ORDER IN THE CHAOS OF THE ULTRALUMINOUS X-RAY SOURCE VARIABILITY

FABIO PINTORE (INAF/IASF PALERMO)

Collaborators: C. Pinto, G. Rodriguez-Castillo, G. Israel, N. Pinciroli Vago, D. Walton, F. Fuerst, S.Motta A. D'Aì, M. Del Santo, R. Salvaterra, E. Ambrosi, A. Wolter, L. Zampieri , Wladimiro Leone, Luciano Burderi and many more

IASF Istituto di Astrofisica Spaziale e Fisica cosmica Palermo

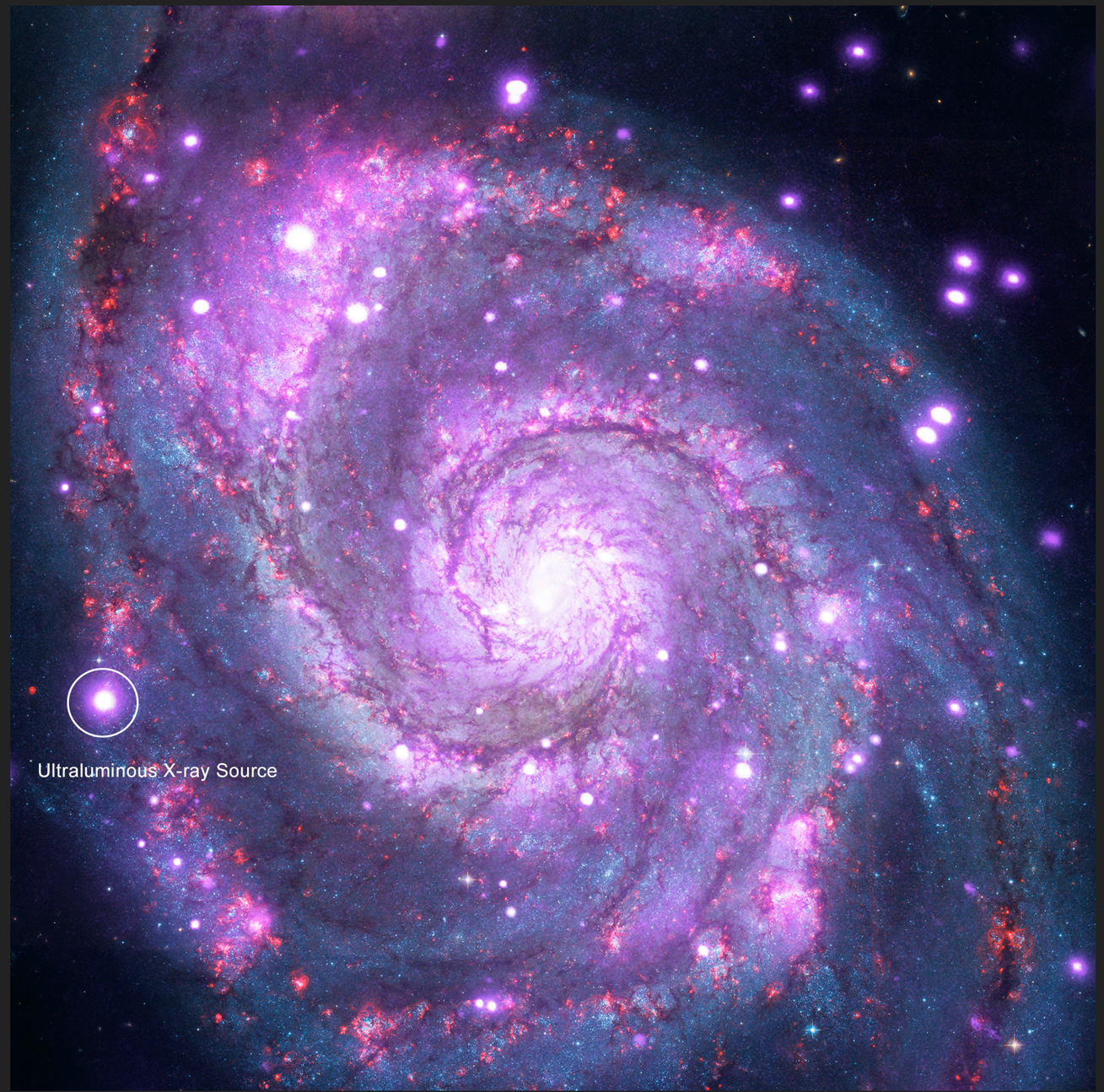
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

OUTLOOK

- Introduction to the ultraluminous X-ray sources (ULX)
- Open problems
- The search for pulsating ULXs (PULX): looking for PULX-like candidates in ULX
- The peculiar cases of the sources NGC 4559 X7 and NGC 7456 ULX1

ULTRALUMINOUS X-RAY SOURCES

- POINT-LIKE X-RAY SOURCES
- OFF-NUCLEAR (I.E. NO SUPERMASSIVE BH)
- $L_X >> 10^{39}$ ERG/S >> L_{EDD} OF 10 M_{SUN} BH



$L_{edd} \sim 1.4e38\ (M/M_{sun})\ erg/s$

ULTRALUMINOUS X-RAY SOURCES

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

KNOX S. LONG
Columbia Astrophysics Laboratory, Columbia University

SANDRO D'ODORICO
European Southern Observatory

PHILIP A. CHARLES[1]
Space Sciences Laboratory, University of California

AND

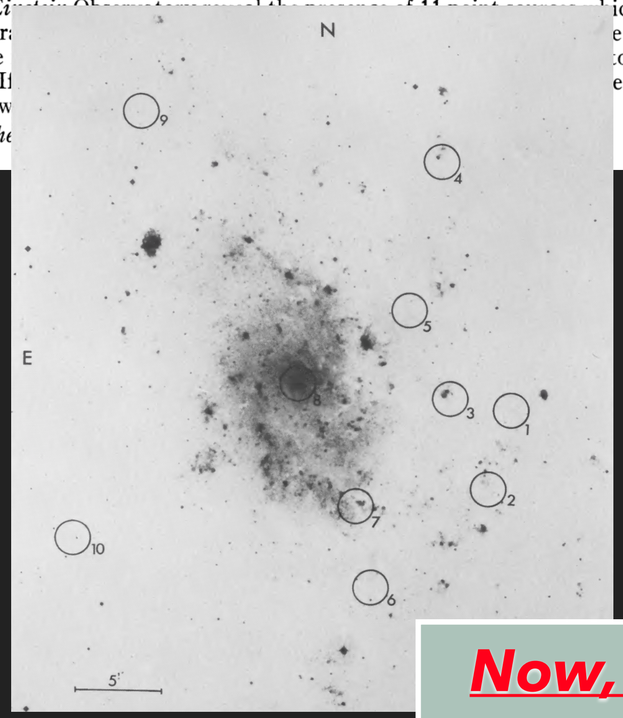
MICHAEL A. DOPITA
Mt. Stromlo and Siding Spring Observatory, Australian National University

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 *Ei*... ...ich, if at the distance of M33, have X-r... ...e brightest source, coincident with the ... ...otal X-ray luminosity of the galaxy. If... ...ent from the compact binary sources w...

Subject he...

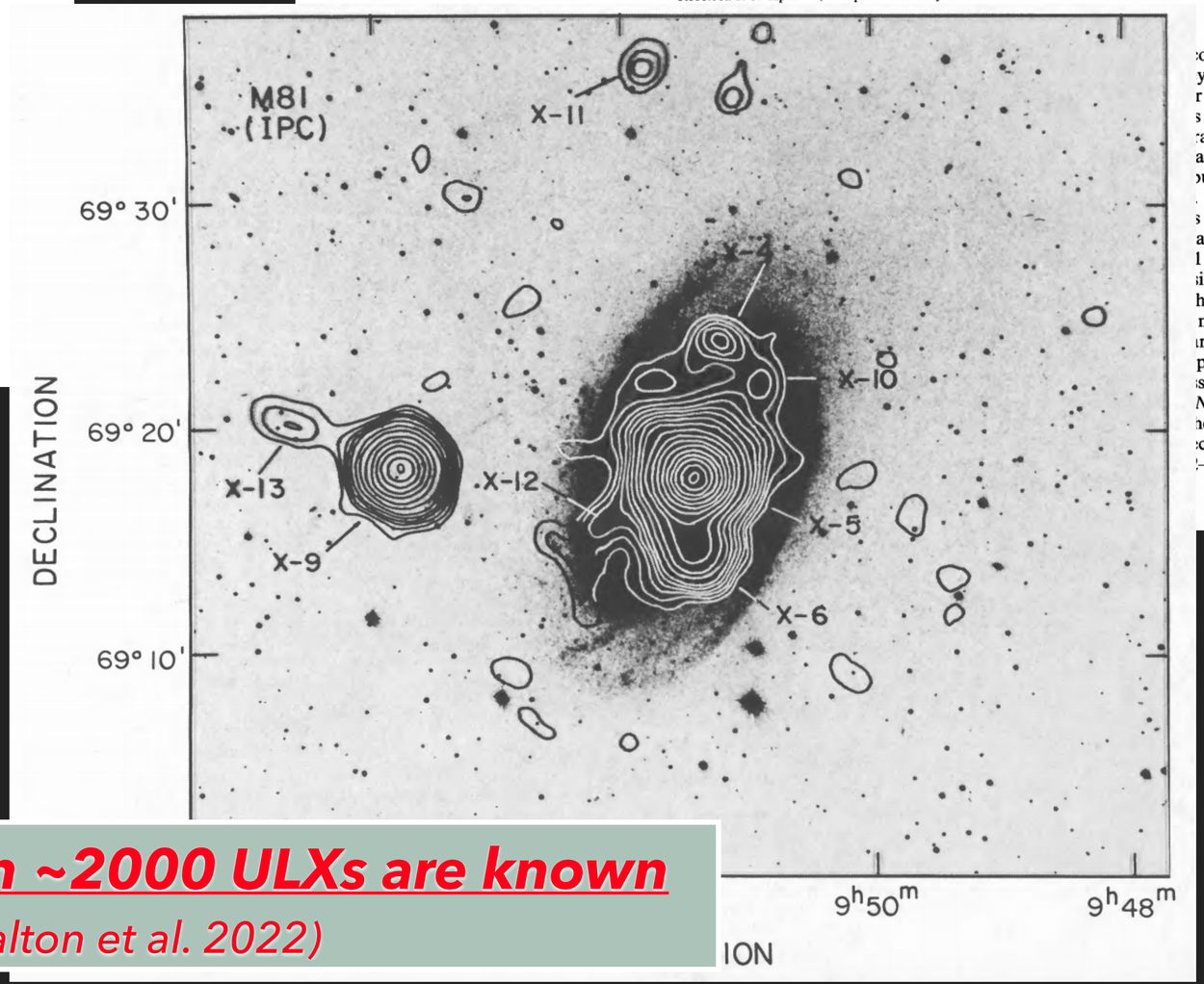


THE ASTROPHYSICAL JOURNAL, 325:544–562, 1988 February 15

THE X-RAY EMISSION OF M81 AND ITS NUCLEUS

G. FABBIANO
Harvard-Smithsonian Center for Astrophysics

Received 1987 April 14; accepted 1987 July 29

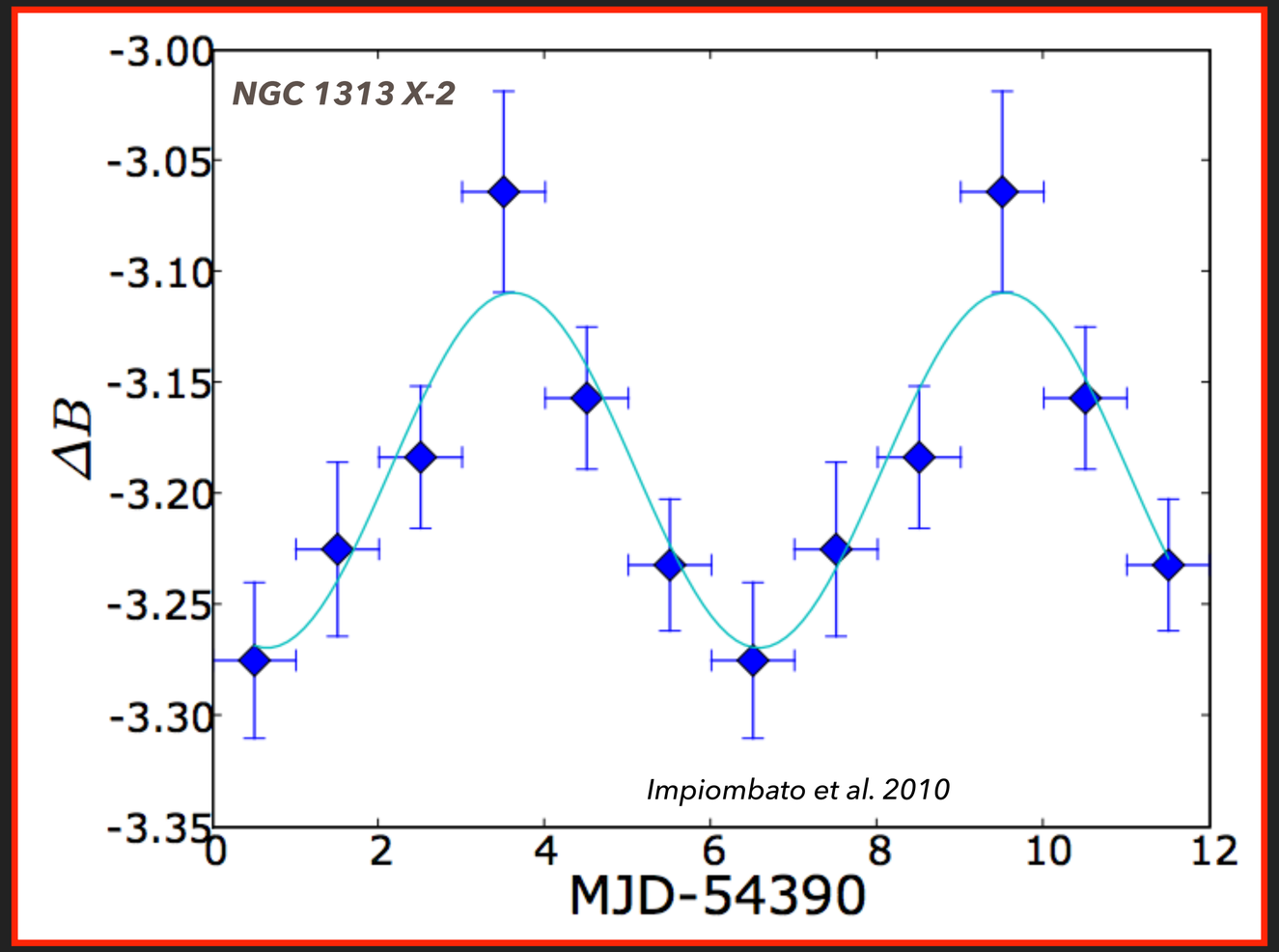


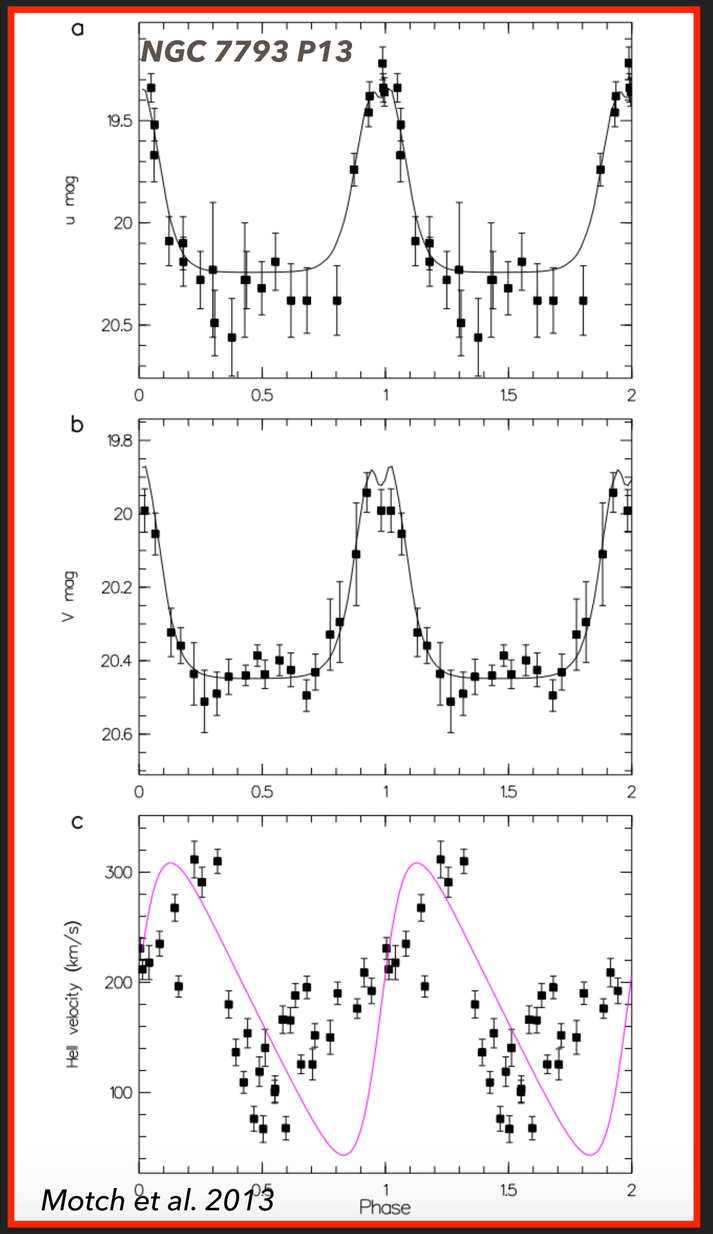
Now, more than ~2000 ULXs are known

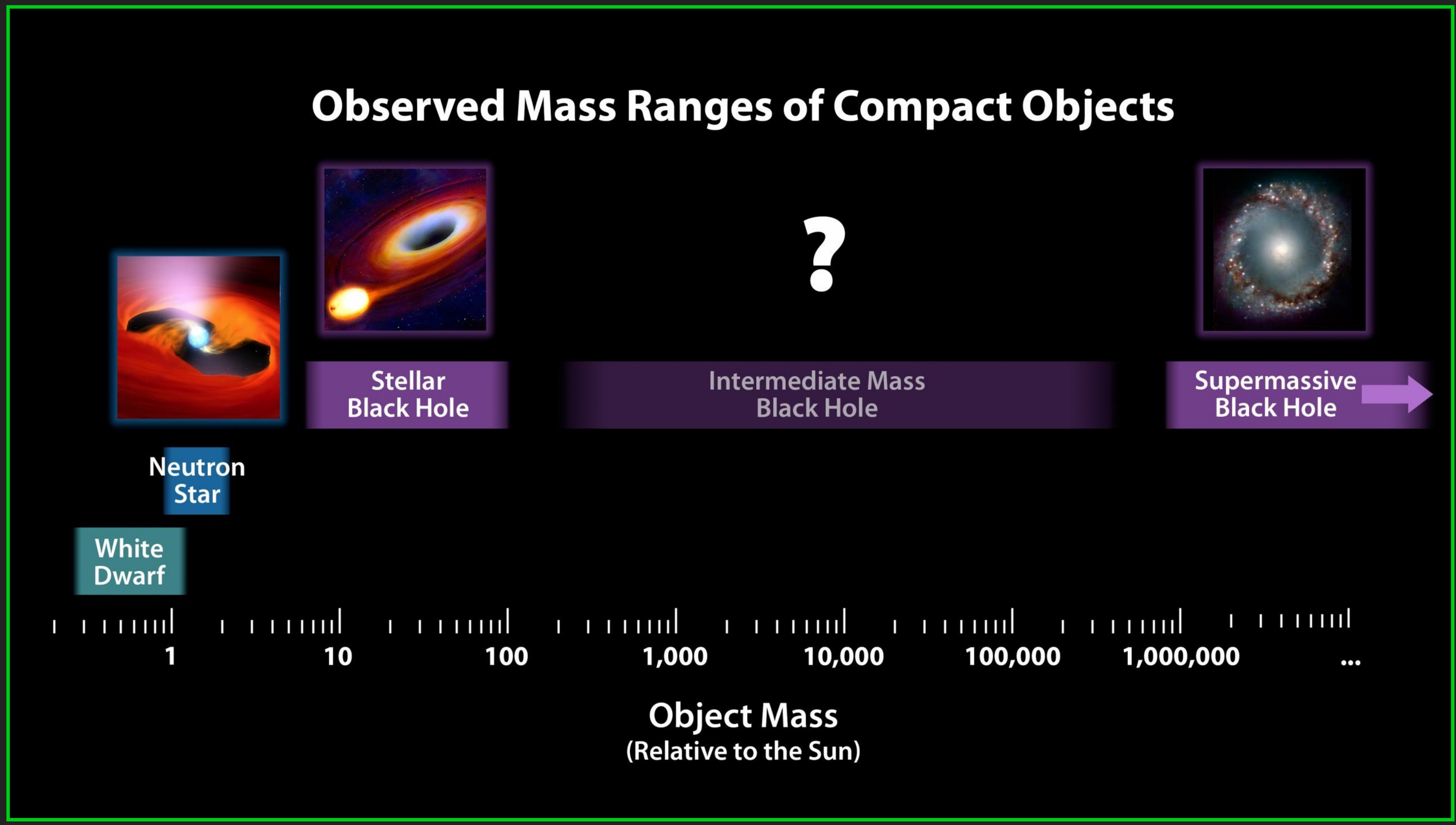
(Walton et al. 2022)

