Non-Equatorial UFOs with High-Density Disks in BH XRBs

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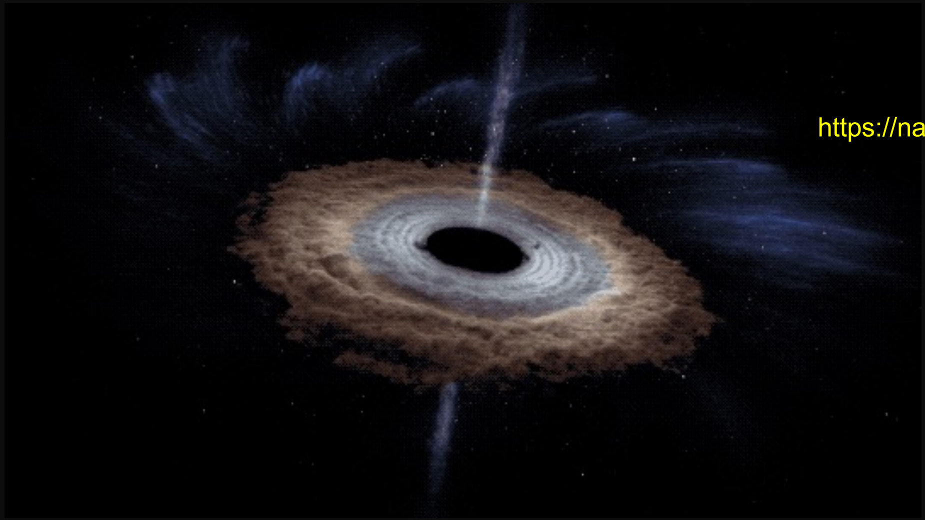

https://nasa.tumblr.com

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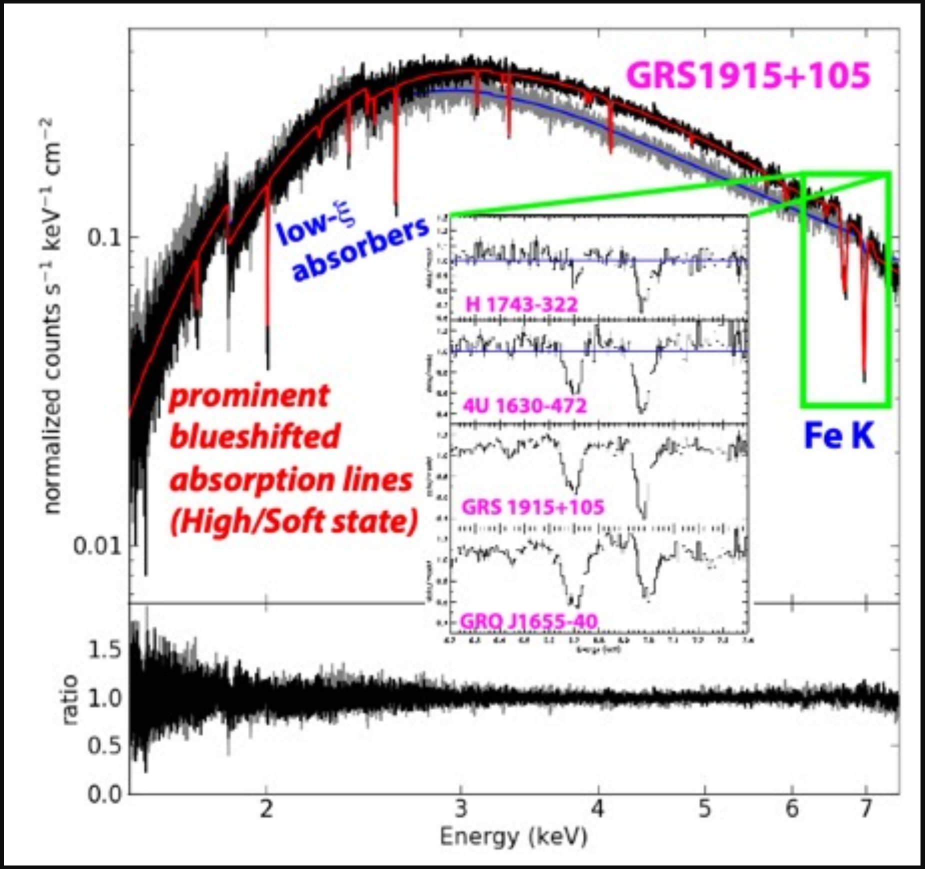
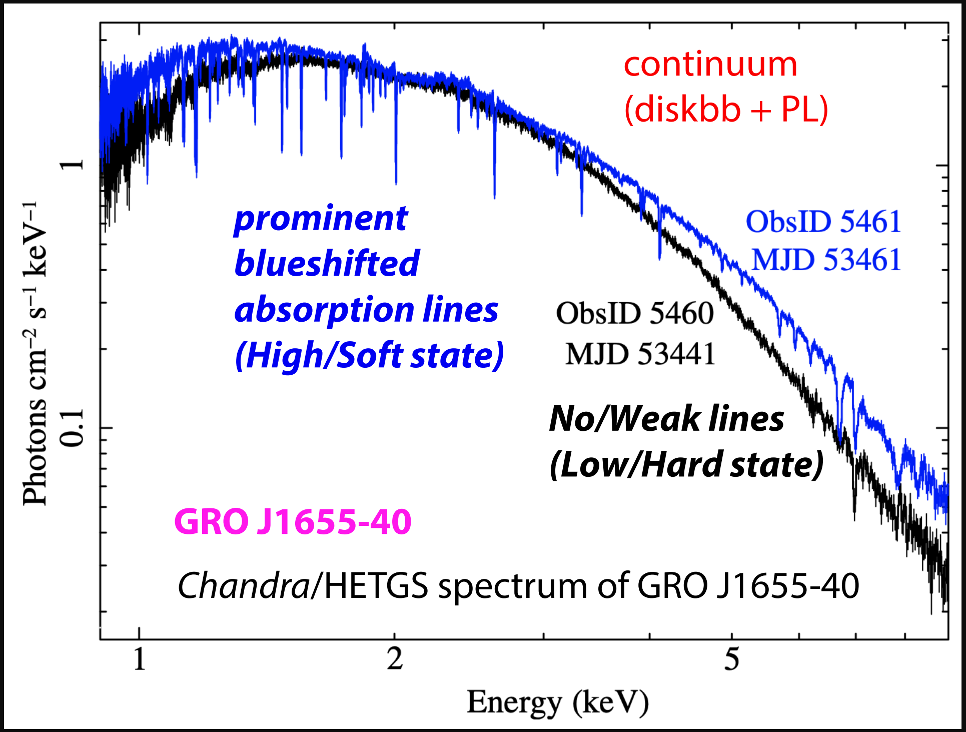
Agenda

