ASTRO-Hによる中性子星の研究

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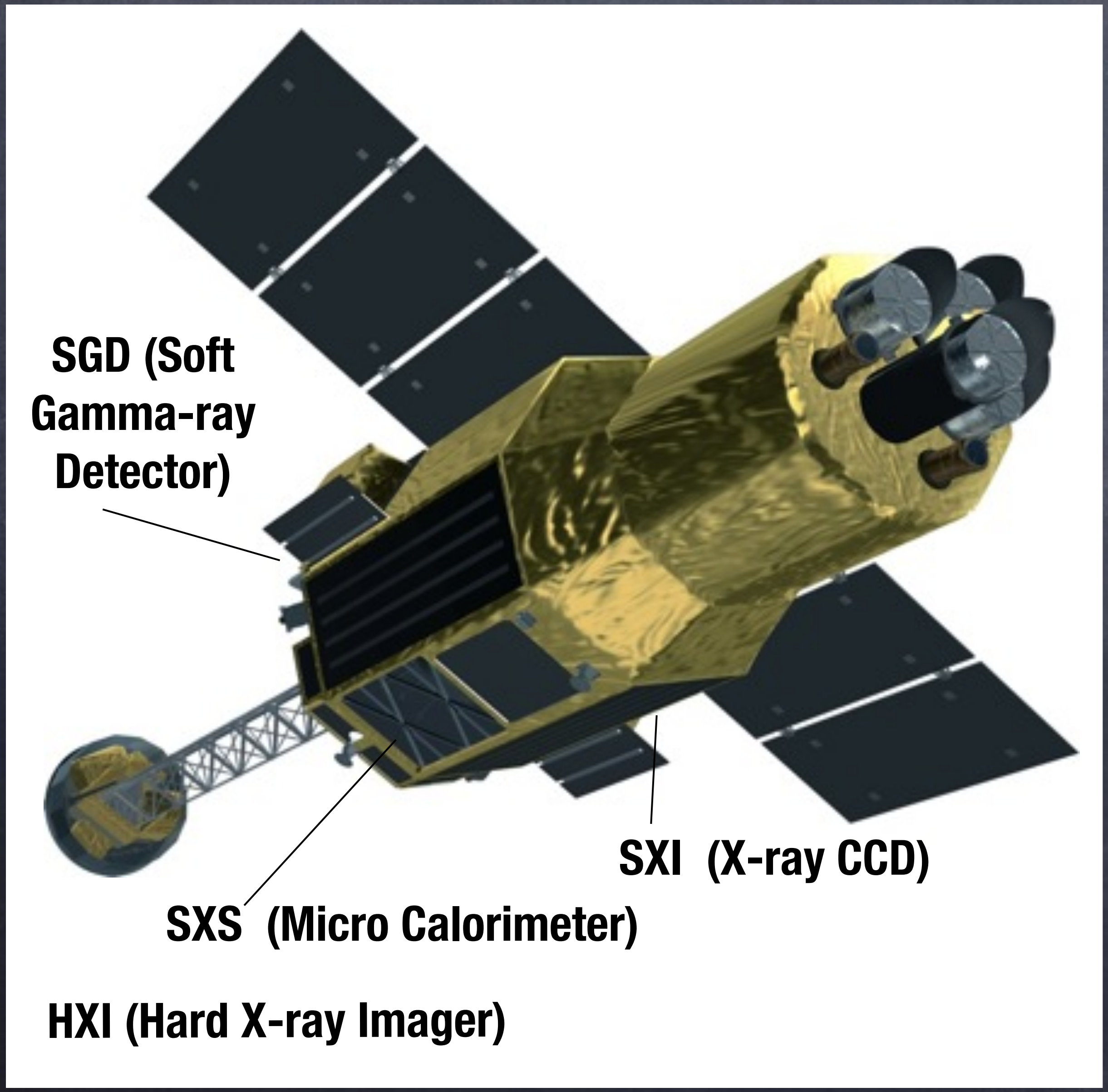
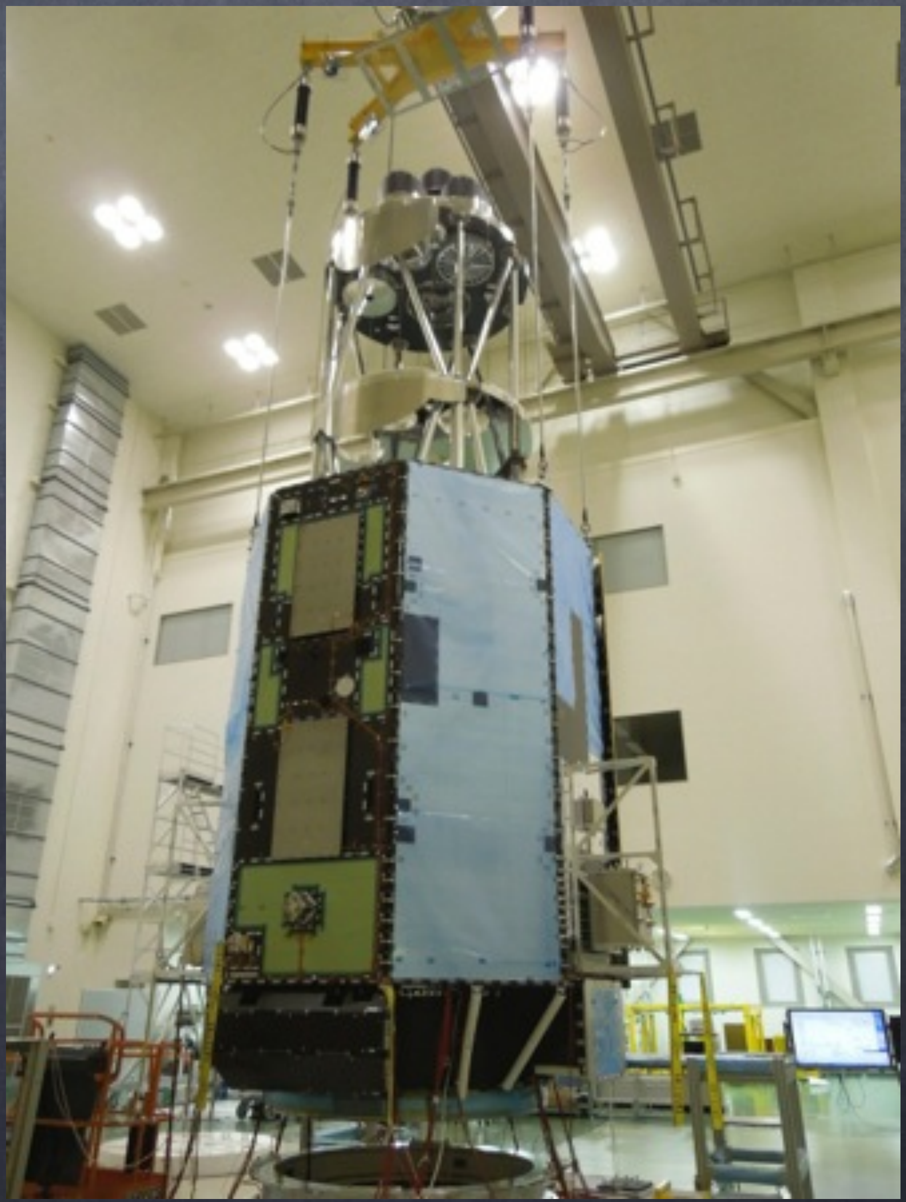
Image: NASA

ASTRO-H

Takahashi et al. 2012, 2014, SPIE

ASTRO-H is an international X-ray observatory, which is the 6th Japanese X-ray satellite scheduled for launch in 2015 FY from Tanegashima Space Center, Kagoshima, Japan.

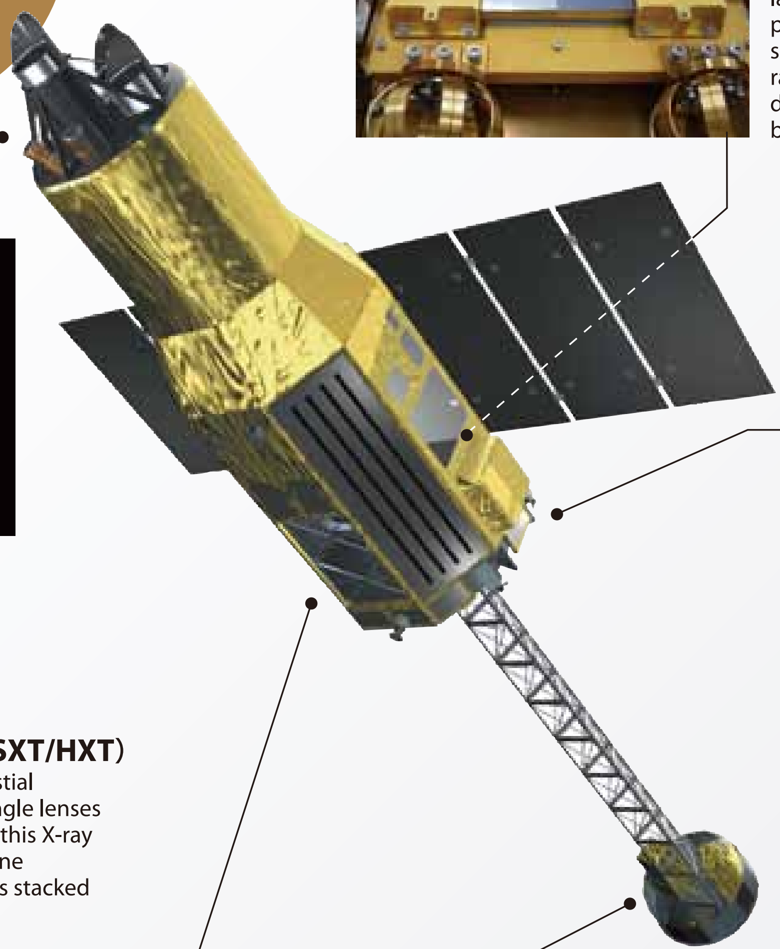




Cutting-edge Instruments

Soft X-ray Imager (SXI)

This is a wide field-of-view X-ray camera using an array of four large-format X-ray CCD chips. It provide simultaneous imaging and spectroscopic data in the energy range of 0.5 keV to 12 keV. The detector will be placed in the main body of the satellite.



