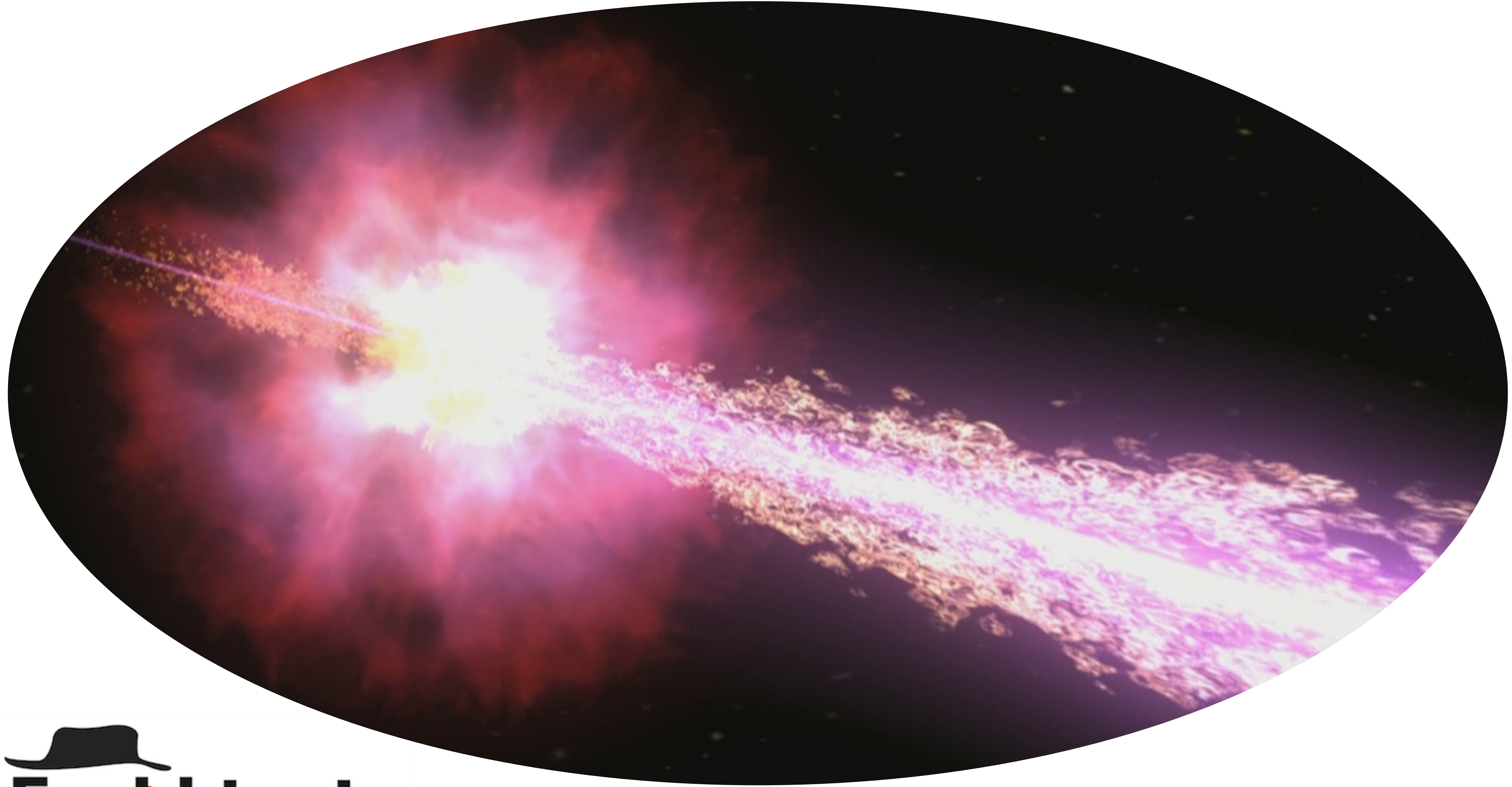
GRB V

Trieste - 12-15/09/2022

THE HUNT FOR THE GRB CENTRAL ENGINE



Fellini

Fellowship for Innovation at INFN

H2020 MSCA COFUND

G.A. 754496

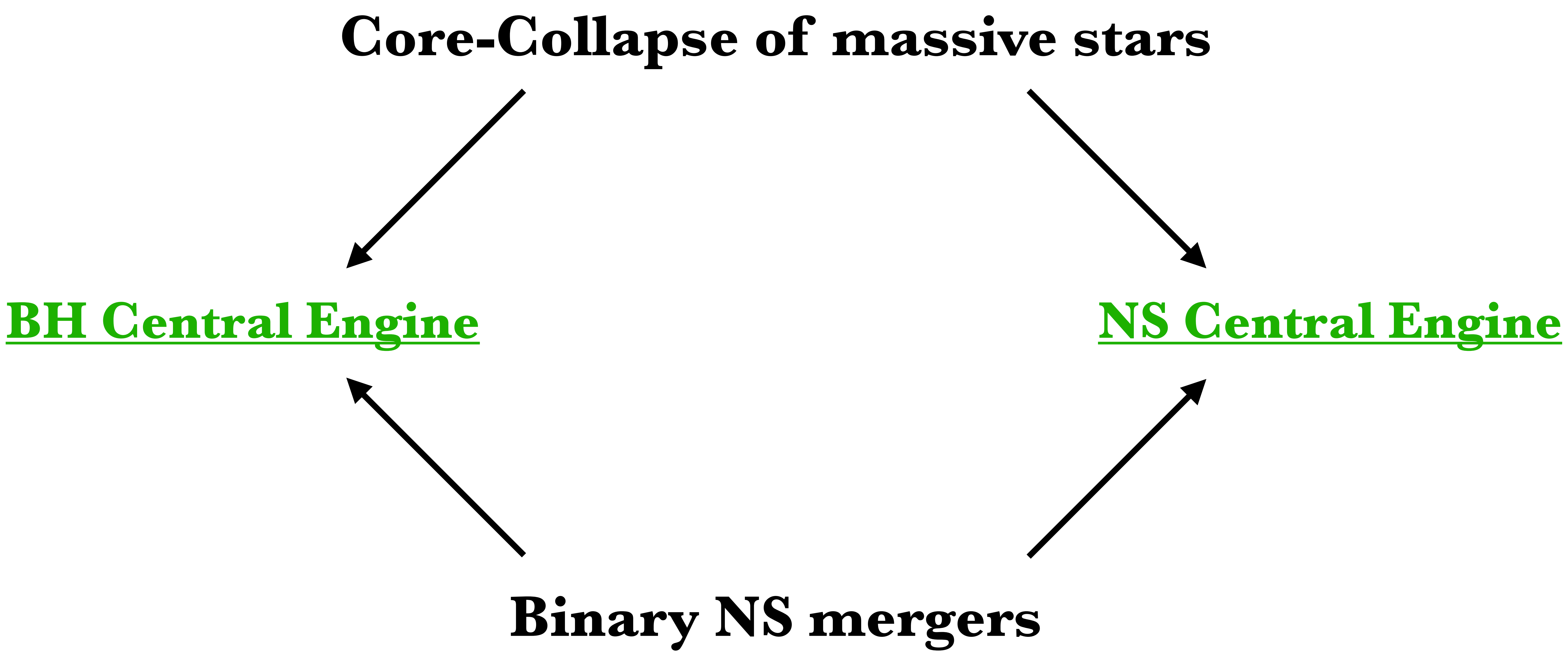
Simone Dall'Osso

INFN - Roma 1

INFN

Istituto Nazionale di Fisica Nucleare

TWO PROGENITORS AND TWO CENTRAL ENGINES



Core-Collapse of massive stars

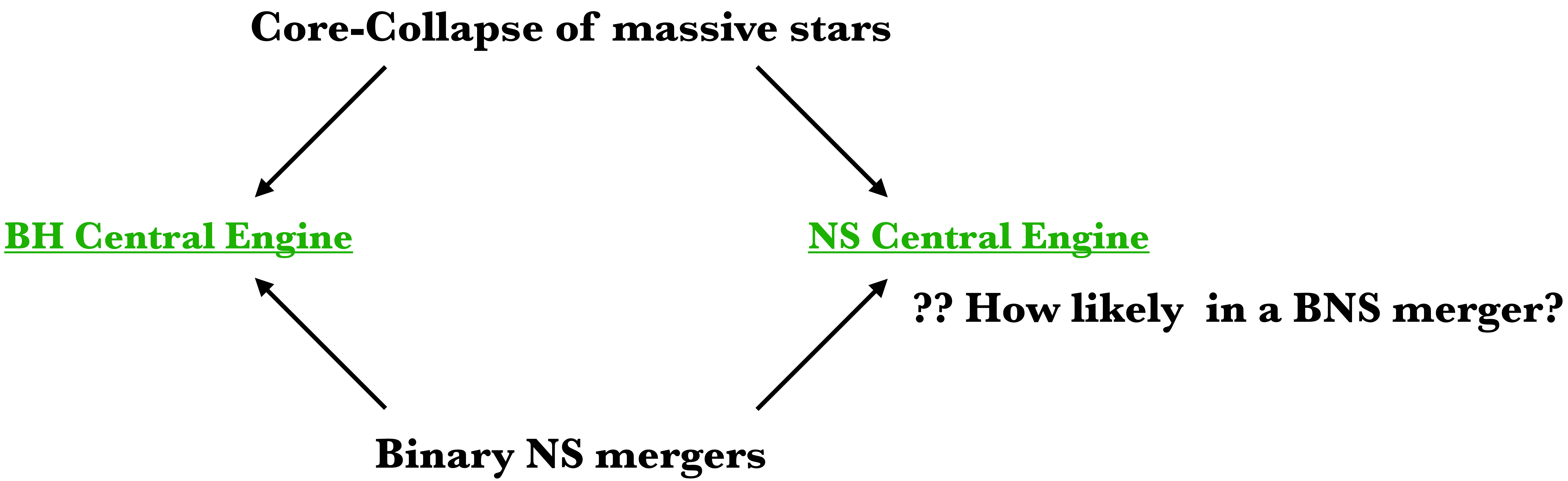
BH Central Engine

NS Central Engine

Binary NS mergers

..and, YES, TWO CLASSES OF GRBs

TWO PROGENITORS AND TWO CENTRAL ENGINES



Core-Collapse of massive stars

BH Central Engine

NS Central Engine

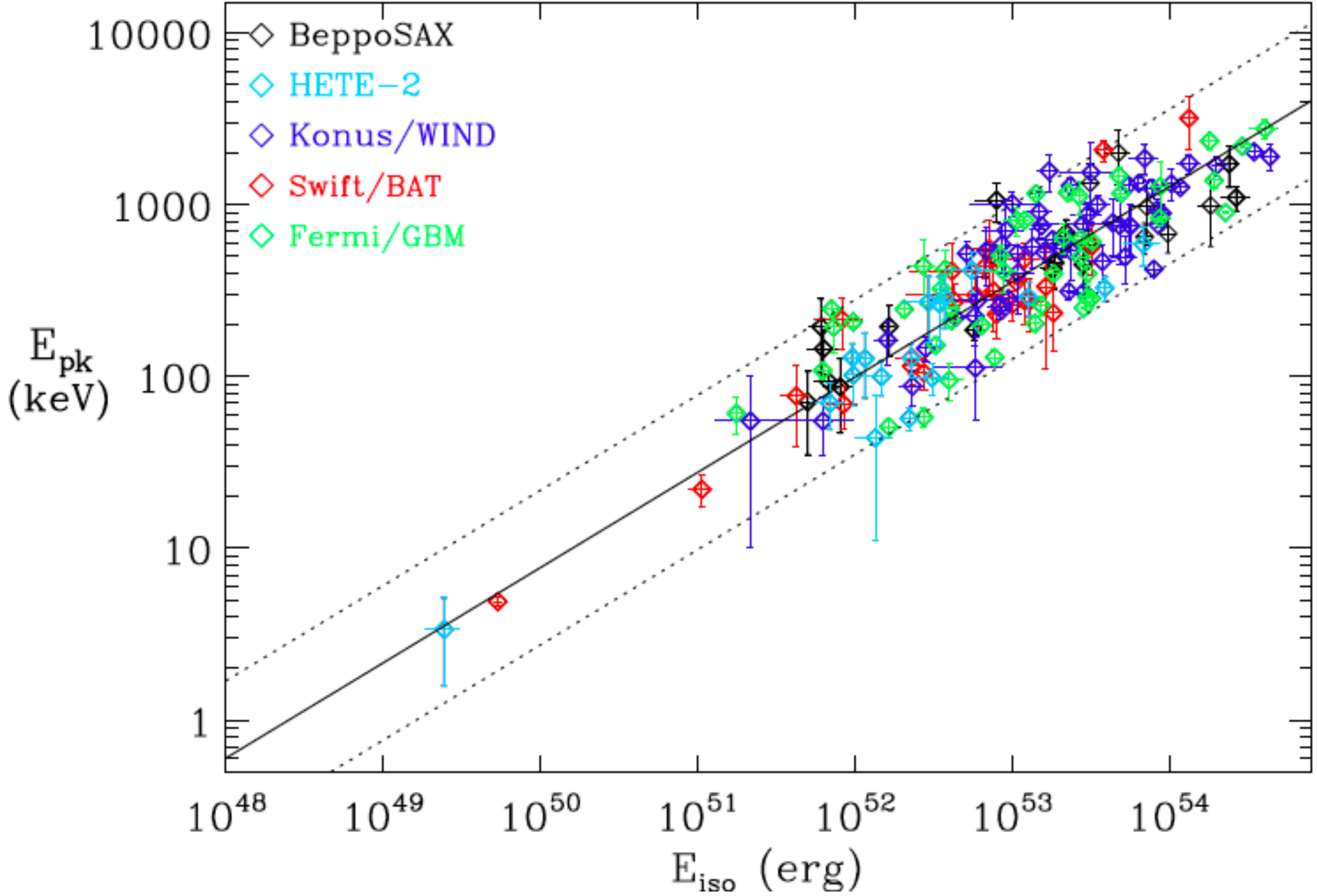
?? How likely in a BNS merger?

Binary NS mergers

..and, YES, TWO CLASSES OF GRBs

BASIC CONSTRAINTS ON PROGENITORS

Amati & Della Valle (2013)



For beaming factors ~ 30-10^3

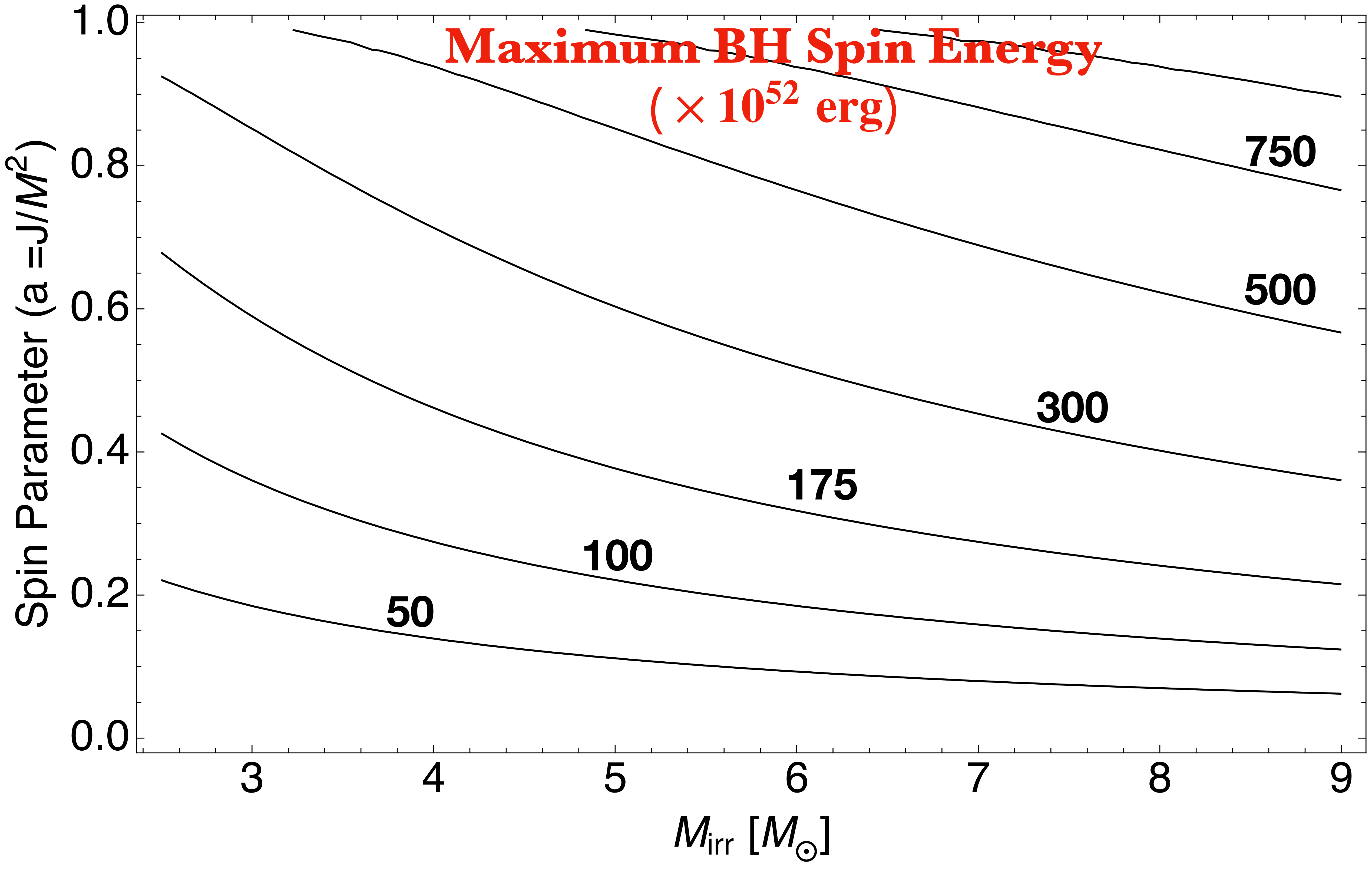
($\theta_{jet} \sim 3 - 15$ deg)

and radiative efficiency > 0.1 the large majority of events require

$E_{engine} < 10^{53}$ erg

BASIC CONSTRAINTS ON PROGENITORS

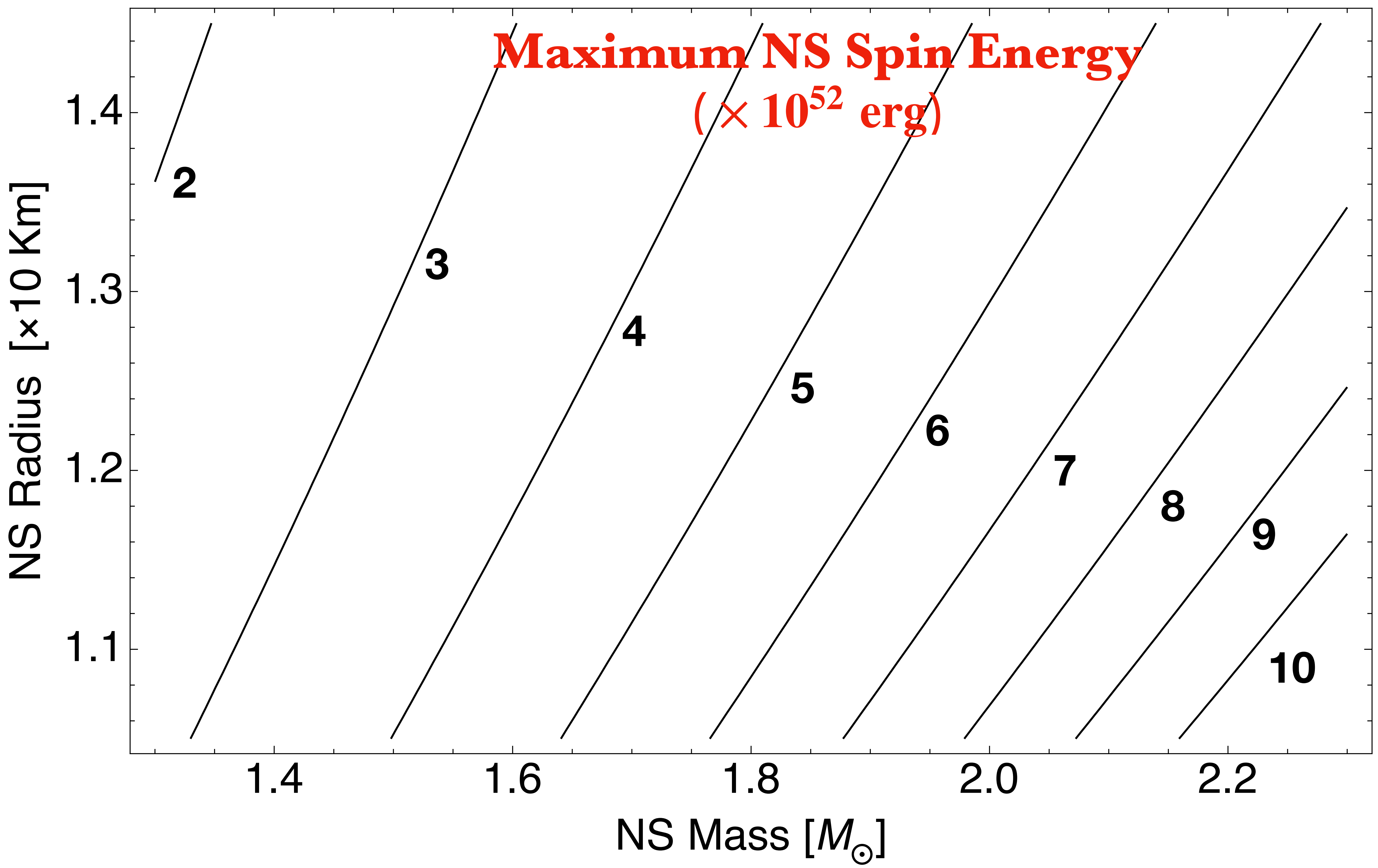
BH Central Engine


Maximum BH Spin Energy

($\times 10^{52}$ erg)

$$M^2 = \frac{J^2}{4M_{irr}^2} + M_{irr}^2 \quad \Rightarrow \quad E_{\rm spin} = Mc^2\sqrt{\frac{1-\sqrt{1-a^2}}{2}}$$