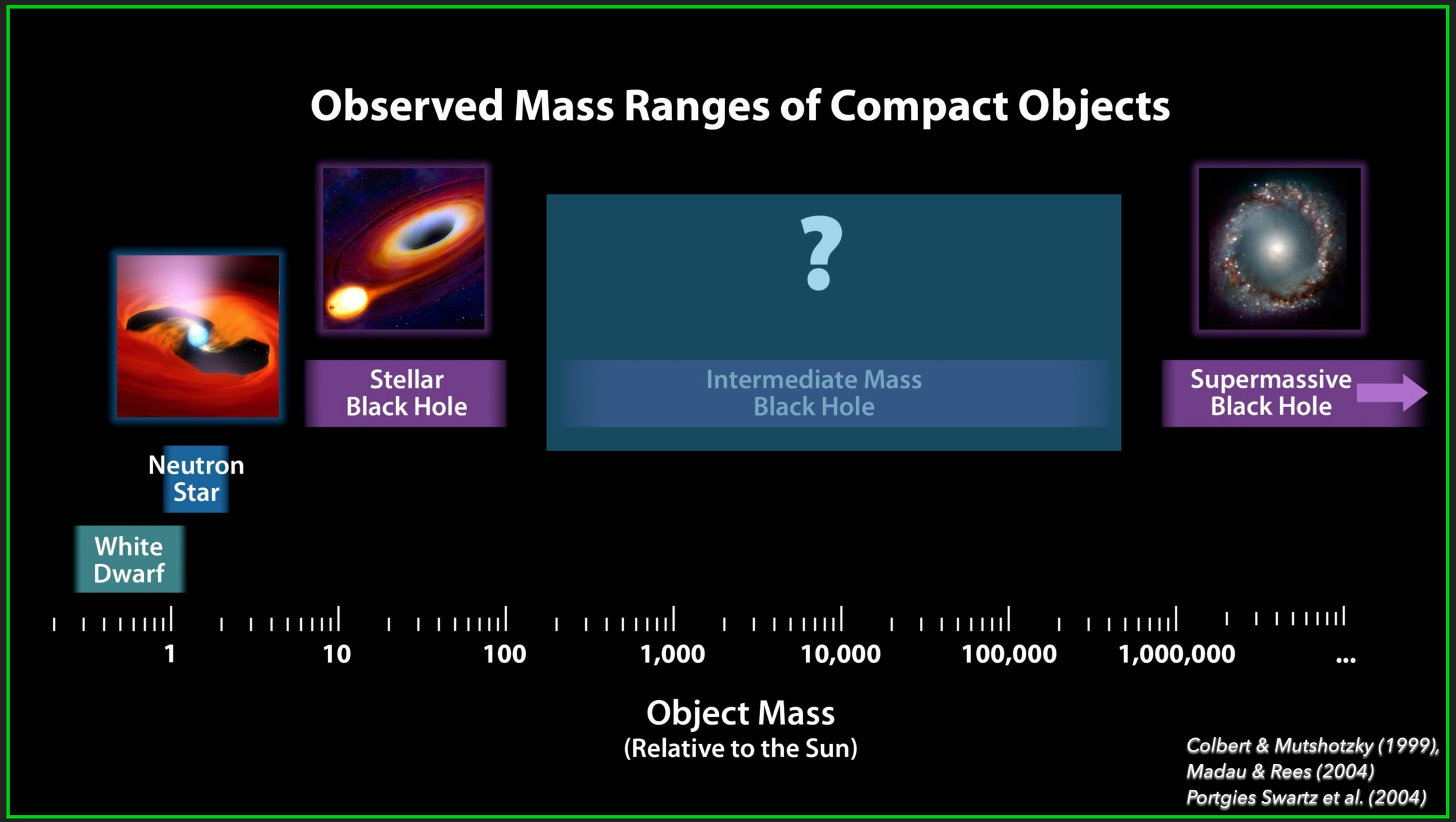
ULTRALUMINOUS X-RAY SOURCES

ULXs are thought to be accreting compact objects in binary system






Observed Mass Ranges of Compact Objects
?
Stellar Black Hole
Intermediate Mass Black Hole
Supermassive Black Hole
Neutron Star
White Dwarf
1
10
100
1,000
10,000
100,000
1,000,000
...
Object Mass
(Relative to the Sun)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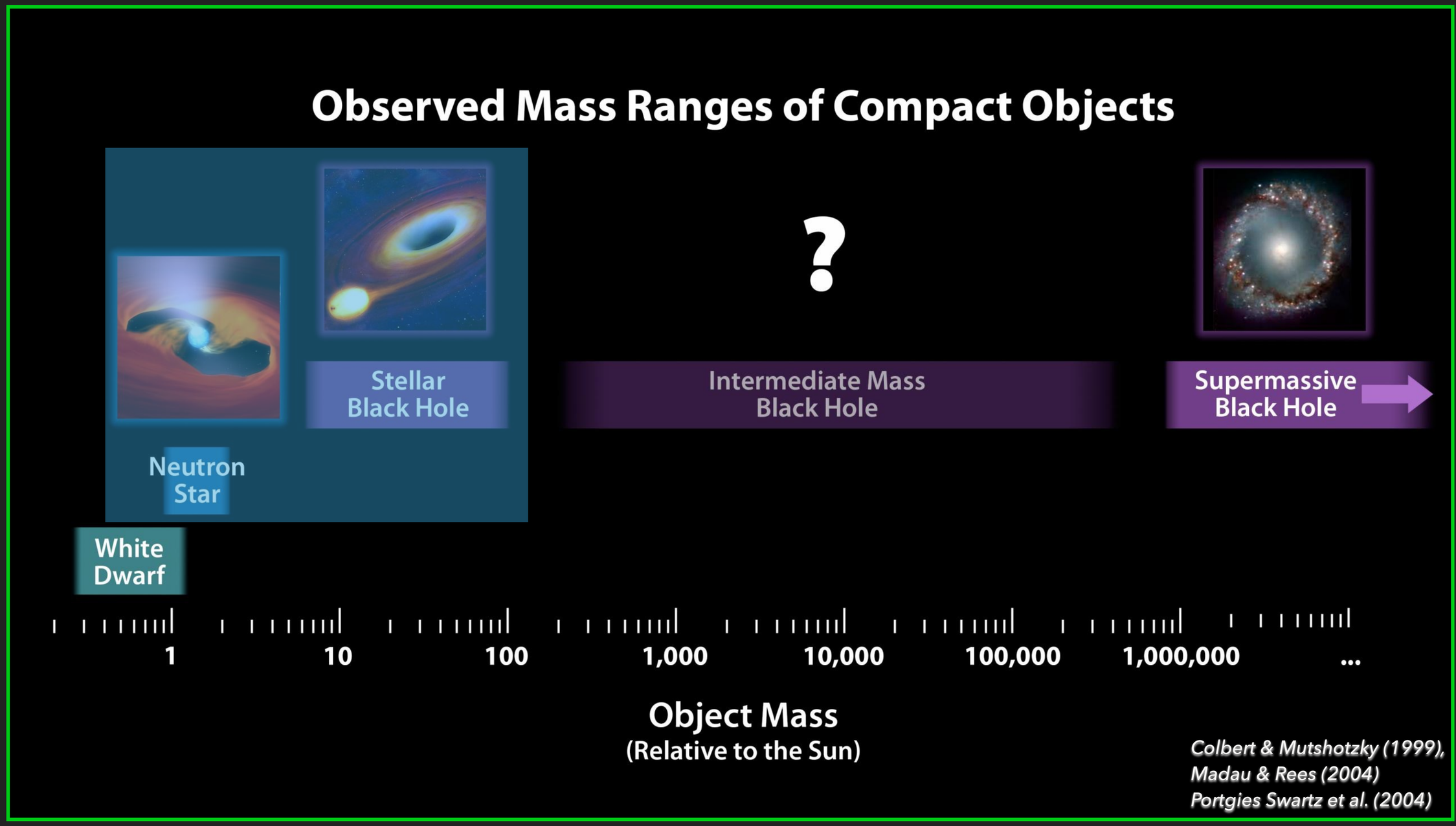
Colbert & Mutshotzky (1999),
Madau & Rees (2004)
Portgies Swartz et al. (2004)

ULTRALUMINOUS X-RAY SOURCES

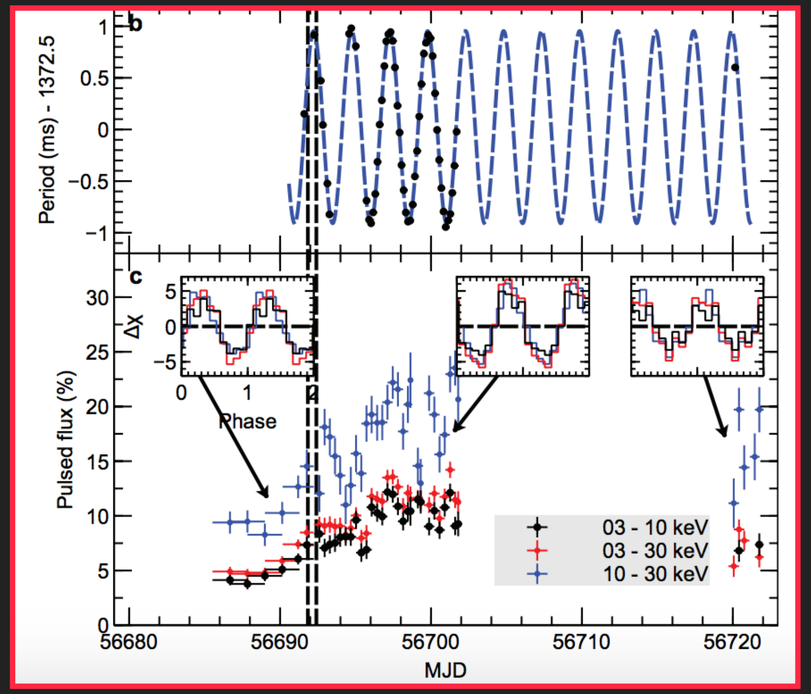


THE LATEST STRIKING DISCOVERY IN ULX: PULSATIONS

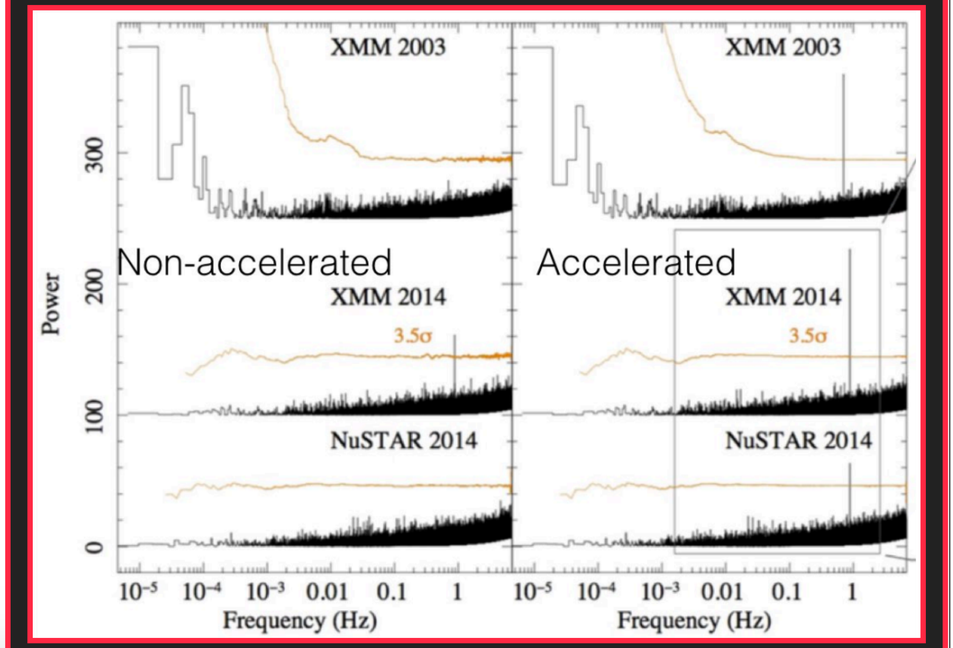
- Pulsation have been discovered in some ULXs using observations with high counting statistics (XMM-Newton and NuSTAR)

- P_{spin} in the range ~ 0.4 - 20 s

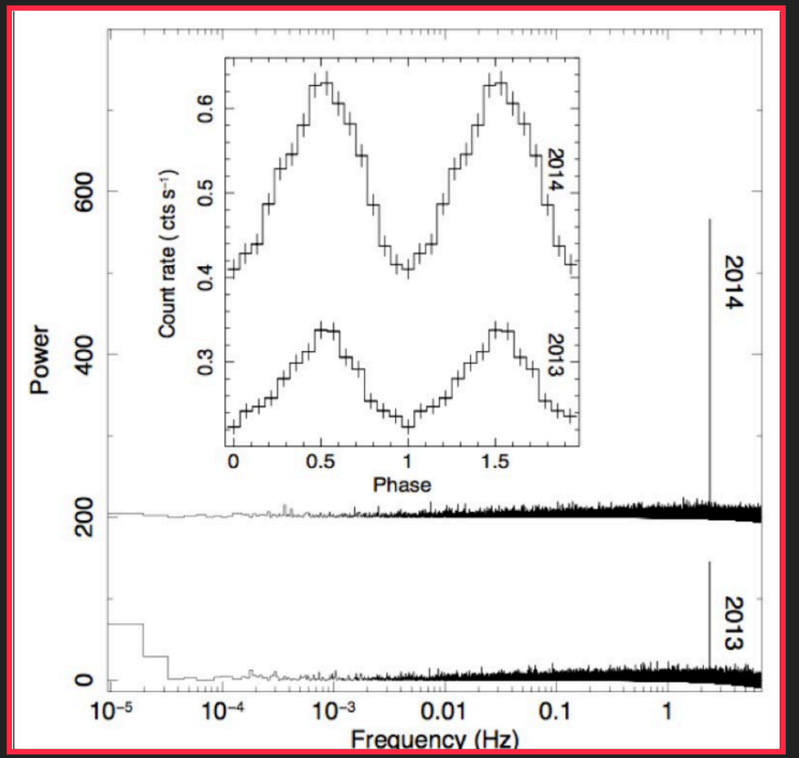
M82 X-2 (BACHETTI ET AL. 2014)



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



NGC 7793 P13 (ISRAEL ET AL.2017)



