



SUPER-EDDINGTON ACCRETION UNDER THE MAGNIFIER: THE CASE OF ULTRALUMINOUS X-RAY SOURCES

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Cefalù, 14- 19 September 2025

ULTRALUMINOUS X-RAY SOURCES

- Point-like X-ray sources
- Off-Nuclear (i.e. no supermassive BH)
- $L_x \gg 10^{39} \text{ erg/s} \gg L_{\text{edd}}$ of $10 M_{\text{Sun}}$ BH
- X-ray Luminosities as high as 10^{41-42} erg/s



ULTRALUMINOUS X-RAY SOURCES

OBSERVATIONS OF THE X-RAY SOURCES IN THE NEARBY Sc GALAXY M33

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European Southern Observatory

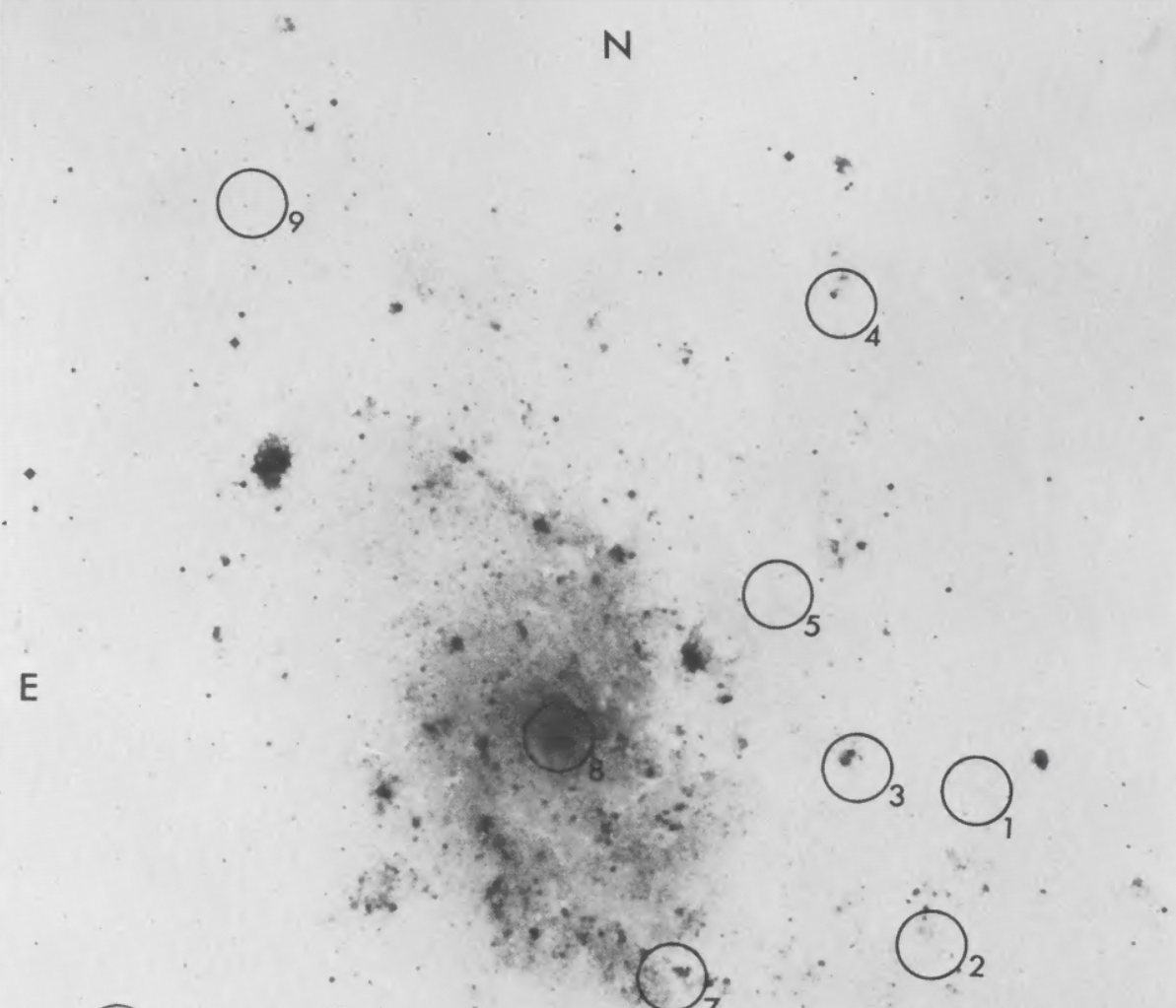
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Space Sciences Laboratory, University of California

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MICHAEL A. DOPITA
Mt. Stromlo and Siding Spring Observatory, Australian National University
Received 1980 December 29; accepted 1981 February 25

ABSTRACT

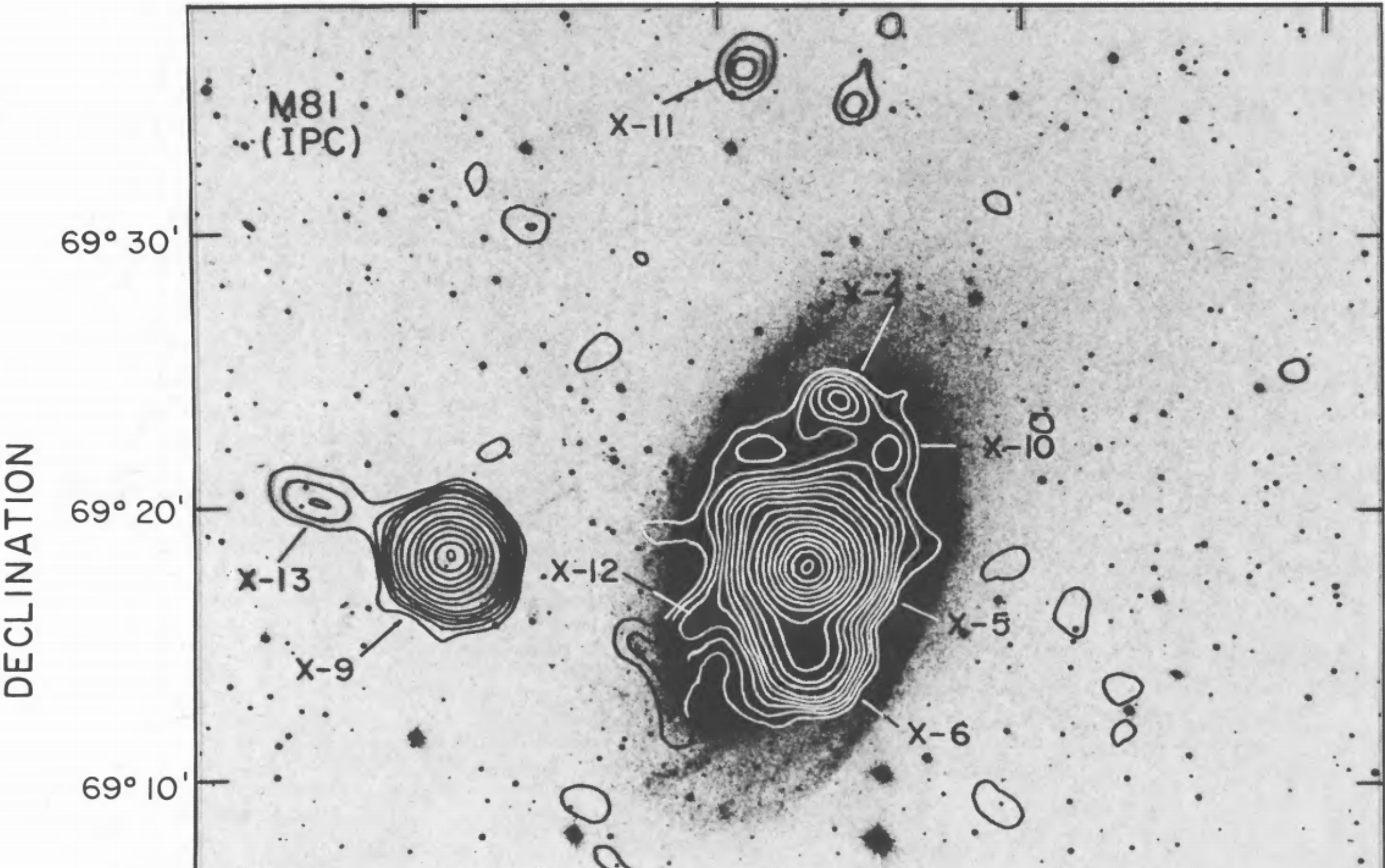
Two observations of the Local Group spiral M33 with the Imaging Proportional Counter (IPC) on the *Einstein* Observatory have revealed 11 sources. The brightest source, coincident with the galaxy nucleus, has a total X-ray luminosity of 10^{39} erg s⁻¹, which, if at the distance of M33, is the most luminous point source known. The other sources are located within 10 arcmin of the nucleus. The total X-ray luminosity of the galaxy is estimated to be 10^{40} erg s⁻¹. The sources are identified with the compact binary sources in the galaxy. The sources are identified with the compact binary sources in the galaxy. The sources are identified with the compact binary sources in the galaxy.



THE ASTROPHYSICAL JOURNAL, 325:544-562, 1988 February 15
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THE X-RAY EMISSION OF M81 AND ITS NUCLEUS

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Received 1987 April 14; accepted 1987 July 29



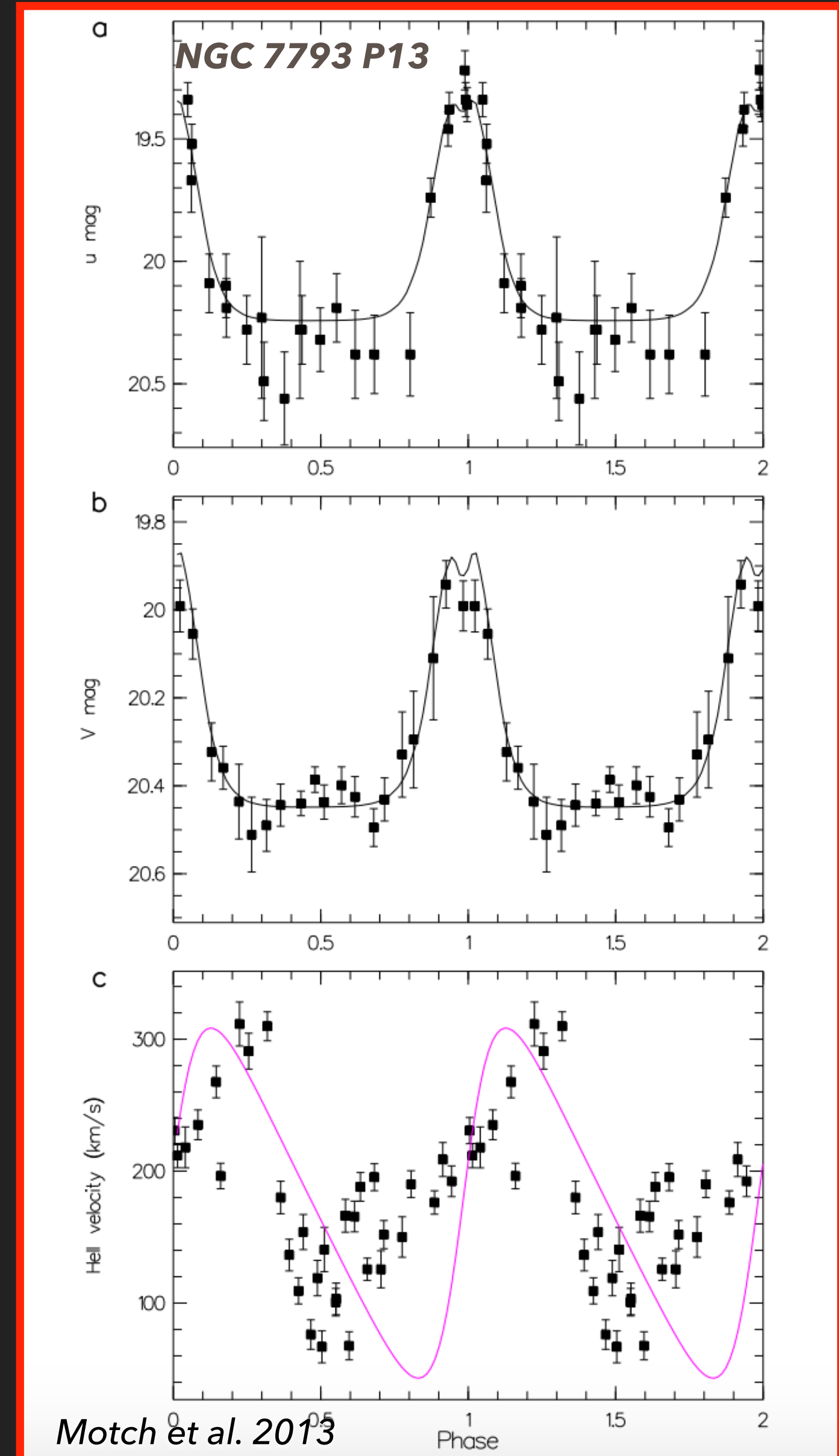
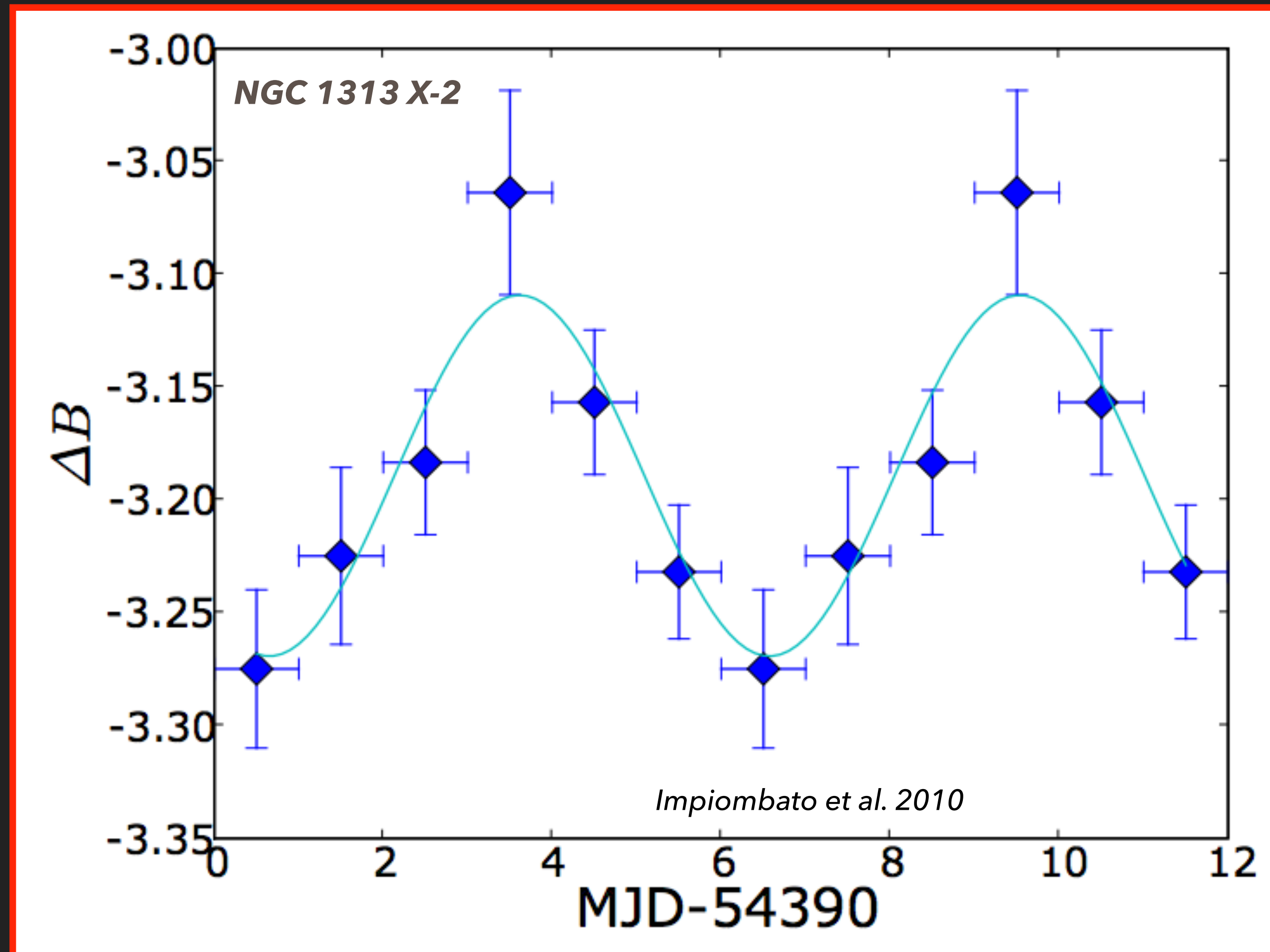
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pectrum, if
-10 keV

More than ~2000 ULXs have been catalogued (e.g. Walton et al. 2022)!

However, mostly are poorly known in terms of spectral and temporal properties

ULTRALUMINOUS X-RAY SOURCES

ULXs are thought to be accreting compact objects in binary system



ULTRALUMINOUS X-RAY SOURCES

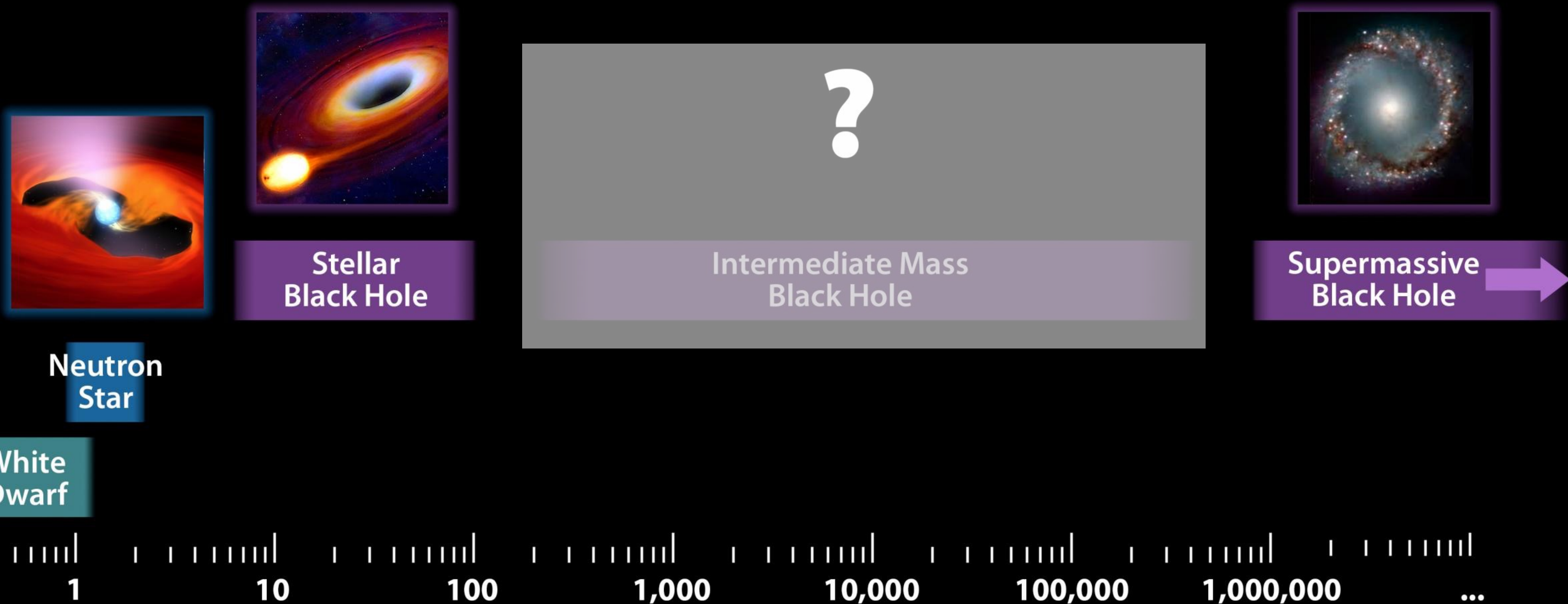
ULXs were initially considered as a rescaled version of the Galactic BH binaries, and therefore accreting sub-eddington.



To sustain luminosities higher than 10^{39} erg/s up to 10^{41-42} erg/s, the BH mass should be increased up to very large masses!

$$M \sim 100-10^5 M_{\text{sun}}$$

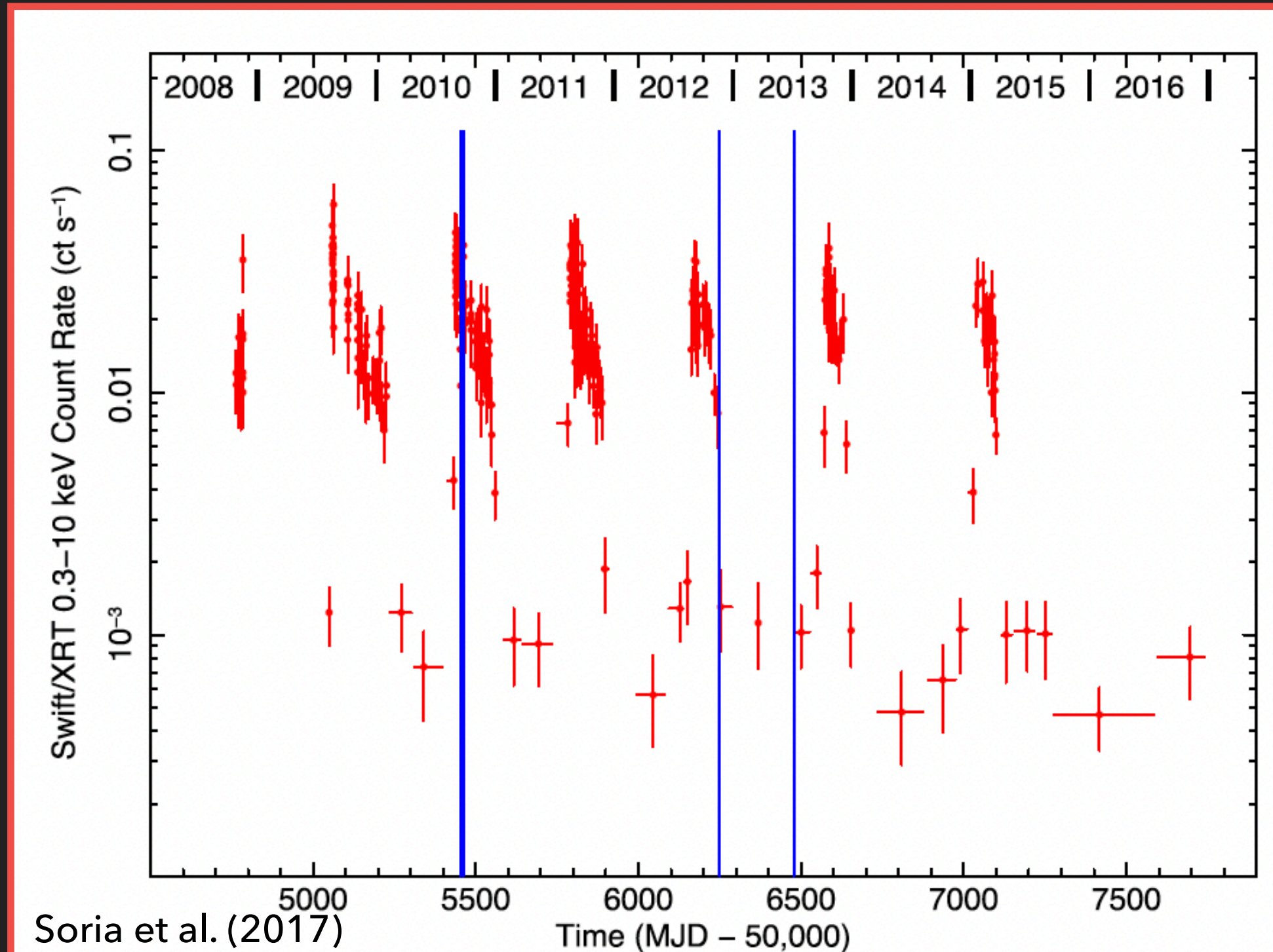
Observed Mass Ranges of Compact Objects



Colbert & Mutshotzky (1999),
Madau & Rees (2004)
Portgies Swartz et al. (2004)

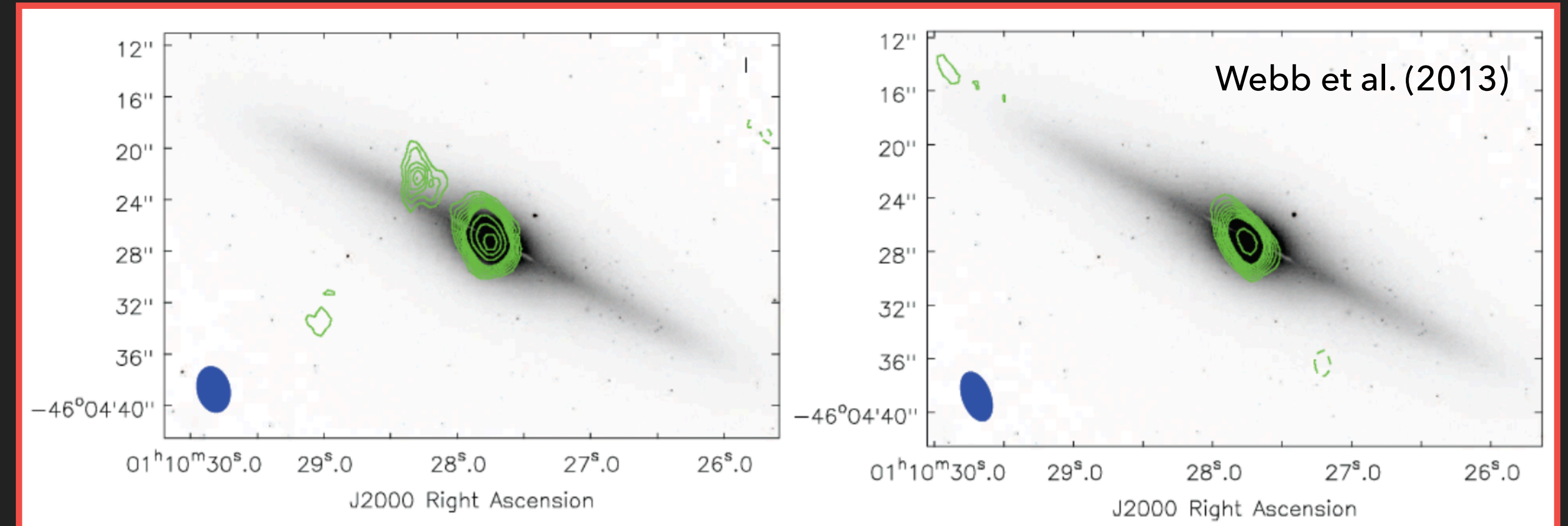
IMBH IN ULTRALUMINOUS X-RAY SOURCES

HLX-1 in ESO 243-49 is the best candidate to host an IMBH (Farrel et al. 2009, Webb et al. 2013)

