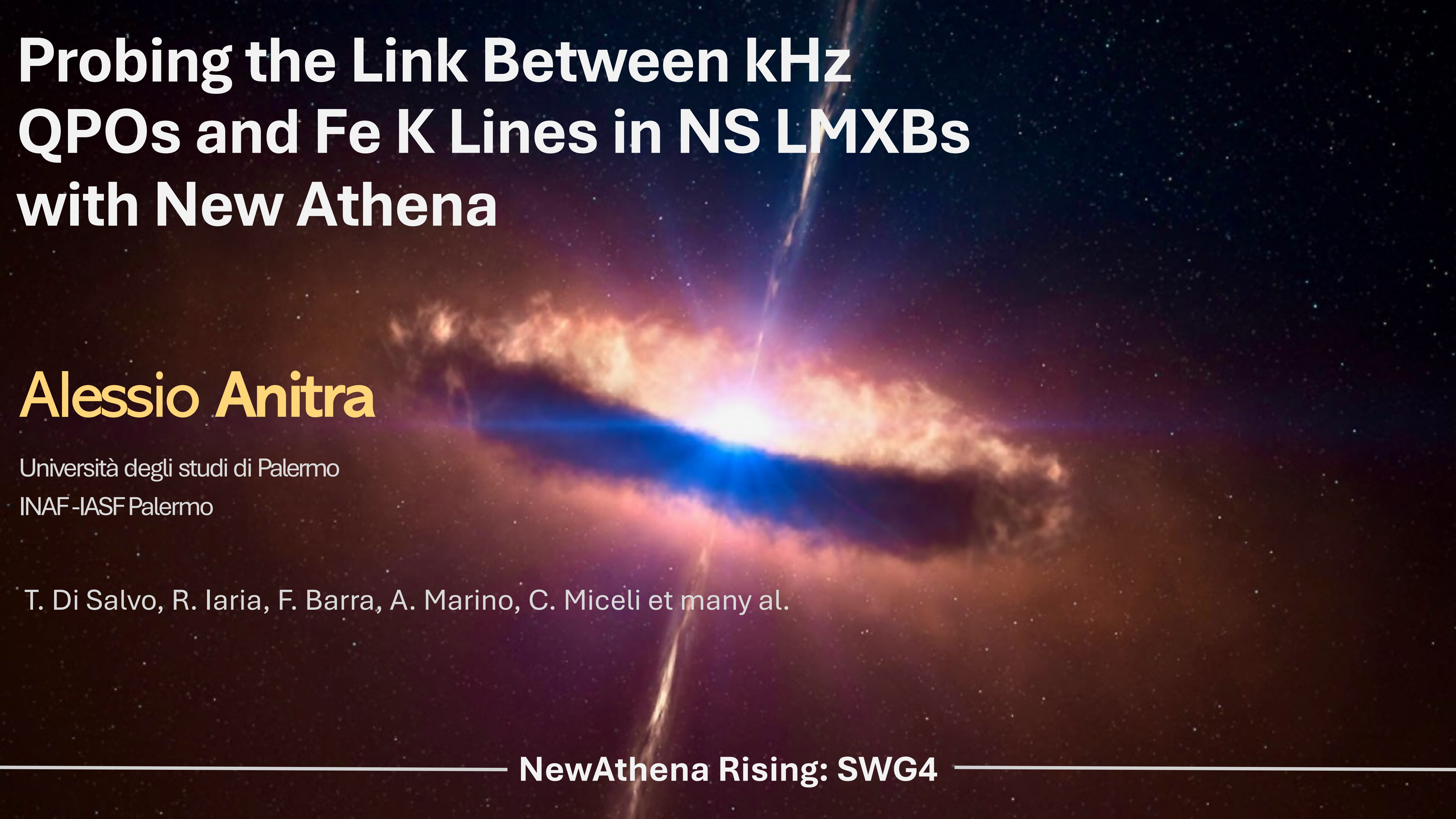

Probing the Link Between kHz QPOs and Fe K Lines in NS LMXBs with New Athena

Alessio Anitra

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INAF -IASF Palermo

T. Di Salvo, R. Iaria, F. Barra, A. Marino, C. Miceli et many al.

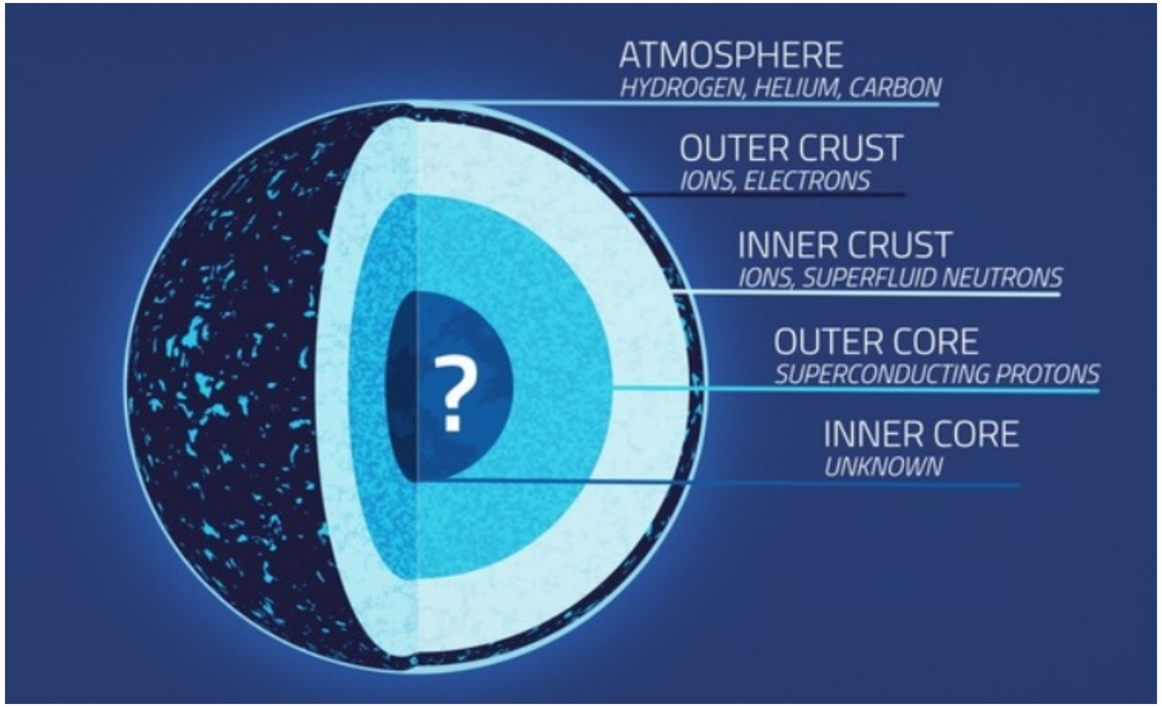
NewAthena Rising: SWG4

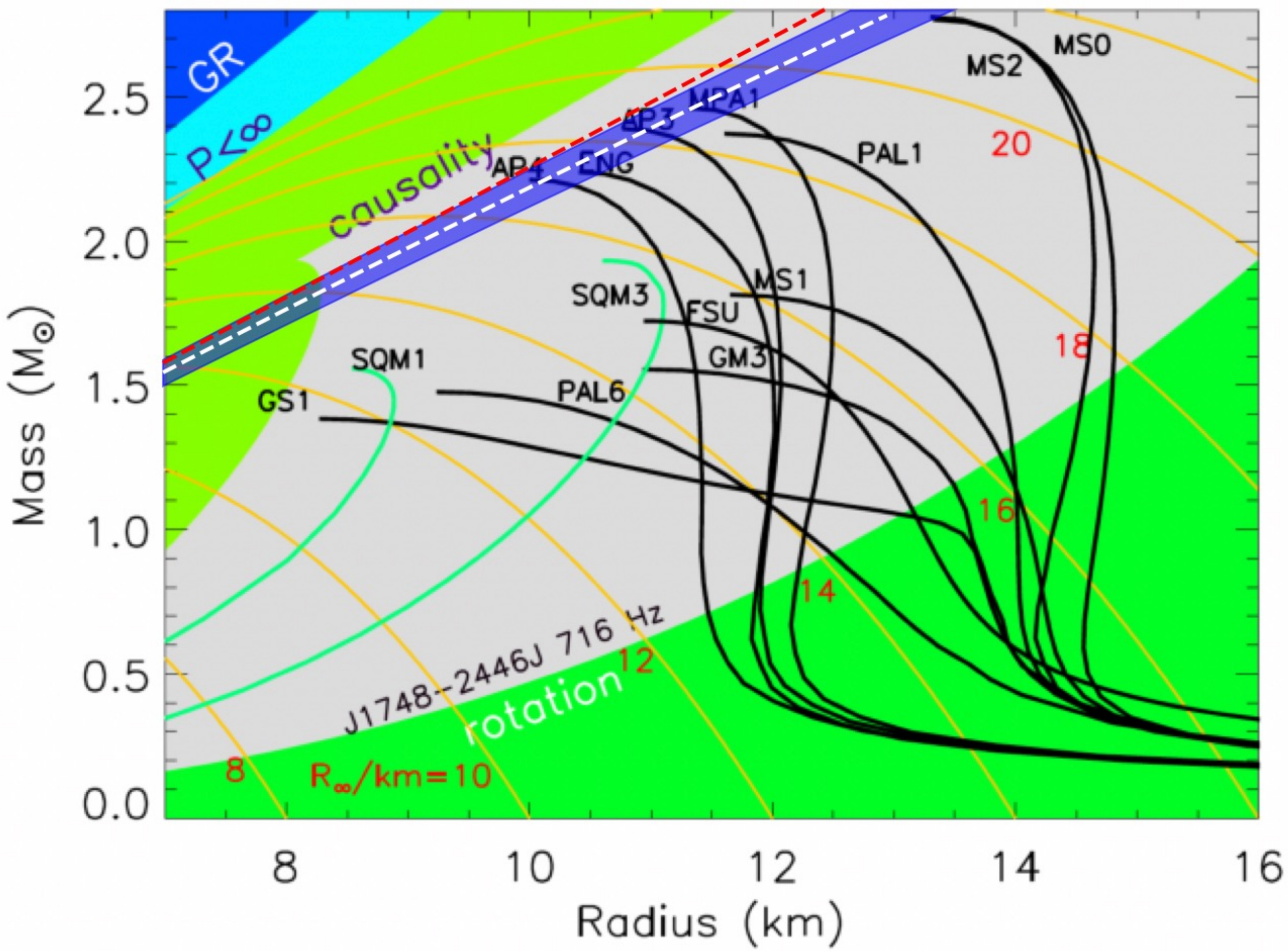
Why is the mass/radius of NS important ?

What’s inside a neutron star?

Equations of State (EOS) of dense matter predicts a specific mass–radius relation of NS.

Constrains on radius and mass can can test dense-matter EOS.

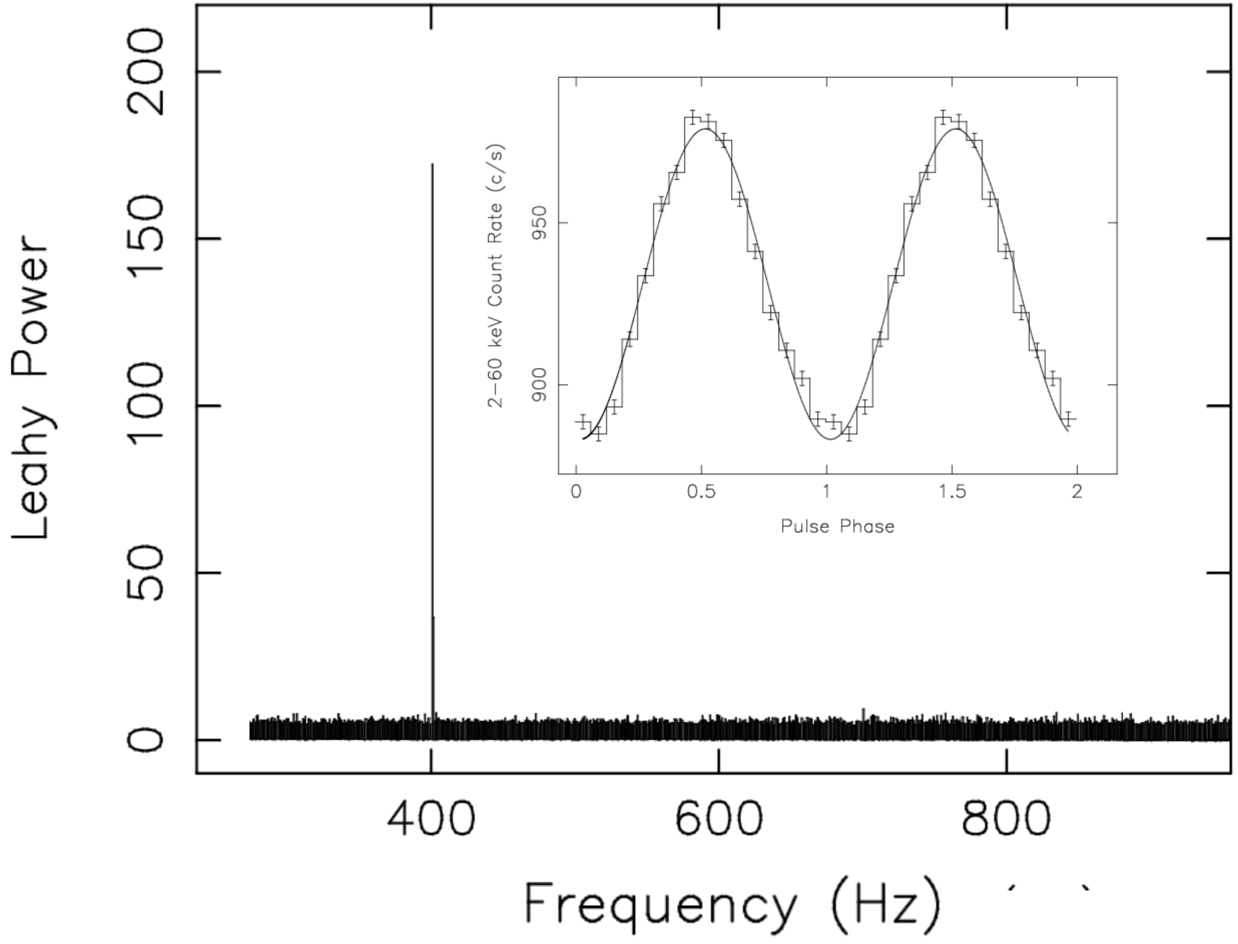




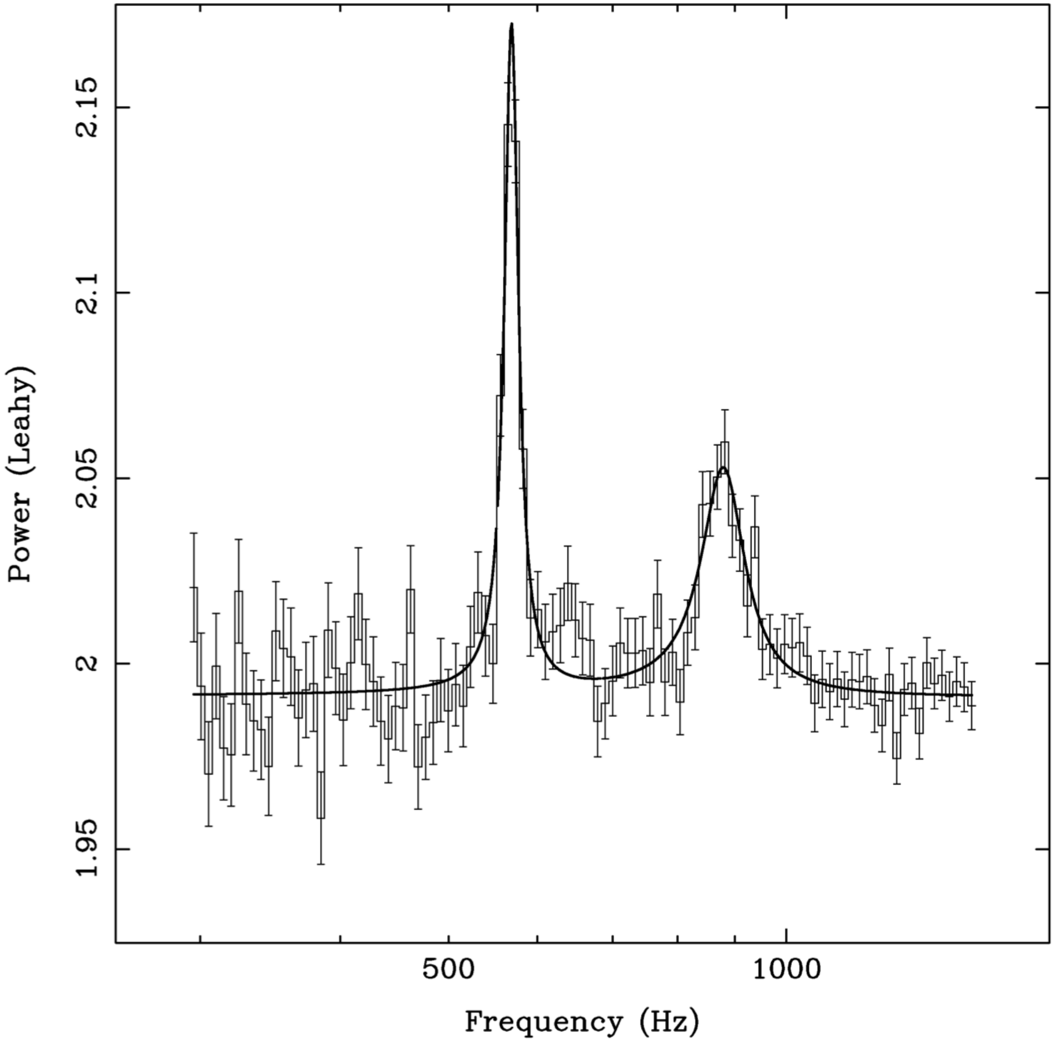
Iaria+26 Mass–radius diagram for neutron stars. The red dashed line shows the best-fit compactness for 4U 1820-30

What are QPOs?

