Revealing the circumnuclear environment of Centaurus A through high-resolution X-ray spectroscopy of the iron emission line

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The circumnuclear environment of SMBHs

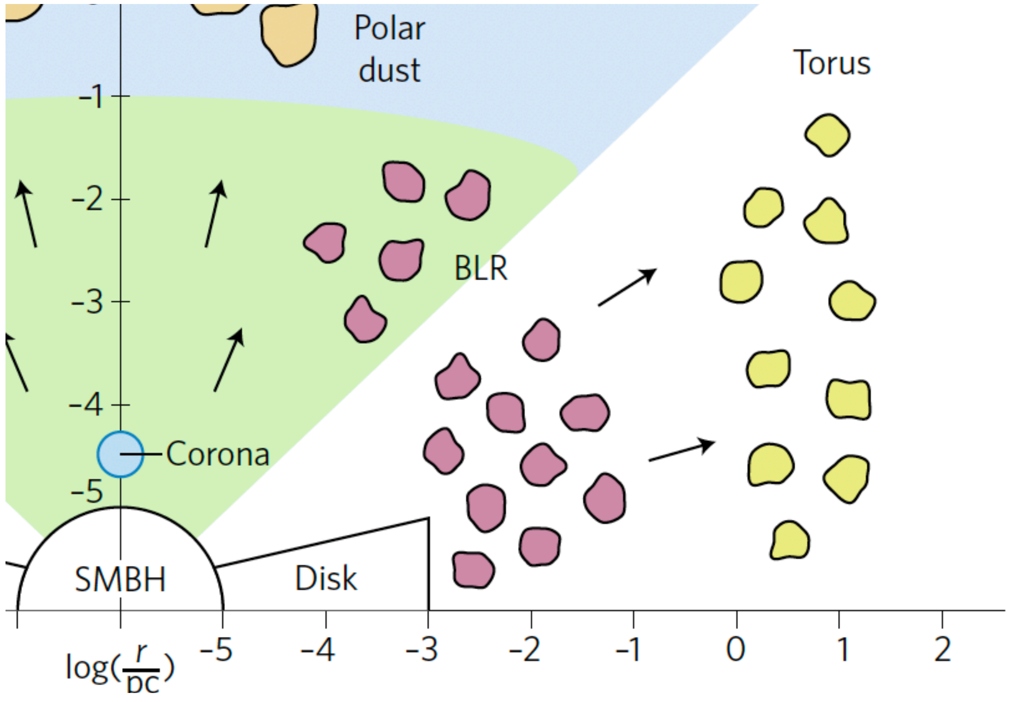
The circumnuclear materials

*broad-line region (BLR), torus..

Connect AGNs and their host galaxies

- Feeding SMBHs
- AGN feedback

Ramos Almeida & Ricci 2017



The circumnuclear environment of radio galaxies is still uncertain

(e.g., Tazaki et al. 2011,13)

- Difference between radio-loud and radio-quiet AGNs

X-ray reverberation mapping

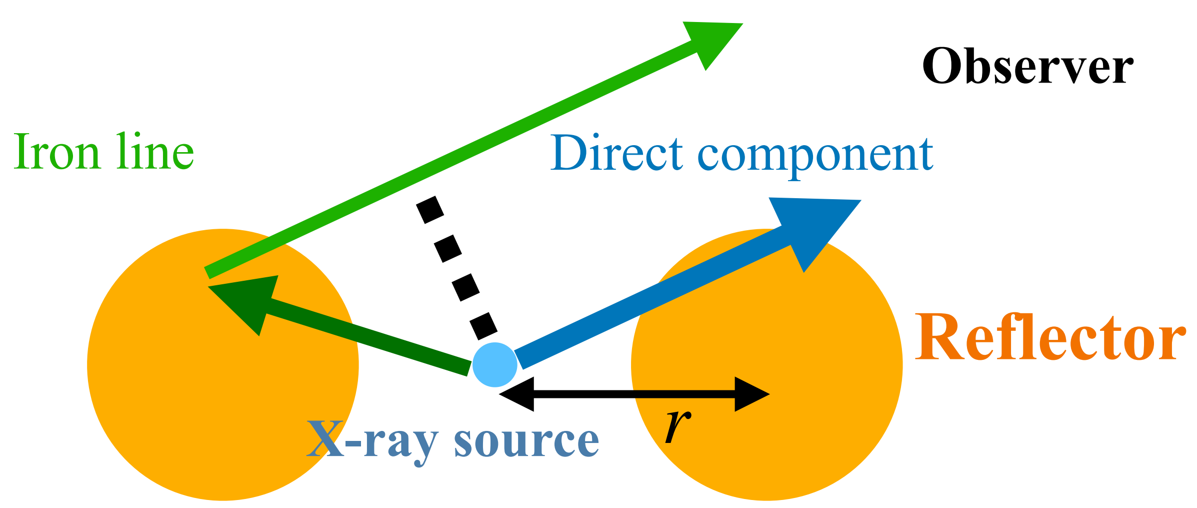
Compare the light curve of direct component and that of iron line

- The direct component comes directory from the X-ray source
- The iron line (~6.4 keV) is emitted from a reflector irradiated by the X-ray source
- The iron line is delayed from the direct component due to the difference in the light travel distance.

The lag of the iron emission line

➡ the geometry of the circumnuclear materials

the distance from the X-ray source to the reflector, r



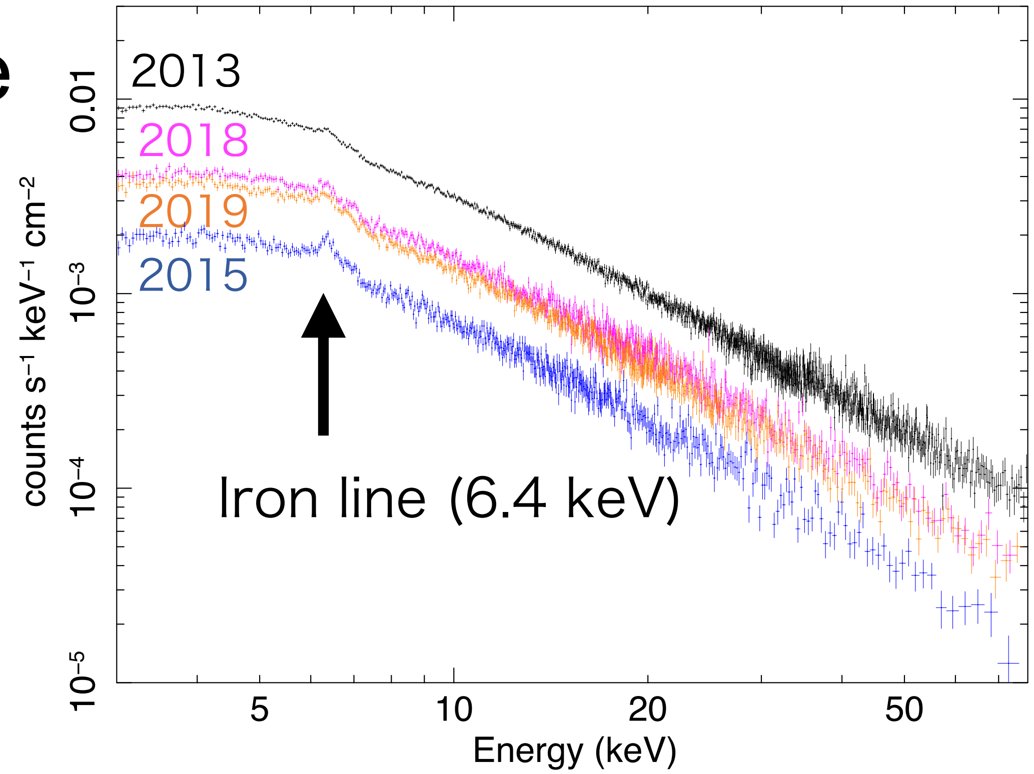
Target: Centaurus A

Centaurus A (Cen A)

a suitable target to study the structure around the SMBH in radio galaxies.

- the iron line (~6.4 keV) was detected
- observed repeatedly in the X-ray energy range

The NuSTAR spectra of Cen A



The origin of the iron line is still an open question.

