X-ray study of non-thermal plasma in stellar flares triggered by MAXI

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GT Mus target team, HR 1099 target team, *Resolve* energy cal team

2024/12/10　MAXI 15 year WS @Nihon University

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Overview – Why flares in other stars?

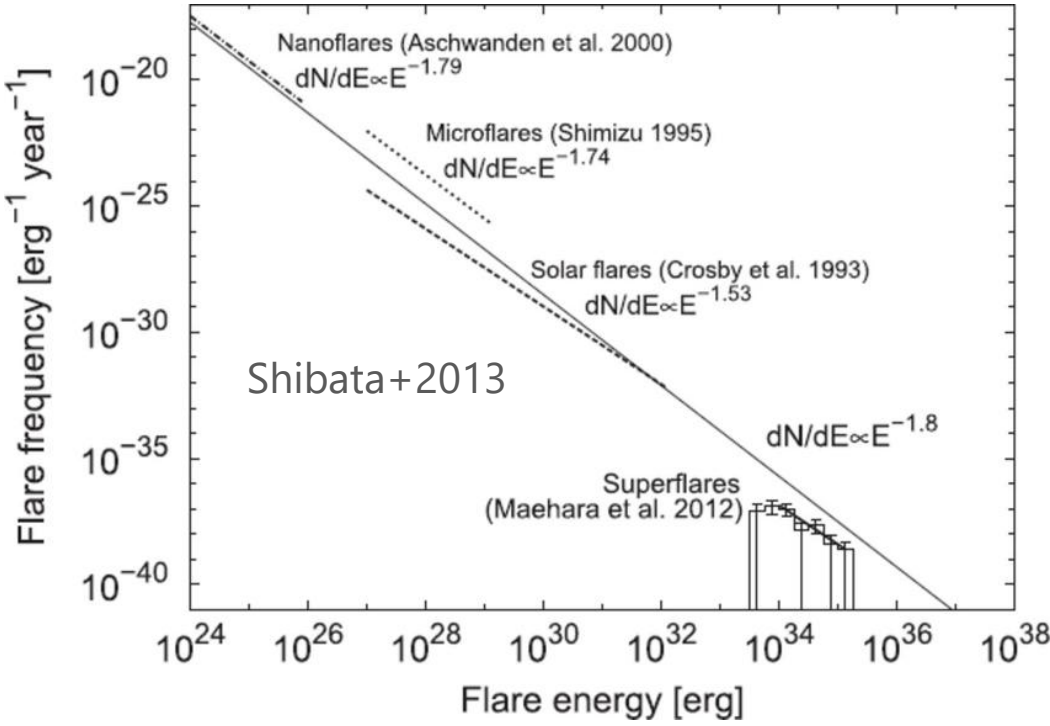
☆ **Same physical process as solar flares**

- cf.) Neupart effect, scaling law,,, (Bentz & Güdel 2010, ARAA)
- But with different scales of time/space

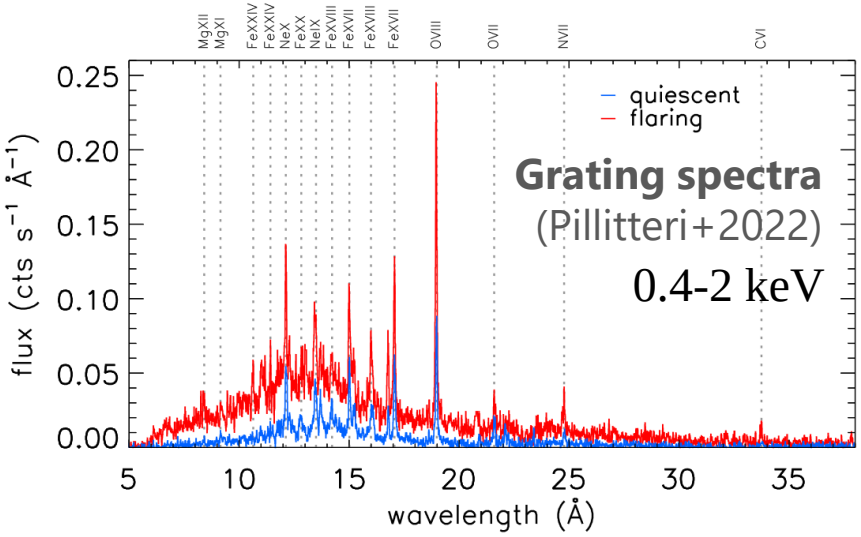
☆ **We can investigate giant flares!!**

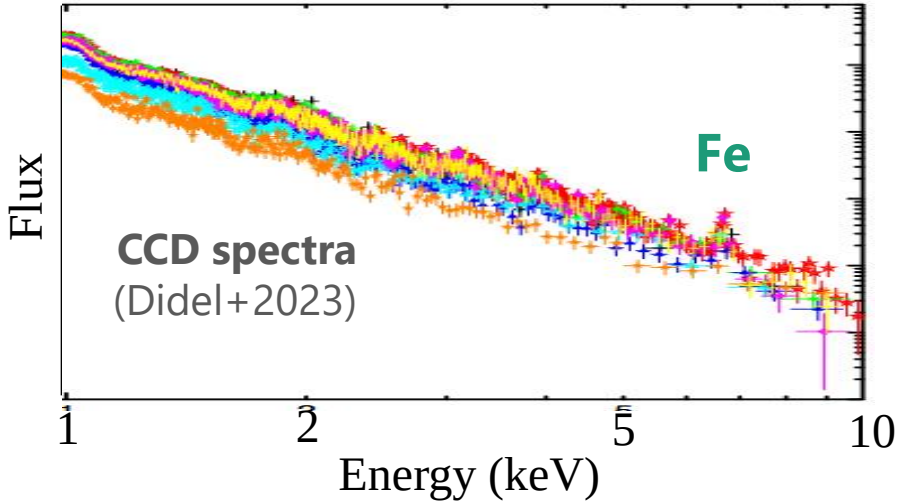
- Lower occurrence rate for the larger flares (See Figure)
- Stellar flares can help cover the high-end of the flare dynamic range.