- ❑ Non-canonical BH XRB disk-winds
  1) non-equatorial (polar) fast, massive winds
     - equivalent to AGN ultra-fast outflows (UFOs)
  2) accompanied by high-density disks
- ❑ Reflection + wind spectroscopy
- ❑ Plausible launching mechanisms
  - *thermal-radiative* vs. *magnetic*
- ❑ UFOs with HRXS
- ❑ Take-home message

Equatorial (slow) X-ray Disk-Winds



Miller+15, Ratheesh+21



Neilsen+Homan12

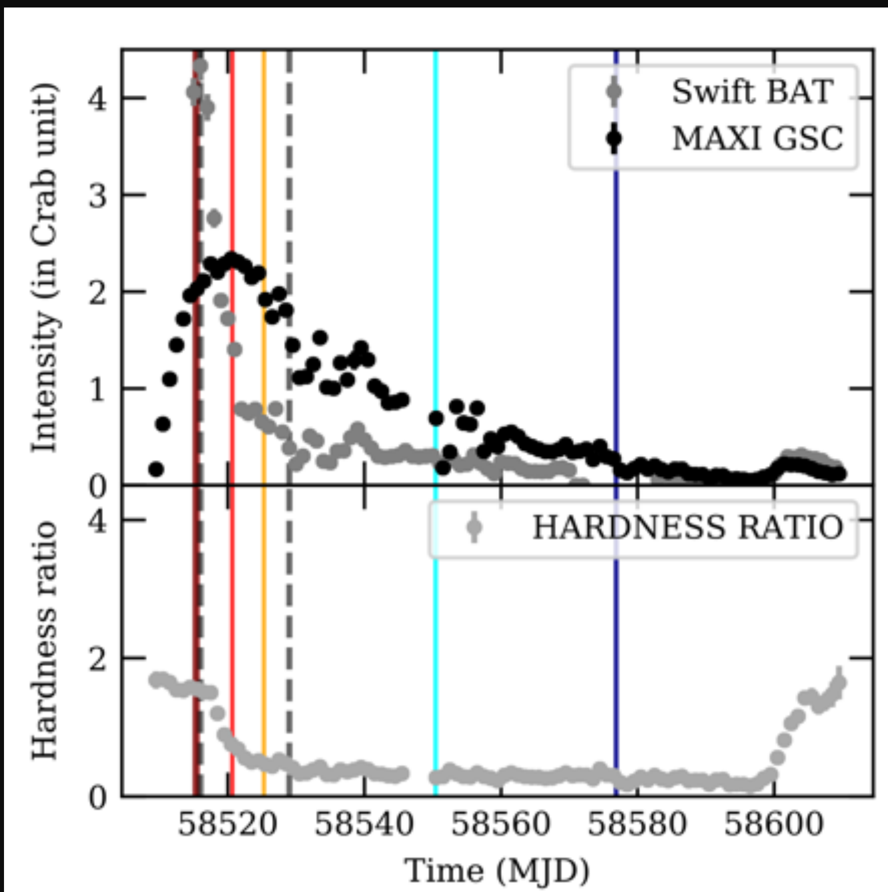
See talks by M. Parra and P. Kosec

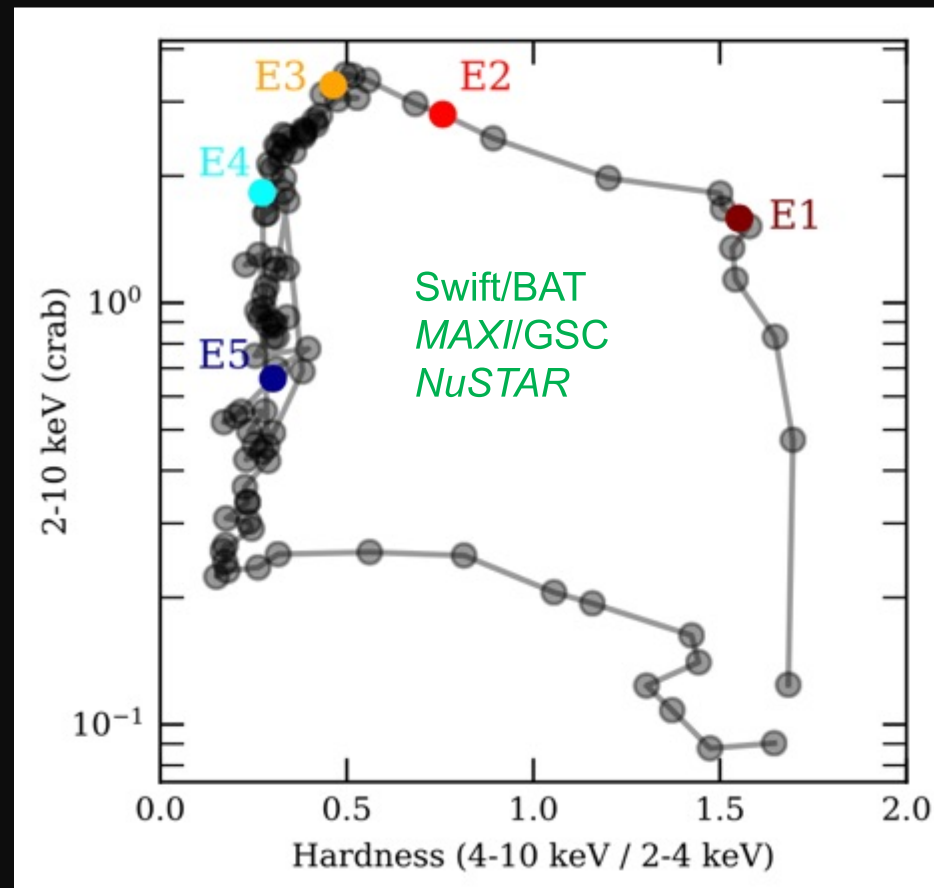
V ~ 100-1,000 km/s
N_H ~10^{21} cm^{-2}

What other disk winds do we see?

MAXI J1348-630, 2019 Outburst

- M_{BH} ~ 11 M_{sun} , D ~ 3.4kpc, L_X/L_E ~ 0.06 - 0.24
- Multi-epoch *NICER*/*NuSTAR* observations **(2019 E1-E5 epochs)**



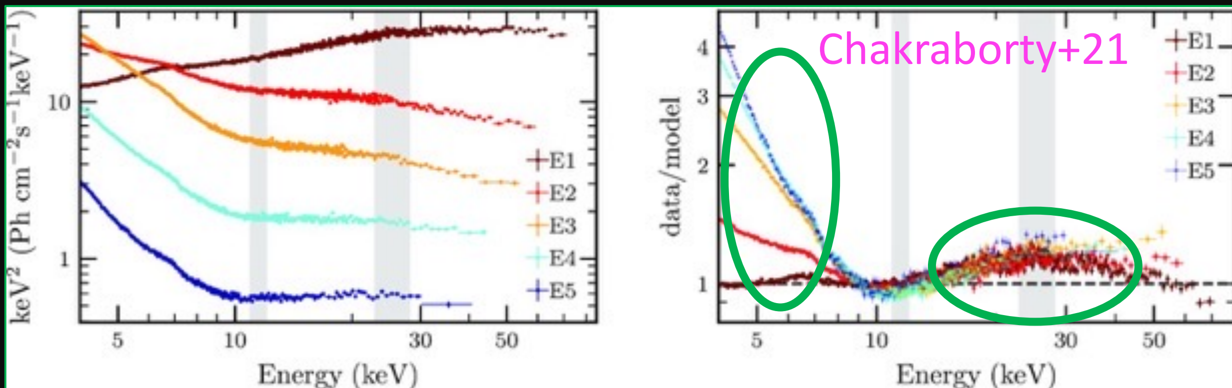


Chakraborty+21

Reflection and Outflow Signatures

❑ Reflection Spectroscopy

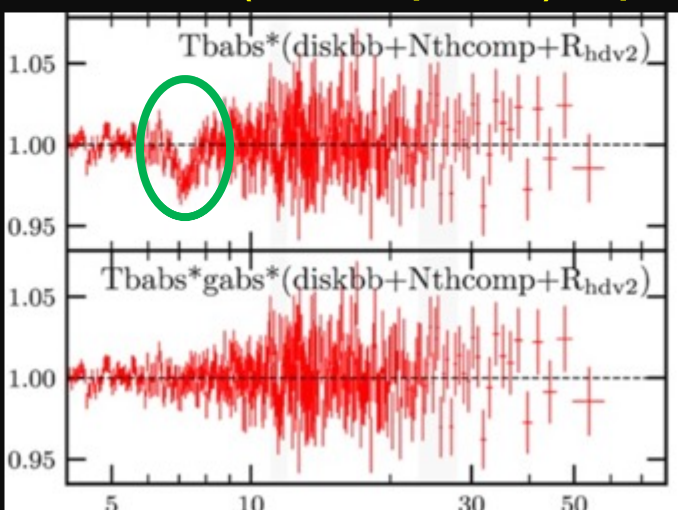
NuSTAR spectra



"Strong reflection process"

- Compton hump
- soft excess
- Fe abundances
- BH spin
- **inclination**
- **disk density**

❑ Wind (Absorption) Spectroscopy



Chakraborty+21

"high-velocity, high-column (UFOs)"

- V_{out} /c ~ 0.07 (assuming Fe XXVI)
- N_H ~ $10^{22\text{-}23}$ cm^{-2} - massive
