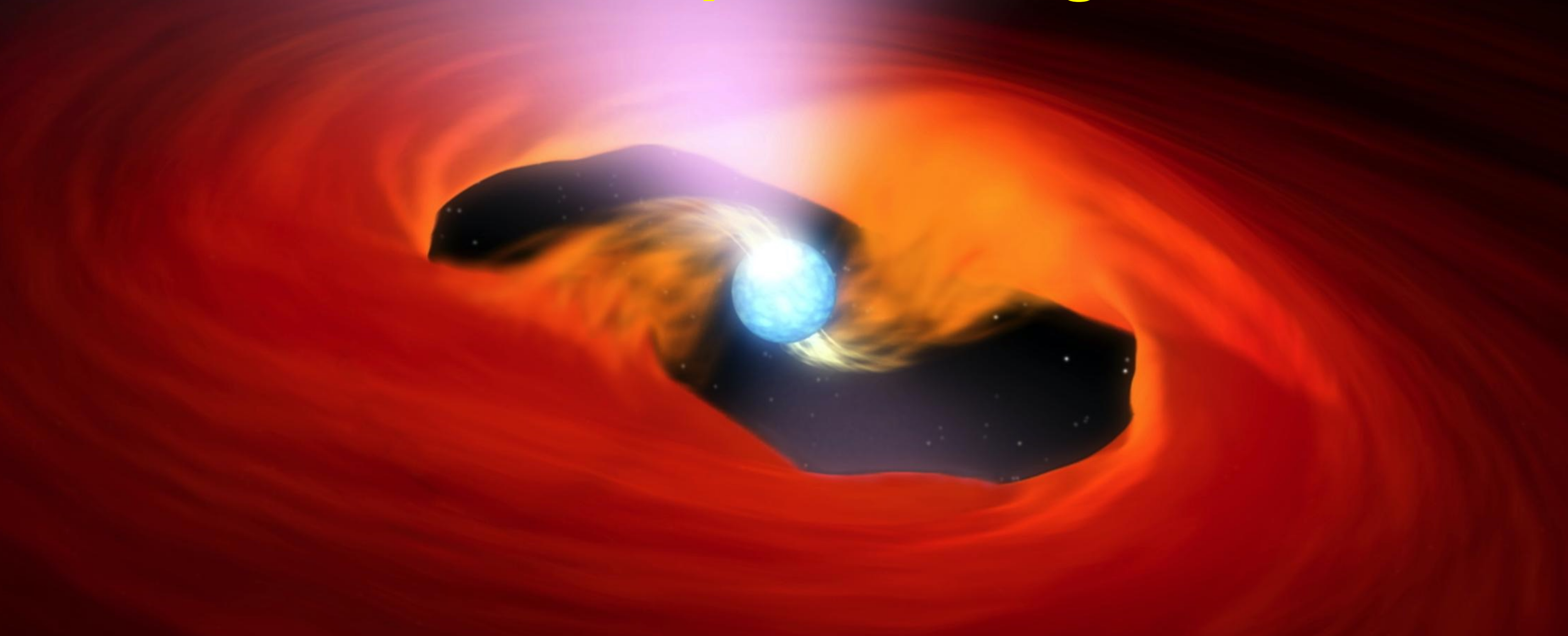
The Extremes of Accretion: Ultraluminous X-ray Sources and Super-Eddington Pulsars



Dom Walton

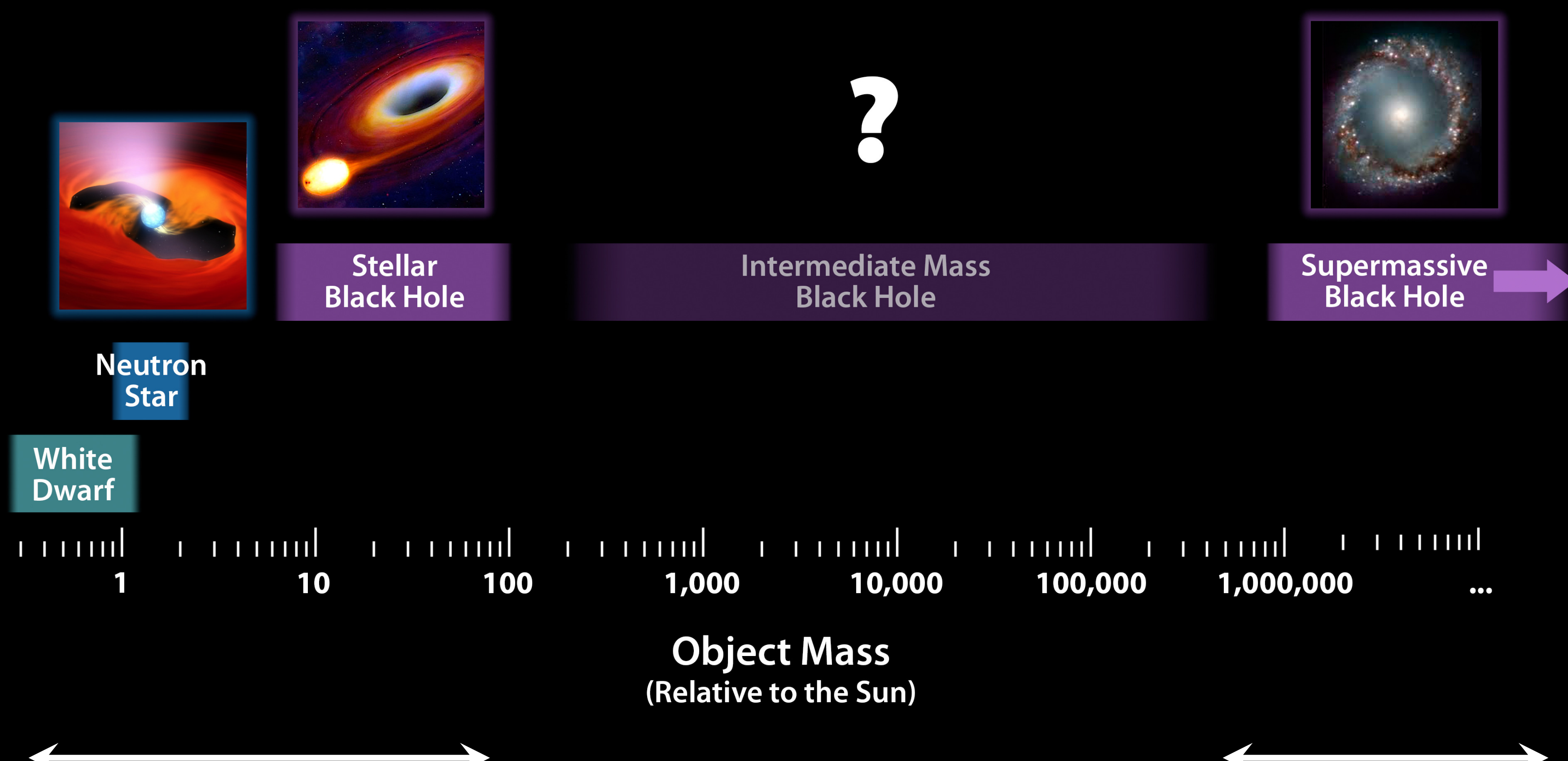
Centre for Astrophysics Research
University of Hertfordshire

University of Hertfordshire UH

Small but Loud

Black Holes and Neutron Stars

Observed Mass Ranges of Compact Objects



Stellar remnants, X-ray binaries

Active galactic nuclei

Ultraluminous X-ray Sources (ULXs)

Ultraluminous X-ray sources (ULXs) are off-nuclear point sources with luminosities in excess of **10^{39} erg s^{-1}** (~L_E for a 10 M_{sun} black hole)

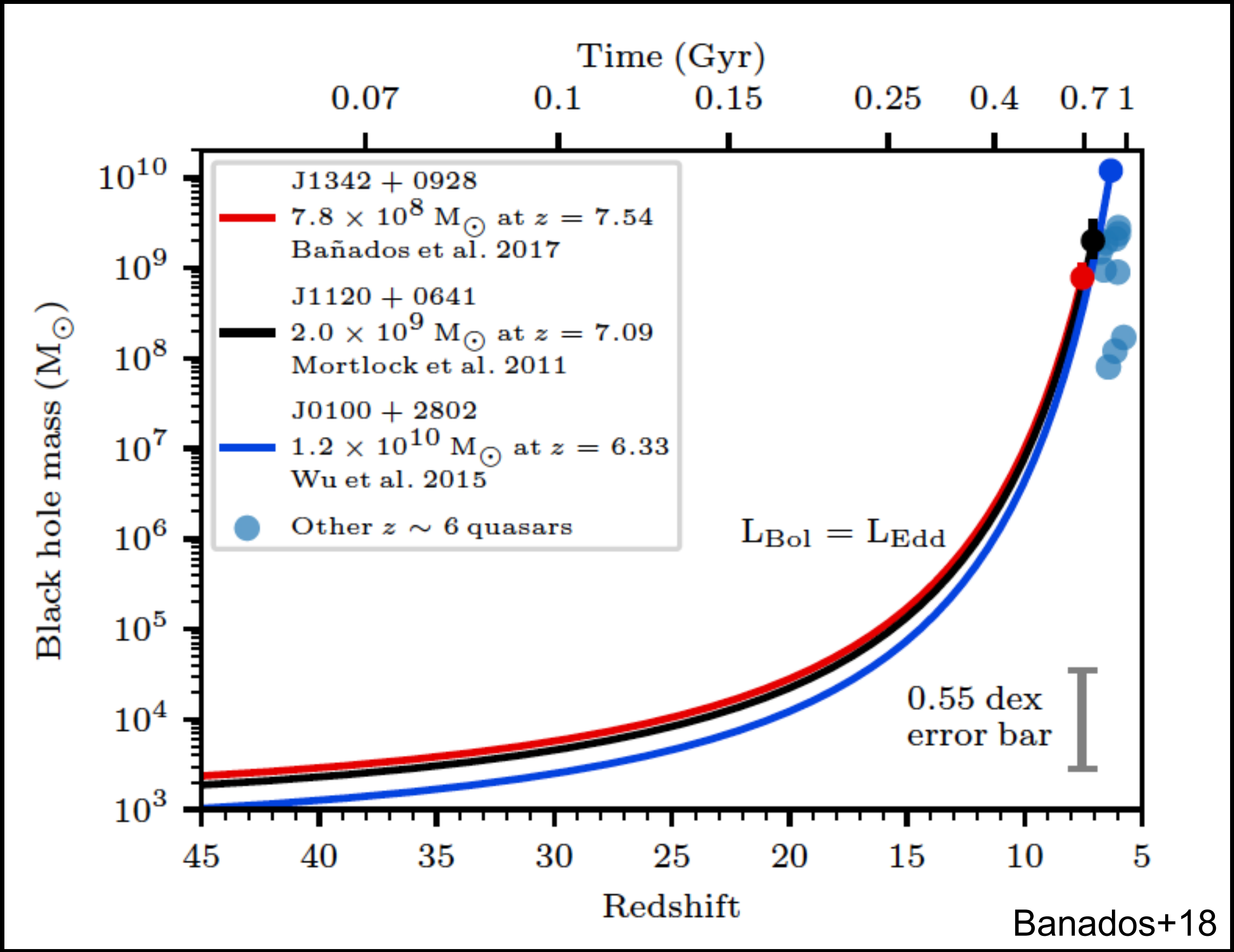
Explanations for these extreme luminosities include:

- Larger black holes (possibly 'intermediate mass' black holes with $M_{BH} \sim 10^{3-4}$ M_{sun})
- Super-Eddington accretion onto stellar remnant black holes

IC 342 in optical, X-rays (*NuSTAR*) in purple

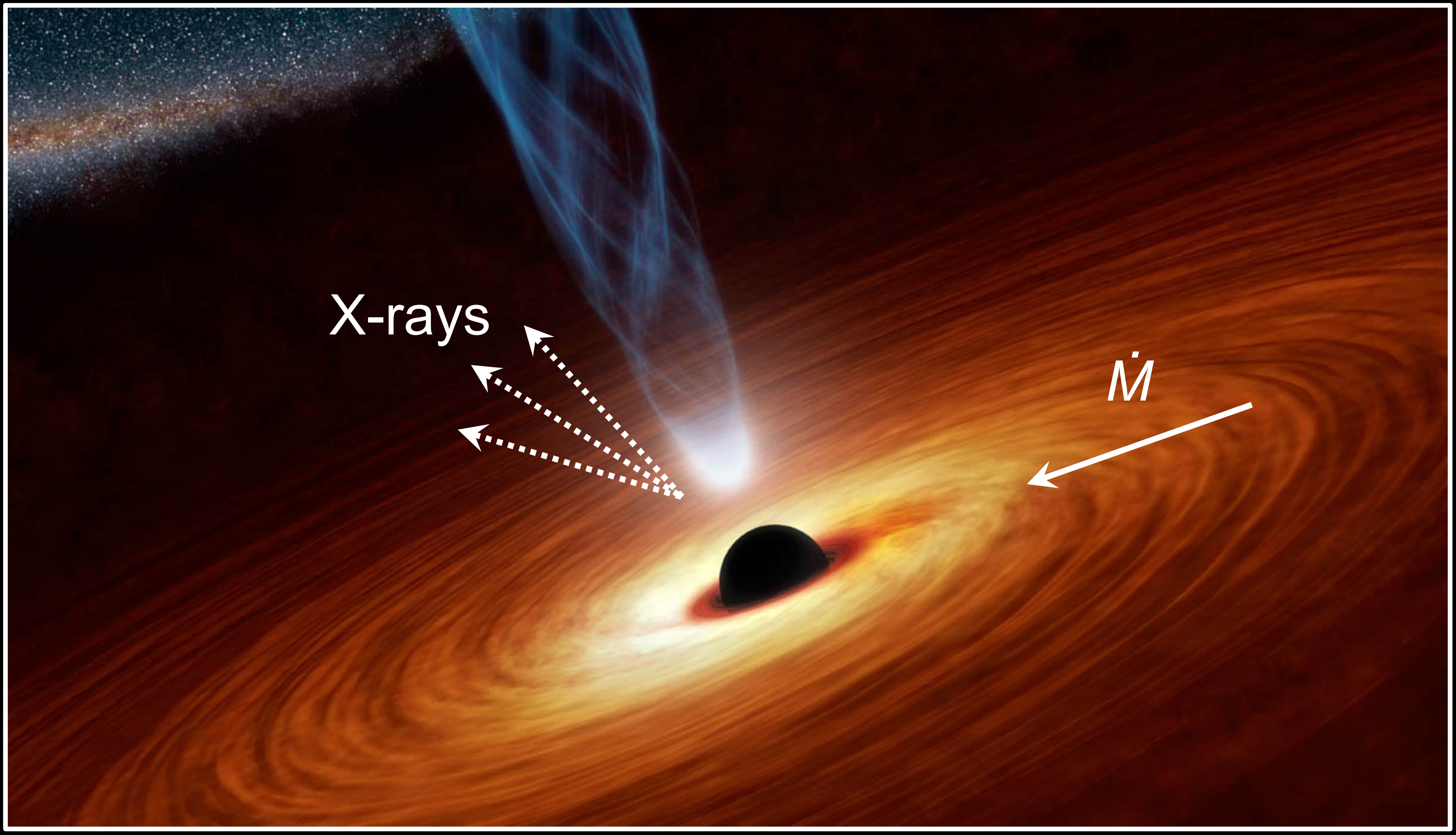
Both possibilities potentially important for understanding SMBH growth