< Flare occurrence rate in G-type stars >



Overview – Previous SXR spectra



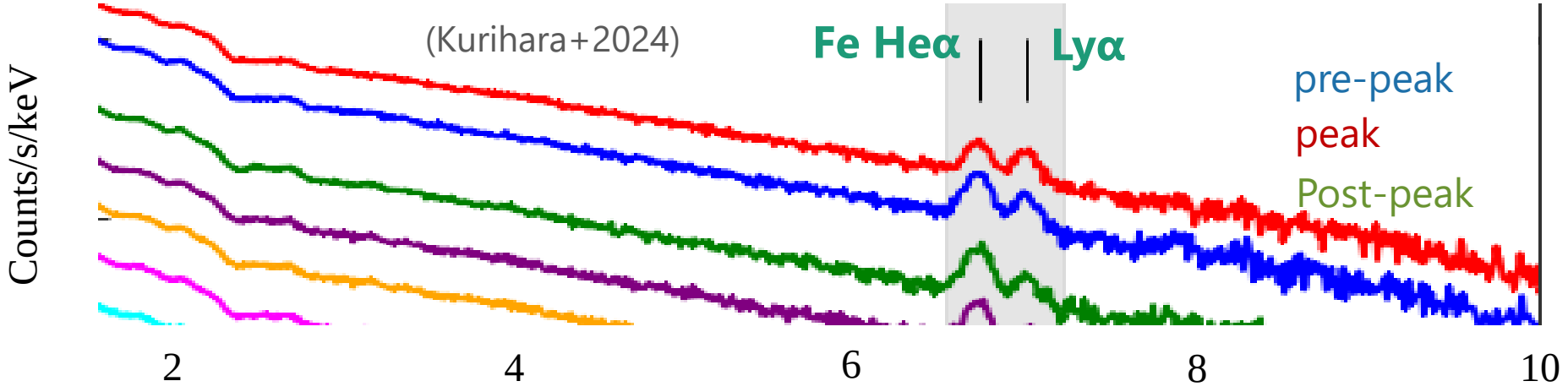


	Energy band	
	Low E (< 2 keV)	High E (Fe K-shell band)
Continuum	○	○
Lines	◎	△

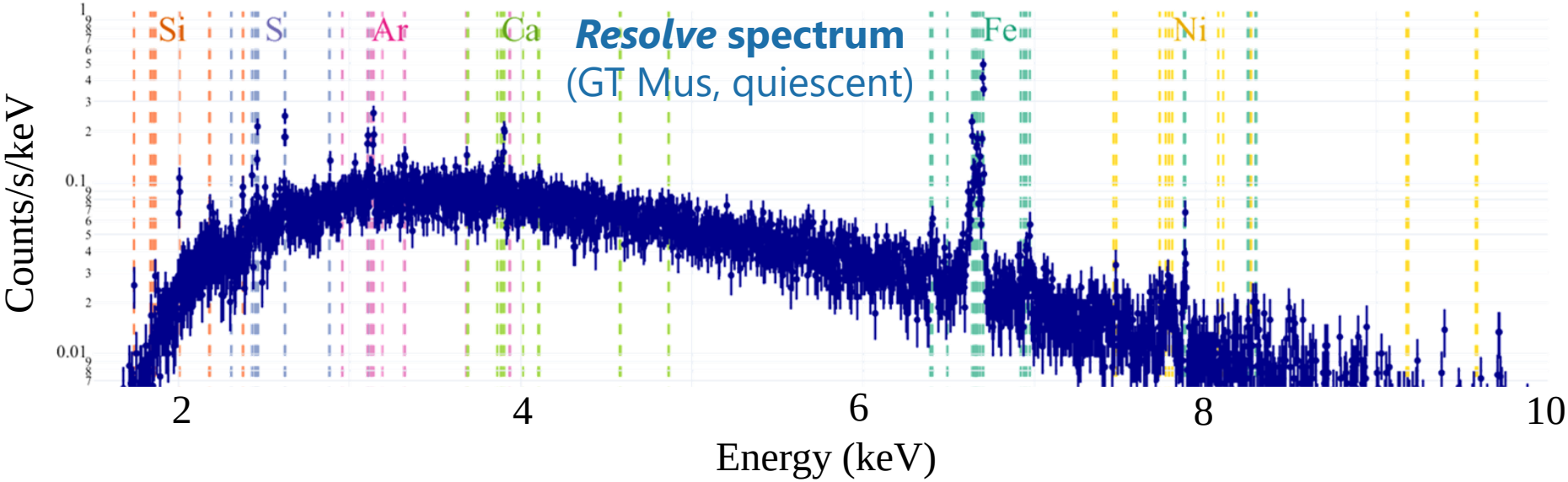
- Continuum：Good coverage for 0.1-10 keV
- Lines：Grating missions (Chandra, XMM-Newton,,) cover the low E side,
  but the high E side had not been unexplored in detail.

Overview – Game changers

☆ NICER (Neutron Interior Composition ExploreR): 2017~



☆ X-Ray Imaging Spectroscopy Mission (XRISM): 2023 ~



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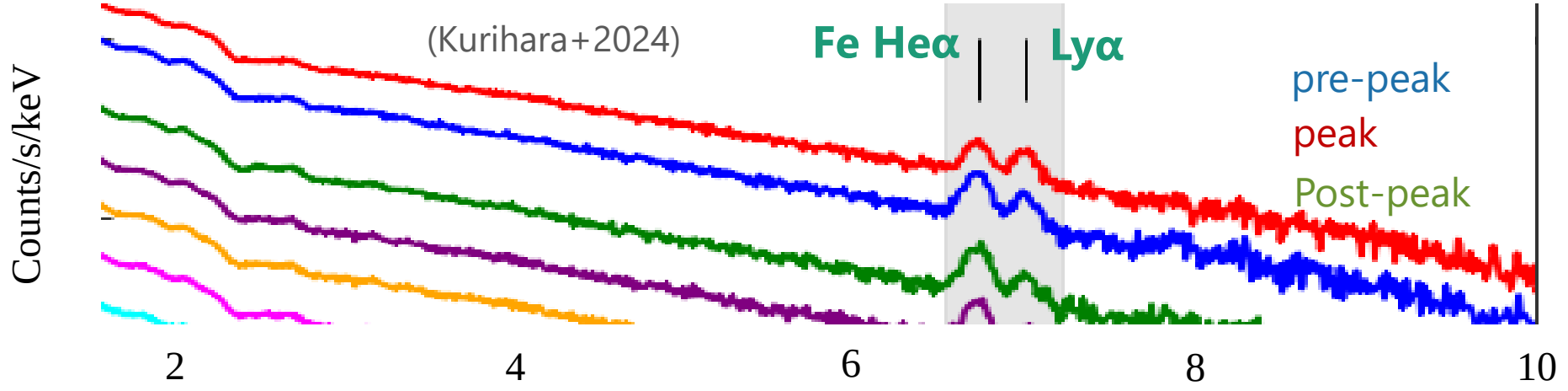
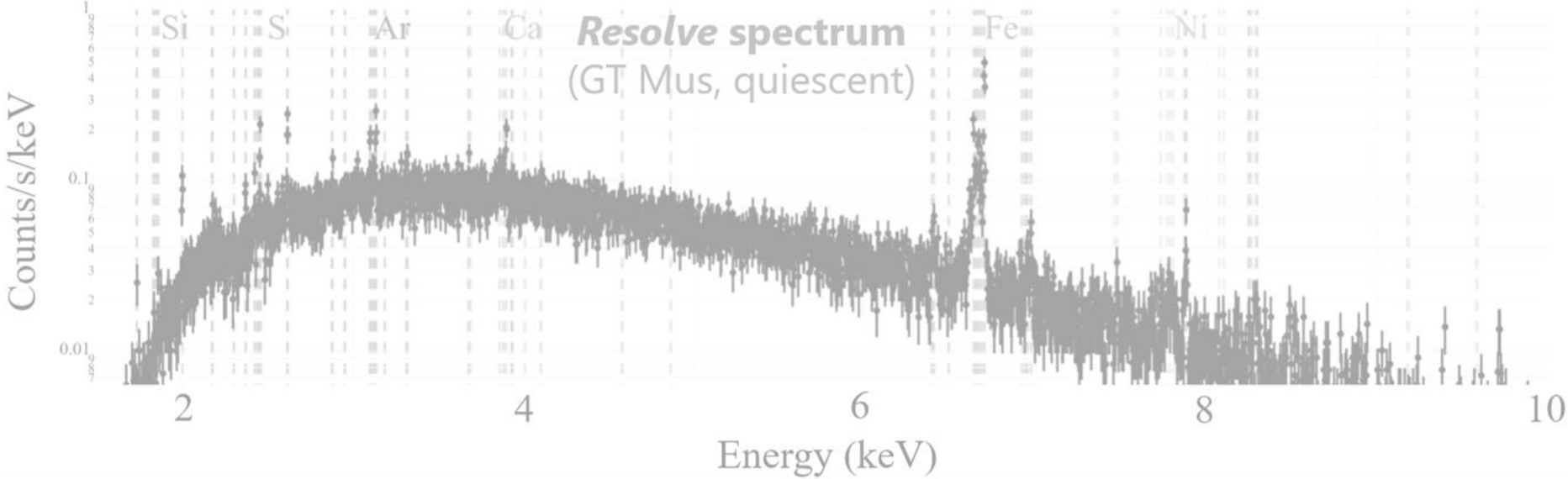


NICER resolved lines from He-like & H-like Fe on the broad continuum



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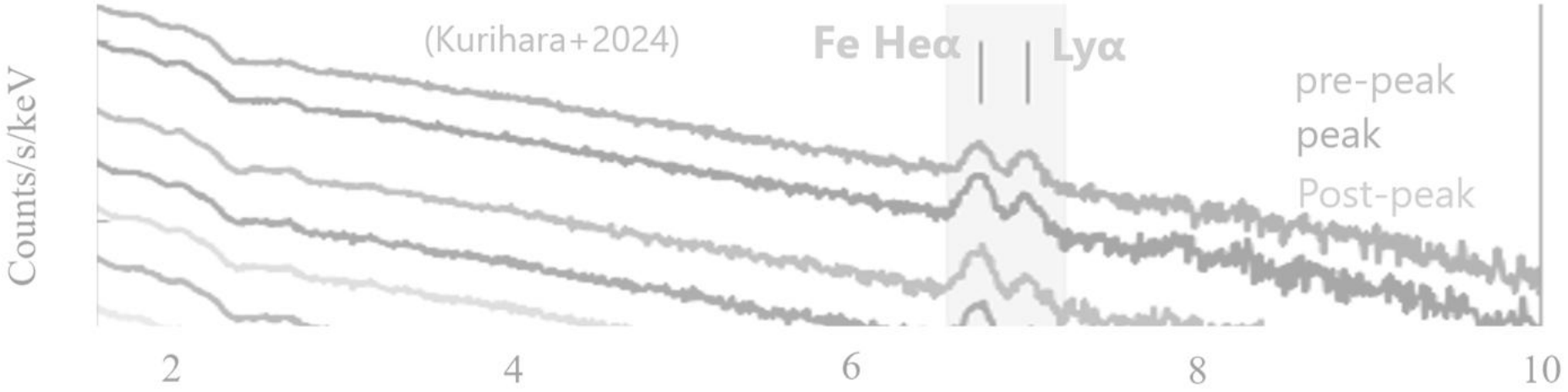

