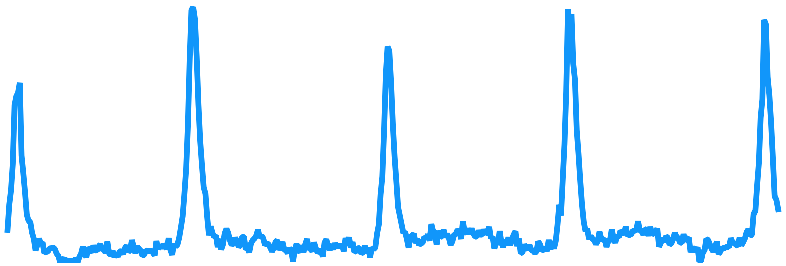
X-ray Quasi-Periodic Eruptions:

a potential electromagnetic counterpart of extreme mass ratio inspirals



Margherita Giustini

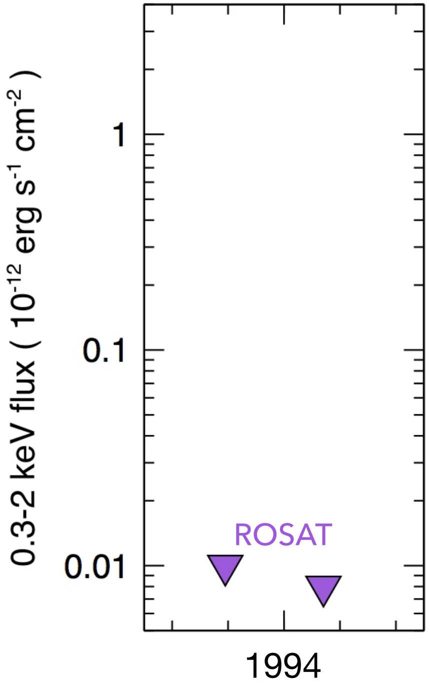
Centro de Astrobiología (CAB), CSIC-INTA

with Giovanni Miniutti, Riccardo Arcodia

and Joheen Chakraborty, Erwan Quintin, Richard Saxton,

Erin Kara, Natalie Webb, Alessia Franchini, Matteo Bonetti, et al.

The discovery of QPEs

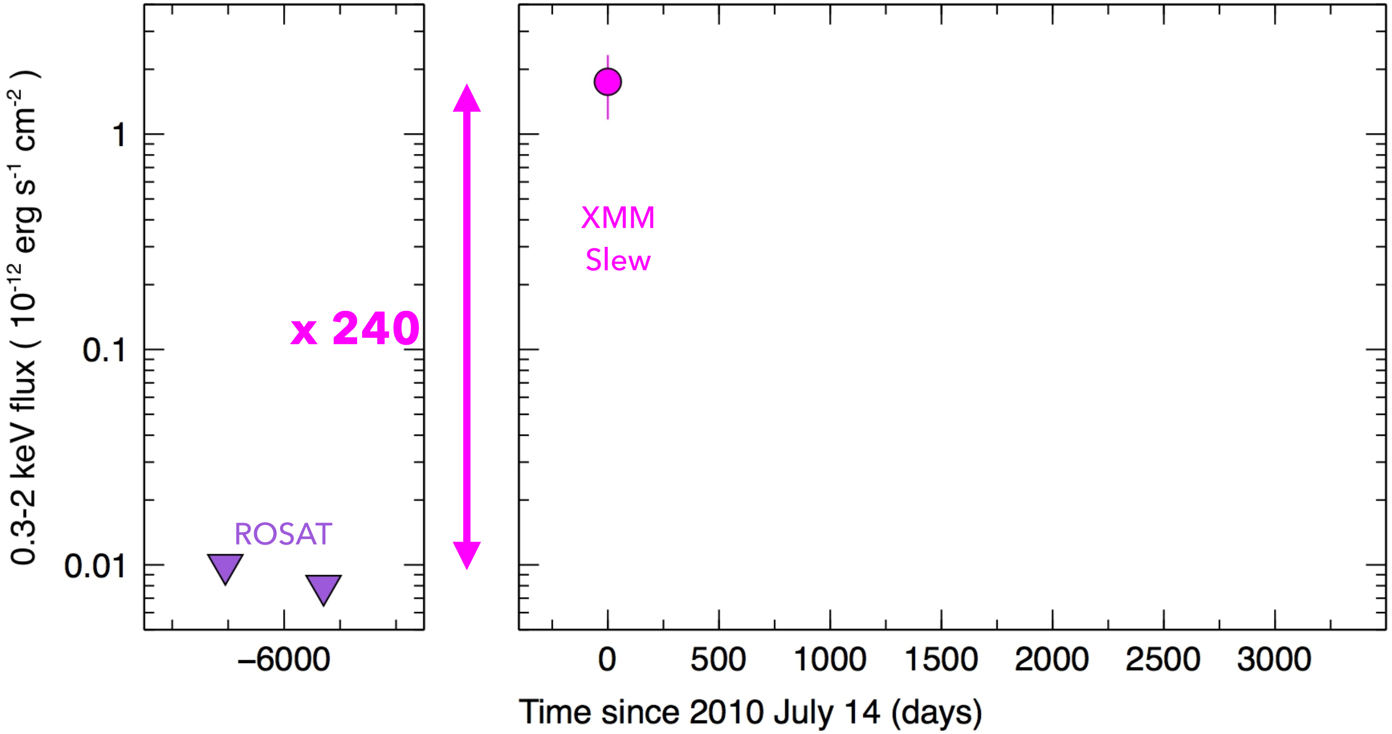


GSN 069

redshift z = 0.018

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

The discovery of QPEs



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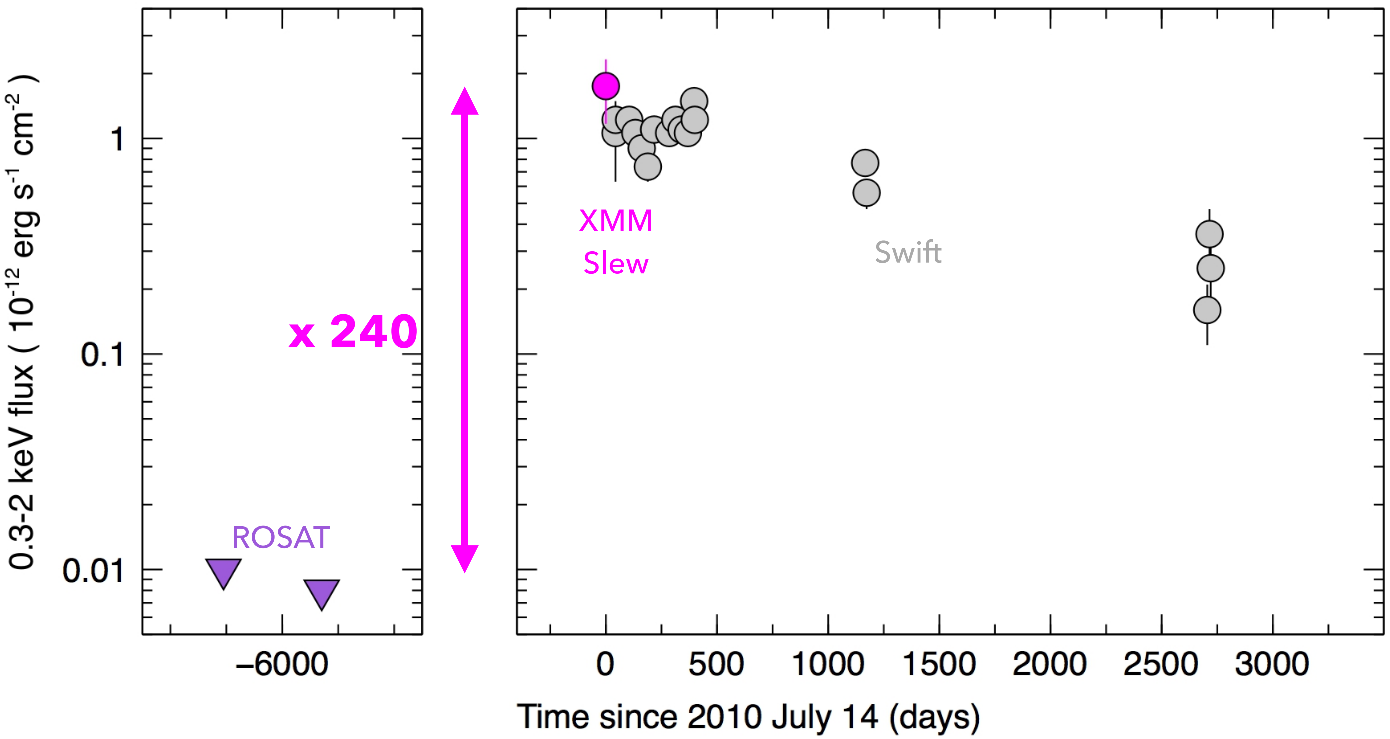
The discovery of QPEs



GSN 069
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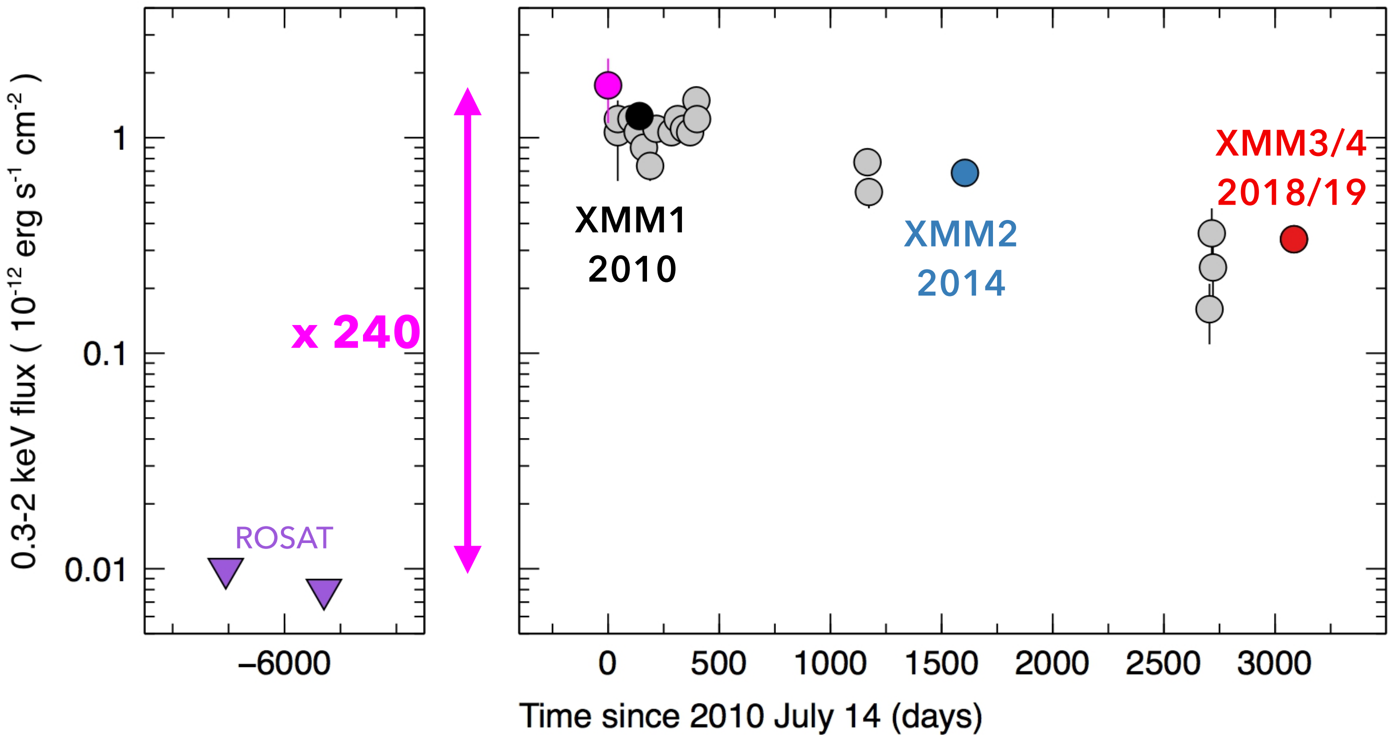
- Long-term slow decay in flux: red giant TDE?
- Low C/N ratio consistent with such a pTDE

Sheng et al. 2021, ApJ 920, 25

The discovery of QPEs



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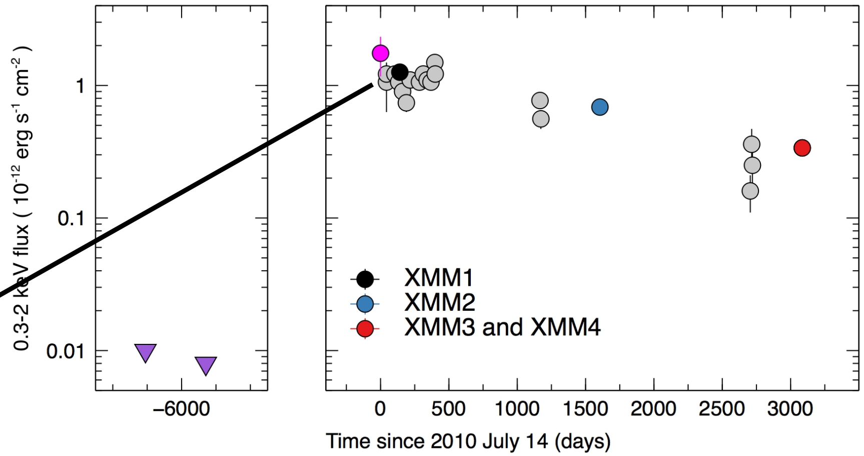
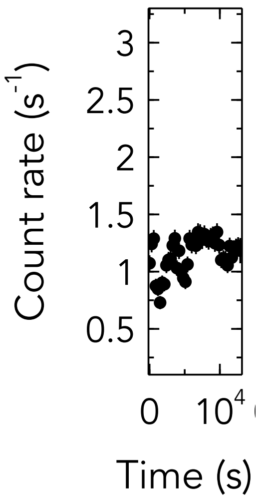


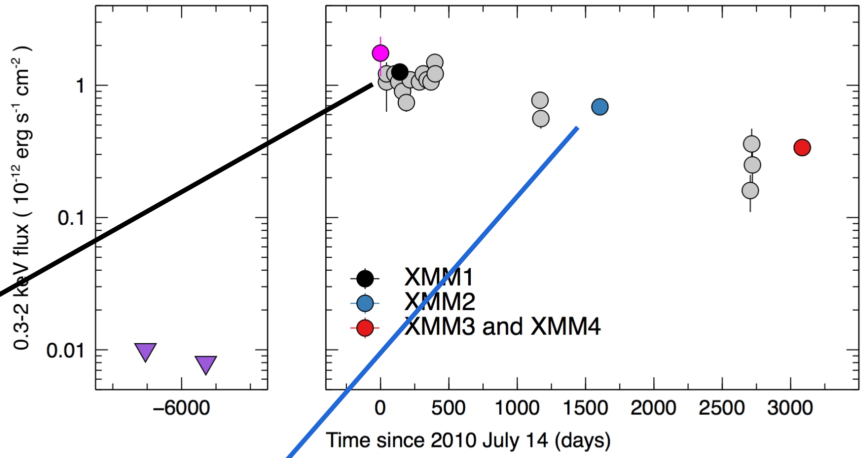
GSN 069

redshift z = 0.018

2010



The discovery of QPEs

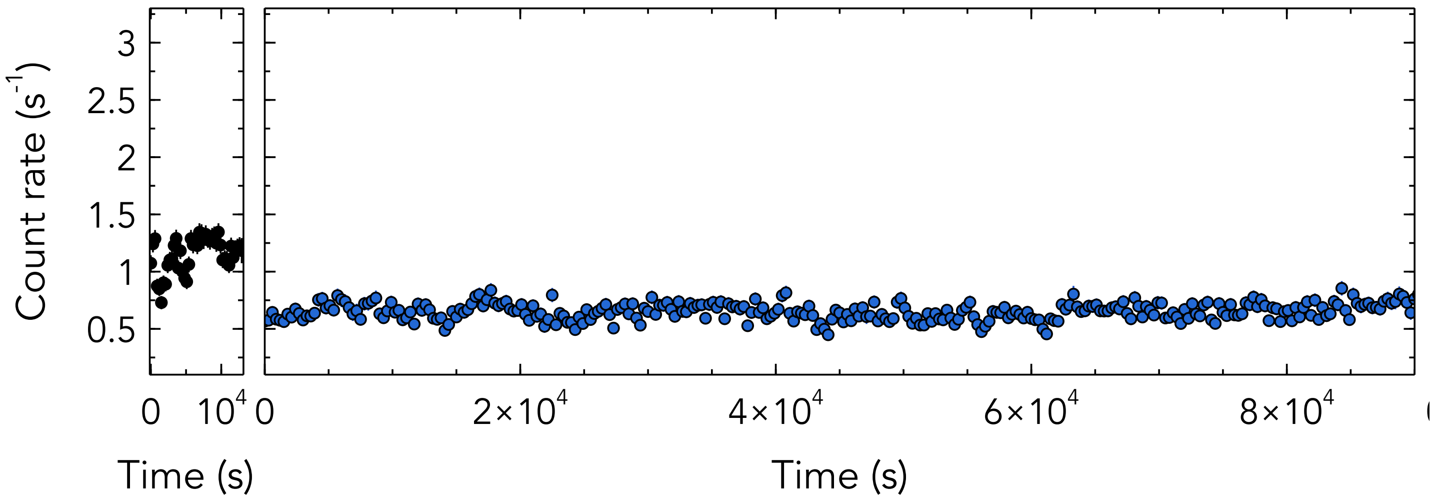


GSN 069

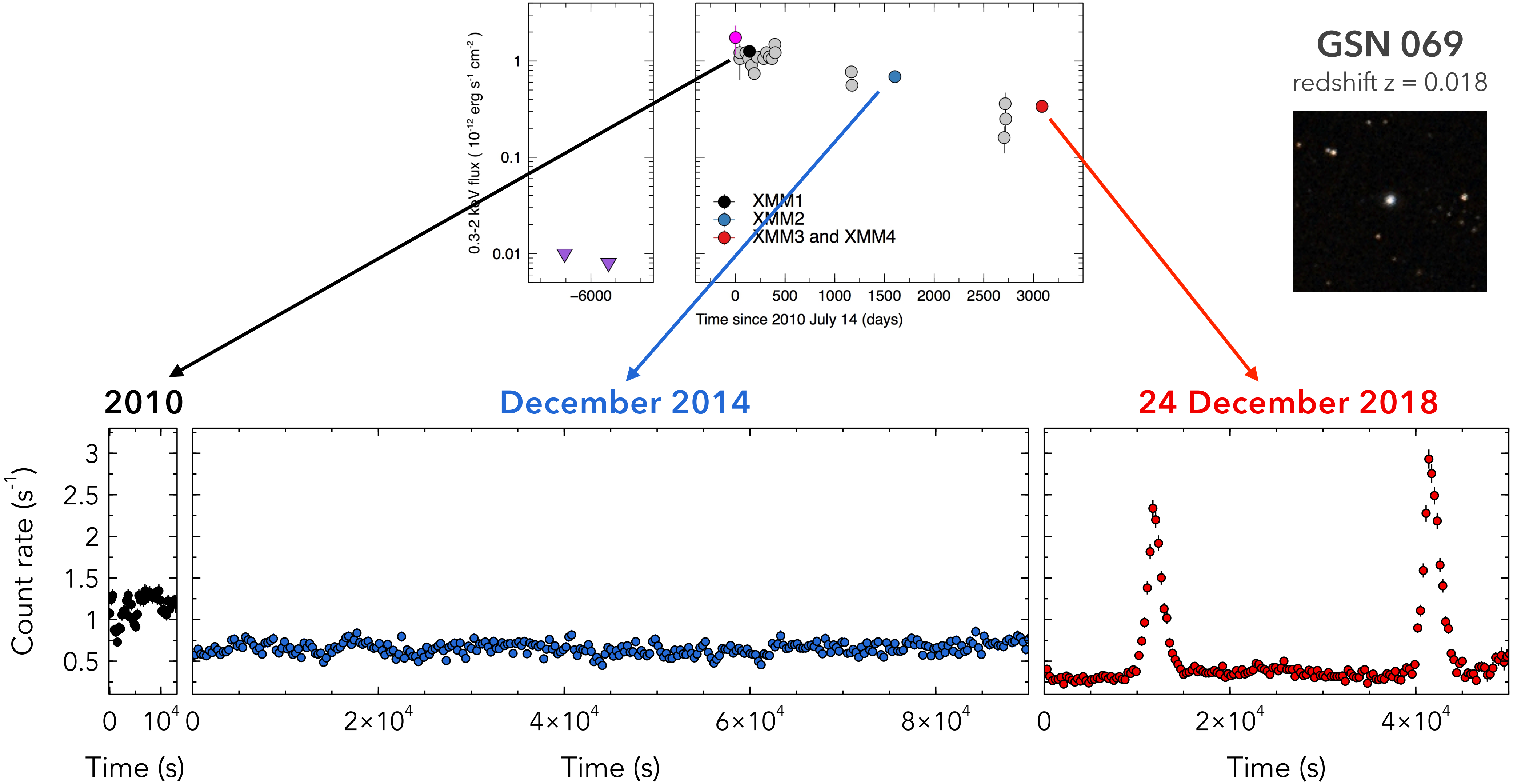
redshift z = 0.018

2010

December 2014

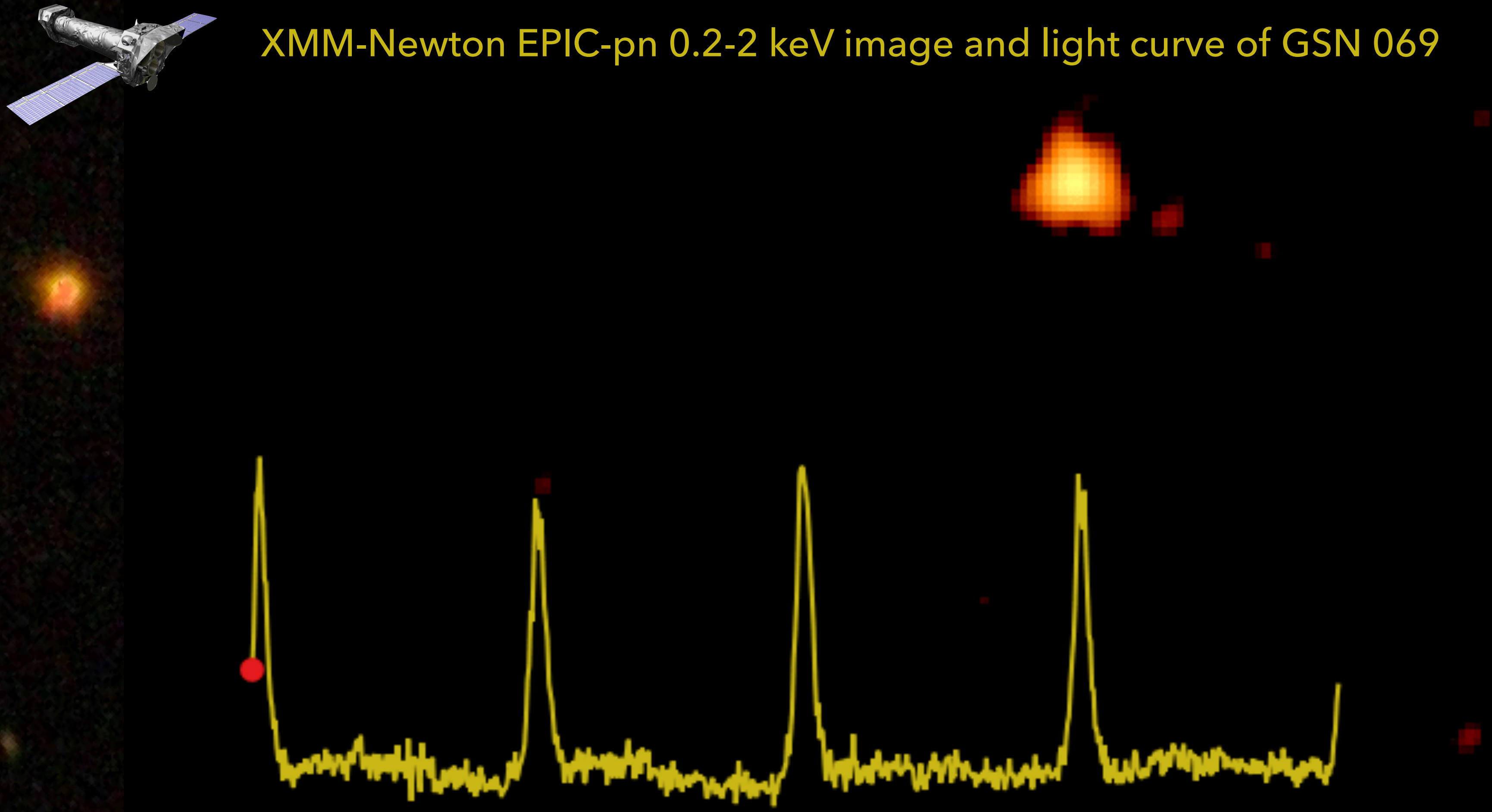


The discovery of QPEs



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

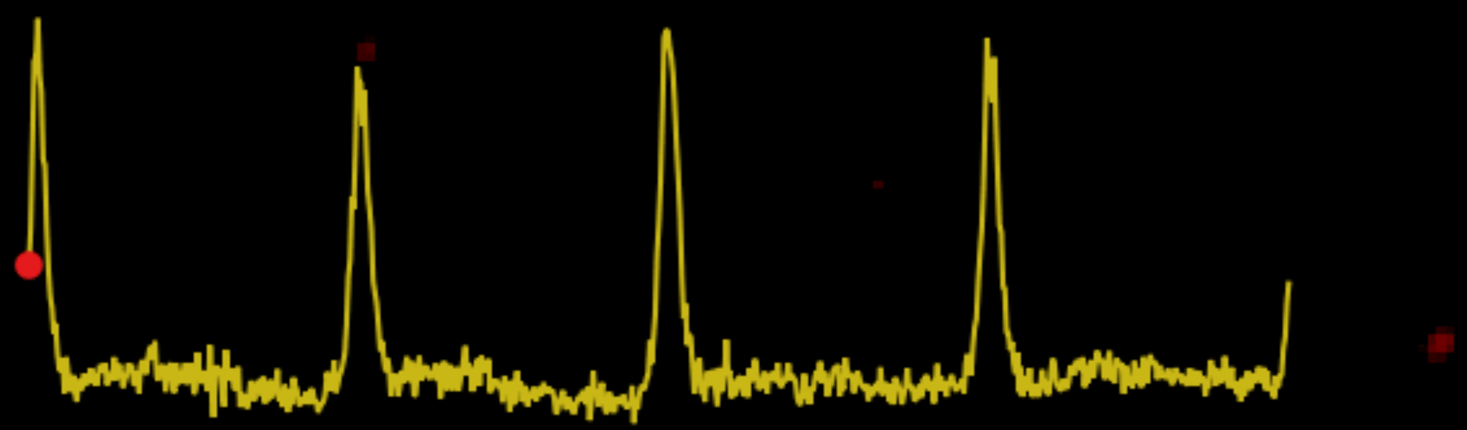
Miniutti et al. 2019, Nature 573, 381

X-ray Quasi-Periodic Eruptions

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

Thermal soft X-ray spectra with kT ~ 50 eV in quiescence, doubling during QPEs

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



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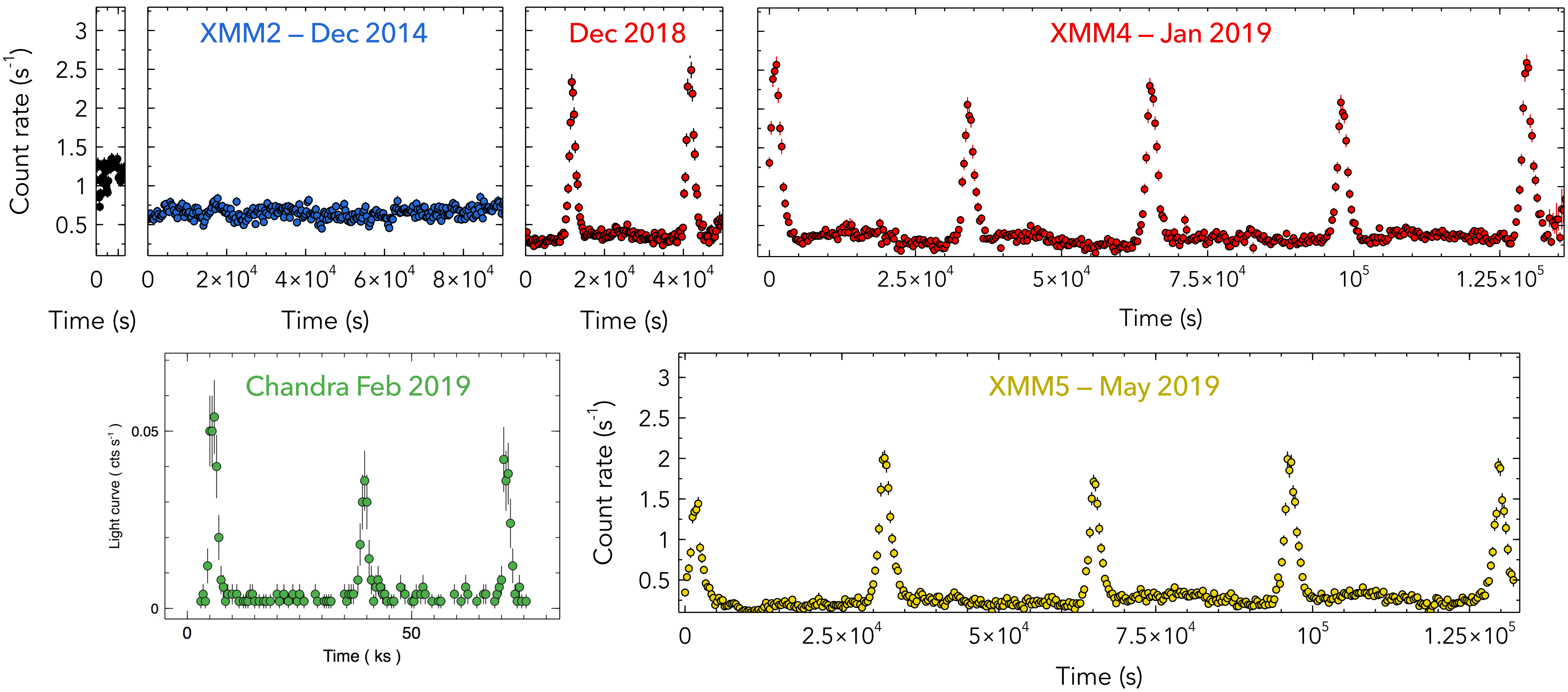
Miniutti et al. 2019, Nature 573, 381

