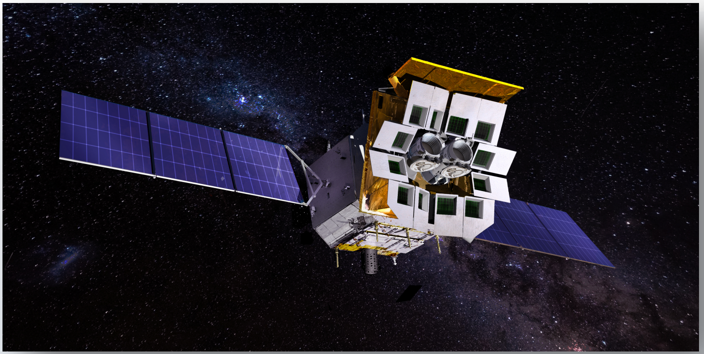

The Extragalactic High-energy Transients

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In this talk:

- ✧ "Well-known" extra-galactic high-energy transients
  - ✧ Models of event rate density and luminosity function
  - ✧ Simulations by Einstein Probe

- ✧ X-ray transients powered by magnetar from binary neutron star merger
  - ✧ Models
  - ✧ Candidates: CDF-S XT1 and XT2

Extra-galactic high-energy transient universe

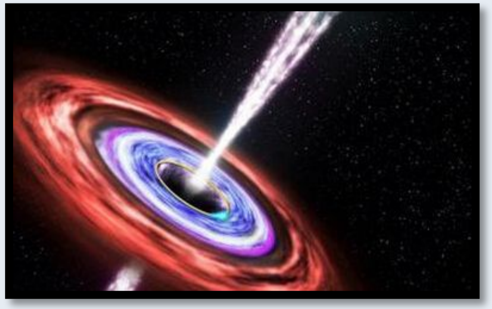
The high-energy transient universe, especially in X-ray band, is rich, Yet to be explored.

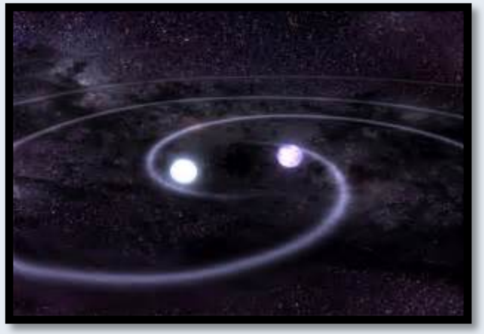
Well-known

- ✧ Gamma Ray Bursts (Low-luminosity -, long-, short -)
- ✧ SN Shock Breakouts
- ✧ Tidal Disruption Events (X-ray)

Emerging

- ✧ Magnetar powered X-ray emissions from binary neutron star merger



Transient characteristics

✧Transient, Explosive, High luminosity.

✦But relatively short duration, small amount of detections

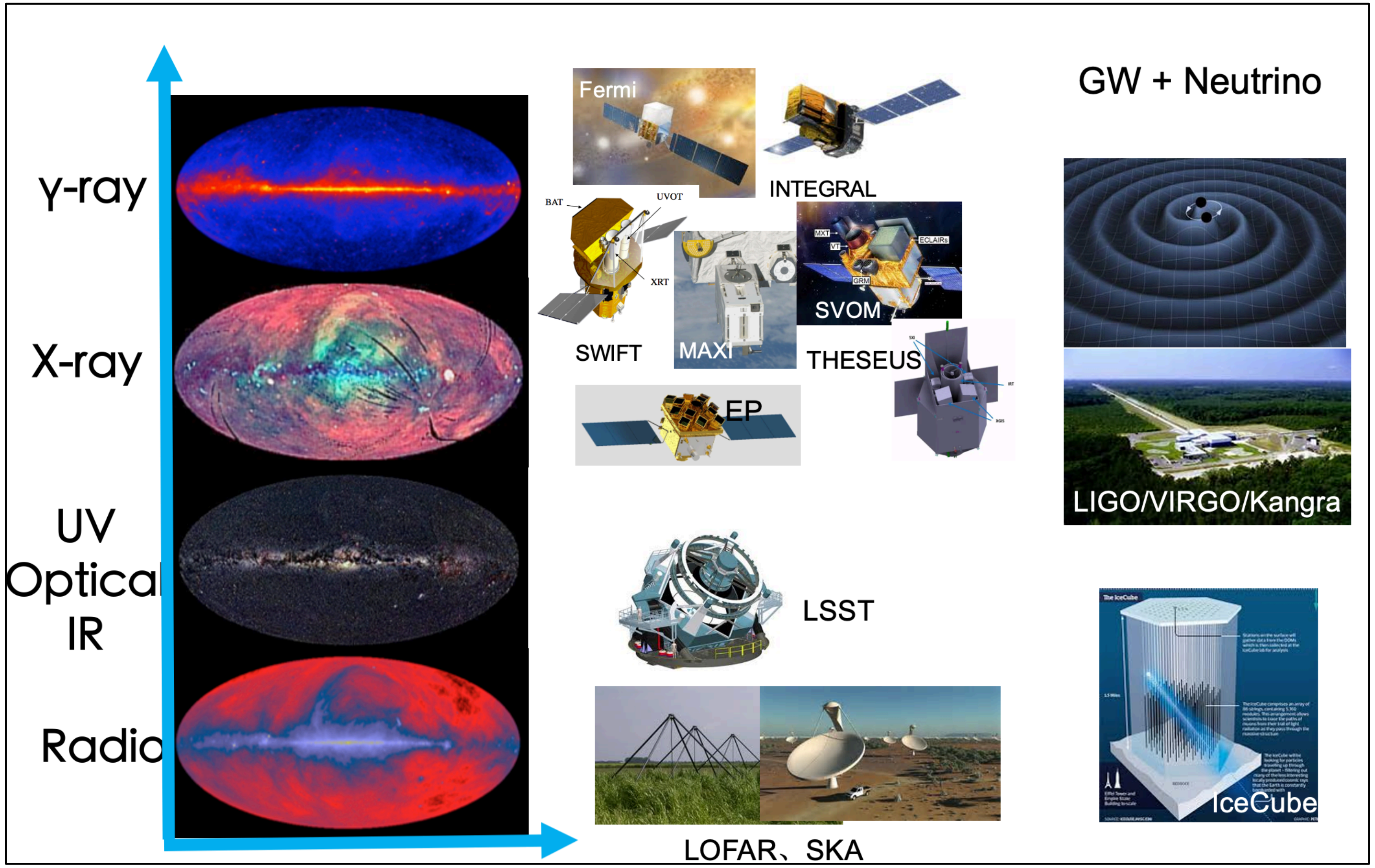
	long GRB		short GRB	SN shock breakout	Tidal disruption event /JETTED TDE
	LL-lGRB	HL-lGRB			
luminosity	10^{46}-10^{49} erg/s	10^{49} -10^{54} erg/s	10^{49} -10^{54} erg/s	10^{43}-10^{46} erg/s	10^{42}-10^{45} /10^{47}-10^{48} erg/s
duration	2s--~1000s	2s--~10^{4} s	<2s	10s to a few 1000s	peak ~ days to weeks, fade on years
event number	<10	~ 1200 [a] 300 with z	~120 [a] 26 with z	2+12 new	~ 20 normal TDEs 3 jetted TDEs