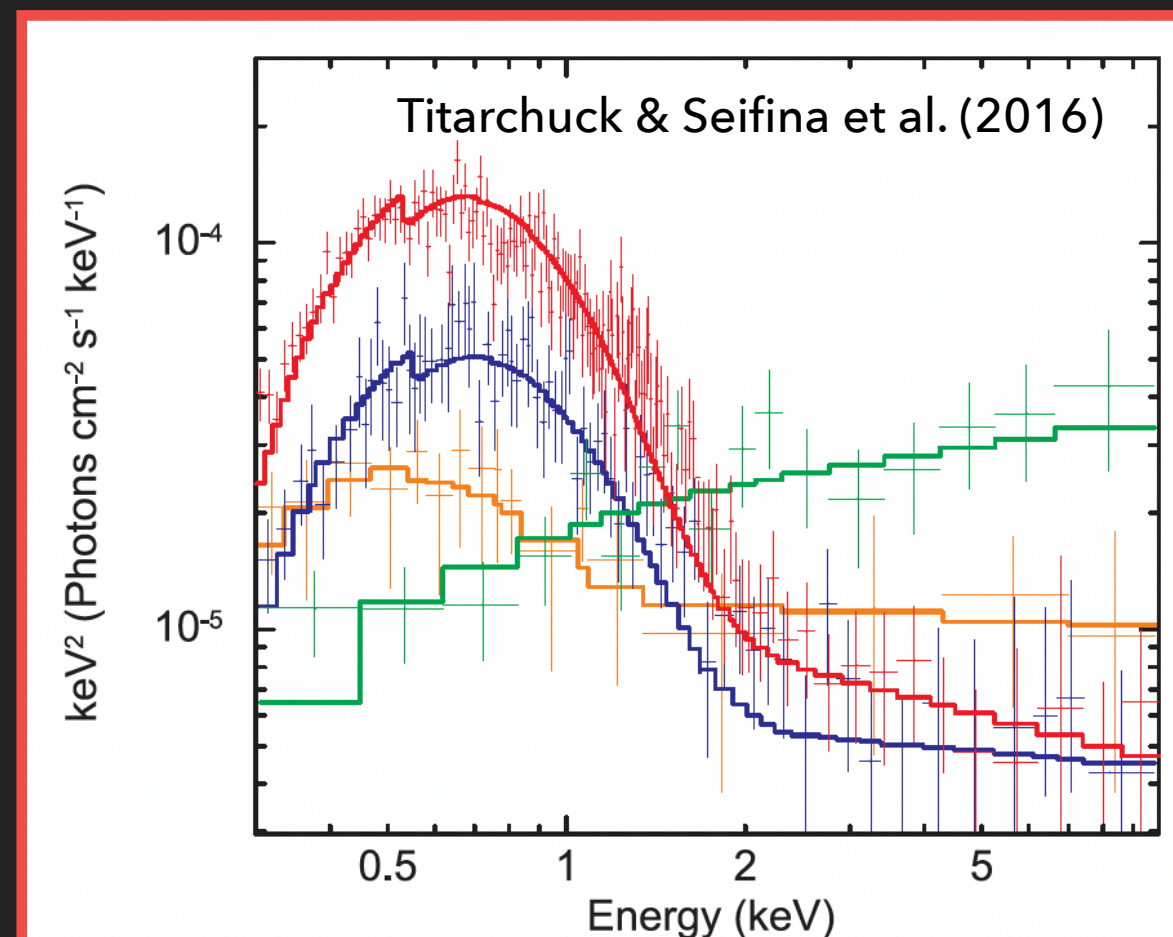


$$L_x \rightarrow 10^{42} \text{ erg/s}$$

$$M_{\text{BH}} \gg 10^3 M_{\text{sun}}$$



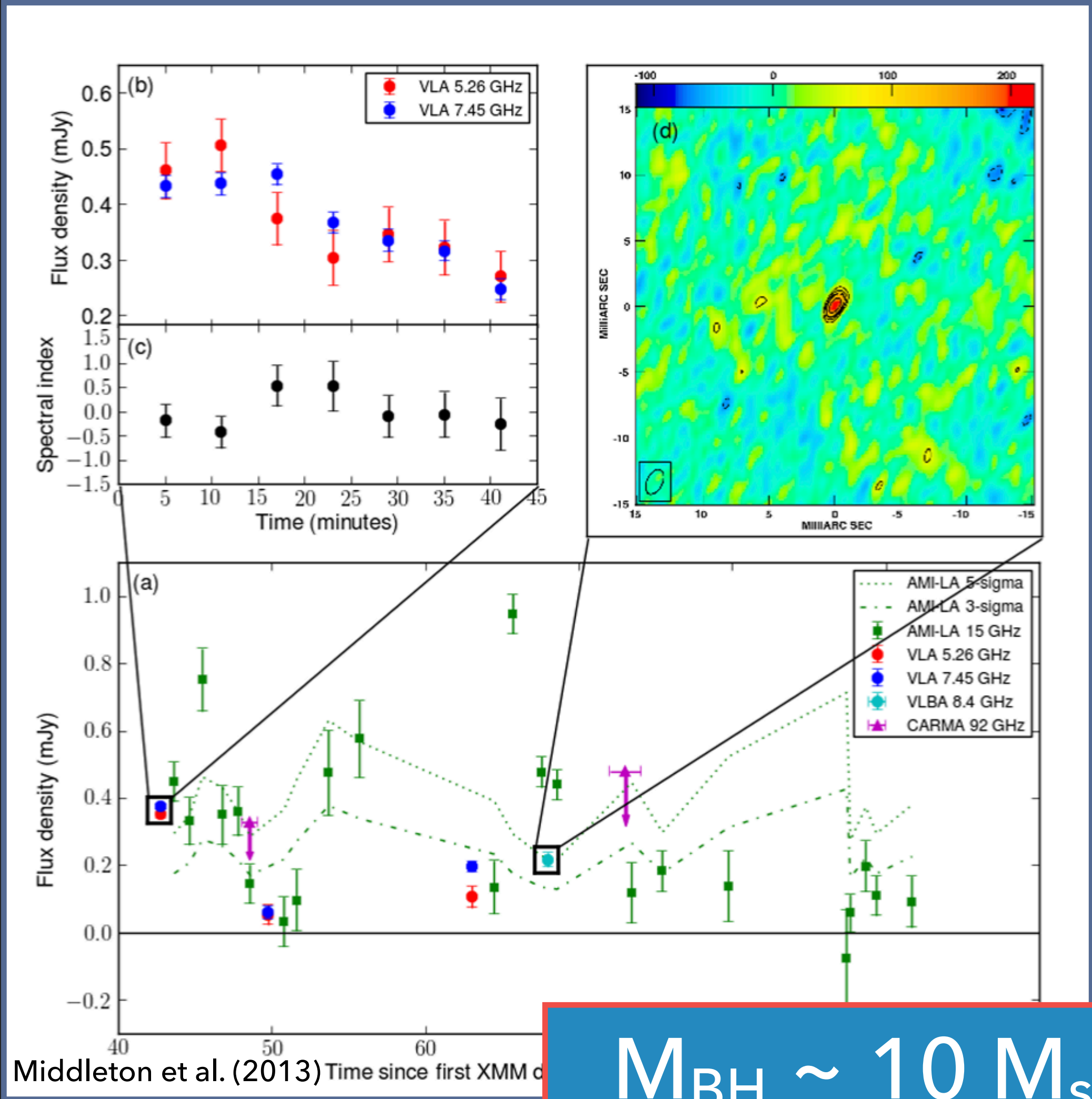
ATCA observed a variable radio emission at 5 GHz and 9 GHz, likely associated to a jet



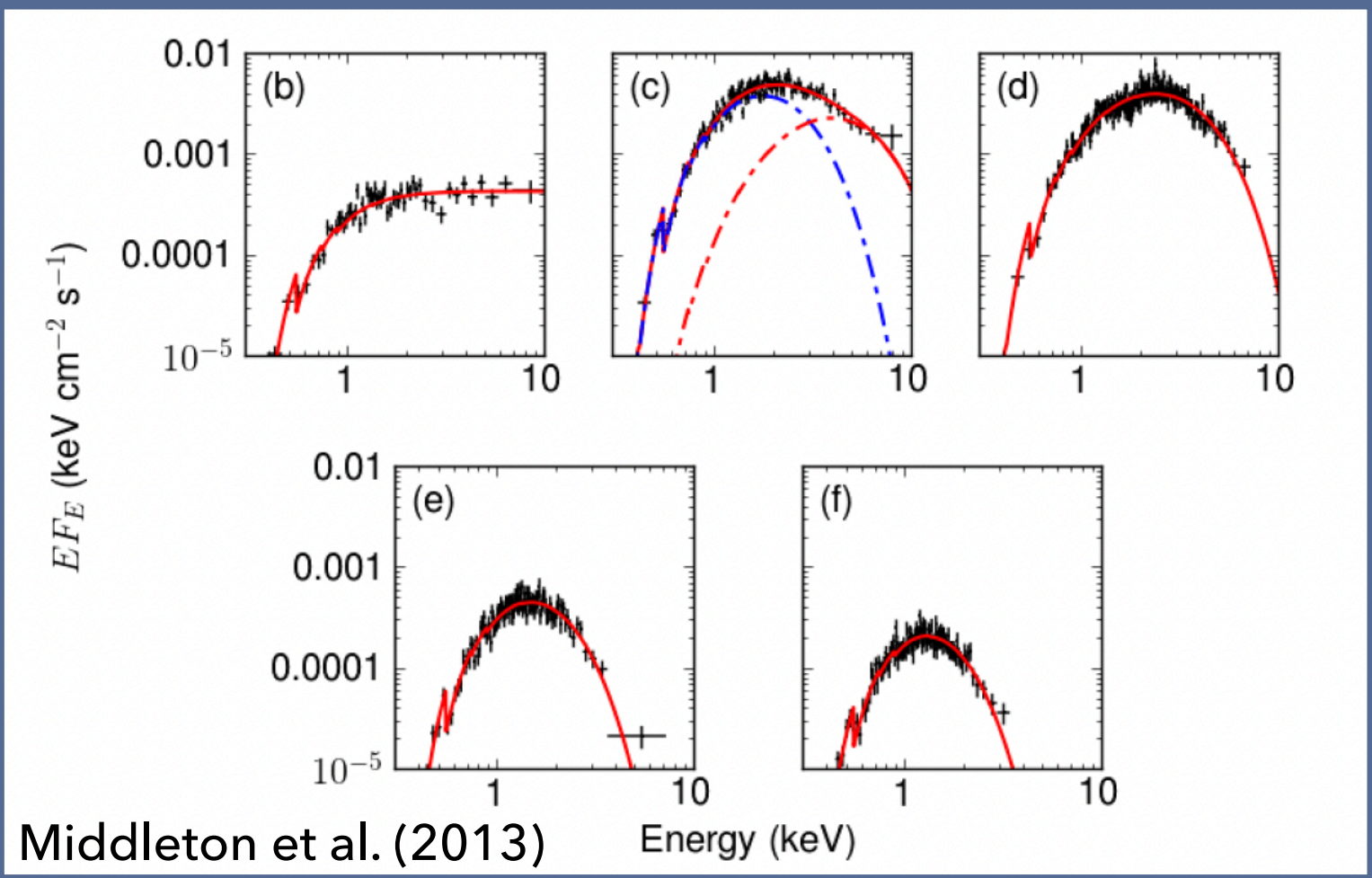
Spectral evolution compatible with a hard-to-soft

SUPER-CRITICAL ACCRETION REGIME

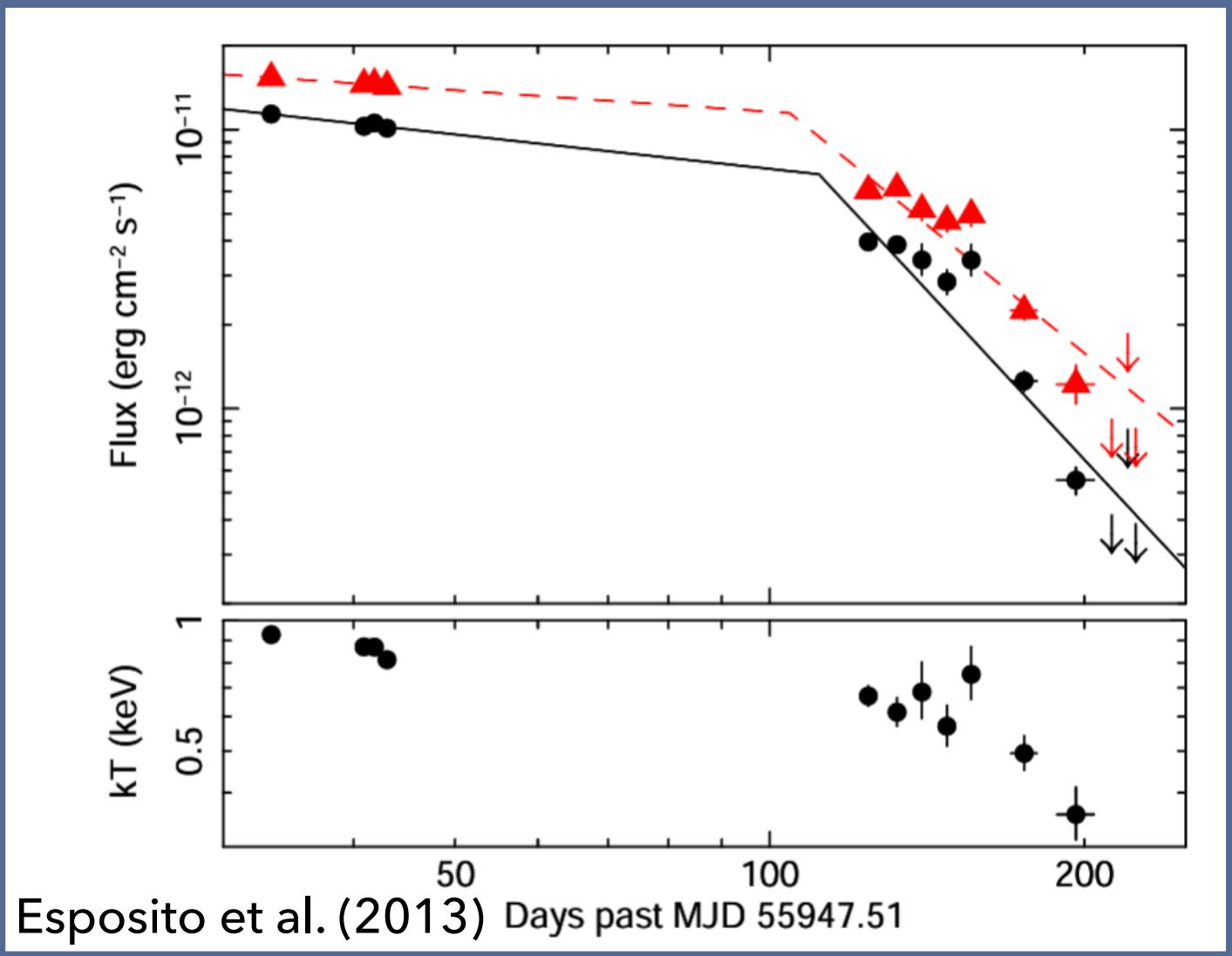
A jet was observed in radio in the source M31 ULX-1 during its 2013 outburst



$M_{\text{BH}} \sim 10 M_{\text{sun}}$

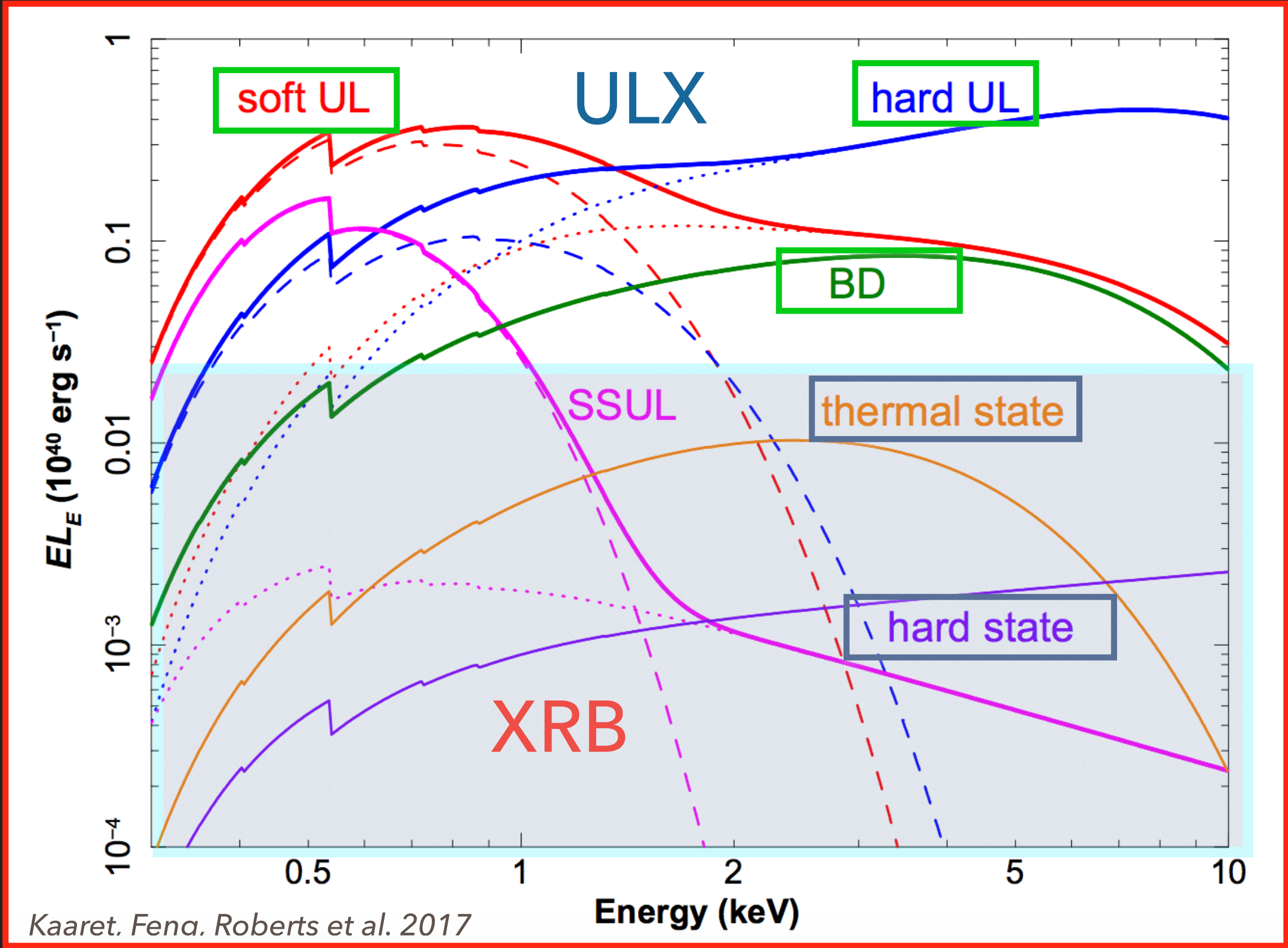


Clear spectral evolution resembling the hard-to-soft transition of Galactic BH binaries



Swift/XRT long-term lightcurve of the only registered outburst of this ULX.

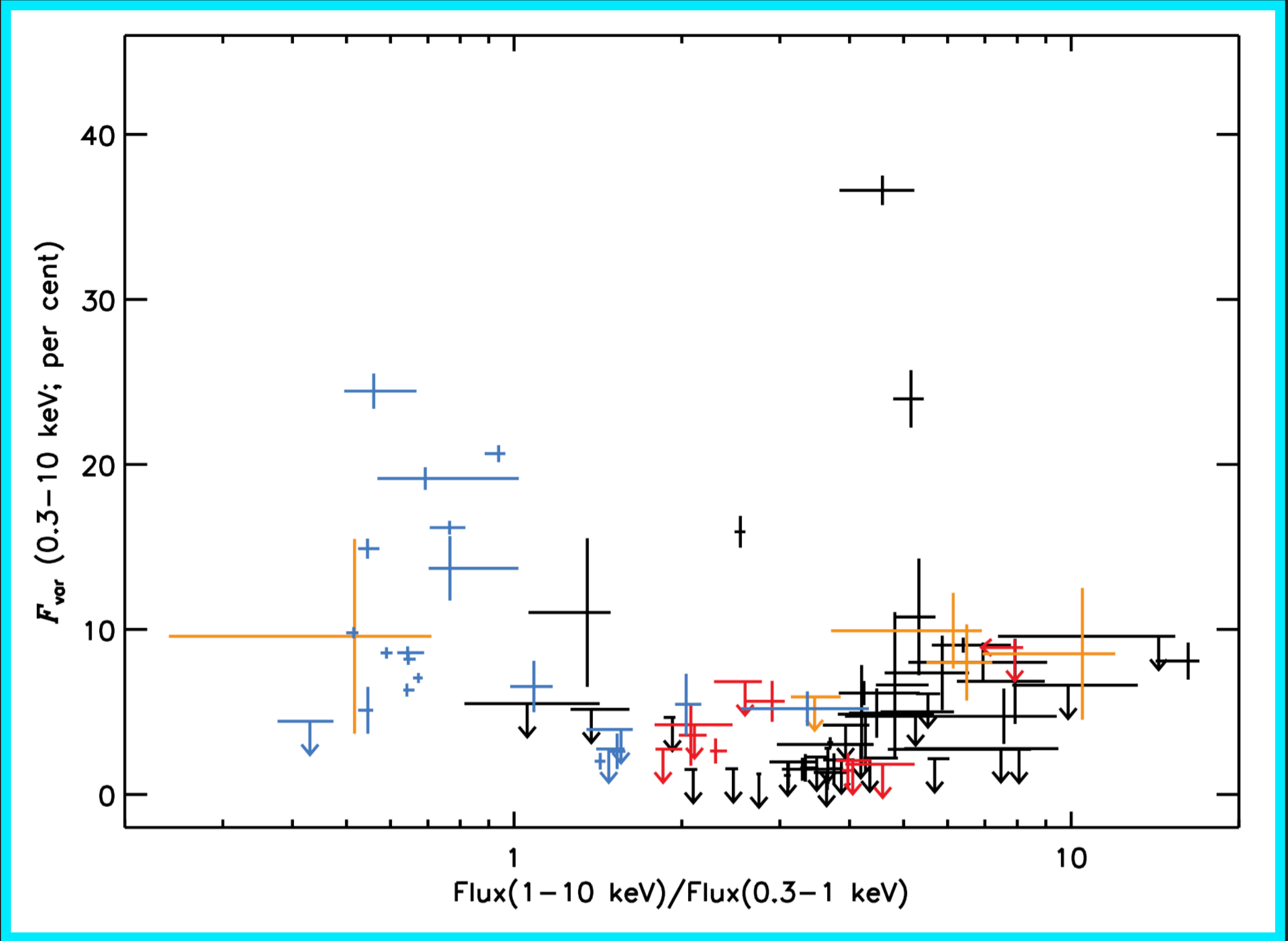
A CRACK IN THE IMBH SCENARIO



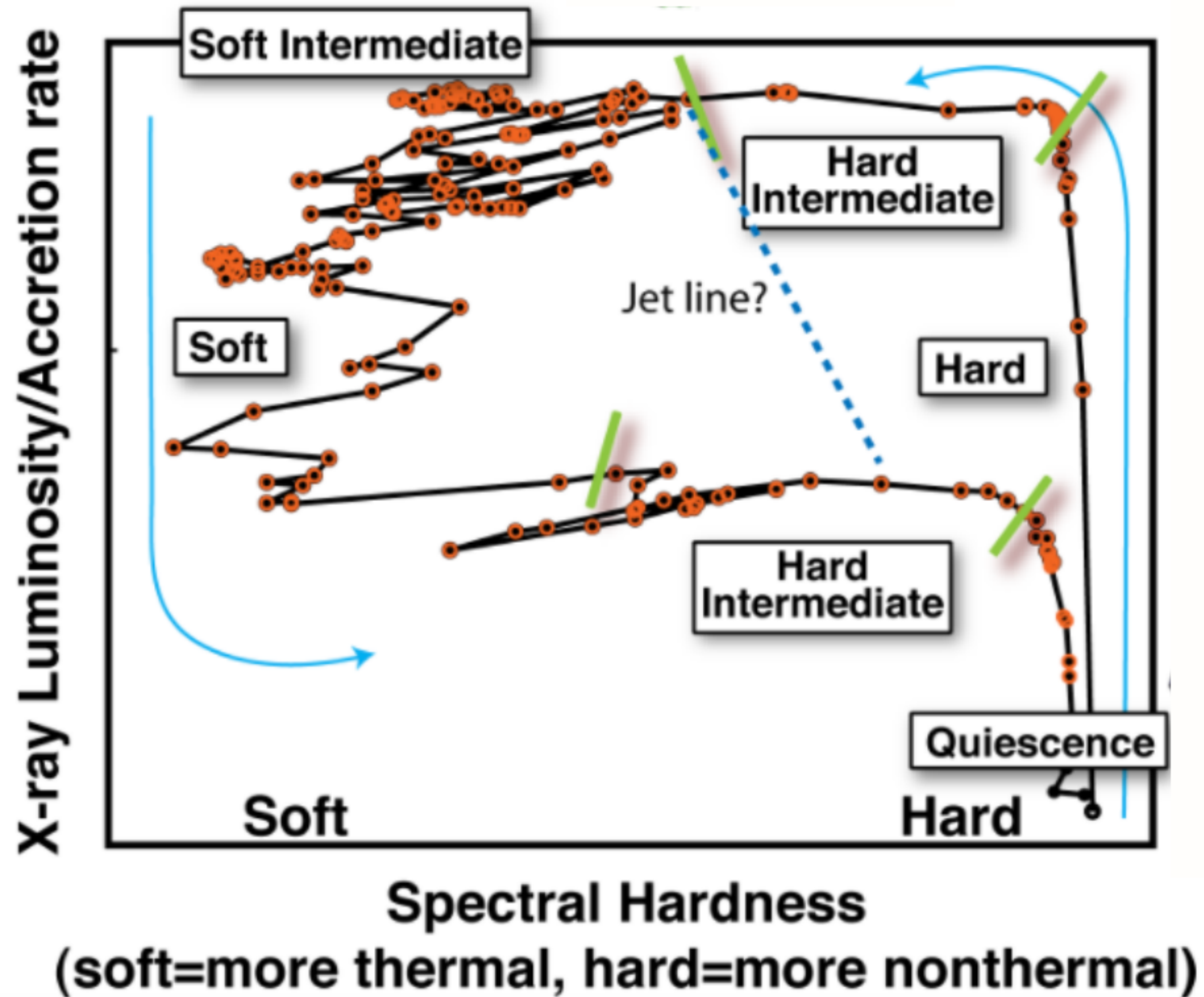
ULXs

Hard Ultraluminous
Soft Ultraluminous
Broadened disc

Fractional variability (F_{var})
significantly higher in ULX
soft ultraluminous states,
unlike Galactic BH binaries