X-ray QPEs in GSN 069



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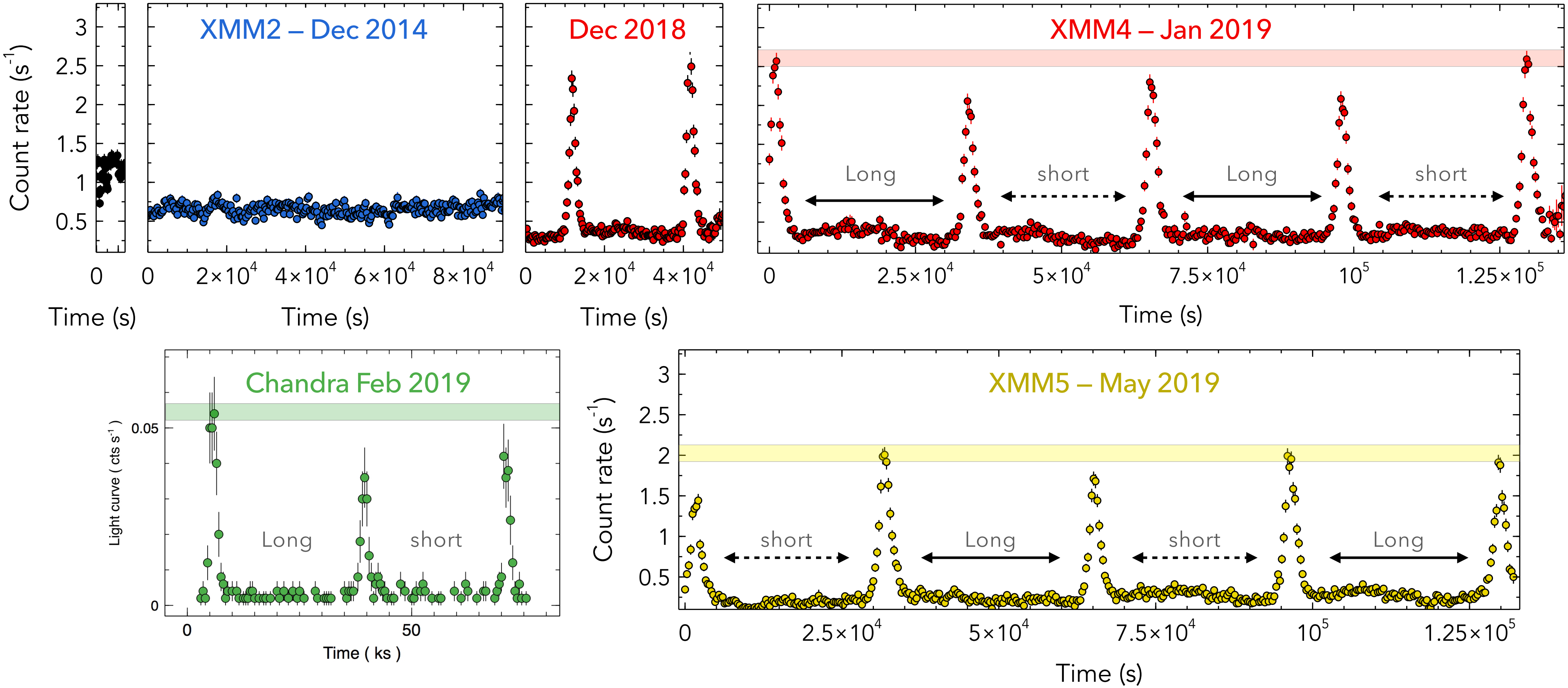
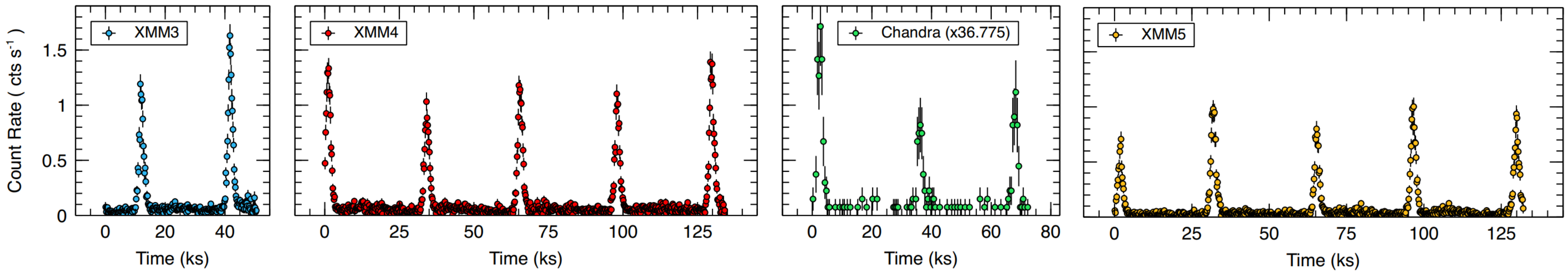
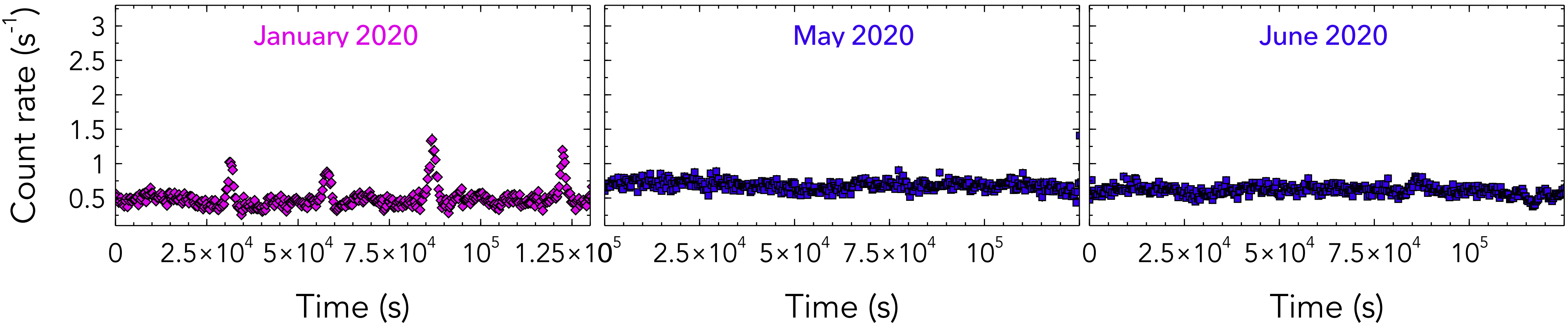


Alternating strong/weak QPE and long/short recurrence time

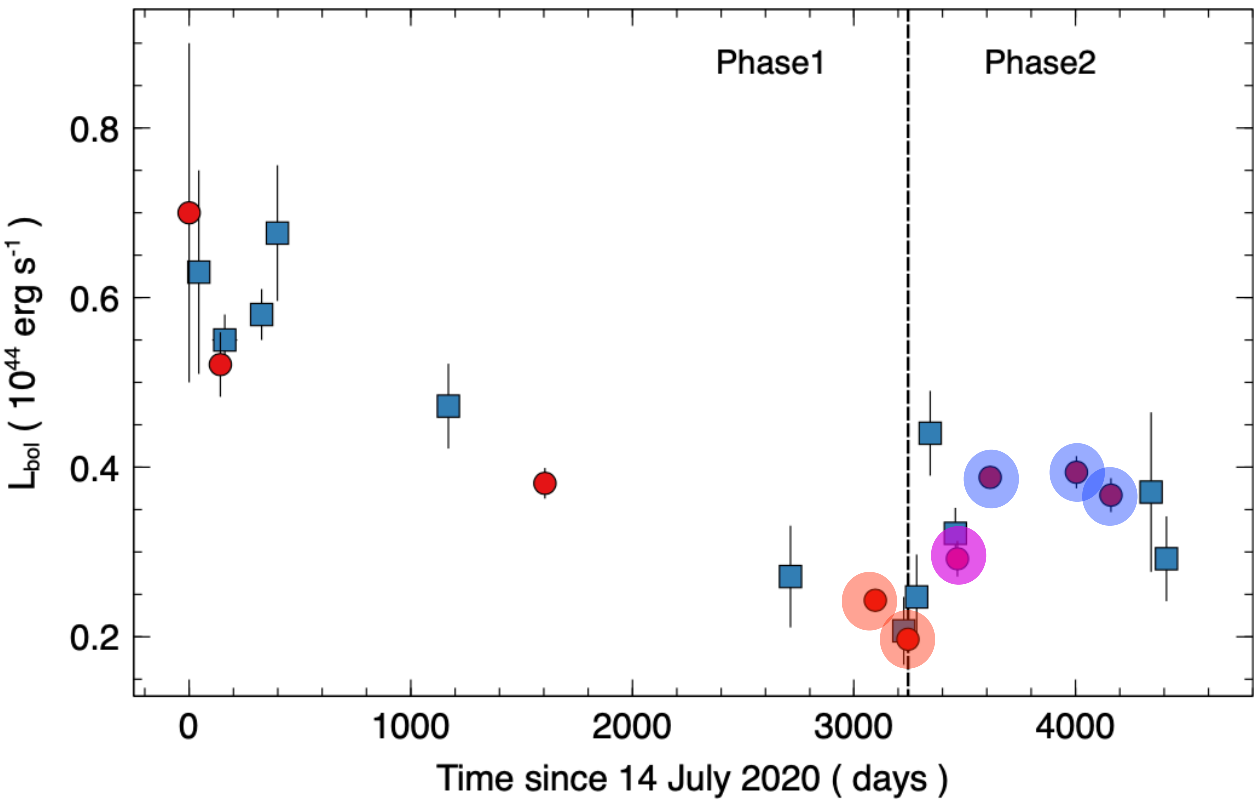
X-ray QPEs in GSN 069

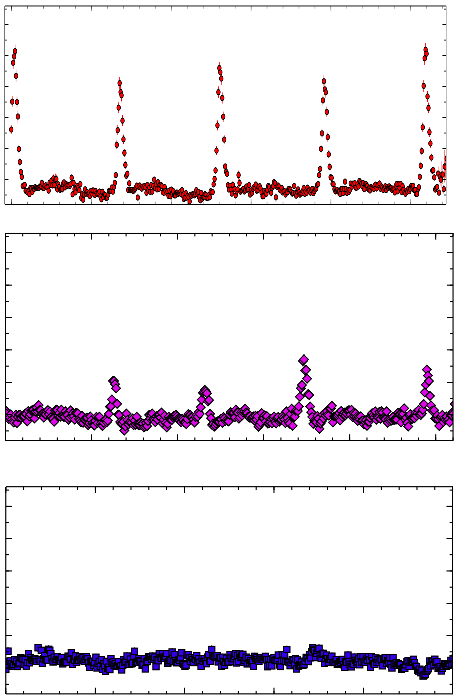




- QPEs are much weaker in January 2020
- No QPEs are evident during the 130 ks-long observations of May/June 2020

X-ray QPEs in GSN 069

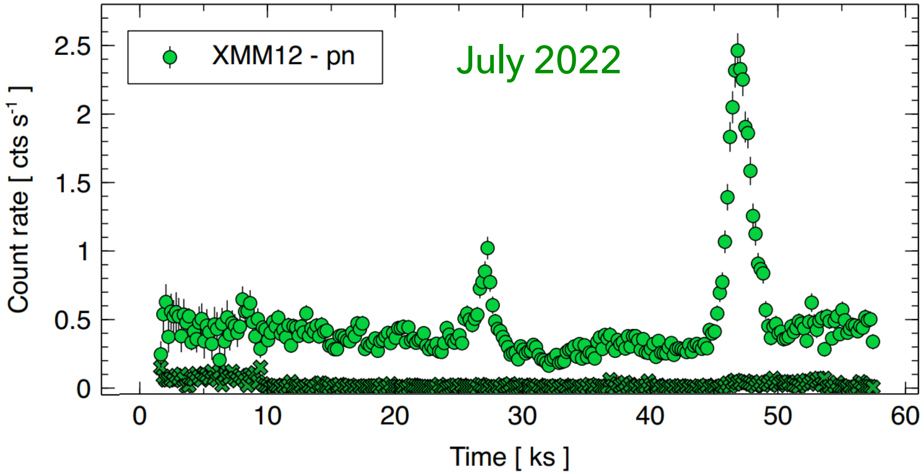




Are QPEs last detected at the beginning of a new rising phase?

X-ray QPEs in GSN 069

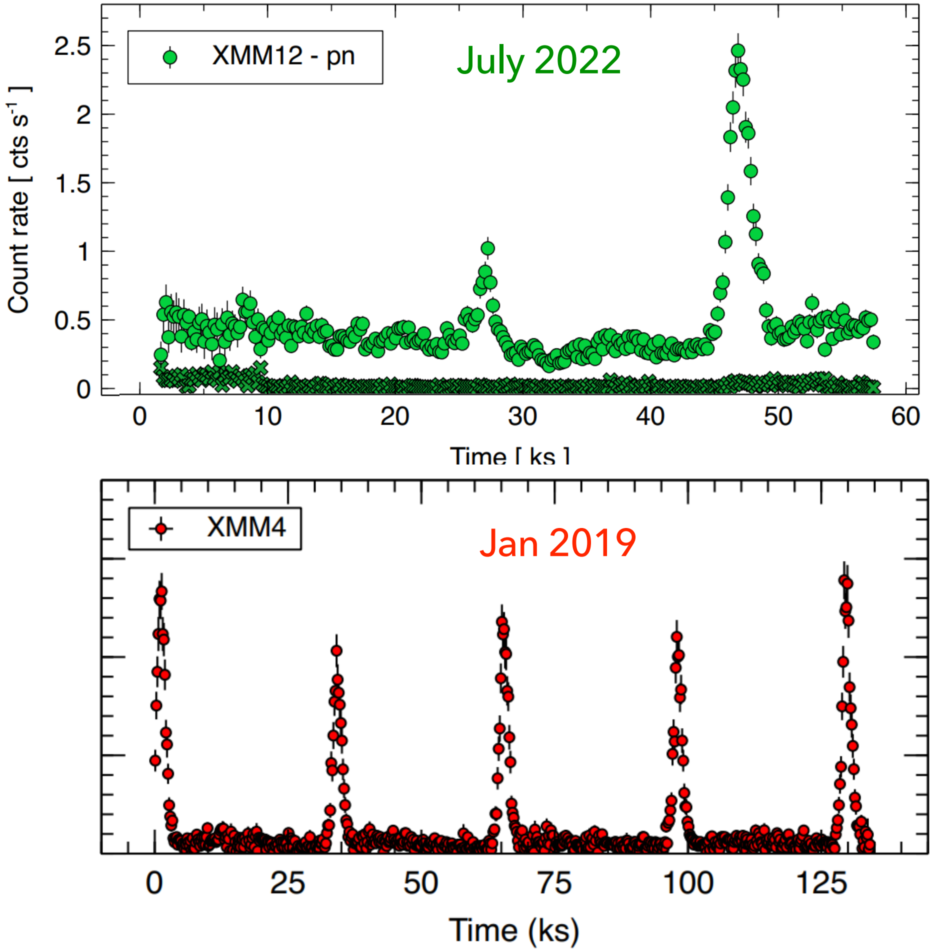
Miniutti et al. 2023, A&A 674, 1

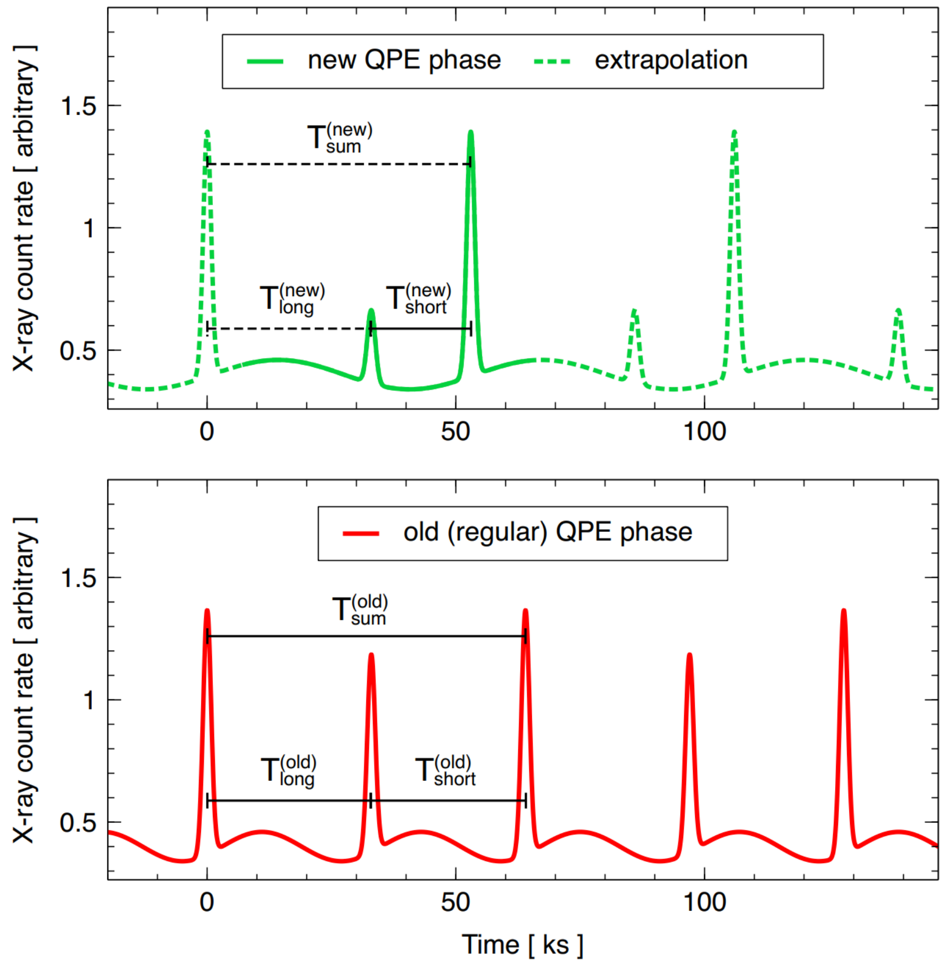


QPEs are back!

X-ray QPEs in GSN 069

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

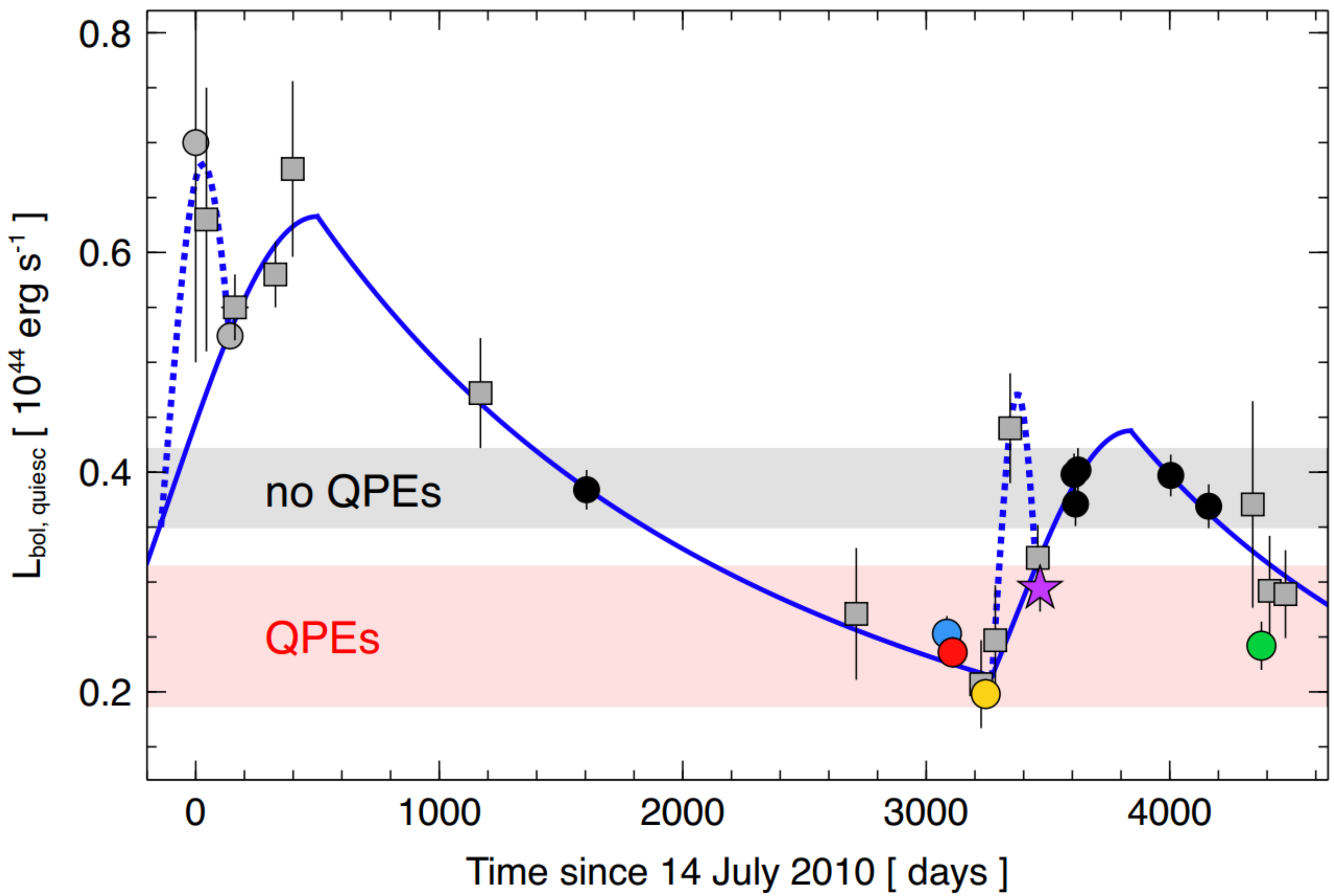




QPEs are back! – with a new shorter period?

X-ray QPEs in GSN 069

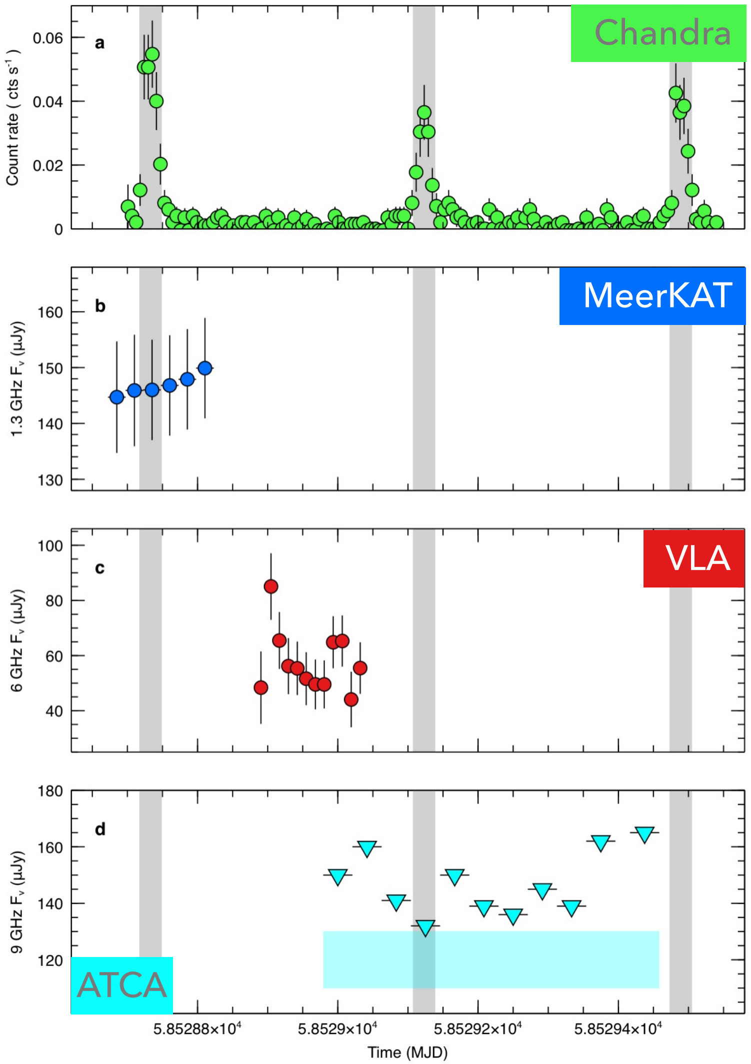
Miniutti et al. 2023, A&A 674, 1



A quiescent luminosity threshold for the QPE presence?