- log ξ ~ 3 - 5
- seen in soft-intermediate state
- **inclination**
- **wind density as launched from the disk**

Note: BH Disk Density in General

Assuming that BH thin-disk is intrinsically characterized by optically-thick inner edge as

$$\tau_{disk} \sim \sigma_T \, n_{disk} \, R_g \sim \text{unity or higher}$$

One generally expects

$$n_{disk} > 10^{18} \, M_1^{-1} \ [\text{cm}^{-3}] \rightarrow \textit{BH XRBs}$$

$$10^{12} \, M_7^{-1} \ [\text{cm}^{-3}] \rightarrow \textit{AGNs}$$

Reflection Models ➔ high-n, low-θ

1) *RELXILL* model suite (relxill v1.3.10: Dauser+14; Garcia+14)
assuming an extended corona with *RELXILLCP* that internally includes thermal Comptonisation (*NTHCOMP*: Zdziarski+96; Zycki+99) continuum

Issue 1: $A_{fe} > 10$ at times (confirmed with MCMC analysis).
Issue 2: Accompanied by systematic residuals above 50 keV

2) *RELXILL*-based high density reflection model *RELXILLD + XILLVER*
- E_{cut} is fixed@300 keV
- Disk density up to **10^{19} cm^{-3}**
- Atomic data from *XSTAR* (also considering density-dependent transitions)
- Self-consistent GR calculations (Dauser+13)

Issue: A_{fe}~1.5-4 but still disk densities pegged at the upper limit of 10^{19} cm^{-3}.

