X-ray flare and plateau as a tool for probing the GRB central engine

Reporter: TianCi Zheng (郑天赐)

Collaborator： Da-Ming Wei (PMO), Xiang-Gao Wang (GXU), Long Li (UCTS),

Le Zou (XTU), Yun Wang (PMO), Hao Zhou (PMO)

Purple Mountain Observatory, CAS, Nanjing

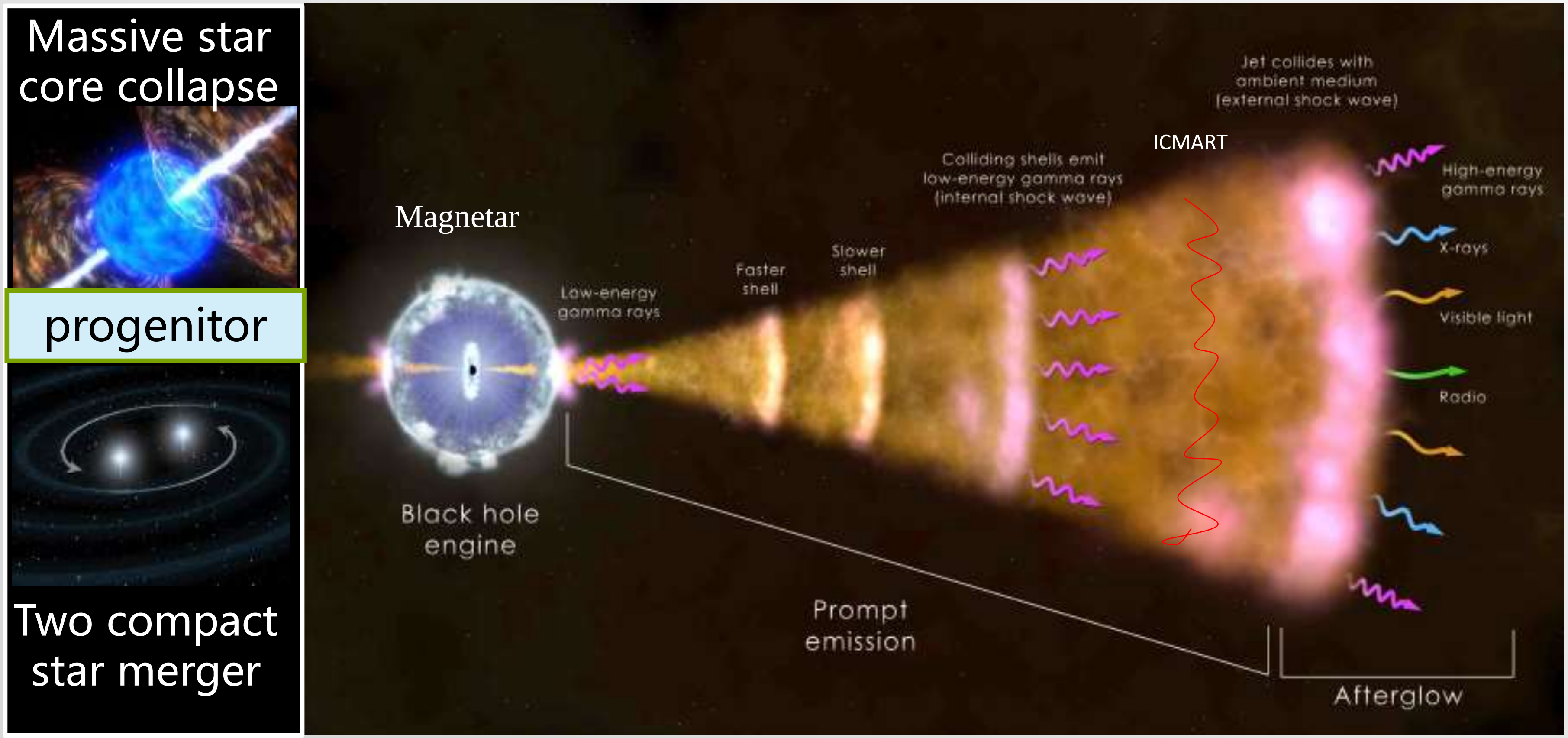
University of Science and Technology of China, Hefei

