Magnetar emergence in a peculiar GRB 230307A from a compact star merger

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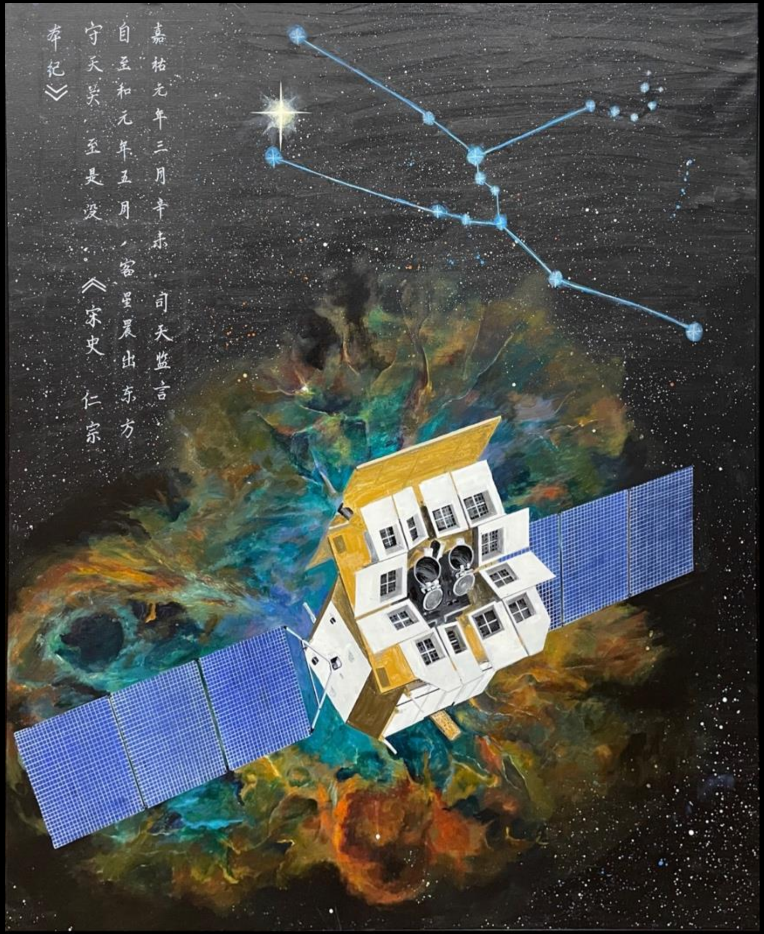
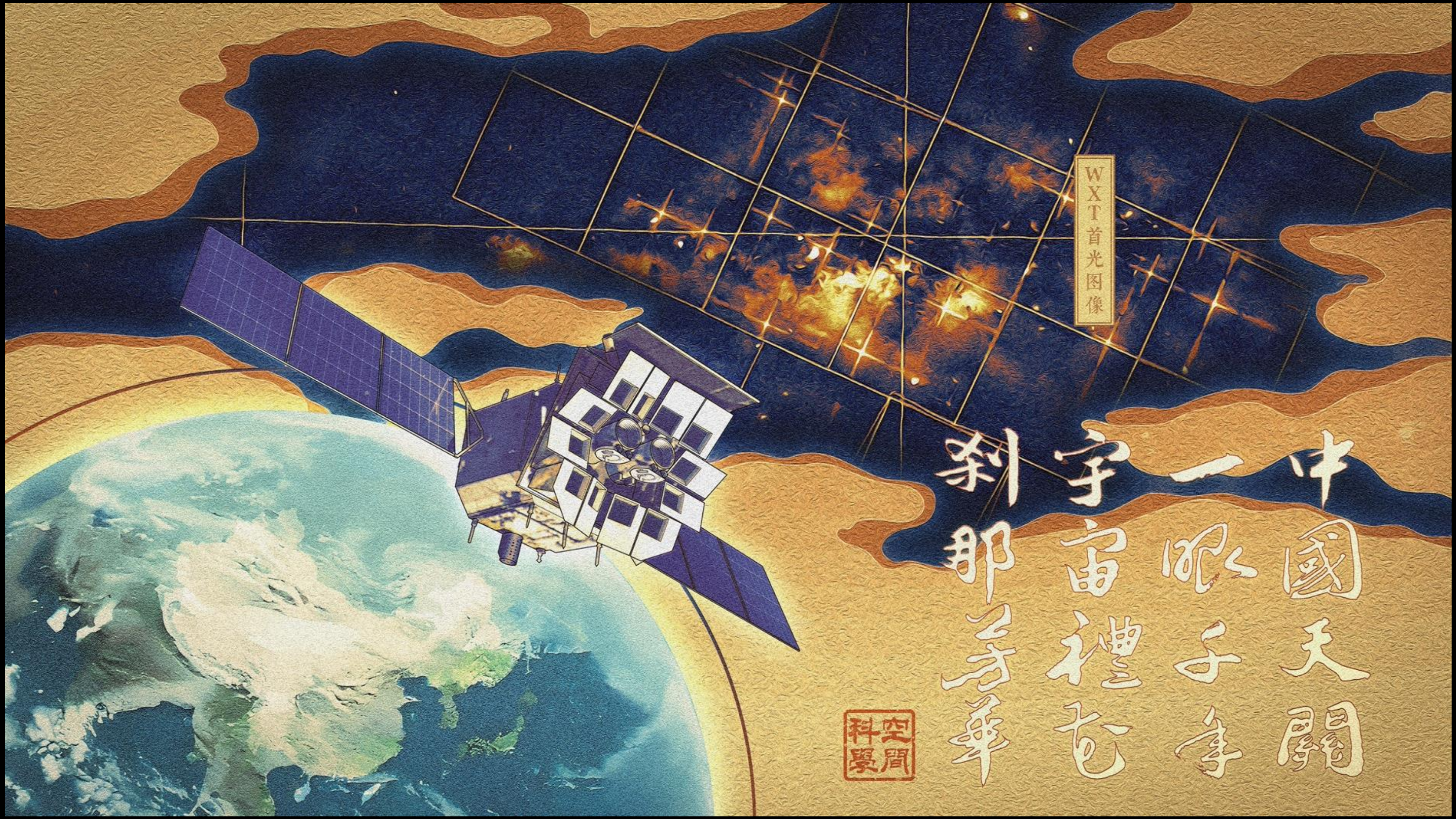
MAXI 15 Year Workshop | 12-14, Dec. 2024

Outline

- Introduction
  - X-ray transients powered by magnetar from binary neutron star merger
- Magnetar emergence in a peculiar GRB 230307A
- Fast X-ray transients discovered by EP
  - EP240315a & EP240414a

Einstein Probe (Tianguan)





The Einstein Probe Mission *Yuan et al. 2022* Handbook of X-ray and Gamma-ray Astrophysics

