Stanford

A statistical approach to measuring X-ray reverberation in gravitationally lensed quasars

Dan Wilkins

# Outline

- X-ray reverberation mapping of the inner accretion flows around black holes

- The Gaussian process framework

- Measuring reverberation around high-mass black holes in radio galaxies

- X-ray reverberation in Chandra observations of gravitationally lensed quasars

Corona

Accretion disc of gas
spiralling in to black hole

Redshifted wing of
emission line from
inner disc

Energy / keV

Corona

Redshifted wing of emission line from inner disc

Accretion disc of gas spiralling in to black hole

Delayed echoes of variability in the iron line

See variability in the continuum first

Energy / keV

Energy / keV

Lag / s
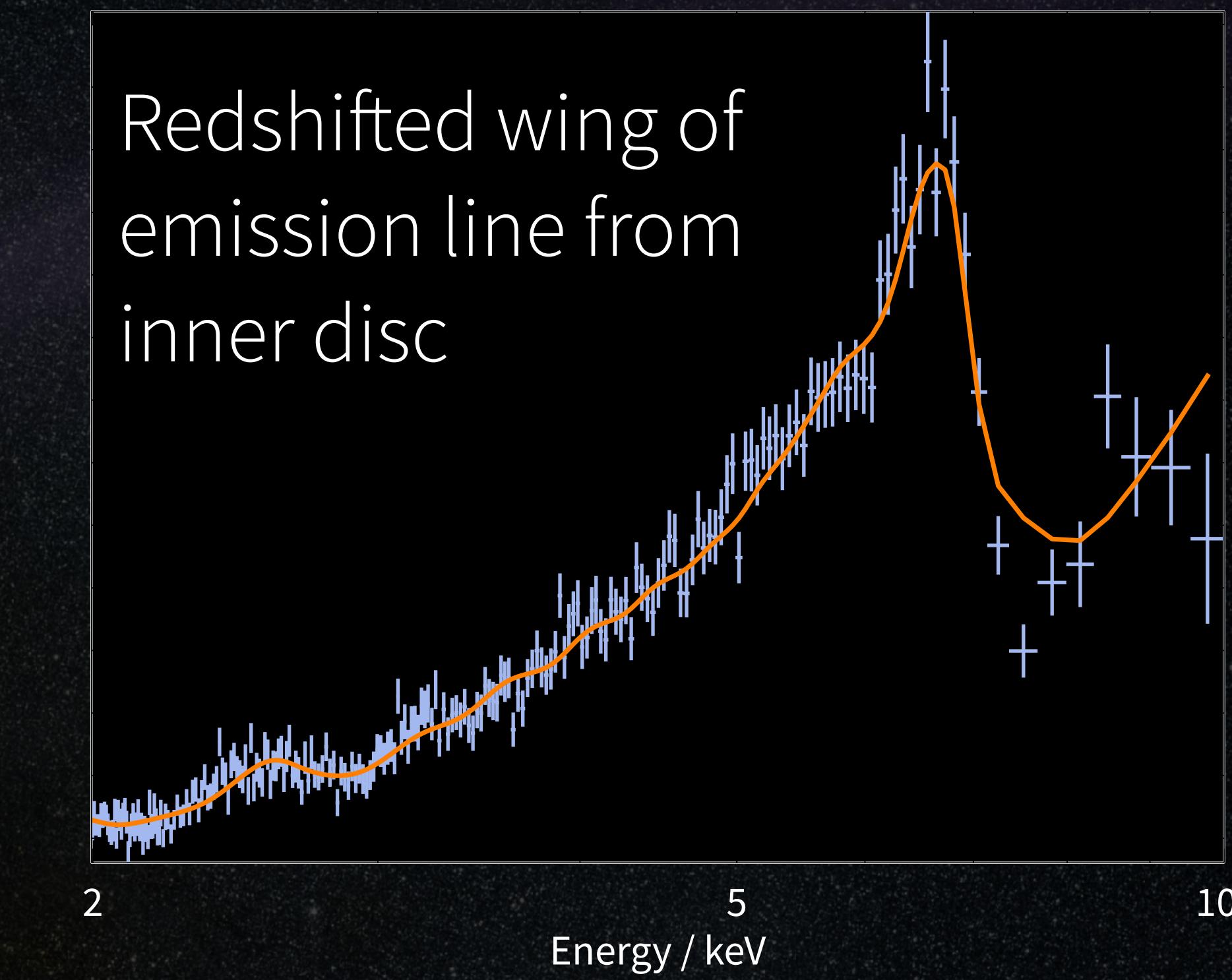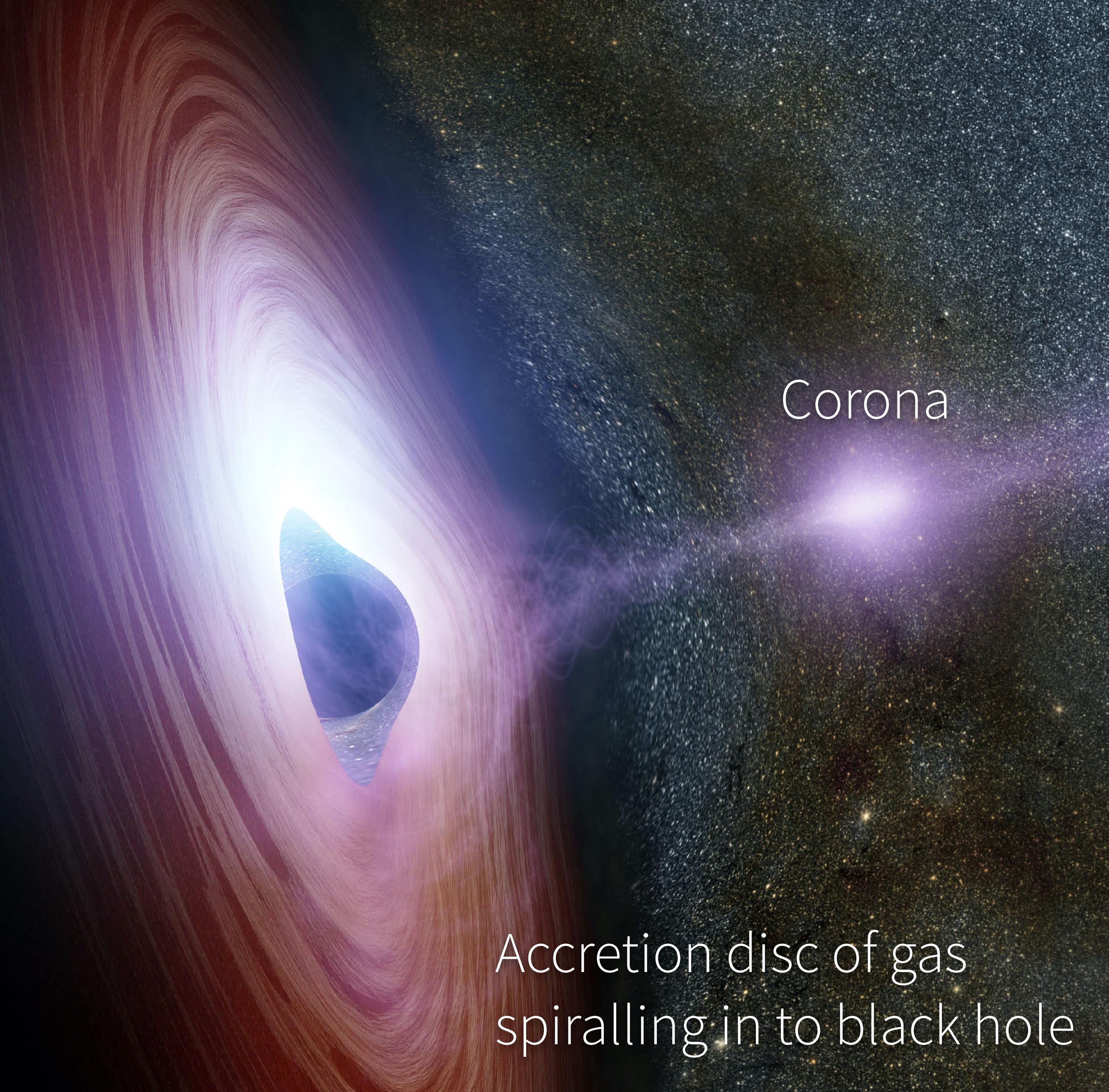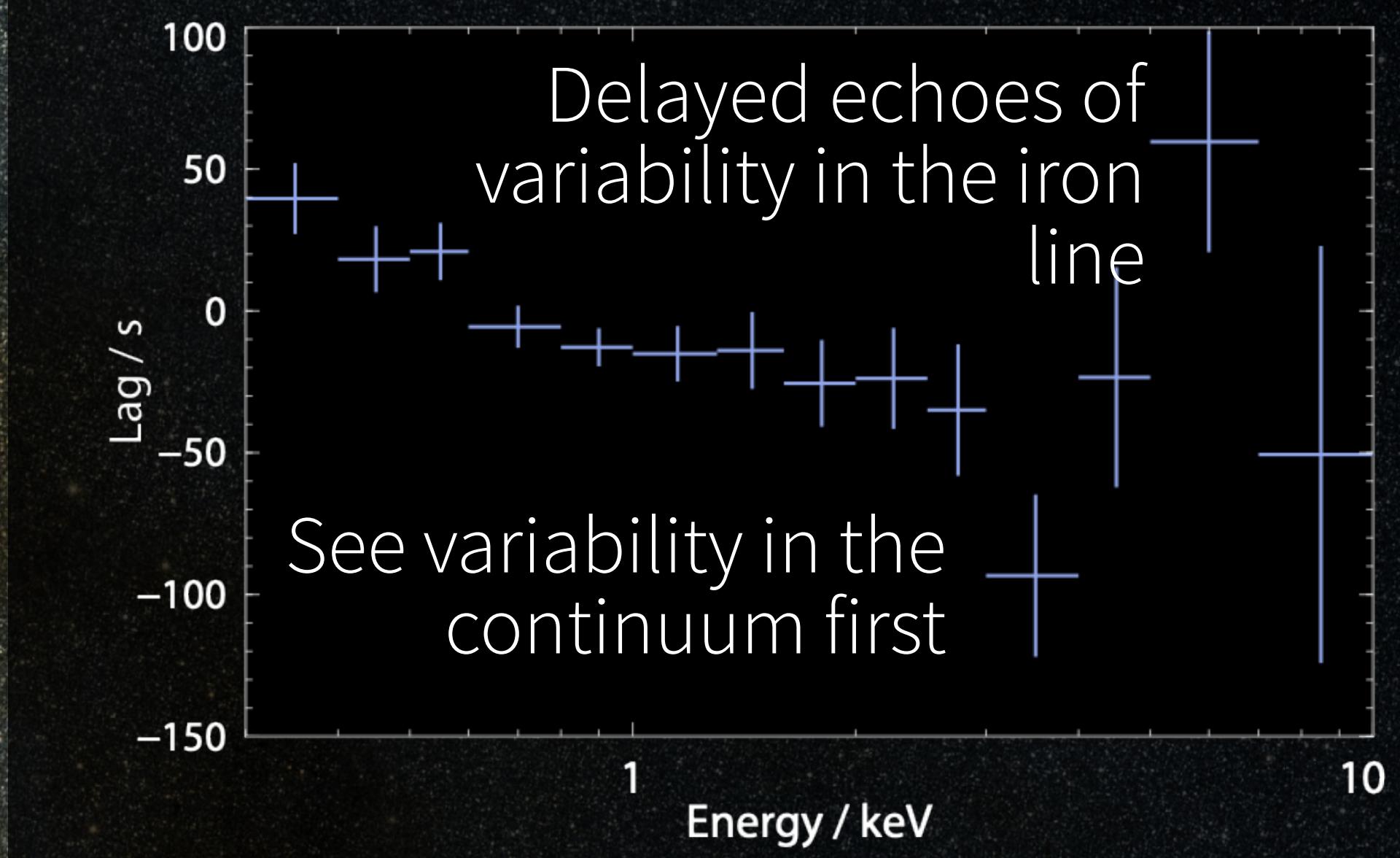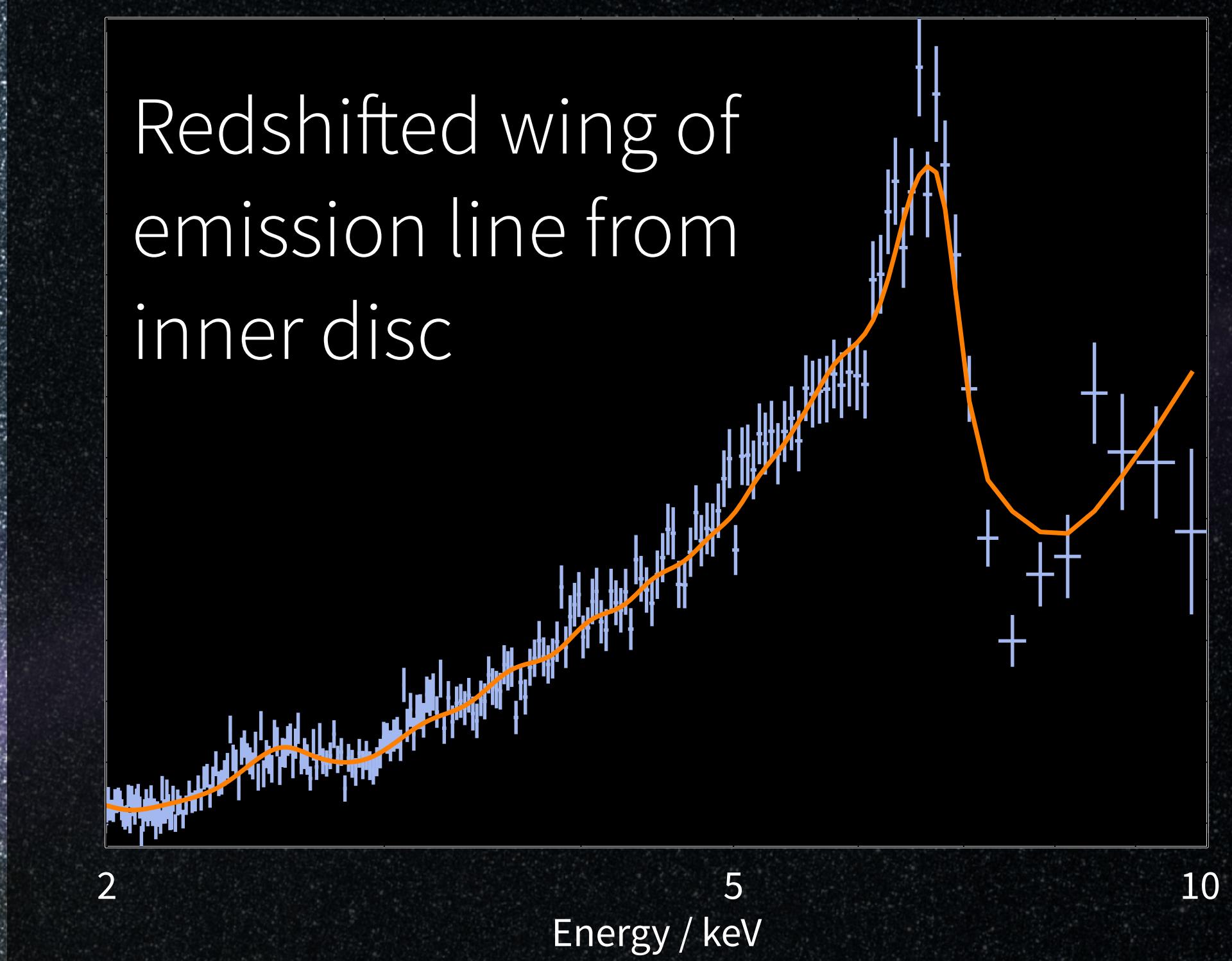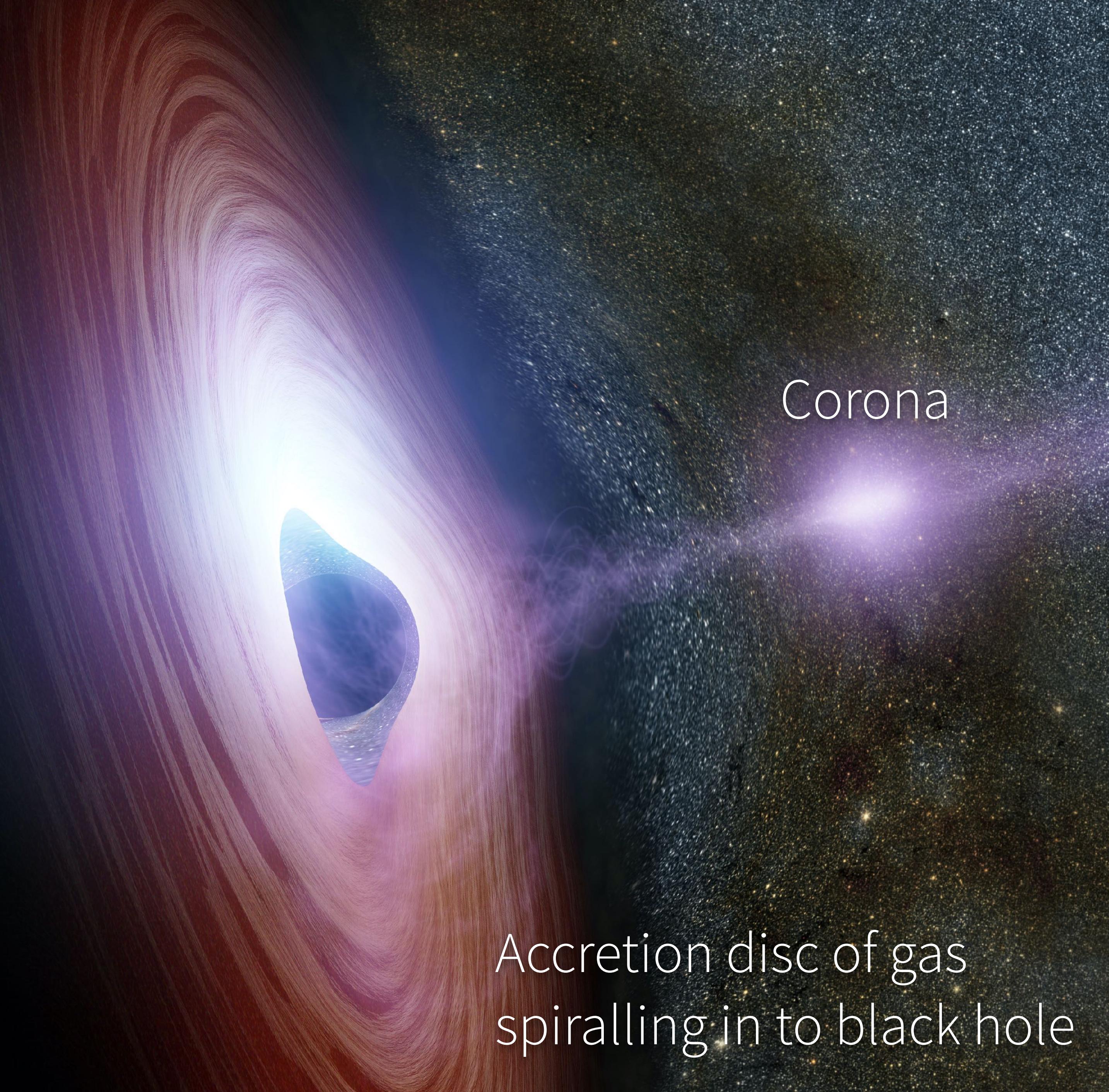
Fourier Timing

