Probing Extreme Accretion Outflows in ULXs: The NewAthena Era

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Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

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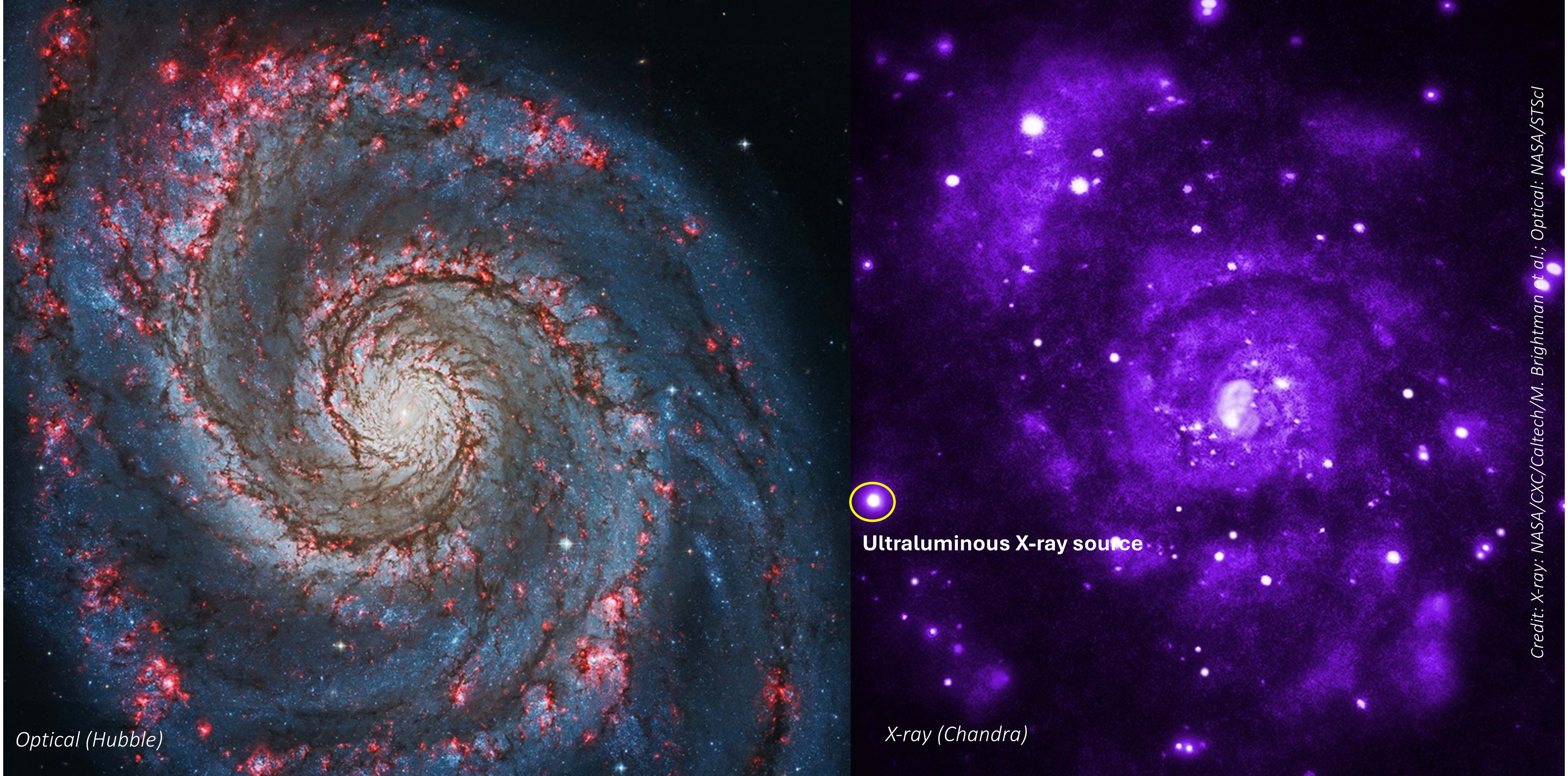
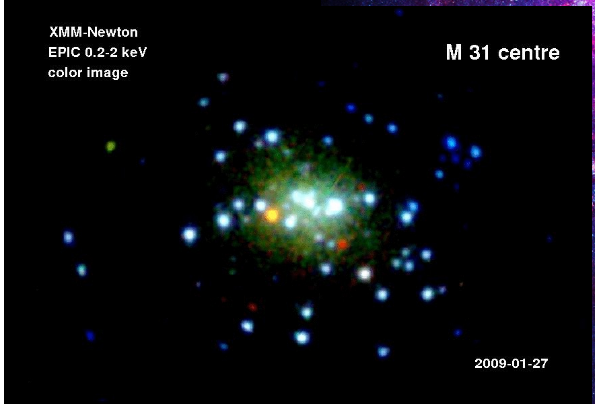
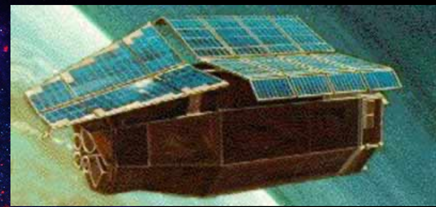
WHIRLPOOL GALAXY



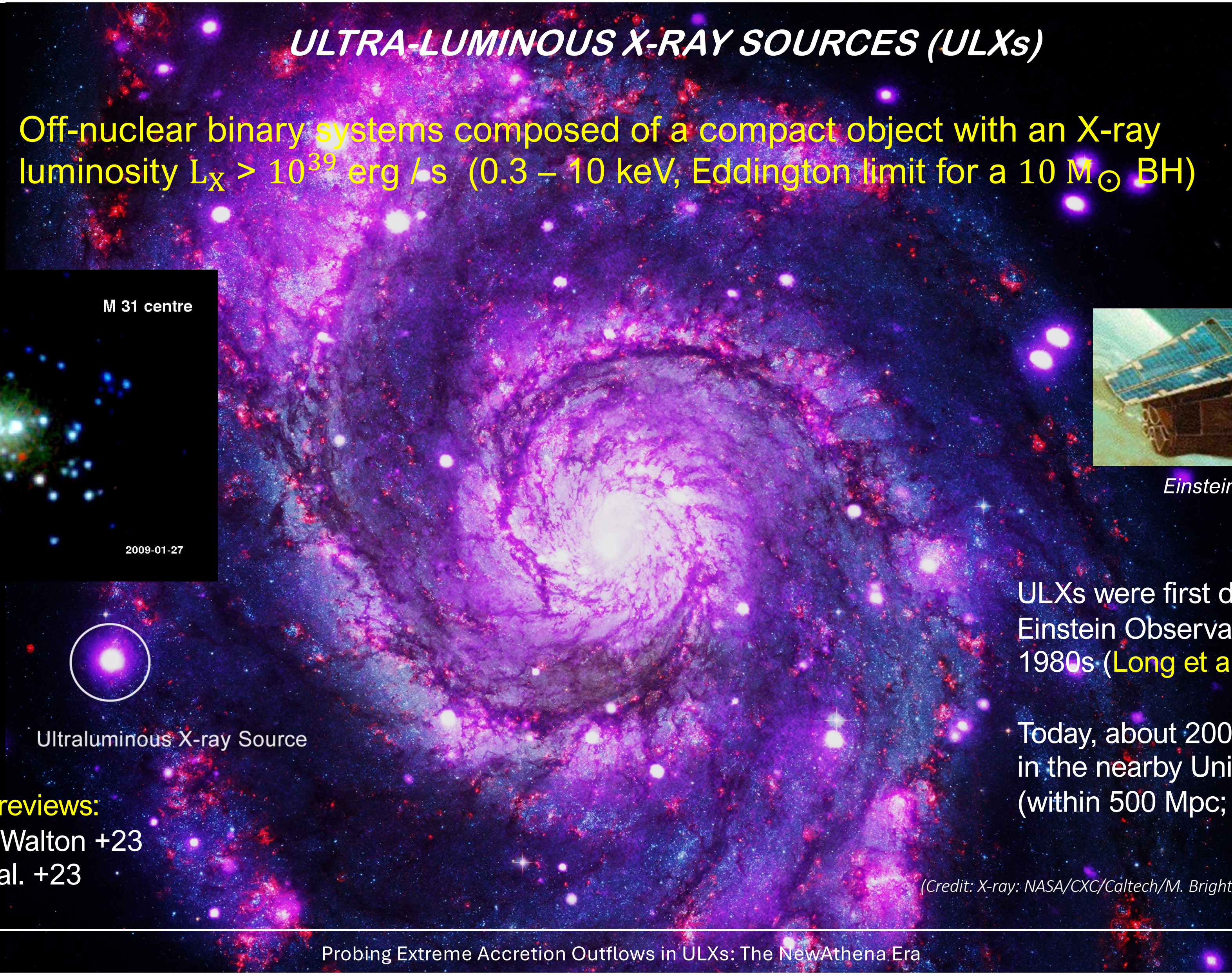
ULTRA-LUMINOUS X-RAY SOURCES (ULXs)

Off-nuclear binary systems composed of a compact object with an X-ray luminosity $L_X > 10^{39}$ erg / s (0.3 – 10 keV, Eddington limit for a $10\ M_{\odot}$ BH)





Einstein observatory



ULXs were first discovered with the Einstein Observatory in the early 1980s (Long et al. 1981)

Today, about 2000 ULXs are known in the nearby Universe (within 500 Mpc; Walton +22)

Recent reviews:
Pinto & Walton +23
King et al. +23

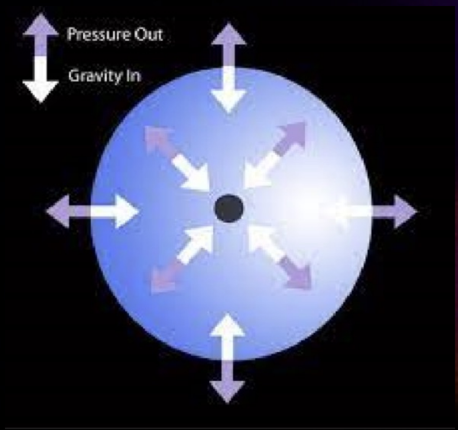
(Credit: X-ray: NASA/CXC/Caltech/M. Brightman et al.; Optical: NASA/STScI)