NS Central Engine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$$\Omega_{\rm shed} = \left(\frac{2}{3}\right)^{3/2}\sqrt{\frac{GM}{R^3}} \quad \Rightarrow \quad E_{\rm shed} \propto \Omega_{\rm shed}^2 \approx \frac{1}{10}E_{\rm bind}$$

$\sim$ same as in tidal disruption : $a_T \approx (2.1-2.3)\dfrac{R}{q^{1/3}}$

BASIC CONSTRAINTS ON PROGENITORS

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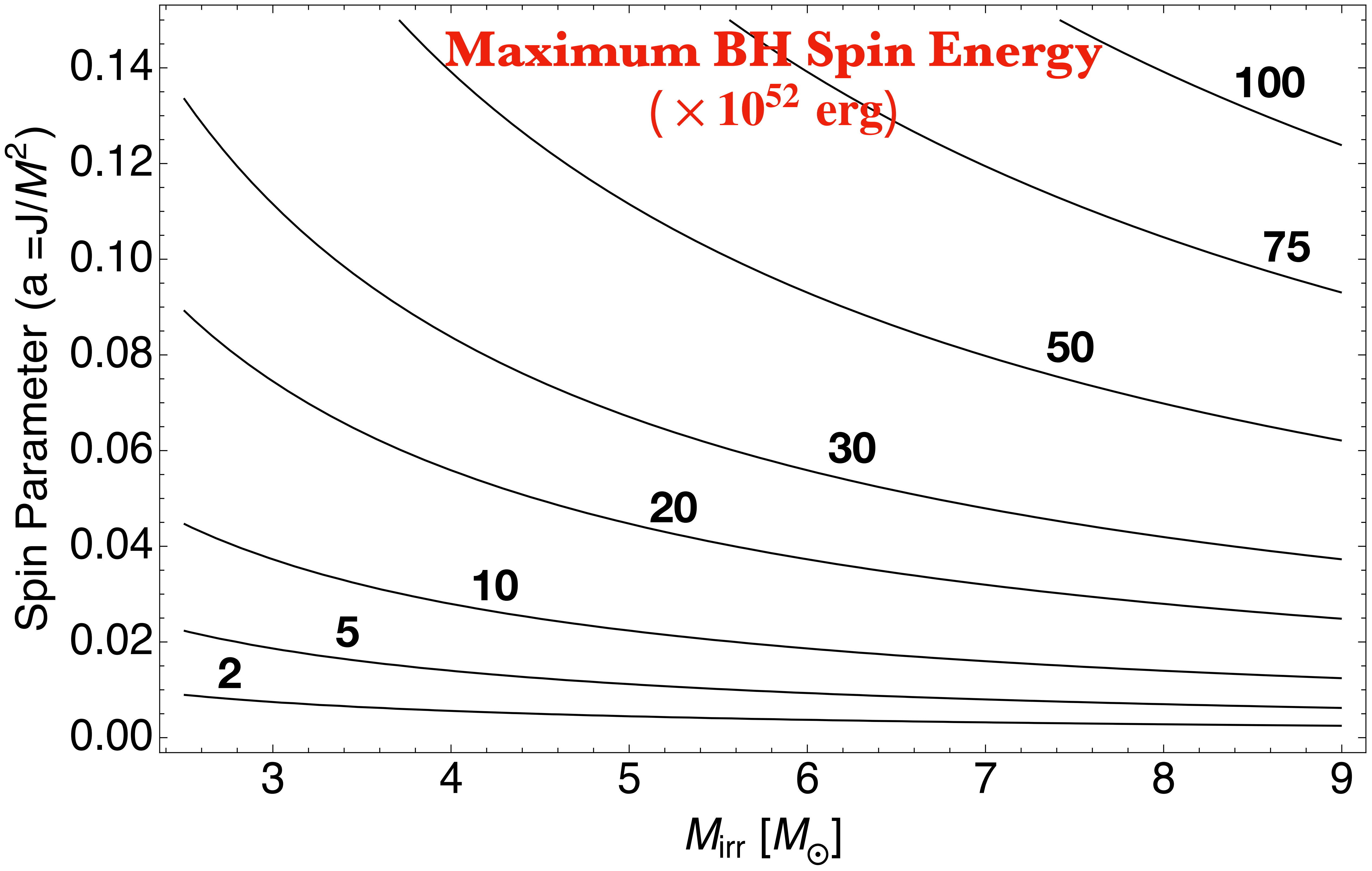

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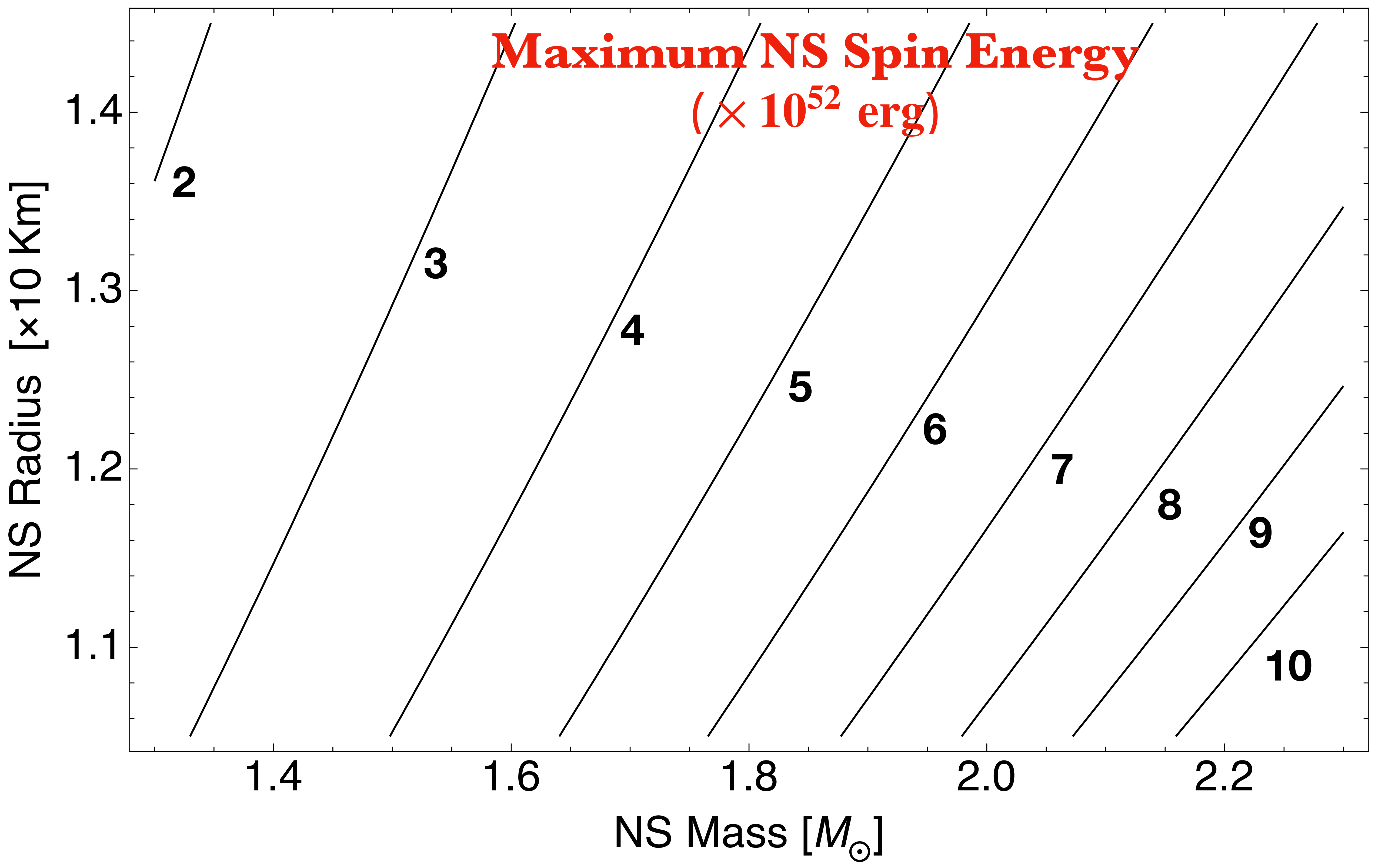

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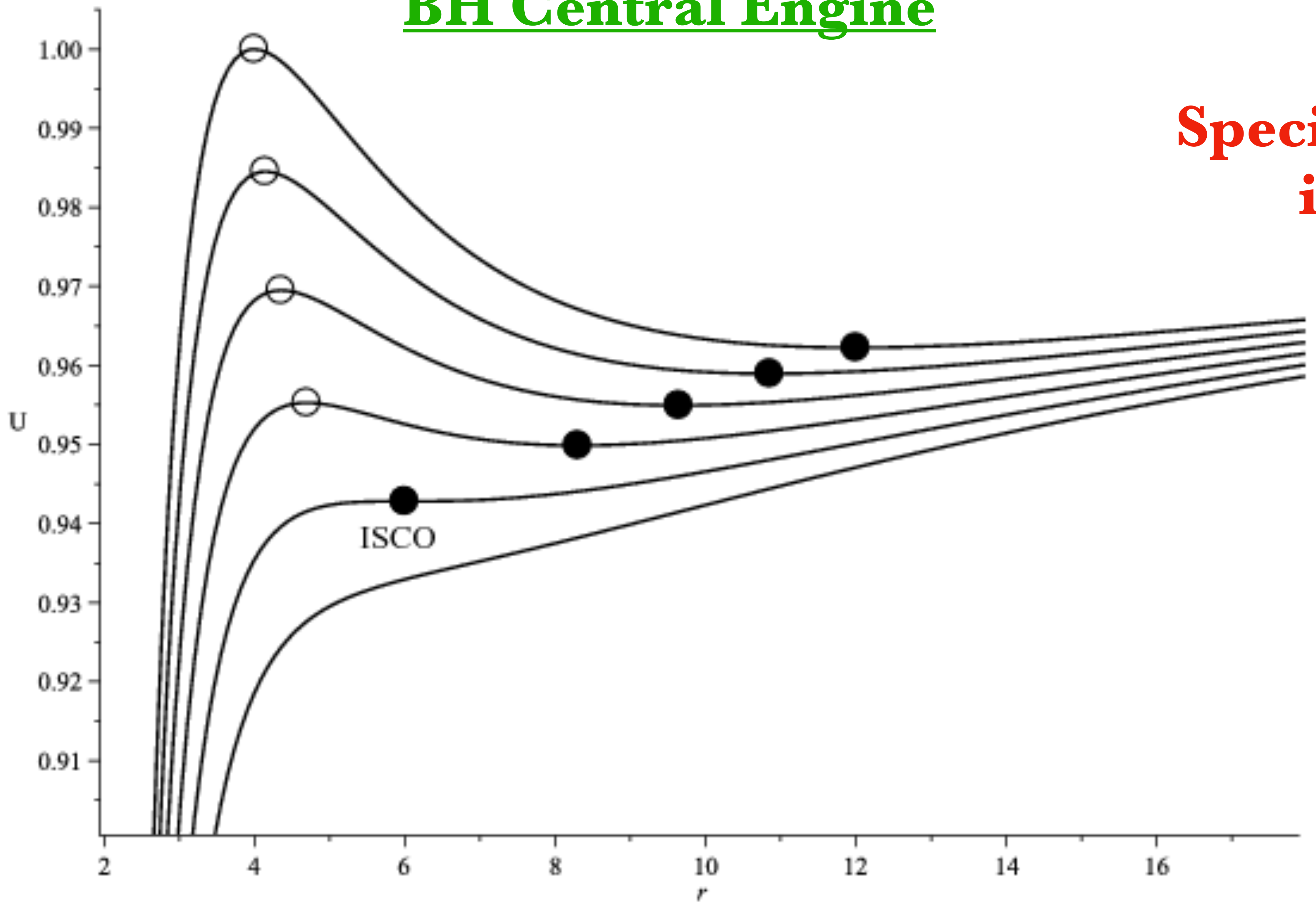
BASIC CONSTRAINTS ON PROGENITORS

Specific angular momentum in progenitor's core

BH Central Engine



$$\ell = \frac{L}{m} > \sqrt{12}\frac{GM}{c} \approx 5\times 10^{16}\ \mathrm{cm^2/s}\ \left(\frac{M}{3\ M_\odot}\right)$$

NS Central Engine

$$\begin{cases} L = I(\beta)\Omega \ \Rightarrow \ E_{\rm spin} = \dfrac{L^2}{2I(\beta)} \\ I(\beta) = MR^2\left(0.247 + 0.642\beta + 0.466\beta^2\right) \\ \beta = \dfrac{GM}{c^2R} \end{cases}$$

Lattimer 2016

$$\ell = \frac{L}{m} > \frac{\sqrt{2I\ E_{\rm spin}}}{M} \approx 3\times 10^{15}\ \mathrm{cm^2/s}\ \frac{R_6^2}{P_{\rm ms}}$$

BASIC CONSTRAINTS ON PROGENITORS

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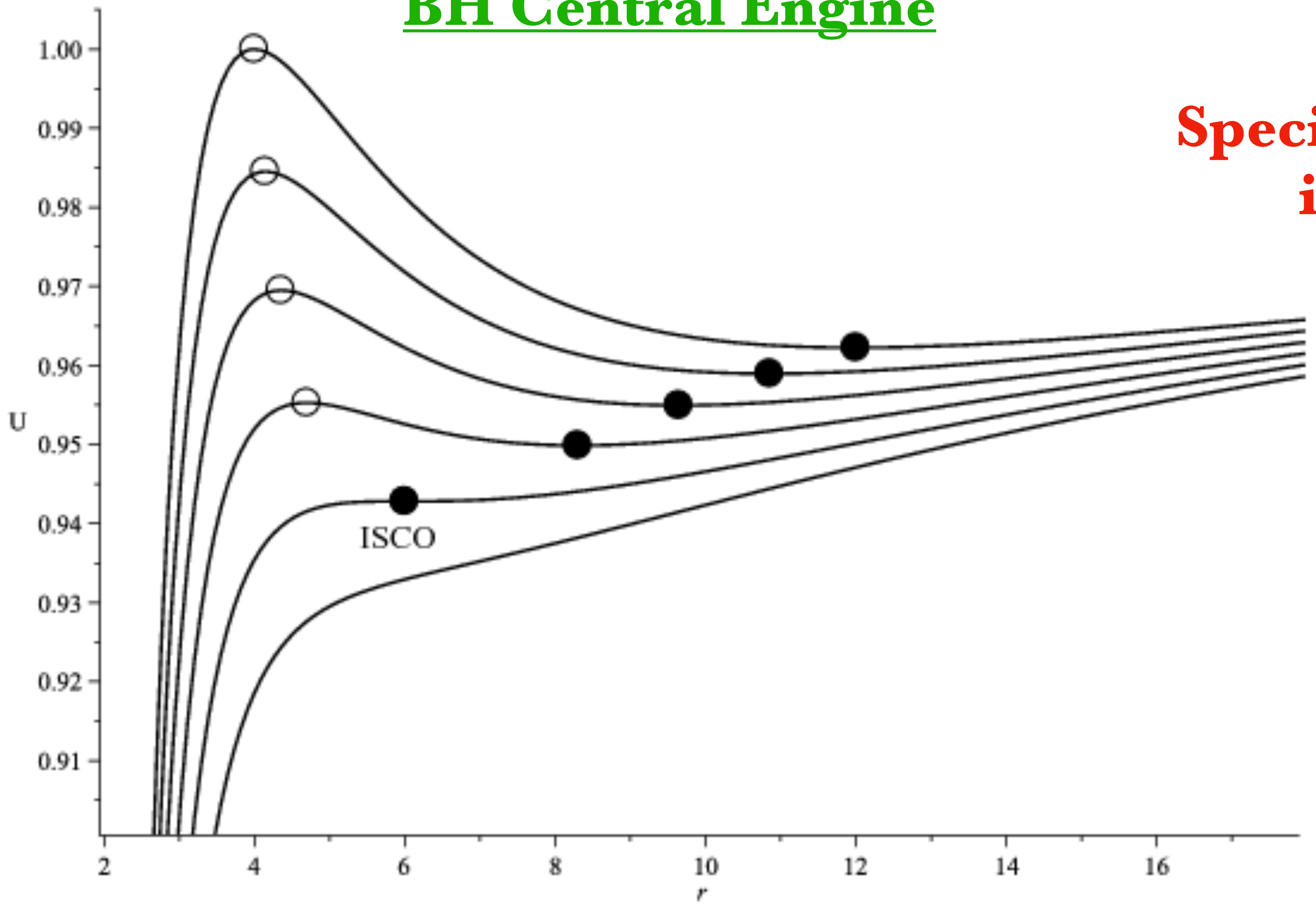

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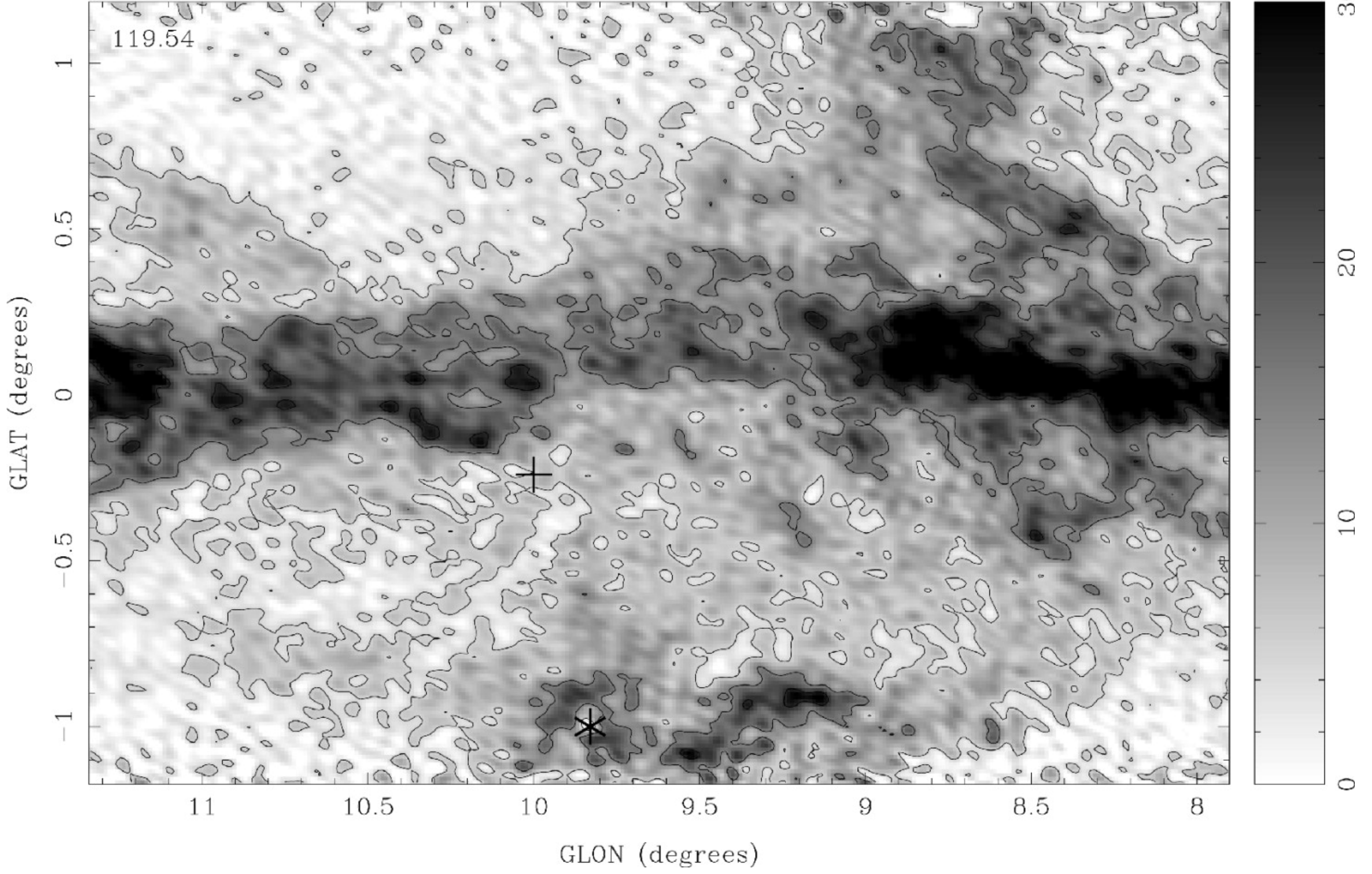
In BNS mergers the formation of a stable NS depends sensitively on the NS maximum mass, the mass distribution of binary components and the amount of ejecta.

