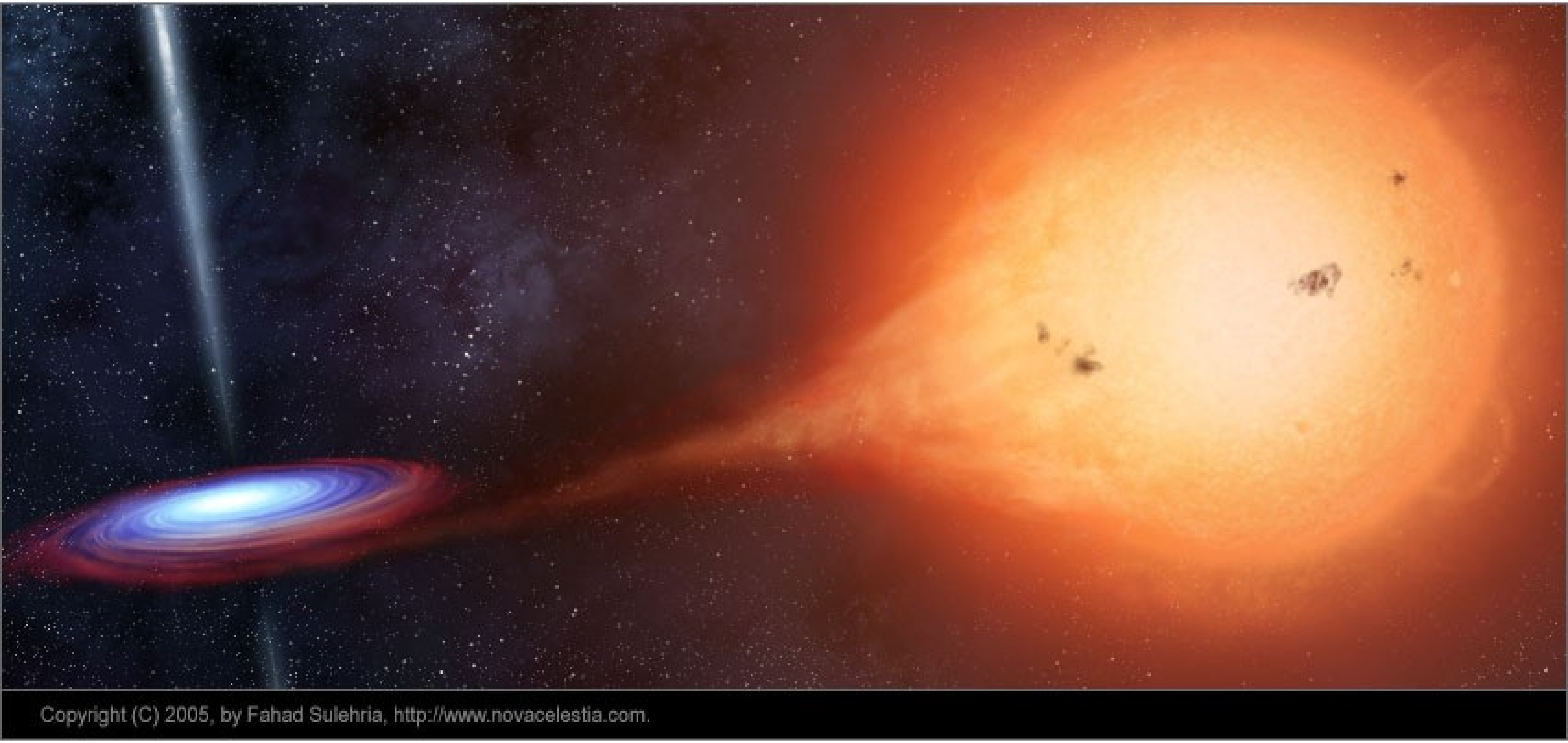
The *NICER-NuSTAR* View of NS LMXBs



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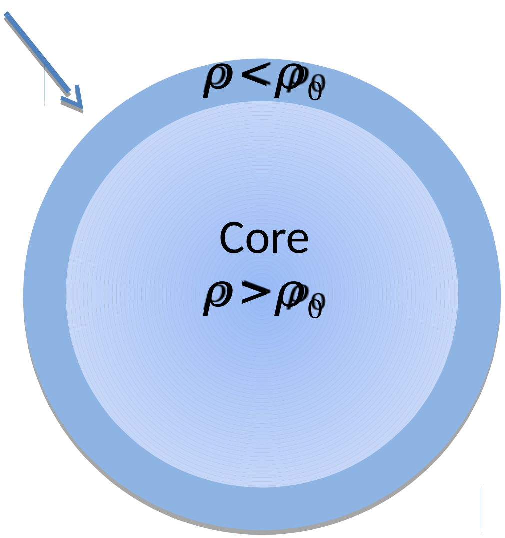
Collaborators: J. M. Miller, M. Bachetti, D. Barret, E. M. Cackett, T. Dauser, N. Degenaar, A. C. Fabian, J. A. García, L. Natalucci, M. L. Parker, J. A. Tomsick, NICER bursts & accretion working group

Why Neutron Stars?

- Earth based laboratories are unable to replicate cold, ultradense matter

Crust 10-20% of the NS



Neutron Star

?

Nucleons?

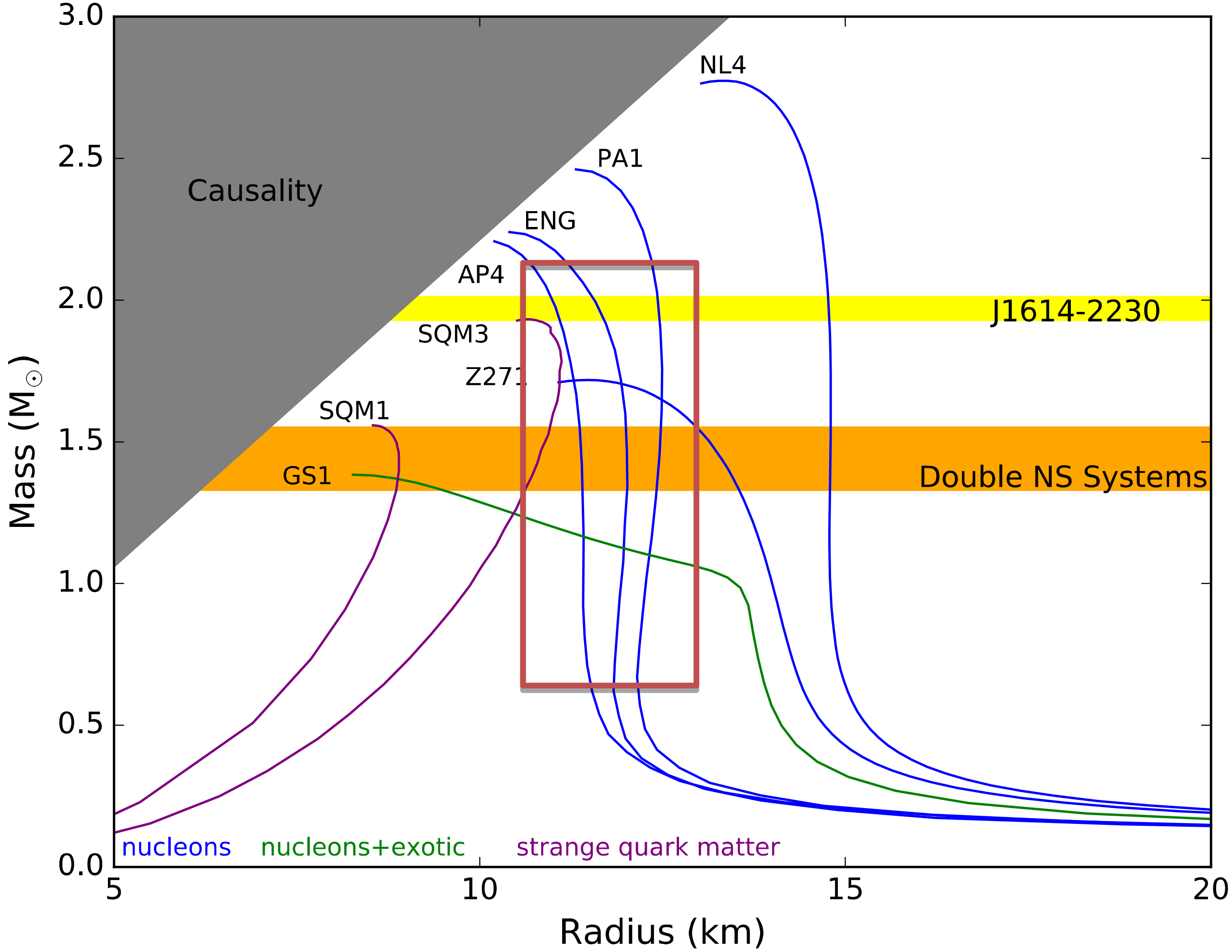
Exotic Matter?

Strange Quark Matter?

Combination?

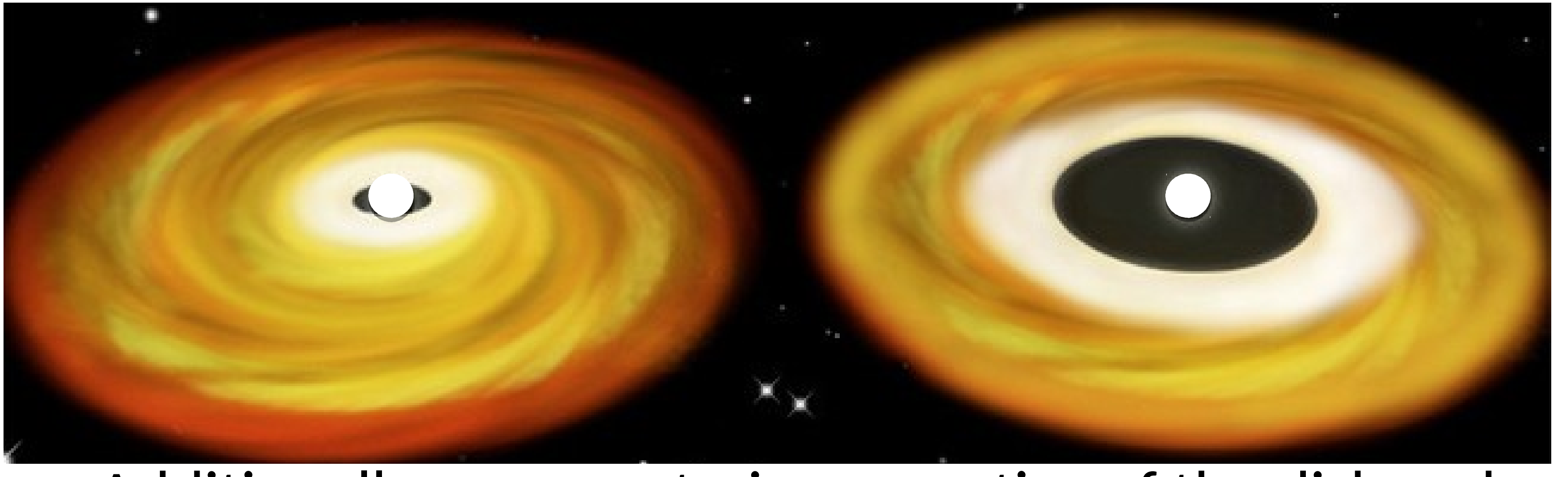
ρ_0 = nuclear saturation density
ρ_0 = nuclear saturation density

Equation of State



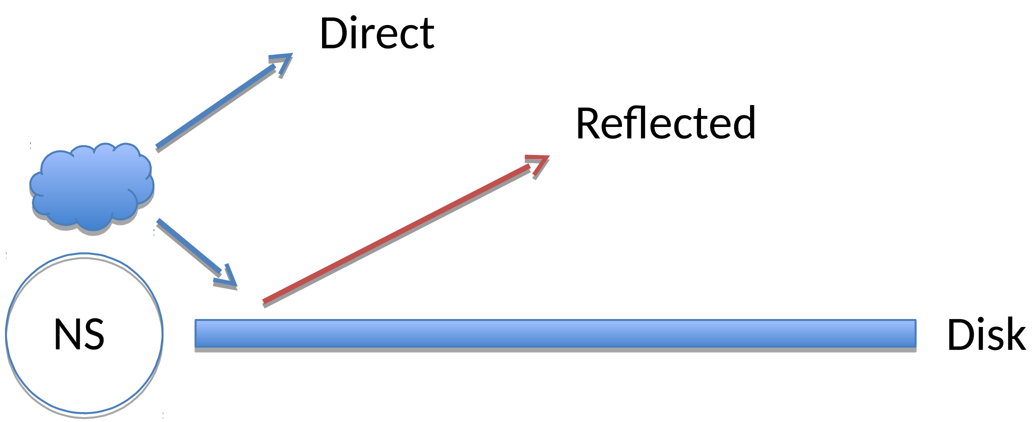
Why Study Disk Reflection in Neutron Stars?

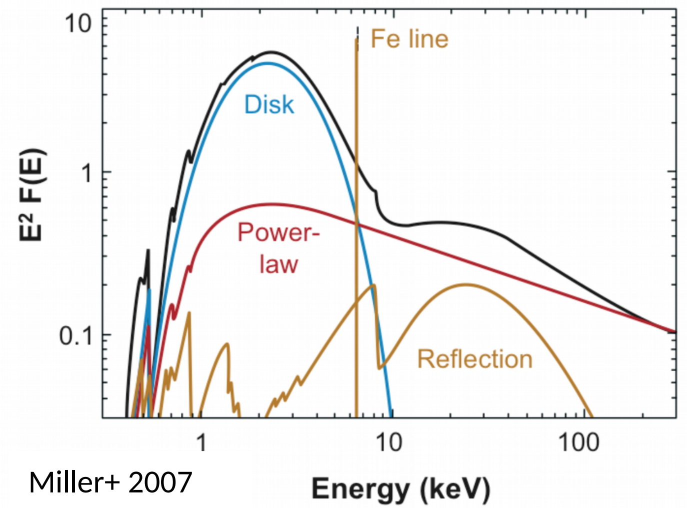
- The disk must truncate at or prior to the NS surface
- Whether the radius of a NS is > or < their innermost stable circular orbit (ISCO) is not known
- If R_{NS} < ISCO, you obtain an angle on the EOS



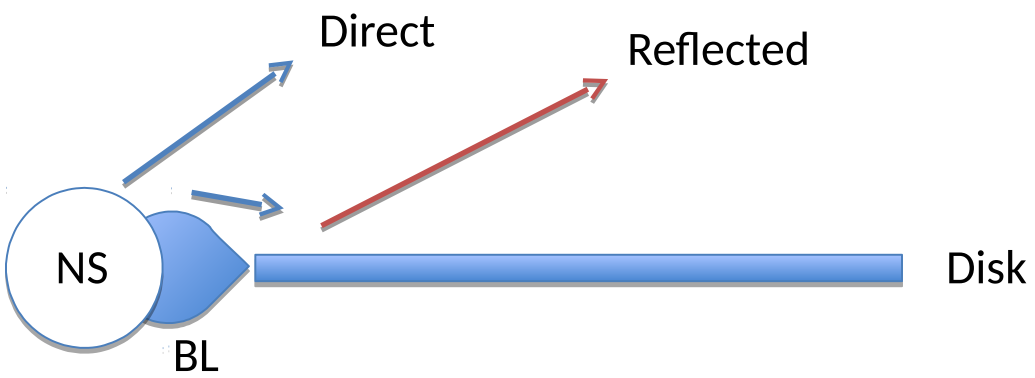
- Additionally, can constrain properties of the disk and NS itself

