FELLINI General Meeting **Ferrara - 30-31/05/2022**

Multi-messenger Magnetar Observations (MMOBS)

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Fellini
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INFN
Istituto Nazionale di Fisica Nucleare

PROJECT OVERVIEW

First direct detection of the birth of a (millisecond spinning, highly-magnetised) neutron star, via its its multi-messenger signatures.

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2. **EM signature triggering the GW search (e.g. shock breakout, supernova)**
3. **Other EM transients may be associated to newborn/young magnetars (e.g. gamma-ray bursts, Super-Luminous Supernovae and Fast Radio Bursts). They are being studied in order to**
   - **(i) constrain the parameter space of our searches**
   - **(ii) maximizing the extraction of physics information from future detections**

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Science payback (besides the detection itself):

(a) measuring the birth spin and mass of a newborn NS

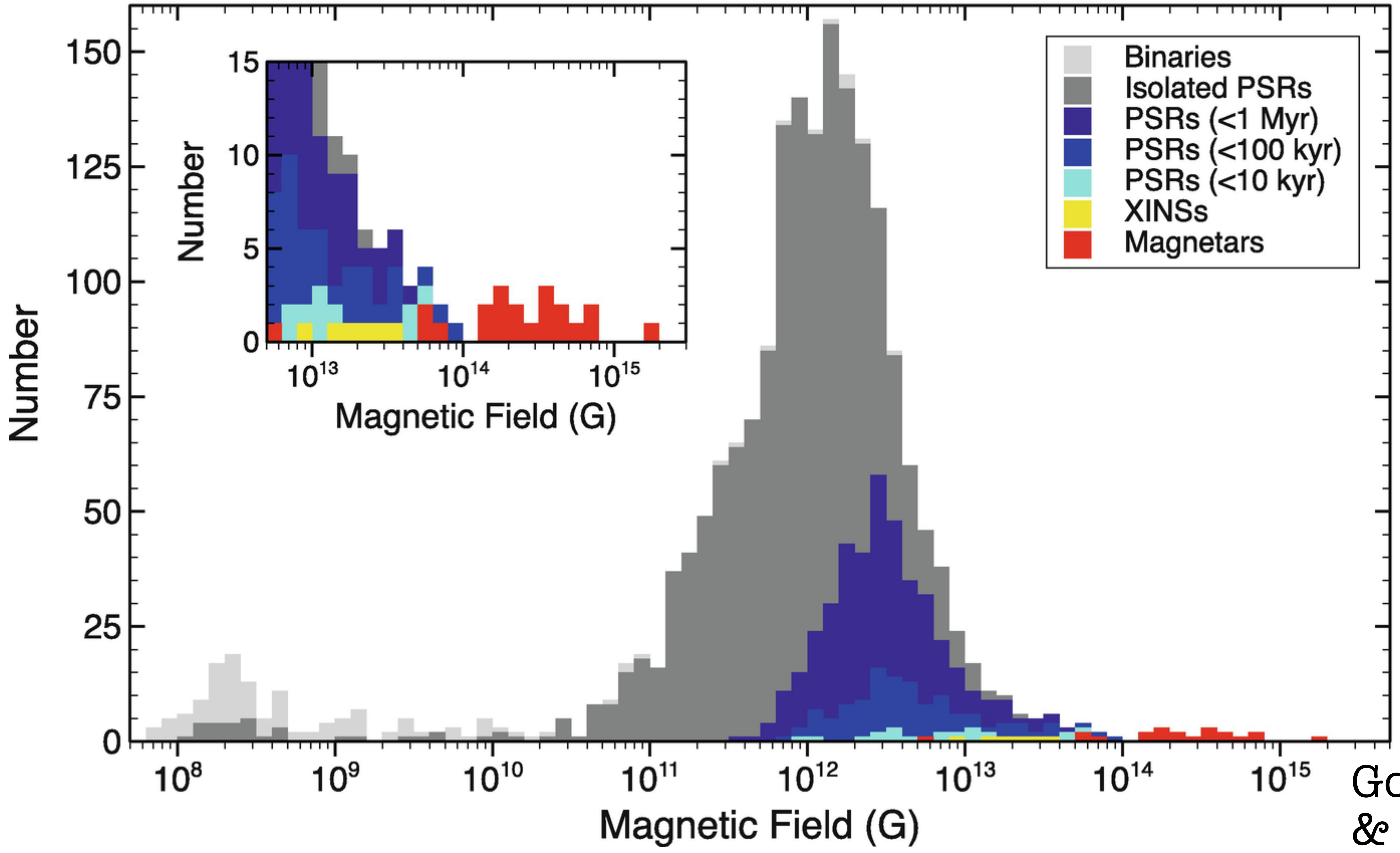
(b) setting strong constraints on the EoS of matter at supra-nuclear densities

(c) measuring the magnetic field strength (and interior geometry) of a newborn NS, shedding new light on the origin of NS magnetism and clarifying the link between magnetars and "ordinary" NS

Why magnetars?

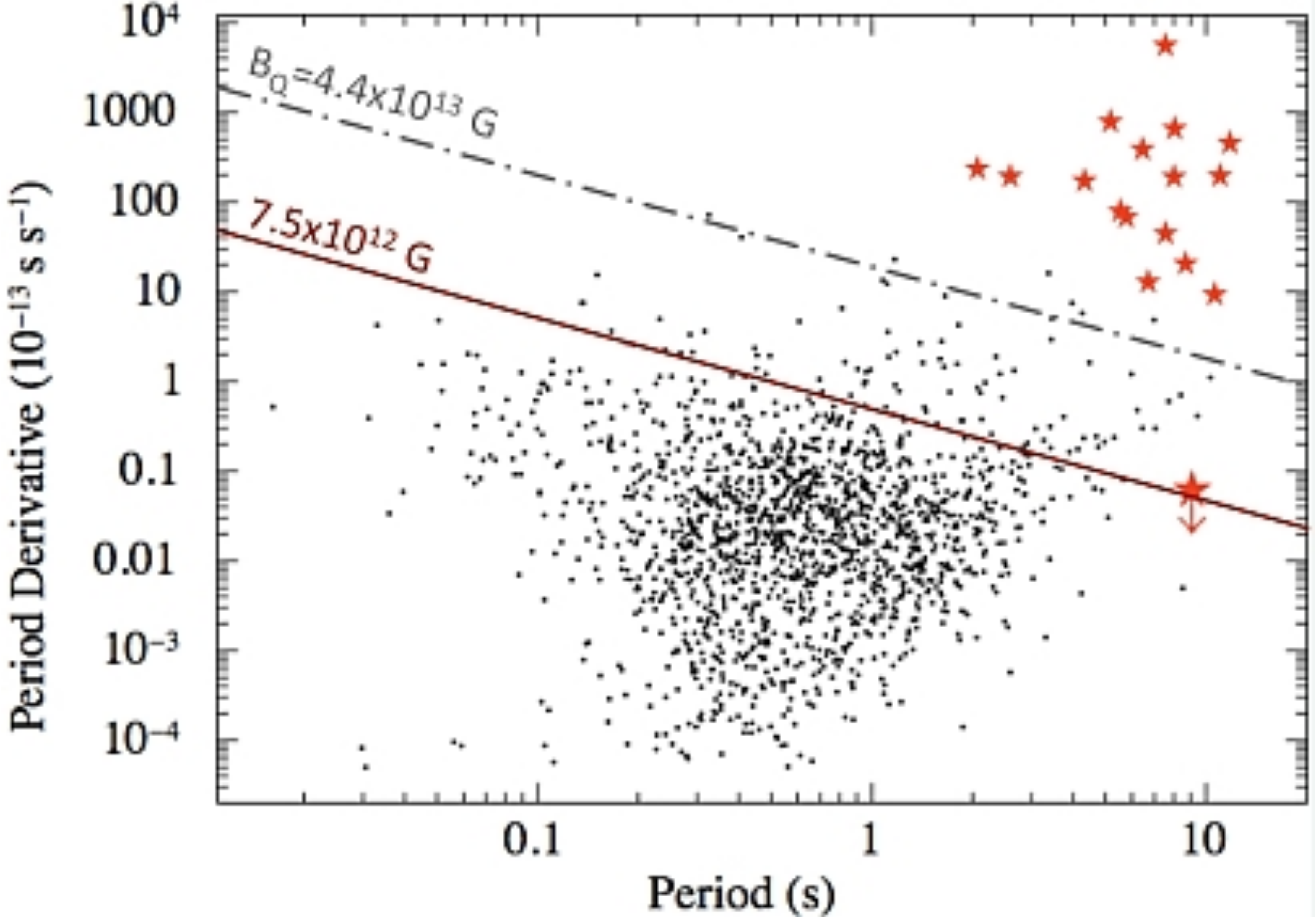
Magnetars
and their signature flares

1. Slow-spinning NS (P ~ 2-12 s) with super-critical dipole B
$B_d > B_{QED} \approx 4.4 \times 10^{13}\ G$ (inferred from spindown rate)
and (spindown) age ~ $200 - 10^5$ yr



Gourgouliatos & Esposito 2019

Rea et al. 2010

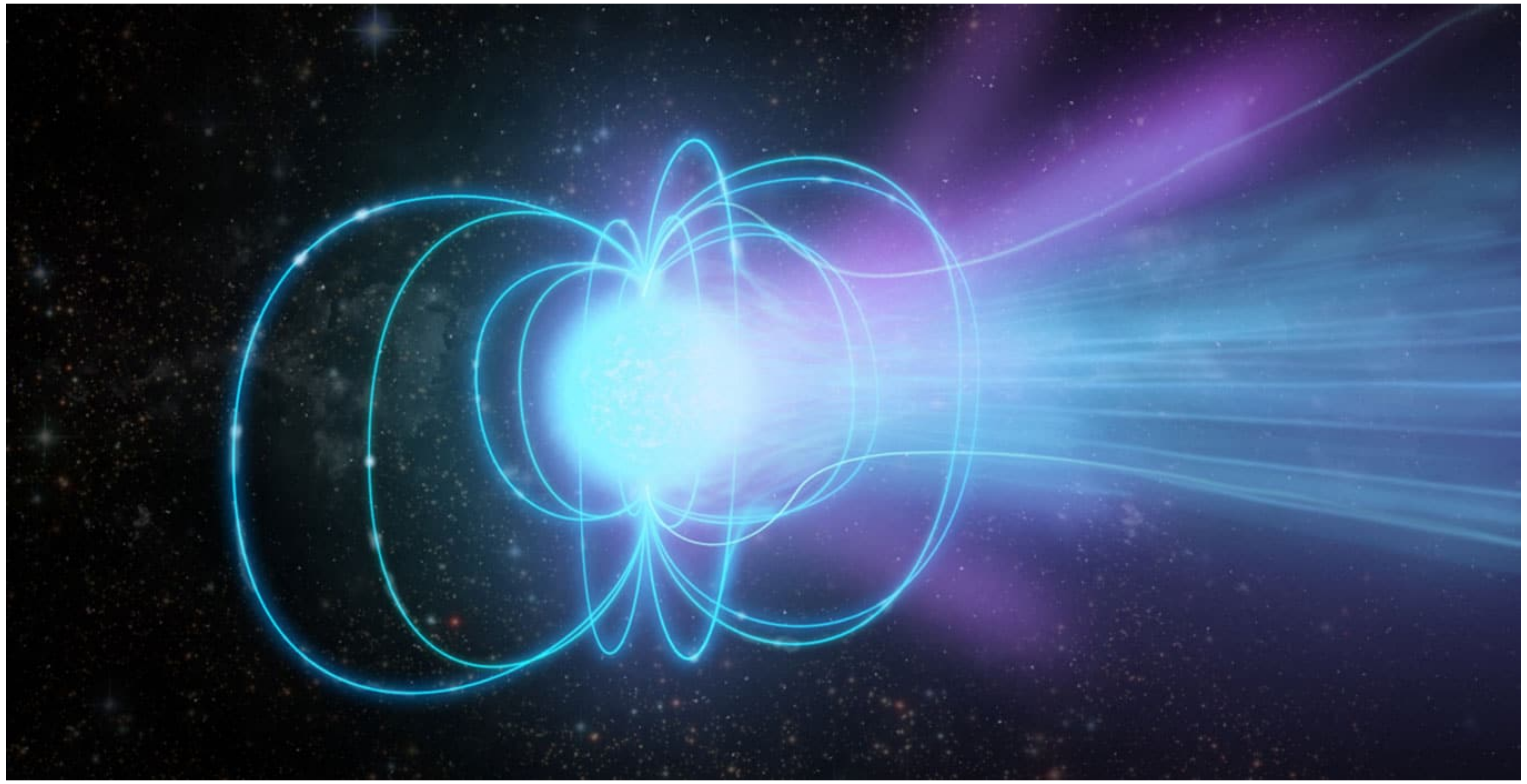


2. X-ray bright pulsators (either persistent or transient) with
$L_X \sim 10^{34} - 10^{36}\ \text{eg s}^{-1} \gg \dot{E}_{\text{rot}} = I\omega\dot{\omega} \sim 10^{31} - 10^{34}\ \text{erg s}^{-1}$

3. Their clustering in P and wide spread in $\dot{P}$ testifies of the decay of the magnetic dipole **Dall'Osso et al. 2012**

Beniamini et al. 2019

Magnetars and their signature Flares



Magnetic energy is the source of their emission

The exterior dipole is not sufficient, though.

