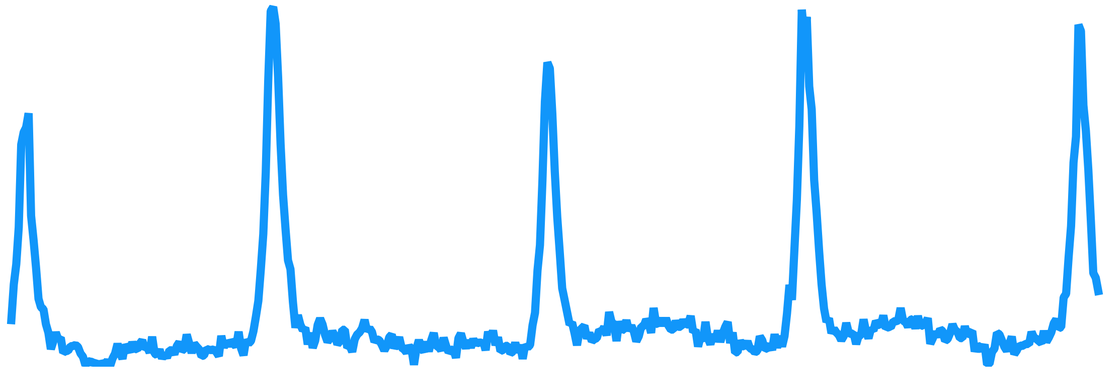
Extreme variability around supermassive black holes:

X-ray Quasi-Periodic Eruptions



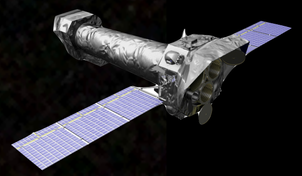
Margherita Giustini

Centro de Astrobiología (CAB), CSIC-INTA

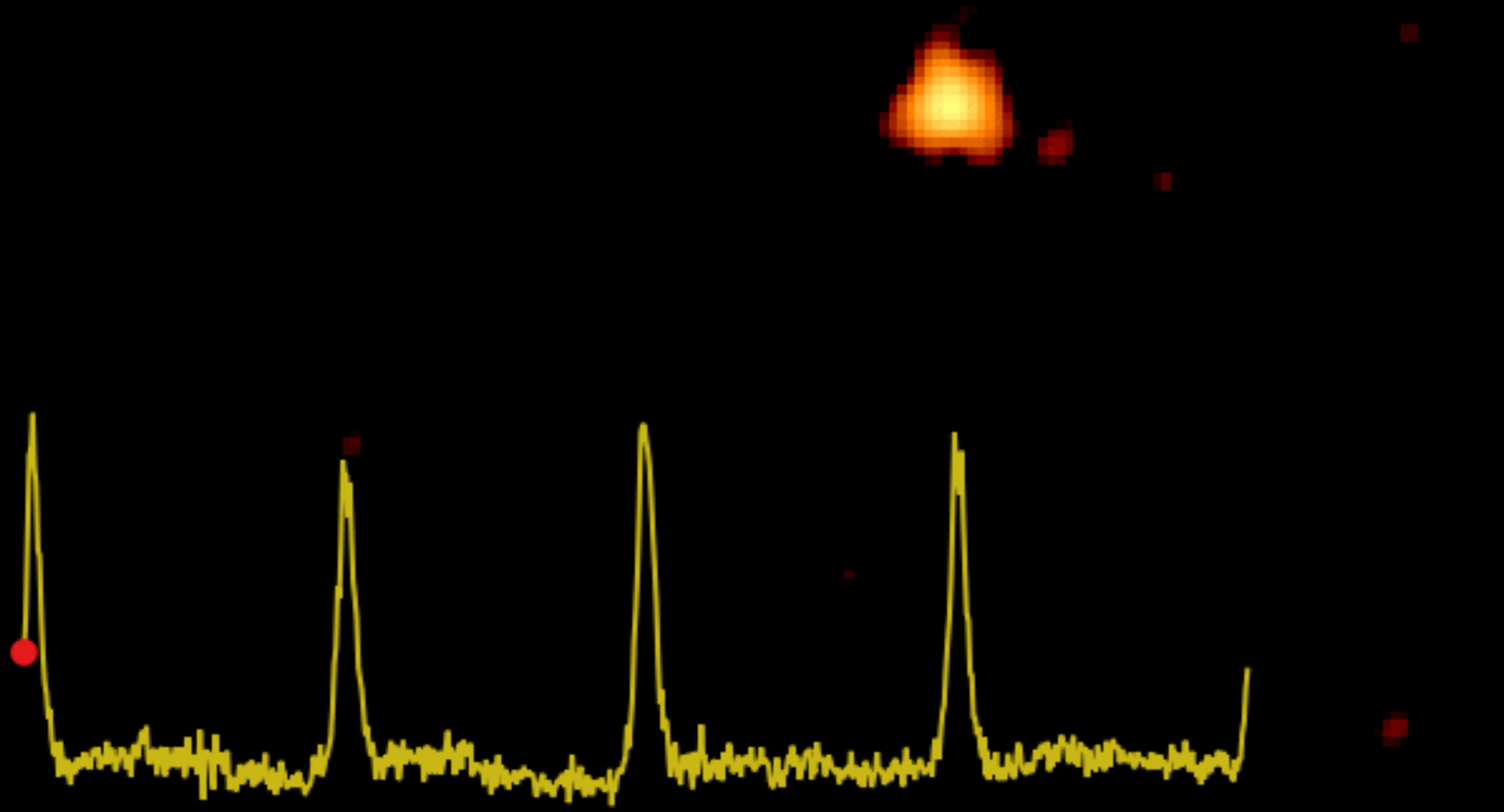
with Giovanni Miniutti, Riccardo Arcodia, Joheen Chakraborty, Erwan Quintin

and Richard Saxton, Erin Kara, Natalie Webb, Xinwen Shu, Andy Read, Keith Gendreau, Gabriele Ponti, Andrea Merloni, Kate Alexander, Adelle Goodwin, Johannes Buchner, et al.

X-ray Quasi-Periodic Eruptions



XMM-Newton EPIC-pn 0.2-2 keV image and light curve of GSN 069



Credits: G. Miniutti, M. Giustini, ESA XMM-Newton

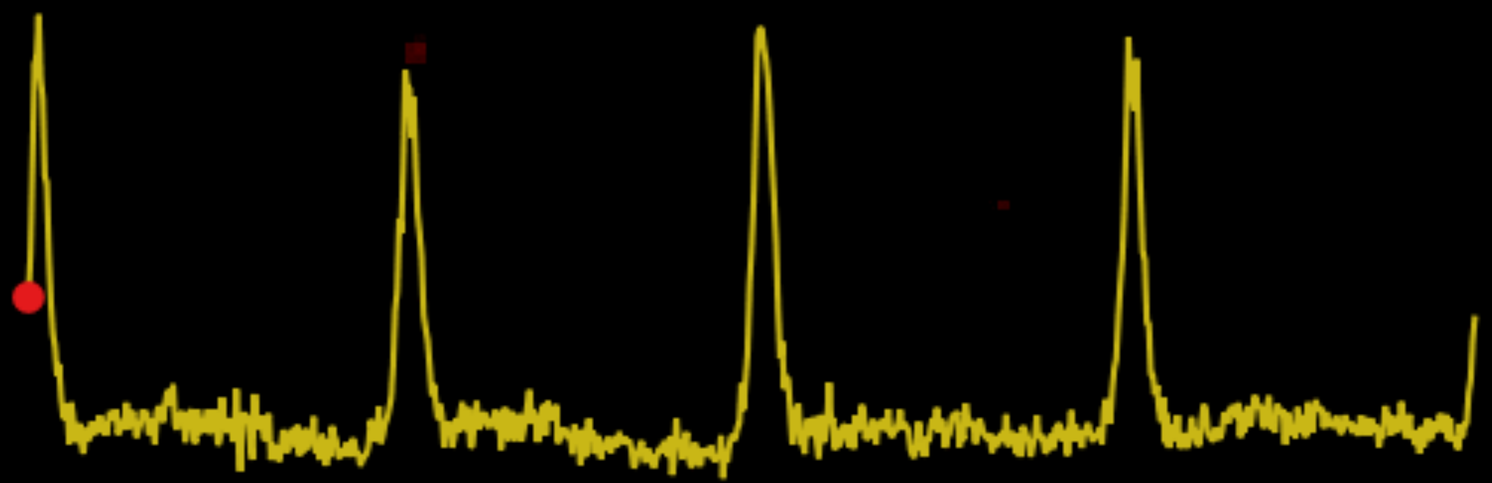
Miniutti et al. 2019, Nature 573, 381

X-ray Quasi-Periodic Eruptions

Intense, recurrent flares of soft X-rays with a luminosity of ~ $10^{42\text{-}43}$ erg/s

Observed in galaxies with central BHs of $<10^7\ M_\odot$ and likely connected to TDEs

Most likely explanation: extreme mass ratio inspirals and/or accretion flow instabilities



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Miniutti et al. 2019, Nature 573, 381

GSN 069

Redshift z = 0.018

- No Broad Optical/UV Emission Lines
- X-rays: non-detected by ROSAT

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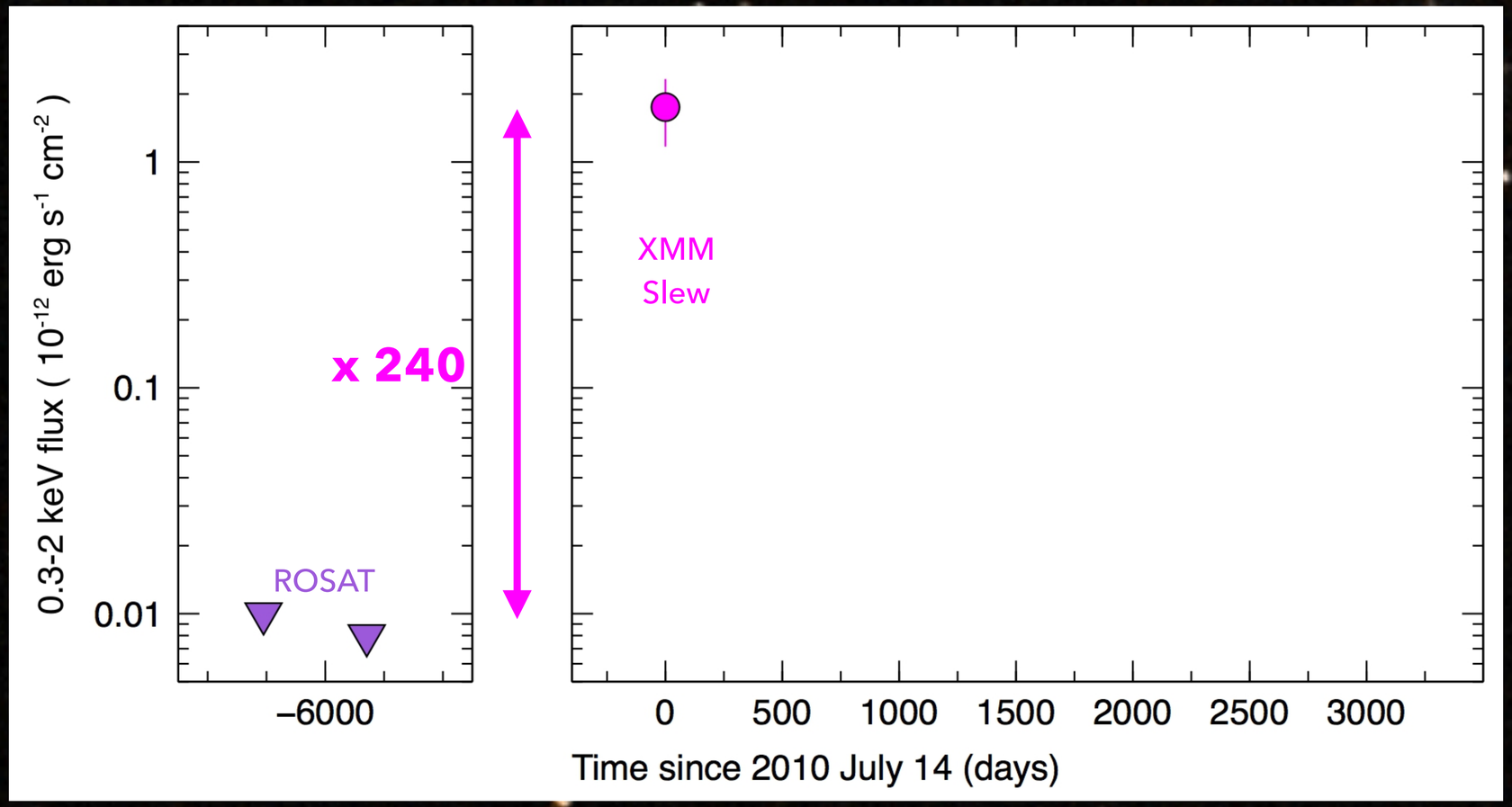

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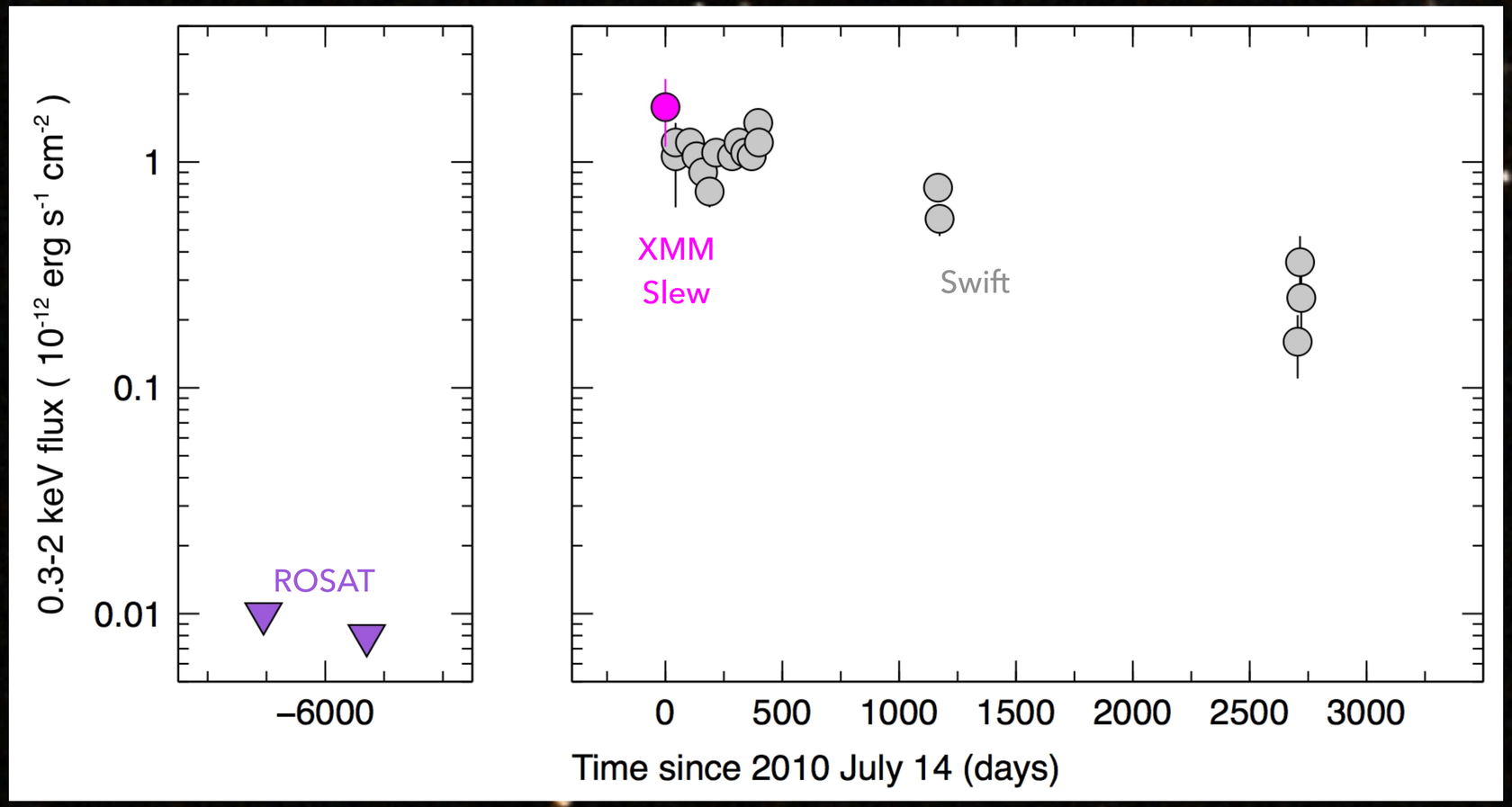

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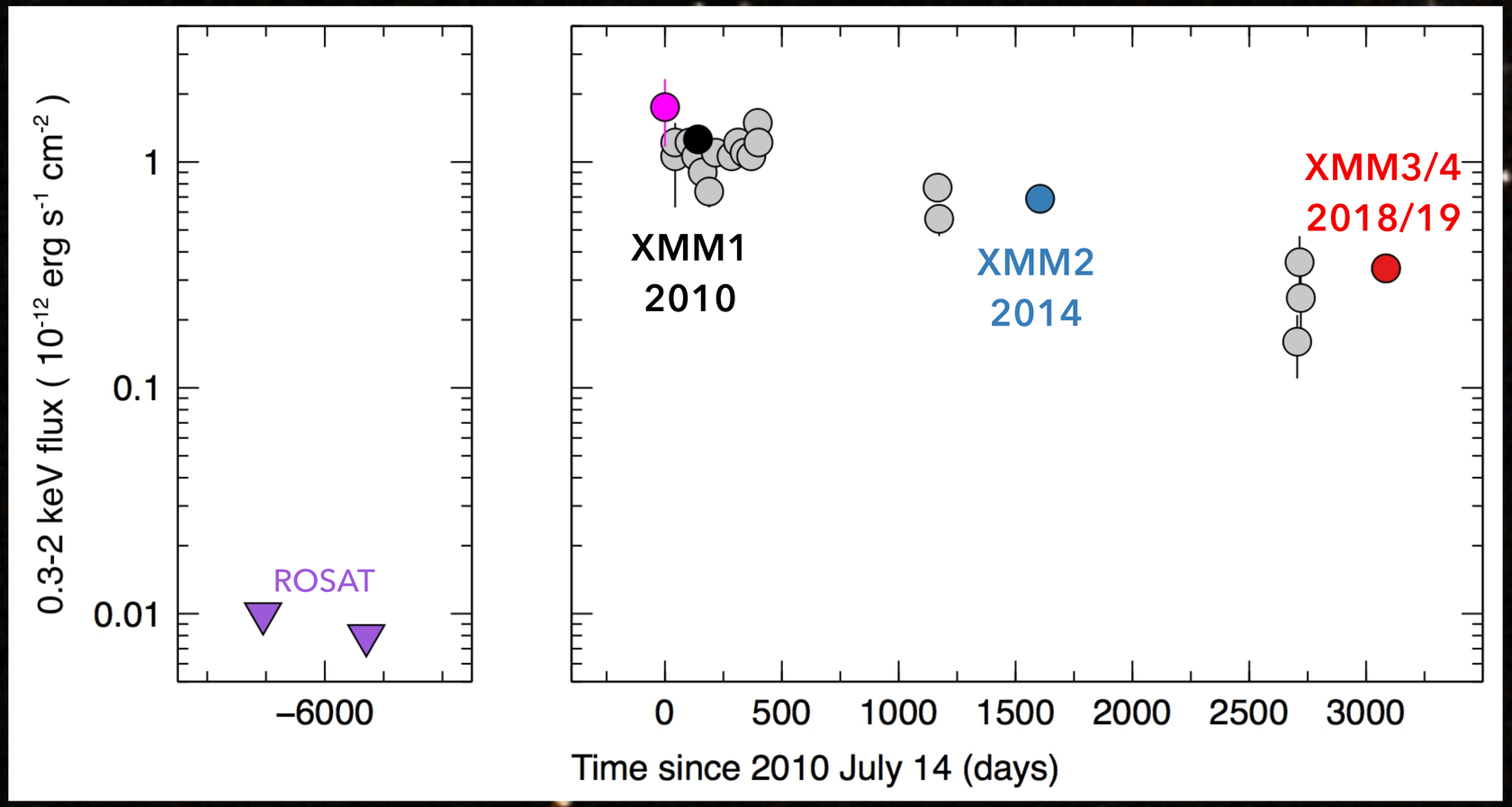
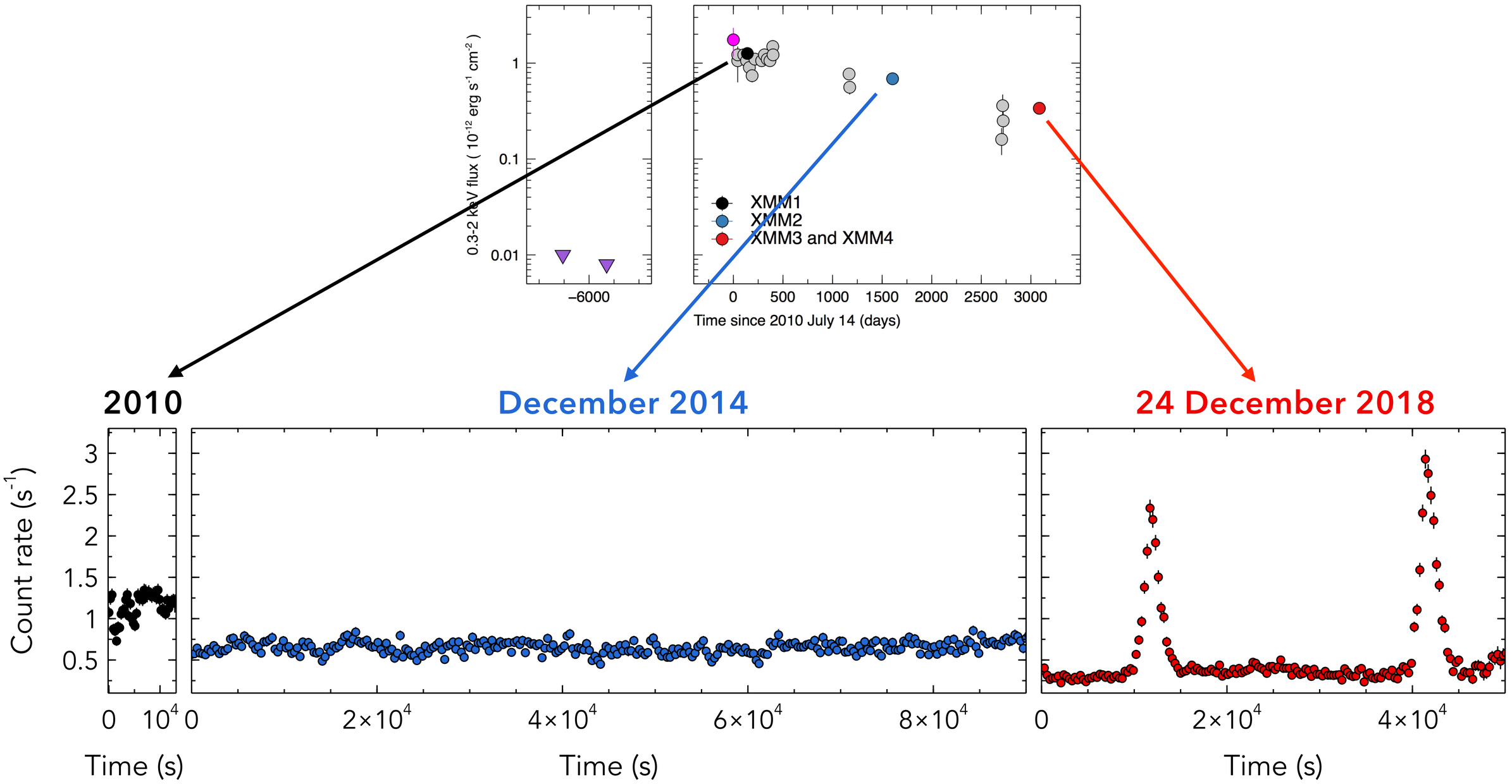
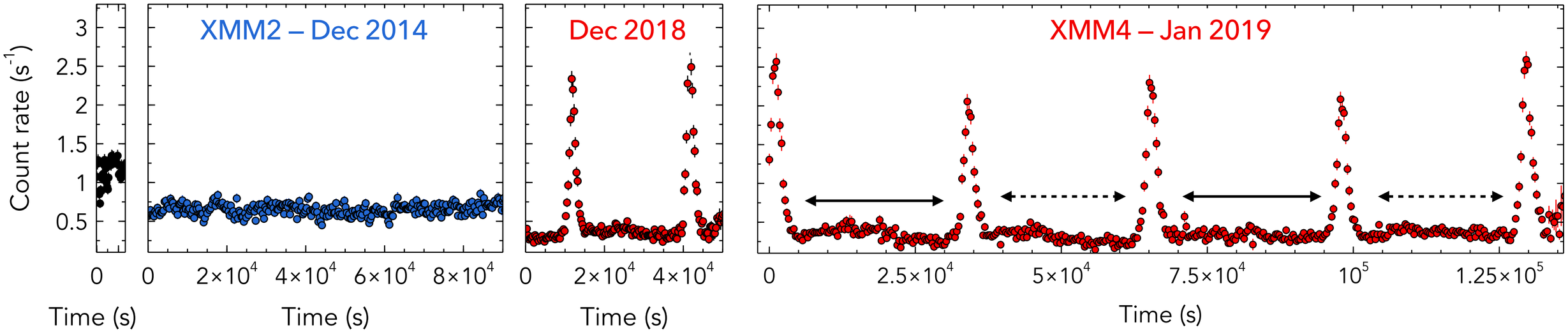