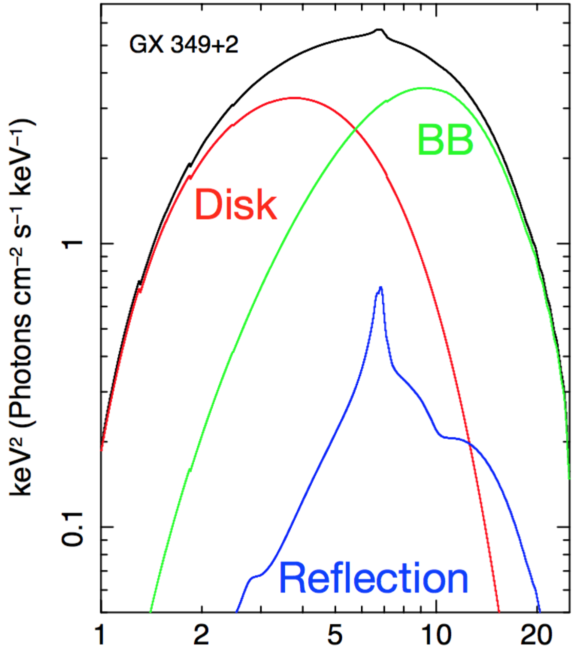
X-ray Reflection





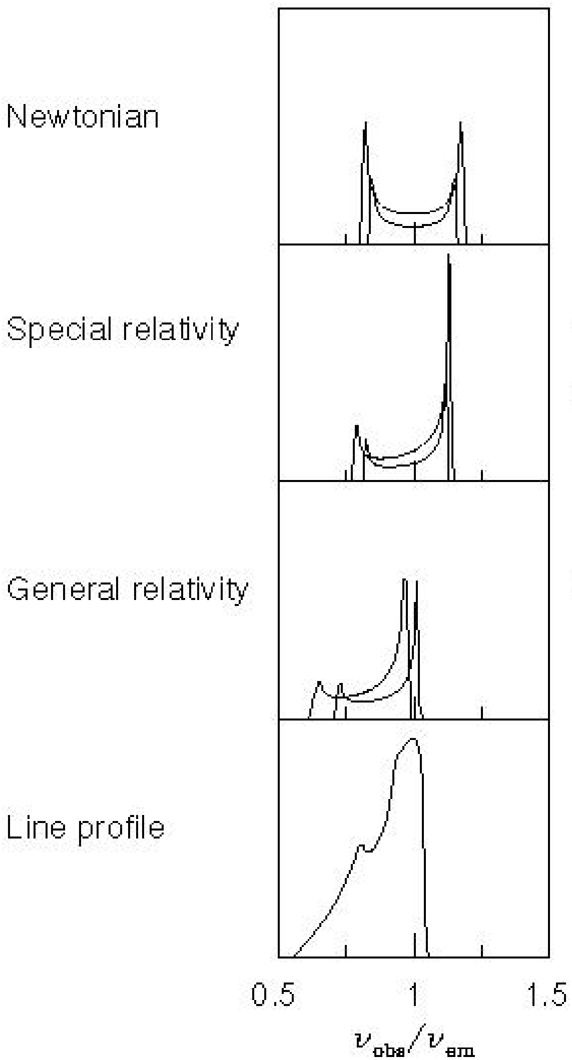
Miller+ 2007





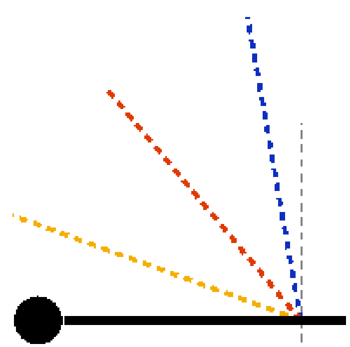
Cackett+ 2010

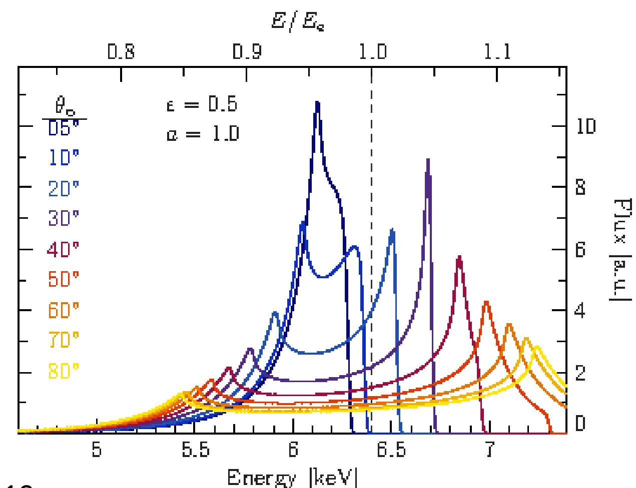
Fe Line Profile



Degree of broadening in the red wing directly correlates with proximity to compact object.

Broadening in the blue wing indicates inclination.

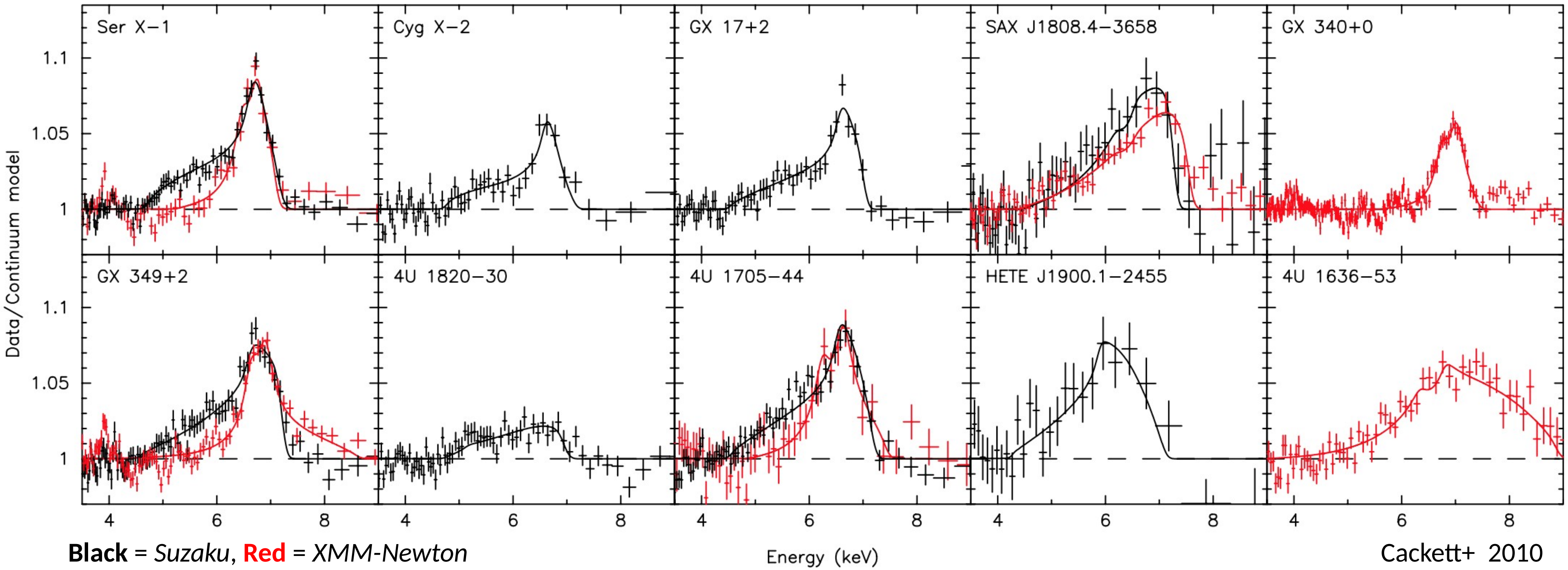




Fabian+ 1989

Dauser+ 2010, 2013

Fe Lines in Neutron Star Systems

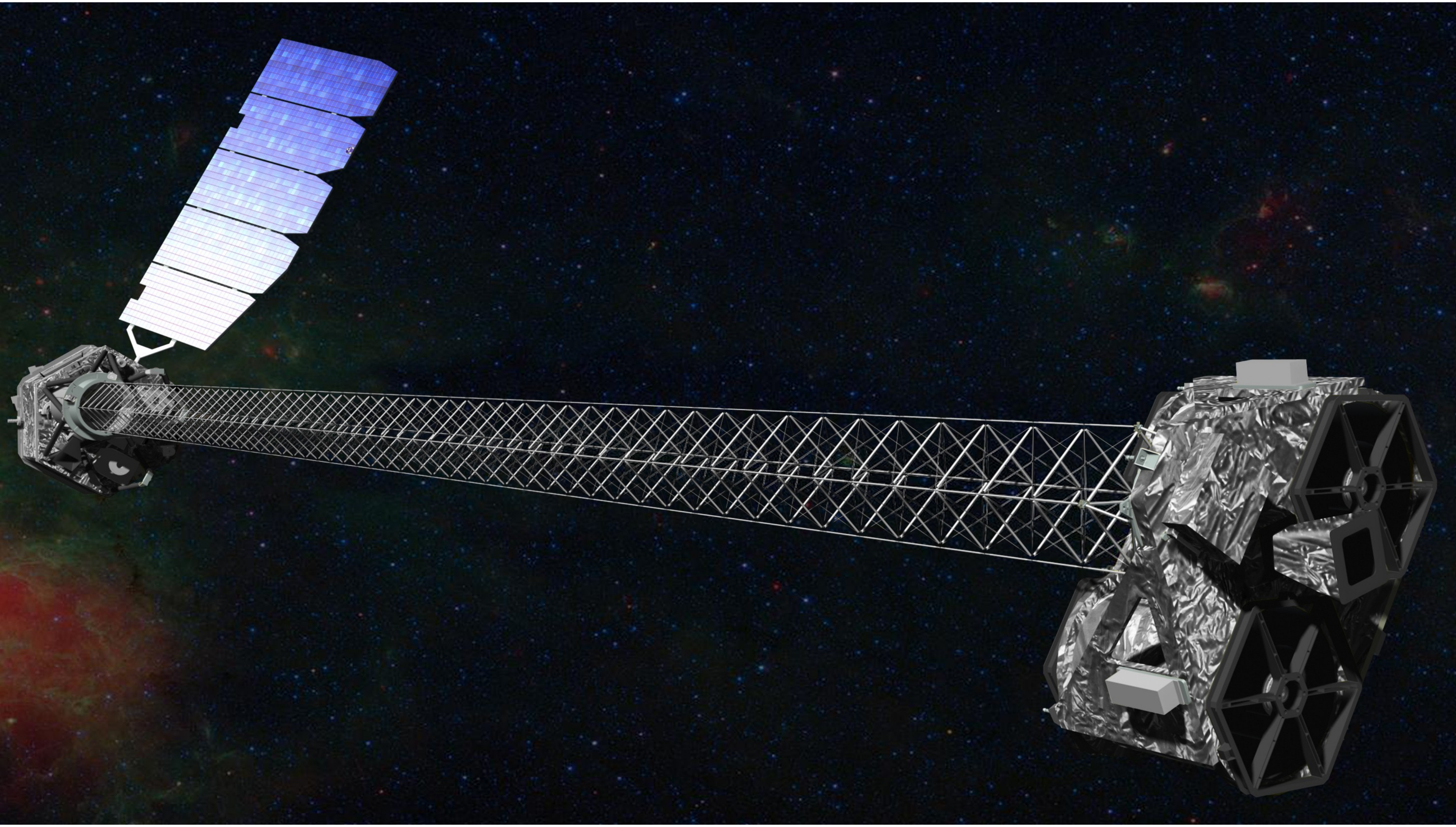


Black = *Suzaku*, **Red** = *XMM-Newton*

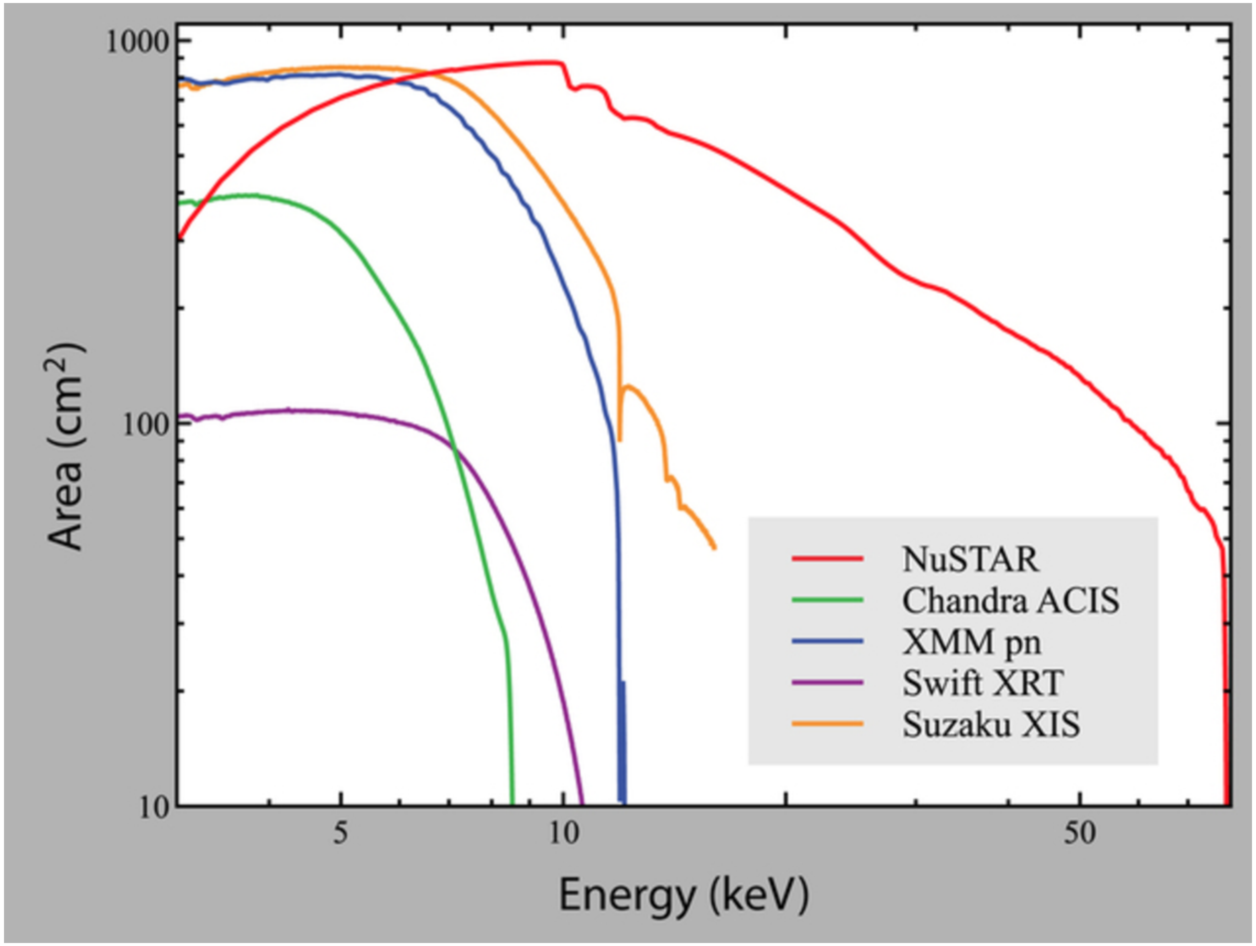
Cackett+ 2010

- Pile-up skews Fe line profile
  - Falsely narrows line (Miller+ 2010)
  - Problem for determining NS radii and location of disk as a function of mass accretion rate (Done & Diaz Trigo 2010, Ng+ 2010)