An even stronger interior B-field must be present

(e.g. Thompson & Duncan 1996; Rea et al. 2010;
Perna & Pons 2011; **Dall'Osso et al. 2012**)

$$E_{B,\mathrm{int}} > \text{ a few} \times 10^{48}\ \mathrm{erg} \qquad B_{\mathrm{int}} > 3 \times 10^{15}\ \mathrm{G}$$

Strict lower limit

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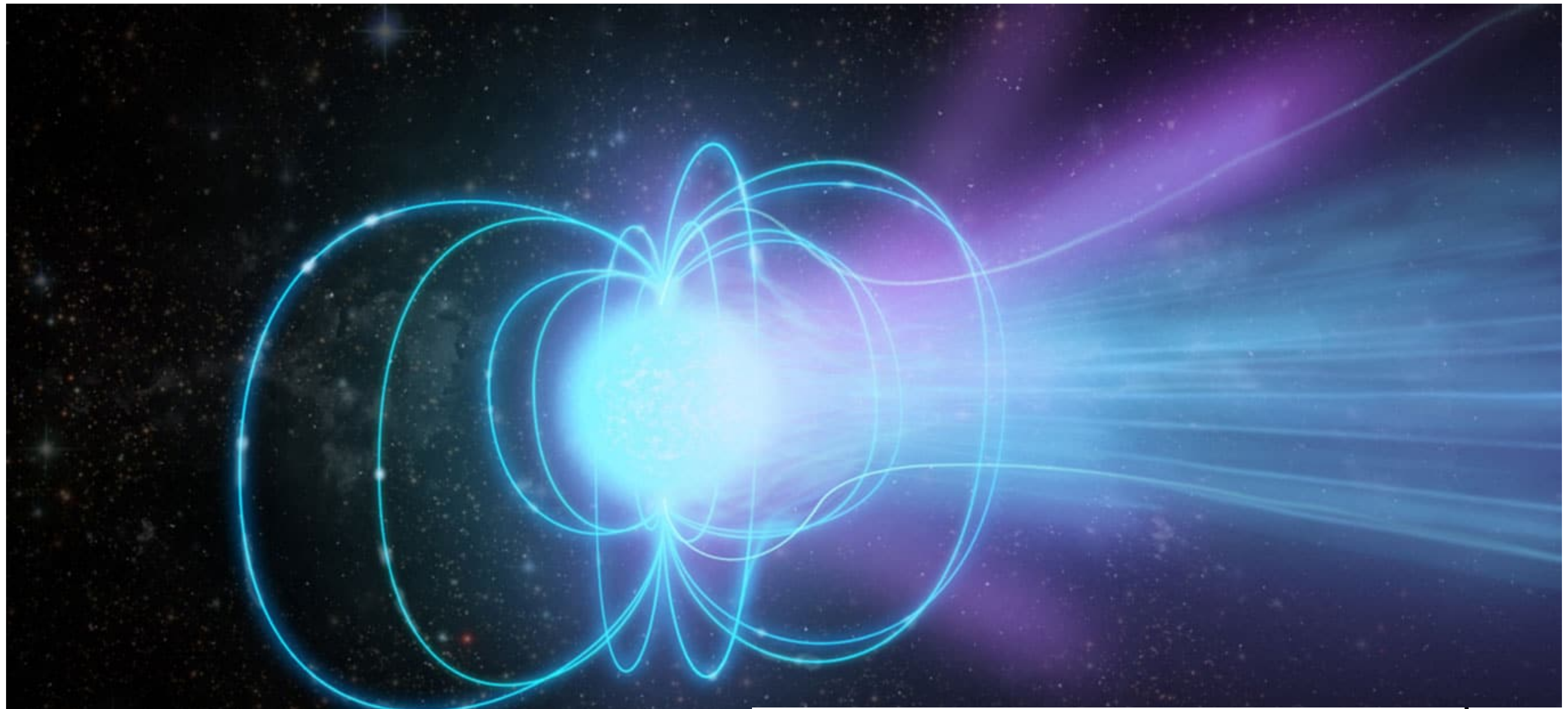
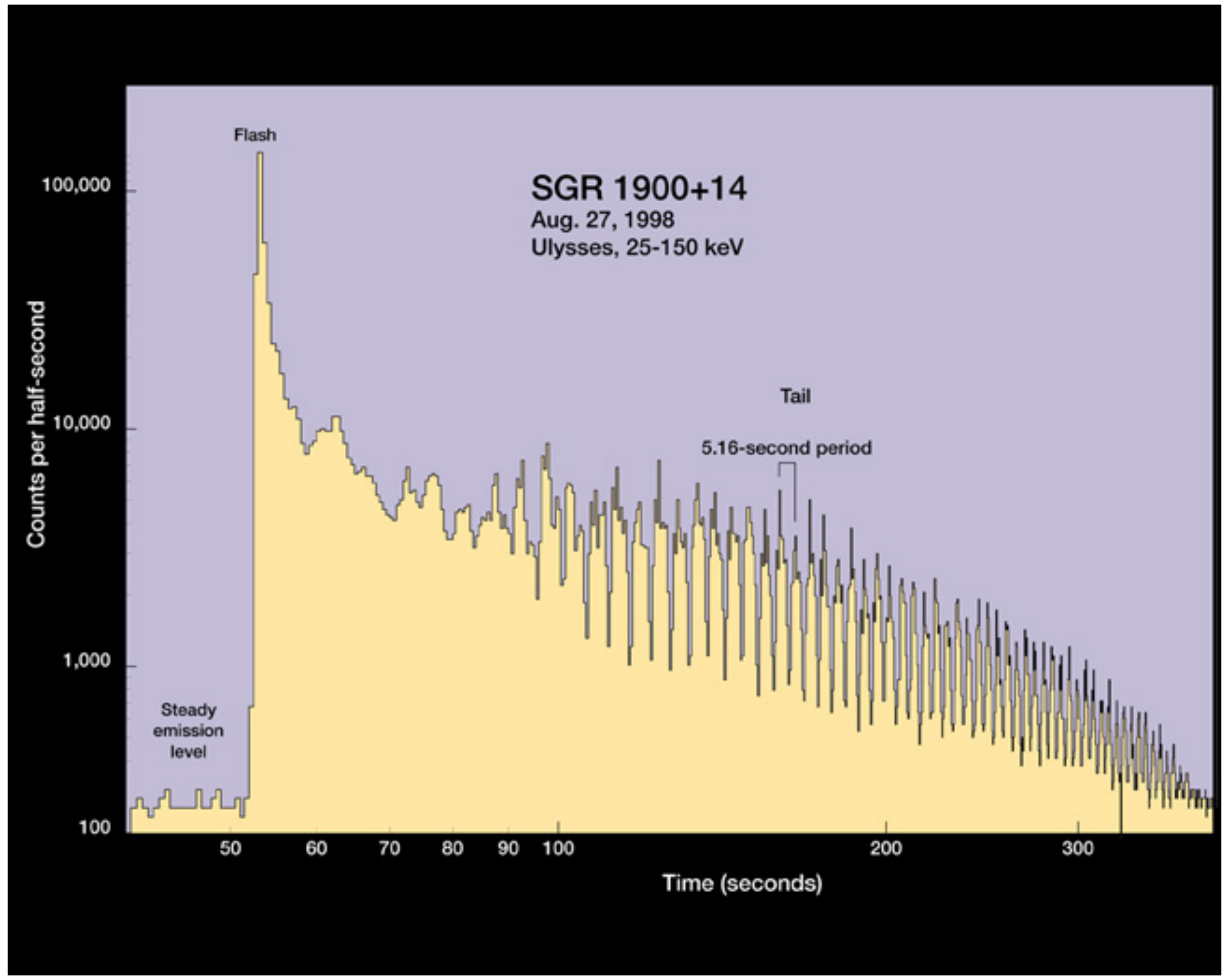
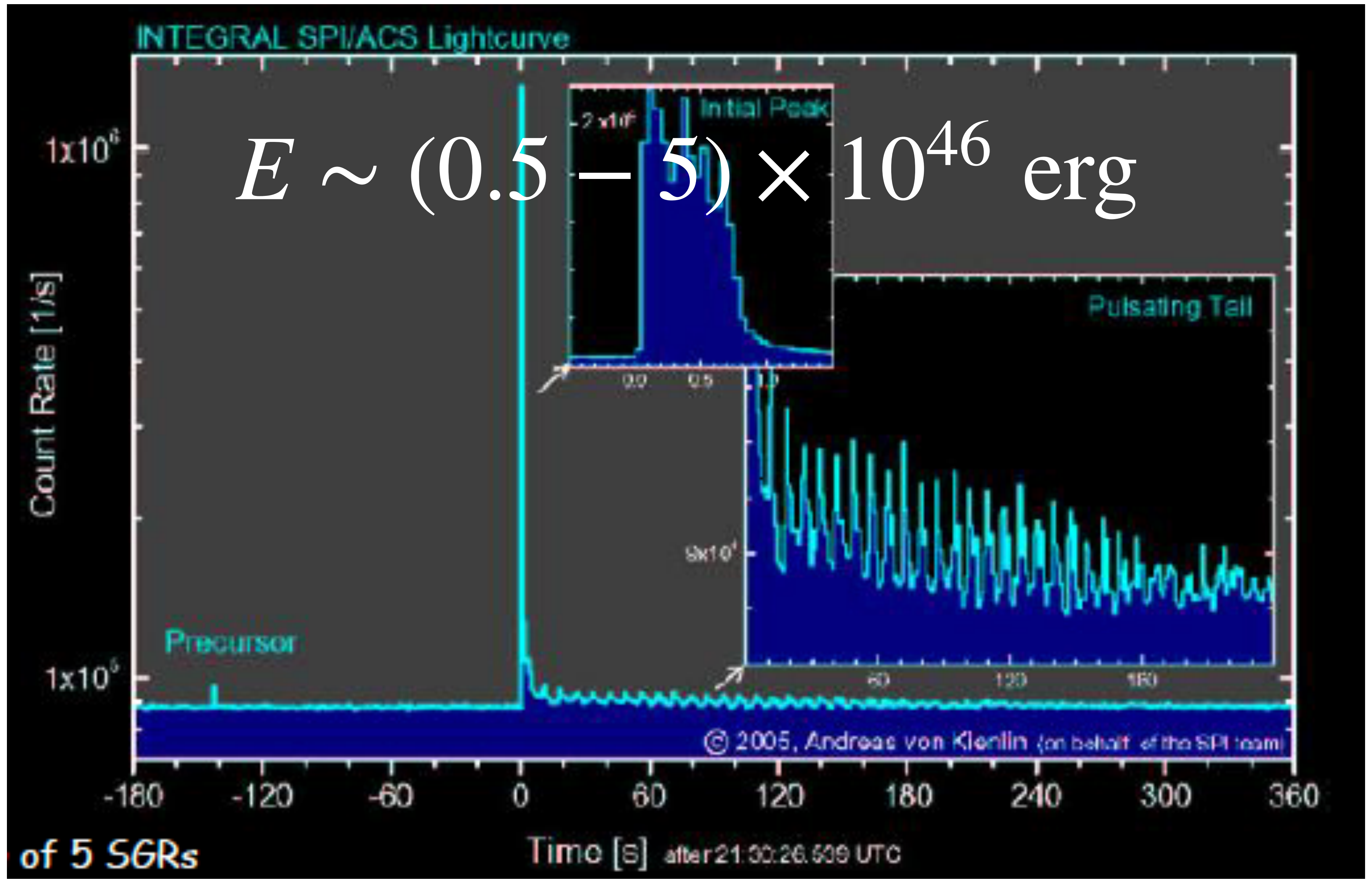
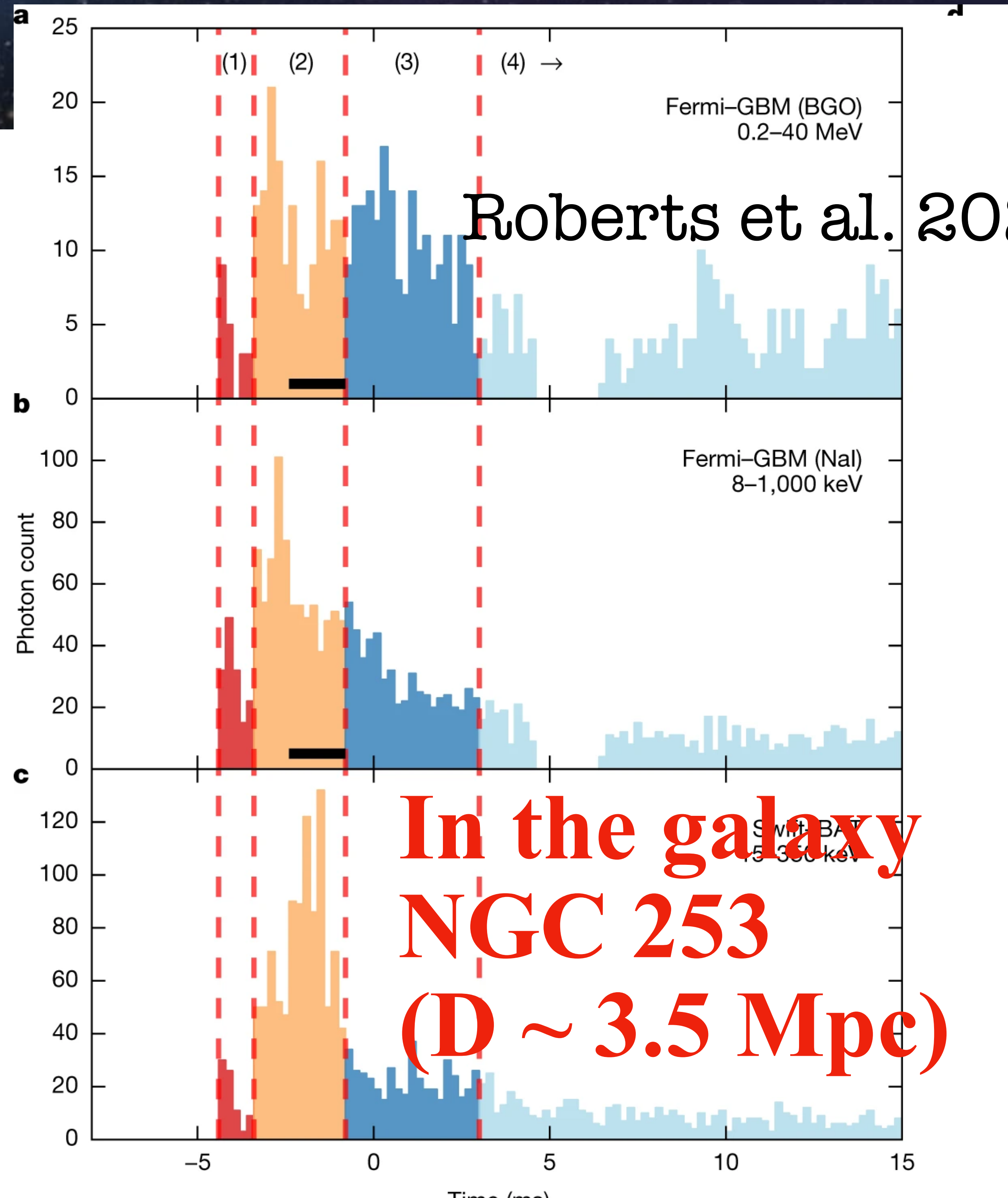






