Modeling of Clocked Bursters

~ center on SRGA J144459.2-604207 ~

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Based on arXiv: 2411.10992, 2411.10993 (PASJ Letter)

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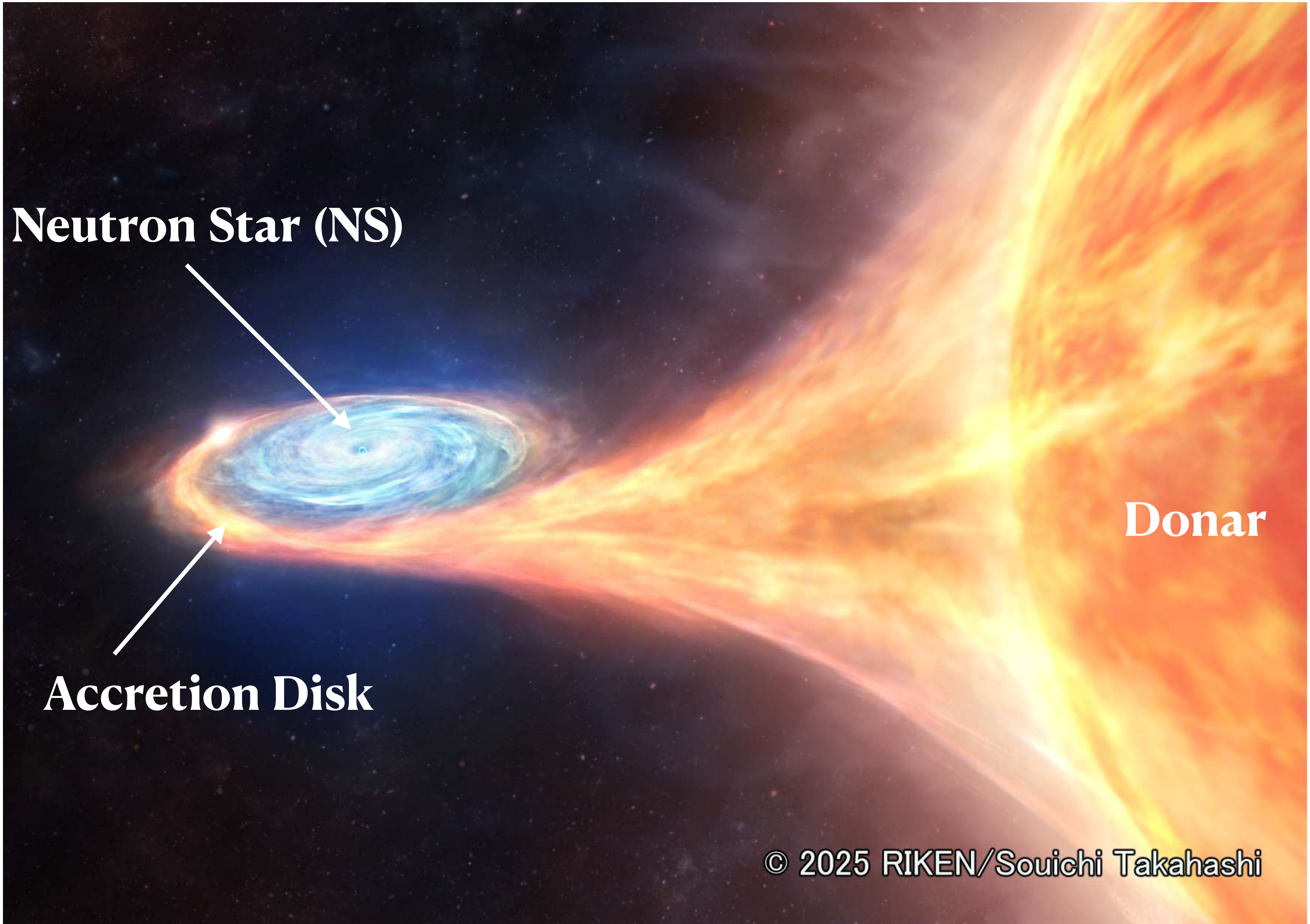
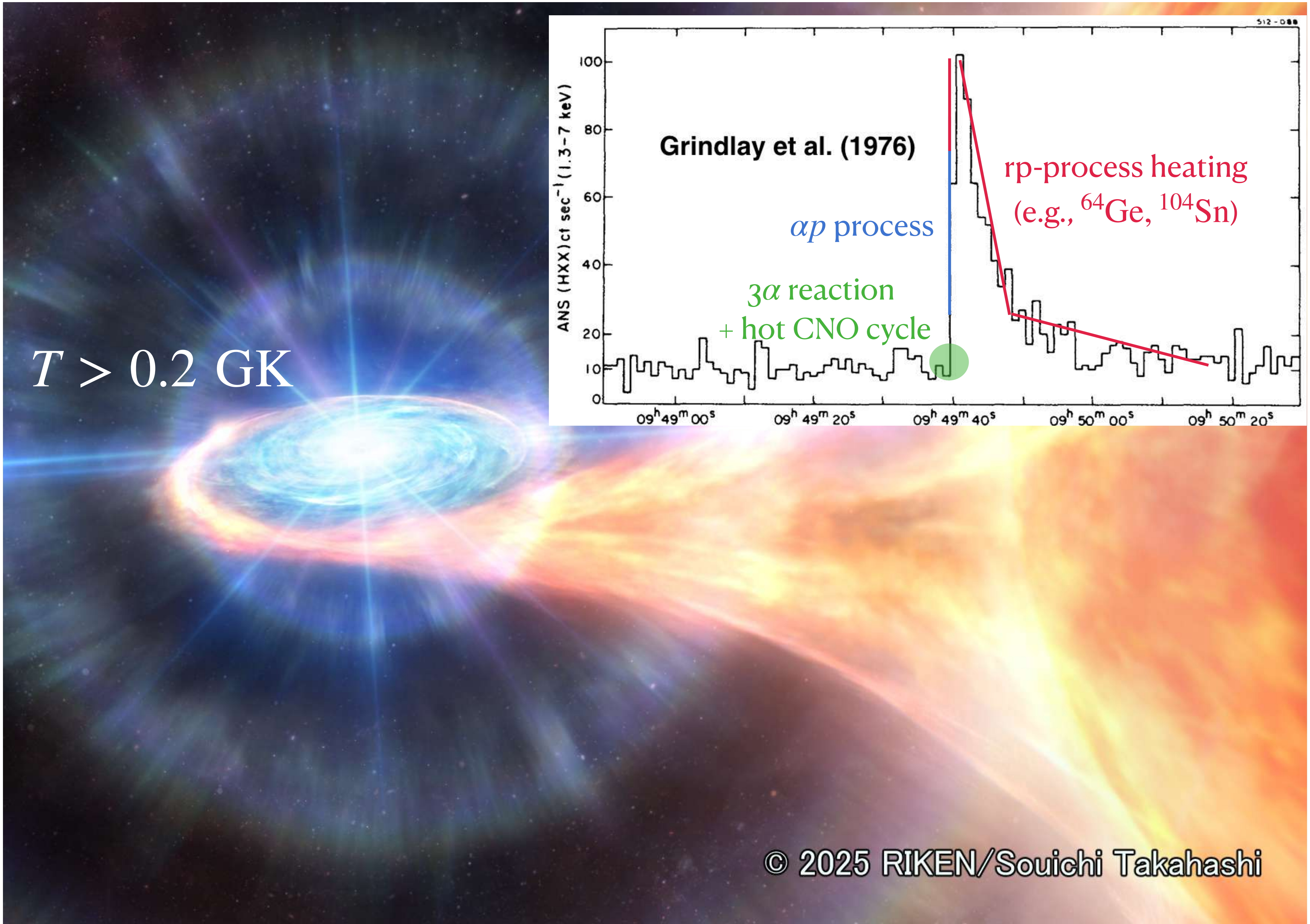
1/4 Introduction

