Observations of Ultra Fast Outflows in AGN

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Outflows from Active Galactic Nuclei

✦Introduction:

✳The discovery of the ultra fast AGN winds.

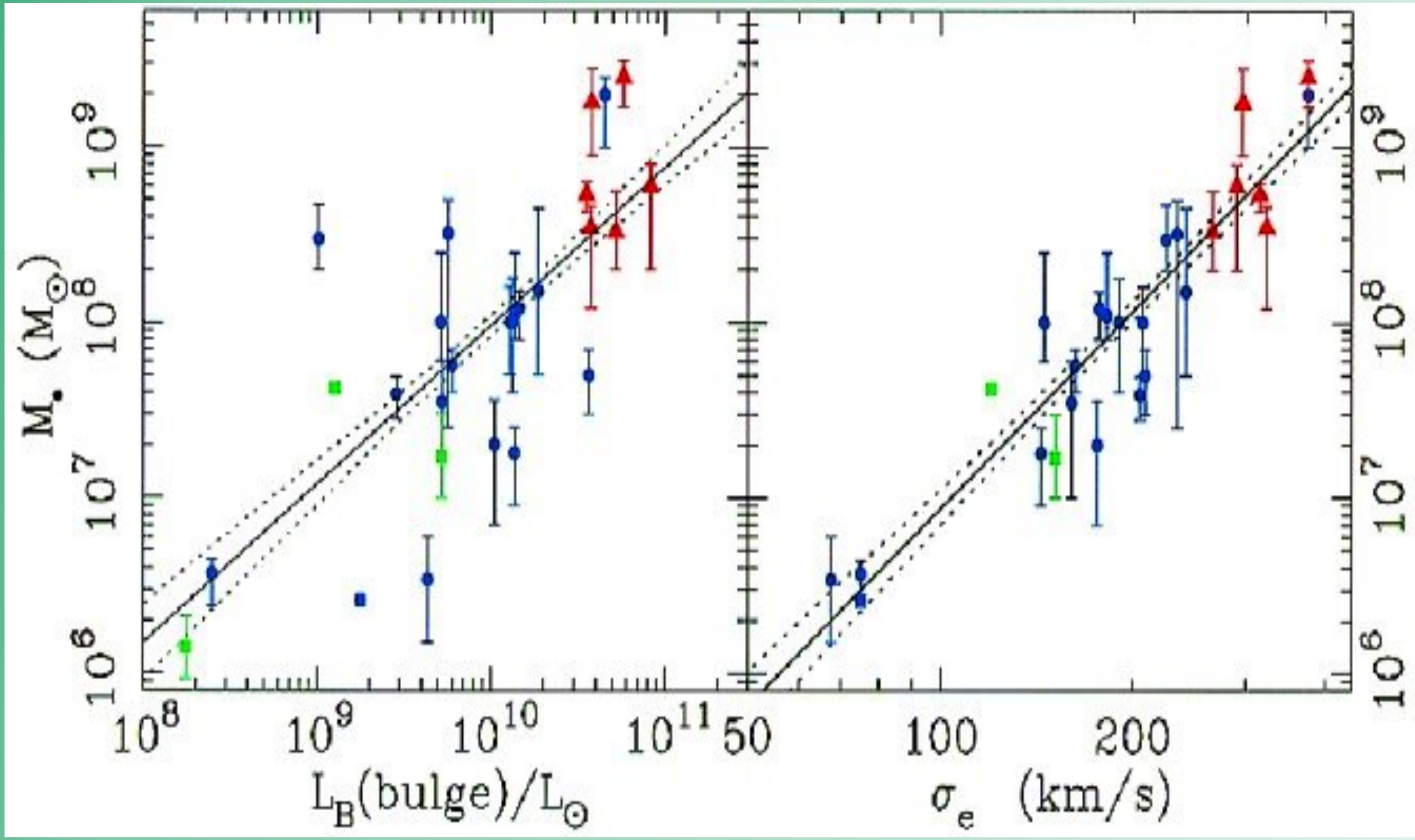
✦Recent results:

✳CASE STUDY 1: Recent results on the prototypes of the ultra fast winds PDS456.

✳CASE STUDY 2: MCG-03-58-007, extraordinary variability of the disk wind.

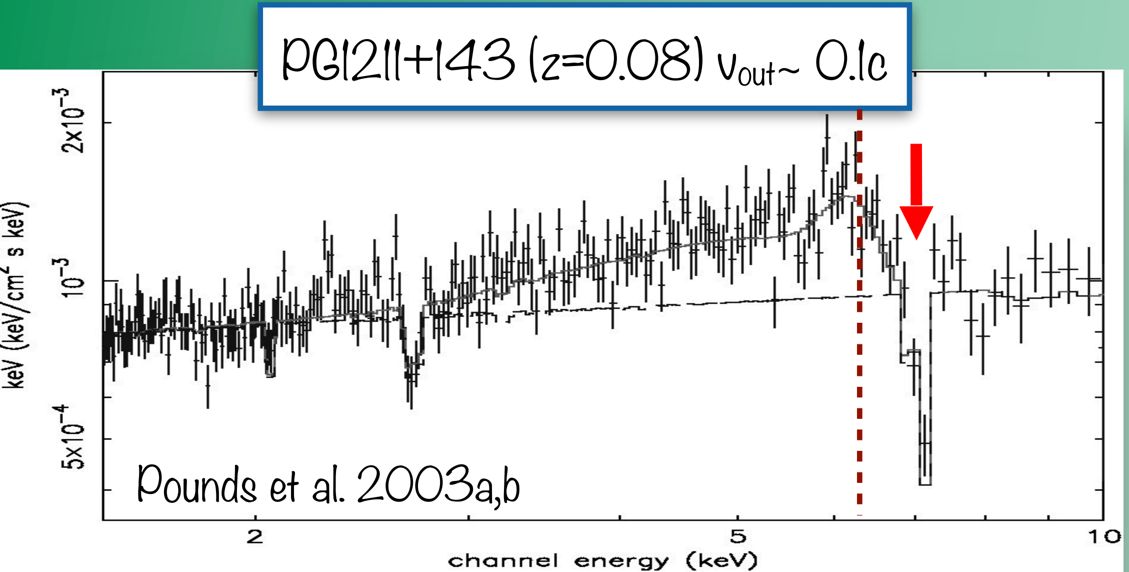
✳CASE STUDY 3: PG1448+273 a new variable disk wind.

Why do we care?

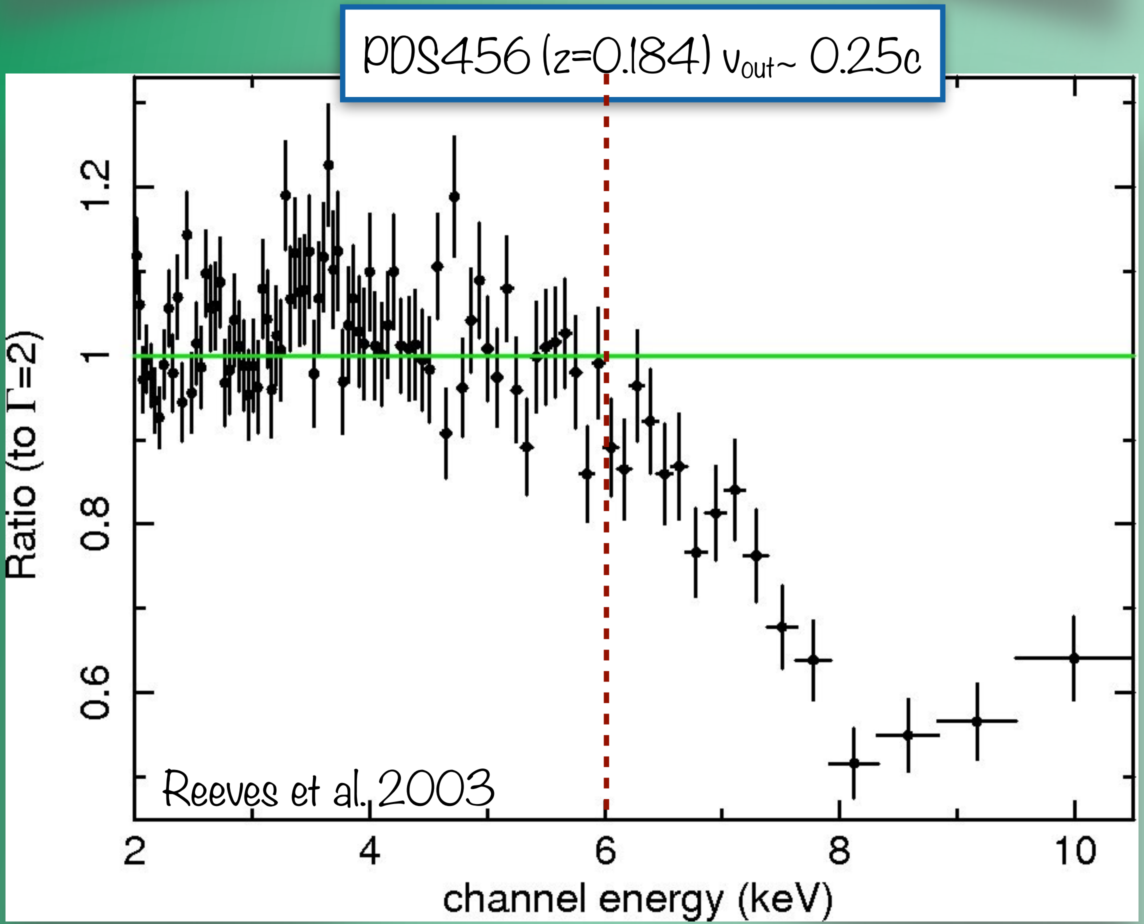


- ✳SMBH ubiquitous at center of local galaxies
- ✳Tight relation between the black hole mass and bulge vel. dispersion - the M-σ relation, where $M \propto \sigma^{4\text{-}5}$ (Ferrarese & Merritt 2000, Gebhardt et al. 2000).
- ✳But how do the hosts know about the central SMBH? SMBH sphere of influence ~ few x pc!
- ✳Are AGN winds a potential source of feedback? (e.g. Silk & Rees 1998, Fabian 2003, King 2003, Di Matteo et al. 2005)

Discovery of the ultra fast winds


PG1211+143 (z=0.08) v_{out}~ 0.1c

Pounds et al. 2003a,b


PDS456 (z=0.184) v_{out}~ 0.25c

Reeves et al. 2003

✶ First detections of blueshifted Fe K absorption profiles in PG 1211+143 and PDS 456.

✶ No known atomic transition that could explain the observed absorption structures.

✶ If interpreted as Fe XXV (6.7 keV) or Fe XXVI 1s-2p (6.96 keV).

➡high velocity (v~0.1-0.2c) and highly ionized winds.

➡Disk winds are launched from < 100Rg.

✶Detection of absorption in the Fe K band requires a large column density: $N_H \sim 10^{23} - 10^{24}$ cm^{-2}.

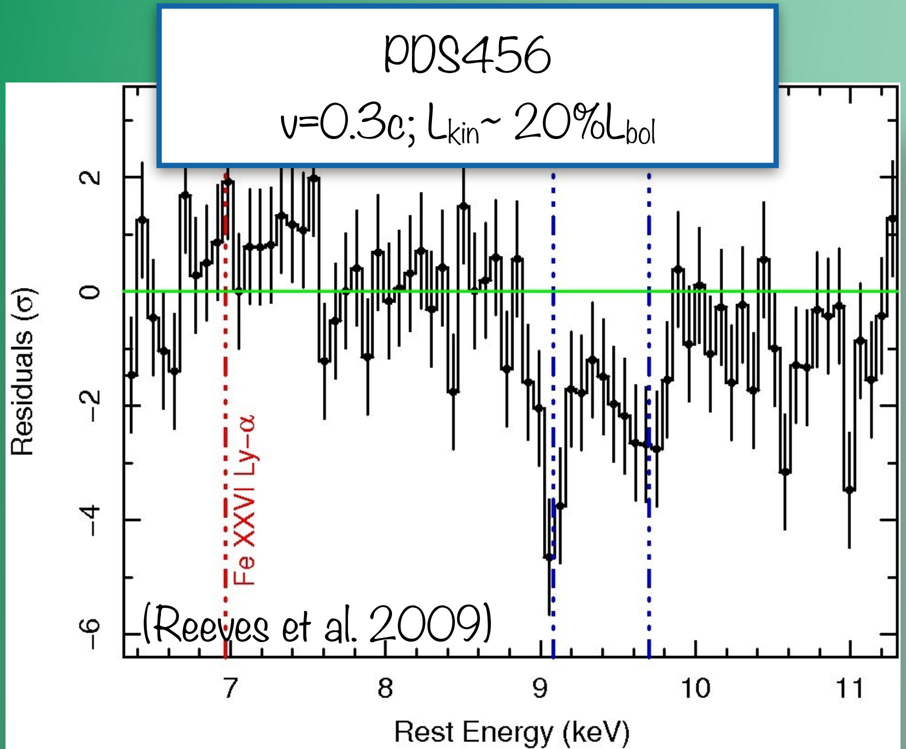
These winds are massive (few M_{SUN}/yr), highly ionized and ultra fast (0.1-0.2c)!

The ultra fast outflows (UFOs)

✓Evidence in the X-ray band for winds with high N_H, $\log\xi \simeq 3-6$ erg cm s^{-1} & v_{out} up to 0.3 c in ~ 40% of the radio quiet AGN (Gofford et al. 2013, Tombesi et al. 2010)!

✓Powerful winds are expected at high accretion rates (King 2003).

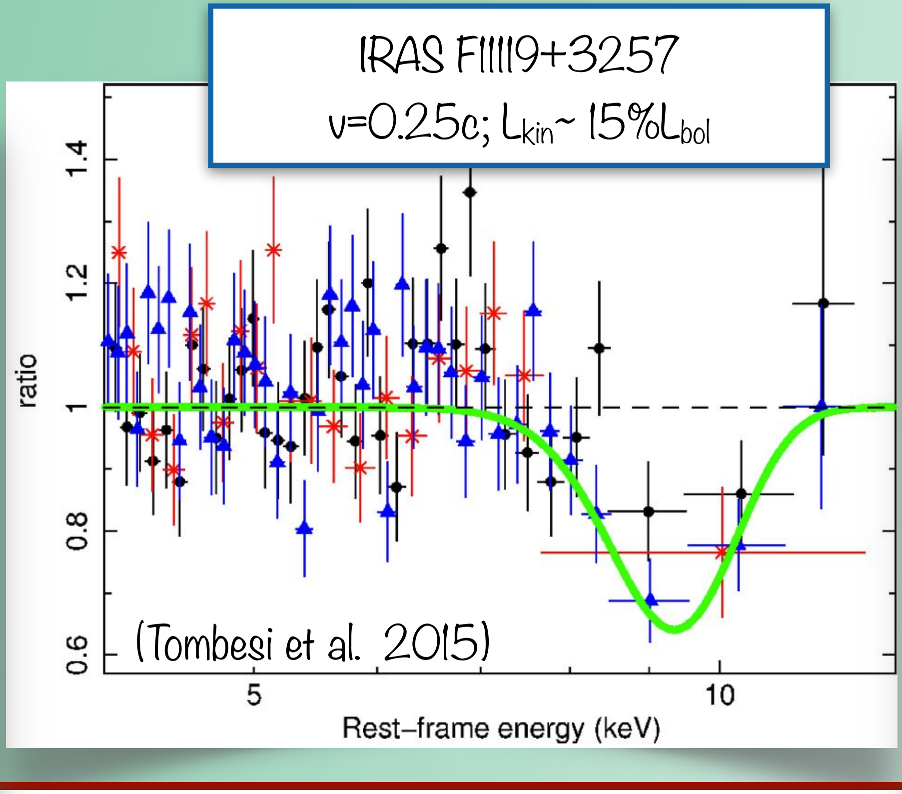
✓Disk wind simulations naturally produce blue-shifted Fe K absorption (Sim et al. 2010, Proga & Kallman 2004 & Fukumura et al. 2015).