Close-up view of the aperture.

Reflecting X-ray Telescopes (SXT/HXT)

This instrument focuses X-rays from celestial objects onto the detectors. Unlike the single lenses and mirrors usually used for visible light, this X-ray reflecting telescope is made up of over one thousand reflector-coated aluminum foils stacked into concentric circles.

Soft Gamma-ray Detector (SGD)

Many layers of semiconductor sensors are stacked to optimize the sensitivity of the gamma-ray spectrometer. Since gamma-rays have a higher penetrating power than X-rays, this instrument plays an important role investigating astronomical objects surrounded by dense gas.

Soft X-ray Spectrometer (SXS)

Specialized detector elements are cooled down to near absolute zero (-273 degrees Celsius) using a series of refrigeration units. When an X-ray hits a detector element, its temperature slightly rises. This increase in "heat" is measured, and from this the energy of the incident X-ray can be estimated to a higher degree of accuracy than any achieved to date. Researchers from around the world have great expectations for this instrument, the centerpiece of ASTRO-H.

Close-up view of the main sensor part.

X-ray sensor and signal-processing electronics

Hard X-ray Imager (HXI)

This produces images of objects in the hard X-rays above 5 keV using a combination of silicon and cadmium telluride semi-conductors. Since this imaging telescope has a 12-meter focal length, this sensor will be placed at the end of a boom which will be extended in orbit.

Neutron Star: Unique Lab

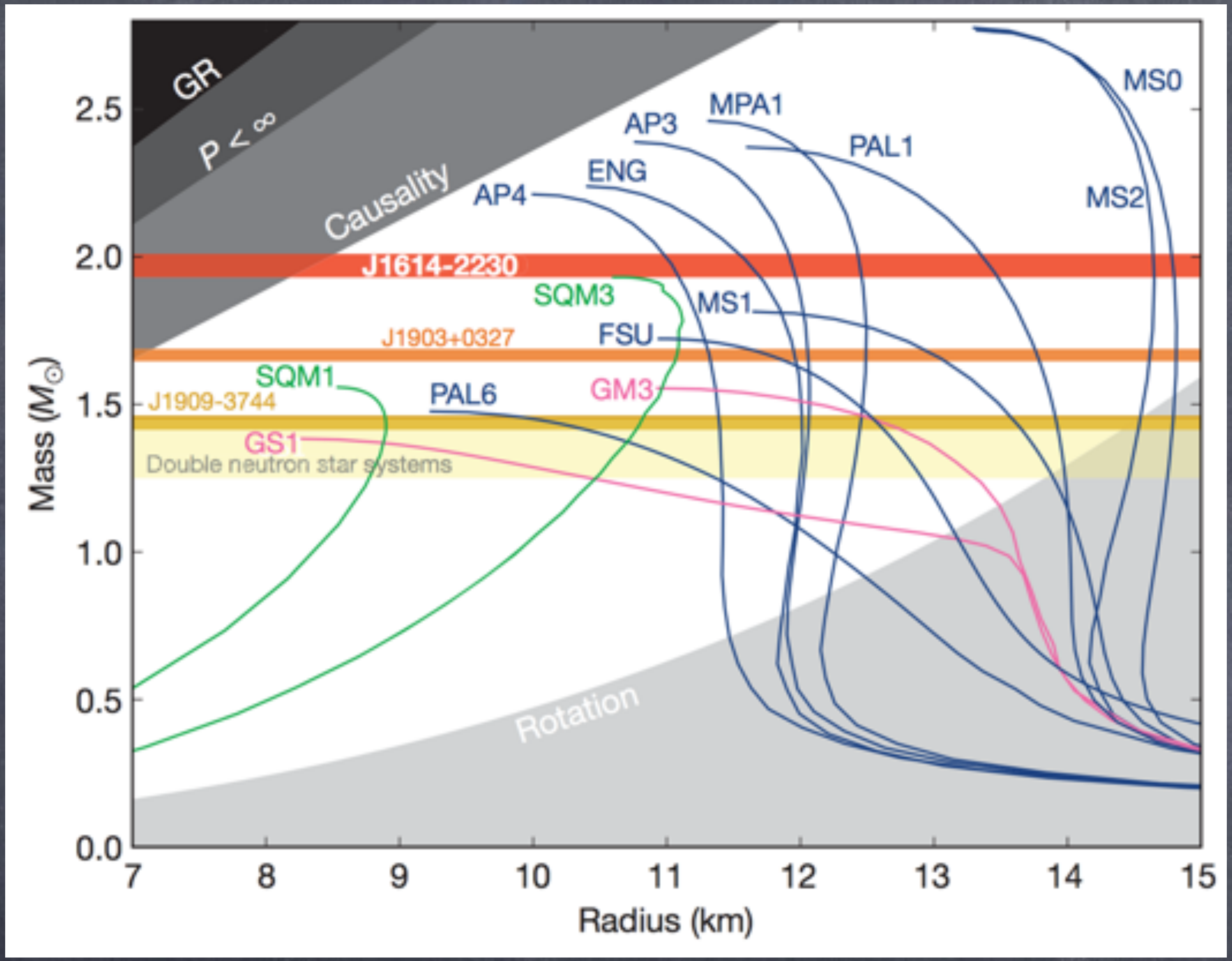
- A neutron star (NS) is a unique physics laboratory where we can see a macroscopic amount of matter in extreme physical conditions.

- We can investigate via neutron stars
  - ✓ strong gravitational field
  - ✓ strong radiation field

  ⇨ physics of accretion

  - ✓ strong magnetic field
    (typically 10^{8-12} G; $>10^{14}$ G for magnetars)
  - ✓ high density matter
    ⇨ Equation of state beyond nuclear density

Equation of State (EOS)



Demorest et al. 2010
Nature, 467, 1081

An EOS, which relates pressure and energy density, gives a mass-radius relation. Macroscopic properties of neutron stars such as mass, radius, or mass-to-radius ratio (or moment of inertia) can be constrained by astrophysical observations.

Types of Neutron Stars

- Rotation powered

  Radio pulsars (isolated)

  Millisecond pulsars (binary)

- Accretion powered

  Low-mass X-ray binaries

  High-mass X-ray binaries

- Magnetically powered: magnetars
- X-ray dim isolated neutron stars (emit thermal X-rays)

All types may be useful for the study of the EOS.

Accretion-Powered NS

A neutron star in a binary system can accrete matter from the other star. Being a binary allows us to measure masses of the stars by observing their orbital motion via Doppler shifts.

Low-mass X-ray binary (LMXB)

low-mass star + old NS

B: 10^{9-10} G

Spin period: 1-10 ms

can be an X-ray burster

High-mass X-ray binary (HMXB)

high-mass star + young NS

B: 10^{12} G

Spin period: 1-1000 s

can be an X-ray pulsar

How to get M-R relation

Done, Tsujimoto+ ASTRO-H White Paper on LMXBs;
Review by Ozel 2013;

- Gravitational redshift
  - ✓ narrow absorption lines from NS surface
  - ✓ broad iron line from inner edge of accretion disk
- Pulse profile
  - ✓ (rotation-powered) millisecond pulsars
  - ✓ X-ray pulsars (high-mass X-ray binaries)
- Thermal emission from NS surface

All methods should give consistent solutions within their uncertainties for obtaining the true physical model.

Gravitational Redshift

Narrow absorption lines from the neutron star surface should be red-shifted by the GR effect.

$$\frac{E_{\rm obs}}{E_{\rm lab}} = \sqrt{1 - \frac{2GM}{Rc^2}} \sim 0.8$$

⇨ an unambiguous, model-independent way to determine M/R.

Despite many attempts there have been no significant results.

=> ASTRO-H

When can we see the lines?

✓ Ions are not fully ionized. => low temperature: < 1 keV

✓ The stellar surface is not hidden by accreted matter.
=> low accretion rate

✓ The lines are not broadened.
=> slow spin (or low inclination) + weak B-field

Doppler effect

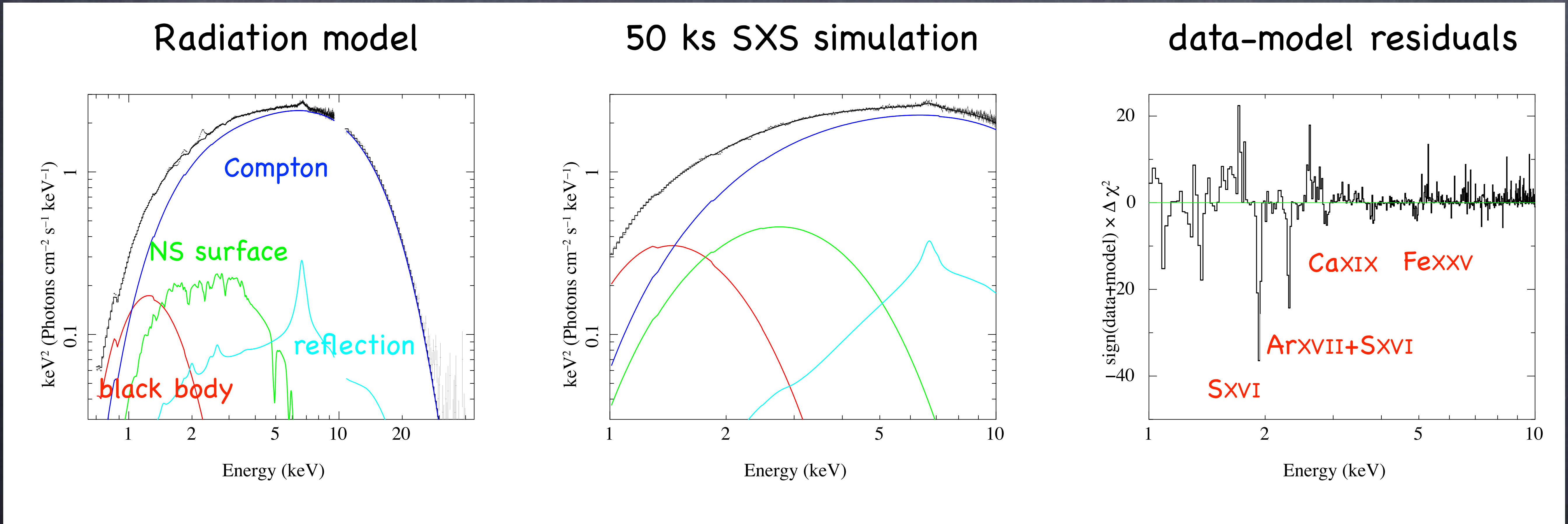
$$\Delta E = 1600 \left(\frac{\nu_{\rm spin}}{600\ {\rm Hz}}\right)\left(\frac{R}{10\ {\rm km}}\right)\ {\rm eV}$$

