Leveraging NICER to Understand Accretion in NS LMXBs

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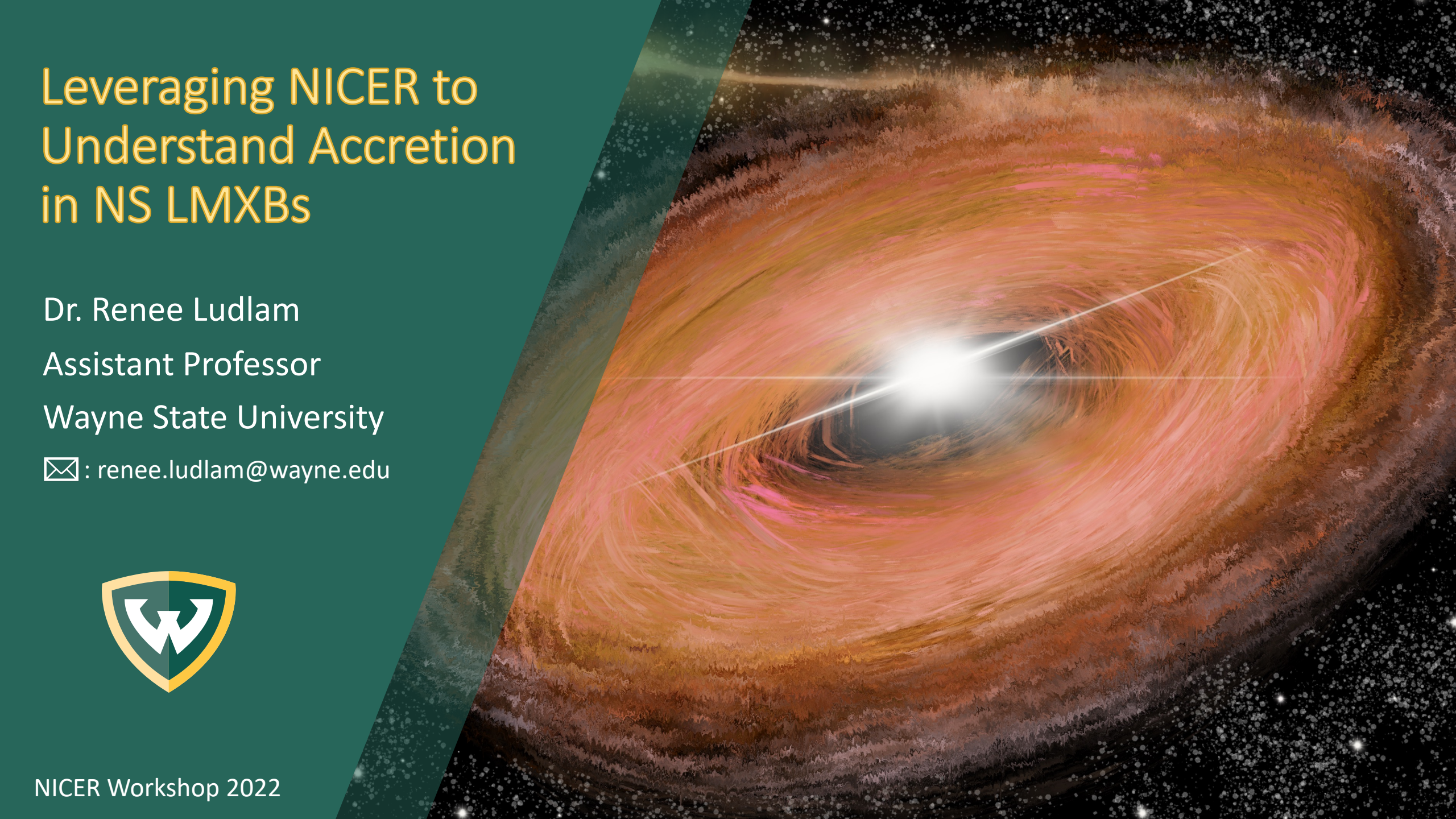
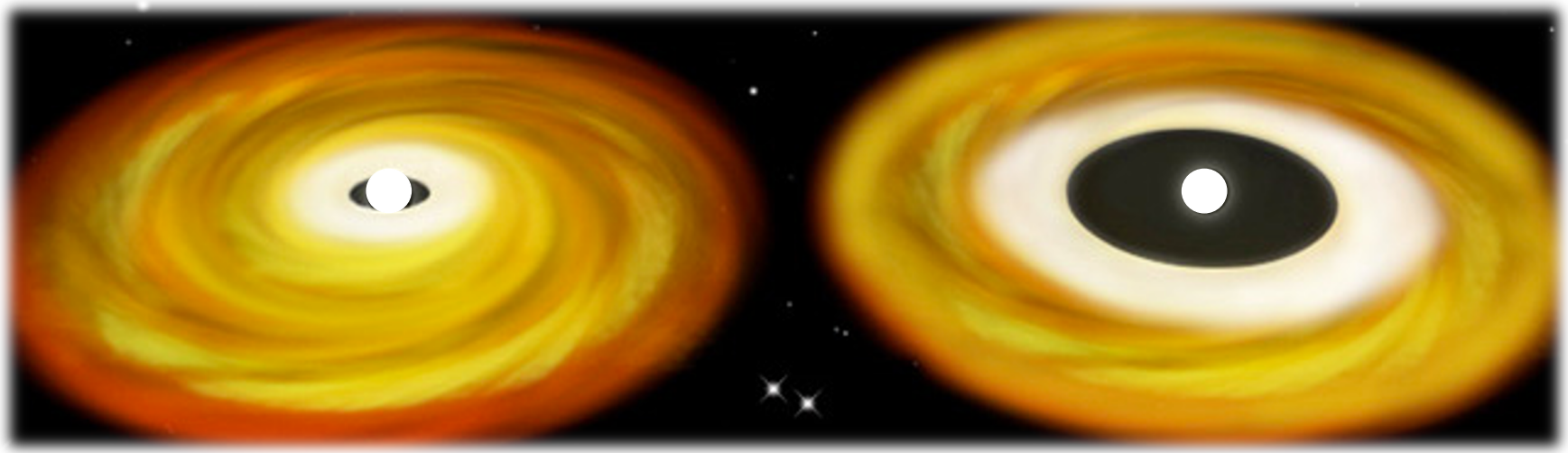


NICER Workshop 2022

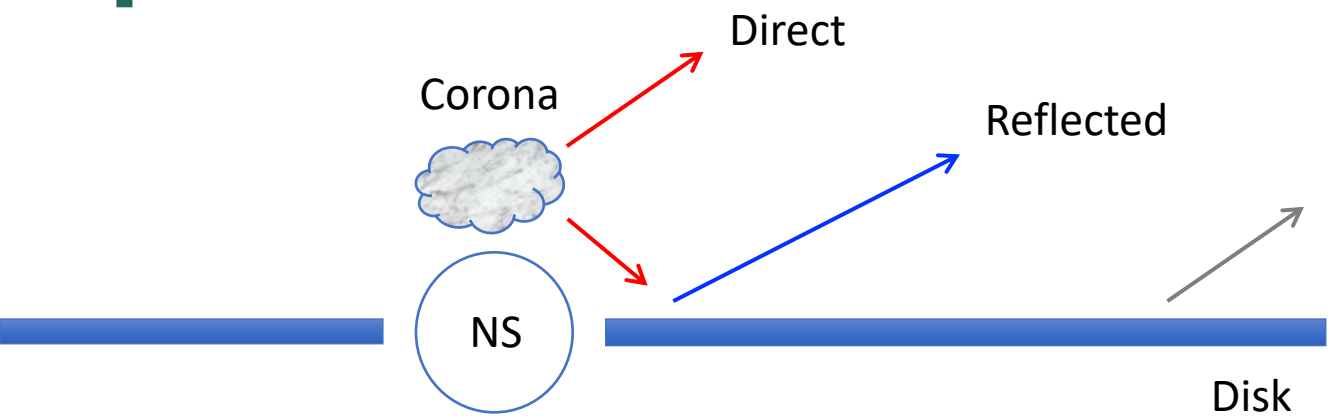
Why Study Disk Reflection in Neutron Stars?

