The new era of extragalactic Fast X-ray Transients

Jonathan Quirola-Vásquez
Radboud University-The Netherlands, Gruber-IAU fellow

Collaborators: P. Jonker, F. E. Bauer, A. Levan, W. Brandt, M. Ravasio, J. Sanchez, D. Eappachen, J. van Dalen, J. Chacon, A. van Hoof,…

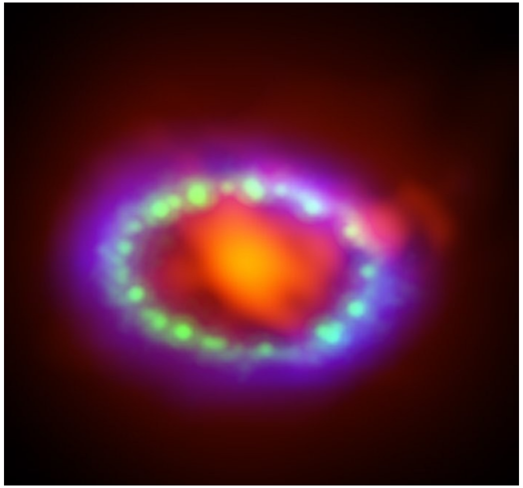
Radboud Universiteit

High Energy Astrophysics and Cosmology in the era of all-sky surveys

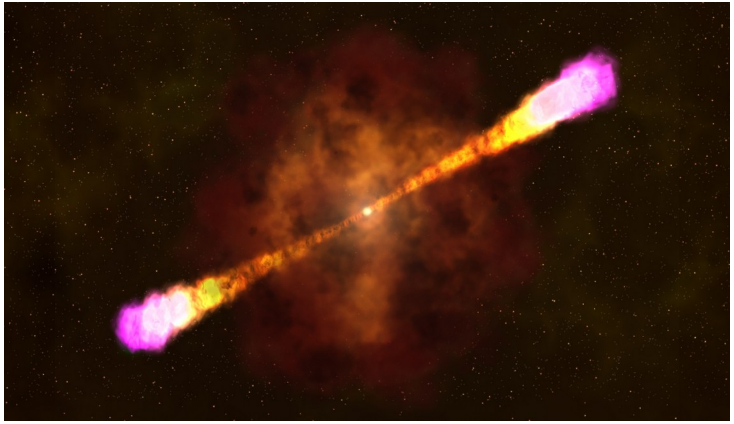
Introduction

Transients refer to astronomical phenomena with durations of fractions of a second to weeks or years

Fast Radio Bursts (FRBs)



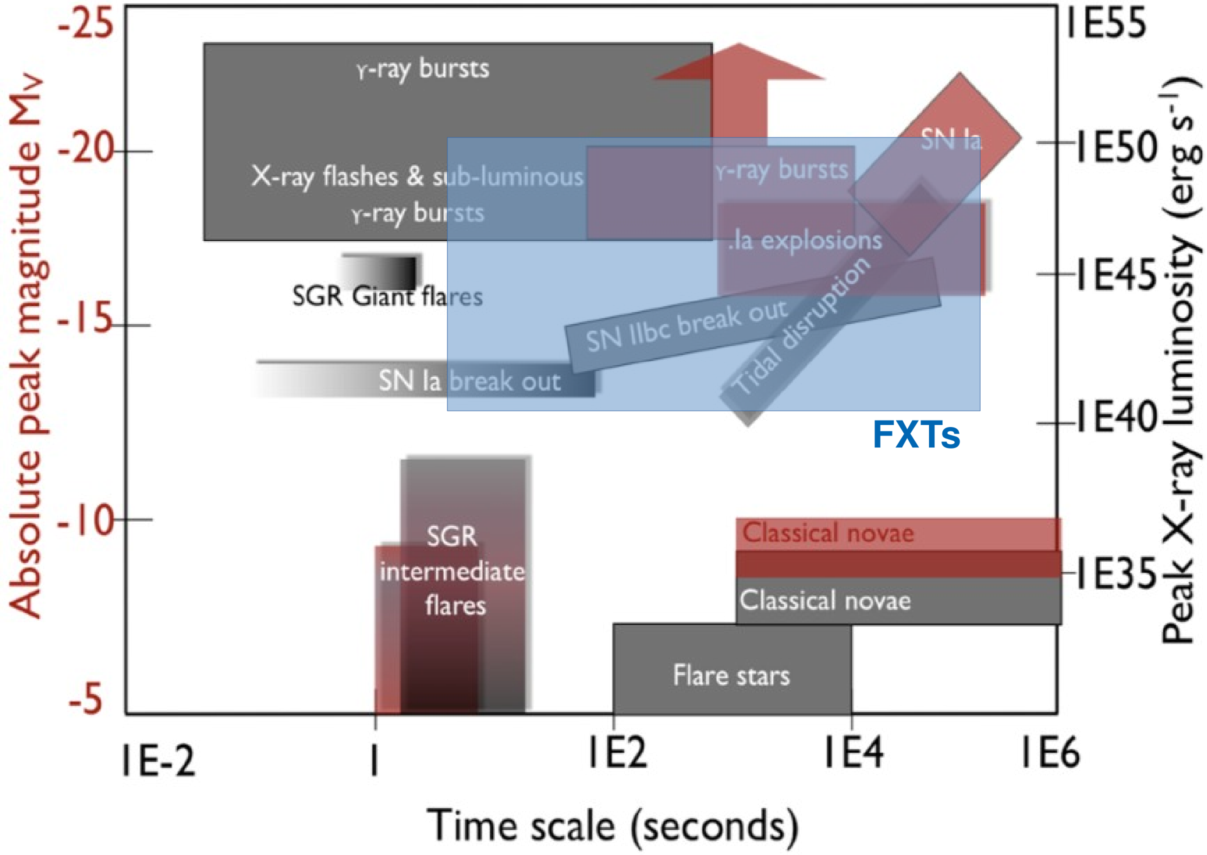
Supernovae (SNe)



Gamma-Ray Bursts (GRBs)

Introduction

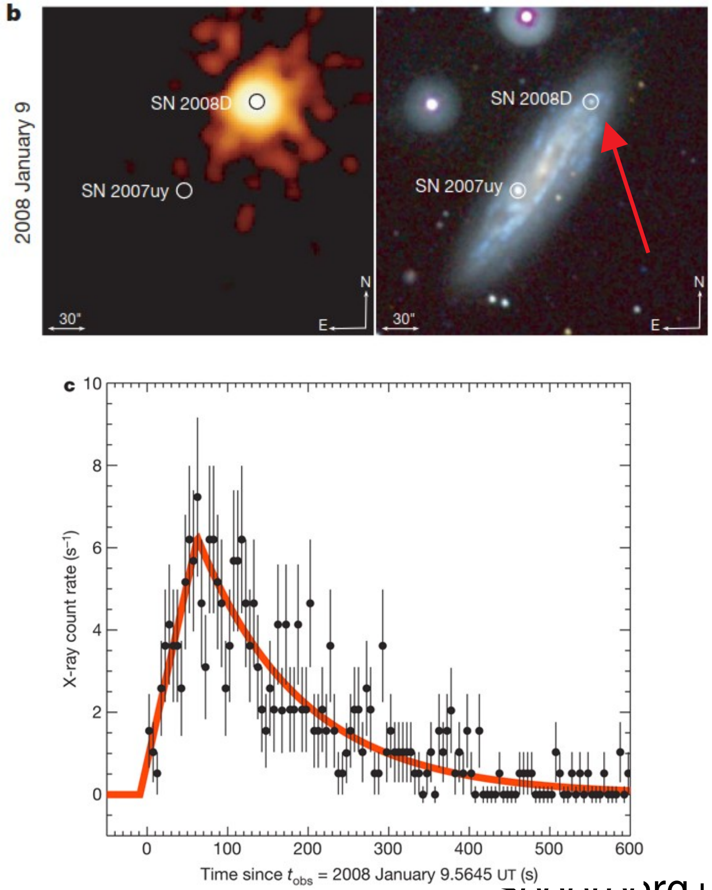
- X-ray transients are related with a huge range of astronomical objects (stars, NSs, AGNs) over a large time range.
- Time-domain astronomy is experiencing tremendous growth, particular in response to potential for multi-messenger events.
- Extragalactic Fast X-ray Transients (FXT) potentially probe a unique range of astronomical events.



The majority of the diagram is theoretical

Possible origins: SBOs

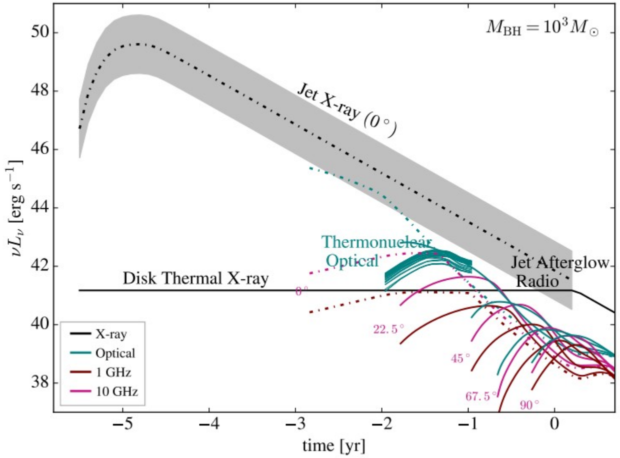
- A shock breakout (SBO) from a core-collapse supernova.
- The X-ray SBO emission is generated from the SN explosion shock once it crosses the surface of a star (e.g., Soderberg et al. 2008; Novara et al. 2020; Alp & Larsson 2020).
- In early 2008, while following up SN2007uy, Swift/XRT captured an X-ray flash, which coincided with an electromagnetic counterpart, the Type Ibc SN 2008D.



