Impact of the X-ray Surveyor on Supermassive Black Hole Spin Measurements

Laura Brenneman

Smithsonian Astrophysical Observatory

X-ray Vision Workshop

October 6, 2015

Outline

- Intro: what reflection can tell us about the immediate environs of black holes
- Point of focus: measuring black hole spins
- Where we are now: the current spin distribution in AGN, its implications and caveats
- Improvements in the near term: *Astro-H* and *Athena*
- Future directions: how the X-ray Surveyor could advance progress in this field

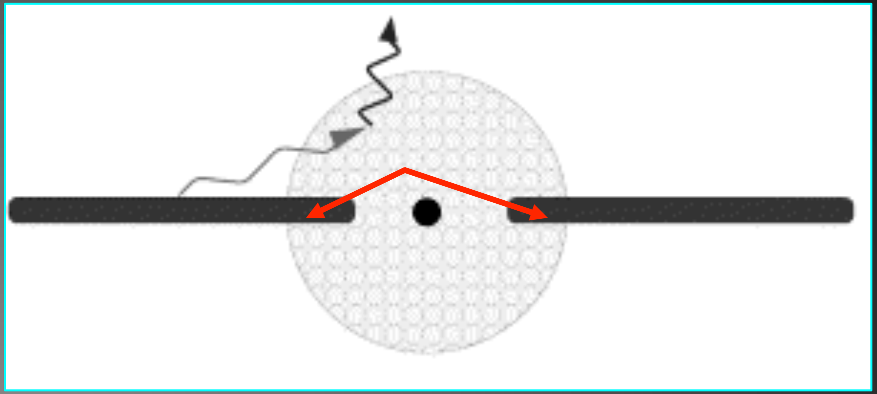
Modeling the Reflection Spectrum

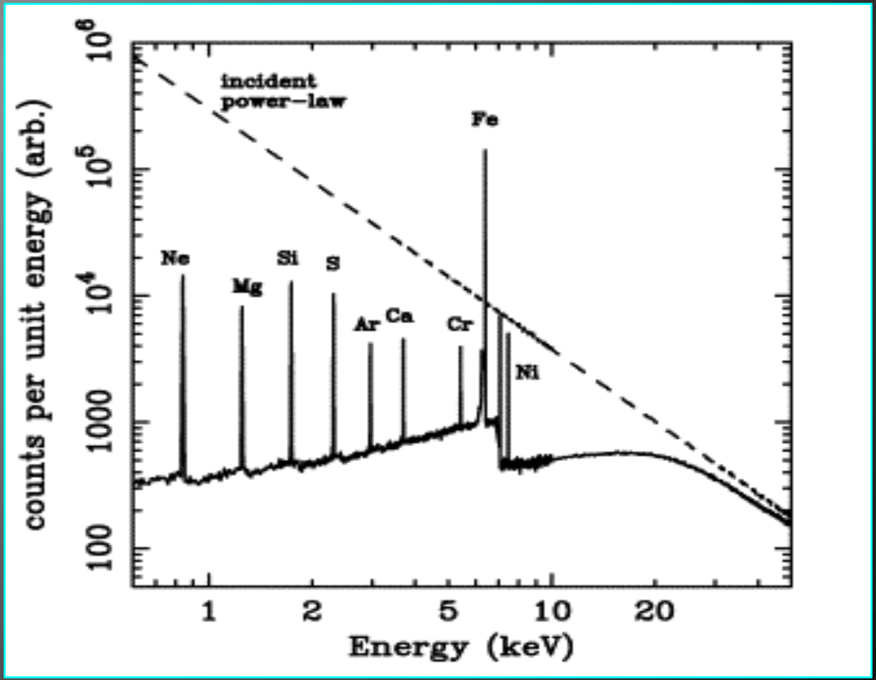
• Relativistic electrons in corona Compton scatter thermal photons (UV) from the accretion disk, producing power-law continuum spectrum in X-rays.

• Some X-ray continuum photons are scattered back down onto the inner disk ("reflected").

