Credits: Luís Calçada

GRBs and magnetars in the multi-messenger era

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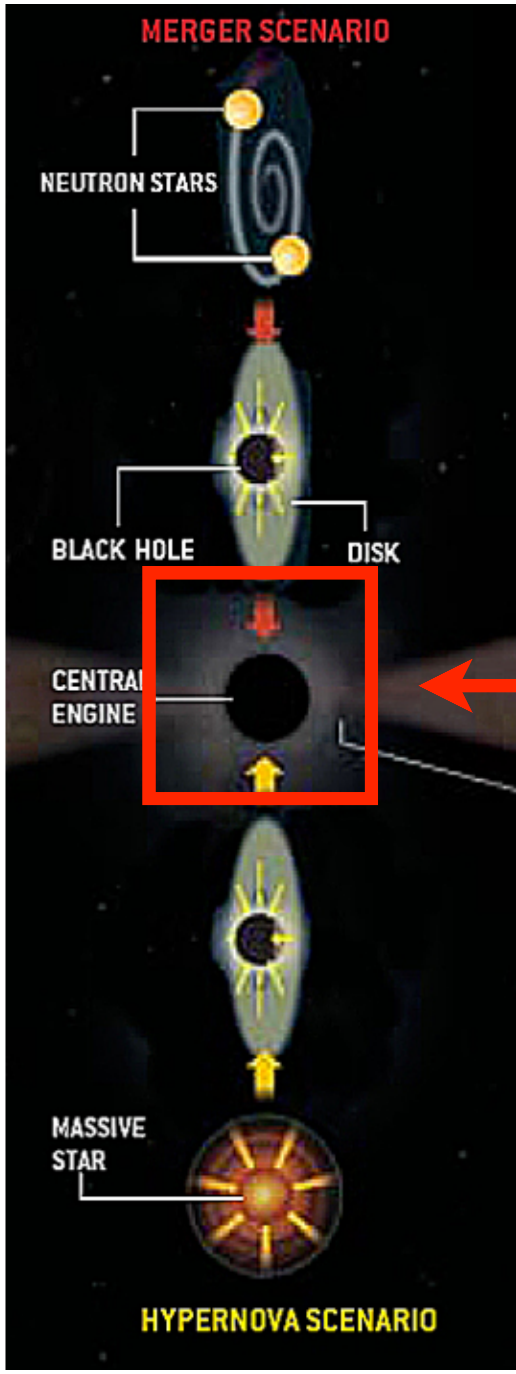
High redshift Gamma-Ray-Bursts in the JWST era,

Sexten (BZ), January 9-13, 2023

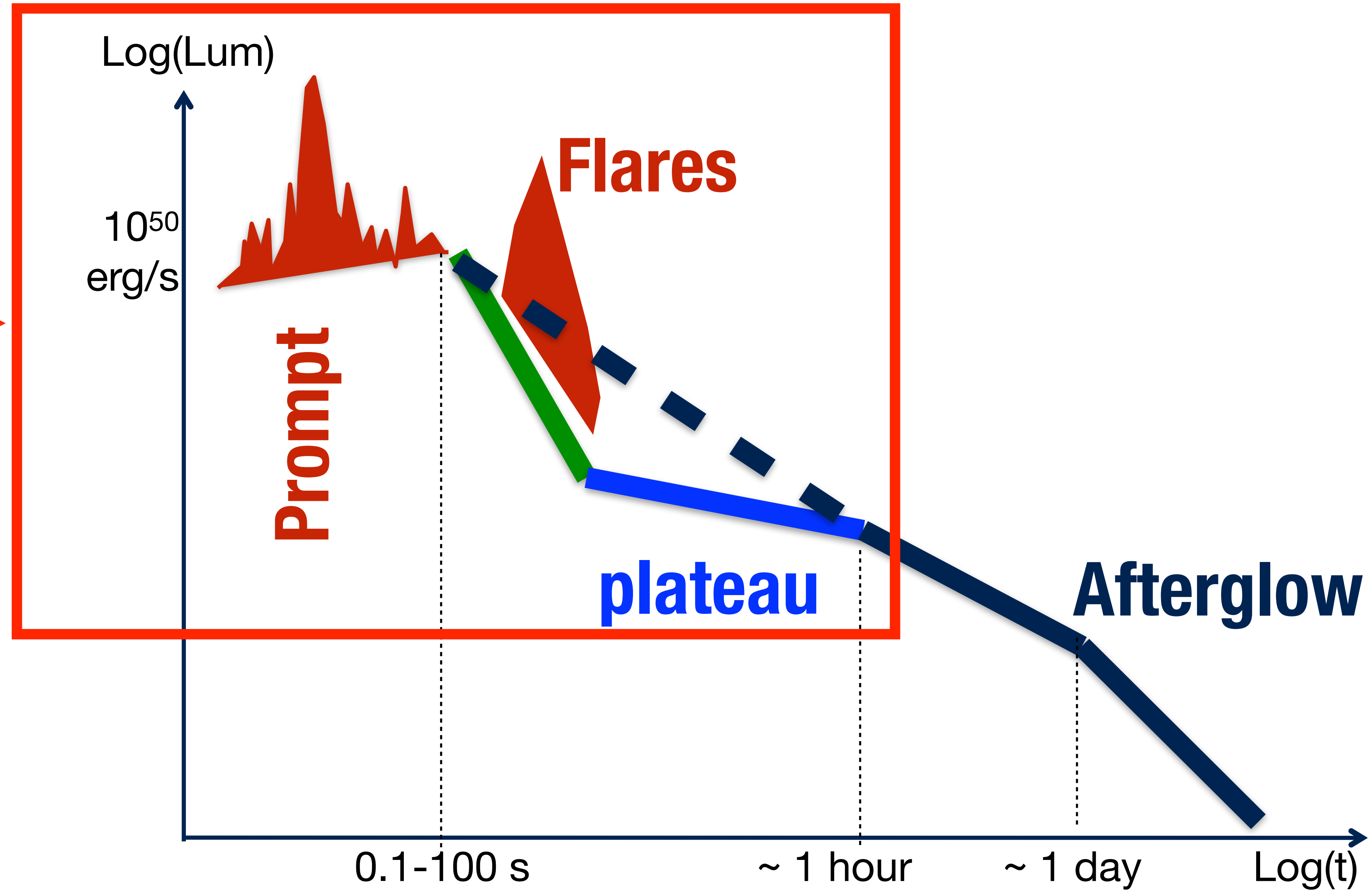
The central engine of GRBs

Short GRBs

Long GRBs



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

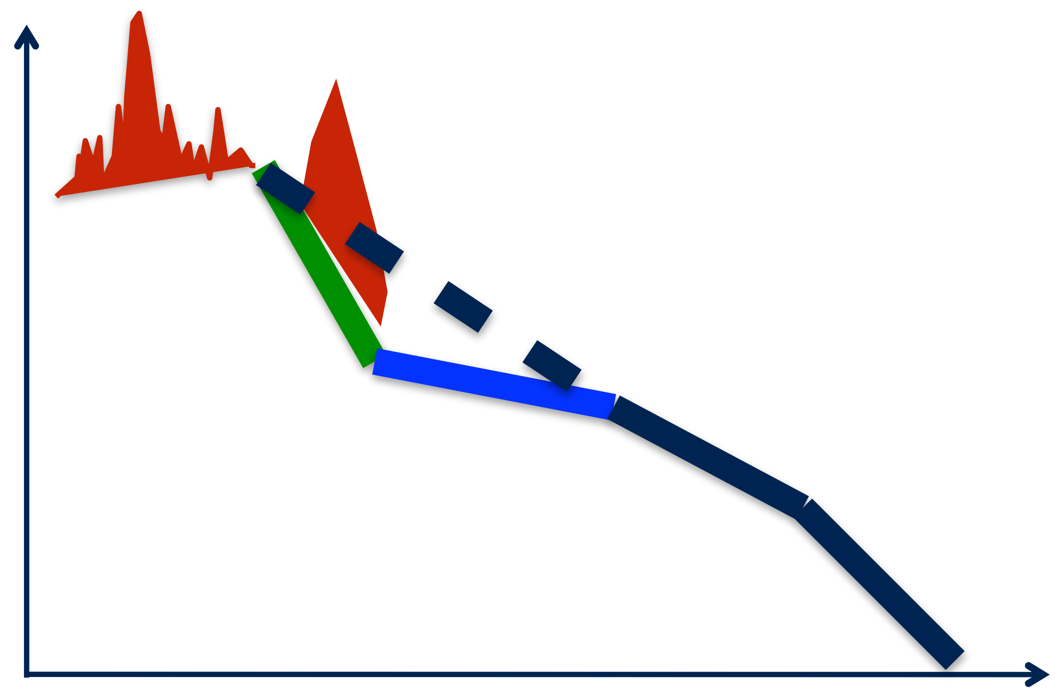


Magnetars are competing with BHs as source of GRB power

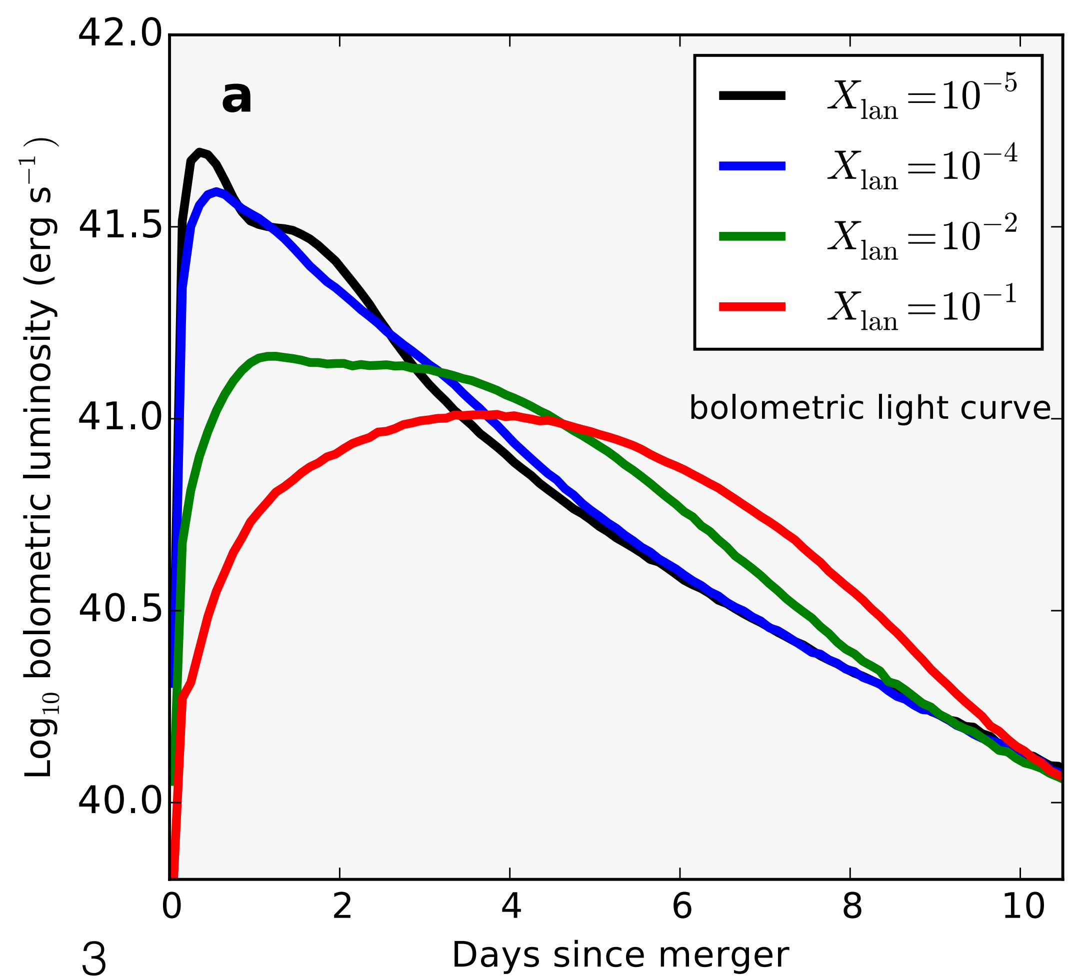
Usov 1992, Duncan & Thompson 1992, Dai & Lu 1998, Zhang & Meszaros 2001, Metzger et al. 2011, ….