X-ray QPEs in GSN 069

Miniutti et al. 2019, Nature 573, 381



February 2019

Coordinated campaign between space – with the Chandra X-ray Observatory – and Earth, with radio observations performed with the MeerKAT in South Africa, the Very Large Array in the USA, and the Australia Telescope Compact Array

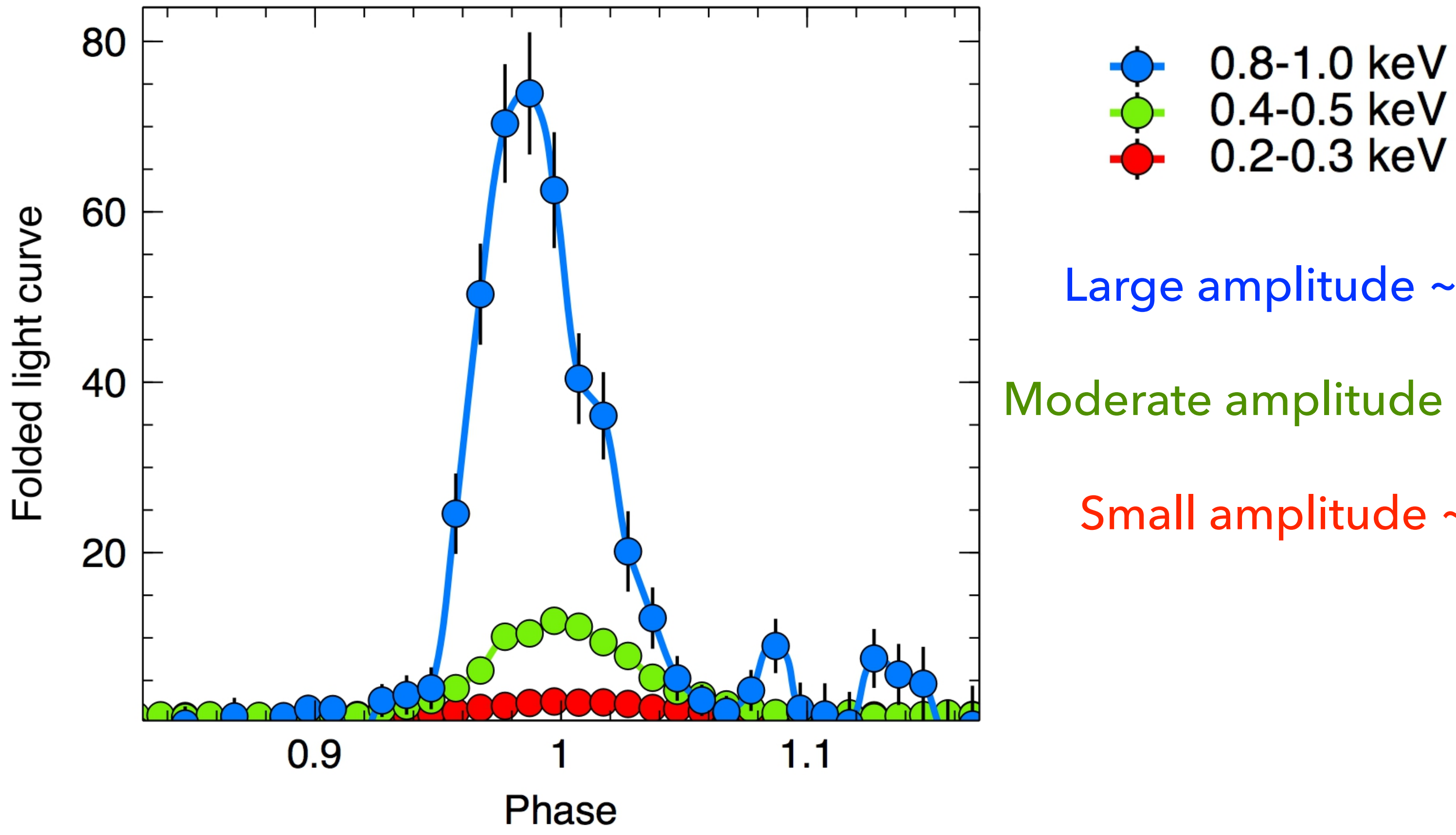
Only one radio exposure with enough sensitivity is performed during an X-ray QPE

No clear radio-variability associated to the X-ray QPEs in GSN 069

X-ray QPEs properties

Miniutti et al. 2019, Nature 573, 381

QPEs have higher amplitude at higher energies



Large amplitude ~ 80

Moderate amplitude ~ 10

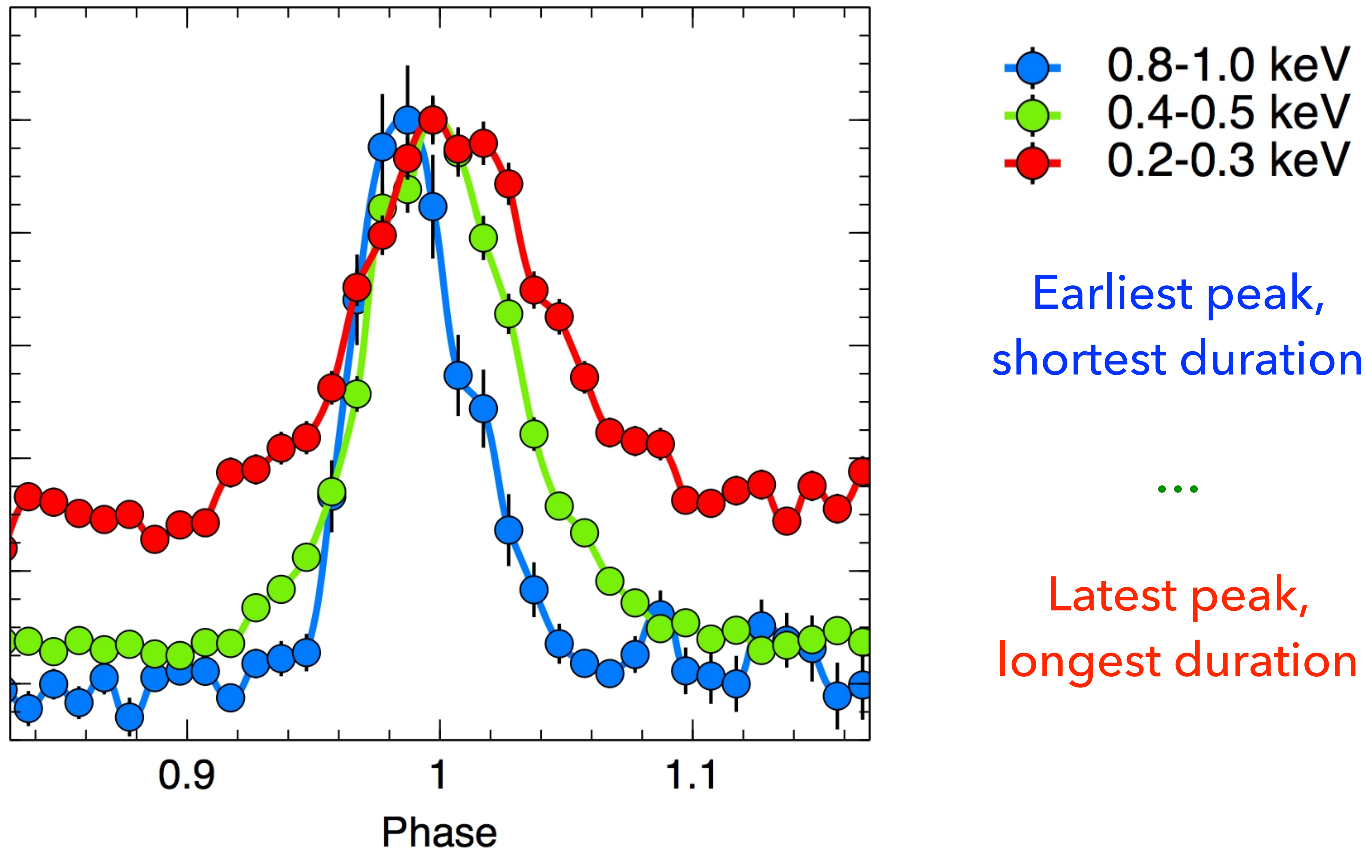
Small amplitude ~ 2

Folded light curve normalised to the quiescent count rate. Amplitude = count rate (QPE) / count rate (quiescence)

X-ray QPEs properties

Miniutti et al. 2019, Nature 573, 381

QPEs peak earlier and last less at higher energies



Earliest peak,
shortest duration

...

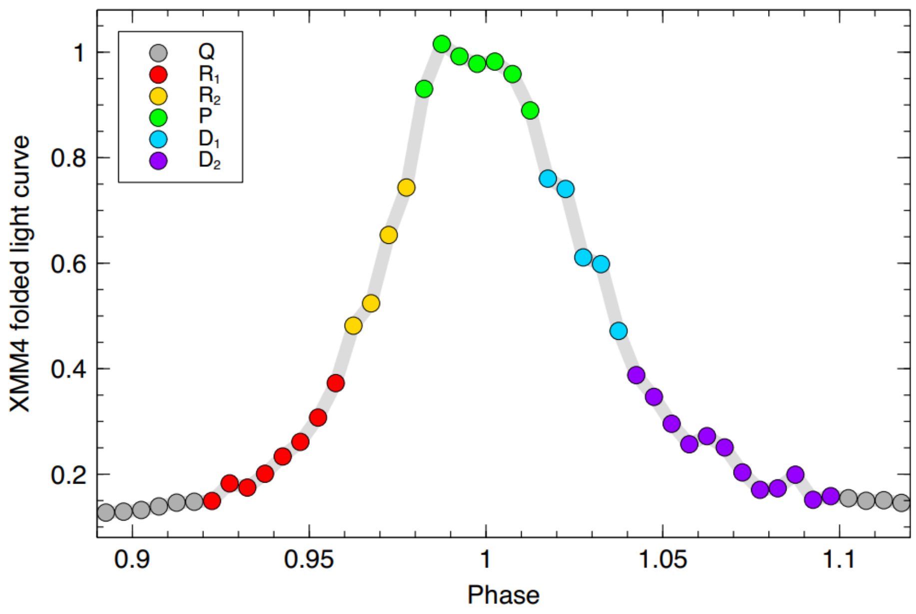
Latest peak,
longest duration

Folded light curve normalised to the peak count rate

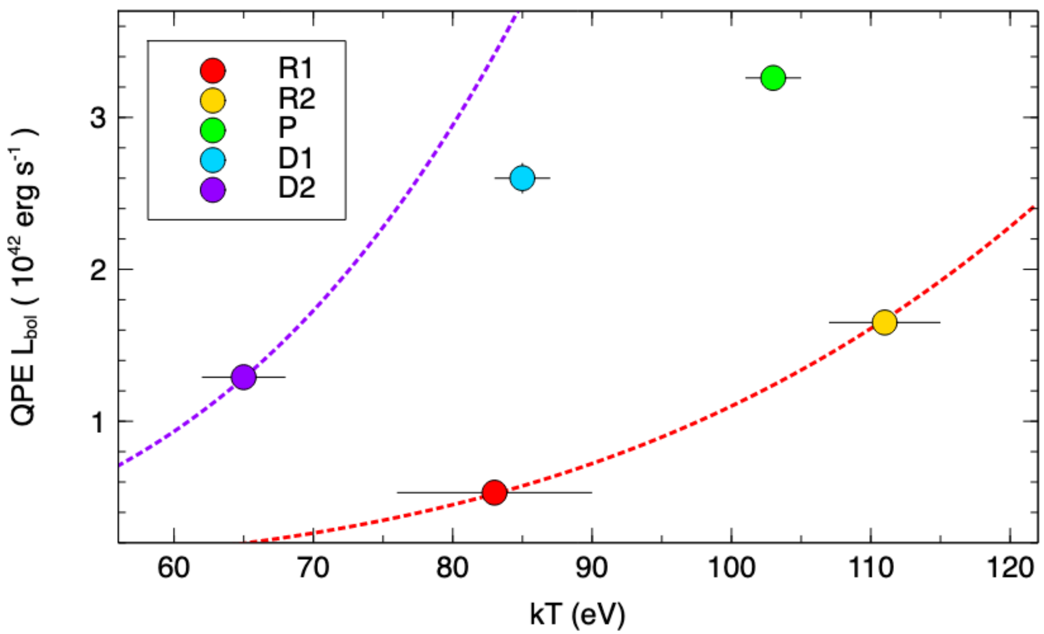
The QPE spectral evolution is chromatic

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

QPEs peak earlier and last less at higher energies



Folded light curve normalised to the peak count rate

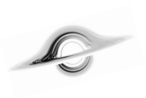


Simple blackbody model for the QPE spectra

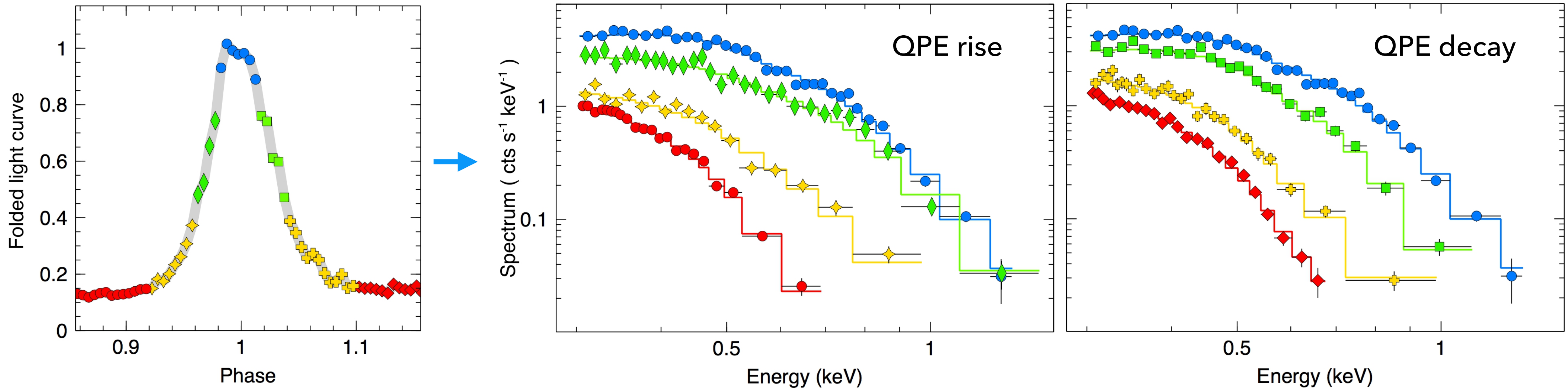
–> The QPEs rise is harder than the QPE decay

QPE spectral evolution

Miniutti et al. 2019, Nature 573, 381



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

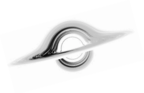


kT ~ 50 eV in quiescence, kT ~ 100 eV at the peak

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

QPE spectral evolution

Miniutti et al. 2019, Nature 573, 381



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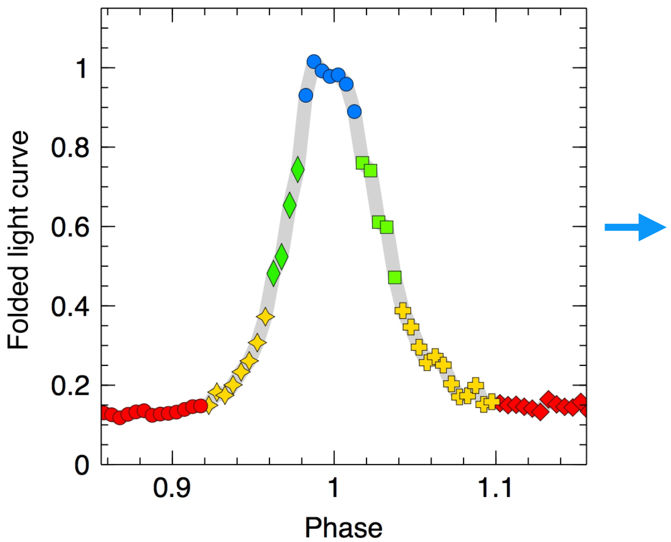
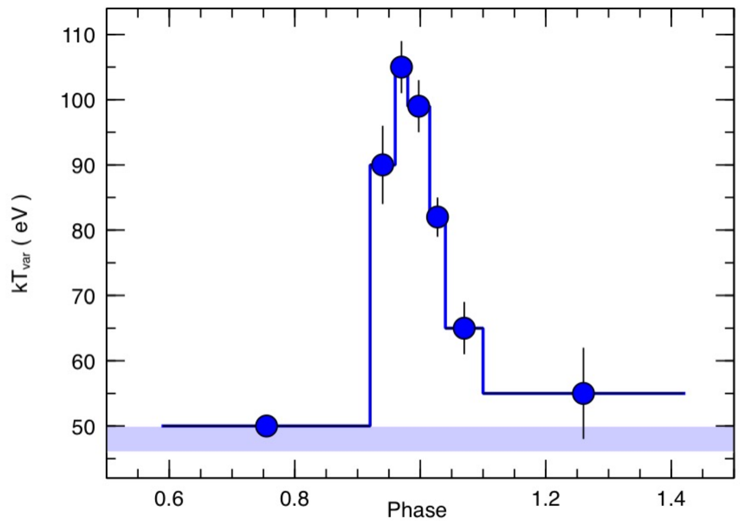
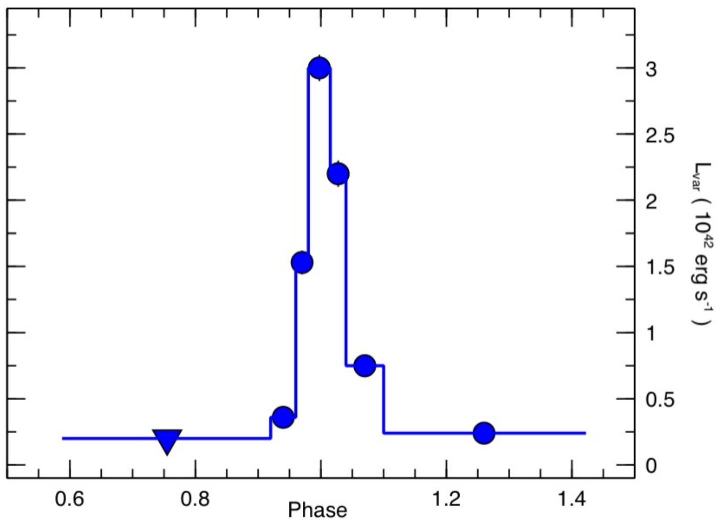


QPE Temperature (eV)



QPE Luminosity (10^{42} erg/s)



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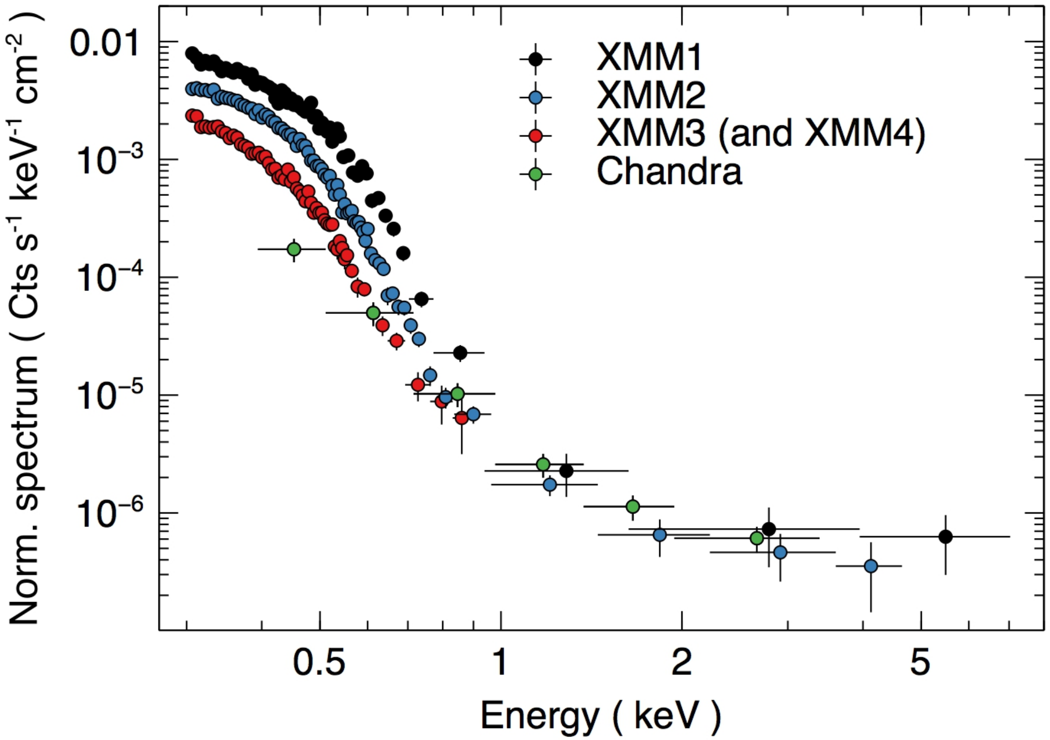
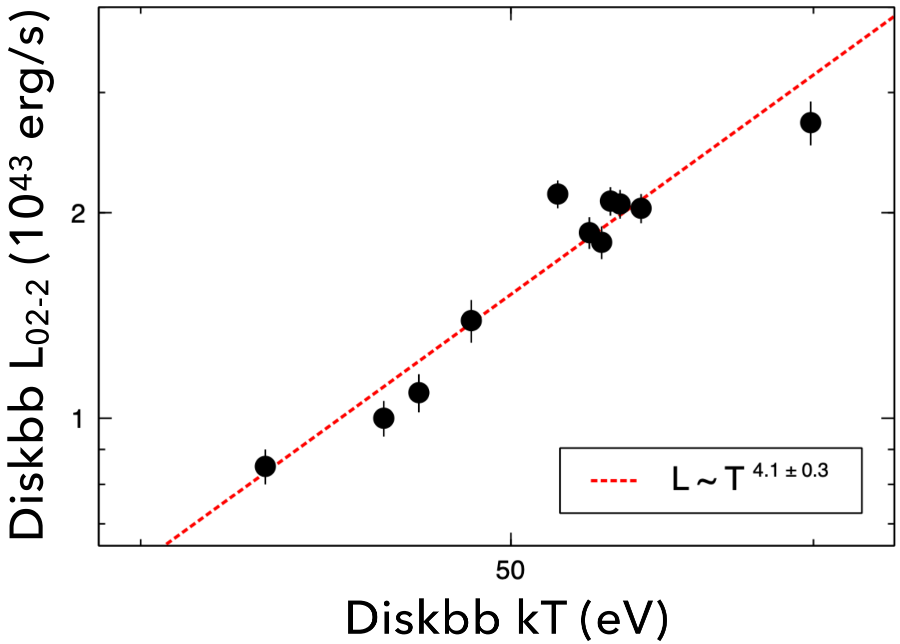
The quiescent emission

Miniutti et al. 2019, Nature 573, 381

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



Remarkable L ~ T^4 relation

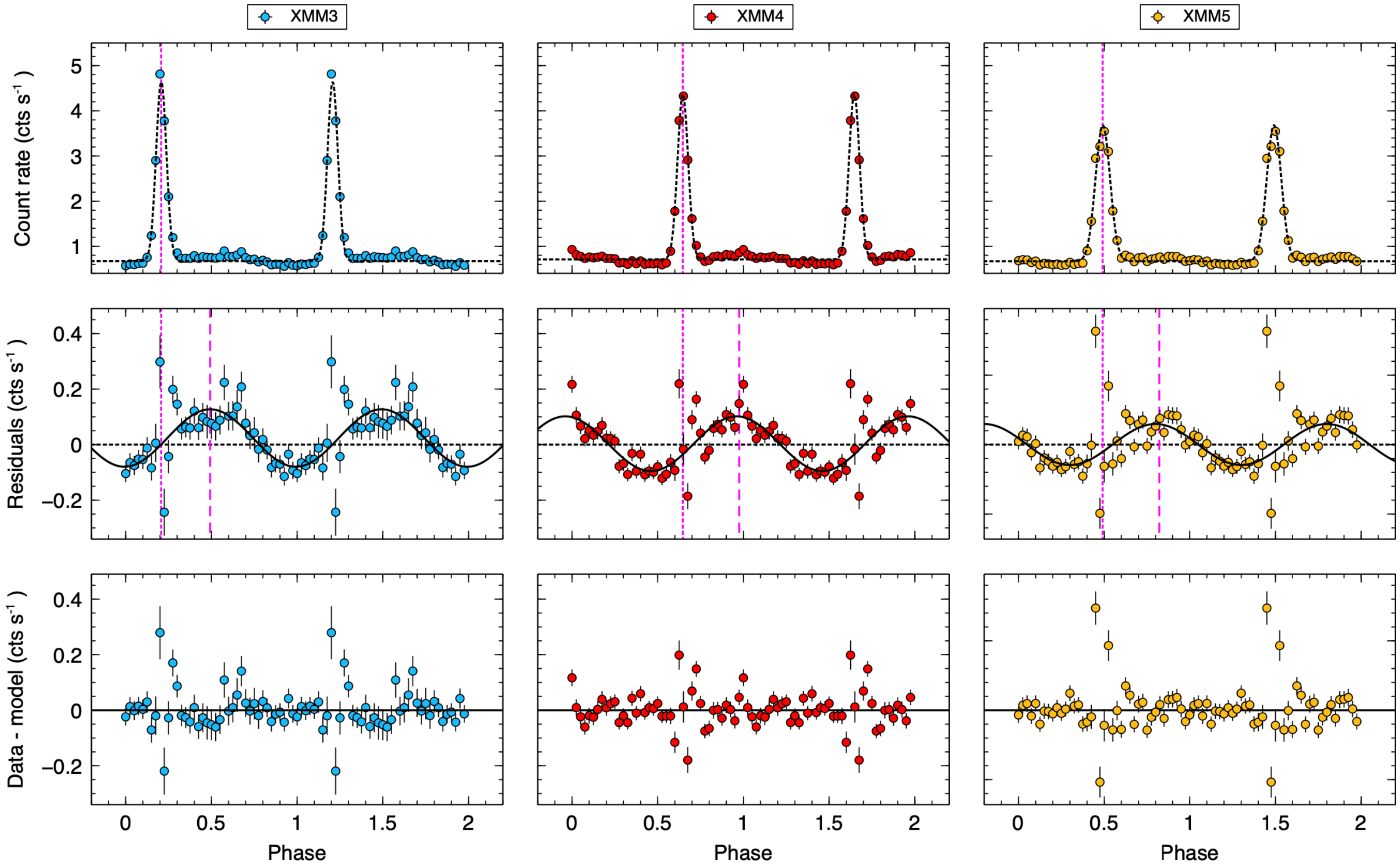


Fitting the spectra assuming thermal emission from the disk:

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

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

Quasi-periodic oscillations of the quiescent emission



X-ray QPEs in GSN 069: summary

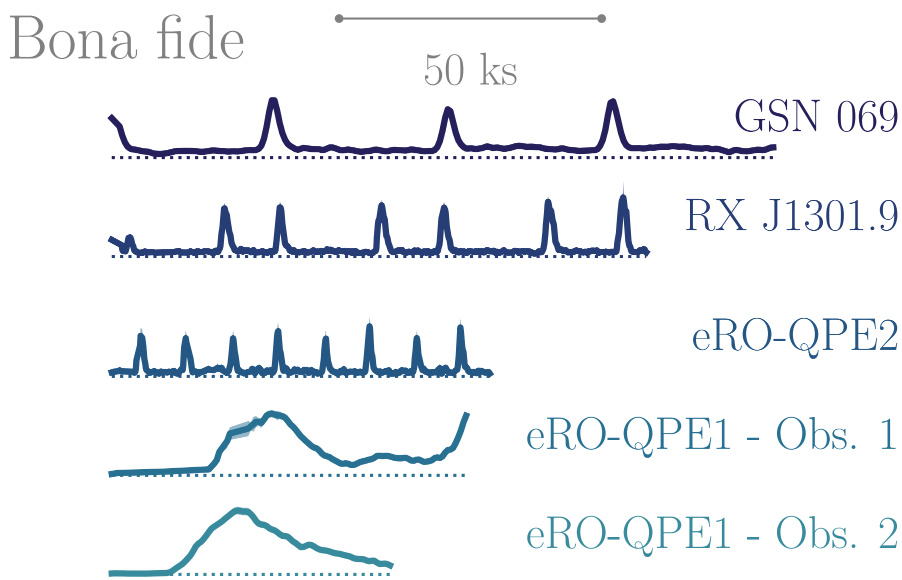
QPEs

- Soft X-ray bursts of $L_{0.2\text{-}2}$~10^{42} erg/s over a ~10^{41} erg/s quiescent emission
- Thermal-like emission with kT ~ 100 eV over a kT ~ 50 eV quiescence
- Duration ~ 1 hour, time separation ~ 9 hours
- Alternating strong/weak and long/short recurrence time
- First appeared ~ 8 years after the first X-ray detection
- Disappeared during a quiescence rebrightening, reappeared at lower flux
- Oscillations of the quiescence emission
- No evident multi-wavelength properties observed (so far)

Are QPEs a peculiarity?

