Constraining the equation of state in neutron stars with XRISM/Resolve

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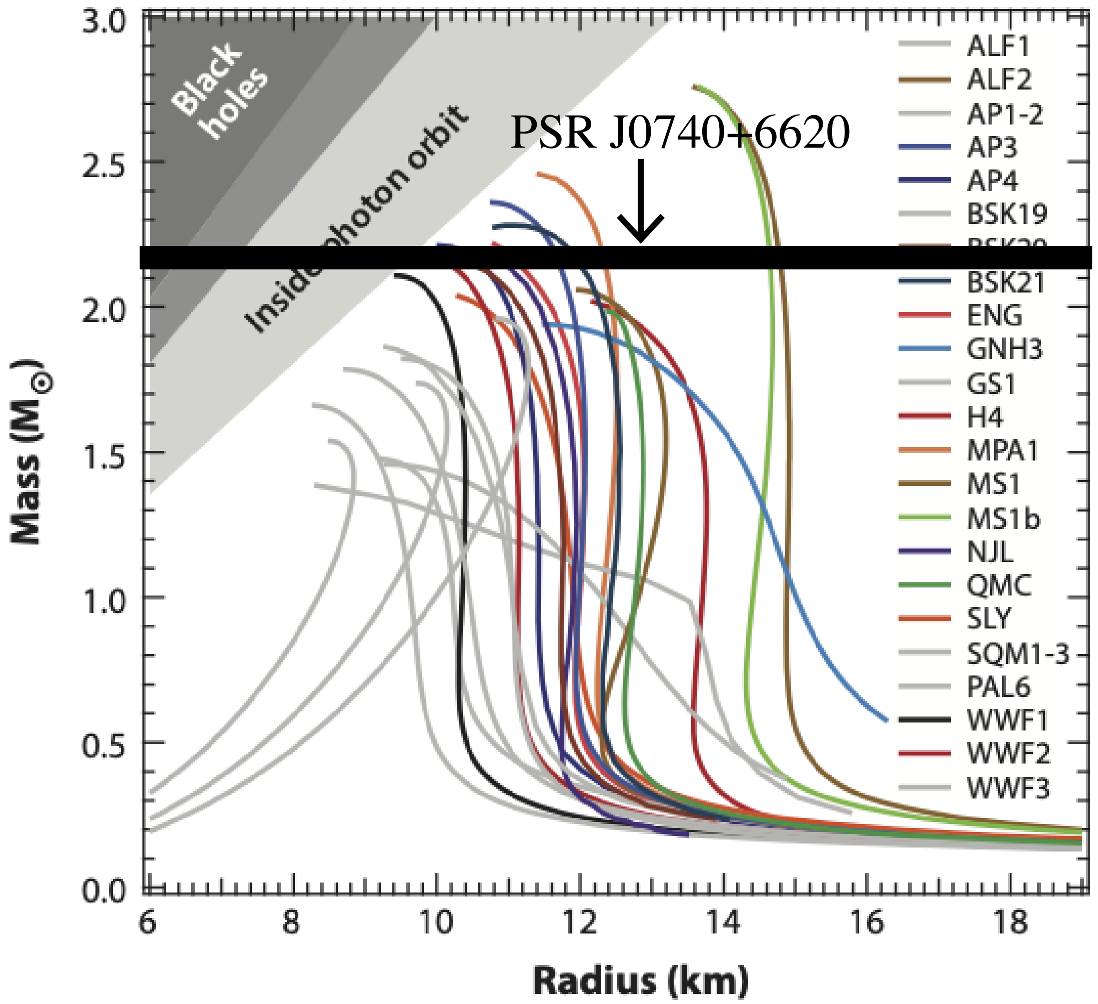
Equation of state in neutron stars

- Equation of state (EoS) in neutron stars is one of the most fundamental questions in both astronomy and nuclear/particle physics.
- EoS, expressing relation between microscopic density and pressure, can be constrained by measuring macroscopic mass (M) and radius (R).

Various models of EoS (özel+ 16)