Fourier transform
Cross spectrum
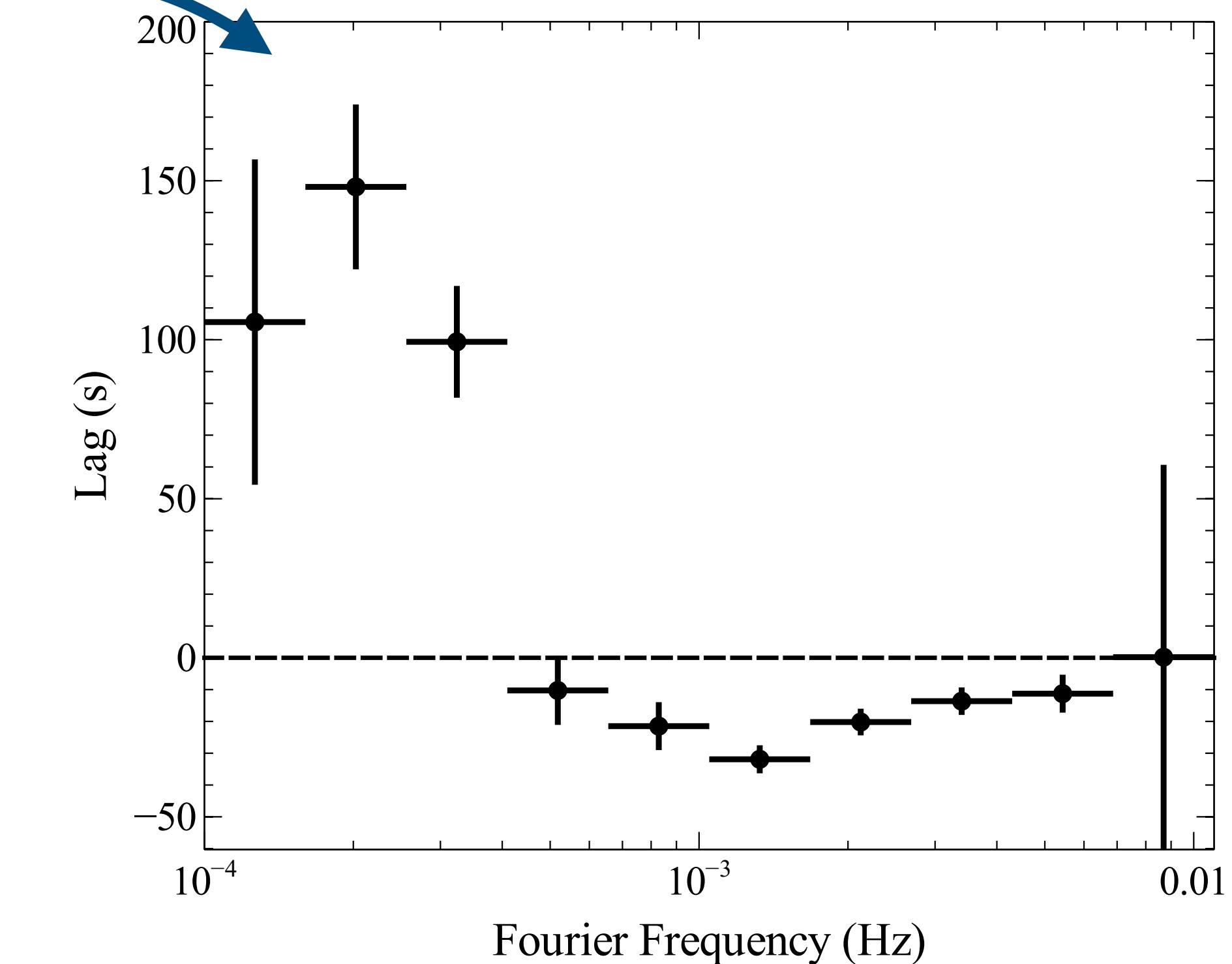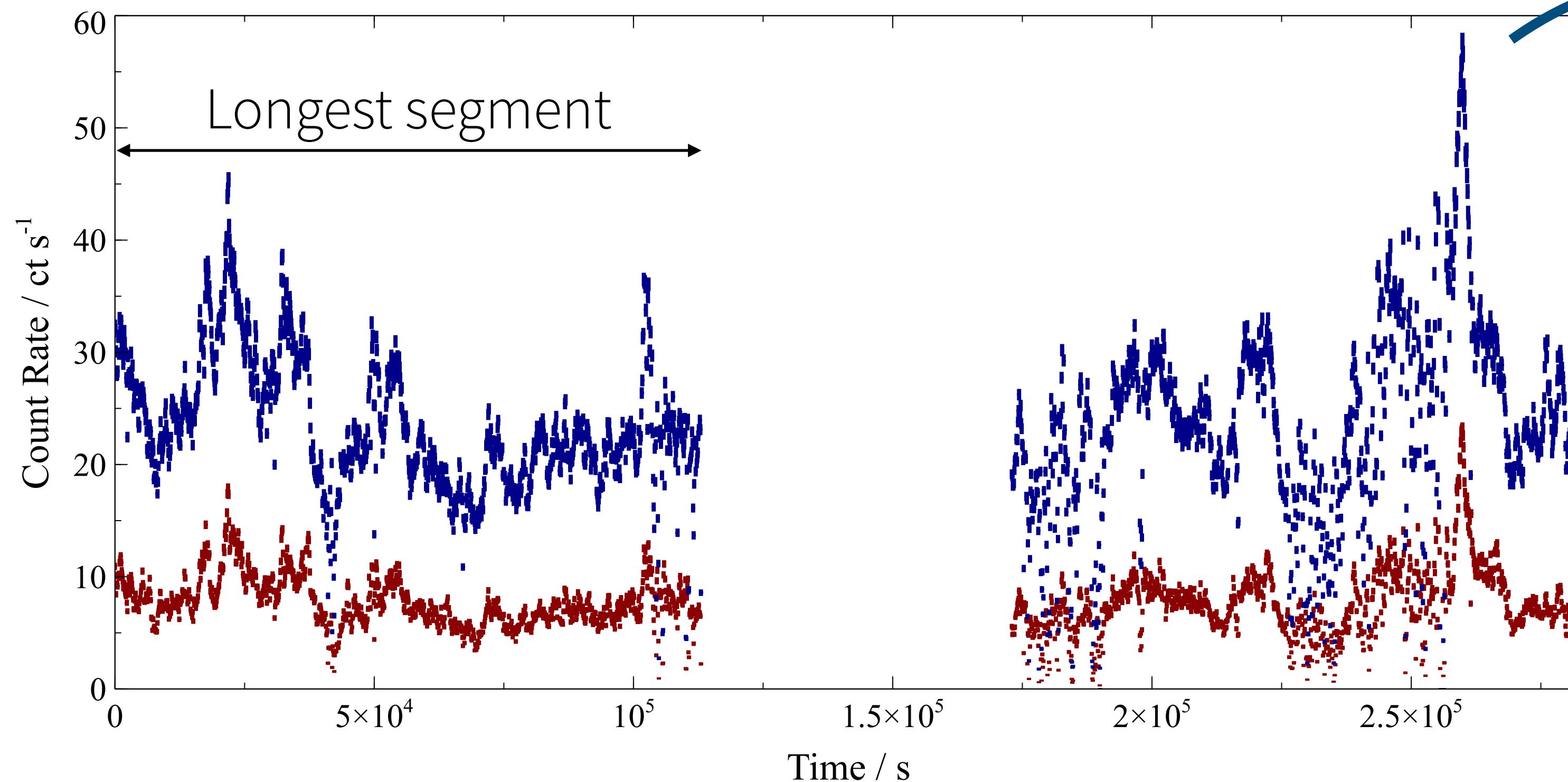