May. 21, 2024, The 3rd Nanjiung GRB conference, Suzhou

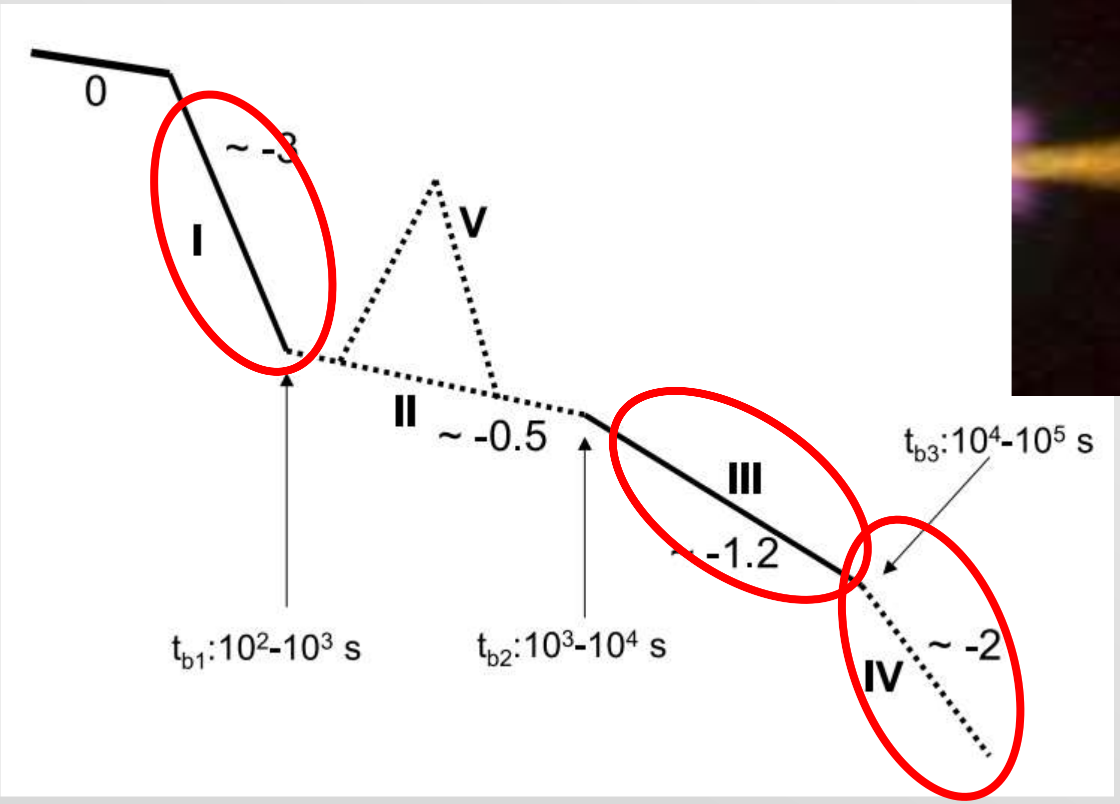
Tianci Zheng’s homepage

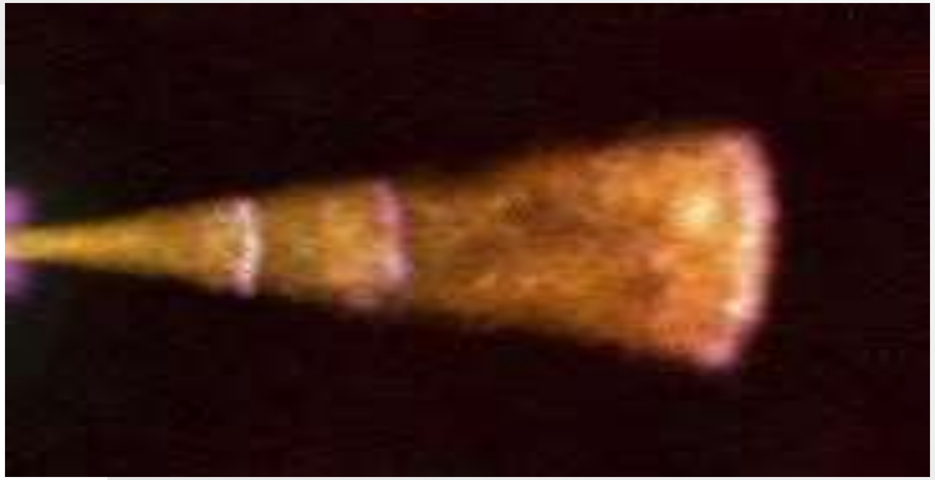
Background

The basic picture of GRBs



The connection between the afterglow and the central engine activities



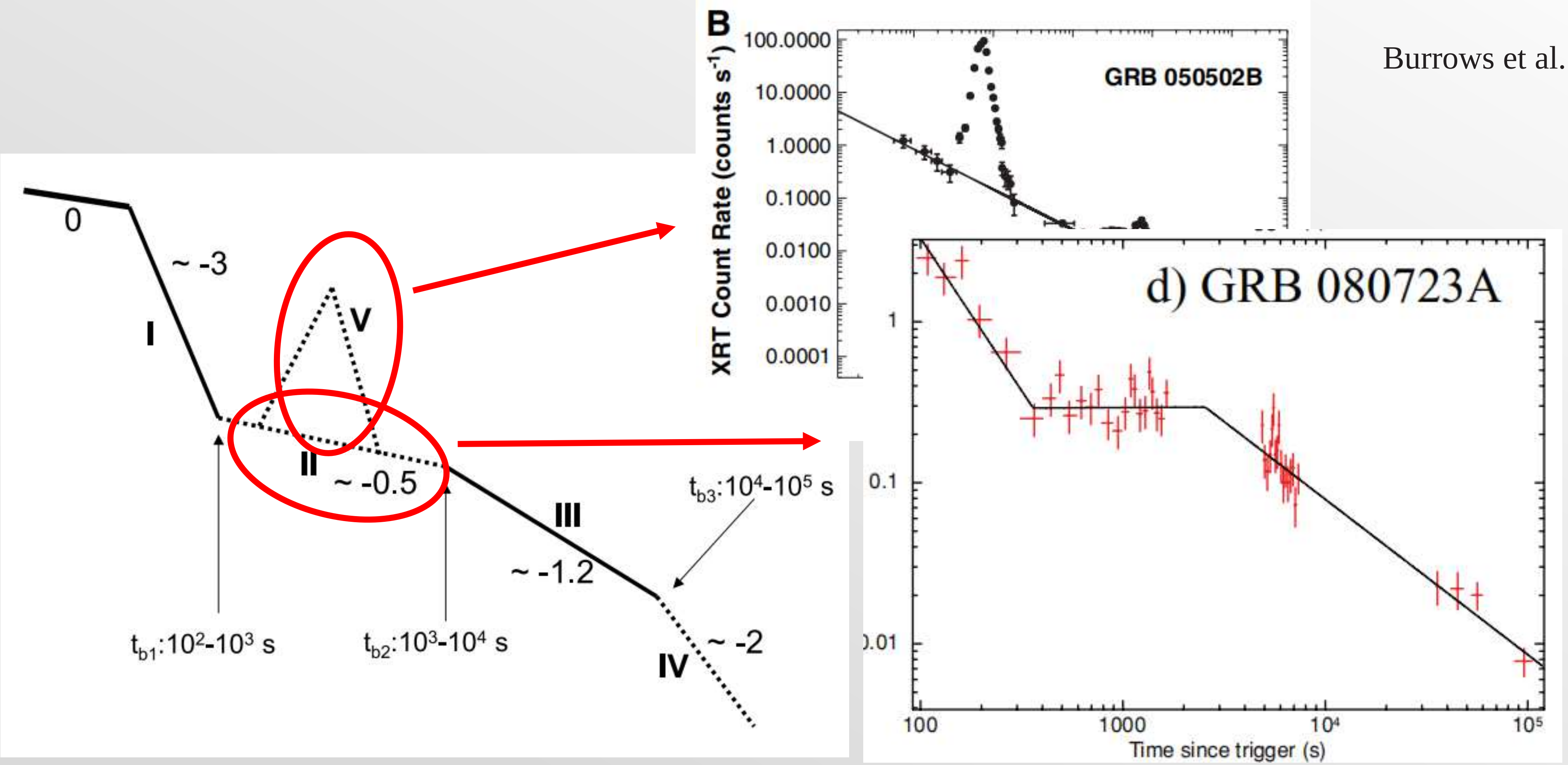


Zhang et al. 2006; Nourse et al. 2006

Rapid decay, normal decay, and jet break → jet

Sari et al. 1998; Huang et al. 1999

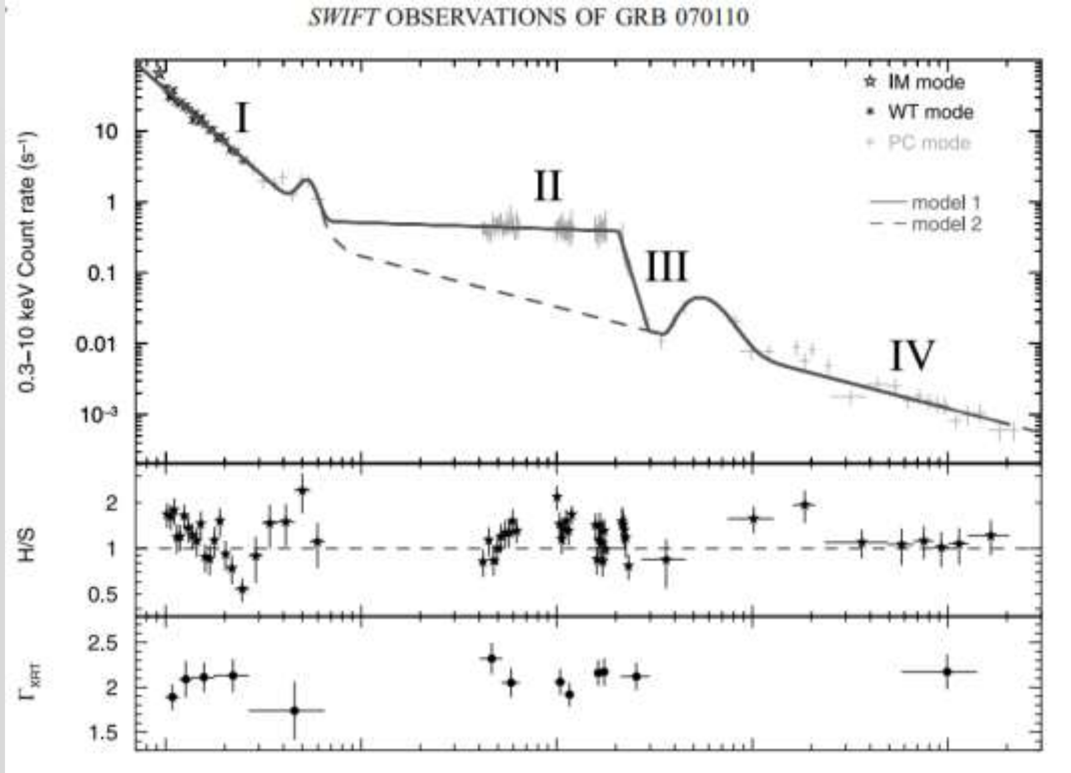
Burrows et al. 2005

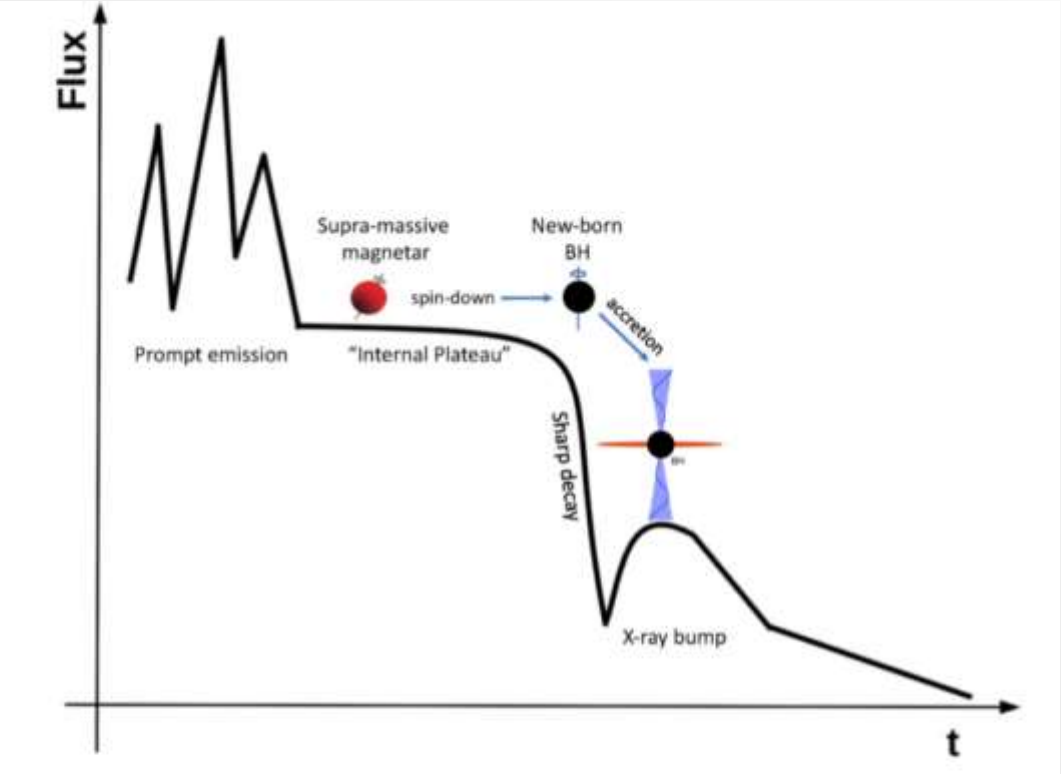


Evans et al. 2009

X-ray flare and plateau → long-lasting central engine

Plateau and the magnetar central engine

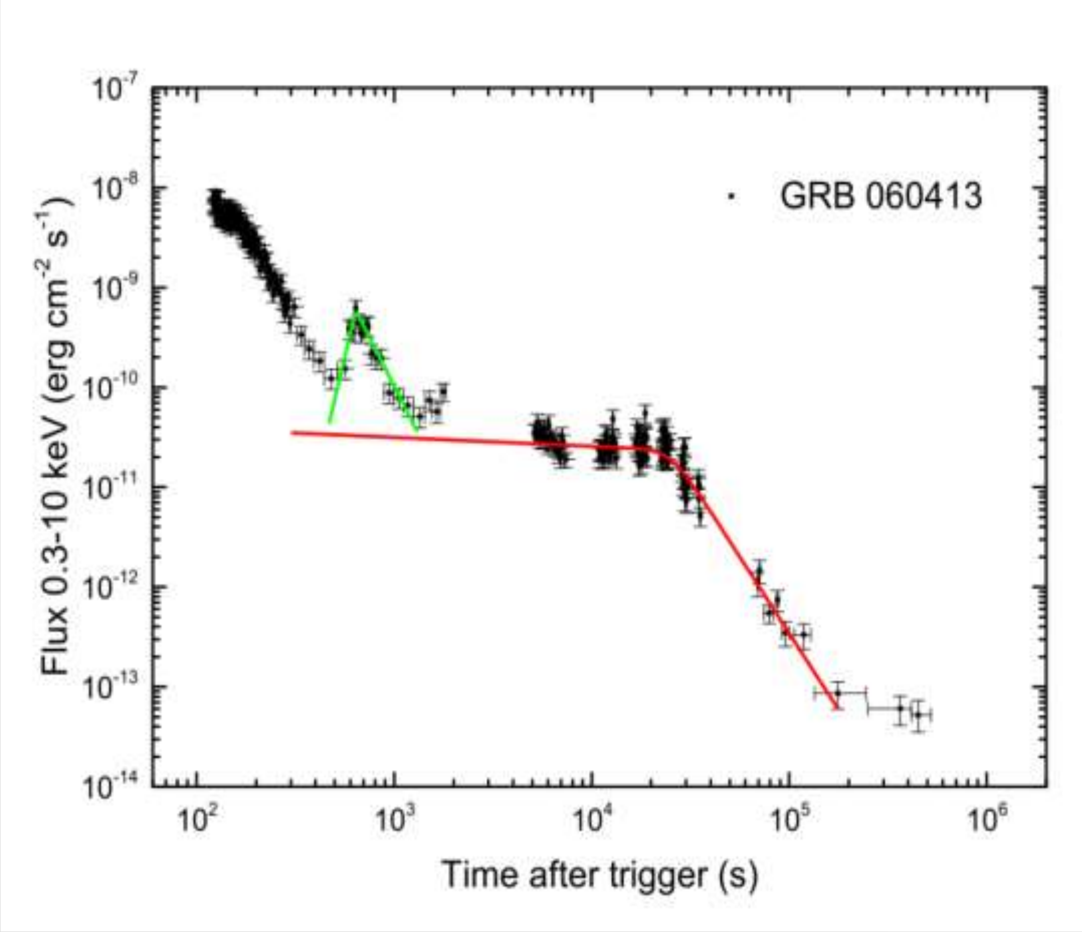




X-ray plateau (followed by sharp decay) → Magnetar central engine

e.g., Dai & Lu 1998; Zhang & Mészáros 2001; Troja et al. 2007,
Chen et al. 2017 etc.

X-ray flares rising upon the magnetar plateau give an implication for magnetar-disk configuration
(Zheng et al. 2021, RAA, 21, 300)



Propellor effect of Magnetar

Surrounding Material forms a magnetosphere with the affection of the magnetic field. The magnetosphere protects the material from fallback onto the surface of the magnetar.

