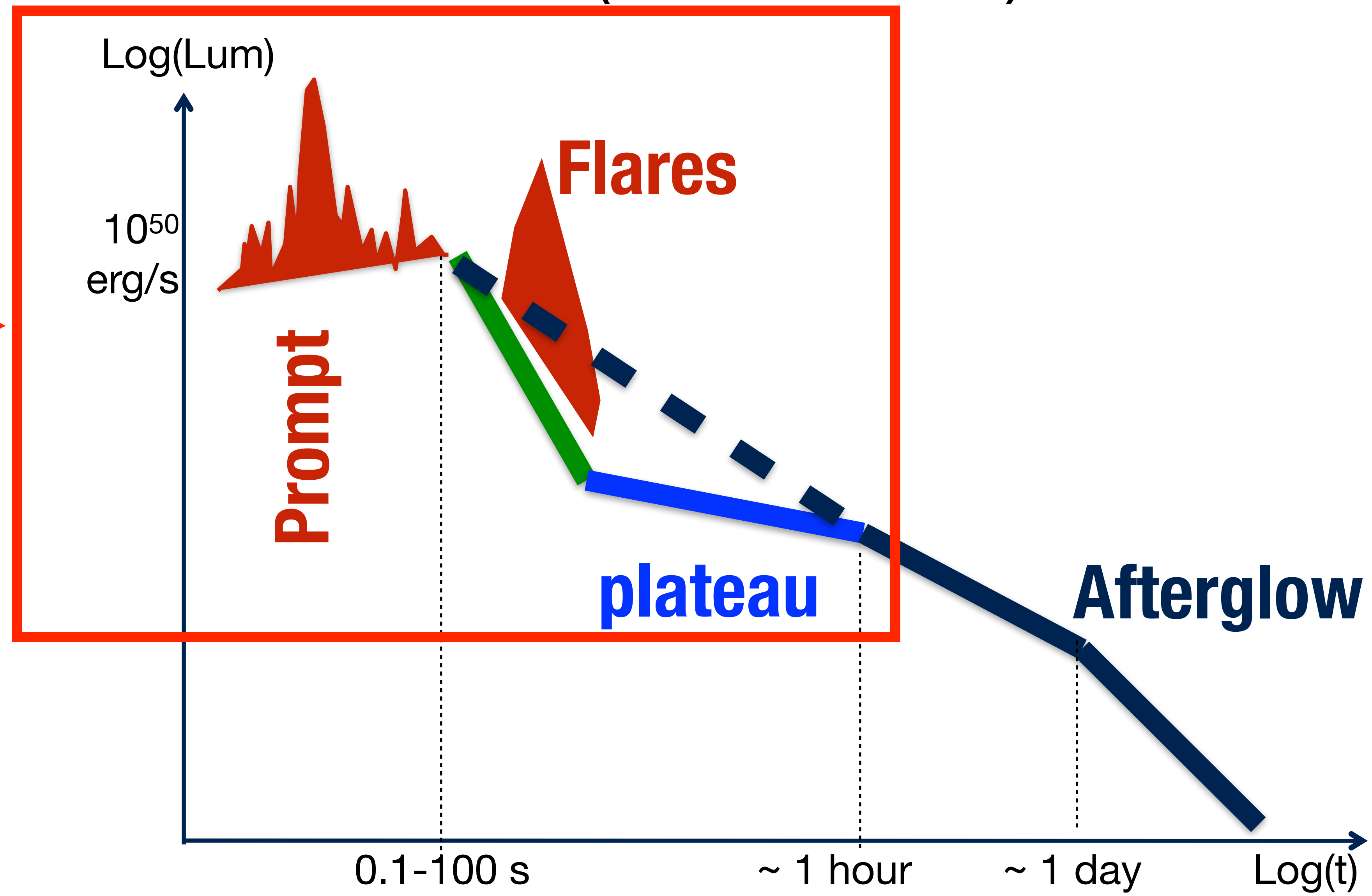
The central engine of GRBs

Short GRBs



Long GRBs

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

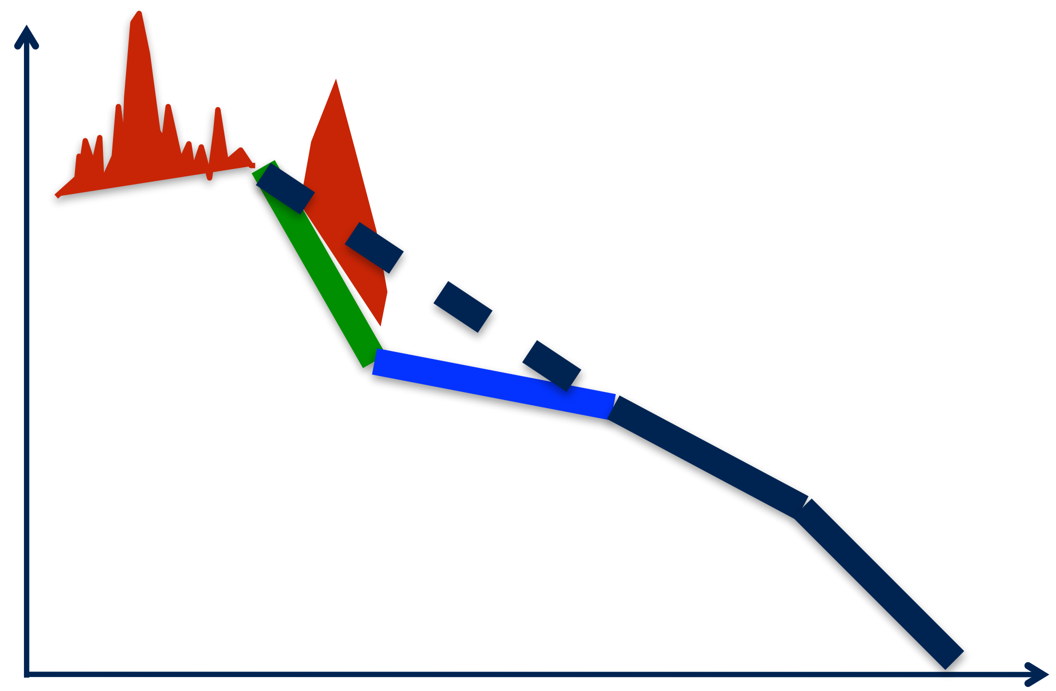


Magnetars are competing with BHs as source of GRB power

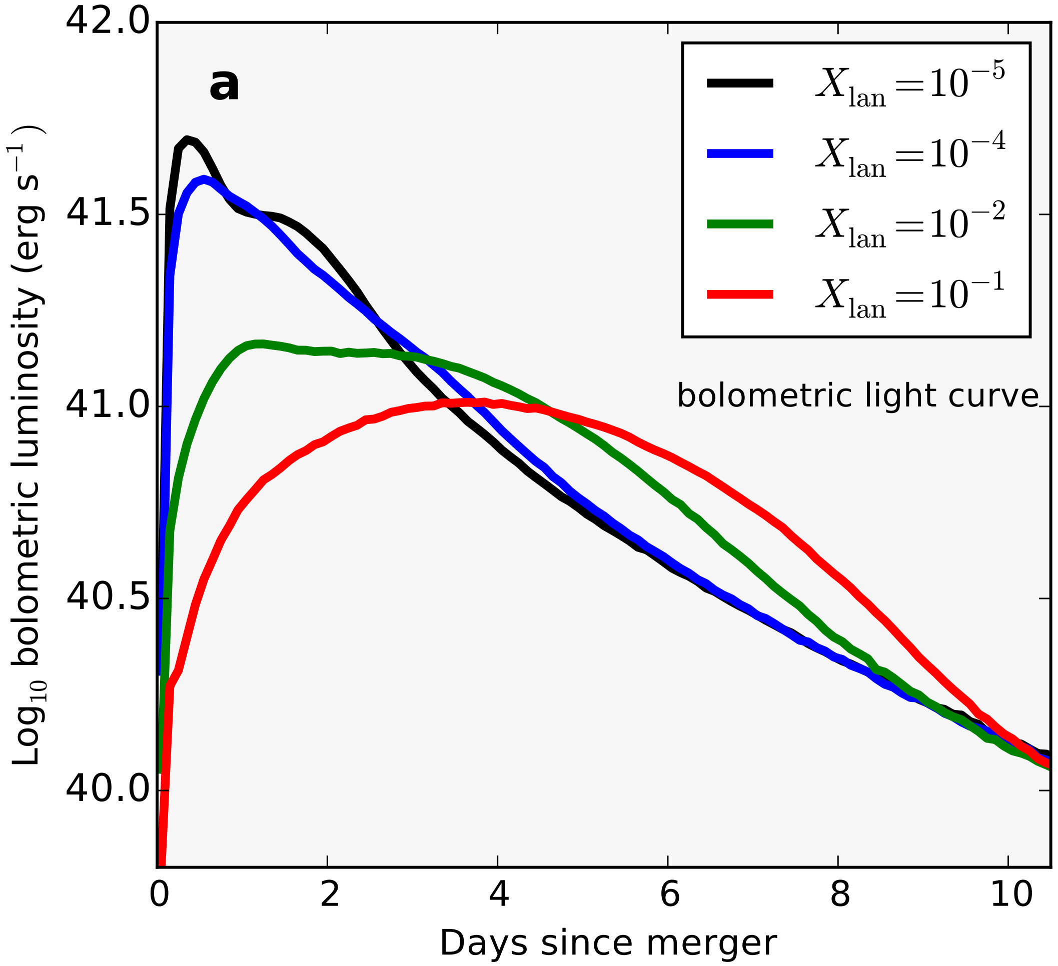
Usov 1992, Duncan & Thompson 1992, Dai & Lu 1998, Zhang & Meszaros 2001, Metzger et al. 2011