Observational imprints of the magnetar

- The **GRB** emission

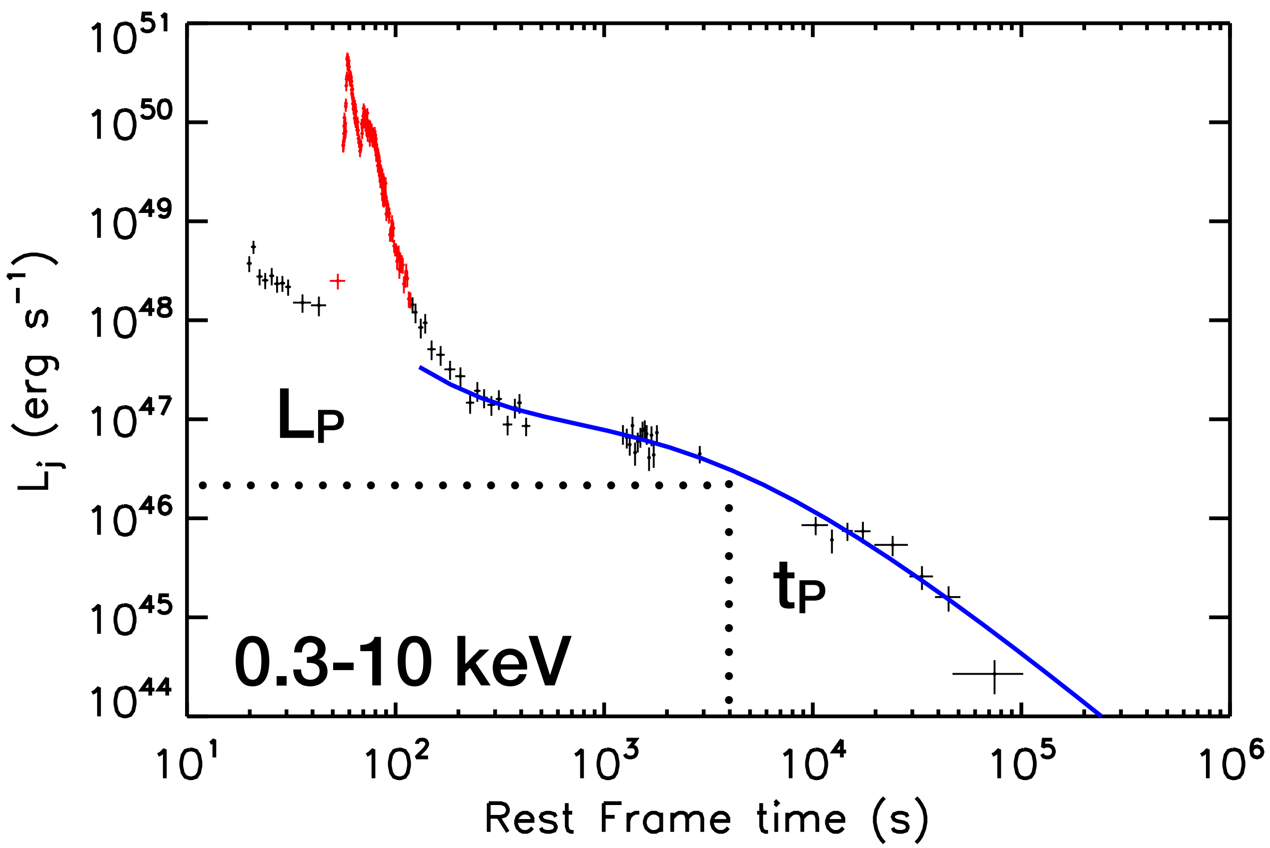


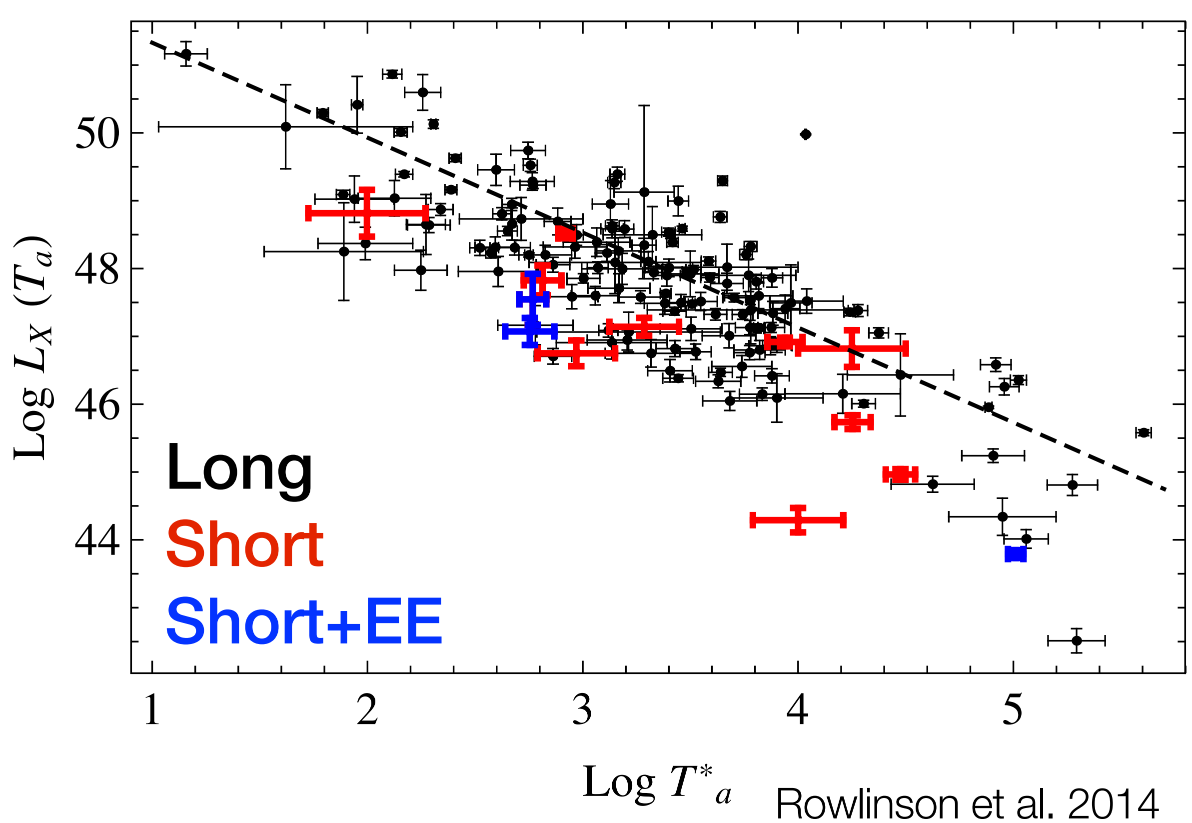
- The **kilonova** emission associated to **SGRBs**



Kasen et al. 2017

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**

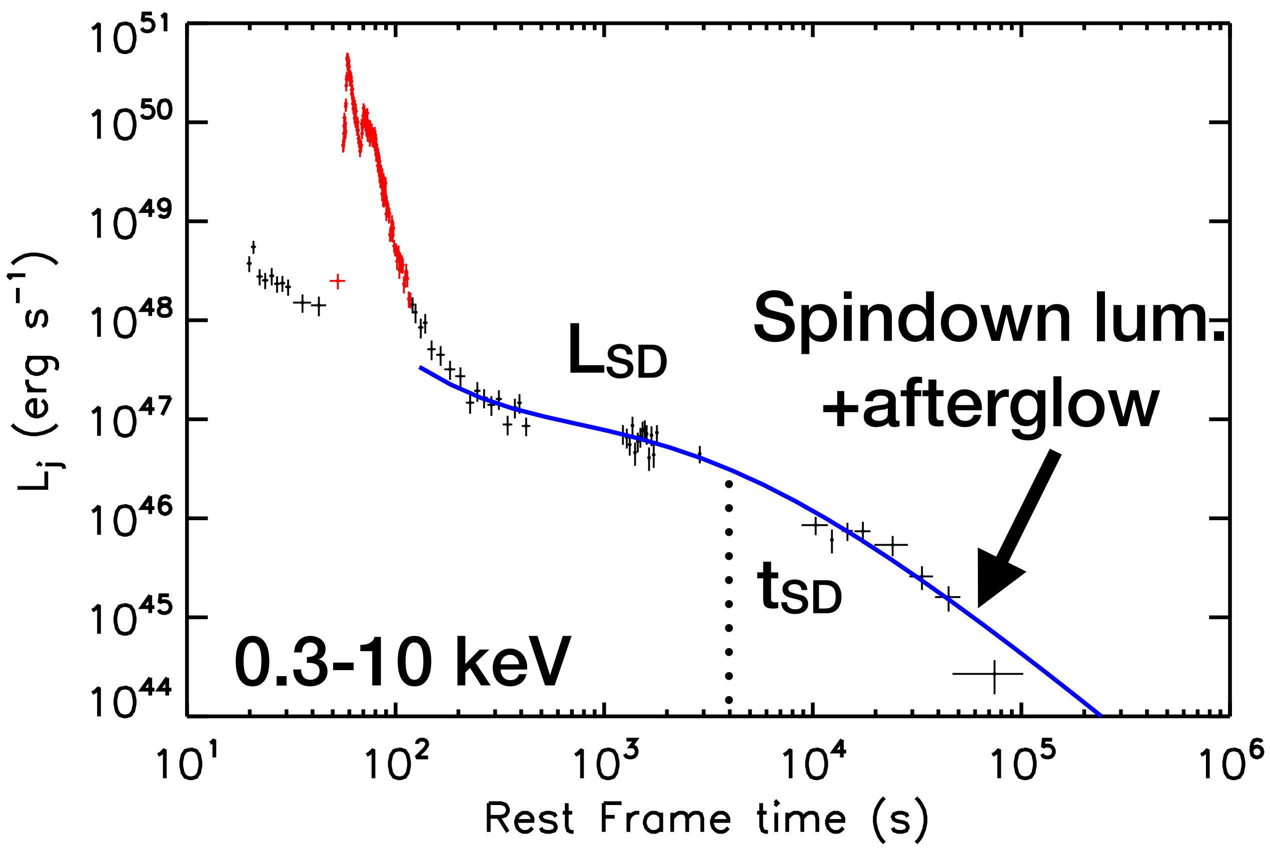
- Correlations between the **plateau** properties and the prompt emission (Dainotti et al. 2008, 2010, 2013, 2015)

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.

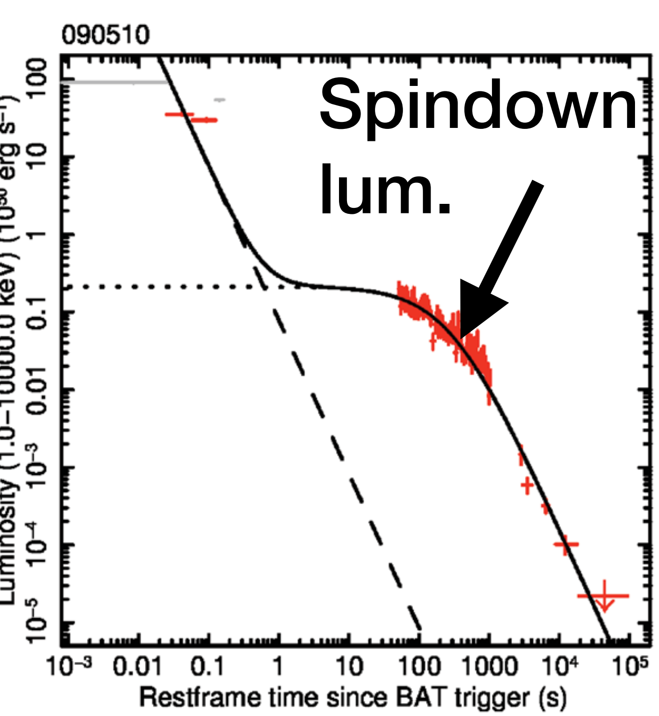
First evidence for magnetars: the X-ray plateau