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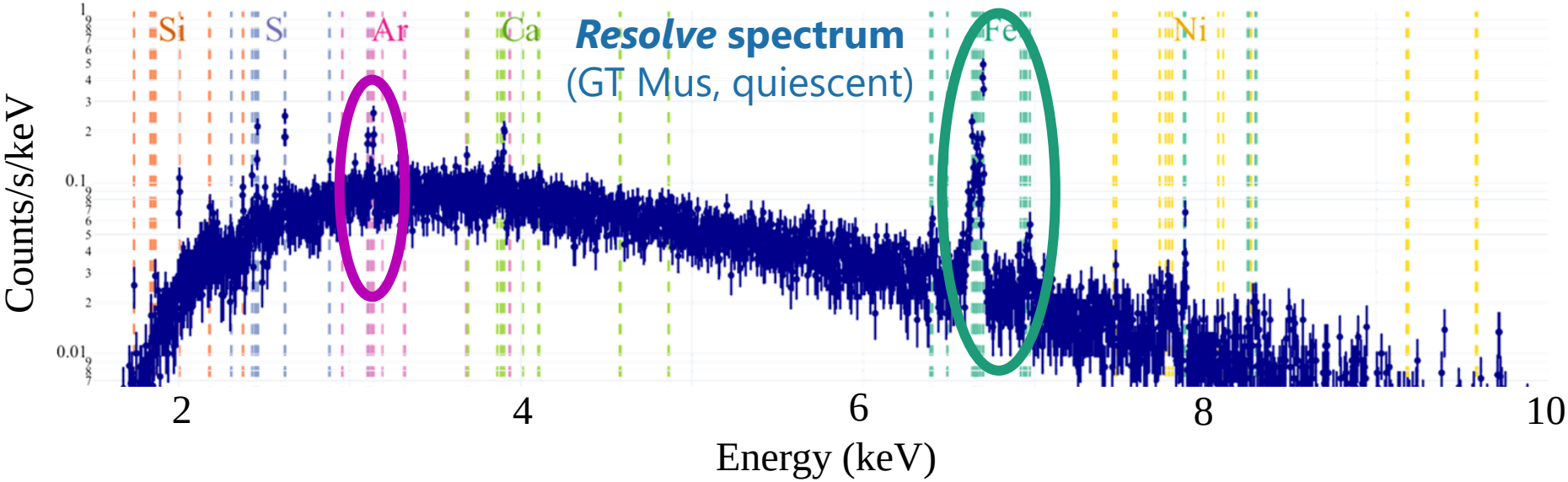

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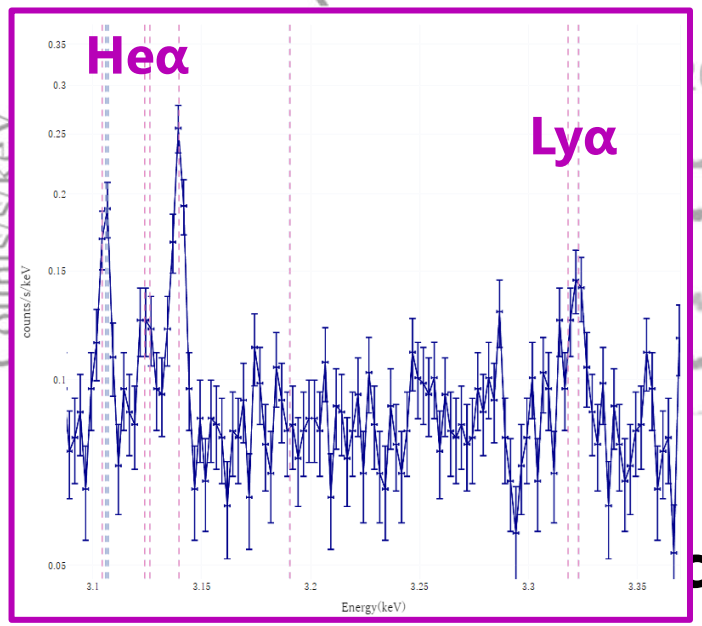

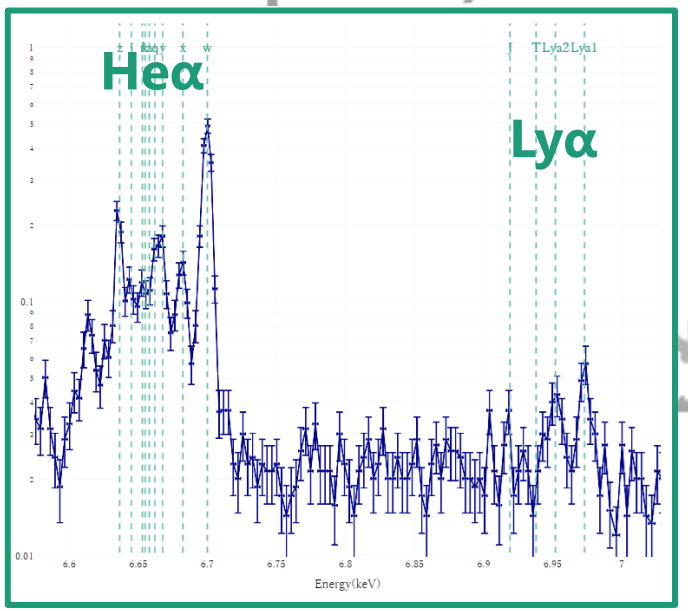

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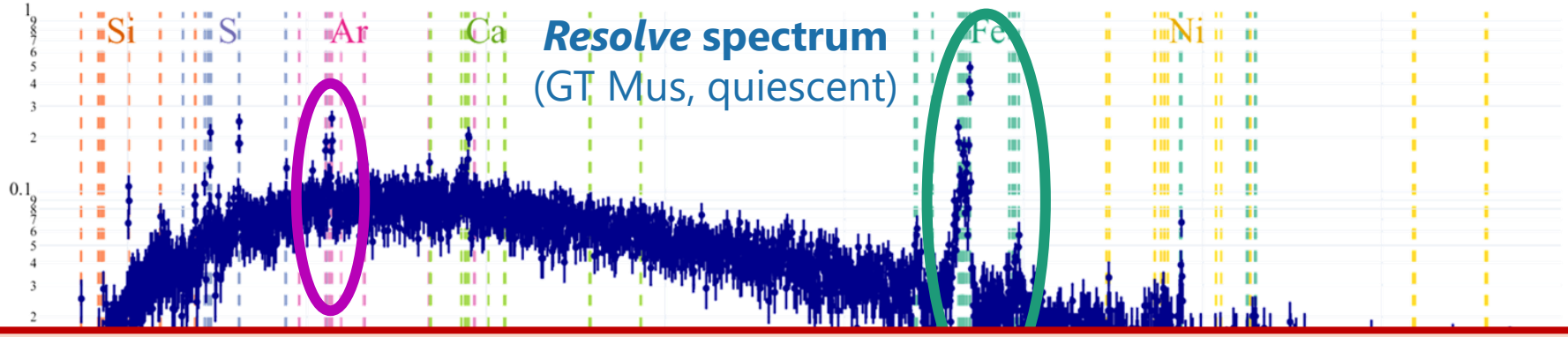

***Resolve* spectrum**
(GT Mus, quiescent)

Line profiles & broad continuum can be now accessible for Si-Ni!
(Even solar observations has not realized this broad-band, high-res spectrum)

