# X-ray variability in AGN

**Guglielmo (Gullo) Mastroserio**

INAF ISTITUTO NAZIONALE DI ASTROFISICA

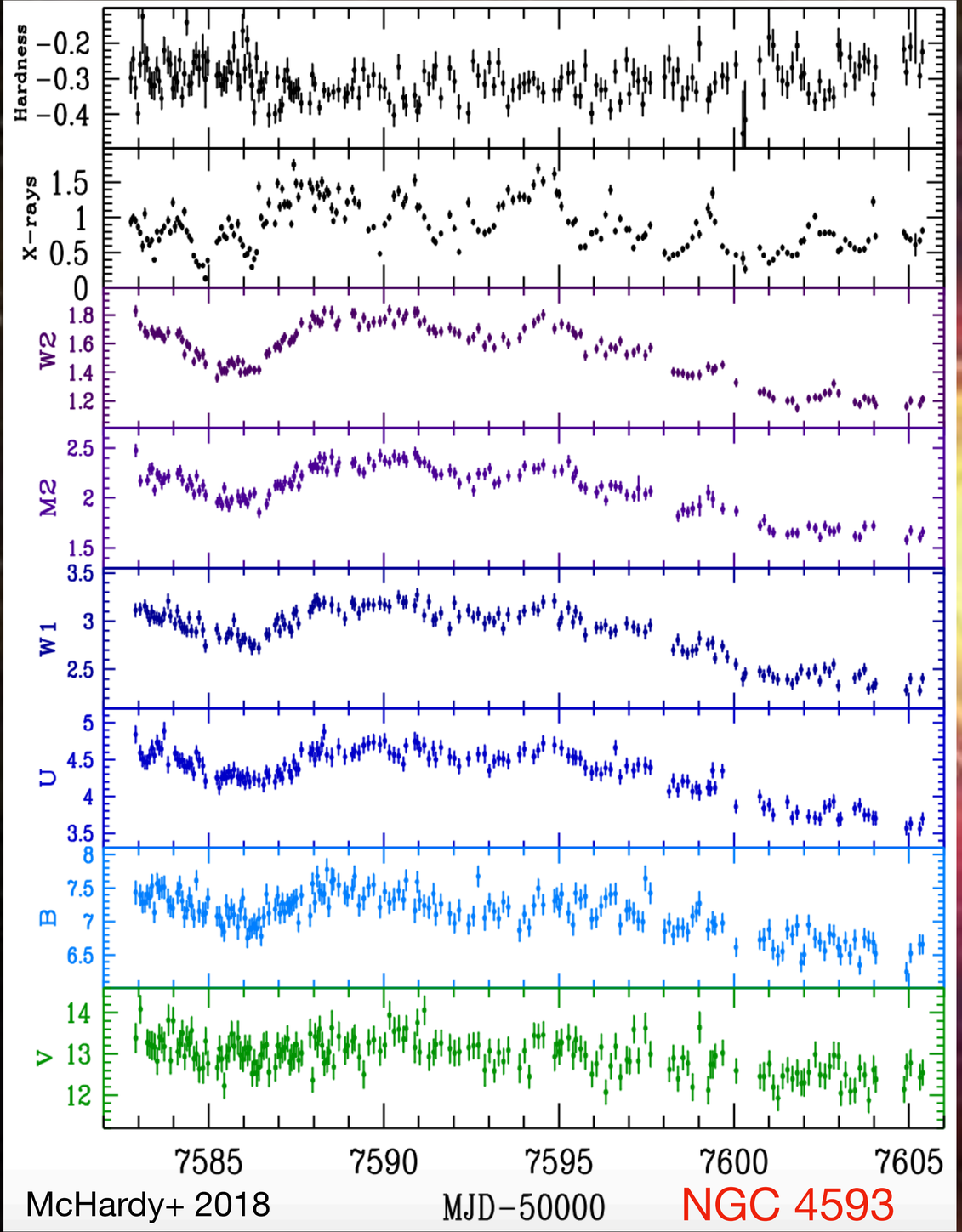
SpecTemPolar

OAC

# X-ray variability: why?

# X-ray variability: why?

We can measure properties of the innermost region of AGN systems: such as coronal geometry and BH mass




# X-ray variability in AGN

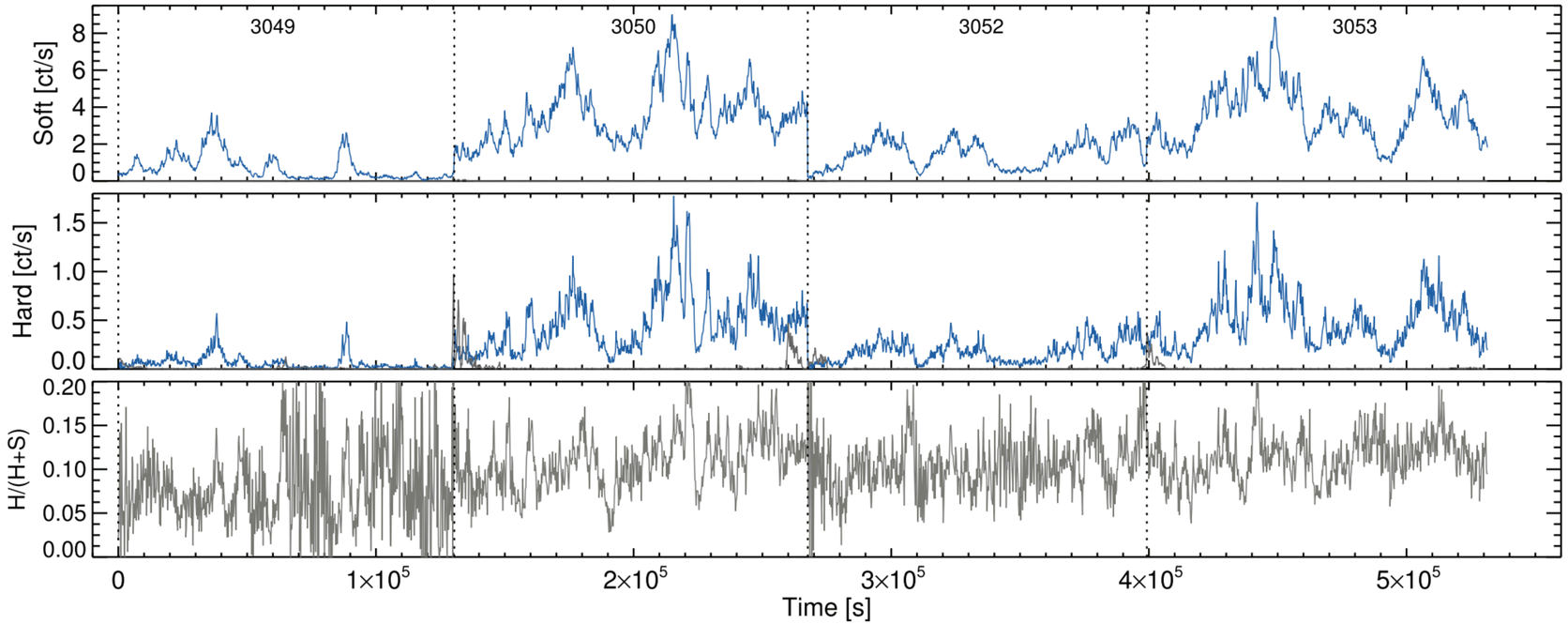
# AGN X-ray variability

It is a feature that characterise accreting systems!
Important to study the phenomenology

It is a great tool to understand accretion: coronal geometry, nature of the absorber, BH mass

# Stocastic variability vs transient events

IRAS 13224-3809




Alston+ 2019

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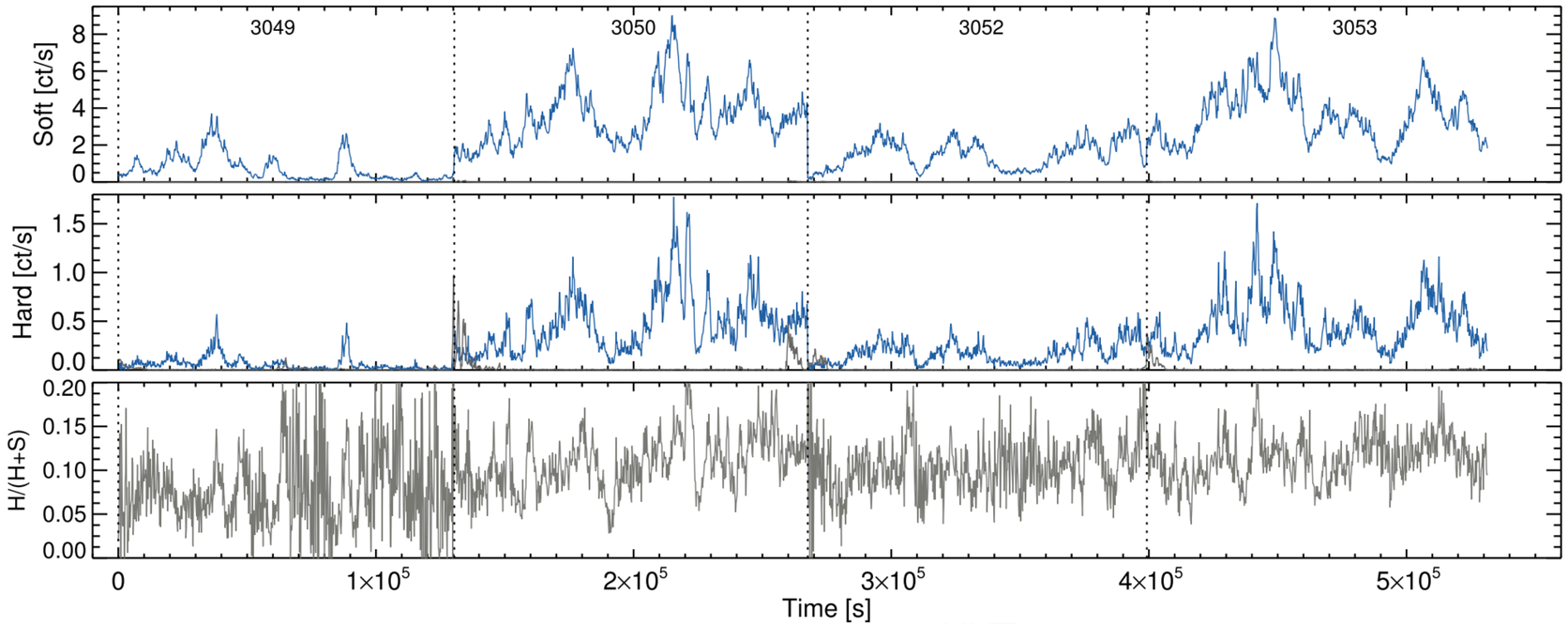
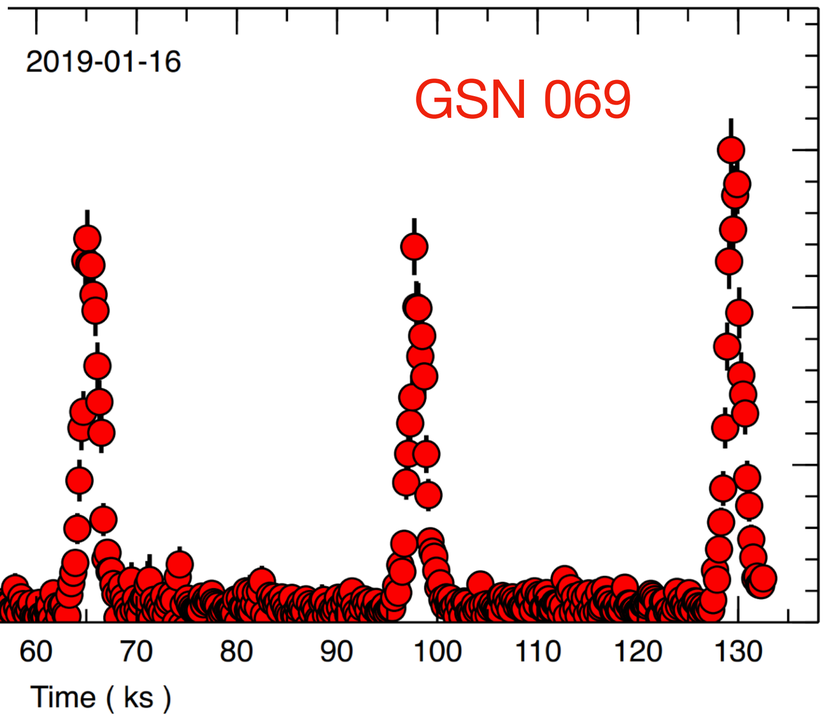



Alston+ 2019

Miniutti+ 2019



# The restless nature of AGNs:
## variability as a probe of the central engine

Naples, Italy, 20-23 May 2013

# Have we understood X-ray variability?

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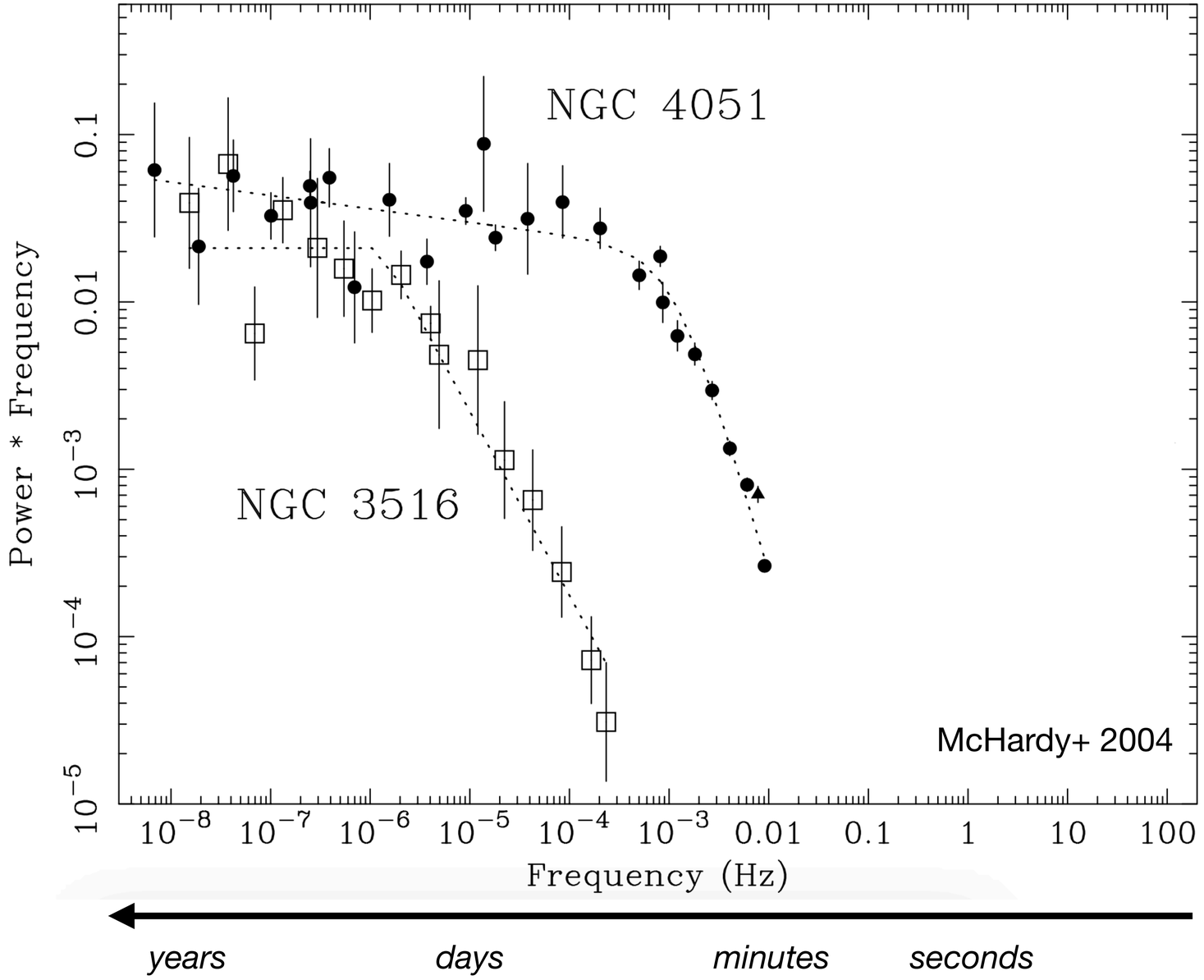
Not really…

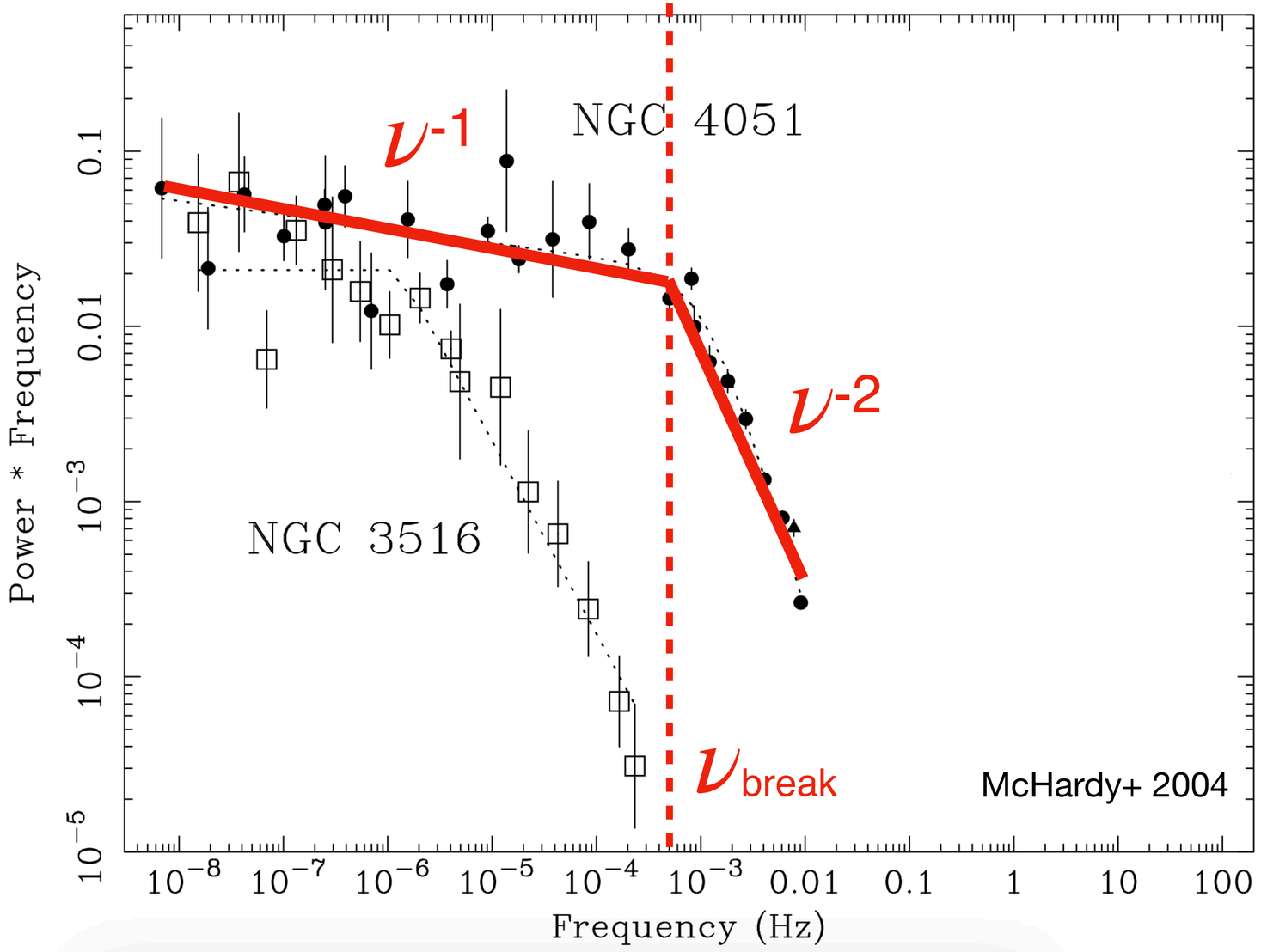
# X-ray variability phenomenology

# Phenomenology: power density spectrum




Power spectrum: distribution of variability power over frequencies (timescale-1)

# Phenomenology: power density spectrum




years days minutes seconds

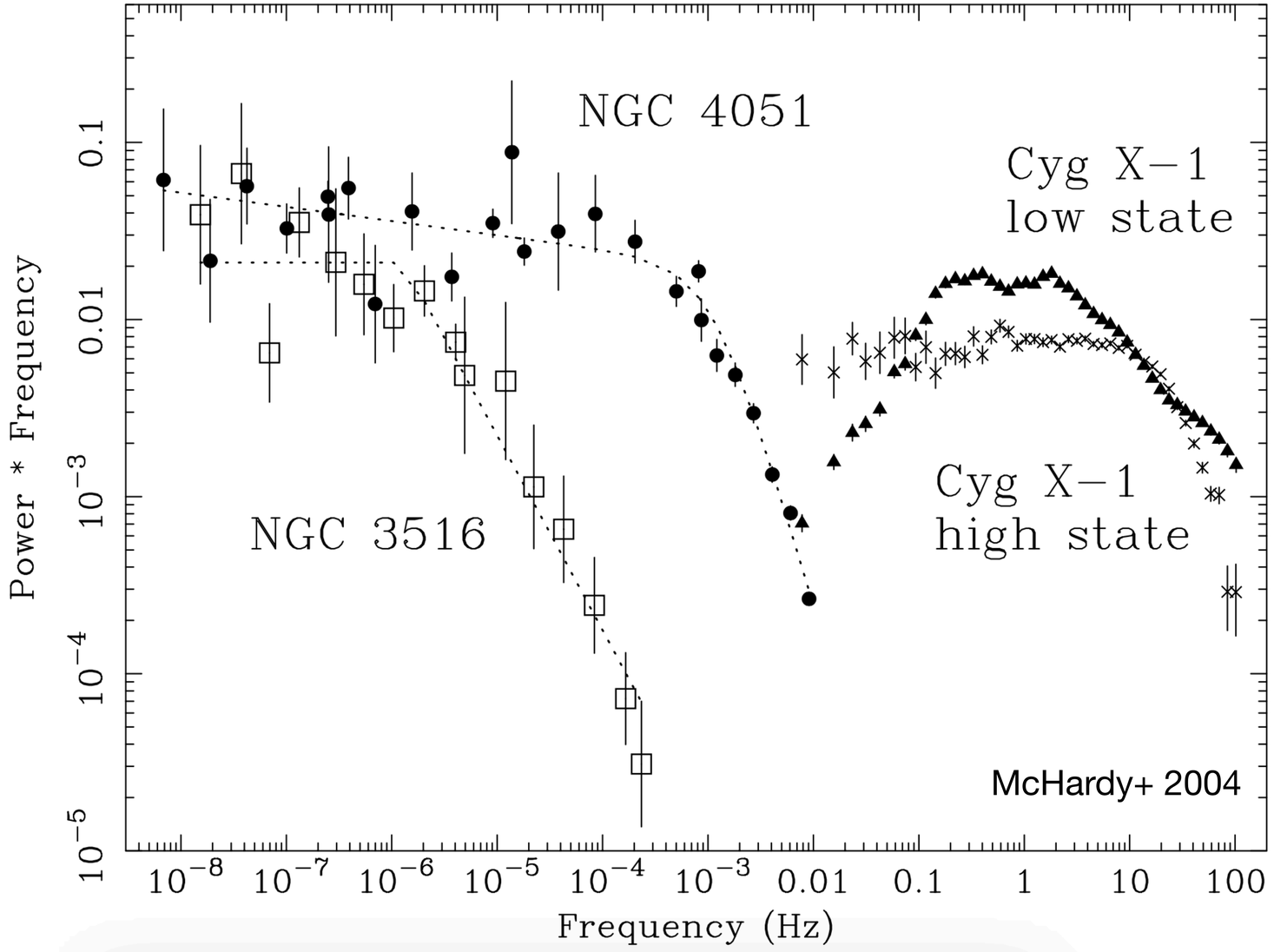
Power spectrum: distribution of variability power over frequencies (timescale-1)

Red noise: power is increasing at lower frequency faster than $\nu$-1

Most of the time power spectra show a characteristic frequency break

PDS with break frequency
Edelson & Nandra 1999; Uttley+ 2002; Markowitz+ 2002
See also see also e.g. Edelson & Nandra 1999; Gonzalez-Martin & Vaughan 2012; Uttley+ 2012, and others that I missed, sorry…

# Phenomenology: power density spectrum




*years* *days* *minutes* *seconds*

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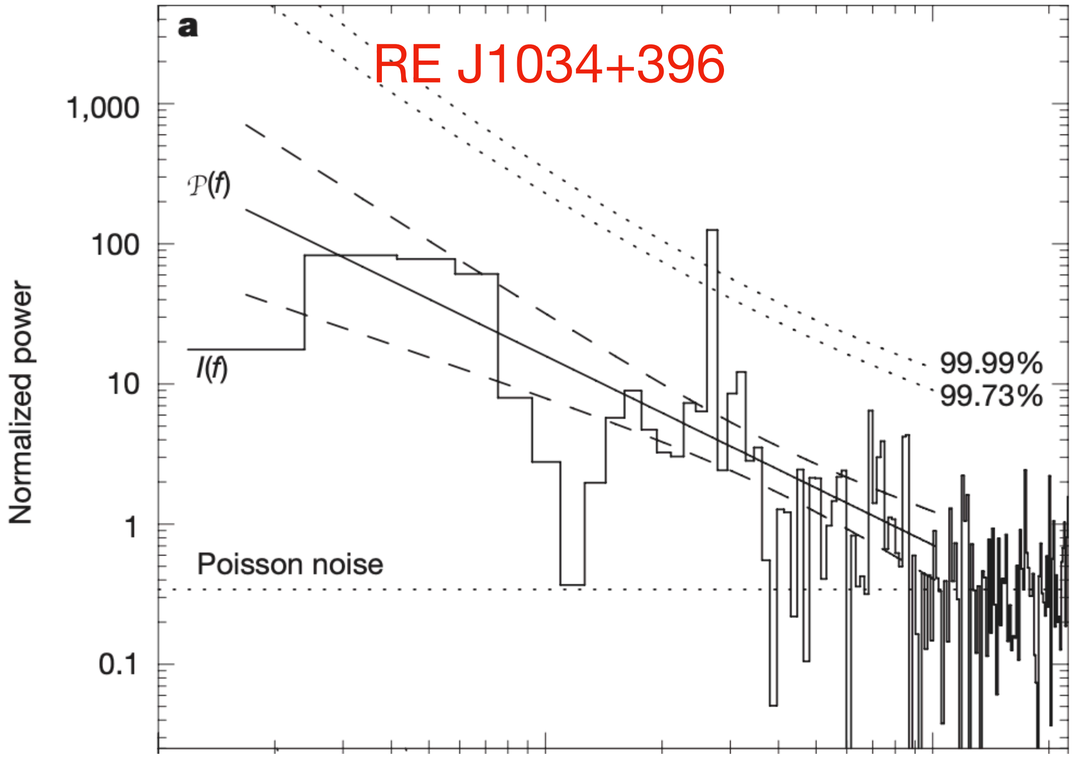
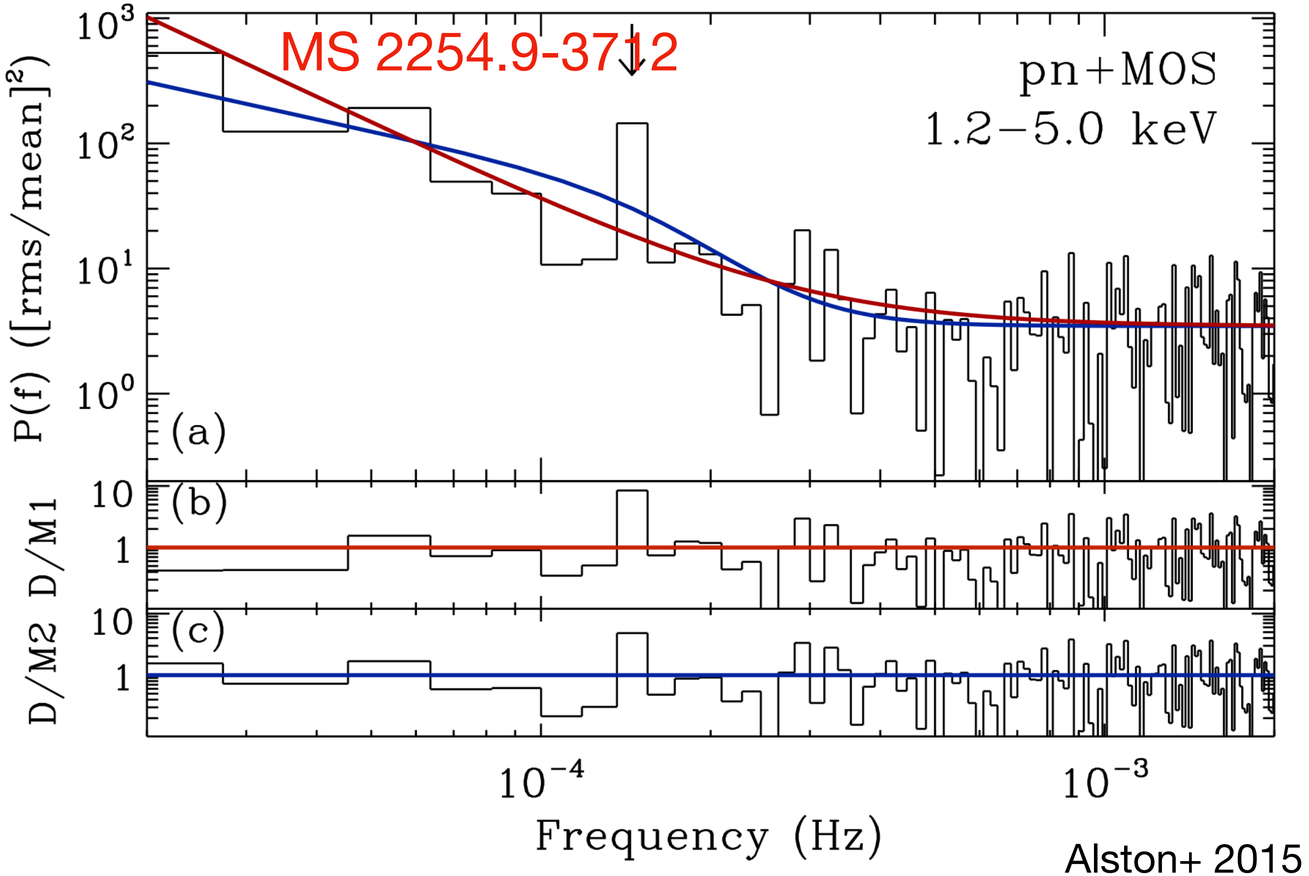
# Phenomenology: quasi periodic oscillations (QPOs)