THE LATEST STRIKING DISCOVERY IN ULX: PULSATIONS

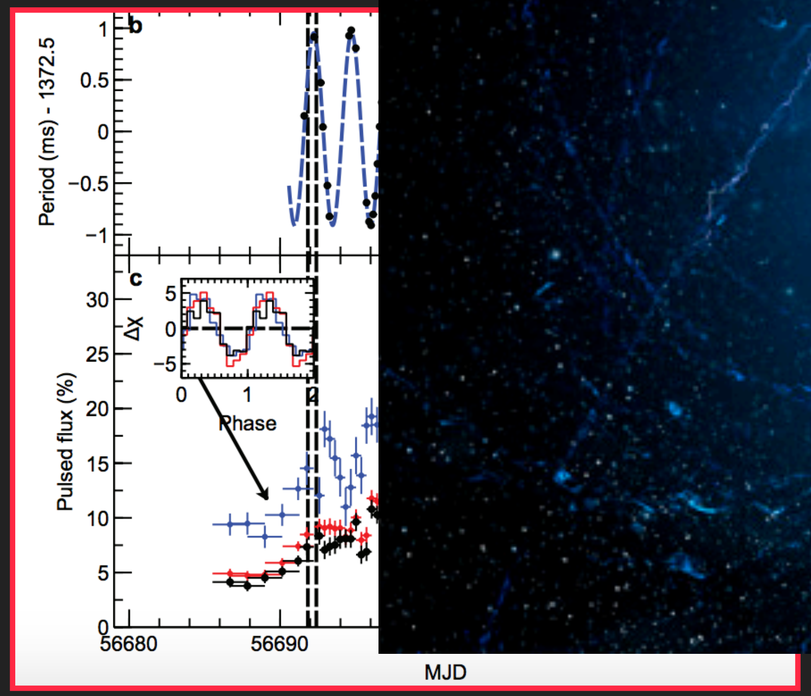
- Pulsatic
counting

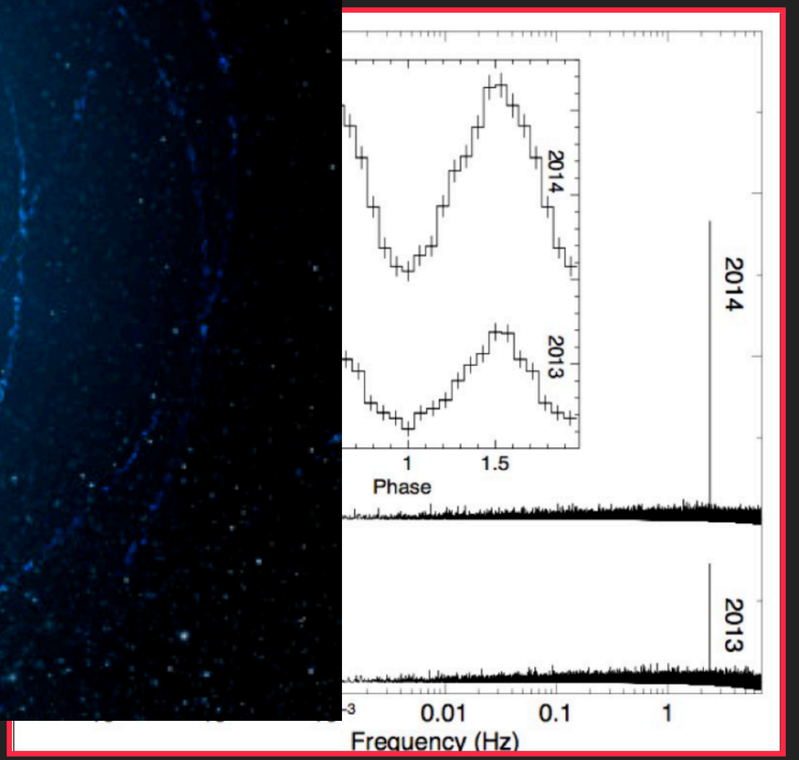
- P_{spin} in t

s with high

93 P13 (ISRAEL ET AL.2017)

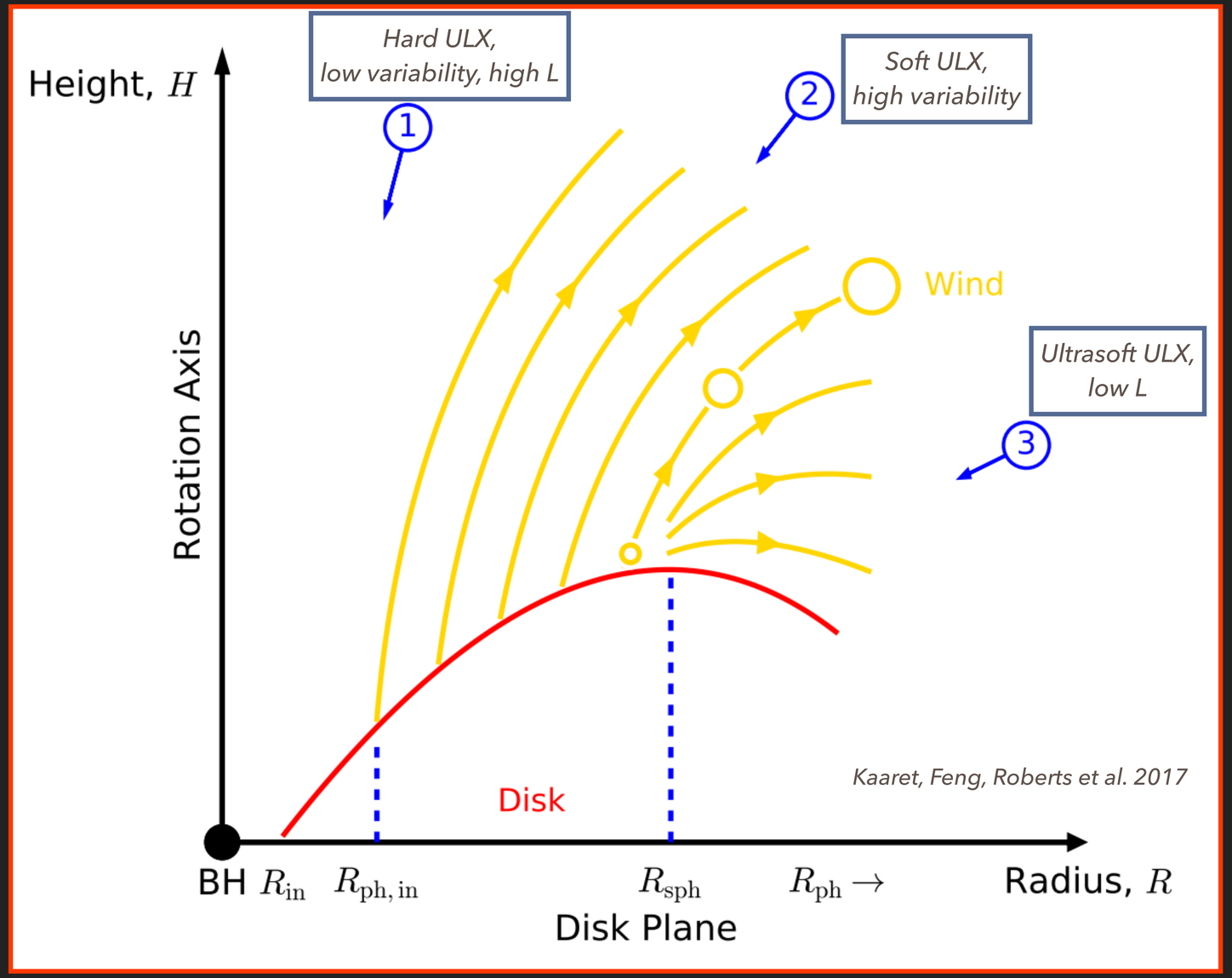
M82 X





SUPER-CRITICAL ACCRETION REGIME

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



See Poutanen et al. (2007)

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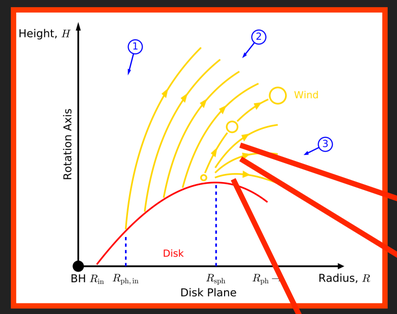
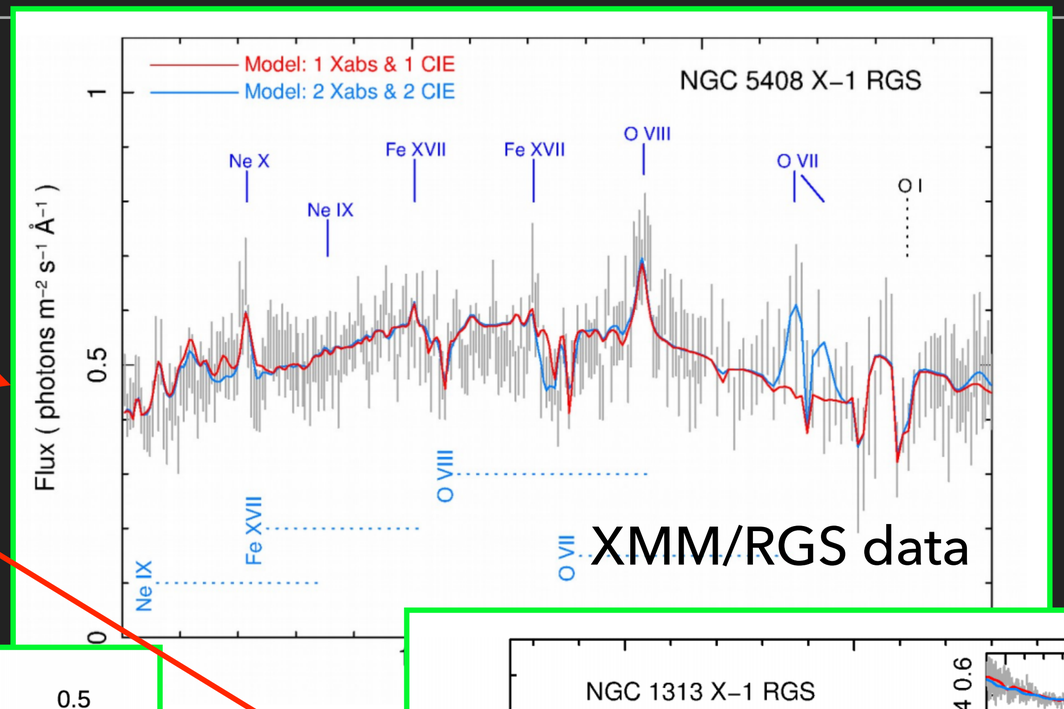
Kawashima et al. (2016)

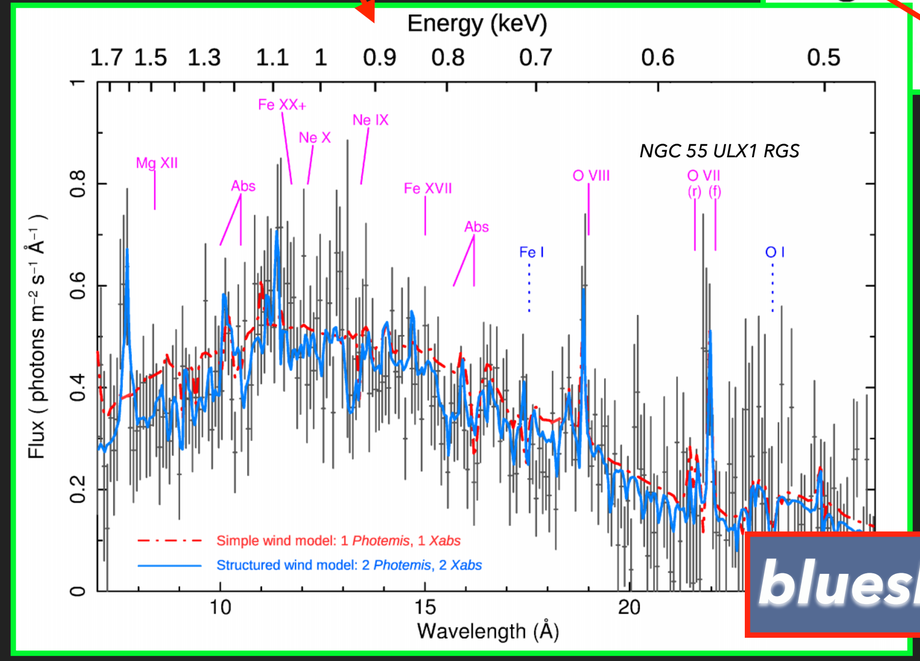
SUPER-CRITICAL ACCRETION REGIME

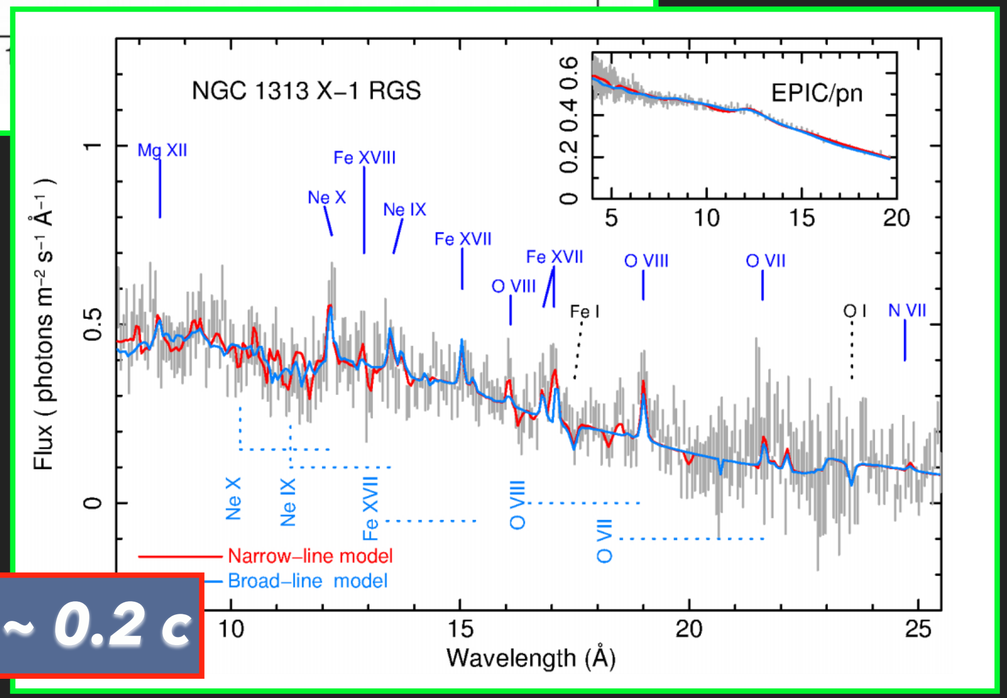




Absorption and emission features were found in several ULX spectra

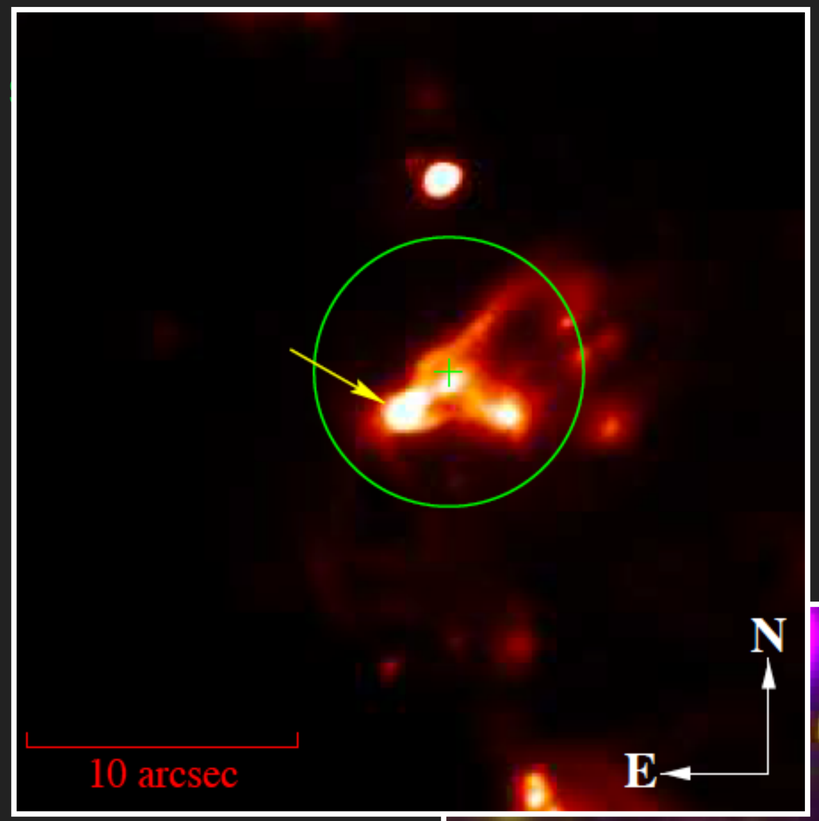
Pinto et al. (2015, 2017)



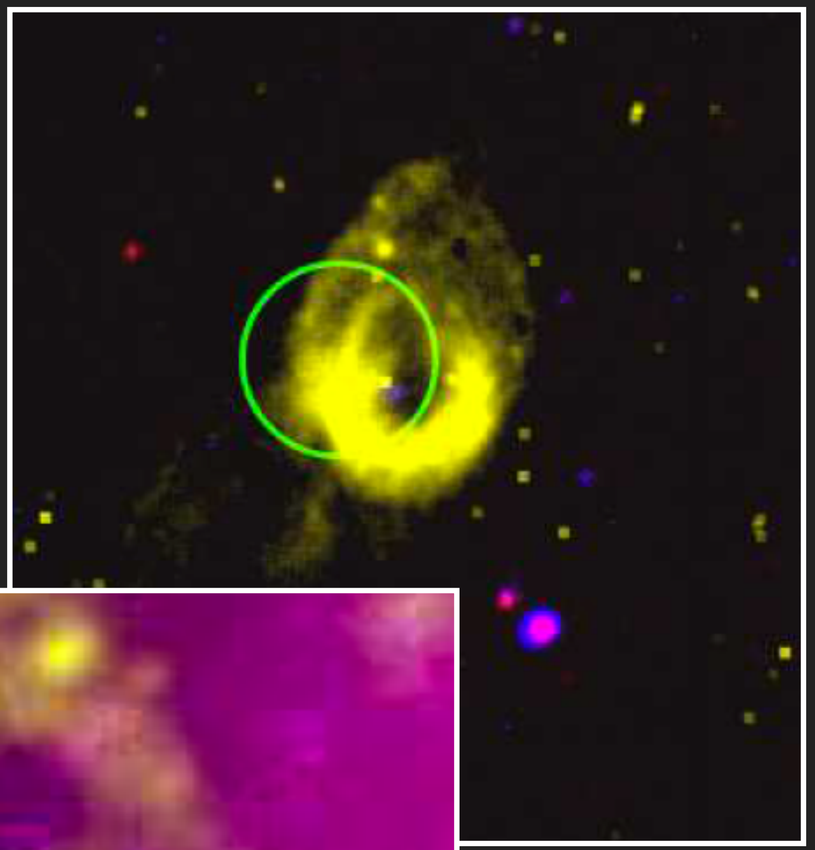


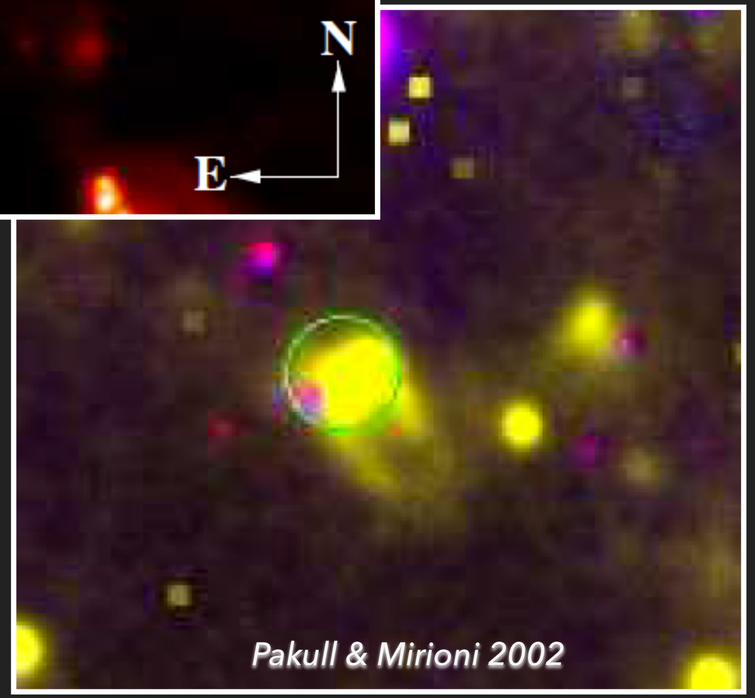
blueshift of z ~ 0.2 c

SUPER-CRITICAL ACCRETION REGIME



Optical nebulae, inflated by outflows?





