

# FOUR SHALT THOU (NOT?) COUNT: NEW DETECTIONS OF mHZ QPOs IN PULSATING ULXs

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Martina Veresvarska  
and many others



NEWATHENA RISING  
3/6/2026

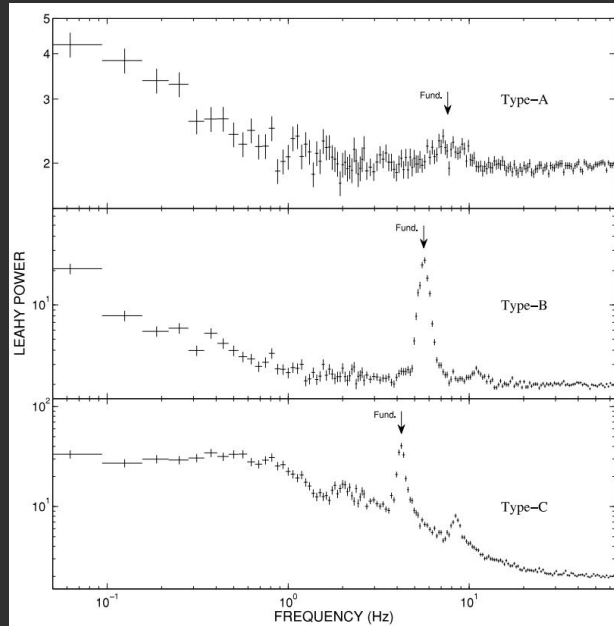
# WHAT WAS THAT?

A LITTLE TREAT FOR MONTY PYTHON FANS

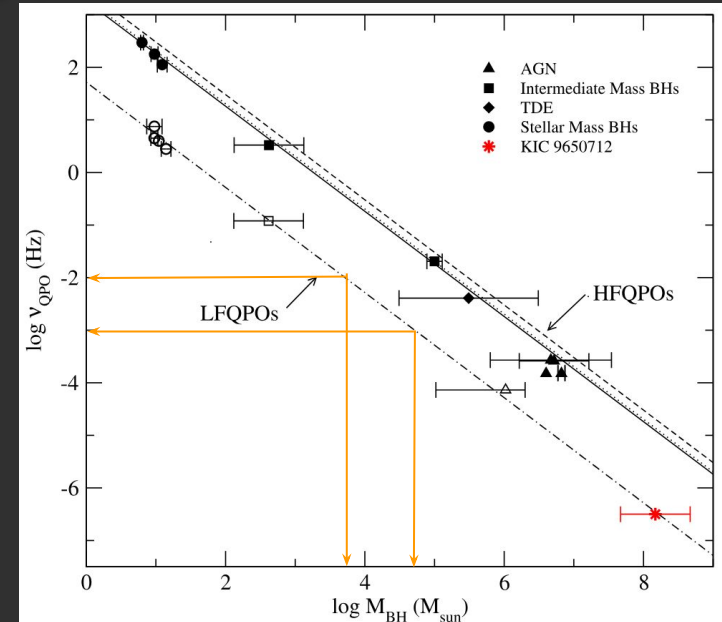


[Monty Python - Holy Hand Grenade](#)

# WHAT WAS I TALKING ABOUT? AH YES, QUASI-PERIODIC OSCILLATIONS



Motta+ 2011

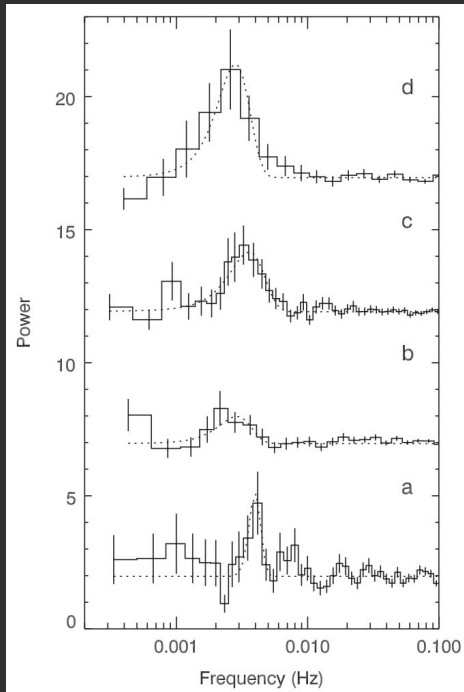


Smith+ 2018

- QPOs: broad features in the PDS.
- **Quality factor**:  $Q = \nu / \Delta\nu > 2$ .
- Related to **instabilities in the disk** and/or **precession of the disk**.

- Relation between the frequency  $\nu$  and the mass  $M_{\text{BH}}$  of the accretor.
- Lower  $\nu$   $\longrightarrow$  higher mass.

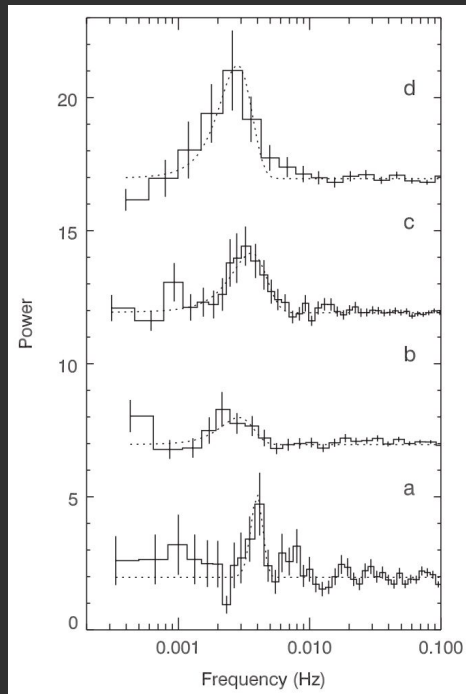
# X42.3+59: AN INTERMEDIATE-MASS BH?



Feng+ 2010

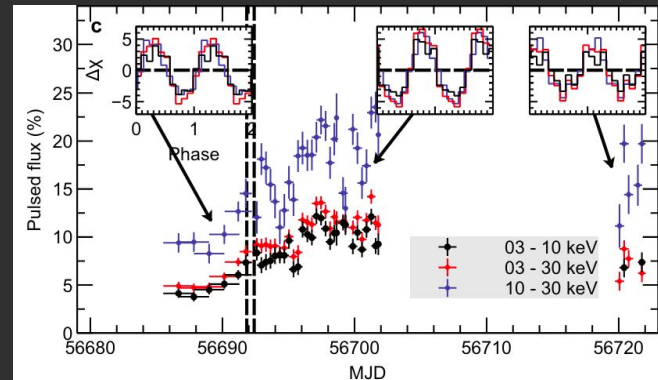
- **Early 2000's: we finally found the IMBHs...right?**
- QPOs at  $\nu \simeq 3\text{-}4$  mHz in X42.3+59, a ULX in M82.
- Scaling the mass with the frequency:  
 $M_{\text{source}} \sim 12000 - 43000 M_{\odot}$ .  
**A new IMBH?**