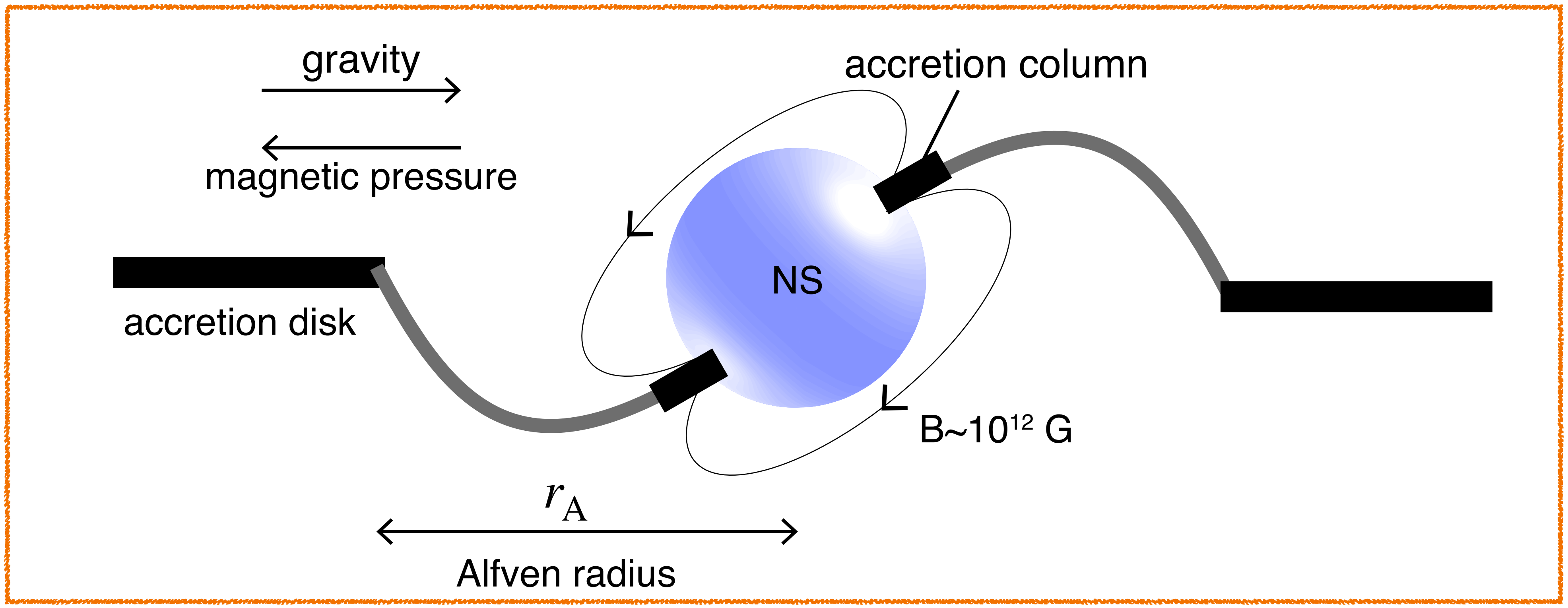
- Various EoS models have been proposed, but the observational examination is still under way.
- A recent observational examination in the X-ray band is conducted with NICER, calculating mass and radius from light bending by analyzing pulse profiles of pulsars.
  ex. PSR J0030+0451 (Miller+ 2019)
- A neutron star with $M \sim 2.14 M_\odot$ was discovered by measuring relativistic Shapiro delay, by which some of the EoS models could be rejected (PSR J0740+6620; Cromartie+ 20).

Still, we need more samples of M and R with a different observational approach.
The spectroscopy with XRISM/Resolve can provide a totally new approach to measuring M and R.

How to measure M and R of NS with XRISM

Target: X-ray pulsars with strong magnetic fields ($\sim 10^{12}$ G) and accretion disks.

- M is already known from the binary motion.
- We can estimate R from the geometrical configuration unique to highly magnetized X-ray pulsars.



The Alfvén radius r_A can be calculated by

$$r_A = 2.6 \times 10^8 \text{ cm} \left(\frac{\mu_B}{10^{30} \text{ G cm}^3}\right)^{4/7} \left(\frac{M}{M_\odot}\right)^{1/7} \left(\frac{R}{10 \text{ km}}\right)^{-2/7} \left(\frac{L_x}{10^{37} \text{ erg s}^{-1}}\right)^{-2/7}$$

μ_B is the magnetic moment, expressed by $\mu_B = B_s R^3$, where B_s is the surface magnetic field strength.

If we can measure r_A and B_s , we can calculate the radius of the neutron star (R).