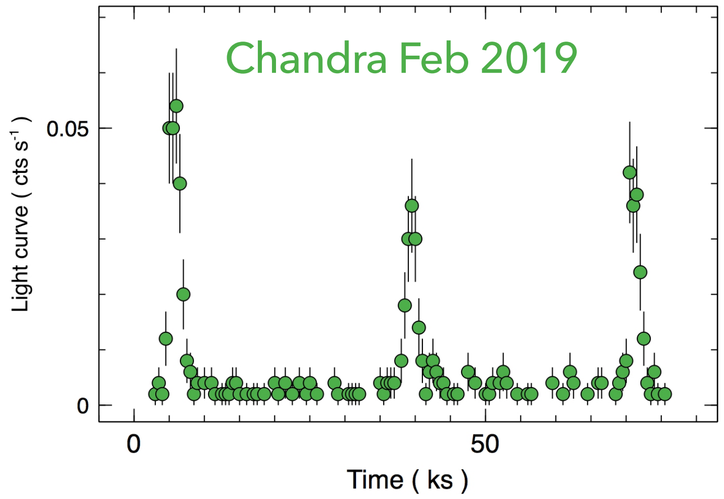
The discovery of QPEs in GSN 069

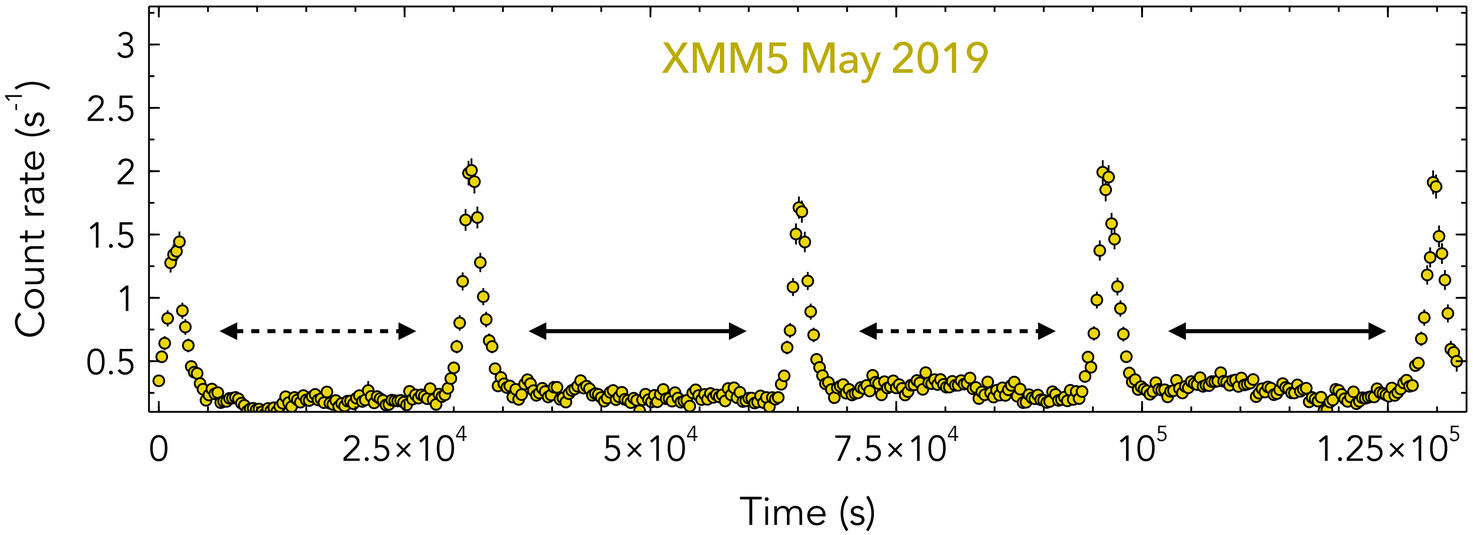


X-ray QPEs in GSN 069

Alternating strong/weak QPE and long/short recurrence time

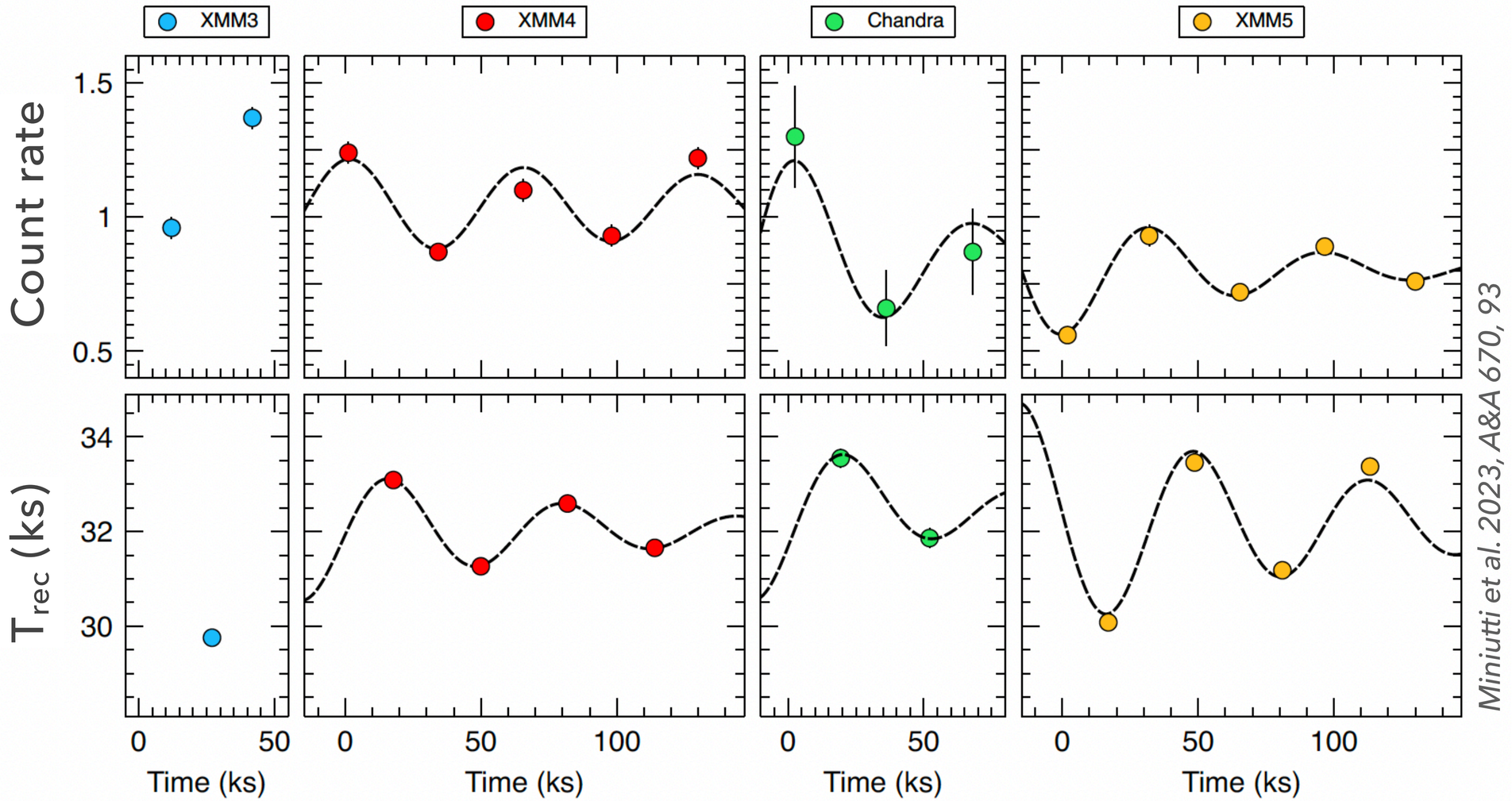






X-ray QPEs in GSN 069

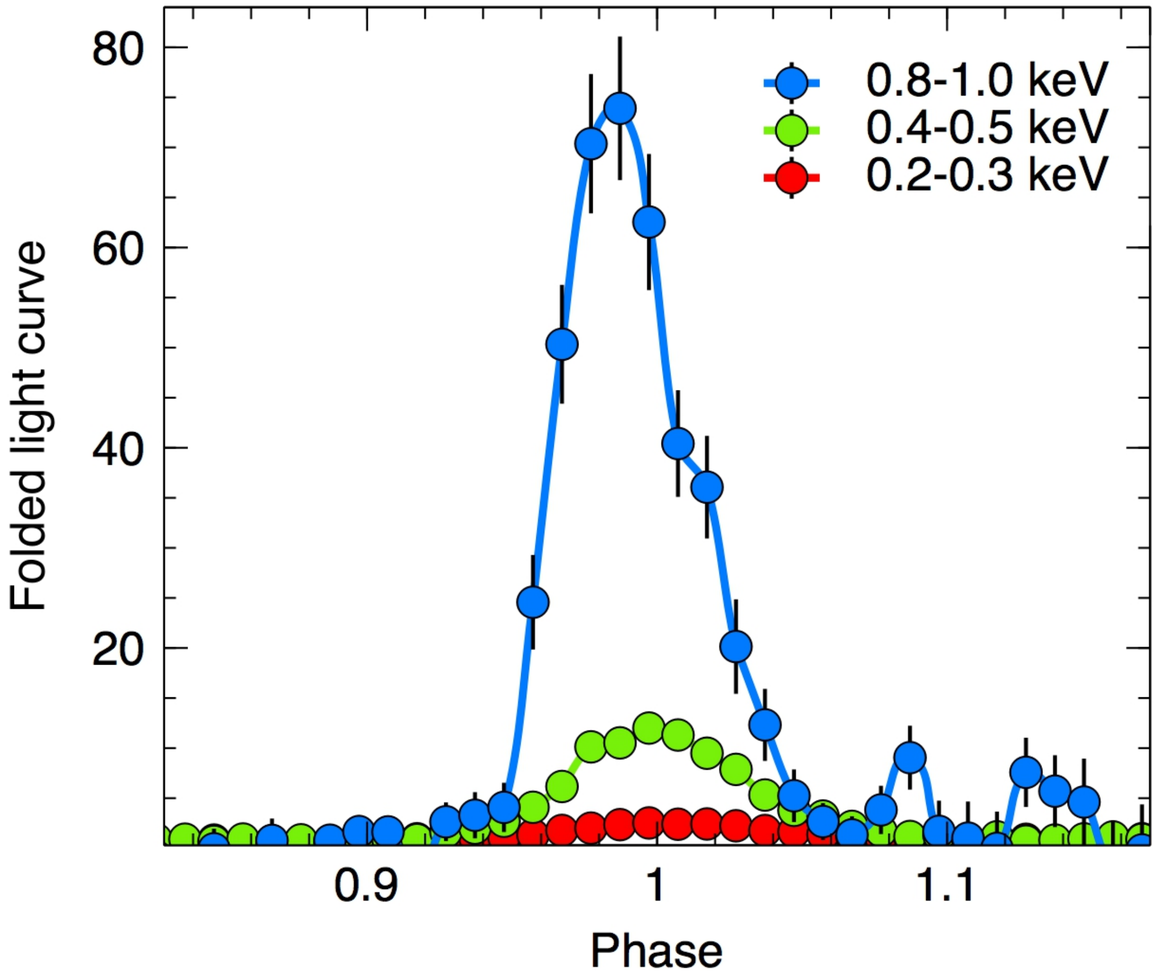
Alternating strong/weak QPE and long/short recurrence time



Scatter in recurrence times of the order of 6-7%

X-ray QPE properties

QPEs have higher amplitude at higher energies

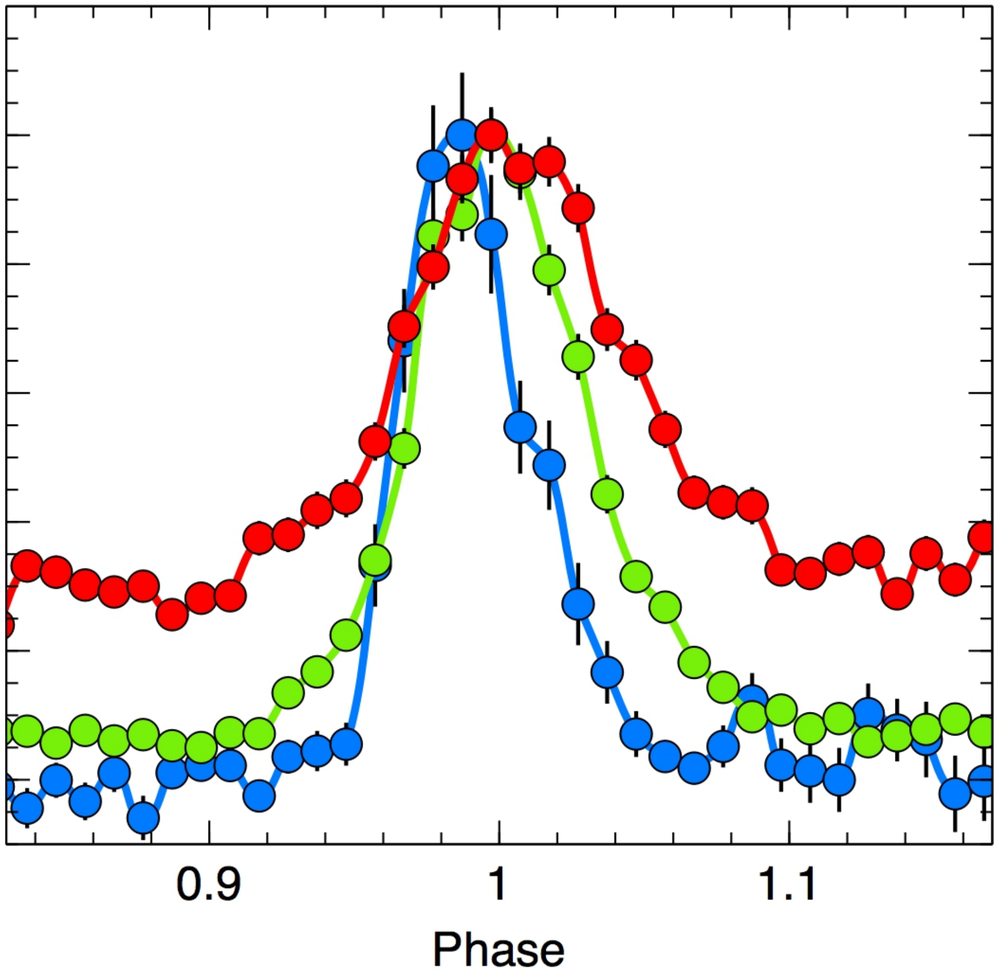


Miniutti et al. 2019, Nature 573, 381

Folded light curve normalised to the quiescence level

X-ray QPE properties

QPEs peak earlier and last less at higher energies



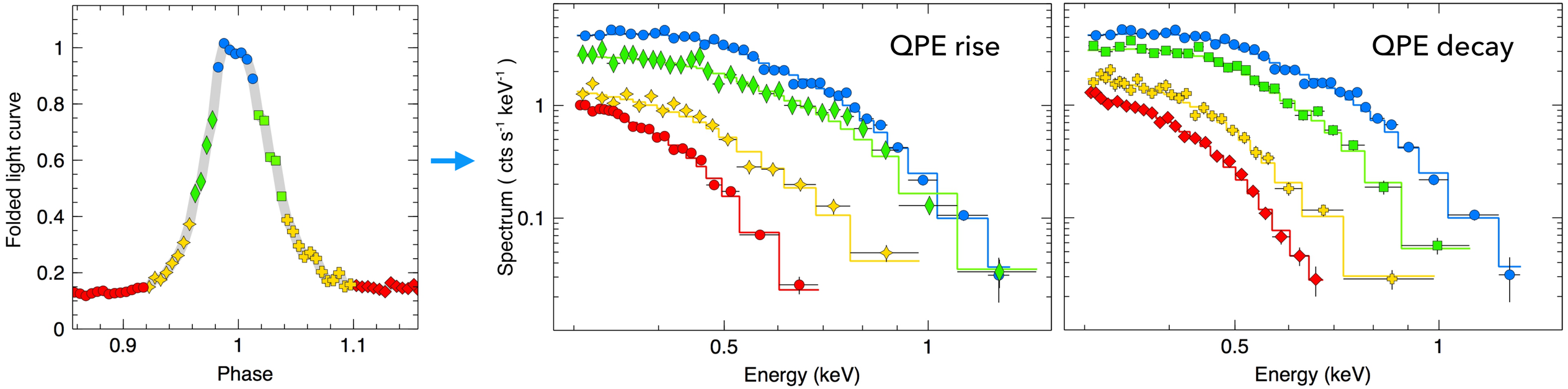
Miniutti et al. 2019, Nature 573, 381

Folded light curve normalised to the peak

GSN 069 spectral properties

During QPEs, the X-ray emission evolves from a softer quiescent state up to a harder brighter state, and back.

Miniutti et al. 2019, Nature 573, 381

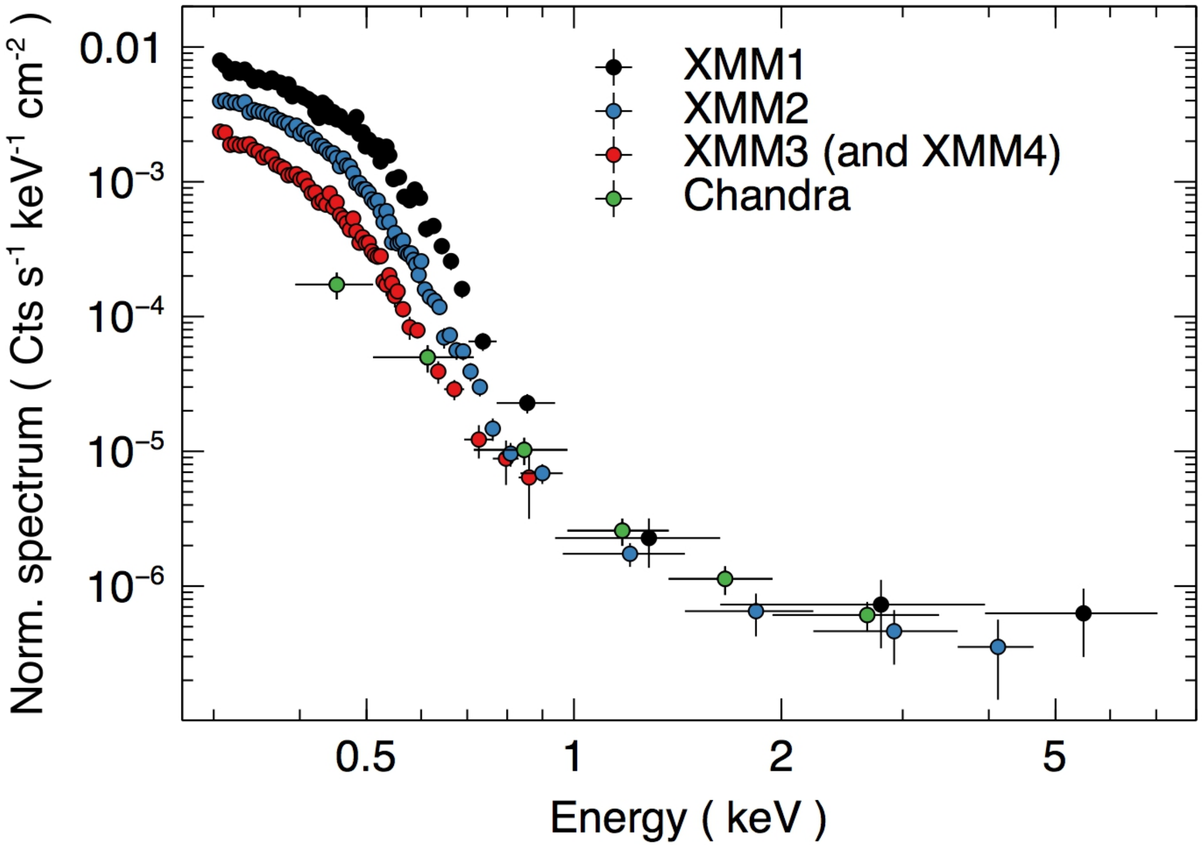


kT ~ 50 eV in quiescence, kT ~ 100 eV at the peak

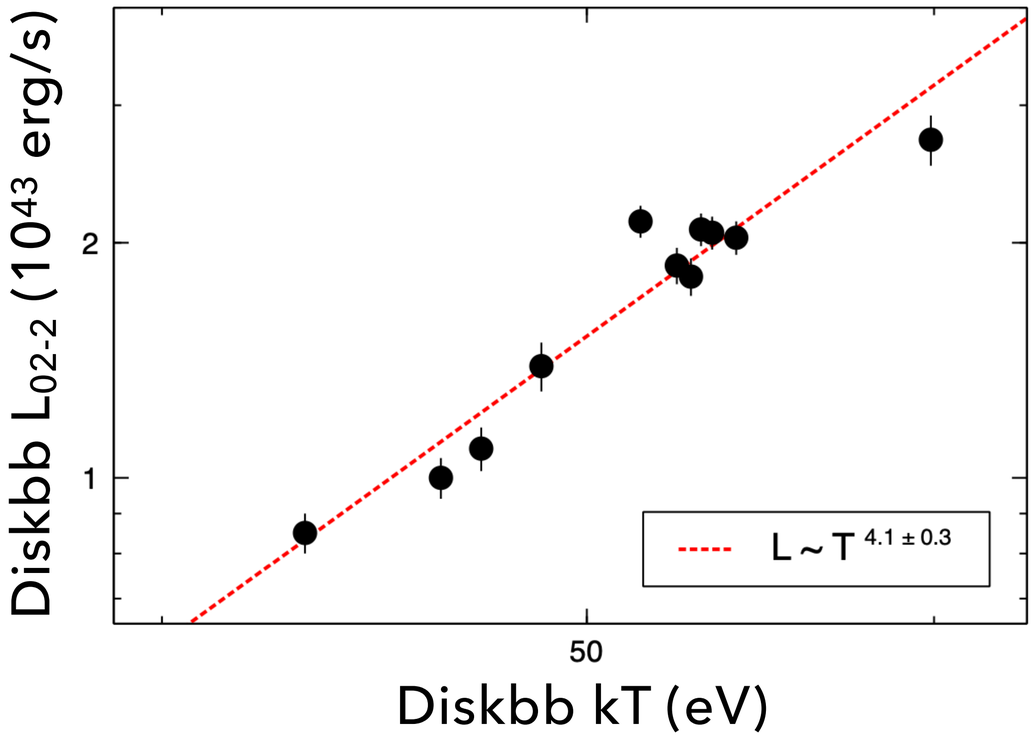
L ~ 10^{41} erg/s in quiescence, a few 10^{42} erg/s at the peak

GSN 069: the quiescent emission

Super-soft, blackbody-like spectra with negligible hard X-ray power law



Remarkable L ~ T^4 relation



Fitting the spectra assuming thermal emission from the disk:

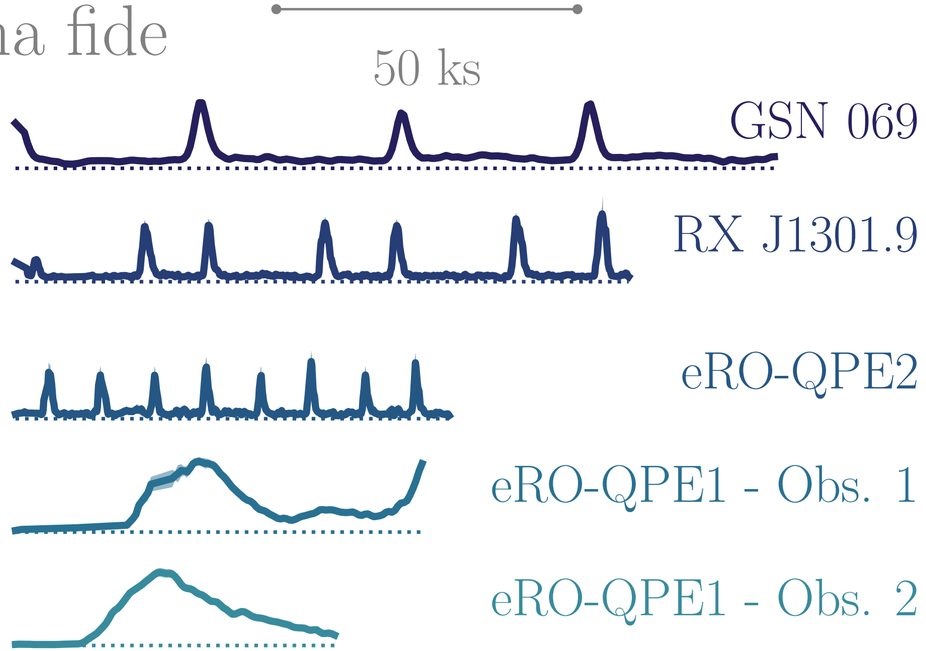
$M_{BH} \sim 4 \times 10^5 M_\odot$

Are QPEs a peculiarity?

Not anymore!