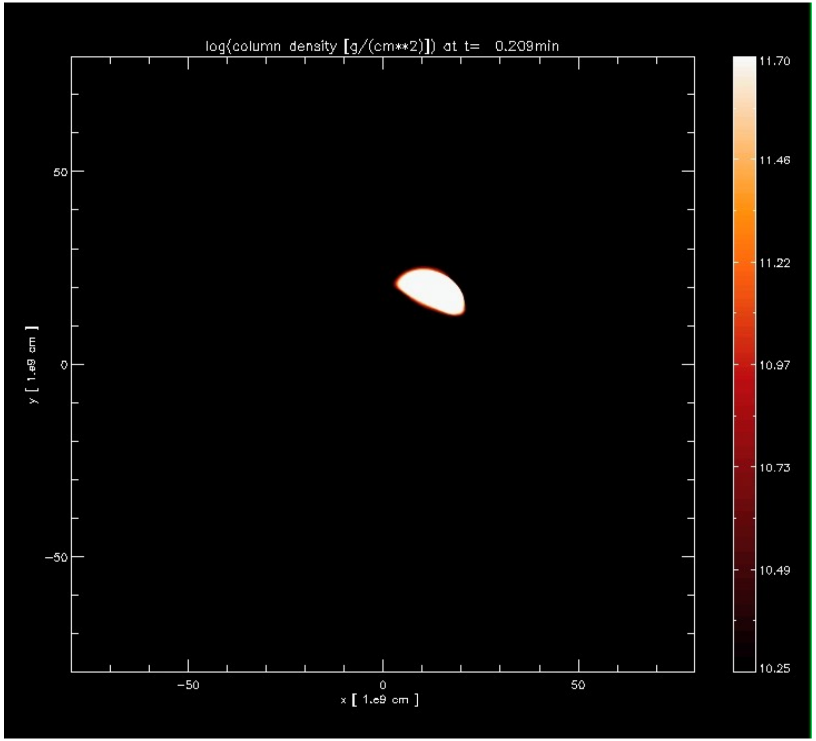
Soderberg+, 2008

Possible origins: TDEs

- A tidal disruption event (TDE) involving a white dwarf (WD) and an intermediate-mass black hole (IMBH)
- The X-rays are produced by the tidal disruption and accretion of the compact WD in the gravitational field of the IMBH (e.g., **Jonker et al. 2013**; Glennie et al. 2015).



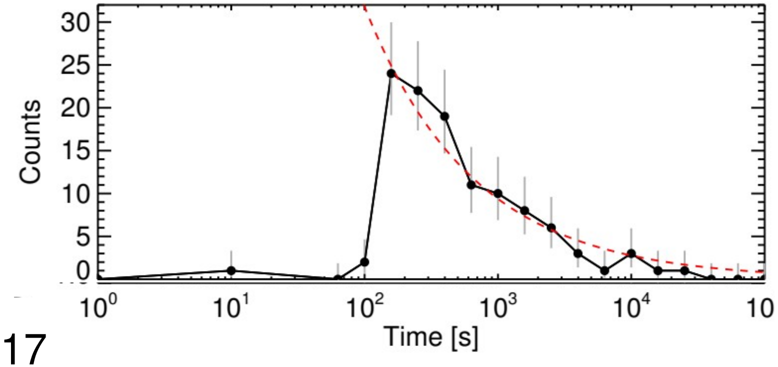
MacLeod+, 2016



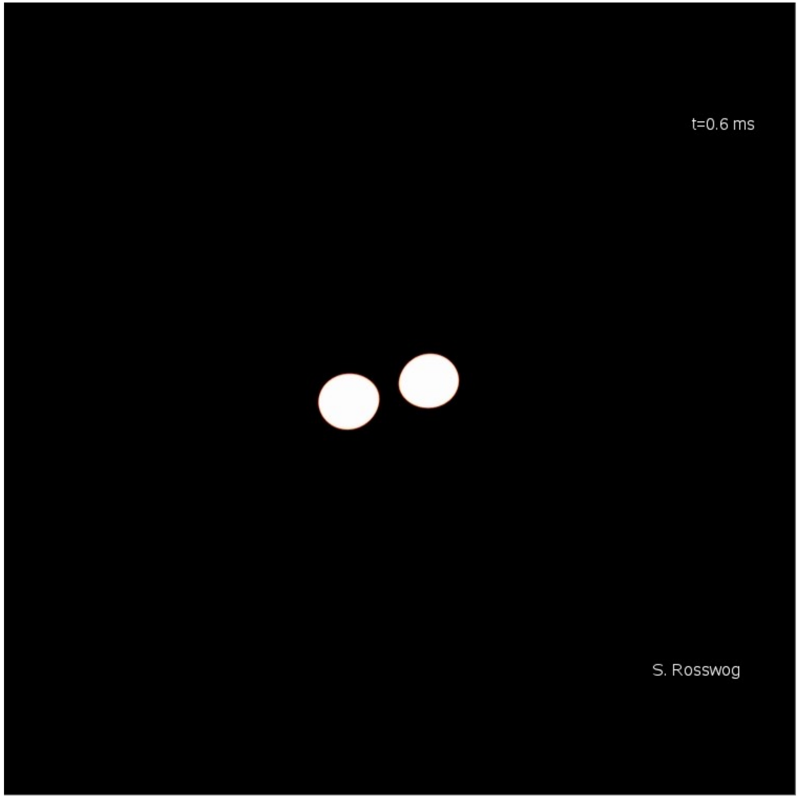
Stephan Rosswog

Possible origins: BNSs

- A type of X-ray transient associated with the merger of binary neutron stars (BNS) and gamma-ray bursts (GRBs).
- The X-rays are produced by a BNS, a rapidly spinning magnetar, where our line of sight is offset from the jet of a sGRB. (e.g., Dai et al.; 2018; Jonker et al. 2013; **Bauer et al. 2017; Xue et al. 2019**).



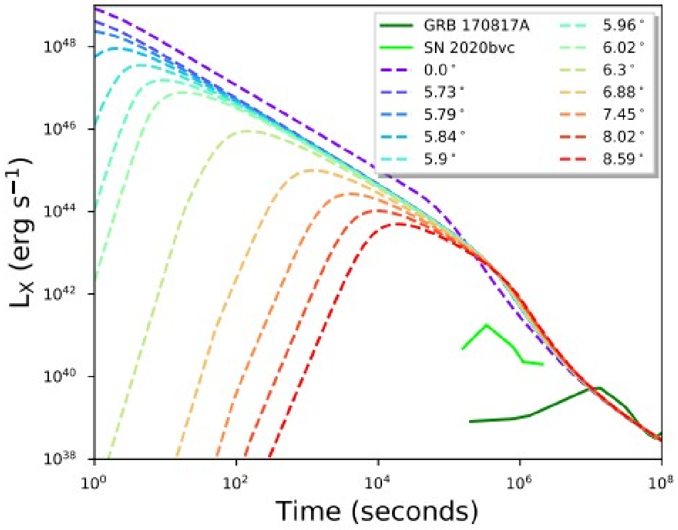
Bauer+, 2017



Stephan Rosswog

Possible origins: GRB

- Orphan emission related to cocoon jet breakout of massive star. LL-Long GRBs seen slightly off-axis, Xrays+opt+radio from afterglow emission, expanding viewing angle with time.
- Also, subluminous and/or frustrated jet GRBs.
- None confirmed as yet (e.g., **Bauer et al. 2017**).



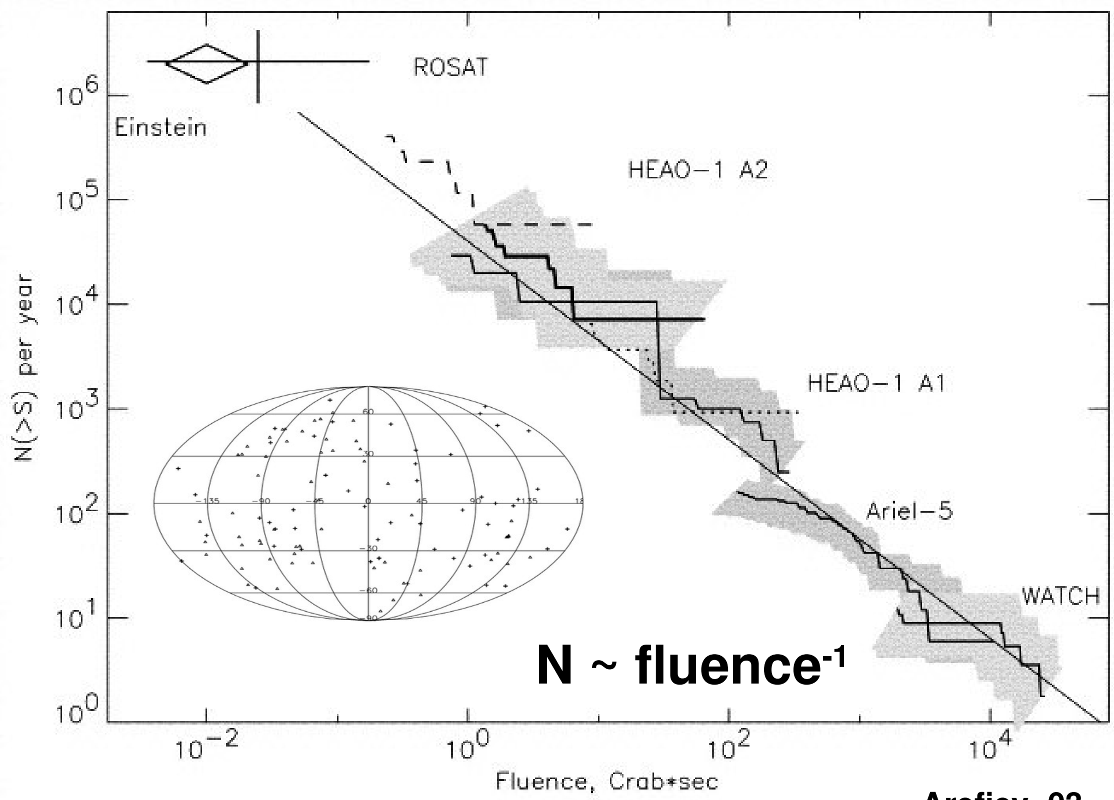
Brief History of FXTs (pre-2000)