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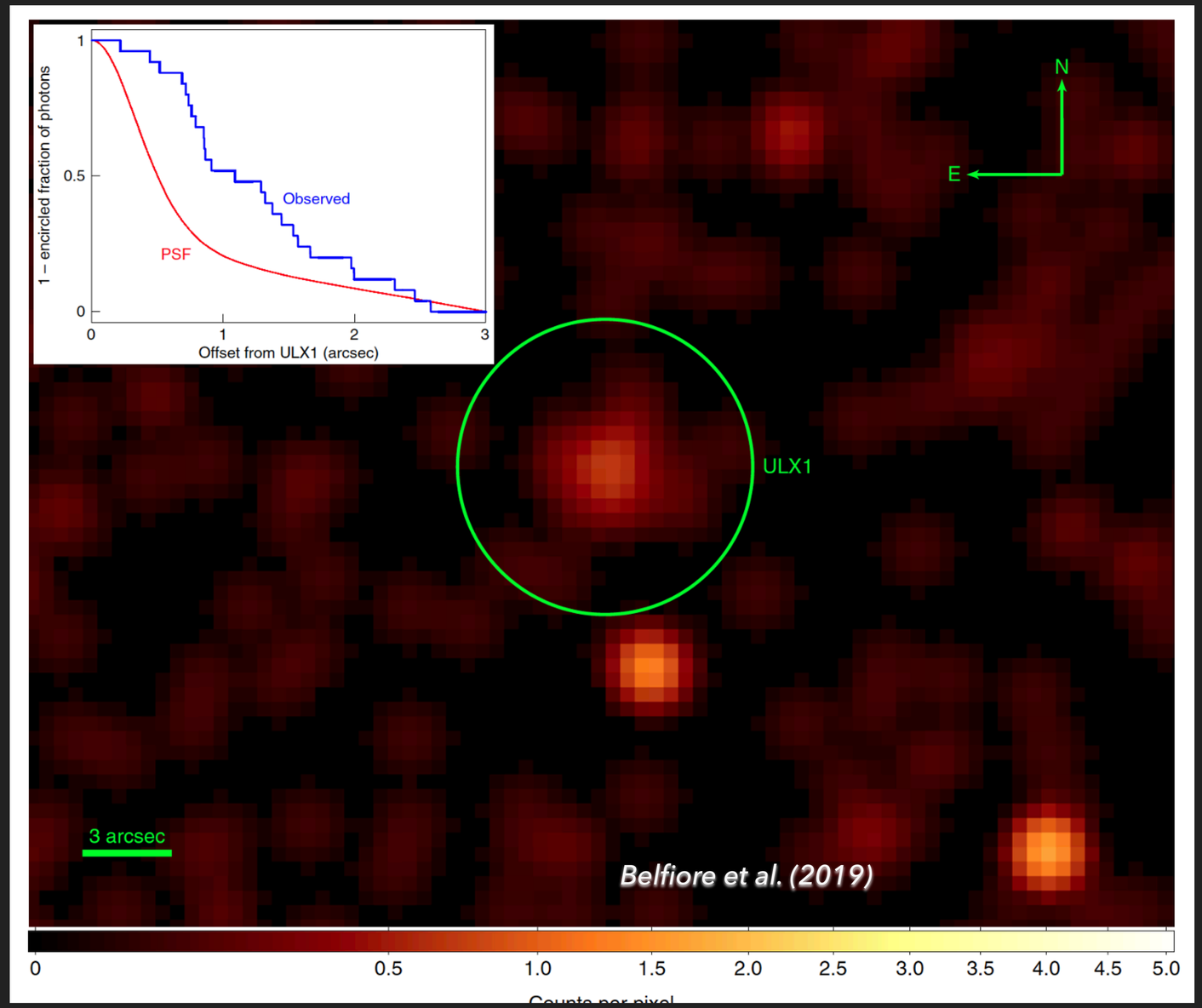


A nebula was also found in X-rays around the pulsating ULX called NGC 5907 ULX-1, in one Chandra observation

ULTRALUMINOUS X-RAY SOURCES: OPEN QUESTIONS

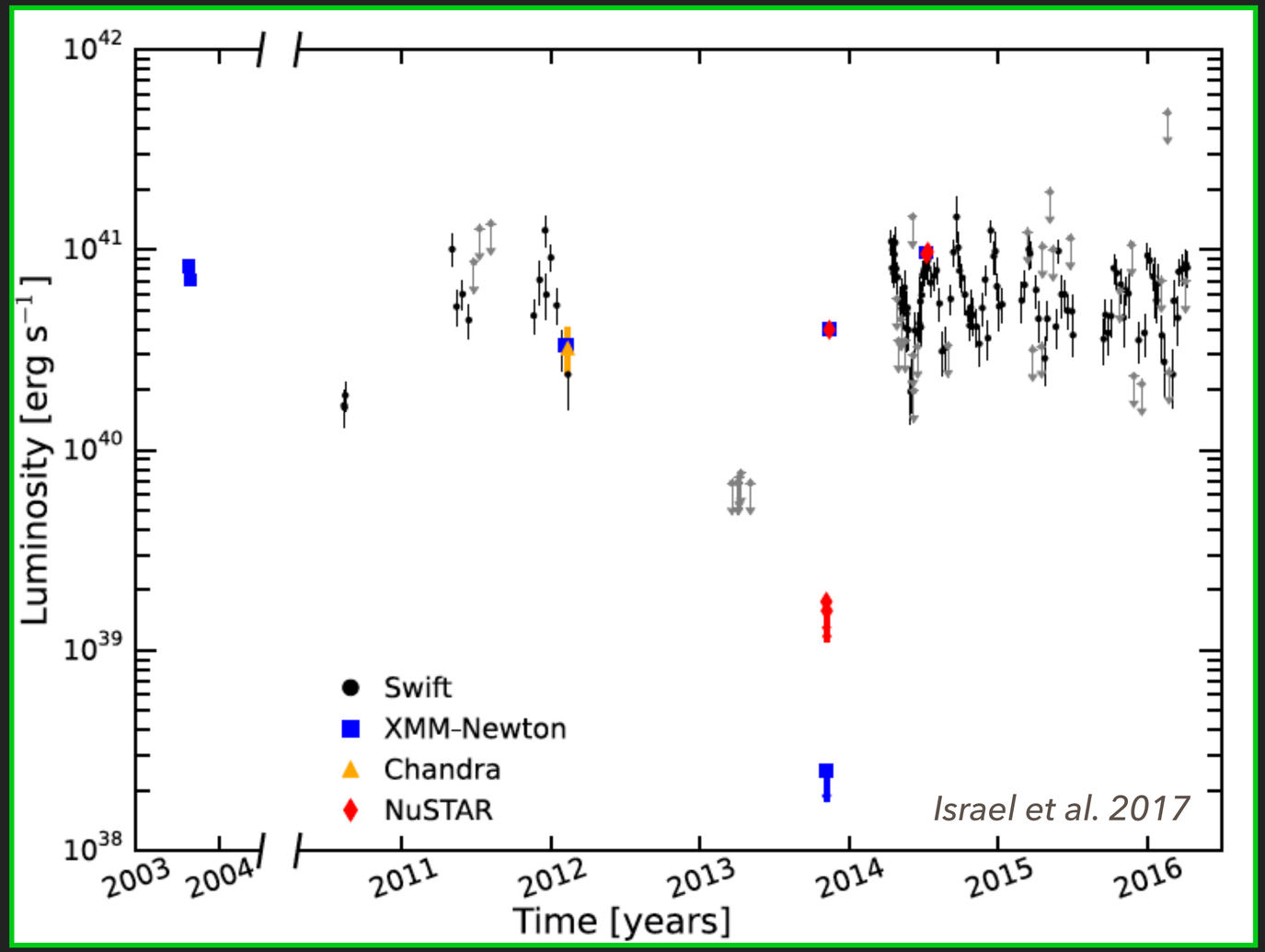
- What's the nature of the companion stars (HMXBvs LMXB)?
- How are the outflows properties?
- How do outflows imprint on the surrounding medium?
- What's the compact object mass in ULXs?
- What's the BH vs NS ratio in the ULX population?
- Unknown NS magnetic field (dipolar vs quadrupolar)? Magnetar-like (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?

NEUTRON STARS VS BLACK HOLES IN THE ULX POPULATION

- Only 6 PULXs amongst a population of ~2000 ULXs
- However, PULXs are ~20-30% of the limited ULXs population with high quality observations (~30 sources)
- Are the vast majority of ULXs hosting BH then?
- We have to increase the sample of PULXs in order to perform population studies
- One of the main goal is to look for candidate NS in ULXs: search for pulsations!
- However, pulsations are intermittent in PULXs!
- Search for PULX-like sources amongst ULXs

HUNT FOR PULX CANDIDATES

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



HUNT FOR PULX CANDIDATES

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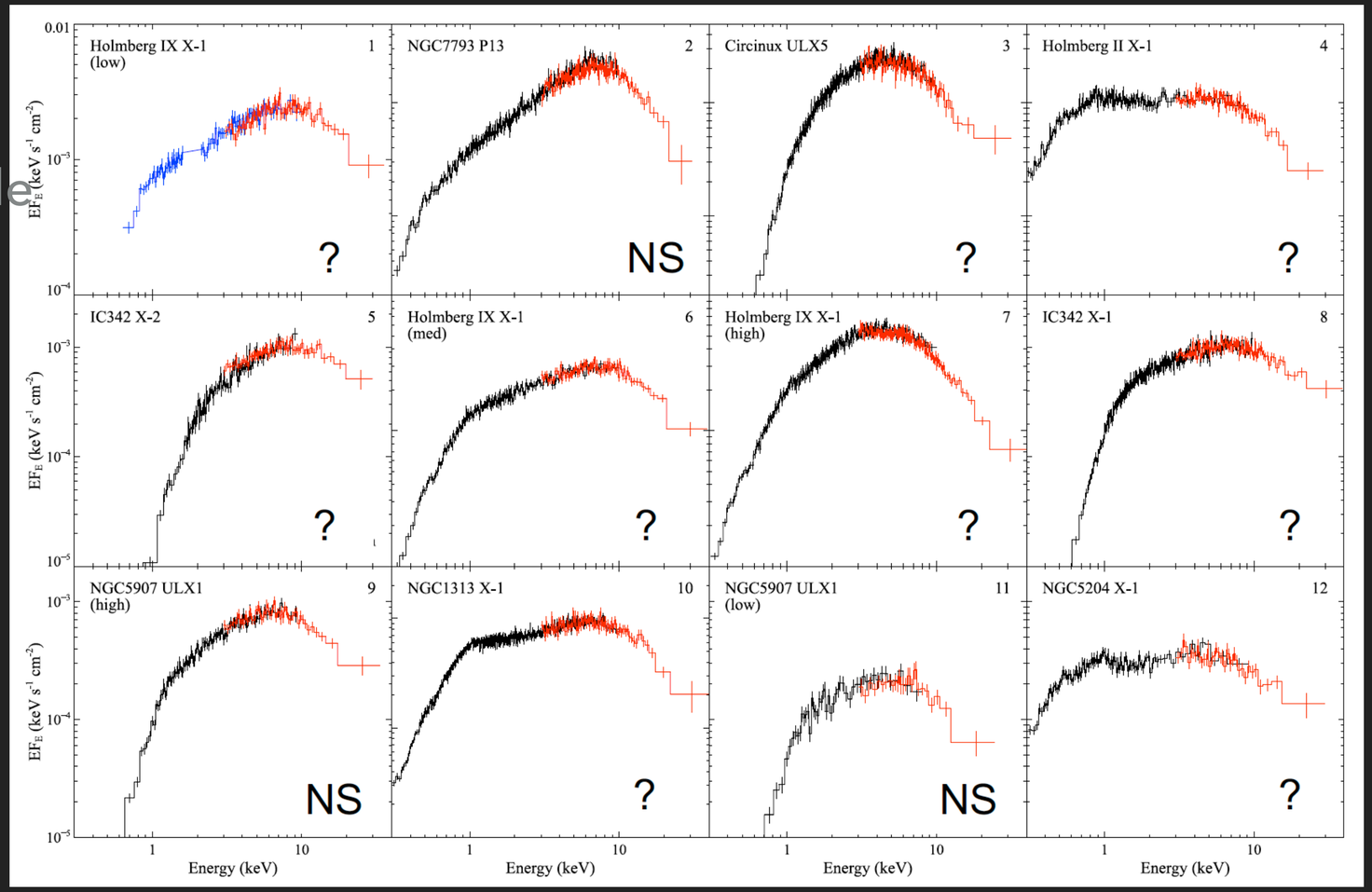

Credits: Walton et al. (2018)

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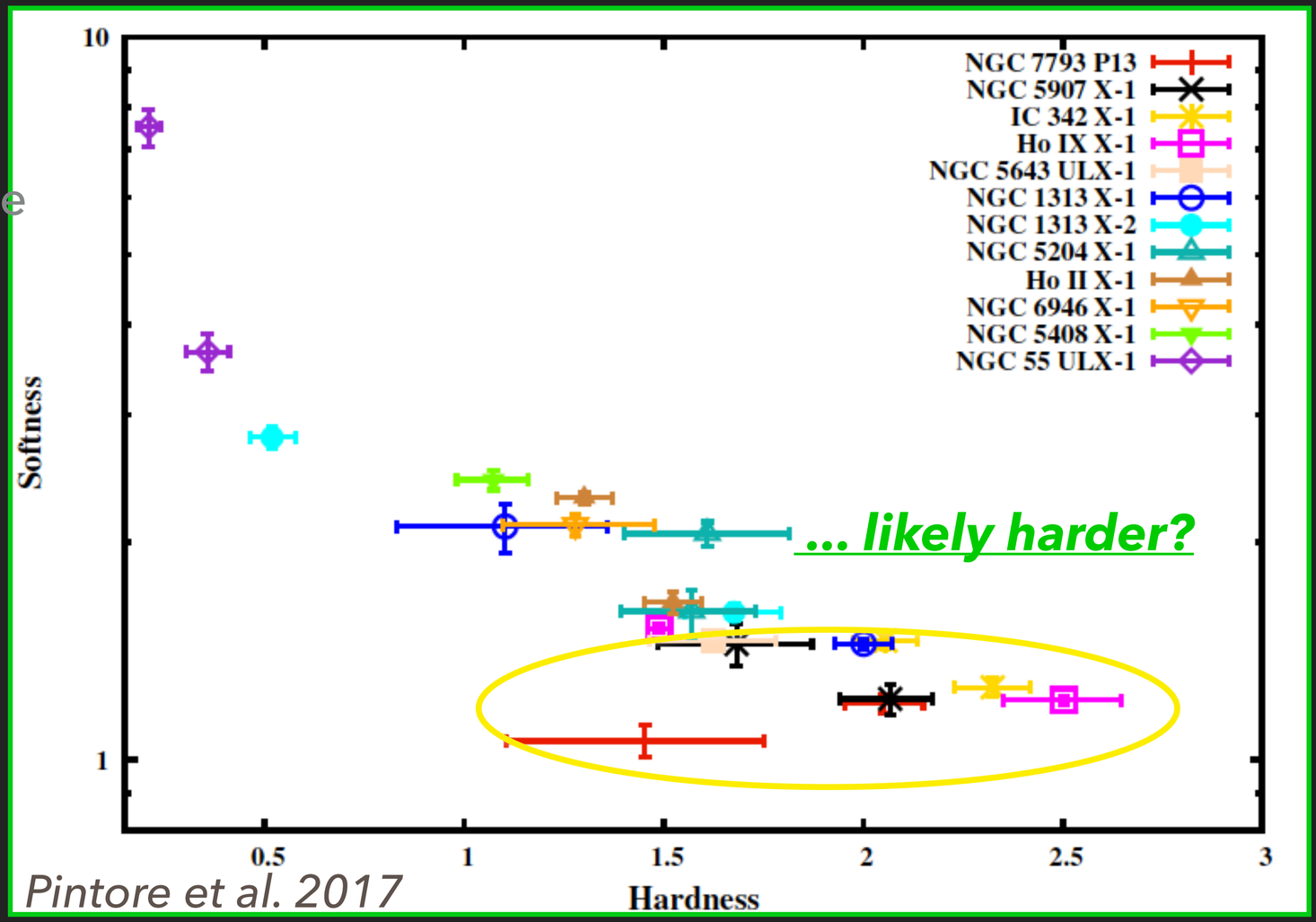
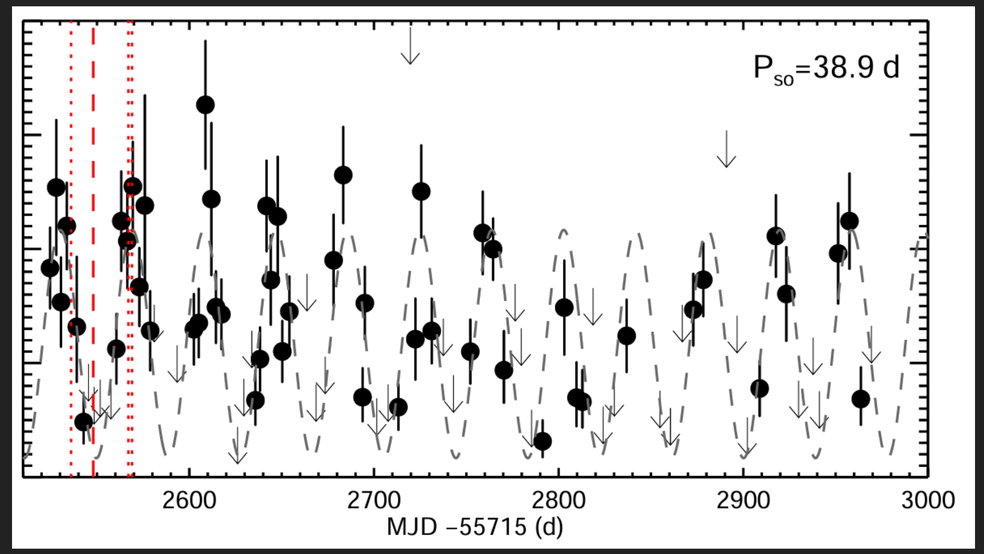


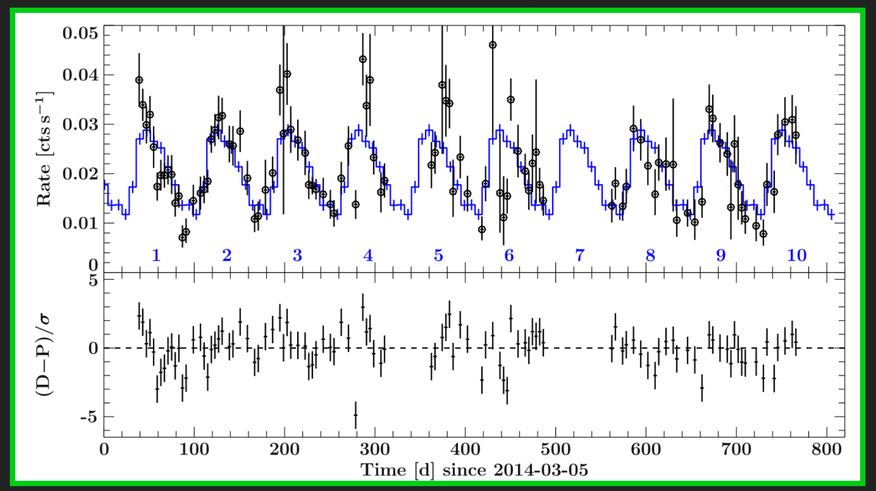
Pintore et al. 2017

HUNT FOR PULX CANDIDATES

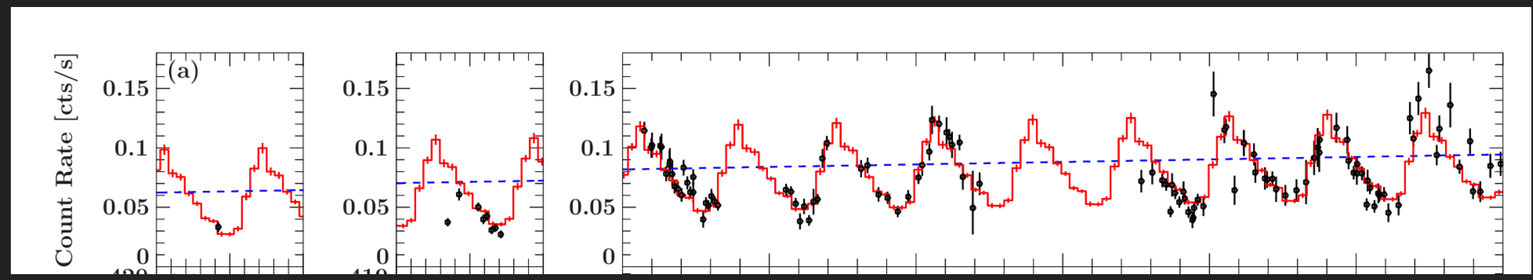
- Pulsating ULXs:
  - All transient sources (with a possible by-modality)
  - Spectrally similar to most ULXs
  - Super-orbital modulations of tens-to-hundreds of days

M51 ULX-7 (Vasilopoulos et al.2019)