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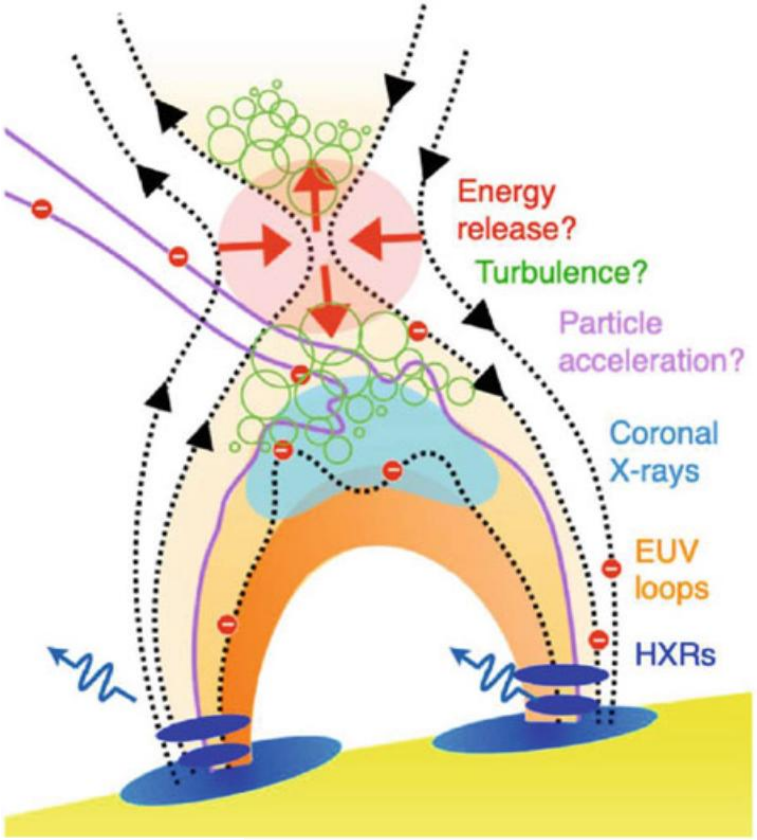
Research scope – non-thermal aspects

☆ **X-ray band can capture the site of a flare in action.**

Traditional assumptions:

- Optically thin
- Low density
- Ignorable photo ionizations
- Thermal plasma
  - ✓ CIE (Collisional Ionization Equi.)
  - ✓ Maxwell electron E distribution



F. Effenberger & N.L.S. Jefferey 2021

Research scope – non-thermal aspects

☆ **X-ray band can capture the site of a flare in action.**

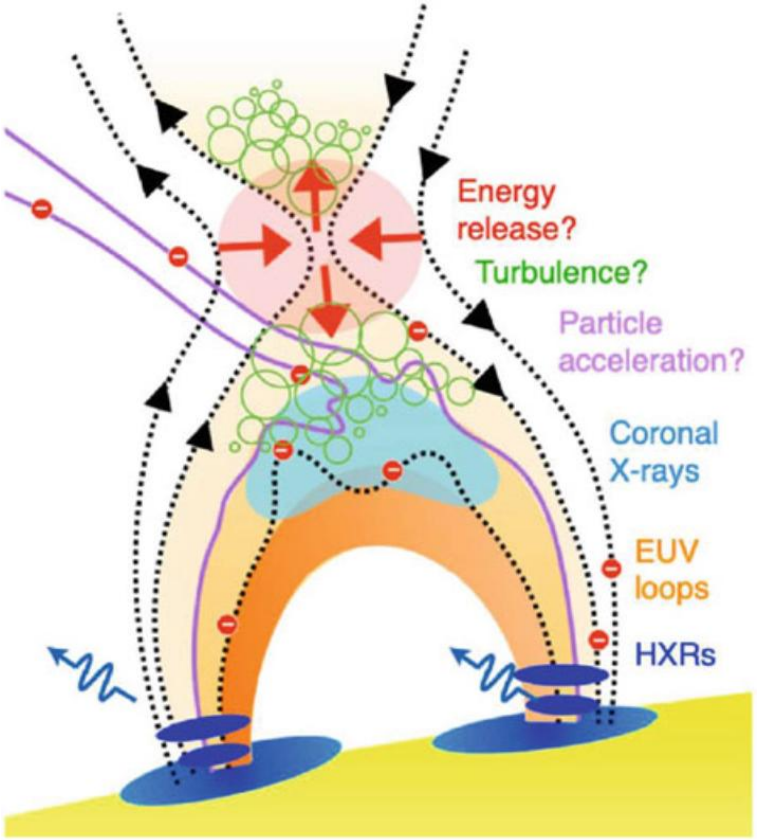
Traditional assumptions:

--During flare?

- Thermal plasma
  - ✓ CIE (Collisional Ionization Equi.)?
    - Timescale for the equilibration t ~ 100 s Imada+2011, 2021

    → w/ NICER (Kurihara+2024)
  - ✓ Maxwell electron E distribution ?
    - Hard tail associated w/ particle acceleration observed in solar flares

    → w/ XRISM (Kurihara+ in prep)



F. Effenberger & N.L.S. Jefferey 2021

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Overview

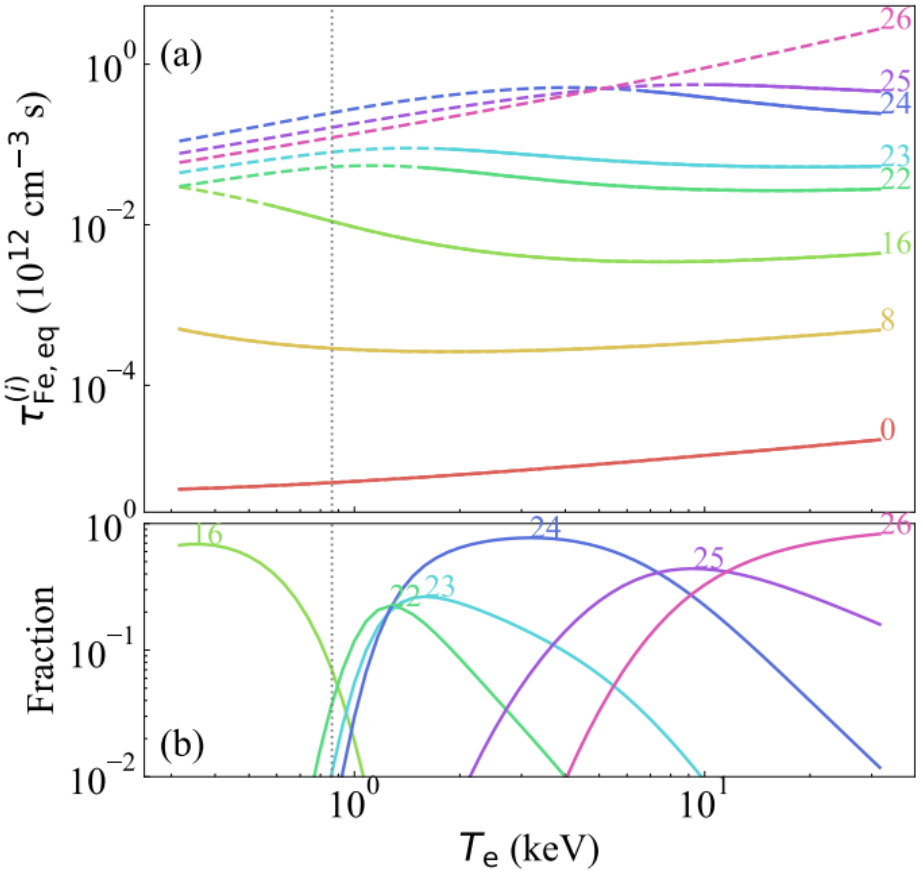
☆ **Compared to solar flares, giant stellar flares:**

- ➢ last order of magnitude longer, taking several days to decay
- ➢ exhibit higher temperature

  → Longer ionization time scale τ

  ✓ For Fe XXV, XXVI,
  τ ~ 100-1000 s
  (with $n_e = 10^{9-10}$ cm^{-3})

- Despite the limitations of continuous observation and spatial resolution, stellar flares can be valuable for NEI study.