Zeeman effect

$$\Delta E = 12 \left(\frac{B}{10^9\ {\rm G}}\right)\ {\rm eV}$$

Feasible Target: Ser X-1

- persistent radiation
- low inclination: 10 degrees   Cornelisse et al. 2013
- not fully ionized. kT: 0.6 keV
- weak B-field

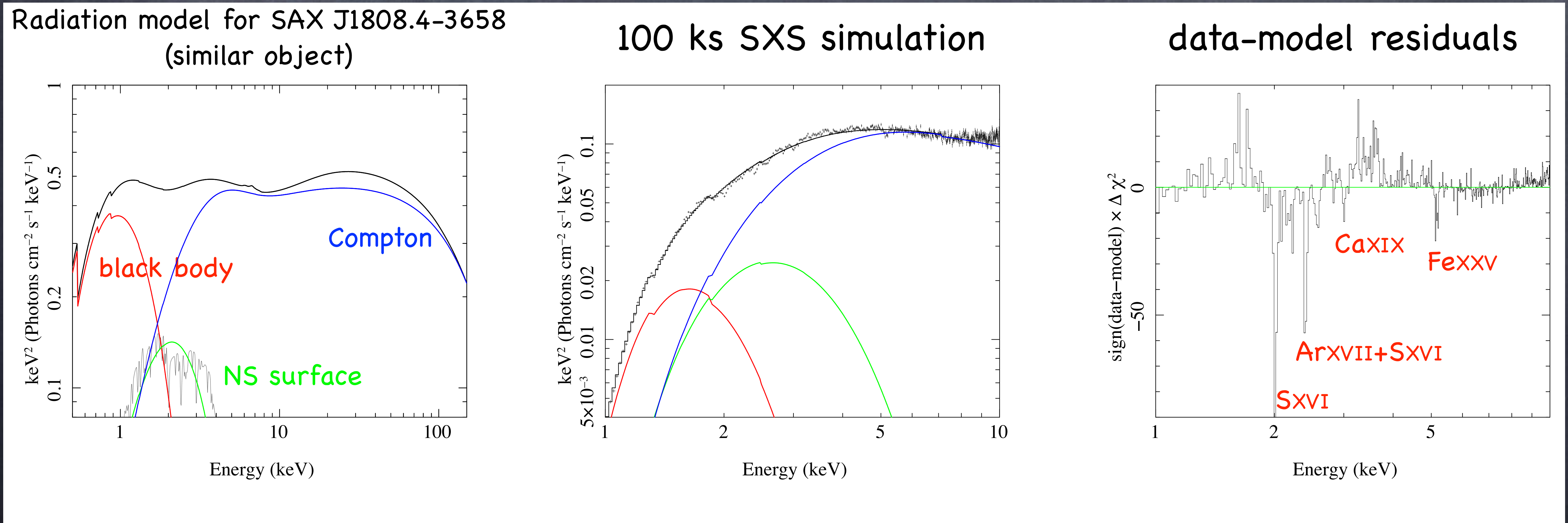


For a 50 ks exposure, z=0.356 is measured with 1% error.

Done, Tsujimoto & ASTRO-H Science Team

Feasible Target: Tarzan 5 X2

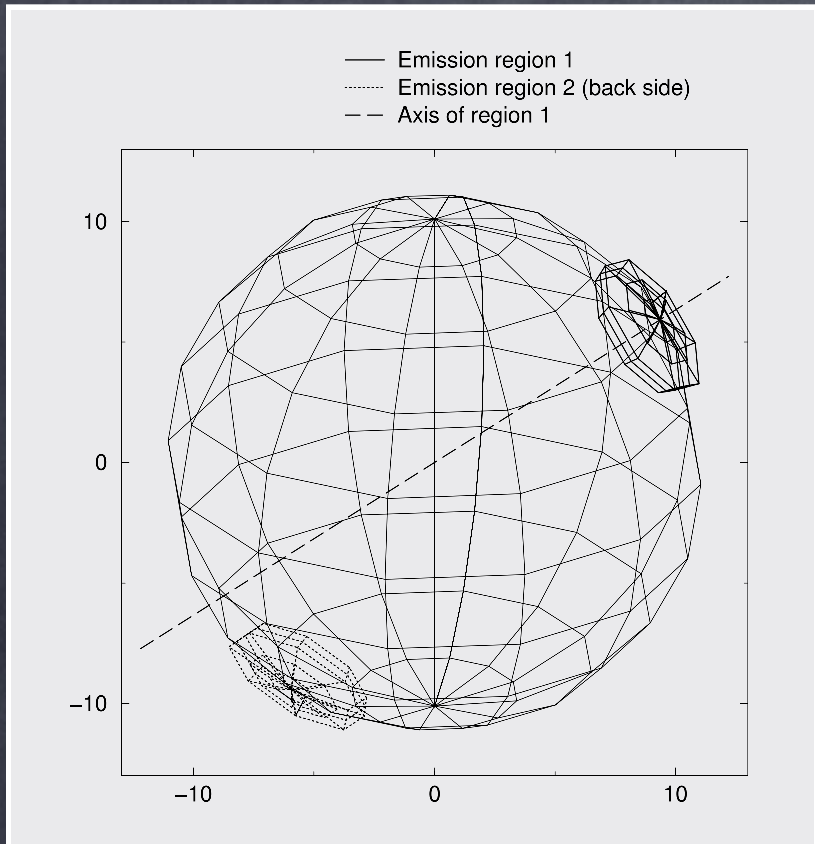
- IGR J17480-2446 (Terzan 5 X2)
- transient; observable in an X-ray burst phase.
- very slow spin 11 Hz => delta E = 30 eV Cavecchi et al. 2011, ApJ, 740, L8
- B = 10^{9-10} G => delta E ~ 100 eV (?)



For a 100 ks exposure, z=0.300 is measured with 1% error.