PDS456

$v=0.3c$; $L_{kin}\sim 20\%L_{bol}$

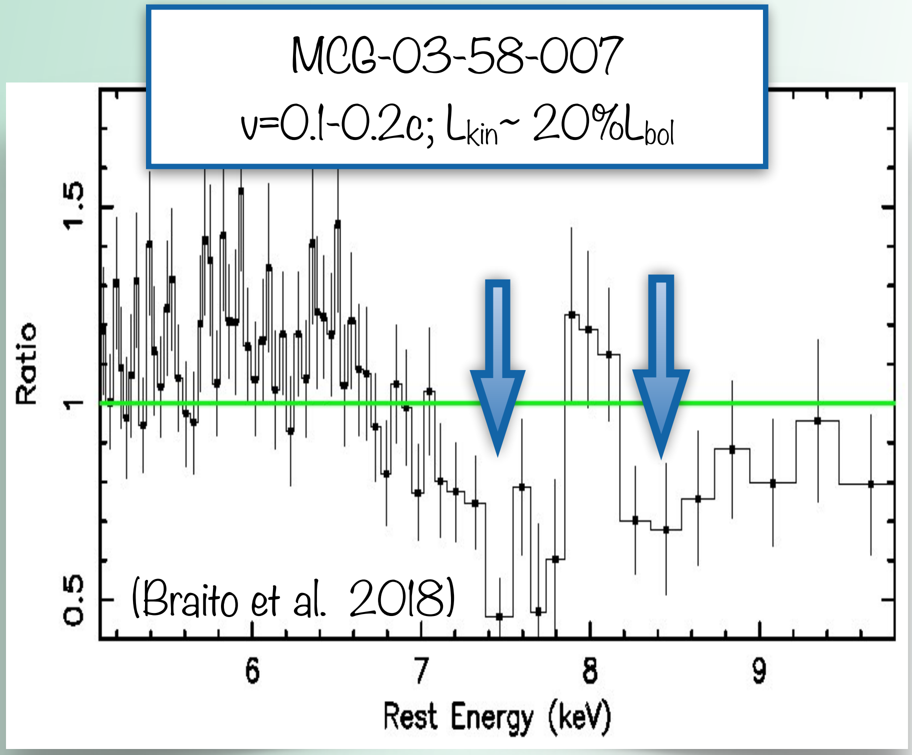
(Reeves et al. 2009)



IRAS F11119+3257

$v=0.25c$; $L_{kin}\sim 15\%L_{bol}$

(Tombesi et al. 2015)



MCG-03-58-007

$v=0.1\text{-}0.2c$; $L_{kin}\sim 20\%L_{bol}$

(Braito et al. 2018)

UFO (high ξ & N_H zones): velocities up to tens of thousands km/s

May carry a significant Kinetic power - equivalent to the bolometric output

PRIME CANDIDATES FOR THE FEEDBACK!

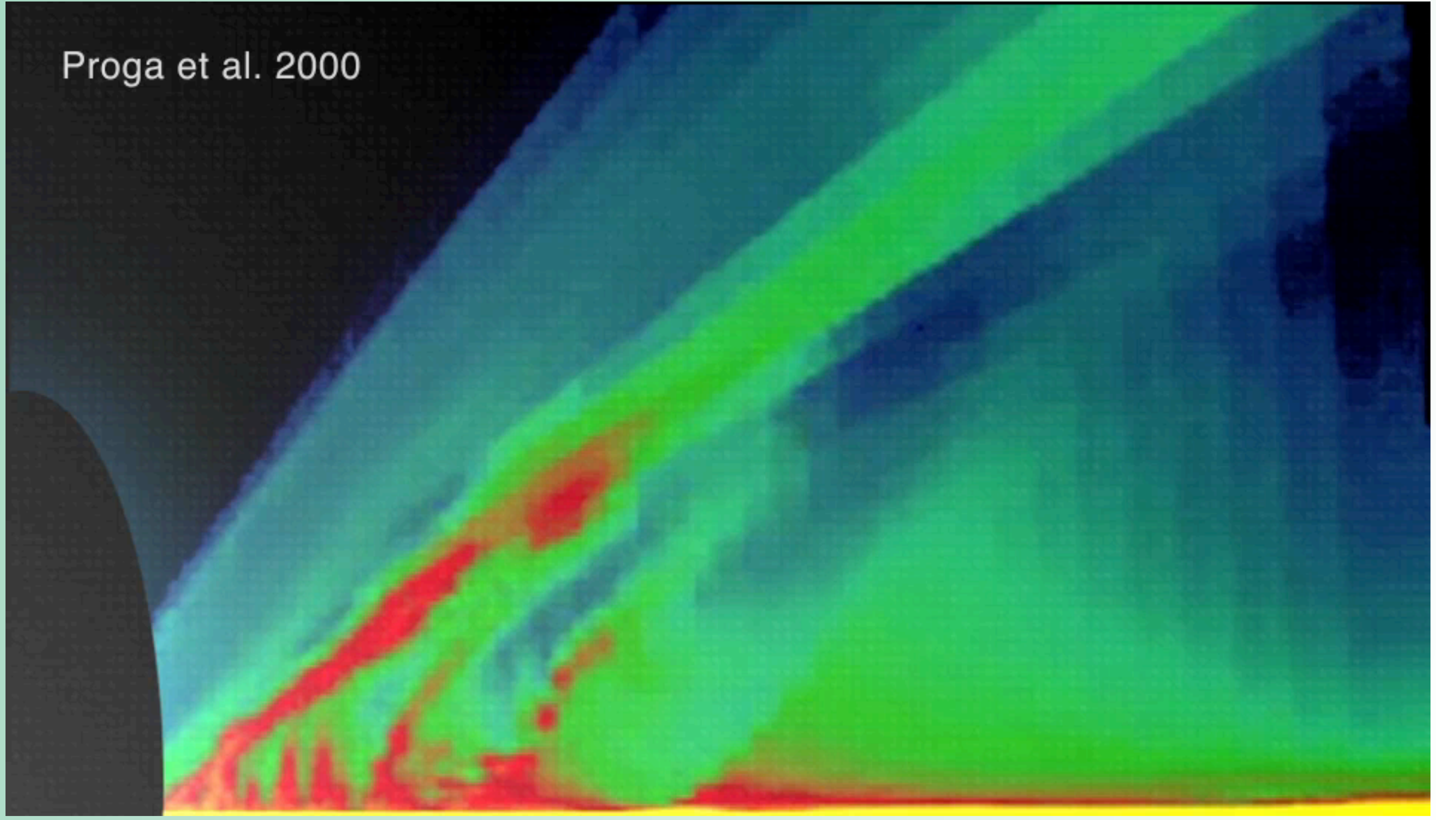
OUTFLOWS ENERGETICS

Are the Ultra fast winds the physical explanation of the MBH-σ relation?

- ★How much mass is carried out by these outflows?
- ★What's their kinetic output?
  - ★ Mass rate is: $\dot{M}_{out}=4\pi b m_p v\, n R^2=4\pi b m_p v\, L_{ion}/\xi$
  - ★covering factors (b), N_H, R
- ★How much of this mechanical energy will reach the bulge gas ?
  - ★velocity structure/ionisation, how do they evolve?

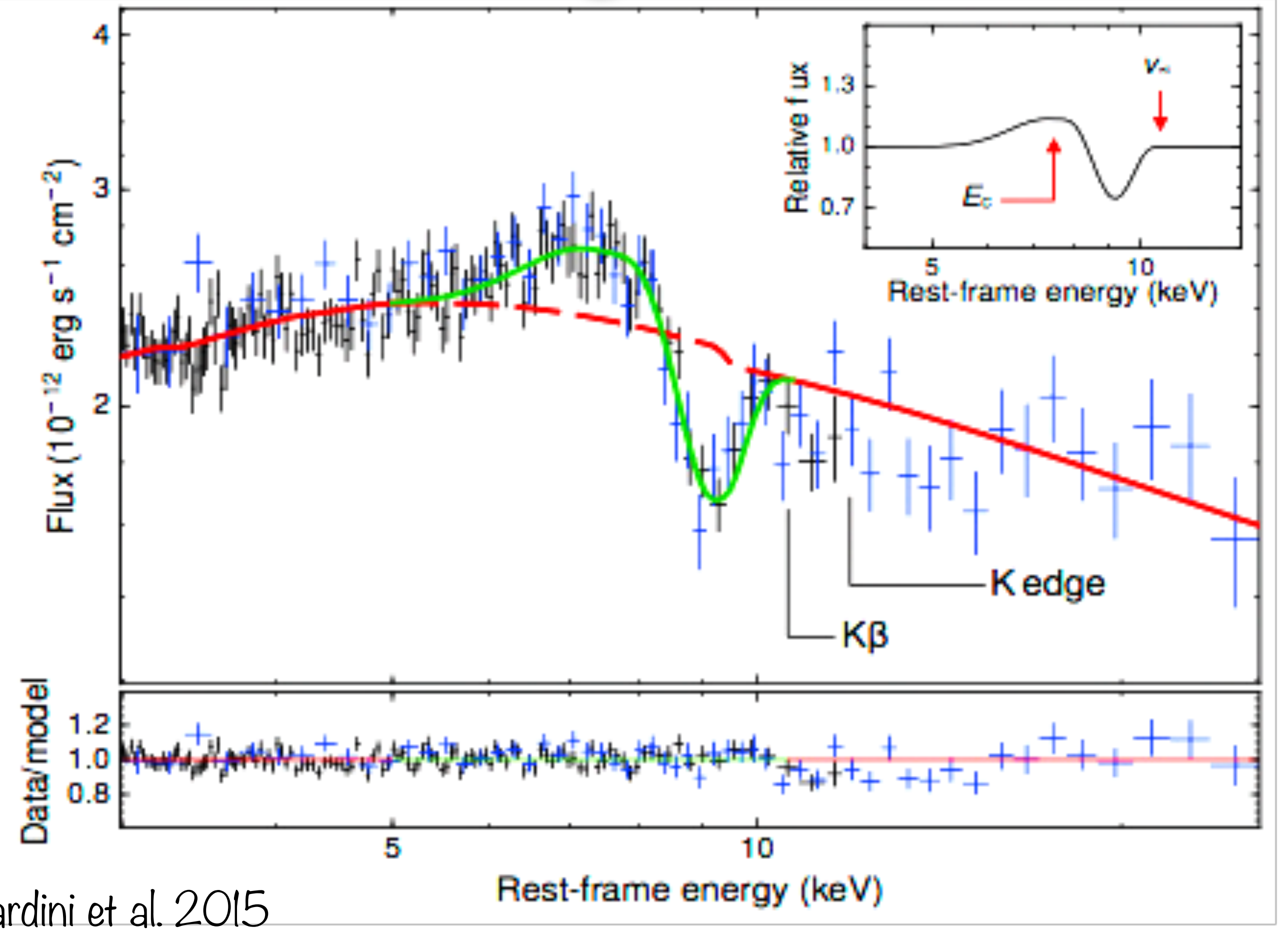
Major uncertainties:
launch radius & solid angle

First we need to map them:
N_H, velocity, ionisation, location,
duty cycle & driving mechanisms!



Wide-angle UFO in PDS 456

For the first time we had all the informations to derive M_{OUT}



Nardini et al. 2015

2013/14 campaign: 5 simultaneous XMM + NuSTAR observations

$$M_{out} \sim \Omega\, m_p\, N_H\, v_{out}\, R_{in}$$

✓N_H & V_{out} - modelling of absorption by photoionised gas

✓Ω - P Cygni profile - directly measure for the first time the opening angle of the wind: $\Omega > 2\pi$

✓Variability - constrains location R_{in}-30-100 R_g

$M_{out} \sim 10\ M_{SUN}/yr$

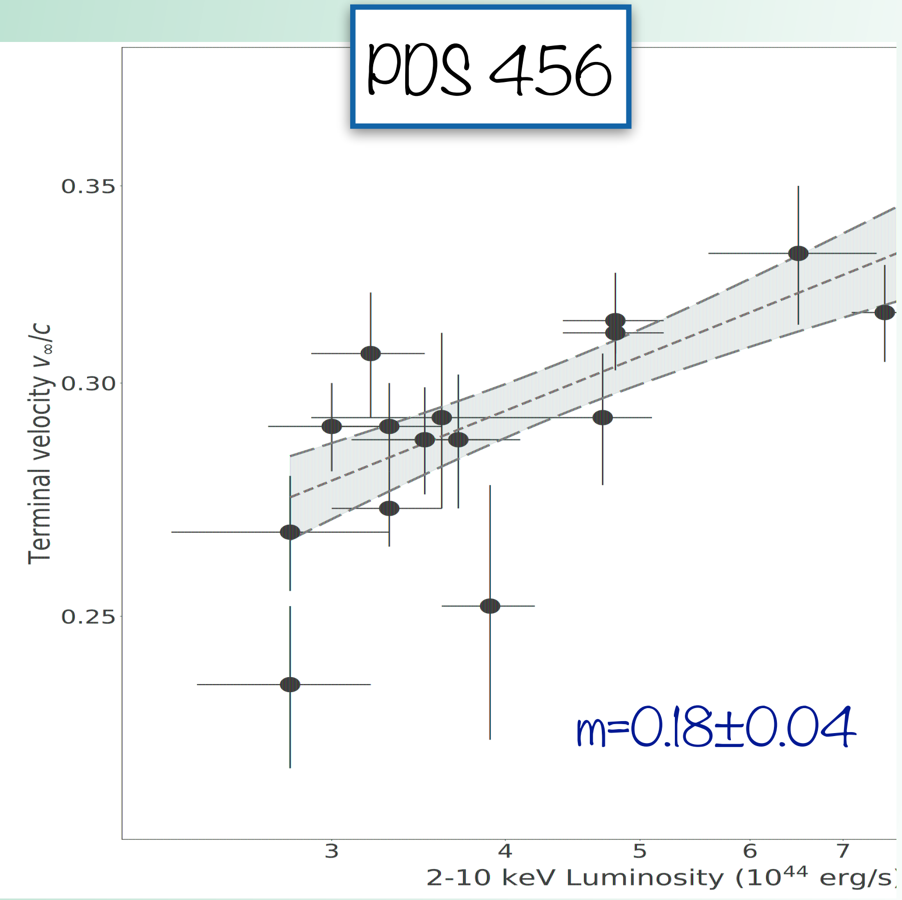
$E_{KIN} \sim 2 \times 10^{46}$ erg/s ~ 20% L_{BOL}

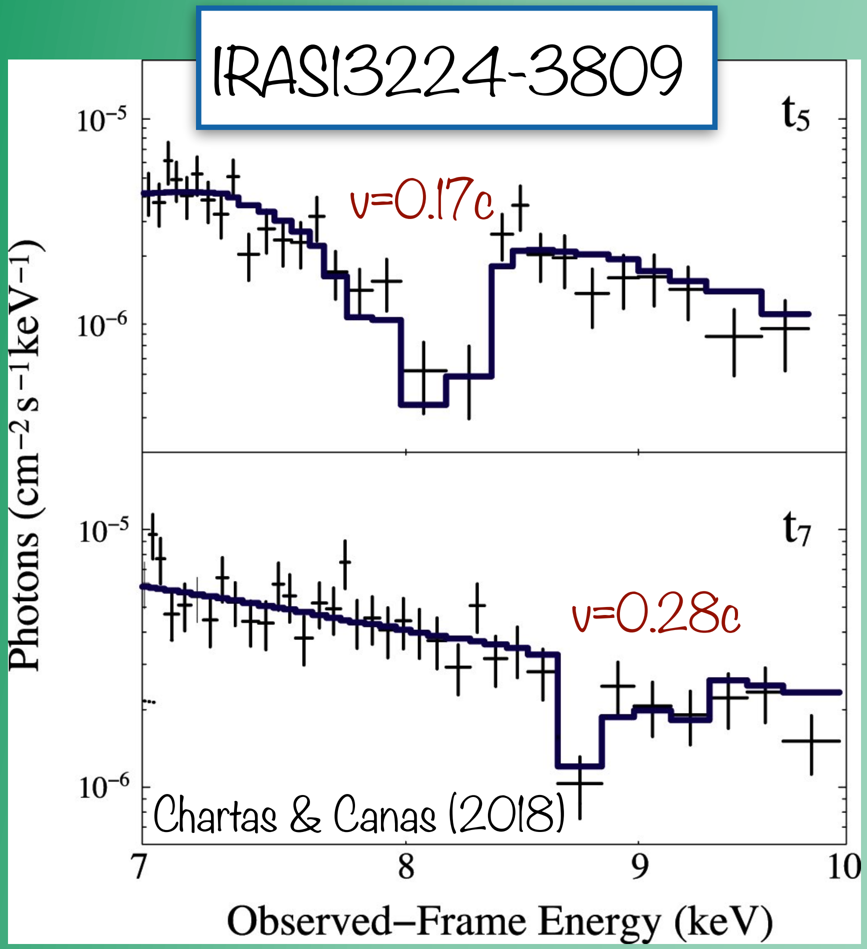
Over a lifetime of 10^7 yr the energy released through the accretion disk wind likely exceeds the binding energy of the bulge $E \sim 10^{61}$ erg

Disk Wind variability

- ✶Disk winds are extremely variable on timescales as short as a few weeks or even days
- ✶Variations seen in their ionization, N_H & velocity
- ✶Variability can inform us on their nature (i.e. clumpiness) and ultimately the driving mechanism. What causes the variability? Are we intercepting different clumps or streamlines? Are the winds responding to the ionizing X-ray flux?