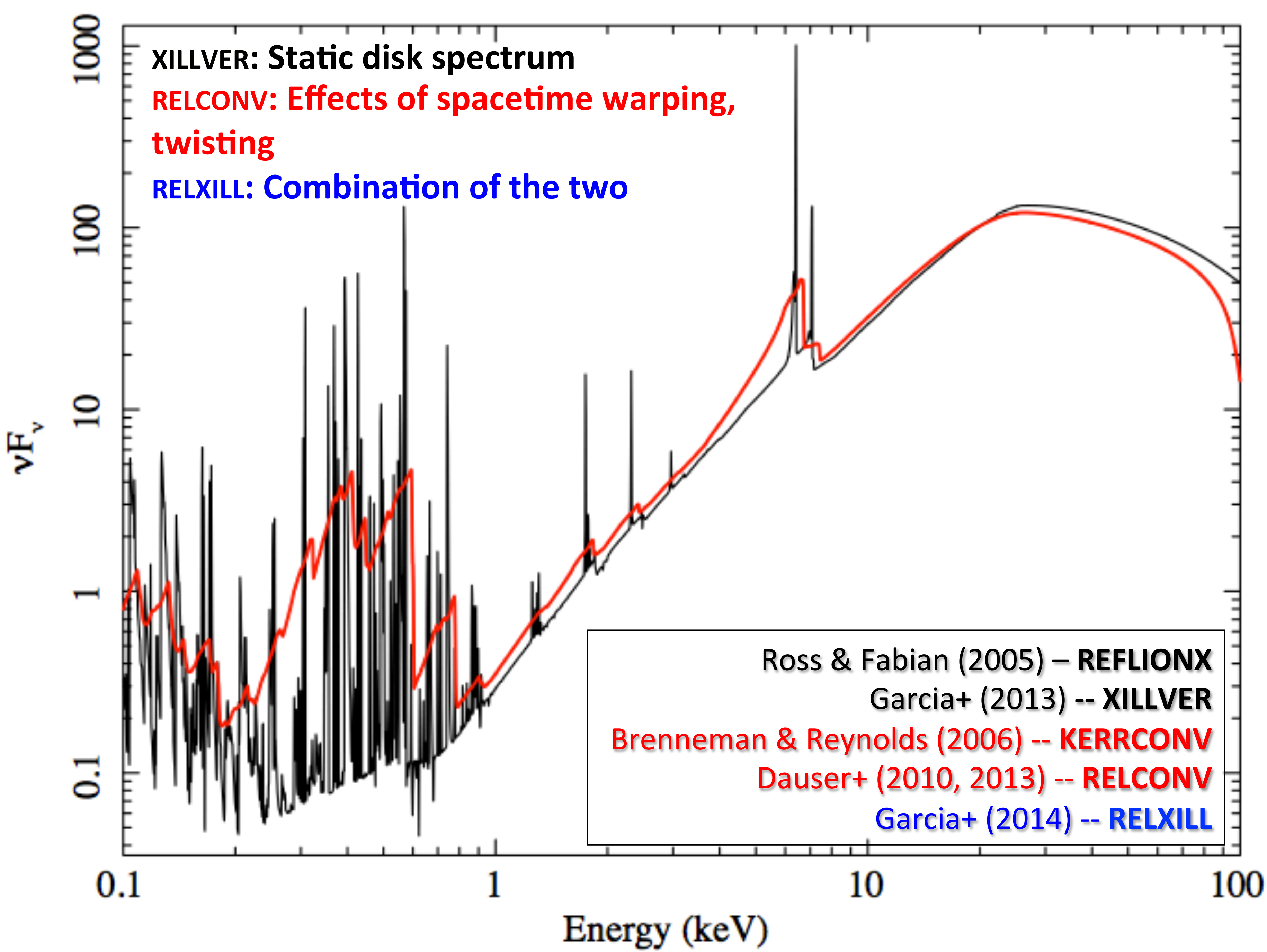
• Fluorescent lines are produced when a "cold," optically thick disk is irradiated by X-ray continuum photons, exciting a series of fluorescent emission lines.