- Requires high signal-to-noise light curves

- Longest measurable time lag limited by longest continuous segments

(see Uttley et al. 2014)
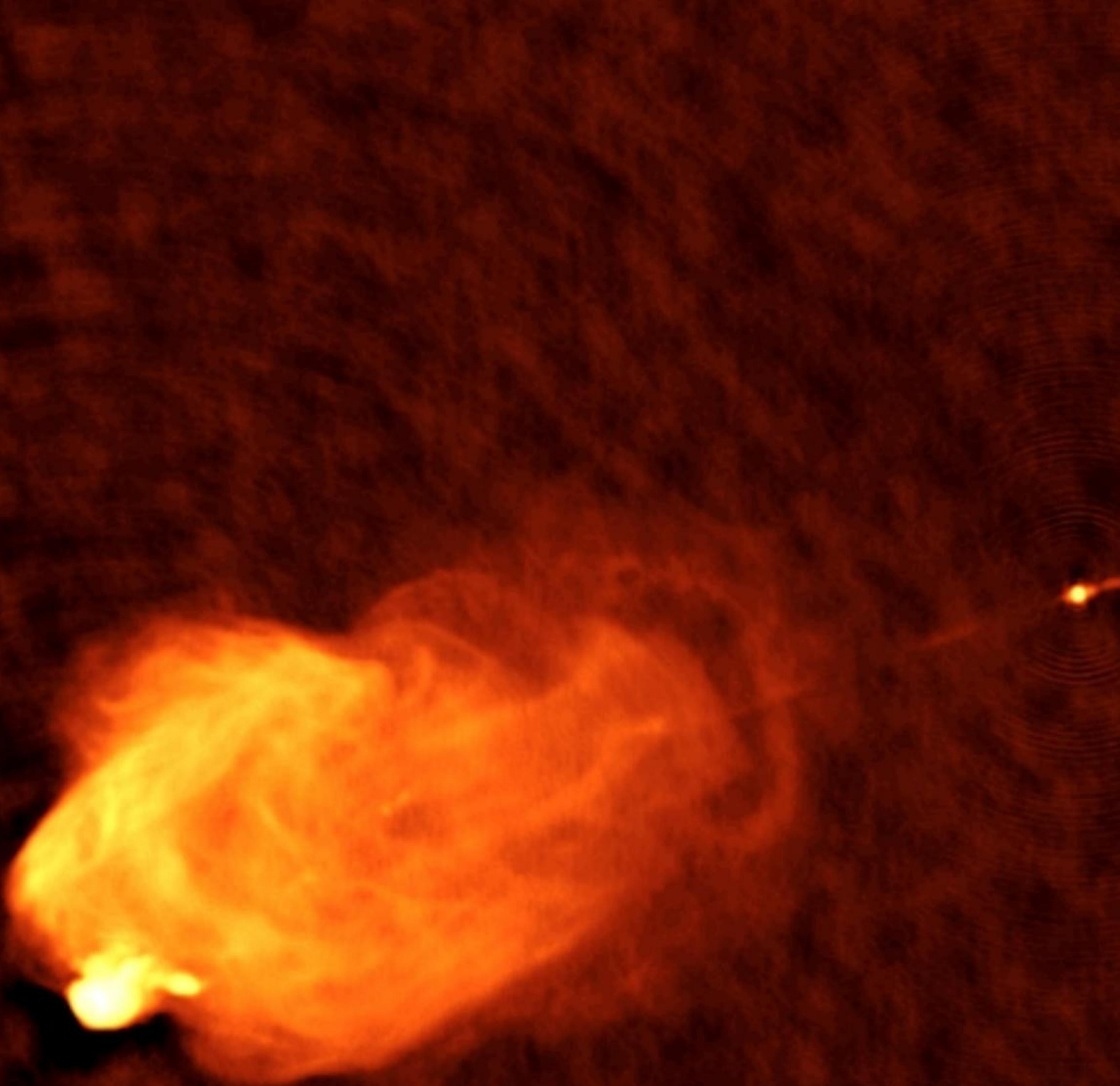
X-ray reverberation
in radio galaxies

Statistical frameworks for modelling time lags

Low-frequency X-ray timing with Gaussian processes and reverberation in the radio-loud AGN 3C 120

D. R. Wilkins ⭐†

Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, 452 Lomita Mall, Stanford, CA 94305, USA

CALCULATING TIME LAGS FROM UNEVENLY SAMPLED LIGHT CURVES

A. ZOGHBI[1,2], C. REYNOLDS[1,2], AND E. M. CACKETT[3]

[1] Department of Astronomy, University of Maryland, College Park, MD 20742-2421, USA; azoghbi@astro.umd.edu

[2] Joint Space-Science Institute (JSI), College Park, MD 20742-2421, USA

[3] Department of Physics and Astronomy, Wayne State University, 666 W. Hancock Street, Detroit, MI 48201, USA

Gaussian Processes (Wilkins 2019)

- Data vector containing the time series (N bins)

$$\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{pmatrix}$$

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- Assume data vector is a random draw from an N-dimensional Gaussian – gives the likelihood function

$$p(\boldsymbol{x}|\boldsymbol{\Sigma}_{xx}) = \frac{1}{(2\pi)^N |\boldsymbol{\Sigma}_{xx}|} \exp\left(-\frac{1}{2}\boldsymbol{x}^T \boldsymbol{\Sigma}_{xx}^{-1} \boldsymbol{x}\right)$$

