Constraining Supermassive Black Hole spin over mass scale from observational estimates
Current state and a hopeful future

With: Chris Reynolds (Cambridge, UK and Maryland, US),
James Matthews (Oxford, UK), Robyn Smith (Maryland, US),
Acknowledgements: Andy Fabian and Jiachen Jiang (Cambridge, UK)

Structure

1. Introduction: The X-ray reflection method

2. Motivation: SMBH mass-spin predictions and observations

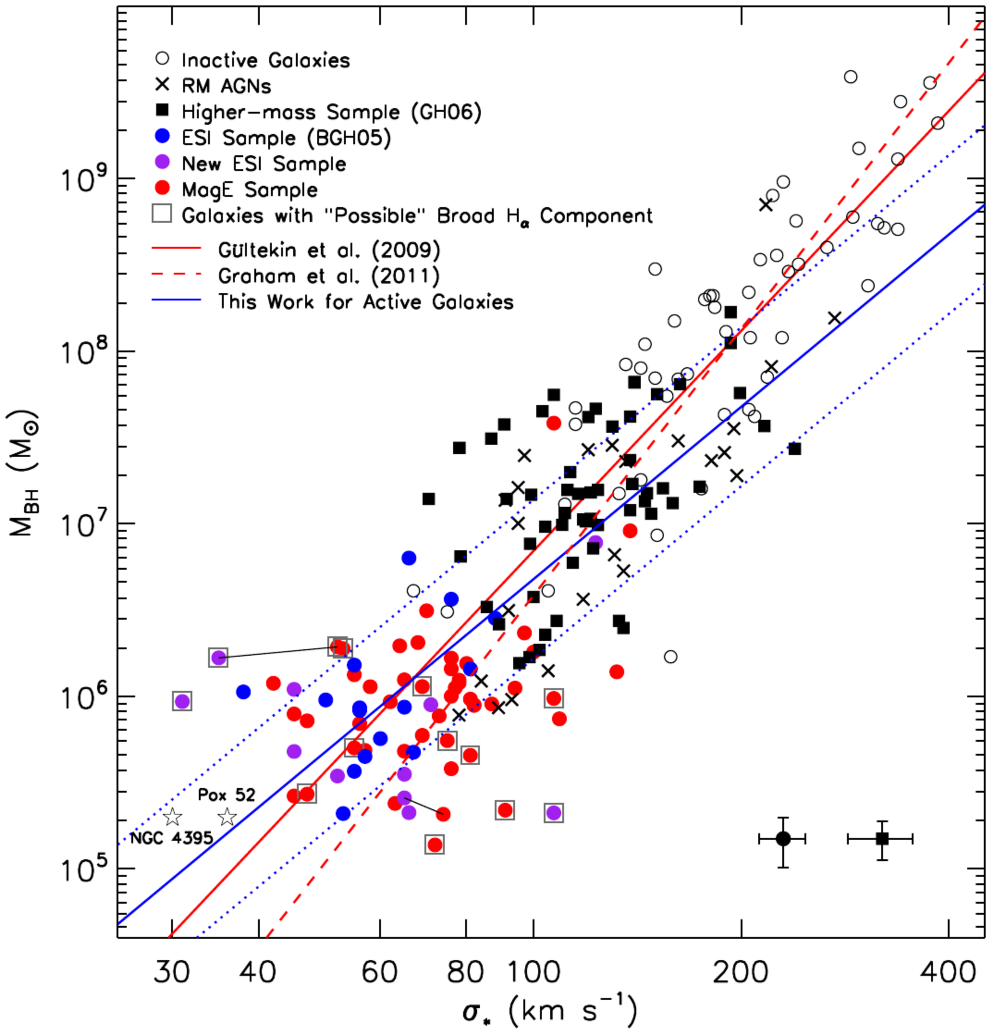
3. Results: Spin of the ultra-massive BH candidate H1821+643
   Sisk-Reynes, J., et al., 2022, MNRAS, 514, 2

3. Ongoing and future work

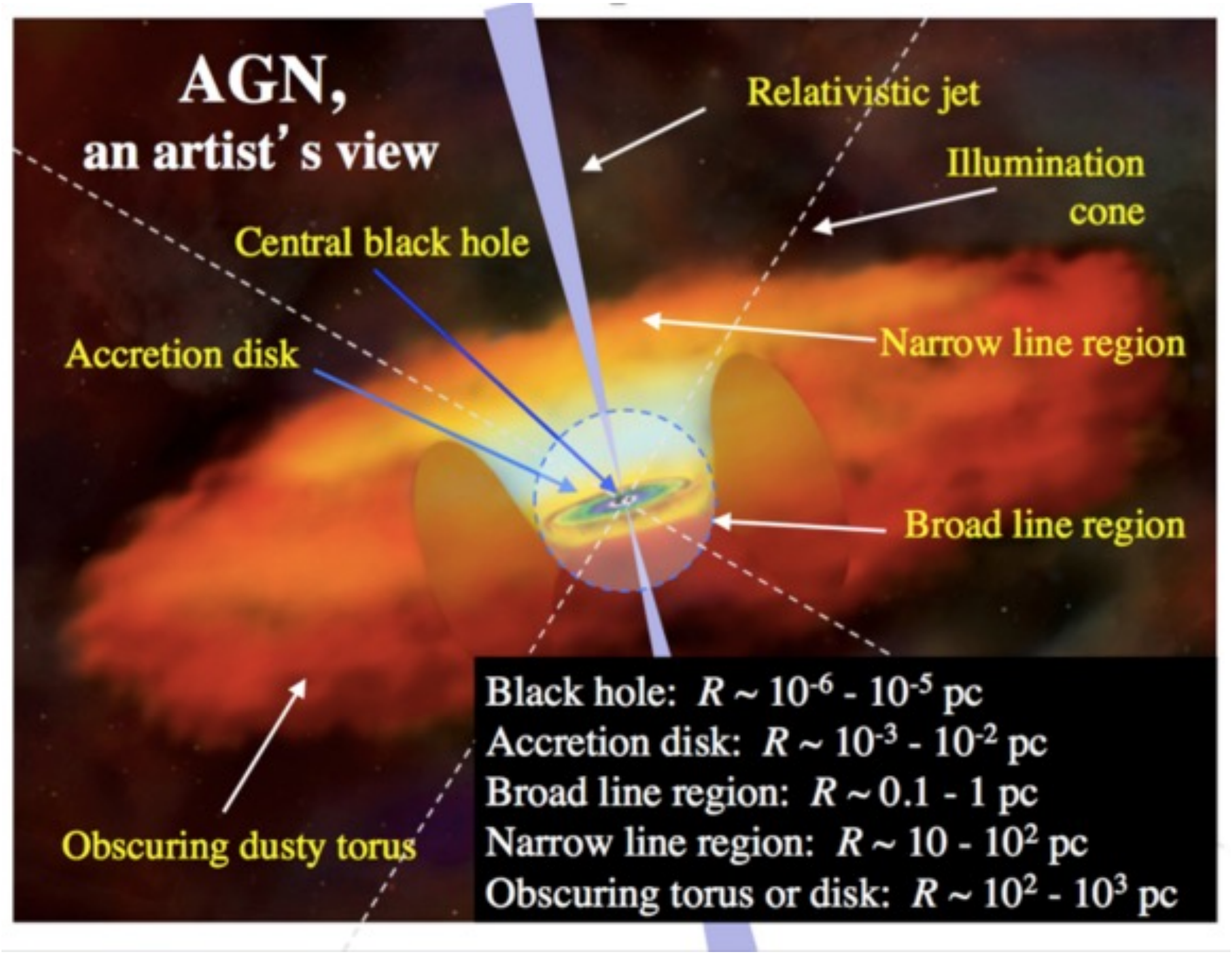
4. Conclusion

Introduction

SMBHS and their host galaxies



Xiao et al., 2011, AAS, 739, 1



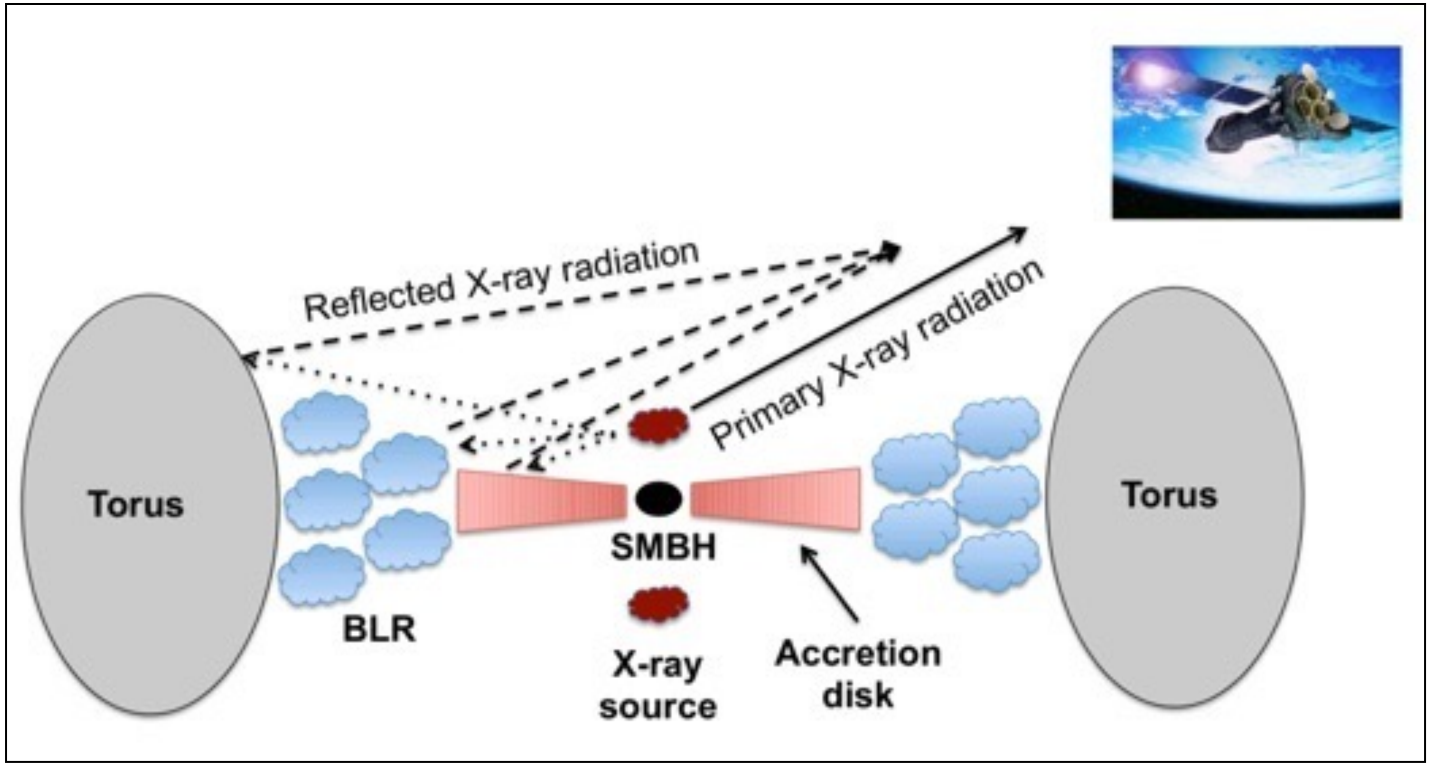
An Artist's View of an AGN. From astrobites.

Introduction

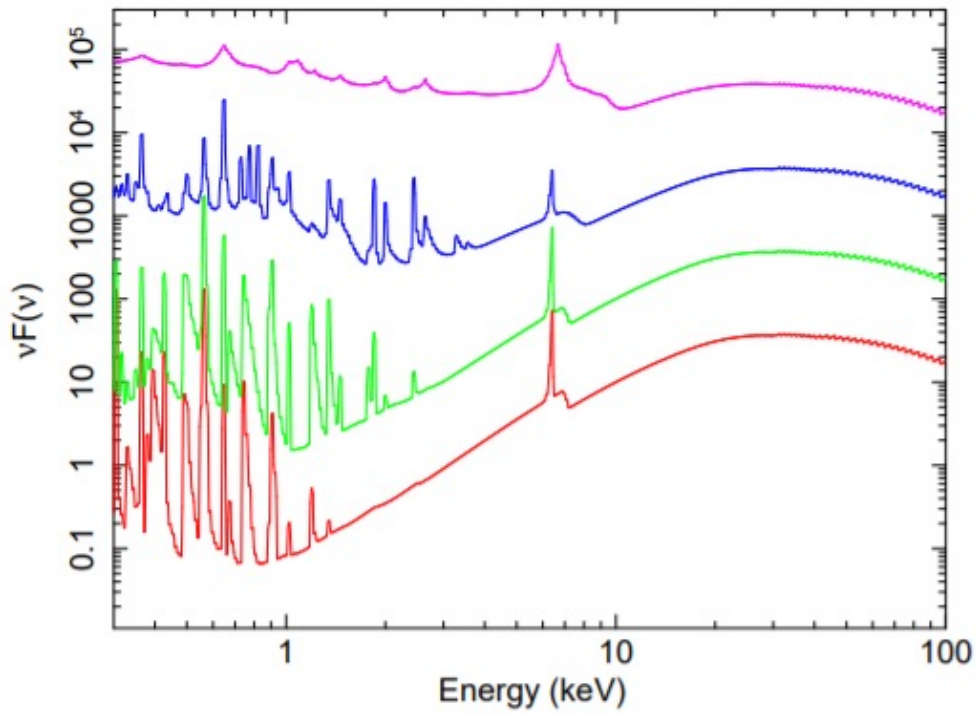
Relativistic X-ray reflection

"Vanilla" **relativistic reflection models depend on:**

$$a^*, R_{\rm in}[R_{\rm g}], R_{\rm out}[R_{\rm g}],\ i[^\circ], \log(\xi[{\rm erg\ cm\ s^{-1}}]),\ A_{\rm Fe}[Z_\odot]$$



Cartoon of X-ray reflection (*Ricci, C., Ph.D. Thesis*)