# MAYBE NOT...



Feng+ 2010

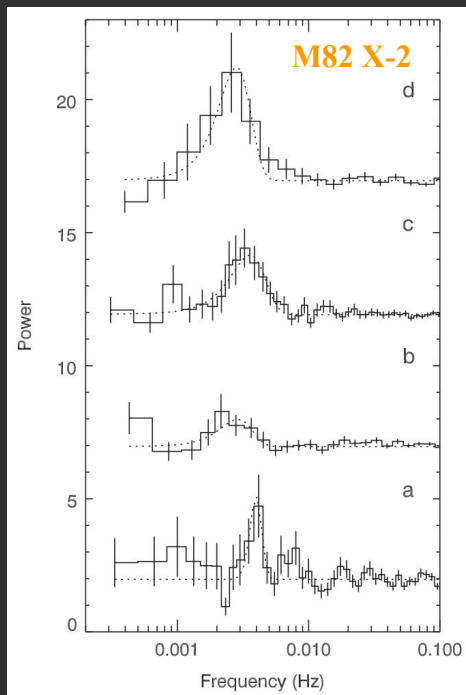
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 $M_{\text{source}} \sim 12000 - 43000 M_{\odot}$   
**A new IMBH?**
- The source is now known as **M82 X-2, the first PULX**, with spin pulsations at a period  $P \approx 1.3$  s.
- $M_{\text{NS}} \sim 1.4 - 2.5 M_{\odot}$ :  
**be careful with mass estimates!**



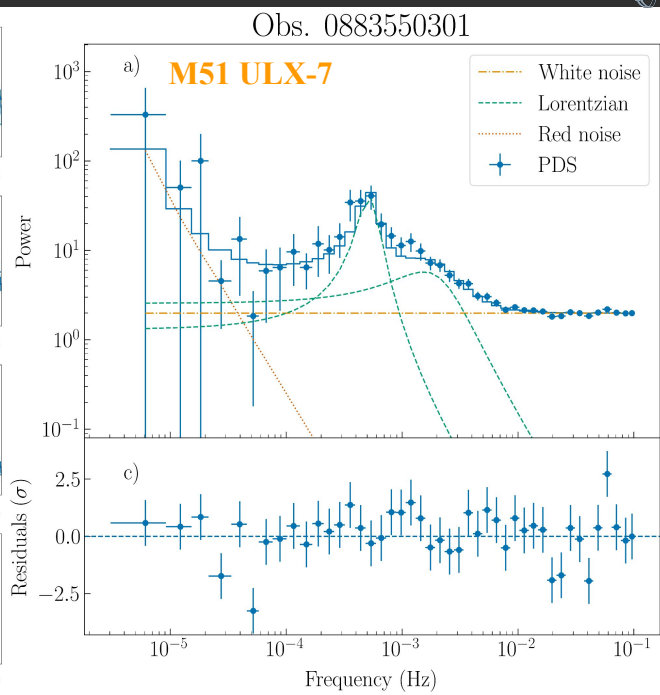
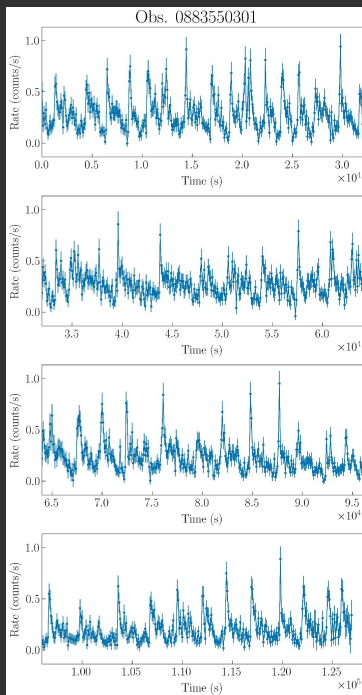
Bachetti+ 2014

# M82 X-2 AND M51 ULX-7: THE TWO PULXs WITH QPOs

- ULX-7: no coherent signal at 2.8 s, PF  $3\sigma$  upper limit at 6%. **Mis-detection caused by the QPO?**