Simulations reveal difficulties in launching a relativistic jet with a NS merger remnant, although some details still need to be addressed (Ciolfi et al. 2020 + yesterday's talk)

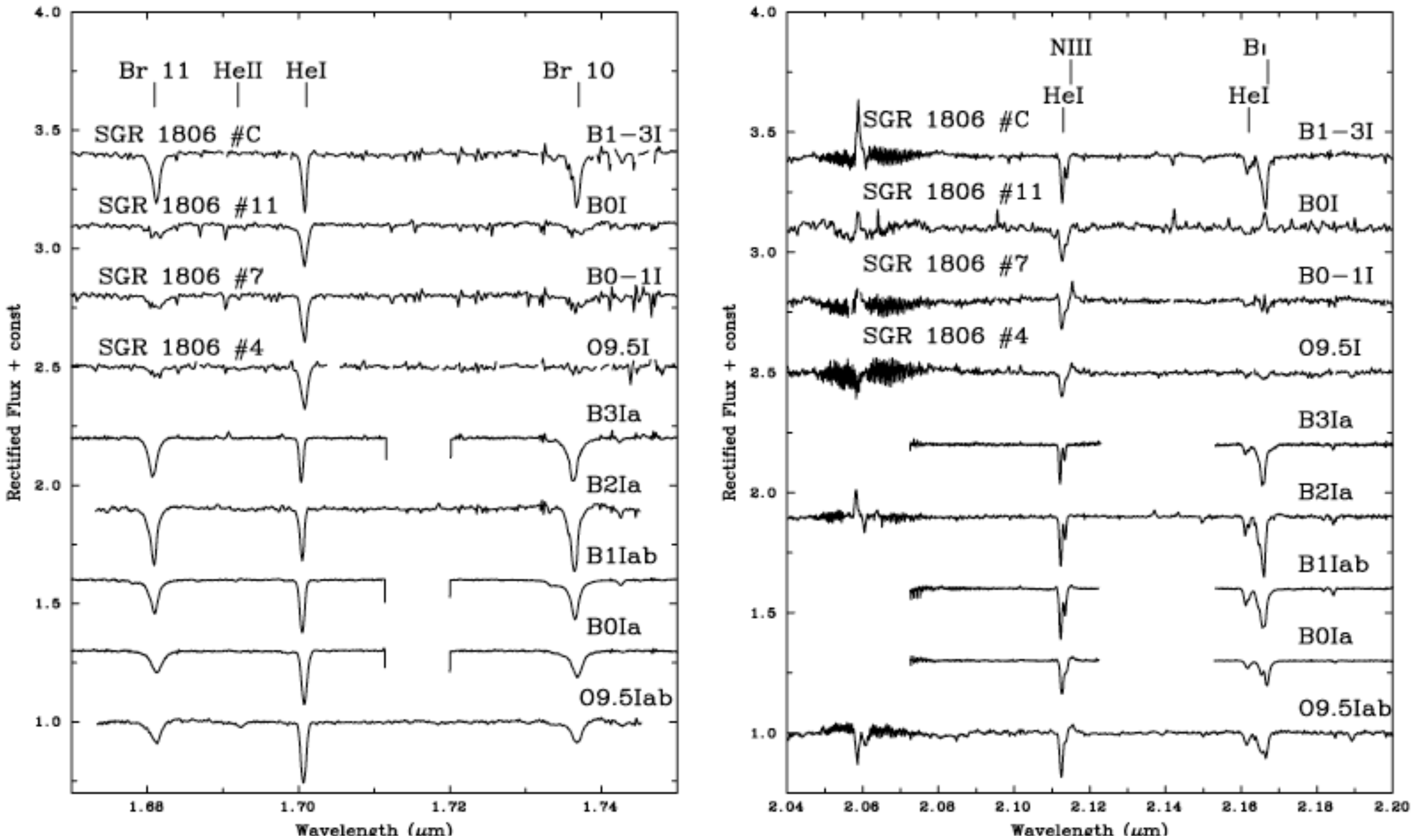
STELLAR PROGENITORS OF GALACTIC MAGNETARS

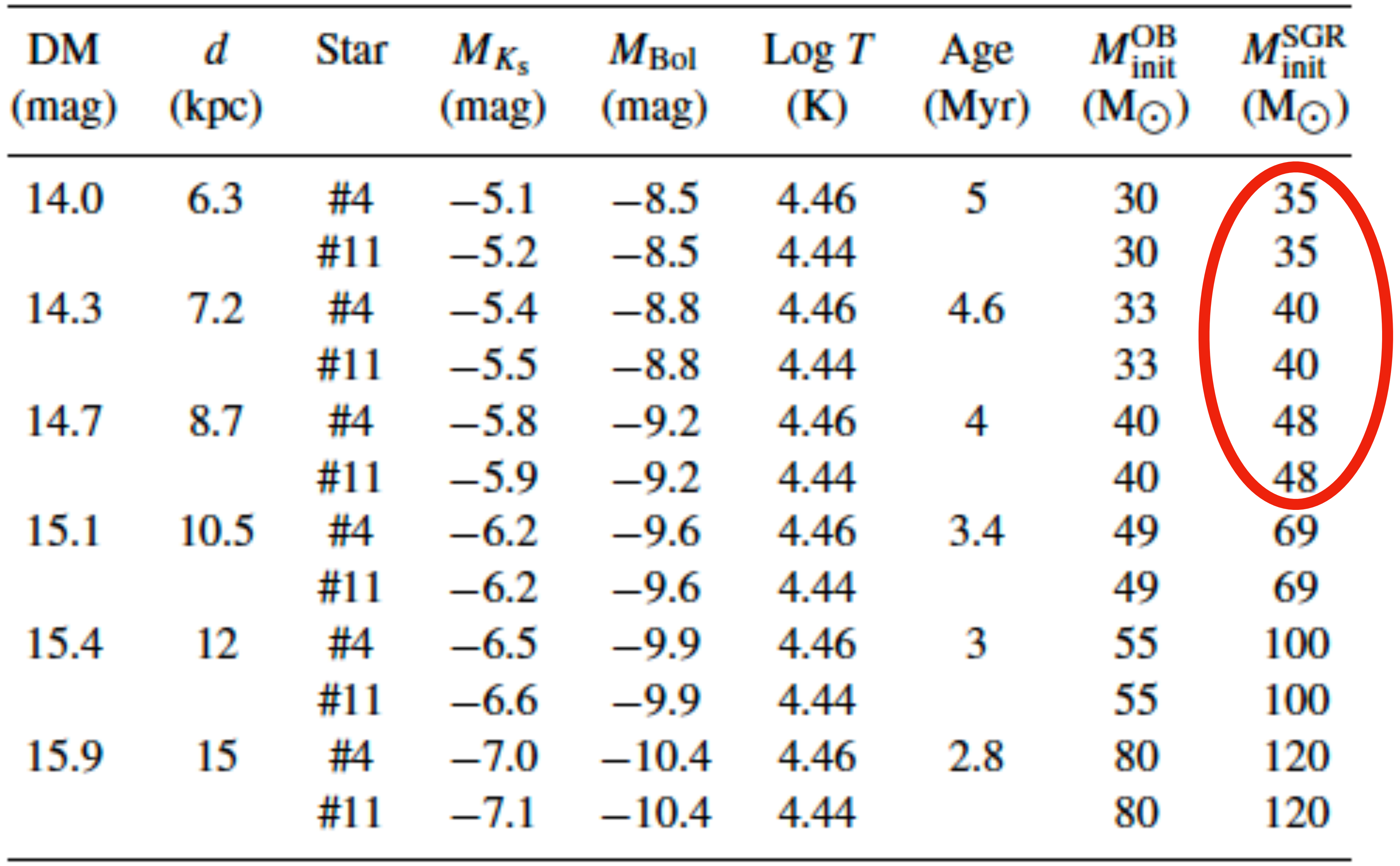
SGR 1806-20

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



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





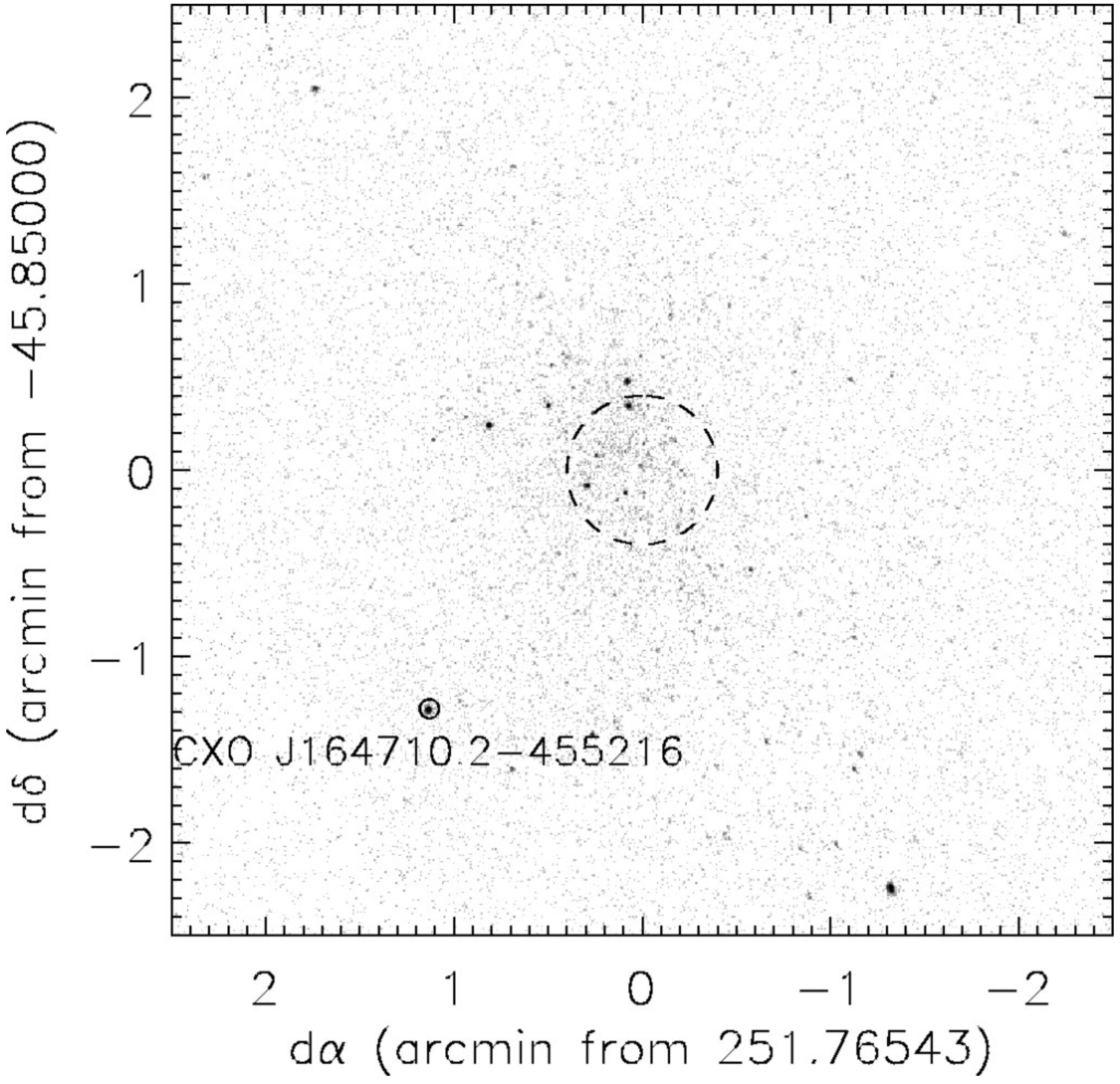
DM (mag)	d (kpc)	Star	M_{K_s} (mag)	M_{Bol} (mag)	Log T (K)	Age (Myr)	$M^{\mathrm{OB}}_{\mathrm{init}}$ ($M_\odot$)	$M^{\mathrm{SGR}}_{\mathrm{init}}$ ($M_\odot$)
14.0	6.3	#4	−5.1	−8.5	4.46	5	30	35
		#11	−5.2	−8.5	4.44		30	35
14.3	7.2	#4	−5.4	−8.8	4.46	4.6	33	40
		#11	−5.5	−8.8	4.44		33	40
14.7	8.7	#4	−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)

STELLAR PROGENITORS OF GALACTIC MAGNETARS

CXO J164710.2-455216 (Westerlund 1)

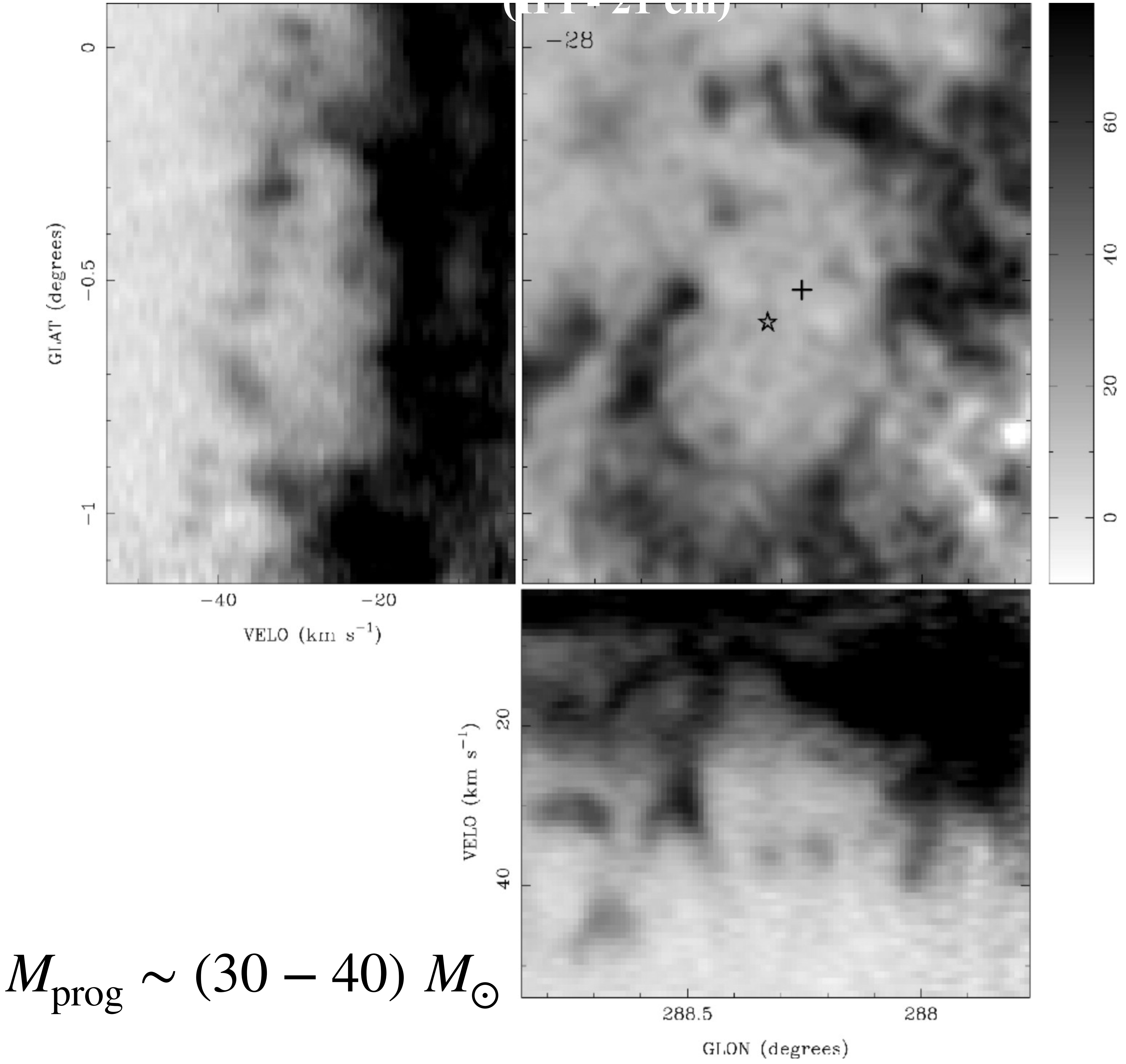
Muno et al. (2006)



$M_{\rm prog} > 35\ M_\odot$

AXP - 1E 1048.1−5937

Gaensler et al. (2005)