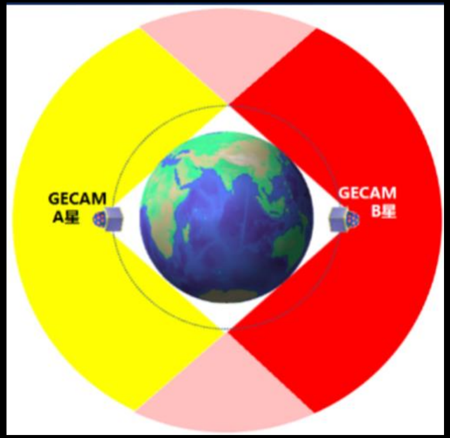
Weimin Yuan's talk

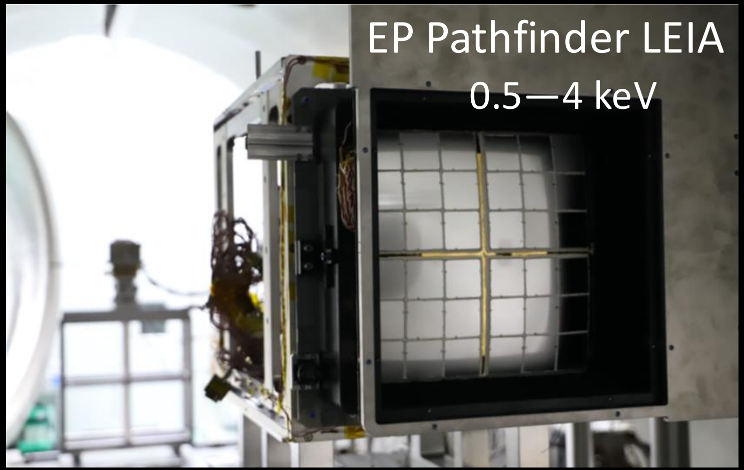
GRB 230307A by GECAM and LEIA

Sun et al. 2024, arXiv: 2307.05689

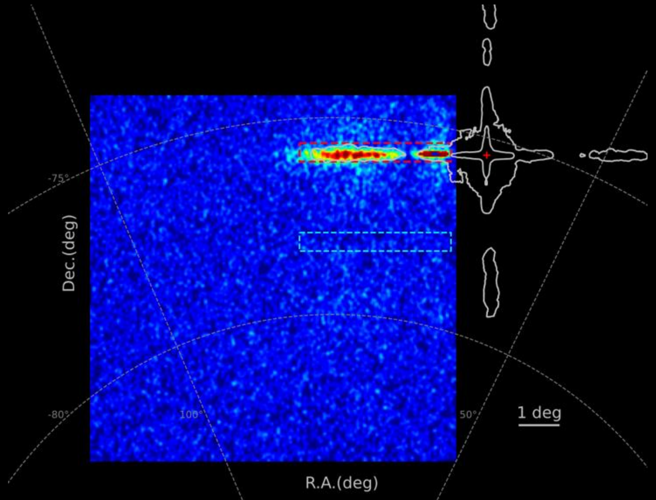
National Science Review, in press

Heyang Liu's talk





Launched in July 2022
FoV ~ 300 deg^2

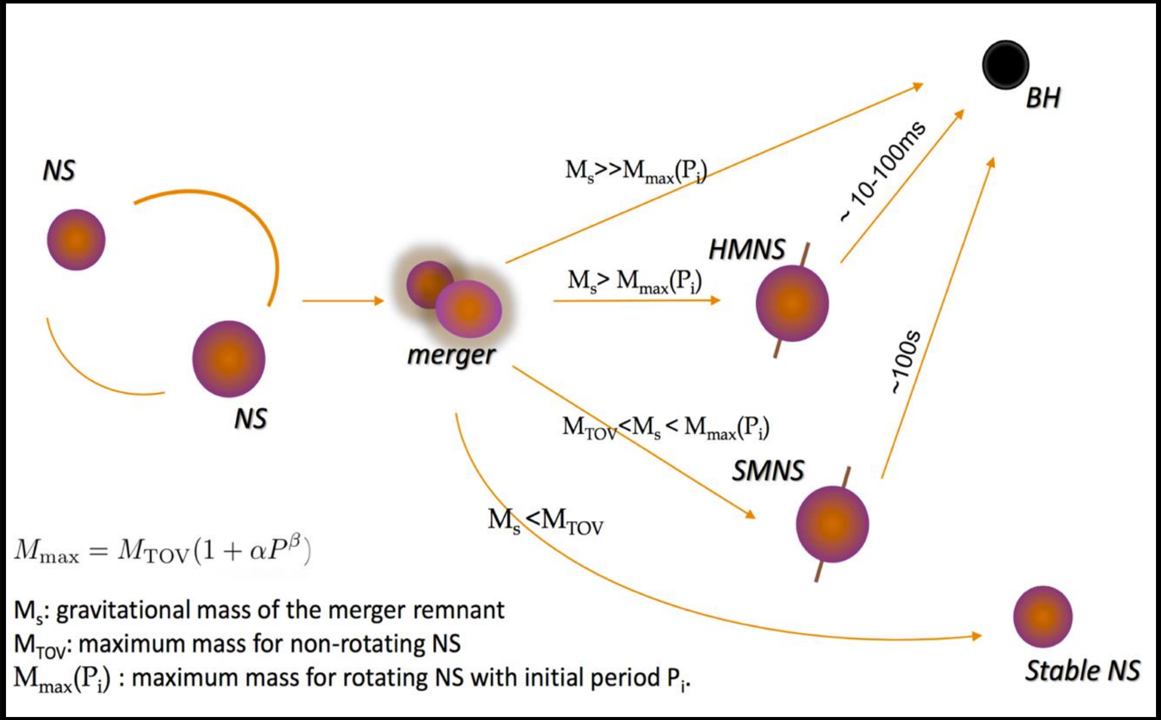


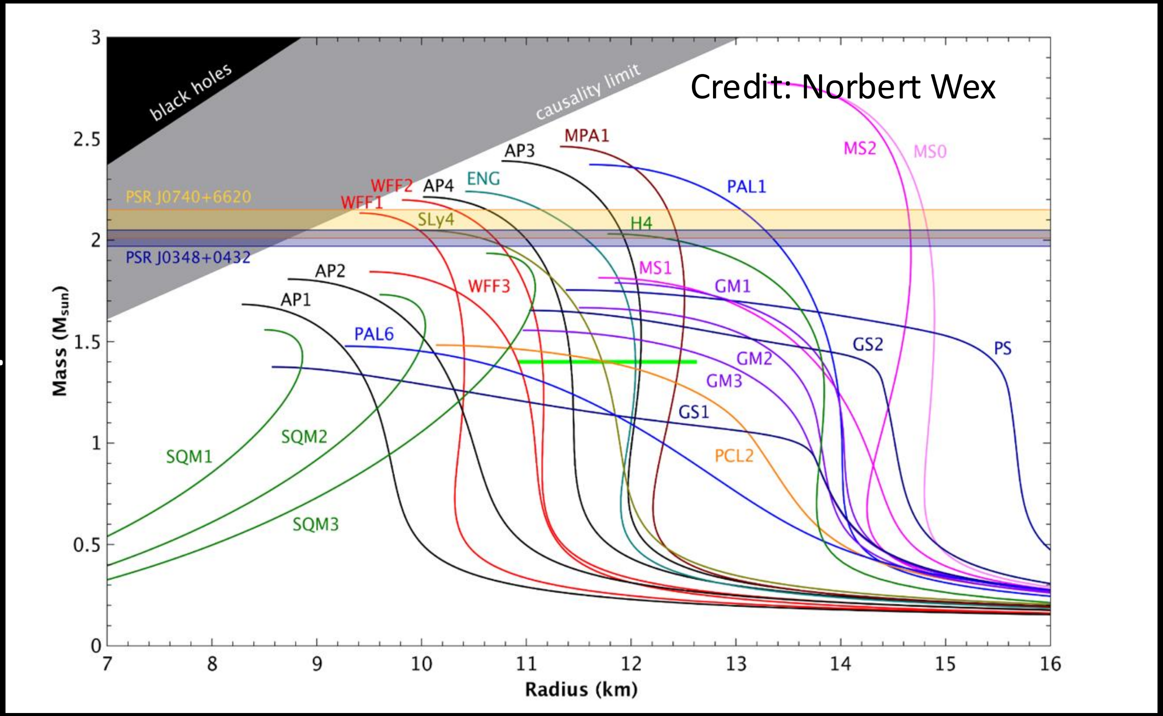
LEIA Image of GRB 230307A

Refs: Zhang et al. 2022, Ling et al. 2023

Binary Neutron Star merger remnants

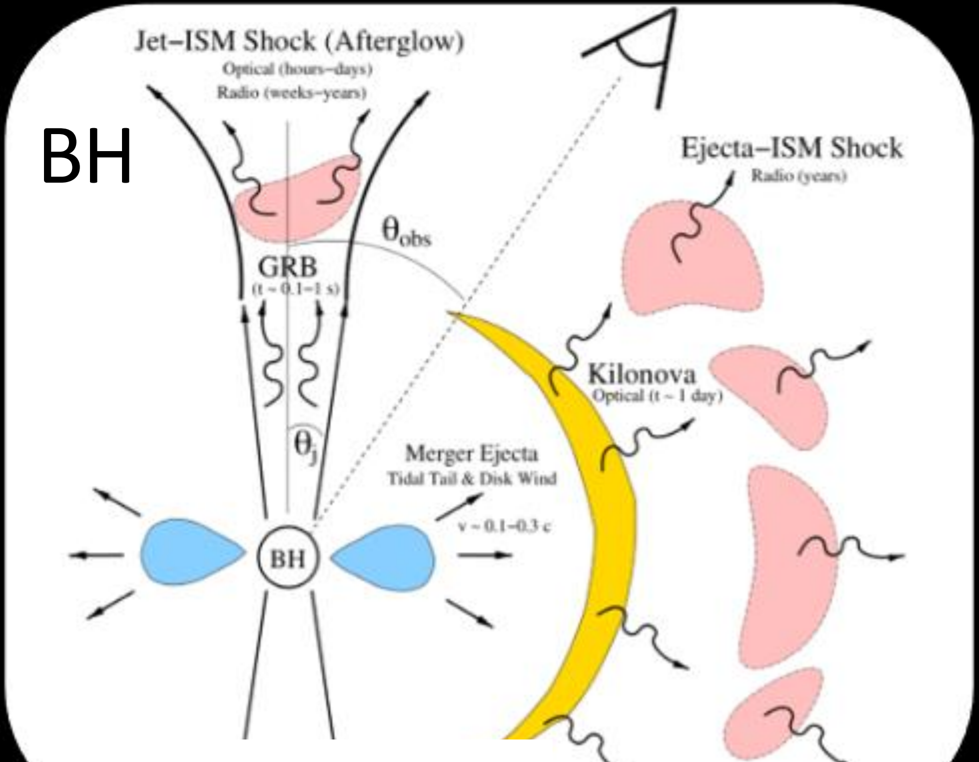
✧ The BNS merger may have various outcomes, depending on the NS equation of state and the mass of merger remnant.



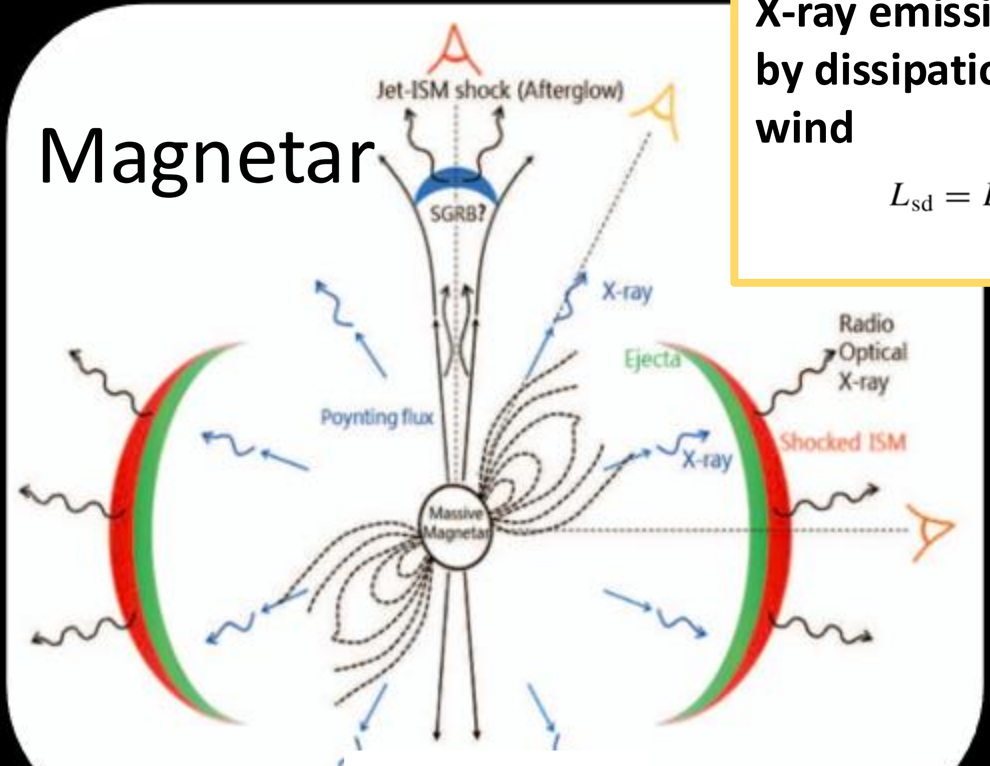


Rosswog et al. 2000, 2014, Rezzolla et al. 2010, 2011, Dai et al. 2006, Zhang 2013, Yu et al. 2013, Gao et al. 2013, 2016, Lasky et al. 2014