ULX engines: accretion beyond Eddington

Off-nuclear binary systems composed of a compact object with an X-ray luminosity $L_X > 10^{39}$ erg / s (0.3 – 10 keV, Eddington limit for a 10 $M_\odot$ BH)

Eddington limit $(F_{grav} = F_{rad})$

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} \sim 1.3 \cdot 10^{38} \frac{M}{M_\odot} \text{ erg / s}$$



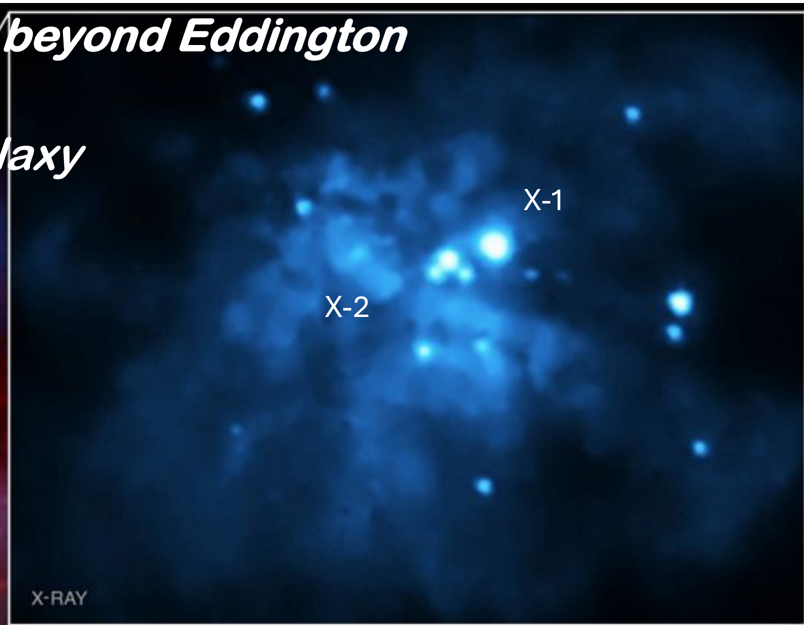
Initially, such high luminosities suggested accretion onto massive black holes:

- BH with a mass $> 10\ M_\odot$ (& up to 100s)
- Accretion rate of the BH $> \dot{M}_{Edd} = \frac{L_{Edd}}{\eta c^2}$ (up to 100 $\dot{M}_{Edd}$)

(Cartwheel Galaxy – Image credit: X-ray: NASA/CXC; Optical: NASA/STScI)

ULX engines: accretion beyond Eddington

M82 Galaxy

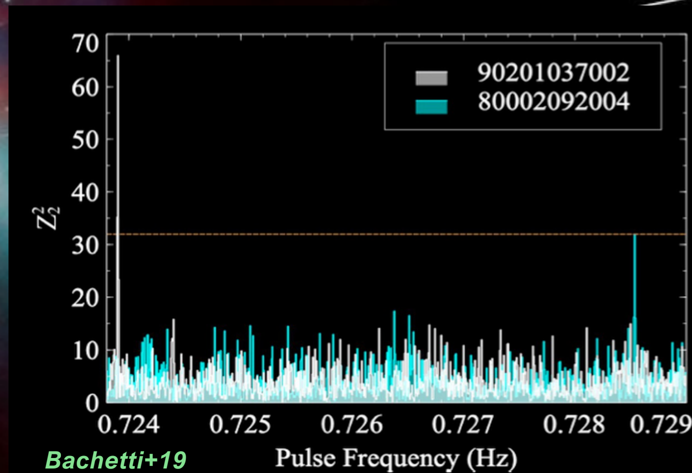


An ultraluminous X-ray source powered by an accreting neutron star

M. Bachetti, F. A. Harrison, D. J. Walton, B. W. Grefenstette, D. Chakrabarty, F. Fürst, D. Barret, A. Beloborodov, S. E. Boggs, F. E. Christensen, W. W. Craig, A. C. Fabian, C. J. Hailey, A. Hornschemeier, V. Kaspi, S. R. Kulkarni, T. Maccarone, J. M. Miller, V. Rana, D. Stern, S. P. Tendulkar, J. Tomsick, N. A. Webb & W. W. Zhang

Nature **514**, 202–204 (2014) | Cite this article

region of the galaxy M82 that reveal pulsations with an average period of 1.37 seconds and a 2.5-day sinusoidal modulation. The pulsations result from the rotation of a magnetized neutron star, and the modulation arises from its binary orbit. The pulsed flux alone corresponds to an X-ray luminosity in the 3–30 kiloelectronvolt range of 4.9×10^{39} ergs per second. The pulsating source is spatially coincident with a variable source[4] that can reach an X-ray luminosity in the 0.3–10 kiloelectronvolt range of 1.8×10^{40} ergs per second[1]. This



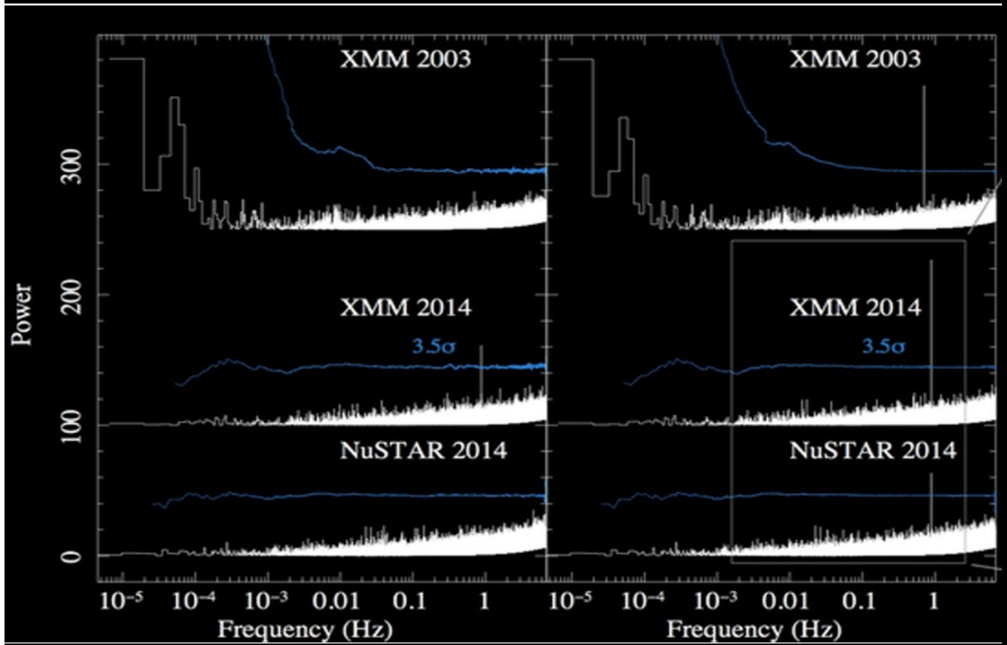
X-RAY, INFRARED & OPTICAL

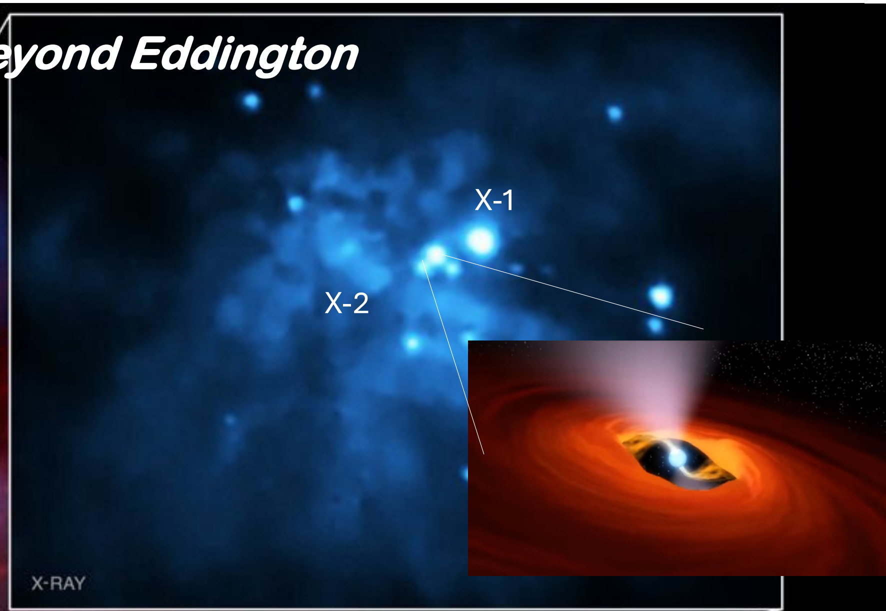
ULX engines: accretion beyond Eddington

Pulsations were detected in ~30% of high-quality observations

NGC 5907 X-1 is the most luminous pulsating ULX with a luminosity up to $L_X \sim 10^{41}$ erg/s (500 $L_{Edd,NS}$)

