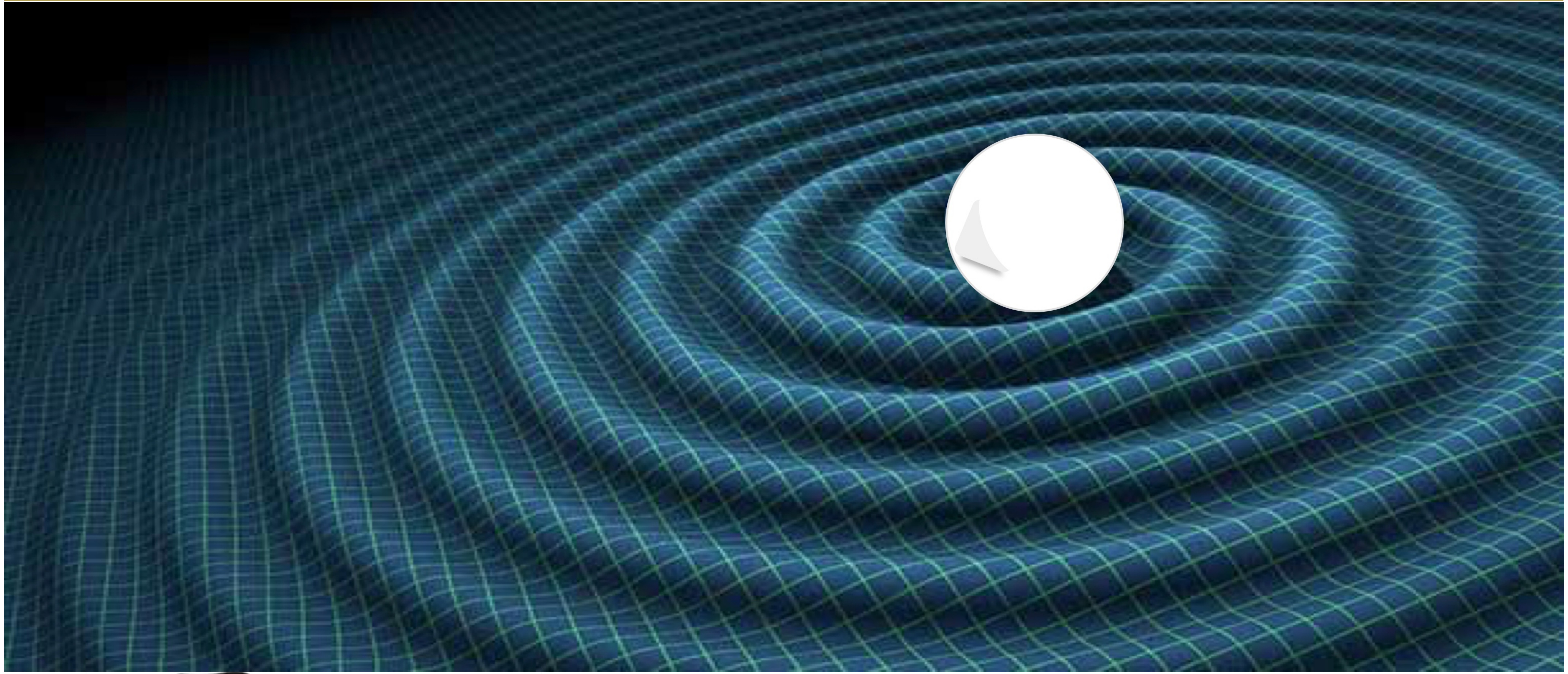
13/12/2023

The Magnetar Legacy

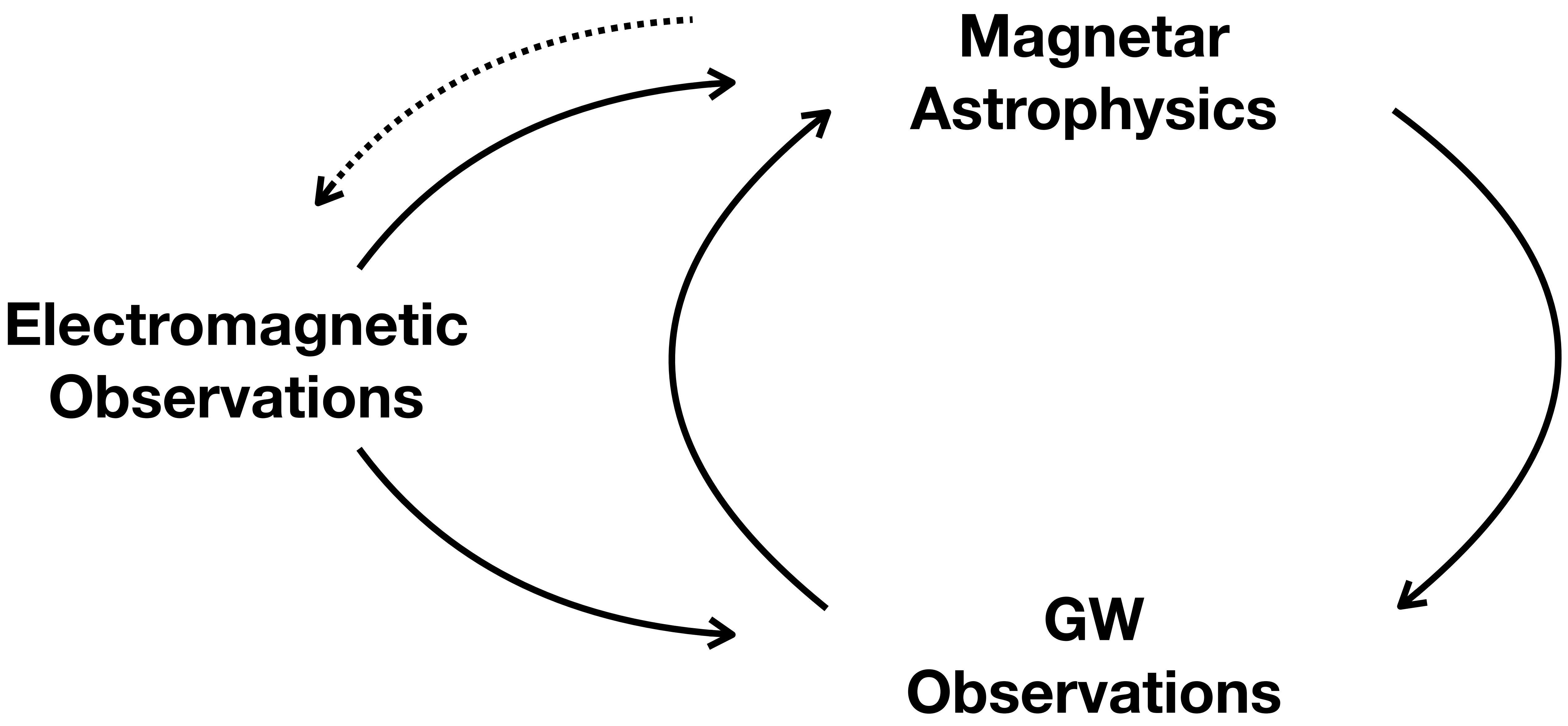


Fellowship for Innovation at INFN
H2020 MSCA COFUND
G.A. 754496

Simone Dall'Osso
INFN - Roma 1 - Virgo

Istituto Nazionale di Fisica Nucleare

OVERVIEW



1. INTRO: What are magnetars and why do we care so much?

2. Constraints on newly born and very young magnetars from astrophysical transients:
   Gamma-Ray Bursts and Fast Radio Bursts

3. Crucial role of GW detectors: long transient GW signal searches from newly born magnetars
   (O4, O5, post-O5, ET) and the need for EM counterparts

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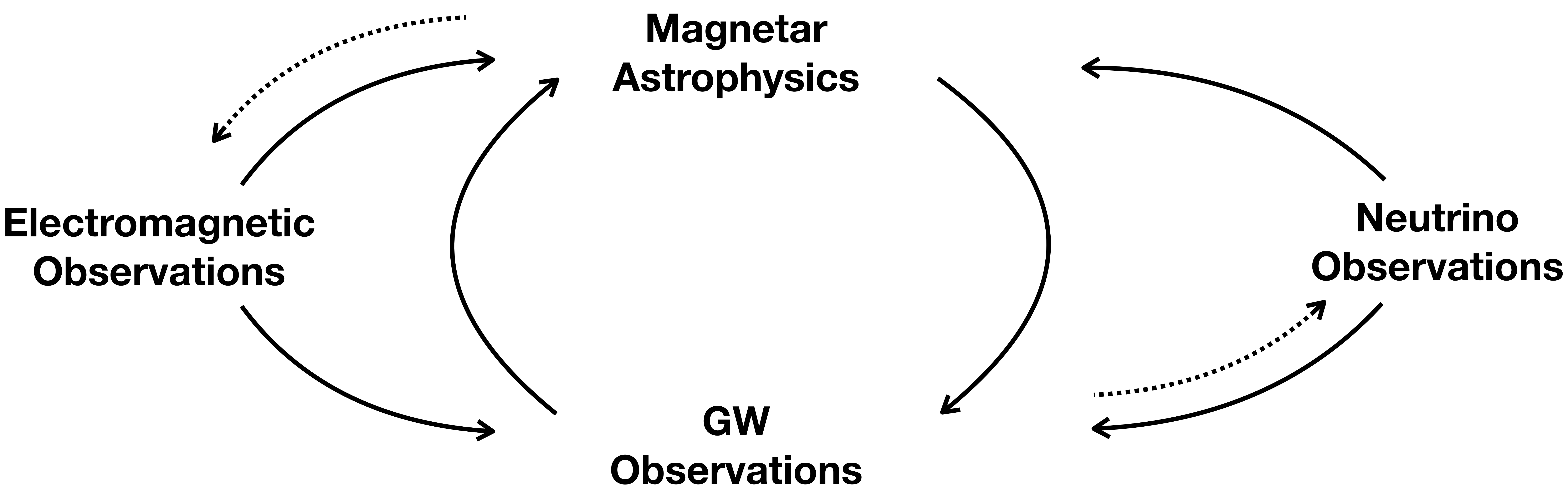

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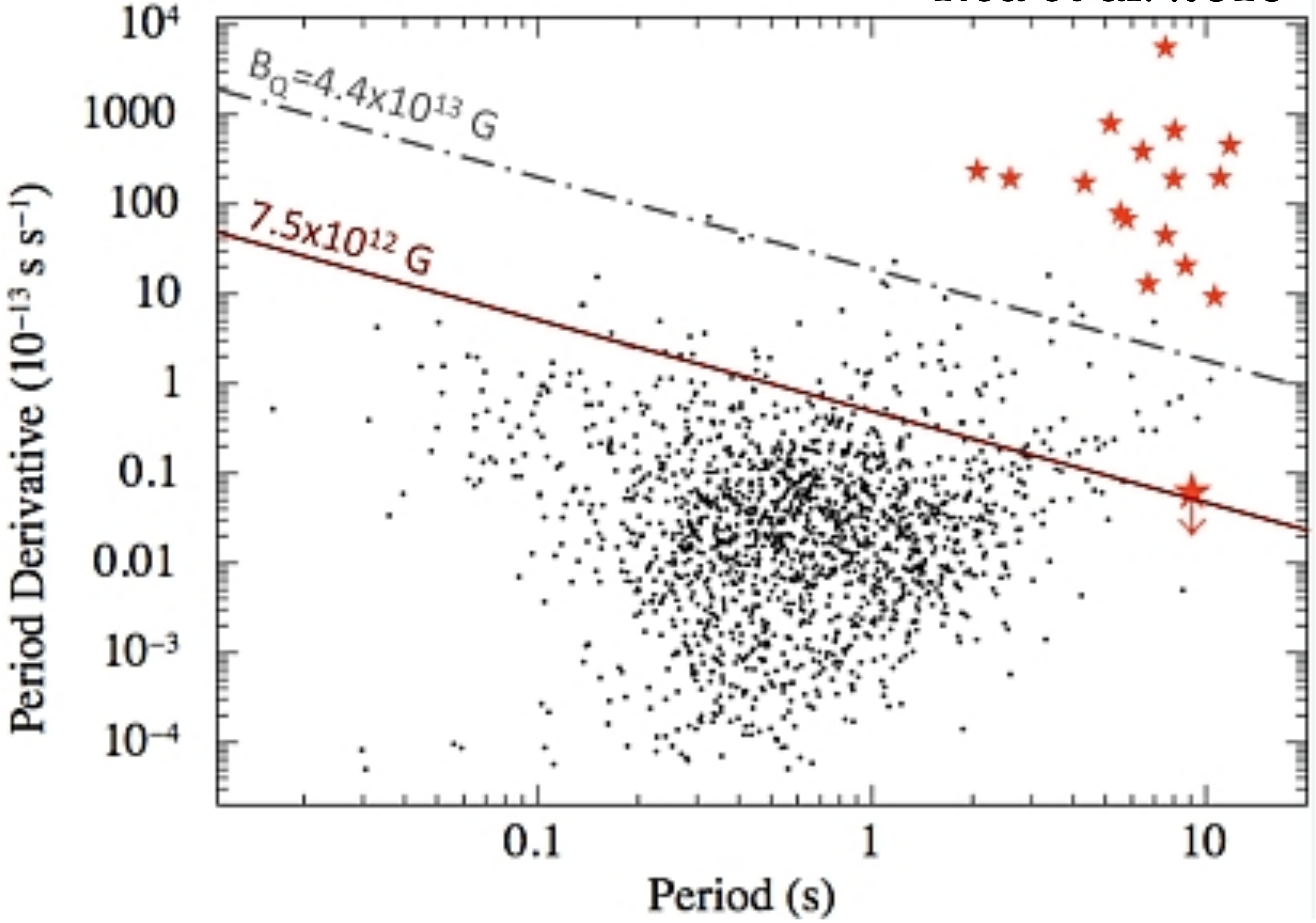
WHAT ARE MAGNETARS?

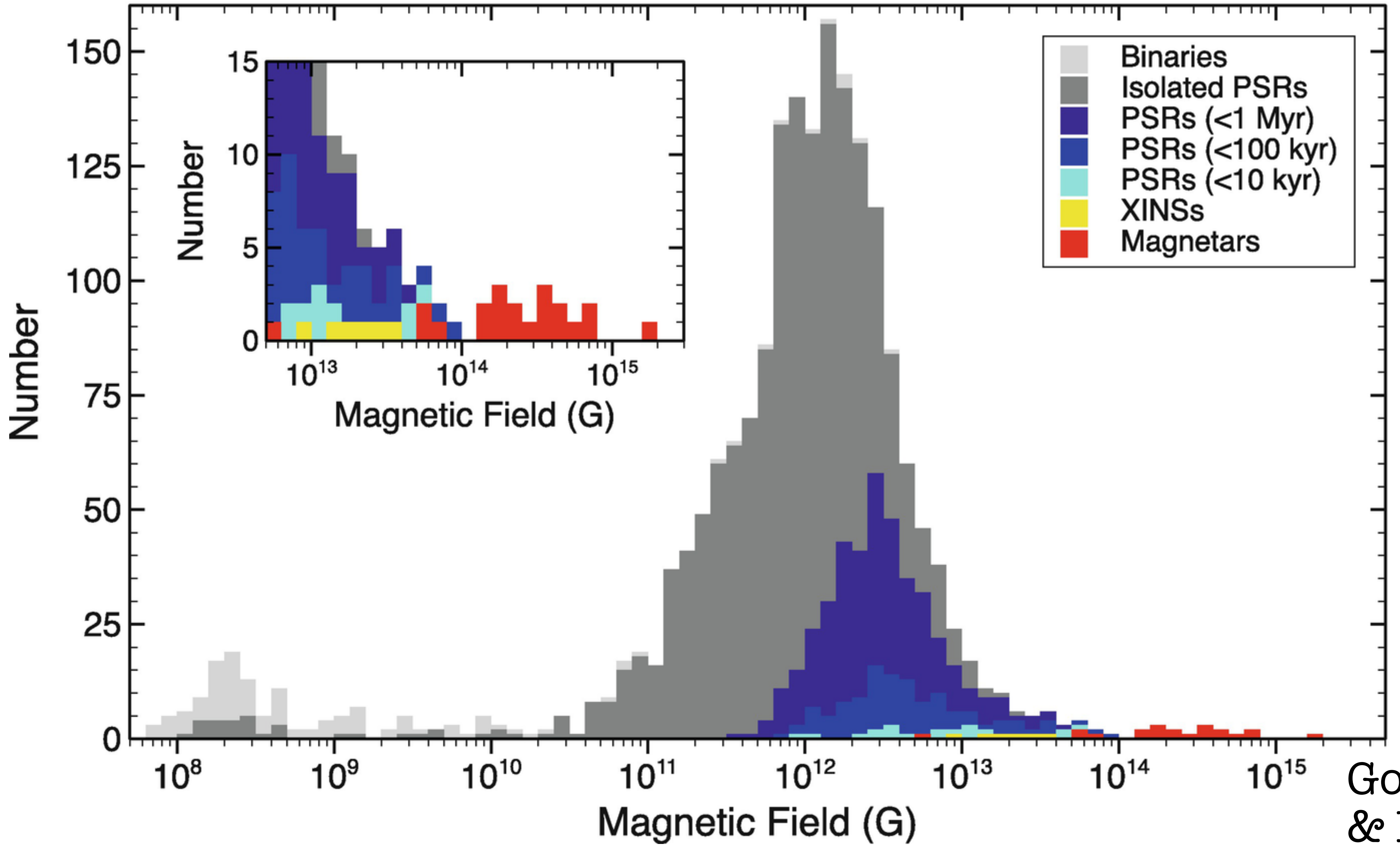
Magnetars and their signatures

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

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

Rea et al. 2010





Gourgouliatos & Esposito 2019

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

WHAT ARE MAGNETARS?

Magnetic energy is the source of their emission

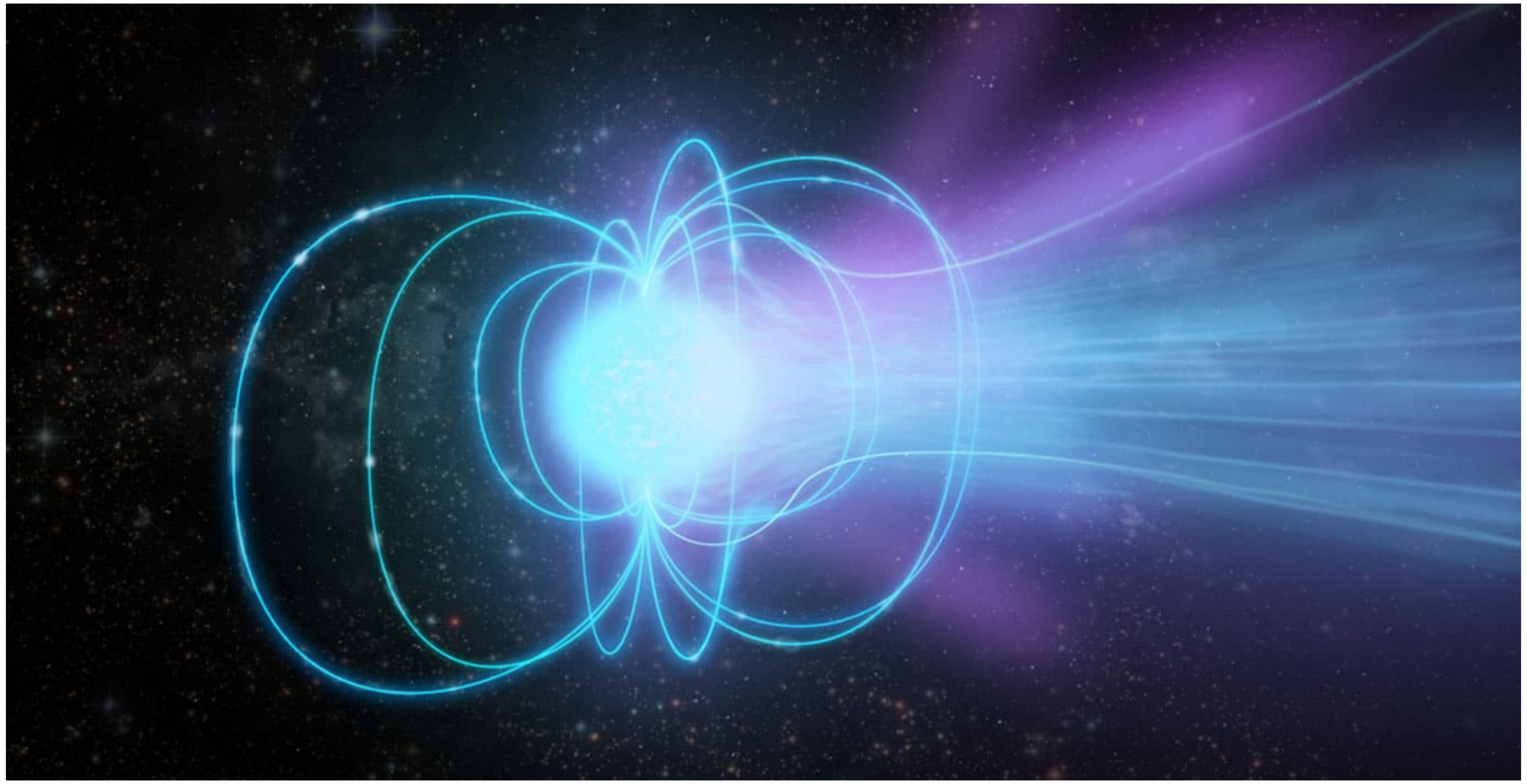
The exterior dipole is not sufficient, though.

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)

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

Strict lower limit



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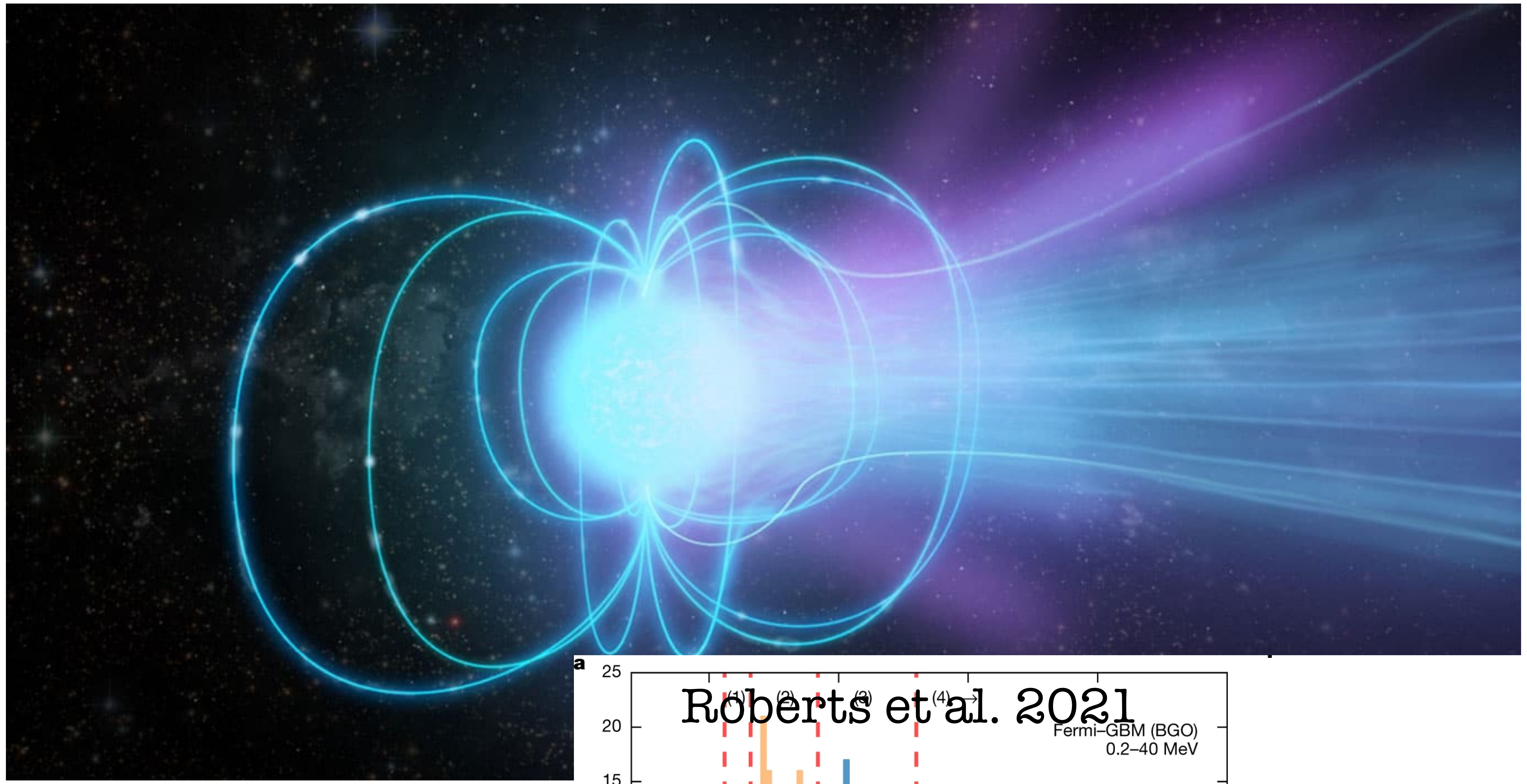
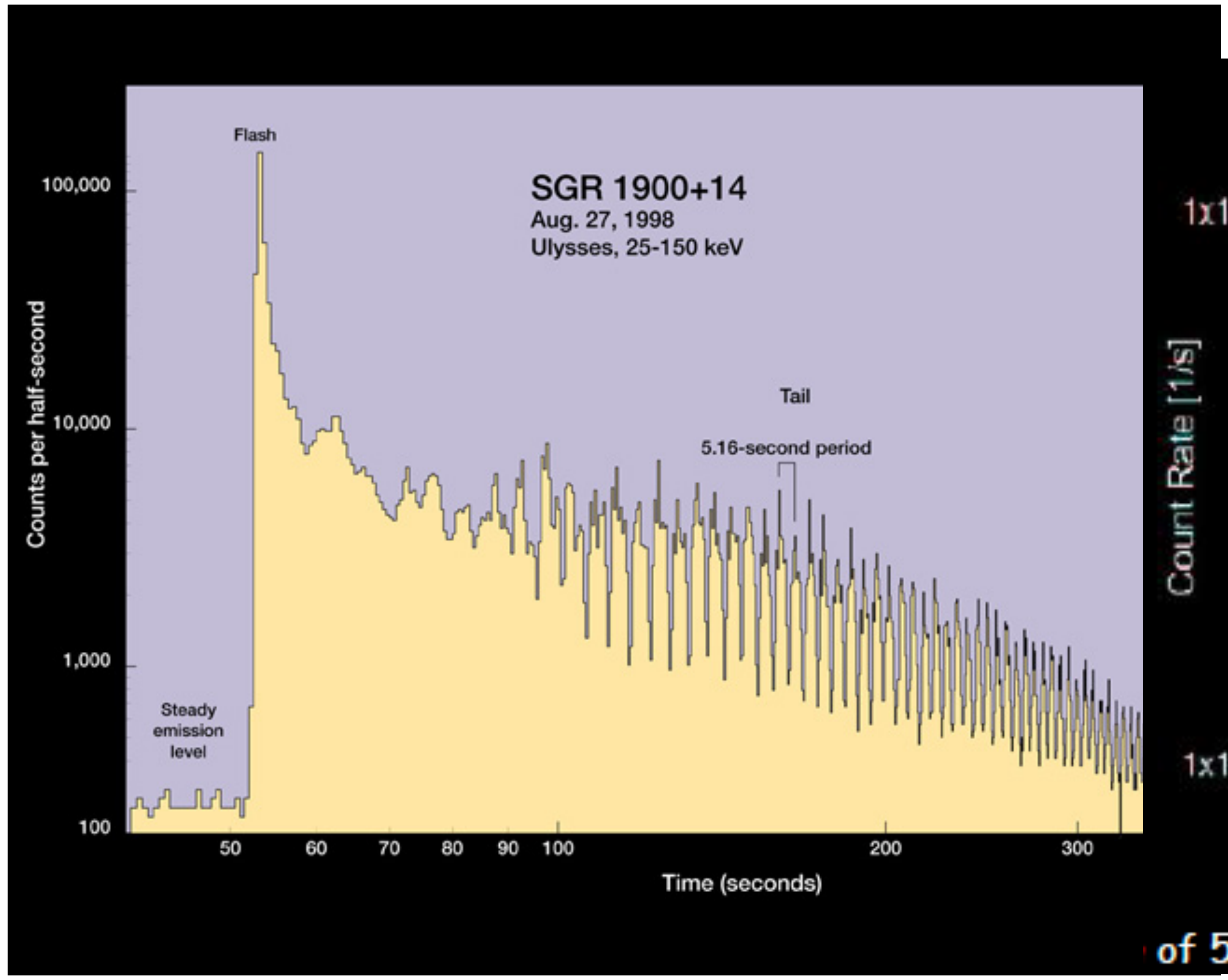
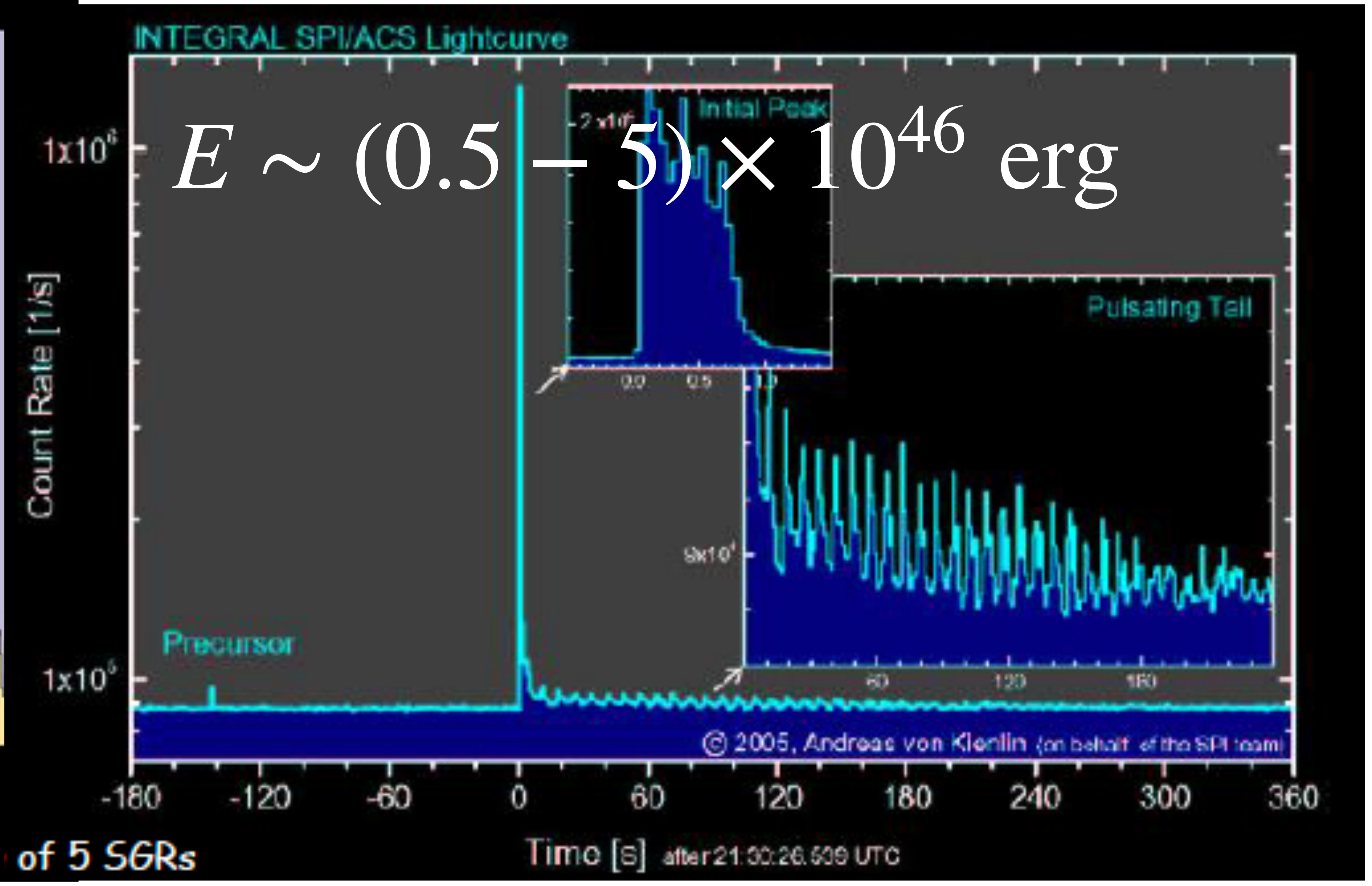
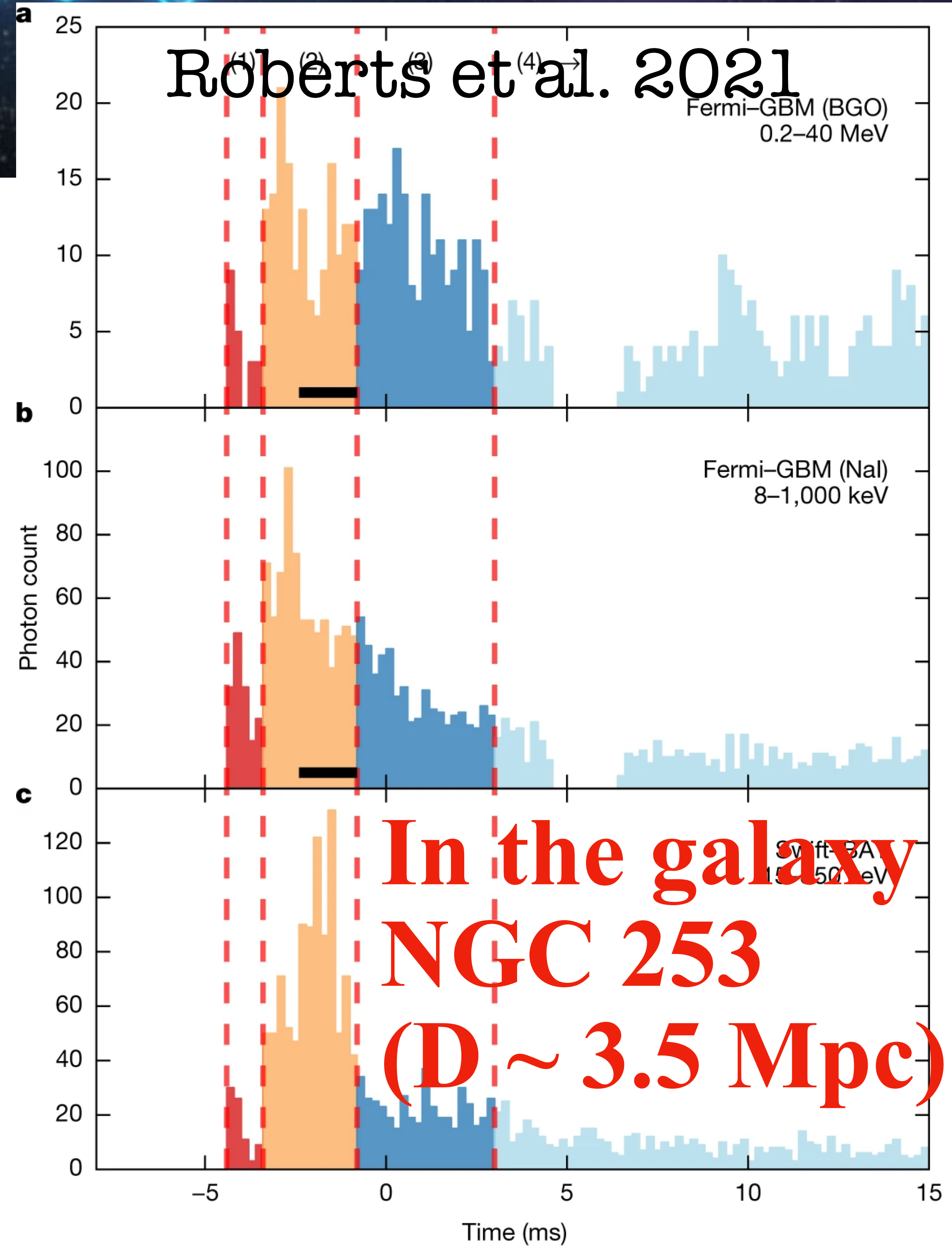






$E \sim (0.5 - 5) \times 10^{46}$ erg



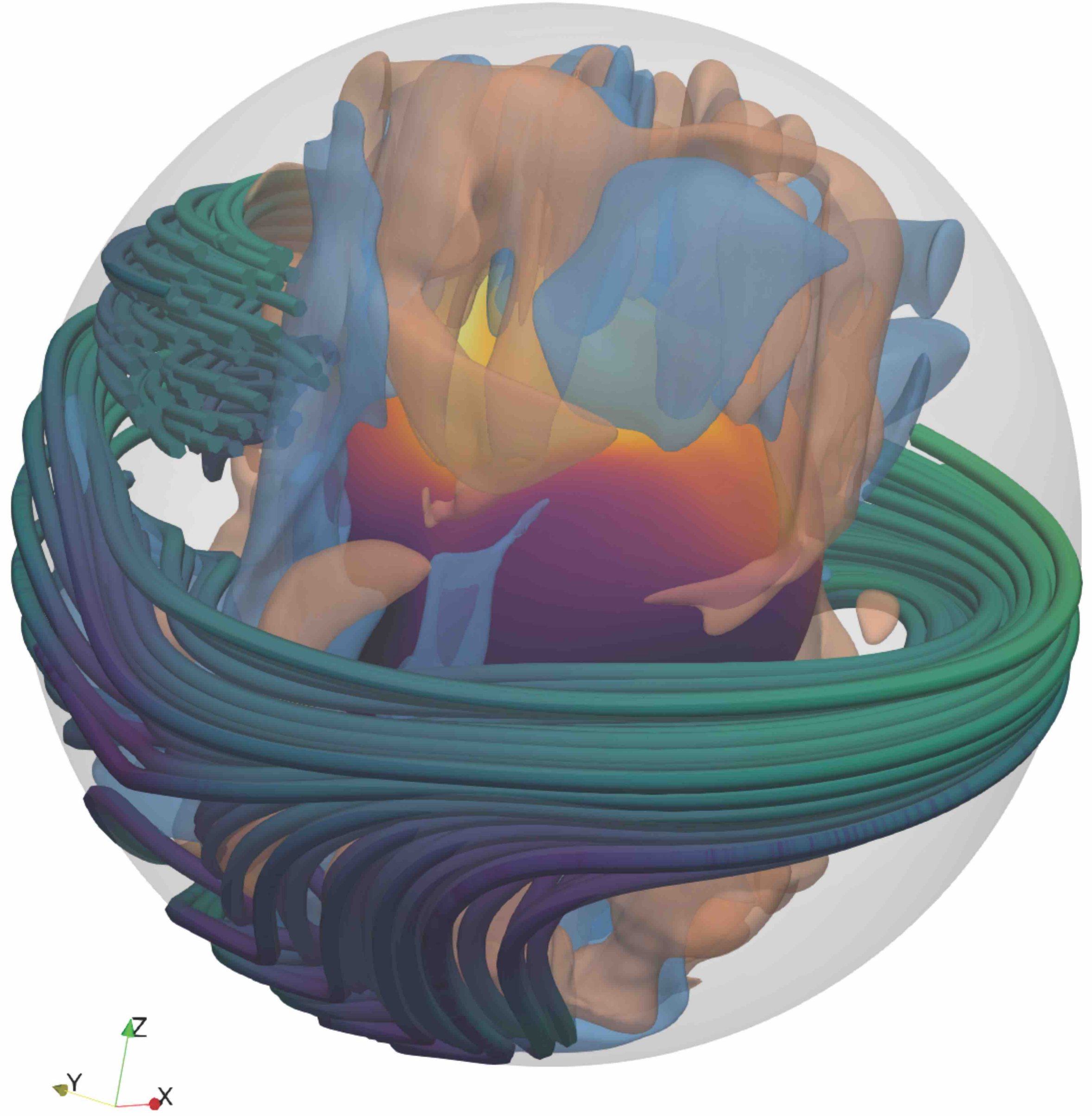
Roberts et al. 2021

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.

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

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

interior, toroidal B-field

Duncan & Thompson 1992
Thompson & Duncan 1993

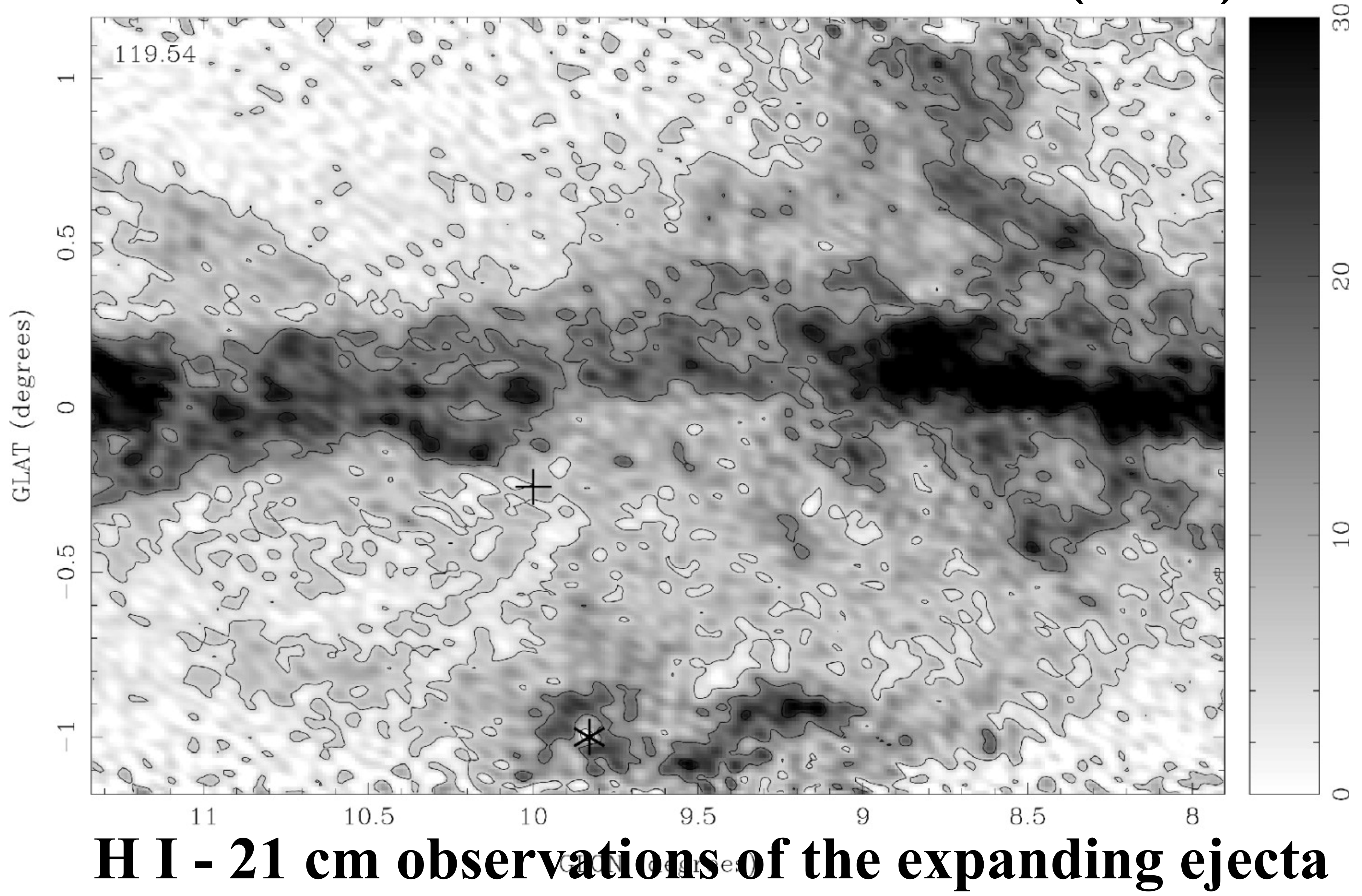
(b) We don't know yet. The mass of the progenitor star is a possibility under scrutiny.