3) ***REFLIONX***-based (Ross+Fabian05) high-density reflection model ***REFLIONX_HDv2*** by Tomsick+18 based on the code by Ross+Fabian07
* *NTHCOMP continuum* + Variable (E_{cut} , A_{Fe})
* Disk density up to **10^{22} cm^{-3}**
* Atomic data from *CHIANTI*…still in progress

e.g. Chakraborty+21
Tomsick+18 & priv. comm.

high-N_H, low-θ ➔ MHD Disk-Wind Models

Steady-state, self-similar, axisymmetric ideal MHD scheme:

Disk treated as BC

$$\nabla \cdot (\rho \mathbf{v}) = 0 \quad \text{(mass conservation)},$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} \quad \text{(Ampere's law)},$$

$$\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} = 0 \quad \text{(ideal MHD)},$$

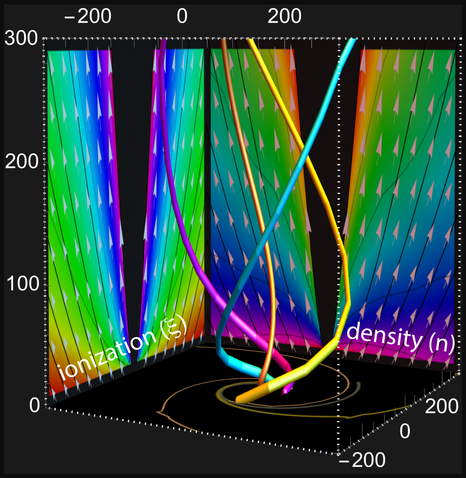
$$\nabla \times \mathbf{E} = 0 \quad \text{(Faraday's law)},$$

$$\rho(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla \mathbf{p} - \rho\nabla\Phi_g + \frac{1}{c}(\mathbf{J}\times\mathbf{B}) \quad \text{(momentum conservation)},$$

$$n(r,\theta) \equiv \frac{\rho(r,\theta)}{\mu m_p} = n_o x^{2q-3}\mathcal{N}(\theta)$$

$$N_H(\Delta r, \theta) \equiv \int_{\Delta r} n(r,\theta)dr$$

(P_{rad}=0)



Main characteristics of magnetically-driven wind:

e.g.
Blandford+Payne82
Contopoulos+Lovelace94
KF+10; Kazanas+12
Chakravorty+16

- ❑ Paraboloidal 2D geometry + Rotation
- ❑ Wind density given by **$n(r, \theta_W) \sim n_W(r/r_o)^{-p} f(\theta_W)$**
- ❑ Assume p=1.7 (to reduce low-ξ absorbers)
- ❑ *Faster* inner layer, *slower* outer layer

Post-process radiative transfer with XSTAR ➔ **library of spectra**

$f(\theta_W)$ from Grad-Shafranov + MHD eqns

n_W = wind density normalization@launching site ~ disk density **n_D**

Complementary Reflection+Wind Spectroscopy

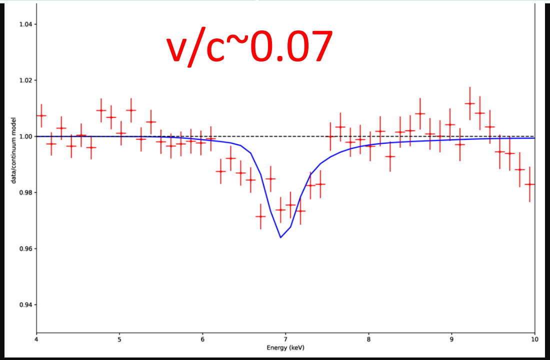
Preliminary

tbabs*mhdwind*(diskbb+reflionx_hdv2)

MAXI J1348-630, 2019 Outburst

NuSTAR Data	mhdwind log n_W[cm^{-3}]	reflionx_hdv2 log n_D[cm^{-3}]	mhdwind θ_{obs} [deg]	reflionx_hdv2 θ_{obs} [deg]	χ^2/dof
E1 (3.7ks)	$21.9^{+0.03}_{-0.01}$	$20.7^{+0.3}_{-0.3}$	$31.5^{+2.2}_{-0.6}$	50^{+8}_{-6}	2353.6/2112
E2 (4.5ks)	$21.1^{+0.03}_{-0.01}$	$20.3^{+0.4}_{-2.4}$	$41.3^{+0.2}_{-0.2}$	30^{+5}_{-4}	1084/1008
E3 (4.6ks)	$21.0^{+0.9}_{-0.02}$	$20.7^{+0.6}_{-2.5}$	$39.9^{+0.3}_{-0.4}$	32^{+4}_{-5}	939.4/875
E4 (9.7ks)	$21.1^{+0.07}_{-0.05}$	>21.8	$35.5^{+0.8}_{-0.5}$	38^{+1}_{-1}	883.0/829
E5 (12.5ks)	$20.7^{+0.1}_{-0.1}$	$20.4^{+0.4}_{-0.2}$	$40.0^{+3.4}_{-2.7}$	34^{+1}_{-1}	601.8/595

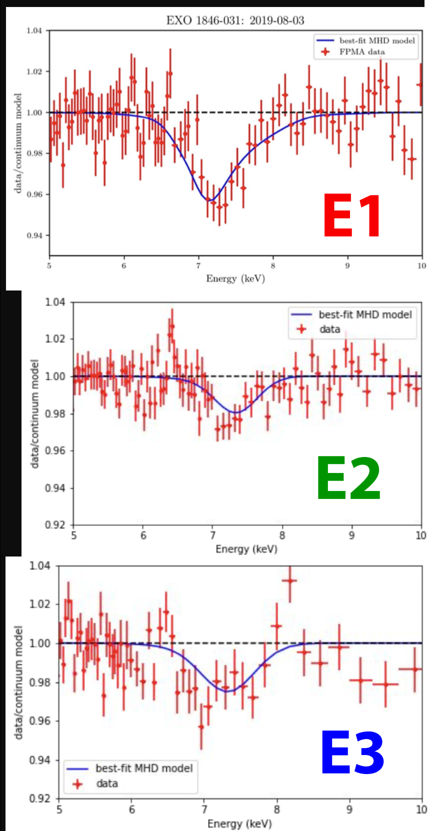
Chakraborty+23 (in prep)