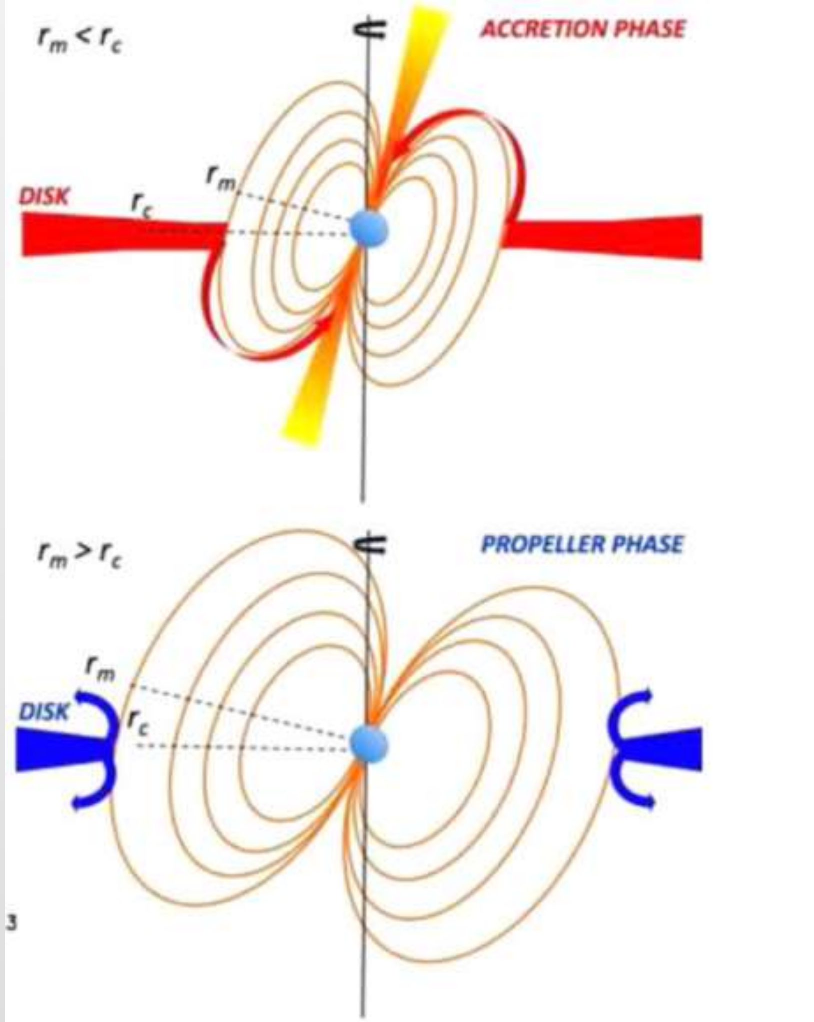
For comparable ram pressure **P**mag and magnetic pressure **P**ram

$$P_{\mathrm{mag}} = \frac{\mu^2}{2\mu_0 r^6}.$$

$$P_{\mathrm{ram}} = \frac{\dot{M}}{8\pi}\left(\frac{2GM_*}{r^5}\right)^{1/2}.$$

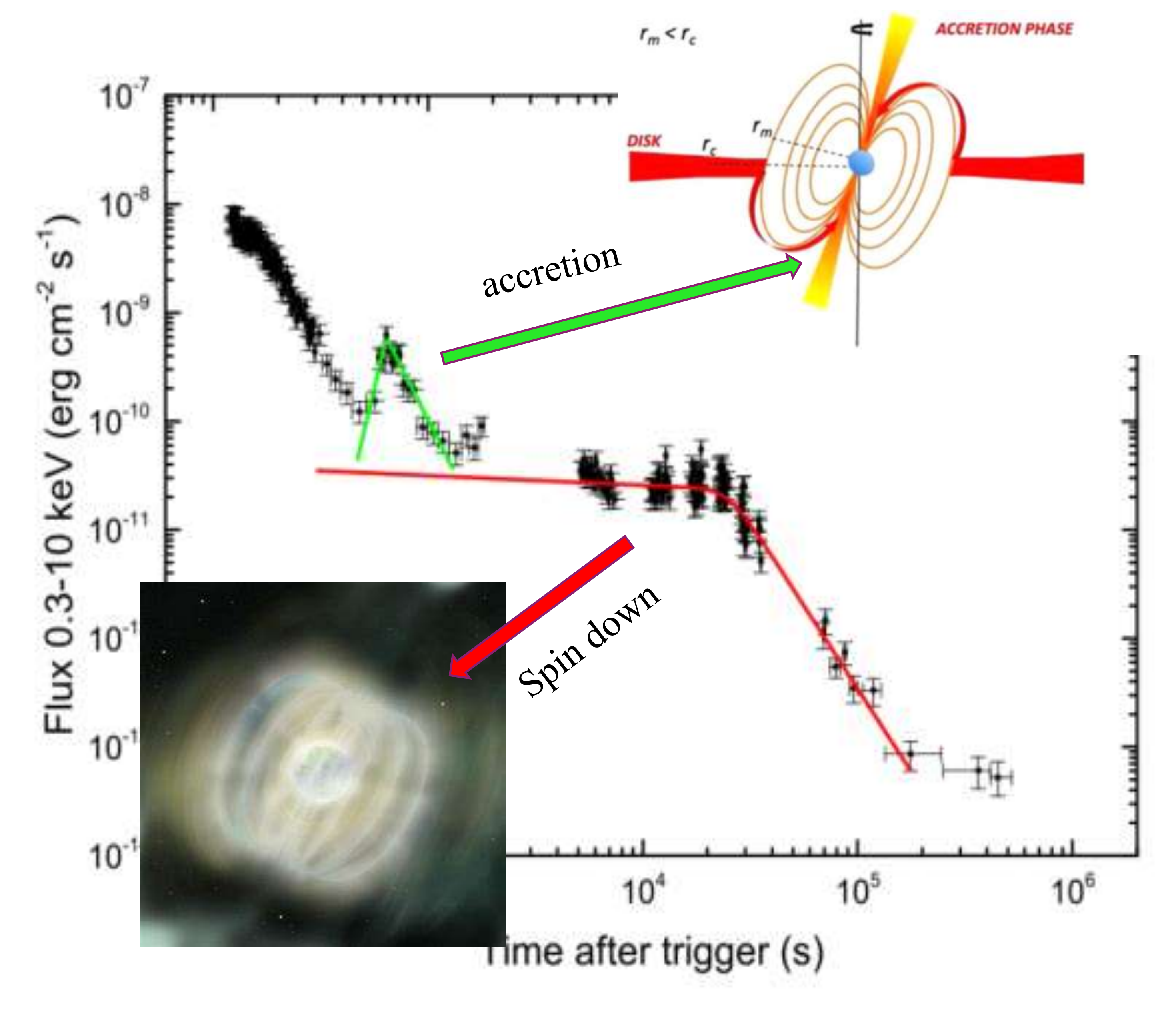
$$r_{\mathrm{m}} = \mu^{4/7}(GM_*)^{-1/7}\dot{M}^{-2/7}.$$