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- Covariance matrix encodes autocorrelation (i.e. covariances between pairs of time bins)

- Analytic form for $\langle x_i x_j \rangle$ — the kernel function

$$\boldsymbol{\Sigma}_{xx} = \begin{pmatrix} \langle x_1 x_1 \rangle & \langle x_1 x_2 \rangle & \dots & \langle x_1 x_N \rangle \\ \langle x_2 x_1 \rangle & \langle x_2 x_2 \rangle & \dots & \langle x_2 x_N \rangle \\ \vdots & \vdots & \ddots & \vdots \\ \langle x_N x_1 \rangle & \langle x_N x_2 \rangle & \dots & \langle x_N x_N \rangle \end{pmatrix}$$

Filling in the gaps
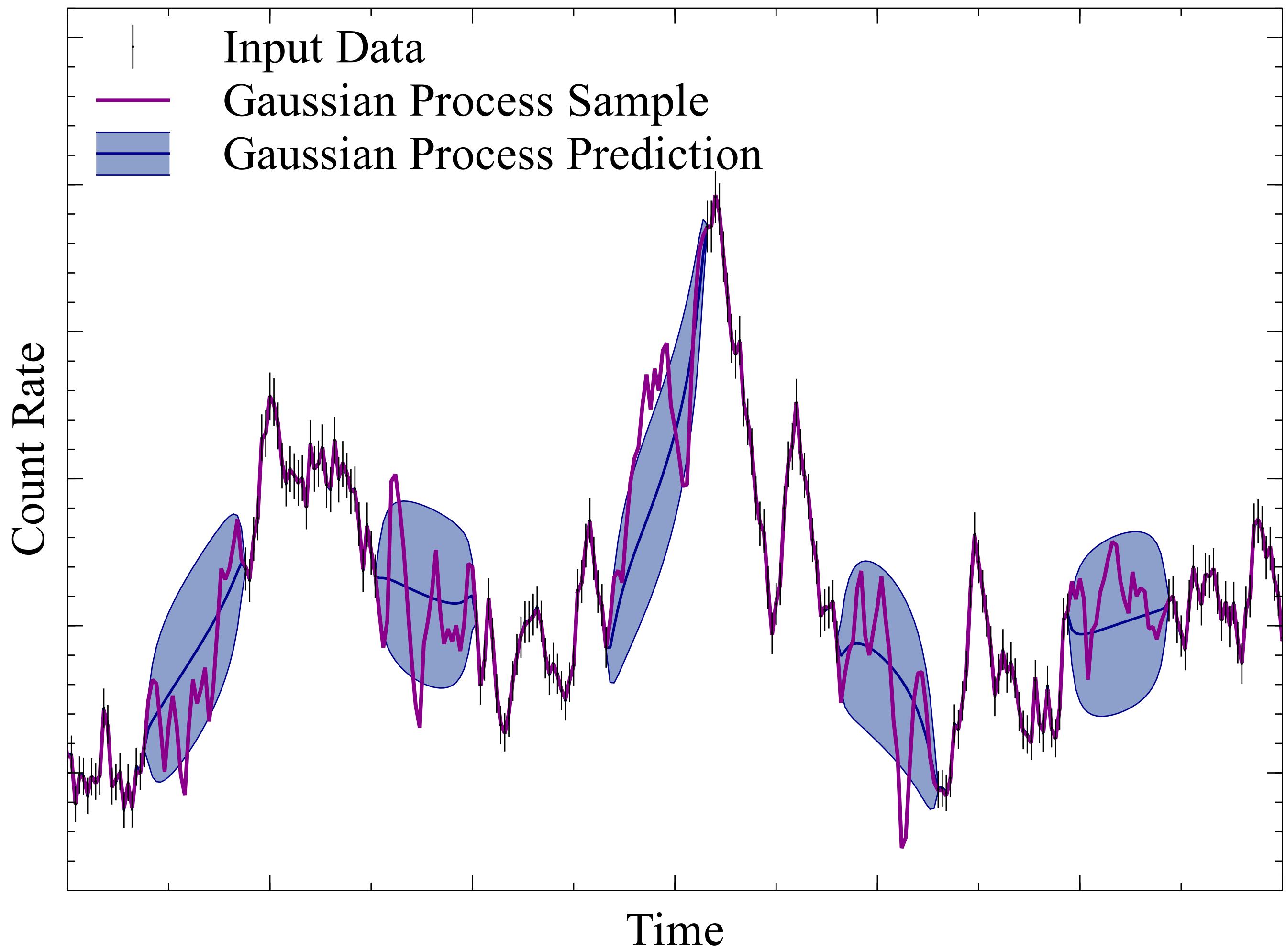
Adopt simple analytic function for covariances

Fit hyper-parameters to observed time bins

Draw samples from $(x_\mathrm{sample}|x_\mathrm{obs})$ with these parameters to predict missing time bins

Average predictions over many samples

Wilkins 2019

X-ray Reverberation in 3C 120

Wilkins 2019

Broad line radio galaxy
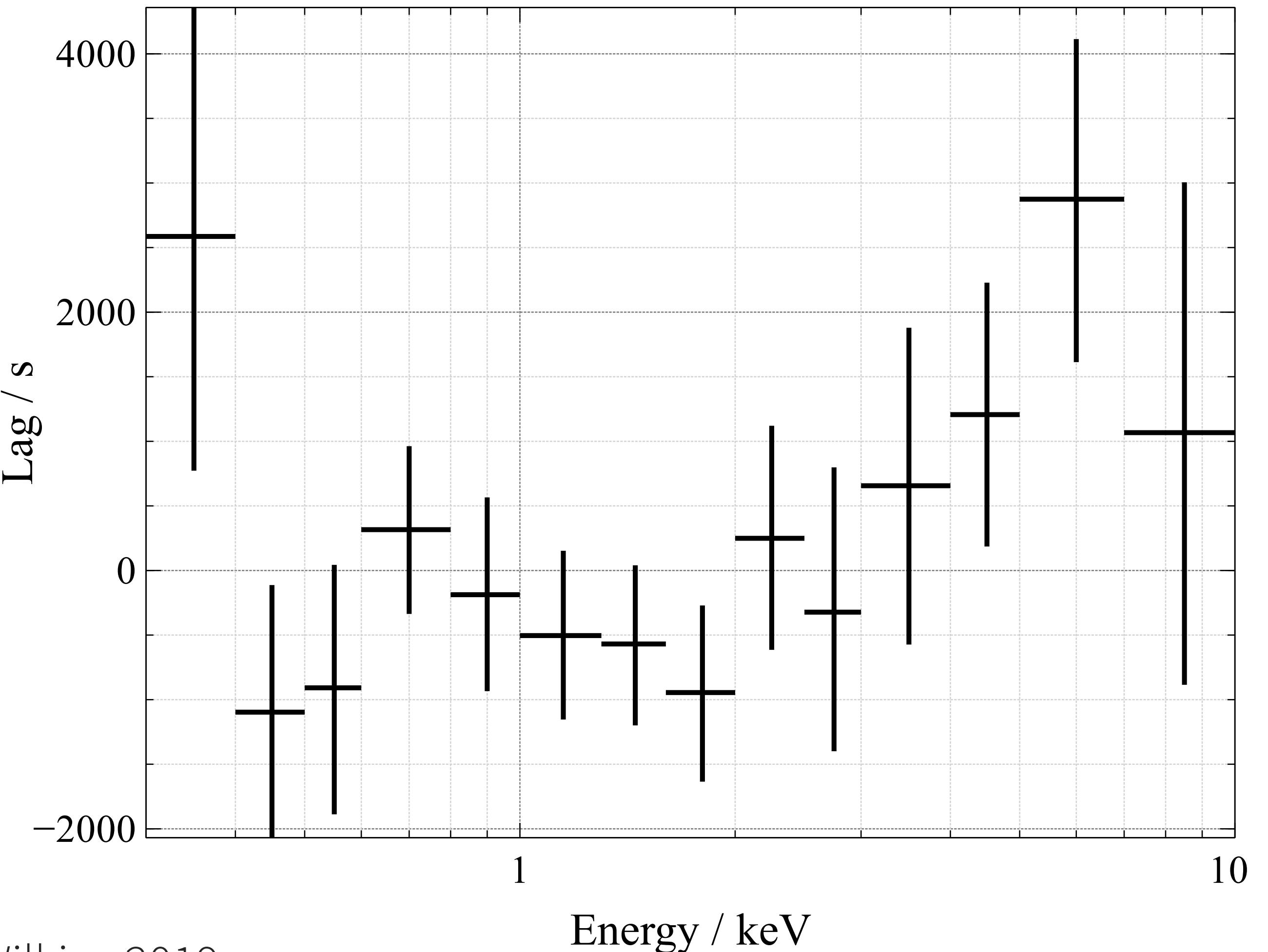
$M_{BH} = 5.7 \times 10^7\ M_{\odot}$

Gaussian process fit to light curve in each energy bin

Predict missing time bins and calculate time lag using conventional Fourier method