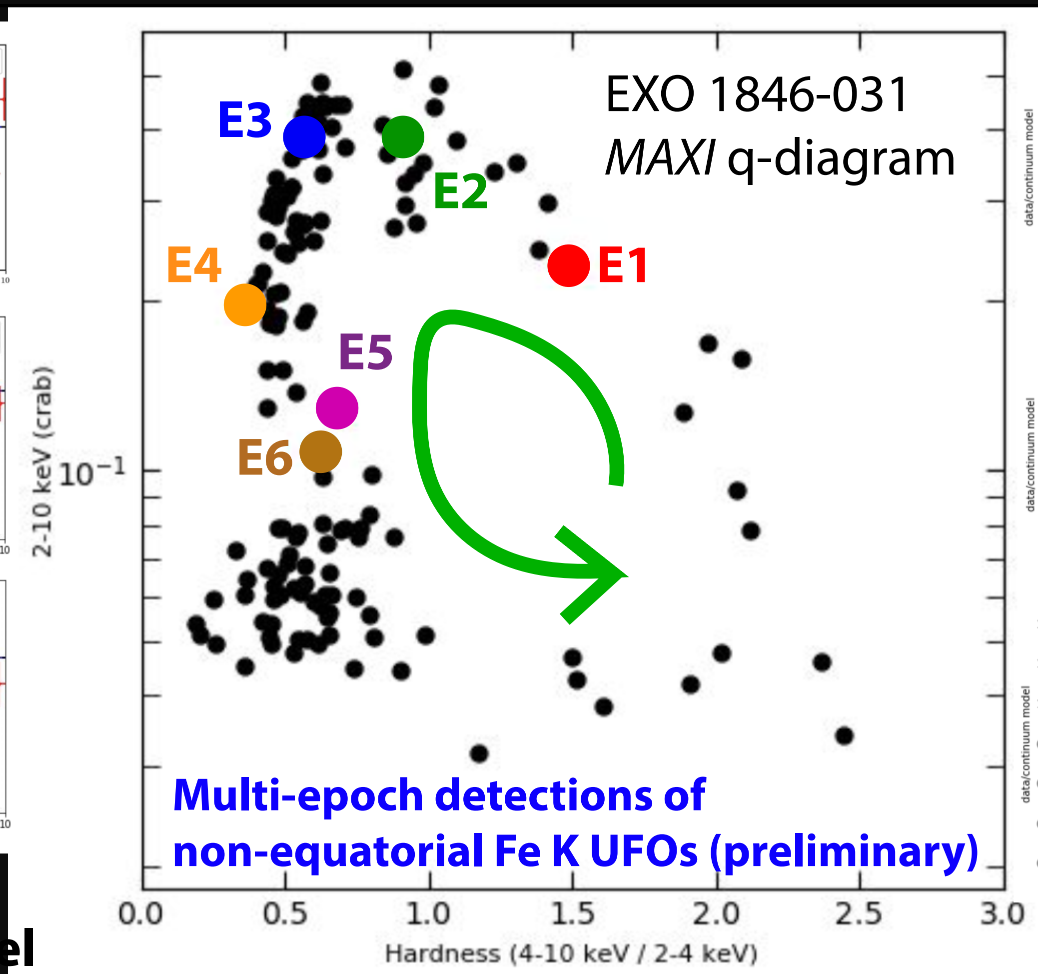


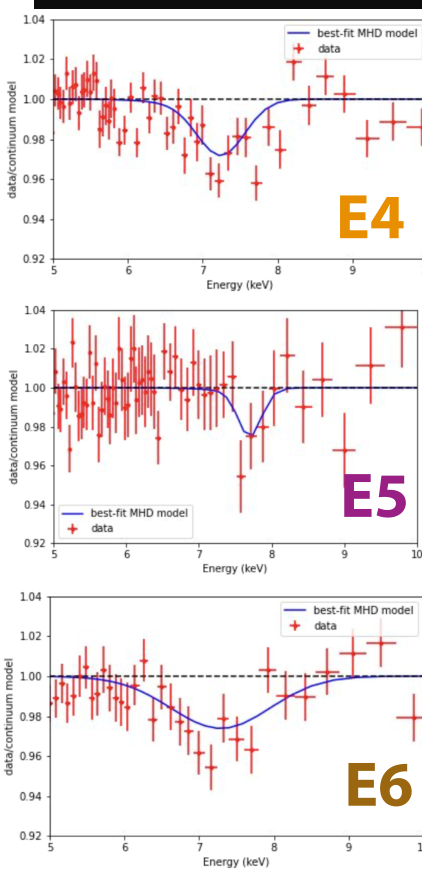
Non-equatorial UFOs accompanied by high density disks…