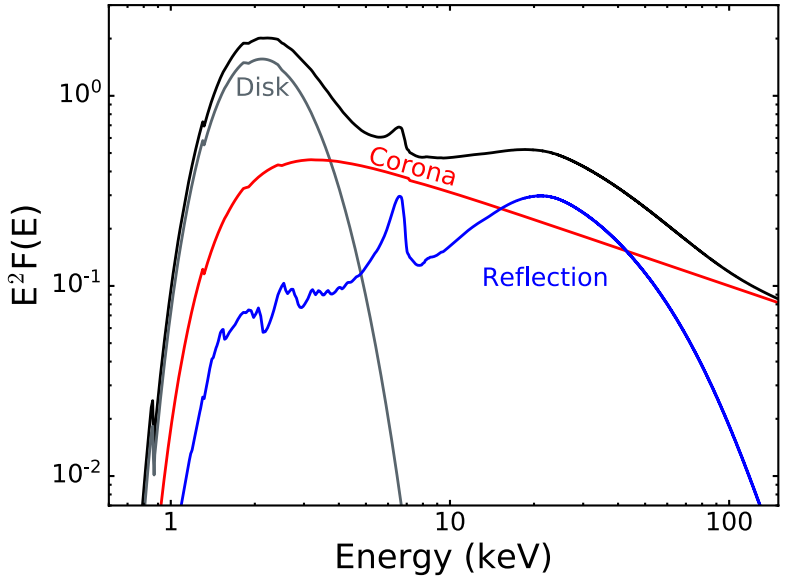
- The disk must truncate at or prior to the neutron star (NS) surface
- If R_{NS} < innermost stable circular orbit (ISCO); rule out equations of state that predict a larger radius

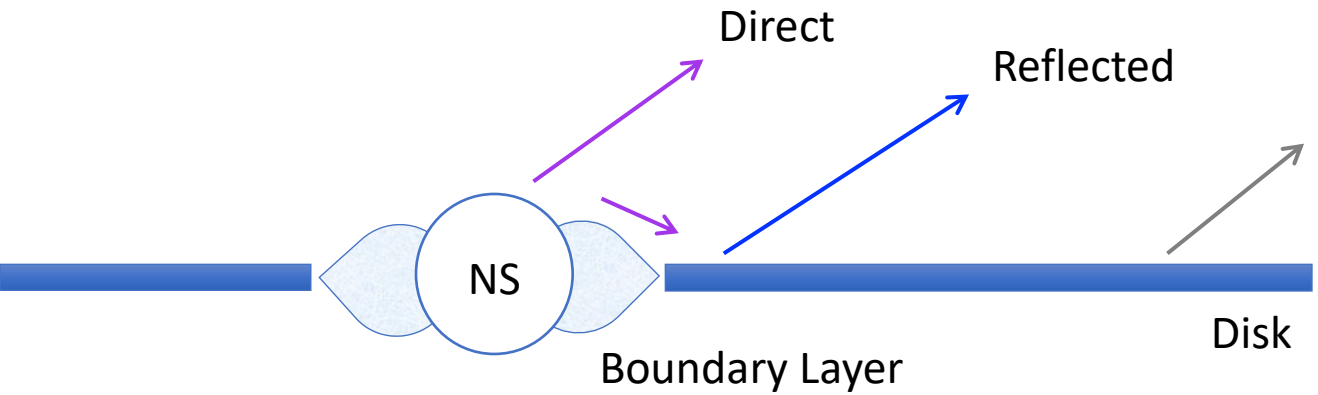


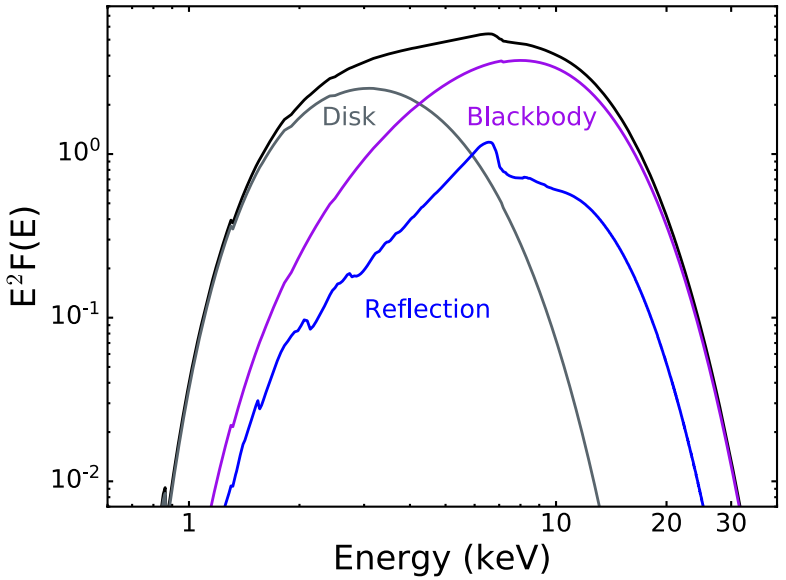
- Can constrain properties of the disk and NS itself