Observational imprints of the magnetar

- The GRB emission



- The kilonova emission associated to SGRBs



Kasen et al. 2017

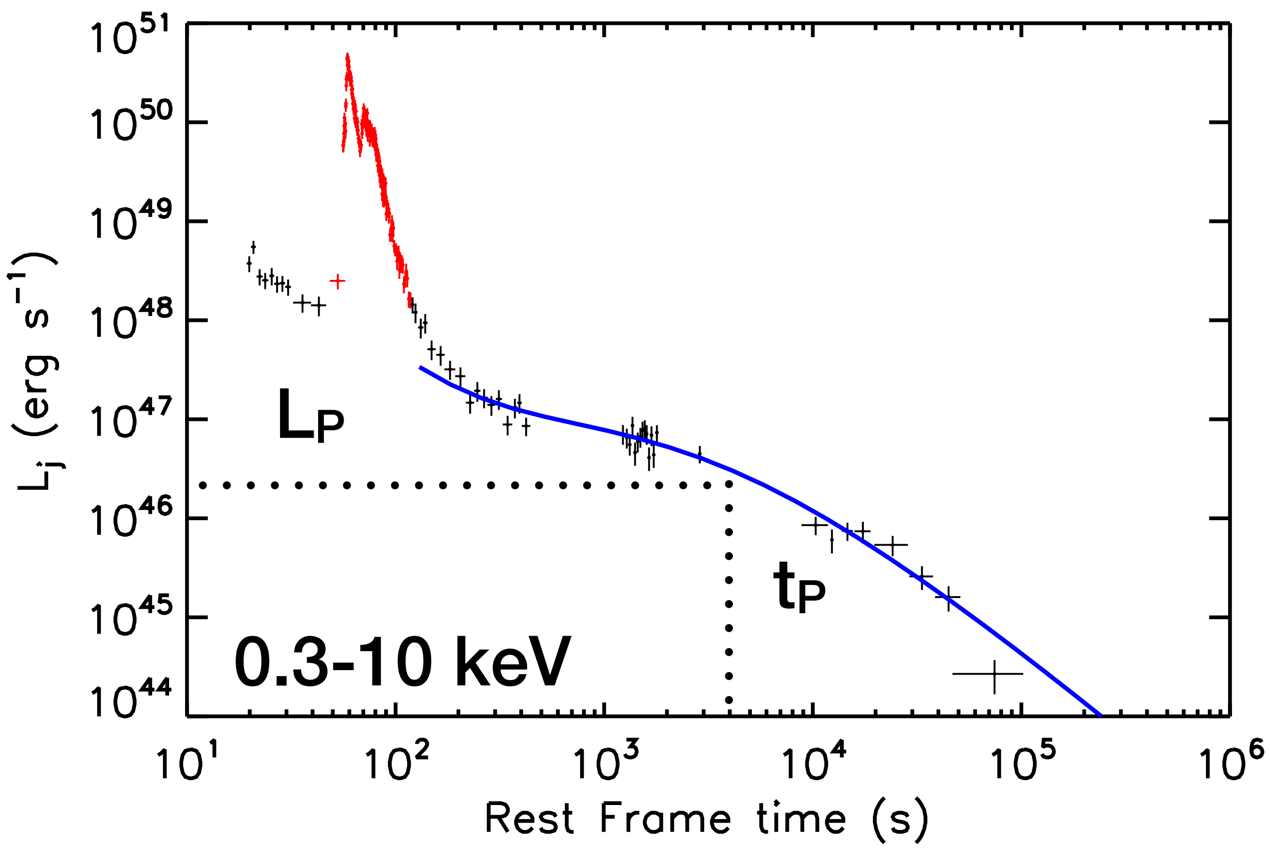
Observational imprints of the magnetar

The GRB emission:

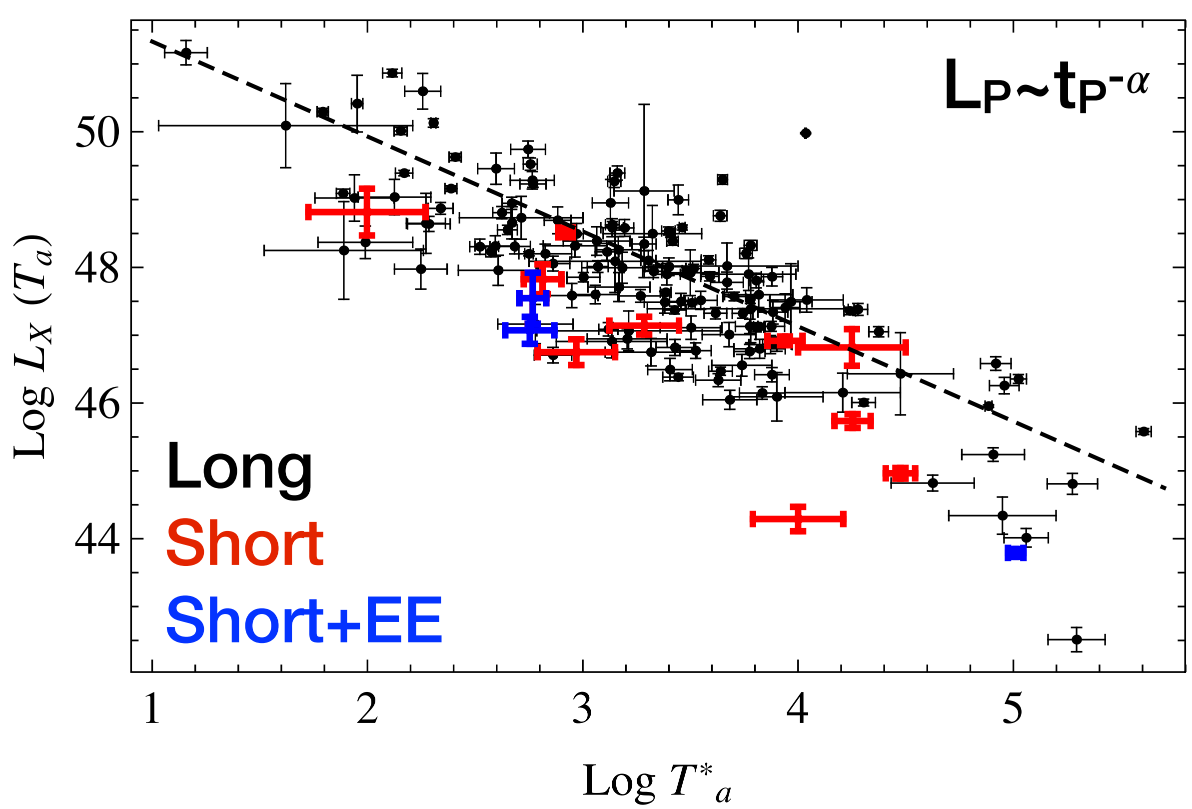
- X-ray plateau
- Extended emission in SGRBs
- Pre- and post-cursors in the prompt emission

The kilonova emission associated to SGRBs

First evidence for magnetars: the X-ray plateau



Rowlinson et al. 2014



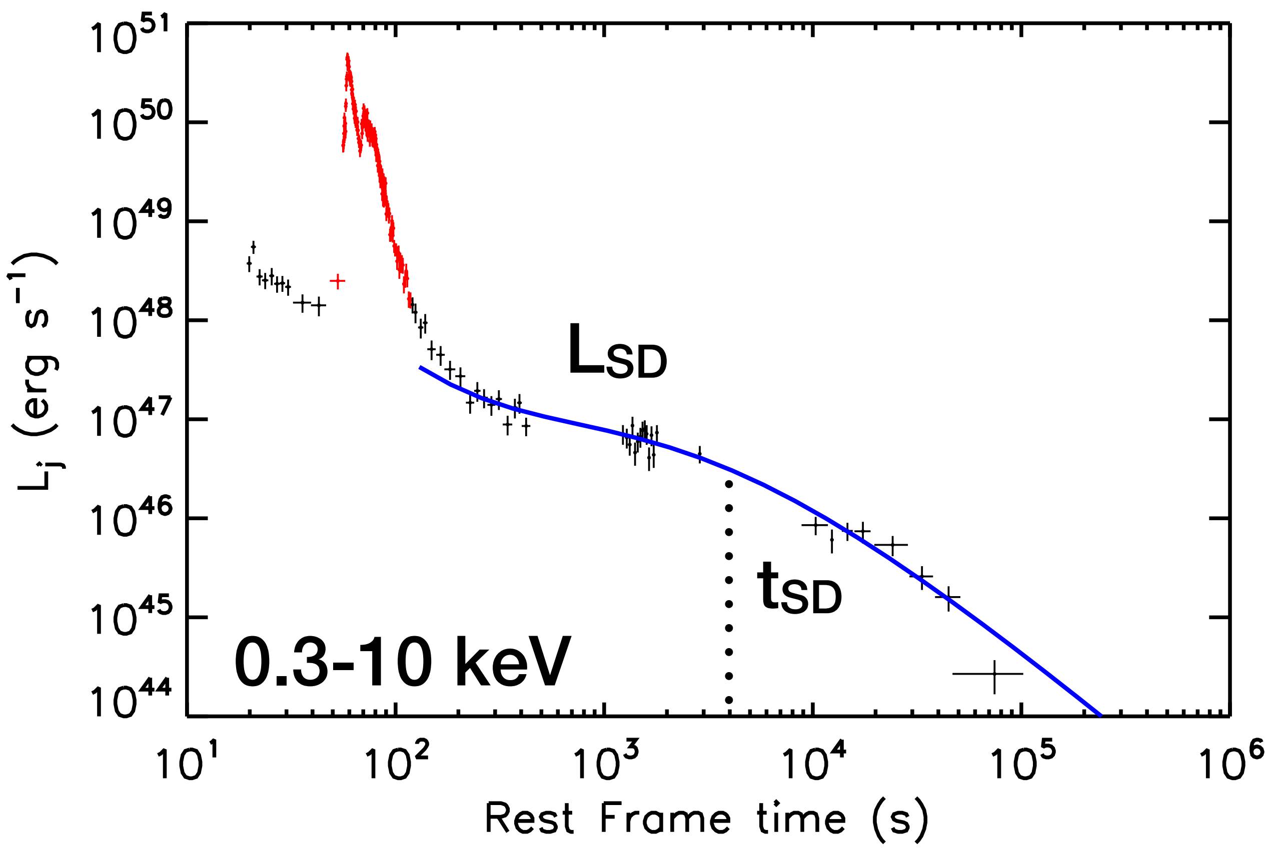
- **Plateau** phase in the X-ray afterglow of LGRBs and SGRBs

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

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

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, …….

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~10^{15} G
P~1 ms

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

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

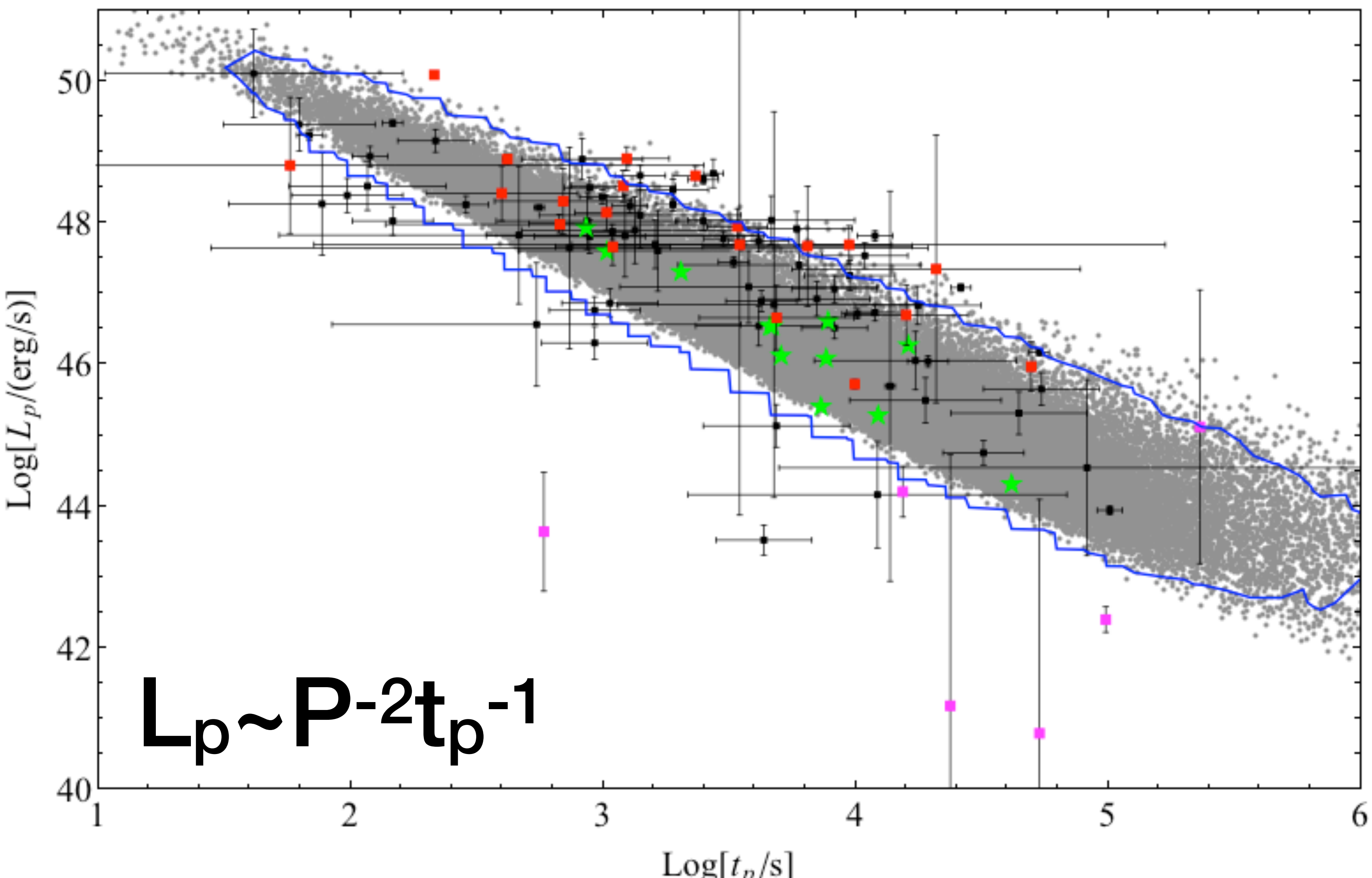
Direct estimates of **B** and **P** from X-ray data

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, …….