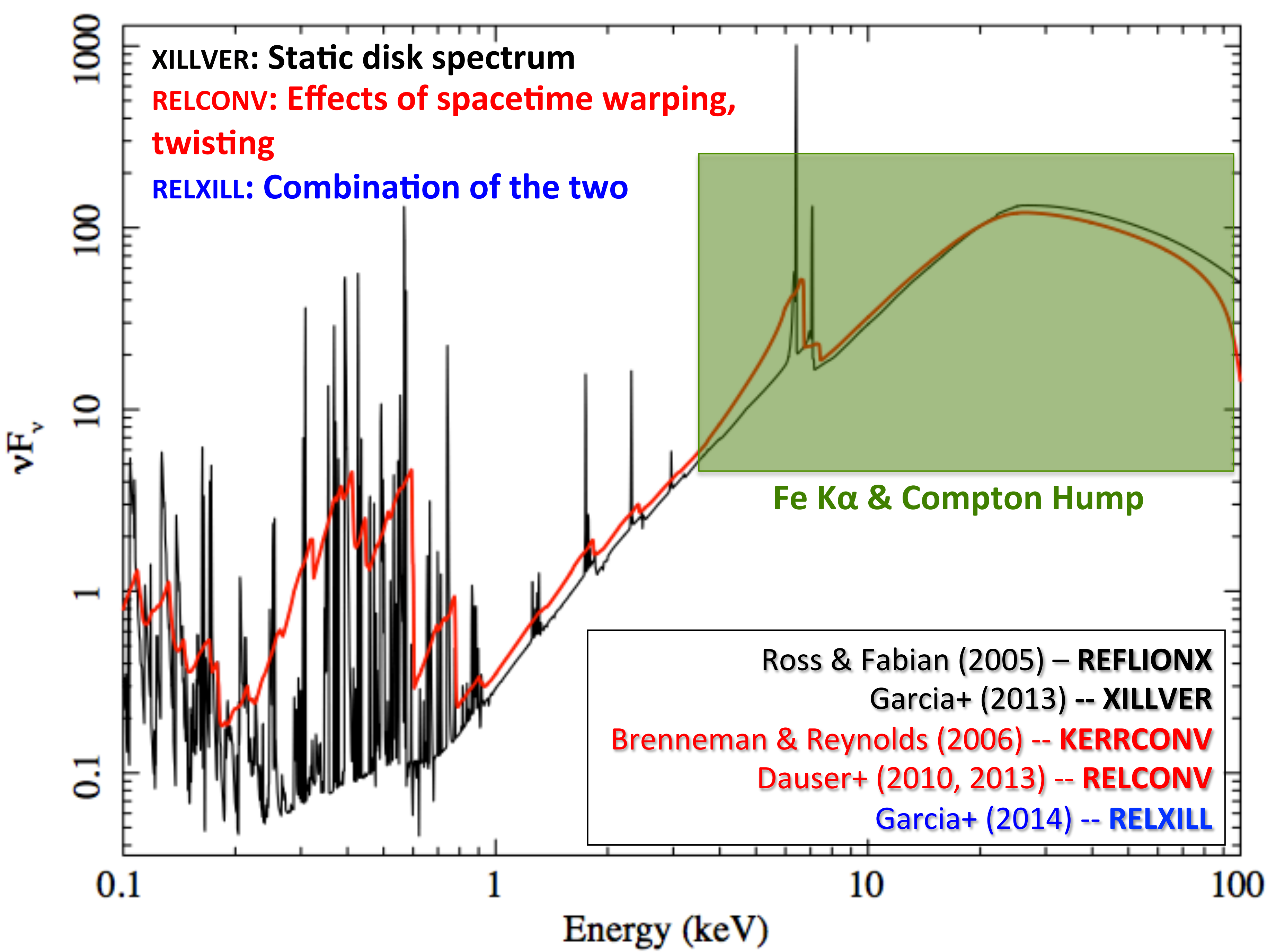
• The high energy, abundance and fluorescent yield of iron enable visibility above the power-law continuum, making it a better diagnostic feature than lines of other elements.





Reynolds & Nowak (2003)