QPEs in 2023: a mini-population

Bona fide



GM

RA

Miniutti et al. 2019, Nature 573, 381

Giustini et al. 2020, A&A 636, 2

Miniutti et al. 2023, A&A 670, 93

Miniutti et al. 2023, A&A 674, 1

Arcodia et al. 2021, Nature 592, 704

Arcodia et al. 2022, A&A 662, 49

Candidates

JC

Erin Kara

EQ Natalie Webb

Chakraborty et al. 2021, ApJL 921, 40

Quintin et al. 2023, A&A in press, arXiv:2306.00438

Image credits: Erwan Quintin

QPEs in 2023: a mini-population

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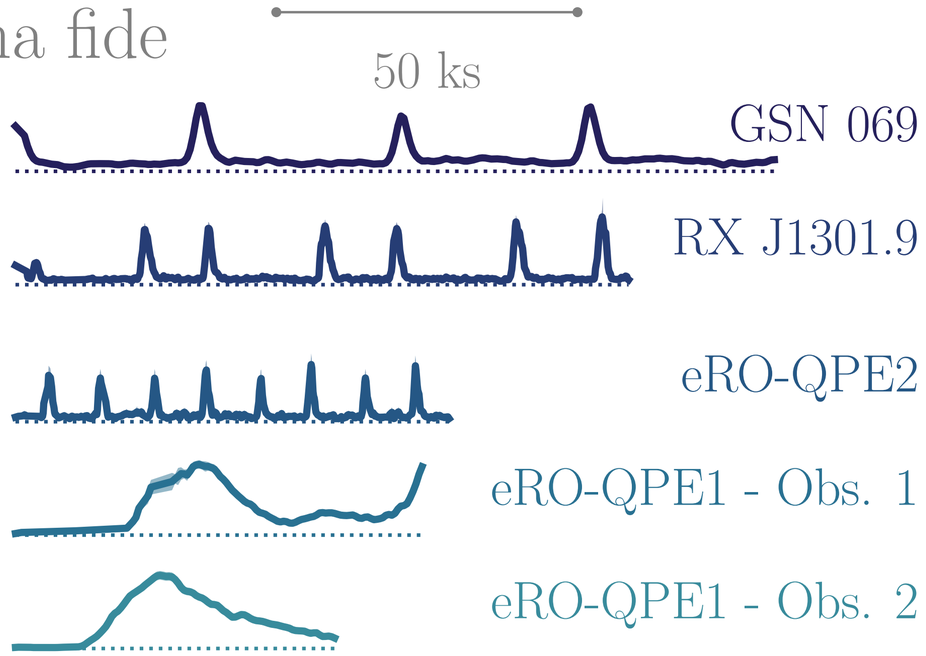


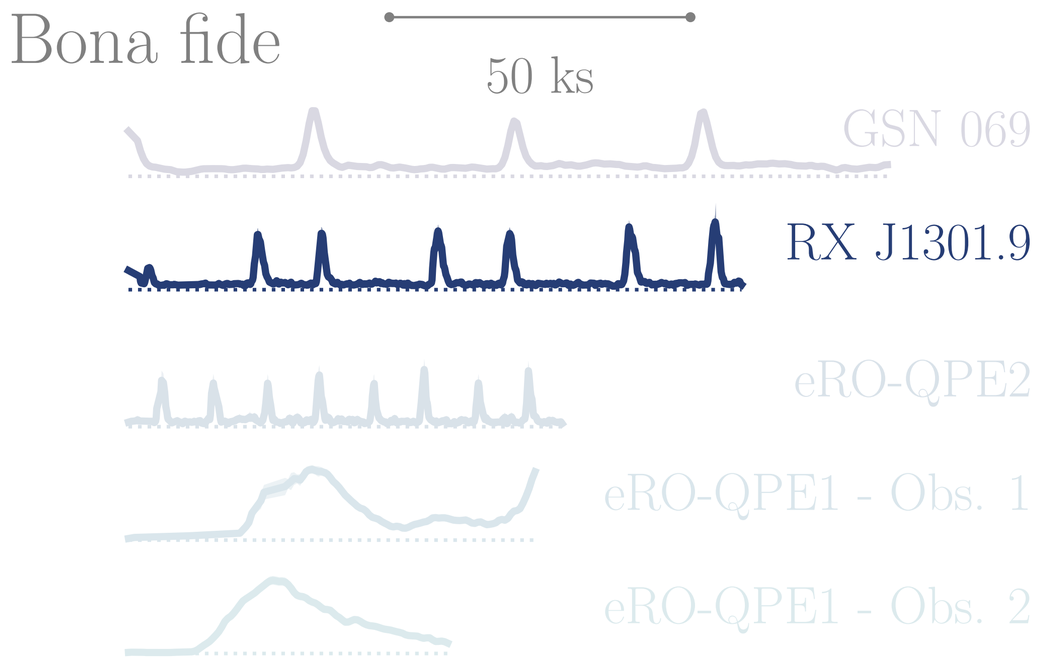
Candidates

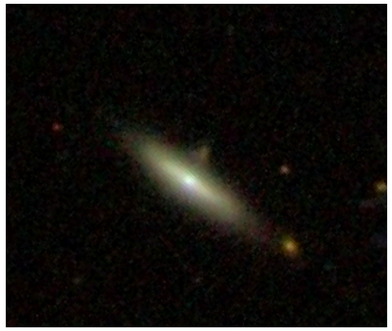
- Lack of broad emission lines
- Narrow emission lines: nuclear activity
- Small black hole mass $10^{4\text{-}7}$ Msun
- Small galaxies < 10^{9} Mstar
- Super-soft X-ray emission
- Not significantly absorbed
- Likely or certain TDE connection
- **Lots of complexities**

See also Wevers et al. 2022, A&A 659, 2

Image credits: Erwan Quintin

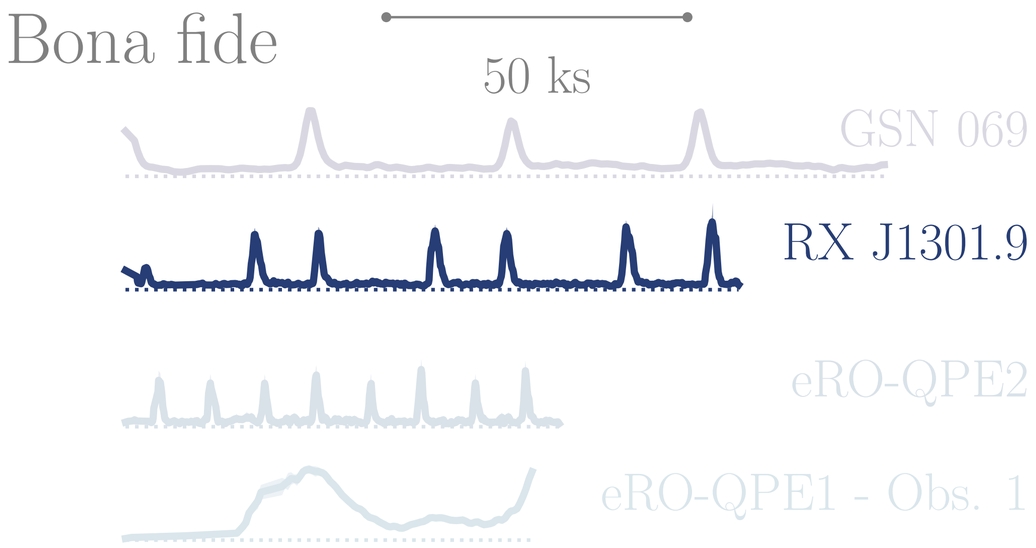
RX J1301.9+2747





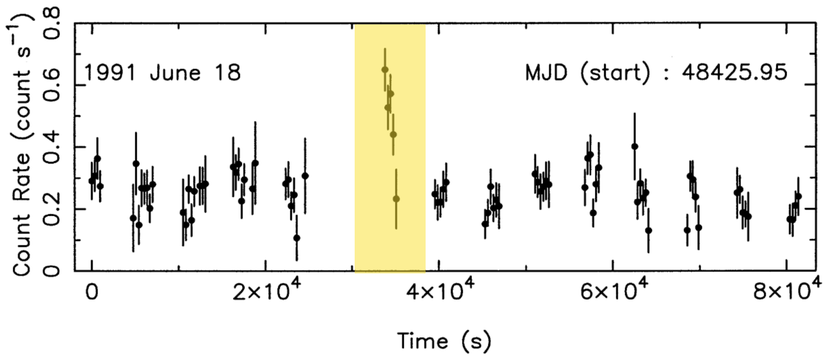
- Young post-starburst galaxy at the periphery of the Coma Cluster (z = 0.024)
- Small M_{BH} ~ (8–40) x 10^5 $M_\odot$
- No Broad Optical/UV Emission Lines
- High Eddington Ratio ~0.1
- Super-soft X-ray source
- Peculiar X-ray variability

RX J1301.9+2747

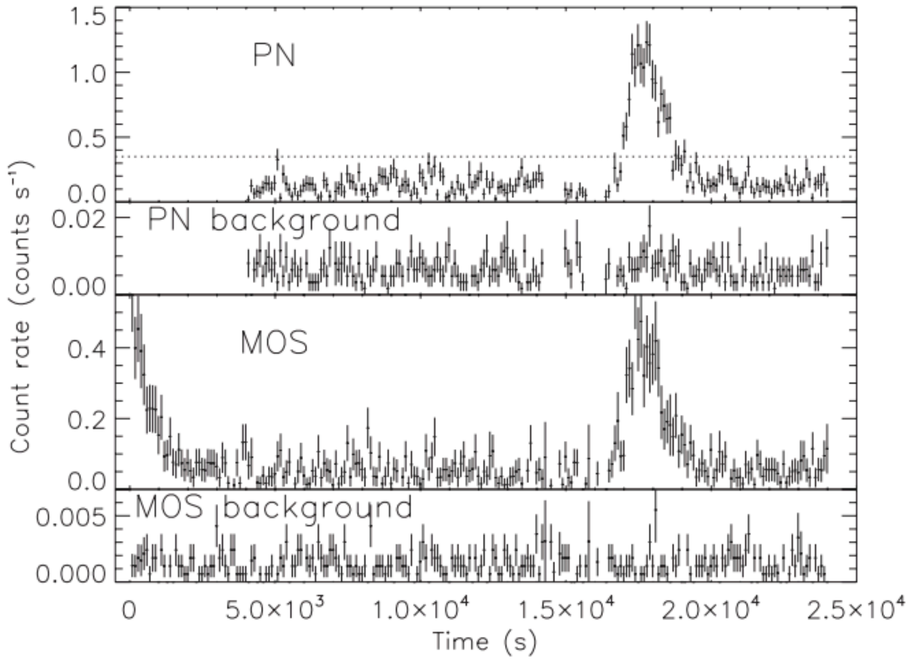


Evident QPE-like variability

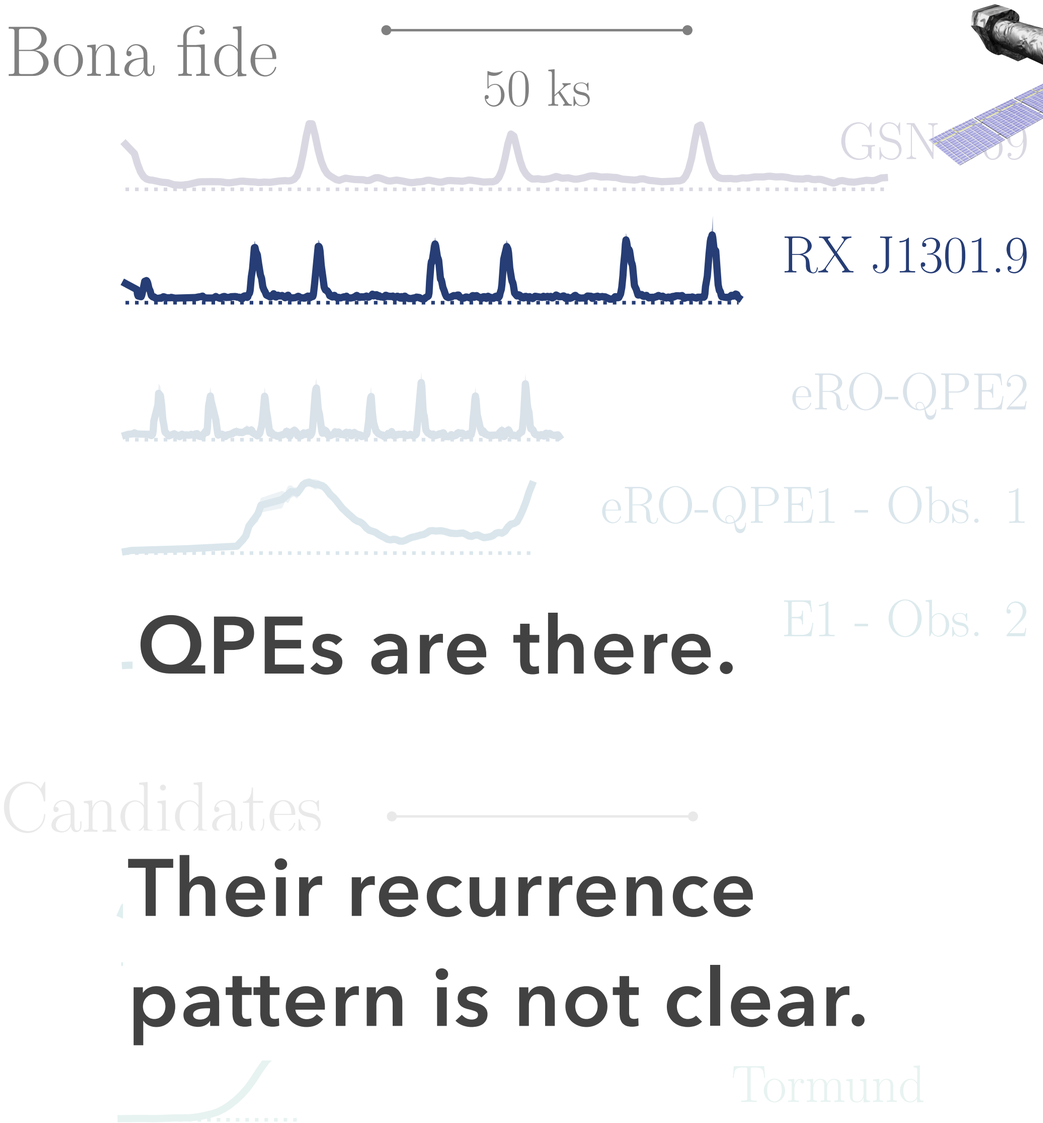
Dewangan et al. 2000, MNRAS 318, 309

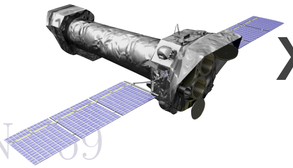


Sun, Shu & Wang 2013, ApJ 768, 167



RX J1301.9+2747

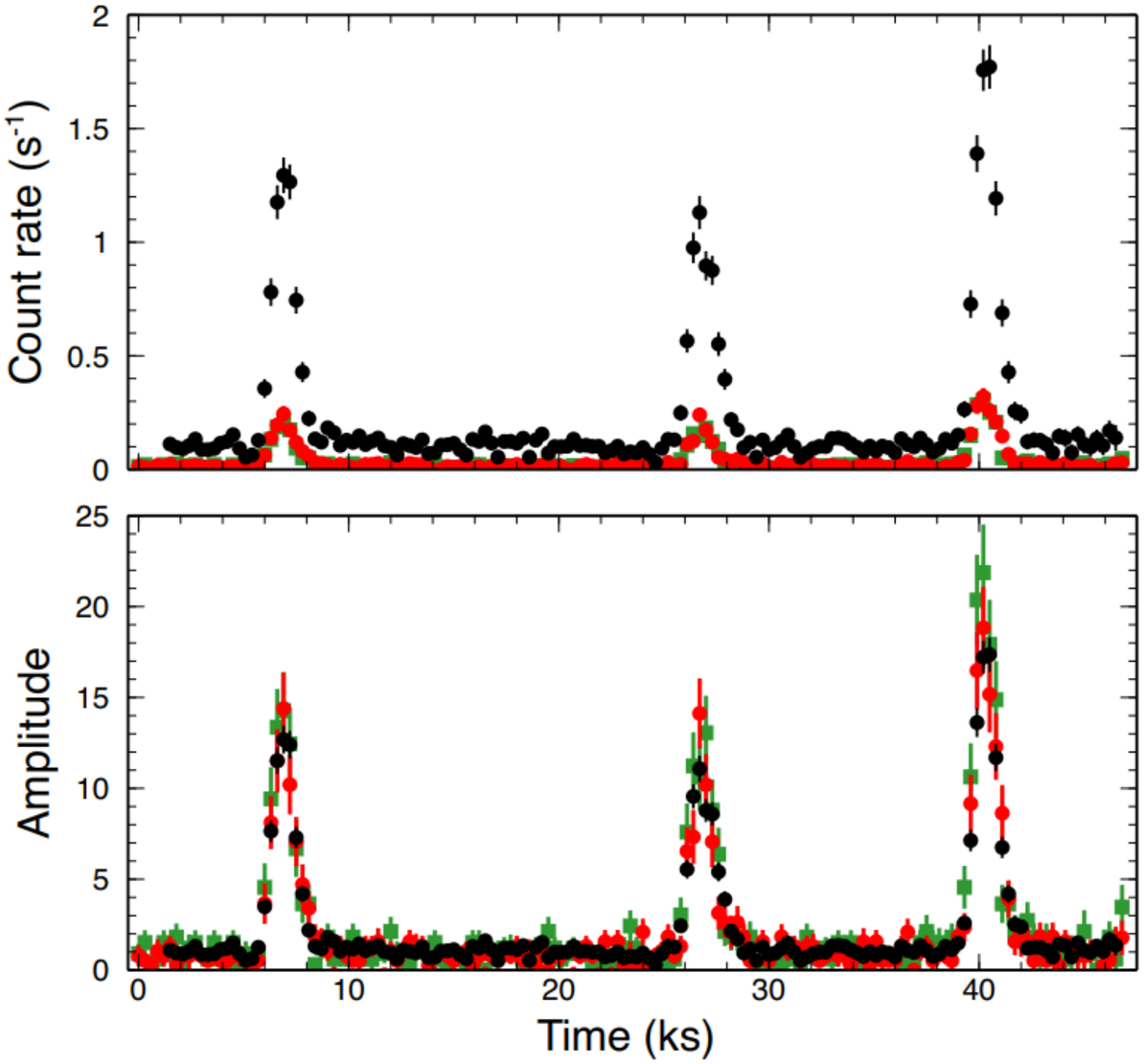




QPEs are there.

Their recurrence pattern is not clear.

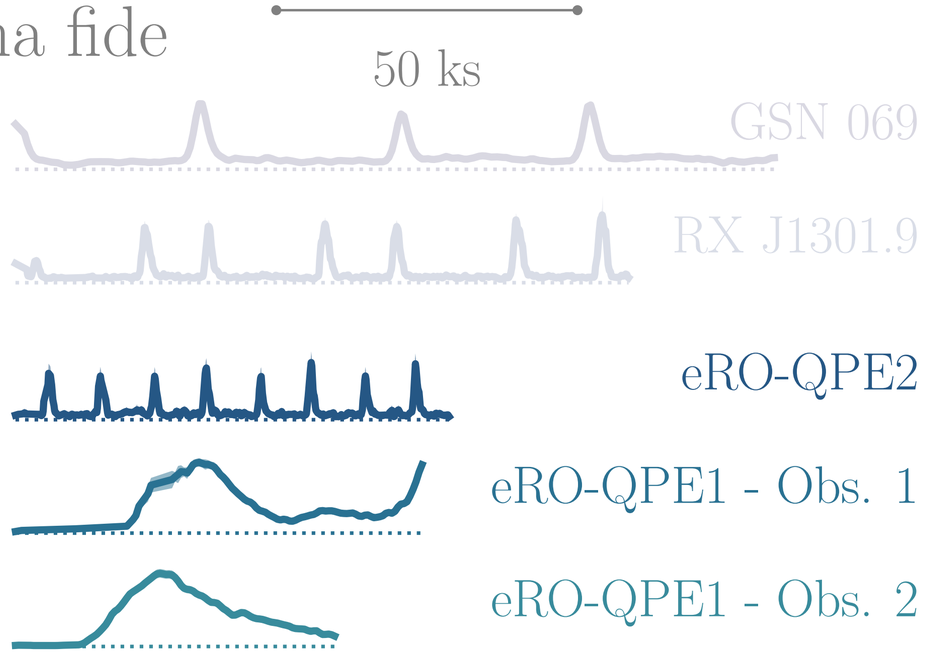
XMM-Newton DDT observation on June 2019

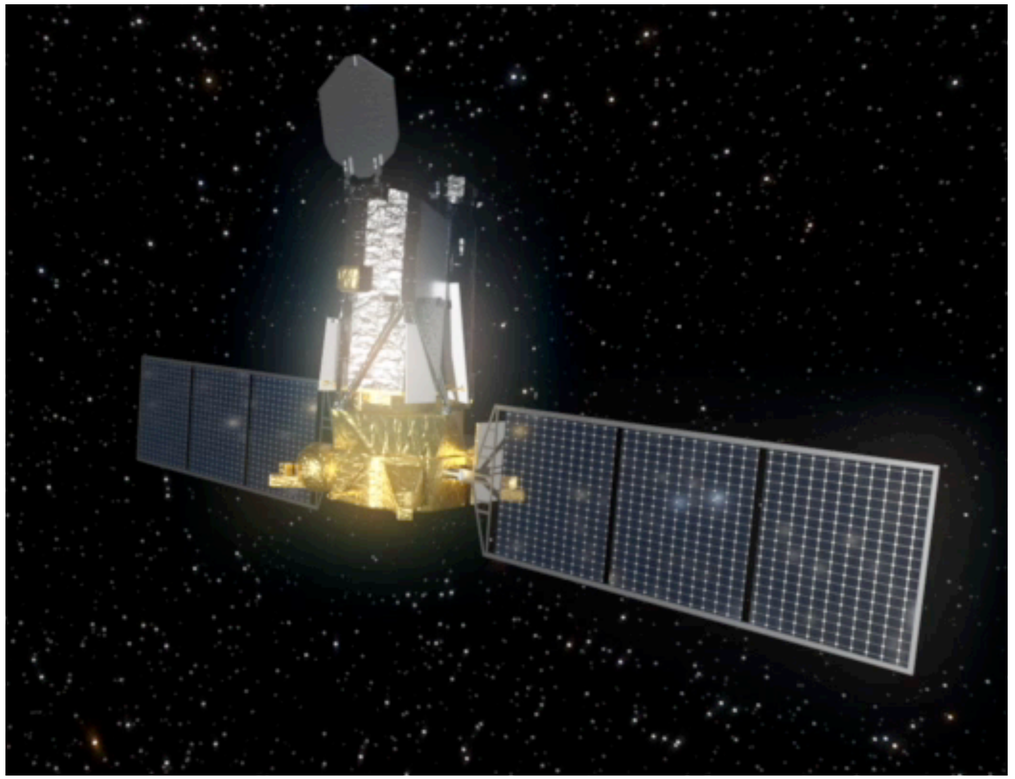


Giustini et al. 2020, A&A 636, 2

eROSITA catches QPEs

Bona fide





Candidates

eROSITA catches QPEs

Bona fide

50 ks

GSN 069

RX J1301.9

eRO-QPE2

eRO-QPE1 - Obs. 1

eRO-QPE1 - Obs. 2

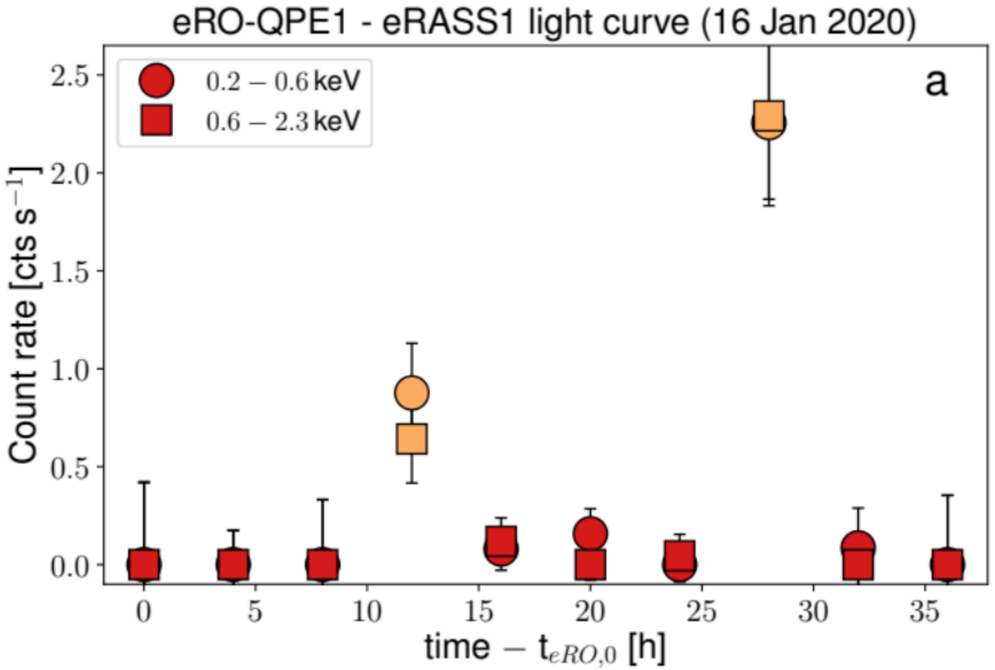
Candidates

50 ks

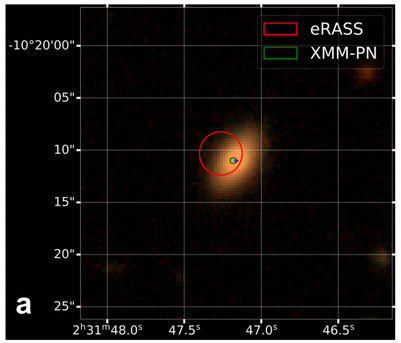
XMMSL1 J0249

Tormund

Arcodia et al. 2021, Nature 592, 704



eRO-QPE1, z = 0.0505



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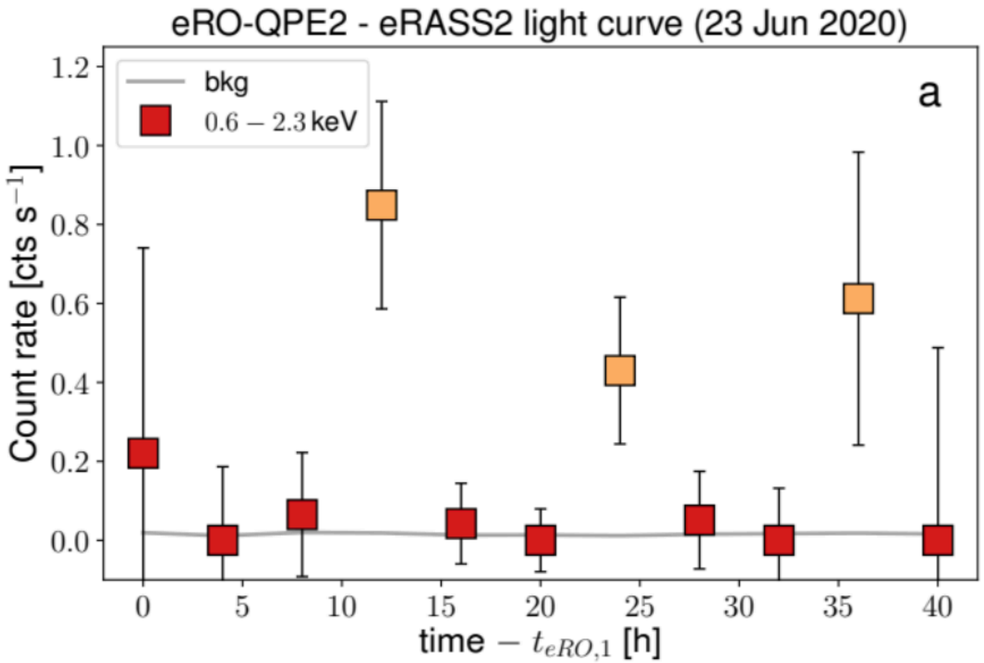
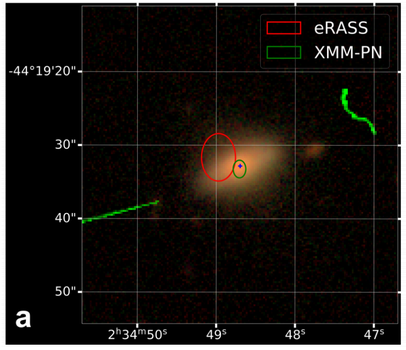
Arcodia et al. 2021, Nature 592, 704