X-ray Emission & Reflection

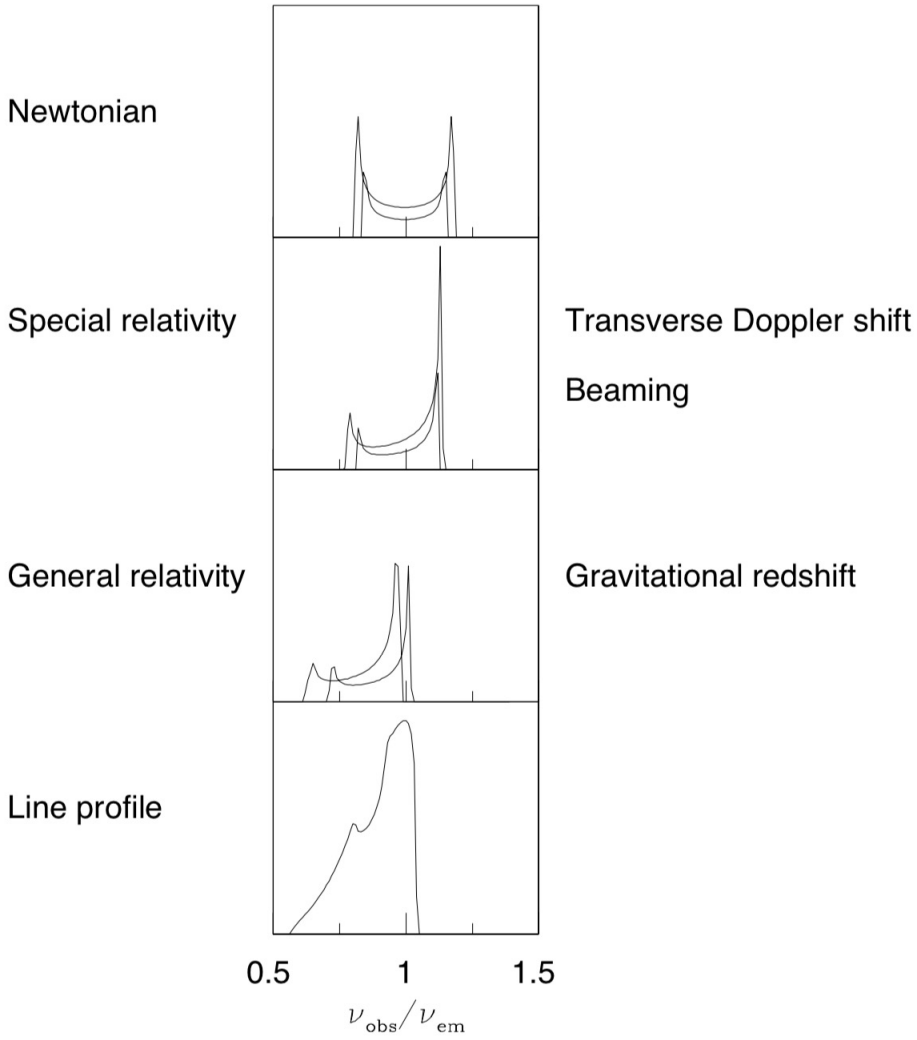






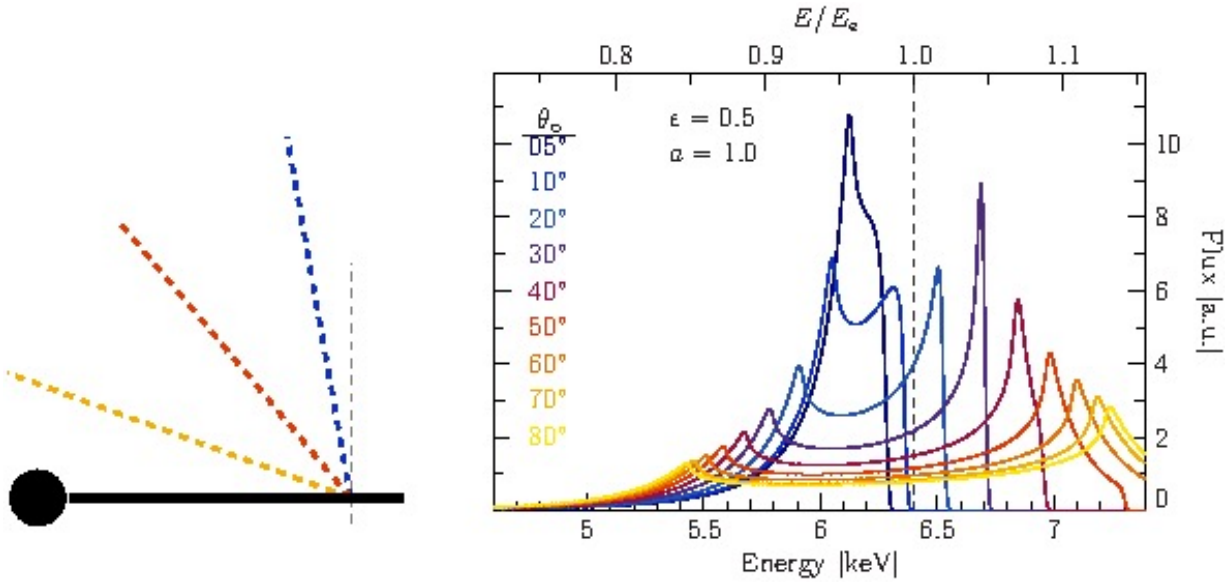


Line Broadening Effects



Fabian+ 1989

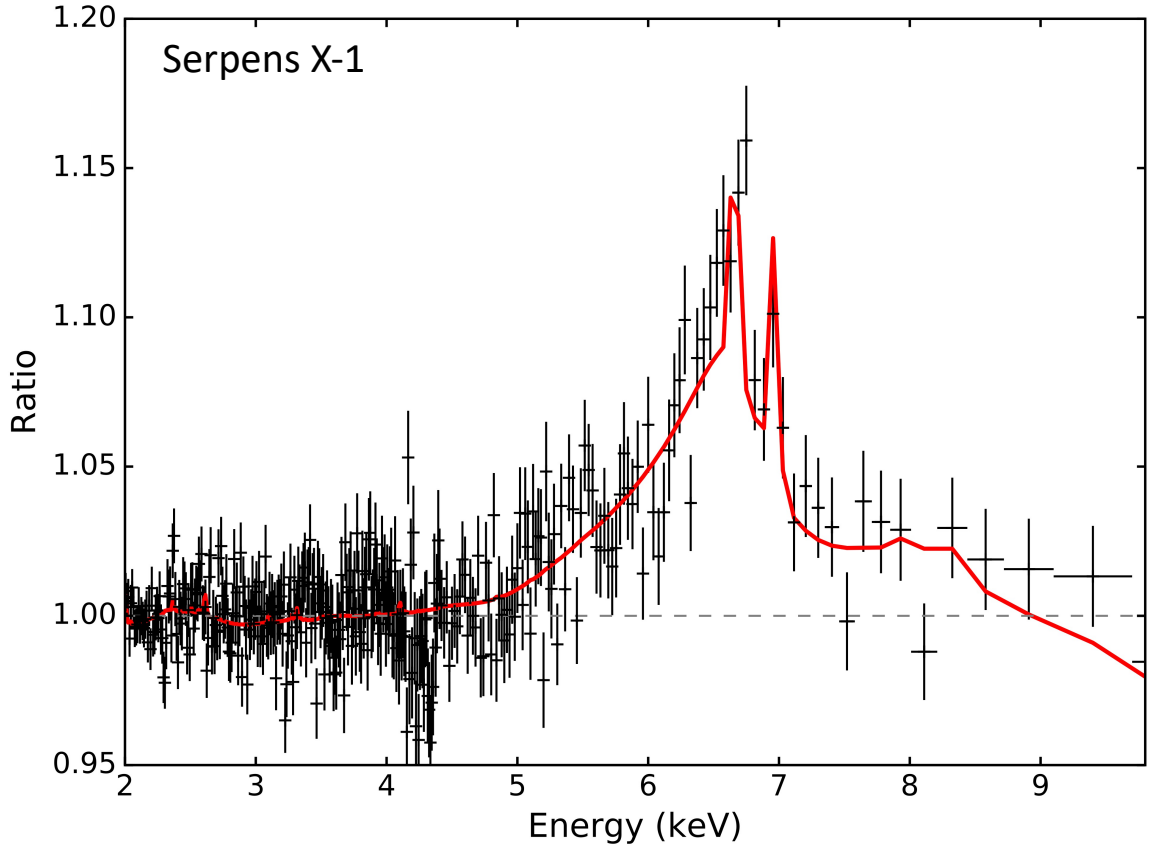
- Degree of broadening in the red wing directly correlates with proximity to compact object.
- Broadening in the blue wing indicates inclination.