$$r_{\mathrm{c}} = (GM_*/\Omega^2)^{1/3}.$$

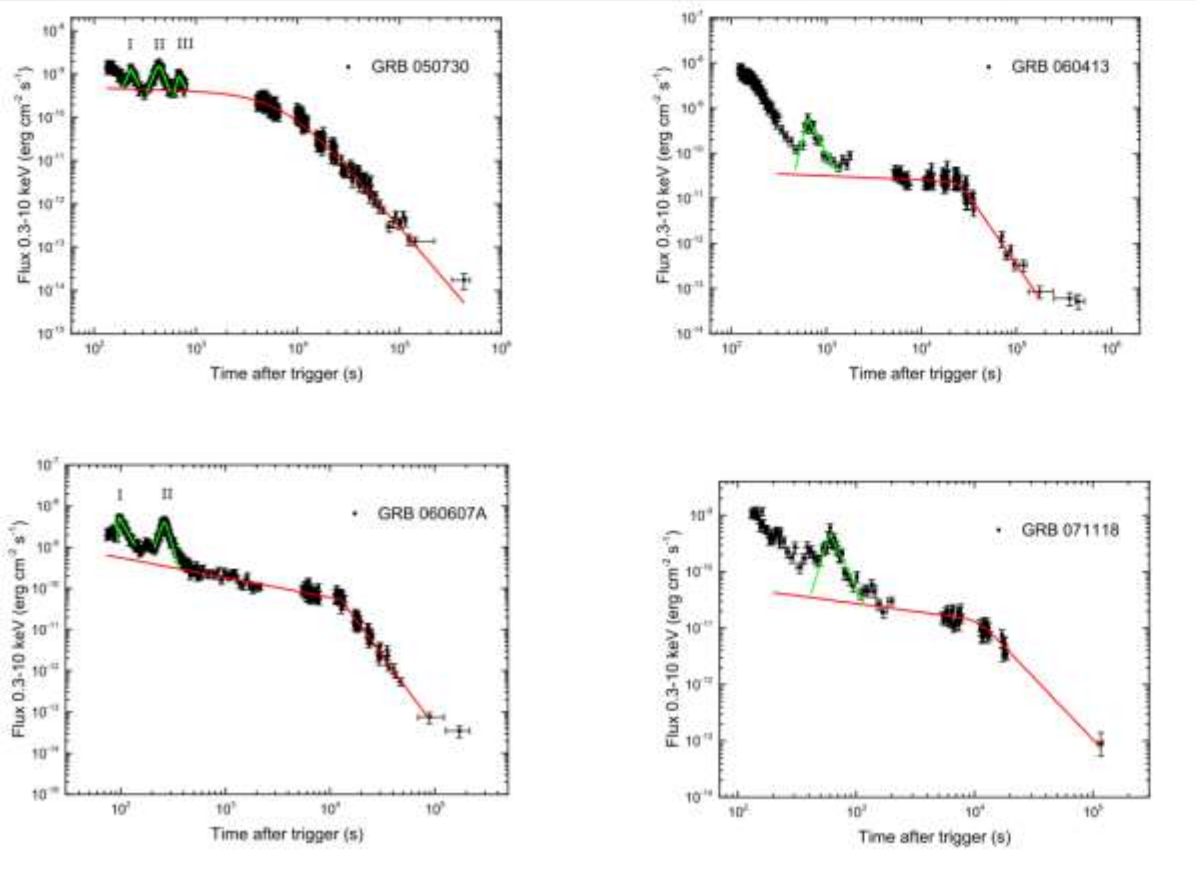


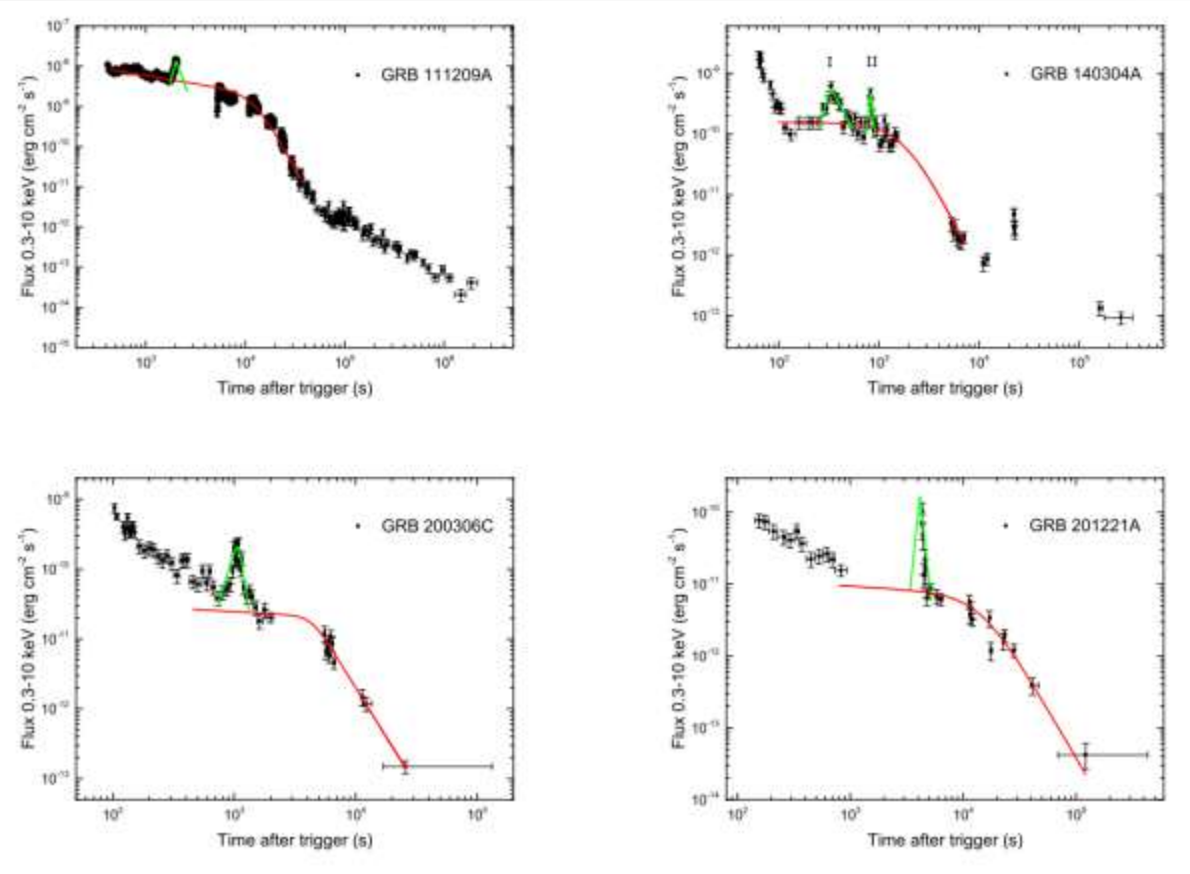
Bernardini et al. 2013

Physical model: X-ray plateau + flare → Magnetar-disk configuration



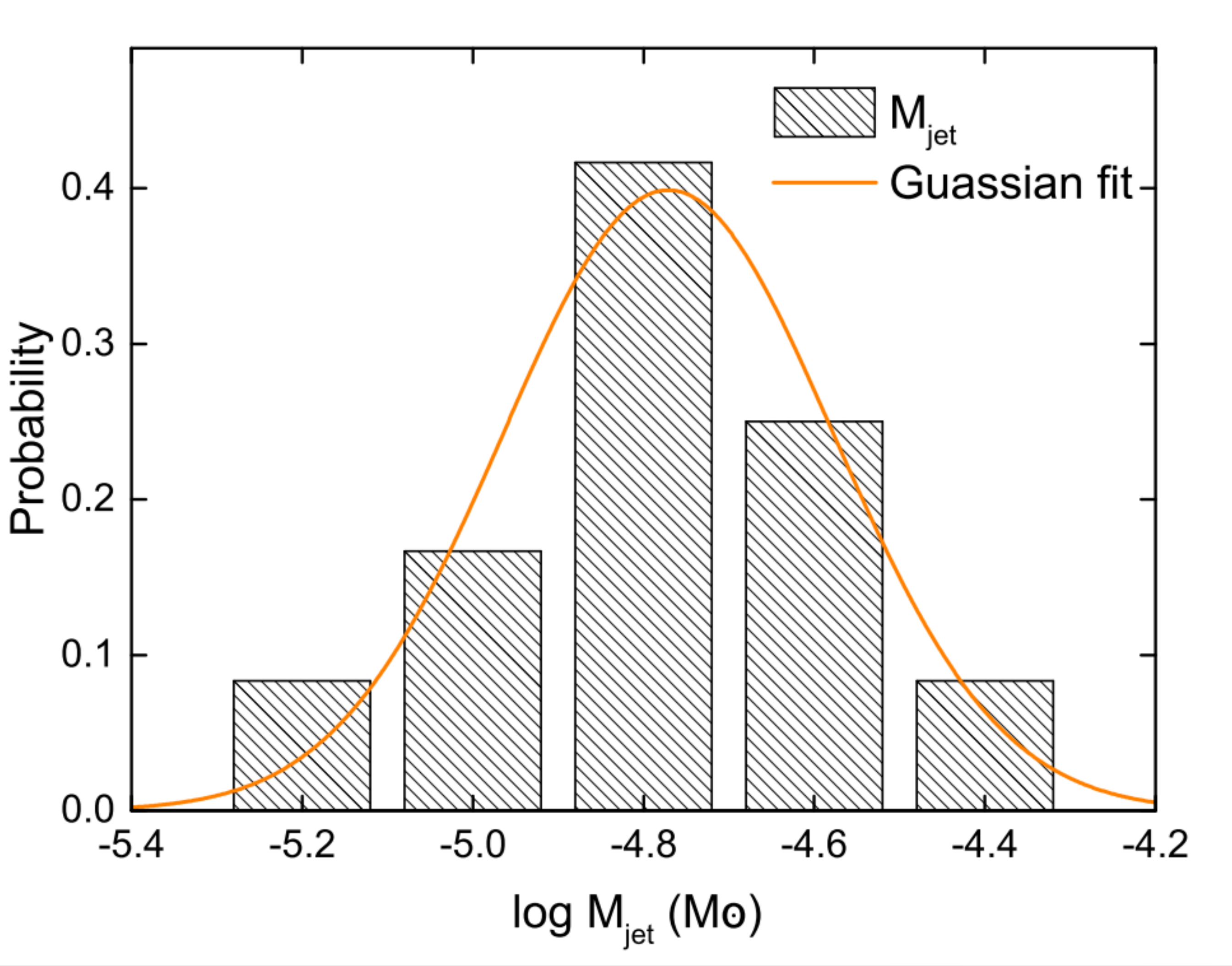
Sample (Swift/XRT): X-ray flare(s) upon X-ray plateau





12 X-ray flares displayed on the 8 magnetar plateaus

Statistics: Estimating the baryon loading in each X-ray flare



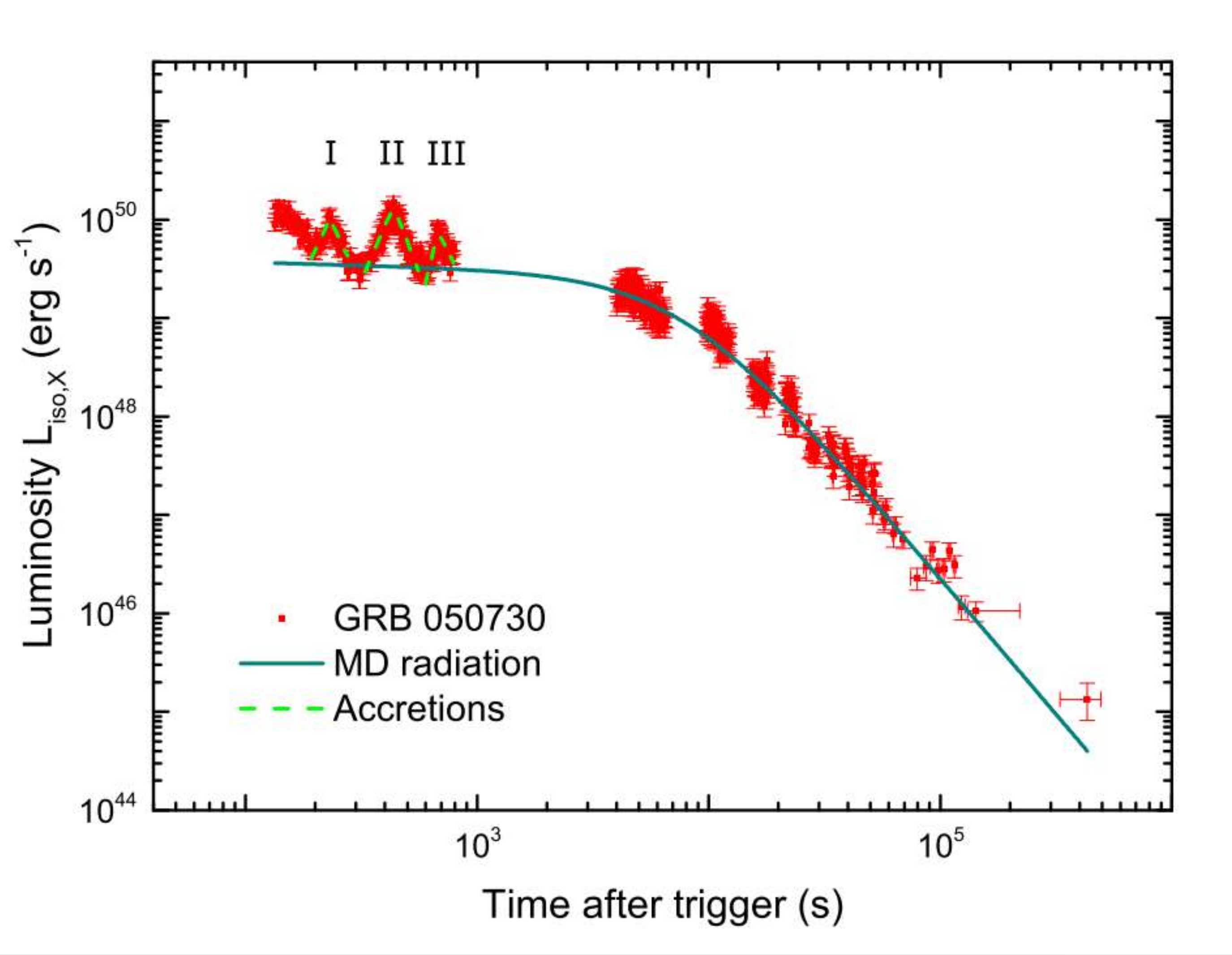
Adopted parameters：

M = 1.4 $M_\odot$

R = 12 km

The medium value is estimated to be $\sim 2 \times 10^{-5}\ M_\odot$

Some questions: repeating accretion



How can we understand multiple flares upon one plateau?

Is the accretion and propellor ongoing all the time? Or display alternate?

e.g., Goodson et al. 1997; Goodson & Winglee 1999; Miller & Stone 1997; Romanova et al. 2002, 2005, 2009, 2018, Ustyugova et al. 2006; Lavelace et al. 2014; Bernardini et al. 2013; Dall'Osso et al. 2023.

Cyclic accretion process: quasi-steady-state disk and possible magnetohydrodynamic instability