Low-mass X-ray Binaries



Type-I X-ray Burst

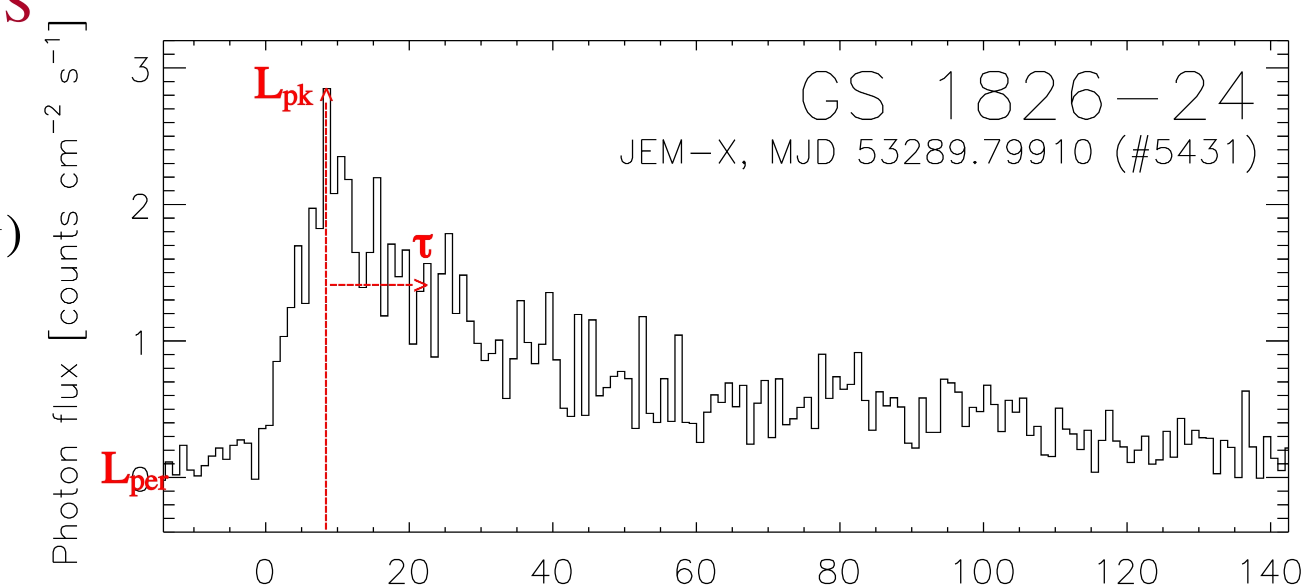


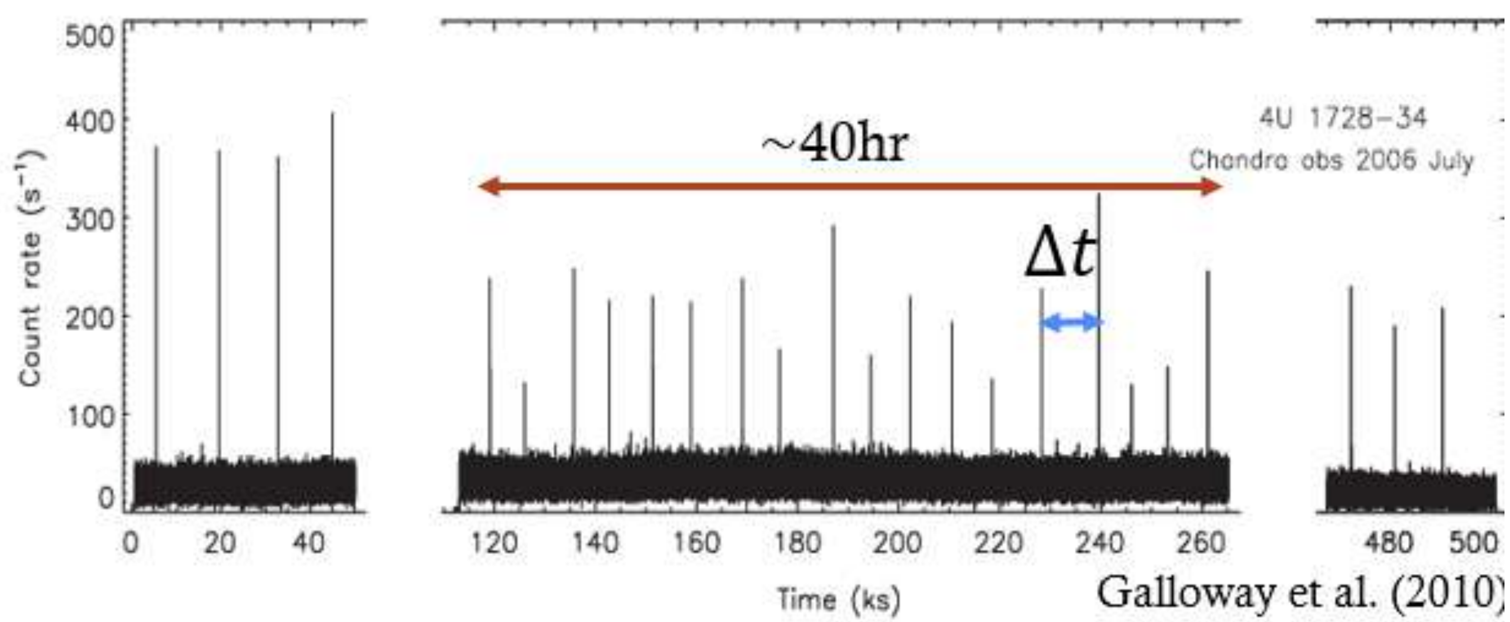
Properties of XRB

- Some parameters to charactrise XRB light curves

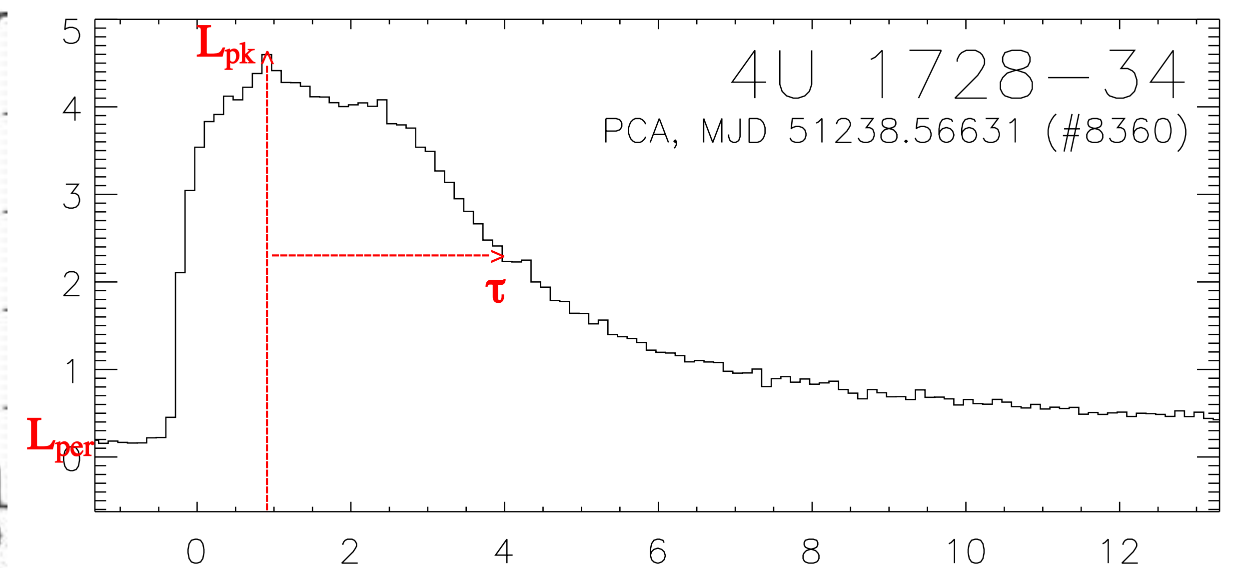
- Recurrence time Δt: hour-yr
- Persistent Luminosity: $L_{\rm per} \propto \frac{GM_{\rm NS}}{c^2 R_{\rm NS}} \dot{M} c^2 \sim 10^{37} \dot{M}_{-9}$ erg/s
- Peak Luminosity $L_{\rm pk}$: 10^{38} erg/s

  $\dot{M}_{-9} \equiv \dot{M}/(10^{-9}\ M_\odot\ {\rm yr}^{-1})$
- Burst duration τ: sec-min
- Rise time $\simeq t(L_{\rm pk}) - t(L_{\rm per})$



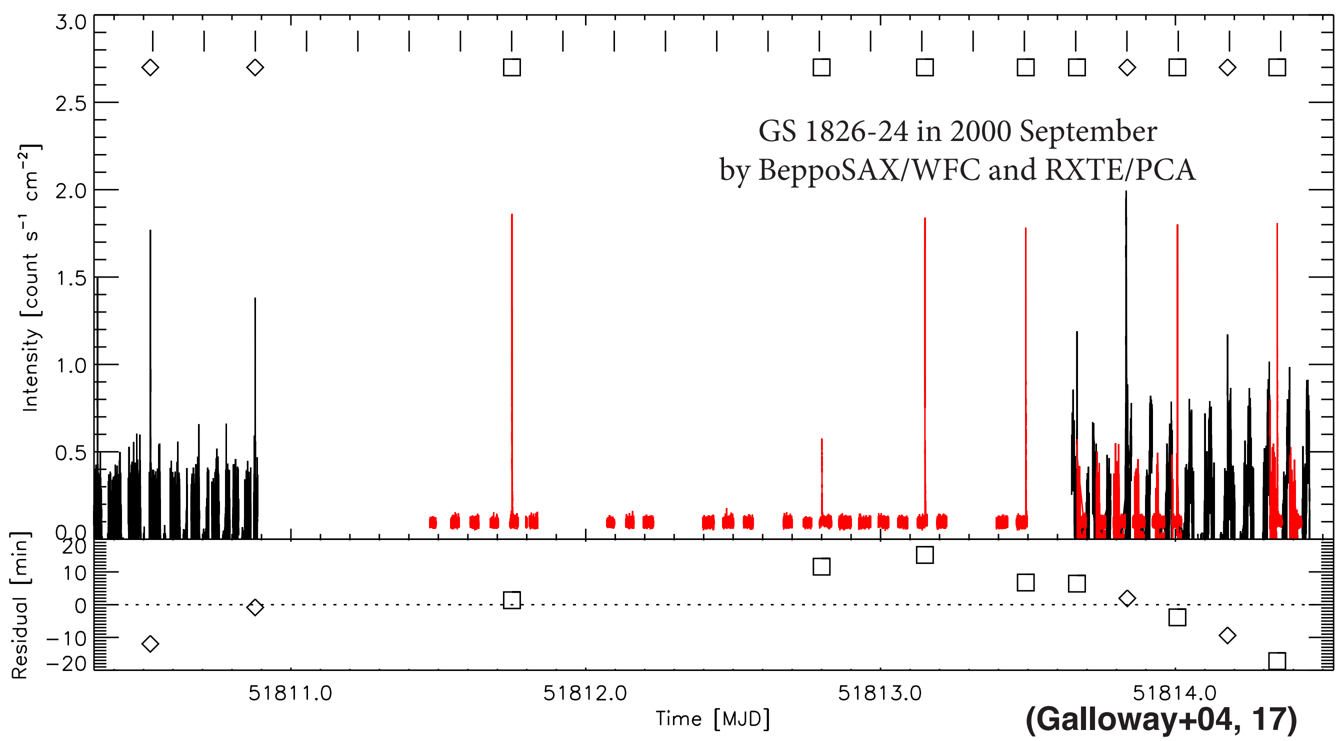


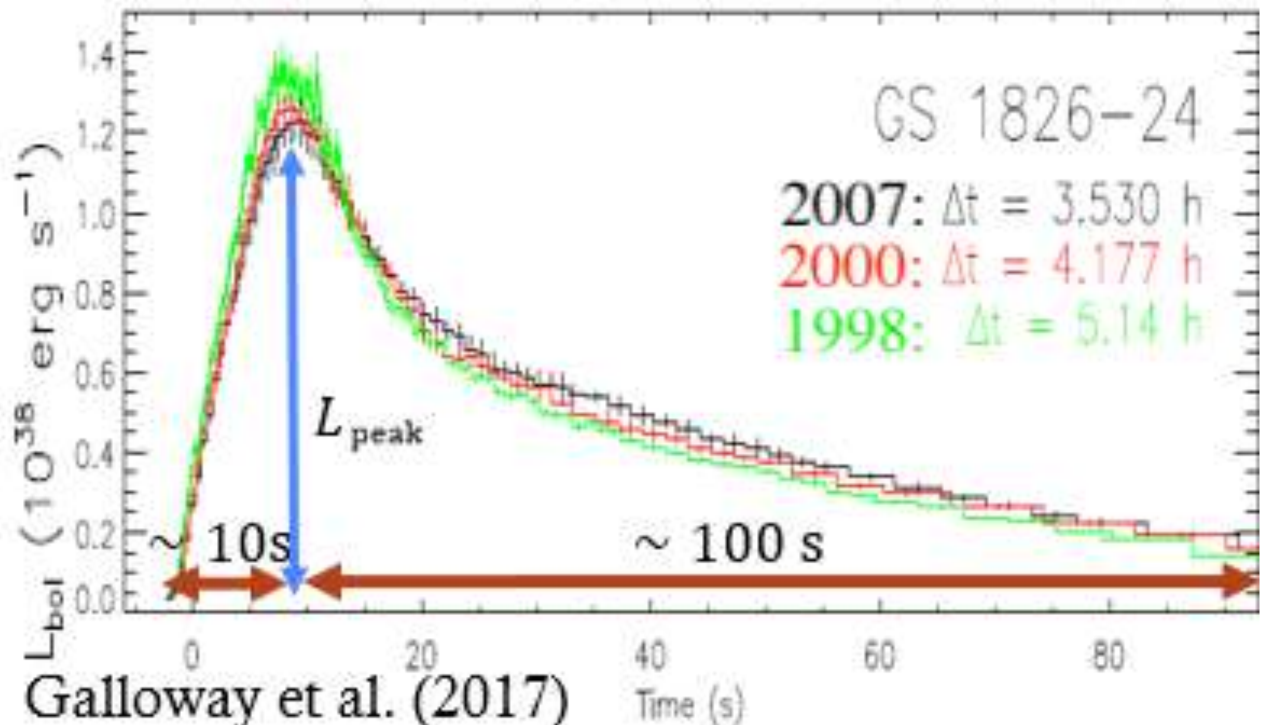
Galloway et al. (2010)



Galloway+2020 (see also Wikipedia of ``X-ray burster")

Clocked Bursters (CXRBs)





In case of GS 1826−24

- Constant light curves in a epoch—> constant Δt and $L_{per}(\propto \dot{M})$
- Very regular burst sequence with the same shape of light curves
- Useful to constrain model parameters, such as hydrogen. helium, metal's mass fraction, X, Y, $Z_{\rm CNO}$, EOS, NS mass, and reaction rates.

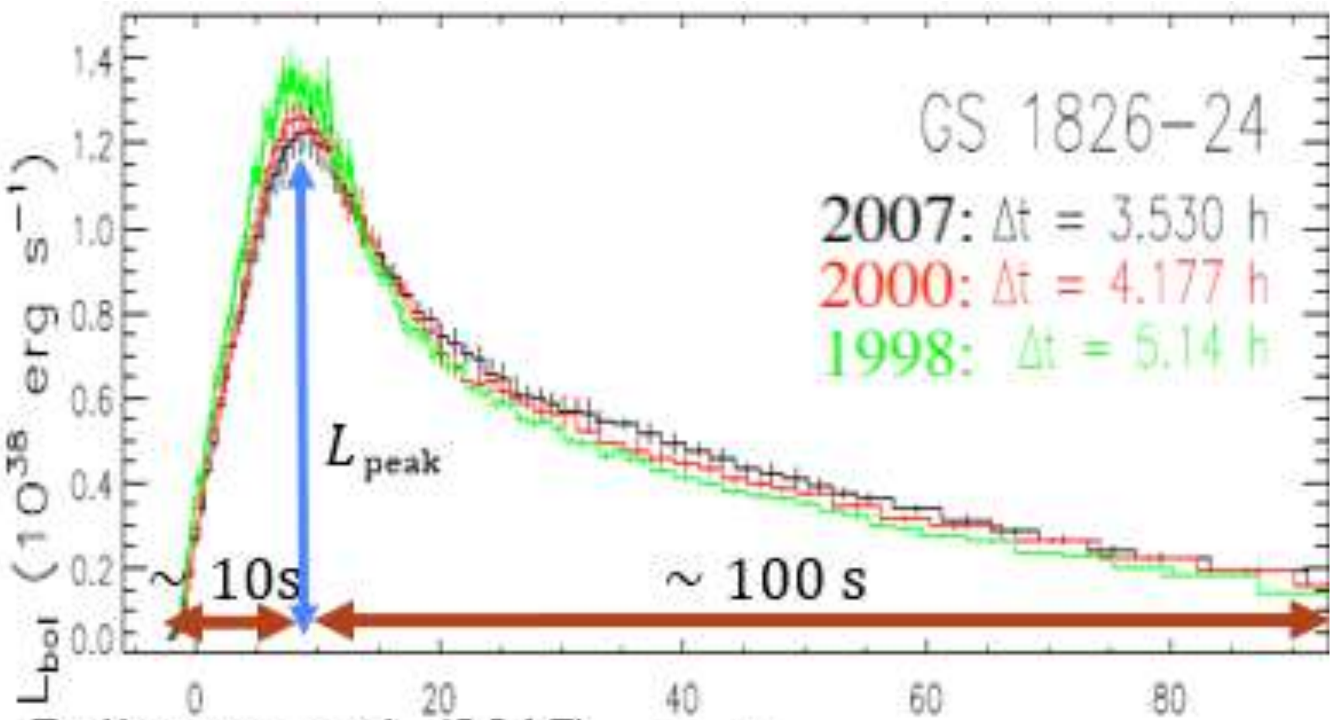
(Heger+07, Lampe+16, Meisel+18,19, Johnston+20,
AD+20-22, 24, Hu+21, 24?, Lam+21, 22, Zhou+23, Zhen+AD+23, Lam+, Lam+AD+, ……)