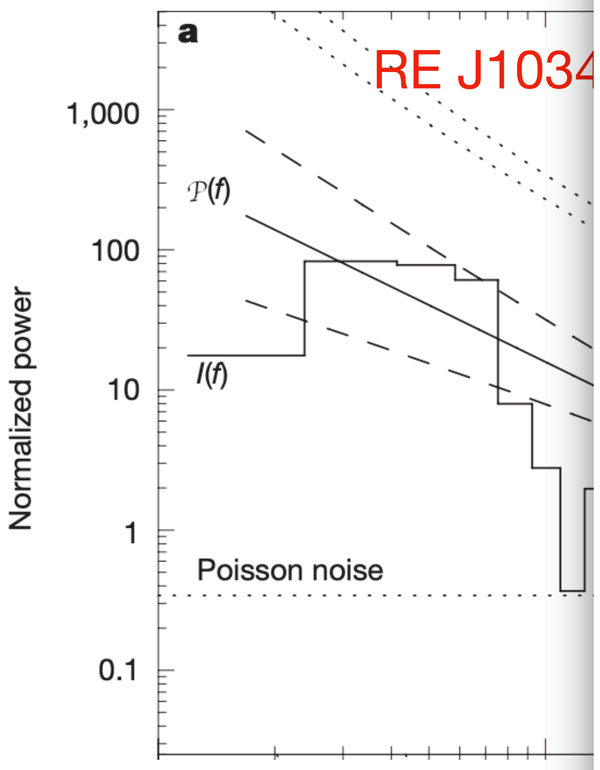

Gierlinski+ 2008




Alston+ 2015

Also in 1H 0707-495, MRK 766, IRAS 13224-3809 and ARK 564
(McHardy+ 2007; Pan+ 2016; Zhang+ 2017, Zhang+ 2018; Alston+ 2019)

# Phenomenology: quasi periodic oscillations (QPOs)

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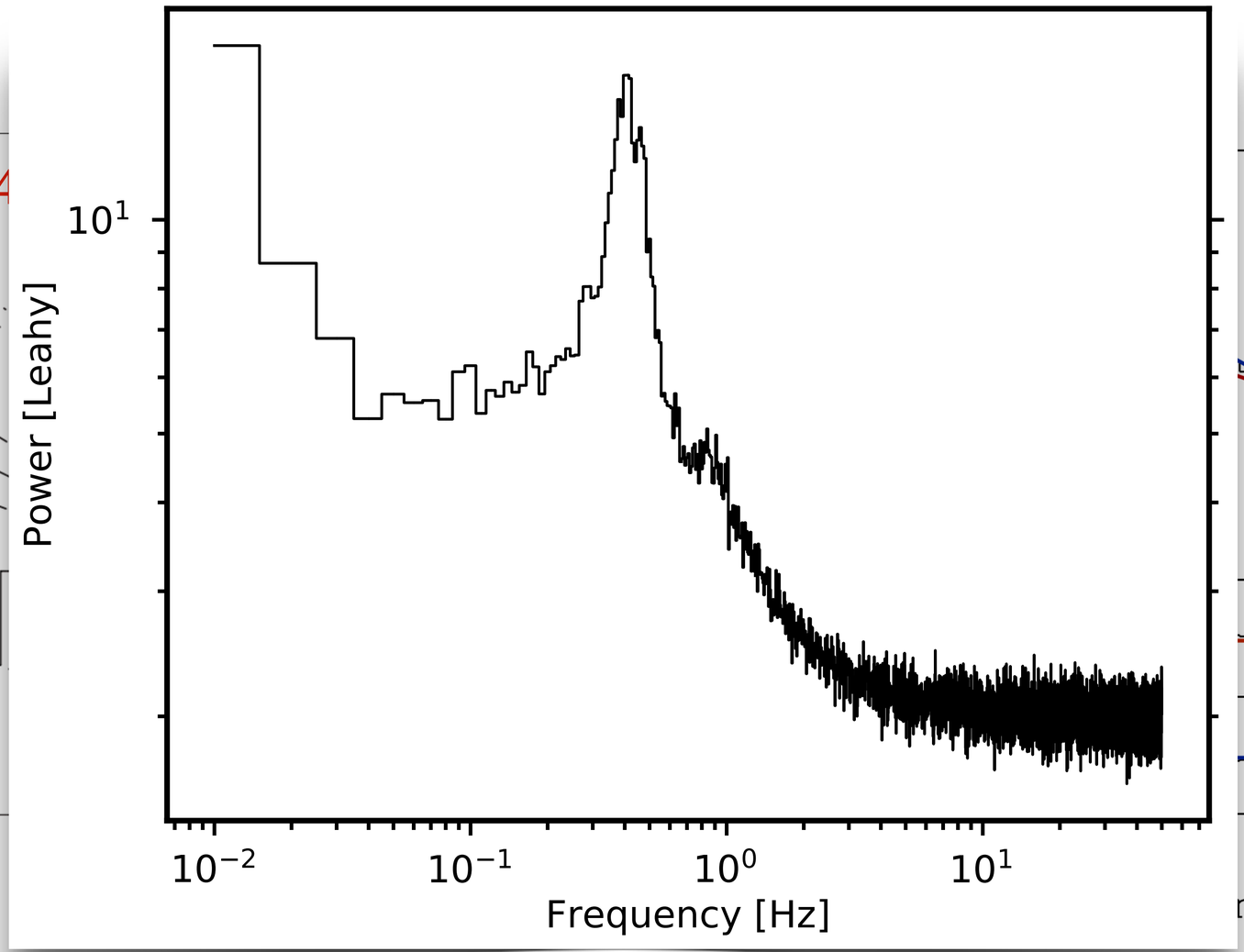


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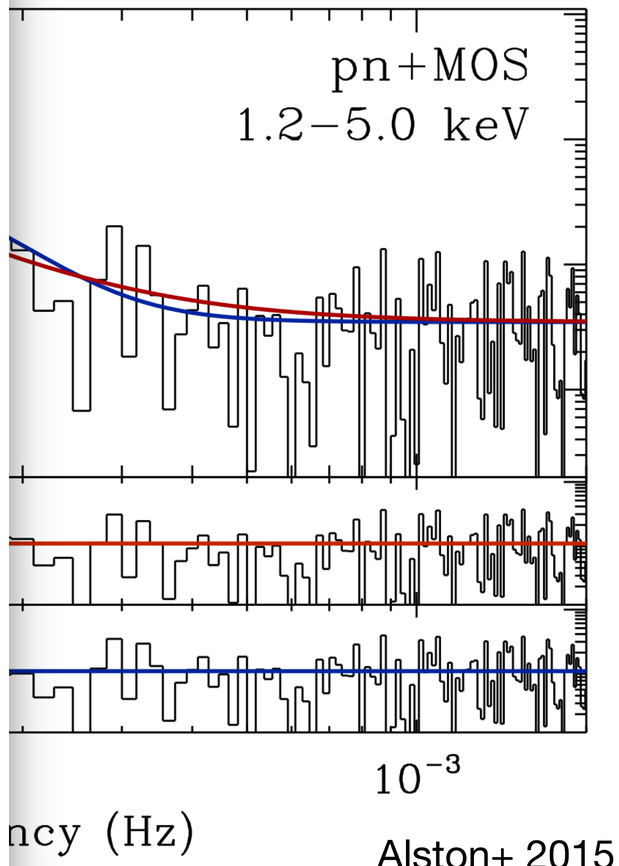


Alston+ 2015

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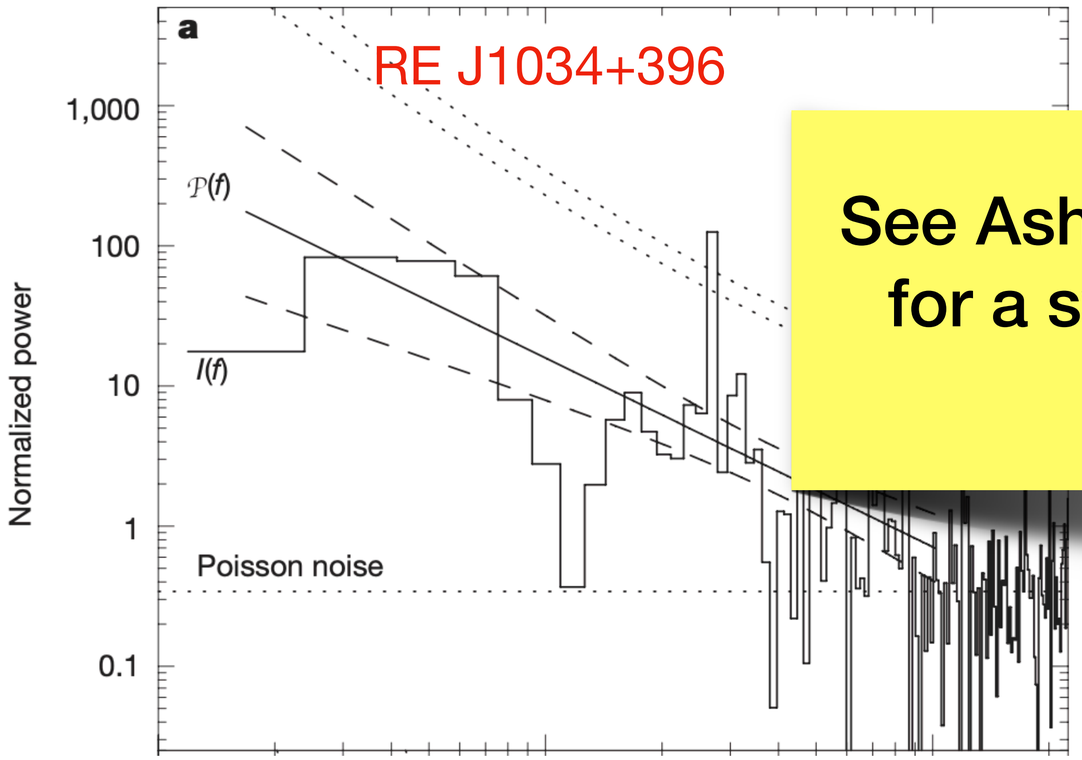
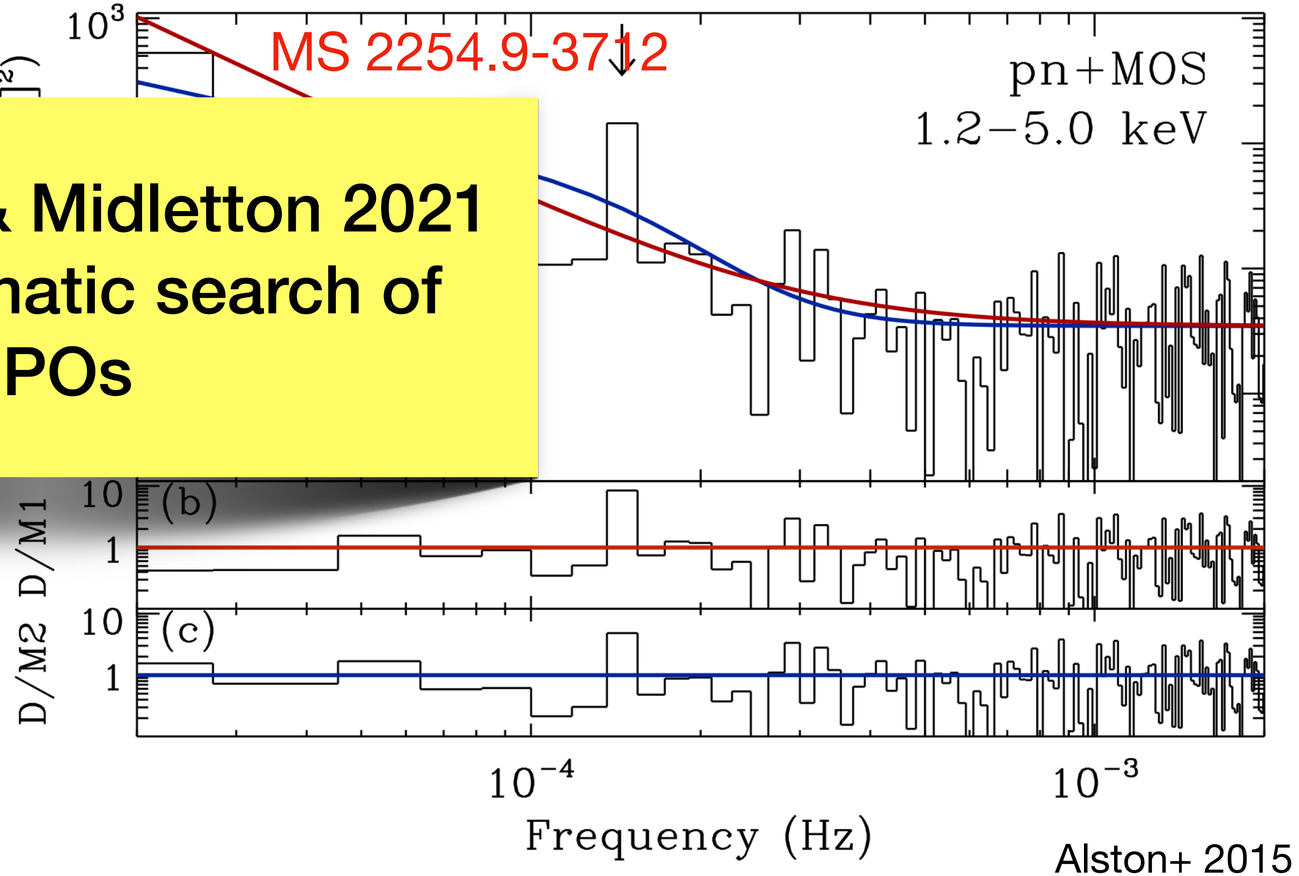



Gierlinski+ 2008

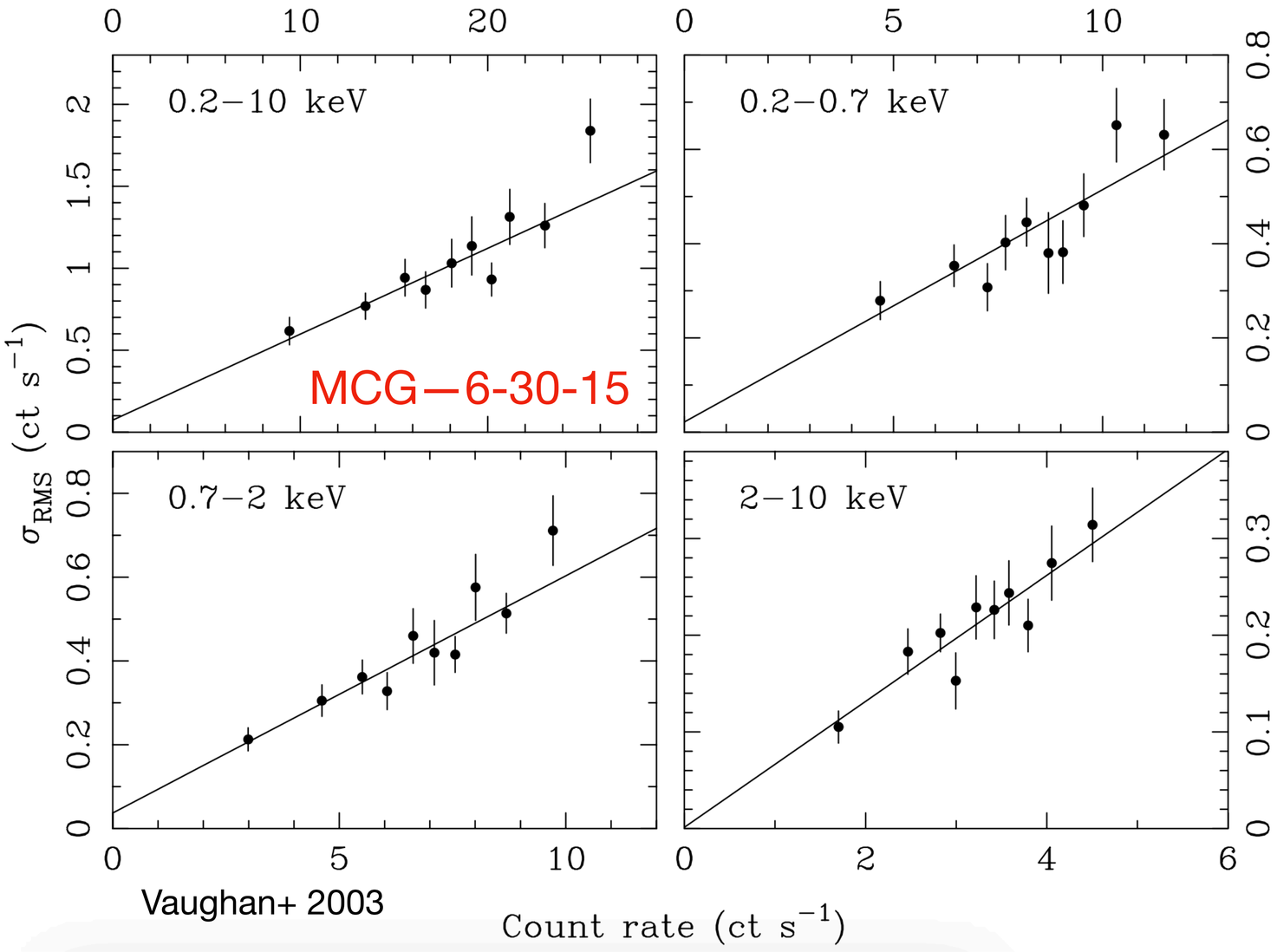



Alston+ 2015

**See Ashton & Midletton 2021 for a systematic search of QPOs**

Also in 1H 0707-495, MRK 766, IRAS 13224-3809 and ARK 564
(McHardy+ 2007; Pan+ 2016; Zhang+ 2017, Zhang+ 2018; Alston+ 2019)

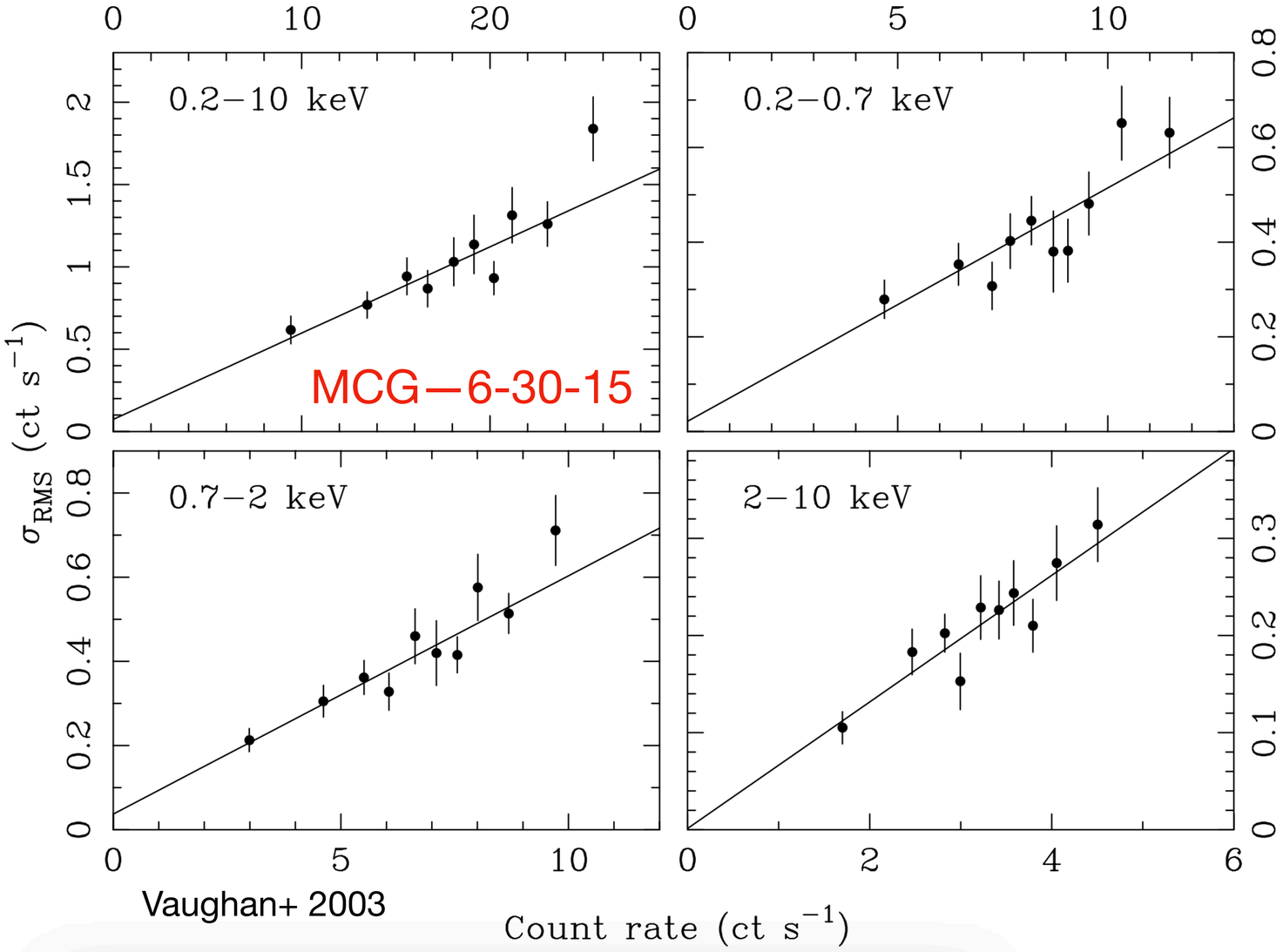
# Phenomenology: linear RMS-flux relation



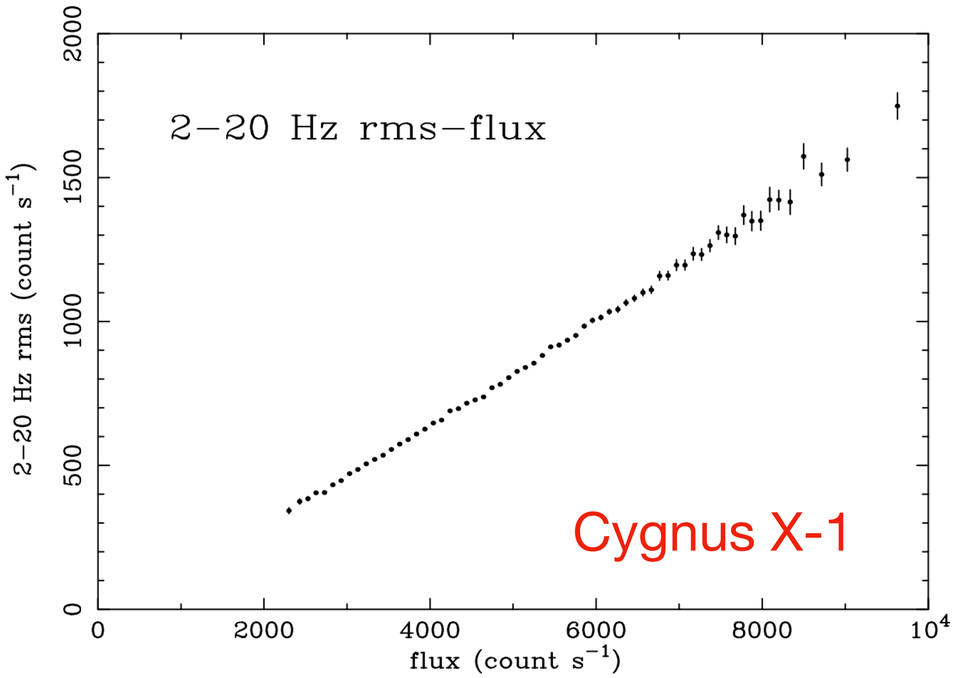

Vaughan+ 2003

See also e.g. Uttley & McHardy+2001; Vaughan+ 2003; McHardy+ 2004; Gleissner+ 2004; Uttley+ 2005; Heil+2012, and others…