note(a): in Swfit GRB catalog

Motivation for rate and LF study

The study of event rate density and luminosity function is naturally expected

- ✧ Estimate the detectability for wide field of view telescopes.
- ✧ Models (**luminosity function** & redshift evolution) for related simulations.
- ✧ Multi-messenger estimations.
- ✧ Investigate unknown transients in archival data.



Method

It is feasible to obtain the event rate density ρ_0 and the normalized luminosity function $\Phi(L)$ from the observations taking into account the selection effects.

$$N_{det} = \frac{\Omega T}{4\pi} \times \int \Phi(L)dL \cdot \rho_0 V_{\max}(L)$$

$$V_{max}(L) = \int_0^{z_{\max}(L)} \frac{f(z)}{1+z}\frac{dV(z)}{dz}dz$$

$$F_{\rm th} = \frac{L}{4\pi D_{\rm L}^2(z_{\max})k}$$

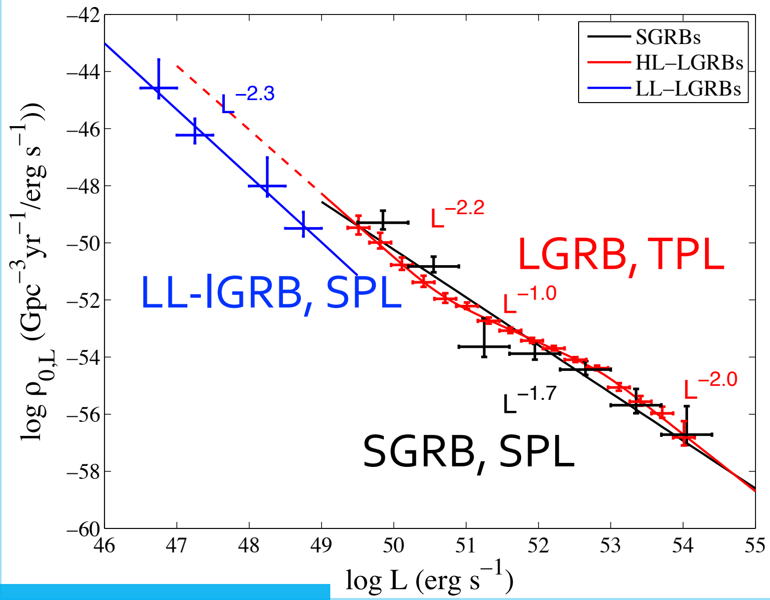
- ✧Observed sample N_{det}
- ✧Corrected by the sky and time coverage of instruments Ω, T
- ✧Redshift evolution models f(z)
  - ✧Star formation history for LGRB, SN SBO
  - ✧Supermassive black hole mass function evolution for TDE
  - ✧Merger model for BNS merger

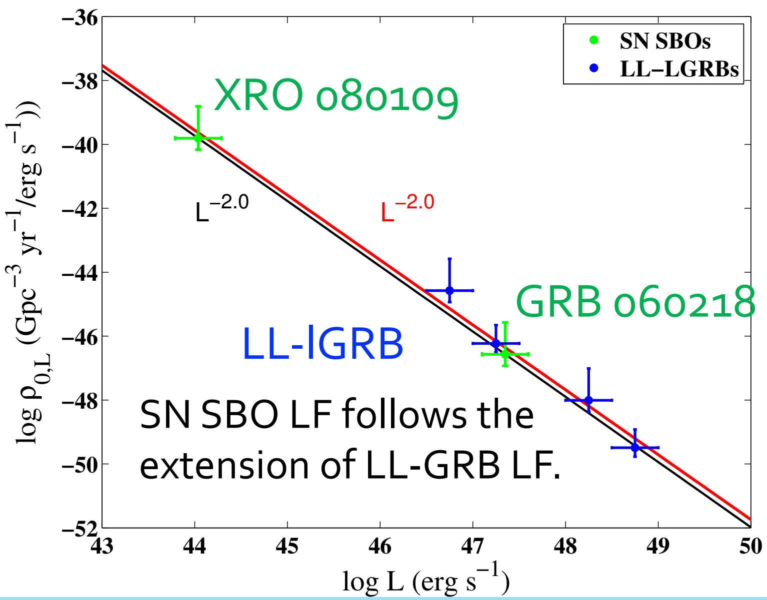
$$\rho_0\Phi(L) \simeq \frac{4\pi}{\Omega T}\frac{1}{\ln 10}\frac{1}{V_{\max}(L)}\frac{1}{L}\frac{\Delta N}{\Delta(\log L)}\,, \qquad \rho_0(>L_t) = \int_{L_t} \rho_0\Phi(L)dL$$