- Line width ($v_{\rm FWHM}$): $1000–3000$ km s^{-1} (Evans et al. 2004) ➡ $10^{-2}–10^{-1}$ pc
- Stable iron line flux $\gtrsim$ 10 lt-yr (Fürst et al. 2016) ➡ $\gtrsim 1$ pc

Goal: to reveal the origin of the iron line

Comparison of the light curves

Direct component and iron line

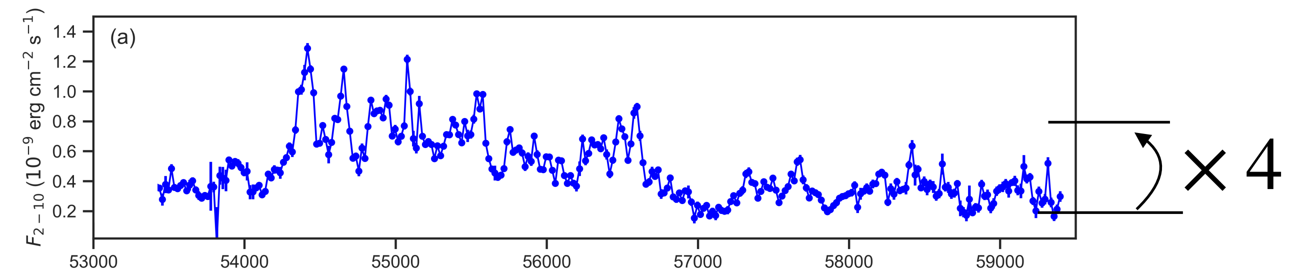
The iron line flux dropped between 2013 and 2015

→ short lag ($\lesssim$ 1 year)

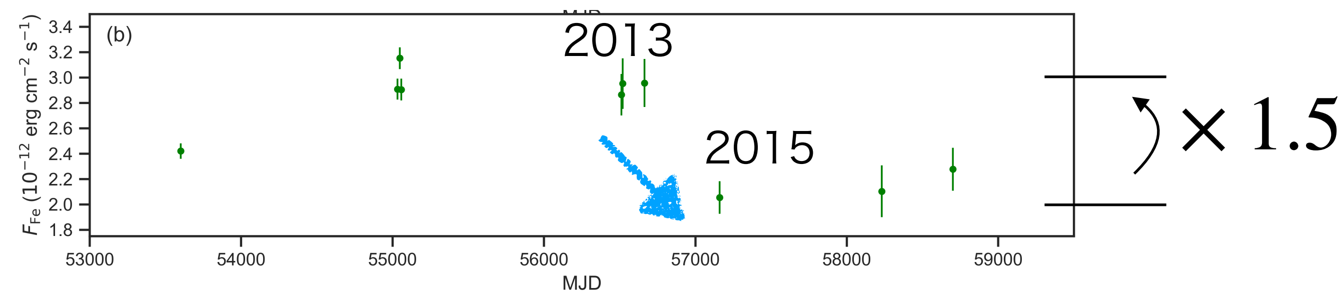
The flux variation was suppressed

→ Long lag (~ 10 years)

The light curve of Swift/BAT (Krimm+2013)



The flux of the iron emission line



There seem to be both short-lag and long-lag components

Transfer function

How the flux of iron line
respond to the irradiate flux

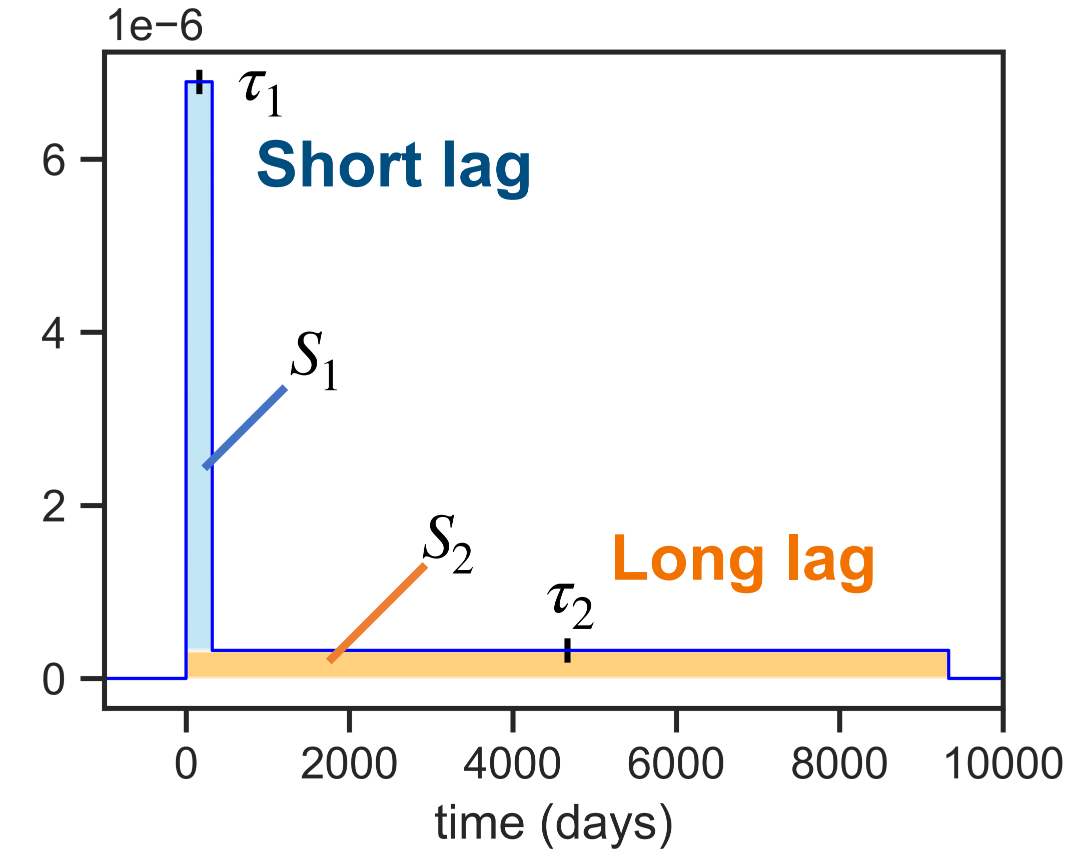
Transfer function

- $L(t;\mathbf{p}) = \int d\tau \Psi(\tau;\mathbf{p}) C(t-\tau)$

Light curve of the iron line

Light curve of the direct component

Assumed transfer function
double-top-hat function

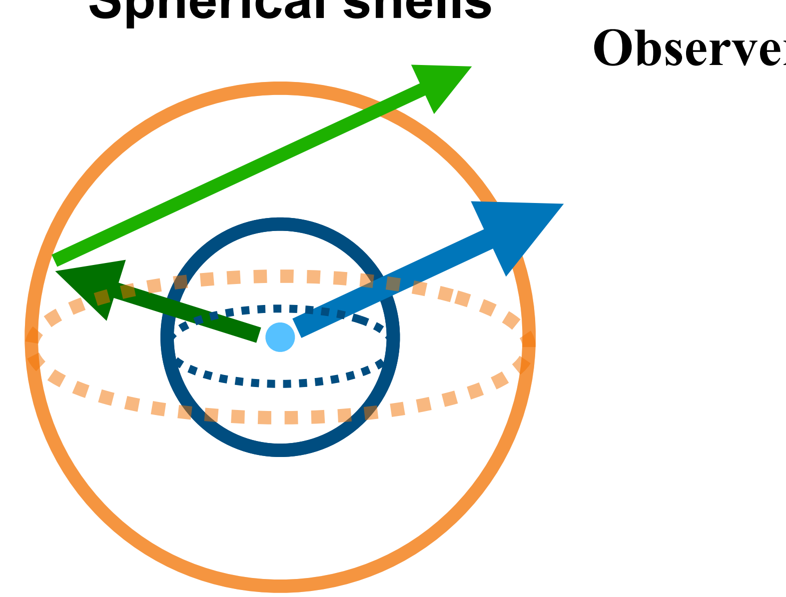


Assumed transfer function

double-top-hat function

- Contains short-lag and long-lag components
- transfer function for two spherical shells