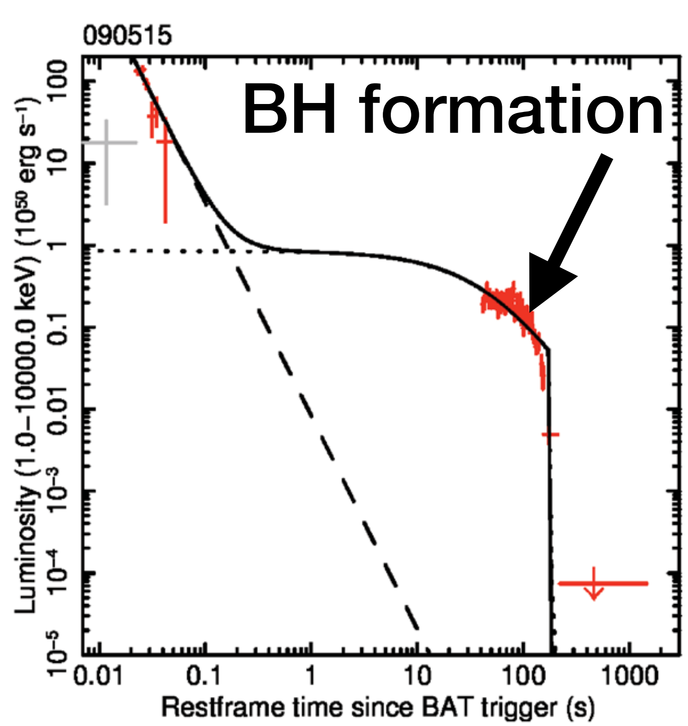


- **External plateau**: continuous energy injection into the forward shock

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

Dall'Osso et al. 2011



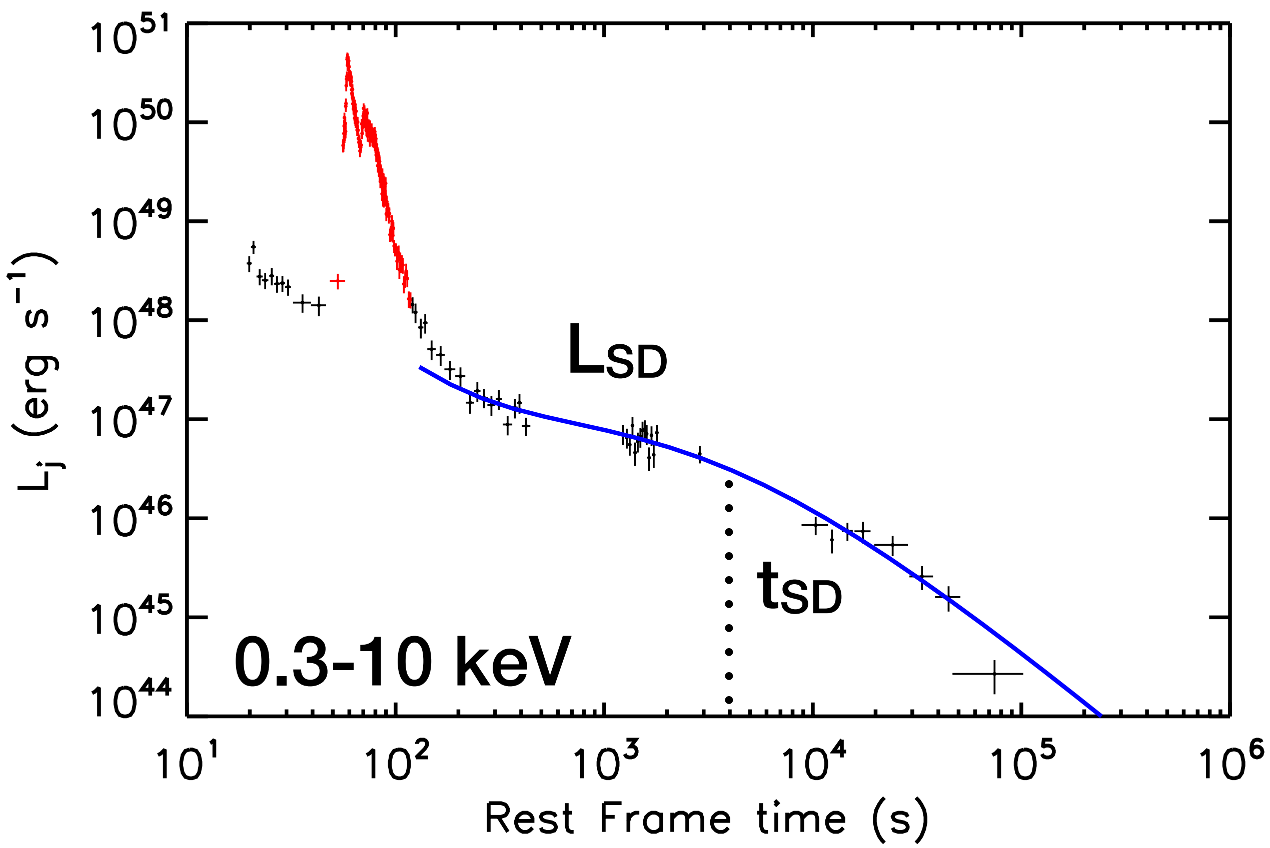


Rowlinson et al. 2013

- **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

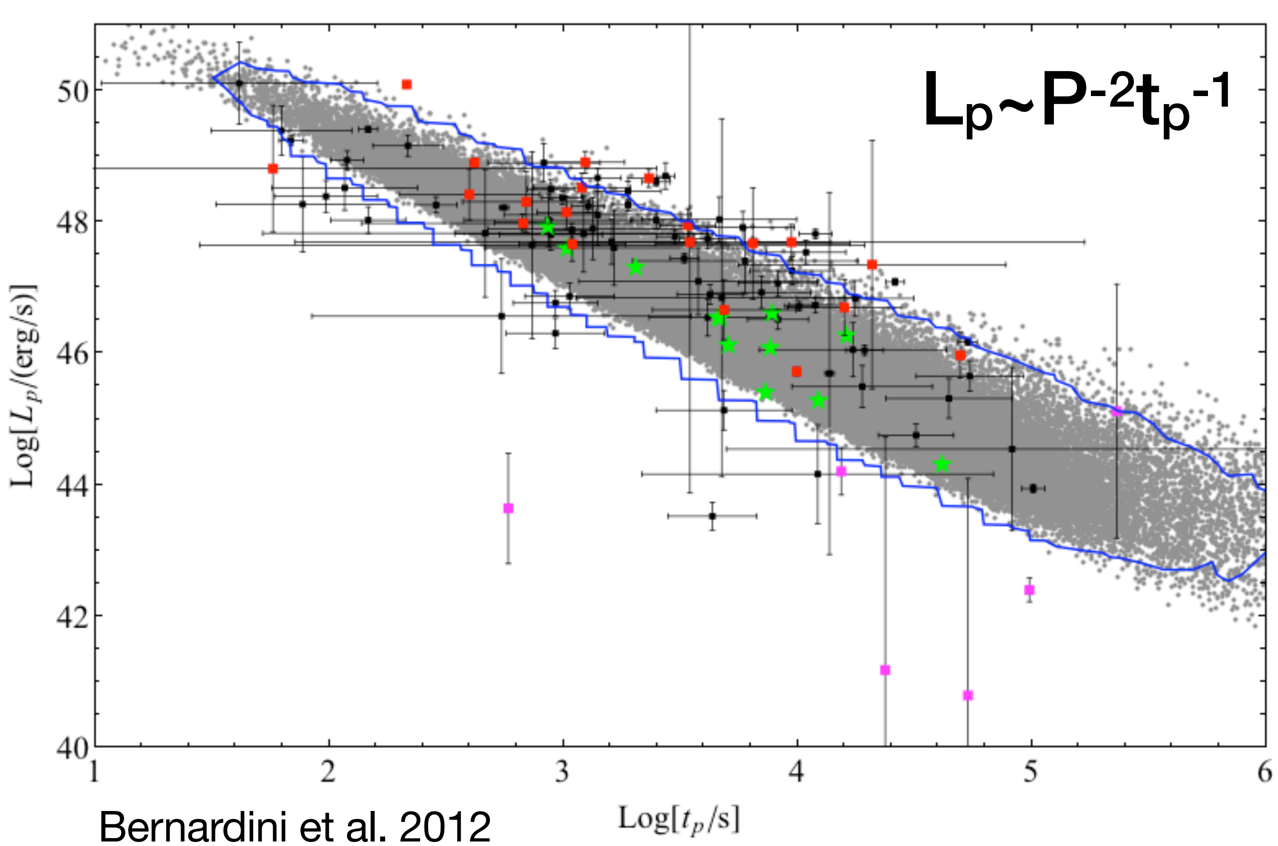


$$L_{\rm sd} = 10^{49} B_{15}^2\, P_{-3}^{-4}\, {\rm erg\, s^{-1}}$$

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

➡ **B~10^{15} G**
P~1 ms

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



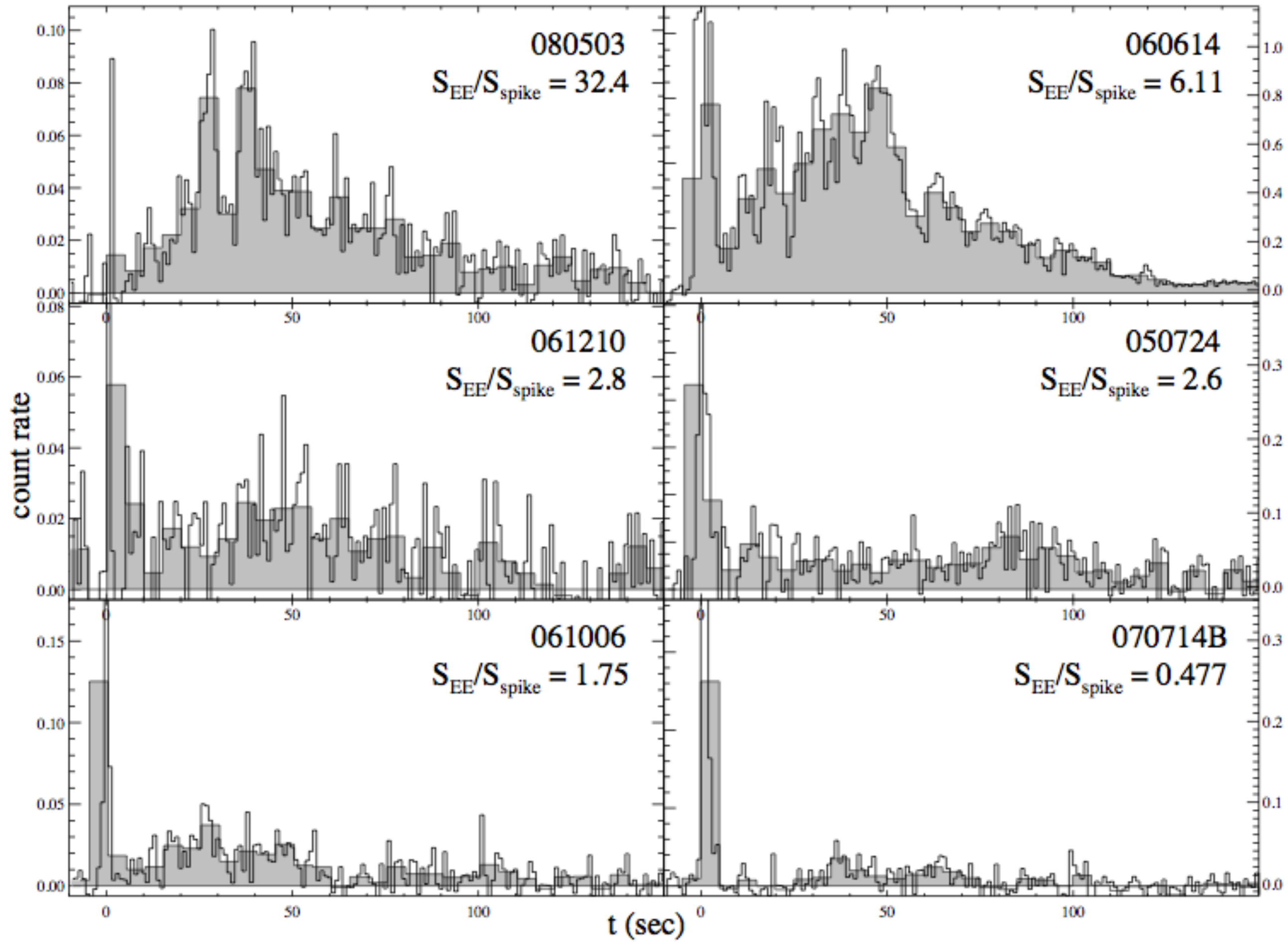
Bernardini et al. 2012

➡ **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.

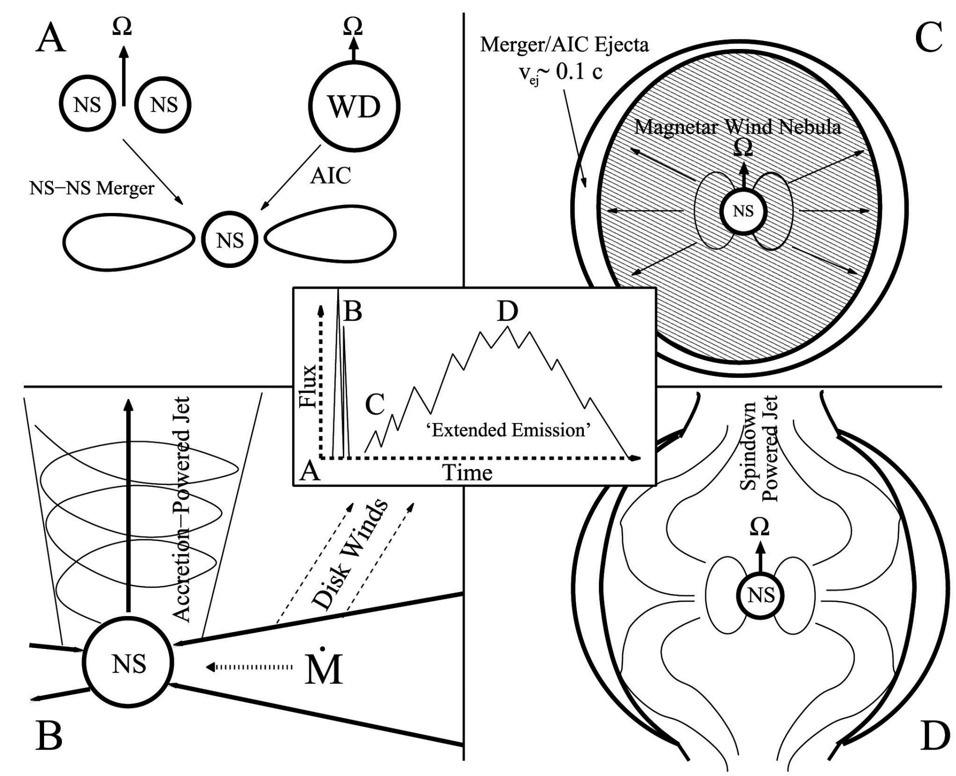
Extended Emission in SGRBs



~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:

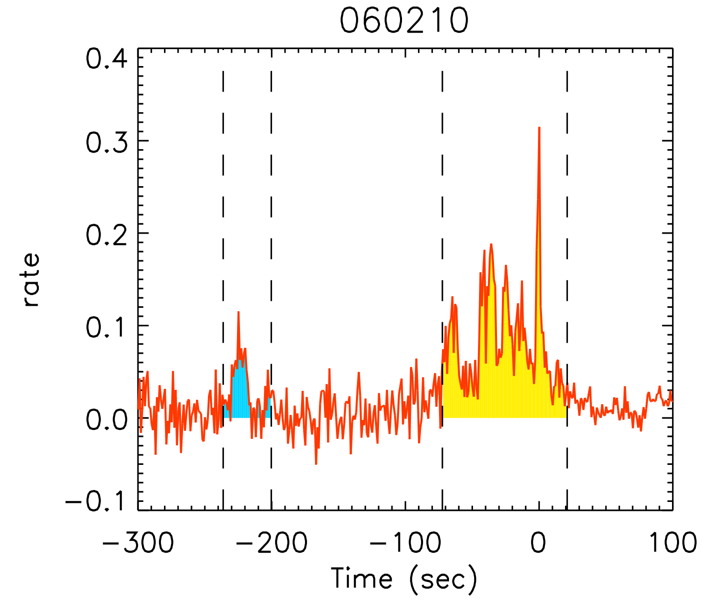
- **EE** + **X-ray plateau**: rotational powered wind (Metzger et al. 2008)
- **EE**: propeller mechanism (material ejected by centrifugal forces) + **X-ray plateau**: rotational powered wind (Gompertz et al. 2014)



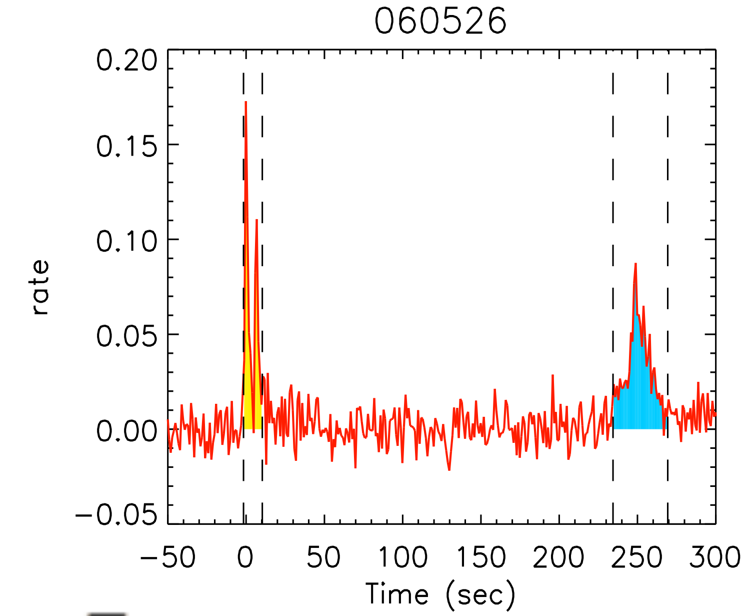
Gompertz et al. 2014

The GRB prompt emission activity

Precursors



Post-cursors



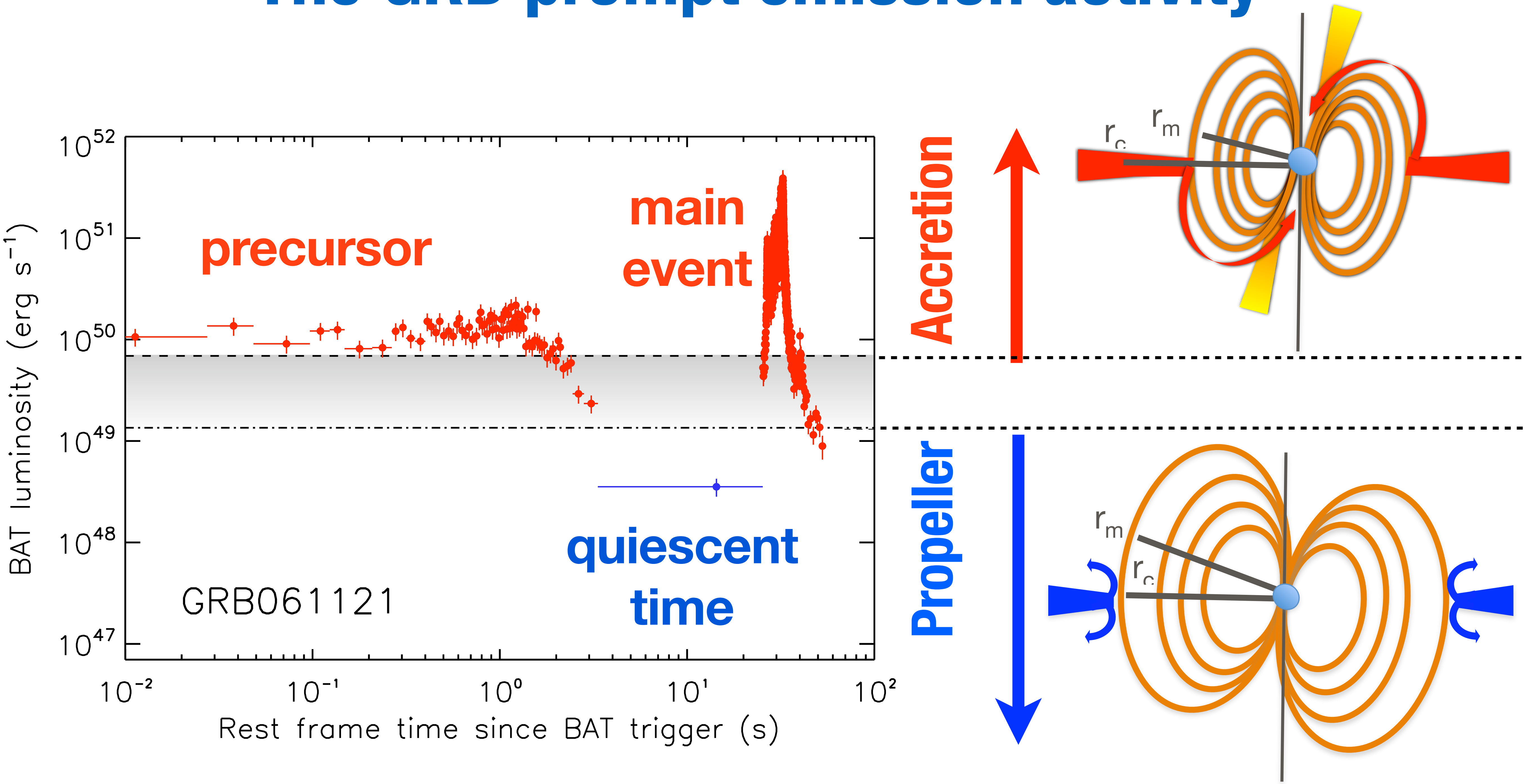
intermittent prompt emission activity

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 GRB prompt emission activity