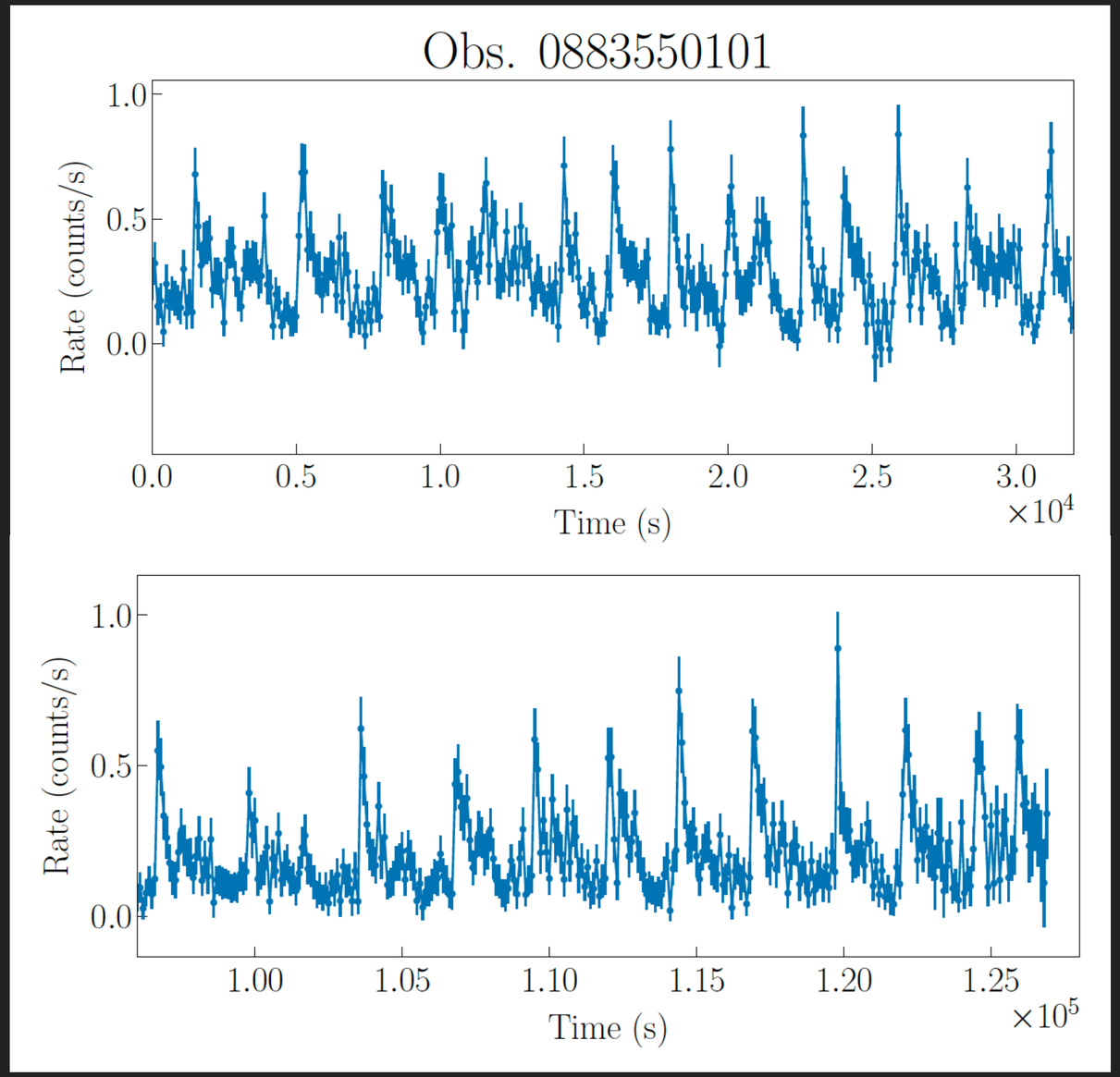
NGC 5907 X-1 (Walton et al.2016)



NGC 7793 P13 (Fuerst et al.2018)

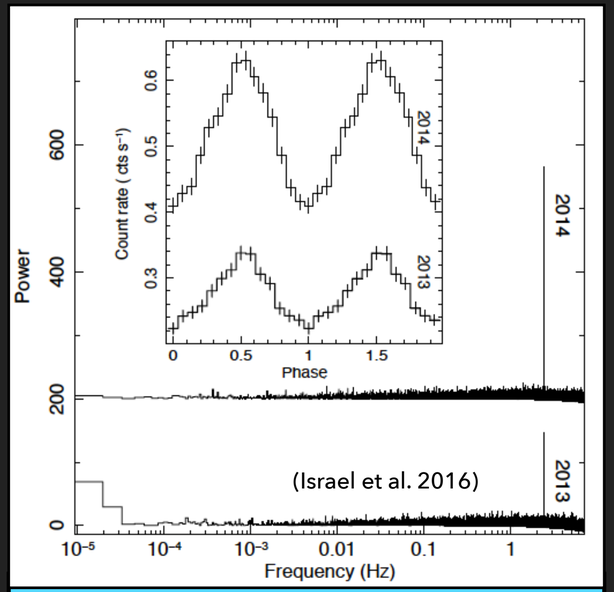
HUNT FOR PULX CANDIDATES

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



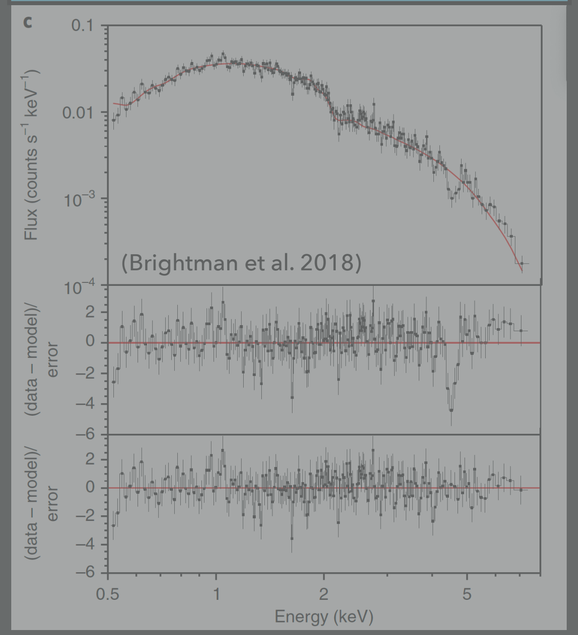
M51 ULX-7 (Imbrogno et al. 2024)

HUNT FOR NEW PULX CANDIDATES

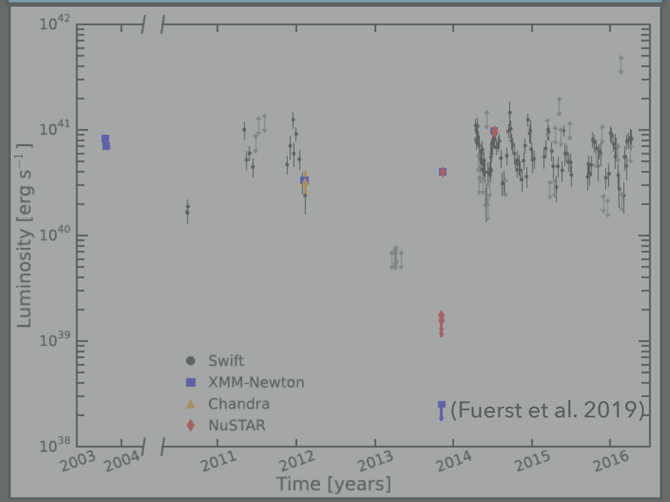


PULSATIONS

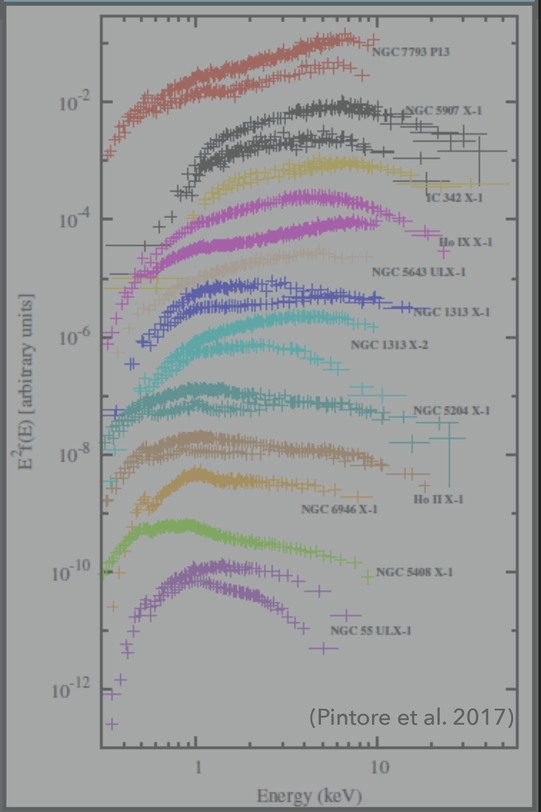
CYCLOTRON LINES



VARIABILITY



SPECTRA



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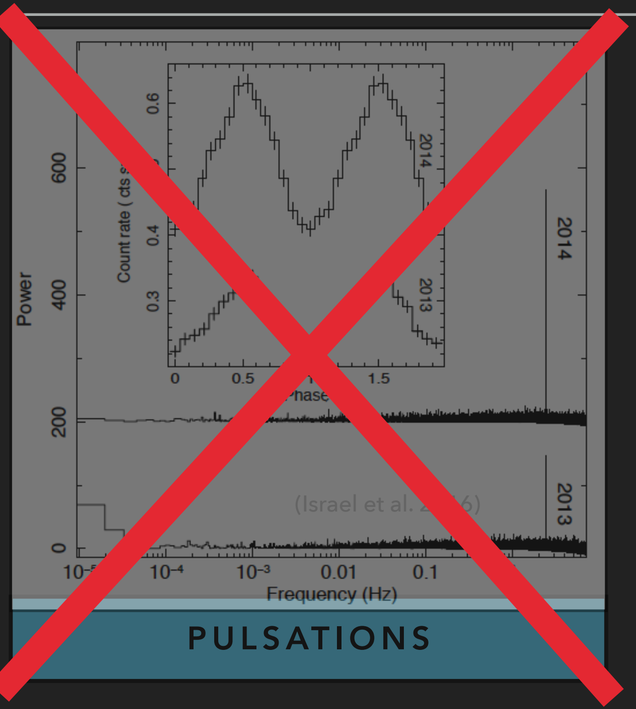
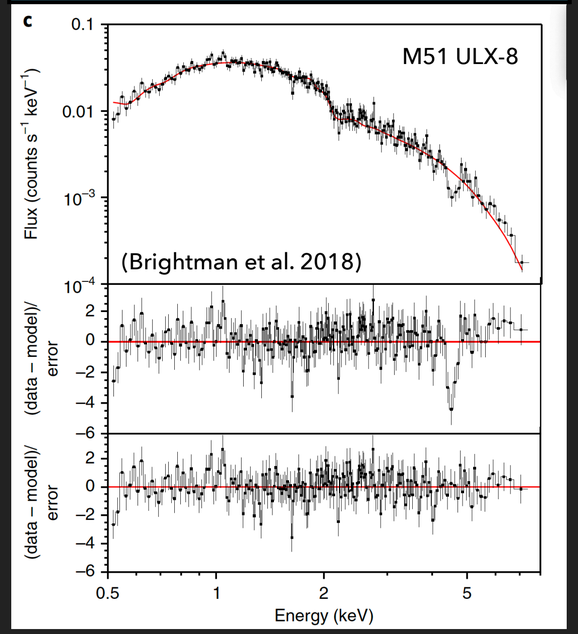


In the absence of pulsations, we need to look for indirect proofs (i.e. variability or spectral properties)

CYCLOTRON LINES



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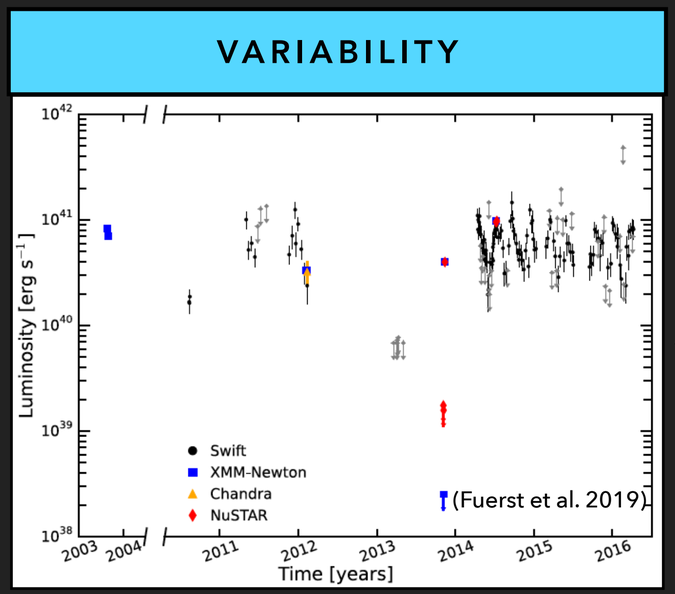

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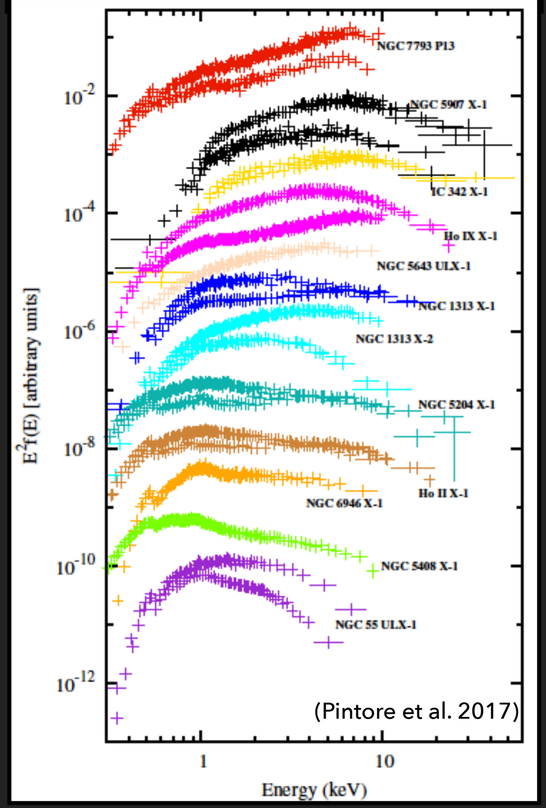
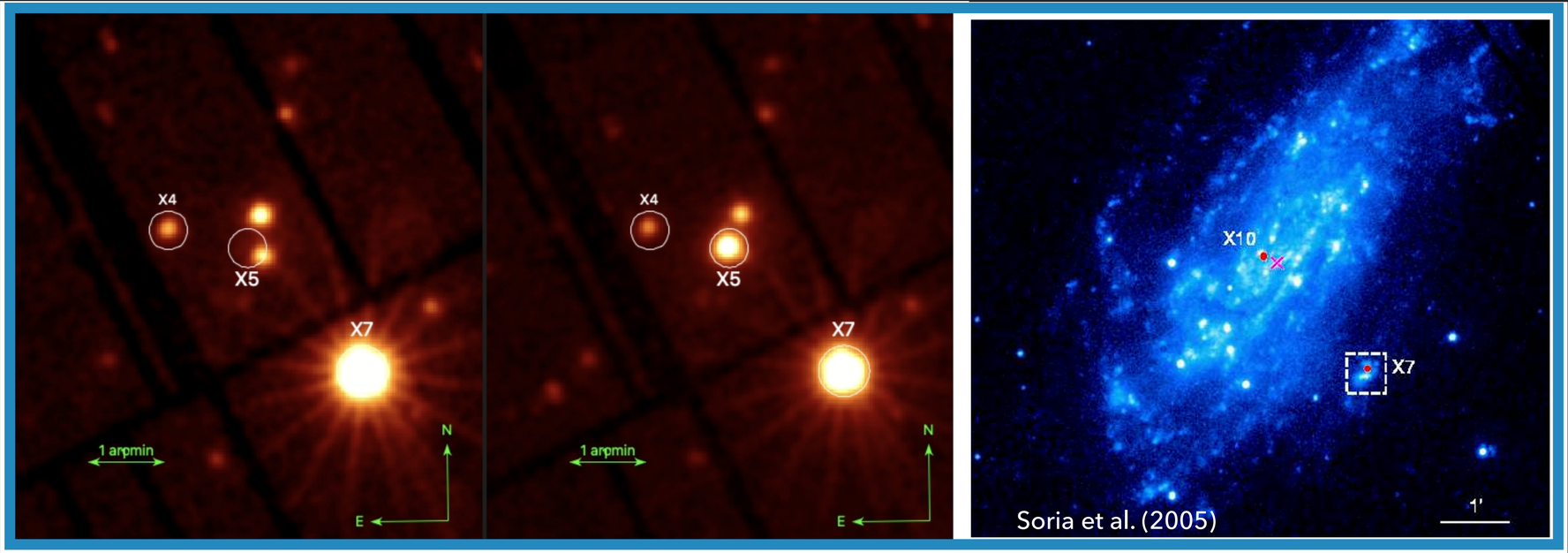


NGC 4559 AND NGC 7456: HIGH VARIABLE ULXS

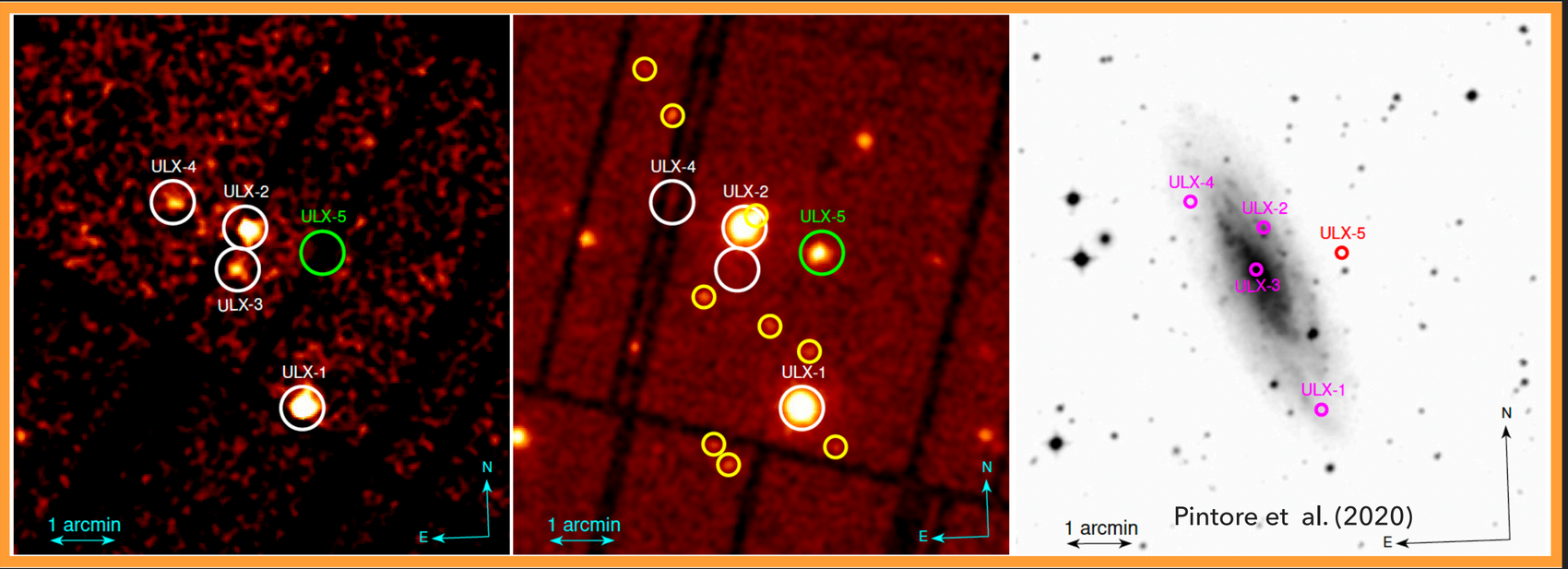
NGC 4559 (7.5 Mpc):

- Three ULXs
- One transient
- X7 is highly variable



NGC 7456 (~16 Mpc):