Feng+ 2010

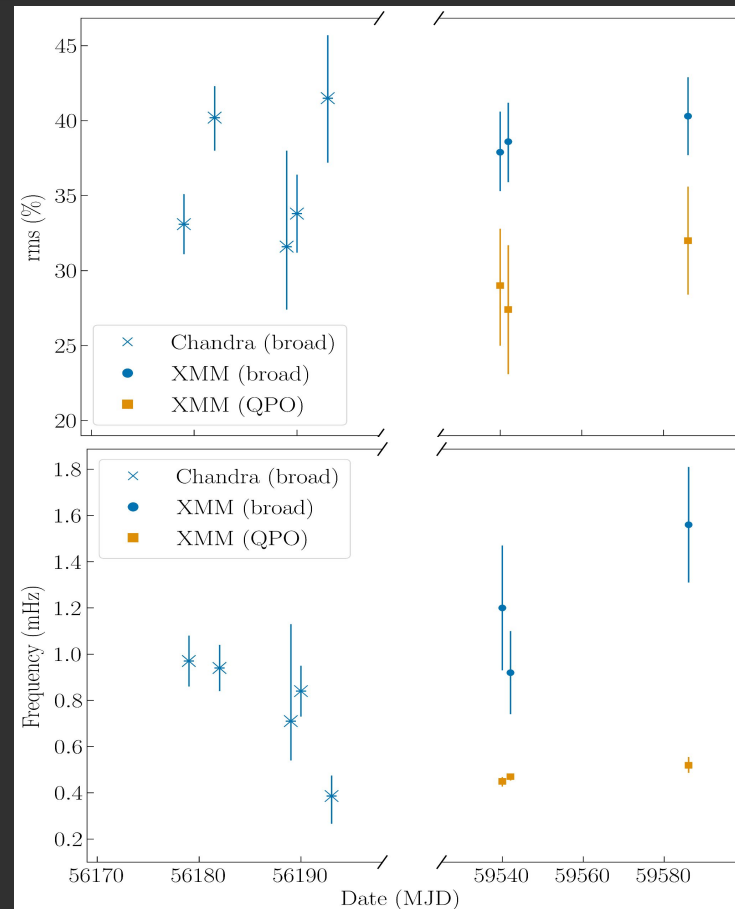


Imbrogno+ 2024



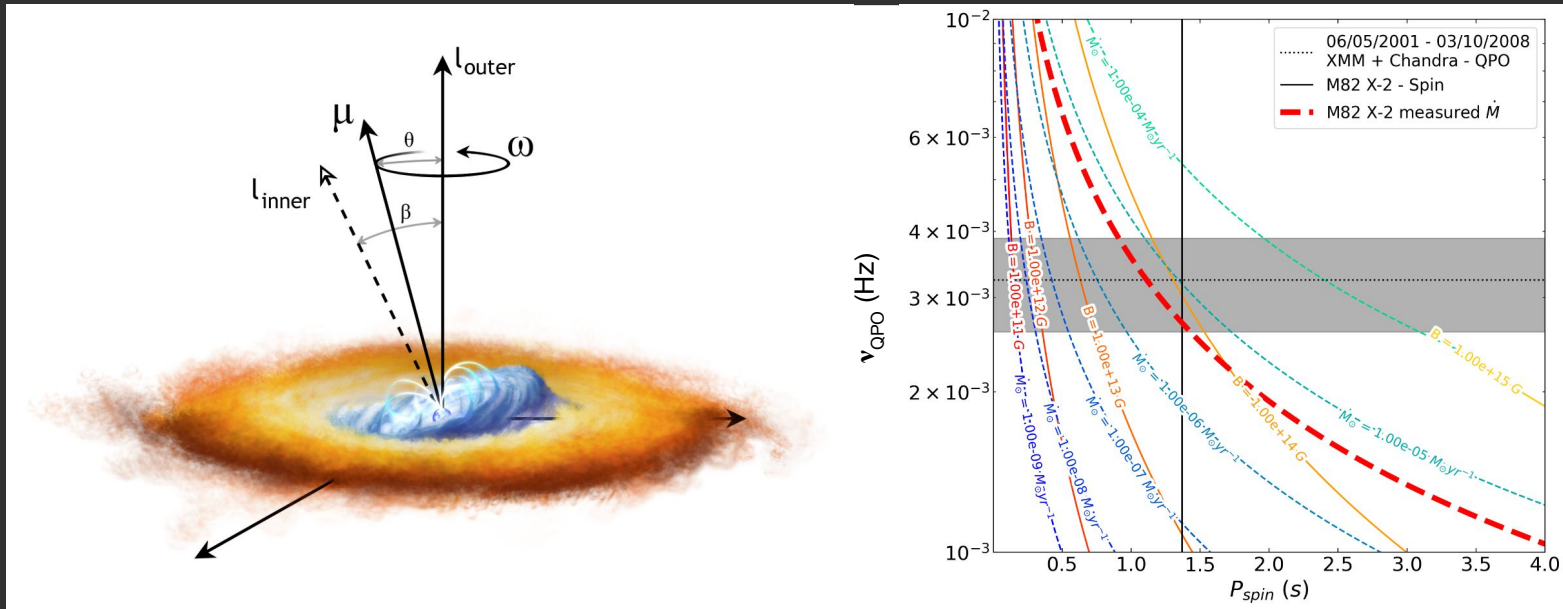
# ULX-7: ARCHIVAL DATA AND POSSIBLE EXPLANATIONS

- Feature detected in 5 consecutive Chandra archival observations. **Little variability between the two epochs** (10 years apart).
- QPO detected at super-Eddington luminosities, like M82 X-2.  
**Never present in XMM observations in which the pulsation is detected.**
- Energy spectra consistent with Castillo+ 2020: **no change in spectral state.**
- Our hypothesis: **the QPO is decreasing the pulsed fraction of the spin signal.**



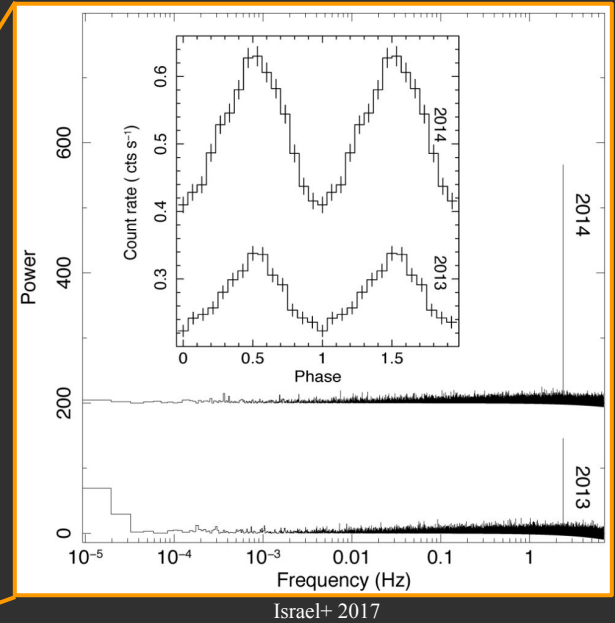
# MAGNETICALLY DRIVEN QPOs?

- Possibility: **magnetically driven QPOs**.
- **Results** on M51 ULX-7 and (especially) M82 X-2, with the given spin and QPO frequencies, are **very promising**:  $B \sim 10^{12} - 10^{14}$  G,  $\dot{M} \sim 10^{-7} - 10^{-5} M_{\odot} \text{ yr}^{-1}$ , no extreme beaming is needed. See also Cemelijic+ 2025.



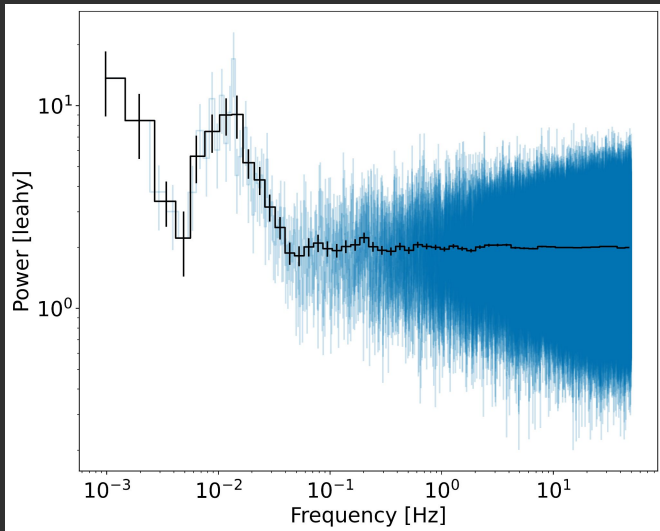
# NGC 7793 P13

- **Fastest known PULX:**
  - $P_{\text{spin}} \approx 410 \text{ ms}$
  - $\dot{P}_{\text{sec}} \sim -4 \times 10^{-11} \text{ s s}^{-1}$
- Observed multiple times: Chandra, NICER, NuSTAR, XMM.  
**Lots of archival data.**
- Long-term monitoring ongoing (see Fuerst+ 2021).



# NGC 7793 P13: A NEW QPO IN TOWN

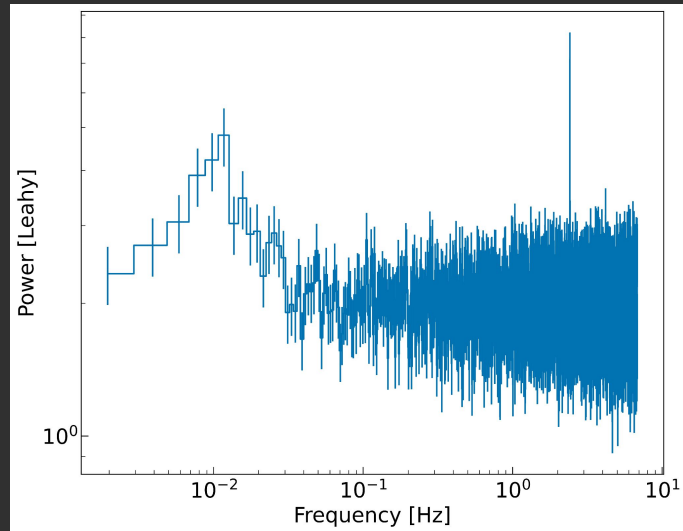
PRELIMINARY



Imbrogno+ in prep.