2 most conventional cases of XRBs

Case of CXRB

* Except for long XRBs

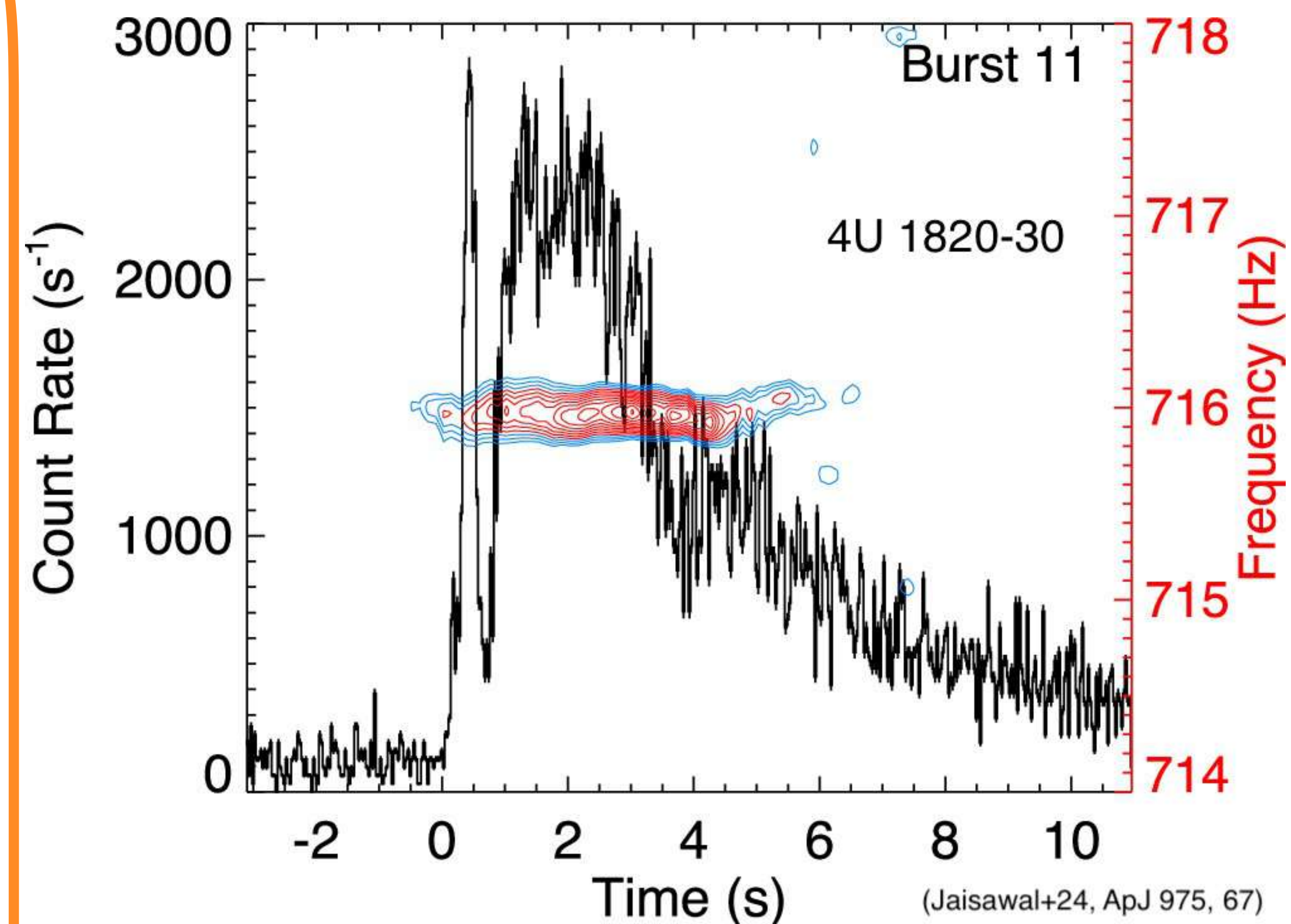
Solar-composition-like accretion (H rich)



Galloway et al. (2017)

- Linear increase + mild decay owning by strong rp-process
- No photospheric radius expansion (PRE)

(Almost) pure-He accretion

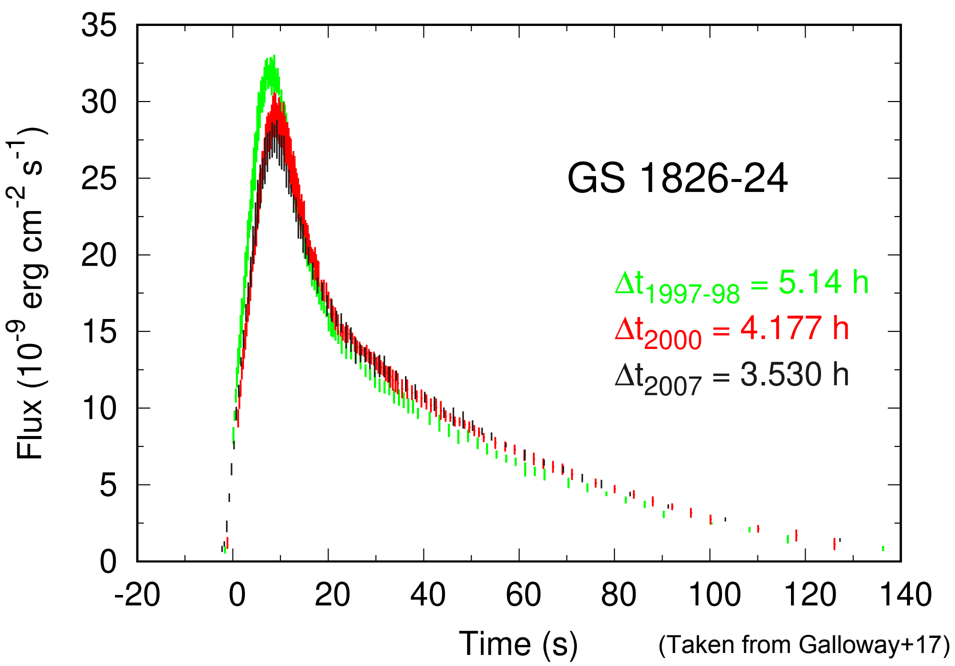


(Jaisawal+24, ApJ 975, 67)

- Rapid rising + short platou + rapid decay owing by α process
- Likely ultra-compact X-ray binaries
- Strong PRE, leading to possibly observable ejecta (e.g., Barra+2024)

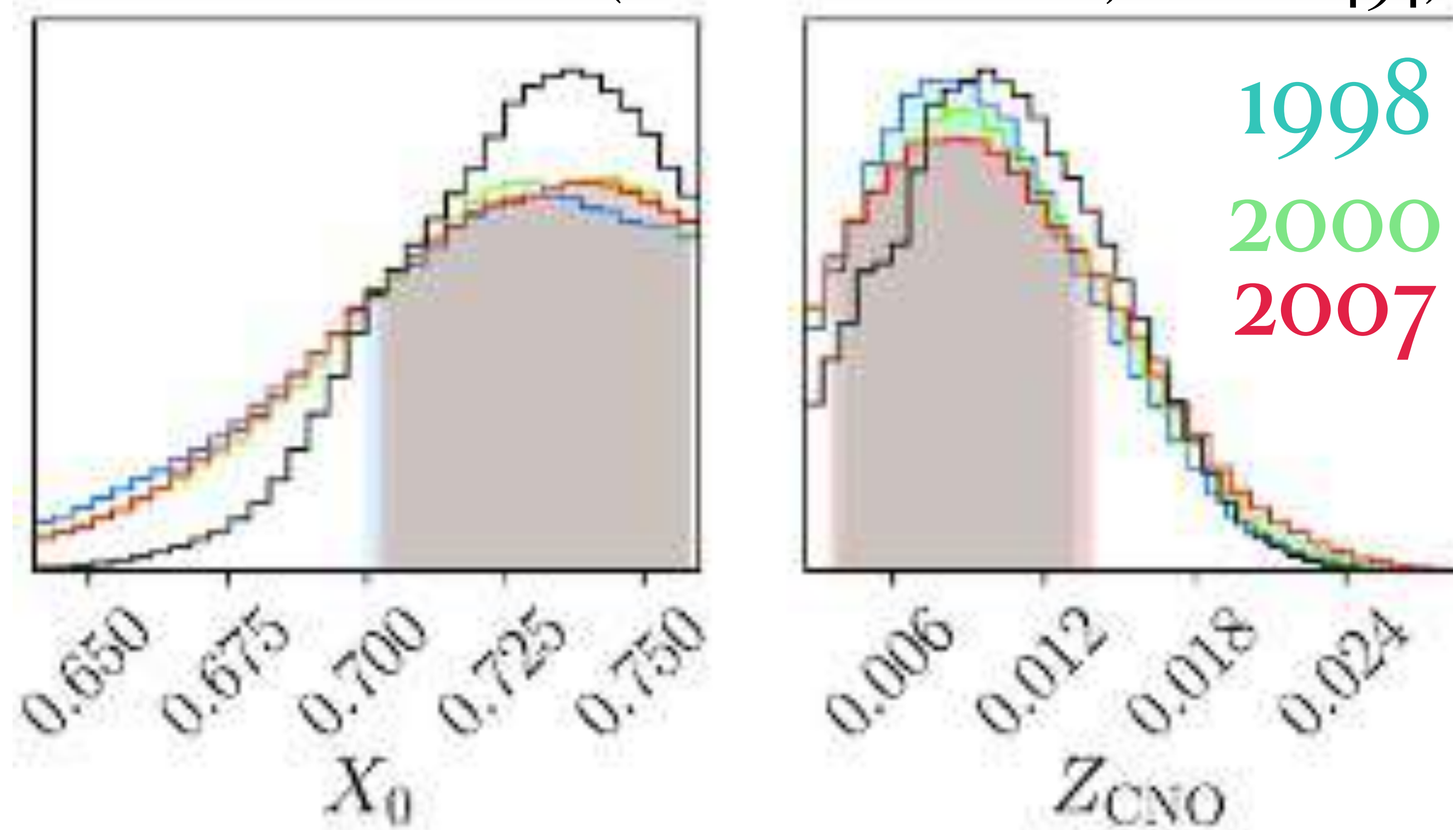
The case of most famous CXRB GS 1826-24

(Heger+07, Lampe+16, Johnston et al. 2020, Meisel 18, 19, AD+2020, 21)



(Taken from Galloway+17)

(Johnston et al. 2020, MNRAS 494, 4576)

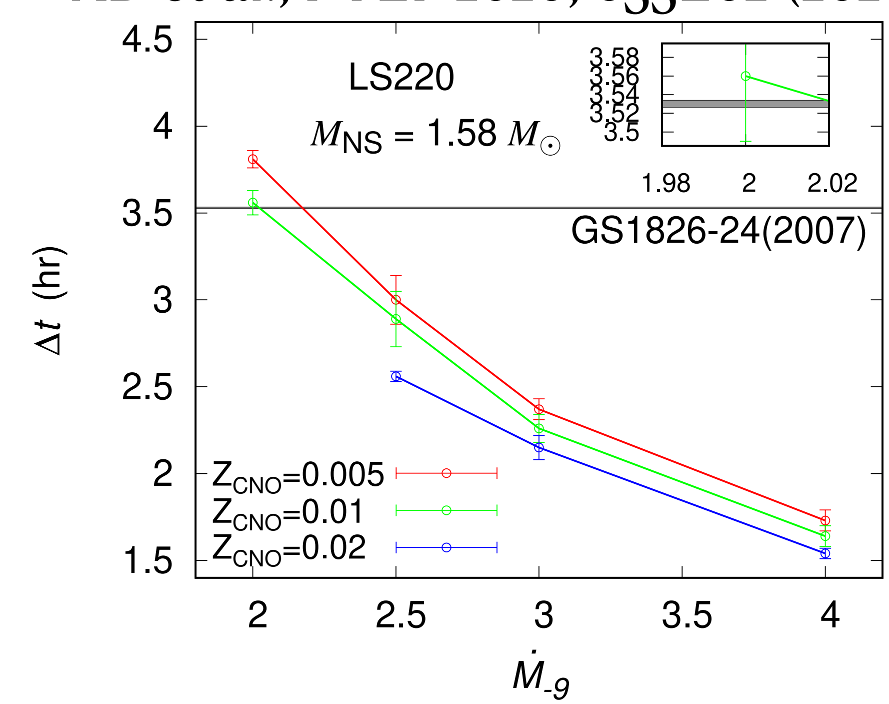


1D XRB models + MCMC analysis

- $X = 0.74^{+0.02}_{-0.03}, Z_{CNO} = 0.010^{+0.005}_{-0.004}$,

which is close to solar compositions

AD et al., PTEP 2020, 033E02 (2020)