$$E \sim (0.5 - 5) \times 10^{46} \text{ erg}$$

of 5 SGRs



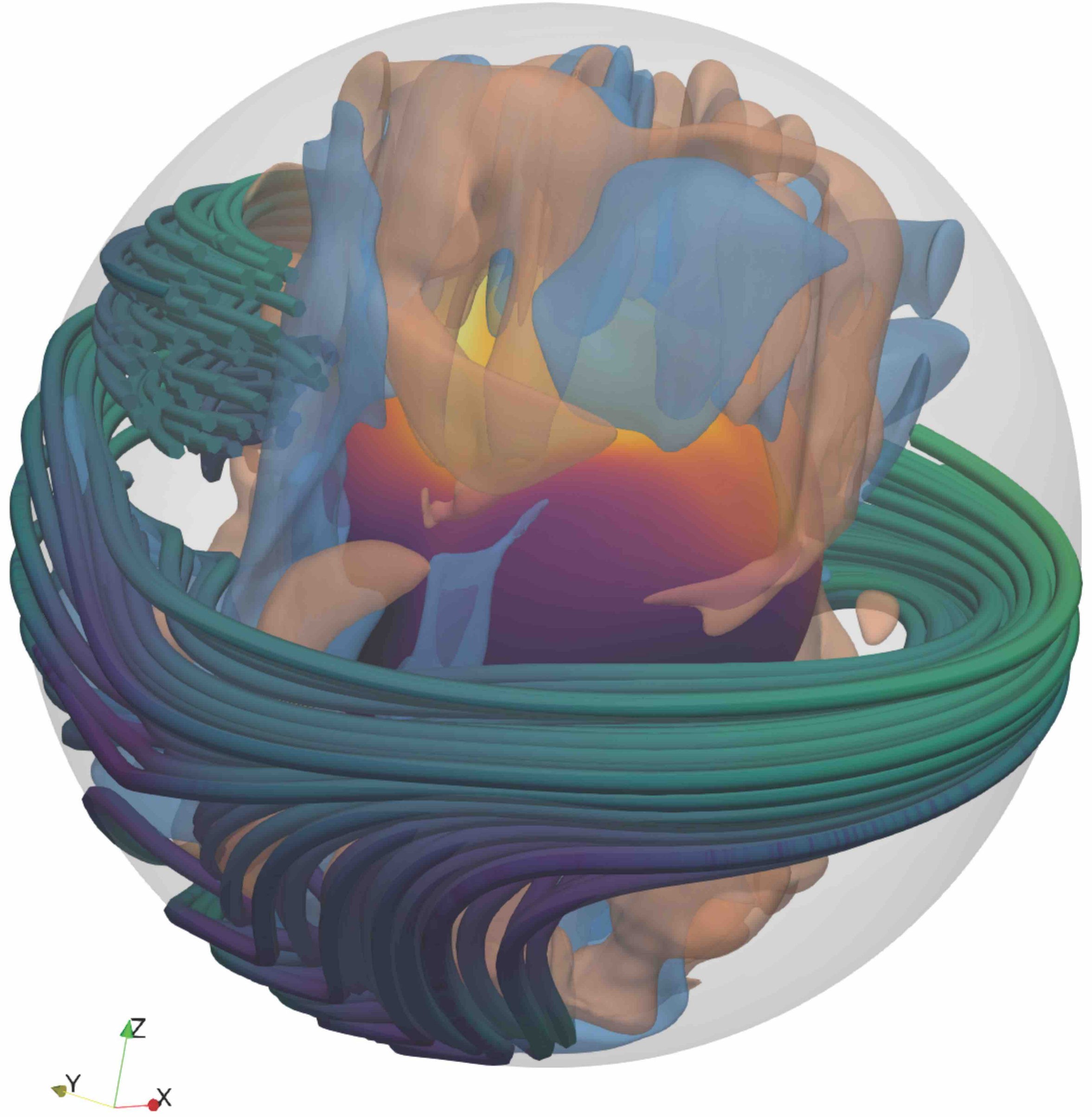
Roberts et al. 2021

In the galaxy NGC 253 (D ~ 3.5 Mpc)

What makes them so special?

(a) How do magnetars acquire such strong B-fields?

(b) Which factors decide whether a nascent NS will become a magnetar?



Raynaud et al. 2020

(a) A ms-spin at birth was suggested as the key condition for a proto-NS to generate a super-strong B-field through an efficient dynamo.

$$E_{\rm rot} = \frac{1}{2} I\omega^2 \sim 3 \times 10^{52}\ {\rm erg}$$

$$\boxed{\Rightarrow B_{\rm int} \sim (1-3) \times 10^{16}\ {\rm G}} \Rightarrow \sim (0.3-1) \times 10^{50}\ {\rm erg}$$

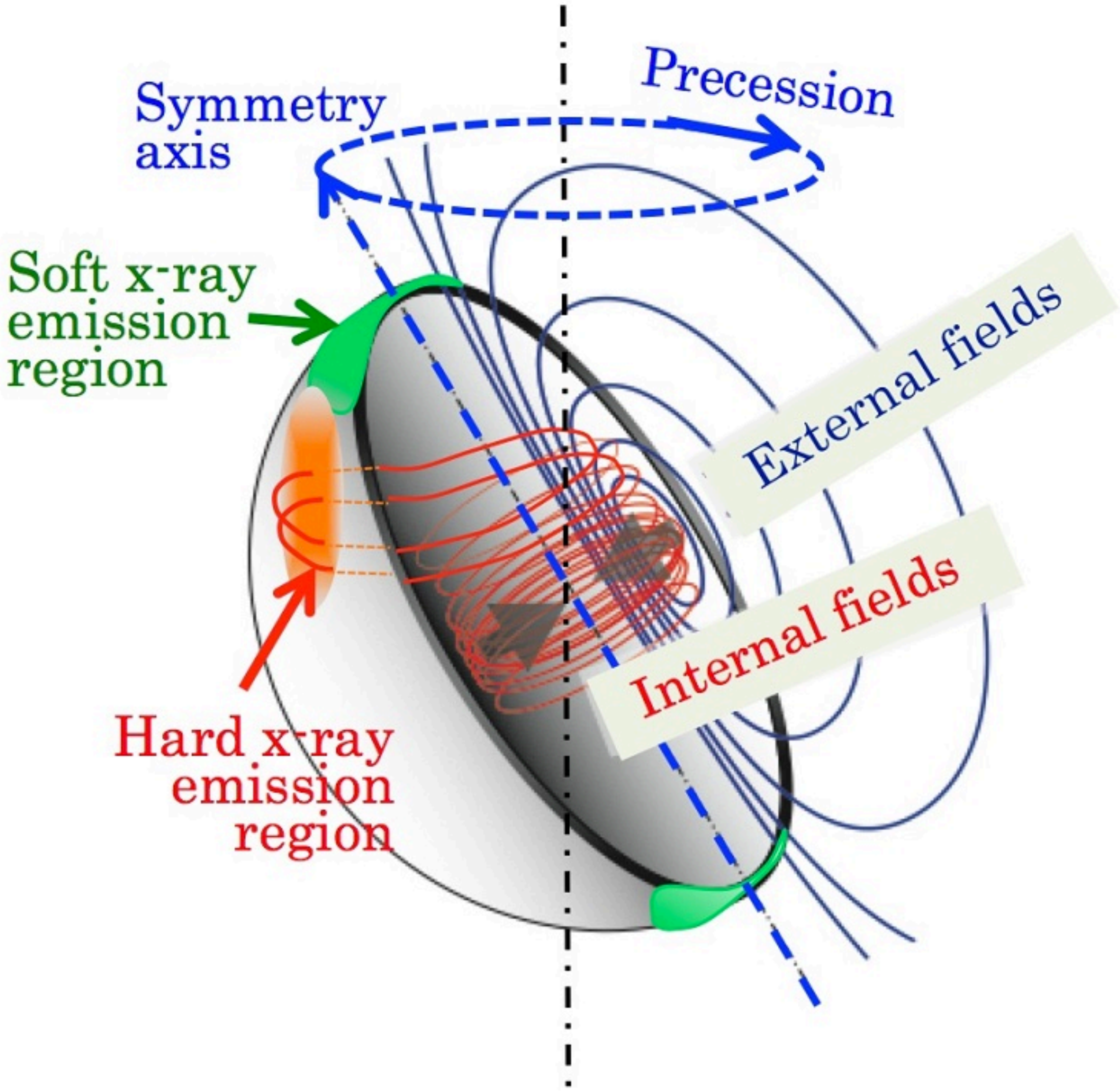
interior, toroidal B-field

Duncan & Thompson 1992
Thompson & Duncan 1993

(b) We don't know yet. The mass of the progenitor star is a possibility under scrutiny.

In BNS mergers we may see the effect of fast spin at work

GW astronomy and the key to magnetar formation



$$E_{\rm spin} \approx 3 \times 10^{52}\ {\rm erg}\ \ P_{\rm ms}^{-2} \sim 0.01\ M_{\odot} c^2\ P_{\rm ms}^{-2}$$

$$h \sim \frac{25G}{c^4}\frac{I\epsilon}{D} f^2 \approx 5 \times 10^{-25} \epsilon_{-3} f_{\rm kHz}^2 D_{\rm Mpc}^{-1}$$

VISCOSITY-DRIVEN INSTABILITIES

SPIN-FLIP

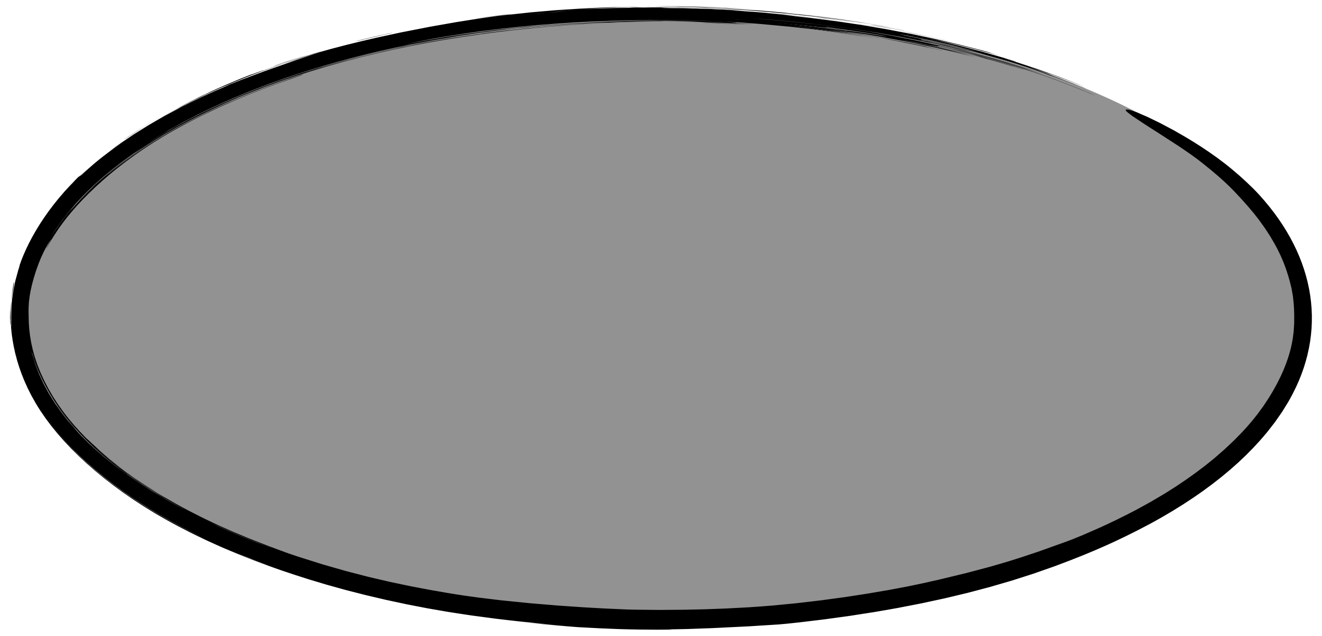
Cutler 2002 Dall'Osso et al. 2007; 2009; 2015; 2018

Lander & Jones 2020

$$\epsilon_B \sim \frac{E_B}{E_{\rm G}} \approx 5 \times 10^{-4}\ B_{16}^2 R_6^4 M_{1.4}^2$$

$$f = 2\nu_{\rm spin} \approx 2\ {\rm kHz}\ P_{\rm ms}^{-1}$$

$$E_{\rm rot} = \frac{L^2}{2I} \Rightarrow E_{\rm rot,min} = \frac{L^2}{2I_{\rm max}}$$



SECULAR BAR-MODE

Corsi & Meszaros (2009)

$$\epsilon \lesssim 0.1\ @\frac{T}{|W|} \gtrsim 0.14\ ({\rm i.e.\ spin\ period}\ \approx 1\ {\rm ms})$$

$$f \ll \nu_{\rm spin} \approx 100 - 150\ {\rm Hz}$$

GW astronomy and the key to magnetar formation

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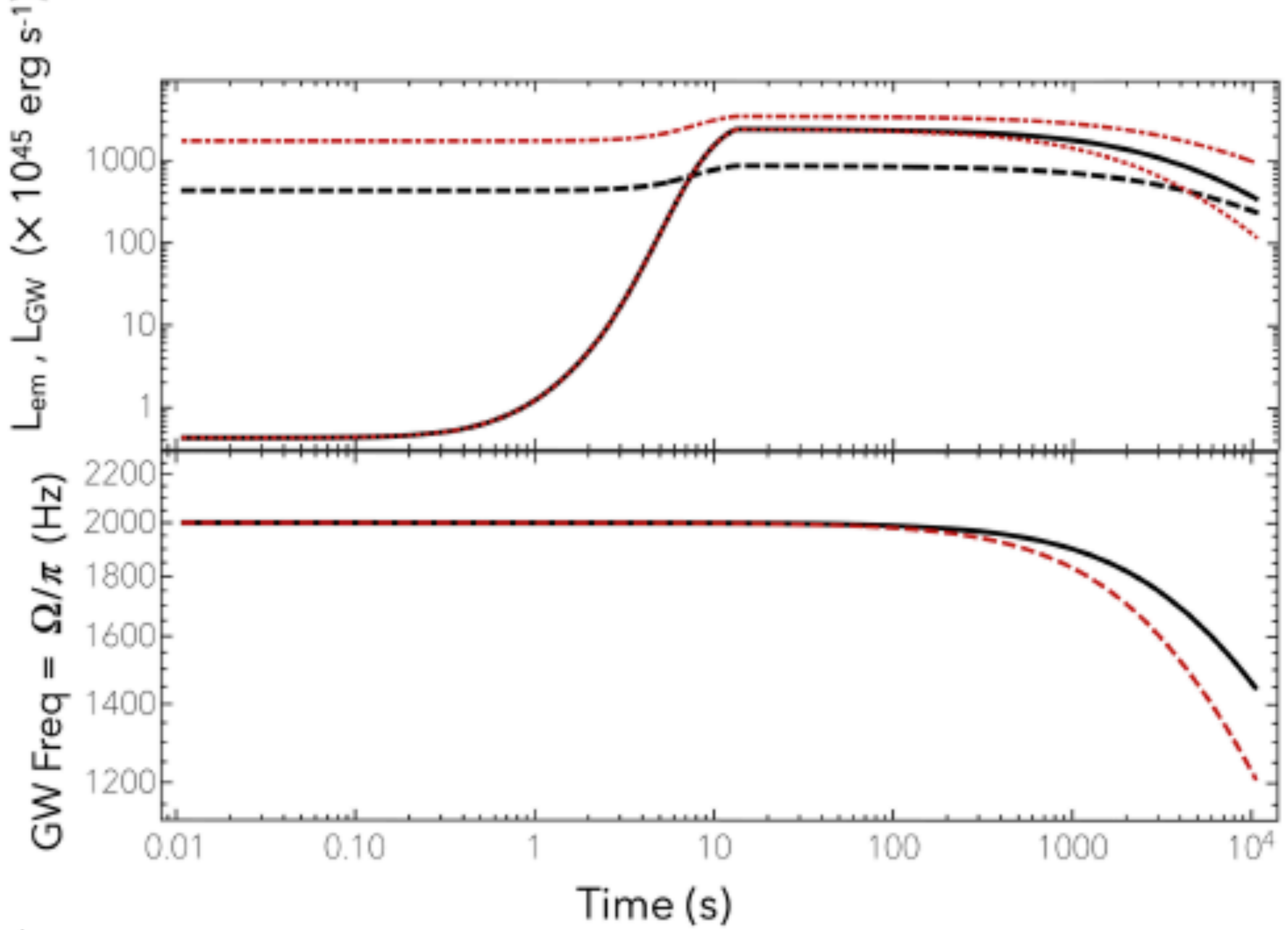