Reynolds, C., 2013, ISSI-Bern workshop

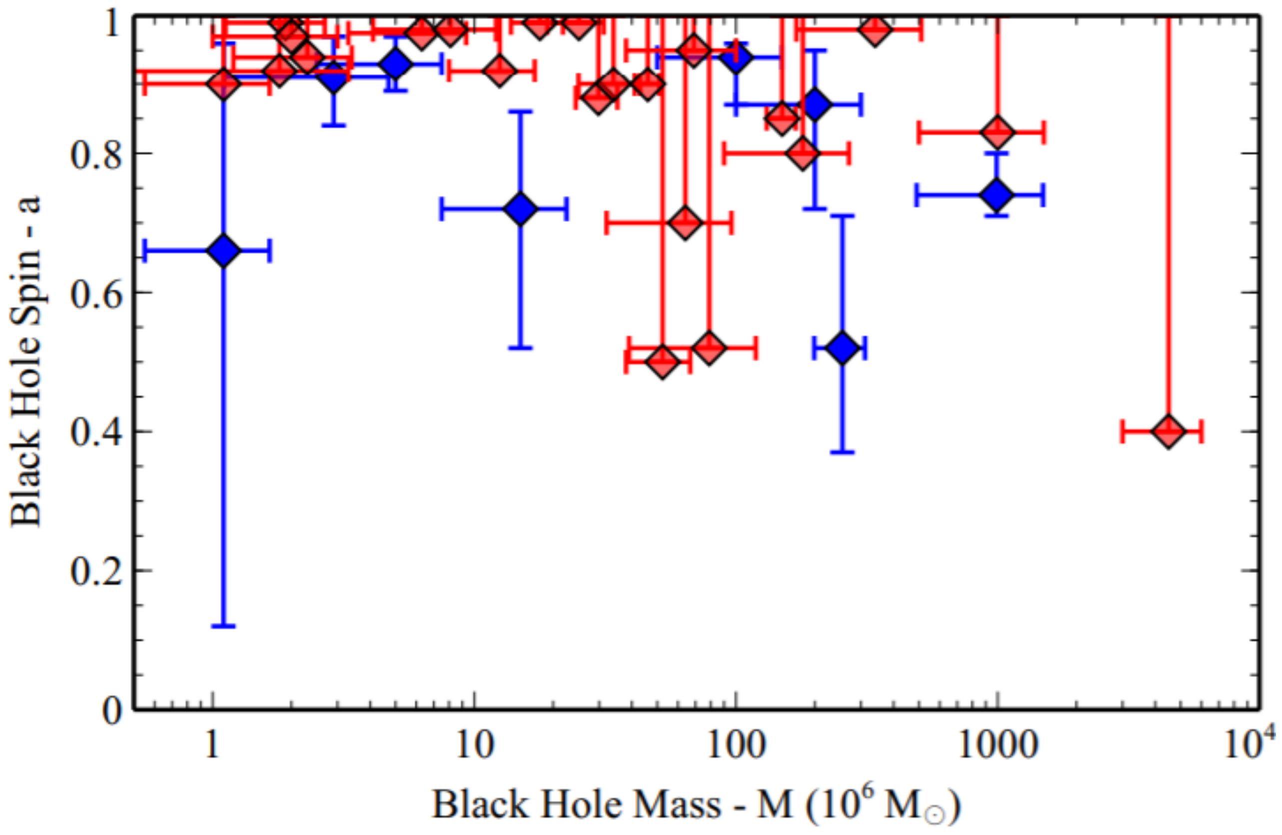
Predicted reflection spectrum for
$\Gamma = 2$, i = 30 deg, given change in ionization state

Motivation

Observational SMBH mass-spin constraints

No-hair theorem of GR

Quantities of an uncharged black hole (BH) are its **mass** and **angular momentum**



Reynolds, C., 2021, ARA&A, 59

$$M_{BH}[M_\odot],\ J$$

J quantified via dimensionless spin parameter

$$a^* = Jc/GM_{BH}^2$$

$$a^* \in [-0.998, +0.998]$$

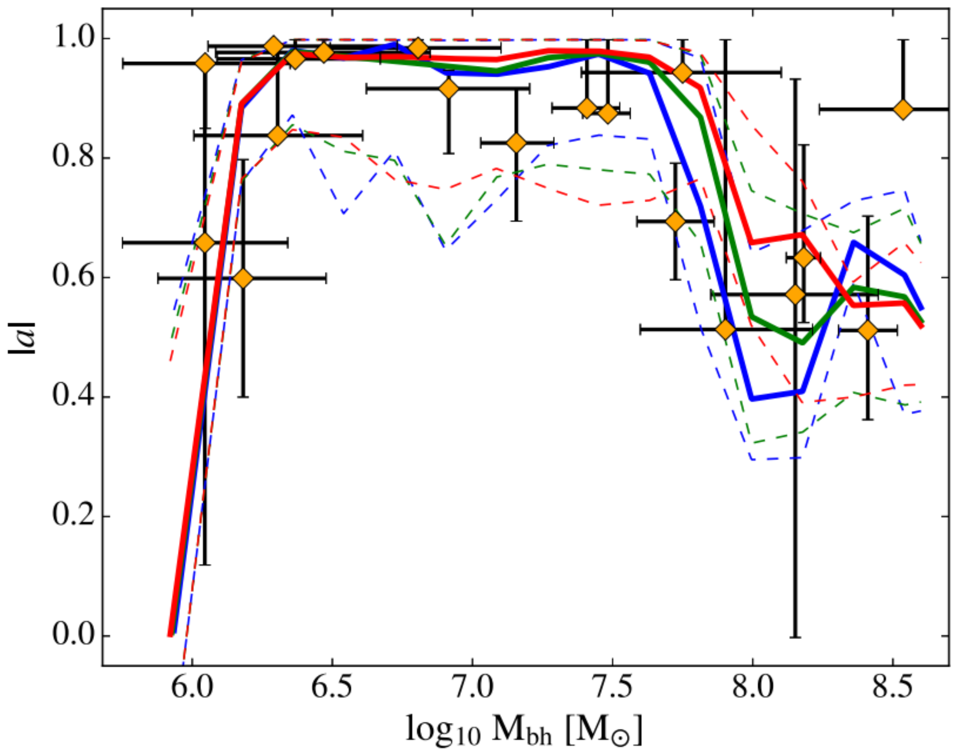
$$a^* > 0 \text{ Prograde}$$

$$a^* < 0 \text{ Retrograde}$$

Motivation

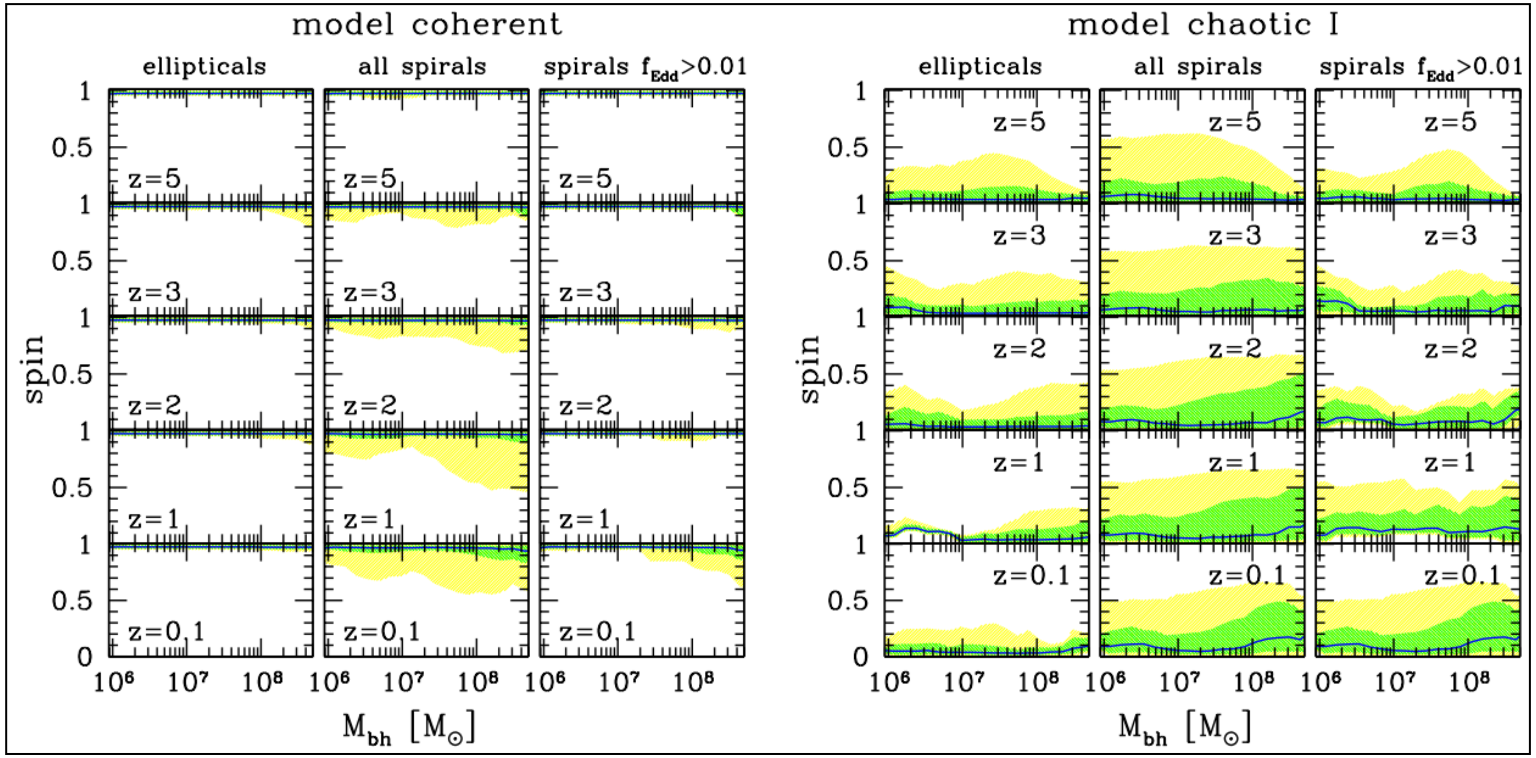
Numerical and semi-analytic predictions

Hydrodynamic simulations



Bustamante, D. and Springel, V., 2019, MNRAS, 490, 3

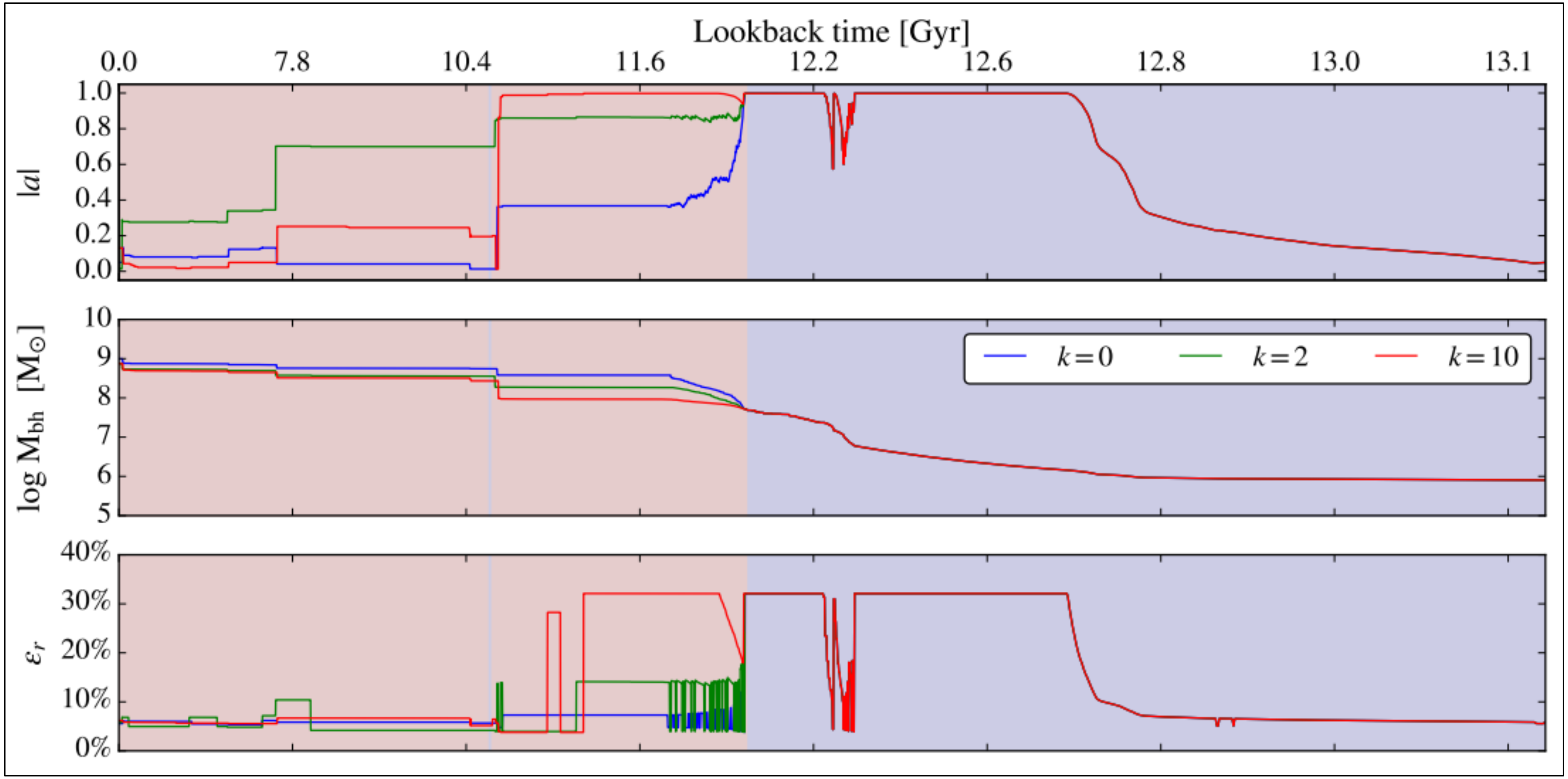
Semi-analytic models



Sesana, A., et al., 2014, ApJ, 794, 2

Motivation

Hydrodynamic simulations



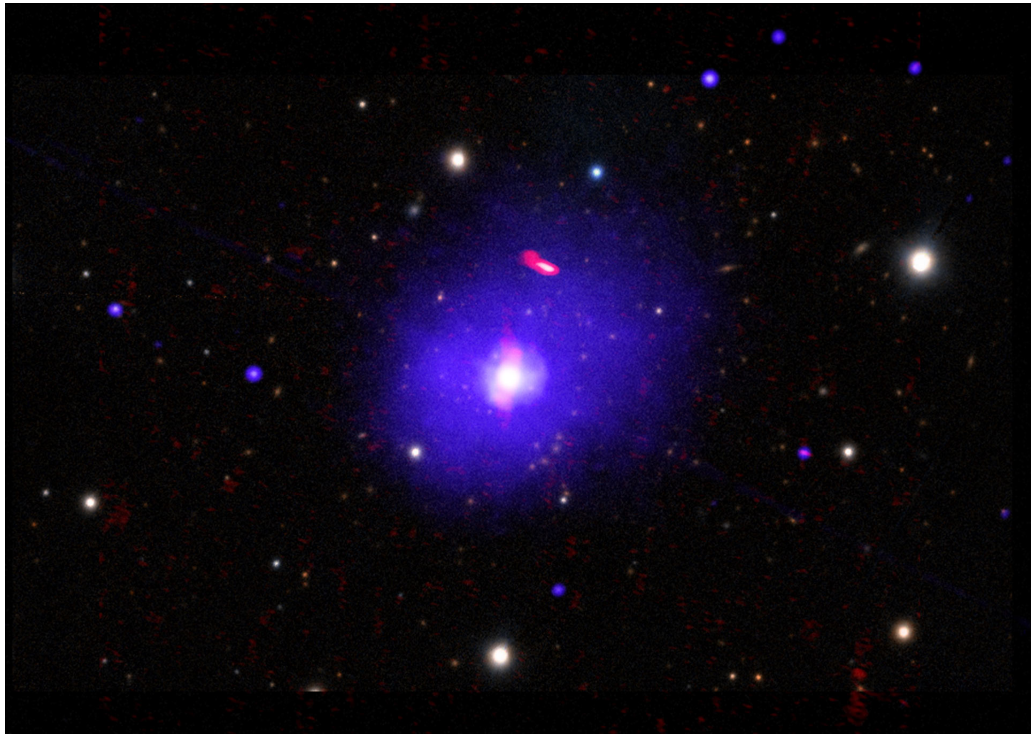
Bustamante, D. and Springel, V., 2019, MNRAS, 490, 3