- Five ULXs
- Three transients
- ULX-1 is highly variable



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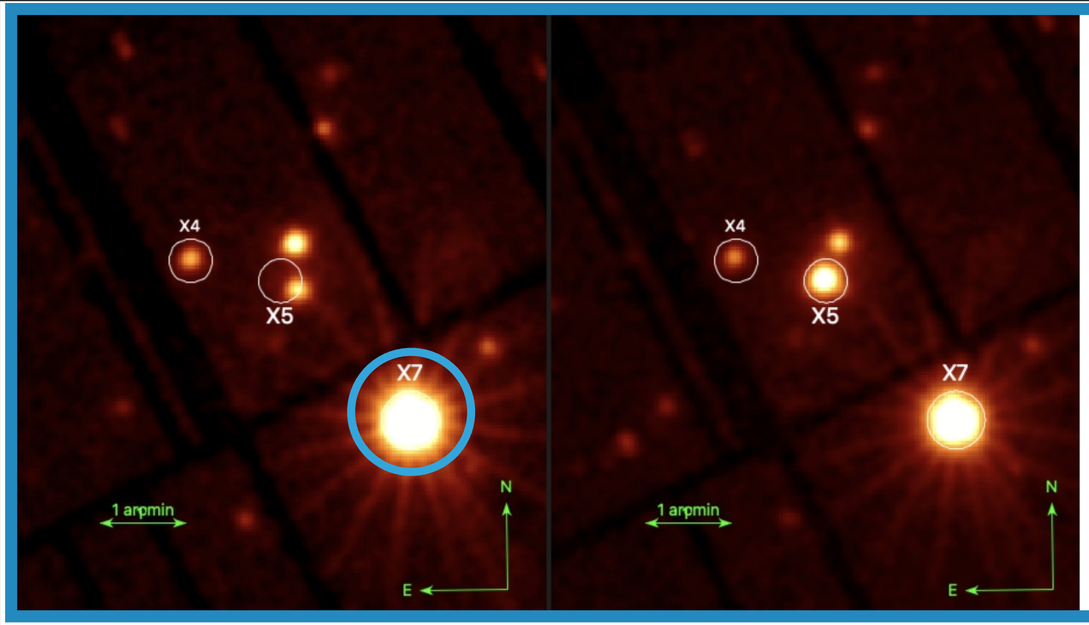

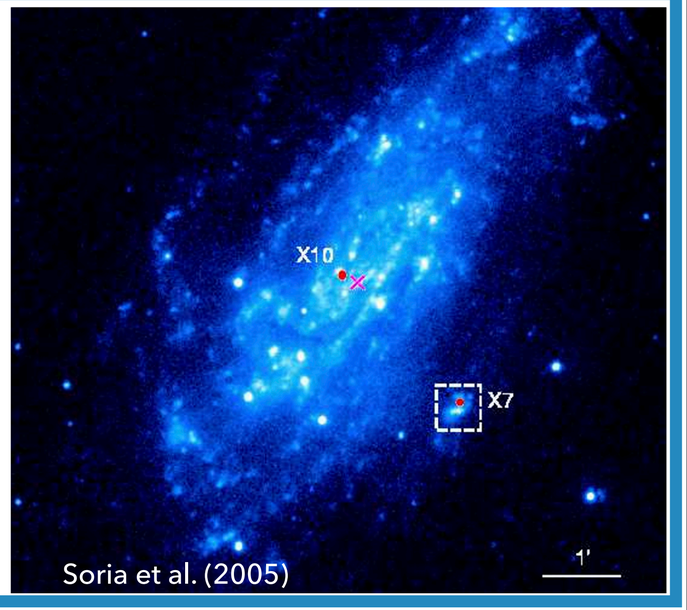

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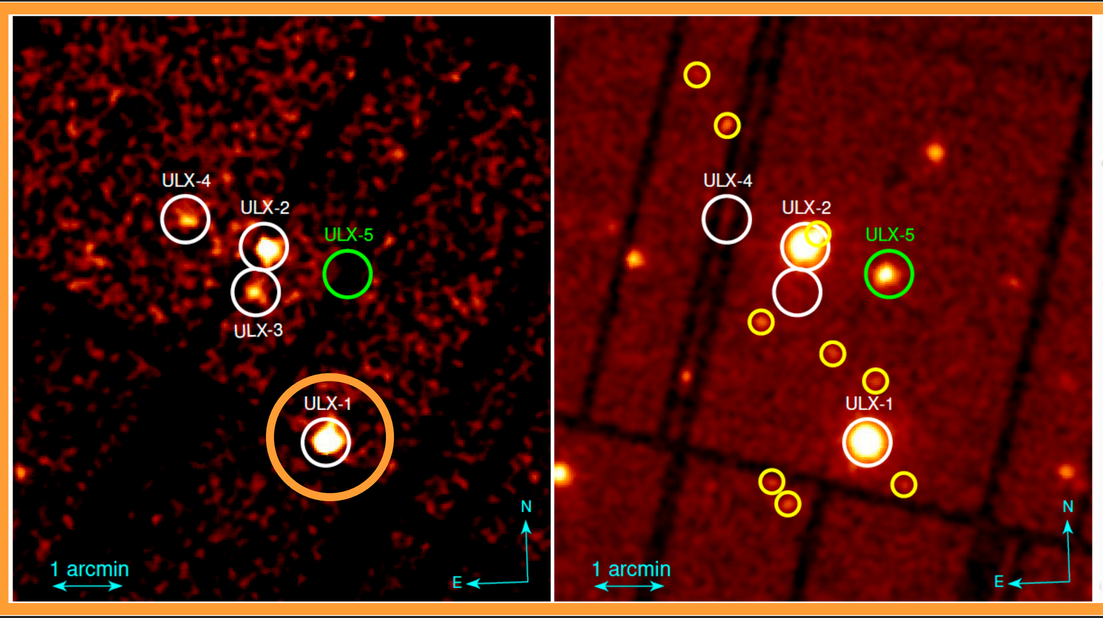
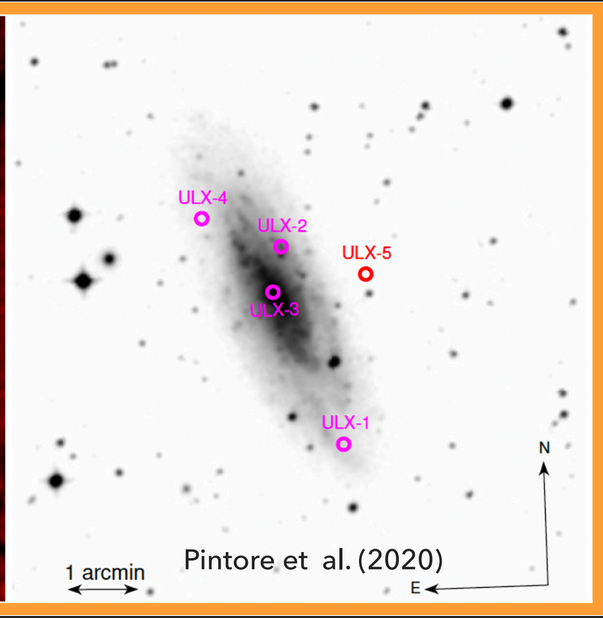
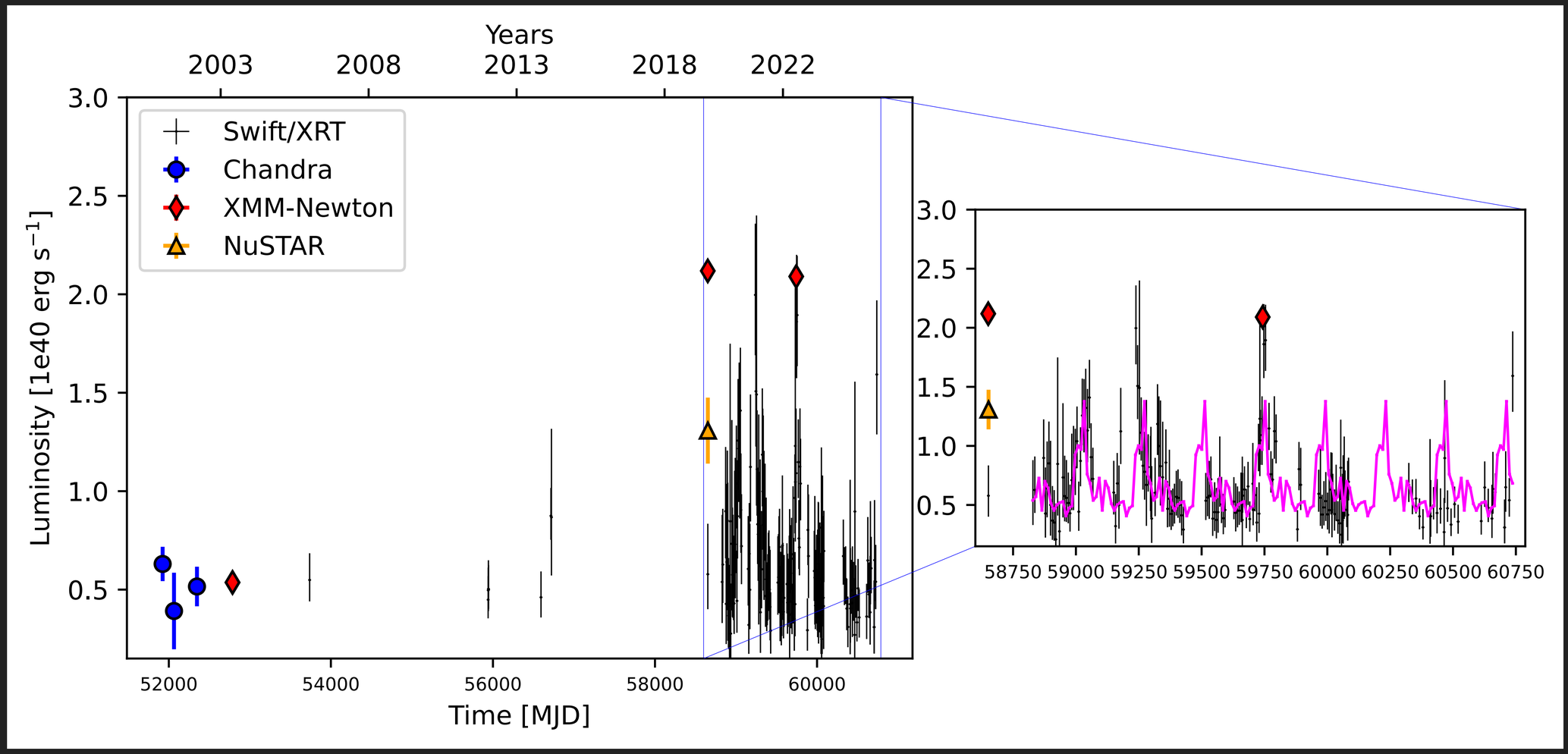




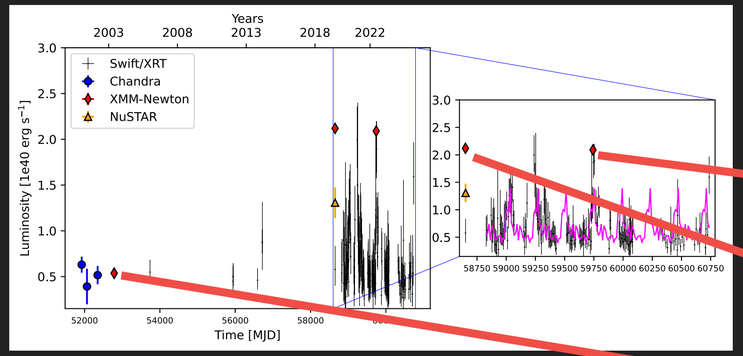
NGC 4559 X7: LONG-TERM VARIABILITY



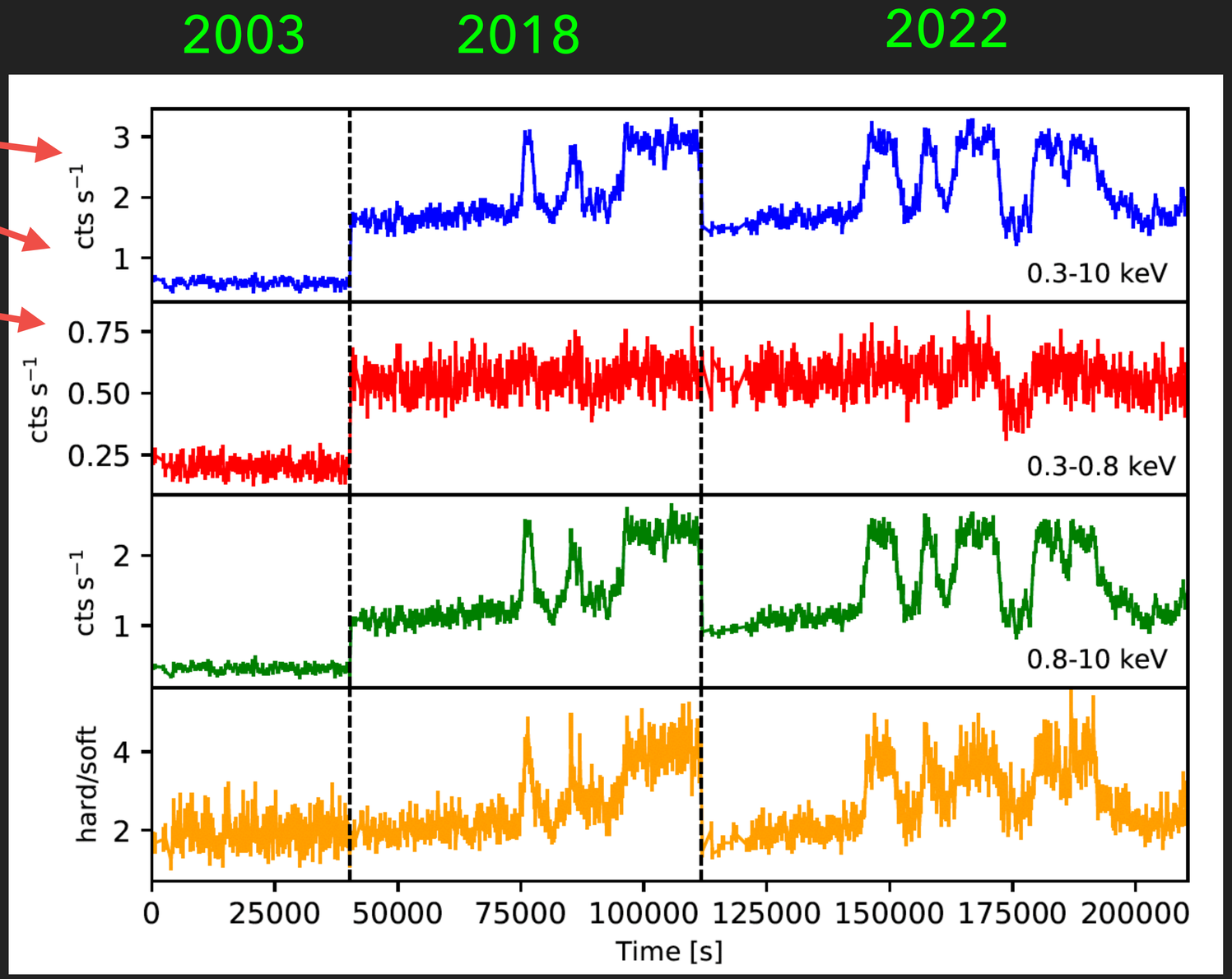
- X-ray isotropic luminosity >> 10^{40} erg/s
- Long-term variability up to a factor of 5
- Possible super-orbital periodicity of ~240d

Pintore et al. (2025)

NGC 4559 X7: SHORT-TERM VARIABILITY

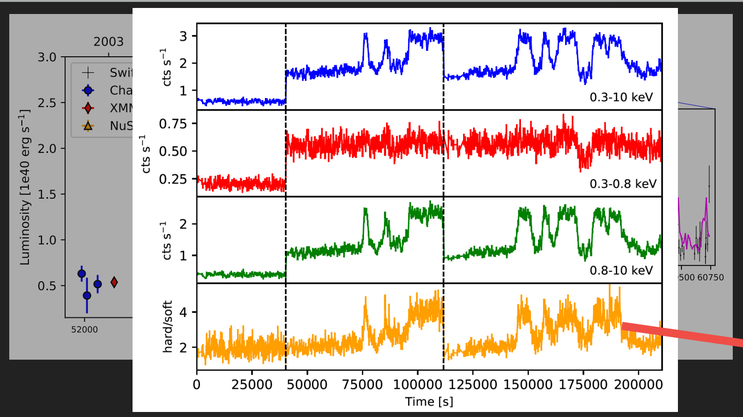


- Three XMM observations showed that X7 is even more variable on short-term timescales (almost an order of magnitude in total)
- Flaring activity on timescales of a few hours
- Flares are all flat-topped in flux
- Clear spectral variability

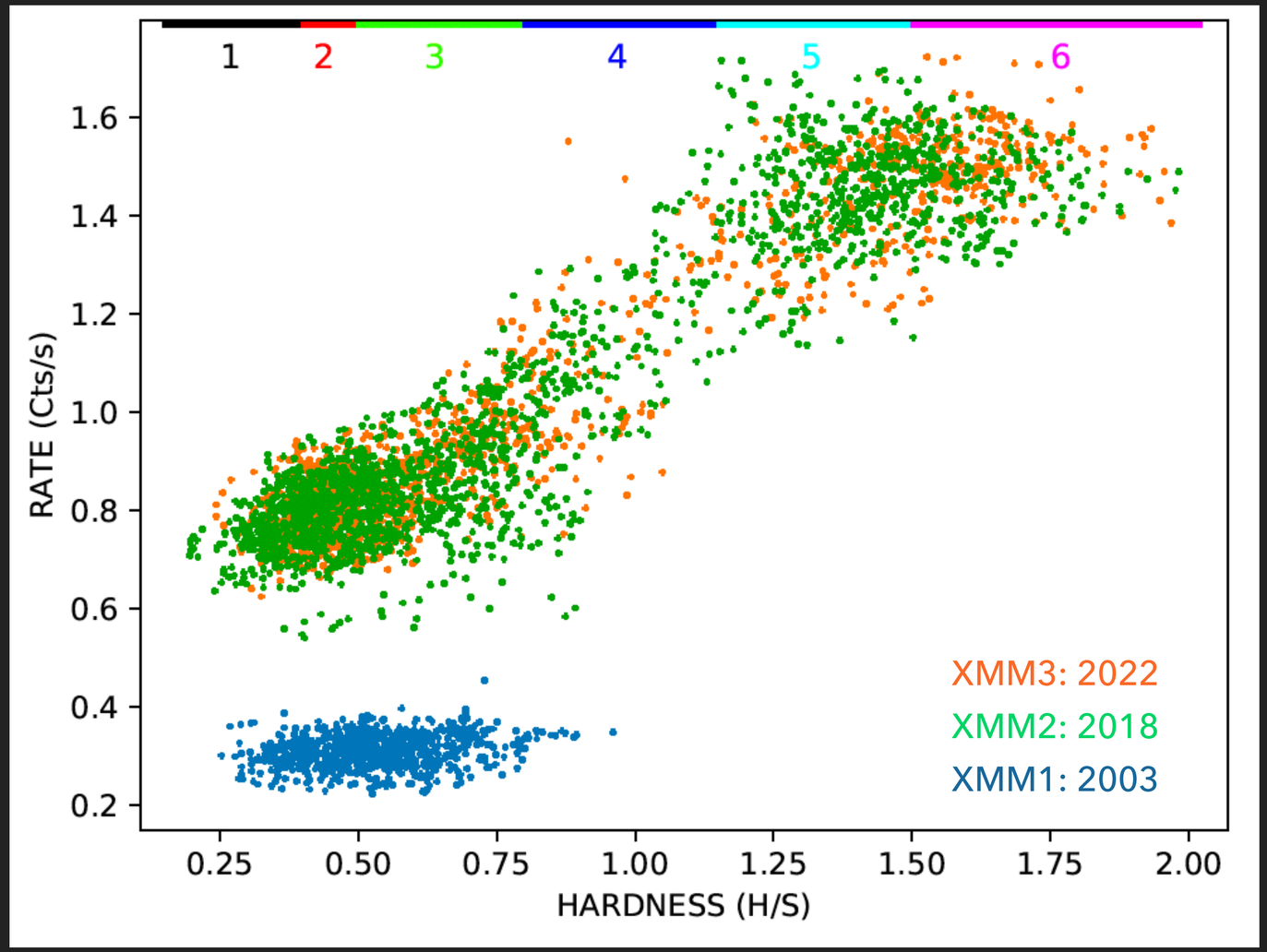


Pintore et al. (2025)