Not anymore!

QPEs in 2023: a mini-population



GM

RA

Miniutti et al. 2019, Nature 573, 381

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

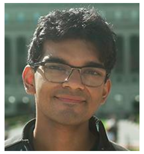
Miniutti et al. 2023, A&A 670, 93

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

Arcodia et al. 2021, Nature 592, 704

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

JC



Erin Kara

EQ

Natalie Webb

Chakraborty et al. 2021, ApJL 921, 40

Quintin et al. 2023, A&A 675, 152

Image credits: Erwan Quintin

QPEs in 2023: a mini-population

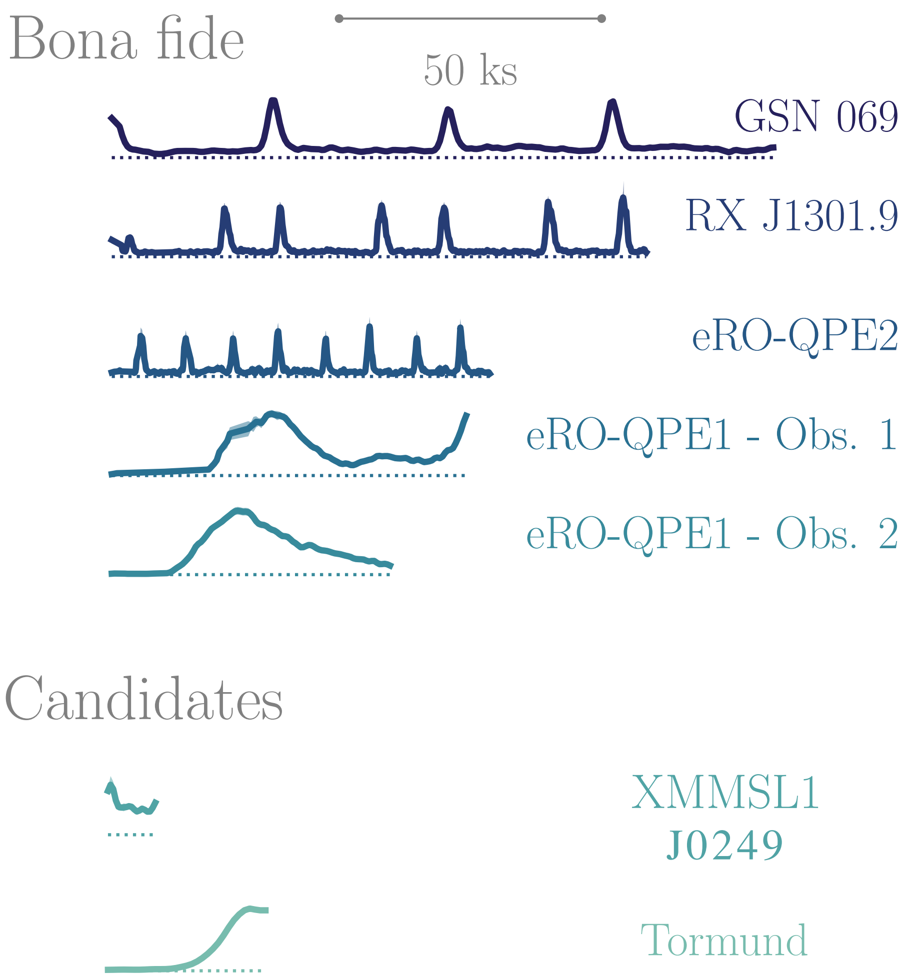
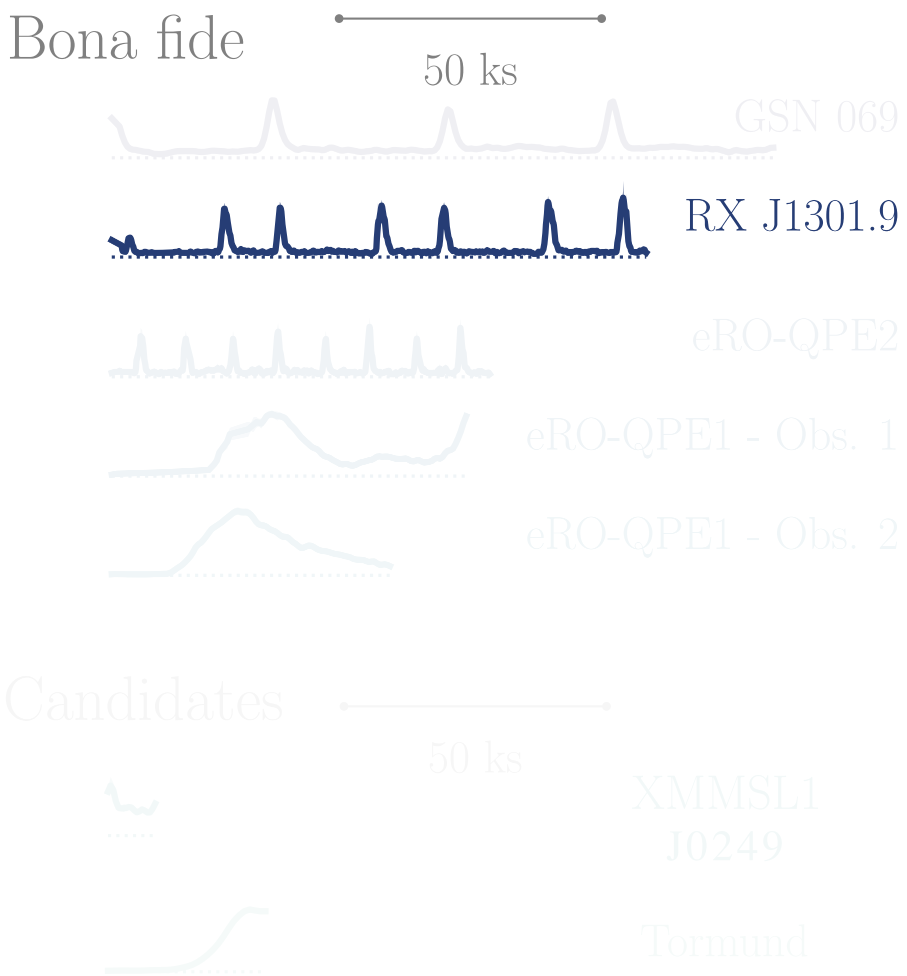


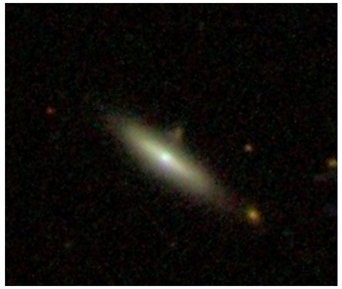
Image credits: Erwan Quintin

- 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

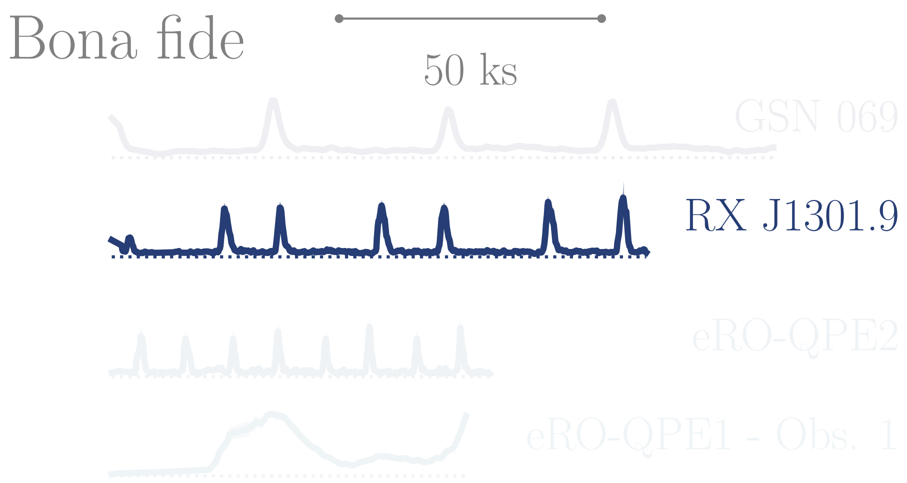
RX J1301.9+2747





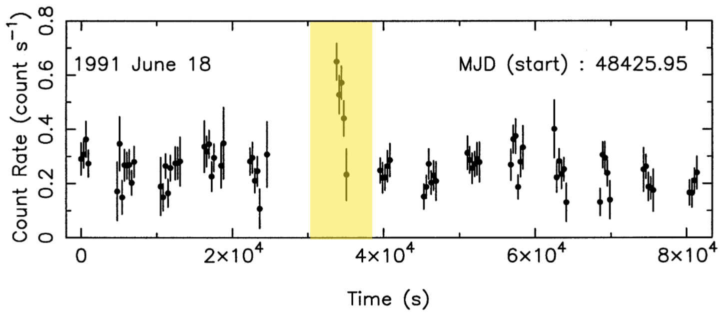
- Young post-starburst galaxy at the periphery of the Coma Cluster (z = 0.024)
- Small $M_{BH} \sim (8\text{–}40) \times 10^5\ M_\odot$
- No Broad Optical/UV Emission Lines
- High Eddington Ratio ~0.1
- Nuclear Star Cluster
- Super-soft X-ray source
- Peculiar X-ray variability

RX J1301.9+2747

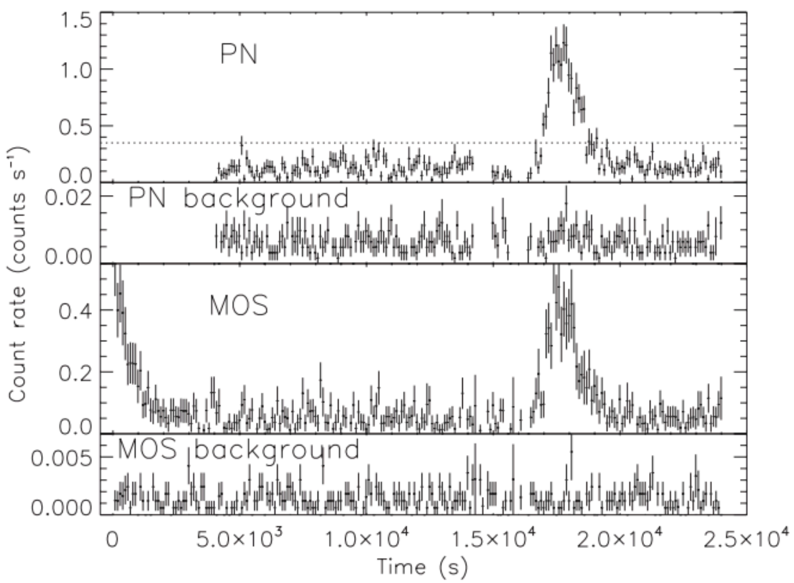


Evident QPE-like variability

Dewangan et al. 2000, MNRAS 318, 309



Sun, Shu & Wang 2013, ApJ 768, 167



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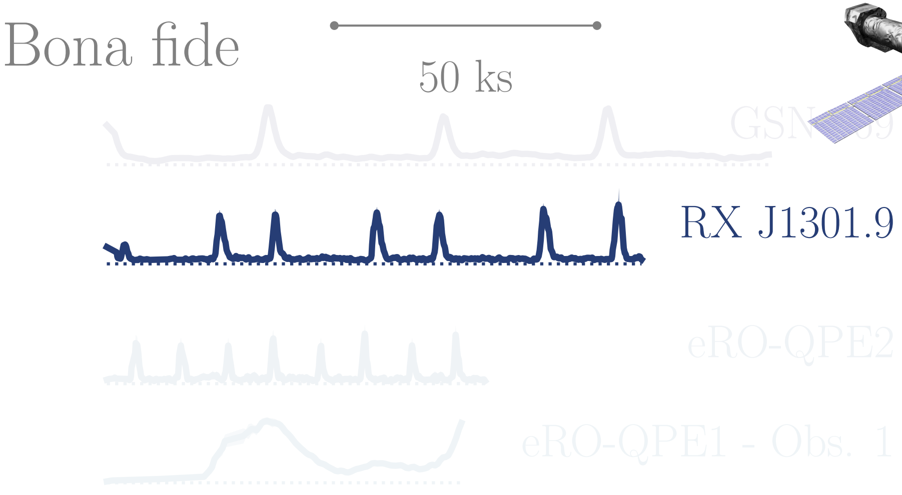
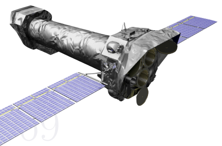
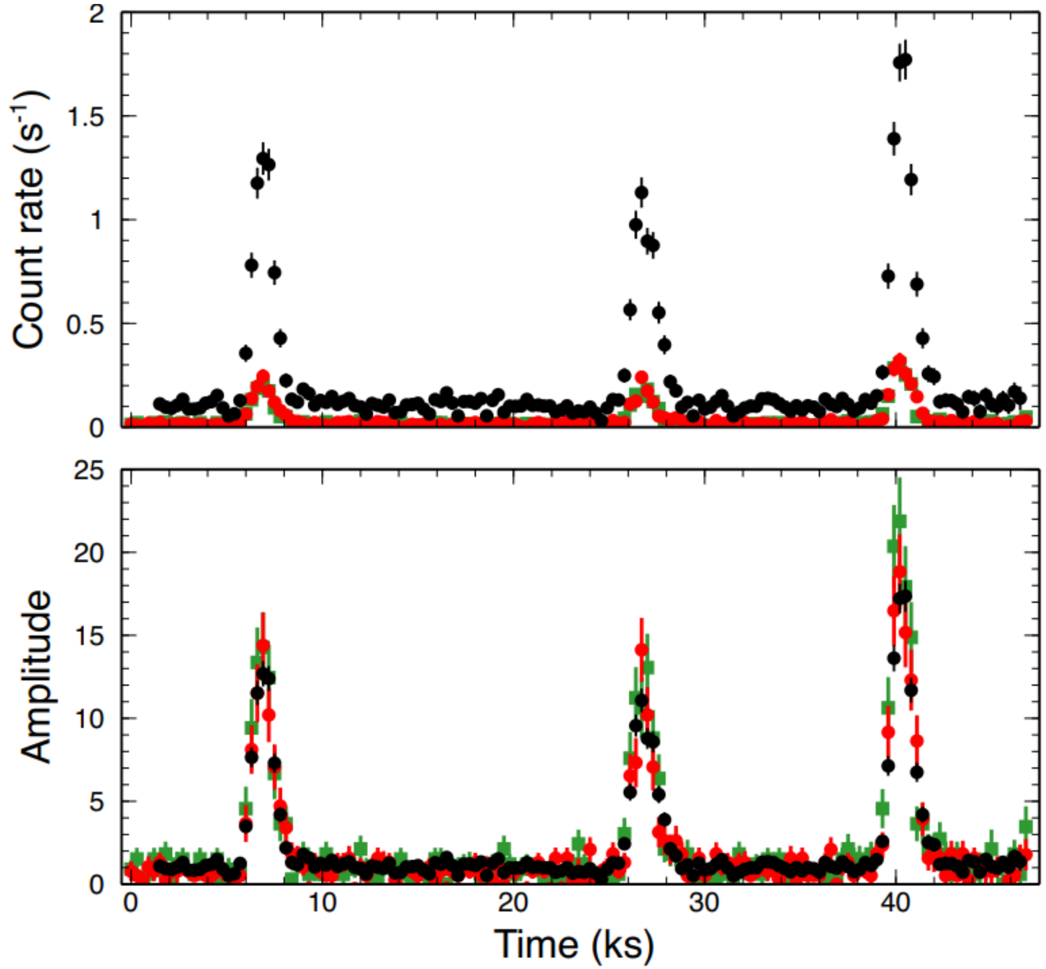
Giustini et al. 2020, A&A 636, 2





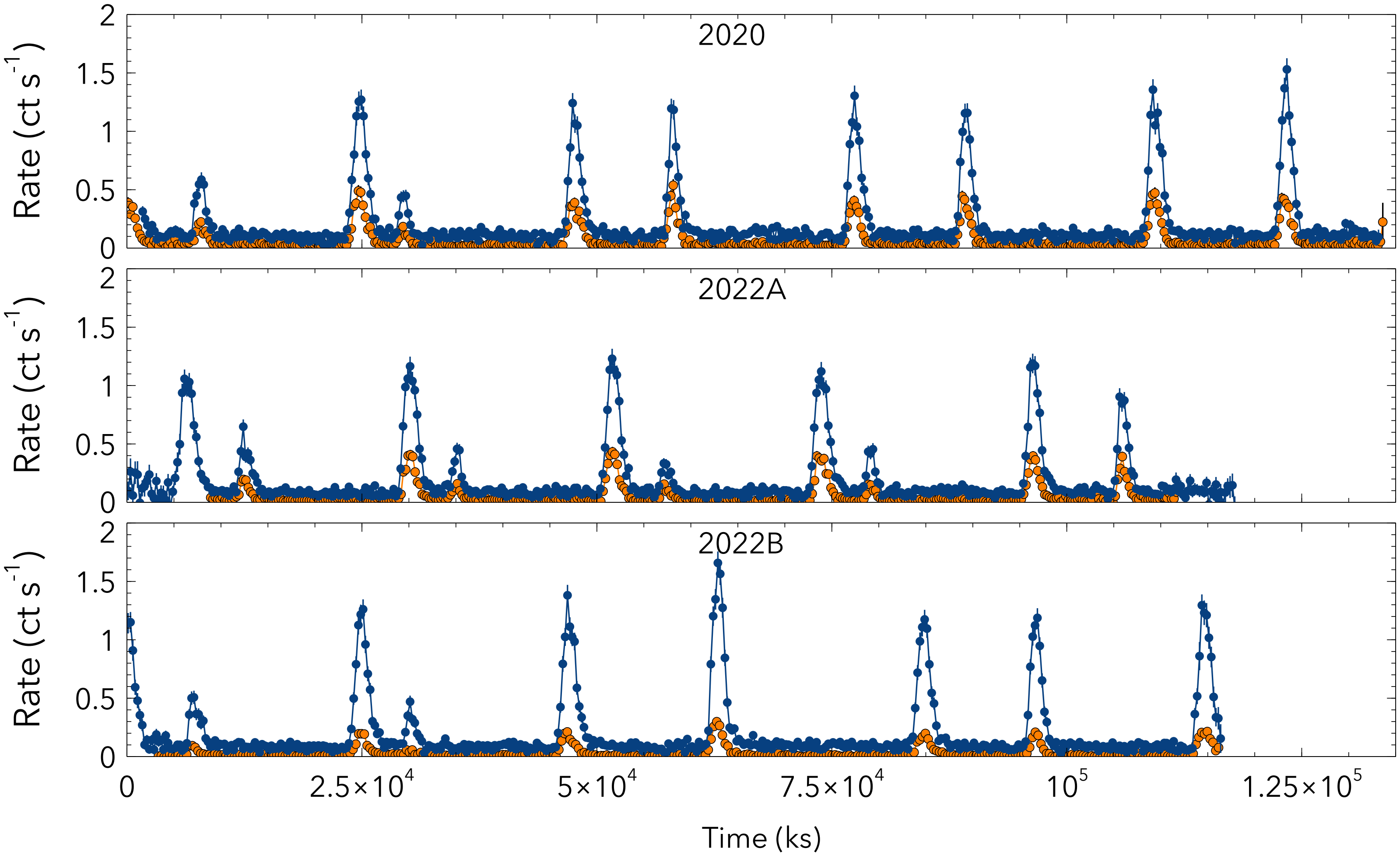
- **QPEs are there.**
- **Their recurrence pattern is not clear.**

XMM-Newton DDT observation on June 2019



RX J1301.9+2747

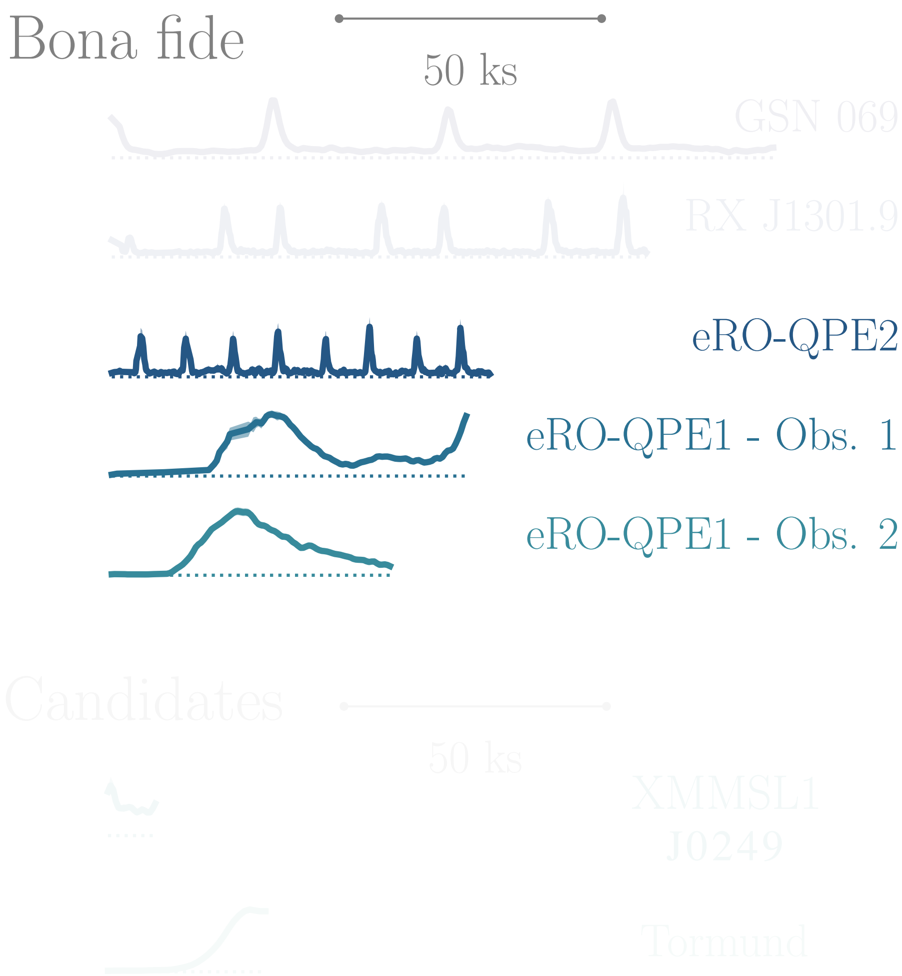
Giustini et al. in prep.