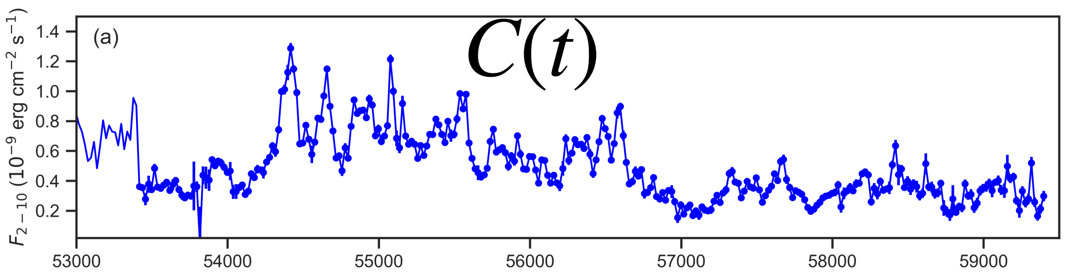
Spherical shells

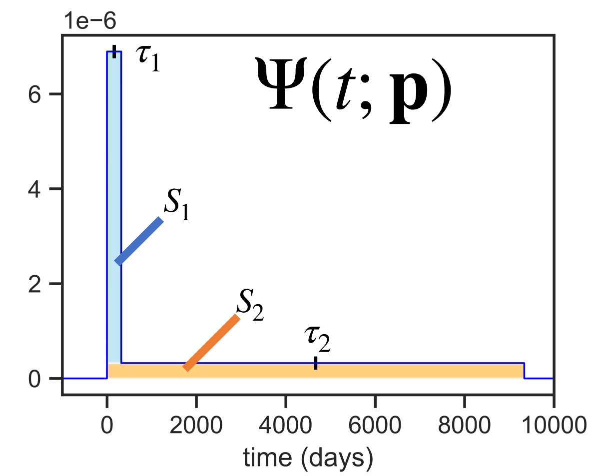


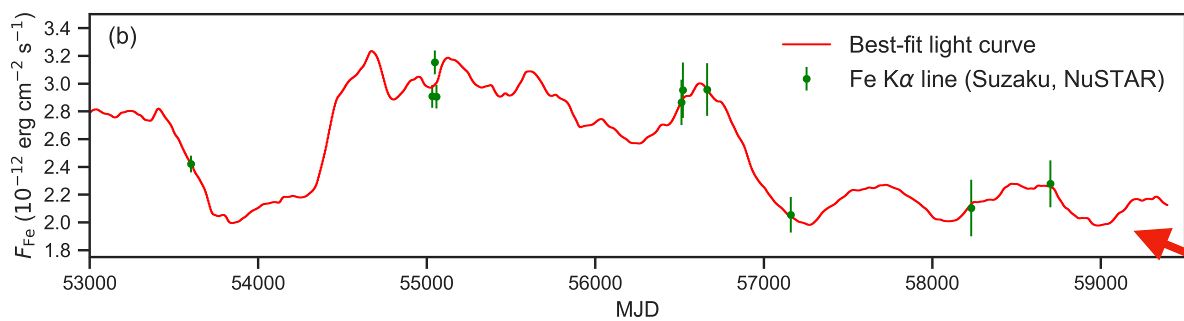
Analysis using the the transfer function

Parameters estimation

Fit the convolution to the iron line data







$$L(t; \mathbf{p}) = \int d\tau \Psi(\tau; \mathbf{p}) C(t - \tau)$$

- $\tau_1 < 2.8 \times 10^2$ days ➡ < 0.24 pc
- $\tau_2 > 2.1 \times 10^3$ days ➡ > 1.8 pc

Since the number of iron line flux data is limited, alternative models can also explain the data

More realistic model

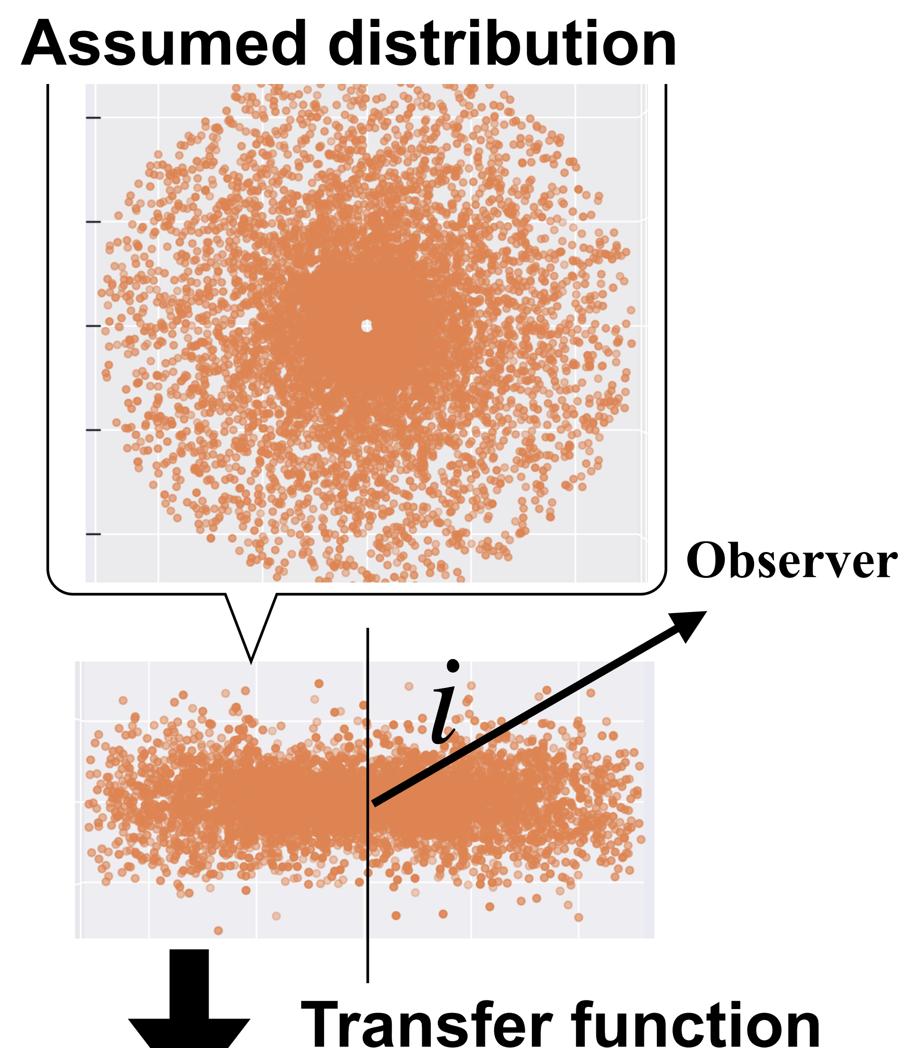
XClumpy-like model

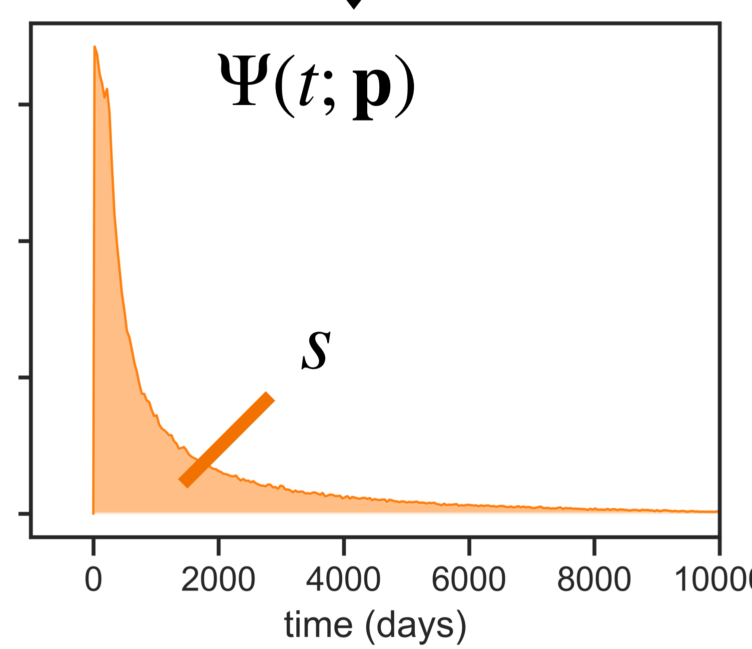
Assume the distribution of the origin of the iron line as follows