EM emissions for BH & Magnetar central engines



Metzger & Berger 2012



Gao et al. 2013

X-ray emissions powered by dissipation of magnetar wind

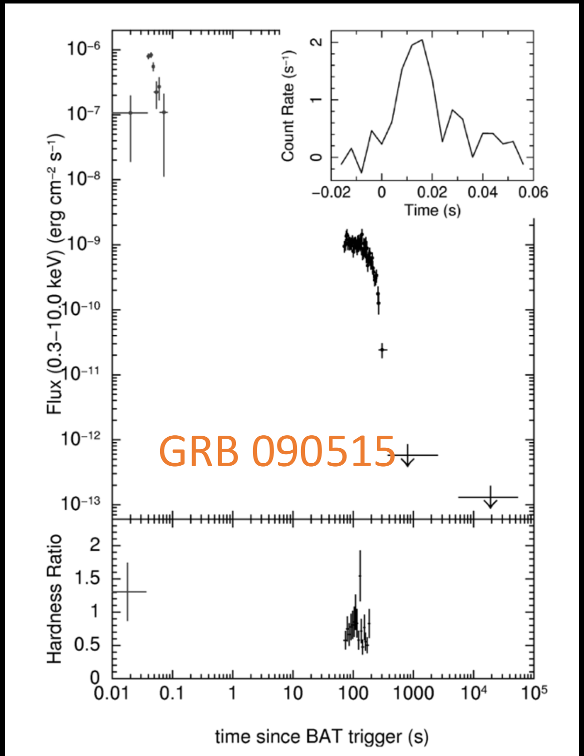
$$L_{\rm sd} = L_{\rm sd,i}\left(1 + \frac{t}{t_{\rm md}}\right)^{-2}$$

- ✧ Magnetar-powered X-ray emission: last for a few hundred seconds & wider solid angle
- ✧ Early X-ray detection can play a unique role in differentiating the post-merger products and provide strong constraint on the NS EoS in the case of joint GW detection.

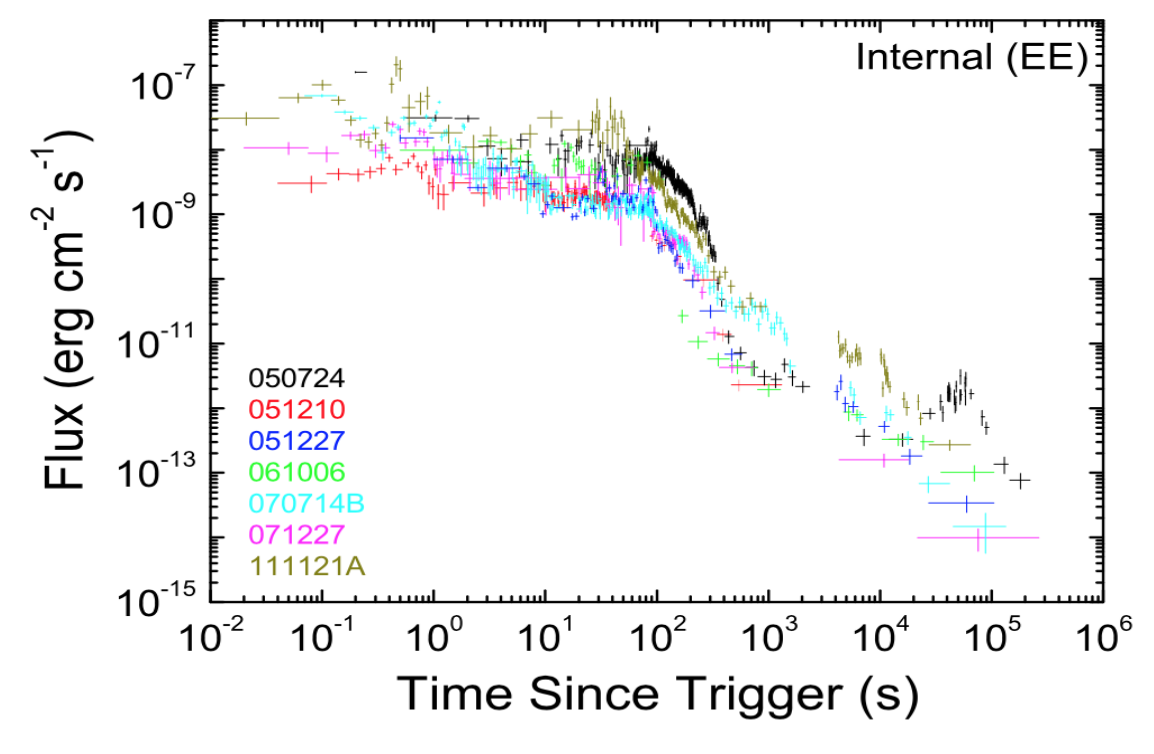
Dai et al. 2006, Fan & Gao 2006, Zhang 2013， Sun et al. 2017,2019

Internal plateau in short GRBs

- ✧ Internal plateau with decay slopes of -2 or steeper, implying a magnetar origin.
- ✧ Observed in the afterglows, no direct signatures in the prompt emission.



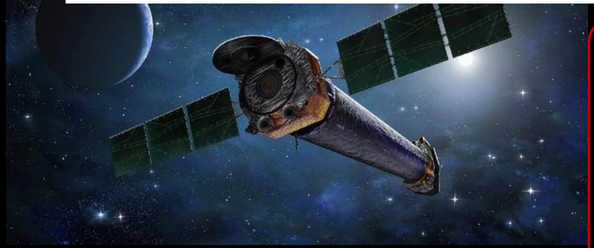
Rowlinson et al. 2010

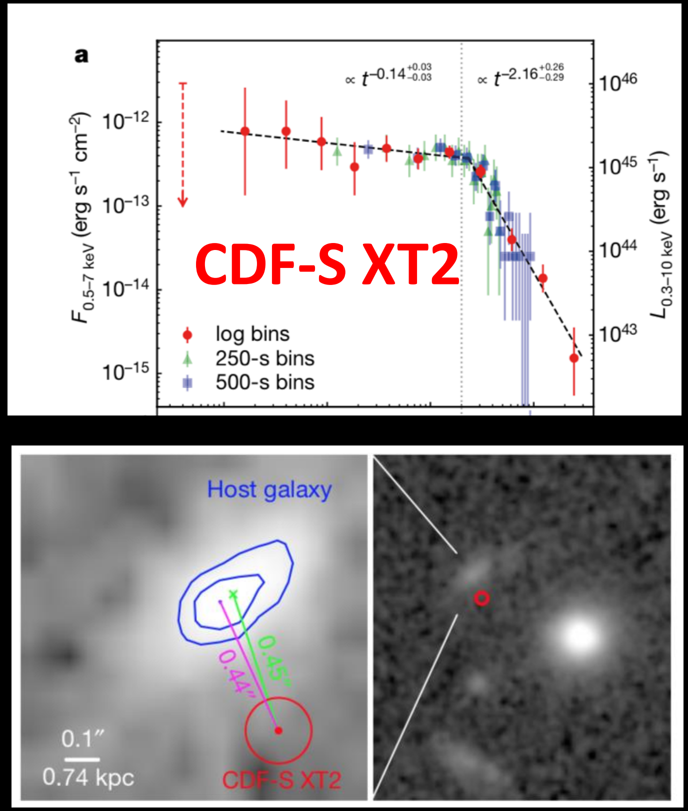


Lü et al. 2015

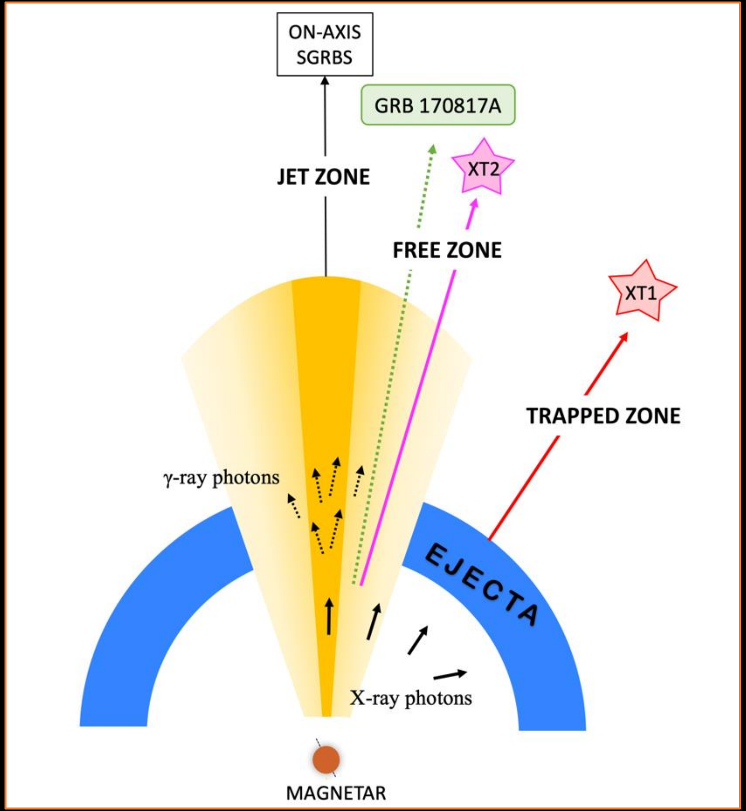
SGRB-less X-ray transients in archival data