- Detected by different telescopes: NICER, NuSTAR, XMM.
- **When present, always the same frequency:**

$$\nu \simeq 15 \text{ mHz}$$



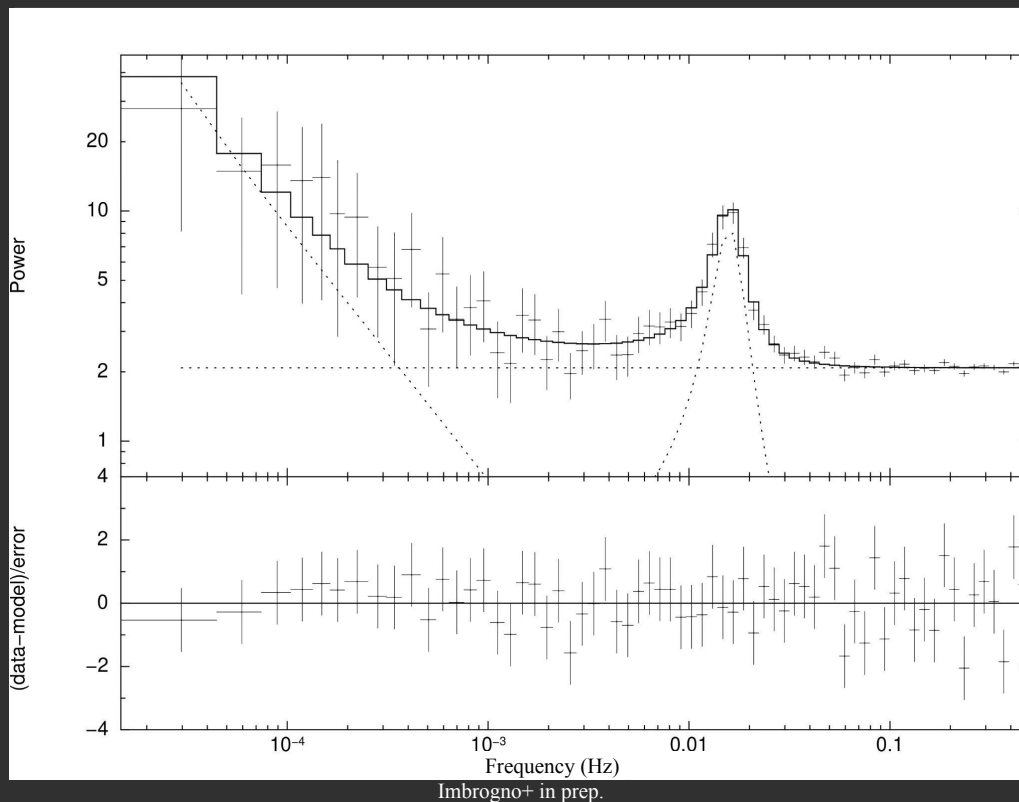
Imbrogno+ in prep.

- When both the QPO and the signal are present, the latter has a **very low pulsed fraction:**  
 $PF \simeq 5\text{-}10\%$
- Typical  $PF > 20\%$ .

# NGC 7793 P13: A NEW QPO IN TOWN

PRELIMINARY

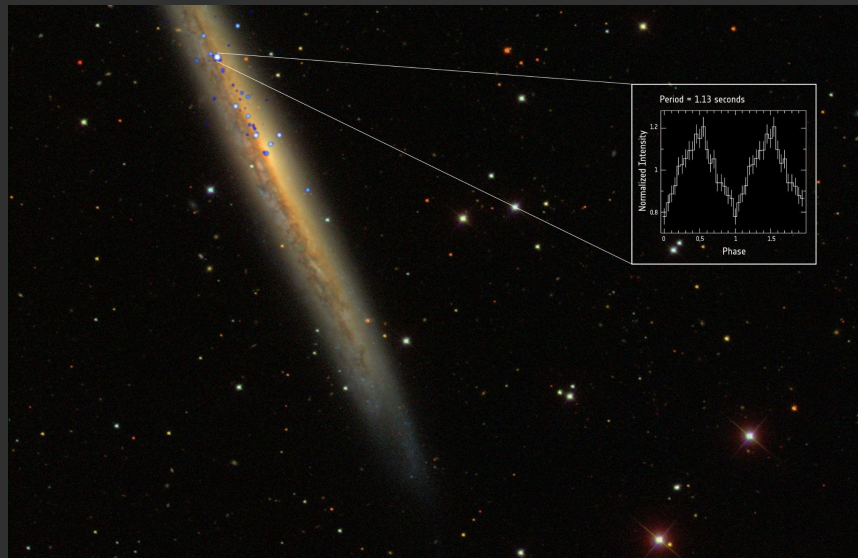
- This time, we can study its behaviour in different energy bands and study any correlations with e.g. the spin signal PF. **Work in progress!**
- Typical values:
  - $\nu \simeq 15.8(2)$  mHz
  - rms  $\simeq 26.5(7)$  %
  - PF  $\simeq 11\%$



Imbrogno+ in prep.

# NGC 5907 ULX-1

- NGC 5907 ULX-1 (Israel+ 2017):  
**the most distant and most luminous NS known**
  - $L_X \simeq 10^{41} \text{ erg s}^{-1}$
  - $d \simeq 17 \text{ Mpc}$
- Luminosity up to  $1000L_{\text{Edd}}$   
**Unique window into super-critical accretion regime.**
- $P_{\text{spin}} \simeq 1 \text{ s}$  near spin equilibrium (Fuerst+ 2023)



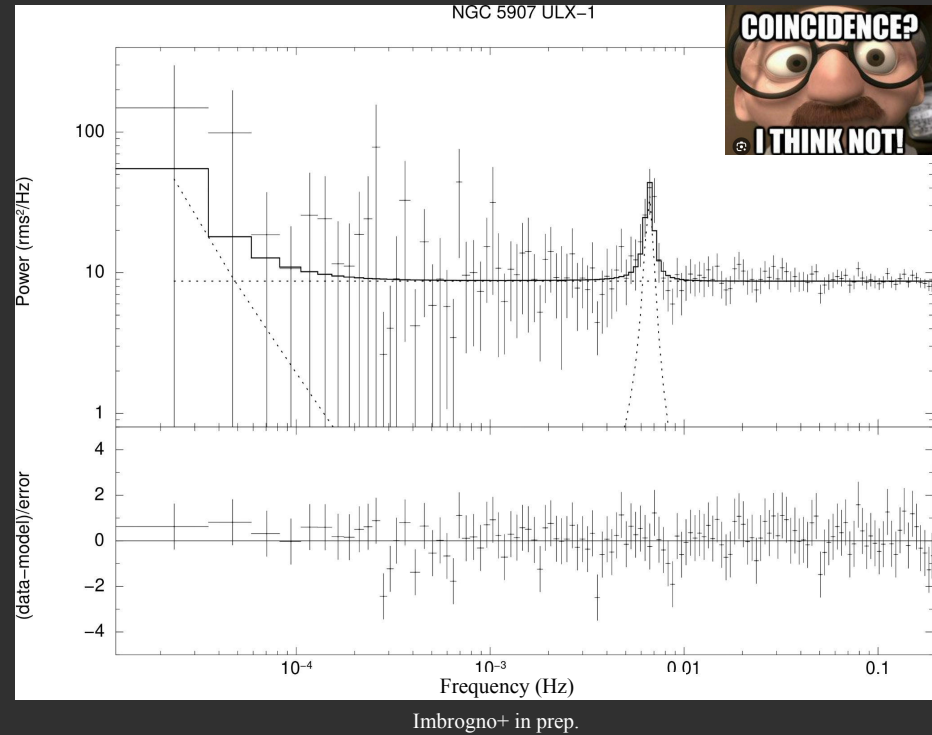
# NGC 5907 ULX-1: MAYBE I'M JUST SEEING QPOs EVERYWHERE

PRELIMINARY

- New QPO? Candidate? Is it just me seeing them everywhere?