Results H1821+643

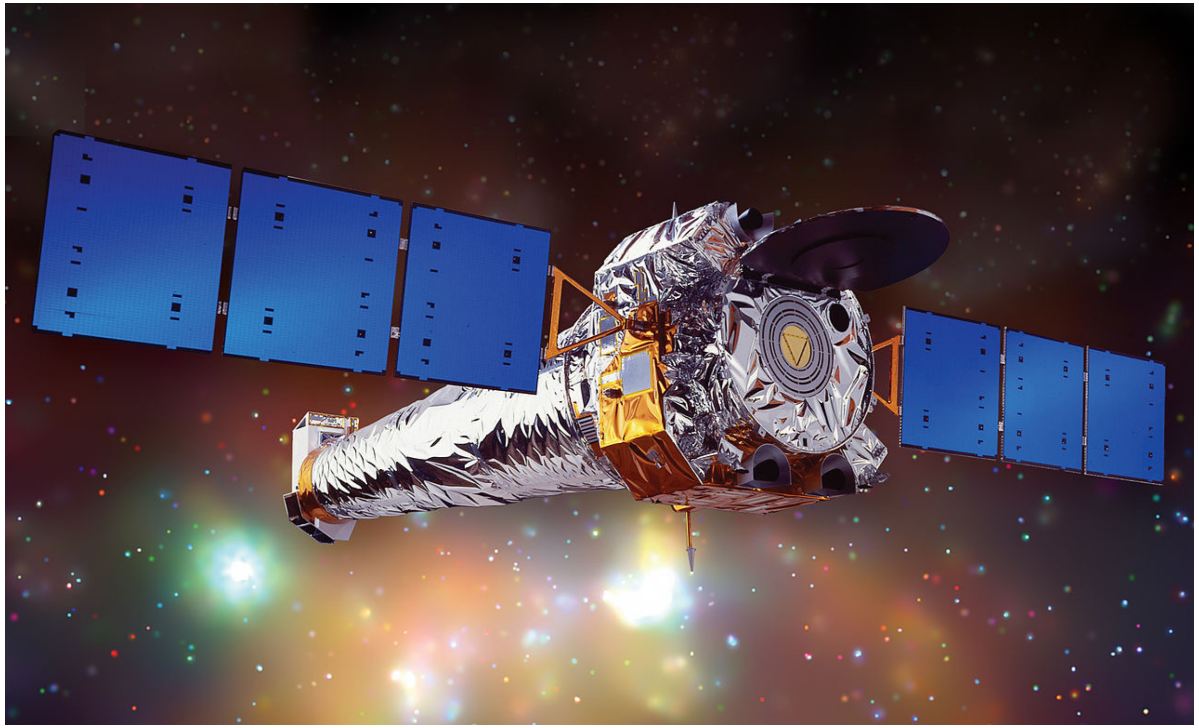
Evidence for a moderate spin from X-ray reflection of the high-mass supermassive black hole in the cluster-hosted quasar H1821+643

Júlia Sisk-Reynés,[1★] Christopher S. Reynolds,[1] James H. Matthews[1] and Robyn N. Smith[2]
[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 OHA, UK*
[2]*Dept. of Astronomy, University of Maryland, College Park, MD 20742, USA*

Sisk-Reynes, J., et al., 2022, MNRAS, 514, 2



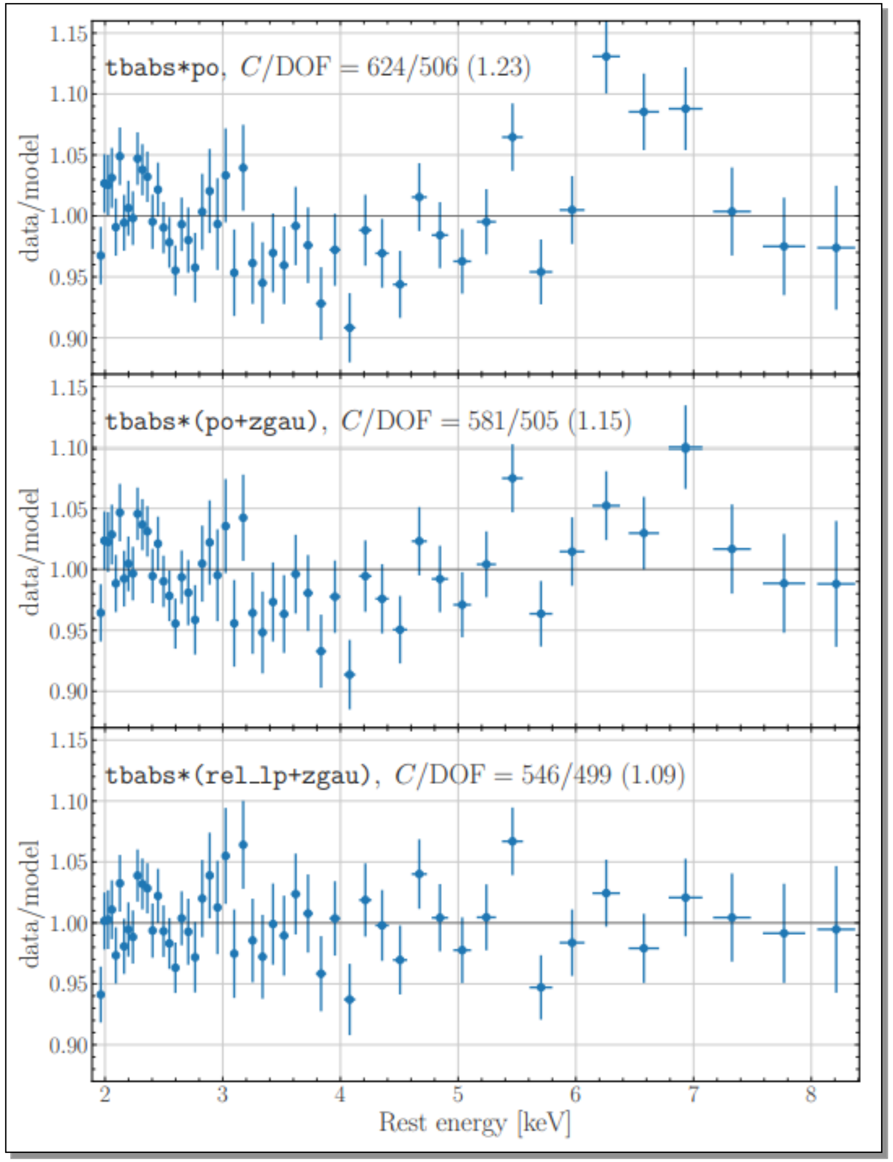
Russell, H. and Smith, R., Chandra Press Release (Link)

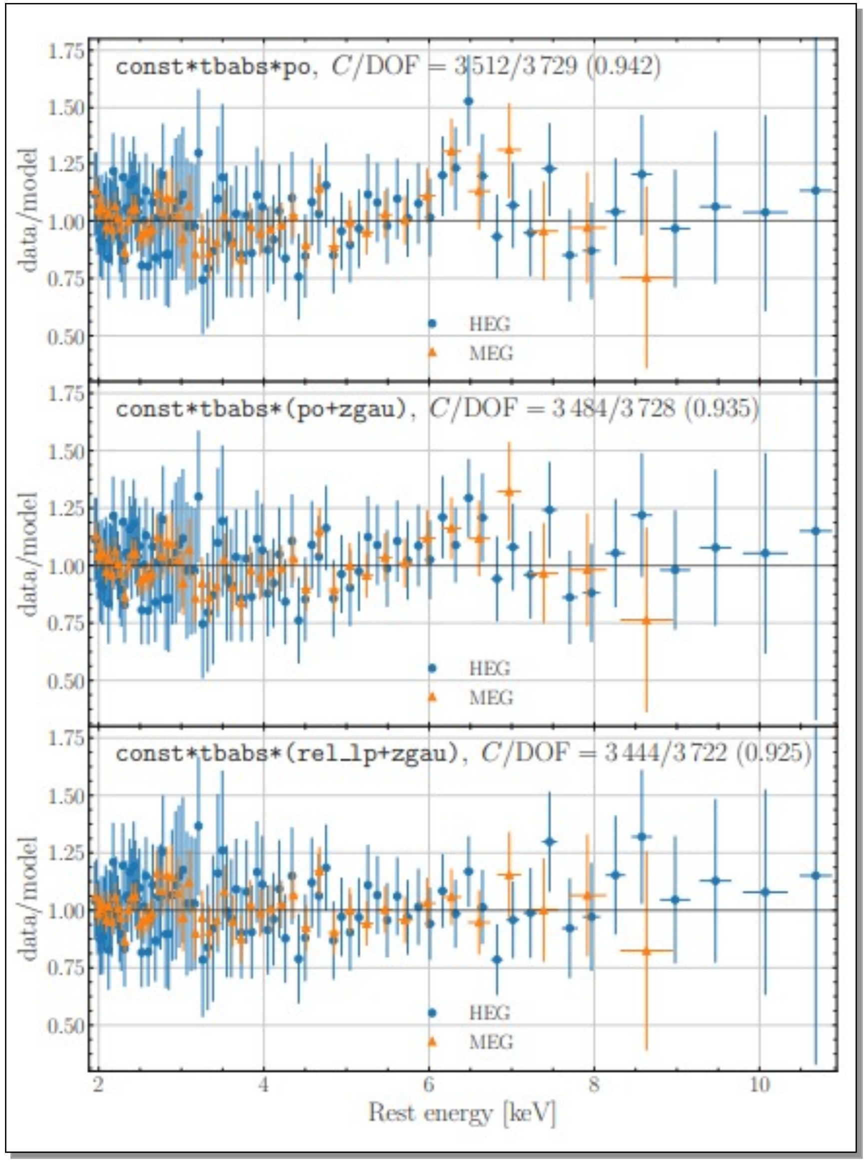


An artist's view of the Chandra X-ray Observatory (Link)