NGC 4559 X7: SPECTRAL VARIABILITY



- Three well defined spectral states in the hardness-intensity diagram
- We performed an hardness-intensity resolved spectral analysis



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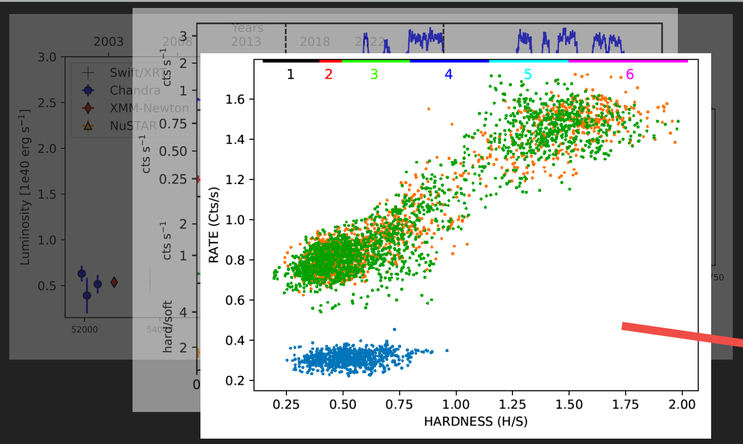
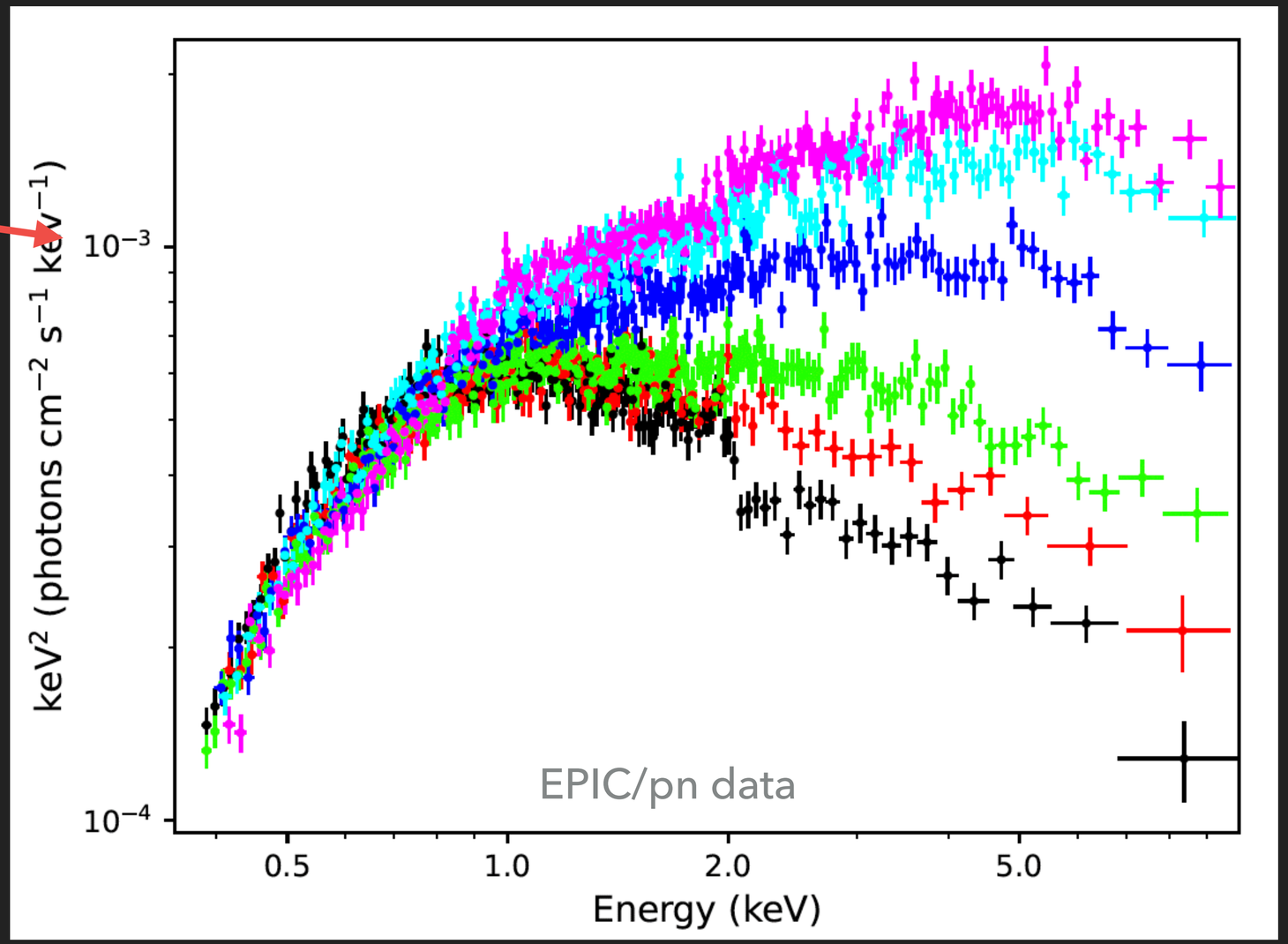
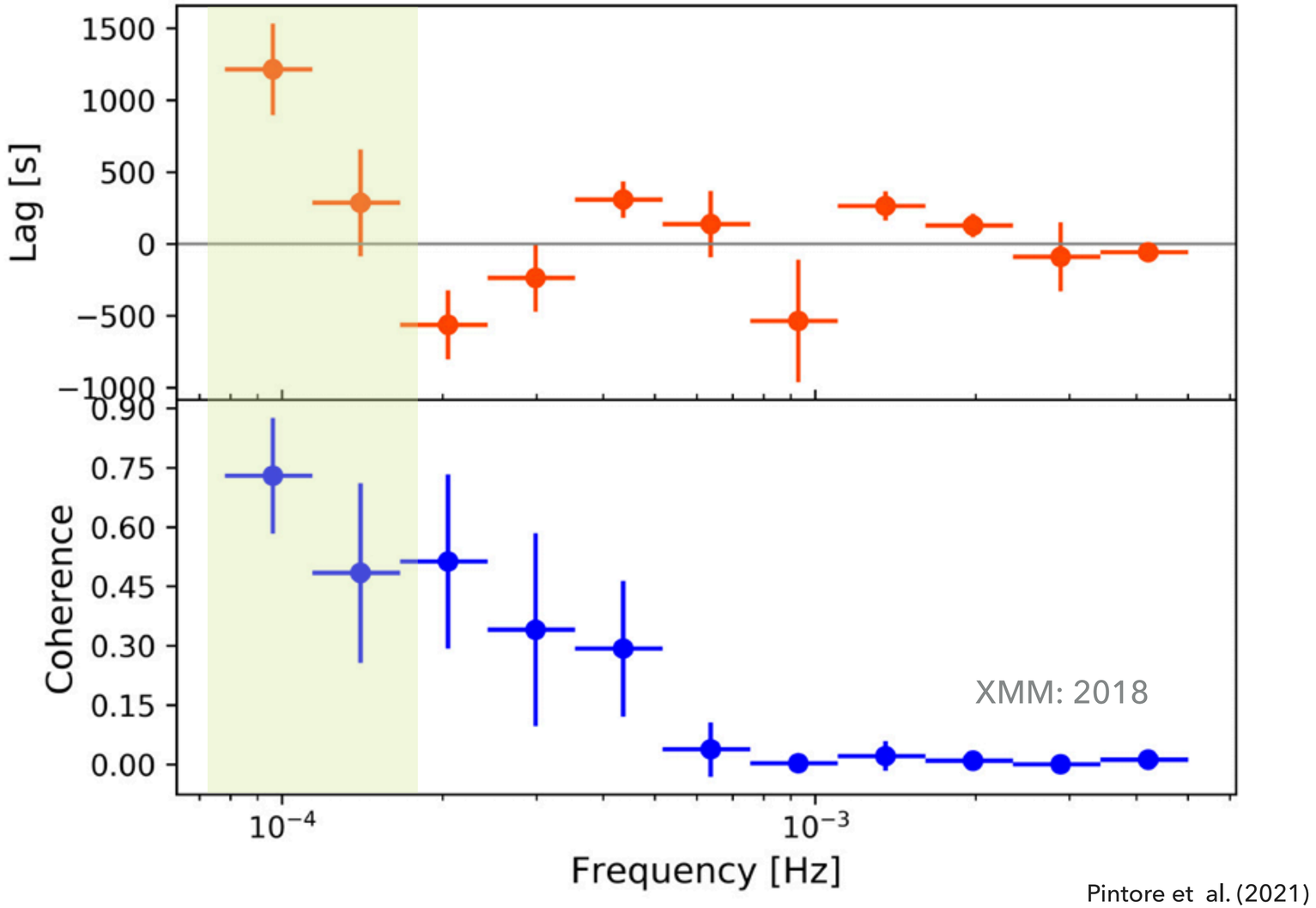


- No remarkable low energy (< 1 keV) variability during time
- All the variability associated to the emission above 1 keV and strongly driven by the flaring activity
- Spectral decomposition in three components (two thermal plus a cut-off powerlaw)



Pintore et al. (2025)

NGC 4559 X7: TEMPORAL PROPERTIES



Pintore et al. (2021)

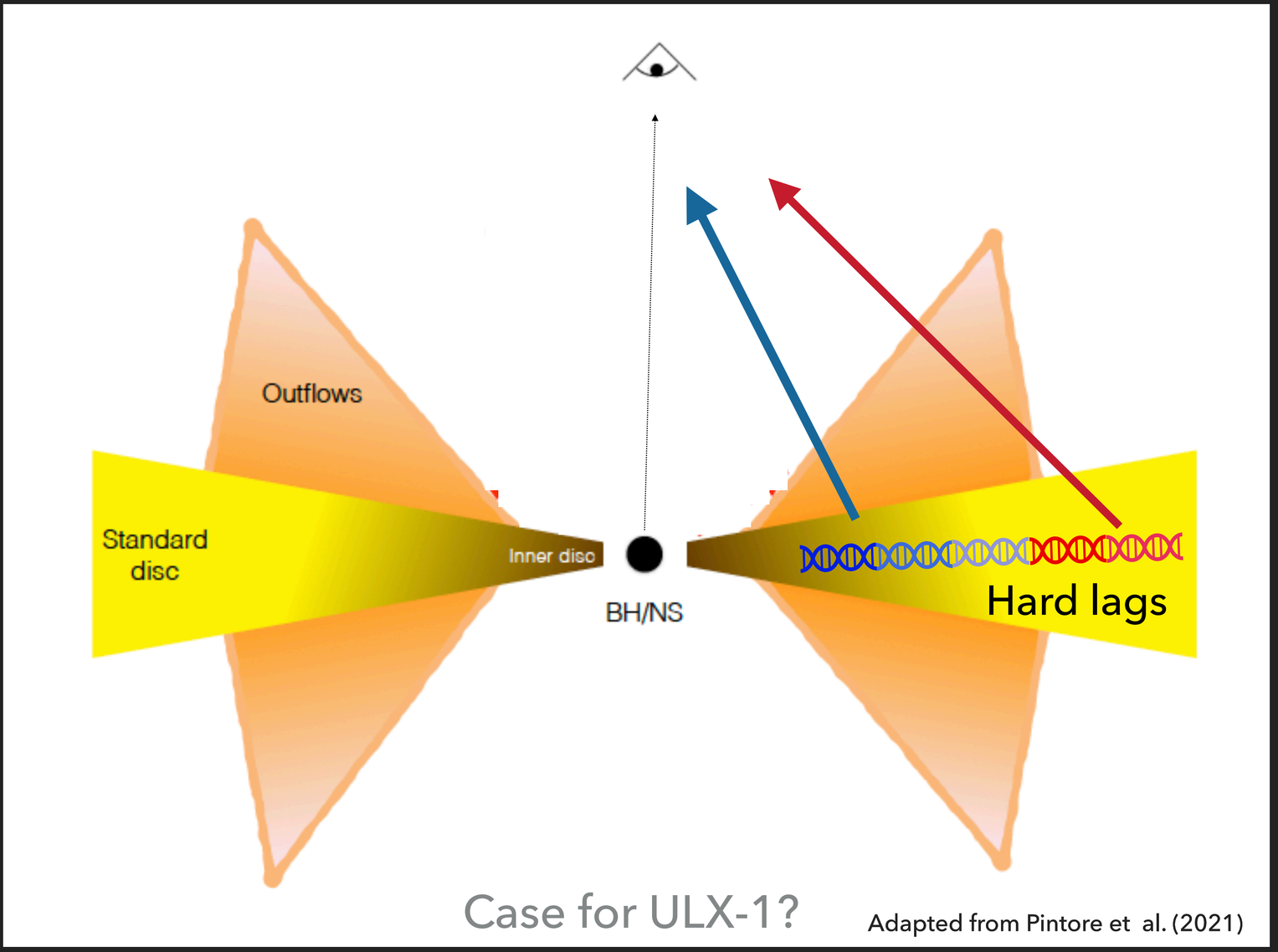
High significance (>>3 sigma) hard lag (i.e. hard lags soft band) of about 1000s on long timescales in NGC 4559 X7 between the 0.3-1 keV and 1-10 keV.

Found only in 2018 observation.

No lags at all in the 2022 XMM observation.

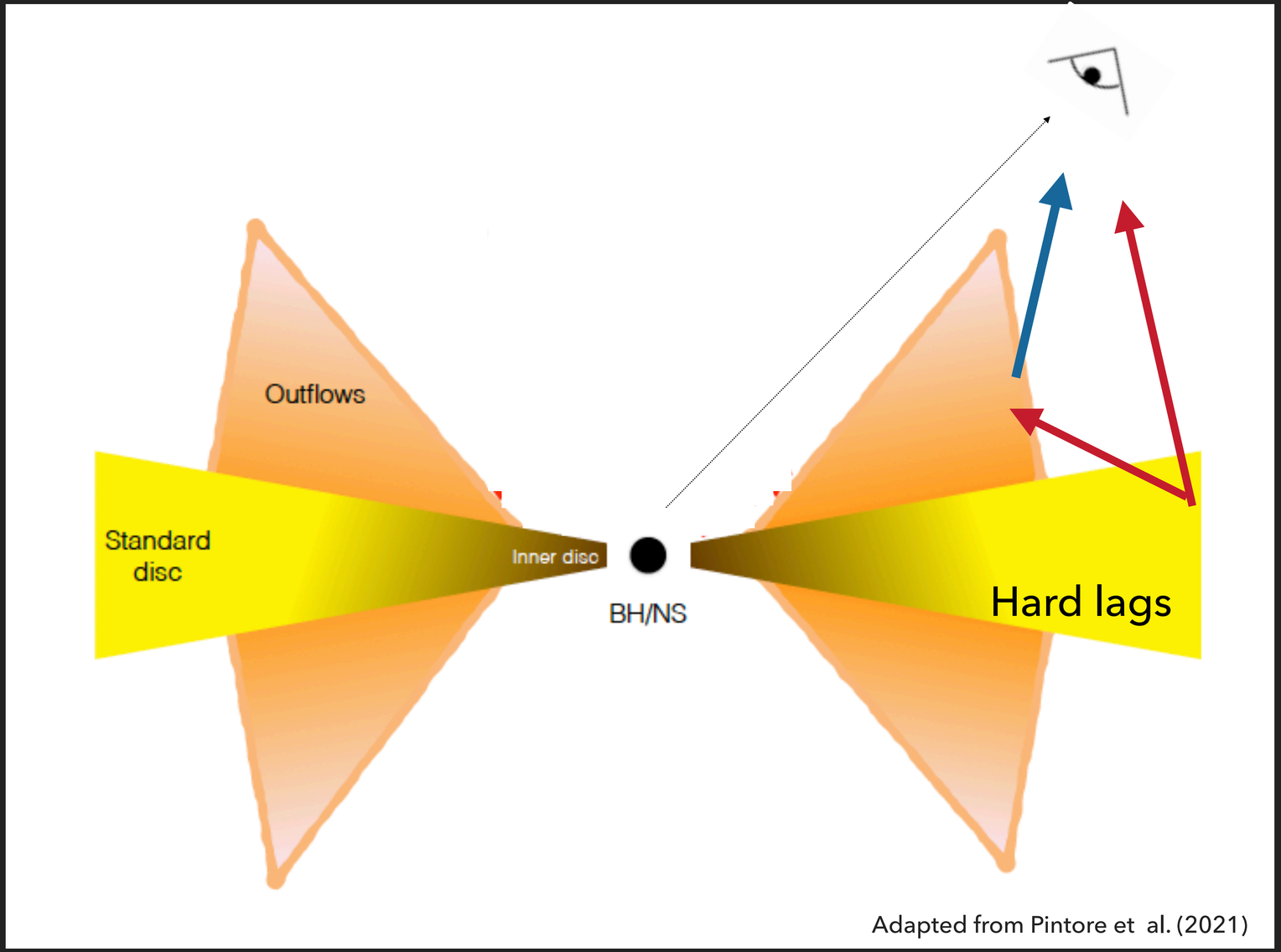
NGC 4559 X7: TIME LAGS

- Hard lags usually associated to the accretion flow propagating inward (hard lags soft)



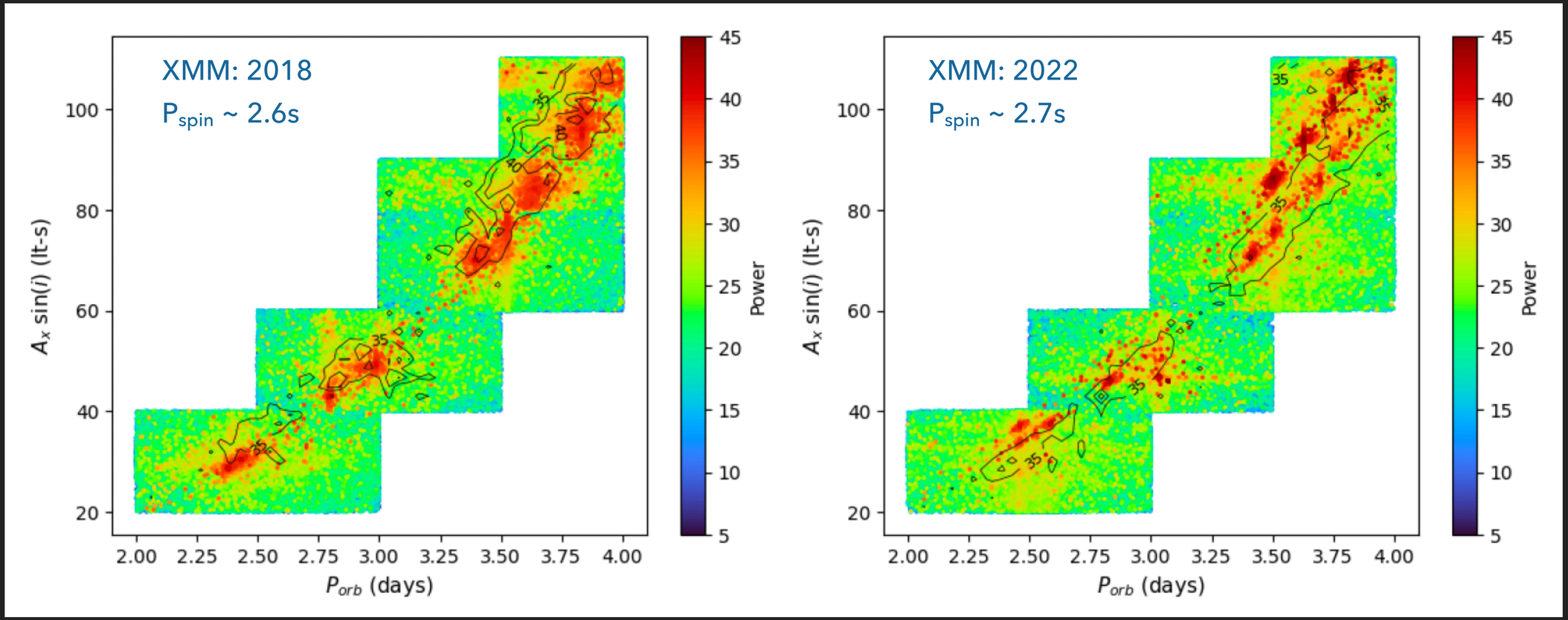
NGC 4559 X7: TIME LAGS

- Hard lags usually associated to the accretion flow propagating inward (hard lags soft)
- Reprocessing of soft photons from the external part of the outflow ?