First evidence for magnetars: the X-ray plateau

➡Luminosity-duration correlation implied by the model

(Bernardini et al. 2012, Rowlinson et al. 2014)



Bernardini et al. 2012

- normalization and slope from B and P distributions
- scatter from P: 0.66-35 ms

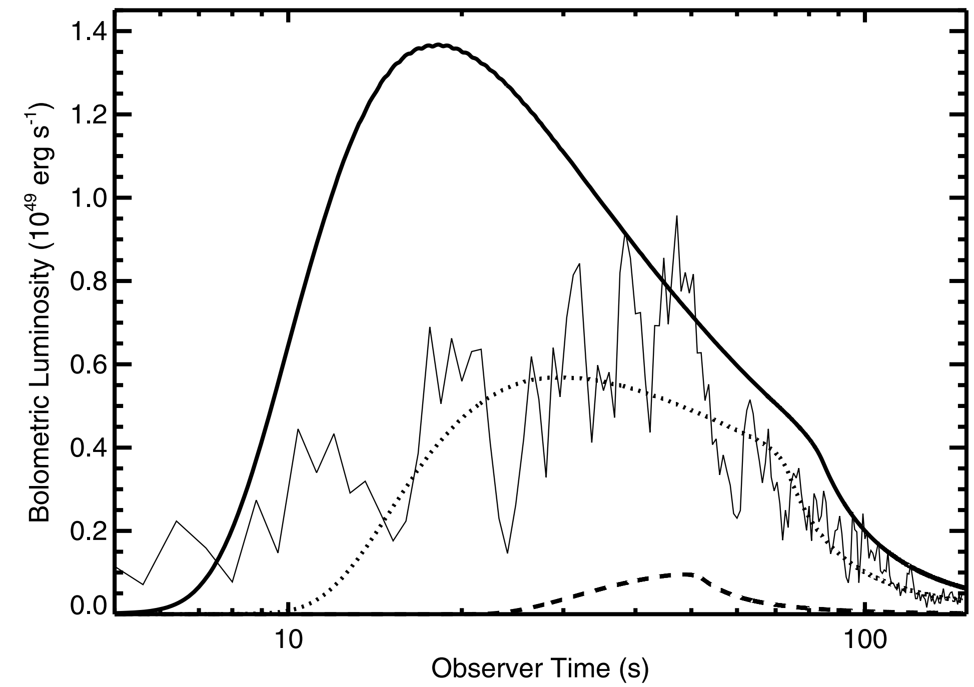
Dai & Lu 1998, Zhang & Meszaros 2001, Corsi & Meszaros 2009, Lyons et al. 2010, Dall'Osso et al. 2011, Metzger et al. 2011 Bernardini et al. 2012, 2013, Rowlinson et al. 2013, 2014, Lu & Zhang 2014, Lu et al. 2015, …….

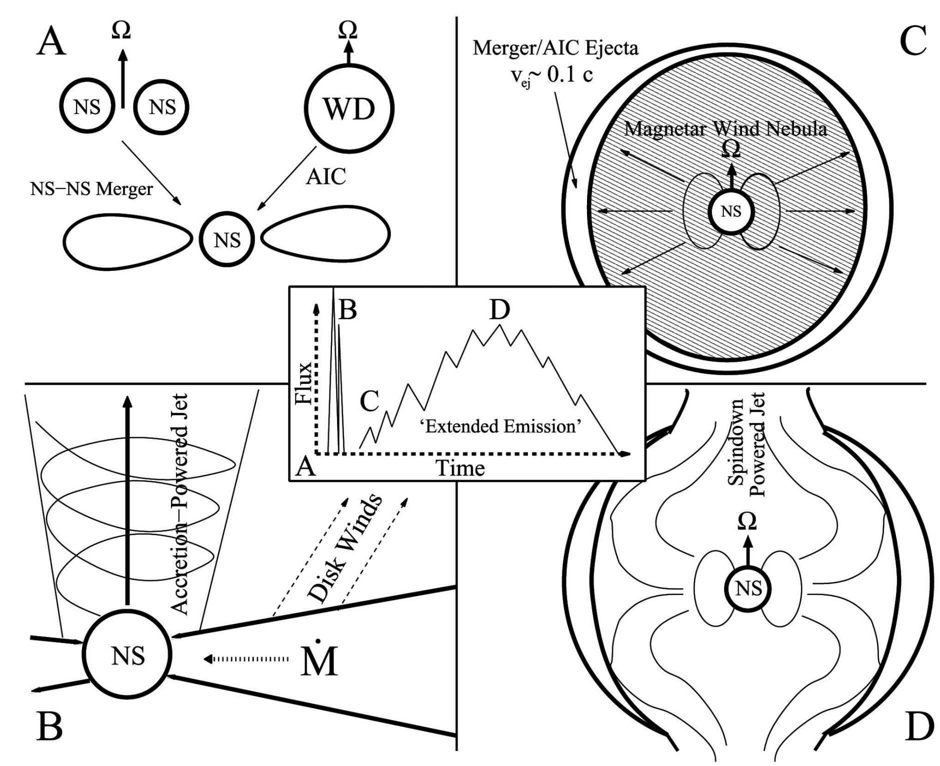
Extended Emission in SGRBs

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

- **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)

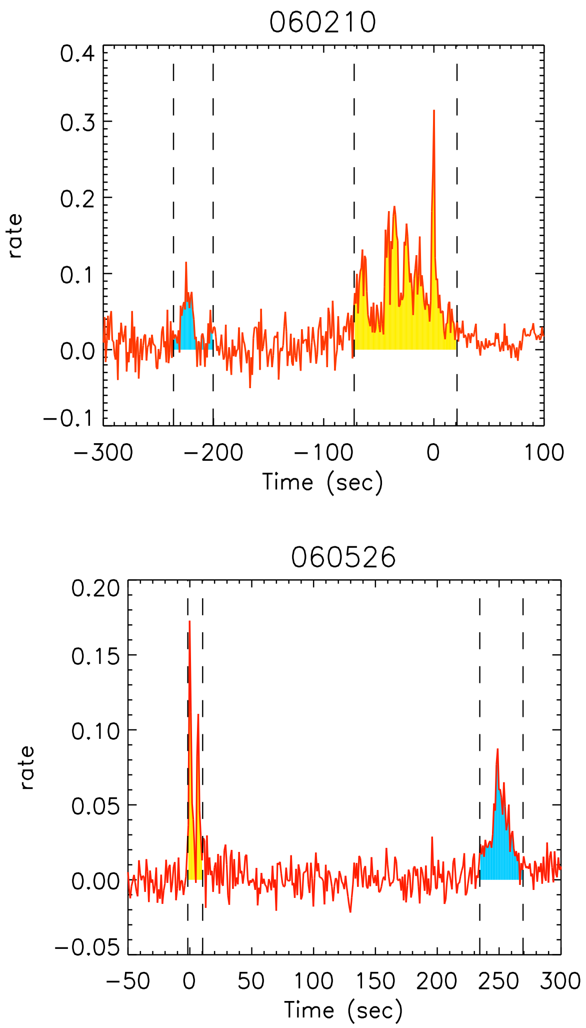
Metzger et al. 2008





Gompertz et al. 2014

The GRB prompt emission activity



Precursors

Post-cursors (giant flares)

- similar properties
- relatively common
- both in L and SGRBs

⇩

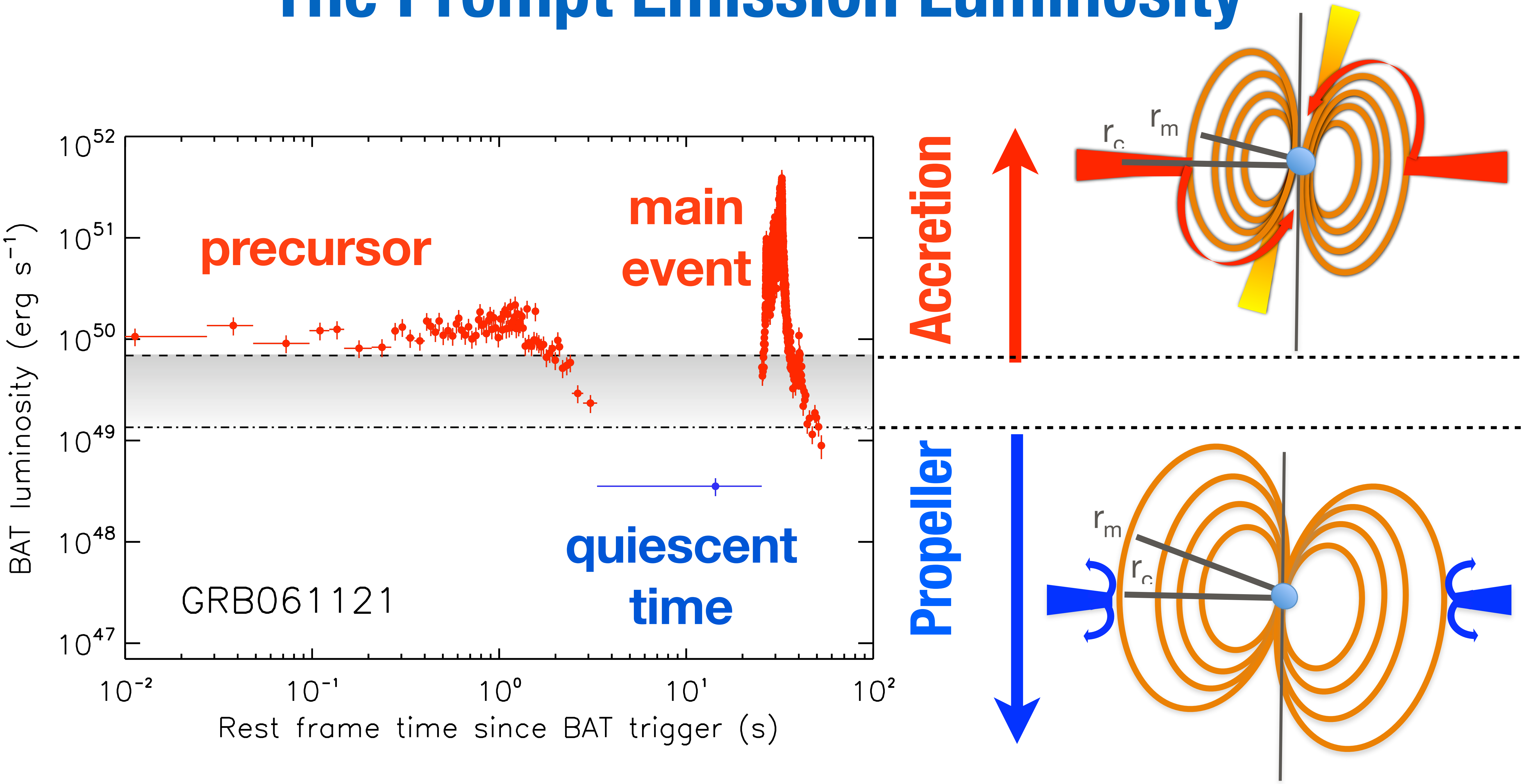
intermittent prompt emission activity

How to switch on and off a GRB?