Orbital correction



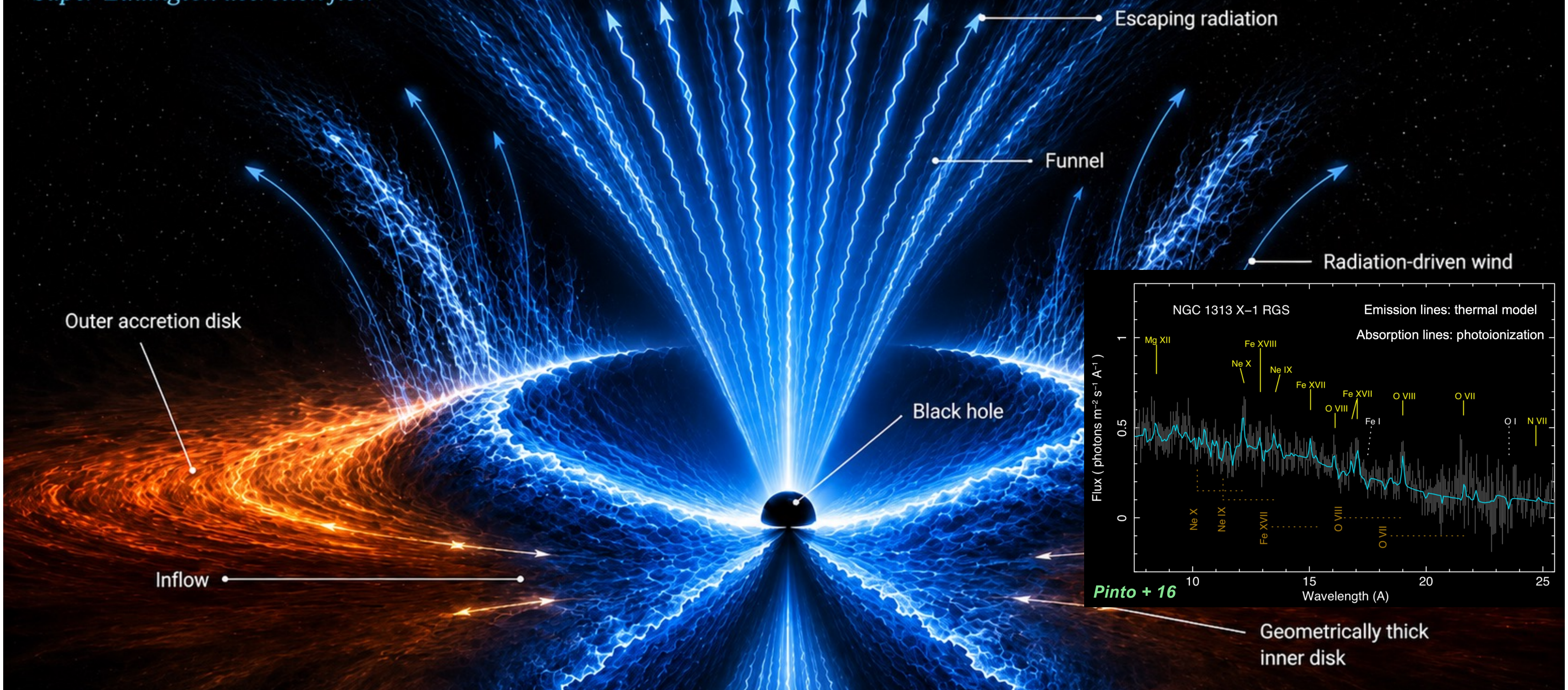


Known pULXs: 6 confirmed extragalactic systems; ~8 including Galactic/SMC ULX pulsars.

Bachetti +14, Israel +17a,b
Fuerst +16, Carpano+18
Sathyaprakash +19,
Rodriguez-Castillo+20

X-RAY, INFRARED & OPTICAL

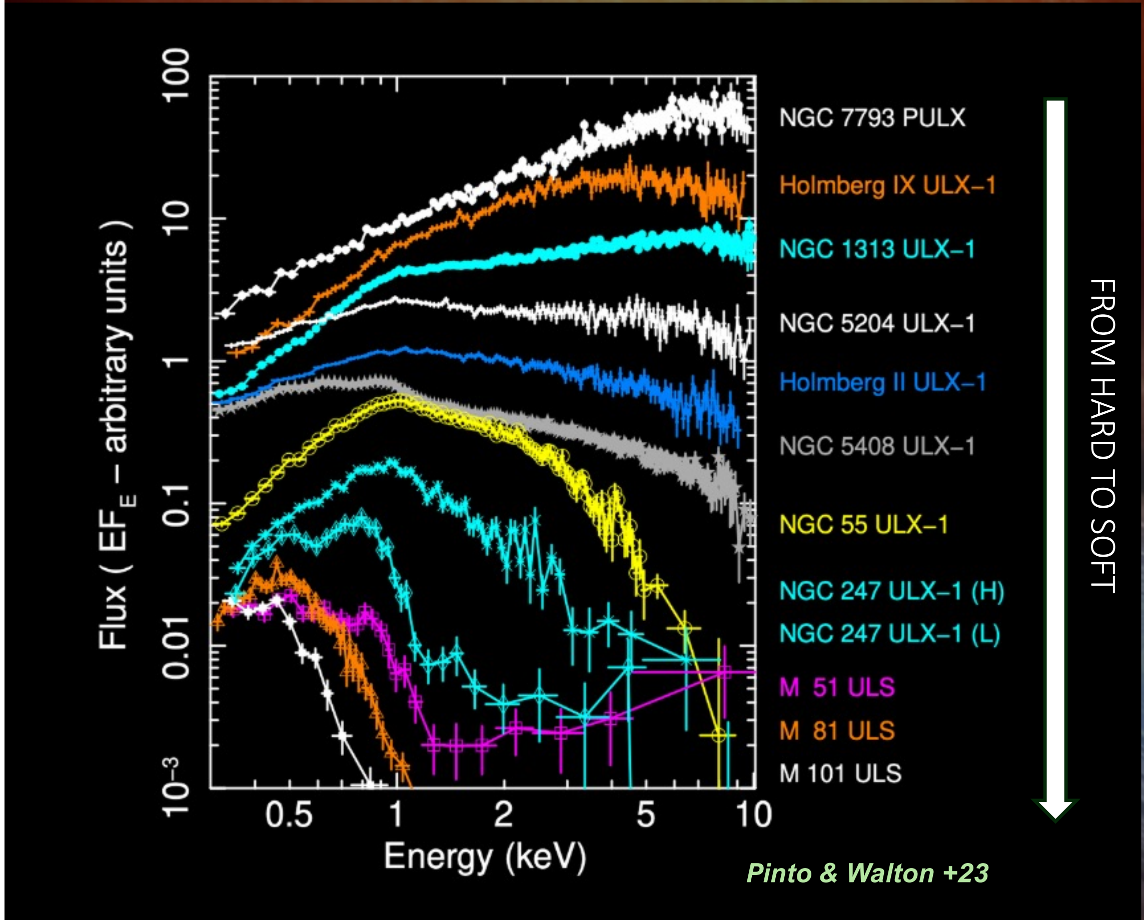
Super-Eddington accretion flow



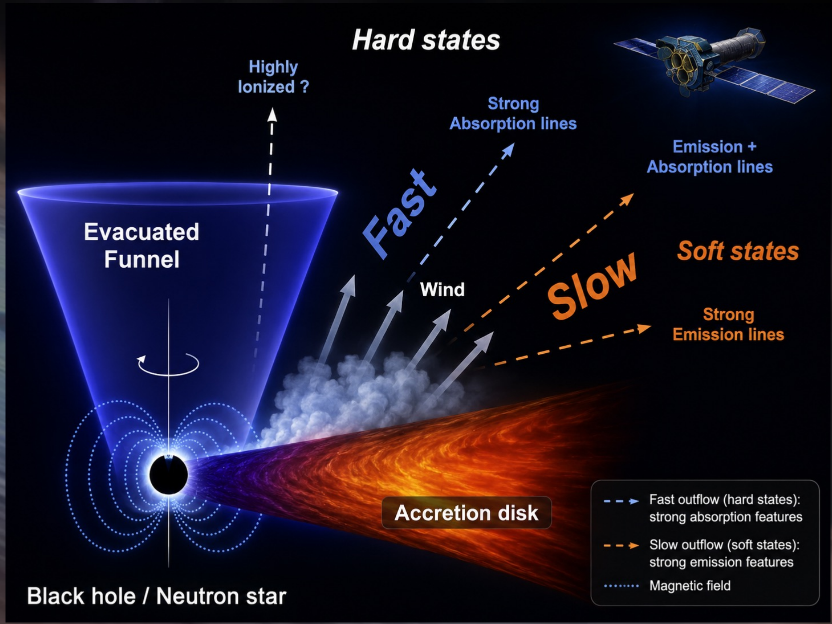
The radiation pressure inflates the disc and launches the powerful, relativistic wind (0.1-0.2c)