Fourier power spectrum showing 401 Hz X-ray pulsations in SAX J1808.4 3658
(Adapted from **Wijnands & van der Klis 98**)

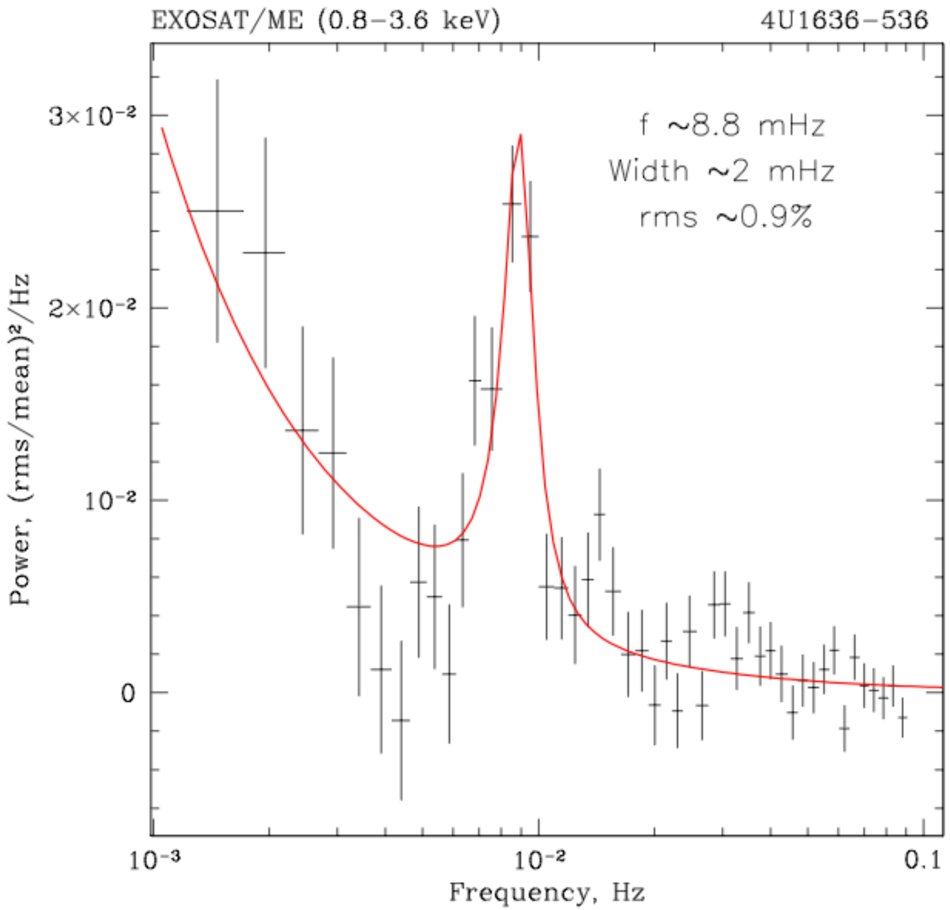


QPO in the atoll source 4U 1608-52
(**Mendez+98**)



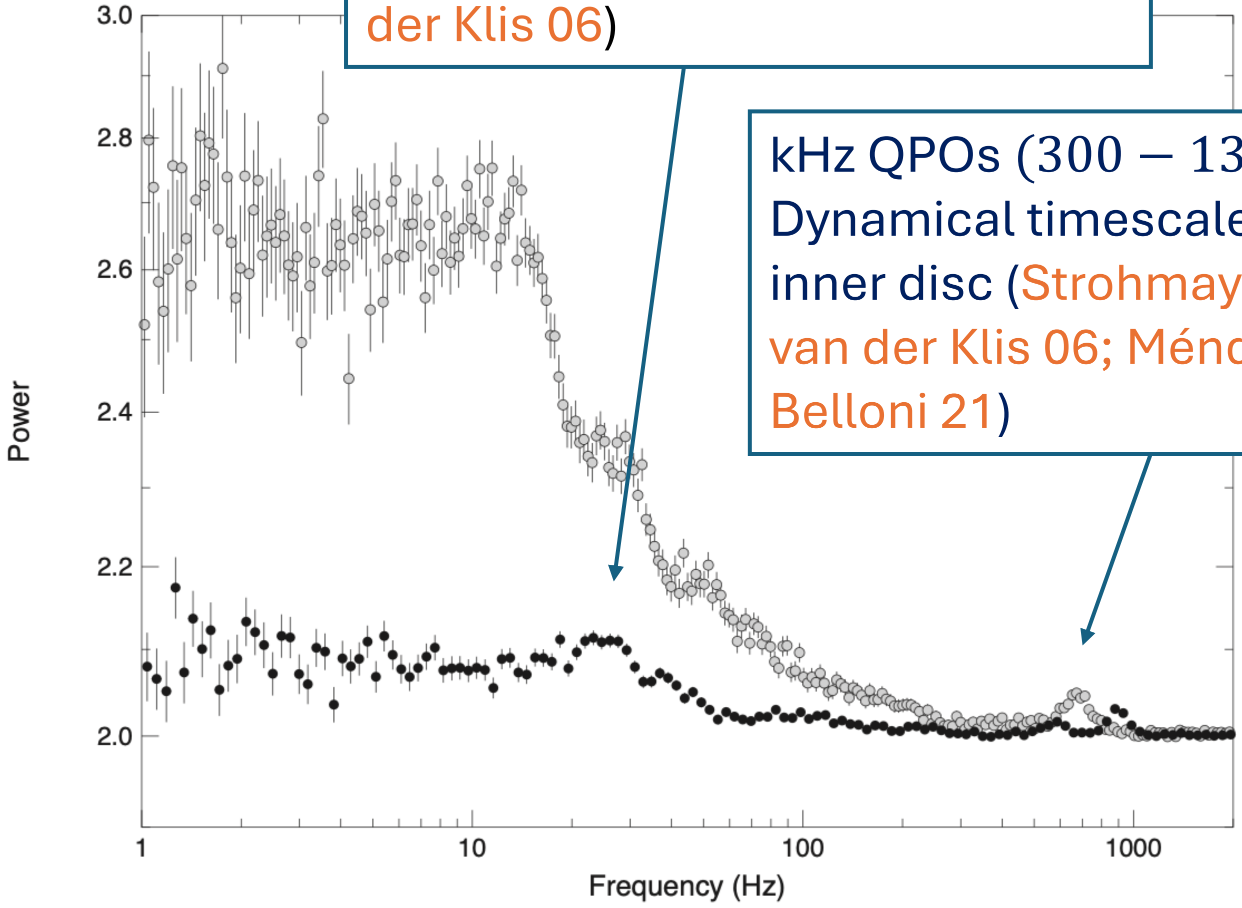
QPO zoo in neutron-star LMXBs

mHz QPOs (1 −15 mHz)
stable nuclear burning
(Revnivtsev+01; Heger+07)



LF QPOs (0.1 - 30 Hz) accretion-state / inner-flow variability (Hasinger & van der Klis 89; van der Klis 06)

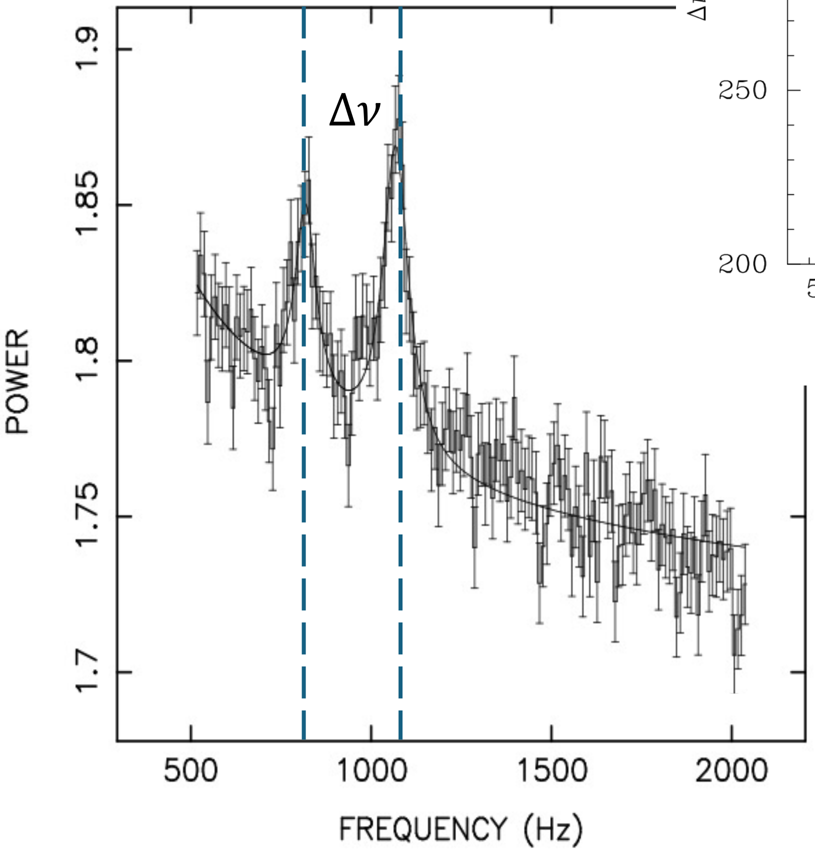
kHz QPOs (300 – 1300 Hz) Dynamical timescales in the inner disc (Strohmayer+96; van der Klis 06; Méndez & Belloni 21)

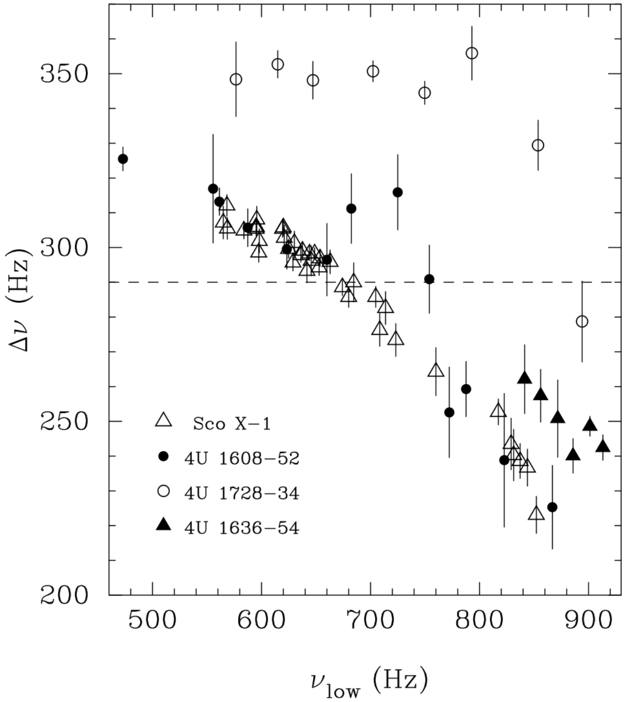


kHz QPOs

Δν as a function of the frequency of the lower peak (**Di Salvo+03**)

Sco X-1 **van der Klis+96**





Sonic-point beat-frequency model (Miller, Lamb & Psaltis 98) :

upper kHz QPO = Keplerian frequency at sonic point radius.

lower kHz QPO = beat with the NS spin.

But: Δν is not constant (van der Klis+97, Méndez +98, Di Salvo+03)

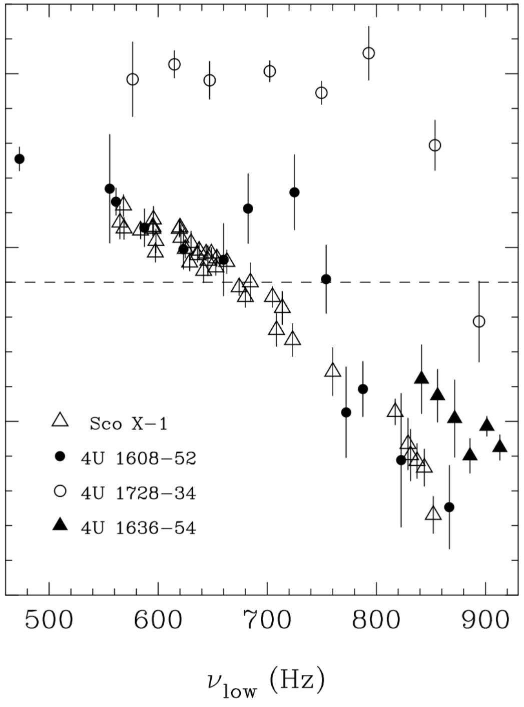
Relativistic precession model (Stella & Vietri 99):

upper kHz QPO = Keplerian frequency.

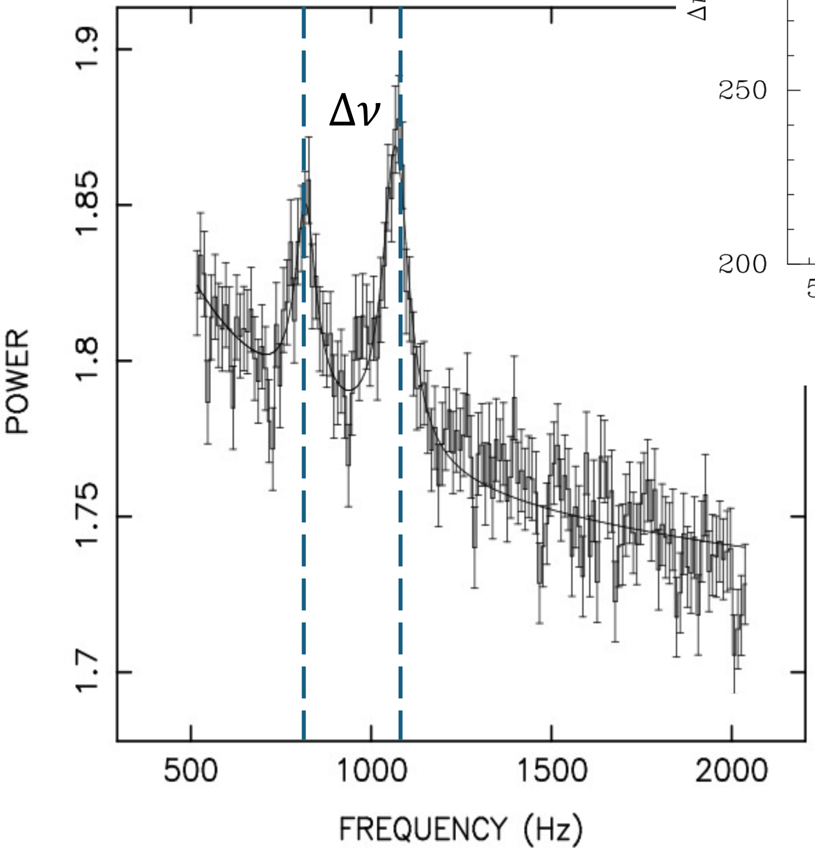
lower kHz QPO = periastron-precession frequency.

kHz QPOs

Δν as a function of the frequency of the lower peak (**Di Salvo+03**)



Sco X-1 **van der Klis+96**



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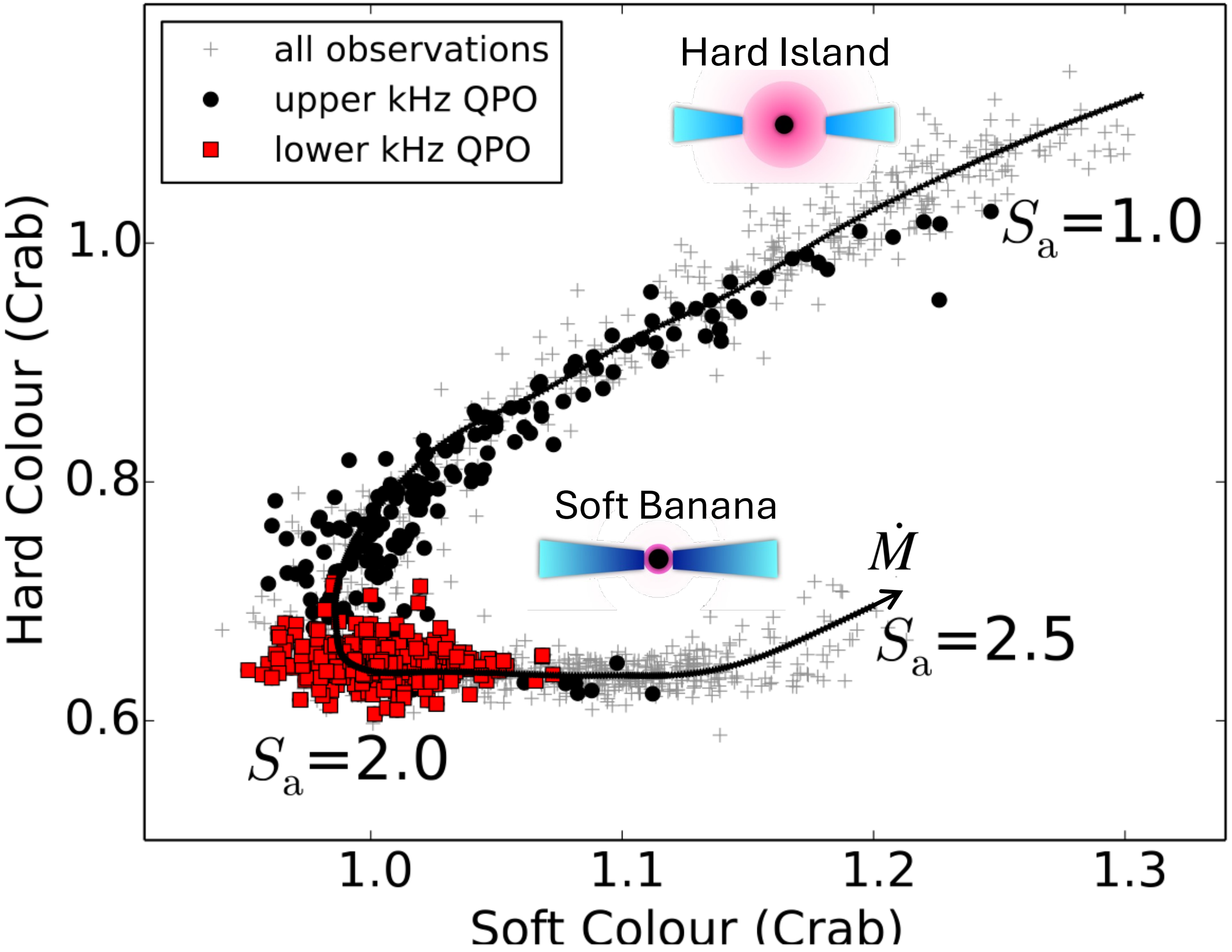
Relativistic precession model (Stella & Vietri 99):
upper kHz QPO = Keplerian frequency.
lower kHz QPO = periastron-precession frequency.