A CRACK IN THE IMBH SCENARIO



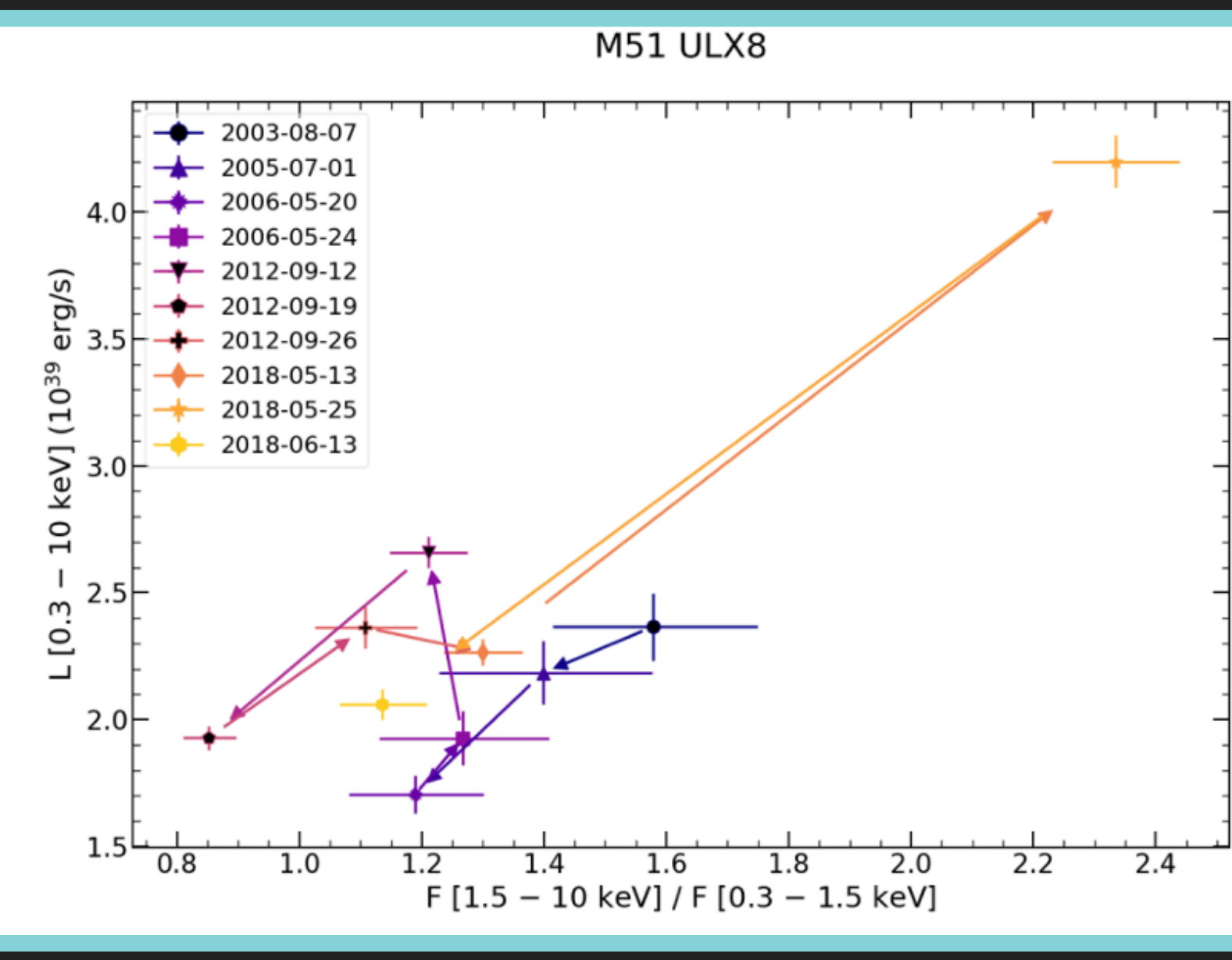
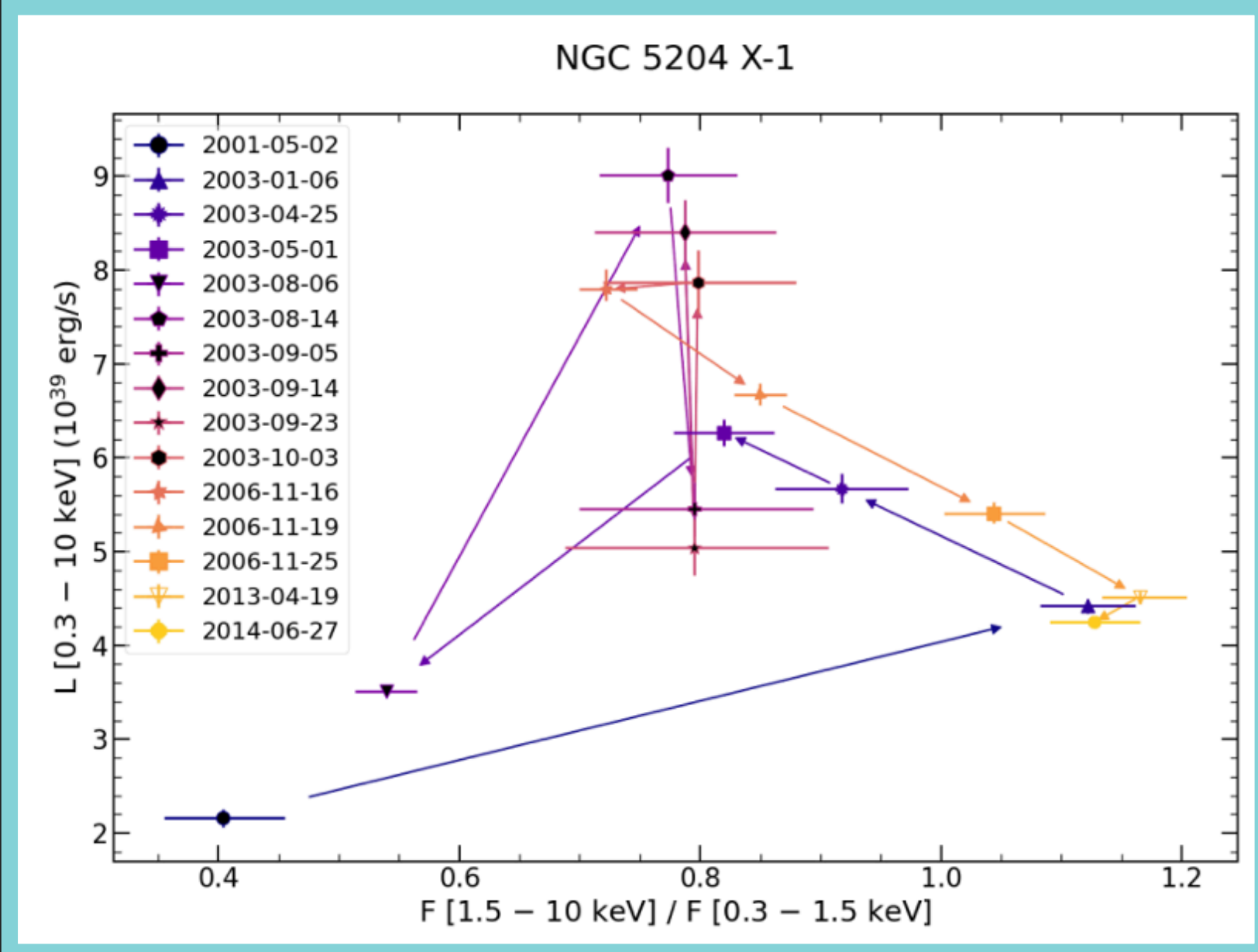
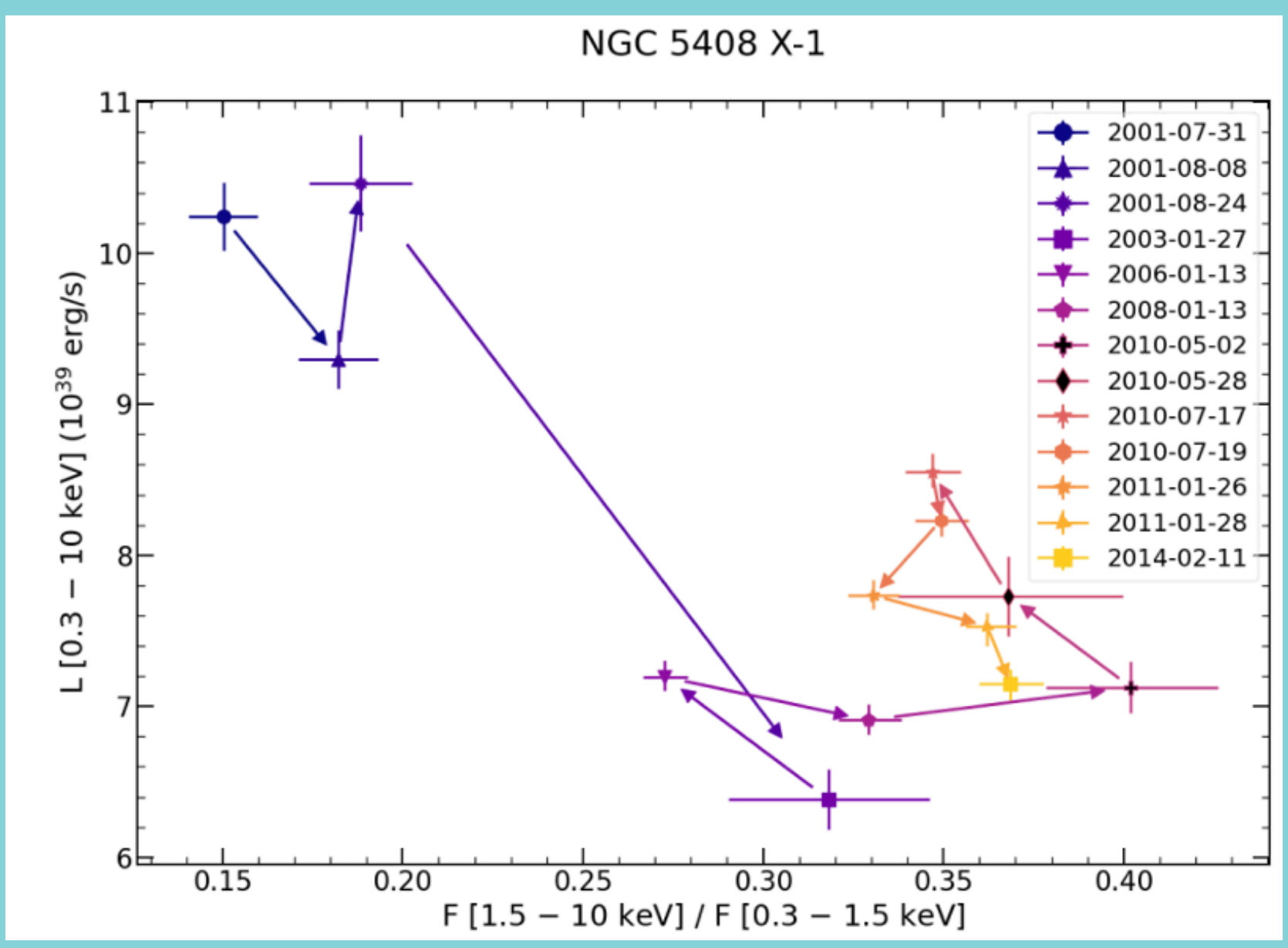
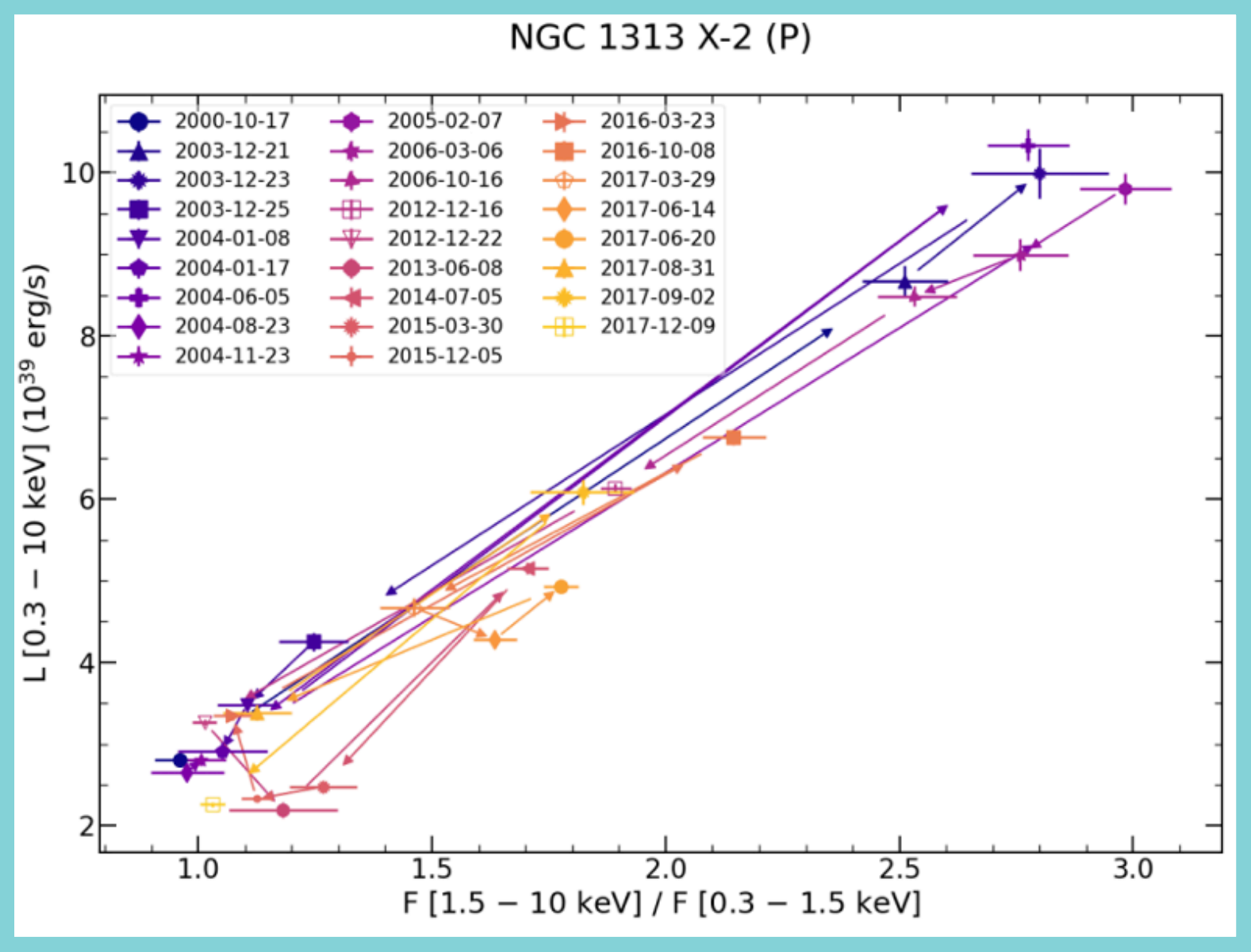
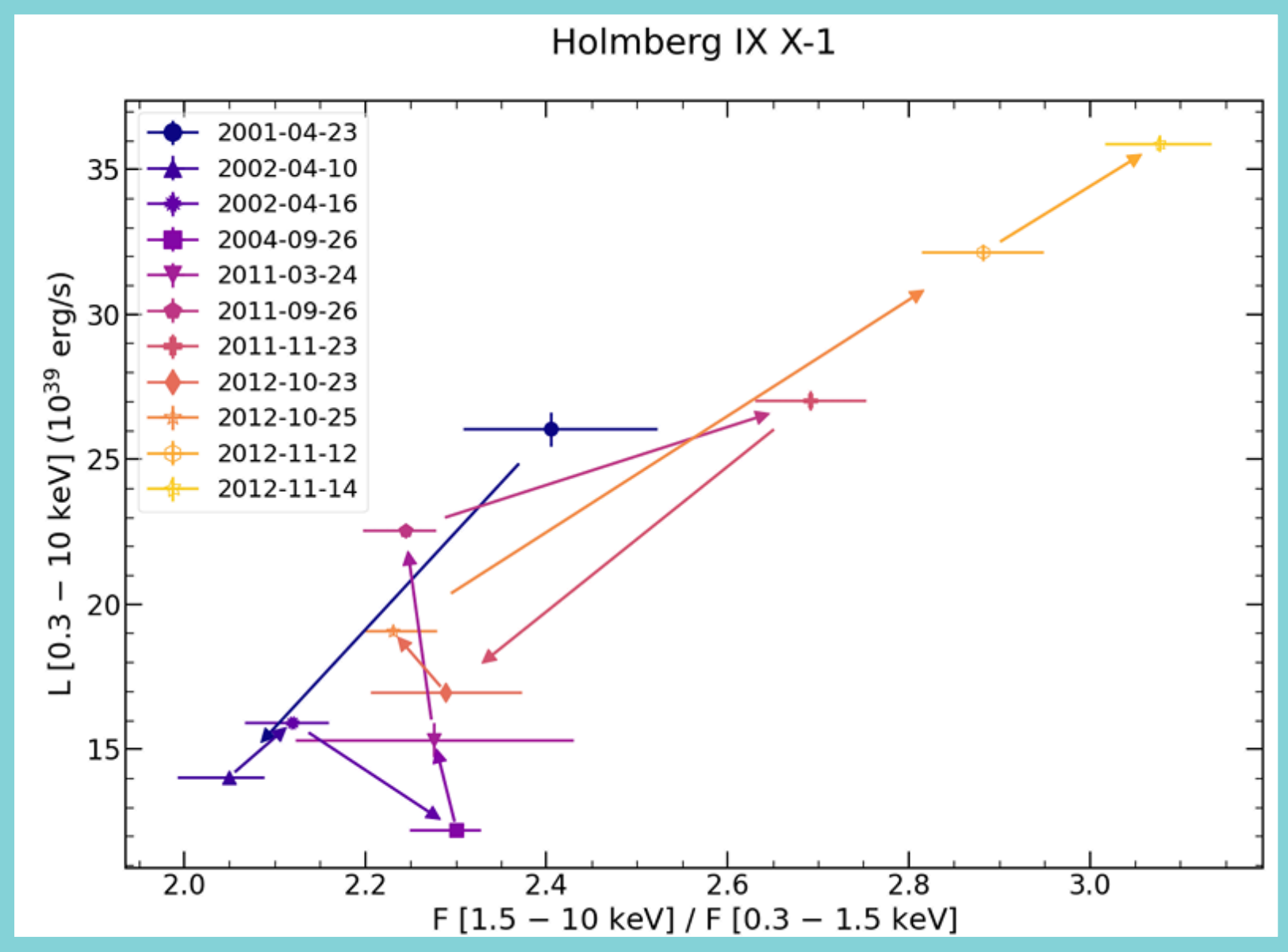
Hysteresis cycle?
ULXs do not follow it...

ULTRALUMINOUS X-RAY SOURCES

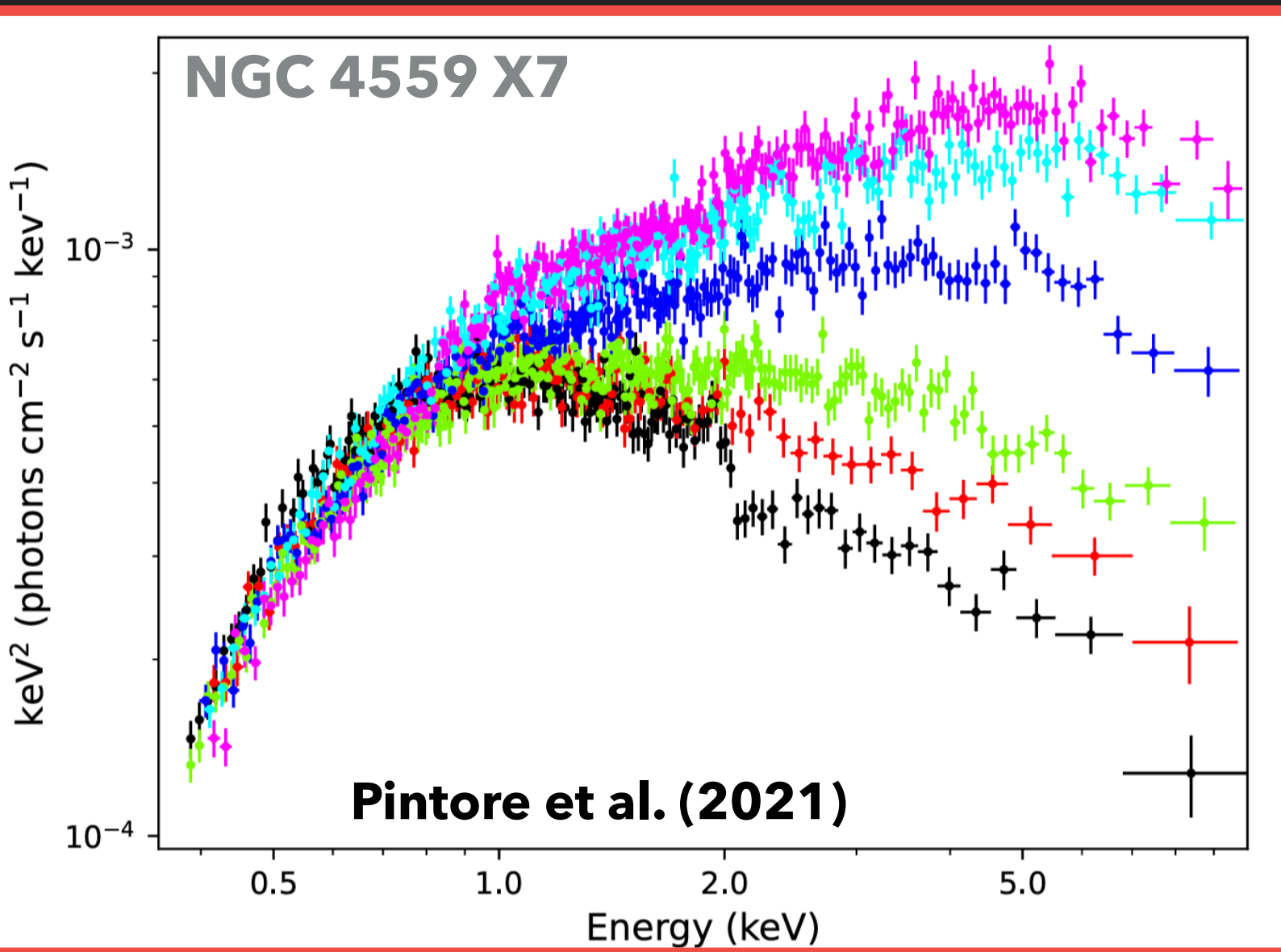
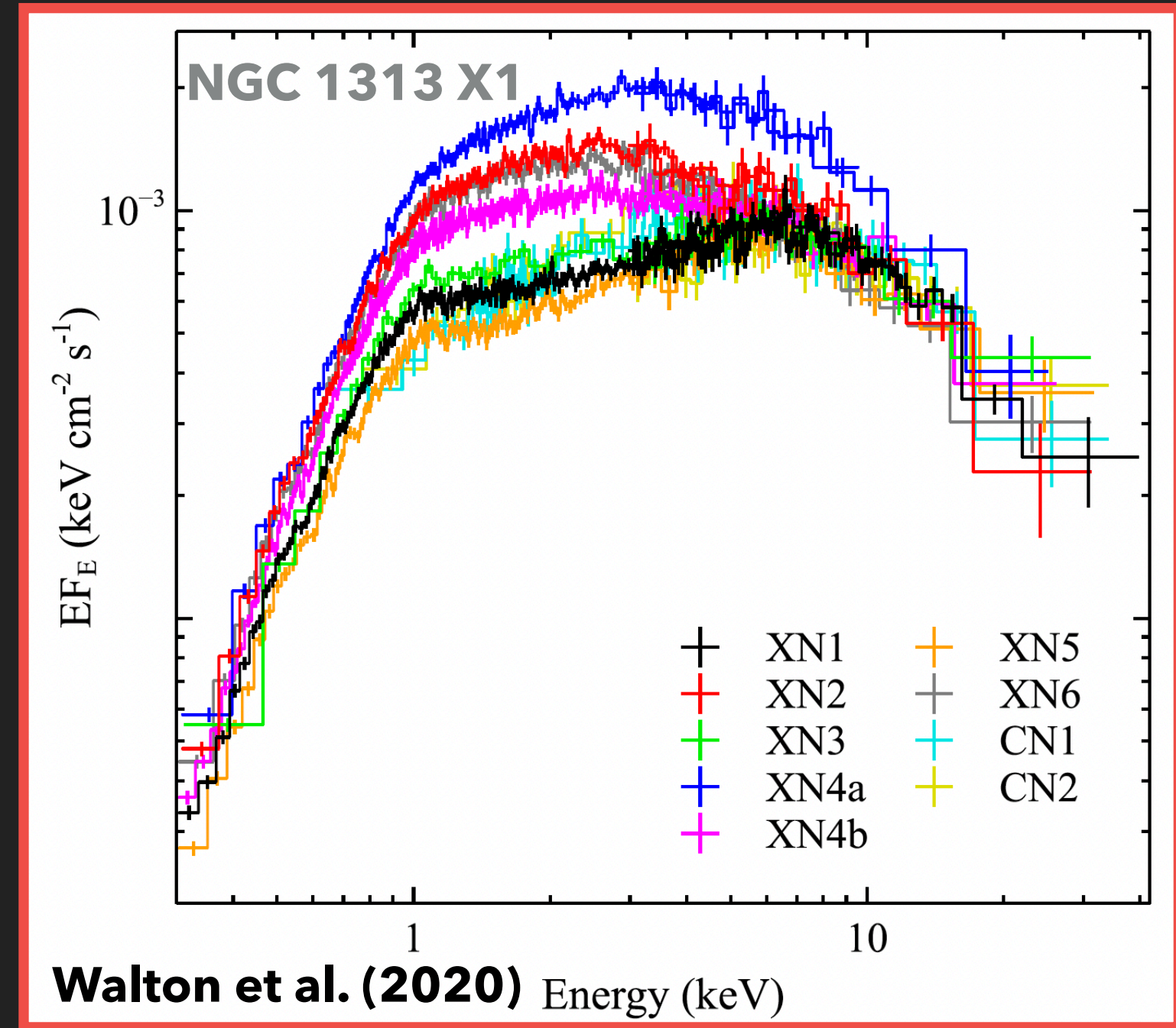
**ULX spectral
properties are show
a plethora of
behaviours**