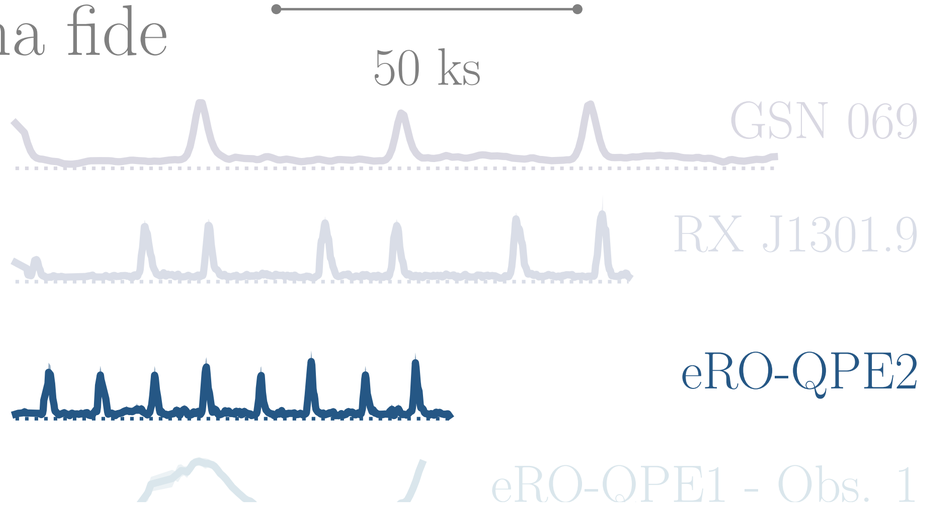


eRO-QPE2, z = 0.0175

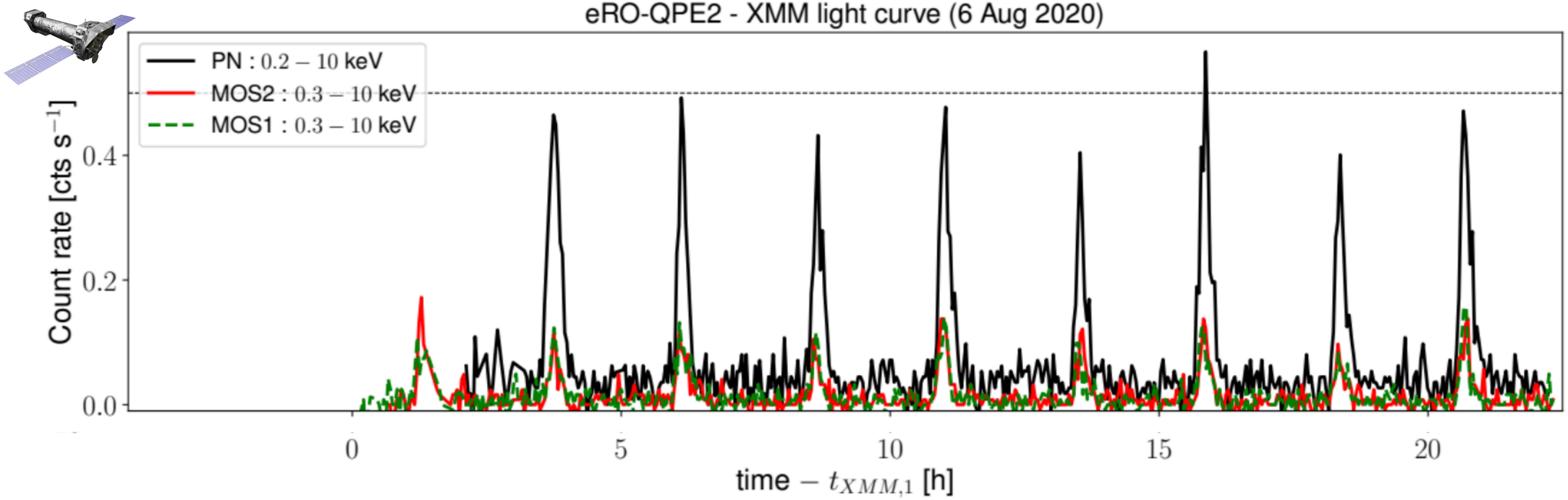


eRO-QPE2

Arcodia et al. 2021, Nature 592, 704

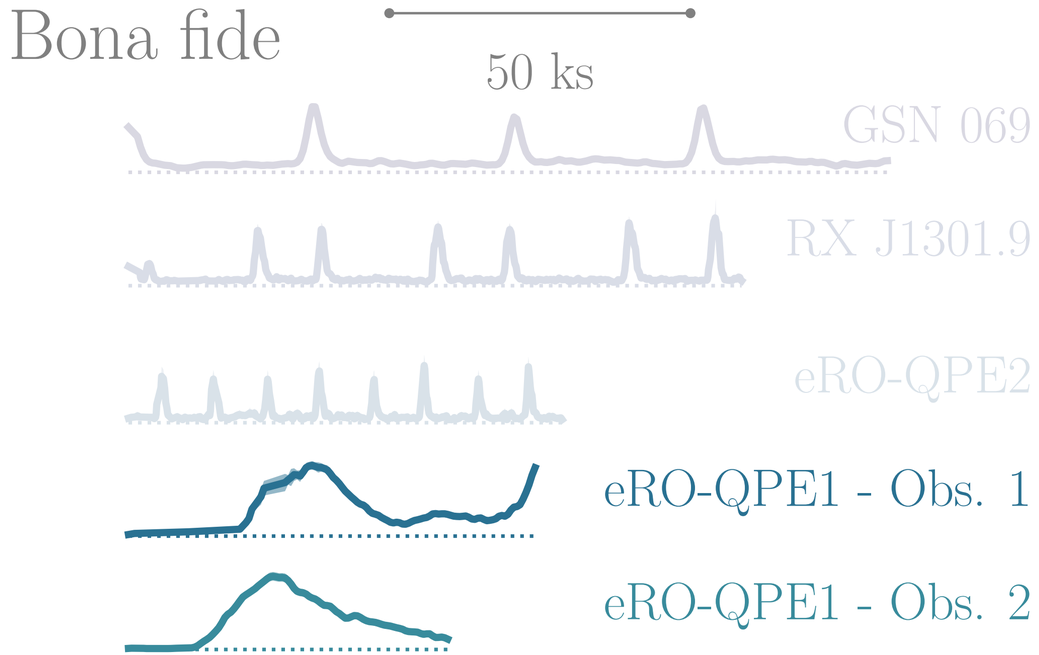


- QPEs last about half an hour
- Release between 10^{41} and 10^{42} erg/s
- Repeat every about 2.5 hr

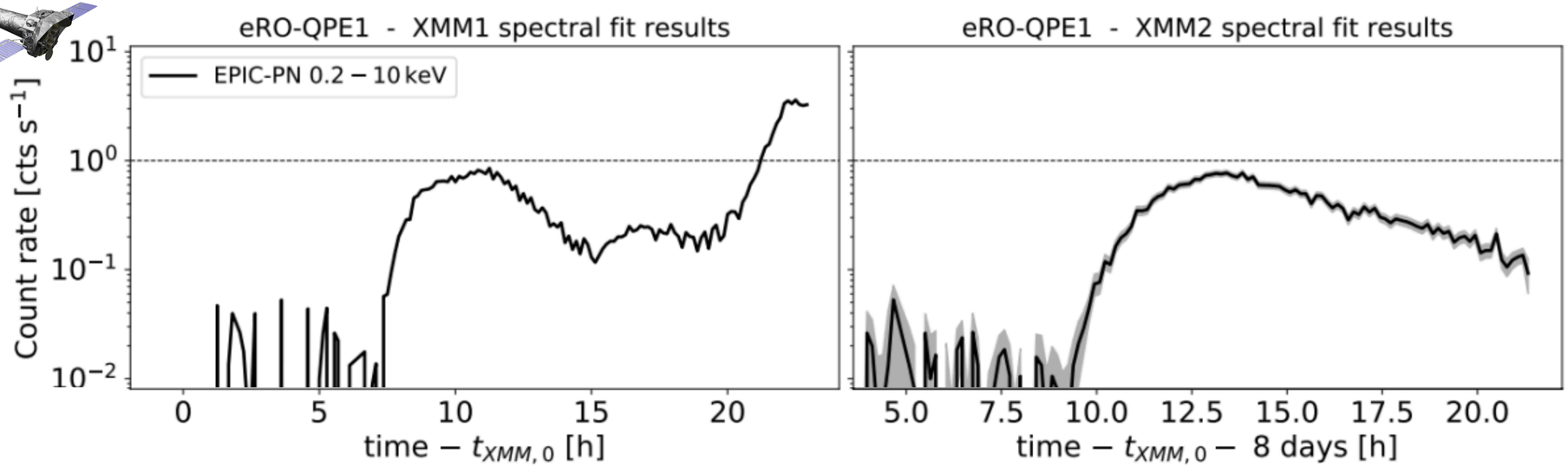


eRO-QPE1

Arcodia et al. 2021, Nature 592, 704

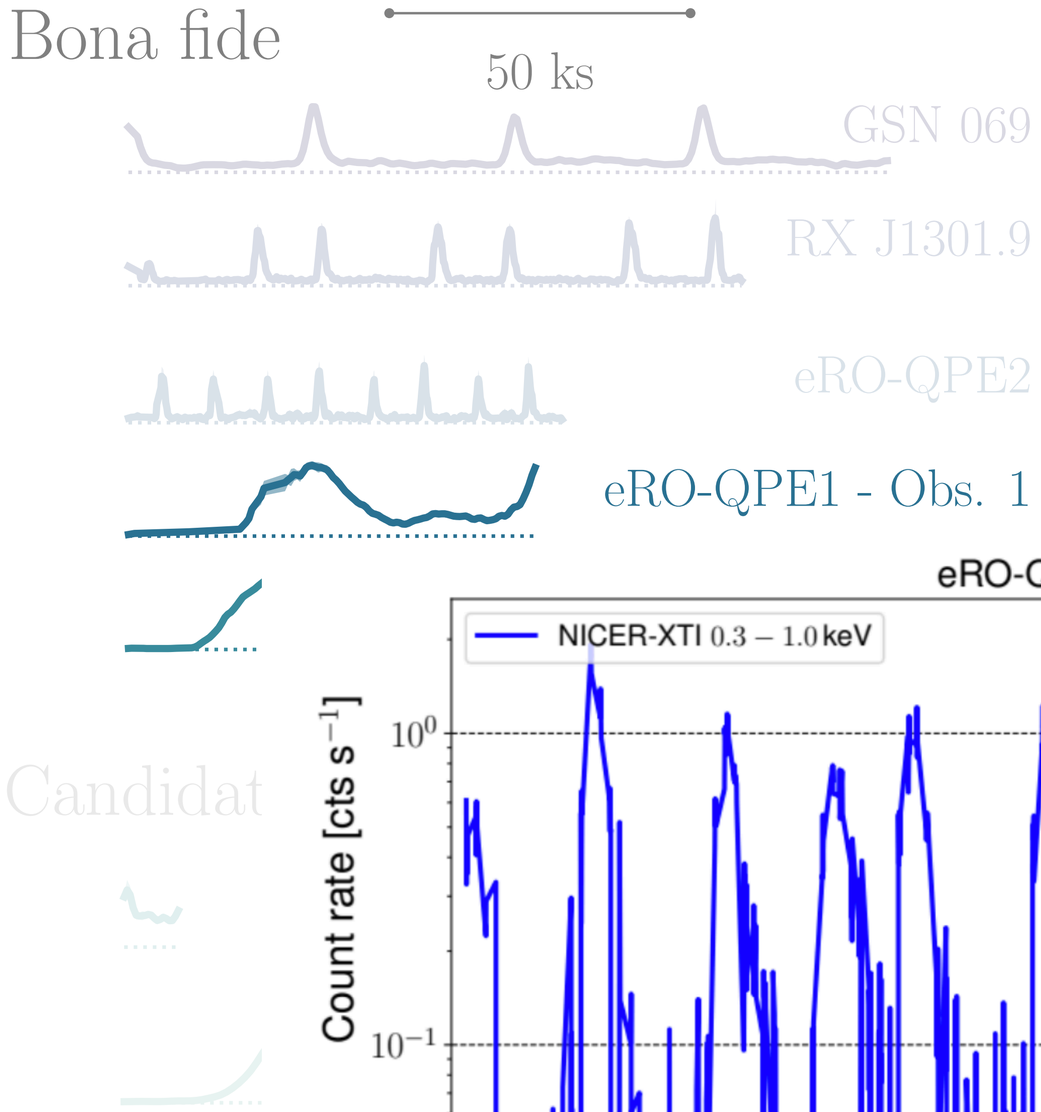


- QPEs last about 7.5 hours
- Emit between 3 x 10^{42} and 2 x 10^{43} erg/s
- Repeat every about 18 hr



eRO-QPE1

Arcodia et al. 2021, Nature 592, 704



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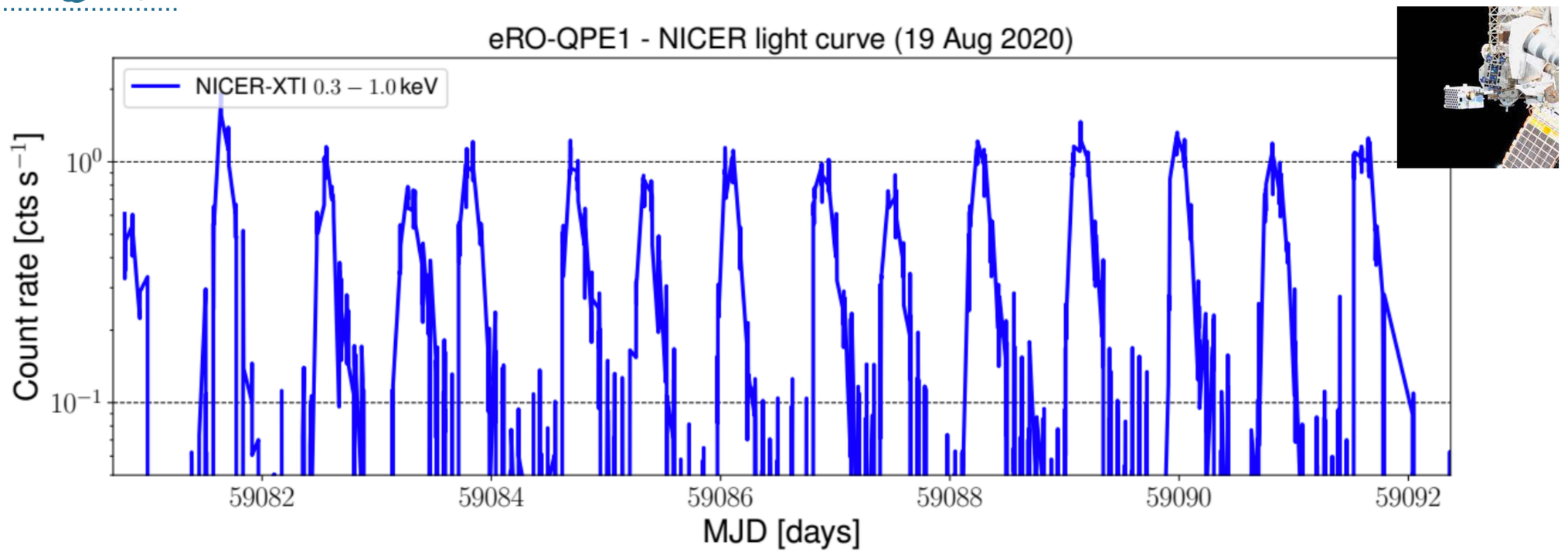
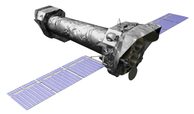
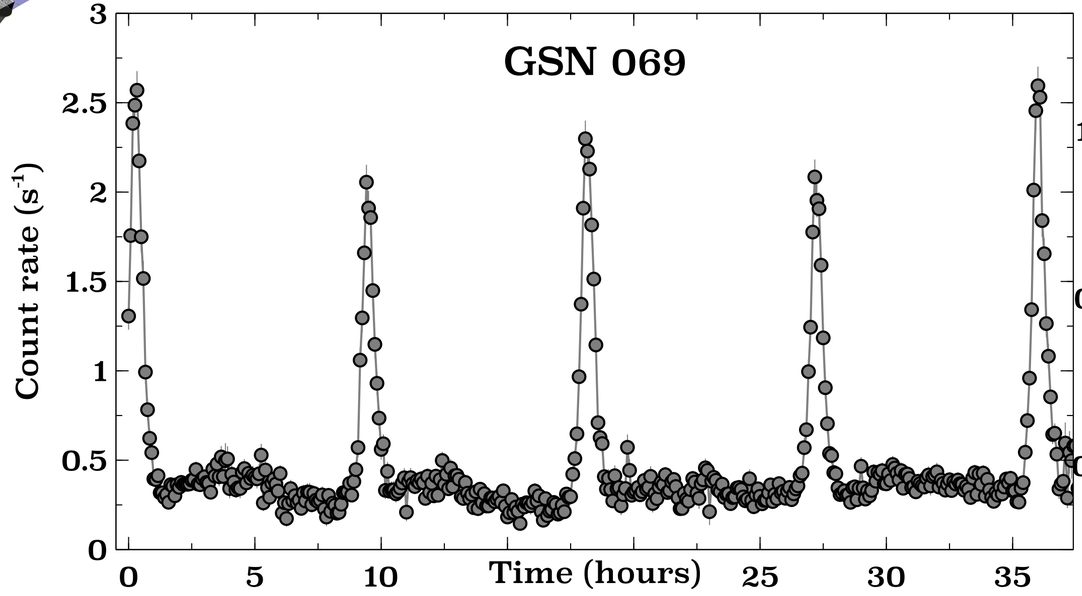
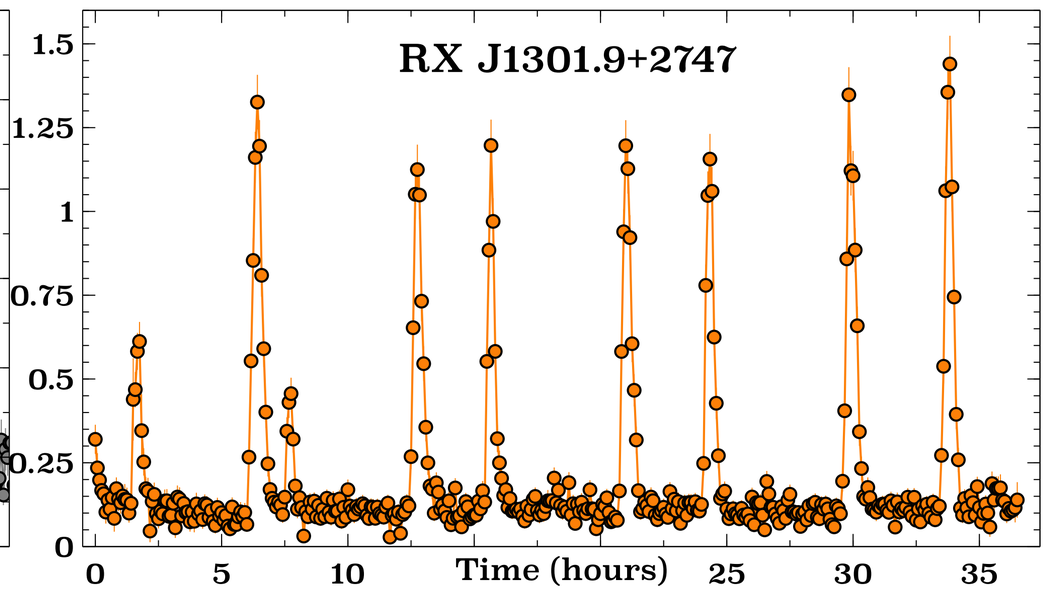
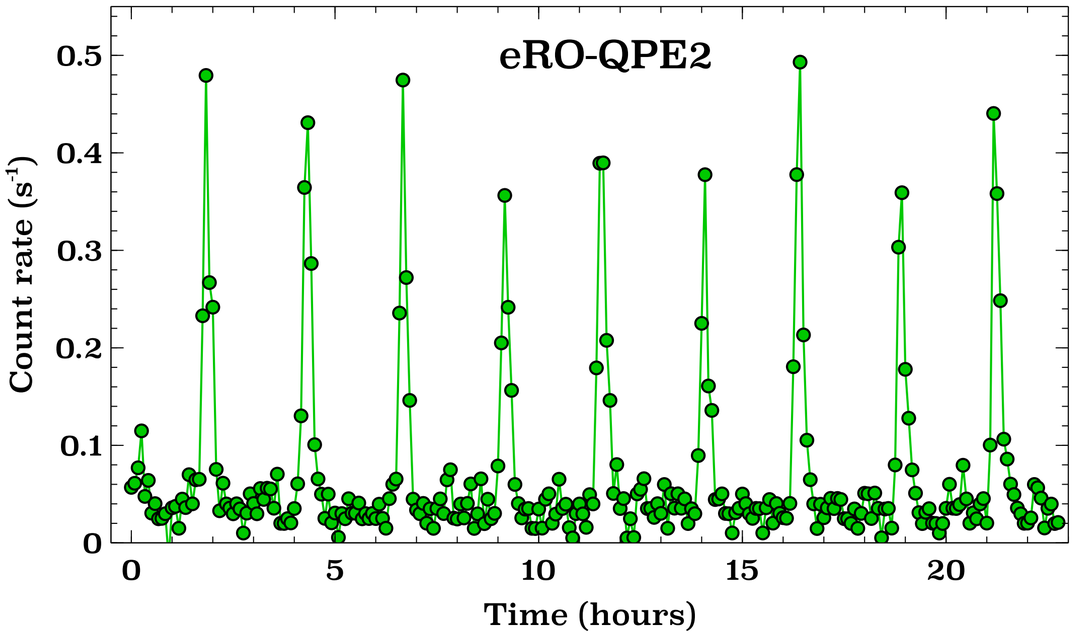


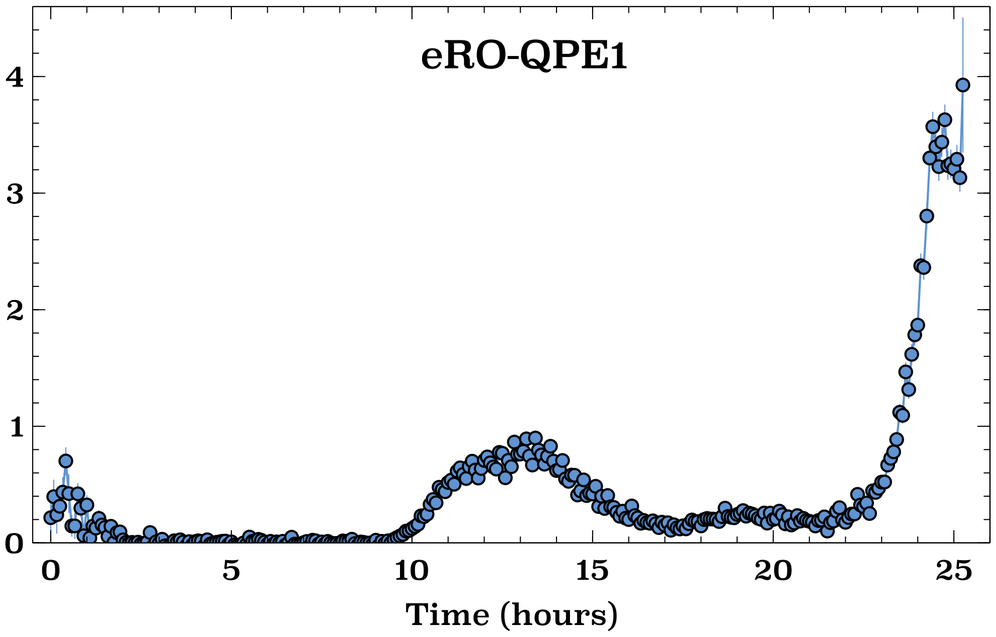
X-ray light curves of QPE sources binned to 5 minutes











QPE-candidates

The QPE-candidate XMMSL1 J0249

Bona fide

50 ks

GSN 069

RX J1301.9

eRO-QPE2

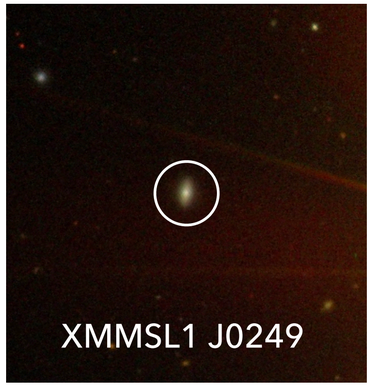
eRO-QPE1 - Obs. 1

eRO-QPE1 - Obs. 2

Candidates

XMMSL1 J0249

Tormund

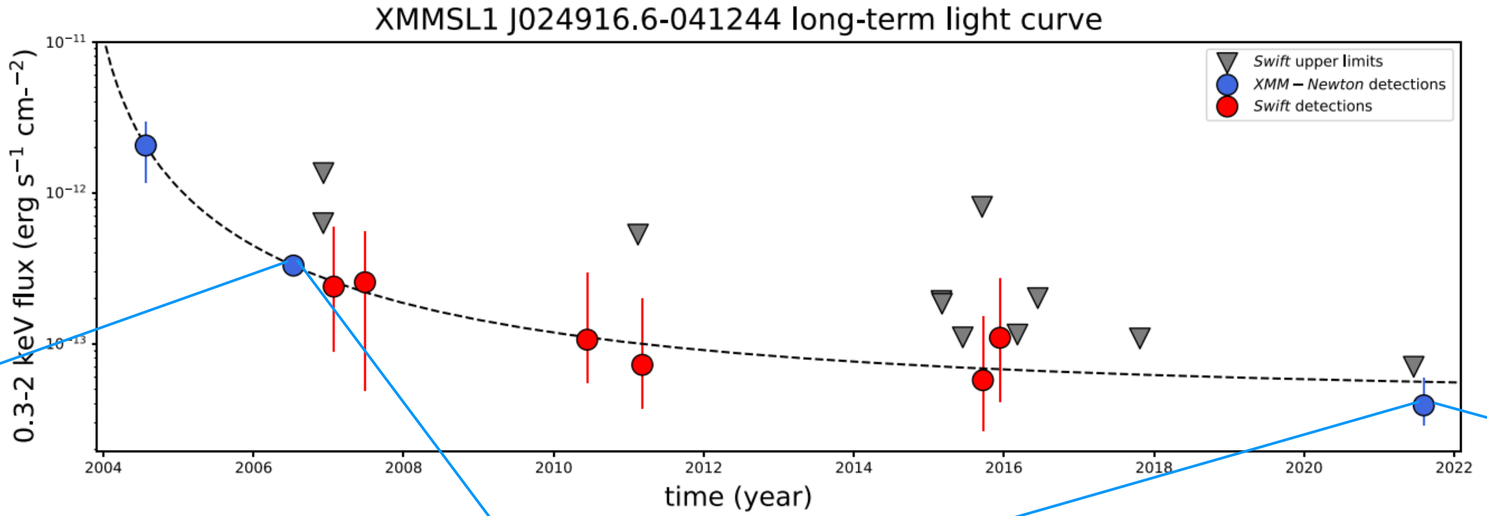


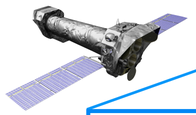
- Star-forming/AGN galaxy, z = 0.019
- Small black hole mass M_{BH} ~ 8–50 x 10^5 $M_\odot$
- Detected in 2004 by the XMM-Newton Slew
- Flux increase ~90x compared to ROSAT
- Clever application of the Quasi-periodic Automated Transit Search algorithm to the XMM-Newton archive: QPE-like flare identified