The Chandra Deep Field South Luo et al. 2017





z~0.738, L_p~3e45 erg/s
Xue et al. 2019

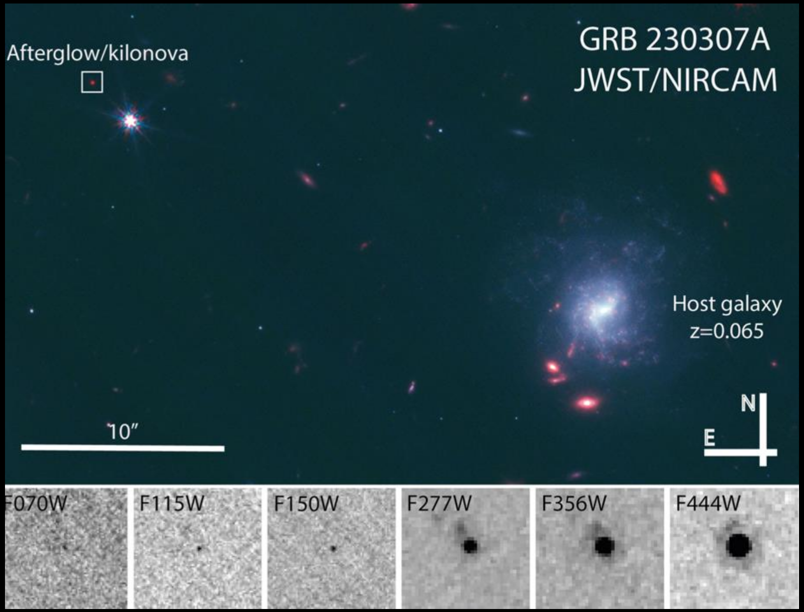


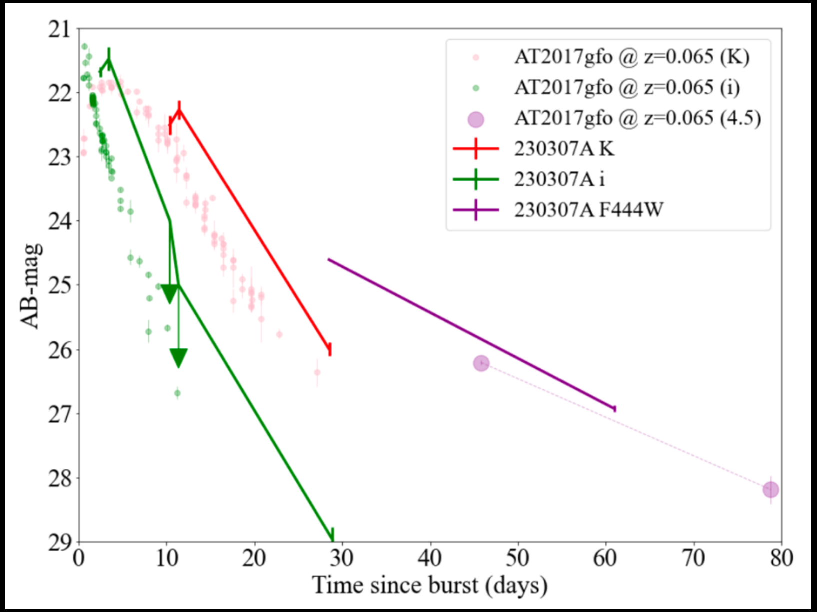
Sun et al. 2019

NO associated GRB/GW detection =>smoking gun evidence is still lacking

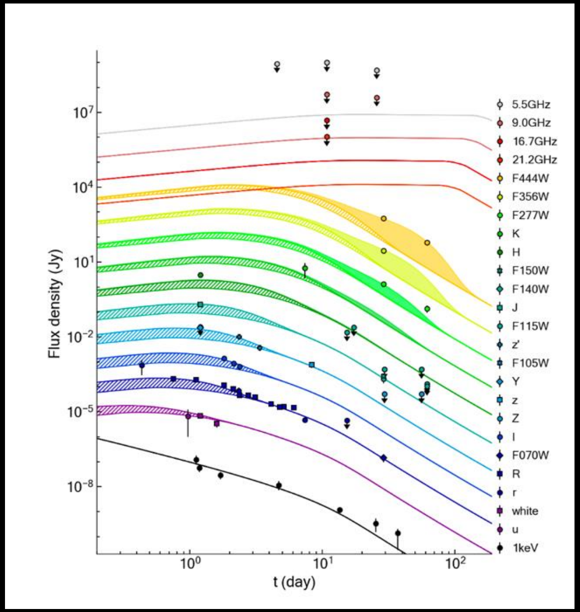
GRB 230307A: long GRB associated with a kilonova

- ✧ Long ($T_{90,\gamma} \sim 40s$) and extremely bright detected on 7 March 2023
- ✧ Kilonova signature detected by JWST
- ✧ Large off-set (36.6kpc) from its host galaxy at z=0.065





The multi-wavelength counterpart of GRB 230307A

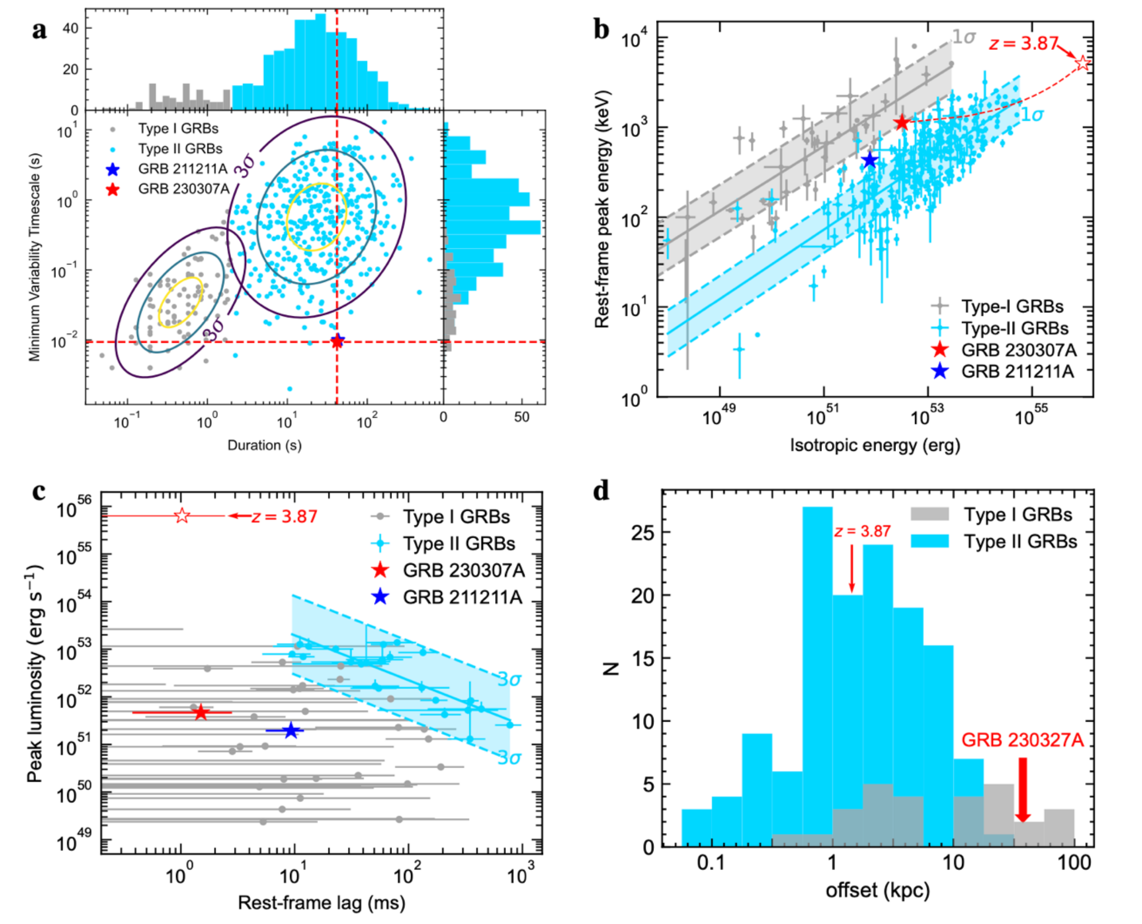


Levan et al. 2023, Nature

Yang et al. 2024, Nature

Broad-band (0.5–6000 keV) prompt emission

Observed Properties	GRB 230307A
Gamma-Ray [10–1000 keV]:	
Duration (s)	41.52 ± 0.03
Effective amplitude	1.23 ± 0.07
Minimum variability timescale (ms)	9.35
Rest-frame spectral lag*(ms)	$1.6^{+1.4}_{-1.2}$
Spectral index α_1	$-0.92^{+0.05}_{-0.03}$
Spectral index α_2	$-1.274^{+0.005}_{-0.008}$
Spectral index β	$-3.85^{+0.03}_{-0.09}$
Break energy E_b (keV)	24^{+3}_{-2}
Peak energy E_p (keV)	1052^{+16}_{-8}
Peak flux (erg cm^{-2} s^{-1})	$4.26^{+0.08}_{-0.07} \times 10^{-4}$
Total fluence (erg cm^{-2})	$(3.10 \pm 0.01) \times 10^{-3}$
Peak luminosity (erg s^{-1})	$4.64^{+0.09}_{-0.08} \times 10^{51}$
Isotropic energy (erg)	$(3.18 \pm 0.01) \times 10^{52}$
Soft X-Ray [0.5–4 keV]:	
Duration (s)	$199.6^{+5.1}_{-2.2}$
Spectral index α	$-1.70^{+0.06}_{-0.06}$
Peak flux (erg cm^{-2} s^{-1})	$3.6^{+0.6}_{-0.5} \times 10^{-7}$
Total fluence (erg cm^{-2})	$2.24^{+0.07}_{-0.06} \times 10^{-5}$
Peak luminosity (erg s^{-1})	$3.9^{+0.6}_{-0.5} \times 10^{48}$
Isotropic energy (erg)	$2.44^{+0.07}_{-0.06} \times 10^{50}$
Host Galaxy:	
Redshift	0.065
Half-light radius (kpc)	4.0
Offset (kpc)	36.60
Normalized offset	9.2
Probability of chance coincidence	0.11
Associations:	
Kilonova	Yes
Supernova	No