Doppler-shifted absorption lines reveal the long sought relativistic winds

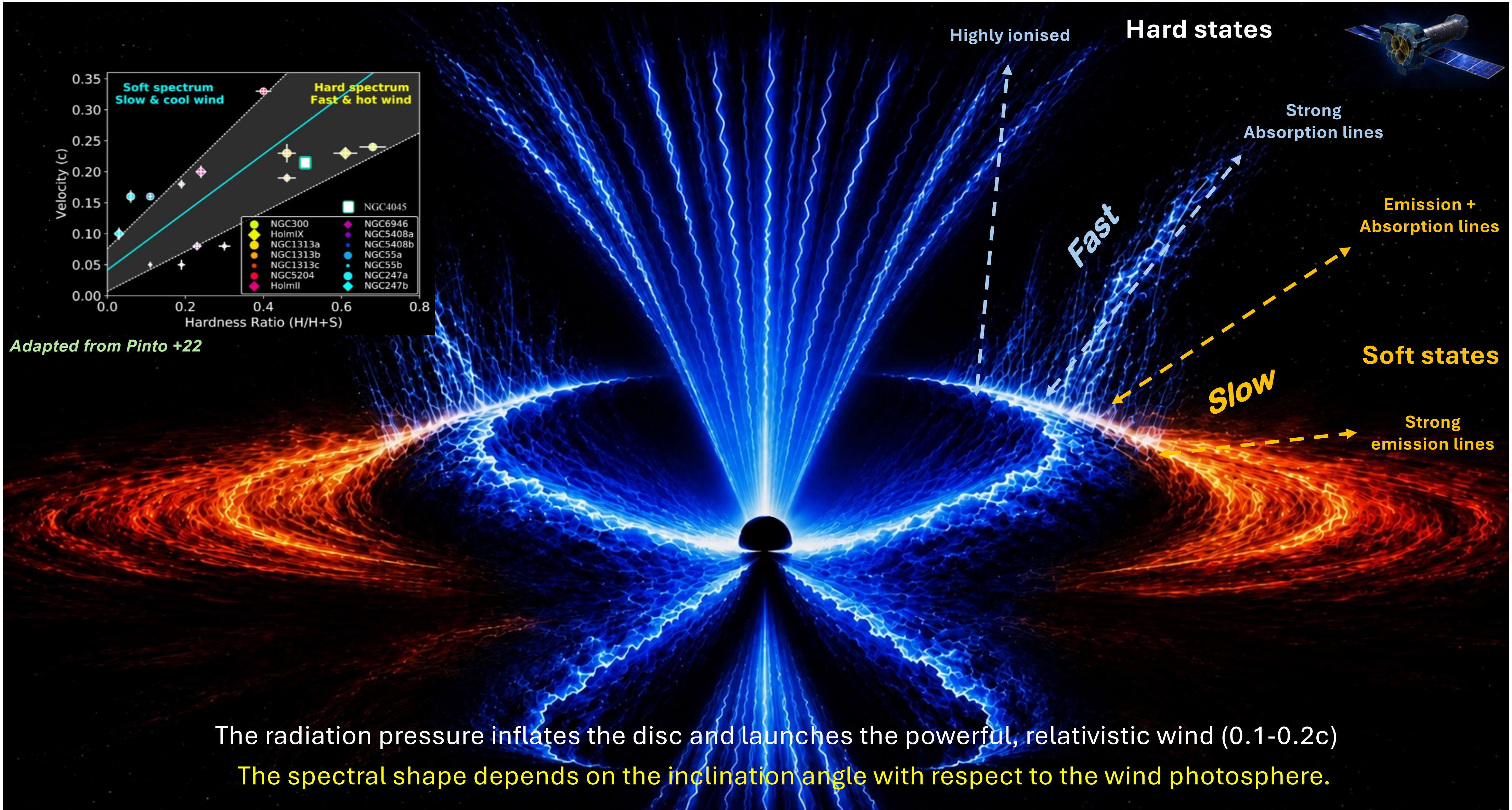
ULX spectra: complexity and variability



Presence of variability in ULX spectra: from hard to soft



The spectral shape depends on the inclination angle with respect to the wind photosphere.



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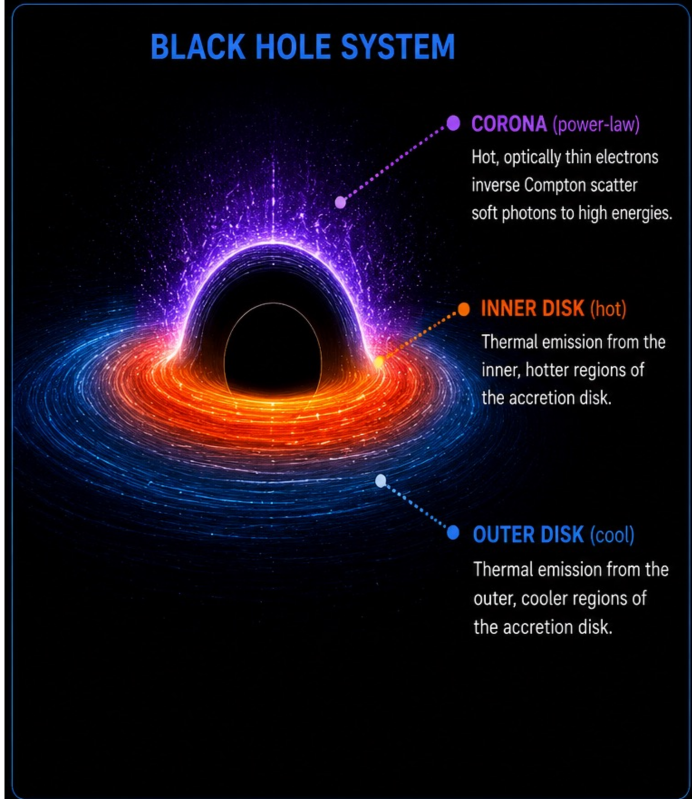
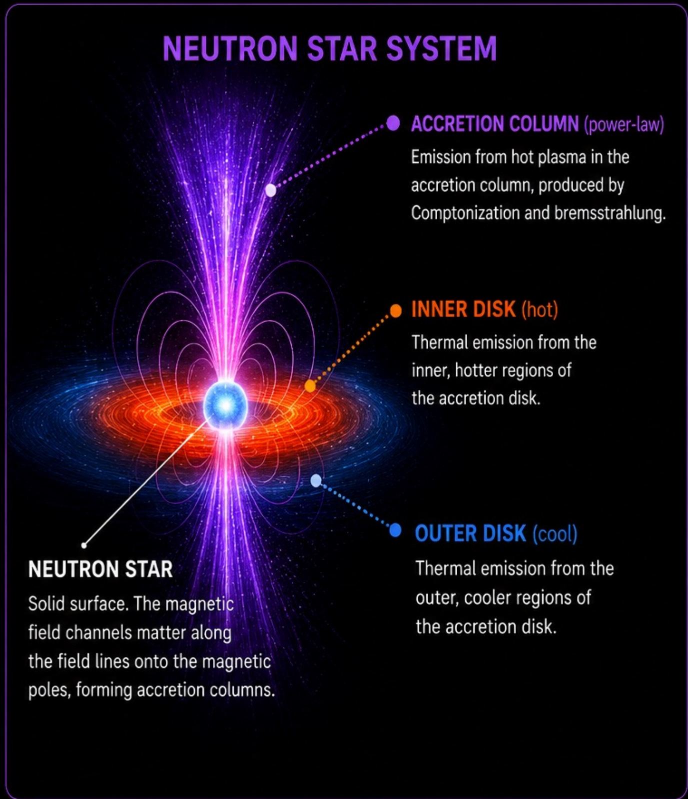
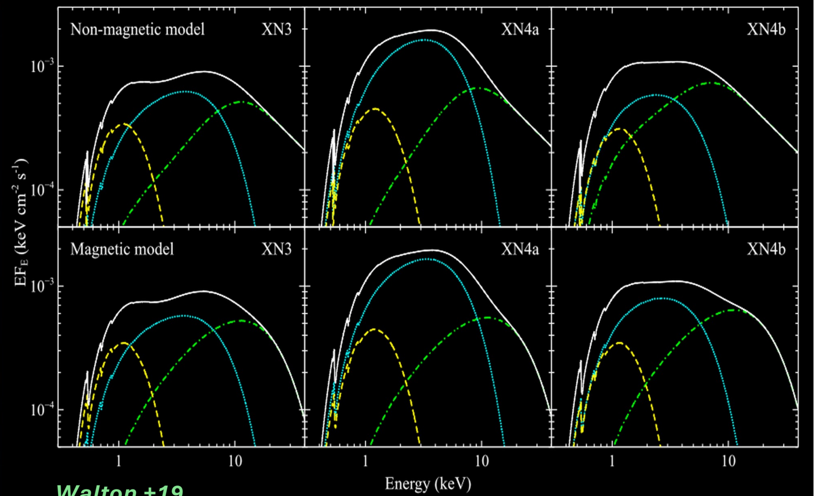
ULX spectral components

Geometry of the emitting regions





Non-magnetic vs magnetic spectral models



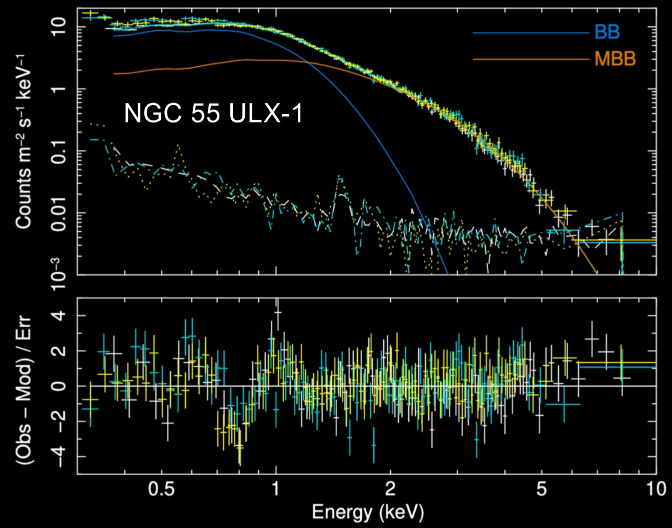
Walton +19

The model decomposition separates low-energy thermal emission, hotter disk emission, and a hard tail produced either by a black-hole corona or by a neutron-star accretion column.

- **Cool outer disk emission**
  0.1 – 0.5 keV
- **Hot inner disk emission**
  1 – 5 keV
- **Hard component emission**
  corona / accretion column ≥ 7 keV

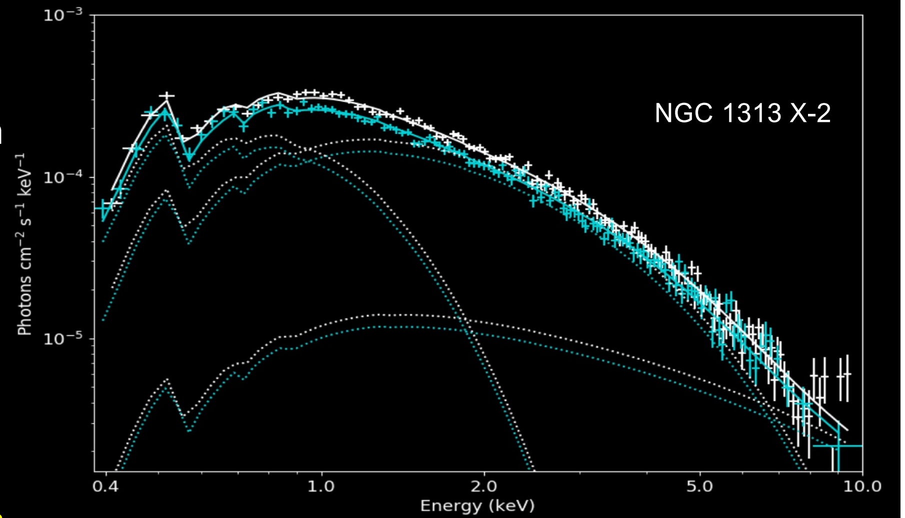
ULX spectra are commonly described by multiple components tracing distinct physical zones of the accretion flow