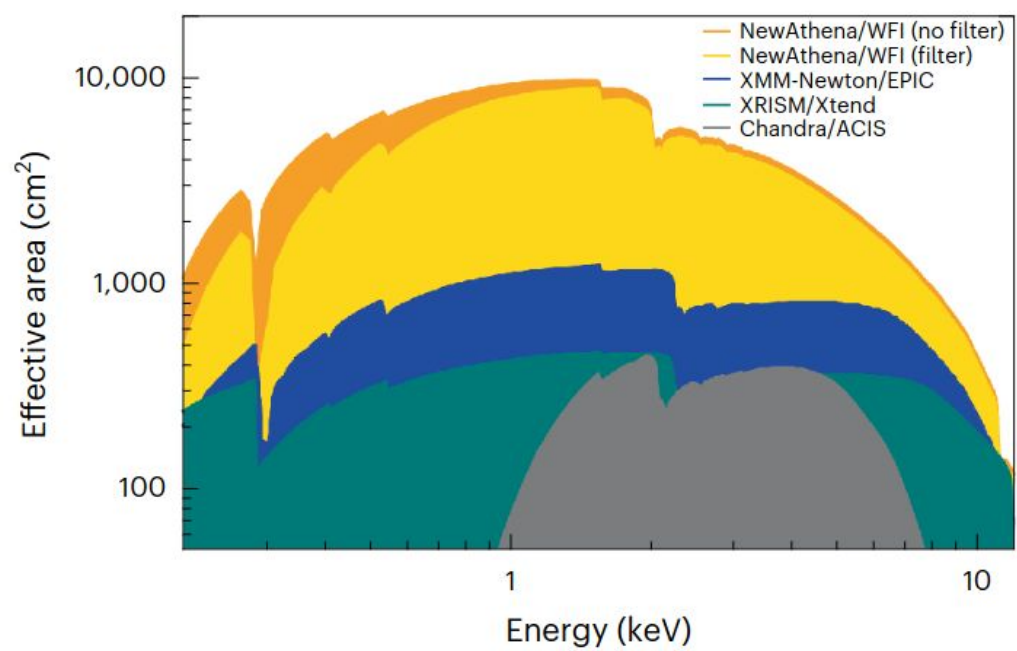


- Detection in a single observation:
  - $\nu \approx 7.0(3)$  mHz
  - $\text{rms} \approx 20\%$
- Marginal detection ( $\geq 3\sigma$ ).



# NEWATHENA TO THE RESCUE

- Most detections of (P)ULXs QPOs from XMM.
- What will be better than XMM for timing?  
**An even bigger XMM!**
  - Effective area  $\approx 10x$  XMM
  - Typical obs length  $\approx 100$  ks
  - Time resolution  $\approx 80 \mu s$
- **Perfect combination to study both the mHz QPOs and the spin signals of PULXs**, even at low pulsed fractions.



Effective areas (on-axis, 1, 3, 7 keV)	$> 9300 \text{ cm}^2, > 4600 \text{ cm}^2, > 1350 \text{ cm}^2$
Energy resolution	$< 170 \text{ eV}$ at 7 keV
Astrometric reconstruction accuracy	$< 1 \text{ arcsec}$ (LDA)
Time resolution	$< 80 \mu s$ (FD), 2 ms (LDA)
Non-X-ray Background intensity	$< 8 \times 10^{-3} \text{ counts/s/keV/cm}^2$

# FINAL THOUGHTS

- **NGC 7793 P13**: QPO at about 10 mHz. This time, in a few observations the spin signal is also present. Usually, it has a lower pulsed fraction.
- **NGC 5907 ULX-1**: is it a new QPO? Or is it just me seeing them everywhere?
- **Fraction of PULX over the whole ULX population even higher than previously estimated?**
- **NewAthena**, with its unique combination of high effective area, long uninterrupted observations, and high time resolution, **will allow us to study both the low-frequency QPOs and the spin signals of (P)ULXs.**
- For example, **given the higher number of detected photons, it will allow us to probe smaller pulsed fractions**, and verify the presence of the spin signal also in those observations in which the QPOs is seemingly turning the spin signal off.

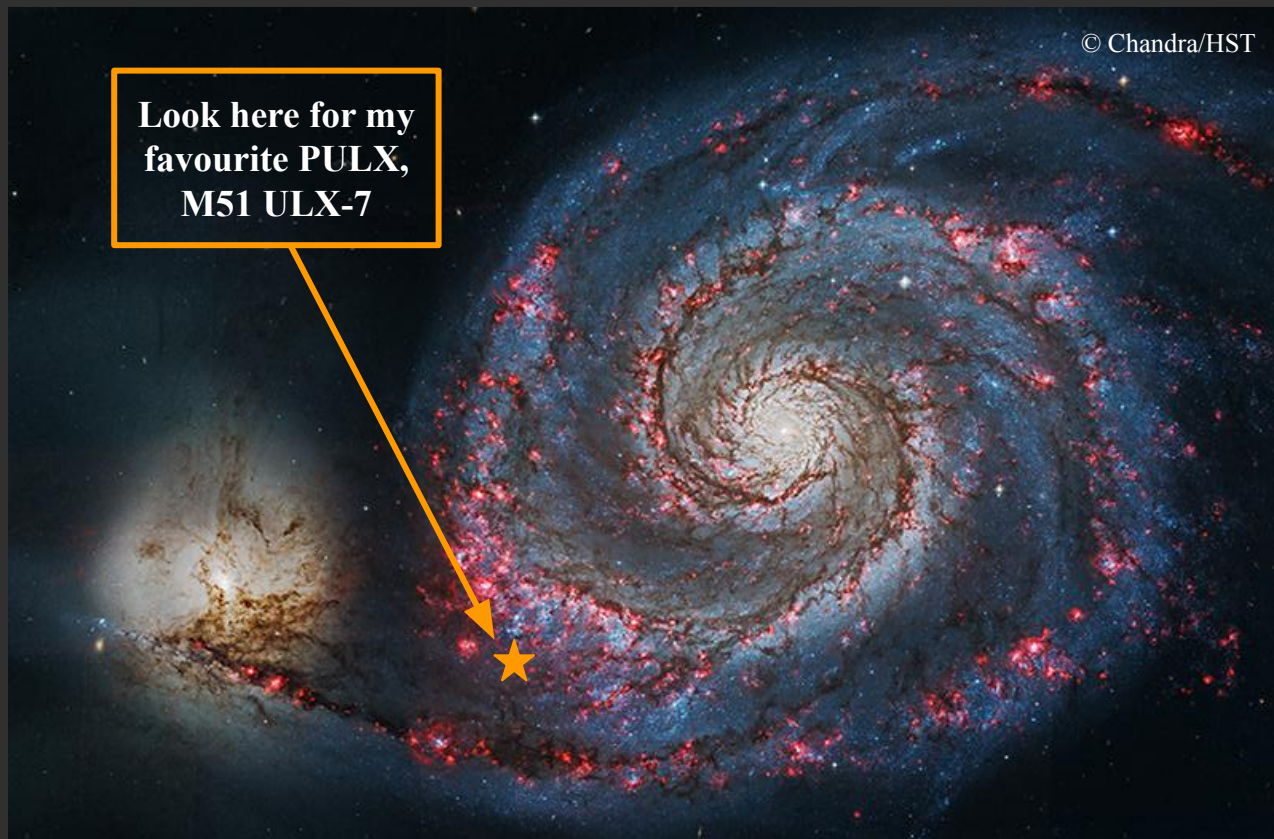
SO LONG AND...