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

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

The Prompt Emission Luminosity



$$L_{\rm min} = 4 \times 10^{50} B_{15}^2 \, P_{-3}^{-7/3} \, {\rm erg \, s^{-1}}$$

$$L(r_{\rm m}) = 2 \times 10^{50} B_{15}^2 \, P_{-3}^{-3} \, {\rm erg \, s^{-1}}$$

⇦ **B~10^{15} G**
P~1 ms

Bernardini et al., 2013, 2015

Observational imprints of the magnetar

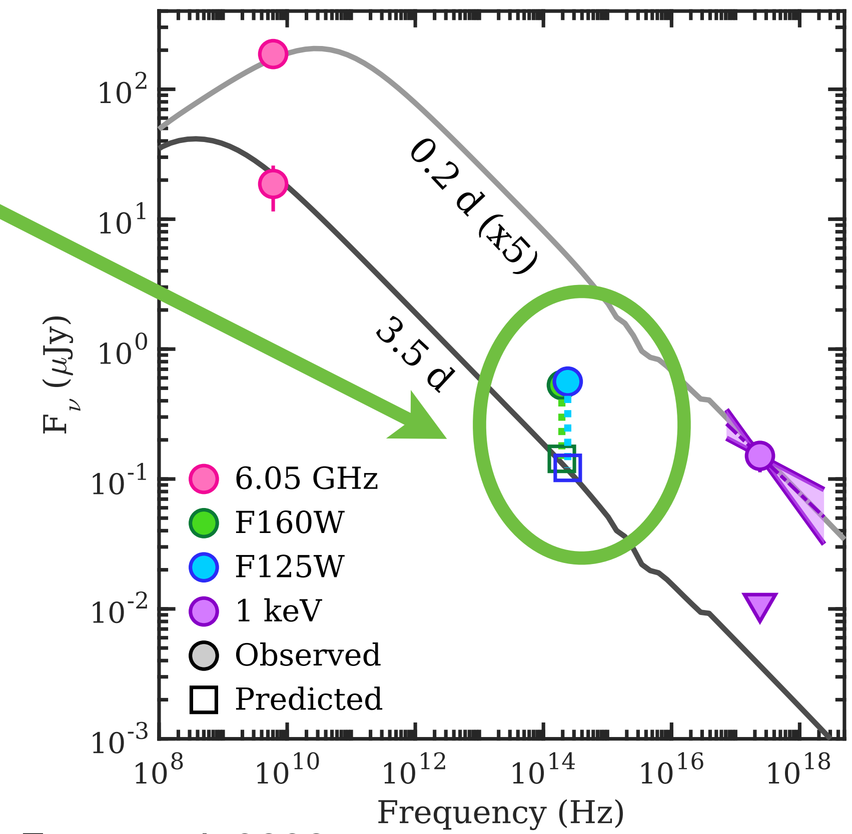
- The GRB emission:
  - X-ray plateau
  - Extended emission in SGRBs
  - Pre- and post-cursors in the prompt emission

- **The kilonova emission associated to SGRBs**

The magnetar-boosted Kilonova

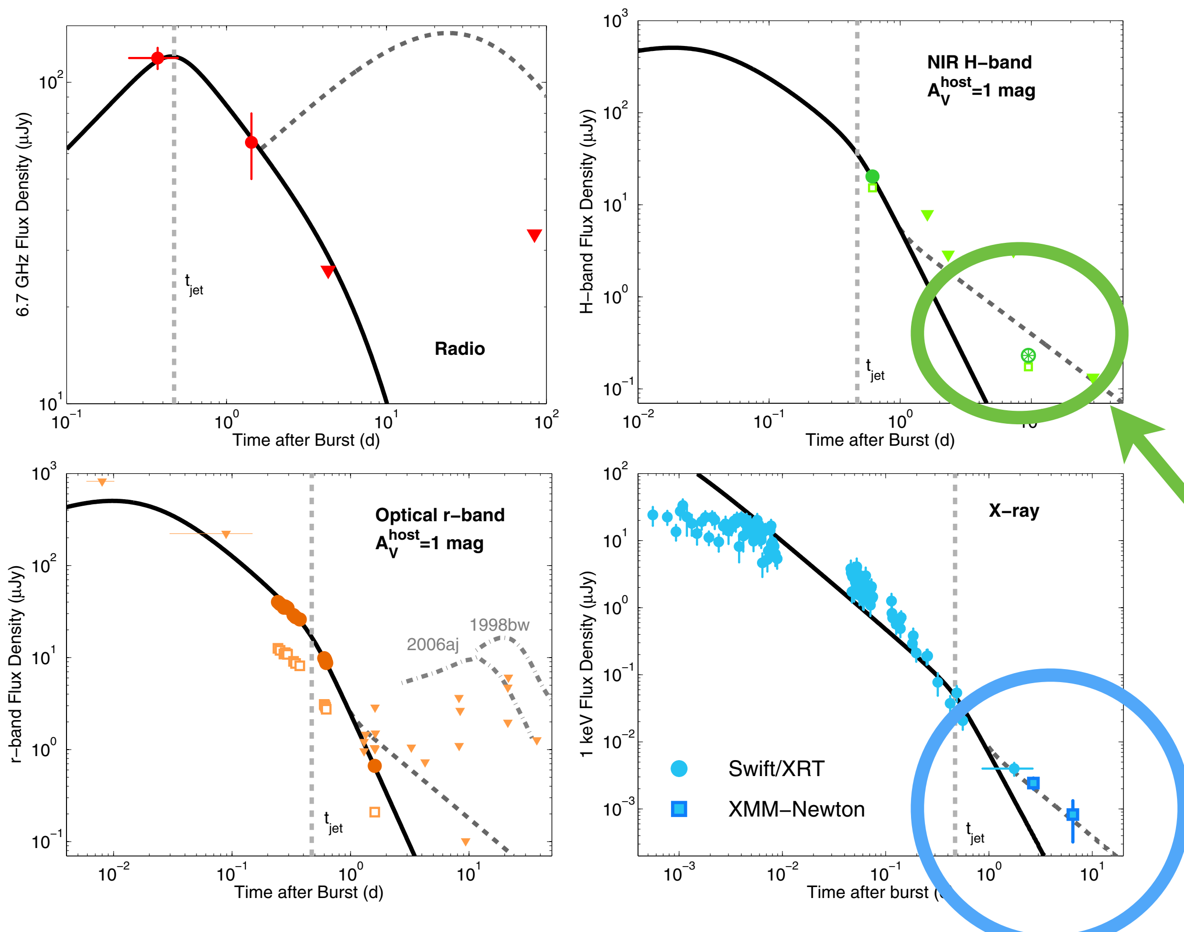
- The magnetar can provide an additional source of heating in the kilonova
- Magnetar boosting claimed in the **kilonova** associated to **GRB200522A** (Fong et al., 2020)
- Imprint of the magnetar in three other SGRBs and their associated kilonovae (Gao et al., 2017)

GRB200522A



Fong et al. 2020

GRB130603B

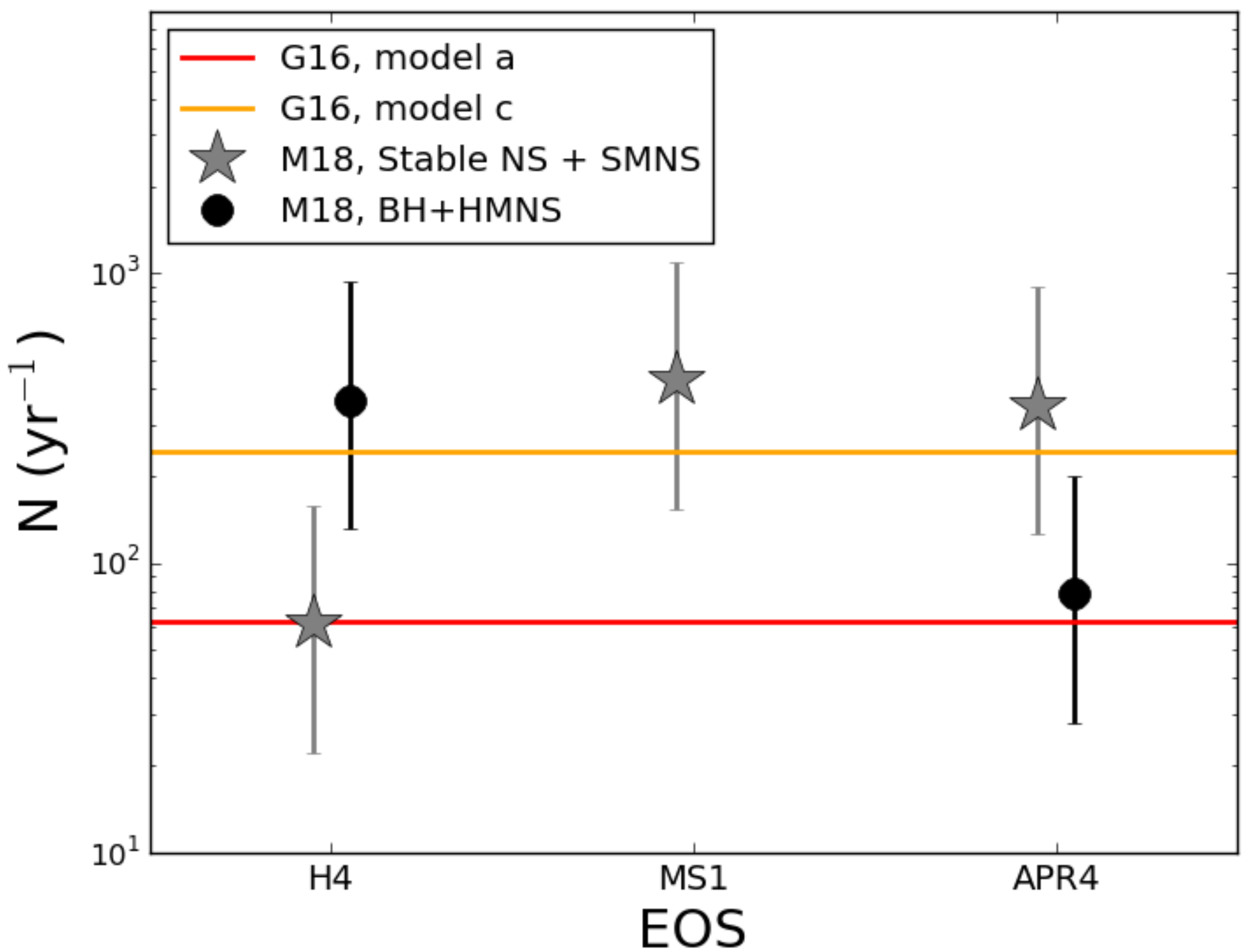


Fong et al. 2014

- 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?