(e.g. Gurpide et al. 2021)

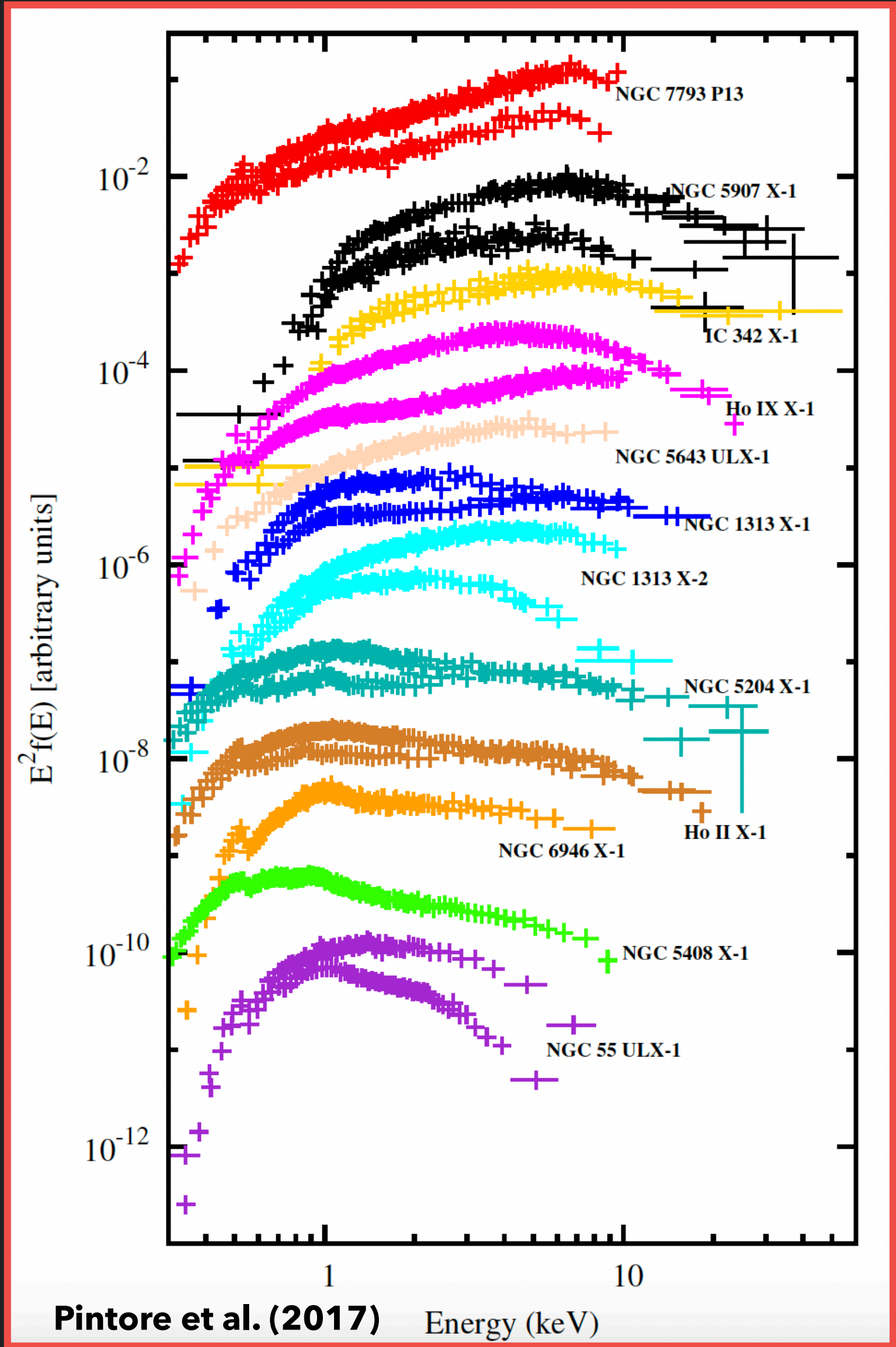
XMM-Newton data



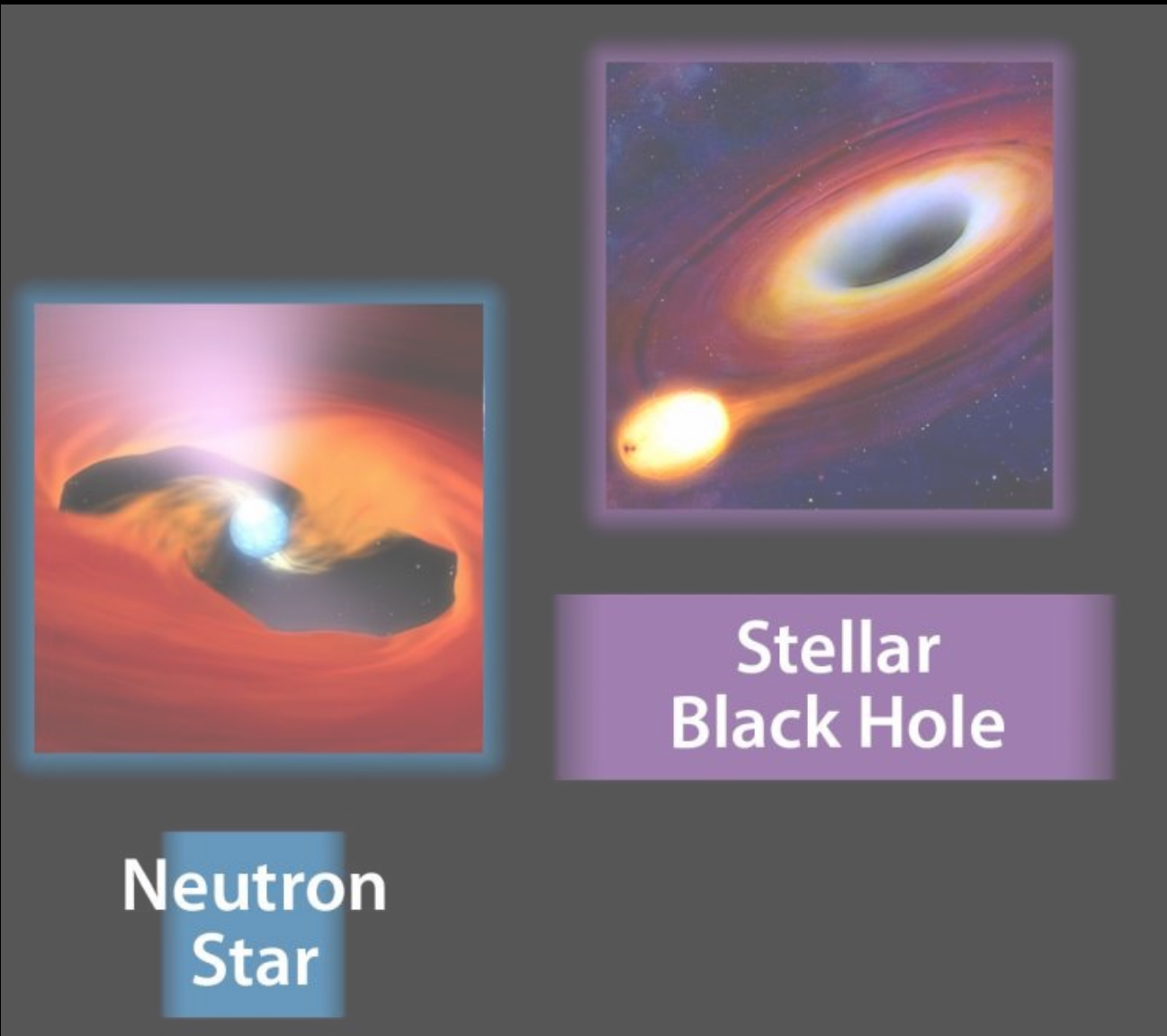
ULTRALUMINOUS X-RAY SOURCES



Transitions from **soft ultraluminous** to **hard ultraluminous states** observed in several ULXs, but different global spectral behaviour



Observed Mass Ranges of Compact Objects



White Dwarf

Super-Eddington accretion!



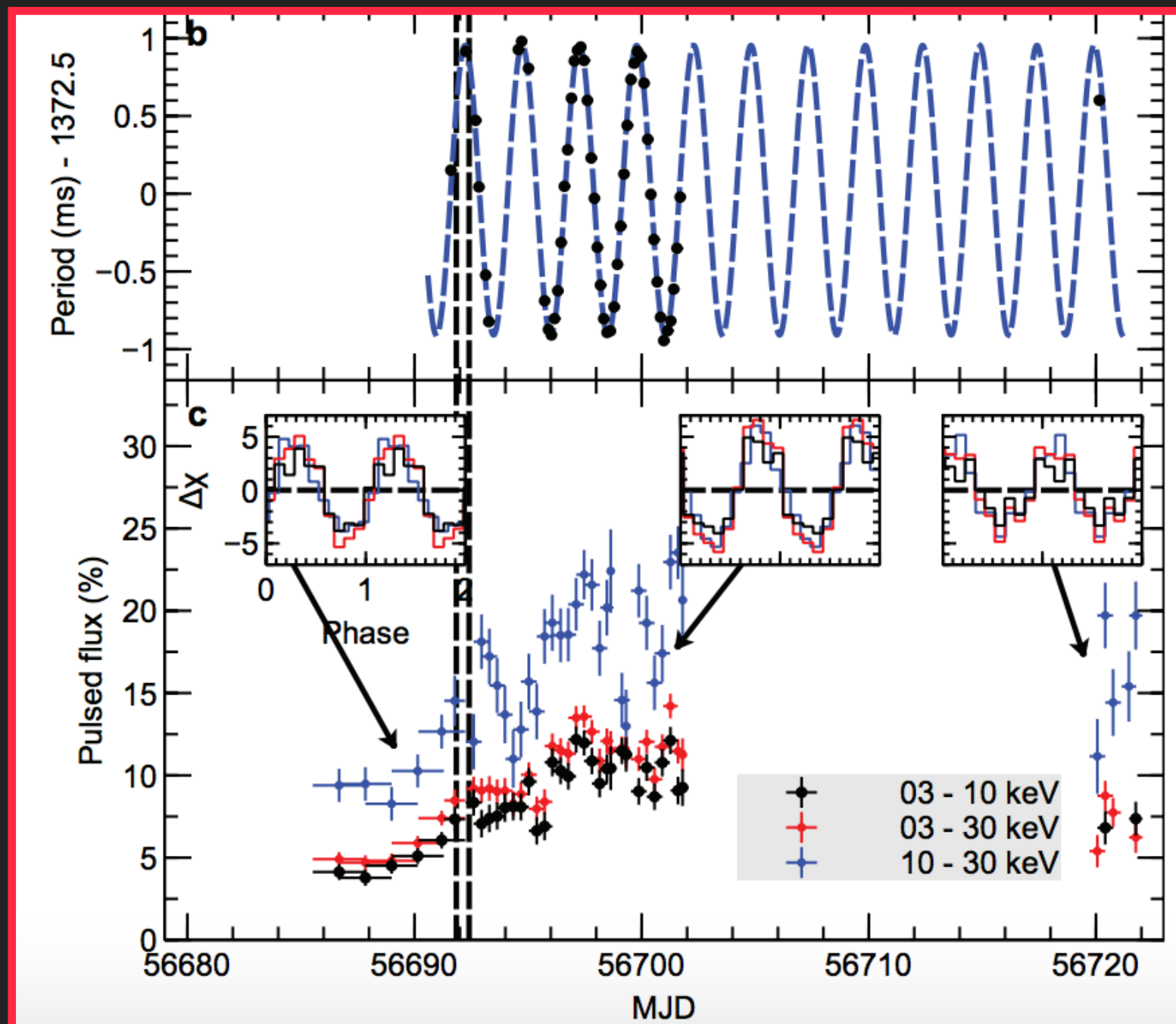
Object Mass
(Relative to the Sun)

Colbert & Mutshotzky (1999),
Madau & Rees (2004)
Portgies Swartz et al. (2004)

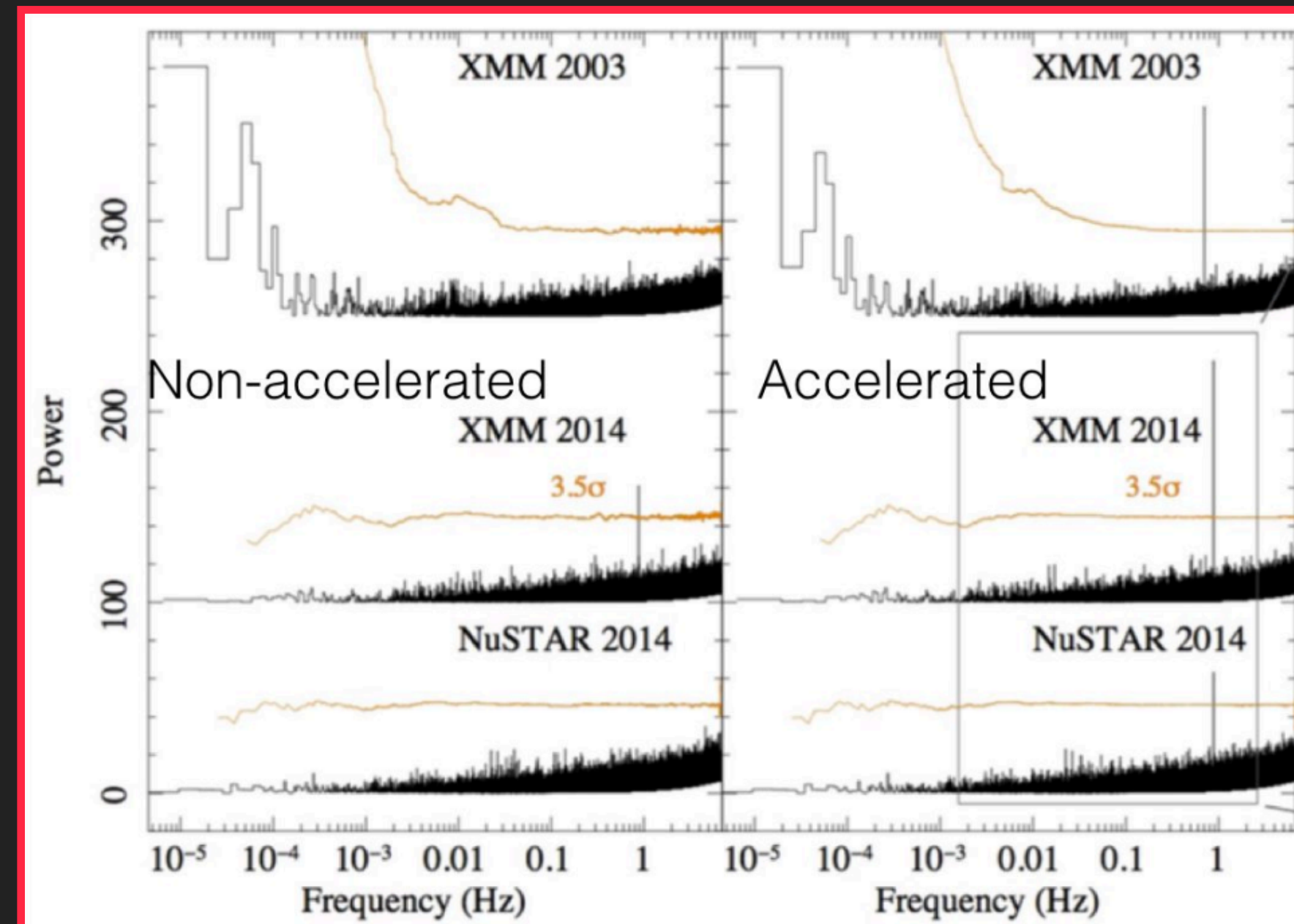
THE LATEST STRIKING DISCOVERY IN ULX: PULSATIONS

- Pulsation have been discovered in at least 6 extragalactic ULXs using observations with high counting statistics (XMM-Newton and NuSTAR)
- P_{spin} in the range $\sim 0.4 - 20$ s

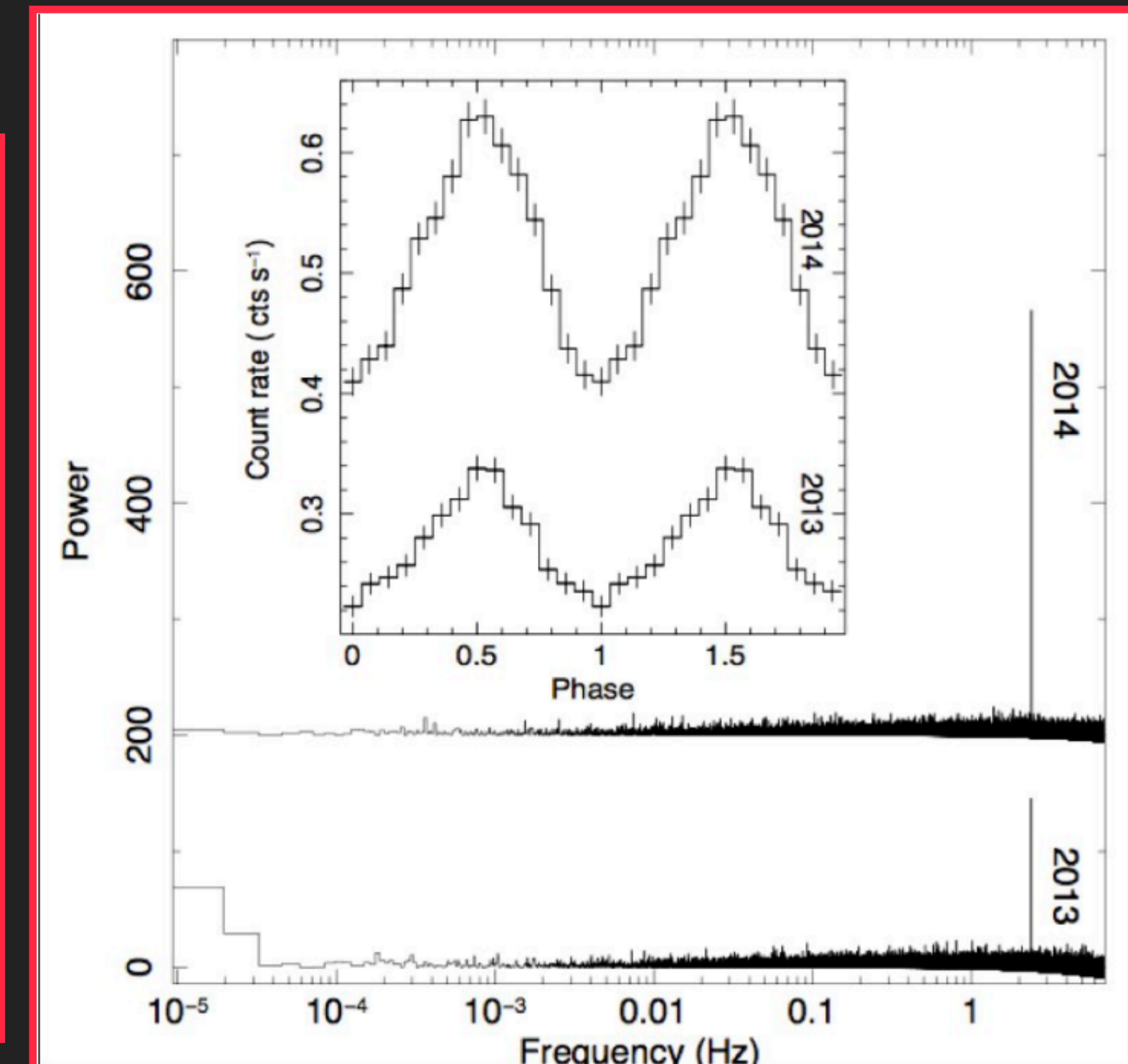
M82 X-2 (BACHETTI ET AL. 2014)



NGC 5907 ULX-1 (ISRAEL ET AL. 2016A)

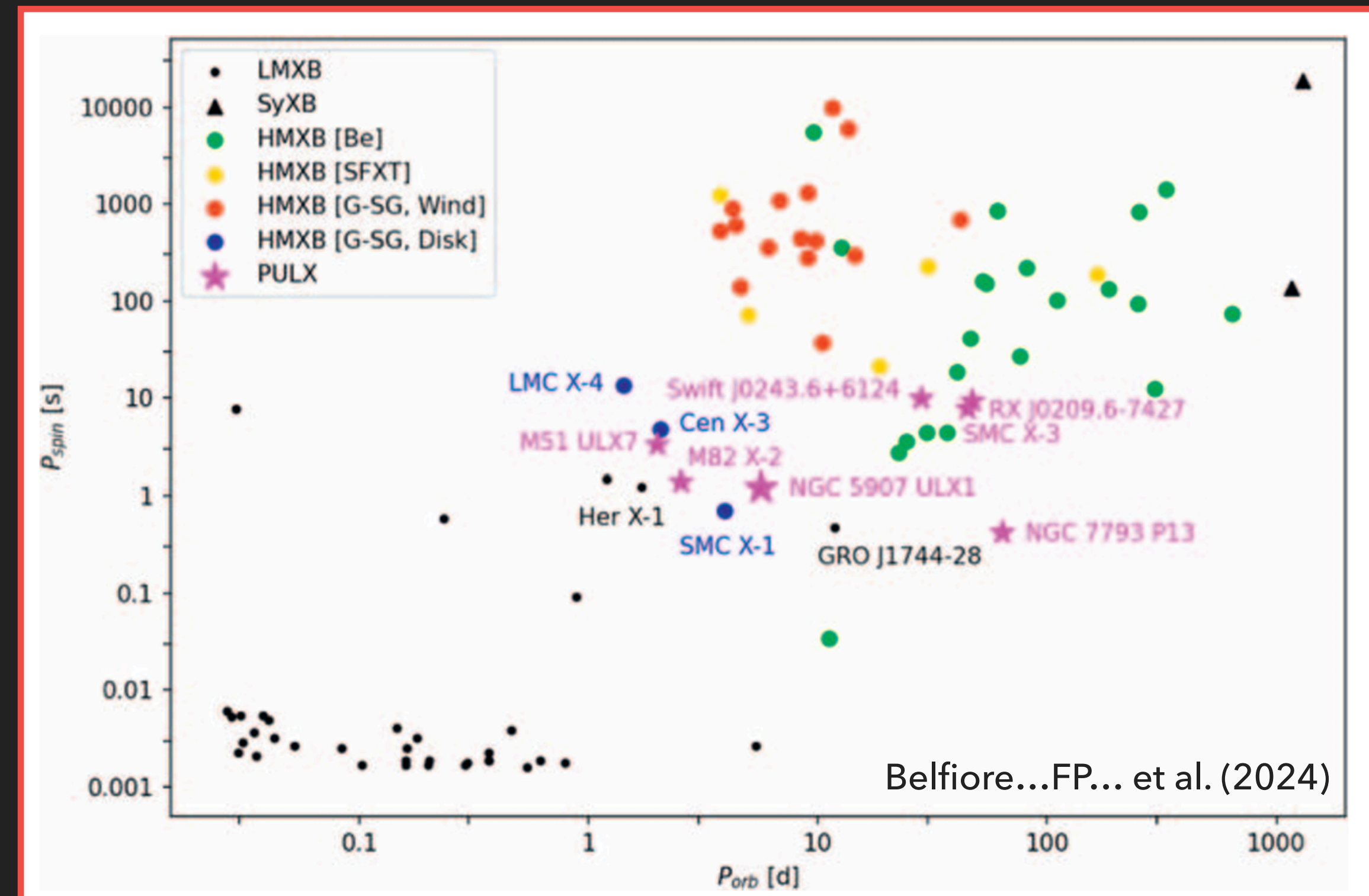
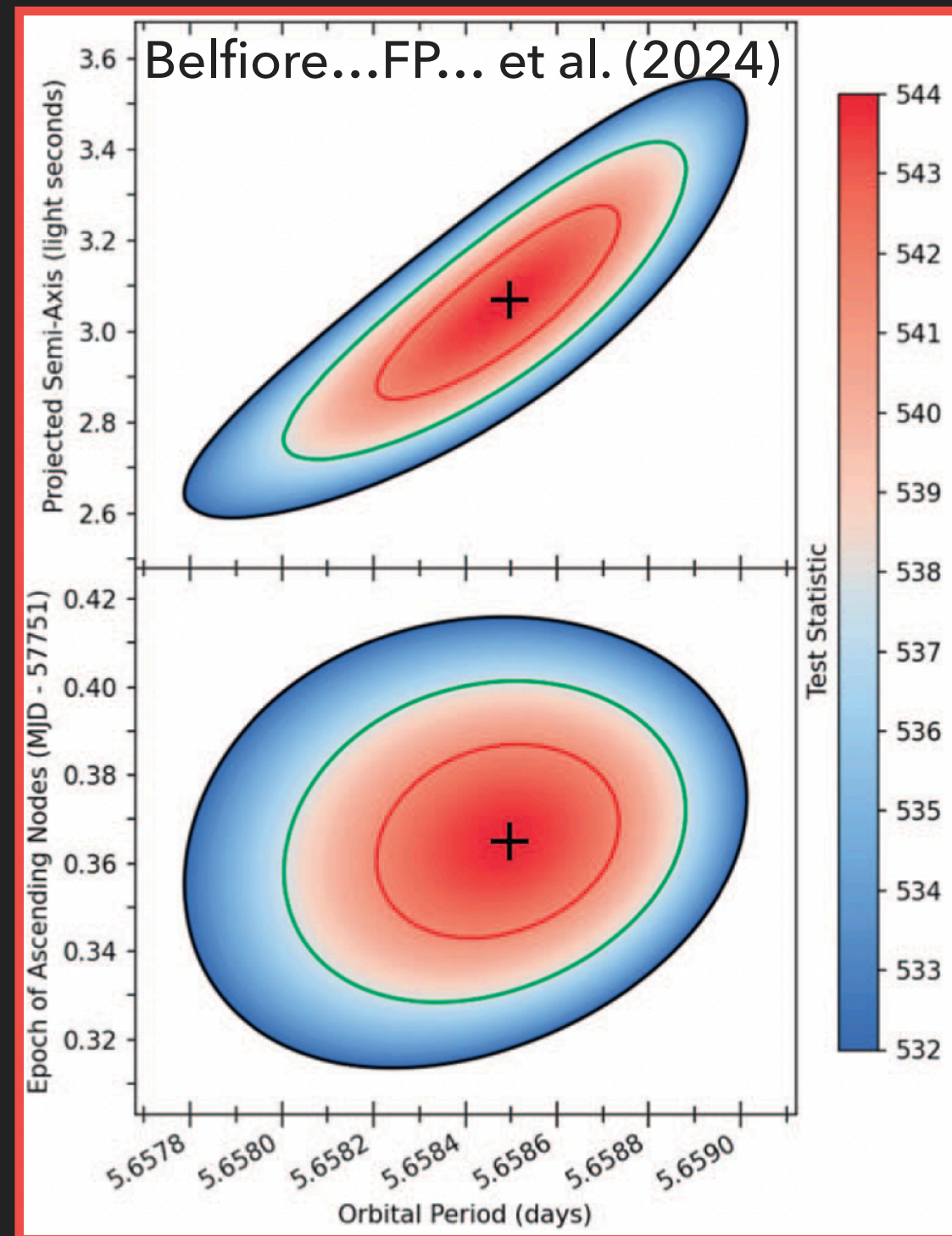