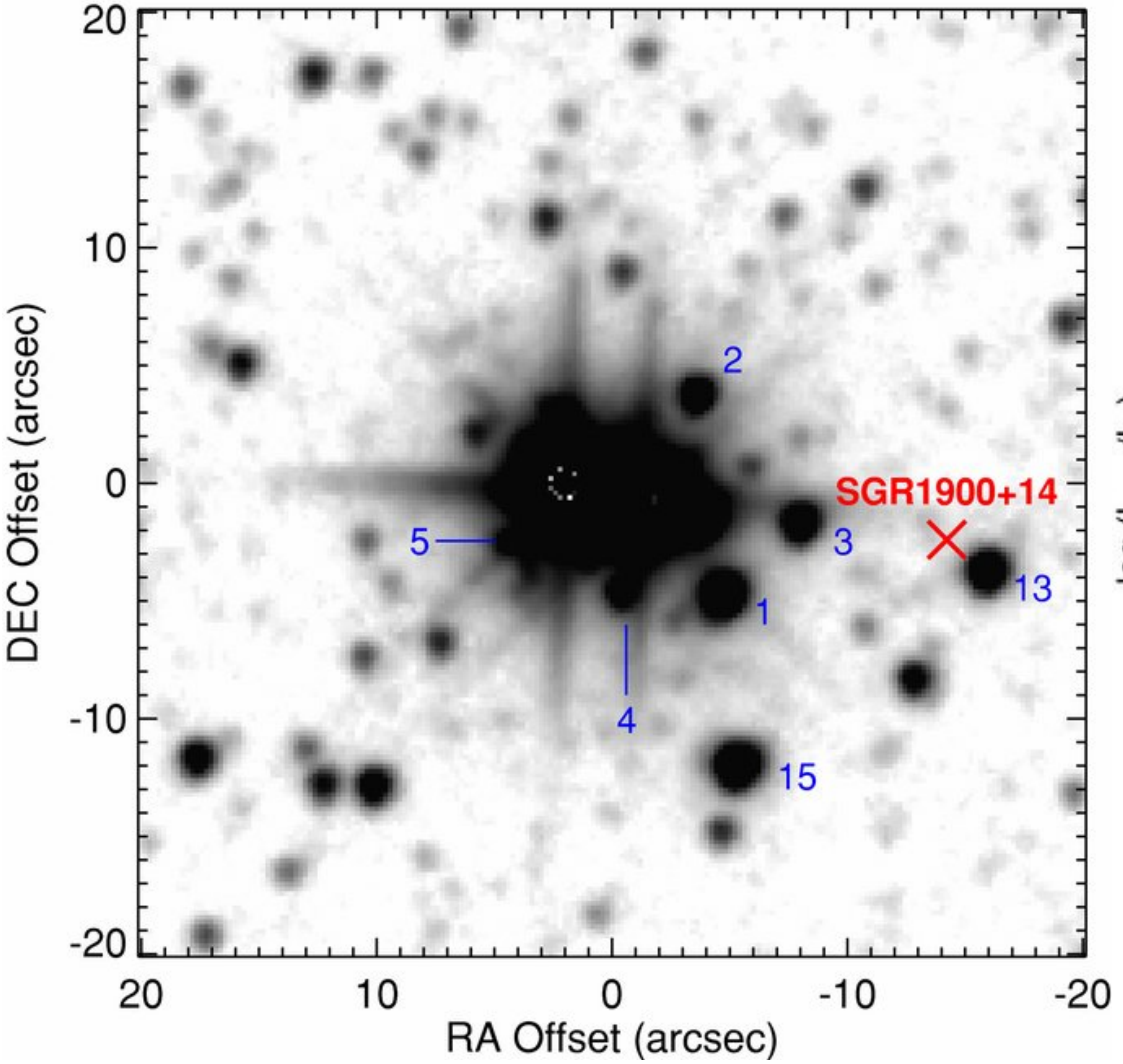


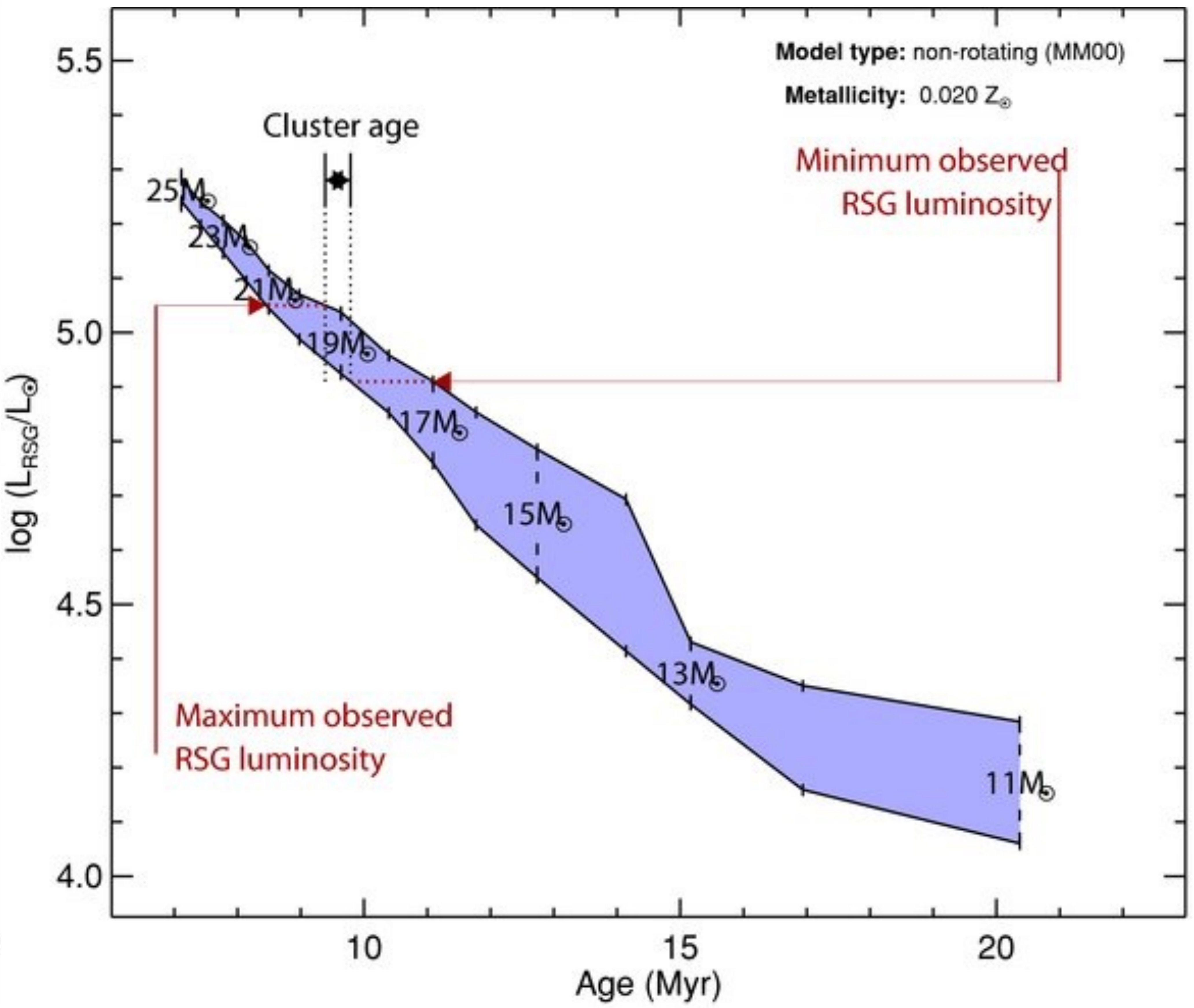
$M_{\rm prog} \sim (30 - 40)\ M_\odot$

STELLAR PROGENITORS OF GALACTIC MAGNETARS

SGR 1900+14

Davies et al. (2009)

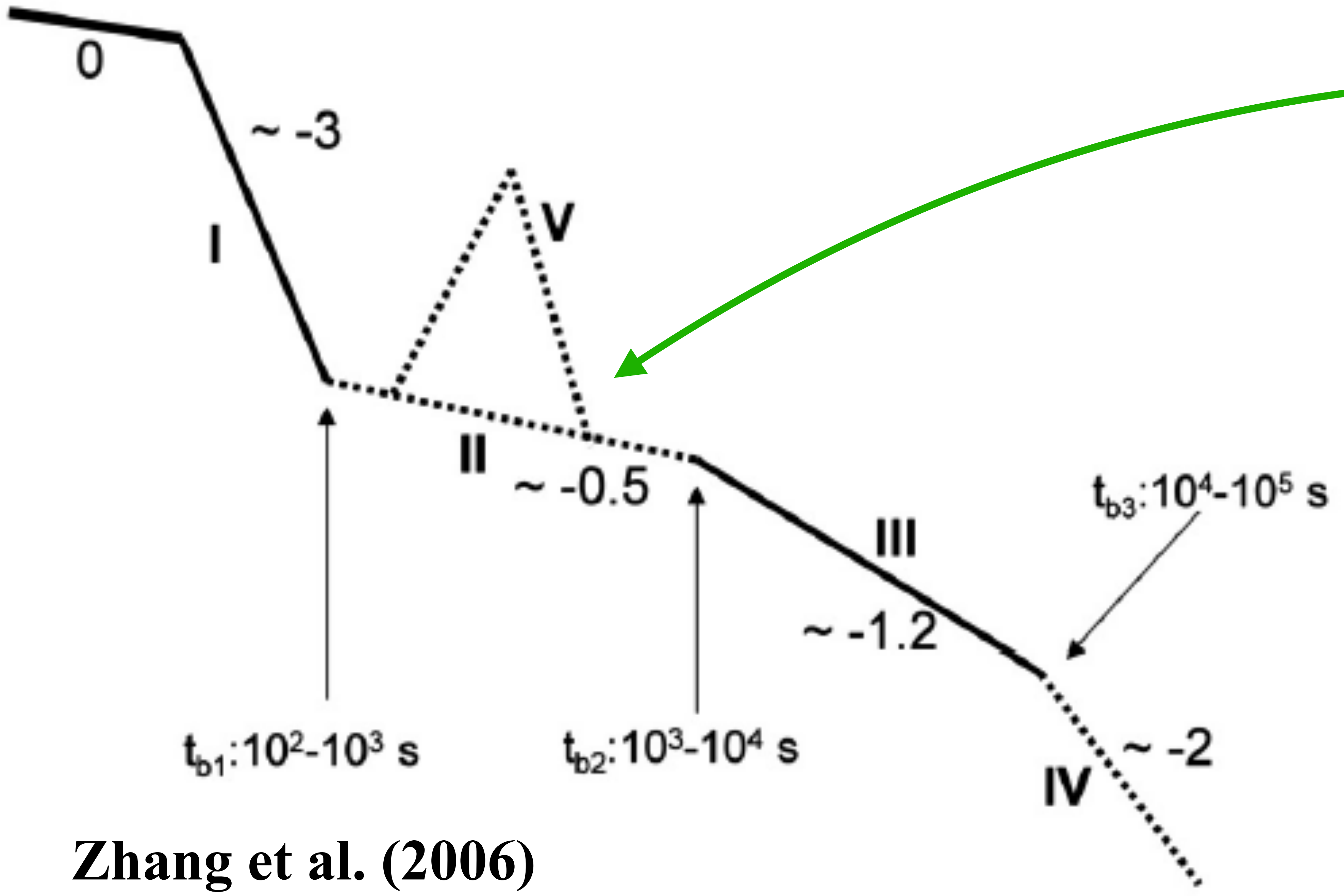




$$M_{\rm prog} \sim (17 - 21)\ M_{\odot}$$

AFTERGLOW SHALLOW DECAY

Nousek et al. (2006)



Zhang et al. (2006)

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, highly magnetised NS

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

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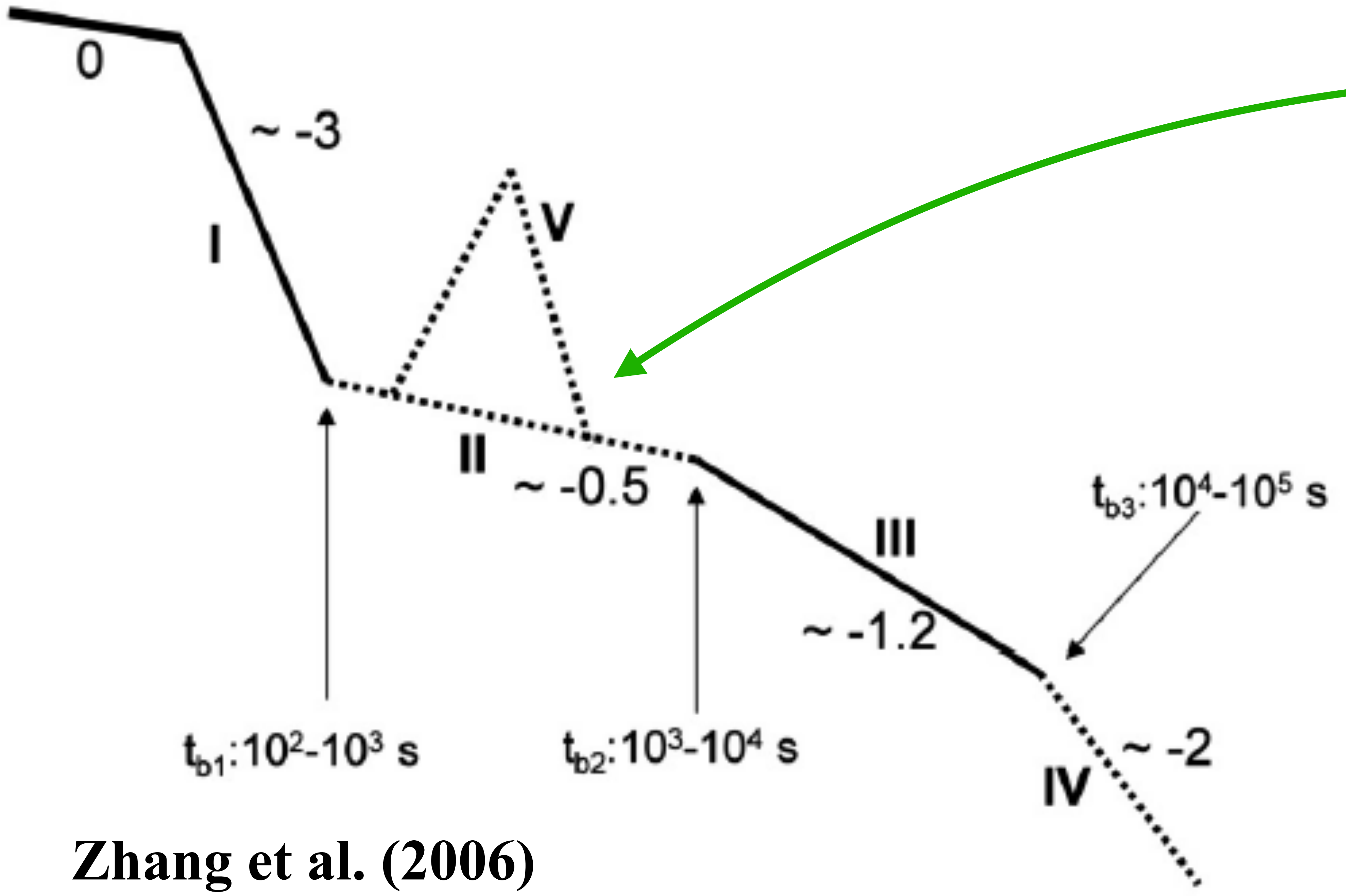

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- **Off-axis emission from structured jets: high-latitude and/or off-axis view**

The X-ray spectrum typically doesn’t evolve during the shallow decay or across the later transitions
A fraction of plateaus do show chromatic behaviour (to different degrees) in multi-band obs.

AFTERGLOW SHALLOW DECAY

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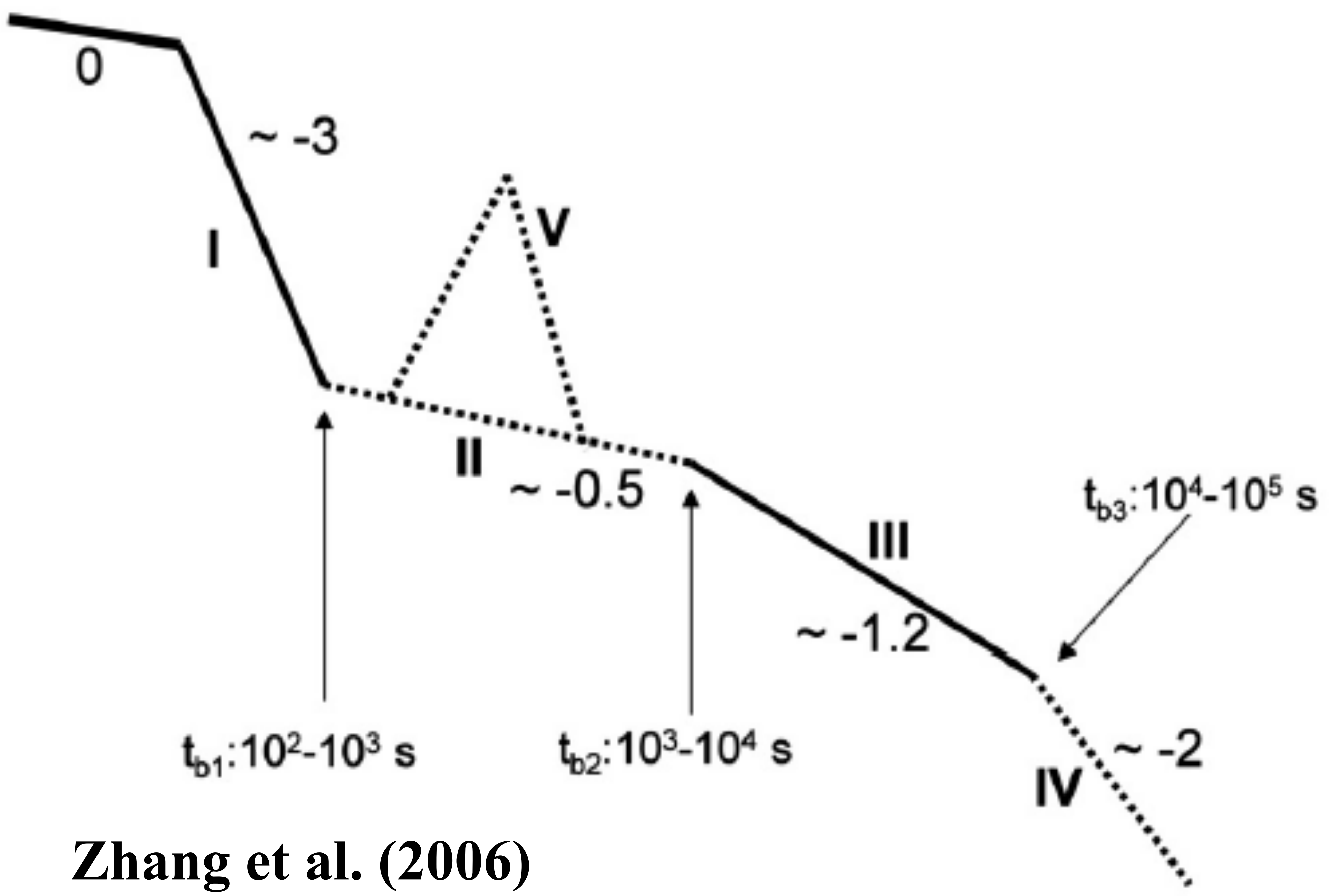
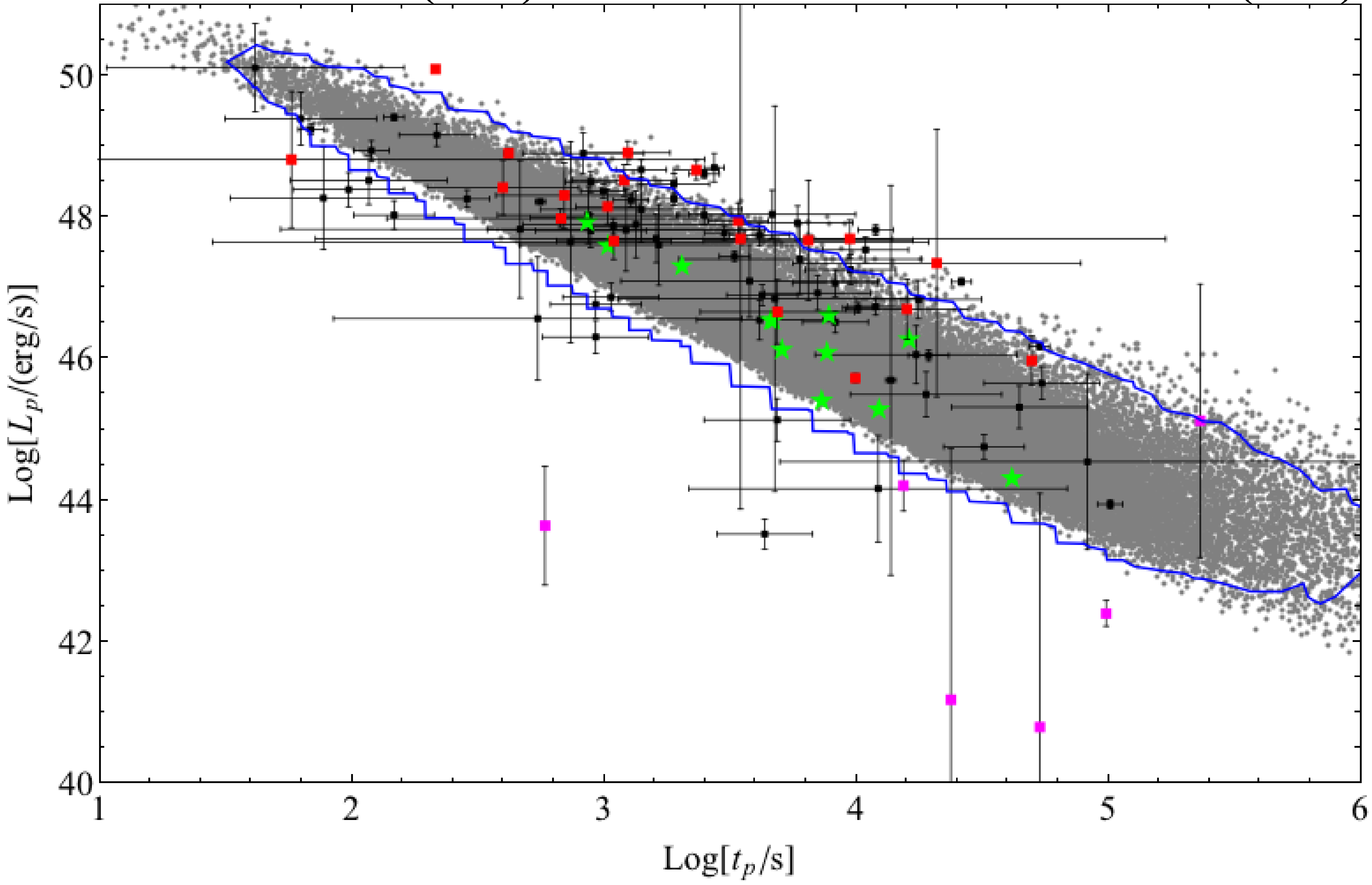


Zhang et al. (2006)