# Phenomenology: linear RMS-flux relation



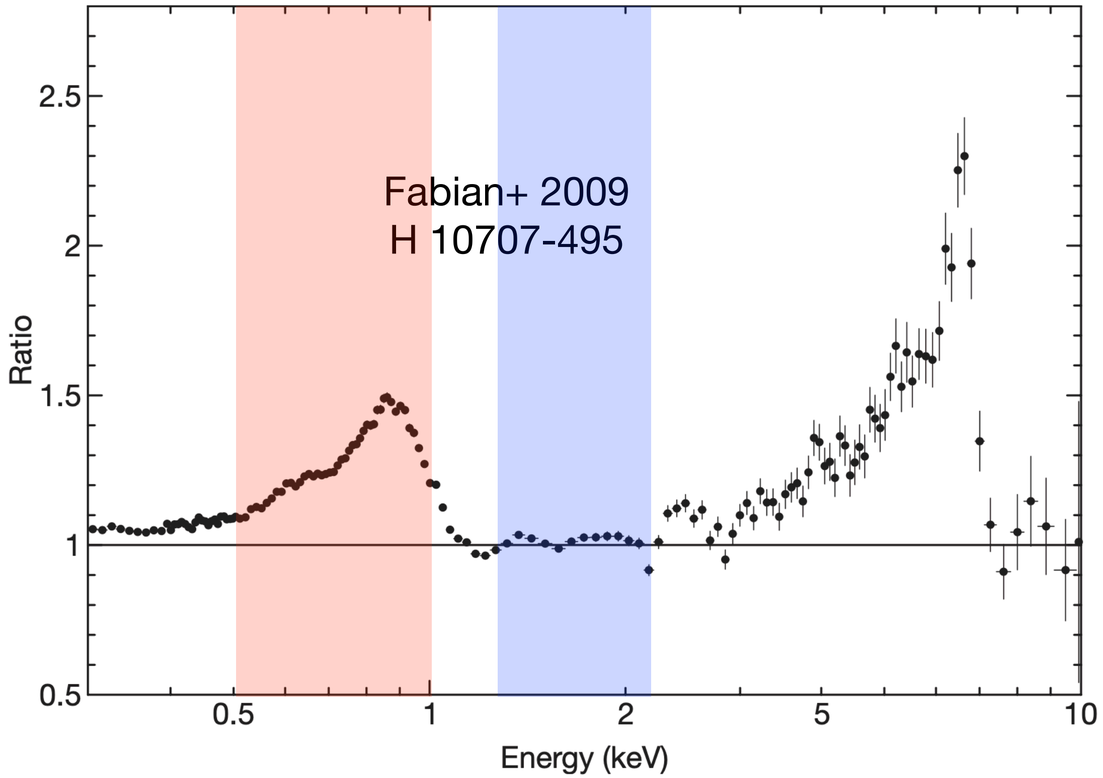

Vaughan+ 2003



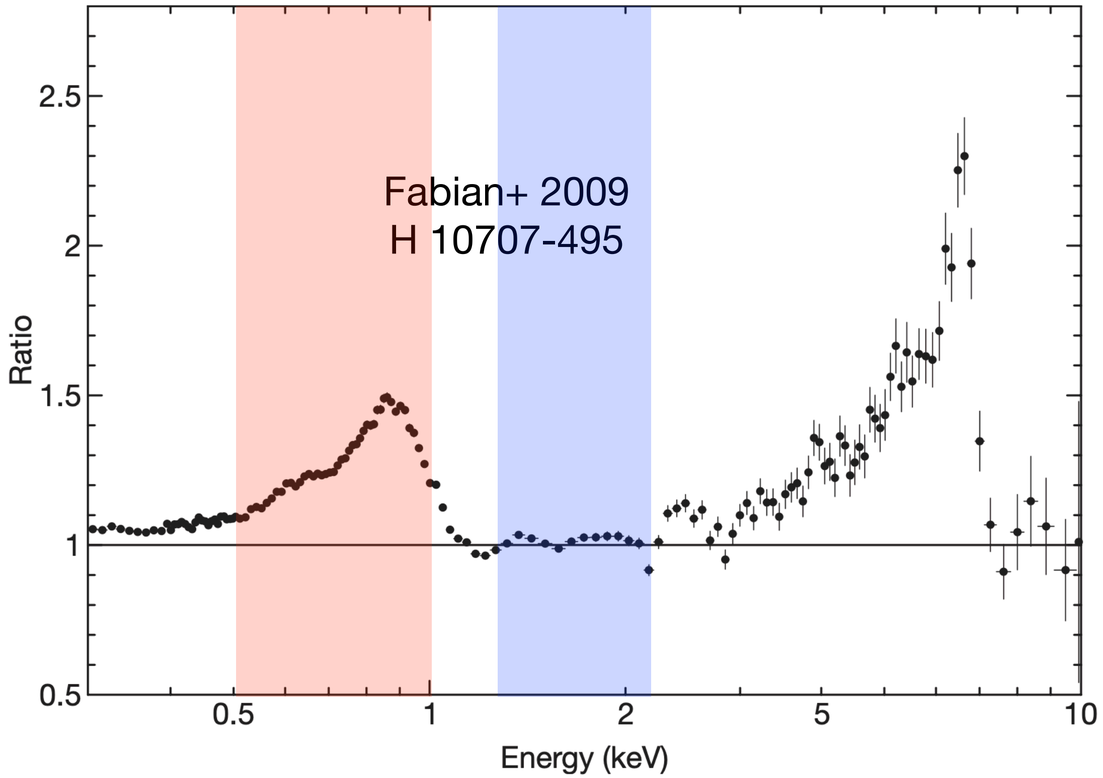

Uttley+ 2005

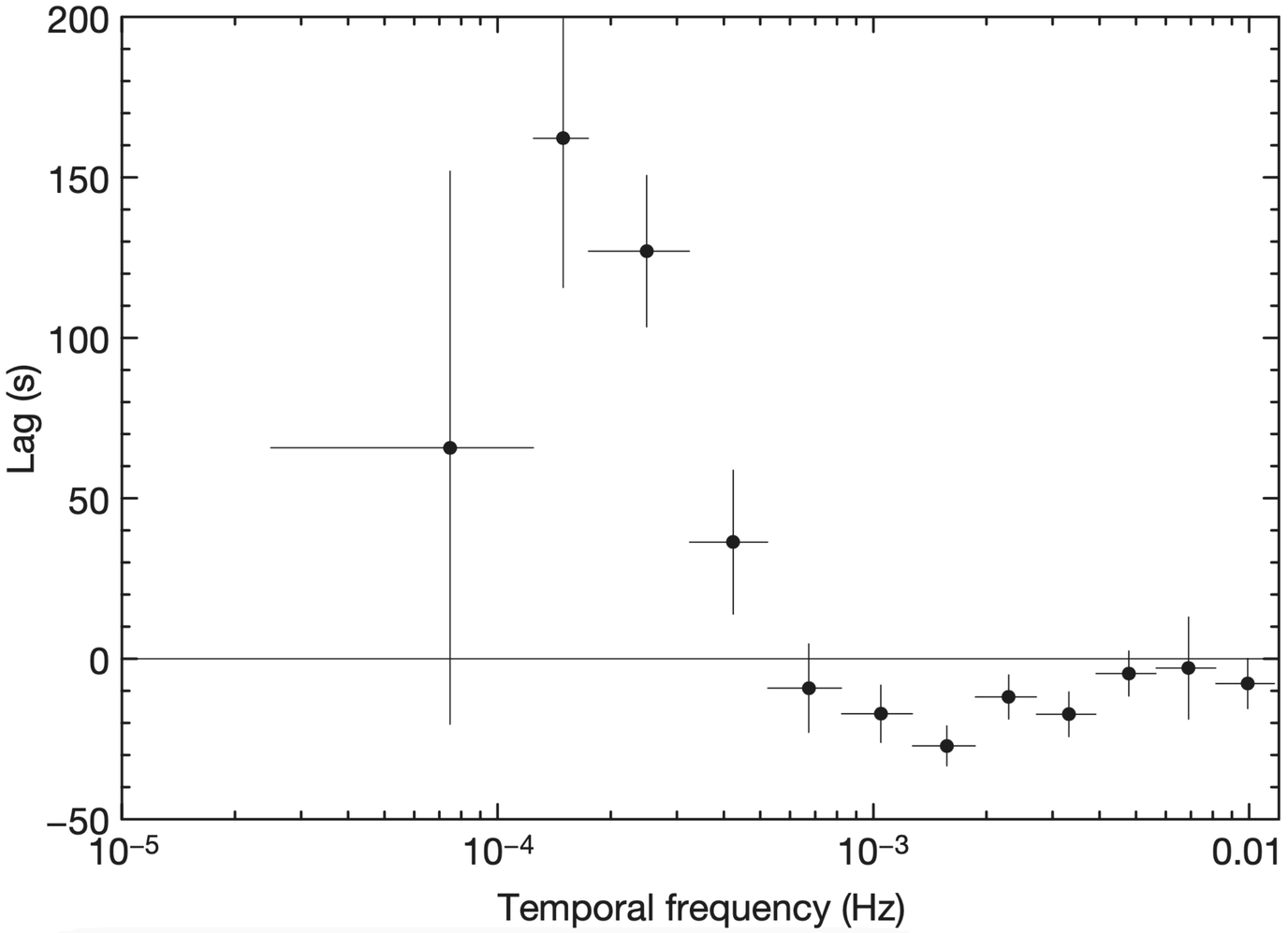
but see Alston+ 2019 for the first detection of a non-linear rms-flux relation in IRAS 13224–3809

# Phenomenology: lags



# Phenomenology: soft lags



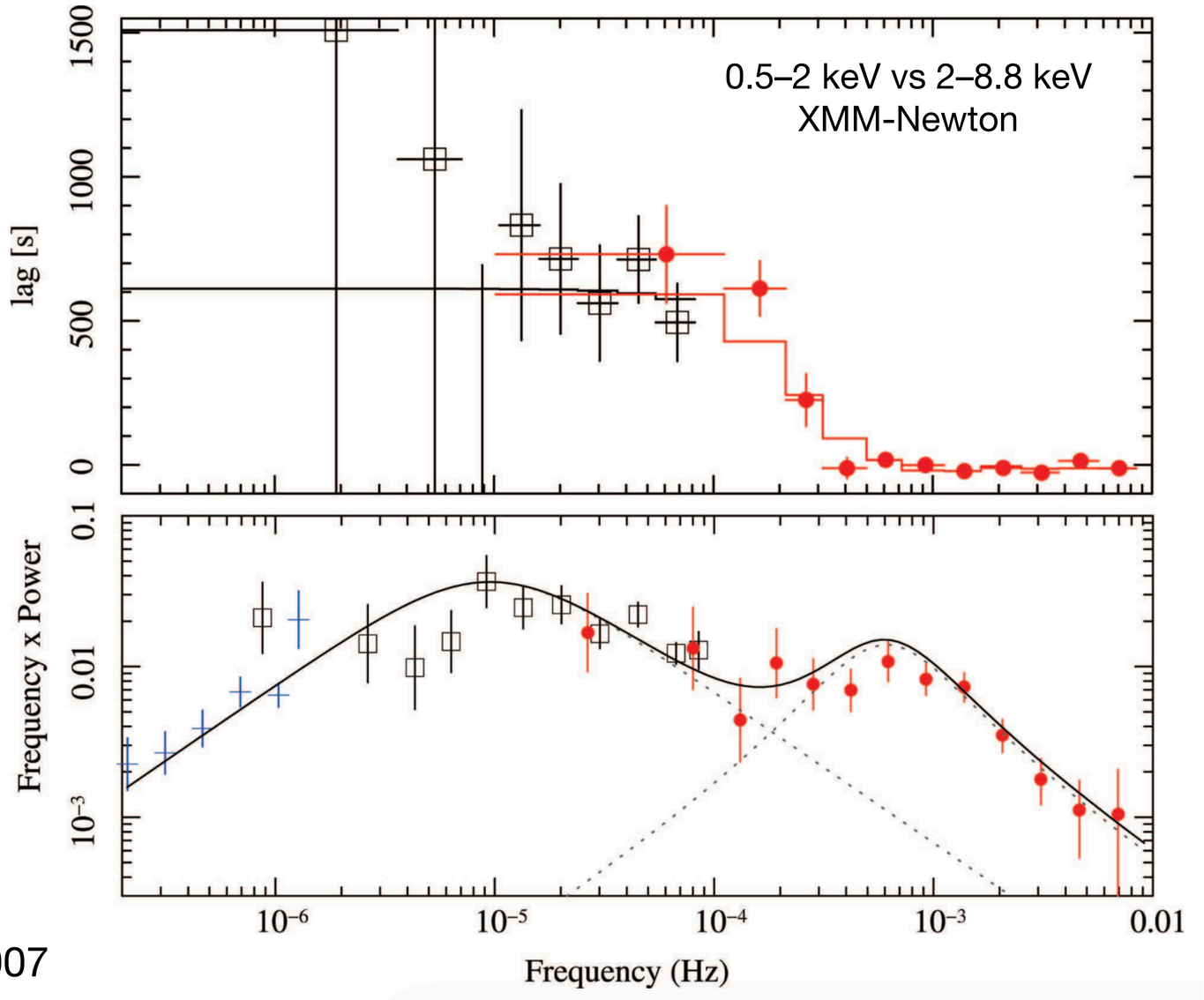




OTHER SOFT LAGS

Emmanoulopoulos, McHardy & Papadakis 2011 in MCG–6-30-15 and Mrk 766

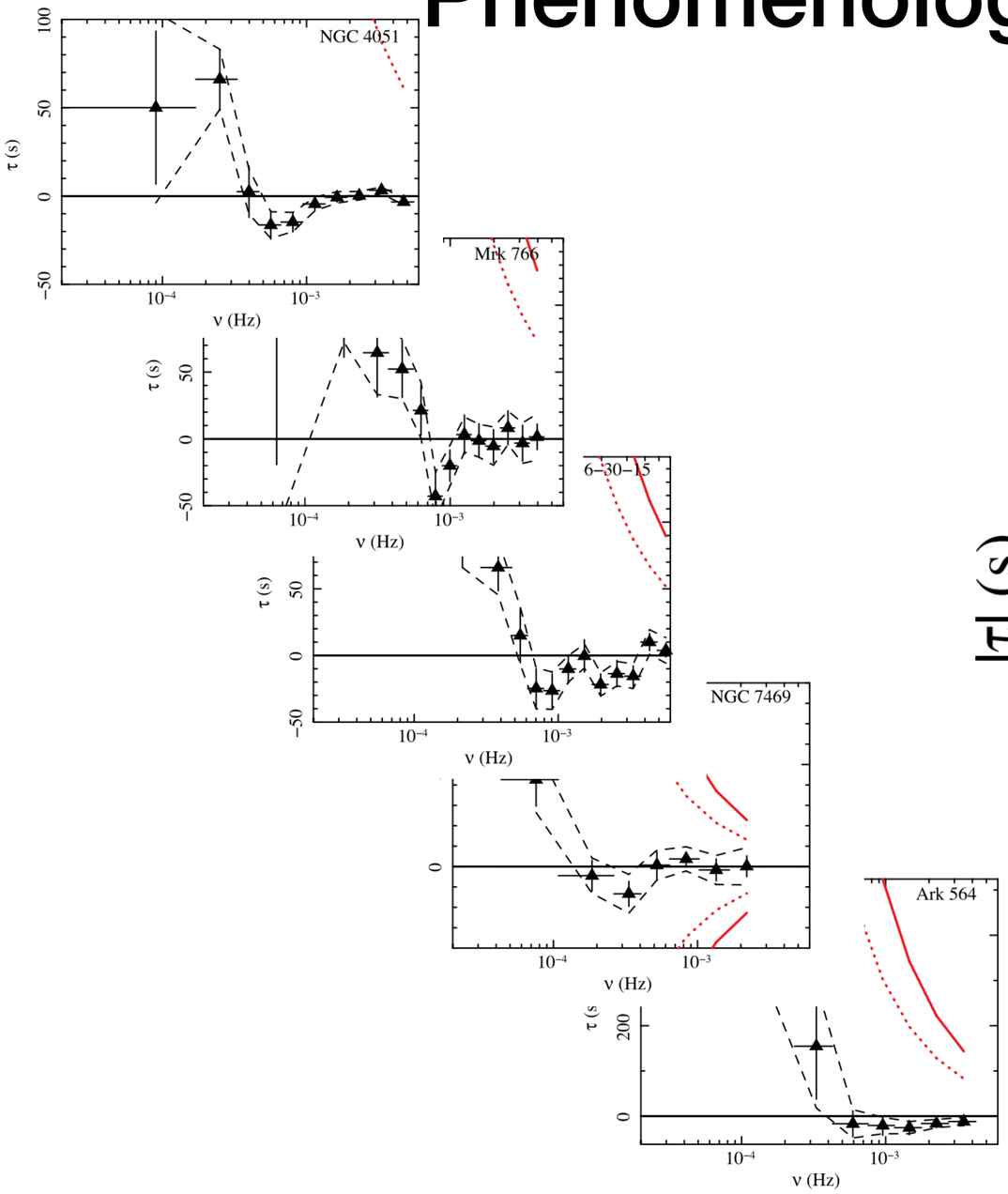
Zoghbi et al. 2011 In RE J1034+396; Cackett et al. 2013 in ESO 113–G010; Alston et al. 2014 PG 1244+026