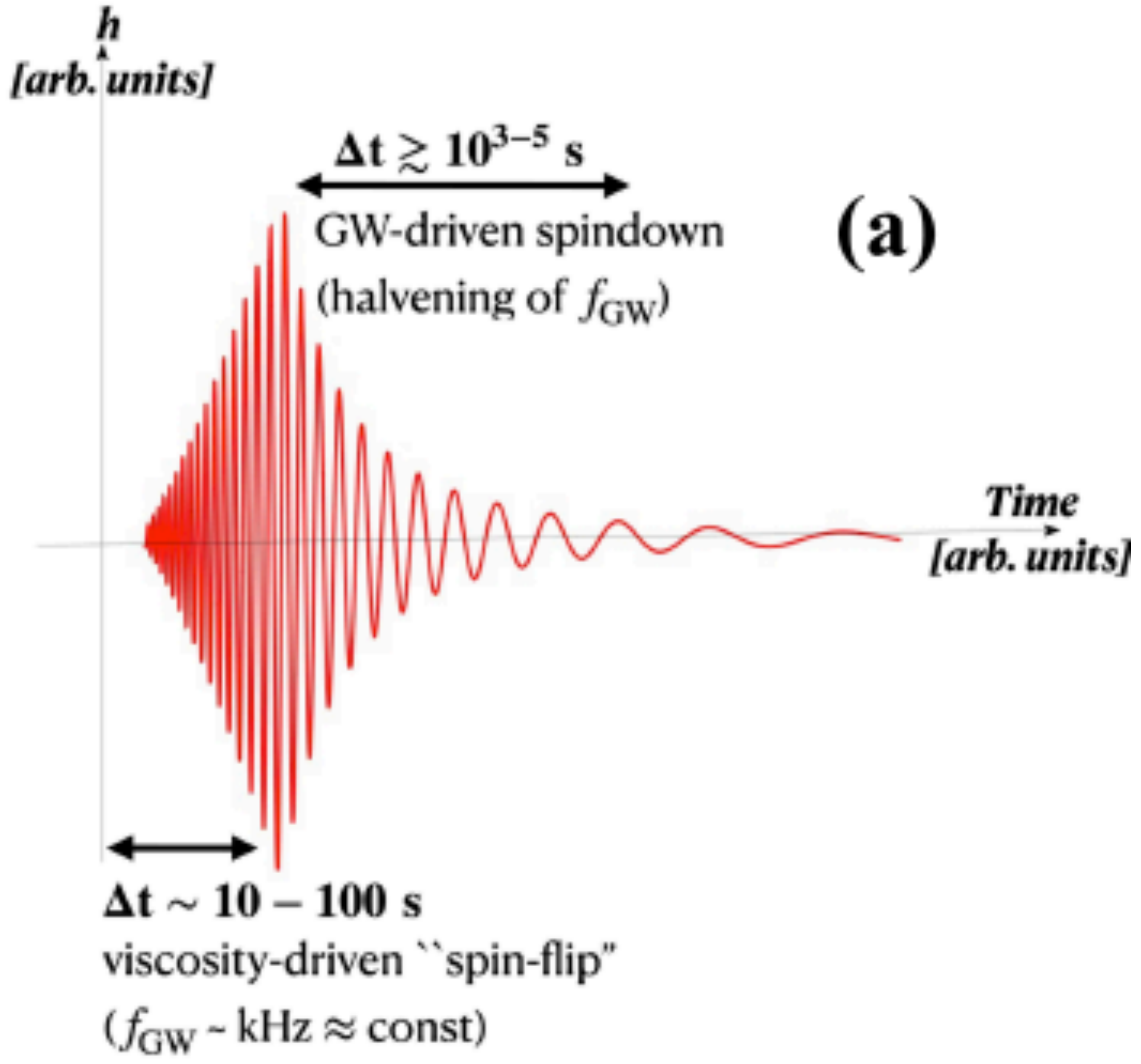

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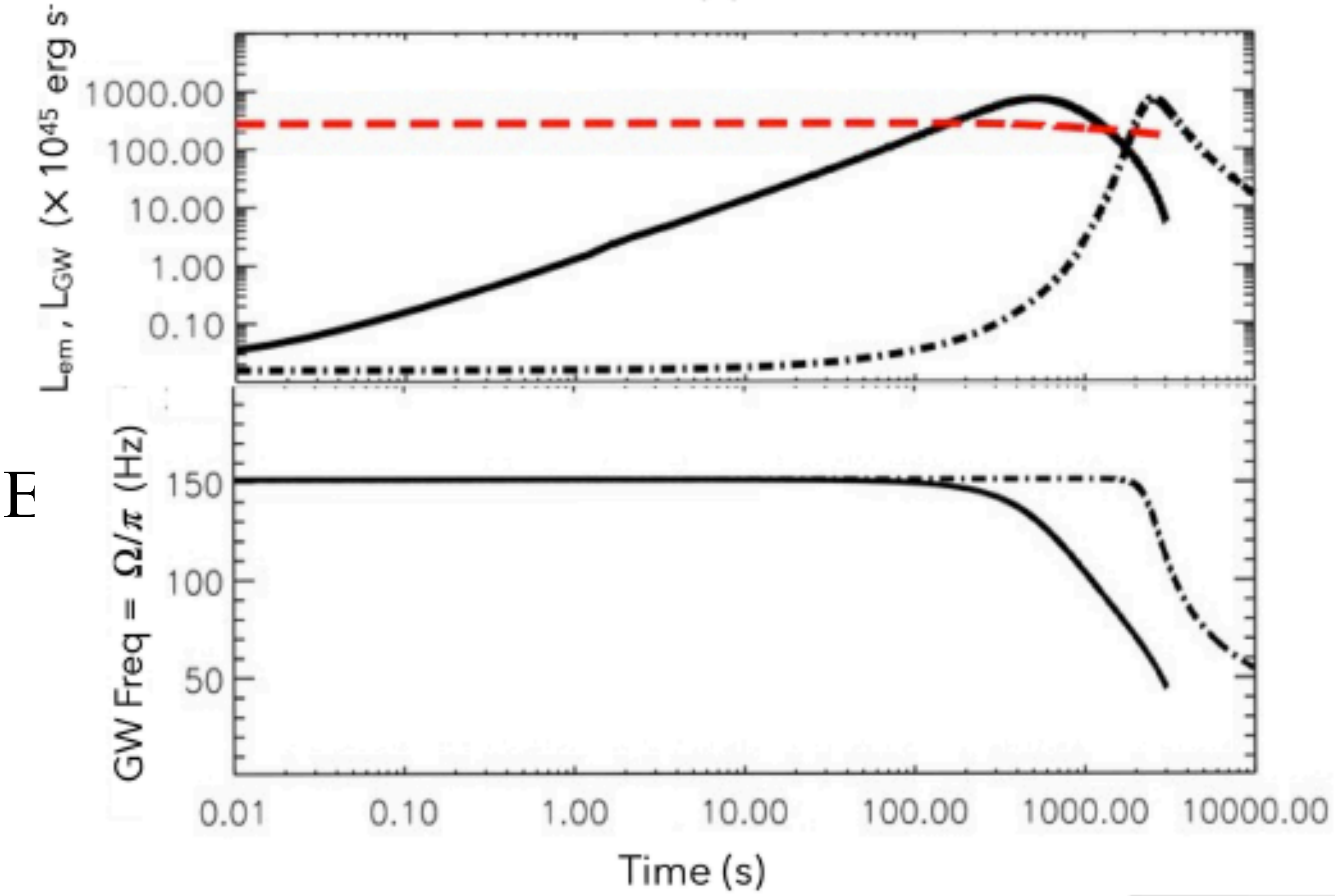

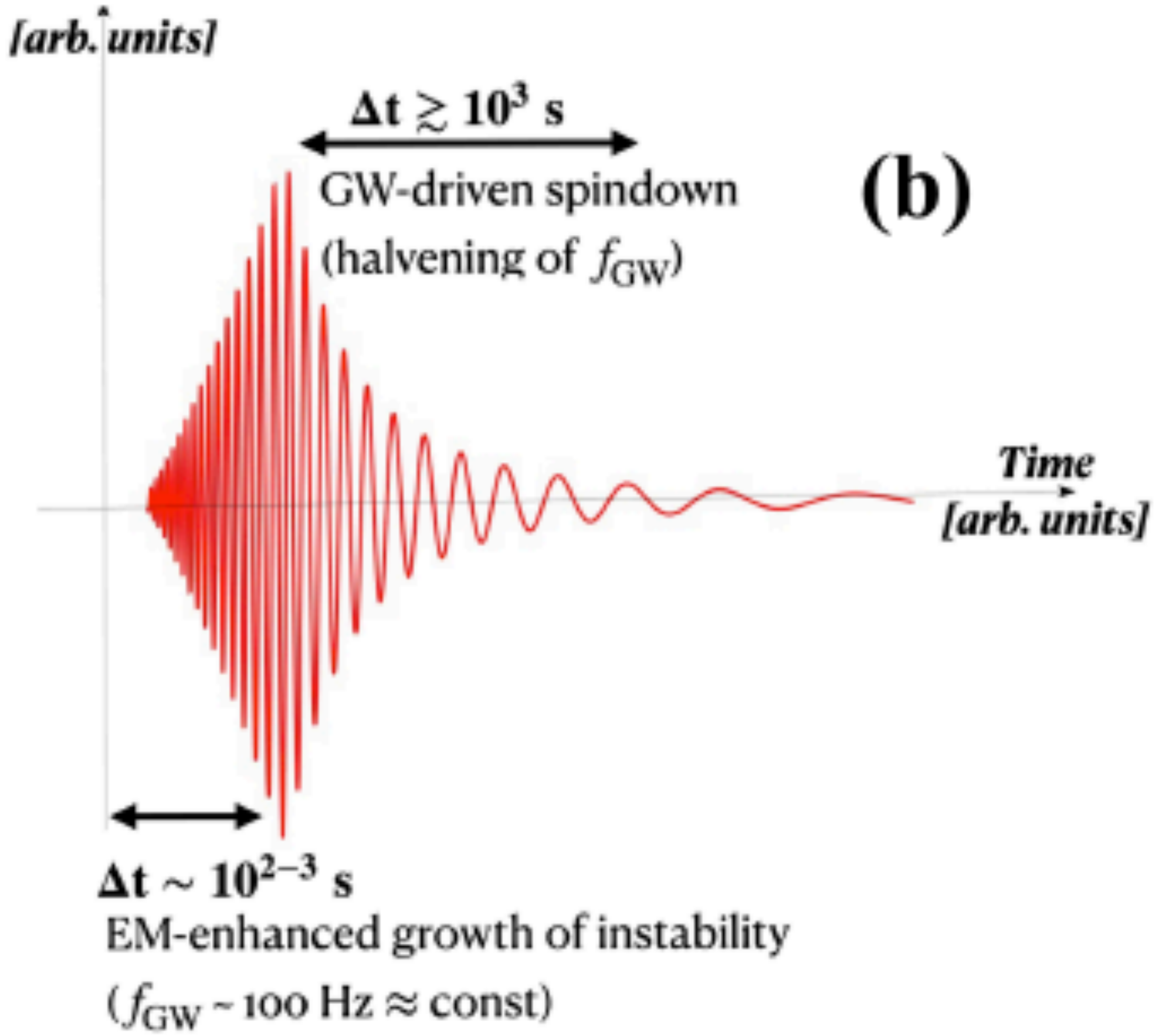

GW astronomy and the key to magnetar formation

Top priority @this stage: observation and data analysis efforts, in order to be ready to reveal both the GW and EM transients associated to a newborn magnetar.

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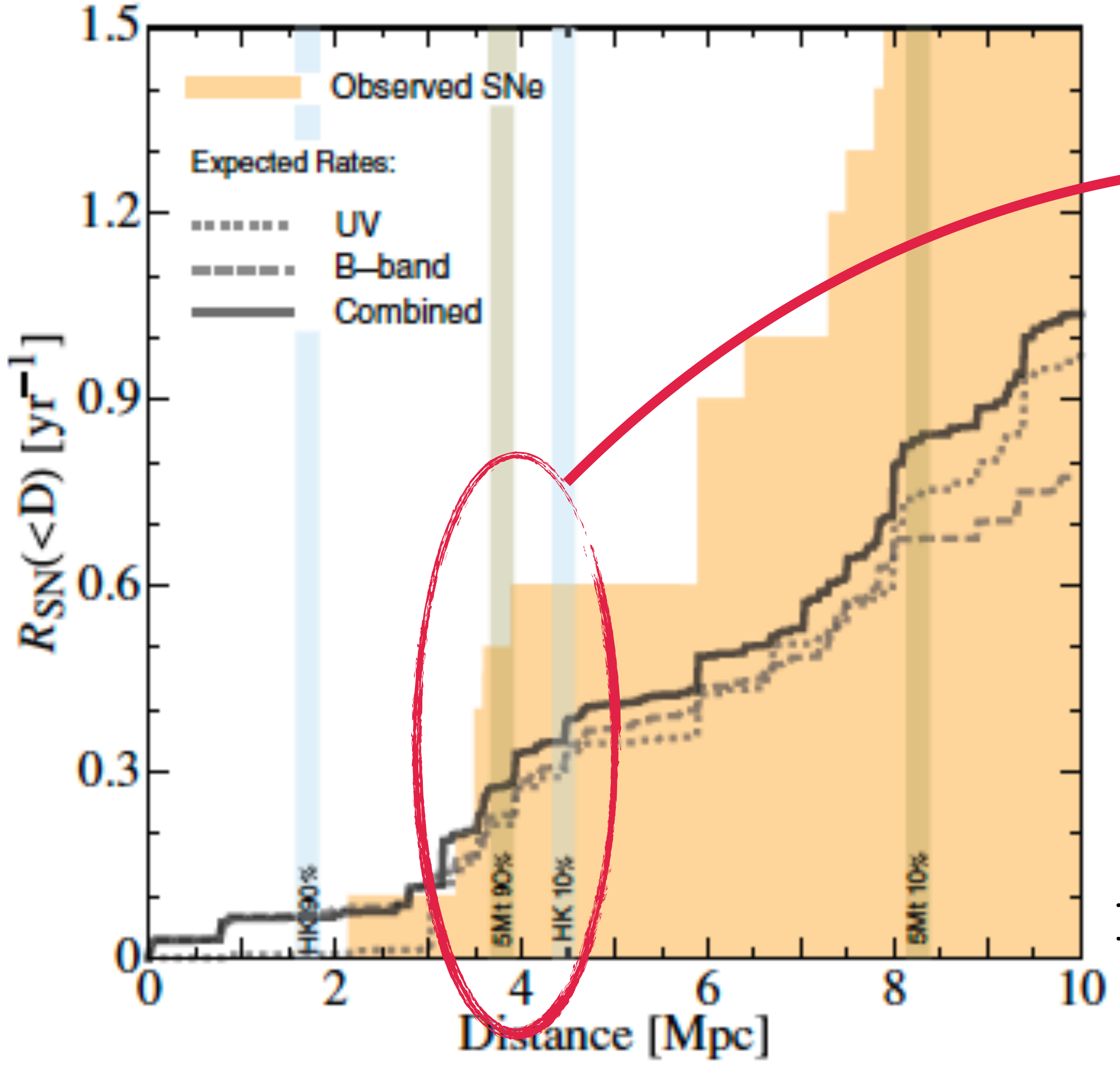
CCSNe? BNS mergers?