Ariel 5	27 FXTs	(Pye+McHardy83)
HEAO 1 A-1	10 FXTs	(Ambruster+Wood86)
HEAO 1 A-2	8 FXTs	(Connors+86)
ROSAT	141 FXTs	(Vikhlinin98)
Einstein	18 FXTs	(Gotthelf+96)

Poor localization, largely archival searches

Little/no division here between
Galactic/Extragalactic
Persistent/One-off

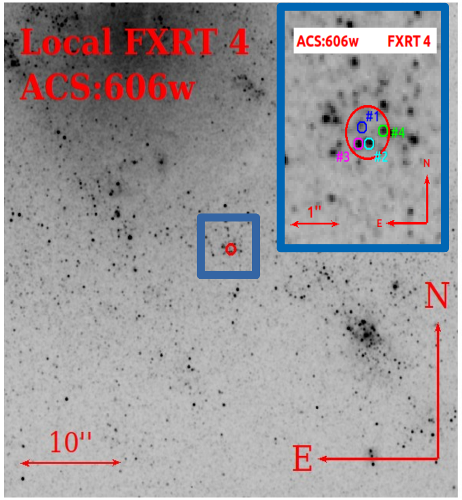
Significant contamination from flare stars
some confirmed GRBs

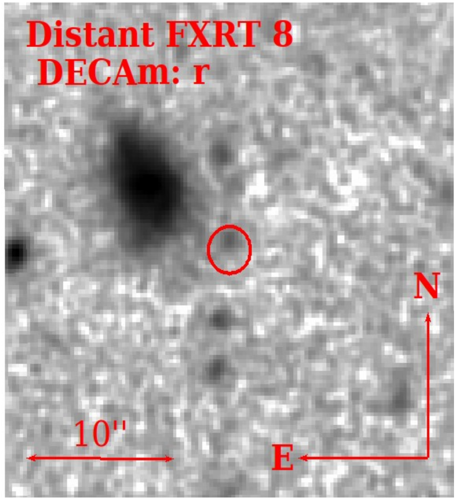


Arefiev+03

Brief History of FXTs (post-2000)

- **22 FXTs identified by Chandra (2000-2022)**
- Five FXTs appear related with galaxies (called *Local FXTs*) at <100 Mpc ($L_{X,peak} \approx 10^{39\text{-}40}$ erg/s), rate ≈ 34.3 deg^{-2} yr^{-1} at *Chandra* depth.
- 17 FXTs are non-local events (>100 Mpc, called *Distant FXTs*). Seven of them have extended sources with $z_{photo/spec}$ ~0.7-3.5, so $L_{X,peak} \approx 10^{44\text{-}47}$ erg/s, rate of distant FXTs≈ 36.9 deg^{-2} yr^{-1} at *Chandra* depth.





Brief History of FXTs (post-2000)

DISCOVERY OF A NEW KIND OF EXPLOSIVE X-RAY TRANSIENT NEAR M86

P. G. Jonker[1,2,3], A. Glennie[4], M. Heida[1,2], T. Maccarone[5], S. Hodgkin[6], G. Nelemans[2,7], J. C. A. Miller-Jones[8], M. A. P. Torres[1], and R. Fender[4]

→ XRT 000519

Jonker et al., 2013
Eappachen et al., 2022

A new, faint population of X-ray transients

Franz E. Bauer,[1,2,3,4★] Ezequiel Treister,[1,4,5★] Kevin Schawinski,[6★] Steve Schulze,[2,1] Bin Luo,[7,8] David M. Alexander,[9] William N. Brandt,[10,11,12] Andrea Comastri,[13] Francisco Forster,[14,2] Roberto Gilli,[13] David Alexander Kann,[15] Keiichi Maeda,[16,17] Ken'ichi Nomoto,[17†] Maurizio Paolillo,[18,19,20] Piero Ranalli,[21] Donald P. Schneider,[10,11] Ohad Shemmer,[22] Masaomi Tanaka,[23] Alexey Tolstov,[17] Nozomu Tominaga,[24] Paolo Tozzi,[25] Cristian Vignali,[26,13] Junxian Wang,[27] Yongquan Xue[27] and Guang Yang[10,11]

→ CDF-S XT1

Bauer et al., 2017

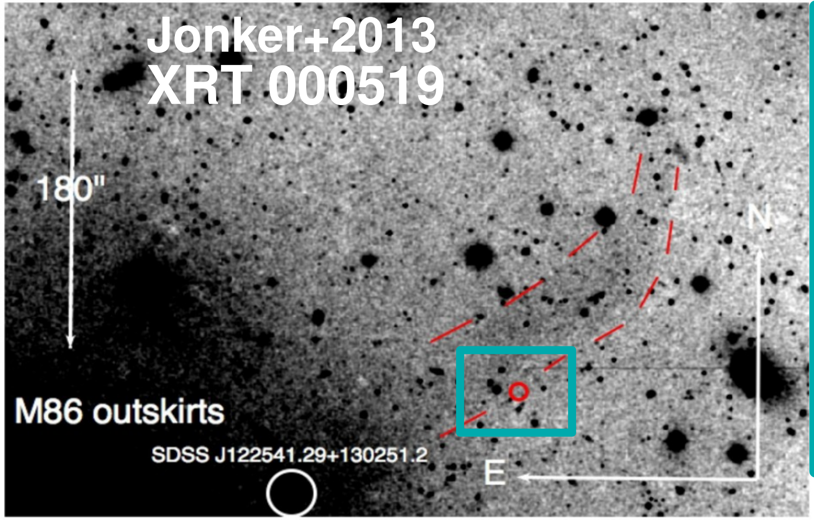
A magnetar-powered X-ray transient as the aftermath of a binary neutron-star merger

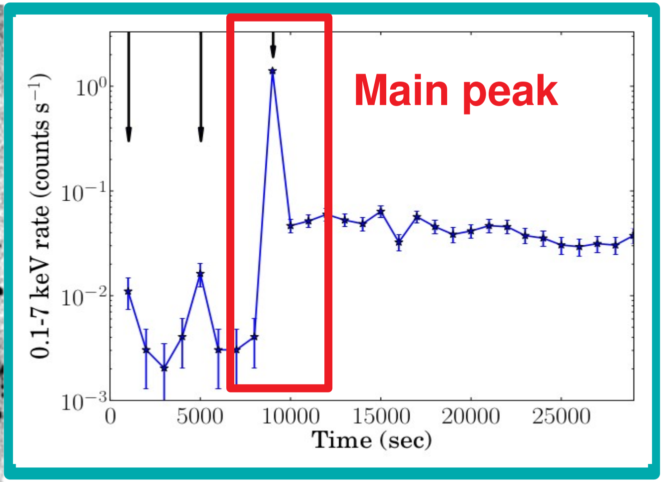
Y. Q. Xue[1,2*], X. C. Zheng[1,2,3*], Y. Li[4], W. N. Brandt[5,6,7], B. Zhang[8,9,10*], B. Luo[11,12,13], B.-B. Zhang[11,12,13], F. E. Bauer[14,15,16], H. Sun[9], B. D. Lehmer[17], X.-F. Wu[2,18], G. Yang[5,6], X. Kong[1,2], J. Y. Li[1,2], M. Y. Sun[1,2], J.-X. Wang[1,2] & F. Vito[14,19]

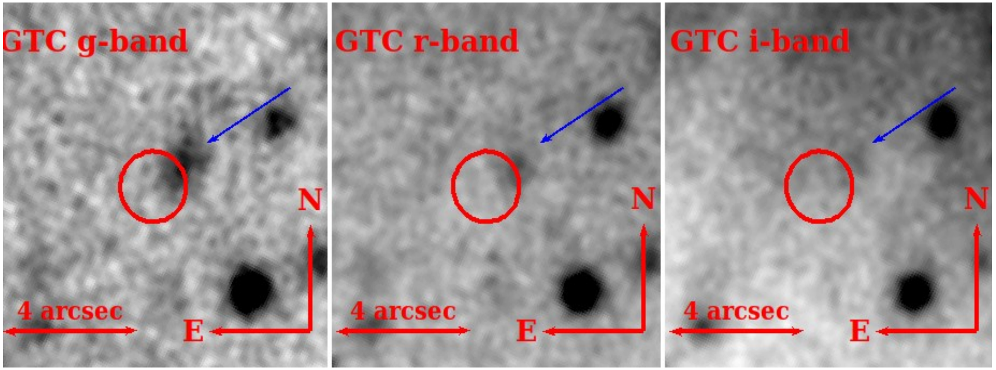
→ CDF-S XT2

Xue et al., 2019

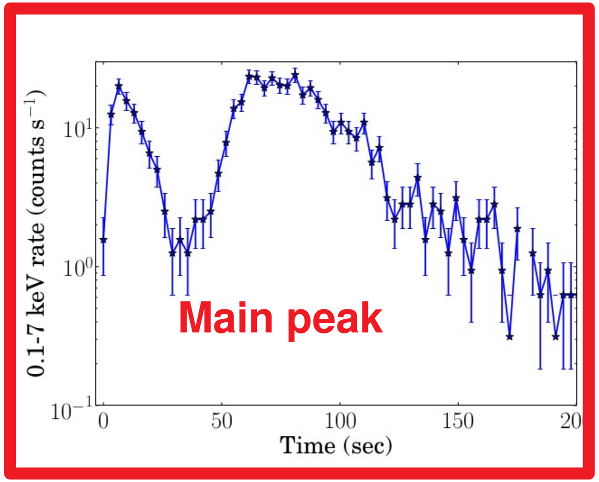
Brief History of FXTs (post-2000)