< Fe ionization/recombination time scale vs. kT for different charged ions >

Overview

☆ **Requirements for the SXR data**

- (1) Sufficient spectral resolution for lines from different charged ions over the broad SXR band
- (2) Capturing the early stage of flares
- (3) Without relying on chance

Luxury request for X-ray observation,,,

Overview

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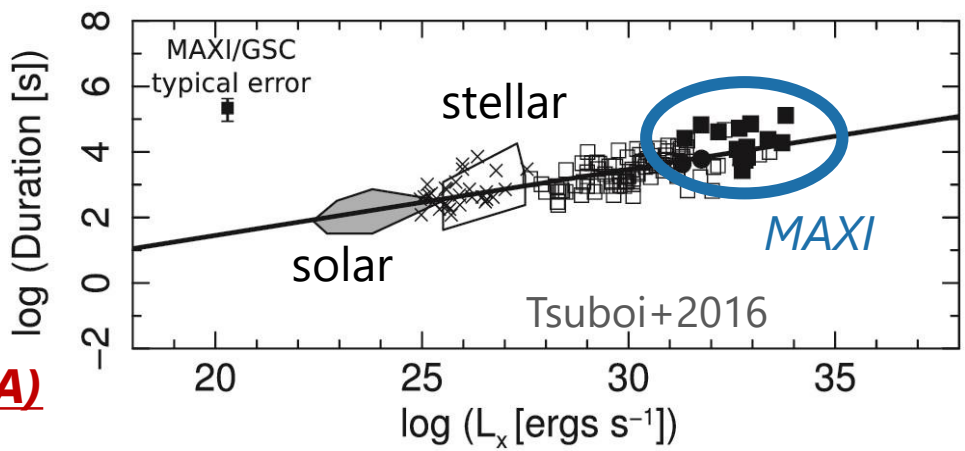
Luxury request for X-ray observation,,,

☆ **Strategy: NICER + complementary instrument**

- ➢ MAXI (Monitor of All-sky X-ray Image) on ISS
  - ✓ Update the all-sky image in 2-20 keV every ~90 mins
  - ✓ ~130 detection/9yrs for large flare



MAXI And NICER Ground Alert (MANGA)

See Iwakiri-san's talk!

Overview

☆ **Requirements for the SXR data**

- (1) Sufficient spectral resolution for lines from different charged ions over the broad SXR band
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- (3) Without relying on chance

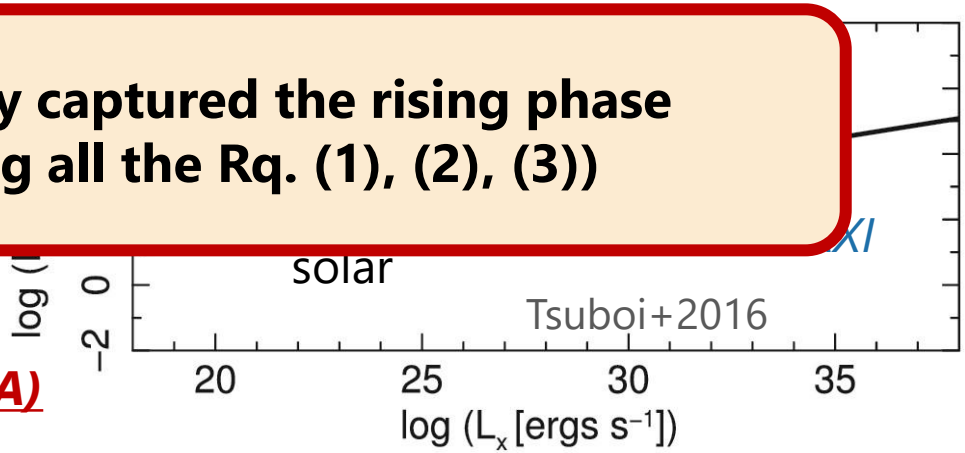
Luxury request for X-ray observation,,,

☆ **Strategy: NICER + complementary instrument**

- MAXI (Monitor of All-sky X-ray Image) on ISS

Only data that successfully captured the rising phase with MANGA (satisfying all the Rq. (1), (2), (3))

large flare



MAXI And NICER Ground Alert (MANGA)

See Iwakiri-san's talk!

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Observation

☆ **Target : UX Ari**

- RS CVn binary

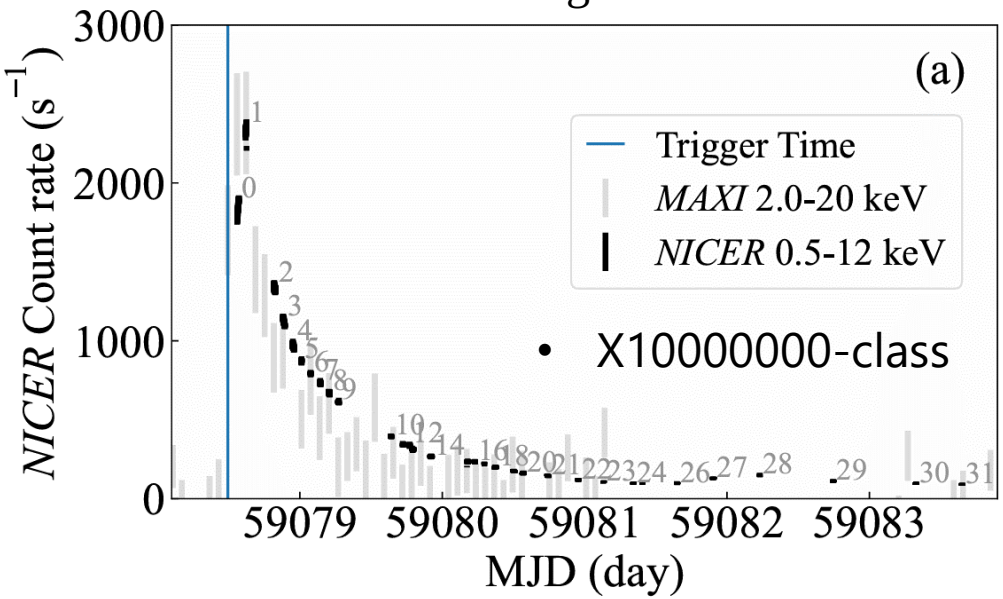
	Aa	Ab
Spectral class	K0	G5
$T_{\rm eff}$ (K)	4520	5780
R $(R_\odot)$	5.6	1.6
Distance (pc)	52.1	
Separation	~ 0.1AU ~ $20R_\odot$	