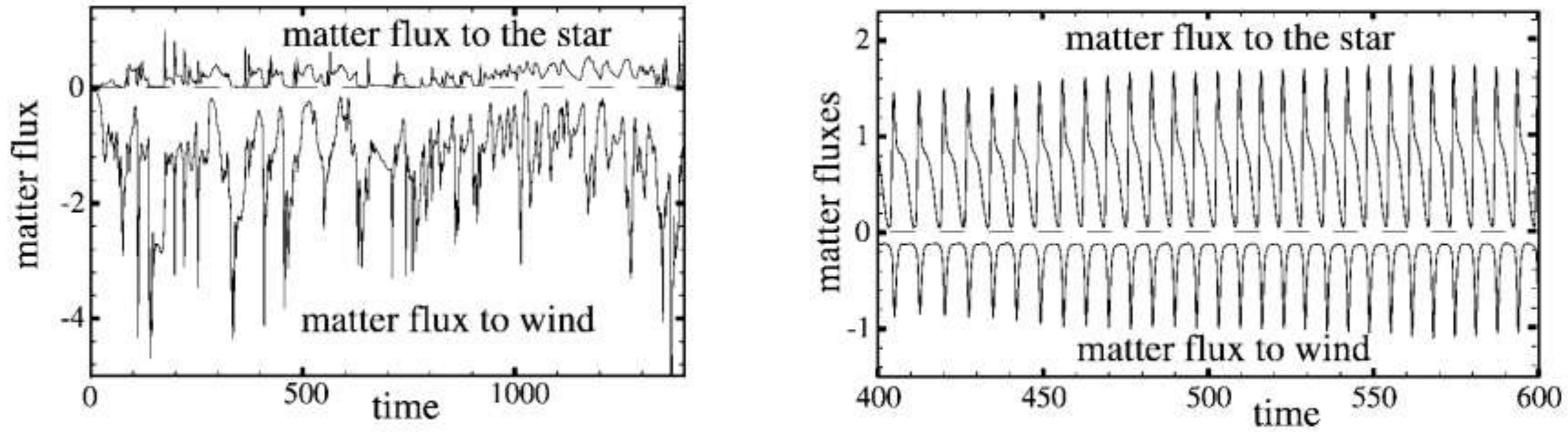
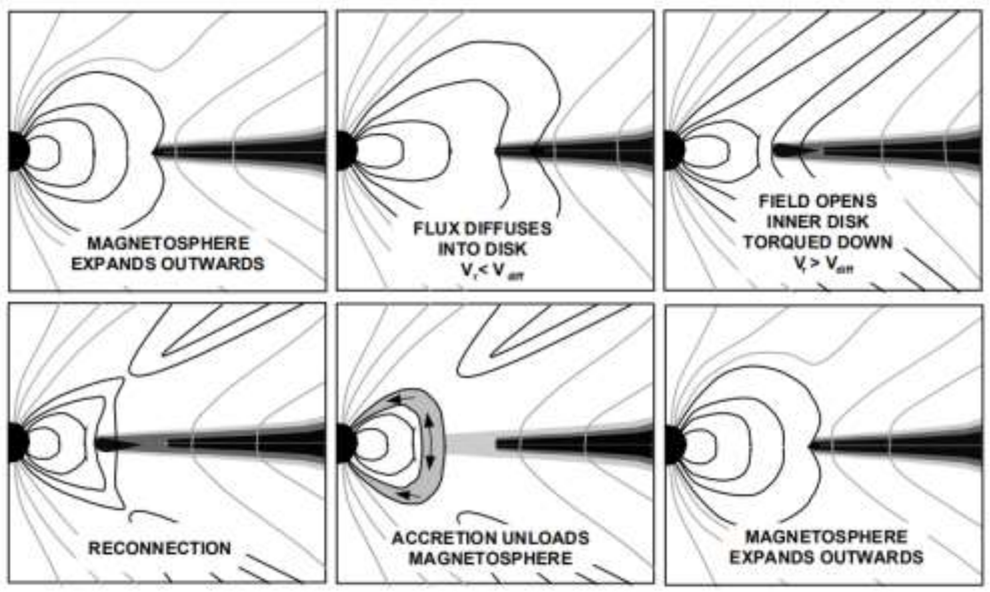


FIG. 3.—Left panel shows matter fluxes to wind and to star for reference case. The right panel shows the quasi-periodic variations of the mass fluxes that we find for larger viscosity, in this case, $\alpha_v = 0.6$.

Romanova et al. 2005



Goodson et al. 1999;
Goodson & Winglee 1999;

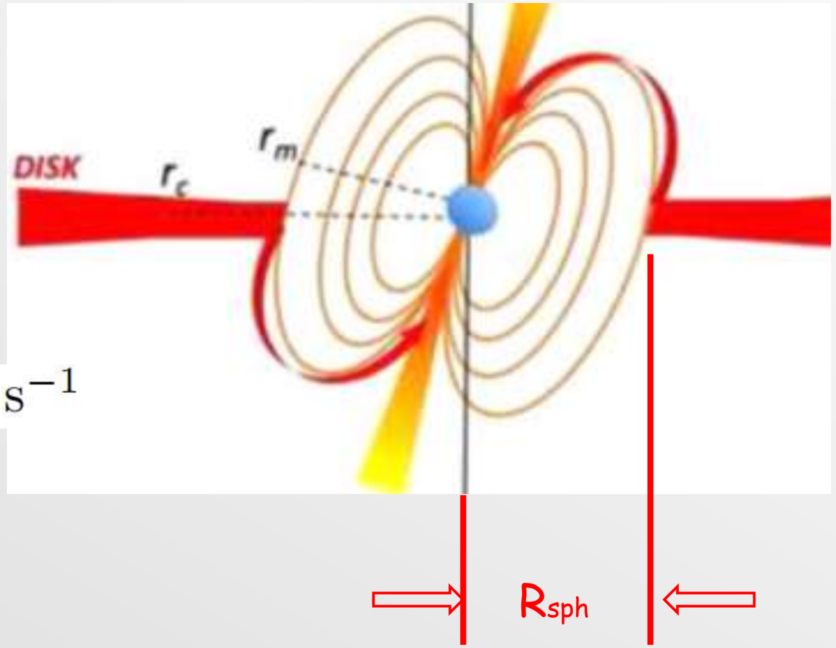
Average mass flow rate and size of the magnetosphere

There are multiple flares displayed in GRBs 050730, 060607A, and 140304A， by adopting $M = 1.4\ M_\odot$, $R = 12$ km， We derive the average mass flow rate

$$3.53 \times 10^{-4}\ M_\odot\ \mathrm{s}^{-1},\ 4.23 \times 10^{-4}\ M_\odot\ \mathrm{s}^{-1},\ \text{and}\ 4.33 \times 10^{-4}\ M_\odot\ \mathrm{s}^{-1}$$

And average size of magnetosphere R_{sph} are

$$5.01 \times 10^6\,\mathrm{cm},\ 6.45 \times 10^6\,\mathrm{cm},\ \text{and}\ 1.09 \times 10^7\,\mathrm{cm}$$

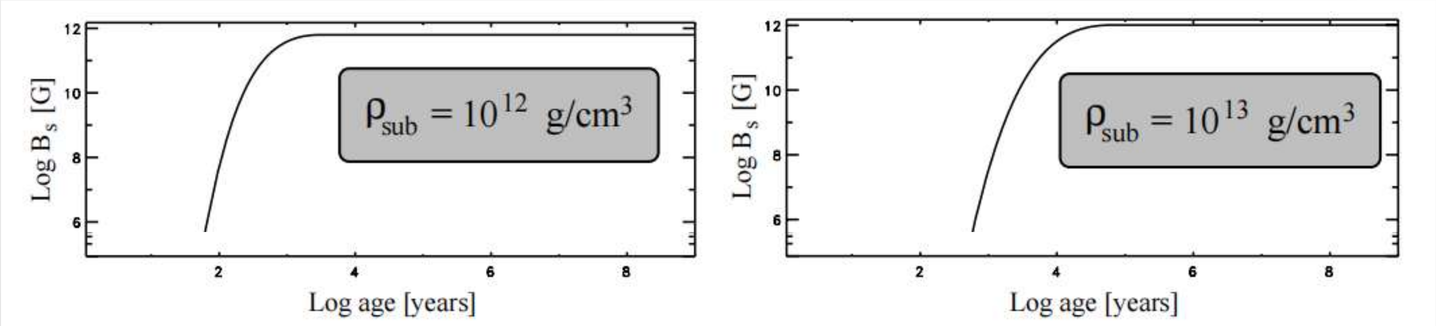


Some questions: magnetic field bury and its re-magnetization

For a neutron star has survived thousands of years:

Yes, the magnetic field will be buried

(Refer to Taam & van den Heuvel 1986; Shibazaki et al. 1989; Fu & Li 2013)



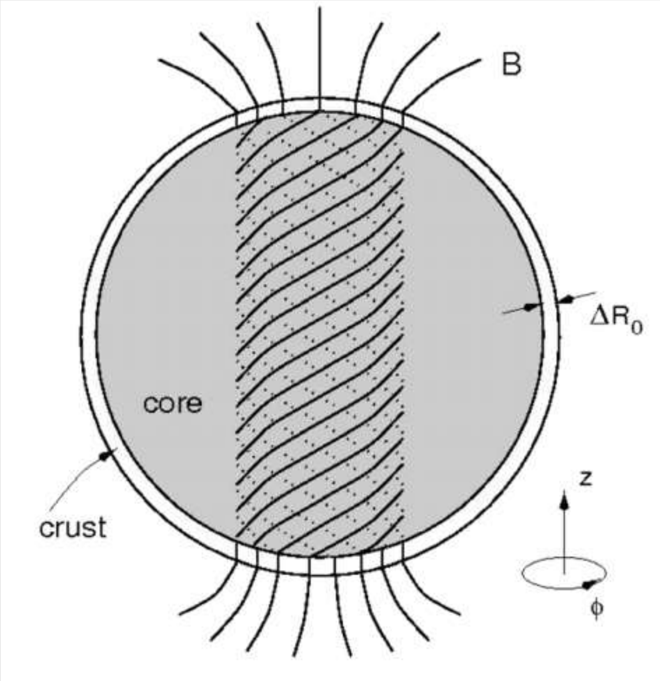
Geppert et al. 2021

Re-magnetized process and time scale:

The Ohmic diffusion and the Hall drift

At least 1000 year

(Geppert et al. 1999; Ho 2011; Fu & Li 2013)



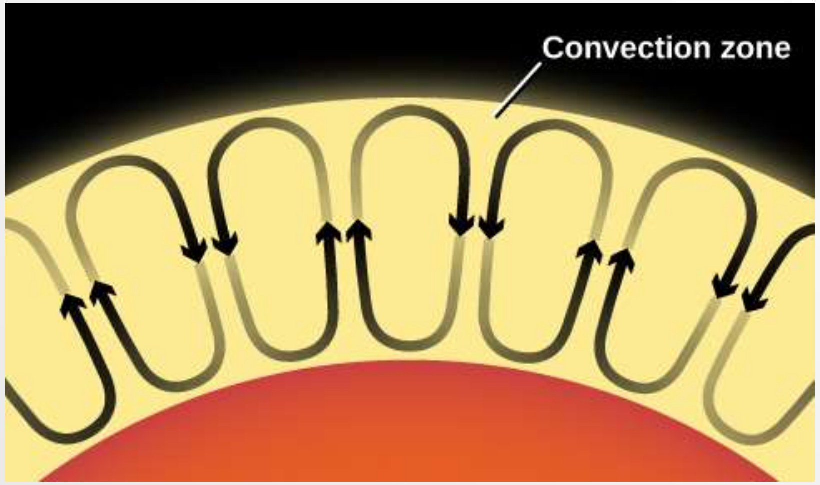
Thompson & Duncan 2001

A newborn magnetar born in GRBs

How about a newborn magnetar?

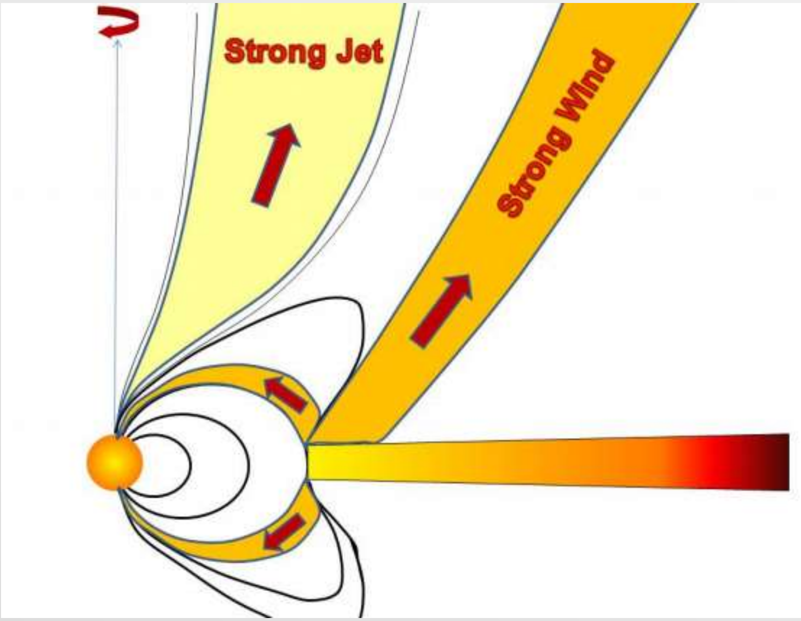
The age of magnetars born in GRB is hundreds to thousands of seconds only. The re-magnetization process at this phase should be dominated by the convection process inside the magnetars.