Produces posterior distribution of time lag in each energy bin

X-ray reverberation in gravitationally lensed quasars

Reverberation in lensed quasars

The Einstein Cross
Q2237+0305

ACIS-I

Continuum

Reflection from Disk

E F$_E$

Energy / keV

0.5 1 2 5
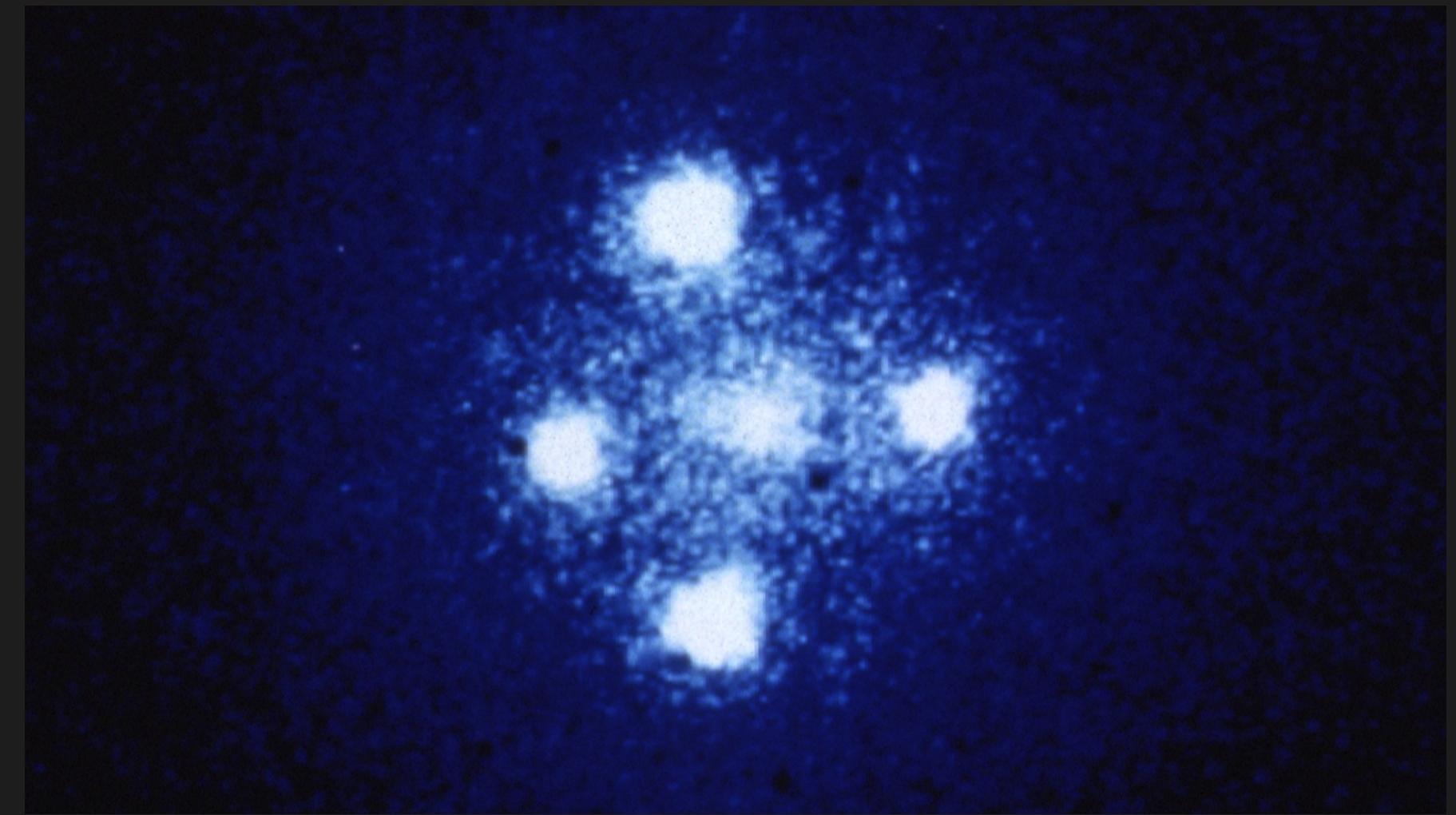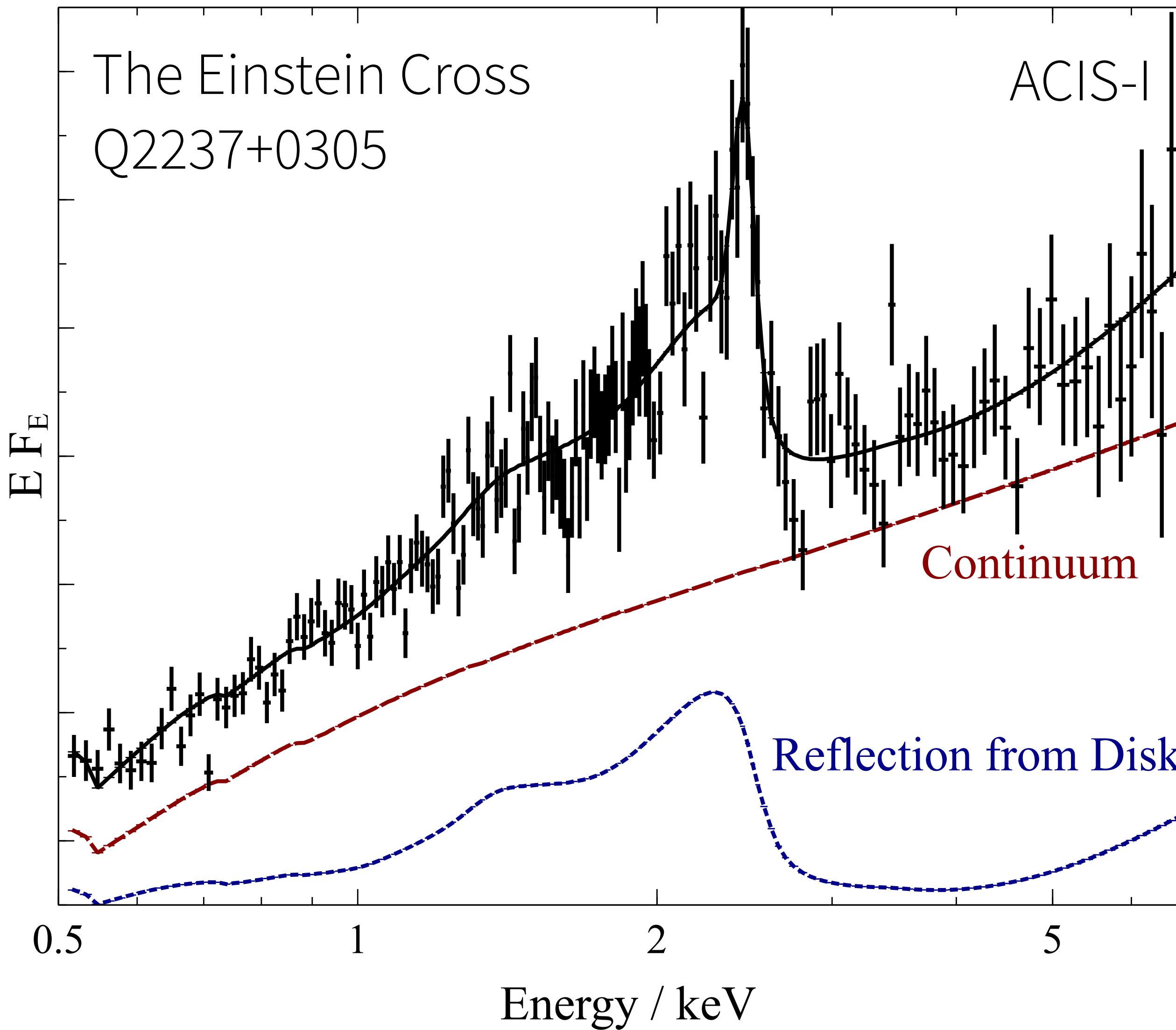
Chandra observations of lensed quasars show broad iron K lines, reflected from inner accretion disk — Reis et al. 2014, Reynolds et al. 2014, Walton et al. 2015

Lower count rates – direct lag measurement difficult

What range of time lags are consistent with the data?

Fitting the lag between two energy bands (Zoghbi et al. 2013)

- Stacked data vector of the two time series, x and y

$$\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \\ y_1 \\ y_2 \\ \vdots \\ y_N \end{pmatrix}$$

Fitting the lag between two energy bands (Zoghbi et al. 2013)

- Stacked data vector of the two time series, x and y

$$\mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \\ y_1 \\ y_2 \\ \vdots \\ y_N \end{pmatrix}$$

- Covariance matrix encodes autocorrelation of each time series, and the cross-correlation

- Time lag a parameter of cross-correlation model

- Use MCMC to obtain $P(\mathrm{lag}|\mathrm{data})$

$$\boldsymbol{\Sigma} = \begin{pmatrix} \boldsymbol{\Sigma}_{xx} & \boldsymbol{\Sigma}_{xy} \\ \boldsymbol{\Sigma}_{yx} & \boldsymbol{\Sigma}_{yy} \end{pmatrix}$$

Reverberation in the Einstein Cross

Iron K Lag ~1600s

The Einstein Cross
Q2237+0305
Chandra ACIS-I

Frequency

Time Lag / s

Wilkins et al. (in prep)

Auto-correlation model: power law PSD

Cross-correlation model: power law PSD with constant time lag

Posterior distribution of time lag between iron K and continuum band in the Einstein Cross