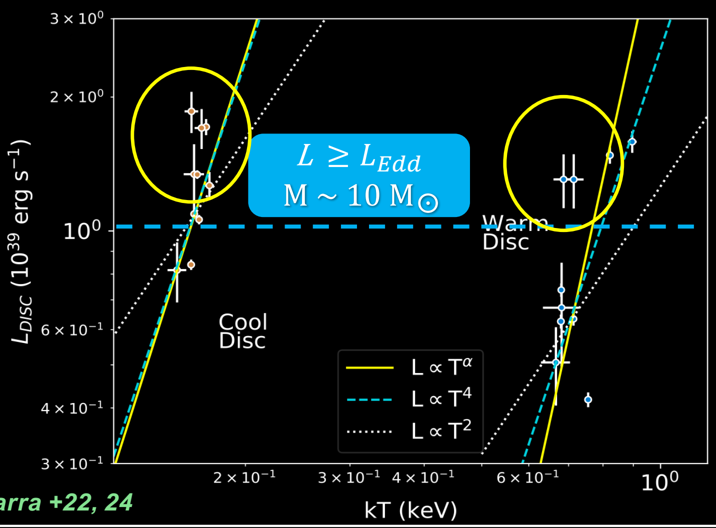
ULX thermal components: tracing the L–T relation



NGC 55 X-1: broadly agrees with Shakura-Sunyaev disc model

NGC 1313 X-2 soft component disagrees with SS73





Barra +22, 24

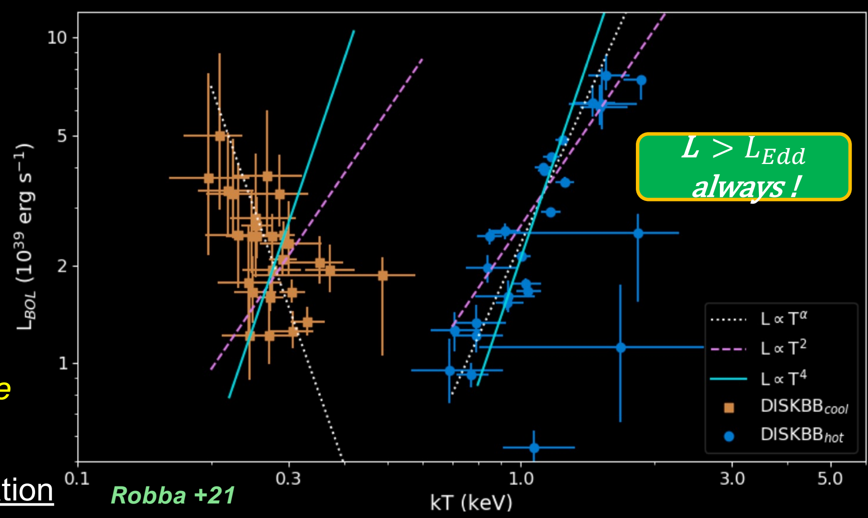
At high luminosity: deviations from SS73 thin disc: $L \neq T^4$

↓

Mass estimation?

Assumption: Deviations occur above the supercritical limit

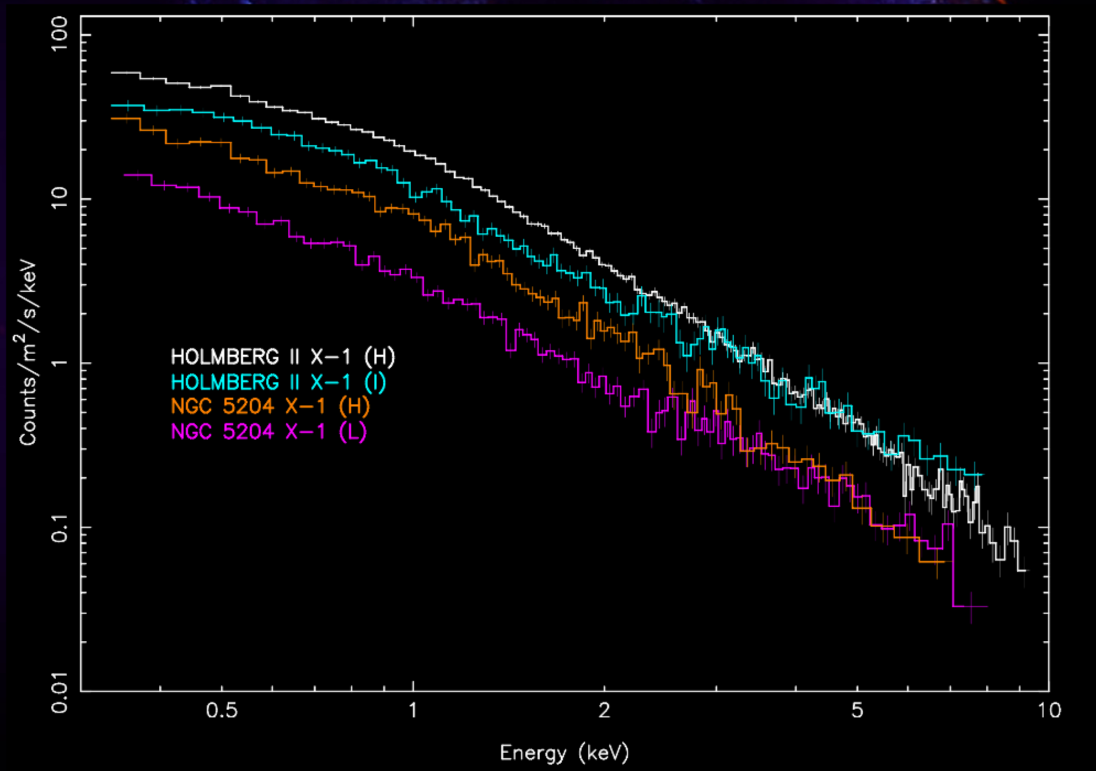
Need statistical sampling of the population



Robba +21

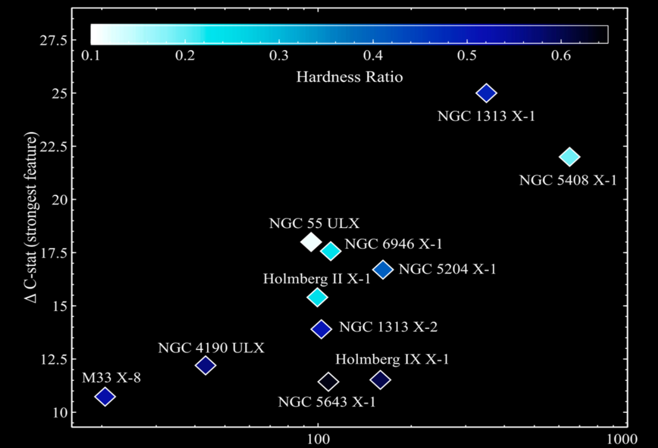
OPEN QUESTIONS

- Are ULX spectral transitions driven by stochastic changes in the wind or variations in the accretion rate/geometry?
- Can we distinguish BH from NS ULXs?
- What is the fraction of ULXs harbouring NSs?
- L-T α trends differ in ULXs → $L\text{-}T_{BH} \neq L\text{-}T_{NS}$?

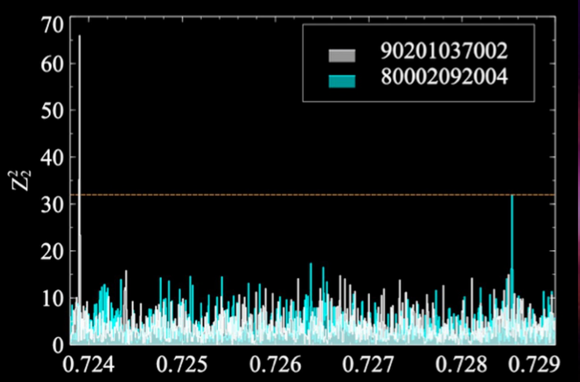


Current observational limitations

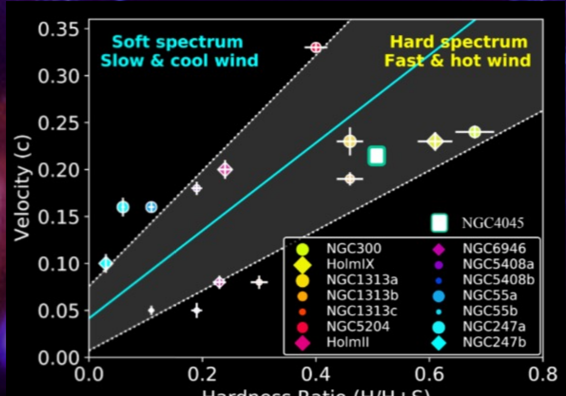
- Transient pulsations: ≥ **14** canonical + transients pULXs
- High-resolution wind studies: **> 100 ks** currently needed
- L - T relations: α measured only for a dozen ULXs
- Limited sample studies of wind properties' trends
- Lack of effective area, stacking is required
- Lack of resolution for absorption line shape
- Lack of completeness (pulsations & winds at < 20 Mpc)