Chakraborty et al. 2021, ApJL 921, 40

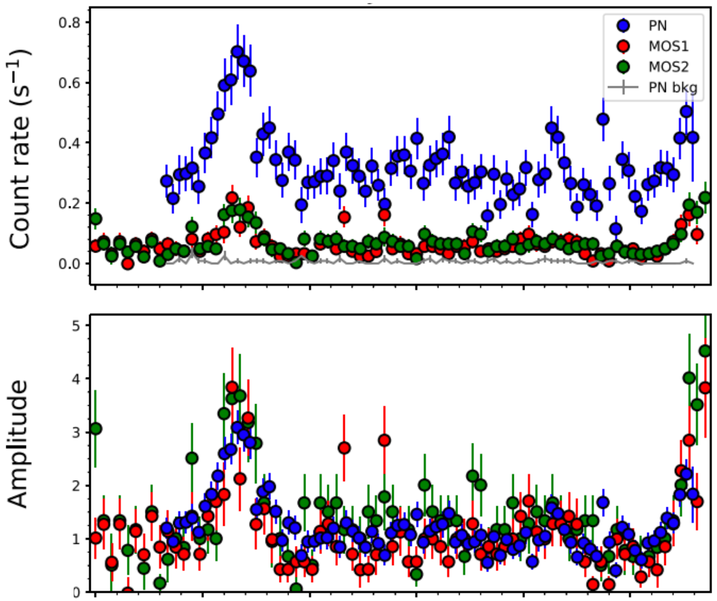
Image credits: Erwan Quintin

The QPE-candidate XMMSL1 J0249

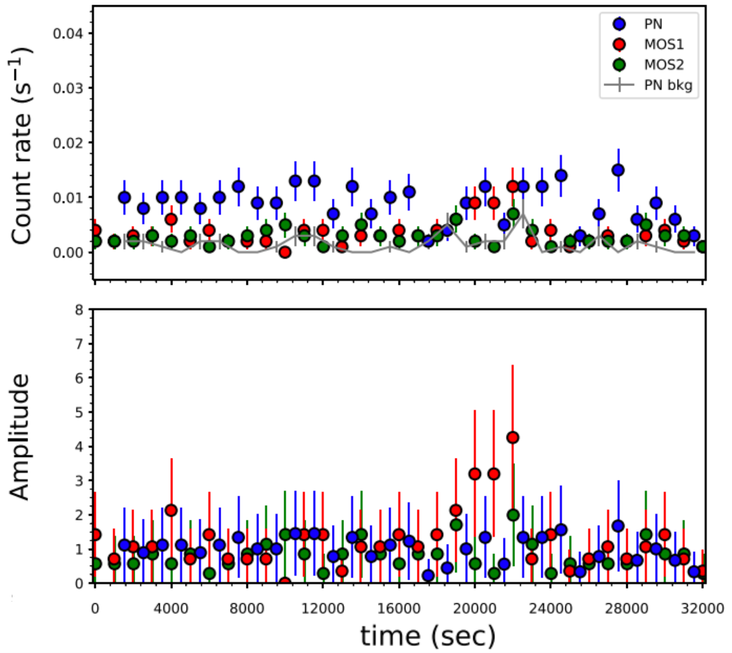




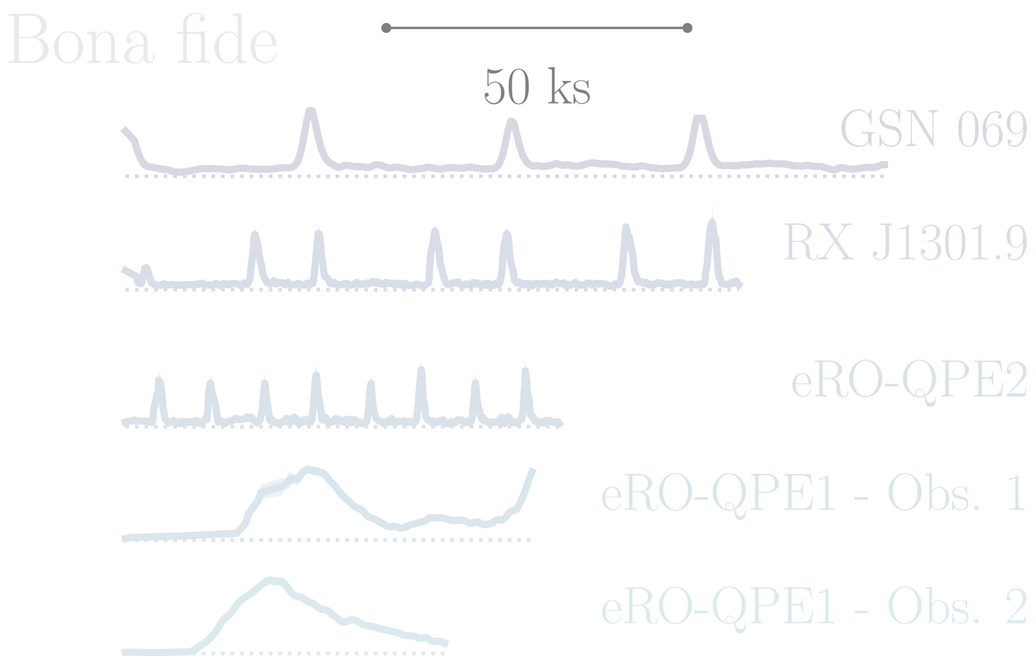
2006: ~1.5 QPE-like flares separated by 9 ks

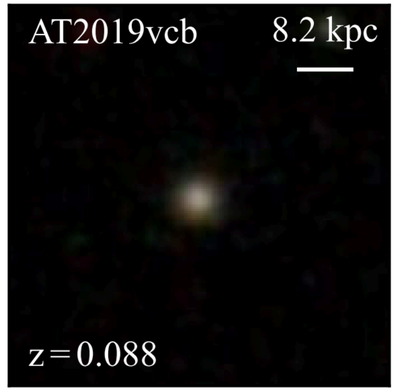


2021: stable quiescent flux, no QPEs in 32 ks



The QPE-candidate Tormund





Hammerstein et al. 2022

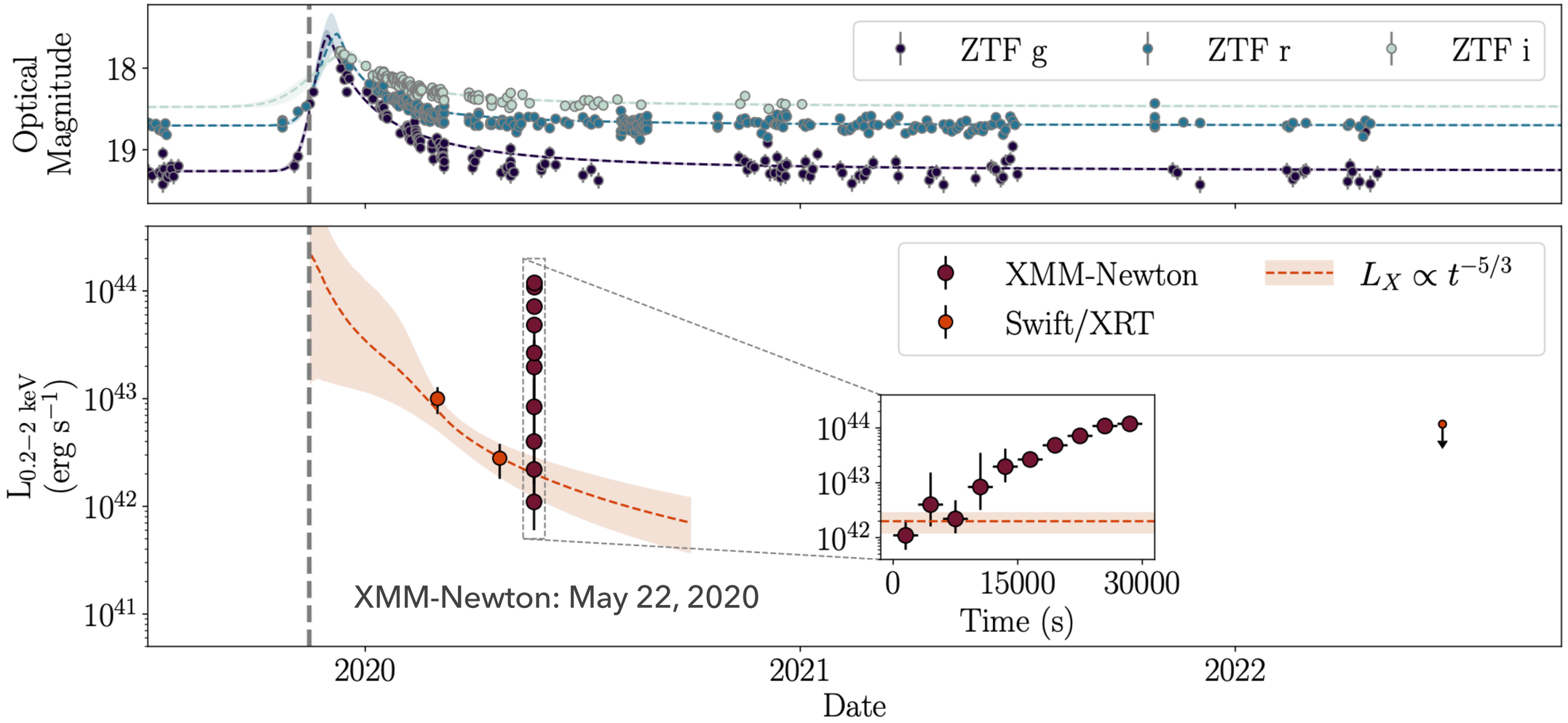
- Detected by the ZTF on November 15, 2019
- Optical counterpart: tidal disruption event
- z = 0.088
- Low-mass galaxy with $M_{star} \sim 3 \times 10^9\ M_\odot$
- Black hole mass $M_{BH} \sim 6\text{–}80 \times 10^6\ M_\odot$
- Data mining multi-instrument X-ray archives: QPE-like flare identified

Quintin et al. 2023, A&A in press, arXiv:2306.00438

Tormund returns as QPE-candidate

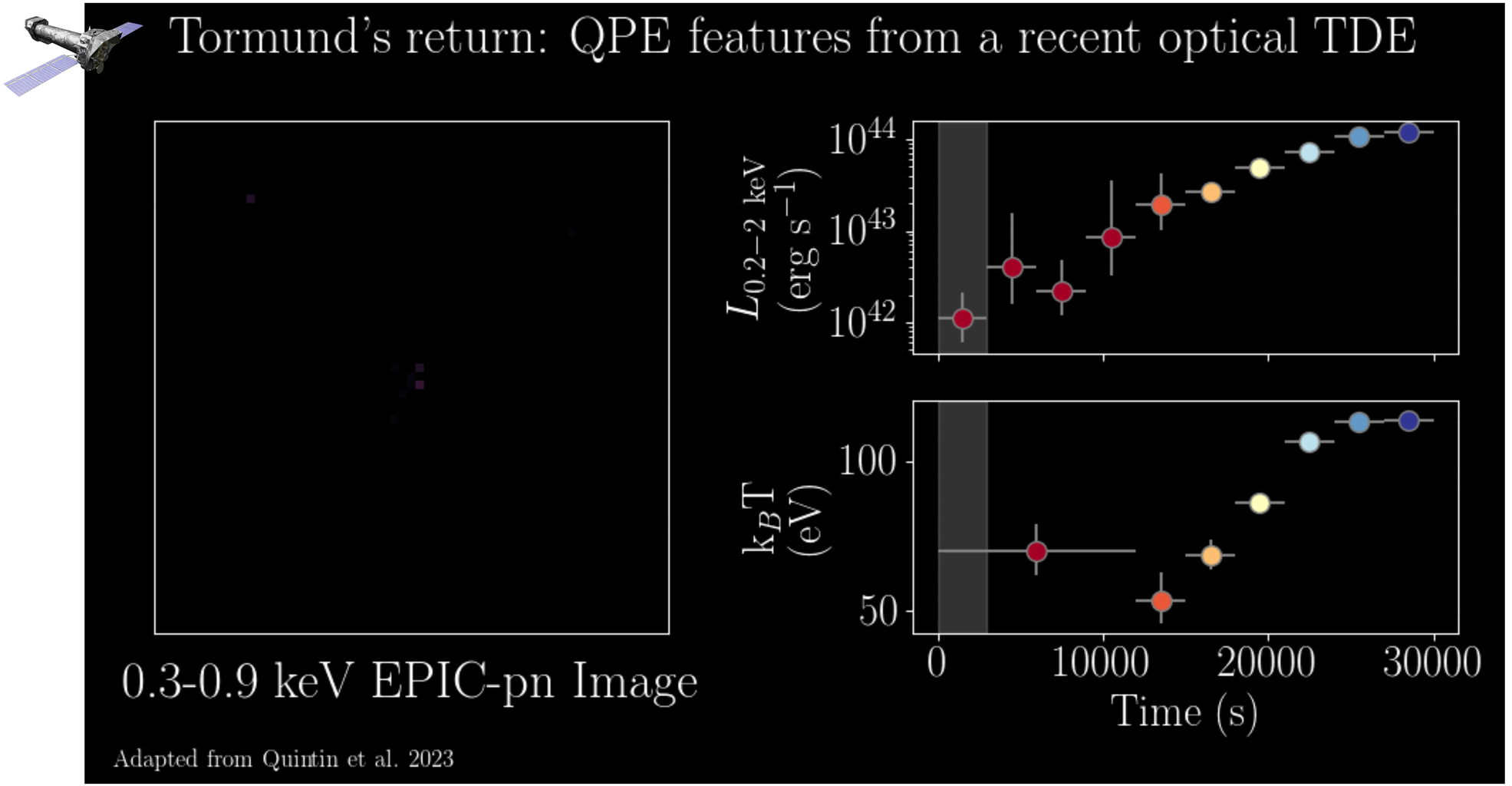
Optical peak: Nov 15, 2019

Quintin et al. 2023, A&A in press, arXiv:2306.00438



X-ray flare detected ~ 6 months after the optical TDE peak

Tormund returns as QPE-candidate

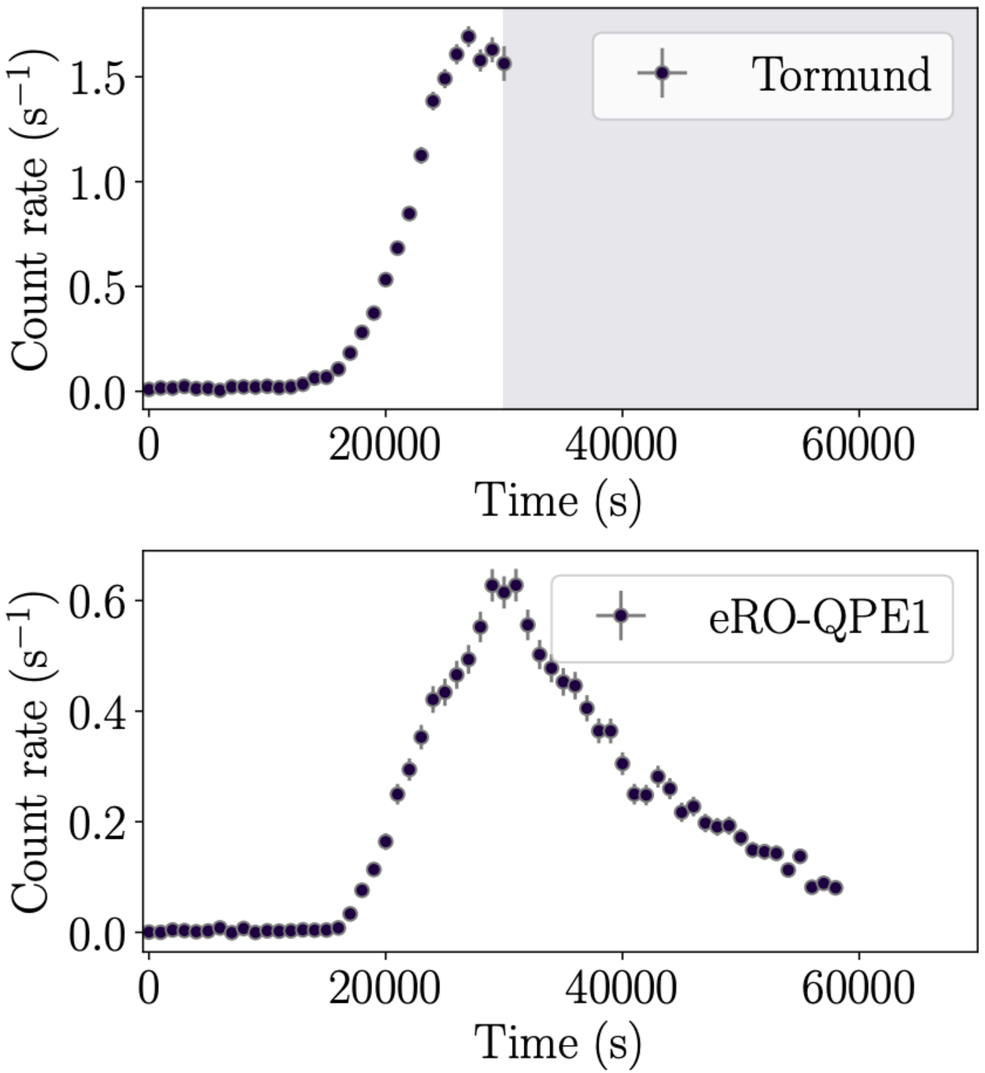


Animation credits: Erwan Quintin

Rise of a flare very similar to eRO-QPE1

Tormund returns as QPE-candidate

Quintin et al. 2023, A&A in press, arXiv:2306.00438



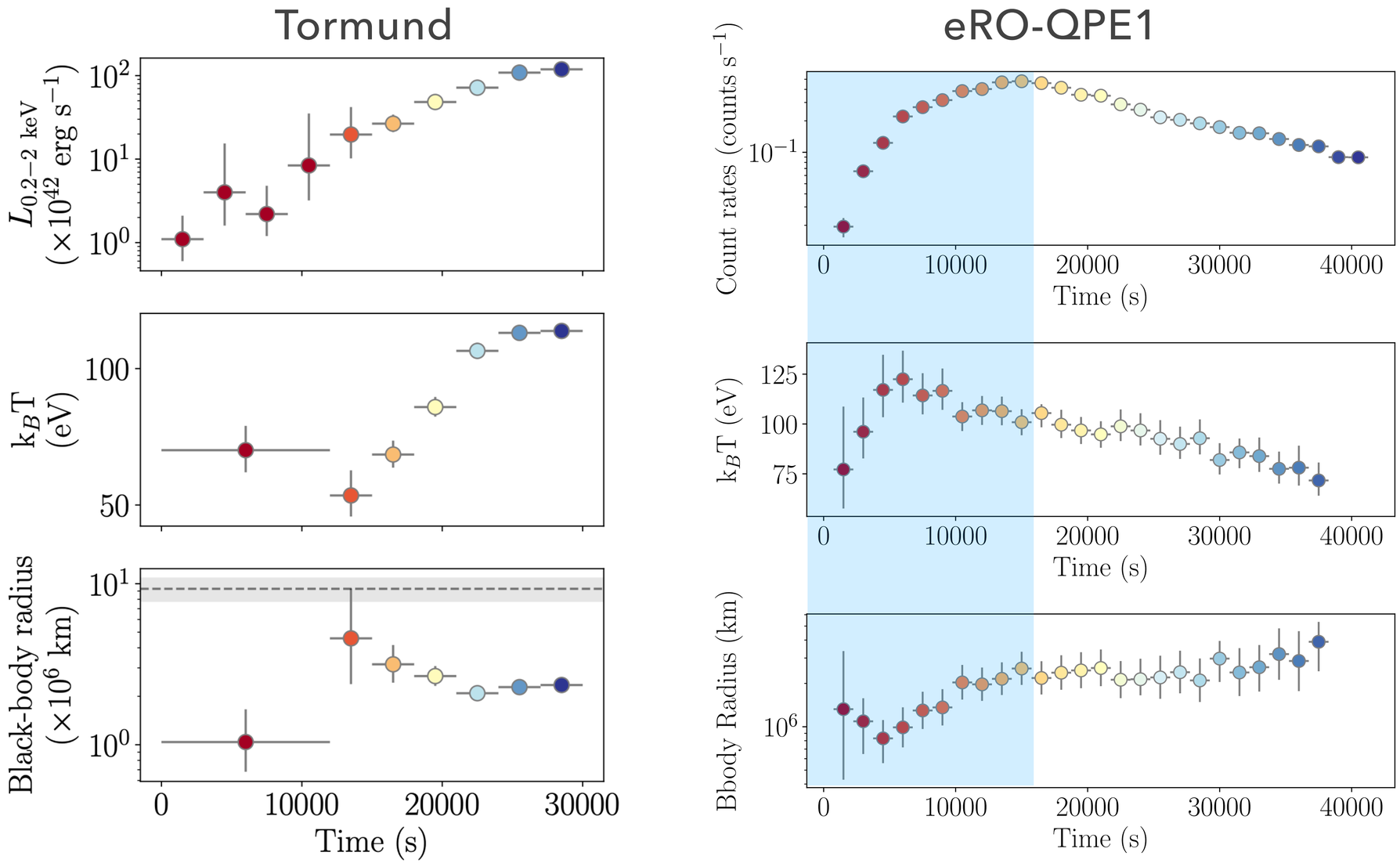
Release between 10^{43} and 10^{44} erg/s

Release between 10^{42} and 10^{43} erg/s

Rise of a flare very similar to eRO-QPE1

Image credits: Erwan Quintin

Tormund returns as QPE-candidate



Rise of a flare very similar to eRO-QPE1

Image credits: Erwan Quintin

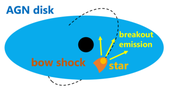
QPE general properties

- QPEs: a new transient phenomenon around $<10^7\ M_\odot$ black holes
- Sharp, recurrent flares of soft X-ray emission with luminosity of $10^{42\text{-}43}$ erg/s
- QPE duration: ~1 hour, up to ~10 hours
- QPE recurrence times: ~ a few hours, up to a few days
- Thermal-like X-ray spectra with kT ~ 100-250 eV at the peak
- Harder when brighter: the quiescence (when present) is thermal with kT ~ 50-70 eV
- Observed in the nuclei of low-mass galaxies, likely connected to TDEs

What are QPEs due to?

QPEs physical scenarios

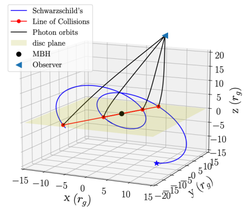
"Almost as many models as eruptions observed" [GM]



Sniegowska et al. 2020, A&A 641, 167

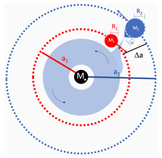
King 2020, MNRAS 493, 120

Pan, Li & Cao, arXiv:2305.02071

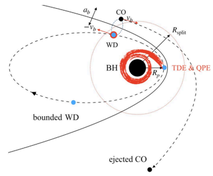


Kaur, Stone & Gilman, arXiv:2211.00704

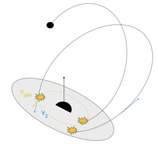
Raj & Nixon 2021, ApJ 909, 82



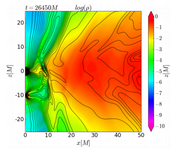
Zhao et al. 2022, A&A 661, 55



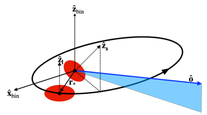
Wang et al. 2022, ApJ 933, 2



Metzger et al. 2022, ApJ 926, 101

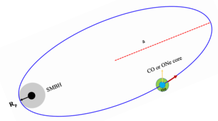


Sukova et al. 2021, ApJ 917, 43



Ingram et al. 2021, MNRAS 503, 1703

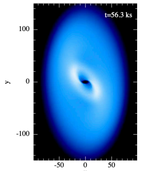
Linial & Sari 2023, ApJ 945, 86



Xian et al. 2021, ApJL 921, 32

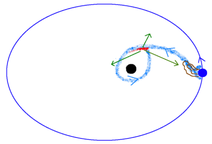
Linial & Metzger, arXiv:2303.16231

Sniegowska et al. 2023, A&A 672, 19



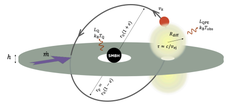
Franchini, Bonetti et al. 2023, arXiv:2304.00775

Lu & Quataert, arXiv:2210.08023



Krolik & Linial 2022, ApJ 941, 24

Tagawa & Haiman, arXiv:2304.03670



QPEs physical scenarios

Accretion flow instabilities

- Radiation pressure instability
- Inner disk tearing
- Magnetic instabilities

Orbital phenomena

- Self-lensing Massive Black Hole Binaries
- Extreme Mass Ratio Inspirals

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Radiation pressure instability

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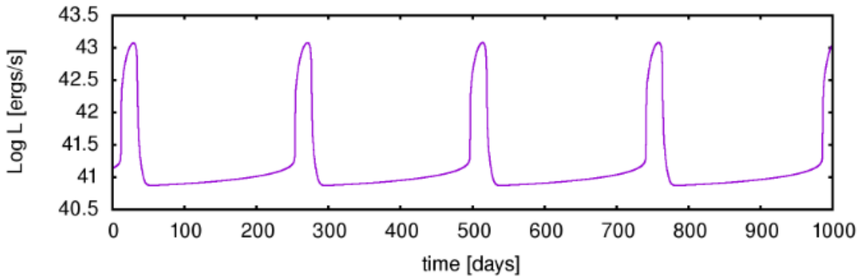
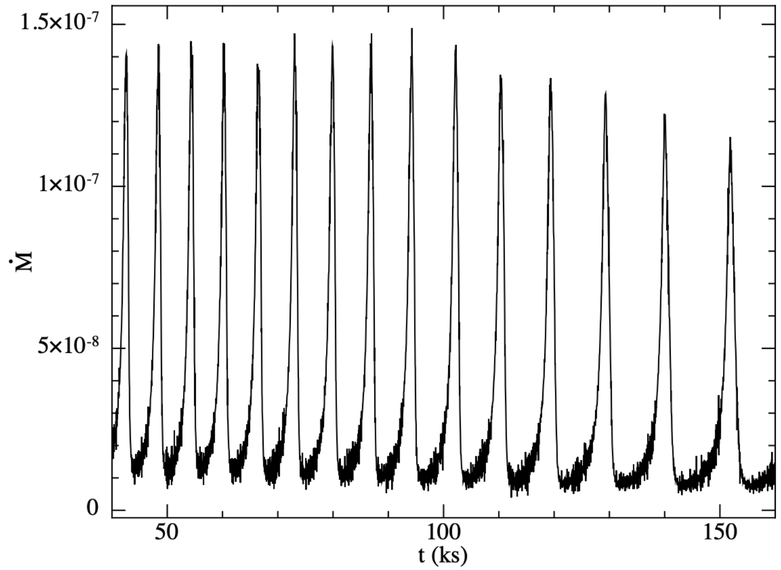
QPEs physical scenarios