SMBH Growth



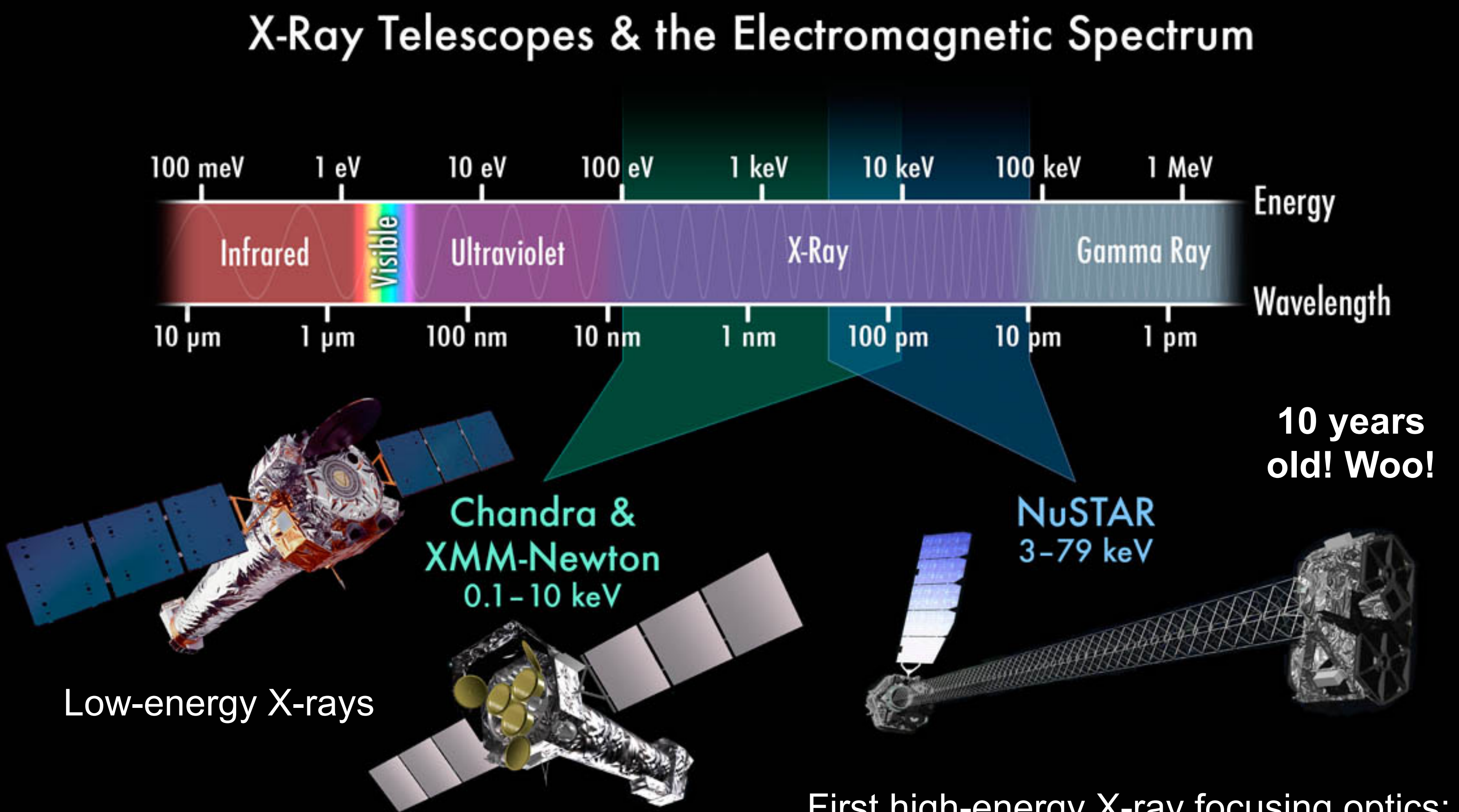
Growing the SMBHs now being observed at high redshift may require accretion at super-Eddington rates and/or large 'seed' BHs

Black Hole Accretion



Black hole accretion thought to be ‘scale-invariant’

X-ray binary ⟷ active galaxy



10 years old! Woo!

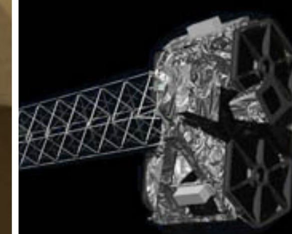
Low-energy X-rays

First high-energy X-ray focusing optics: unprecedented broadband sensitivity

X-Ray Telescopes & the Electromagnetic Spectrum

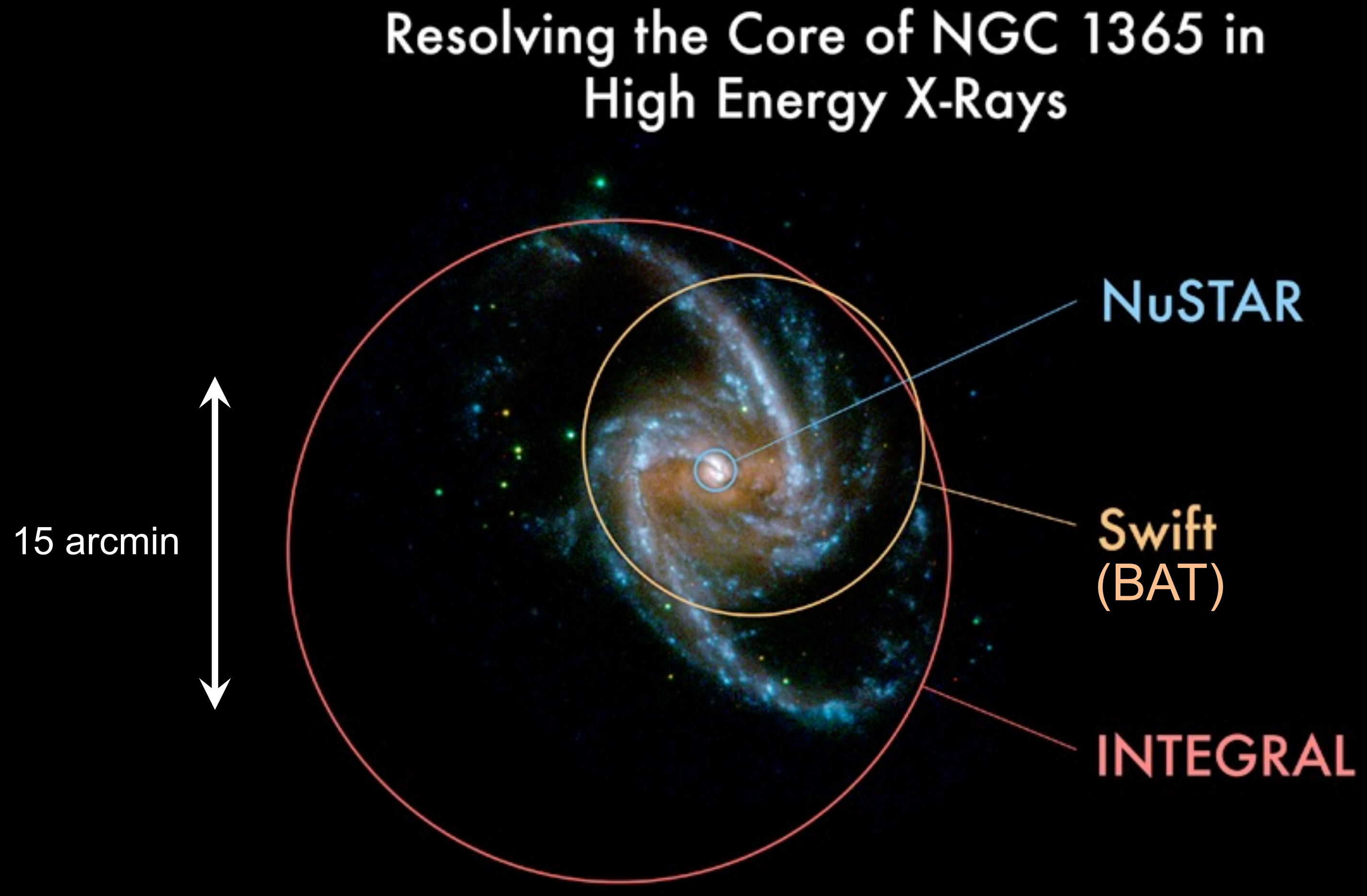
10 years old! Woo!

Low-energy X



focusing optics:
band sensitivity

NuSTAR and ULXs



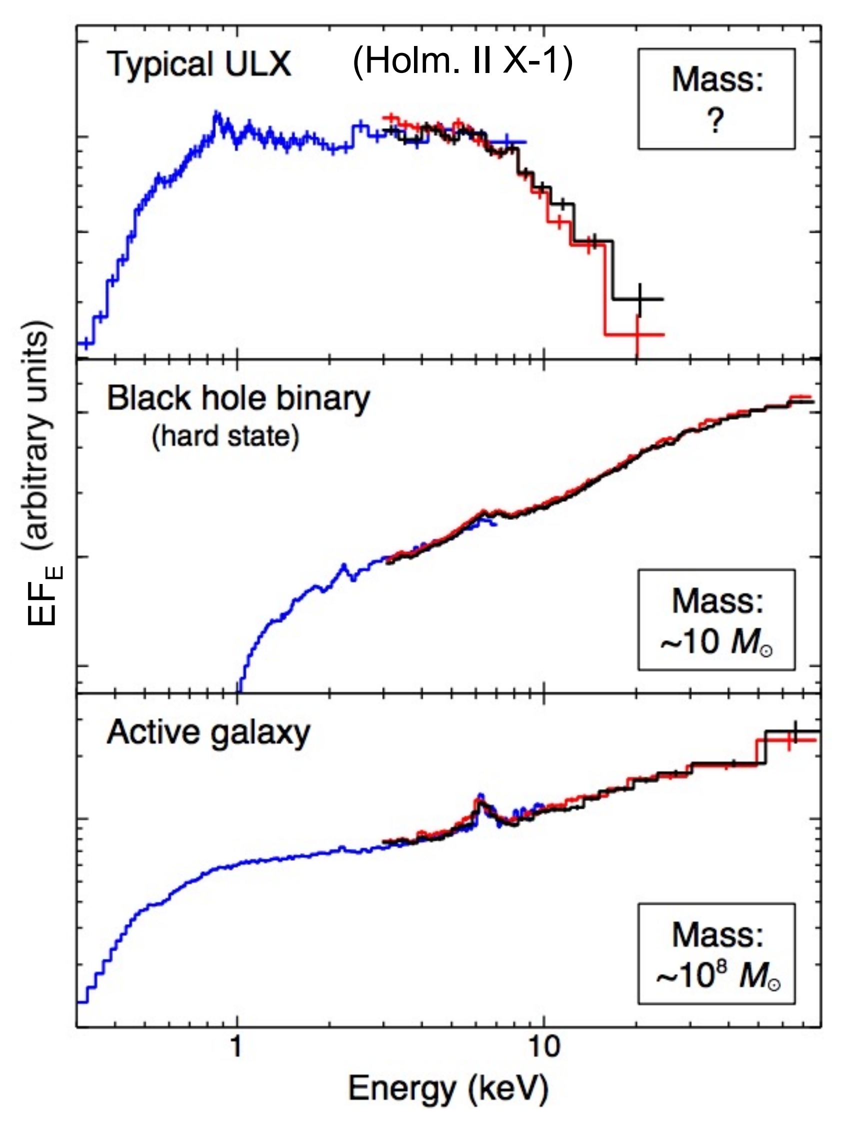
Previous high-energy X-ray detectors integrated over entire galaxies,
i.e. cannot resolve ULXs

Holmberg II X-1

- Performed a series of coordinated *XMM*+*NuSTAR* observations of ULXs soon after launch (e.g. Holmberg II X-1, $L_X \sim 10^{40}$ erg/s)

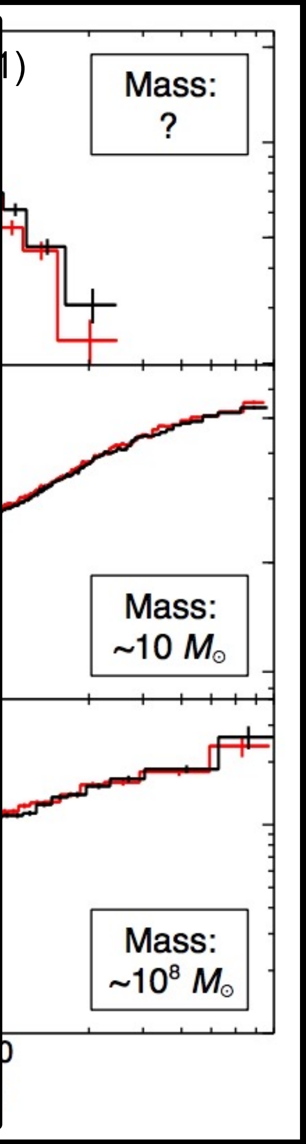
- *NuSTAR* data shows the spectrum >2 keV is not a powerlaw, the basic expectation for an IMBH (e.g. Walton+2015a)

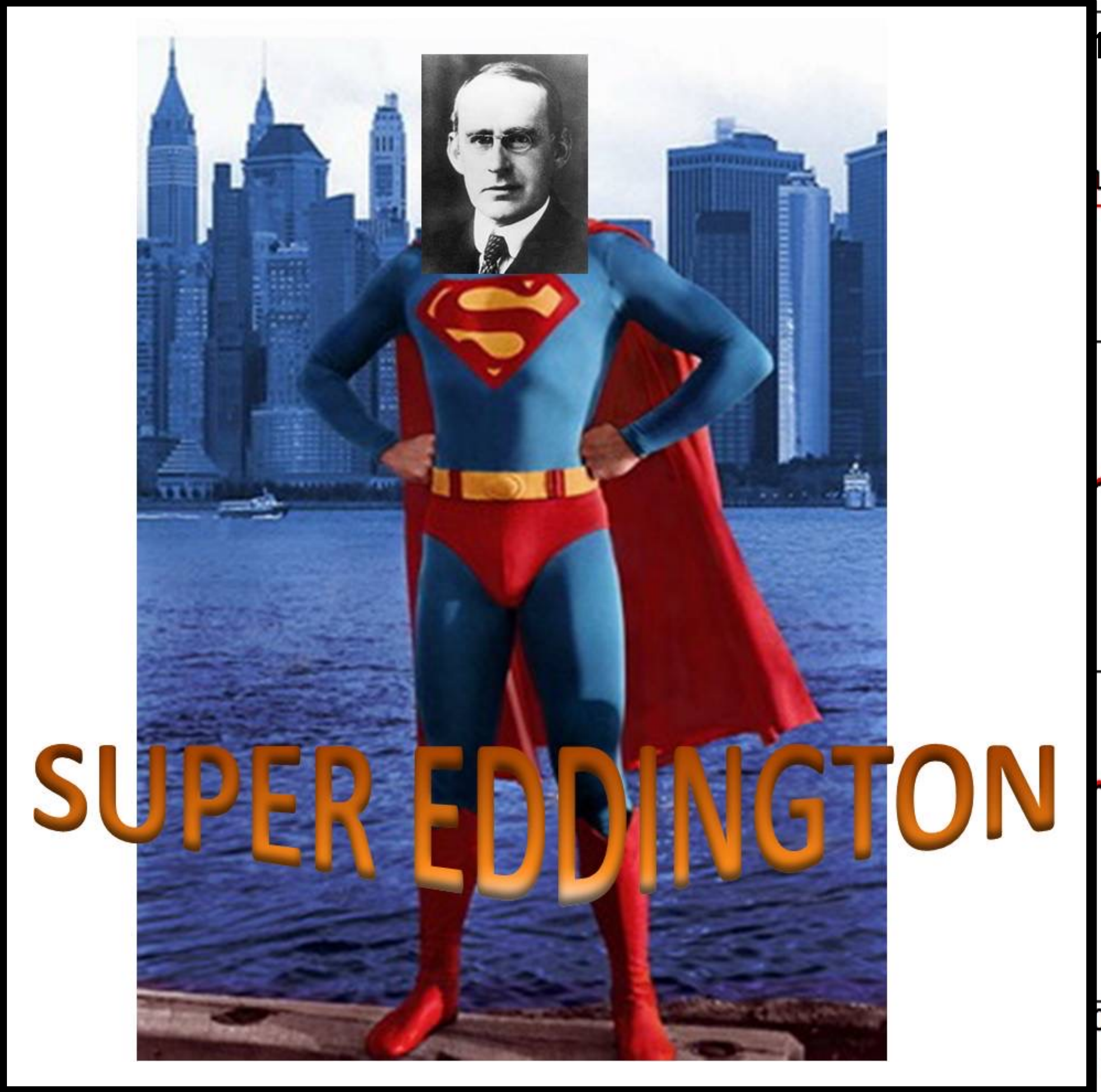
- Confirms high-energy curvature hinted at by the best available *XMM* data (e.g. Gladstone+09)