The crucial point is:

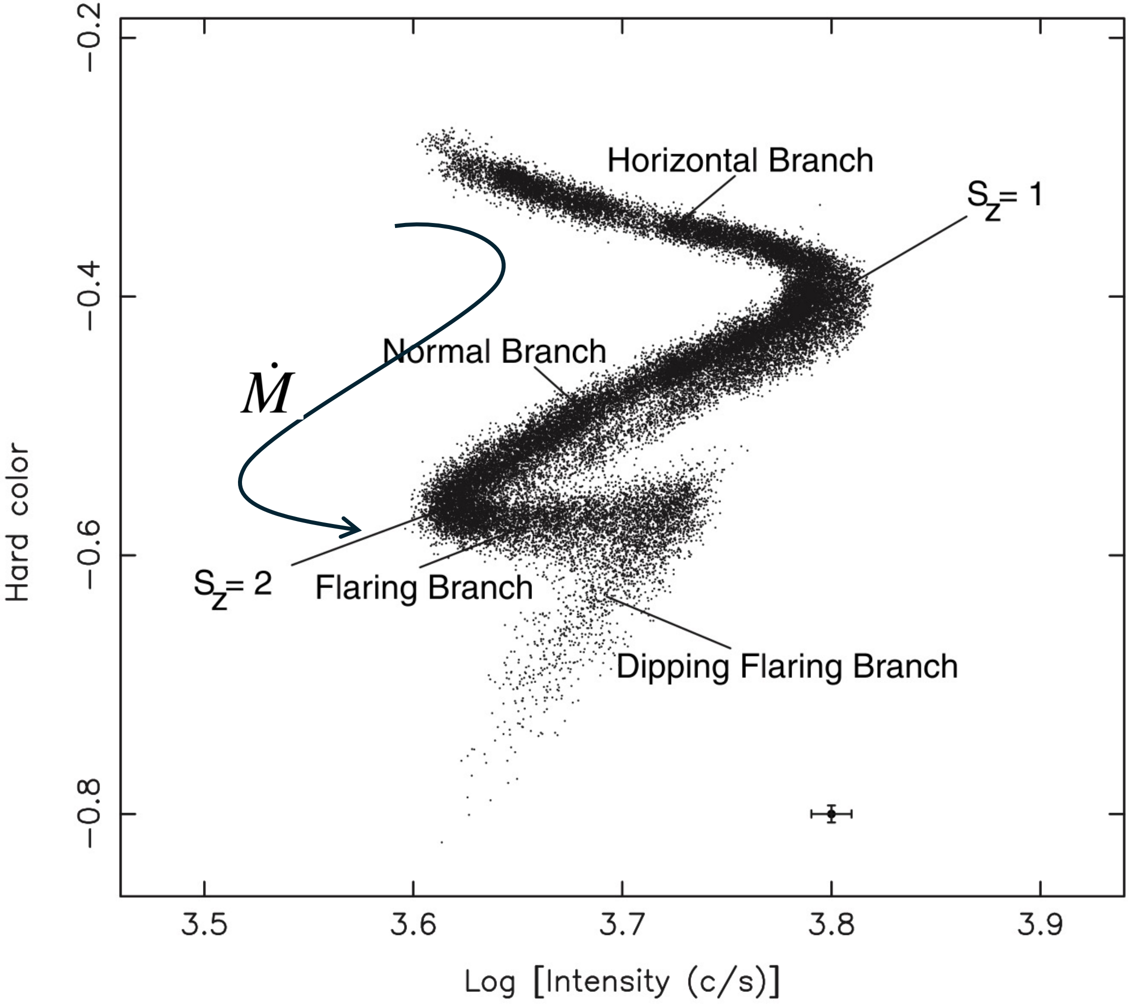
the upper kHz QPO is associated with orbital motion in the inner accretion flow

kHz QPOs and spectral state

Atoll sources

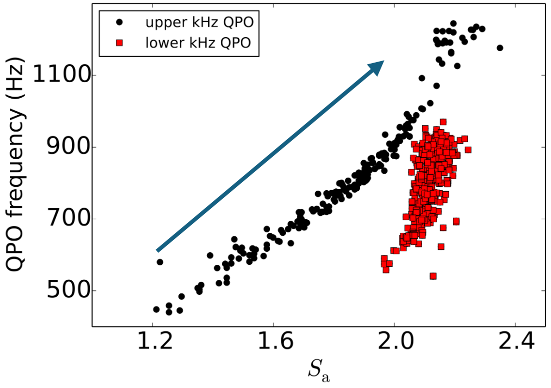


Z- sources

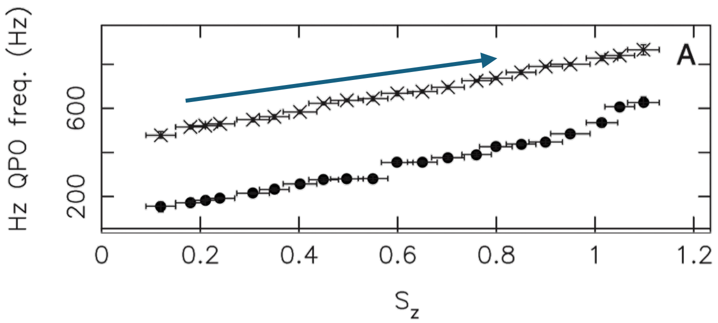


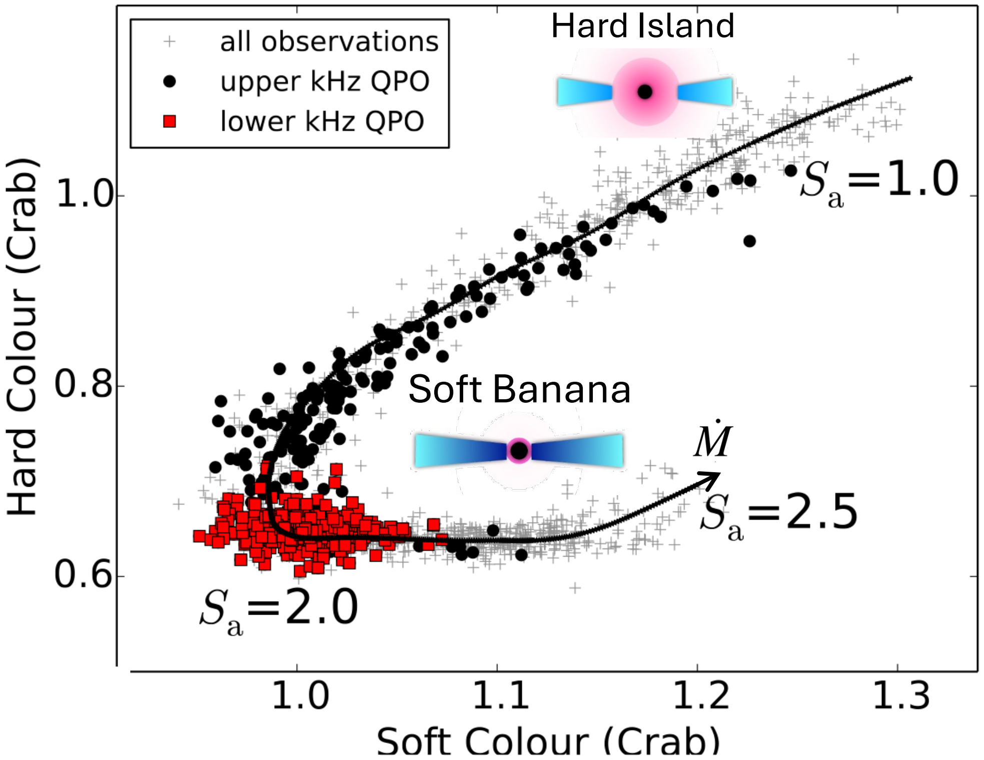
kHz QPOs and spectral state

The kHz QPO frequency as a function of spectral state in the atoll 4U 1636-53 (**Zhang+16**)

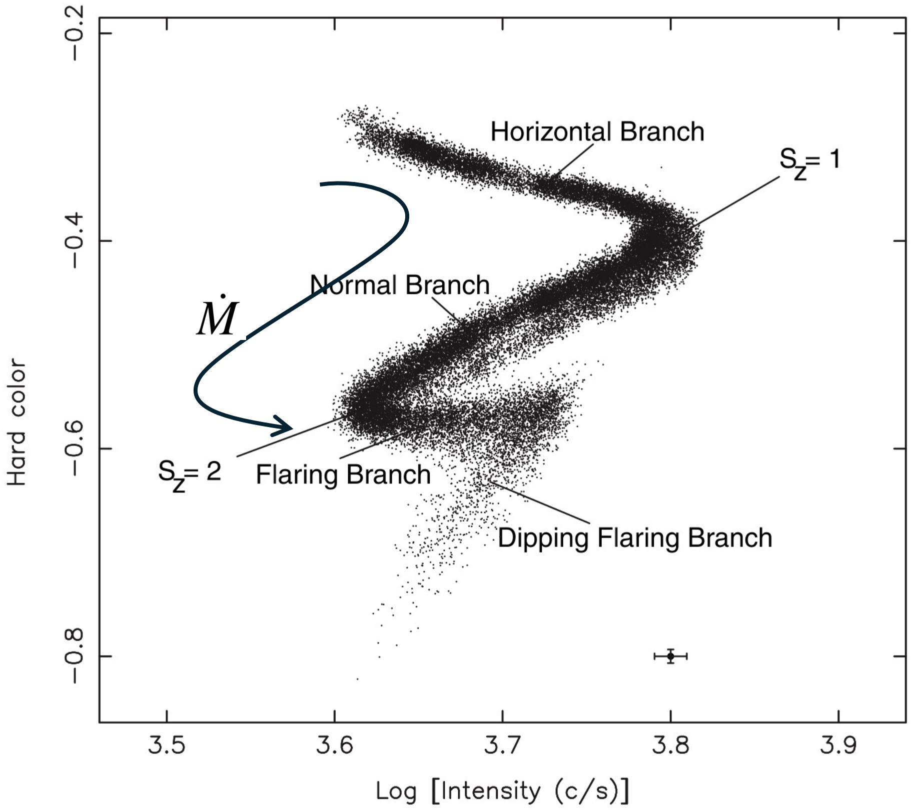


In Z-sources (GX 5–1), kHz QPO frequencies increase along the HB/upper NB (**Jonker + 02**)





Higher frequency at higher accretion rate means smaller radius



kHz QPOs as mass-radius/EOS constraints

From frequency to Radius

$$R_{QPO} = \left(\frac{GM}{4\pi^2\nu_{upper}^2}\right)^{1/3} \quad \Rightarrow \quad R_{\mathrm{NS}} < R_{\mathrm{QPO}}.$$

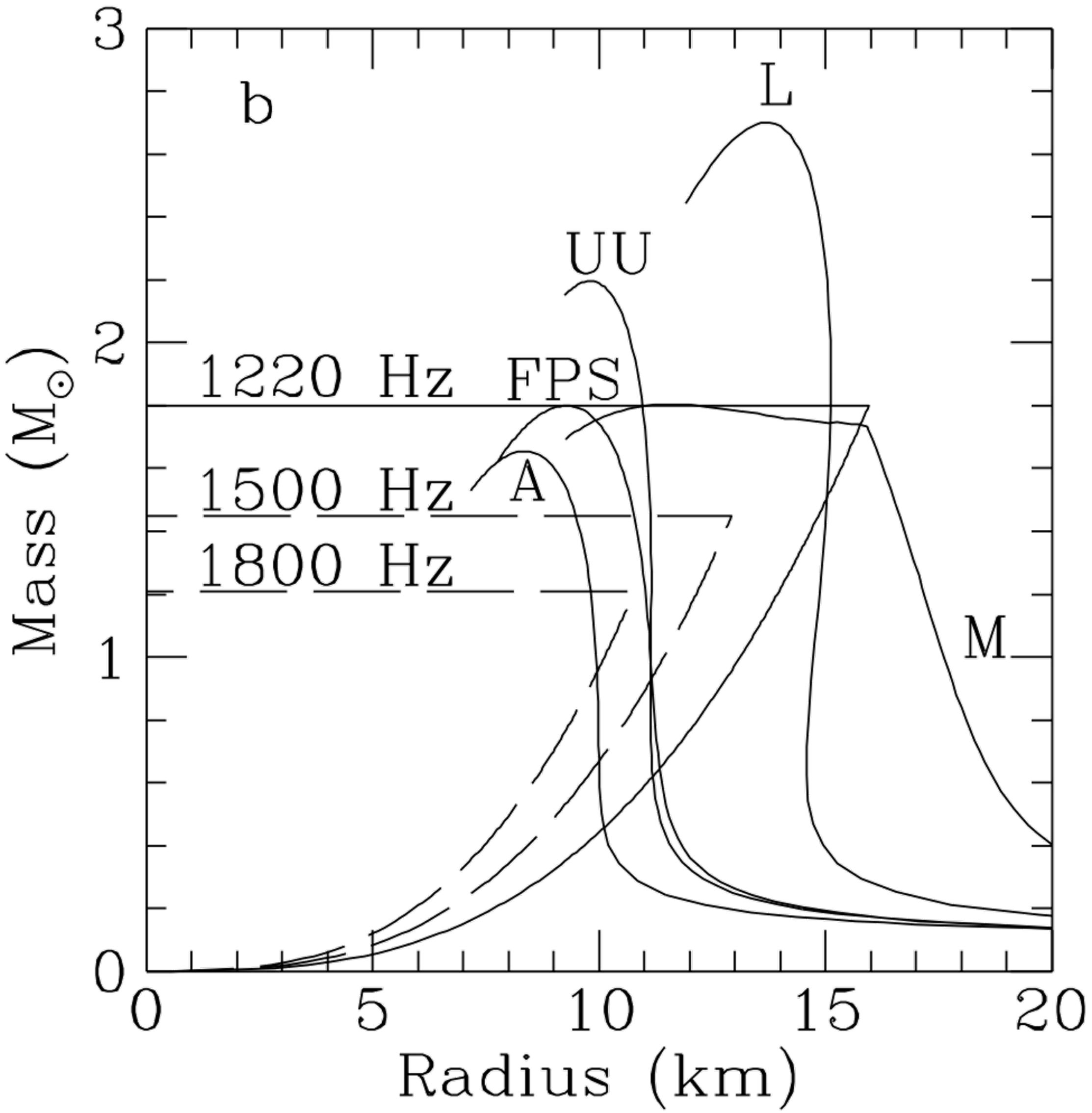
The highest kHz QPO frequencies define **exclusion regions** in the M-R plane.

In 4U 0614+09

$$\nu_{\mathrm{upper}} = 1288 \pm 8Hz \ \Rightarrow M < 2.1, M_\odot$$

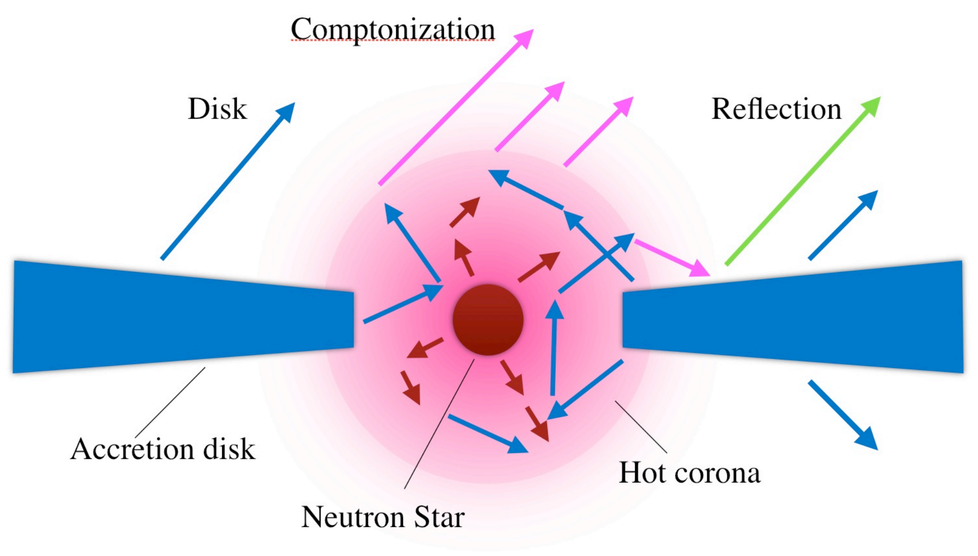
Limitation: without an independent mass or radius, the QPO gives limit in the M-R plane, not a unique solution.