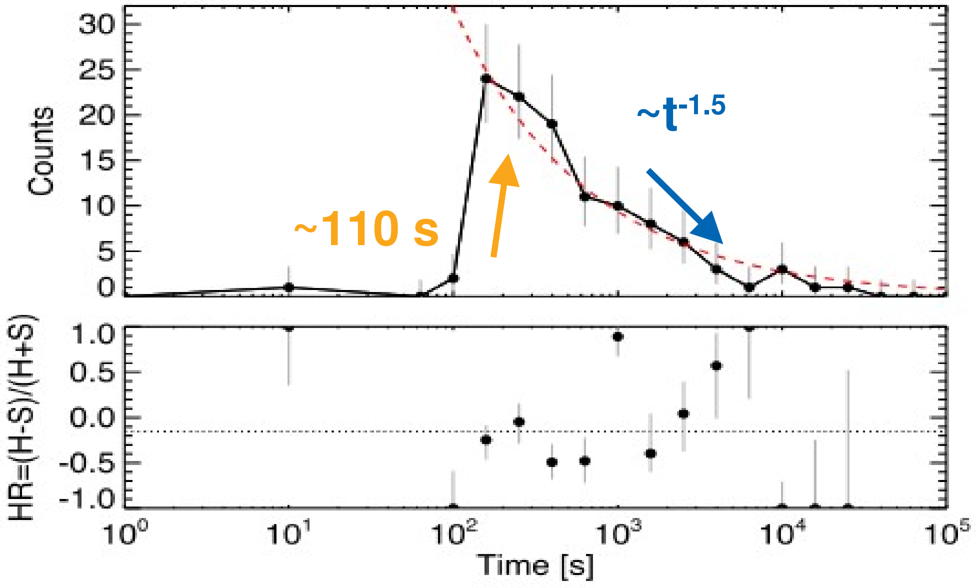
GTC/HiPERCAM; Eappachen+ 2022

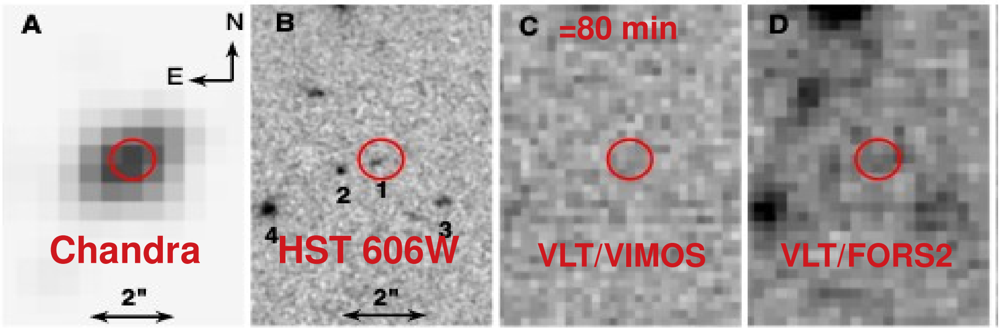


- If associated to M86, has peak luminosity of 6x10^{42} erg/s., potentially related to WD-IMBH TDE with M~4.6x10^{4} M_{Sun}.
- However, other scenarios could be considered. An extended source found coincident with XRT 000519 was detected with a Kron magnitude of g_s=25.40±0.13.

Brief History of FXTs (post-2000)

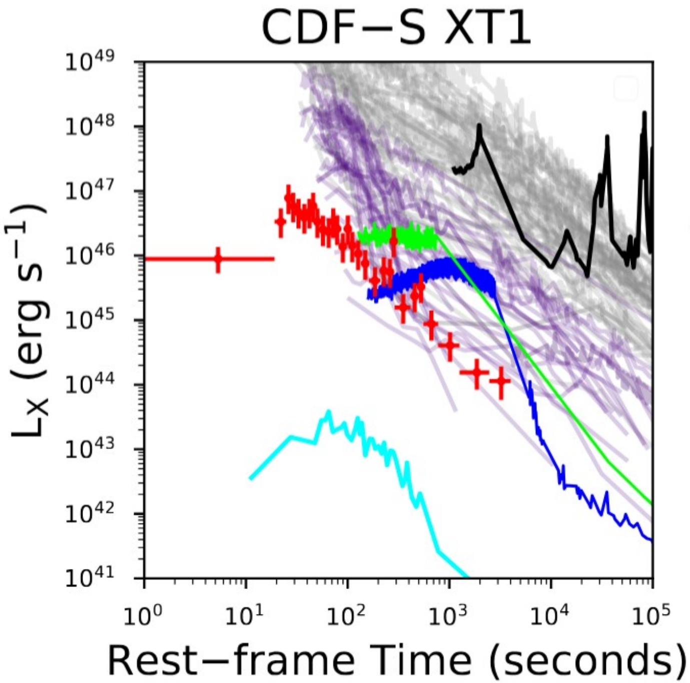
- Called CDF-S XT1: found in near real-time (<2 days; Luo, Brandt & Bauer 2014).
- The X-ray light curve has 110 photons, shows 110±50 s rise and power-law decline ($\sim t^{-1.5}$), with T_{90} of ~5.0ks.
- Robustly associated with host galaxy (m_{110W}=27.4, m_R=27.5) at z_{photo}=2.7-2.9 (from **HST+JWST** data) ==> $L_{peak} \sim 10^{47}$ erg/s.
- VIMOS observation taken just 80 min after the X-ray trigger.



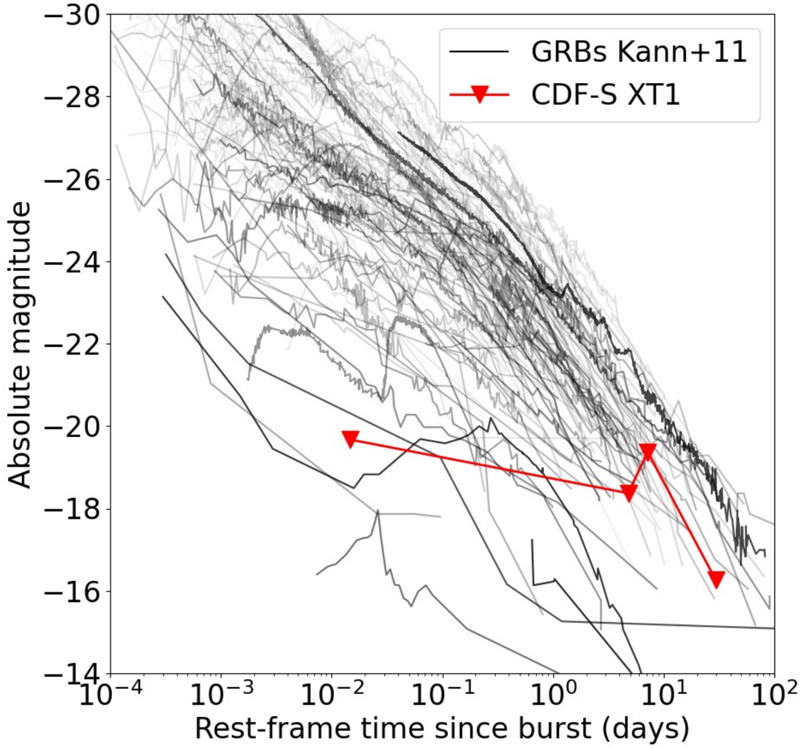


Bauer+2017

Brief History of FXTs (post-2000)



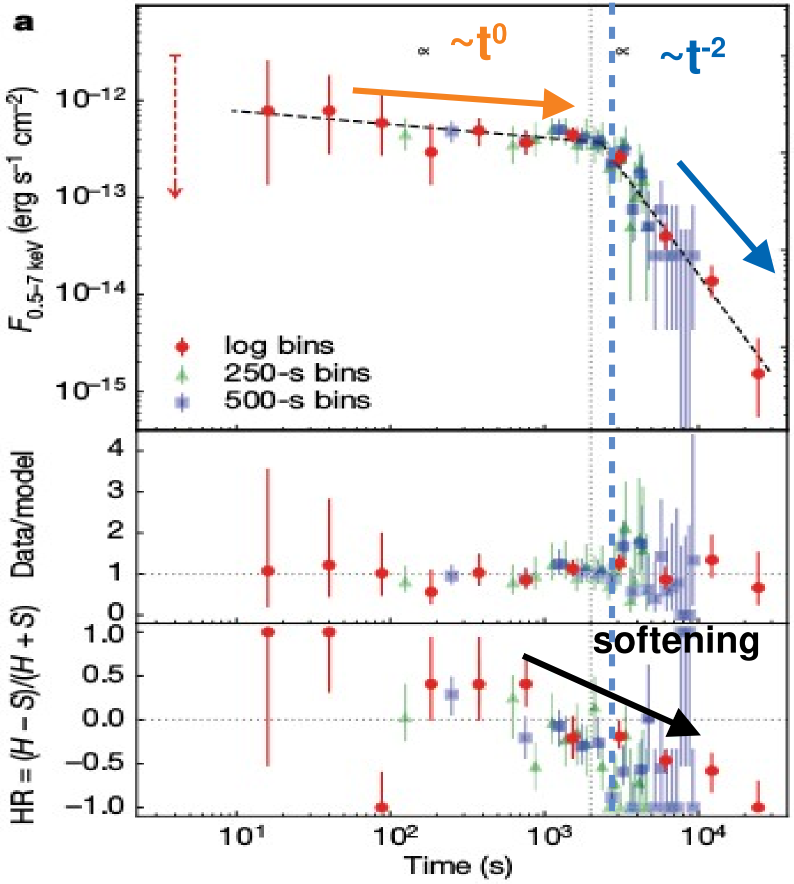
Quirola-Vasquez+,
2024 submitted



- The best progenitor scenario for XT1 is a **low-luminosity GRB**, where the X-rays are associated with the shock breakout of a chocked jet, although we cannot fully rule out other channels.