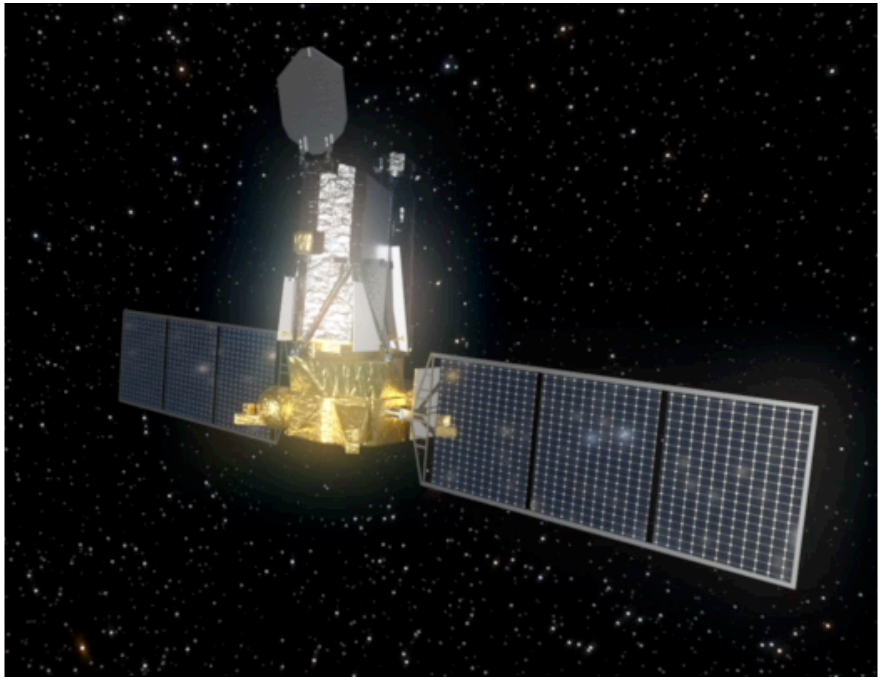


Not a single repeating time separation between QPEs + small-amplitude QPEs

Catch them if you can: eROSITA

Arcodia et al. 2021, Nature 592, 704





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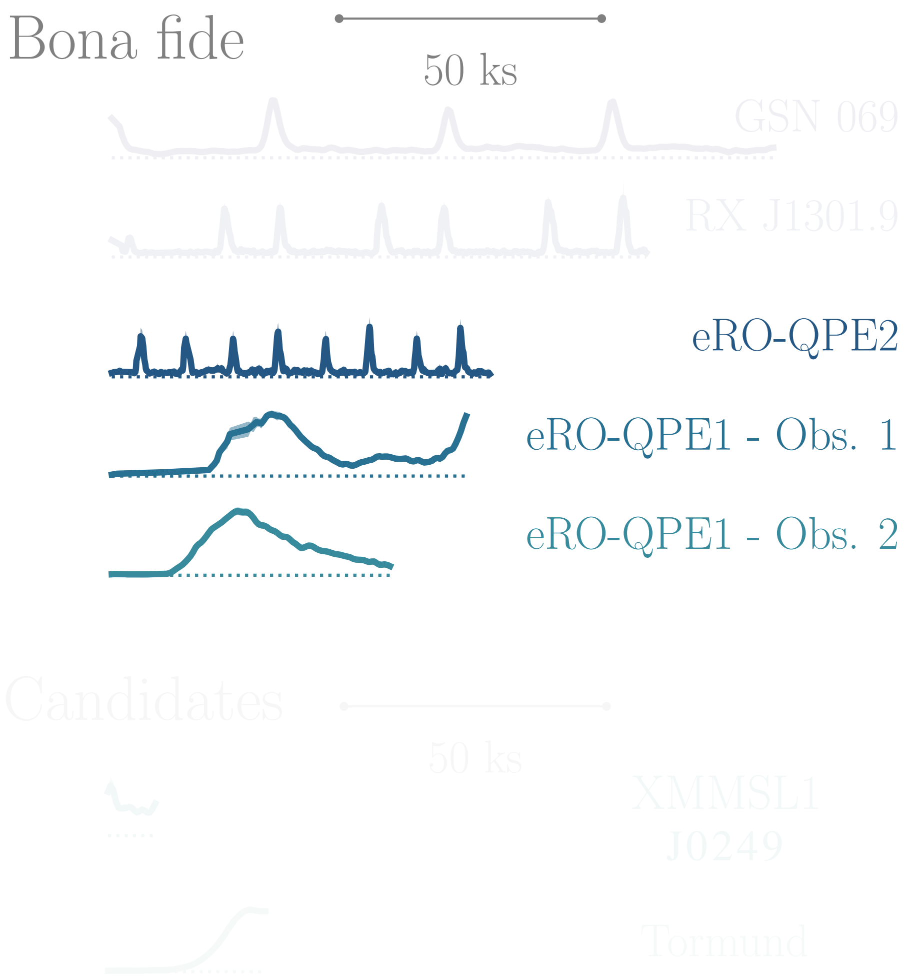
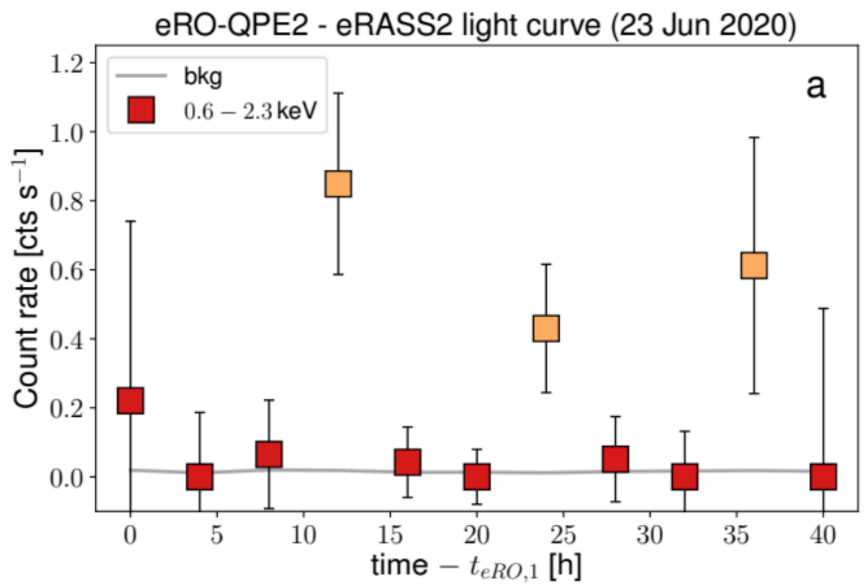
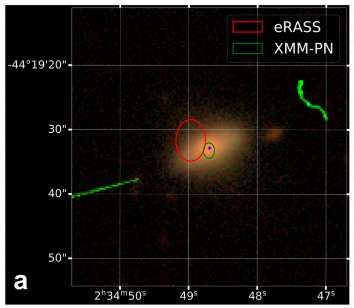




eRO-QPE2, z = 0.0175



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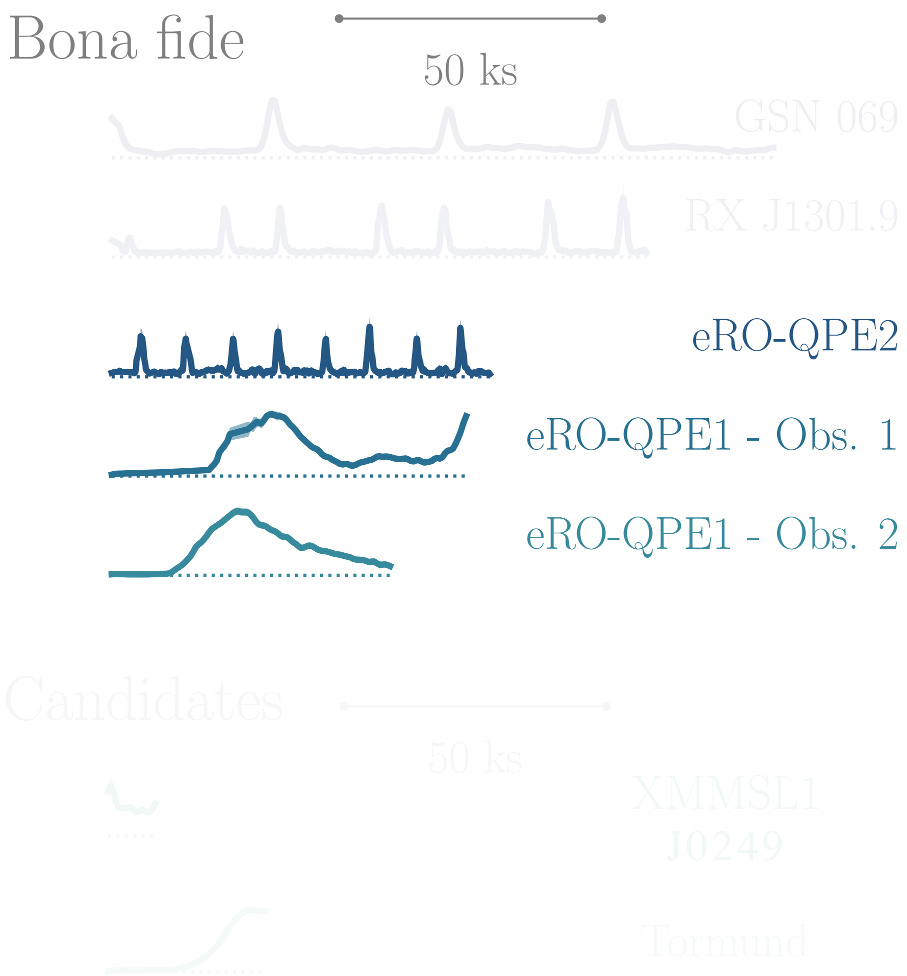
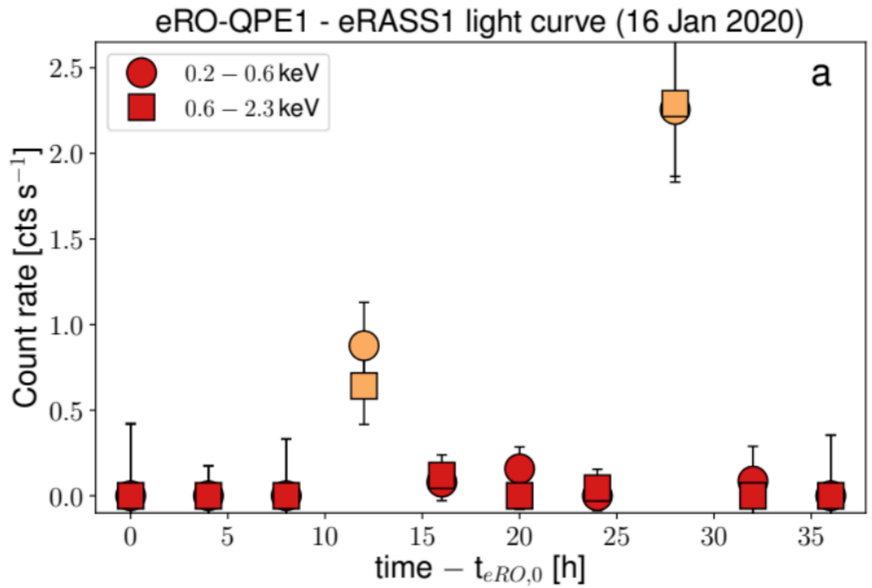
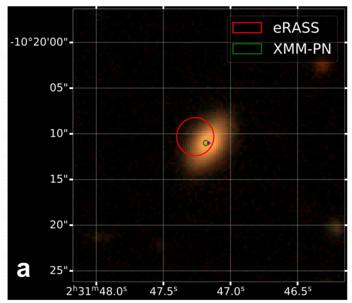
Arcodia et al. 2021, Nature 592, 704



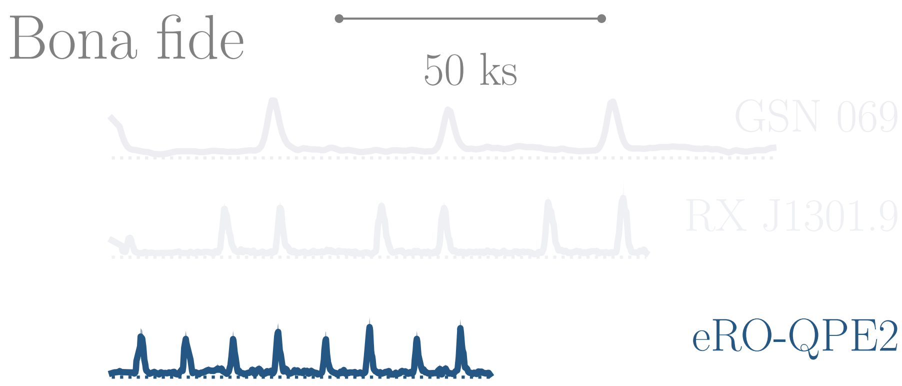


eRO-QPE1, z = 0.0505

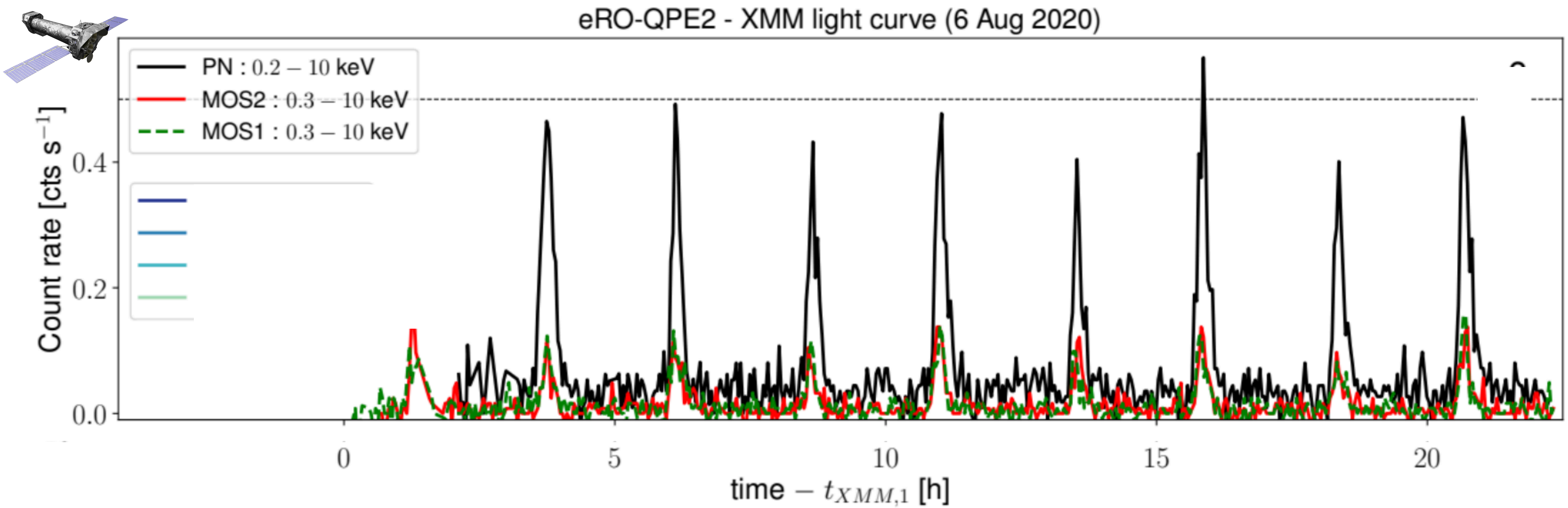


eRO-QPE2

Arcodia et al. 2021, Nature 592, 704

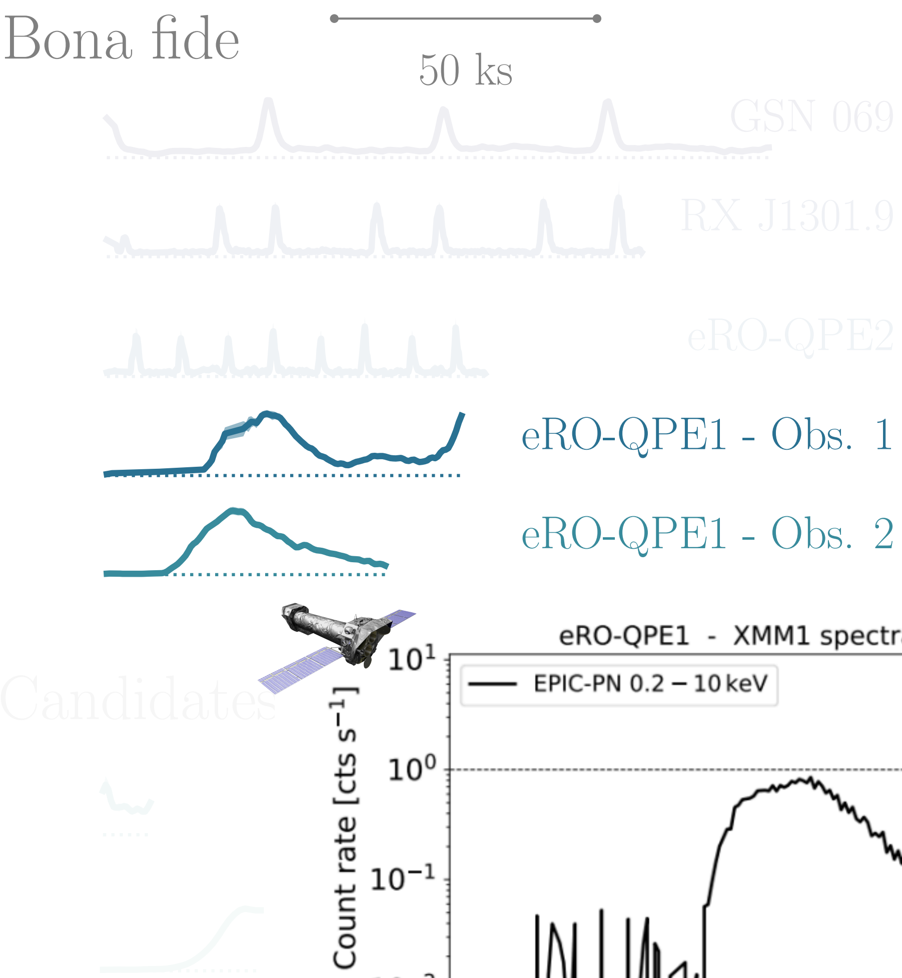


- QPEs last about half an hour
- Release between 10^{41} and 10^{42} erg/s
- Repeat every about 2.5 hr

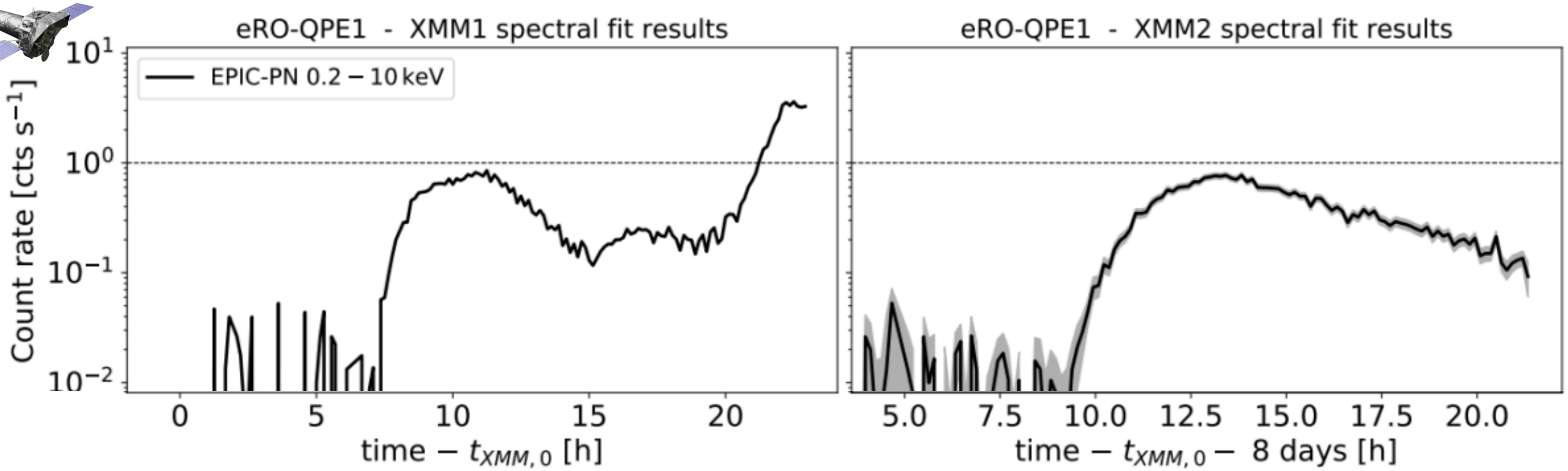


eRO-QPE1

Arcodia et al. 2021, Nature 592, 704

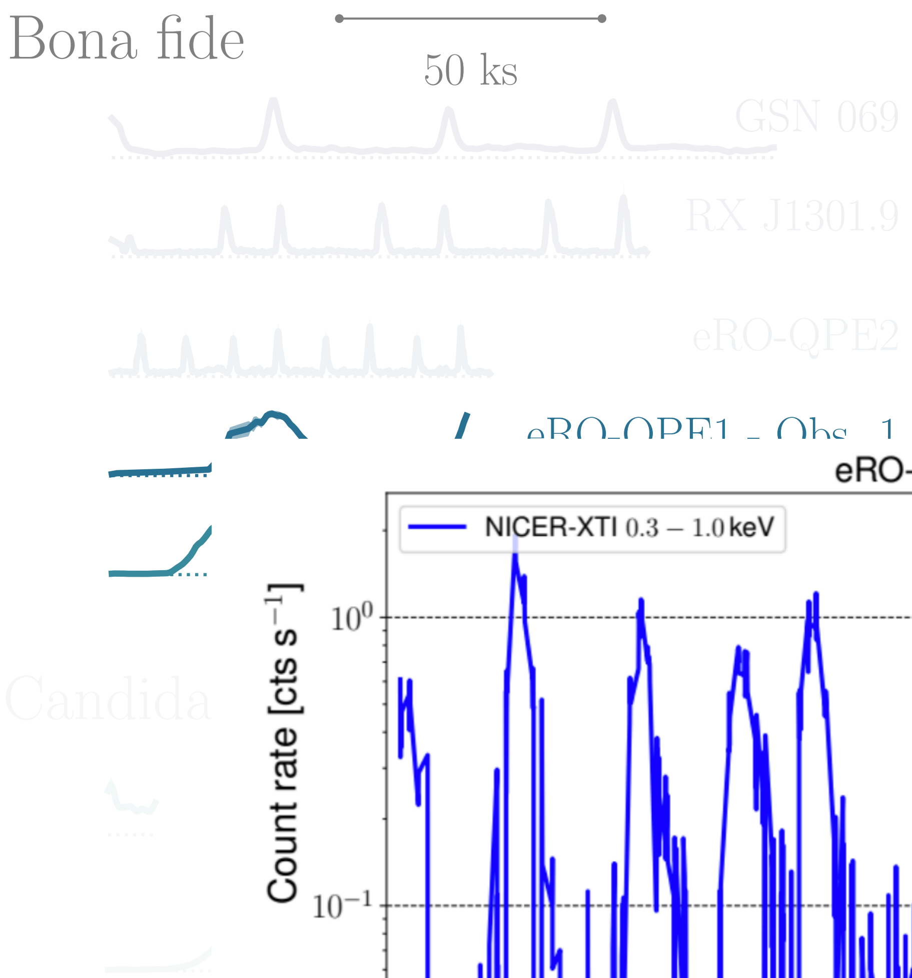


- QPEs last about 7.5 hours
- Emit between 3 x 10^{42} and 2 x 10^{43} erg/s
- Repeat every about 18 hr



eRO-QPE1

Arcodia et al. 2021, Nature 592, 704



- QPEs last about 7.5 hours
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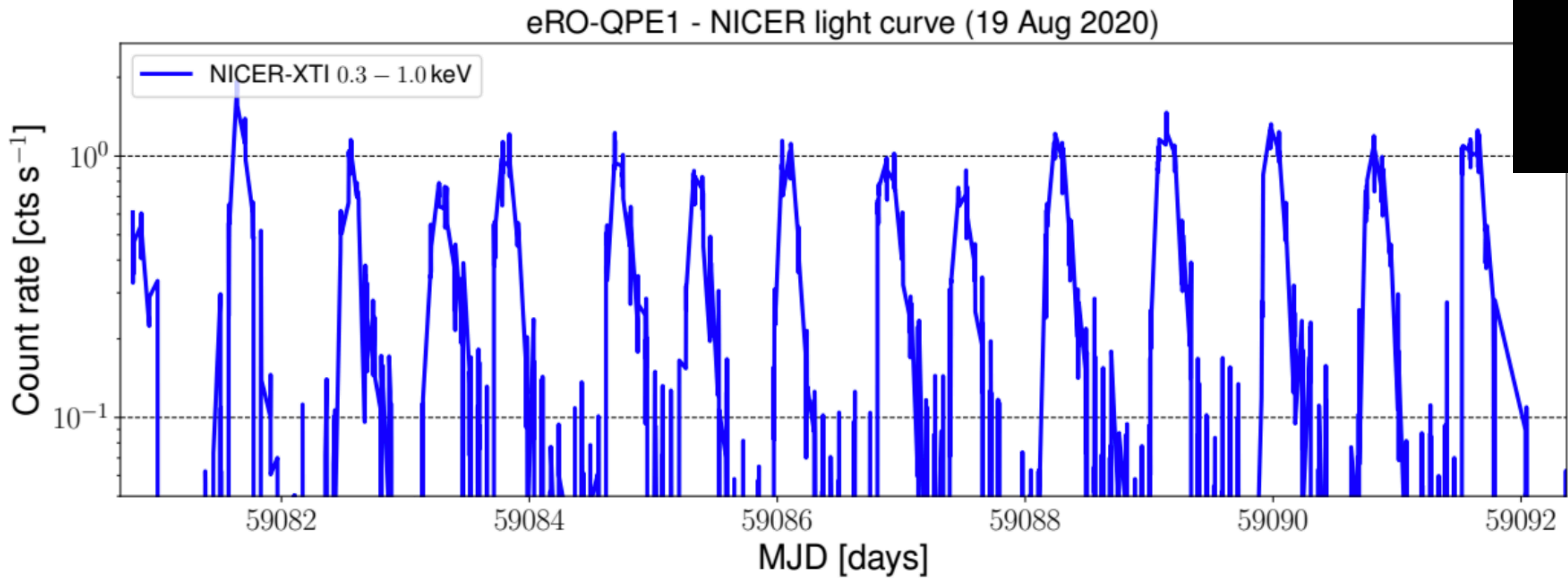
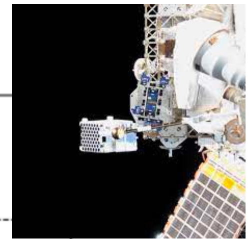
- Repeat every about 18 hr