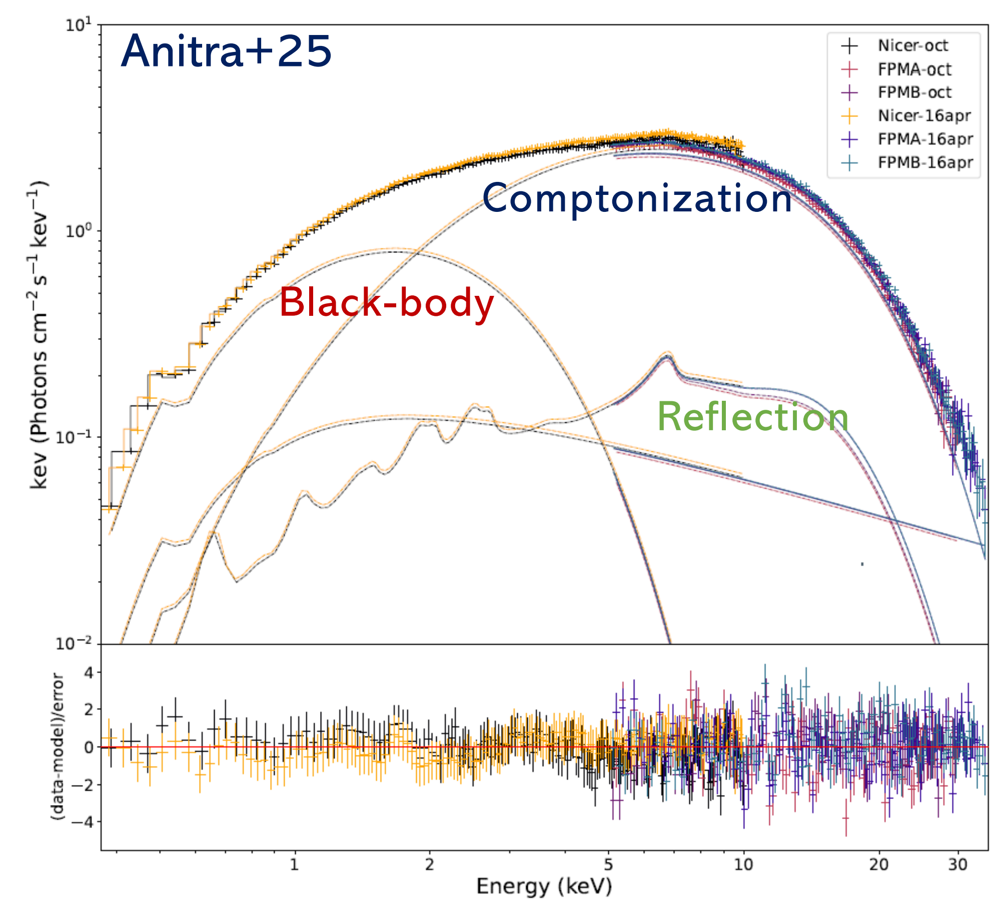
Lamb, Miller and Psaltis *98*



LMXBs Spectra

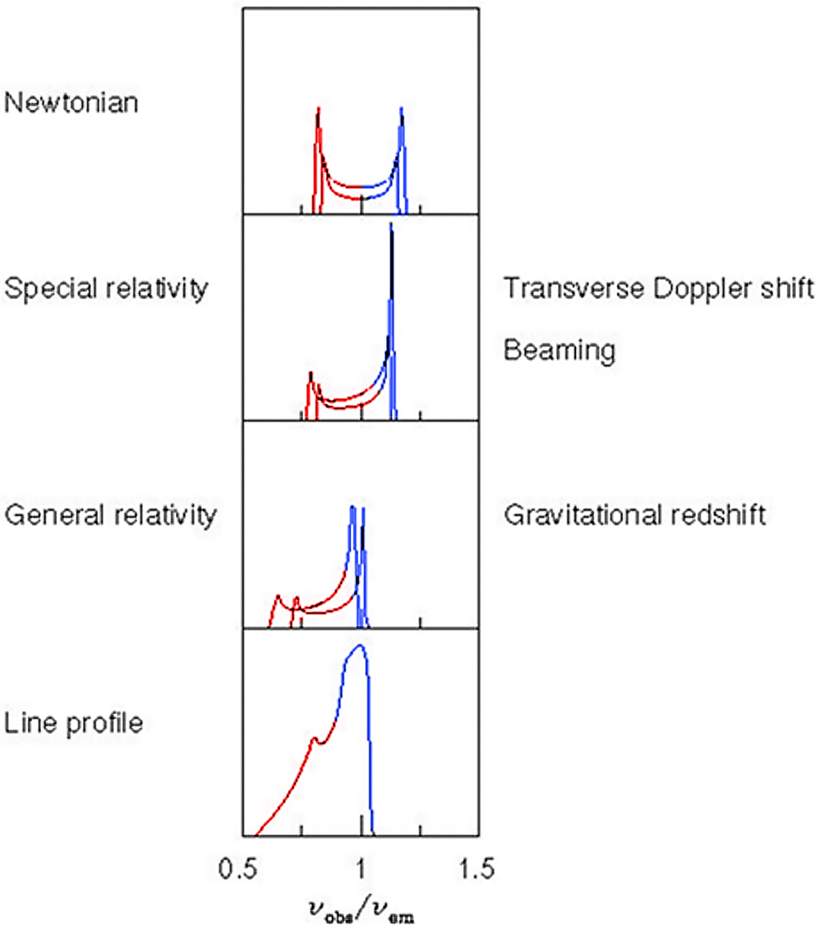
LMXBs Spectra

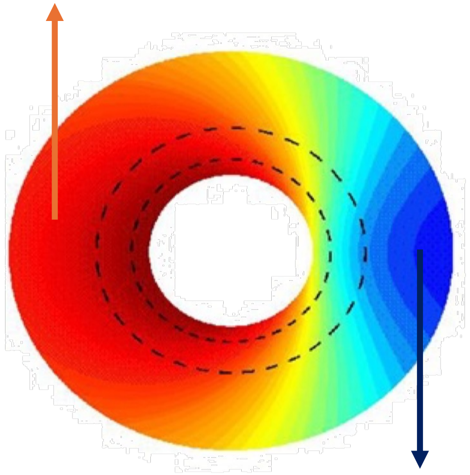




Reflection component

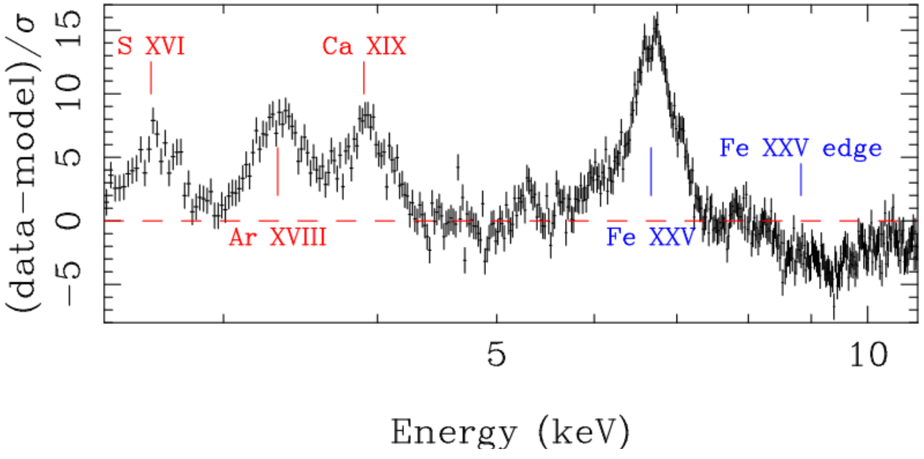
Reflection component is characterized by a thick forest of absorption edges and fluorescence lines, of which the most prominent is the Fe Kα line (6.4 - 7 keV).

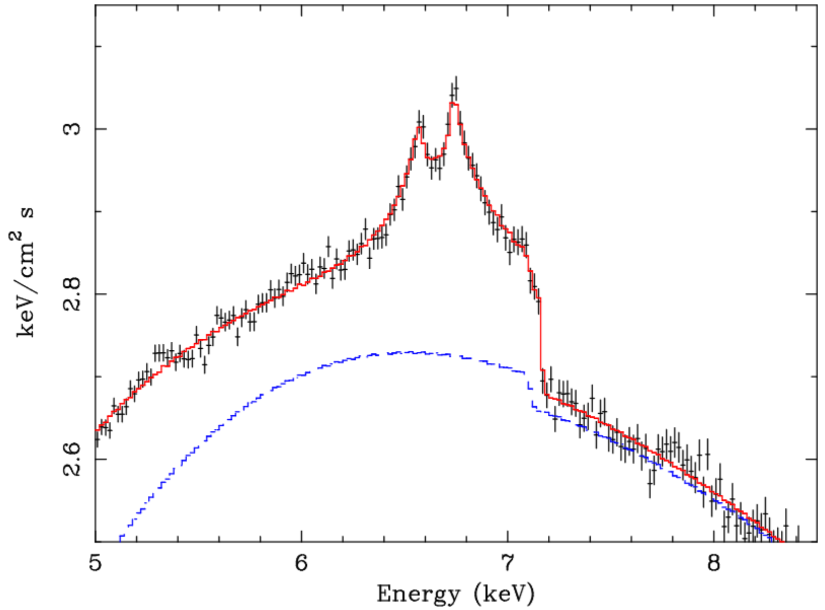




The profile of the Fe K line is influenced by system's inclination, emissivity, and the outer and inner radius of the disc.

Sketch of the accretion disc from above and distortion of the Iron line.

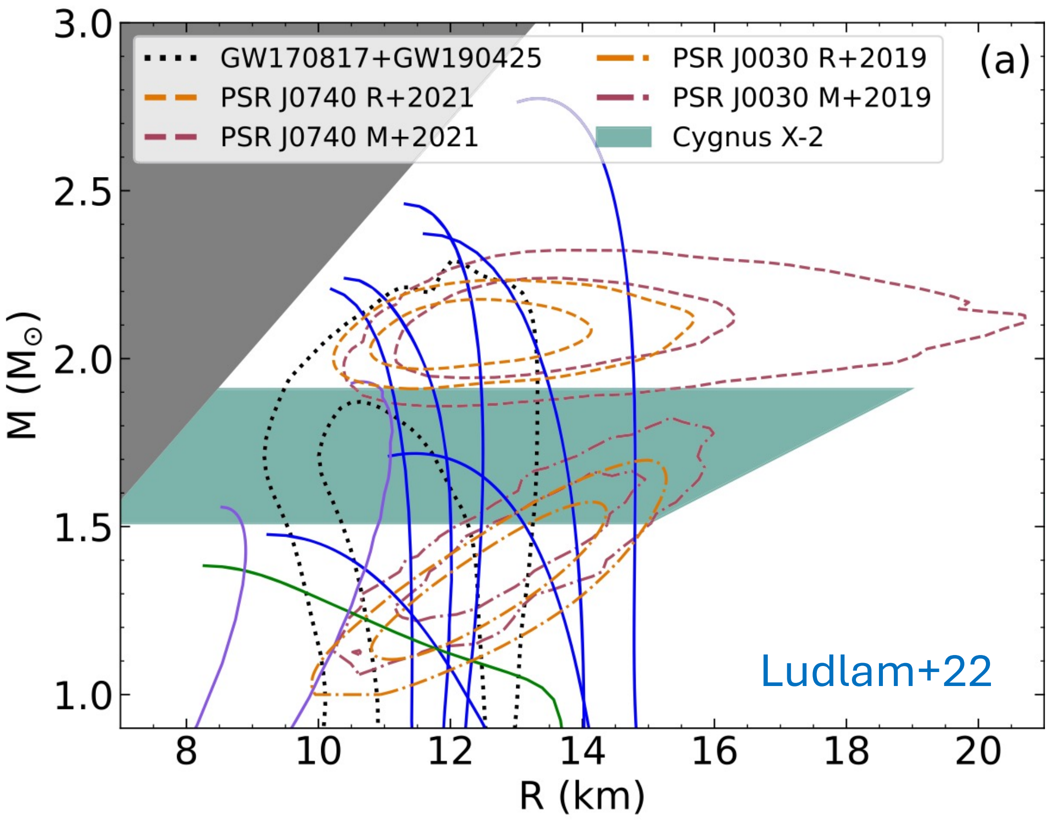




Unfolded spectrum of 4U 1705-44
(Di Salvo+09)

Combining timing and spectroscopy

Fe K reflection provides an independent estimate of the disc inner radius (see e.g. **Cackett+10, Egron+11, Di Salvo+19**)

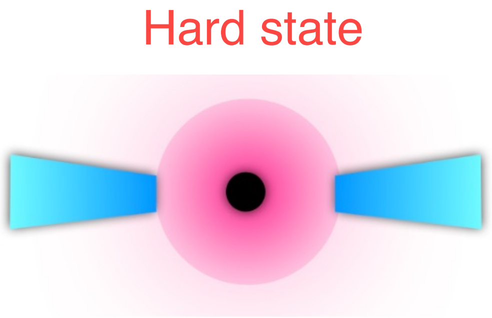


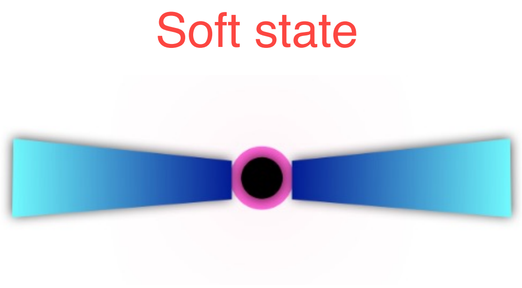
Mass - radius constraints from Fe K reflection in Cygnus X-2 and other sources (**Ludlam+22, Riley+19,21, Miller+10,21**)

If both diagnostics trace the disc:

$$R_{\rm in}^{\rm QPO}(M) = \left(\frac{GM}{4\pi^2\nu_{\rm upper}^2}\right)^{1/3} =?\ R_{\rm in}^{\rm Fe}(M)$$

their combination can constrain the mass

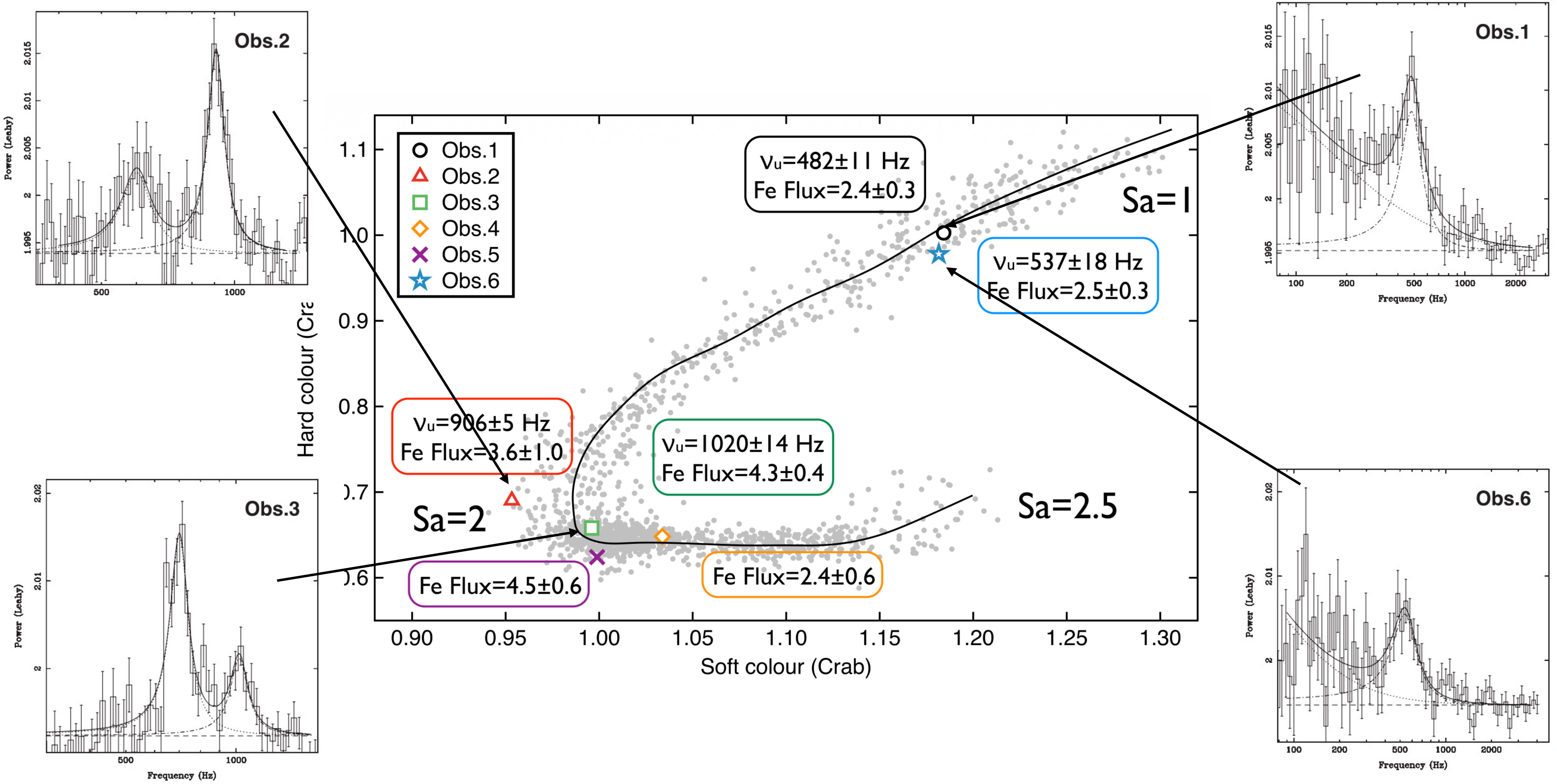




State-resolved test

$R_{\rm in}$ may change with spectral state, but the neutron-star mass must remain the same.

Sanna+14 4U 1636-53



νu=482±11 Hz
Fe Flux=2.4±0.3

νu=537±18 Hz
Fe Flux=2.5±0.3

νu=906±5 Hz
Fe Flux=3.6±1.0

νu=1020±14 Hz
Fe Flux=4.3±0.4

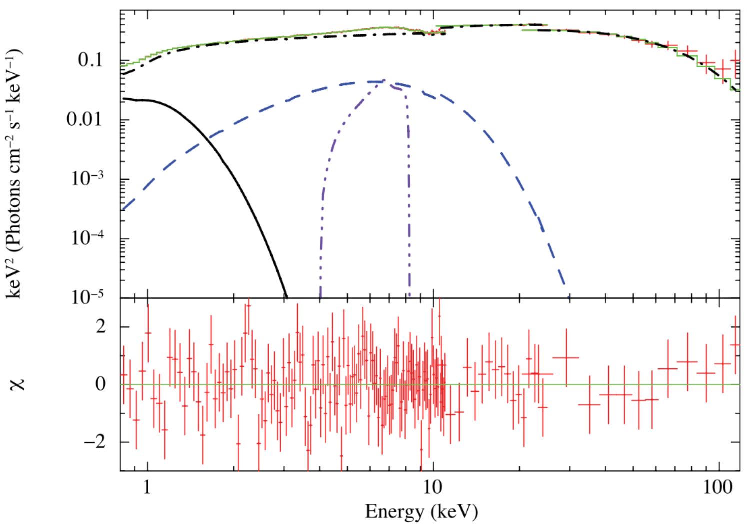
Fe Flux=4.5±0.6

Fe Flux=2.4±0.6

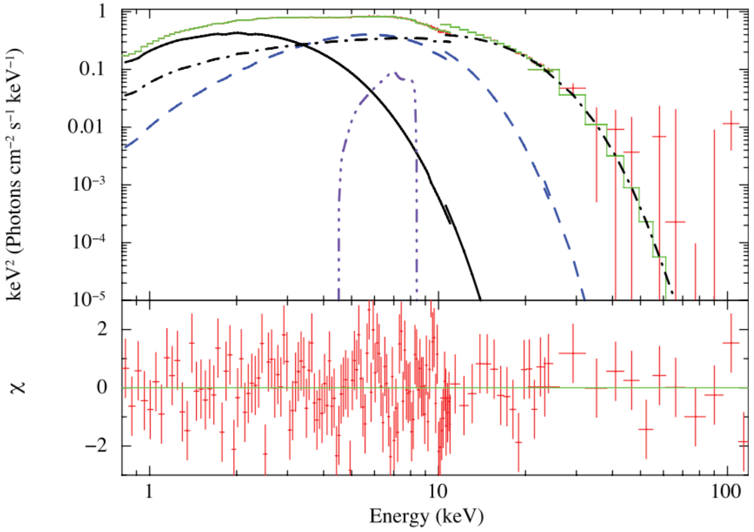
Spectral analysis

Kyrline

Obs 1

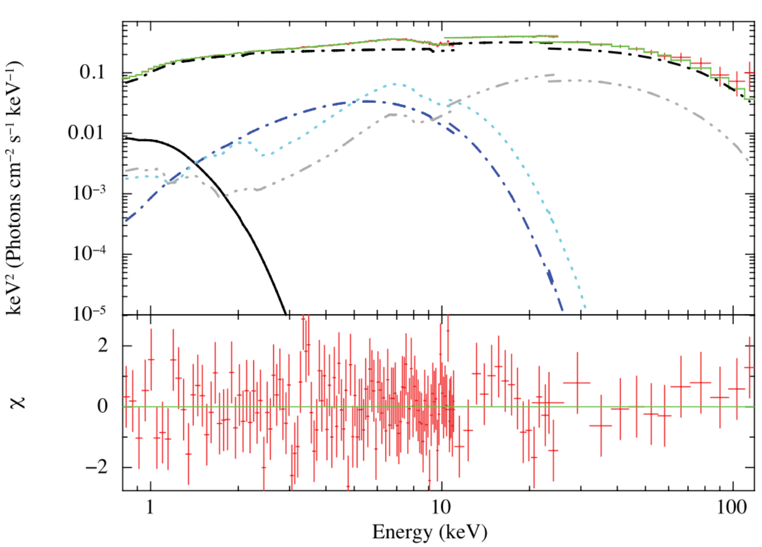


Obs 3

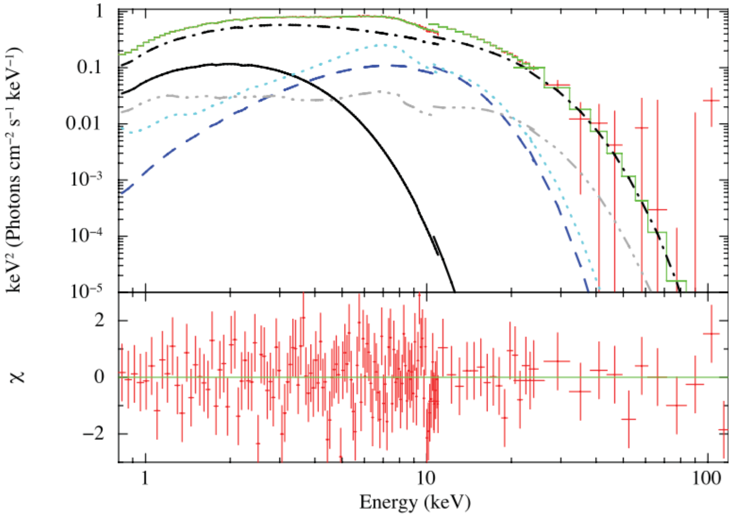


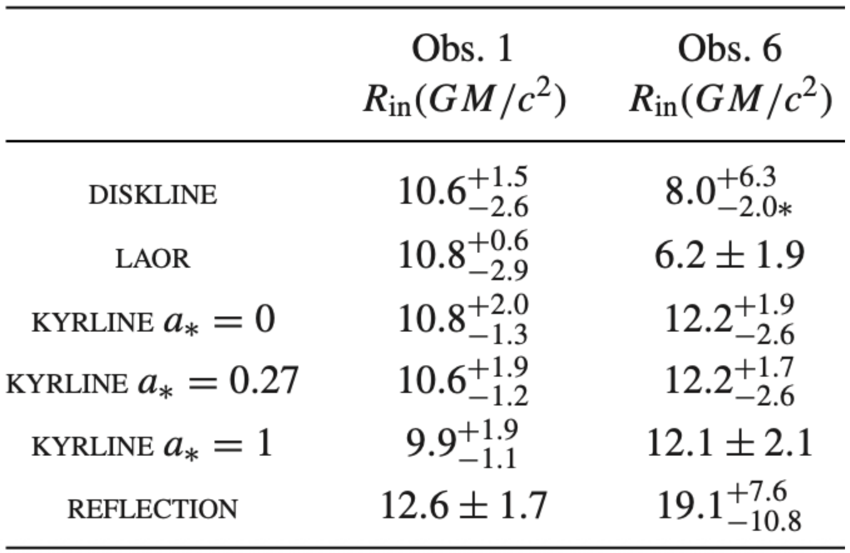
KERRCONV*(BBREFL + RFXCONV*NTHCOMP)