In BNS mergers ms-spin is expected, yet a stable NS is not very likely: maximum NS mass plays a crucial role

STELLAR PROGENITORS OF GALACTIC MAGNETARS

SGR 1806-20

Cameron et al. (2005)
McLure et al. (2005)



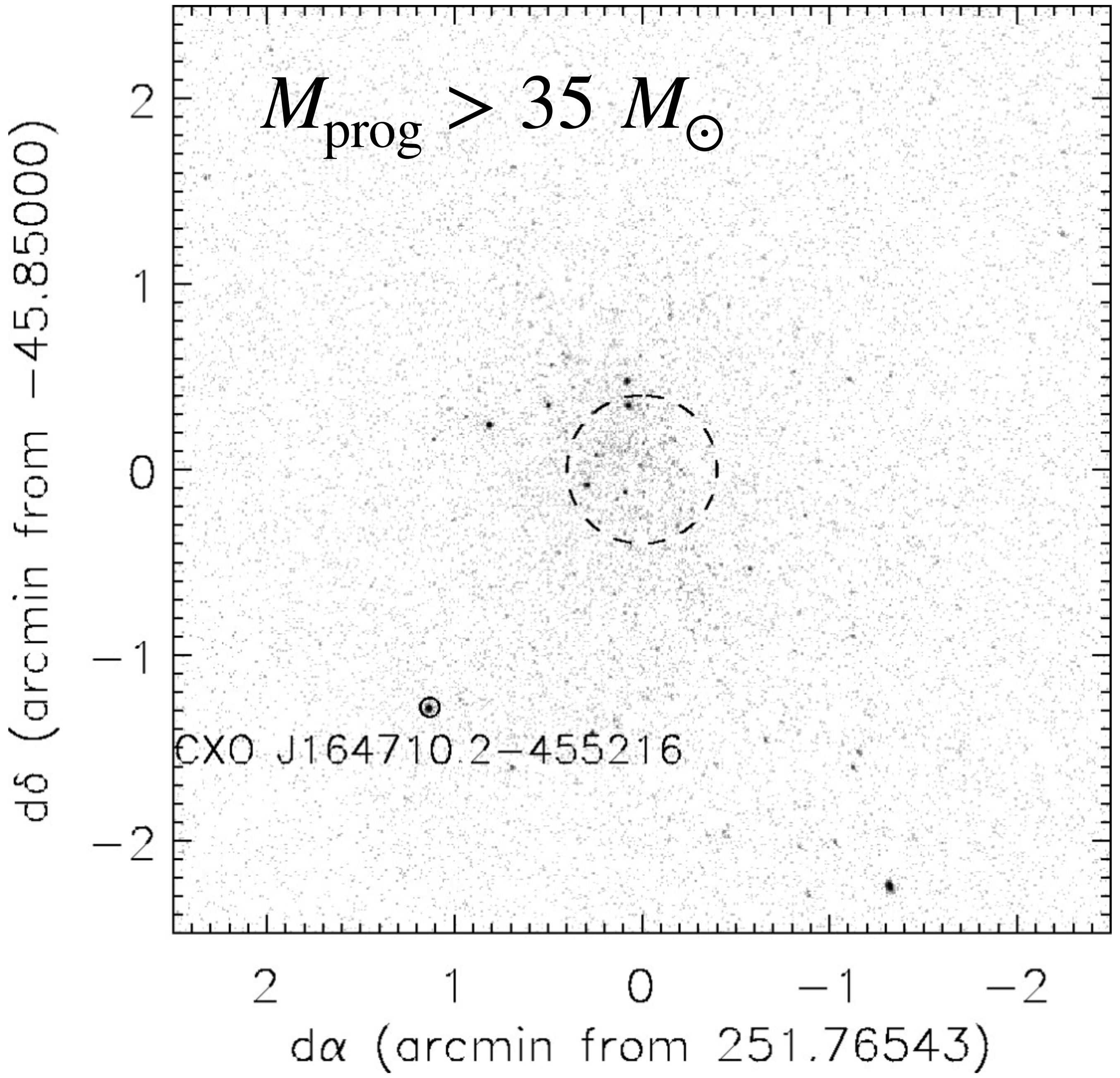
H I - 21 cm observations of the expanding ejecta following the 2004 Giant Flare

DM (mag)	d (kpc)	Star	M_{K_s} (mag)	M_{Bol} (mag)	Log T (K)	Age (Myr)	M_{init}^{OB} ($M_\odot$)	M_{init}^{SGR} ($M_\odot$)
14.0	6.3	#4	−5.1	−8.5	4.46	5	30	35
		#11	−5.2	−8.5	4.44		30	35
14.3	7.2	#4	−5.4	−8.8	4.46	4.6	33	40
		#11	−5.5	−8.8	4.44		33	40
14.7	8.7	#4	−5.8	−9.2	4.46	4	40	48
		#11	−5.9	−9.2	4.44		40	48
15.1	10.5	#4	−6.2	−9.6	4.46	3.4	49	69
		#11	−6.2	−9.6	4.44		49	69
15.4	12	#4	−6.5	−9.9	4.46	3	55	100
		#11	−6.6	−9.9	4.44		55	100
15.9	15	#4	−7.0	−10.4	4.46	2.8	80	120
		#11	−7.1	−10.4	4.44		80	120

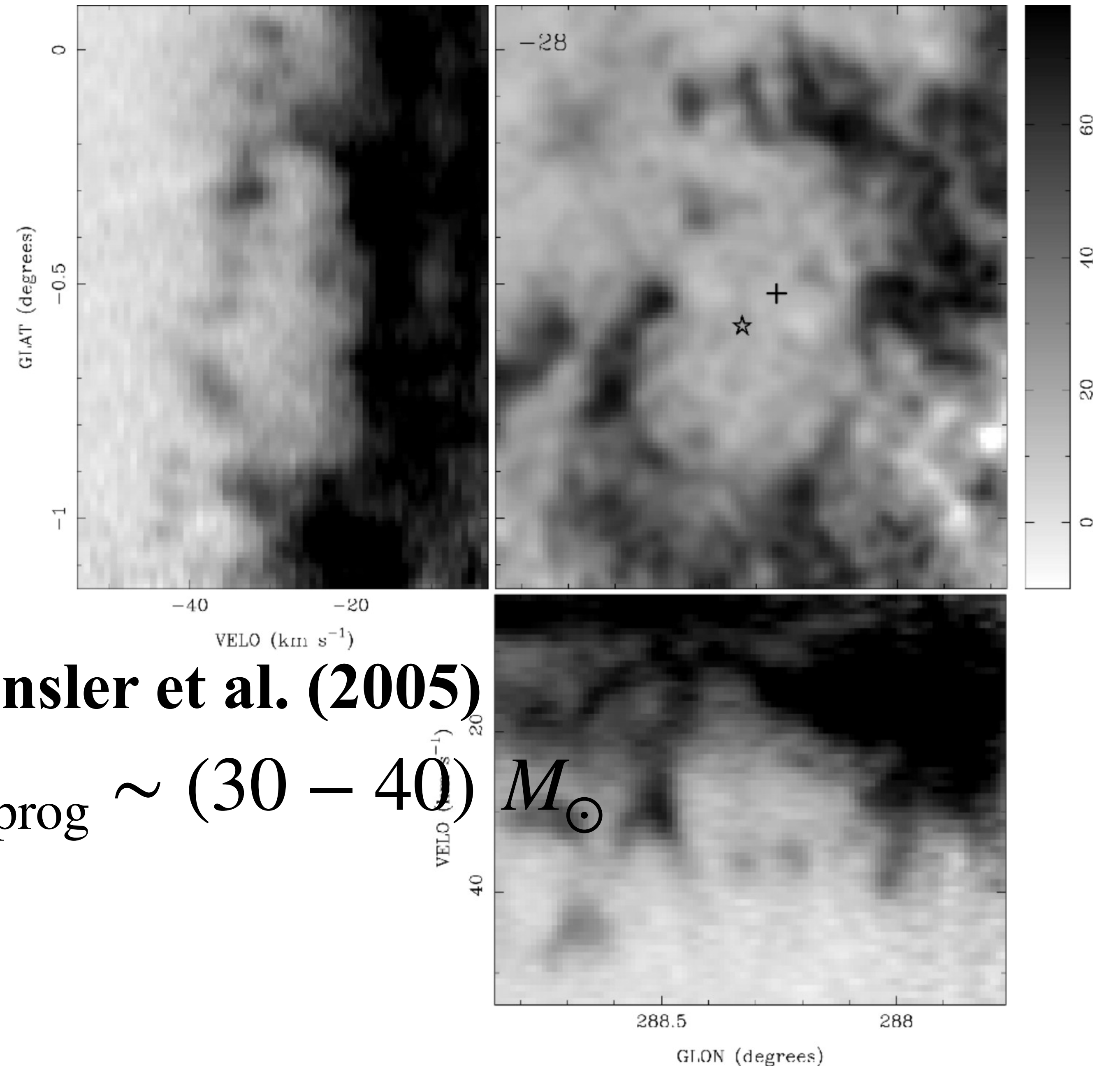
Bibby et al. (2009)

CXO J164710.2-455216

Muno et al. (2006)



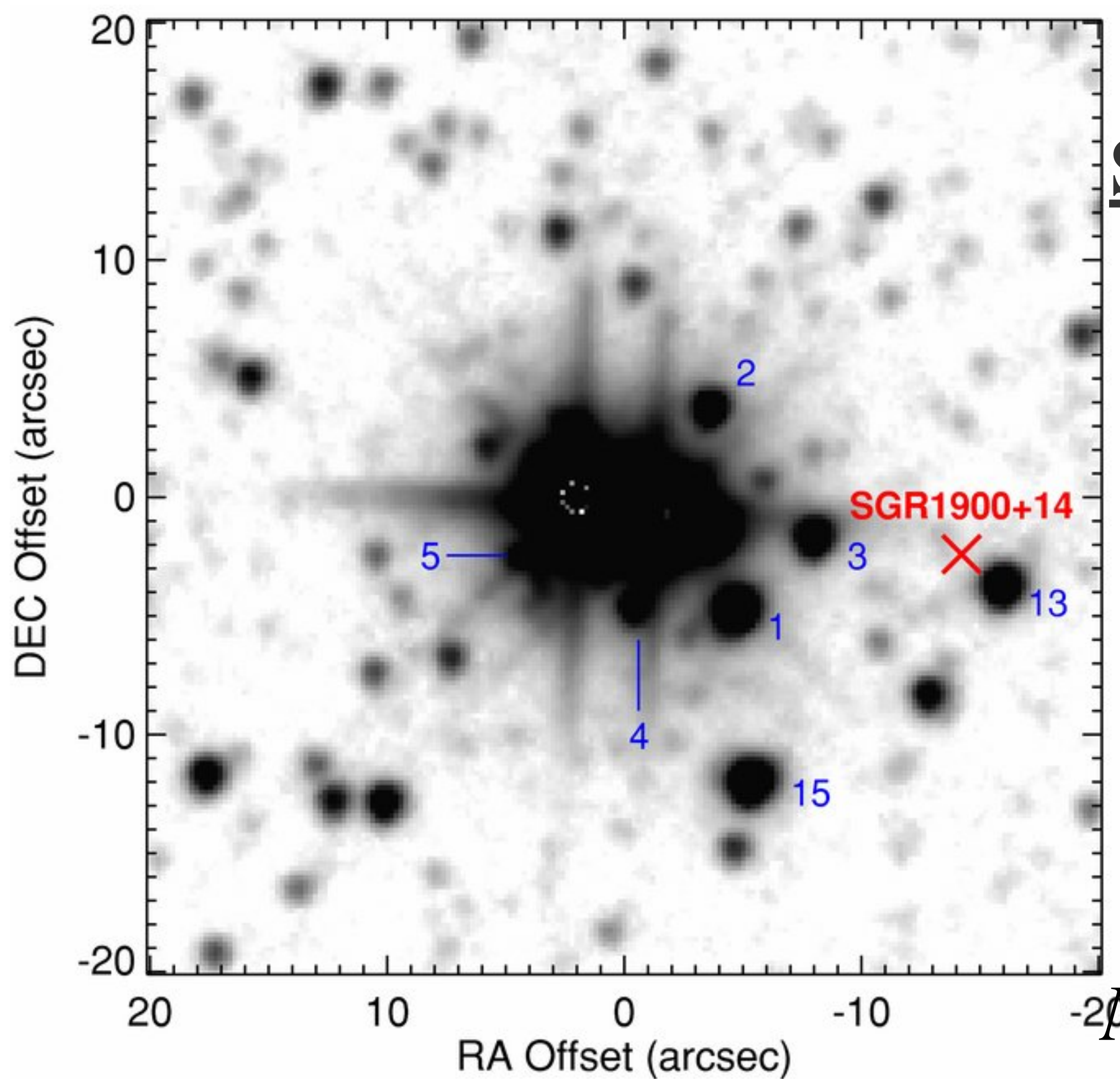
AXP - 1E 1048.1−5937

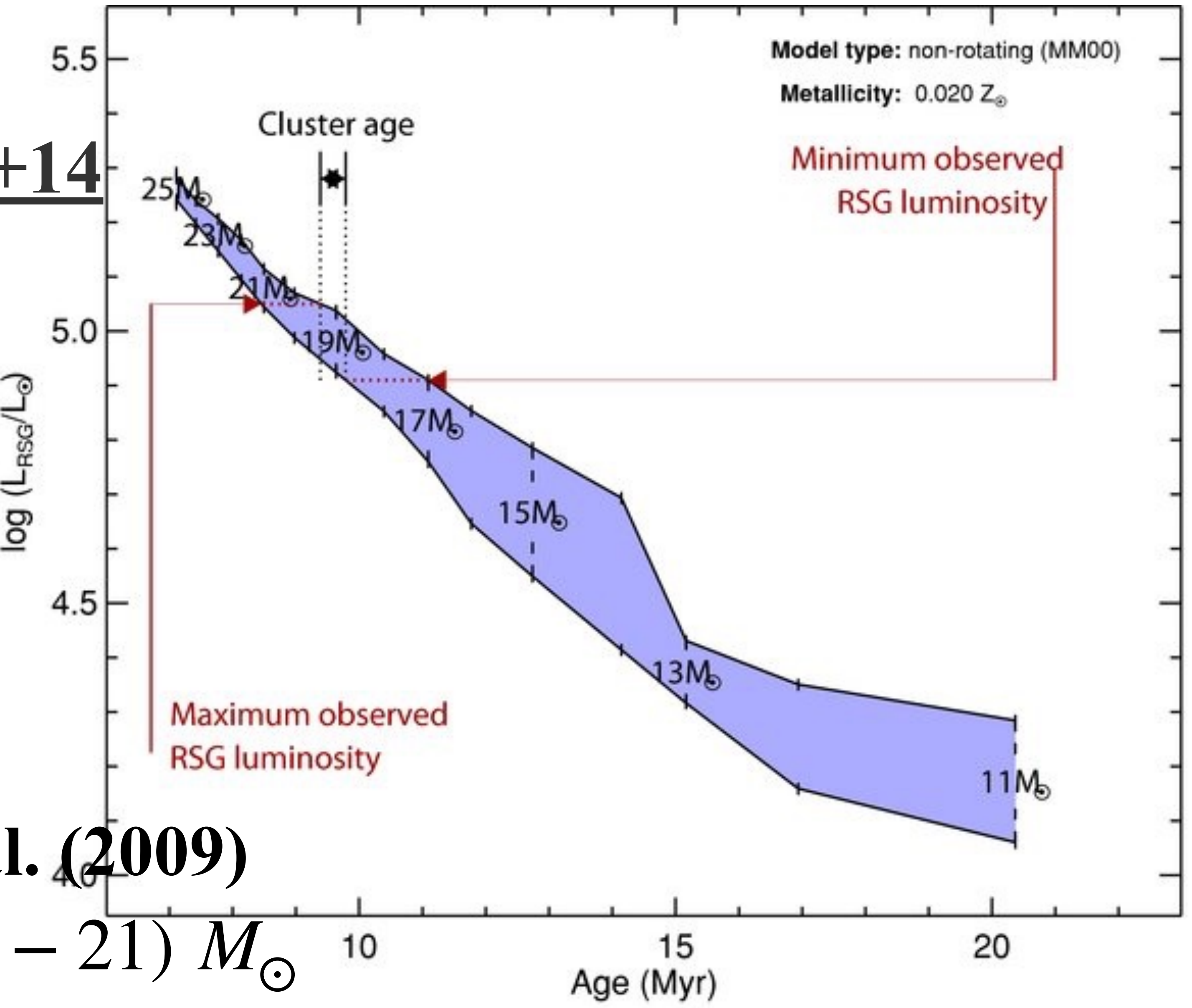


Gaensler et al. (2005)

$M_{prog} \sim (30 - 40)\ M_\odot$

SGR 1900+14

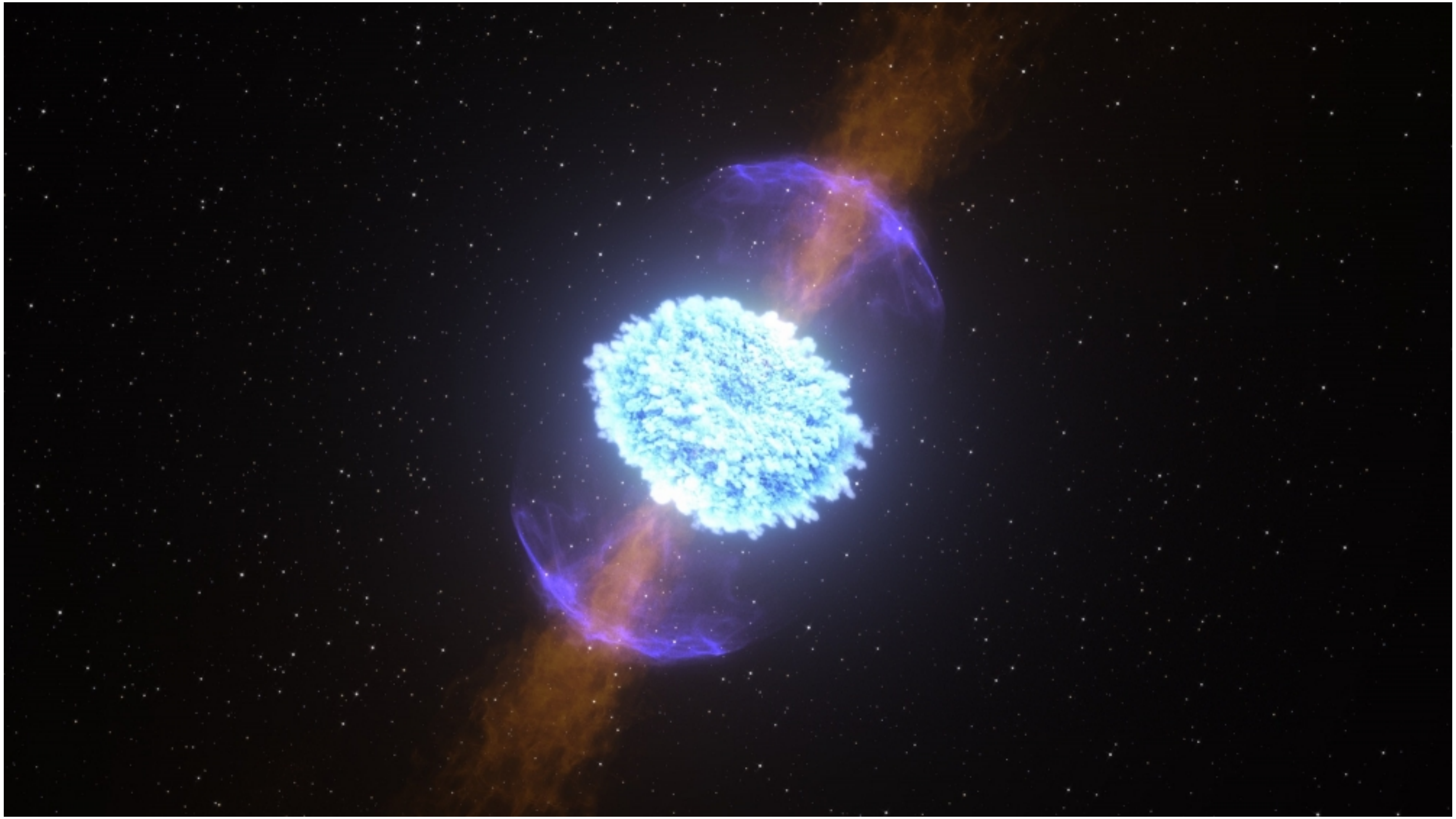




Davies et al. (2009)

$M_{prog} \sim (17 - 21)\ M_\odot$

SEARCHING MORE INFO FROM EM OBSERVATIONS: GRBs



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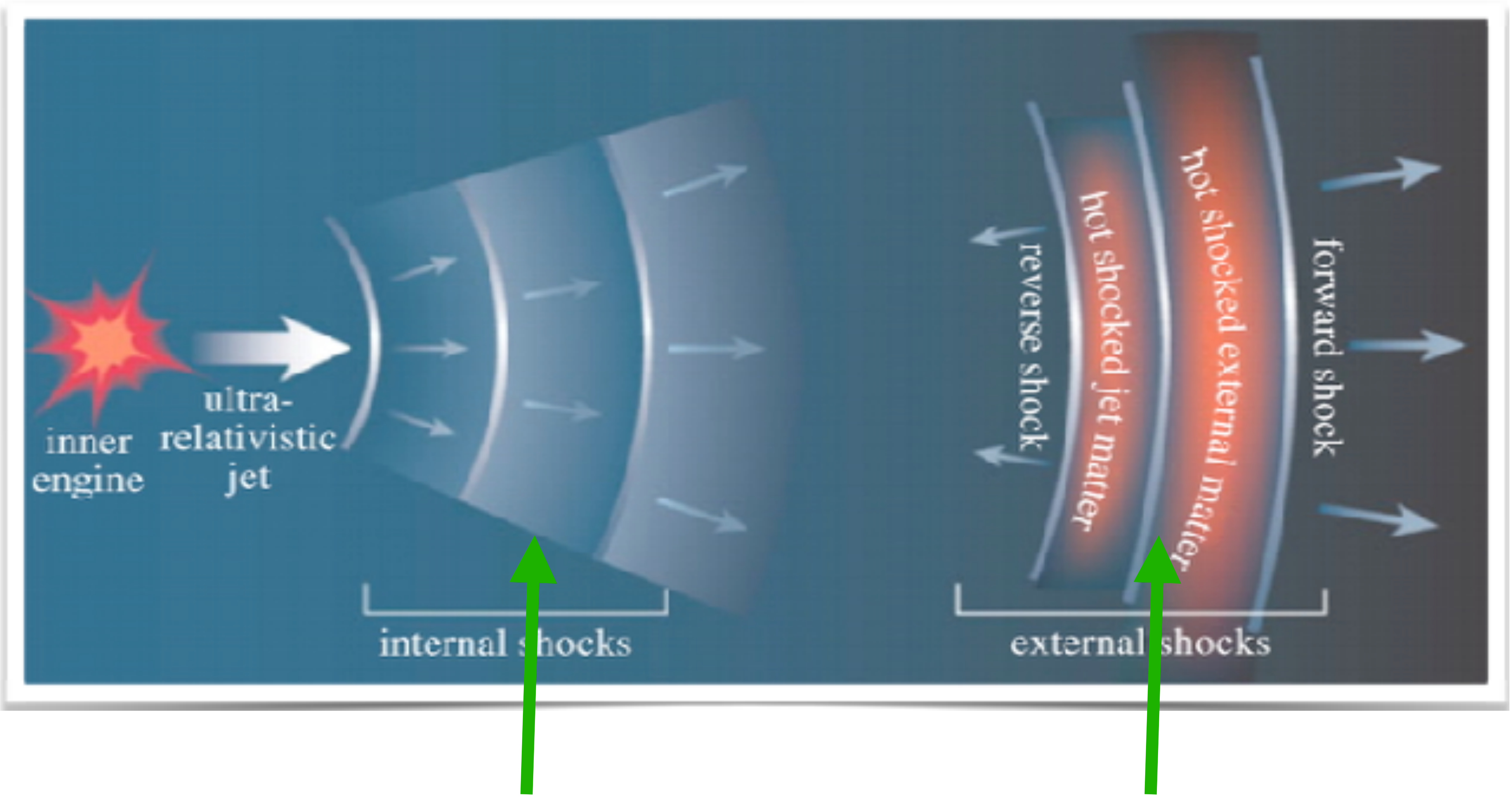
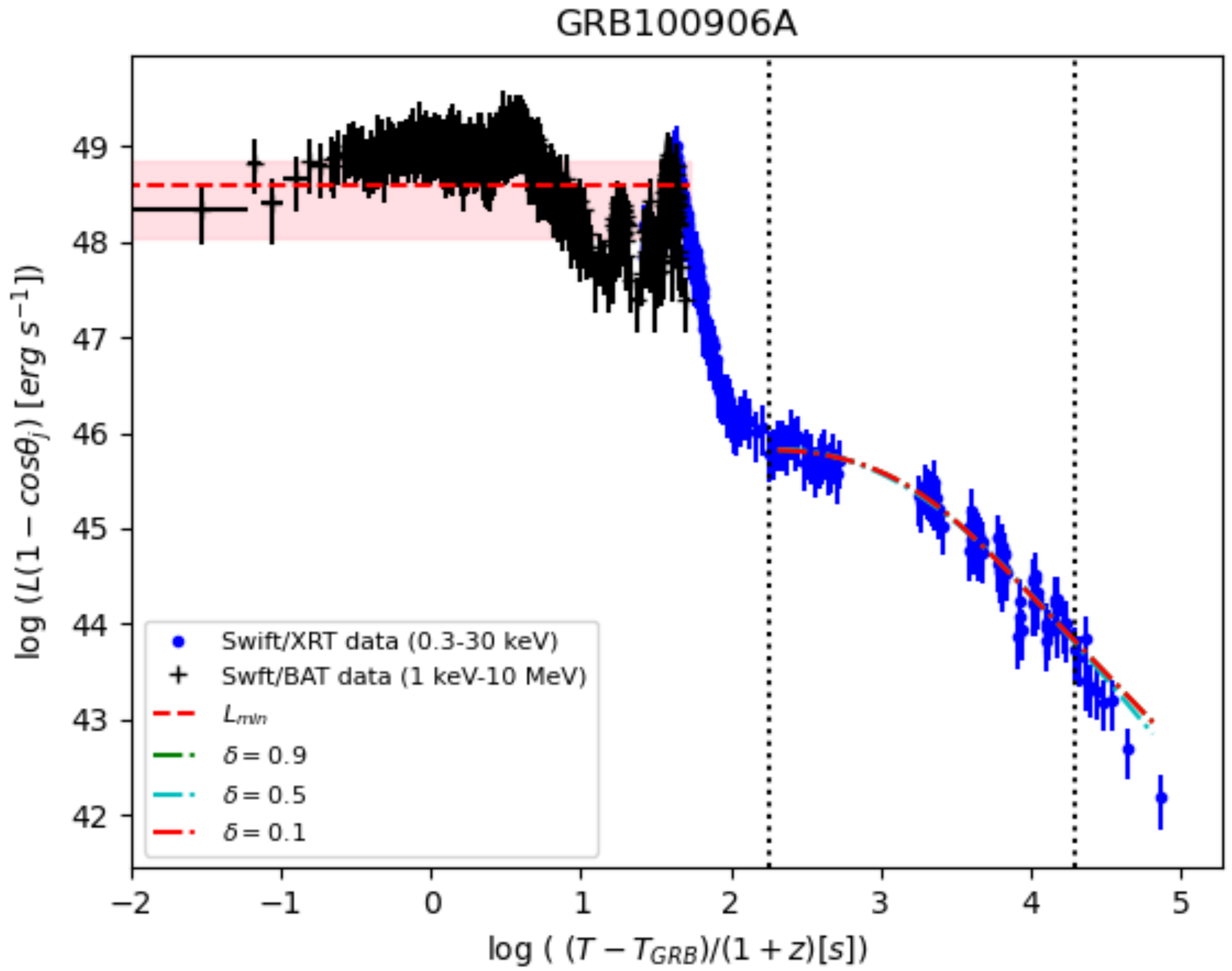
GAMMA-RAY BURSTS CENTRAL ENGINES



Prompt phase (~ seconds)

Afterglow emission (~hours/days)



Dall'Osso et al. 2023a

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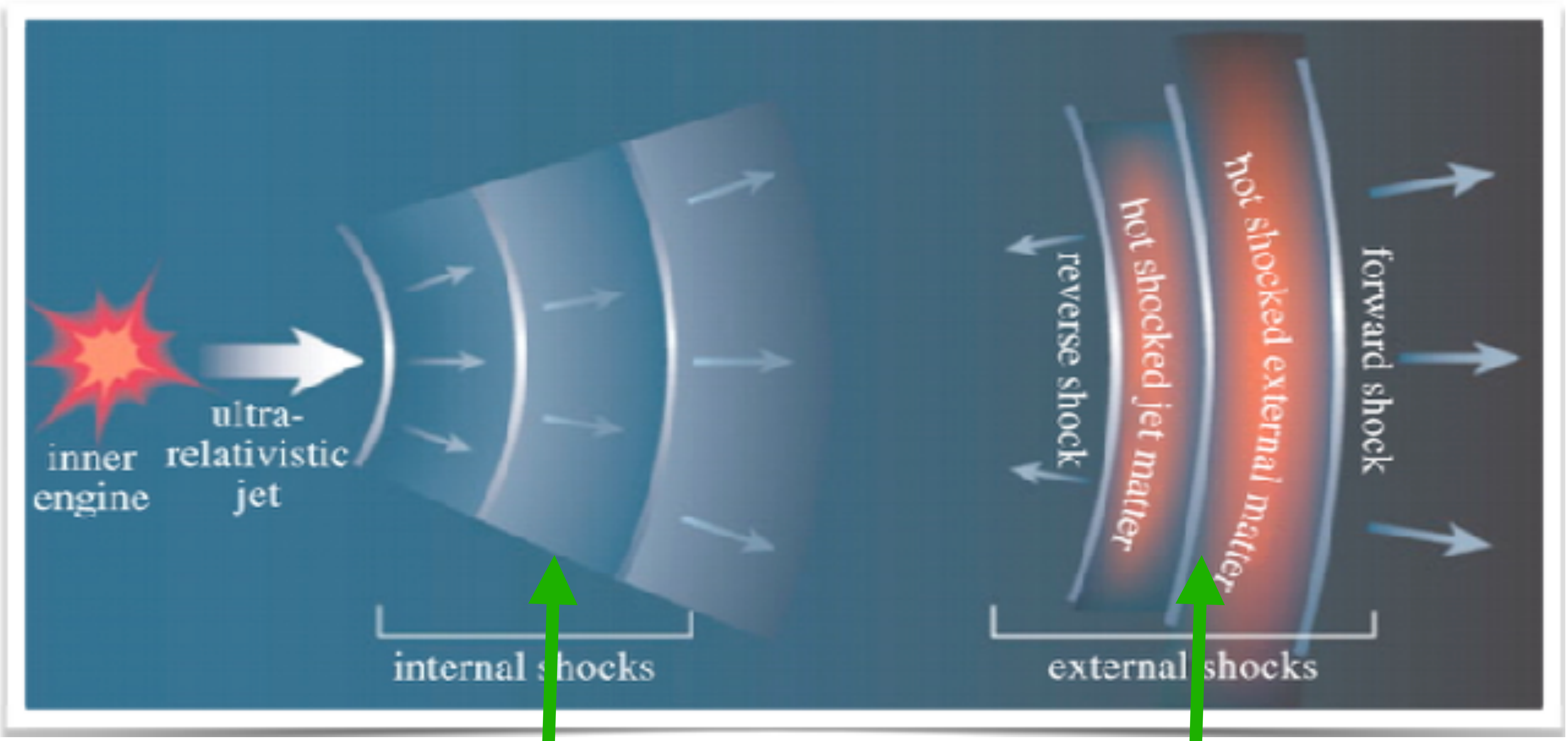

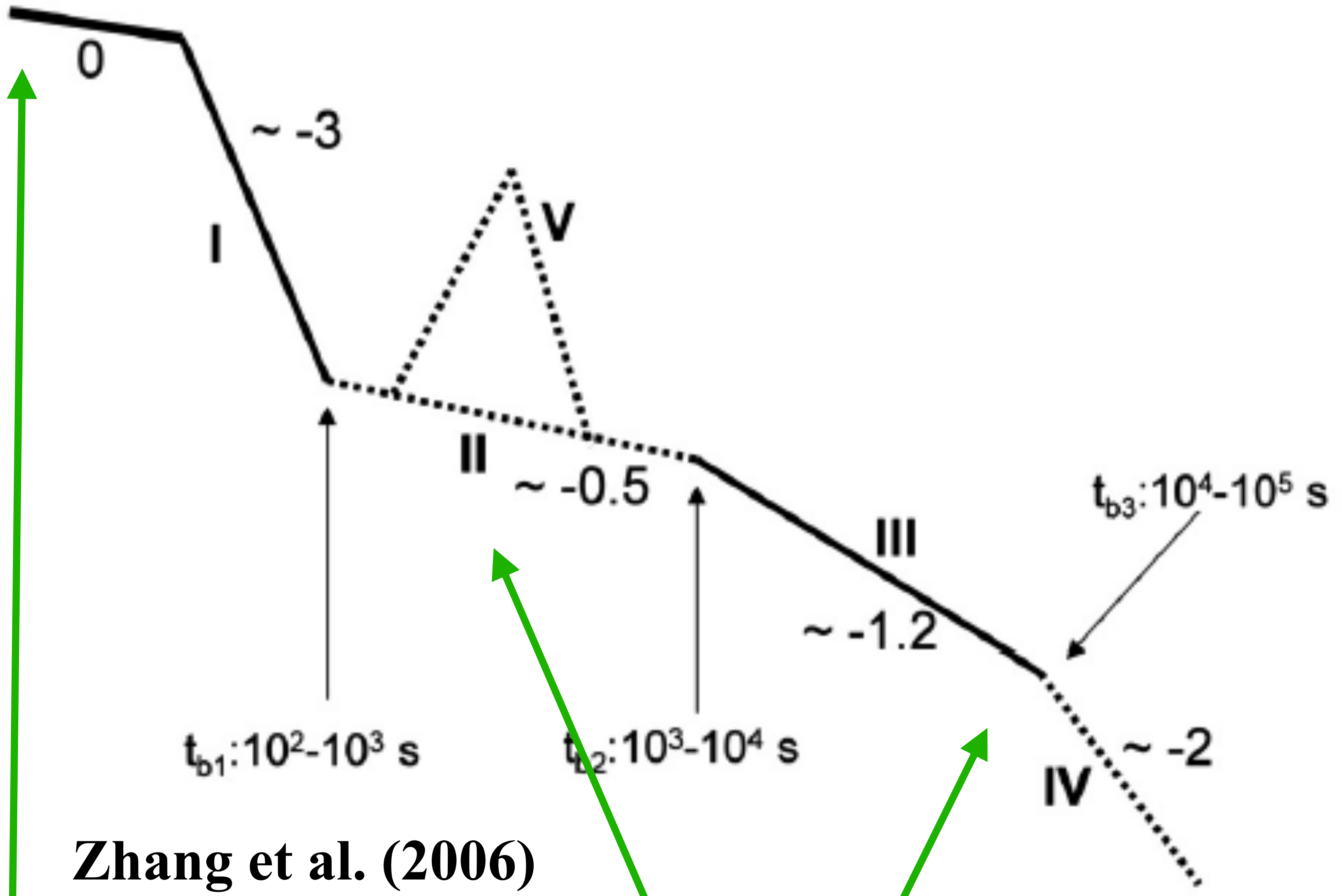

Zhang et al. (2006)
Nousek et al. (2006)

Prompt phase (~ seconds)

Afterglow emission (~hours/days)

Prompt

Afterglow

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Afterglow shallow decay

Some kind of ``energy injection" is required

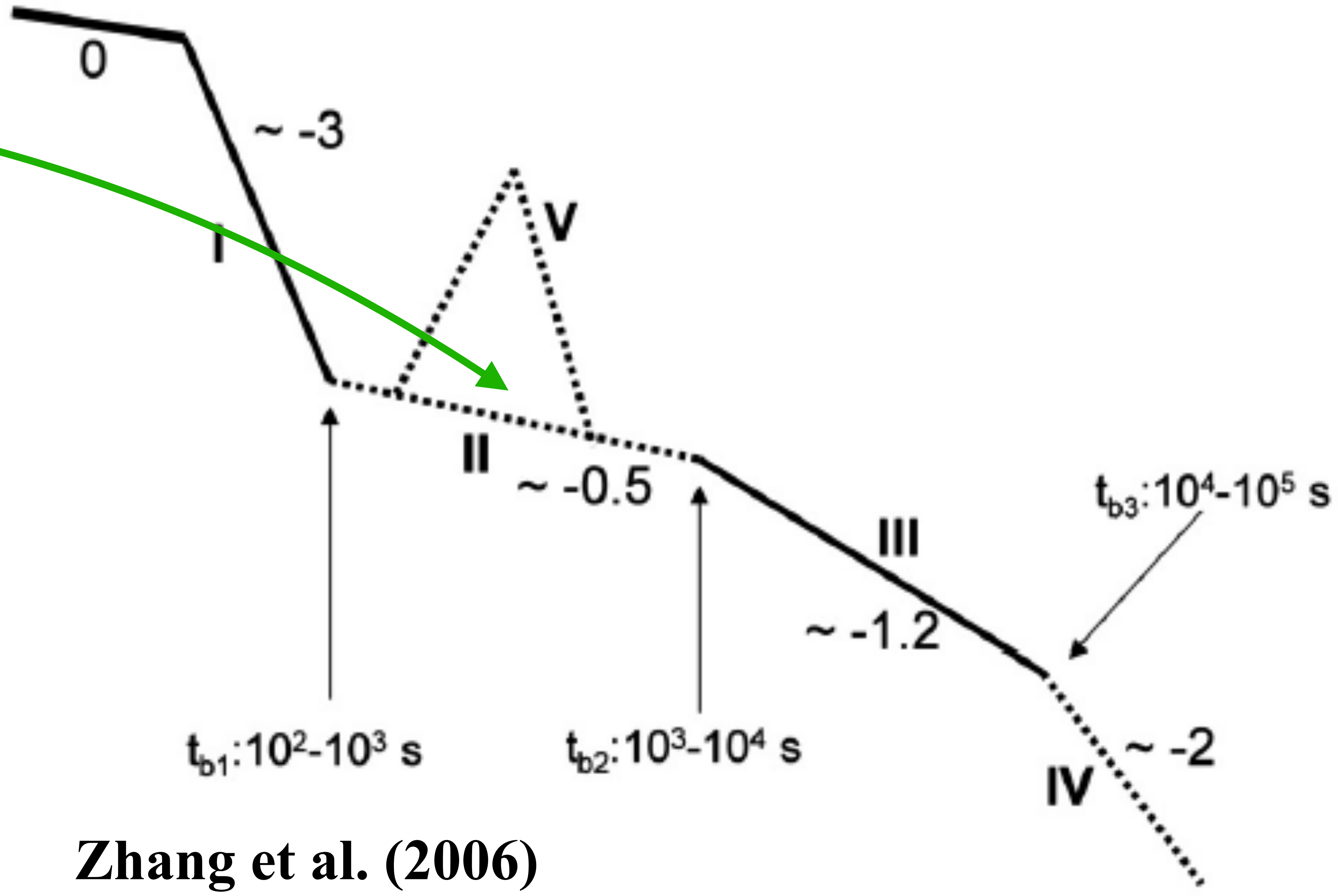
- broad radial profile of ejecta Lorentz factor

- prolonged activity of the central engine
  (a) problematic for a BH given the long timescale involved (~ 10^4 s)
  (b) more ``natural" for a fast spinning, high-B NS

$$\mathbf{L}_{\mathrm{EM}} = \frac{\mu^2}{\mathbf{c}^3}\Omega^4(1 + \sin^2\alpha)$$

- Off-axis emission from structured jets: high-latitude and/or off-axis view

Rossi et al. (2002)
Eichler & Granot (2006)
Oganesyan et al. (2020)
Ascenzi et a. (2020)
Beniamini et al. (2020)



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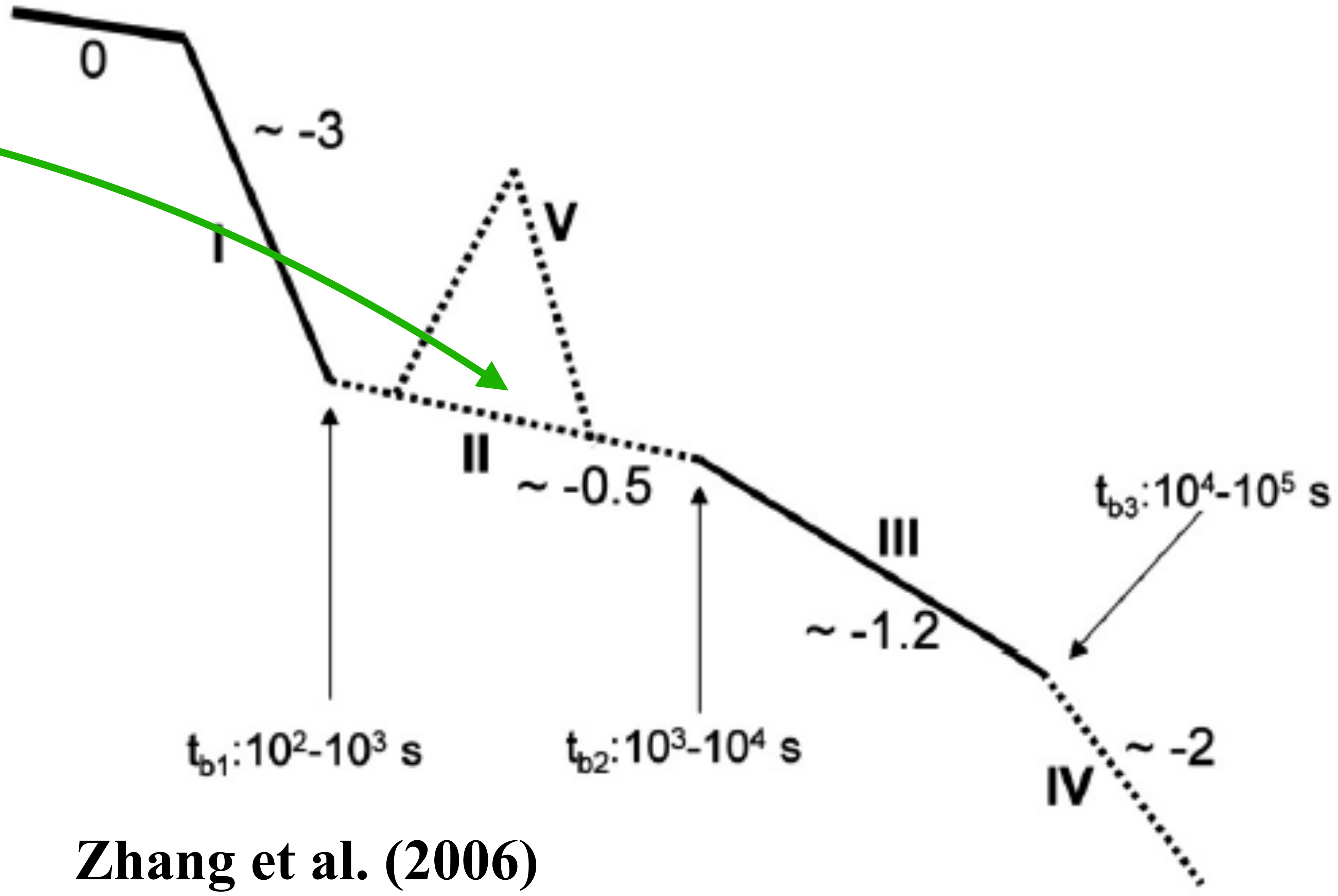

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Most GRBs show mild/no chromaticity in multi-band observations: 1 broadband emission region

Stratta et al. 2022 **Ronchini et al. 2023**

A smaller subset has chromatic behaviour in multi-band obs: hints at 2 separate emission regions?

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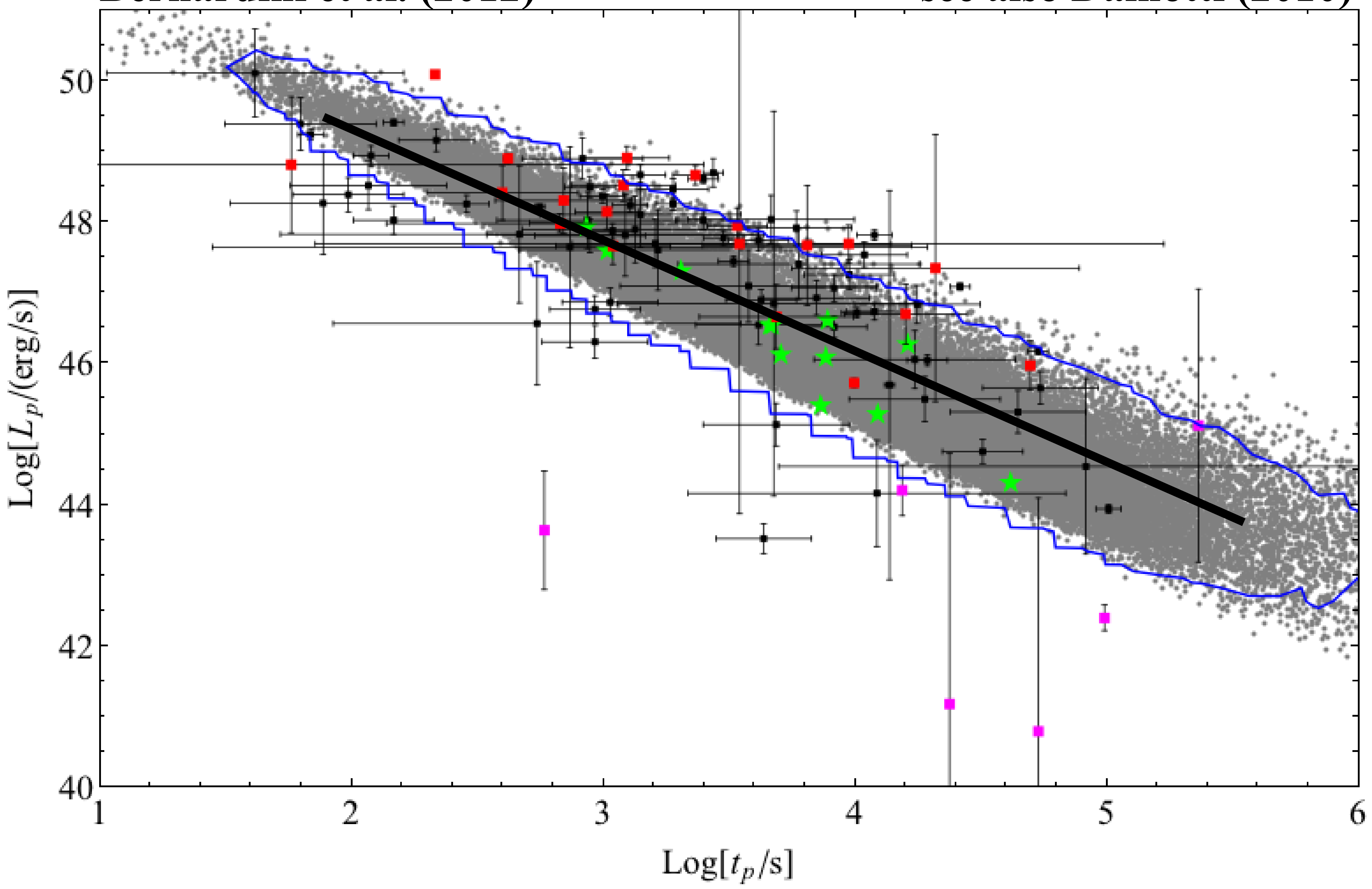
Bernardini et al. (2012) see also Dainotti (2010)



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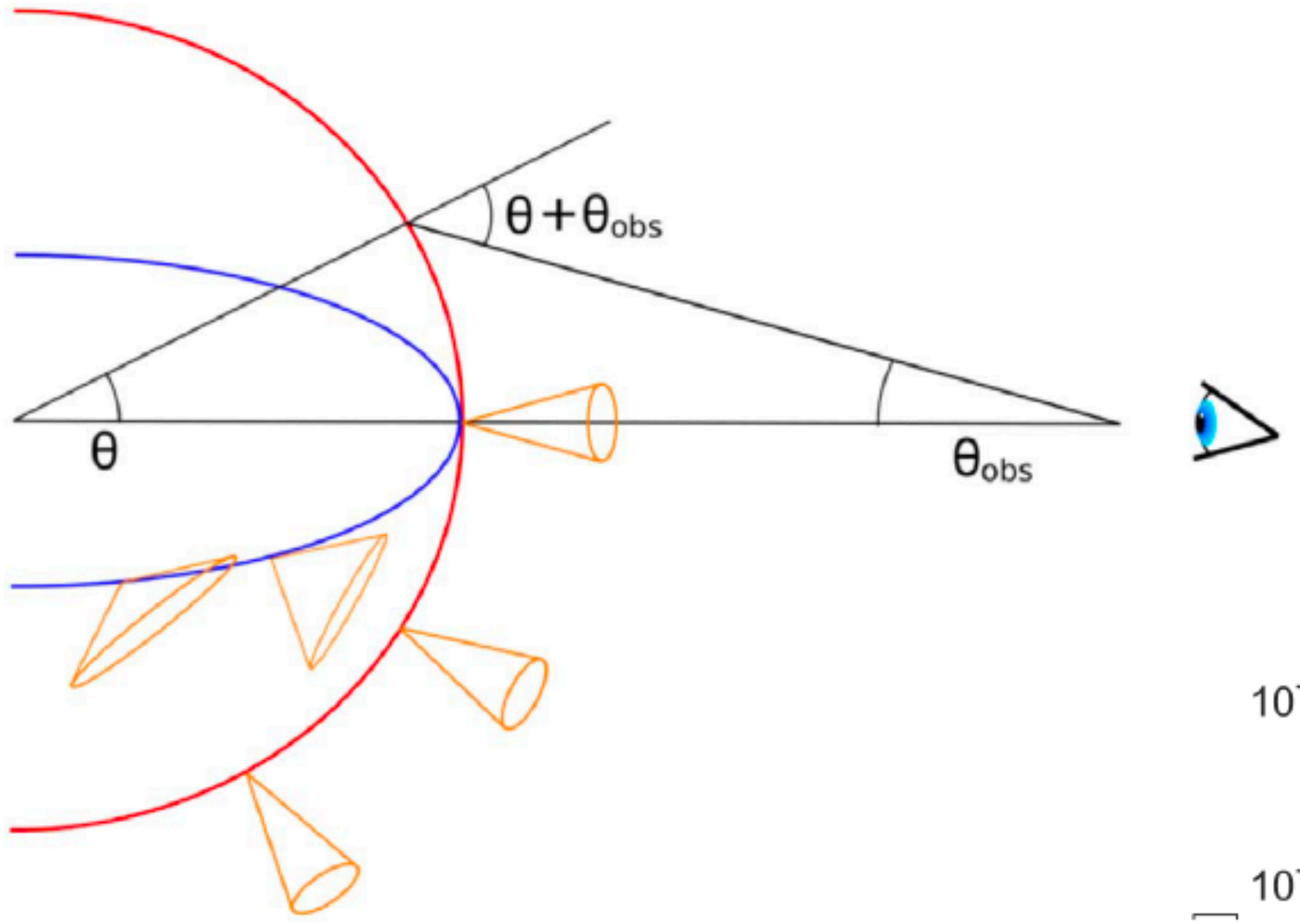
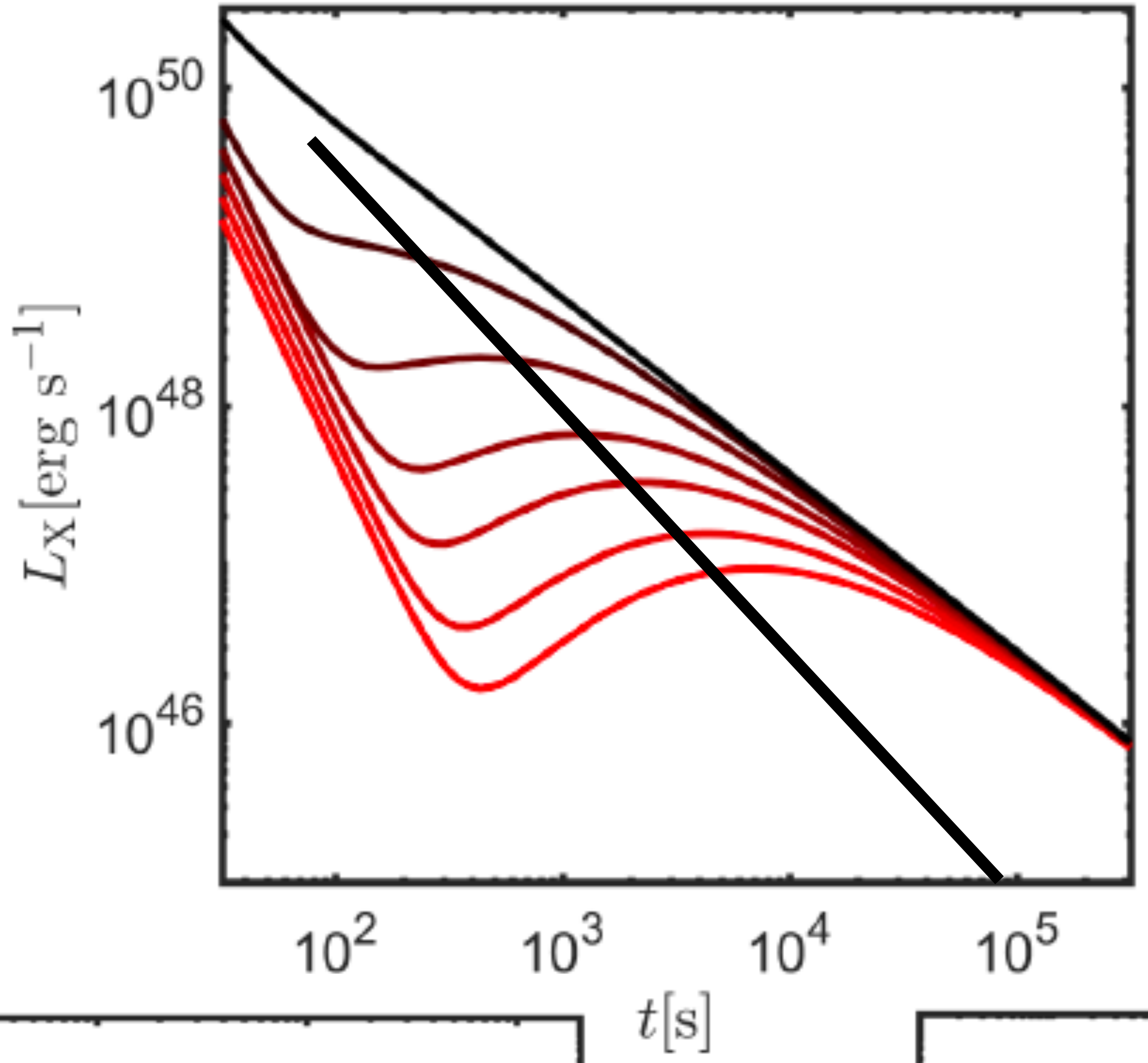
Structured afterglow jet (slightly) off-axis



Oganesyan et al. (2020)