How to measure M and R of NS with XRISM

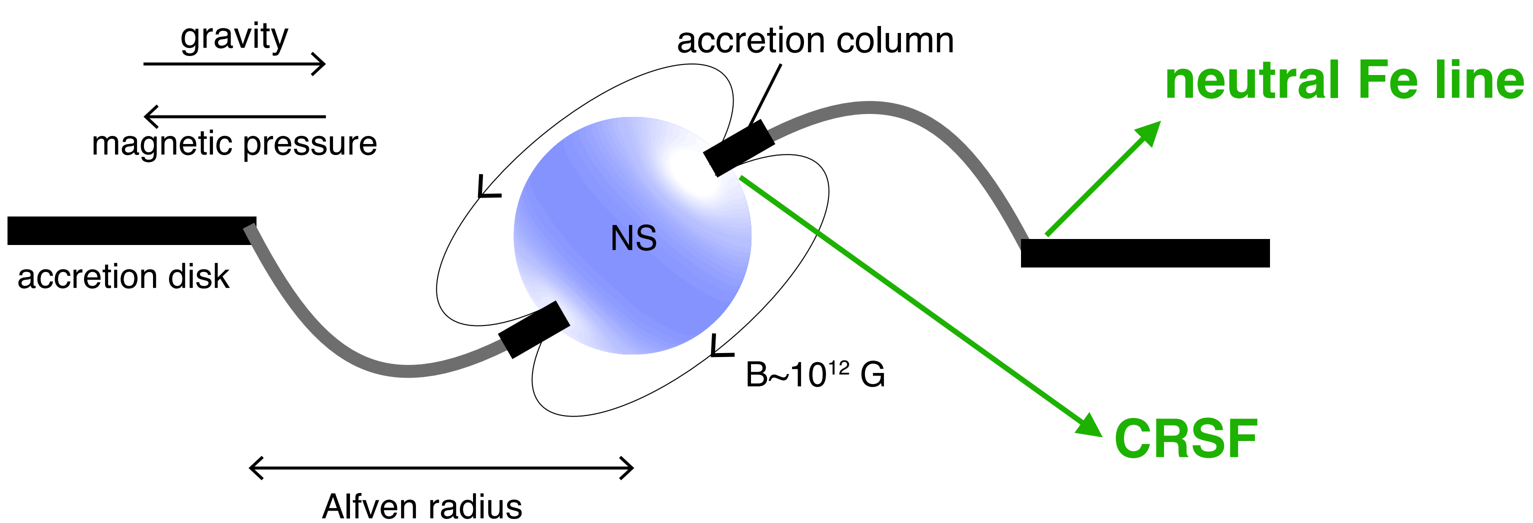
To estimate the radius of an X-ray pulsar, we need to measure
- r_{A}: Alfvén radius
- B_{s}: surface magnetic field strength (magnetic field strength at magnetic poles)

Measurement of r_{A}

- In X-ray pulsars accompanying accretion disks, neutral Fe emission line originates from the accretion disk while highly ionized Fe lines come from stellar wind.
- By measuring the width of the neutral Fe line, we can estimate Kepler velocity of the innermost region of the accretion disk. This leads to the estimation of Alfven radius r_{A}.
- XRISM/Resolve can precisely measure the width of the neutral Fe line.

Measurement of B_{s}

- The surface magnetic field strength can be estimated from the central energy of cyclotron resonance scattering feature (CRSF).
- The CRSF is usually observed in 20–50 keV, so we need the observation data in the hard X-ray band.



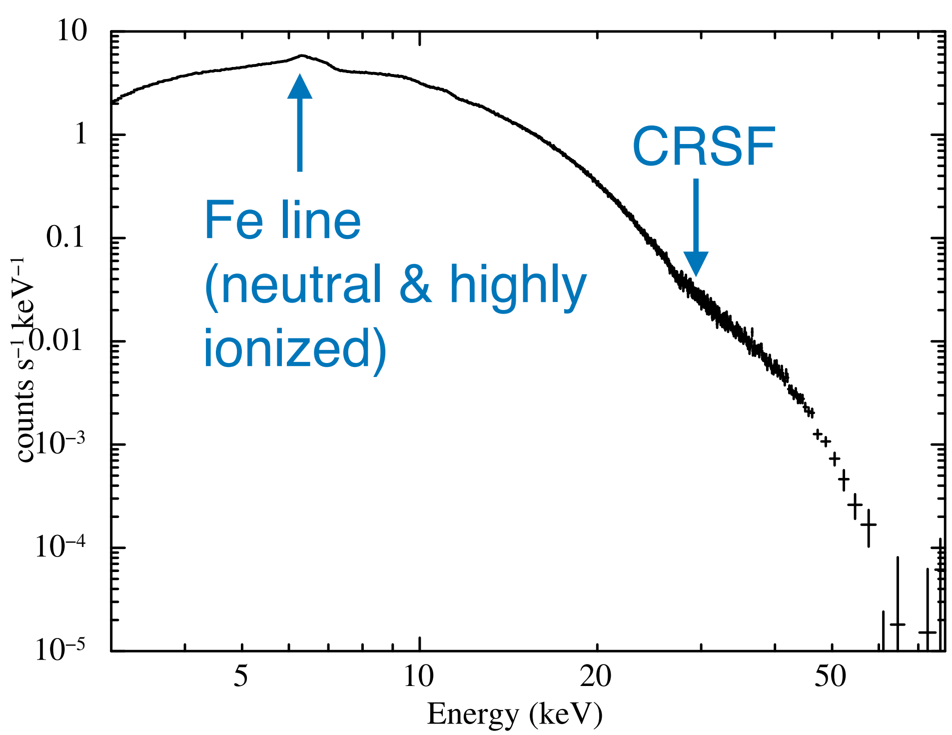
Cen X-3: best target for measuring M and R

$$r_{\mathrm{A}} = 2.6 \times 10^{8}\ \mathrm{cm} \left(\frac{B_{\mathrm{s}} R^{3}}{10^{30}\ \mathrm{G\ cm^{3}}}\right)^{4/7} \left(\frac{M}{M_{\odot}}\right)^{1/7} \left(\frac{R}{10\ \mathrm{km}}\right)^{-2/7} \left(\frac{L_{\mathrm{x}}}{10^{37}\ \mathrm{erg\ s^{-1}}}\right)^{-2/7}$$

Cen X-3, a PV target (priority A), is an ideal source to measure $M - R$ relation with X-ray spectroscopy.