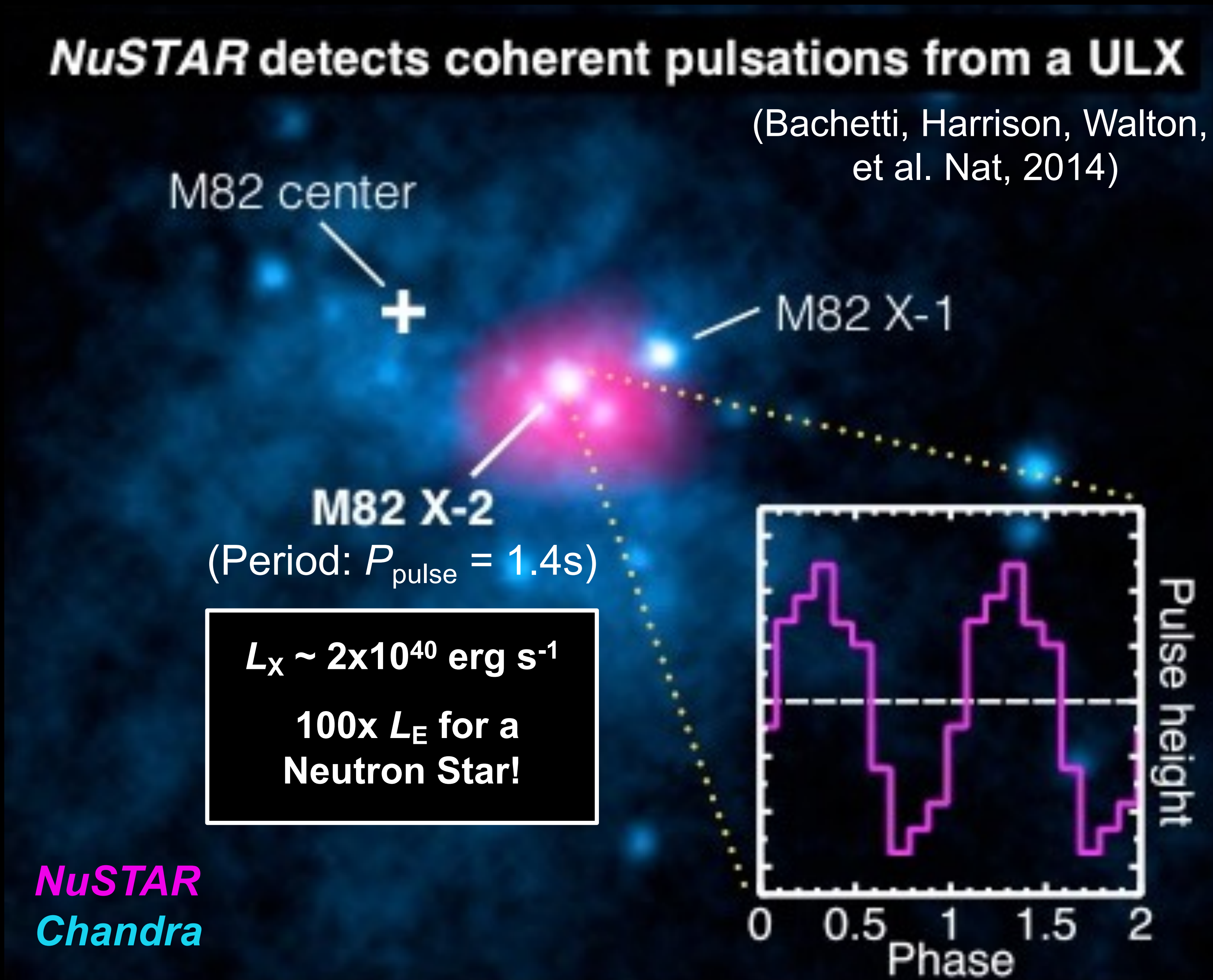


Holmberg II X-1

- Performed coordinate observatio after launc X-1, L_X ~ 1
- *NuSTAR* d spectrum > powerlaw, expectatio (e.g. Walto
- Confirms h curvature h best availa (e.g. Glads






NuSTAR detects coherent pulsations from a ULX
(Bachetti, Harrison, Walton, et al. Nat, 2014)
M82 center
M82 X-1
M82 X-2
(Period: P_{pulse} = 1.4s)
L_X ~ $2x10^{40}$ erg s^{-1}
100x L_E for a Neutron Star!
NuSTAR
Chandra
Pulse height
0
0.5
1
1.5
2
Phase

M82 X-2

Bachetti+14

$L_{X,\ peak}$ ~ 2×10^{40} erg/s

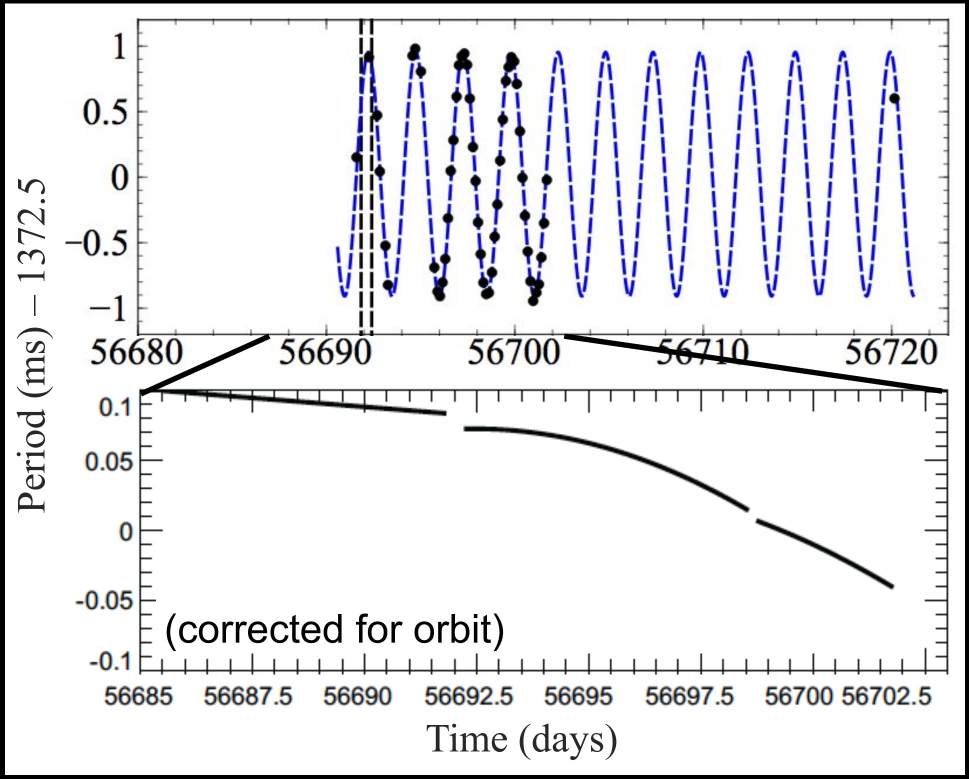
This is ~*100x* L_E for a neutron star!

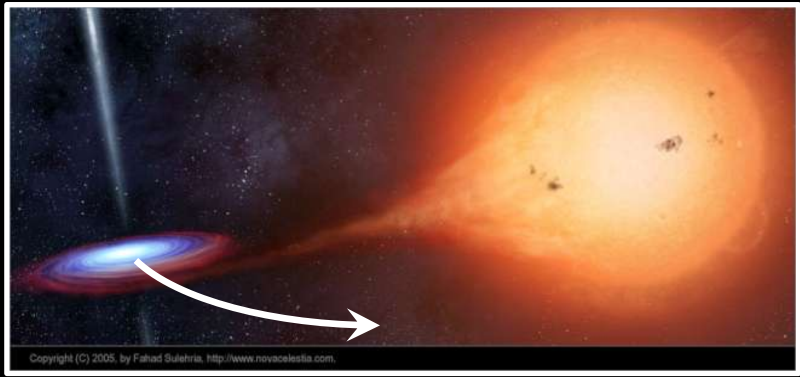
(Also >10x brighter than any other neutron star known at the time)

Variations in ***pulse*** period revealed an ***orbital*** period of 2.5 days

Stellar companion is a star of mass $M > 5.2\ M_{sun}$

Neutron star is spinning up





Key Open Questions

1. How many of these sources are there? (Demographics)

2. How are such extreme luminosities possible? (Accretion physics)

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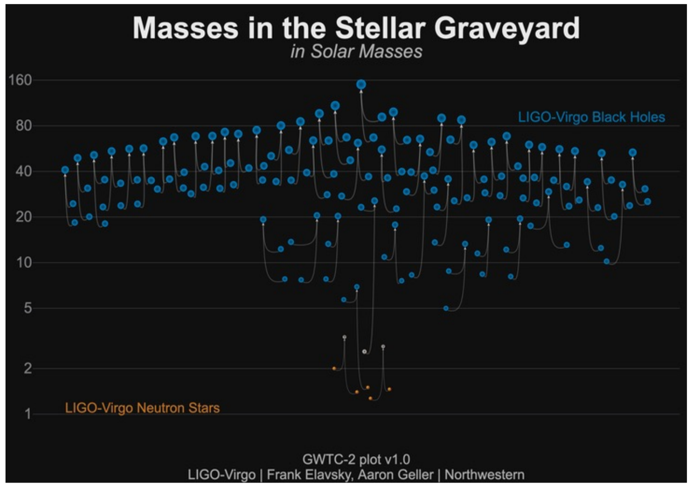

X-ray populations, binary evolution

SMBH growth, galaxy evolution

ULX Pulsars: A Growing Sample

Current sample of known ULX pulsars:

Source	P_{spin} (s)	$L_{X,peak}$ (10^{39} erg/s)	Discovery Reference(s)
M82 X-2	1.4	20	Bachetti+14
NGC7793 P13	0.4	15	Furst+16, Israel+17a
NGC5907 ULX1	1.1	100	Israel+17b
NGC300 ULX1	17**	4	Carpano+18
NGC1313 X-2	1.5	10	Sathyaprakash+19
M51 ULX-7	2.8	10	Rodriguez Castillo+20

** Latest measurement, extreme changes in P_{spin} seen here; see Vasilopoulos+19

(**Note**: $L_E \sim 2 \times 10^{38}$ erg/s for a 1.4 M_{sun} neutron star)

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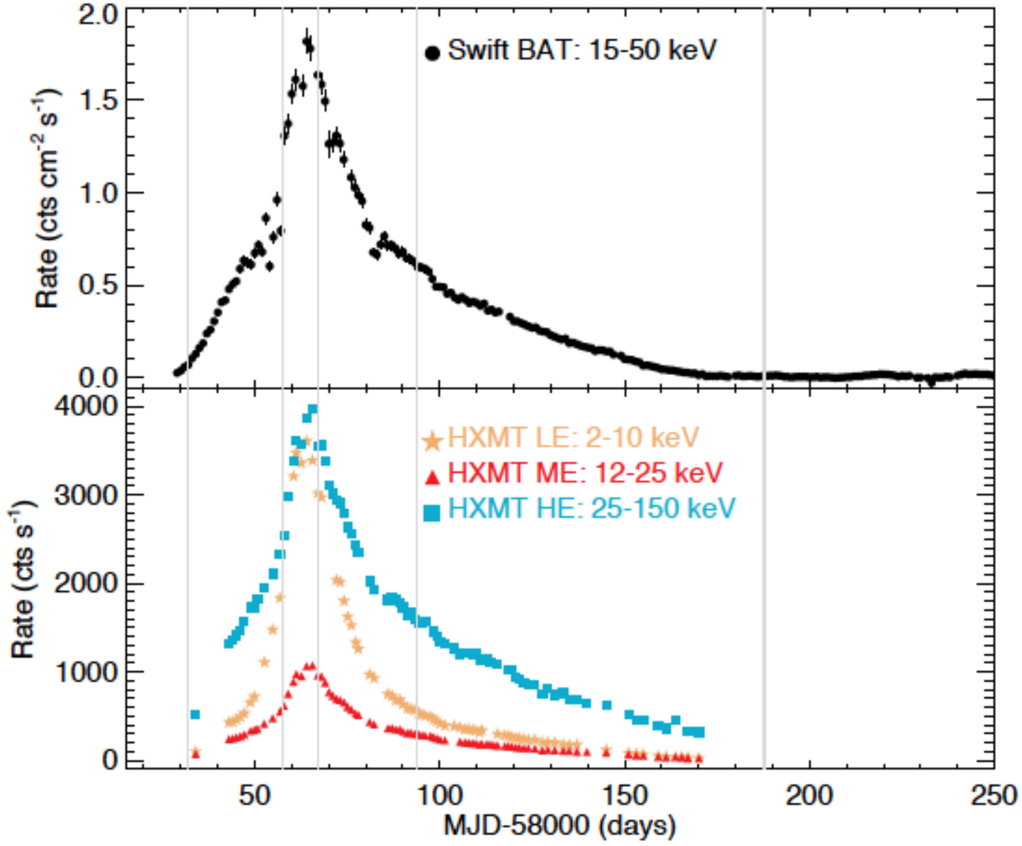
ULX Pulsars: A Growing Sample

c

Honourable mention: Swift J0243.6+6124 (and friends)



Galactic Be/X-ray binary

Pulsar with P ~ 9.8s

Distance updated by *Gaia* DR2:
$D \sim 2.5 \longrightarrow 7$ kpc

↓

$L_{X,peak} \sim 10^{39}$ erg s^{-1}

Wilson-Hodge+18, Doroshenko+18, van den Eijnden+18,19, Tao+19

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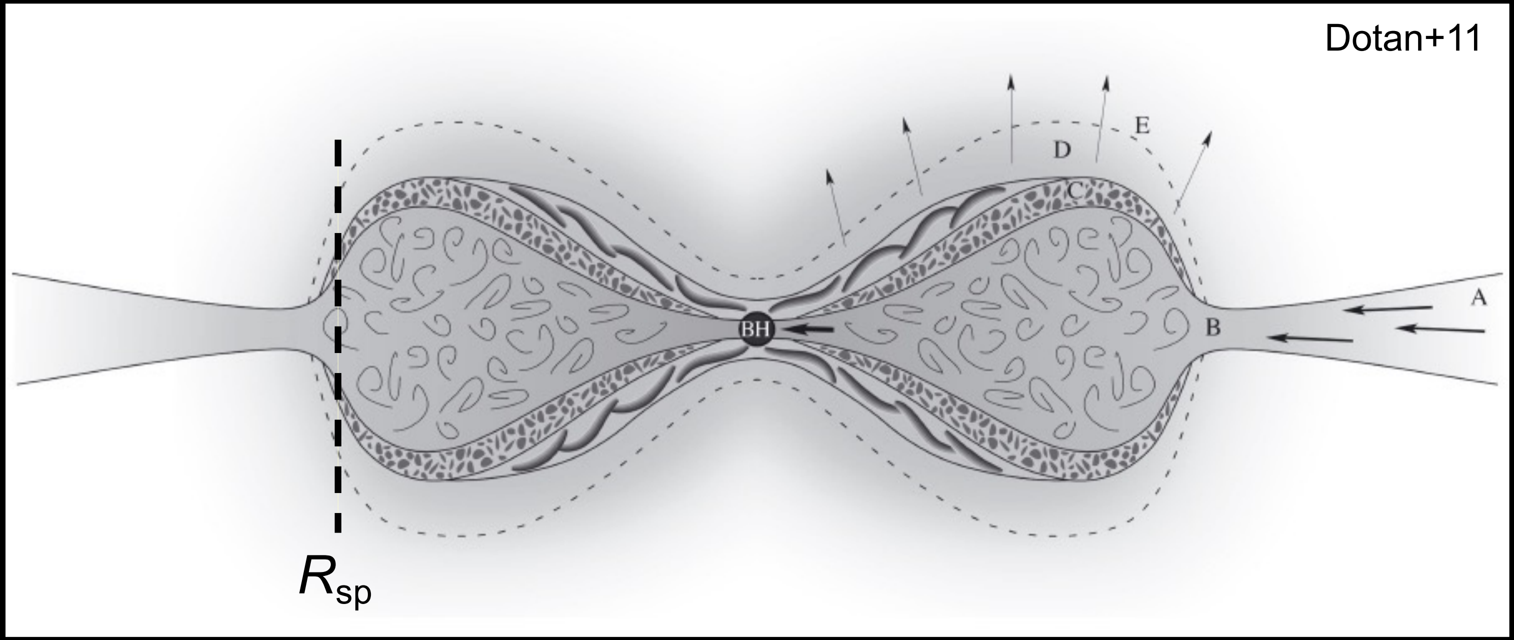
Super-Eddington Accretion

- Possible to exceed the Eddington limit, L_E, for disk accretion (non-spherical geometry gives radiation avenues to escape; Shakura+73)
- Innermost flow becomes dominated by radiation pressure and thickens (‘slim’ disc); transition occurs at the ‘spherization’ radius, R_{sp}, defined as $L(R > R_{sp}) = L_E$
- Supported by MHD sims (Ohsuga+11)