Constraints on the aftermath of BNS merger:



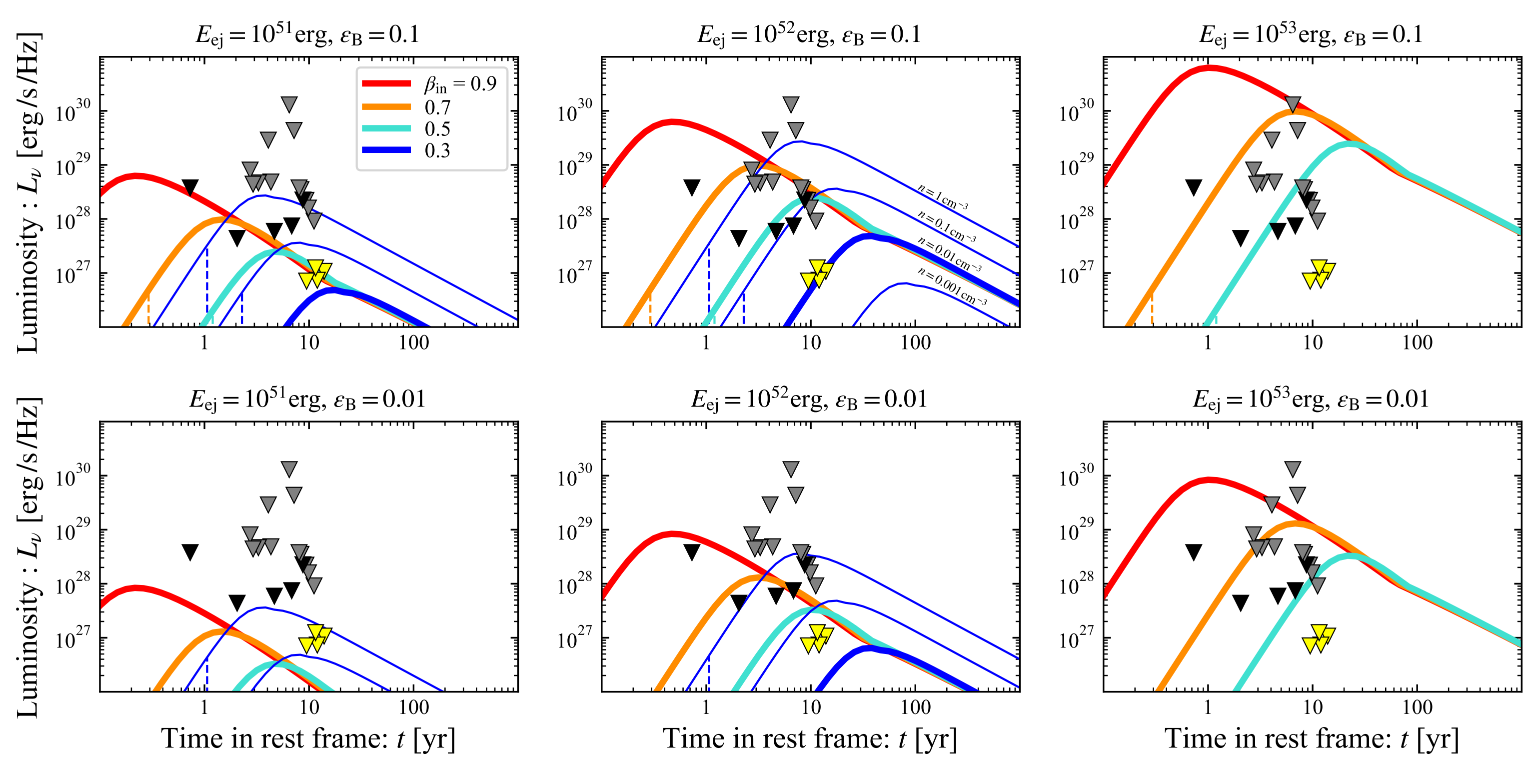
Patricelli & MGB, 2020
See also Piro et al., 2017

- 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**

Can magnetars power all GRBs?

1. Magnetars have a **limited energy budget (few x 10^{52} erg)**
   - ➡ **LGRBs often above limit.** However:
     - •**Accretion**: further energy supplier
     - •True $E_\gamma < E_{iso}$ due to collimation
     - •Sufficient to energise the accompanying SN (Mazzali et al., 2014)
     - •Several LGRBs too energetic
   - ➡ **SGRBs often below limit**:
     - •Radio upper limits in SGRBs rule out very energetic merger ejecta, thus excluding powerful magnetars as central engine (Ricci et al., 2020)
2. **Difficult for magnetars to launch ultra-relativistic jets** (e.g. Ciolfi, 2020)
3. Magnetars powering GRBs are inconsistent with galactic magnetar population (Rea et al., 2016)
   - ➡ **population of "super-magnetars" connected with GRBs**



Ricci et al. 2020

The GRB central engine in the MM era

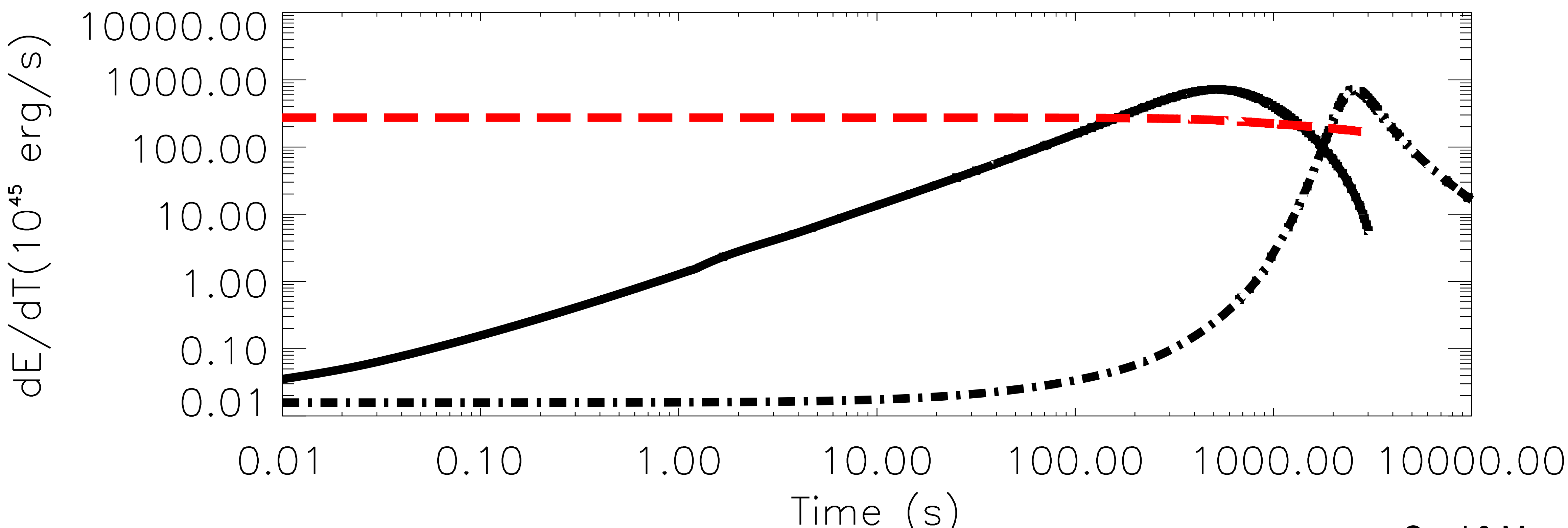
Lesson learned from GW 170817/GRB 170817A:

- 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~10^9 G (Hajela et al. 2021)
- **Thermal emission:**
  - ➡ The blue component and the large mass of lanthanide-free ejecta with E_{kin}~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

- Magnetars source of GW if they spin fast enough to excite dynamical (ß=0.27) or secular instabilities (ß>0.14)
- Onset of dynamical instabilities at magnetar birth, more likely thanks to spin-up induced by accretion
- Signal from secular instabilities detectable over long timescales (~ hours)

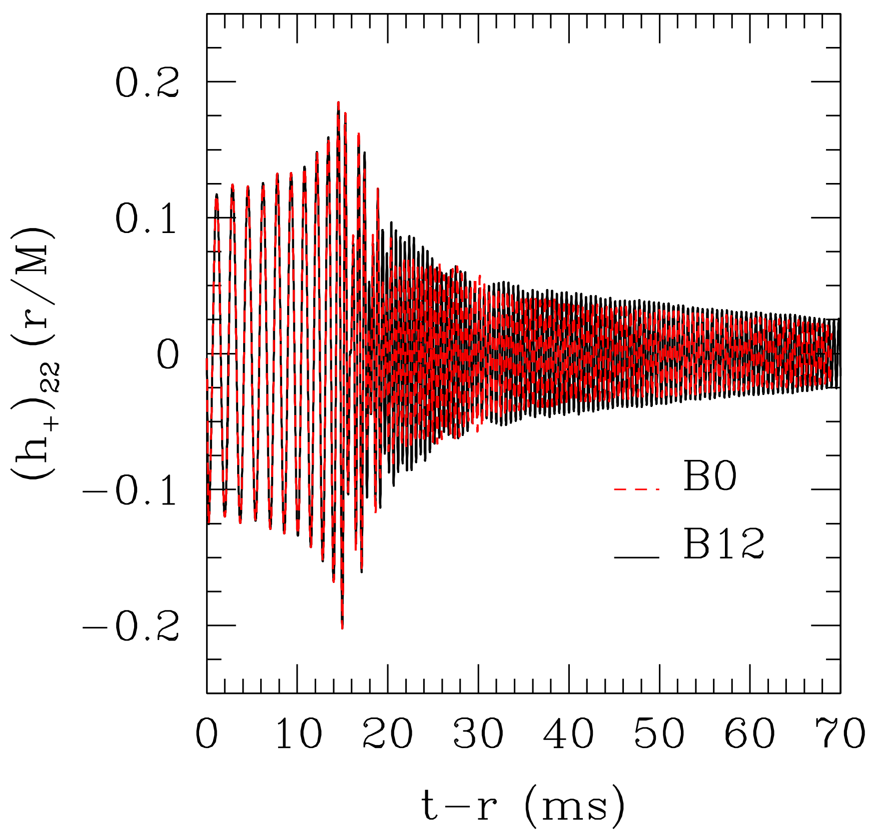


Corsi & Meszaros, 2009
Piro & Ott, 2011

Direct detection of GWs from the magnetar

- Long-lasting post-merger signals are the best direct detection to distinguish between magnetar and BH
- 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)