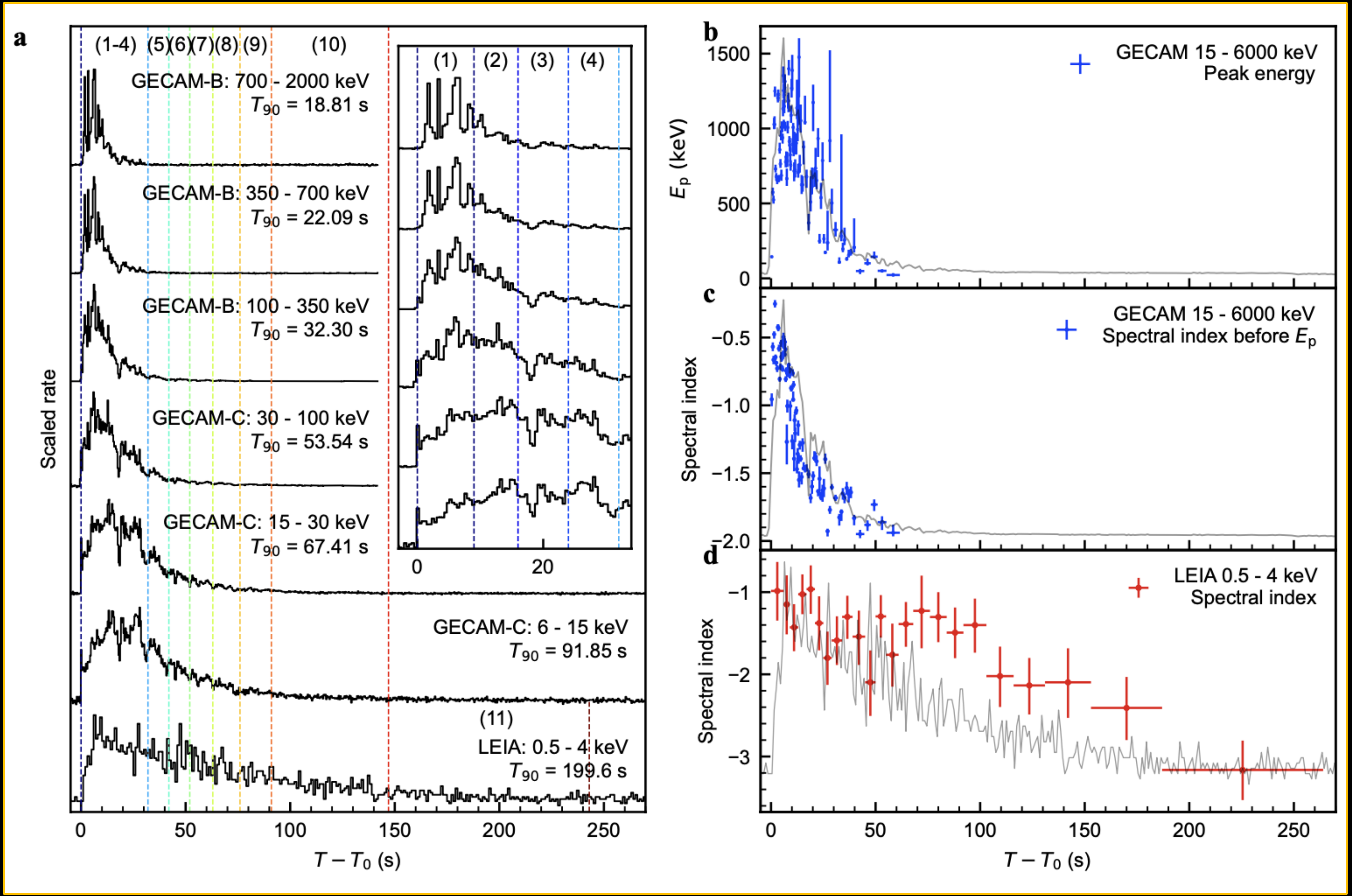
Type I: compact star merger origin

Type II: massive star core collapse origin

Zhang et al. 2009

The burst's placement on various correlation diagrams is consistent with the type I GRBs, as suggested by its association with a kilonova.

Broad-band (0.5–6000 keV) prompt emission

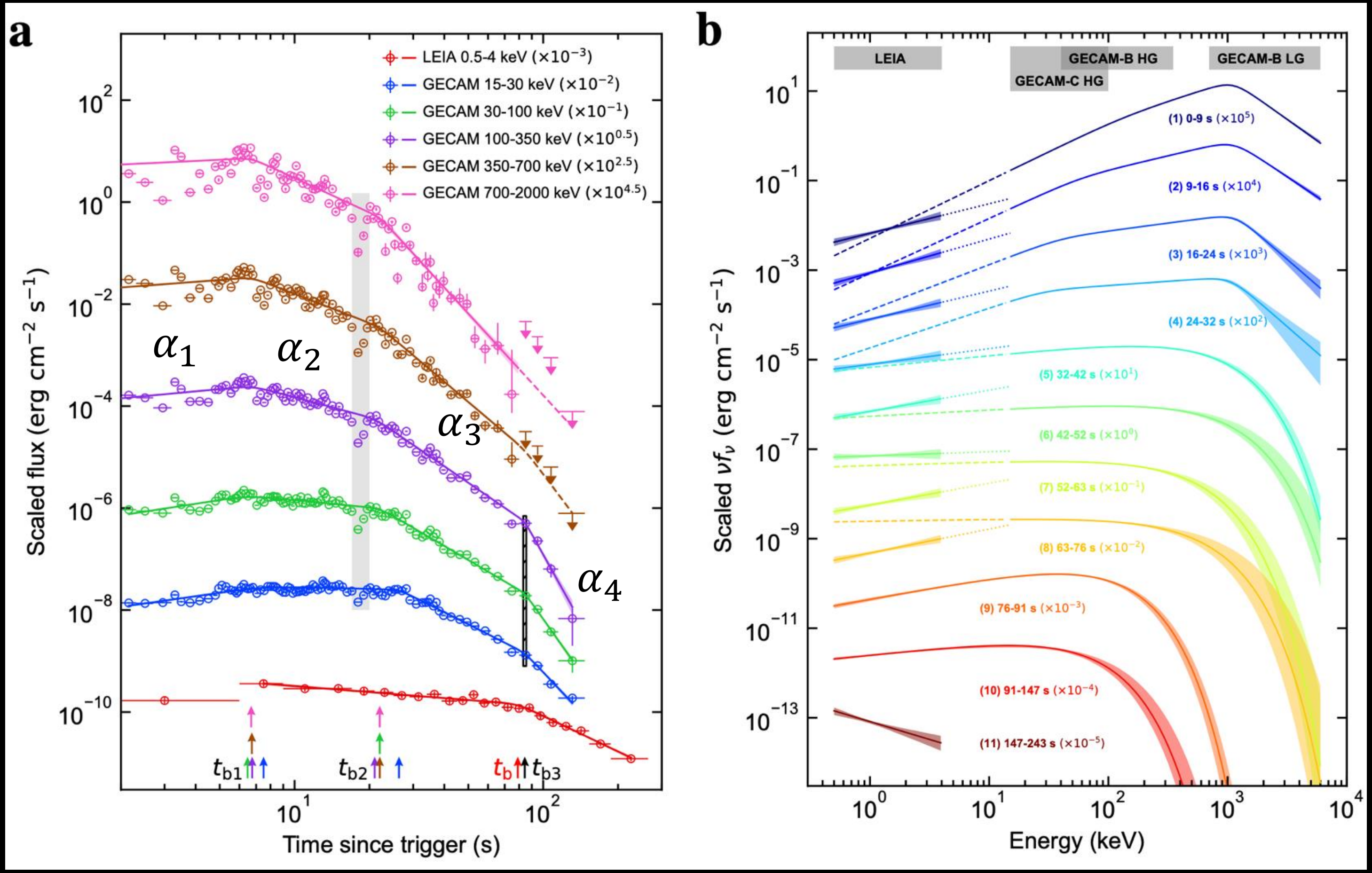


- ✧ **Hard X-rays and gamma-rays (GECAM, 15-6000keV)**
- ✧ synchronized pulses with matching peak and dip features
- ✧ "intensity tracking" pattern

- ✧ **Soft X-rays (LEIA, 0.5-4keV)**
- ✧ longer duration
- ✧ less significant evolution within the first 100 s

Comparison I

Distinct temporal and spectral behaviors



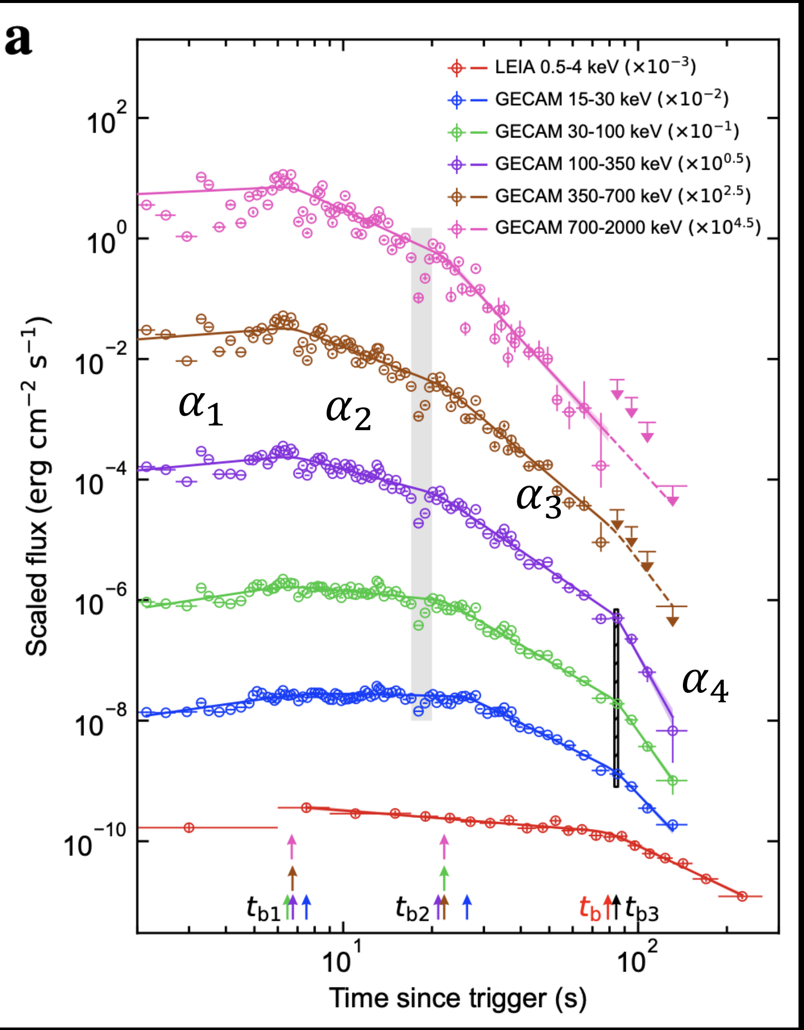
Log-log flux light curve

Spectral Energy Distribution

- ✧ Spectral shape deviates strongly from the extrapolation
- ✧ Plateau + shallower decline in soft X-ray