Done, Tsujimoto & ASTRO-H Science Team

Pulse Profile



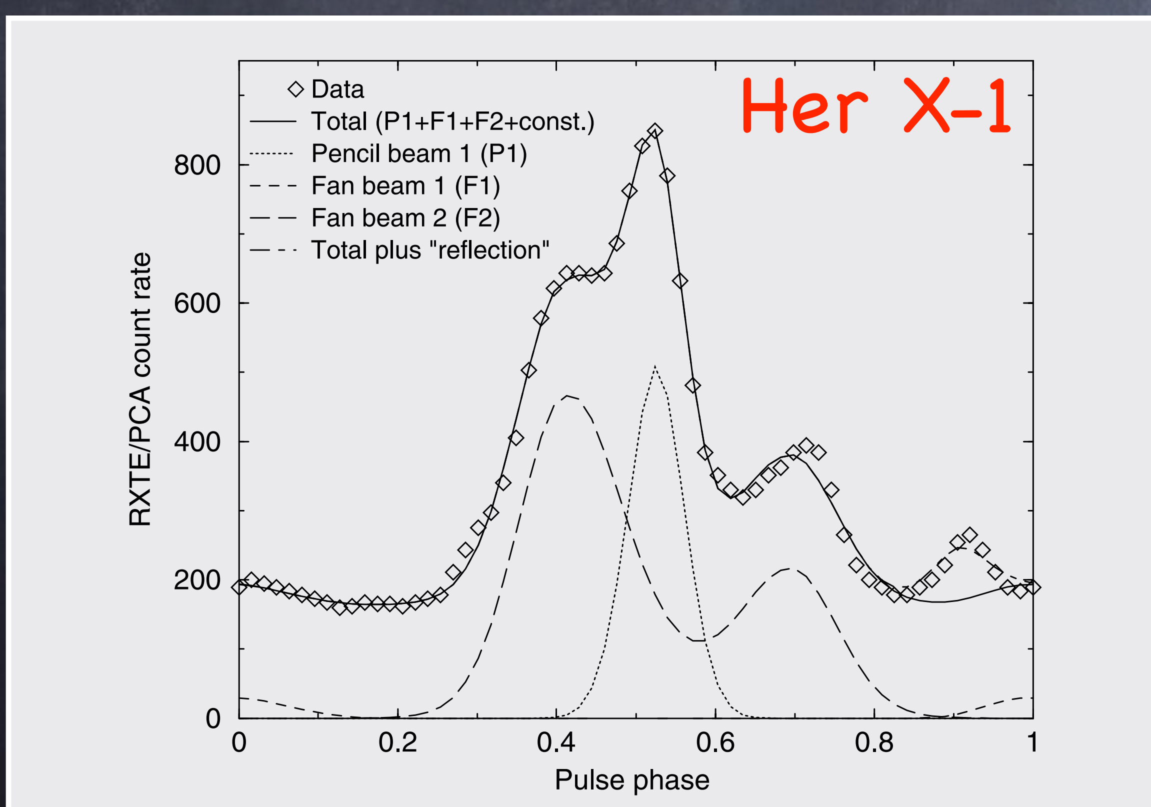
Leahy 2004, ApJ, 613, 517

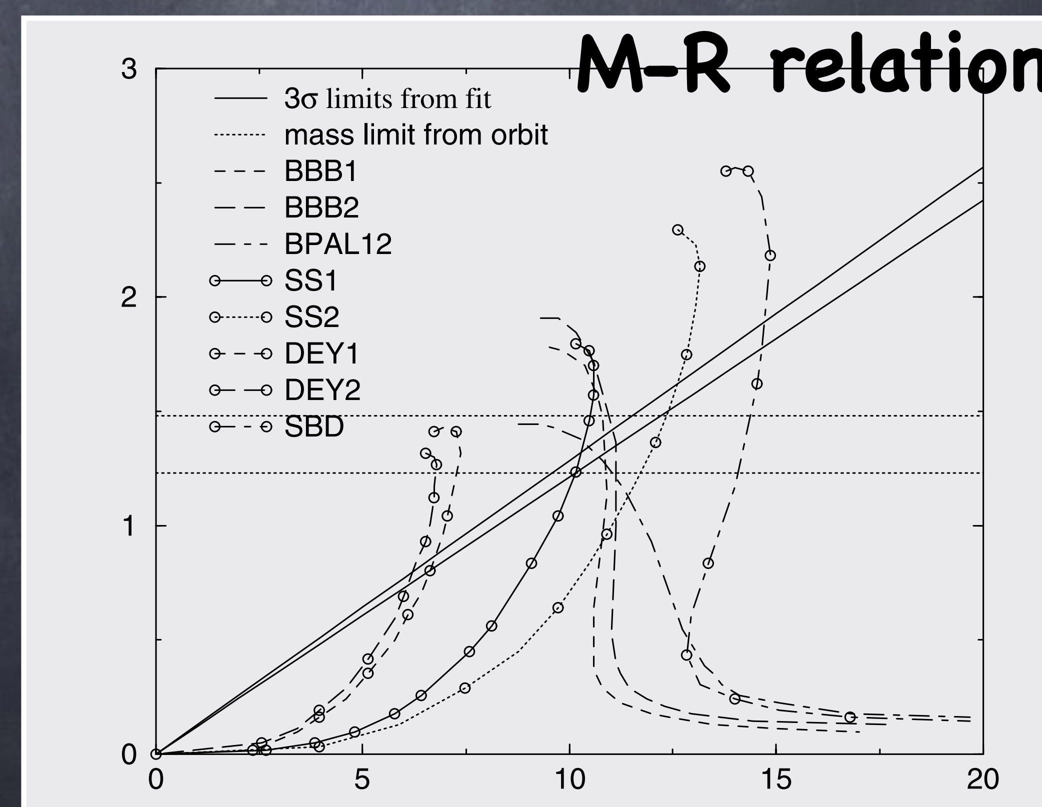
X-ray pulsation (HMXB)

A detailed modeling of the X-ray pulsation in gives M/R.

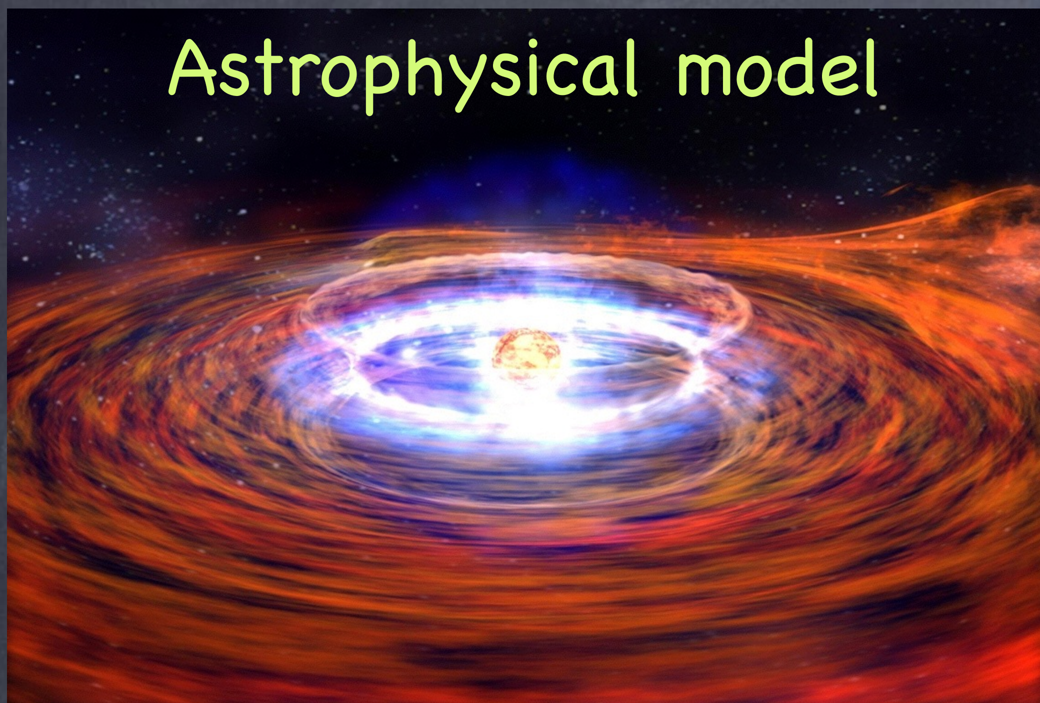
Caveat: dependence on the radiation model

Similar analysis is applicable to rotation-powered millisecond pulsars.