Giacomazzo & Perna 2013



Direct detection of GWs from the magnetar

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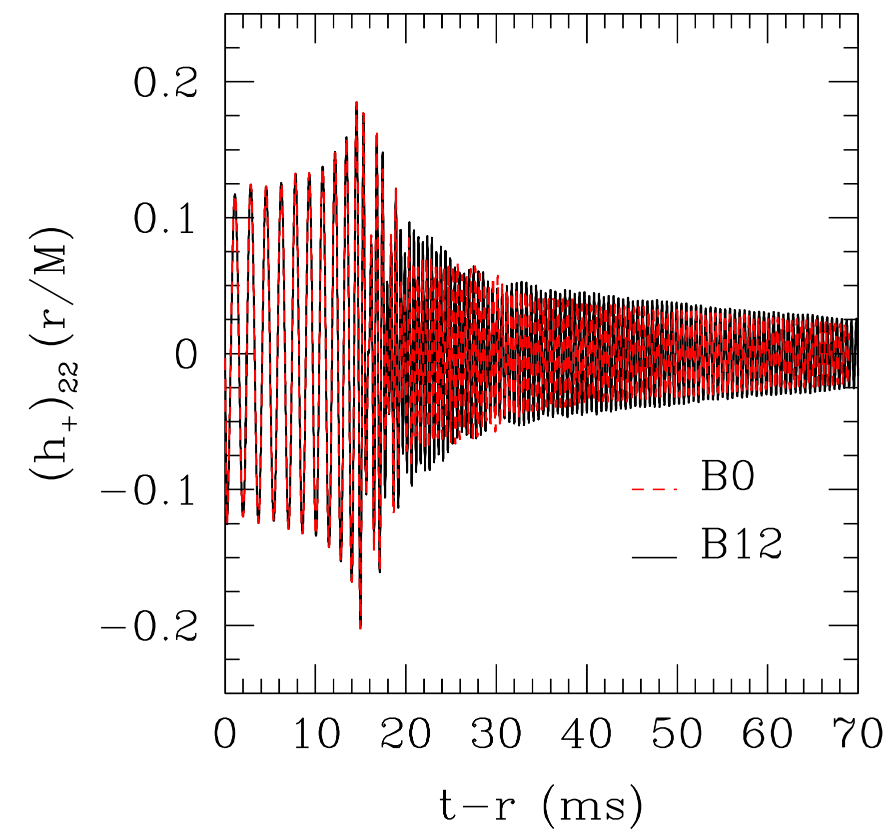
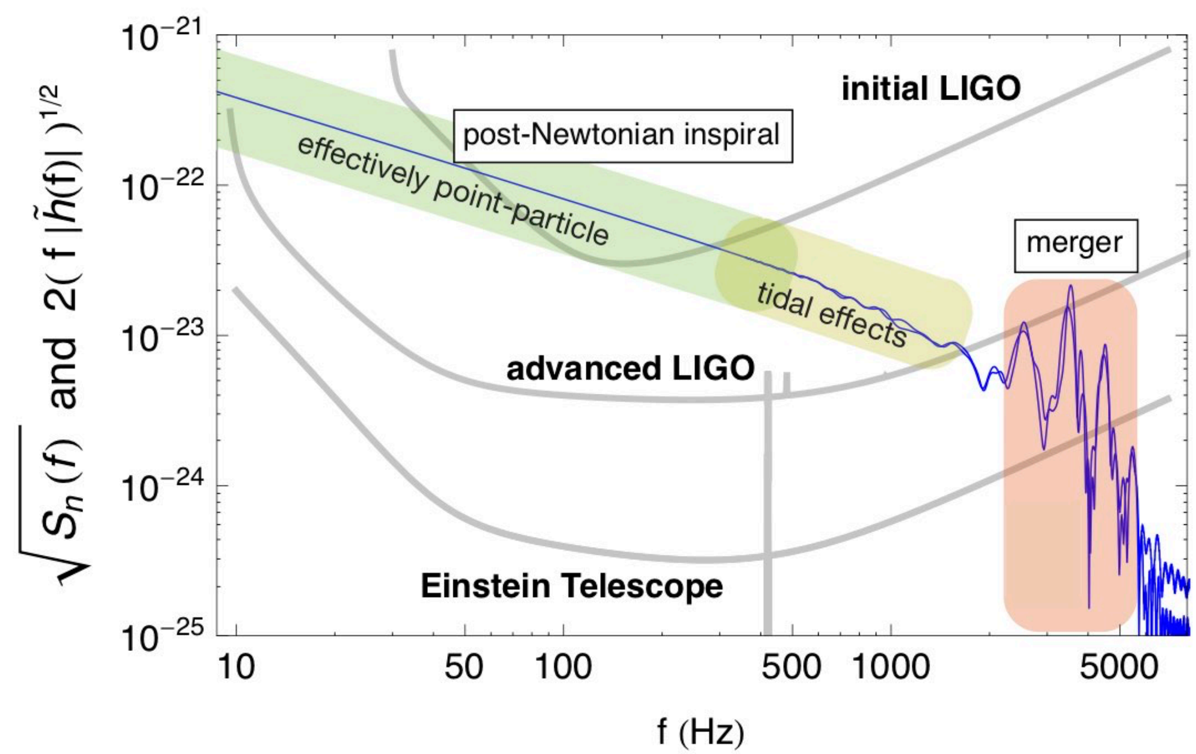
- Hard to get it any time soon, but **good prospects with 3rd generation of detectors, as the ET**

Giacomazzo & Perna 2013





Andersson, 2017

Conclusions

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

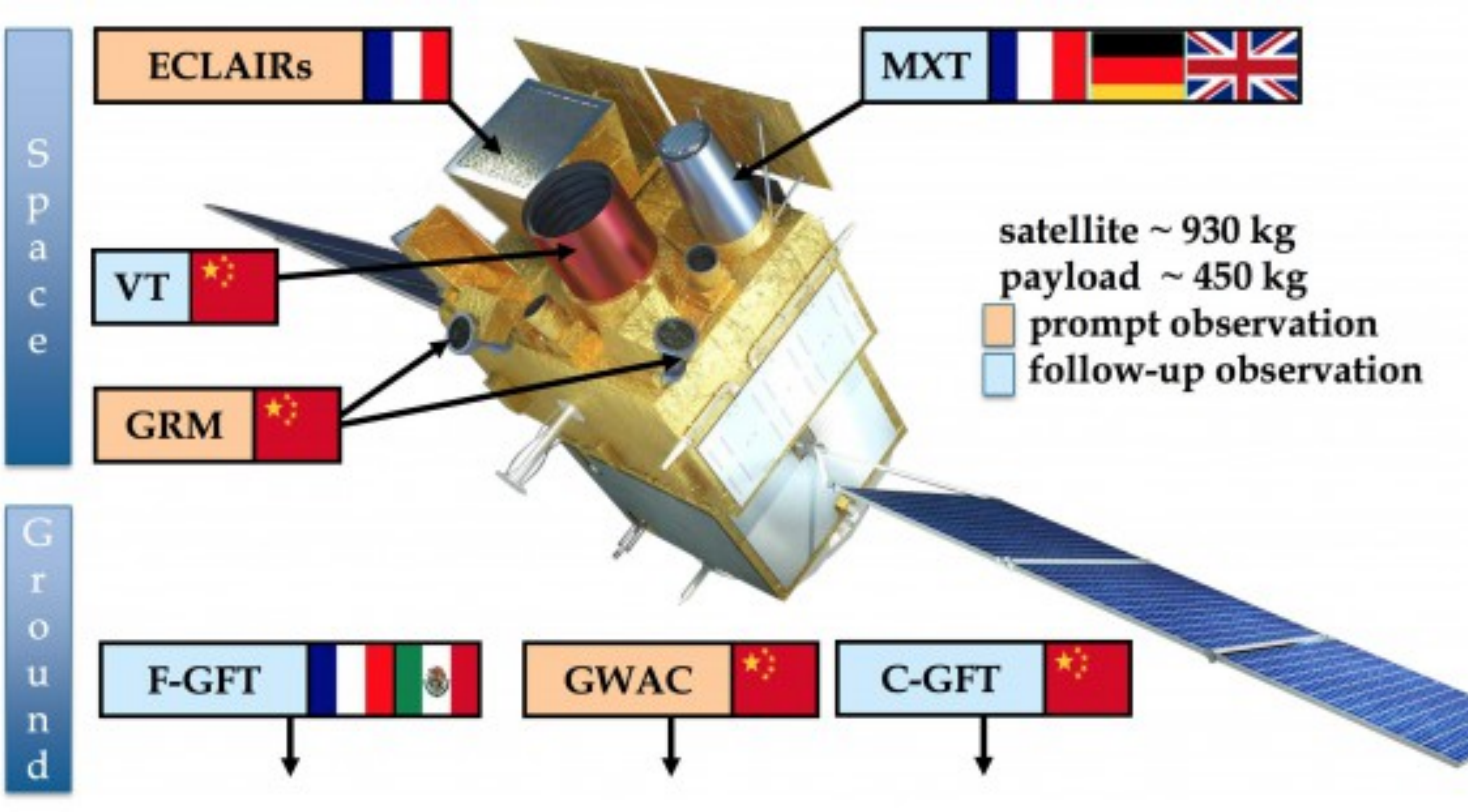
✓ Are all GRBs powered by magnetars?

- ➡ There are enough magnetars to power all SGRBs
- ➡ Not likely (at least not 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**:

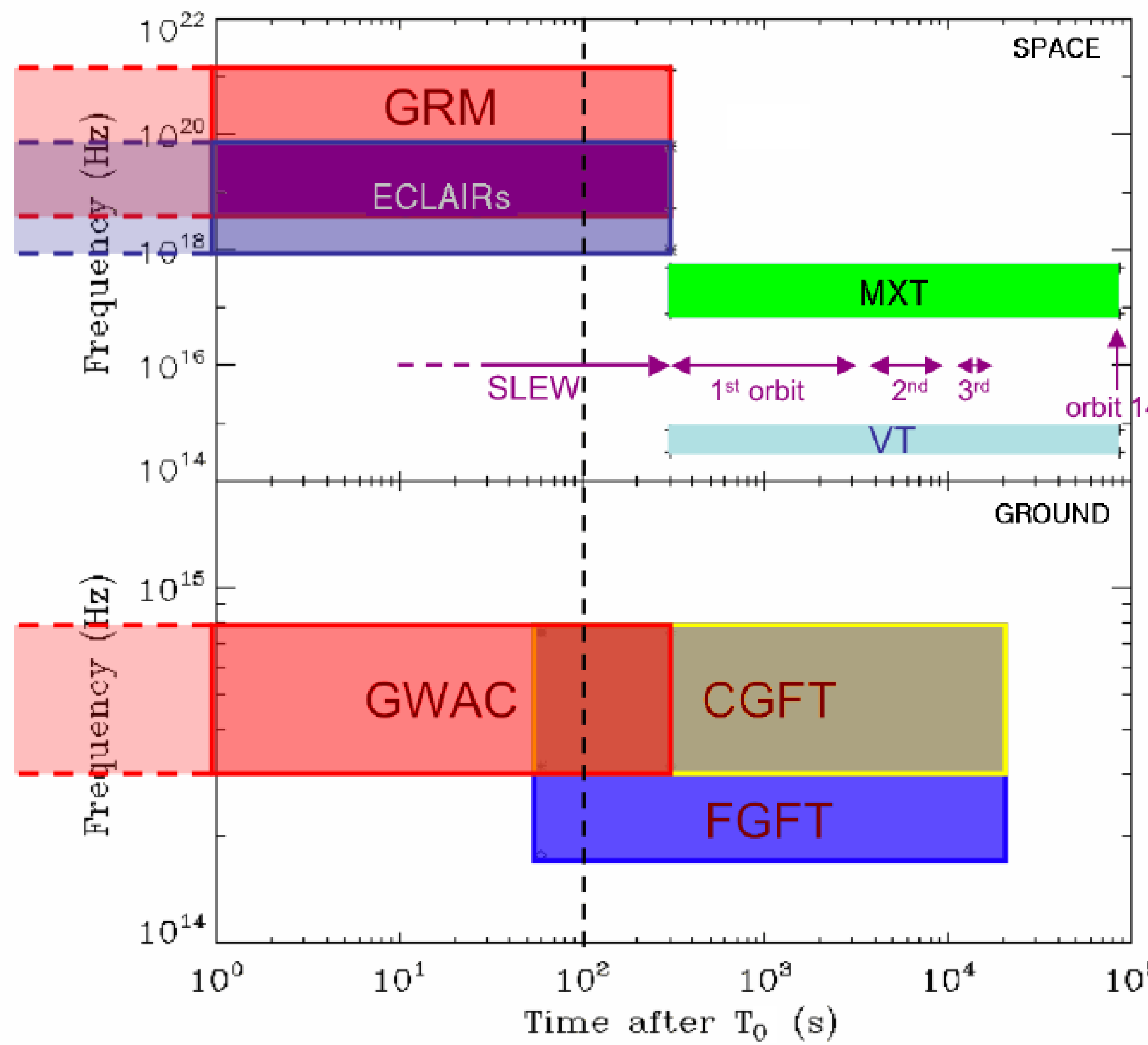
- ➡ clues from GW 170817/GRB 170817A: from EM observations only, still inconclusive
- ➡ definitive answer form direct detection of **GW signal from the remnant: one of the expected breakthrough, but hardly achievable with the current generation detectors**
- ➡ **much better prospects with the 3rd generation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