6 CXRBs observed so far:

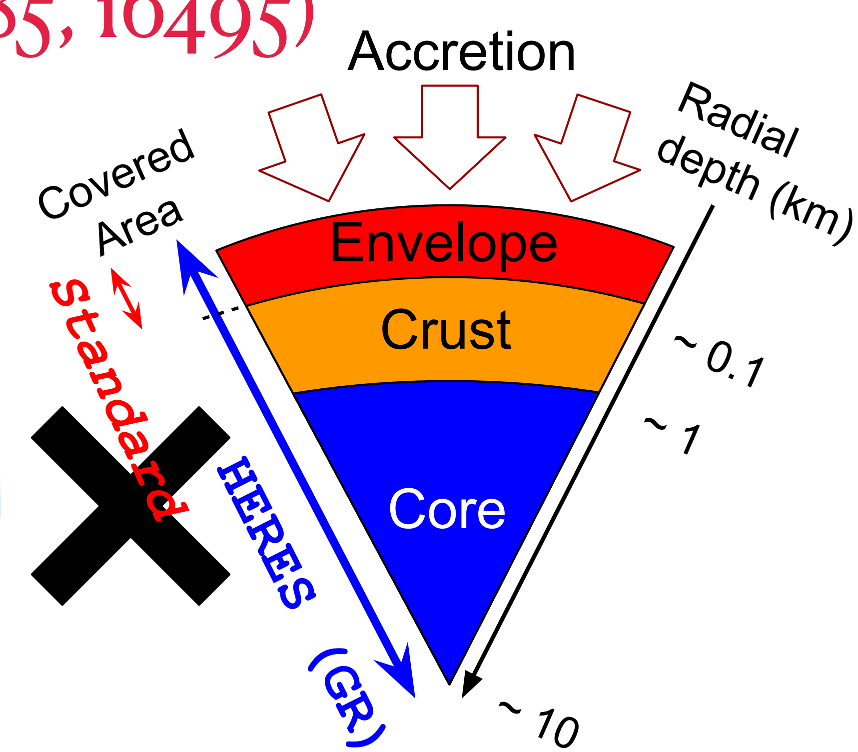
- GS 1826-238 (e.g., Galloway+17)
- EXO 1745–248 (Matranga+17b)
- GS 0836–429 (Aranzana+16)
- 1RXS J180408.9–342058 (Fiocchi+19, AD+24)
- MAXI J1816-195 (Bult+22, Wang+24)

Solar compositional donor (H-rich CXRBs)

- New CXRBs, SRGA J144459.2-60420 (ATel #16485, 16495)
- Motivation: We analyze SRGA J1444 through:

• Long-term monitoring by NinjaSat

• Numerical modeling by XRB-GR code HERES



* HERES: Hydrostatic Evolution of RElativistic Stars

2/4 Long-term evolution of SRGA J144459.2-604207

First Japanese 6U (10*20*30 cm³) CubeSat X-ray Satellite: NinjaSat

(Tamagawa et al., arXiv: 2412.03016)

- General-purpose X-ray observatory for time domain astronomy
- World's largest effective area in CubeSat missions
  → target candidate : 90+ X-ray sources
- Dedicated and agile CubeSat is a suitable tool for long-term observation of
  (i) persistently bright X-ray sources
  (ii) X-ray transient.

(Courtesy: T. Takeda)

Persistent flux observed by NinjaSat

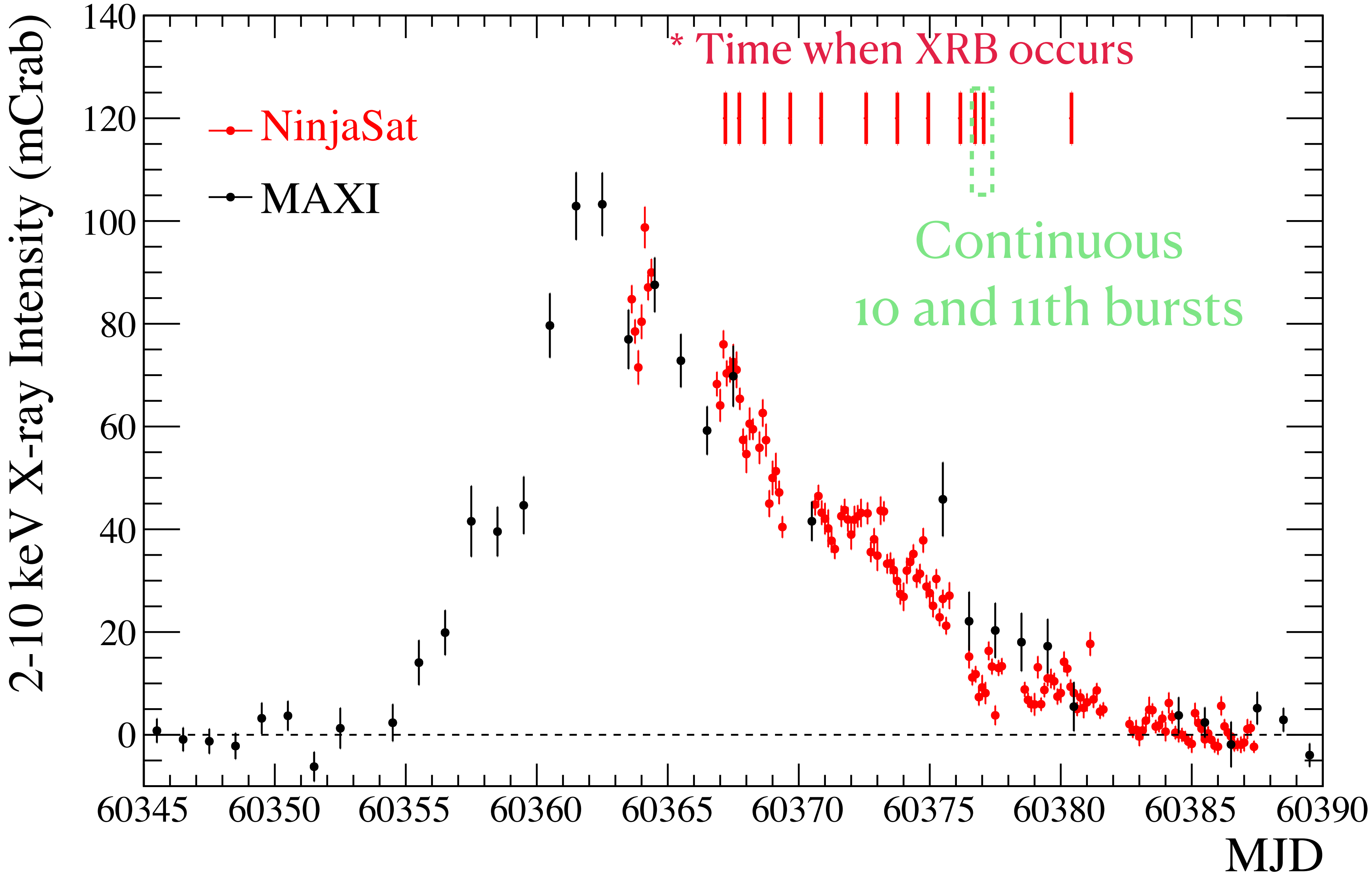
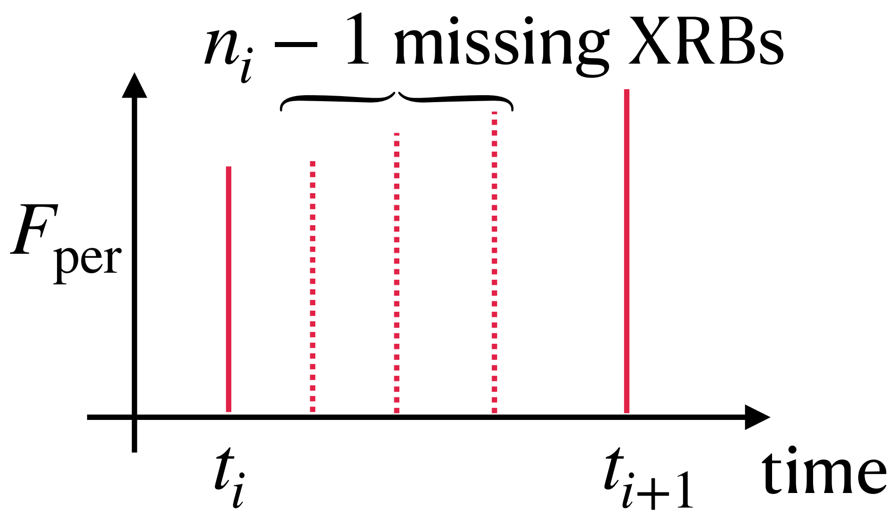


Fig. 1. 2–10 keV light curves of SRGA J1444 monitored by NinjaSat (red) and MAXI (black) with the binsizes of 3.0 hr and 24 hr, respectively.

- Many XRBs have been detected, covering wide range of persistent flux

The analysis of persistent flux



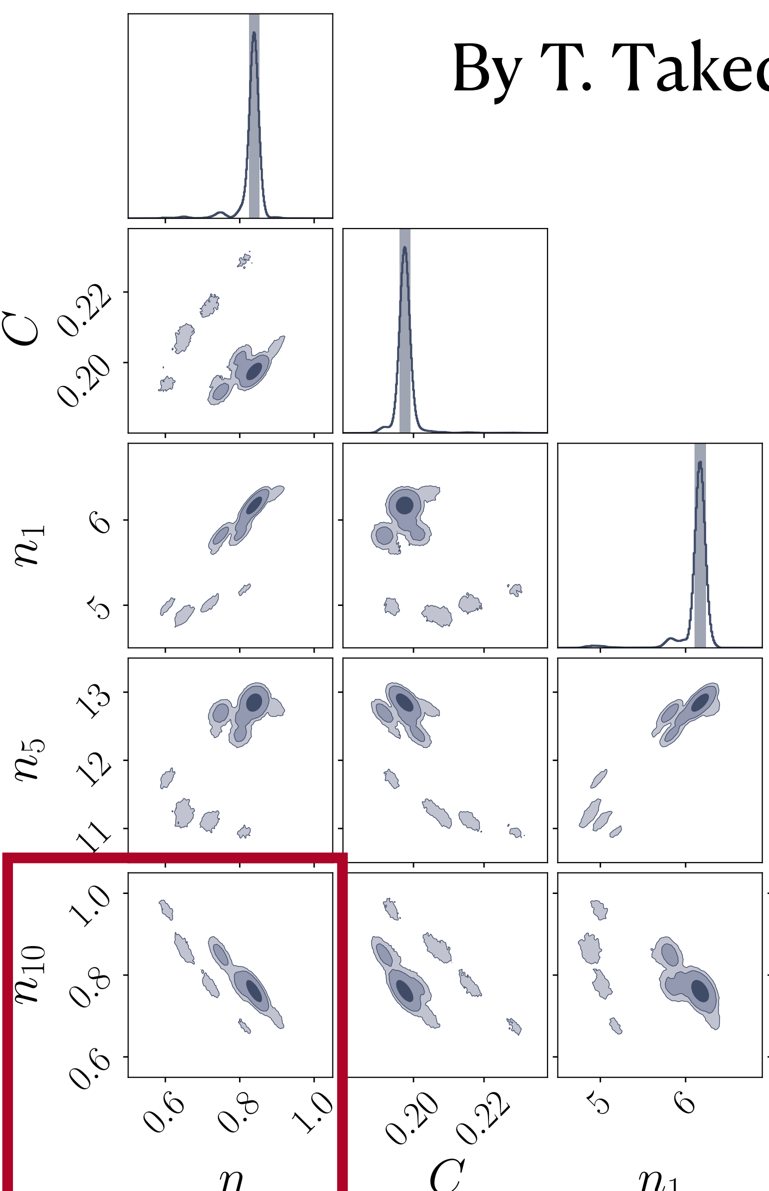
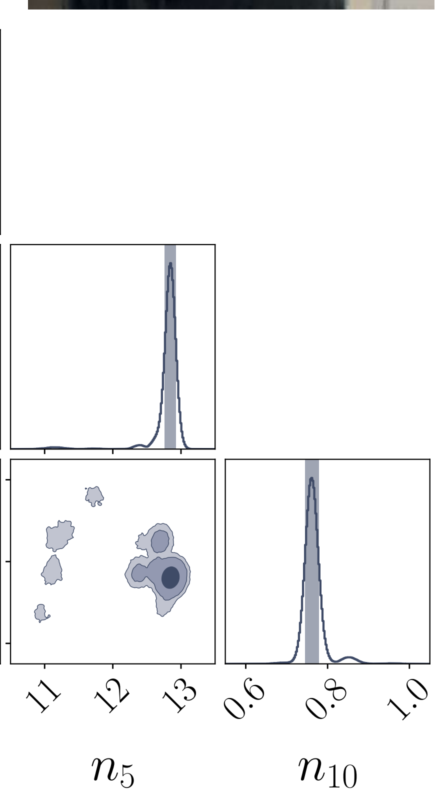
- Emprical η relation:

$$\Delta t = C F_{\rm per}^{-\eta} \propto \dot{M}^{-\eta}$$

- More practically, $\int_{t_i}^{t_i+1} F_{\rm per}^{\eta} = n_i C$

  with NinjaSat data t_i, $F_{\rm per}$ $(i = 1, \cdots, 11)$

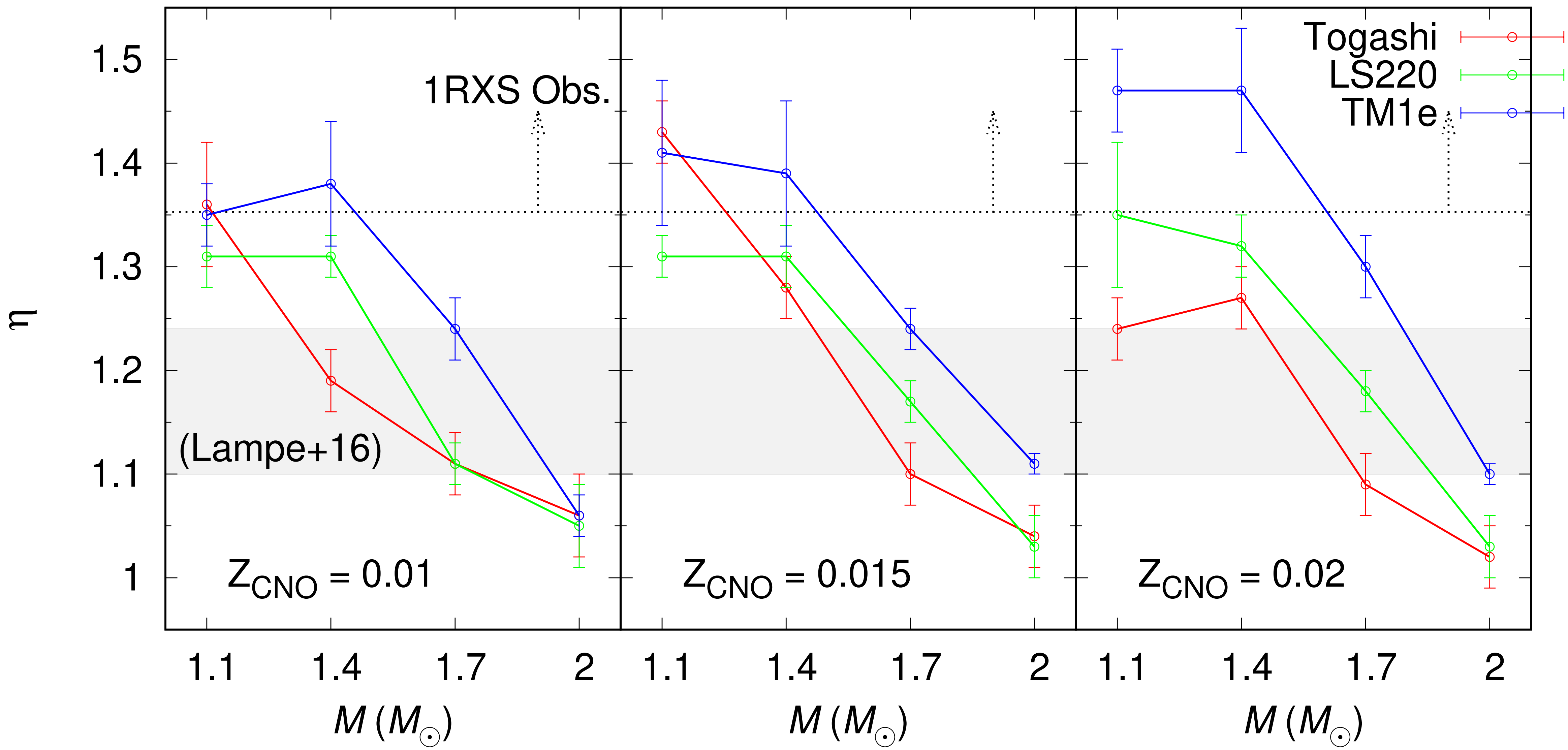
By T. Takeda (Tokyo U Sci.)

- MCMC analysis shows $\eta = 0.84^{+0.02}_{-0.01}$
- $\eta \sim 0.8 - 0.9$ is consistent with other works (Papitto+24, Fu+24).
- Most n_i were integers, except $n_{10} \sim 0.8$ (while $n_{10,obs} = 1$).

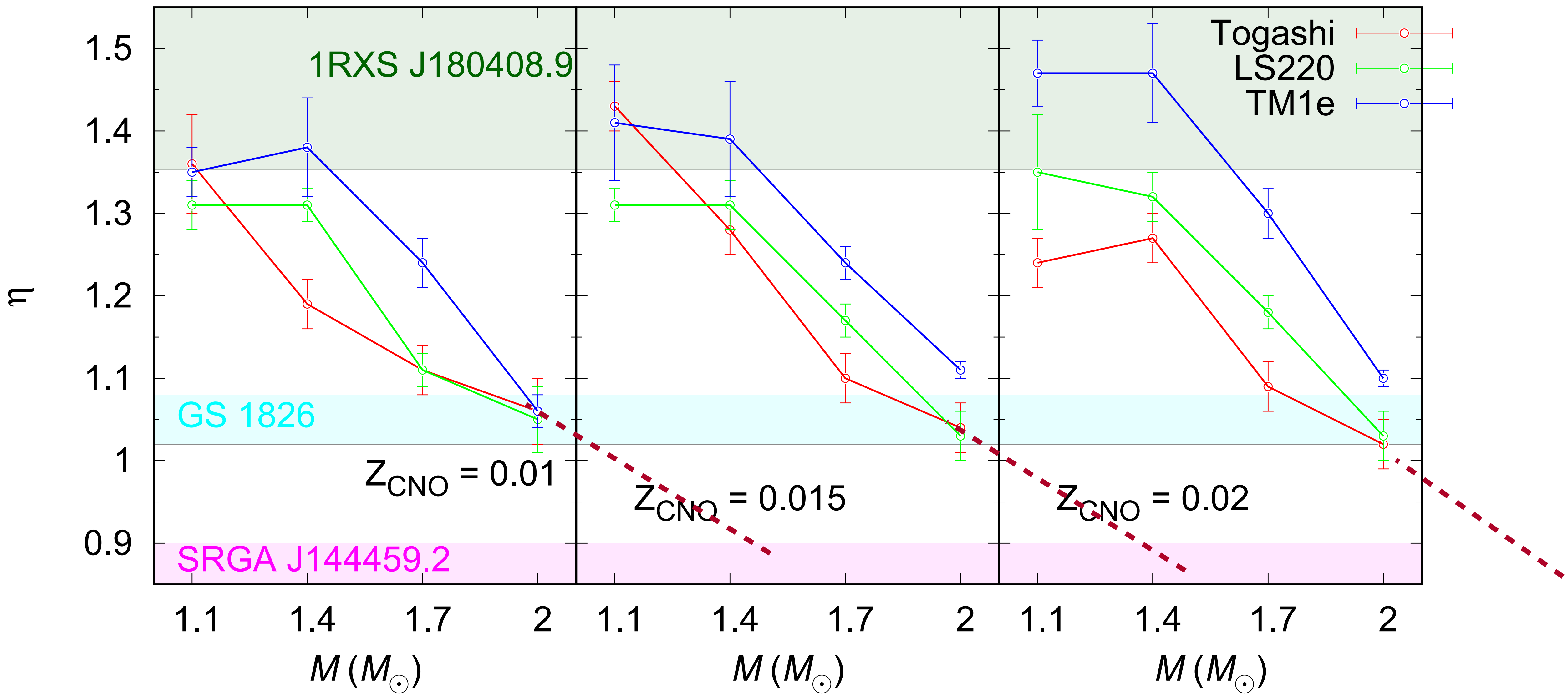
What makes you happy to know η ?

(AD+2024, ApJ 960, 14)



- Lampe+2016: various $(\dot{M}_{-9}, Z_{\rm CNO})$ models —> $\eta = 1.1 - 1.24$
- AD+24: various $(\dot{M}_{-9}, Z_{\rm CNO}, M_{\rm NS}, R_{\rm NS})$ —> wide η values
- From observed η value, one can specify NS mass and radius.

Massive SRGA J1444 ?!



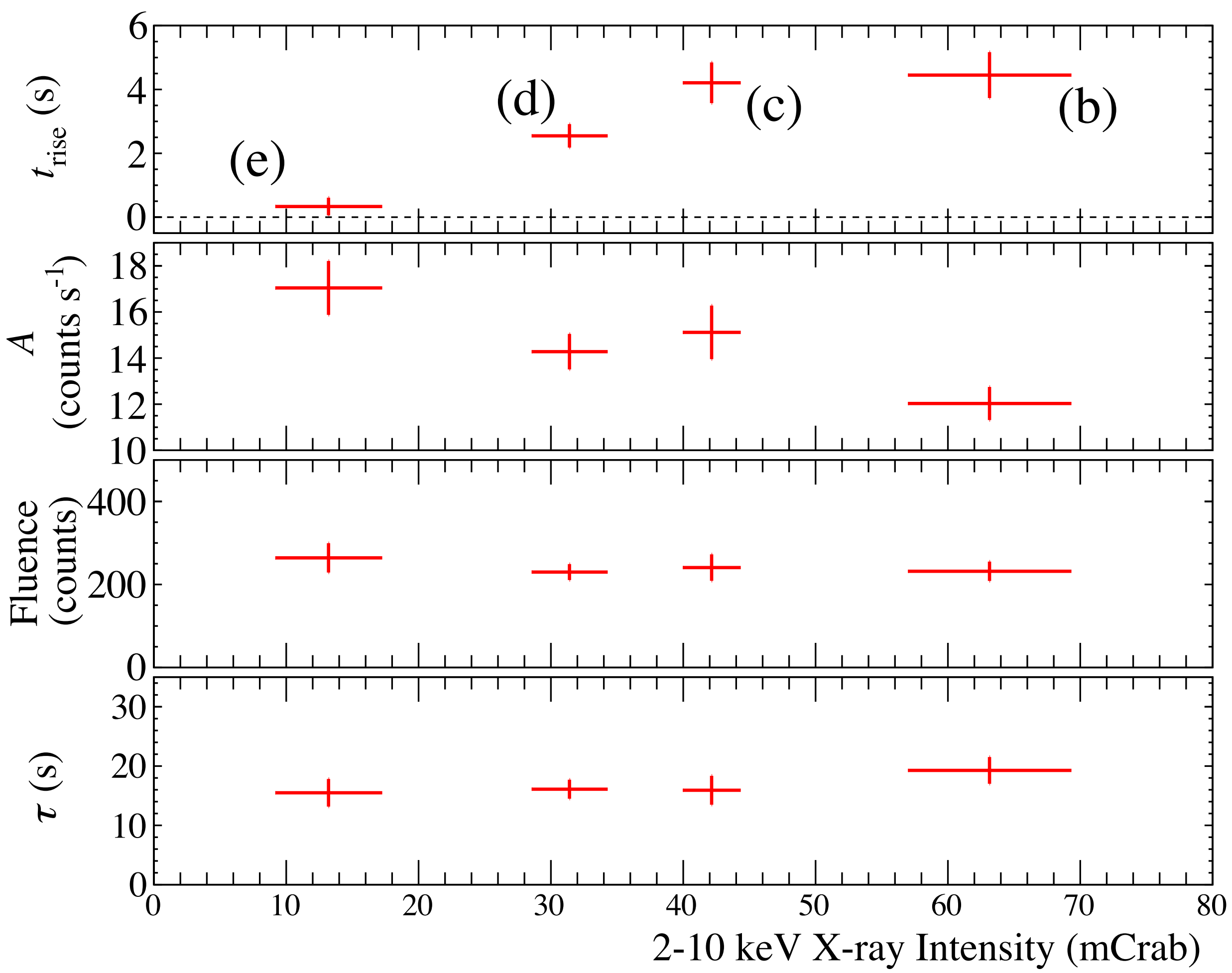
- SRGA J1444 is not reproduced by our current models, but allowing extrapolation, SRGA J1444 must be massive with $M_{NS} > 2\ M_\odot$ (our future work for confirmation)