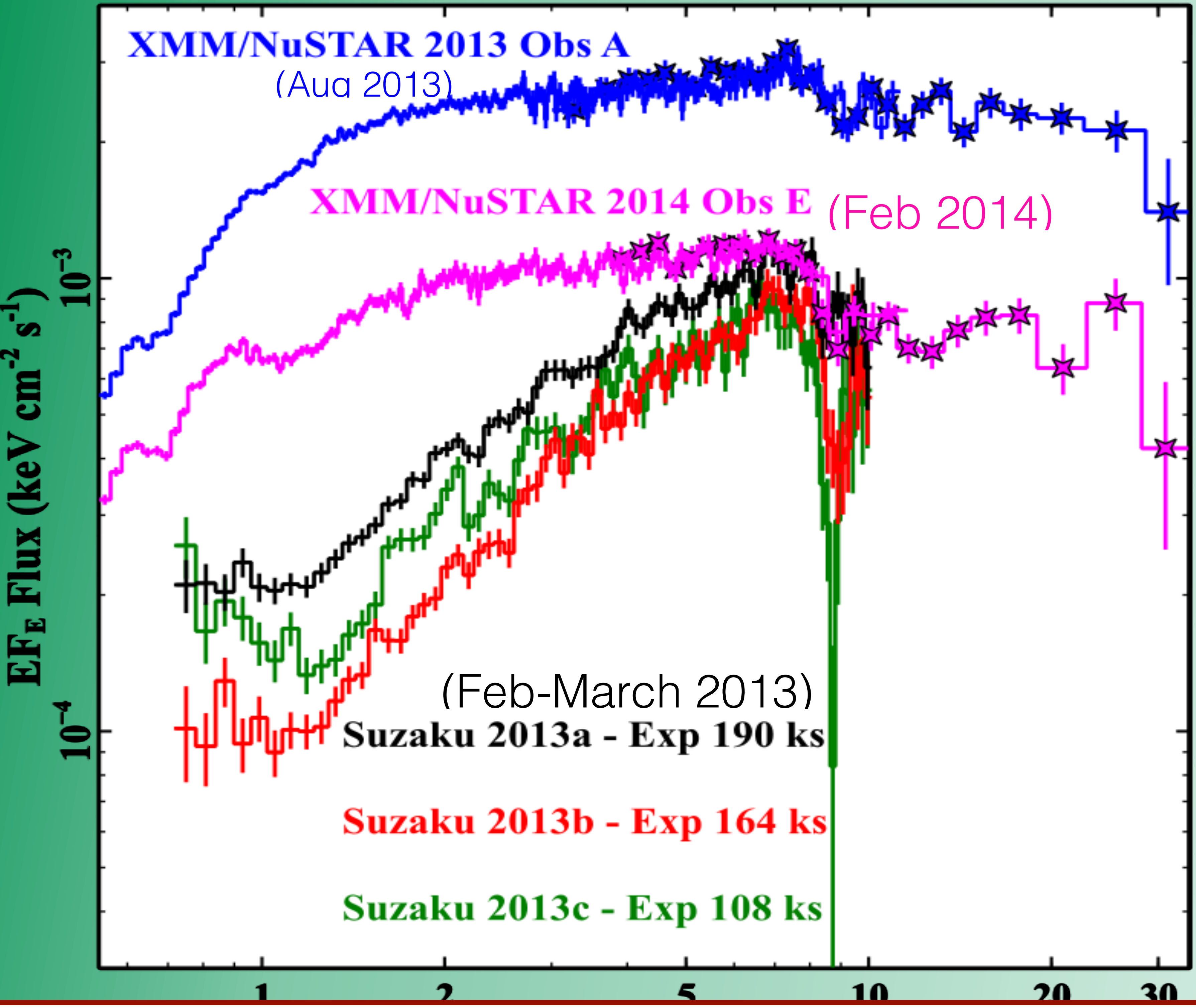
In PDS456 the outflow velocity correlates with X-ray luminosity (Matzeu et al. 2017). Radiation driven wind ?


PDS 456


IRAS13224-3809

Similar corr. seen for IRAS13224 (Parker et al. 2017; Pinto et al 2018; Chartas & Canas 2018) & APM 08279+5255 (Saez & Chartas 2011) and more ...

Case Study 1 - One Year in the Life of PDS 456!

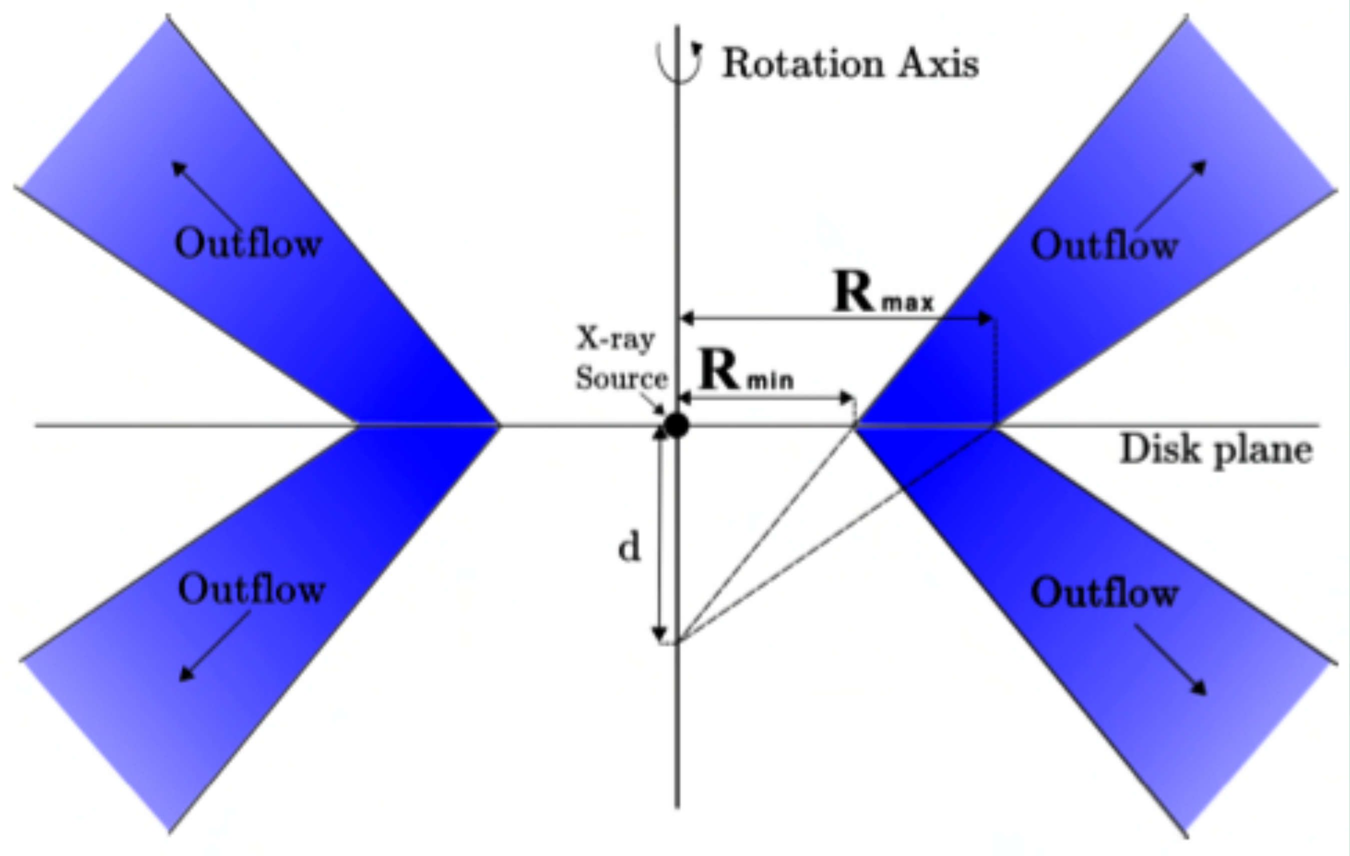


Most luminous radio-quiet AGN in the local Universe:

- $L_{BOL} \sim 10^{47}$erg/s
- $M_{BH} \sim 10^{9} M_{SUN}$
- $z \sim 0.184$

Does the wind respond to the variability of the primary emission?

Disk Wind Modelling



- ✳Radiative transfer code of Stuart Sim (Sim et al. 2008, 2010) used for disk wind modelling. Special relativistic effects are included as is the (scattered) emission from the wind
- ✳Computes synthetic X-ray spectra for homogeneous wind streamlines - (Matzeu et al. in prep)

Fixed wind geometry:- an opening angle of 45 degrees (or d=1)

Wind thickness:- $R_{out} / R_{in} = 1.5$ – ratio of outer to inner launching radii

Launch radii, $R_{in}=32R_g$ and $R_{out}=48\ R_g$ (for PDS 456)

Variable parameters:- mass outflow rate $\dot{M} = \dot{M}out/\dot{M}Edd$

Ionizing X-ray luminosity $L_X = L_{2\text{-}10} / L_{Edd}$ – set according to the X-ray luminosity per observation.

Terminal velocity parameter, f_v, calculated in terms of the launch radius as $v\infty = fv\sqrt{2GM/R}$

(f_v=0.9-1.4 for PDS 456, or max terminal velocities of 0.225c – 0.35c)

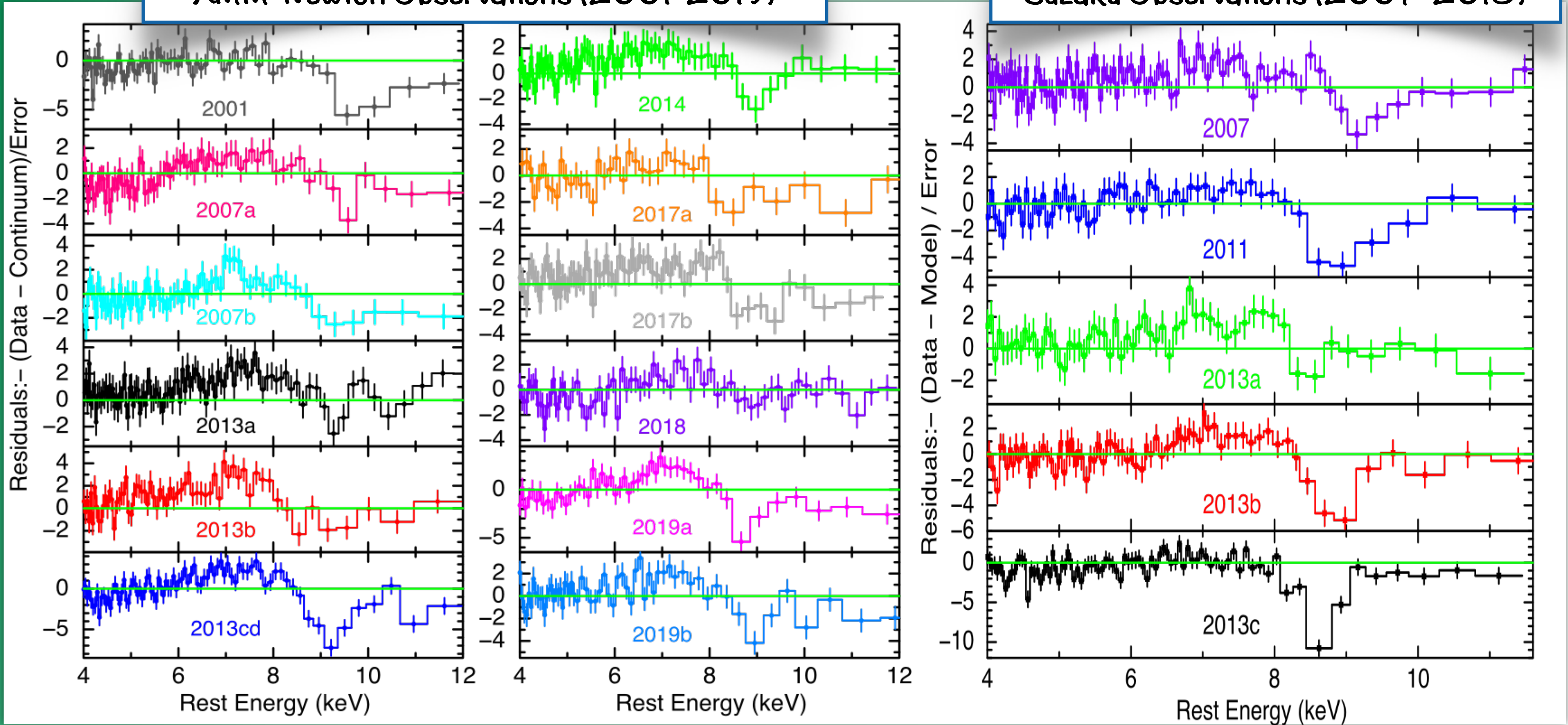
Inclination angle μ=cosθ $\mu = \cos\theta$ - where $\mu < 0.7$ intercepts the wind.

Photon index – set equal to that of the primary continuum per observation.

20 years of the Ultra Fast Outflow in PDS 456

XMM-Newton Observations (2001-2019)

Suzaku Observations (2007-2013)