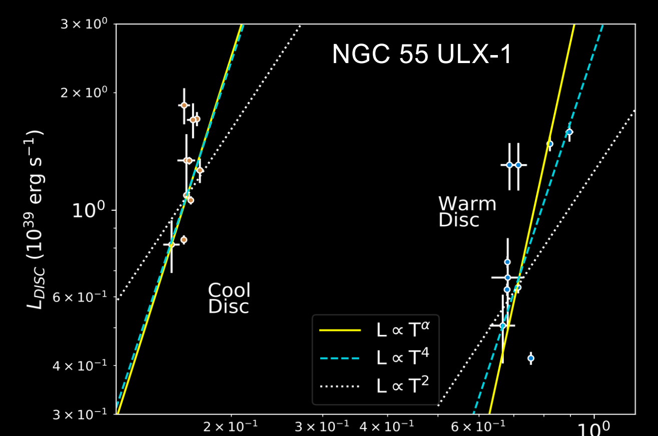
Kosec +18a



Bachetti+19

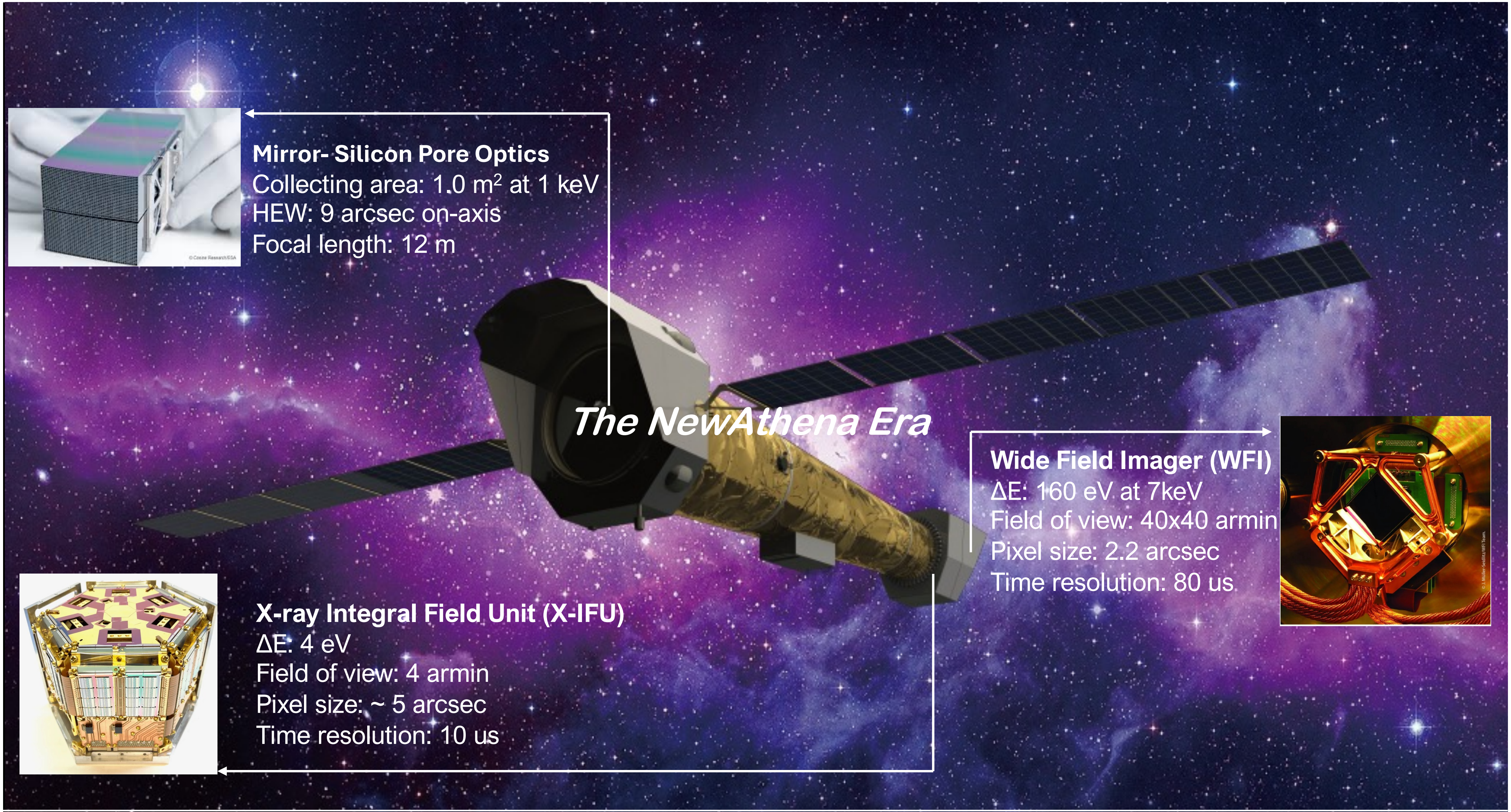


Pinto +22

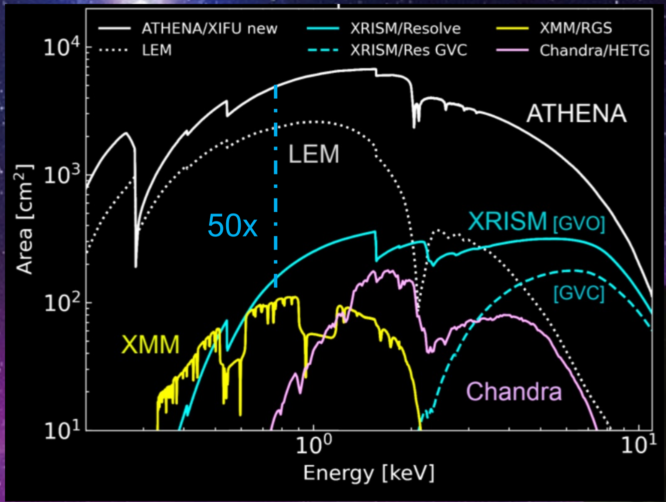


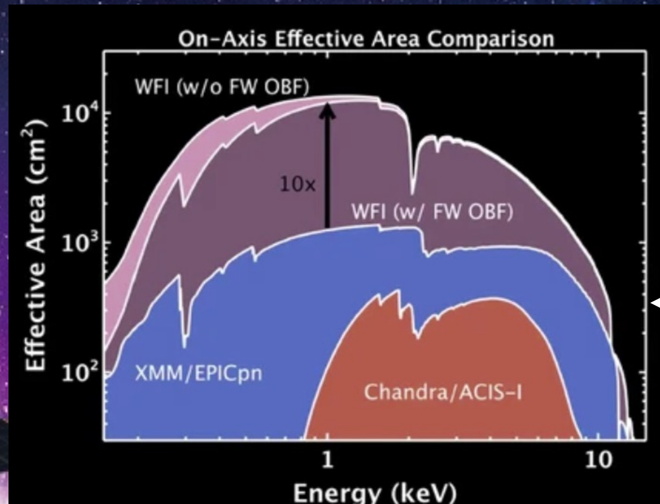
Barra +22

(Cartwheel Galaxy – Image credit: X-ray: NASA/CXC; Optical: NASA/STScI)

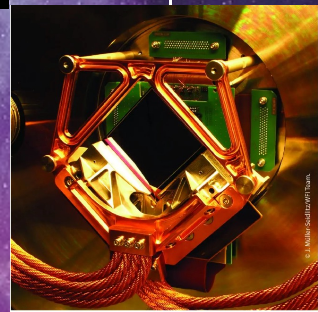

The NewAthena Era
Mirror- Silicon Pore Optics
Collecting area: 1.0 m² at 1 keV
HEW: 9 arcsec on-axis
Focal length: 12 m
Wide Field Imager (WFI)
ΔE: 160 eV at 7keV
Field of view: 40x40 armin
Pixel size: 2.2 arcsec
Time resolution: 80 us
X-ray Integral Field Unit (X-IFU)
ΔE: 4 eV
Field of view: 4 armin
Pixel size: ~ 5 arcsec
Time resolution: 10 us

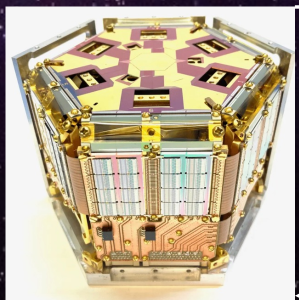
The NewAthena Era





Wide Field Imager (WFI)
ΔE: 160 eV at 7keV
Field of view: 40x40 armin
Pixel size: 2.2 arcsec
Time resolution: 80 us

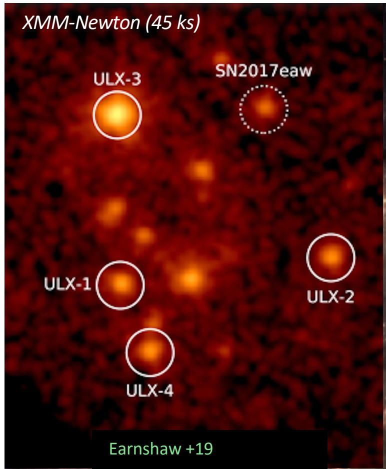


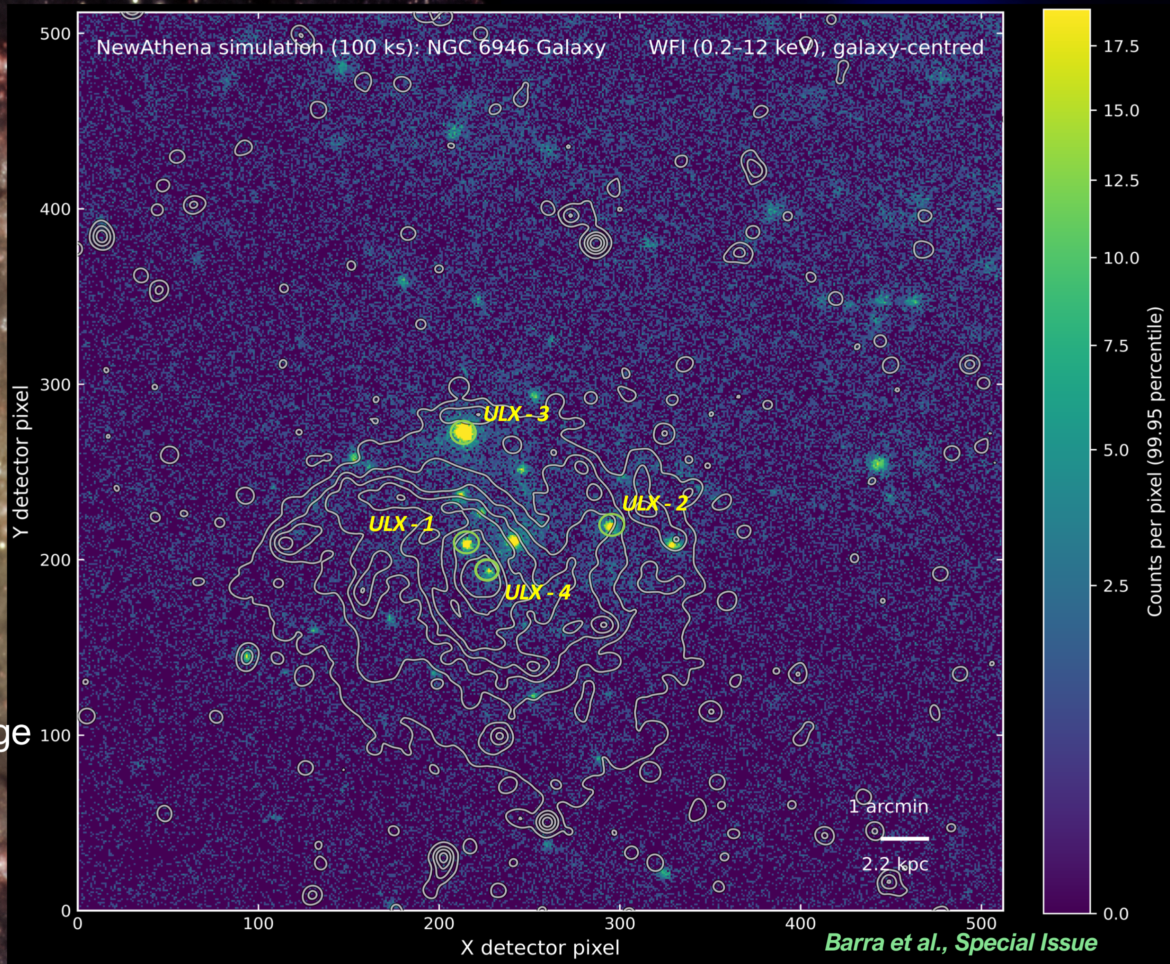


X-ray Integral Field Unit (X-IFU)
ΔE: 4 eV
Field of view: 4 armin
Pixel size: ~ 5 arcsec
Time resolution: 10 us