Timing between images

The Einstein Cross
Q2237+0305
Chandra ACIS-I

Time Lag / s

Frequency

Wilkins et al. (in prep)
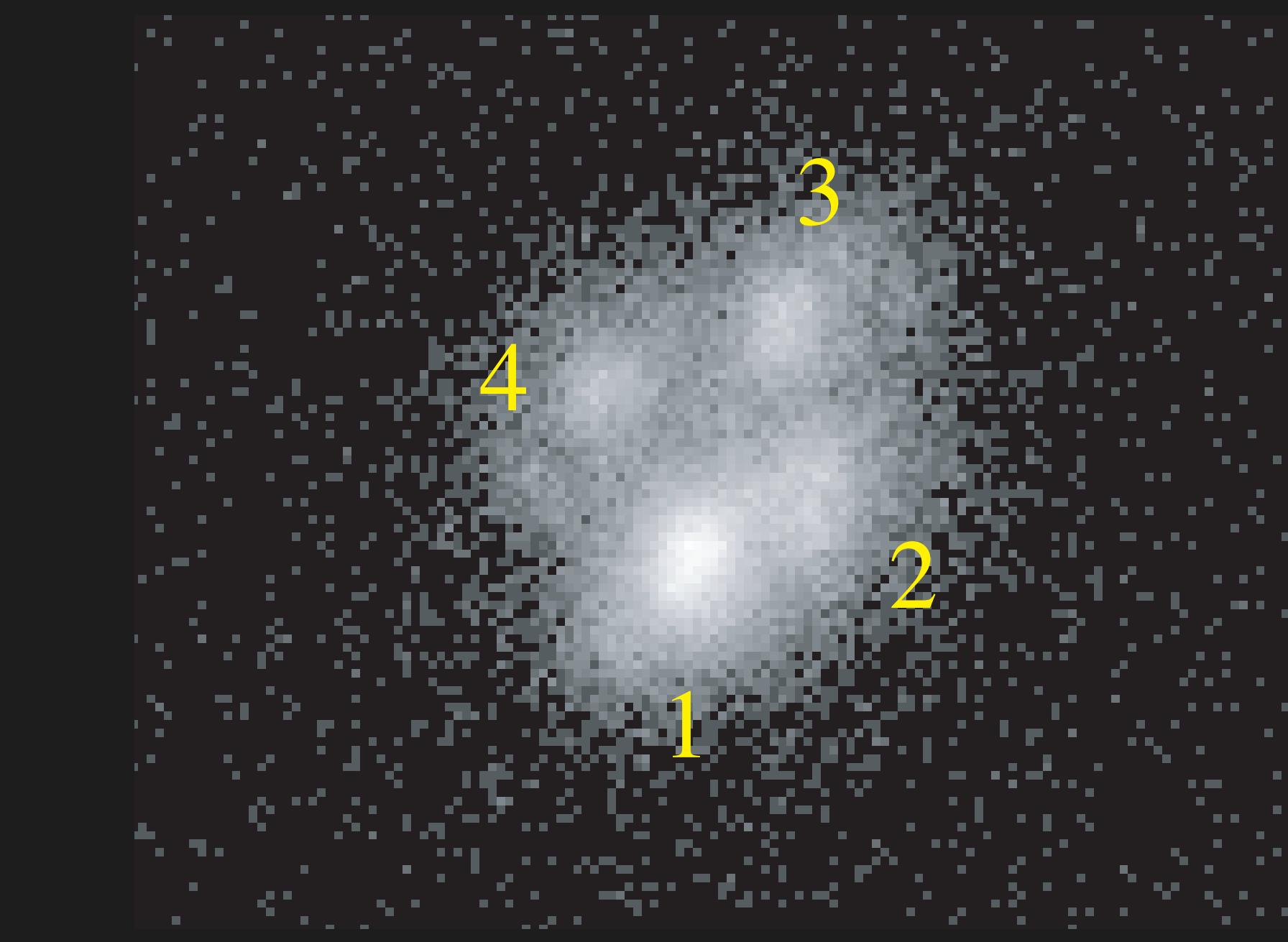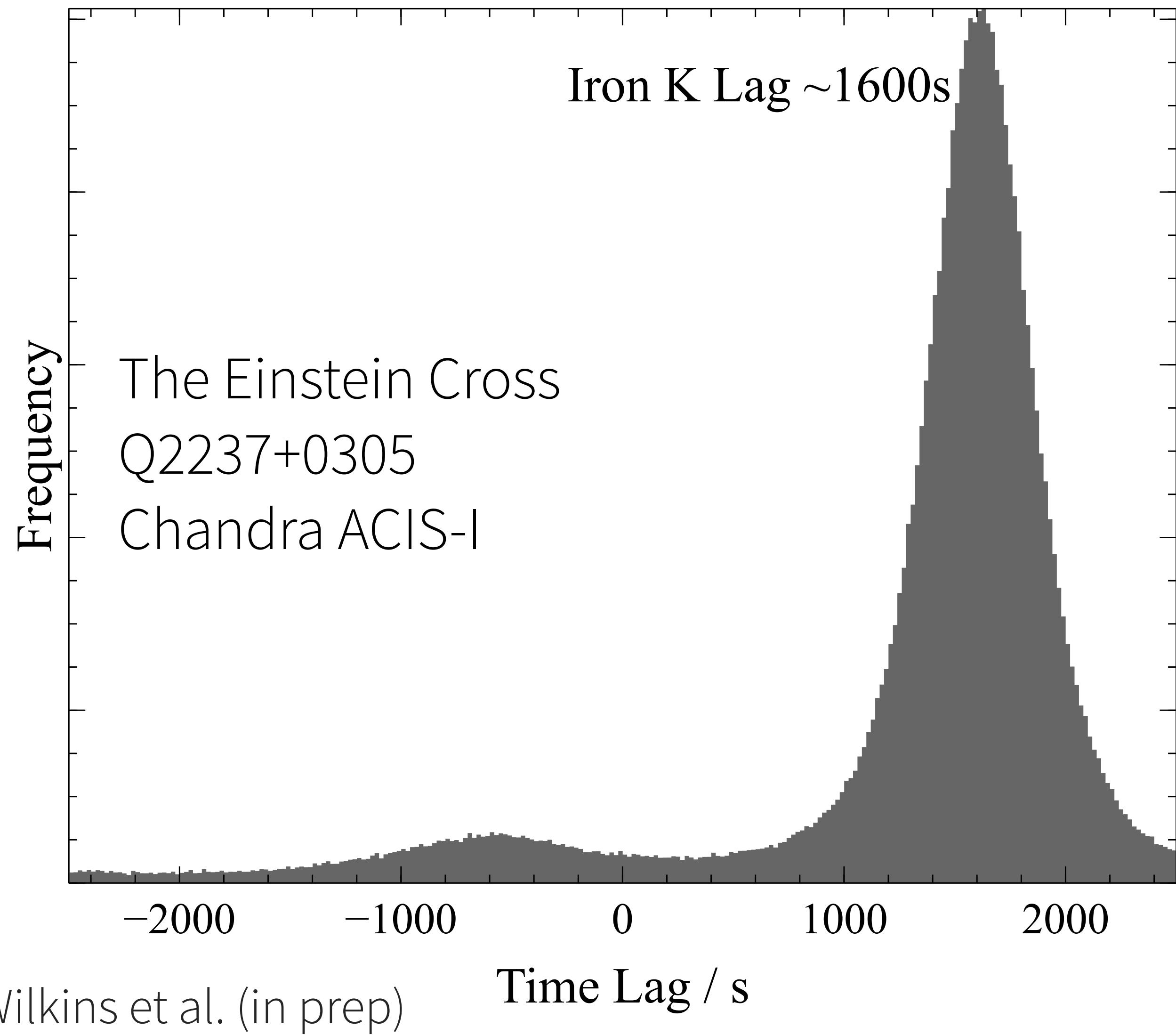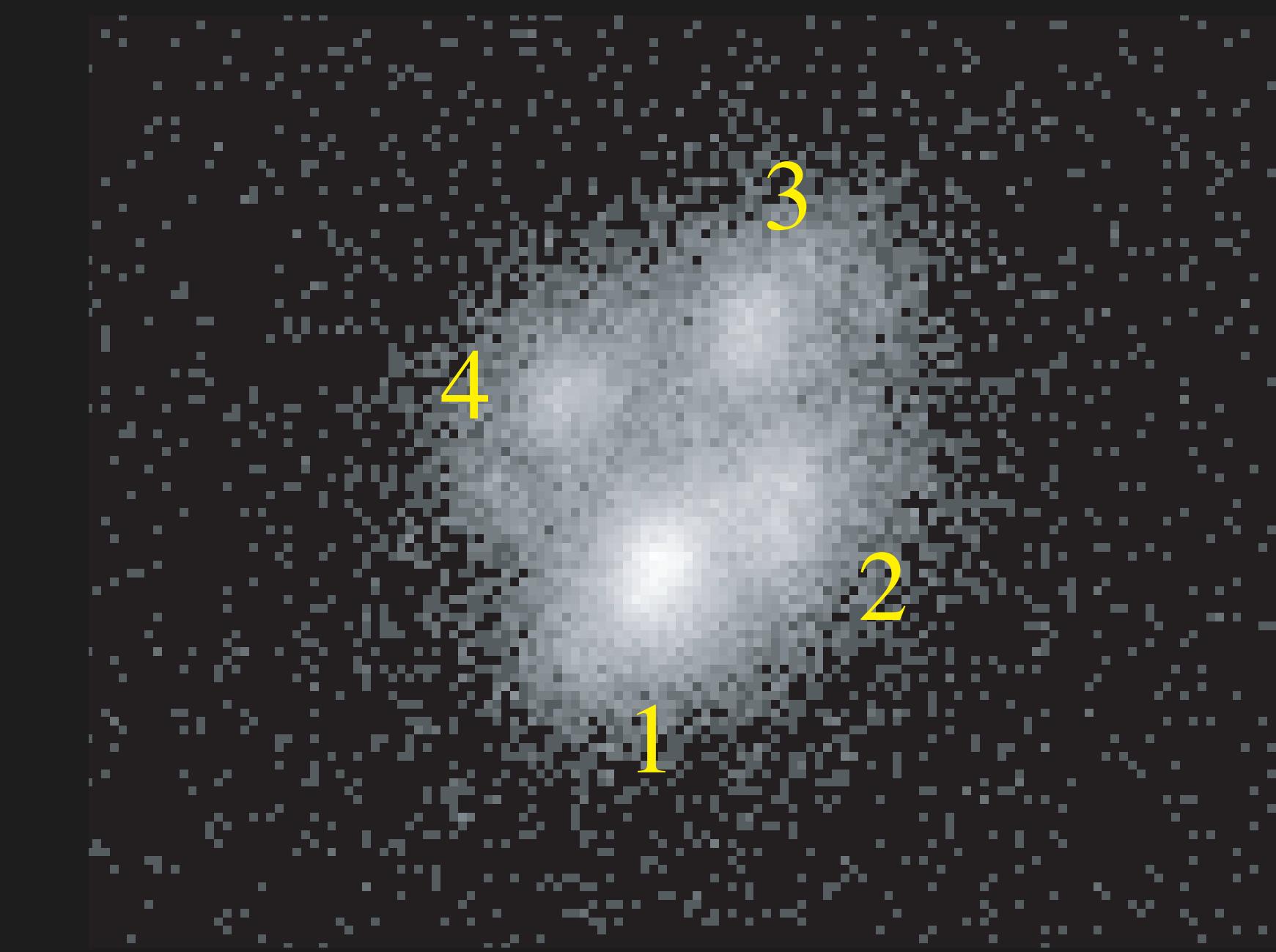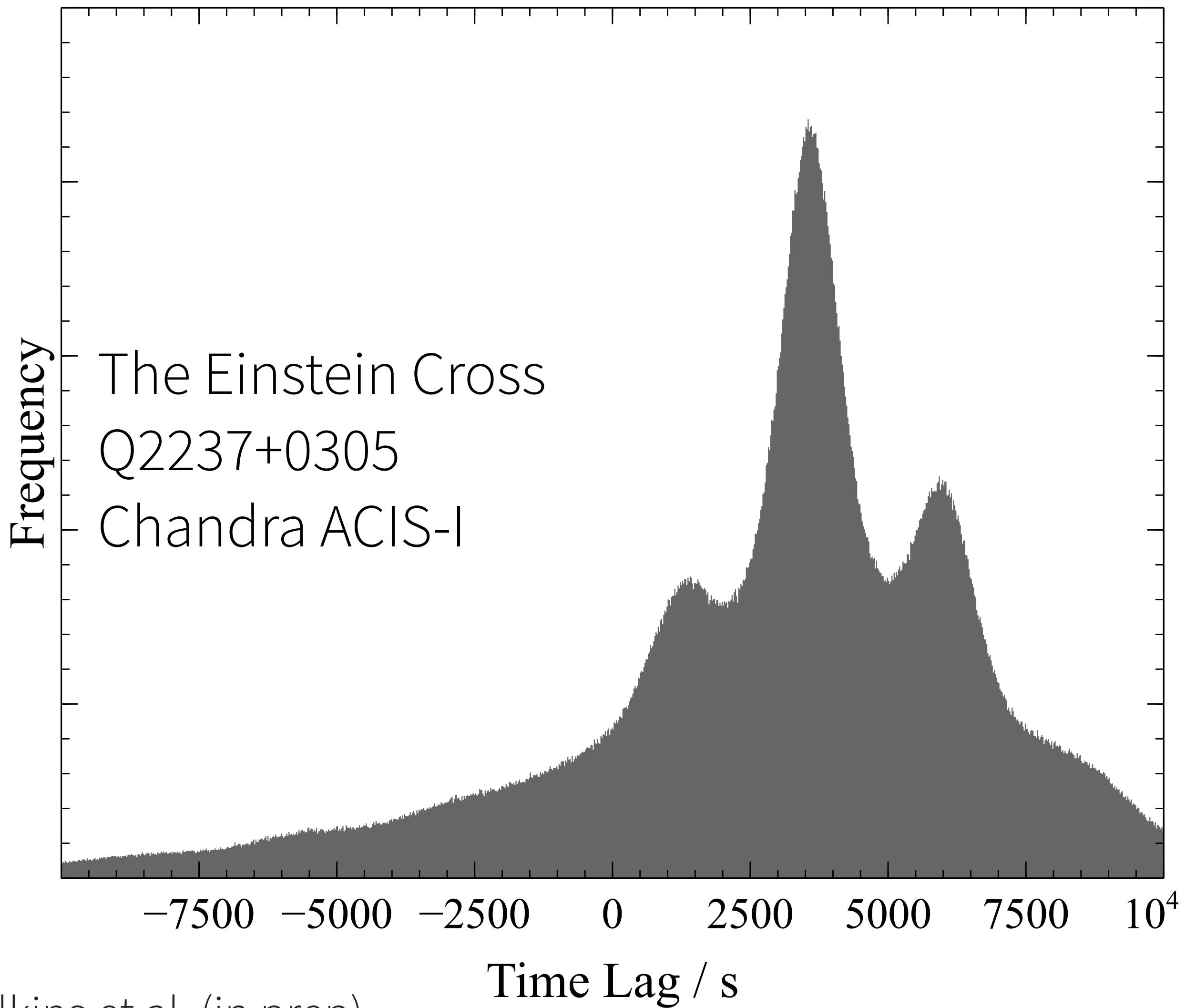
Fit time lag between continuum in image 3 and iron K in image 1