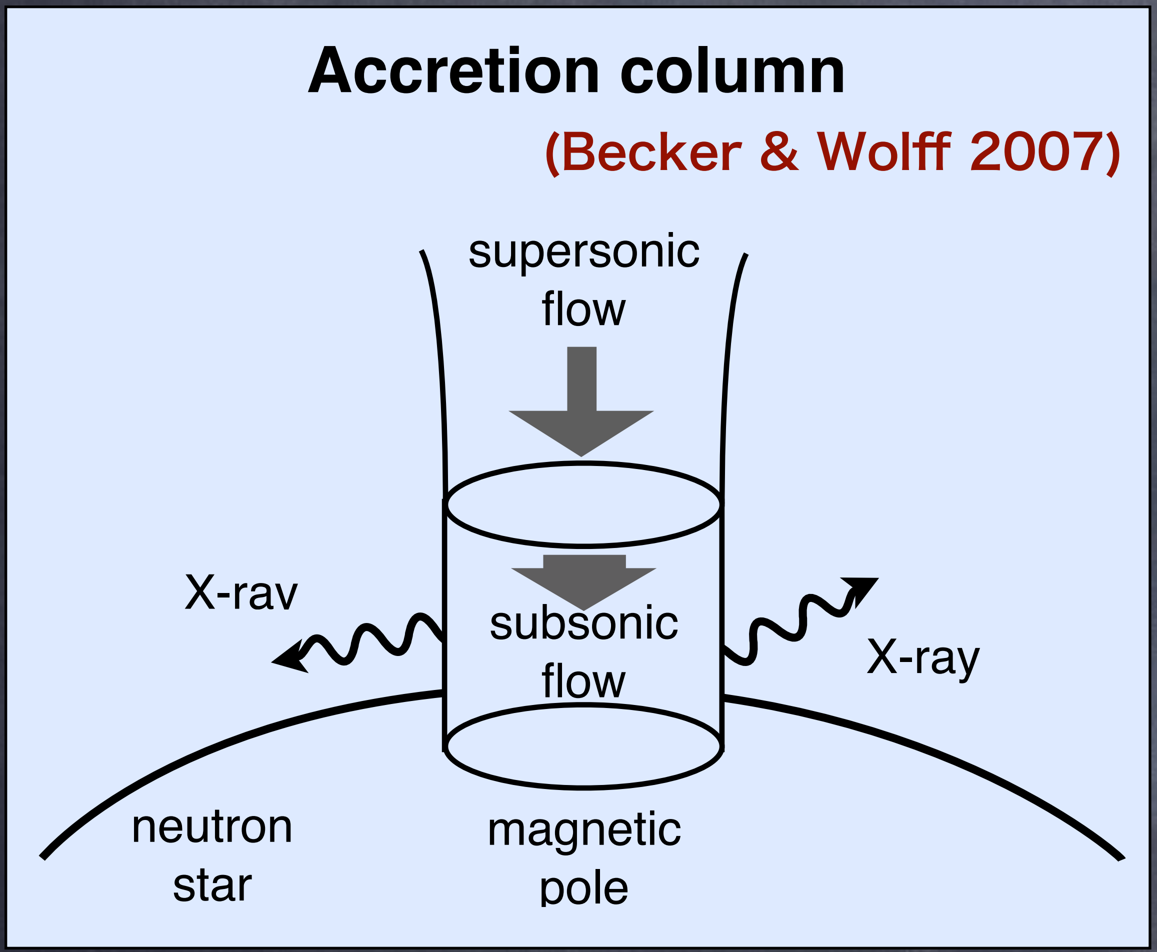
Precise Modeling of Radiation



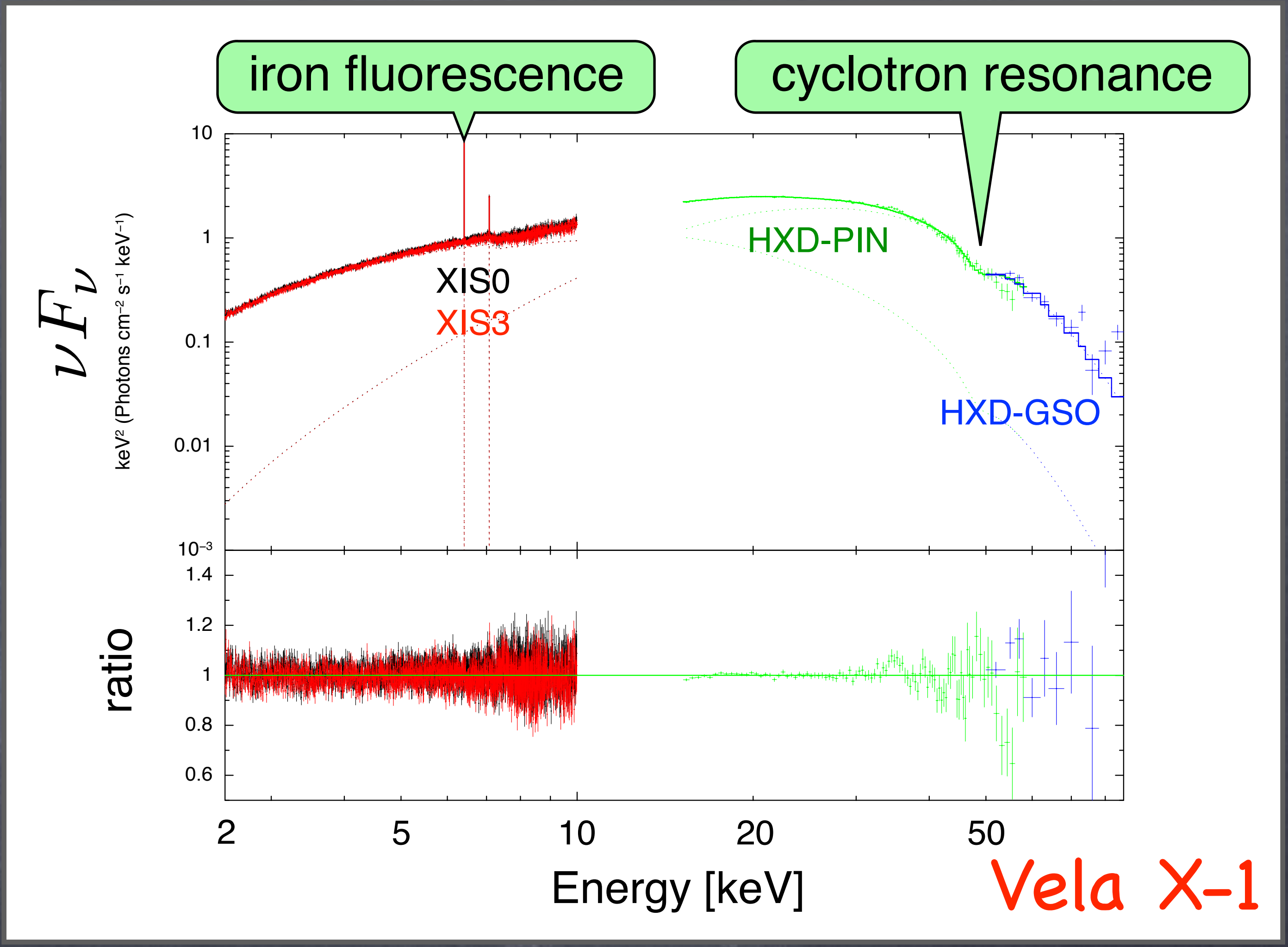
Radiation

- There are many methods to measure the macroscopic properties of neutron stars.
- However, most of them depend on radiation models that include radiative processes & astrophysical properties of the emitting sites.
- High S/N data obtained with ASTRO-H would require even more precise astrophysical models.
- In addition, we should understand uncertainties due to the models, not only due to instruments.

Case of X-ray pulsars



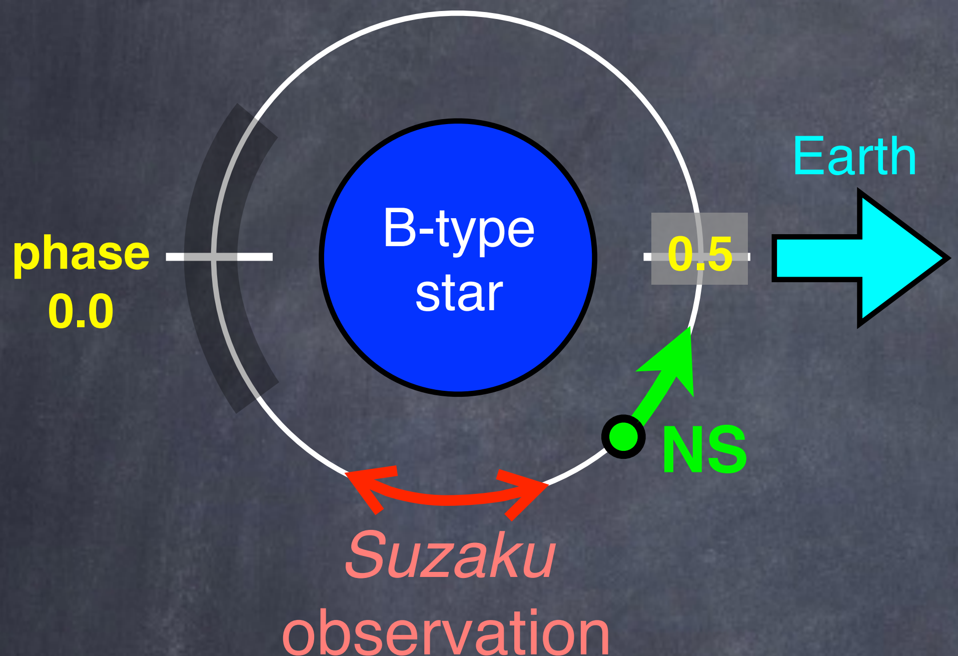
Odaka et al. 2013, ApJ, 767, 70

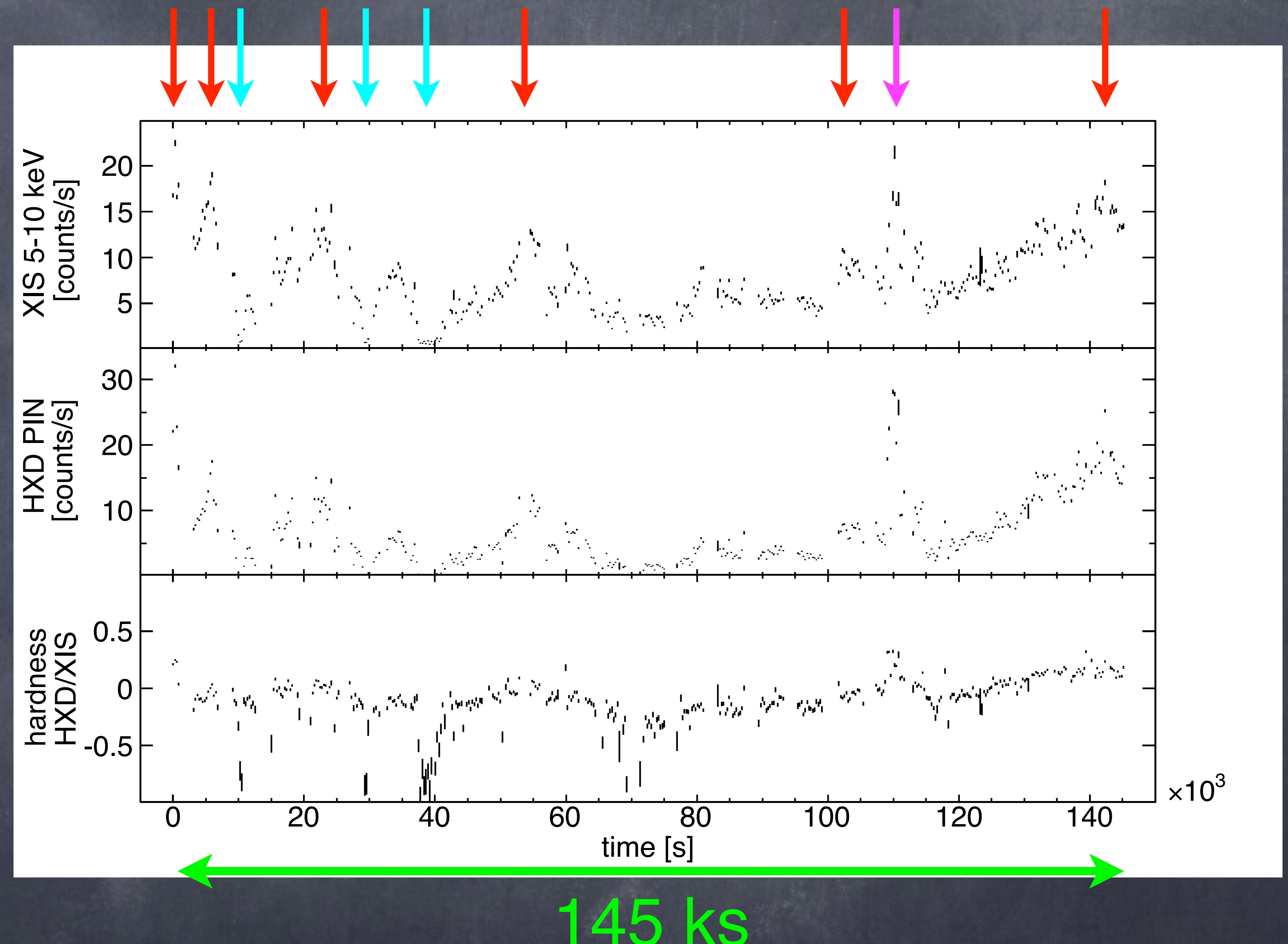


X-ray radiation mechanism of X-ray pulsars has still been unclear, so their X-ray spectra have been analyzed based only on phenomenological models.