Comparison II

Distinct temporal and spectral behaviors



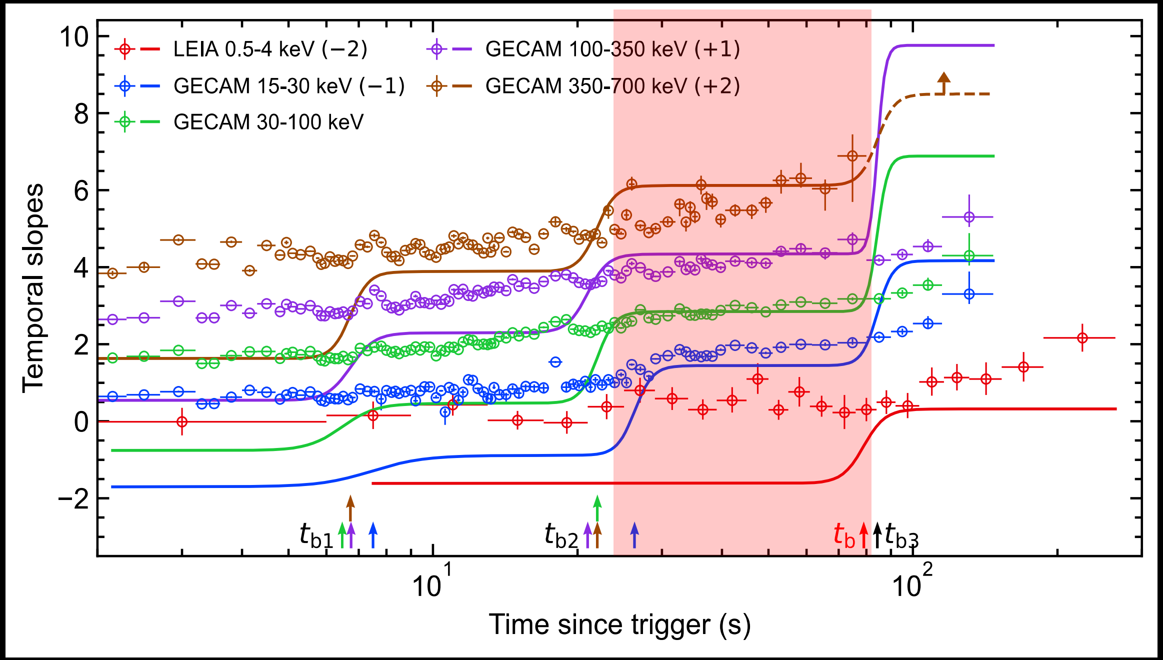
Log-log flux light curve

Gamma-rays (GECAM):

- **Curvature effect:** photons from higher latitudes arrive at the observer at progressively later epochs, defining a decaying lightcurve.
- **Edge effect of a narrow jet**

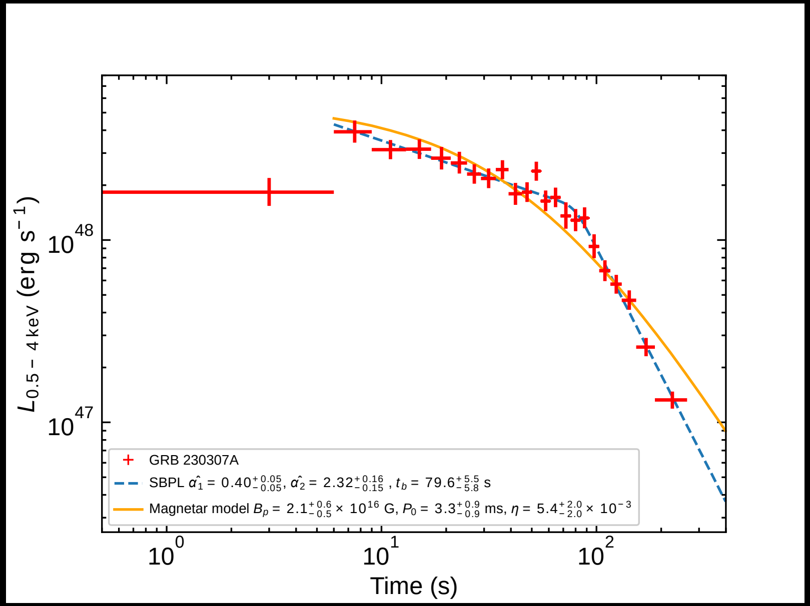
$\alpha \approx \beta + 2$

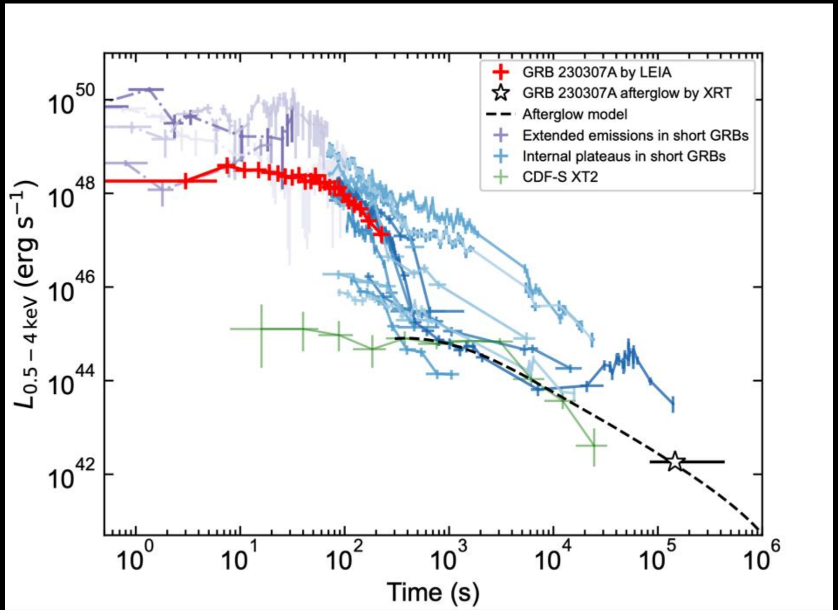
$F_\nu \propto t^{-\hat{\alpha}} \nu^{-\hat{\beta}}$

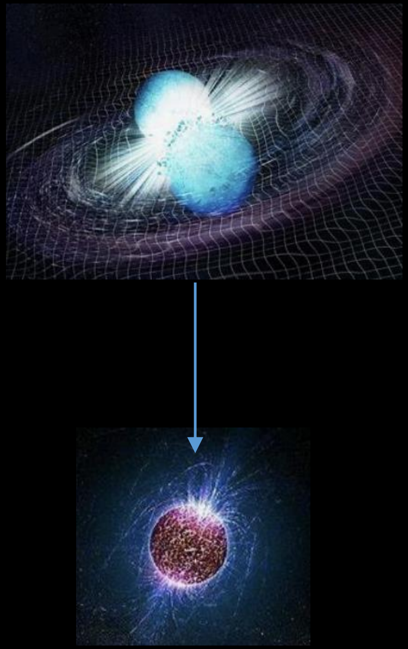


Magnetar emergence

- LEIA soft X-ray emission: a distinct component from the GRB
- Well explained by magnetar dipole radiation model
- Consistent with internal plateau but displays the whole light curve from the burst onset
- Direct evidence of a magnetar from binary compact star merger