Need to account for lensing time delay between images

Simultaneously fit broadband lag between images 1 and 3

Reverberation in the Einstein Cross

Simultaneous fit to image 1 and 1/3
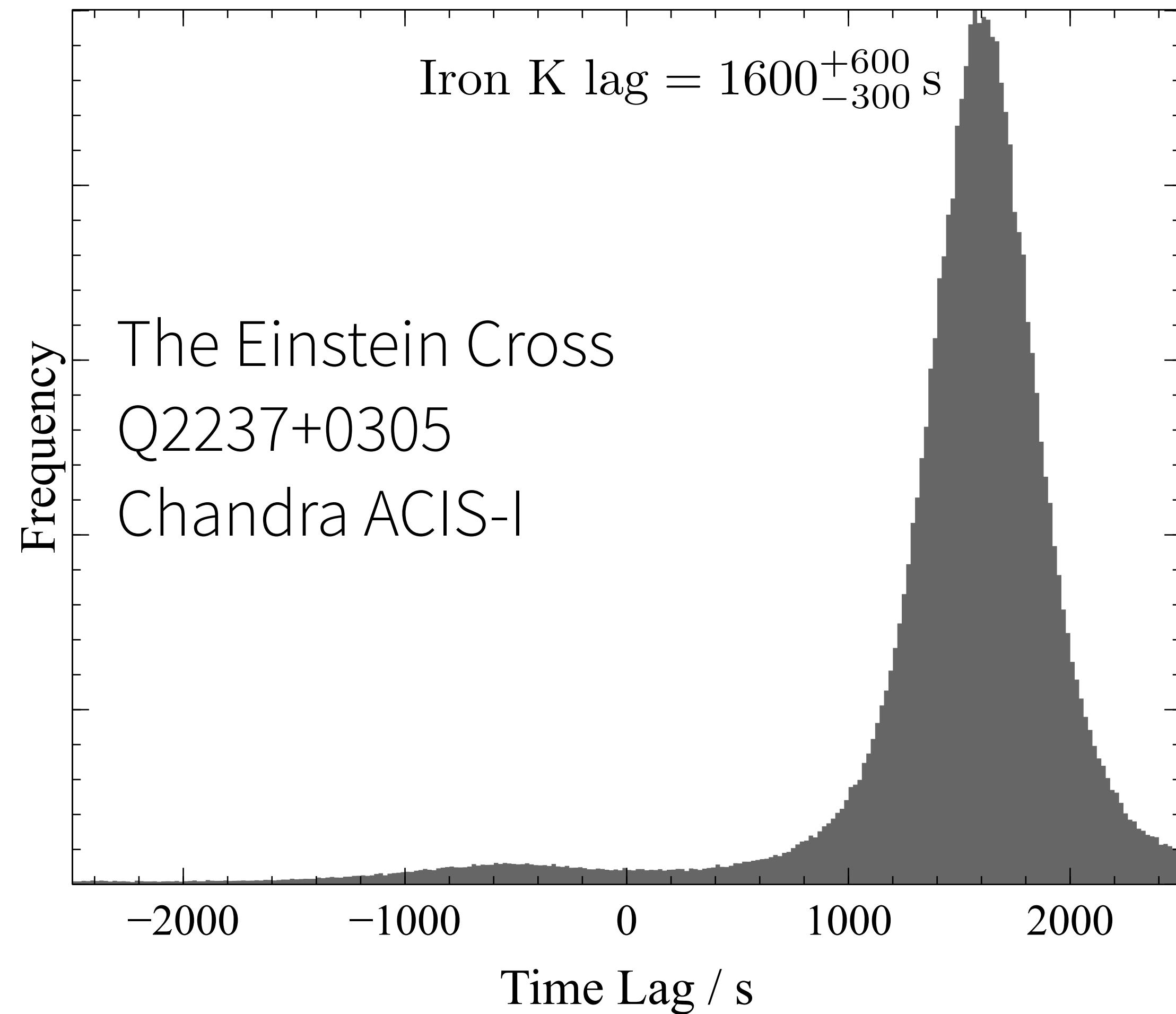
Prediction from spectral model

Iron K lag $= 1600^{+600}_{-300}$ s

The Einstein Cross
Q2237+0305
Chandra ACIS-I

Frequency (y-axis)

Time Lag / s (x-axis)

Iron K line delayed
w.r.t. continuum

FeK Band

Lag ~1500s

Continuum Band

Lag / s (y-axis)

Energy / keV (x-axis)

Wilkins et al. (in prep)

Reverberation in the Einstein Cross

Simultaneous fit to image 1 and 1/3

Iron K lag $= 1600^{+600}_{-300}$ s

The Einstein Cross
Q2237+0305
Chandra ACIS-I

Frequency

Time Lag / s
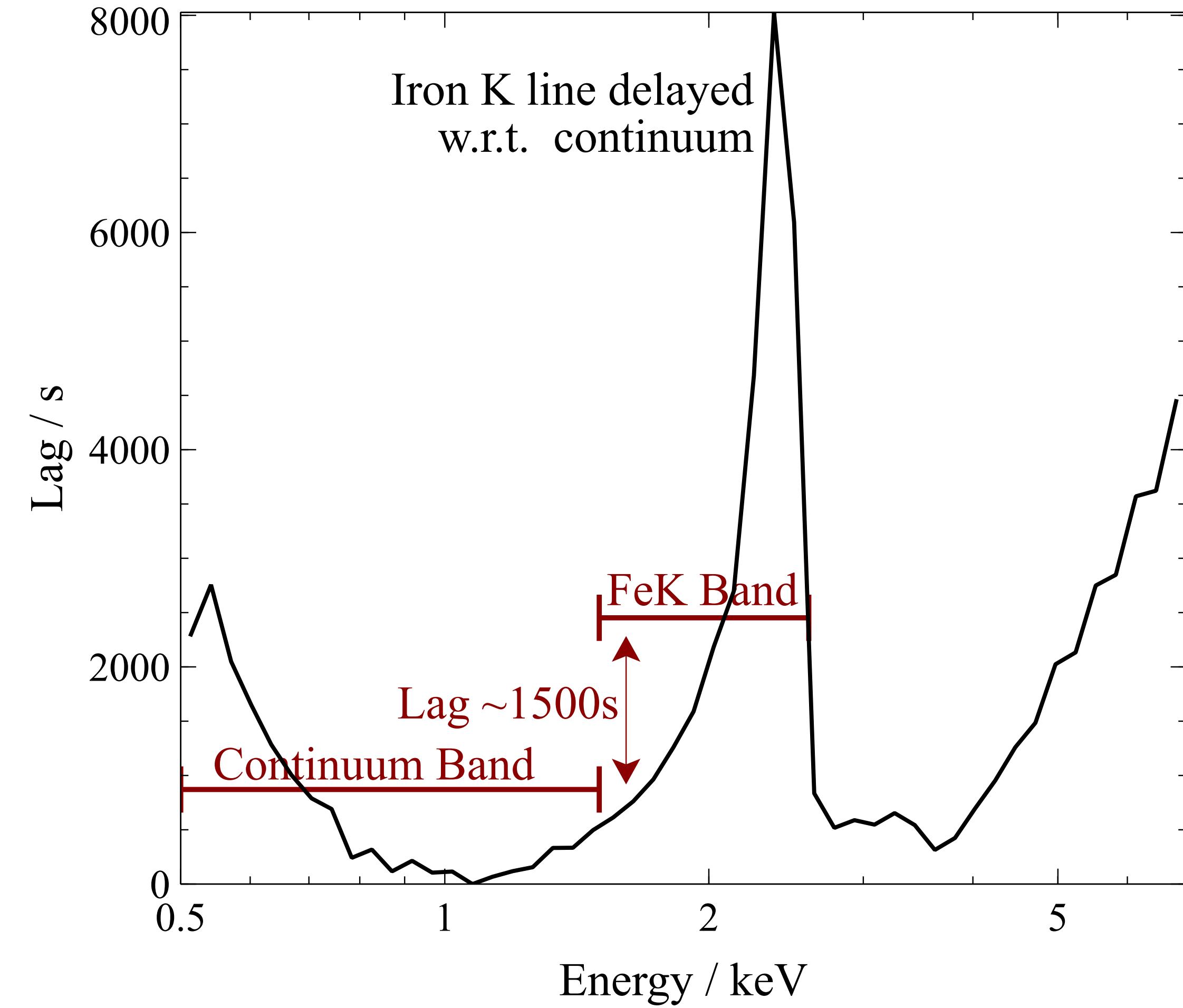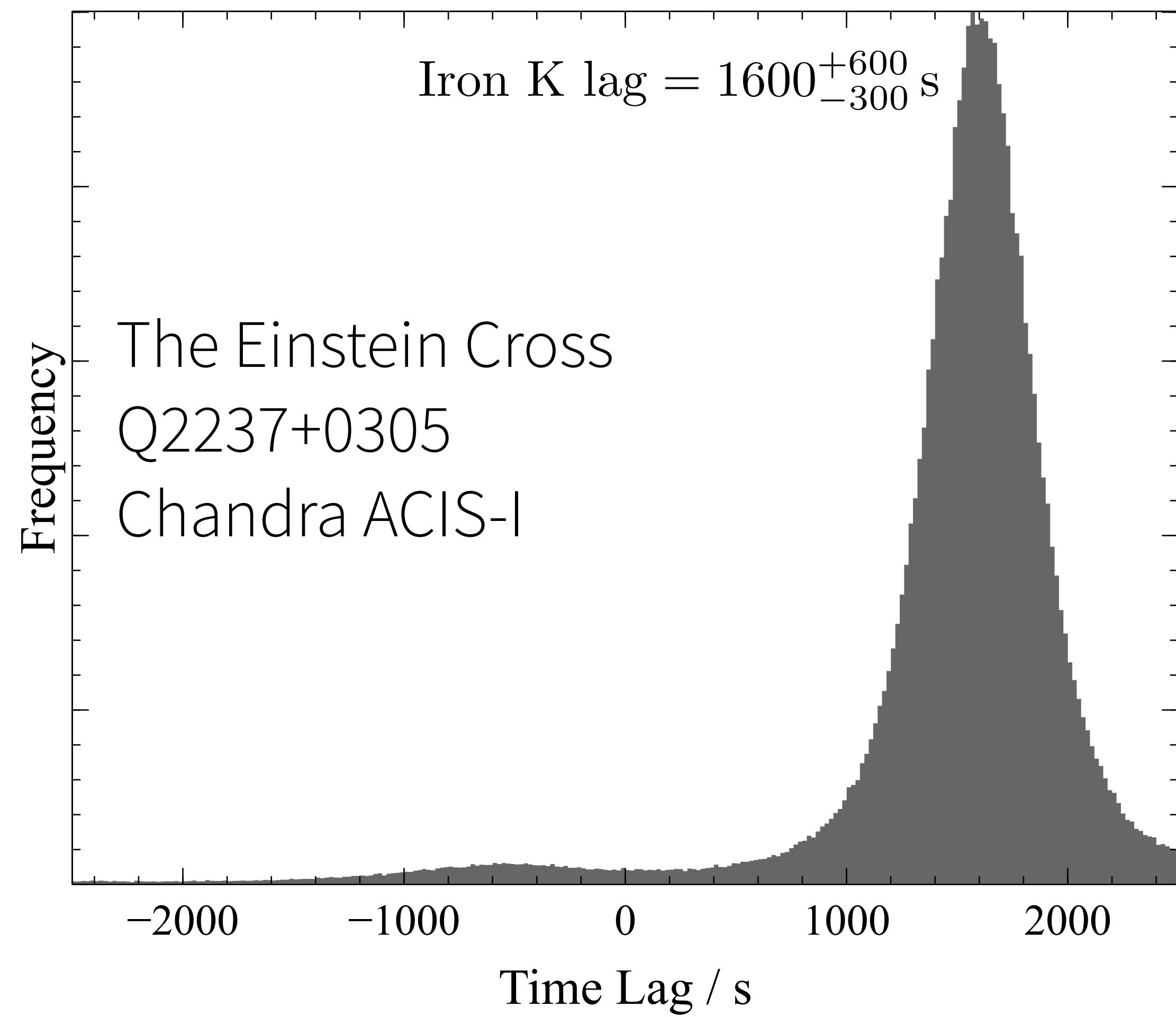
Comparison to lags in Seyfert galaxies