Adapted from Pintore et al. (2021)

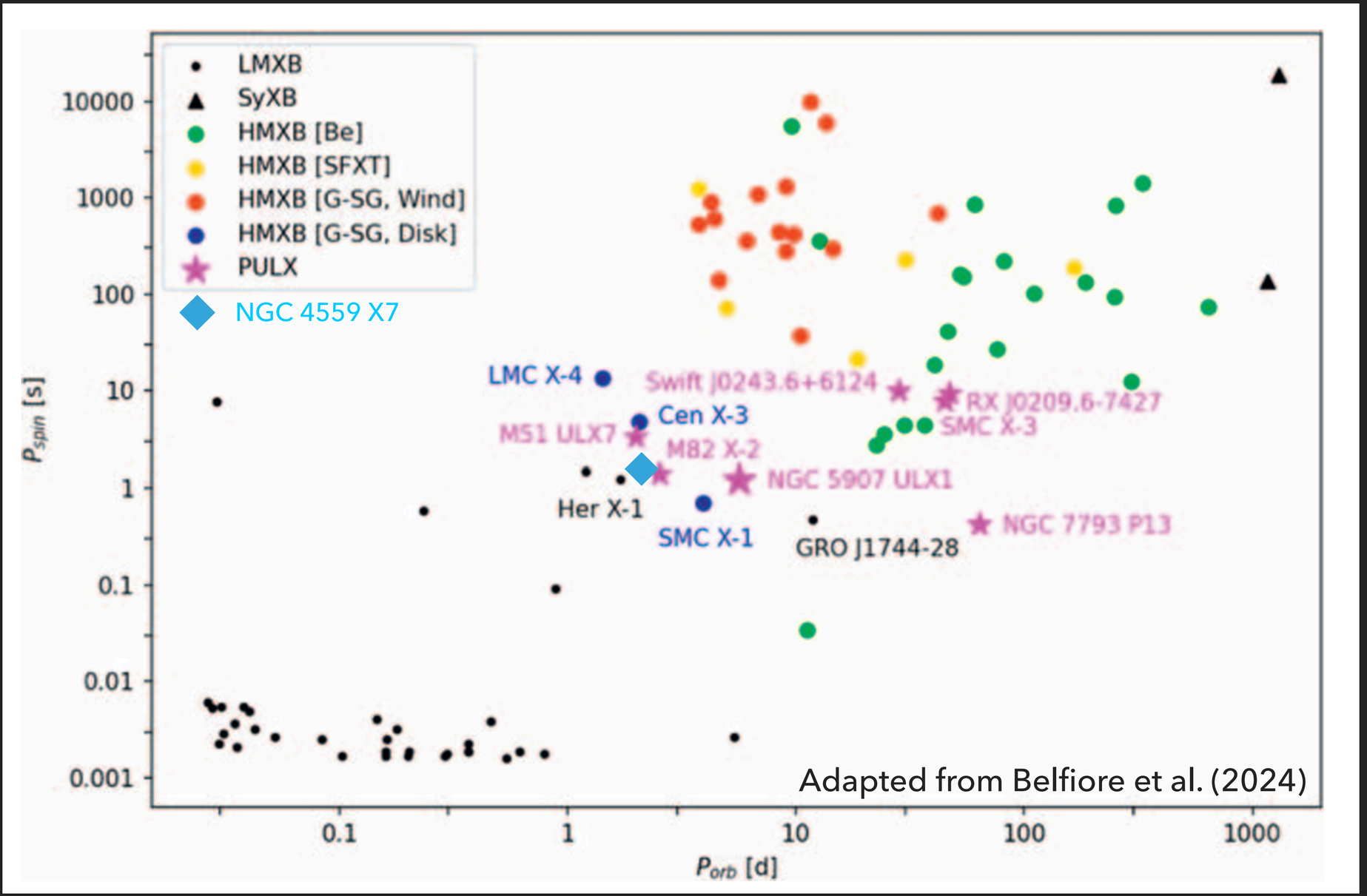
NGC 4559 X7: CANDIDATE PULSATION?



- In two XMM observations, coherent pulsations at 2.6s and 2.7s were found
- Significance of ~3.5σ; statistically weak, but they share the same “banana” in the orbital parameter space
- Orbital parameters compatible with the other PULXs
- If confirmed, it implies spin-down –> the source was always active though

Pintore et al. (2025)

NGC 4559 X7: CANDIDATE PULSATION?



NGC 4559 X7: A NEW PULX CANDIDATE?

- Highly variable on both long and short-timescales
- Very hard spectra
- Softening of the emission when decreasing in flux (i.e. brighter when harder effect)
- Possible pulsation at ~2.6-2.7 s
- Secular spin-down of 10^{-9} s/s? Quite extreme and the source was always active:
  - Drop in luminosity not compatible with propeller ($\Delta L \sim P^{2/3}$; too small than expected)
  - Trading of the magnetic field at large radius?
  - Retrograde disc (Makishima et al. 1988)? Hard to sustain it for a long time
  - Another PULX showed spin-down while accreting (M82 X-2 - e.g. Bachetti et al. 2022) as well as Galactic sources (e.g. GX 1+4 (10^-7 s/s) - Gonzalez Galan et al. 2012)

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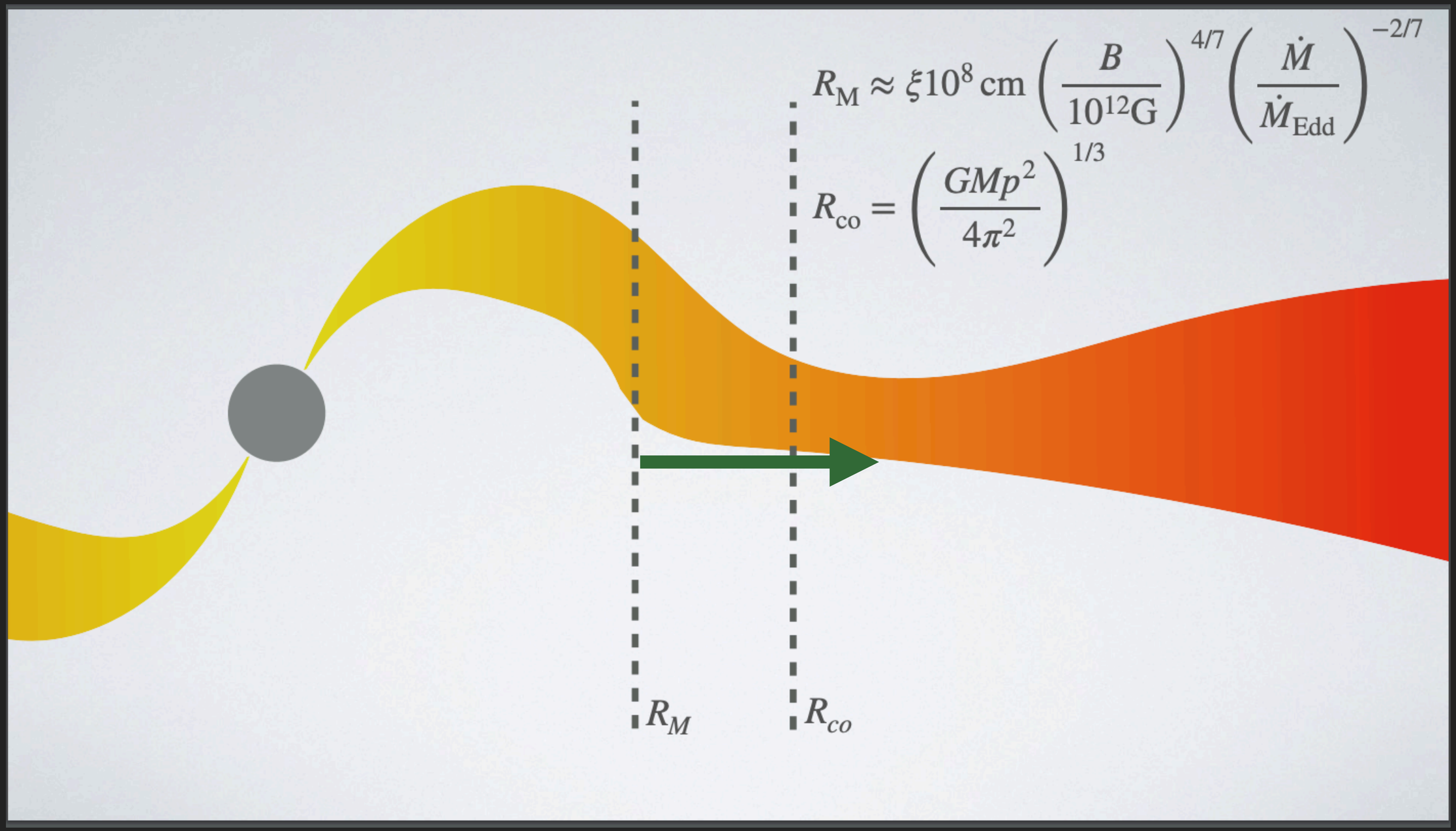

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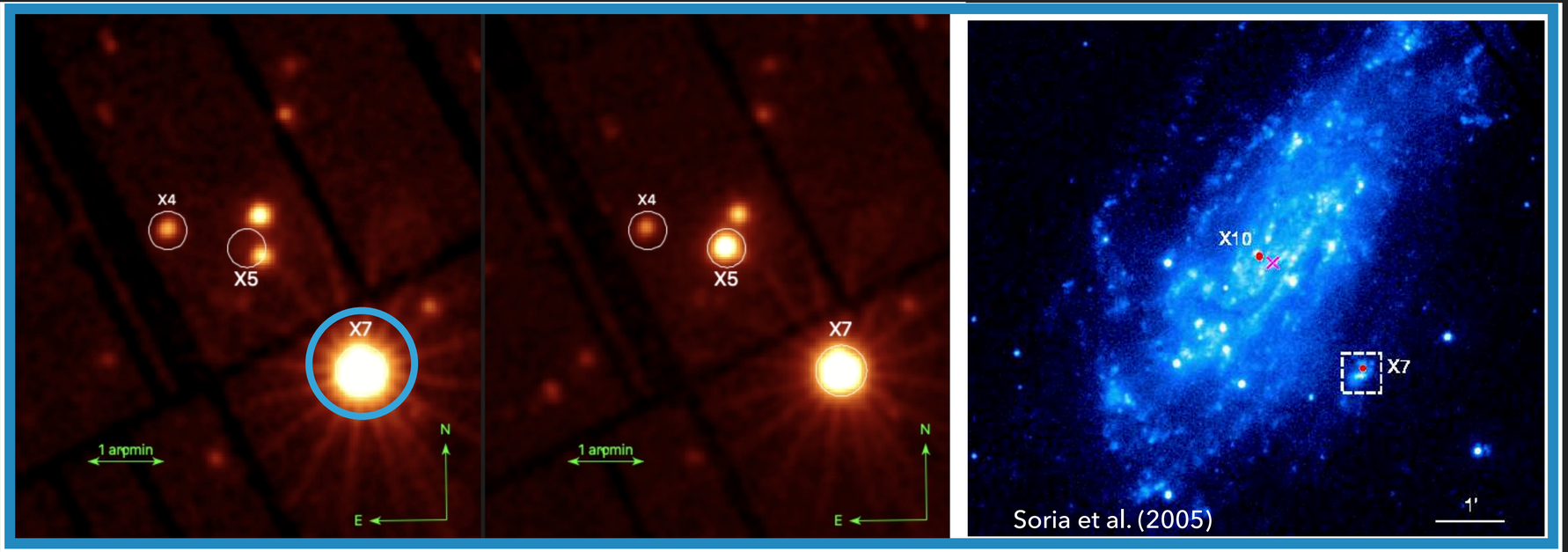
NGC 4559 AND NGC 7456: HIGH VARIABLE ULXS

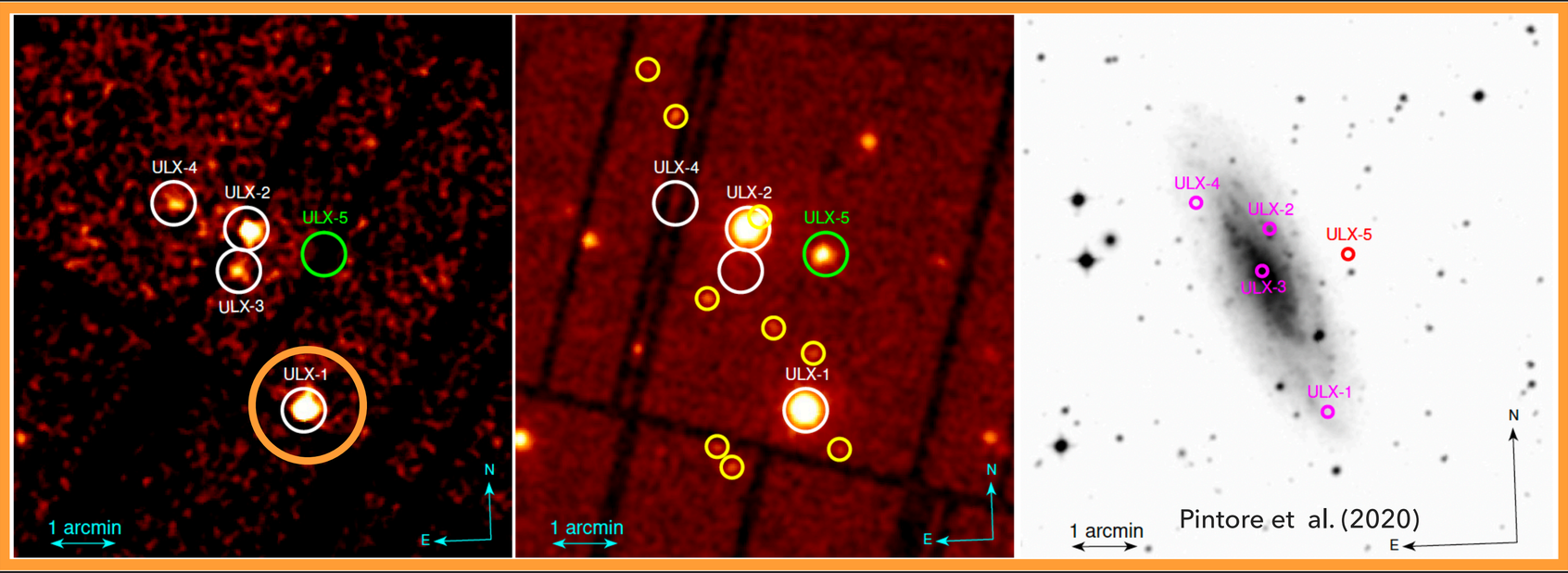
NGC 4559:

- Three ULXs
- One transient
- ***X7 is highly variable***



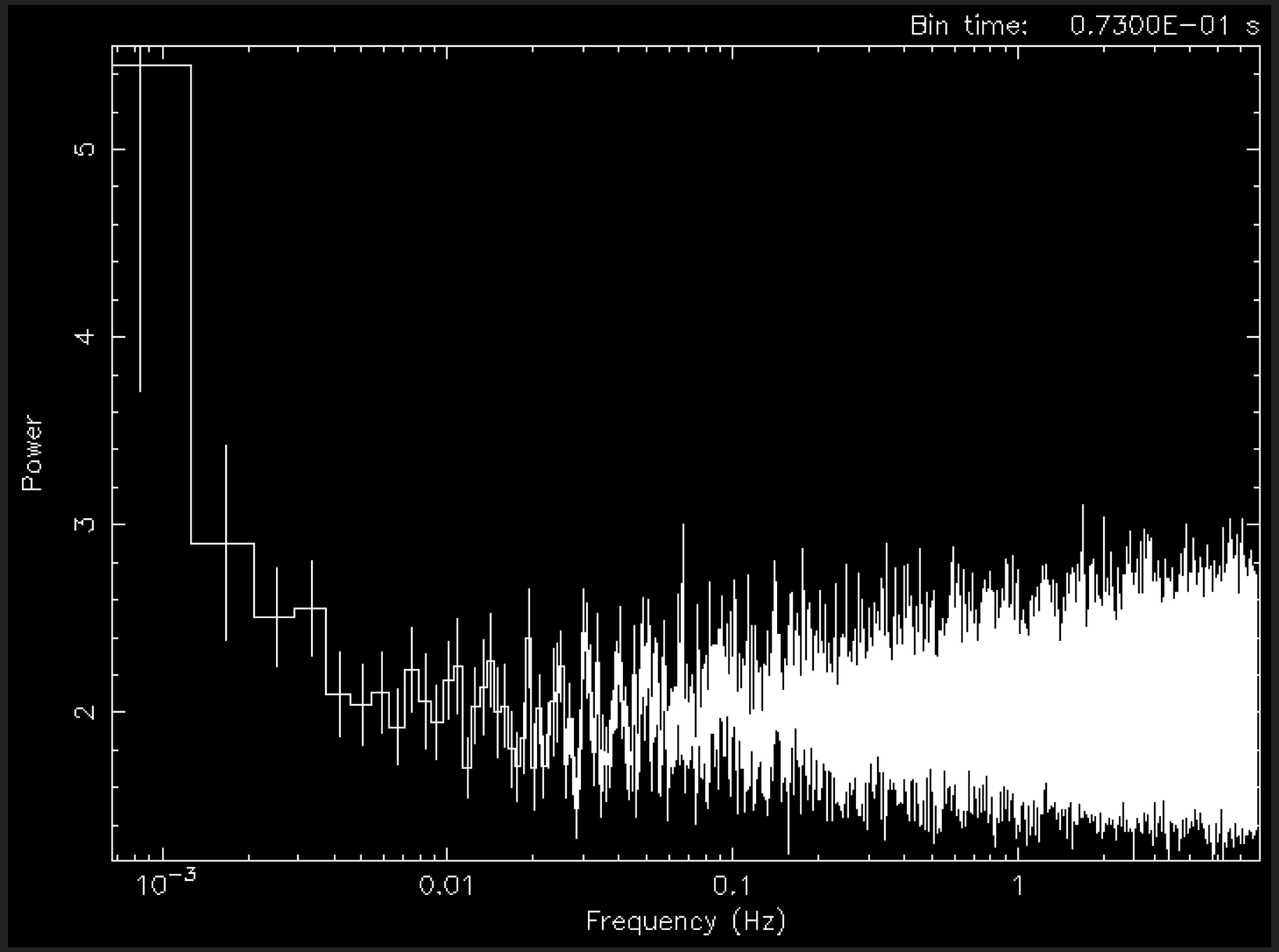
NGC 7456:

- Five ULXs
- Three transients
- ***ULX-1 is highly variable***



NGC 7456 ULX1: PULSATION

- Search in progress, no pulsation found… yet



CONCLUSIONS

- It is possible that the population of NS is significantly larger than expected
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- It is possible that the population of NS is significantly larger than expected
- The search for pulsations is certainly the best way to find them …
- BUT…. indirect proofs can help finding new candidate NS!

- No pulsations found in NGC 7456 ULX-1… yet
- Pulsation (to be confirmed) for NGC 4559 X7
- The latter could be a candidate NS
- There is no solid approach yet to identify new NS candidates

Thanks for the attention