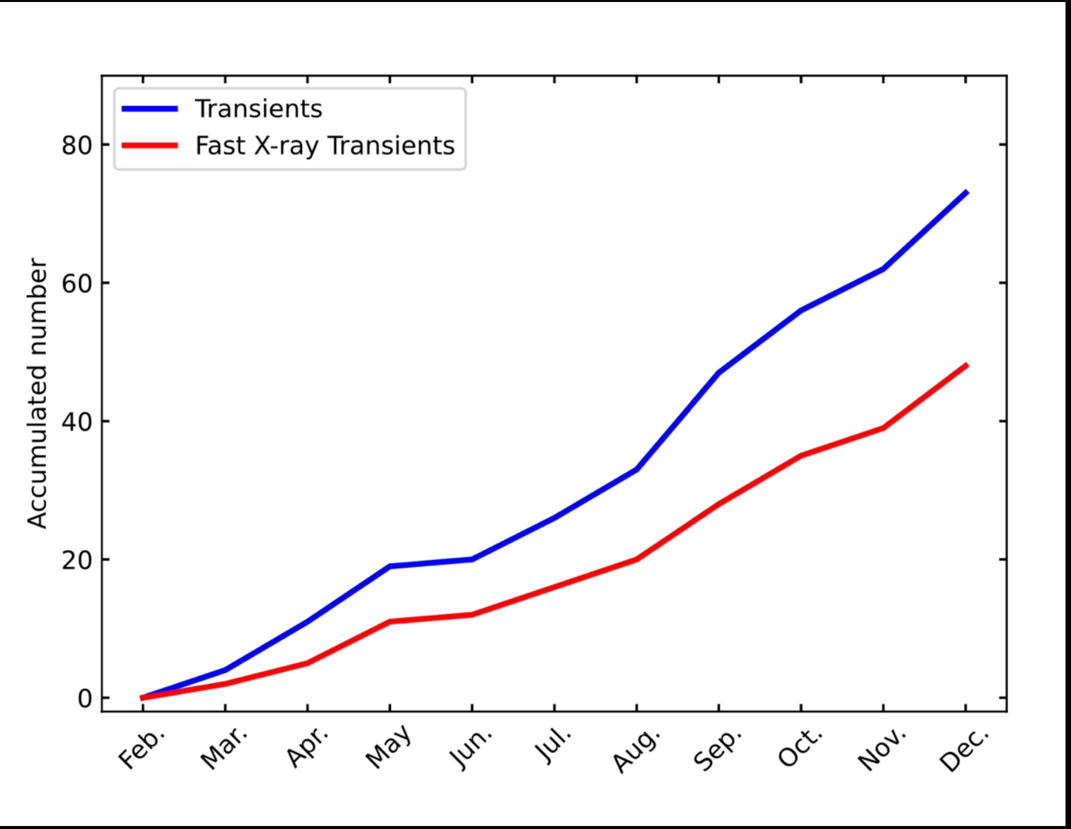


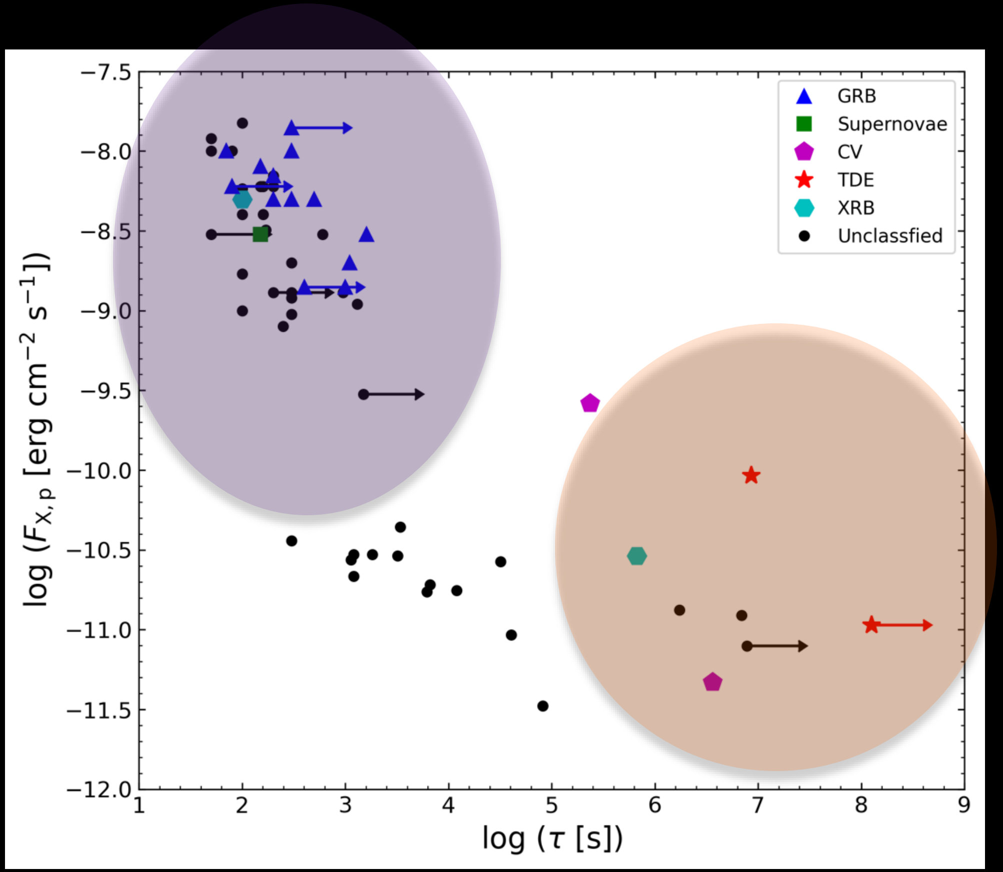




Fast X-ray transients detected with EP-WXT

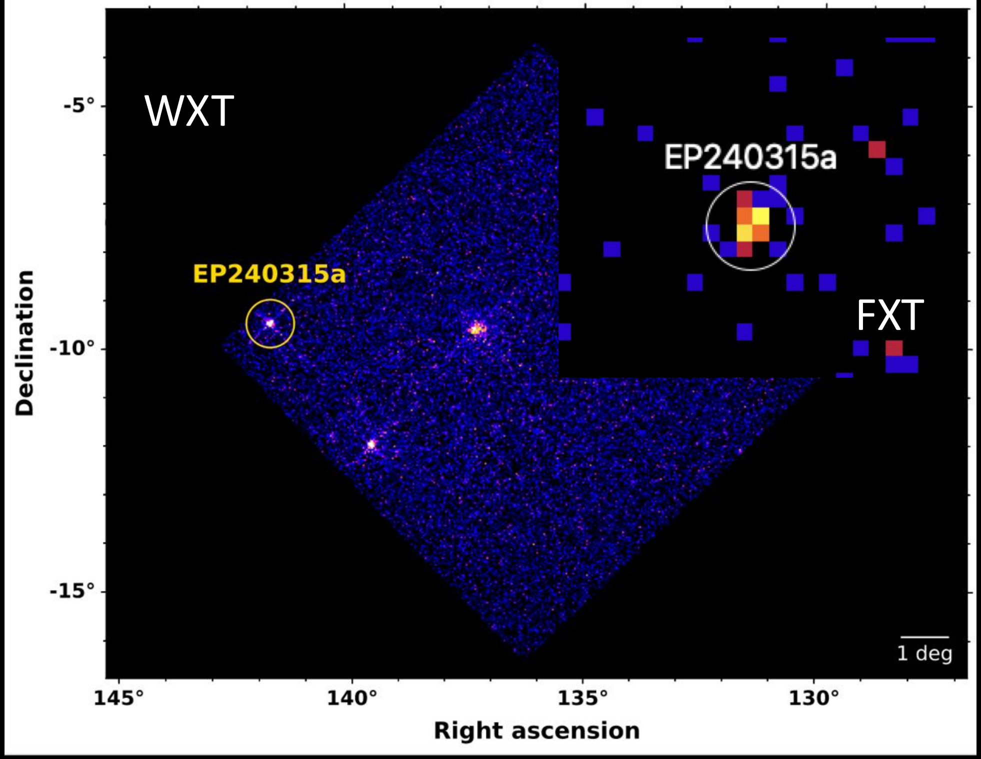
Since the launch, EP has detected around 80 X-ray transients with high S/N