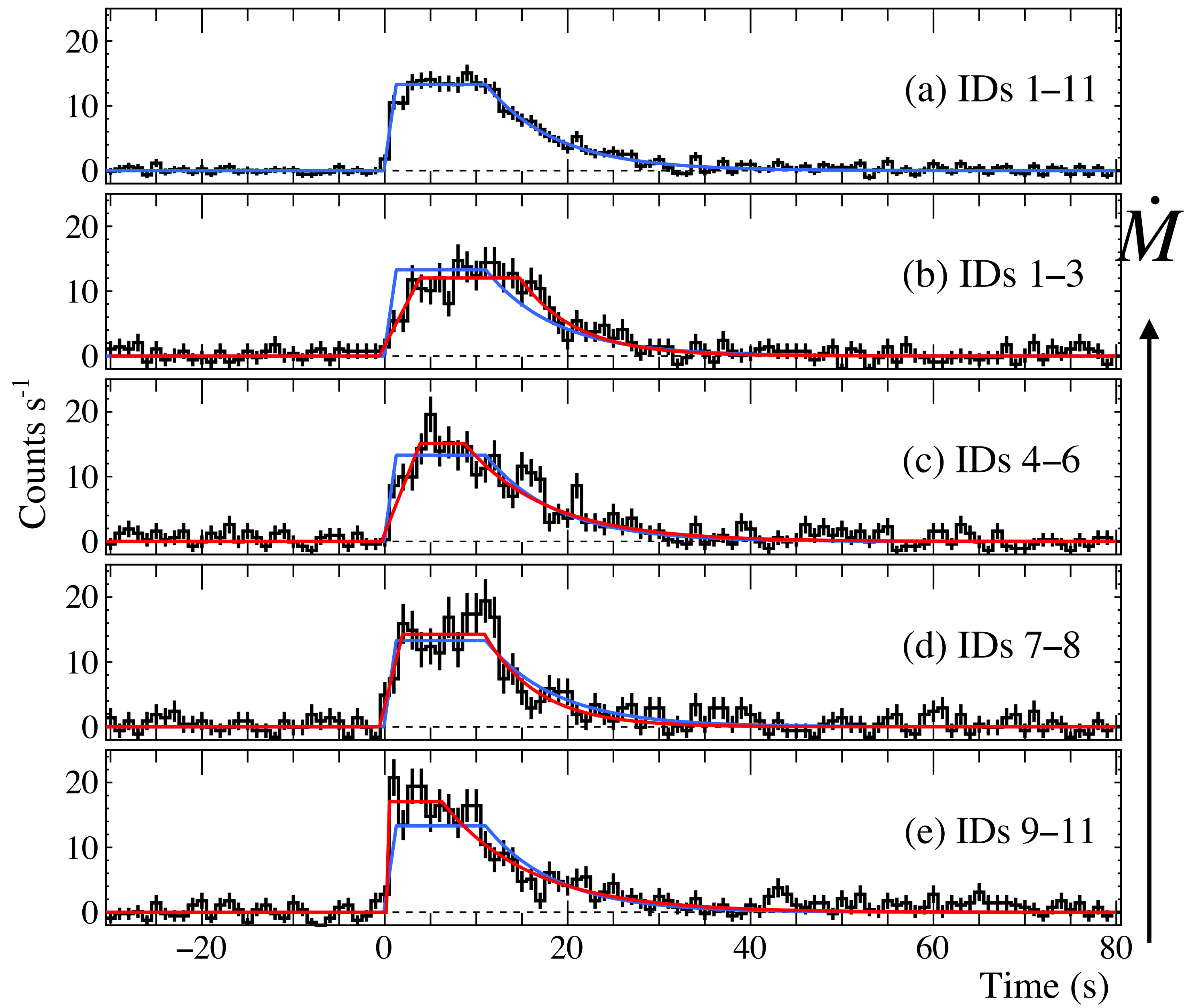
3/4 Analysis of XRB light curves of SRGA J144459.2-604207

Burst light curves: Platou + rapid decay

- fitted by exp. decay trapezoidal function

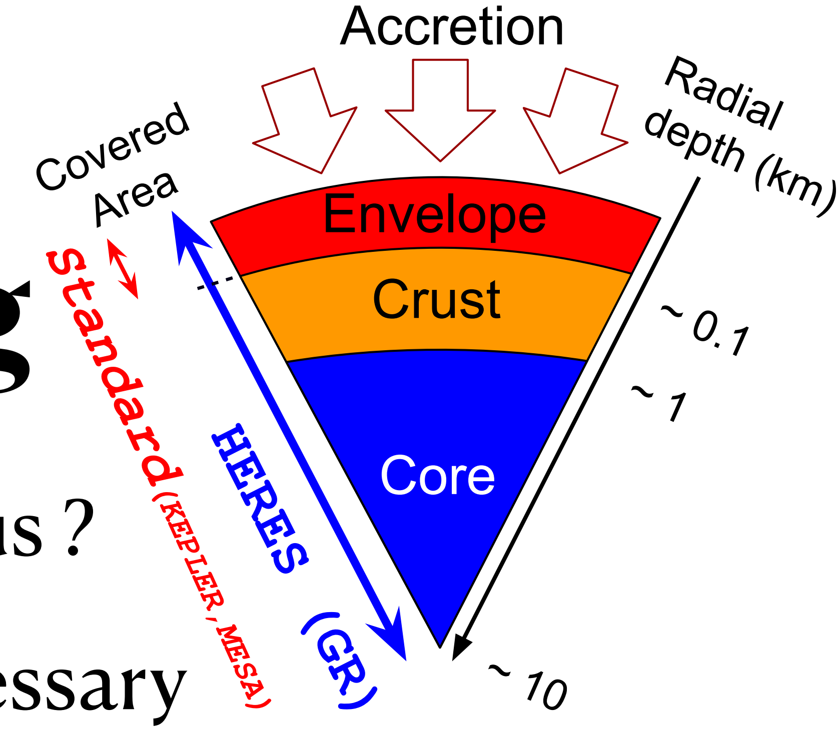
—> Unlike standard CXRB (linear func. + exp. decay)





Blue: Fitting curve with all 11 bursts (a)
Red: Fitting curve with each burst sequence, (b)-(e)

Setup of light-curve modeling



- What does the *unconventional* clocked bursters tell us ?
- To reveal the mystery, theoretical prediction is necessary

—> HERES (AD+2020 PTEP 2020, 033E02; Zhen+AD+23 ApJ 950, 110):

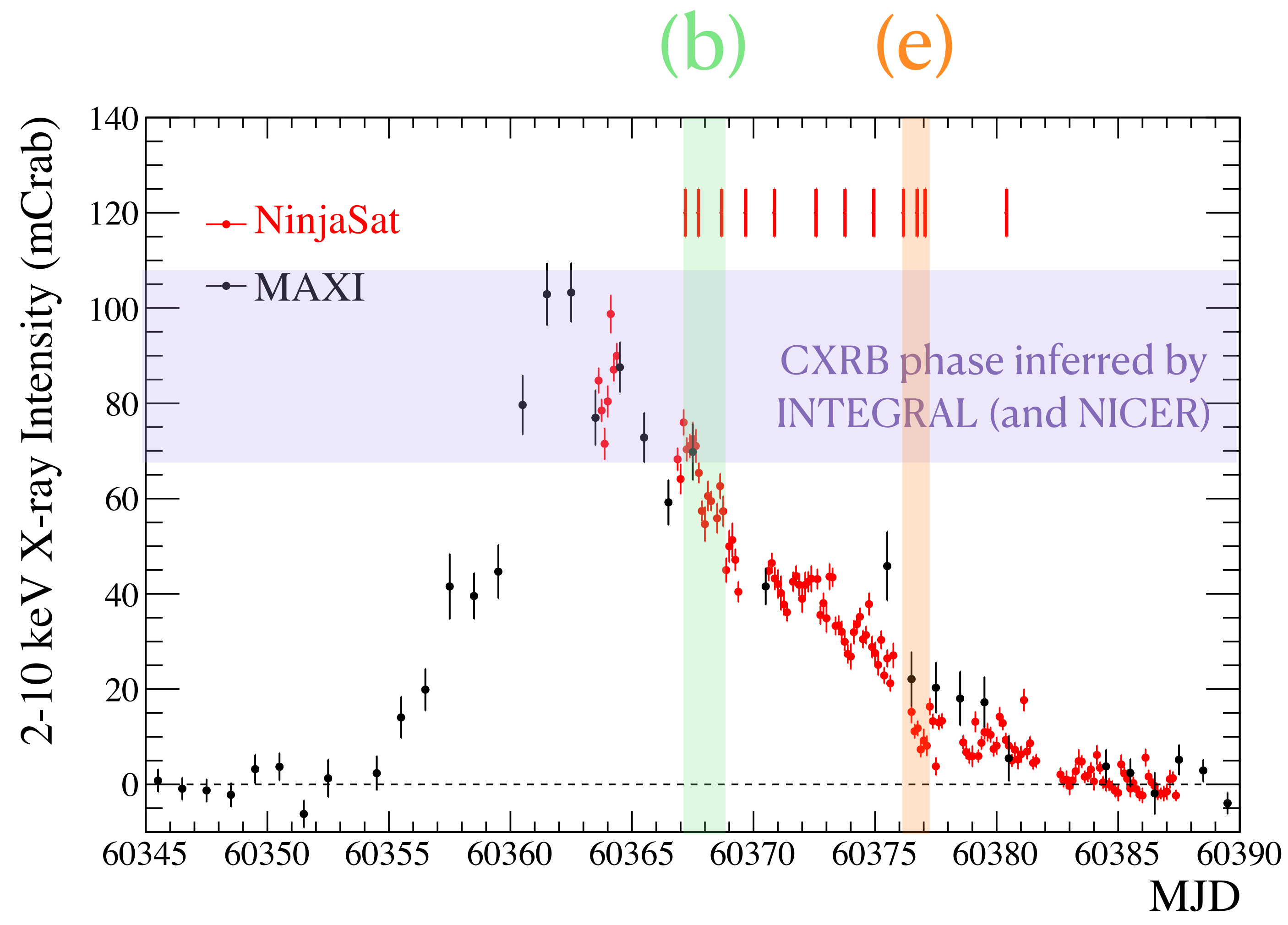
Following quasi-hydrostatic evolution of NSs with 88-nuclei network

- We focus on two phase

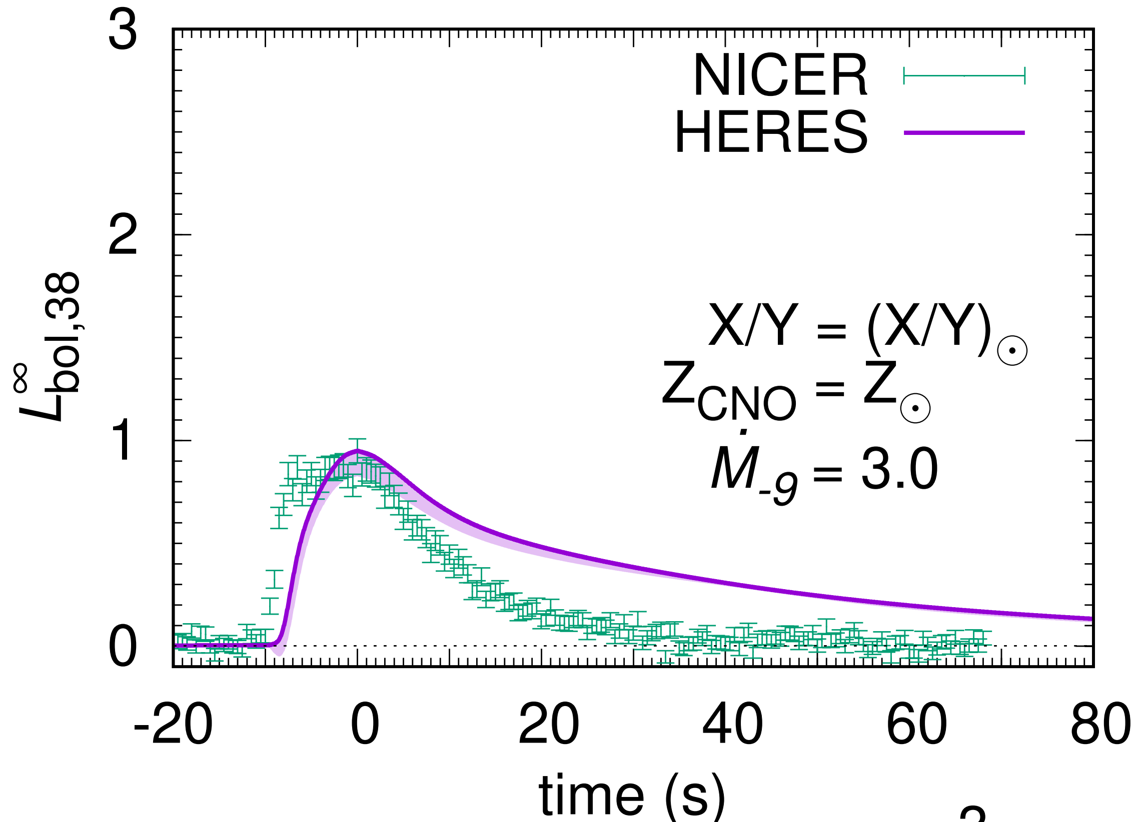
- CXRB phase (b) with $\dot{M}_{-9,\mathrm{CXRB}}$
- Decline phase (e) with $\dot{M}_{-9,\mathrm{Decline}}$

Accretion-rate ratio is inferred as

$$\frac{\dot{M}_{-9,\mathrm{Decline}}}{\dot{M}_{-9,\mathrm{CXRB}}} = \left(\frac{\Delta t_{\mathrm{CXRB}}}{\Delta t_{\mathrm{Decline}}}\right)^{\eta} \simeq 0.2 - 0.3$$