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



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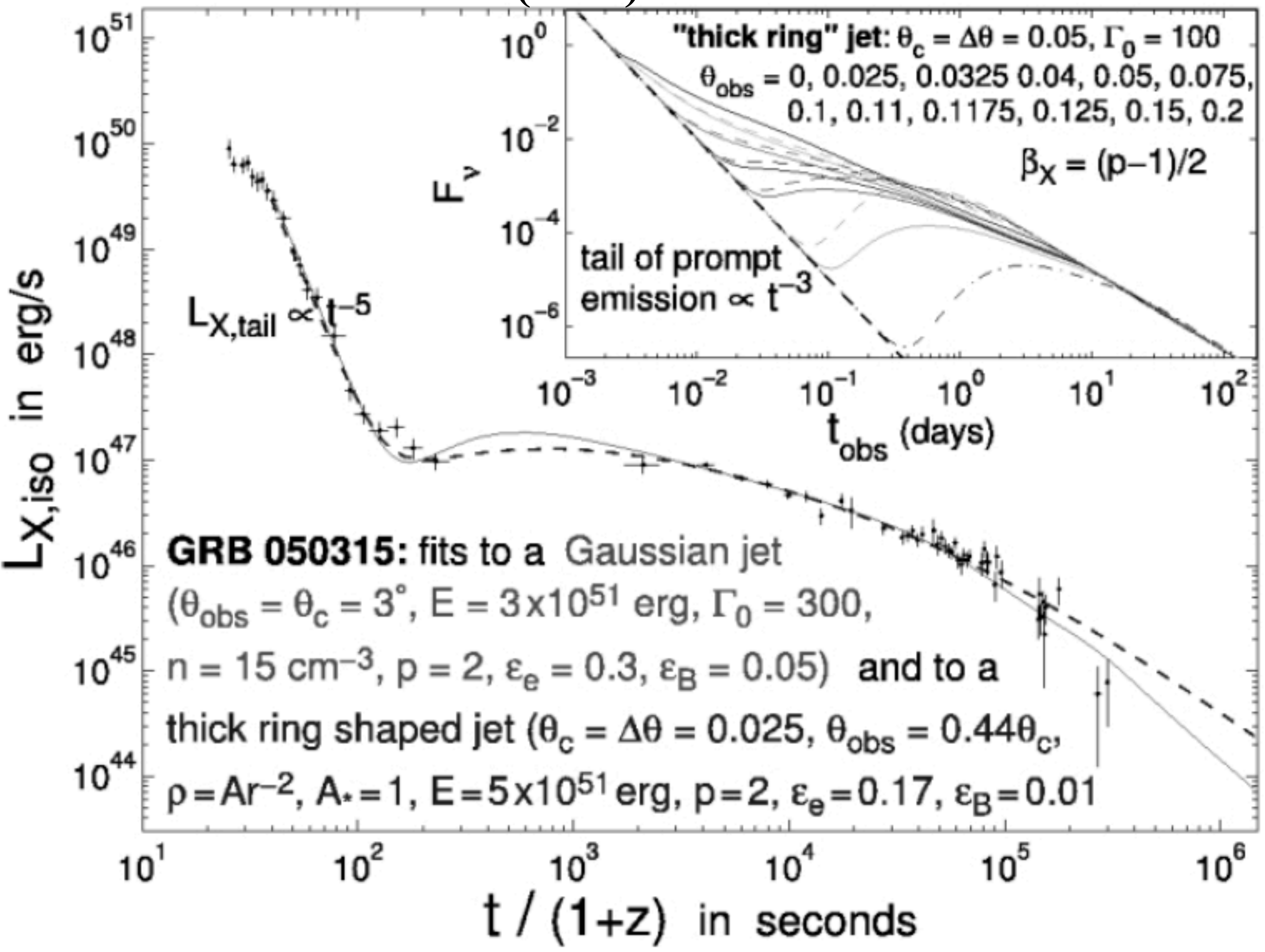
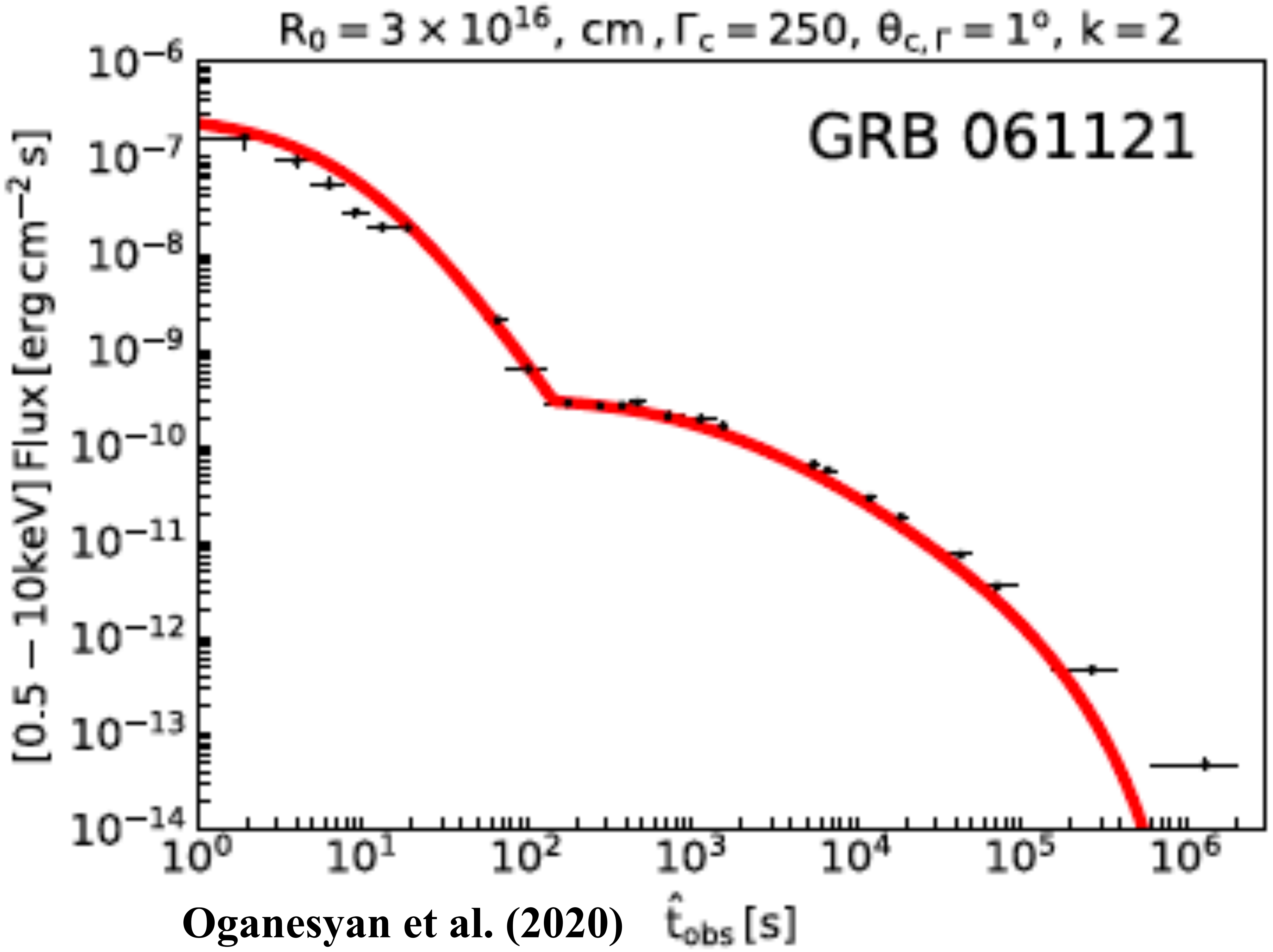
AFTERGLOW SHALLOW DECAY

Structured jet observed (slightly) off-axis

Eichler & Granot (2006)



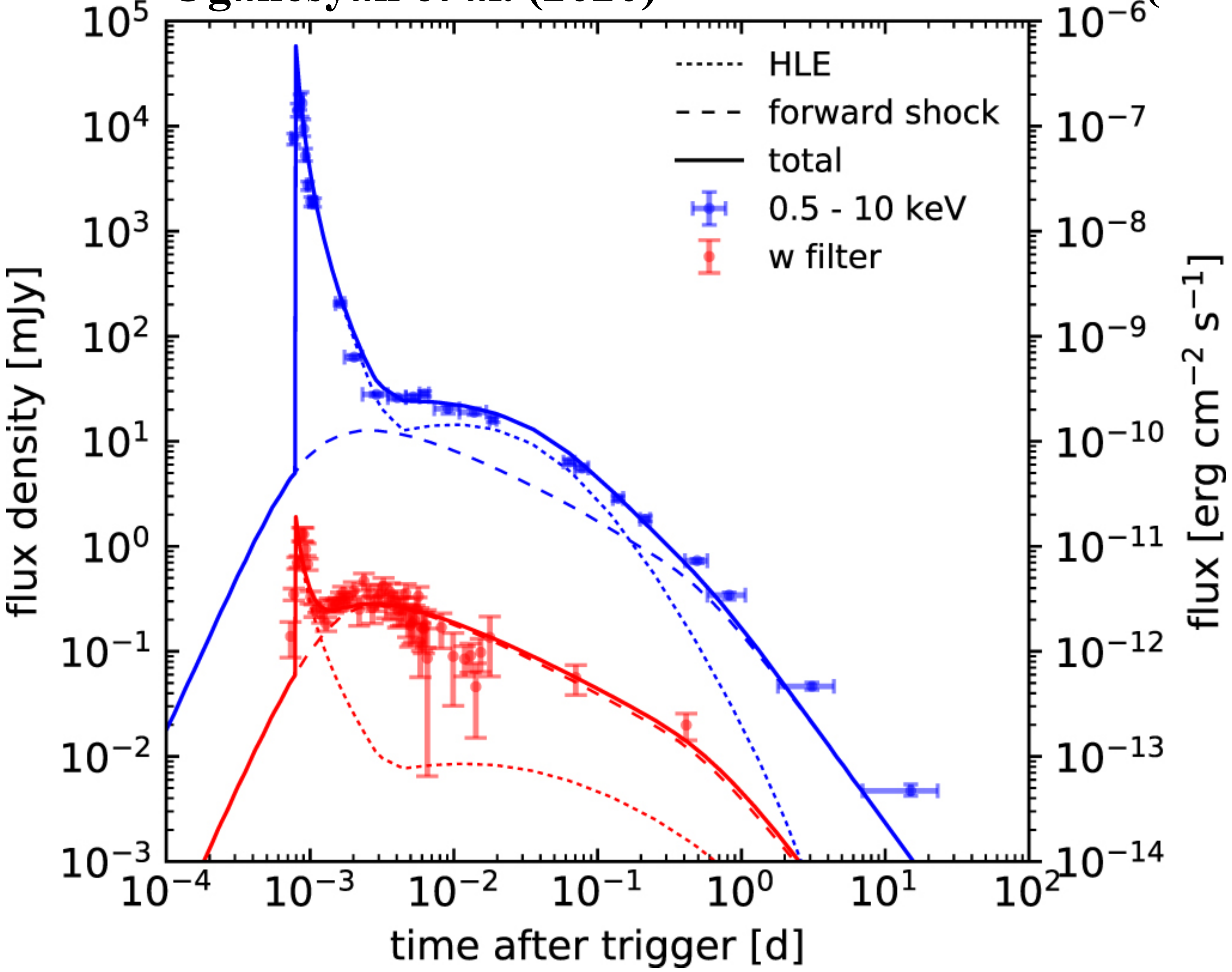
Wide-angle emission towards on-axis observer



Oganesyan et al. (2020)

AFTERGLOW SHALLOW DECAY

Oganesyan et al. (2020) see also Ascenzi et al. (2020)



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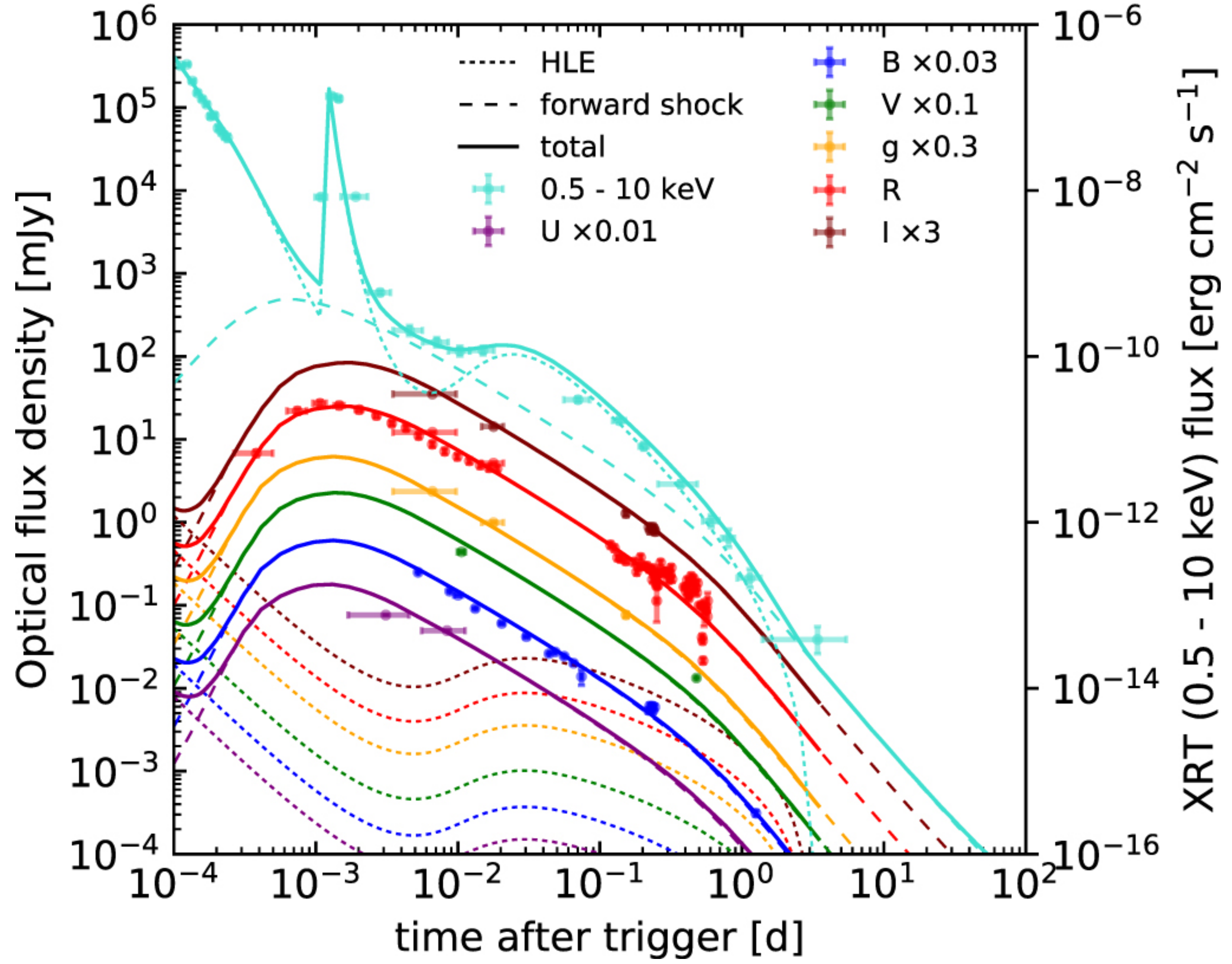
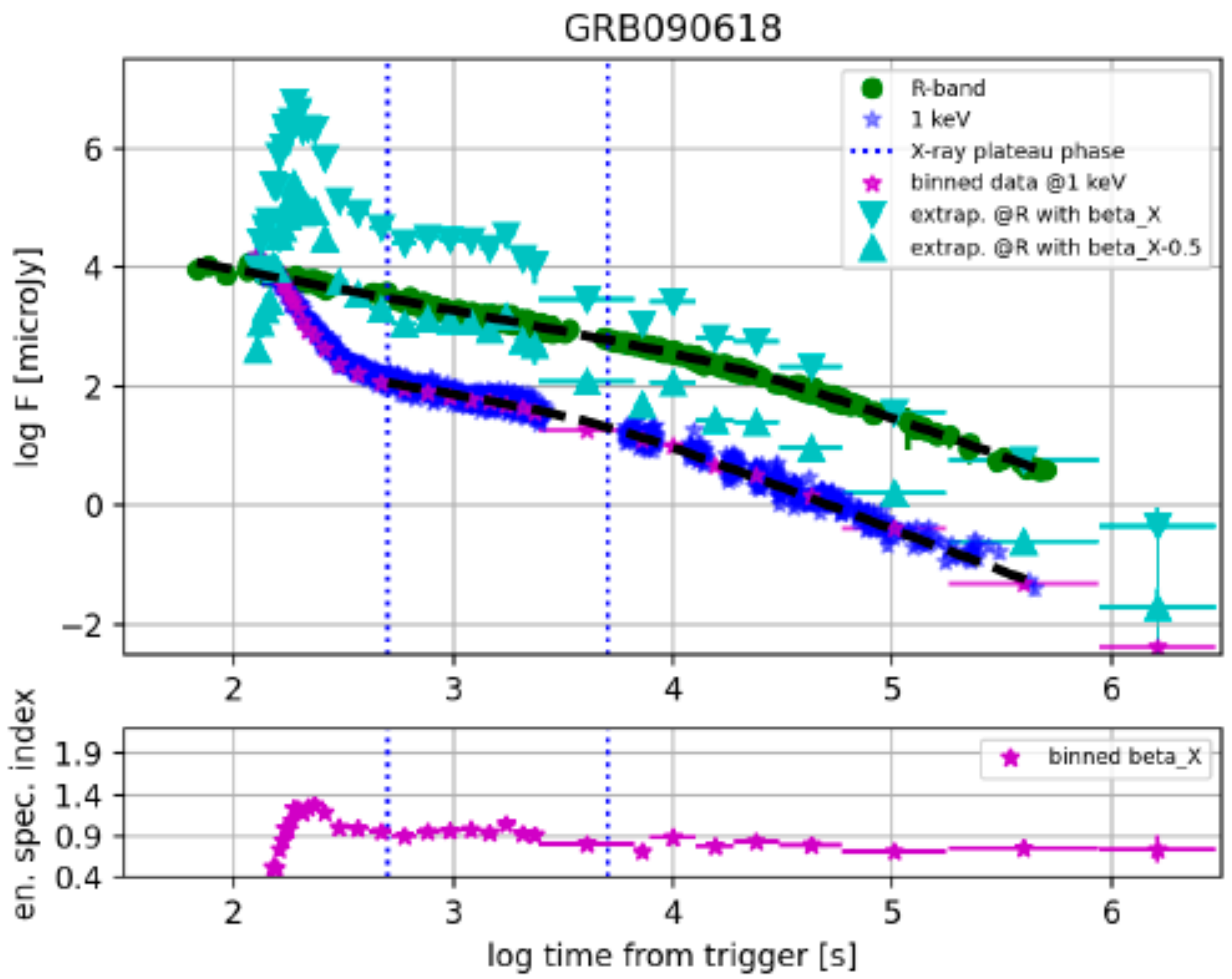


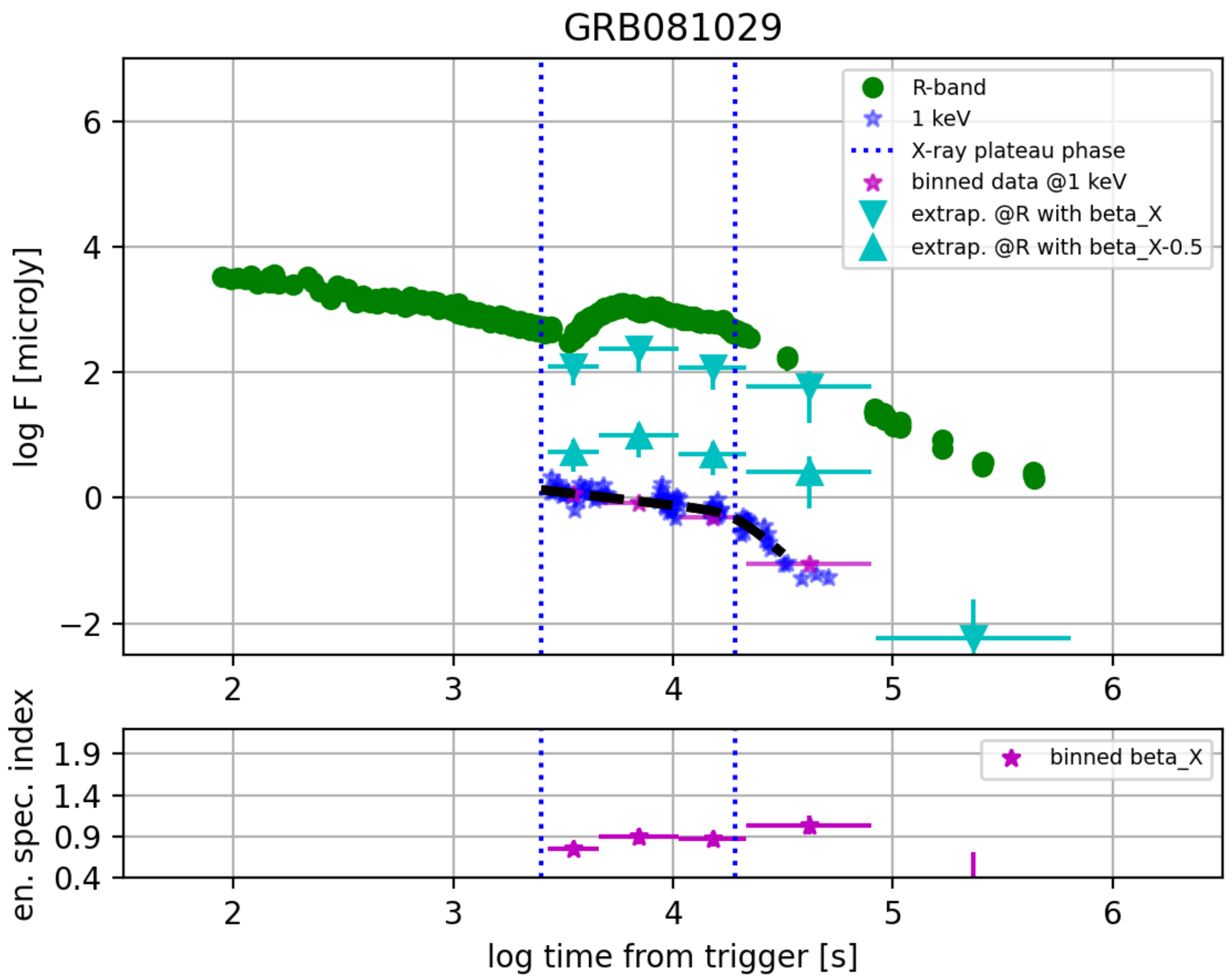
A specific feature of this scenario is the expectation of chromatic behaviour in the shallow phase
Two distinct active regions: (a) the X-ray emitting prompt region and (b) the afterglow-producing external shock (dominating in the optical)