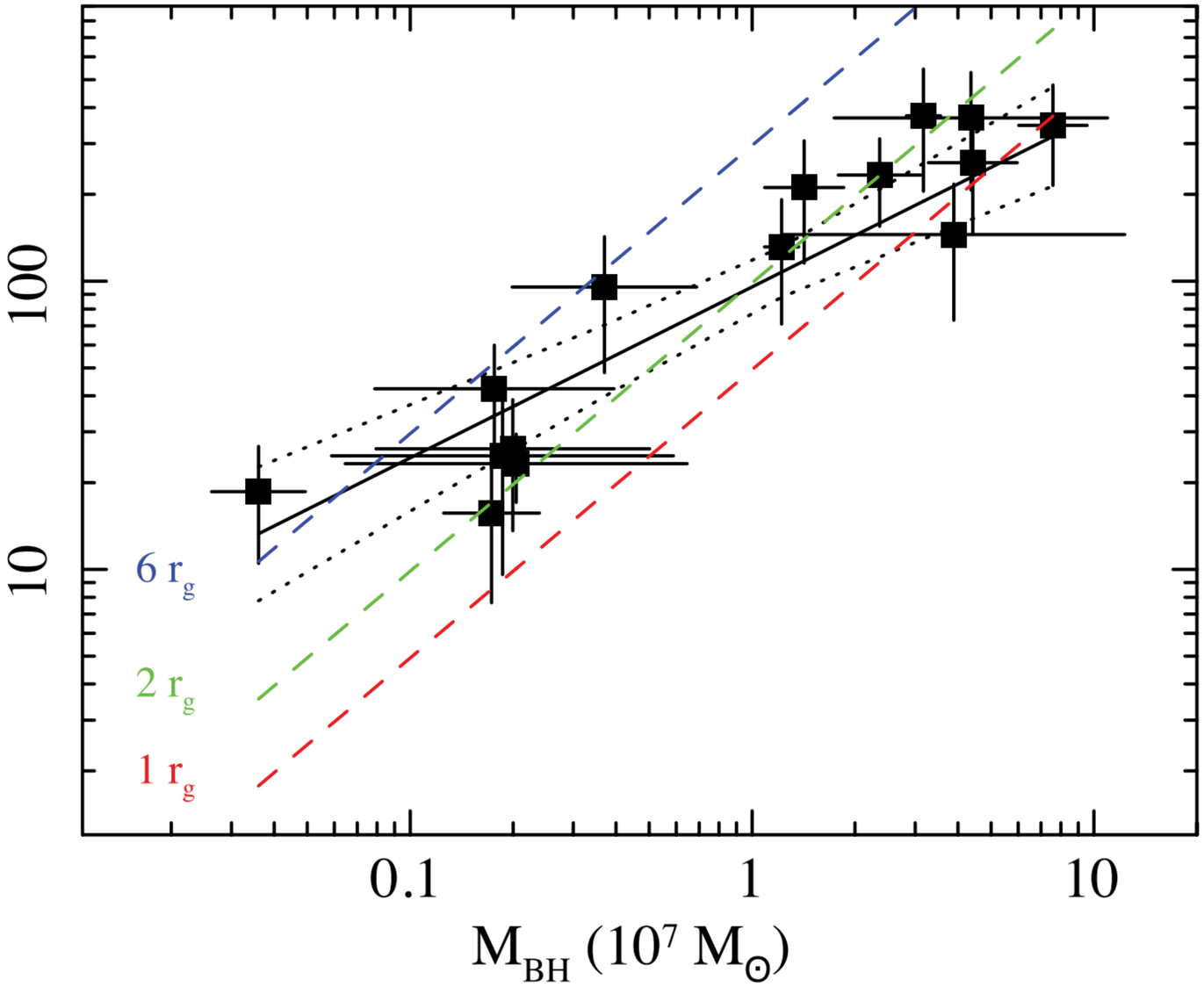
# Phenomenology: lag vs frequency




McHardy et al. 2007
Ark 564

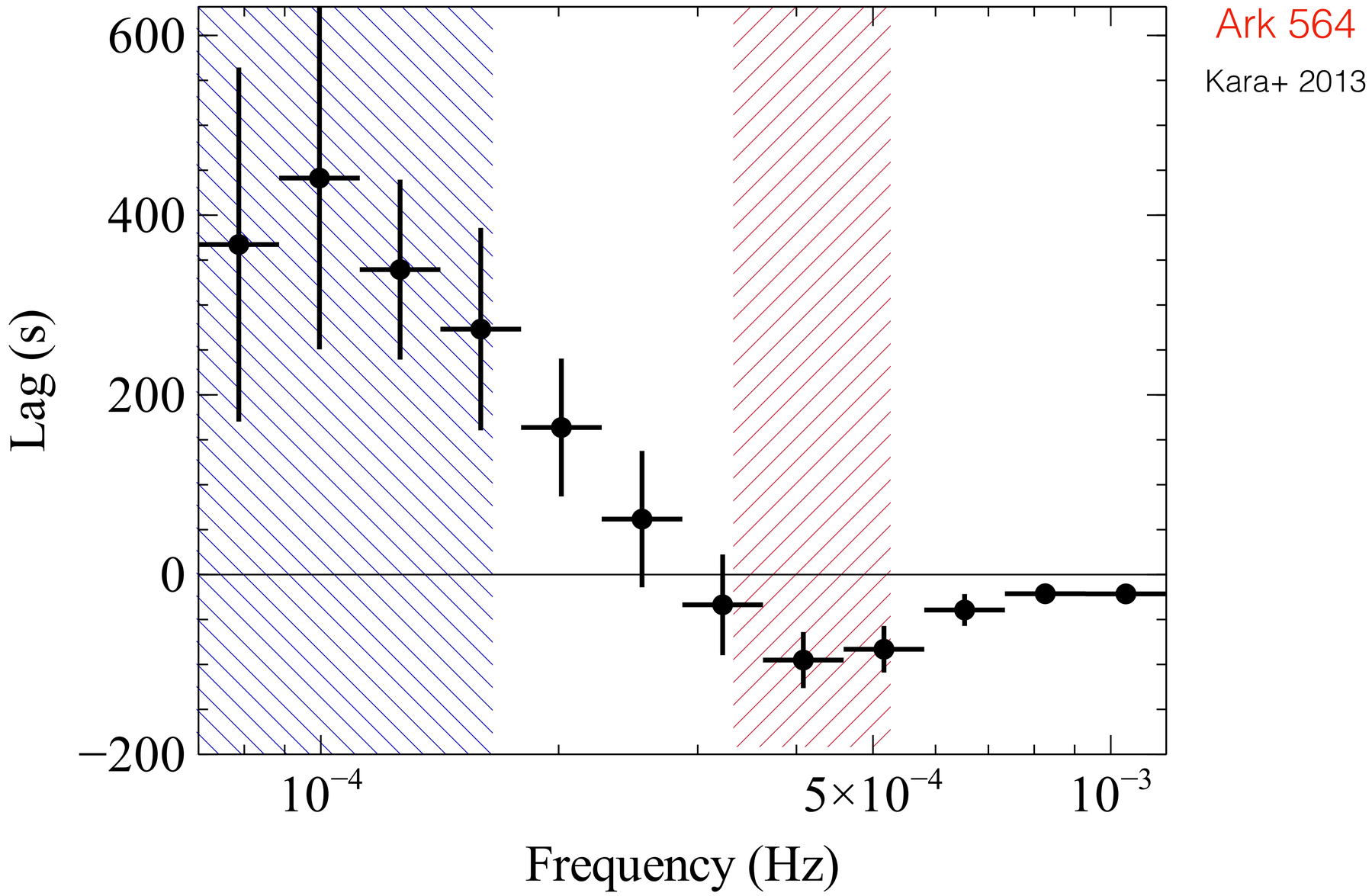
# Phenomenology: a sample of soft lags




De Marco+ 2013

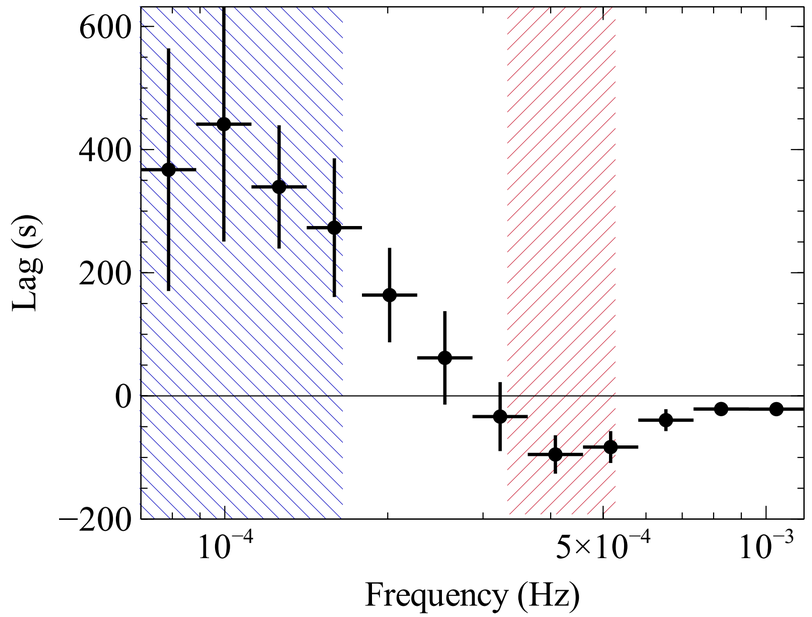
# Phenomenology: lags vs frequency




Ark 564

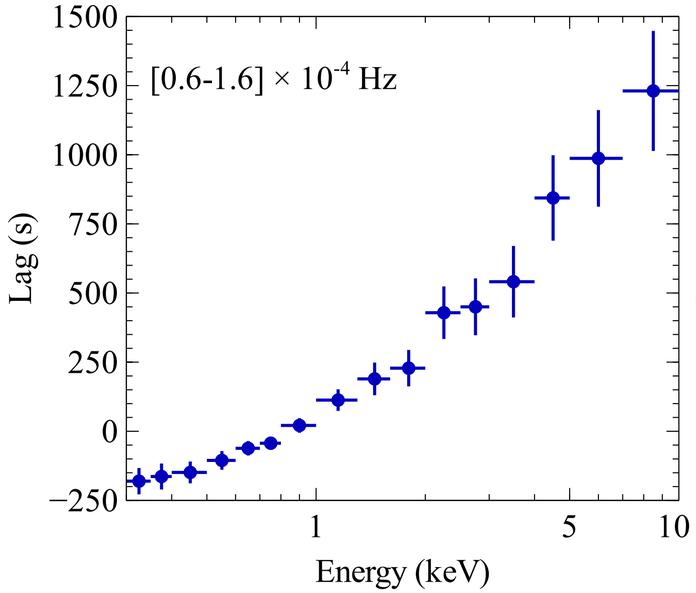
Kara+ 2013

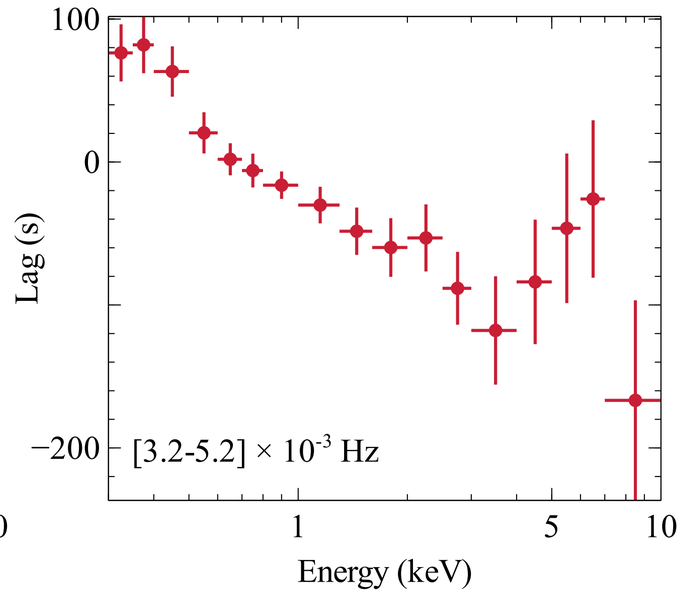
# Phenomenology: lags vs energy




Ark 564

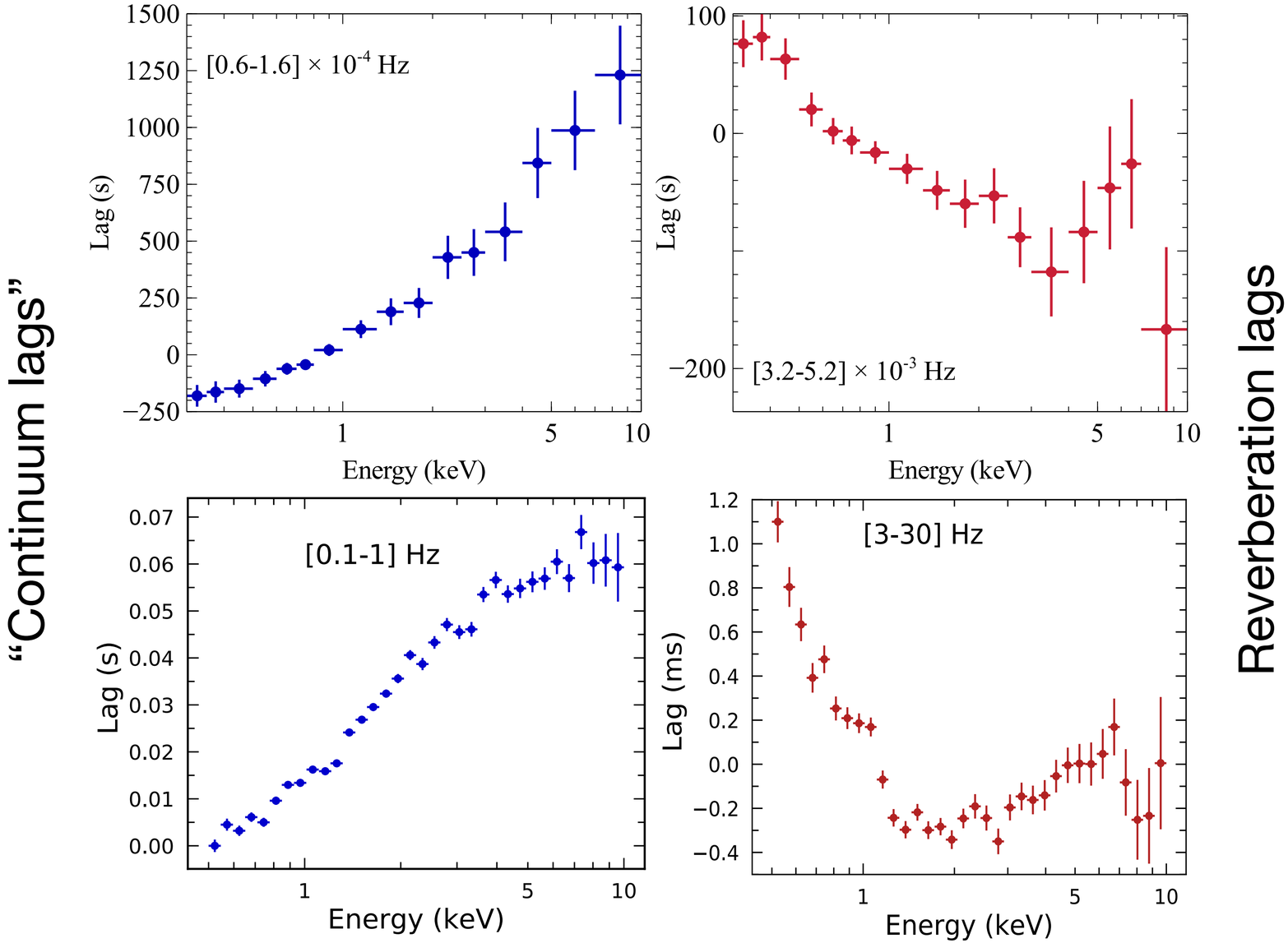
Kara+ 2013



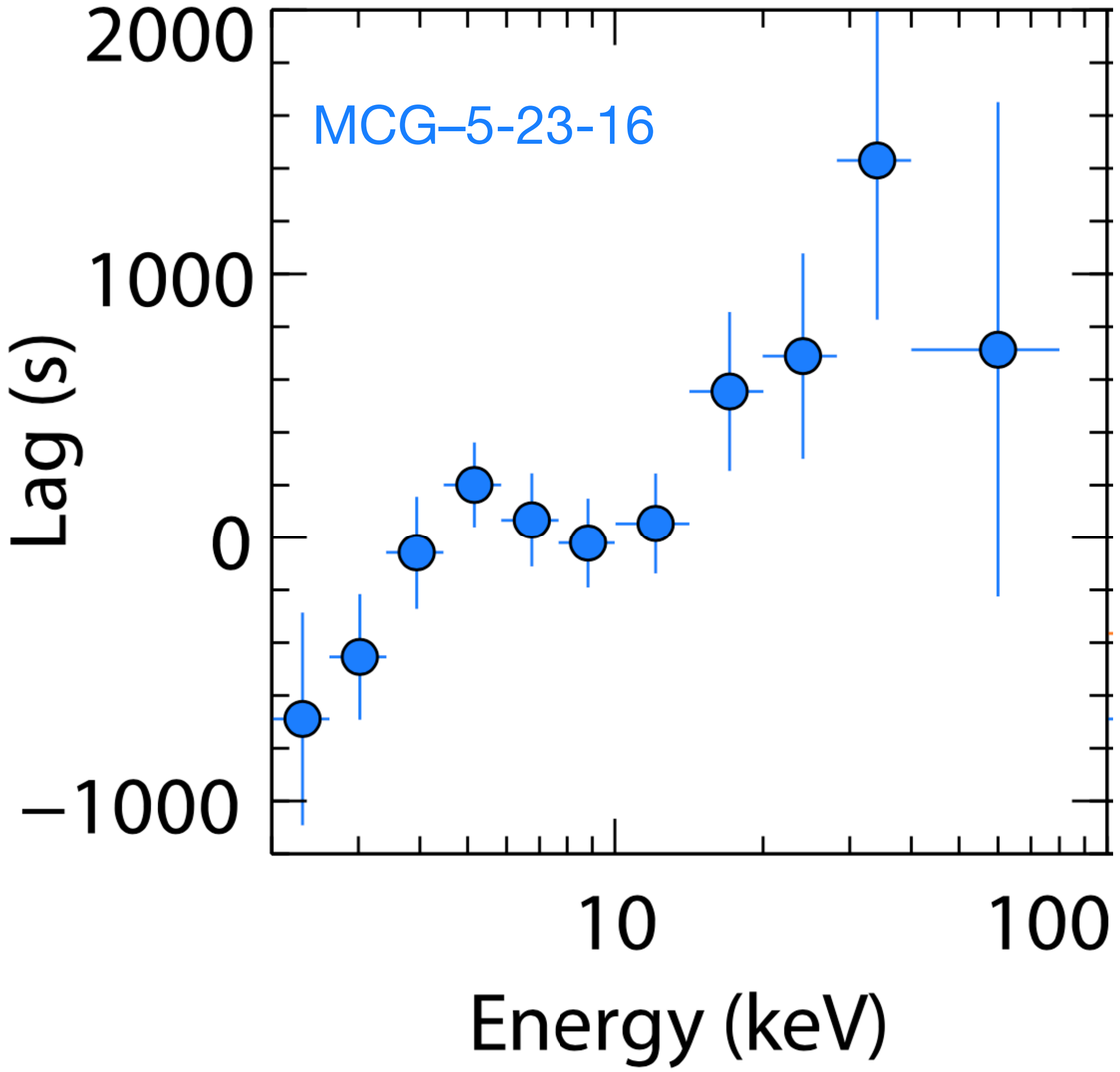
# Phenomenology: lags vs energy - AGN and BHB

AGN (Mass ~ 6 - 25 million $M_\odot$): Ark 564



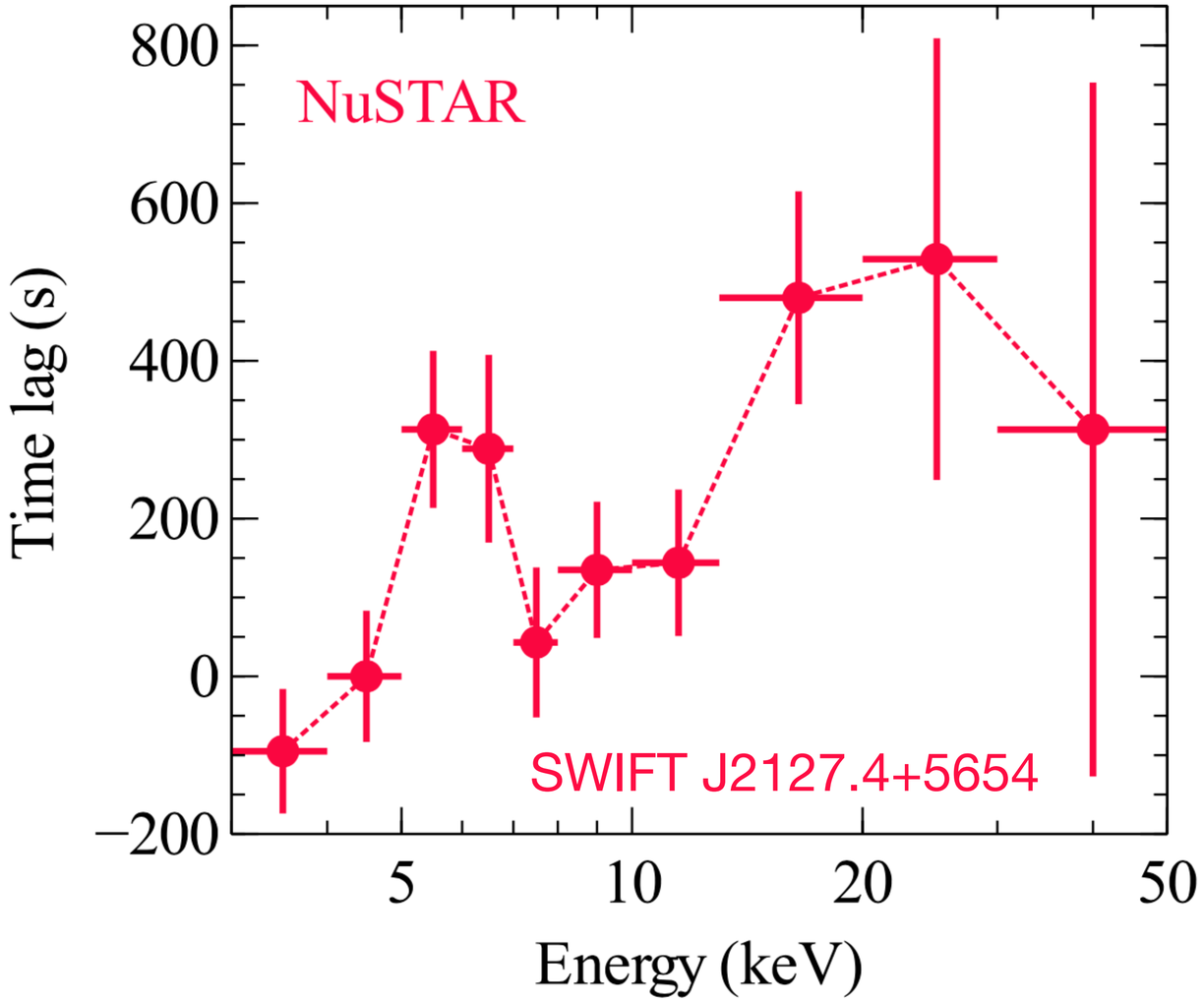

XRB (Mass ~7-8 $M_\odot$): MAXI J1820+070

# X-ray reverberation - NuSTAR

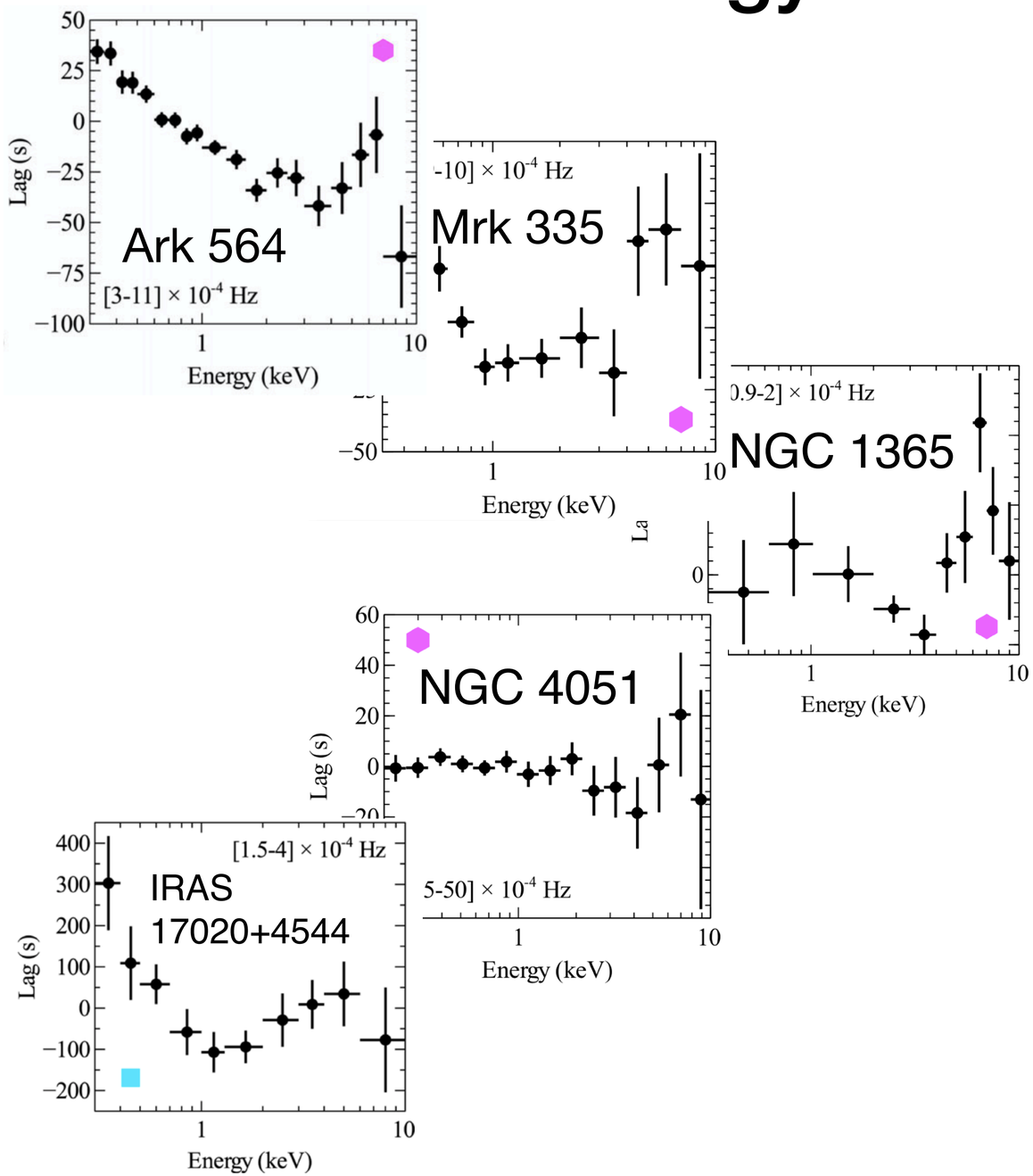


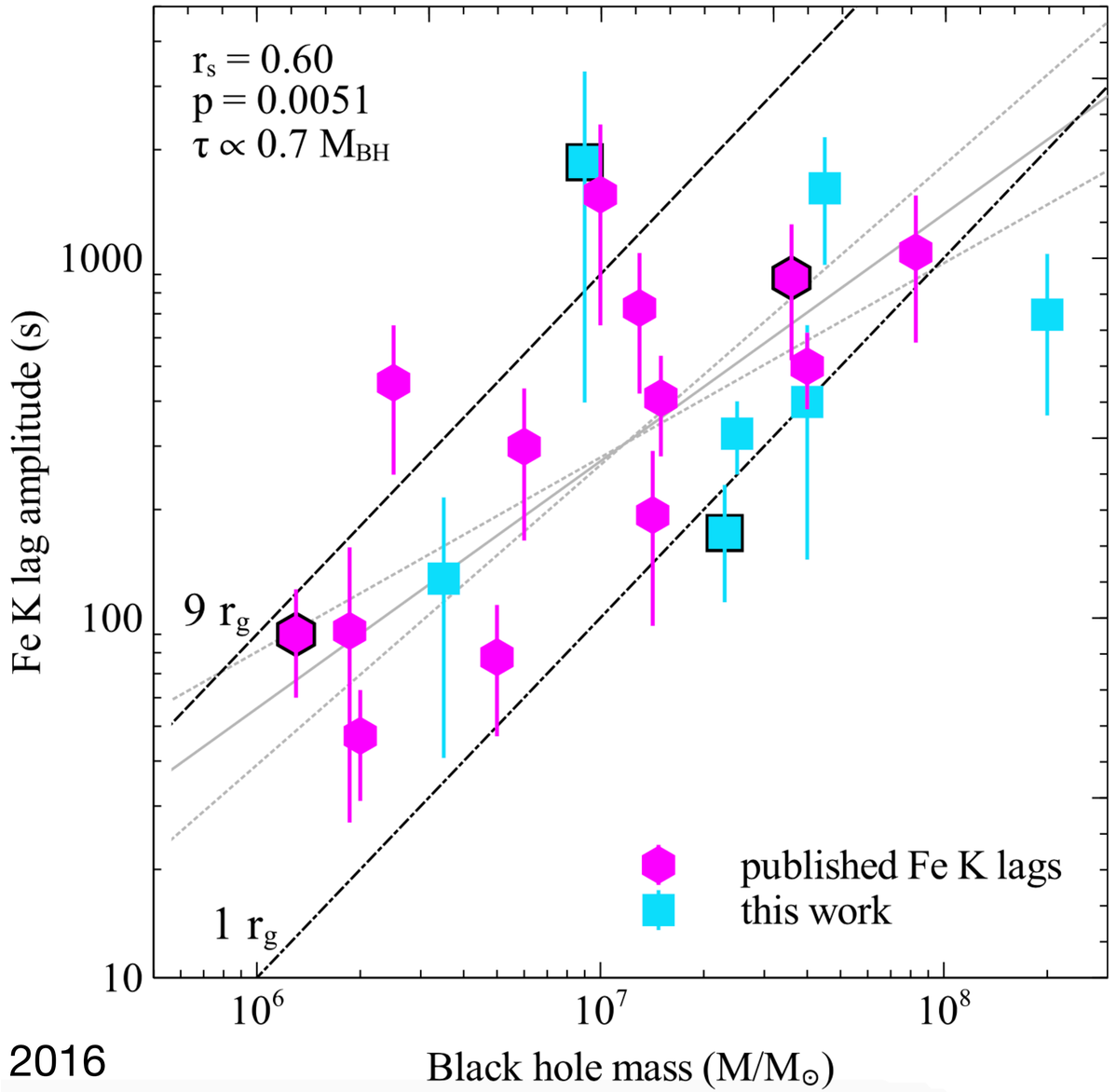

Zoghbi+ 2014

Kara+ 2015



# Phenomenology: a sample of reverberation lag




Kara+ 2016

# How can we use X-ray variability in AGN?

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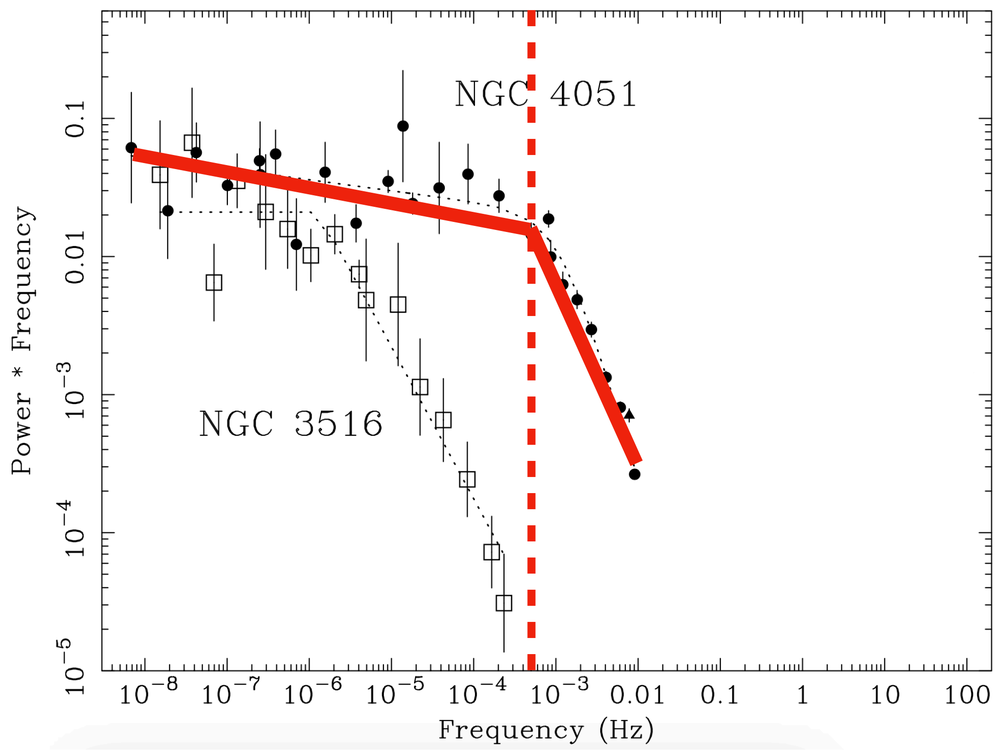
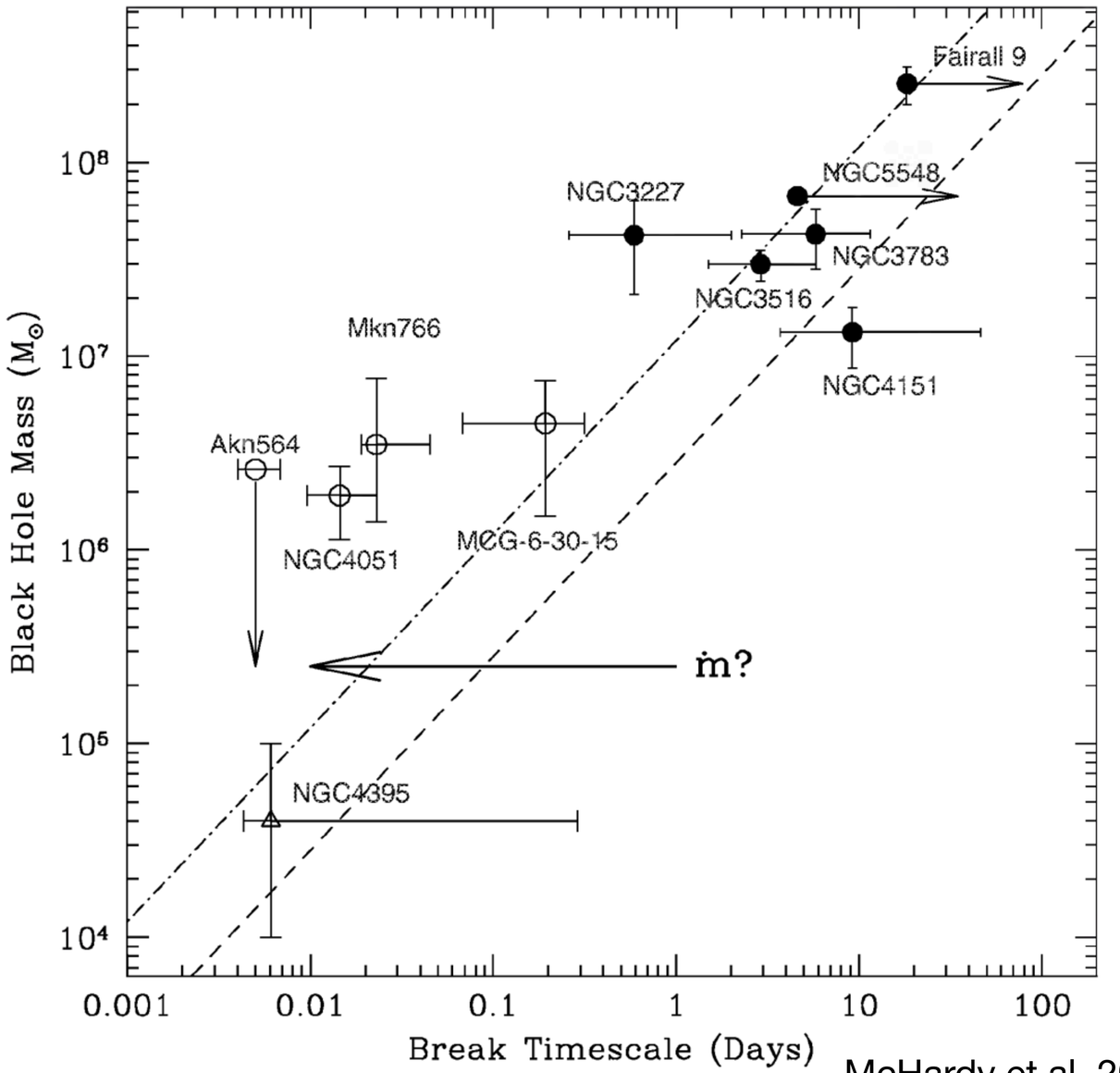
If we model the X-ray variability we can characterise the geometry of the innermost region and BH mass