- $N\left(r/r_{\mathrm{in}}\right)^{-q}\exp\left(-(\theta-\pi/2)^2/\sigma^2\right)r^2\sin\theta drd\theta d\phi$
  $(r_{\mathrm{in}} < r < r_{\mathrm{out}})$
  *Same as the clump distribution in XClumpy (Tanimoto et al. 2019)
- $r_{\mathrm{out}} = 5\ \mathrm{pc},\ \sigma = 40^\circ$
- Inclination angle $i = 60^\circ$

Calculate the transfer function from the distribution

- Short-lag and long-lag components





The limitation of the reverberation mapping

Iron line flux estimation

Both cases with $r_{\rm in} = 1 \times 10^{-2}$ pc and 1×10^{-1} pc consistent with the light curve

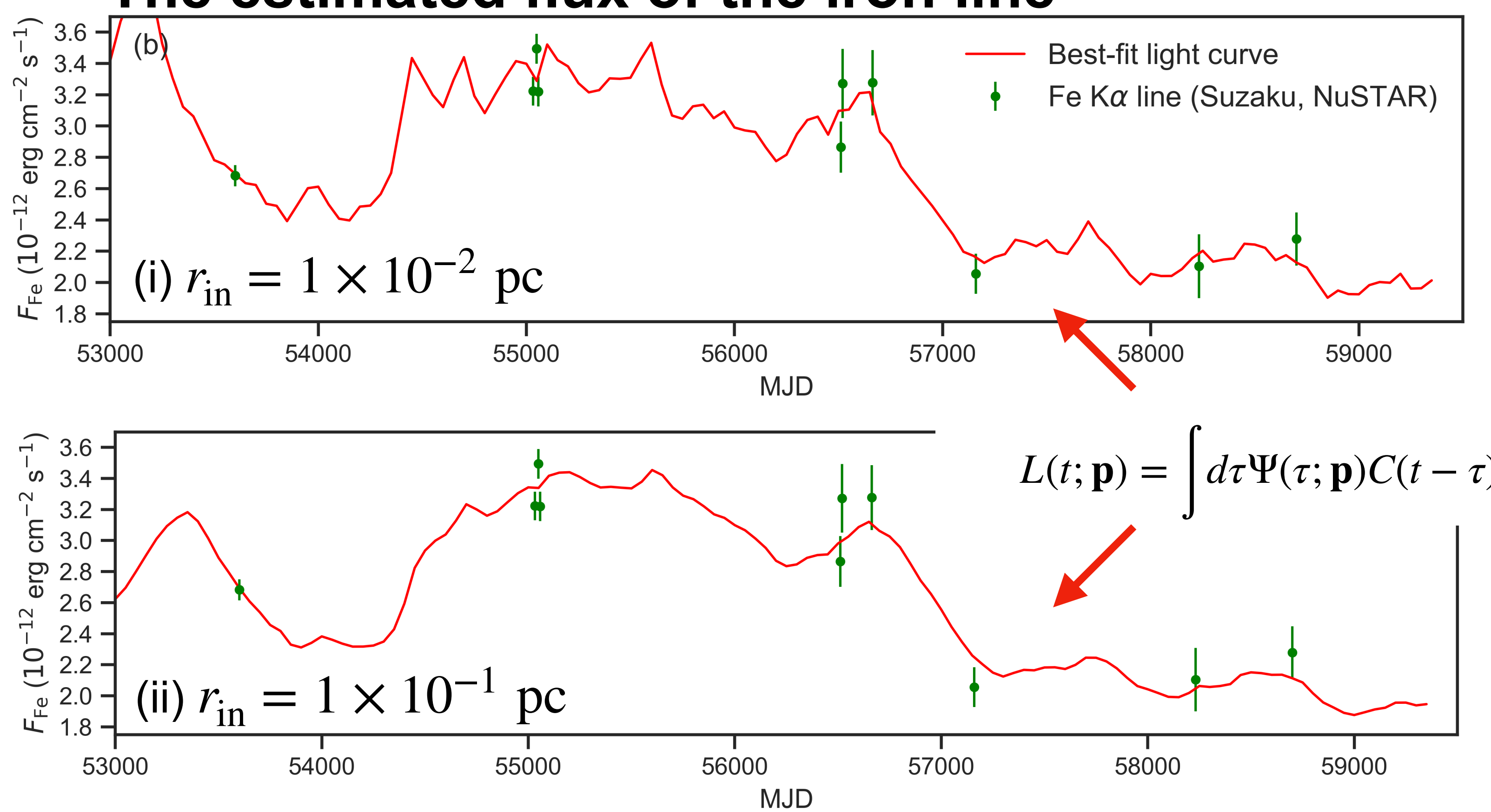
↓

X-ray reverberation cannot distinguish between these cases

↓

It is difficult to obtain further constraints on the short-lag component

The estimated flux of the iron line



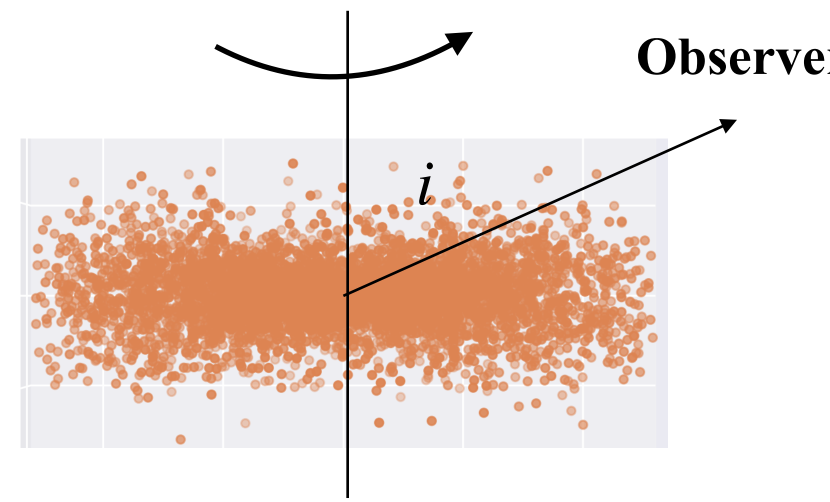
Since Resolve on XRISM has an energy resolution of < 7 eV,
the analysis of the line profile will be the most promising way

Simulation of XRISM iron line profile

Assumption for the iron line origin

XClumpy-like model

Keplerian motion



Simulated two cases:

(i) $r_{\rm in} = 1 \times 10^{-2}$ pc

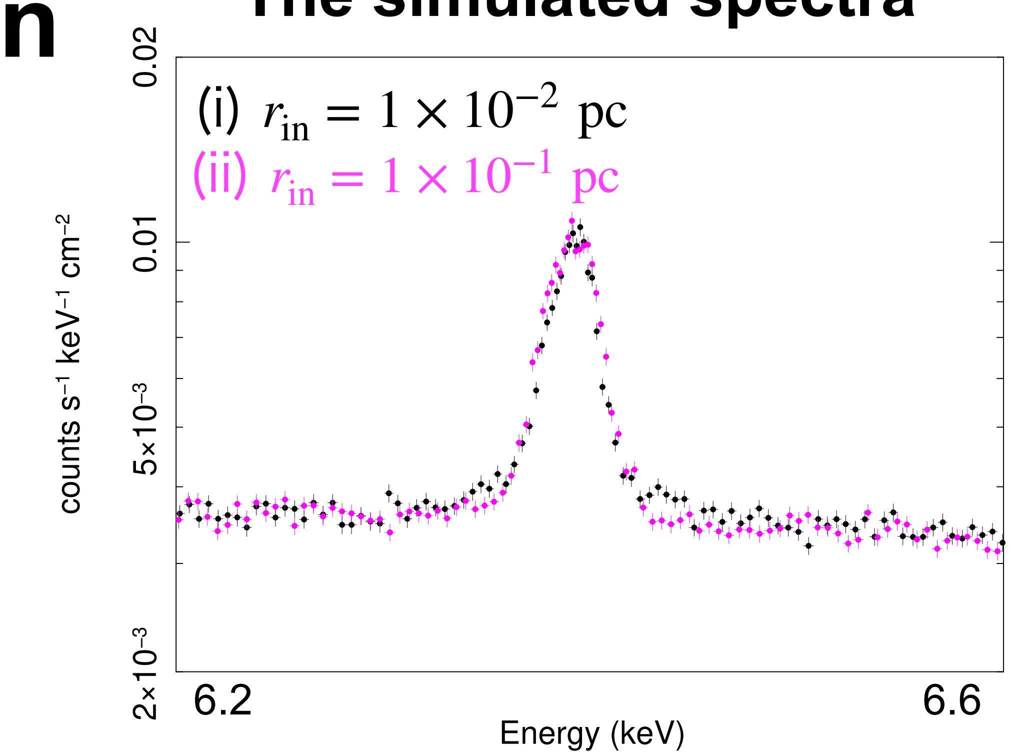
(ii) $r_{\rm in} = 1 \times 10^{-1}$ pc

Simulation of XRISM observation

The continuum flux is the same as the NuSTAR observation in 2018

Exposure 200 ks

The simulated spectra



Analysis of the simulated spectra

Analysis procedure

Fit the XClumpy-like model to the simulated spectra

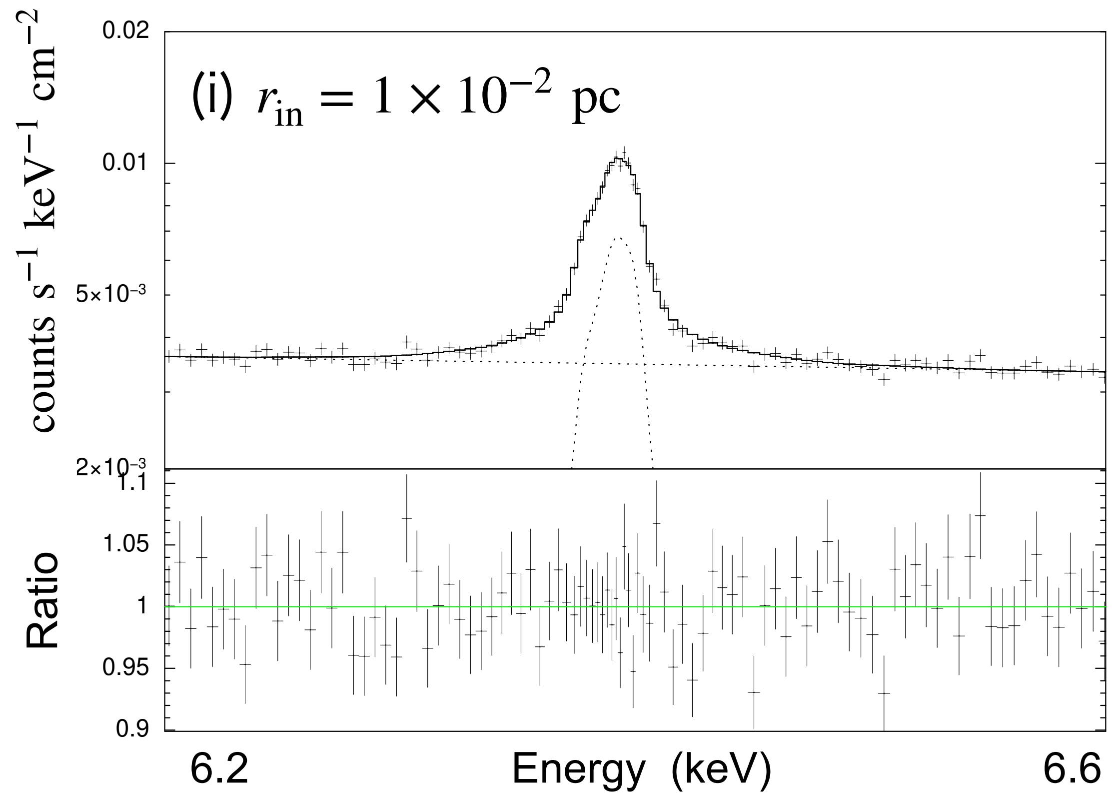
- Four free parameters: r_{in}, q, s and i

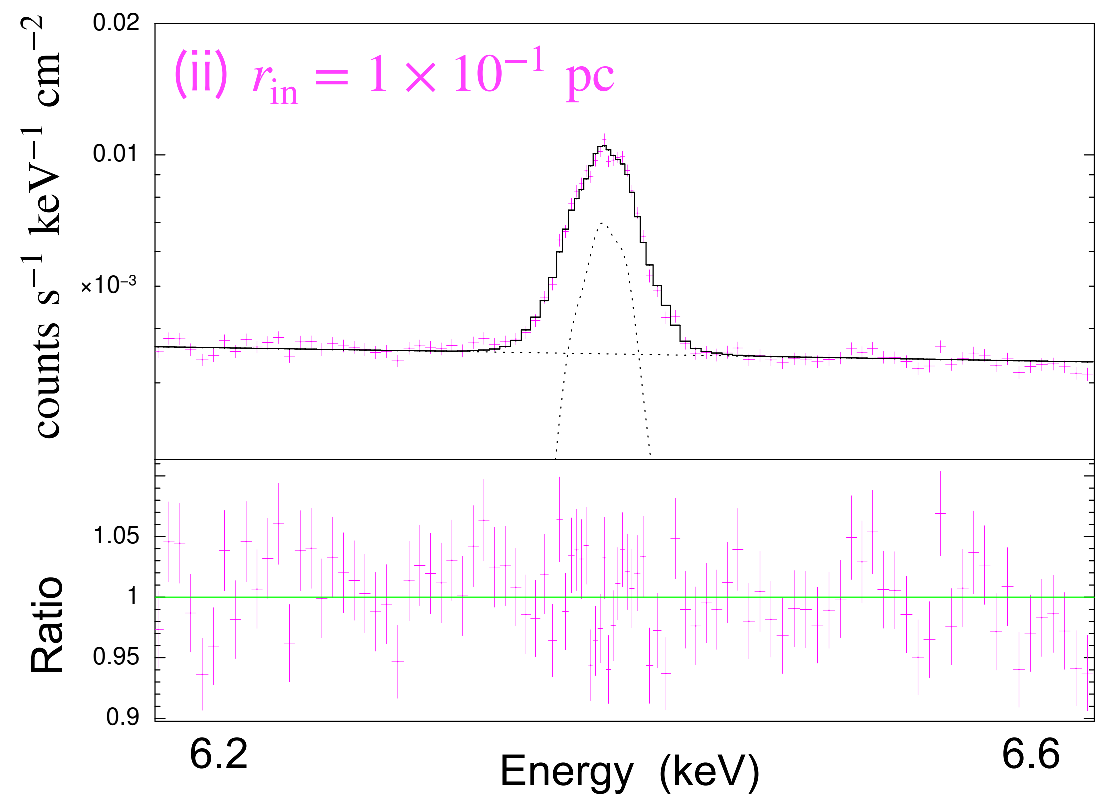
The results

r_{in} (assumed)	r_{in}
(i) 1×10^{-2} pc	$(8.5^{+3.6}_{-2.4}) \times 10^{-3}$ pc
(ii) 1×10^{-1} pc	$(9.2^{+2.1}_{-0.9}) \times 10^{-2}$ pc

XRISM observation will enable us to estimate **the size of the iron line origin when $r_{in} \sim 10^{-2}$–10^{-1} pc**

The analysis results of simulated spectra





Summary

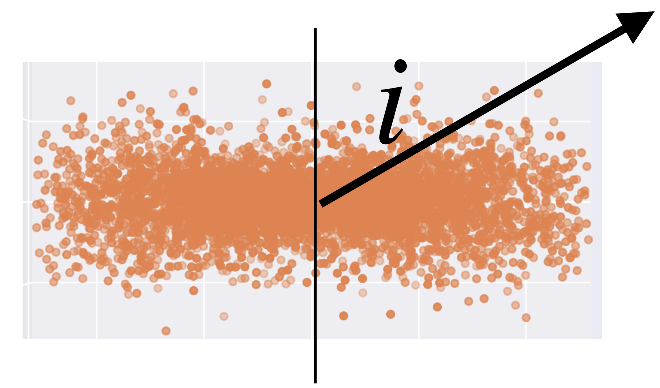
- X-ray reverberation mapping suggests that the reflection component is originated from the reflectors whose sizes are $< 0.24\ \mathrm{pc}$ **and** $> 1.8\ \mathrm{pc}$.
- Obtaining additional constraints on the short-lag component through x-ray reverberation mapping is challenging.
- Observation of Cen A with XRISM will enable us to estimate **the size of the iron line origin from the line profile, which is particularly sensitive to an inner reflector at $r_{\mathrm{in}} \sim 10^{-2}$–$10^{-1}$ pc.**

Thank you for listening!