The **"Space-based multi-band astronomical Variable Objects Monitor" (SVOM)** is a Sino-French mission dedicated to **GRBs** and **transient sources**
to be launched mid-2022, duration 3+2 years



The GRB "core" program

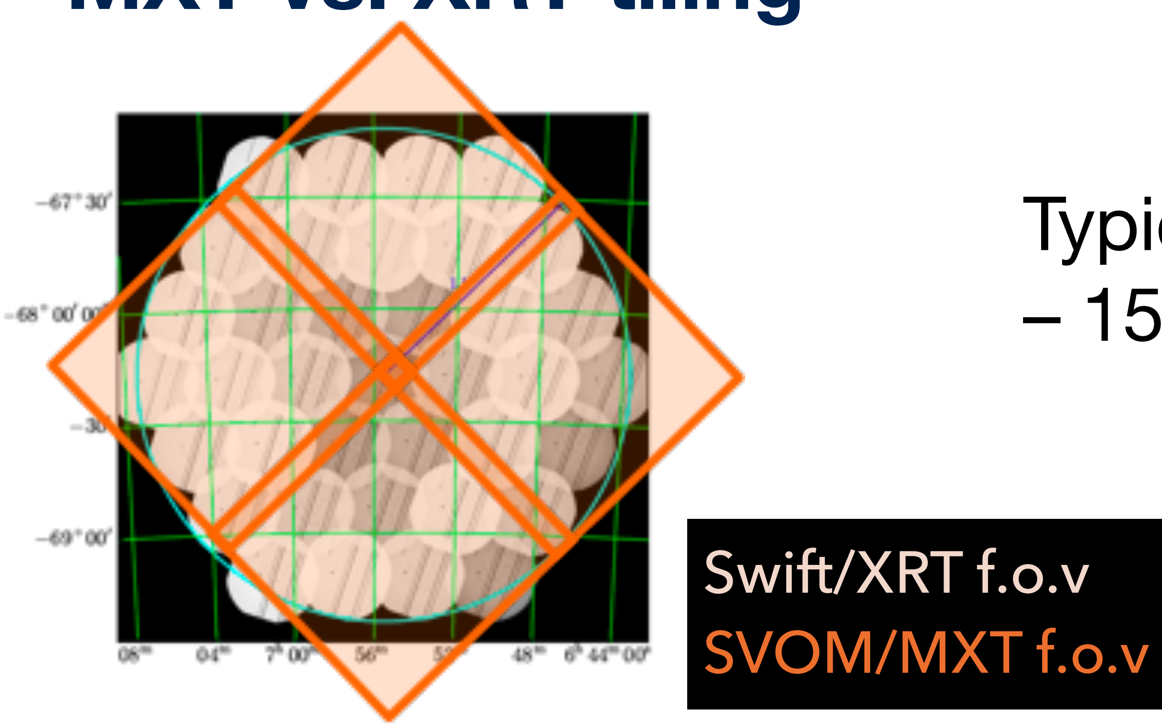
- **Trigger and locate GRBs,** alerts and localization distributed in **real-time**
- Optimal pointing strategy for ground-based follow-up
  - ➡ **Synergy with other space and ground based facilities**
  - ➡**Larger fraction of GRBs with redshift**
- Synergy among **7 instruments in space and on ground** for a multi-wavelength follow-up
  - ➡ Complete coverage of the GRB emission over **7 decades in energy** from the trigger up to the late afterglow phase



SVOM reaction to a MM trigger

ECLAIRs/GRM	Large fov, independent trigger or search in the fov
MXT/VT	Slew following the alert **ToO-MM** (max 1/week)
	Tiling strategy if the error box is larger than 1 deg^2
GWAC	Rapid automatic response
	Large fov, wide field search for counterpart
C-GFT/F-GFT	Rapid response
	Need accurate localization, photometric follow-up

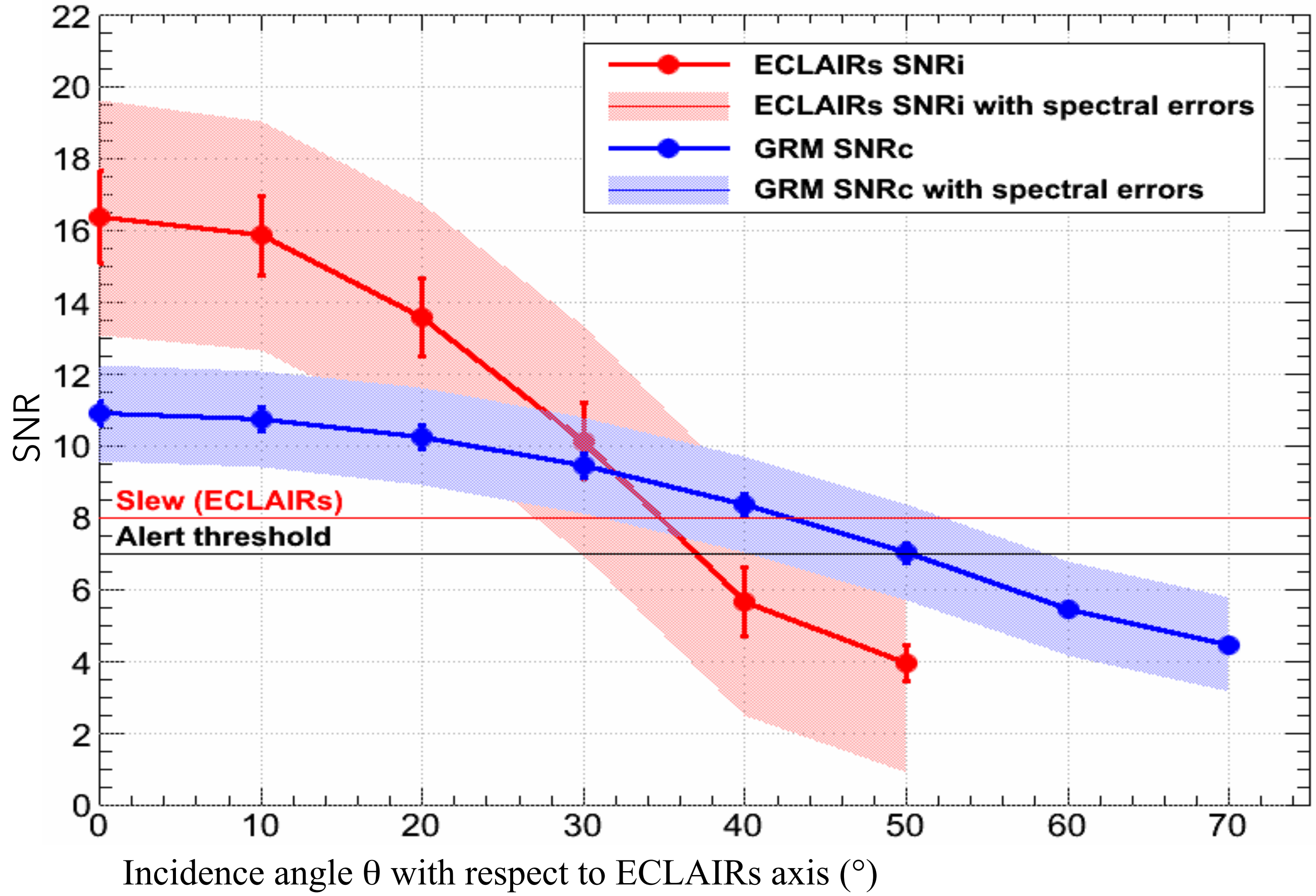
MXT vs. XRT tiling

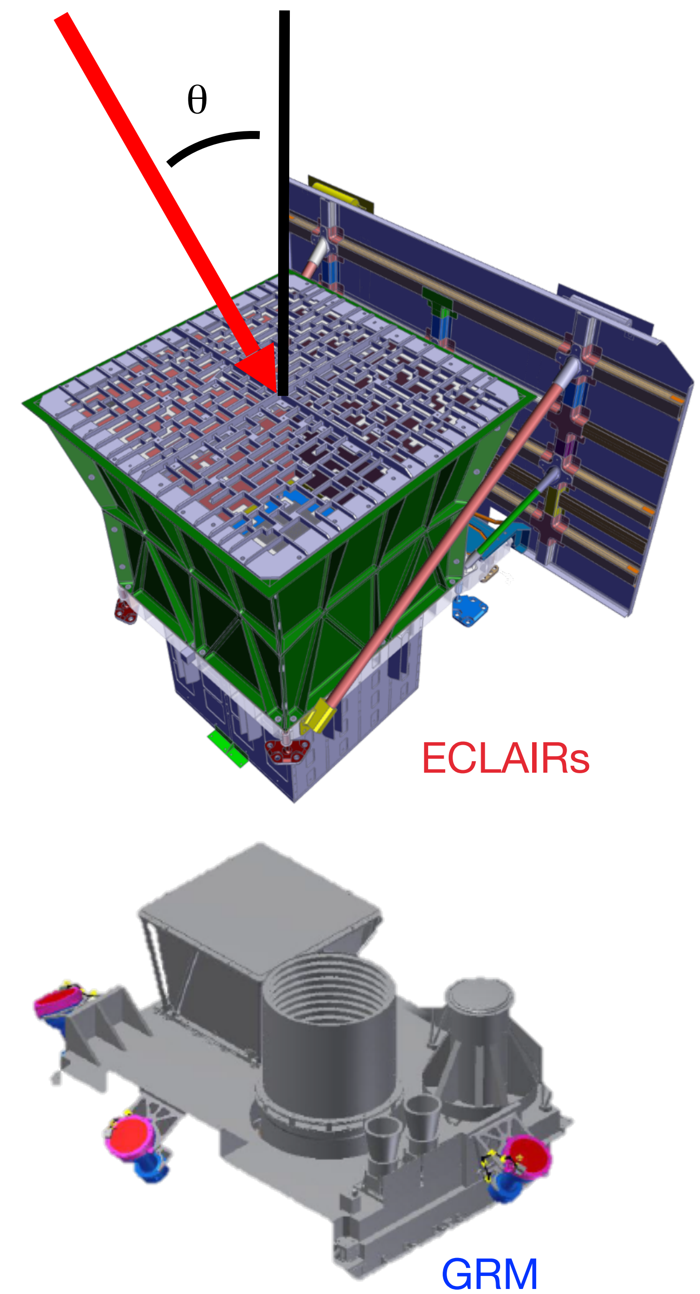


Typical scenario: 5 tiles/orbit
– 15 orbits (~ 1 day)