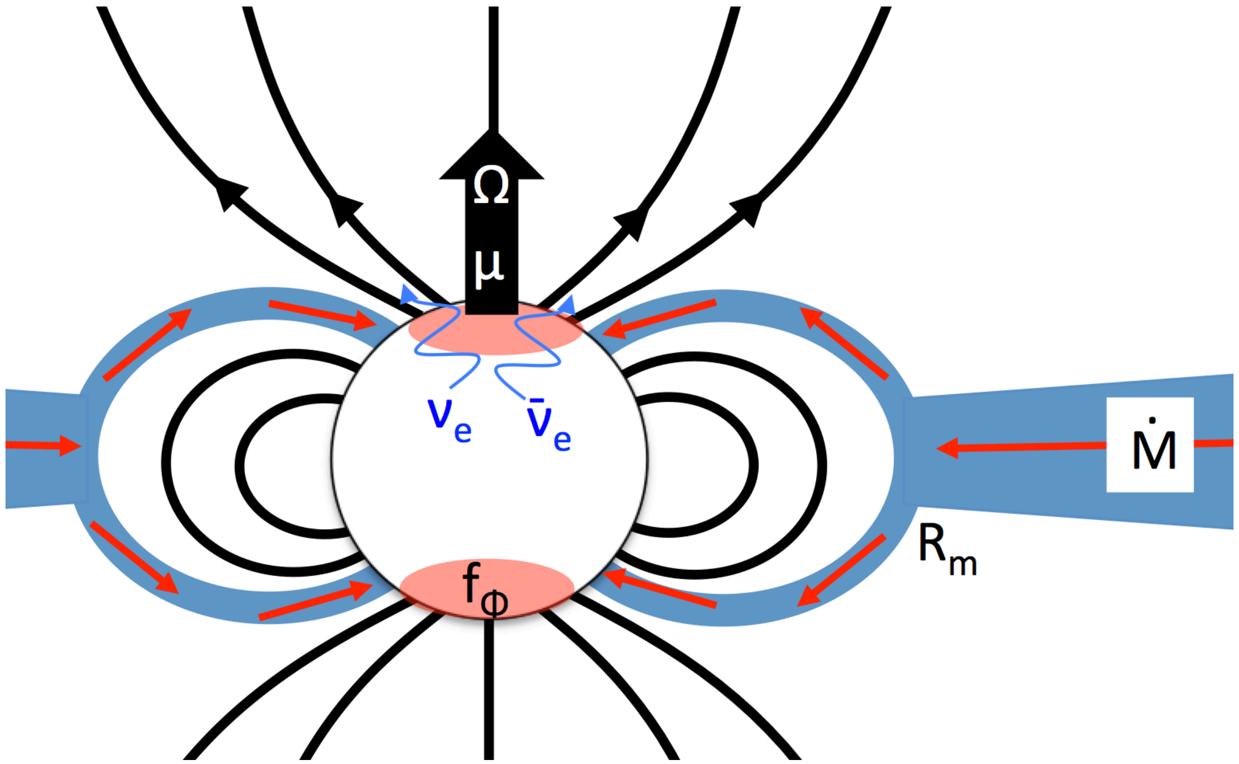


$$L_{\rm min} = 4 \times 10^{50} B_{15}^2 \, P_{-3}^{-7/3} \, {\rm erg\,s^{-1}}$$

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

⇦ **B~10^{15} G**
P~1 ms

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**

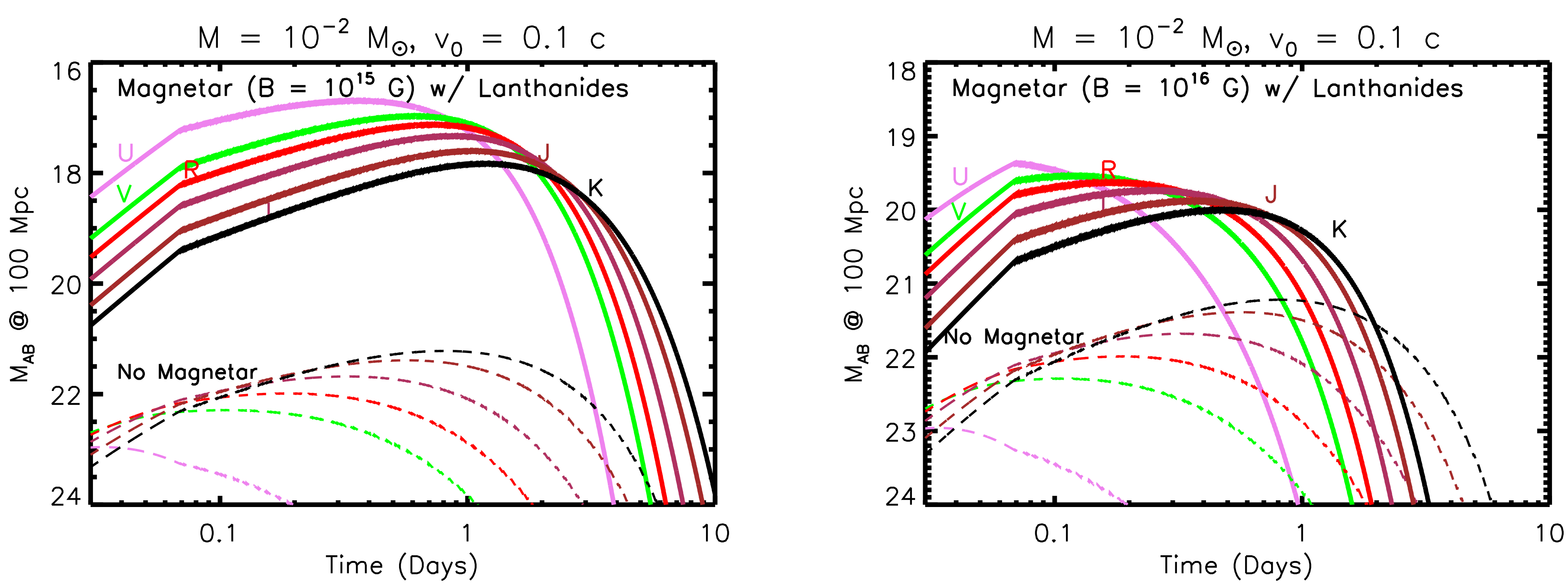
Effects of **accretion**:

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

- **The kilonova emission associated to SGRBs**

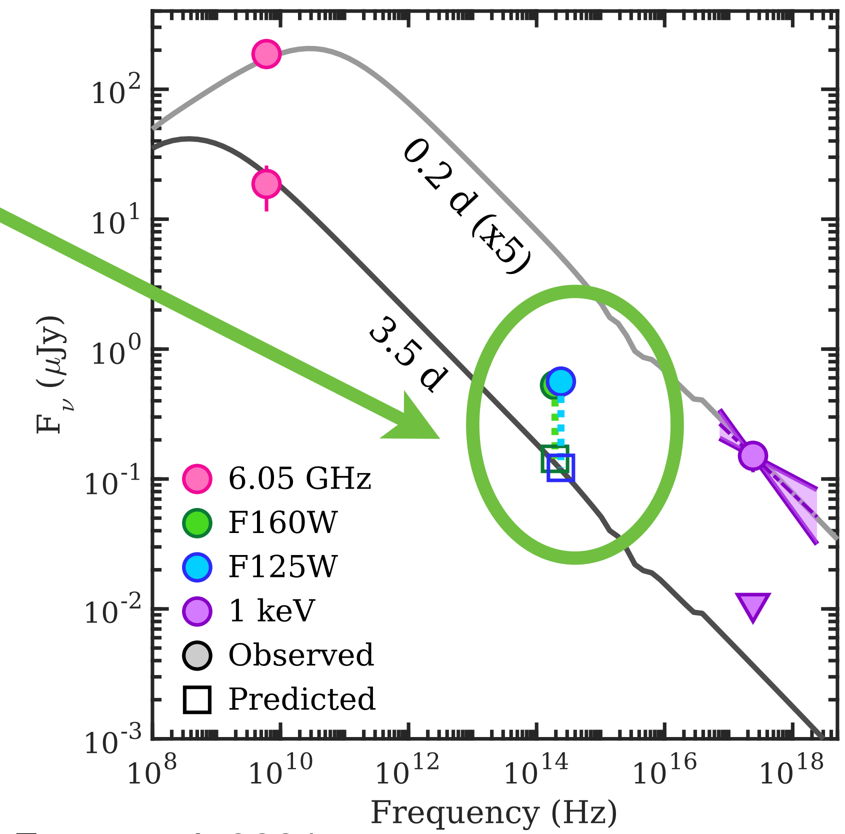


Metzger 2019

The magnetar-boosted Kilonova

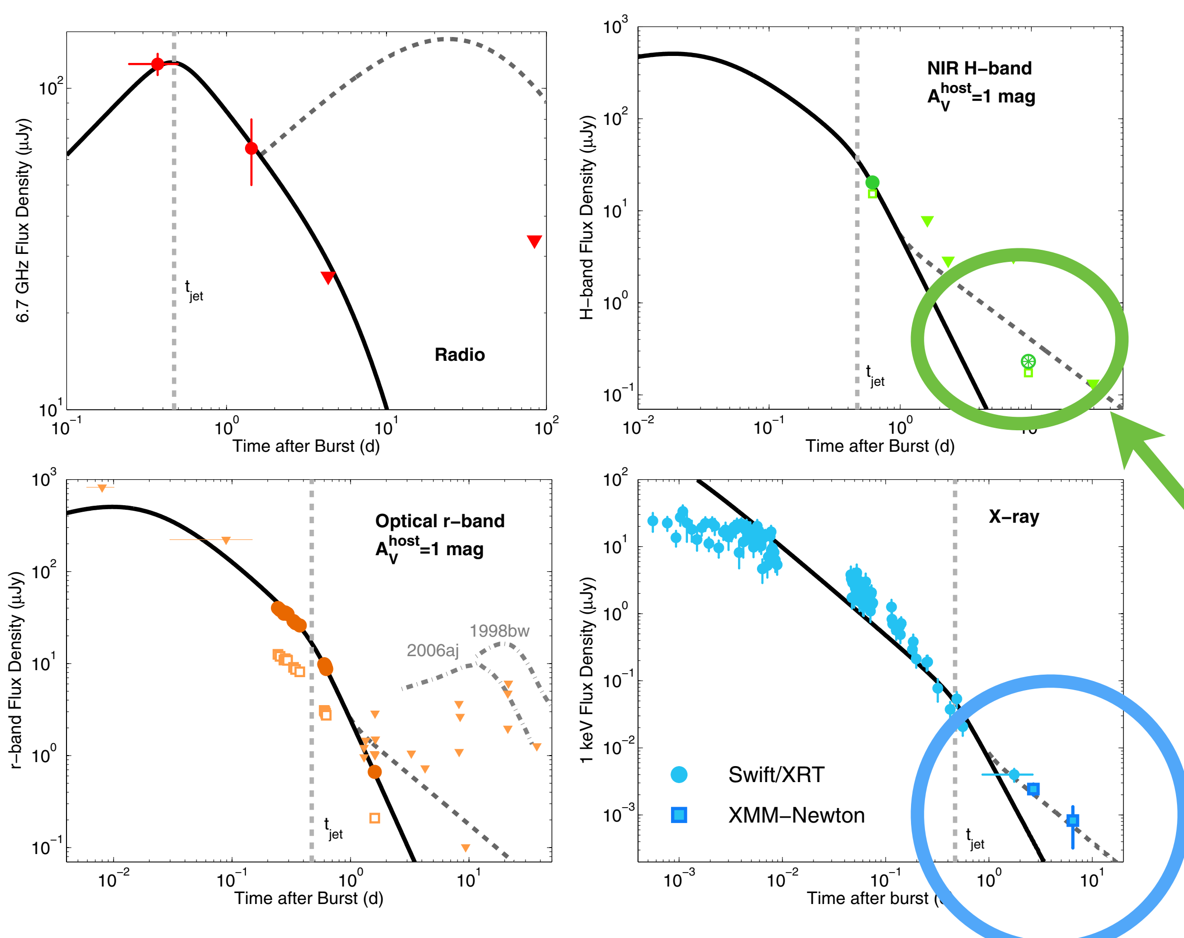
- The magnetar can provide an additional source of heating in the kilonova
- Magnetar boosting claimed in the **kilonova** associated to **GRB200522A** (Fong et al., 2021, see however O'Connor et al., 2021)
- Imprint of the magnetar in three other SGRBs and their associated kilonovae (Gao et al., 2017)

GRB200522A



Fong et al. 2021

GRB130603B



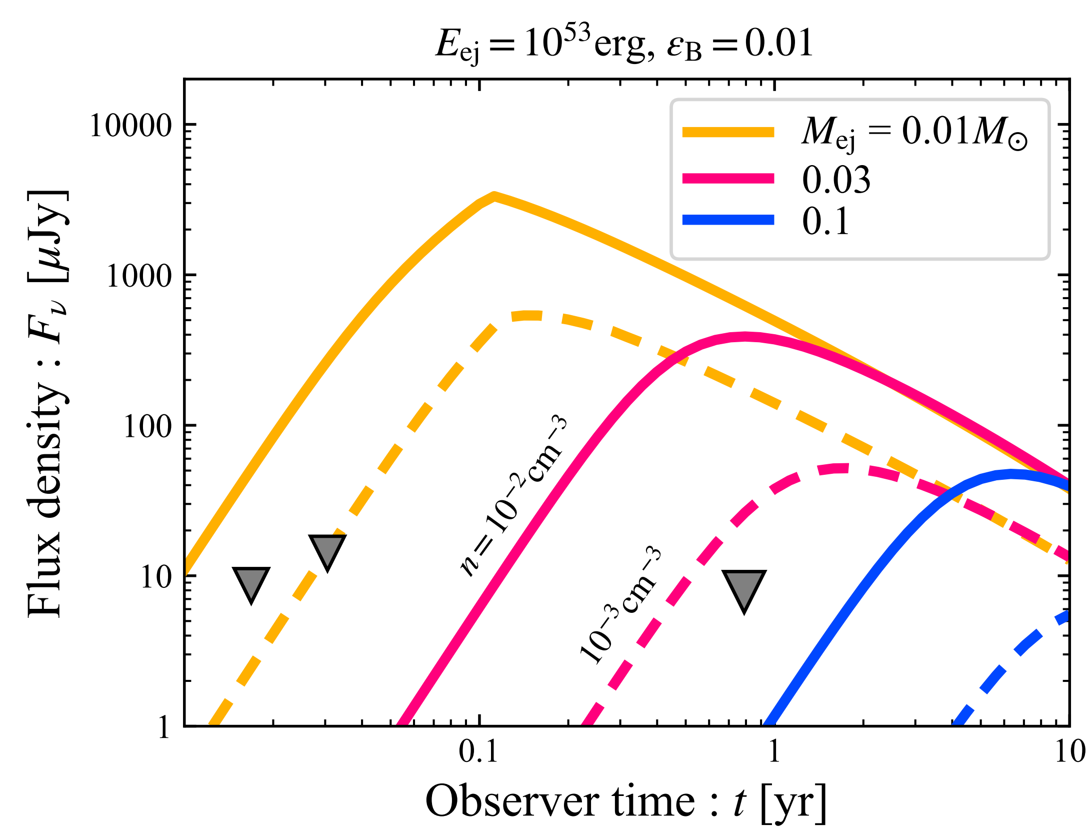
Fong et al. 2014

- 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. 2018)
     - 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:**
     - Luminous radio afterglow expected when the KN ejecta energized by the magnetar interacts with the surrounding medium (Nakar & Piran, 2011). Radio upper limits rule out very energetic merger ejecta, disfavoring the presence of a stable magnetar (Ricci et al., 2021, Bruni et al. 2022)

GRB200522A



Bruni et al., 2022

Can magnetars power all GRBs?