Radiation pressure instability





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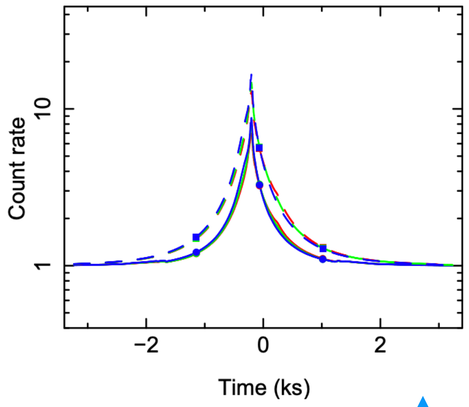
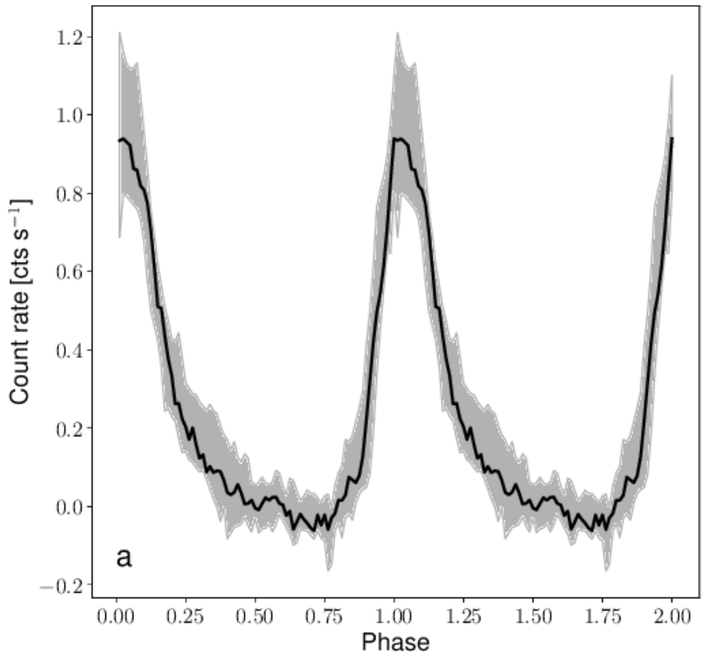


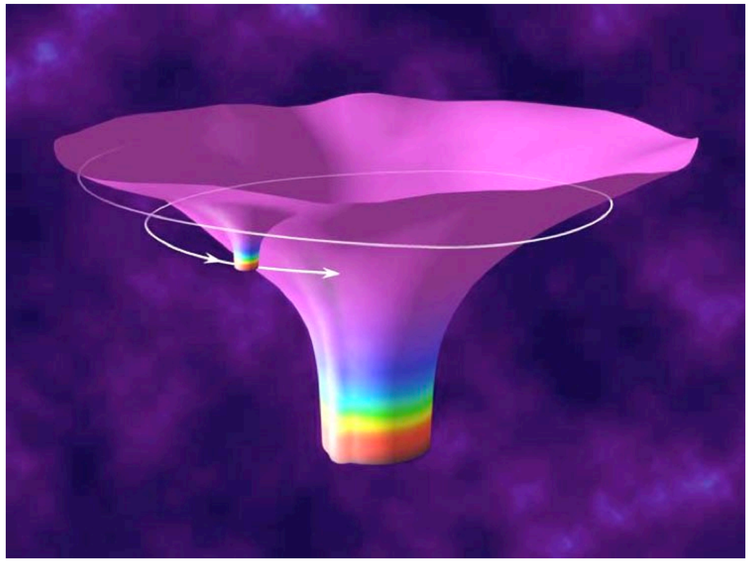
Expected profile: symmetric

← or slower rise, fast decay



QPEs are generally asymmetric, with a faster rise and a slower decay

QPEs physical scenarios: EMRIs



SMBH accretion of streams from episodic mass transfer in an EMRI

[King 20, 22 - Chen+22 - Wang+22 - Zhao+22 - Metzger+22 - Linial+22]

Circularization shocks from episodic mass transfer in an EMRI

[Krolik+23]

Stream/disc interaction (shocks) from episodic mass transfer in an EMRI

[Lu+22]

Secondary-disc collisions in an EMRI

[Sukova+21 - Xian+21 - Linial+23 - Franchini+23 - Tagawa+23]

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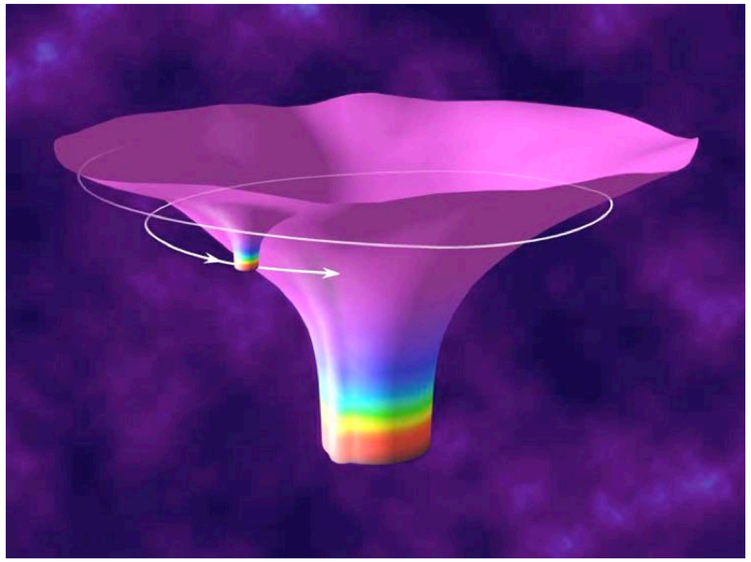

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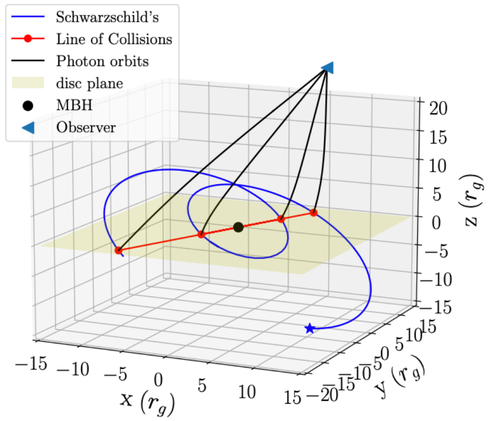
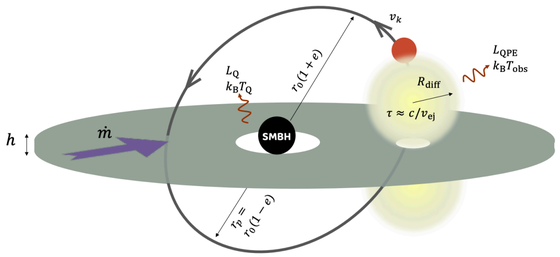
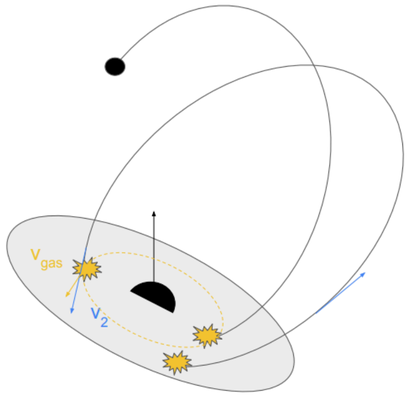
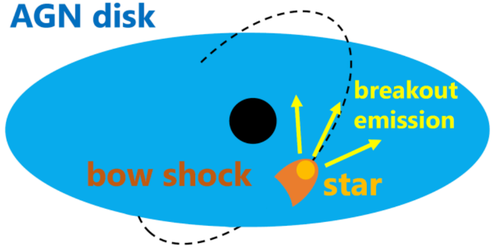
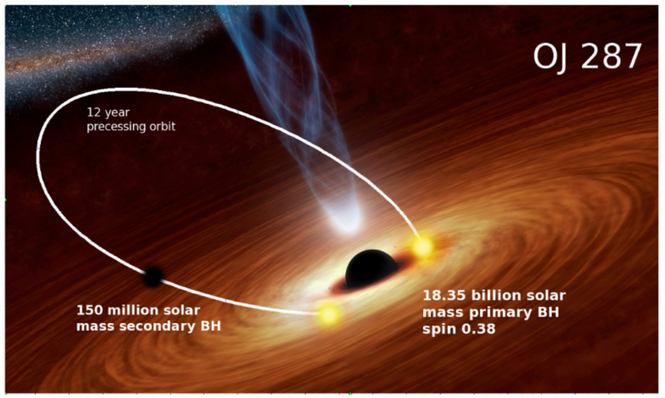








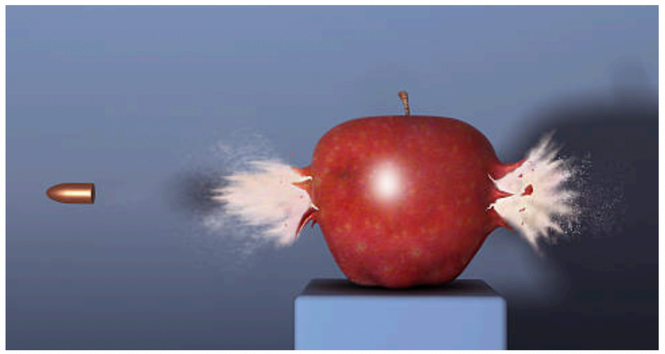
QPEs physical scenarios: secondary-disk impacts in an EMRI



Primary Black Hole with mass >> mass of secondary compact object

Secondary: star or BH of 10-100 Msun

Can easily explain alternating long/short recurrence times, strong/weak QPEs



The impact rises a two-sided expanding cloud [e.g. Pihajoki16]

The cloud is optically thick (BB emission) and expands while cooling

The QPE peak temperature depends on R_{imp} and on disc properties (mainly H/R)

The QPE peak luminosity is a function of V_{rel}

Soft X-ray emission with luminosity dependent on the cloud size (hence on relative velocity), timing properties dependent on the EMRI dynamics and the disk properties

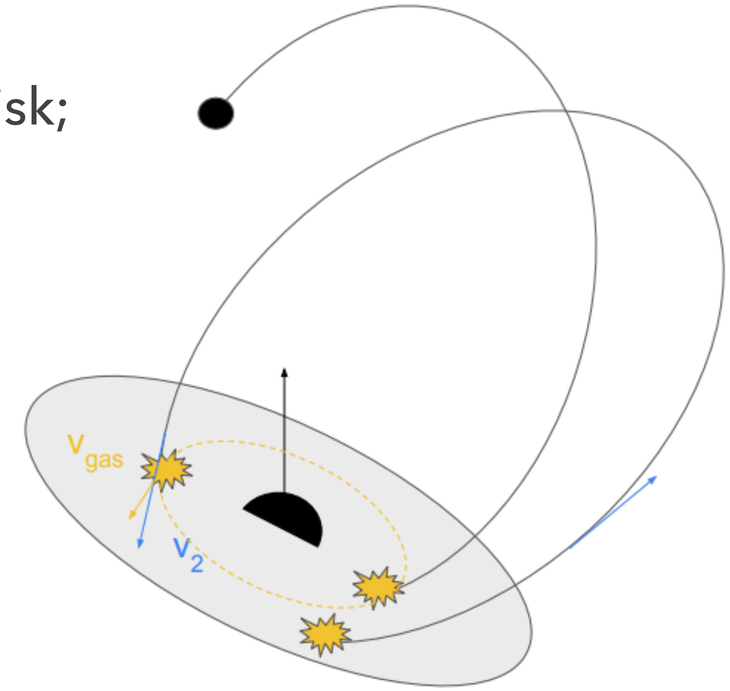
QPEs physical scenarios: secondary-disk impacts in an EMRI

Franchini, Bonetti, et al., 2023, A&A in press, arXiv:2304.00775

Scenario:

A Massive Black Hole is surrounded by a misaligned, rigidly precessing disk; and is orbited by a stellar-mass BH (the "EMRI companion").

The EMRI companion crosses the disk between 1 and 3 times per orbit (complexities induced by disk and EMRI companion orbital precessions).



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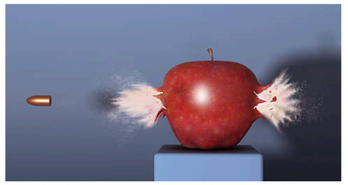

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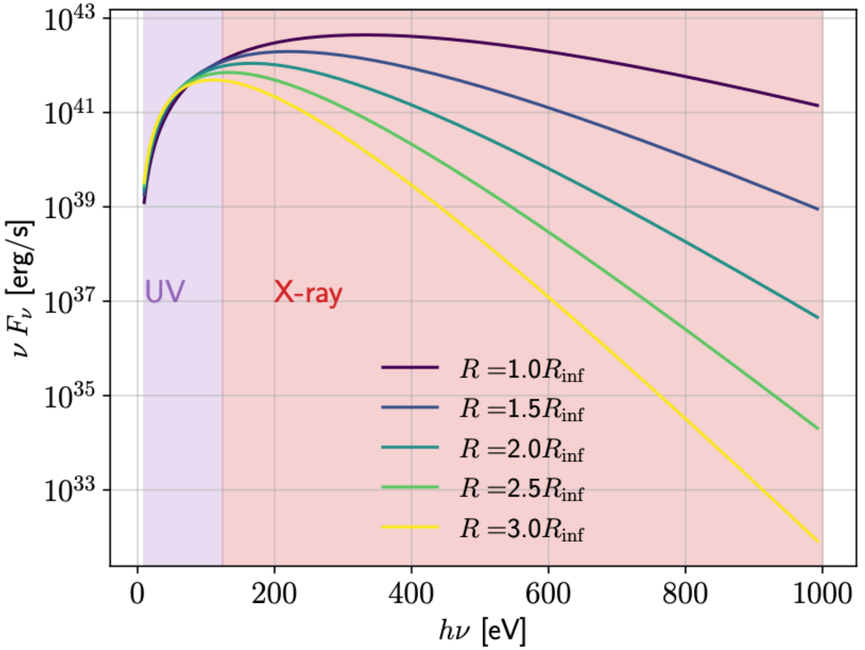
At each crossing, a gas cloud is pulled out from the disk; the cloud emits thermally while it expands adiabatically.



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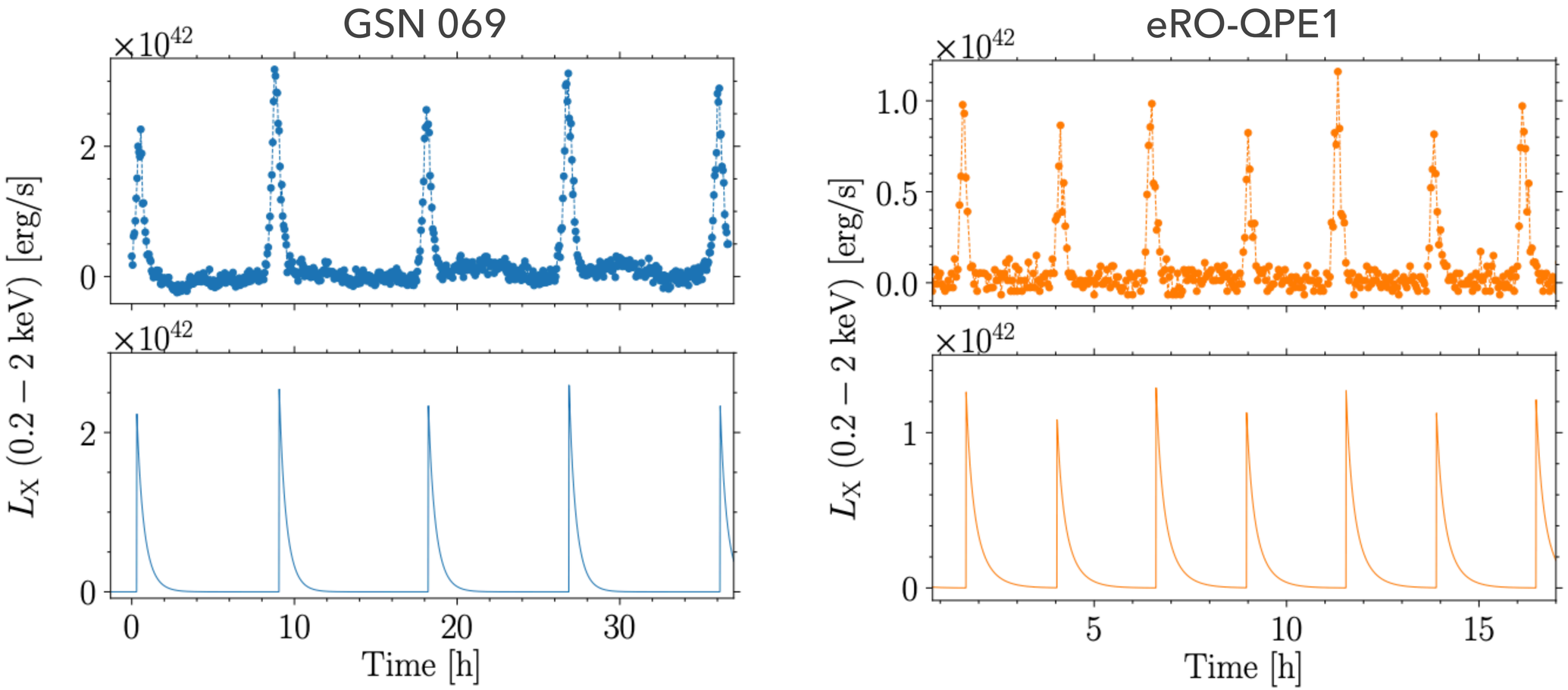
Franchini, Bonetti, et al., 2023, A&A in press, arXiv:2304.00775

Results:



Very good results for timing properties, fair results for QPE amplitudes and temperatures

QPEs physical scenarios: secondary-disk impacts in an EMRI

Franchini, Bonetti, et al., 2023, A&A in press, arXiv:2304.00775

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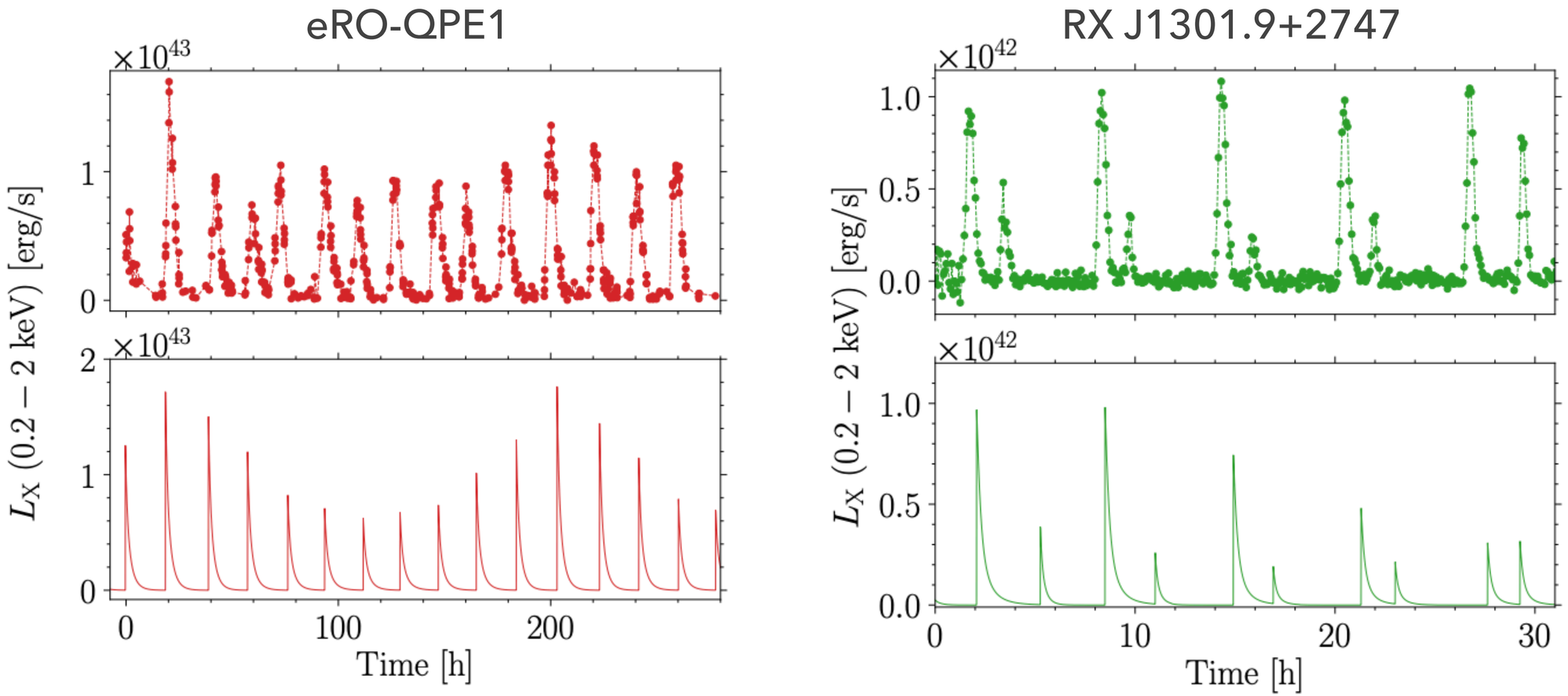
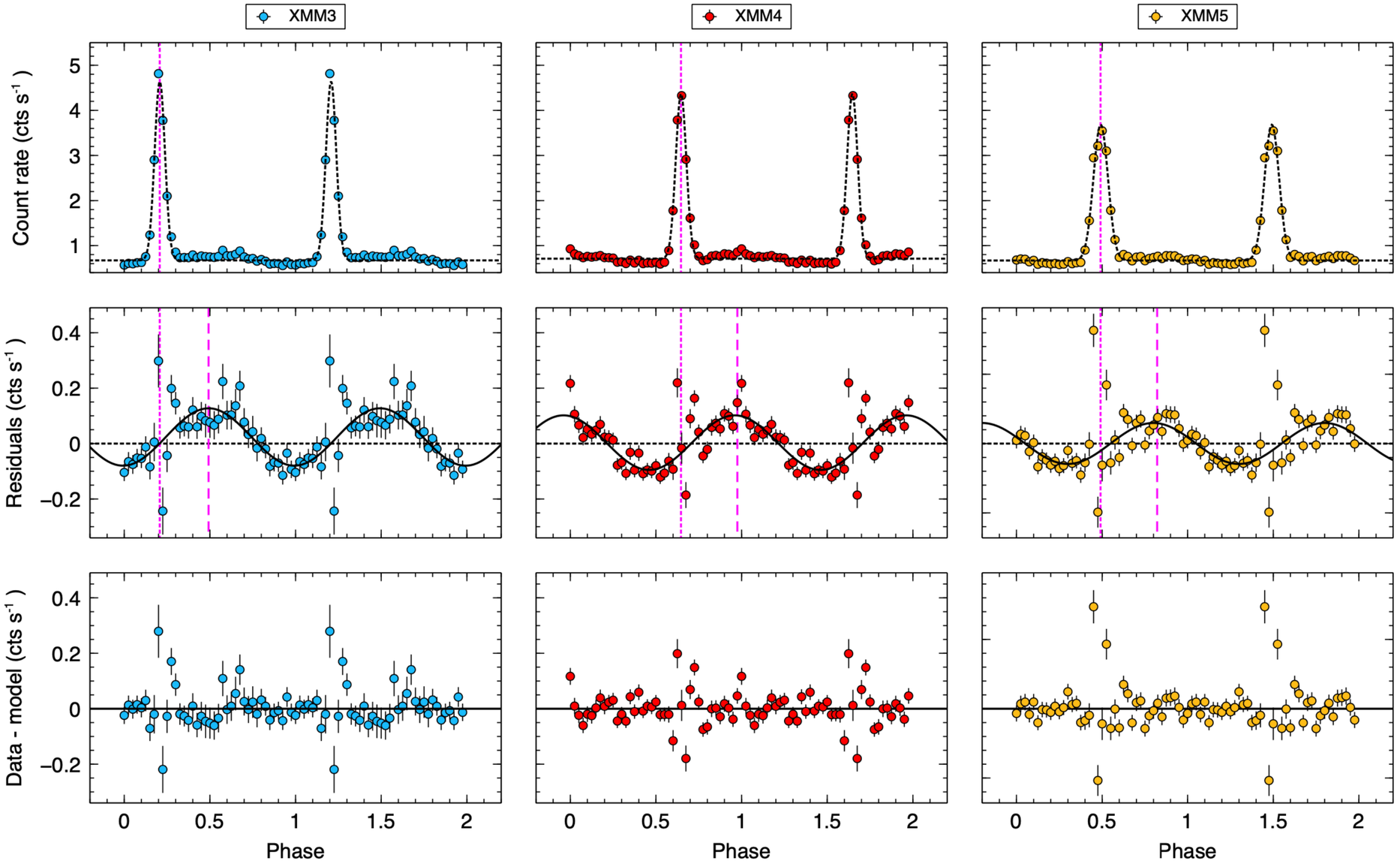


Very good results for timing properties, fair results for QPE amplitudes and temperatures

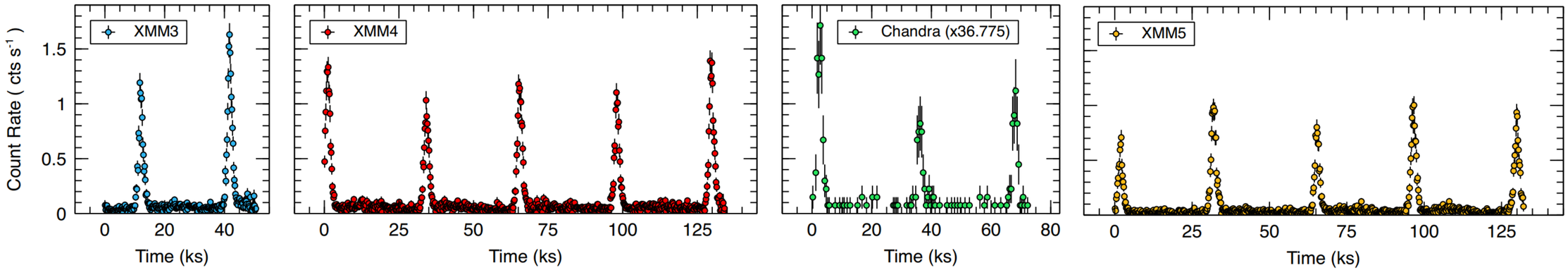
(Many) more complexities

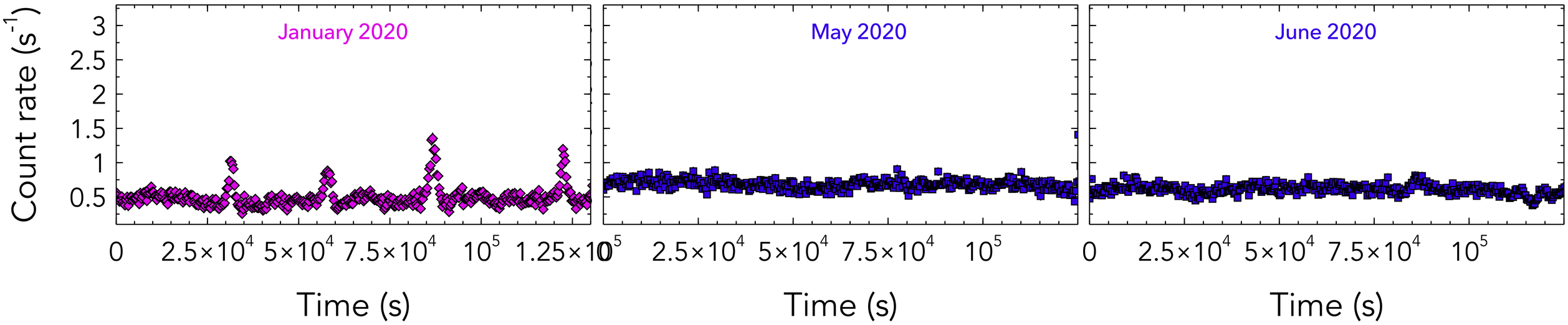
GSN 069's complexities



Quasi-periodic oscillations of the quiescent emission

GSN 069: are QPEs gone?