(Thompson & Duncan 1993 and this work)

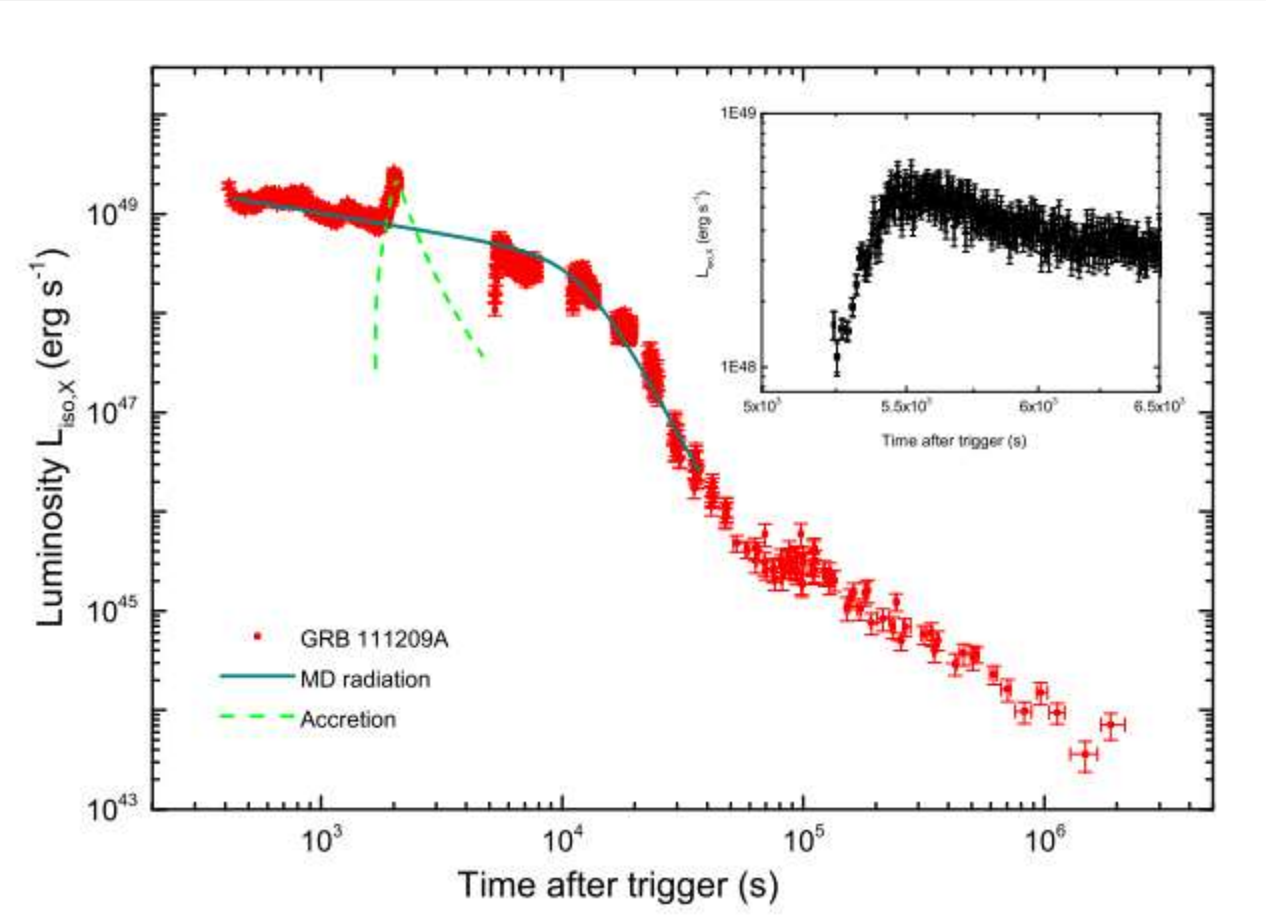


In addition, when accreting material, it opens a channel for the jet in the form of a funnel, which hints that the magnetic field located at the magnetic poles may not be buried.

(Lamb et al. 1973; Elsner & Lamb 1977; Romanova et al. 2002, 2009)



Convection dominate re-magnetization

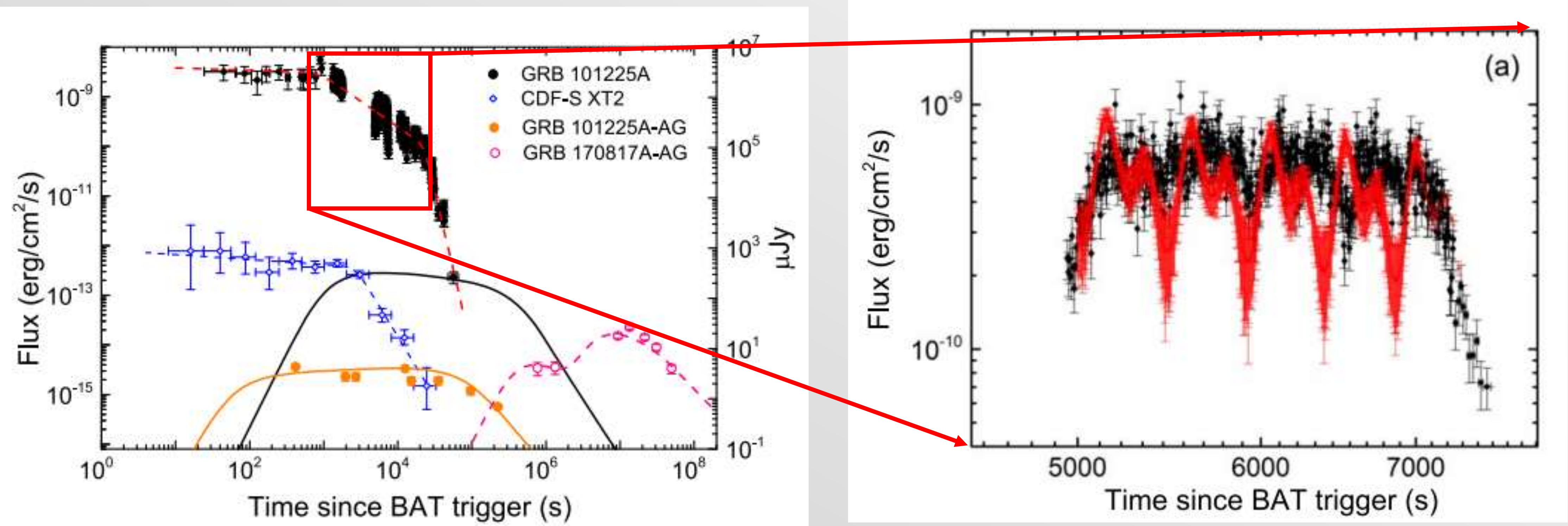


X-ray afterglow of GRB 111209A

The convection process dominated the re-magnetization process.

The brightness of the magnetar plateau **changes from dark to normal levels** immediately after a flare. One suggested that the **re-magnetization** process of newborn magnetars may be as **short as thousands or even hundreds of seconds**.

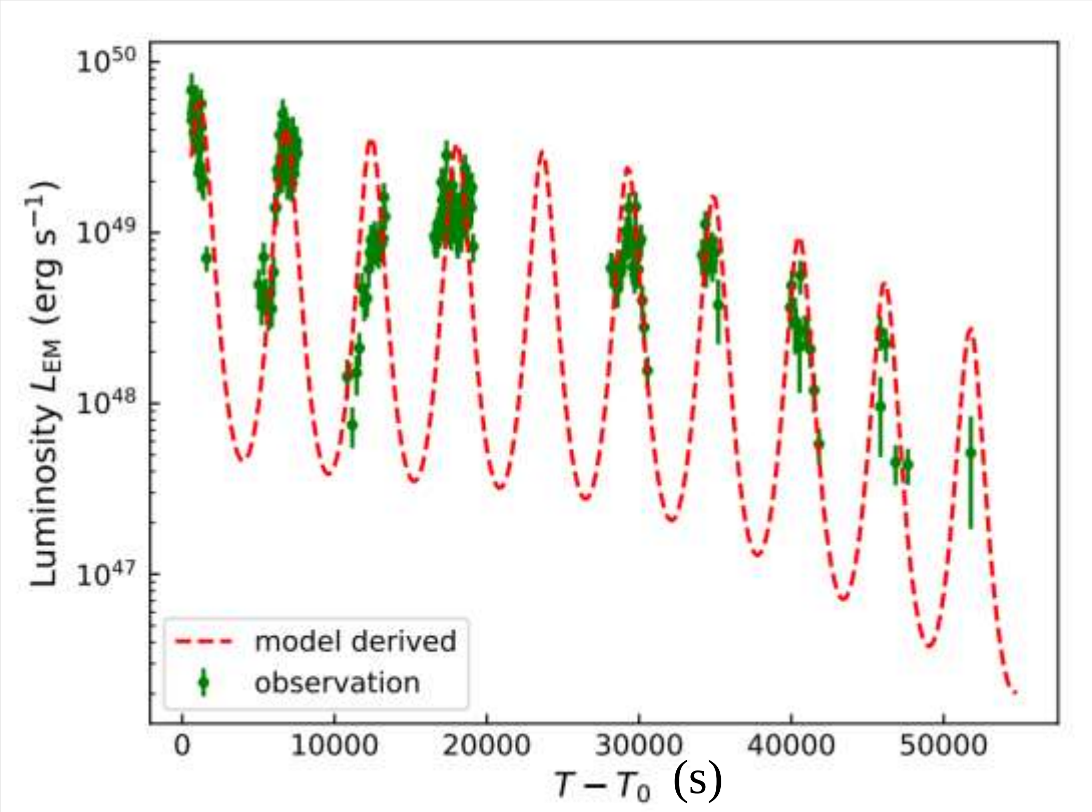
BH activity imprint on the QPO modulate X-ray plateau
(Zheng et al. 2024, ApJ, 964, 169)