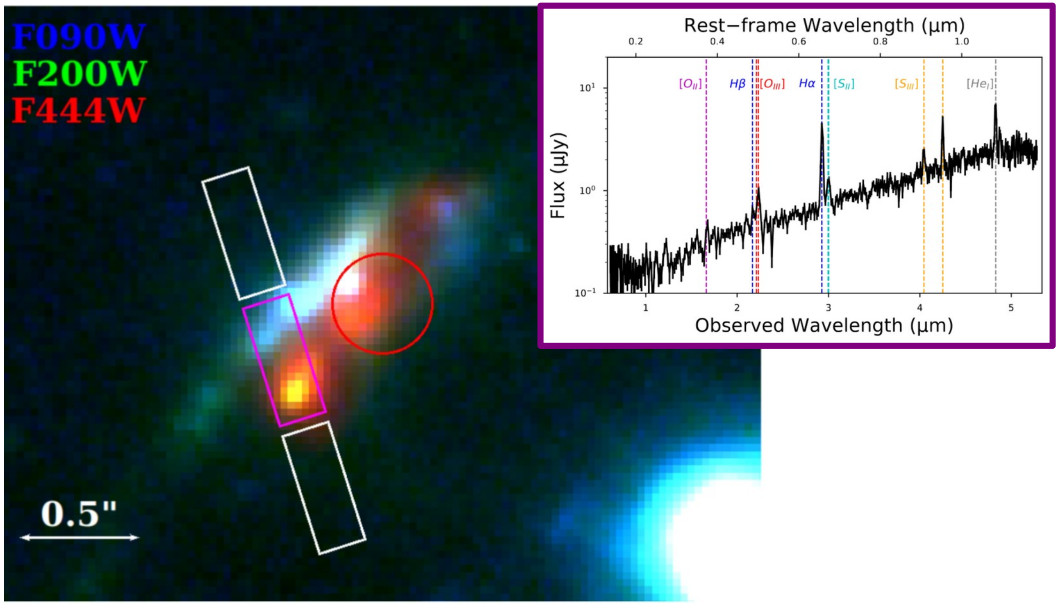
Brief History of FXTs (post-2000)

- Called CDF-S XT1: light curve contains 136 photons, with the T_{90}~11.1 ks (ObsId 16453), and shows a plateau (~2 ks) followed by a power law decay (~t-^{2}), with spectral softening.
- Xue et al (2019) explain CDF-XT2 as powered by a millisecond magnetar.
- $L_{sd} \propto L_0(1+t/t_{sd})^{-2}$ =>rapidly spinning magnetar has a spindown luminosity

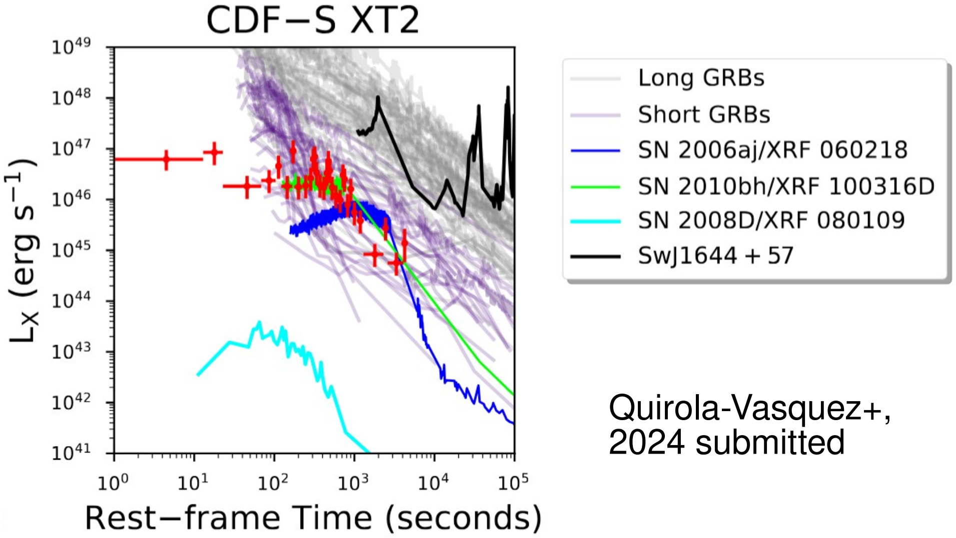


Xue+ 2019

Brief History of FXTs (post-2000)



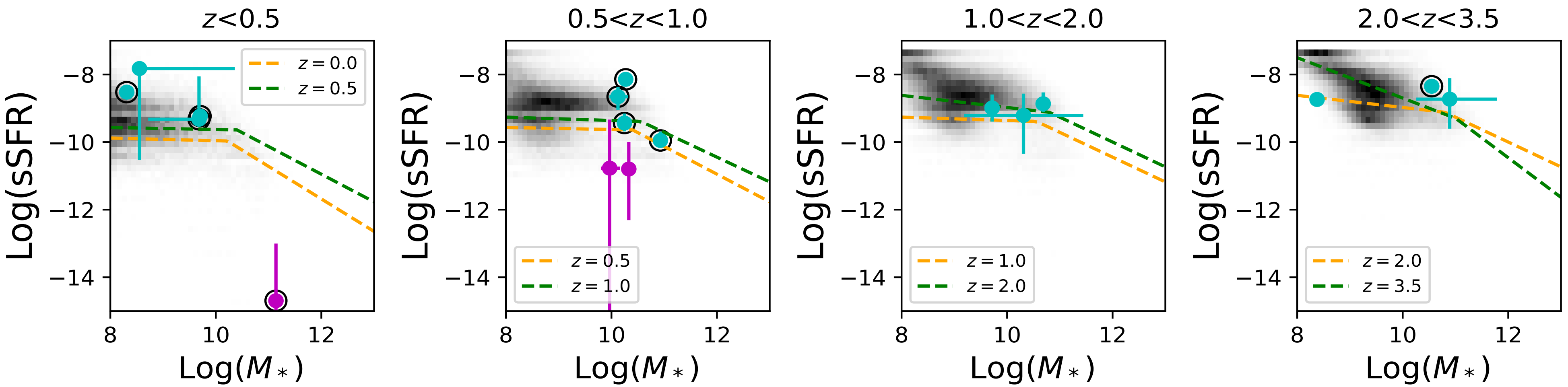
- Robust host galaxy (**NIRSpec-JWST**), z_{spec}=3.4598 ==> L_{peak}~10^{47} erg/s.

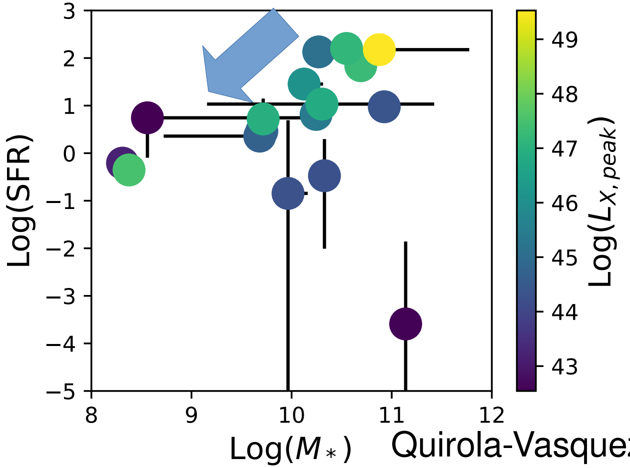


Quirola-Vasquez+, 2024 submitted

- Based on the X-ray and host properties, the similarity to X-ray flash event light curves, small host offset, and high host SFR (~180 Msun/yr), a low-luminosity collapsar progenitor appears to be a good fit for CDF-S XT2.