- It is a disk-fed X-ray pulsar, accompanying a strong magnetic field of $B \sim 10^{12}$ G.
- The binary parameters (NS mass, companion star mass, orbital period, inclination) are well known.

NuSTAR spectrum of Cen X-3



- The neutral, He-like, and H-like Fe emission lines are observed, but not resolved well with previous observations.
- The neutral Fe line originates from accretion disk while the highly ionized Fe lines from stellar wind.
- The central energy of CRSF is 29.0 keV, corresponding to a surface magnetic field of $B_{\mathrm{s}} \sim 2.4 \times 10^{12}$ G.

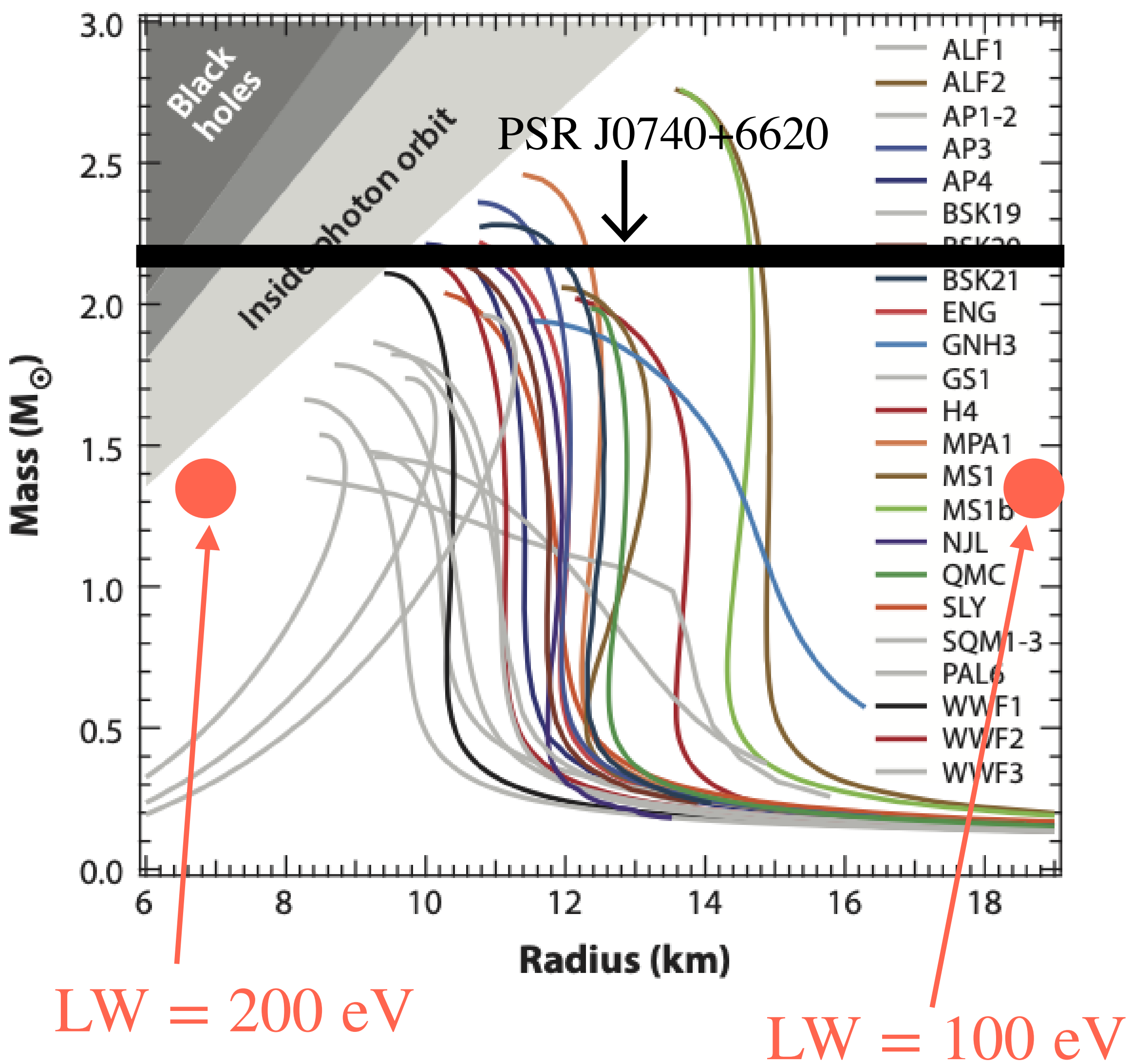
The only thing we need to do with XRISM/Resolve is to measure the width of the neutral Fe line!