Results
H1821+643

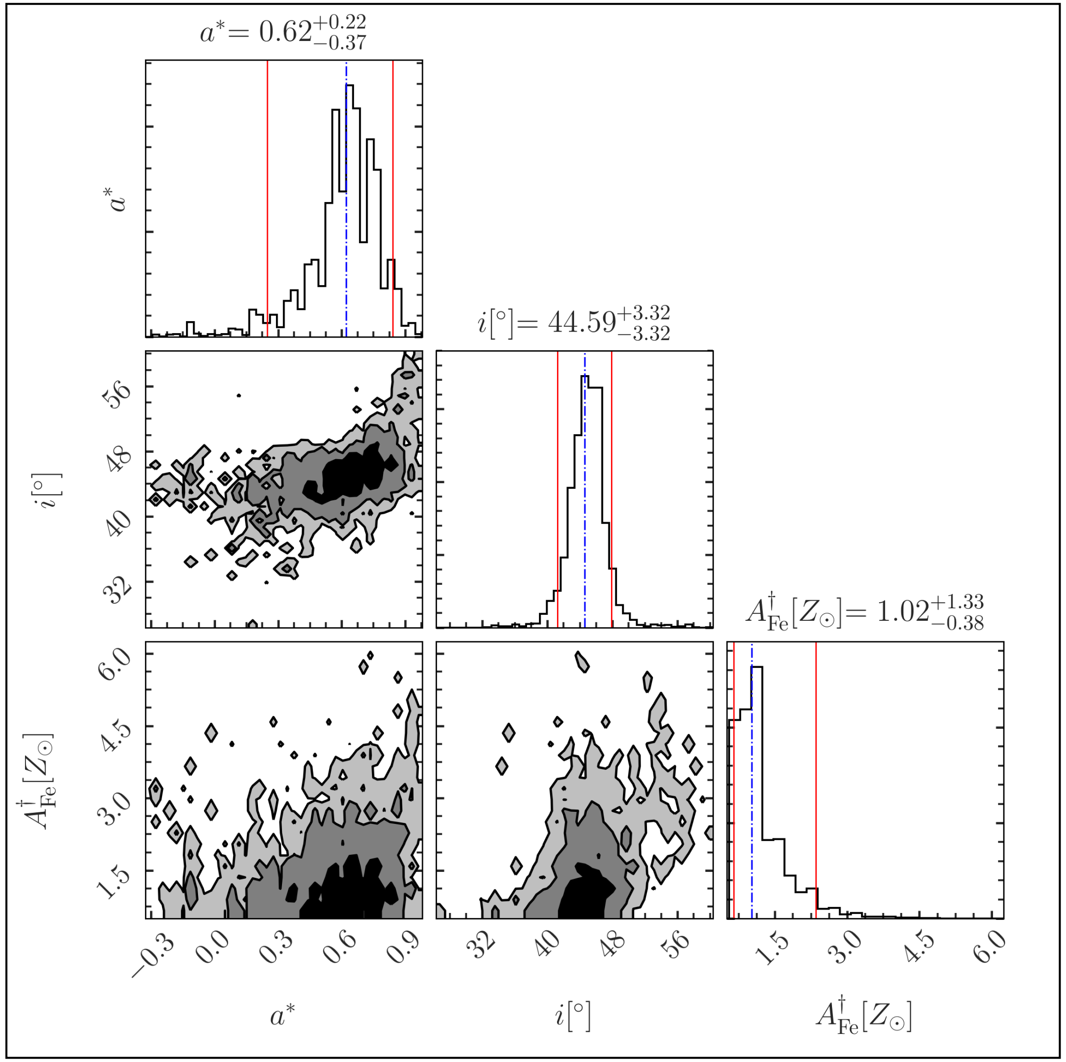
LETG/HETG views of H1821+643

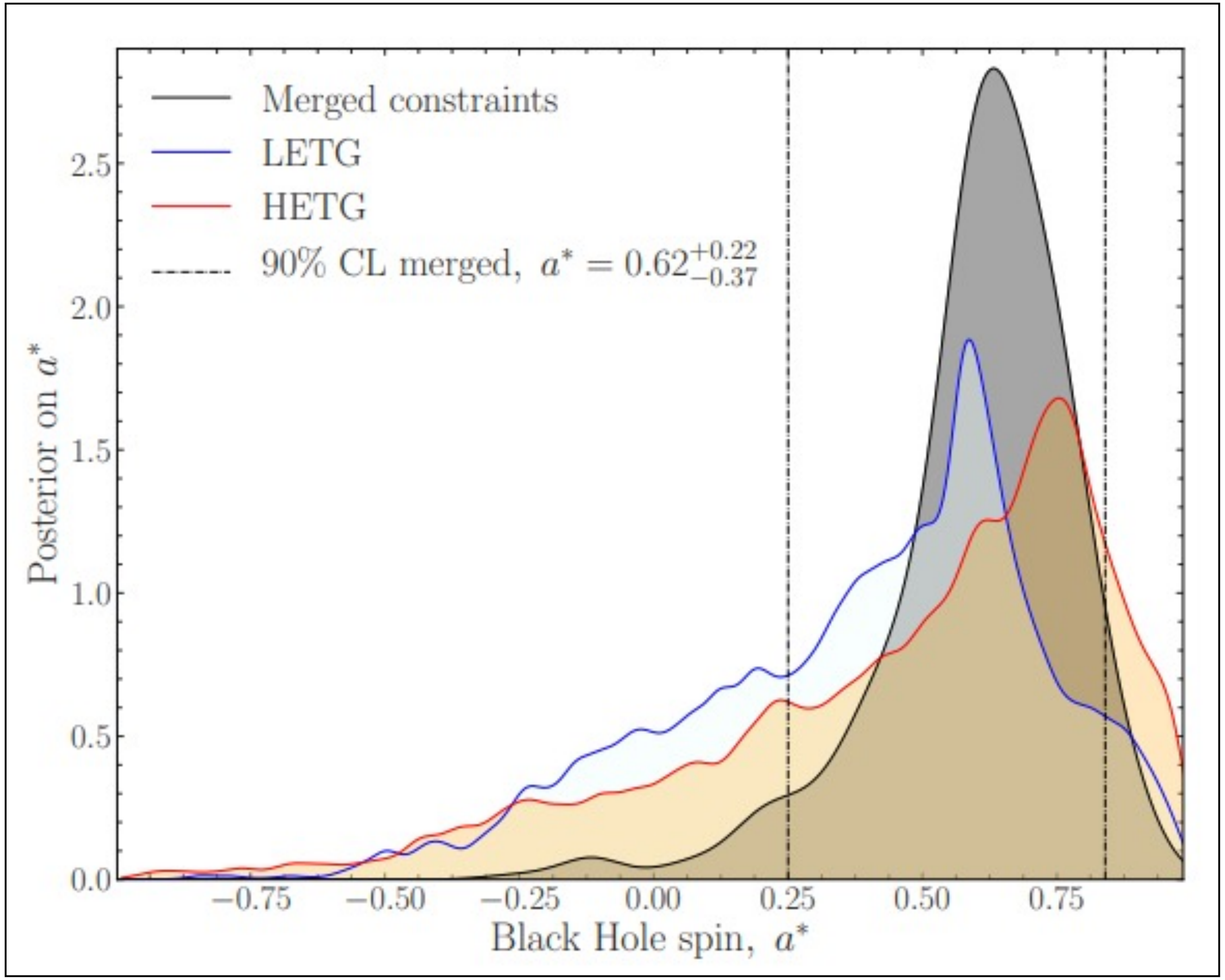




Results
H1821+643

Constraints from merged HETG/LETG posteriors

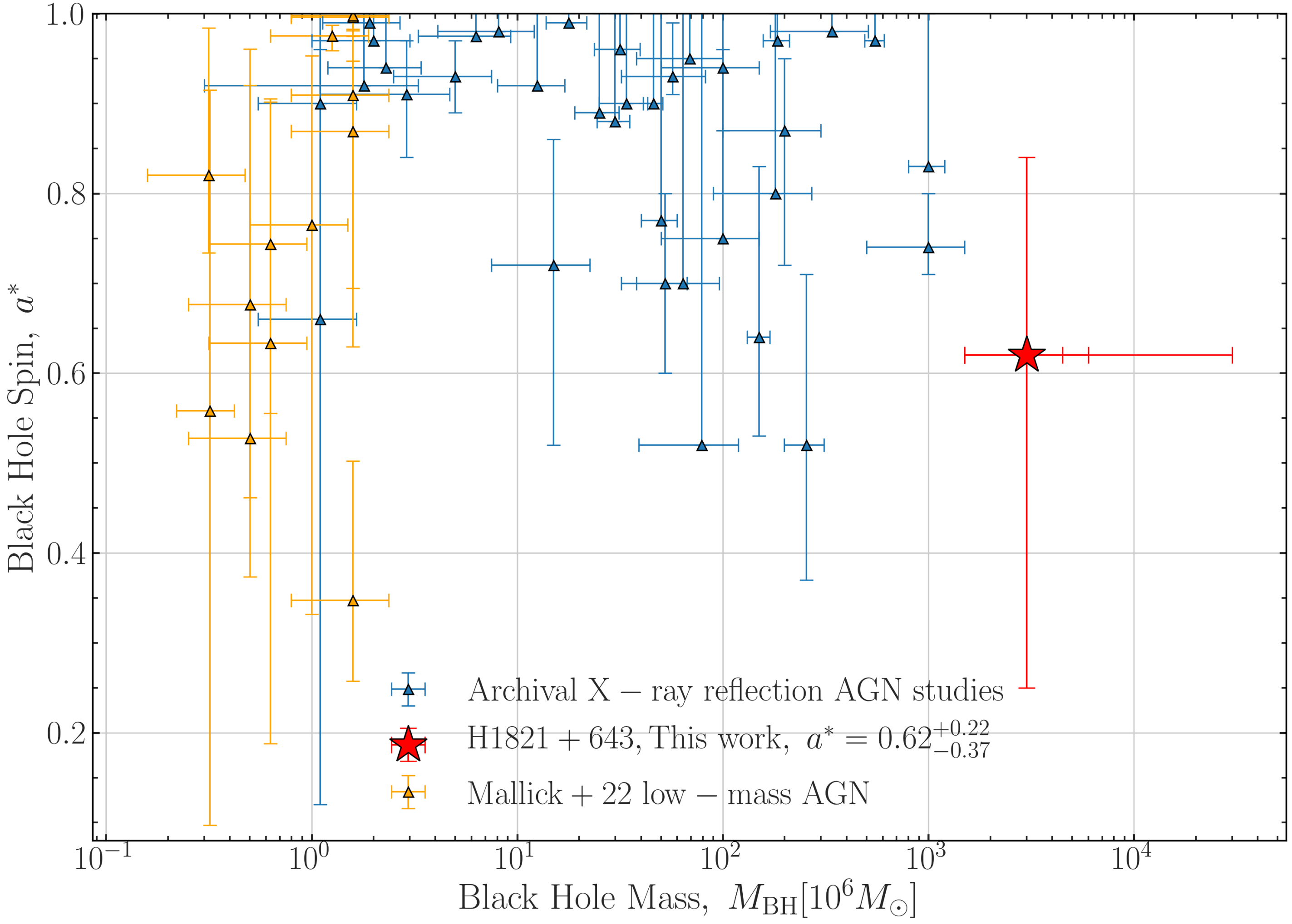




Results
BH mass-spin

SMBH mass-spin over mass scale: UPDATED

Preliminary!

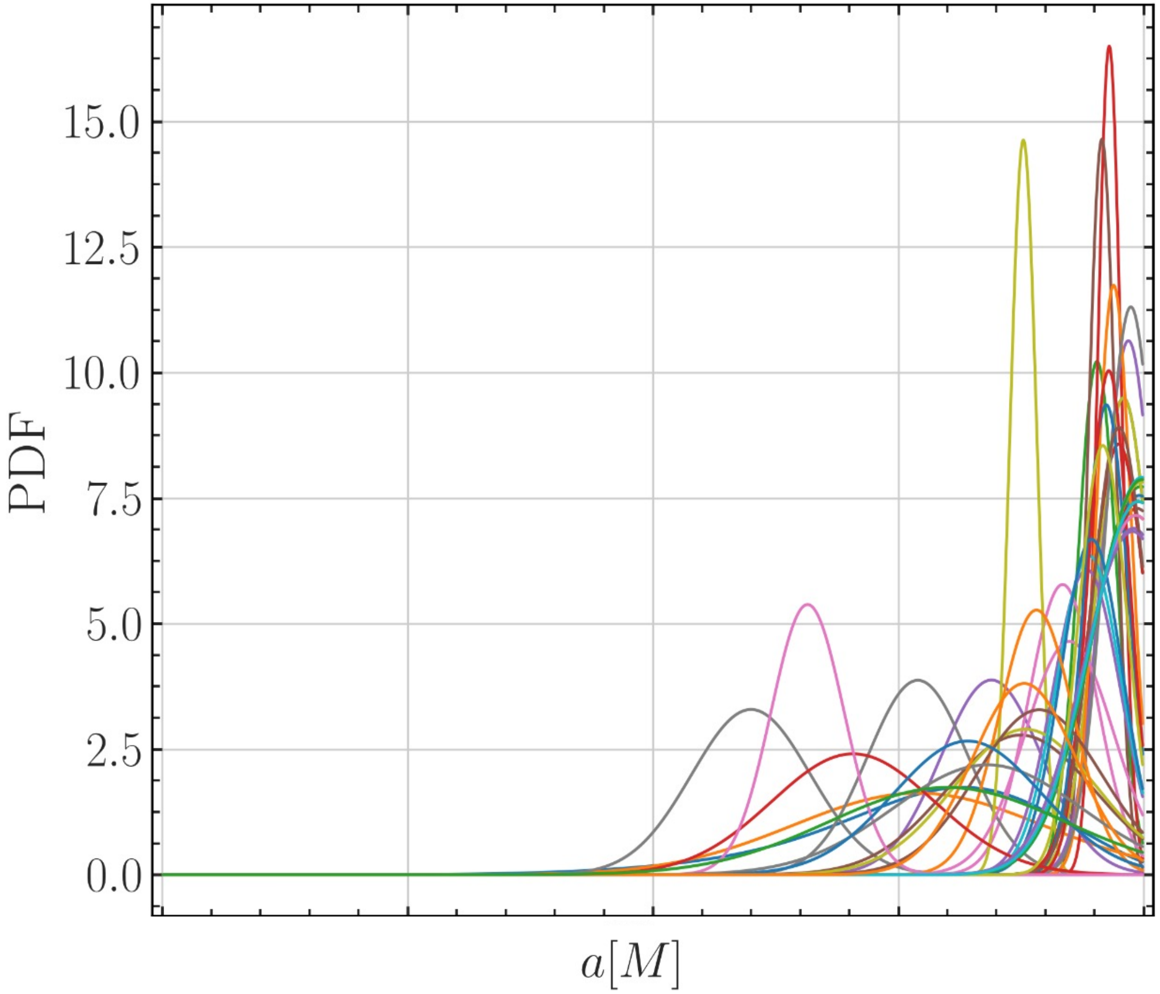


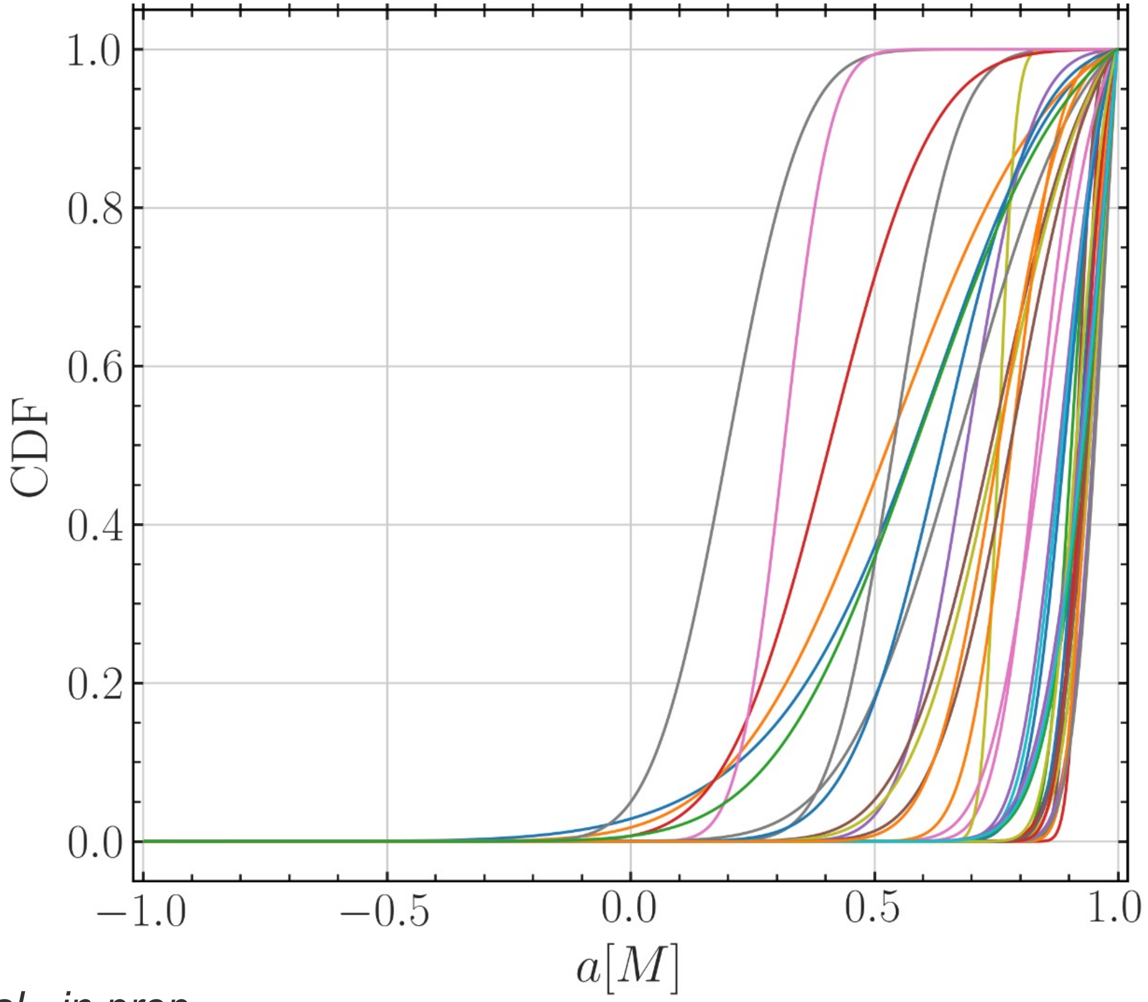
Sisk-Reynes, J., et al., in prep.