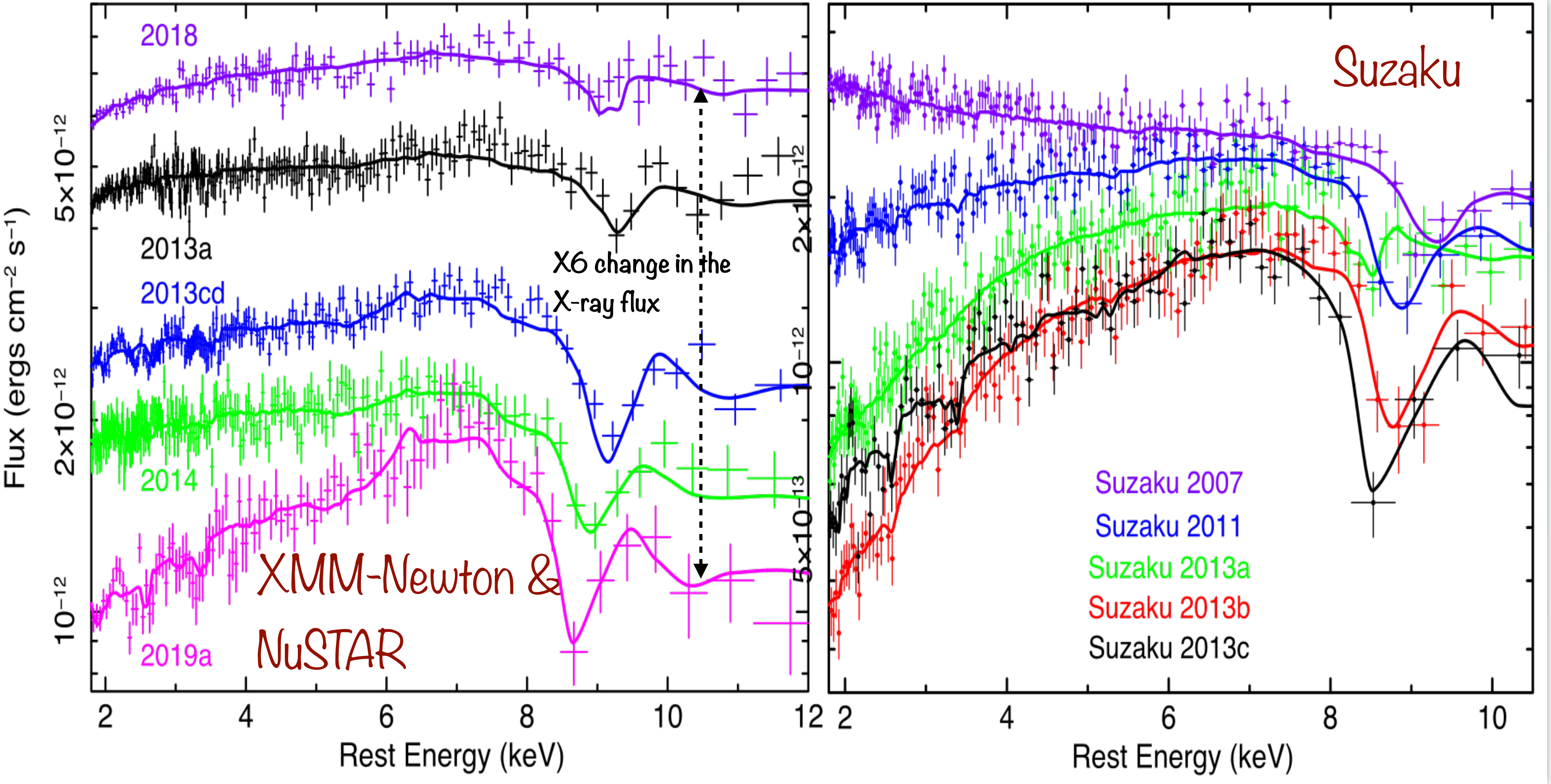


Archival Observations of PDS 456 (2001-2019) for disk wind modelling:-

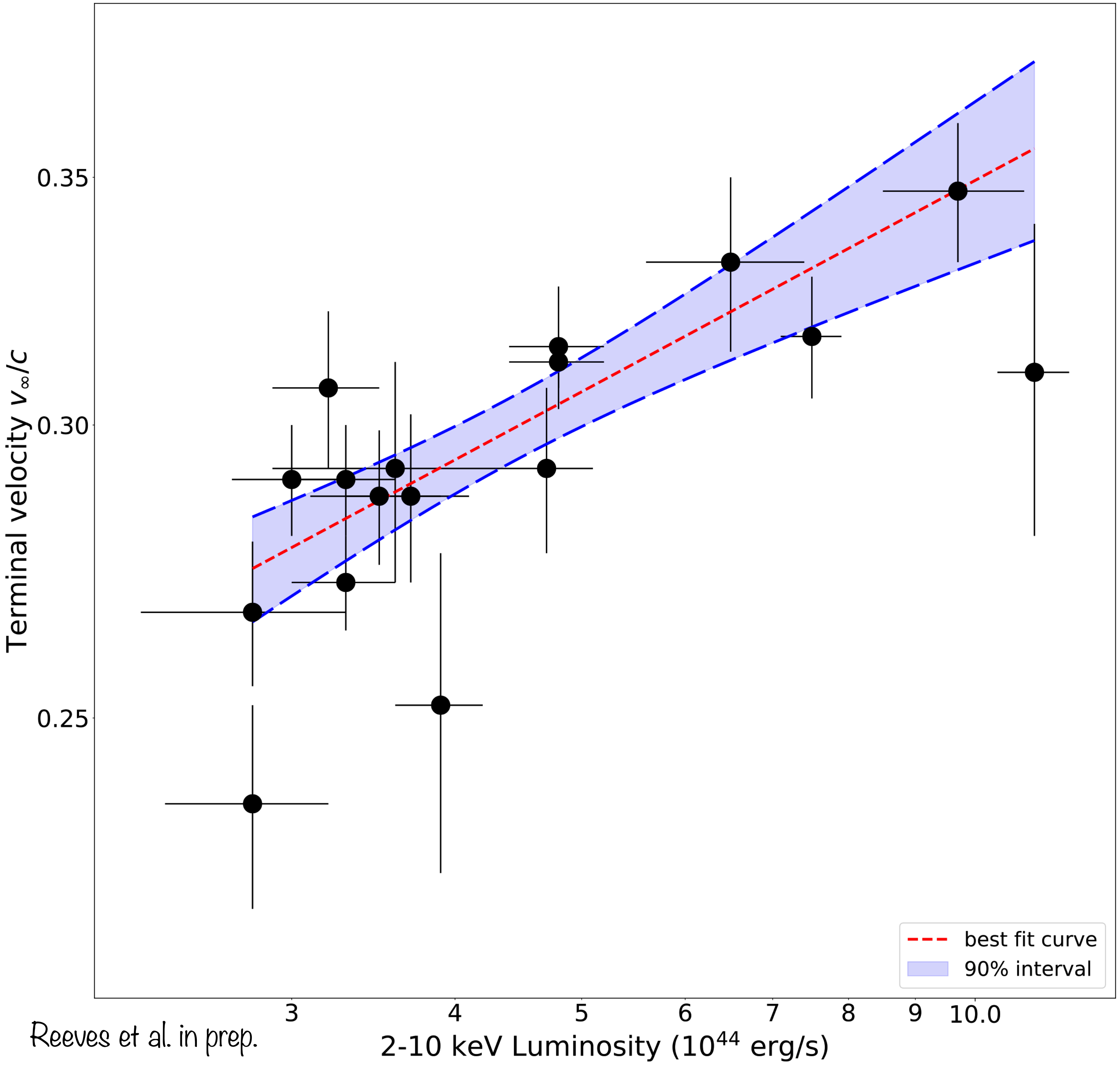
- 12 independent XMM-Newton epochs from 2001-2019 (2013c and 2013d combined into 2013cd)
- 8 of these are simultaneous with NuSTAR (included in fitting)
- 5 Suzaku observations (2007, 2011, 2013a, b, c)
- Thus 17 epochs for diskwind fitting covering a wide range of fluxes!

Disk Wind Modelling

- Mass outflow rate varies between 10-50% of $\dot{M}_{Edd}$
- Wind terminal velocity ranges between 0.25-0.35c.
- 2-10 keV luminosity typically 0.2-1% of L_{Edd} (which sets wind ionization level).
- Variable soft X-ray absorption accounted for by low ionization partial coverer.



Wind velocity increases with X-ray luminosity

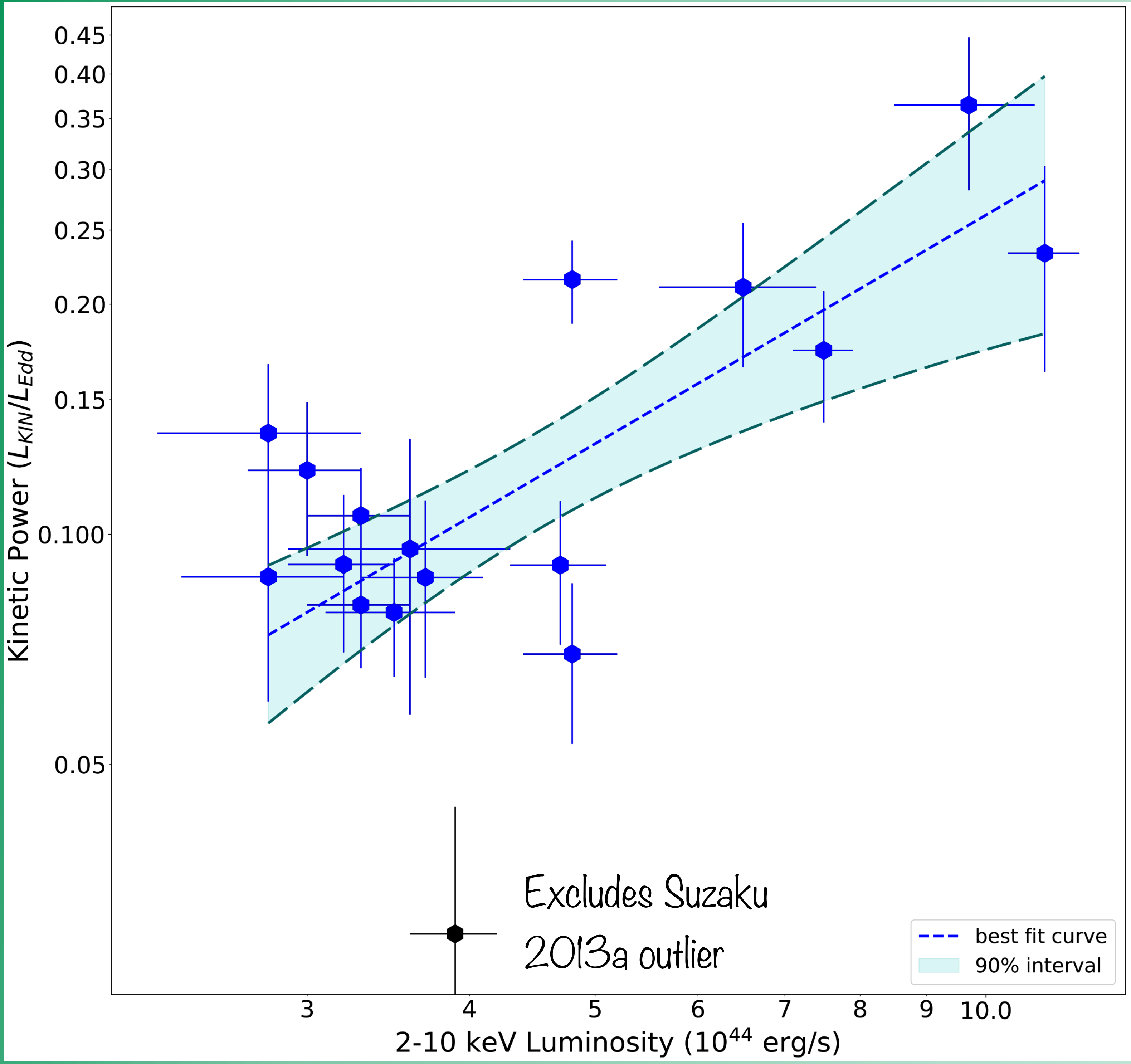


Reeves et al. in prep.

- ✦Wind terminal velocity increases with X-ray luminosity.
- ✦Follows power-law relation with slope of α=0.18±0.04
- ✦Consistent with relation found by Matzeu et al. (2017, MNRAS. 427, L15) for PDS 456 as possible evidence of effect of radiation pressure on wind

see e.g. Chartas & Canas 2018 for IRAS 13224

Wind Kinetic power vs Luminosity



Excludes Suzaku 2013a outlier

- ✦Wind kinetic power increases with X-ray luminosity.
- ✦Power-law relation with slope of α=0.84±0.26.

➡Thus the wind is more powerful as the QSO becomes more luminous.

- ✦Correlation partly as a result of trend between wind velocity and luminosity – wind kinetic power is proportion to v^3.
- ✦Scatter due to variation in mass outflow rate, e.g. Suzaku 2013a observation.
- ✦Similar correlation between p-dot vs Lx.

Case Study 2:The extraordinary MCG-03-58-007

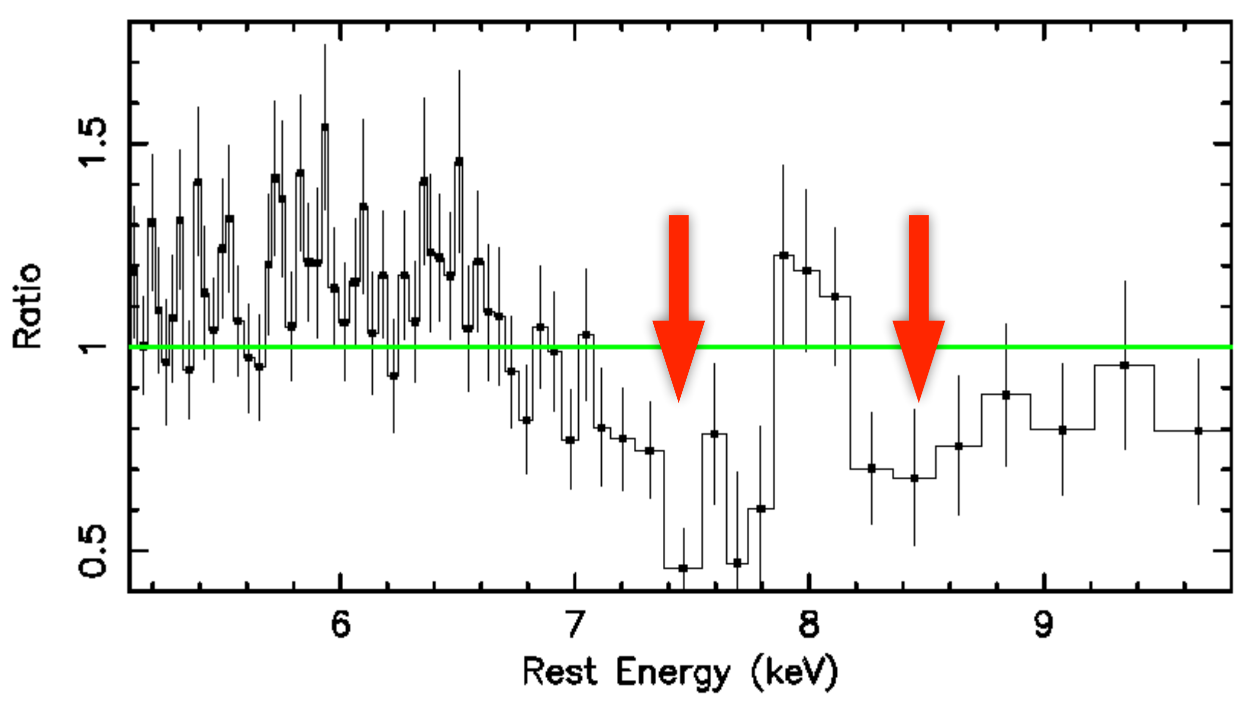
Smaller system than PDS456: $M_{BH} \sim 10^8\ M_{SUN}$ & $L_{BOL} \sim 3\times10^{45}$ erg/s

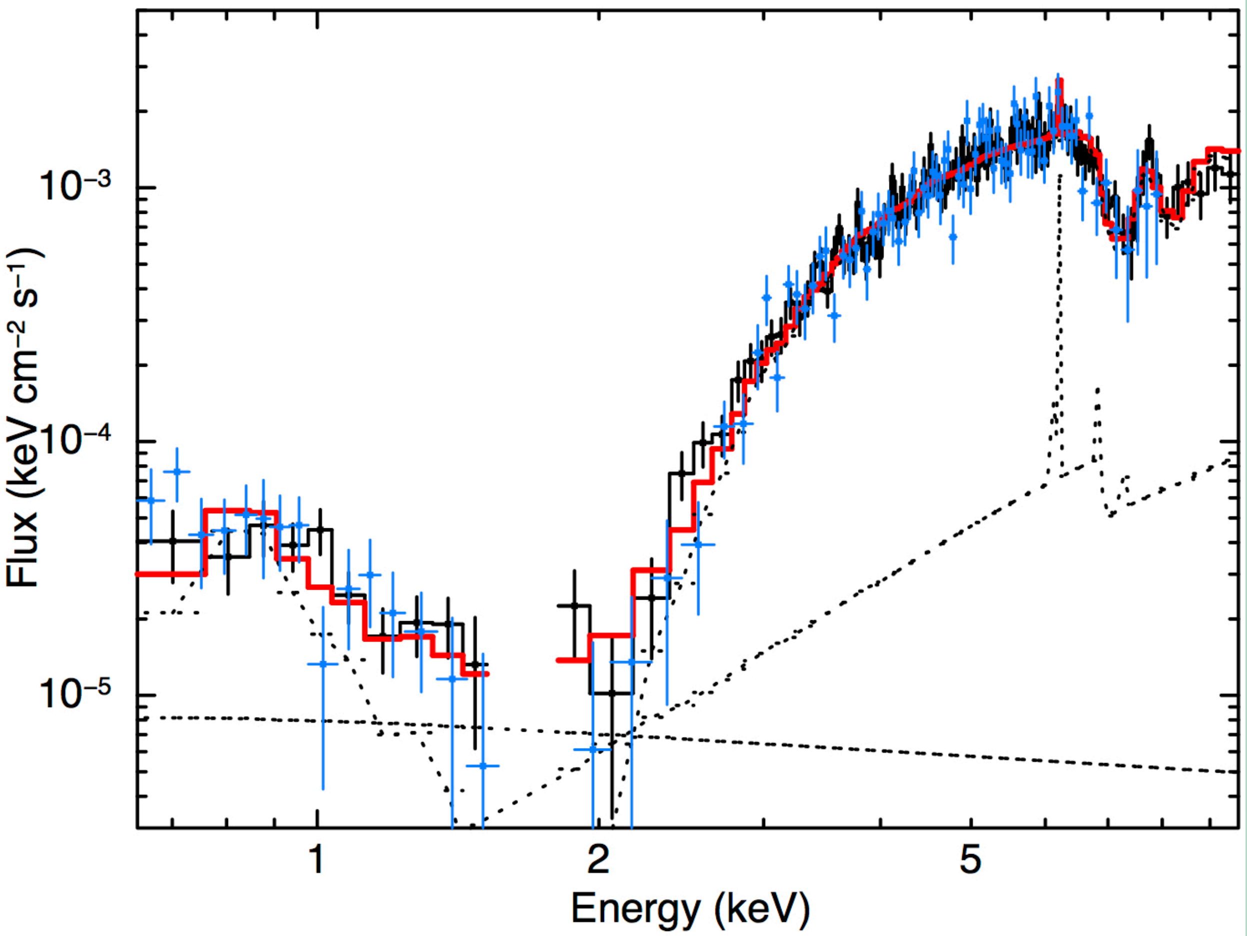
$L_X \sim 10^{43}$ erg/s ; $F_X \sim 1\text{-}4\times10^{-12}$ erg cm^{-2} s^{-1}

MCG-03-58-007 is LIRG (L_{FIR}=1.7x $10^{11} L_{SUN}$) with a SFR ~ 20 M_{SUN}/yr