NGC 7793 P13 (ISRAEL ET AL. 2017)



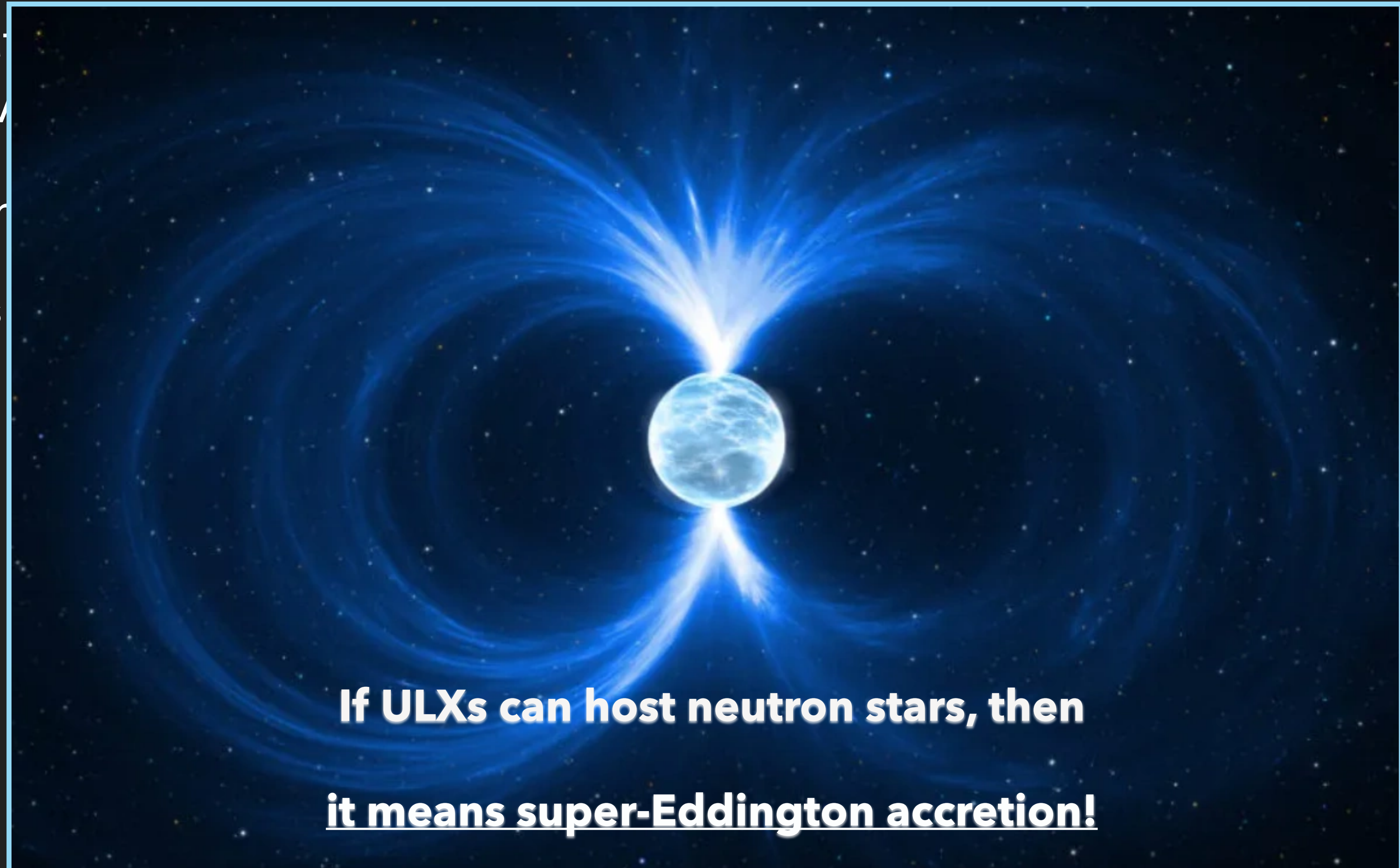
THE LATEST STRIKING DISCOVERY IN ULX: PULSATIONS

- Pulsation have been discovered in at least 6 extragalactic ULXs using observations with high counting statistics (XMM-Newton and NuSTAR)
- P_{spin} in the range $\sim 0.4 - 20$ s
- PULXs orbital properties suggest periods of a few days and giant OB companion stars



THE LATEST STRIKING DISCOVERY IN ULX: PULSATIONS

- Pulsar observations
- P_{spin} in
- PULXs



5.62 5.62 5.62 5.62 5.62 5.62 5.62
Orbital Period (days)

0.1

1

10

100

1000

P_{orb} [d]

ars

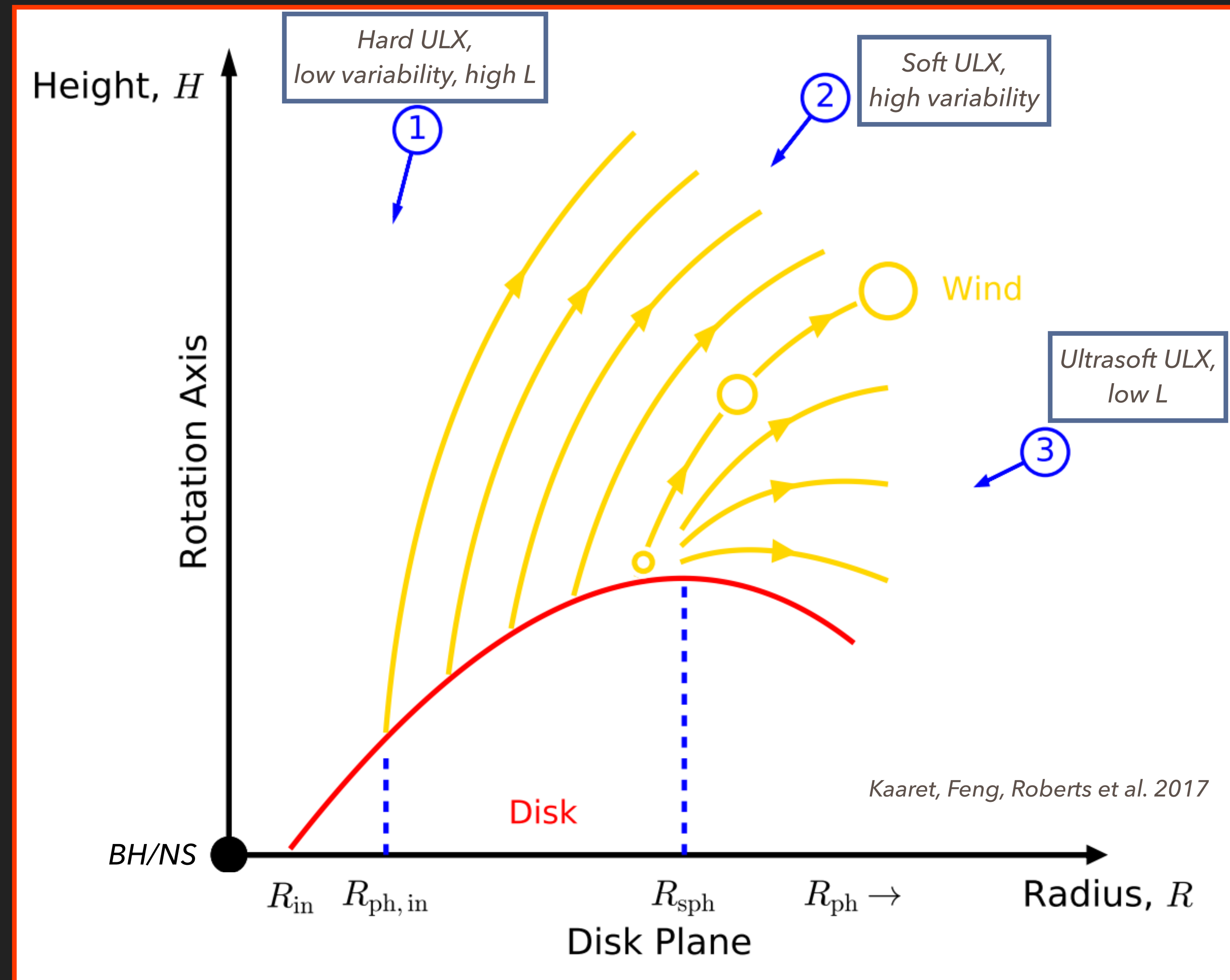
SUPER-CRITICAL ACCRETION REGIME

To explain luminosities well above 10^{39} erg/s, super-Eddington accretion has to be taken into account;

At super-Eddington accretion, a standard disc is not expected;

Radiatively emitted outflows with an equatorial geometry

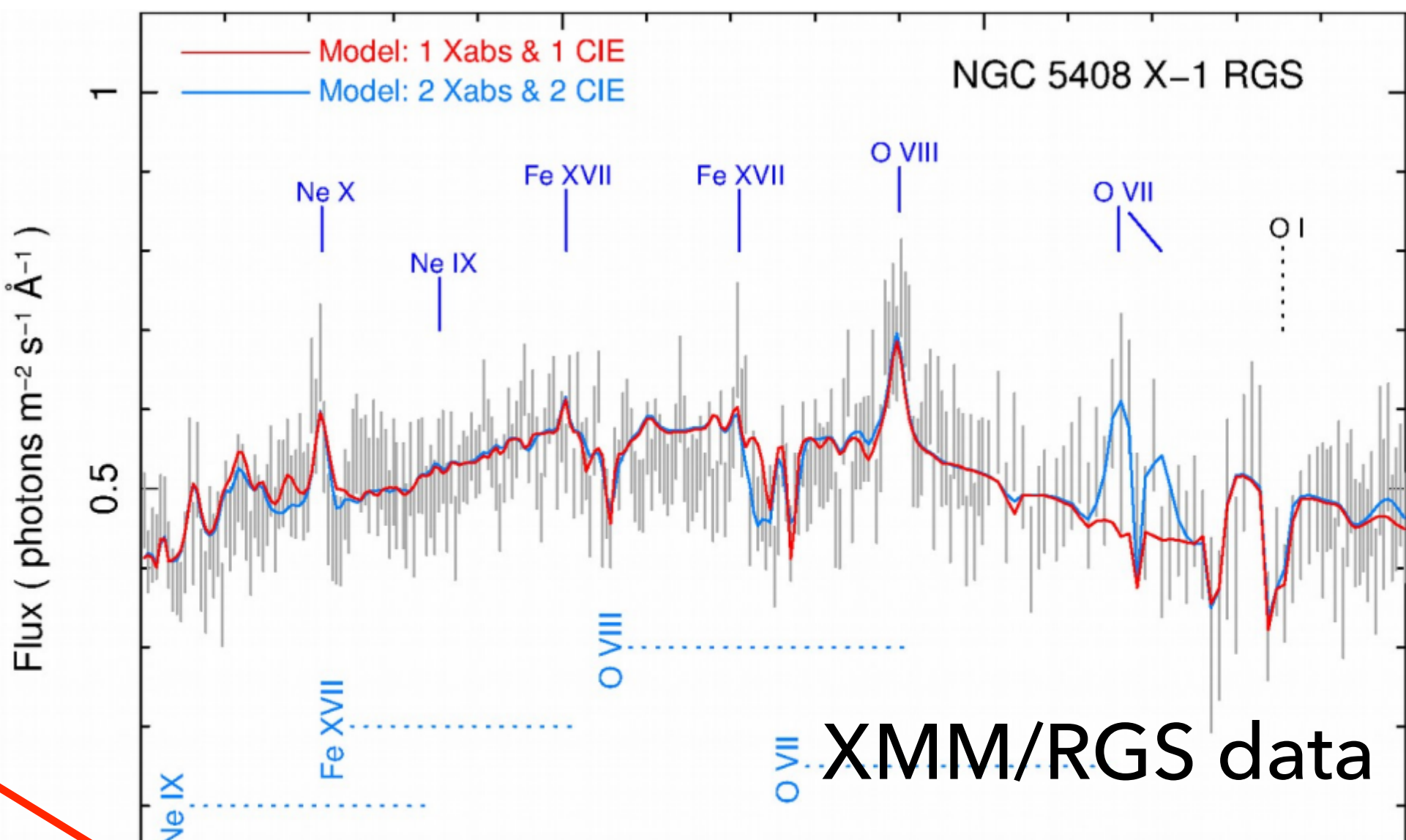
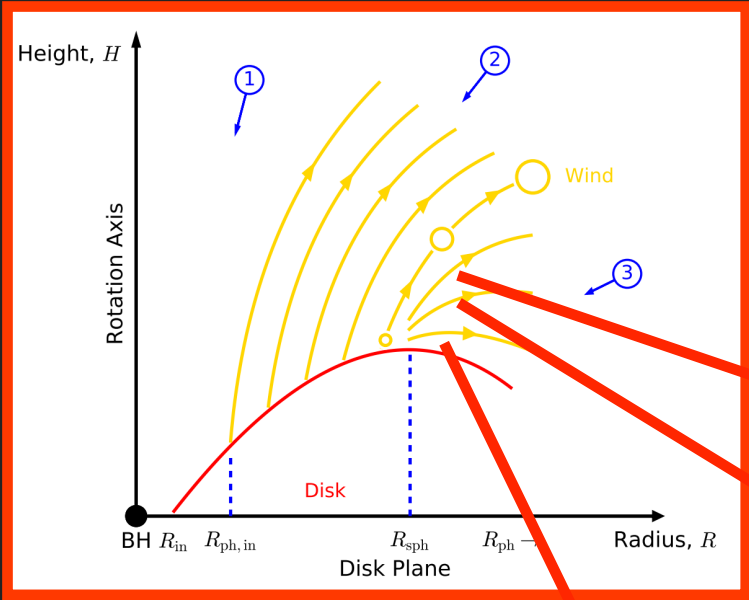
$$R_{\text{sph}} \sim \dot{M}_0$$



See Poutanen et al. (2007)

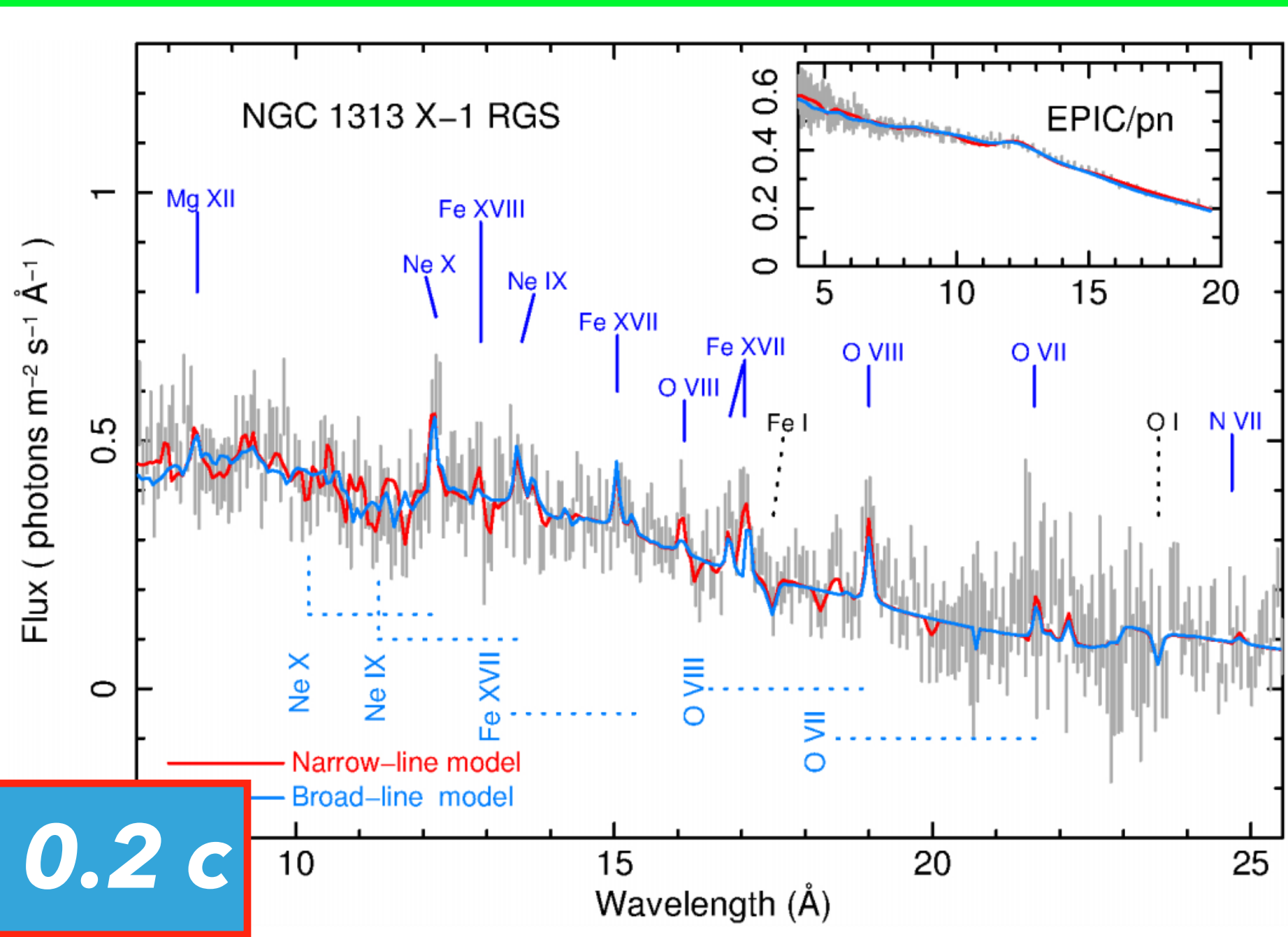
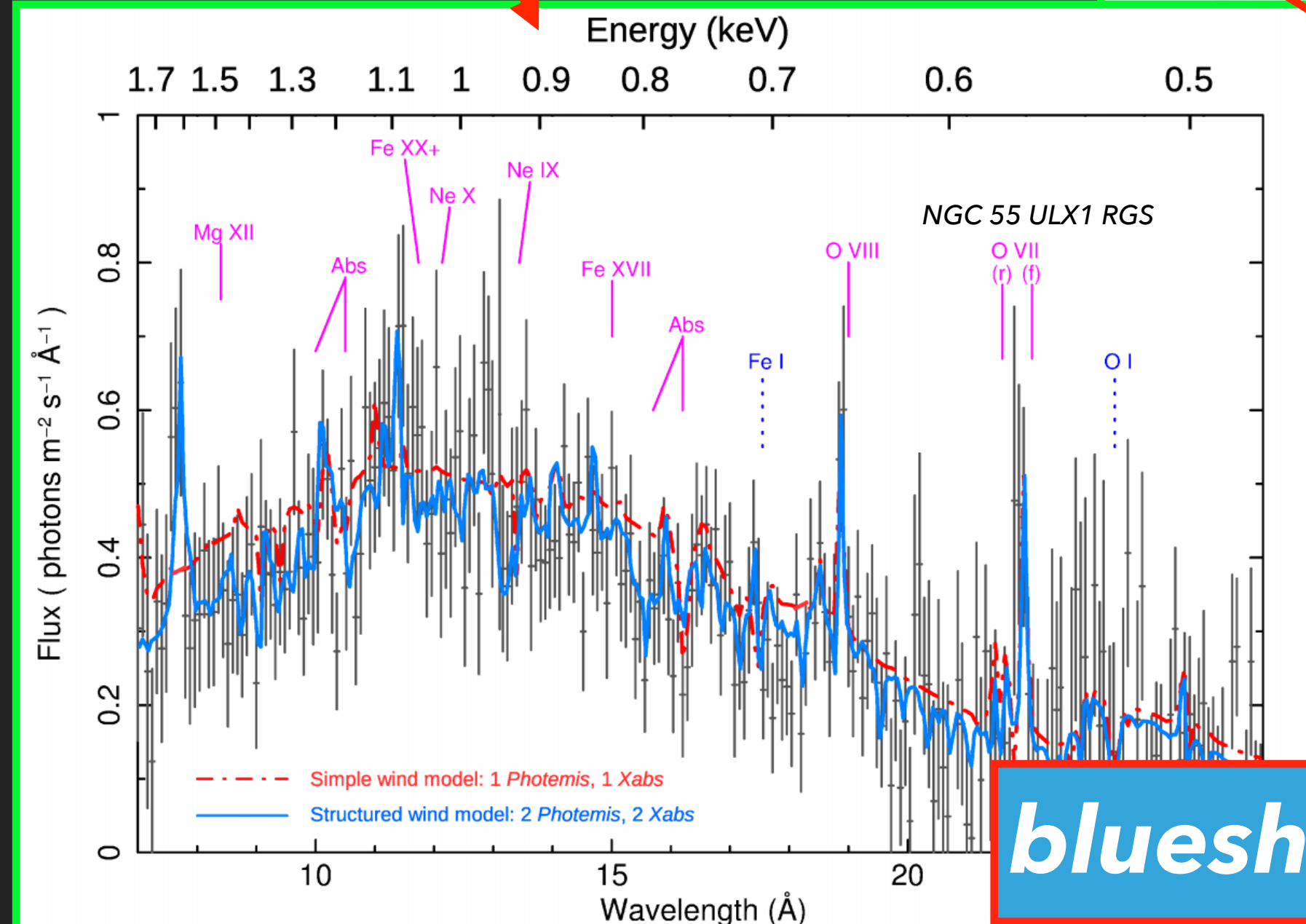
MHD:
Ohsuga et al. (2009)
Kawashima et al. (2014)
Romavoa et al. (2014)
Mushtukov et al. (2015)
Mushtukov et al. (2016)
Kawashima et al. (2016)

SUPER-CRITICAL ACCRETION REGIME



Absorption and emission features were found in several ULX spectra

Pinto et al. (2015, 2017)
Kosec et al. (2018, 2021)