$\sim 7 \times 10^4\ \mathrm{Gpc^{-3} yr^{-1}}$ $\lesssim 300\ \mathrm{Gpc^{-3} yr^{-1}}$ (LVK O3)



Local Staburst Galaxies

Kistler et al. 2013

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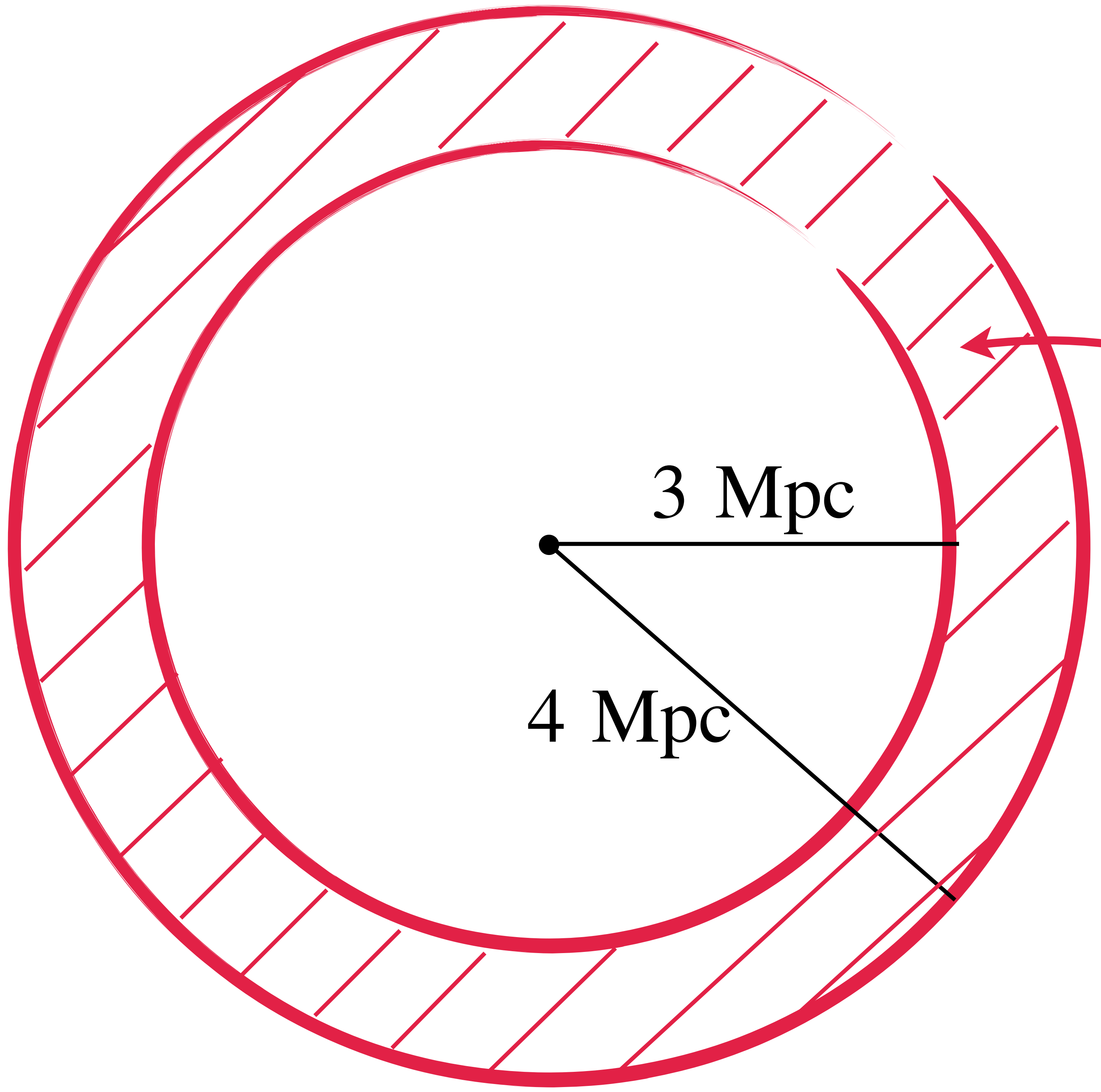
$\sim 0.6\ \mathrm{yr^{-1}}$ $\lesssim 10^{-4}\ \mathrm{yr^{-1}}$ $\Leftarrow$ within 4 Mpc

$$\boxed{\mathscr{R}_M \gtrsim 0.06\, f_{M,-1}\ \mathrm{yr^{-1}}\ \text{within 4 Mpc}}$$

comparable to BNS merger rate
@D < 40 Mpc, i.e. GW170817

KEY GOAL: ad-hoc search strategies with sensitivity up to 3-4 Mpc



interesting magnetar birth rate by reaching this region, at least

GW astronomy and the key to magnetar formation

Top priority @this stage: observation and data analysis efforts, in order to be ready to reveal both the GW and EM transients associated to a newborn magnetar.

In O2 an estimated horizon $D_{max} \sim 0.5\text{-}0.8$ Mpc was reached in searches targeted to the BNS merger GW170817

Sensitivity upgrade expected to lead to $D_{\rm max} \sim 1.6 - 2.5$ Mpc in next science runs
Might get a little better in post-O5 scenarios (the several yr gap expected between LIGO/Virgo O5 and ET coming online)

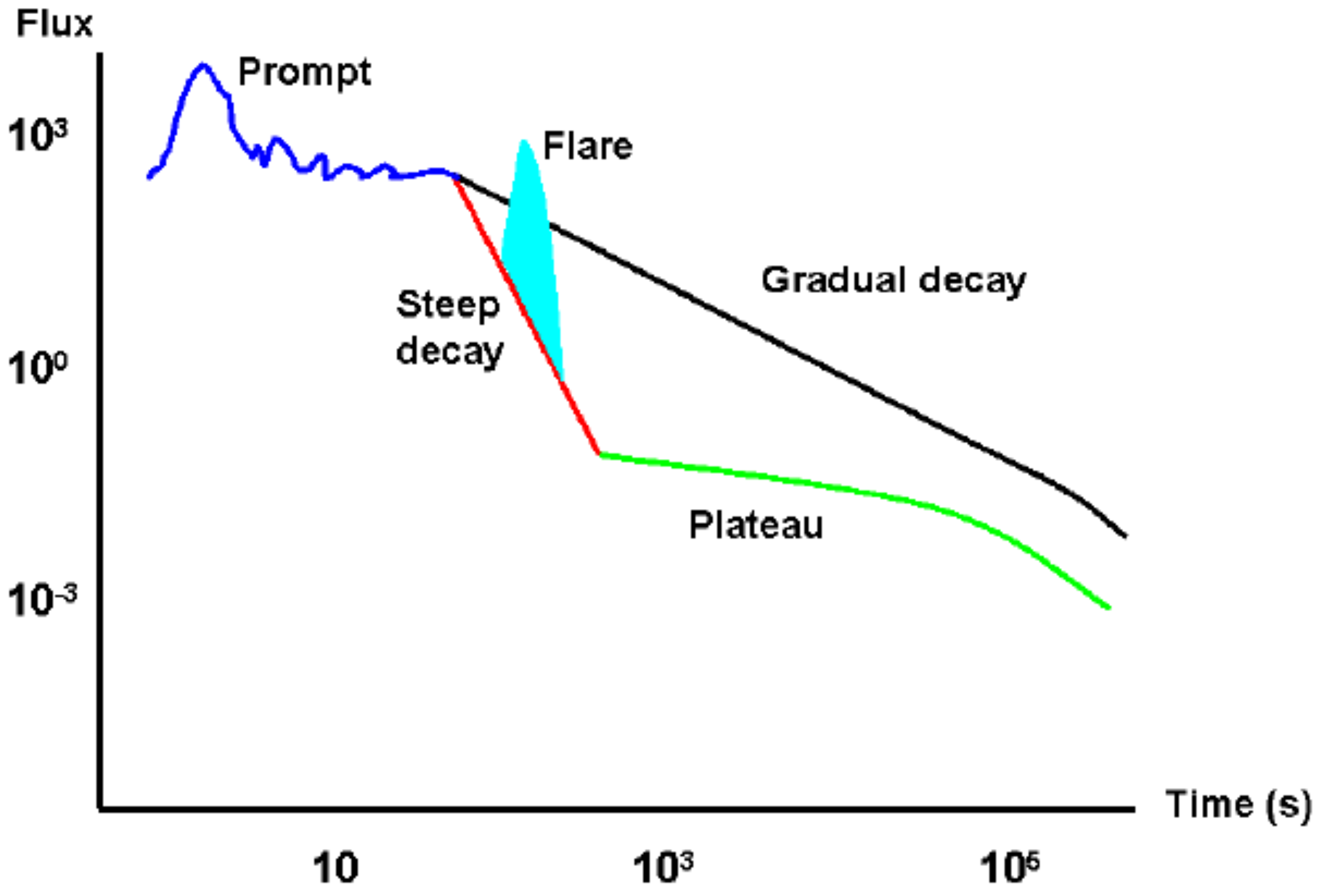
In order to reach our target horizon it will be crucial to:

(1) improve existing pipelines or develop novel search methods, by means of template signal injections to check the efficiency of different schemes

(2) obtain external EM triggers, that help enhance the statistical significance of possible candidates and help the search efficiency by restricting the parameter space

ASTROPHYSICAL IMPLICATIONS (A)

Gamma-Ray Bursts (GRBs)



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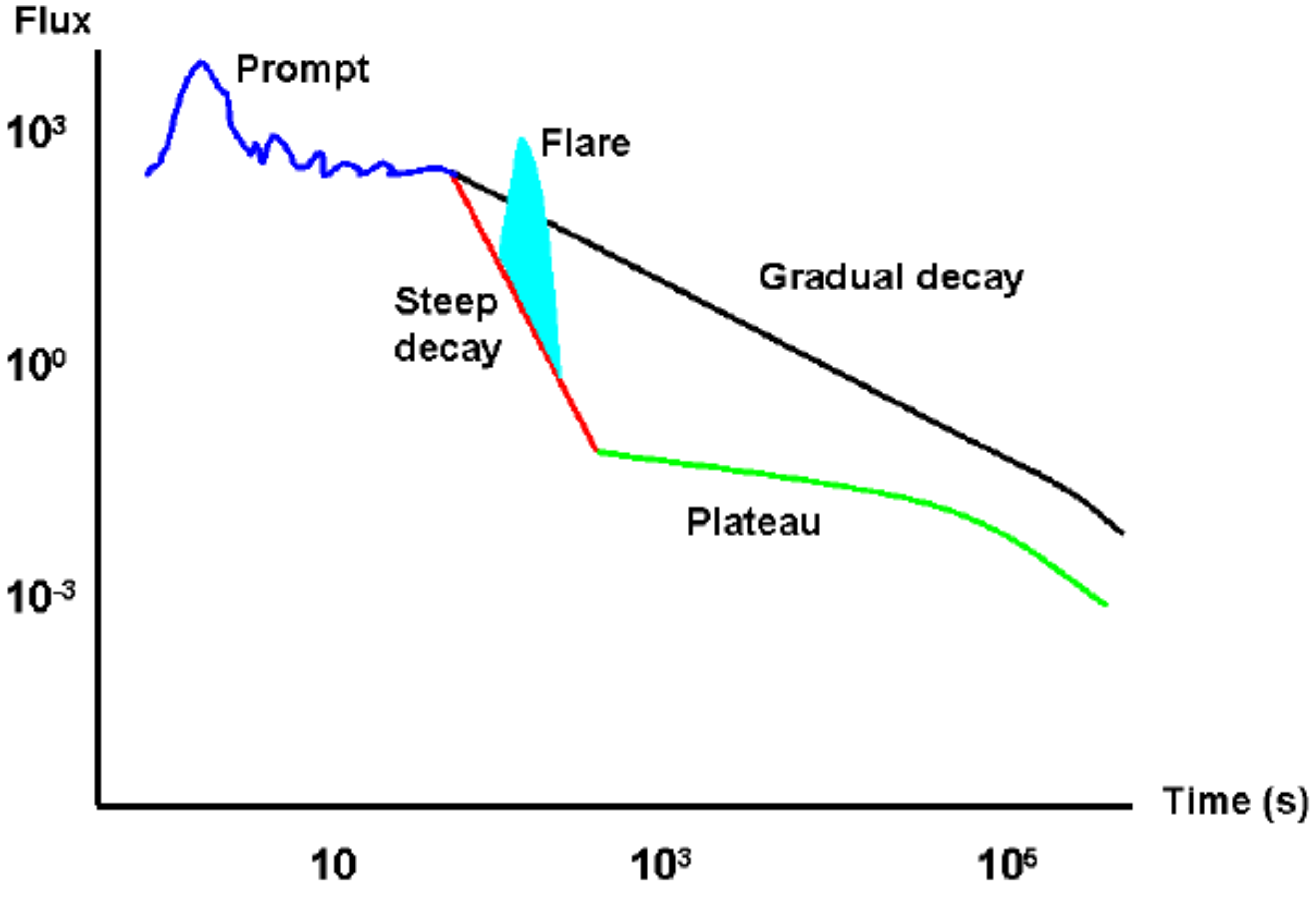
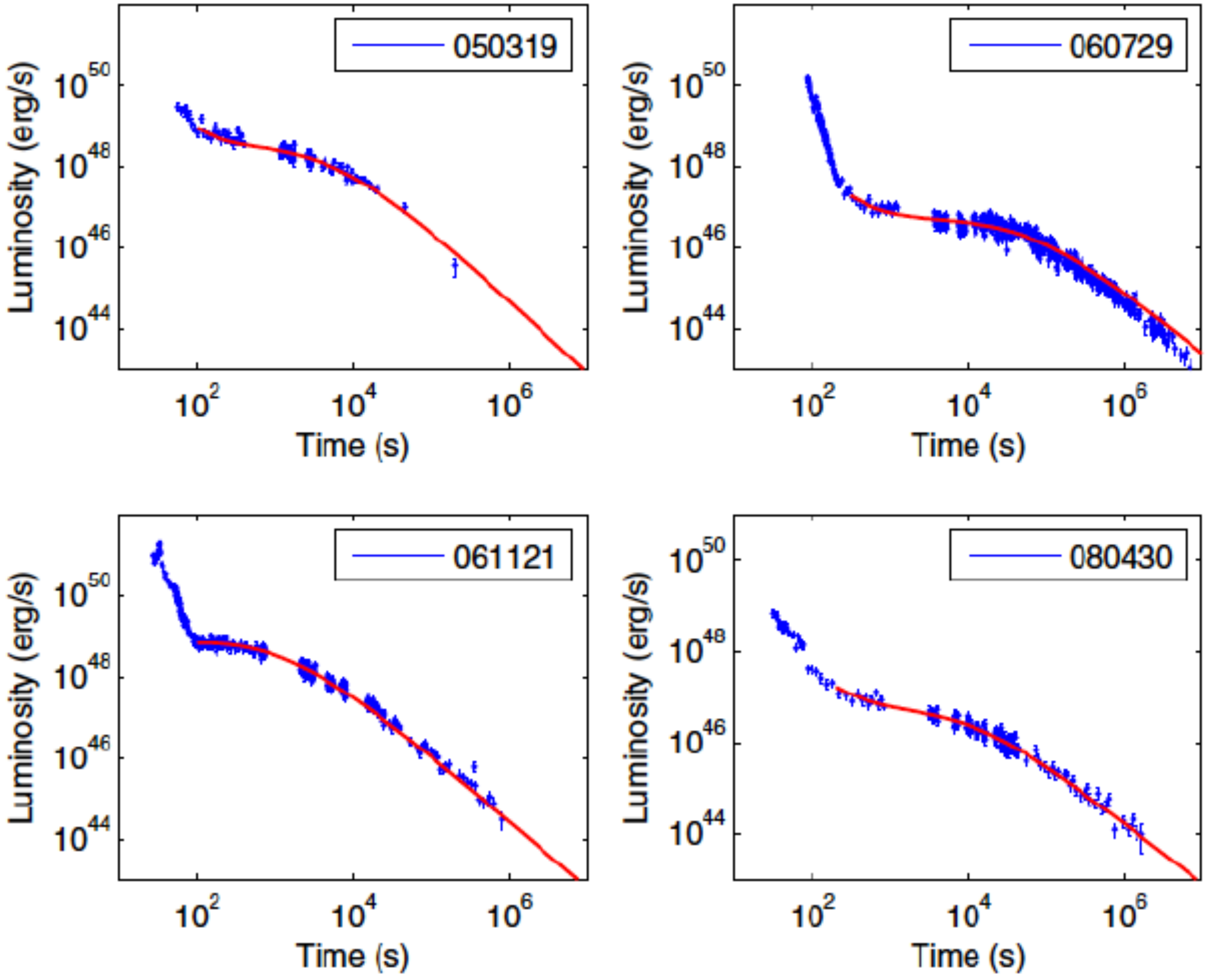