Ongoing work

A phenomenological model for BH spin over mass scales

Preliminary!

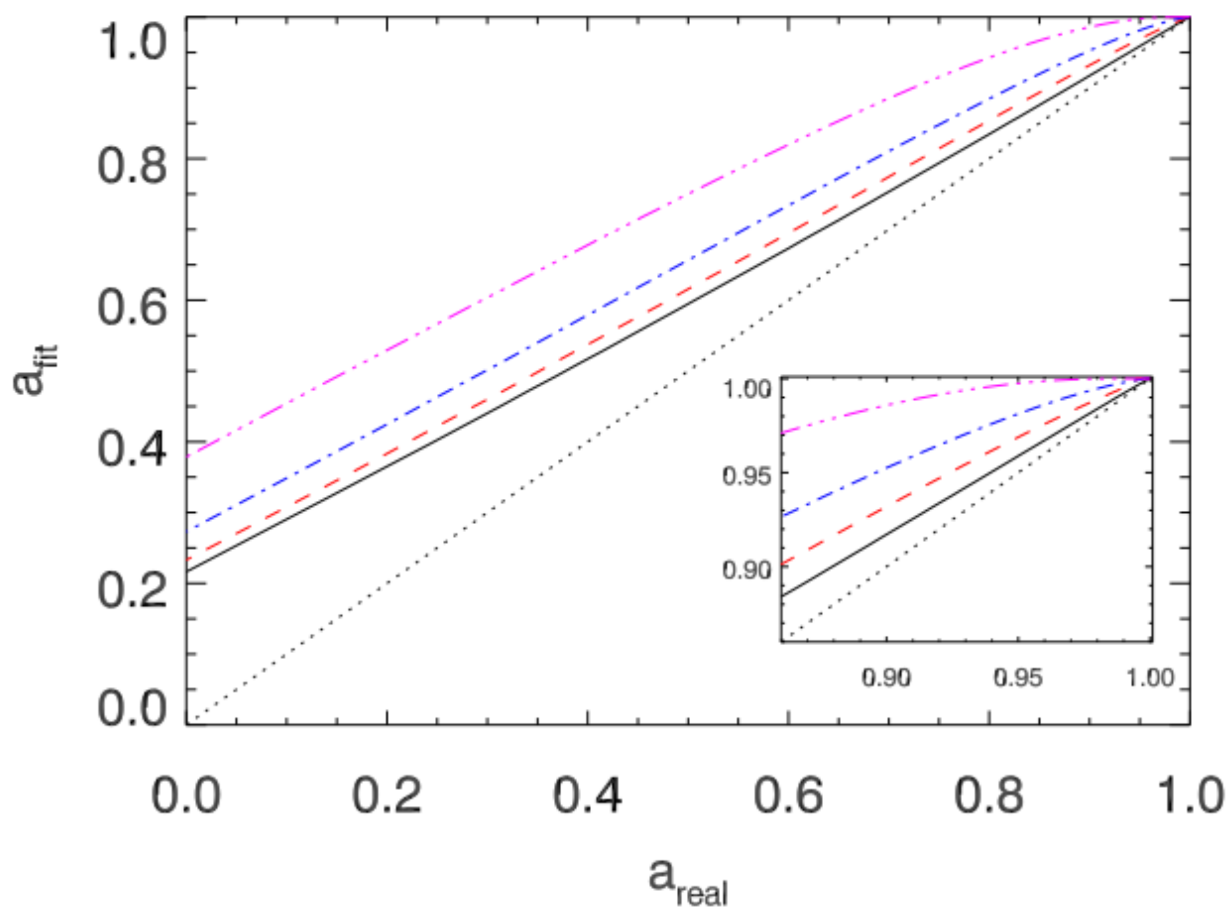




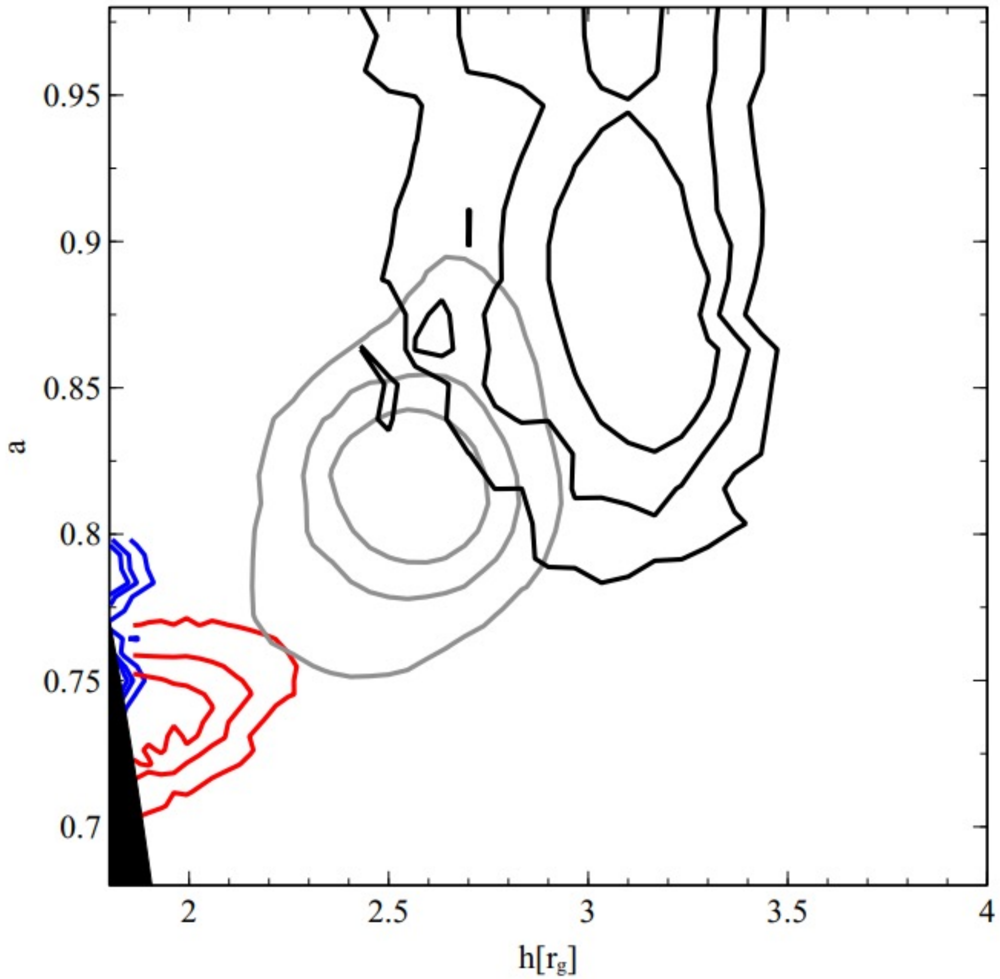
Sisk-Reynes, J., et al., in prep.

Ongoing work

Systematic errors (I)
Disc thickness



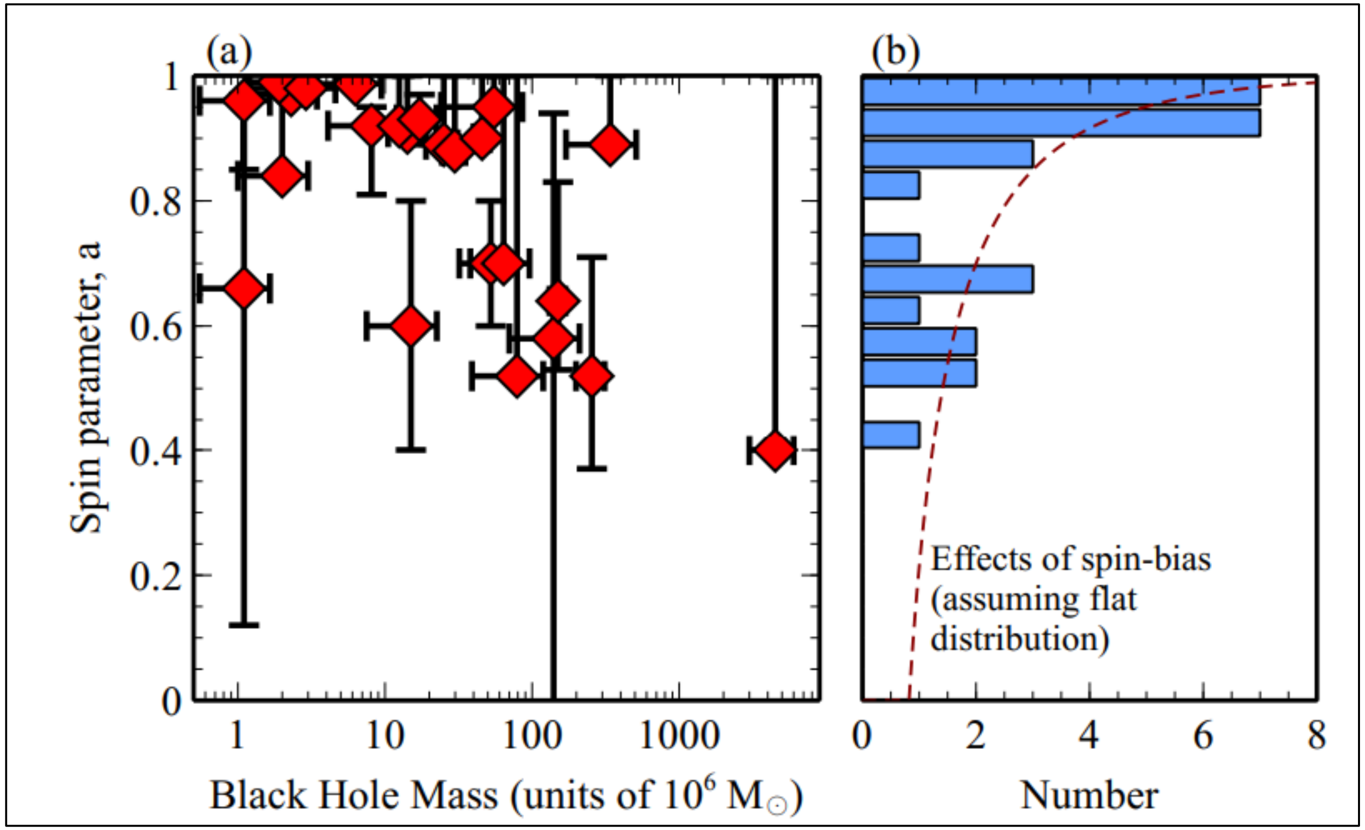
Reynolds, C. and Fabian, A., ApJ, 675, 2



Taylor, C. and Reynolds, C., ApJ, 855, 2

Ongoing work

Systematic errors (II)
Selection bias from flux-limited samples



Reynolds, C., 2019, Nat. Ast., 3

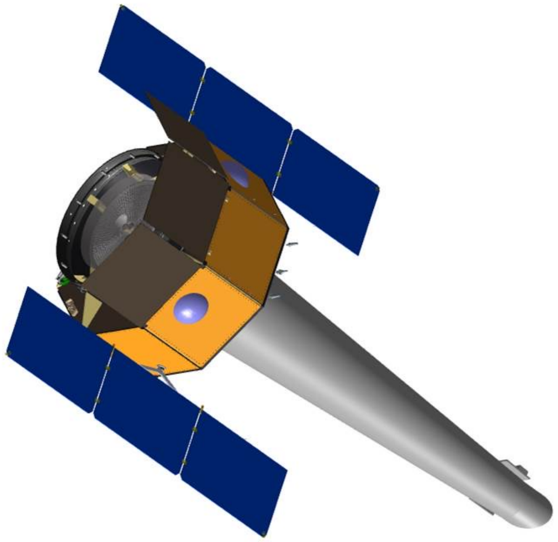
See also: *Brenneman, L., et al., 2011, 736, 2*
Raimundo, S. and Fabian, A., 2012, MNRAS, 419, 2
Davis, S and Laor, A., ApJ, 728, 2