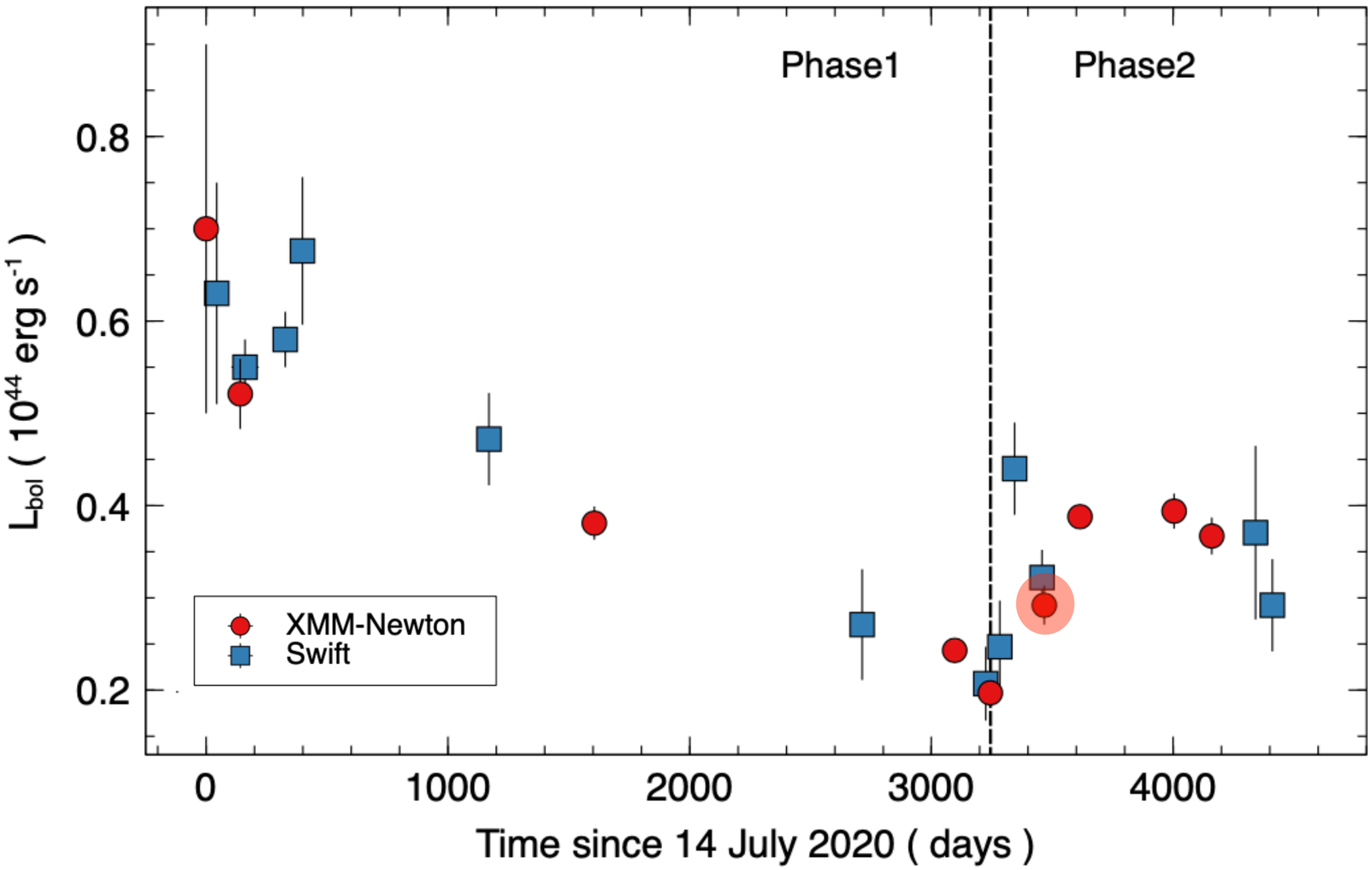




XMM-Newton 2020 observations of GSN 069: QPEs are much weaker in January, while no QPEs are evident during the 130 ks-long observations of May/June.

GSN 069: rebrigthening of the quiescent emission

Last observation where QPEs were detected

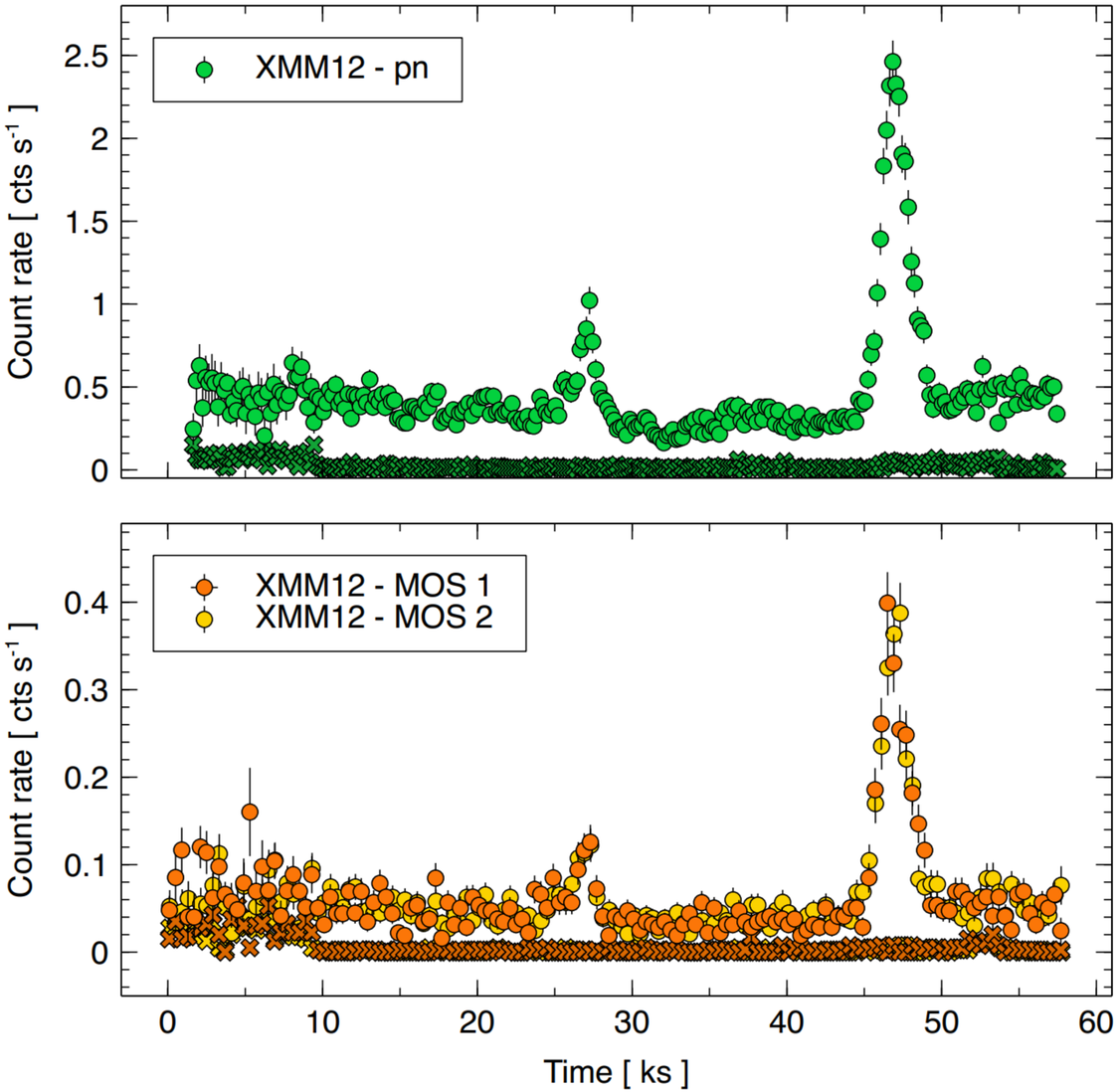


QPEs are last detected at the beginning of a new rising phase?

GSN 069: QPEs are back

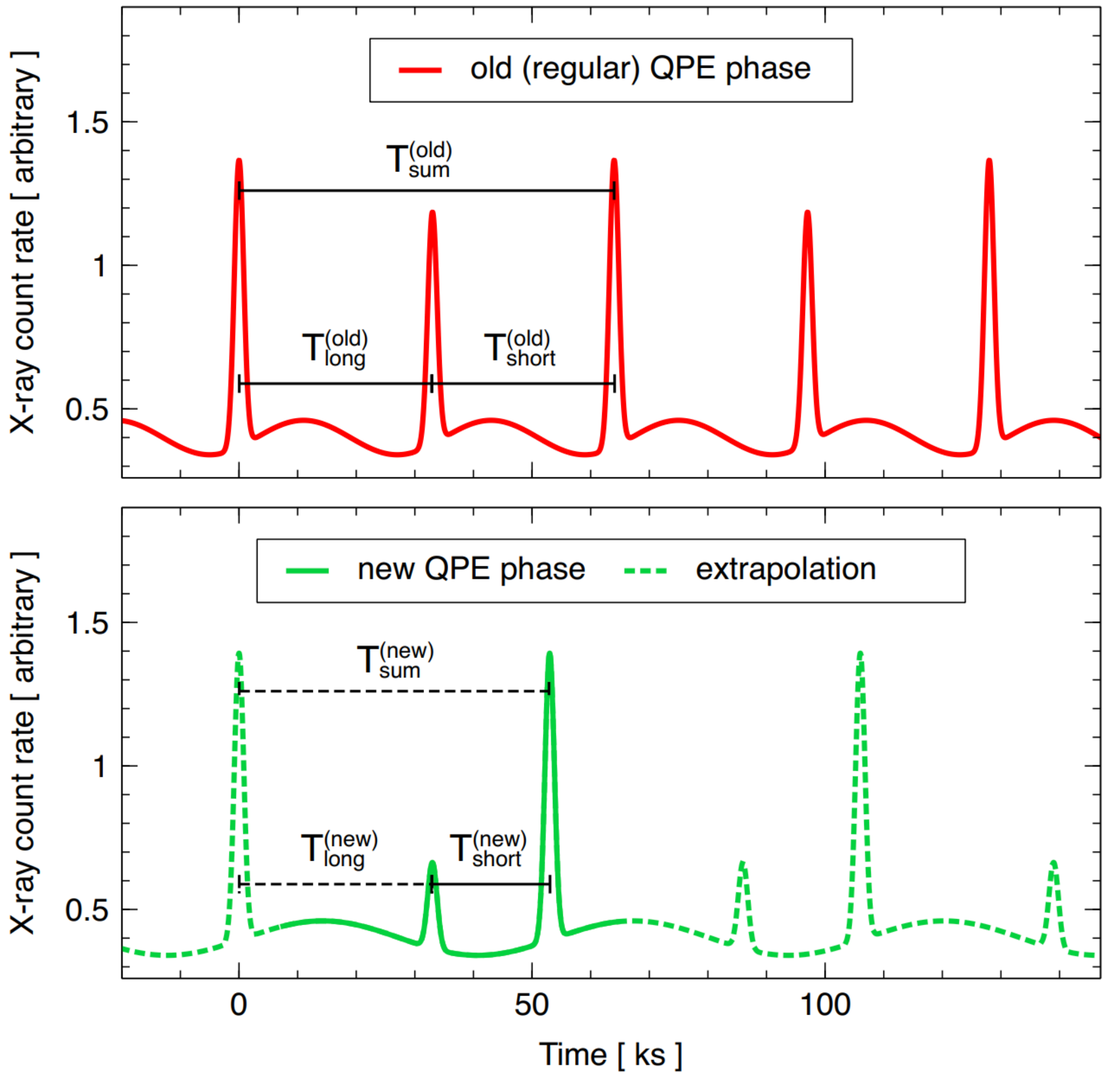
07 June 2022

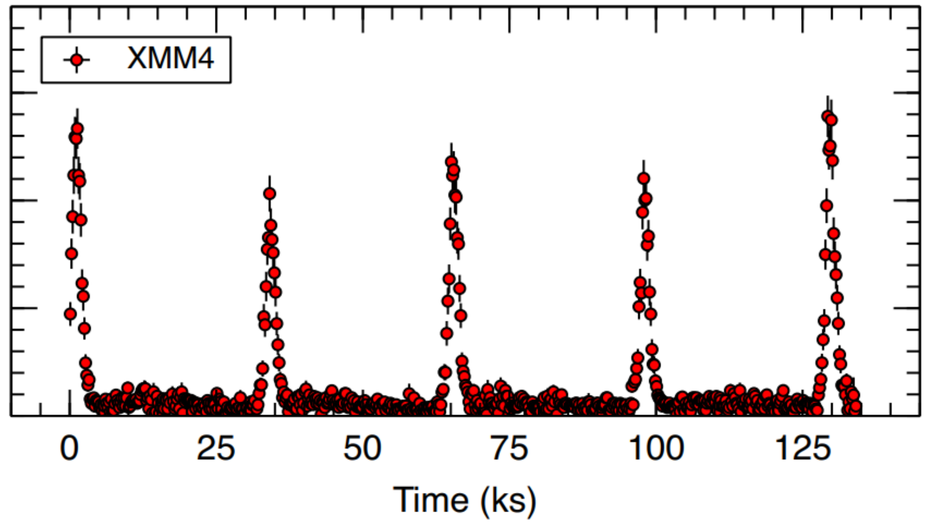
Miniutti et al. 2023, A&A 674, 1

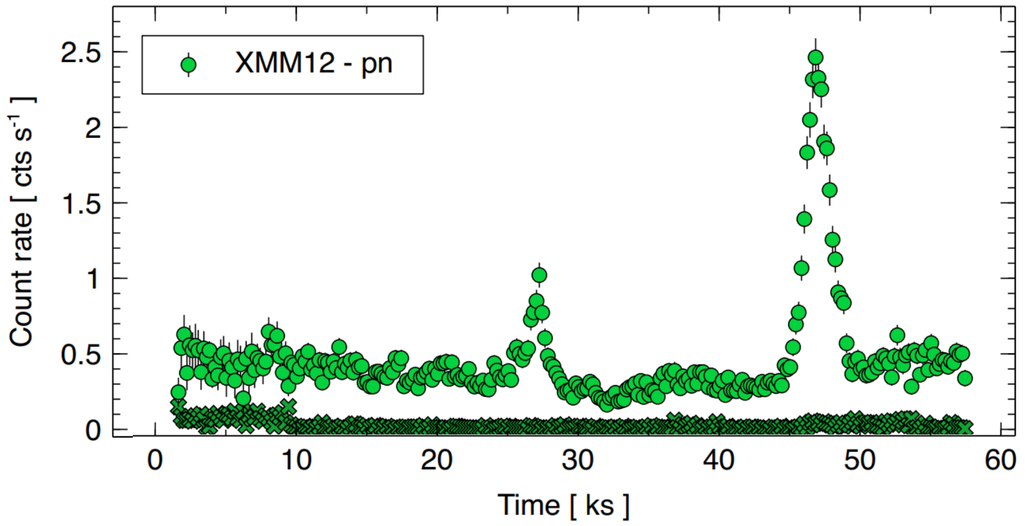


QPEs are back – with different properties?

GSN 069: QPEs are back



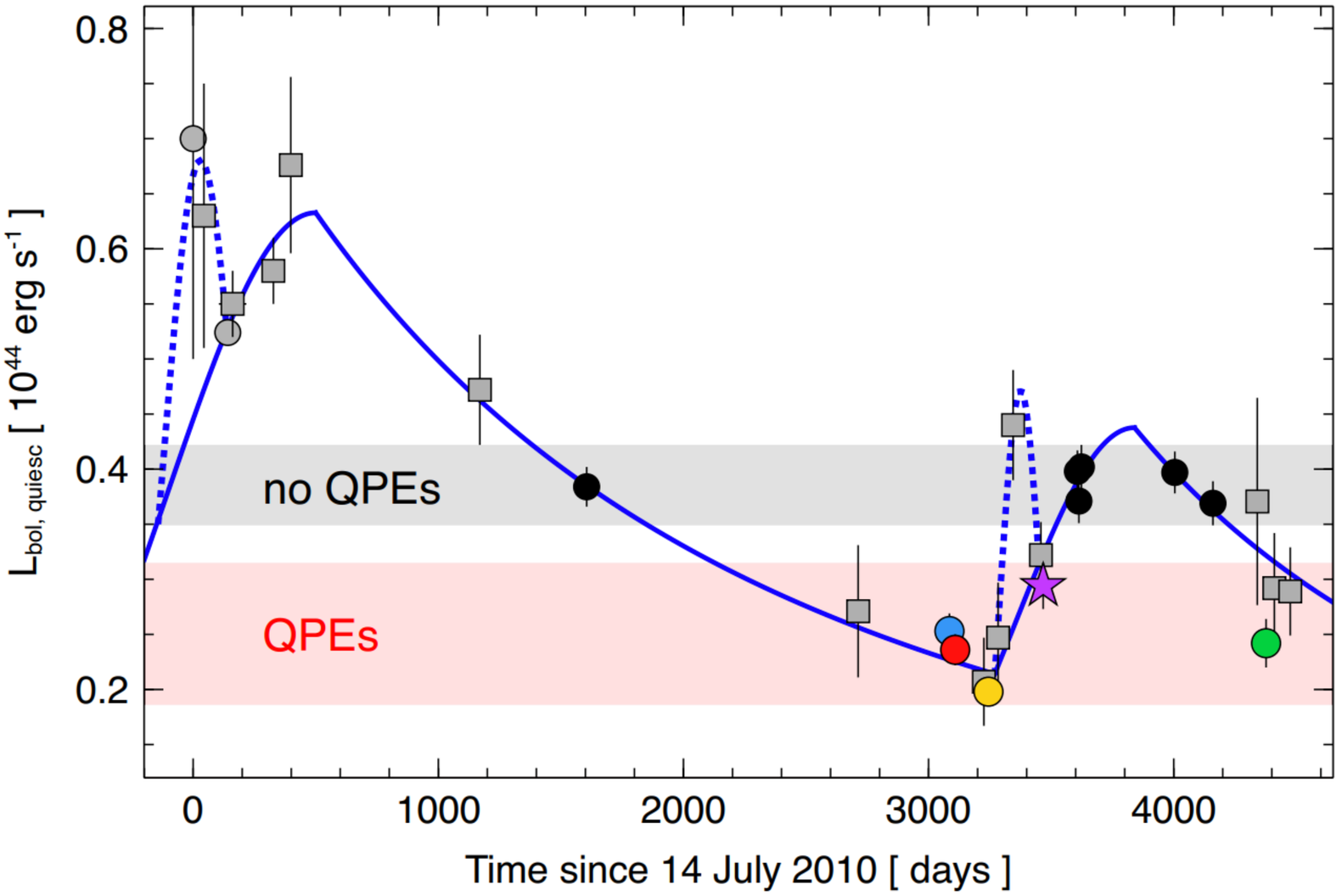




A shorter new period?

Miniutti et al. 2023, A&A 674, 1

GSN 069: QPEs are back

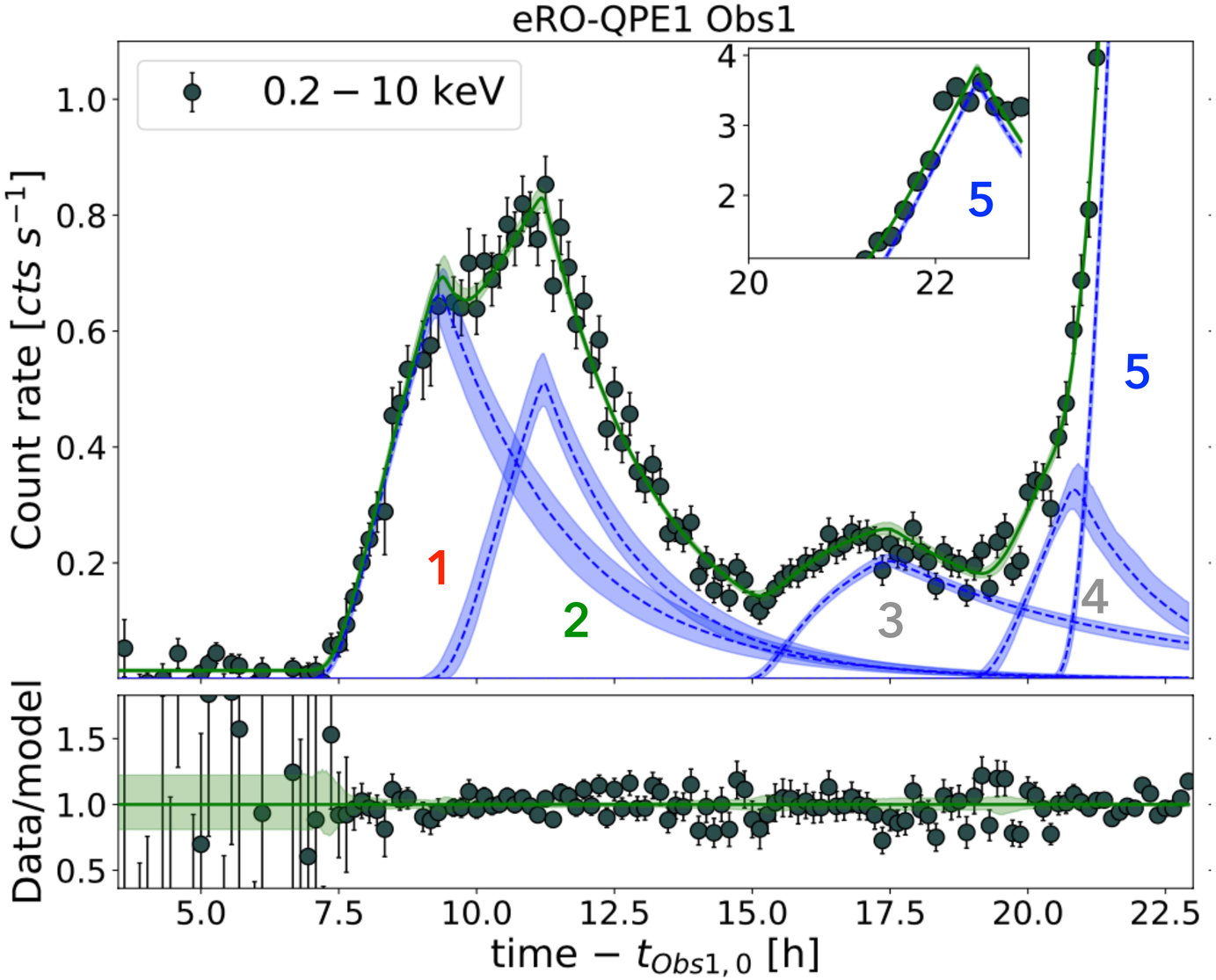


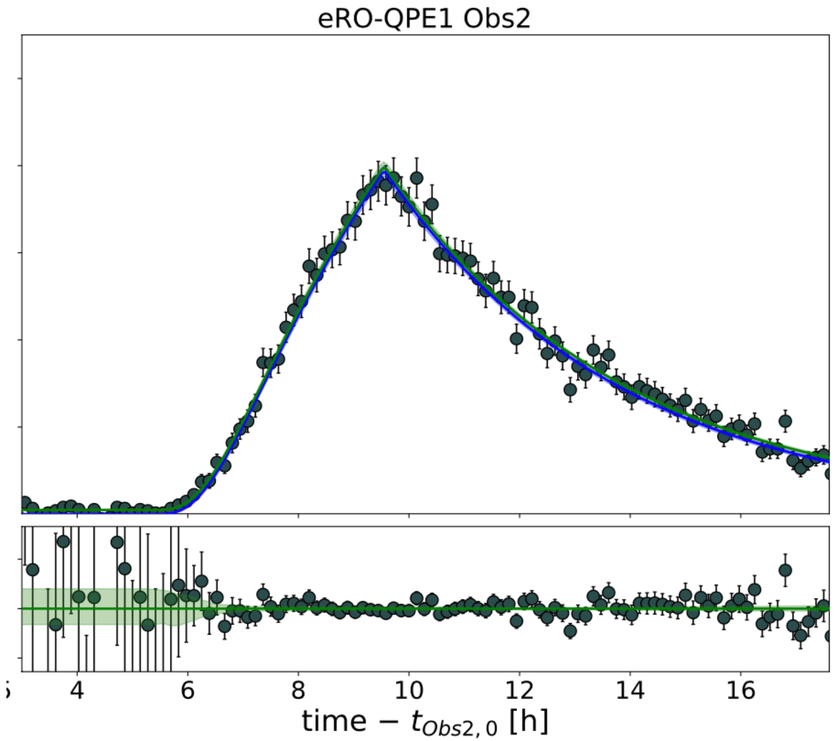
A luminosity threshold for QPEs?