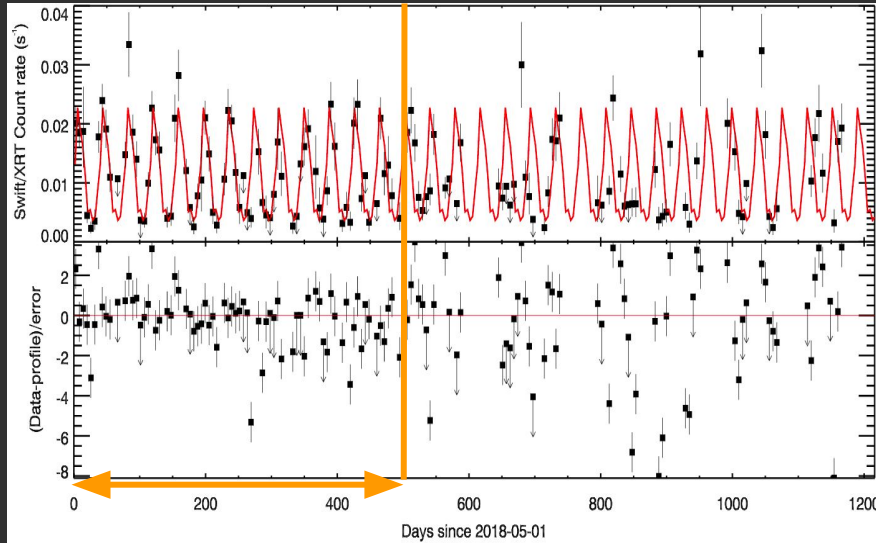
# M51: THE WHIRLPOOL GALAXY

- Pair of interacting galaxies, hosting 9 ULXs (Terashima & Wilson, 2004).
- $d \approx 8.58$  Mpc.
- **At least another NS-powered ULX:** M51 ULX-8 (CRSF in the spectrum, no detected pulsation yet; Brightman+ 2018).

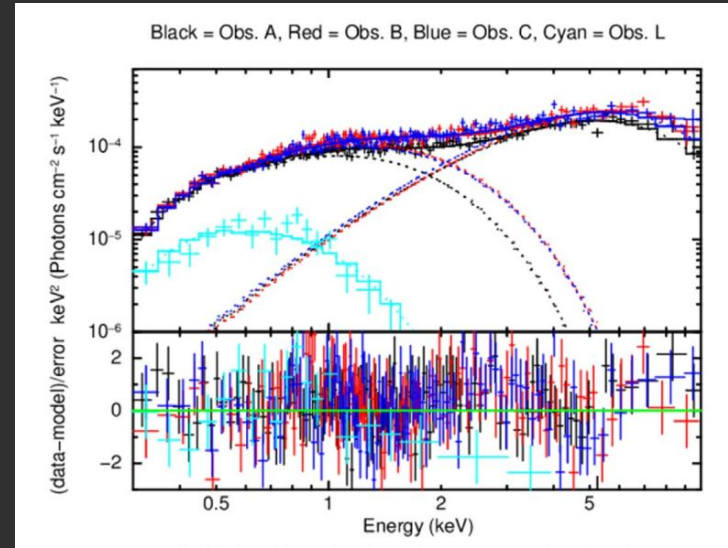


# GET TO KNOW ULX-7 A BIT MORE

Brightman+ 2022



Rodríguez Castillo+ 2020



- **Superorbital modulation**: Brightman+ 2020 ( $P \approx 38$  d), **signs of evolution** towards  $P \approx 44$  d (Brightman+ 2022).
- Peak luminosity:  $L_x \approx (5-7) \times 10^{39} \text{ erg s}^{-1}$

- Persistent source (detected in 13 out of 14 XMM observations).
- 2018: Pulsation detected when the hard component is visible.

**Table 3.** Best-fit spectral parameters of the latest *XMM-Newton* observations with the double-disk model.

Observation	$n_{\text{H}}^a$ ( $10^{20} \text{ cm}^{-2}$ )	$kT_{\text{soft}}$ (keV)	Norm.	$kT_{\text{hard}}$ (keV)	Norm. ( $10^{-4}$ )	Flux <sup>b</sup> ( $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ )	Lum. <sup>c</sup> ( $10^{39} \text{ erg s}^{-1}$ )	$\chi^2/\text{dof}$	n.h.p.
B	$9.1^{+3.1}_{-2.7}$	$0.32^{+0.04}_{-0.03}$	$0.7^{+0.6}_{-0.3}$	$2.63^{+0.20}_{-0.17}$	$5.7^{+1.5}_{-1.3}$	$5.37 \pm 0.08$	$5.34 \pm 0.08$	297.93/309	0.664
C	$8.1^{+2.5}_{-2.3}$	$0.33 \pm 0.03$	$0.6^{+0.4}_{-0.2}$	$2.78^{+0.21}_{-0.17}$	$4.6^{+1.2}_{-1.0}$	$5.37 \pm 0.07$	$5.31 \pm 0.07$	306.91/337	0.879
B+C	$8.5^{+1.7}_{-1.8}$	$0.33 \pm 0.02$	$0.6^{+0.3}_{-0.2}$	$2.71^{+0.13}_{-0.12}$	$5.0^{+0.9}_{-0.8}$	$5.37 \pm 0.05$	$5.33 \pm 0.05$	607.21/651	0.889

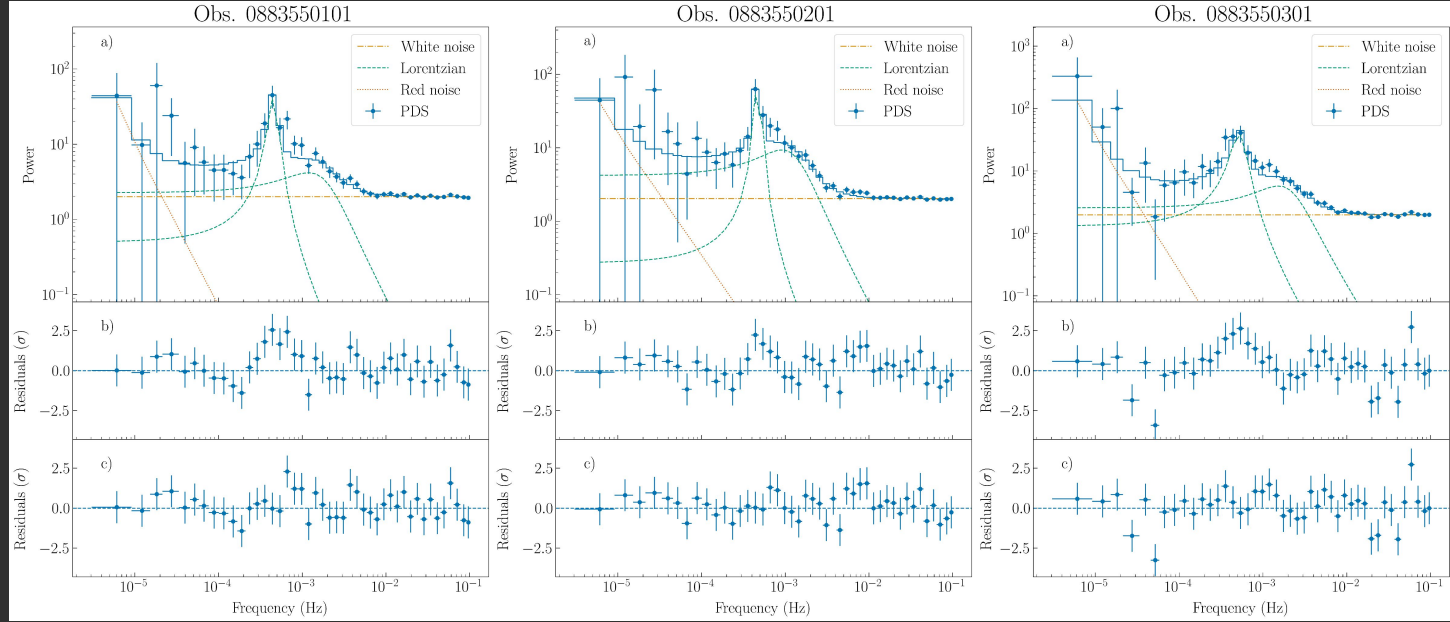
**Notes.** <sup>(a)</sup> The Galactic absorption component was fixed to  $n_{\text{H,gal}} = 3.3 \times 10^{20} \text{ cm}^{-2}$  (HI4PI Collaboration et al. 2016). <sup>(b)</sup> Observed flux in the 0.3–10 keV band. <sup>(c)</sup> Unabsorbed luminosity in the 0.3–10 keV band.