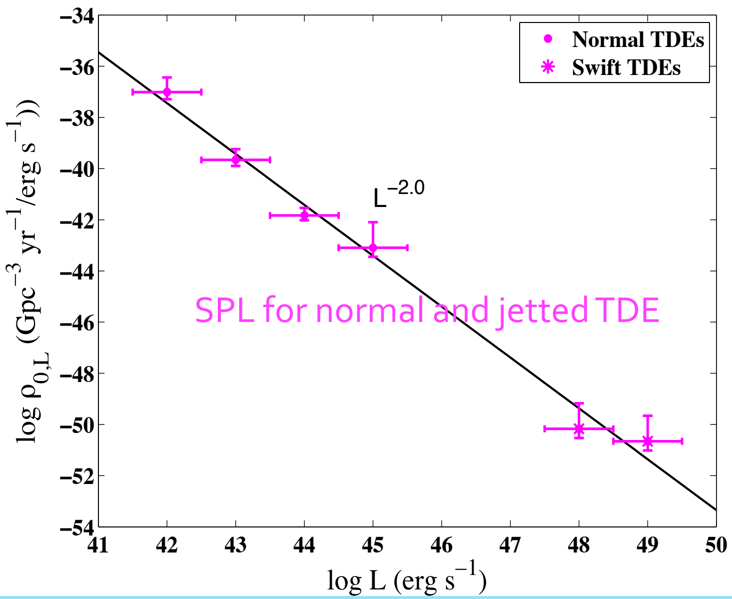
This method can be uniformly applied to the calculations of all type of transients.

Sun et al. 2015

Rate and LF for various tranisients







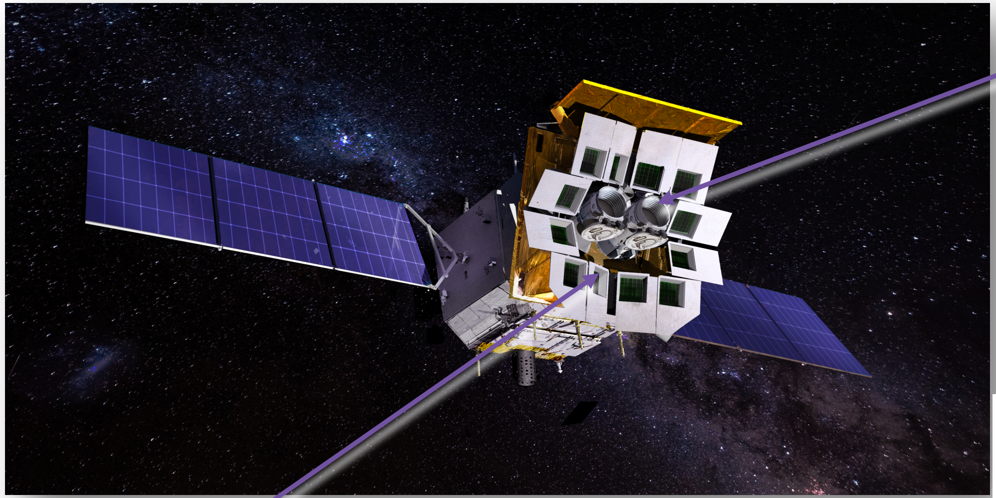
Luminosity functions

Event rate densities

Type	L_m (erg s^{-1})	$\rho_{0,>L_m}$ (Gpc^{-3} yr^{-1})
HL-LGRBs	3×10^{49}	$2.4^{+0.3}_{-0.3}$
LL-LGRBs	5×10^{46}	164^{+98}_{-65}
SGRBs (G)	7×10^{49}	$4.2^{+1.3}_{-1.0}$
SGRBs (LN)	7×10^{49}	$3.9^{+1.2}_{-0.9}$
SGRBs (PL)	7×10^{49}	$7.1^{+2.2}_{-1.7}$
SBOs	10^{44} [a]	$1.9^{+2.4}_{-1.2} \times 10^4$
TDEs	10^{42}	$1.0^{+0.4}_{-0.3} \times 10^5$
Swift TDEs	10^{48}	$0.03^{+0.04}_{-0.02}$

Sun et al. 2015

Detectability for Einstein Probe



http://ep.nao.cas.cn/

FXT (2 modules)

Follow-up X-ray Telescope

esa

Wolter-1 type + CCD

FoV: ~ 1 deg

band: 0.3-10keV

eff. area: 2x 300cm² @1keV

resolution: 30” (HPD)

WXT (12 modules)

Wide-field X-ray Telescope

esa

lobster-eye MPO + CMOS

FoV: 3600 sq deg (1.1 sr)