Obs 1

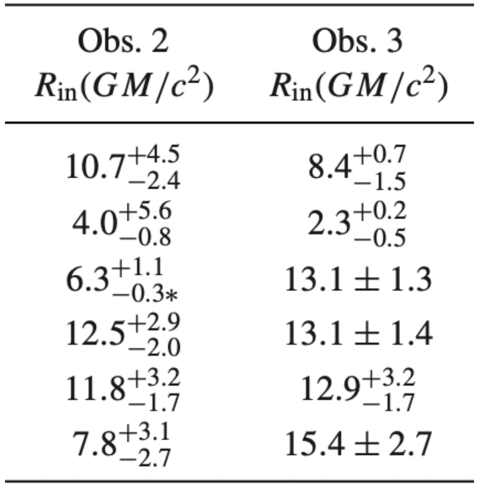


Obs 3





	Obs. 1 $R_{\text{in}}(GM/c^2)$	Obs. 6 $R_{\text{in}}(GM/c^2)$
DISKLINE	$10.6^{+1.5}_{-2.6}$	$8.0^{+6.3}_{-2.0*}$
LAOR	$10.8^{+0.6}_{-2.9}$	6.2 ± 1.9
KYRLINE $a_* = 0$	$10.8^{+2.0}_{-1.3}$	$12.2^{+1.9}_{-2.6}$
KYRLINE $a_* = 0.27$	$10.6^{+1.9}_{-1.2}$	$12.2^{+1.7}_{-2.6}$
KYRLINE $a_* = 1$	$9.9^{+1.9}_{-1.1}$	12.1 ± 2.1
REFLECTION	12.6 ± 1.7	$19.1^{+7.6}_{-10.8}$

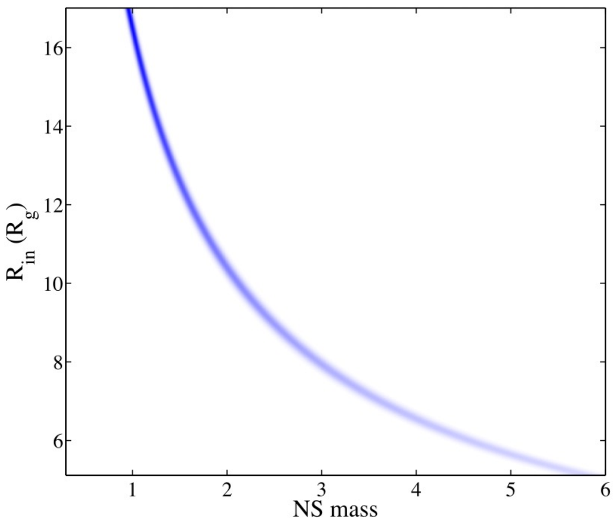


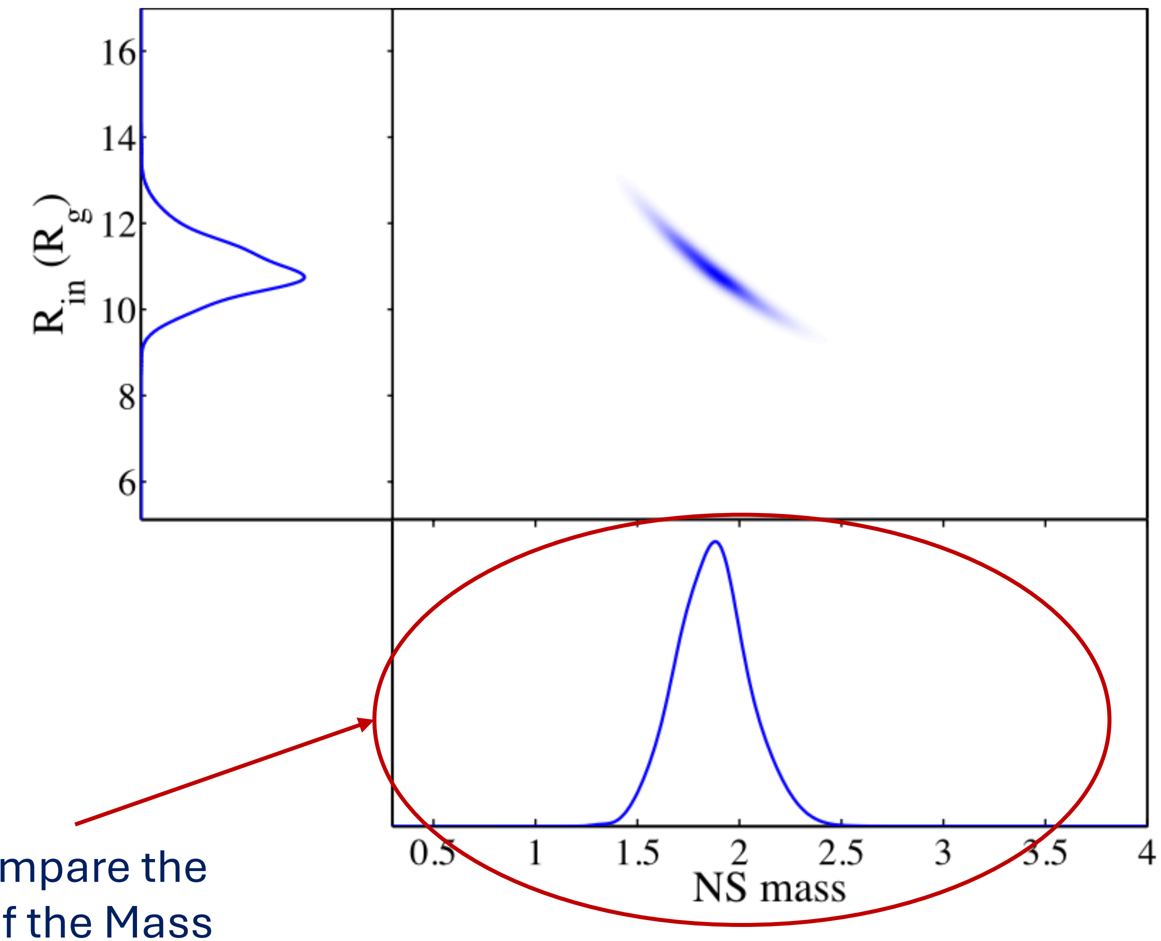
Obs. 2 $R_{\text{in}}(GM/c^2)$	Obs. 3 $R_{\text{in}}(GM/c^2)$
$10.7^{+4.5}_{-2.4}$	$8.4^{+0.7}_{-1.5}$
$4.0^{+5.6}_{-0.8}$	$2.3^{+0.2}_{-0.5}$
$6.3^{+1.1}_{-0.3*}$	13.1 ± 1.3
$12.5^{+2.9}_{-2.0}$	13.1 ± 1.4
$11.8^{+3.2}_{-1.7}$	$12.9^{+3.2}_{-1.7}$
$7.8^{+3.1}_{-2.7}$	15.4 ± 2.7

How to compare the two radii

The joint probability function identifies which values of mass and radius make the two diagnostics consistent

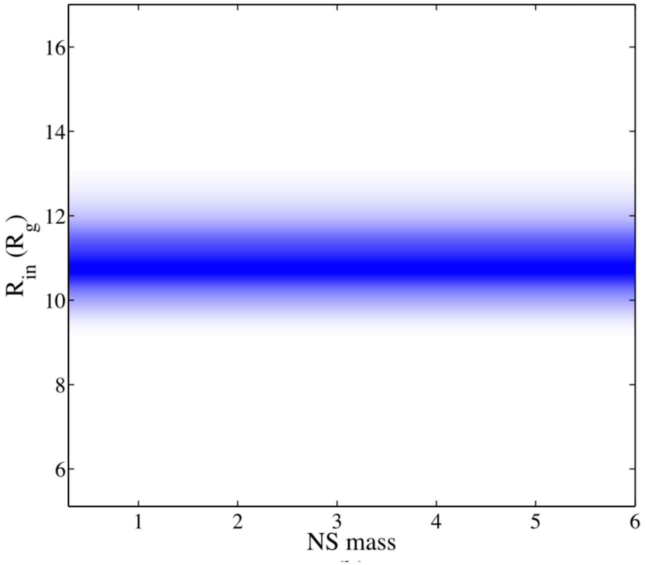
Probability distribution inferred from the upper kHz QPO





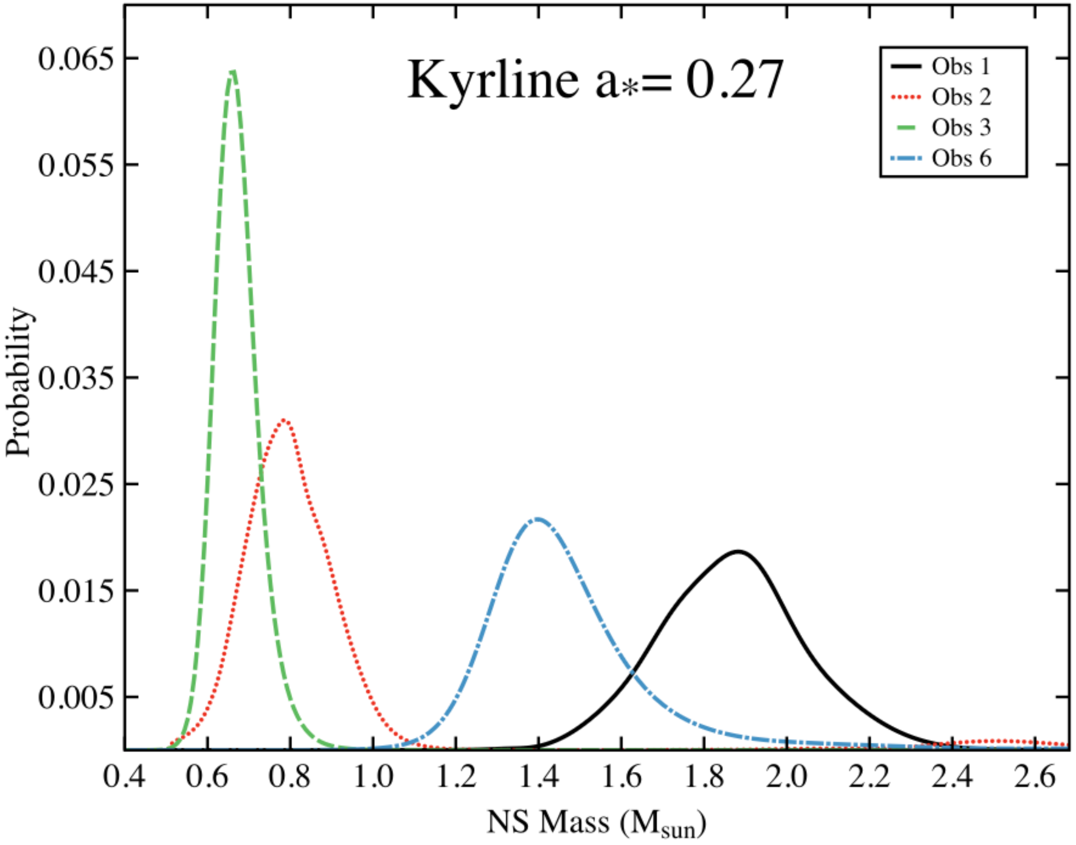
We want to compare the distributions of the Mass for all the observations

Probability distribution inferred from the Fe line

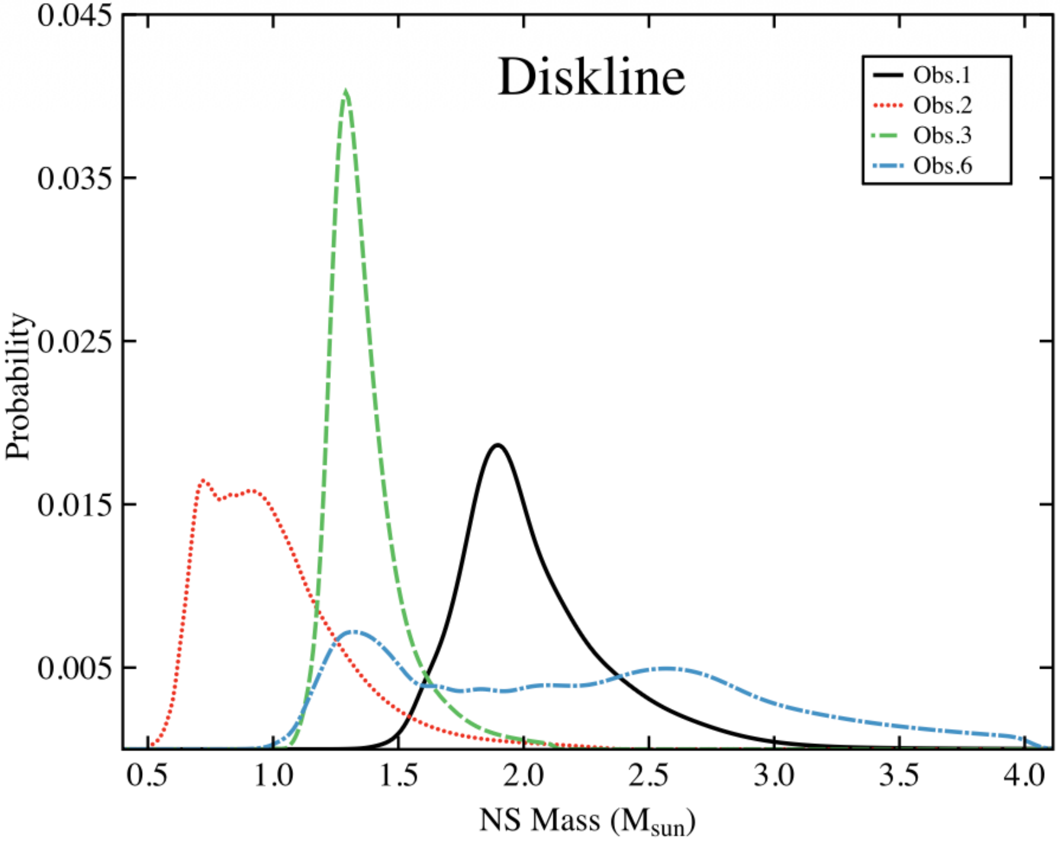


Do the inferred masses agree?

Different observations prefer clearly different masses



Different mass and model-dependent distributions



Now, timing and spectroscopic radii do not yield a consistent neutron-star mass across different source states

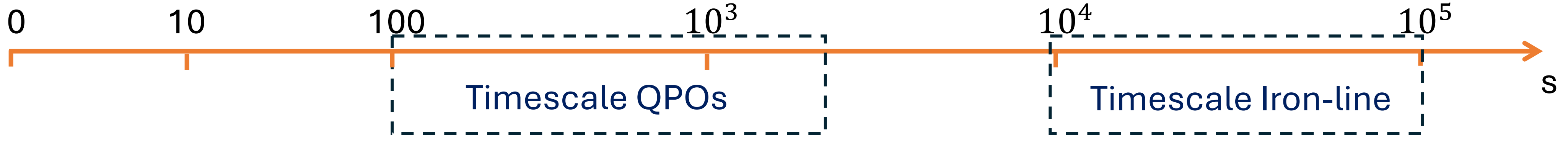
The bottleneck: spectroscopy is too slow

To constrain the Fe K line profile with current instruments we need 20 – 30 ks

Obs.	Sanna exposure
Obs. 1	**26.2 ks**
Obs. 2	**26.9 ks**
Obs. 3	**25.3 ks**
Obs. 6	**18.4 ks**

In Obs. 3 and Obs. 5, the kHz QPO frequency varied significantly (of about 200 Hz) during the same 20 - 30 ks interval needed to detect and model the iron line.

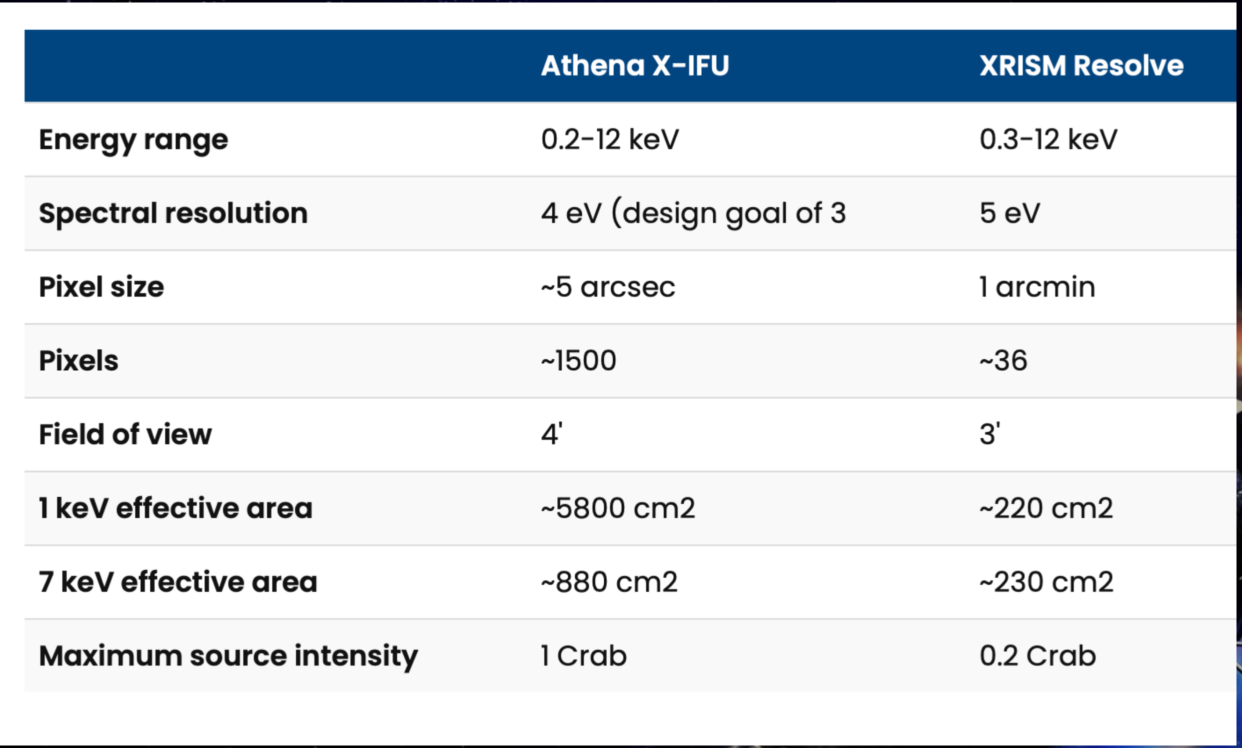
The Fe line gives a radius averaged over a long interval during which the condition of the disc can change.