Vela X-1

Odaka et al. 2013, ApJ, 767, 70





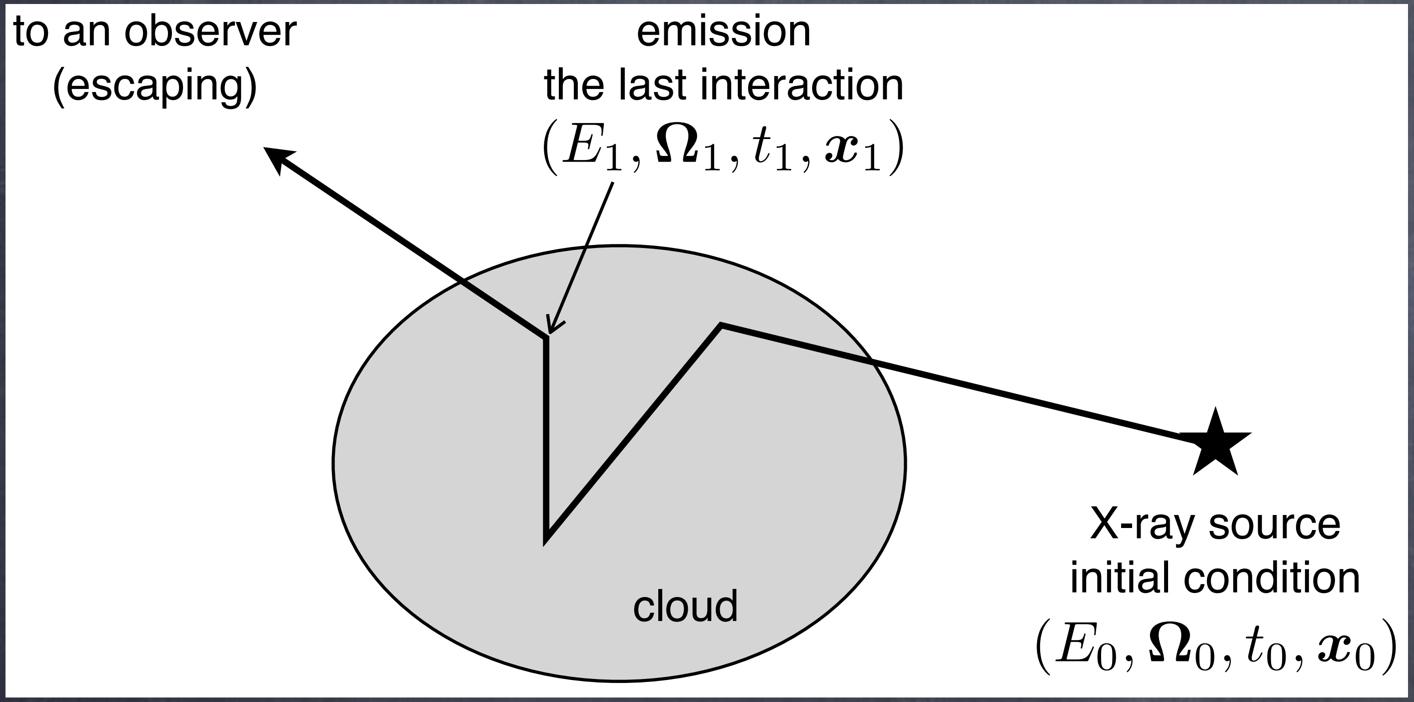
The brightest wind-fed accreting pulsar

The origin of the strong time variability is unknown:

clumpiness of the stellar wind or magnetic barrier?

Monte Carlo Approach

Tracking photons by calculating their propagation and interactions based on Monte Carlo method



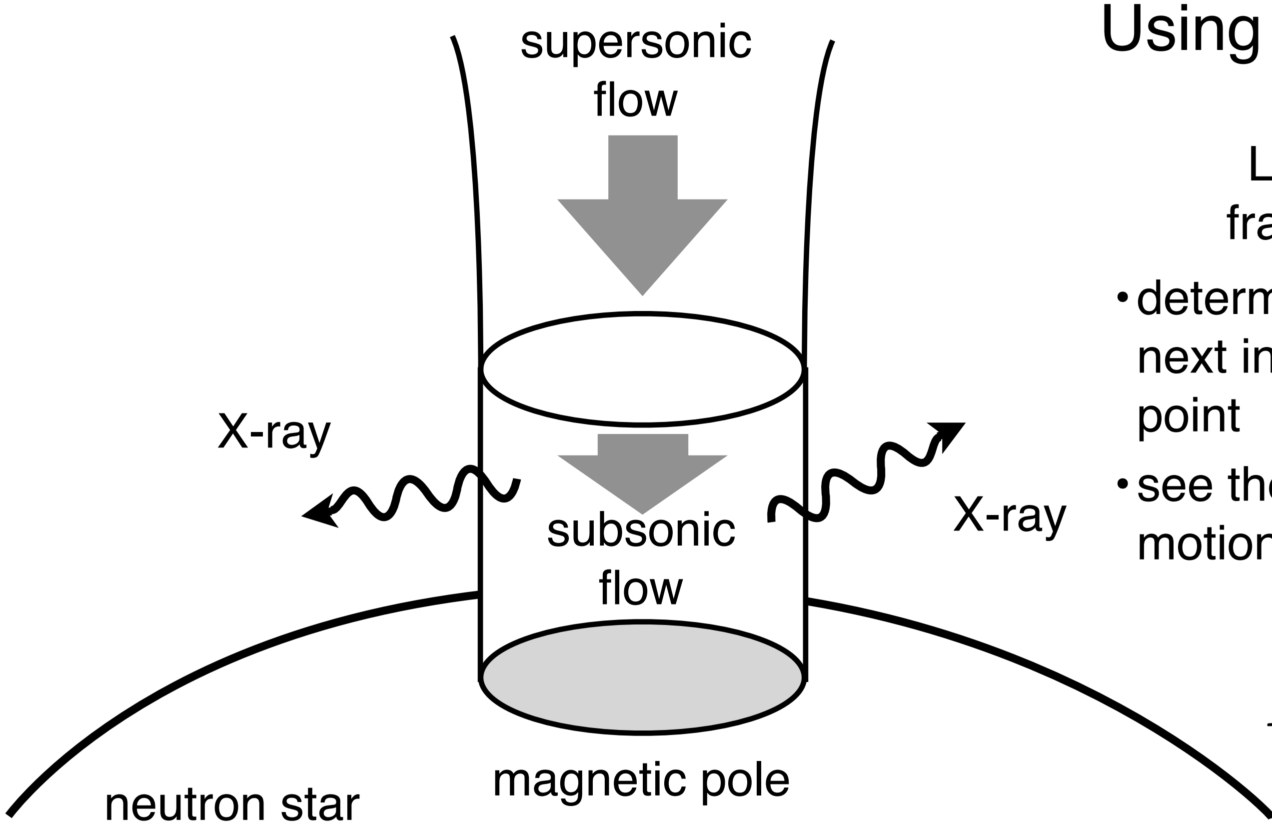
MC simulations can treat
- discrete process
- competing processes
- multiple interactions
- complicated geometry

We have developed a multi-purpose photon tracking simulator in the framework of Monte Carlo methods.
MONACO: MONte Carlo simulation for Astrophysics & COsmology

Odaka PhD thesis (2011)
Odaka et al. (2011)

Comptonization in Accretion Flow

Optically thick	Analytical/numerical methods of differential Equation
Optically thin Complicated geometry High energy band	Processes are essentially discrete. => Monte Carlo approach is suitable.



Thermal & bulk Comptonization

Using Lorentz transformation (Odaka et al. 2014)

Lab frame
- determine the next interaction point
- see the bulk motion

Bulk motion's frame
- select the target electron
- see the thermal motion

Target electron's frame
- calculate scattering by a rest electron

$p^{\mu} \longrightarrow p'^{\mu} \longrightarrow p''^{\mu}$

Lorentz transformation — Lorentz transformation

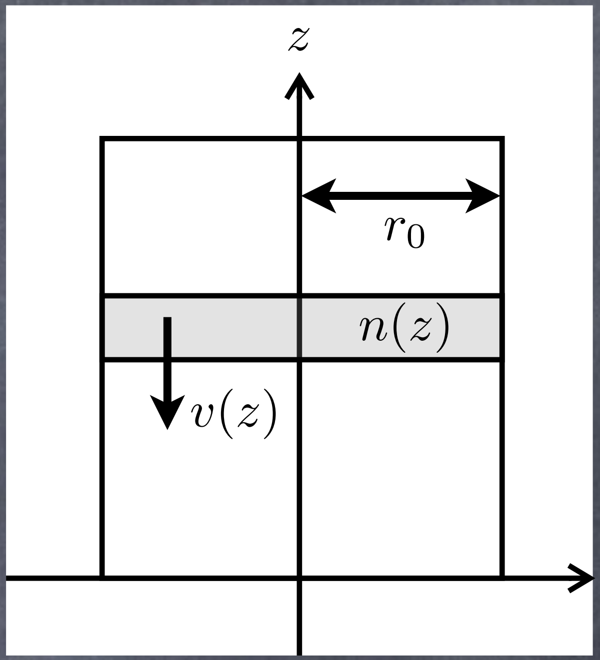
$p_1^{\mu} \longleftarrow p_1'^{\mu} \longleftarrow p_1''^{\mu}$

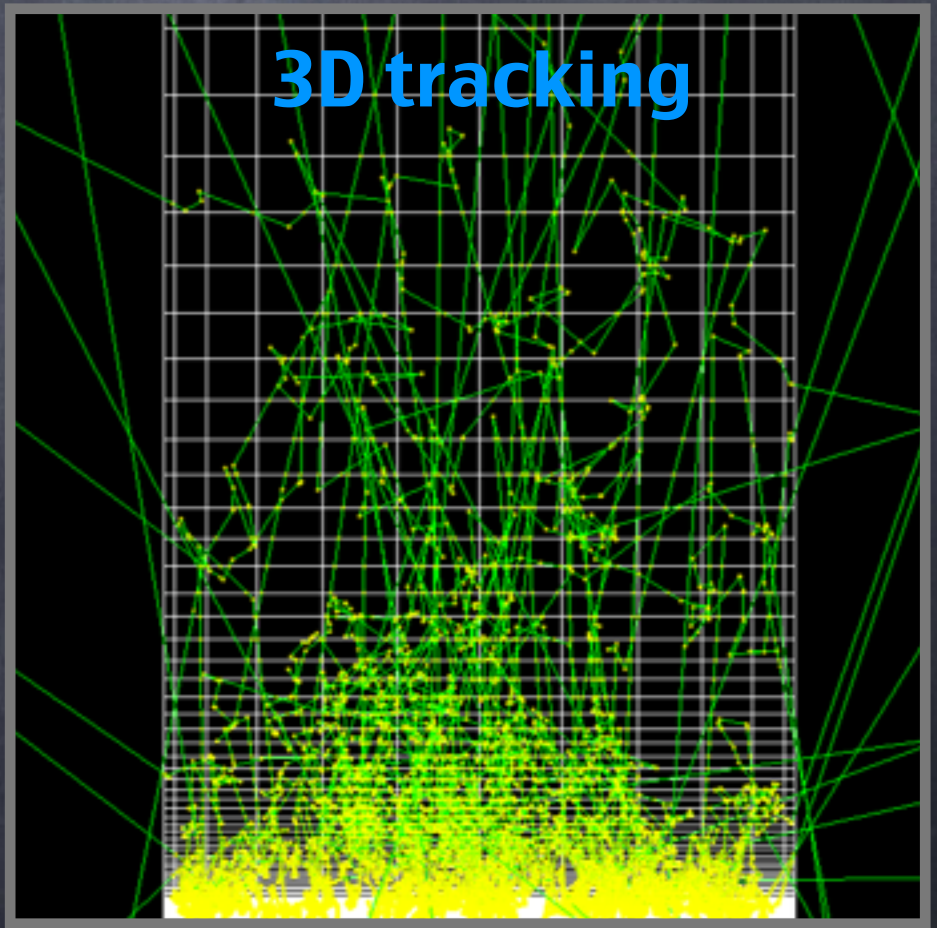
Magnetic field effects can be included.