**Table 4.** Best-fit parameters of the spectra during the peaks and the minima (no-peak) of the modulation of the latest *XMM-Newton* observations. We considered the same double-disk model as before.

Observation	$n_{\text{H}}^a$ ( $10^{20} \text{ cm}^{-2}$ )	$kT_{\text{soft}}$ (keV)	Norm.	$kT_{\text{hard}}$ (keV)	Norm. ( $10^{-4}$ )	Flux <sup>b</sup> ( $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ )	Lum. <sup>c</sup> ( $10^{39} \text{ erg s}^{-1}$ )	$\chi^2/\text{dof}$	n.h.p.
B									
peak	$10.0^{+5.8}_{-4.7}$	$0.31^{+0.07}_{-0.05}$	$1.1^{+2.0}_{-0.7}$	$2.7^{+0.4}_{-0.3}$	$7.0^{+3.6}_{-2.7}$	$7.4 \pm 0.2$	$7.4 \pm 0.2$	159.28/162	0.546
no-peak	$7.8^{+3.5}_{-3.1}$	$0.34^{+0.05}_{-0.04}$	$0.5^{+0.5}_{-0.3}$	$2.8 \pm 0.3$	$4.0^{+1.7}_{-1.3}$	$4.67 \pm 0.09$	$4.61 \pm 0.09$	288.73/255	0.072
C									
peak	$10.8^{+5.1}_{-4.3}$	$0.30^{+0.05}_{-0.04}$	$1.4^{+1.9}_{-0.8}$	$2.9^{+0.4}_{-0.3}$	$5.7^{+2.8}_{-2.1}$	$7.30 \pm 0.18$	$7.46 \pm 0.18$	175.12/180	0.589
no-peak	$5.8^{+3.0}_{-2.6}$	$0.36^{+0.05}_{-0.04}$	$0.32^{+0.28}_{-0.15}$	$2.8^{+0.3}_{-0.2}$	$4.0^{+1.4}_{-1.1}$	$4.62 \pm 0.08$	$4.45 \pm 0.08$	277.37/277	0.482
B+C									
peak	$10.5^{+3.7}_{-3.2}$	$0.31^{+0.04}_{-0.03}$	$1.3^{+1.2}_{-0.6}$	$2.8^{+0.3}_{-0.2}$	$6.2^{+2.1}_{-1.7}$	$7.35 \pm 0.13$	$7.45 \pm 0.13$	337.69/347	0.63
no-peak	$6.6^{+2.2}_{-2.0}$	$0.35^{+0.04}_{-0.03}$	$0.39^{+0.23}_{-0.14}$	$2.76^{+0.20}_{-0.17}$	$4.0^{+1.0}_{-0.8}$	$4.64 \pm 0.06$	$4.52 \pm 0.06$	567.63/537	0.174