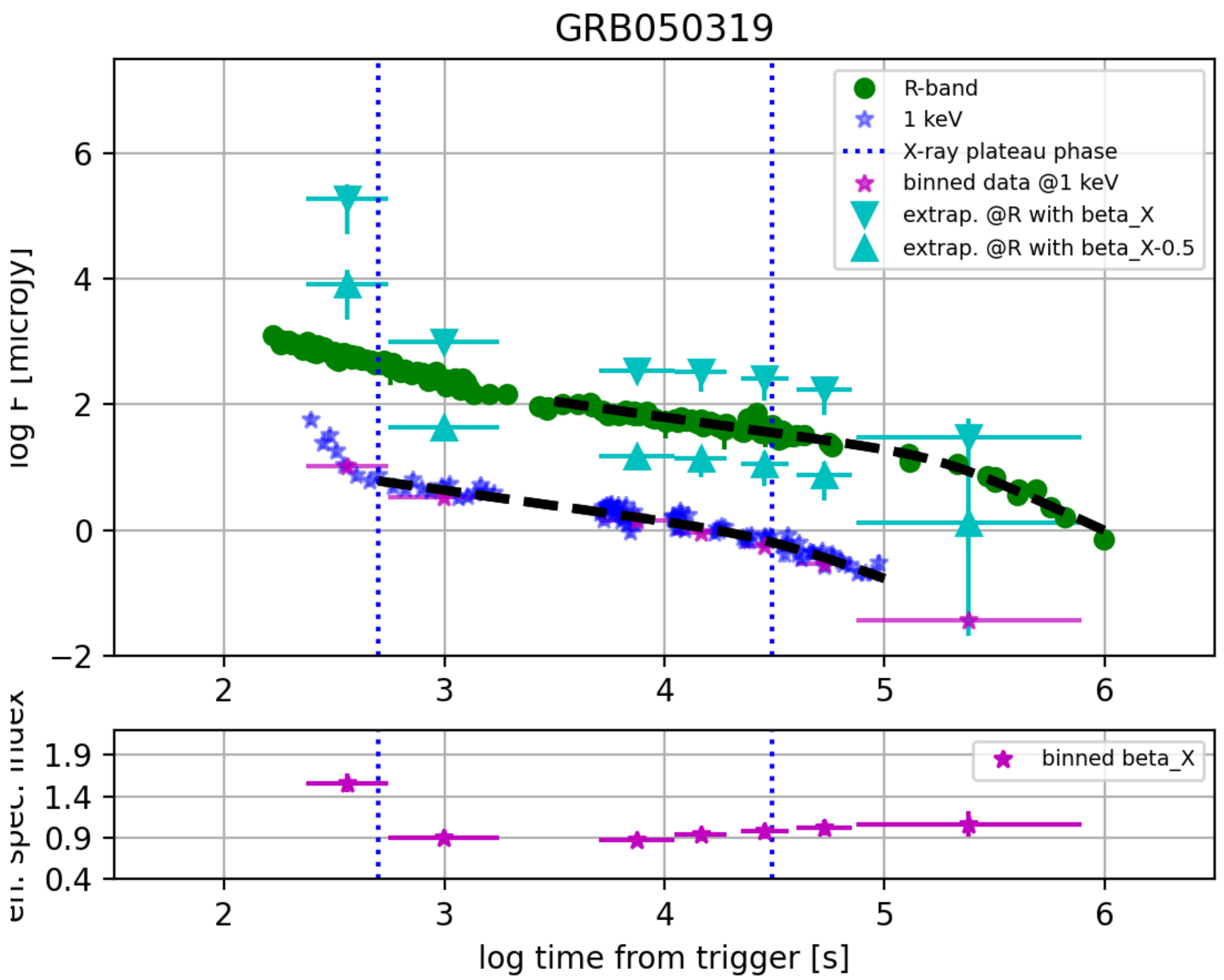
AFTERGLOW SHALLOW DECAY

Multi-band study of ``plateaus”

Stratta et al. 2022







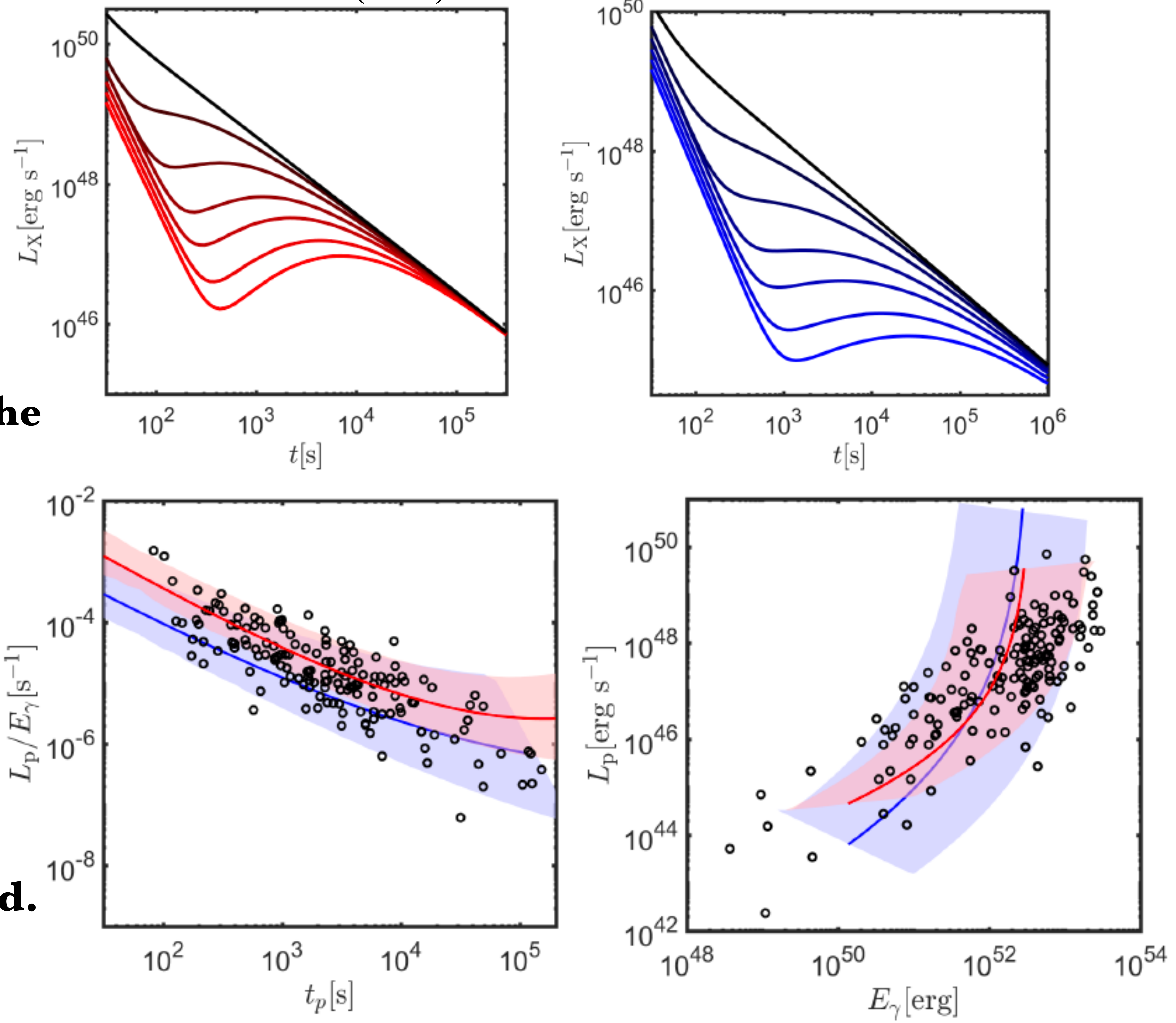
3 out of 29 GRBs have strictly chromatic behaviour, i.e. the optical data are above (or below) the extrapolation of the X-ray spectrum.

At face value, it favours a single emission region in most cases

Still ongoing work to enlarge the sample and refine the study

AFTERGLOW SHALLOW DECAY

Beniamini et al. (2020)



Structured jet observed (slightly) off-axis

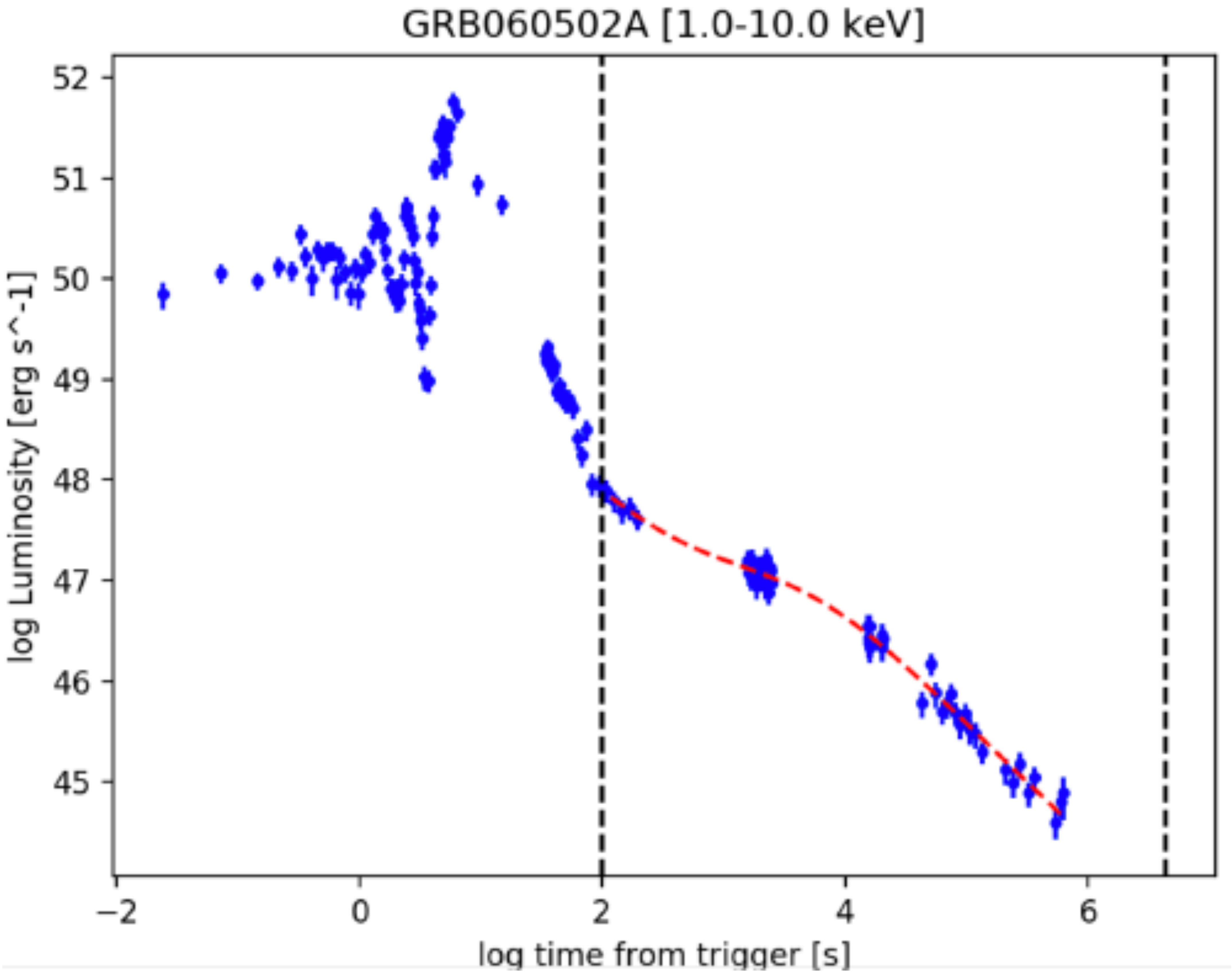
A correlation between prompt energy and plateau properties is a specific prediction

Some fine-tuning of the (many) model parameters can provide agreement with the data

Need to check self-consistency of the required model parameters at the level of the population.
There are some issues there!

No obvious L_p vs. t_p correlation is predicted.
Is it a model's fault or just forgotten?

``MAGNETAR” CENTRAL ENGINE REVIVED



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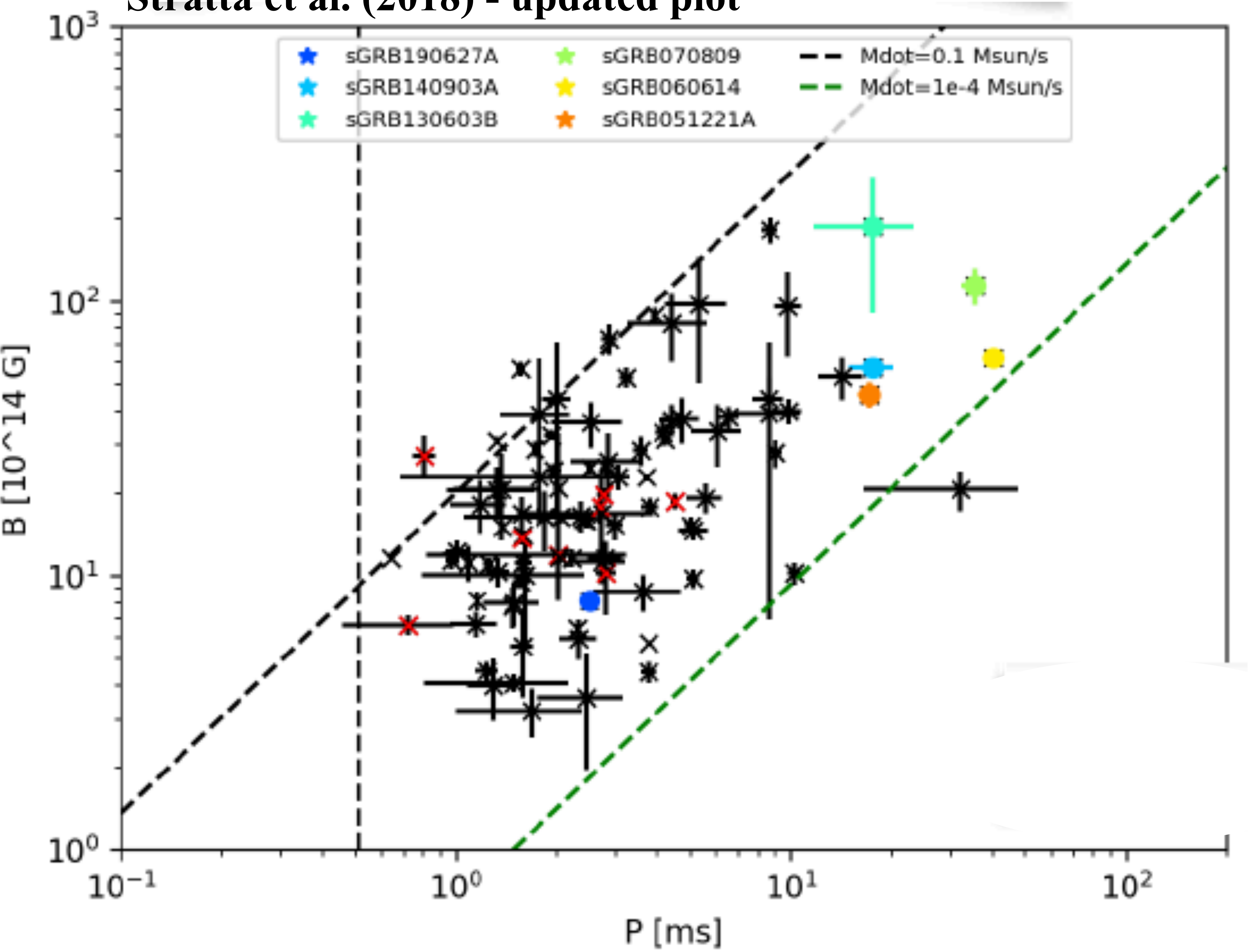

Stratta et al. (2018) - updated plot

A correlation $B \propto P^{7/6}$ is reminiscent of the spin-up line for accreting NS

$$\frac{B}{10^{14}\ \mathrm{G}} = 10 \times \left(\frac{P}{\mathrm{ms}}\right)^{7/6} \left(\frac{\dot{M}}{0.01}\right)^{1/2} R_{10\mathrm{km}}^{-3}\ M_{1.4}^{5/6}$$

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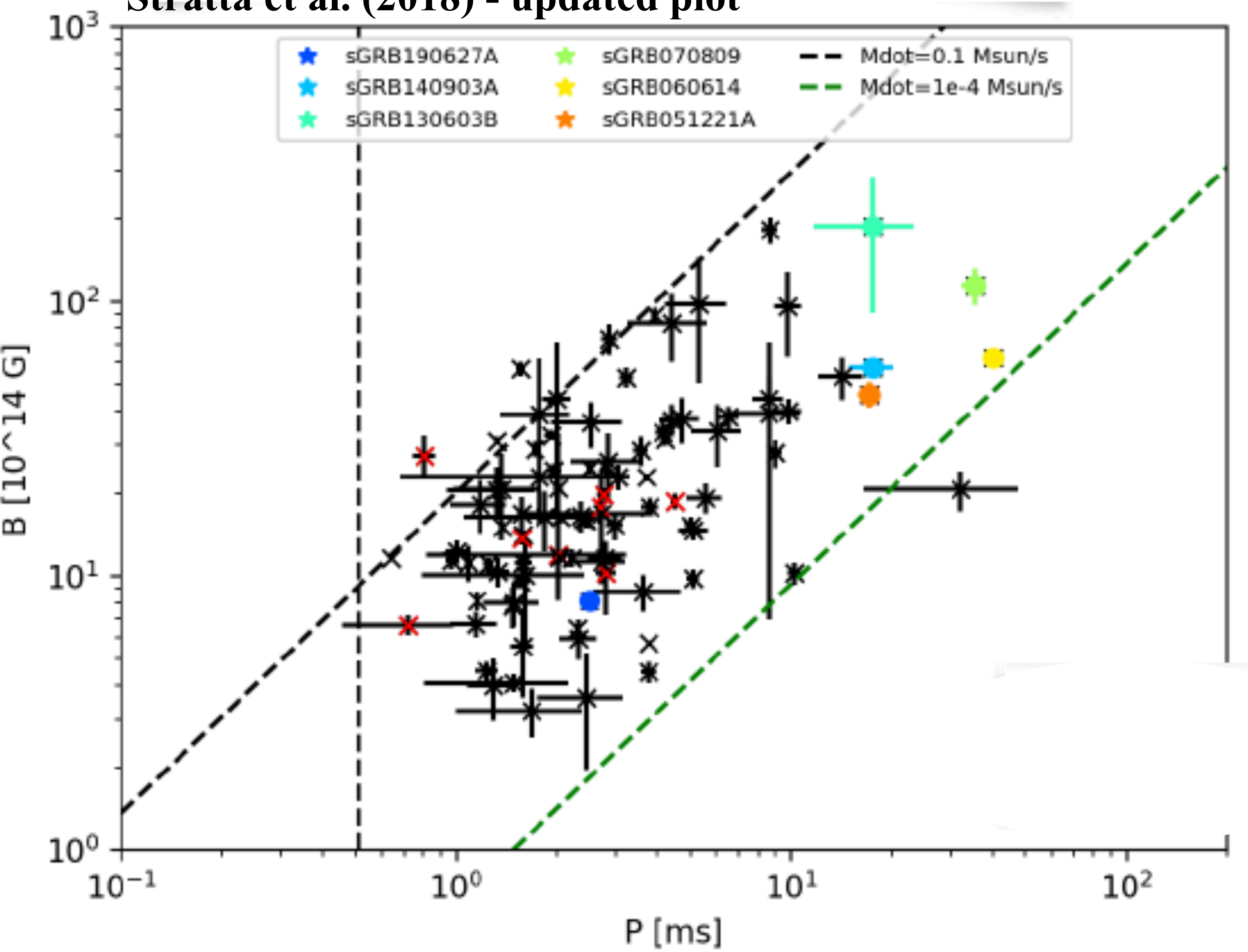