The bottleneck is spectroscopy, not timing.

What NewAthena can do

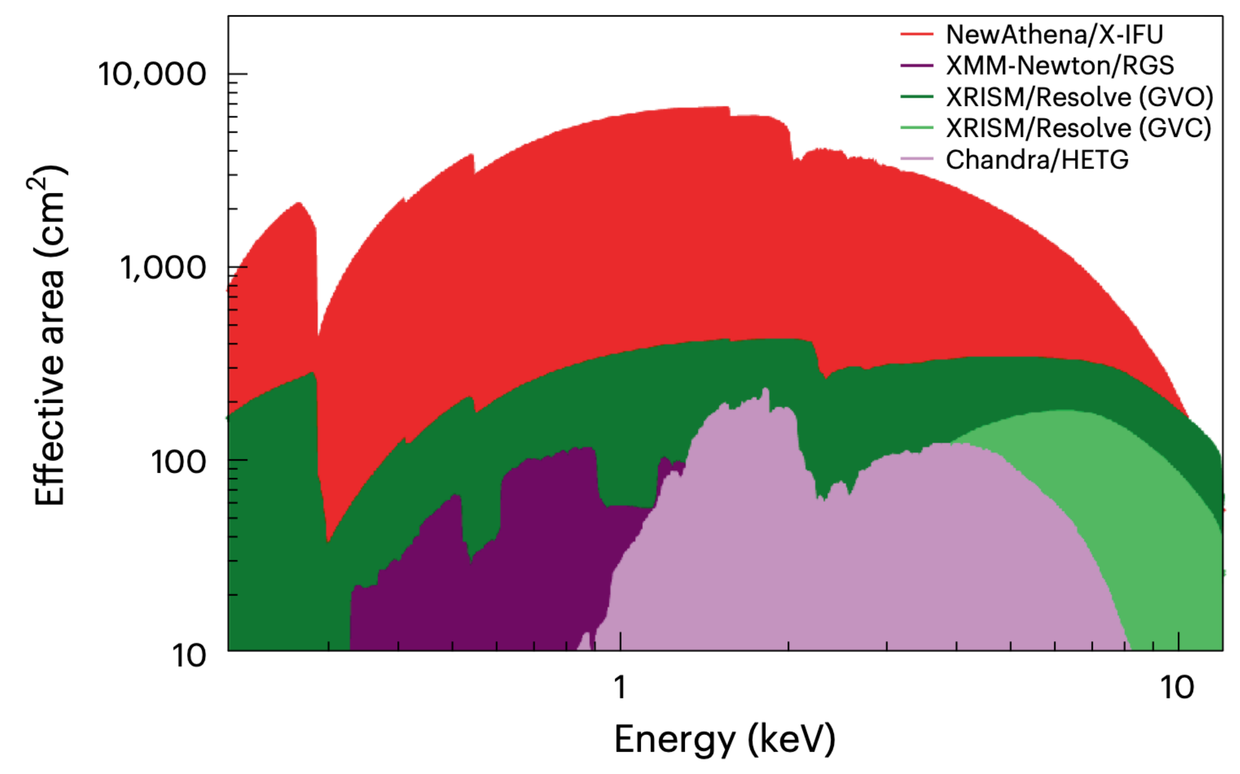
What NewAthena can do



	Athena X-IFU	XRISM Resolve
Energy range	0.2-12 keV	0.3-12 keV
Spectral resolution	4 eV (design goal of 3	5 eV
Pixel size	~5 arcsec	1 arcmin
Pixels	~1500	~36
Field of view	4'	3'
1 keV effective area	~5800 cm2	~220 cm2
7 keV effective area	~880 cm2	~230 cm2
Maximum source intensity	1 Crab	0.2 Crab

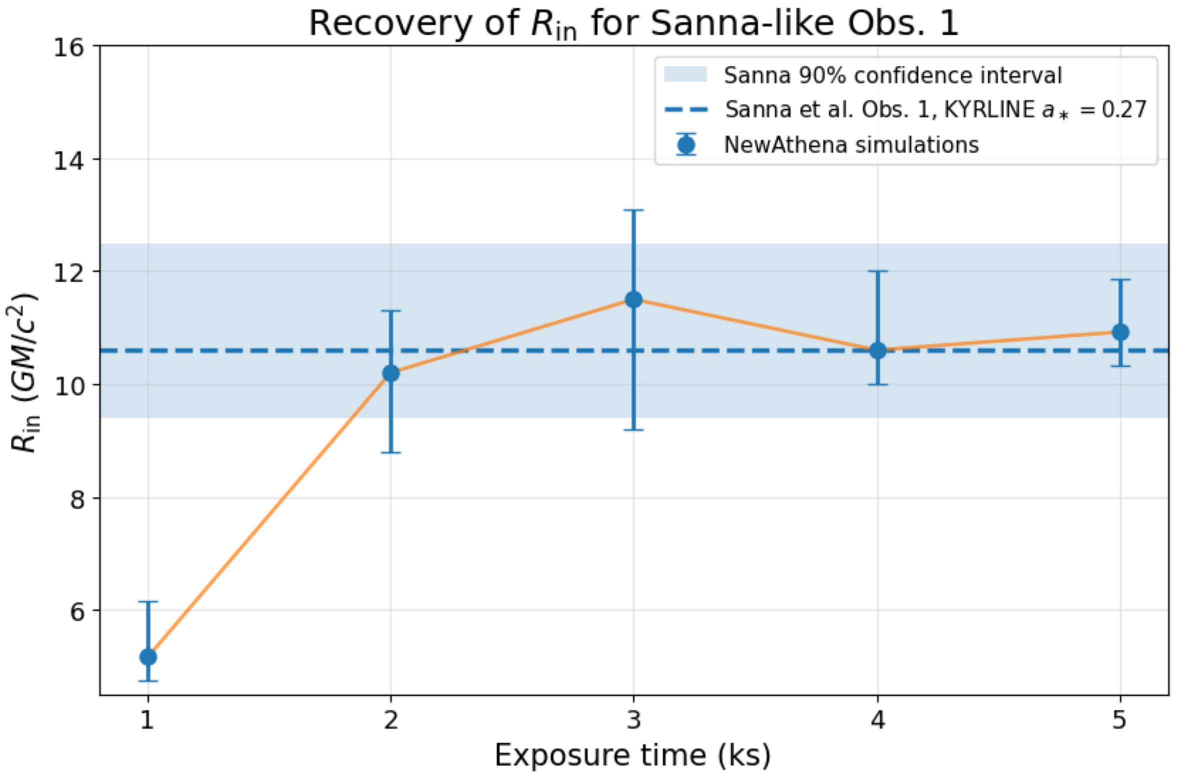
NewAthena can bring Fe-line spectroscopy onto the QPO timescale.

At the Fe K band, NewAthena provides about four times the collecting area of XRISM, with comparable spectral resolution

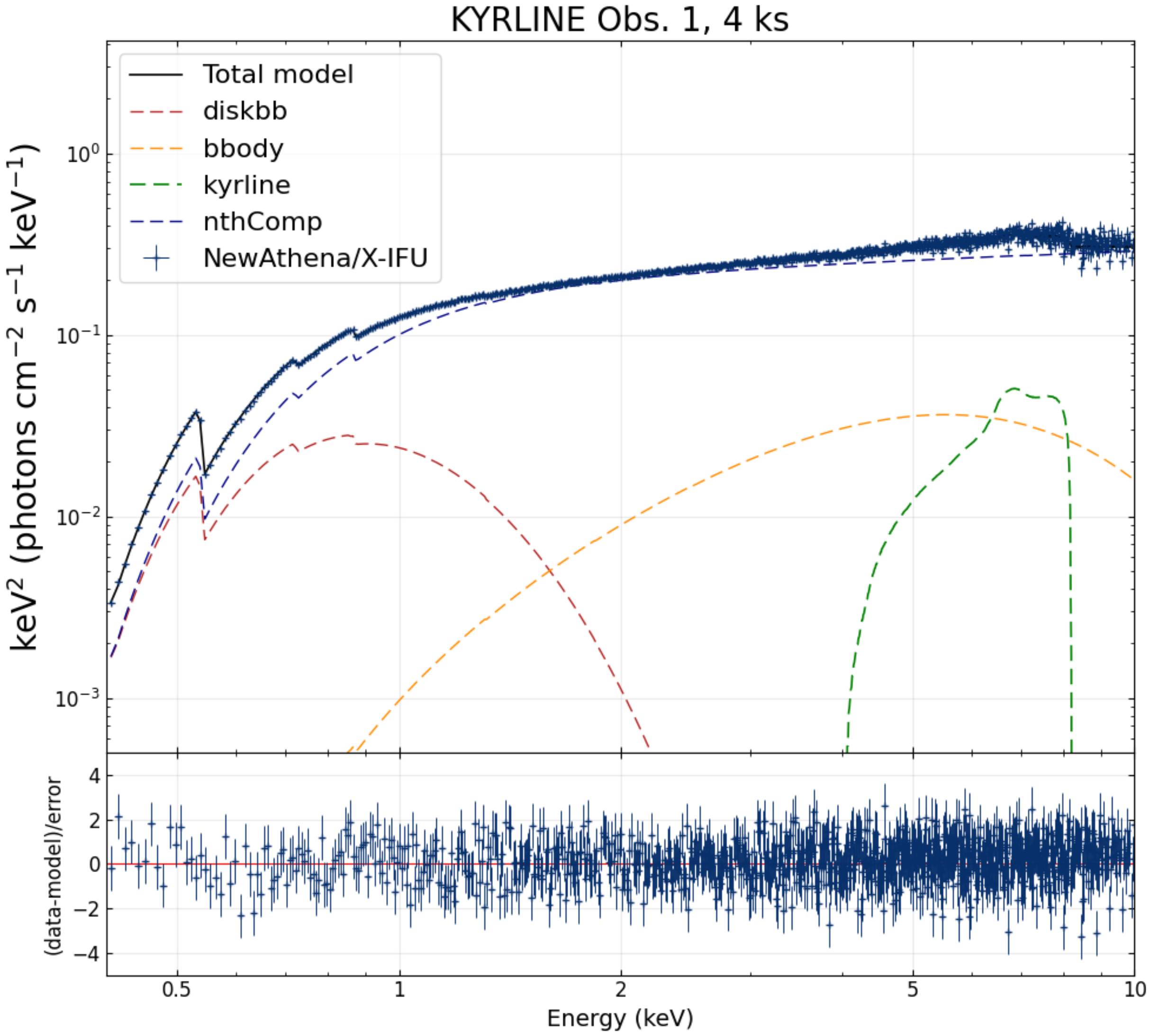


Kyrline with NewAthena

Can NewAthena recover Rin with much shorter exposures?



phabs*(diskbb + bbody + **kyrline** + nthcomp)



NewAthena simulations:

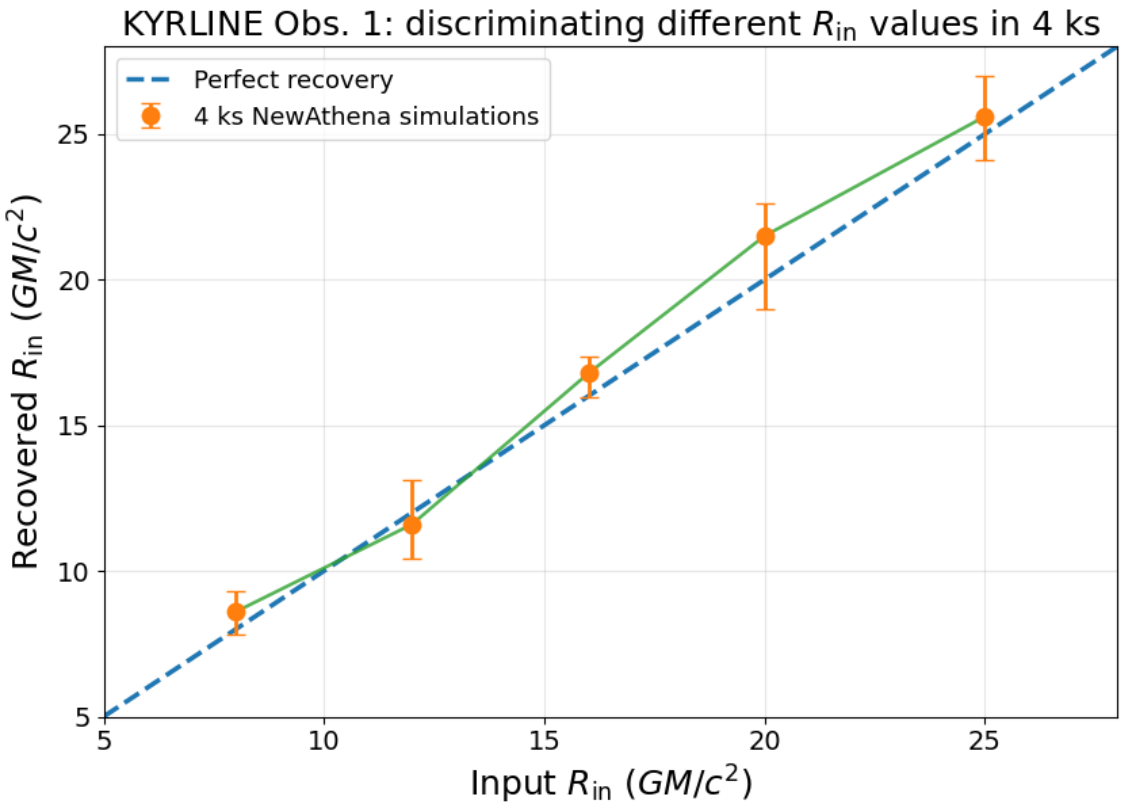
$R_{\text{in}} = 10.6^{+1.4}_{-0.6}, R_g$ in ~ 4 ks

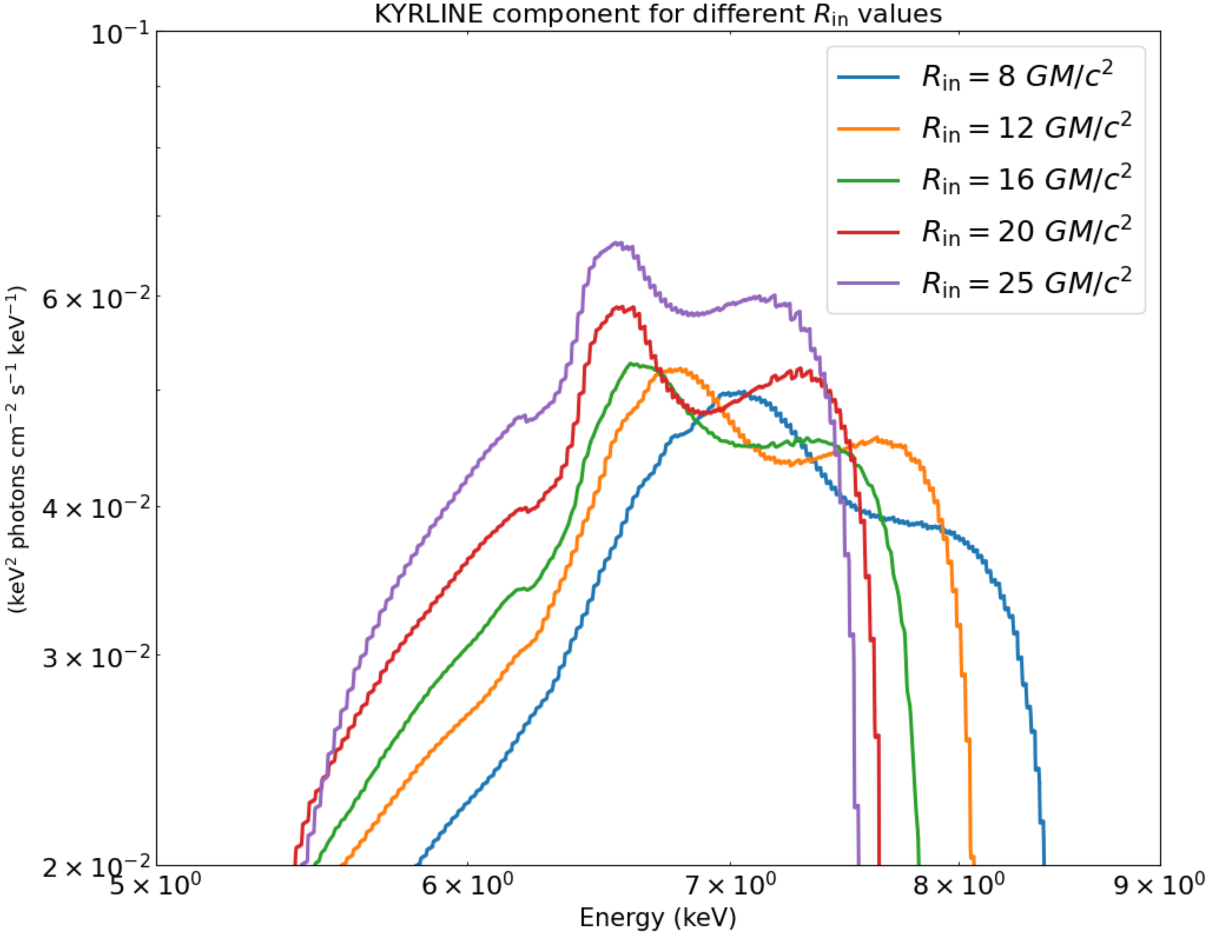
Sanna et al.:

$R_{\text{in}} = 10.6^{+1.9}_{-1.2}, R_g$ in ~ 25 ks

Kyrline with different radii at 4 ks

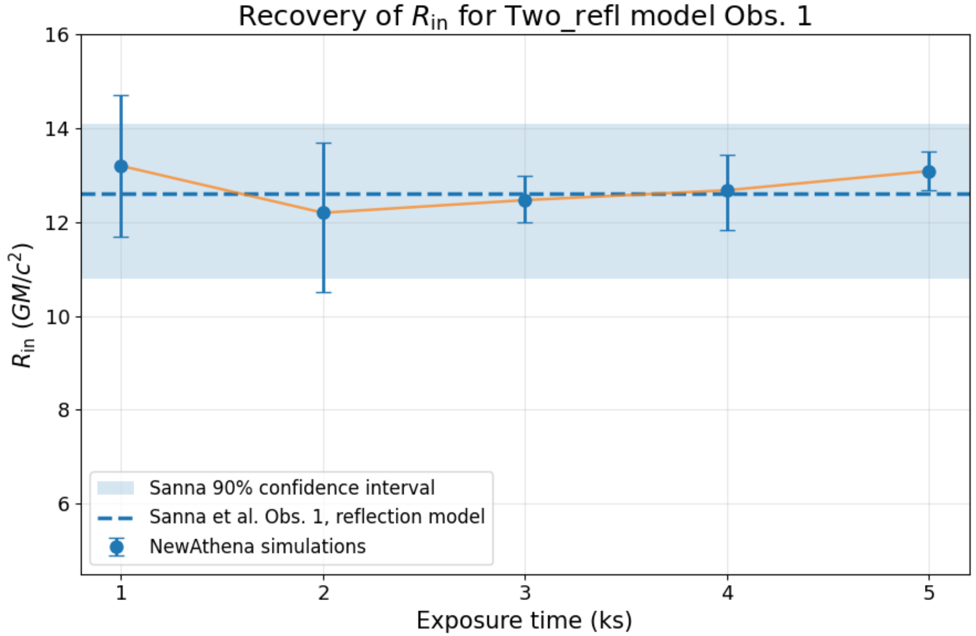
Can NewAthena discriminate different $\mathrm{R_{in}}$ values in short exposures?