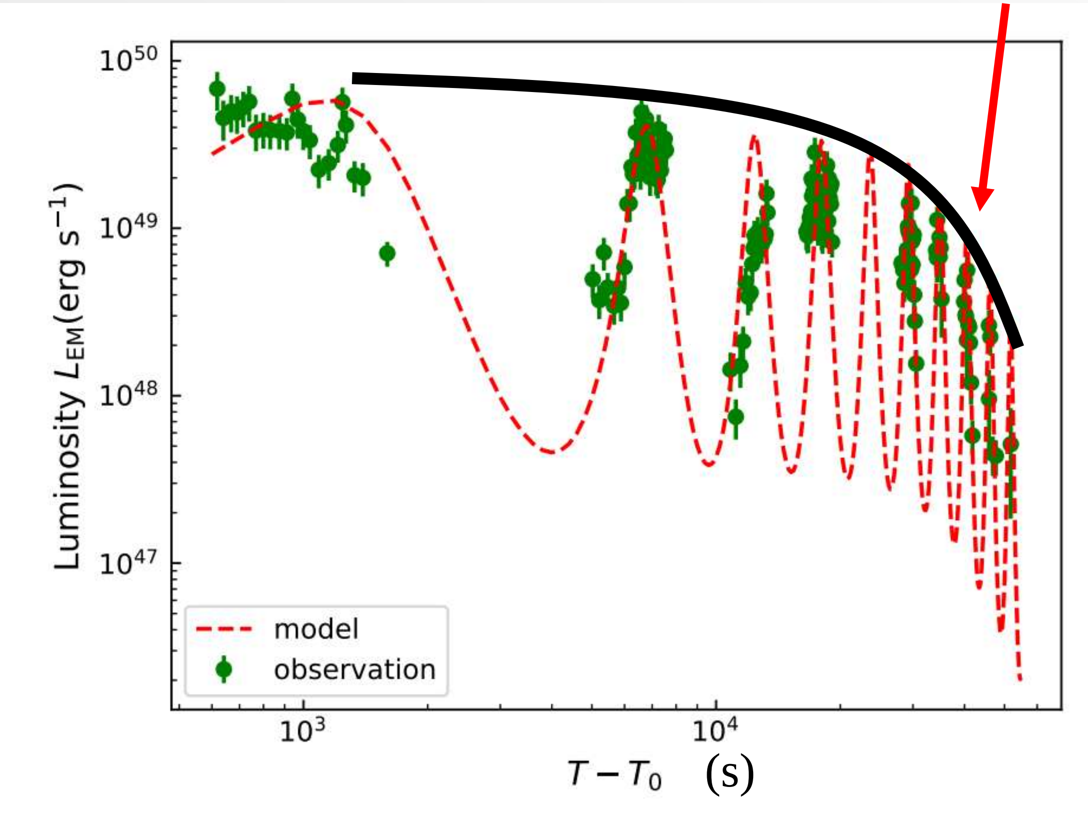
Le Zou, **Tianci Zheng** et al. 2021

multi-flare composed X-ray afterglow of GRB 050904

Decay slop α ~ -6

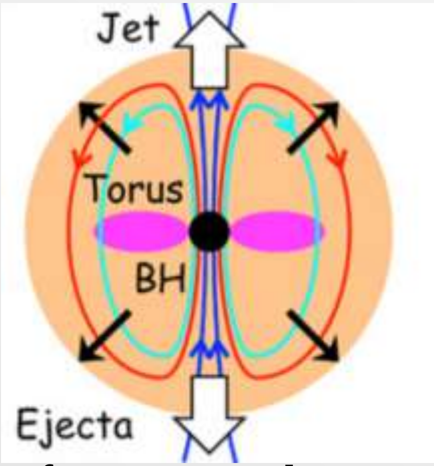


Linear time axis



Logarithmic time axis

Physics: Evolving magnetic flux in BZ mechanism powered jet



Power of BZ jet

$$L_{\rm BZ} \approx \frac{kf}{4\pi c}\,\Phi_{\rm BH}^2\,\Omega_H^2,$$

Magnetic pressure VS ram pressure: determining of magnetosphere

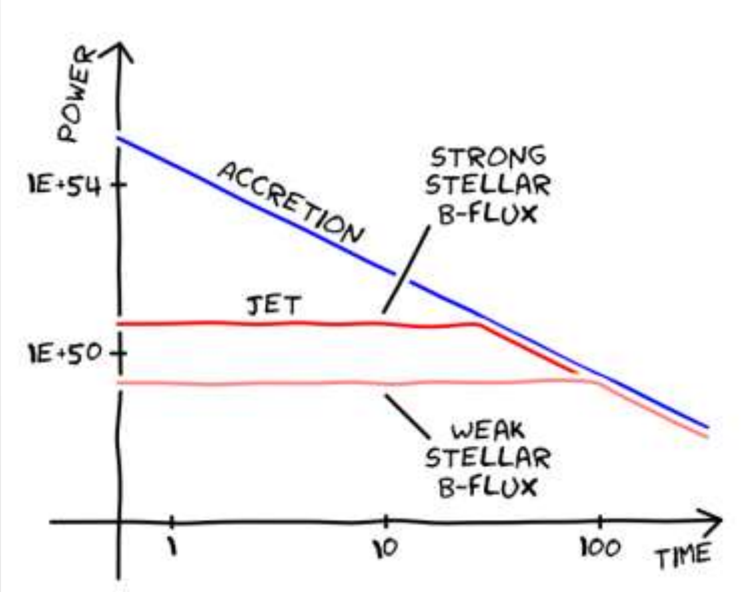
$$P_B = \frac{B_H^2}{8\pi}\left(\frac{R}{r_H}\right)^{-4}$$

$$P_f = \frac{GM_{\rm BH}\dot{M}}{2\pi R^3 \nu_R},$$

The connection between magnetic flux and the size of magnetosphere

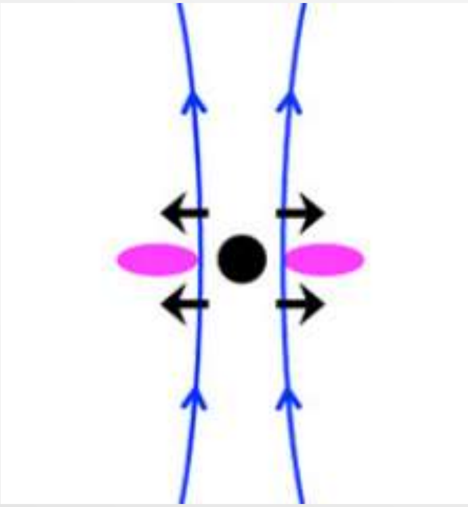
$$\frac{\Phi_{\rm tot}}{\Phi_{\rm BH}} = \left(\frac{R_m}{r_H}\right)^2,$$

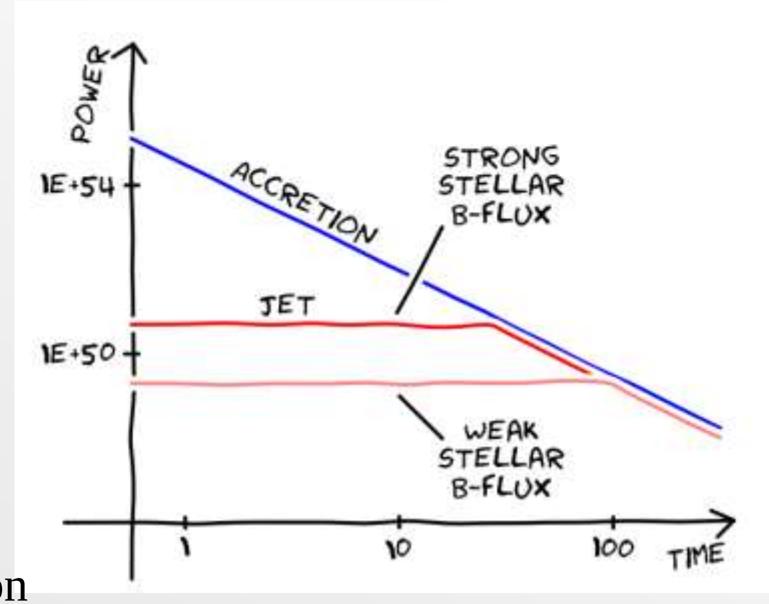
$$\sim 2\left(\frac{\epsilon}{10^{-2}}\right)^{4/3}\left(\frac{B_H}{10^{12}\ {\rm G}}\right)^{8/3}\left(\frac{M_{BH}}{3M_\odot}\right)^{8/3}\left(\frac{\dot{M}}{10^{-11}M_\odot{\rm s}^{-1}}\right)^{-4/3}.$$



From Kisaka & Ioka 2015; Tchekhovskoy et al. 2015 mass accretion rate at later phase (Chevalier 1989)

$$\dot{M} = M_p \left(\frac{t - t_0}{t_p - t_0} \right)^{-5/3},$$





Evolution of BZ power at later phase

$$L_{\rm BZ} \propto \Phi_{\rm BH}^2 \propto \dot{M}^{8/3} \propto t^{-40/9}.$$

BH no hair & magnetic diffusion

From Kisaka & Ioka 2015; Tchekhovskoy et al. 2015

The characteristic timescale of BZ power

$$T \sim 8 \times 10^3 \left(\frac{\dot{M}_p}{10^{-3} M_\odot {\rm s}^{-1}} \right)^{3/5} \left(\frac{\epsilon}{10^{-2}} \right)^{-3/5} \left(\frac{B_H}{10^{12}\ {\rm G}} \right)^{-6/5} \left(\frac{M_{BH}}{3 M_\odot} \right)^{-6/5}.$$

BZ power act as a plateau light curve

$$L_{\rm BZ} = L_{0,BZ} \left(1 + \frac{t}{T} \right)^{-40/9}$$

See also Shota Kisaka & Kunihito Ioka (2015)

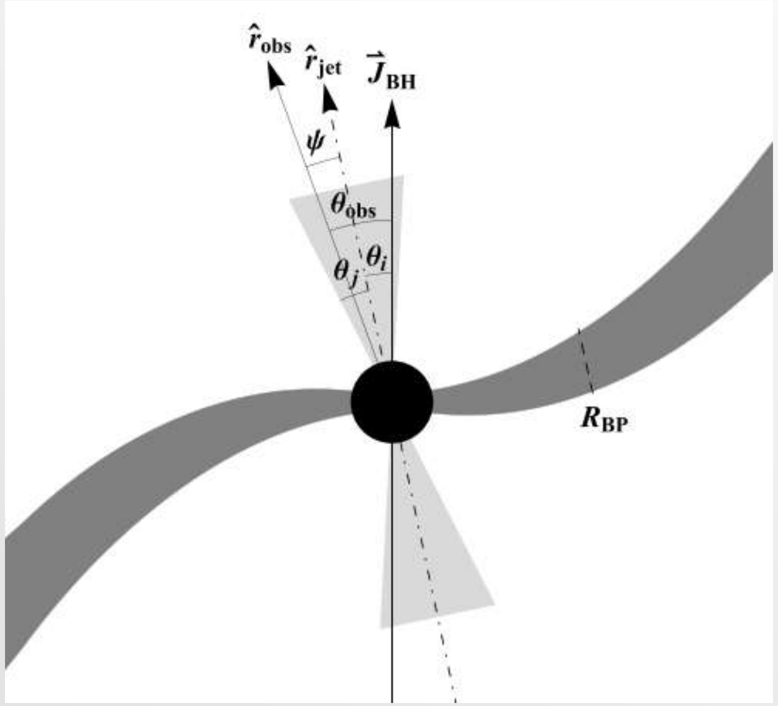
BZ mechanism powered processional jet: Lense-Thirring effect

Lense-Thirring effect: while an object contains angular moment, then it would exert a drag effect on the nearby time-space.

Relationship between precession angular frequency and physical parameters:

$$\Omega = \frac{2GJ_{\mathrm{BH}}}{c^2 r^3},$$

r is the orbit radius, for a disk, r = R_{BP} (see Bardeen & Petterson 1975).



The picture is from Lei et al. (2013)

The disk rotary with a precession orbit and compels the BZ jet precession either.