Expected NS radius in Cen X-3

$$r_A = 2.6 \times 10^8 \text{ cm} \left(\frac{B_s R^3}{10^{30} \text{ G cm}^3}\right)^{4/7} \left(\frac{M}{M_\odot}\right)^{1/7} \left(\frac{R}{10 \text{ km}}\right)^{-2/7} \left(\frac{L_x}{10^{37} \text{ erg s}^{-1}}\right)^{-2/7}$$

r_A is directly linked with the line width of the neutral Fe line by setting the following values.

$M = 1.34 M_\odot$, $B_s = 2.4 \times 10^{12}$ G , $L_x = 5 \times 10^{37}$ erg s^{-1}
inclination angle $= 70.2°$



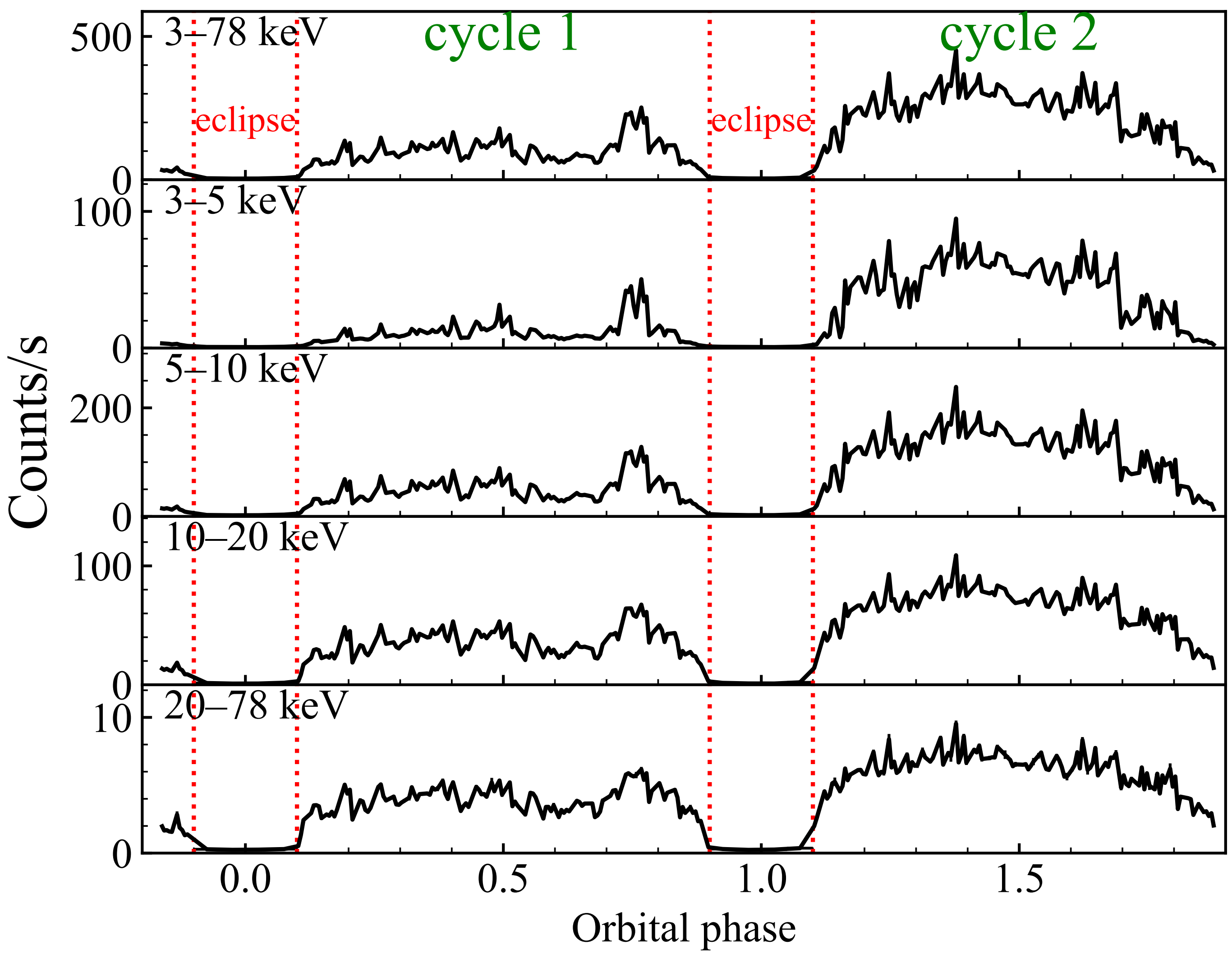
Expected results of measuring the radius of NS