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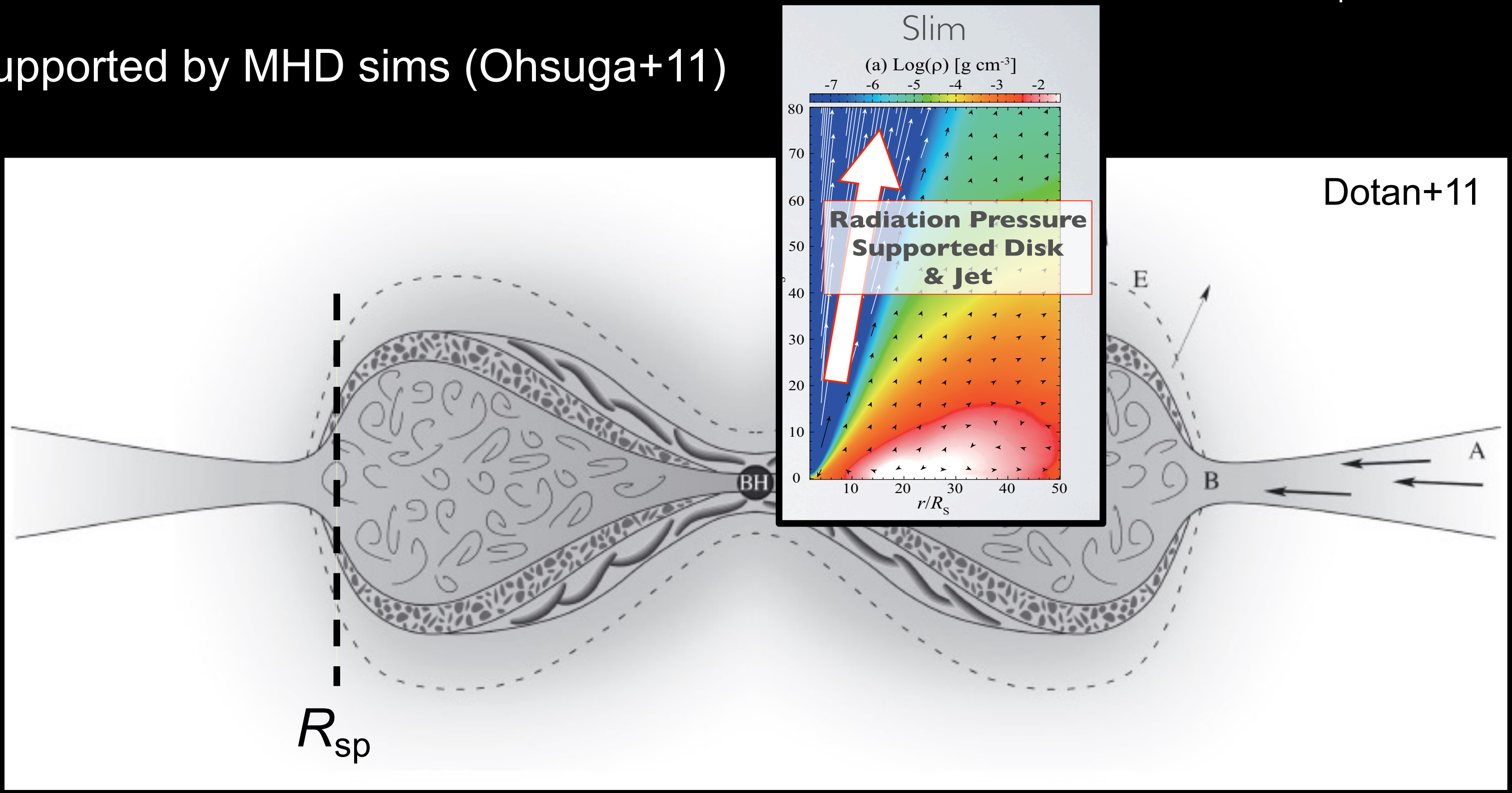
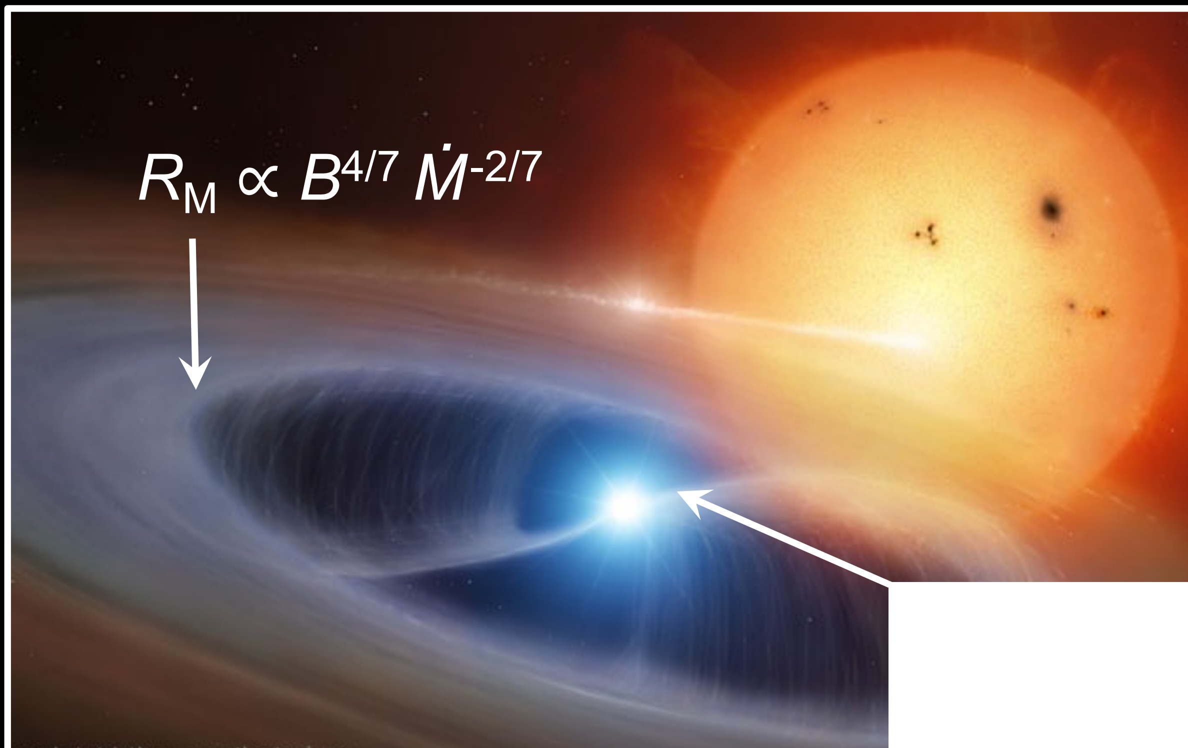
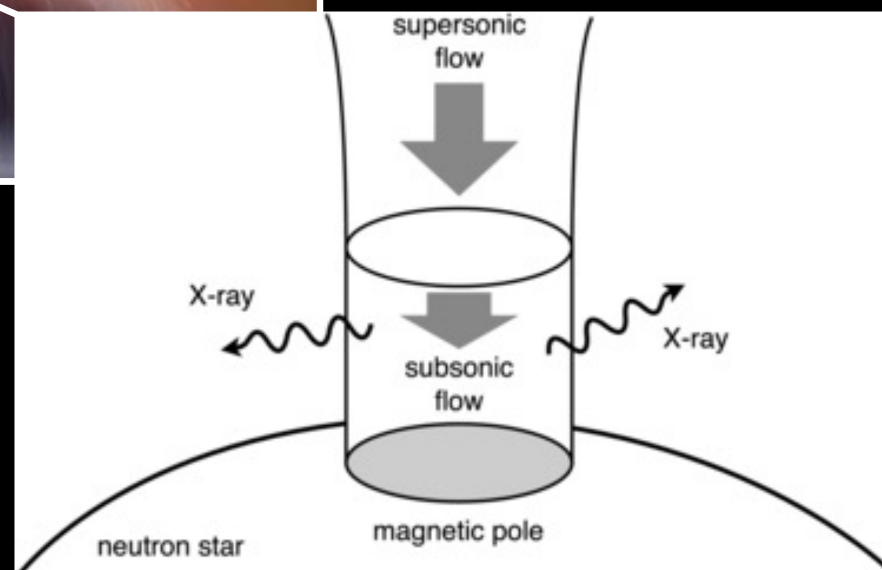


Magnetic Accretion

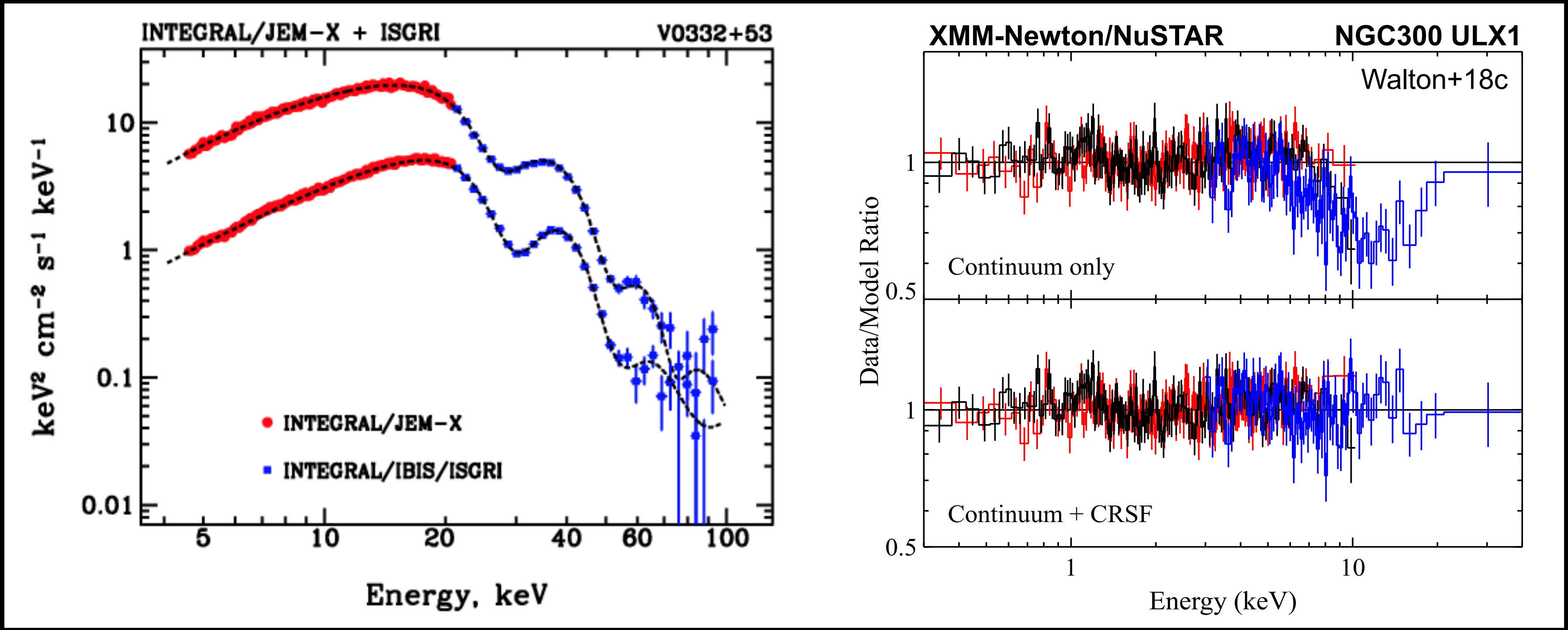


For X-ray pulsars, the magnetic field (B) of the neutron star eventually truncates the disc (magnetosphere), and material accretes via magnetically-channelled accretion 'columns'



Provided that $R_M < R_{sp}$, disc structure outside of R_M should be broadly similar to the black hole case (i.e. thick, inner disc forms)

NGC300 ULX1 – Cyclotron Line?



Potential CRSF in NGC300 ULX1; these offer the most robust way to measure NS *B*-field

E_{cyc} ~ 13 keV implies B ~ 10^{12} G, typical of accreting Galactic X-ray pulsars; **consistent with $R_M < R_{sp}$**

(***Note***: other potential ULX CRSF in M51 ULX8 suggested to be a proton line at ~4.5 keV based on *Chandra* data, implying B ~ 10^{15} G; Brightman+18)

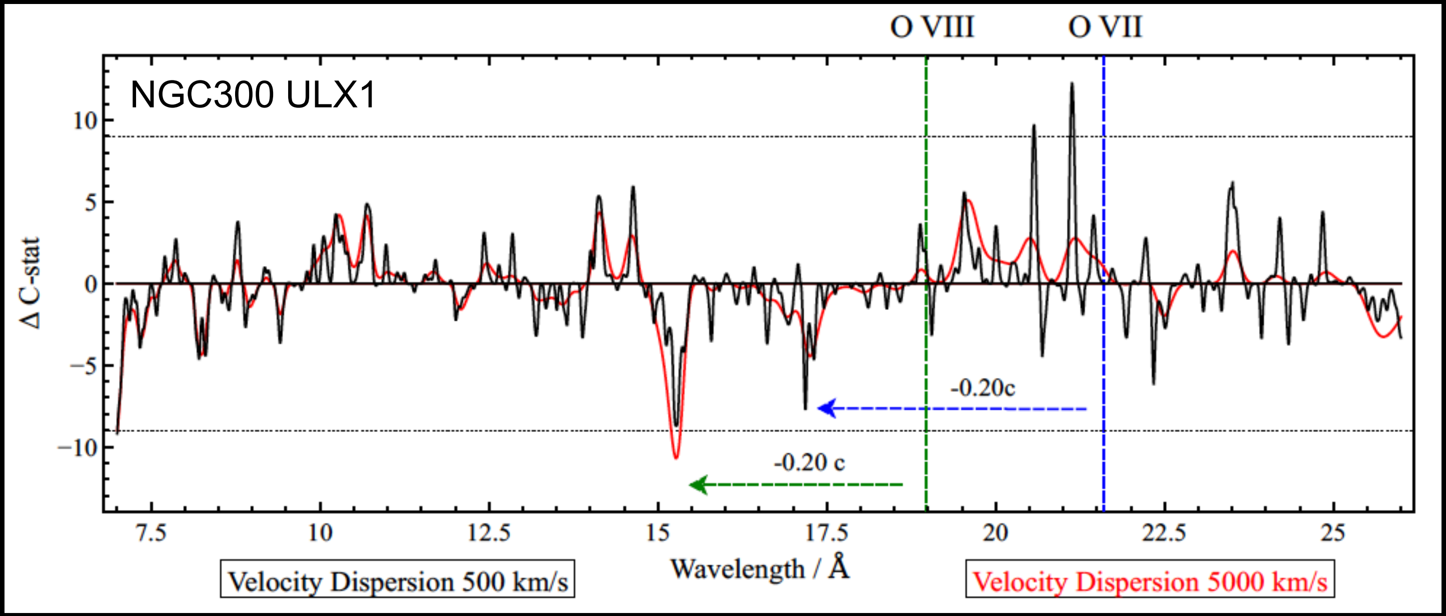
Powerful Outflows

Extreme outflows (v_{out} ~ 0.1-0.3c) now seen via blueshifted absorption in a few ULXs

(Pinto+16,17,20,21, Kosec+21; occasionally incl. Fe K via *NuSTAR*, Walton+16)

Now includes one of the ULX pulsars – NGC300 ULX1 (v_{out} ~ 0.2c; Kosec+18)

(detected at the ~4σ level, based on MCMC sims)



Also suggests inner super-Eddington disc ***does*** form (i.e. $R_M < R_{sp}$)

Long-Term, Multi-Epoch Programs

In order to understand the accretion in these extreme systems, we have been executing long-term, multi-epoch studies of known ULX pulsars combining deep observations with *XMM-Newton* and *NuSTAR* and monitoring with *Swift*

NGC7793 P13, NGC5907 ULX1 and M82 X-2 have been particularly key targets:

NGC7793 P13:

- *XMM-Newton* – 17 obs
- *NuSTAR* – 12 obs
- *Swift* – weekly monitoring since 2016

} 4x coordinated (XMM-Newton and NuSTAR)

NGC5907 ULX1:

- *XMM-Newton* – 31 obs
- *NuSTAR* – 13 obs
- *Swift* – weekly monitoring since 2014

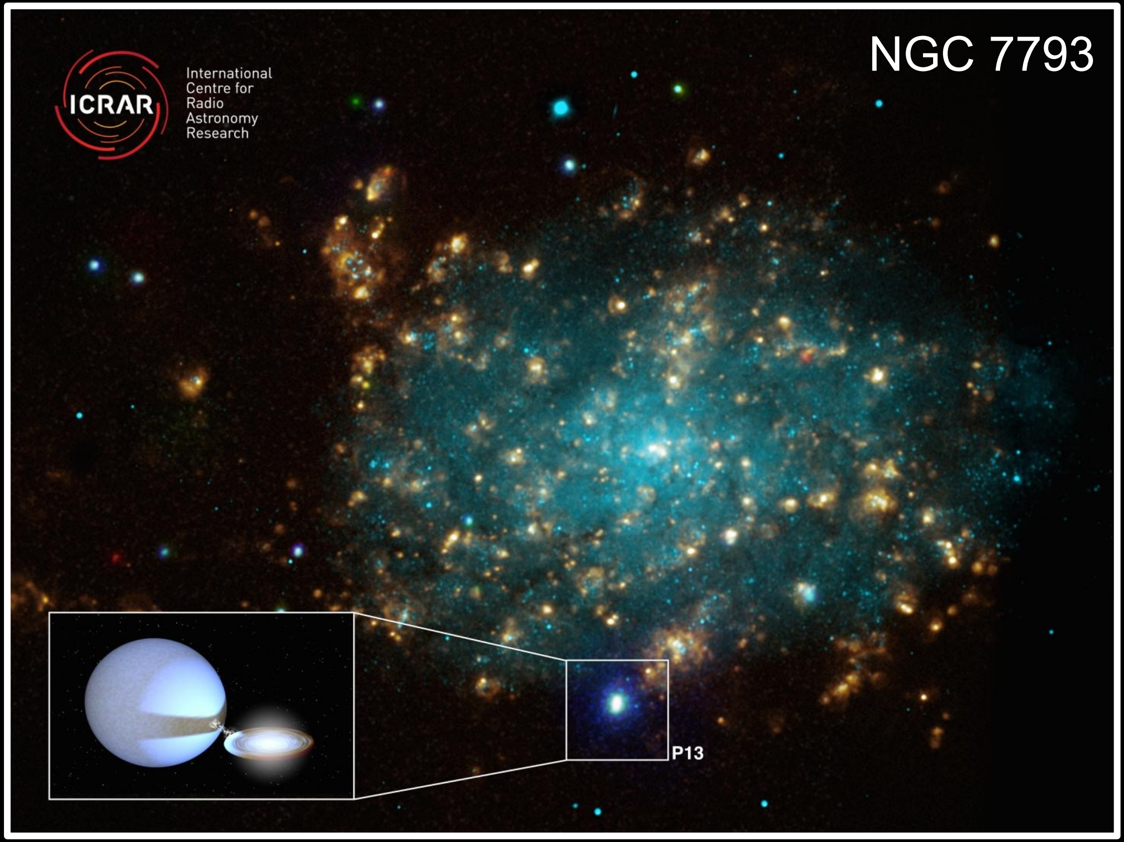
} 10x coordinated (XMM-Newton and NuSTAR)