NuSTAR: Nuclear Spectroscopic Telescope Array

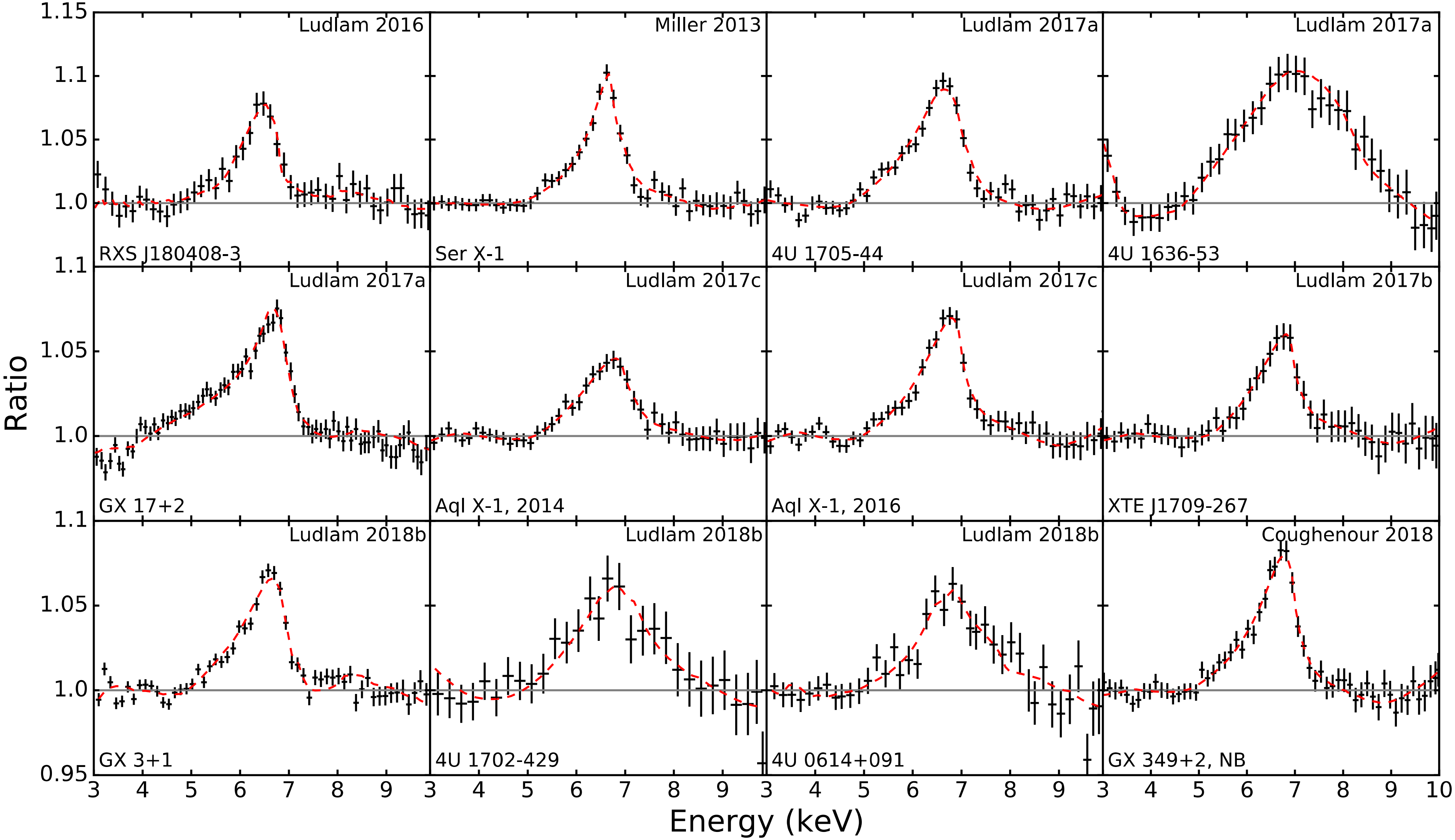


- Launched: June 13th, 2012
- 2 Focal plane modules, 4 detector each composed of 32x32 pixels with individual readouts

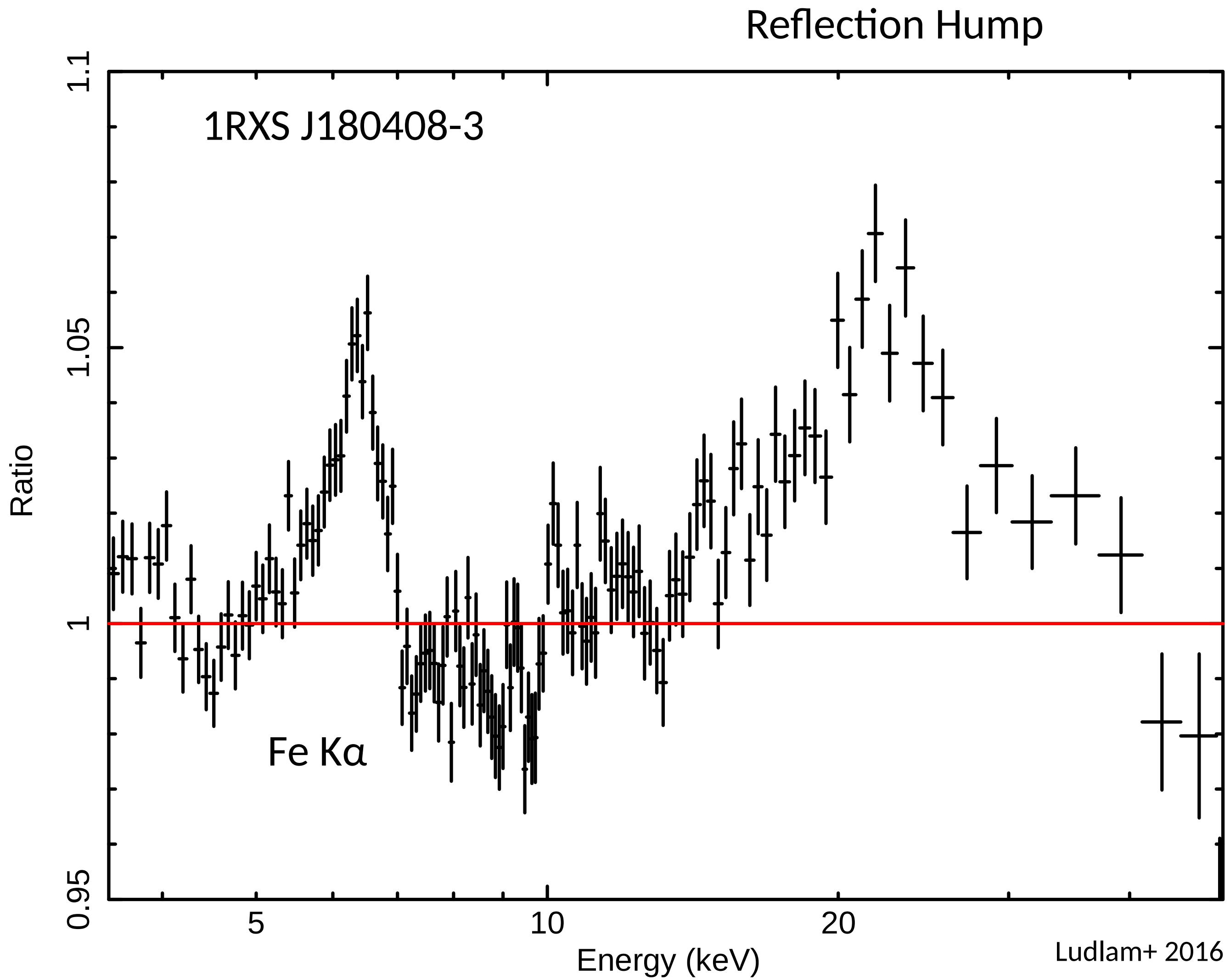


Harrison+ 2013

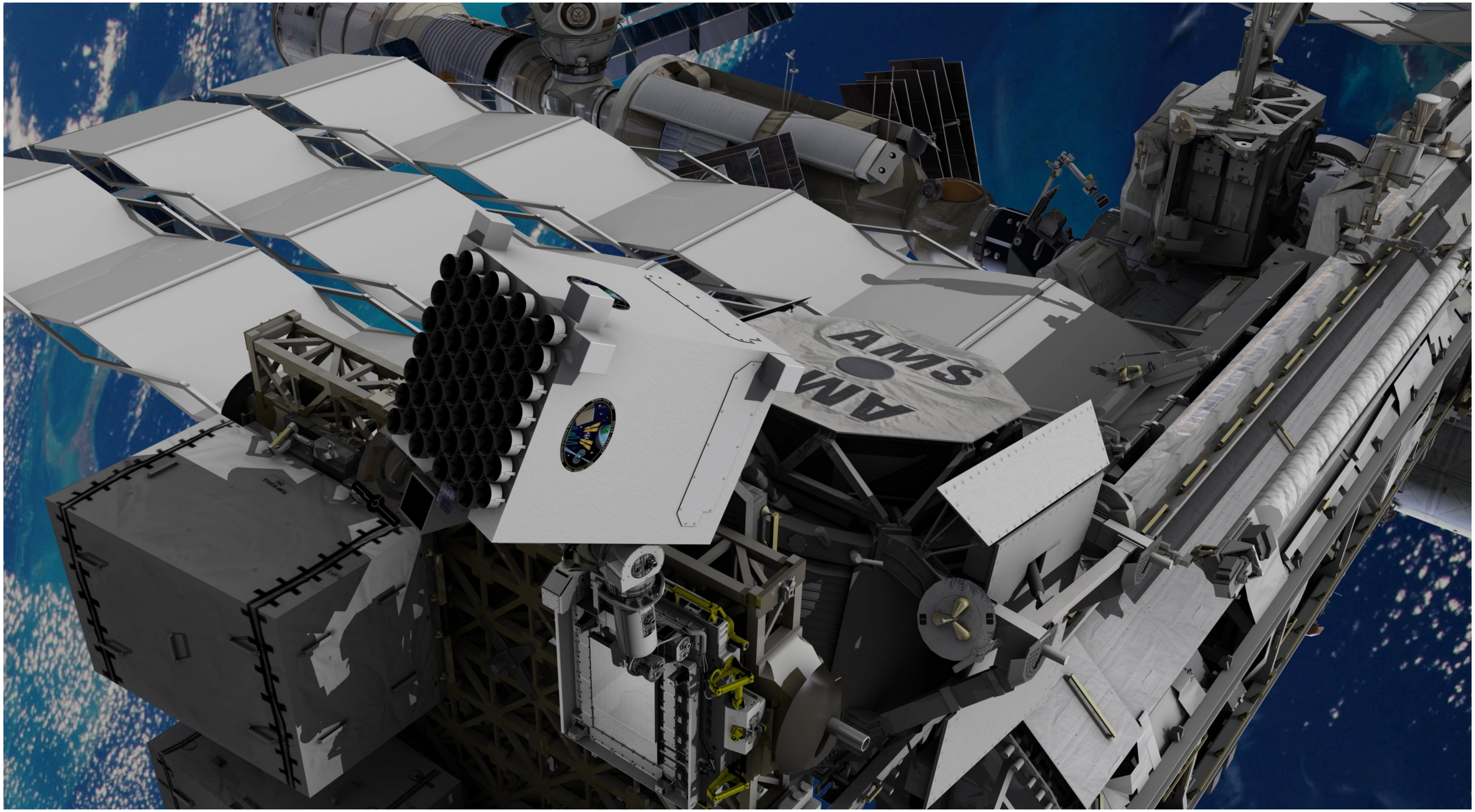
NuSTAR gives us an unhindered view of the Fe line region



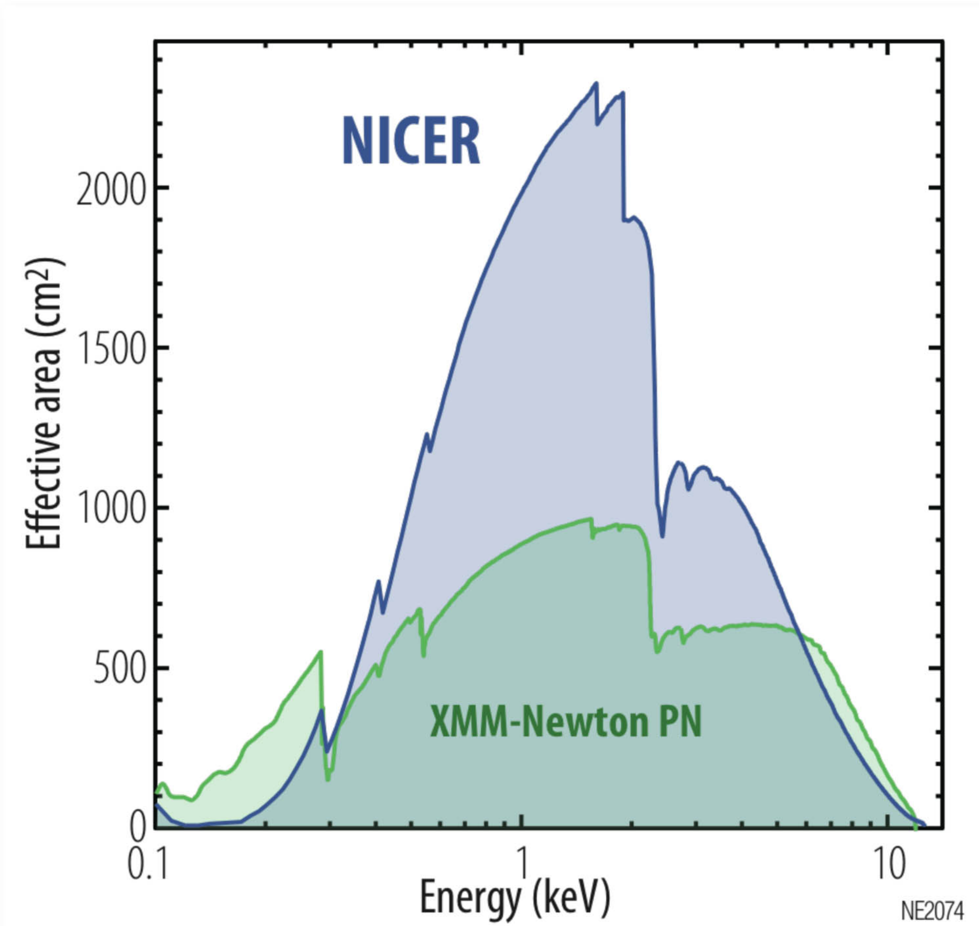
… and higher energy reflection feature



NICER: Neutron star Interior Composition ExploreR



- Launched on June 3rd, 2017
- 52 operational individual concentrating optics and silicon detectors