band: 0.5 – 4 keV

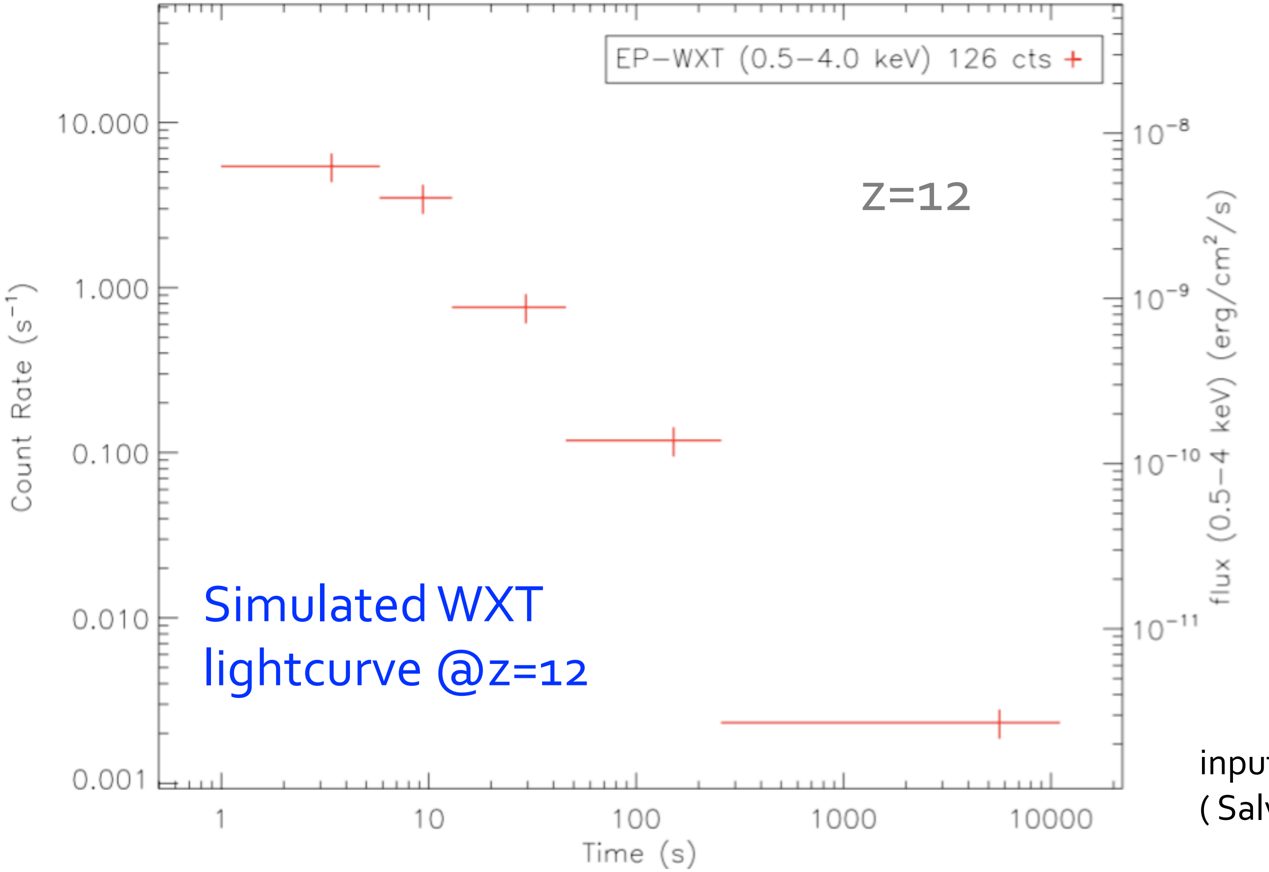
eff. area: ~3 cm² @1keV

resolution: ~ 5′ (fwhm)

Type of transients	detections per year
Tidal disruption event (TDE)	tens ~100
TDE with jet	10 ?
Supernova shock breakout	tens (?)
Long GRB	~ 80
High-z GRB (z > 6)	a few
Short GRB	~ 10
Low-luminosity GRB	~ 10

EP simulations of GRB at high redshifts

Swift GRB 090423 @z=8.2



Estimated detection rate per year:

~ 12 @z> 6

~ 3 @z>8

input LC from Swift BAT/XRT
(Salvaterra el. al., 2009)

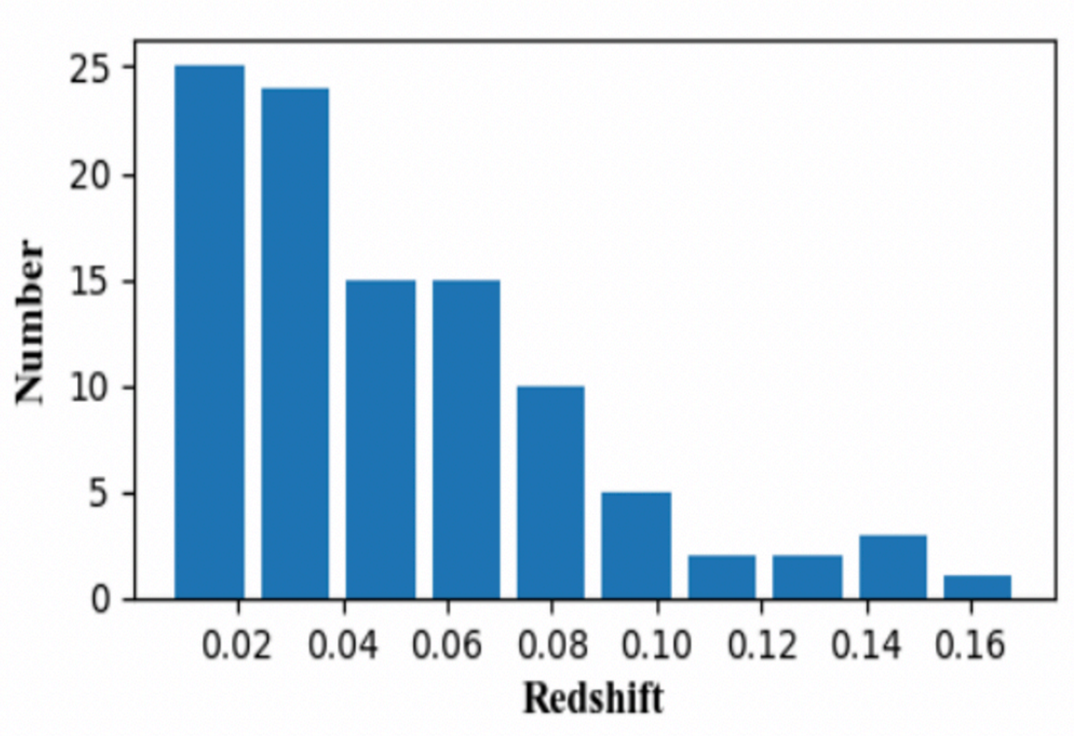
However, identifying them is challenging --> Theseus

EP simulations of tidal disruption event

✧Expected results:

- ✧Large, flux-limited samples of X-ray TDE (rate ~100 per year)
- ✧Some detected at early/rising phase
- ✧Well sampled X-ray light curves and spectra