Back up

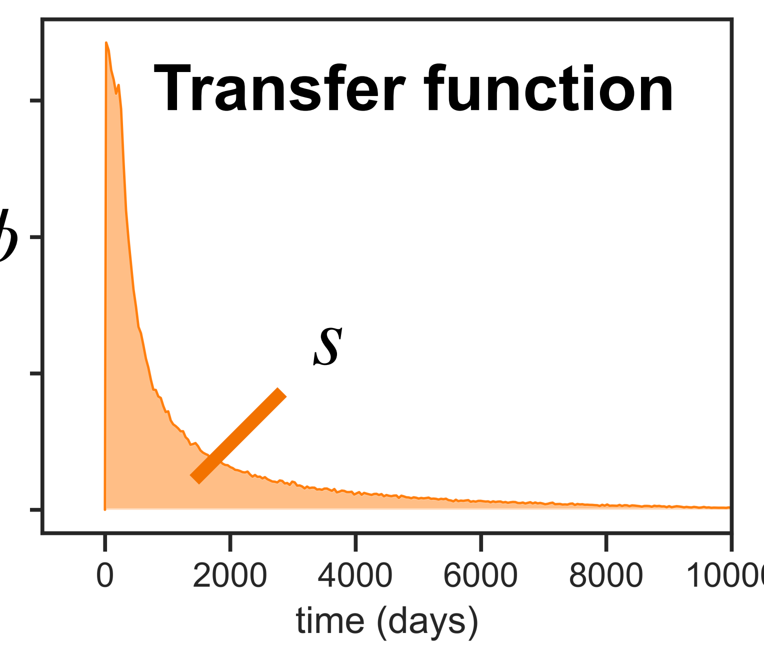
Results of simulated spectra analysis

		$r_{\rm in}$	q	s	i (degree)
(i)	assumed	1×10^{-2} pc	2.7	5.3×10^{-3}	60
	results	$(8.5^{+3.6}_{-2.4})\times10^{-3}$ pc	$2.687^{+0.061}_{-0.058}$	$(5.48^{+0.34}_{-0.30})\times10^{-3}$	70^{+16}_{-12}
(ii)	assumed	1×10^{-1} pc	3.2	5.1×10^{-3}	60
	results	$(9.2^{+2.1}_{-0.9})\times10^{-2}$ pc	$3.16^{+0.22}_{-0.14}$	$(5.08^{+0.28}_{-0.25})\times10^{-3}$	60^{+16}_{-12}