M82 X-2:

- *XMM-Newton* – 15 obs
- *NuSTAR* – 27 obs
- *Swift* – weekly monitoring 2012-2020

} 4x coordinated (XMM-Newton and NuSTAR)

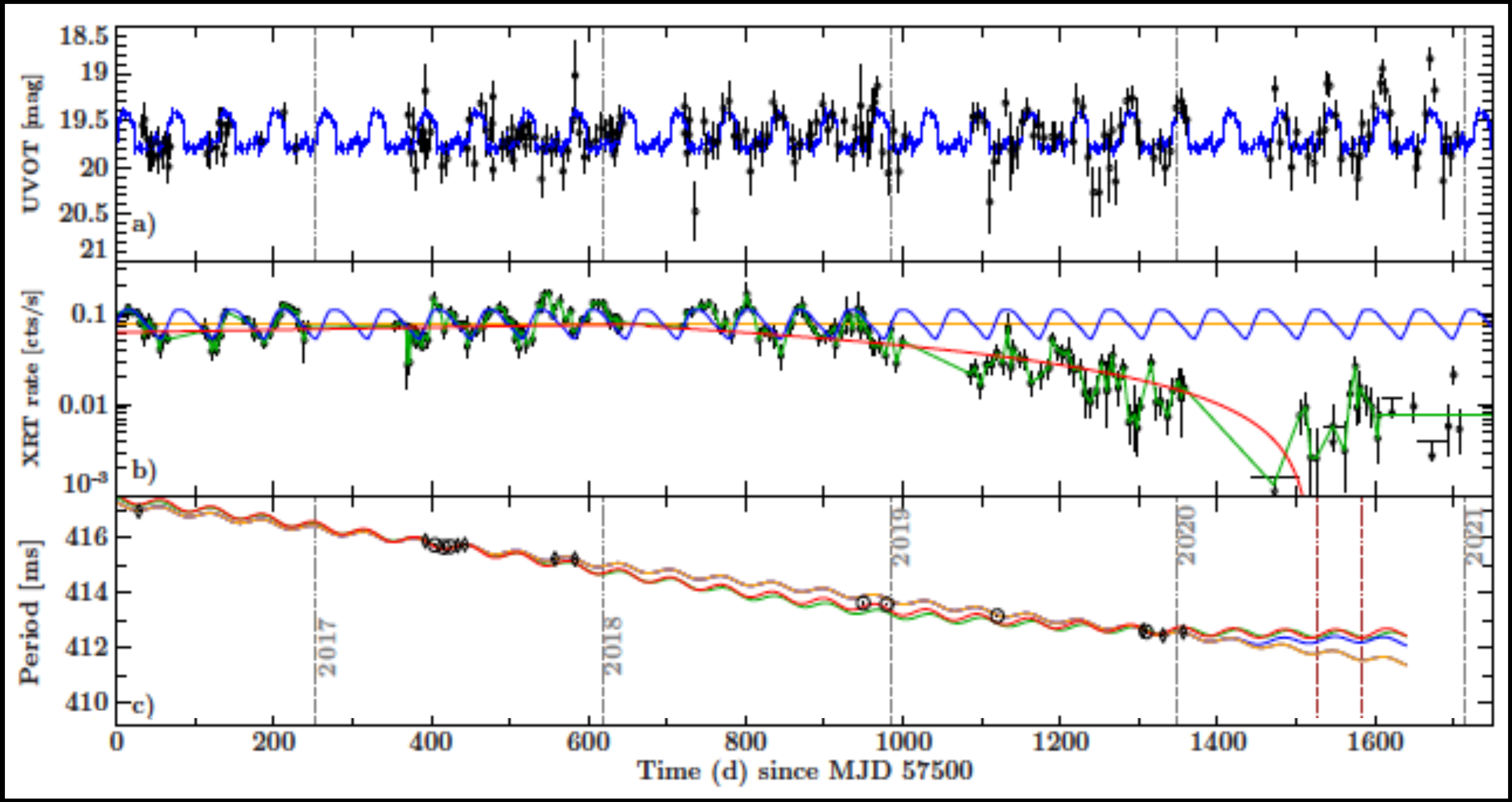
NGC7793 P13



- $L_{X,peak}$ ~ 1.5 x 10^{40} erg/s
- Current P_{spin} ~ 0.4s
- B9Ia (blue supergiant) companion, P_{orb} ~ 65d (Motch+14)
- Pulsations essentially always seen (when bright)

NGC7793 P13 – Spin Evolution

Fürst+21

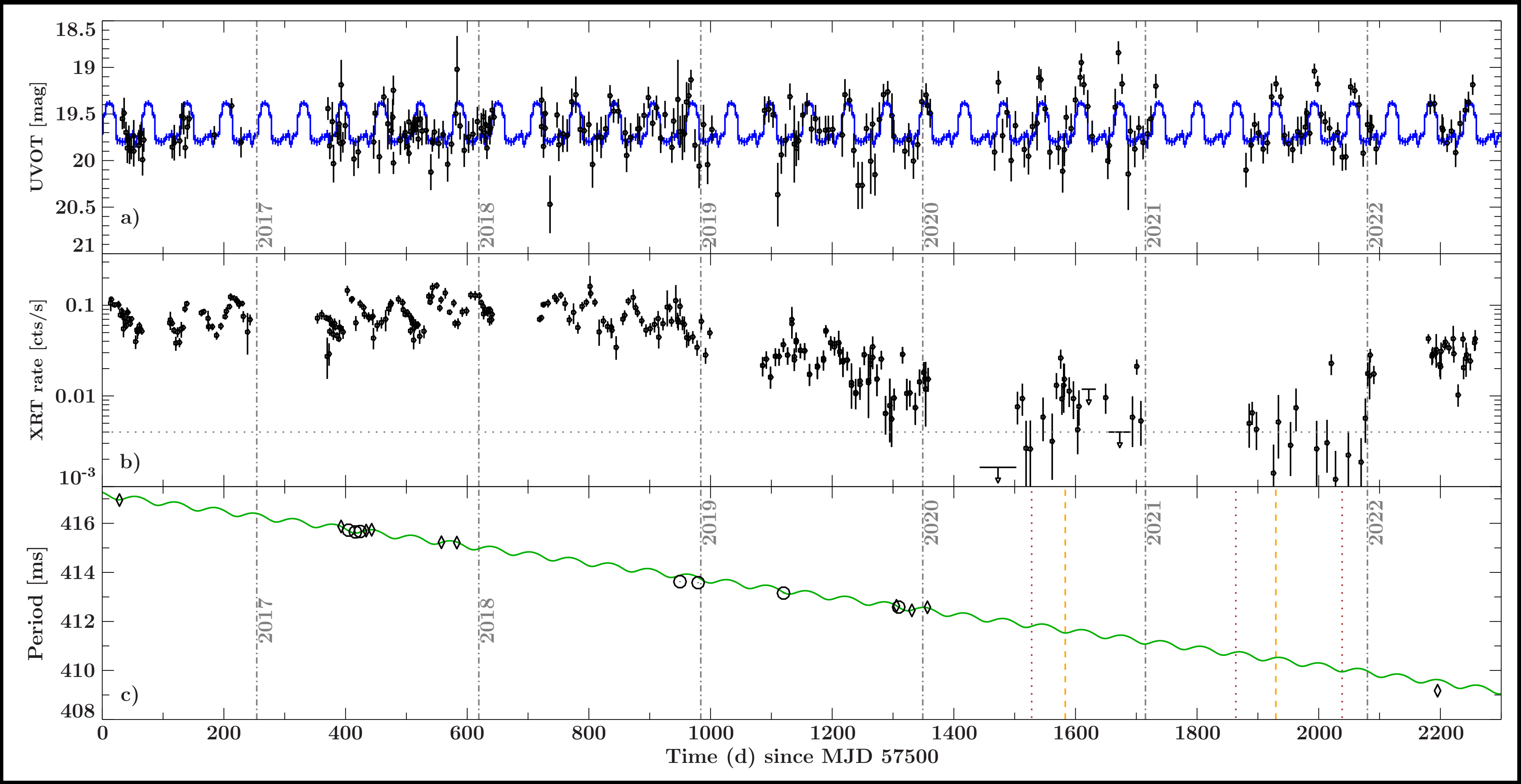


Models for spin-period evolution includes both orbit and secular spin-up

Best fit model prefers ~constant spin-up of $\dot{P} = 4.0\times10^{-11}\ s/s$ despite changes in flux; similar behaviour also seen in NGC 300 ULX1 (Vasilopoulos+19)

Secular spin-up implies $B \sim 10^{12}$ G (Furst+18, based on GL79); consistent with $R_M < R_{sp}$

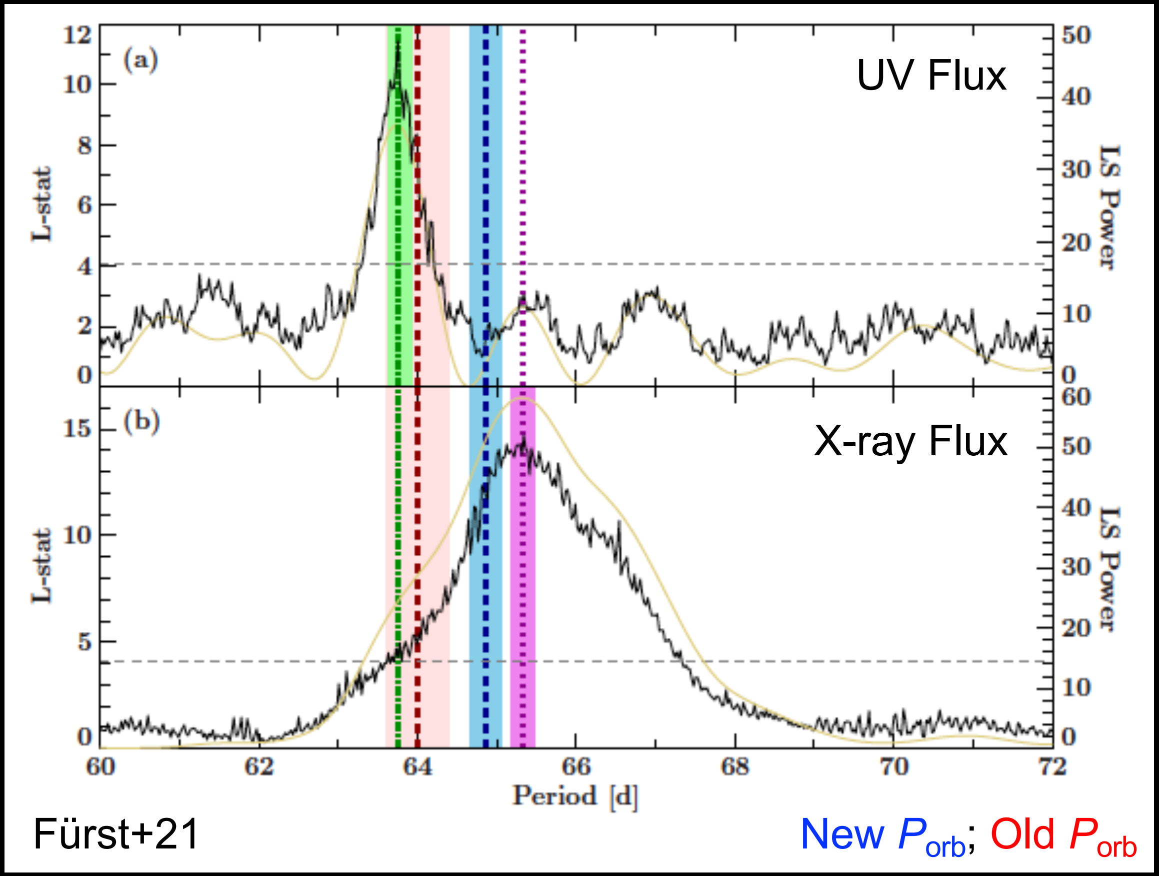
NGC7793 P13 – Spin Evolution



Disconnect between X-ray flux and spin-up confirmed with latest *NuSTAR* obs

Interesting note: amplitude of UV cycle anti-correlated with average X-ray flux

NGC7793 P13 – Interesting Times

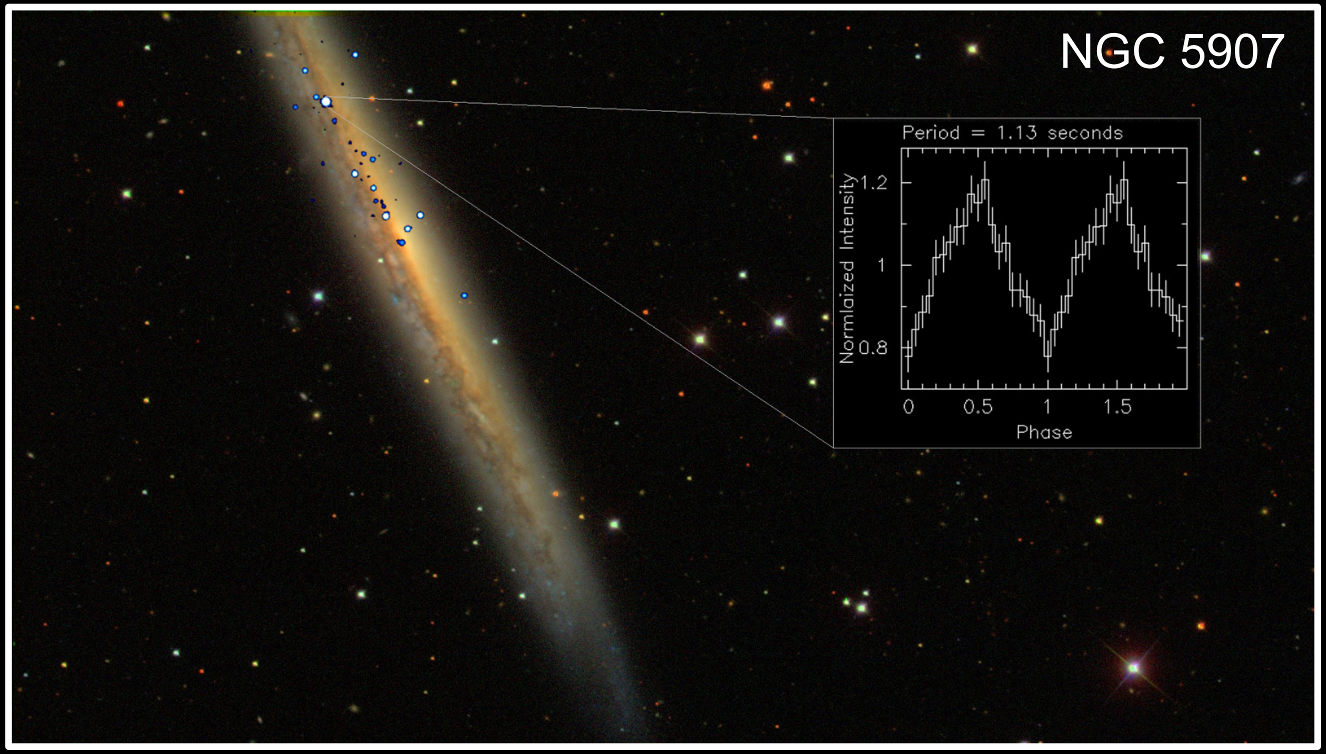


$P_{orb} = 64.89^{+0.18}_{-0.22}$ d (X-ray timing; *XMM*+*NuSTAR*)

$P_X = 65.21^{+0.15}_{-0.15}$ d (X-ray flux; *Swift*)