Accretion Column Model

Model parameters
✓ Electron temperature kT=6 keV
✓ Velocity profile <= height of the sonic point
✓ Column radius r_0
✓ Magnetic field B=2x10^{12} G
its effect is approximately modeled
✓ Mass loss rate <= X-ray luminosity
Here, we assumed typical values of M & R.

Physical process
Compton scattering by electrons in the accreted plasma
✓ thermal motion of the target electron
✓ bulk motion of the target electron
✓ reduction of interaction cross section by the strong magnetic field (depending on energy, direction & polarization mode)

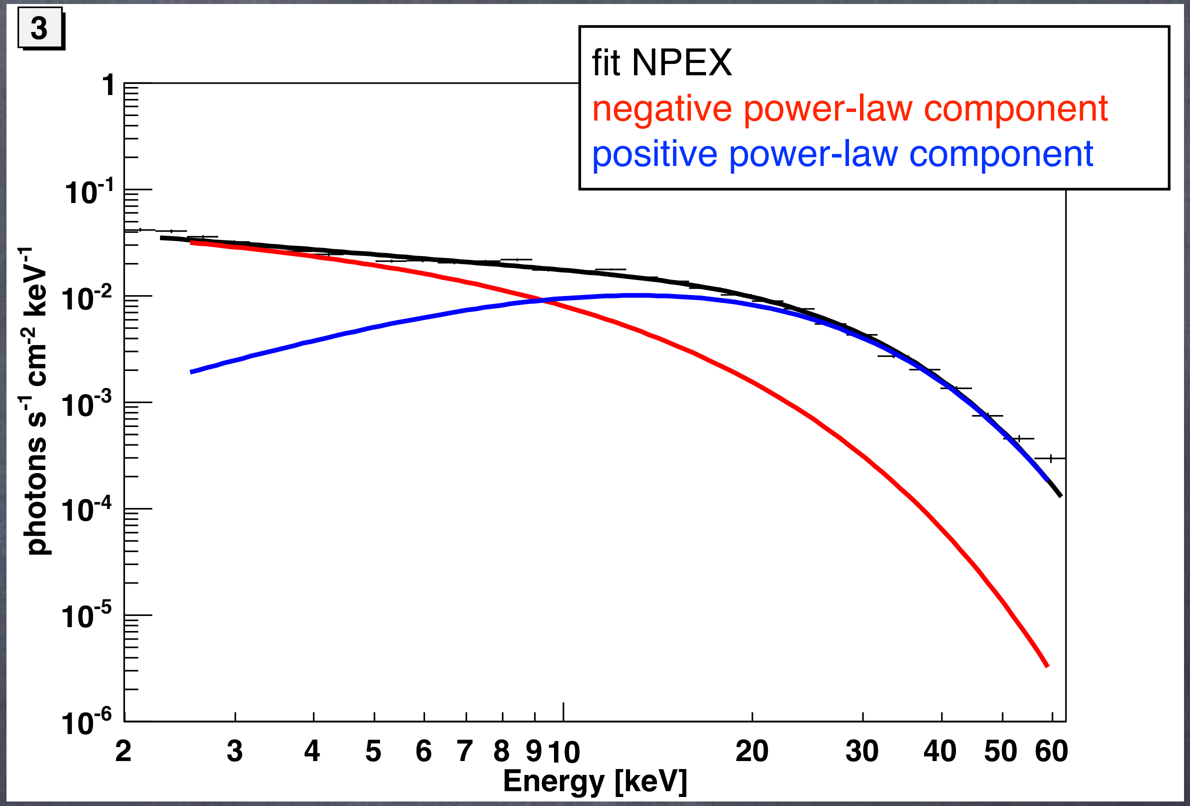




Solutions

We found a set of self-consistent solutions that agree with the observations and have reasonable model parameters. We successfully estimate the physical parameters of the accretion column.

We are going to make this model more robust and apply it to NS observations. This analysis can be applied to spin-phase resolved spectroscopy and may provide new constraint on the NS measurement.

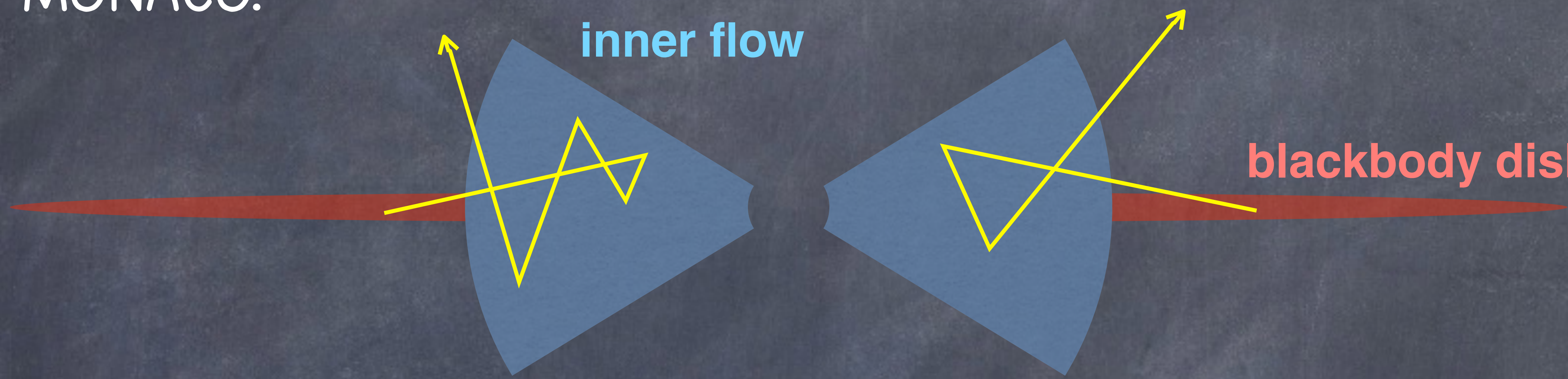


Odaka et al. 2014

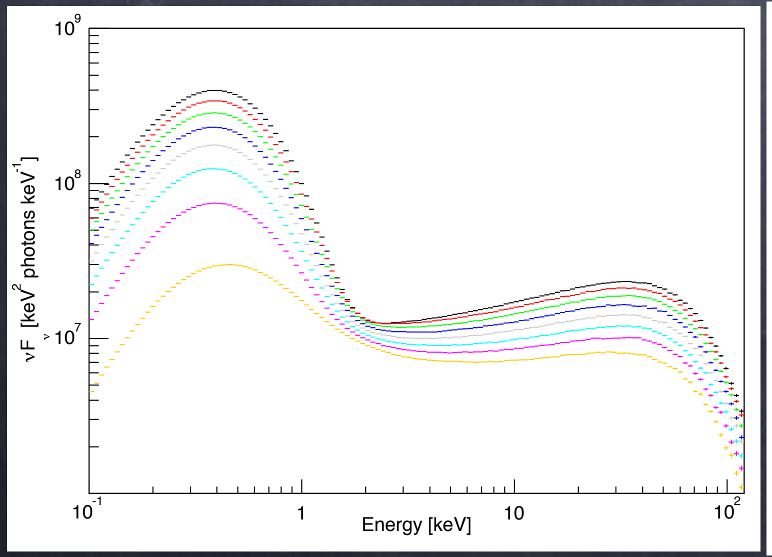
L_{obs} erg s^{-1}	r_0 m	L_0 erg s^{-1}	A_1 ph $s^{-1}cm^{-2}keV^{-1}$	Γ	A_2 ph $s^{-1}cm^{-2}keV^{-1}$	E_f keV	L_X erg s^{-1}	A_2/A_1
1.5×10^{36}	150	9.19×10^{35}	3.4×10^{-2}	0.58	0.0	17	1.2×10^{36}	0
3.0×10^{36}	150	1.68×10^{36}	5.3×10^{-1}	0.34	2.9×10^{-4}	6.6	3.0×10^{36}	5.5×10^{-4}
4.5×10^{36}	200	2.37×10^{36}	5.5×10^{-1}	0.17	4.4×10^{-4}	6.6	4.4×10^{36}	8.0×10^{-4}
6.0×10^{36}	300	3.51×10^{36}	6.7×10^{-1}	0.03	4.4×10^{-4}	6.9	6.2×10^{36}	6.6×10^{-4}

Accretion Flow to Black Hole

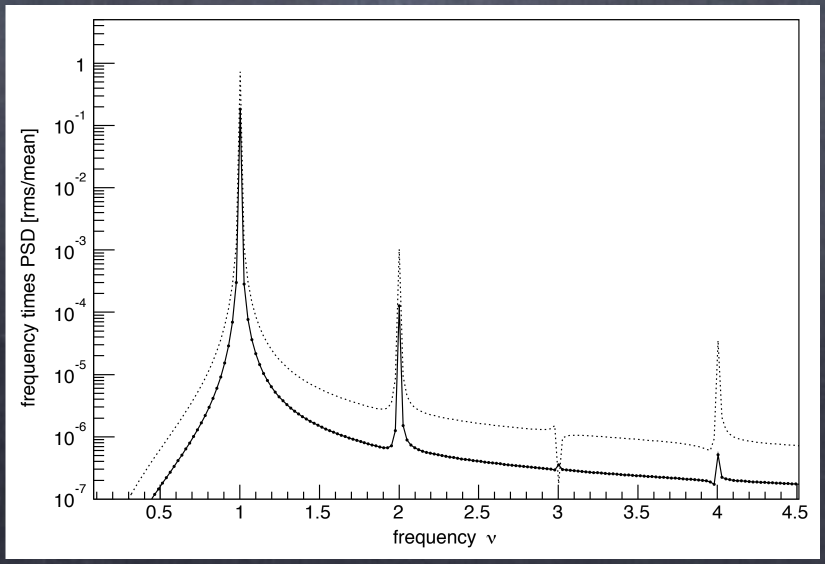
We build a truncated disk + a geometrically thick inner flow model with MONACO.