GW 170817 / GRB 170817A

Simulation of the prompt emission of GRB170817A



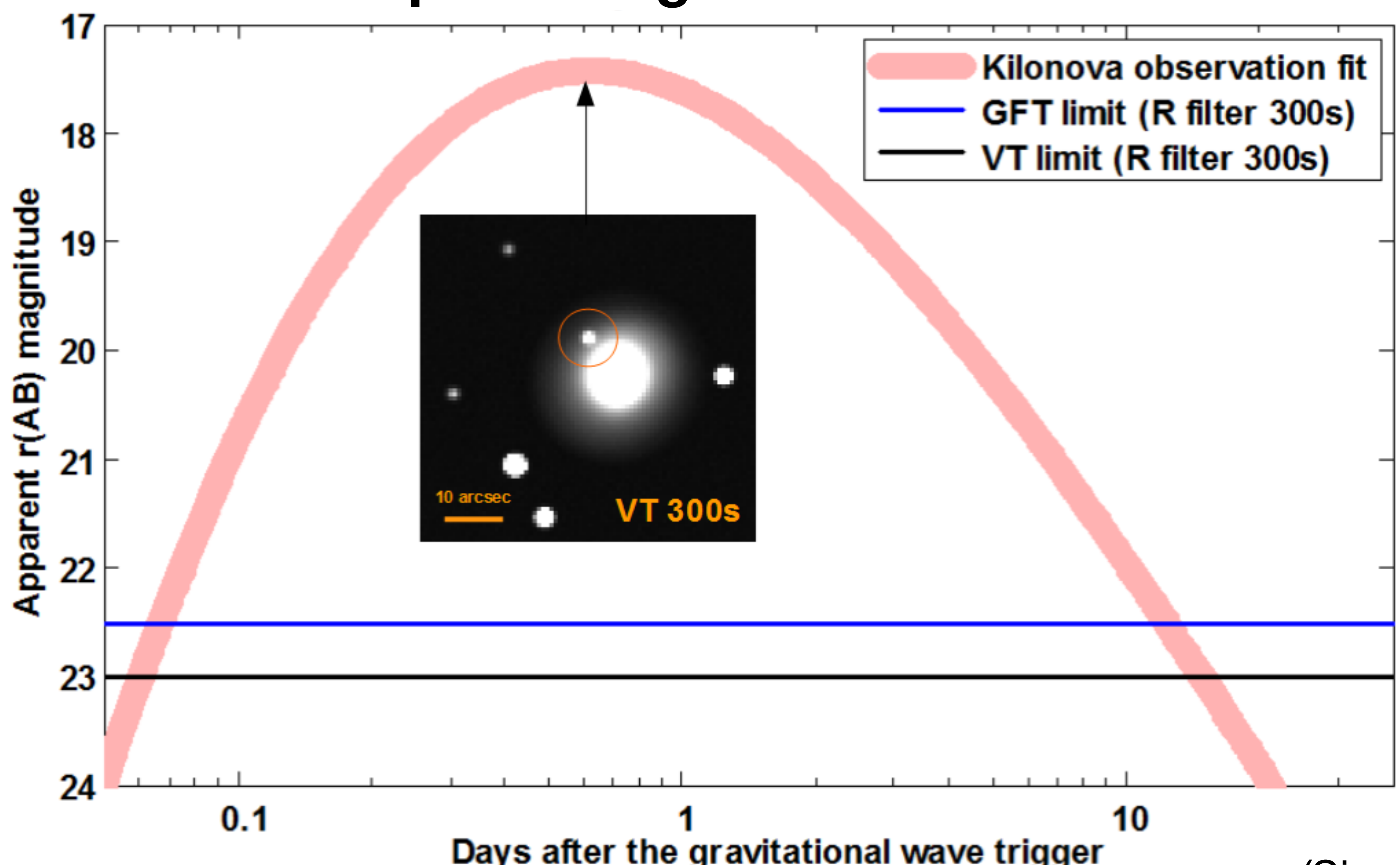


(Simulations by S.Schanne, MG.Bernardini and F.Piron)

- Up to **35° off axis**: ECLAIRs triggers + alert is sent to the ground + slew is requested
- Up to **50° off-axis**: GRM triggers + alert is sent to the ground (with rough localization)

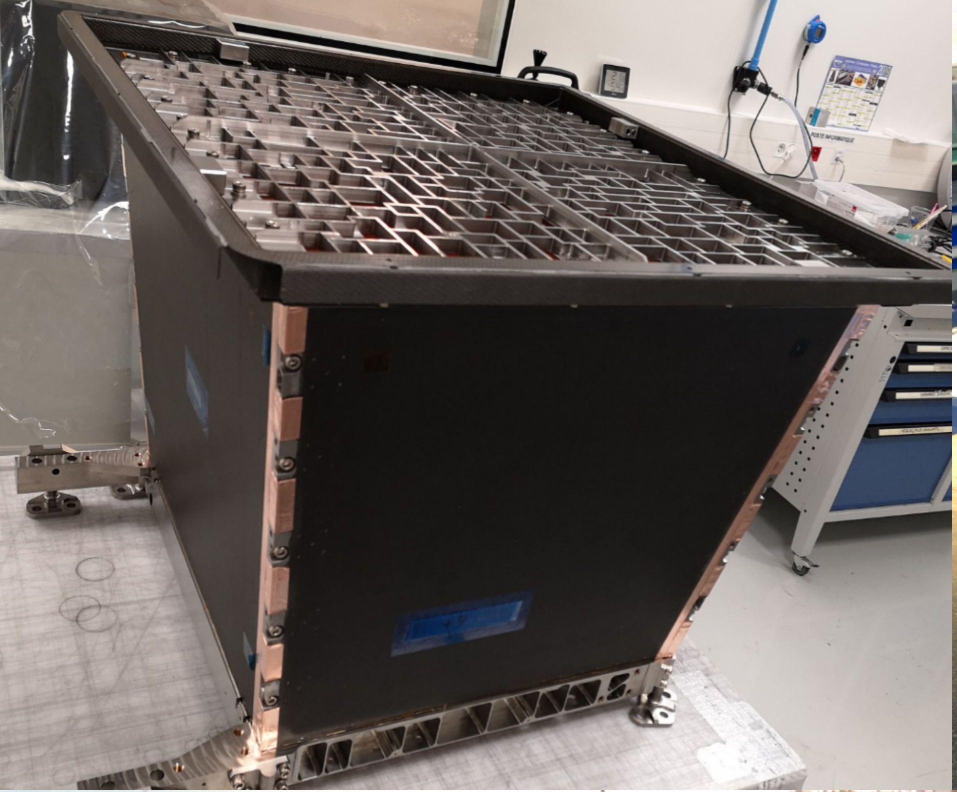
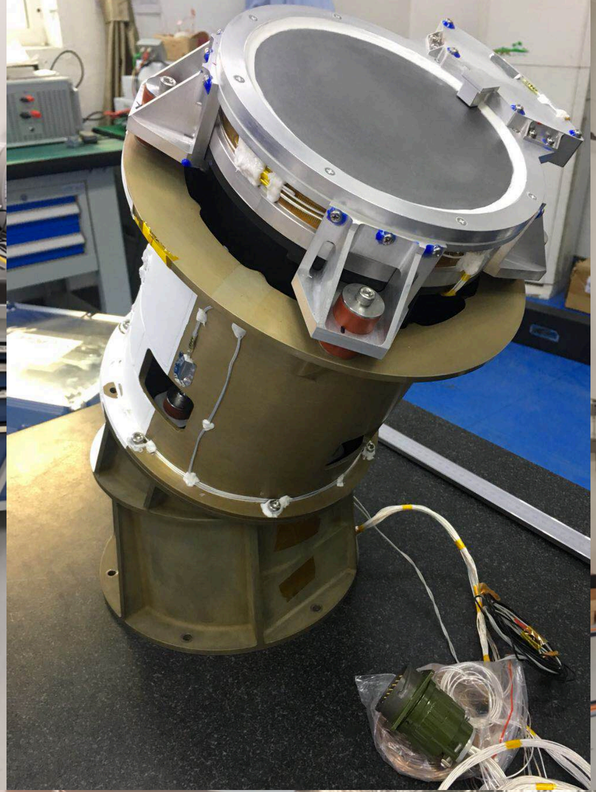
And the associated kilonova

Simulation of the kilonova AT2017gfo as seen by VT in 300 s at peak magnitude

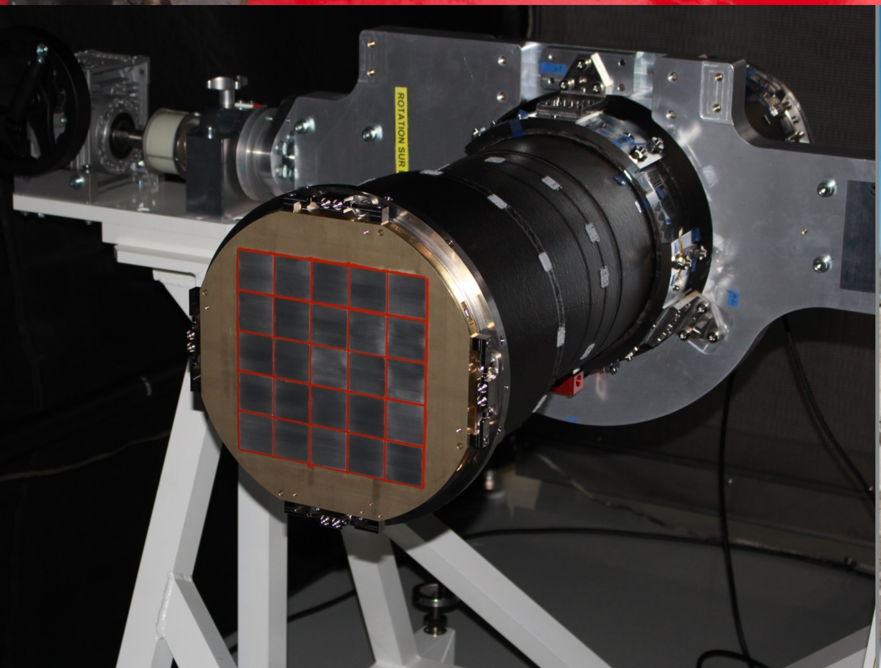


(Simulations by A.Klötz)

- VT and GFTs have the capacity to detect the kilonova since T0+2h and follow it during 10 days




Everything will be ready for mid 2022
Stay tuned!!