Suzaku revealed 2 deep abs. structures at 7.5 keV & 8.5 keV

EW 7.5keV ~ 300 eV





Disk Wind properties: 2 zones

log $\xi \sim 5$ erg cm s^{-1}

both with $N_H \sim 5\text{-}6\times10^{23}$ cm^{-2}

$v_{out} \sim 0.07c$ & $0.2c$

$L_{KIN} \sim 2\text{-}5\times10^{44}$erg/s

An extremely variable disk wind

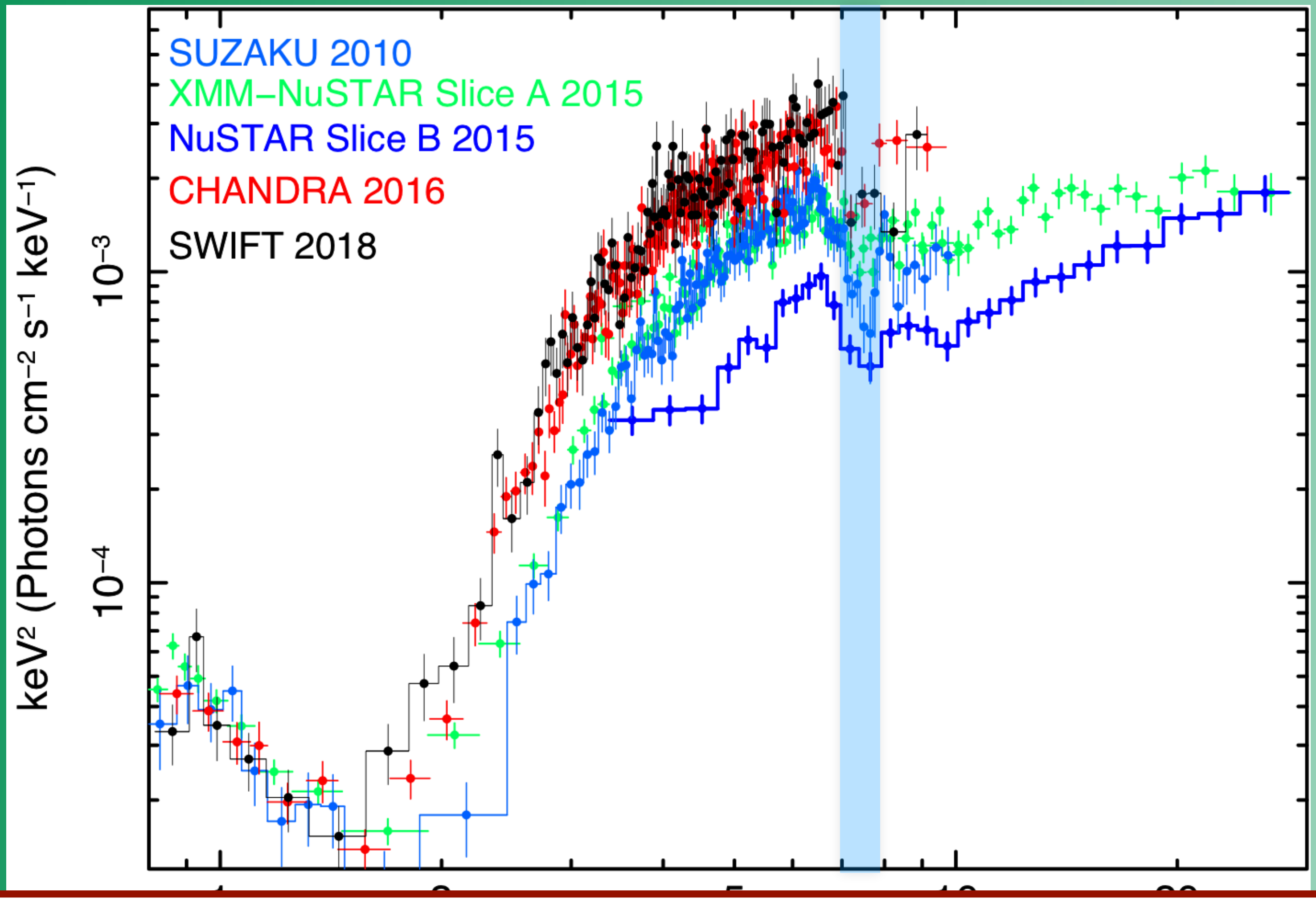
3 follow up OBS in 2015 XMM & NuSTAR, 2016 with Chandra and 2018 with Swift

All confirmed the presence of the wind at @ 7.4 keV with v_{out} =0.07c , log ξ ~ 5 erg cm s^{-1}

*No evidence of the 0.2 c zone in XMM & Chandra

2015- We witnessed an X-ray Eclipse that lasted Δt ~ 120 ks

*N_H increased from N_H ~2.6×10^{23} cm^{-2} to ~5×10^{23} cm^{-2}



This "slow/0.07c" zone is persistent but variable in opacity.

Swift & Chandra: N_H~3.6×10^{23} cm^{-2}

Suzaku 2010: N_H~7×10^{23} cm^{-2}

XMM 2015: N_H~2.6-5×10^{23} cm^{-2}

Swift 2018: a second abs. feature is present at ~8.3 keV

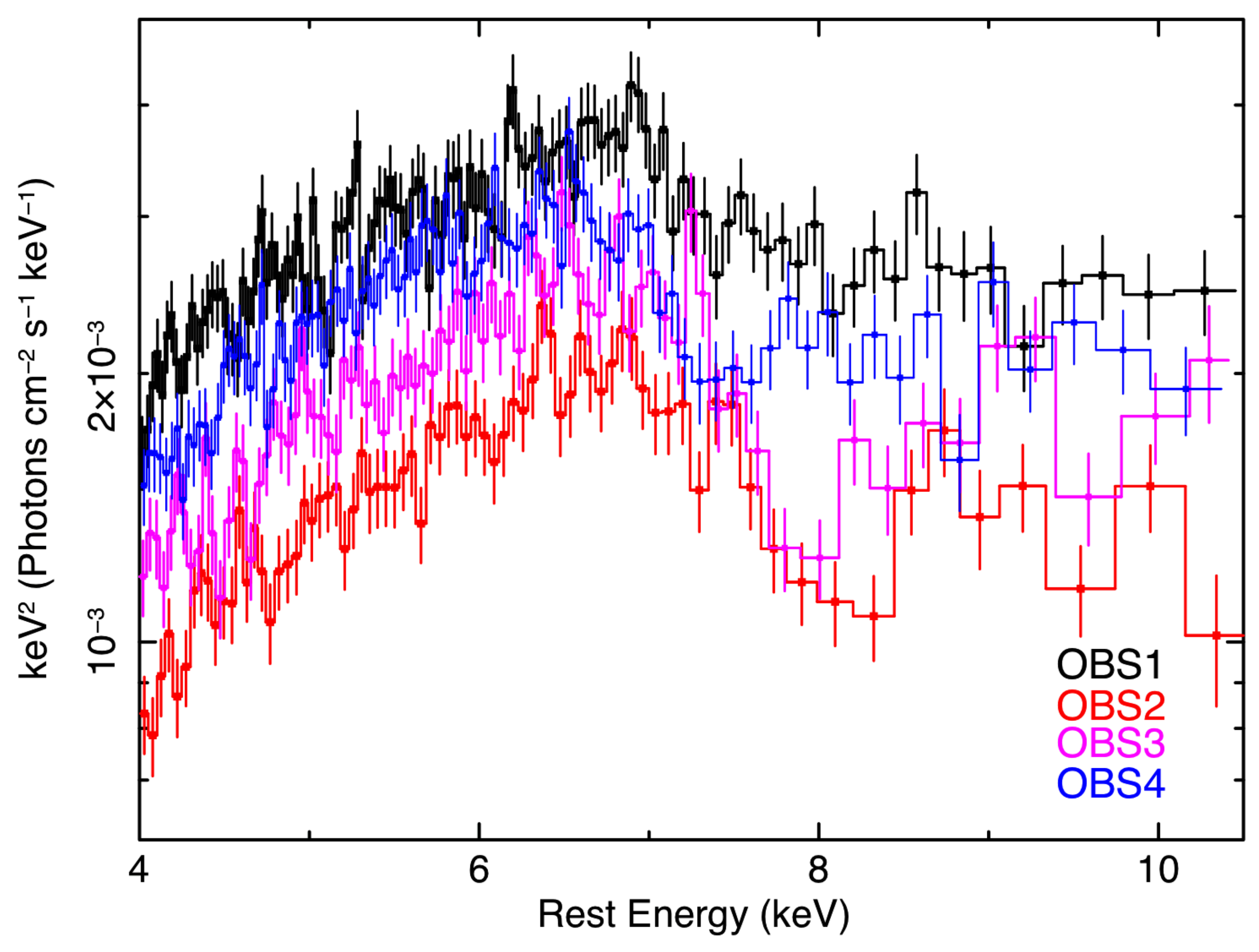
Swift 2018: The 0.2c zone is back & similar to one detected with Suzaku!

The 2019 monitoring

4 XMM & NuSTAR observations spaced by 4-10-16 days.

*MCG03 is still performing!

*The disk wind is detected in all the 4 observations and it is highly variable



OBS 1: 2 shallow abs. structures @8 keV and @10 keV

10 days later

2-10 keV flux dropped by a factor of 2 & the abs. features are stronger

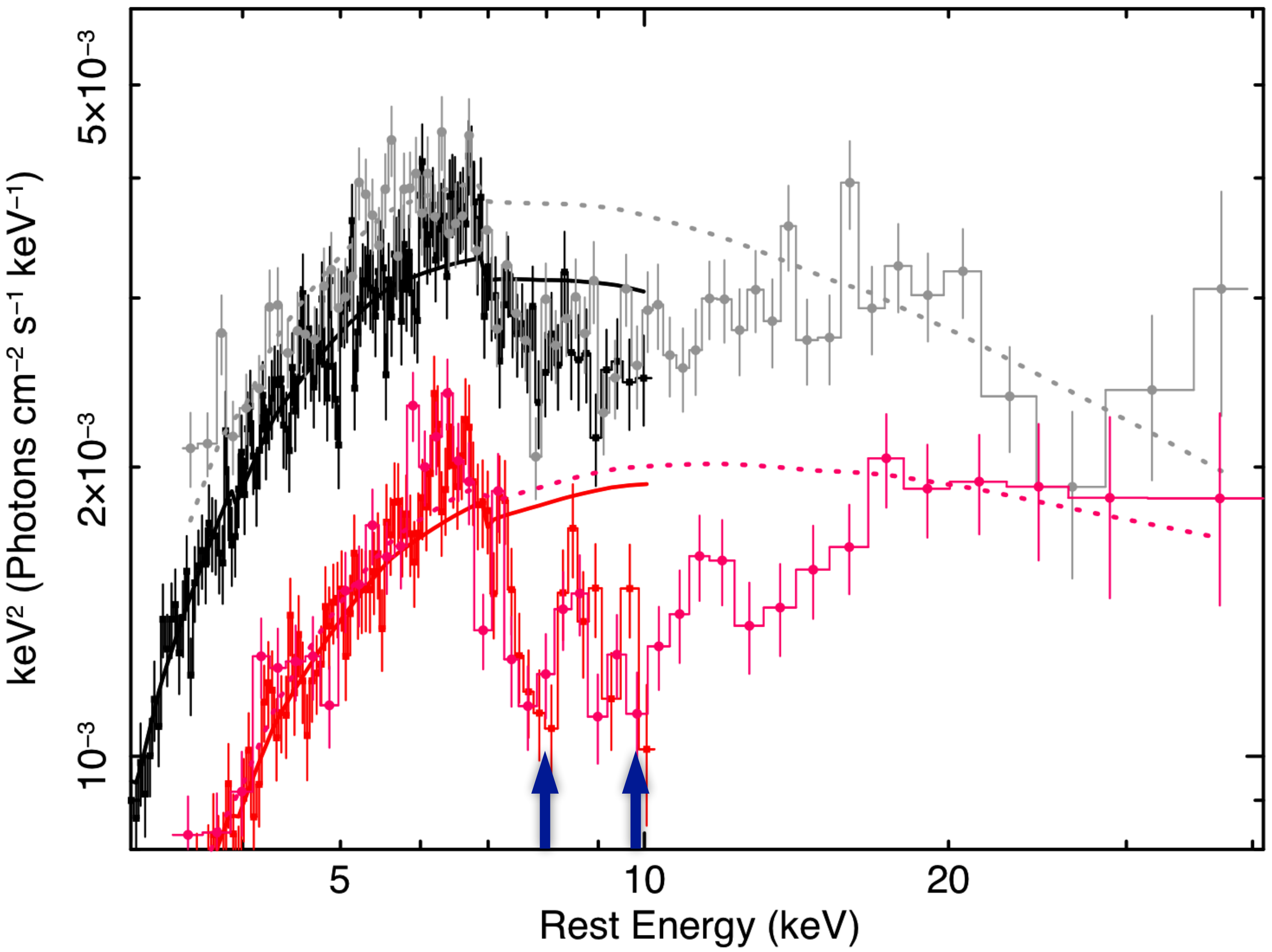
4 days later

The 2-10 keV flux increases & the wind appears to be as strong as in OBS 2

2 weeks later

MCG03 is almost at the same level of OBS1 & the wind varied again...

The 2019 monitoring: change in the opacity



XSTAR FIT:

The disk wind opacity increased in 10 day

Increase of the N_H from ~2×10^{23} cm^{-2} to ~7×10^{23} cm^{-2} & log ξ ~ 5 erg cm s^{-1}

or a decrease in the ionization from

log ξ ~ 5.3 erg cm s^{-1} to

log ξ ~ 5 erg cm s^{-1}

and N_H ~9×10^{23} cm^{-2}

- ✶The ionization varies in proportion with the changes of the 2-10 keV luminosity
  - ➡The flow could be in photo-ionization equilibrium

Note: The low energy feature is now at ~8 keV not 7.4 keV!

The drop in velocity!

Substantial drop in the outflowing velocity from ~0.2c to ~0.07c in just 16 days!

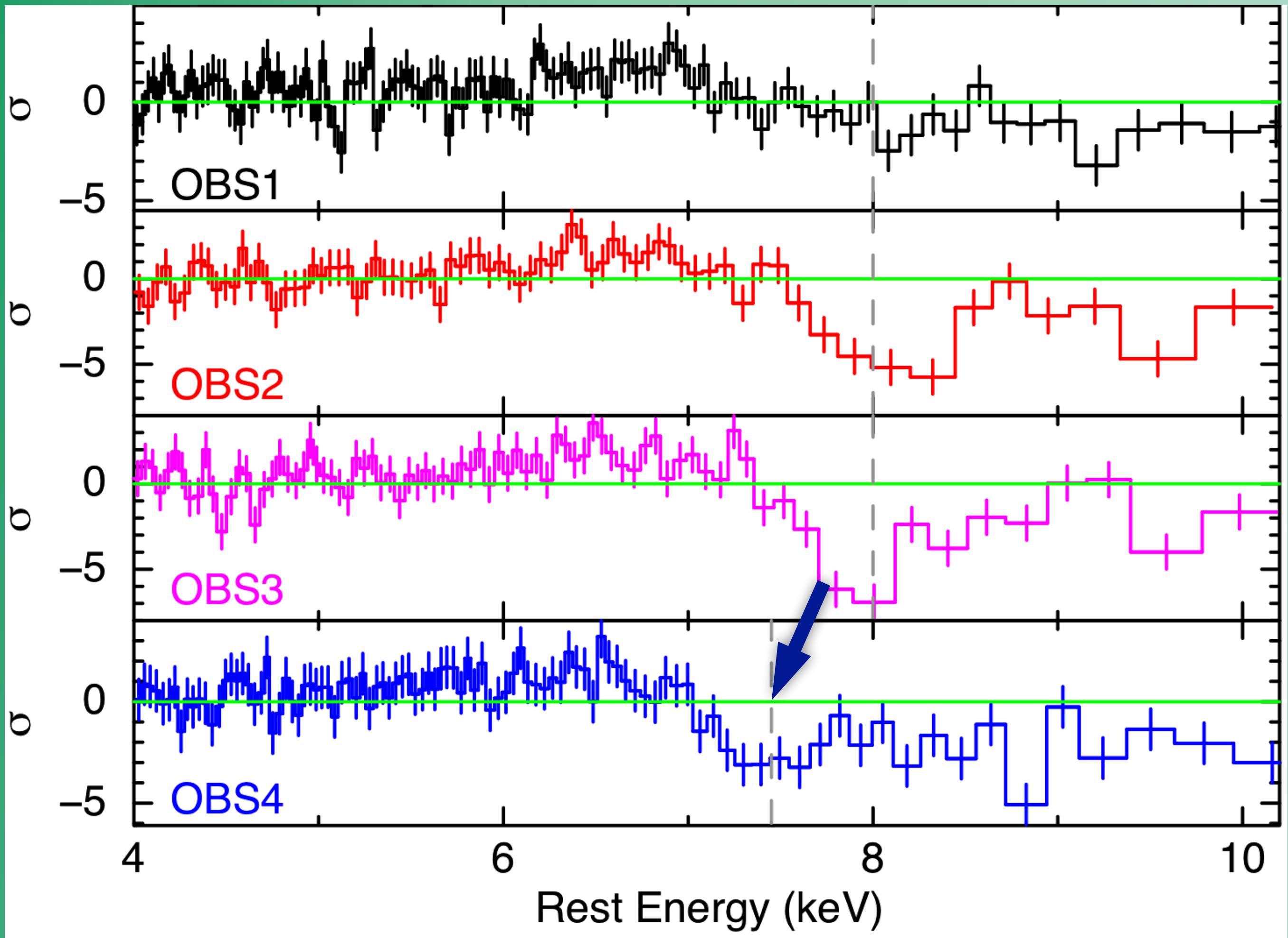
Absorption structures are present in all the observations