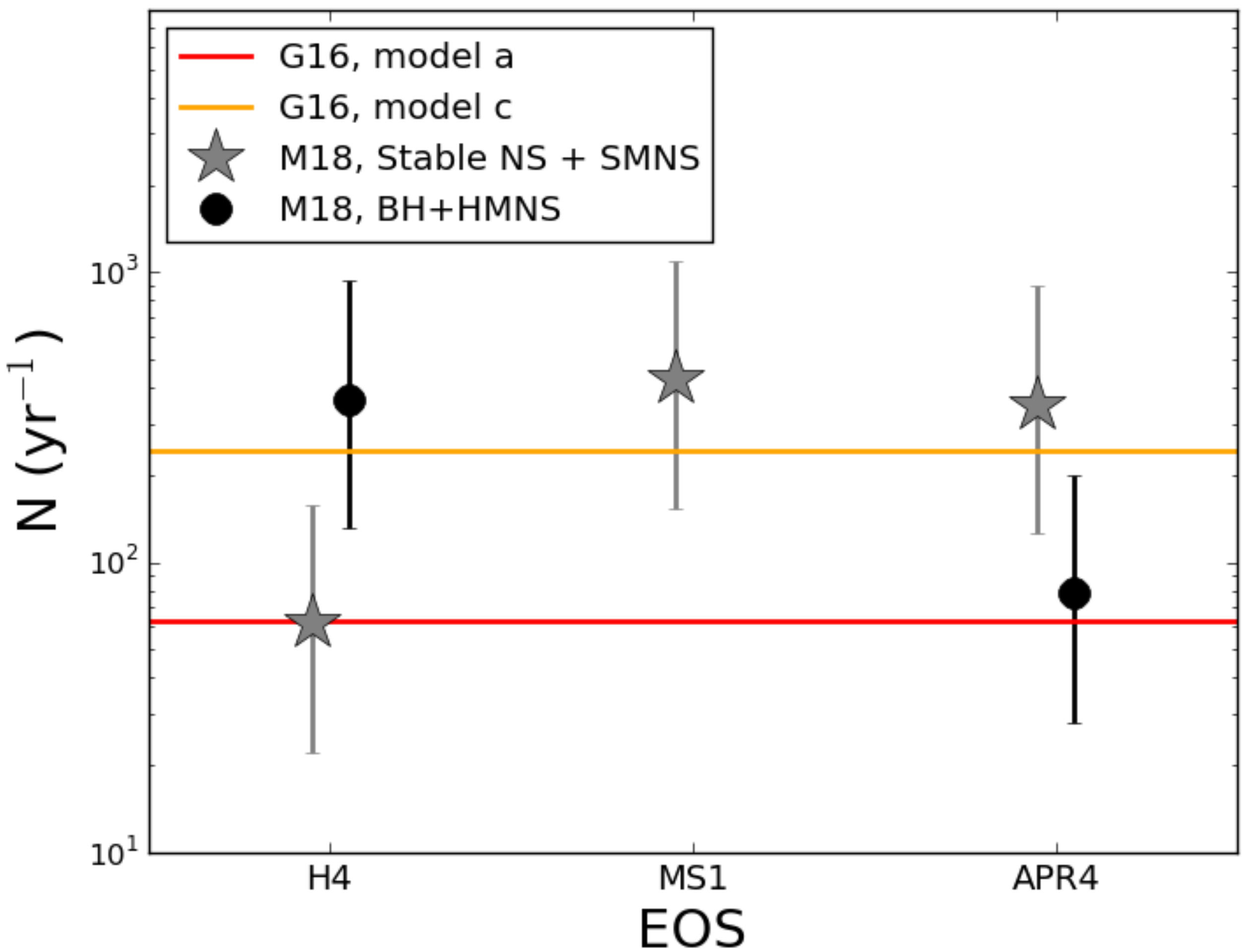
3. **Difficult for magnetars to launch ultra-relativistic jets**
   (e.g. Ciolfi, 2020, see however Uzdensky & MacFadyen 2007 for LGRBs)

4. **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

5. 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 theoretically predicted cosmic BNS merger rate density (Mapelli & Giacobbo 2018) 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 (Ghirlanda et al. 2016)

➡ 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)

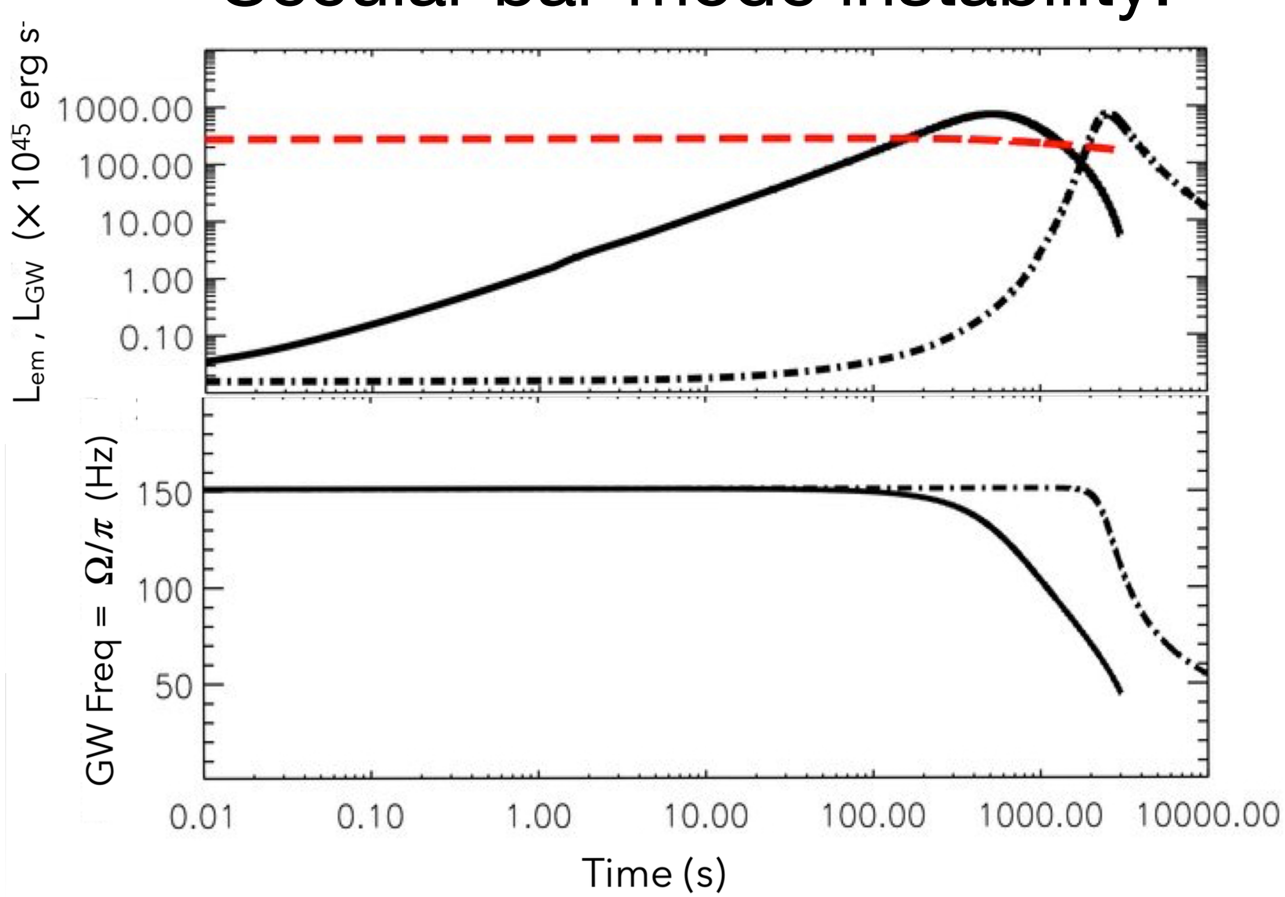
No final proof of the nature of the GRB central engine, however rapid collapse to a BH is the most probable scenario

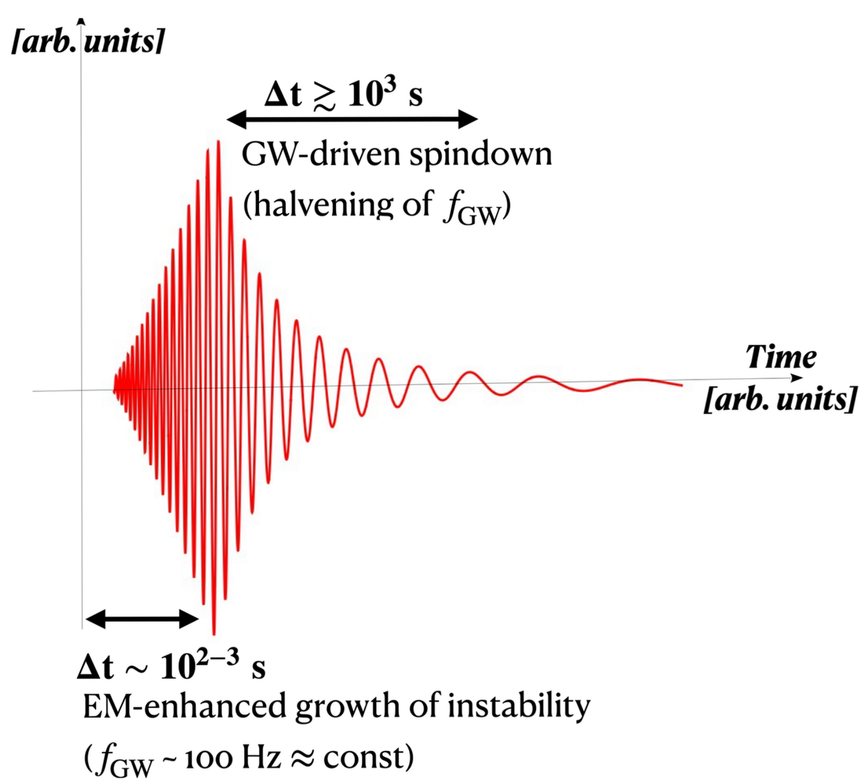
Direct detection of GWs from the magnetar

- 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:



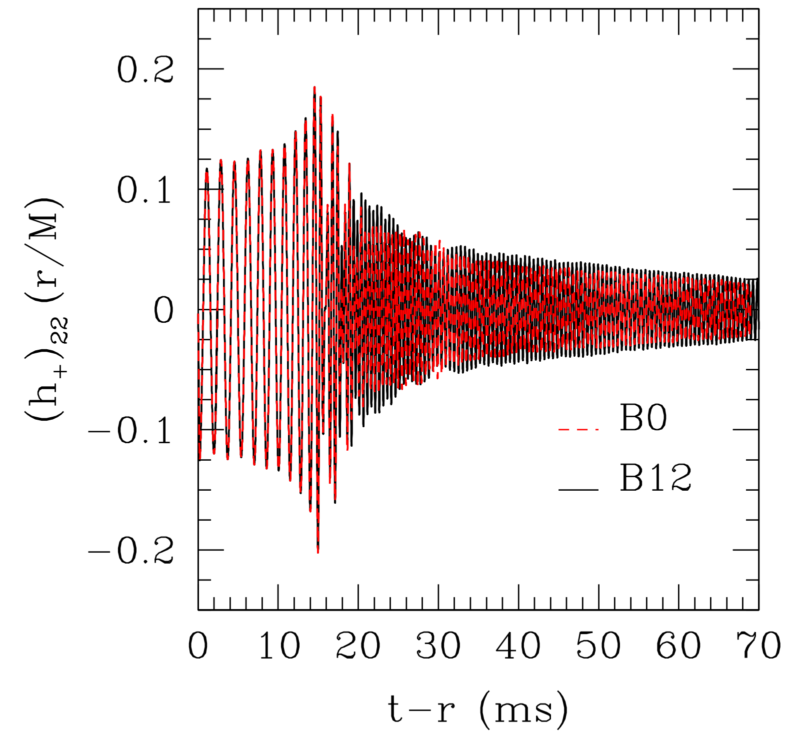


Dall'Osso & Stella 2021, adapted from Corsi & Meszaros, 2009

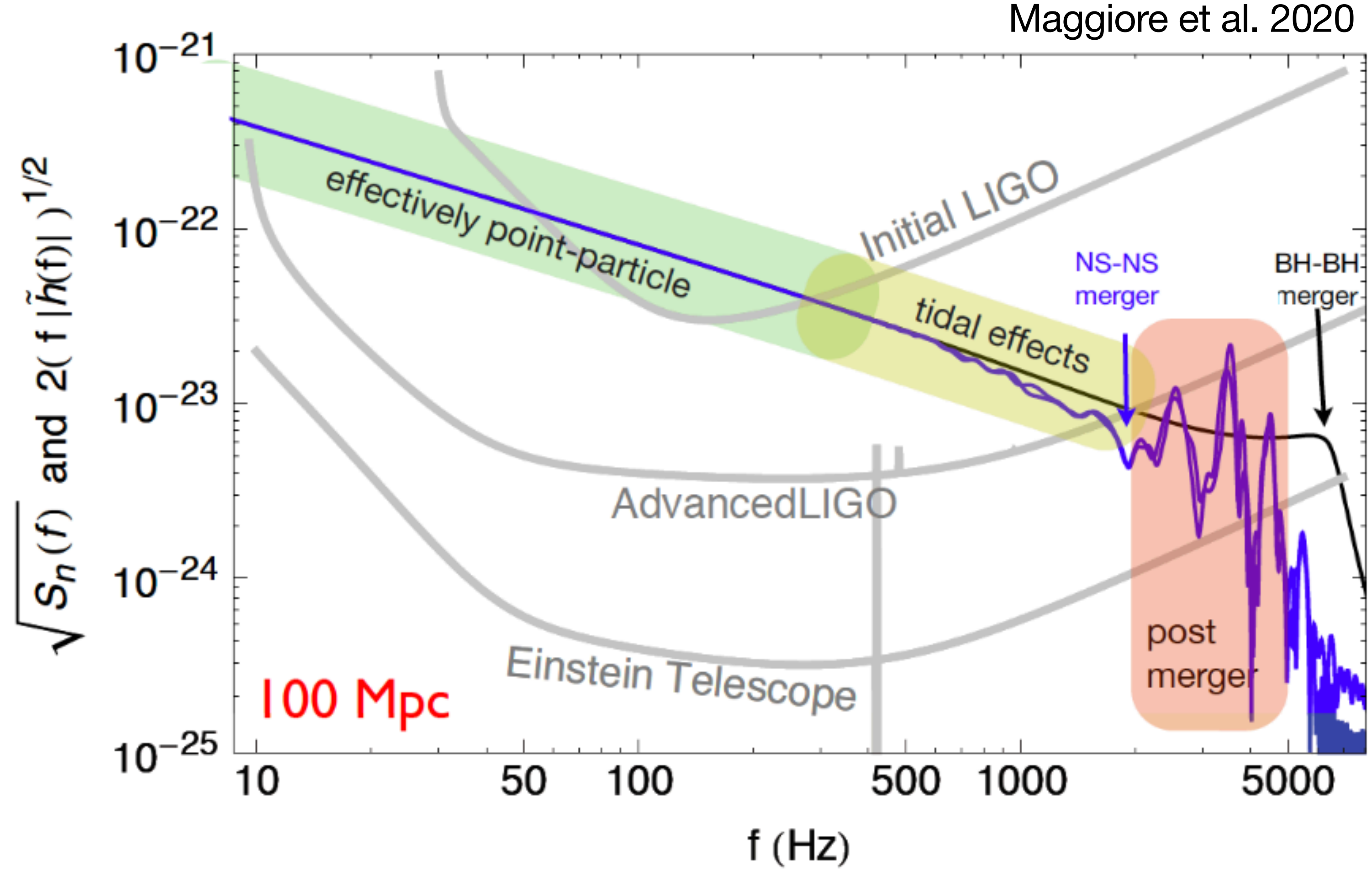
Direct detection of GWs from the magnetar

- 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; 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)**

Time-domain Astronomy with SVOM

Maria Grazia Bernardini

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Laboratoire Univers et Particules de Montpellier (LUPM)

on behalf of the SVOM consortium

High redshift Gamma-Ray-Bursts in the JWST era, Sexten (BZ), January 9-13, 2023

The SVOM consortium

China (PI J.Wei)

- SECM Shanghai
- NSSC Beijing
- NAOC Beijing
- IHEP Beijing
- GuanXi University

Mexico

- UNAM (Colibrì)

UK

- University of Leicester (MXT)