Host galaxy properties

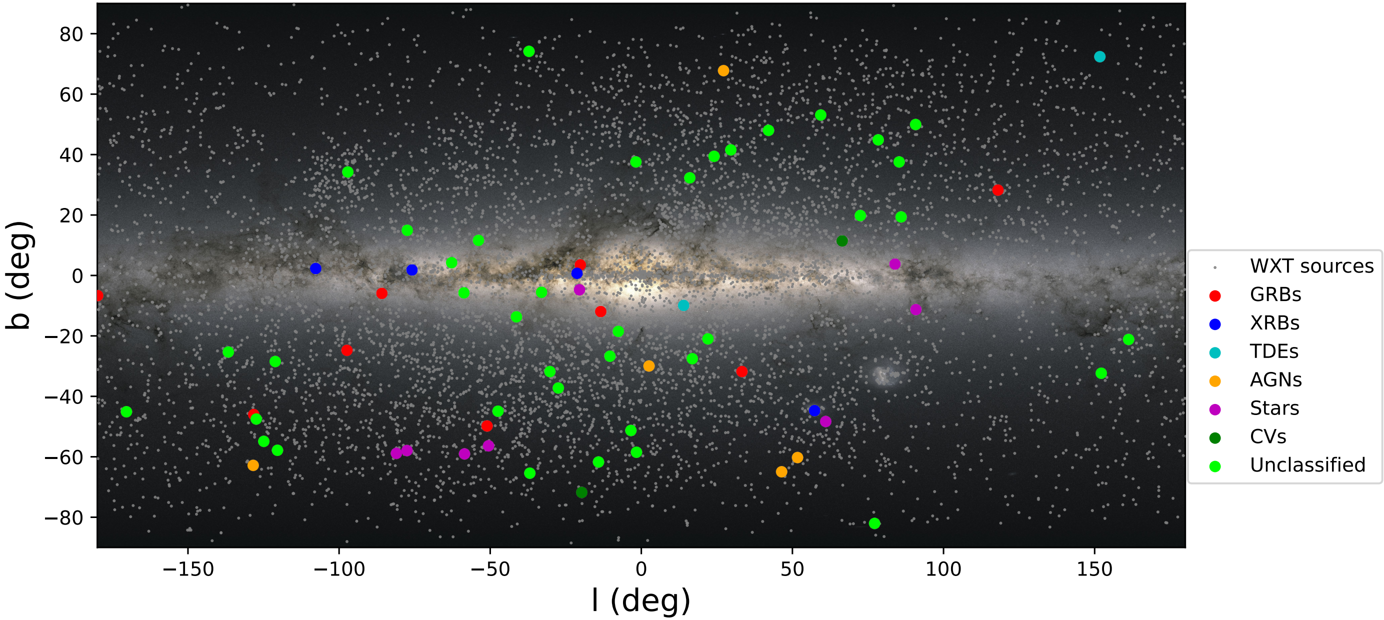




Quirola-Vasquez+, in prep.

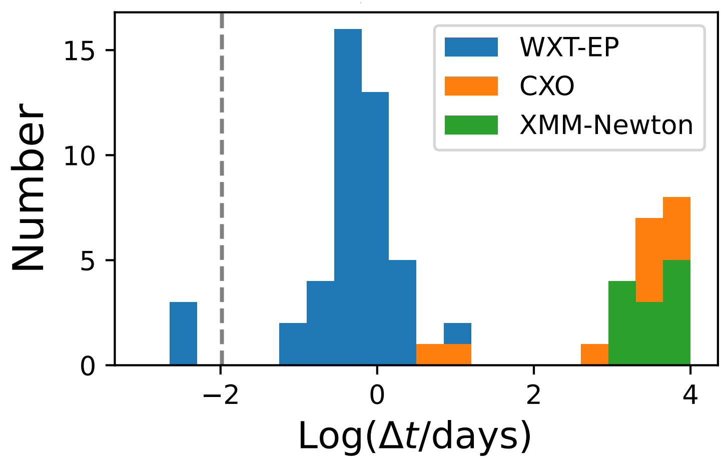
- From 17 FXTs (CXO+XMM) host galaxies: 14 hosts are **star-forming**, and three galaxies are **quiescent or transitioning.**
- Across all redshifts, FXT hosts tend to populate the star-forming main sequence, i.e., FXT hosts are good tracers of star formation given their host stellar masses.

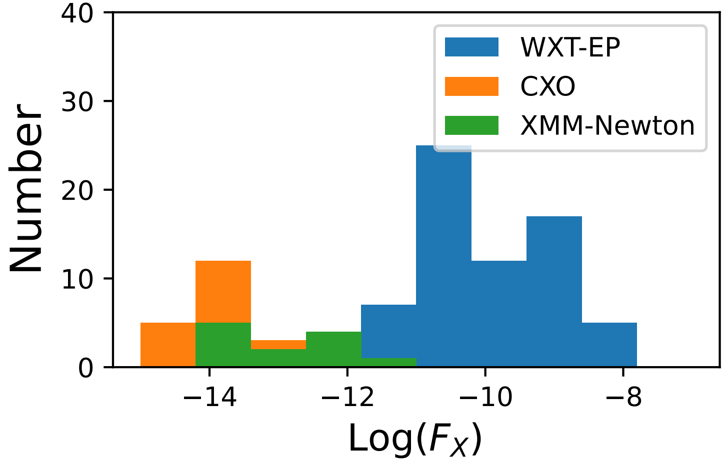
Wide-field X-ray Telescope (WXT)-Einstein Probe (EP) transients



- WXT-EP have detected >7500 X-ray sources.
- ~70 high S/N FXTs (hundreds of low S/N), i.e., a rate of **~90 events/yr**.
- ~40% with optical/NIR and ~20% with gamma-ray counterparts.

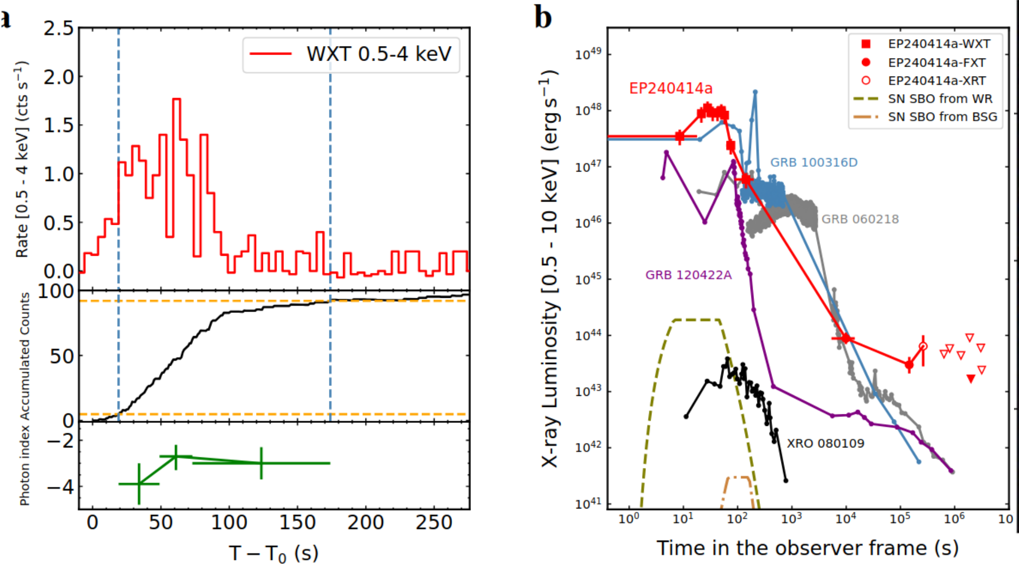
WXT-EP transients



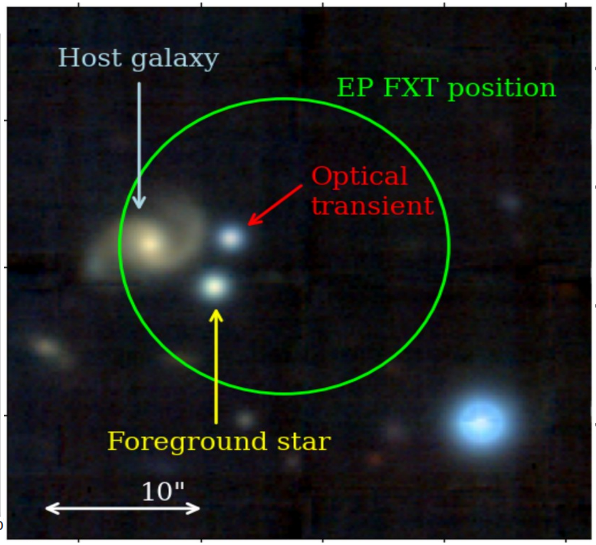


- Before EP mission, only one FXT (CDF-S XT1) was announced <1 week after the X-ray trigger.
- EP has improved >4 orders of magnitude between FXT detection and announcement, regarding previous missions such as Chandra and XMM-Newton.
- Measured redshifts for eight FXTs from ~0.03 to 5 (EP240315a).
- Likely, Chandra and XMM-Newton FXTs are faint/high-redshift versions of EP FXTs(?).