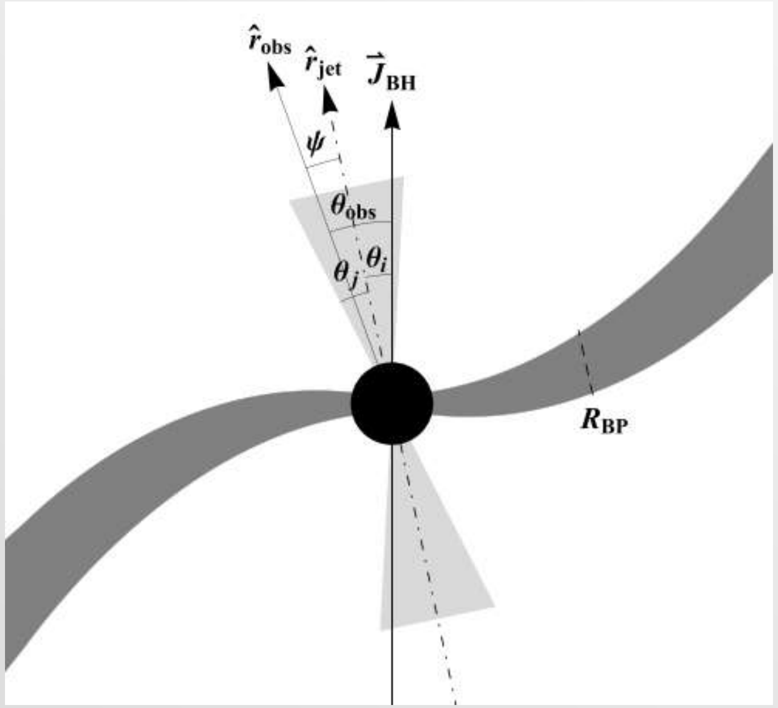
Observational effect of a precessing jet

Angle between the jet and the observer's line of sight:

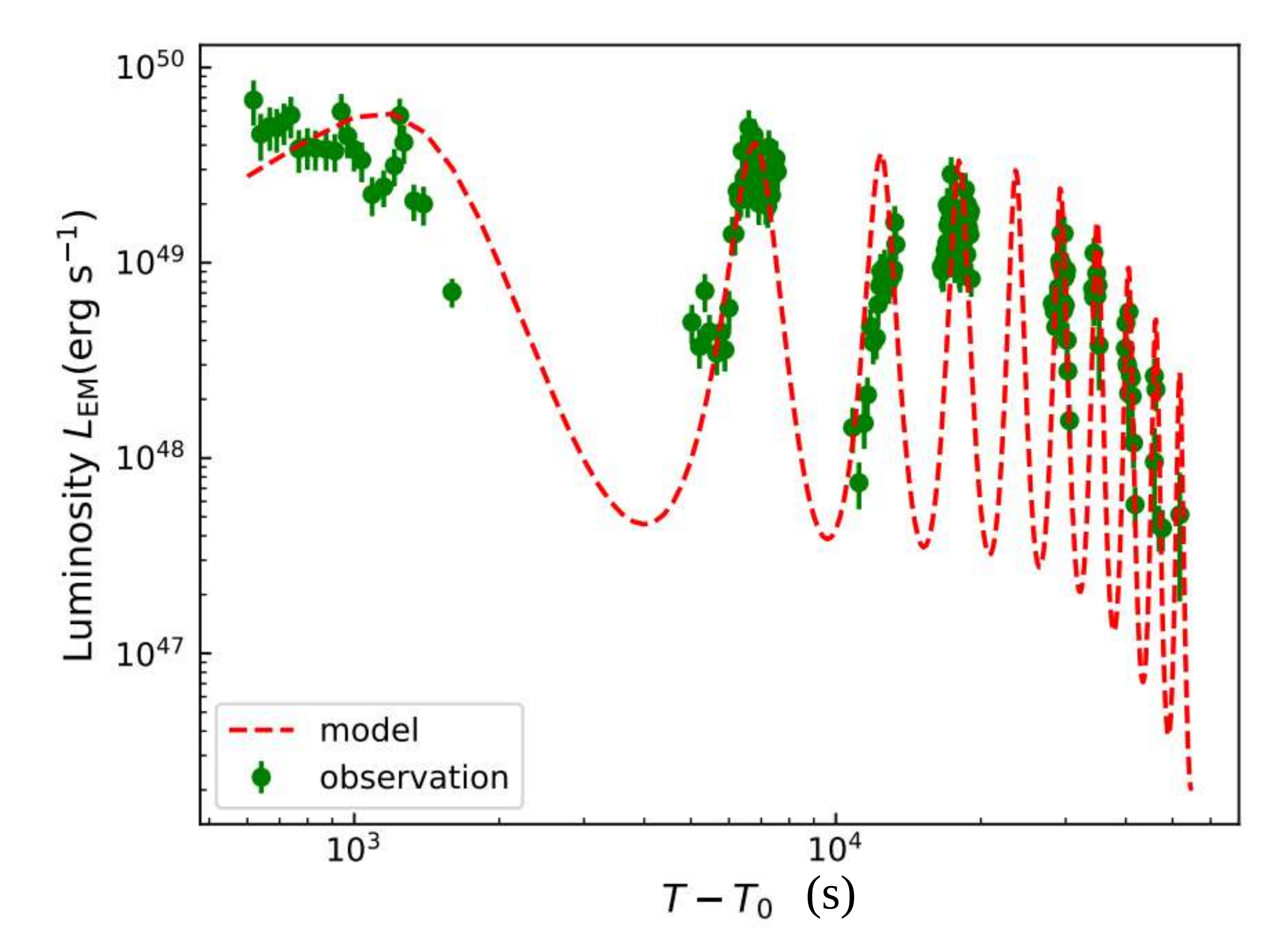
$$\psi = \cos^{-1}(\hat{r}_{\rm obs} \cdot \hat{r}_{\rm jet}).$$

The observed flux correct by doppler effect:

$$F_\nu(\psi, t) = D^3 F_{\nu/D}(0, Dt),$$

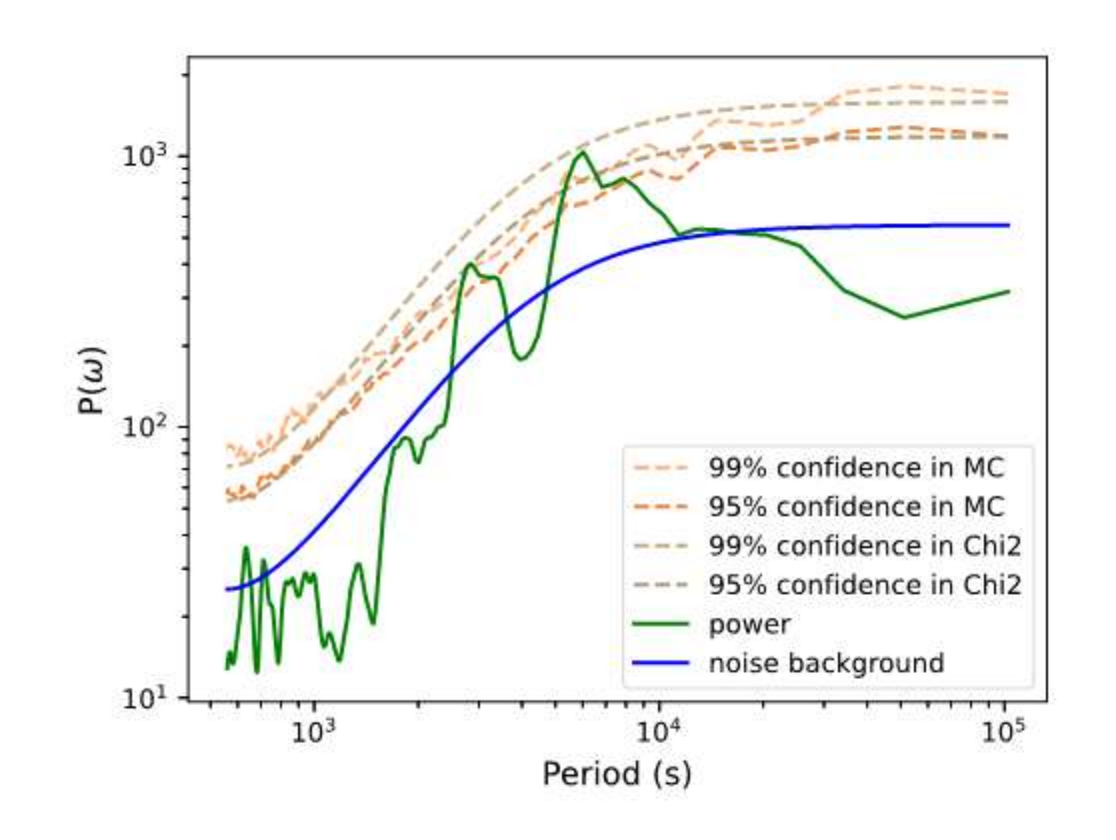


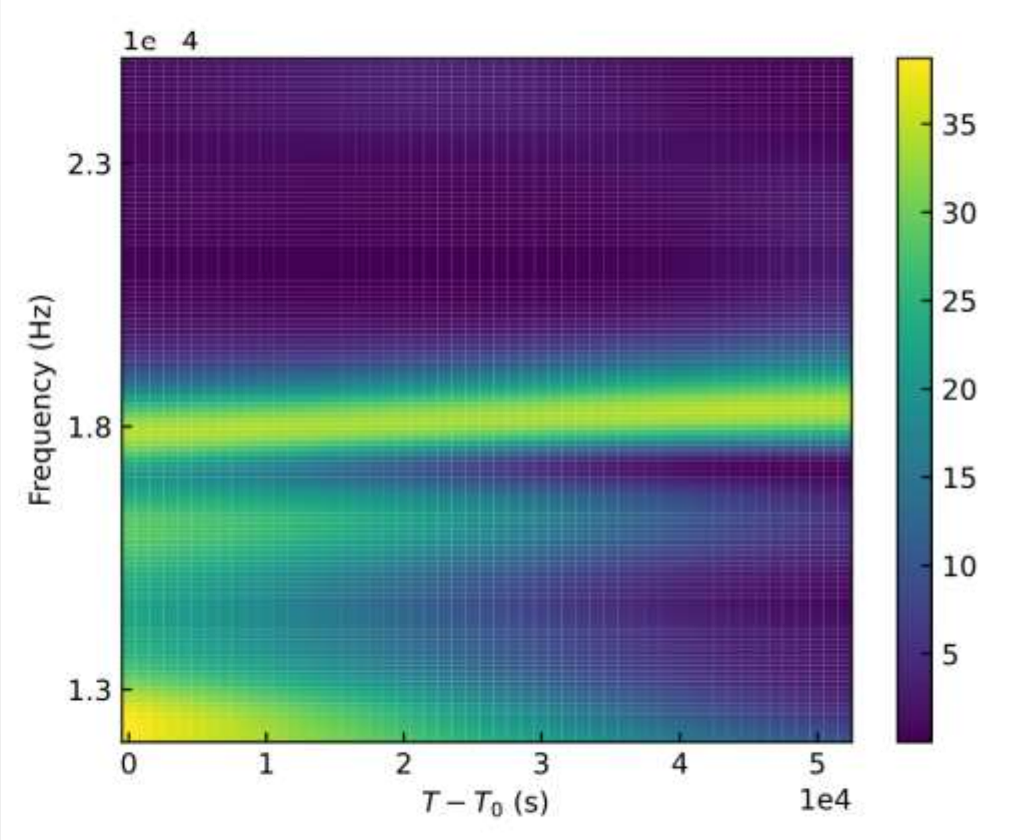
Case study: multi-flare composed X-ray afterglow of GRB 050904



Periodicity

P ~ 56,00 / (1+z) seconds





Methods:
Left: Schulz & Mudelsee (2002) develop a Fortran program (REDFIT)
Right: Weighted wavelet Z-transform (WWZ) by Aydin (2017)

Summary 1

Zheng et al. 2021, RAA, 21, 300

1. The study combines X-ray flare and plateau, putting forward that X-ray flare upon a magnetar plateau is a clue for identifying the central engine with magnetar-disk configuration.
2. By adopting certain parameters, we derived the average baryon loading in single flare, the mass flow rate of the accretion disk, and the average sizes of the magnetosphere.
3. The re-magnetization process of a newborn magnetar may dominate by the internal convection and be as short as hundreds of seconds.

Summary 2

Zheng et al. 2024, ApJ, 964, 169

1. We propose that a precessing BZ jet would manifest a QPO signature on the internal plateau and the subsequent sharp decay. A good case study given by GRB 050904
2. One potential clue for distinguishing magnetar and BH central engines: whether QPO signature throughout the entire plateau and the subsequent sharp decay

Tianci Zheng's homepage

Thanks for your listening!