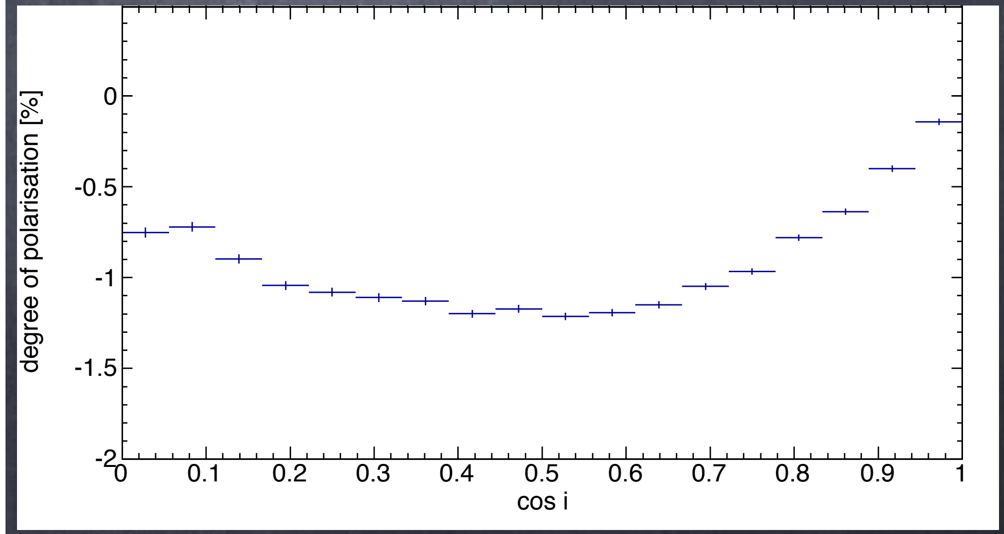
spectra



timing (QPO)



polarization

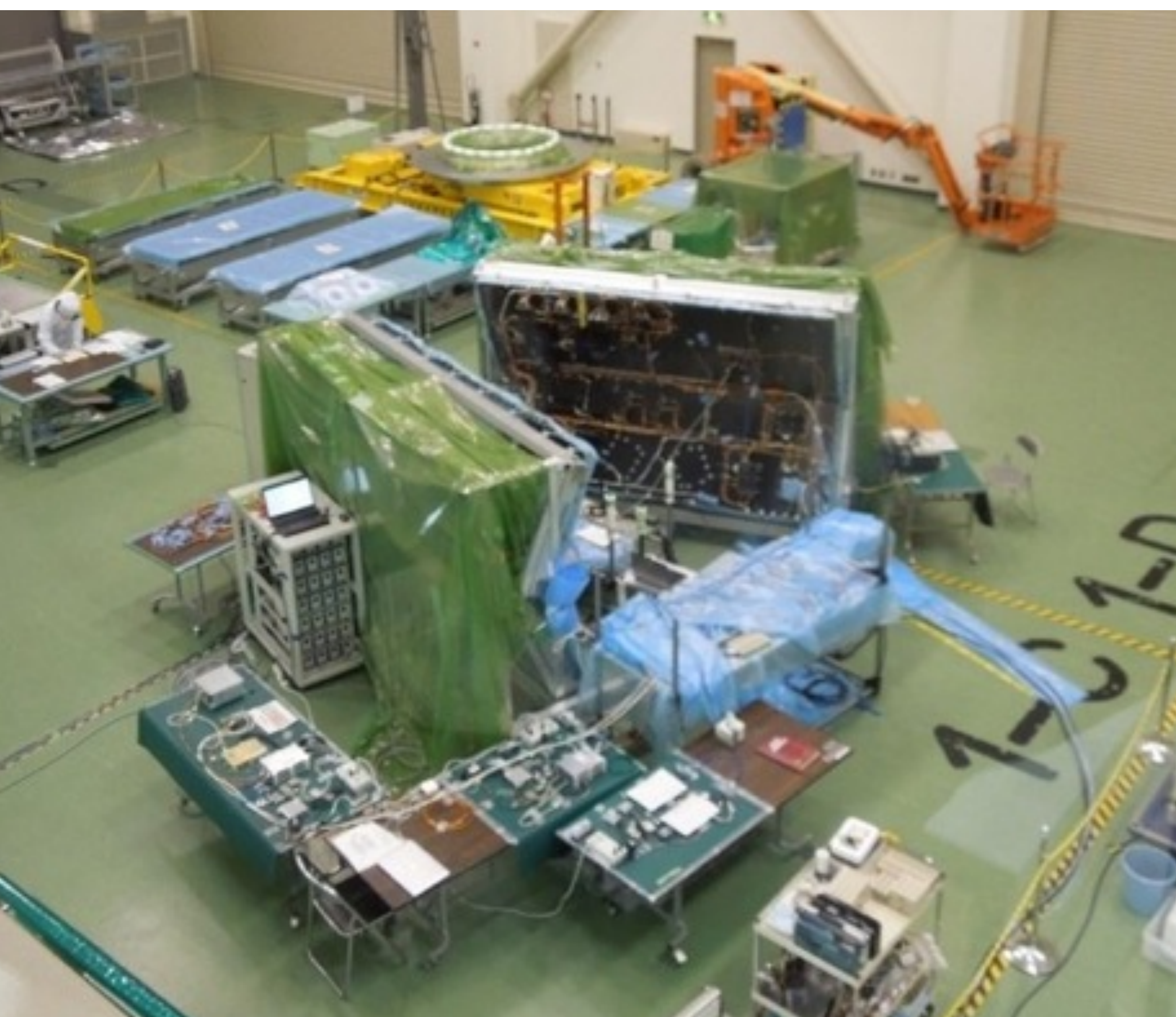


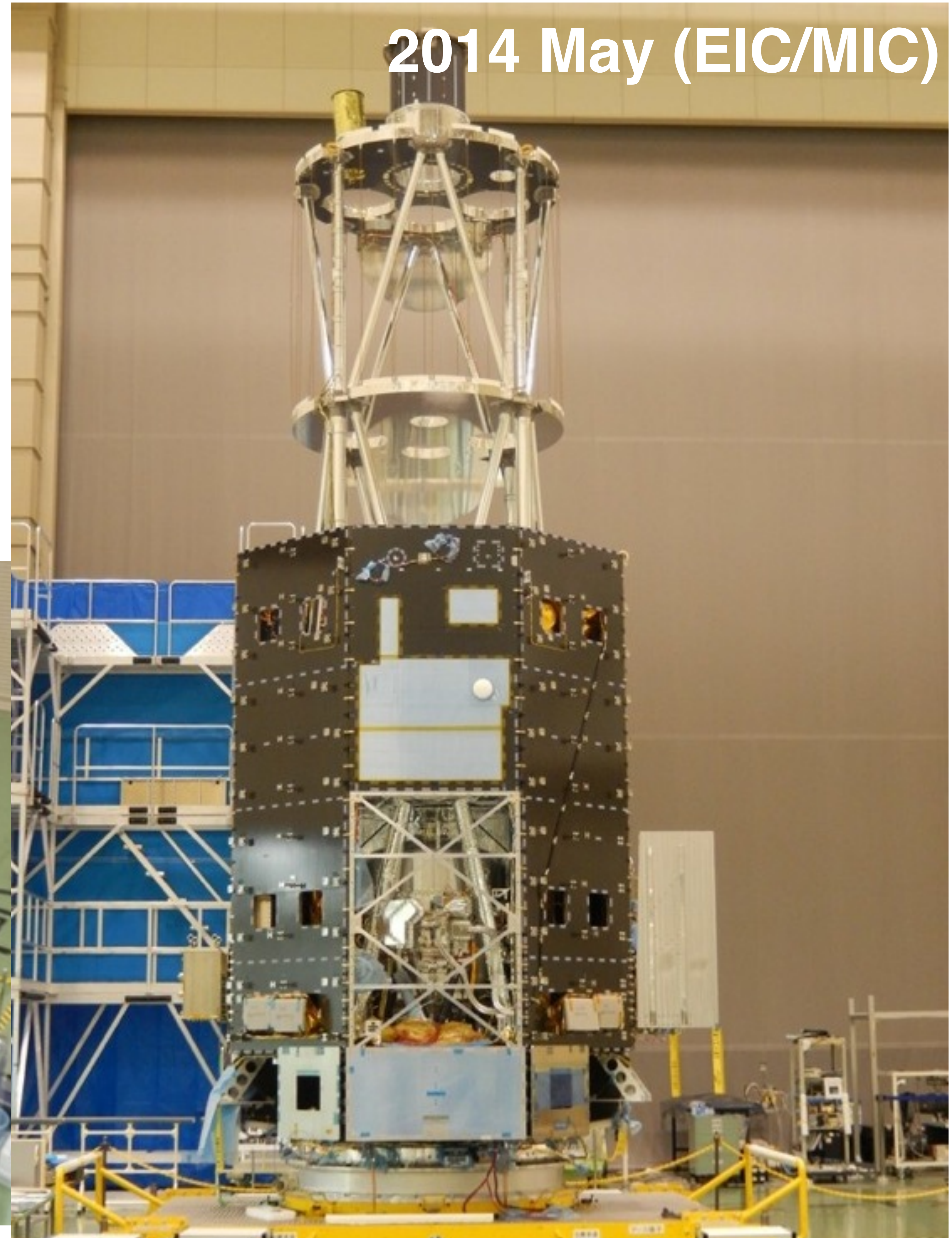
Odaka, Done, & Takahashi submitted.


2012 Aug (TTM)

2013 May (Acoustic Test)

2014 April (EIC/MIC)




2014 May (EIC/MIC)