Case 2: EXO 1846-031, 2019 Outburst

Multi-epoch *MAXI*+*NuSTAR* data **(E1-E6)**







Fe K UFOs and MHD wind model

~32° - 50°

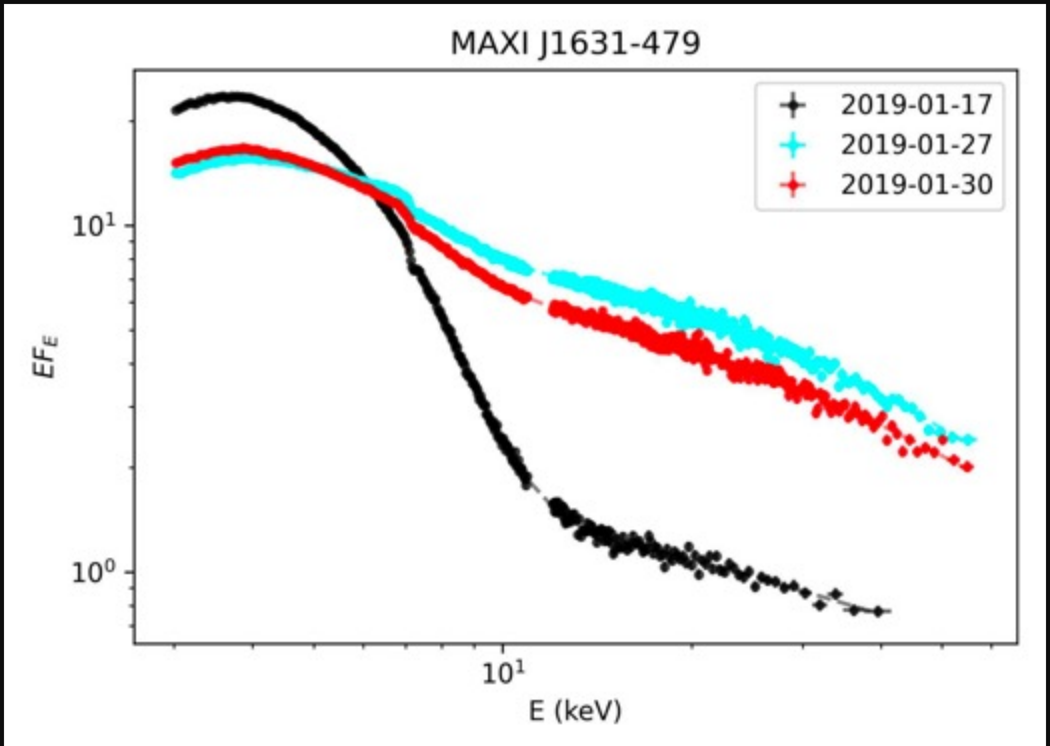
~10^{20-21} cm^{-3}

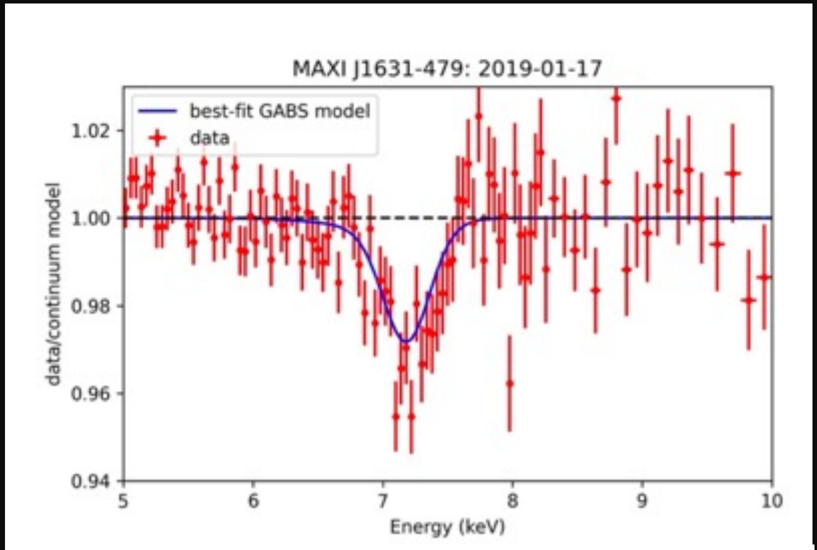
NuSTAR spectra

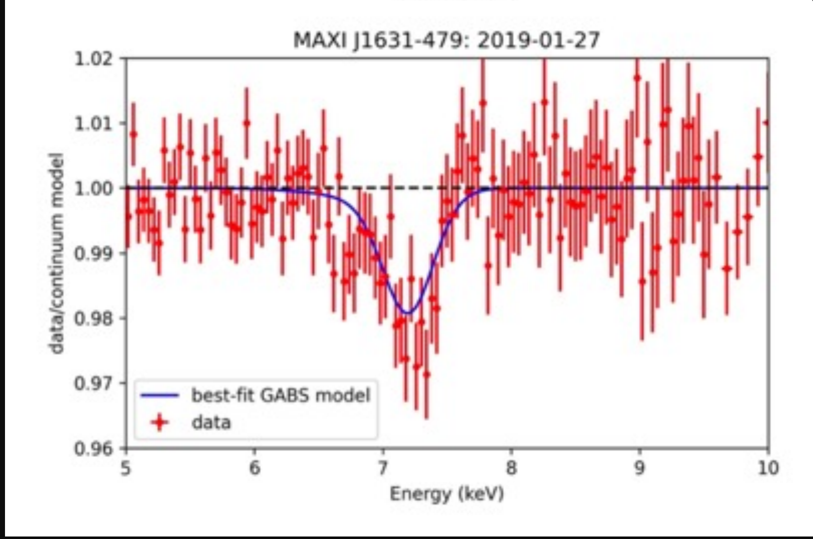