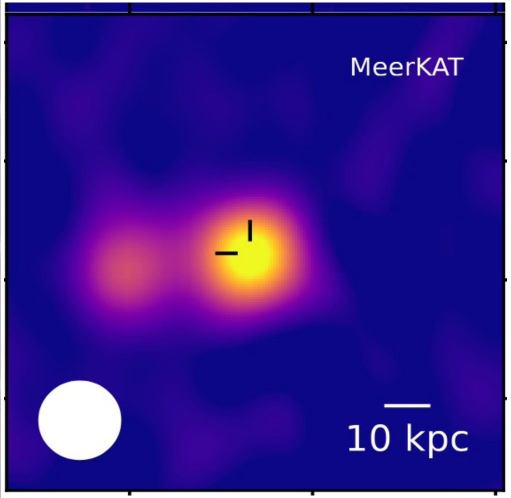
EP240414a



Sun+, submitted



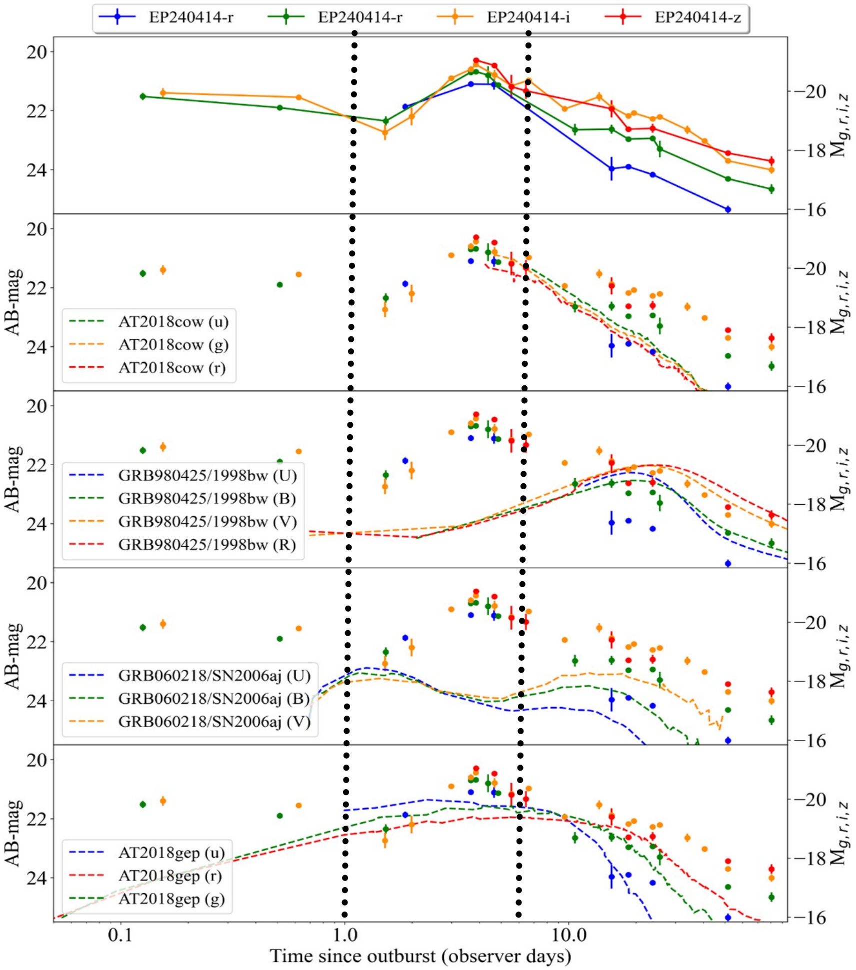
van Dalen+, submitted



Bright+, submitted

- No significant gamma-ray signal, and redshift of ==> **$L_{X,peak}$~1.7x10^{48} erg/s**
- Subsequent follow-up observations of EP240414a revealed counterparts at soft X-ray (at T0 + 2 hrs), optical (at T0 + 3 hrs), and radio (at T0 + 9/30 days) wavelengths.

EP240414a



- The light curve of EP240414a shows three different phases:

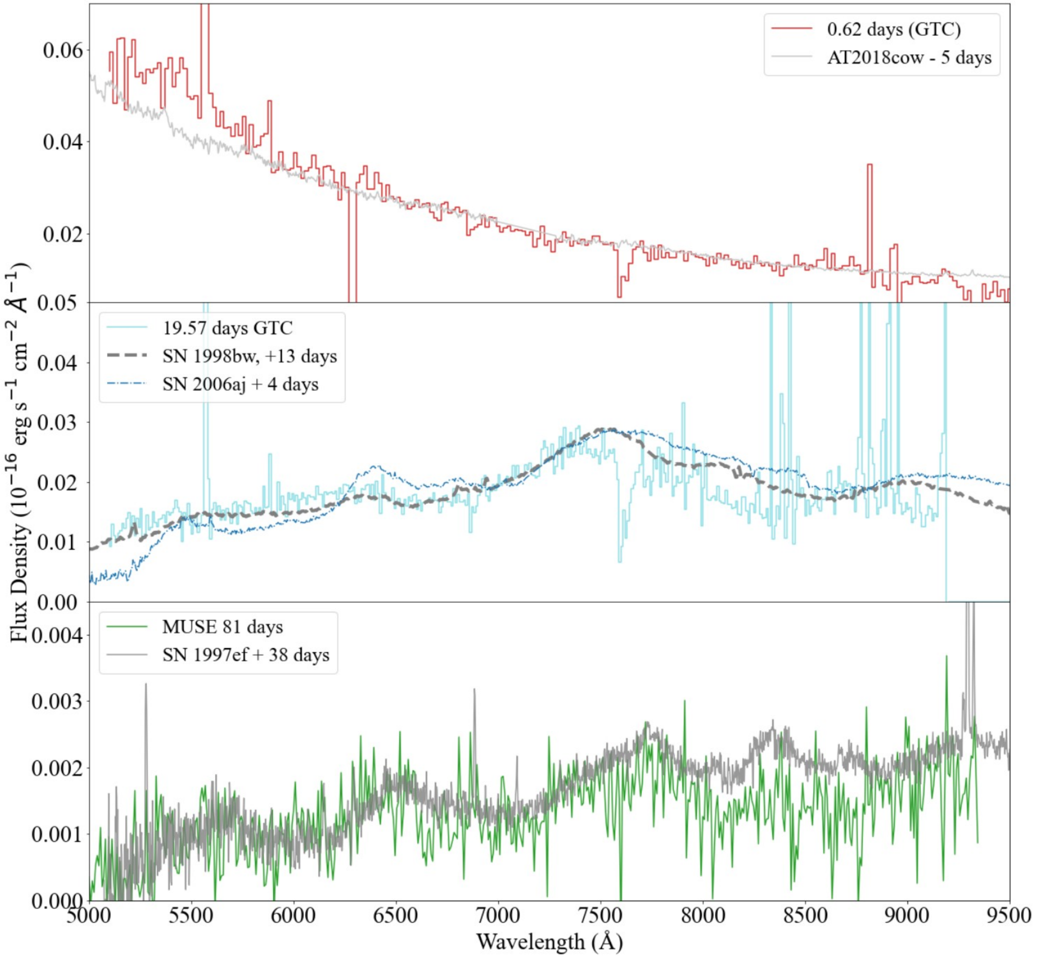
  1) Light curve shows moderate fading within the first day which we call the first peak.

  2) Rebrightening between day 2 and 3 which is followed by rapid fading after 4 days in all bands, to which we refer as the second peak.

  3) Modest rebrightening in i-band and flattening of the slope in the other bands at ∼ 10 days.

Van Dalen+, submitted

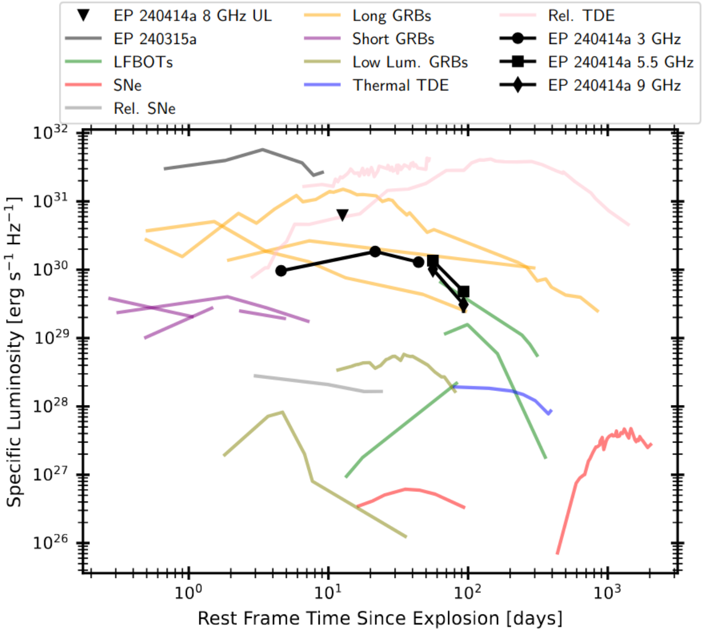
EP240414a



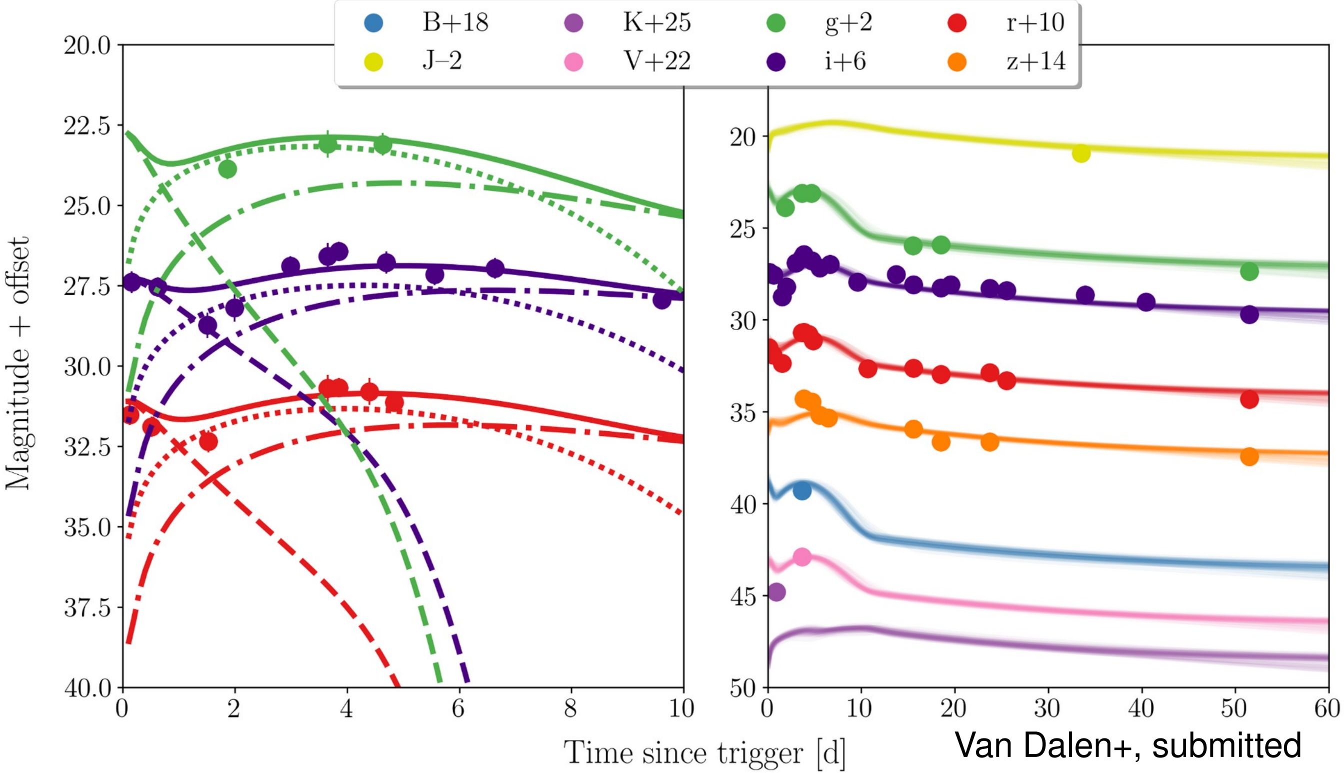
- Spectra of EP240414a show a clear transition in the spectral shape and features as the transient evolve.
- At early epochs (0.62 days), some similarities with AT2018cow, it is extremely blue and inconsistent with GRB afterglow emission.
- Meanwhile at later epochs (during the second peak phase) the spectrum shares similarities with SN Ic-BL such as SN 1998bw and SN 1997ef.