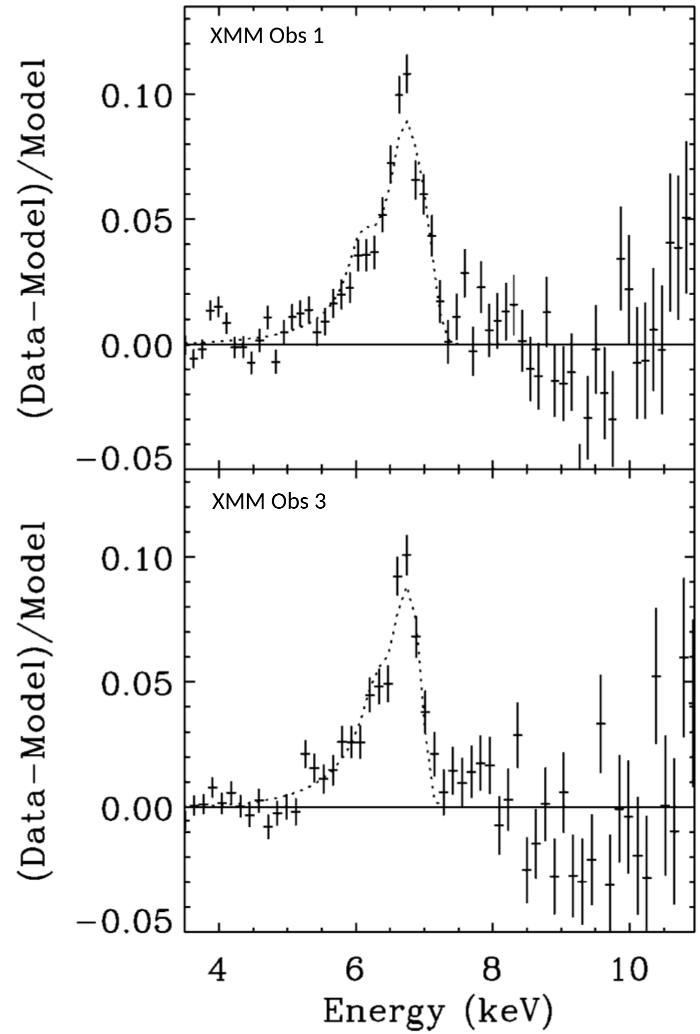
Gendreau, Arzoumanian, Okajima+ 2012

- Time resolution of 0.3 microseconds
  - 25x better than RXTE

- Energy resolution
  - 85 eV @ 1 keV
  - 137 eV @ 6 keV

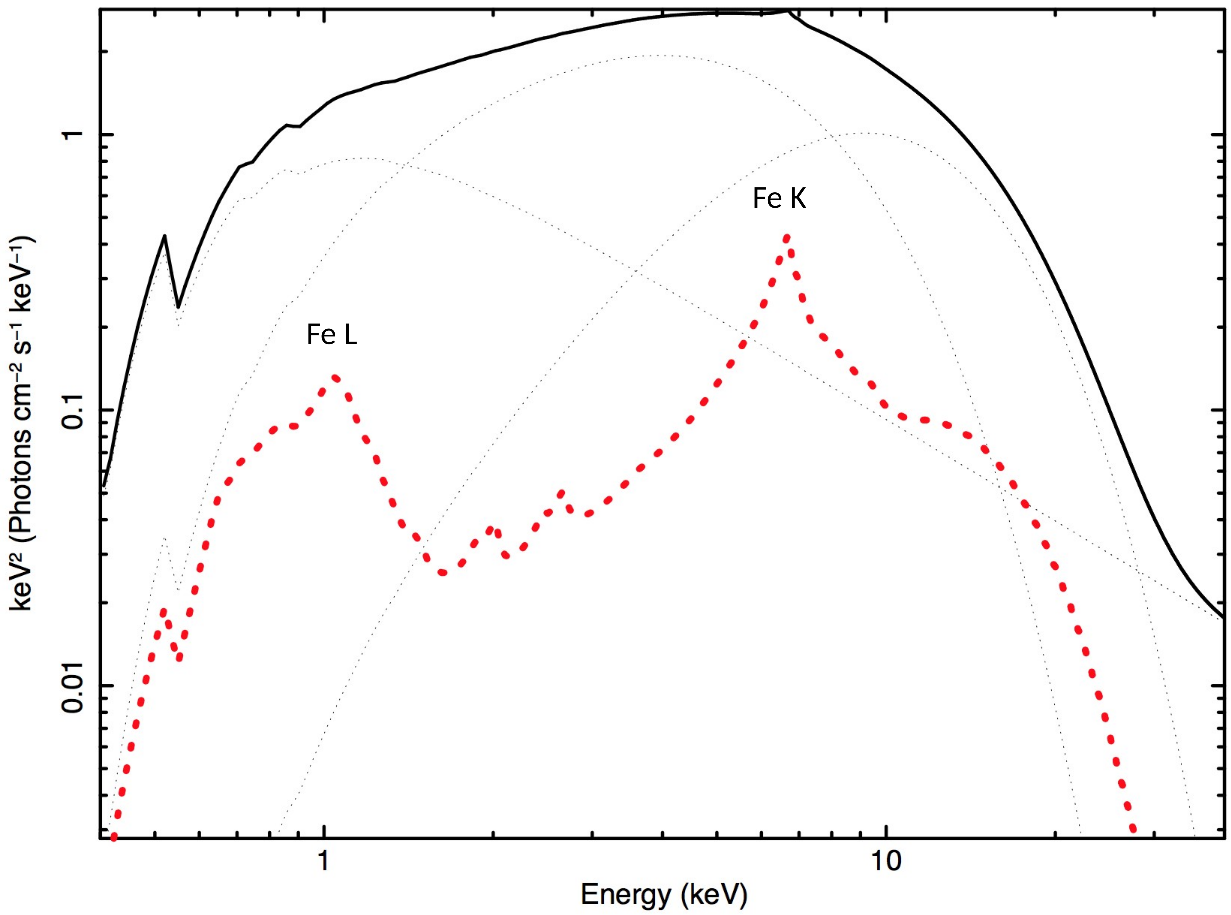
Serpens X-1

- Source located 7.7$\pm$0.9 kpc (Galloway+ 2008)
- Inclination $\pm$ 10° from optical and some X-ray studies (Cornelisse+ 2013, Miller+2013)
- First NS source in which relativistic lines were detected with *XMM-Newton*
  - 65.7 ks total exposure over three observations



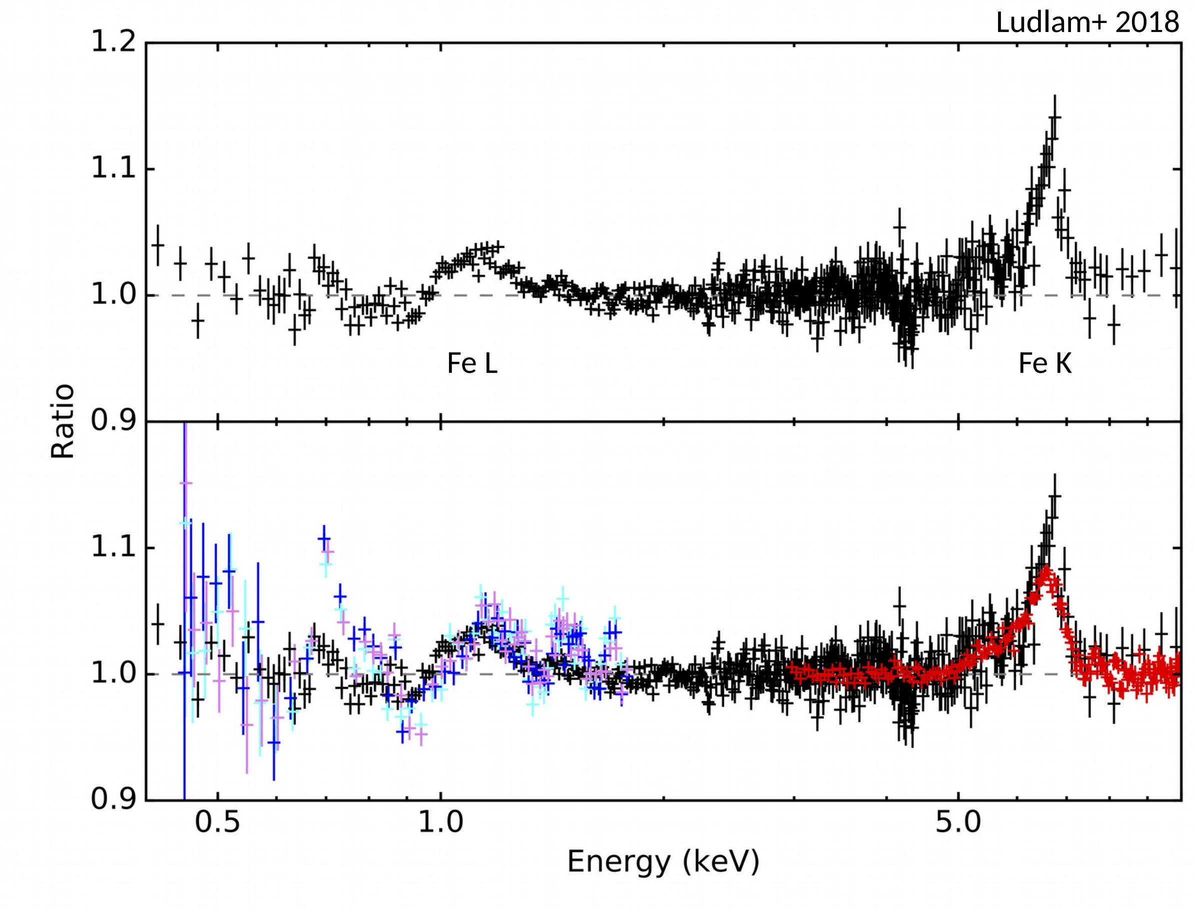
Bhattacharyya & Strohmayer 2007

Predictions of Reflection



The best fit reflection model from the *NuSTAR* data predicts a strong low-energy reflection component near 1 keV.

NICER Observations of Ser X-1

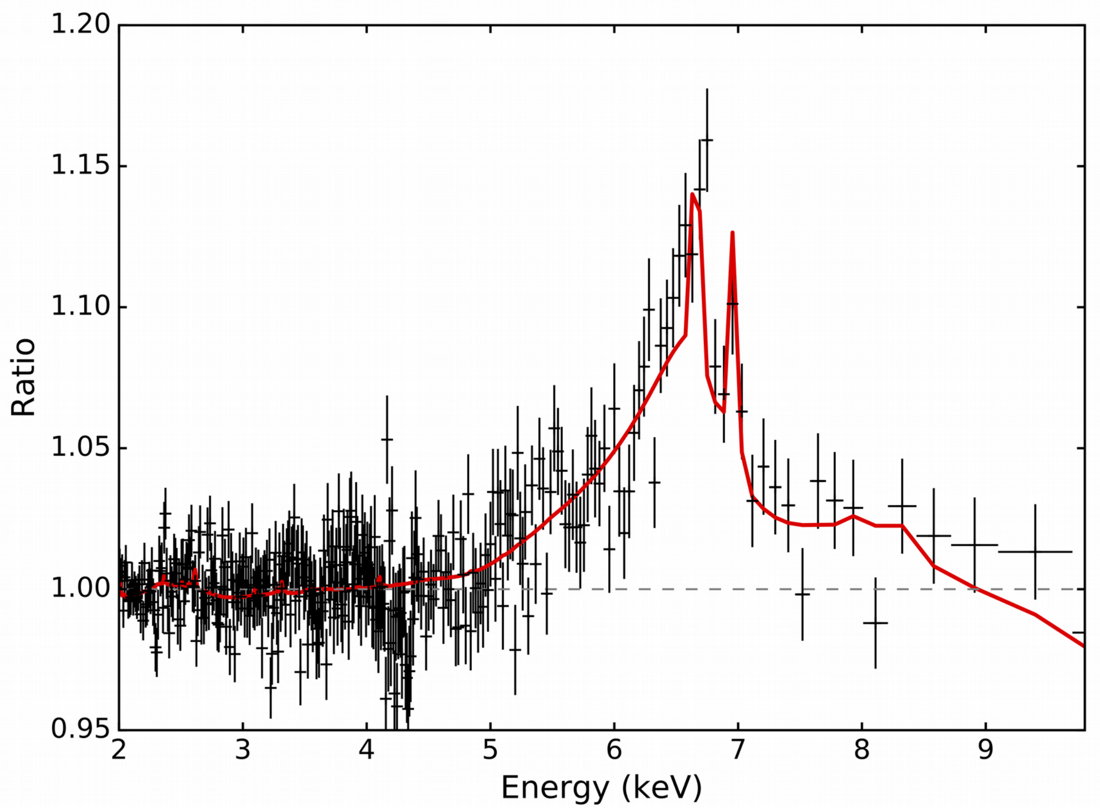


Ratio of data to the continuum model for <u>4.5 ks</u> of *NICER* exposure (black), <u>30.5 ks</u> of *NuSTAR* data (red), and <u>65.7 ks</u> of *XMM-Newton*/RGS data (blue, purple, & cyan).

Fe K Line with *NICER*

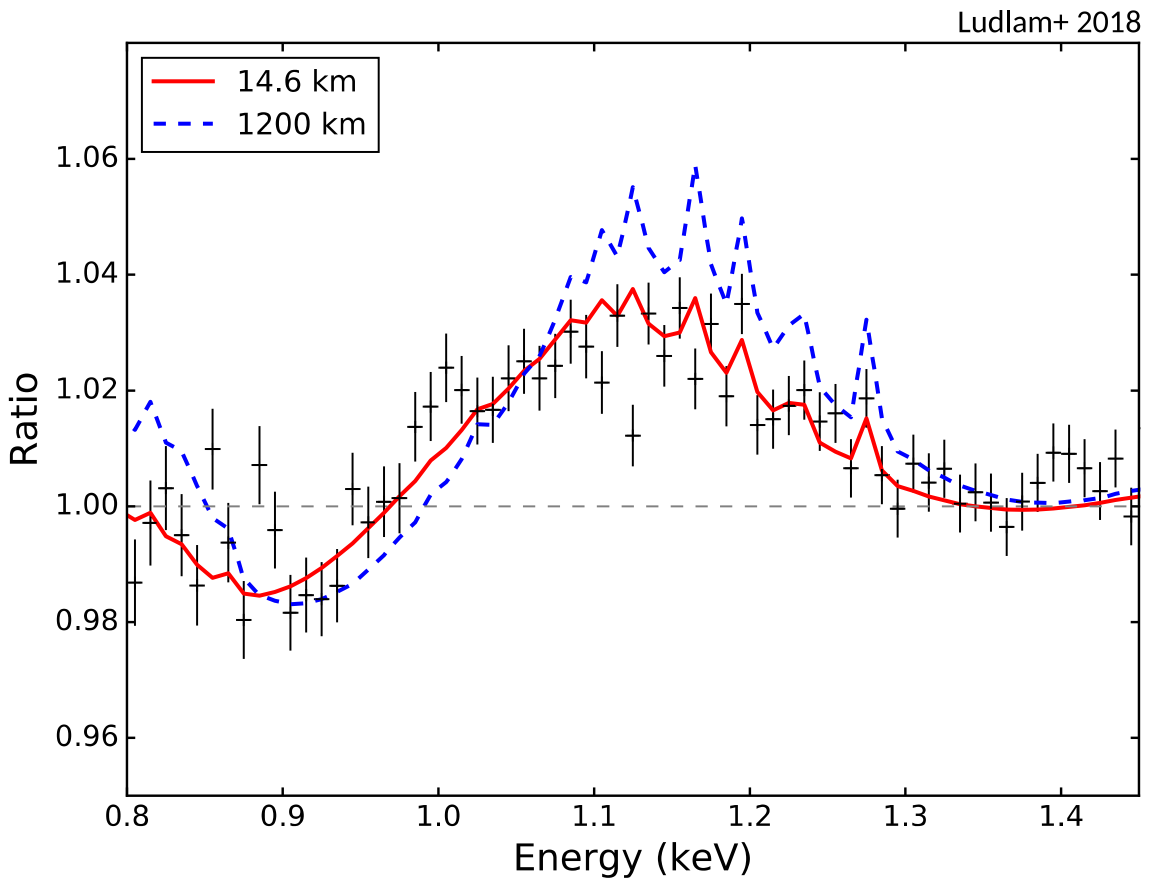
The predicted line profile (red) from the preliminary version of the fully self-consistent reflection model RELXILLNS (Dauser, García, Ludlam+, in prep.).