Miniutti et al. 2023, A&A 674, 1

eRO-QPE1's complexities

Multiple bursts of different amplitude, partially overlapping…



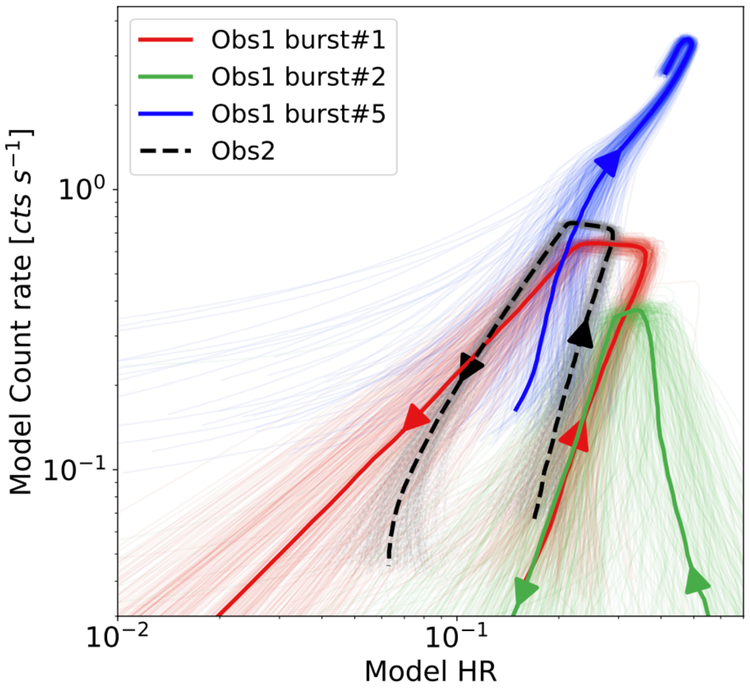


…but not always.

Arcodia et al. 2022, A&A 662, 49

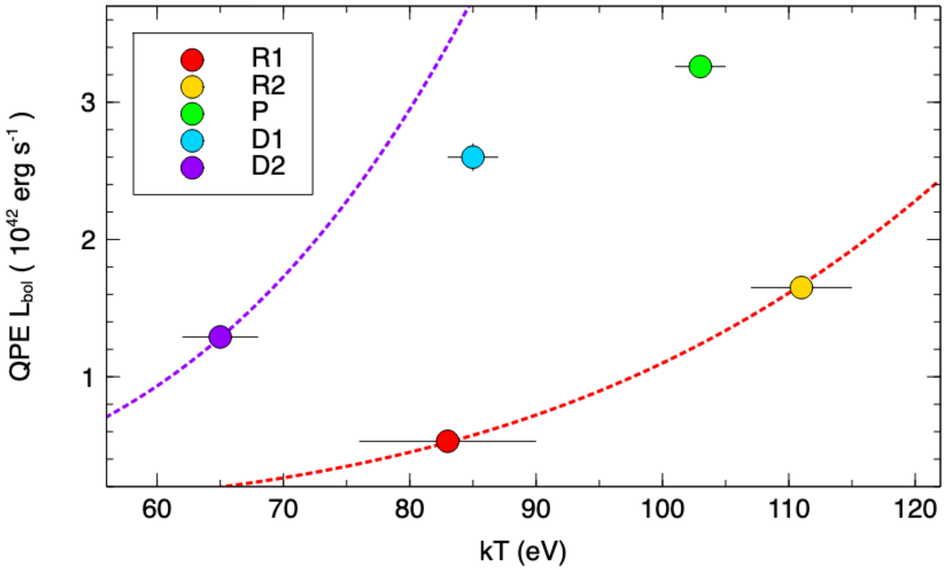
The QPE spectral evolution is chromatic

eRO-QPE1



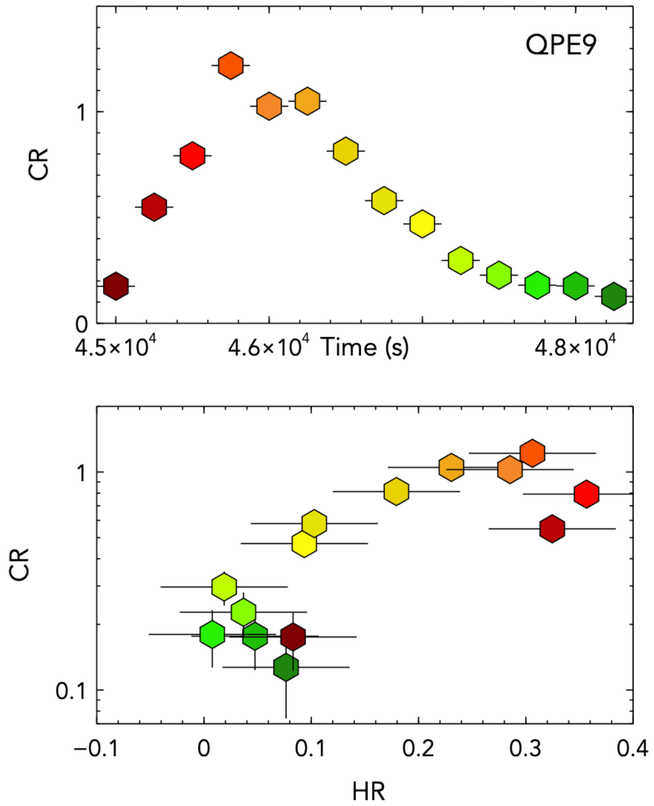
Arcodia et al. 2022, A&A 662, 49

GSN 069



Miniutti et al. 2023, A&A 674, 1

J1301.9+2747

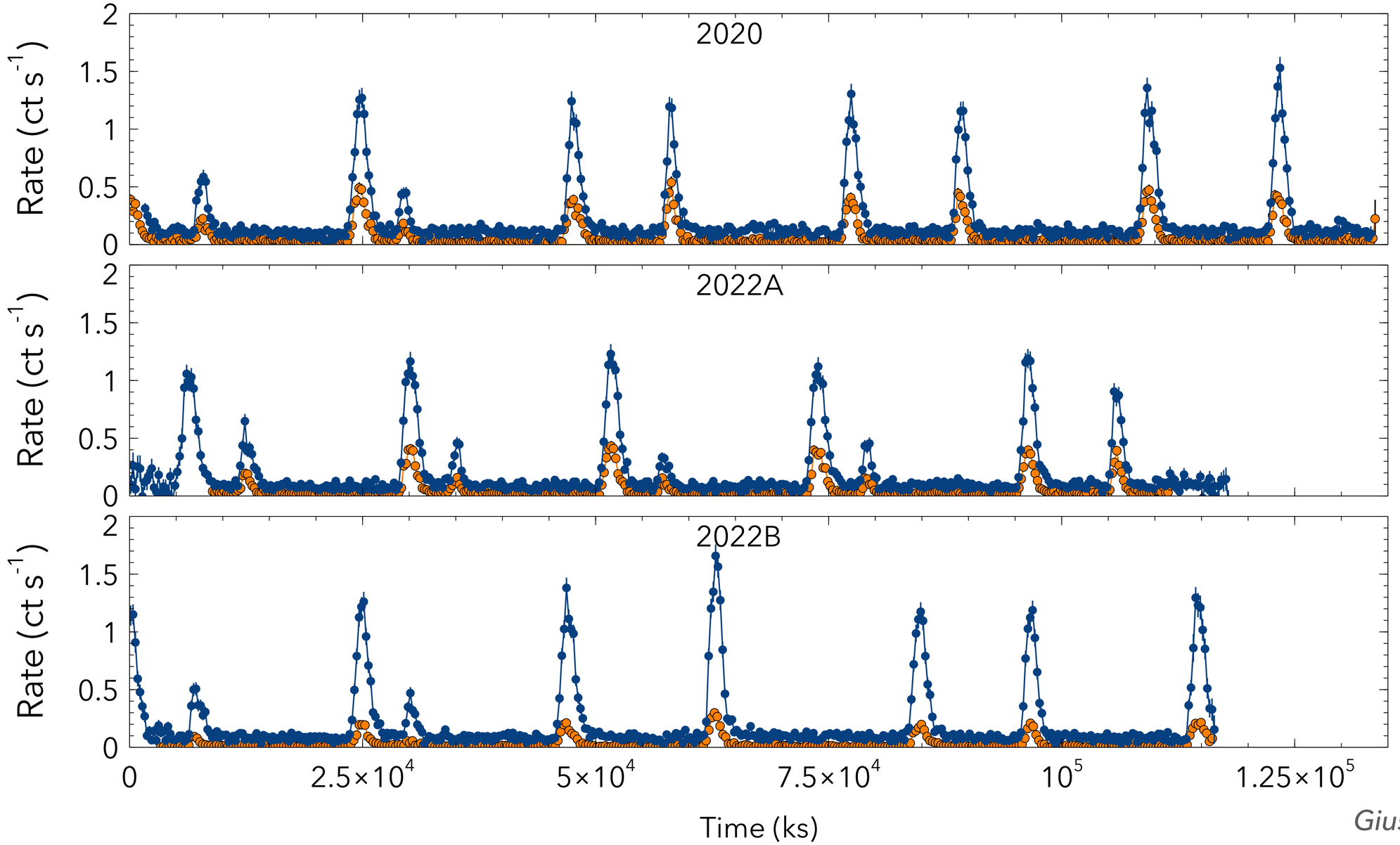


Giustini et al. in prep.

Harder QPE rise, softer QPE decay

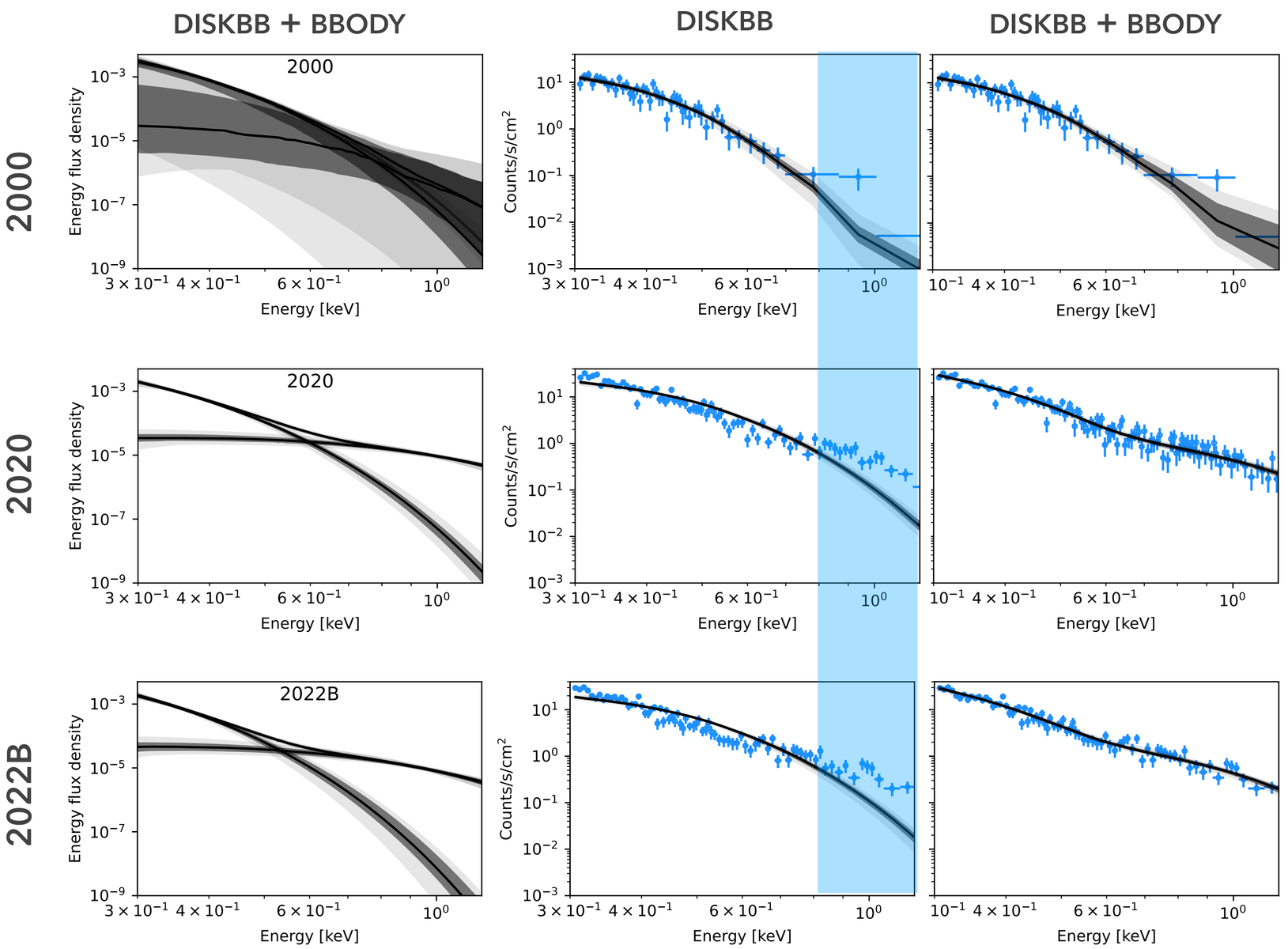
(QPEs last less at high energies)

RX J1301.9+2747: not a single repeating T_{rec}

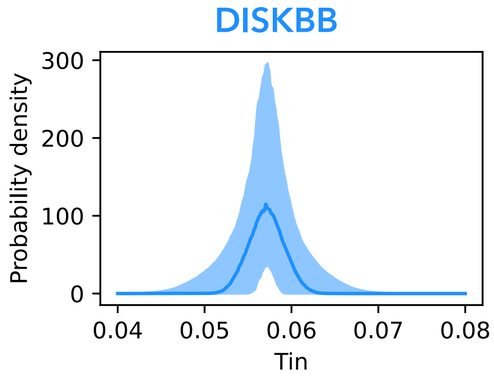


Giustini et al. in prep.

RX J1301.9+2747: soft X-ray excess development?

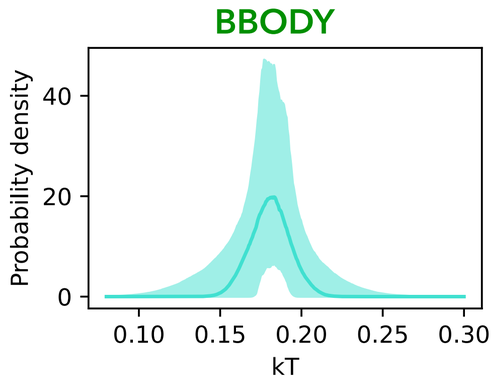


kT (BBODY) >> kT(DISKBB)



kT ~ 58 eV

L ~ 10^{41} erg/s

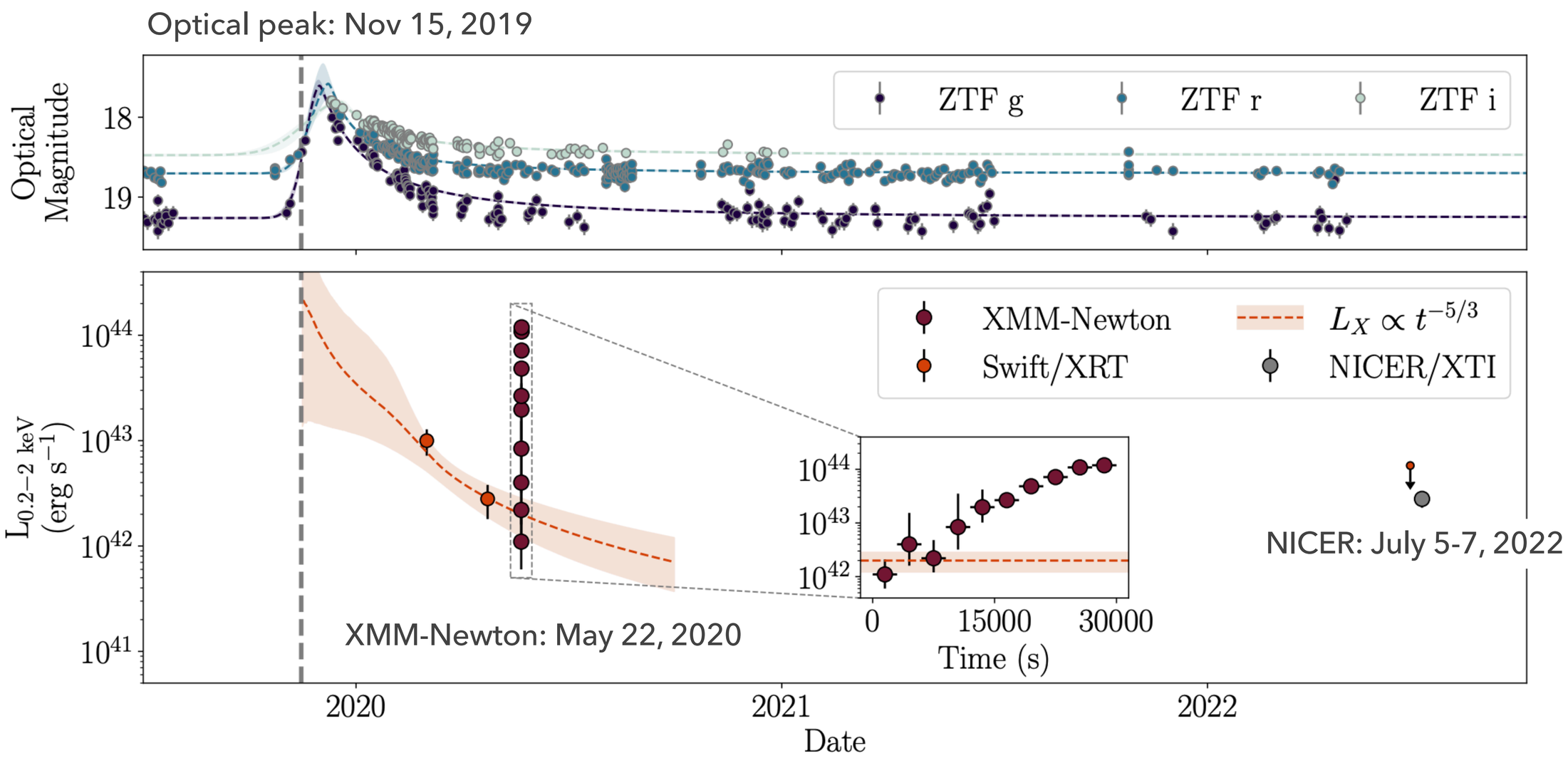


kT ~ 180 eV

L ~ 2 x 10^{40} erg/s

Giustini et al. in prep.

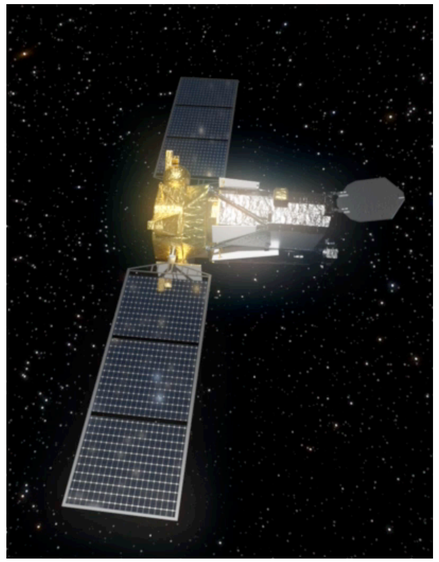
Tormund's complexities



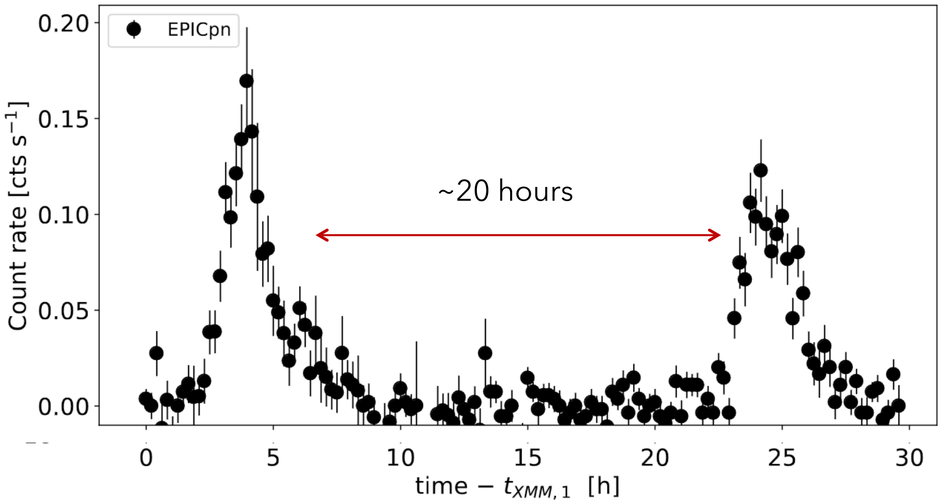
NICER detection ~ 900 days after the TDE optical peak

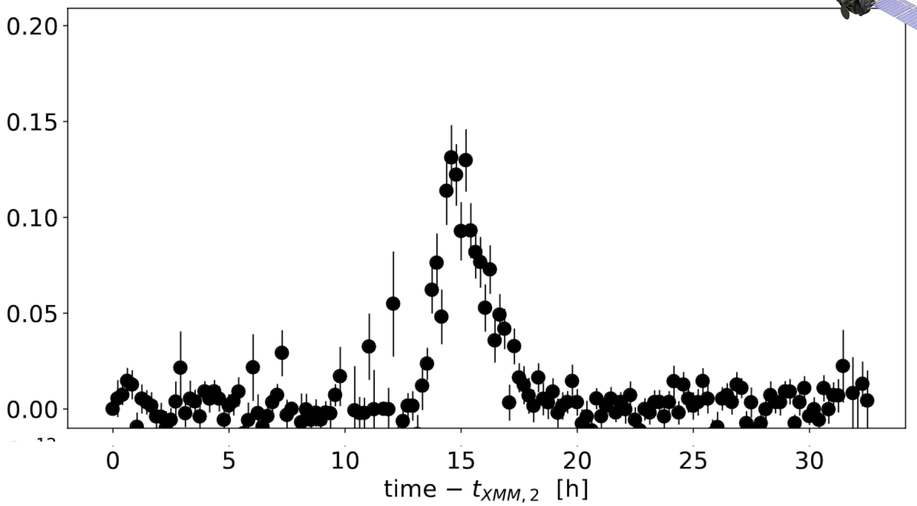
The Future

Future: new QPEs discovered by eROSITA

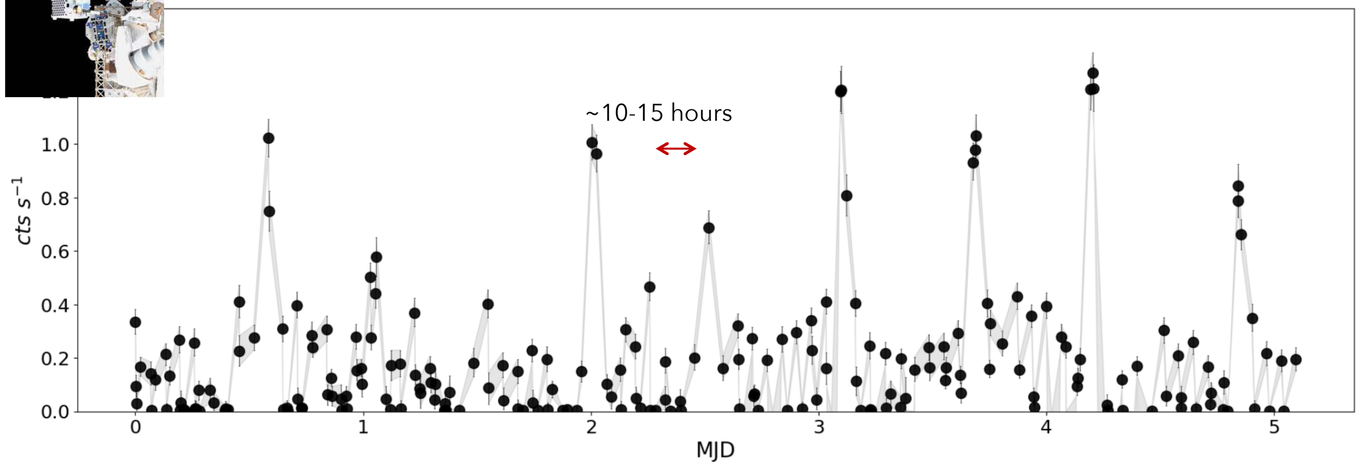


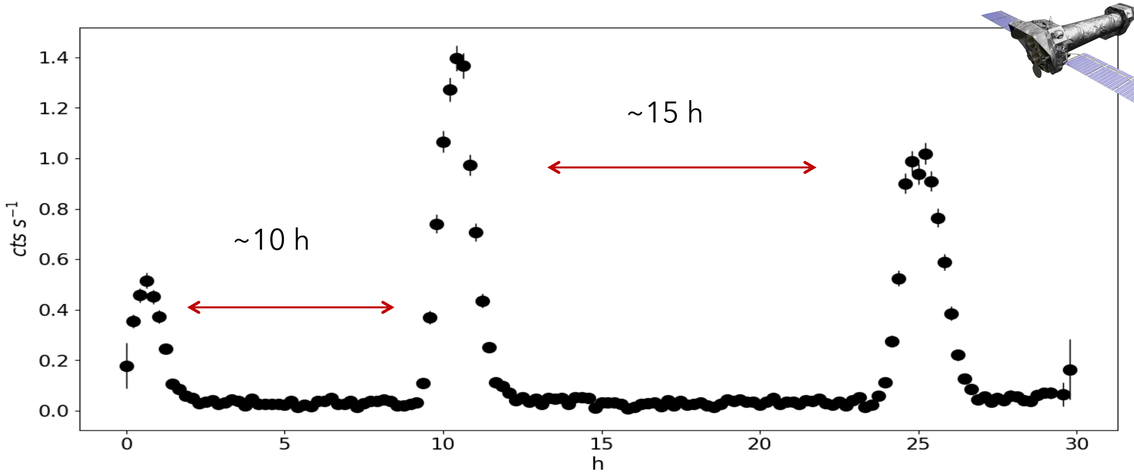
eRO-QPE3





eRO-QPE4





Courtesy of Riccardo Arcodia

Arcodia+ in prep.

The future

- X-ray observations are undergoing, both short monitoring and long staring ones
- Is there any QPE-like emission at other wavelengths? Under investigation
- HST proposals to resolve the BLR – if present – and study the nuclear properties
- VLT/MUSE proposal to image the galactic environment
- Unveiling the activation mechanism of small galaxies?
- Measure the BH spin independent of spectral modelling?
- Multi-messenger observations from space during the next decade?