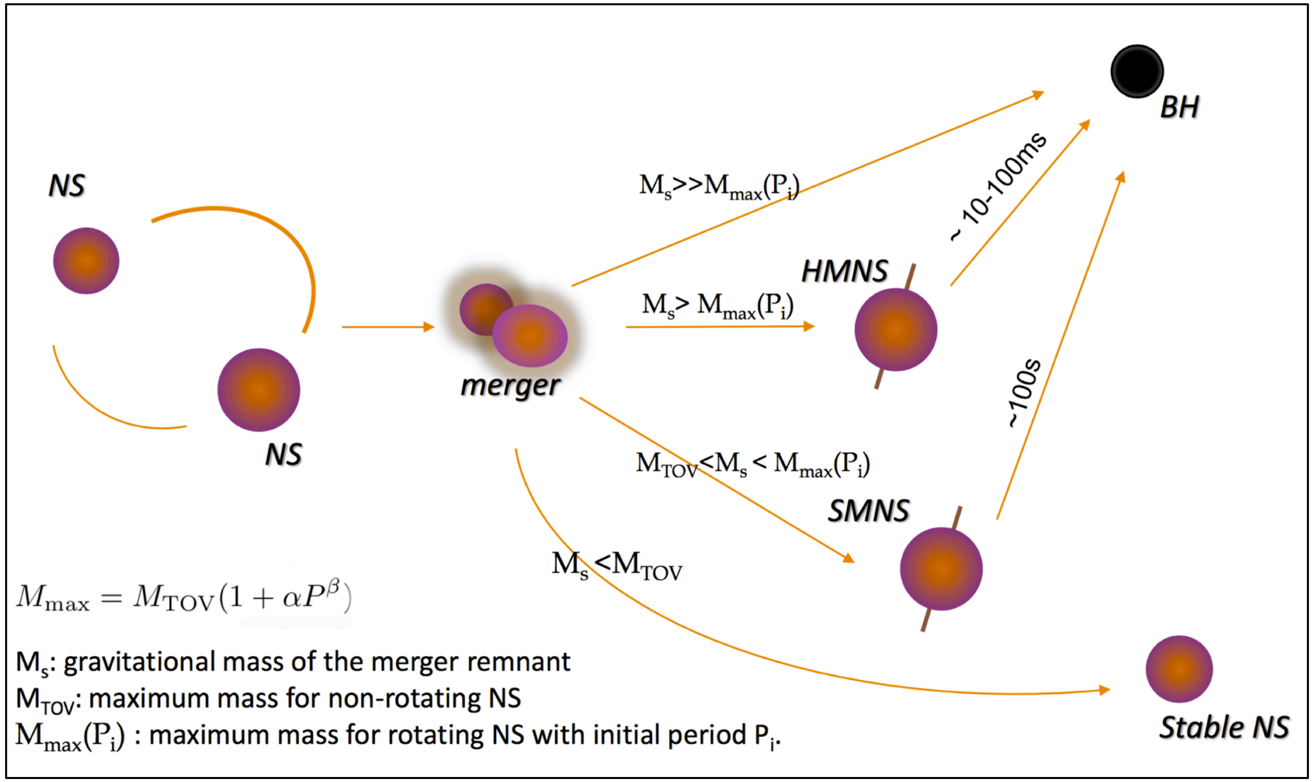
EP Simulated redshift distribution of TDE



X-ray transients from BNS merger magnetar

Binary neutron star (BNS) mergers can produce short Gamma-ray bursts (SGRBs), bright kilonovae, multi-wavelength afterglows (eg.. GW 170817, Abbott et al. 2017, Metzger 2017...)

- ✦ The merger product of the BNS merger can be
  - ✦ black hole
  - ✦ short-lived hypermassive NS
  - ✦ long-lived NS (supramassive NS or stable NS)
- ✦ Depending on the NS equation of state and the mass of merger remnant.