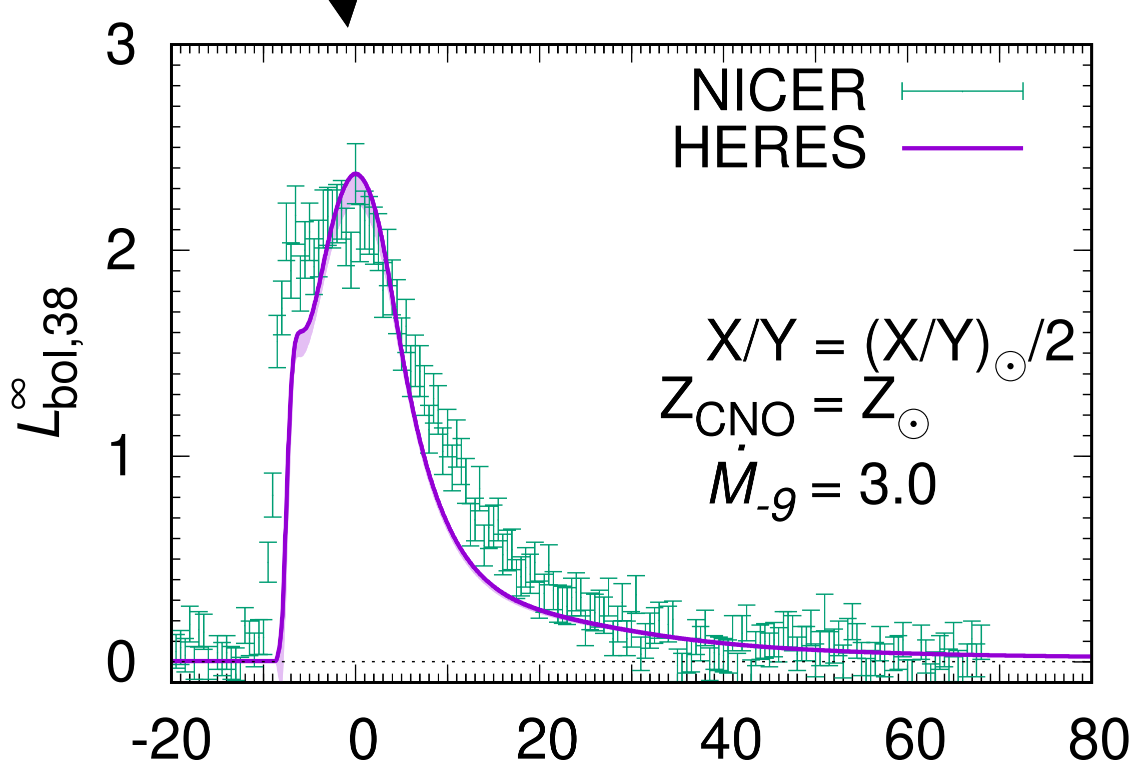


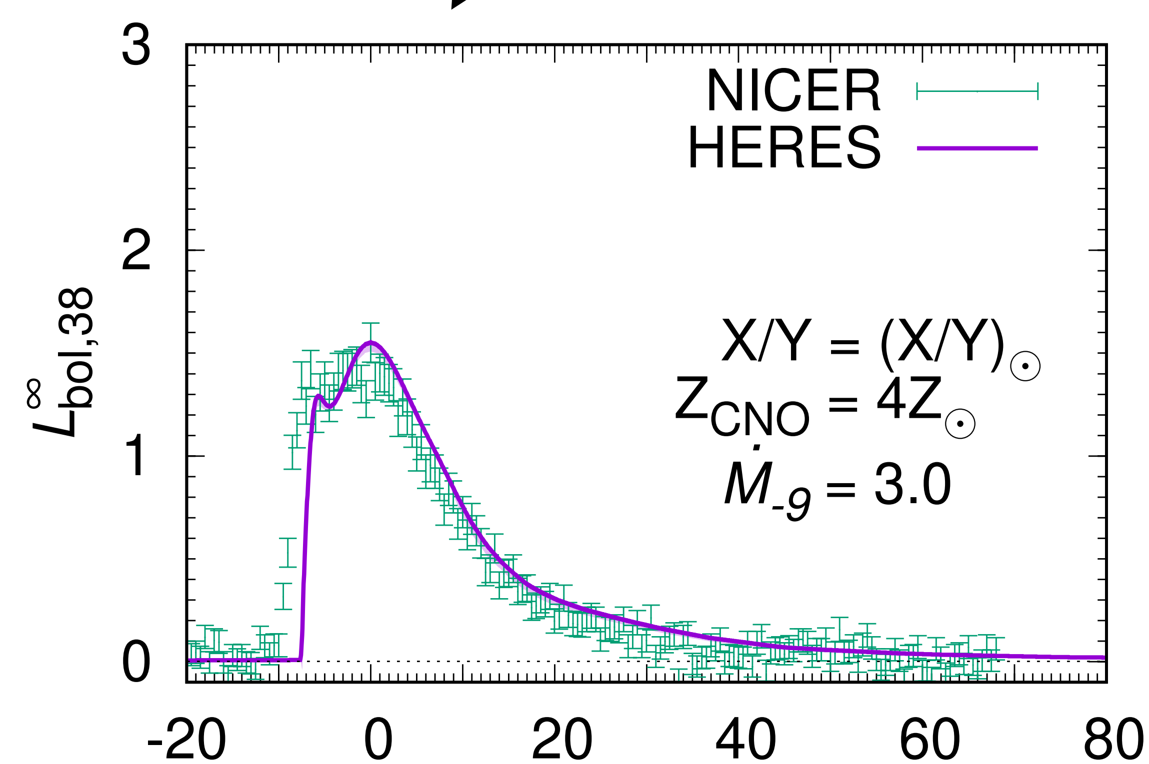
Modeling of CXRB phases (Light curves: NICER)



Lower X/Y

Higher $Z_{\rm CNO}$

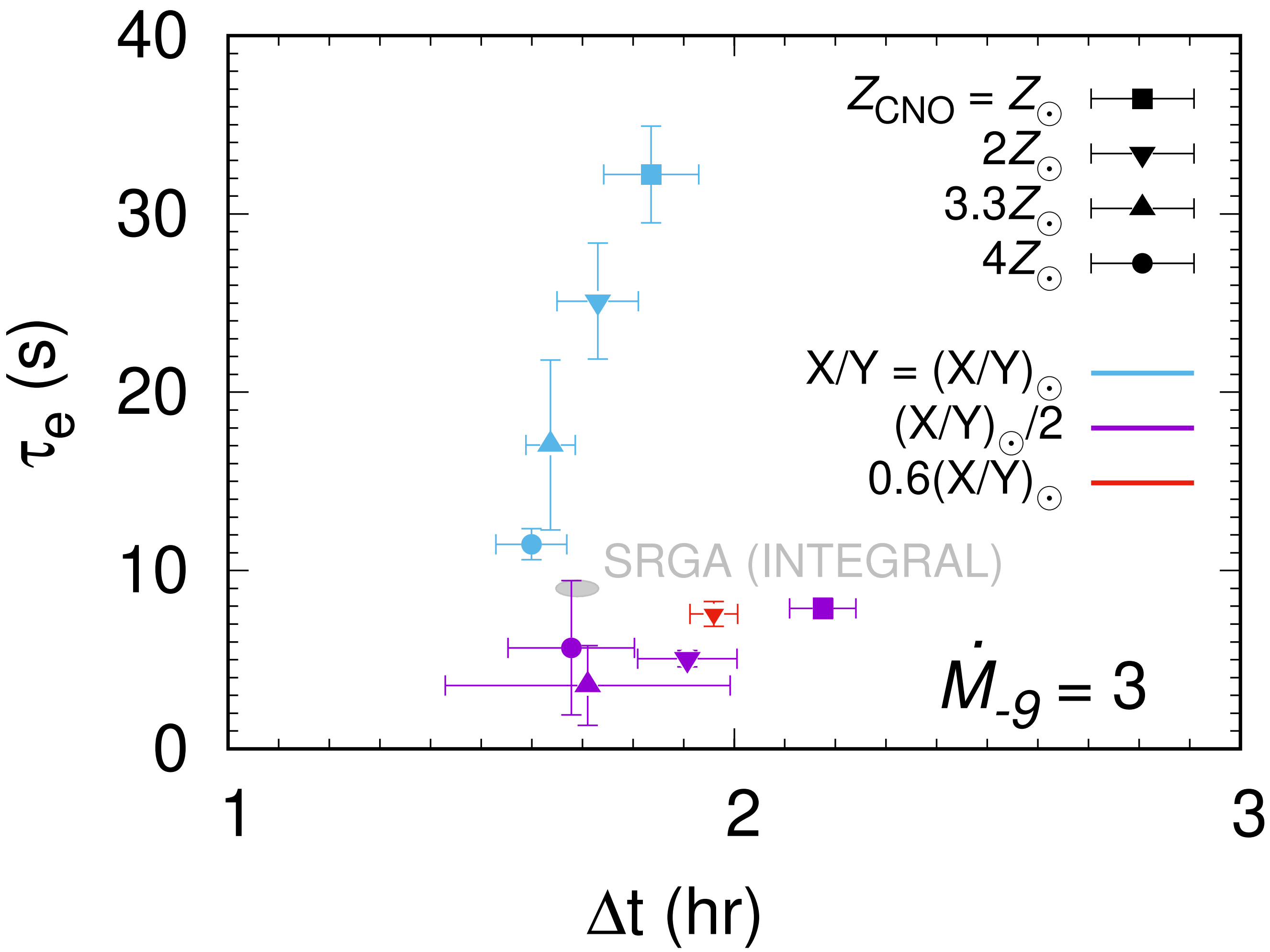


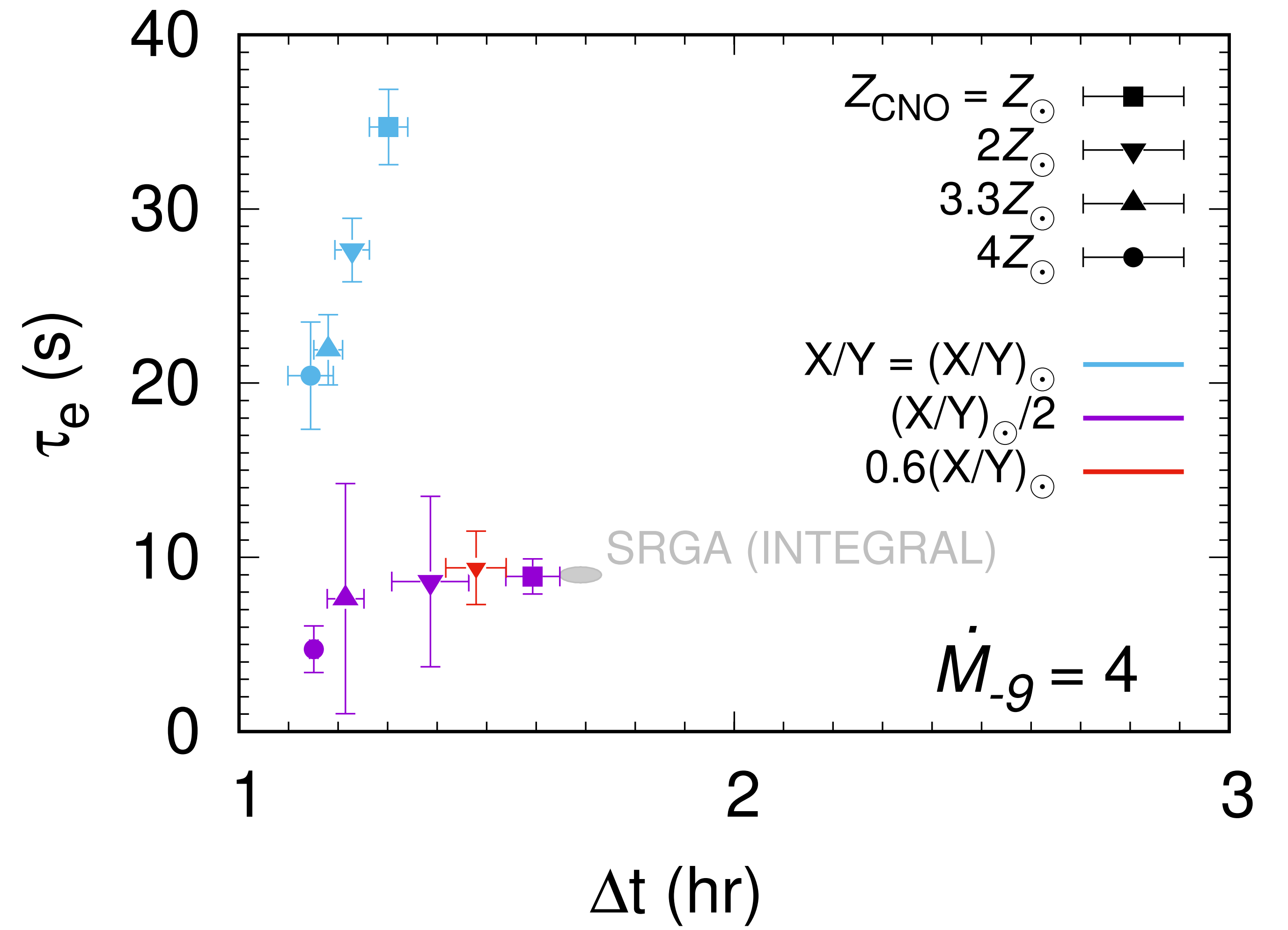


- Low X/Y v.s. High $Z_{\rm CNO}$ —> Unlike the conventional CXRBs !!