$P_{UV} = 63.75^{+0.17}_{-0.12}$ d (UV flux; *Swift*)

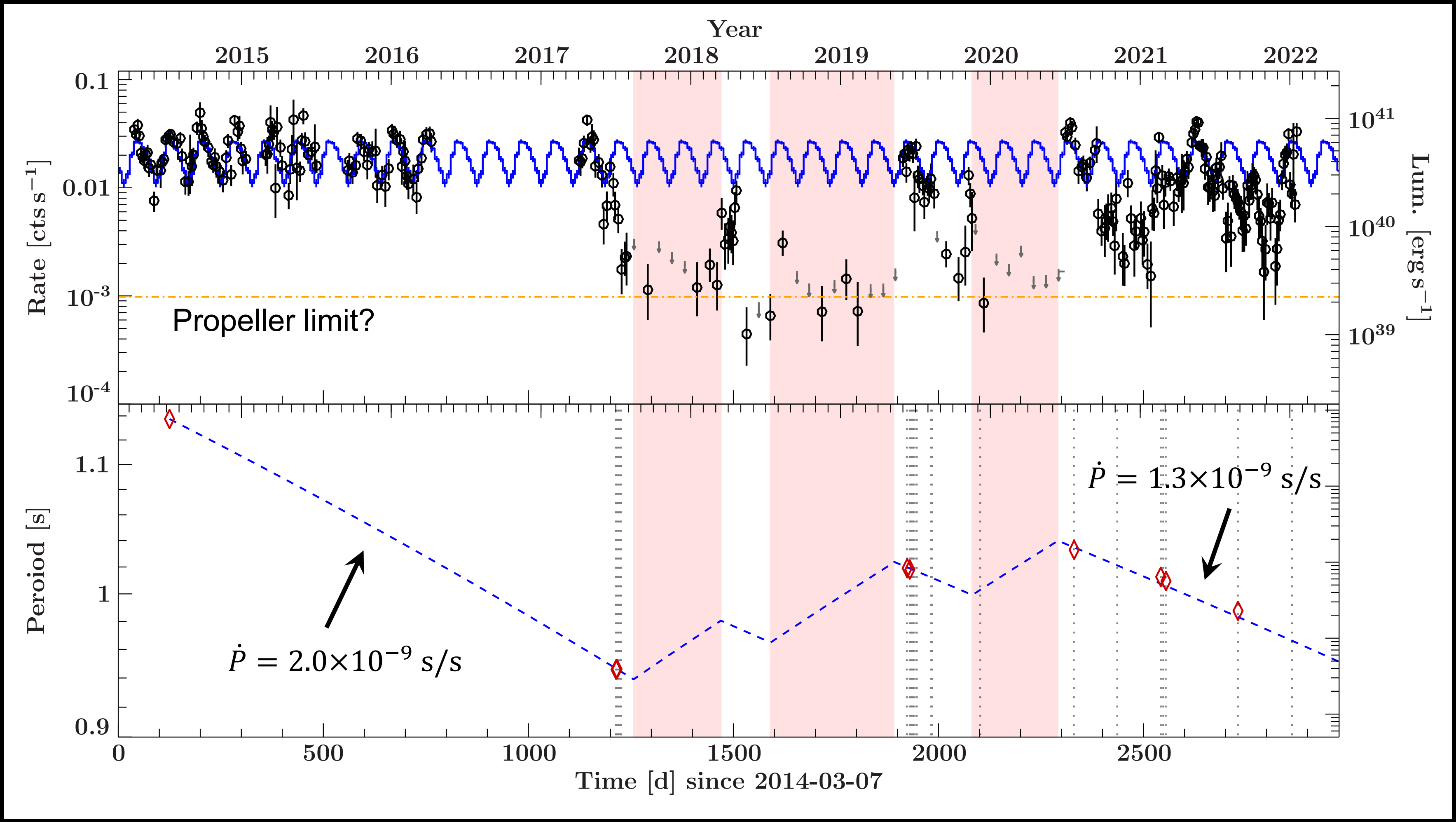
NGC5907 ULX1



- $L_{X,peak}$ ~ 10^{41} erg/s (~500x L_E!!); most luminous NS to date
- Current P_{spin} ~ 1s
- Unknown companion, but P_{orb} likely ~5d (Israel+17)
- Pulsations transient (seen in ~50% of observations with good S/N)

NGC5907 ULX1 – Spin Evolution

Fürst+22



Here, spin-up/down ***does*** track X-ray flux: NS spins down during low-flux periods (propeller?), slower spin-up more recently (corresponding to lower average L_X)

NGC5907 ULX1 – Magnetic Field

- ***B* from spin-up** (2014-2017): either **~3.5x10^{12} G** or **~2x10^{13} G**
- ***B* from spin-up** (2020-2022): either **~2x10^{12} G** or **~2x10^{13}** G

(based on model of Gao & Li 2021, trying to combine super-Edd disc with pulsar magnetosphere, incl. beaming based on King+08 prescription; gives 2 potential solutions)

- ***B* from spin-down** (2017-2020): **~ 6x10^{13} G**

(based on model of Parfrey+16 for propeller regime in which spin-down comes from magnetic braking due to open field lines)

- ***B* from propeller transition:** **<~ 2x10^{13} G**

(assuming propeller transition occurs at $L_X < 2\times10^{39}$ erg/s)

- ***B* assuming spin equilibrium:** **~ 2x10^{13} G**

(based on model of Chashkina+19, trying to combine super-Edd disc with pulsar magnetosphere, incl. outflows, advection and irradiation, adopting min P_{spin} as equilibrium spin period)

NGC5907 ULX1 – Magnetic Field

- ***B* from spin-up** (2014-2017): either **~3.5x10^{12} G** or **~2x10^{13} G**
- ***B* from spin-up** (2020-2022): either **~2x10^{12} G** or **~2x10^{13}** G

(based on mode ... ulsar magnetosphere,
incl ... olutions)

- ***B* from spin-do**

(based o ... n comes from

- ***B* from propell**

s)

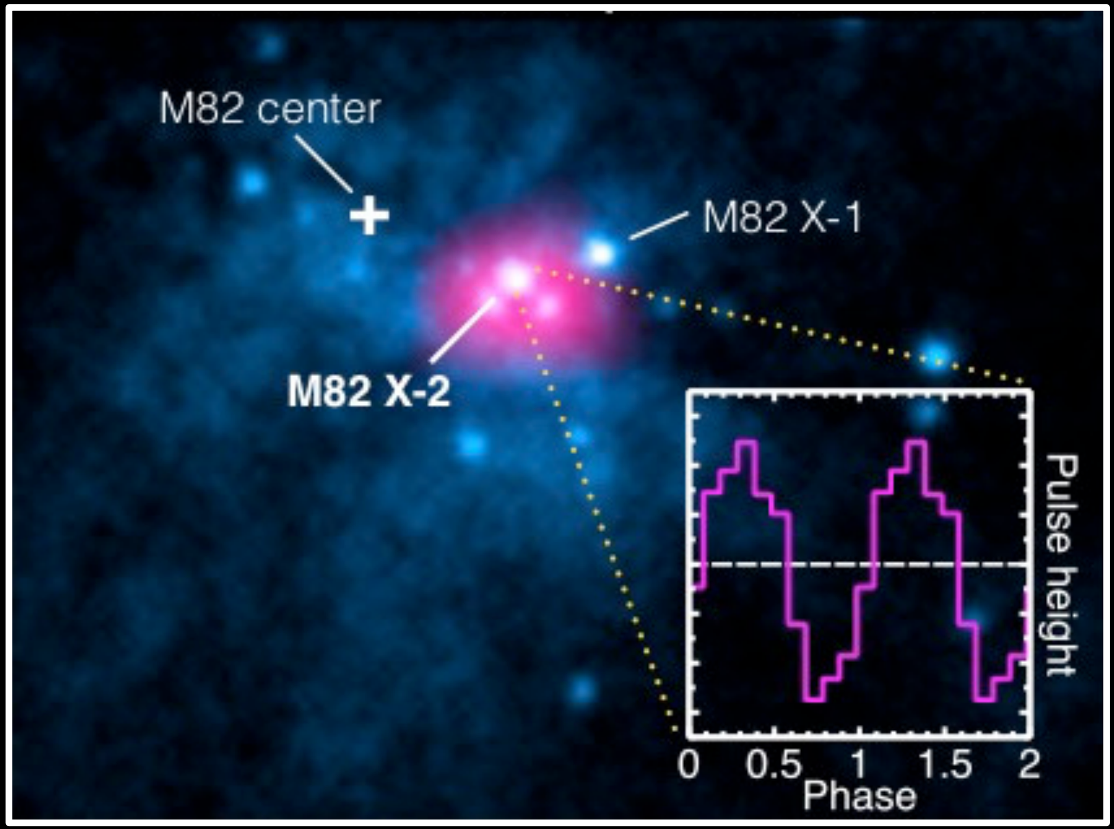
Considering all different models, *B* is therefore likely ~a few x 10^{13} G

Again, solutions are consistent with $R_M < R_{sp}$

- ***B* assuming spin equilibrium:** **~ 2x10^{13} G**

(based on model of Chashkina+19, trying to combine super-Edd disc with pulsar magnetosphere, incl. outflows, advection and irradiation, adopting min P_{spin} as equilibrium spin period)

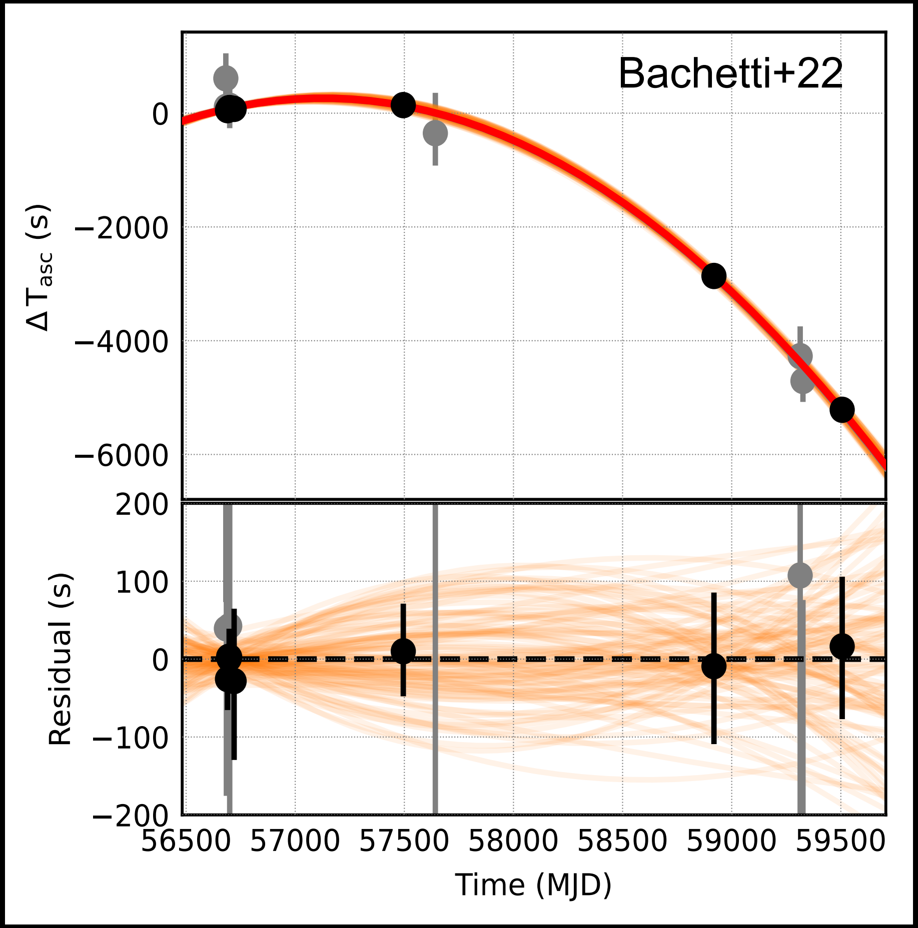
M82 X-2



- $L_{X,peak}$ ~ 2 x 10^{40} erg/s
- Current P_{spin} ~ 1.4s
- Companion unknown but must have M > 5 M_{sun}, P_{orb} ~ 2.5d (Bachetti+14)
- Pulsations transient (and complicated by presence of X-1)

M82 X-2: Orbital Decay

- Long-term monitoring of M82 X-2 reveals several further detections of pulsations
- Long-duration observations (primarily with *NuSTAR*) permit several independent constraints on the binary orbit
- Data reveal evidence for a secularly changing orbit with $\dot{P}_{\rm orb}/P_{\rm orb} \sim -8{\times}10^{6}$ yr^{-1}
- Independently implies a binary mass transfer rate of $\dot{M}_{\rm tr}/\dot{M}_{\rm E} \sim 150$
- Source likely close to spin equilibrium, implying $B \sim 3{\times}10^{13}$ G
- **Still consistent with R_M < R_{sp}**

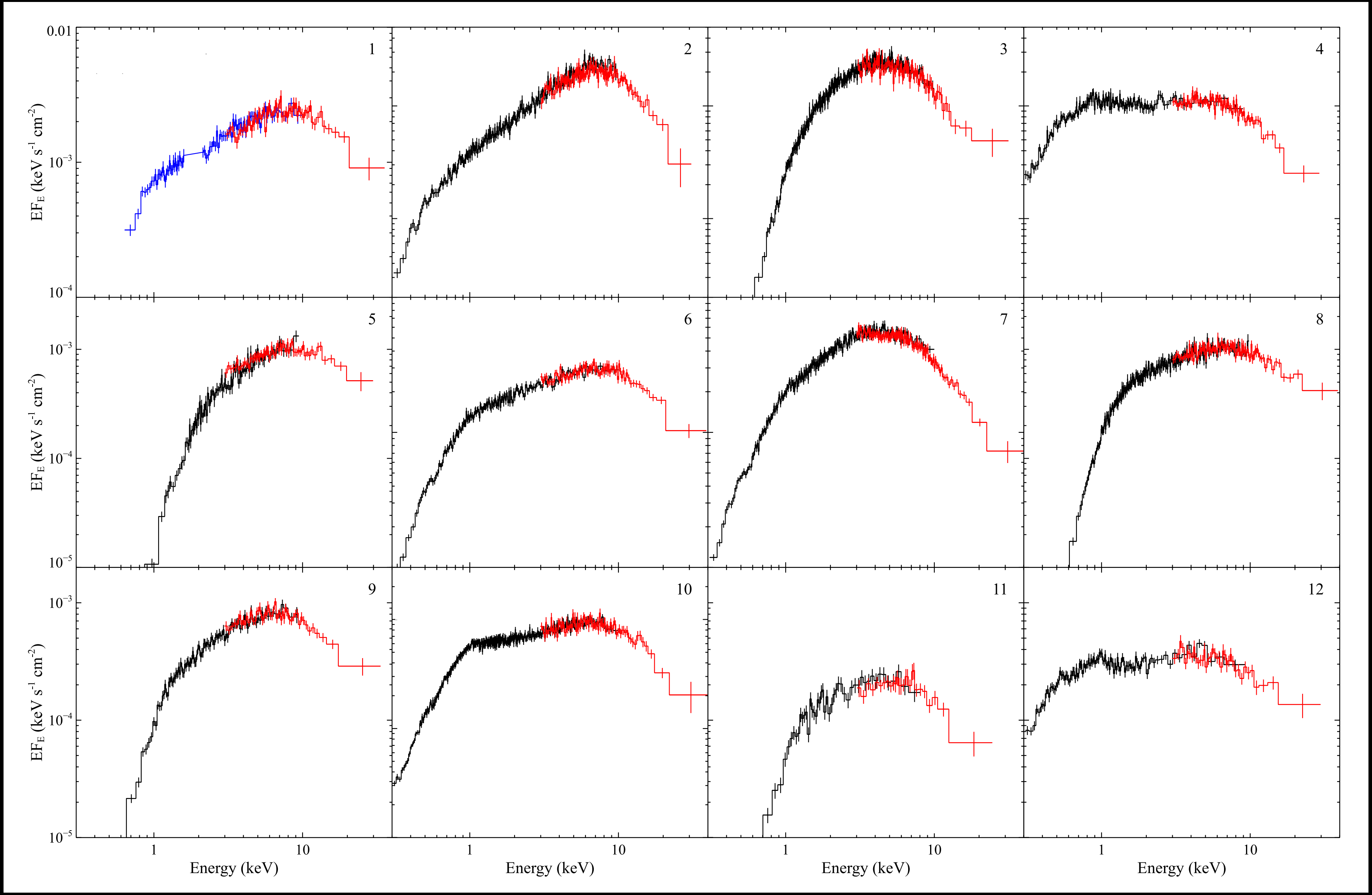


Looking Ahead

Looking Ahead

“Please, sir, can I have some more [ULX pulsars]?”