Based on Hummel+2017

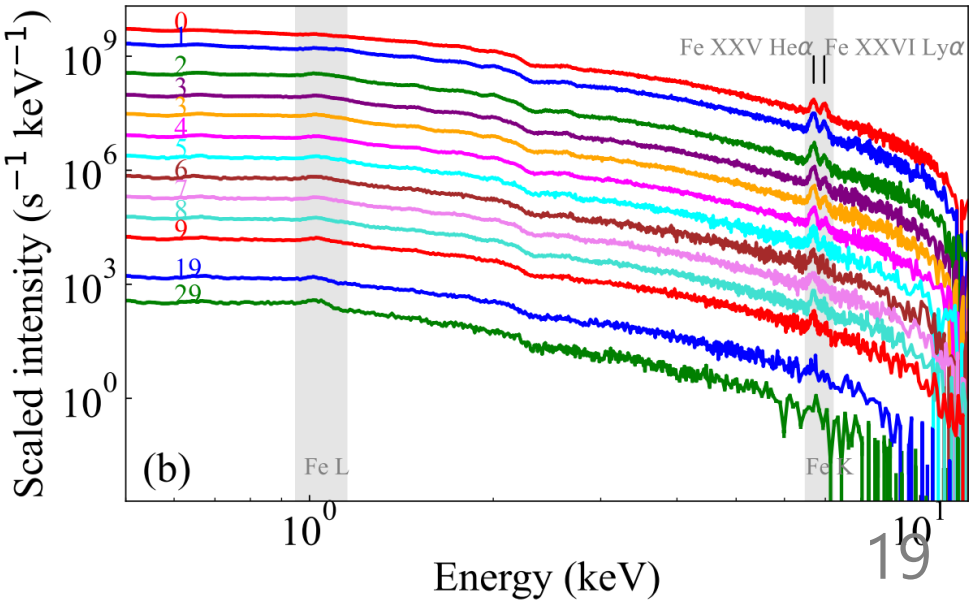
☆ **Event**

- 2020/08/17 11:52:03 (UT) MAXI detection
- After 89 min, NICER followed

< NICER Light Curve >



< NICER SXR spectra>



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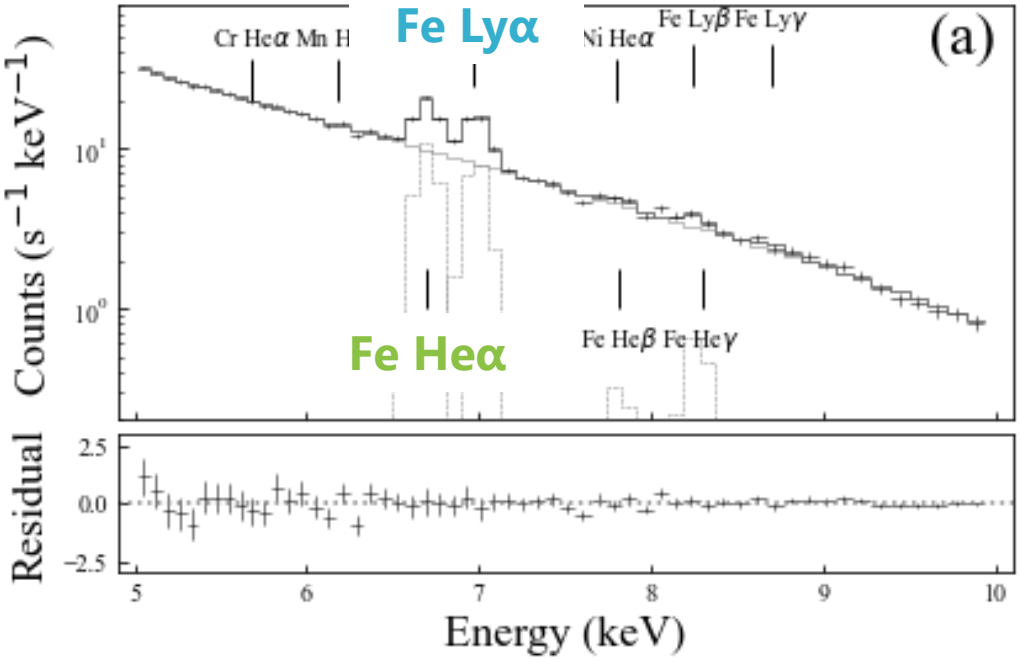
Analysis

☆ **X-ray spectral analysis for 5.0 – 10 keV**

- ➢ Fitting with phenomenological and physical models
- ➢ Investigate time evolution (~ 1 ks exposure for each time step)

☆ **Phenomenological model（xspec：brems＋gauss）**

- ➢ Continuum
  - ✓ Electron temperature kT_e
  - ✓ Emission Measure
- ➢ Lines: Fe Heα, Lyα
  - ✓ Central energy
  - ✓ Width
  - ✓ Norm



Analysis

☆ **Physical model（xspec：apec, nei）**

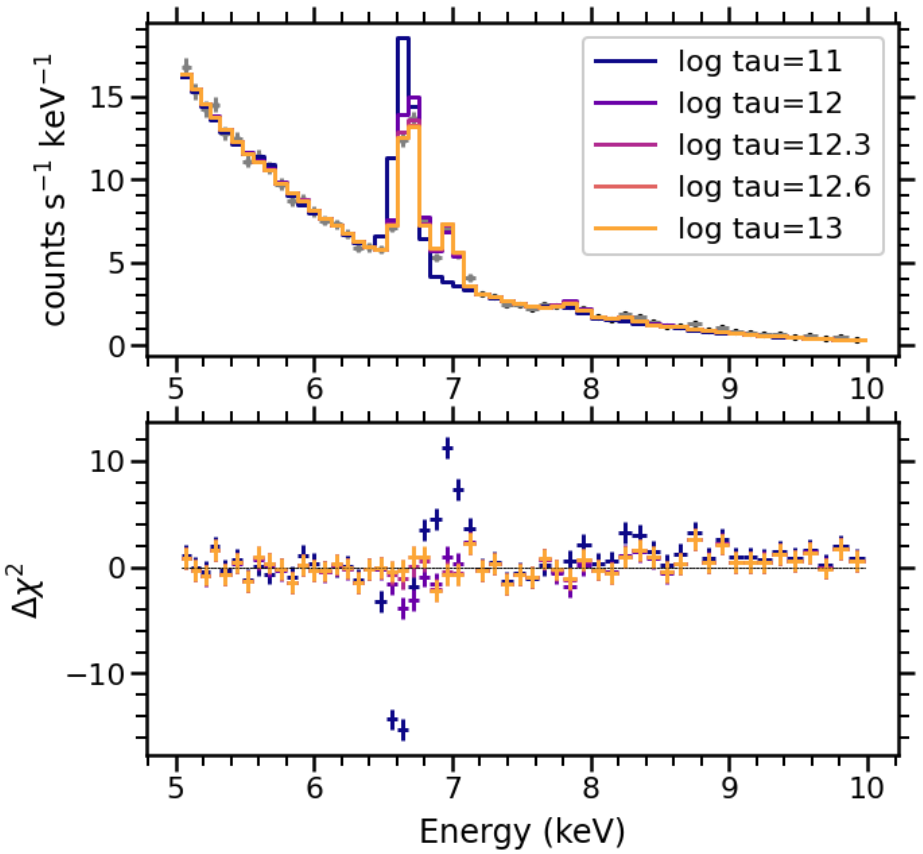
- CIE plasma model (apec)
  - ✓ Temperature,
  - ✓ Emission Measure
  - ✓ Abundance

- Ionizing plasma model (nei)
  - ✓ Temperature,
  - ✓ Emission Measure
  - ✓ Abundance
  - ✓ Ionization parameter

$\tau = \int n_e dt$

Goal: Determine τ

< τ dependency of nei model >



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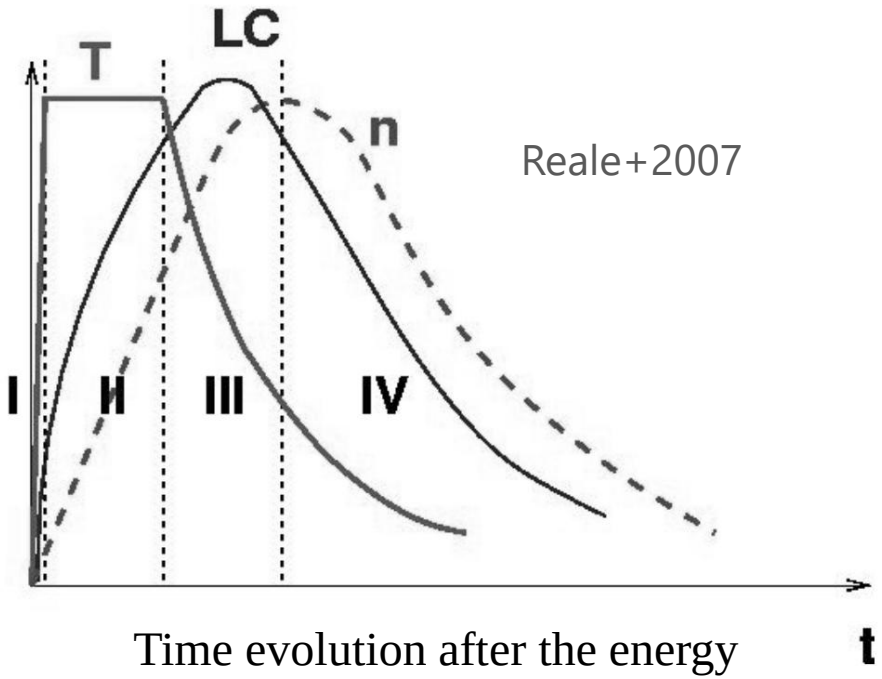
Result & Discussion