NS central engine: spindown energy

e.g. Dall’Osso et al. (2011); Dall’Osso & Stella (2021)



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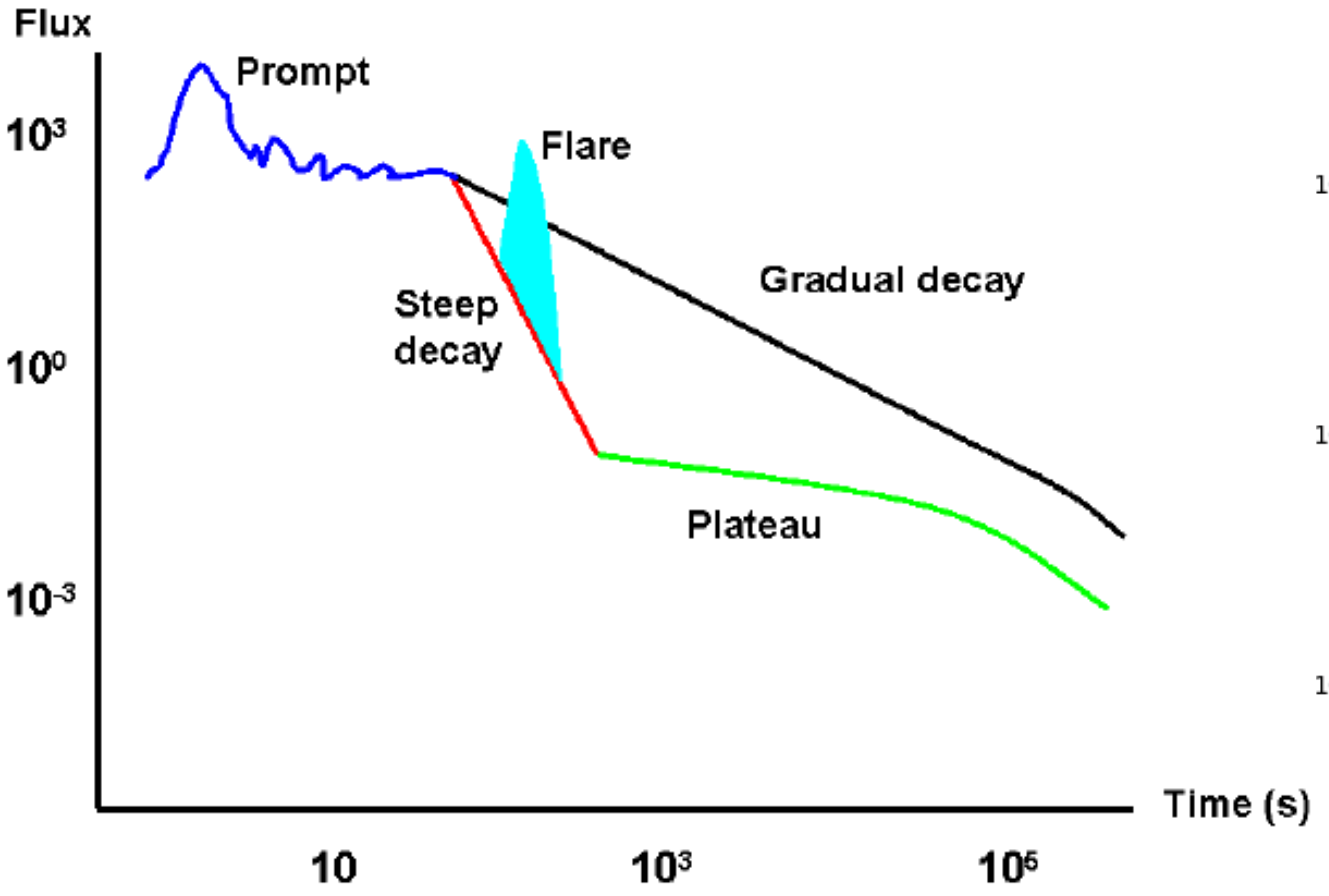

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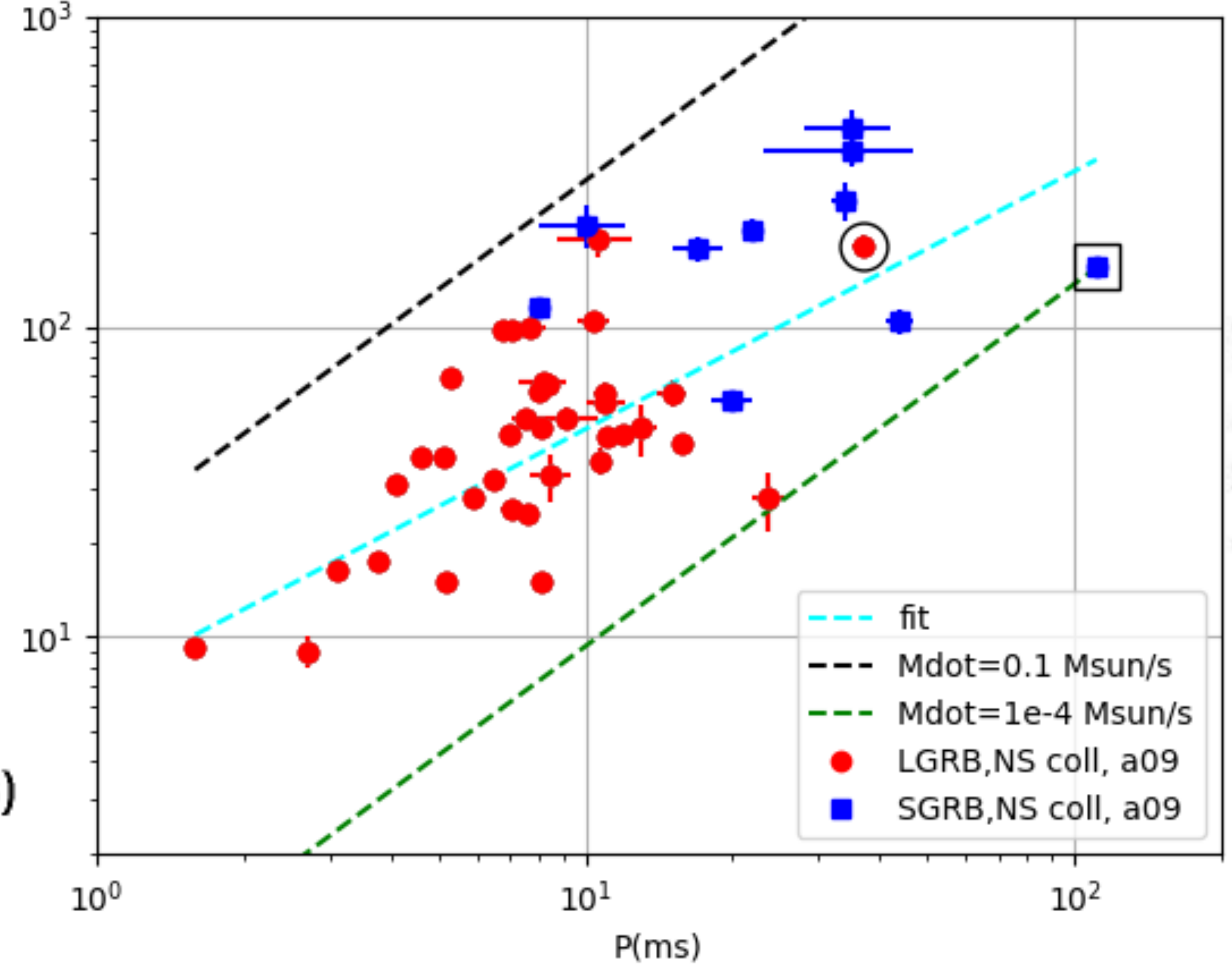
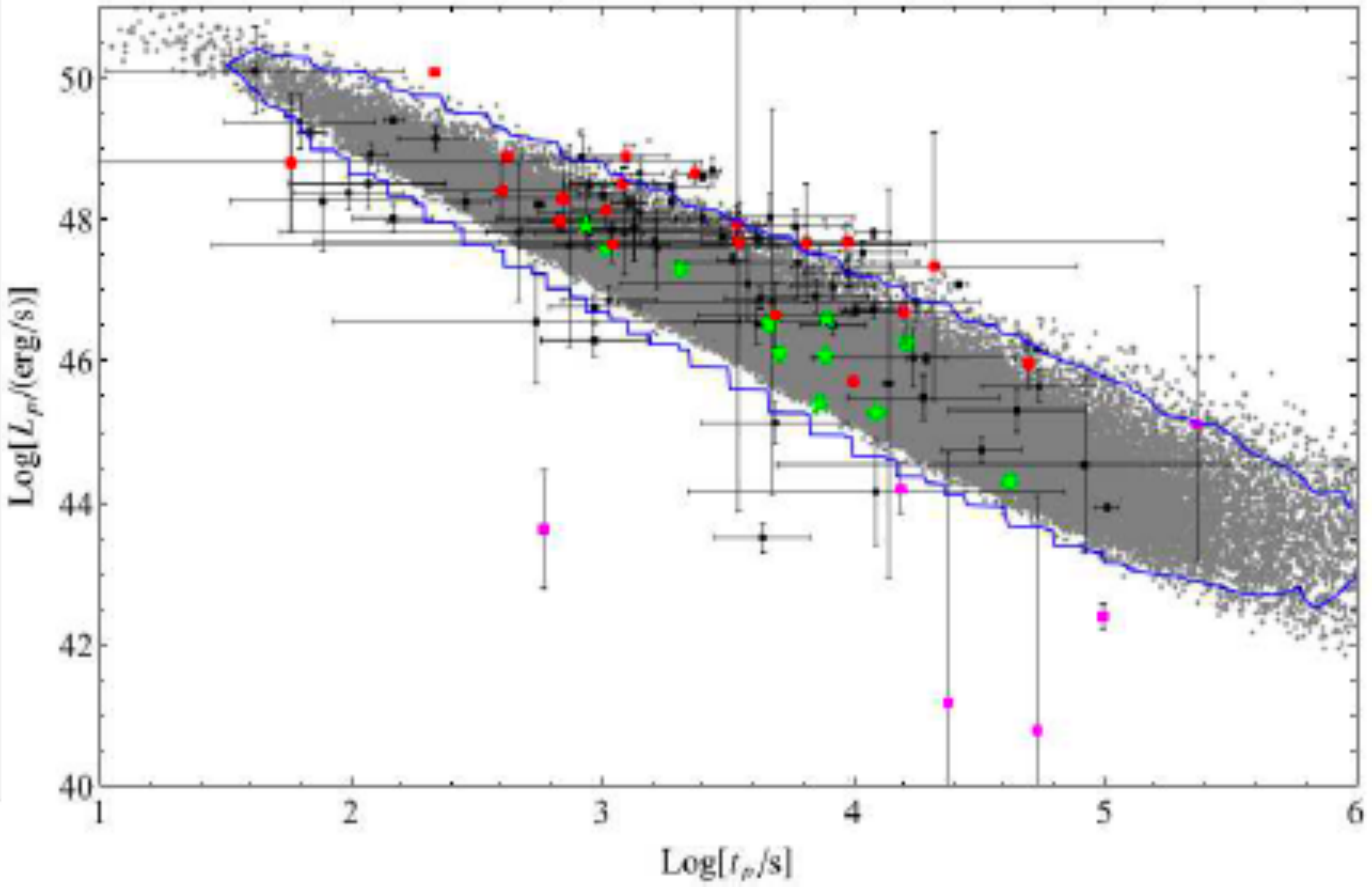
Stratta, Dainotti, Dall'Osso, Hernandez (2018)