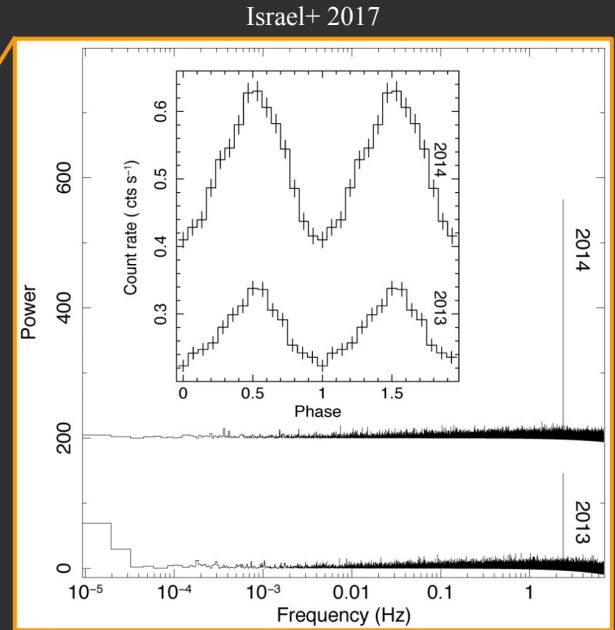
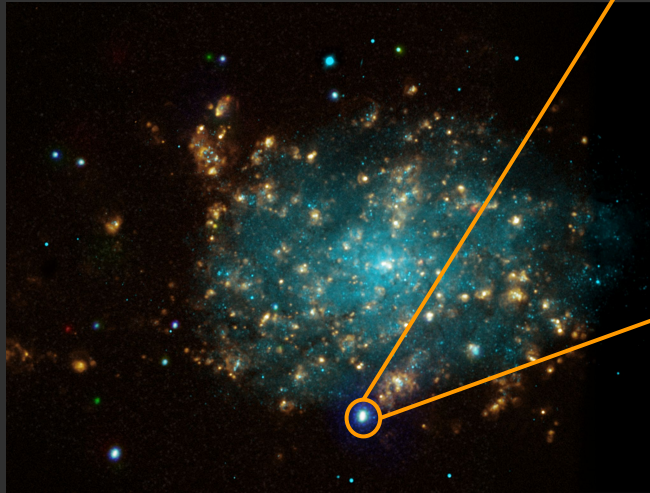
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ObsID	$\nu_{\text{QPO}}$ (mHz)	$\Delta\nu_{\text{QPO}}$ (mHz)	$\nu_{\text{char,QPO}}$ (mHz)	$Q_{\text{QPO}}$	$\text{rms}_{\text{QPO}}$ (%)	$\nu_{\text{broad}}$ (mHz)	$\Delta\nu_{\text{broad}}$ (mHz)	$\nu_{\text{char,broad}}$ (mHz)	$Q_{\text{broad}}$	$\text{rms}_{\text{broad}}$ (%)	$\chi^2/\text{dof}$
0.3–10 keV											
A	$0.449^{+0.019}_{-0.022}$	$0.088^{+0.054}_{-0.035}$	$0.451^{+0.019}_{-0.022}$	5.1	$29.0^{+3.8}_{-4.0}$	$1.20^{+0.26}_{-0.27}$	$2.60^{+0.67}_{-0.53}$	$1.77^{+0.30}_{-0.27}$	0.5	$37.9^{+2.7}_{-2.6}$	27.74/35
B	$0.470^{+0.012}_{-0.017}$	$0.046^{+0.053}_{-0.046}$	$0.470^{+0.011}_{-0.017}$	10.2	$27.4 \pm 4.3$	$0.92^{+0.18}_{-0.14}$	$1.65^{+0.31}_{-0.26}$	$1.24^{+0.17}_{-0.13}$	0.6	$38.6^{+2.6}_{-2.7}$	24.23/35
C	$0.519^{+0.036}_{-0.033}$	$0.183^{+0.069}_{-0.061}$	$0.527^{+0.036}_{-0.033}$	2.8	$32.0 \pm 3.6$	$1.56^{+0.25}_{-0.23}$	$2.74^{+0.53}_{-0.43}$	$2.08^{+0.26}_{-0.22}$	0.6	$40.3 \pm 2.6$	46.66/37
A+B+C	$0.565^{+0.034}_{-0.036}$	$0.269^{+0.067}_{-0.054}$	$0.581^{+0.034}_{-0.035}$	2.1	$29.5 \pm 2.4$	$1.34 \pm 0.17$	$2.45^{+0.37}_{-0.31}$	$1.81^{+0.18}_{-0.16}$	0.5	$36.1 \pm 1.8$	128.31/124
0.3–1.5 keV											
A <sup>a</sup>	$0.534^{+0.024}_{-0.027}$	$0.148^{+0.062}_{-0.081}$	$0.539^{+0.025}_{-0.028}$	3.6	$32.9^{+3.4}_{-4.0}$	$1.48^{+0.18}_{-0.20}$	$1.56^{+0.76}_{-0.53}$	$1.67^{+0.24}_{-0.22}$	0.9	$32.3^{+2.5}_{-3.4}$	32.26/24
B	$0.467^{+0.014}_{-0.017}$	$0.061^{+0.052}_{-0.035}$	$0.468^{+0.014}_{-0.017}$	7.6	$29.7^{+4.2}_{-4.5}$	$1.04^{+0.40}_{-0.18}$	$1.21^{+0.76}_{-0.48}$	$1.20^{+0.39}_{-0.19}$	0.9	$29.7^{+3.7}_{-3.5}$	43.13/35
C	$0.484^{+0.031}_{-0.028}$	$0.184^{+0.058}_{-0.063}$	$0.493^{+0.031}_{-0.028}$	2.6	$31.8^{+3.5}_{-3.6}$	$1.54^{+0.21}_{-0.24}$	$1.81^{+0.43}_{-0.42}$	$1.79^{+0.21}_{-0.24}$	0.9	$33.8 \pm 3.2$	25.33/35
1.5–10 keV											
A <sup>a</sup>	$0.509^{+0.072}_{-0.044}$	$0.25^{+0.22}_{-0.10}$	$0.525^{+0.075}_{-0.045}$	2.0	$36.9^{+5.1}_{-5.5}$	$1.52^{+0.26}_{-0.43}$	$1.21^{+0.66}_{-0.63}$	$1.64^{+0.27}_{-0.42}$	1.3	$32.7^{+7.6}_{-6.3}$	34.30/23
B	$0.469^{+0.014}_{-0.022}$	$0.047^{+0.067}_{-0.047}$	$0.470^{+0.014}_{-0.022}$	9.9	$25.8 \pm 5.3$	$1.03^{+0.19}_{-0.18}$	$1.68^{+0.38}_{-0.31}$	$1.33^{+0.19}_{-0.17}$	0.6	$46.3^{+3.8}_{-3.3}$	22.67/35
C	$0.538^{+0.028}_{-0.041}$	$0.26^{+0.12}_{-0.10}$	$0.553^{+0.030}_{-0.042}$	2.1	$34.6 \pm 5.4$	$1.27^{+0.71}_{-0.53}$	$4.08^{+0.98}_{-0.81}$	$2.40^{+0.55}_{-0.44}$	0.3	$47.5^{+3.9}_{-4.9}$	34.71/35



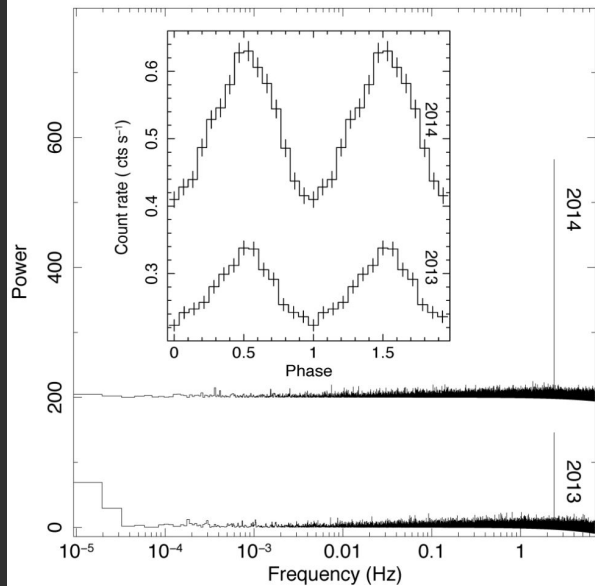
# NGC 7793 P13

- **Fastest known PULX:**
  - $P_{\text{spin}} \approx 410 \text{ ms}$
  - $\dot{P}_{\text{sec}} \sim -4 \times 10^{-11} \text{ s s}^{-1}$
- Observed multiple times: Chandra, NICER, NuSTAR, XMM.  
**Lots of archival data.**
- Long-term monitoring ongoing (see Fuerst+ 2021).



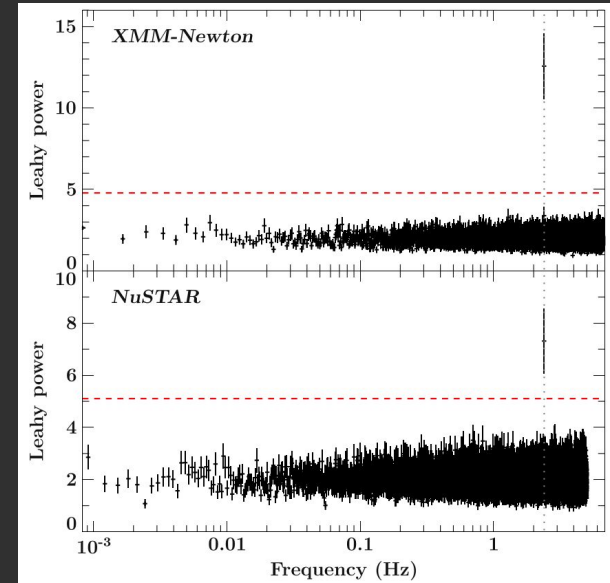
# NGC 7793 P13

Israel+ 2017



- **Fastest known PULX:**
  - $P_{\text{spin}} \approx 410 \text{ ms}$
  - $\dot{P}_{\text{sec}} \sim -4 \times 10^{-11} \text{ s s}^{-1}$
  - $P_{\text{orb}} \approx 65 \text{ d}$
- **Only PULX with a known optical counterpart** (Motch+ 2014)
- Observed multiple times: Chandra, NICER, NuSTAR, XMM.
- **Lots of archival data.**
- Long-term monitoring ongoing (see Fuerst+ 2021).

Fuerst+ 2016



# A PATTERN IS EMERGING

- Are these QPOs a signature of NSs accreting at super-Eddington rates?

Coming soon: systematic search for QPOs.

- Our magnetically driven model works well also for P13.
- $B \sim 10^{13}$  G,  $\dot{M} \sim 10^{-6} M_{\odot} \text{yr}^{-1}$