- High density disk near 10^{19} cm^{-3}
- Both the Fe XXV and Fe XXVI K alpha lines are produced at similar strength



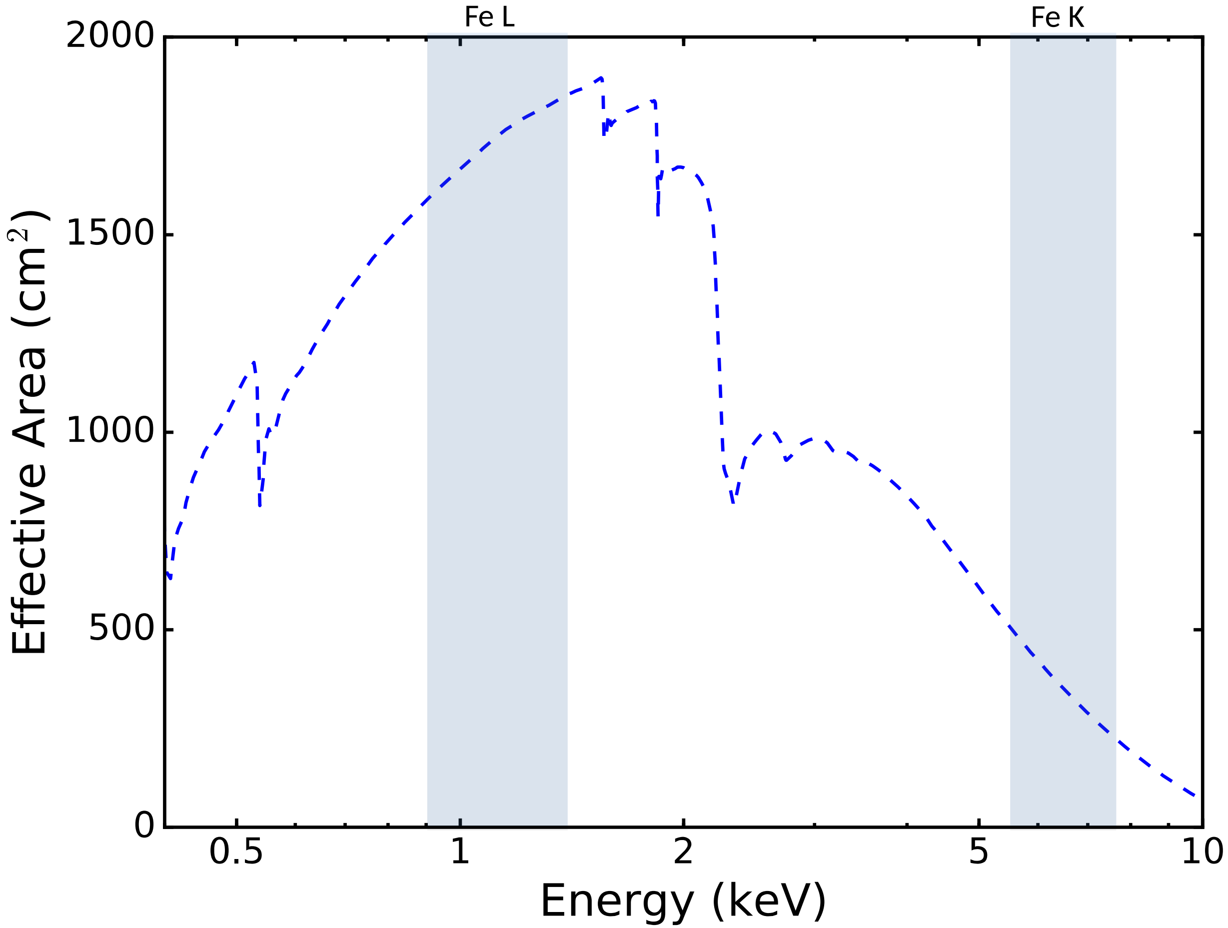
➢ This highlights energy resolution of *NICER* and the need to fit a reflection spectrum, not just a single line model.

Fe L Complex



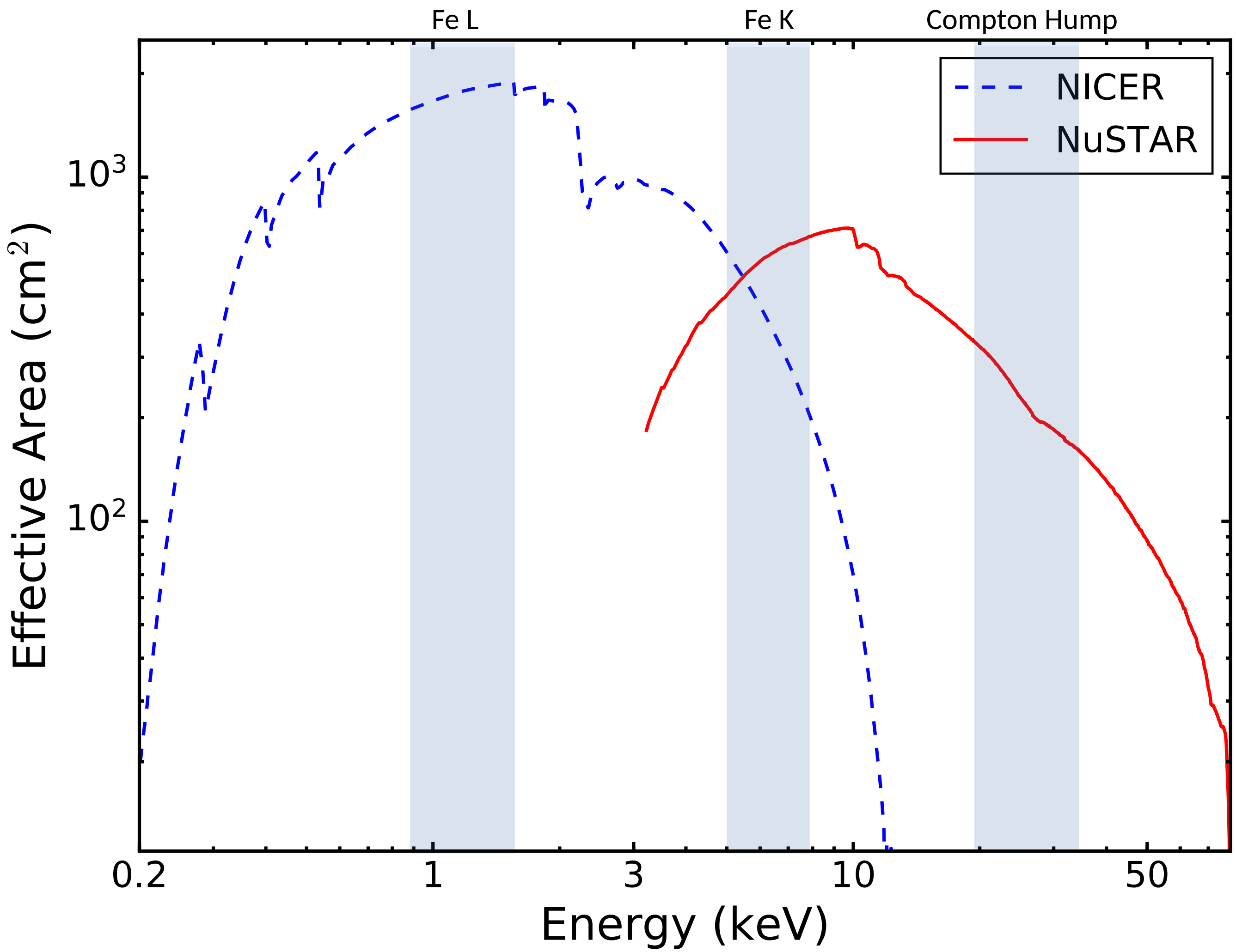
- The Fe L complex with the best fit model predicted line profile (red) and the local-frame emission (blue) for comparison.
- Narrow emission lines in the broad Fe L region likely due to a lower-Z element such as Mg III-VII.

NICER's Collecting Area



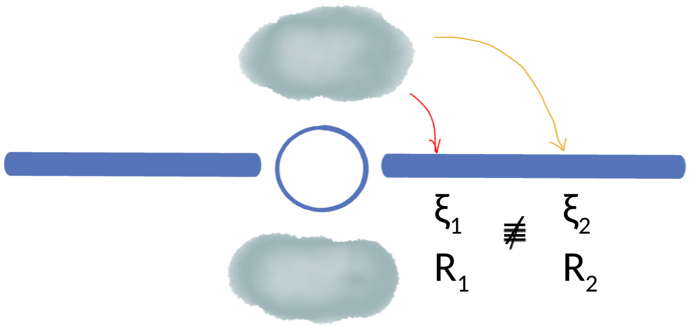
- There is nearly 5 times more collecting area in the Fe L band than in the Fe K band.
- *NICER* captures ~ 1.34×10^6 photons in the Fe L band and ~ 2.75×10^5 photons in the Fe K band in just 4.5 ks.

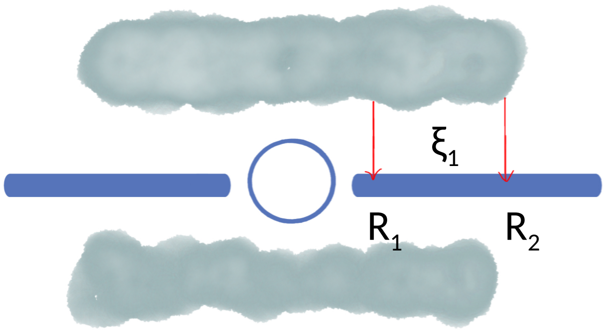
Collecting Area of *NICER* & *NuSTAR*



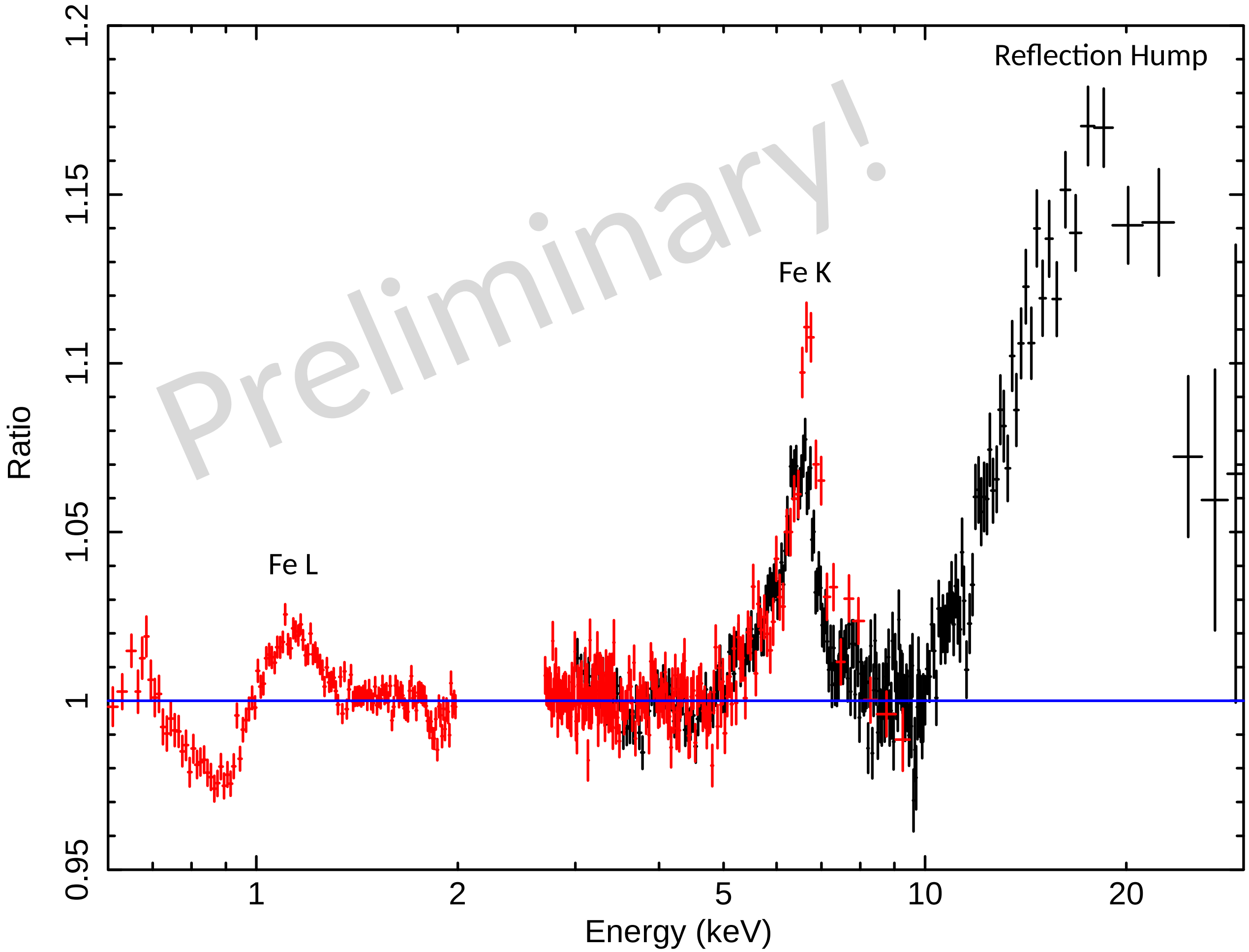
Probes w/ Multiple Emission Lines

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





Simultaneous *NuSTAR* & *NICER* data



NICER ~ 15 ks exposure in **red**

NuSTAR ~ 50 ks (combined FPMA & FPMB) in **black**

Summary

- Fe lines are a valuable tool to learn about NS properties and provide a method to obtain upper limits on NS radii

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

Thank you!