Dauser+ 2010, 2013

Fe K Line with *NICER*

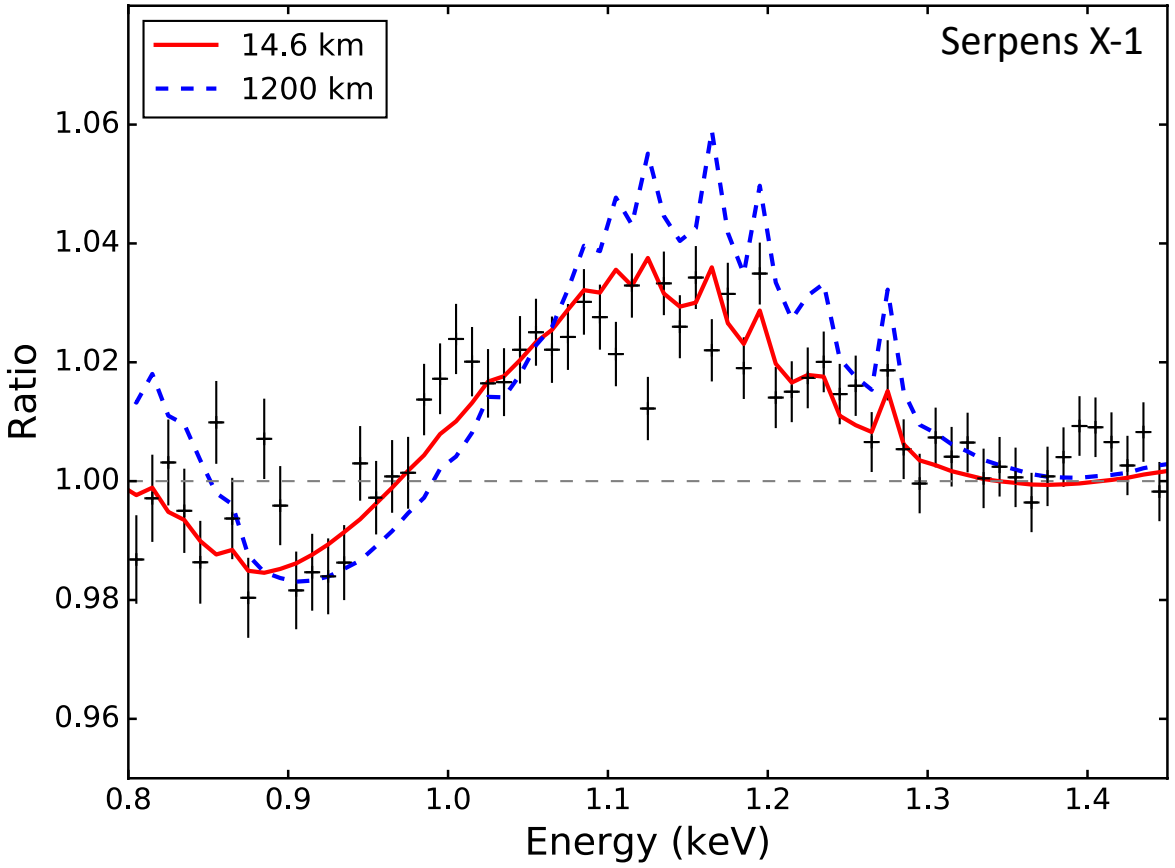
- The predicted line profile (red) from the fully self-consistent reflection model RELXILLNS (García+ 2022)
  - High density disk near 10^{19} cm^{-3}
  - Both the Fe XXV and Fe XXVI K alpha lines are produced at similar strength



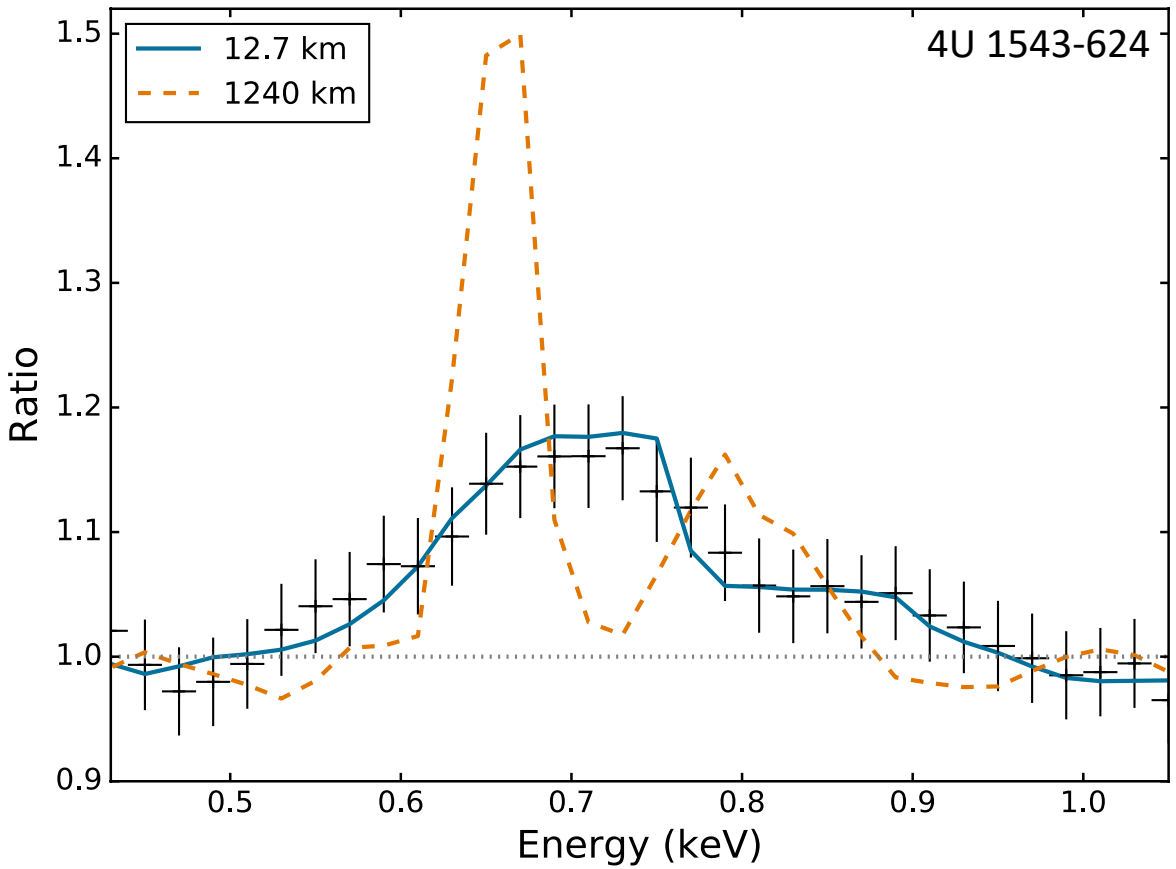
➢ This highlights energy resolution of *NICER* and the need to fit a reflection spectrum.