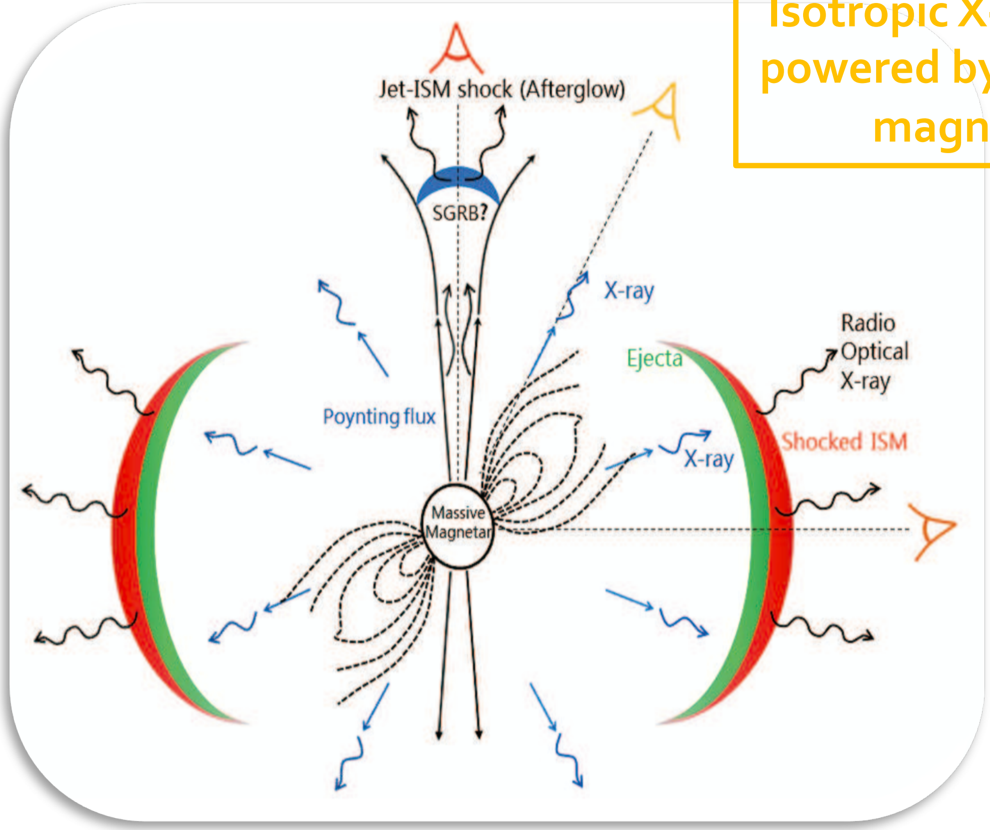


see Sarin & Lasky 2020 for a review

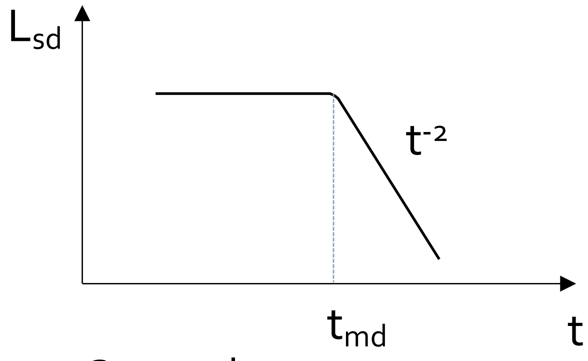
EM counterparts for Magnetar case

- ✧ The bright X-ray emissions are theoretically predicted lasting from several 100s to several 1000s.
- ✧ They are more like isotropic compared with on-axis SGRBs.
- ✧ Early X-ray detection can play a unique role in differentiate the post-merger products.

Isotropic X-ray emissions powered by dissipation of magnetic wind



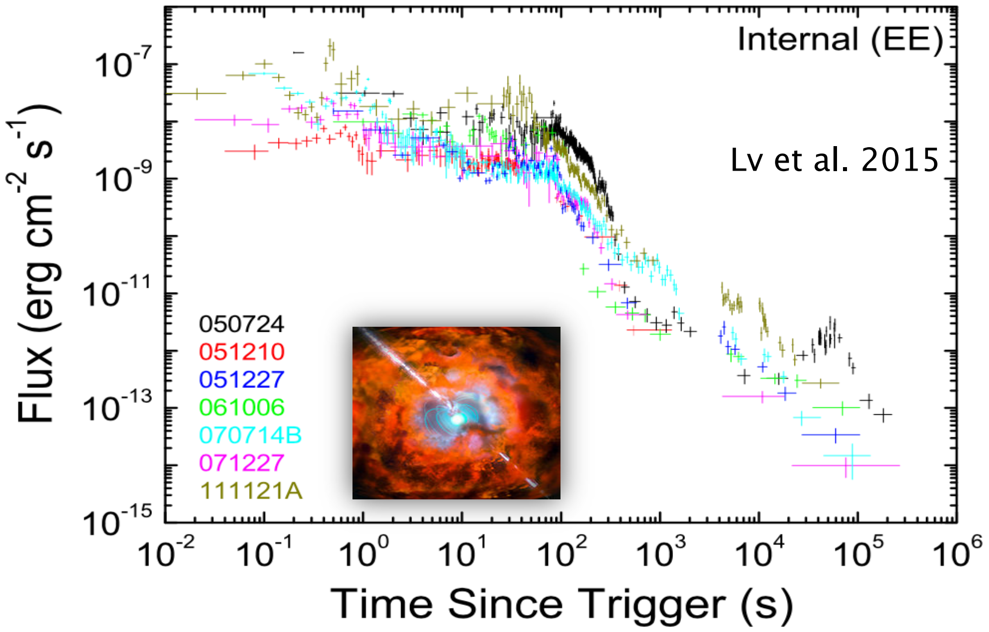
$$L_{\rm sd} = L_{\rm sd,i}\left(1 + \frac{t}{t_{\rm md}}\right)^{-2}$$



Zhang 2013, Gao et al. 2013

From SGRB afterglows (EE+IP) to SGRB-less X-ray transients

- The short GRB data are consistent with the hypothesis that the post-merger product of an NS–NS merger is a supra-massive neutron star.
- The existence of such a long-lived post-merger product opens some interesting prospects in the multi-messenger era.
- However, these GRB-related X-ray transients are rare due to the beaming constraint of GRBs.