Van Dalen+, submitted

EP240414a



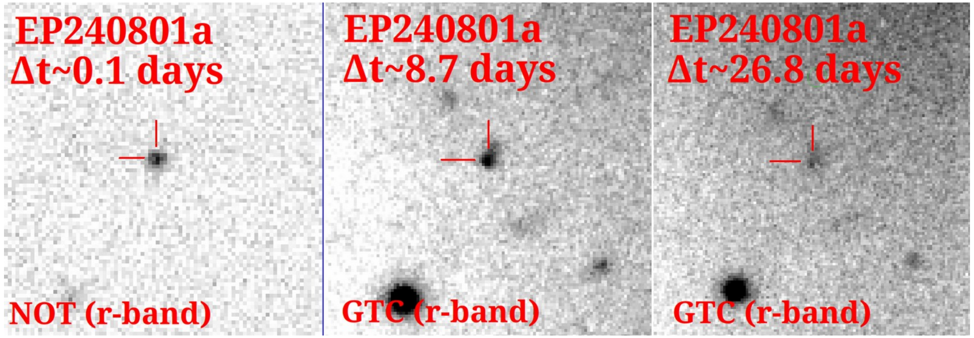
Bright+, submitted



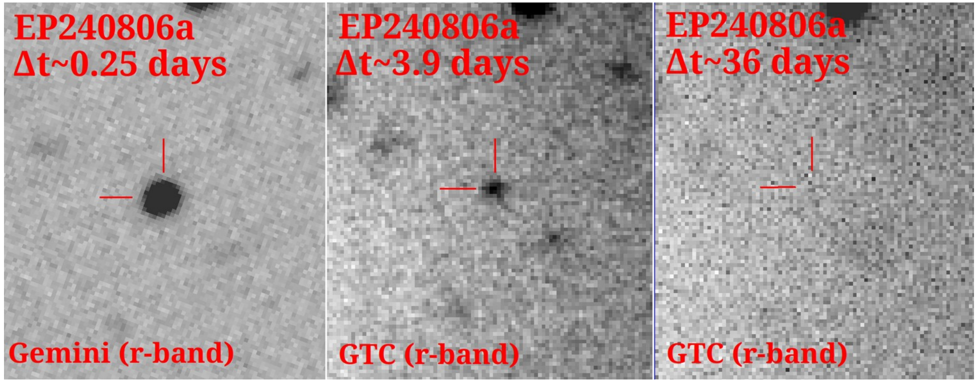
Van Dalen+, submitted

- The interaction of both jet and SN shock waves with the stellar envelope and a dense circumstellar medium (suggested for some Fast Blue Optical Transients) explains the FXT. At late times, the spectrum evolves to a broad-lined Type Ic supernova, similarto those seen in collapsar long-GRBs

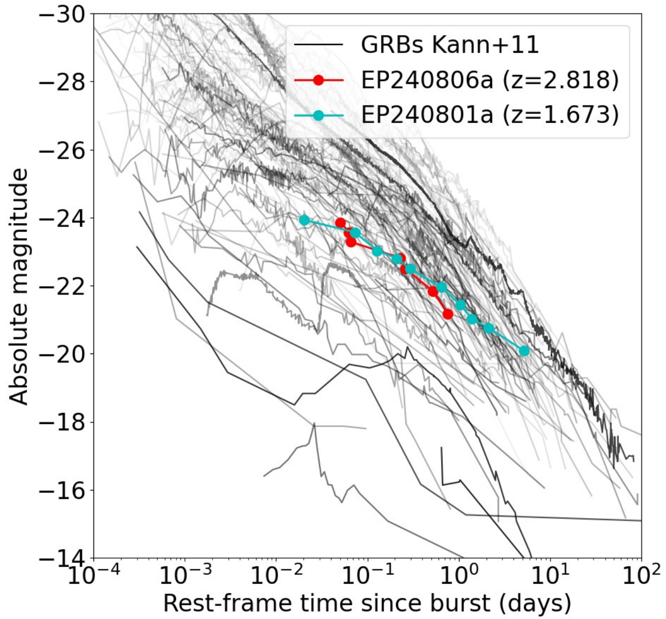
EP240801a and EP240806a



Quirola-Vasquez+, GCN 37013



Quirola-Vasquez+, GCN 37087



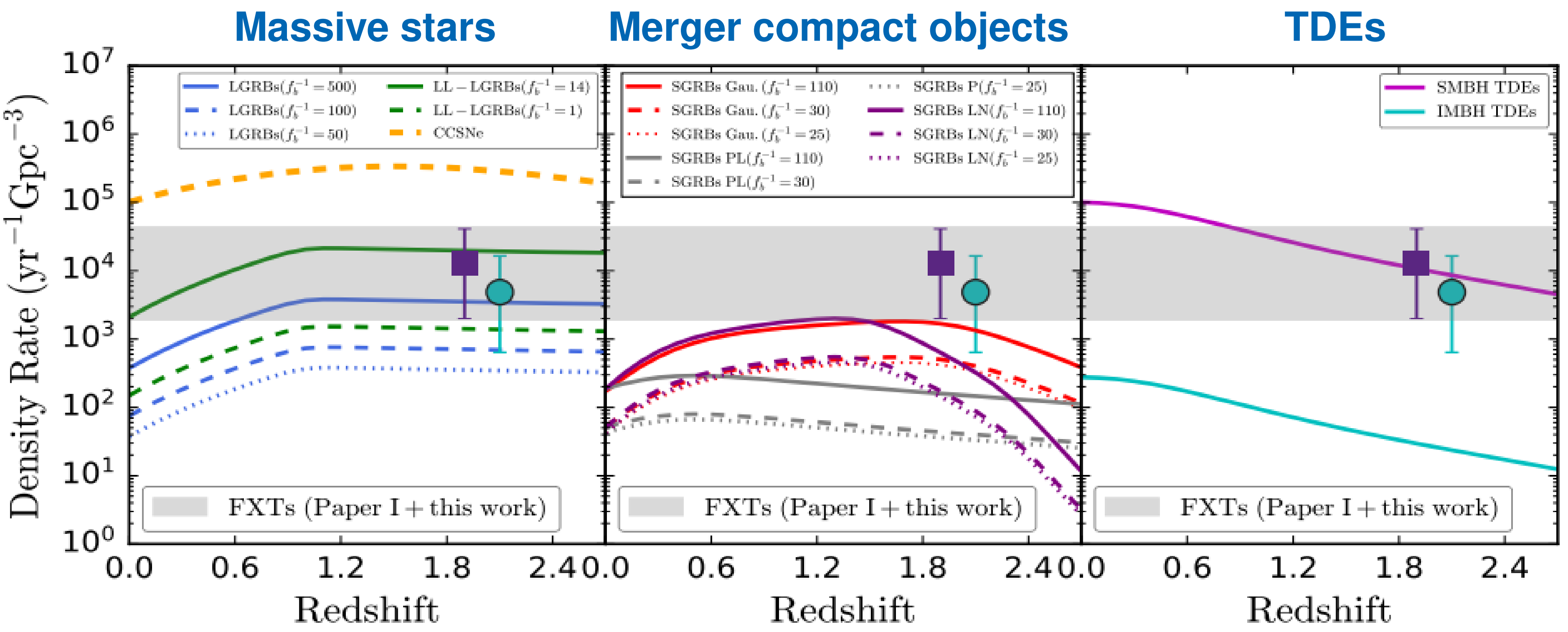
- EP240801a (>80 sec) was associated with a *Fermi*-GBM gamma-ray counterpart (faint), and z=1.673 ==> **L_X~9.3x10^{48} erg/s**
- EP240806a (~150 sec) no gamma-ray counterpart, and z=2.818 ==> **L_X~1.3x10^{50} erg/s**
- Both FXTs might associated with GRBs afterglow?

Conclusions

- Several progenitors have been proposed to explain the properties of the fast X-ray transients (FXTs), from the merger of compact objects to tidal disruption events.
- Before the Einstein Probe (EP) mission, FXTs were identified even ~years after the X-ray detection, lacking the possibility of follow-up using multiwavelenght facilities.
- EP improves the alert timescale by 4-5 orders of magnitudes, regarding previous missions such as Chandra and XMM-Newton.
- Overall, the nature of FXTs is still unknown; however during the next years, thanks to the EP capabilities, we will shed light on their individual nature of FXTs.


Thanks
j.quirolavasquez@astro.ru.nl
@astroquiro90

Cosmic rates



The cosmic volumetric rate, combined with the other properties, may imply that we have a mix of origins.