Low-Energy Emission Lines with NICER

Ludlam+ 2018

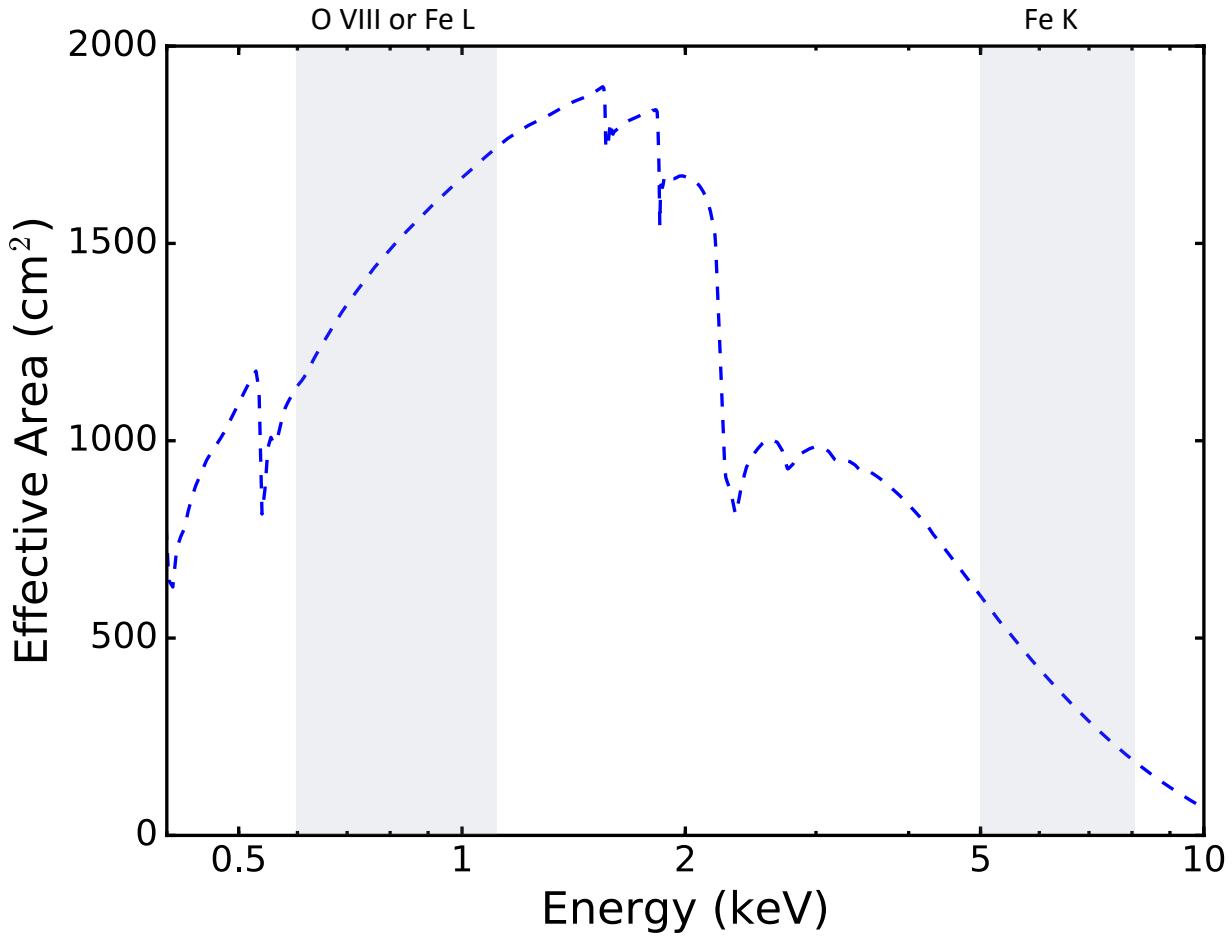


Ludlam+ 2021



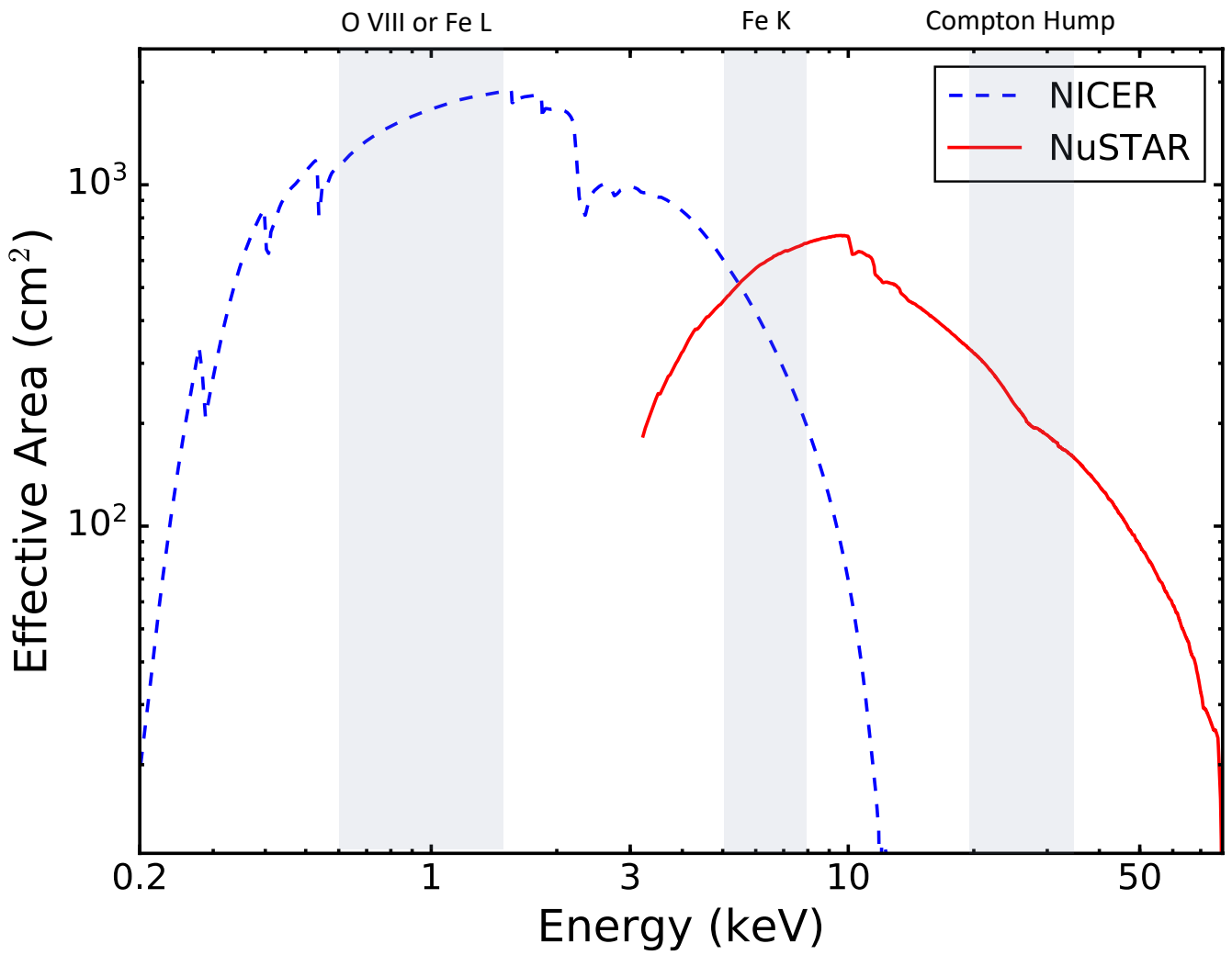
- The Fe L complex with the best fit model predicted line profile from relxillNS (red) and the local-frame emission (blue) for comparison.
- The O VIII line region with the best fit model predicted line profile from xillverCO (teal) and the local-frame emission (orange) for comparison.

NICER's Collecting Area



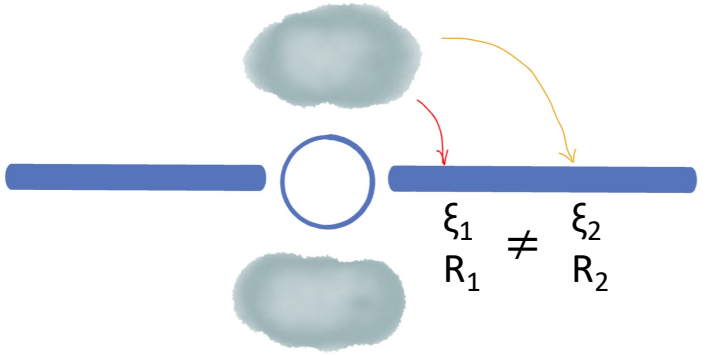
- There is ≥2x (5x) more collecting area in the O VIII (Fe L) band than in the Fe K band