The NewAthena Era

Fireworks Galaxy





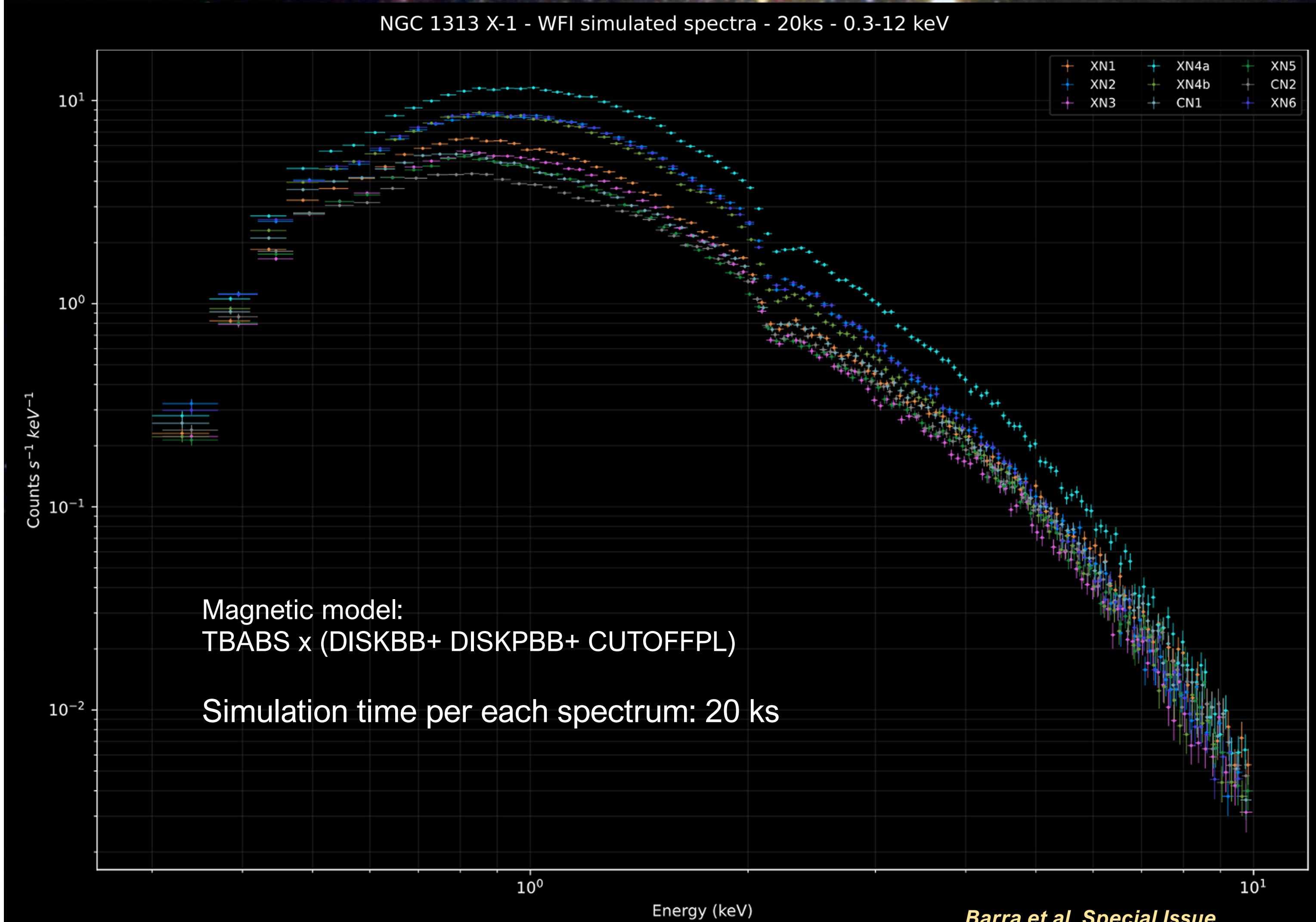
SIXTE simulator, input Chandra image

NewAthena catches and resolve the bright X-ray binaries.

Optical (AURA/Gemini OBs)

X-ray (Chandra)

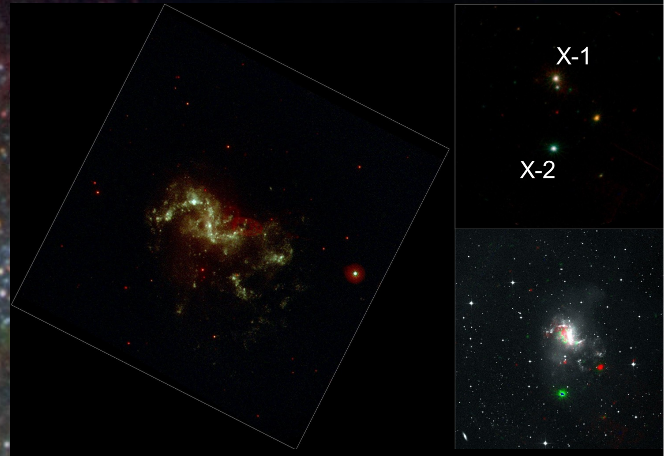
NGC 1313 X-1 broadband spectral shape – WFI



Magnetic model:
TBABS x (DISKBB+ DISKPBB+ CUTOFFPL)

Simulation time per each spectrum: 20 ks

Barra et al, Special Issue

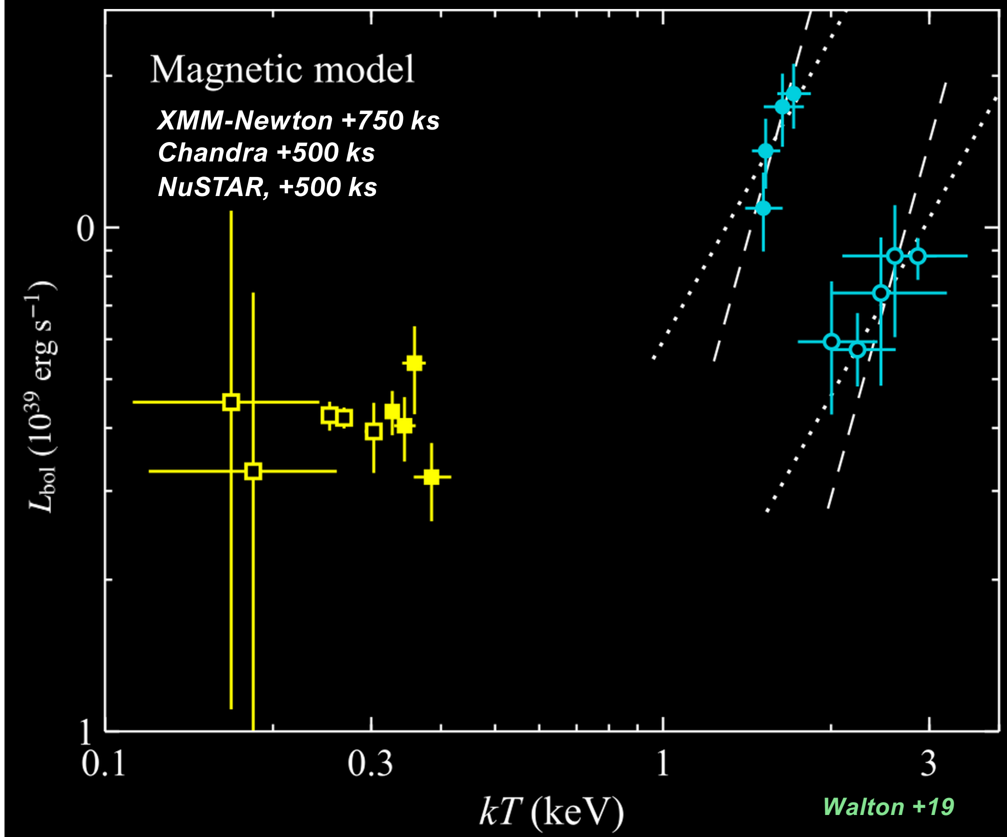


NGC 1313 X-1 ESA/ XMM-Newton image (Optical + X-ray)

Simulation based on the best-fit parameters of magnetic model (Walton +19)