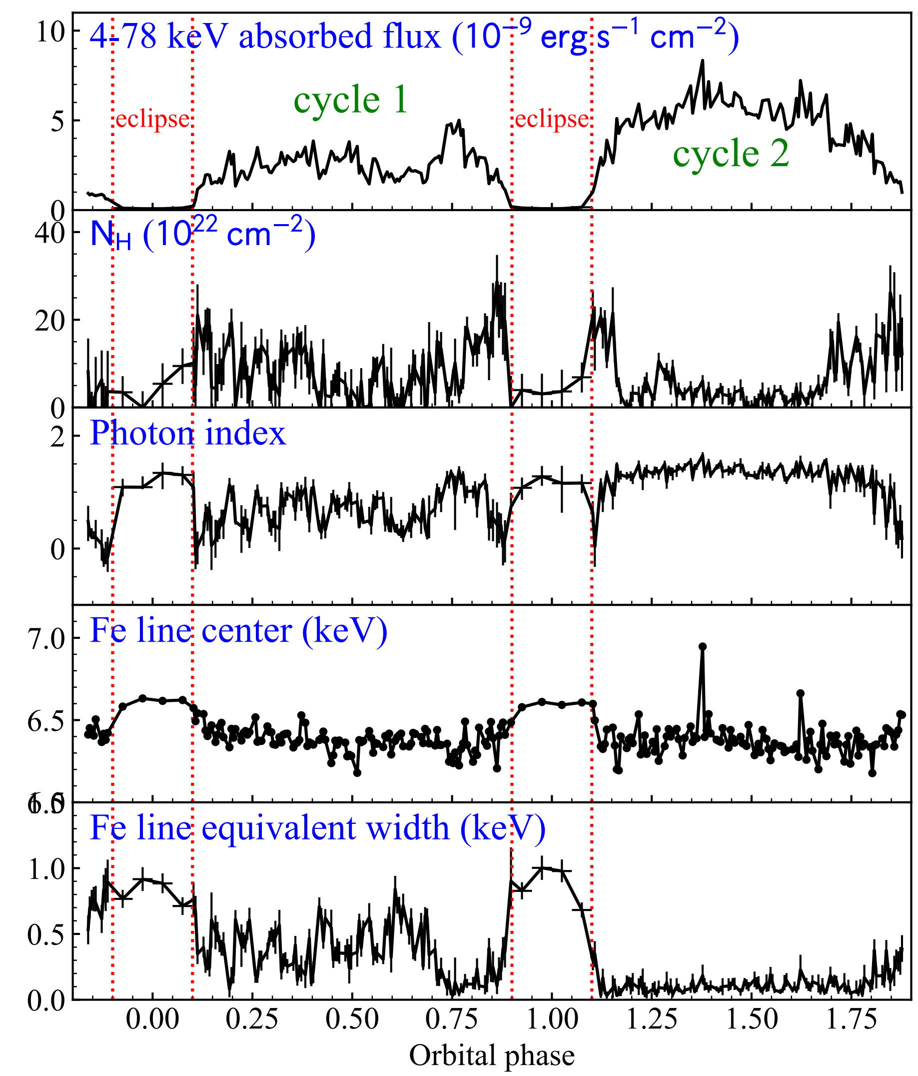
Line width (eV)	Alfvén radius (10^8 cm)	Radius of NS (km)
100	7.1	19.2
125	4.6	14.1
150	3.2	10.9
175	2.3	8.8
200	1.8	7.3

XRISM/Resolve has sufficient capability to constrain the NS radius in Cen X-3.

Drastic spectral variability of Cen X-3

- We observed Cen X-3 with NuSTAR for two consecutive orbits.
- The light curve shows drastic spectral variability over the orbital period. The difference between the first and the second orbit is also remarkable.