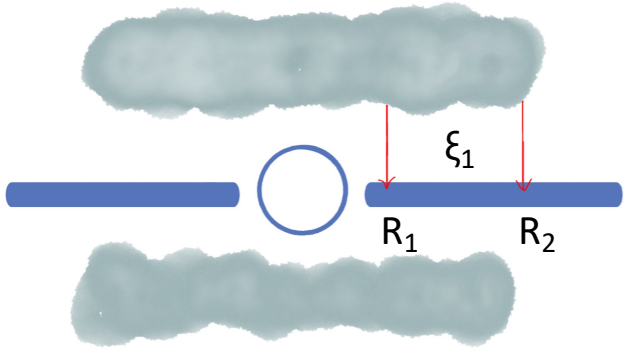
Collecting Area of *NICER* & *NuSTAR*



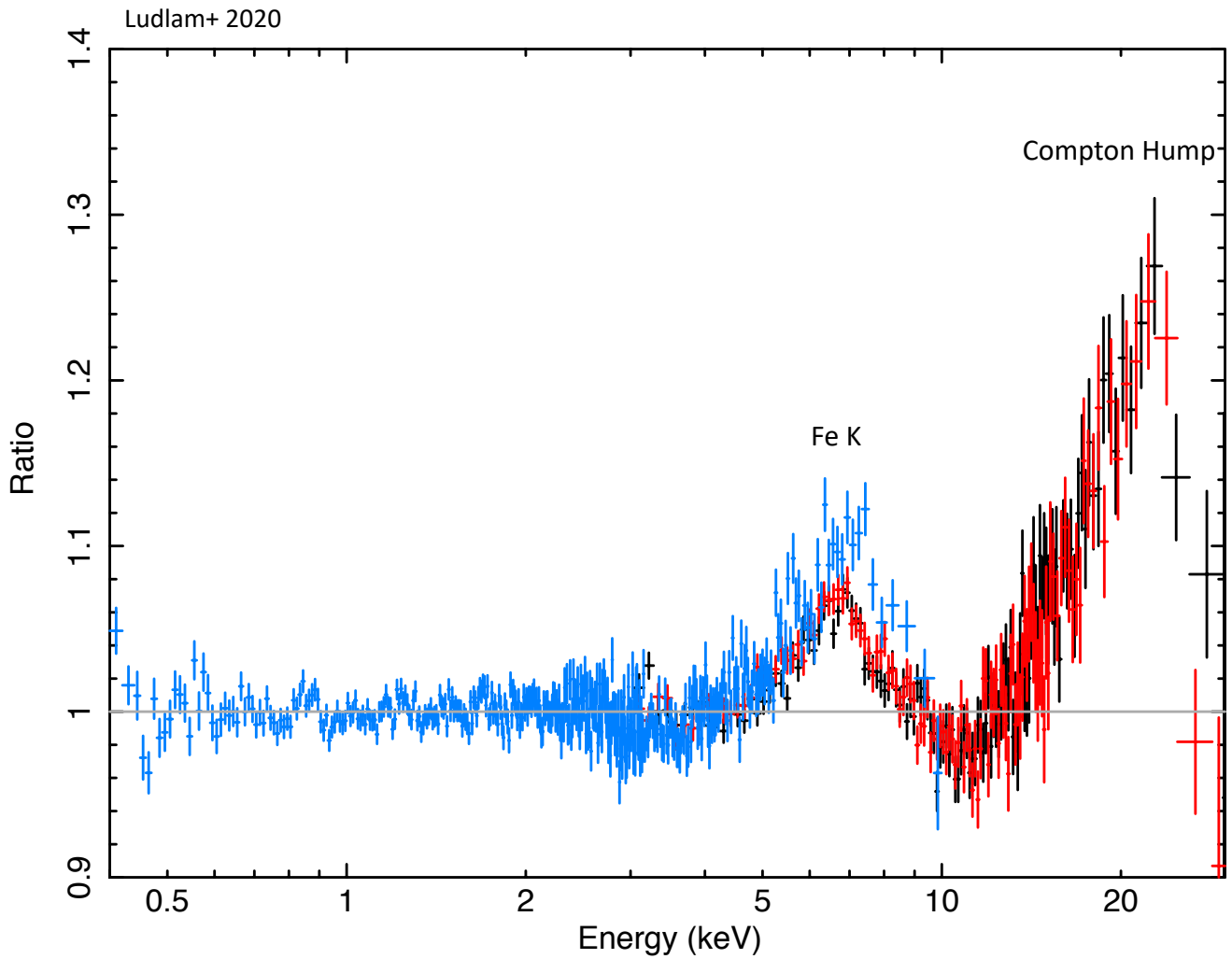
Probes with Multiple Emission Lines

- Additional constraint on the position of the inner disk
- Disk structure
  - Ionization (ξ) with radius (R)
  - Illumination source geometry





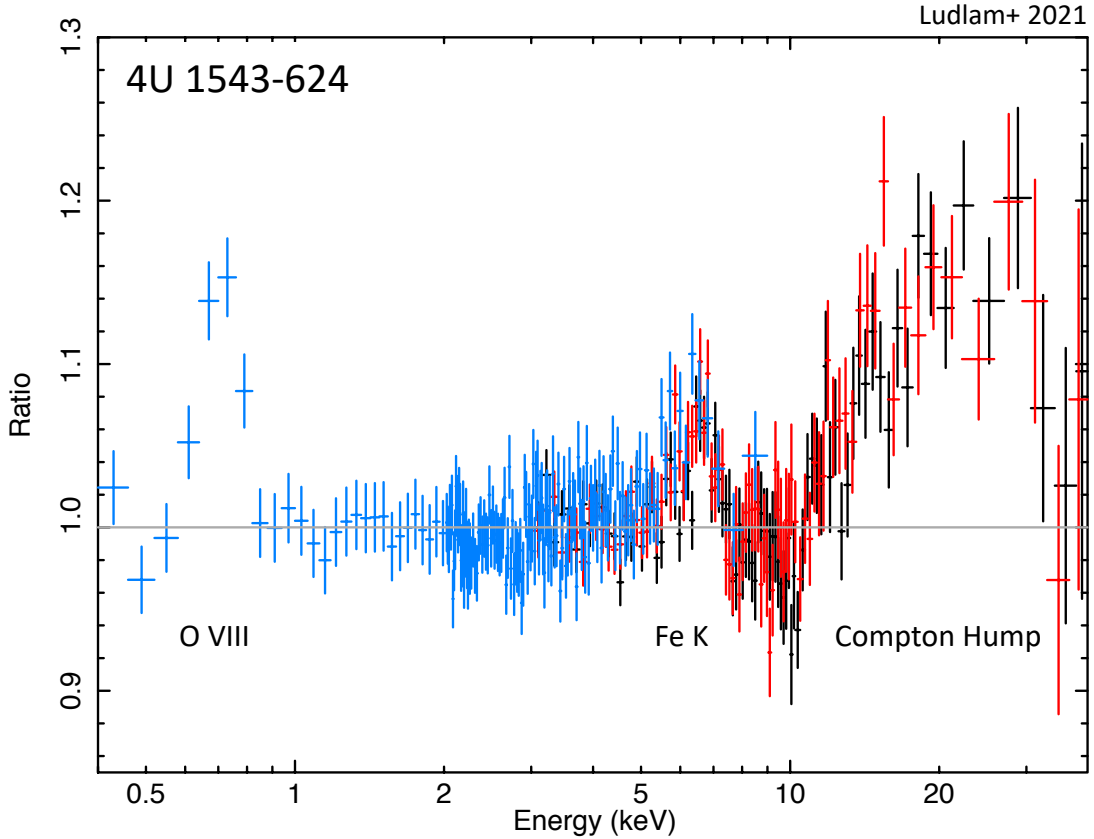
Joint NICER-NuSTAR Spectra of 4U 1735-44