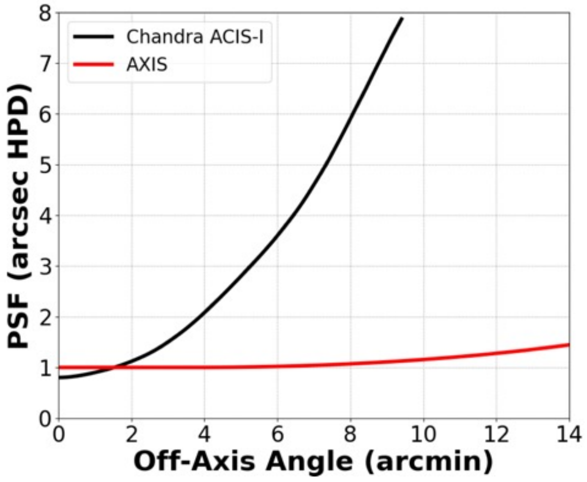
Future work

Constraining SMBH spin with the *Advanced X-ray Imaging Satellite* (*AXIS*)

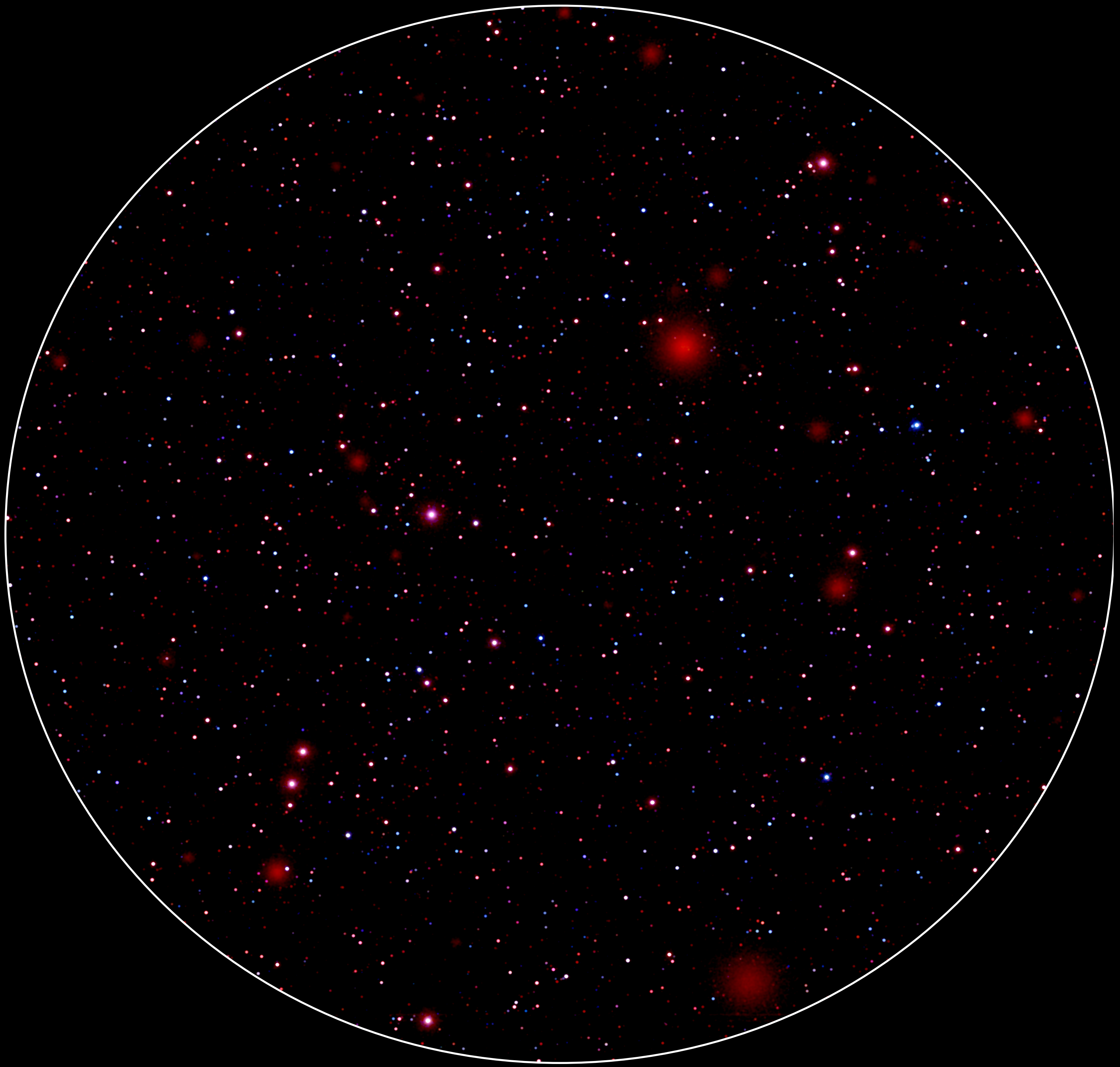
Parameter	Value
PSF	1.0” on-axis, 1.5” FoV-ave (HPD)
Effective Area (incl. detector)	5000 cm^2 at 1 keV; 1000 cm^2 at 6 keV
FoV	24 arcmin diameter circle
Bandpass	0.2-12 keV
Readout rate	>5 fps
Slew rate	120 deg. / 7 min.
Orbit	Low-inclination (5 deg) LEO

Courtesy of Christopher Reynolds (*AXIS* PI)





- Simple, single instrument design
- 5-year prime mission; design for 10-year goal
- Combination of PSF, effective area, low-background, gives exquisite point source sensitivity ($F_{0.5\text{-}2.0keV}=3\times10^{-18}$ erg/s/cm^2 FOV-ave in 5Ms)
- Capable facility for transient science; ~2-hour response time to alerts + onboard rapid transient detection.
- **True community facility; >70% time for Guest Observers**



Courtesy of Stefano Marchesi
*Updated with *AXIS*' latest responses from
Based on Marchesi, S., et al., 2020, A&A, 642

AXIS Deep Field (5Ms, 450arcmin^2)
Sensitivity in 0.5-2.0keV band,
- 1.9E-18 erg/s/cm^2 (20% field, 90arcmin^2)
- 3.7E-18 erg/s/cm^2 (80% field, 360arcmin^2)

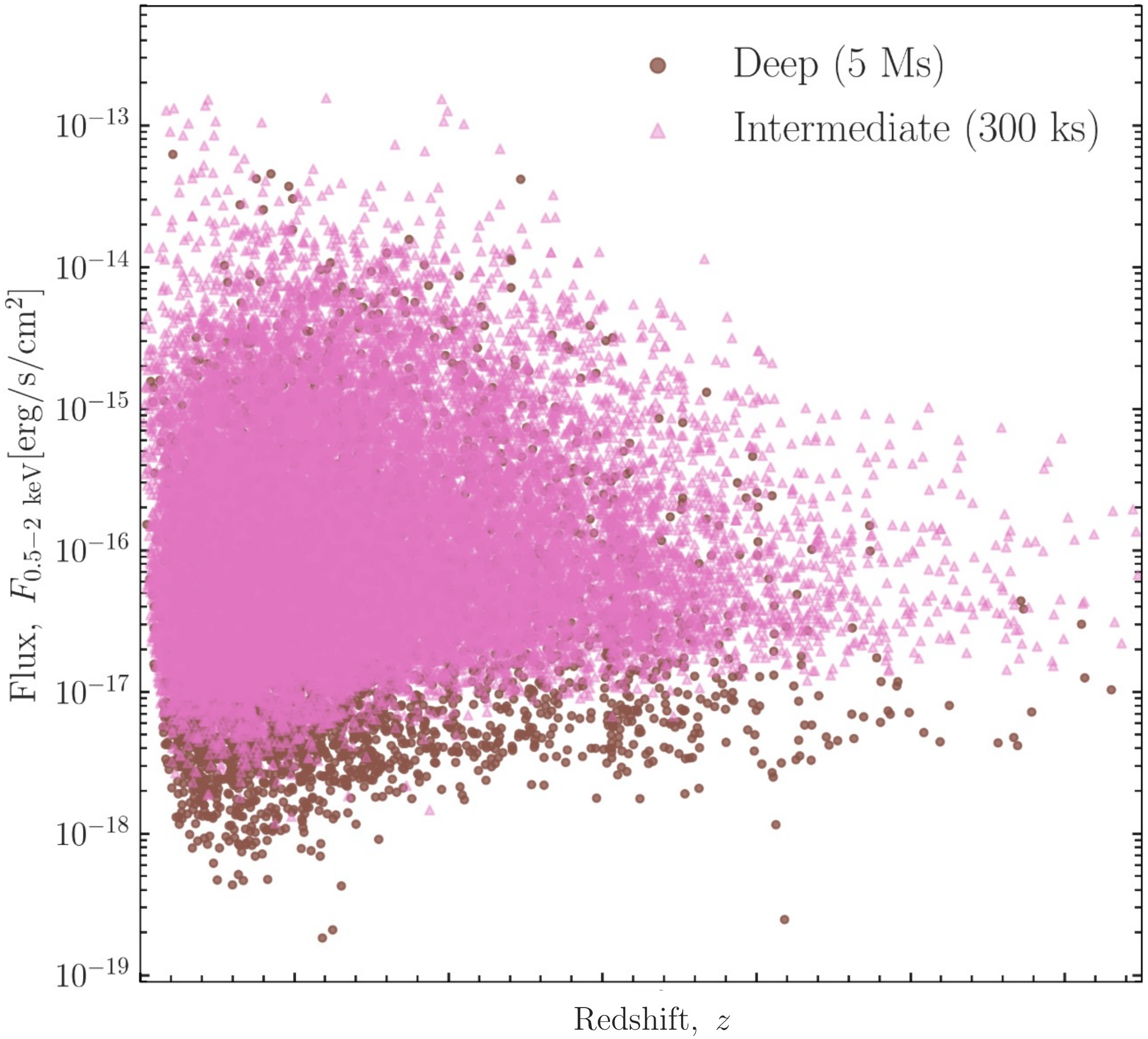
AXIS Intermediate Field (300ks / 2.0 deg^2)
Sensitivity in 0.5-2.0keV band,
- 1.1x10-17 erg/s/cm^2 (20% field, 0.4deg^2)
- 3.7x10-17 erg/s/cm^2 (80% field, 1.6deg^2)

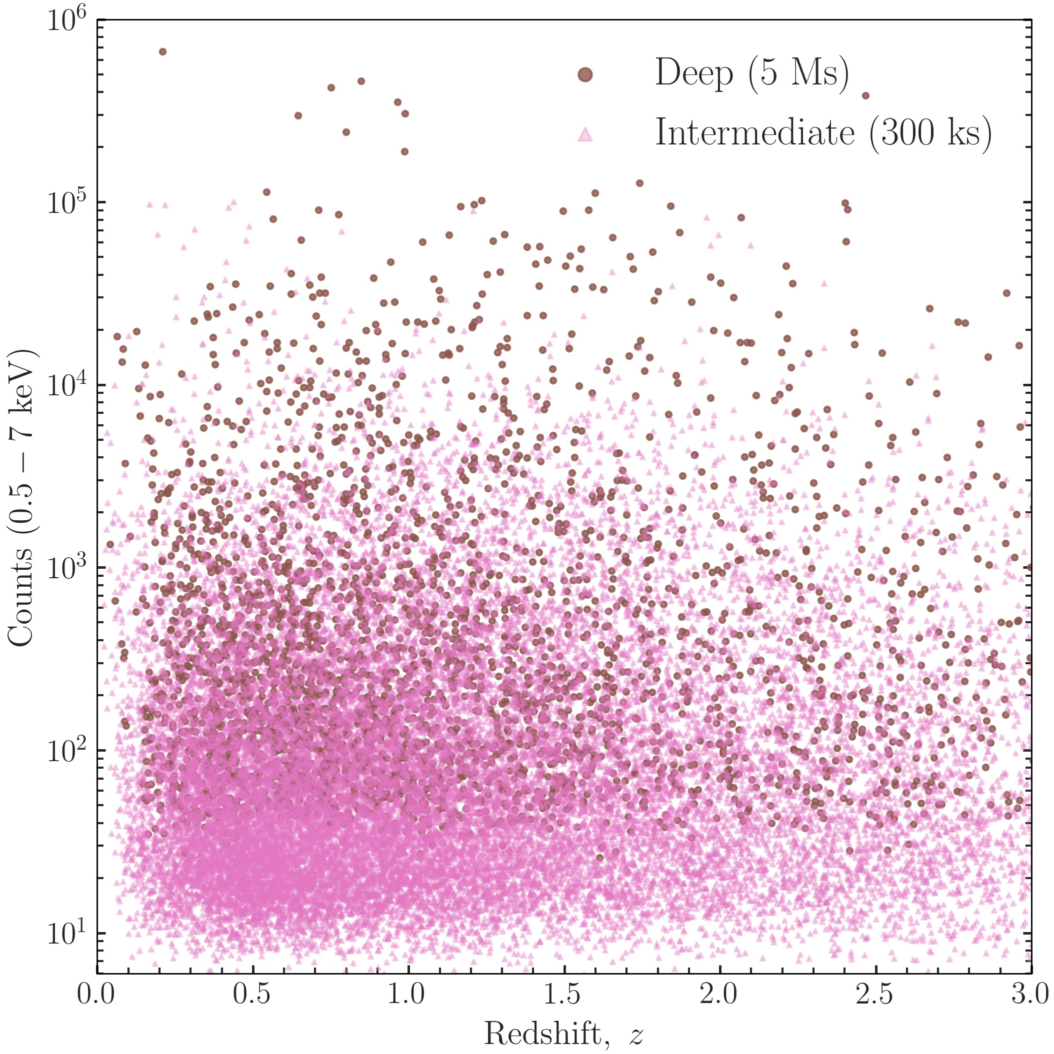
Marchesi et al. (2020) mock catalogues:
- >2,800 AGN (AXIS Deep Field)
- >22,000 AGN (AXIS Intermediate Field)