Case 3: MAXI J1631-479, 2019 Outburst

Multi-epoch *MAXI*+*NuSTAR* data **(E1-E3)**

NuSTAR spectra







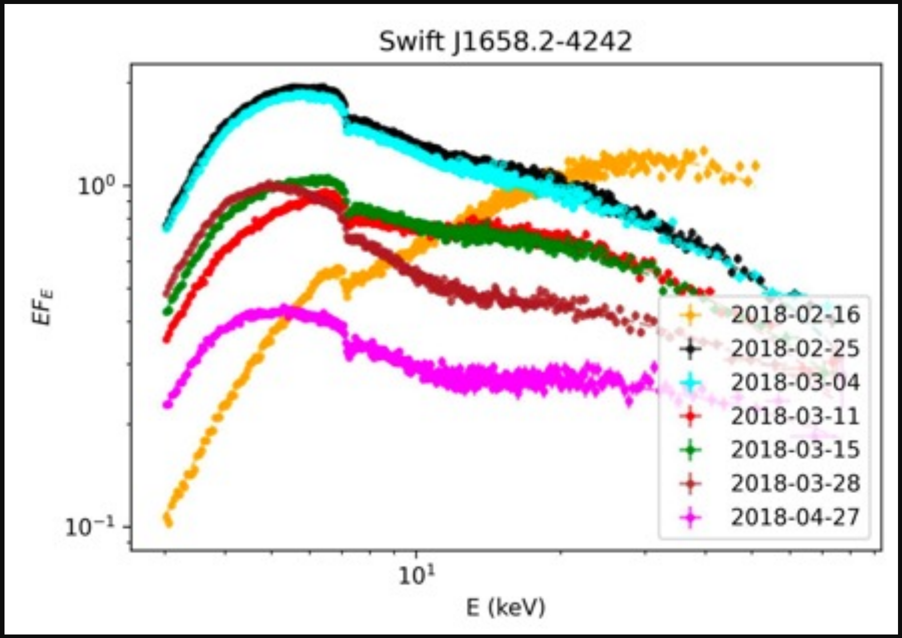
~50°

~10^{21} cm^{-3}

Chandra HRXS 2023

Case 4: Swift J1658.2-4242, 2018 Outburst

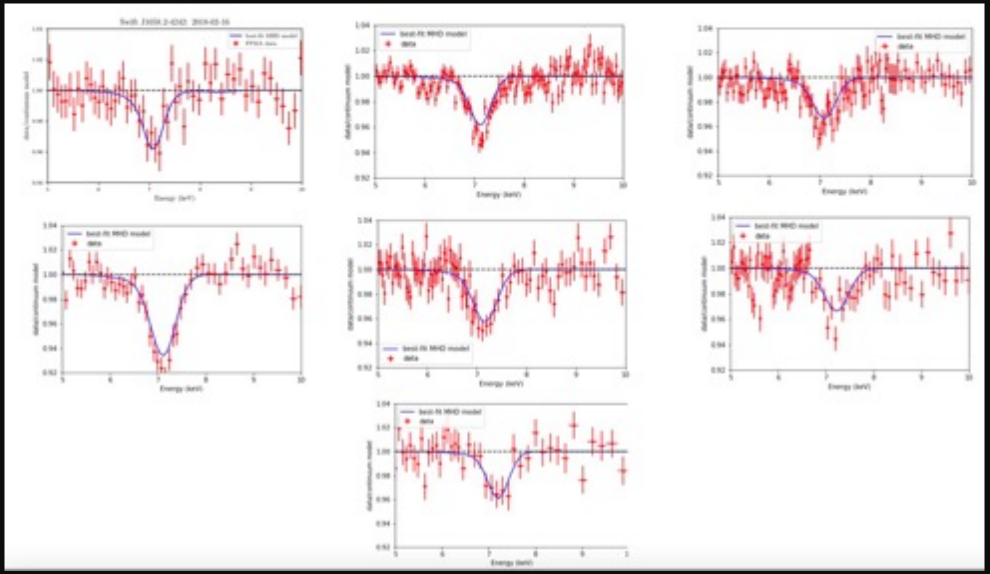
Multi-epoch *MAXI*+*NuSTAR* data **(E1-E7)**