☆ **Phenomenological model fit** *– continuum –*

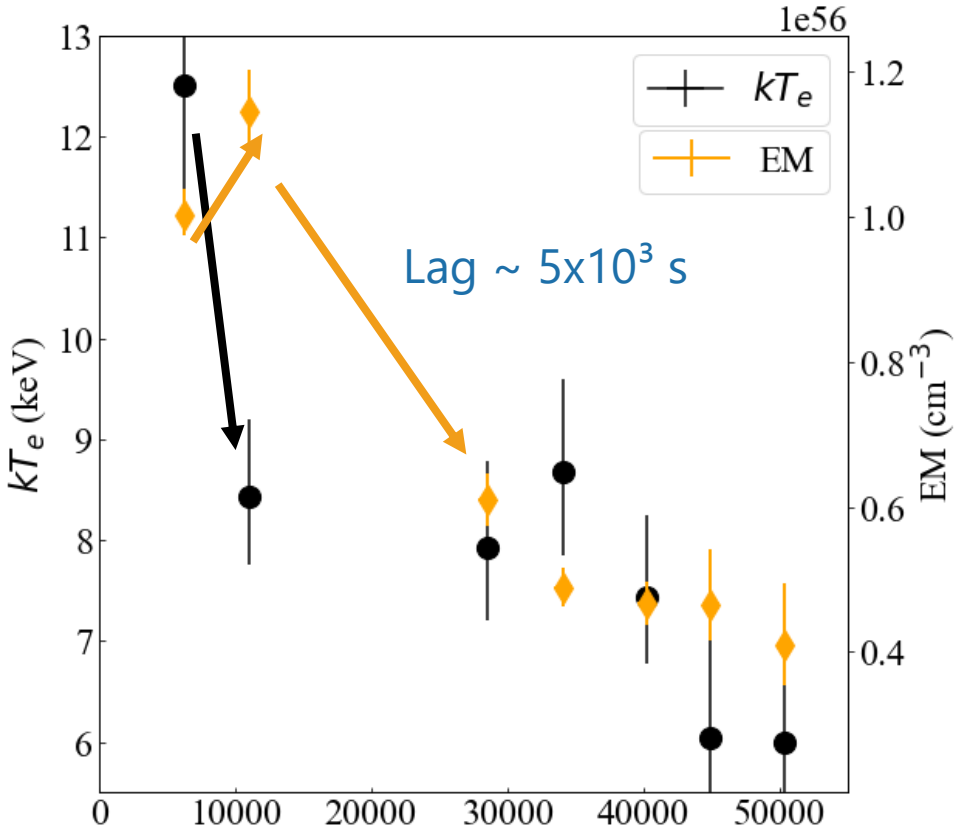
➢ Time lag between peaks of kT_e and Emission Measure (EM)

✓ Consistent with Reale+2007



Reale+2007

Time evolution after the energy injection to the loop



t (s) elapsed from the MAXI trigger

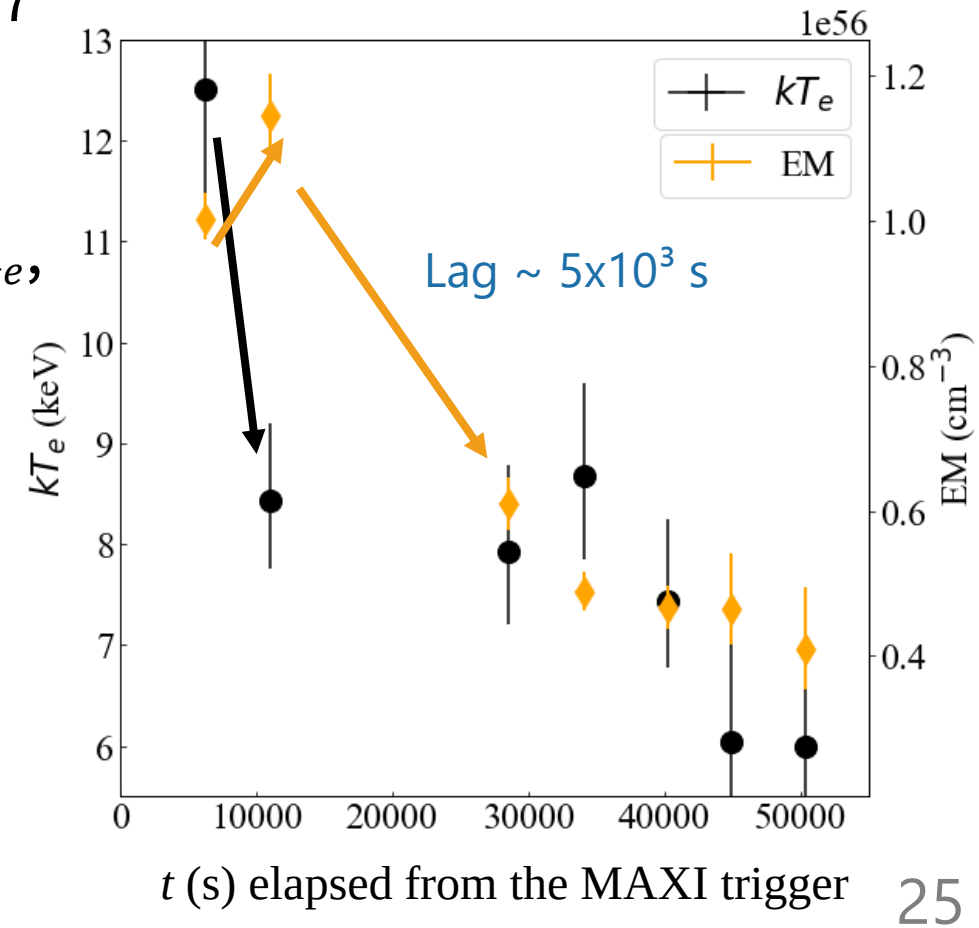
Result & Discussion

☆ **Phenomenological model fit** *– continuum –*

- Time lag between peaks of kT_e and Emission Measure (EM)
  - ✓ Consistent with Reale+2007

⇩

Derives semi-loop length L, maximum electron density n_e, magnetic field B



t (s) elapsed from the MAXI trigger

- $\underline{L \sim 3 \times 10^{11}\ \mathrm{cm} \sim 4\ R_\odot}$
- $\underline{n_e \sim 4 \times 10^{10}\ \mathrm{cm^{-3}}}$

And $P_{mag} > P_{gas}$ yeilds

- $\underline{B > 200\ \mathrm{G}}$

Result & Discussion

☆ **Phenomenological model fit** *– lines (Heα & Lyα) –*

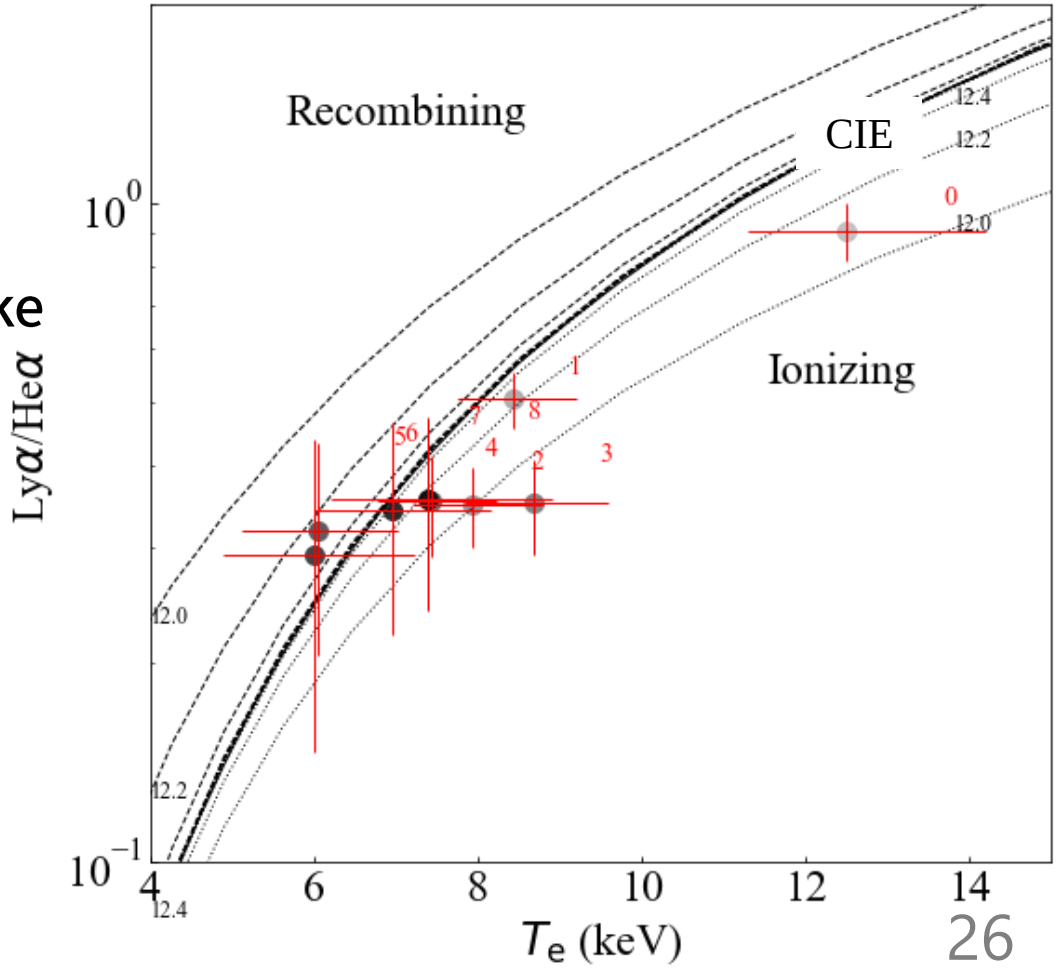
→ **Significantly off from the CIE ratio**