From SGRB afterglows to SGRB-less X-ray transients

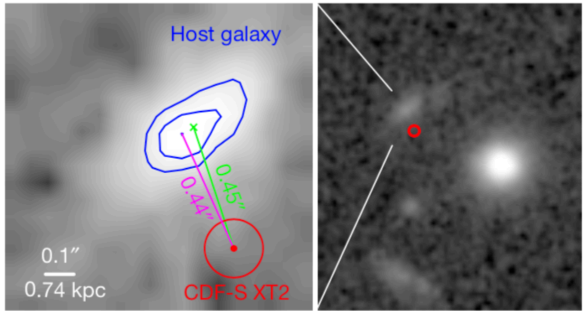
CDF-S XT2

L_{peak}(0.5-7keV) ~ 3×10^{45} erg/s

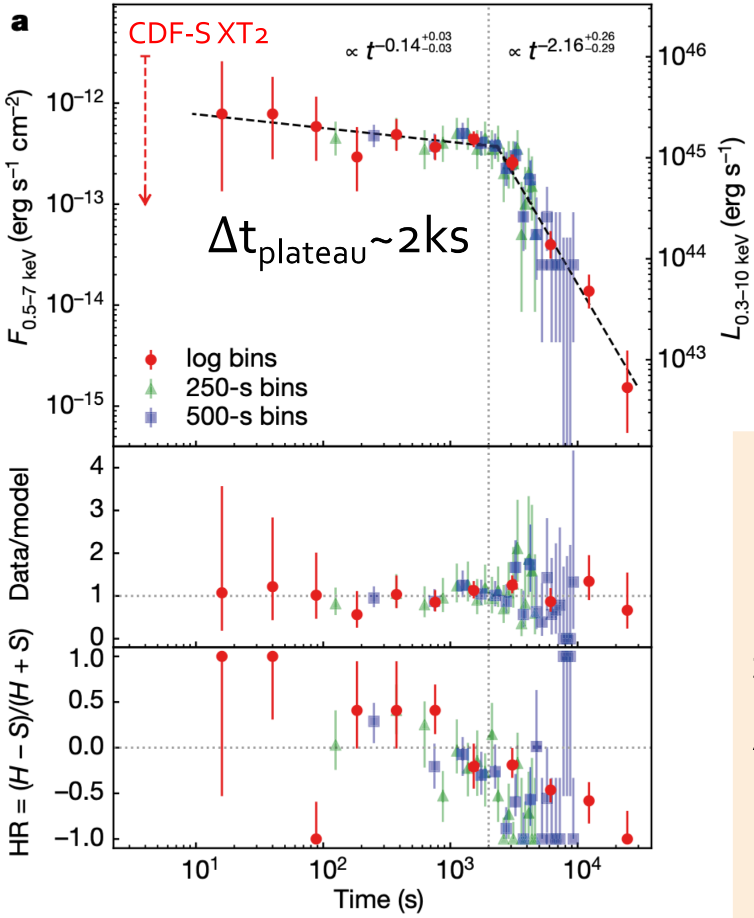
z = 0.738

outskirts of its star-forming host galaxy, as short GRBs often do

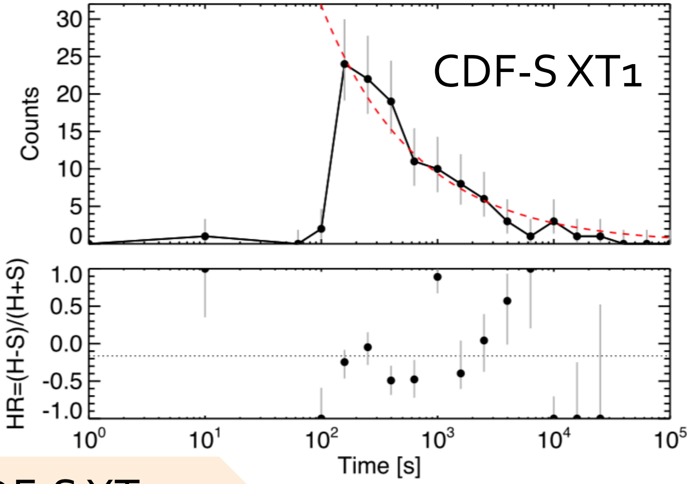
LC is fully consistent with the X-ray transient powered by a millisecond magnetar.



HST/CANDELS F125W-band image



Xue et al. 2019



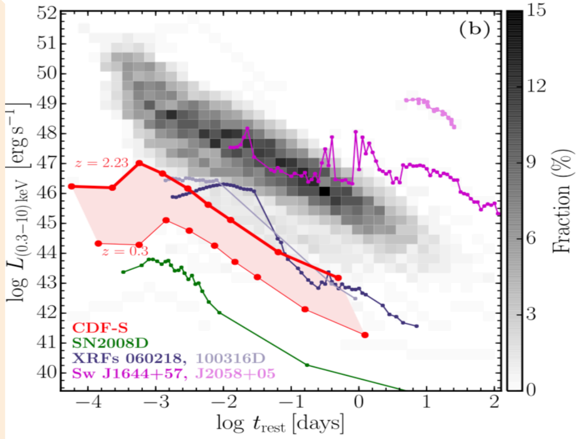
CDF-S XT1

L_{peak}(2-10keV) ~ 7×10^{46} erg/s

z_{ph} = 2.23

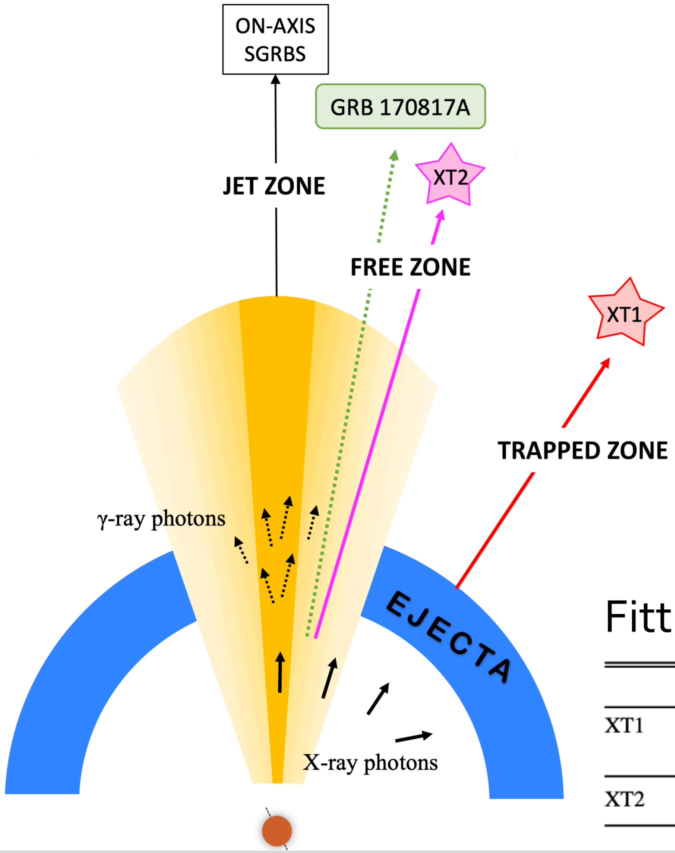
A new type of transient?