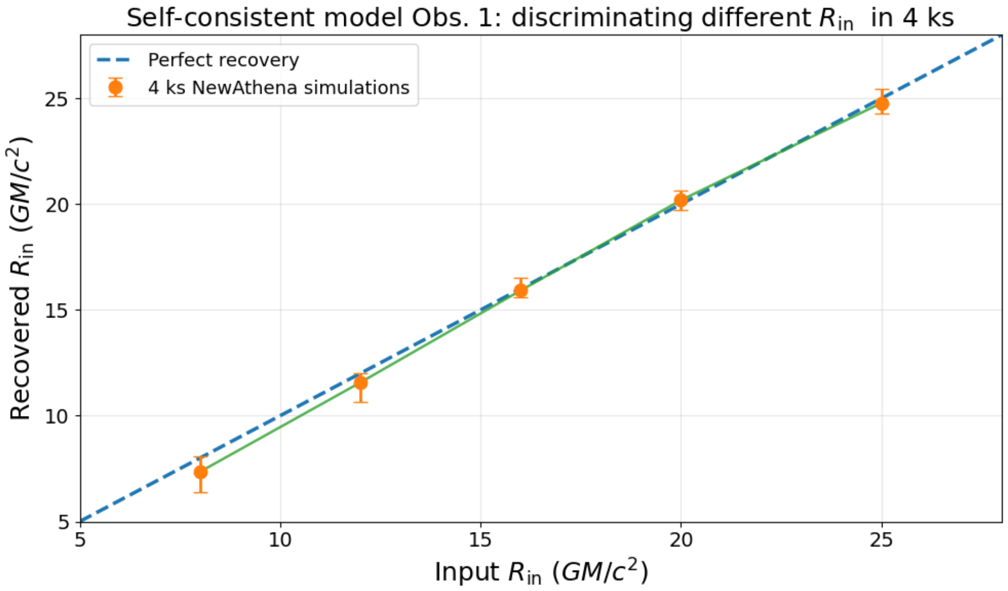




A 4 ks exposure is enough to recover and distinguish different input $\mathrm{R_{in}}$ values

Self-consistent reflection

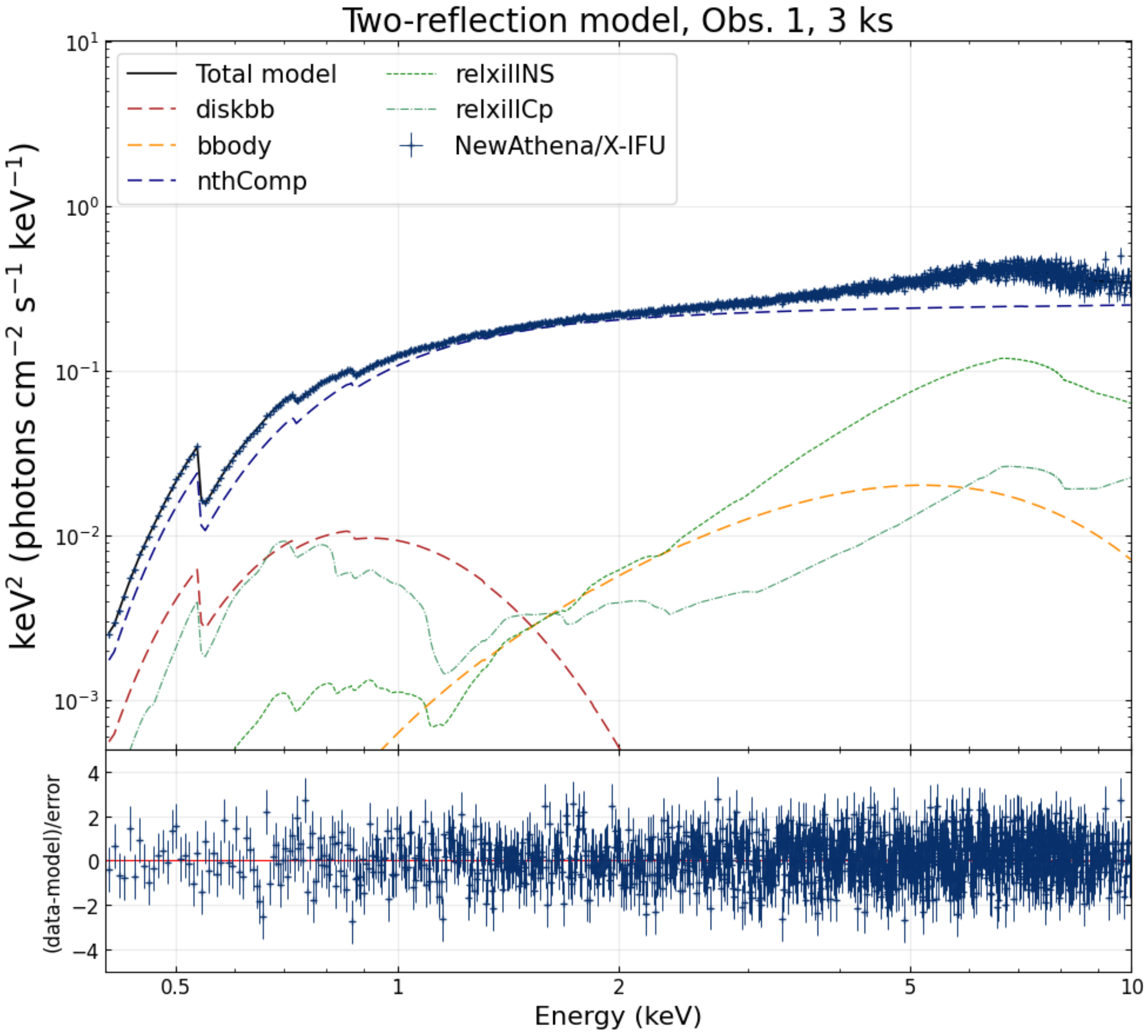




Two-reflection model:

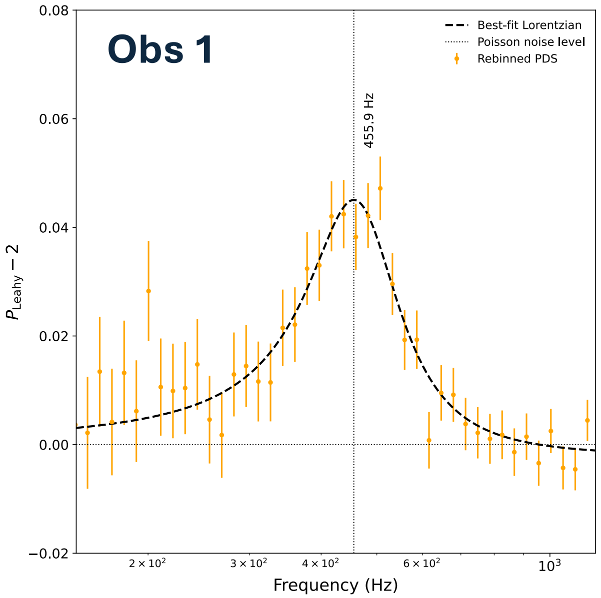
relxillNS thermal illumination from the NS

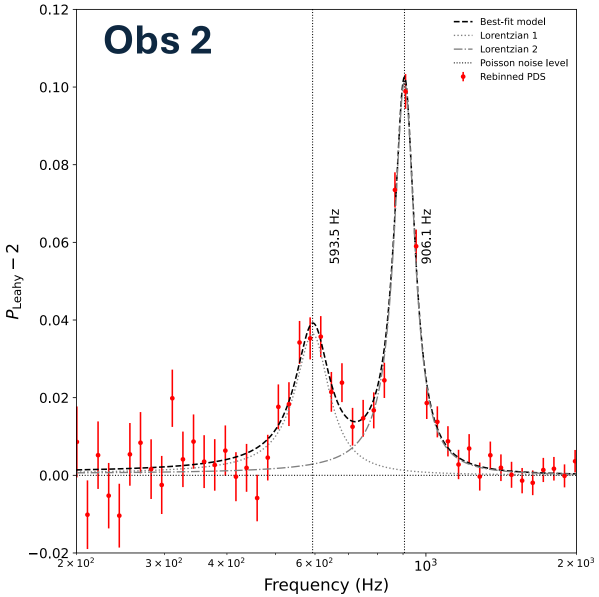
relxillCp Comptonized illumination from the corona

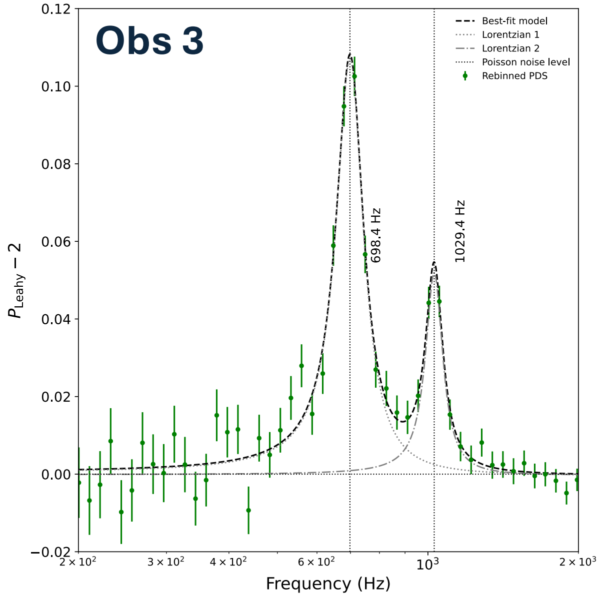


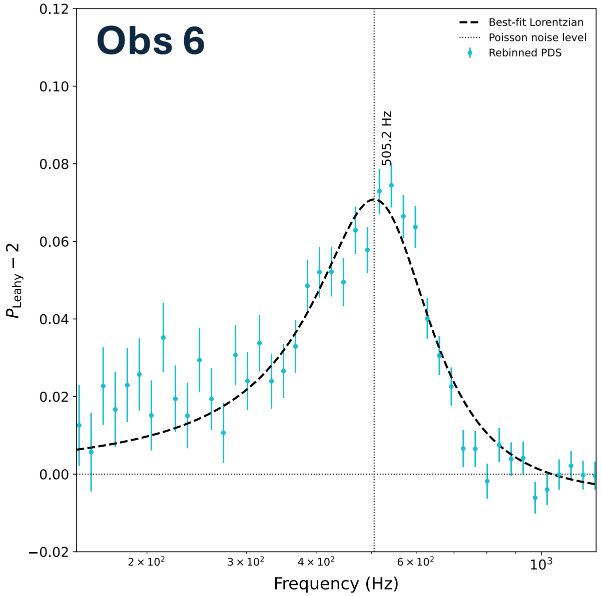
kHz QPOs simulations

Courtesy of Carlotta Miceli









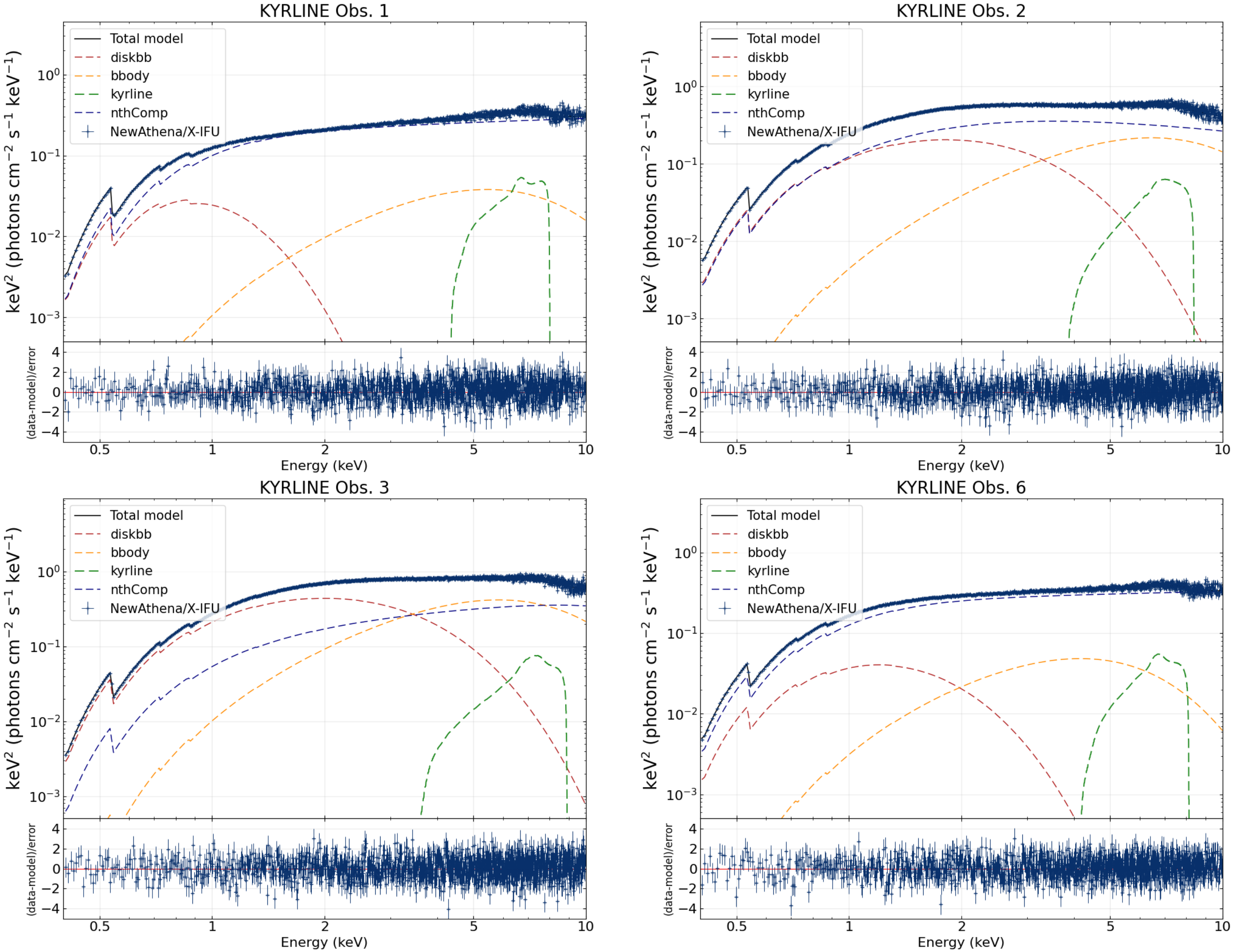
We simulated 4 ks power spectra using the kHz QPO parameters measured by Sanna+14

$$\nu_\phi = \frac{1}{2\pi}\frac{c^3}{GM}\frac{1}{R_{in}^{3/2}+a_*}$$

Assuming $M_{NS} = 1.4\ M_\odot$, the observed upper kHz QPO frequencies are converted into Keplerian radii.

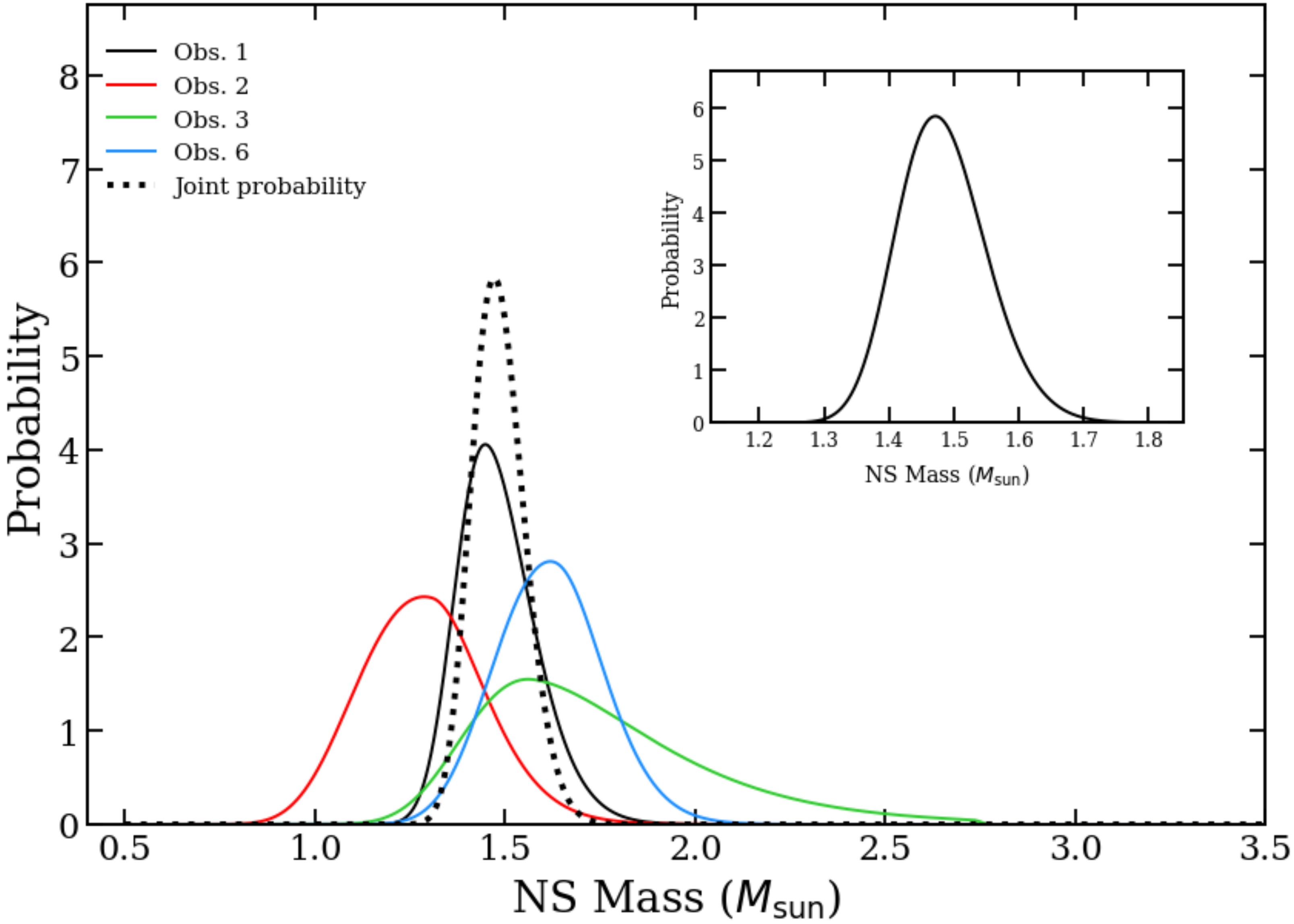
Obs	kHz QPO (Hz)	R_{QPO} (R_g)
Obs.1	457.43 ± 7.16	13.61 ± 0.14
Obs.2	906.01 ± 2.57	8.60 ± 0.02
Obs.3	1026.96 ± 4.55	7.90 ± 0.02
Obs.6	503.01 ± 5.42	12.77 ± 0.09

Spectra simulations



Obs	$\mathbf{R_{in}\ (R_g)}$
Obs. 1	$13.3^{+0.8}_{-1.1}\ \mathrm{R_g}$
Obs. 2	$9.0^{+1.6}_{-1.0}\ \mathrm{R_g}$
Obs. 3	$7.3^{+1.0}_{-1.5}\ \mathrm{R_g}$
Obs. 6	$11.5^{+1.3}_{-0.9}\ \mathrm{R_g}$

Constraint on the NS mass



Obs	NS Mass
Obs. 1	$1.51^{+0.12}_{-0.07}\,M_\odot$
Obs. 2	$1.34^{+0.06}_{-0.04}\,M_\odot$
Obs. 3	$1.39^{+0.02}_{-0.04}\,M_\odot$
Obs. 6	$1.51 \pm 0.02\,M_\odot$

$$\mathrm{M} = 1.47^{+0.13}_{-0.09}\ \mathrm{M}_\odot$$

NewAthena can measure the Fe line radius on ks timescales, combine it with the kHz QPO radius, and recover a coherent NS mass.