Spot the Neutron Star(s)



Adapted from Walton+18a; see also Pintore+17, Koliopanos+17

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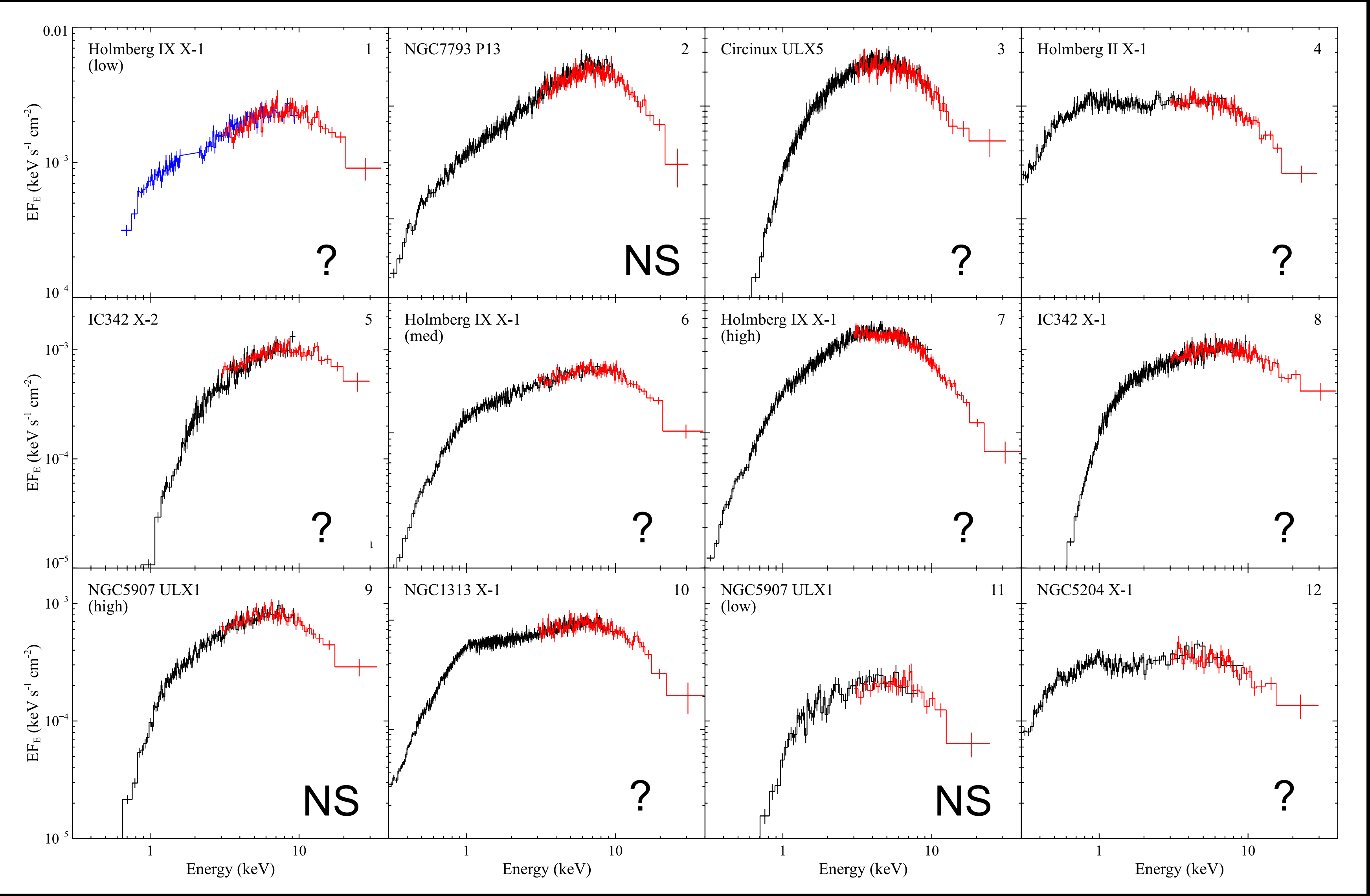

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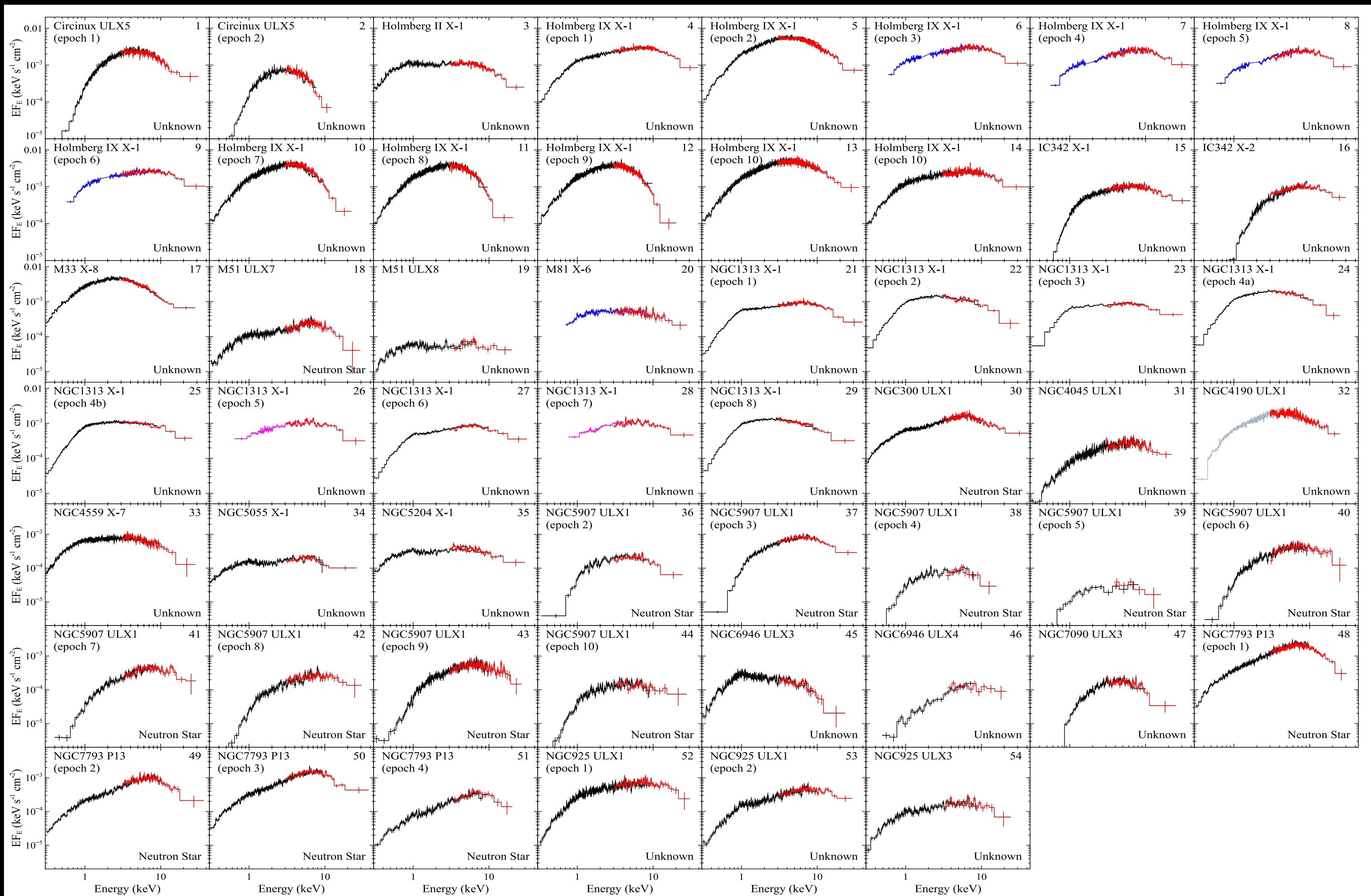
Current Broadband Observations



Adapted from many, many authors

More ULXs!

Several new ULX catalogues released in the last few years:

- Kovlakas+20: CSC2.0
- Traulsen+22: 4XMM-DR9
- Walton+22: CSC2.0 + 4XMM-DR10 + 2SXPS

Available via Vizier!

	4XMM-DR10	2SXPS	CSC2	Combined Sample
Number of ULX Candidates	641	501	1031	1843
(with multiple ULX detections in the parent catalogue)	177	291	246	702
(seen as a ULX by multiple observatories)	241	173	209	293
(HLX candidates)	22	36	17	71
Host Galaxies	403	269	548	951
(average distance, Mpc)	62.3 ± 3.5	34.8 ± 2.7	83.8 ± 3.8	74.7 ± 2.7
(containing multiple ULX candidates)	130	89	190	333

↓

~5-10 ***new*** ULX pulsars

eROSITA still to come (hopefully…), along with CSC2.1 (another 7 years of *Chandra*)

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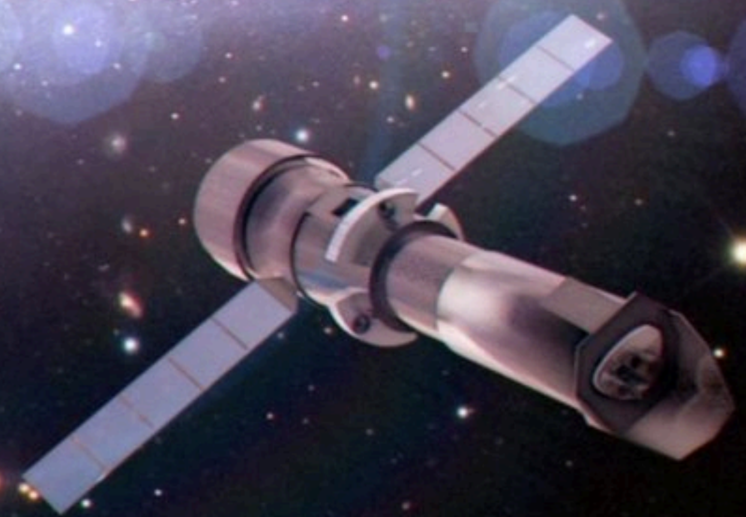
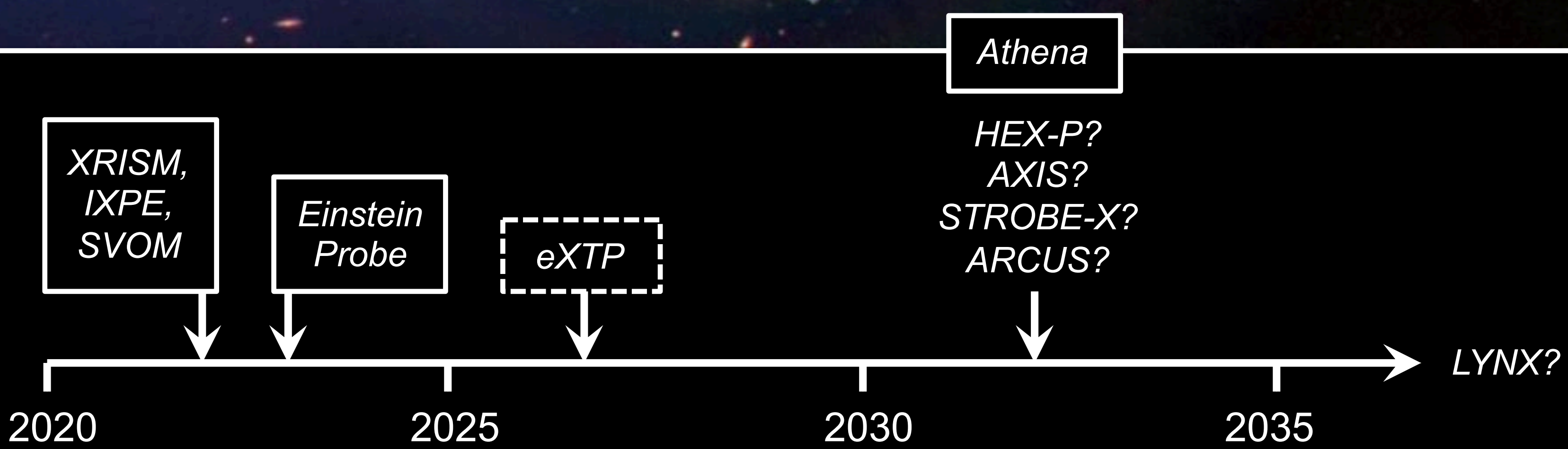
THE ATHENA+ OBSERVATORY

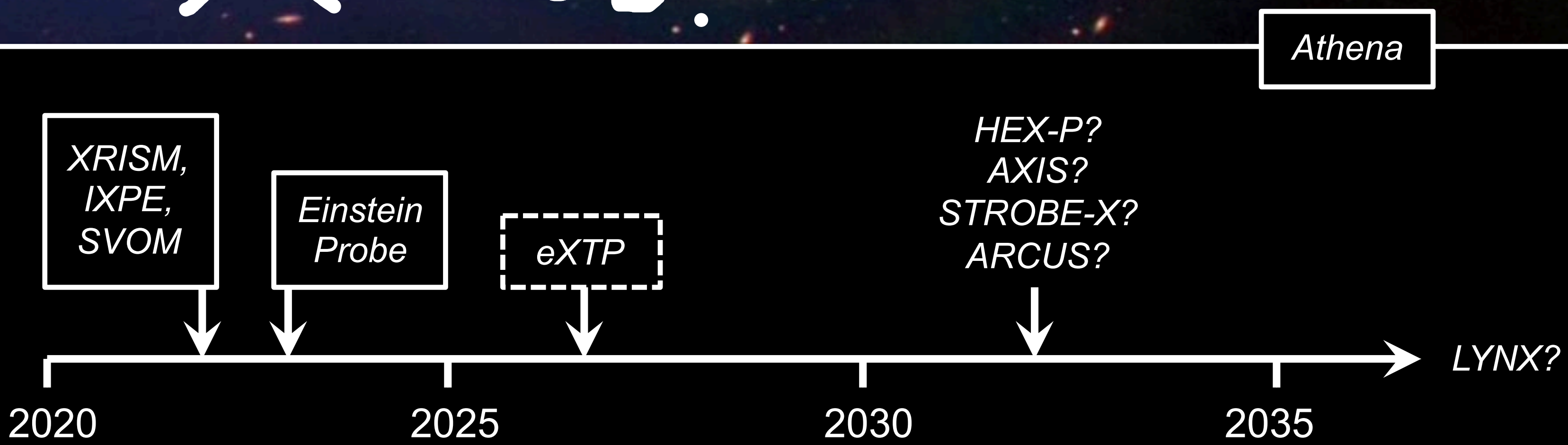
Unprecedented spectral resolution
AND
0.5-10 keV sensitivity

~2032

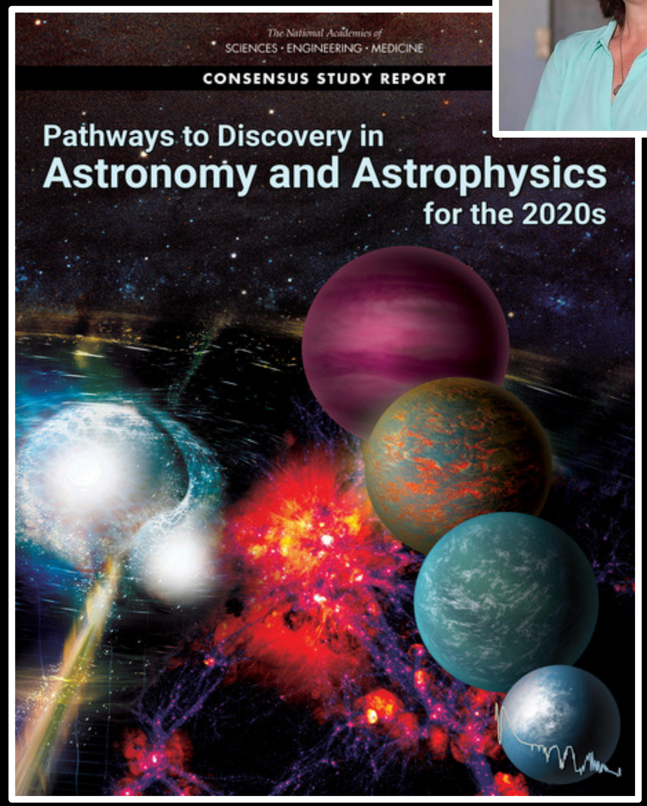





THE ATHENA+
OBSERVATORY
esa
Unprecedented spectral resolution
AND
0.5-10 keV sensitivity
~~~2032~~ 2038?


Athena
XRISM,
IXPE,
SVOM
Einstein
Probe
eXTP
HEX-P?
AXIS?
STROBE-X?
ARCUS?
LYNX?
2020
2025
2030
2035
~~~

NASA 2022 Decadal



Key recommendation: Introduction of a Probe-class line of observatories (up to $1bn), with priority anticipated for X-rays and far IR