# X-ray variability to constrain: BH mass



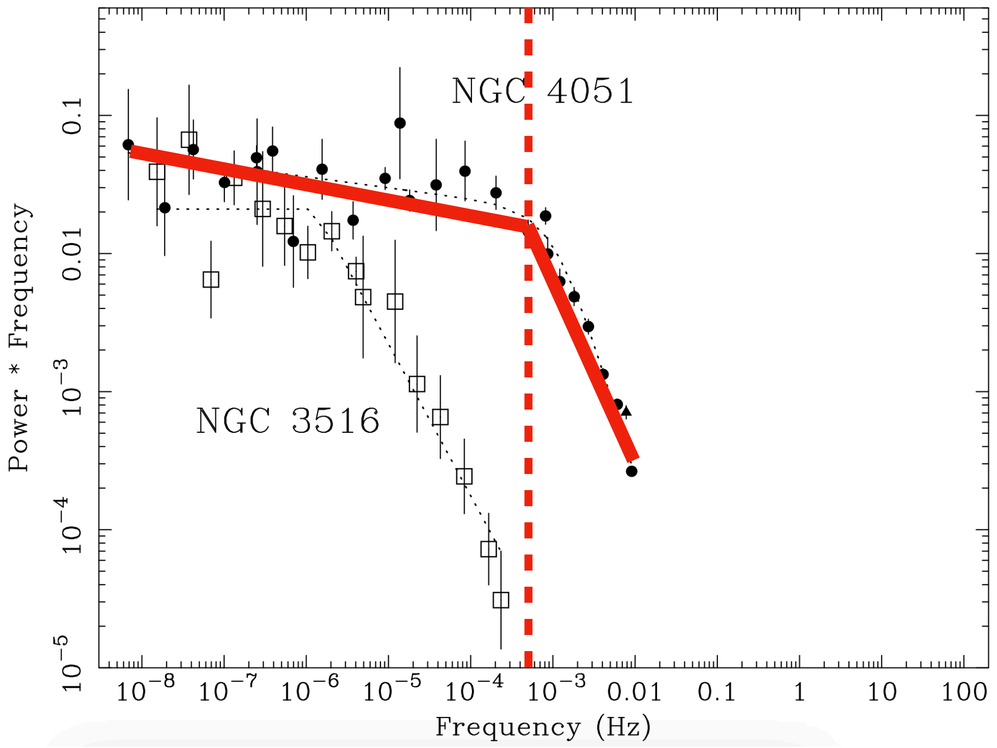

$$T_{break} \propto M_{BH}^{1.12} \dot{M}^{-0.98}$$

McHardy+ 2006; Körding+2007; Gonzalez- Martin & Vaughan 2012, Ponti+ 2012



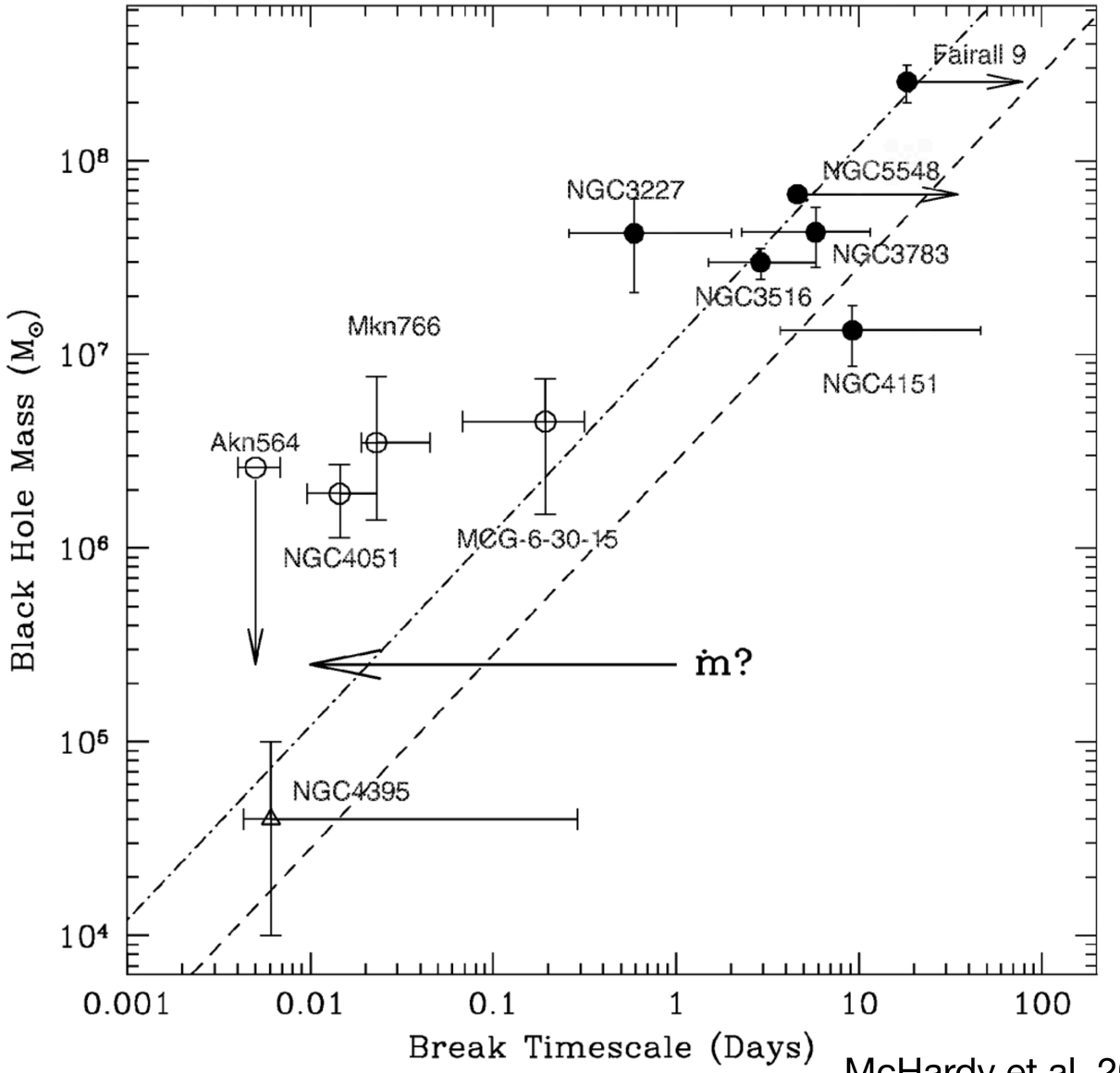

McHardy et al. 2005

# X-ray variability to constrain: BH mass




$T < T_{break}$ $\sigma^2_{rms}$ is anti-correlated with the BH mass

Lu & Yu 2001; Bian & Zhao 2003; Papadakis 2004; O'Neill+2005; Nikolajuk+2006; Zhou+2010, Ponit+ 2012




McHardy et al. 2005

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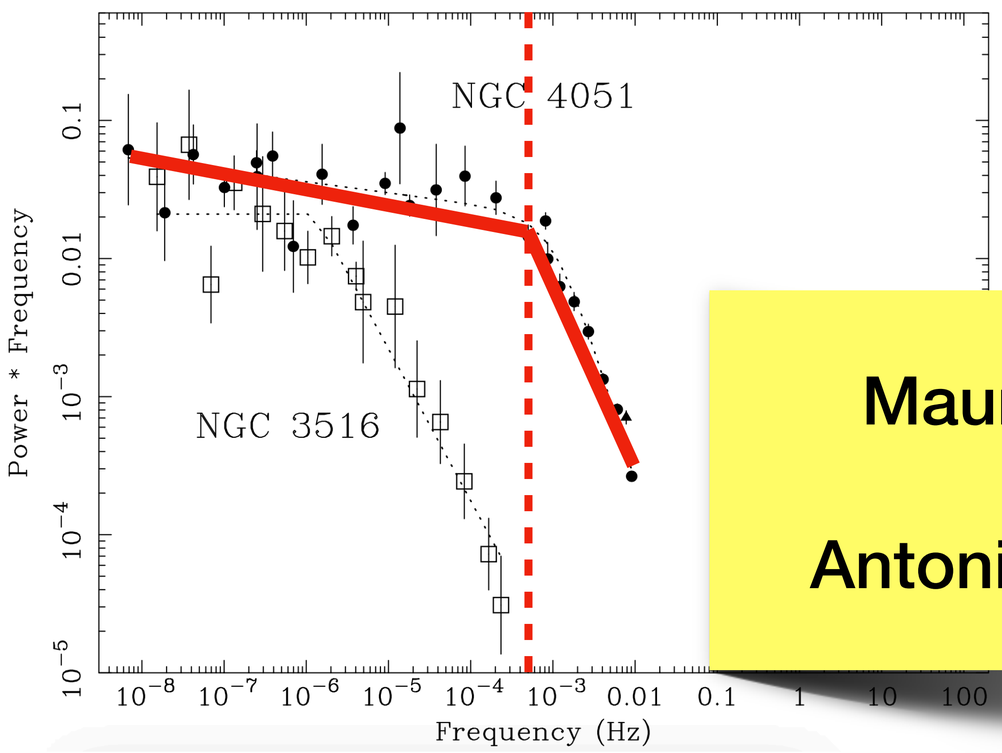
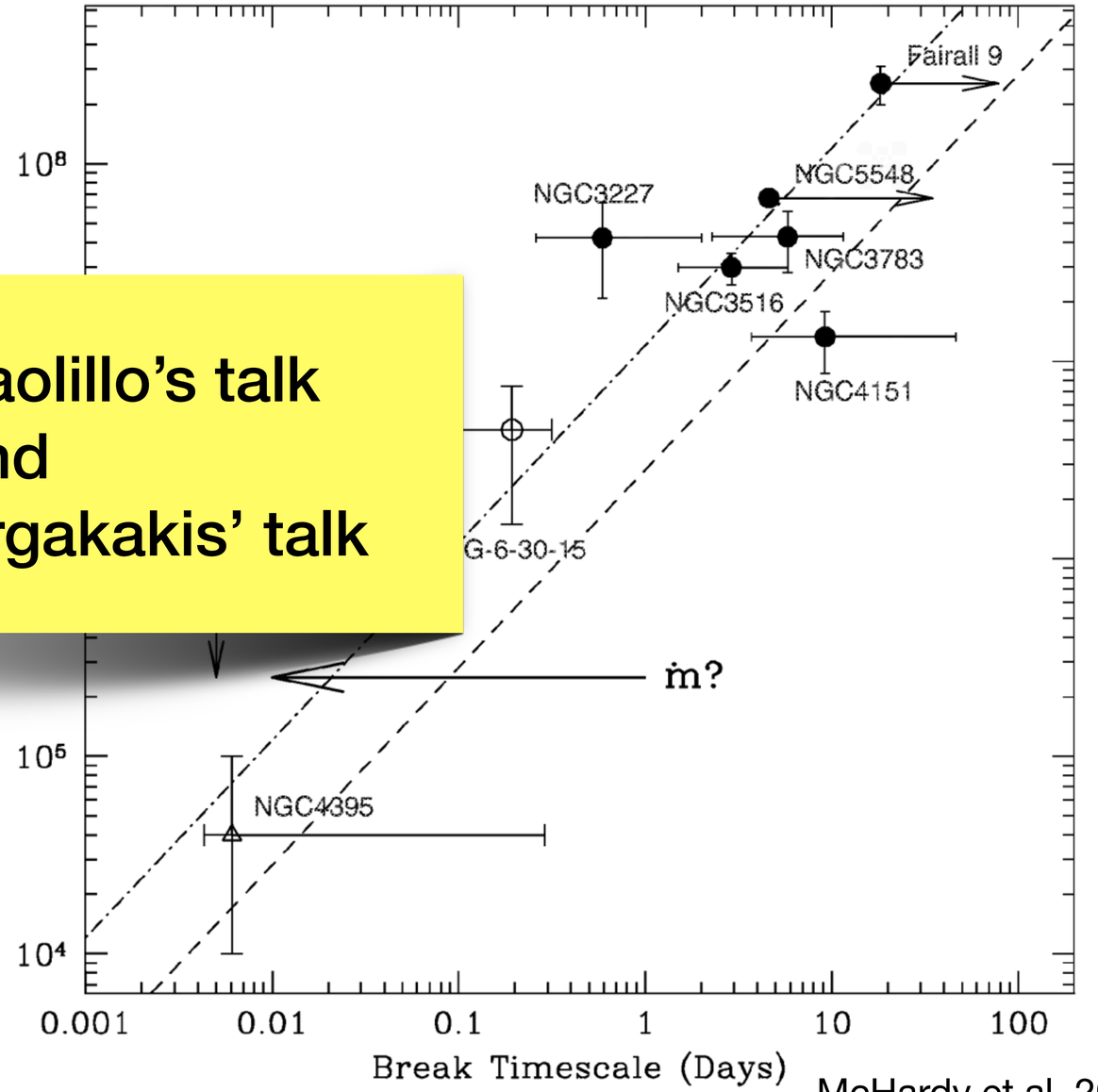



**Maurizio Paolillo's talk**
**and**
**Antonis Georgakakis' talk**

$T < T_{break}$ $\sigma^2_{rms}$ is anti-correlated with the BH mass

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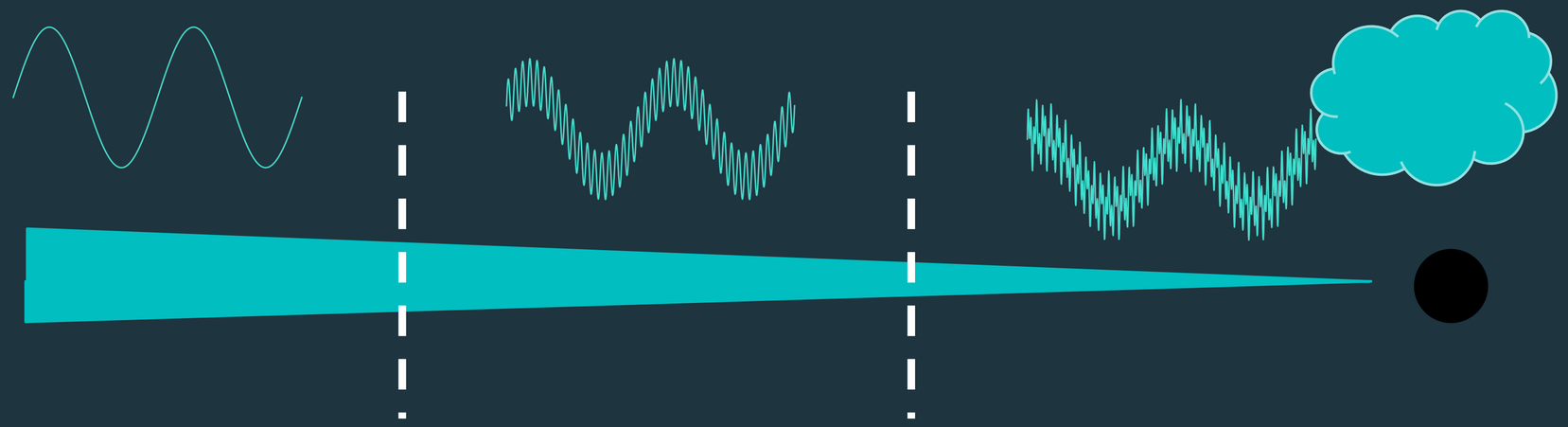
# MODELLING HARD LAGS


## MASS ACCRETION RATE PROPAGATING FLUCTUATIONS

e.g. Lynden-Bell & Pringle 1974, Lyubarskii 1997, Kotov+ 2001, Arévalo & Uttley+ 2006,
Ingram & van der Klis 2013; Hogg & Reynolds 2015, and others…

# MODELLING HARD LAGS




## MASS ACCRETION RATE PROPAGATING FLUCTUATIONS

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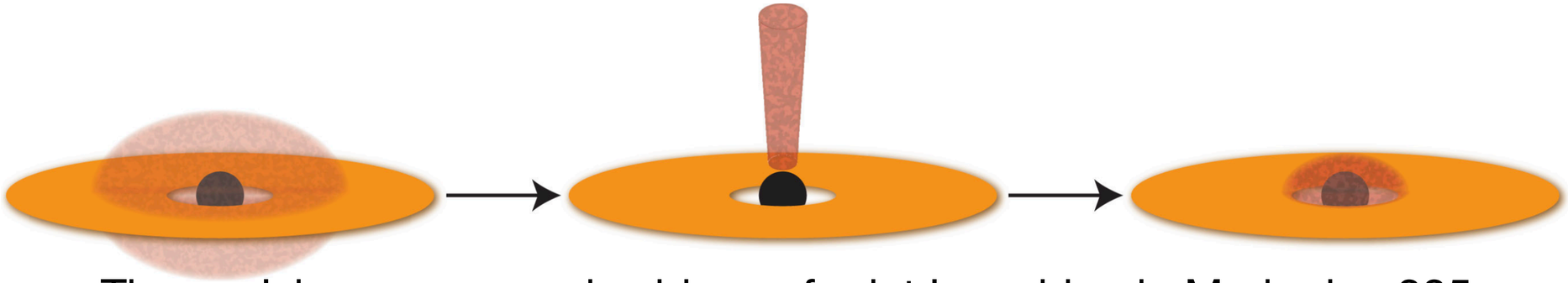
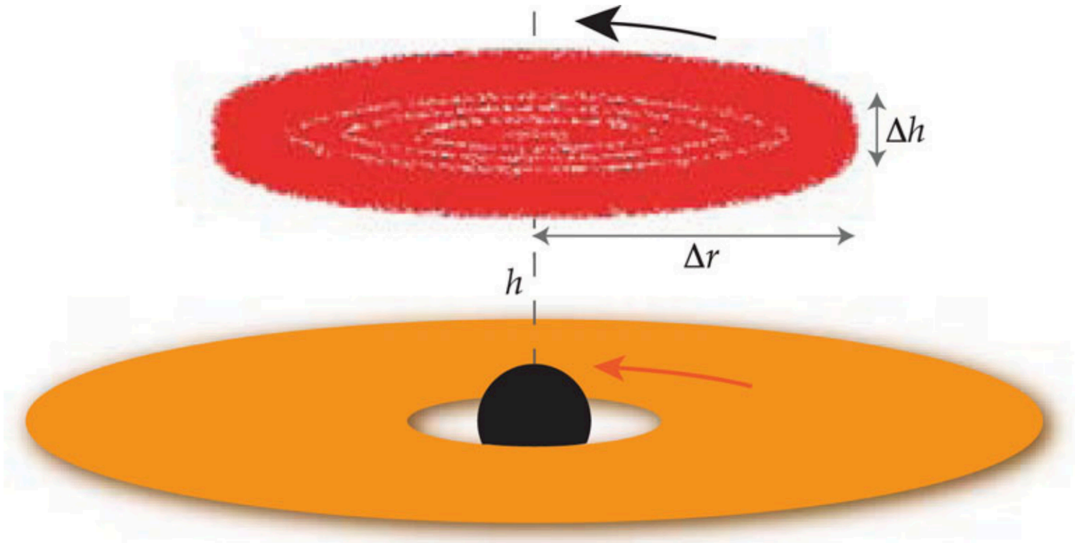
# X-ray variability to constrain: coronal geometry

Not so compact corona

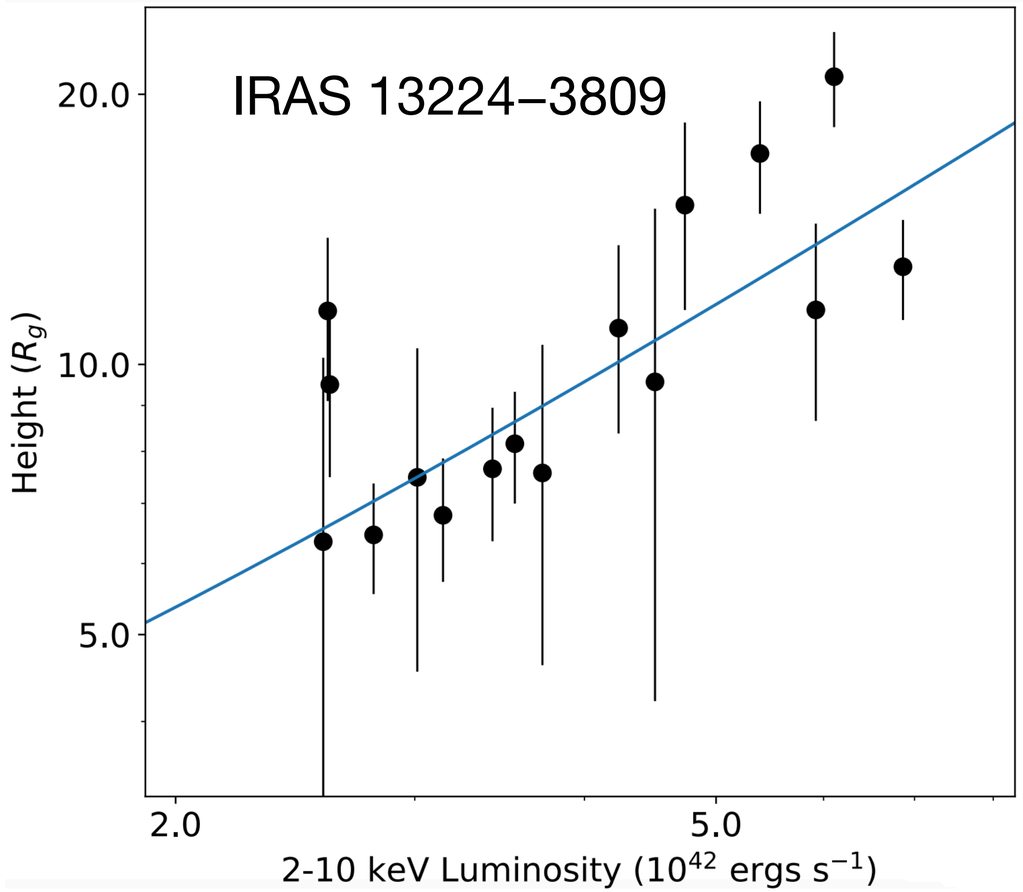


The evolving corona and evidence for jet launching in Markarian 335
Wilkins and Gallo 2015

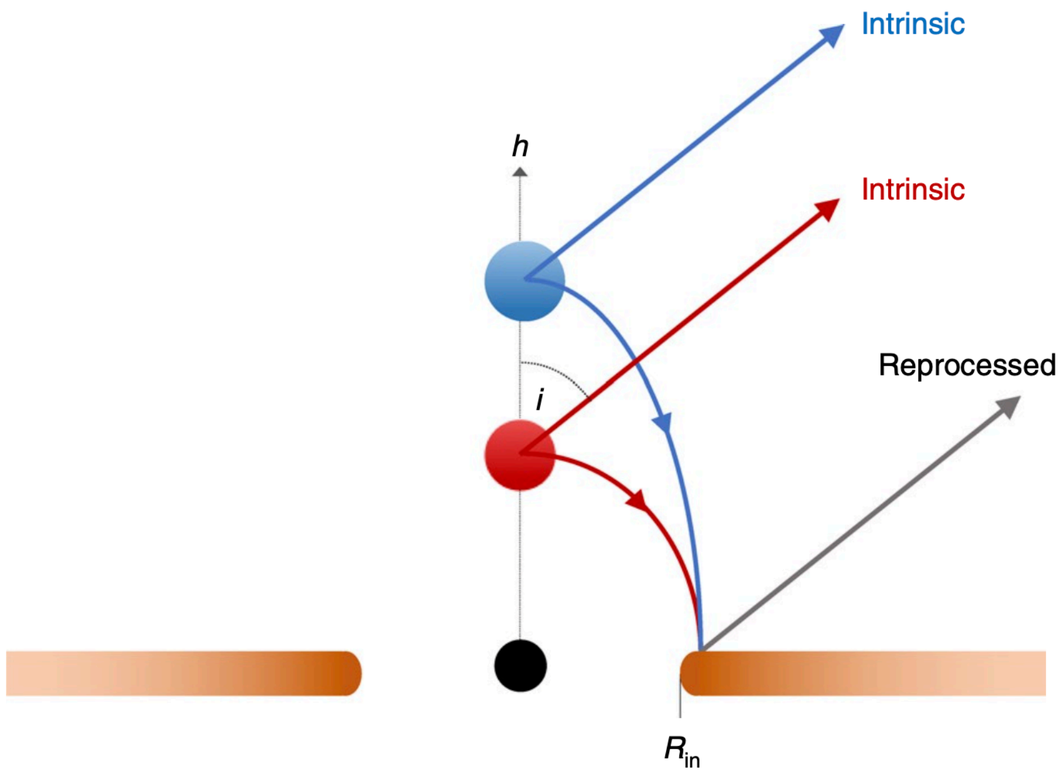



Check Wilkins and Fabian 2013 and Szanecki+ 2020 about the size of the corona in 1H 0707–495