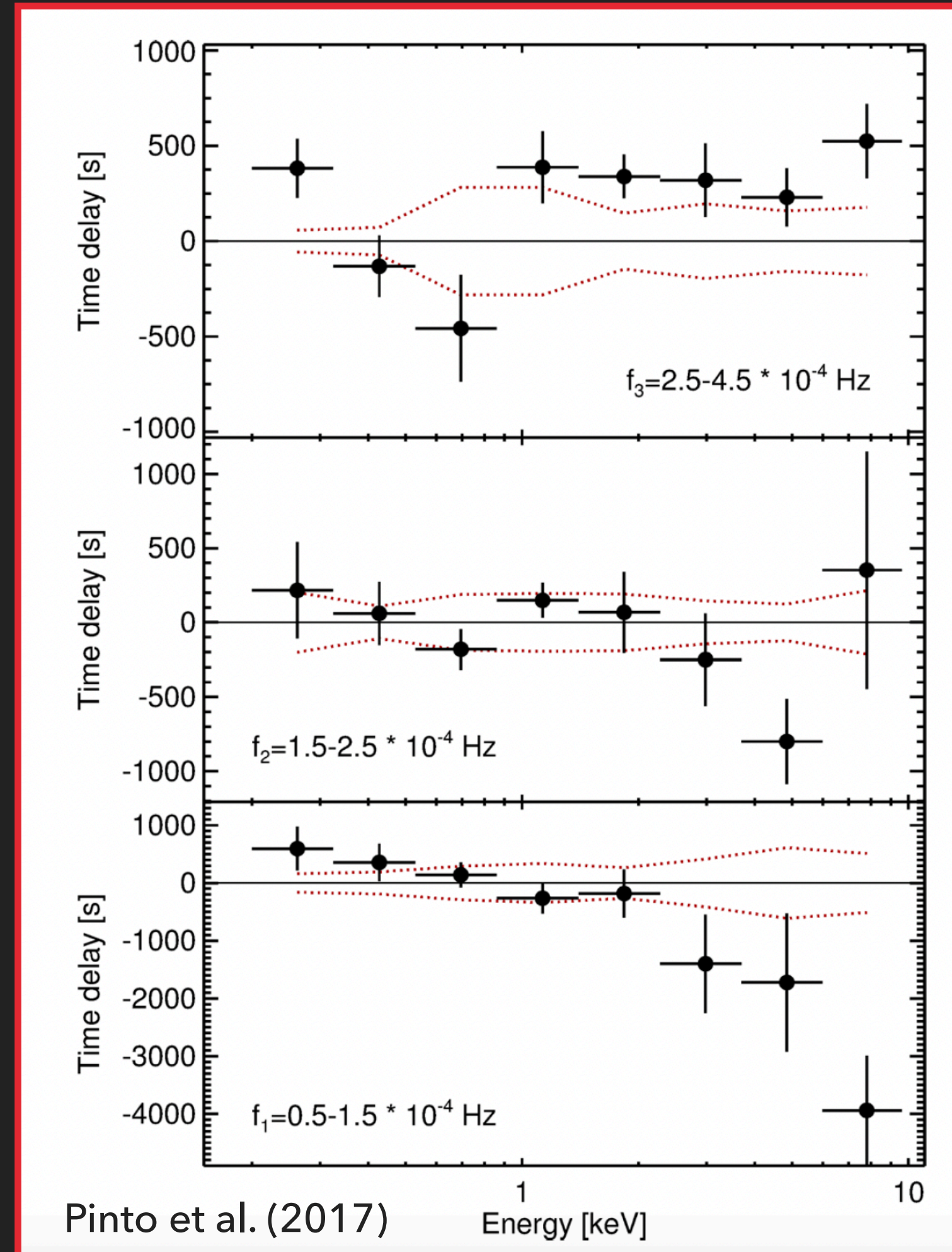
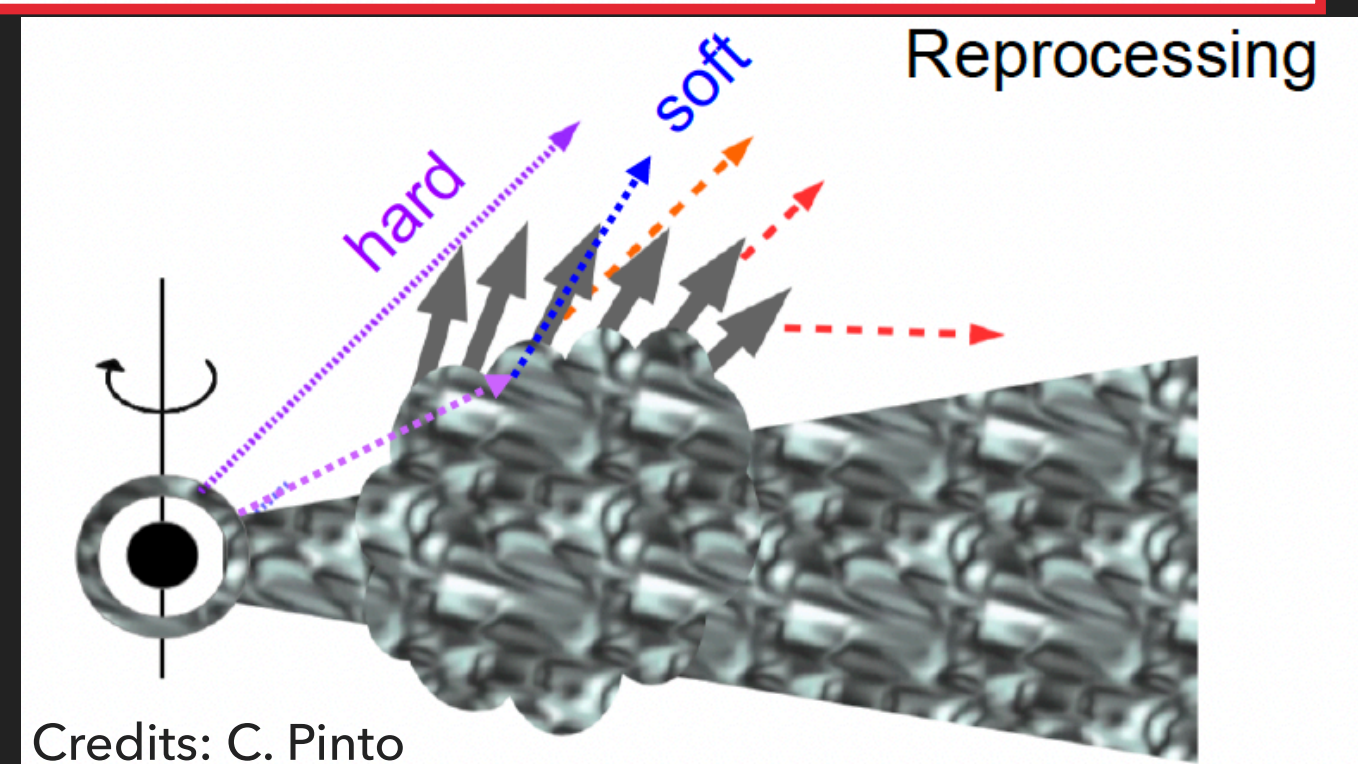
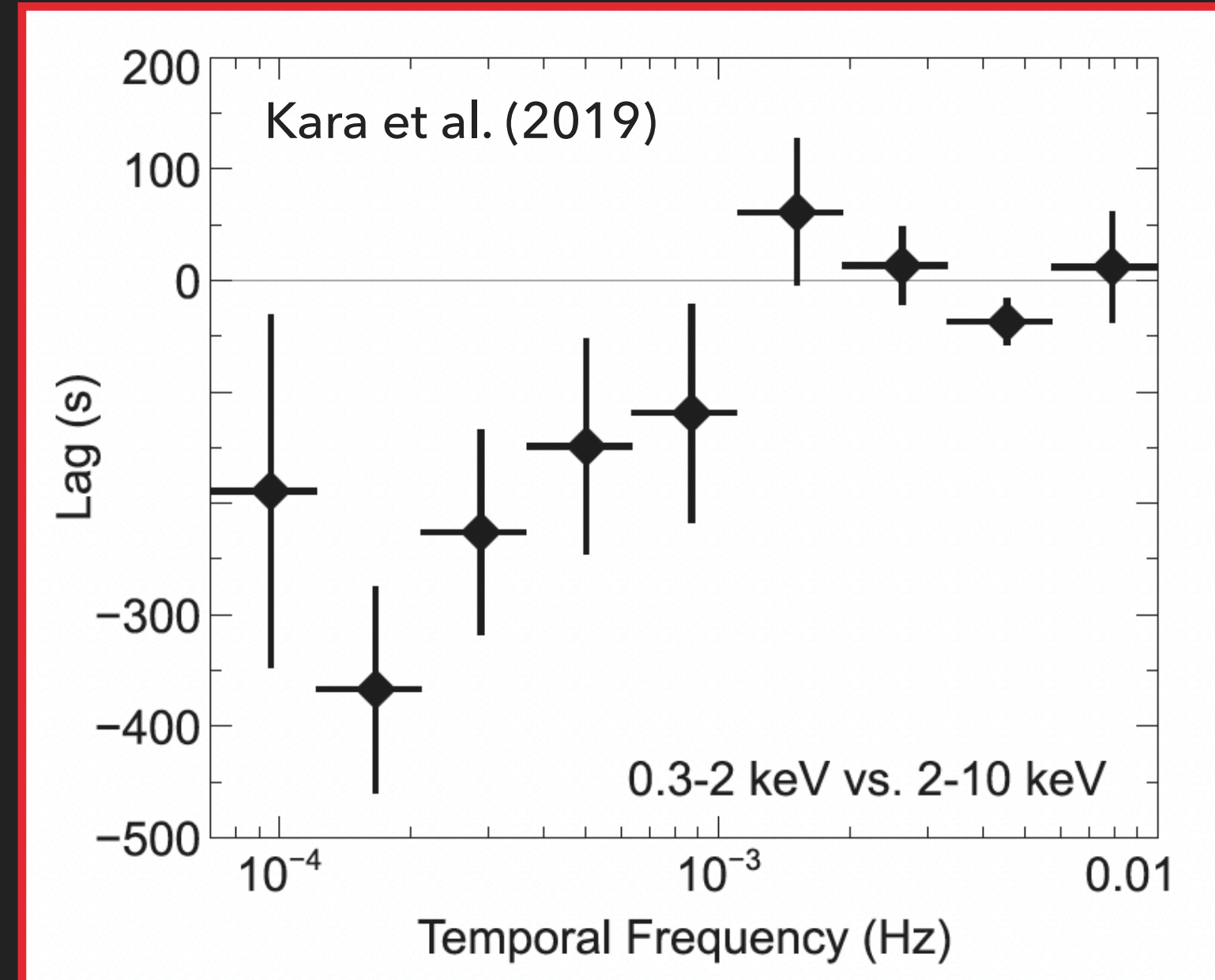
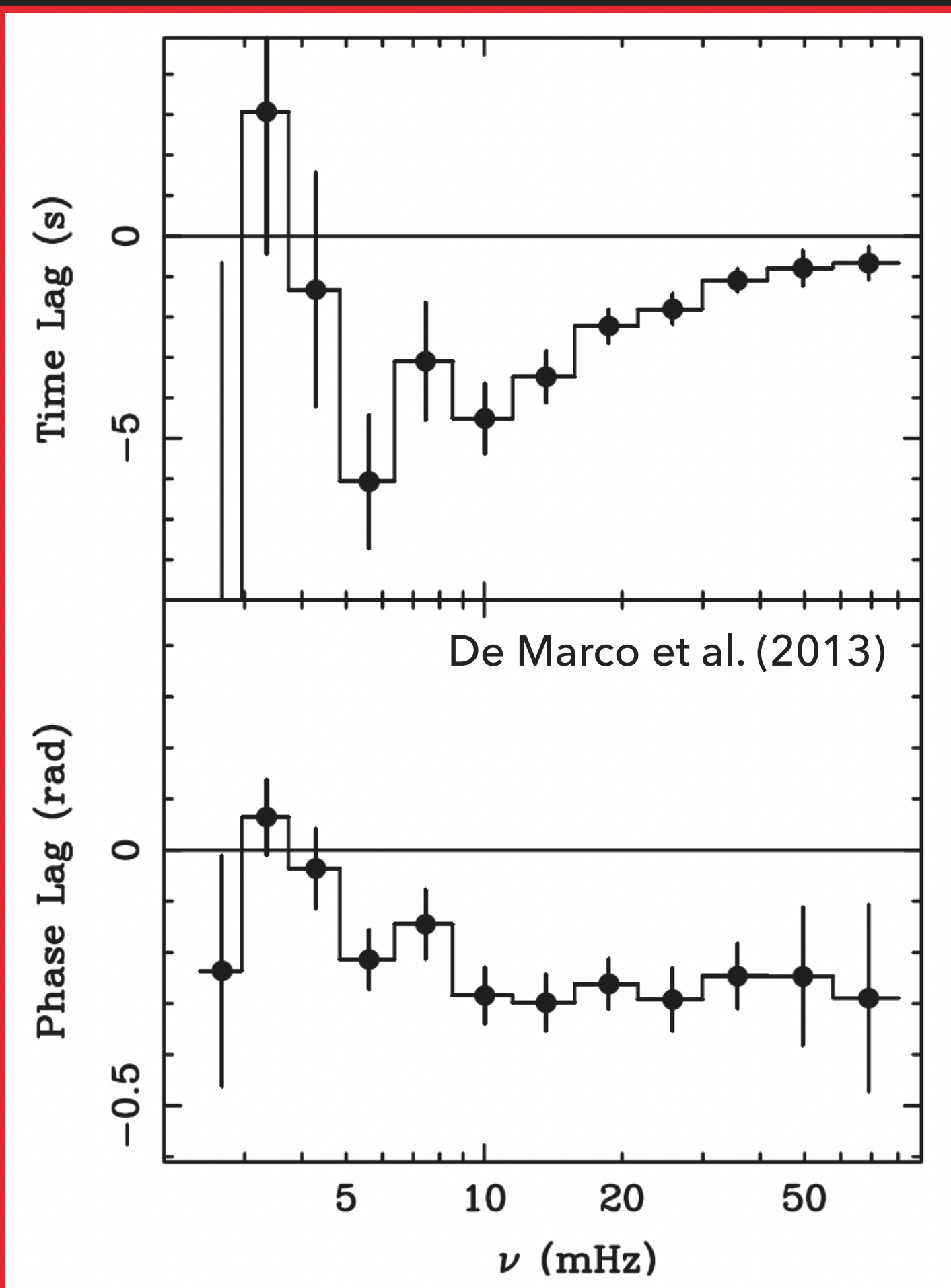


blueshift of $z \sim 0.2 c$

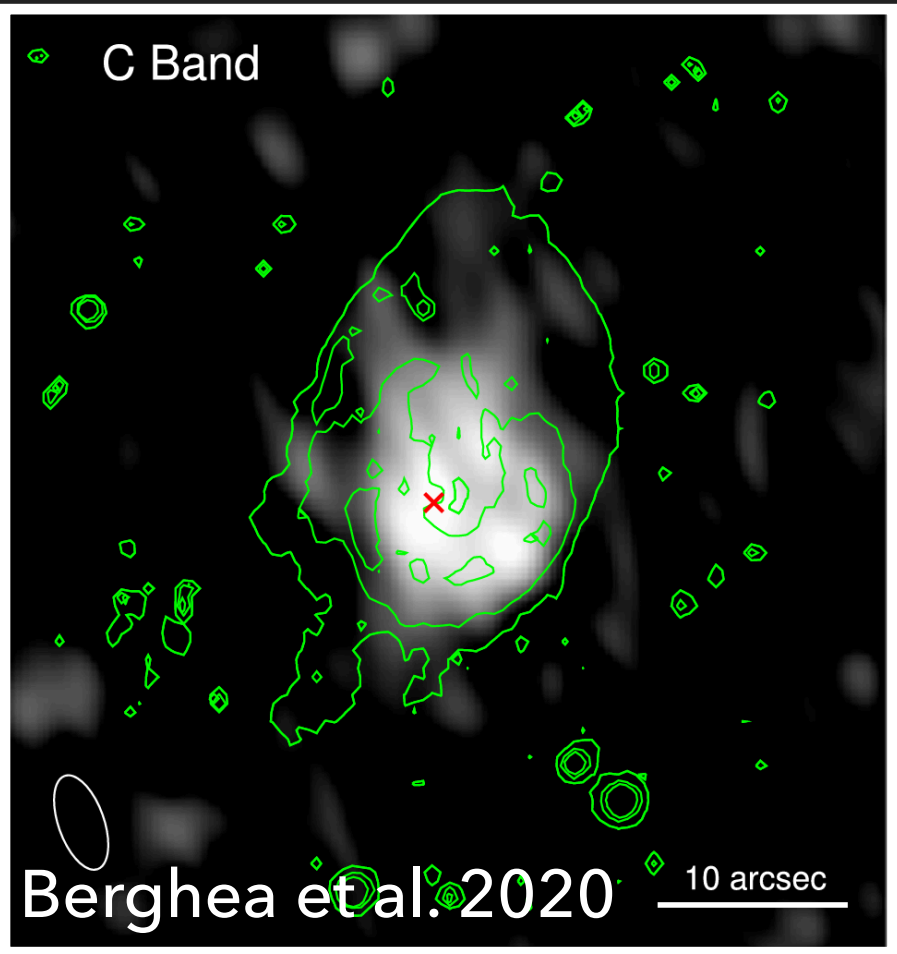
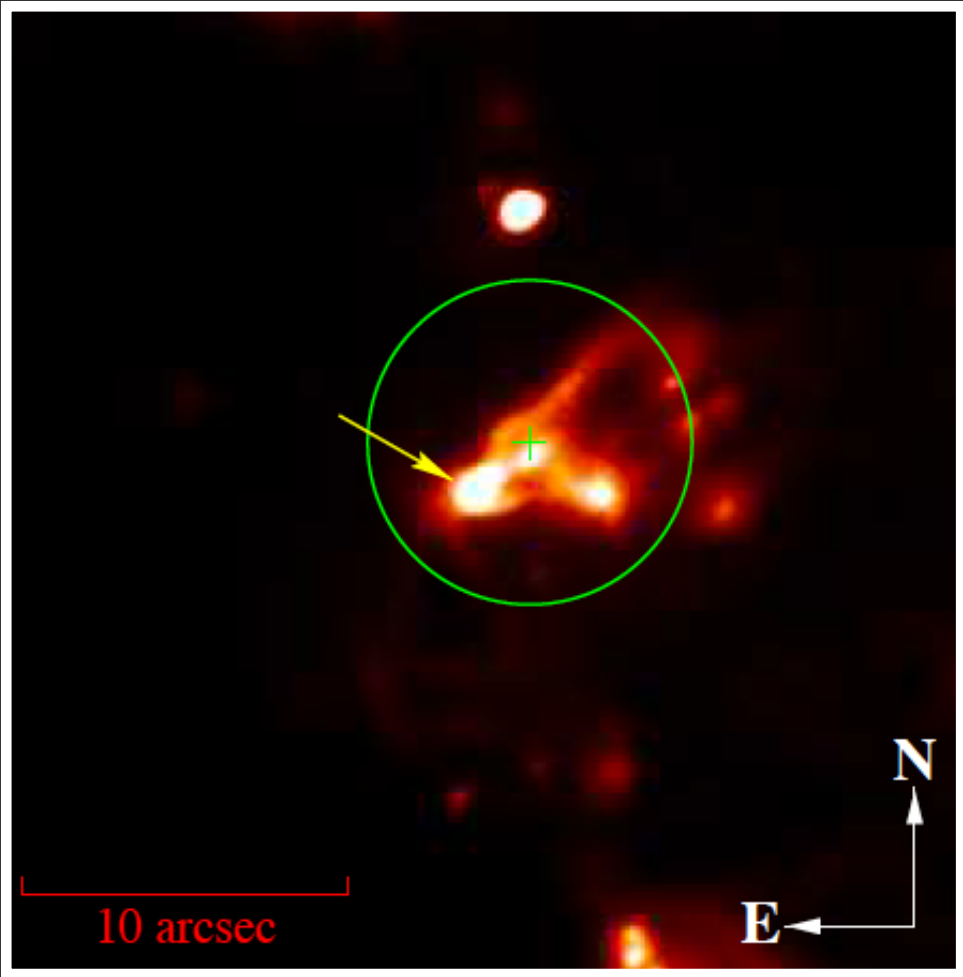
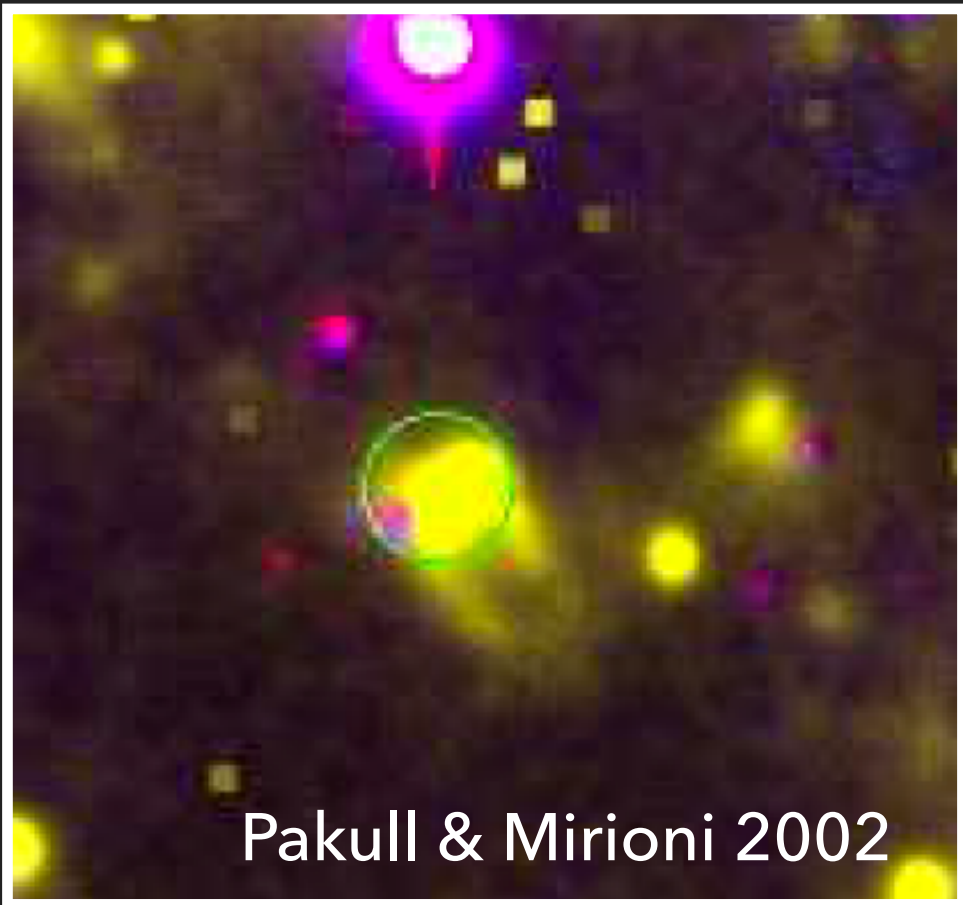
TIME LAGS

Soft lags, i.e. soft emission lags the hard one, observed in several ULXs!

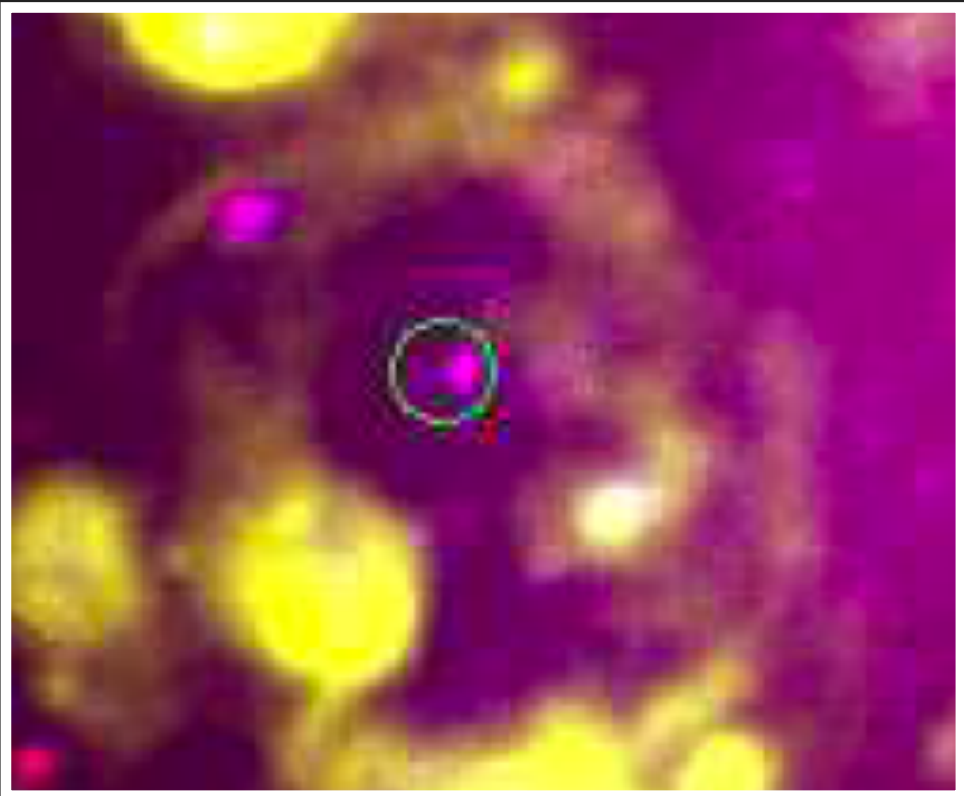
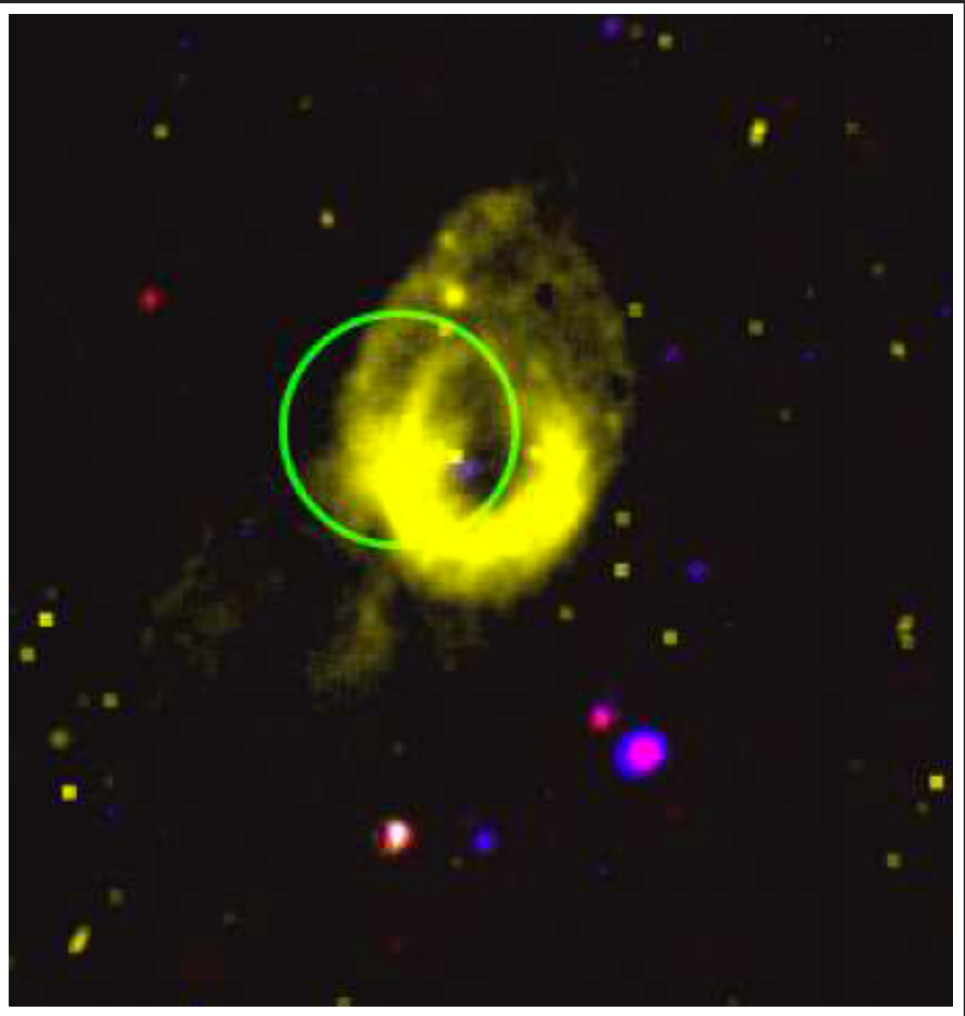
- Lags of hundreds of seconds (compatible with those observed in AGN)
- Possible reprocessing of hard photons from the funnel of wind/outflows.