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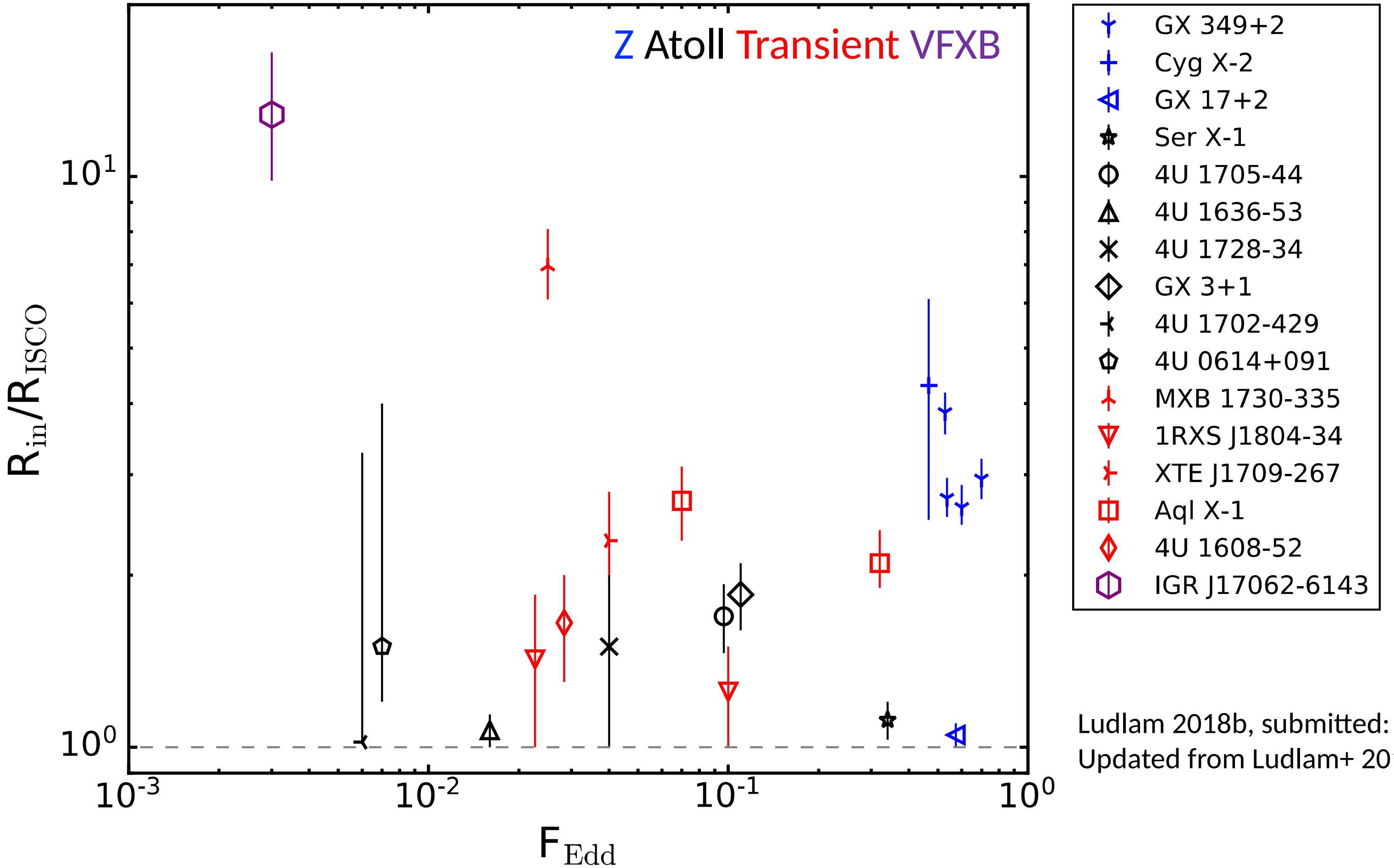
University of Michigan

Inner Disk Radii with *NuSTAR*

- Eddington Fraction, F_{Edd}, is a proxy for mass accretion rate

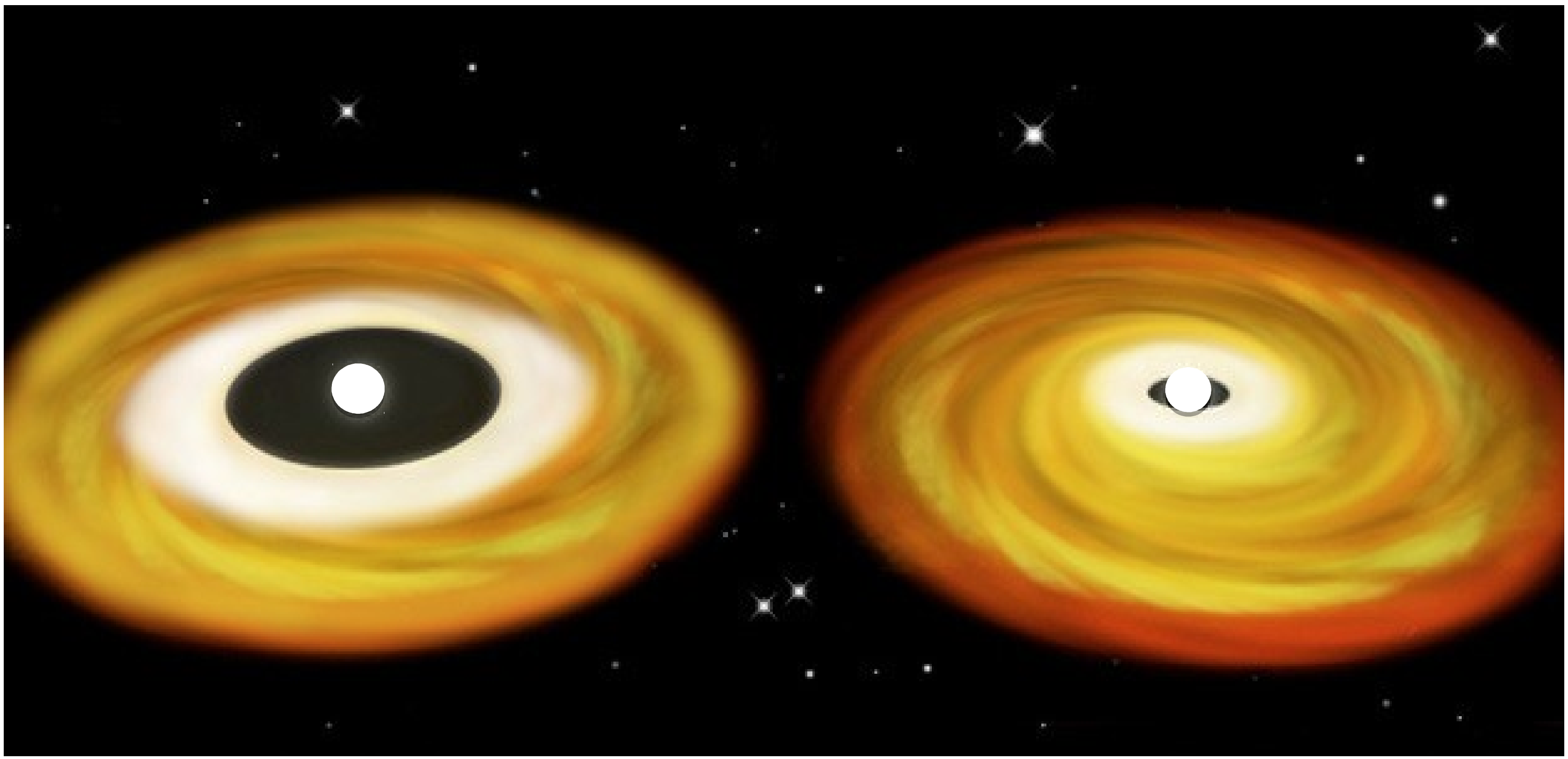


Ludlam 2018b, submitted:
Updated from Ludlam+ 2017a

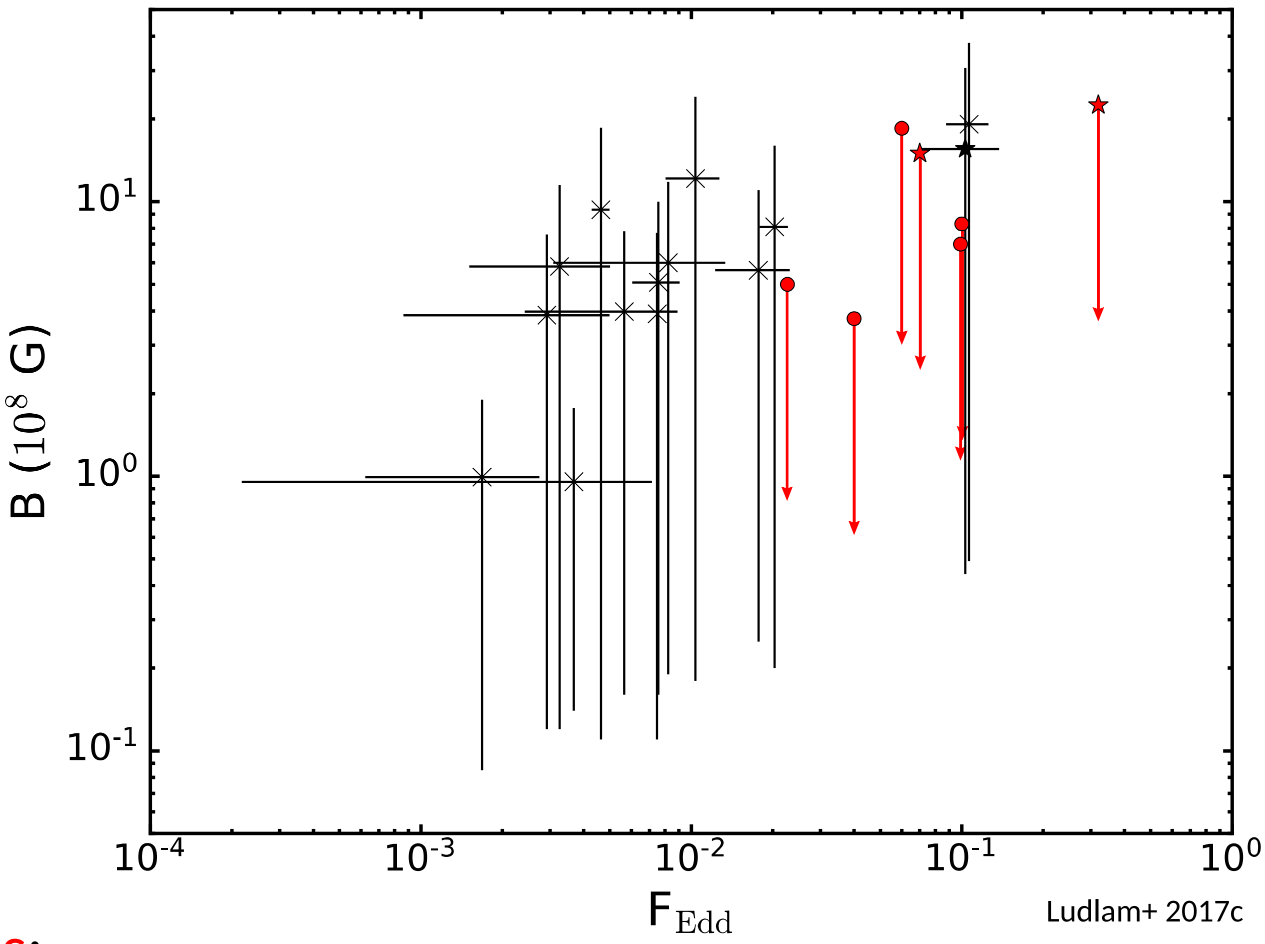
(1) GX 349+2: Coughenour+ 2018; (2) Cyg X-2: Mondal+ 2018; (3) GX 17+2, 4U 1705-44, 4U 1636-53: Ludlam+ 2017a; (4) Ser X-1: Miller+ 2013; (5) 4U 1728-34: Sleator+ 2016; (6) GX 3+1, 4U 1702-429, 4U 0614+091: Ludlam+ 2018b, submitted; (7) MXB 1730-335: van den Eijnden+ 2017; (8) 1RXS J1804-34: Ludlam+ 2016, Degenaar+ 2016; (9) XTE J1709-267: Ludlam+ 2017b; (10) Aql X-1: Ludlam+ 2017c; (11) 4U 1608-52: Degenaar+ 2015; (12) IGR J17062-6143: van den Eijnden+ 2018

Possible Scenarios for Truncation

- Magnetospheric truncation?
- Boundary Layer?



Magnetic Fields



Ludlam+ 2017c

Red Points:

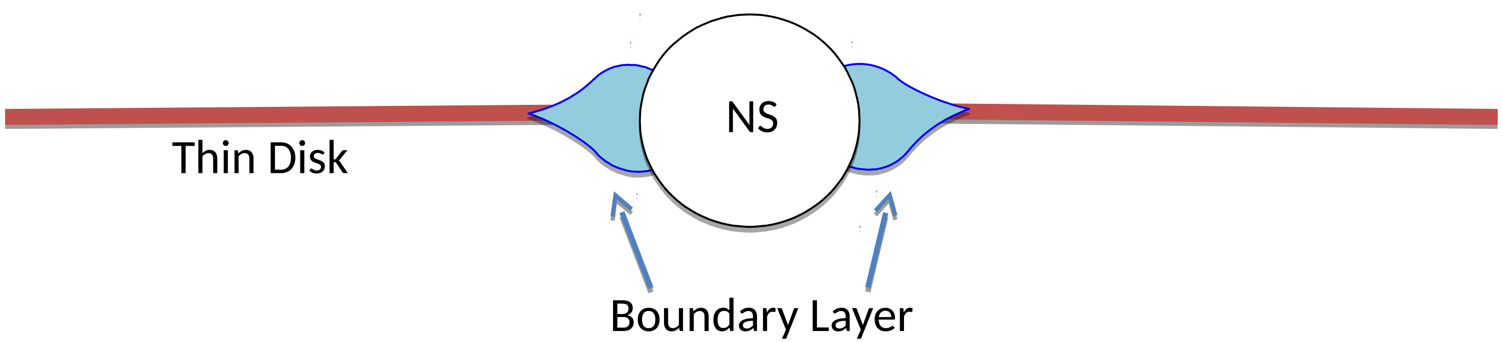
- Magnetic fields estimated from Fe lines within truncated inner disk

Black Points:

- AMXPs from Mukherjee+ 2015

Boundary Layer

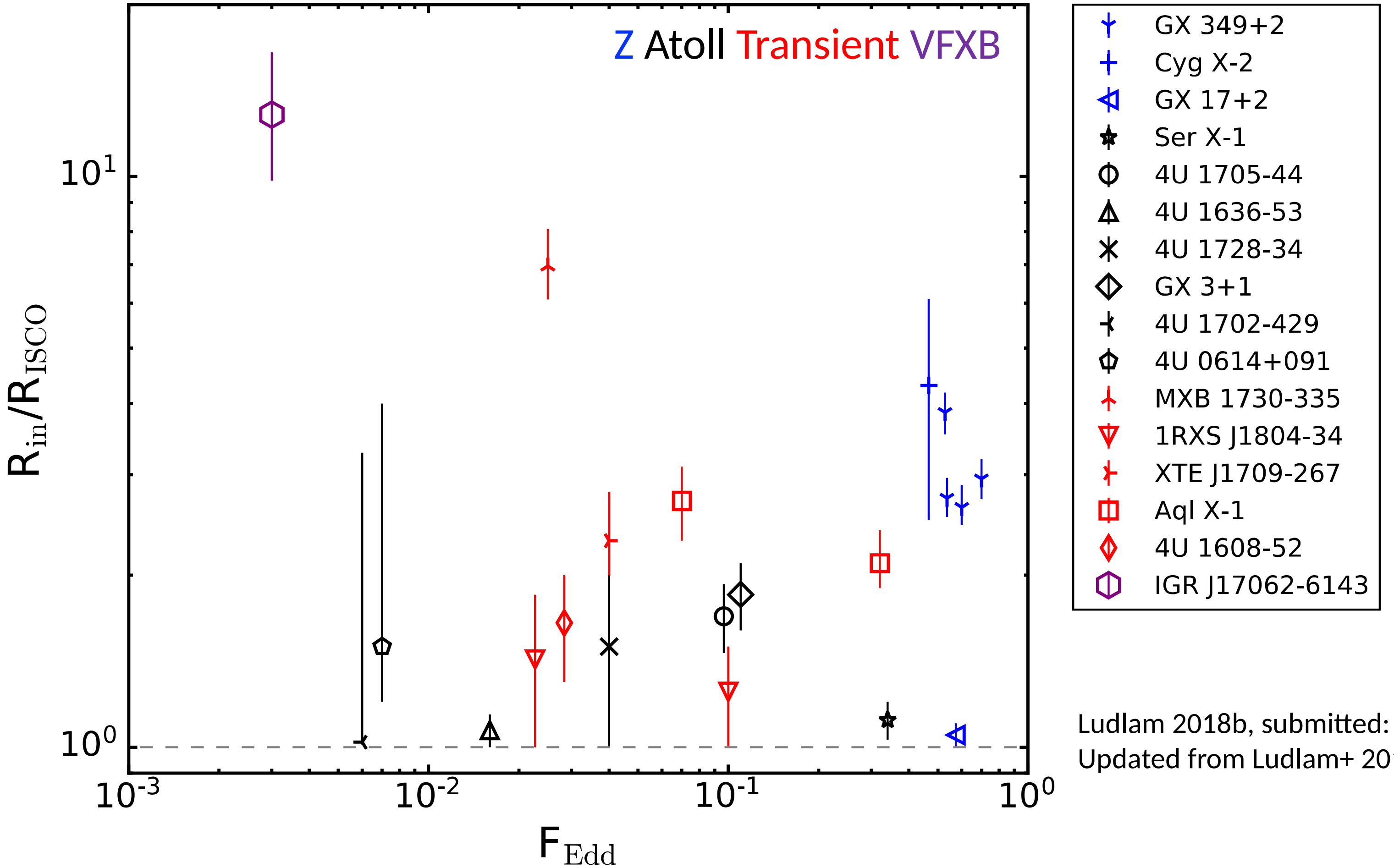
- Region where the rapidly spinning accreting material reaches the slower spinning NS
- Gas cannot cool efficiently
  - Radiation pressure matters
- Vertically and/or radially extended



- Can't directly measure BL in the *NuSTAR* bandpass

Inner Disk Radii with *NuSTAR*

- Eddington Fraction, F_{Edd}, is a proxy for mass accretion rate



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Turning ISCO into Physical Units

Bardeen et al. 1972 to convert ISCO to gravitational radii for a given spin.

ν_{spin} ----> $a = cJ/GM^2$

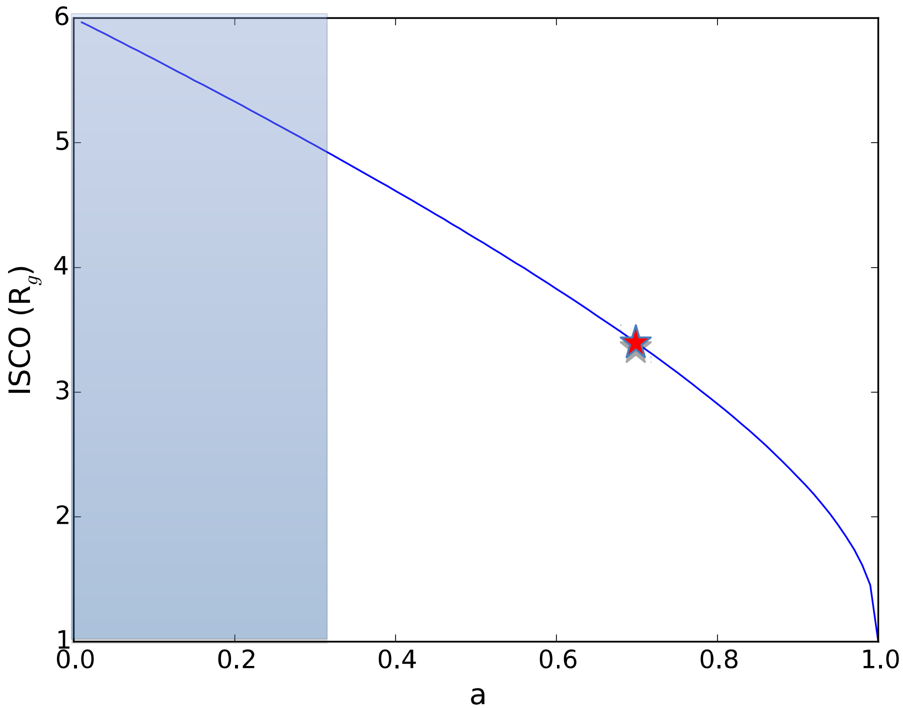
$J=(4/5)\pi MR^2\nu_{spin}$

4U 1636-53: ν_{spin} = 581.0 Hz (Galloway+ 2008)

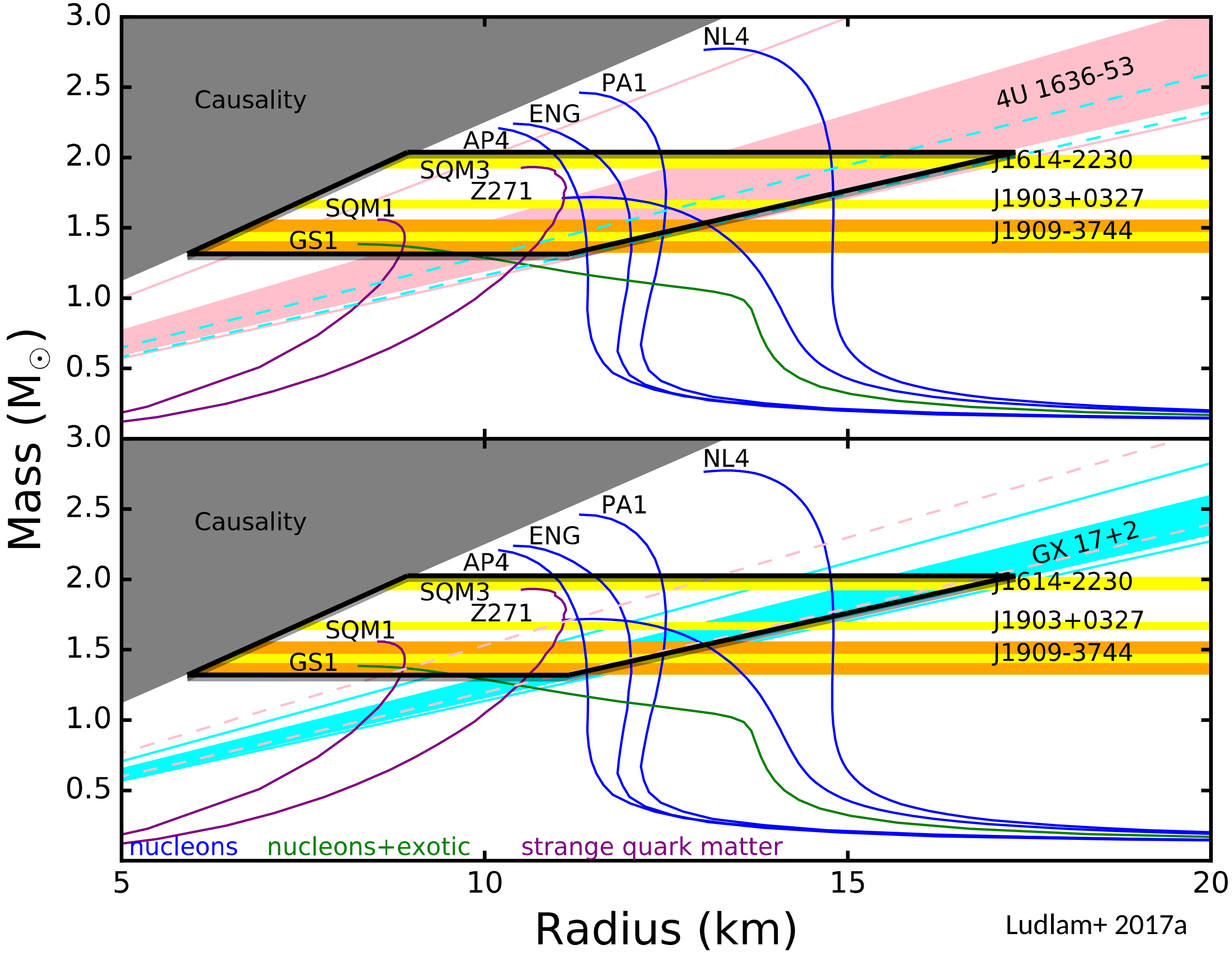
GX 17+2: ν_{spin} = 293.2 Hz (Wijnands+ 1997)