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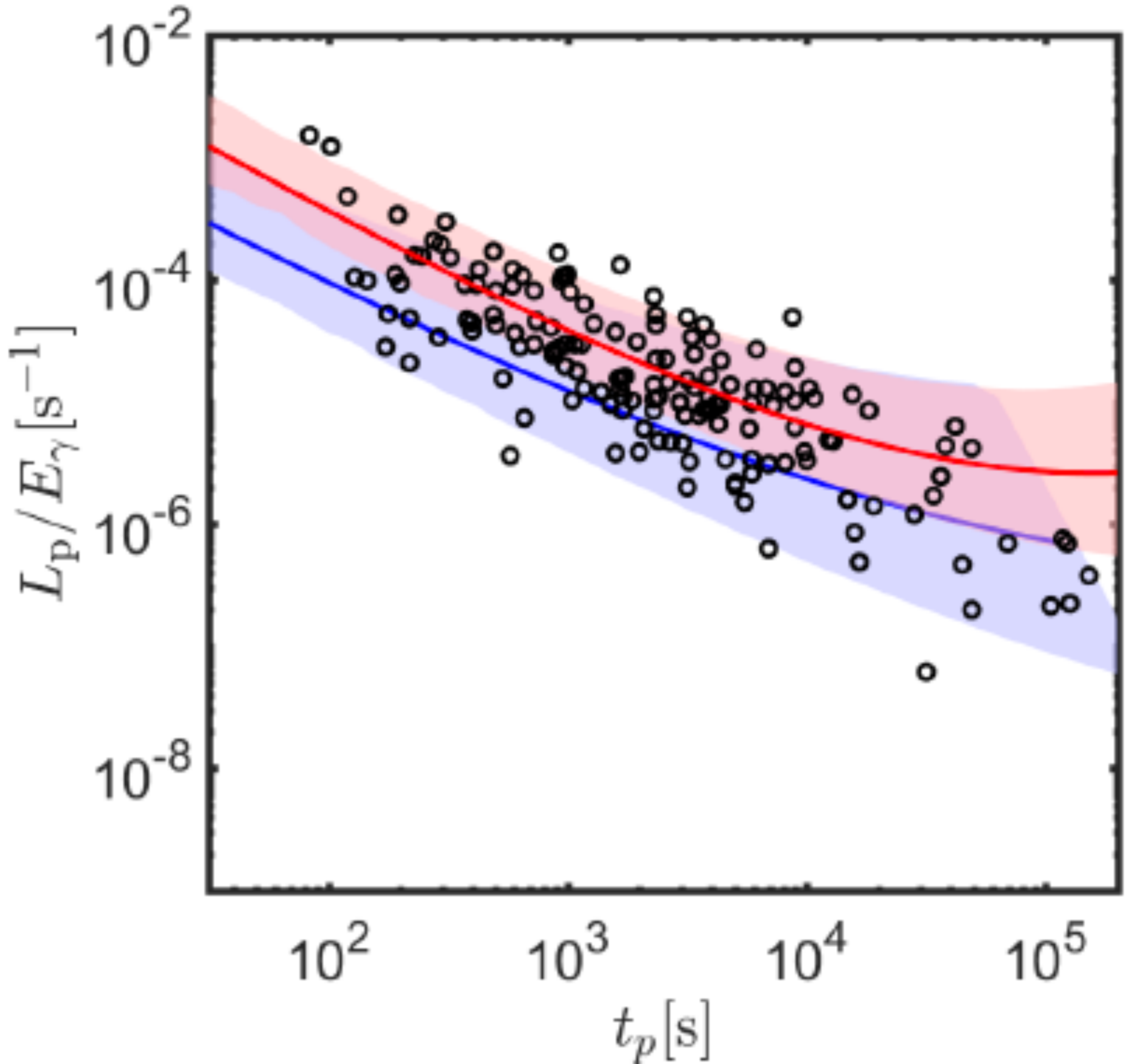

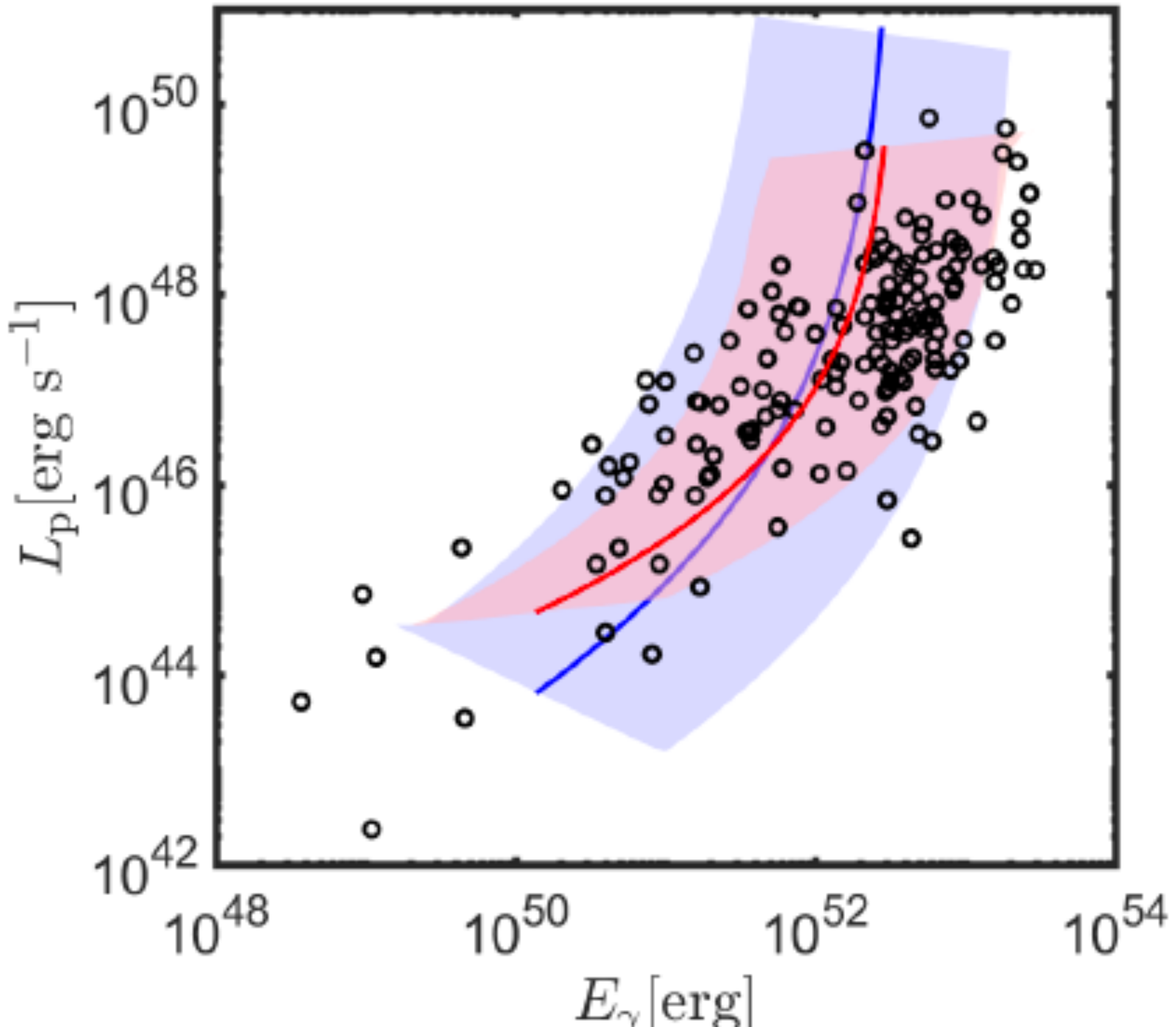

A correlation between prompt and plateau properties is predicted

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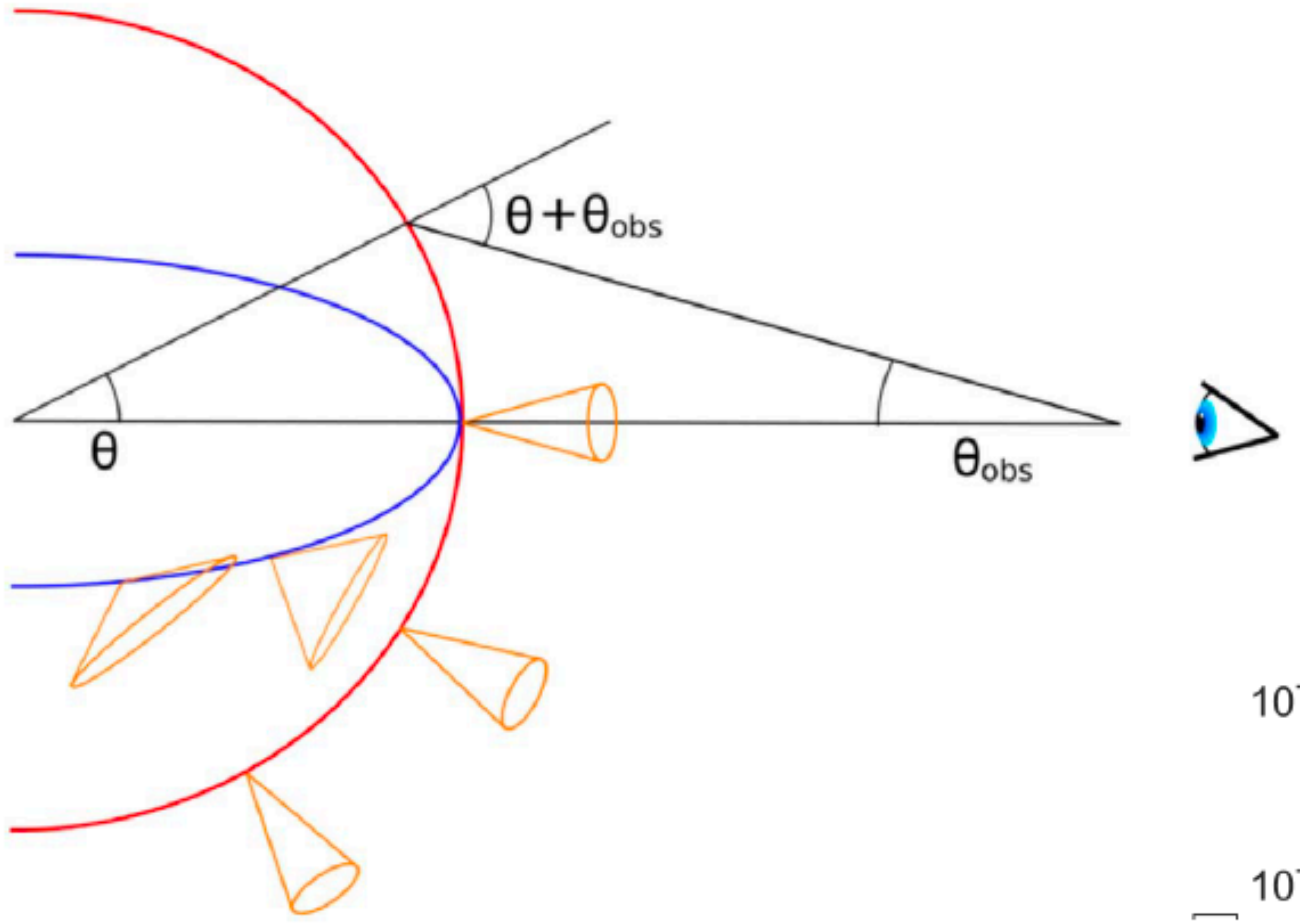

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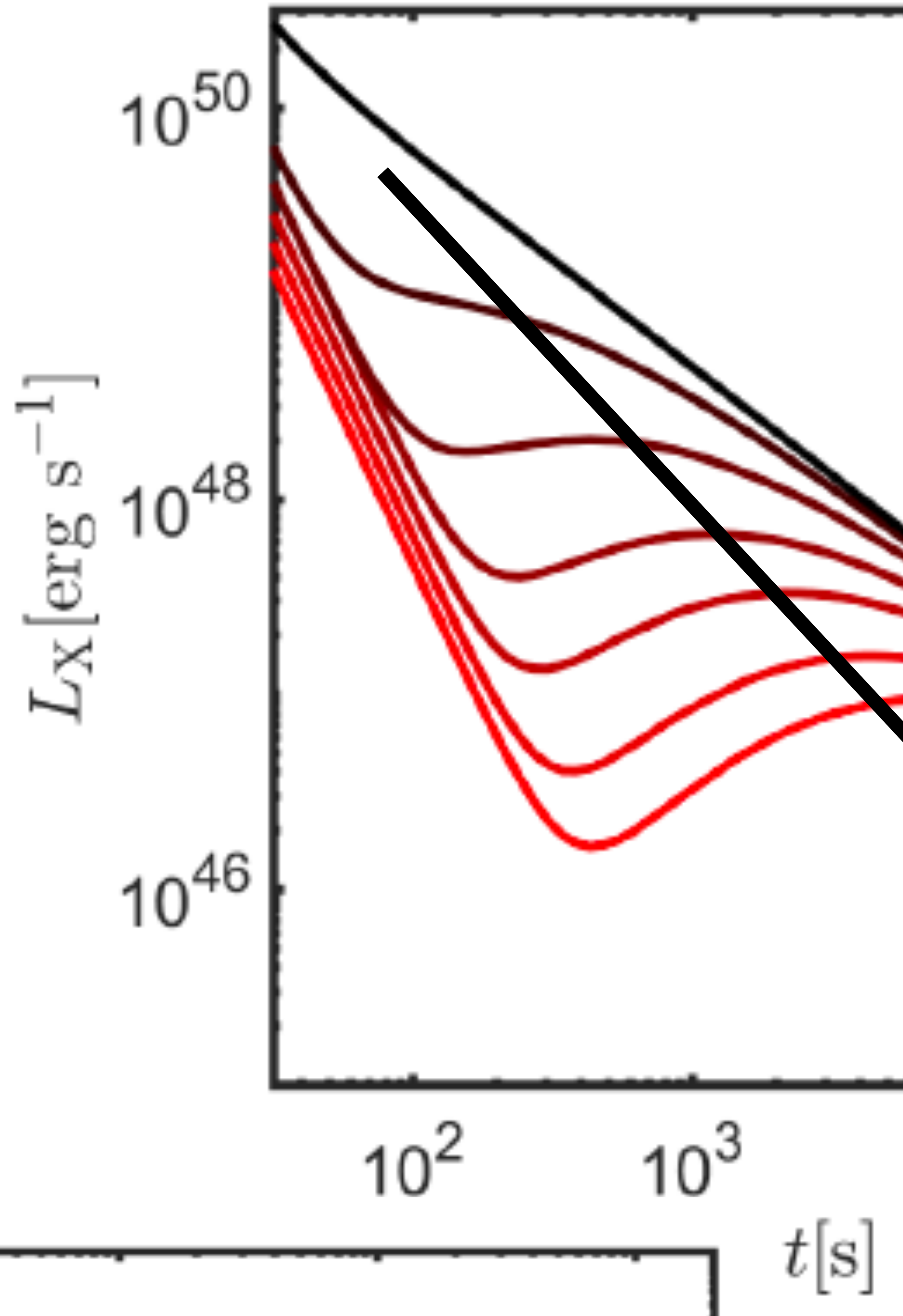

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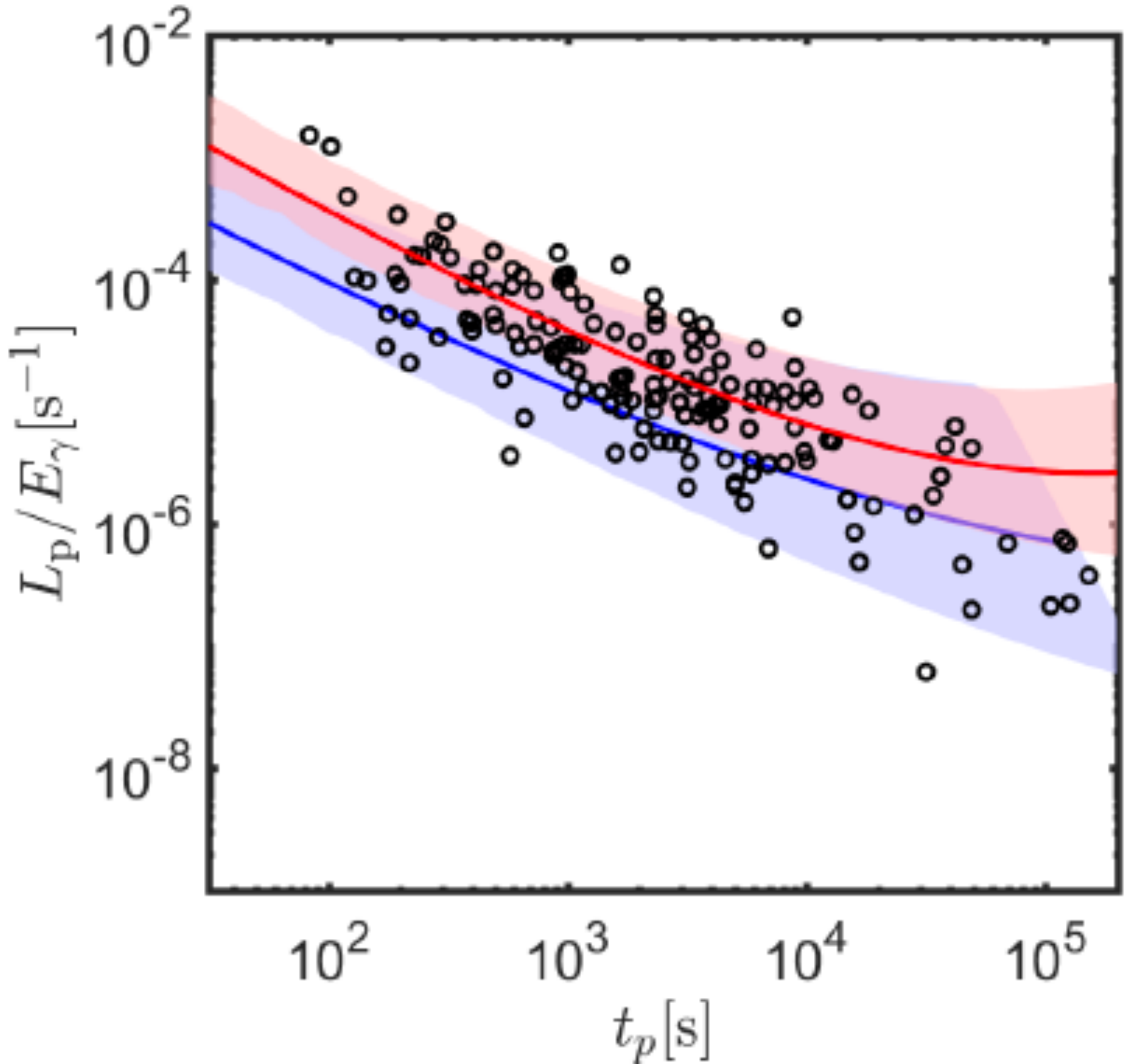

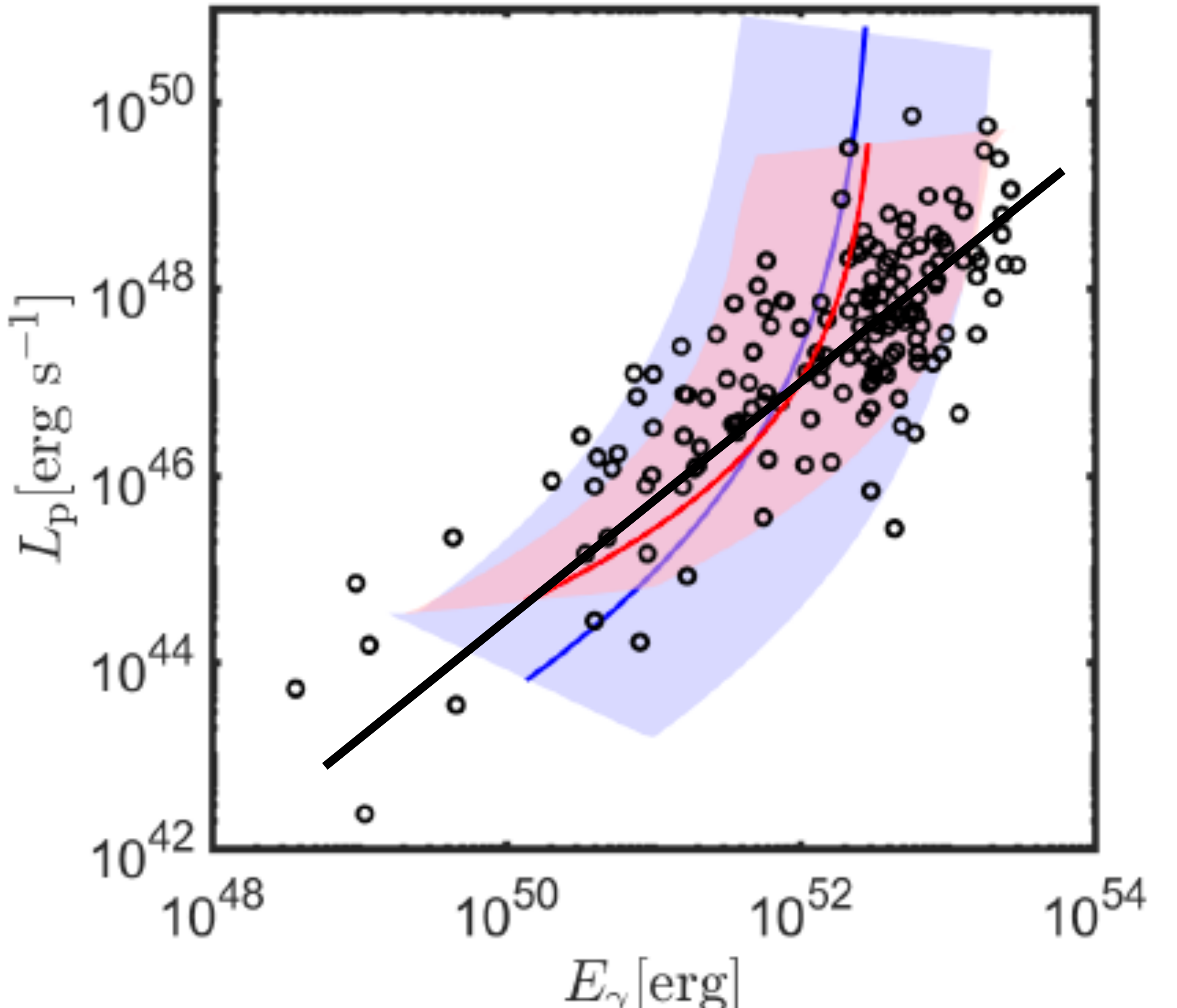

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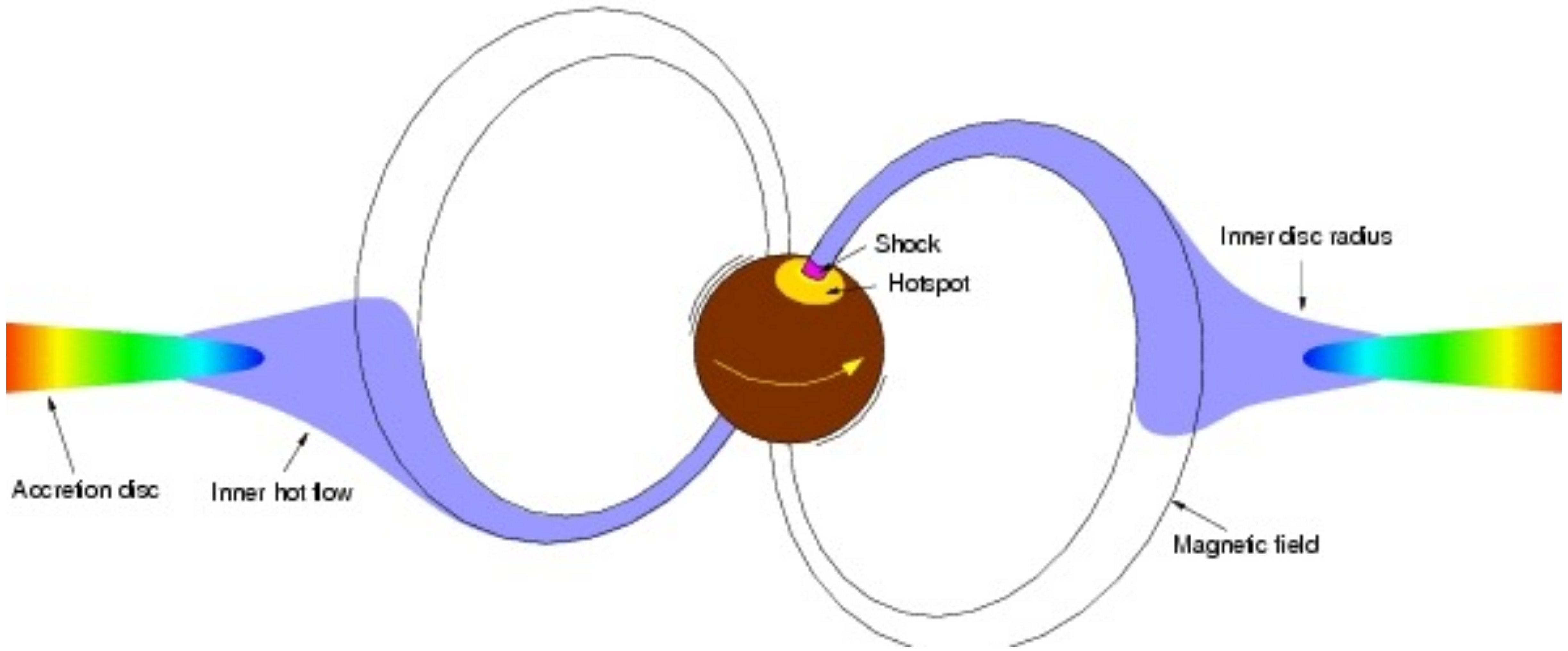
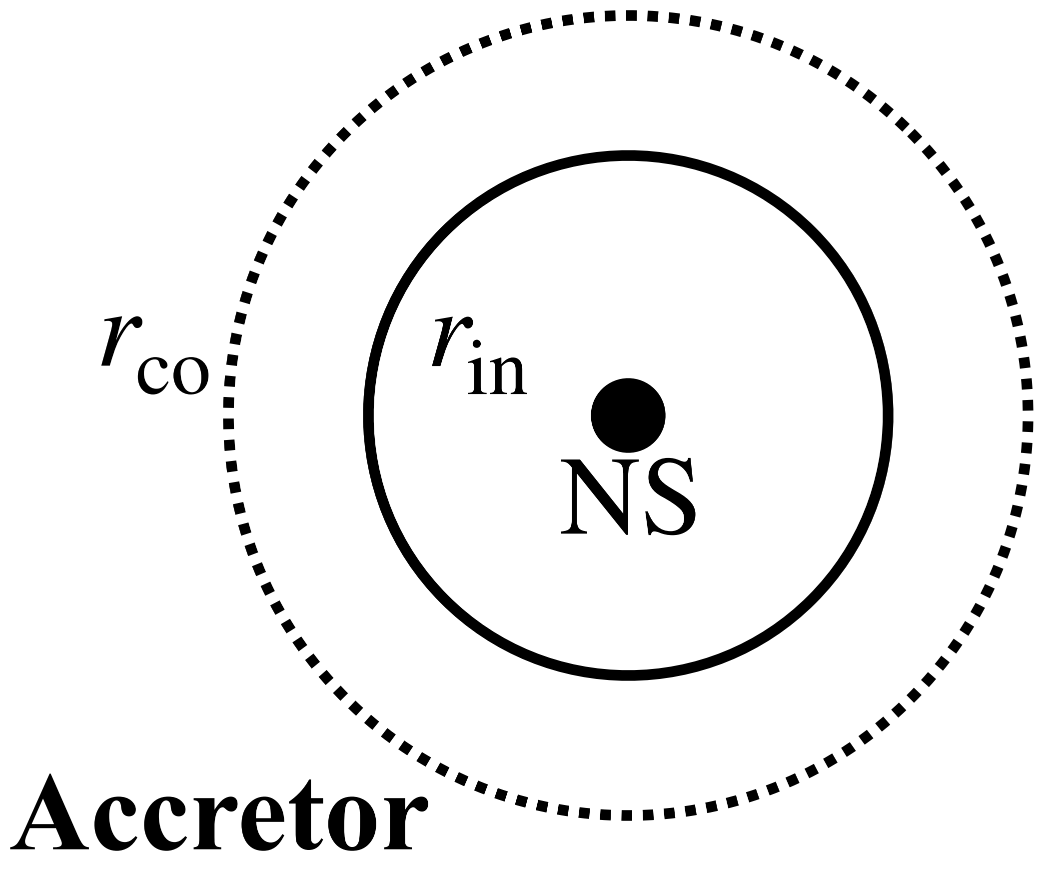
``MAGNETAR” CENTRAL ENGINE REVIVED

Fast-spinning and highly magnetised NS embedded in an accretion disc



$$r_{\rm in} = \xi r_A$$

$$\Omega_K(r_{\rm co}) = \Omega_{\rm spin}$$



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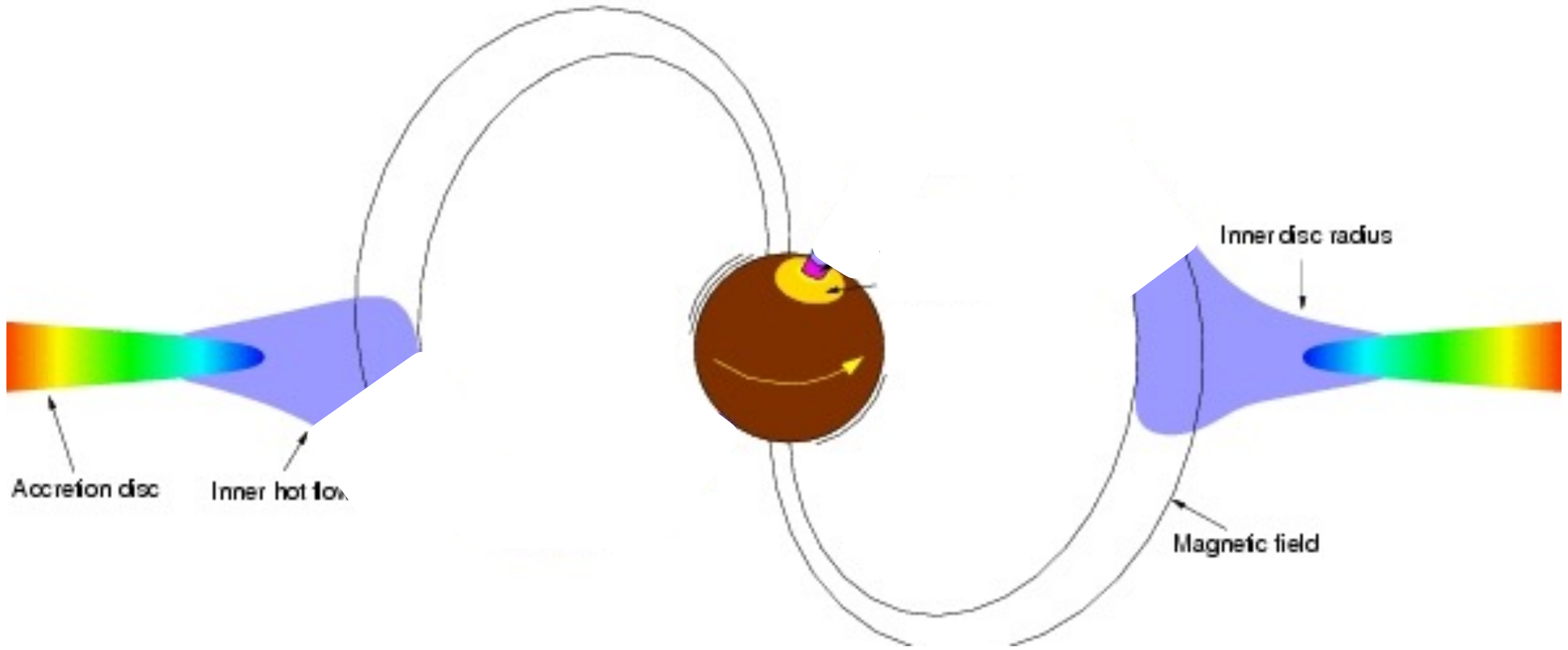

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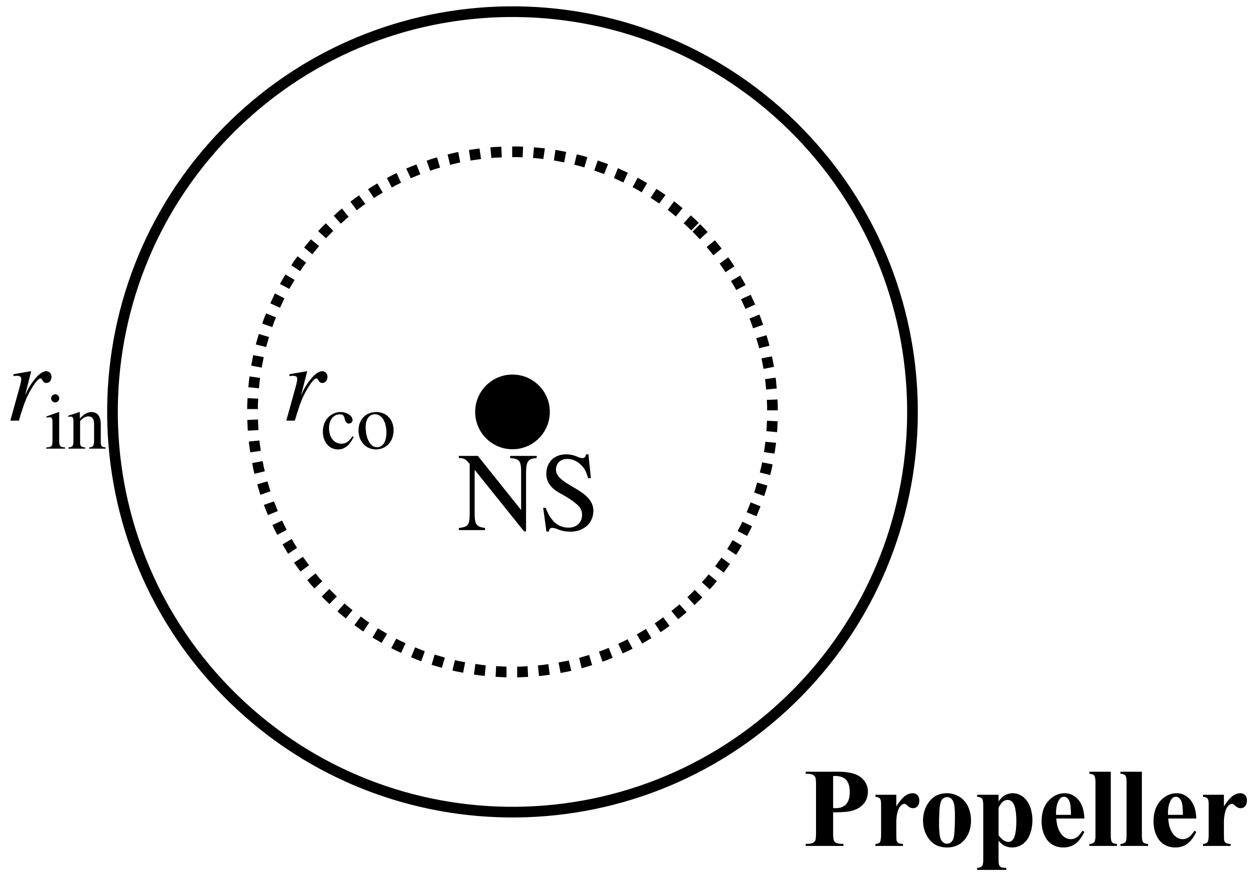

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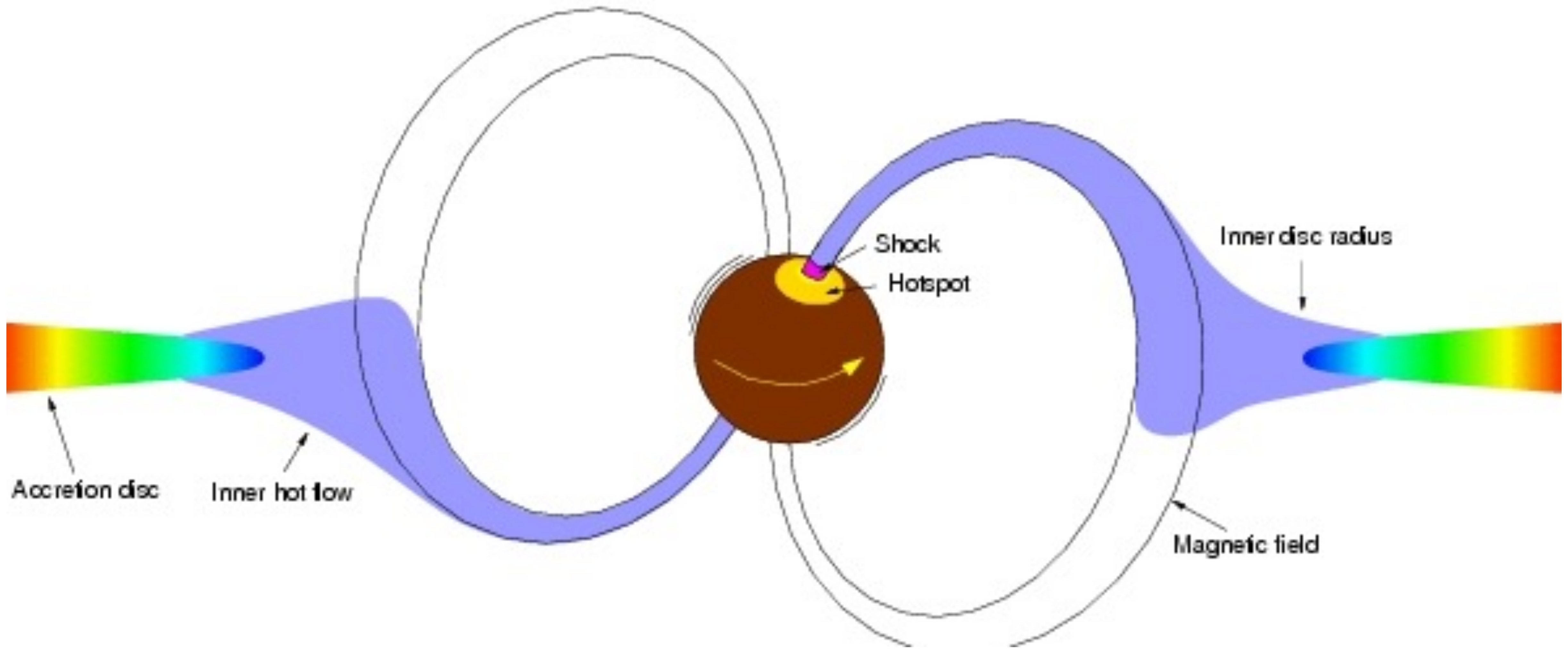

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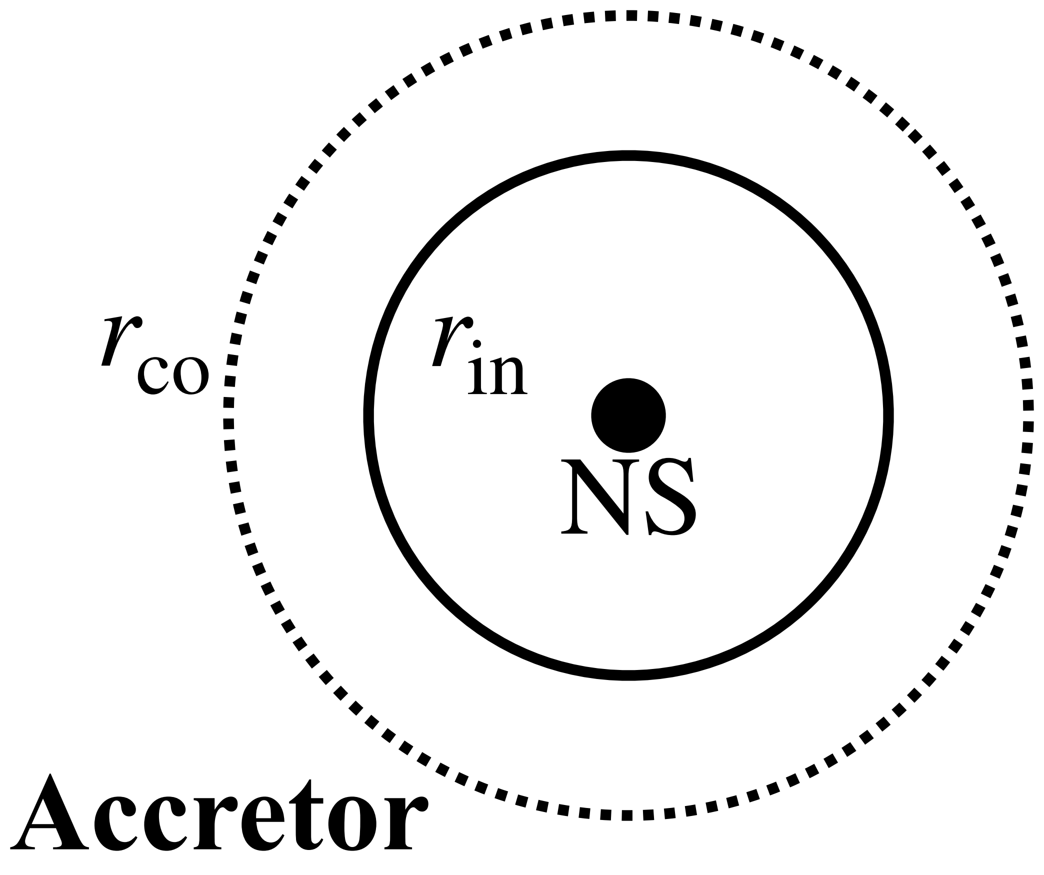

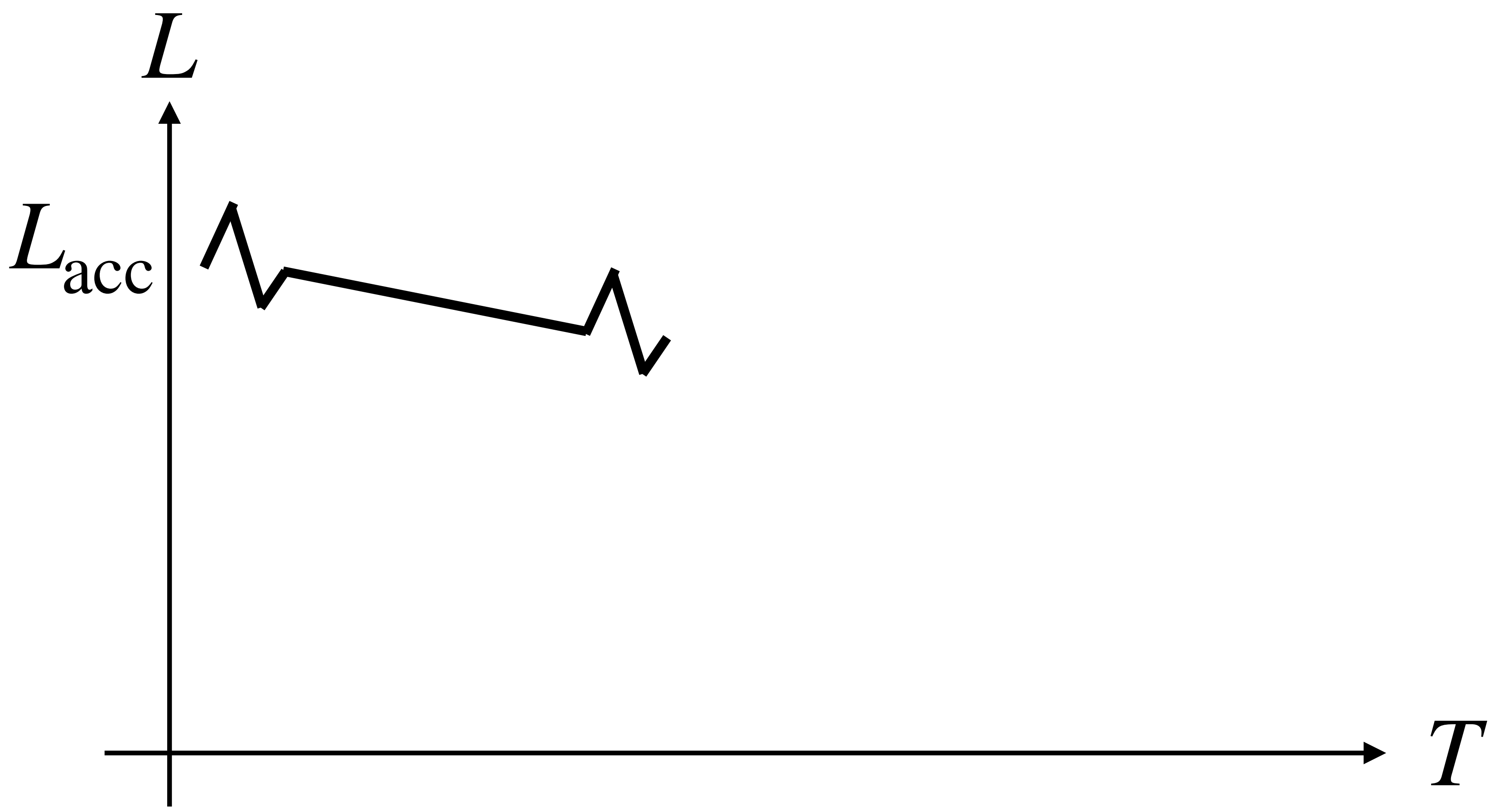

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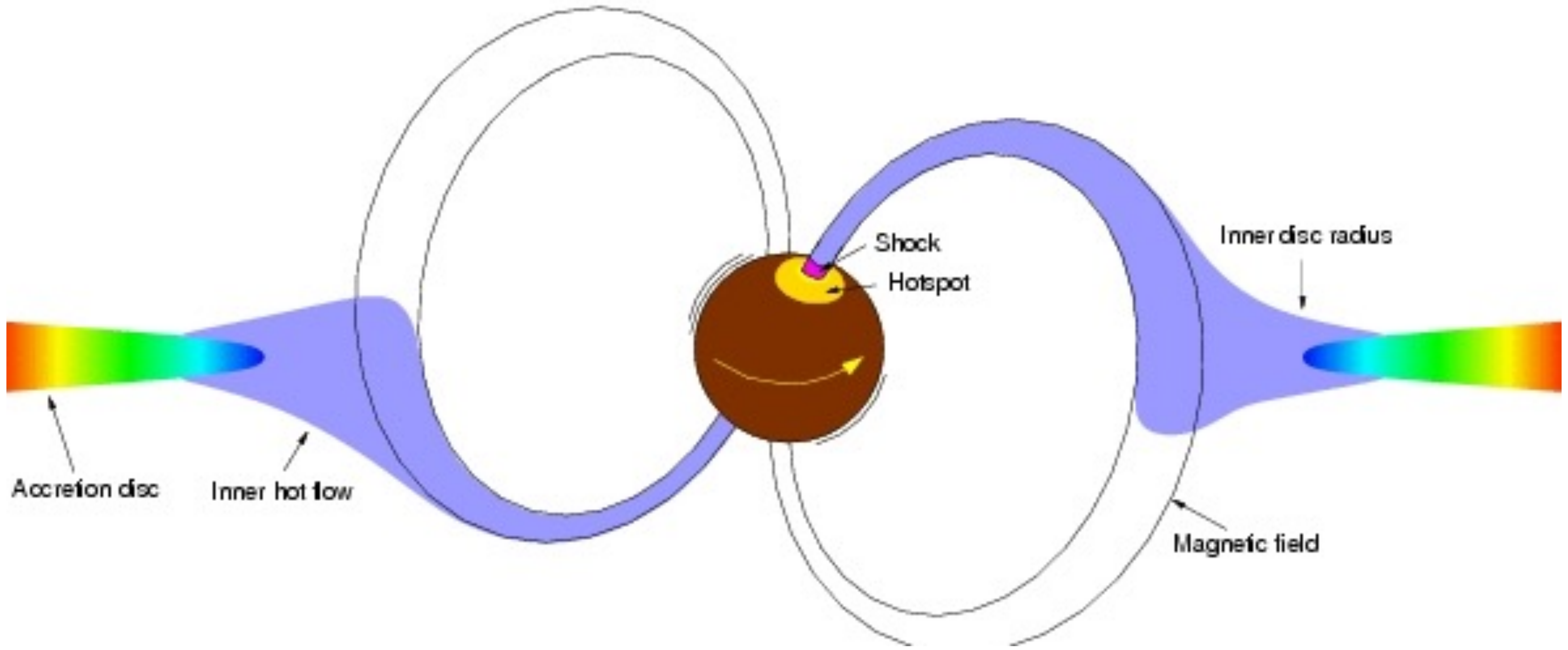

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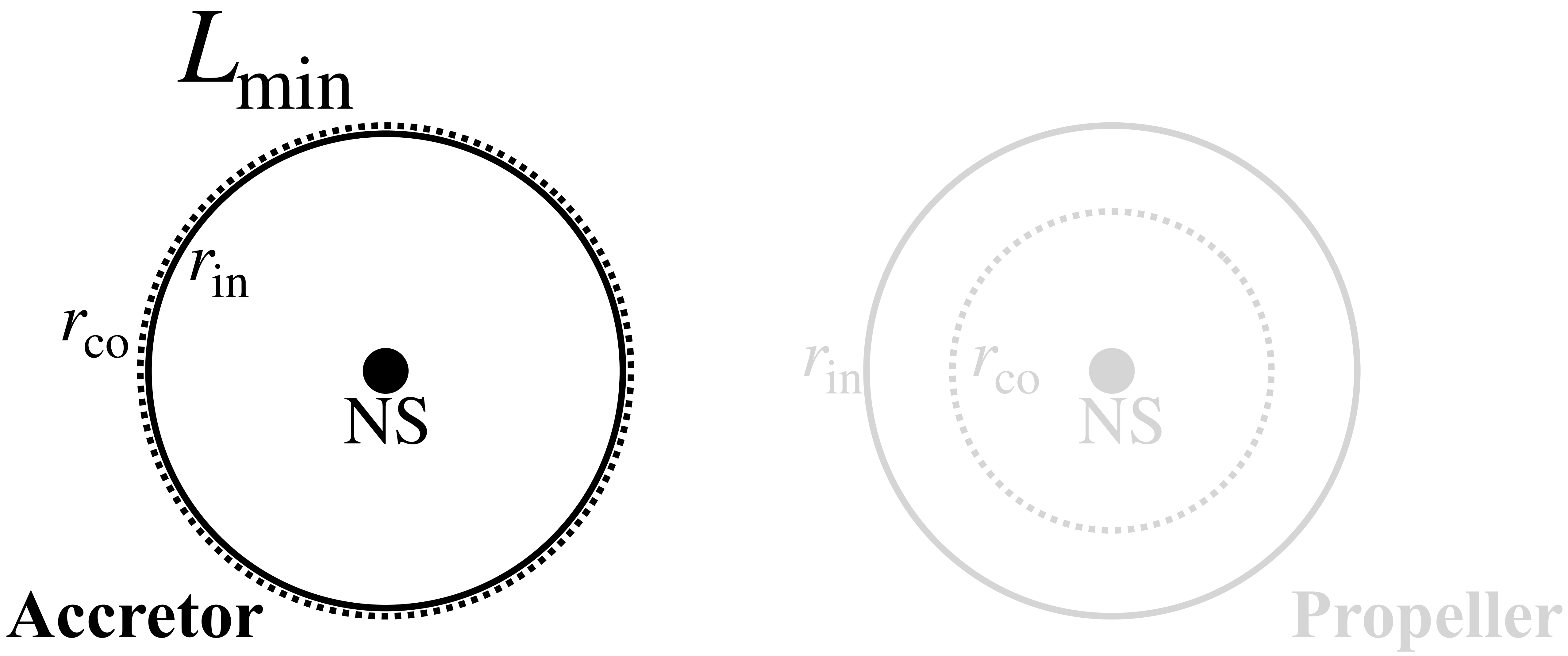