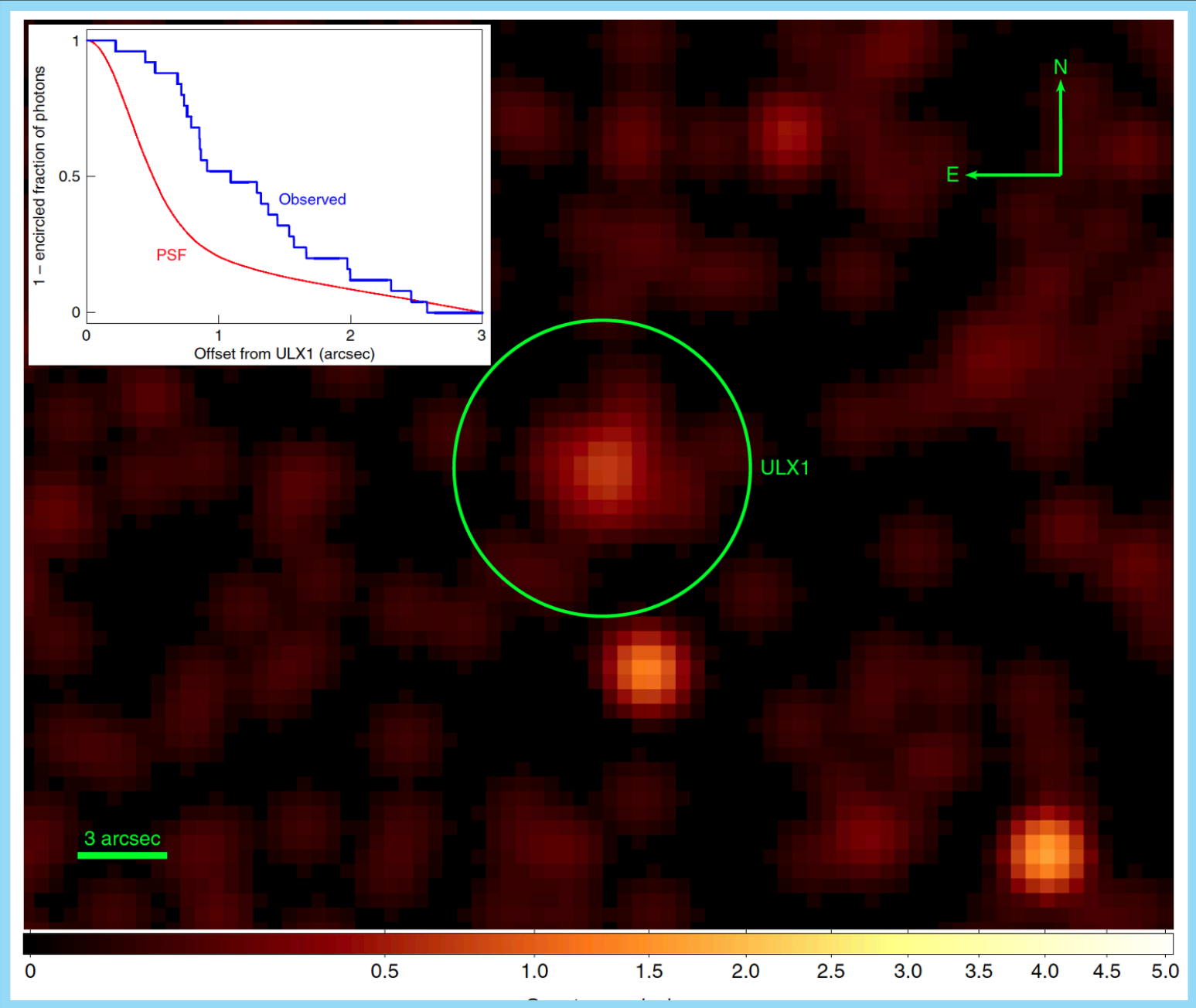
SUPER-CRITICAL ACCRETION REGIME



***Optical/IR/radio nebulae
(>100 pc in size).
Inflated by outflows?***

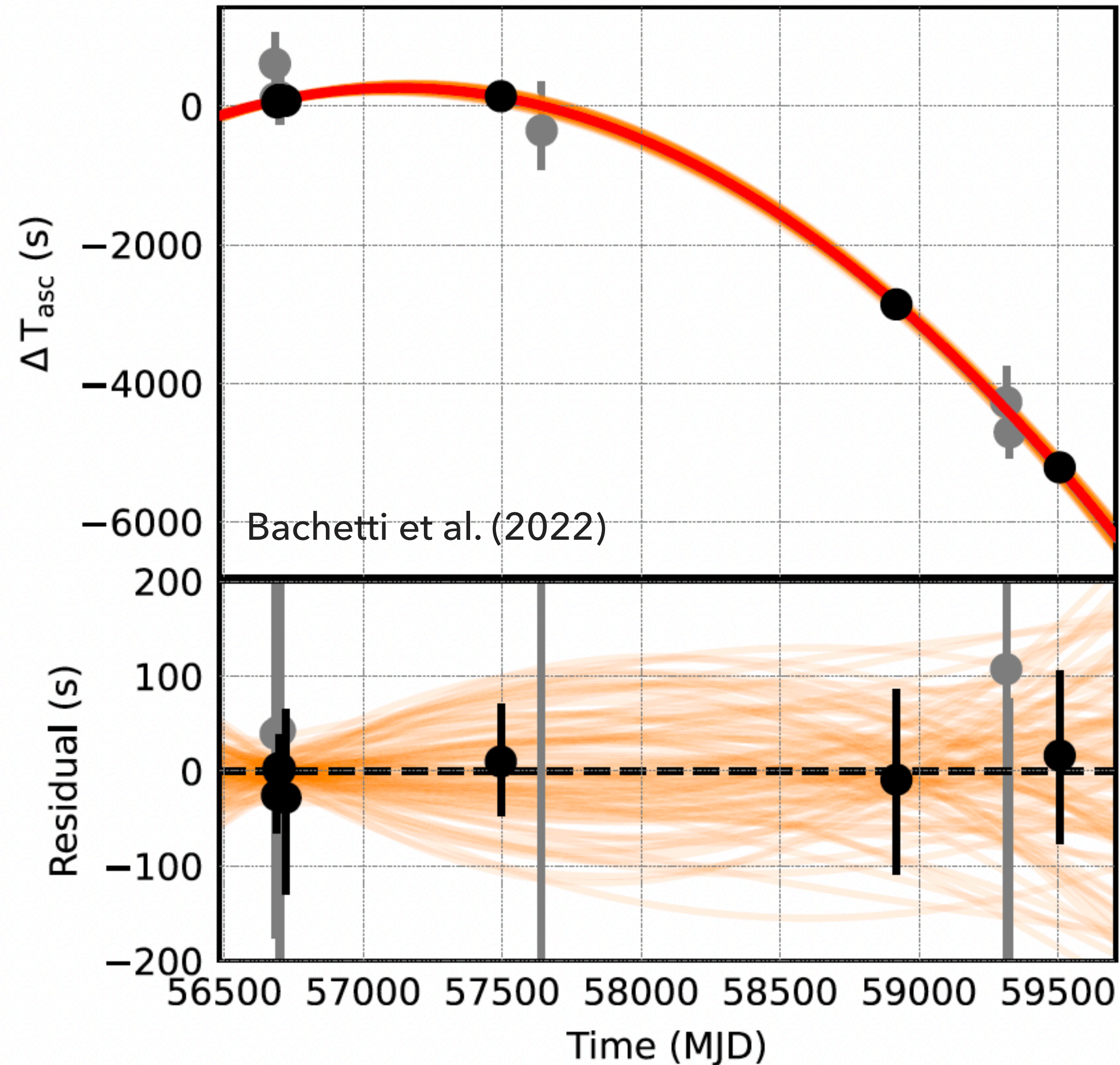


Belfiore, Esposito, FP et al. (2019)



A nebula was also found in X-rays around the pulsating ULX named NGC 5907 ULX-1, in one Chandra observation

ORBITAL PROPERTIES IN PULXS

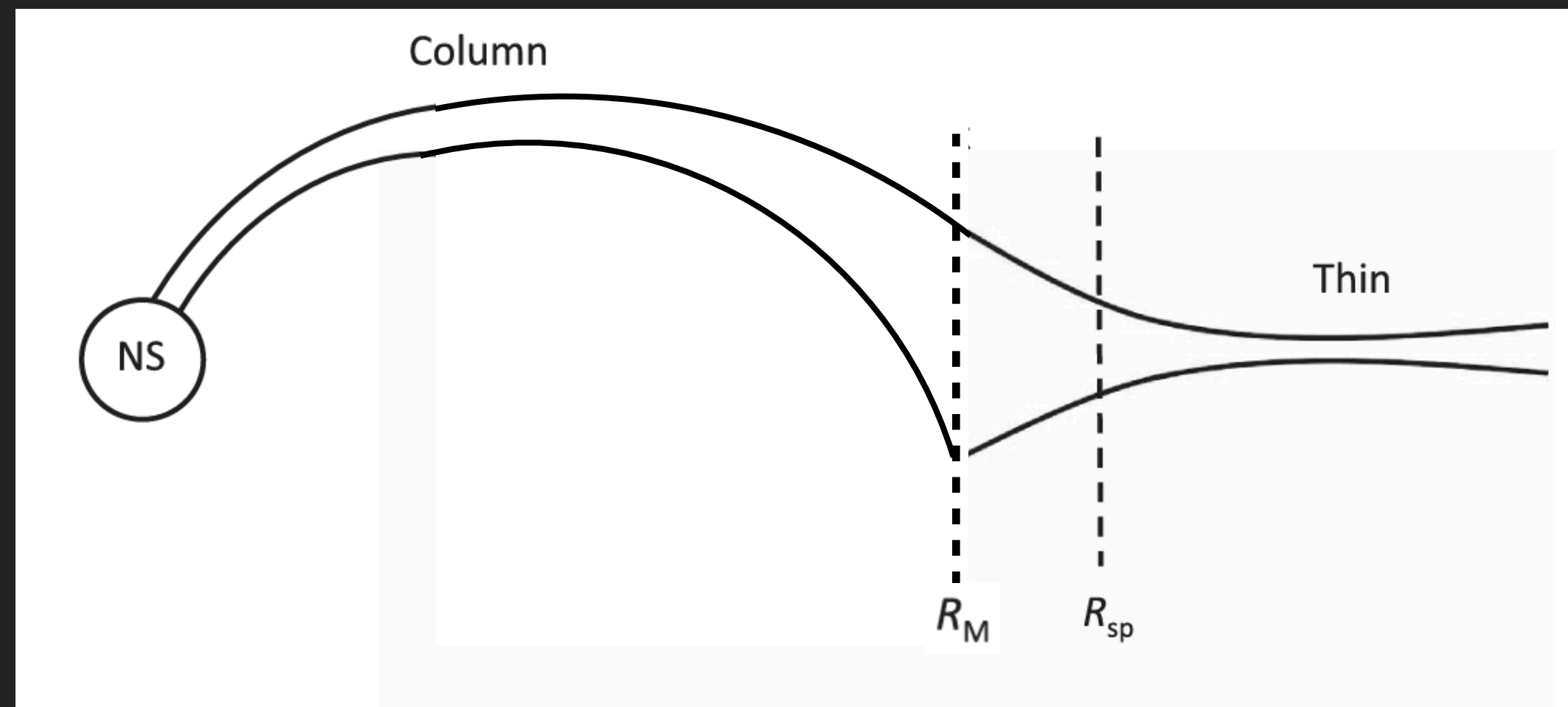


Observed a secular orbital evolution in M82 X-2 which supports the existence of outflows in this source (Bachetti et al. 2022).

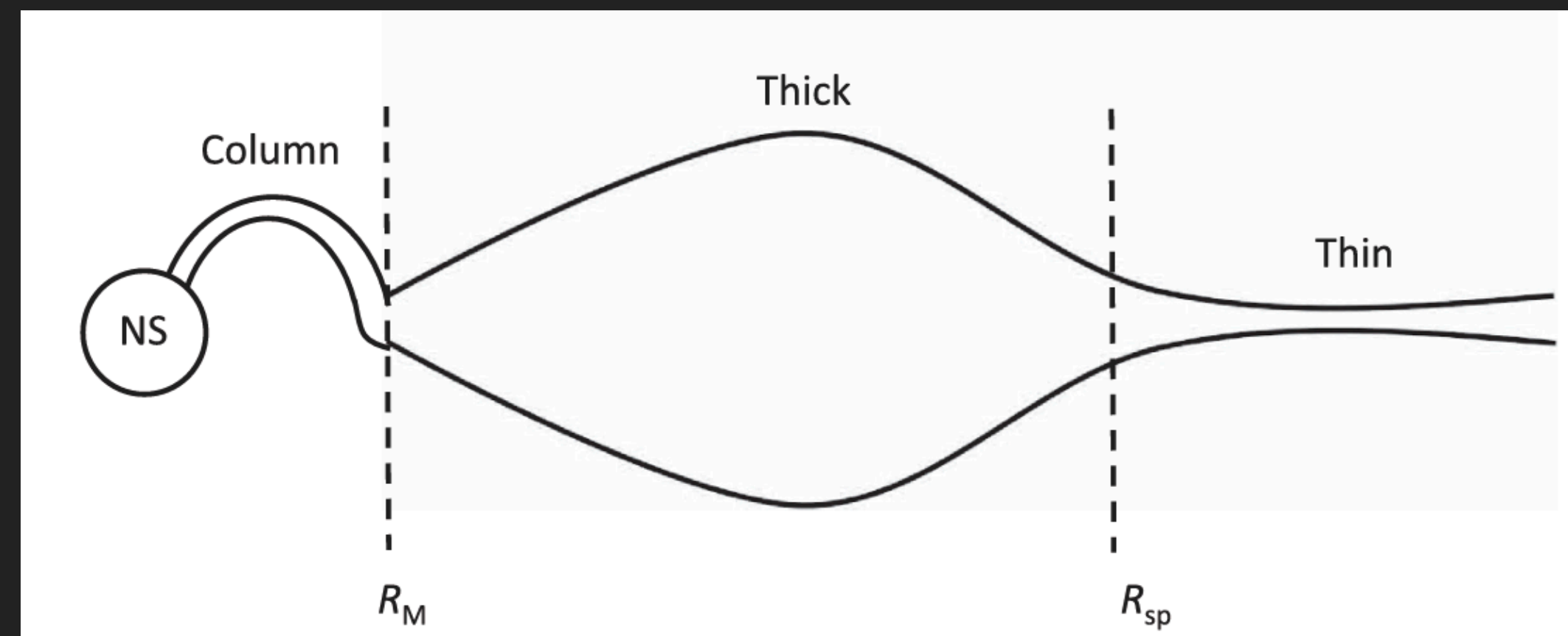
MAGNETIC FIELDS IN PULXS

High magnetic field ($B > 10^{14}$ G) can reduce the scattering cross-section and allows for super-Eddington accretion over the NS polar caps.

$$\frac{\sigma_{B1}}{\sigma_T} \approx \sin^2 \theta + \left(\frac{E_\gamma}{E_{\text{cyc}}} \right)^2 \cos^2 \theta$$
$$\frac{\sigma_{B2}}{\sigma_T} \approx \left(\frac{E_\gamma}{E_{\text{cyc}}} \right)^2, \text{ for } \frac{E_\gamma}{E_{\text{cyc}}} \ll 1,$$



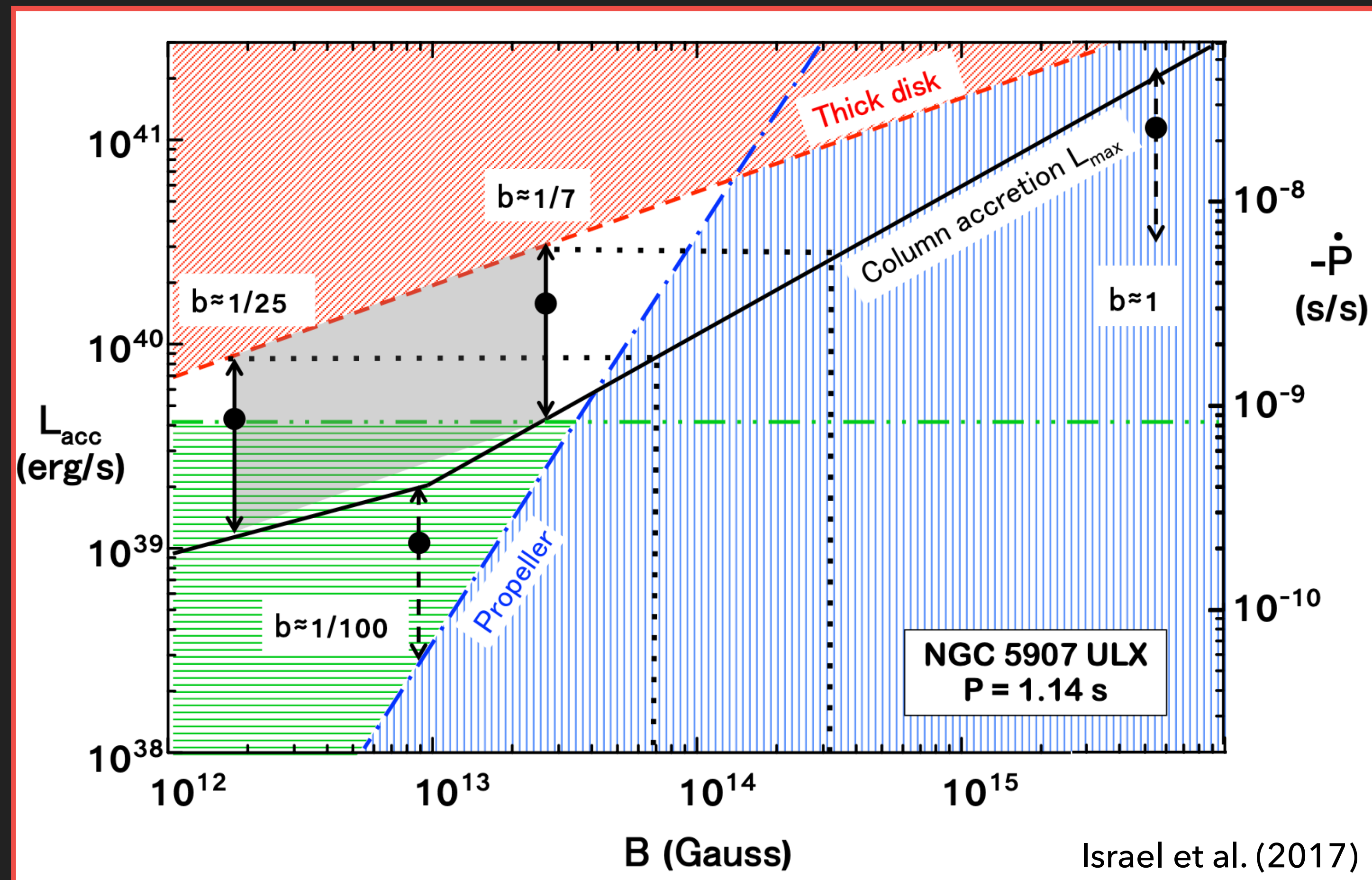
High B field ($B > 10^{14}$ G)



Low B field ($B < 10^{13}$ G)

MAGNETIC FIELDS IN PULXS

High magnetic field ($B > 10^{14}$ G) can reduce the scattering cross-section and allows for super-Eddington accretion over the NS polar caps.



Pieces of evidence support lower dipolar B-fields ($< 10^{13}$ G) in ULXs:

- presence of outflows; ✓
- PULXs should be continuously in propeller; ✗
- sinusoidal shape of the pulsed emission ✓

Quadrupolar magnetic field components?

ULTRALUMINOUS X-RAY SOURCES: OPEN QUESTIONS

- ▶ What's the nature of the companion stars (HMXBvs LMXB)?
- ▶ How are the outflows properties?
- ▶ How do outflows imprint on the surrounding medium?
- ▶ What's the compact object mass in ULXs?
- ▶ What's the BH vs NS ratio in the ULX population?
- ▶ Unknown NS magnetic field (dipolar vs quadrupolar)? Magnetar-like (10^{14-15} G) or more standard (10^{11-13} G)?
- ▶ Can the magnetic field truncate the disc before the spherization radius? Outflows are inhibited in PULXs? Not really, implying non-magnetar like magnetic fields.
- ▶ Is there any geometrical beaming of the emission?
- ▶ How does the spin evolve with time (spin-up/spin-down)?
- ▶ Is the large flux variability seen in PULXs due to propeller?

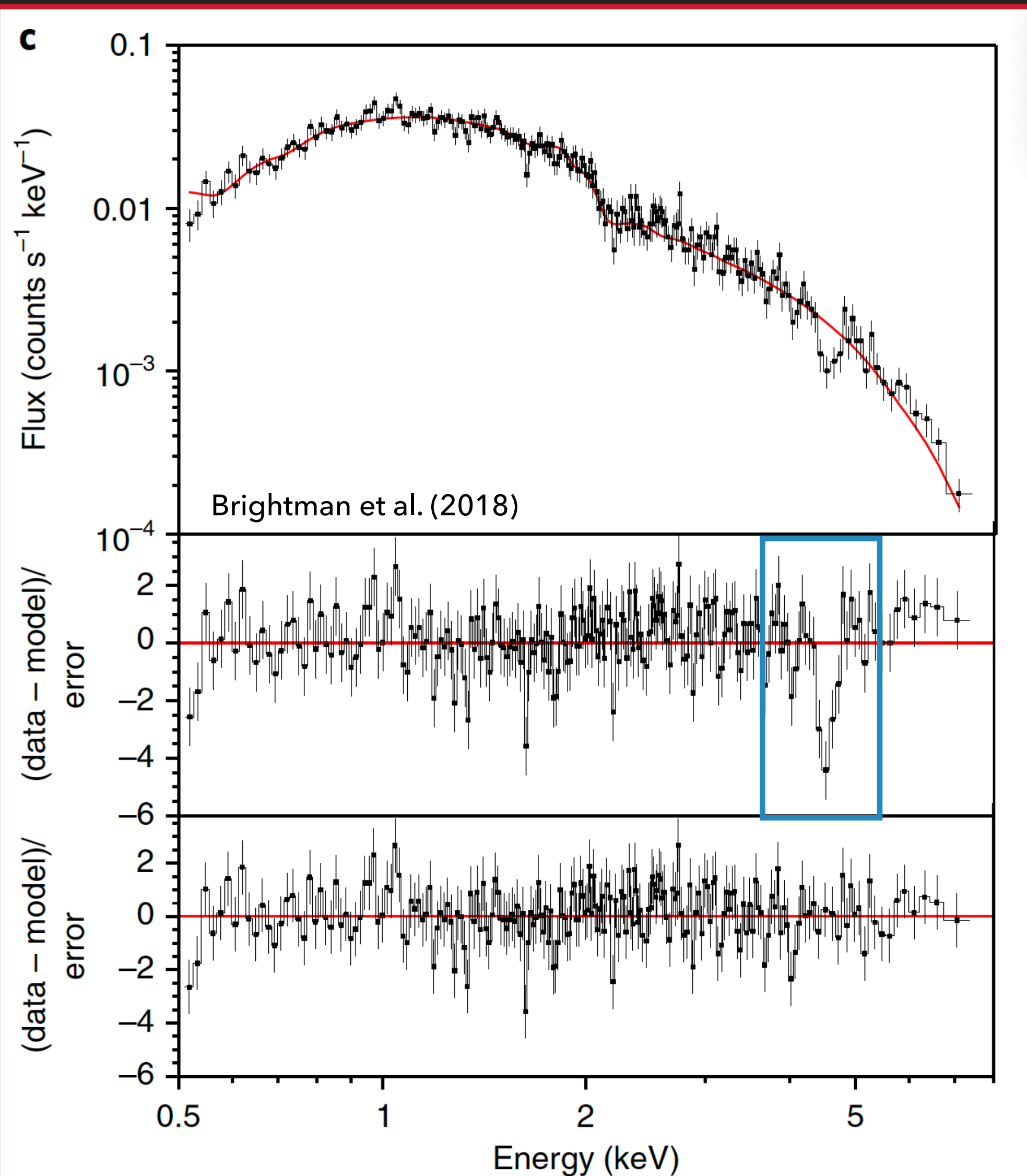
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NEUTRON STARS VS BLACK HOLES IN THE ULX POPULATION

- ▶ Only 6 PULXs over the total population of ~2000 ULXs
- ▶ However, PULXs are ~20-30% of the ULX population which has high quality observations to detect pulsations (~30 sources)
- ▶ Are the vast majority of ULXs hosting BH then?
- ▶ Increase the sample of PULXs. However, pulsations are intermittent in PULXs! Search for PULX-like sources amongst ULXs

NEUTRON STARS VS BLACK HOLES IN THE ULX POPULATION



Cyclotron line at 4.5 keV (3.8 σ detection) in a Chandra spectrum of M51 ULX-8

$(B/10^{12} \text{ G}) = E / (11.6 (1 + z)^{-1}) \rightarrow$ for electrons

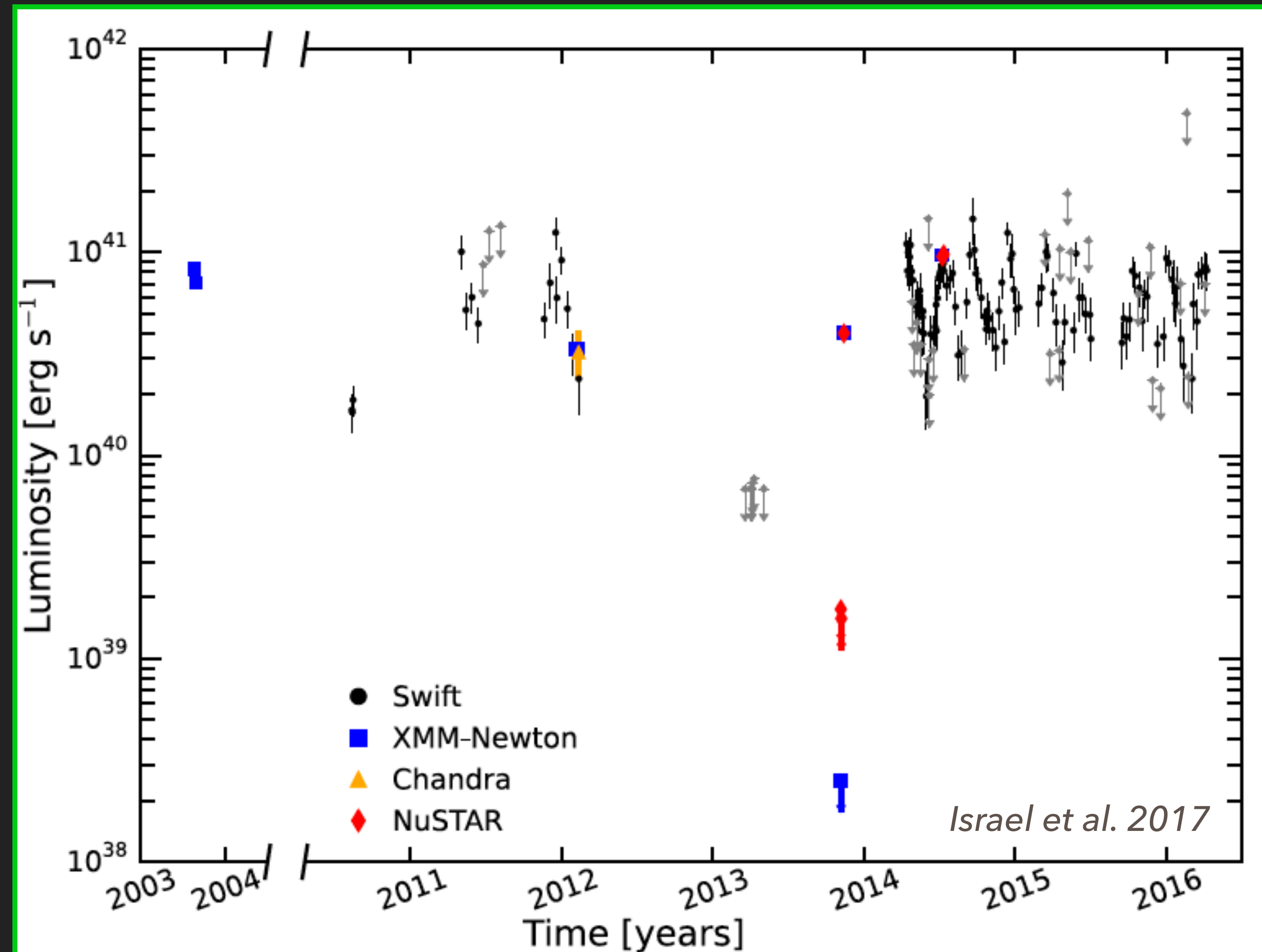
$(B/10^{15} \text{ G}) = E / (6.3 (1 + z)^{-1}) \rightarrow$ for protons

Estimated magnetic field of $B < 10^{12} \text{ G}$ (Brightman et al. 2018; Middleton, Brightman, Pintore et al. 2019)

No pulsation detected yet...