4U 1636-53: $0.10 \pm 0.08 < a < 0.45 \pm 0.25$

GX 17+2: $0.05 \pm 0.04 < a < 0.23 \pm 0.12$

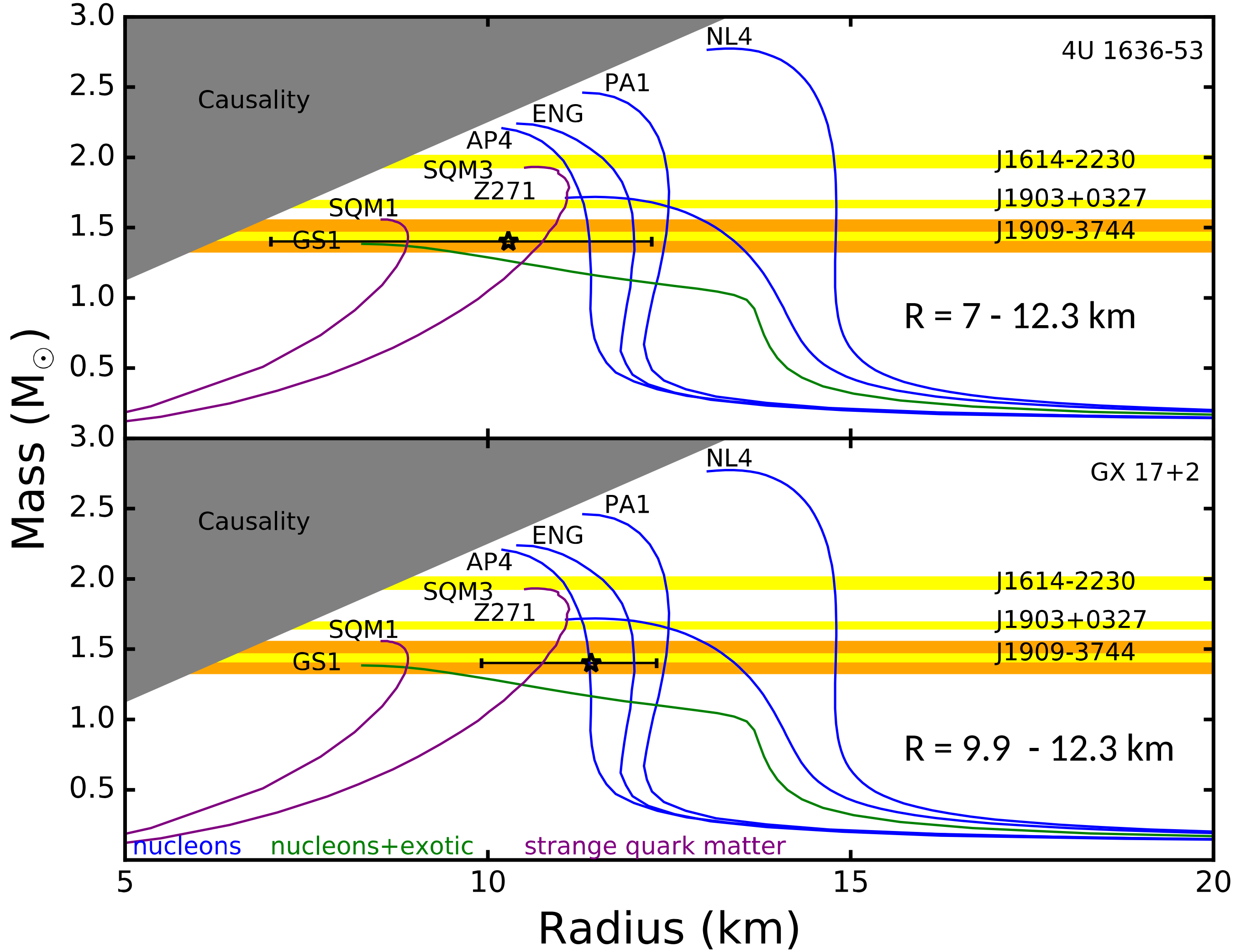


Equation of State

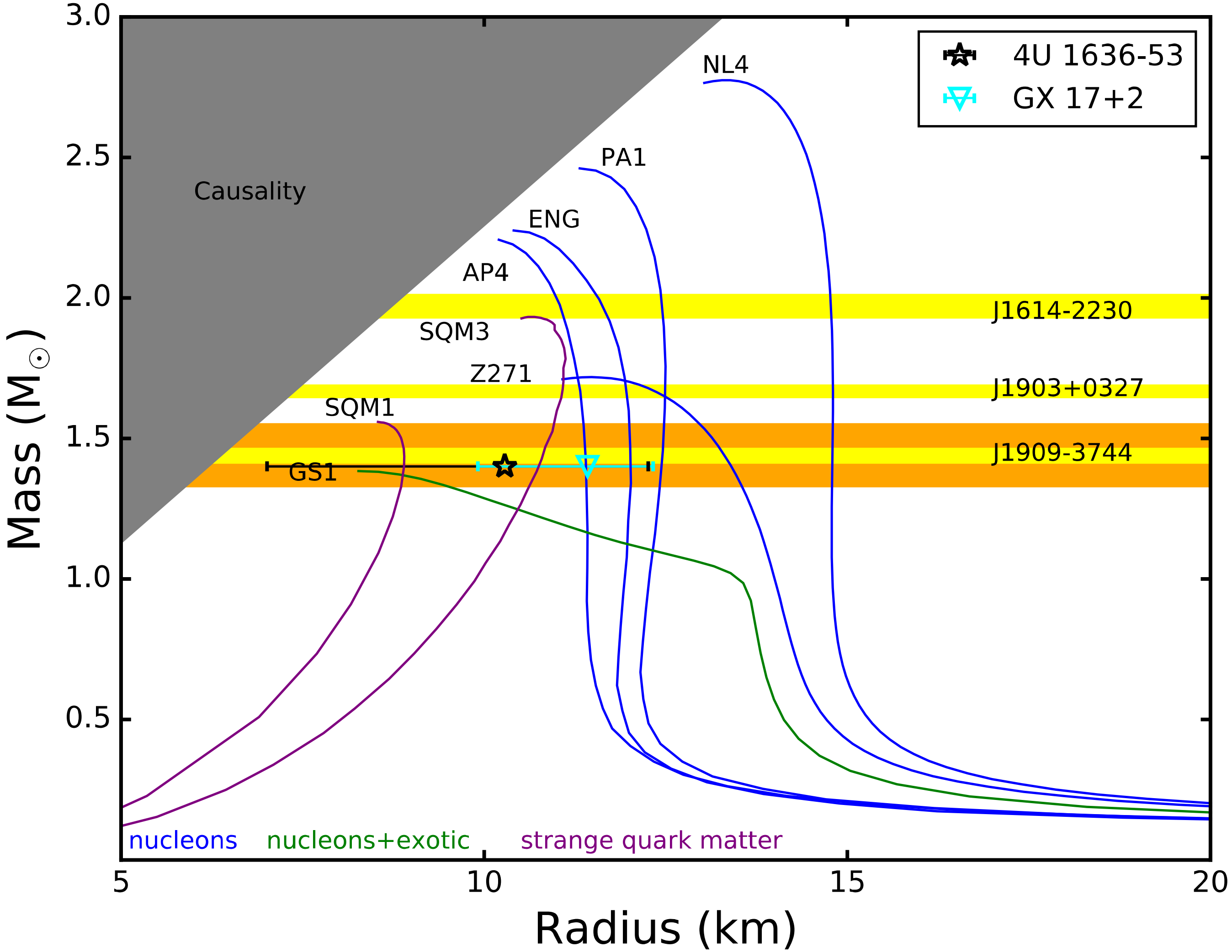


Ludlam+ 2017a

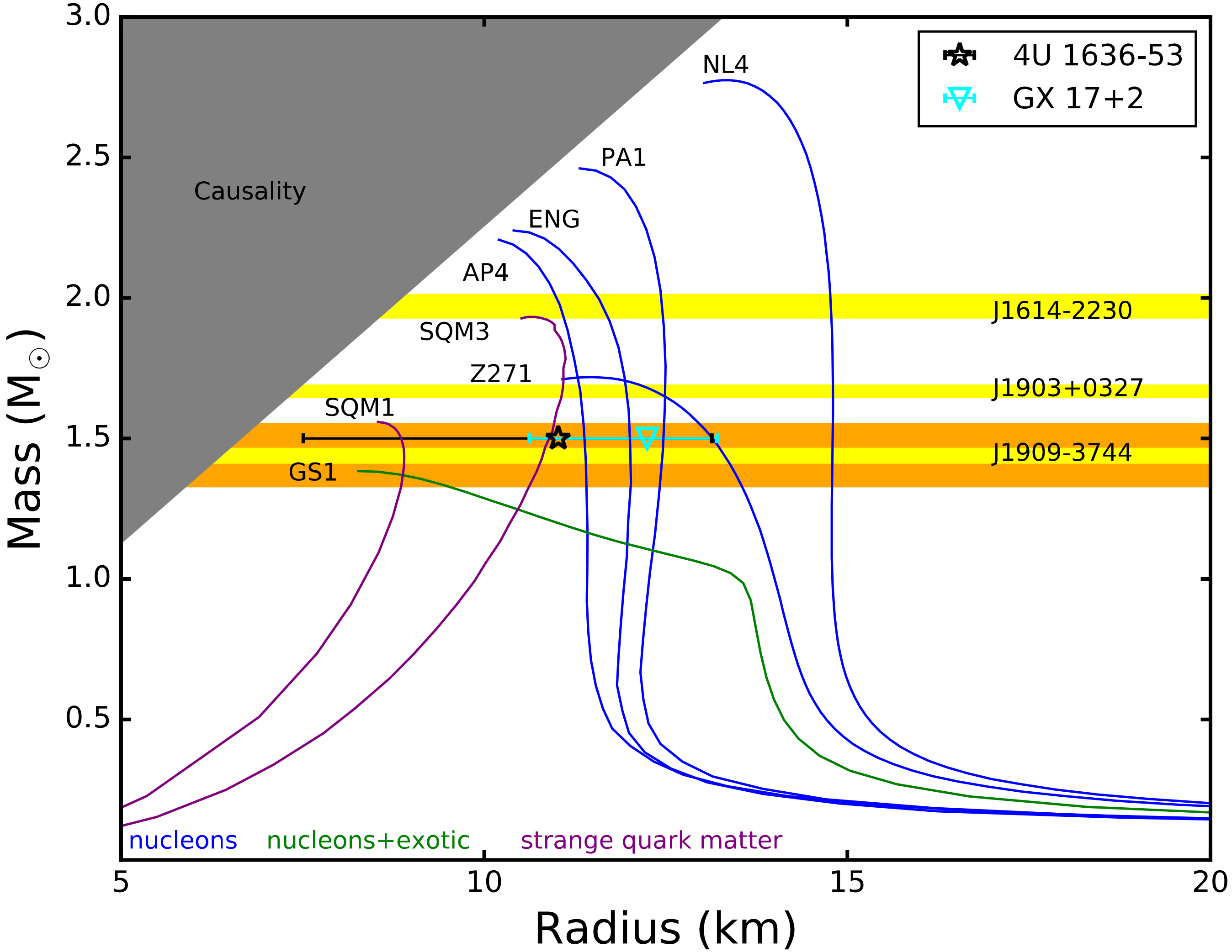
Assuming $M_{NS} = 1.4\ M_{\odot}$



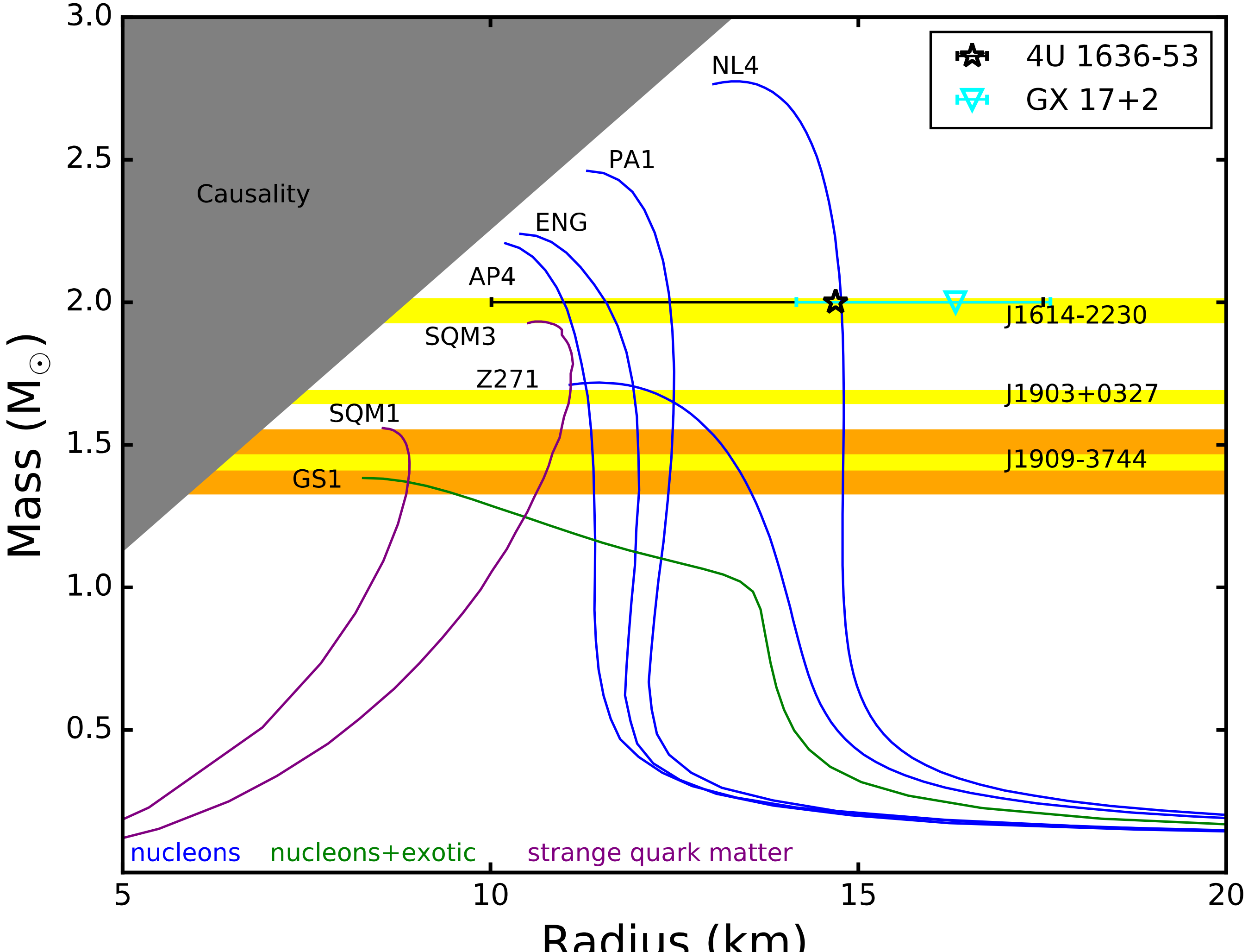
Assuming $M_{NS} = 1.4\ M_\odot$



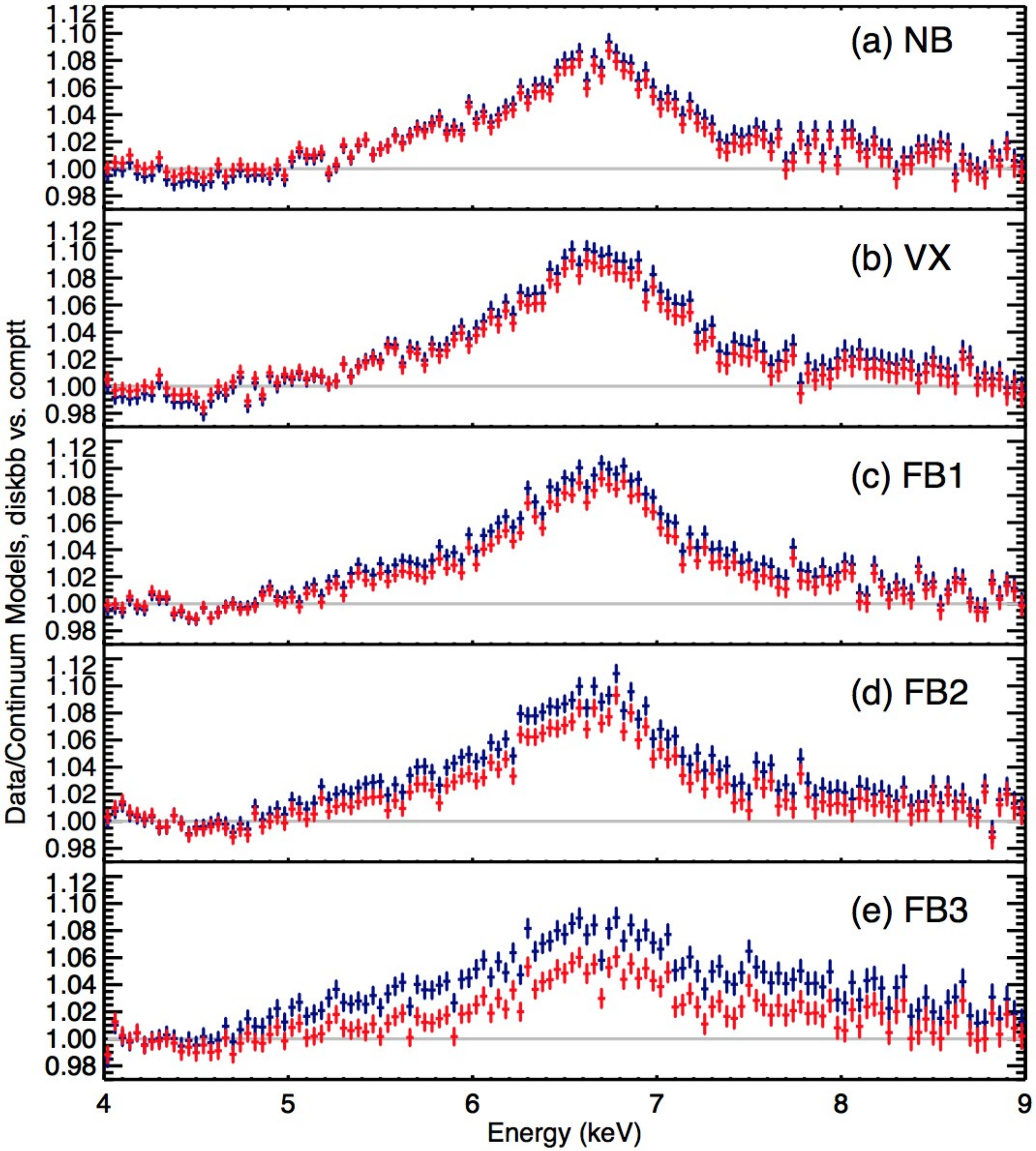
Assuming $M_{NS} = 1.5\ M_\odot$



Assuming $M_{NS} = 2.0\ M_\odot$



Choice of Continuum



Coughenour+ 2018

Fe line profiles for GX 349+2

Fe line profiles for a thermal blackbody continuum and Comptonization continuum.

Fe line profile independent of continuum choice!

Limits of the Test

- We cannot independently determine spin (a/M) and inner disk radius (R_{in})
- The potential at the ISCO around an a/M=0.0, and a few*ISCO around an a/M=0.X object, are fairly similar.
  - i.e.,

R_g	a/M = 0.0	a/M=0.3	a/M=0.7
6	1.0 ISCO	1.2 ISCO	1.7 ISCO

- We have to fix spin to likely values when determining the extent of the inner disk

Estimating Magnetic Field Strength

Magnetic energy density = kinetic energy density

$$\frac{B^2}{8\pi} = \frac{\dot{M}}{4\pi r^2}\left(\frac{2GM_{NS}}{r}\right)^{1/2} \; ; \;\; B = \frac{2\mu}{r^3}$$

$$\mu = \left(\frac{GM_{NS}}{2}\right)^{1/4} \dot{M}^{1/2}\, r^{7/4} \; ; \; \dot{M} = \frac{4\pi D^2 F f_{ang}}{\eta c^2} \; ; r = x\,\frac{GM_{NS}}{c^2}$$

$$\mu = 3.5\times 10^{23} \left(\frac{x}{k_A}\right)^{7/4} \left(\frac{M_{NS}}{1.4\ M_{\odot}}\right)^{2} \left(\frac{f_{ang}}{\eta}\frac{F_{bol}}{10^{-9}\ \mathrm{erg\ cm^{-2}\ s^{-1}}}\right)^{1/2} \frac{D}{3.5\ \mathrm{kpc}}\ \mathrm{G\ cm^3}$$

Illarionov & Sunyaev 1975, Ibragimov & Poutanen 2009, Cackett et al. 2009