✓ At pre-peak & post-peak

➢ Smaller Lyα / Heα

→ smaller H-like / He-like

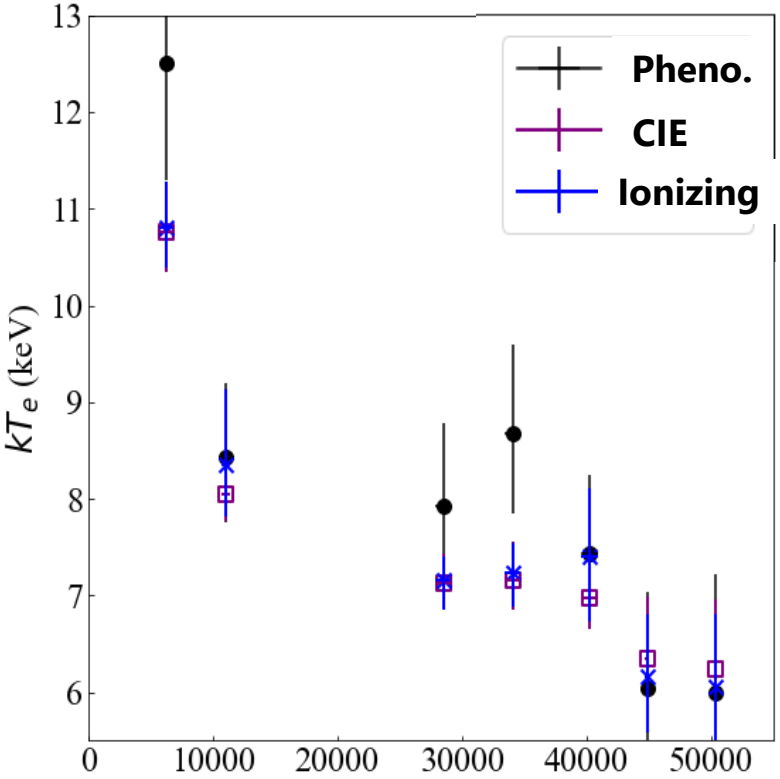
→ Ionizing



Result & Discussion

☆ **Physical model fit → suggesting CIE**

< Best-fit Temperature >



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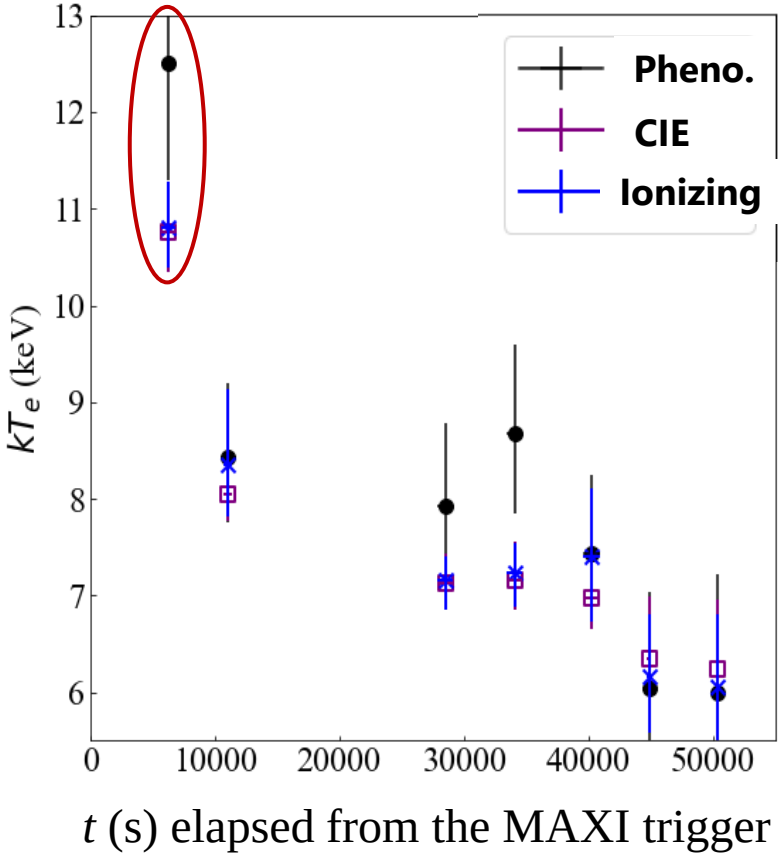
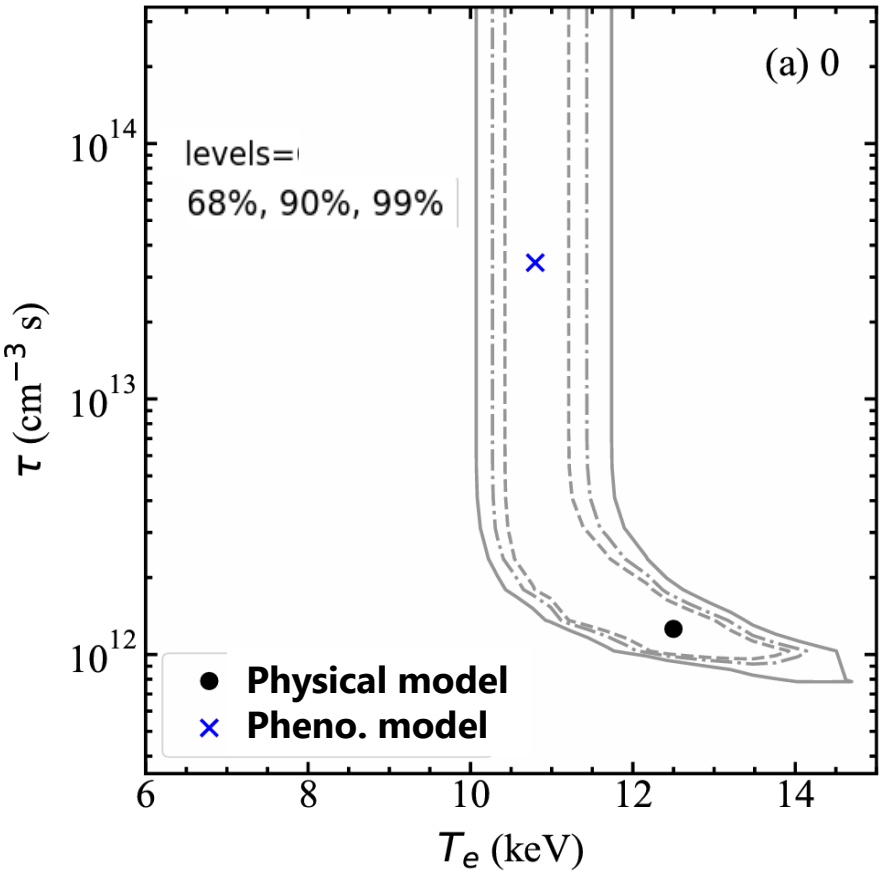


<Confidence interval of (kT, τ)>



Both CIE and Ionizing solutions are acceptable, though the derived n_e prefers CIE

Conclusion

☆ **NICER investigation of off-CIE plasma**

✓ Goal: Determine the ionization parameter τ

- Thanks to the collaboration with MAXI (MANGA system), NICER follow-up was successfully initiated after 89 min from the trigger before the flare flux peak.
- From time-resolved NICER continuum spectra, $L \sim 3 \times 10^{11}$ cm, $n_{e\_max} \sim 4 \times 10^{10}$ cm^{-3}, and $B < 200$ G are derived for UX Ari.
- Given NICER Fe Heα & Lyα ratio, $\tau > 10^{12}$ cm^{-3}s at $t \sim 5$ ks. The ionizing condition is acceptable, though n_{e_max} prefers CIE.

Ambition – MAXI to XRISM

- ☆ **TOO scheme is needed for XRISM follow-up.**
  - ➢ Current response time: > 2 days
    - ✓ Not fast enough to capture the rising phase,,,
- ☆ **Targeting "secondary" flares?**
  - ➢ Solar secondary flare occurrence rate: ~ 0.6 (GOES X-ray obs)
    - ✓ **What about stellar cases? Any info?**
  - ➢ We actually captured consecutive flares from HR1099 during XRISM *Resolve* in-flight cal! (cal work in progress)