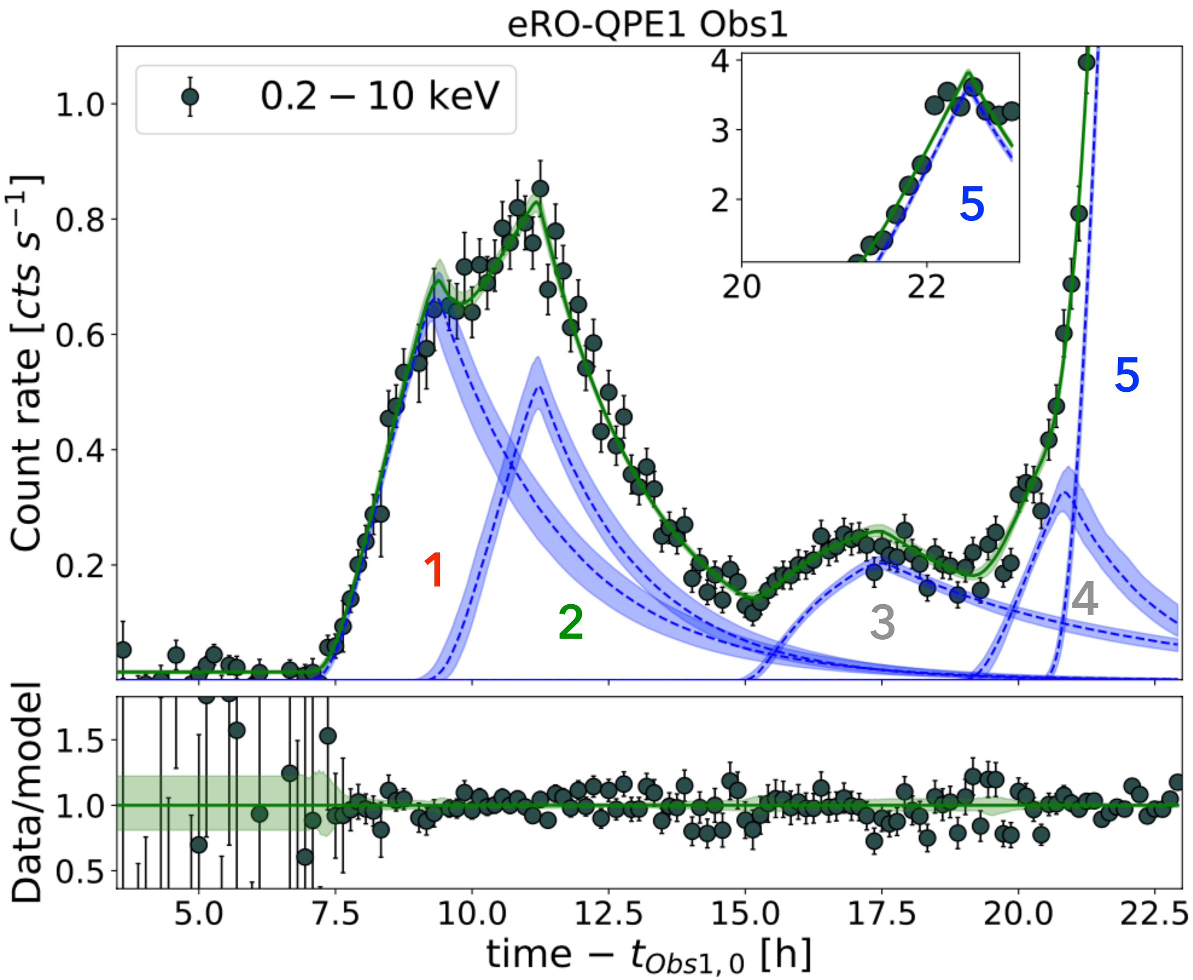




eRO-QPE1

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

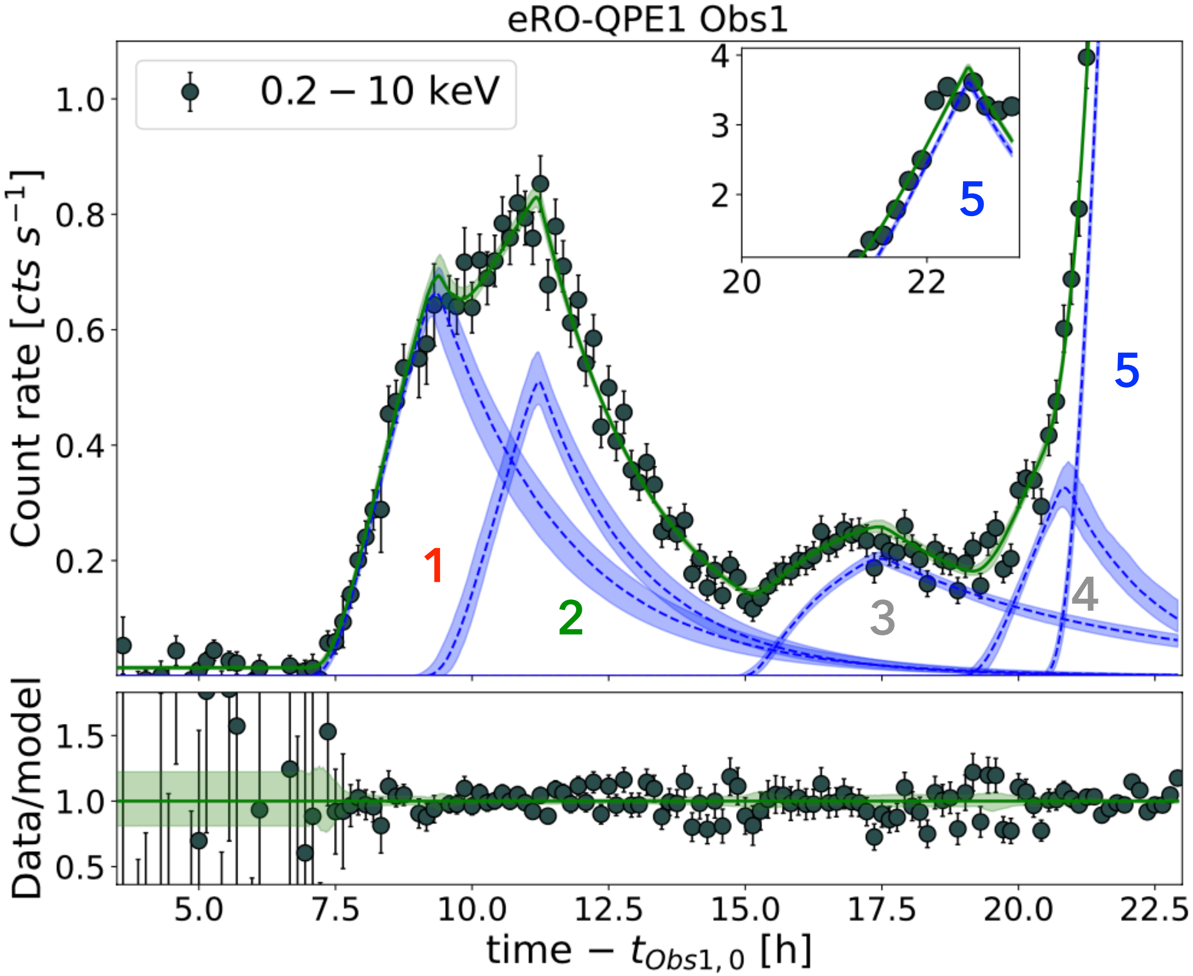
Multiple bursts of different amplitude, partially overlapping…

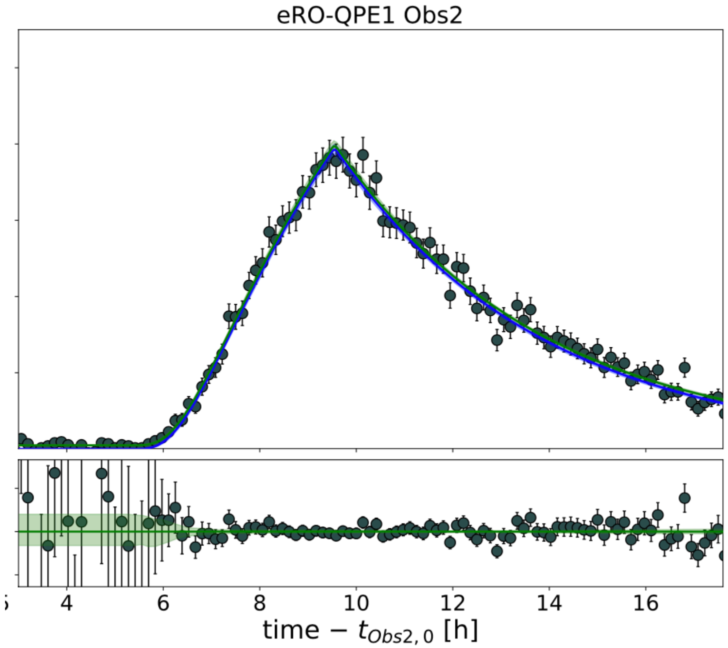


eRO-QPE1

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

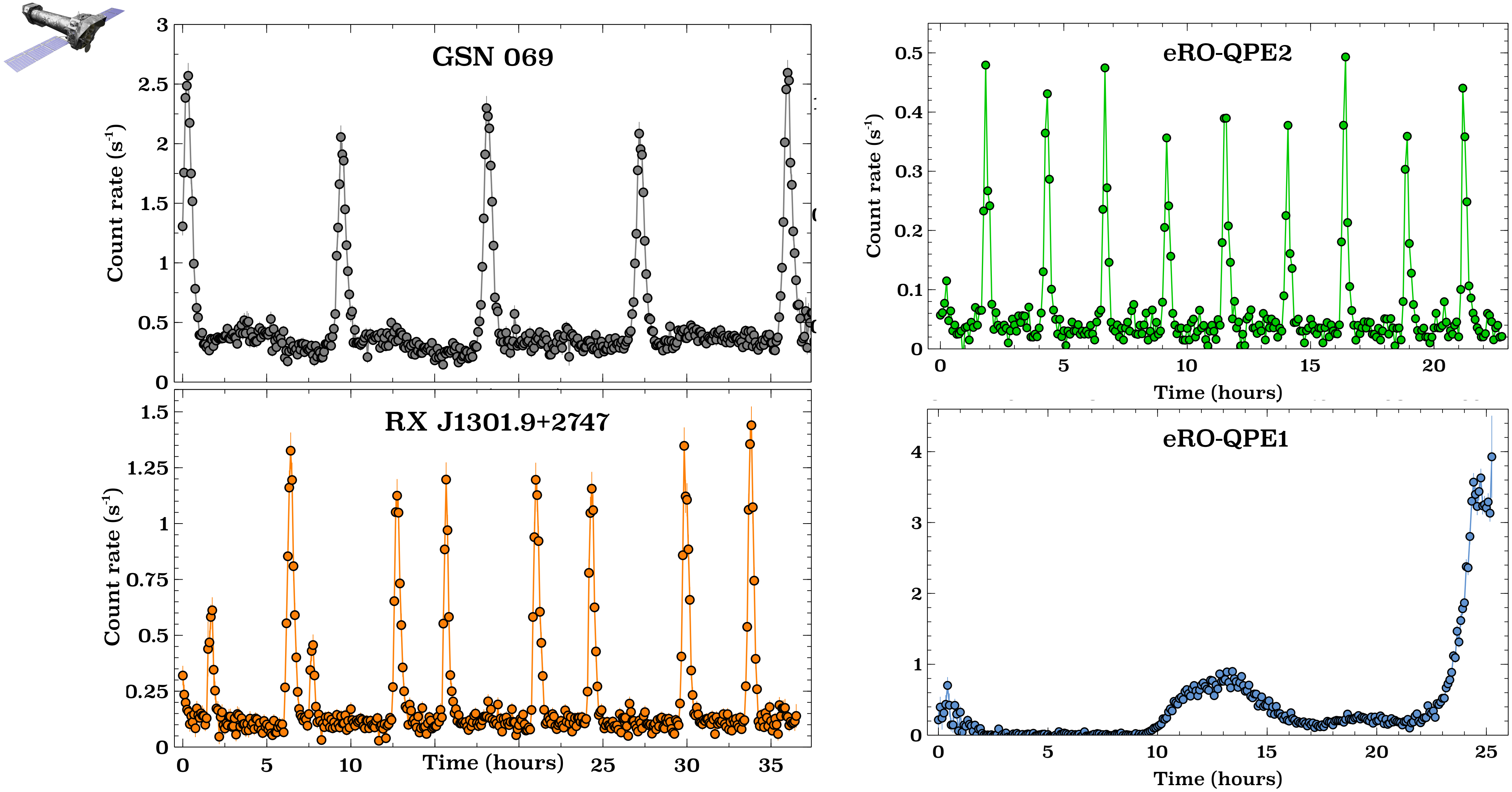
Multiple bursts of different amplitude, partially overlapping…



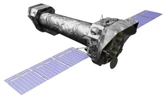


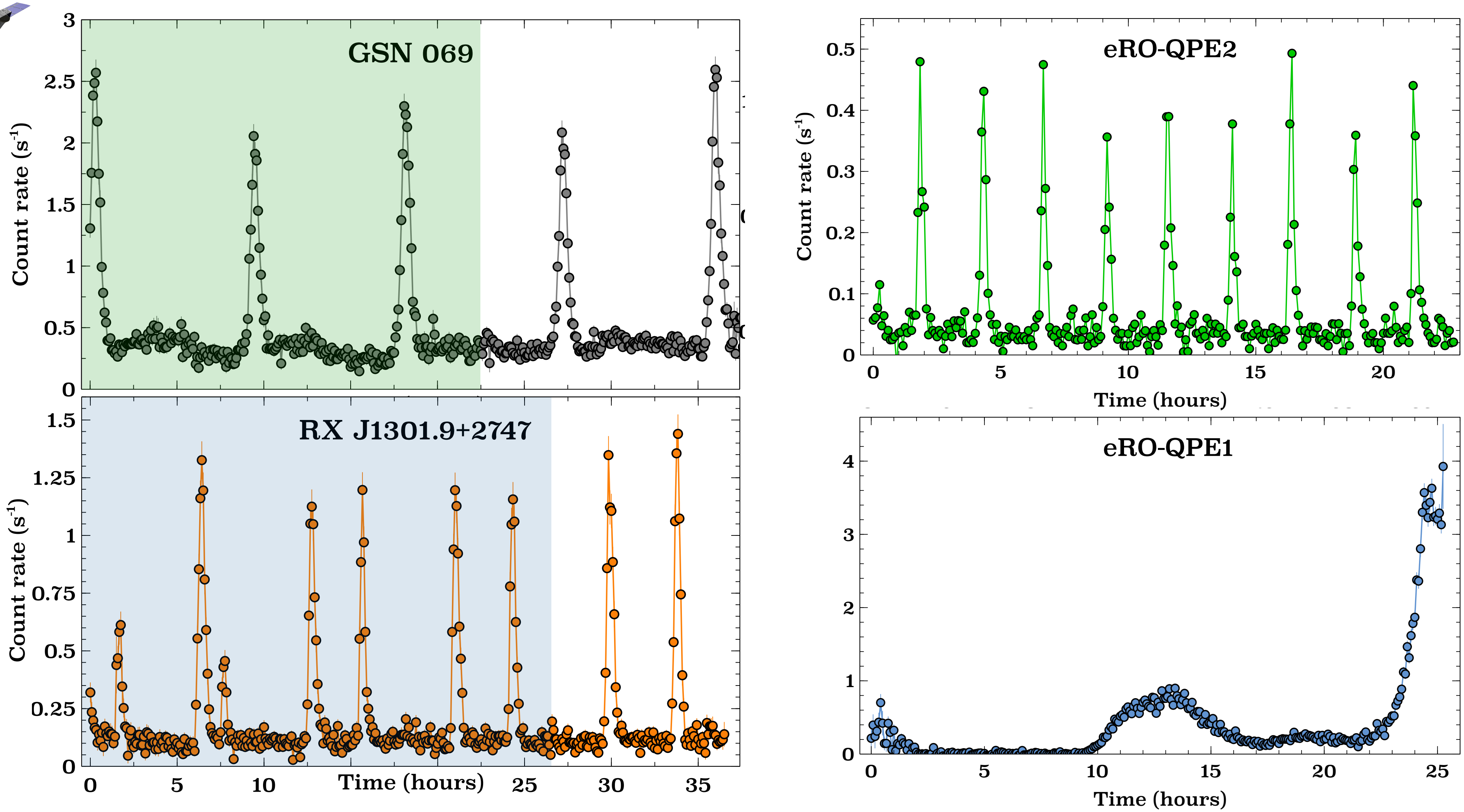
…but not always.

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



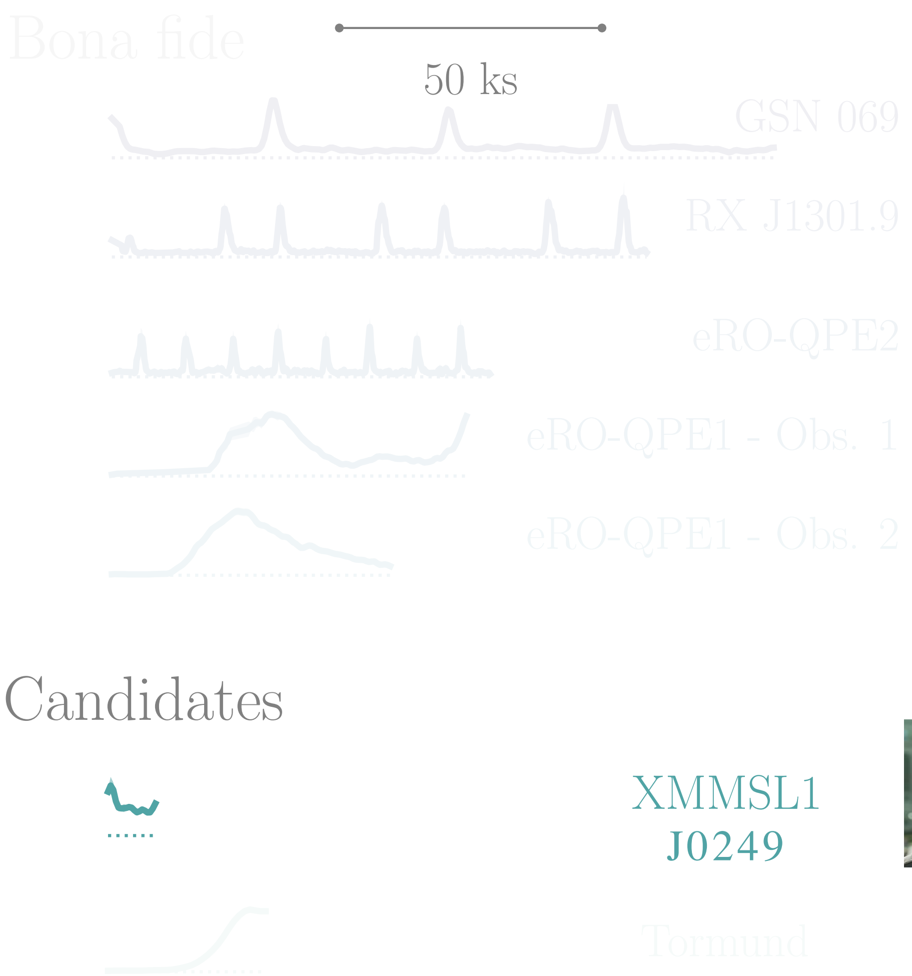
X-ray light curves of QPE sources binned to 5 minutes





QPE-candidates

The QPE-candidate XMMSL1 J0249



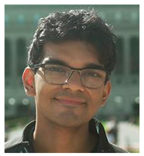
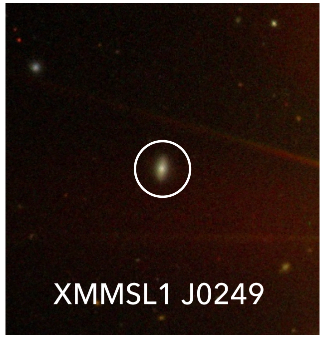


Image credits: *Erwan Quintin*

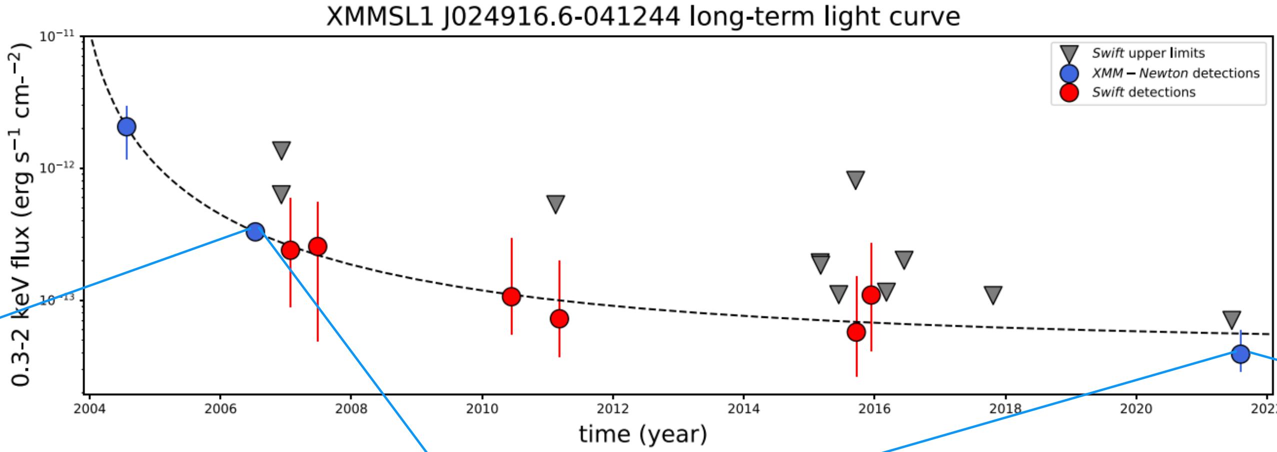


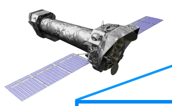
- Star-forming/AGN galaxy, z = 0.019
- Small black hole mass M_{BH} ~ 8–50 x 10^5 $M_\odot$
- Detected in 2004 by the XMM-Newton Slew
- Flux increase ~90x compared to ROSAT
- Clever application of the Quasi-periodic Automated Transit Search algorithm to the XMM-Newton archive: QPE-like flare identified

Chakraborty et al. 2021, ApJL 921, 40

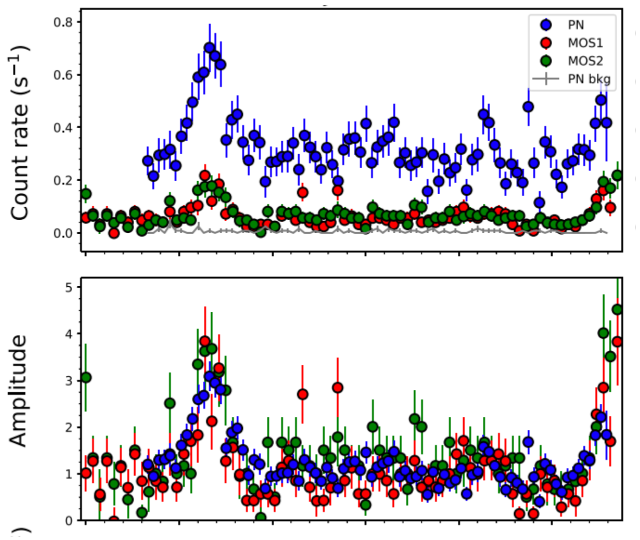
The QPE-candidate XMMSL1 J0249

Chakraborty et al. 2021, ApJL 921, 40

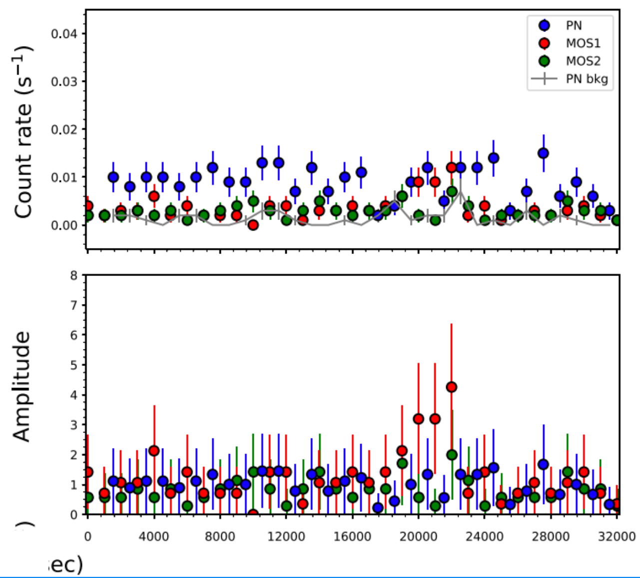




2006: ~1.5 QPE-like flares separated by 9 ks

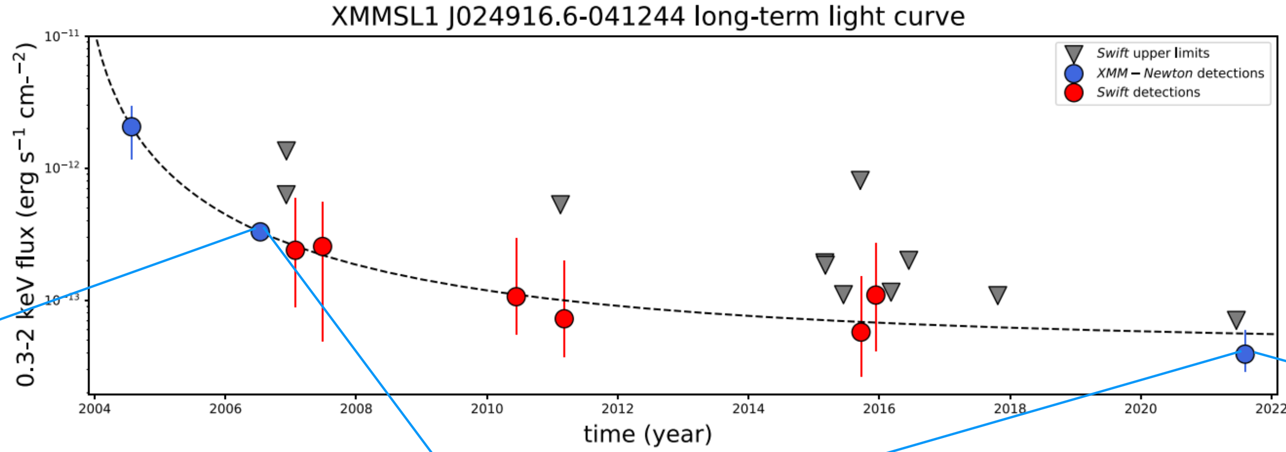


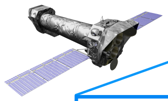
2021: stable quiescent flux, no QPEs in 32 ks



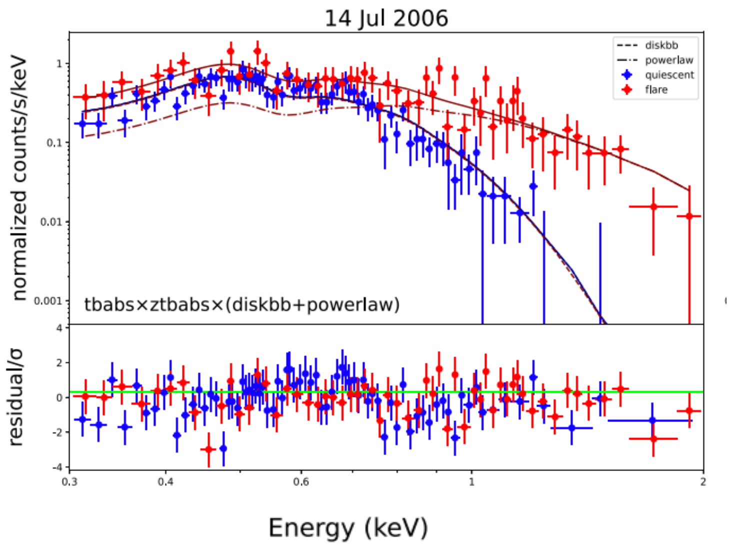
The QPE-candidate XMMSL1 J0249

Chakraborty et al. 2021, ApJL 921, 40

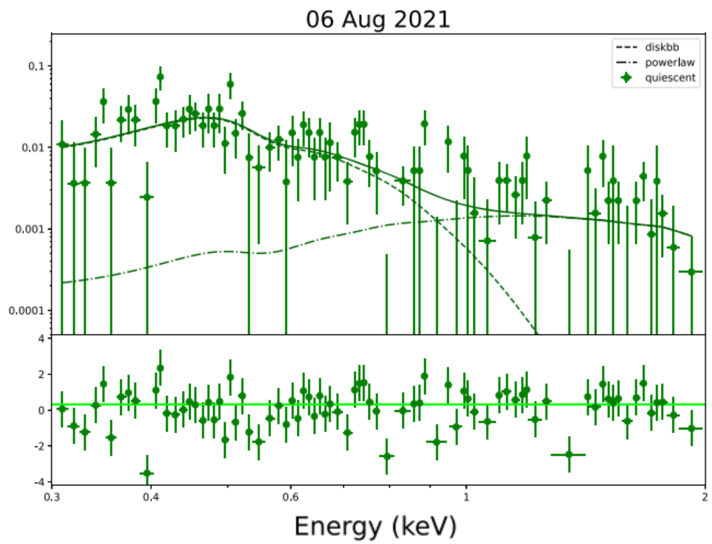




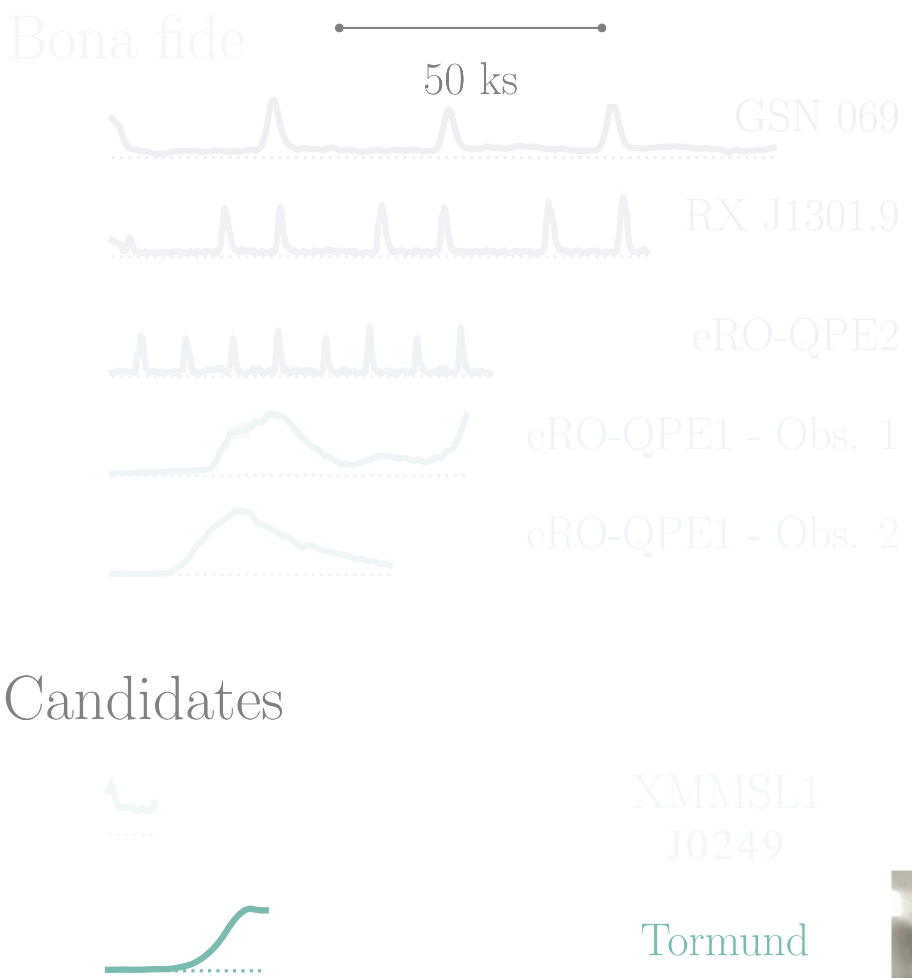
2006: harder when brighter, kT~80-160 eV