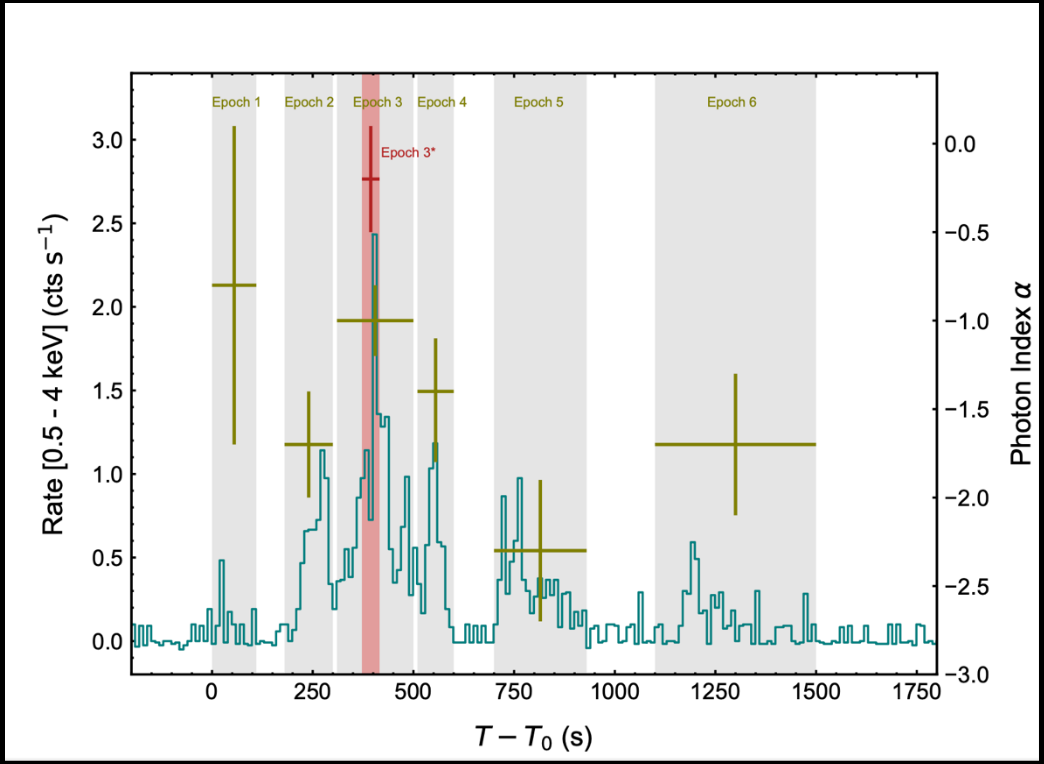




Dongyue Li's talk

EP240315a: 1st transient with measured redshift





✧ Redshift z=4.859

✧ Intense activity before γ-ray detection

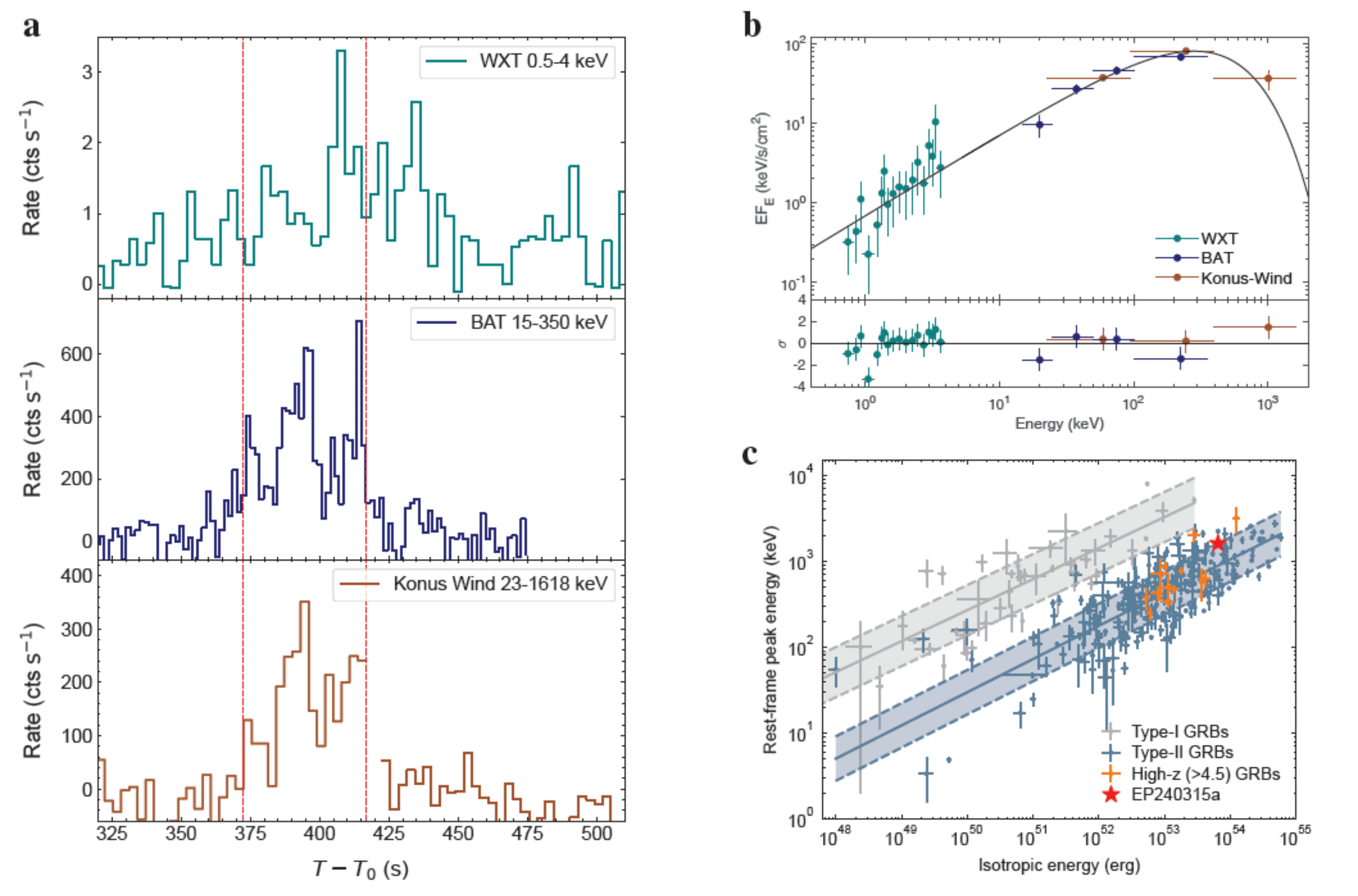
Marked difference in LC of soft X-ray and hard X/γ rays

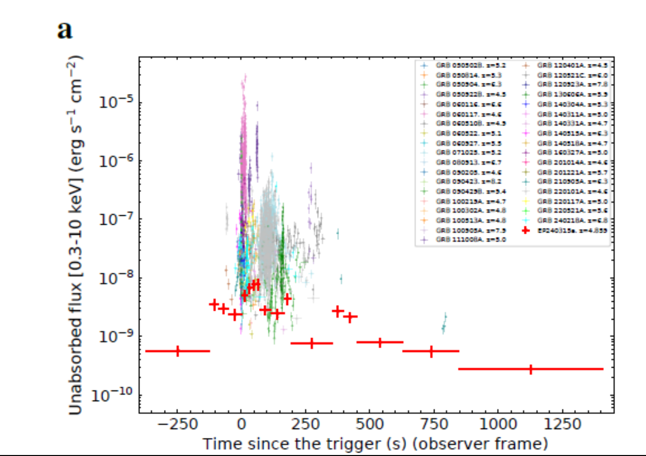
T90 (WXT) = 1034 ± 81 s

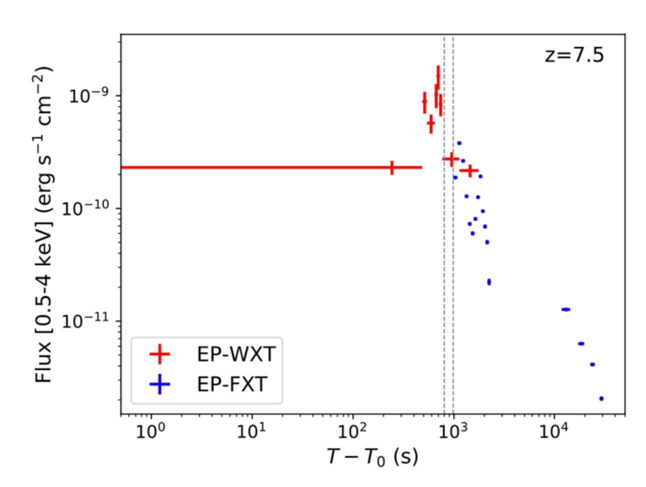
T90 (BAT) = 41.6 ± 1.6 s; T90 (KW) = 38 ± 3 s

Liu, Sun, Xu, et al. Nature Astronomy in press, arXiv:2404.16425

EP240315a: 1st transient with measured redshift



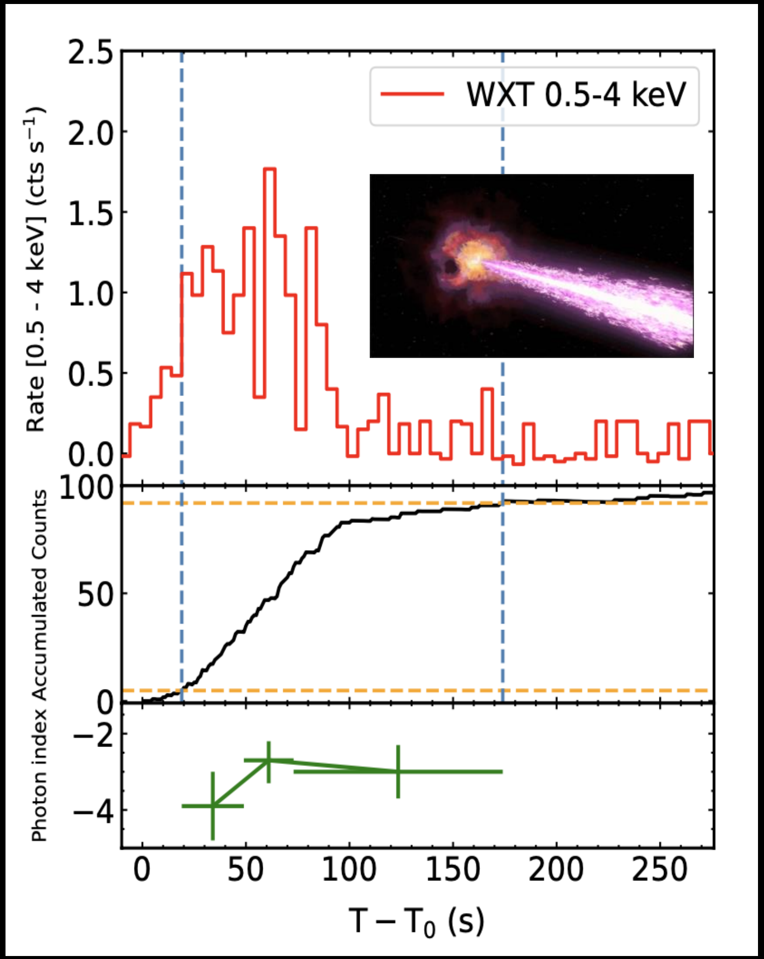


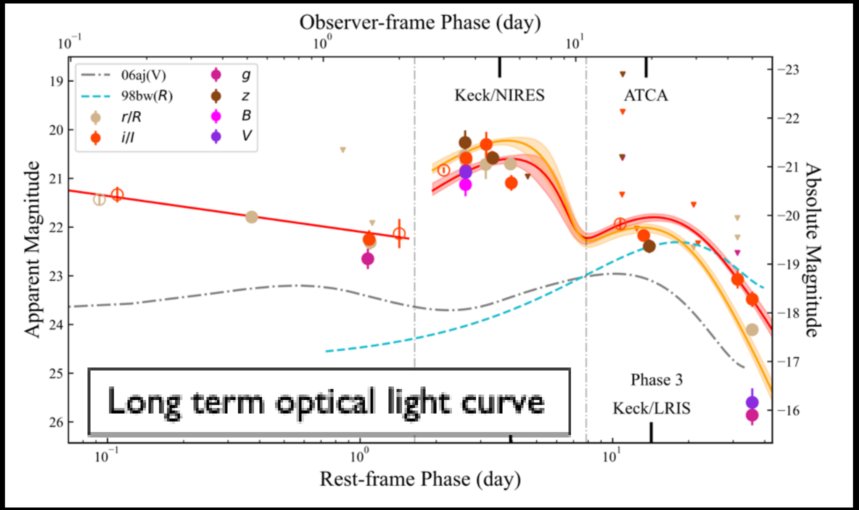


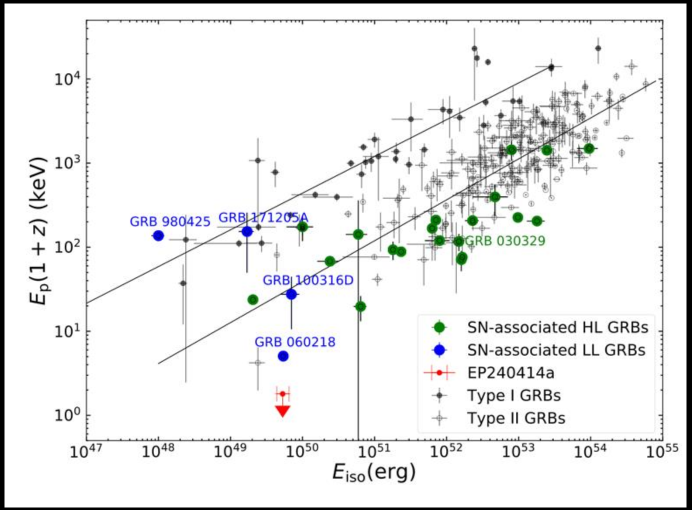
Detectable @ z=7.5

EP240414a: new type of extragalactic fast X-ray transient

- Only detected in soft X-rays, no γ-ray counterpart
- L_x, p = 1.3e48 erg/s
- Very soft energy spectrum Ep < 1.3 keV
- Associated of a Type Ic-BL SN 2024gsa (z = 0.4)
- A weak relativistic jet that interacts with an extended shell surrounding the progenitor star







Sun et al. 2024, submitted
arXiv: 2410.02315

Summary

- GRB 230307A: a peculiar, bright GRB with an extended X-ray emission component, signifying a magnetar central engine
- EP240315a: soft X-ray prompt emission (possible new insight into GRB central engine activity)
- EP240414a: a new type of X-ray transient associated with core-collapse of massive stars
- EP/LEIA has shed new light on the study of GRBs and fast X-ray transients.

Thank you for your attention!

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