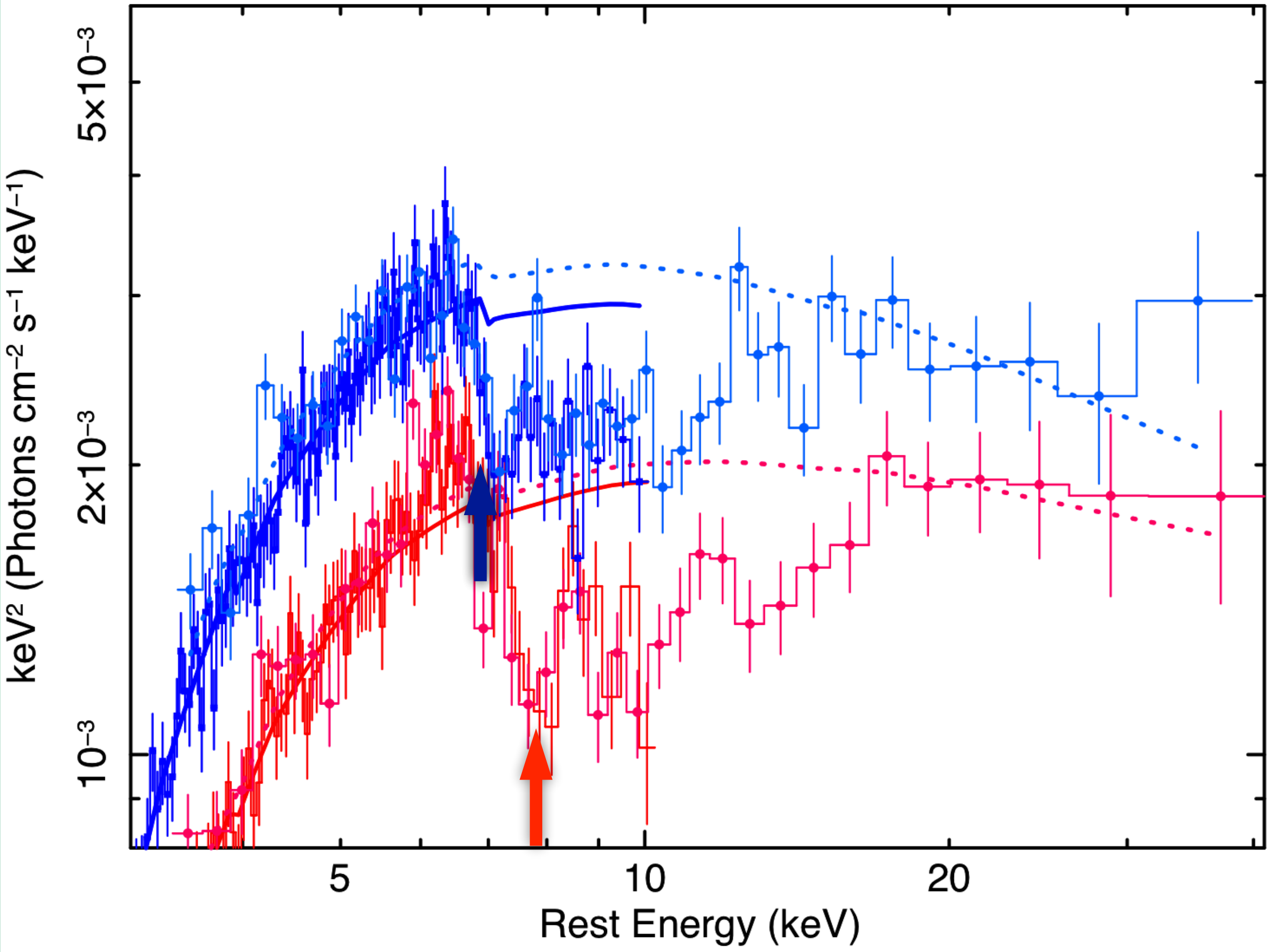
Remarkable variability in depth and energy

OBS2: the main abs. feature is @ 8 keV

16 days later

OBS4: the main abs. feature is @ 7.4 keV





The XSTAR fit vs diskwind

New table of synthetic wind spectra specifically suited for MCG03 wind:

★R_{min}=64Rg i.e. the escape radius for a wind with a terminal velocity of v_∞ =-0.177c

XSTAR requires 2 zones both with high

N_H 8-9x10^{23} cm^{-2}

Requirement of 2nd zone driven by the high

EW of the 10 keV feature

OBS 1-3: v1~0.15c & v2~0.34c

OBS 4: v1~0.07c & v2~0.27c

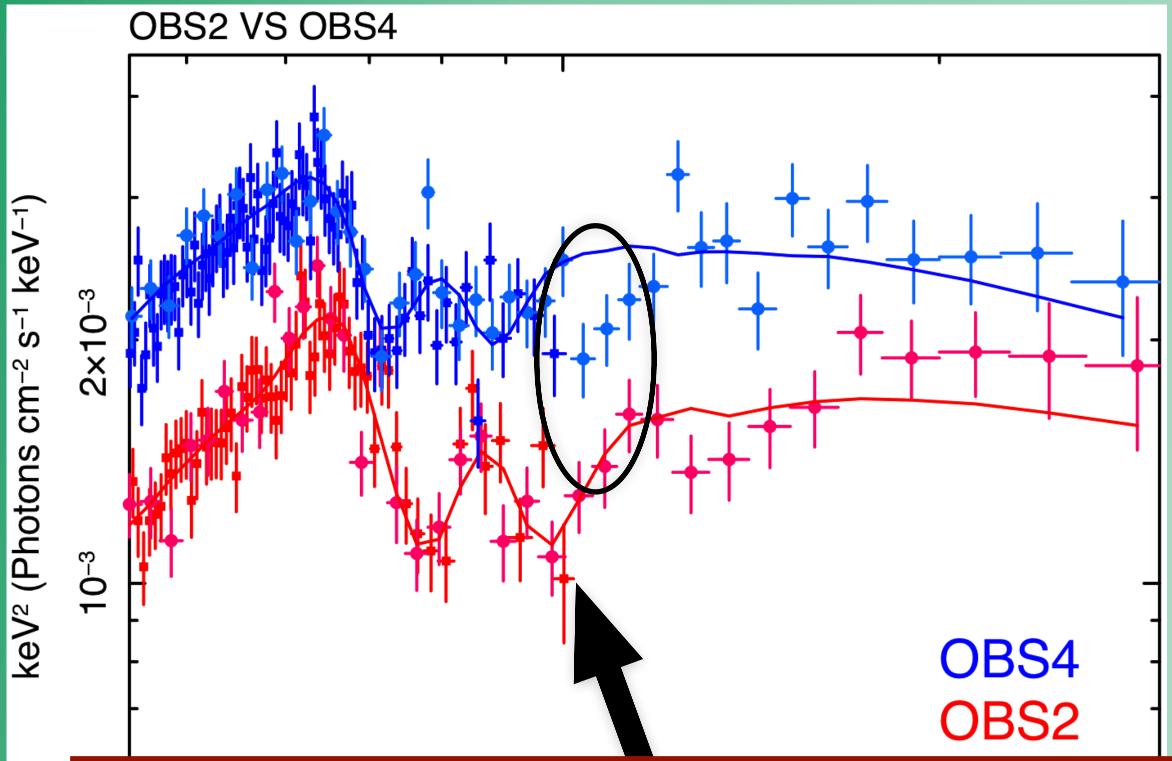
DISK WIND requires only one zone.

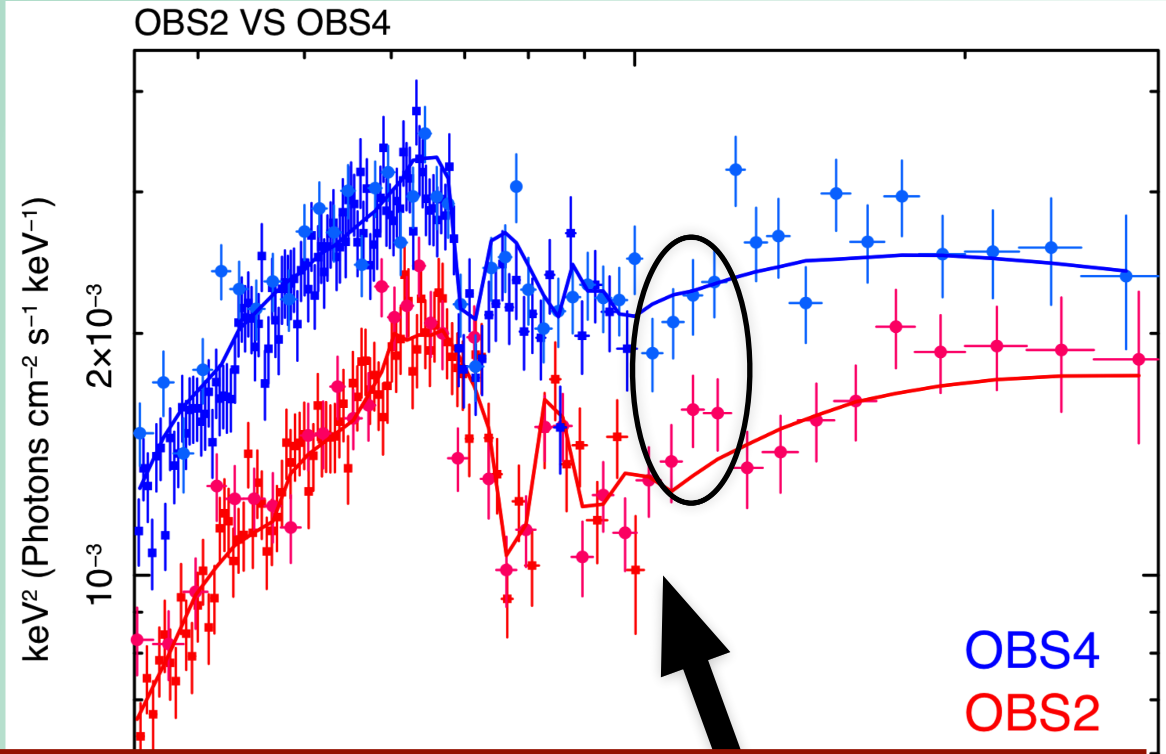
Provides a better description of the continuum ~9-30 keV.

Second drop is now consistent with Fe xxvi Lyβ

OBS 1-3: v~0.2c

OBS 4: v~0.07c





The drop in velocity does not depend on the model: in OBS4 the wind is slower!

Diskwind properties

- OBS 1-3: the disk wind has $\dot{M}_{out}$ ~0.5$\dot{M}_{Edd}$ & $\dot{E}_{out}$~9-11%L_{EDD} or L_{KIN} ~10^{45}erg/s (30% L_{BOL})

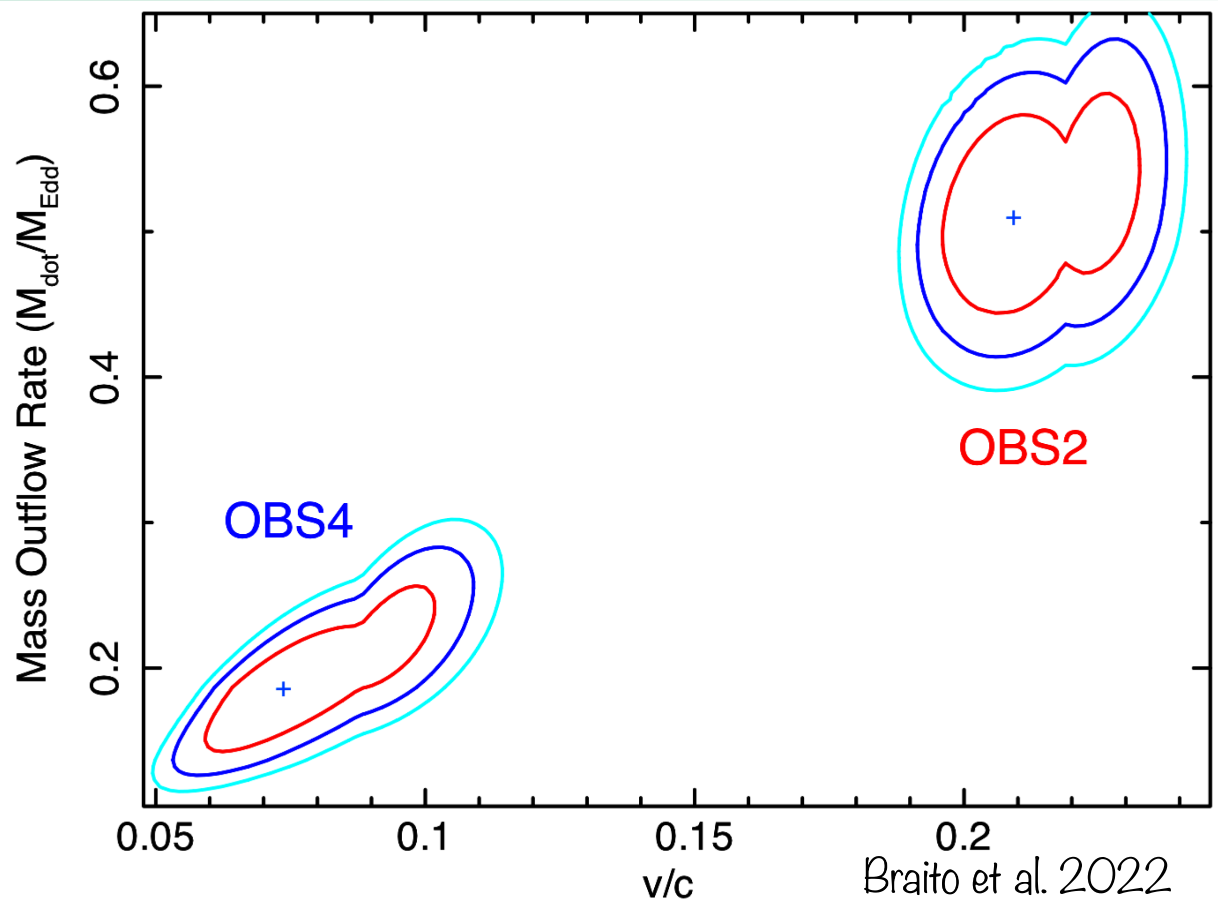
- The corresponding N_H is ~10^{24}cm^{-2} in all 4 observations, in agreement with the XSTAR fit.

    - Change in the opacity is not due to variation of the mass load of the wind but to the wind ionization level

- OBS4: $\dot{M}_{out}$ ~0.2 $\dot{M}_{Edd}$ & $\dot{E}_{out}$ ~ 0.5%L_{EDD}

    - The lower $\dot{M}_{out,4}$ is explained by the lower $v_{out,4}$=0.074±0.01c.

    A factor of 3 lower than $v_{out,2}$=0.21±0.01c!



Braito et al. 2022

We know that disk winds are variable, but the magnitude of the variation in velocity in MCG03 is a factor of ~3!

Much greater than what seen in other disk winds. In PDS456 v_{out} ranges from 0.25c to 0.35c

Location of the disk wind

- The v_{out}~0.2c zone is present for at least 14 days.

- Thus ΔR~7x 10^{15}cm & ne ~ 10^9 cm^{-3} @ R ~10^{16}cm (~700 R_g)
- $\Delta R/R$ ~1 implies a rather homogenous flow

- The v_{out}~0.07c zone emerges 16 days after OBS3

- Thus ΔR<3x 10^{15}cm & ne > 3x10^8 cm^{-3} @ R< 6x10^{15}cm

In OBS4 we intercept a slower stream of the disk wind that could be located closer in then the faster stream...

What causes the drop in v?