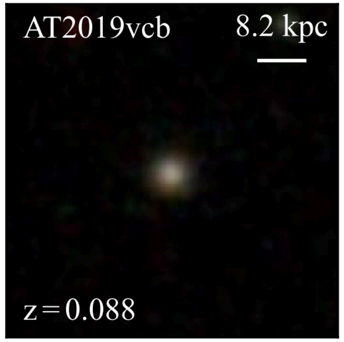


2021: kT~100 eV + hard X-ray power-law



The QPE-candidate Tormund





Hammerstein et al. 2022

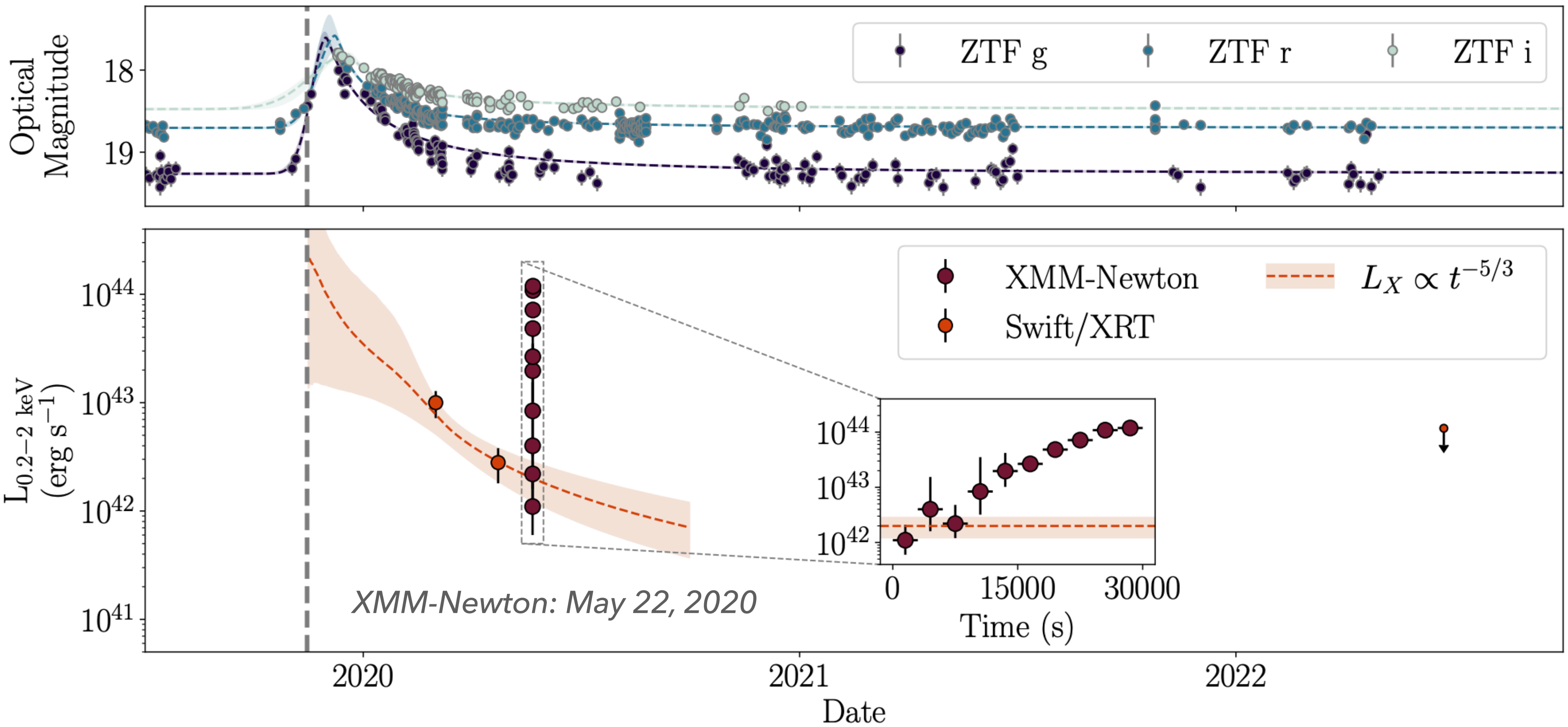
- Detected by the ZTF on November 15, 2019
- Optical counterpart: tidal disruption event
- z = 0.088
- Low-mass galaxy with M_{star} ~ 3 x 10^9 $M_\odot$
- Black hole mass M_{BH} ~ 6–80 x 10^6 $M_\odot$
- Data mining multi-instrument X-ray archives: QPE-like flare identified

Quintin et al. 2023, A&A 675, 152

The QPE-candidate Tormund

Quintin et al. 2023, A&A 675, 152

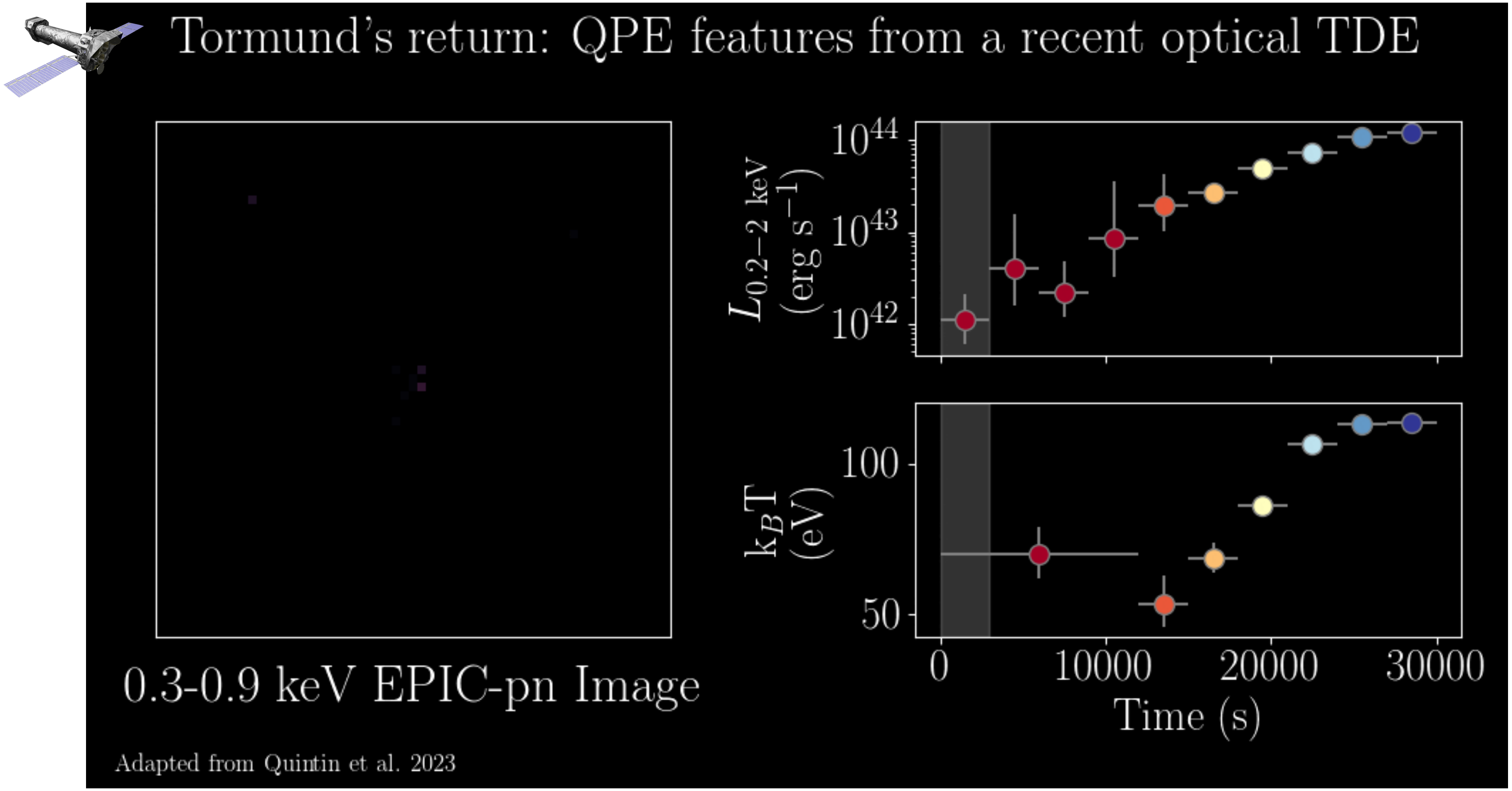
Optical peak: Nov 15, 2019



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

The QPE-candidate Tormund

Quintin et al. 2023, A&A 675, 152

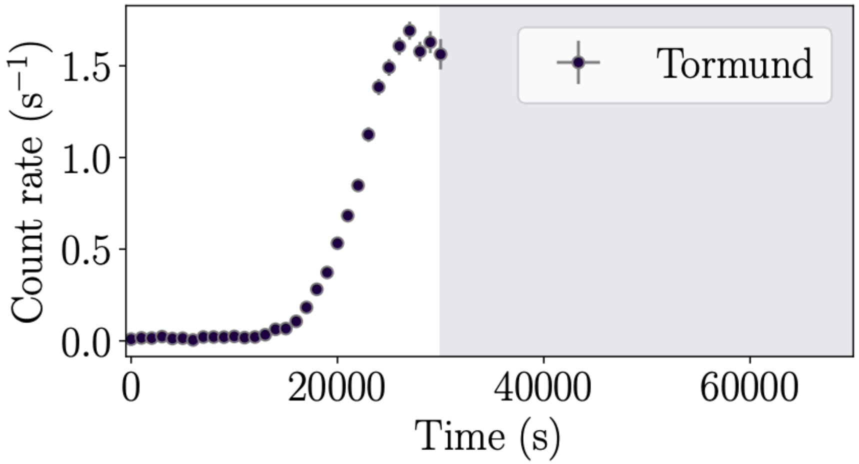


Animation credits: Erwan Quintin

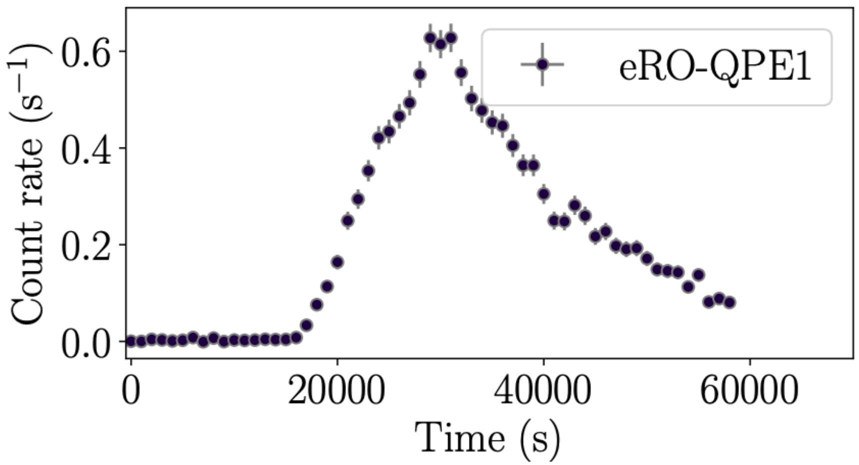
Rise of a flare very similar to eRO-QPE1

The QPE-candidate Tormund

Quintin et al. 2023, A&A 675, 152



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

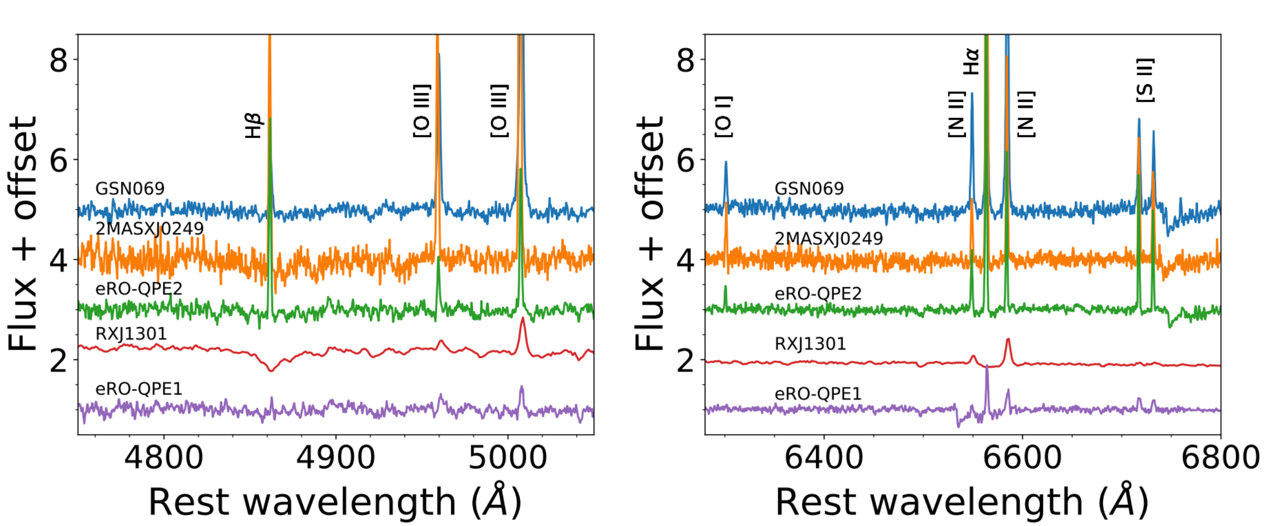


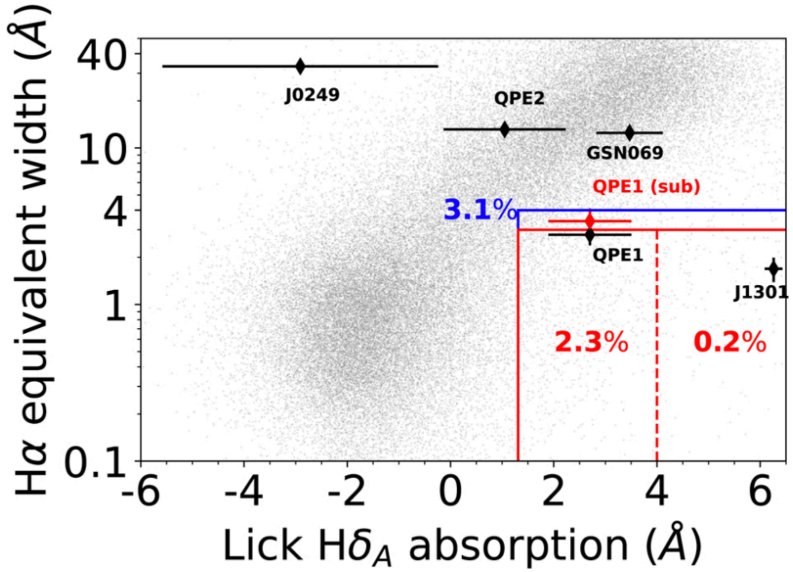
Release between 10^{42} and 10^{43} erg/s

Rise of a flare very similar to eRO-QPE1

QPE host galaxies: ground-base optical spectroscopy

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





- All the QPE-hosting galaxies show evidences of ionising photons in excess of starlight
- Low $M_{BH} = (0.9\text{-}45) \times 10^5\ M_{Sun}$
- Large fraction of very rare galaxies with low Hα EW (little ongoing star formation) and strong $H\delta_A$ absorption (recent starburst)

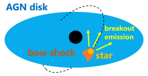
QPEs general properties

QPEs

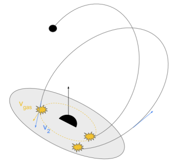
- A new transient phenomenon around $<10^7 M_\odot$ black holes
- Sharp, recurrent flares of soft X-ray emission with luminosity of 10^{42-43} erg/s
- Duration ~ 1 hour, up to 10 hours; time separation ~ few hours, up to few days
- Thermal-like X-ray spectra with kT ~ 100-250 eV at the peak
- Harder when brighter: the quiescence (when present) has kT ~ 50-70 eV
- Observed in the nuclei of low-mass galaxies, likely connected to TDEs
- Nuclear activity: no evident broad emission lines, 10^{40-41} erg/s
- Super-soft X-ray quiescent emission with weak or absent hard power-law

So, what are QPEs due to?

QPEs physical scenarios



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



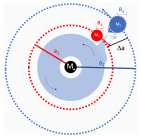
Pan, Li & Cao 2023, ApJ 952, 32

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

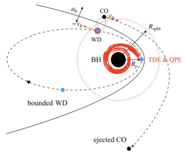
King 2020, MNRAS 493, 120

Kaur, Stone & Gilman 2023, MNRAS 524, 1269

Raj & Nixon 2021, ApJ 909, 82



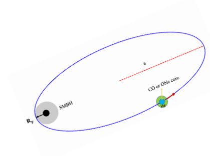
Zhao et al. 2022, A&A 661, 55

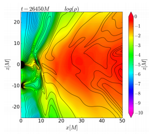


Wang et al. 2022, ApJ 933, 2

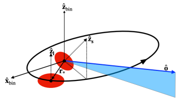
Metzger et al. 2022, ApJ 926, 101

Ingram et al. 2021, MNRAS 503, 1703





Sukova et al. 2021, ApJ 917, 43



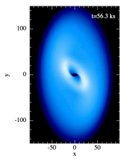
Chen et al. 2022, ApJ 930, 122

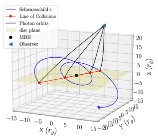
Linial & Sari 2023, ApJ 945, 86

Xian et al. 2021, ApJL 921, 32

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

Linial & Metzger 2023, ApJ in press, arXiv:2303.16231

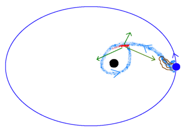




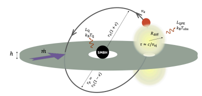
Lu & Quataert 2023, MNRAS 524, 6247

Franchini, Bonetti et al. 2023, A&A 675, 100

Krolik & Linial 2022, ApJ 941, 24



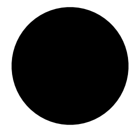
Tagawa & Haiman 2023, MNRAS 526, 69



QPEs physical scenarios

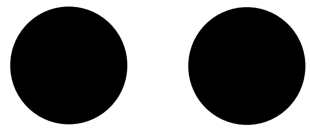
Accretion flow instabilities

- Radiation pressure instability
- Inner disk tearing
- Magnetic instabilities

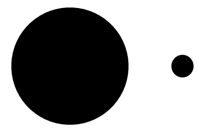


Orbital phenomena

- Self-lensing
  Massive Black Hole Binaries



- Extreme Mass Ratio
  Inspirals



QPEs physical scenarios

Accretion flow instabilities

Radiation pressure instability

Inner disk tearing

Magnetic instabilities

Sniegowska et al. 2020, A&A 641, 167
Sniegowska et al. 2023, A&A 672, 19
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…

Orbital phenomena

Self-lensing Massive Black Hole Binaries

Ingram et al. 2021, MNRAS 503, 1703

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Metzger et al. 2022, ApJ 926, 101
Wang et al. 2022, ApJ 933, 2
Zhao et al. 2022, A&A 661, 55
Lu & Quataert 2023, MNRAS 524, 6247
Krolik & Linial 2022, ApJ 941, 24
Linial & Sari 2023, ApJ 945, 86
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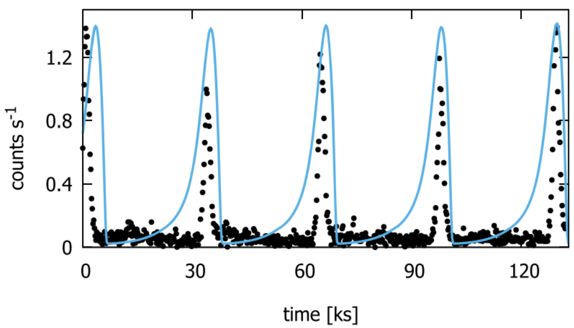
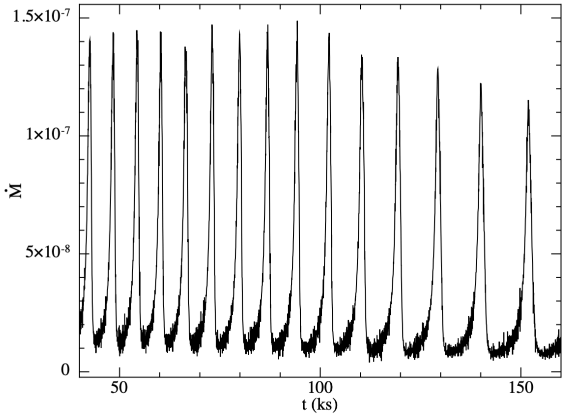
…

QPEs physical scenarios

Pan, Li & Cao 2023, ApJ 952, 32

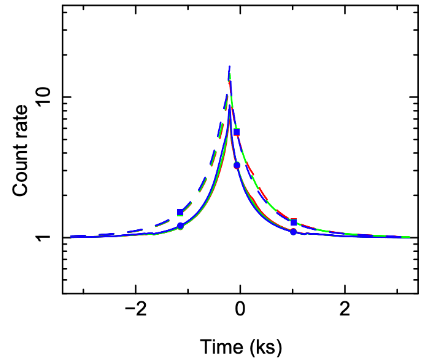
Radiation pressure instability





Ingram et al. 2021, MNRAS 503, 1703

Self-lensing Massive Black Hole Binaries

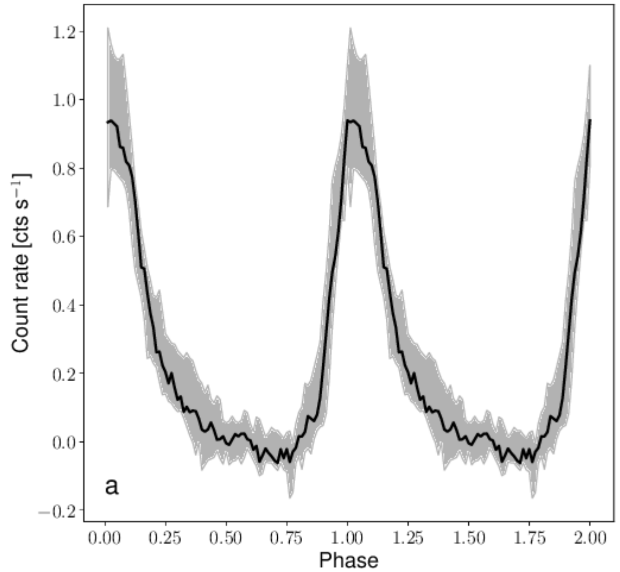


Expected profile: <u>symmetric</u> or

<u>slower</u> rise, fast decay

Arcodia et al. 2021, Nature 592, 704

Observed:

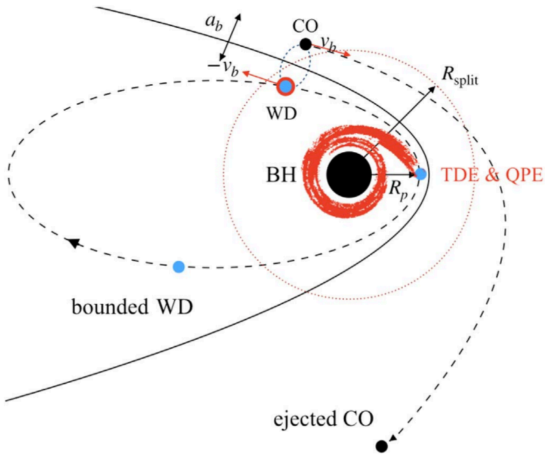


QPEs are generally asymmetric, with a faster rise and a slower decay

QPEs physical scenarios: EMRIs

- SMBH accretion of streams from episodic mass transfer in an EMRI

(King 2020, 2022; Chen et al. 2022; Wang et al. 2022; Zhao et al. 2022; Metzger et al. 2022; Linial & Sari 2022)



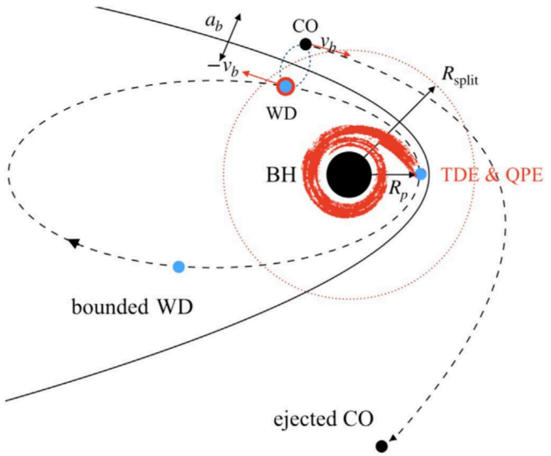
QPEs physical scenarios: EMRIs

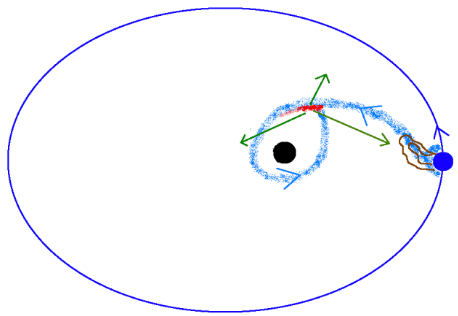
- **SMBH accretion** of streams from episodic mass transfer in an EMRI