Bernanrdini et al. (2012)



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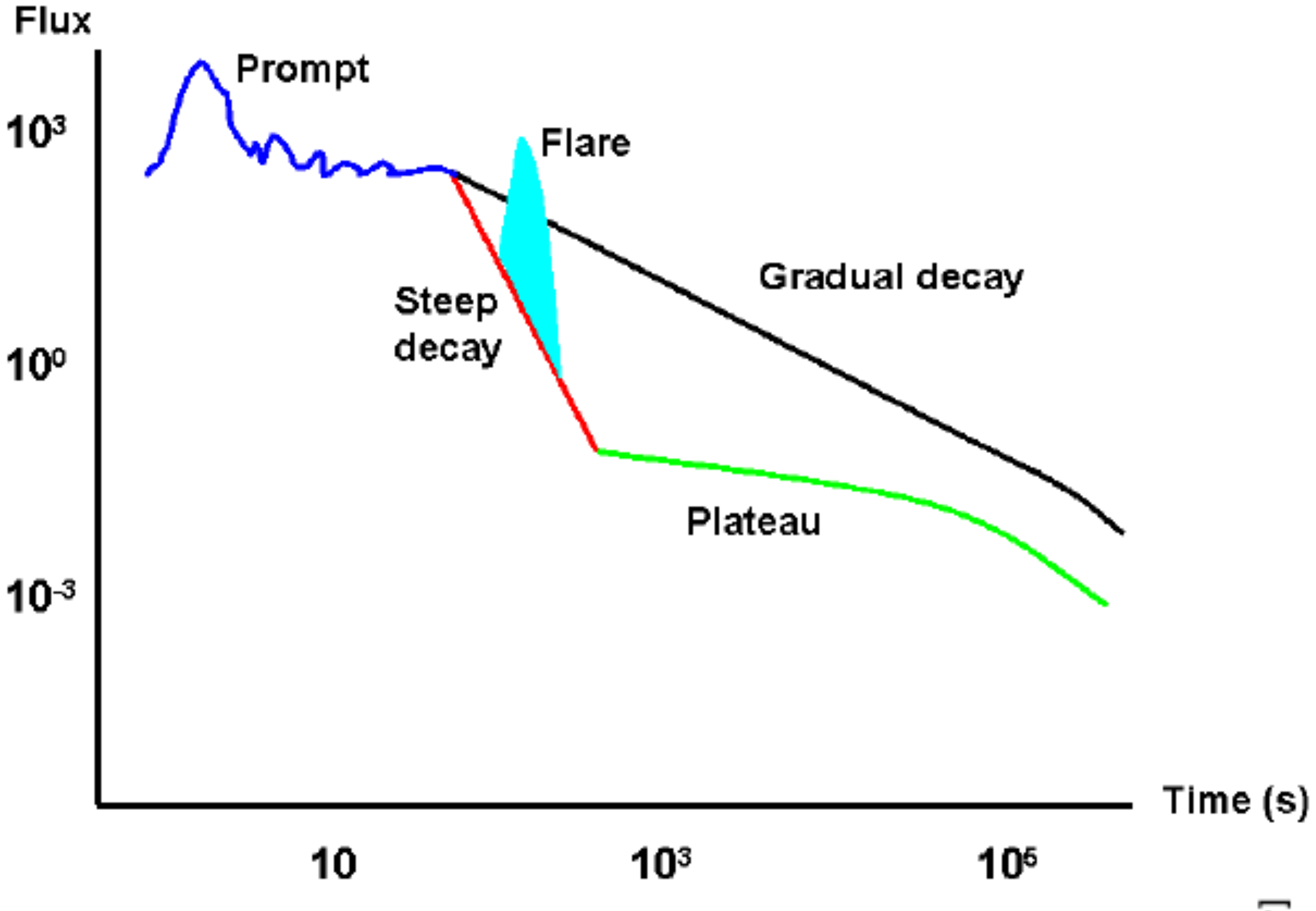
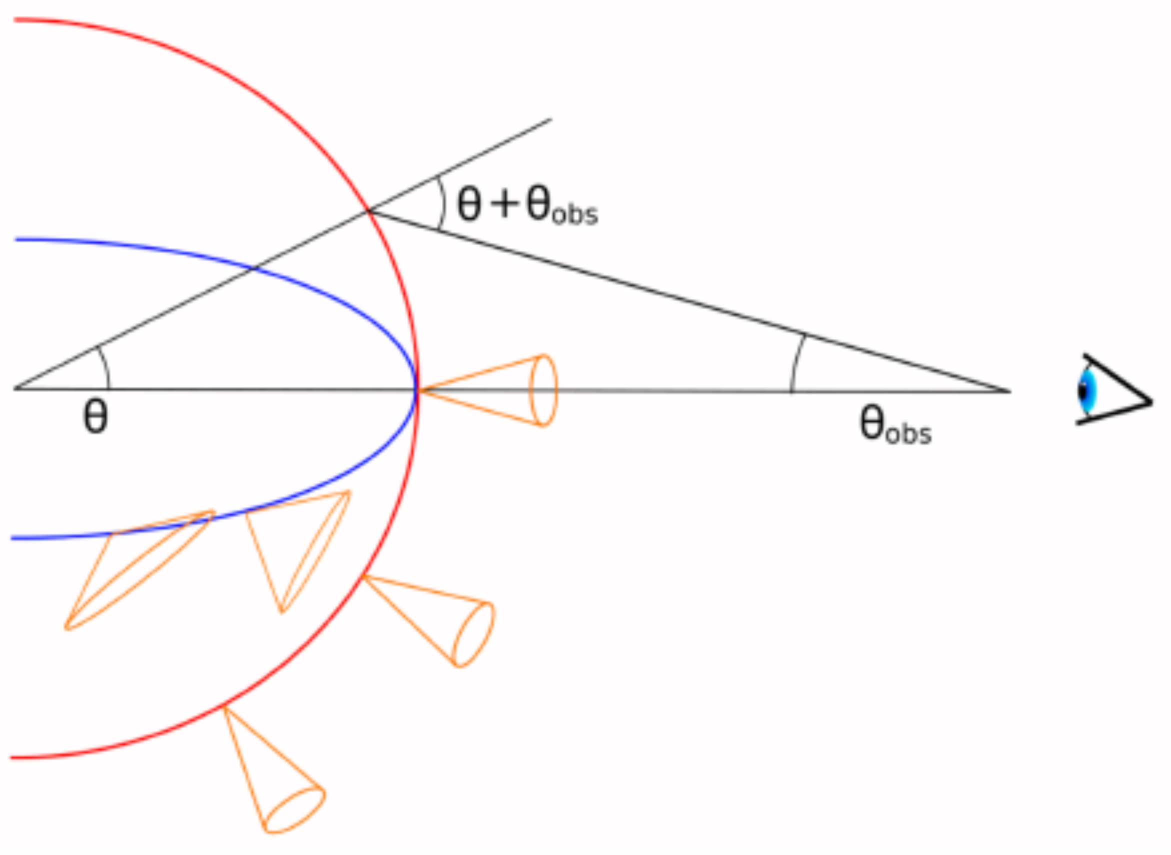
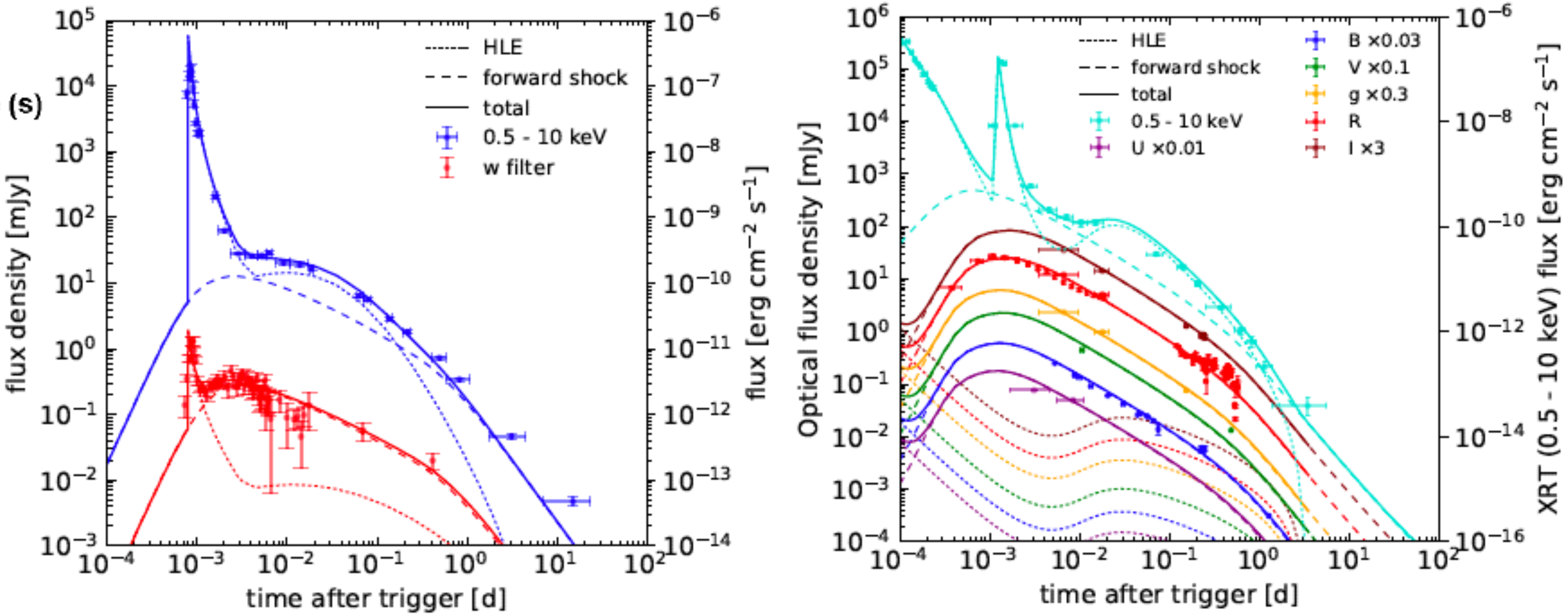




Oganesyan et al. (2020)



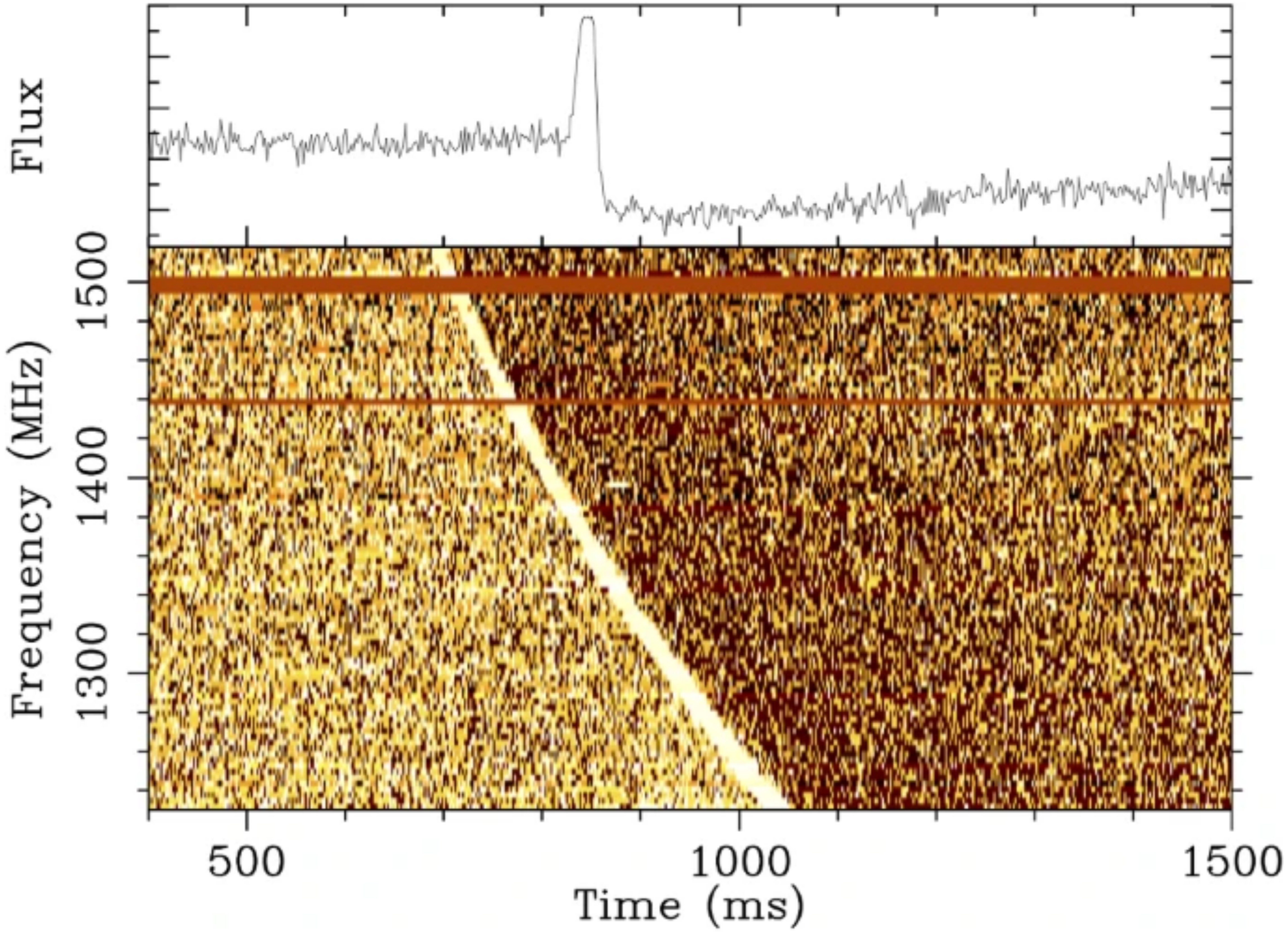
ASTROPHYSICAL IMPLICATIONS (B)

Fast Radio Bursts (FRBs)

(a) ms-long radio bursts with huge brightness temperature $T_b > 10^{31}$ K $\Rightarrow$ coherent emission

$$\boxed{\Delta E \sim 10^{37} - 10^{42} \text{ erg}}$$

(b) some of them are repeating sources, and a few of them have host galaxies/persistent radio counterparts that proved their astrophysical nature