- ✧ Fainter than GRB afterglows
- ✧ Harder (kT > 5 keV at 3σ) than SN SBO
- ✧ Fast rise and harder than TDE

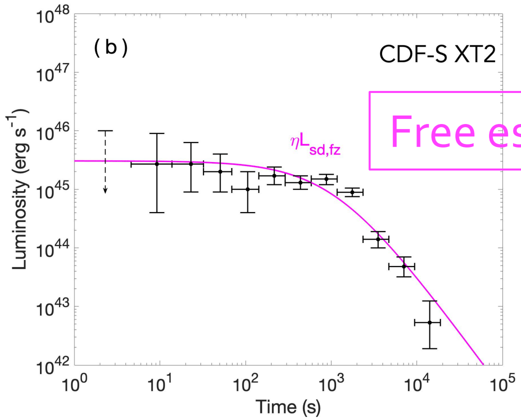


Unified magnetar model for CDF-S XT1 AND XT2

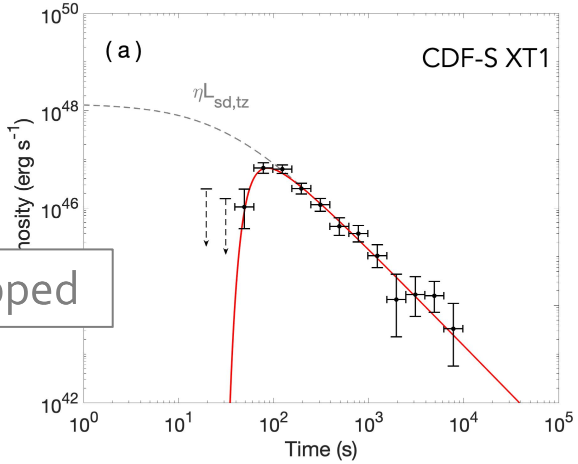
Geometry-dependent



Sun et al. 2019



Free escaping emission



X-ray got trapped

Fitting parameters:

	Viewing Direction	Redshift	L_p/(erg s^{-1})	Γ_p	B_p/(G)	P_i/(ms)	η	$M_{ej}/(M_\odot)$
XT1	Trapped Zone	2.23(z_{ph})	6.8×10^{46}	1.43	10^{16}	1.2	0.001	0.001
XT2	Free Zone	0.738	2.7×10^{45}	1.93	$10^{15.8}$	4.4	0.001	...

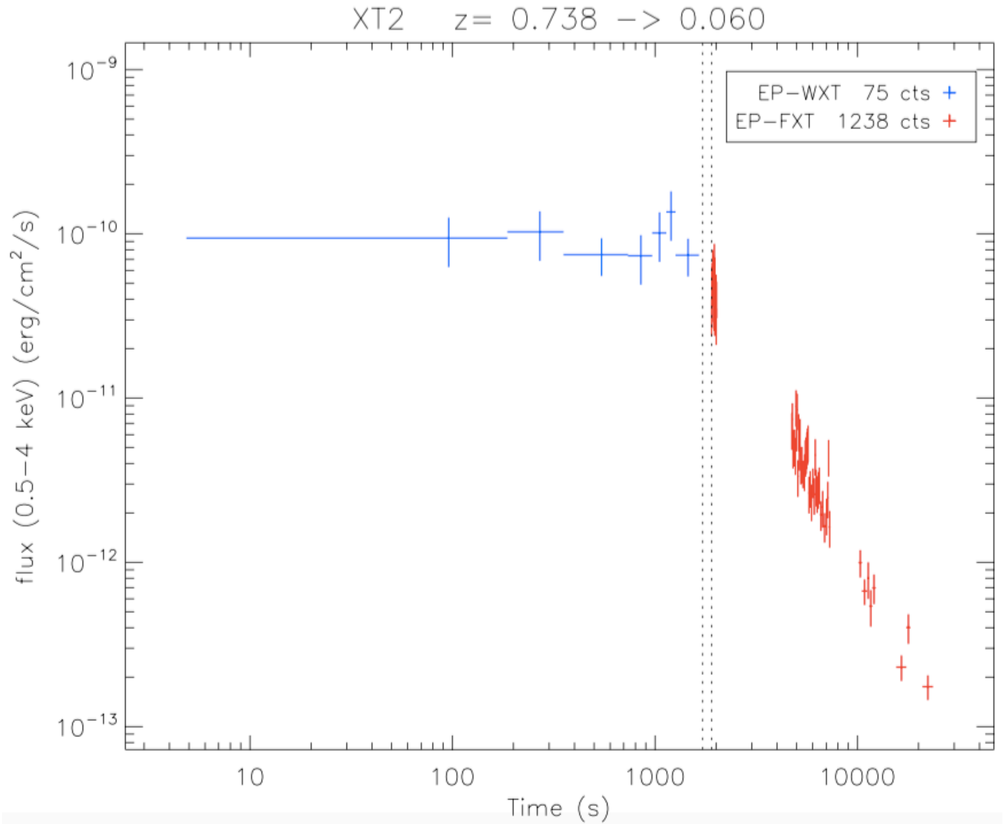
✧ The event rate densities for XT1 (~ 1100^{+2500}_{-900} Gpc^{-3}yr^{-1}) and XT2 (~ 1400^{+3300}_{-1200} Gpc^{-3}yr^{-1}) are consistent with that of BNS mergers from GW 170817 (1540^{+3200}_{-1220} Gpc^{-3} yr^{-1}, Abbott et al. 2017).

✧ It is implied that a fair amount of BNS leave a magnetar as a product, i.e. the M_{TOV} cannot be too small…

Gao et al. 2016

EP detectability of XT2-type X-ray transients

Simulated EP observation of XT2 @ 250 Mpc



- ✧ detectable up to ~300Mpc (z~0.07), match LIGO/VIRGO horizon
- ✧ expected rate: 2 – 40 per year (with possible joint GW detection)

Summary

✧ The event rate density and luminosity function are provided for references of detectability predictions.

✧ Wide field high-energy telescopes, like Einstein Probe and THESEUS, will largely increase the number of extragalactic high-energy transients.

✧ If a fair amount of BNS leave a magnetar, one can expect the increasing detections of the magnetar-powered X-ray transients.

✧ The unified models can also be tested by future observations.

Thanks !