STANDARD SCENARIOS

1. In OBS4 we intercept a slower clump located further out

   ➡ BUT $\Delta R/R \sim 1$ suggests a rather homogeneous flow

2. In OBS4 we intercept a new slower stream launched further out

   ➡ BUT this would imply that the launching radius changes from ~50 R_g to 350 R_g in just 16 days

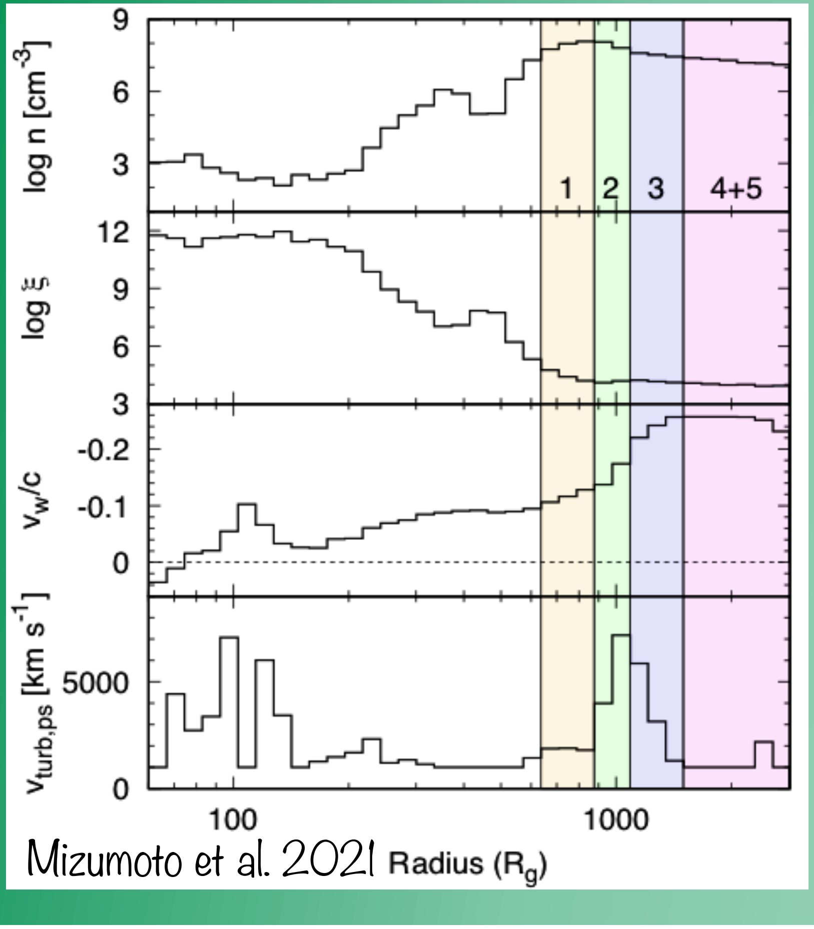
3. The wind is responding to the variation of the intrinsic emission

   ➡ BUT it is faster when fainter…

4. Delayed effect: the wind in OBS4 is reacting to the low intrinsic luminosity of OBS2

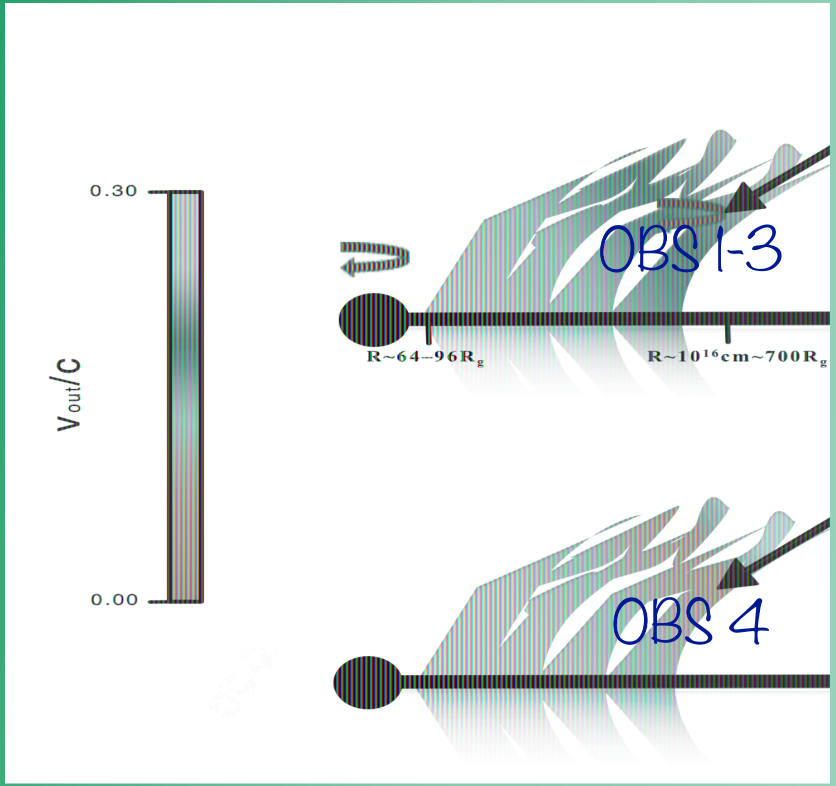
   ➡ BUT according to the scaling relations reported for other winds (PDS456 & IRAS13224) a factor of 3 drop requires a change in the X-ray luminosity of ~9!

Acceleration due to UV line driving?

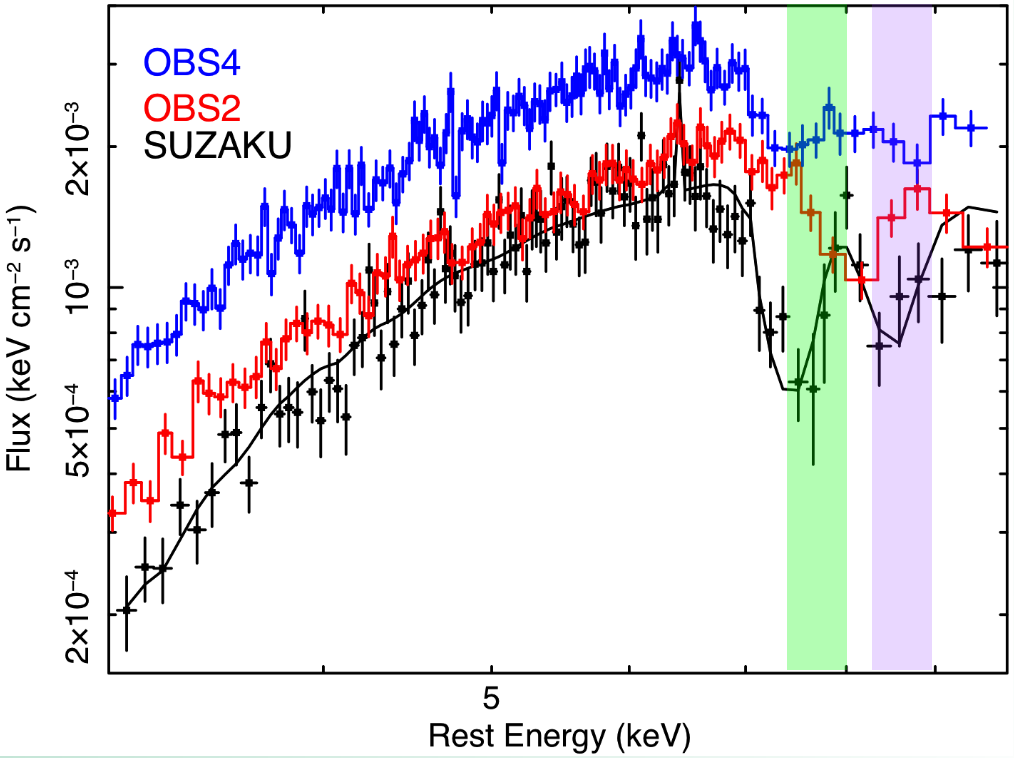


Mizumoto et al. 2021

- ✶Mizumoto et al. 2021: UV line driving could produce multiphase disk winds where the faster phase may be located further out than the slower component.
- ✶In OBS 1-3 our los intercepts the flow after it is fully accelerated!
- ✶In OBS 4 we see a new streamline, which has yet to be accelerated!
- ✶In OBS 4 the faster phase may have simply rotated out of our los.



- ✶Note that the two phases were simultaneously in our los during the Suzaku and Swift obs.!

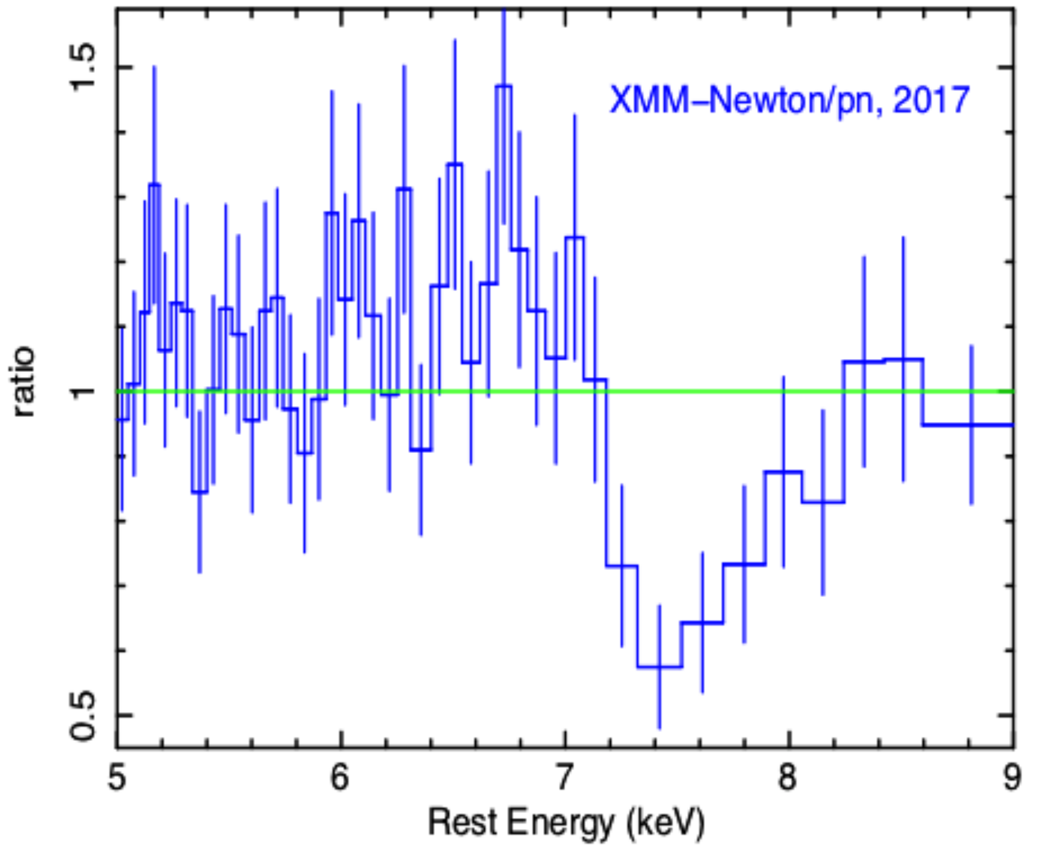


Case Study 3: PG1448+273 another variable wind

PG1448+273 is a NLS1 at z=0.0645 with M_{BH} ~ 10^7 M_{SUN} & L_{BOL} ~ 2-3x10^{45} erg/s

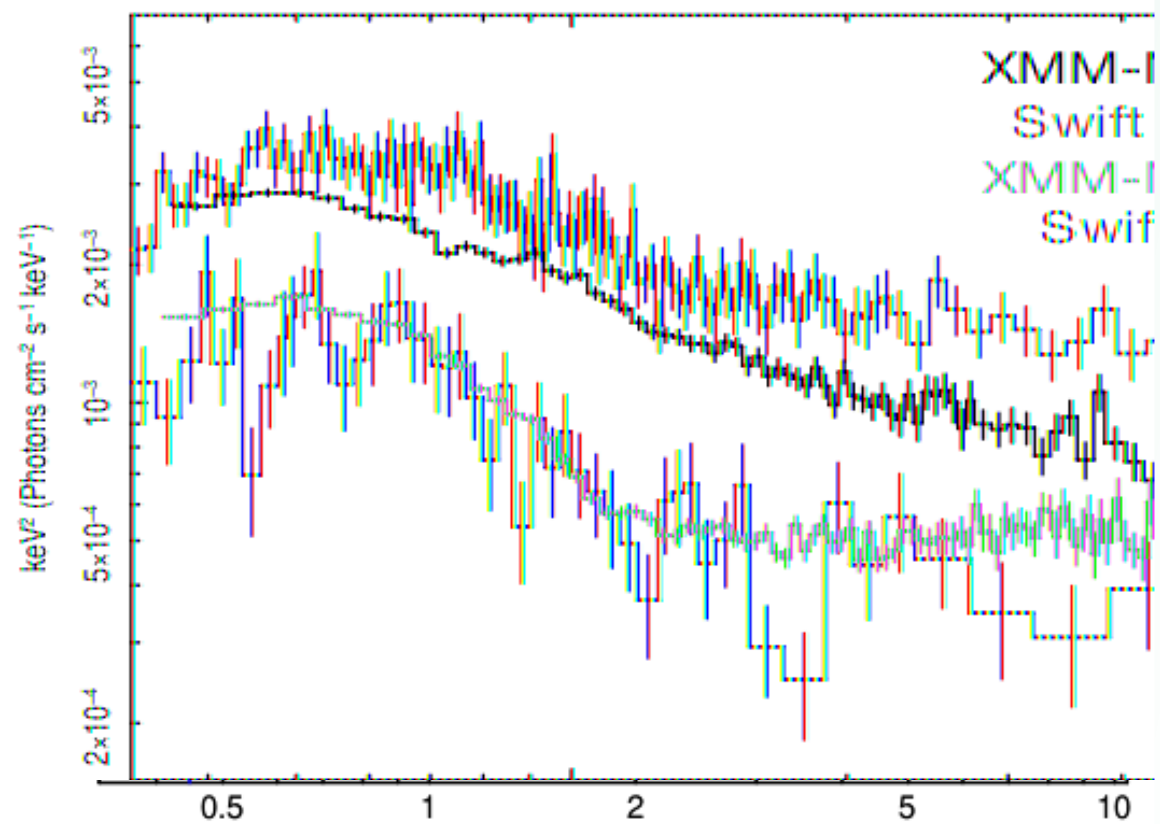
thus likely accreting close to the Eddington limit

High accretion rate and steep SED/X-ray spectrum may be key properties for ultra fast winds



2017 XMM obs. revealed the presence of a fast wind in PG 1448+273 with v_{out} ~0.1 -0.15c depending on the assumed model (Laurenti et al. 2020; Kosec et al 2020).

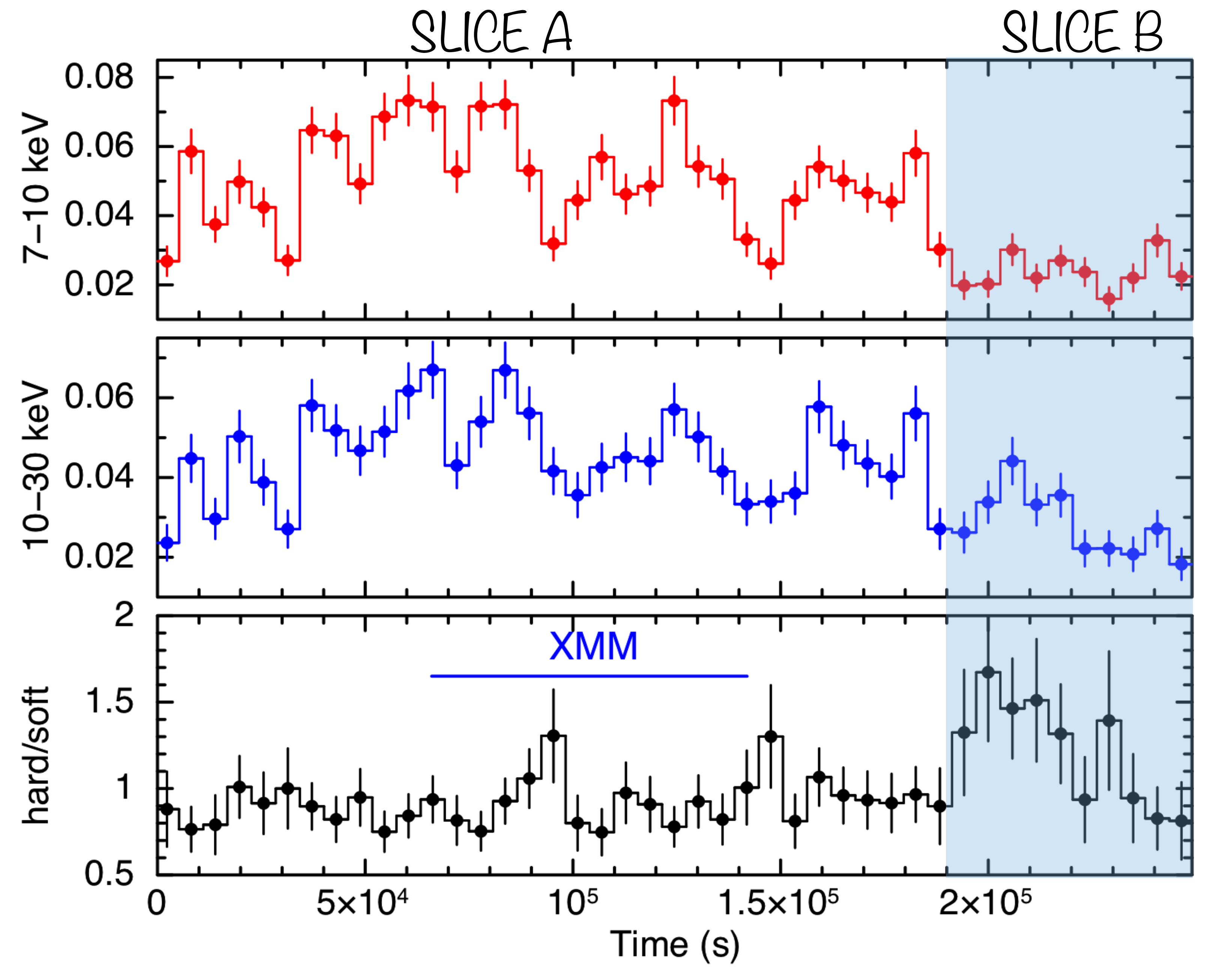
PG1448+273 is also extremely variable as often seen in NLS1