Iron K Lag / s

1000

100

10

9 r_g

1 r_g

Sample of Kara et al. 2016

Black Hole Mass / $M_\odot$

Wilkins et al. (in prep)
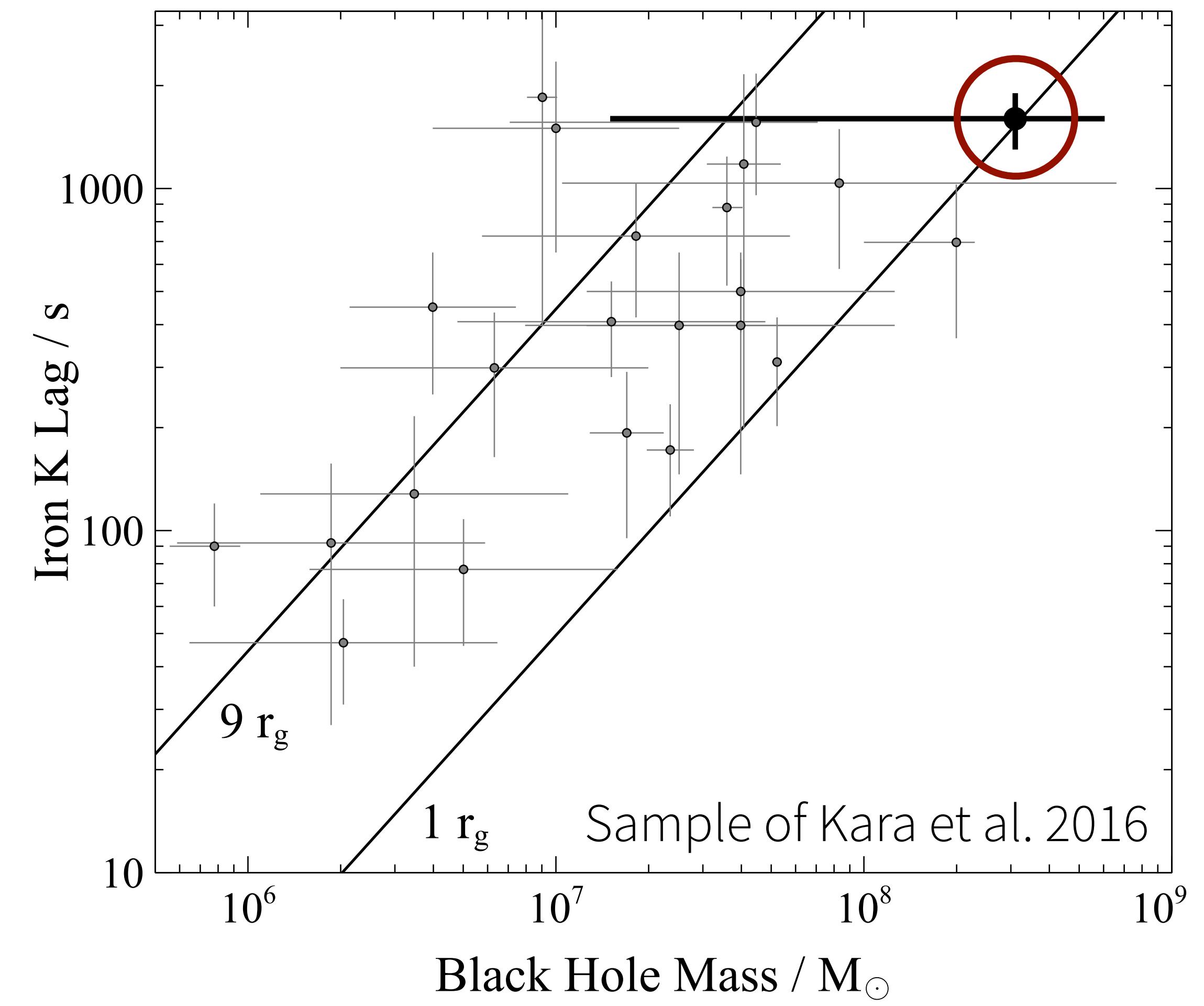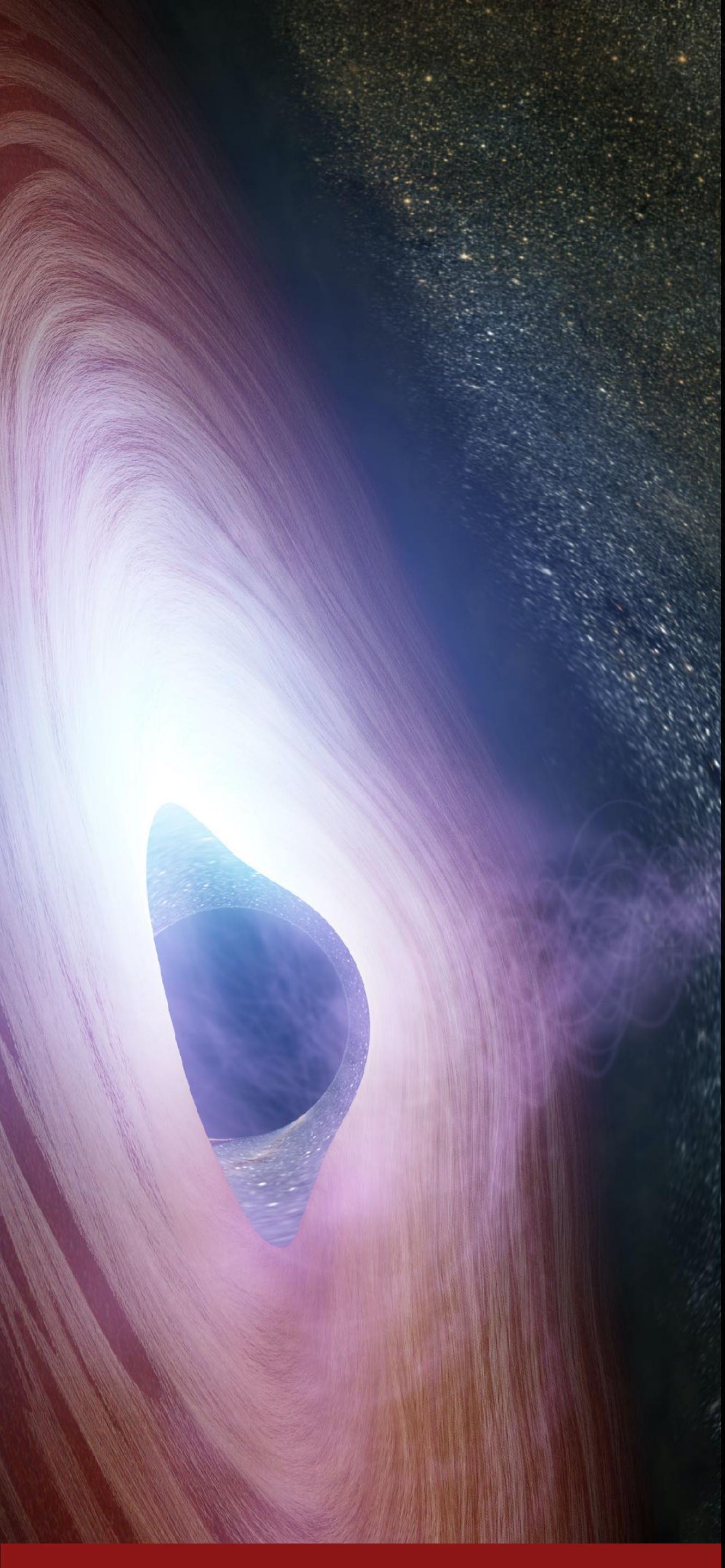
- Statistical frameworks based on Gaussian processes extend measurements of X-ray reverberation beyond Seyfert galaxies in the local Universe

- Gaussian processes probe longer reverberation time scales around high mass black holes in radio galaxies

- Obtain posterior distributions of time lags in low signal-to-noise observations of gravitationally lensed quasars

- Leverage large collecting area, high spatial resolution X-ray missions (Lynx) to probe accretion physics onto growing black holes in high(er)-z quasars