  (King 2020, 2022; Chen et al. 2022; Wang et al. 2022; Zhao et al. 2022; Metzger et al. 2022; Linial & Sari 2022)

- **Shocks** from episodic mass transfer in an EMRI

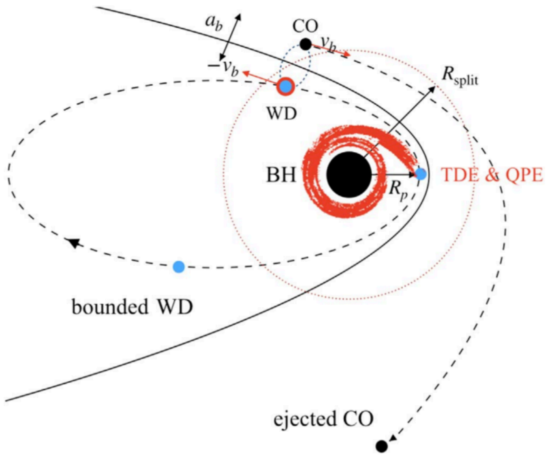
  (Krolik & Linial 2022; Lu & Quataert 2023)

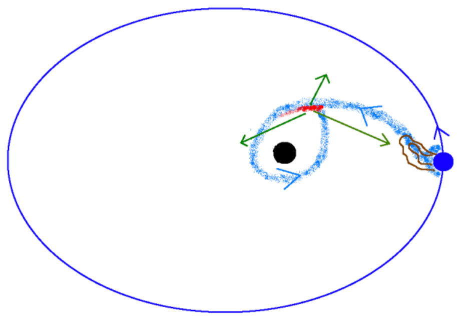


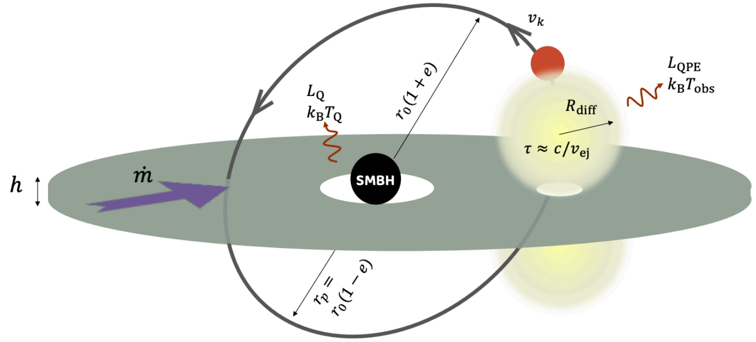


QPEs physical scenarios: EMRIs

- **SMBH accretion** of streams from episodic mass transfer in an EMRI
  (King 2020, 2022; Chen et al. 2022; Wang et al. 2022; Zhao et al. 2022; Metzger et al. 2022; Linial & Sari 2022)
- **Shocks** from episodic mass transfer in an EMRI
  (Krolik & Linial 2022; Lu & Quataert 2023)
- **Secondary-disc collisions** in an EMRI
  (Sukova et al. 2021; Xian et al. 2021; Linial & Metzger 2023; Franchini, Bonetti et al. 2023; Tagawa & Haiman 2023)







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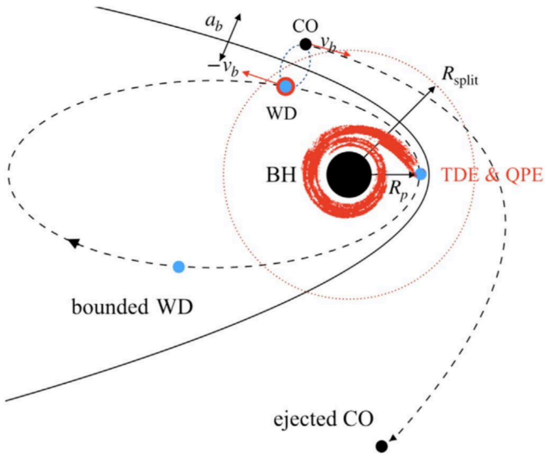
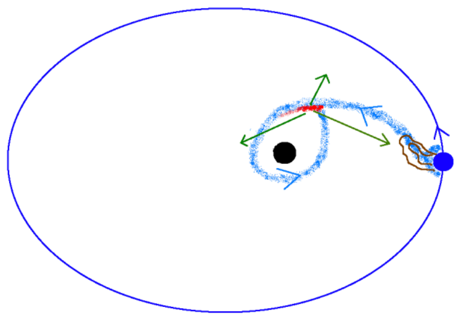
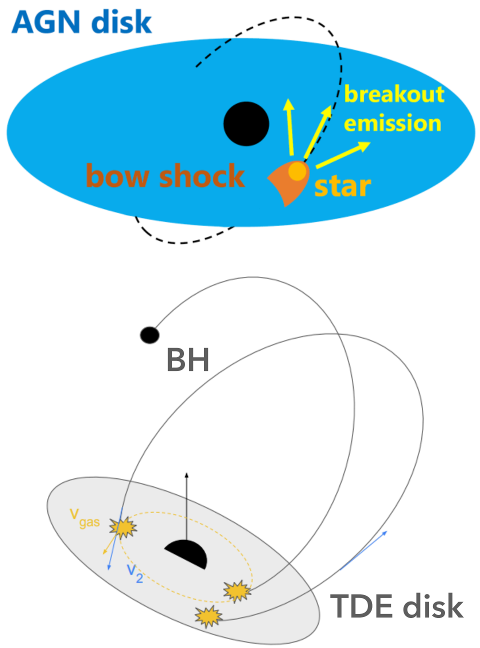


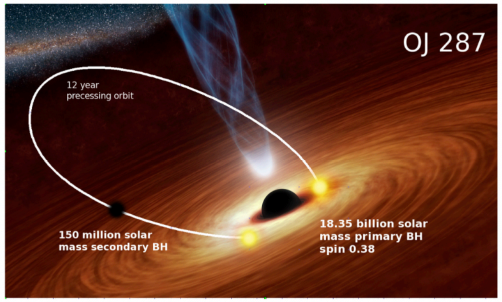




EMRIs: secondary-disk collisions

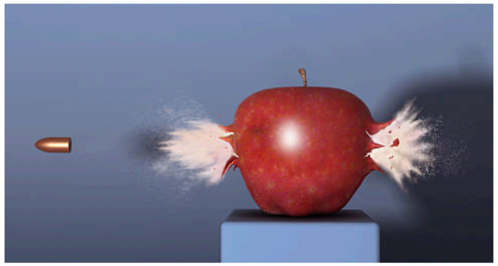
Xian et al. 2021; Linial & Metzger 2023; Franchini, Bonetti et al. 2023; Tagawa & Haiman 2023

- Secondary-disk collisions in an EMRI



Secondary: star or BH of 10-100 M_{sun}

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



The impact rises a two-sided expanding cloud [e.g. Pihajoki 2016]

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

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

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

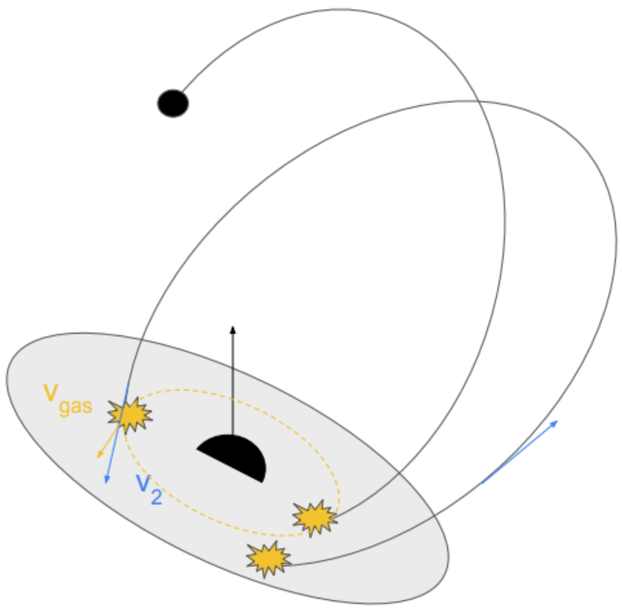
Soft X-ray emission with luminosity dependent on the cloud size (hence on relative velocity),

timing properties dependent on the EMRI dynamics and the disk properties

EMRIs: secondary-disk collisions

Franchini, Bonetti et al. 2023, A&A 675, 100

- Secondary-precessing disk collisions in an EMRI



Secondary: BH of 100 M_{sun}

The Massive BH is surrounded by a misaligned, rigidly precessing disk

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

EMRI eccentricity: 0.5-0.05

EMRI semi-major axis: 50-350 R_g

Disk mass: 0.01-4 M_{sun}

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

Soft X-ray emission with luminosity dependent on the cloud size (hence on relative velocity),

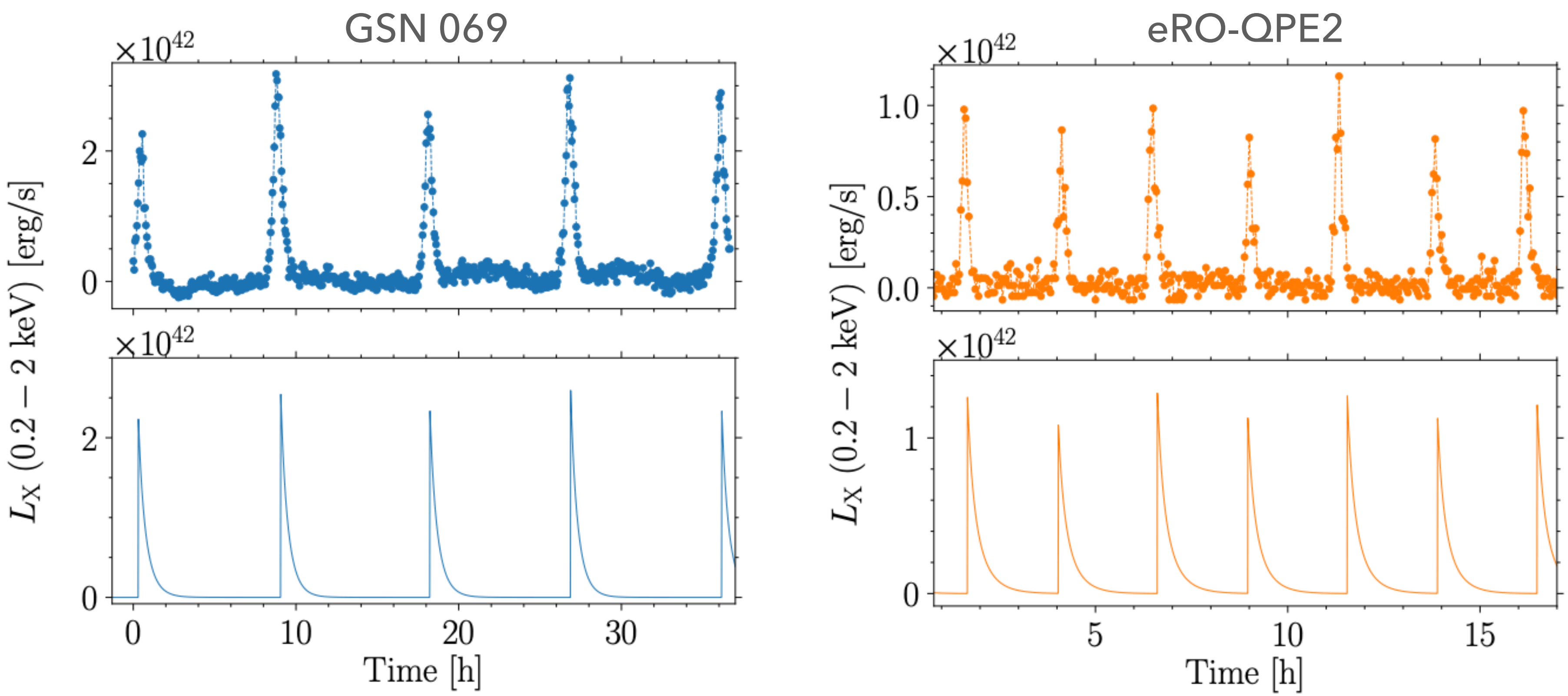
timing properties dependent on the EMRI dynamics and the disk properties

EMRIs: secondary-disk collisions

Franchini, Bonetti et al. 2023, A&A 675, 100

- Secondary-precessing disk collisions in an EMRI

Results:



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

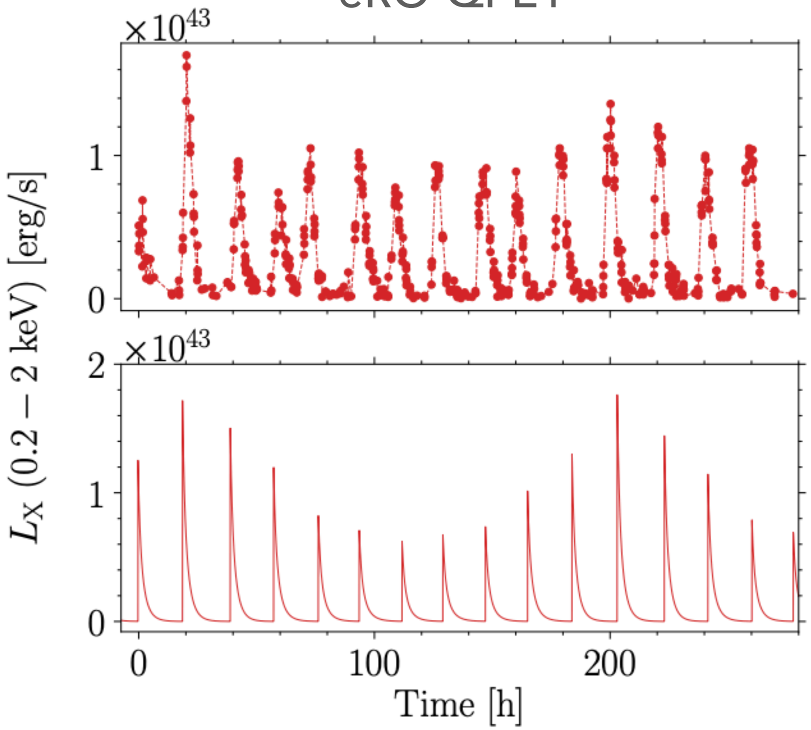
EMRIs: secondary-disk collisions

Franchini, Bonetti et al. 2023, A&A 675, 100

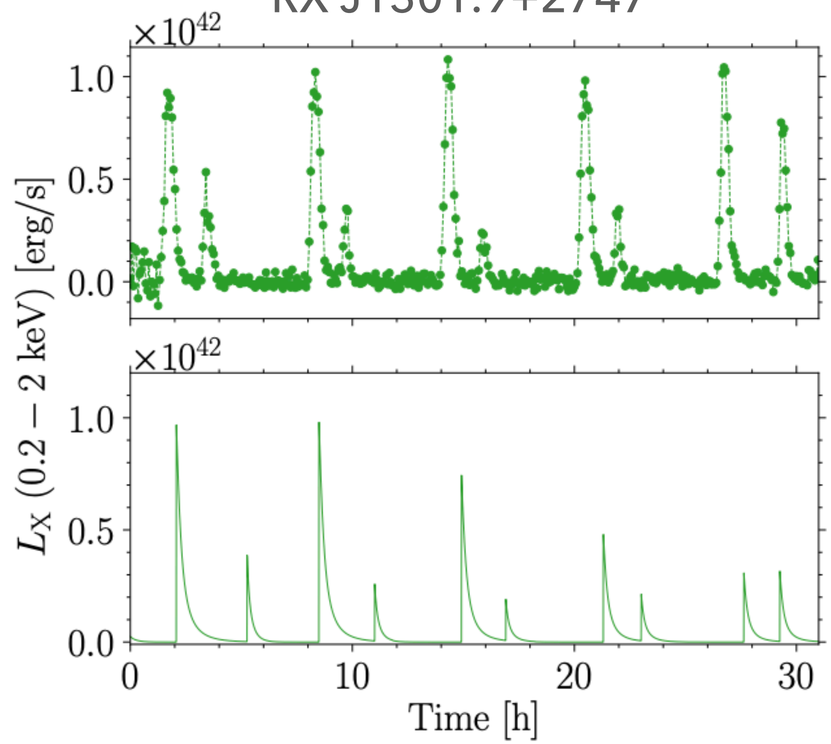
- Secondary-precessing disk collisions in an EMRI

Results:

eRO-QPE1



RX J1301.9+2747



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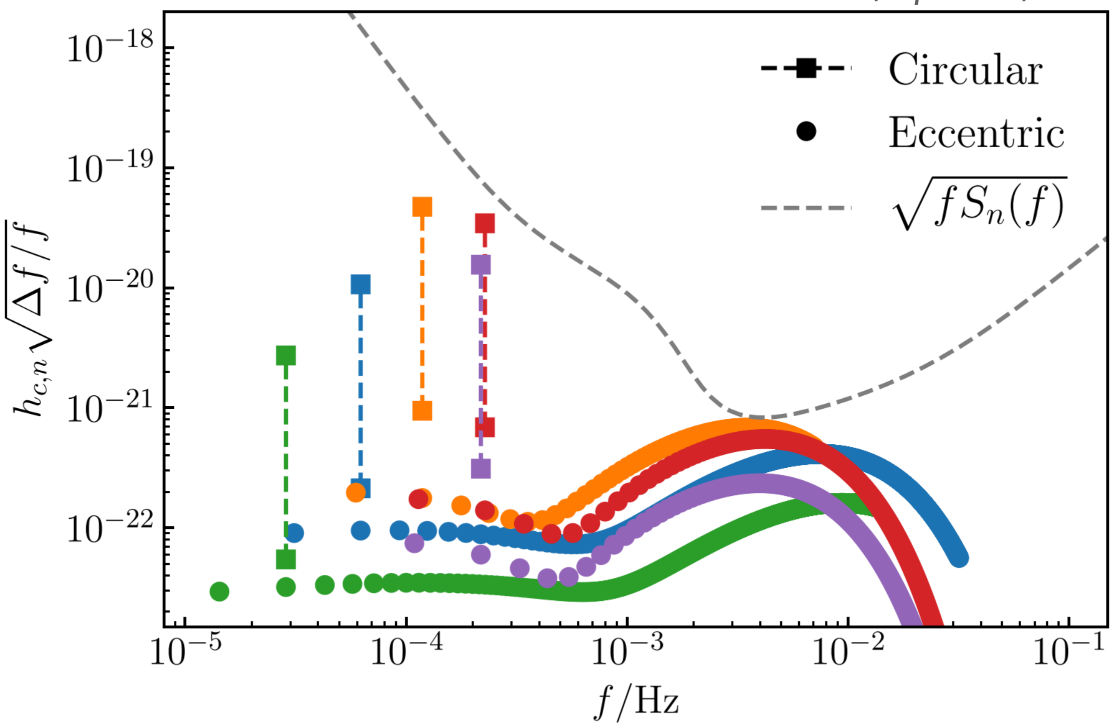
QPEs as GW sources

Chen et al. 2022, ApJ 930, 122



Wang et al. 2022, ApJ 933, 225

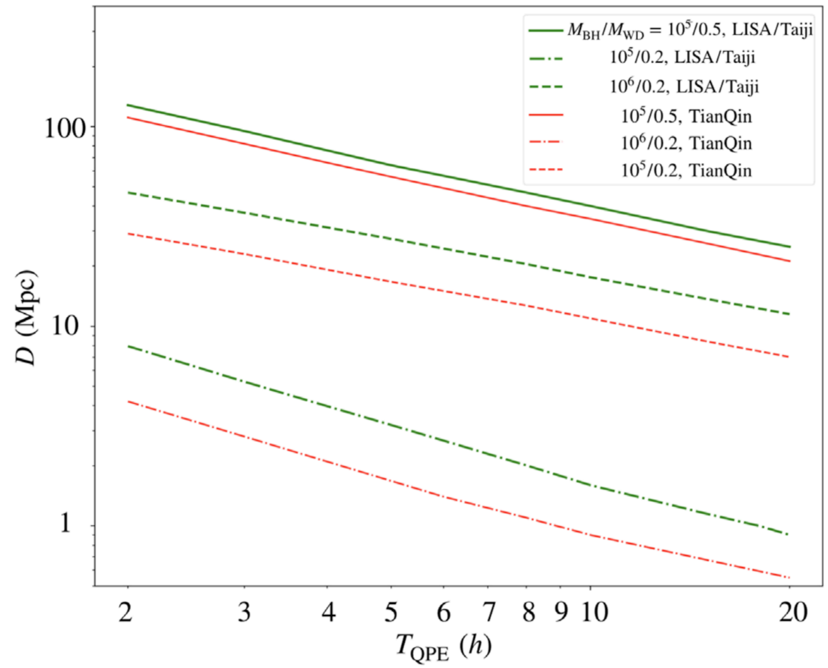


Figure 8. The relation between the distance limit D of GW detection (S/N > 5) and the period T_{QPE} in typical M_{BH} and M_{WD}. The green and red lines represent the detection limit of LISA/Taiji and TianQin, respectively

EMRI-star: does not emit significantly GWs – but can make significant background if in highly eccentric orbit. ***EMRI-BH –> ?***

Present/future developments

QPEs

X-ray observations are undergoing, both short monitoring and long staring ones

Is there any QPE-like emission at other wavelengths? Under investigation; e.g., upcoming HAWK-I @ VLT observations in the IR (PI: F. Vincentelli), HST observations in the UV (PI: T. Wevers)

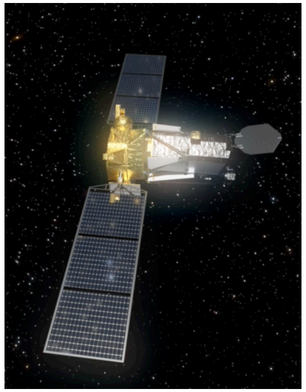
Can we falsify the star-disk collisions models? E.g., measure Pdot due to hydrodynamical drag: efforts undergoing (new XMM-Newton proposal under construction, PI: R. Arcodia)

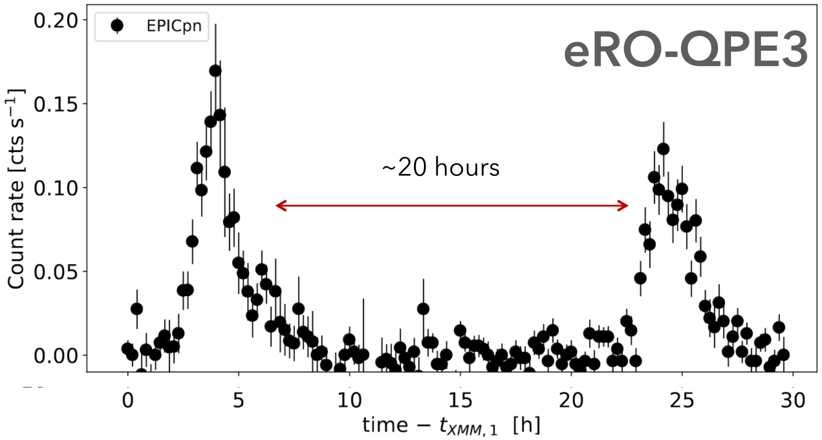
Can we find new candidates? Difficult(*), effort undergoing (NICER, Swift, XMM-Newton proposals, PIs: J. Chakraborty, E. Quintin)

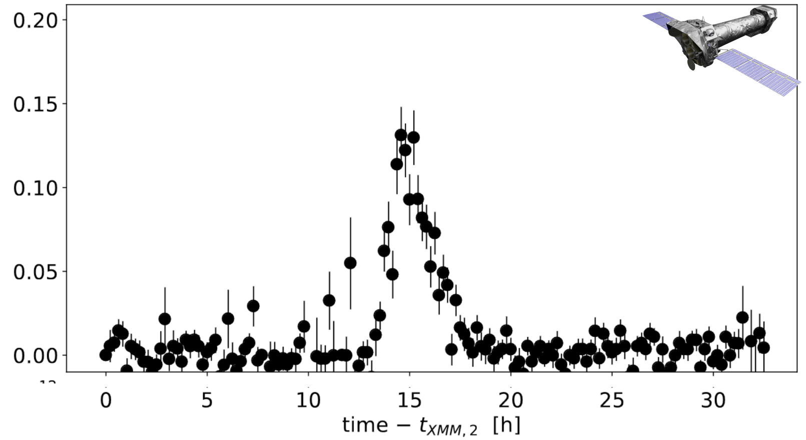
(*) the best QPE-discovering machine eROSITA is in safe-mode since March 2022 due to serious human problems on Earth.

Future: new QPE sources discovered by eROSITA

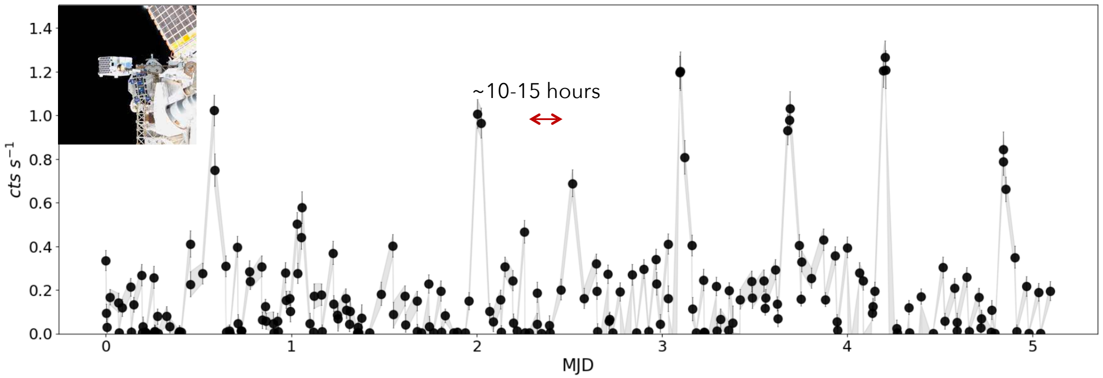
Arcodia et al. in prep.

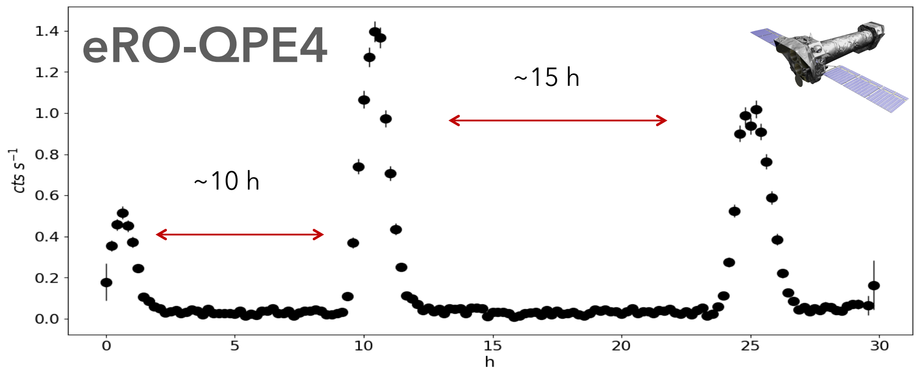






Courtesy of Riccardo Arcodia





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Conclusions

QPEs

- A new transient phenomenon around $<10^7\,M_\odot$ black holes
- Probe of a poorly sampled regime of BH accretion
- Likely connection to (p)TDEs
- Complex phenomenology, complex physics
- Potential electromagnetic counterpart of GW emission due to BH-EMRIs
- Lots of observational and theoretical efforts ongoing