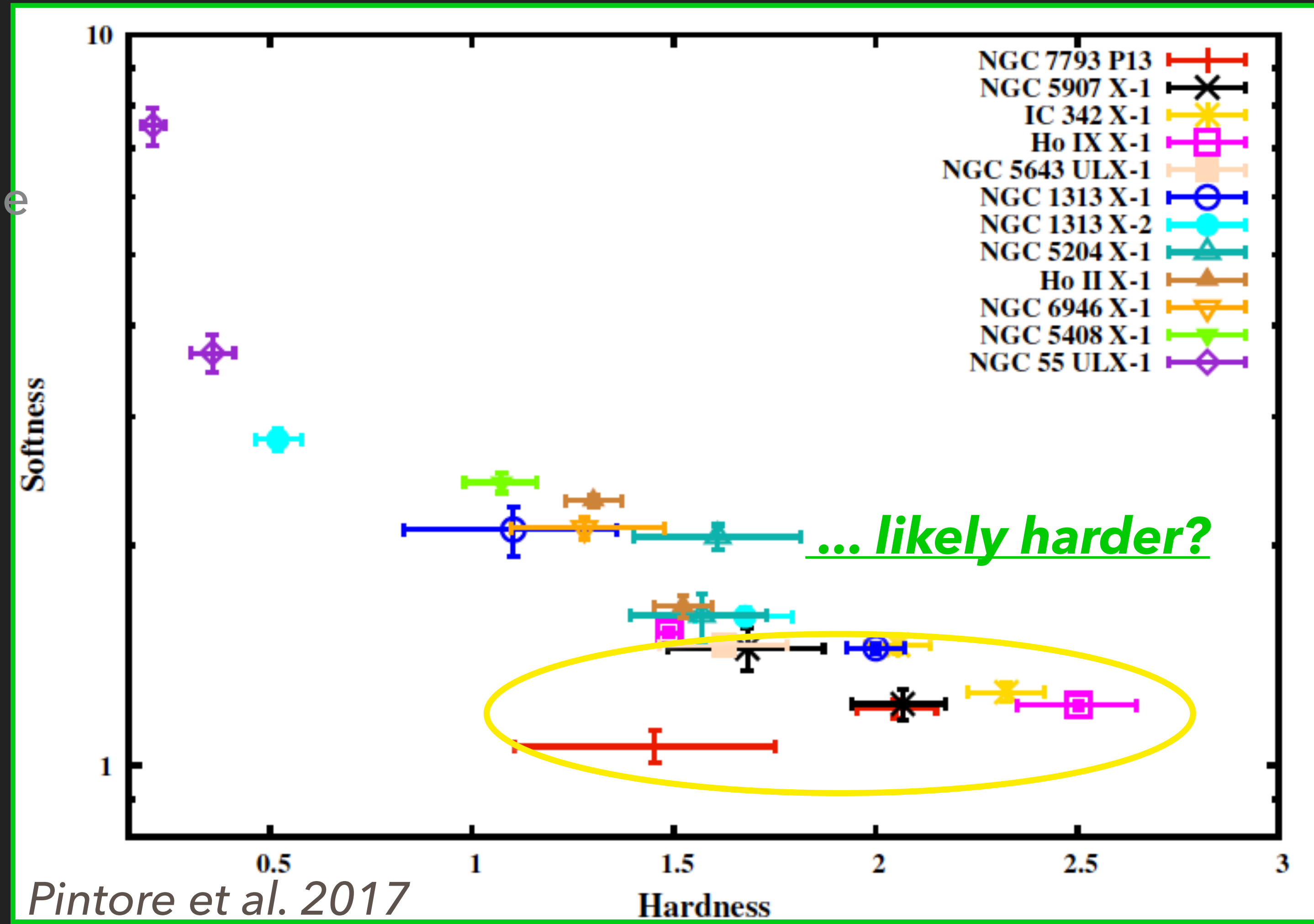
HUNT FOR PULX CANDIDATES

- ▶ Pulsating ULXs:
 - ▶ All transient sources (with a possible by-modality)



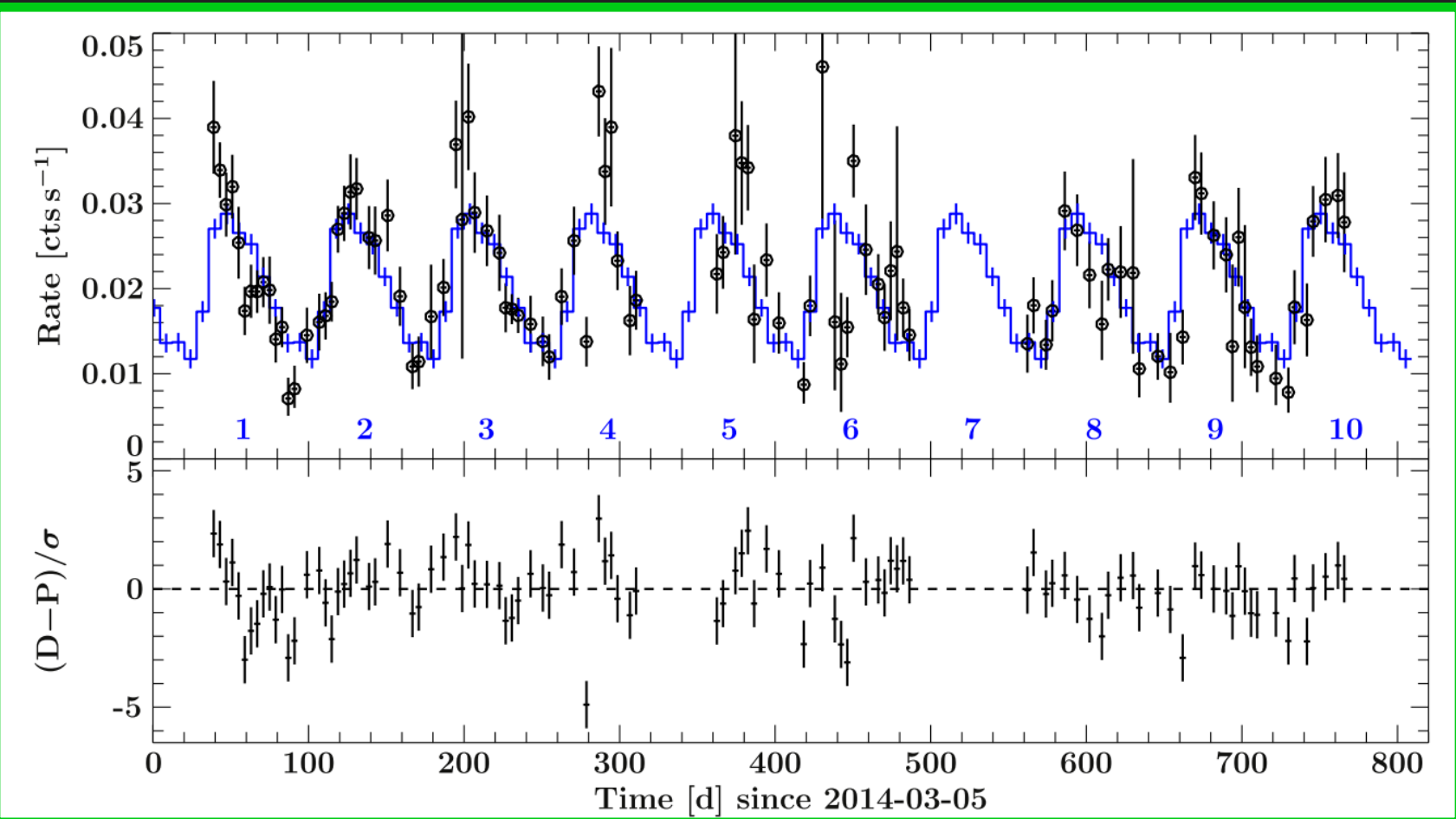
HUNT FOR PULX CANDIDATES

- ▶ Pulsating ULXs:
 - ▶ All transient sources (with a possible by-modality)
 - ▶ Spectral shapes

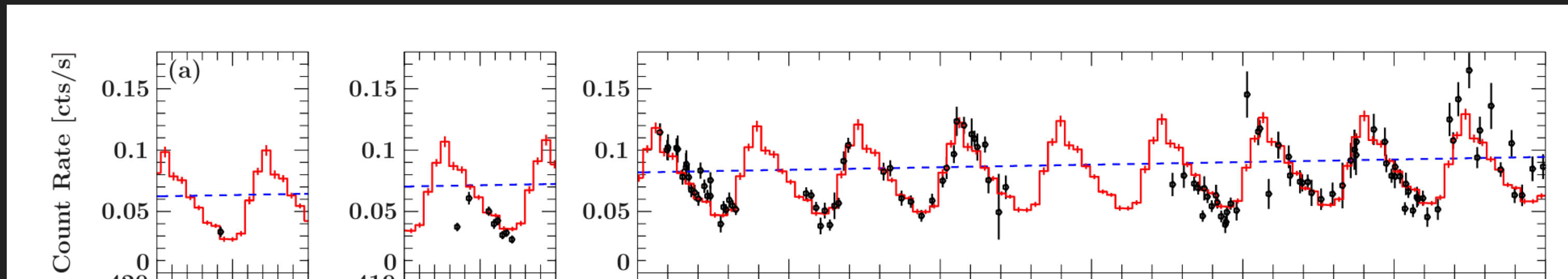
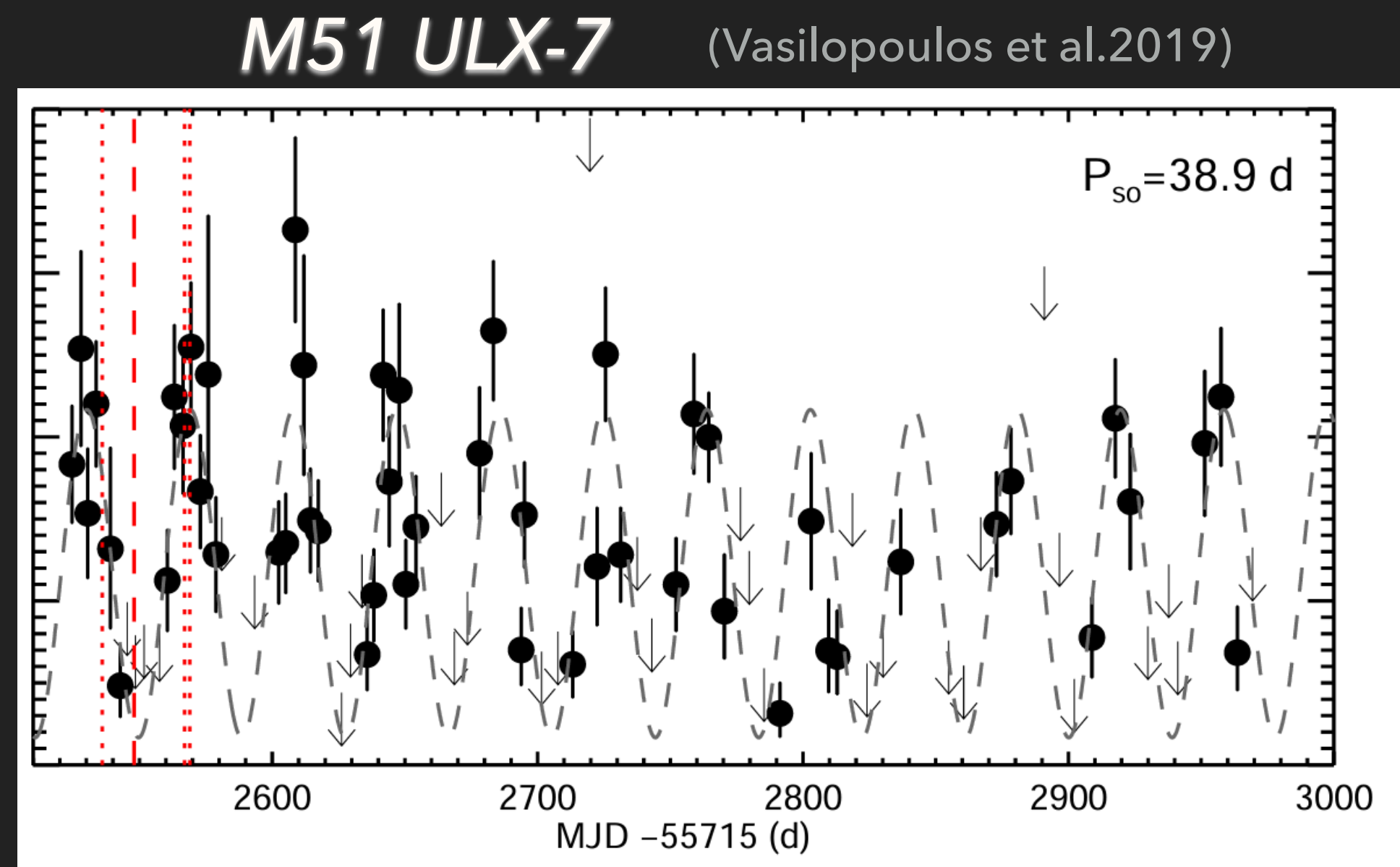


HUNT FOR PULSX CANDIDATES

- ▶ Pulsating ULXs:
 - ▶ All transient sources (with a possible by-modality)
 - ▶ Spectral shapes
 - ▶ Super-orbital modulations of tens-to-hundreds of days



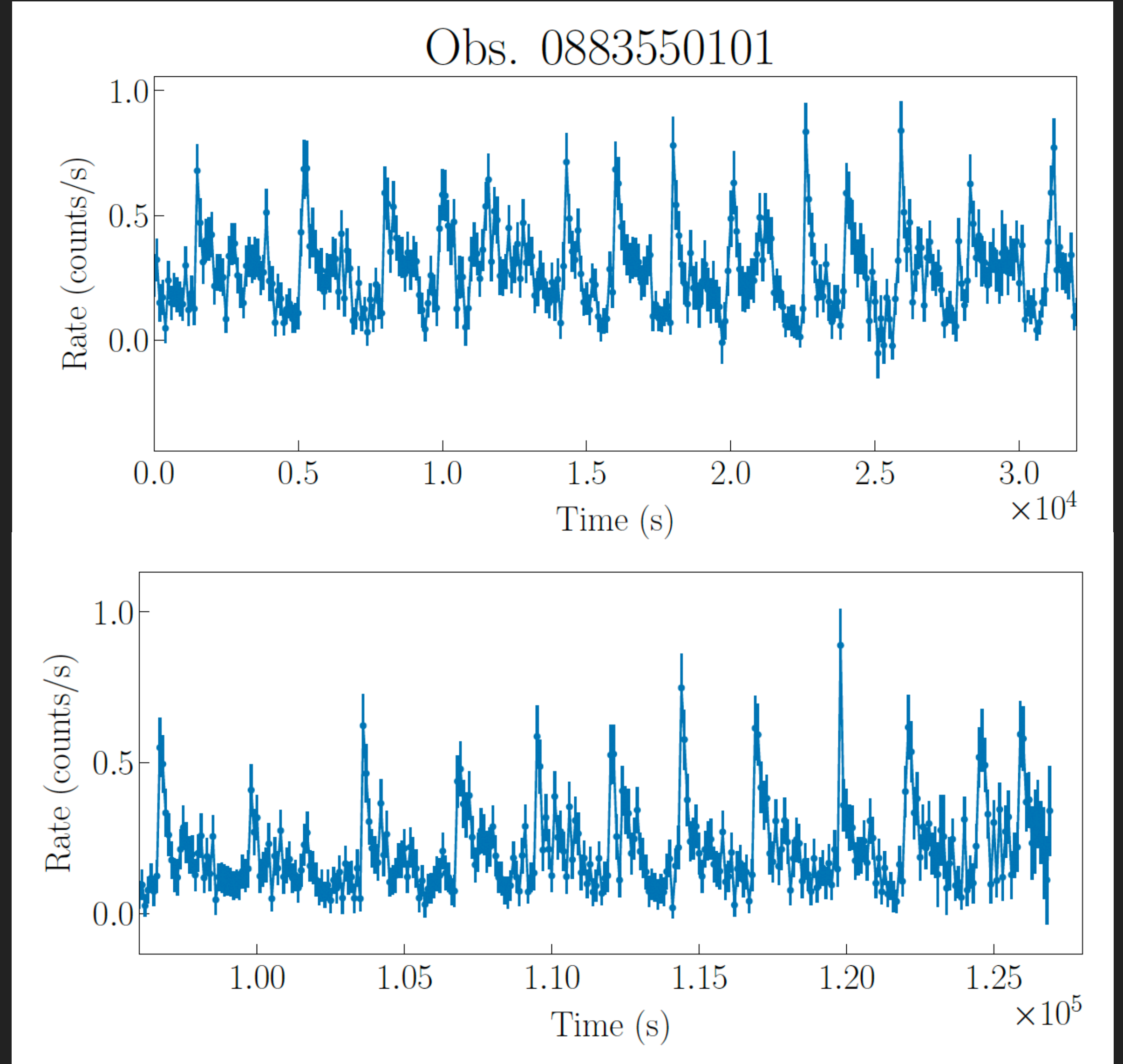
NGC 5907 X-1 (Walton et al.2016)



NGC 7793 P13 (Fuerst et al.2018)

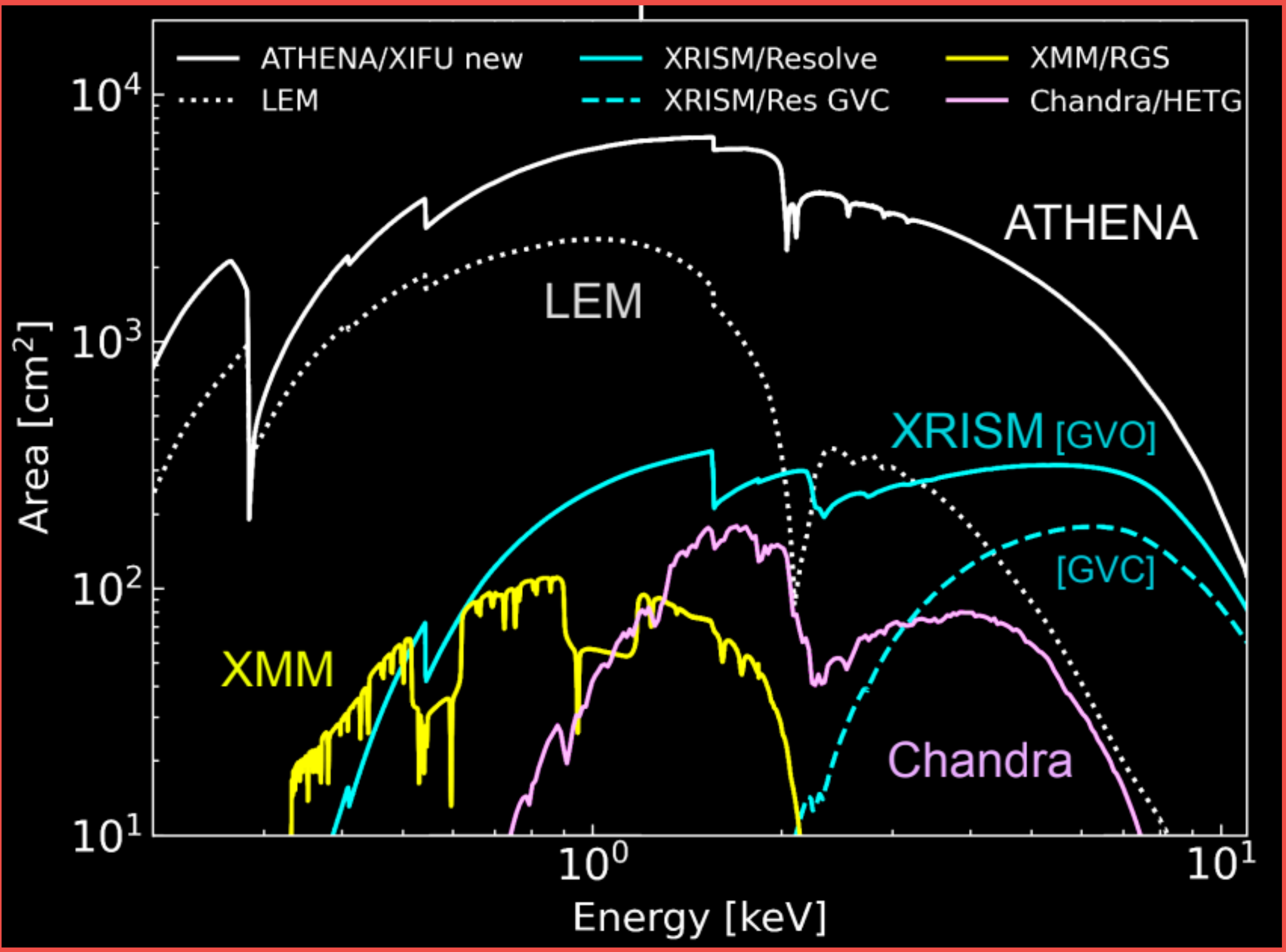
HUNT FOR PULX CANDIDATES

- ▶ Pulsating ULXs:
 - ▶ All transient sources (with a possible by-modality)
 - ▶ Spectral shapes
 - ▶ Super-orbital modulations of tens-to-hundreds of days
 - ▶ (Quasi-periodic) flaring activity

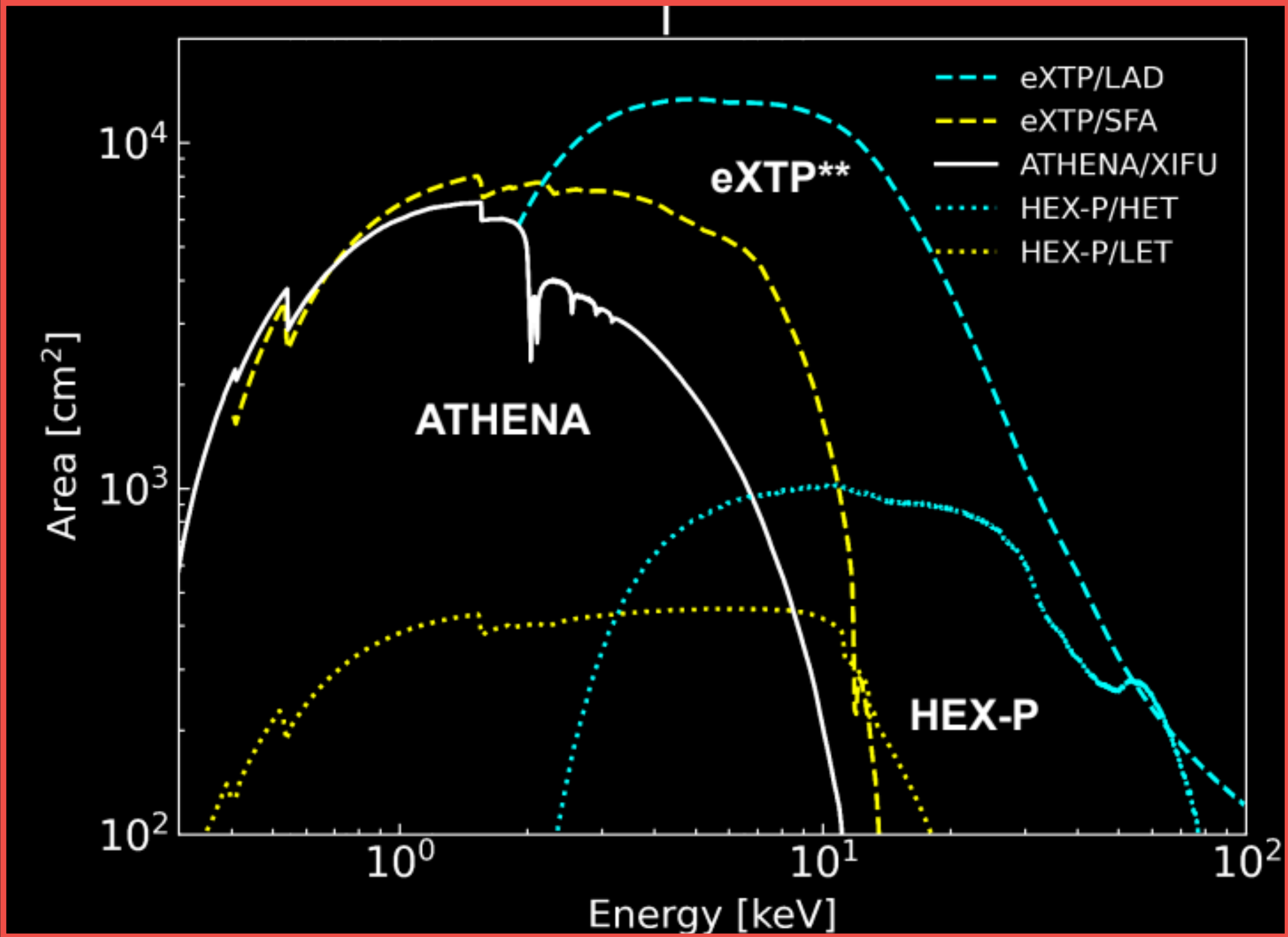


M51 ULX-7 (Imbrogno et al. 2024)

FUTURE DEVELOPMENTS: NewATHENA



NewAthena will help for both
high resolution and
broadband spectroscopy in
the ULX field



CONCLUSIONS

- The vast majority of ULXs is expected to be stellar mass compact objects accreting super-Eddington -> an extreme version of Galactic X-ray binaries
- Still many things to unveil, in particular how super-Eddington accretion processes work in pulsating ULXs
- Outflows are a marked footprint of ULXs and almost ubiquitous in these sources
- Winds -> responsible for most of the temporal and spectral properties observed in ULXs
- Outflows feedbacks on the galactic environment
- Investigating super-Eddington accretion in ULXs can help to understand the process of growing for supermassive BHs in AGN
- Needs for population studies. How many BH are in the ULX population?



Thanks for the attention