# X-ray variability to constrain: coronal geometry

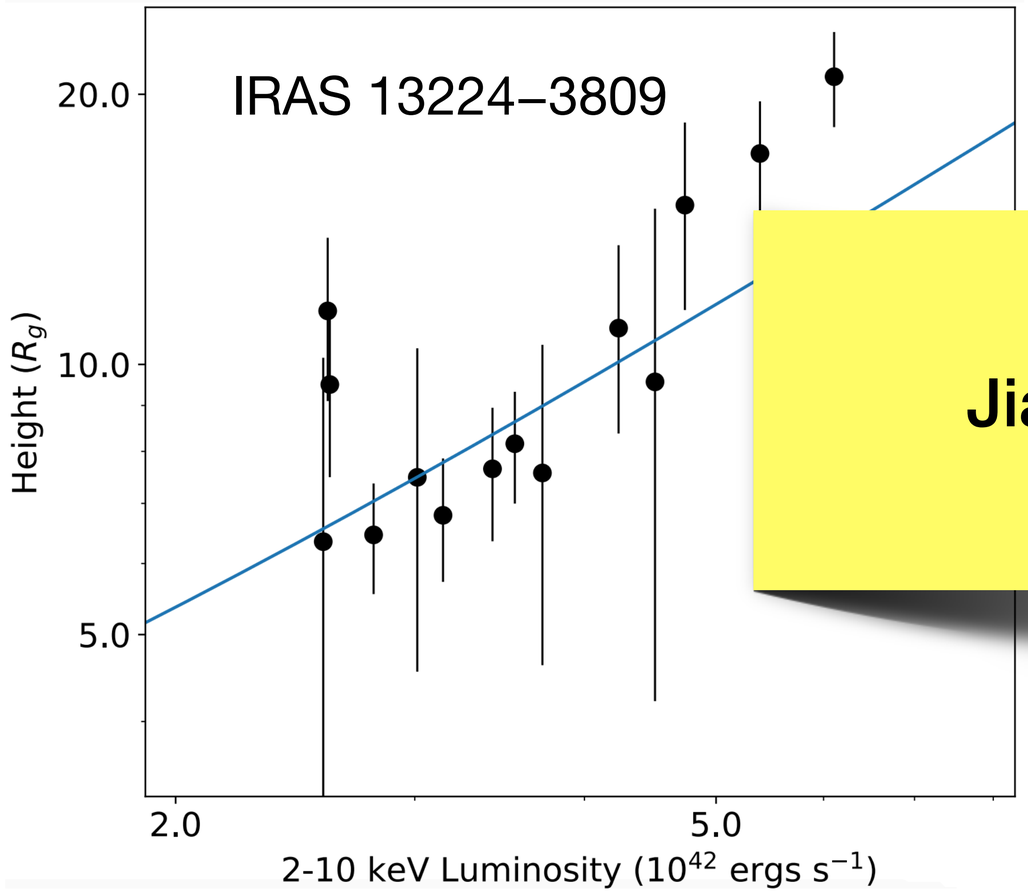



Alston+ 2020



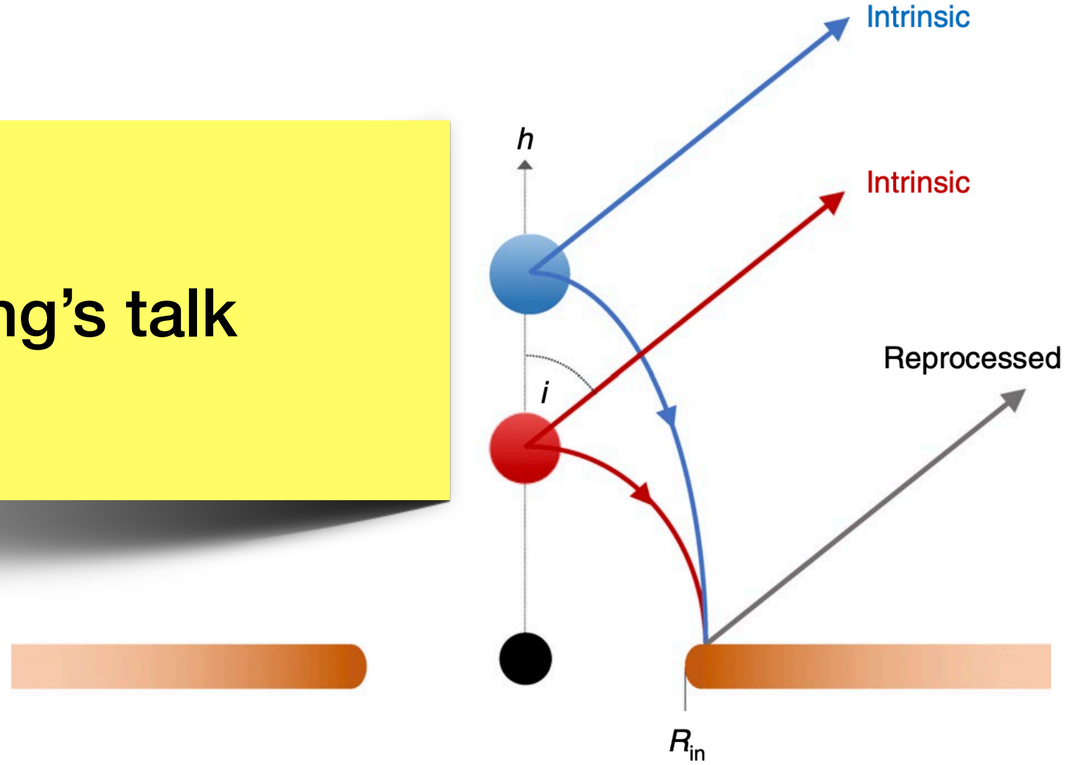

KYNREFREV Model

# X-ray variability to constrain: coronal geometry




Alston+ 2020

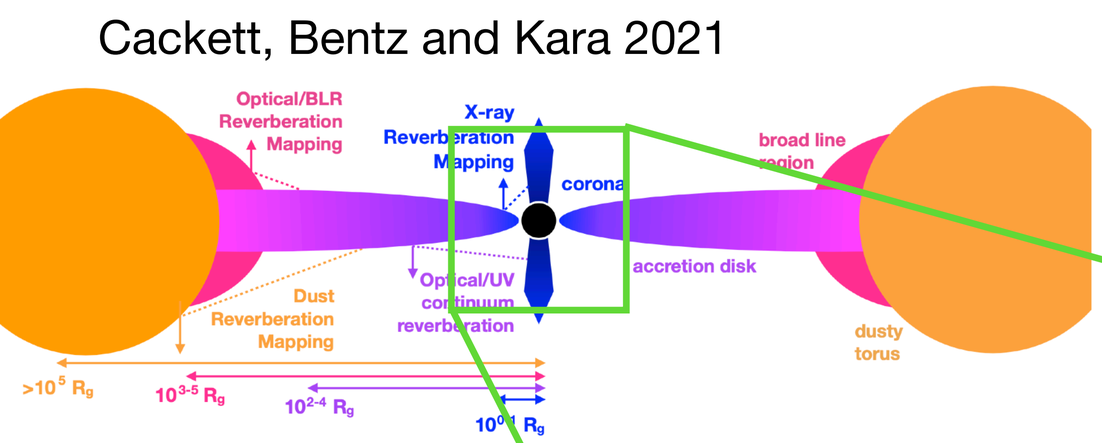
**Jia-Lai Kang's talk**

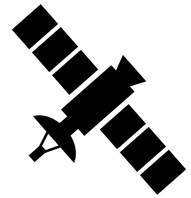


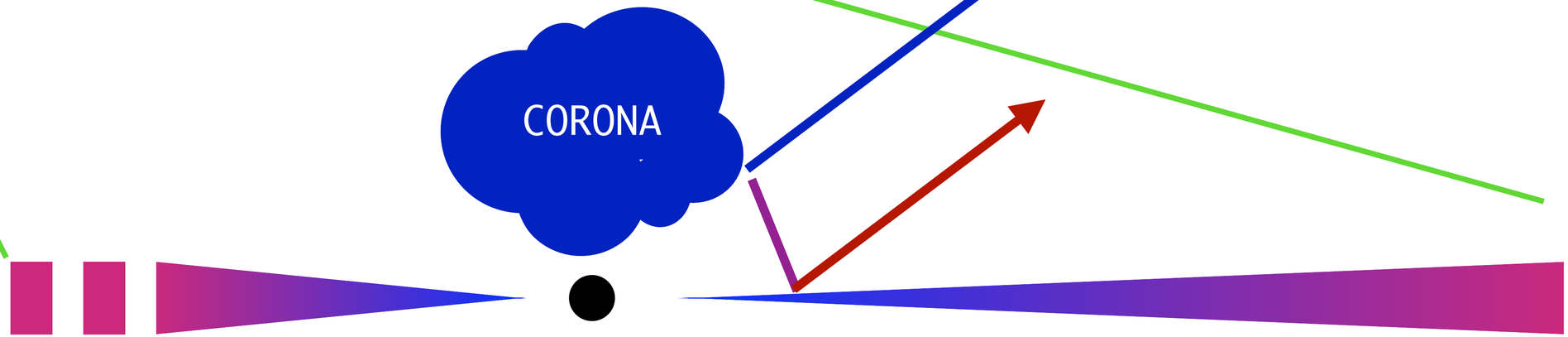

KYNREFREV Model

# X-ray reverberation probing the corona

Cackett, Bentz and Kara 2021

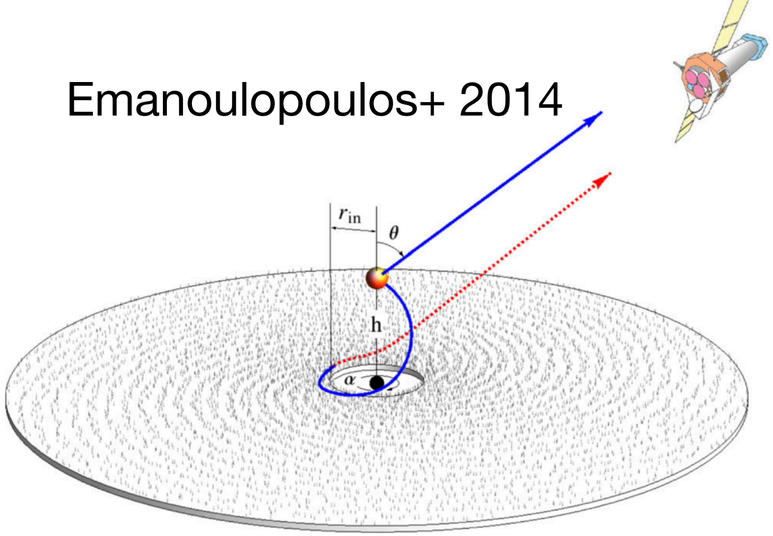


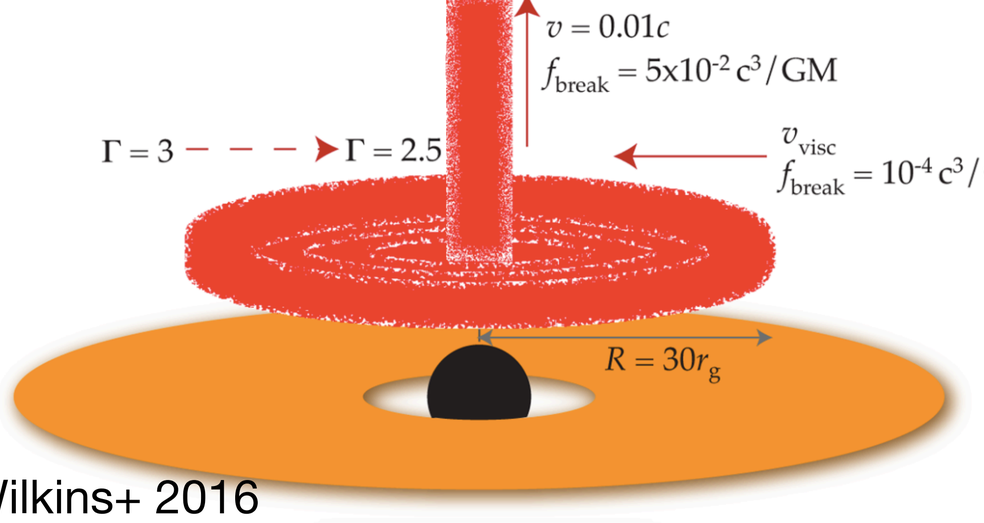





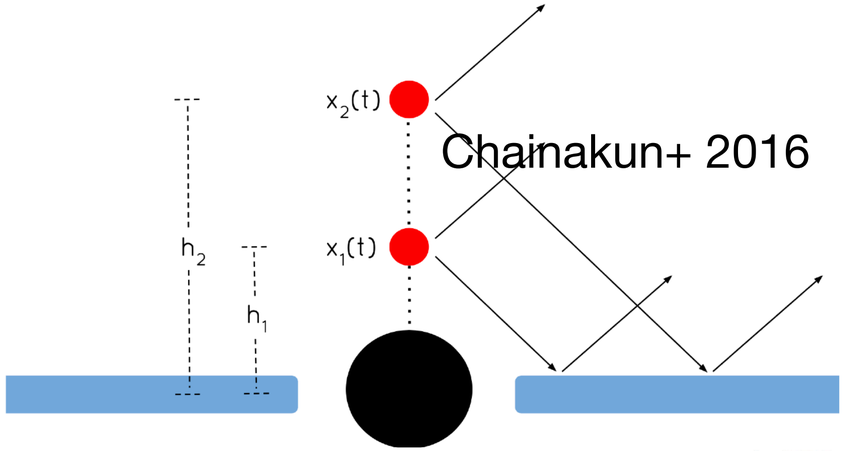
# Models

Emanoulopoulos+ 2014

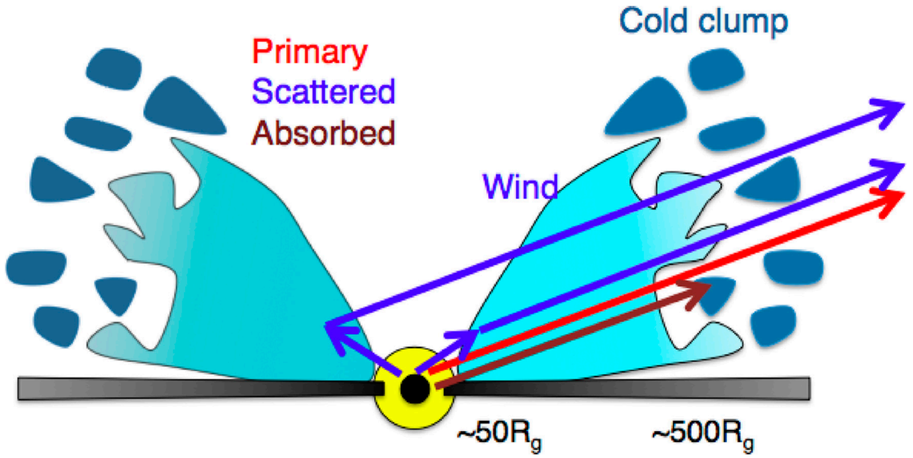


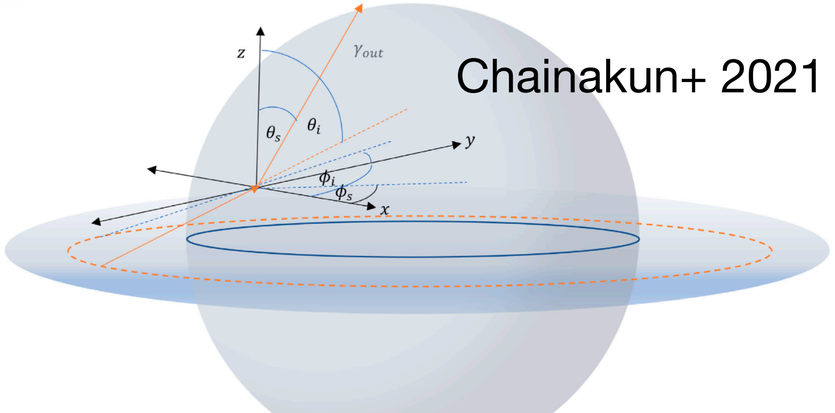

Wilkins+ 2016



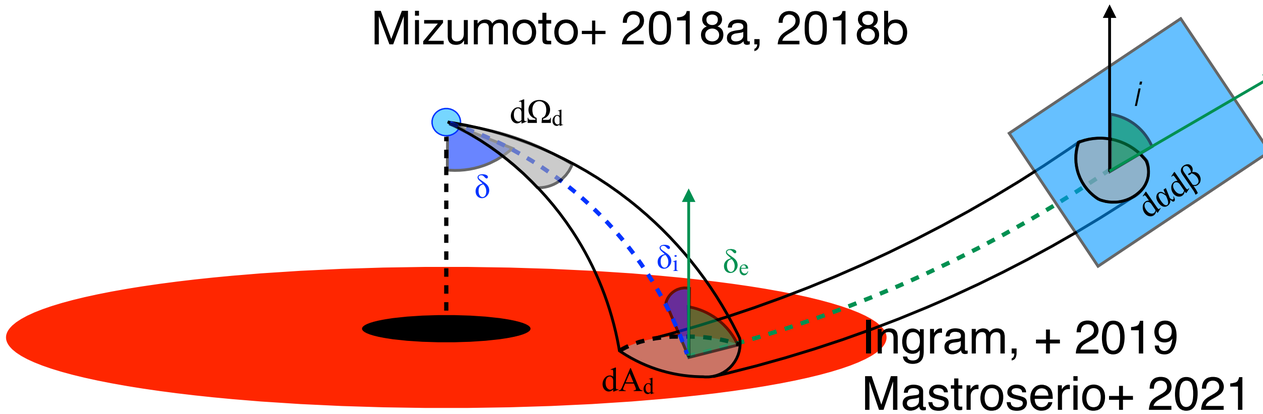

Chainakun+ 2016




Mizumoto+ 2018a, 2018b

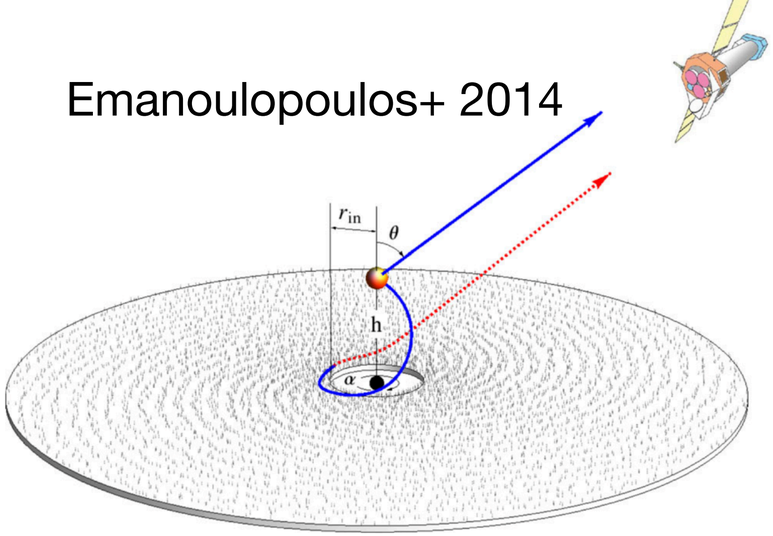


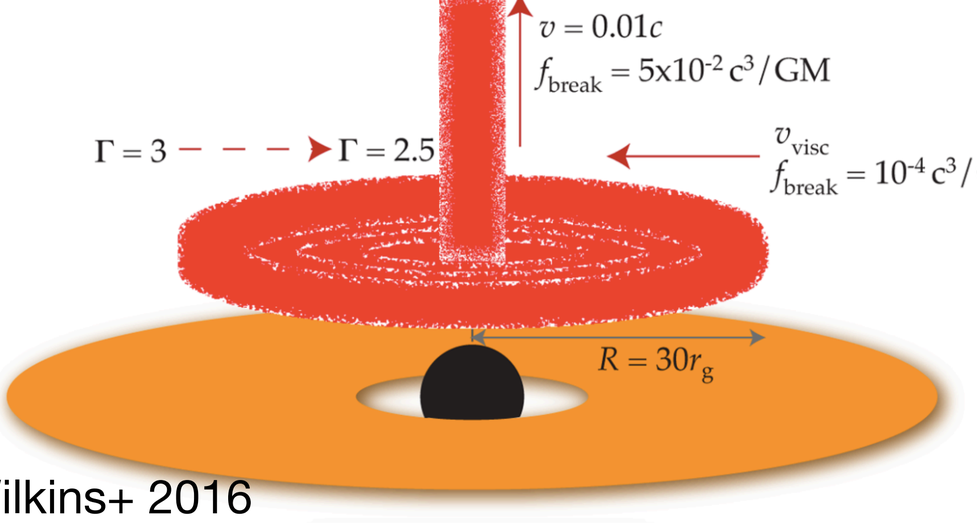

Chainakun+ 2021



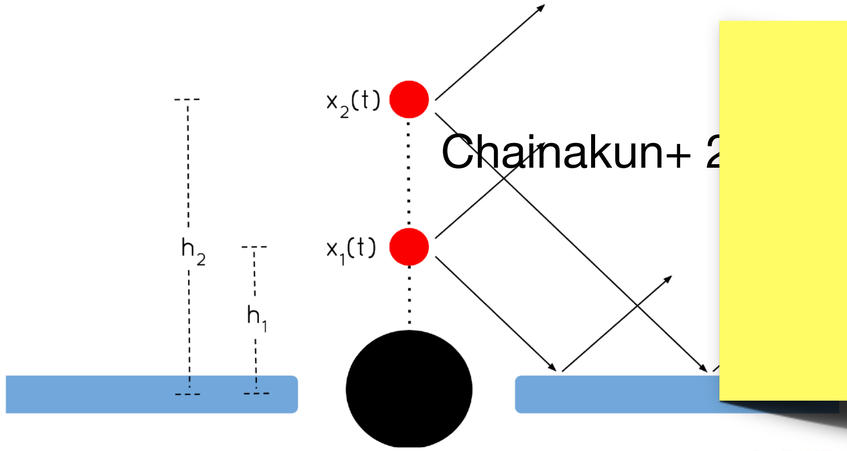

Ingram, + 2019
Mastroserio+ 2021

Emanoulopoulos+ 2014



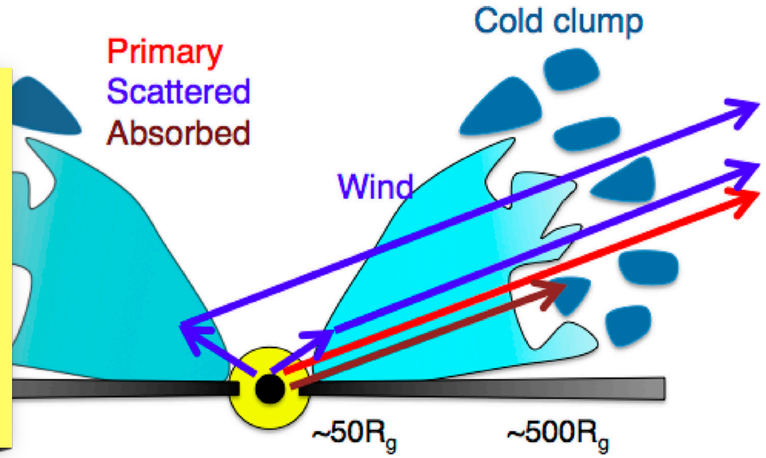




Wilkins+ 2016

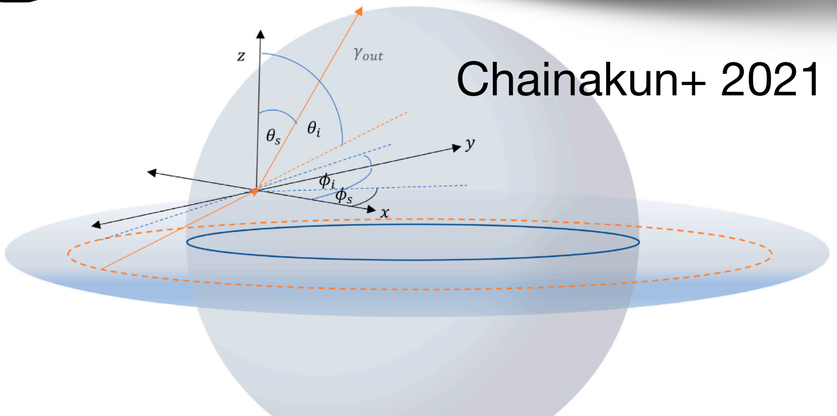



Chainakun+ 2

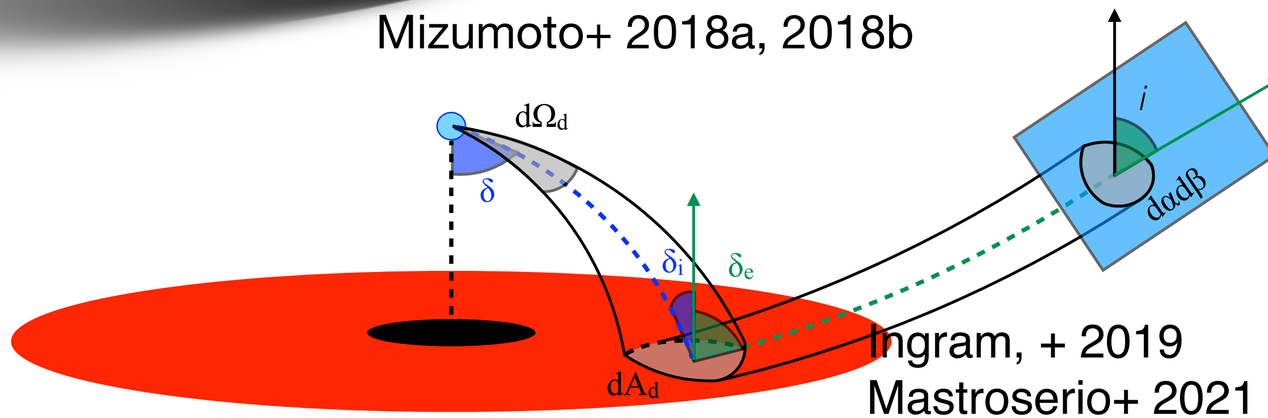
**Andrew Young's talk**




Mizumoto+ 2018a, 2018b

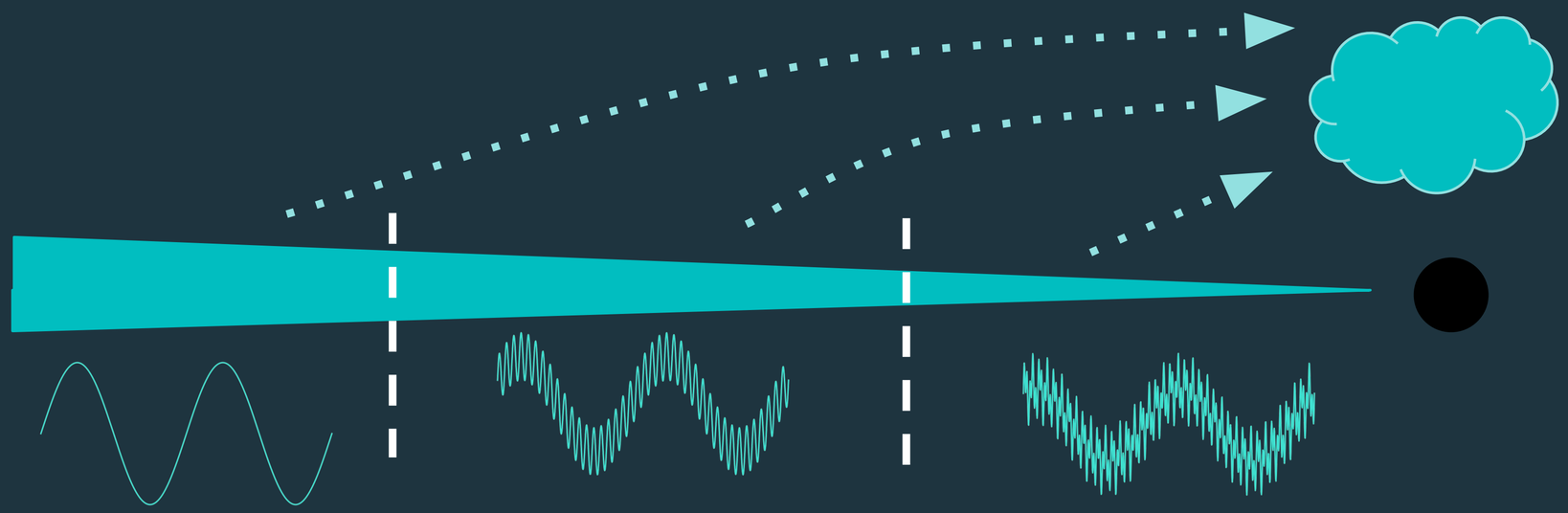



Chainakun+ 2021

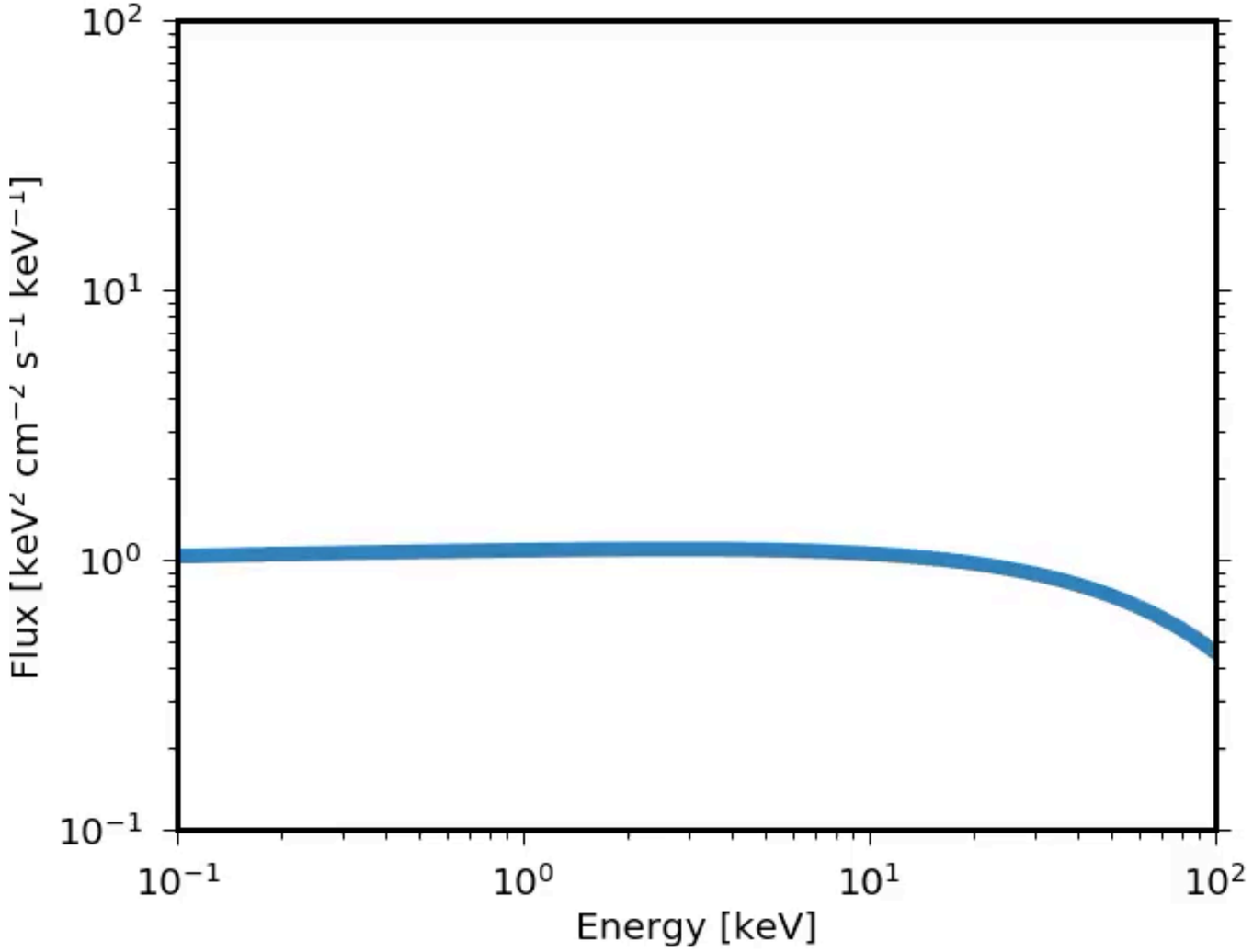



Ingram, + 2019
Mastroserio+ 2021

# MODELLING HARD LAGS



# Spectral Hardness Changes



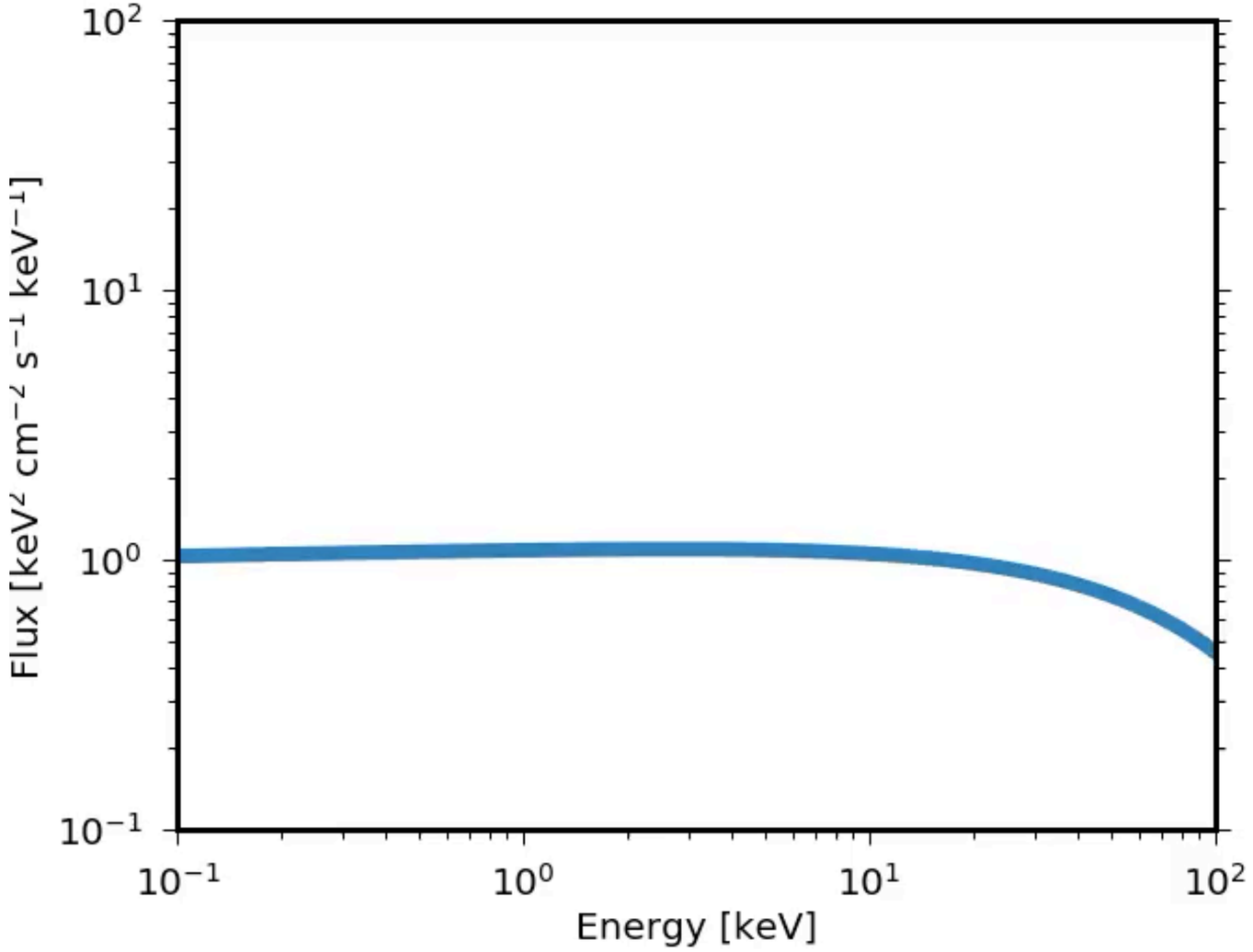

$$\Gamma = -\frac{1}{2} + \sqrt{\frac{9}{4} + \frac{1}{\theta_e \tau_e (1 + \tau_e/3)}}$$