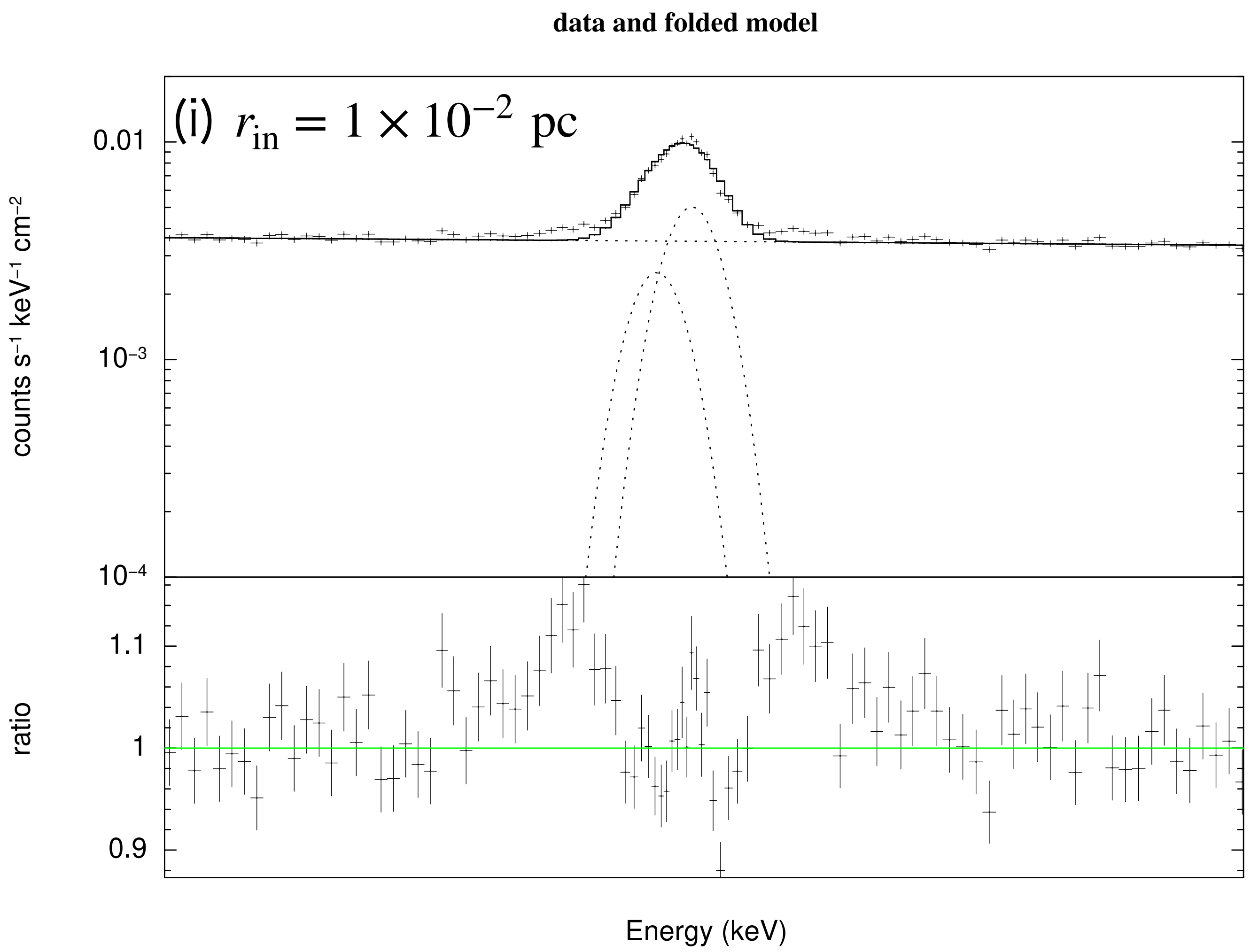


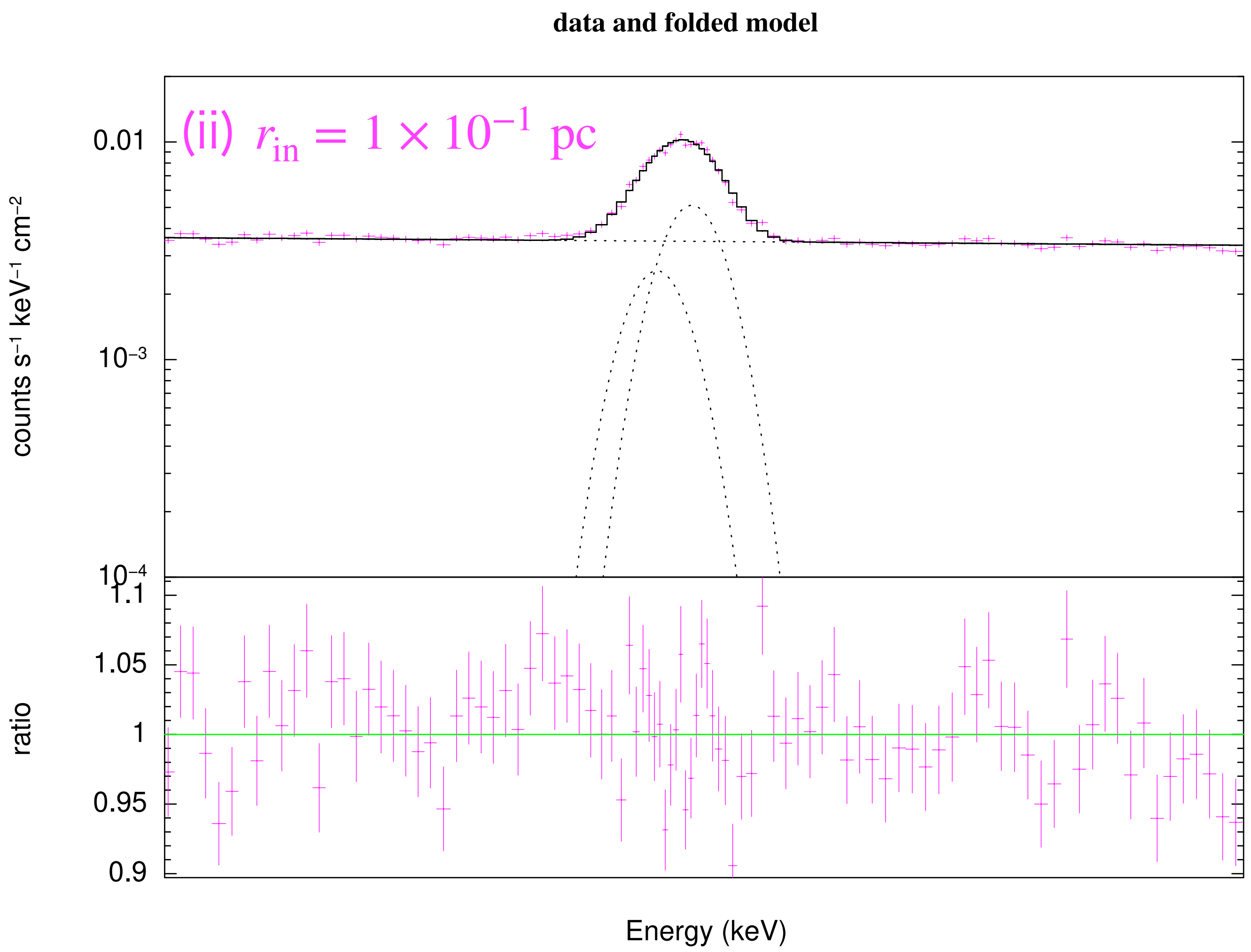
- Assume the distribution of the origin of the iron line as follows

$$N\left(r/r_{\rm in}\right)^{-q}\exp\left(-(\theta-\pi/2)^2/\sigma^2\right)r^2\sin\theta drd\theta d\phi$$
$$(r_{\rm in}<r<r_{\rm out})$$