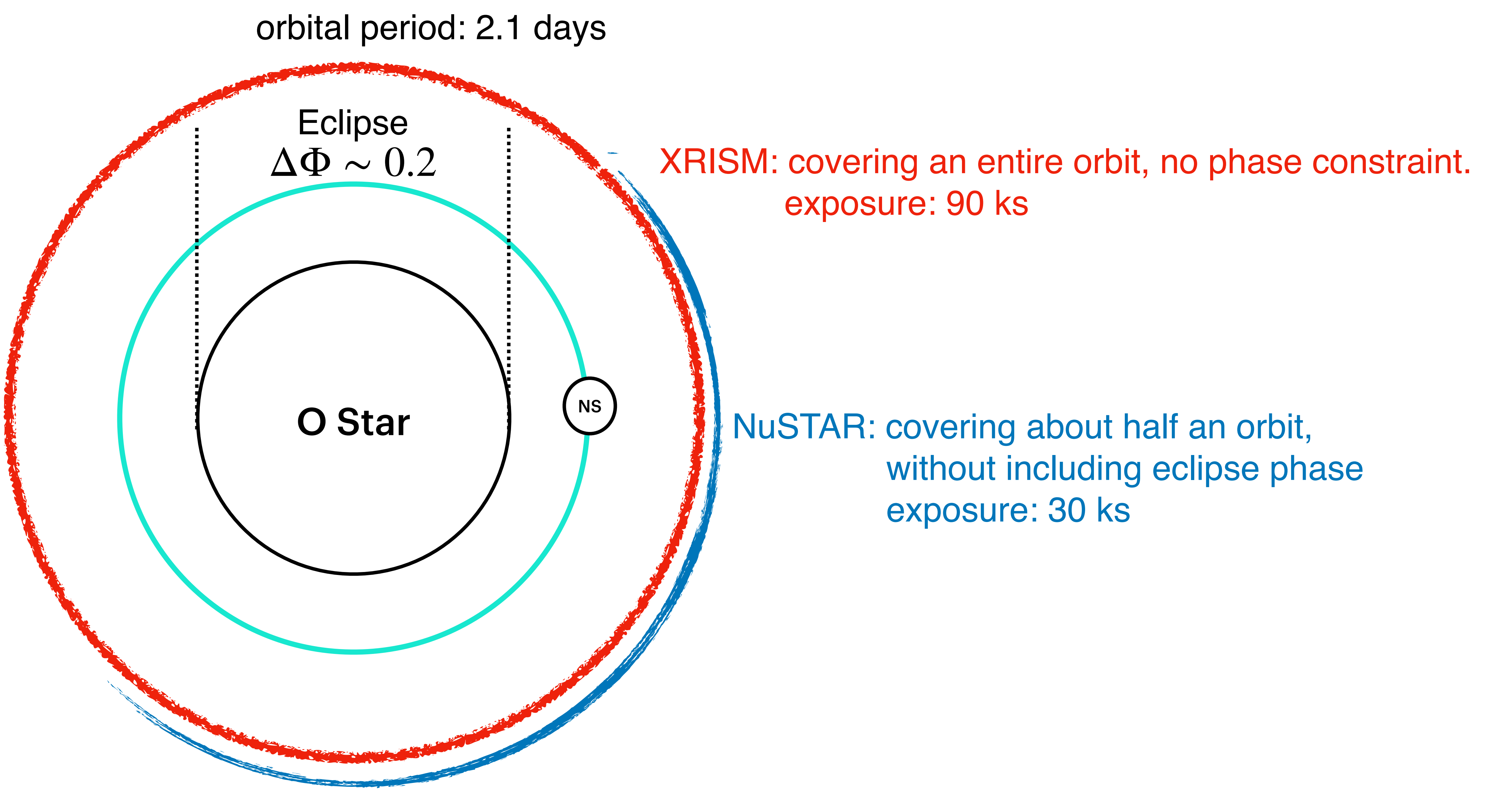




- Our spectral analysis revealed that the spectral variability is mostly due to stellar wind obscuration, but the intrinsic luminosity of NS also shows certain variation (Tamba+22, 24 in prep).
- Over- or under-estimation of the luminosity and magnetic field strength would lead to a wrong measurement of the NS radius.
  → A simultaneous observation with a hard X-ray observatory is required.

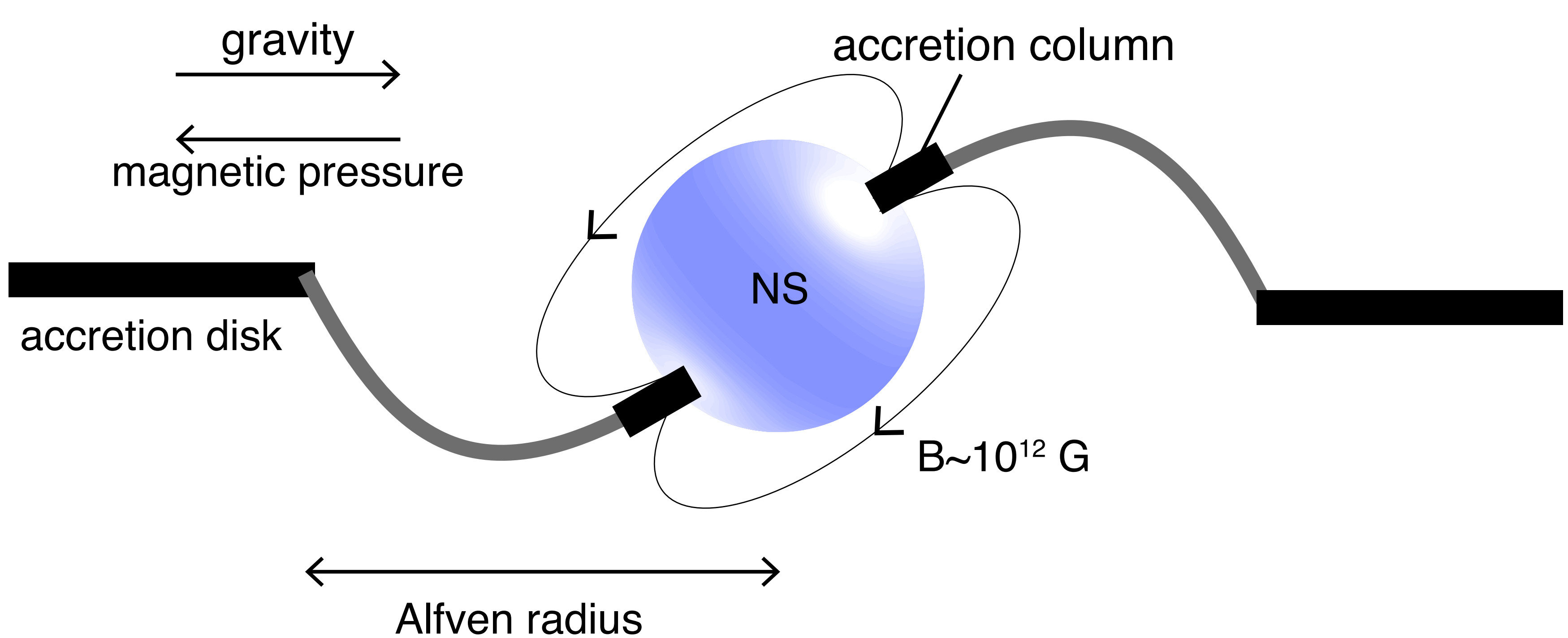
Simultaneous observation of Cen X-3 with XRISM and NuSTAR