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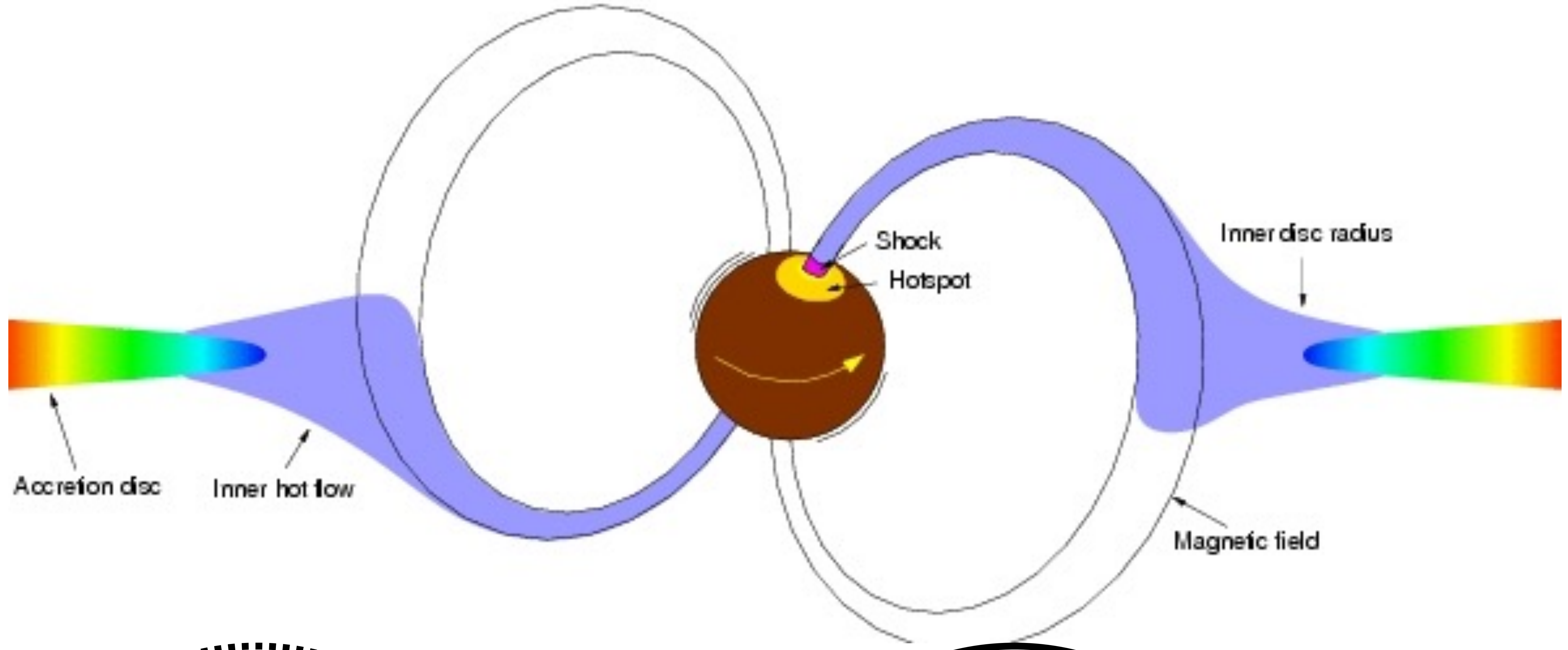
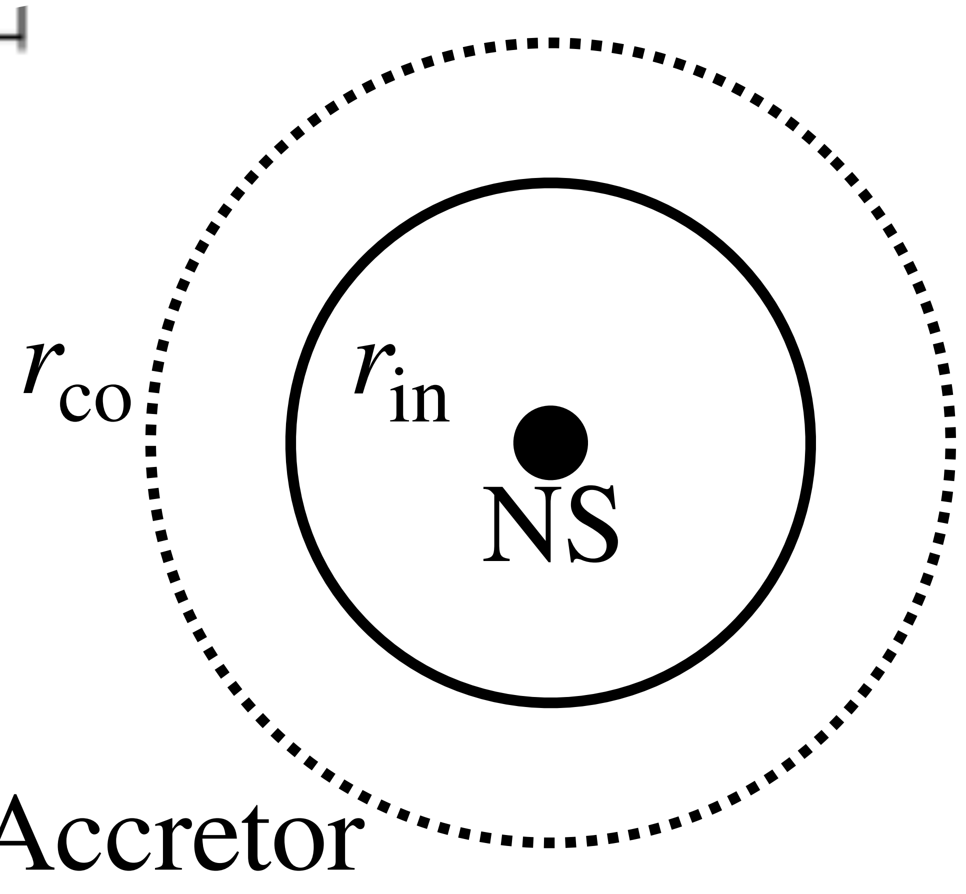
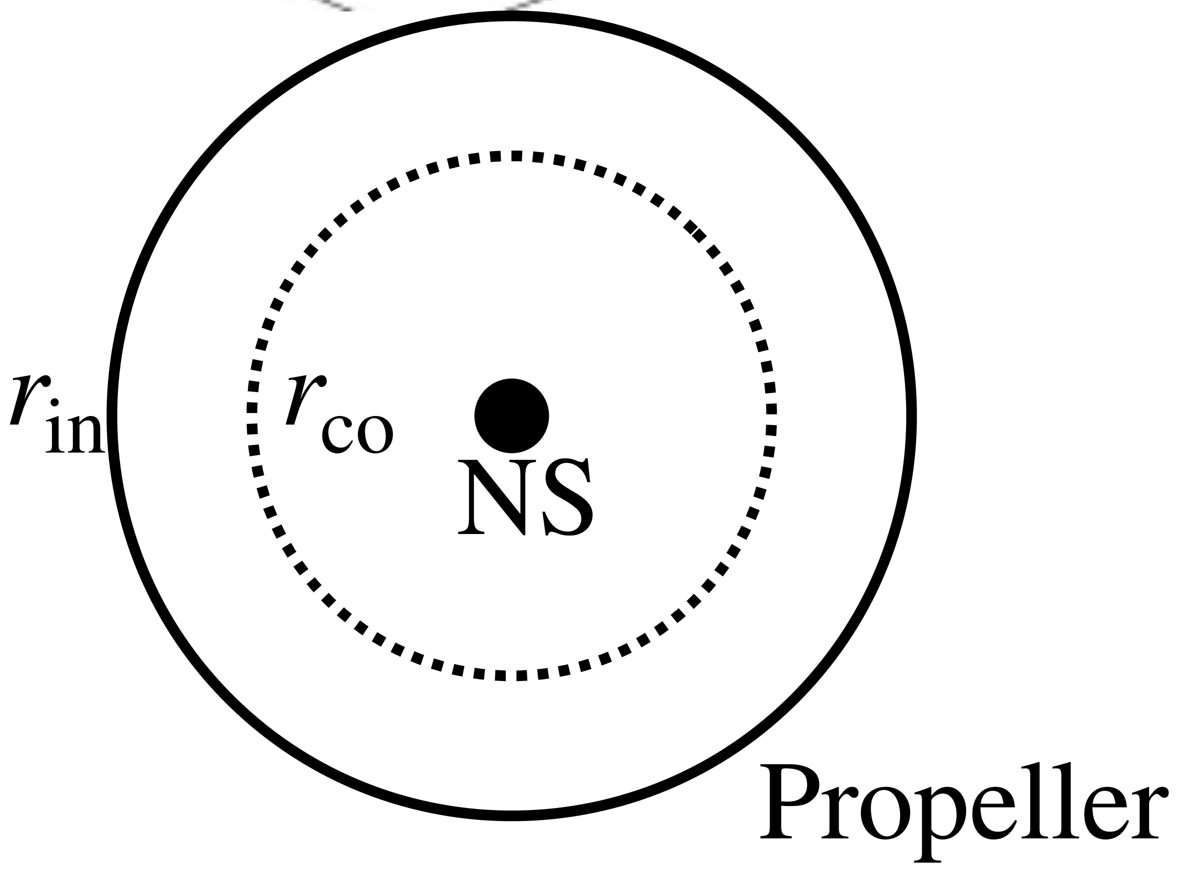




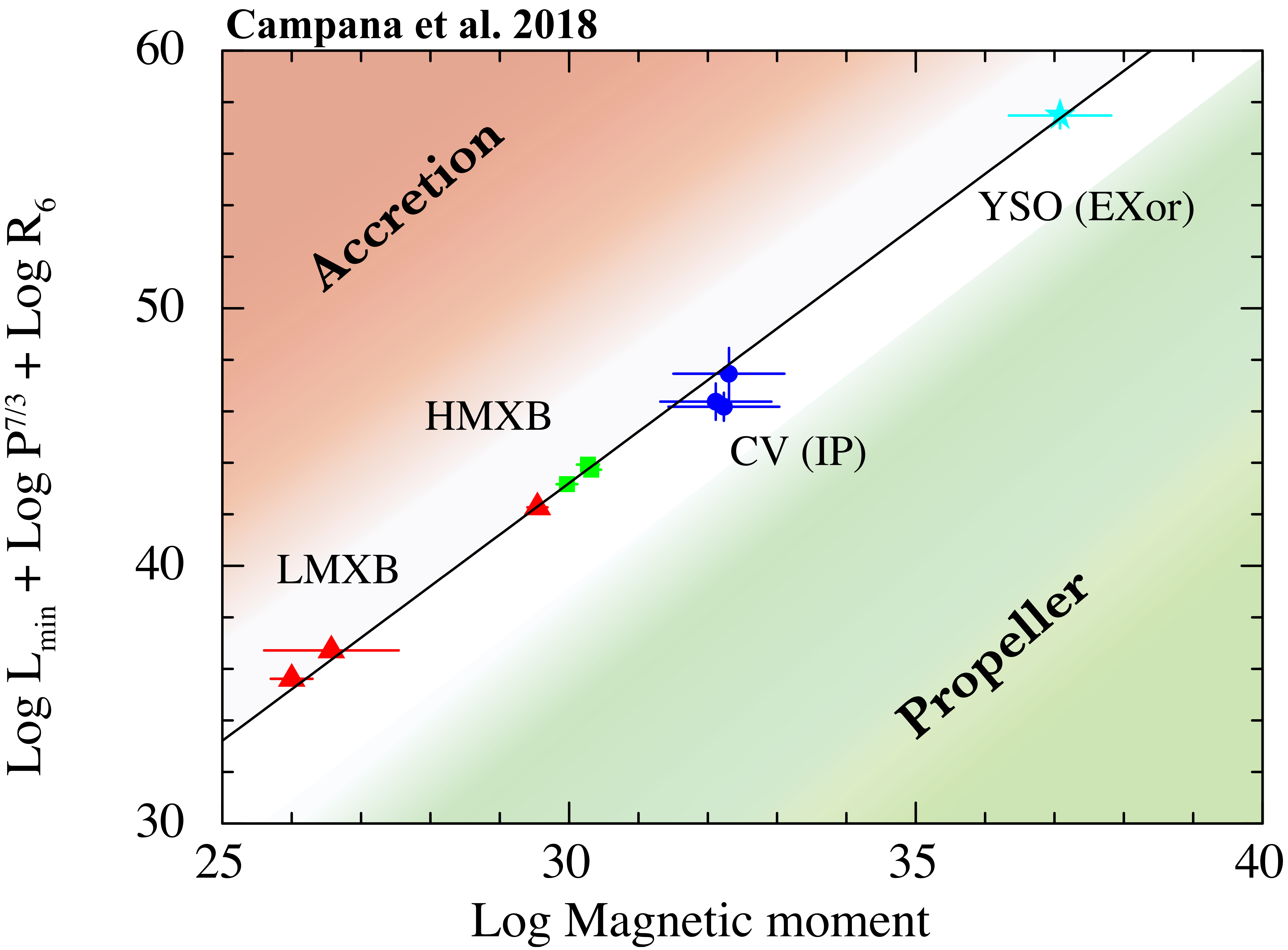
Accretor



Propeller

see Bernardini et al. (2013) for a similar idea in a different context

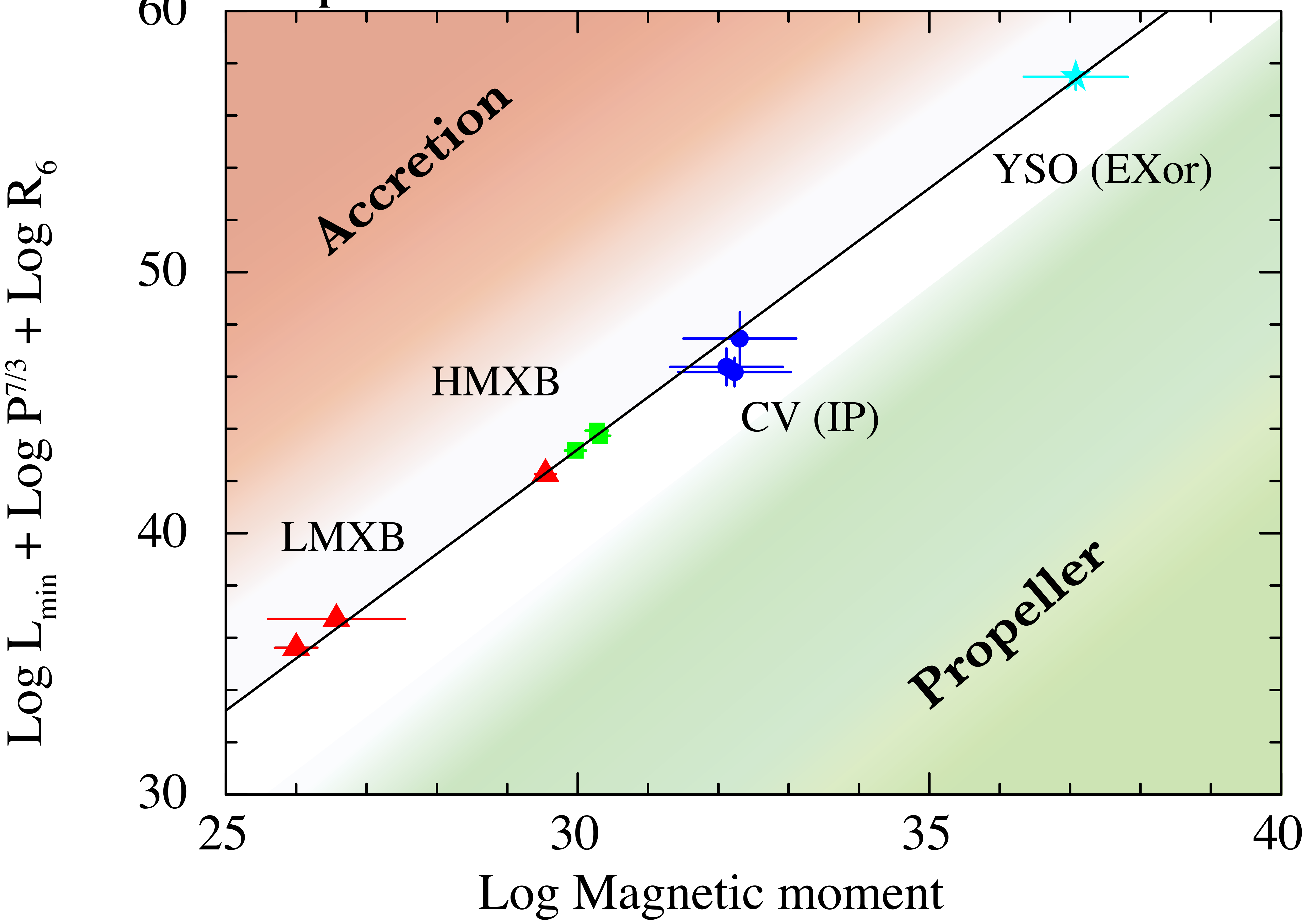
``MAGNETAR" CENTRAL ENGINE REVIVED



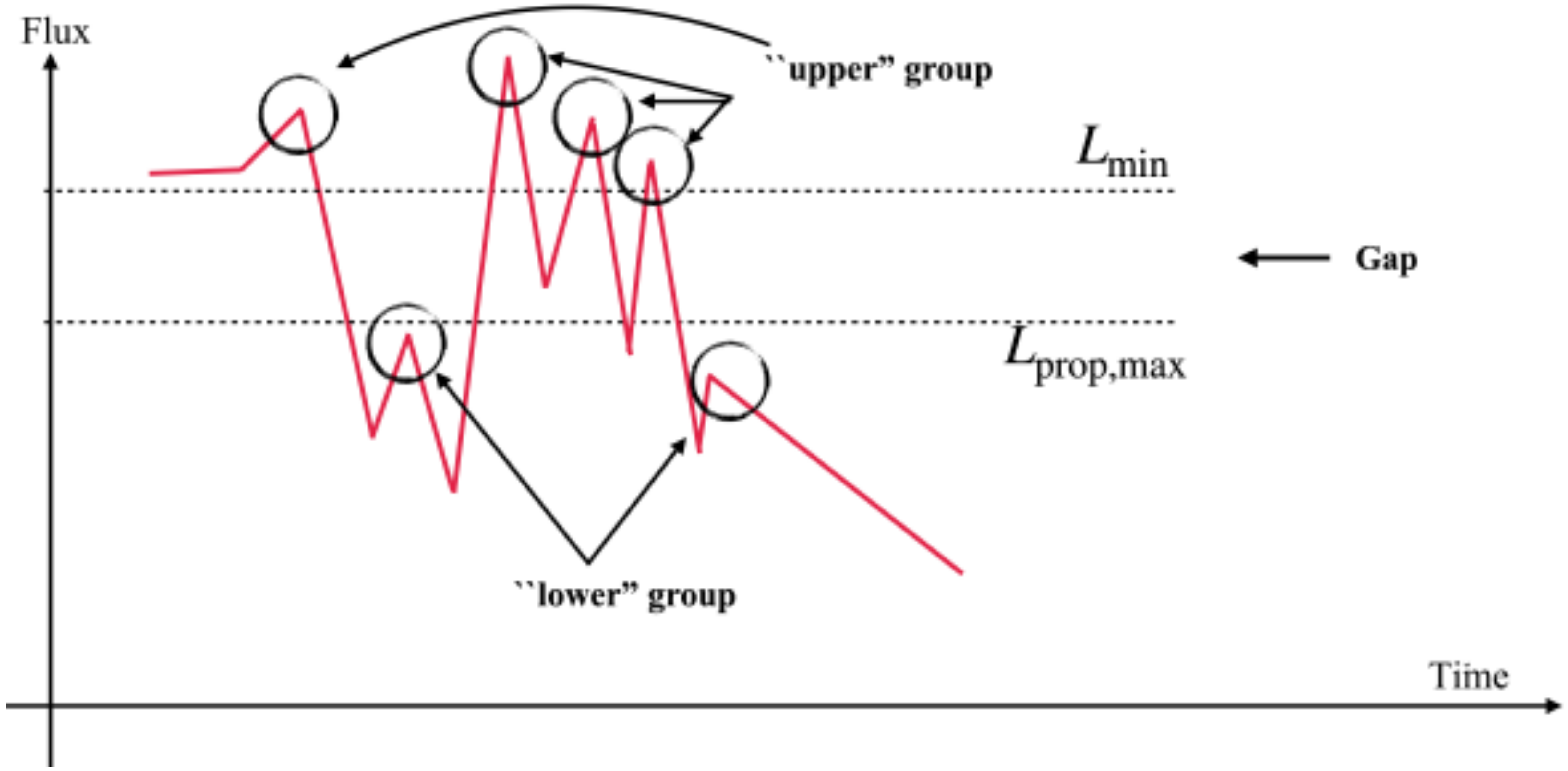
$$L_{\min} = 1.4 \times 10^{37}\ \mathrm{erg\ s^{-1}}\ \epsilon_r \left(\frac{\mu}{10^{30}}\right)^2 P^{7/3} \left(\frac{\xi}{0.5}\right)^{7/2} R_{10\mathrm{Km}}\ M_{1.4}^{-2/3}$$