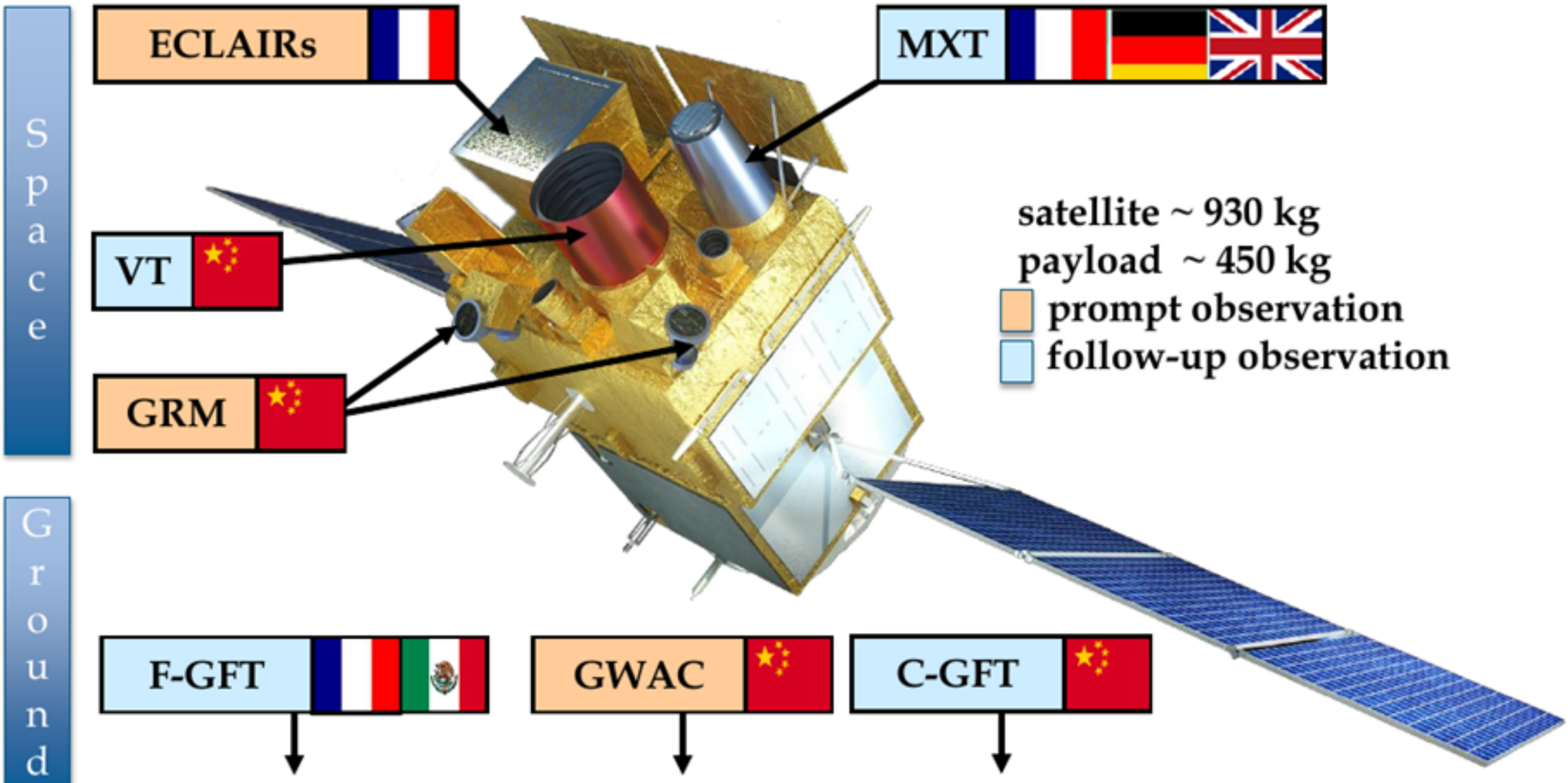
Germany

- MPE Garching (MXT)
- IAAT Tübingen (MXT)

France (PI B.Cordier)

- CNES Toulouse
- APC Paris
- CEA Saclay
- CPPM Marseille
- GEPI Meudon
- IAP Paris
- ICJLab Orsay
- IRAP Toulouse
- LAM Marseille
- LUPM Montpellier
- ObAS Strasbourg

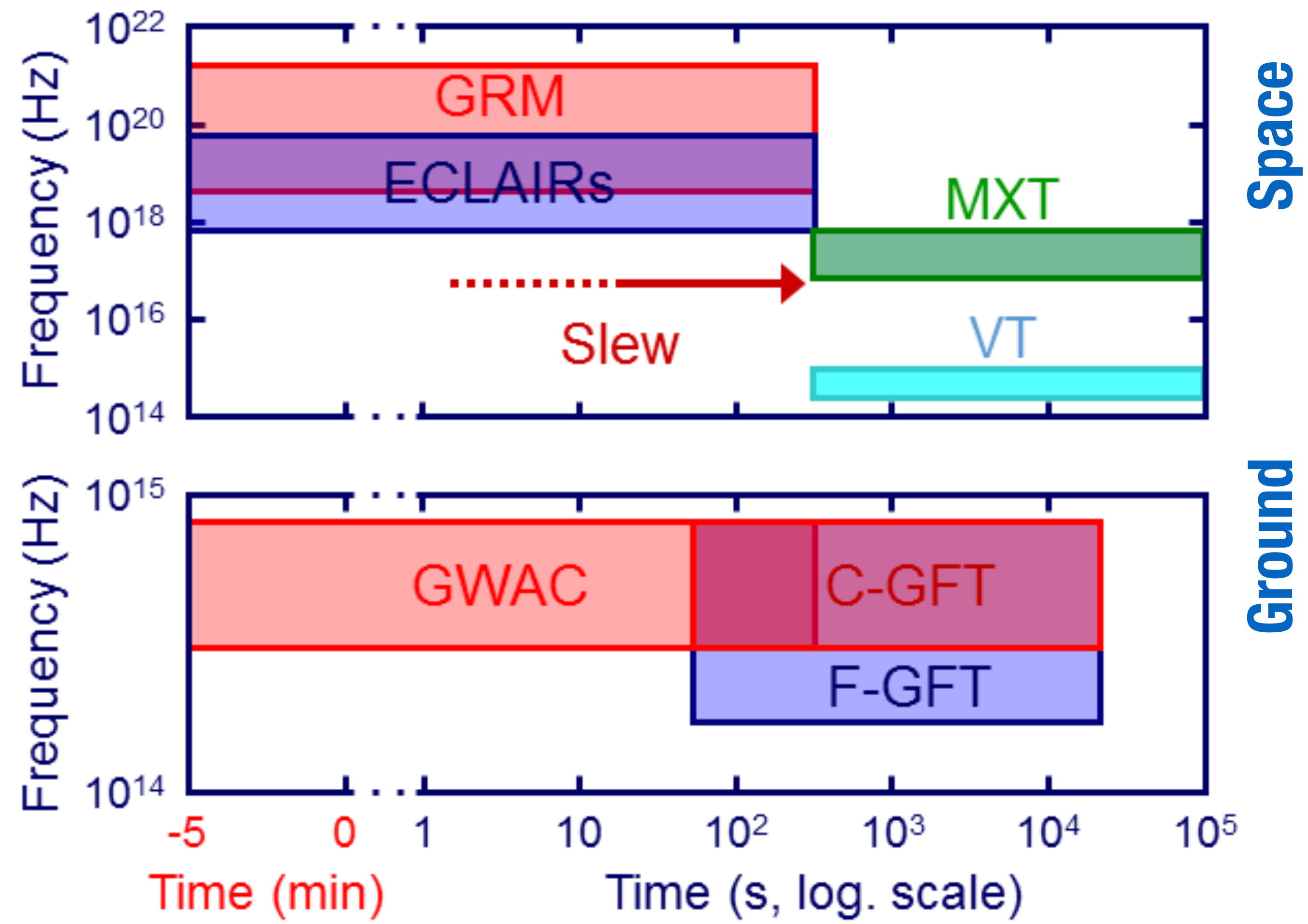
The "Space-based multi-band astronomical Variable Objects Monitor" (SVOM) is a Sino-French mission dedicated to GRBs and transient sources to be launched late-2023, duration 3+2 years



The Core program

Core program: GRBs and transients discovered by SVOM, 25% of time, with the highest priority

- **Trigger and locate GRBs,** alerts distributed in nearly **real-time**
- Slewing capabilities to have accurate location in ~5 min
  ➡ **Synergy with other space and ground based facilities**
- Broadband characterization of the prompt emission
- Quick discovery and long-term follow-up of the afterglow



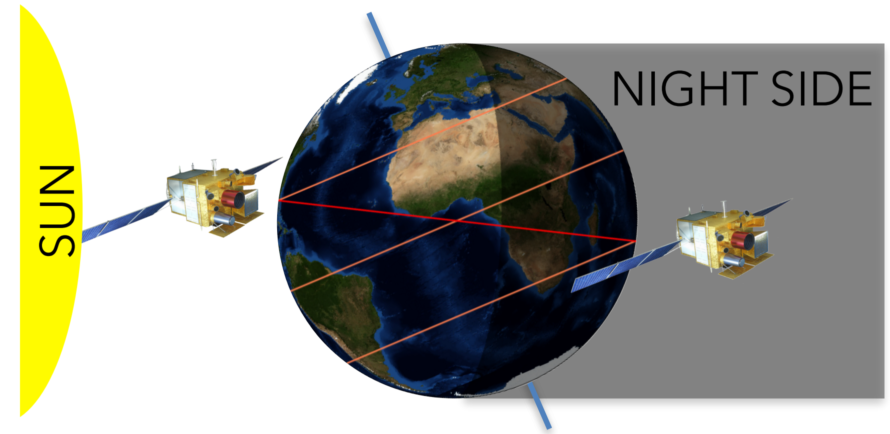
- Synergy among **7 instruments in space and on ground** for a complete monitoring of GRBs and high-energy transients **over 7 decades in energy** and **from the trigger up to the late afterglow**
- Rapid alert dissemination and optimal attitude law for ground-based follow-up to **favor redshift measurement for a large fraction of GRBs**

Orbit, pointing strategy and alerts dissemination

- Low Earth orbit (625 km, 96 min), 30° inclination
- **Nearly anti-solar pointing**
- Avoidance of the galactic plane and bright sources as Sco X-1
- **Alerts transmitted to a network of 40 antennas.** Goal: 65% of alerts within 30s

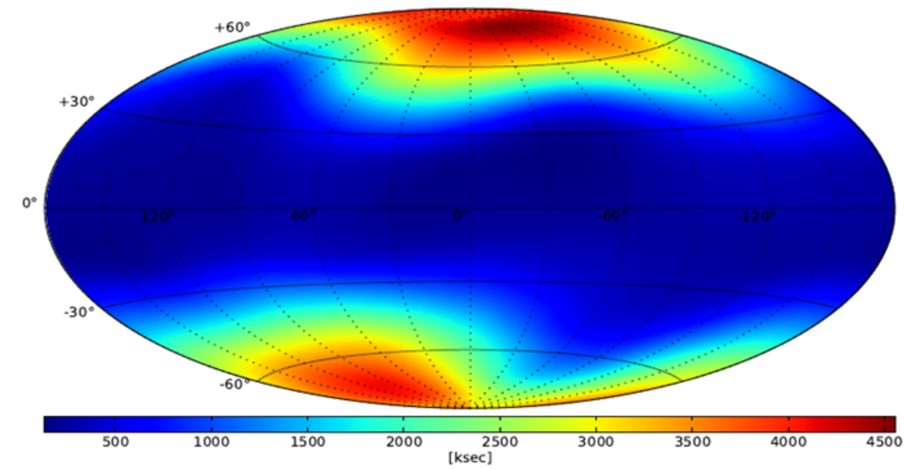
➡Favorable conditions for **early follow-up from other facilities**, especially large ground-based telescopes for **redshift measurement (2/3 of cases)**

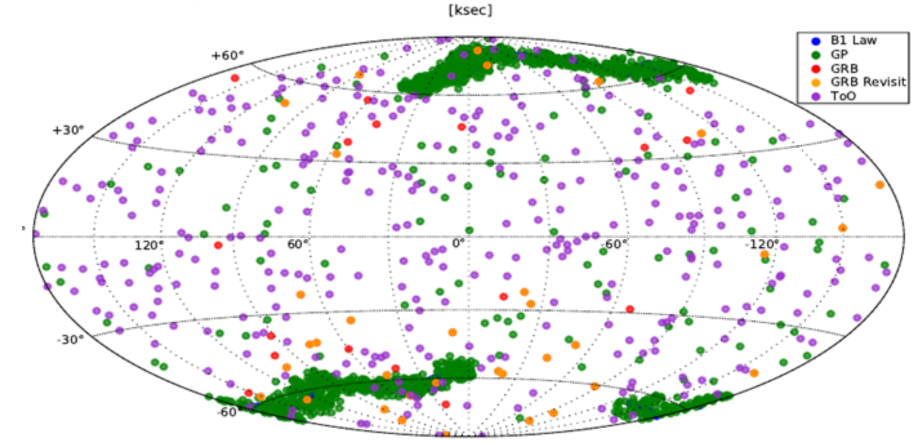
➡**Earth in the fov**: 65% duty cycle for ECLAIRs, 50% for MXT and VT



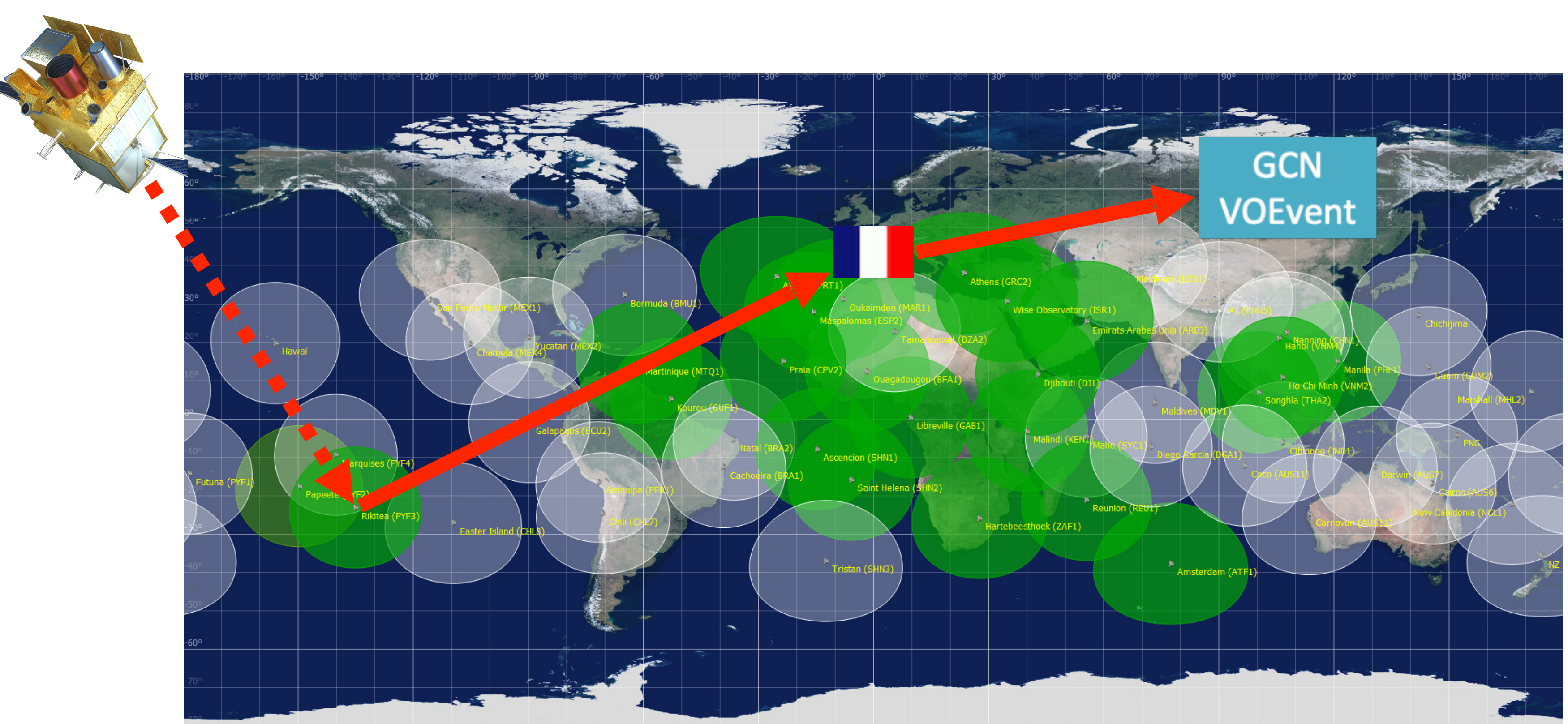
ECLAIRs 1 yr exposure map:

- **4 Ms on the galactic poles**
- **500 ks on the galactic plane**



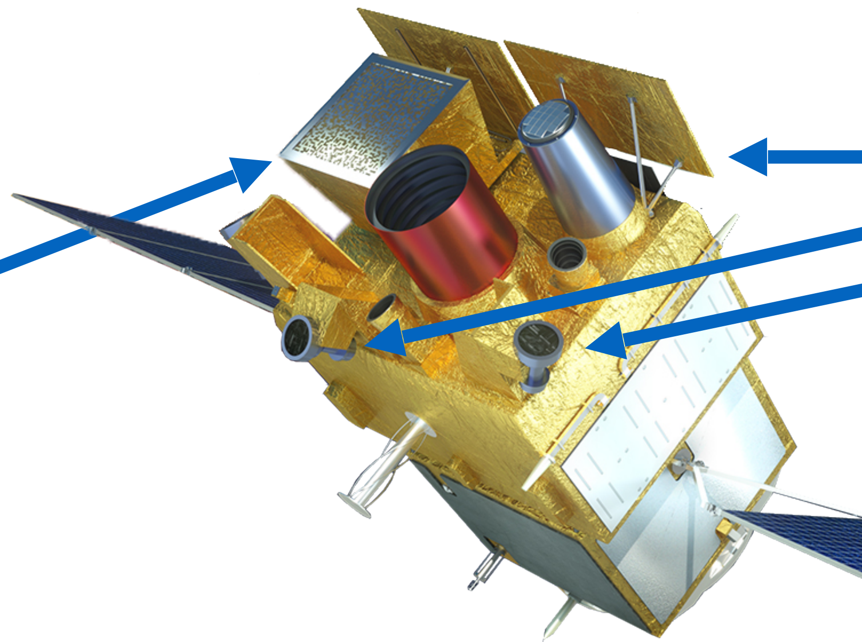


MXT and VT pointings (1yr scenario, including 65 GRBs and 1 ToO/day)



The GRB prompt emission

shutterstock.com • 436735537



GRM (3 GRDs):

- **15 keV - 5 MeV**
- Fov ~ 5.6 sr
- Loc. ~5-10 deg (3 GRDs)
- ~90 GRBs/yr

ECLAIRs:

- **4-120 keV**
- Fov ~ 2 sr
- **Loc. < 12'**
- **42-80 GRBs/yr, including 3-4 GRBs/yr at z>5**

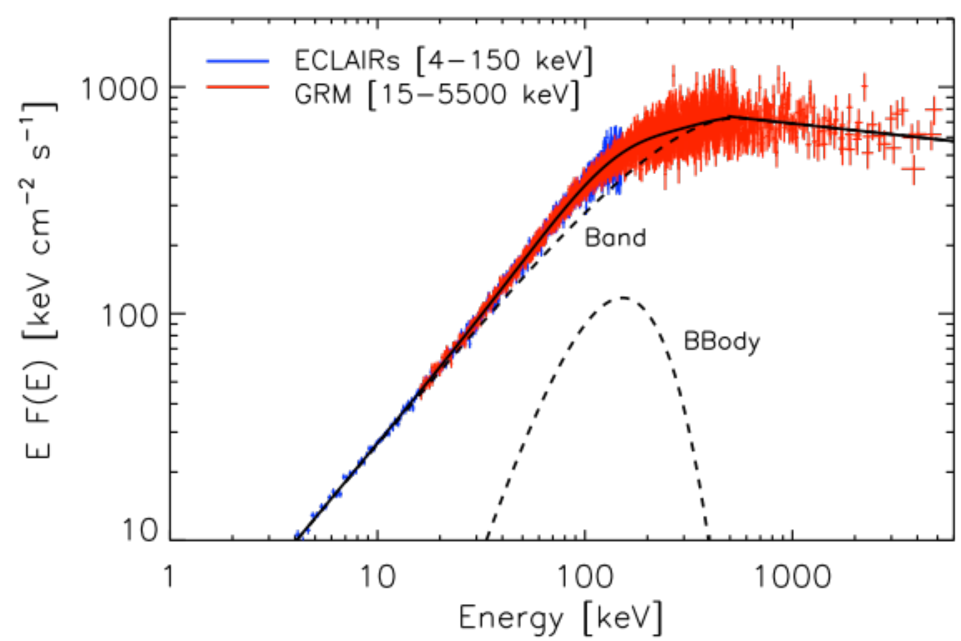
\+

GWAC:

- 2x5400 deg^2 (half of ECLAIRs fov)
- 500-800 nm
- m_{lim} ~ 16-17 (10s exposure)

- ECLAIRs sensitive to **all classes of long GRBs**
- **Sensitivity to short GRBs improved** by combining ECLAIRs+GRM

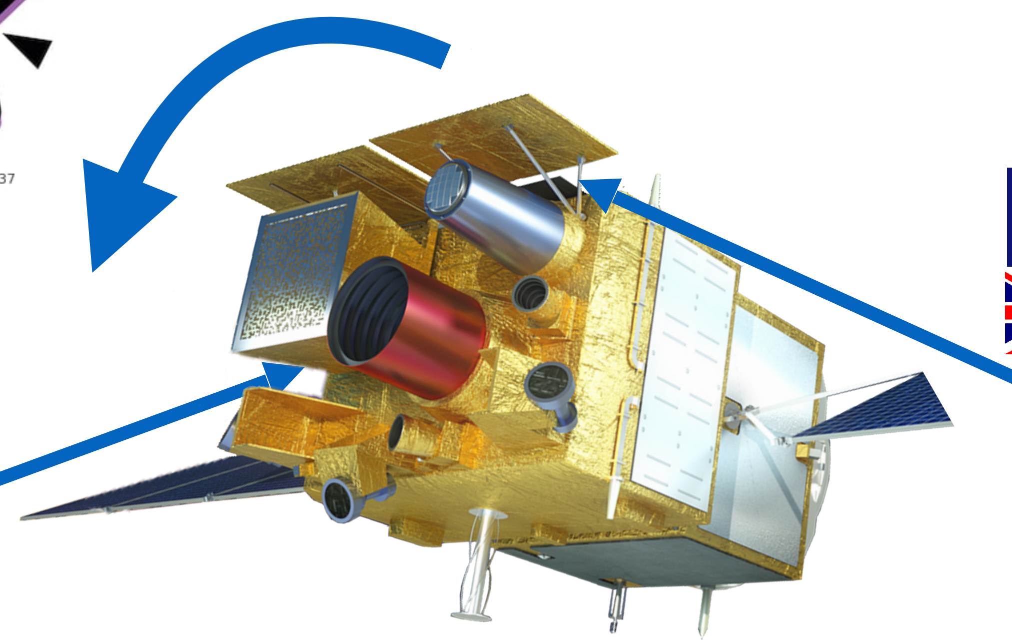
Simulation of the multi-component spectrum of GRB 100724B

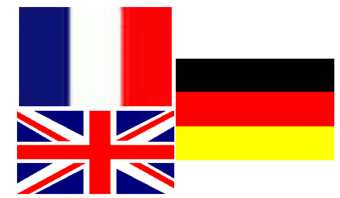


(Bernardini et al., 2017)

- ECLAIRs+GRM measure the **prompt spectrum over 3 decades in energy**
- GWAC will add a constraint on the **associated prompt optical emission** in a good fraction of cases (16%).

The GRB follow-up

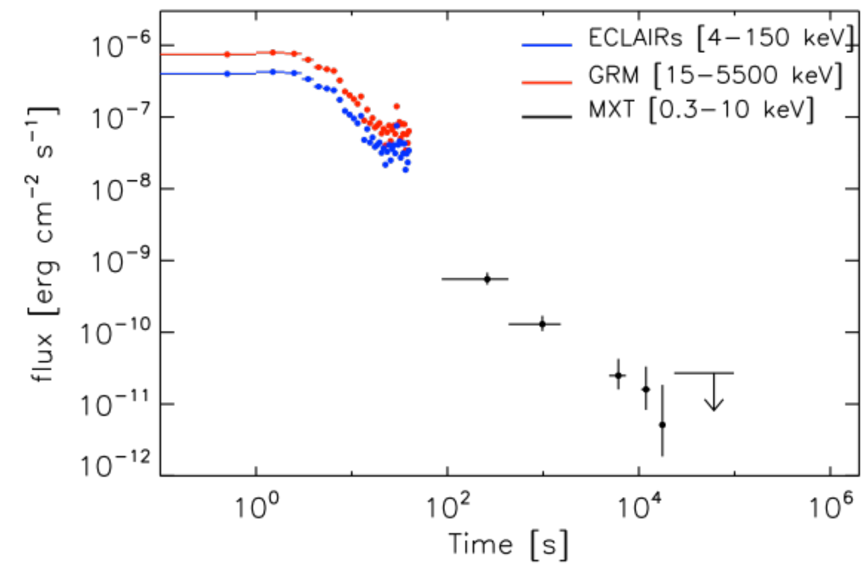




MXT:

- 0.2-10 keV
- 64x64 arcmin^2
- **Loc. <13"** within 5 min after the trigger for 50% of GRBs
- slew request: **~72 GRB/yr**

Simulation of GRB 091020



(Wei, Cordier et al., arXiv:1610.06892)

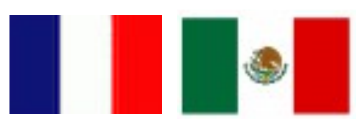
VT:

- 400-1000 nm
- Loc. <1"

\+

GWAC:

- 2x5400 deg^2
- 500-800 nm



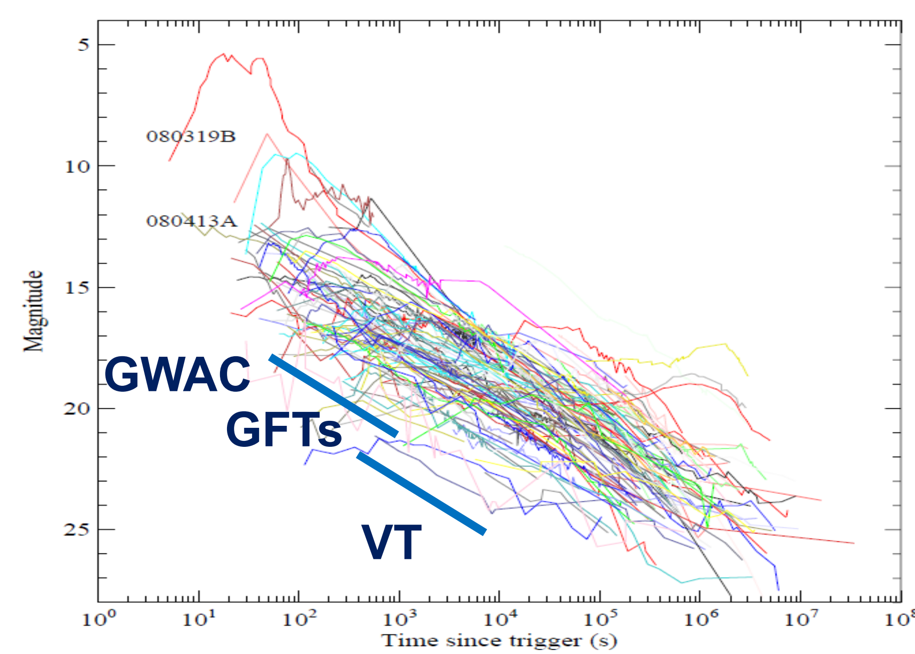
F-GFT (Colibrì):

- 1.3 m
- 400-1700 nm

C-GFT:

- 1.2 m
- 400-950 nm

Optical Light curves of long GRBs



(Wang et al., 2013)

- MXT can **detect and localize the X-ray afterglow** in >90% of GRBs after a slew
- VT + ground segment will **detect, localize and characterize the visible-NIR afterglow**

The SVOM GRB sample

A unique sample of **30-40 GRB/yr** with:
- **prompt emission** over 3 decades (+ optical flux/limit: 16%)
- X-ray and V/NIR **afterglow**
- **redshift**

	Swift	Fermi	SVOM
Prompt	Poor	Excellent 8 keV -100 GeV	**Very Good 4 keV - 5 MeV**
Afterglow	Excellent	> 100 MeV for LAT GRBs	**Excellent**
Redshift	~1/3	Low fraction	**~2/3**

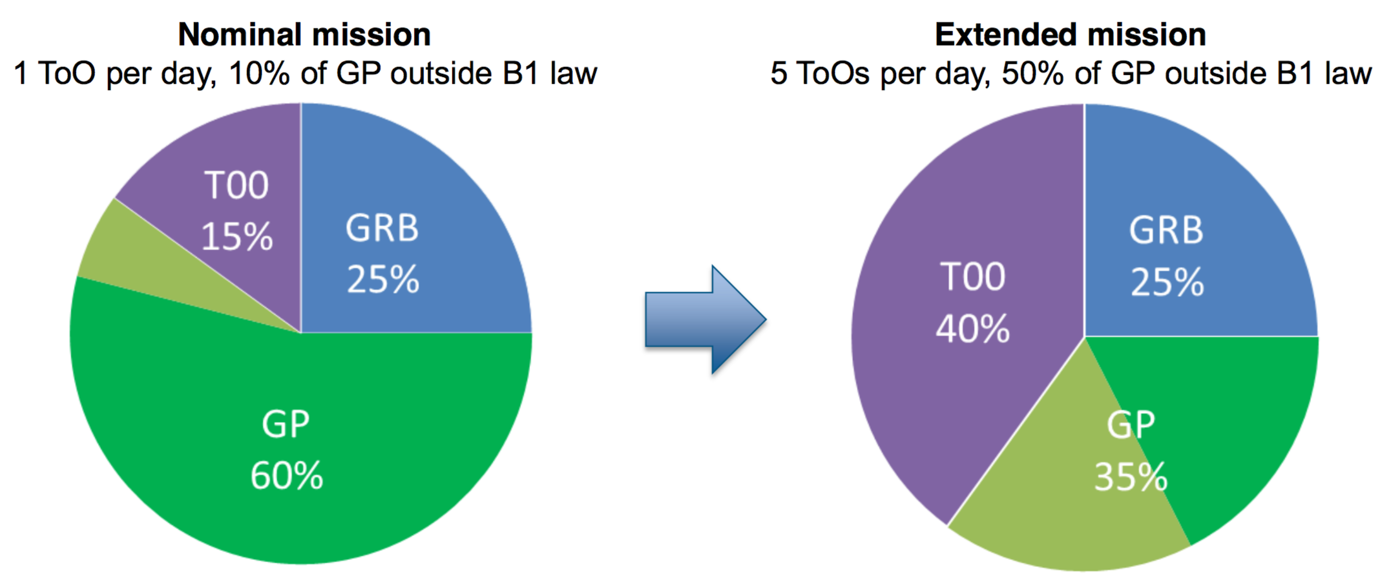
- **Physical mechanisms at work in GRBs**
  - Nature of GRB progenitors and central engines
  - Acceleration & composition of the relativistic ejecta
- **Diversity of GRBs: event continuum following the collapse of a massive star**
  - Low-luminosity GRBs / X-ray rich GRBs / X-ray Flashes and their afterglow
  - GRB/SN connection
- **Short GRBs and the merger model**
  - GW association
- **GRBs as cosmological probes of the early Universe**

SVOM as an open observatory

- **The general program (GP):** Observation proposals being awarded by a TAC (a SVOM co-I needs to be part of your proposal) for astrophysical targets, mostly compliant with the satellite attitude law (form 10% to 50% of time can be spent on low galactic latitude sources). It can include ToOs.