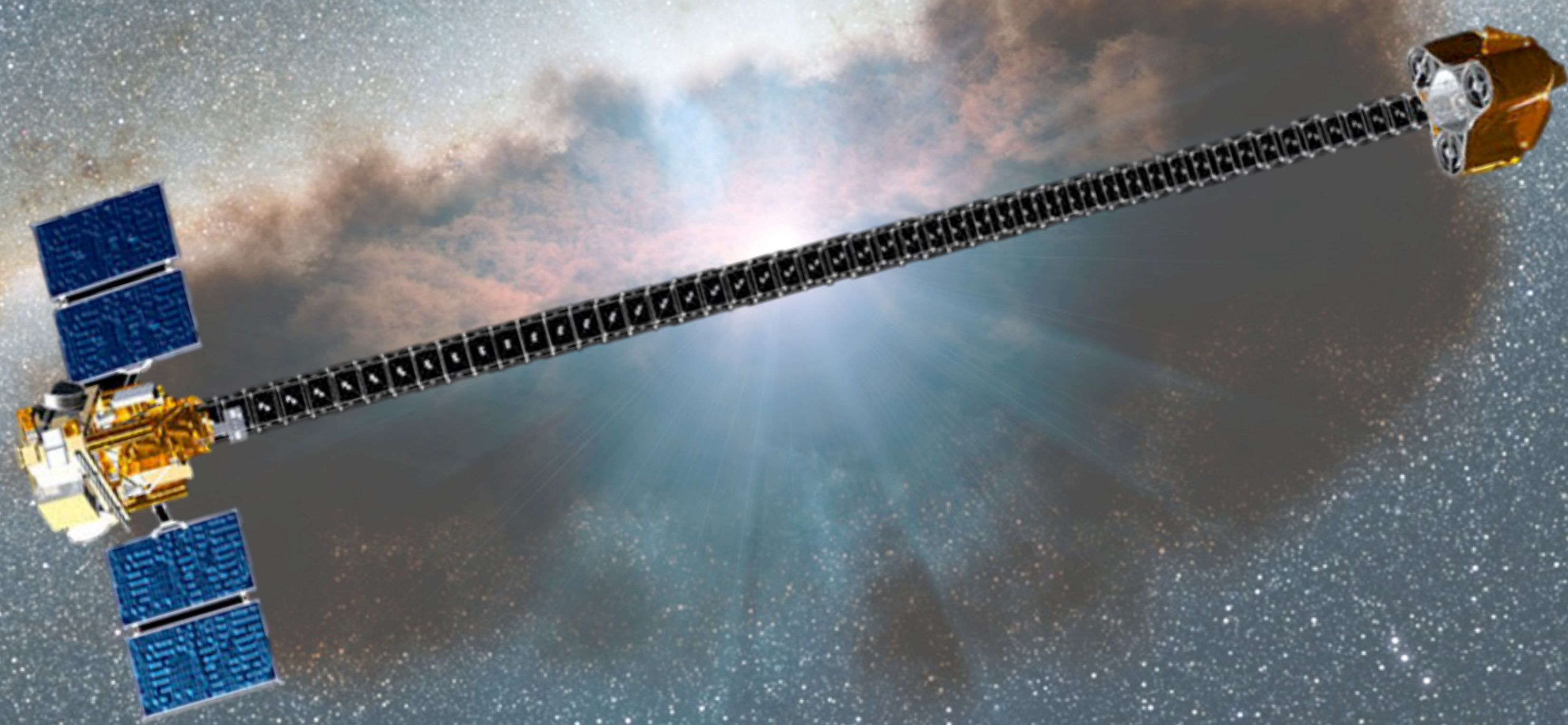
HEX-P

HIGH ENERGY X-RAY PROBE

JPL Jet Propulsion Laboratory

NASA

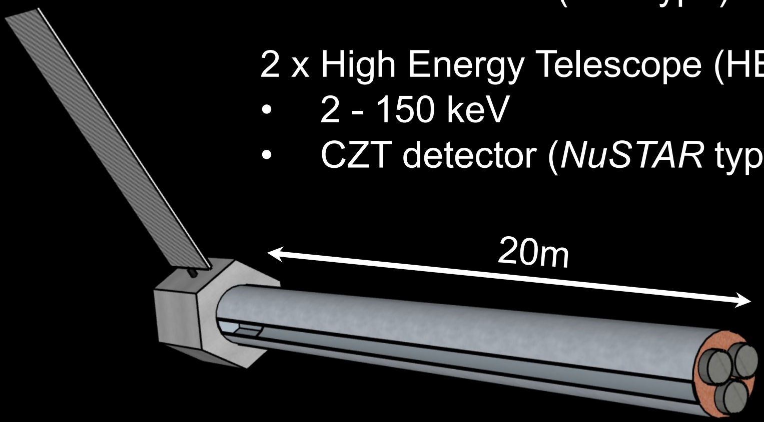
Goddard SPACE FLIGHT CENTER

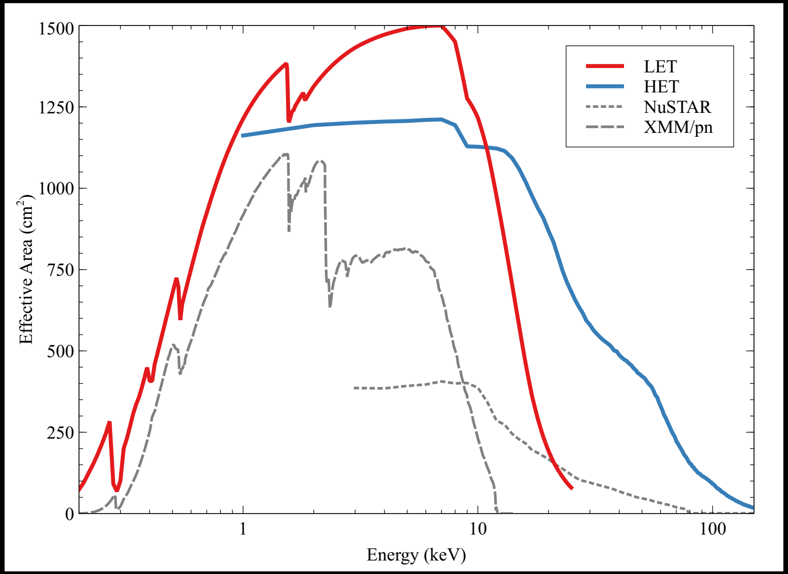


HEX-P

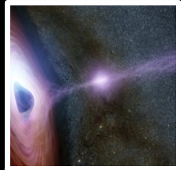
Baseline: 1 x Low Energy Telescope (LET)
- 0.1 – 12 keV
- CCD detector (WFI type)

2 x High Energy Telescope (HET)
- 2 - 150 keV
- CZT detector (*NuSTAR* type)





Science Pillars



Probe the Power Source in Accreting Black Holes And Neutron Stars

Constrain the Endpoints of Stellar Evolution

Black Hole Growth over Cosmic Time: A Census of Obscured AGN

Probe the Aftermaths of Stellar Demise and Compact Object Mergers

Managing center: JPL/Caltech
Principal Investigator (PI): Daniel Stern, JPL
Deputy PI: Kristin Madsen, GSFC
Project Scientist: Javier Garcia, Caltech

To become involved with *HEX-P* please sign up at

HEXP.ORG

HEX-P: Current Specifications

Baseline: 1 x Low Energy Telescope (LET)
- 0.1 – 12 keV
- CCD detector (WFI type)

2 x High Energy Telescope (HET)
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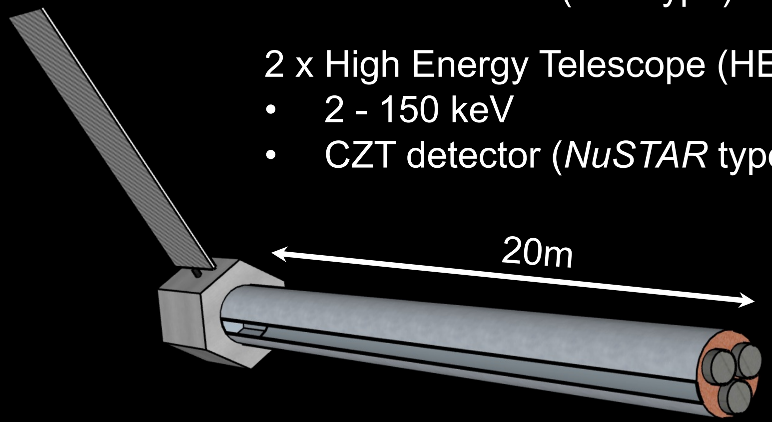
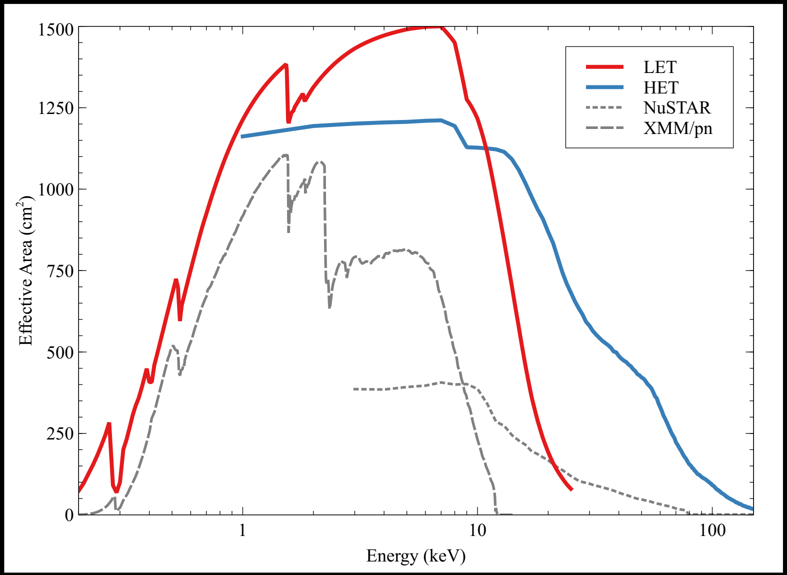
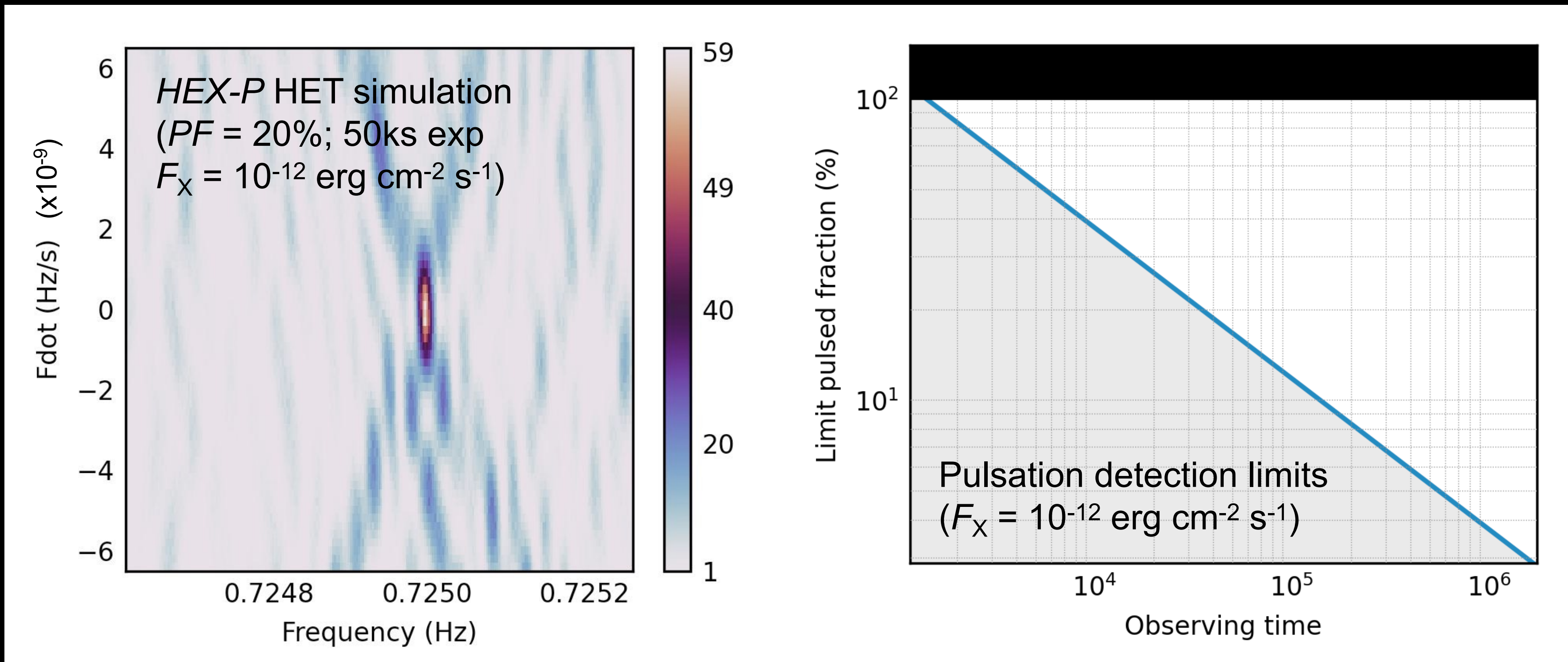




	NuSTAR	***HEX-P***
Bandpass	3-79 keV	0.1-150 keV
Angular resolution	60″	**HET:** ≤10″ **LET:** ≤5″
Spectral resolution [FWHM]	600 eV @ 6 keV 1.2 keV @ 60 keV	**LET** : ≤150 eV @ 6 keV **HET**: ≤300 eV @ 6 keV **HET**: ≤800 eV @ 60 keV
Timing resolution	1 µsec	**LET**: TBD **HET**: ≤1 µsec
Field of view	13′ × 13′	**LET**: ≥ 13’ x 13’ **HET**: ≥ 13′ × 13′

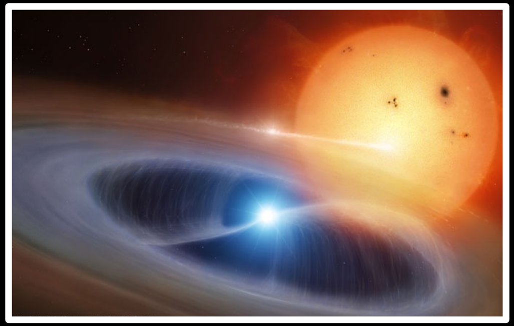
HEX-P: ULX Pulsars



The *HEX-P* HET will be able to provide robust, high-energy detections of pulsations in ULXs down to even relatively faint fluxes in modest observing times, even allowing for “accelerated” searches (considering both f and $\dot{f}$)

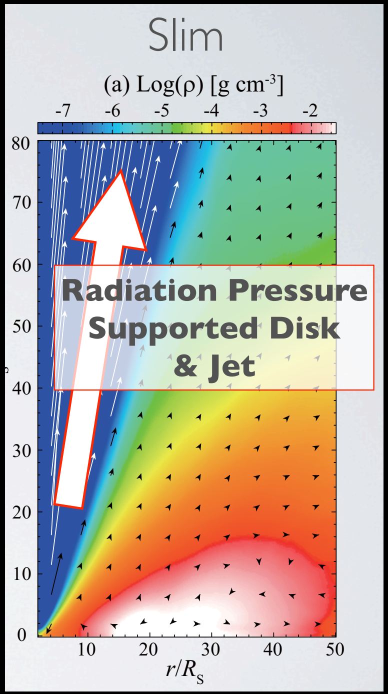

NuSTAR

The Story So Far…



Key Takeaway:

ULXs are the most extreme X-ray binaries known, with (at least) some powered by ***neutron stars*** accreting at up to ~500x Eddington



ULX Pulsars and Open Questions:

- Accretion flow is likely ‘classically’ super-Eddington (slim disk forms outside of R_M); best local examples of conditions needed for early universe SMBH growth?
- Still a lot about these remarkable systems we do not understand; rapidly evolving field of astrophysics!
- Long-term monitoring of ULXPs providing key information relating to B-fields, orbits, accretion rates & geometry, etc.
- Exact make-up of the ULX population still uncertain; could be dominated by neutron stars?

The Story So Far…

Key Takeaway:

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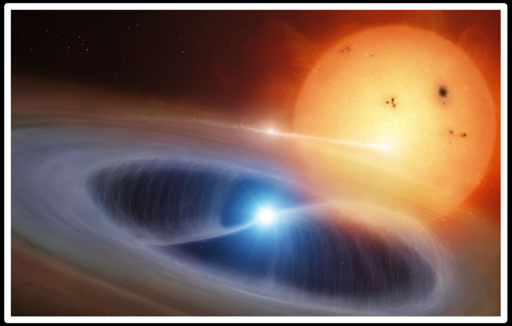

ULX catalogue download:

(also appear via Vizier)

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