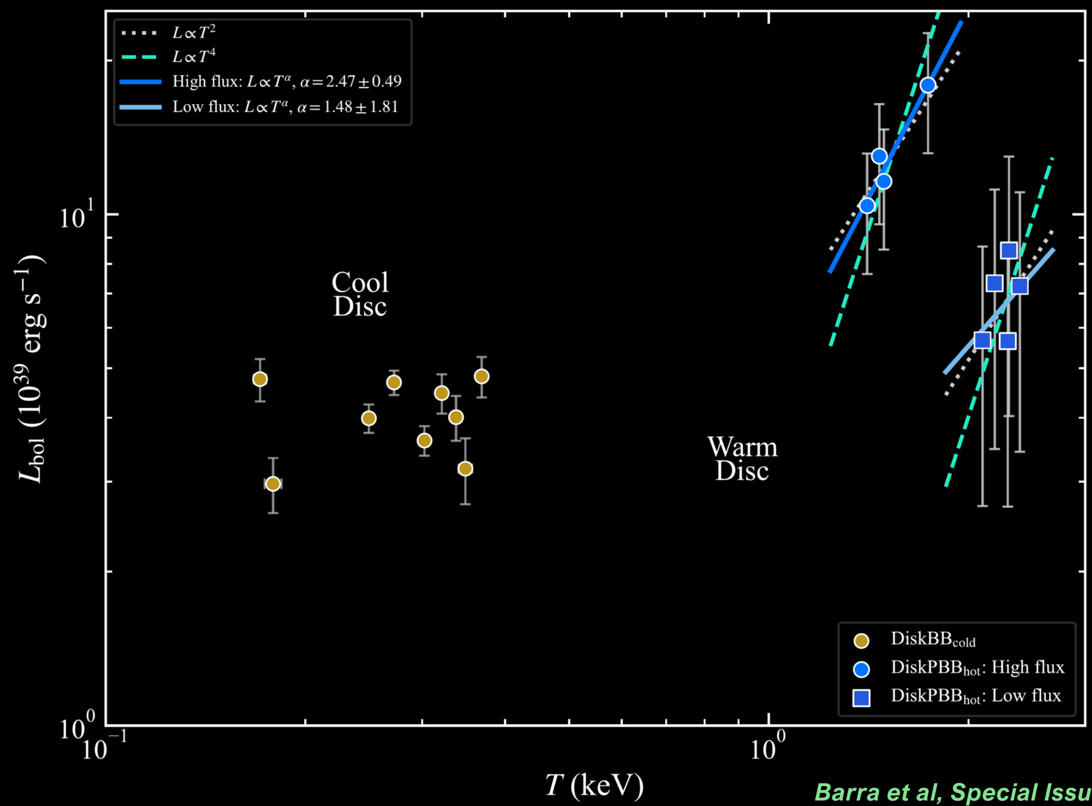
Luminosity temperature plot with NewAthena – WFI vs current facilities

1.75 Ms archival data



Walton +19

NewAthena - WFI simulations, 180 ks

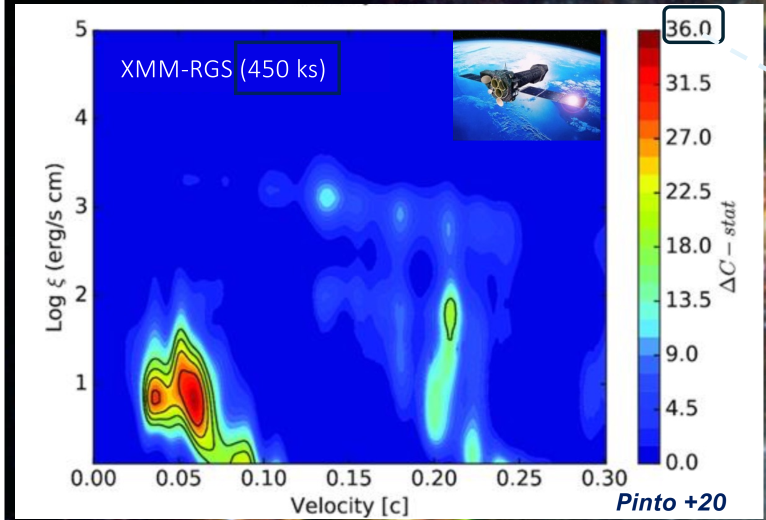


Barra et al, Special Issue

Remarkable deviations beyond 10^{40} erg/s.

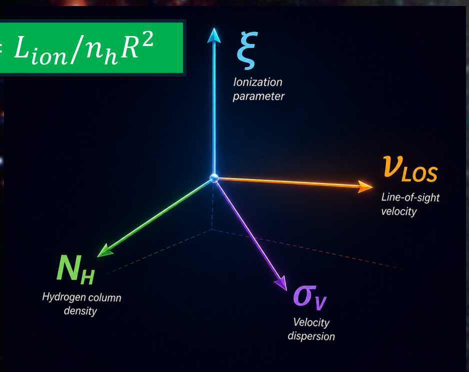
Enables diagnostic for many more ULXs and shorter timescales.

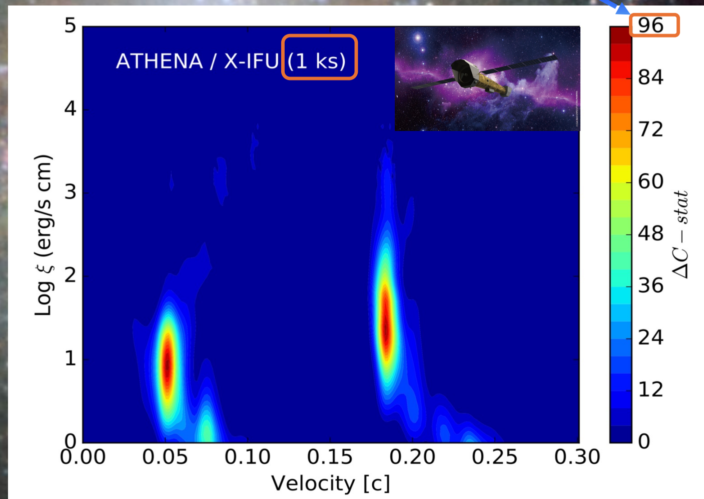
Photoionised scan grids with NewAthena – X-IFU



Exploration of the parameters space for a photoionised plasma in absorption applied on top of the continuum only model (XMM vs Athena)

$\text{Log}\,\mathcal{E} = L_{ion}/n_h R^2$





Enables tracking wind variability on much shorter timescales (1ks)

Take away messages

- **ULXs are powerful laboratories for extreme accretion and feedback**
  They probe super-Eddington accretion, powerful winds, and the impact of compact objects on their surroundings.

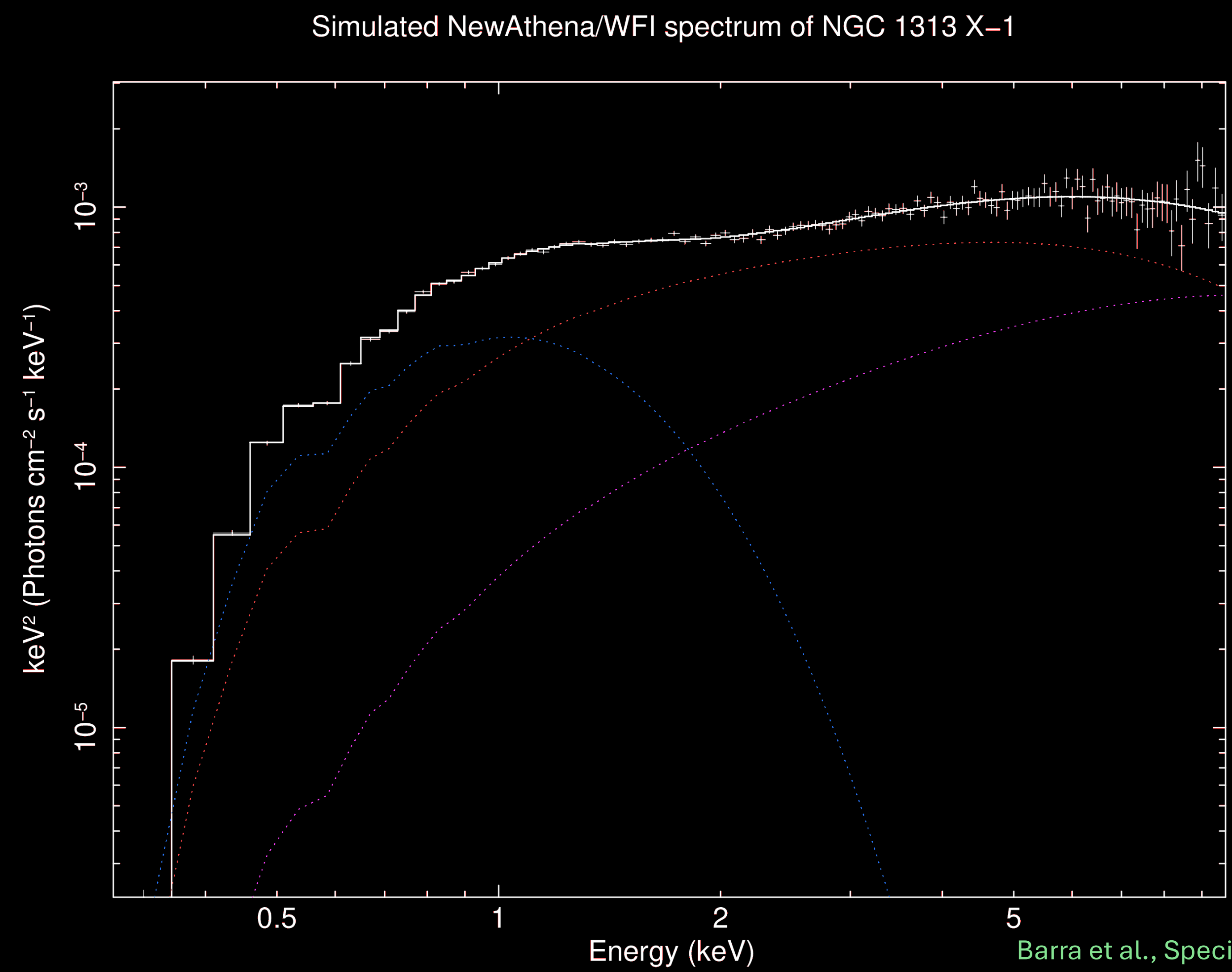
- **Past and current X-ray missions revealed a rich ULX phenomenology**
  ULXs show spectral states, ultrafast outflows, transient pulsations, hard excesses, and complex luminosity–temperature behaviour.

- **Many key questions remain open**
  Is ULX wind variability driven by accretion-rate changes or line-of-sight effects?
  Can L-T trends reveal different accretion geometries in BH and NS ULXs?
  How common are hidden neutron-star ULXs?

- **Current observations are limited by photon statistics and spectral resolution**
  Pulsations are transient and hard to detect, wind studies often require > 100 ks exposures, and L-T relations are measured for only a few ULXs.

- **New missions will transform ULX studies from case studies to population studies**
  NewAthena and future X-ray facilities will enable larger samples, better timing searches, high-resolution wind spectroscopy, and stronger constraints on accretion physics.

Backup Slides



Barra et al., Special Issue

X-IFU NGC 1313 X-1 SIMULATED SPECTRUM (25 ks)