ToO	Latency	Frequency	Duration
ToO-NOM	<48hrs	1-5/day	1 orbit or more
ToO-EX	<12hrs	1/month	7-14 orbits
ToO-MM	<12hrs	1/week	~14 orbits

- **Target of Opportunity (ToO) program:**
  - **ToO-NOM** - nominal ToO which covers the basic needs for efficient transient follow-up alerts (GRB revisit, known source flaring, new transient).
  - **ToO-EX** - exceptional ToO which covers the needs for a fast ToO-NOM in case of an exceptional astrophysical event we want to observe rapidly.
  - **ToO-MM** - ToO-EX dedicated to EM counterpart search in response to a multi-messenger alert (unknown position, tiling of large portion of the sky).



SVOM data policy

- **Core Program:**
  - Real-time VHF scientific products generated under the supervision of the Burst Advocate are public **as soon as they are available** (similar to Fermi or Swift)
  - All the scientific products are public **six month** after the data production

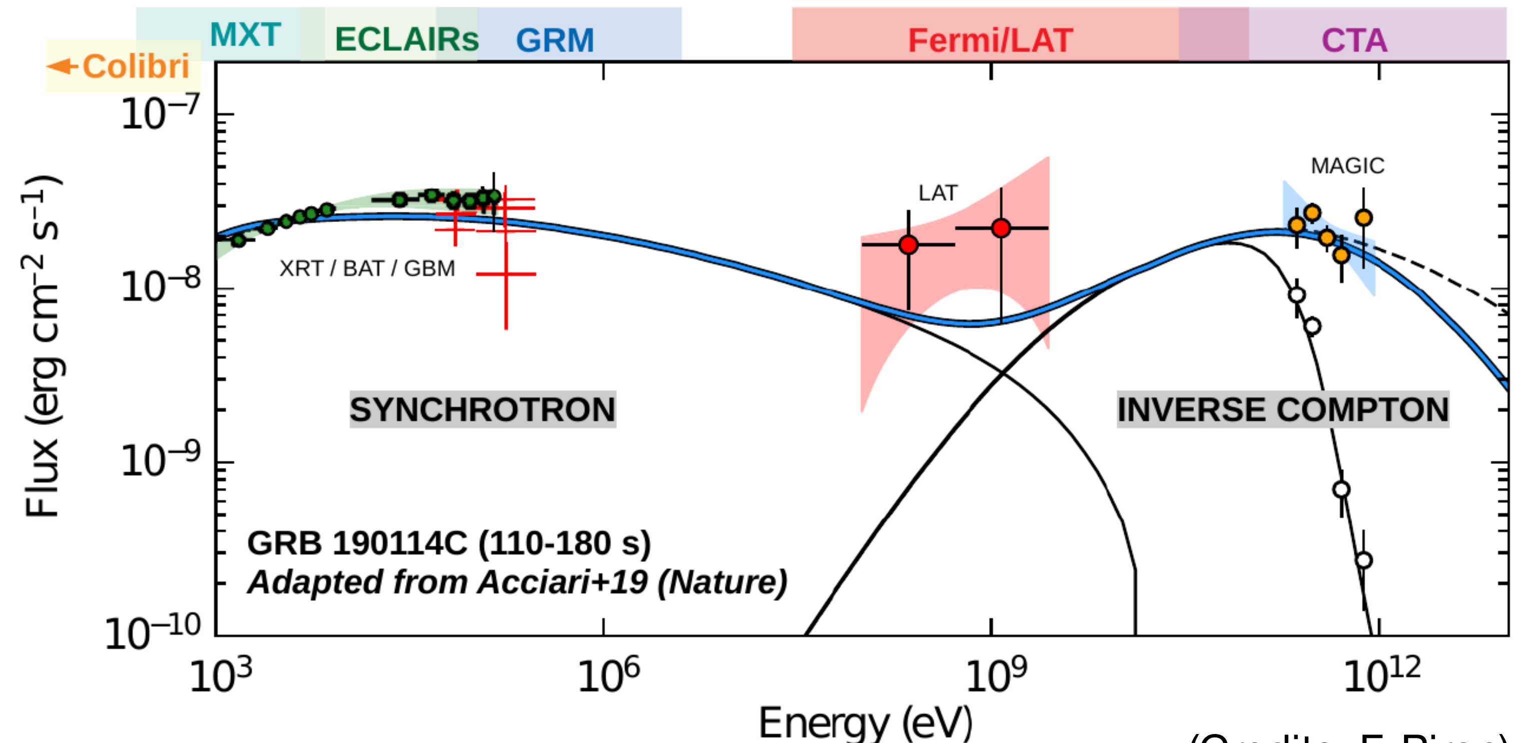
- **General Program:**
  - All the SVOM data will be managed by the Responsible Co-I
  - **One year of proprietary period** before the scientific products become public

- **ToO Program (still under discussion):**
  - **Triggered by SVOM Co-Is**: scientific products relevant to perform follow-up observations will be public as soon as possible. Other scientific products to be released will be decided case by case
  - **Triggered by non SVOM Co-Is**: all the scientific products will be public as soon as they are available

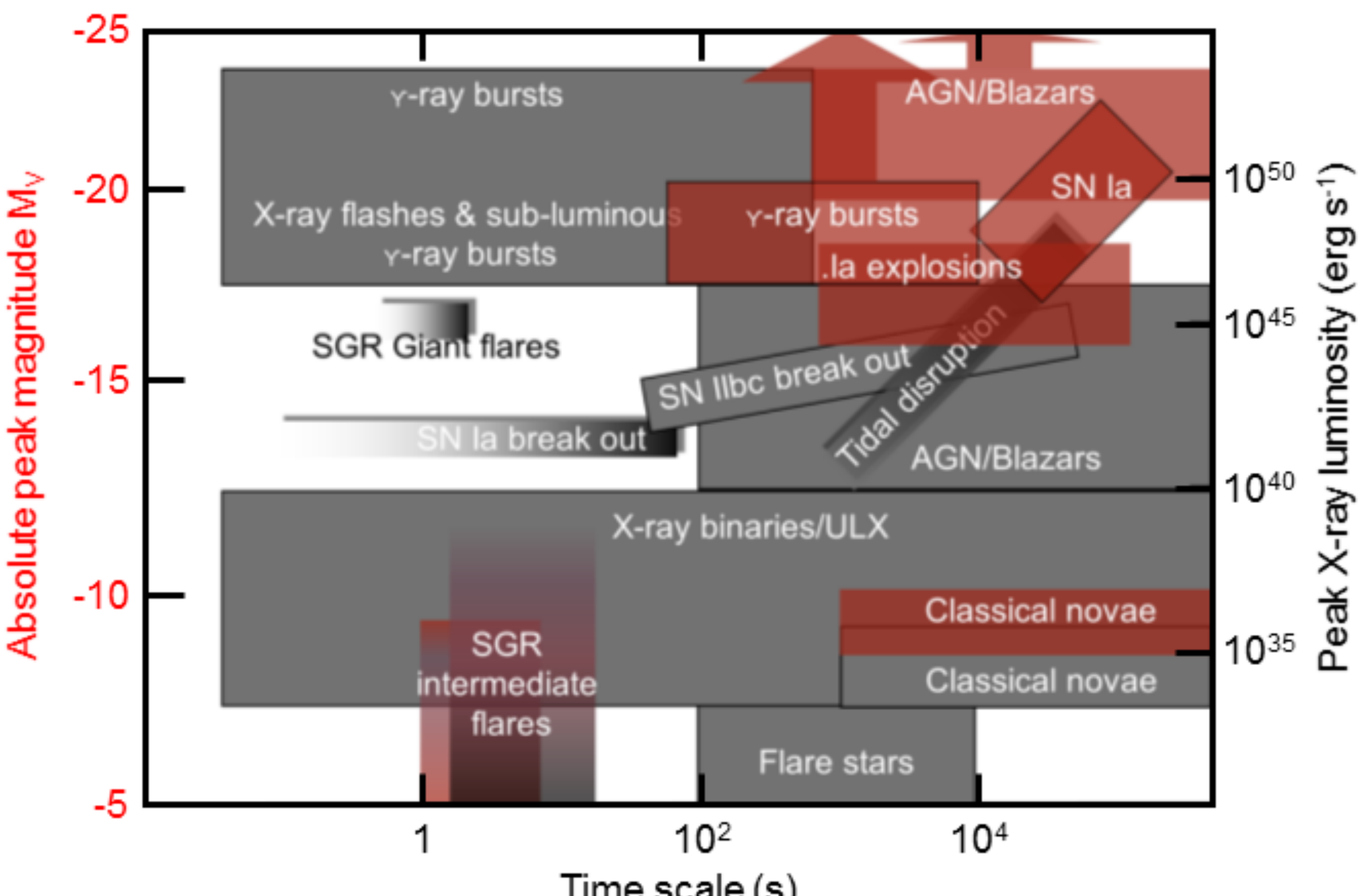
Exploring the Transient sky with SVOM

Core Program (GRBs):

- Multi-wavelength observations of prompt and afterglow emission (in many cases with redshift) that complement the observations at other wavelengths (e.g. HE/VHE with CTA)



(Credits: F. Piron)

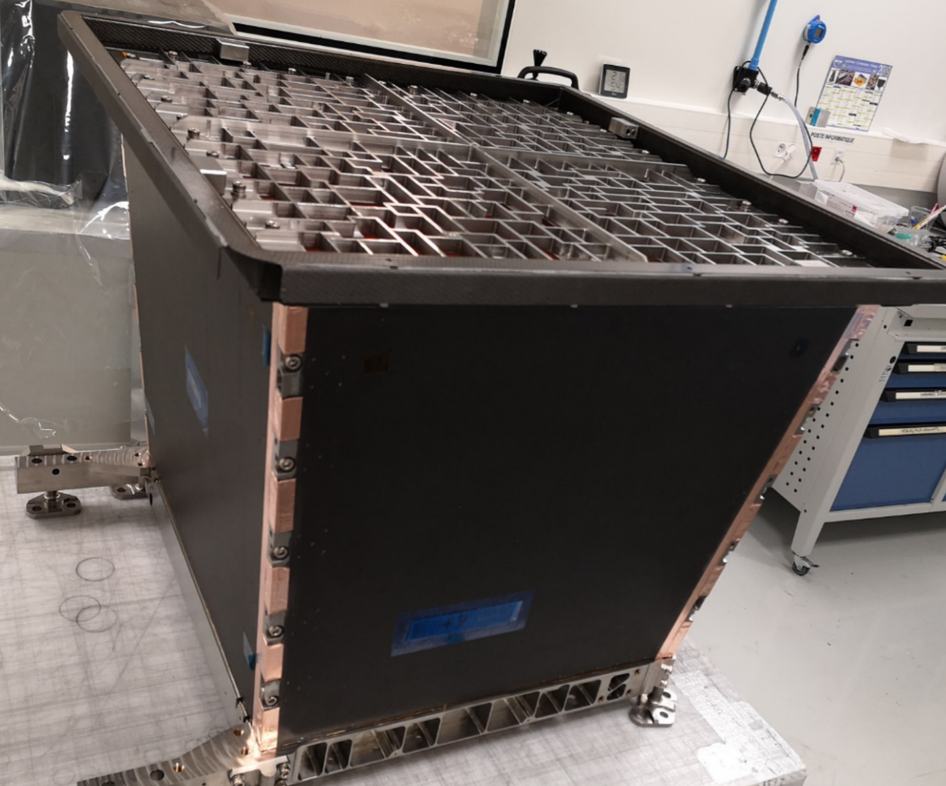
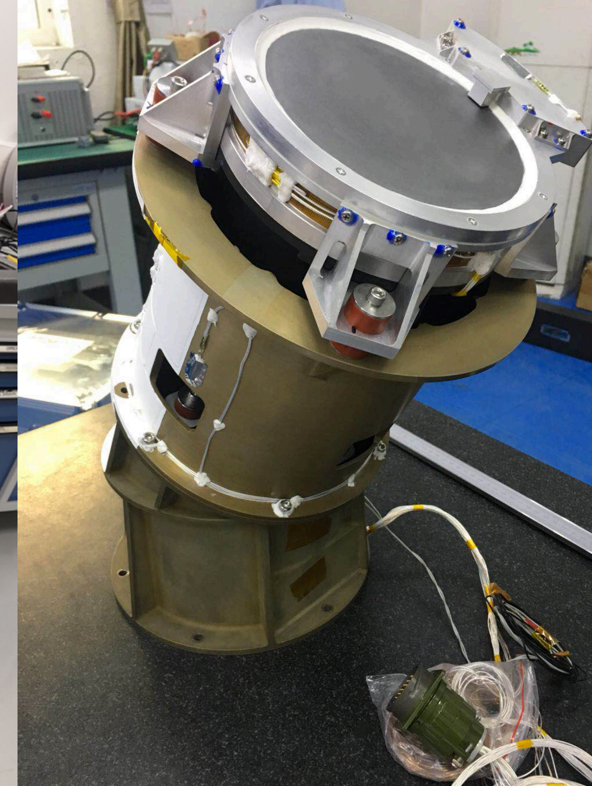


General Program:

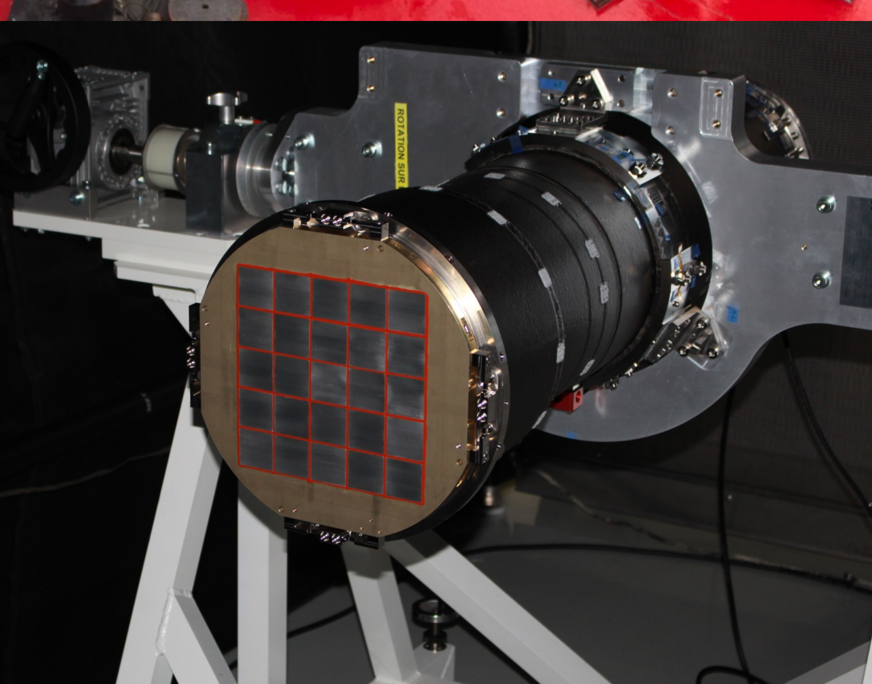
- Multi-wavelength observations of transients or flaring sources (AGNs, blazars, SNe, galactic transients, TDEs, ecc..)

ToOs Program:

- Search for X-ray and optical counterparts of external triggers
- Joint searches for counterparts of MM triggers, and validation of candidates at other wavelengths




Everything will be ready for late-2023.
Stay tuned!!