$(\Delta t, \tau)$ in CXRB phase

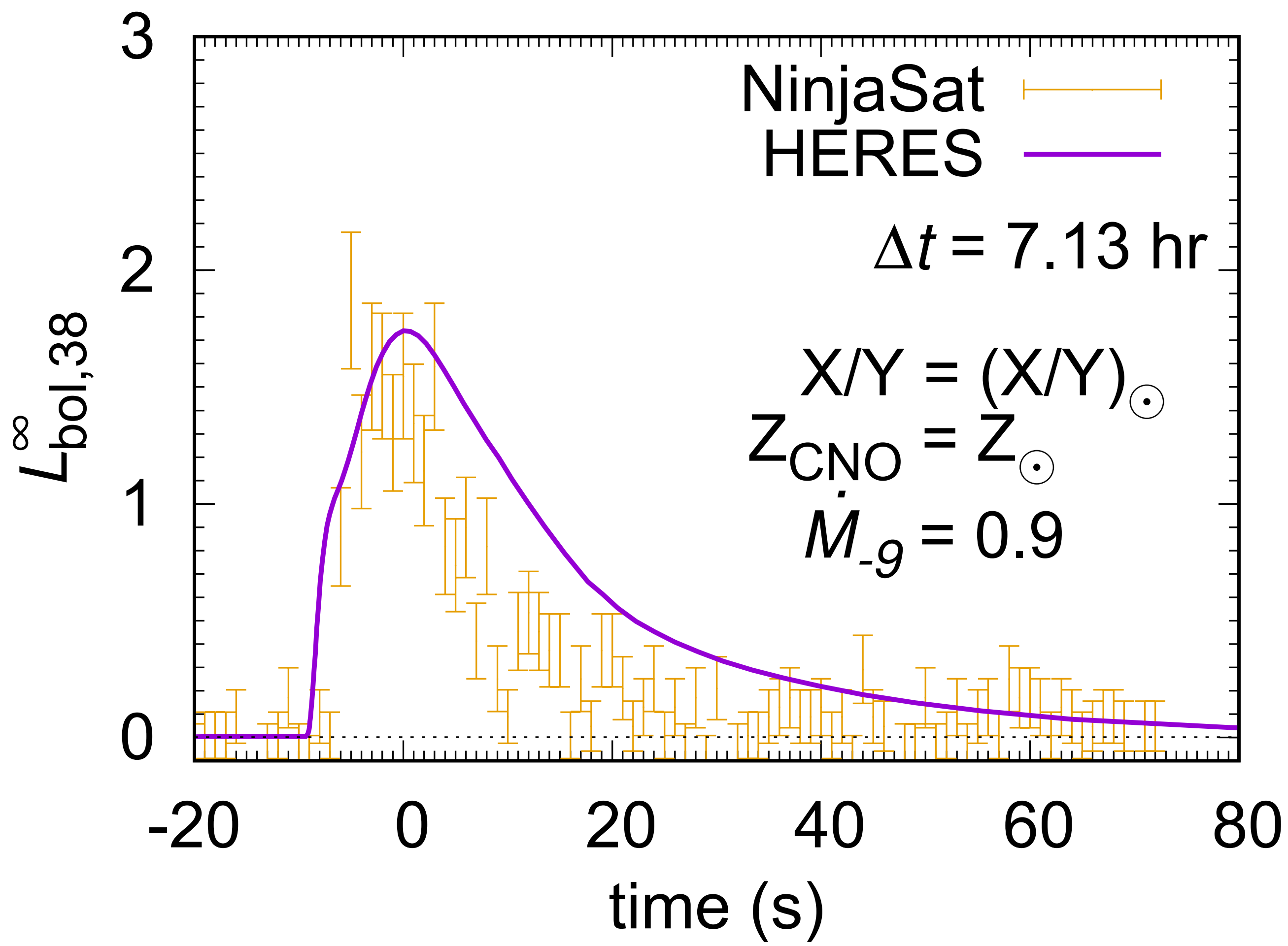
Comparison with INTEGRAL (similar to ID 1-3 in NinjaSat)

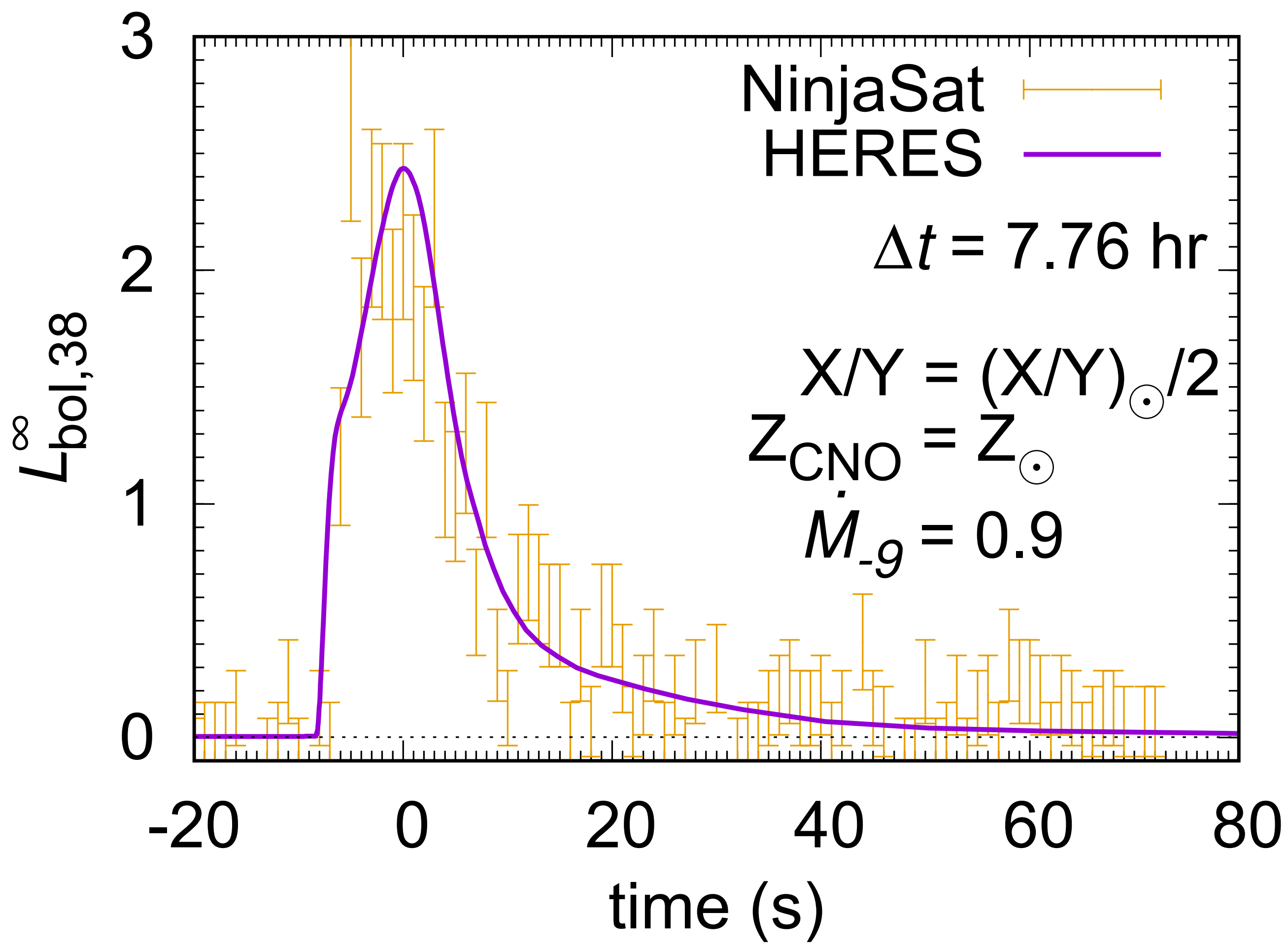




- $\dot{M}_{CXRB,-9} \approx 3 - 4$ from observed Δt.
- High $Z_{\rm CNO}$ for $\dot{M}_{CXRB,-9} = 3$, while low X/Y for $\dot{M}_{CXRB,-9} = 4$

Modeling of Decline phases

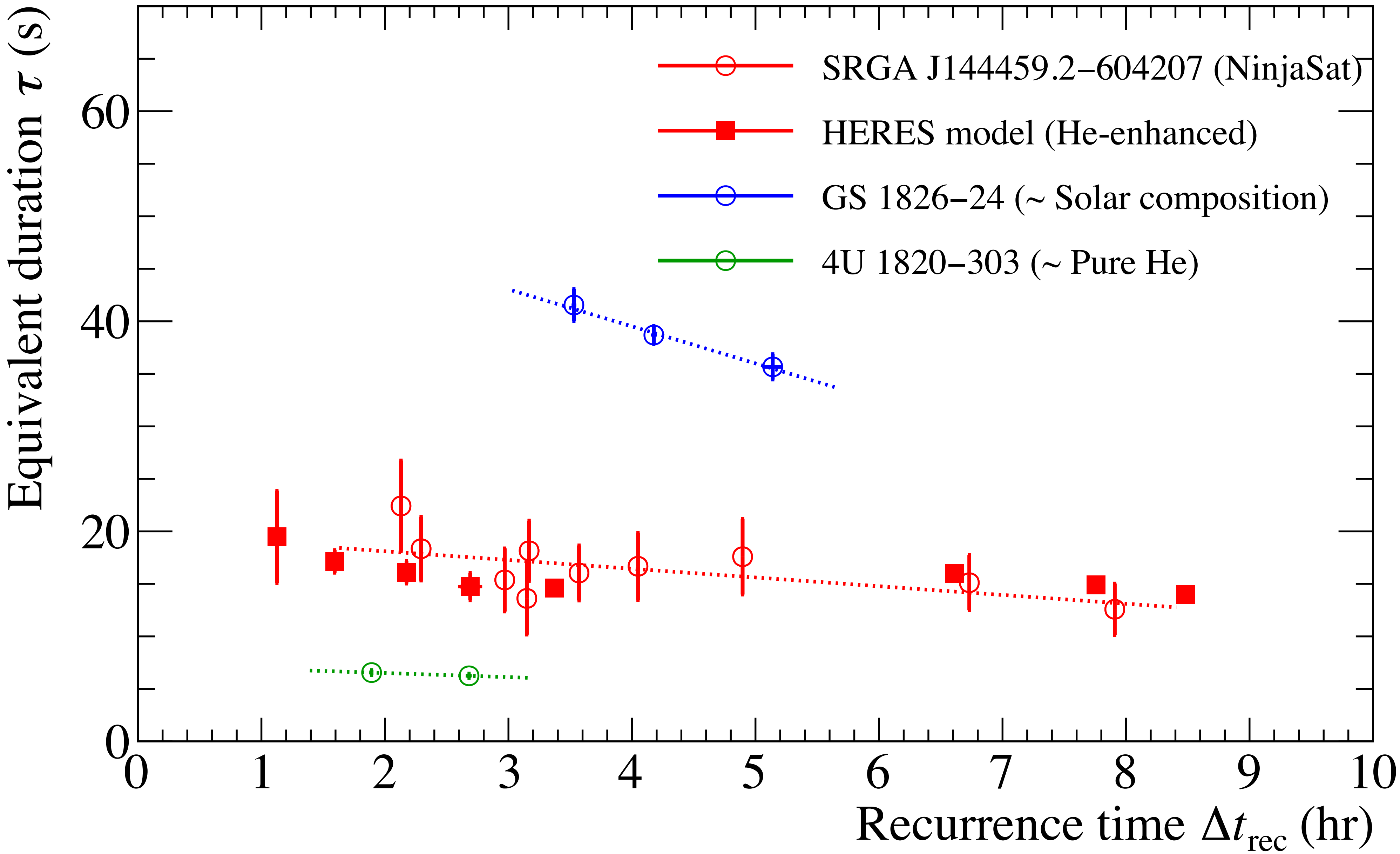




- Low X/Y seems preferred in terms of tail parts of light curves.

—> First Evidence of non-solar composional CXRBs !!

$(\Delta t, \tau)$ in Decline phase



- HERES with $X/Y = 1.5, Z = 0.015$ is pretty good agreement with NinjaSat observations, although it is one of solution.

4/4 Conclusion

Conclusion

- Clocked X-ray bursters (CXRBs) can tell us many information on LMXBs.
- Observed CXRBs so far: Solar compositional donor. Light curves are fitted with linear increase + mild decay.
- We analyzed light curves of New CXRB SRGA J1444 through long-term monitoring (NinjaSat) and our burst models (HERES).
- $\eta = 0.8 - 0.9$, which may imply massive SRGA J1444 with $M_{\rm NS} > 2\ M_{\odot}$
- No possible that the donor has solar composition due to the short burst duration. Light curve are fitted with exp-decay trapezoidal function.
- Our suggestion is He-enhanced scenario: $X/Y \approx 0.5(X/Y)_{\odot}, Z \sim Z_{\odot}$