Future work

The *AXIS* Deep Survey

Updated from *Marchesi, S., et al., 2020, A&A, 642*

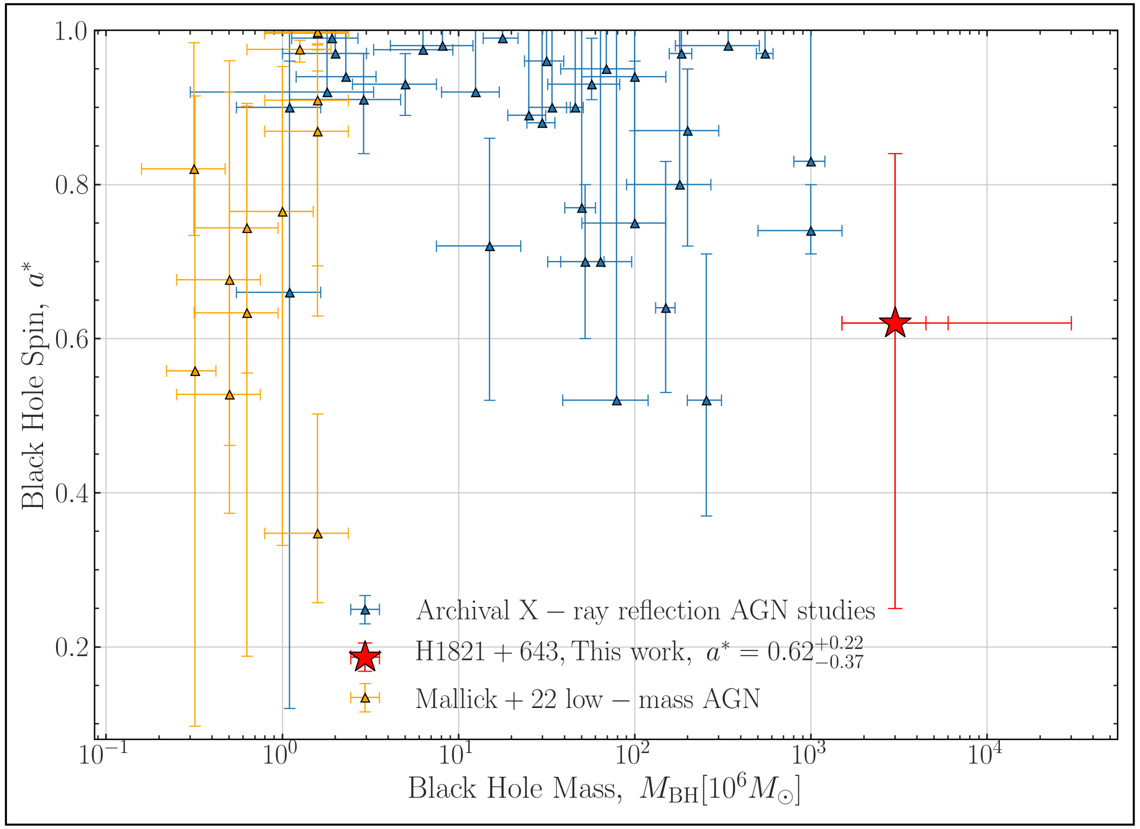




Sisk-Reynes, J., et al., in prep.

Conclusions

Preliminary!



Sisk-Reynes, J., et al., in prep

- Relativistic X-ray reflection allows constraining BH spin upon modelling the broadened Fe-Kα line

- X-ray reflection and reverberation have provided constraints over SMBH mass scale …

… And, mostly, for lower-mass AGNs

- However, **selection biases and systematic errors (effect of disc thickness)** are at play

- **Spin may serve as a diagnostic for growth mechanisms, including:**

❑ **(coherent/chaotic) accretion**

❑ **SMBH/SMBH mergers > <u>May provide indirect evidence for SMBH binaries</u>**

- More constraints are needed …

… A hopeful future: *AXIS* spin Survey (Deep field, 5-Ms)

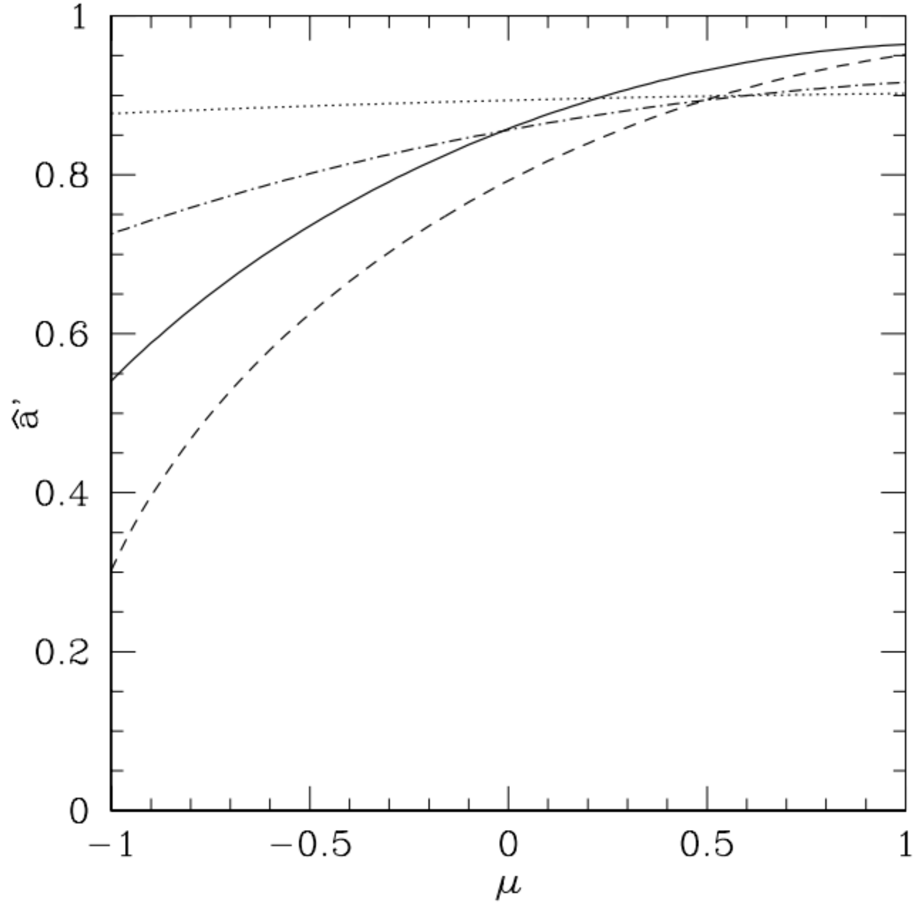
… Also ideal for Physics Beyond the Standard Model (arXiv!)

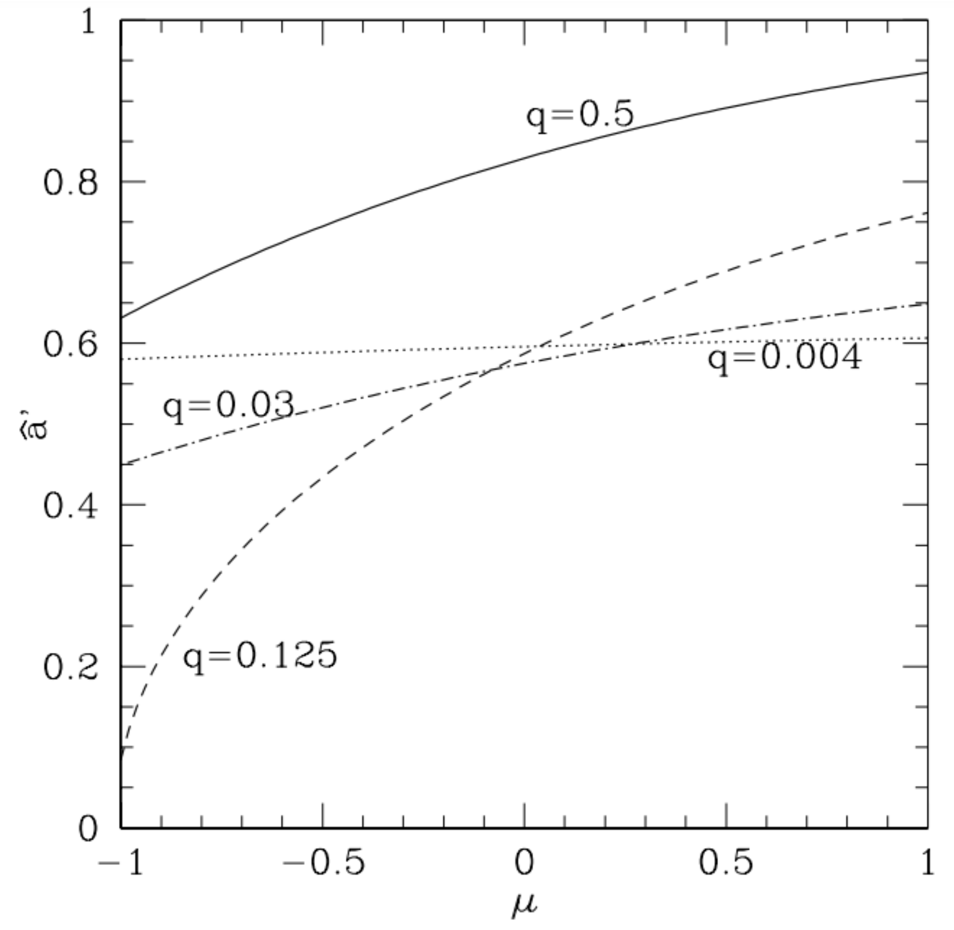
Thank you!

Backup slides

Introduction and Motivation

BH mergers: parent and final spins



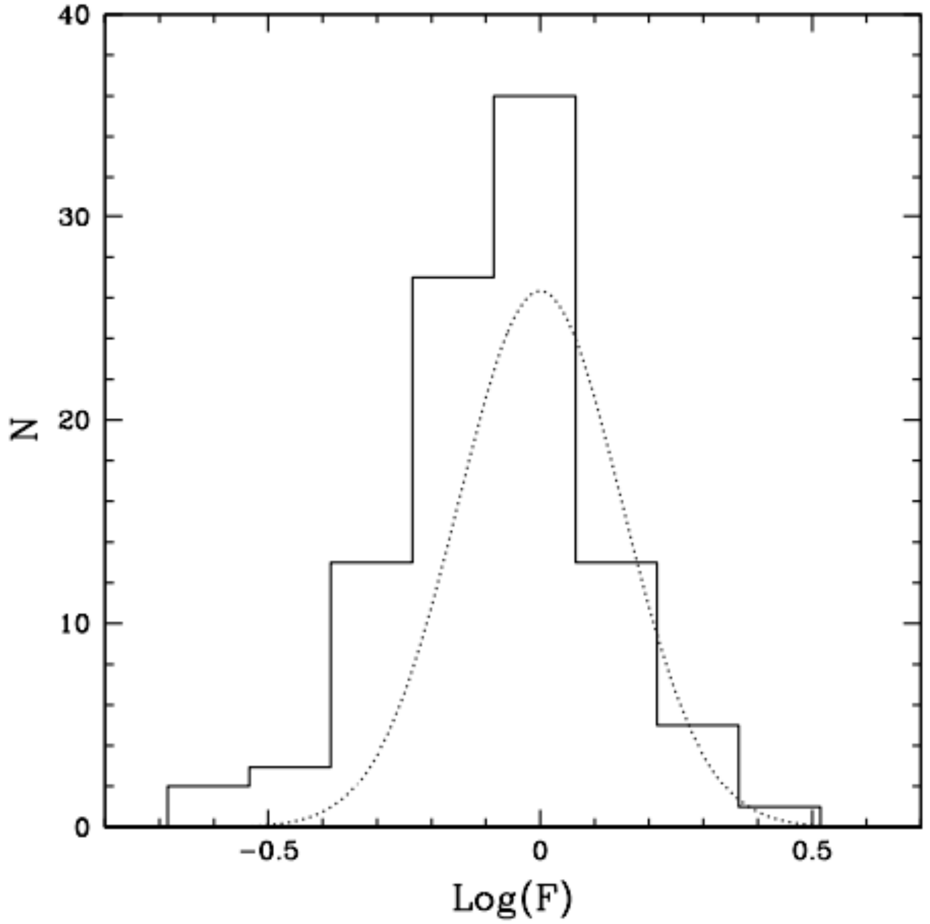


Volonteri, M., et al., 2005, ApJ, 620, 1

See also: *King, A. and Pringle, J., 2006, MNRAS, 373, 1* on chaotic accretion

Pounds, K, et al., 2003, 345, 3 on ionised outflows

SMBH spin constraints inferred from other methods



Daly, R.., 2022, arXiv: 2210.07779

The spin of the high-mass SMBH H1821+643

Sisk-Reynes, J., et al., 2022, MNRAS, 514, 2

LETG/HETG fits

Given potential X-ray variability, we fit the individual HETG/LETG source spectra with reflection models

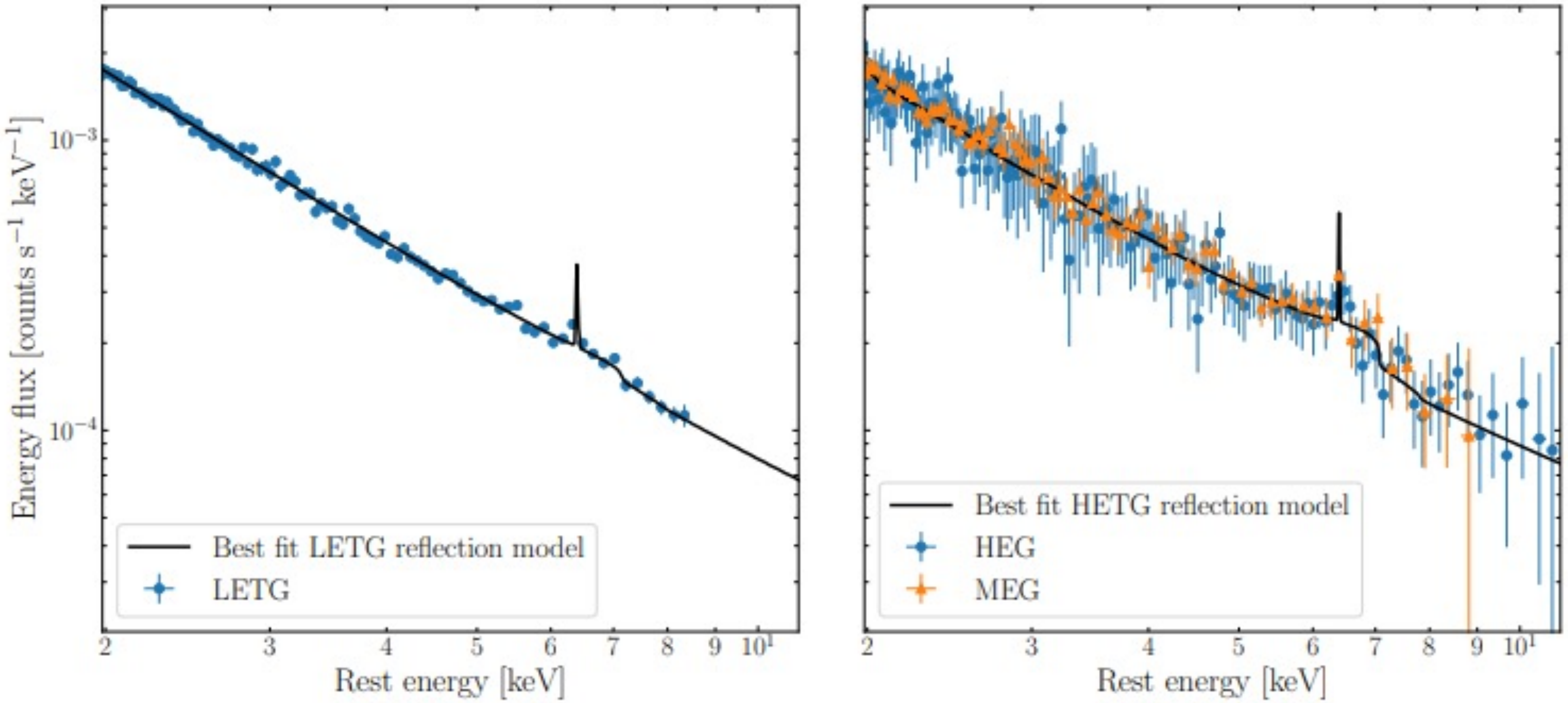
Magnitude	LETG	HETG
Fitted energies (rest frame)	2.0 – 8.5 keV	2.0 – 9.0 keV (MEG), 2.0 – 11.0 keV (HEG)
Cleaned exposure time	471.4 ks	99.6 ks
$L_{2-10\ \mathrm{keV,\ rest}}$	3.23×10^{45} erg/s	3.54×10^{45} erg/s
$F_{2-10\ \mathrm{keV,\ observed}}$	1.16×10^{-11} erg/cm^2/s	1.28×10^{-11} erg/cm^2/s