NuSTAR spectra

~30° - 51°

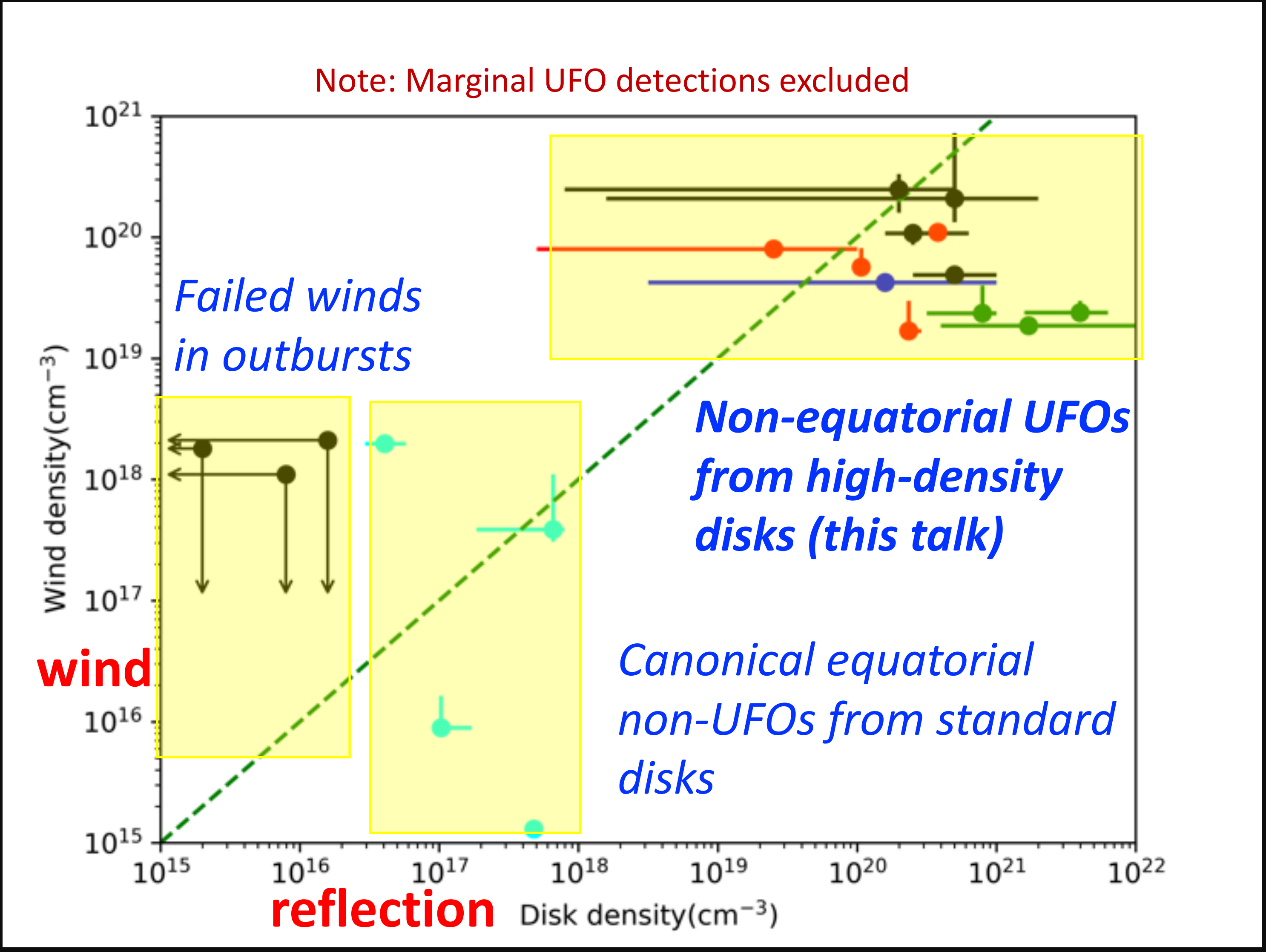
~$10^{19.4 - 21.6}$ cm^{-3}



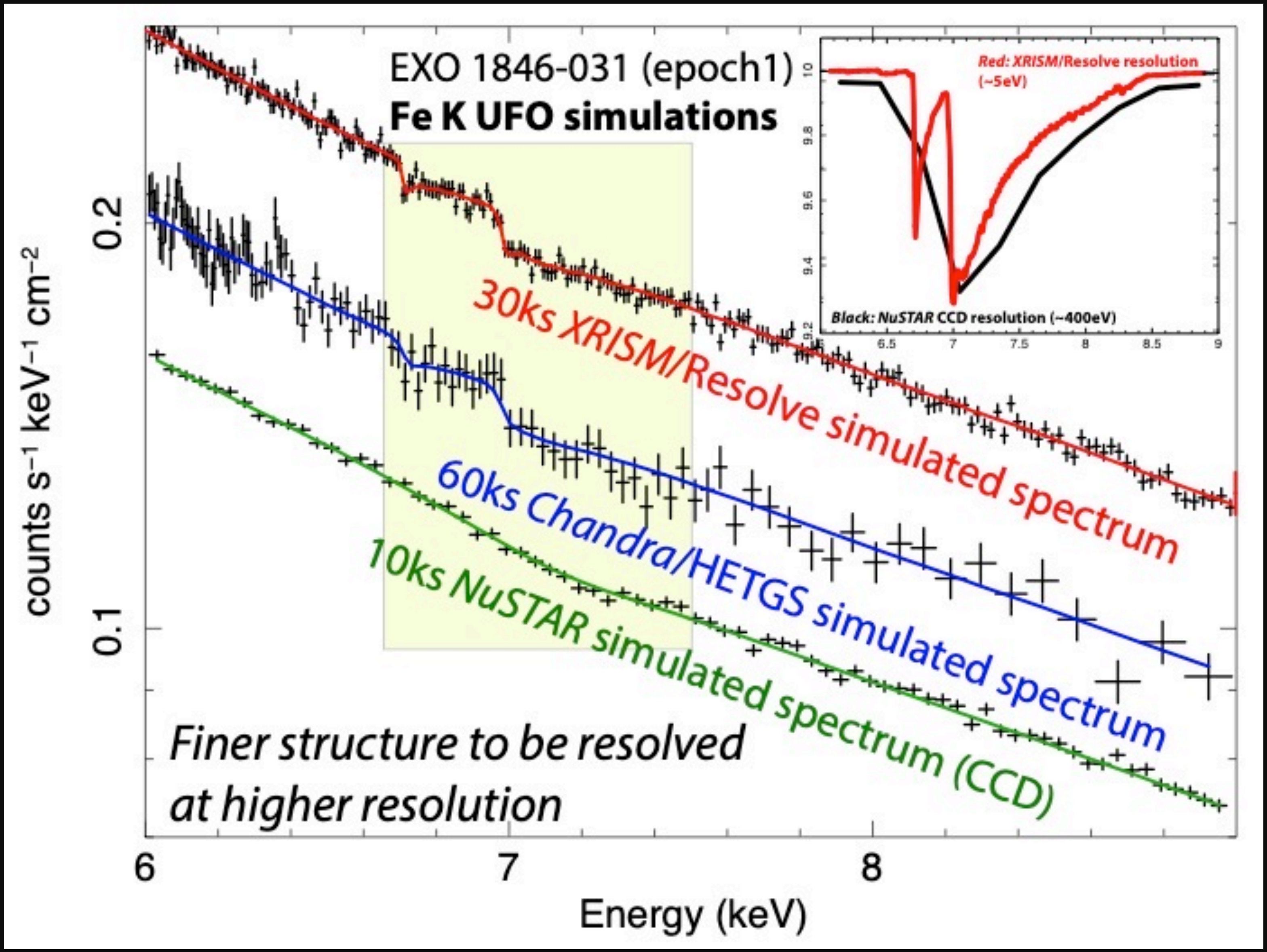
Chandra HRXS 2023

Punchline

Non-equatorial UFOs from High Density Disks



HRXS: Gratings + μ-cal



Take-Home

Implications:

- ❑ Reflection and Wind spectroscopy can complement each other as independent diagnostics; disk density & inclination
- ❑ Non-equatorial BH XRB UFOs
  - ➔ requiring high-density disks (?)
  - ➔ naturally accounted for by magnetic-driving