Lightman & Zdziarski 1987

~2% fractional rms of the spectral index corresponds to 3% fractional rms of disk temperature and optical depth

Mastroserio+ 2018, 2021

# Spectral Hardness Changes

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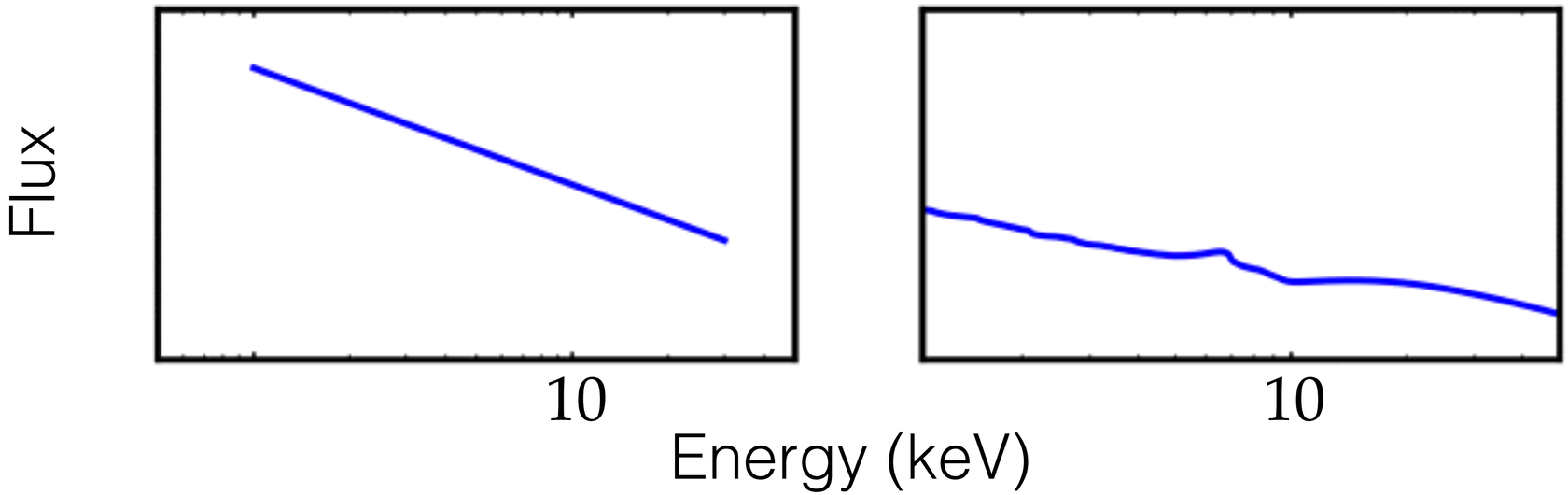
Mastroserio+ 2018, 2021

# Spectral Hardness Changes

**Direct Emission** **Reflection**

**PIVOTING**




The pivoting power-law produces the hard lags we observed in the data

The reflection is changing not only in the slope but also in the atomic physics

Mastroserio+ 2018

# Spectral Hardness Changes

**Direct Emission** **Reflection**

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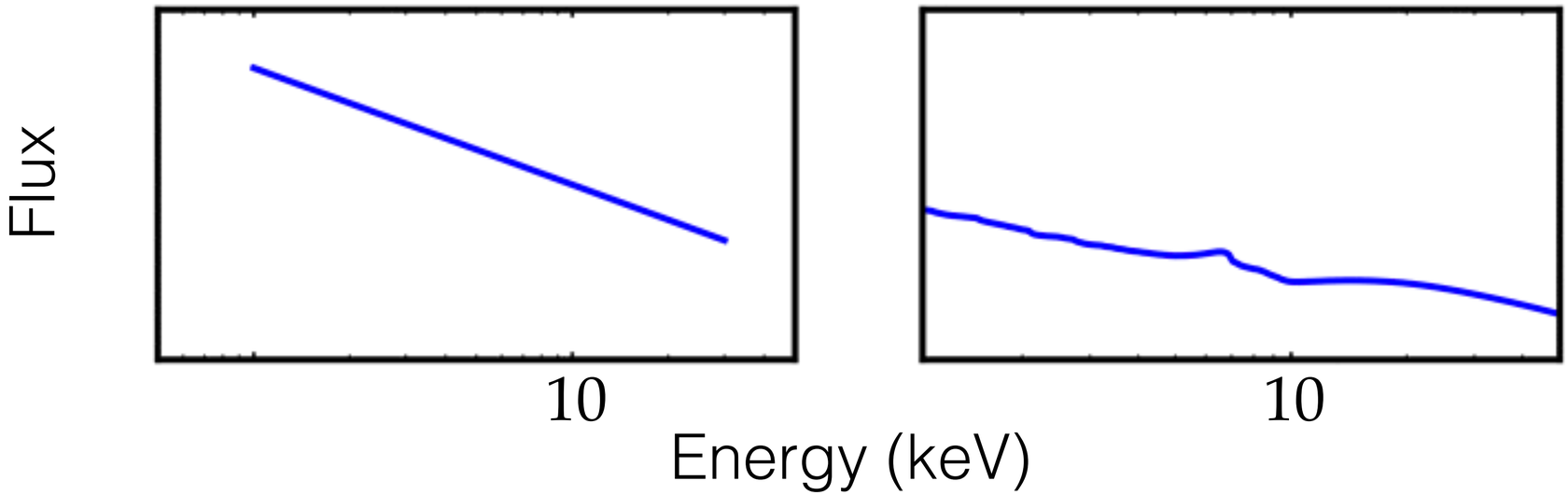


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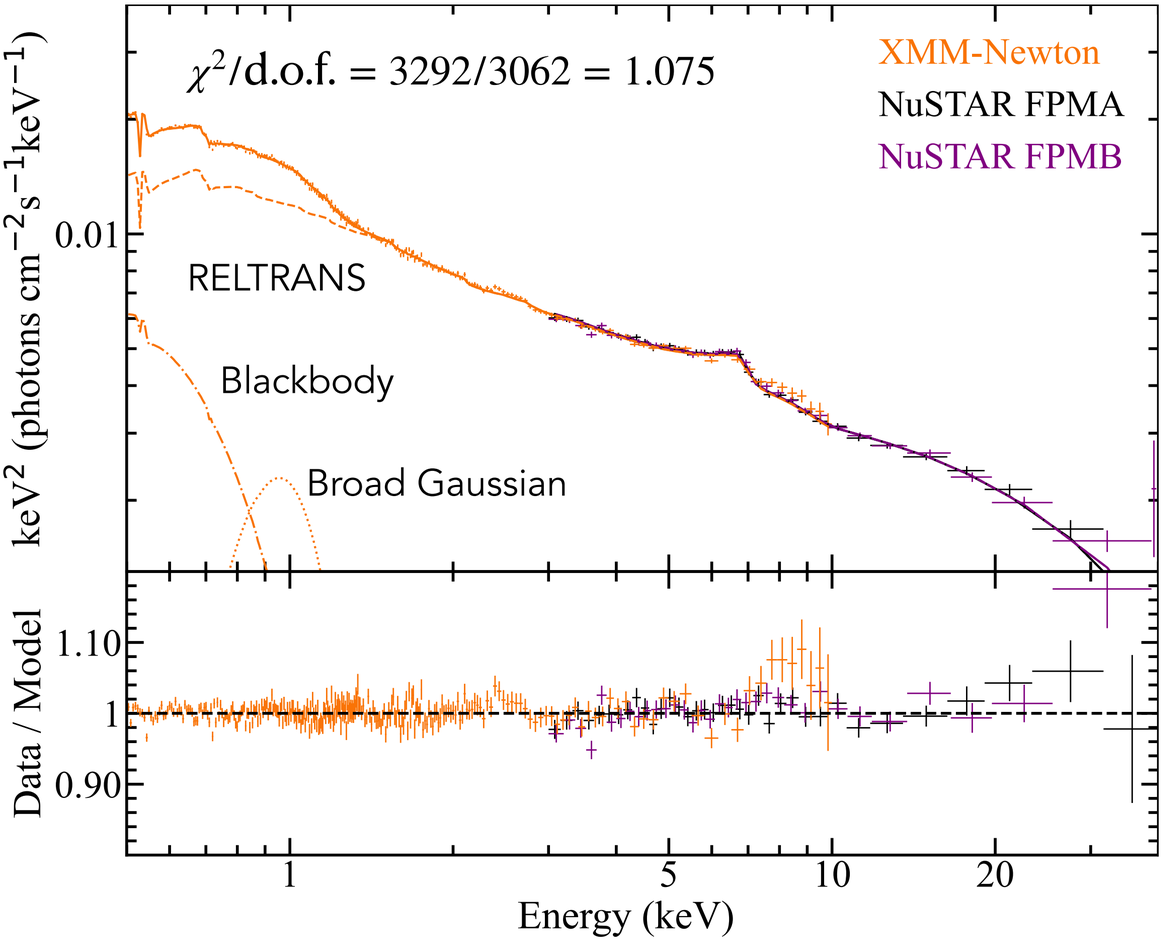
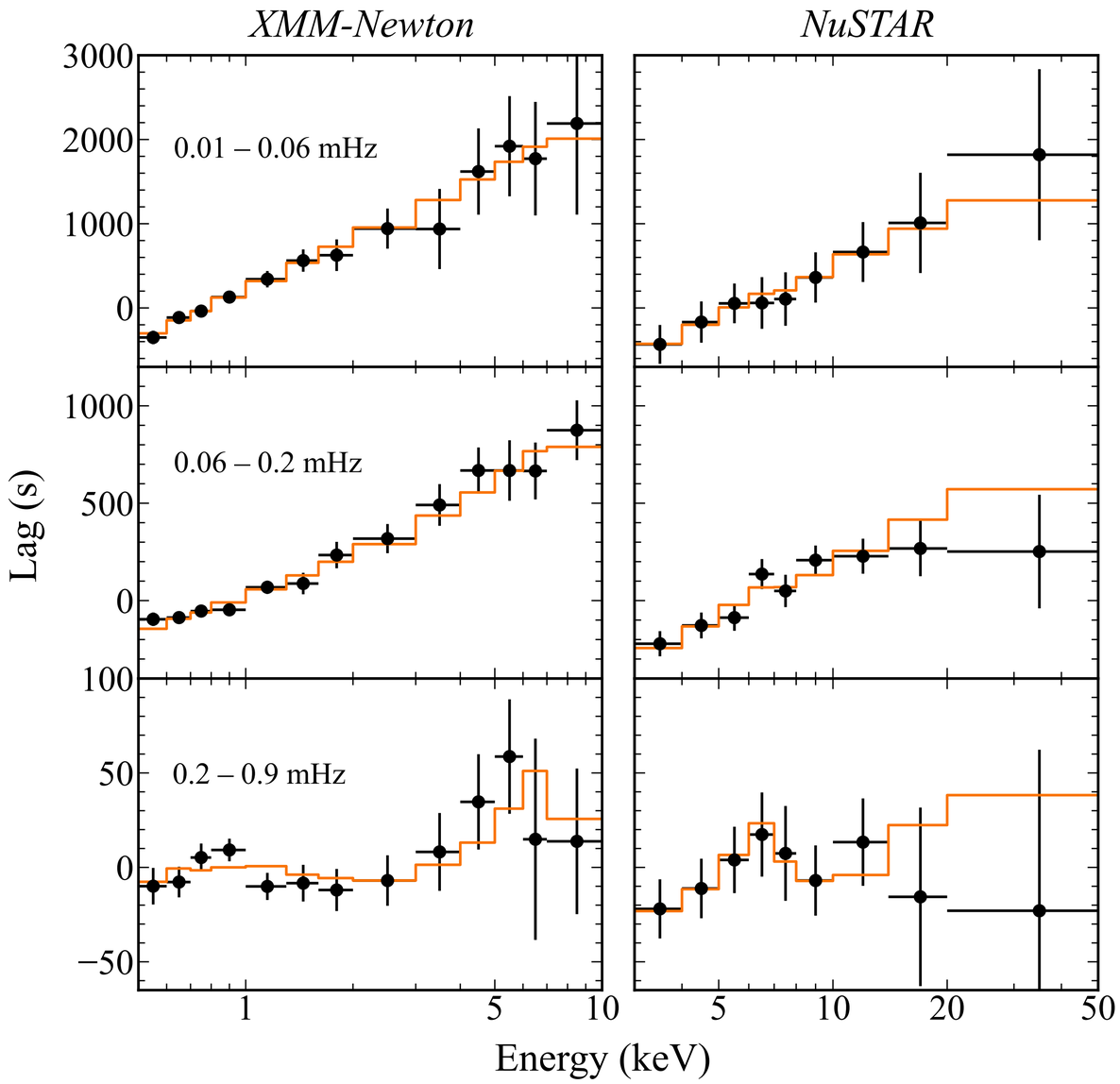
Mastroserio+ 2018

# Ark 564 - simultaneous fit




Lewin, Kara, Wilkins, Mastroserio+ 2022

# Ark 564 - physical constraints

- Mass constraint consistent with Shemmer+ 2001, Nikolajuk+ 2009, Denney+ 2009, Ponti+ 2012

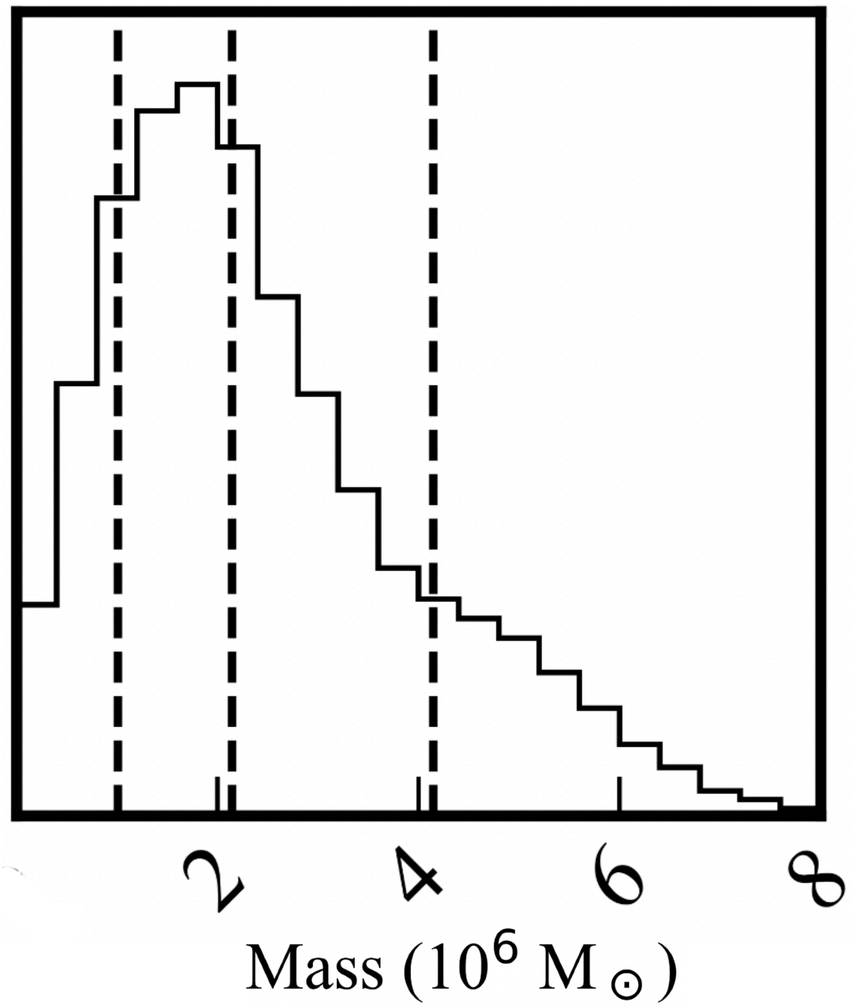
- Temperature of the corona is low, consistent with Kara et al. (2017)

$$H_{corona} = 9.6 \pm 0.6\ R_g$$

$$i = 37.0^{+0.9}_{-1.0}\ \text{deg}$$

$$M_{BH} = 2.14^{+1.96}_{-1.14} \times 10^6 M_\odot$$

$$kT_e = 14.8^{+1.0}_{-0.9}\ \text{keV}$$

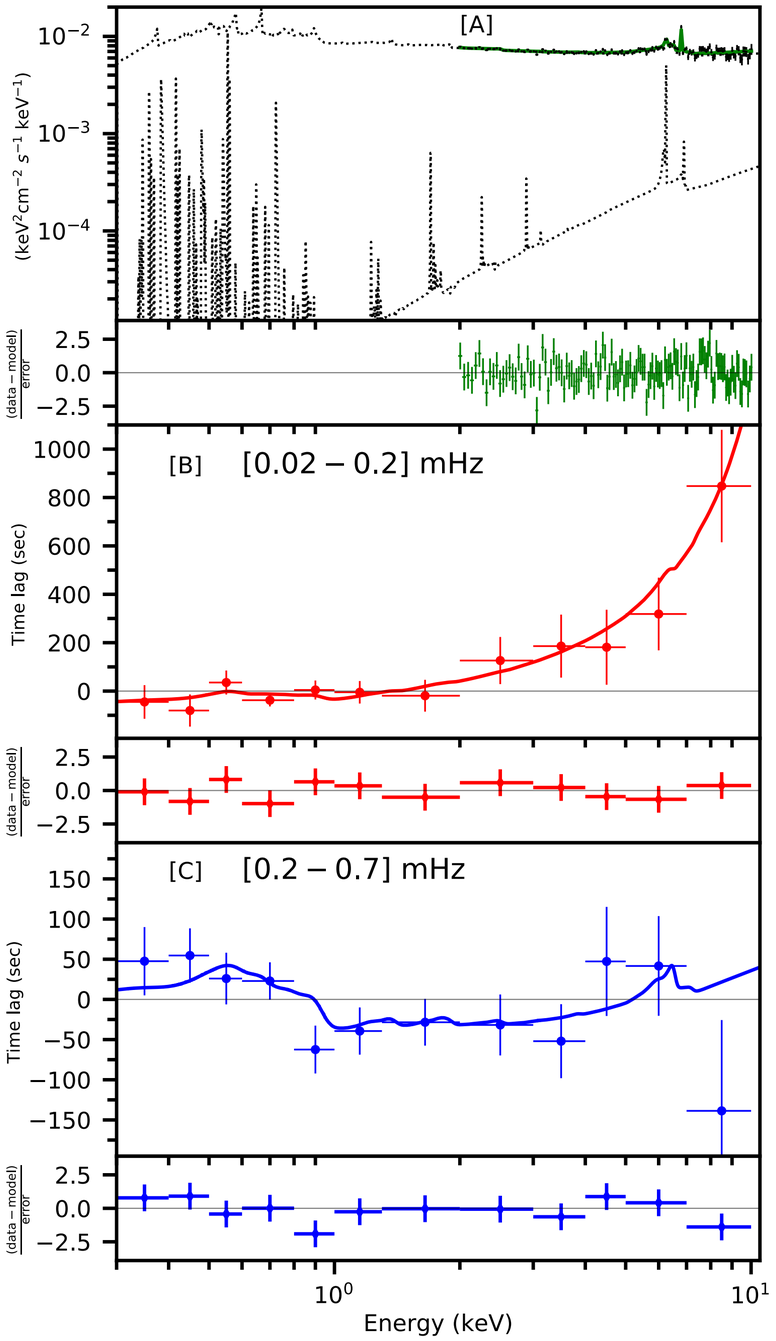


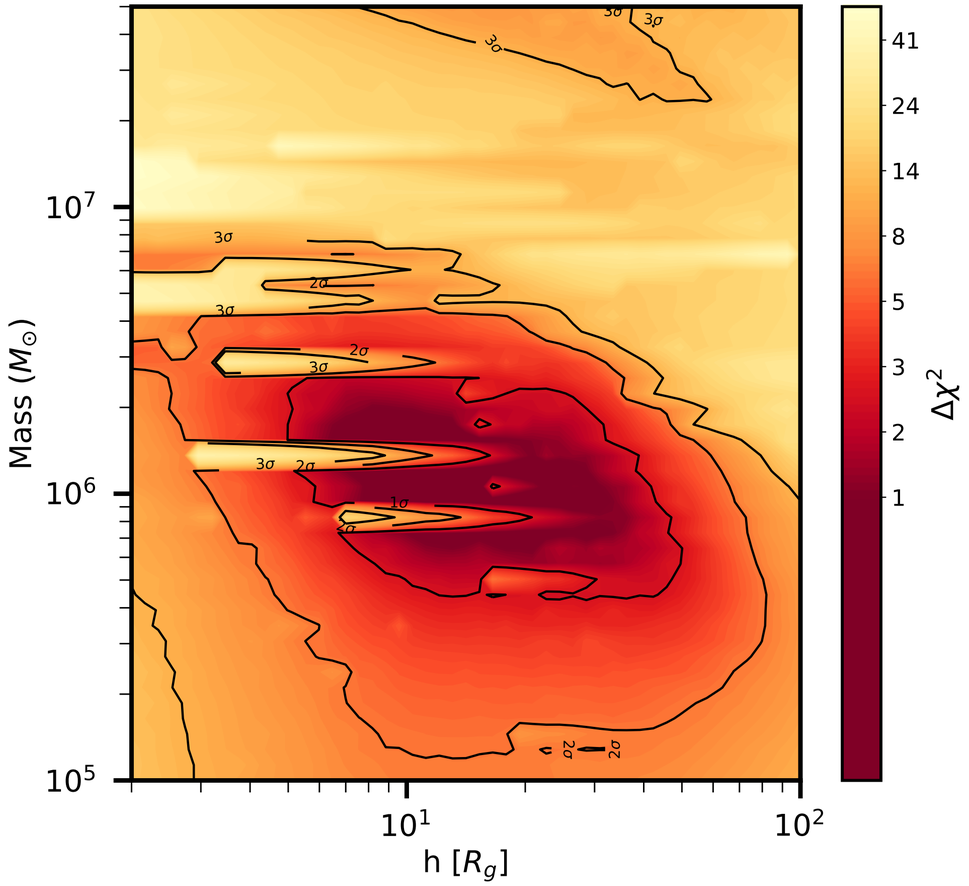

Lewin, Kara, Wilkins, Mastroserio+ 2022

# Mrk 335

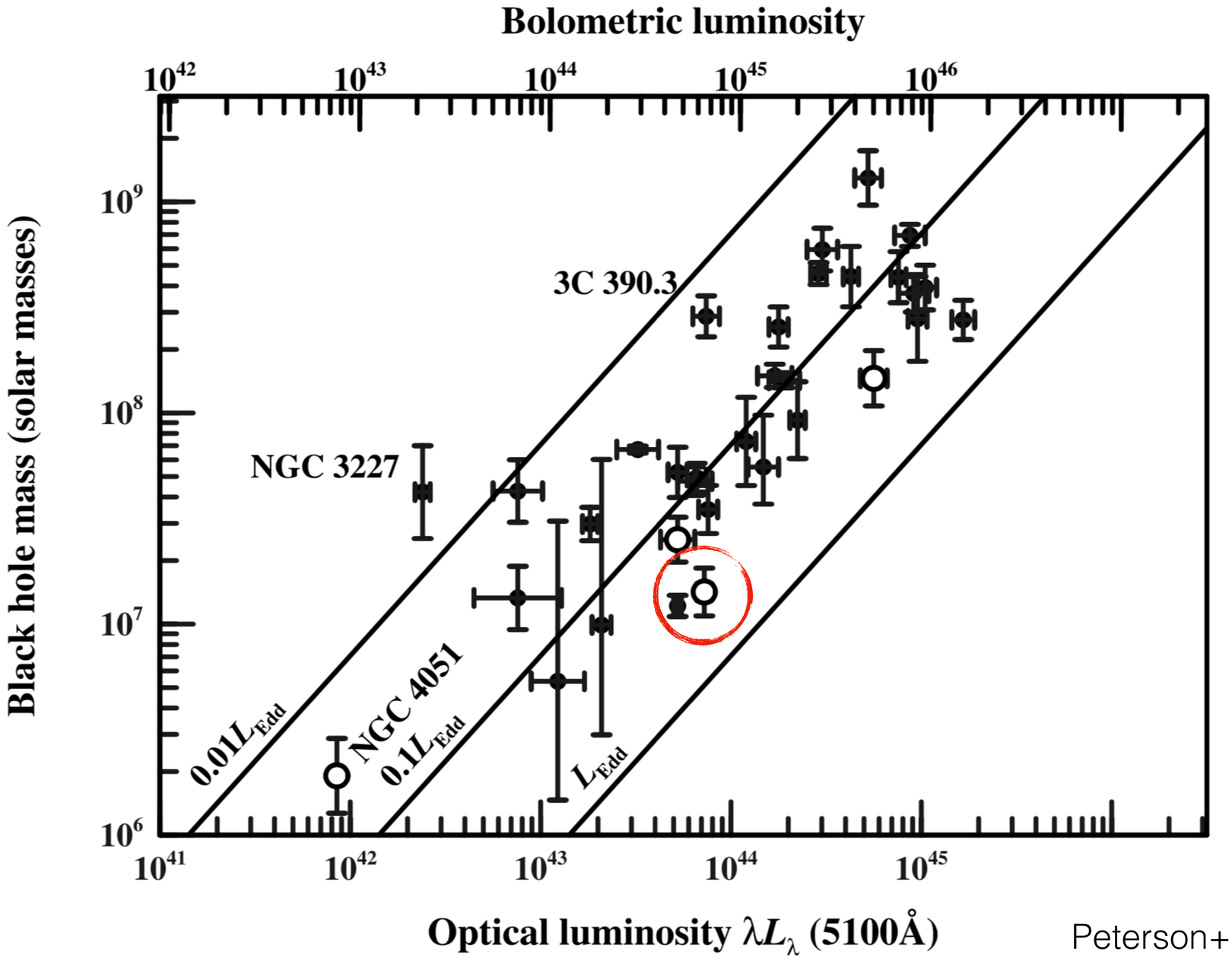
Including low frequency lag spectrum + time averaged spectrum