Low-energy cutoff set to avoid soft excess associated with a very centrally-peaked ICM core

Methods

- **Assume LETG/HETG spectra: well-described by reflection**
  But see *Yaqoob, T. and Serlemitsos, P., 2006, 623, 1*

- Use MCMC functionality in XSPEC to generate samples of the posterior corresponding to X-ray reflection to explore parameter space on LETG/HETG



Combining posteriors on model parameters

- Fundamental parameters of the system $\boldsymbol{f}$ are invariant over observational timescales

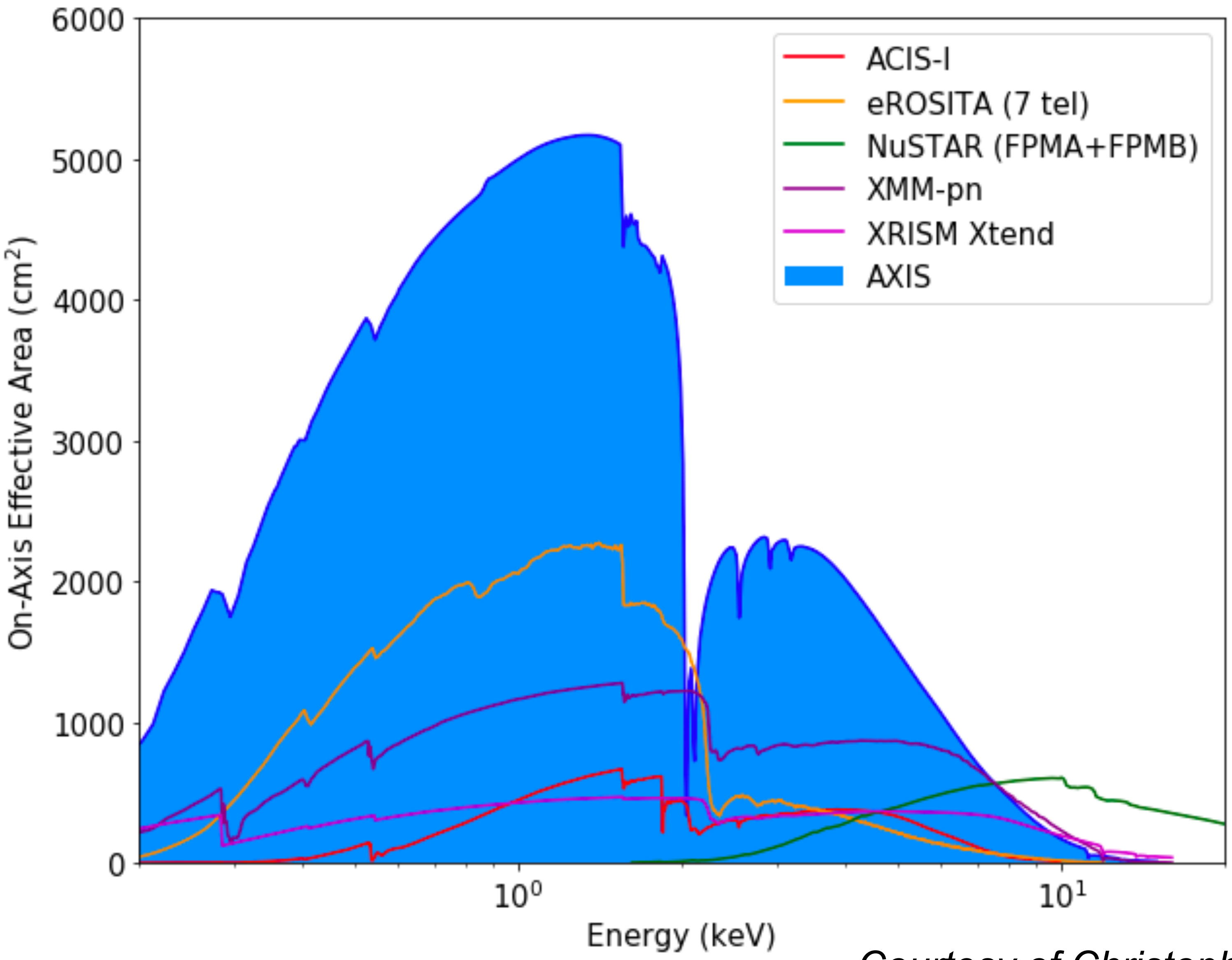
$$\boldsymbol{f} = (a^*, i, A_{\mathrm{Fe}})$$

- Find LETG/HETG posteriors on $\boldsymbol{f}$ by marginalizing over all other parameters of the model

- **Merge posteriors** to infer combined 90% CL constraints on $\boldsymbol{f}$ (identical to joint fit)

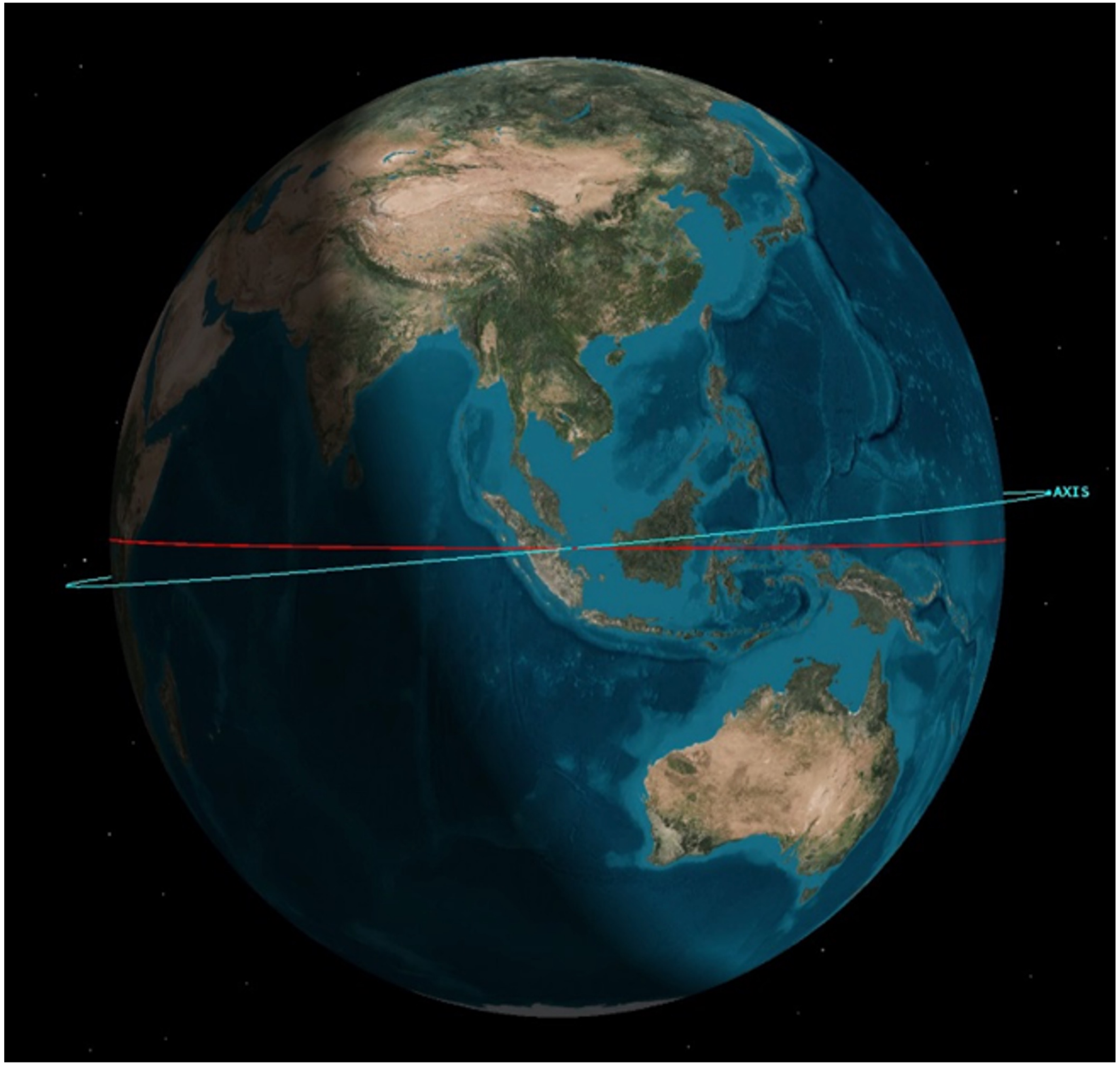
AXIS

Improvement in effective area (0.5 – 10 keV coverage)



Courtesy of Christopher Reynolds (AXIS PI)

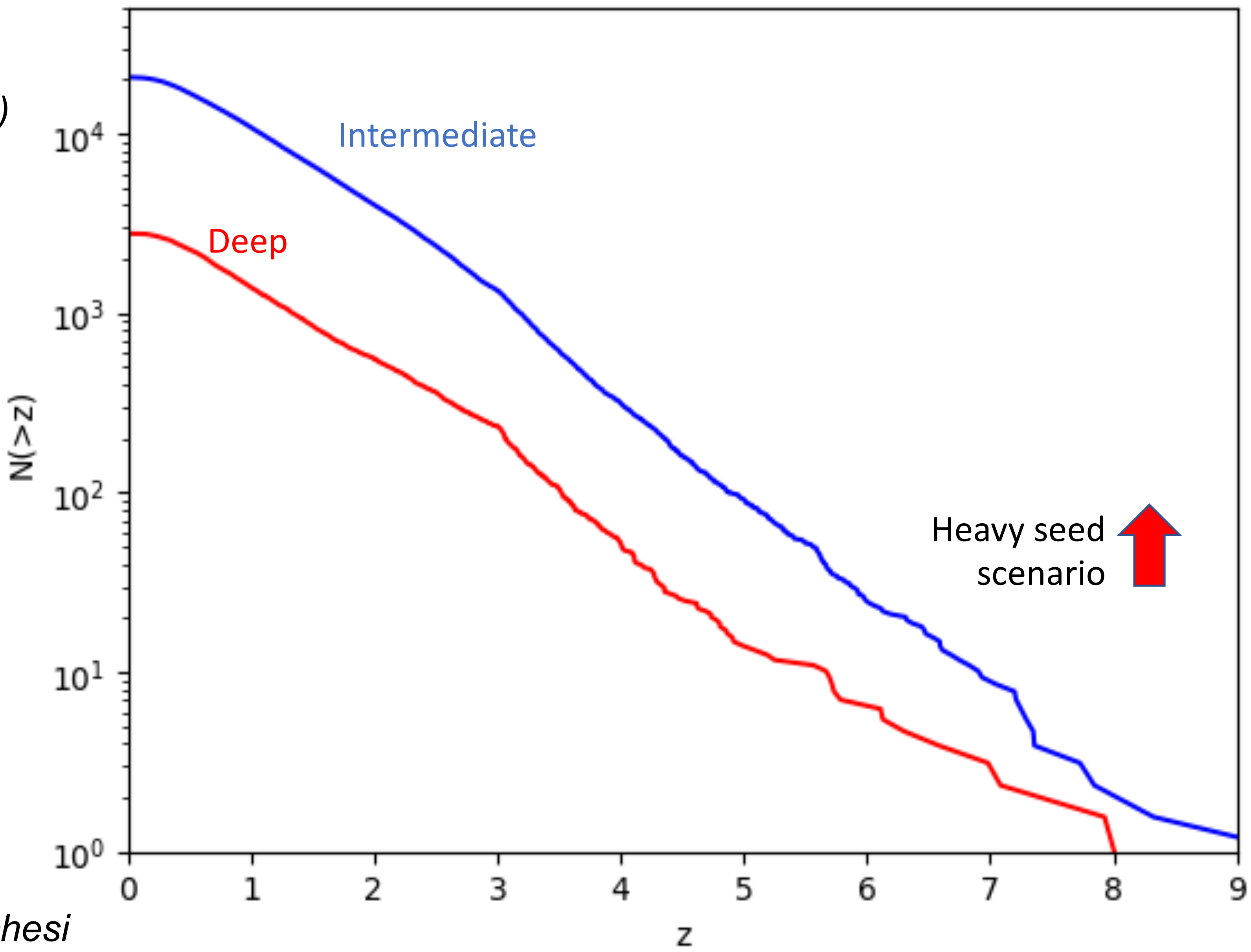
Courtesy of Christopher Reynolds (AXIS PI)



AXIS will operate on a lower-Earth orbit

Constraining BH growth and formation with *AXIS*

High-z mock catalogues based on AGN synthesis model of *Vito et al. (2013)*



Courtesy of Stefano Marchesi