GW astronomy, Magnetar flares and FRBs

FRB-like emission from magnetars

SGR 1935 $\left(\frac{E_X}{E_{\rm radio}} \sim 10^5\right)$

$\left(\frac{E_X}{E_{\rm radio}} \sim 10^9\right)$

1E 1547

Bochanek et al. 2020

Israel et al. 2020

GW astronomy, Magnetar flares and FRBs

Magnetar-like repeating FRB: FRB 121102

(a) Provide a better handle into the properties and energetics of their sources

$$\langle L_{\rm FRB}\rangle \sim 8\times 10^{34}\,\frac{f_b}{\epsilon_r}\ \text{erg s}^{-1}$$

Lu & Kumar 2018
Li et al. 2021

(Based on continued monitoring of a large number bursts)

$$\langle L_{\rm FRB}\rangle \sim 10^{36}\,\frac{f_b}{\epsilon_r}\ \text{erg s}^{-1}$$

Li et al. 2021

This is by far the most frequently repeating FRB source.
It has a "time windowing" of ~ 160 days and during active periods produces energetic bursts on a daily basis

For an active lifetime ~ 30 yrs (the age of its persistent counterpart)

$$E_{\rm min} \sim 8\times 10^{44}\ \text{erg}\ \frac{f_b}{\epsilon_r} \Rightarrow E_{\rm min} \sim 10^{49} - 10^{50}\ \text{erg}$$

$$\left(\frac{E_X}{E_{\rm radio}} \sim f_b/\epsilon_r \sim 10^5\right)$$

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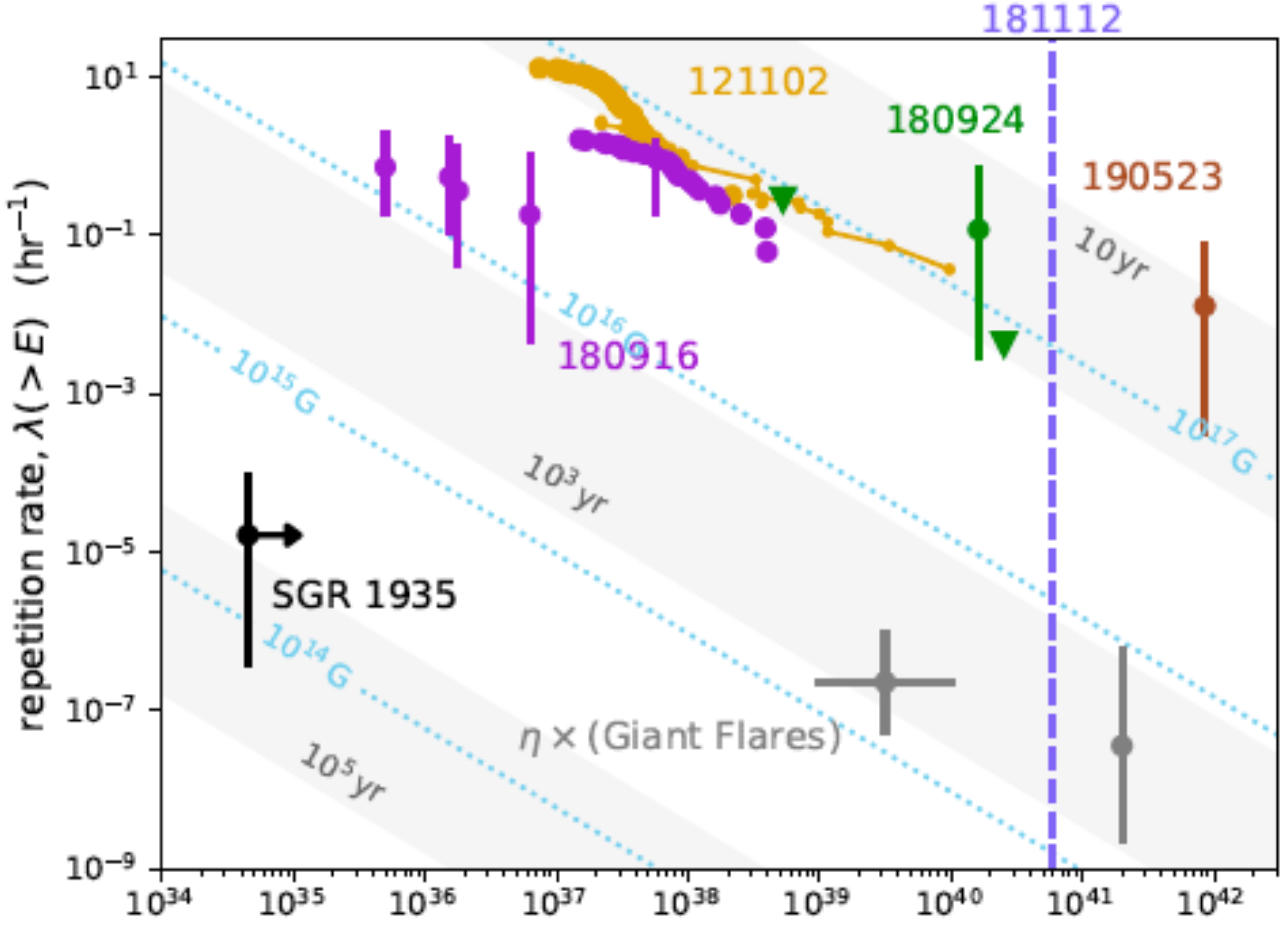

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Li et al. 2021

Surprisingly long timescale

Freebody precession of a ~ 1 s spin NS, with $\chi \gtrsim 80^\circ$ (nearly orthogonal) and $\epsilon \sim 10^{-5} - 10^{-4}$ is possible

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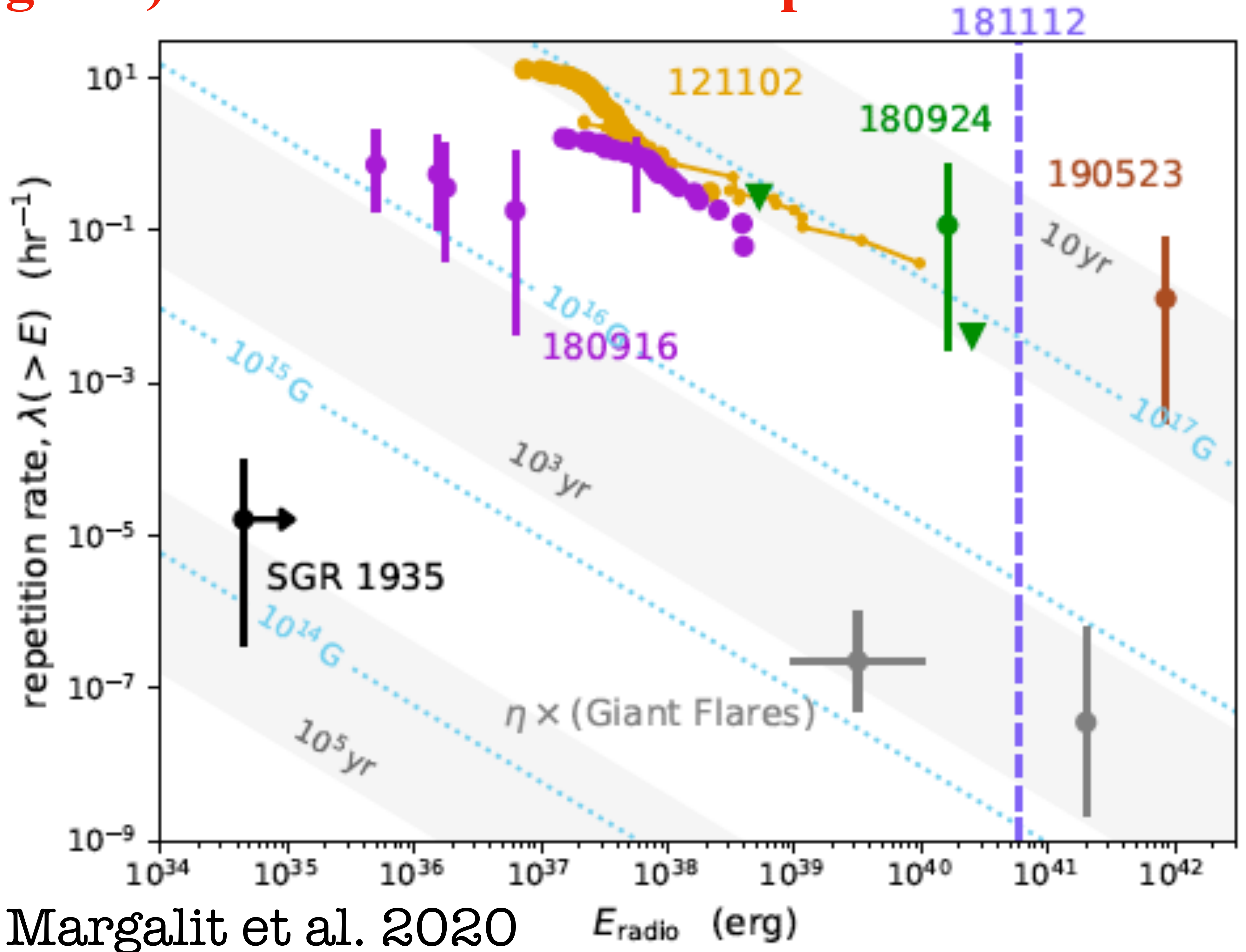

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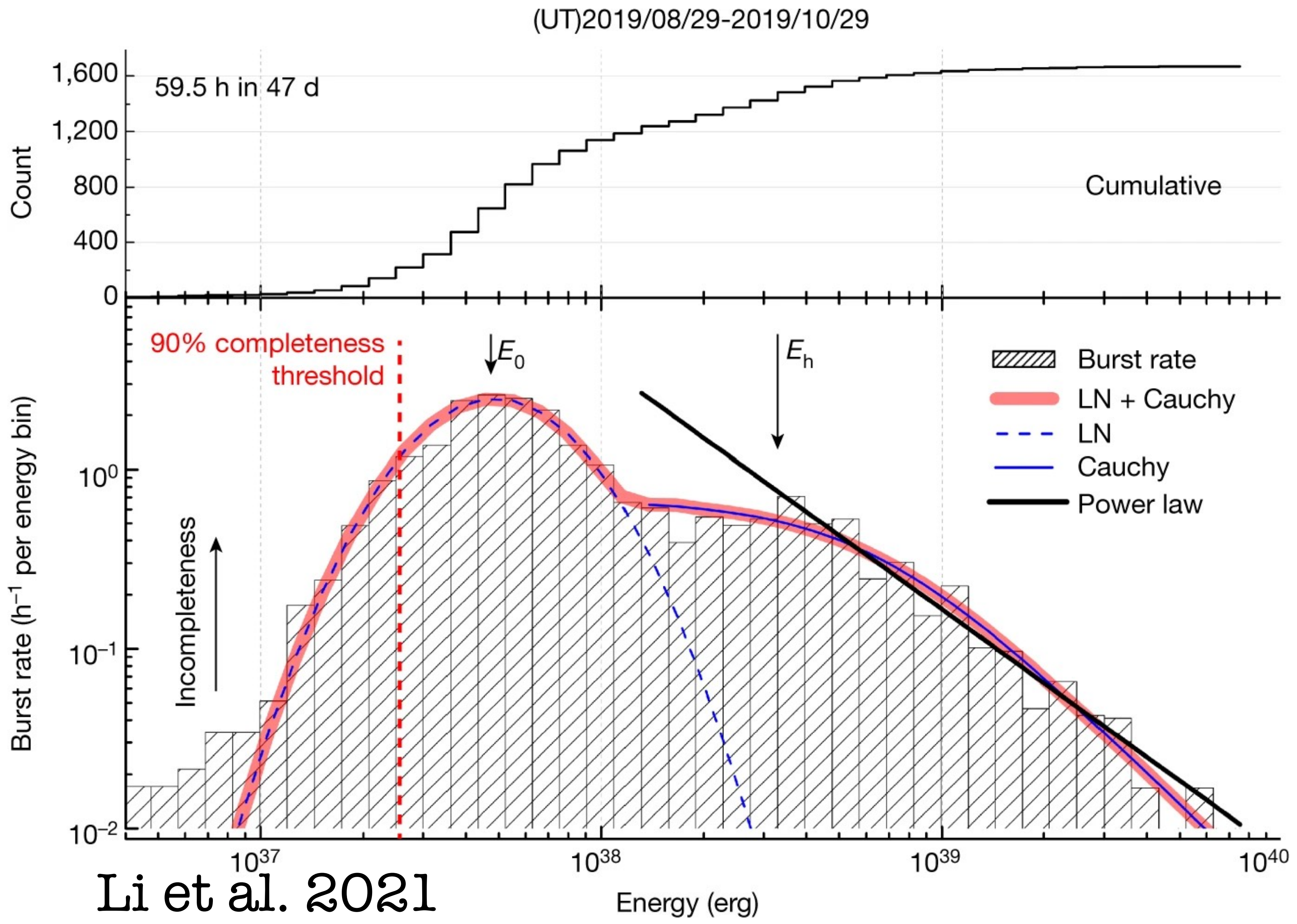

Li et al. 2021

TIMELINE & OUTLOOK

1. **(under way)** close comparison of observed GRB afterglows and afterglow-prompt correlations with different model predictions, in order to rank their credibility and
   Longer-term goal: modelling of GRB broadband afterglows in order to ultimately identify the nature of plateaus and of their central engines. Crucial to characterise the cosmic magnetar population and its physics parameters.

2. **(under way)** detailed study of the FRB population (repeaters vs. non-repeaters, global energetics, energy distribution of individual events, redshift distribution of sources).
   Longer-term goal: clarifying the link between FRBs and the extragalactic population of (young) magnetars.
   Crucial to characterise the cosmic magnetar population and its physics parameters.

3. **(in progress)** developing an ad-hoc search pipeline, building on existing work and expertise in the Rome Group
   Longer-term goal: build signal templates, test search pipeline performances and implement machine learning techniques to optimise search efficiency

TIMELINE & OUTLOOK

4. **(next up)** building a (Bayesian) parameter estimation scheme for future detections, based on signal injections and simulations with our newly developed pipeline(s)

5. **(next up)** preparing a wide observing strategy which includes multi-band EM observations aimed at identifying the early signatures from the core-collapse of a massive star (e.g. shock break-out), or even the EM signal from a newborn magnetar, exploiting existing or forthcoming satellites (optical: Sifap 2;UV: Swift-UVOT/ UltraSat; X-rays: Swift-XRT).
   Crucial to complement GW signal searches, enhancing their sensitivity and maximising the extraction of physics information from even an individual detection.

6. **(future prospect)** the operation of next generation neutrino detectors may add a new, crucial piece to the puzzle, particularly if thermal neutrinos from a few Mpc may be detected. High-energy neutrino signatures may also be identified, but more information is needed to reach robust conclusions about newborn magnetars.