**breaks the degeneracy between black hole mass and source height**

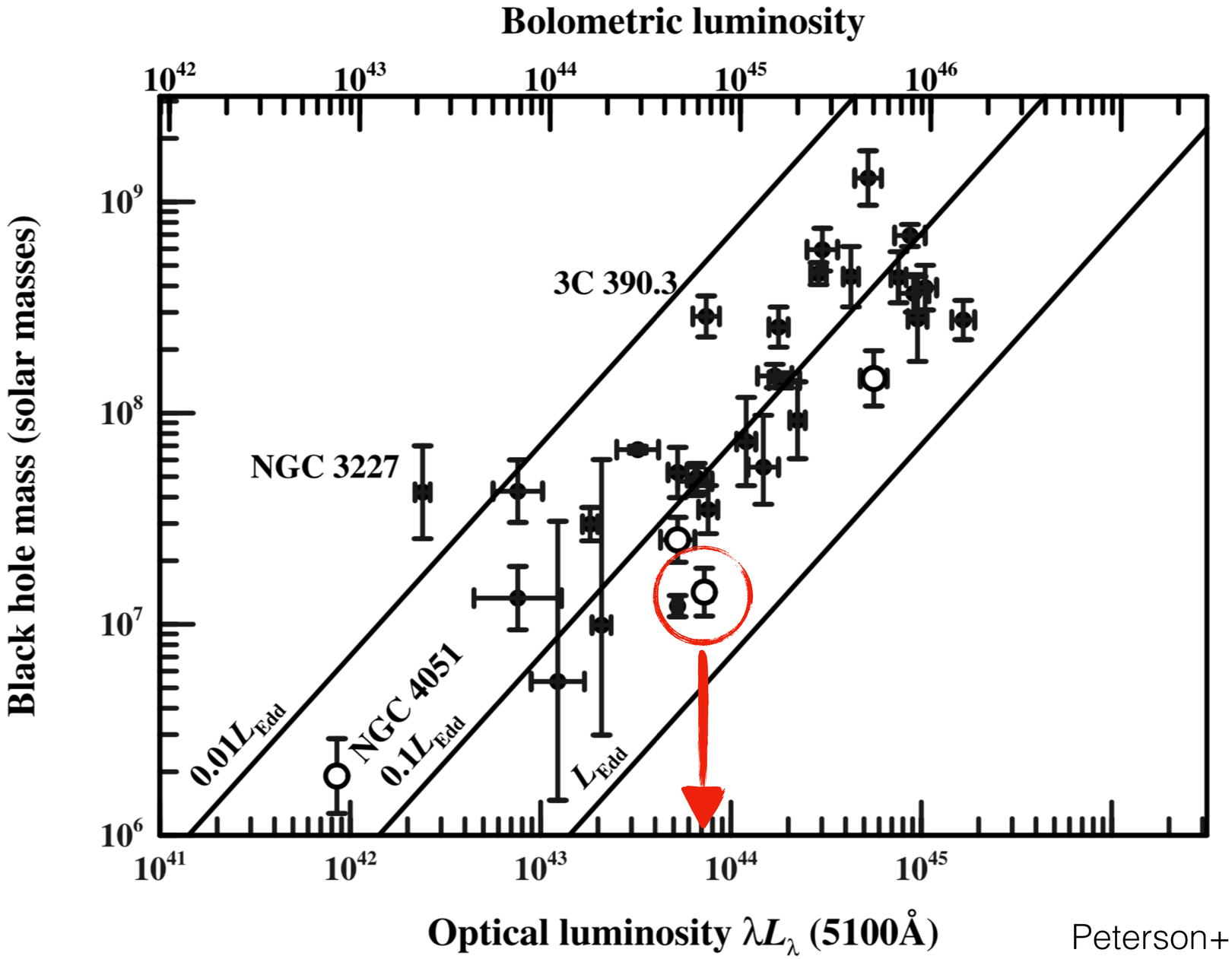



Mastroserio+ 2020

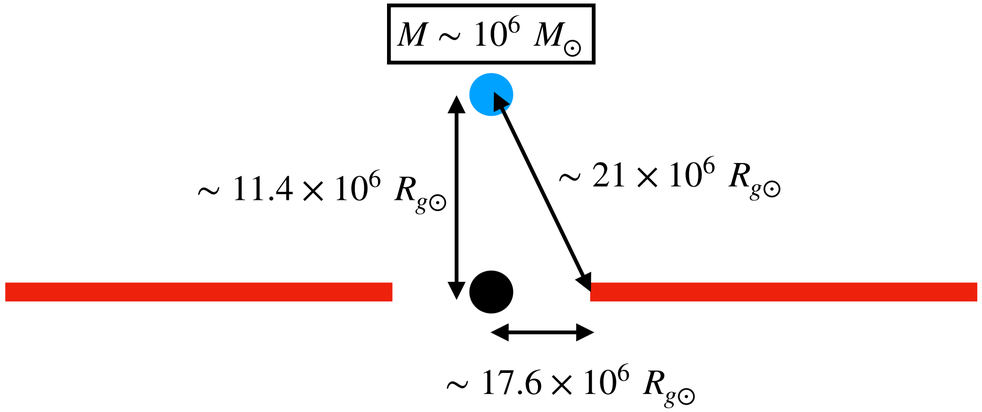



Peterson+ 2004

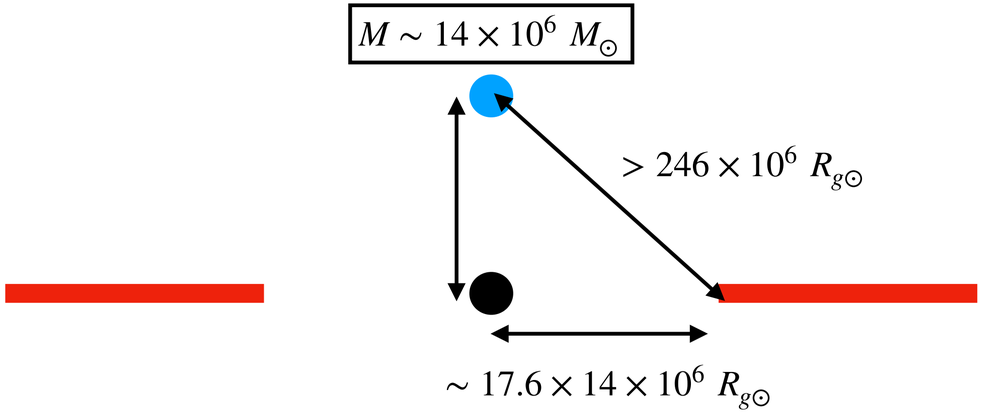



Peterson+ 2004

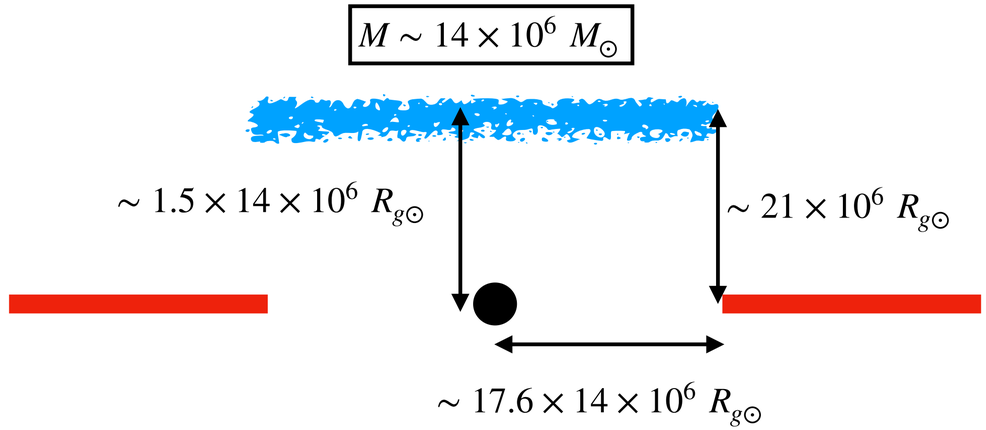
**Inner radius is always fixed at the same value in gravitational radius units**




Increasing the mass increases the physical distance between corona and disc

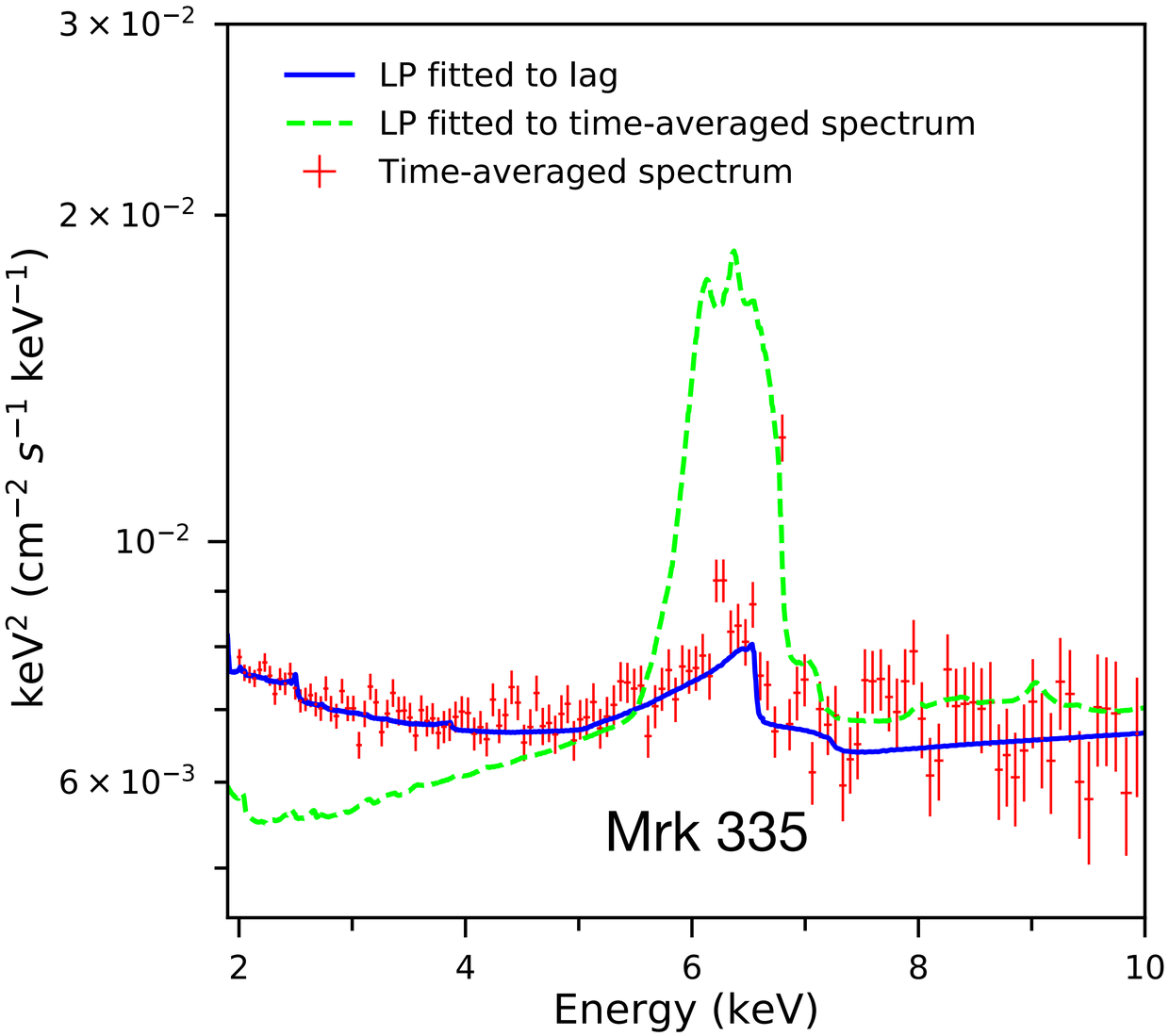



Considering an extended corona decreases the corona and disc physical distance, keeping the same inner radius



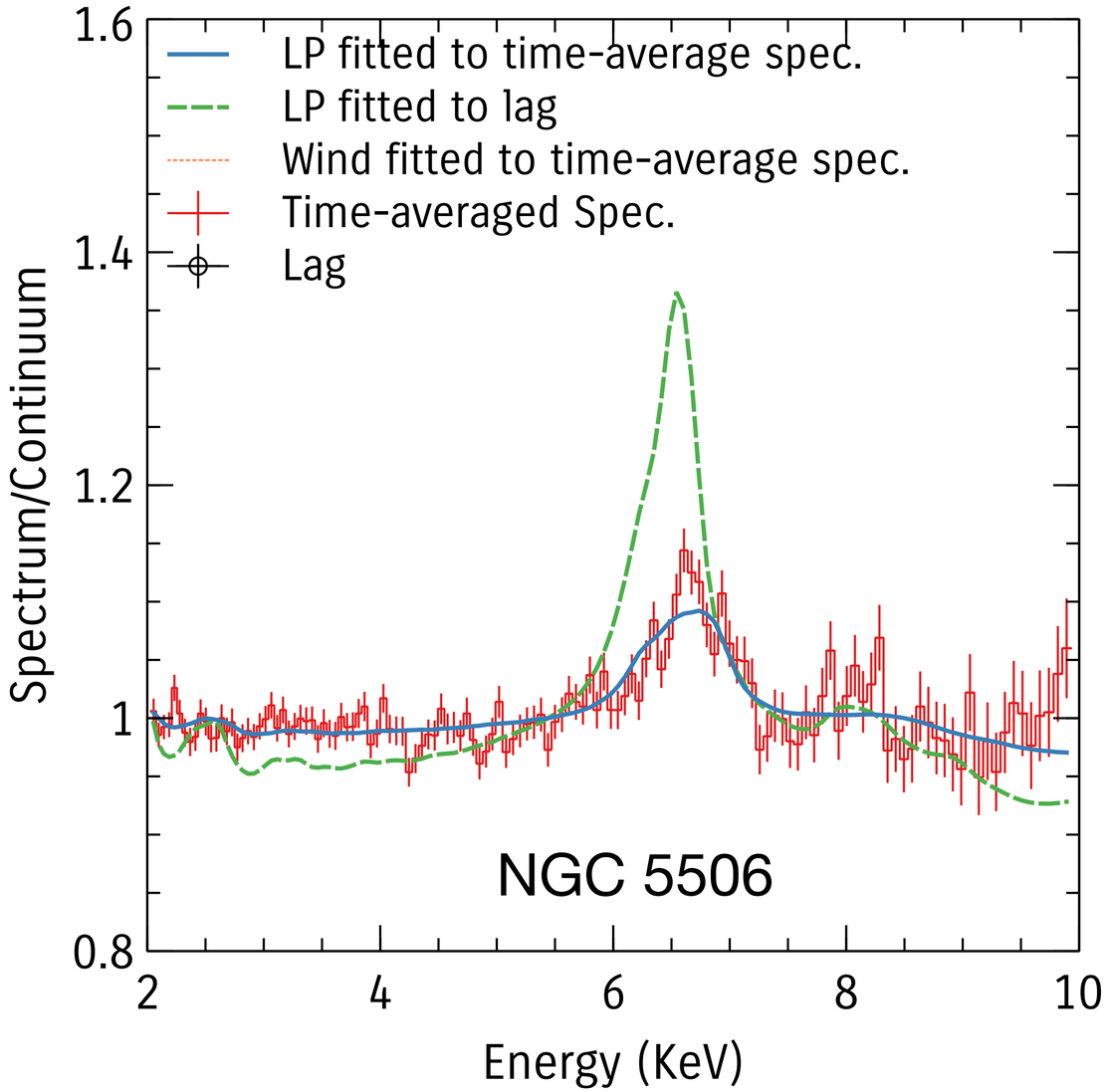

Mastroserio+ 2020

# X-ray reverberation lags vs flux energy spectrum

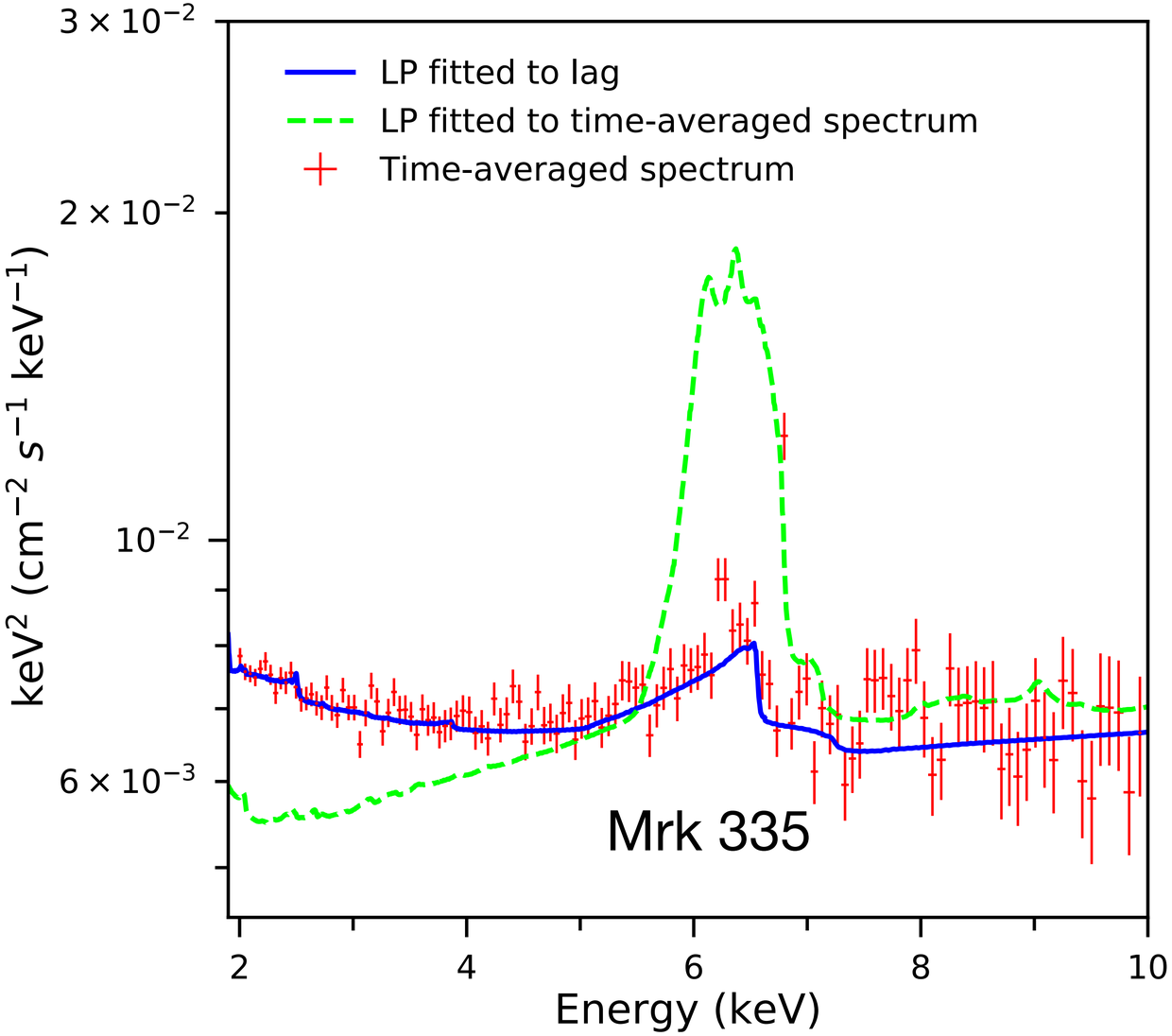



Mastroserio+ 2020

# X-ray reverberation lags vs flux energy spectrum



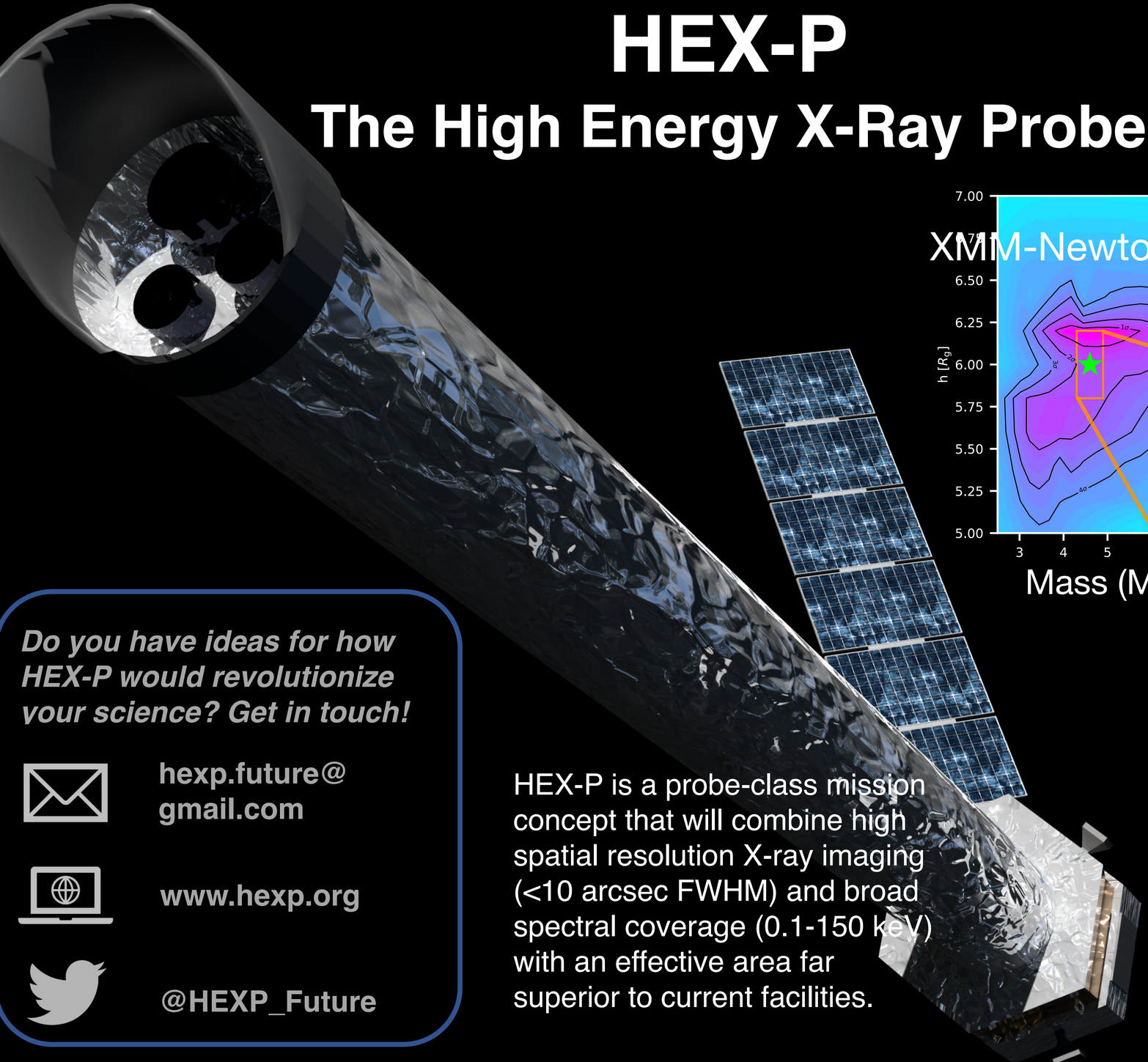

Zoghbi+ 2020




Mastroserio+ 2020

# HEX-P

## The High Energy X-Ray Probe

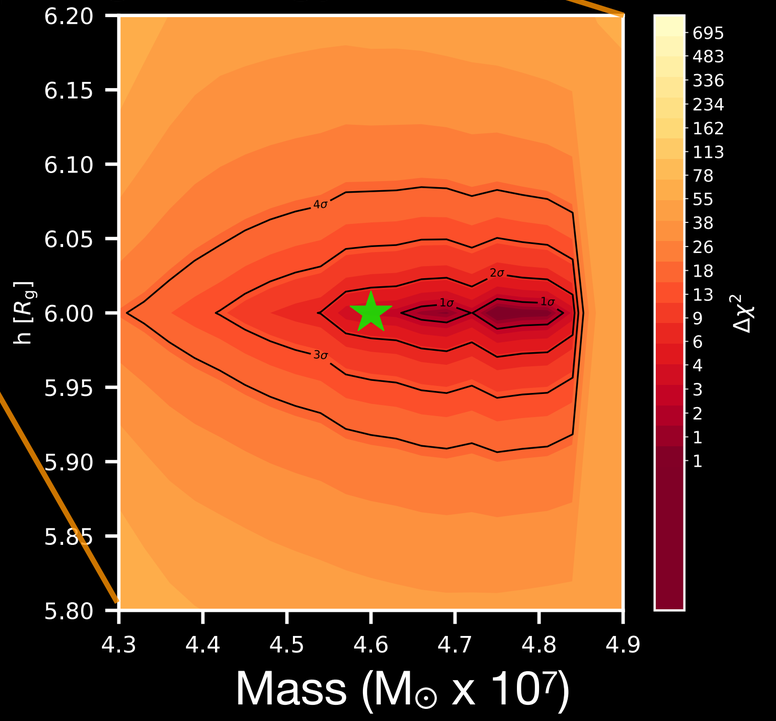





HEX-P X-ray reverberation simulations

Low Energy Telescope LET

High Energy Telescope HET




HEX-P is a probe-class mission concept that will combine high spatial resolution X-ray imaging (<10 arcsec FWHM) and broad spectral coverage (0.1-150 keV) with an effective area far superior to current facilities.

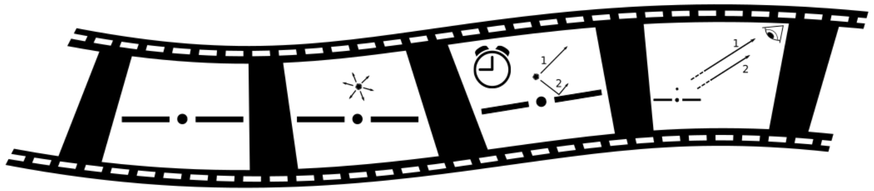
***Do you have ideas for how HEX-P would revolutionize your science? Get in touch!***


**hexp.future@gmail.com**

**www.hexp.org**

**@HEXP_Future**

# Conclusions



- Variability is a defining property of AGN
- Variability is a great tool to constrain the geometry of the innermost regions in AGN
- Modelling X-ray lags is crucial to study characteristic properties of AGN. Several models have been developed to describe the properties of the lag.
- X-ray reverberation is potentially a “new” method to measure BH mass

Guglielmo (Gullo) Mastroserio

# What I left out (too many things)

★ Variable absorption produces soft lags *(see Nicastro+1999; Krongold+ 2007; Silva+ 2016; Parker+ 2017; Juráňová+ 2022, Rogantini+ 2022)*

★ Reprocessing time of the incident radiation (see e.g. Salvesen 2022)

★ Time resolved spectroscopy of FeK line variability to look at orbital motions *(see Tombesi+ 2007; De Marco+ 2009, Nardini+ 2016, Marinucci+ 2020, Costanzo+ 2022)*

★ Spectral slope vs flux relation, softer when brighter, but also harder when brighter (LLAGN) *(e.g. Emmanoulopoulos+ 2012)*

★ Variability to identify AGN in surveys *(see e.g. Paolillo+ 2004; Soldi+ 2014; Lanzuisi+ 2014, De Cicco 2015 Yang+ 2016; Padovan+ 2017, De Cicco 2019)*

★ X-ray polarimetry *(see Orsini's talk)*

★ Measure the Hubble constant with X-ray reverberation in AGN *(Ingram, GM+ 2022)*