``MAGNETAR” CENTRAL ENGINE REVIVED

Campana et al. 2018



Dall’Osso et al. 2022
(submitted)



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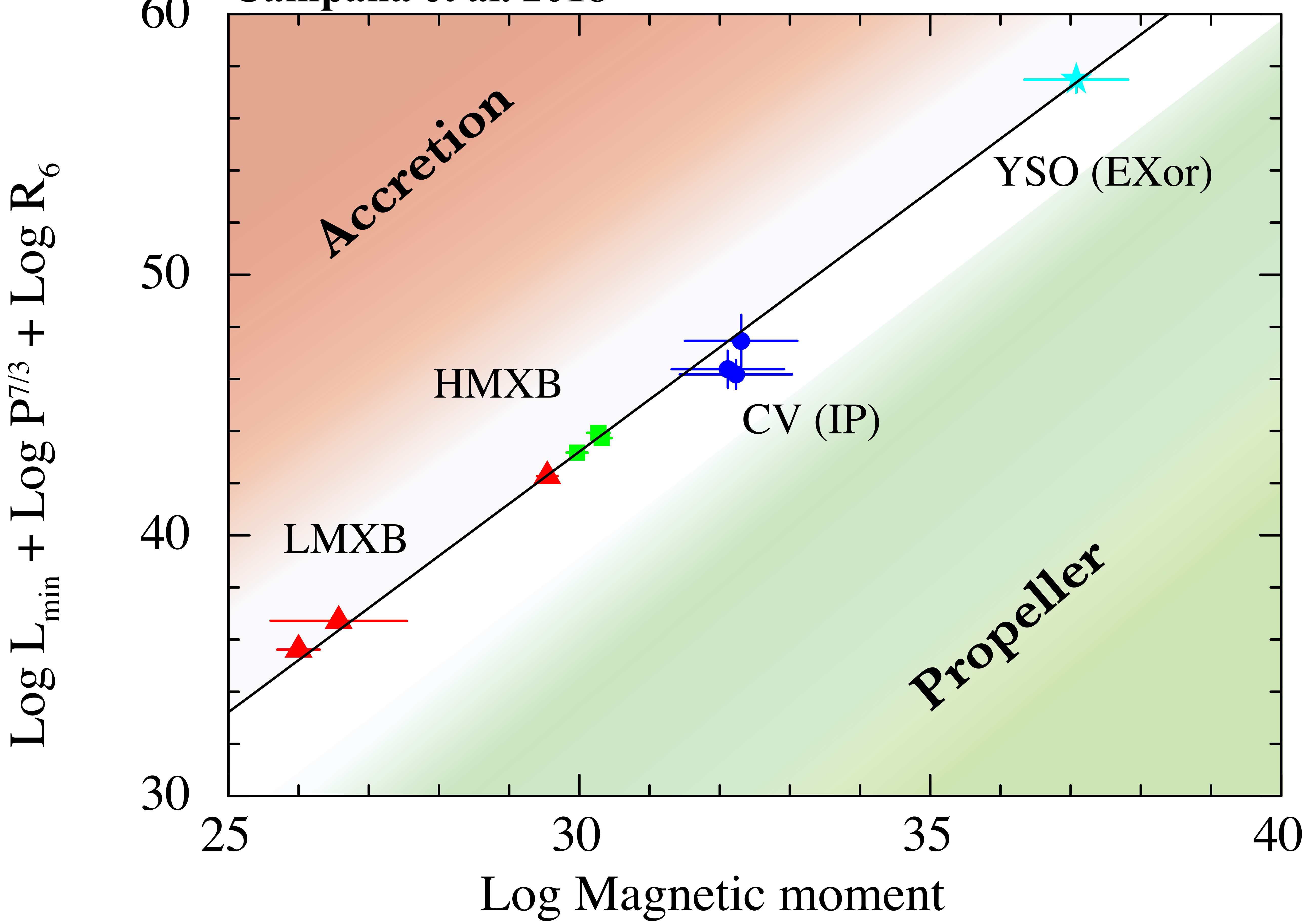

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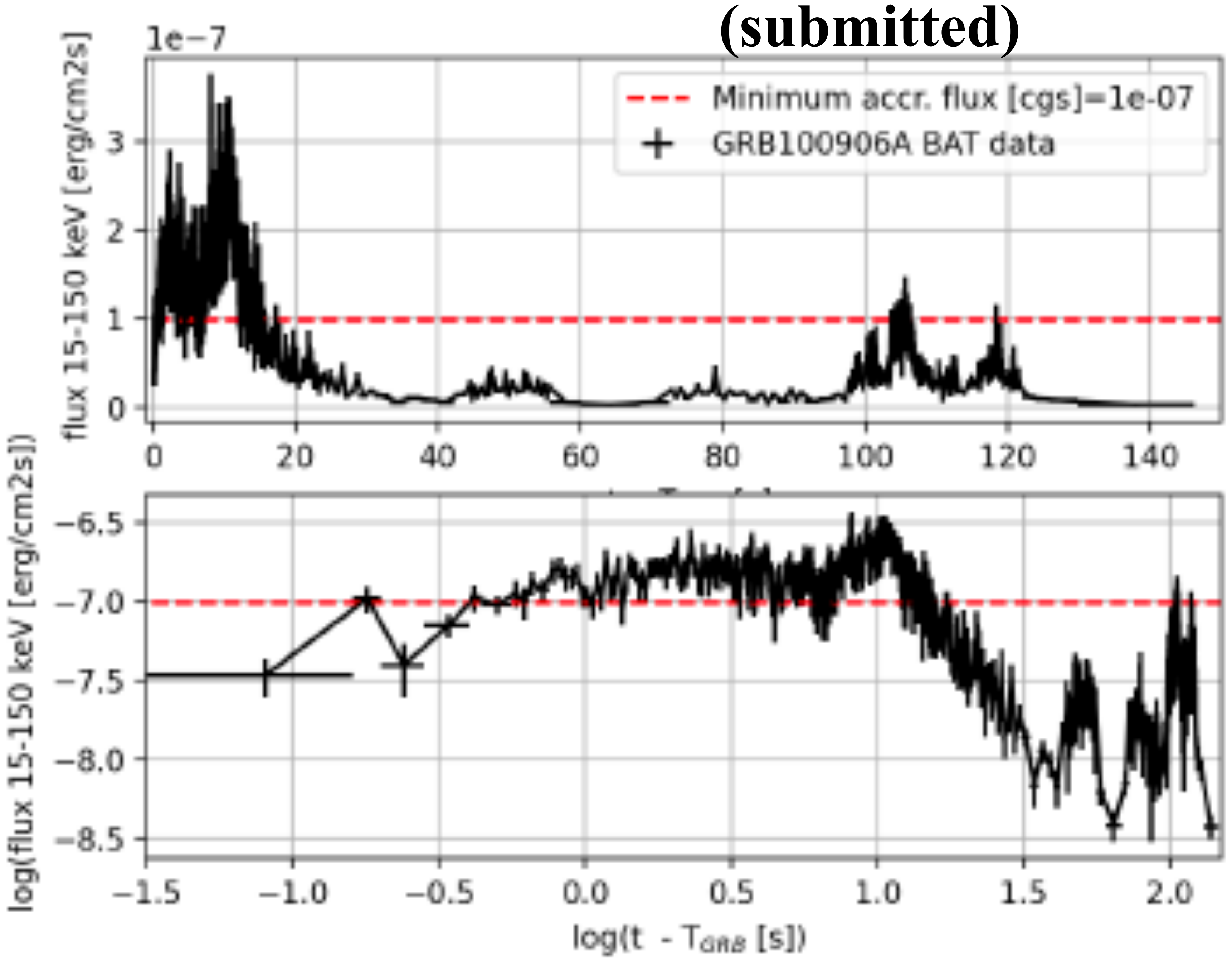
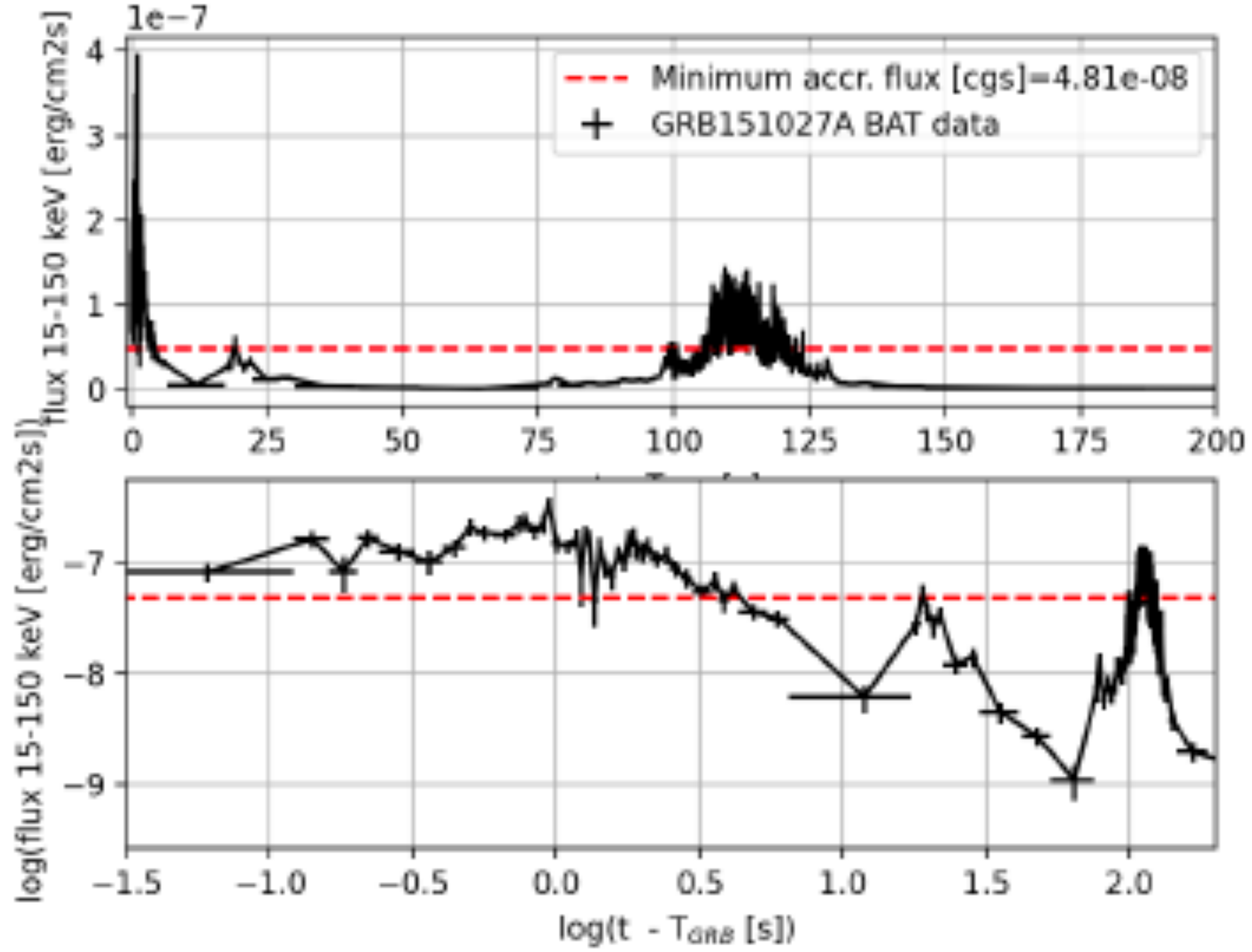
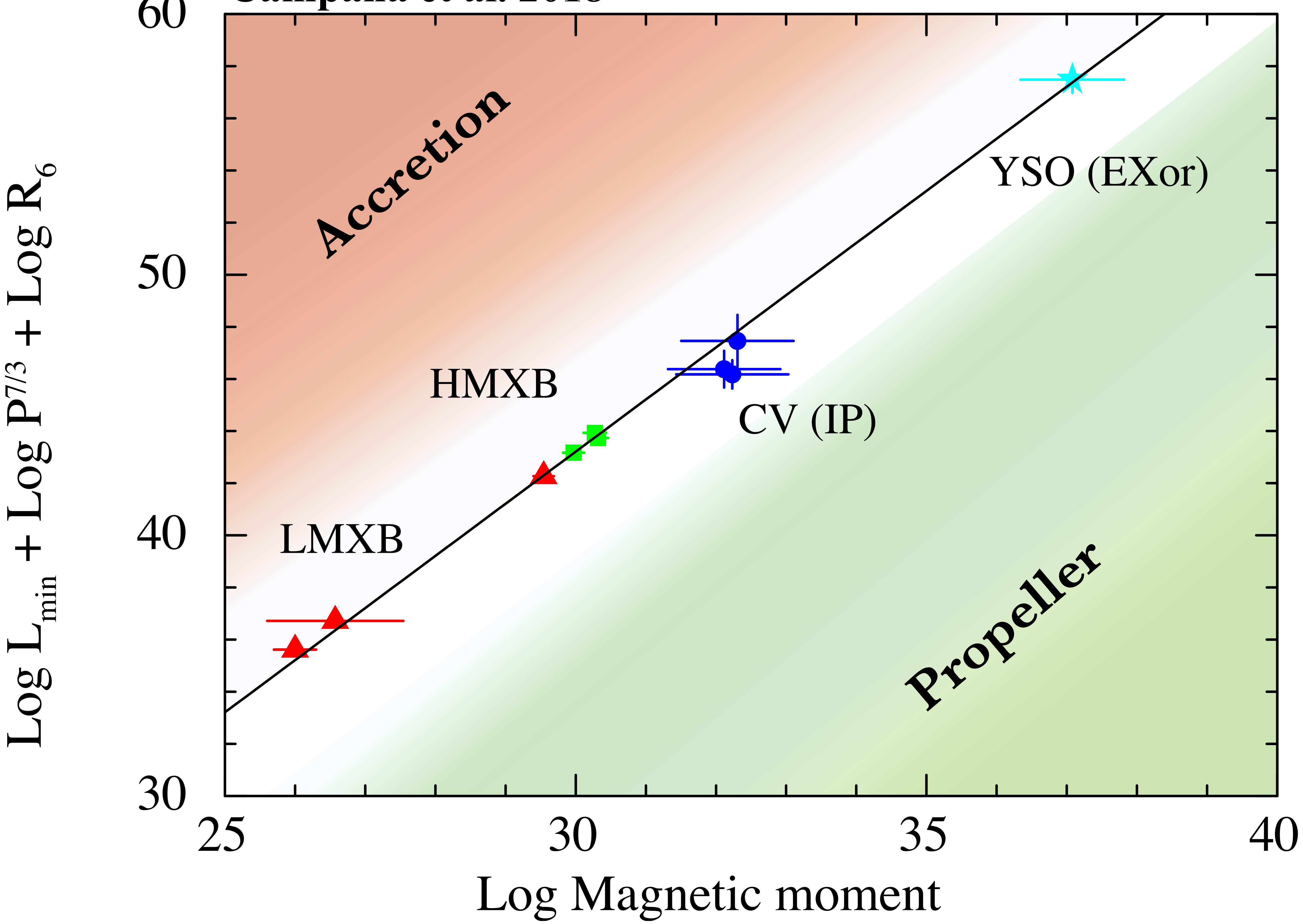
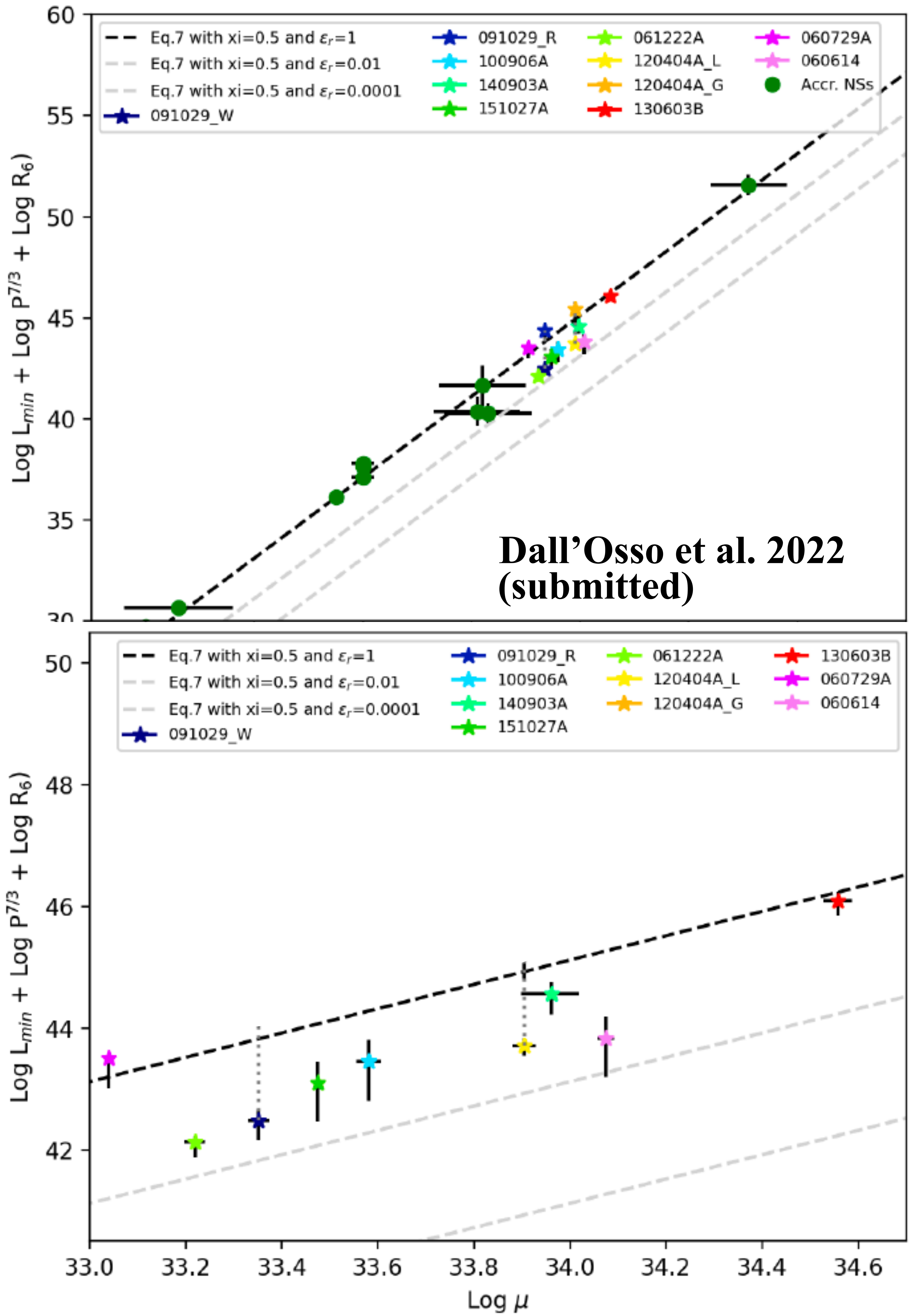




``MAGNETAR” CENTRAL EN

Campana et al. 2018





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CONCLUSIONS AND OUTLOOK

1. **NS central engines have enough energy to account for nearly all GRB prompt events observed**

2. **Magnetar stellar progenitors in the Galaxy have similarities with the expected progenitors of long GRBs: large ZAMS-masses $> 30\ M_\odot$, in young (< few Myr) OB associations with WR stars. Their estimated birth rate (~1 per 10^3 yrs per MWEG) > the beaming-corrected GRB rate**

3. **Highly-magnetized and STABLE NS may be formed in some BNS mergers. Exact fraction sensitive to the NS maximum mass, i.e. EoS of matter at supranuclear densities. Capability to launch relativistic jets needs to be checked.**

4. **Structured jets can produce a plateau phase if observed slightly off-axis (some may also be explained as wide-angle emission from on-axis jets). Need to check fit results at the population level (long-lived plateaus, L_p vs. t_p correlation, required range of model parameters)**

5. **Energy injection from a ms-spinning ``magnetar" can explain the main observed correlations, including a new one found in the framework of the propeller-accretor scenario. The range of implied model parameters is broadly consistent with the expected properties of the population**

CONCLUSIONS AND OUTLOOK

6. **A wide variety of observed properties possibly hints at intrinsic differences in spite of the broad similarity of light-curve shapes: a mix of different models?**

7. **Highly desired: check the consistency of the required model parameters in the structured jet scenario**

8. **Highly required: extension of the sample of GRBs for which the accretor/propeller relation can be verified**

9. **One more wish: models of structured jets with energy injection**