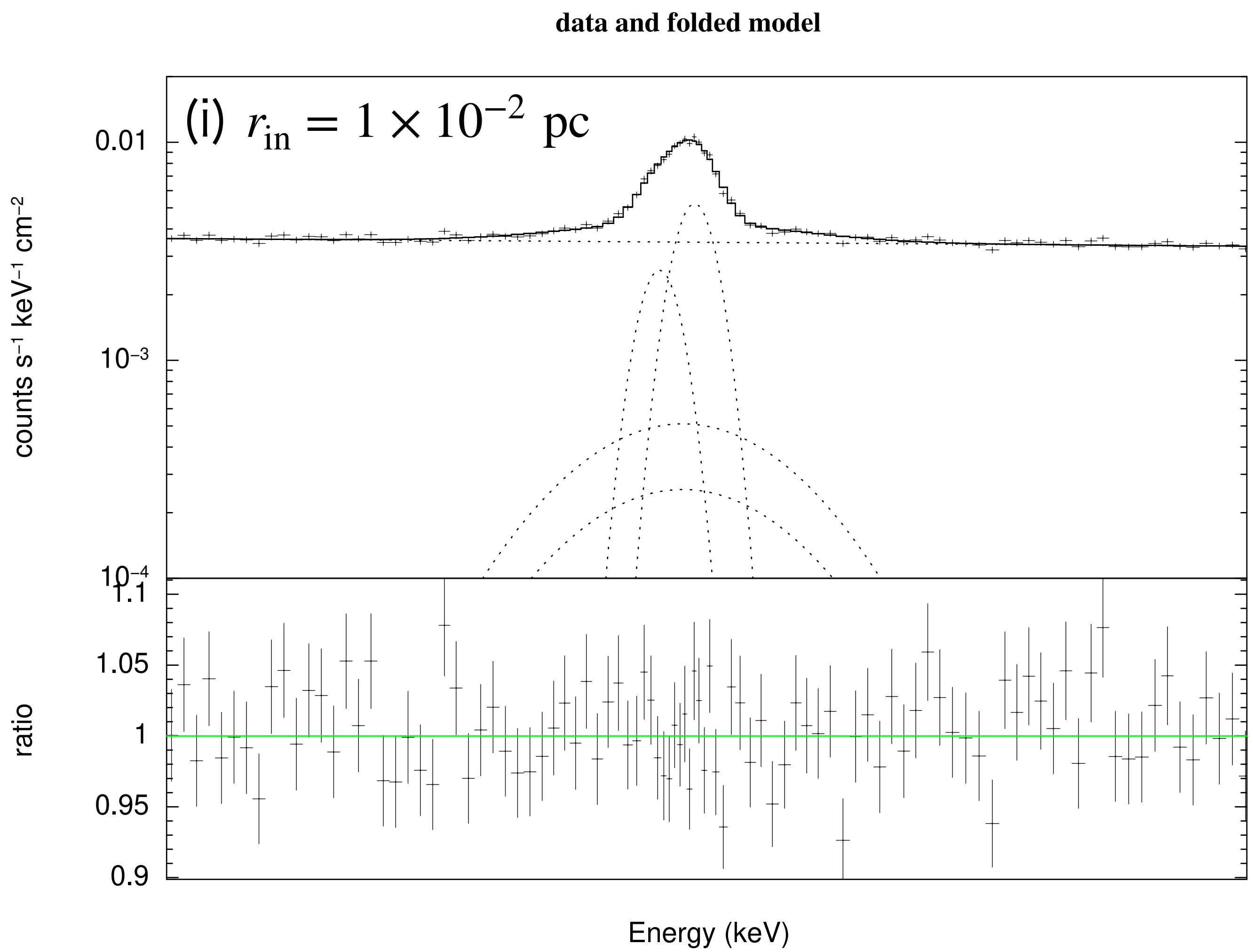
Simulated spectra: gauss

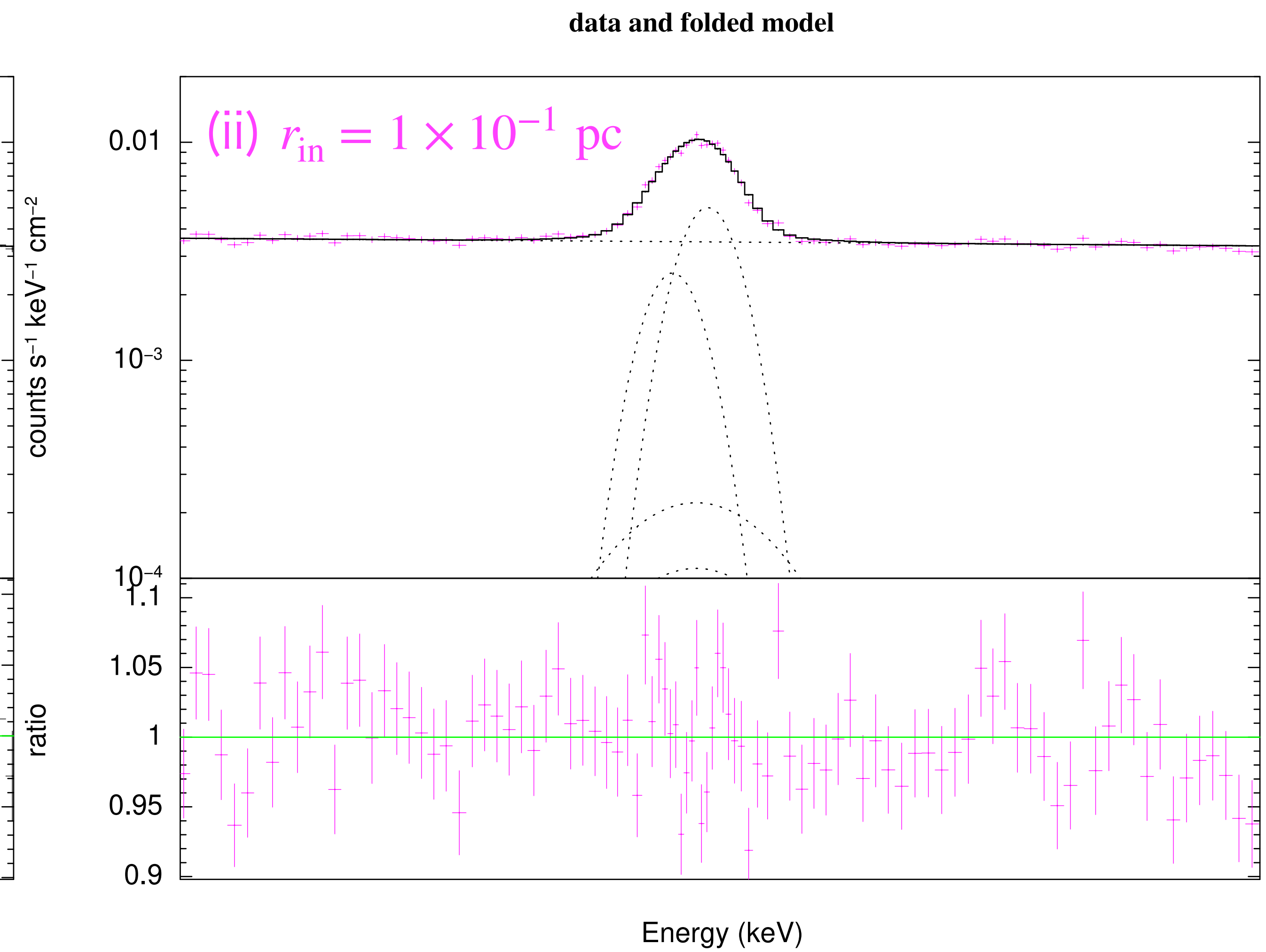




Simulated spectra: gauss (narrow + broad)

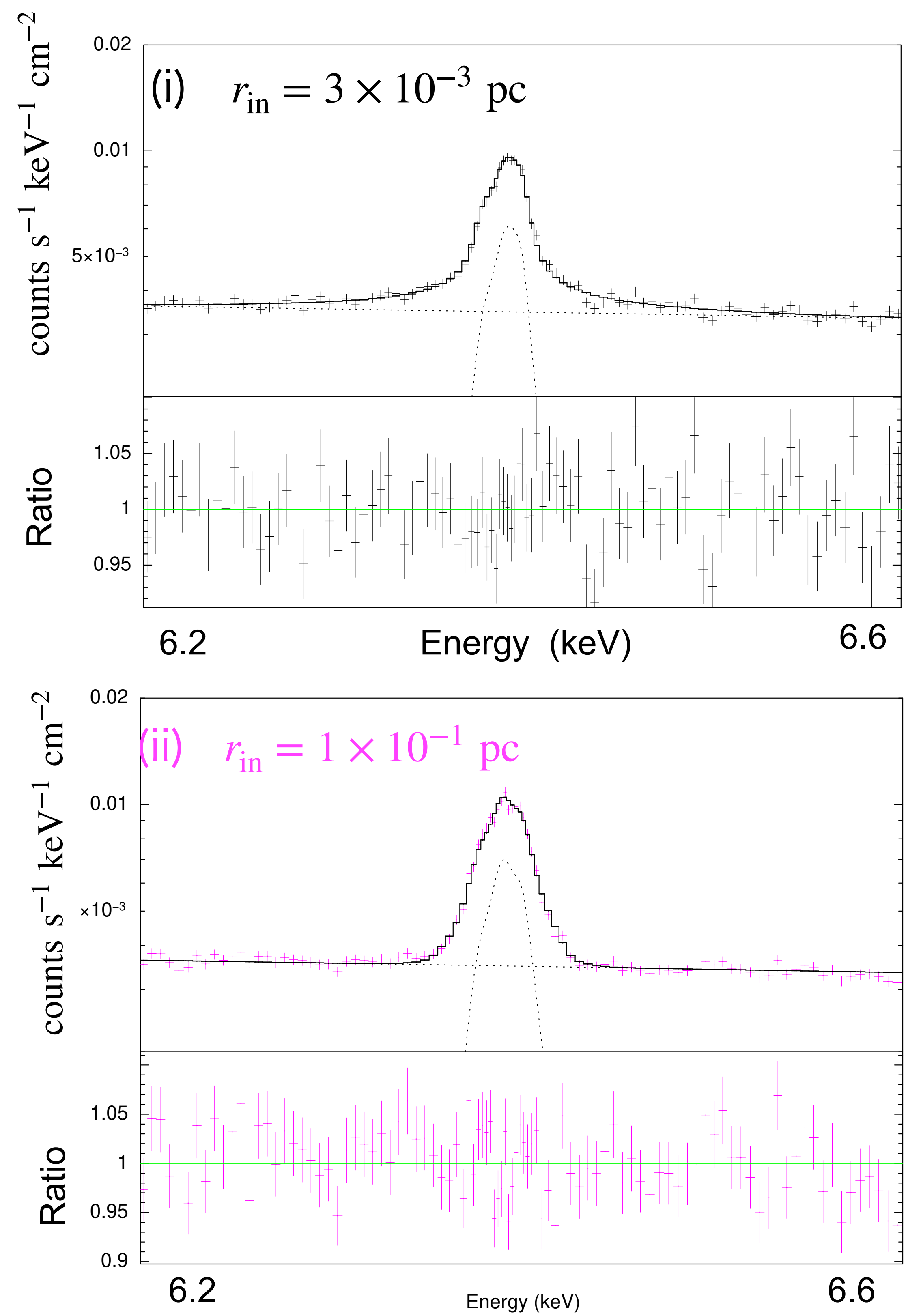
$r_{\rm in}$ (assumed)	σ_1	σ_2
(i) 1×10^{-2} pc	$7.17^{+0.63}_{-0.61}$ eV	$39.2^{+5.5}_{-4.7}$ eV
(ii) 1×10^{-1} pc	$10.4^{+0.7}_{-3.4}$ eV	30^{+50}_{-16} eV





Analysis of the simulated data: 3×10^{-3} pc

The analysis results of simulated spectra



The results

$r_{\rm in}$ (assumed)	$r_{\rm in}$
(i) 3×10^{-3} pc	$(1.9 \pm 1.0) \times 10^{-3}$ pc
(ii) 1×10^{-1} pc	$(9.2^{+2.1}_{-0.9}) \times 10^{-2}$ pc

Analysis of the simulated spectra: 100 ks

Simulated data

Exposure: 100 ks

The results

r_{in} (assumed)	r_{in}
(i) 1×10^{-2} pc	$(8.2^{+9.7}_{-3.7}) \times 10^{-3}$ pc
(ii) 1×10^{-1} pc	$(1.01^{+0.49}_{-0.16}) \times 10^{-1}$ pc

The analysis results of simulated spectra