We are planning a simultaneous observation on Cen X-3 with XRISM and NuSTAR, which is approved as a NuSTAR cycle 9 observation. While XRISM covers an entire orbit (2.1 days), NuSTAR covers about half of the orbit.
It leads to a precise evaluation of the NS radius.



Summary

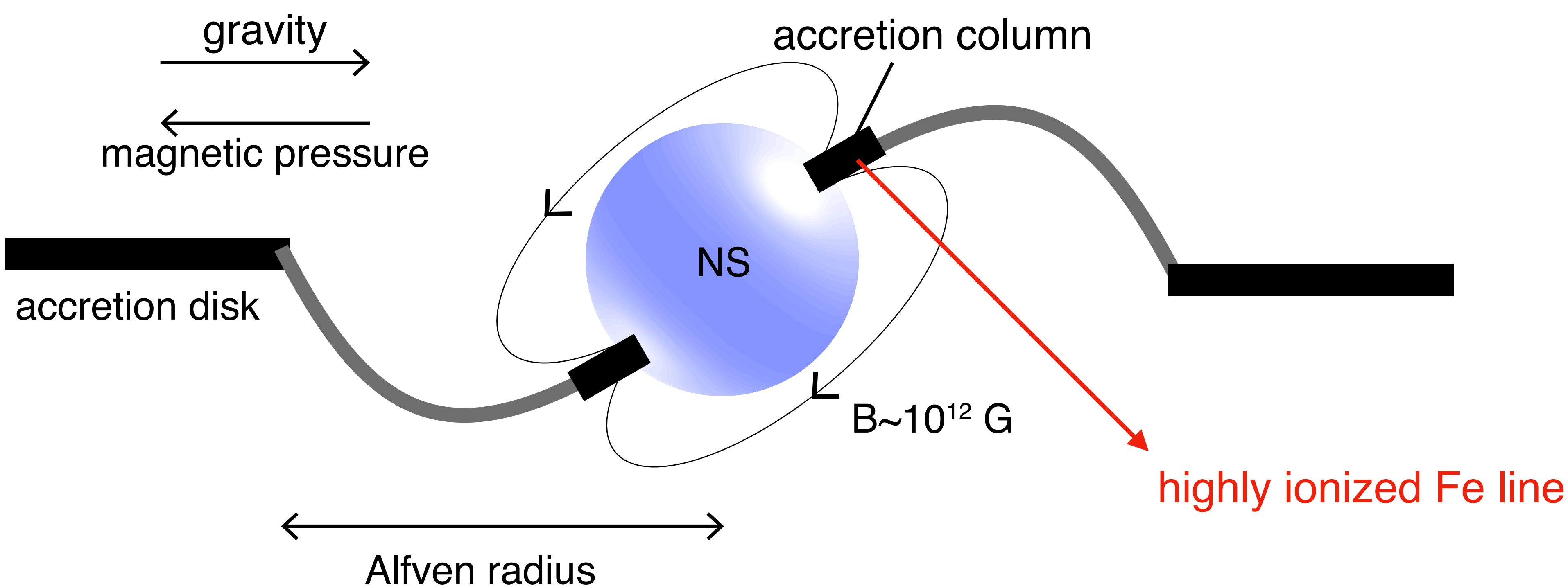
- The equation of state (EoS) in neutron stars is a fundamental question to solve in both astronomy and particle/nuclear physics. Measuring the mass and radius of neutron stars leads to constraining the EoS.
- XRISM/Resolve has capability of measuring the radius of highly magnetized X-ray pulsars. The radius of the neutron star can be estimated from the Alfvén radius and surface magnetic field strength. XRISM/Resolve is the only way to measure the Alfvén radius precisely.
- Cen X-3 is the best target to try this approach, and we are planning to observe it with XRISM and NuSTAR simultaneously.



Backup

Any other approaches to NS EoS with XRISM?

Gravitational redshift in accretion column



- The accretion column consists of highly ionized plasma.
- Spin-phase resolved spectroscopy with Resolve could detect periodically variable highly ionized Fe line.
- If so, the measurement of the gravitational redshift can constrain the radius of the neutron star.