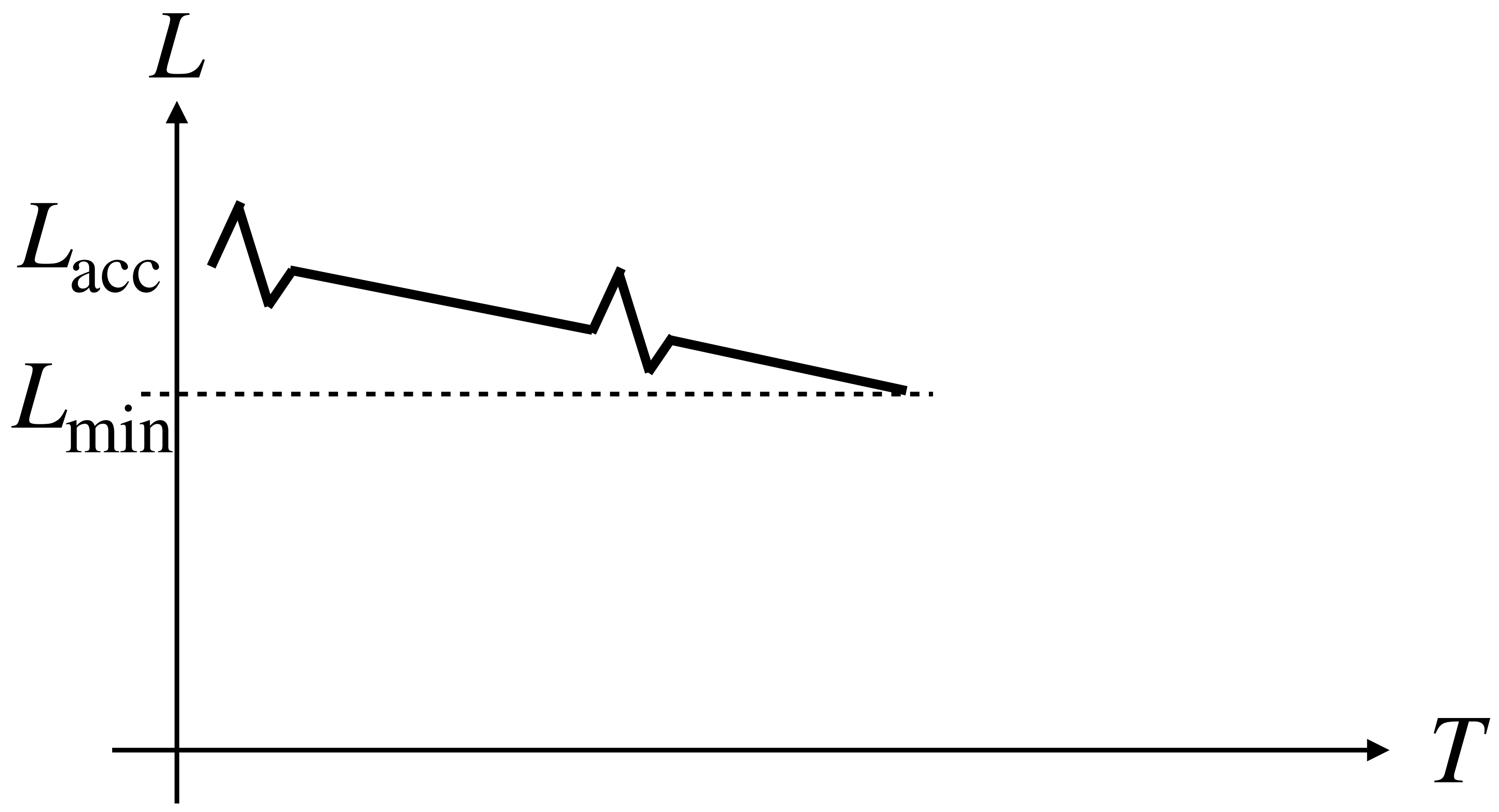

``MAGNETAR'' CENTRAL ENGINE REVIVED

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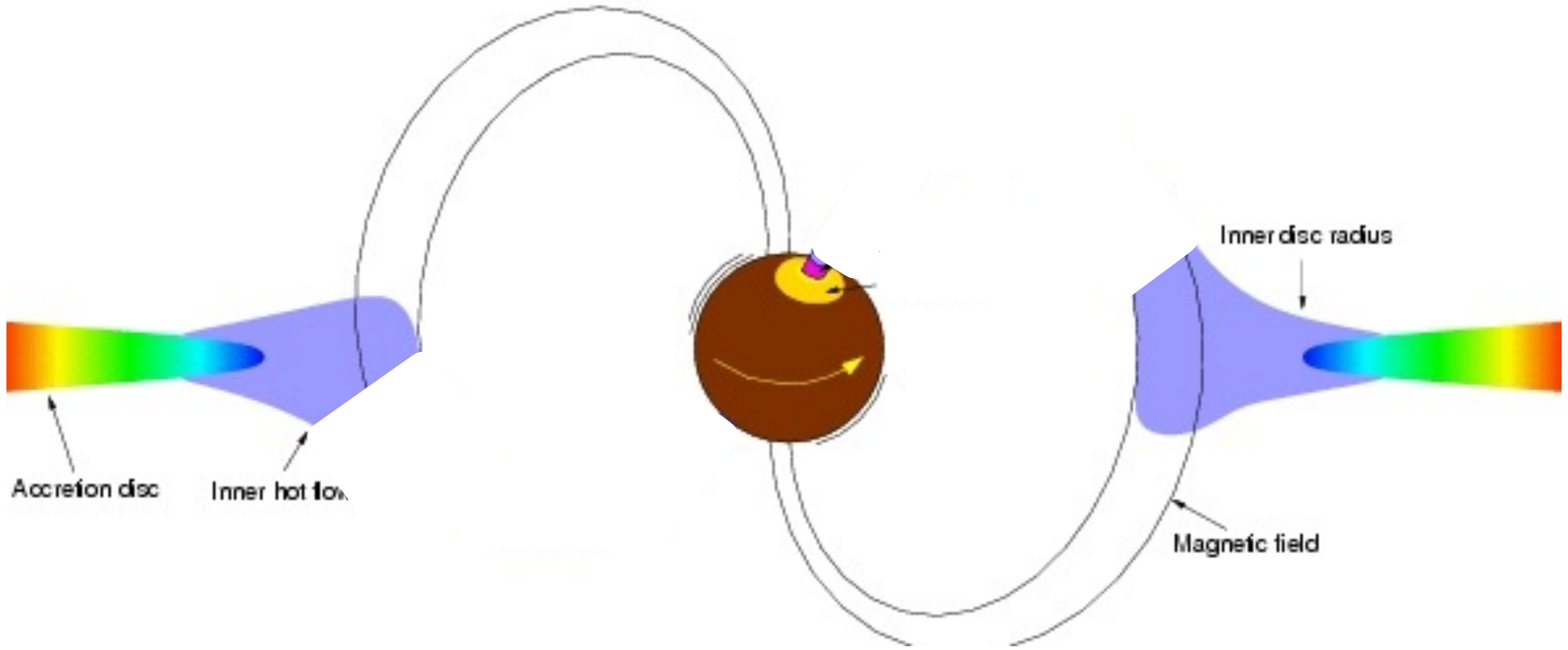

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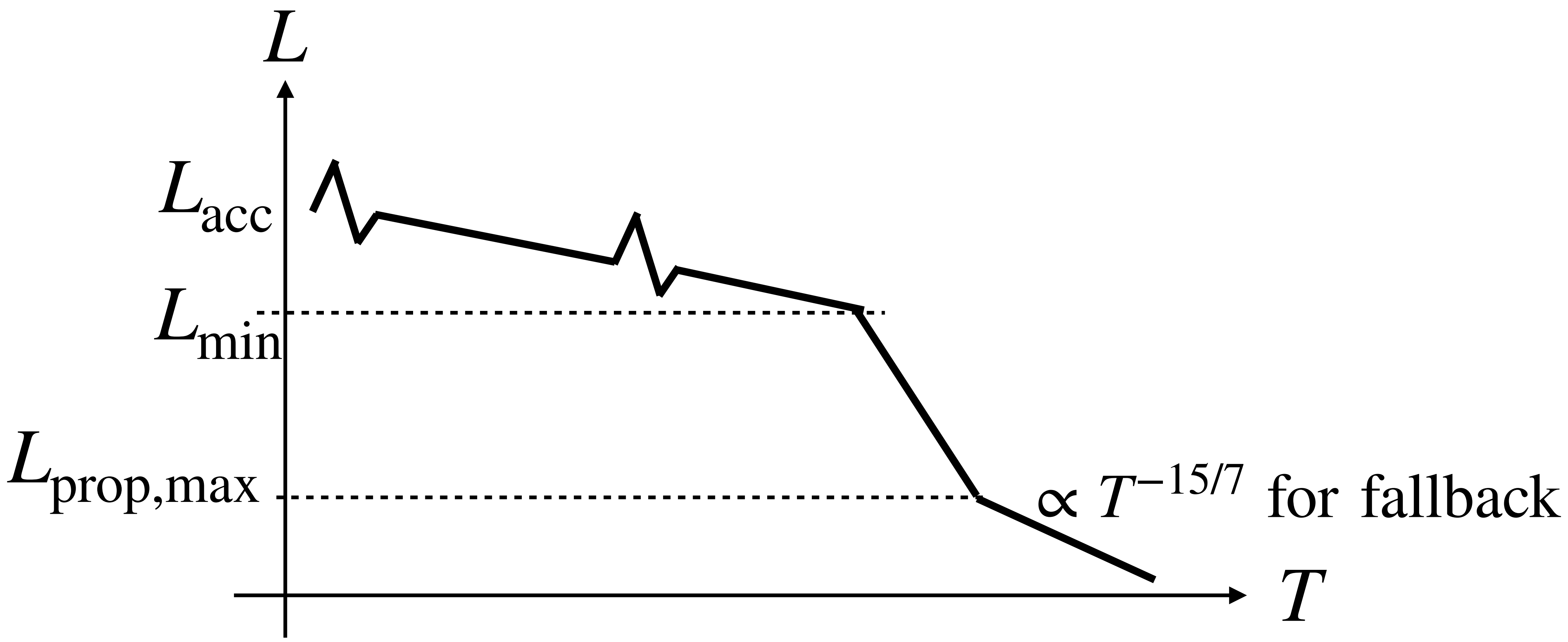

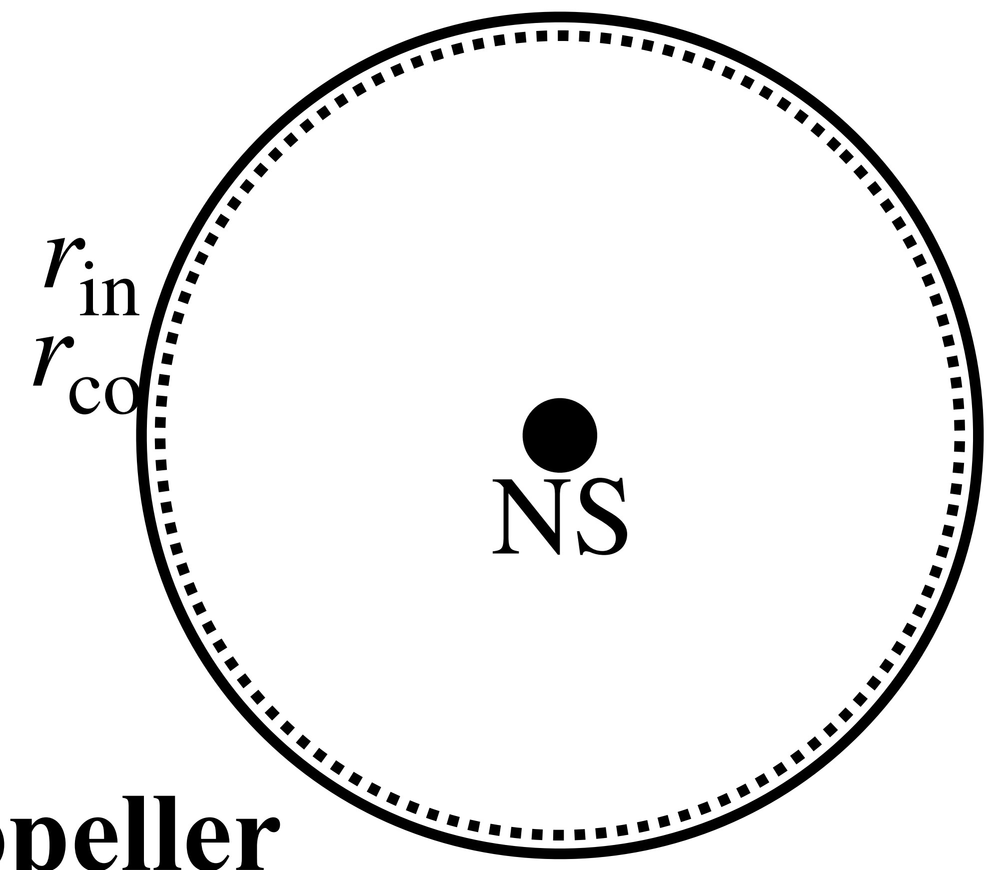

Propeller

Propeller

``MAGNETAR'' CENTRAL ENGINE REVIVED

$$L_{\rm min} = 1.4 \times 10^{37}\ {\rm erg\ s^{-1}}\ \epsilon_r \left(\frac{\mu}{10^{30}}\right)^2 P^{7/3}\ \left(\frac{\xi}{0.5}\right)^{7/2} R_{\rm 10Km}\ M_{1.4}^{-2/3}$$

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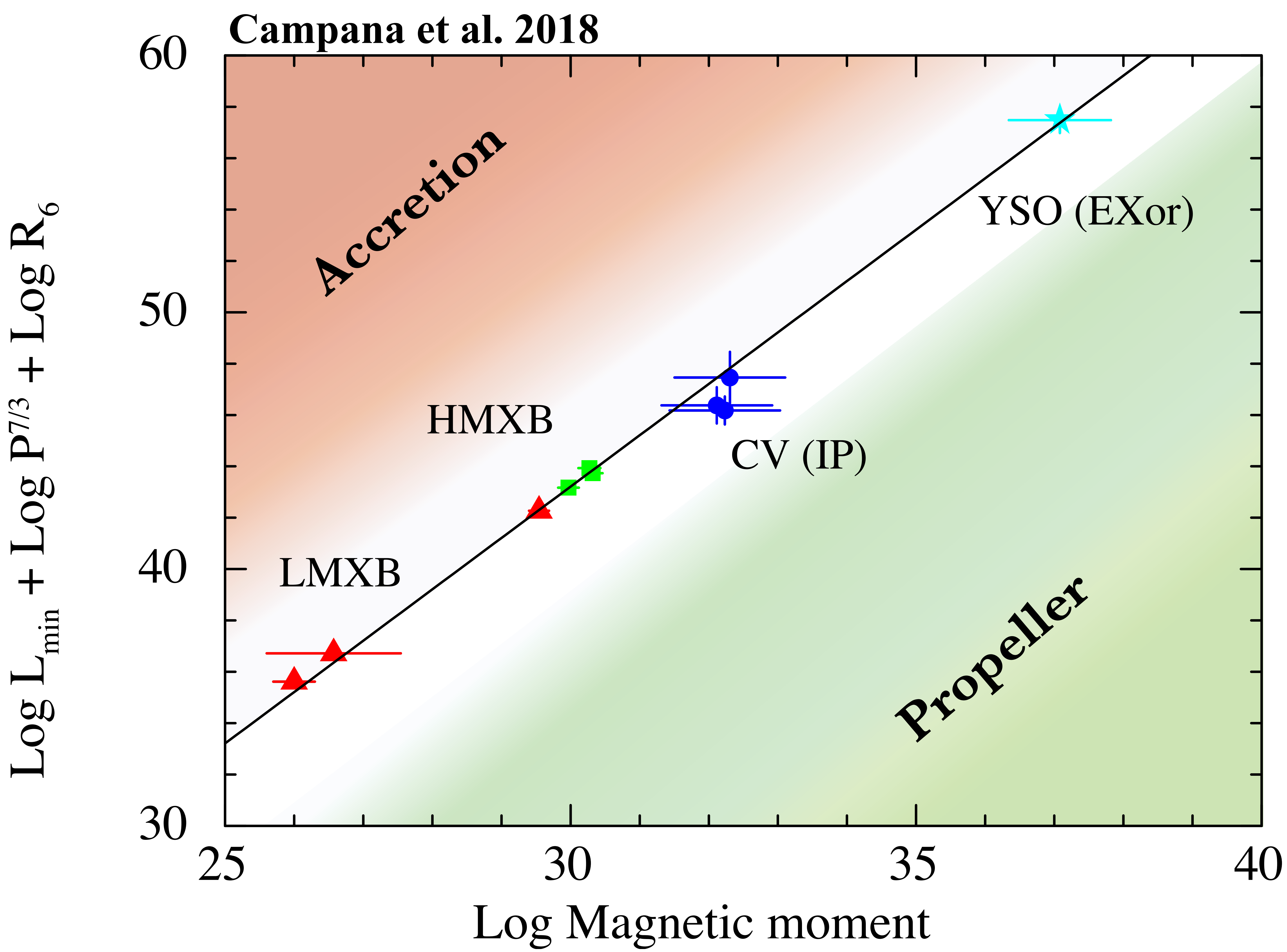

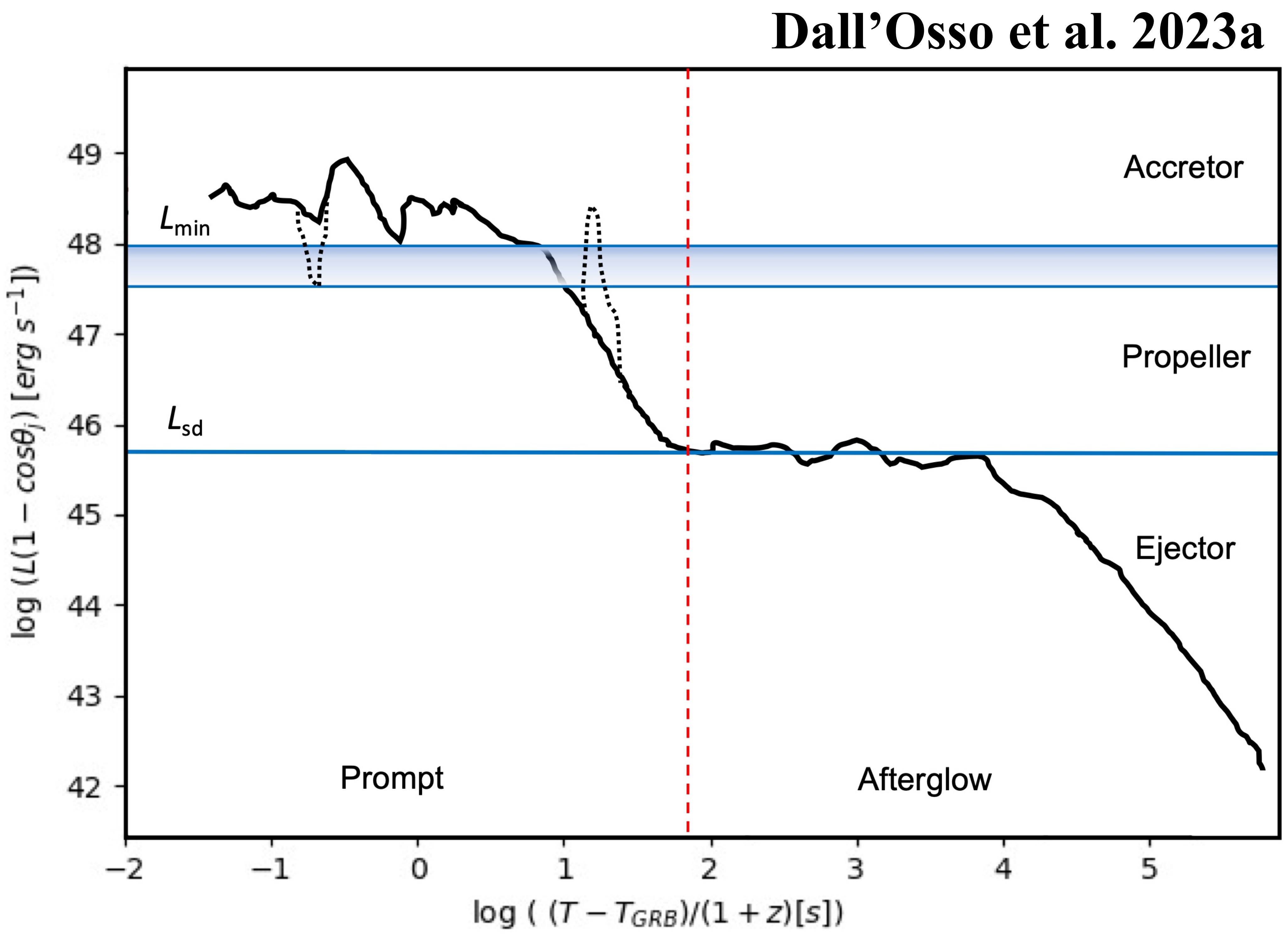

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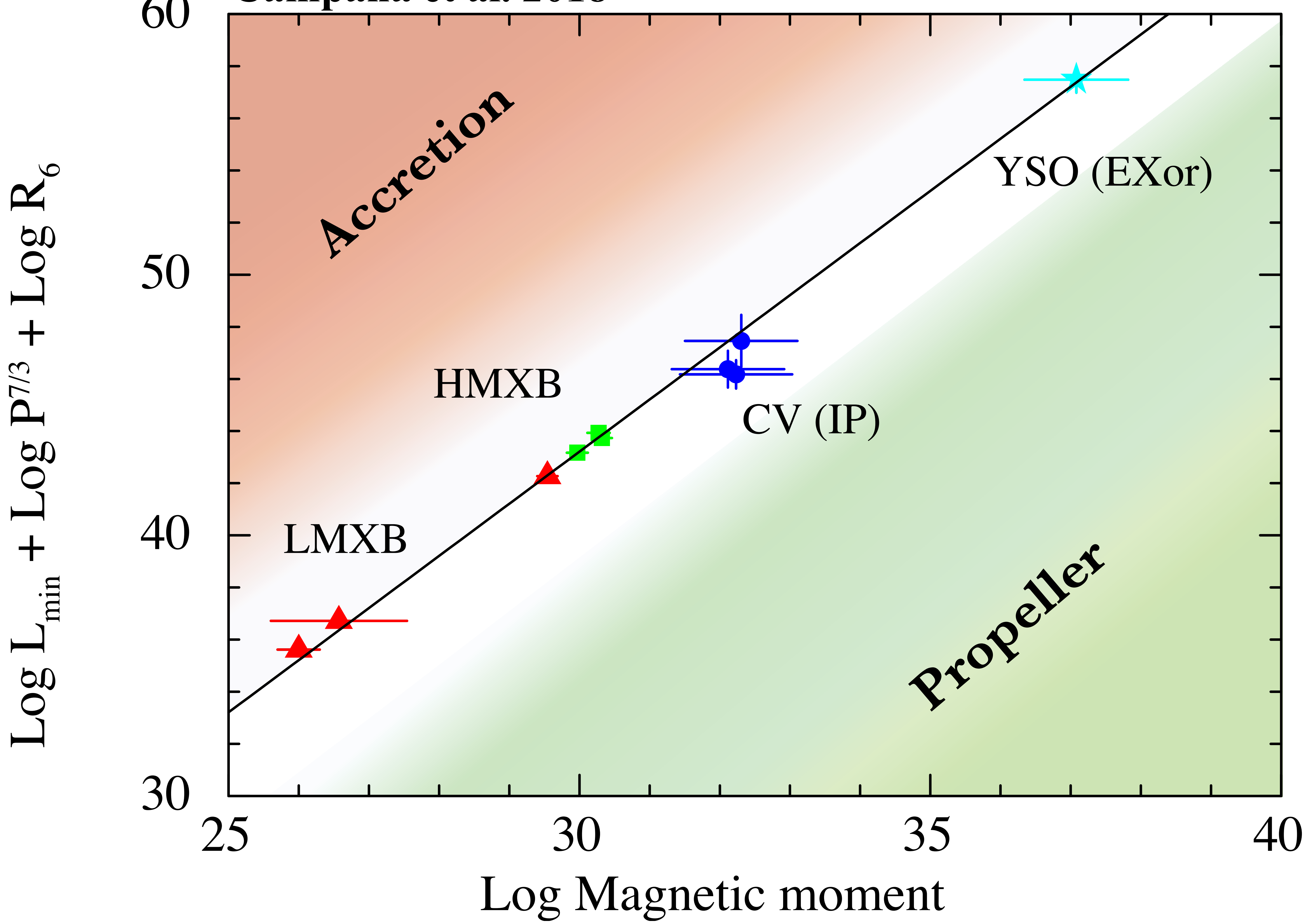
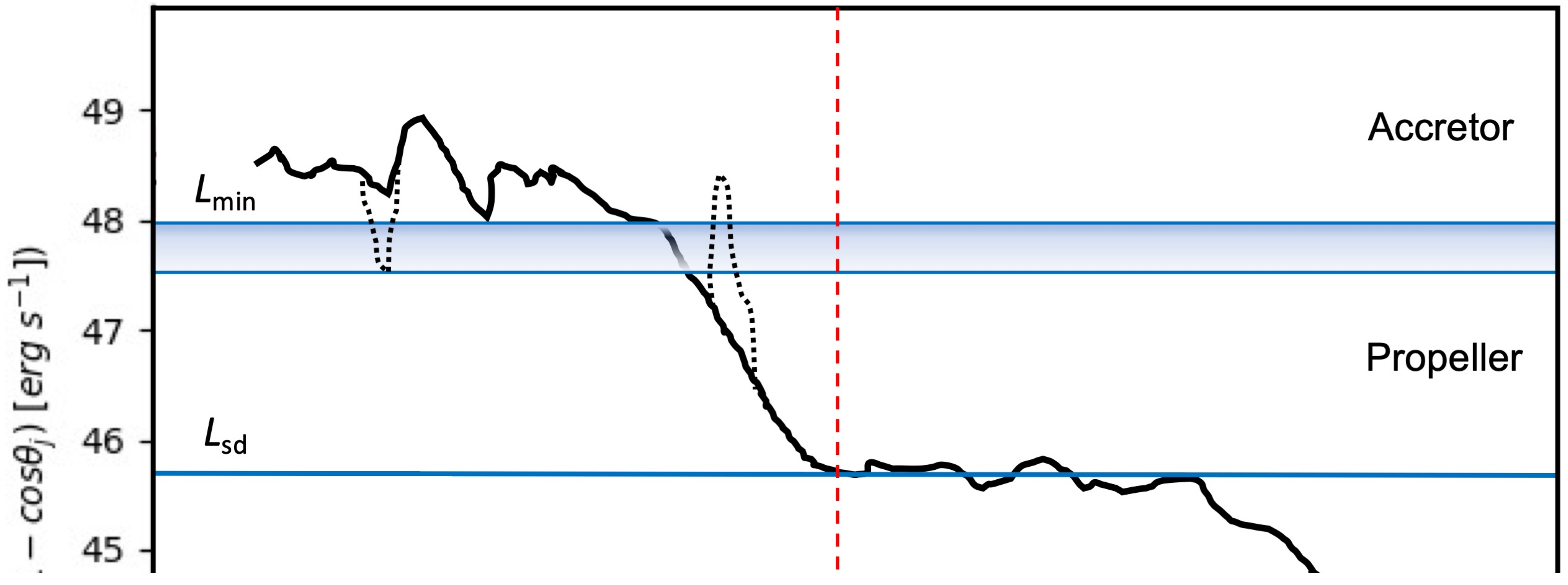
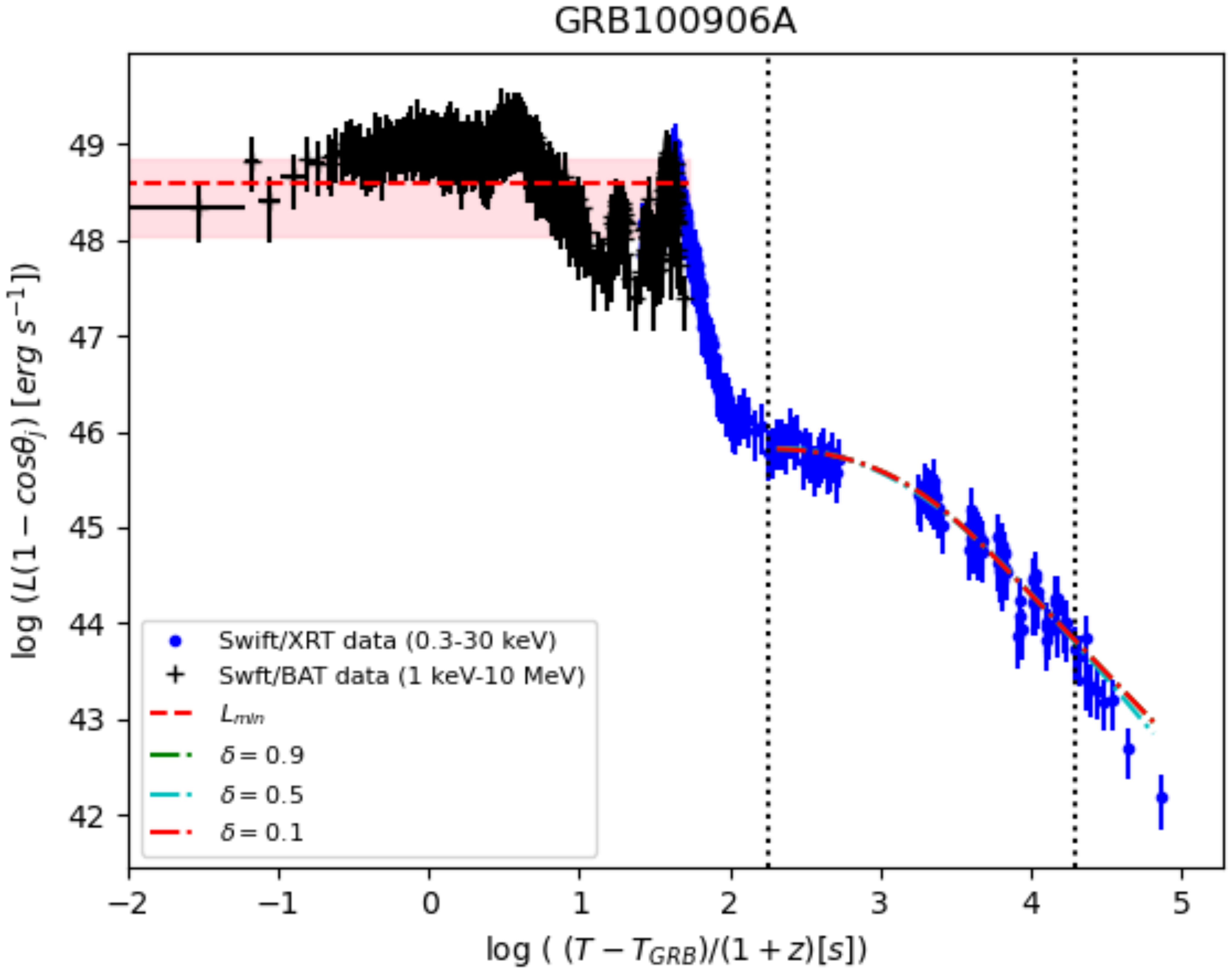
``MAGNETAR” CENTRAL ENGINE REVIVED

Campana et al. 2018



Dall’Osso et al. 2023a

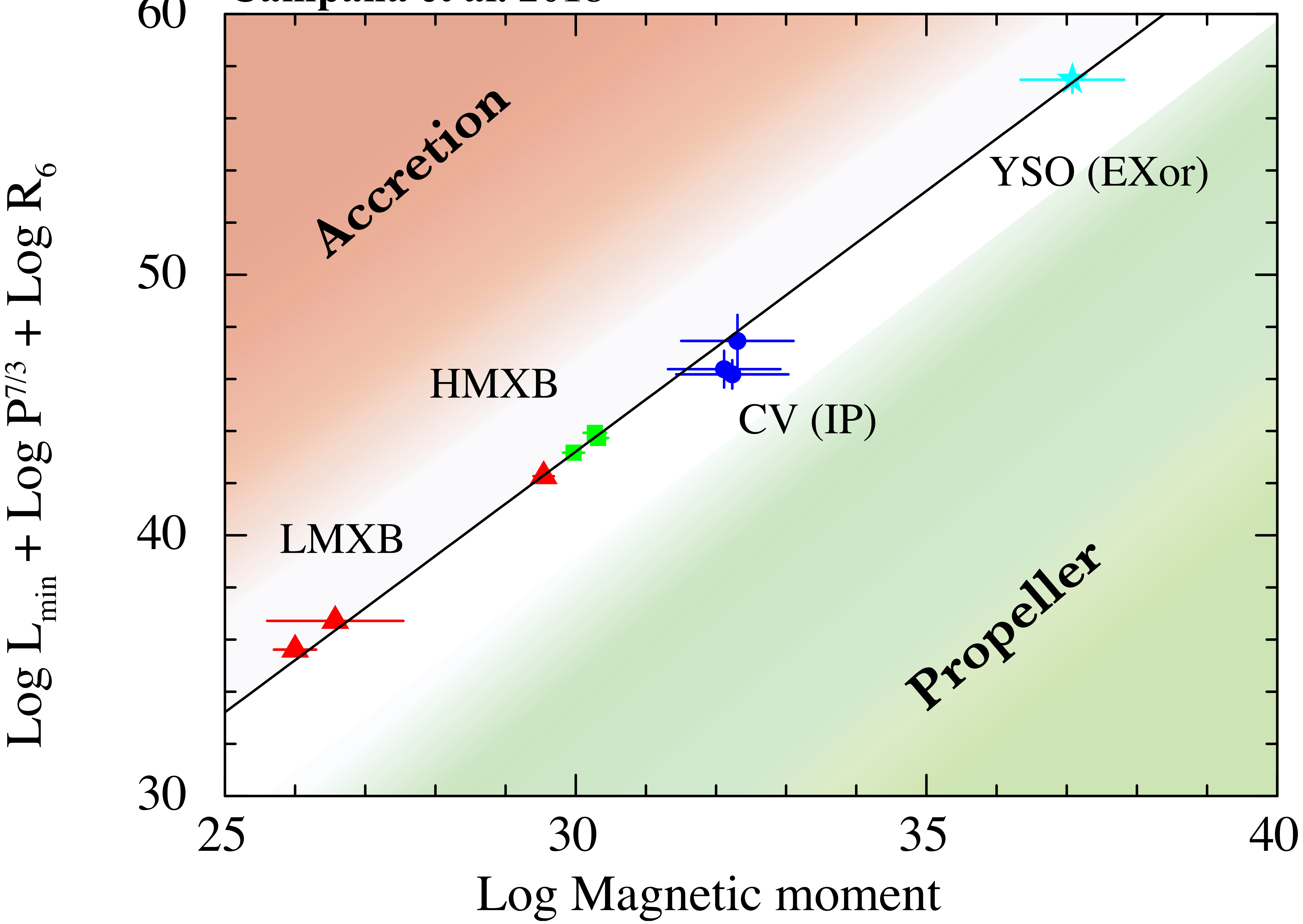




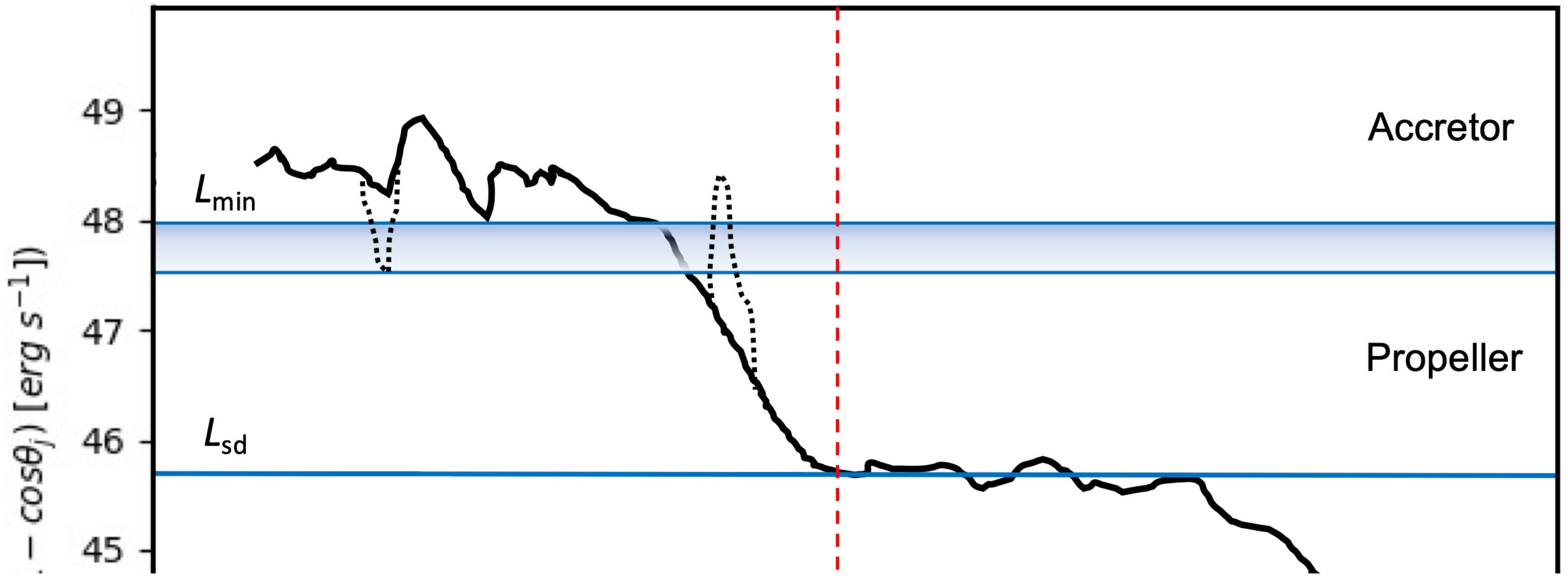
$$L_{\rm min} = 1.4 \times 10^{37}\ {\rm erg\ s^{-1}}\ \epsilon_r \left(\frac{\mu}{10^{30}}\right)^2 P^{7/3} \left(\frac{\xi}{0.5}\right)^{7/2} R_{\rm 10Km}\ M_{1.4}^{-2/3}$$

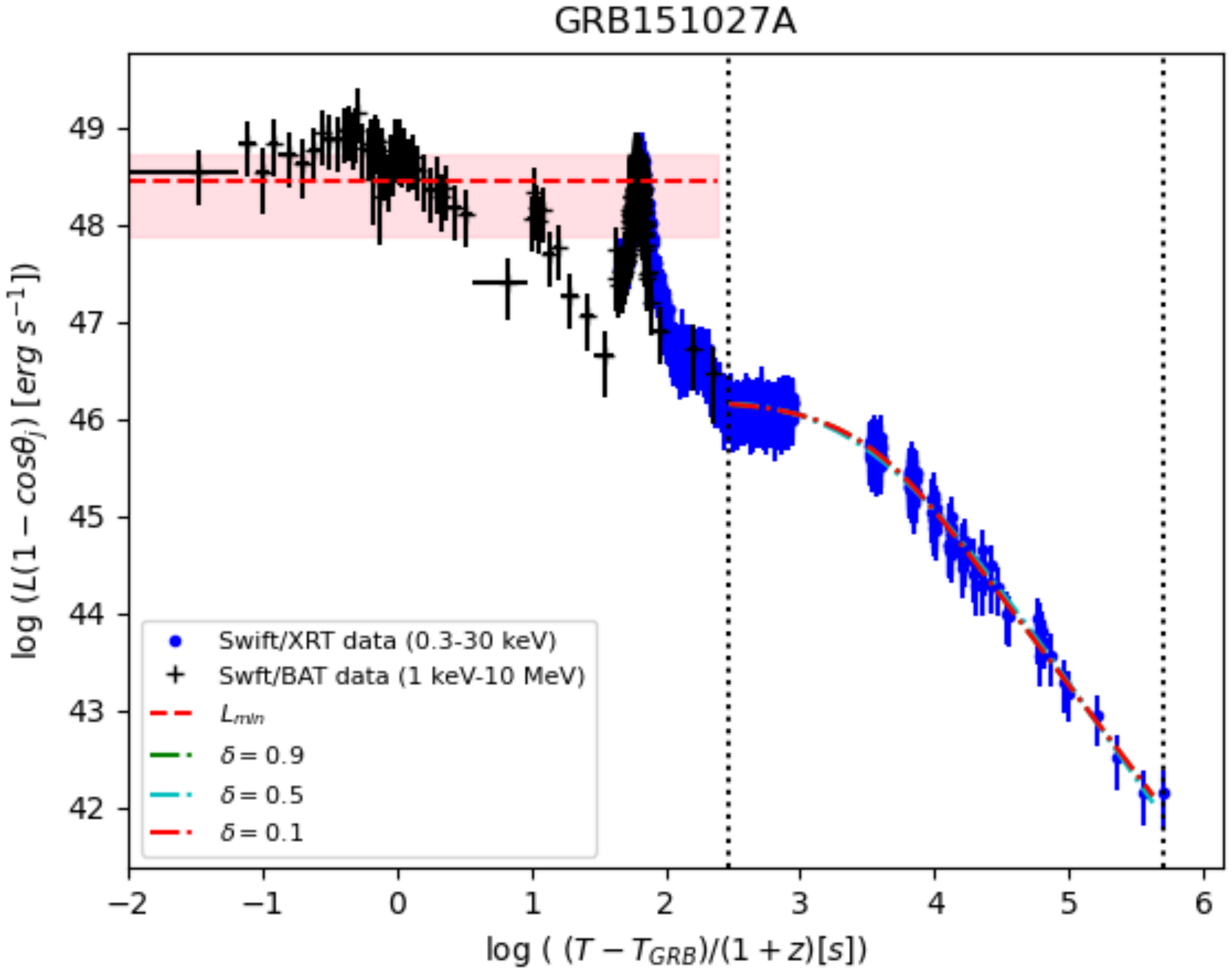
``MAGNETAR" CENTRAL ENGINE REVIVED

Campana et al. 2018



Dall'Osso et al. 2023a





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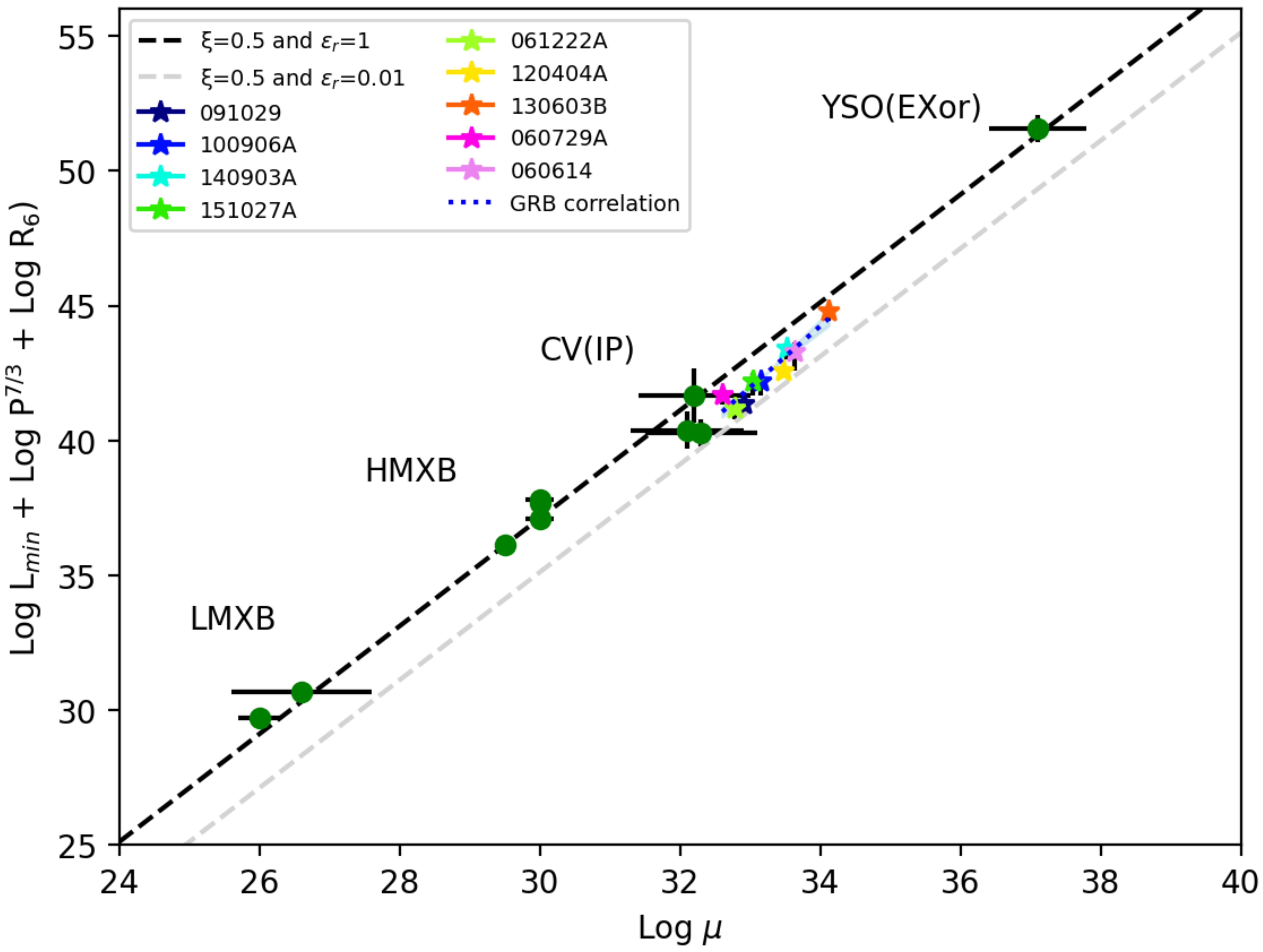