Laurenti et al. 2020

A deep look with XMM & NuSTAR

✦Jan 2022: PG1448+273 was observed with NuSTAR (120 ks) & XMM (75 ks)

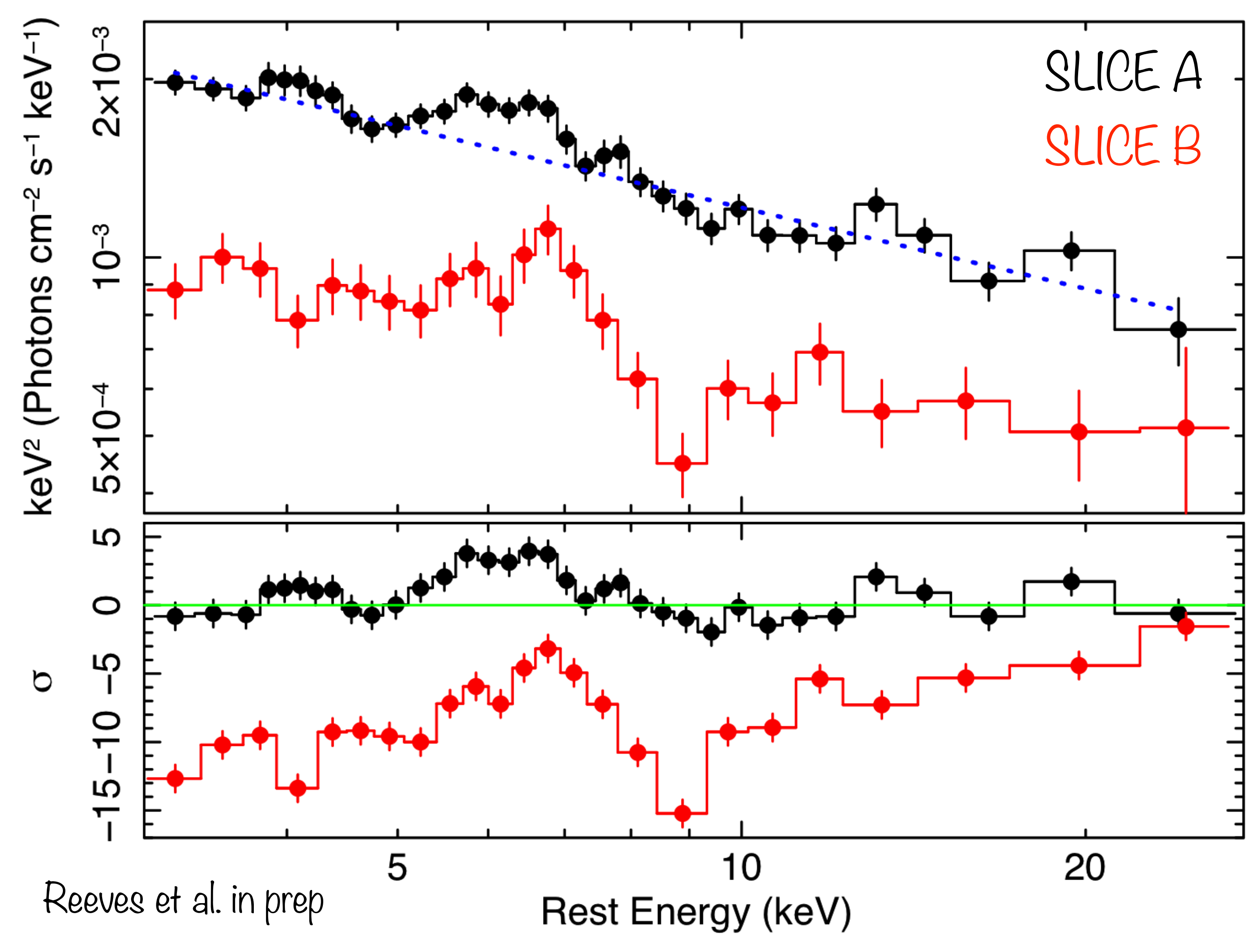


NuSTAR light curves reveal a possible occultation event at around 190 ks.

Flux drop @ 190 ks with a clear hardening.

Unfortunately this part of the OBS has no XMM coverage

Another fast variable wind



Reeves et al. in prep

XSTAR FIT:

The disk wind opacity increase in the last 60 ks be explained with:

- ✶increase of the N_H from <1.7×10^{23} cm^{-2} to~$9\pm4\times10^{23}$ cm^{-2} with $v/c=0.23\pm0.03$ & log ξ ~ 5 erg cm s^{-1}
- ✶or a decrease in the ionization from log ξ > 5.5 erg cm s^{-1} (SLICE A) to log ξ ~4.6 ± 0.3 erg cm s^{-1} with N_H~5×10^{23} cm^{-2}

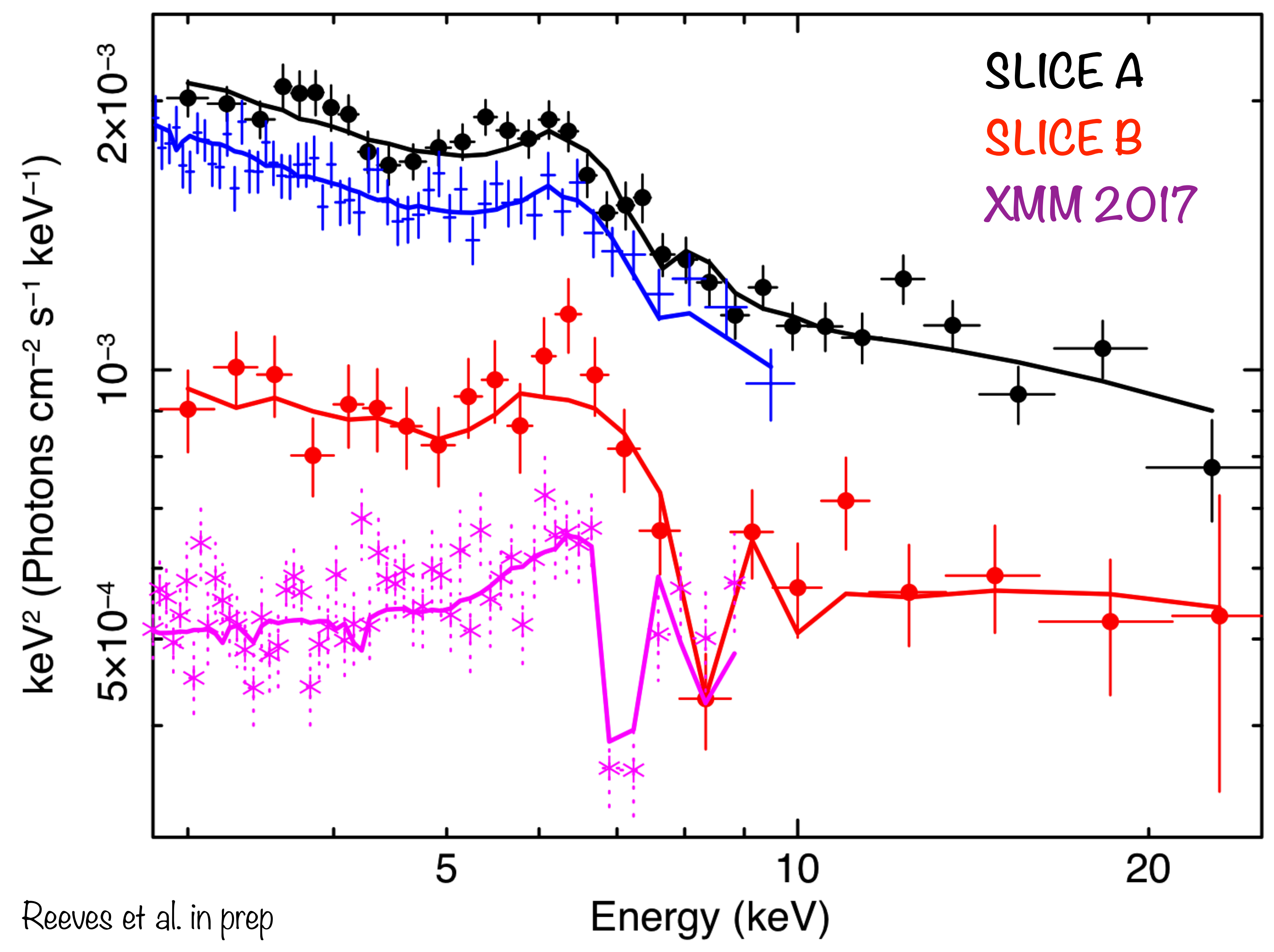
✶At least a factor of 3 change in either N_H or log ξ between SLICE A & B

In 2017 the wind had a much lower velocity

XSTAR FIT: $N_H=6.6\pm1.8\times10^{23}$ & $v/c=0.1\pm0.01$ for log ξ ~ 5 erg cm s^{-1}

or log ξ ~ 4.9 ± 0.15 erg cm s^{-1} & $v/c=0.1\pm0.01$ for $N_H=5\times10^{23}$ cm^{-2}

All epochs with the diskwind model



Reeves et al. in prep

SLICE A: v/c(<0.23)

$\dot{M}_{out}$ <0.59 $\dot{M}_{Edd}$

SLCICE B: v/c=0.29±0.02

$\dot{M}_{out}$=0.47±0.12 $\dot{M}_{Edd}$

XMM 2017: v/c=0.125±0.010

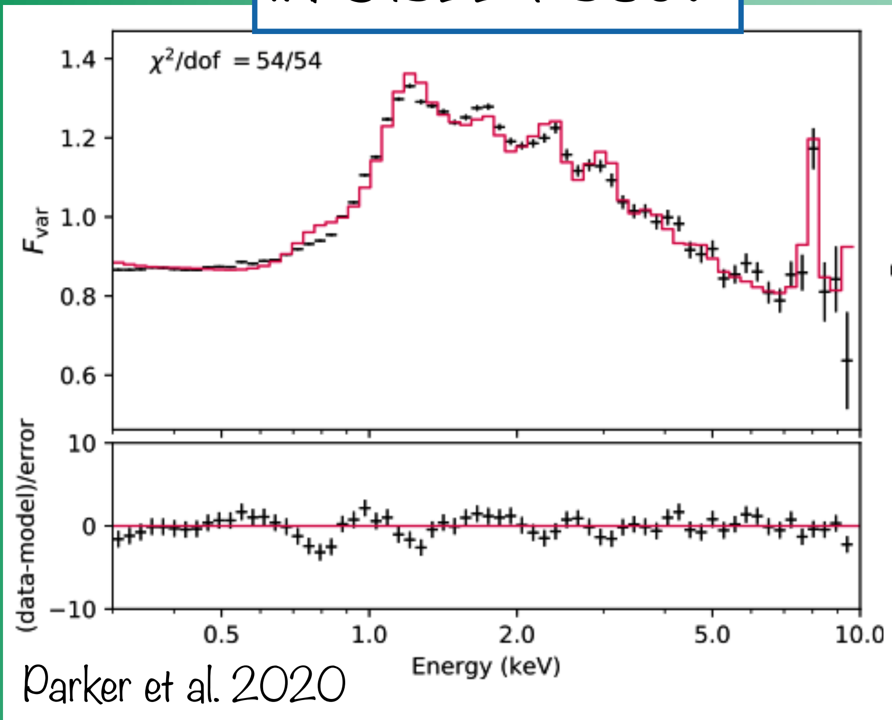
$\dot{M}_{out}$=0.13±0.03 $\dot{M}_{Edd}$

- Another case where - from 2017 to 2022- the velocity changes by at least a factor of 2, which drives corresponding increase in the $\dot{M}_{out}$.
- Behavior similar to other winds, faster when brighter

The Fvar spectrum

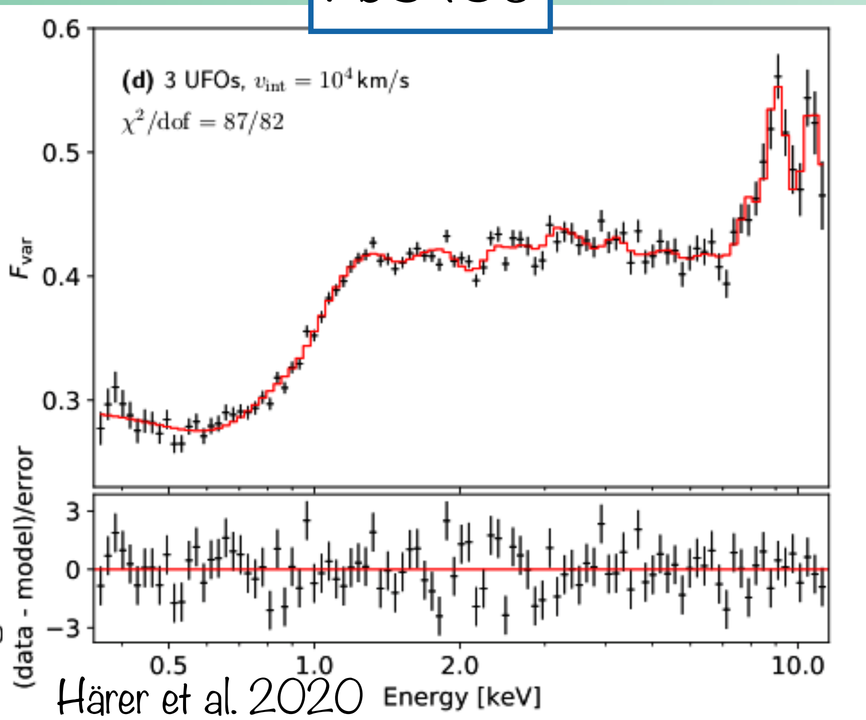
Variable disk winds that respond to the X-ray continuum flux will emerge in the excess variance (Fvar) spectrum as spikes of enhanced variability (Parker et al. 2017, 2018; 2020, Igo et al 2020).

IRAS 13224-3809



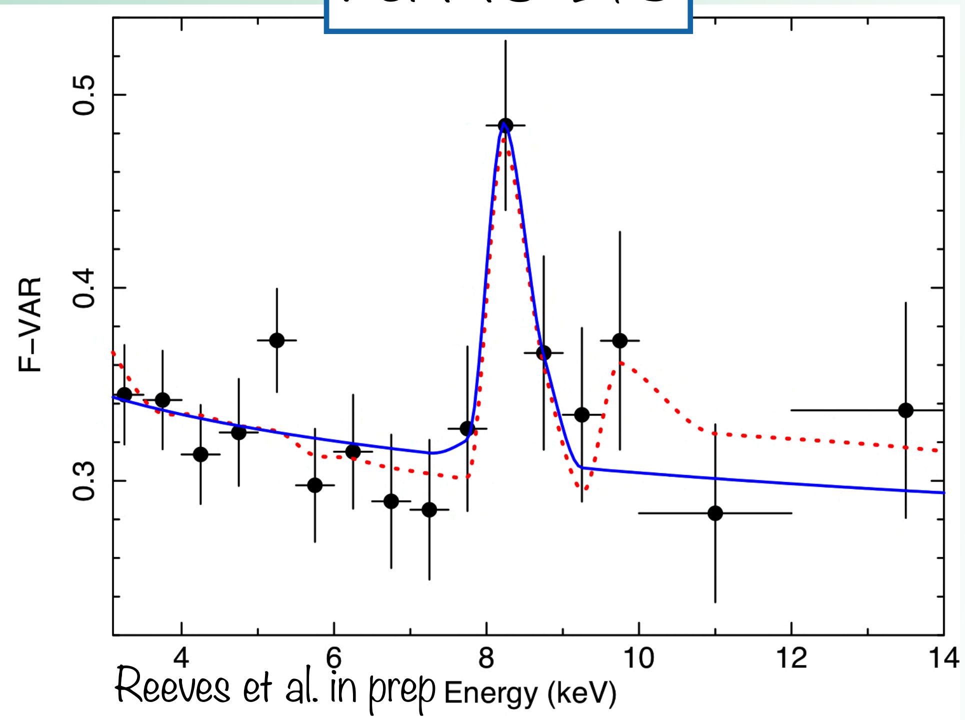
Parker et al. 2020

PDS456



Härer et al. 2020

PG1448+273



Reeves et al. in prep

Like IRAS13224-3809 & PDS456 also PG1448+273 shows a spike in the fvar spectrum @ the energy of abs feature !

Summary

- ✳Disk winds are highly variable in both opacity (N_H and/or ξ) and remarkably in velocity.
- ✳Dedicated monitoring programs of the best examples are the key to unlock their nature, the driving mechanism (see PDS456) and unveil the unexpected (see MCG03).
- ✳Physically motived models like our diskwind model are crucial to solve the disk wind geometry, ionization structure and ultimately the mass outflow rate, terminal velocity and launch radius from the black hole.
    - ✳Extend the parameter space of the diskwind model, test it on more winds
- ✳Complementary modelling of the RMS spectra is promising and most likely will provide new insights into the variability of AGN and disk winds.