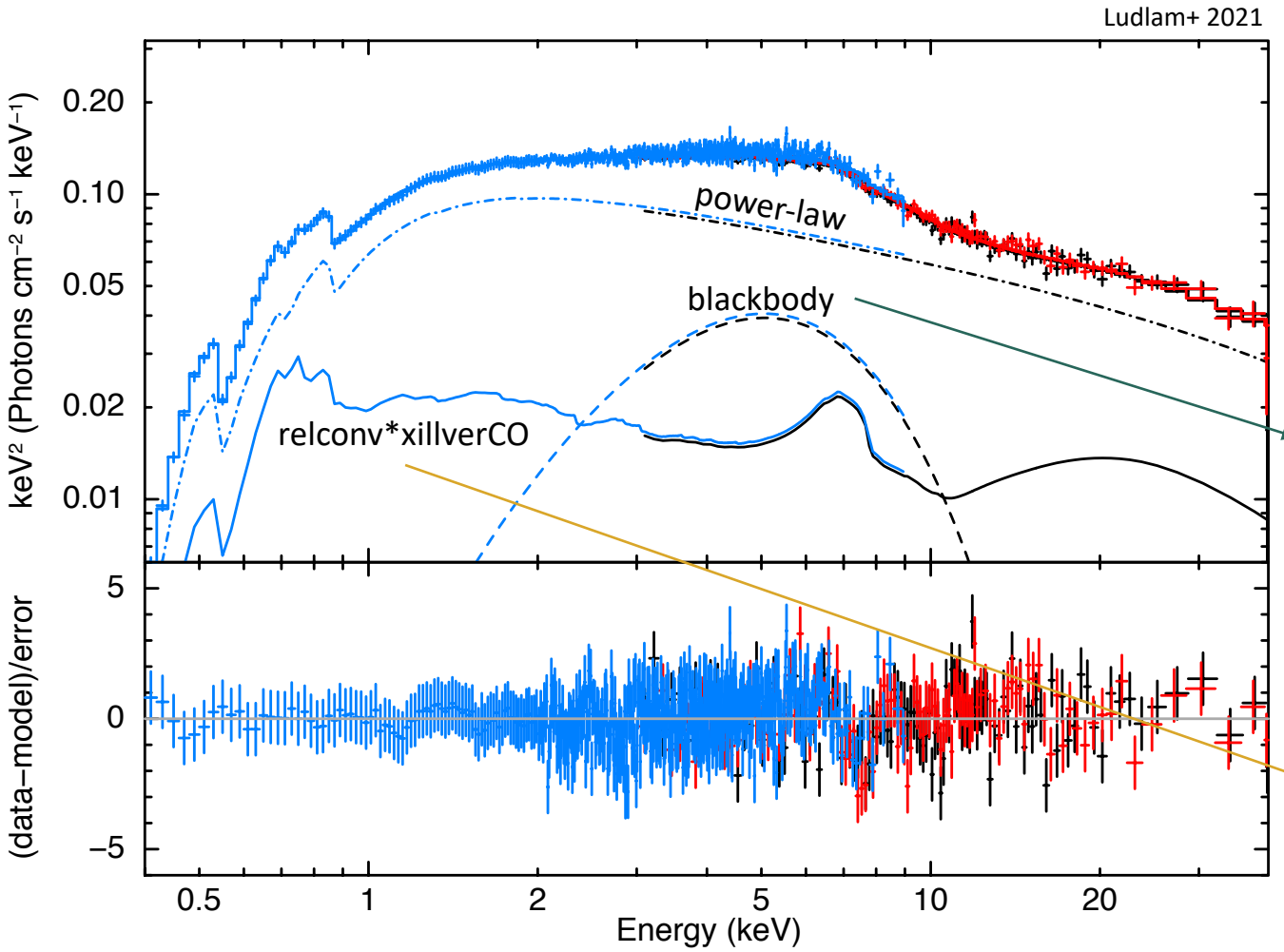
- Clear evidence of reflection, but no lower-energy emission feature in the spectrum
- Need a unique set of conditions for Fe L:
  - Density
  - Ionization
  - Low Column Density
  - Thermal component

Ultra-compact X-ray Binaries

- Orbital periods of < 90 minutes
- Donor companion WD or He stars
- Typically Fe is the most prominent feature, but O takes center stage



Joint NICER-NuSTAR Spectra

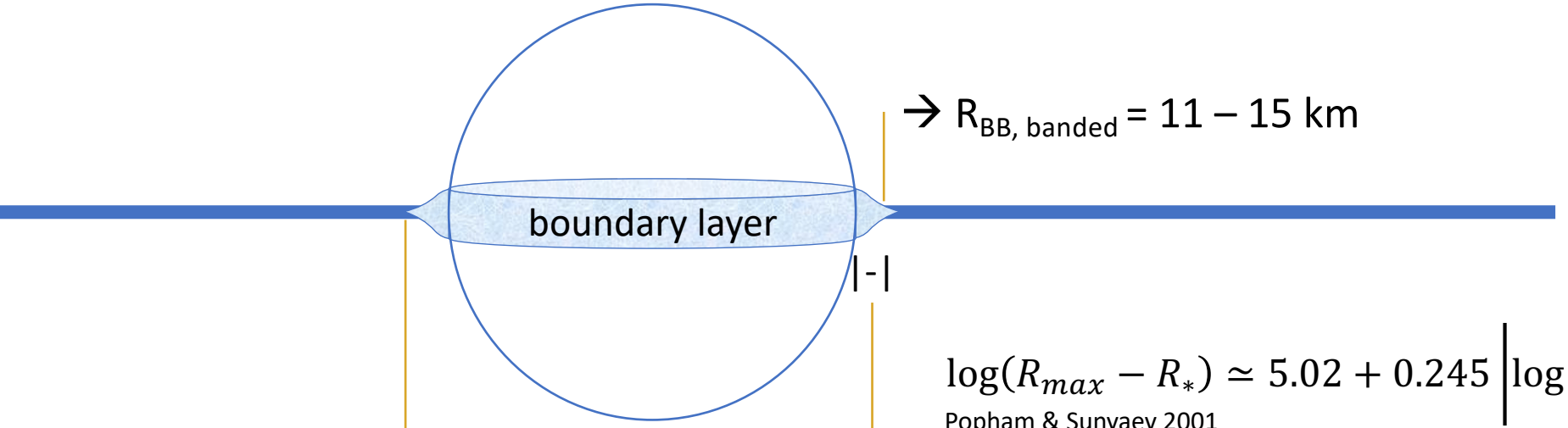


R_{BB} = 3.4 km

R_{in} = 12.4 – 13.3 km

Radius Estimates from Other Spectral Components

Spherical emission → Narrow banded emission with a height 5%-10% the radial extent



→ $R_{BB,\ banded} = 11 - 15$ km

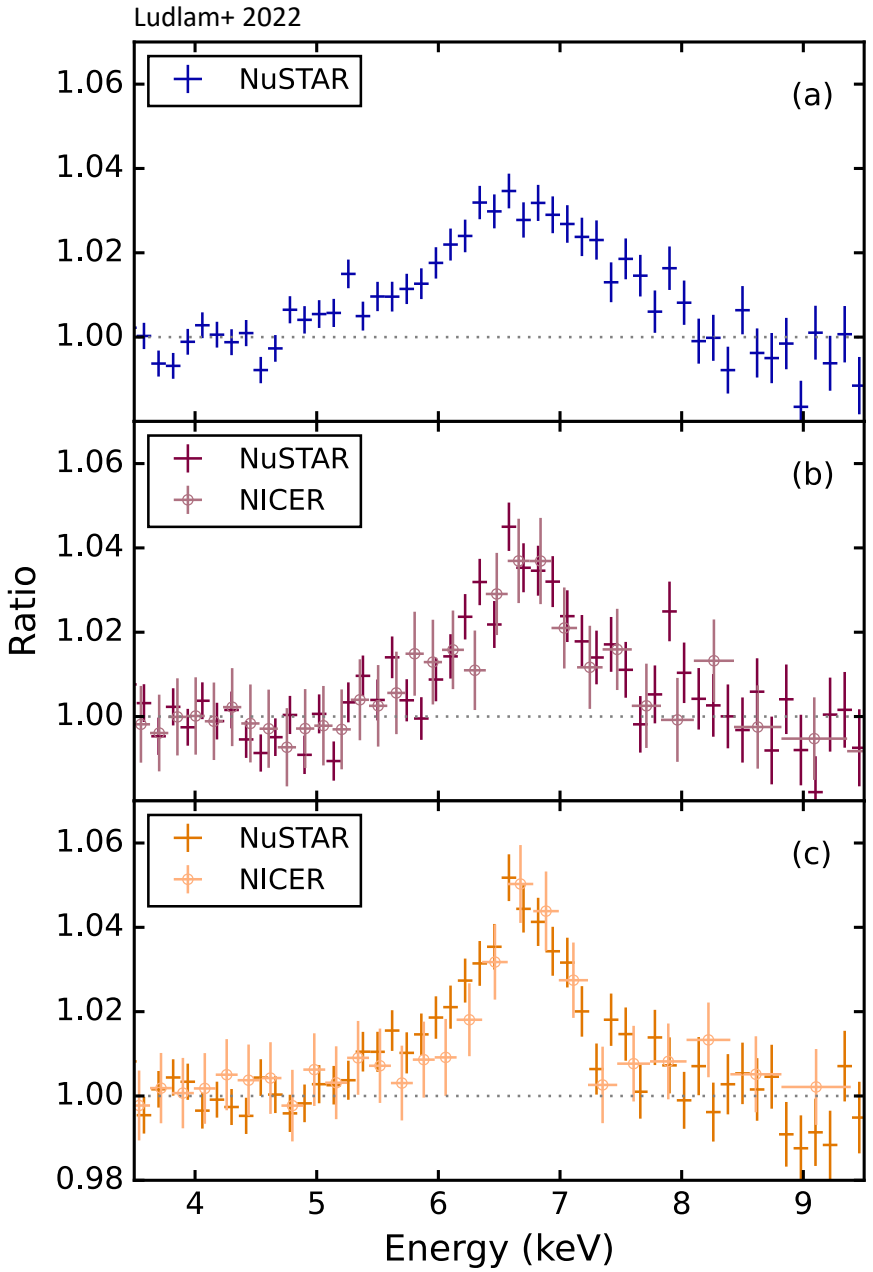
$$\log(R_{max} - R_*) \simeq 5.02 + 0.245 \left| \log \frac{\dot{M}}{10^{-9.85}} \right|^{2.19}$$