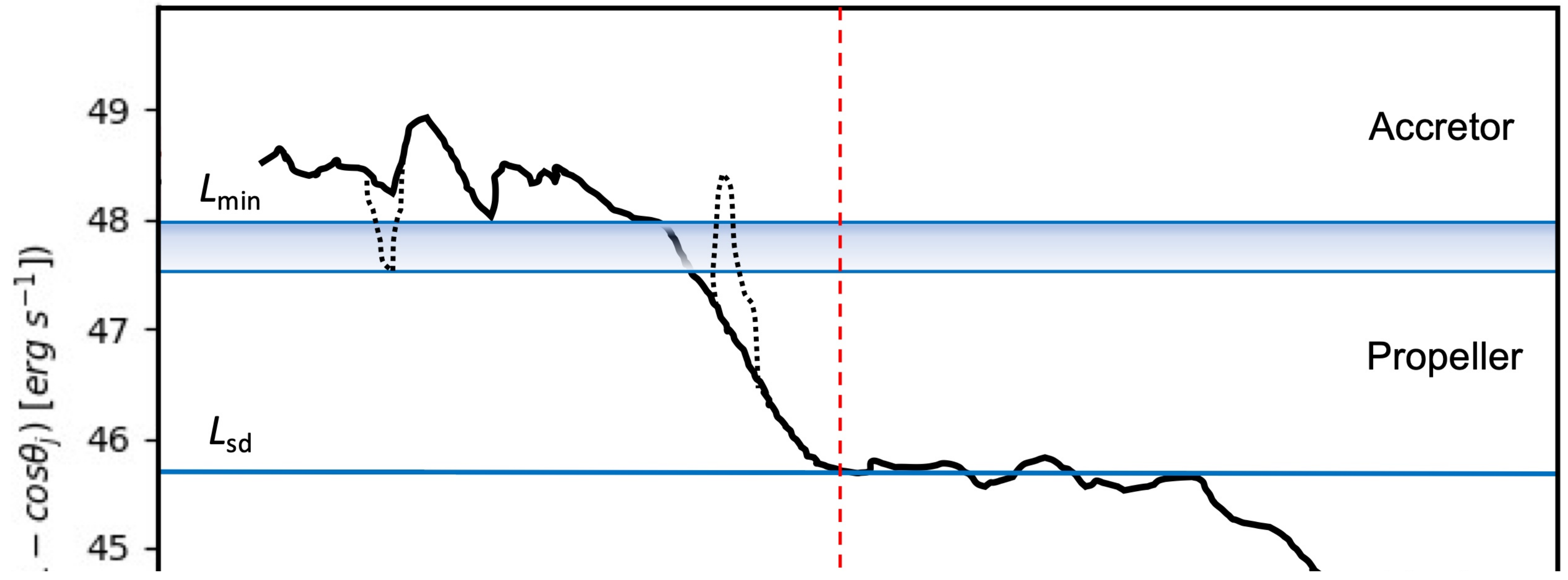

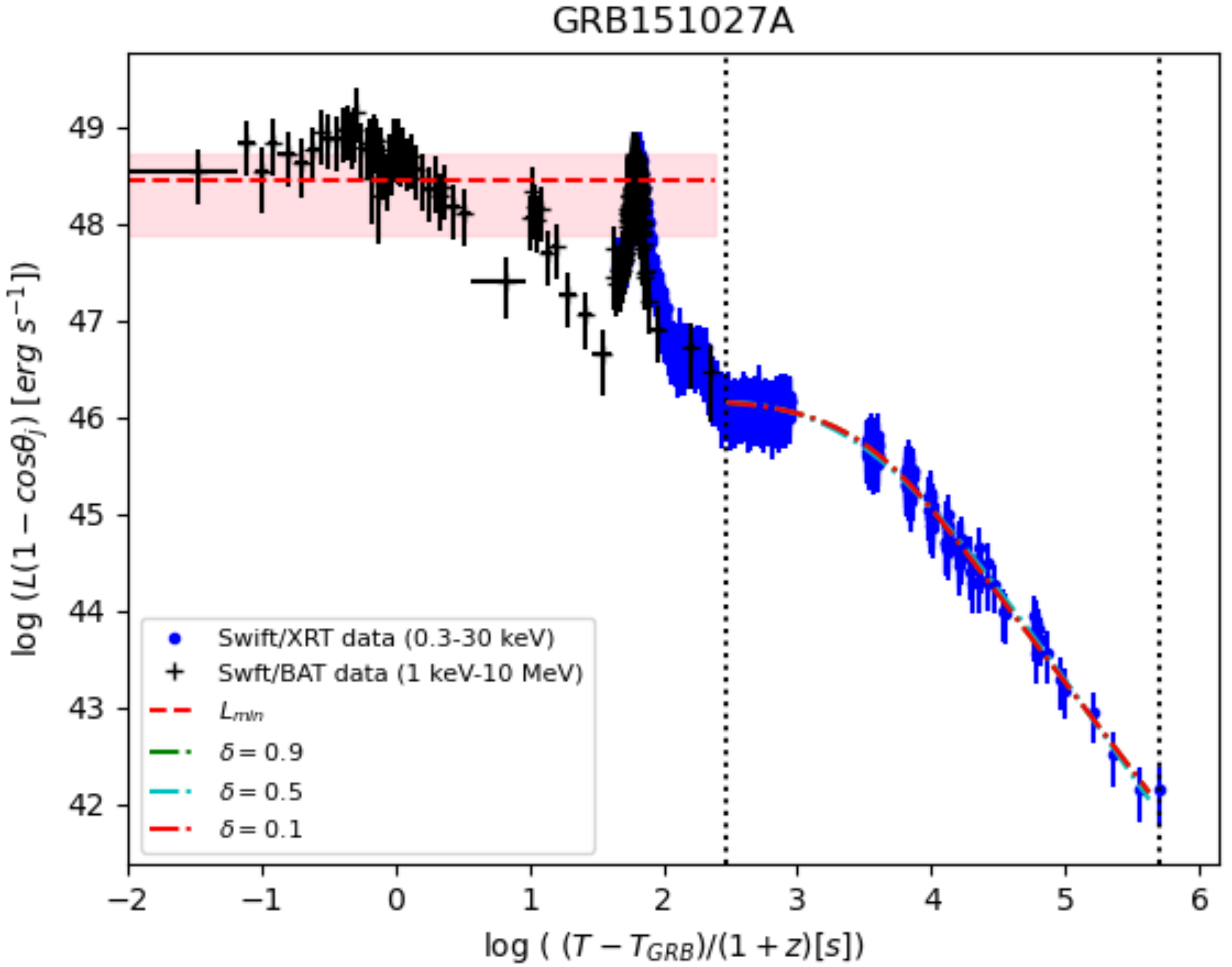

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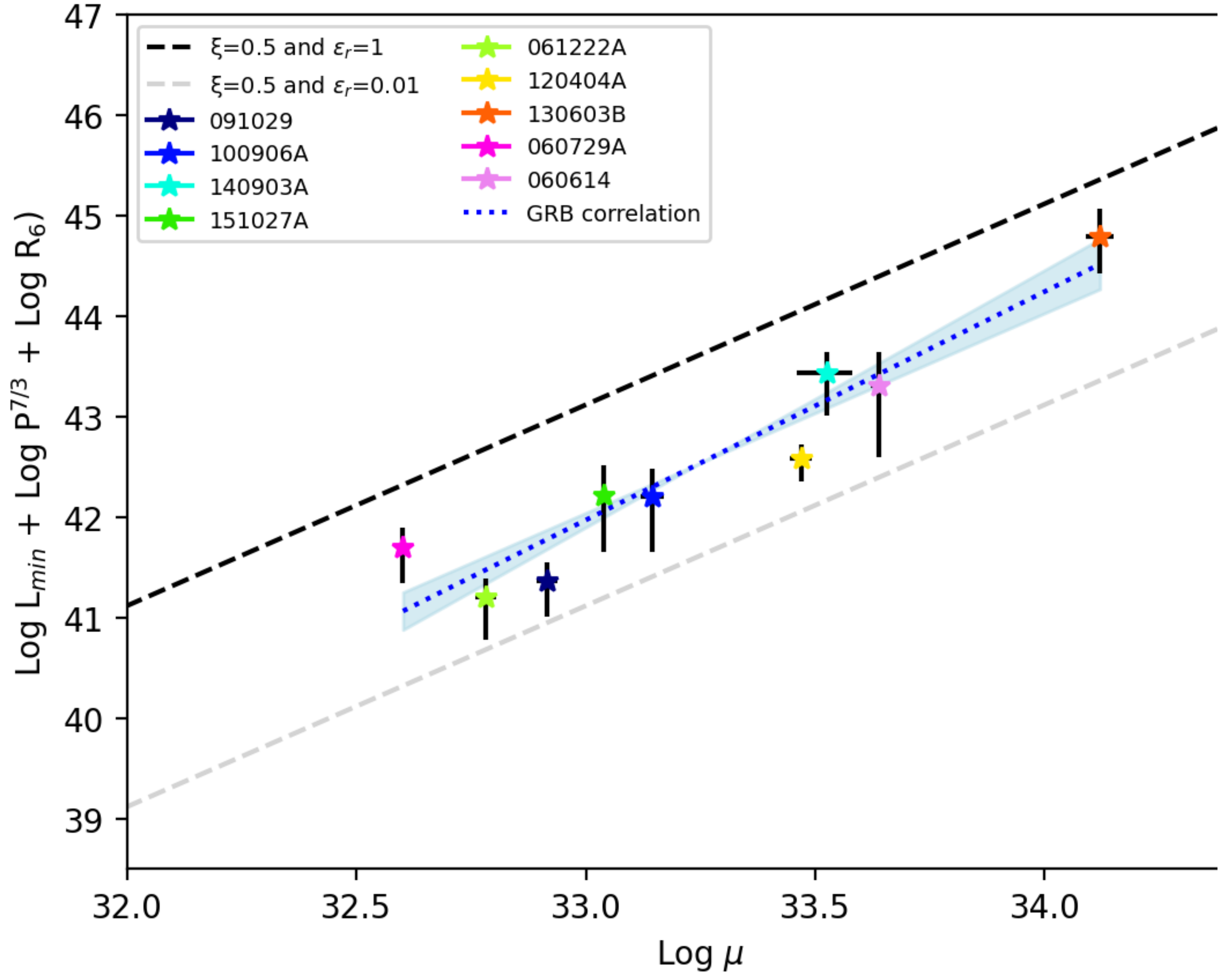
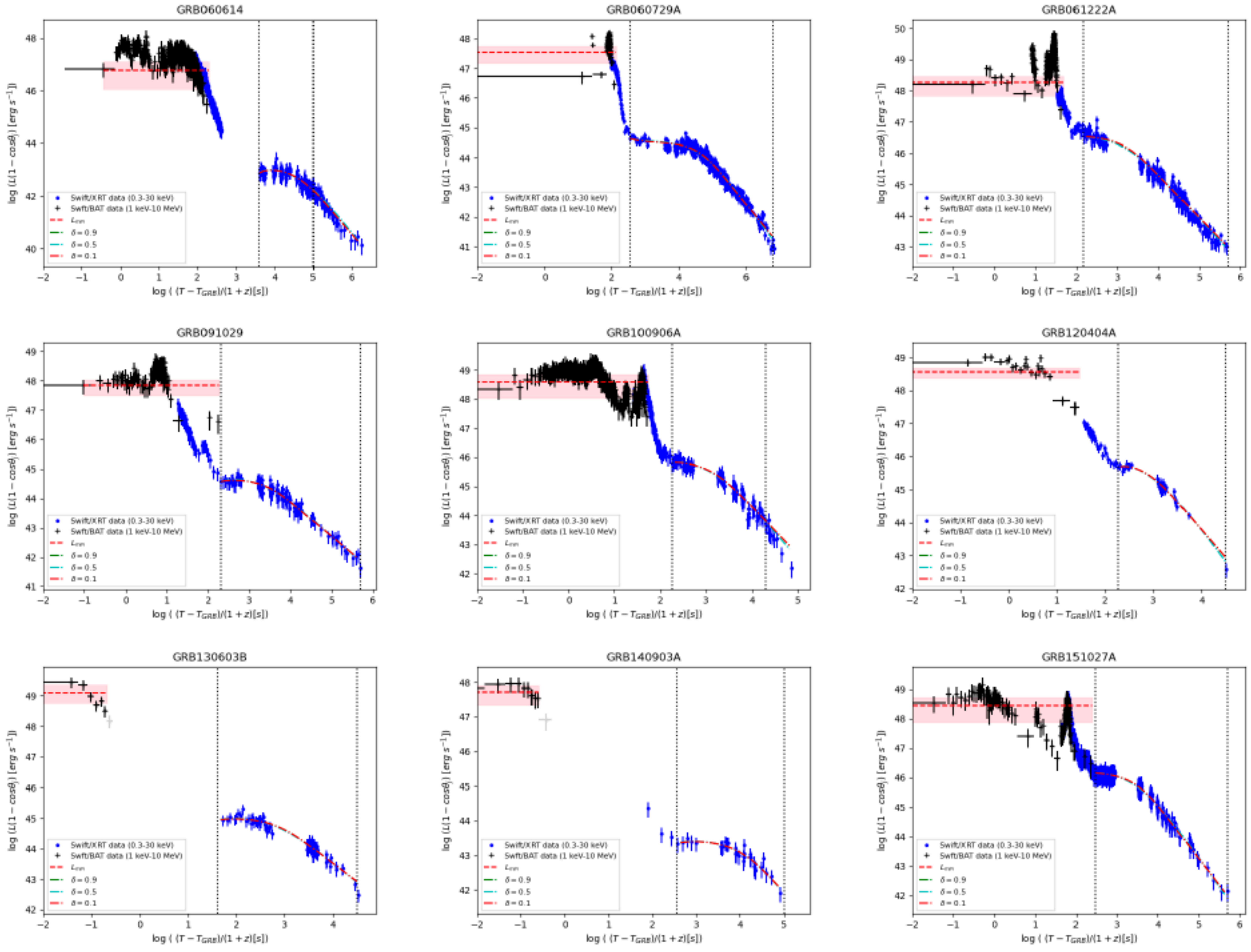
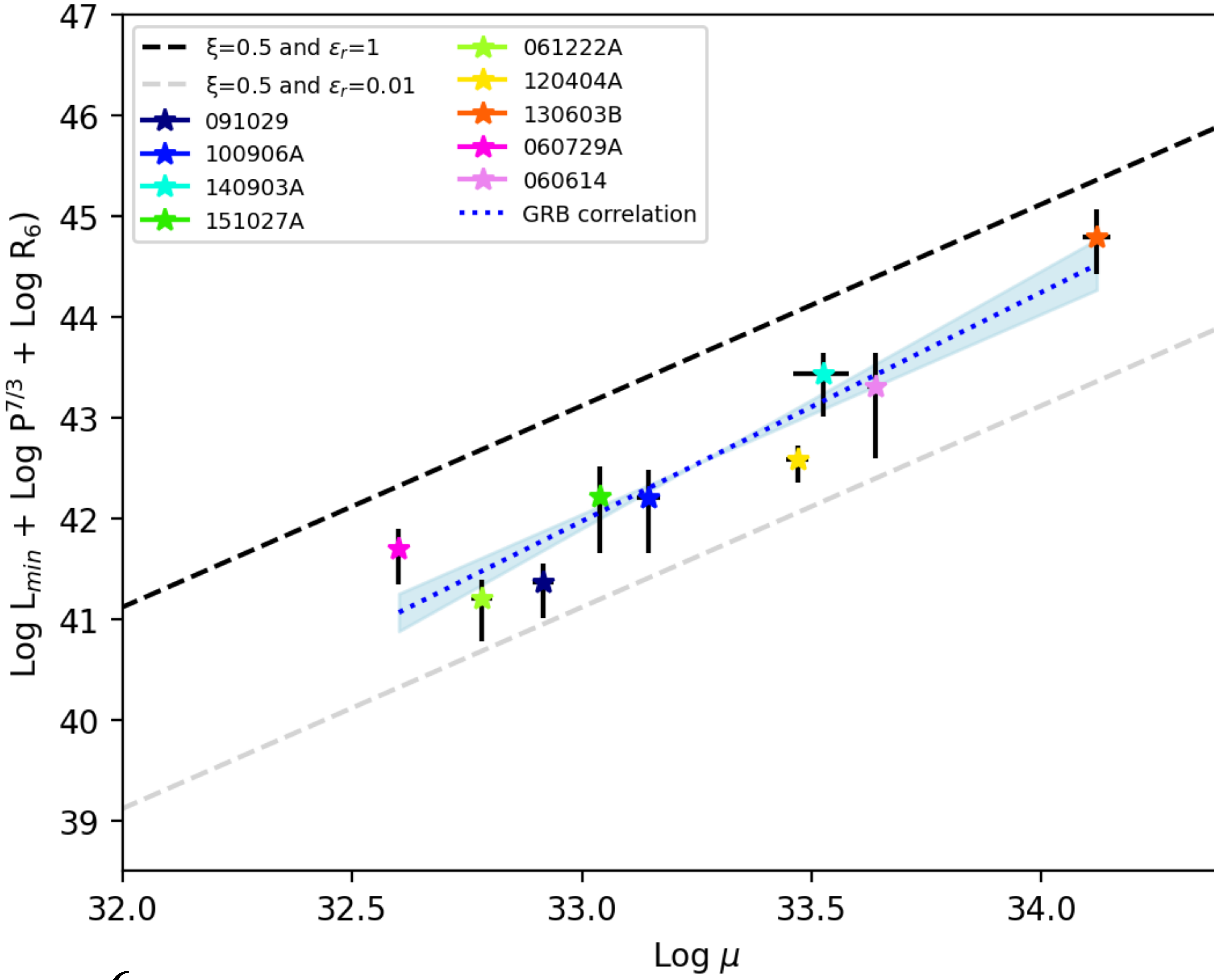


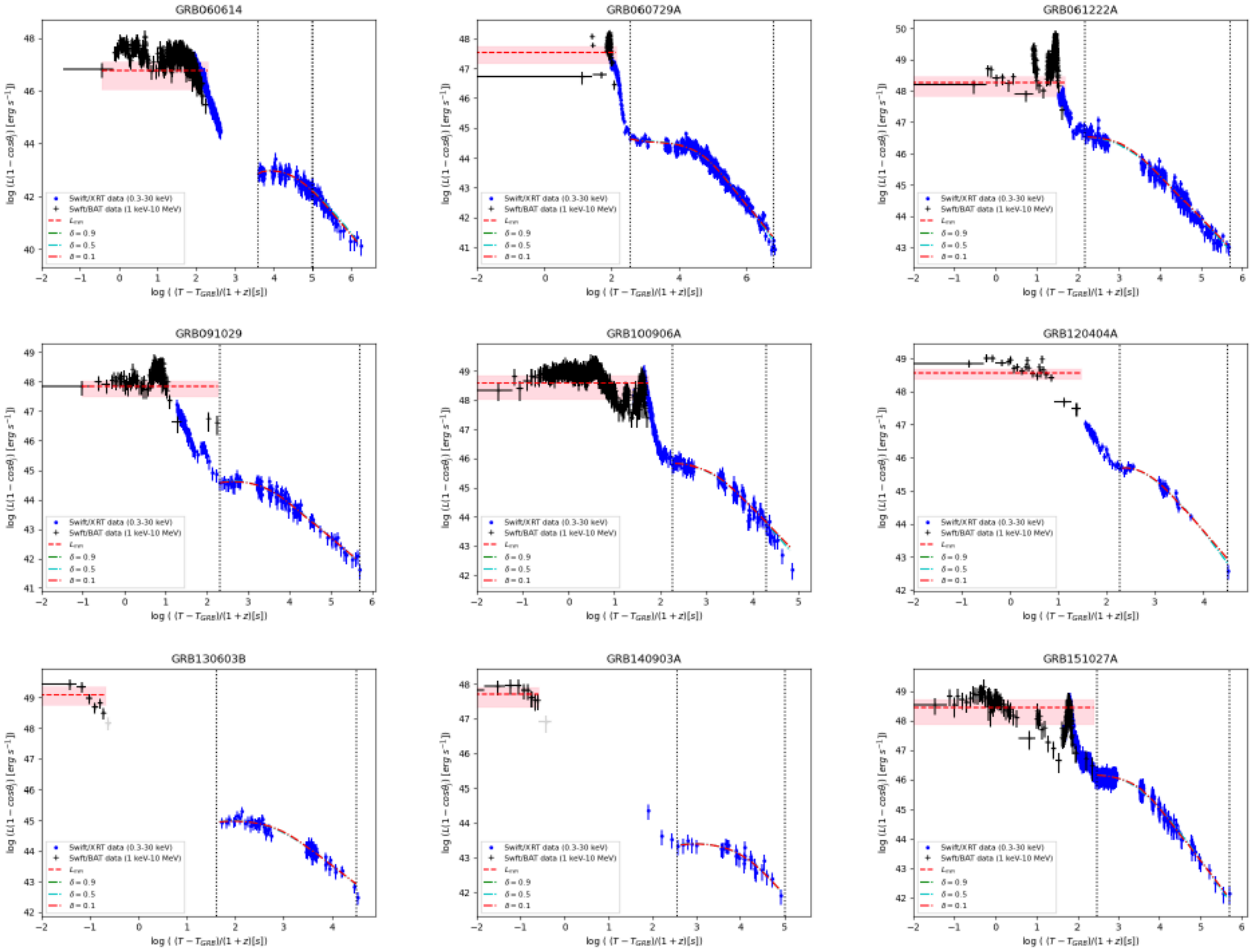


A correlation between prompt and afterglow luminosities is expected in energy injection models and is verified <u>with a minimal set of free parameters</u>

``MAGNETAR” CENTRAL ENGINE REVIVED

Dall’Osso et al. 2023a





$$\begin{cases} \epsilon_r \sim 0.01 - 0.1 \Rightarrow \eta = \dfrac{L_{\rm prompt}}{\dot{M}c^2} \sim 10^{-3} - 10^{-2} \\ \xi \approx 0.5 \quad \text{in} \quad r_{\rm in} = \xi r_A \\ P_{\rm prompt} \approx P_{\rm plateau} \Leftrightarrow \dfrac{L_{\rm plateau}}{L_{\rm sd}} = \epsilon_{\rm sd} \sim 0.15 - 0.3 \end{cases}$$

``MAGNETAR" CENTRAL ENGINE IN SHORT GRBs?

Systematic study of the incidence of afterglow plateaus in short GRBs
using the full sample of Swift short GRBs with known redshift (82 events)
(Master Thesis by Luca Guglielmi at Bologna University - in collab. with Goethe University, Frankfurt)

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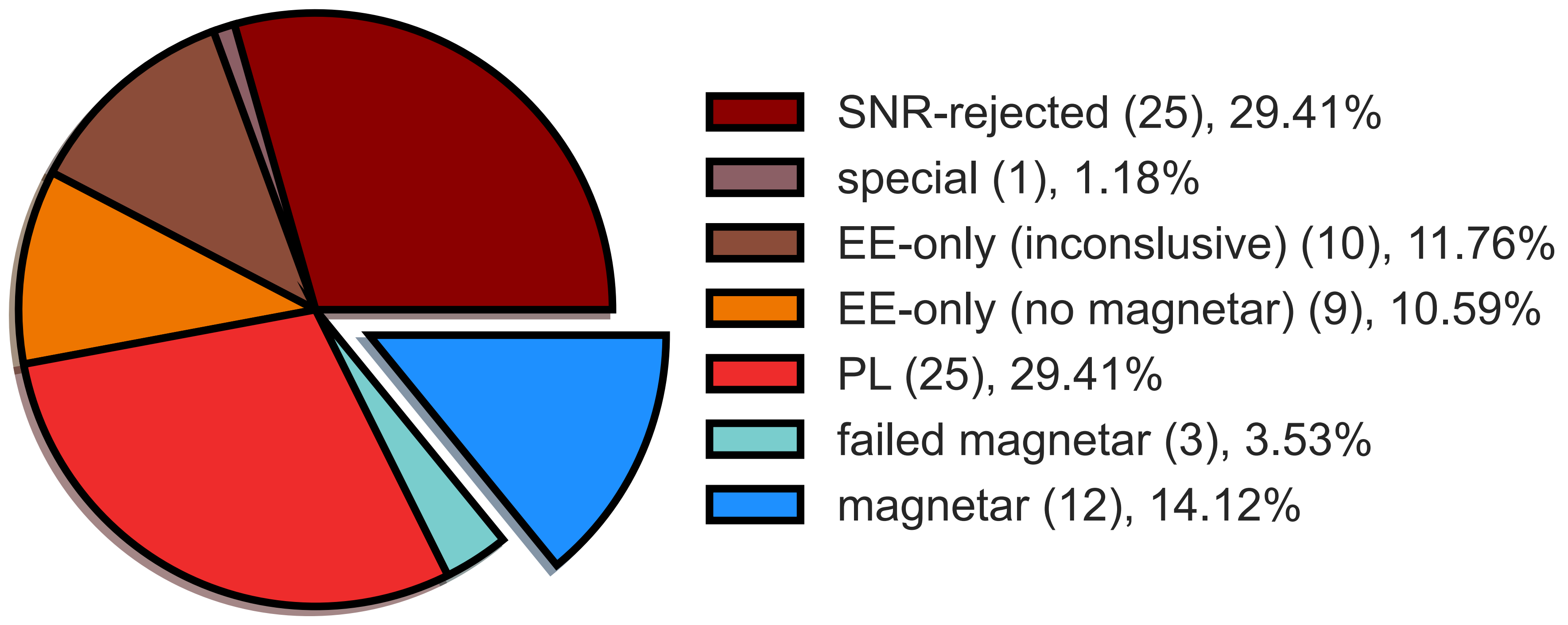
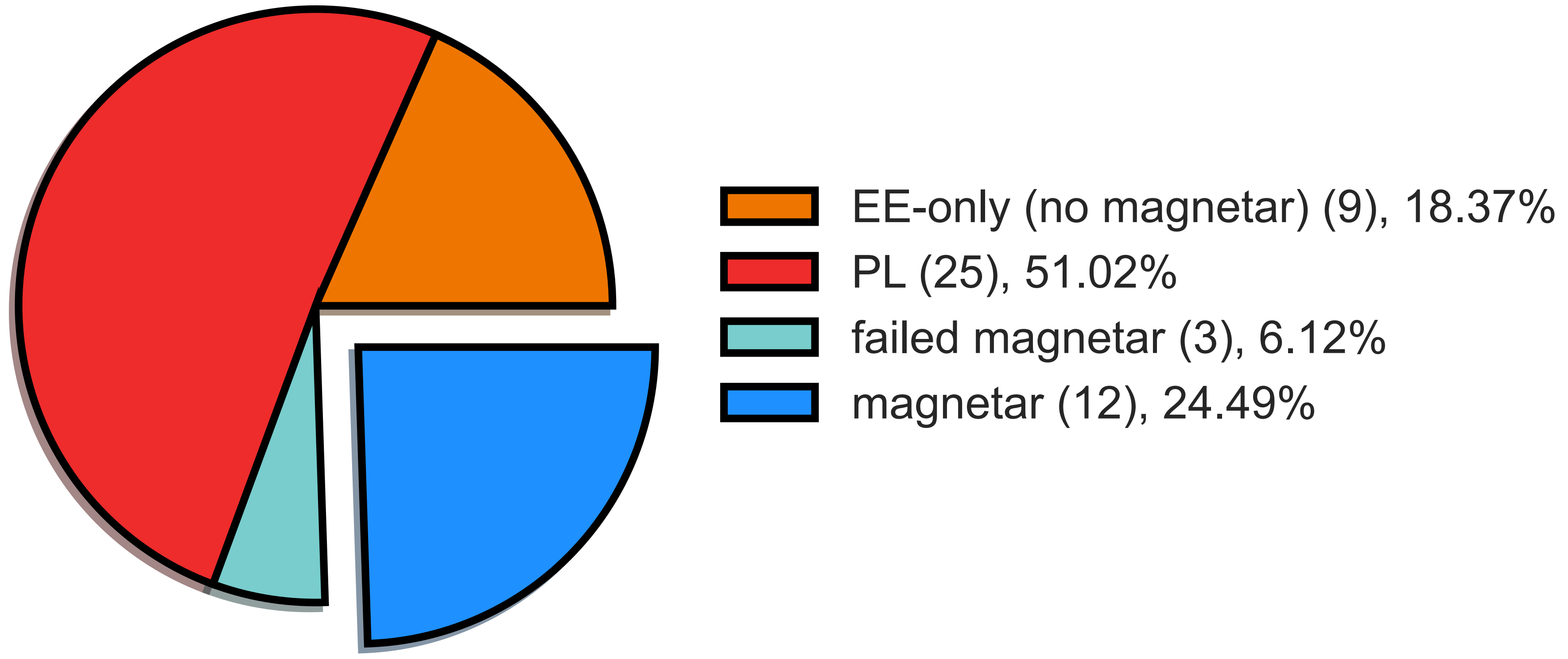


Only (14-24)% sGRBs display plateaus as
opposed to > 50% in long-GRBs



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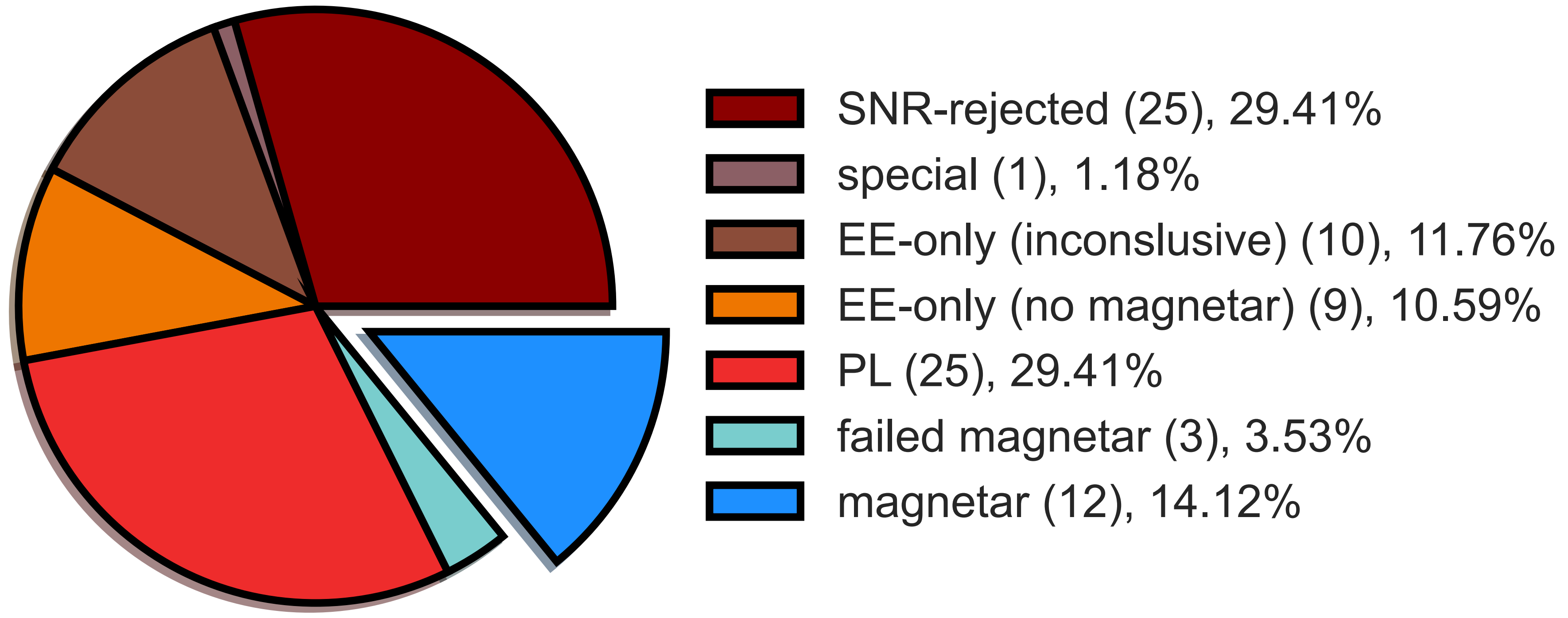

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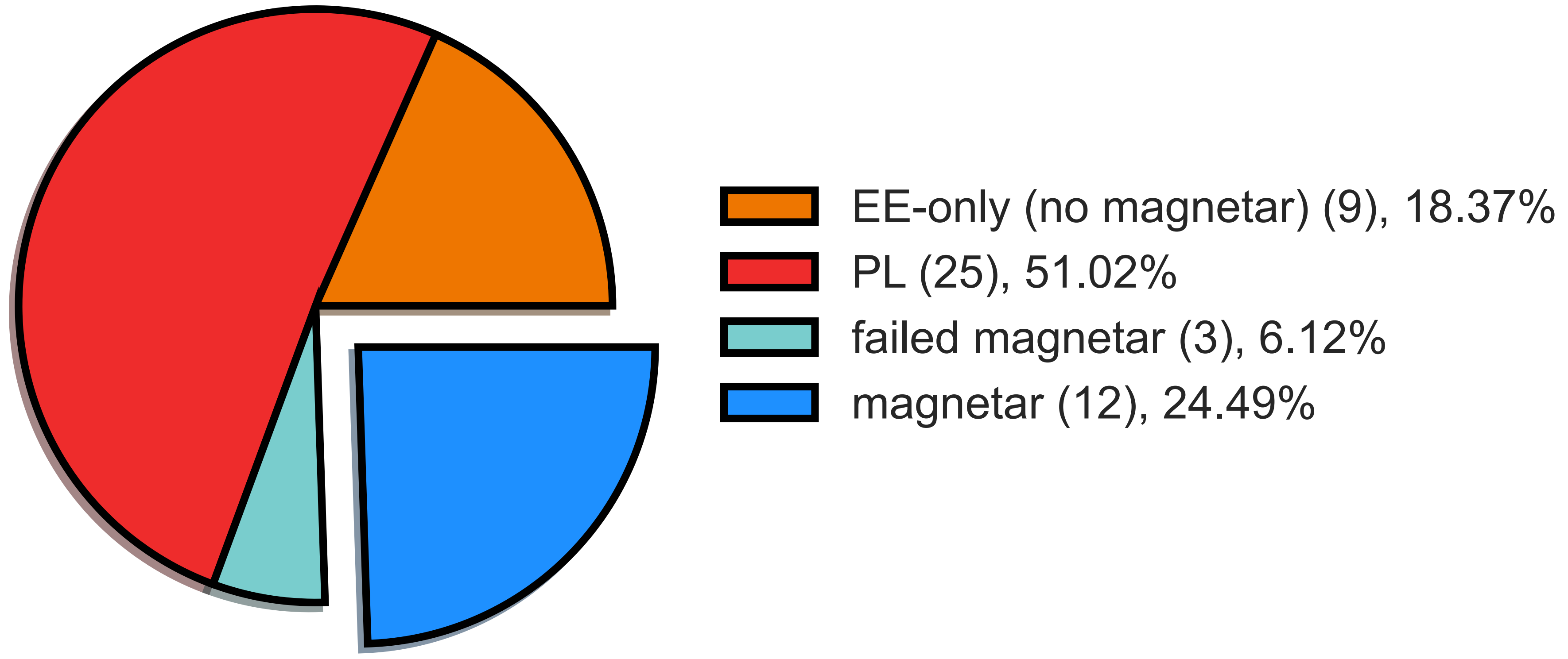
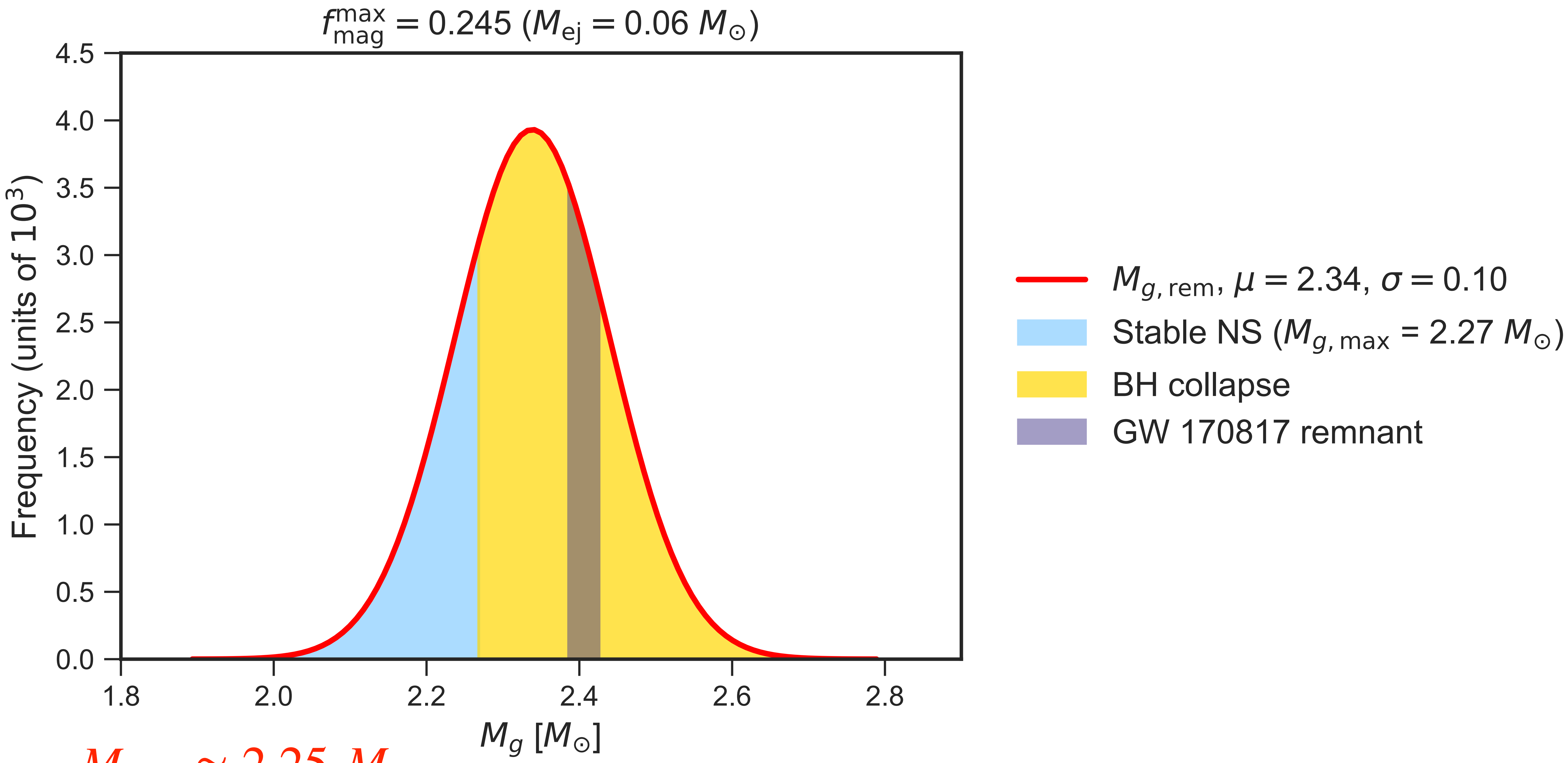
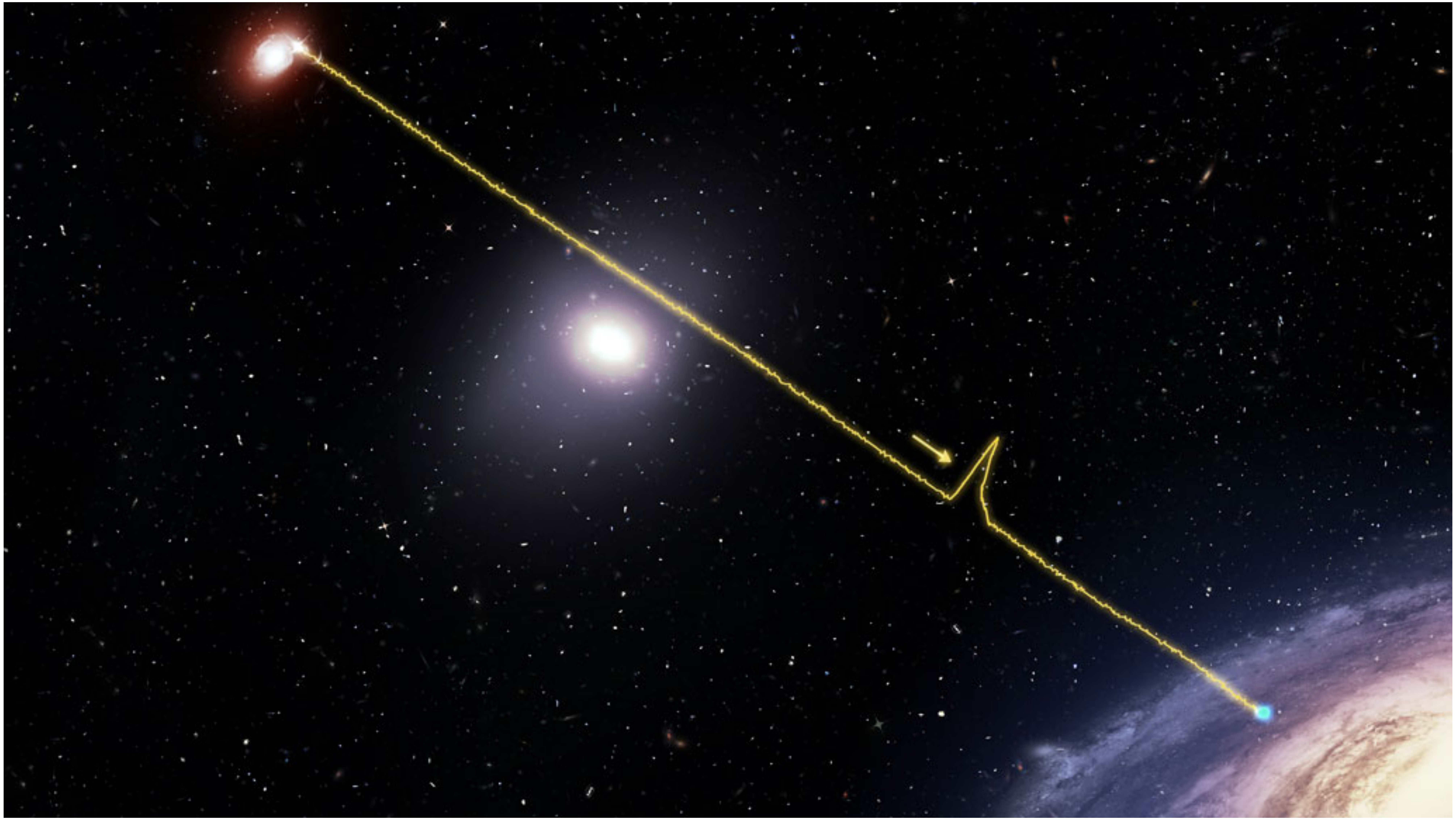




$M_{\rm max} \approx 2.25\ M_\odot$

e.g.,
Rezzolla et al. 2018
Margalit & Metzger 2018

SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs



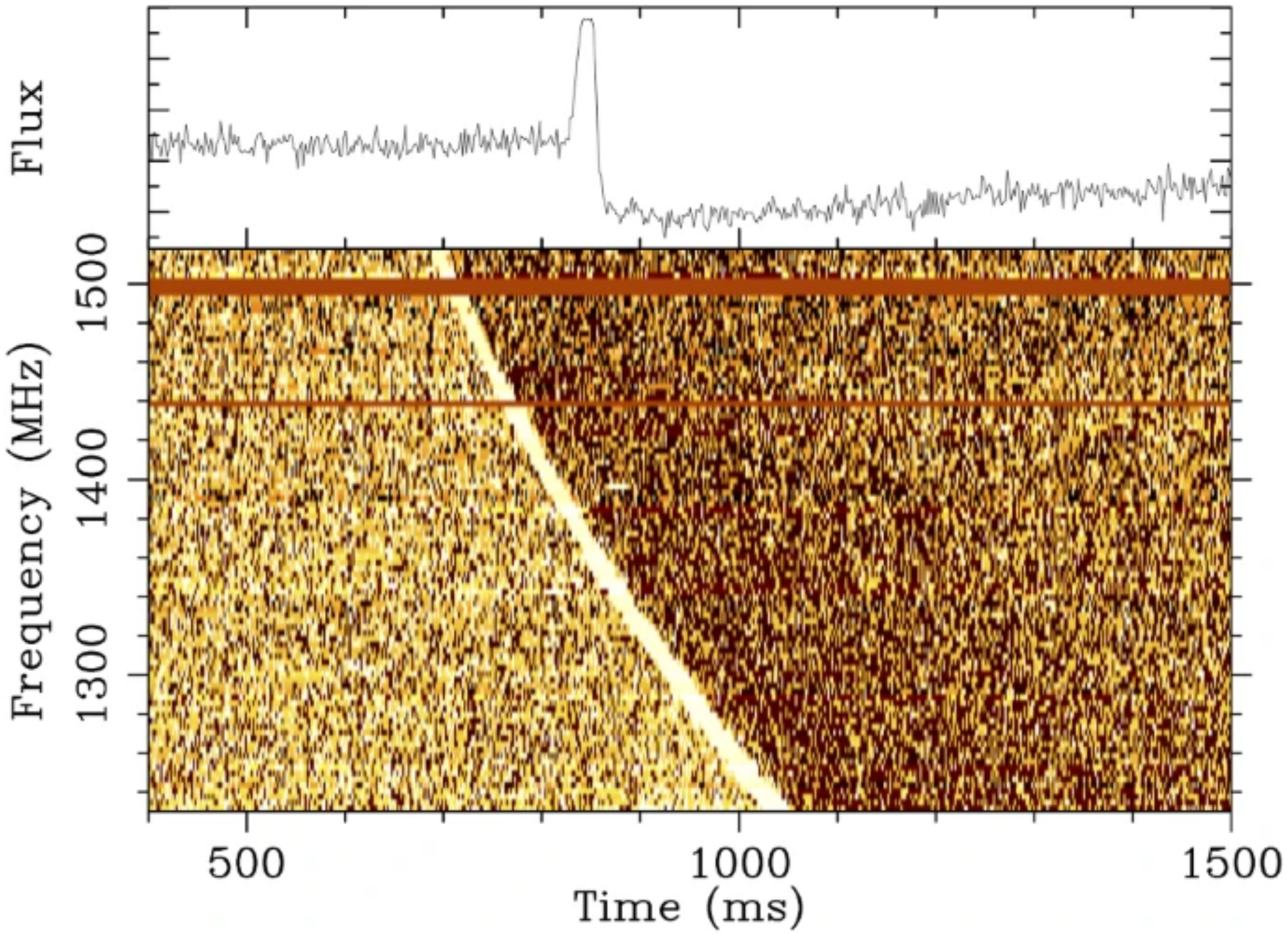
SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs

Fast Radio Bursts (FRBs)

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

$$\Delta E_{\rm iso} \sim 10^{37} - 10^{42} \text{ erg}$$

(b) some of them are repeating sources, and a bunch of the latter have host galaxies/persistent radio counterparts



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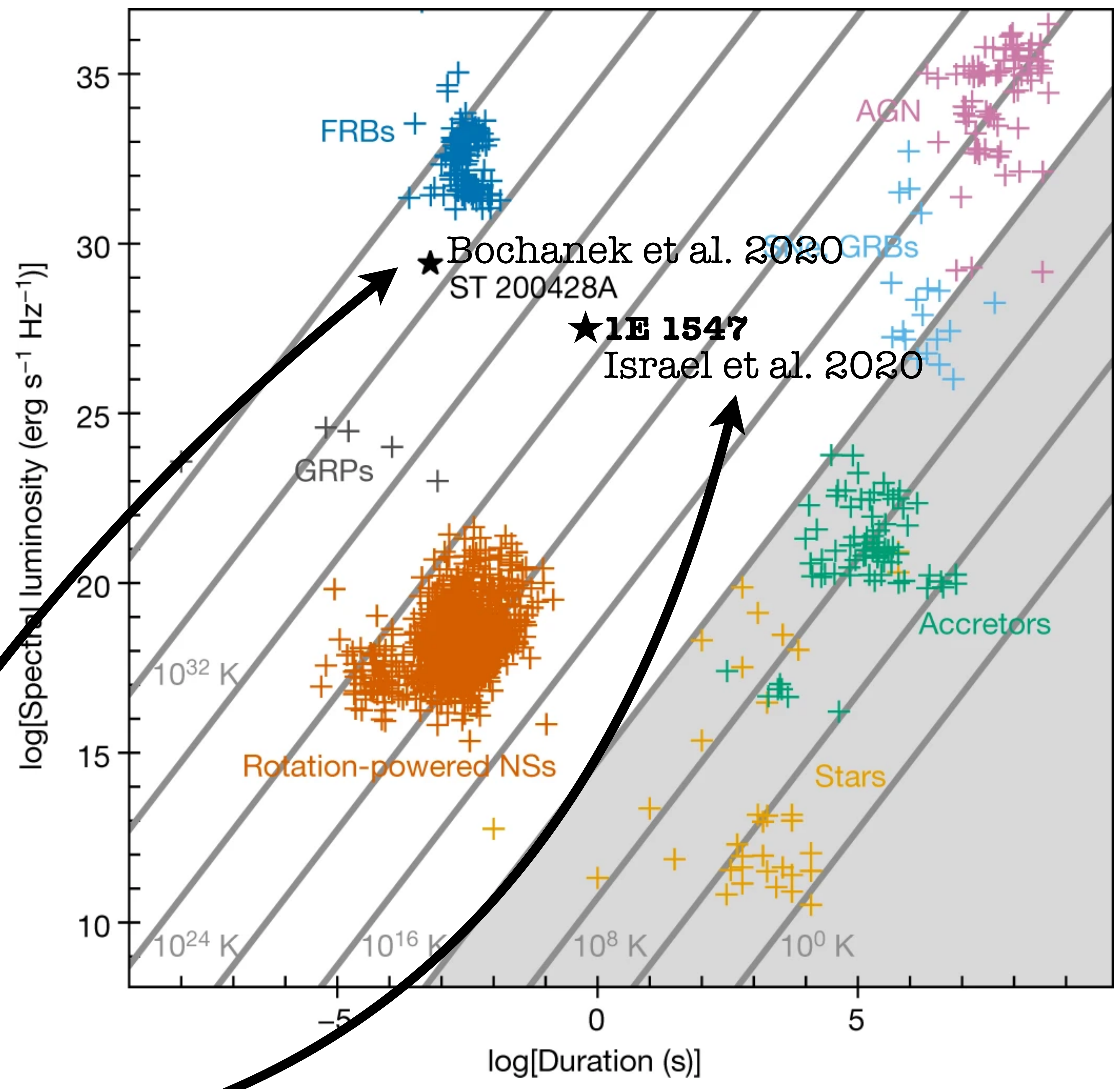

(b) some of them are repeating sources, and a bunch of the latter have host galaxies/persistent radio counterparts

(c) a couple of galactic magnetars are the only known objects that have emitted FRB-like flares

(d) some of them clearly indicate a highly magnetised environment (very large linear polarisation)

(e) the huge energy budget (and very short timescales) strongly favour magnetic over, e.g. spin, energy

ARE WE SEEING VERY YOUNG ($<$ 100 yrs) MAGNETARS?

SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs

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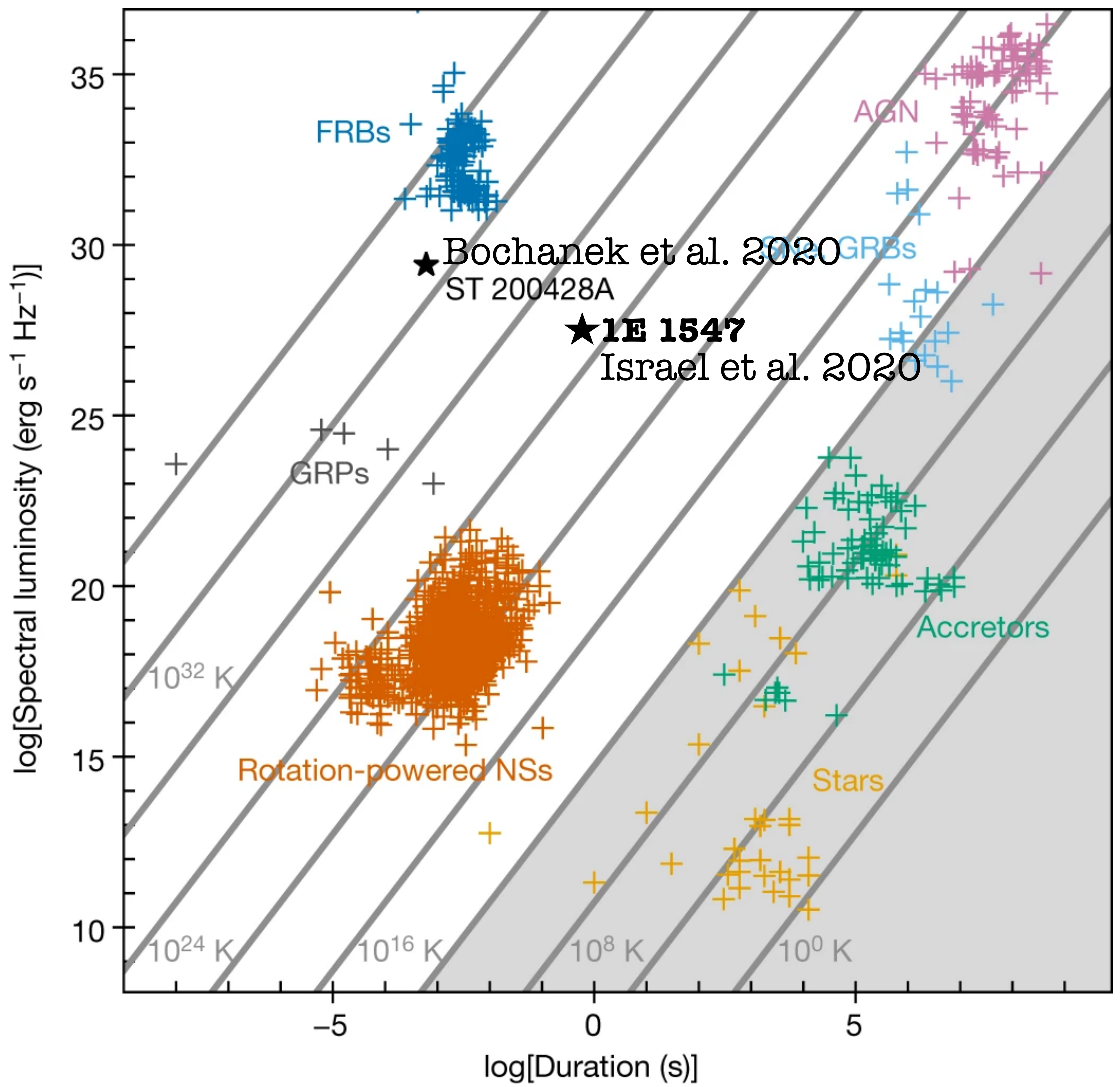


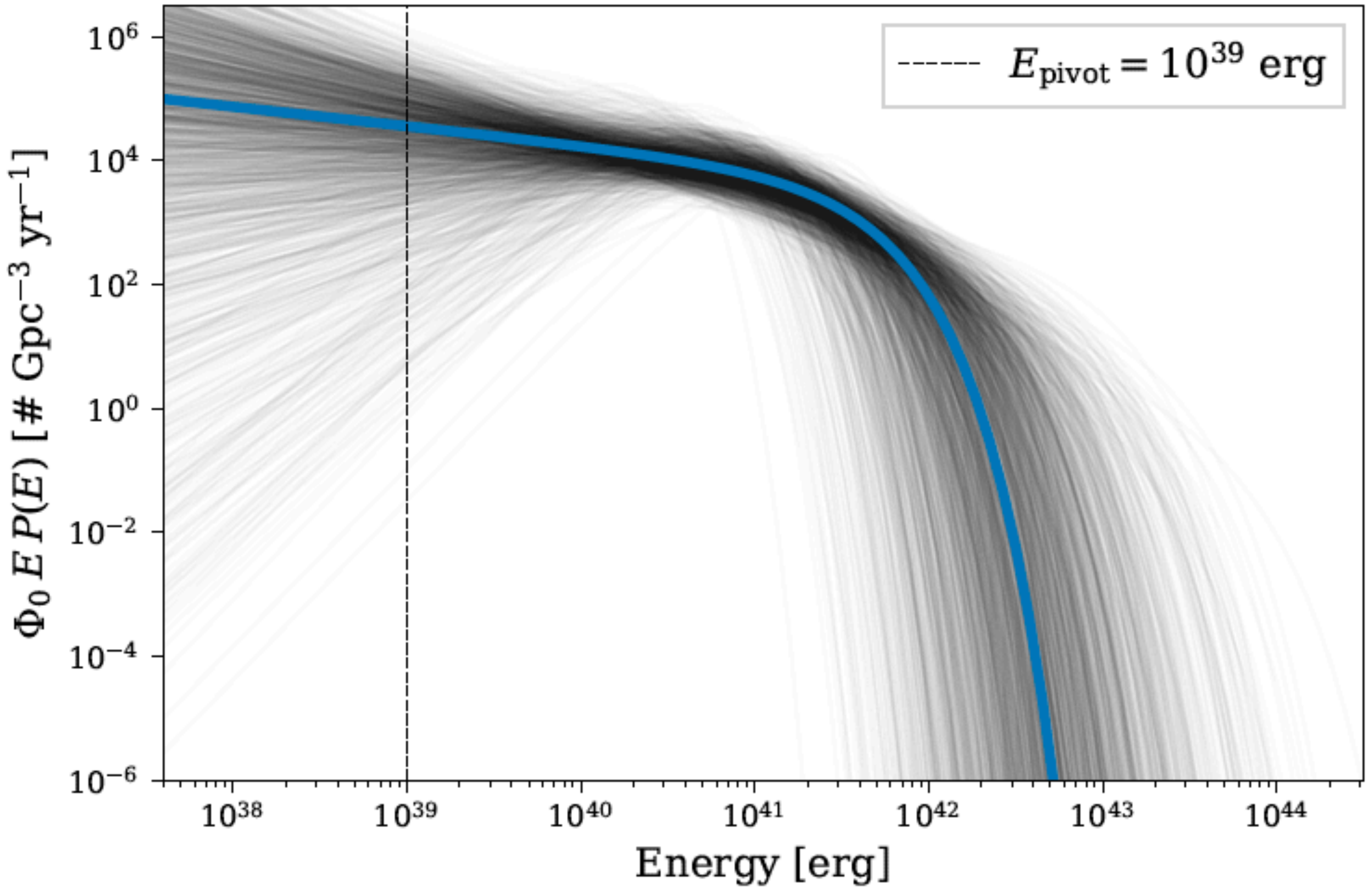
(f) two different FRBs recently proposed to be associated to a BNS merger, with ~ 1-2 hr delay (Moroianu et al. 2022; Rowlinson et al. 2023).

(i) both associations are quite arguable, yet the potential is clear

(ii) BNS mergers may, at best, contribute a small minority of FRBs, given the widely different all-sky rates. Magnetars formed in core-collapse represent a viable progenitor for the bulk of FRBs

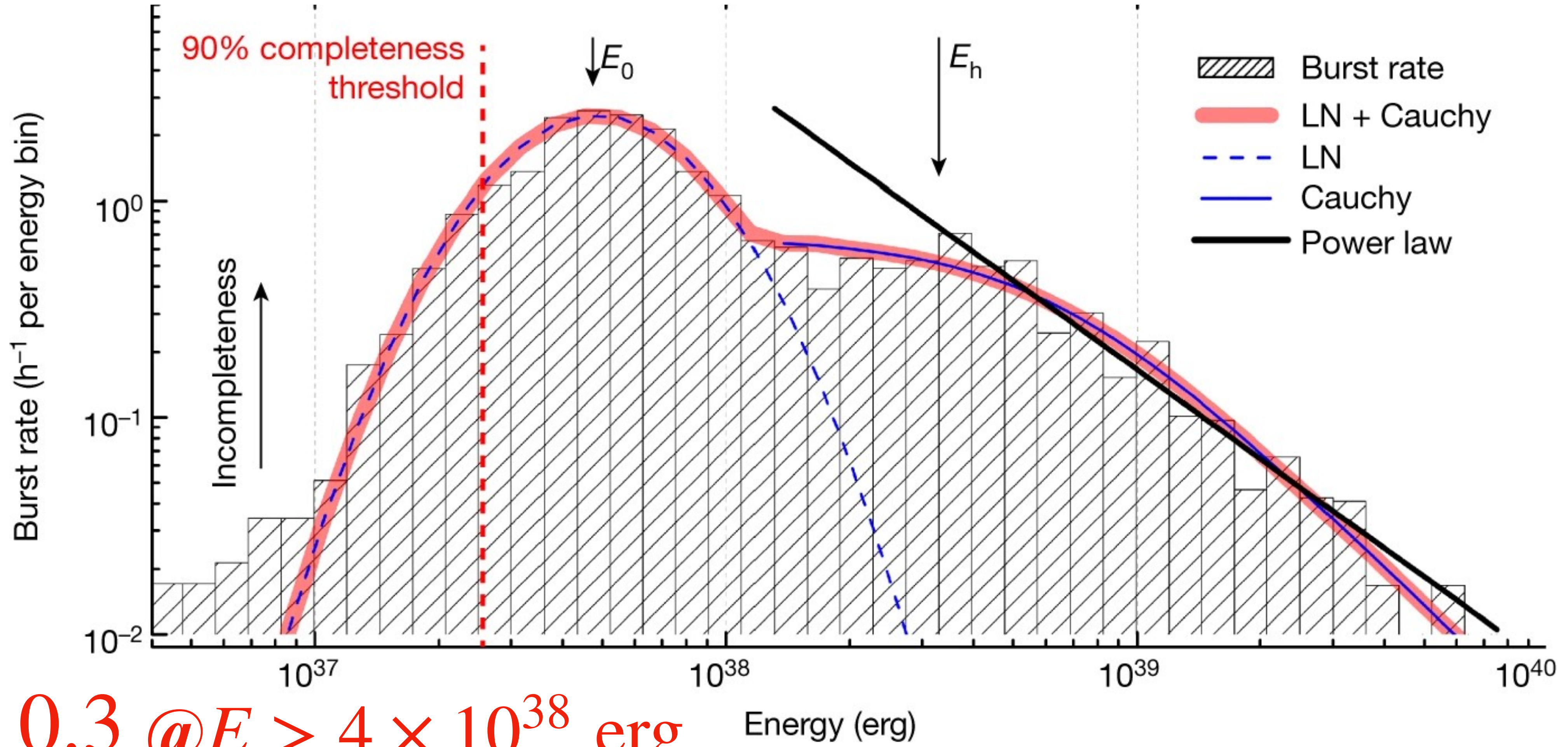
SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs

FRBs: Event energy distribution



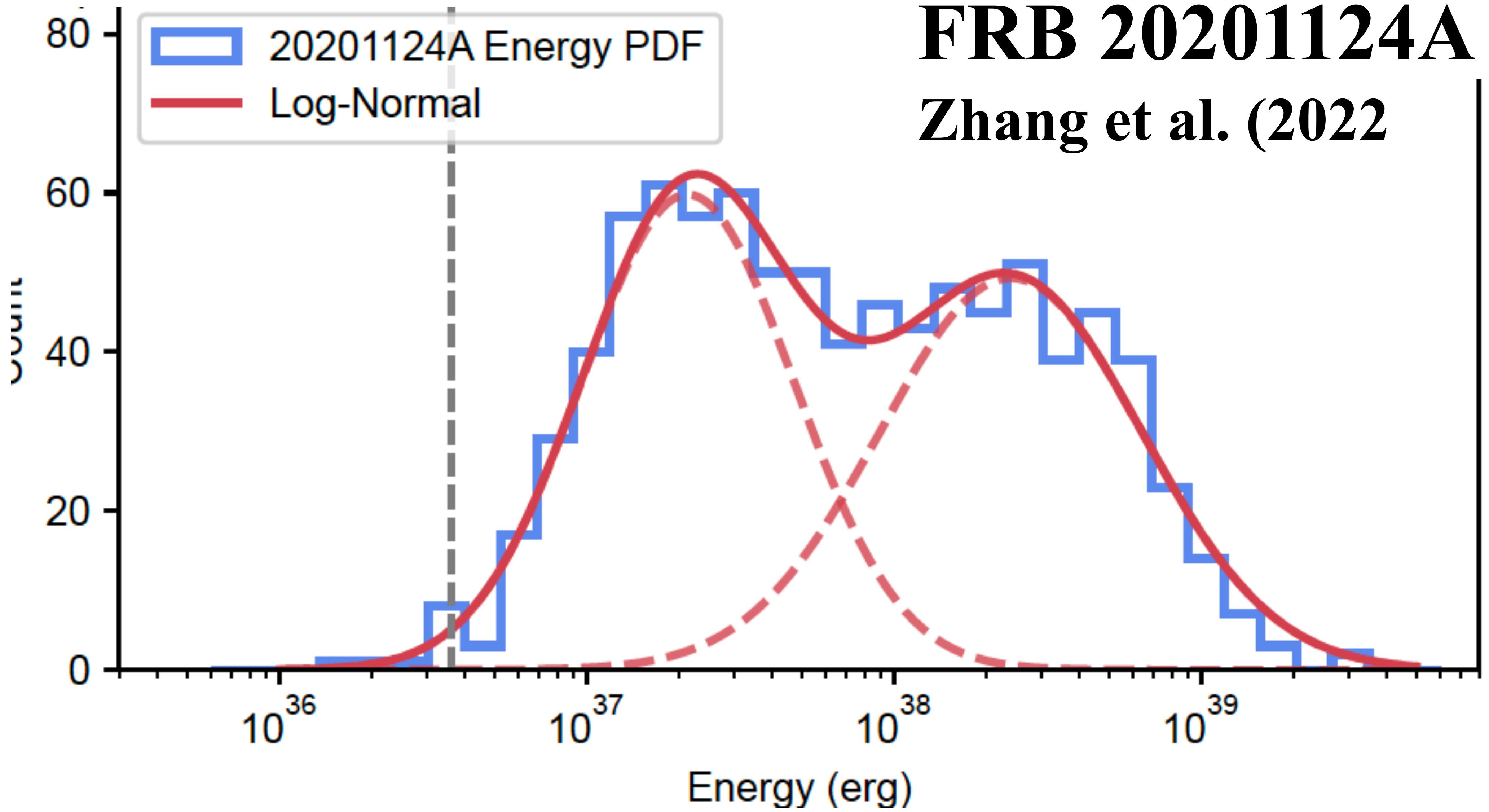
$$\frac{dN}{dE} \propto E^{-\gamma}$$

FRB 20121102
Li et al. (2021)



$\gamma = 1.85 \pm 0.3$ @$E > 4 \times 10^{38}$ erg

FRB 20201124A
Zhang et al. (2022

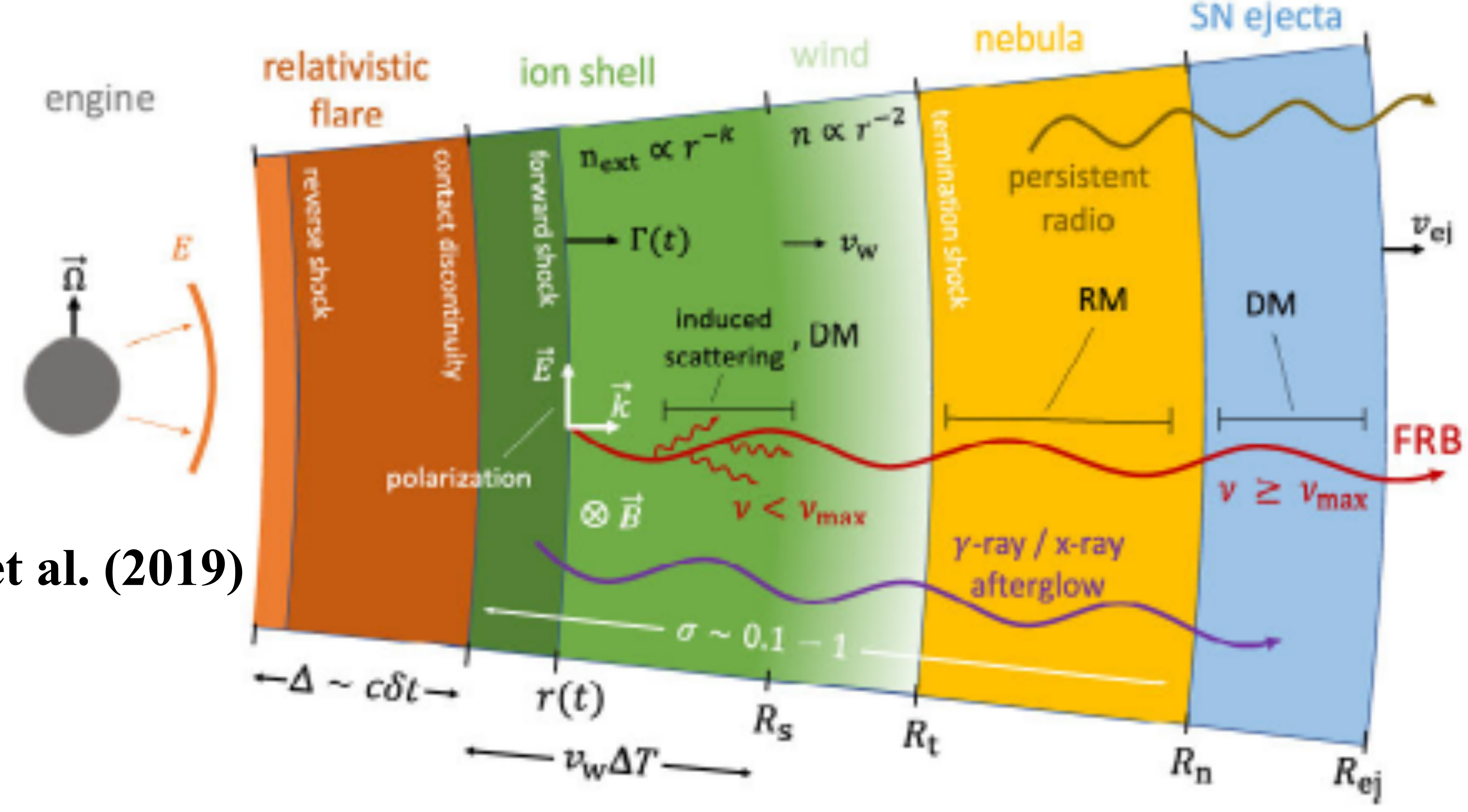


$\gamma = 2.2^{+0.7}_{-0.4}$ **Shin et al. (2022)**
1st CHIME Catalog

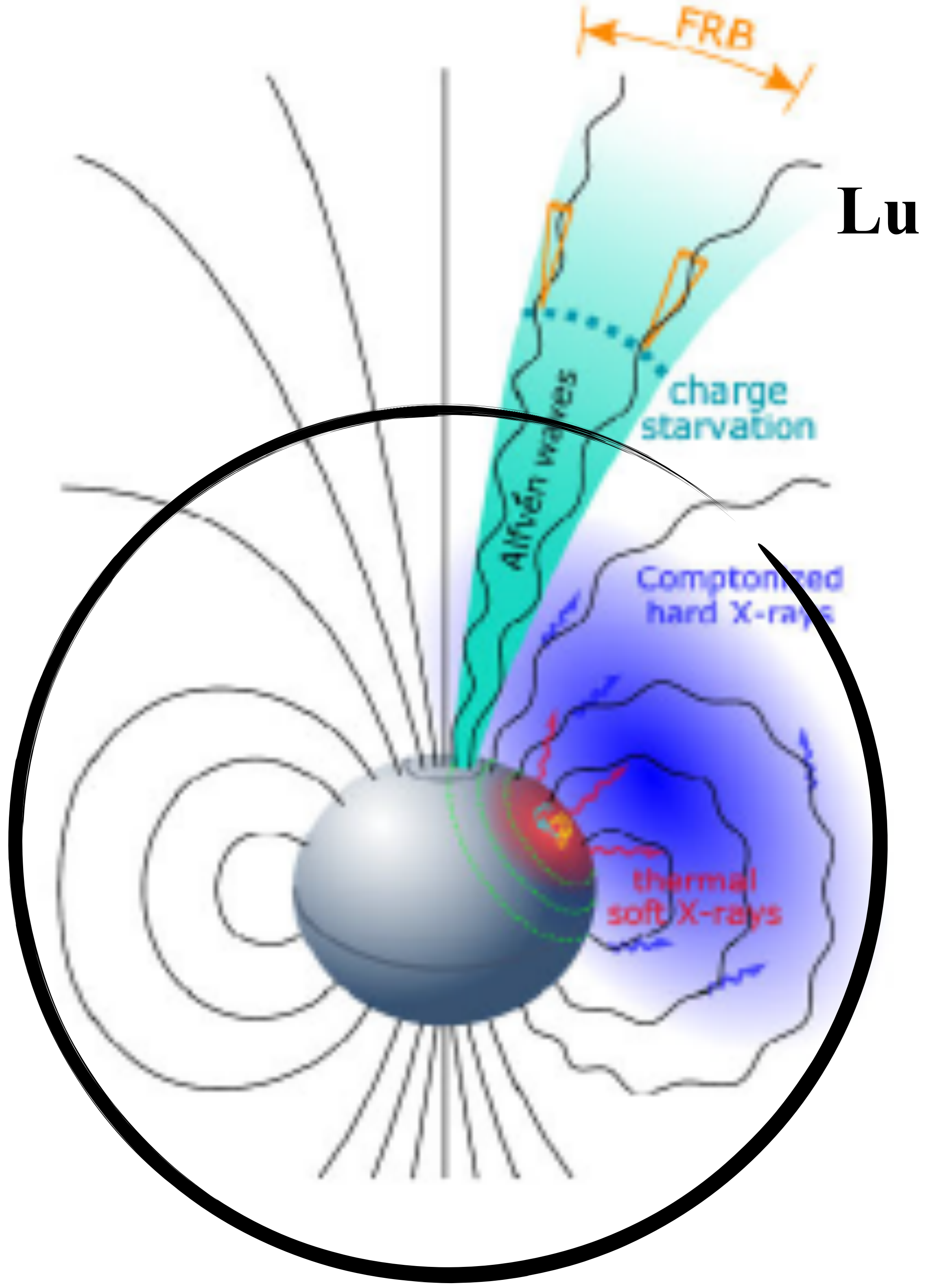
$\gamma = 2.3^{+0.15}_{-0.1}$ **James et al. (2022)**
ASKAP & Parkes

$\gamma = 2.8^{+0.3}_{-0.3}$ **Lu et al. (2020)**
Heterogenous sample of FRBs

SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs



Metzger et al. (2019)



Lu et al. (2020)

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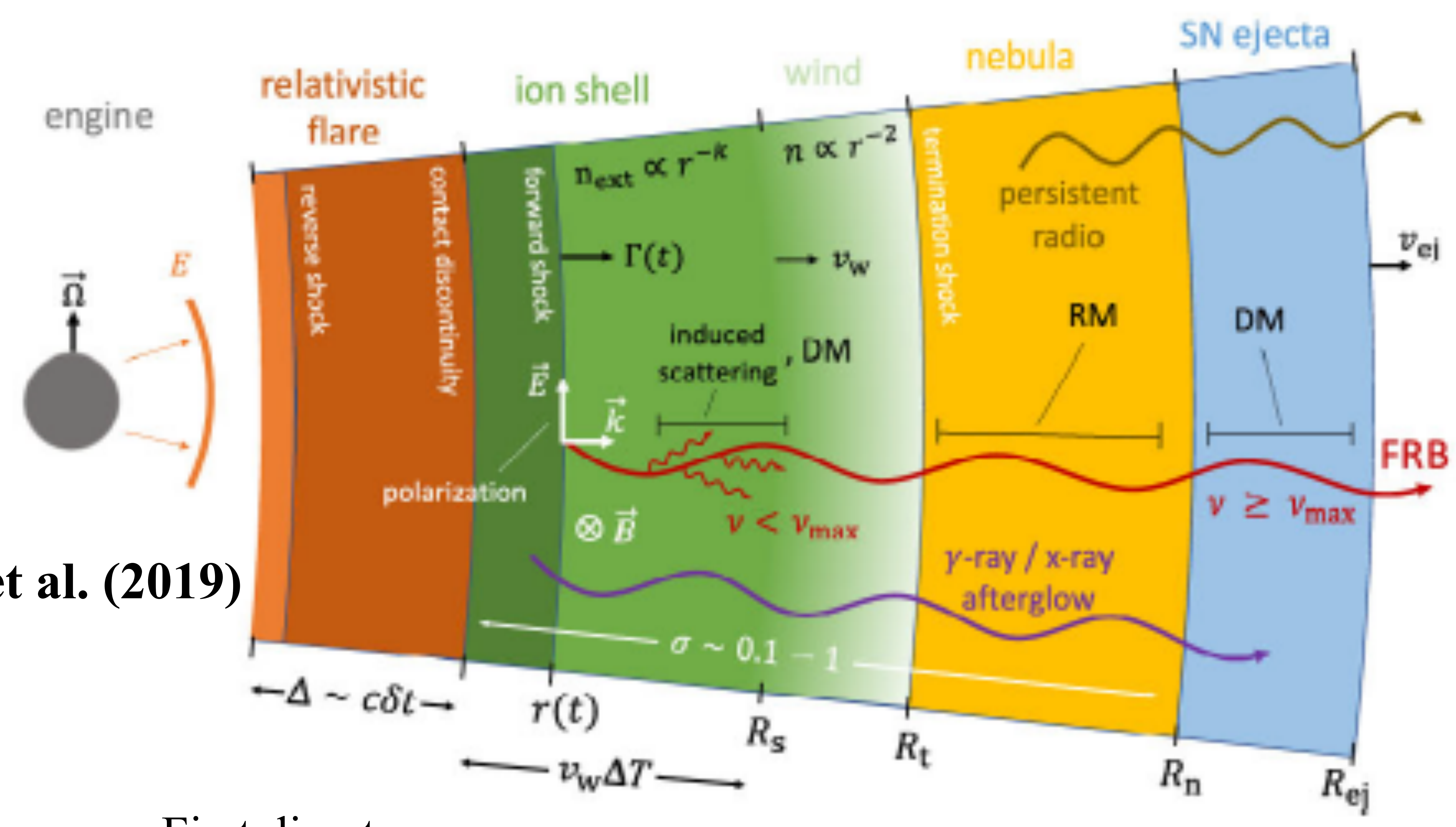

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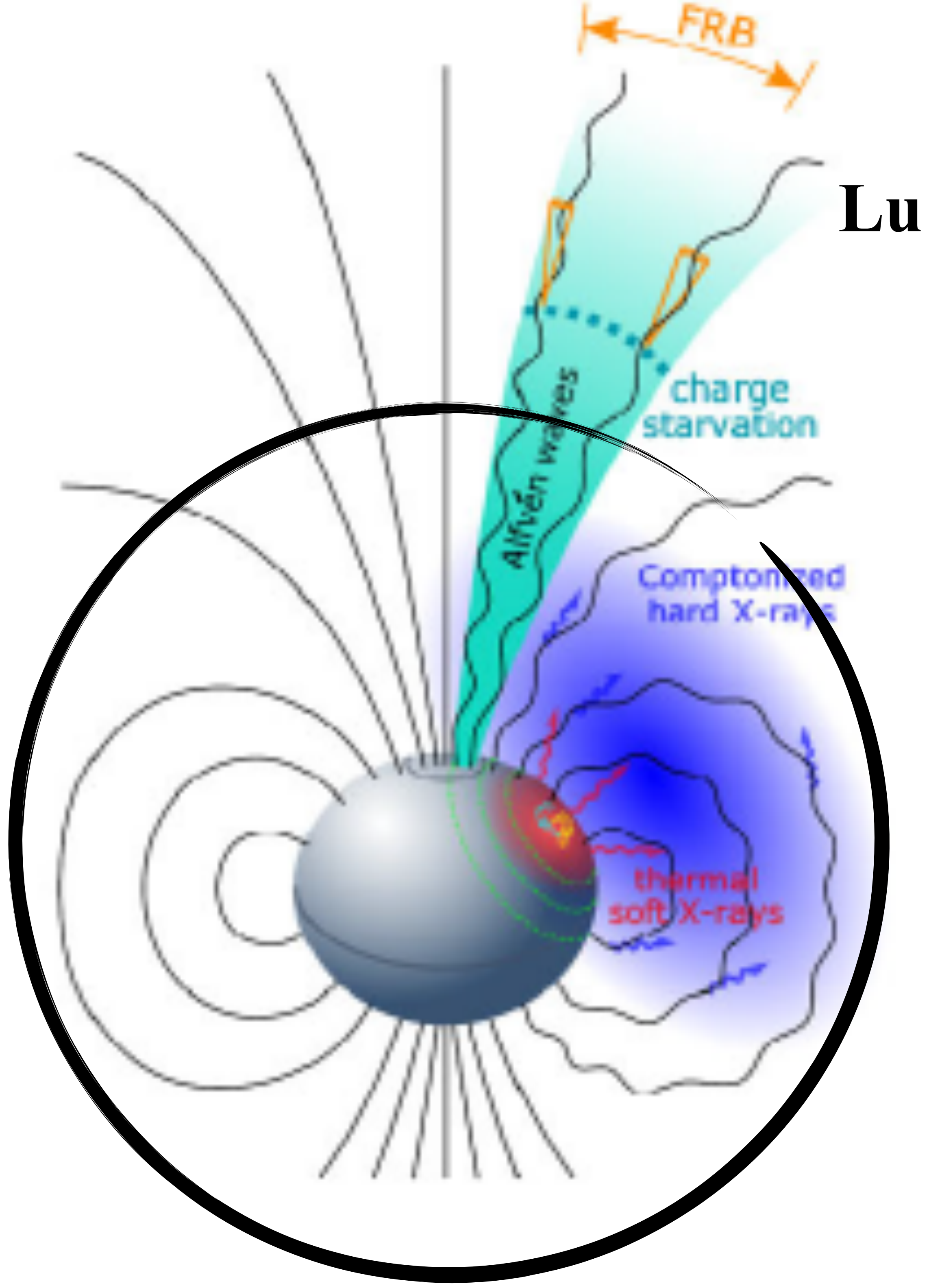
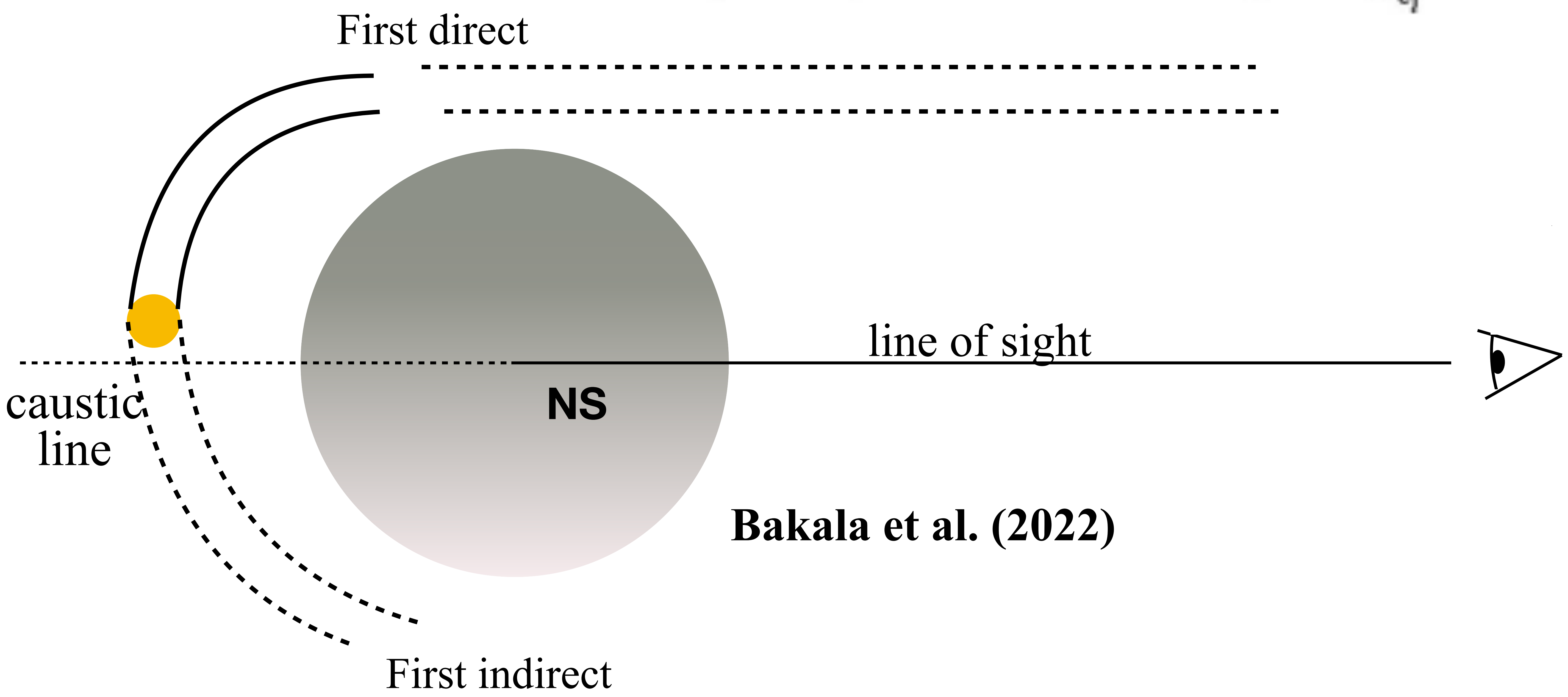
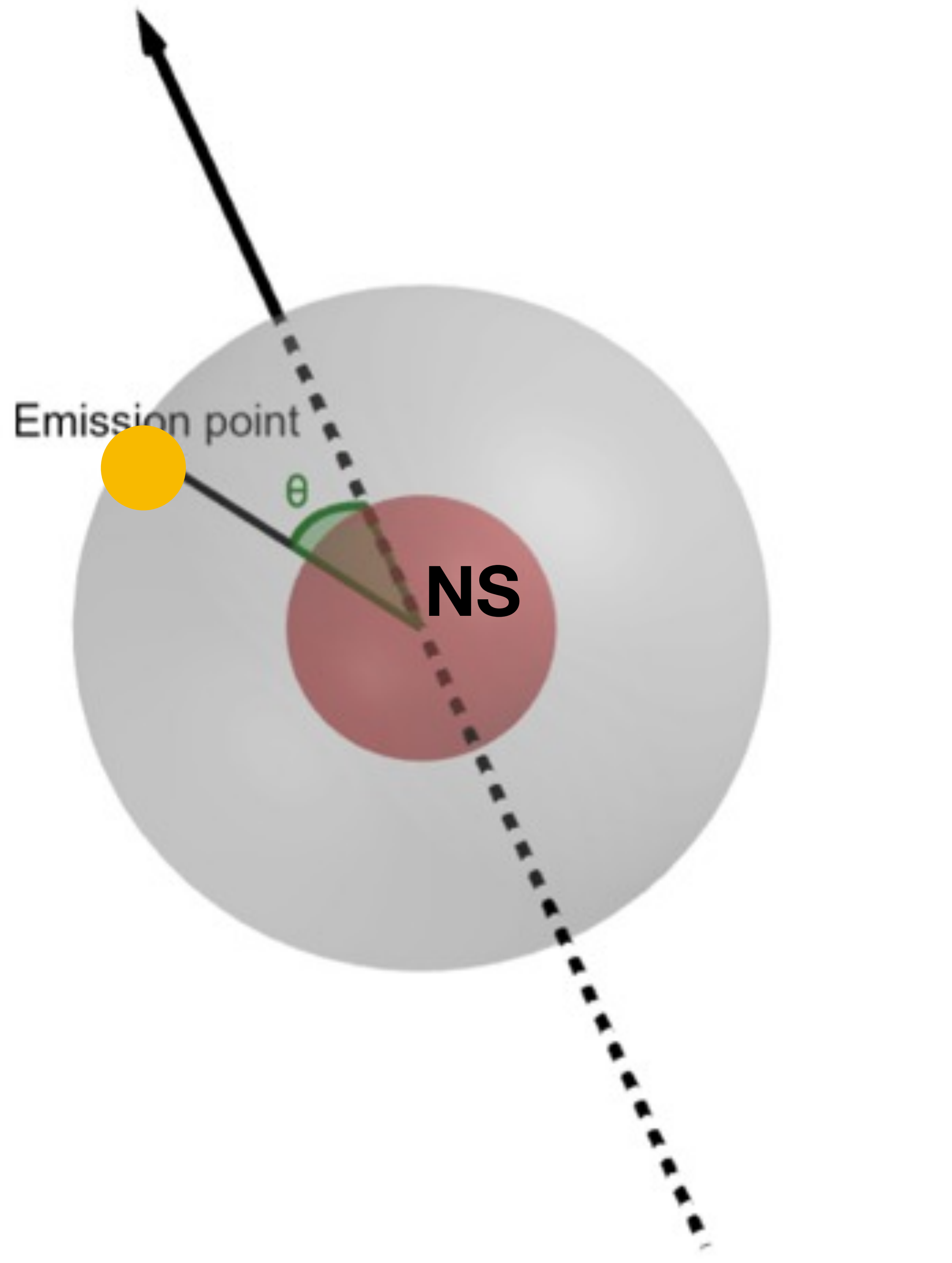


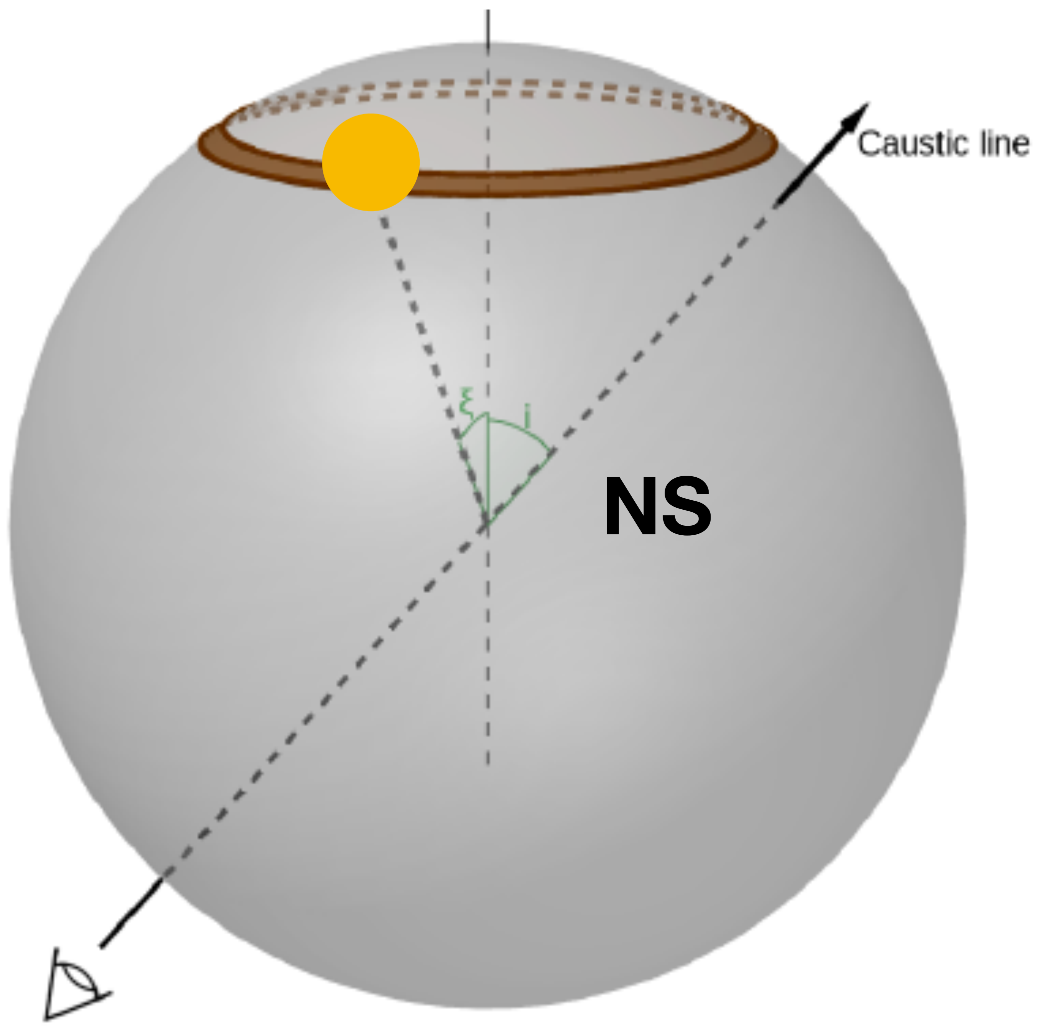
Lu et al. (2020)

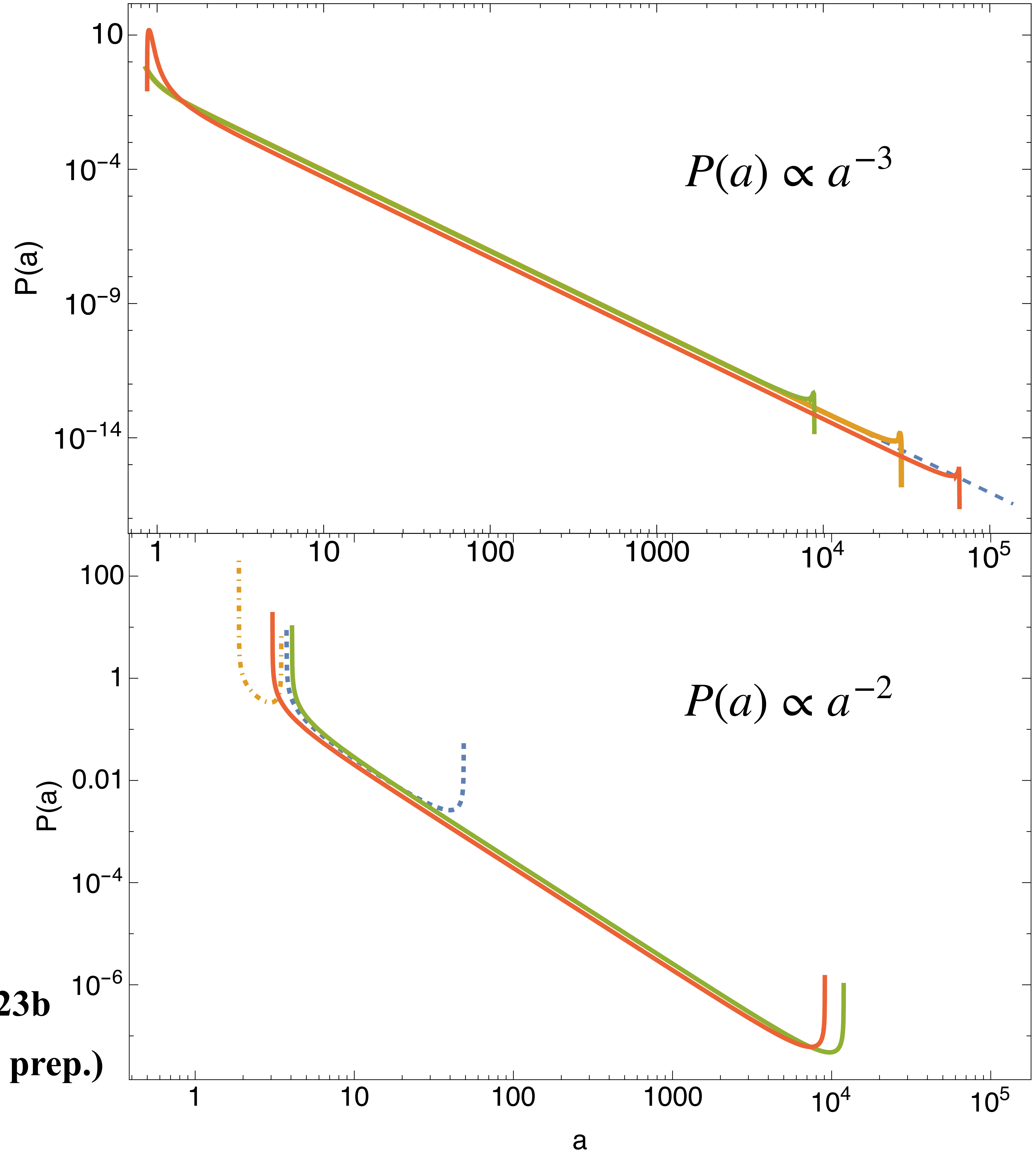


Bakala et al. (2022)

SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs



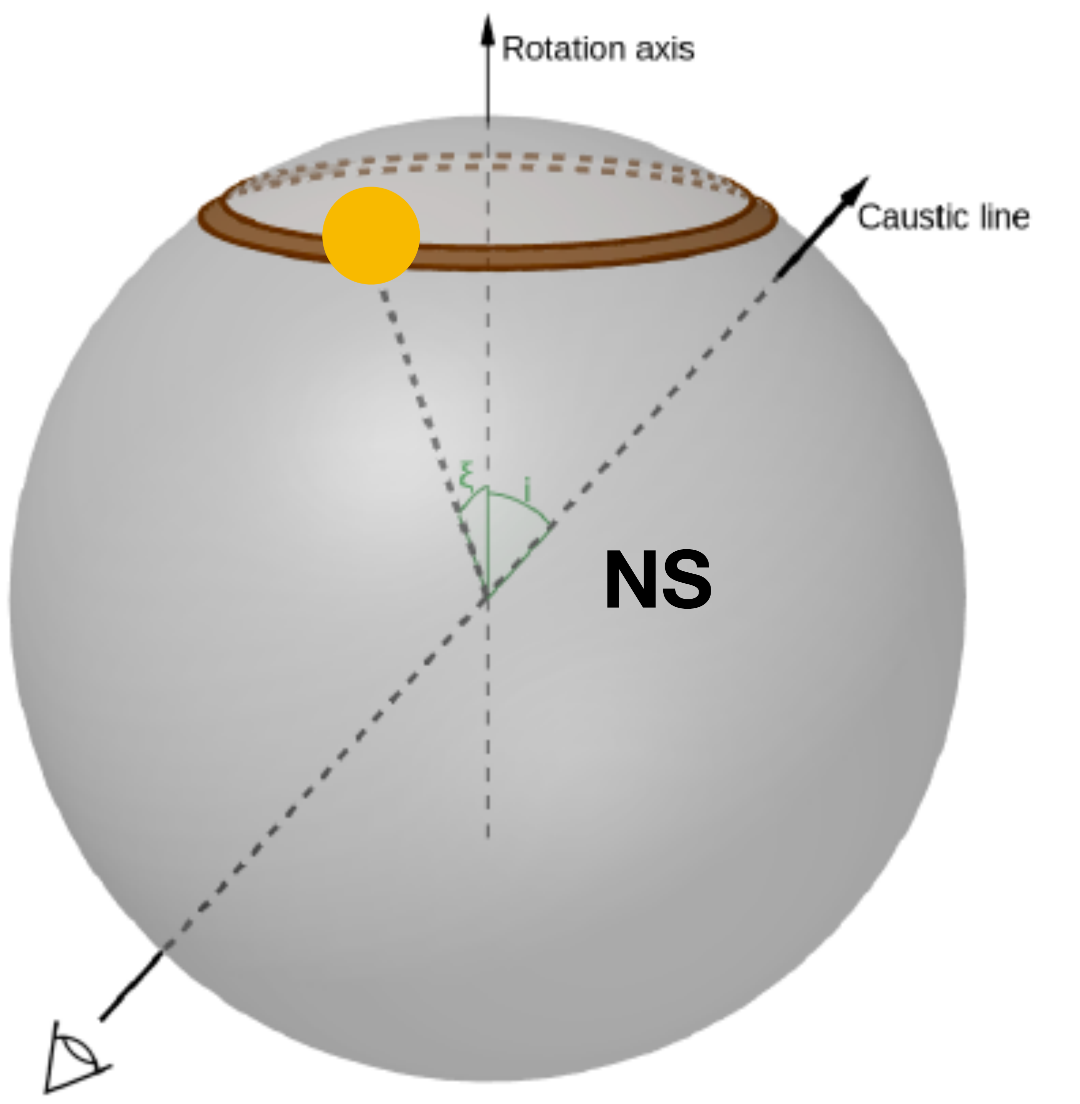


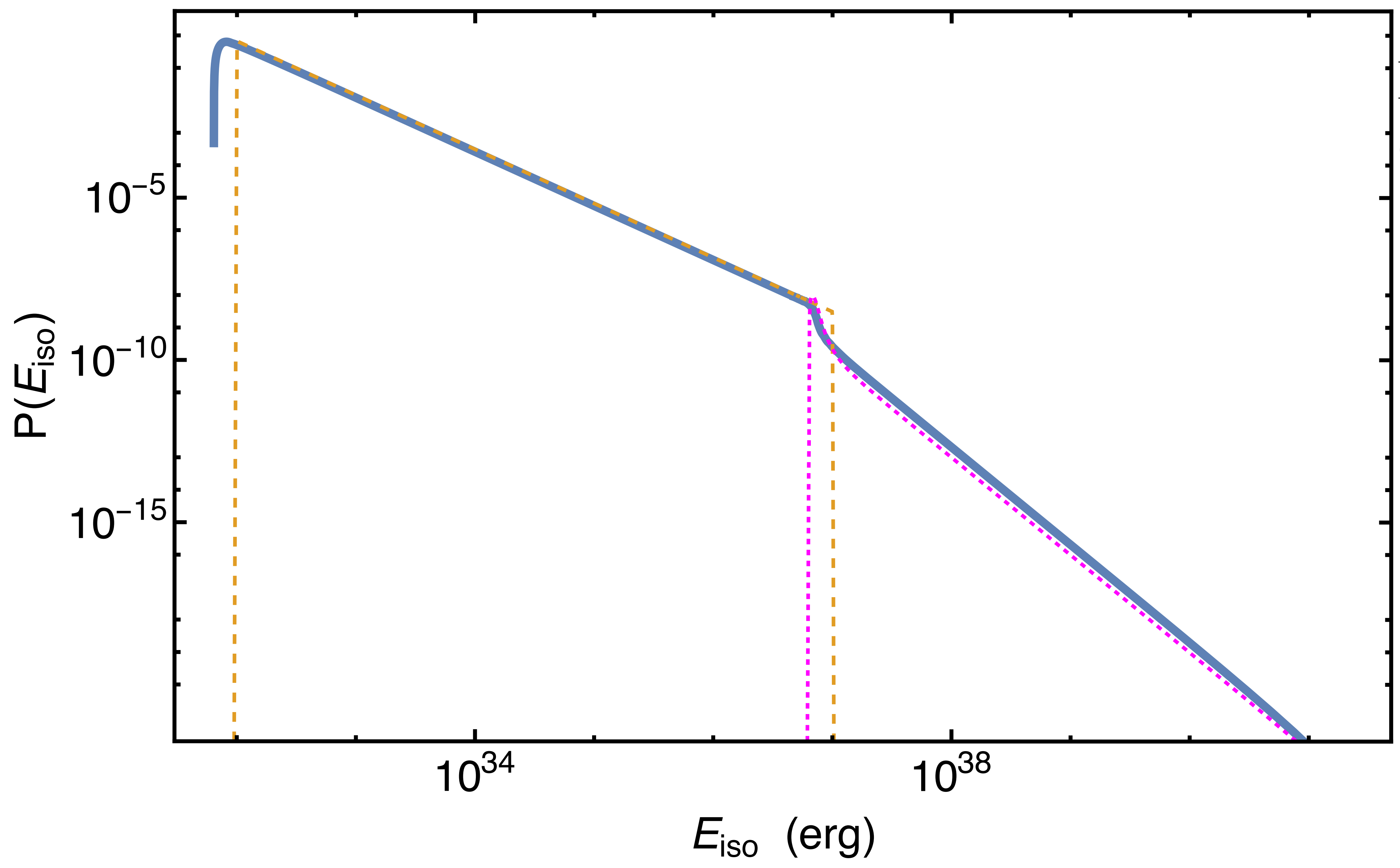


Dall'Osso, LaPlaca et al. 2023b

LaPlaca, Dall'Osso et al. (in prep.)

SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs





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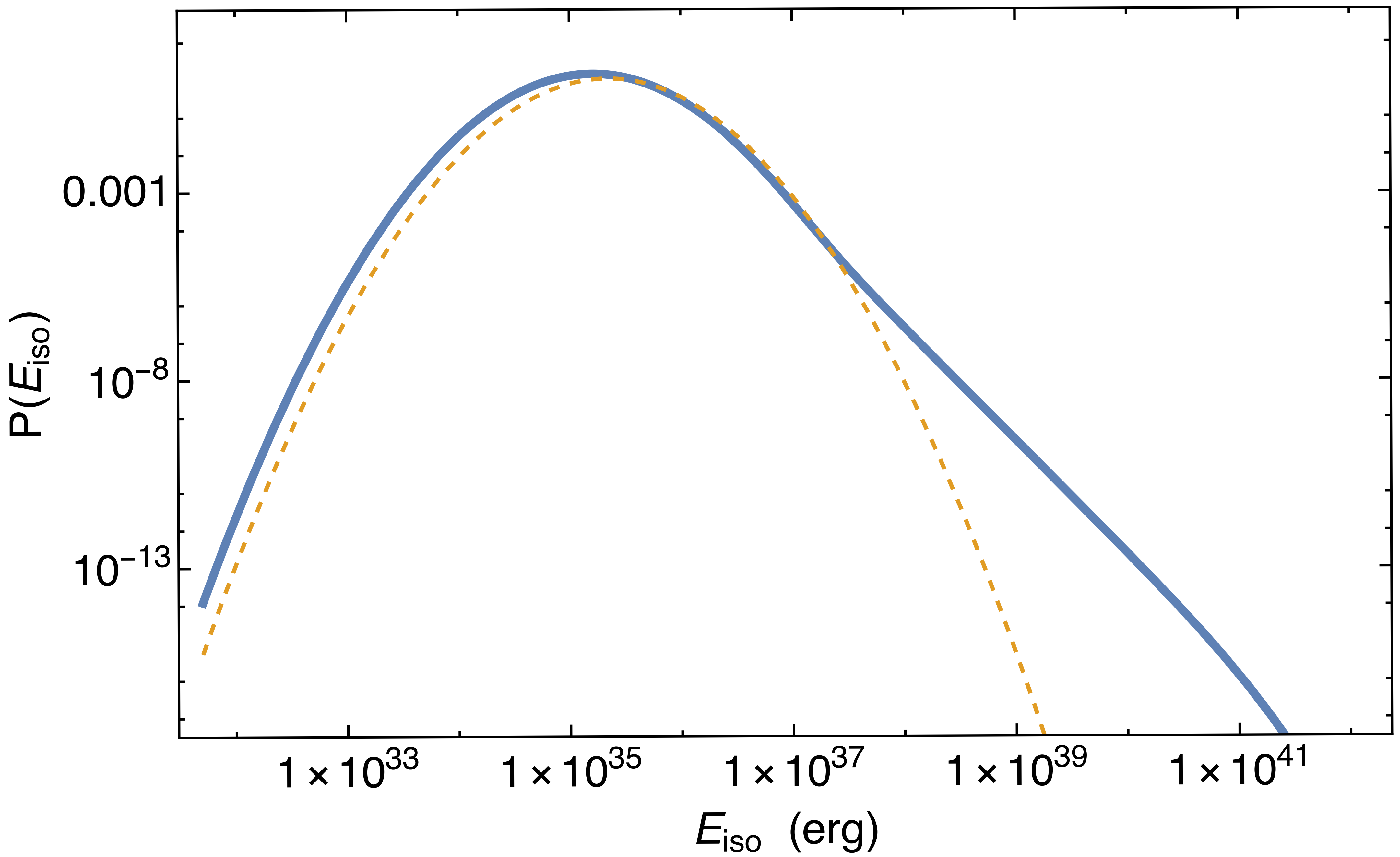

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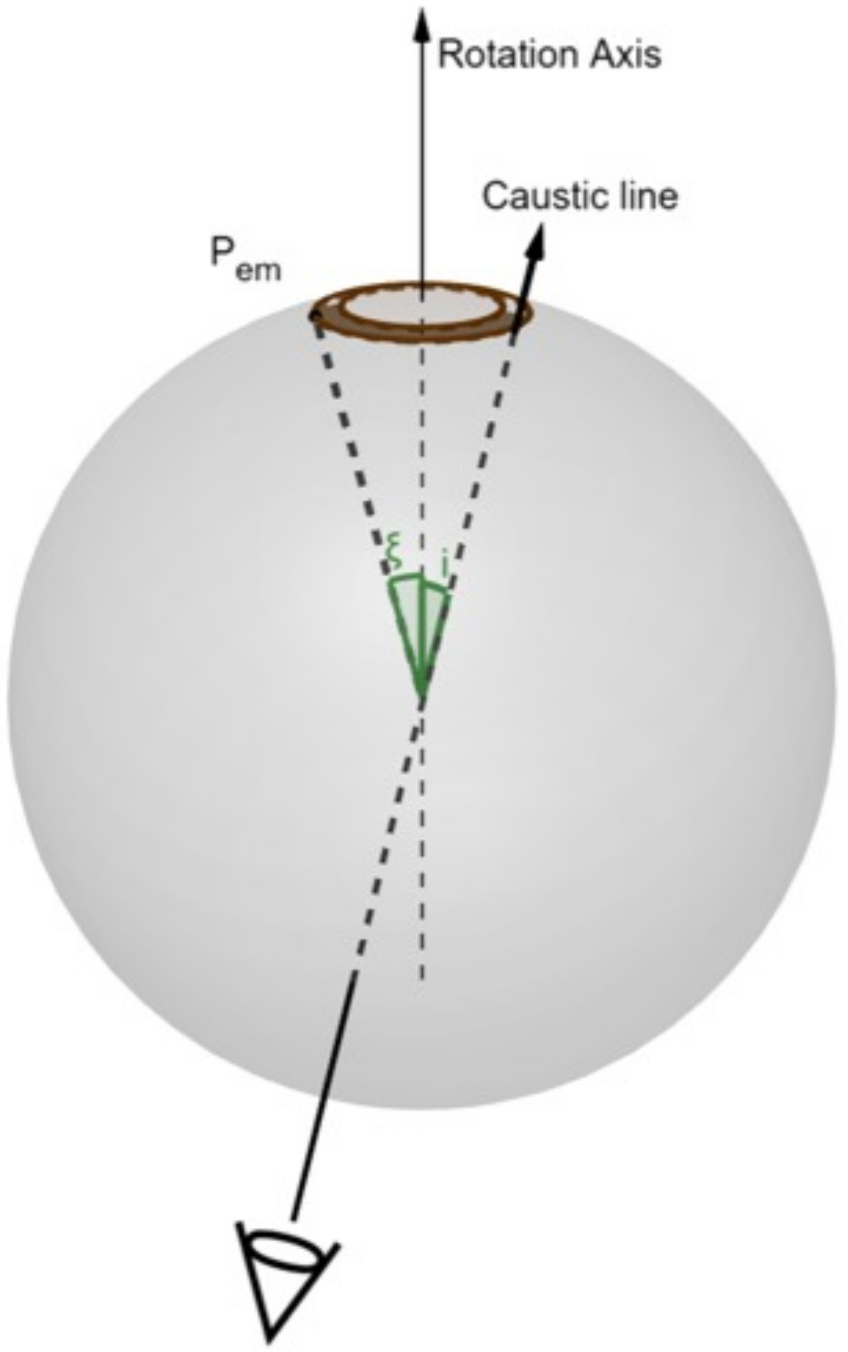
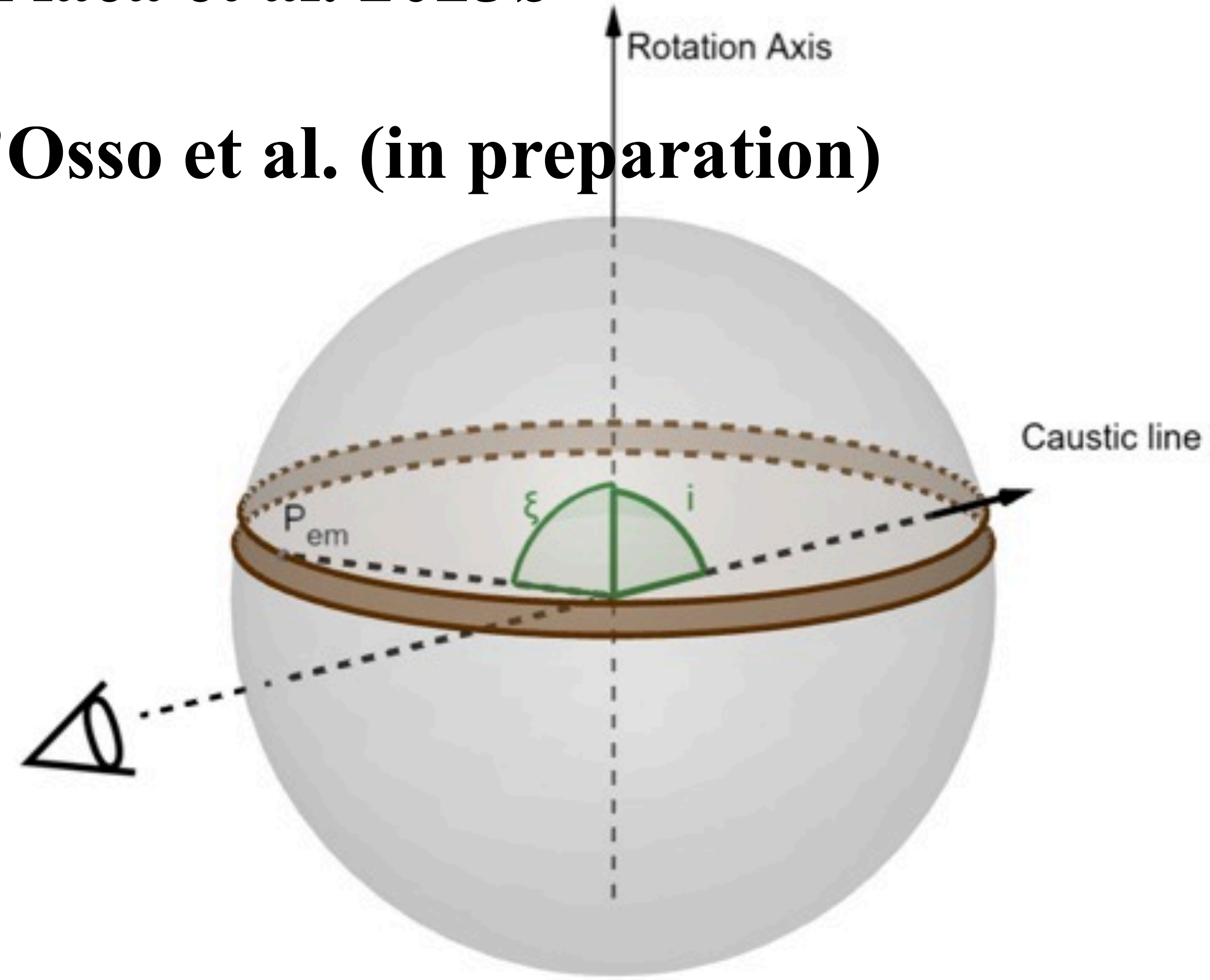
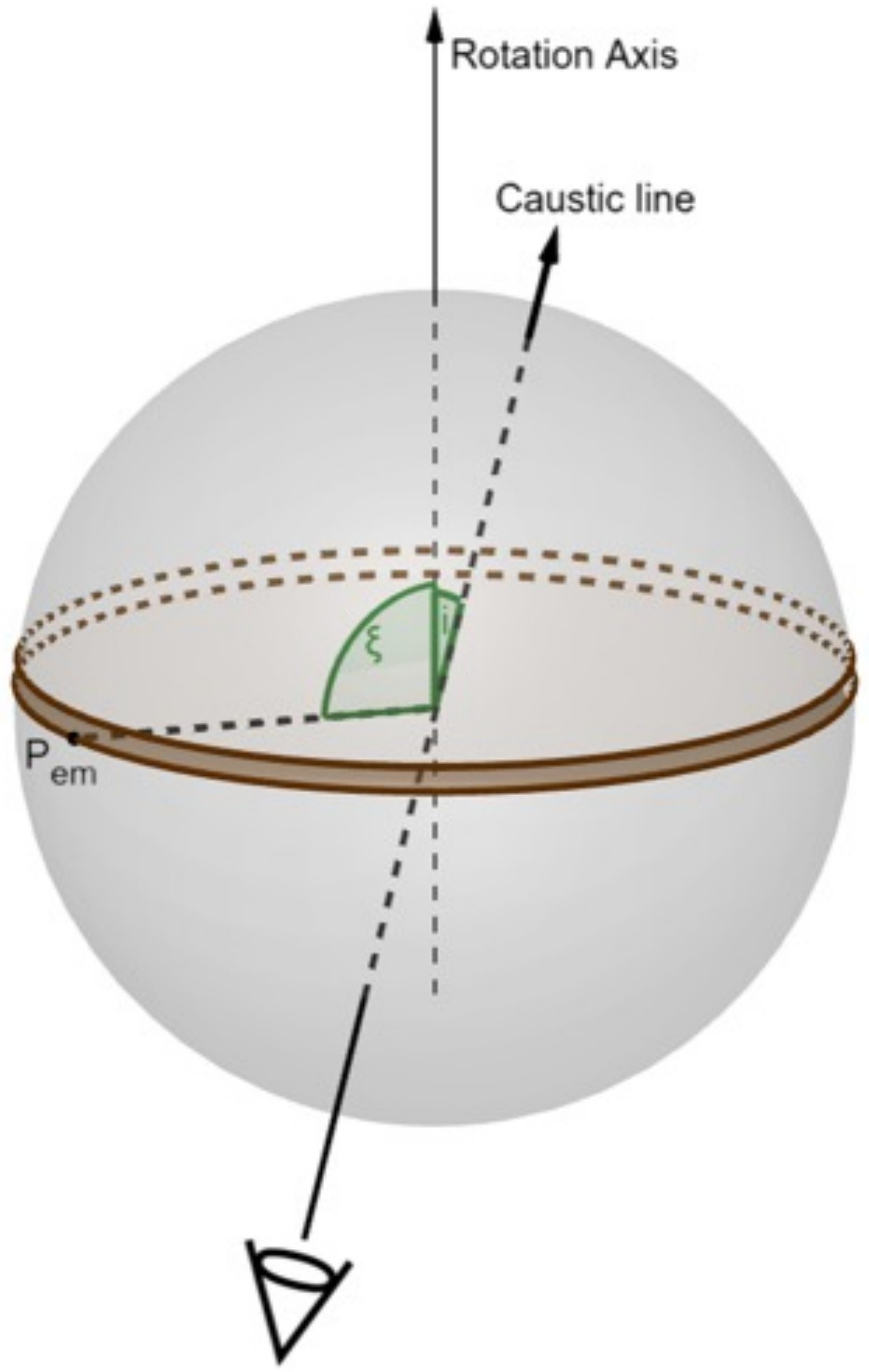


VERY FREQUENT AMPLIFICATION: repeater even with short obs. time



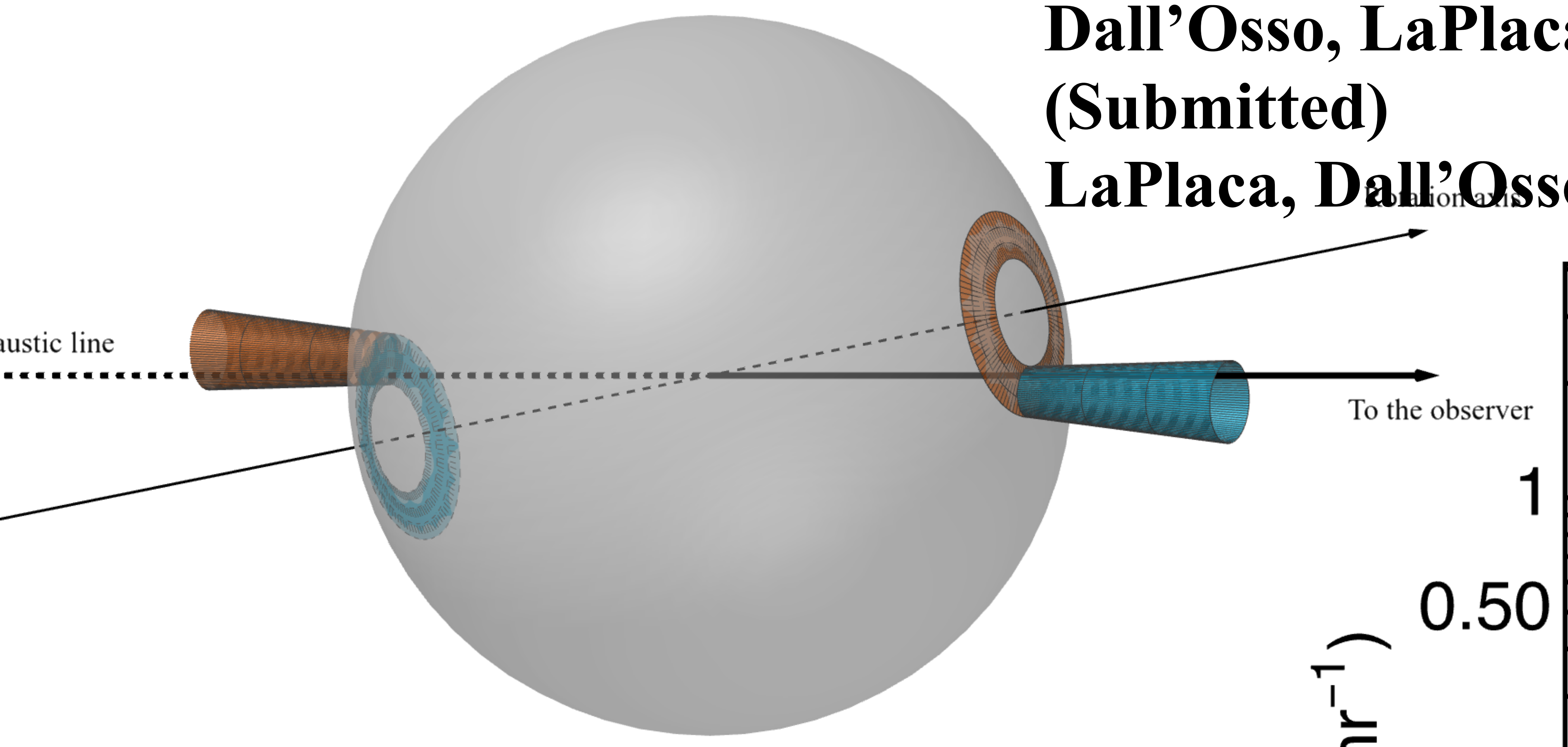
RARE AMPLIFICATION: one-offs (In the future, will become a repeater)

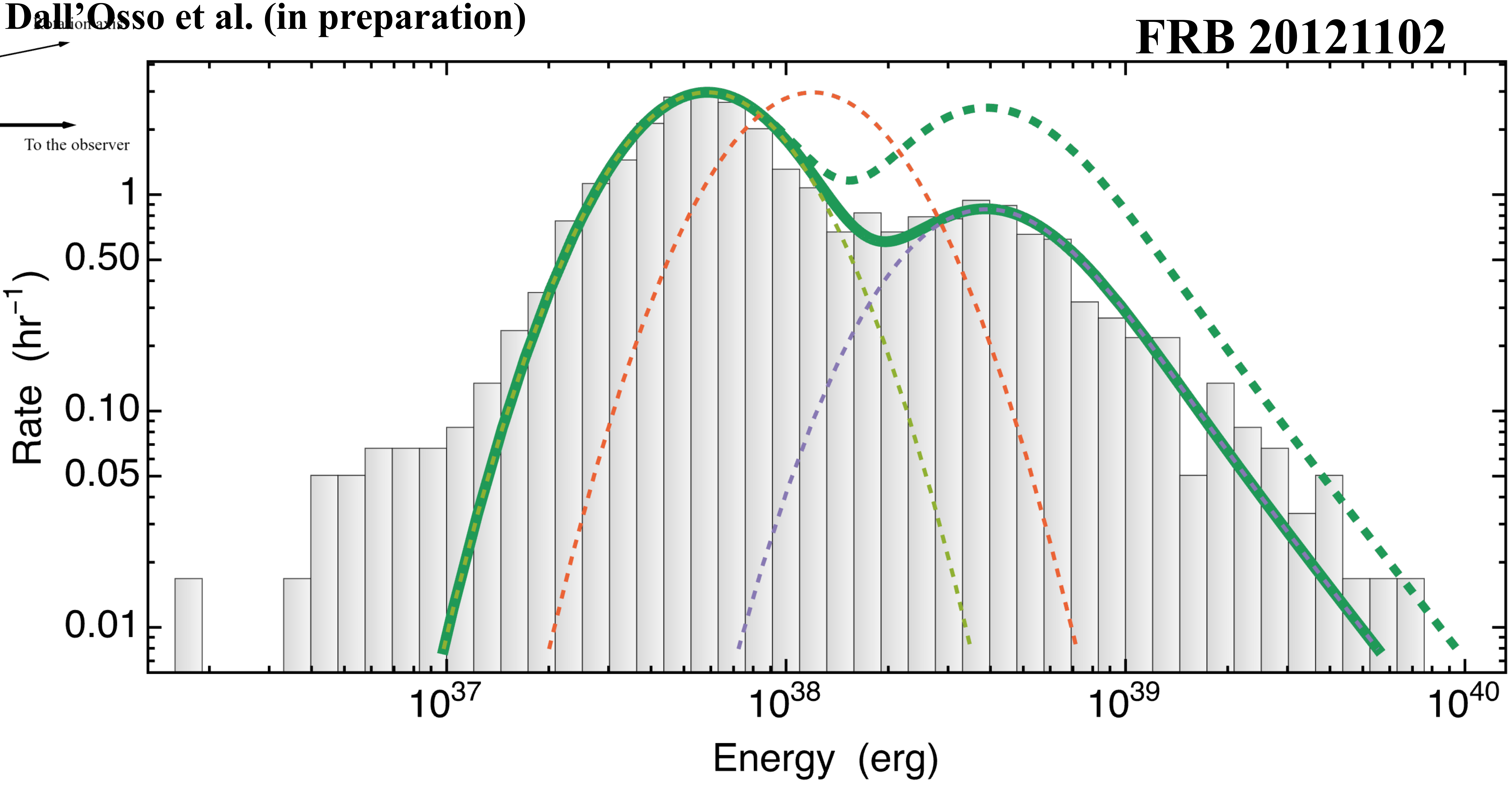


NO AMPLIFICATION: undetected (unless very nearby)

SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs

Dall'Osso, LaPlaca et al. 2023b (Submitted)
LaPlaca, Dall'Osso et al. (in preparation)





VERY FREQUENT AMPLIFICATION:
This source is a very active repeater and we predict this is its geometry

THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS

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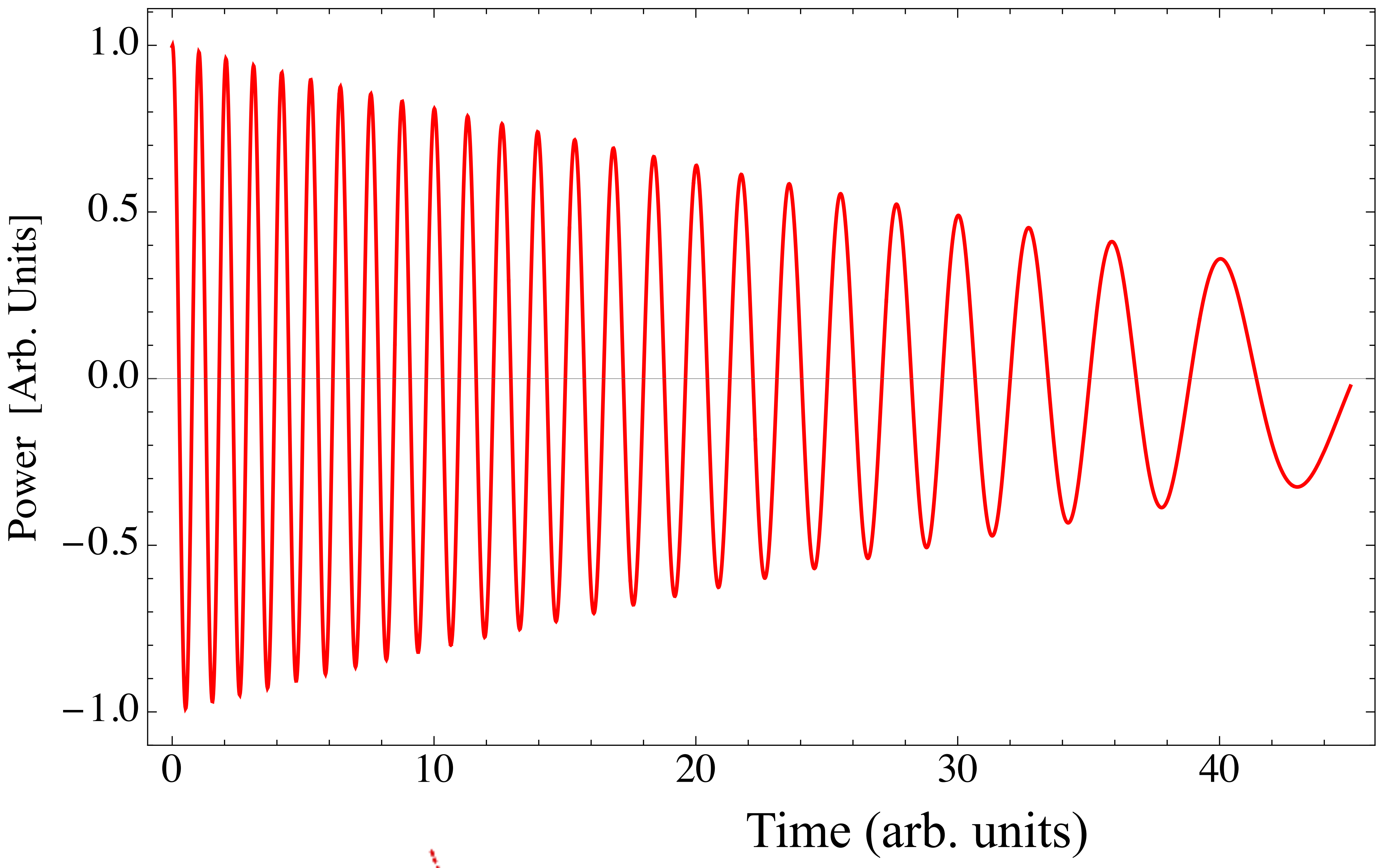
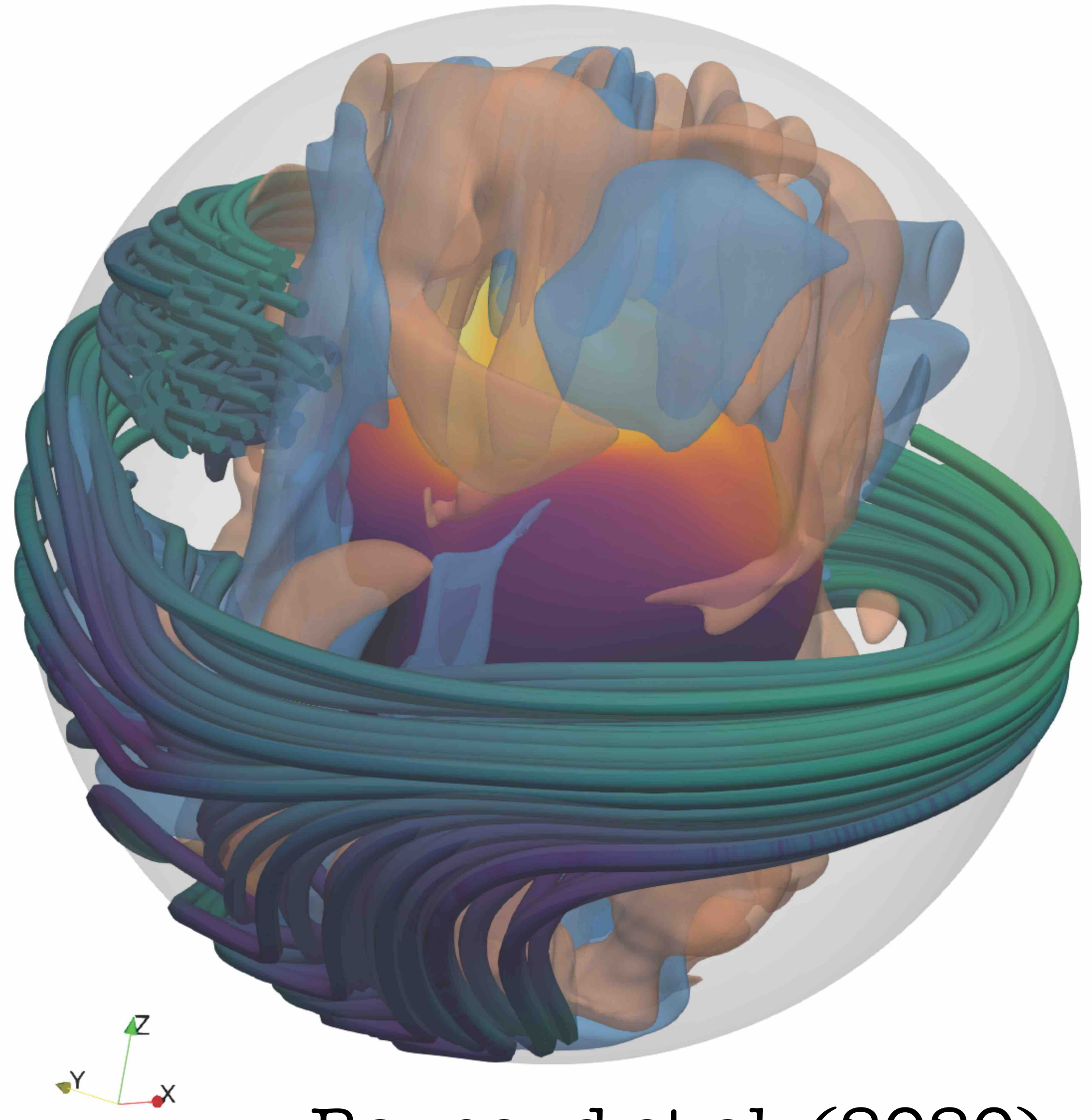


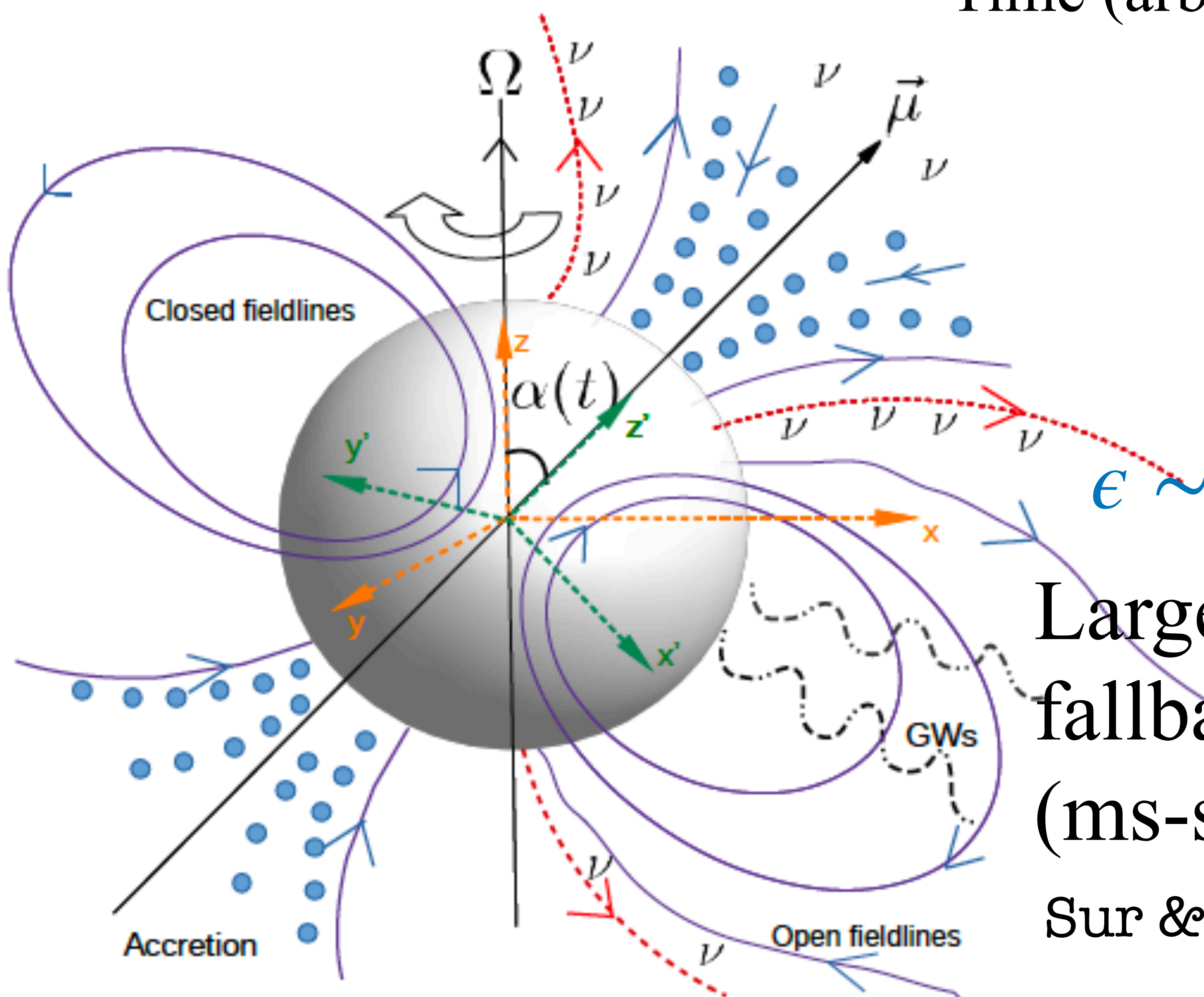
Magnetically-induced large ellipcitity (ms-spinning magnetars)

$\epsilon \sim 10^{-4} - 10^{-3}$

Cutler (2002)
Dall'Osso et al. (2009, 2015, 2018)
Ciolfi & Rezzolla (2013)
Frieden & Rezzolla (2015)
Lander & Jones (2020)



Raynaud et al. (2020)



$\epsilon \sim 10^{-6} - 10^{-5}$

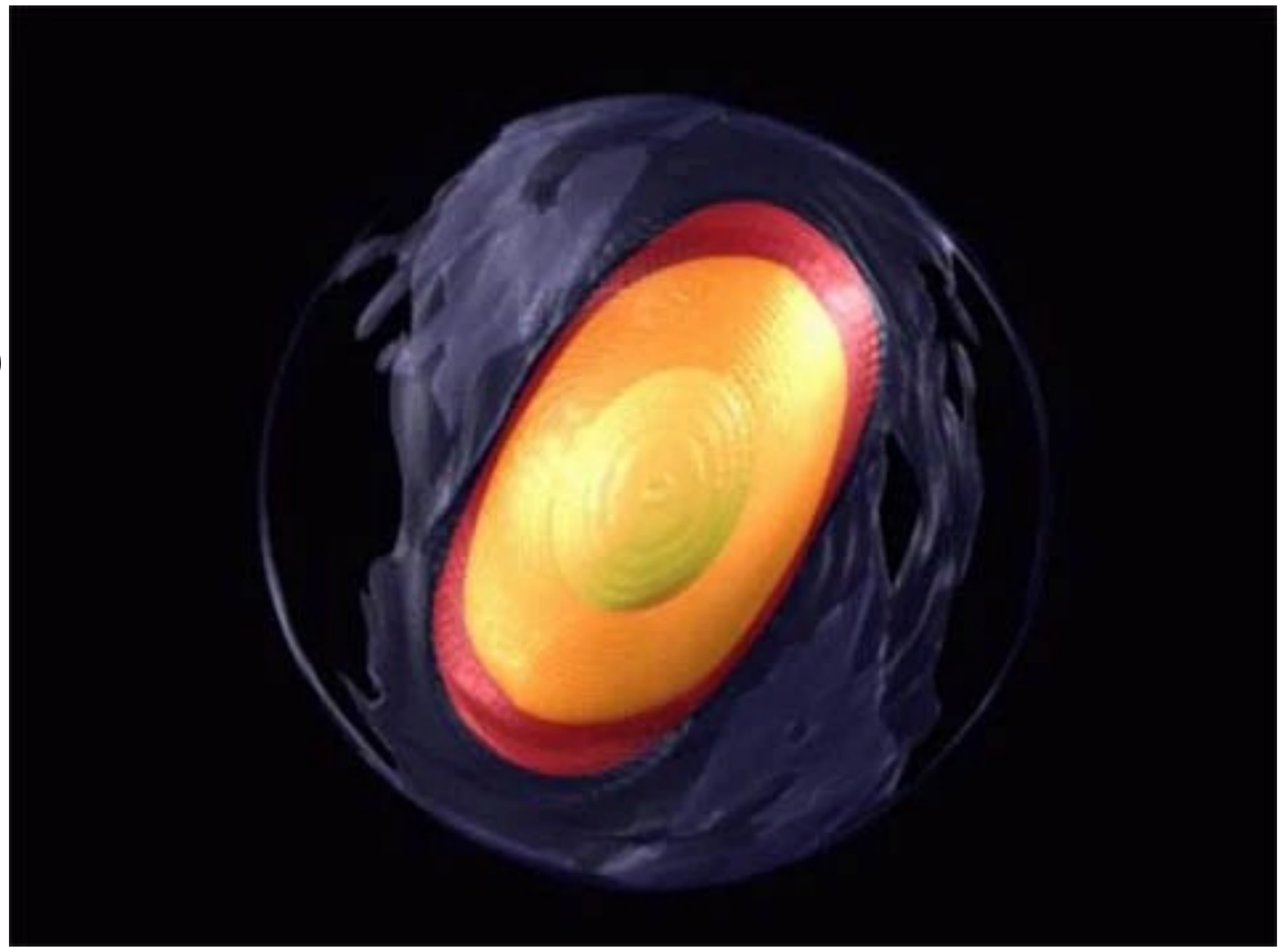
Large "mountains" from fallback accretion (ms-spinning magnetar)

Sur & Haskell (2021)

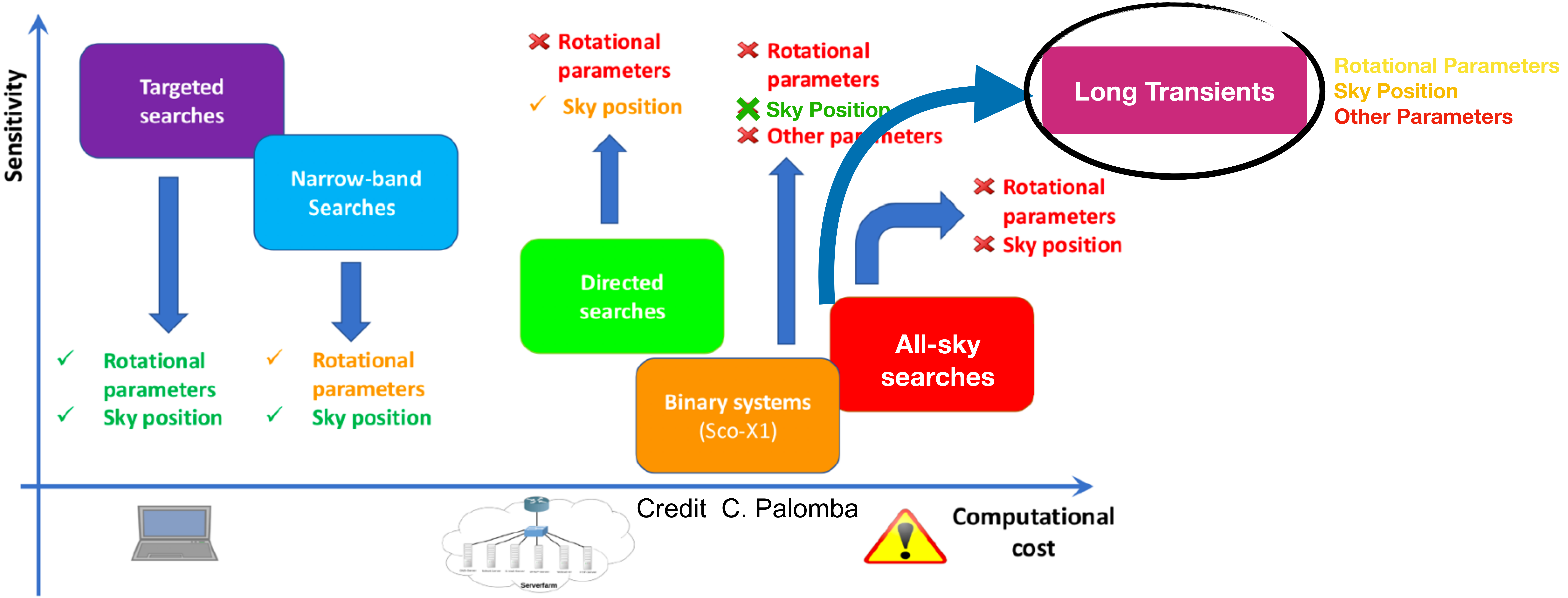
Secular bar-mode instability (ms-spinning NS)

$\epsilon \sim 10^{-2} - 10^{-1}$

Lai & Shapiro (1995)
Corsi & Meszaros (2009)



THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS



Order of magnitude estimate

Frequency Hough hierarchical All Sky search (isolated NS)

1 year - 3 detectors $\sim$ 80 million core-hours

THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS

Development and optimisation of a semi-coherent approach

Starting point: the Generalised FrequencyHough (GFH) pipeline, developed in the Roma 1 Virgo Group
Used in O2 search for merger remnant in GW 170817

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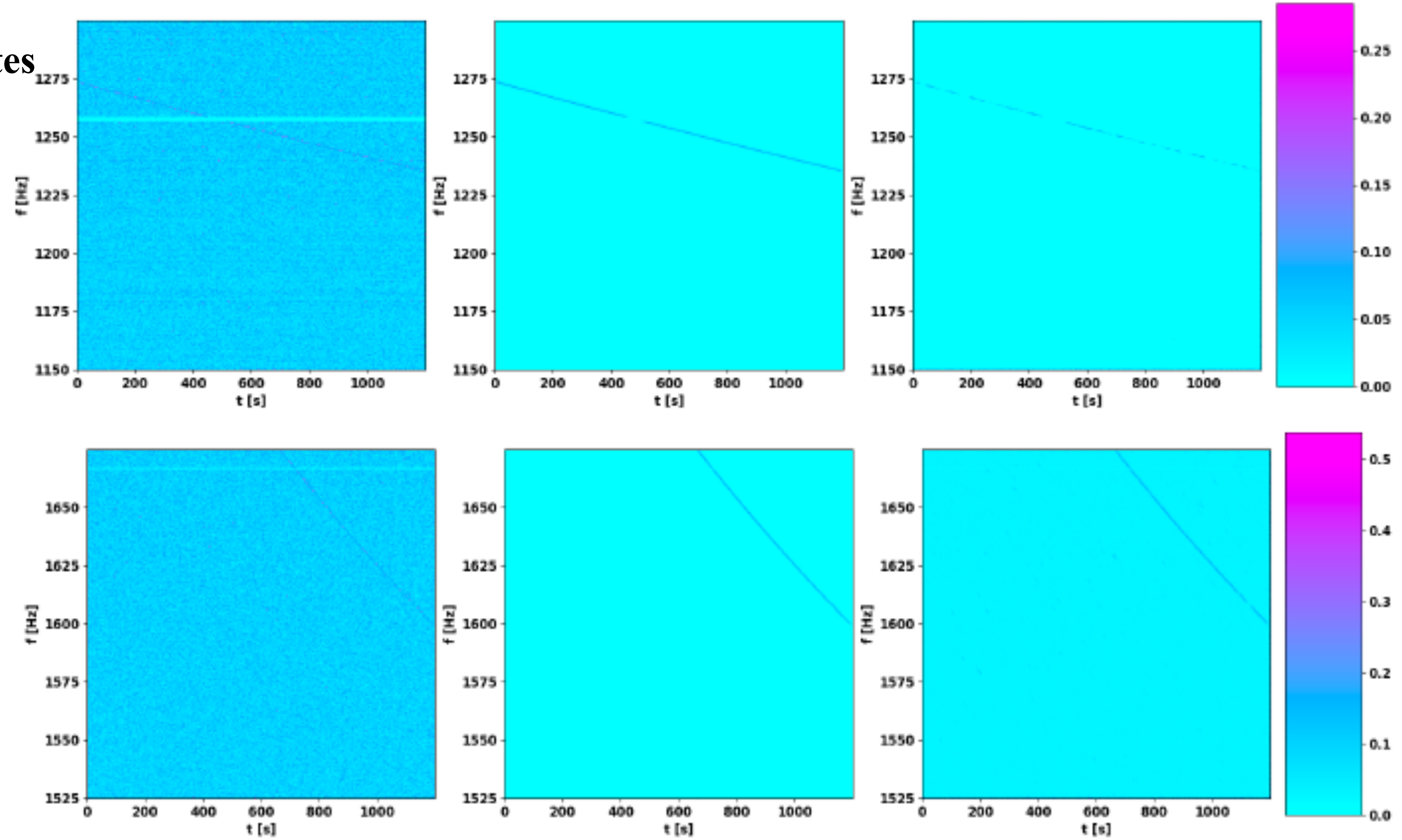
ML-based algorithm to look for candidates

Master Thesis by Francesca Attadio

(Sapienza University/Roma1 Virgo Group)



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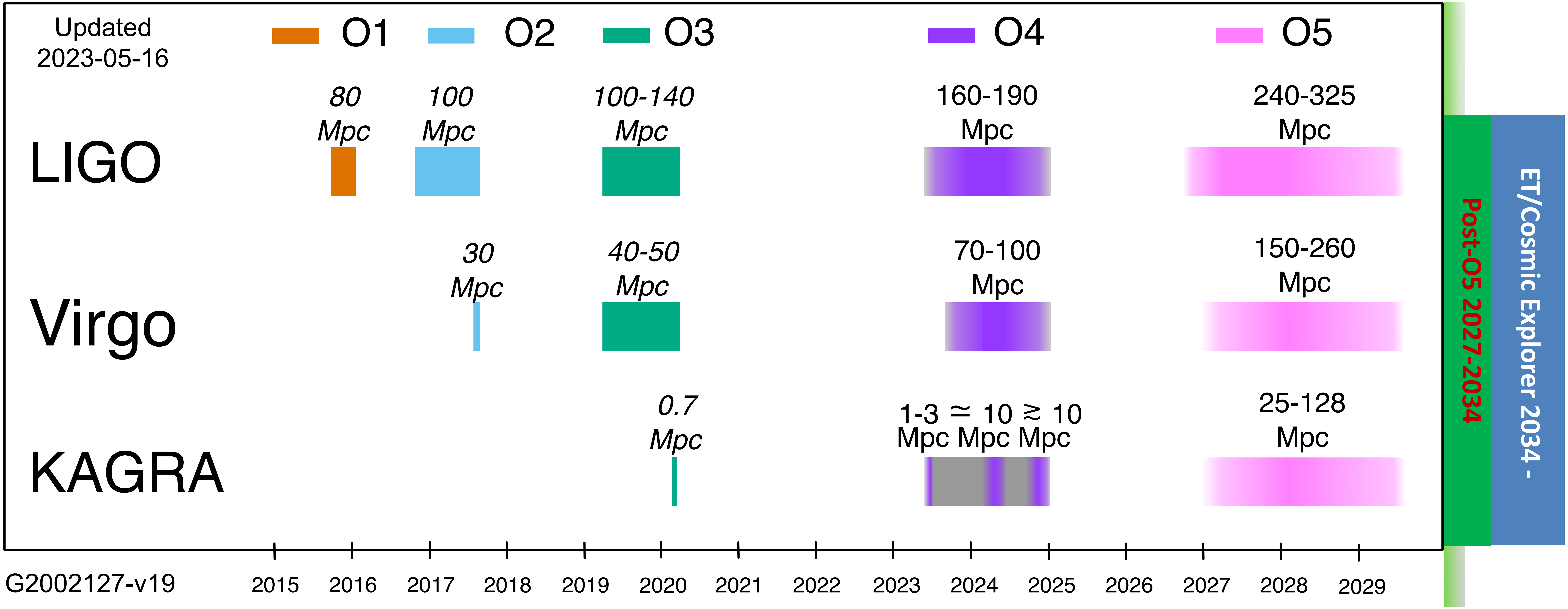
Improvement of GFH and `coupling' with ML-algorithm
PhD project of Sandhya S. Menon (ongoing)
(Sapienza University/Roma1 Virgo Group)

↓

Currently preparing the data for a search directed at the recent SN 2023ixf in the Pinwheel Galaxy (M101) at ~6 Mpc distance

THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS

TIMELINE



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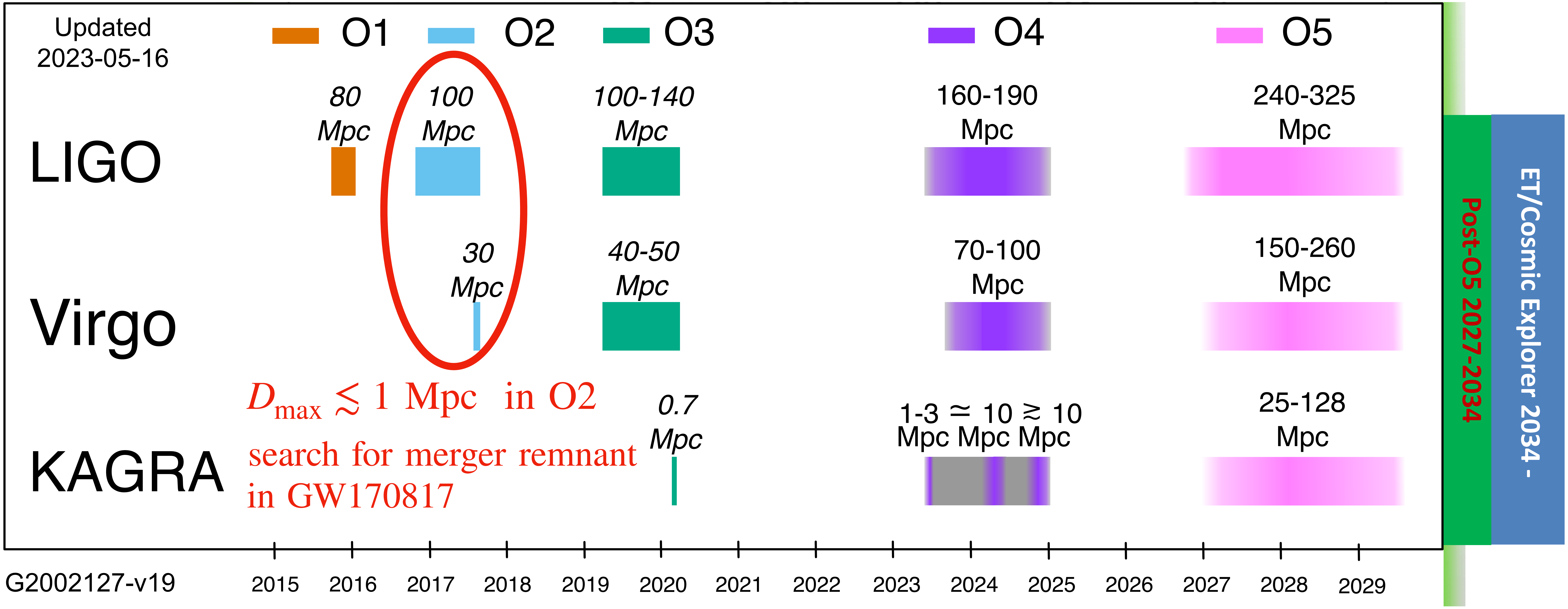

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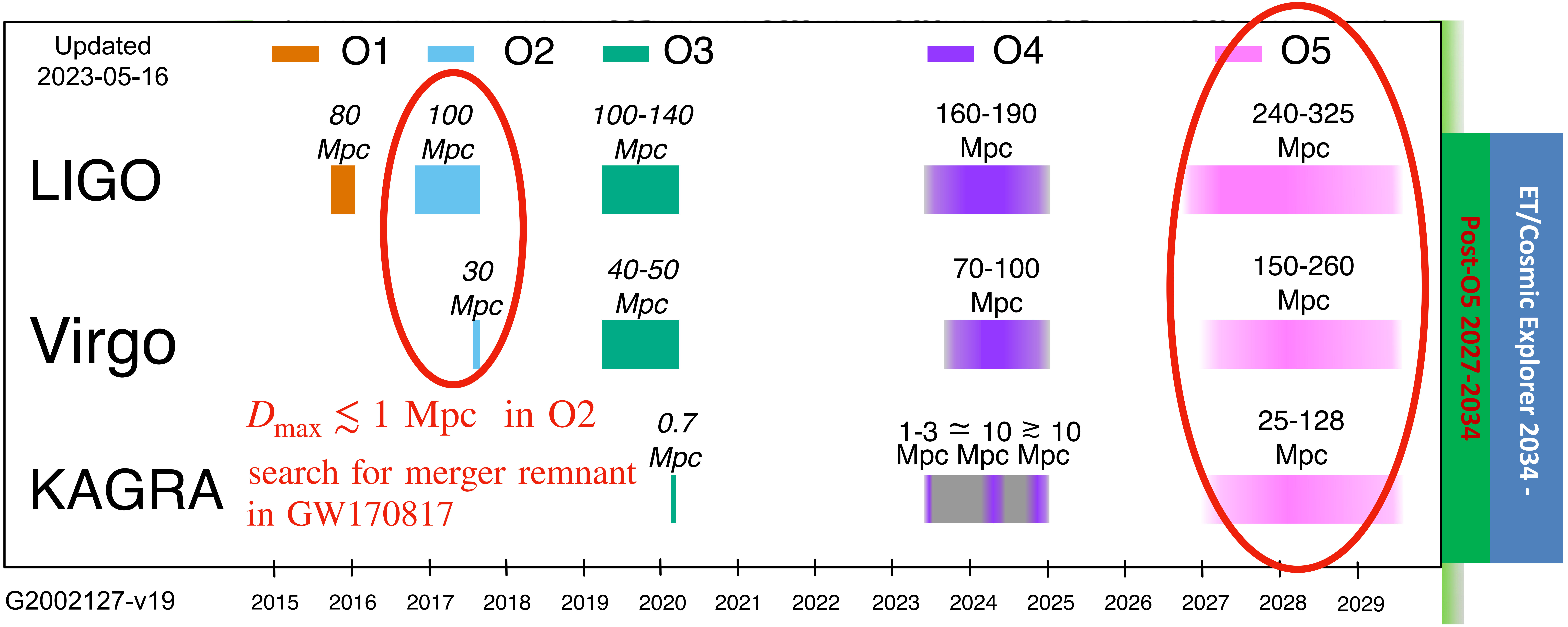
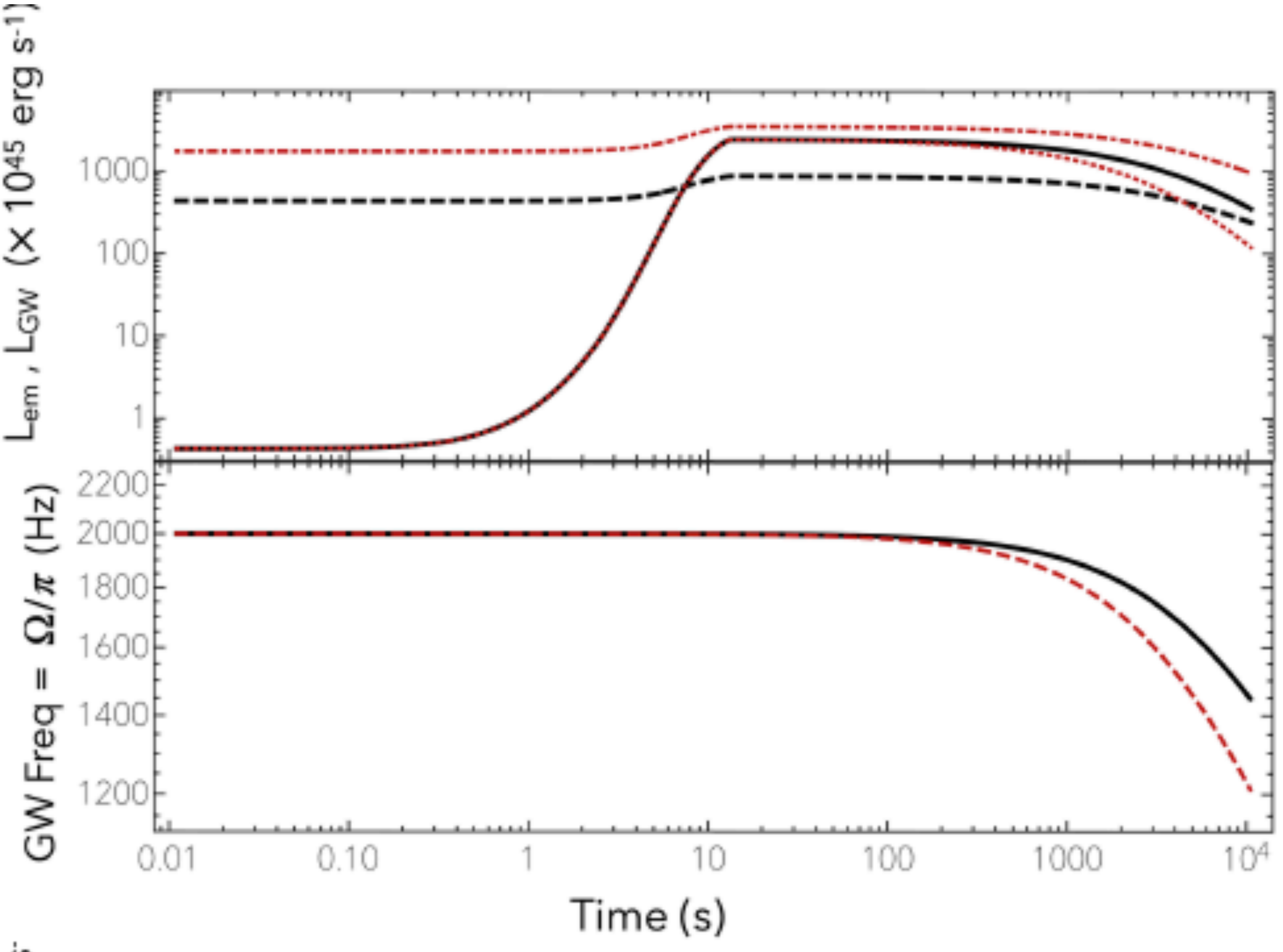
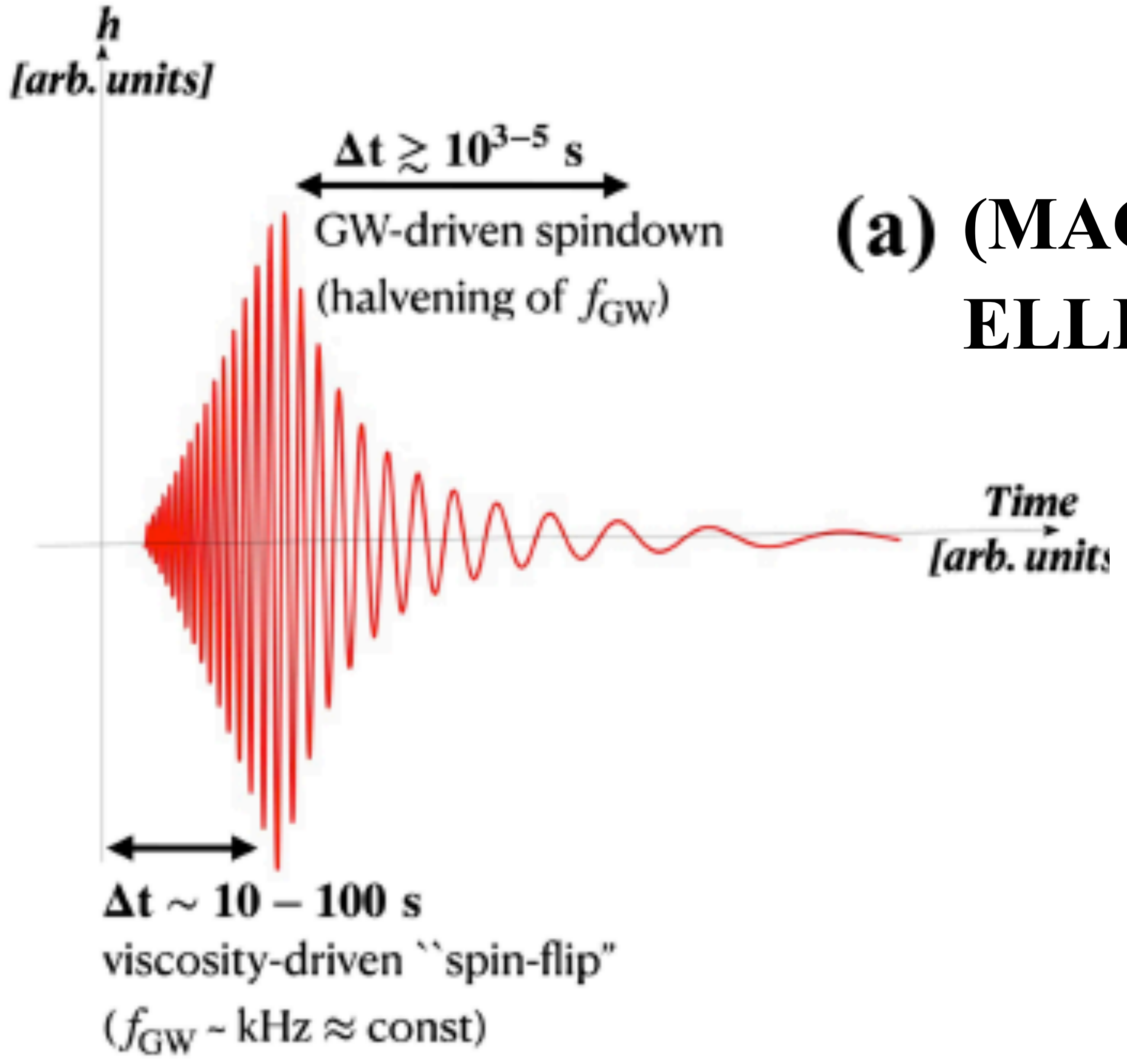
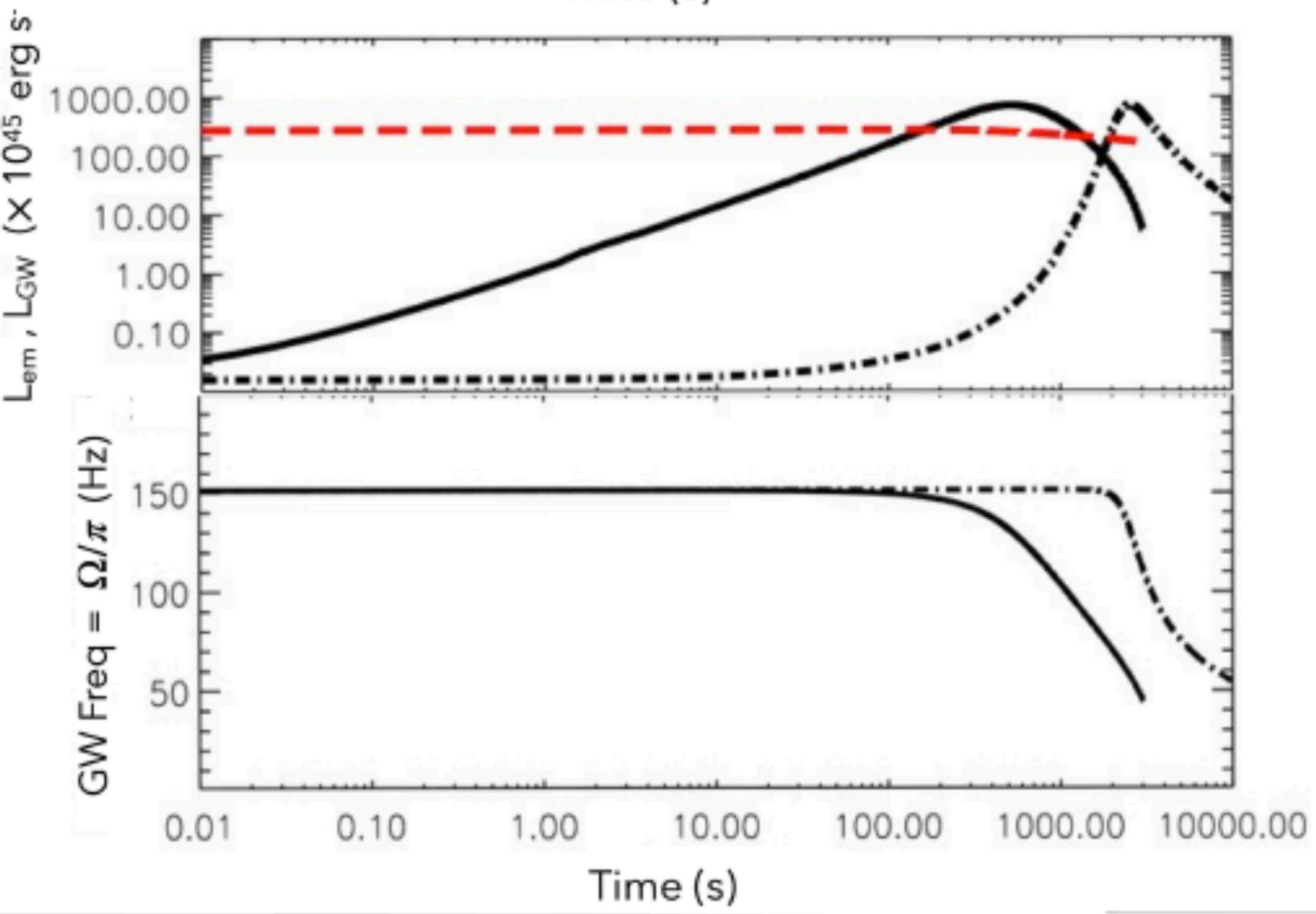


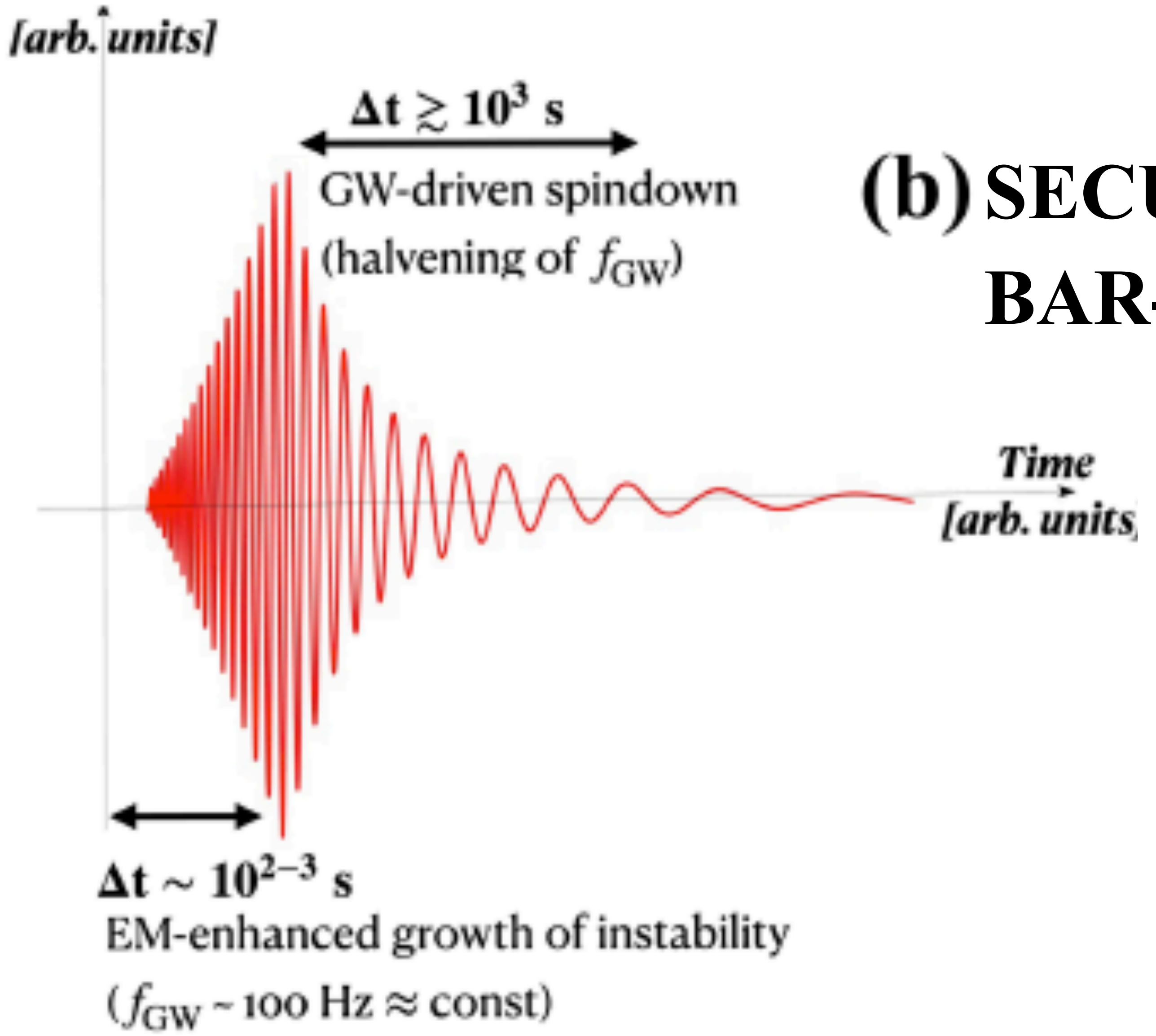
THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS





(a) (MAGNETIC) ELLIPTICITY





(b) SECULAR BAR-MODE

Dall'Osso and Stella (2021)

$D_{max} \lesssim 1$ Mpc in O2 search for merger remnant in GW170817

↓

$\lesssim 3 - 5$ Mpc in O5

Possible targets in O5 (rate ~ 0.1 yr^{-1})

(i) local SN (e.g. SN2023ixf)

(ii) improve the efficiency of search pipelines (under way)

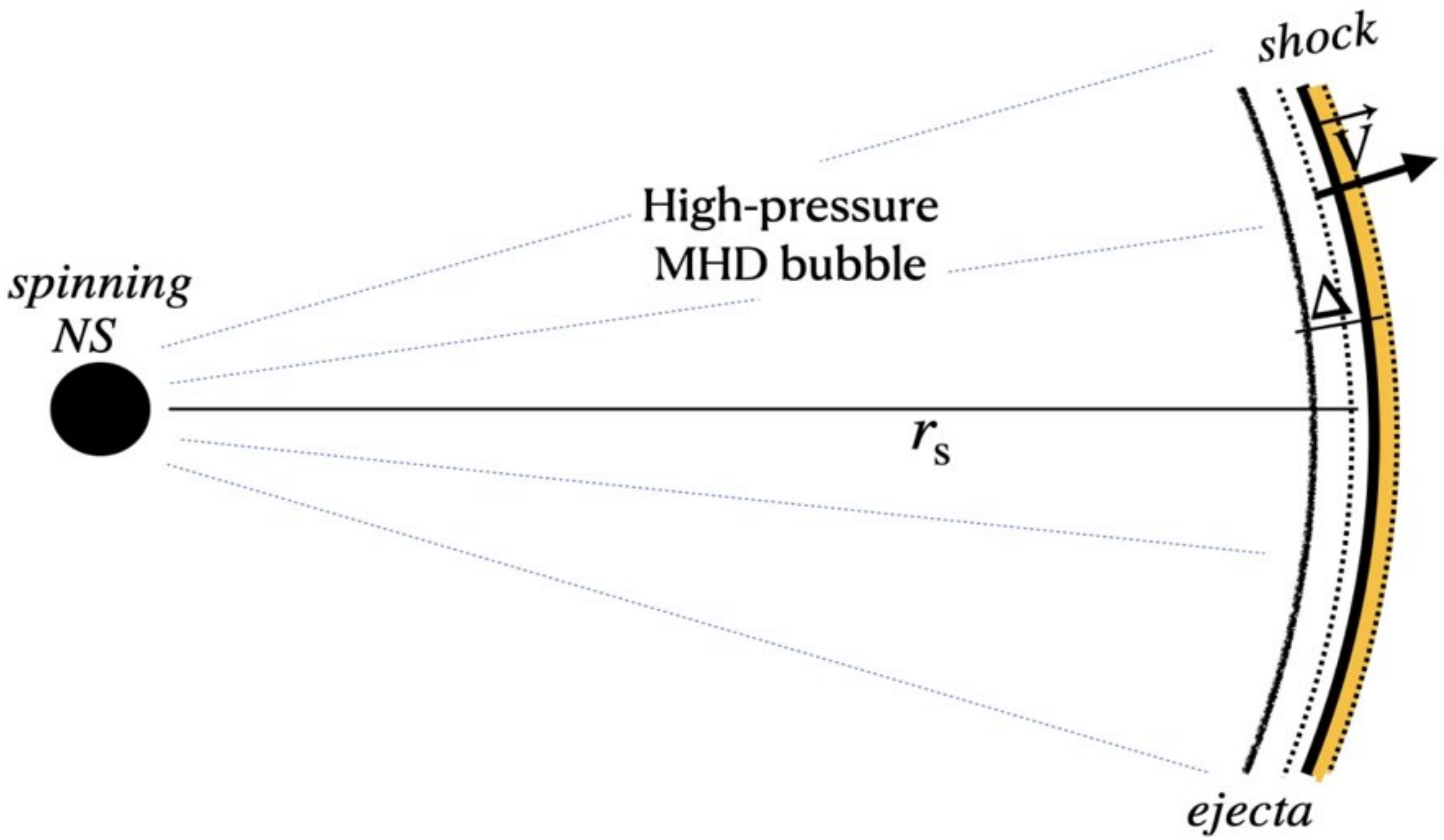
(iii) identify EM counterparts (under way)

↓

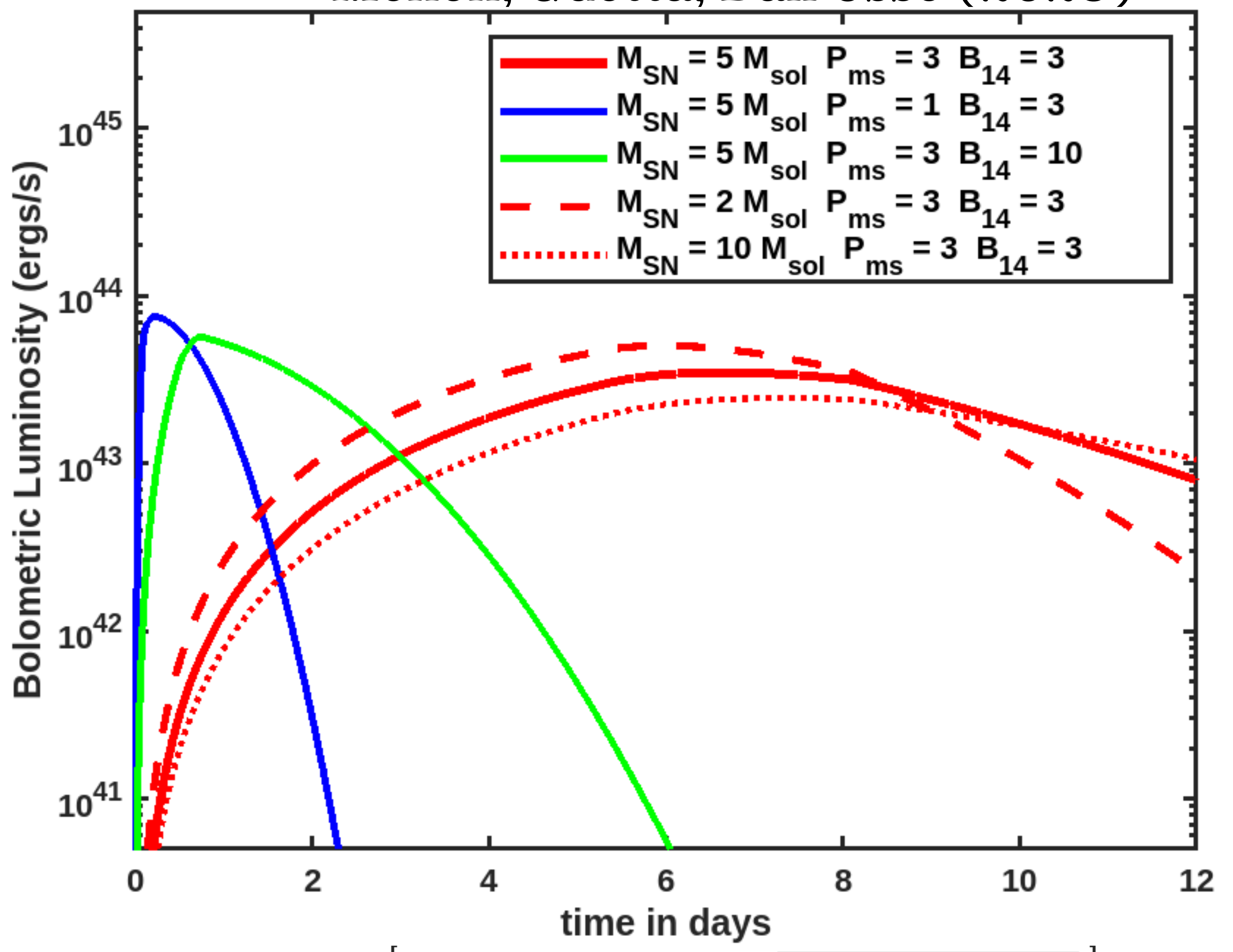
Interesting targets for post-O5 (≳1.5 increase in *h*, ~3 in rate)

Very interesting for ET with a ≳ 7-fold increase in *h*

EM TRIGGERS FOR GW SEARCHES OF LOCAL SOURCES

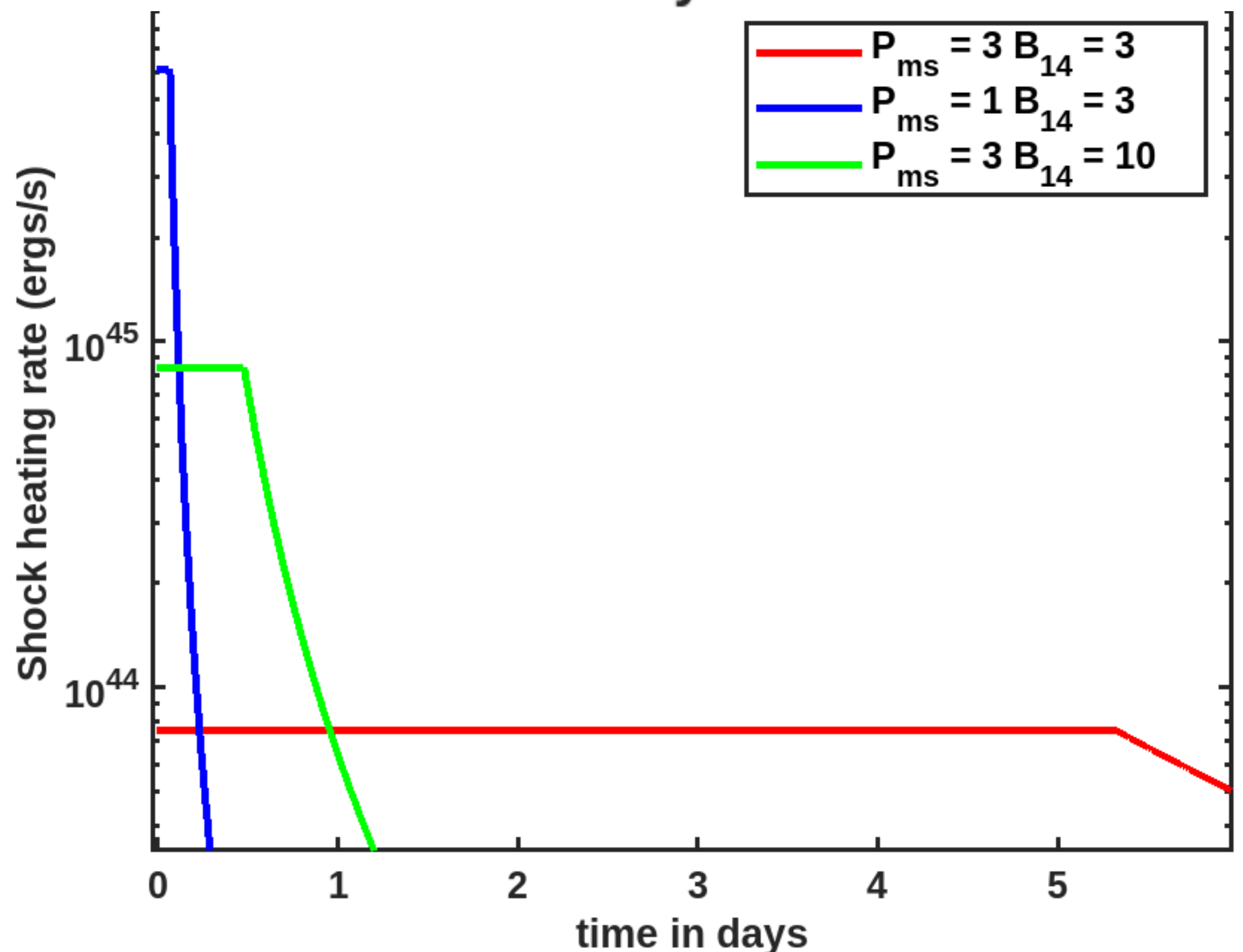


Menon, Guetta, Dall'Osso (2023)



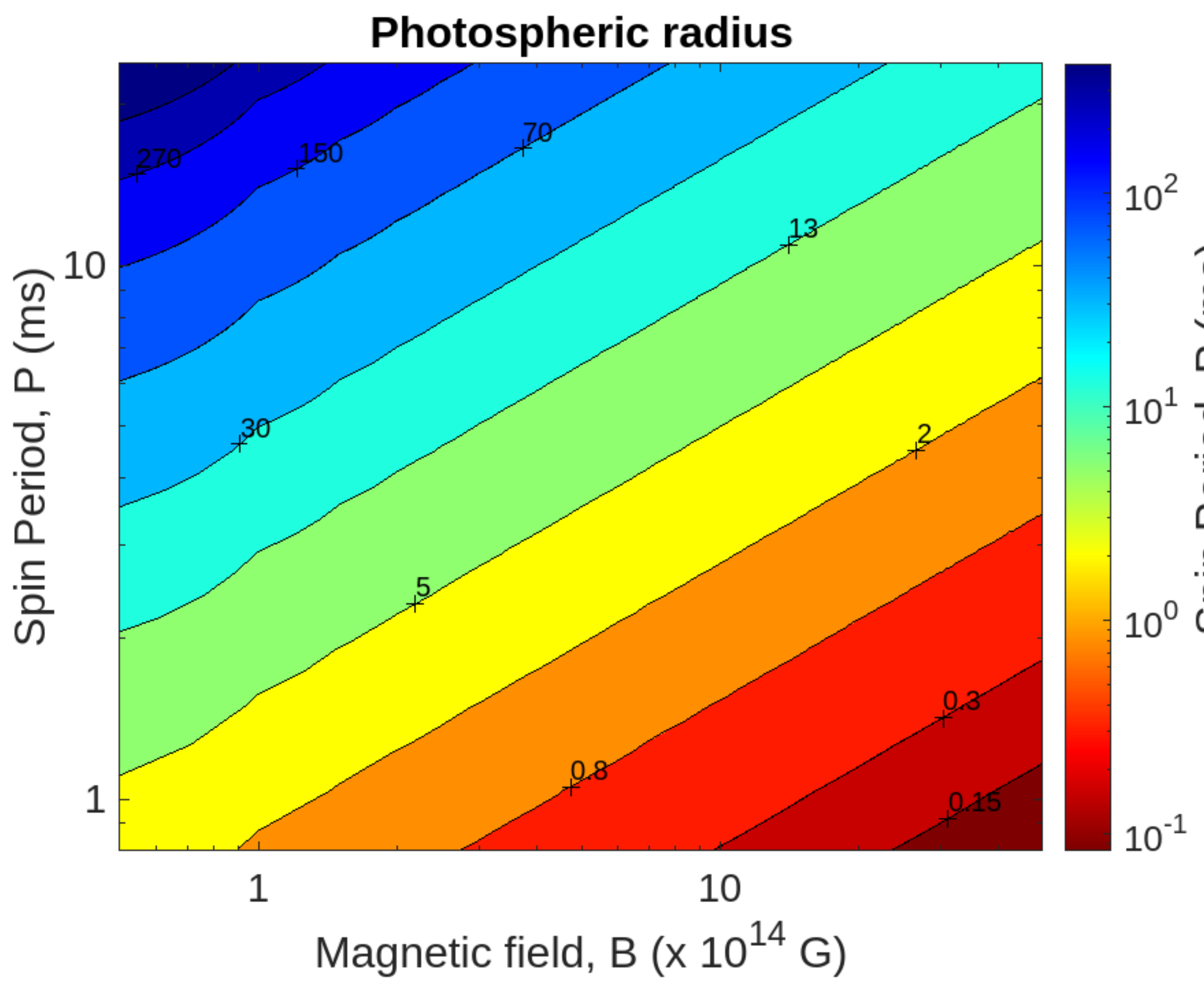
The released energy inflates a high-pressure bubble of relativistic particles and B-field, sweeping the SN ejecta into a thin shell and driving a shock through it. Shock energy is dissipated at the rate $\dot{\epsilon}_{\rm sh} = 4\pi r_s^2 {\rm v}_{\rm ej}^3 (\rho/2)\eta^3$

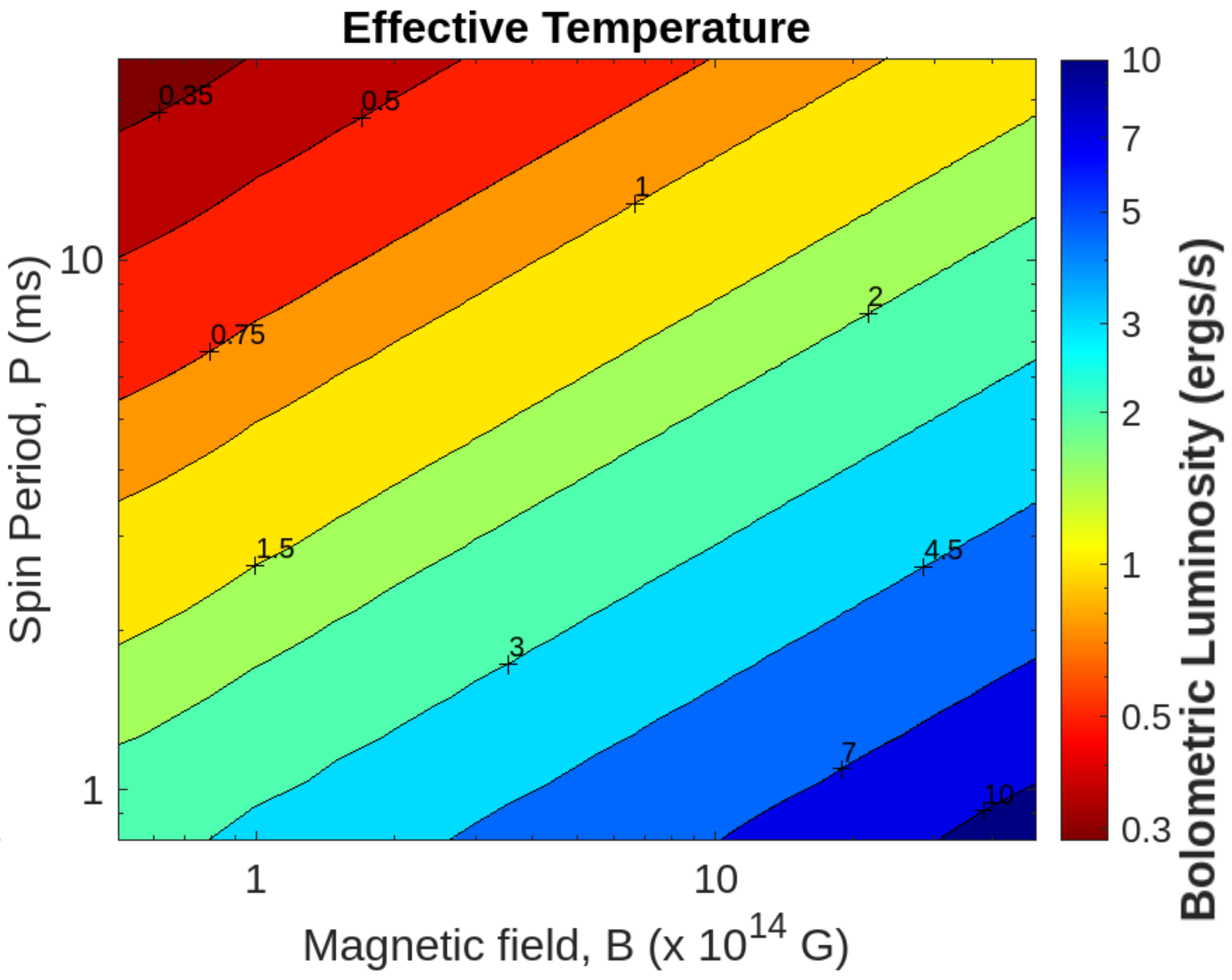
$$\eta = \frac{{\rm v}_{\rm sh} - {\rm v}_{\rm ej}}{{\rm v}_{\rm ej}}$$ shock strength parameter



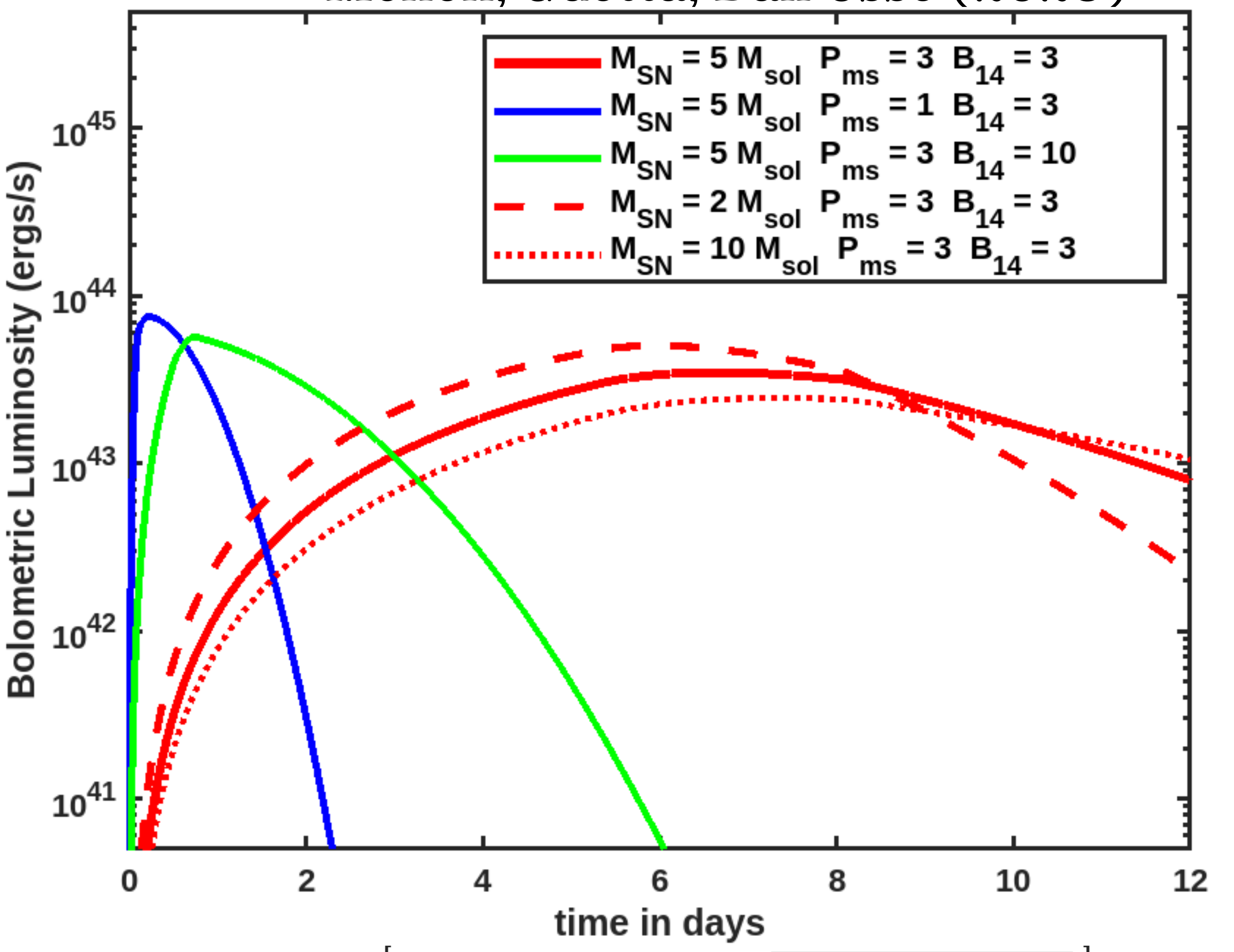
Kasen et al. (2016)

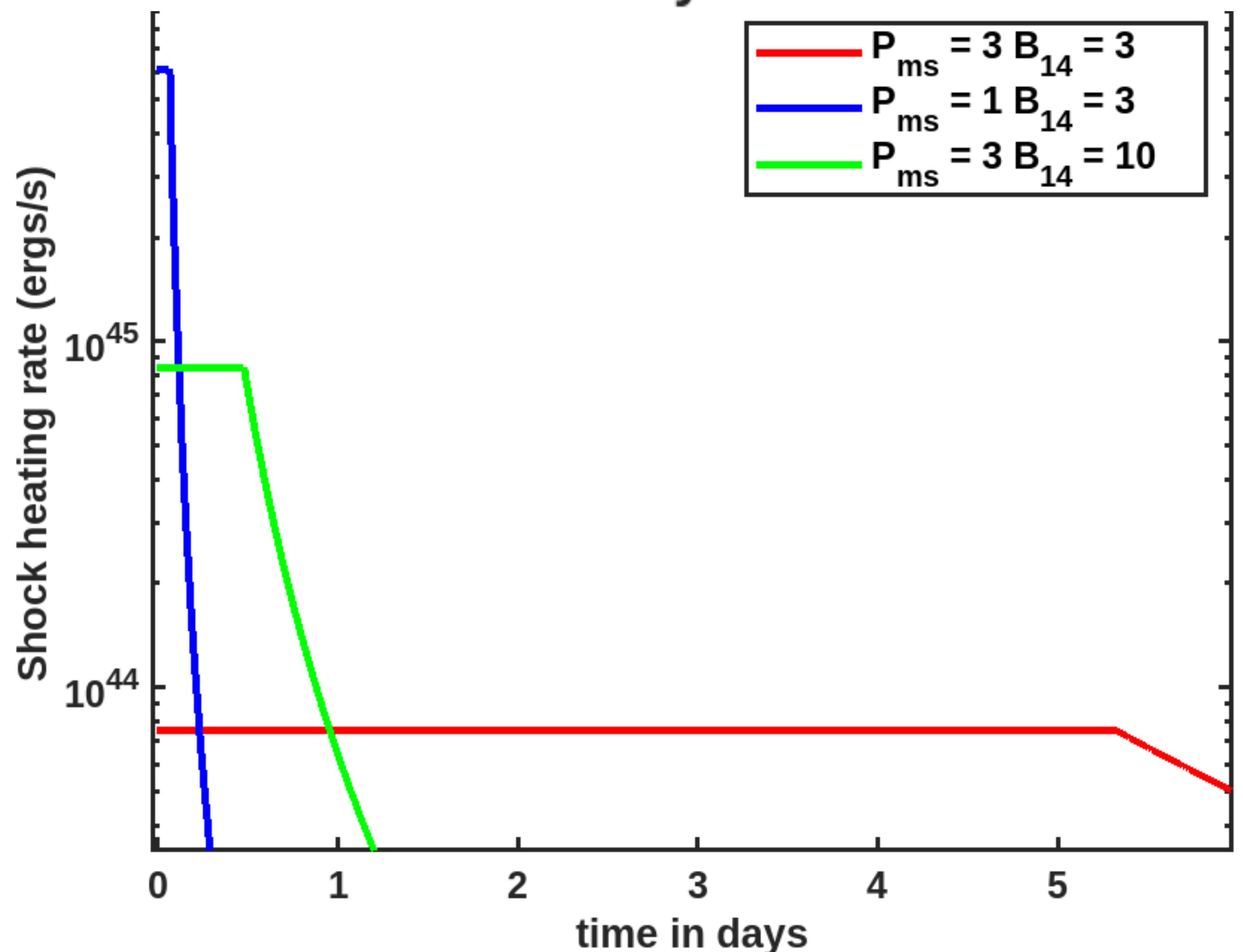
EM TRIGGERS FOR GW SEARCHES OF LOCAL SOURCES





Menon, Guetta, Dall'Osso (2023)





Expected UV event rate	
B-fields	$(0.5–50)\times10^{14}$G
Spin periods	0.8-15 ms
ULTRASAT fov	~ 204 deg^2
A_{NUV}	0 – 1.75 mag
M_{ej}	5 – 15 $M_\odot$
Expected #events per year	≈ (3 – 30) yr^{-1}
	≈ (2 – 20) yr^{-1}

SUMMARY

1. An **intensive multi-messenger approach to the search for newly born magnetars** was developed, aimed at exploiting all of our astrophysical knowledge to enhance the GW search efficiency and the extraction of physics information from future detections

2. **GW searches for long transients:** a thorough improvement of the existing pipeline GFH is under way, which envisions a combination of ML-based algorithms and the refinement of standard semi-coherent methods with the implementation of new filtering techniques.
   The goal is to reach an horizon of $\gtrsim 5$ Mpc during O5 (and post-O5) of the LVK, within which we expect one event every 3-4 yrs.

3. **Gamma-ray Bursts and Fast Radio Bursts can provide us key information on the physical parameters of newly born magnetars**, constraining the GW search parameter space. They may also provide an EM trigger, although not with a high probability (at least for the LVK).

4. **Shock breakouts** - especially in core-collapse SNe - will **represent the most common EM trigger for GW pipelines,** and can also provide key constraints on the GW signal parameters: it will be crucial to further improve theoretical light curve modelling

5. **Future prospect: A neutrino signature**, either from the core-collapse or from the energetic outflow/jet produced by the newly born magnetar, **would be extremely valuable**. Theoretical and observational efforts needed in both these instances.

During the 2 yrs of the project two master theses have been completed and one PhD project has been carried out (still ongoing).

I have started and strengthened collaborations with

- **the Center for Computational Astrophysics at the Flatiron Institute and with Stony Brook University, in the US;**
- **the Ultrasat Collaboration and with Ariel University in Israel;**
- **the eXTP consortium, a China-Europe collaboration to launch an X-ray timing and polarimetry satellite in which I became coordinator of the multi-messenger science program**

- **the Astronomical Observatory and the University of Cagliari, where I am currently working on two separate projects (one related to Fast Radio Bursts and the other on searches for GWs from neutron stars in binaries)**
- **The Astronomical Observatory of Brera-Merate**