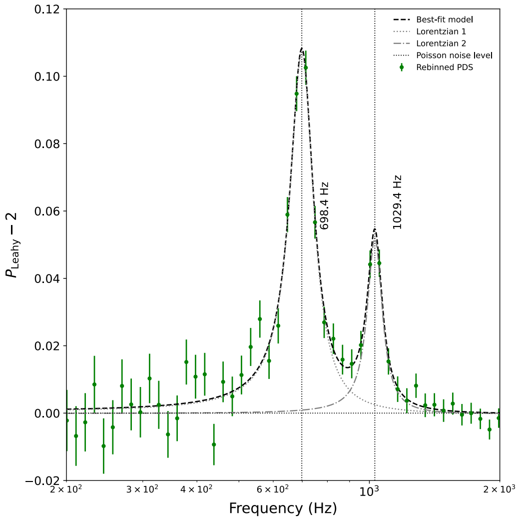
Summary of the results

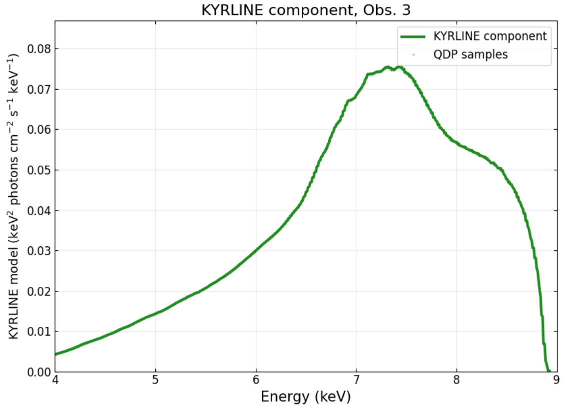
- **Fe-line spectroscopy becomes fast**:
NewAthena recovers $\mathrm{R_{in}}$ from the Iron line spectroscopy in a few ks instead of 10-30 ks

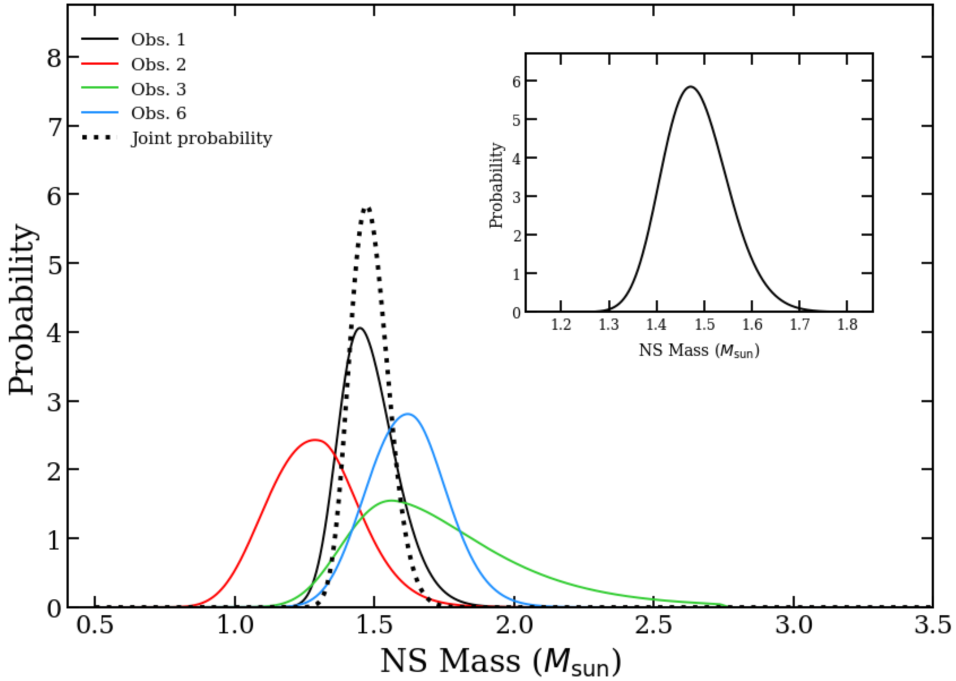
- **Radius changes become measurable**:
4 ks simulations can distinguish different disc configuration and inner radius values

- **QPO and Fe-line radii can be compared on similar timescales**: if the two diagnostic are tracing the same radius NewAthena can test it and constrain the mass-radius of the neutron star

- **Next step**: this approach can be applied to other source that shows kHz QPO and iron line to constrain their mass (GX 349+2, GX 17+2, 4U 1820-30, ...)





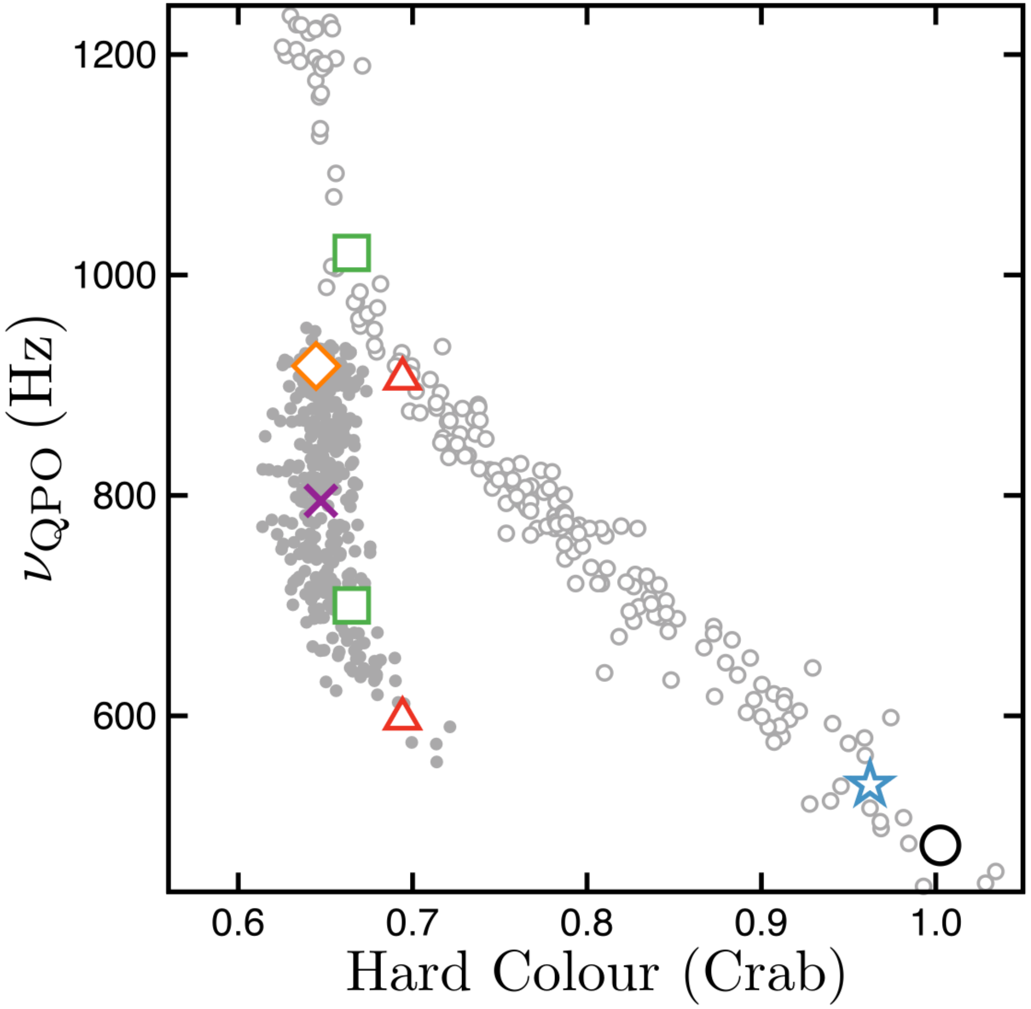


EXTRA SLIDES

Simulation other sources

kHz QPOs and Hardness

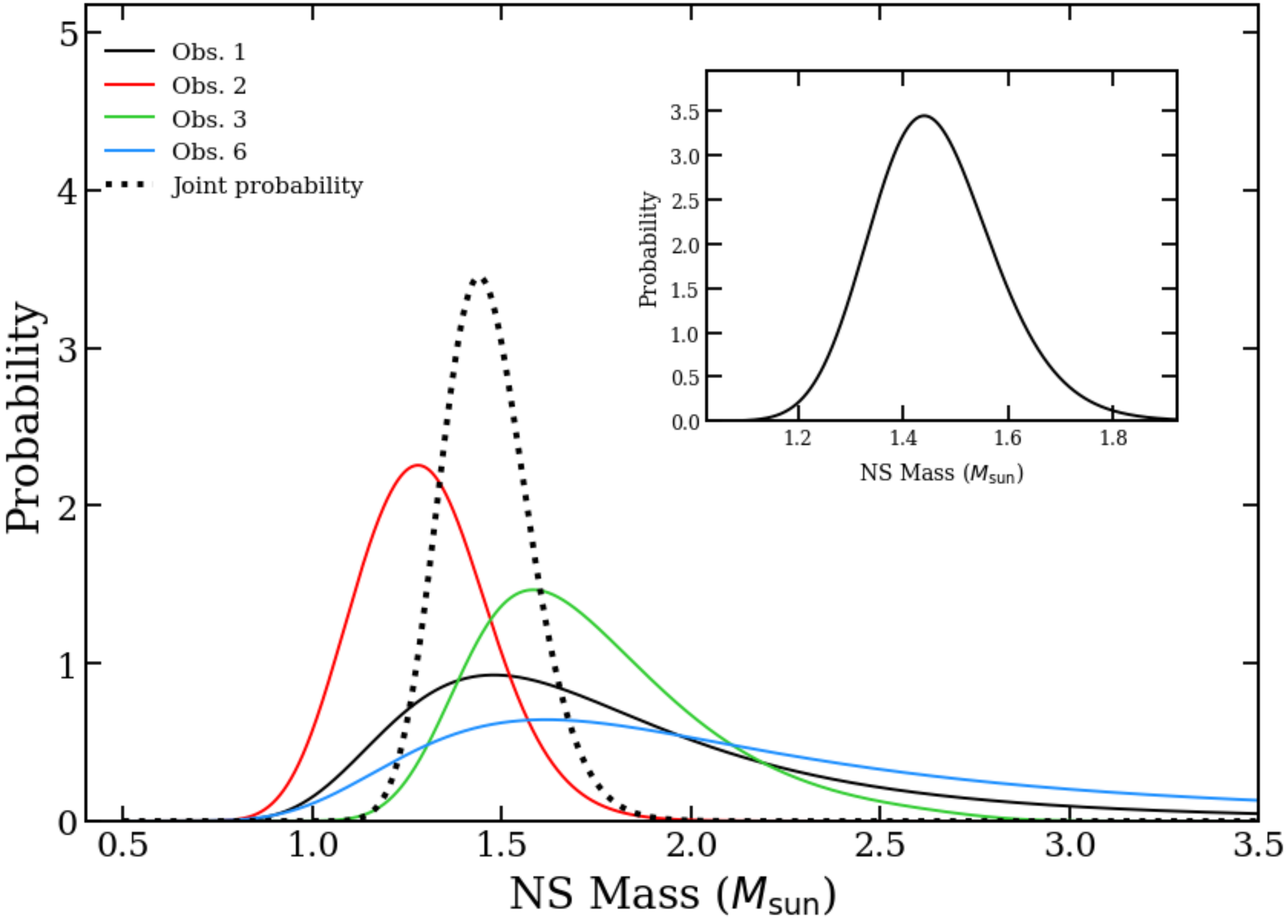
Frequency of the kHz QPOs in 4U 1636−53 as a function of hard colour. Grey filled and empty bullets represent the lower and the upper kHz QPOs, respectively (Sanna+12).



Lower and upper kHz QPOs follow different branches

- In 4U 1636–53, the kHz QPO frequency is correlated with hard colour.
- This relation is used to identify single QPO detections when only one peak is observed.
- the lower and upper kHz QPOs respond differently to changes in the inner accretion flow.

PDF using the FWHM of kHz QPO



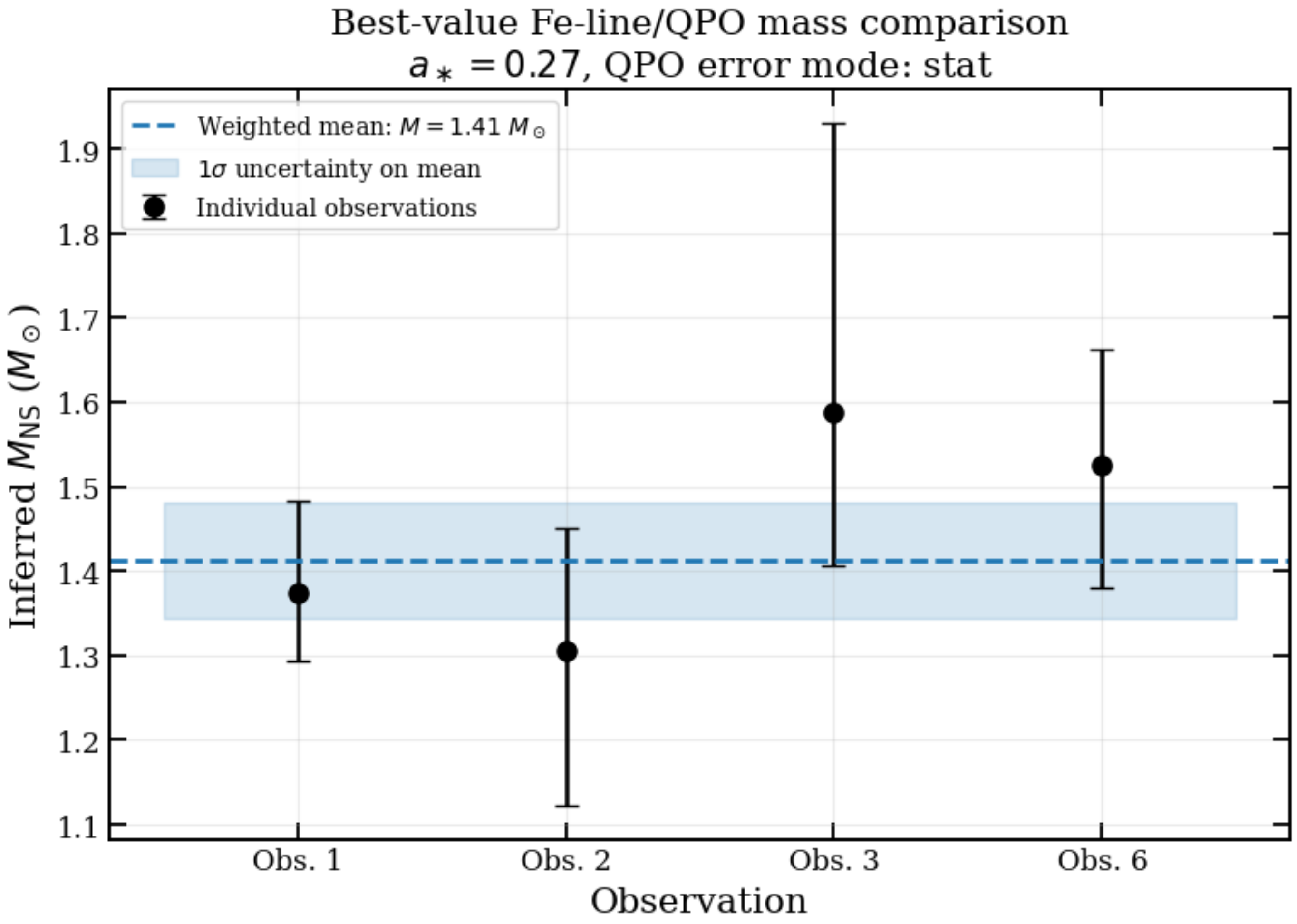
If we want to take account of the drift of the kHz QPO frequencies we can consider the HWHM instead of the frequency.

The probability function of the Mass will be of course broader since the errors on the HWHM are bigger.

As a consequence we obtain a bigger error on the Mass

$$M = 1.44^{+0.23}_{-0.16}\ M_{\odot}$$

Comparing radii using best fit values



$Obs.$	$R_{\rm in}(GM/c^2)$	$\nu_u(Hz)$	$M_{\rm NS}(M_\odot)$
Obs. 1	13.33	482	$1.37^{+0.11}_{-0.08}$
Obs. 2	9.00	906	$1.31^{+0.14}_{-0.18}$
Obs. 3	7.30	1020	$1.59^{+0.34}_{-0.18}$
Obs. 6	11.51	537	$1.53^{+0.14}_{-0.15}$

$$\mathrm{M} = 1.41 \pm 0.07\ \mathrm{M}_\odot$$