Popham & Sunyaev 2001

→ $R_{BL,\ MAX} = 1.2$ km

→ $R_{in,\ reflection} = 12.4 - 13.3$ km

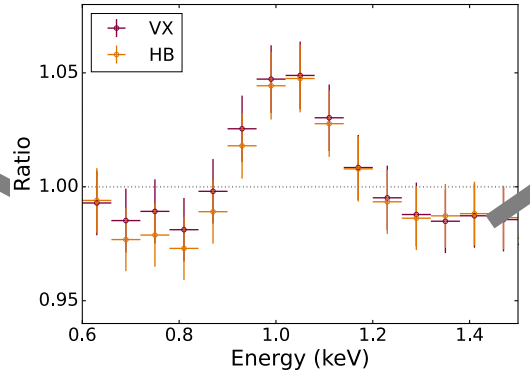
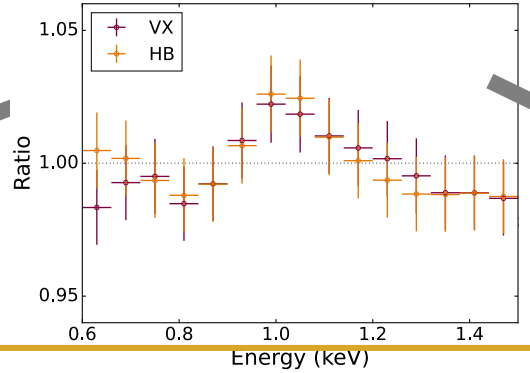
$R_{NS} \leq 12.1$ km



Cygnus X-2

- Binary orbital period of 9.8 days at an inclination of ~63 degrees
- Has an optically determined mass estimate of $M_{NS} = 1.71 \pm 0.21\ M_{\odot}$ (Casares+ 2008)
- Spectra with >10^6 counts/spec
  - (a) Normal Branch from Obs1
  - (b) Vertex from Obs2
  - (c) Horizontal Branch from Obs3

Spectral Modeling

Two different continuum models	Two independent reflection models	1 keV feature	Results
Accretion disk + Single-temp blackbody + power-law	+ RELXILLNS		$R_{in} = 6.0 - 7.0\ R_g$ $i = 67 \pm 4$ degrees
Accretion disk + Thermal Comptonization	+ Rdblur*rfxconv		$R_{in} = 6.0 - 8.5\ R_g$ $i = 60 \pm 10$ degrees

- Regardless of the various spectral model choice, the accretion disk remains close to the neutron star in each branch

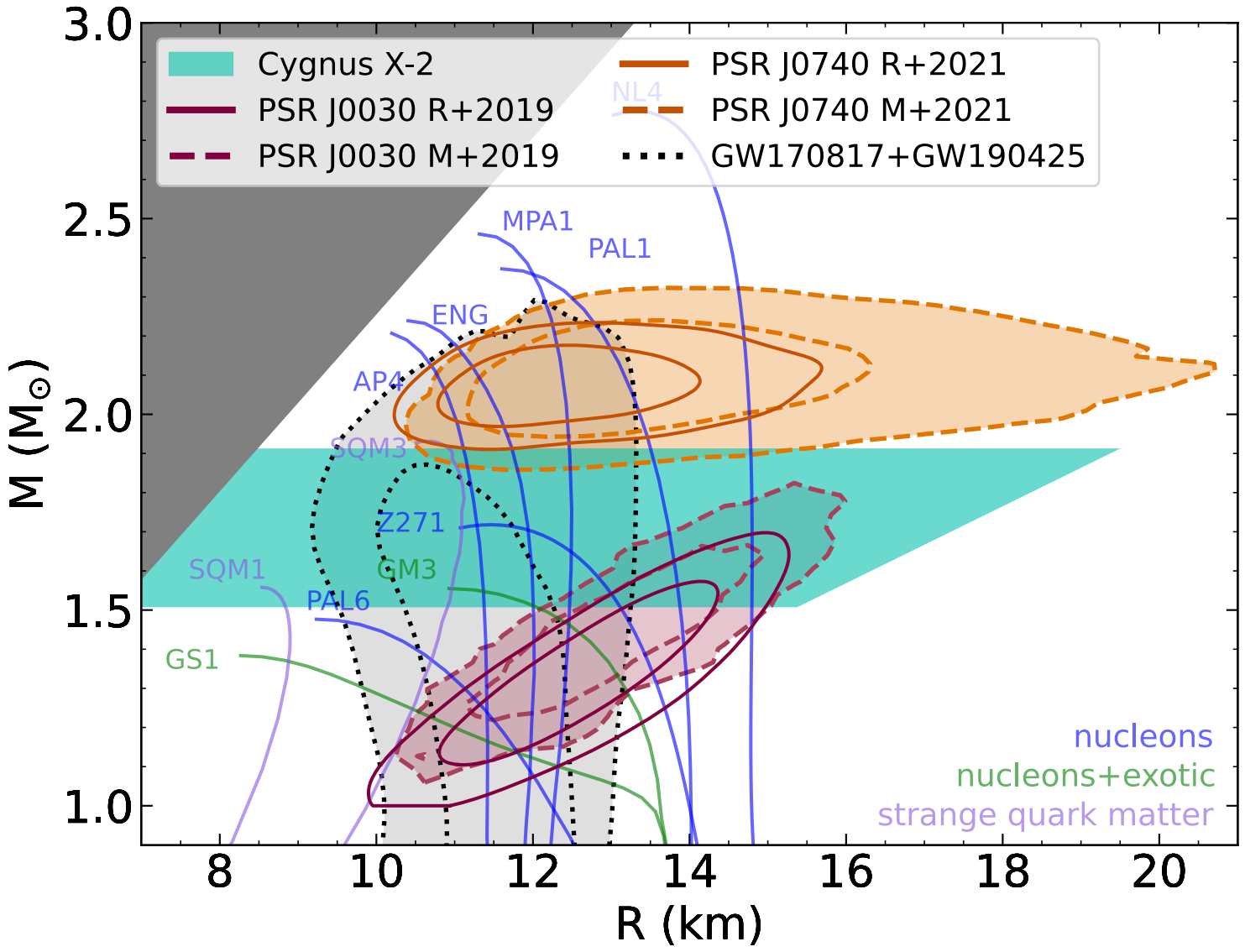
M-R Plane

$$R_g = GM_{NS}/c^2$$
$$M_{NS} = 1.71 \pm 0.21\ M_\odot$$

- $R_{NS} \leq 19.5$ km for $M = 1.92\ M_\odot$
- $R_{NS} \leq 15.3$ km for $M = 1.50\ M_\odot$

- R+2019: Riley+ 2019, ApJL, 887, L21
- M+2019: Miller+ 2019, ApJL, 887, L24
- R+2021: Riley+ 2021, ApJL, 918, L27
- M+2021: Miller+ 2021, ApJL, 918, L28
- GW constraint from Raiijmakers+ 2021, ApJL, 918, L29

Adapted from Ludlam+ 2022



Conclusion

Combined passband of *NICER* and *NuSTAR* can reveal the entire reflection spectrum and shed light on accretion disk properties

The *NICER* and *NuSTAR* cross-calibration constant within 5% with a small slope offset between missions

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