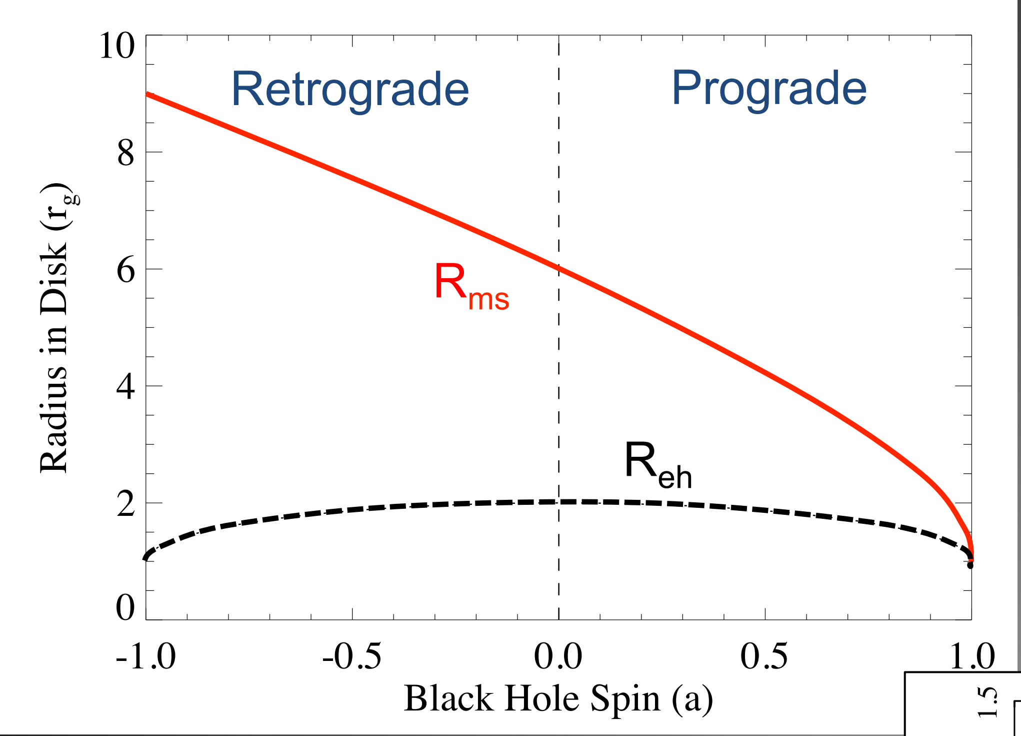

XILLVER: Static disk spectrum
RELCONV: Effects of spacetime warping, twisting
RELXILL: Combination of the two
Ross & Fabian (2005) – REFLIONX
Garcia+ (2013) -- XILLVER
Brenneman & Reynolds (2006) -- KERRCONV
Dauser+ (2010, 2013) -- RELCONV
Garcia+ (2014) -- RELXILL
νFν
1000
100
10
1
0.1
0.1
1
10
100
Energy (keV)



XILLVER: Static disk spectrum
RELCONV: Effects of spacetime warping, twisting
RELXILL: Combination of the two
Fe Kα & Compton Hump
Ross & Fabian (2005) – REFLIONX
Garcia+ (2013) -- XILLVER
Brenneman & Reynolds (2006) -- KERRCONV
Dauser+ (2010, 2013) -- RELCONV
Garcia+ (2014) -- RELXILL
νFν
Energy (keV)
0.1
1
10
100
1000

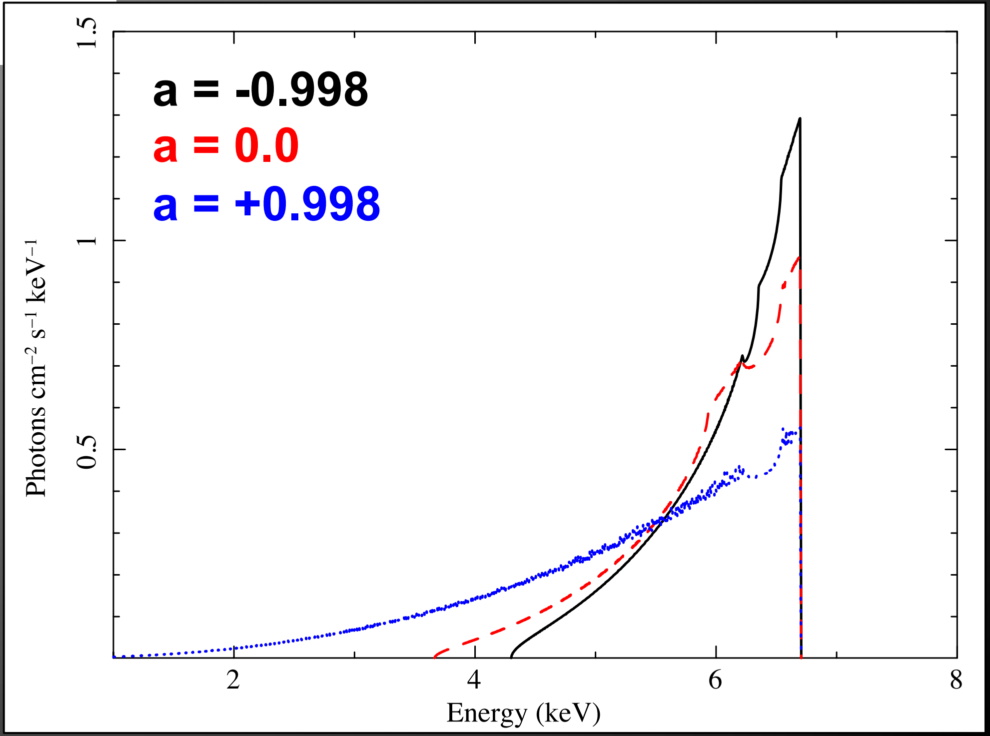
What We Learn From Reflection

- Torus covering fraction
- Fe abundance (disk, torus)
- Coronal height and geometry
- ***Black hole spin***



Monotonic relationship between black hole spin and R_{ms} in the disk enables spin measurements.

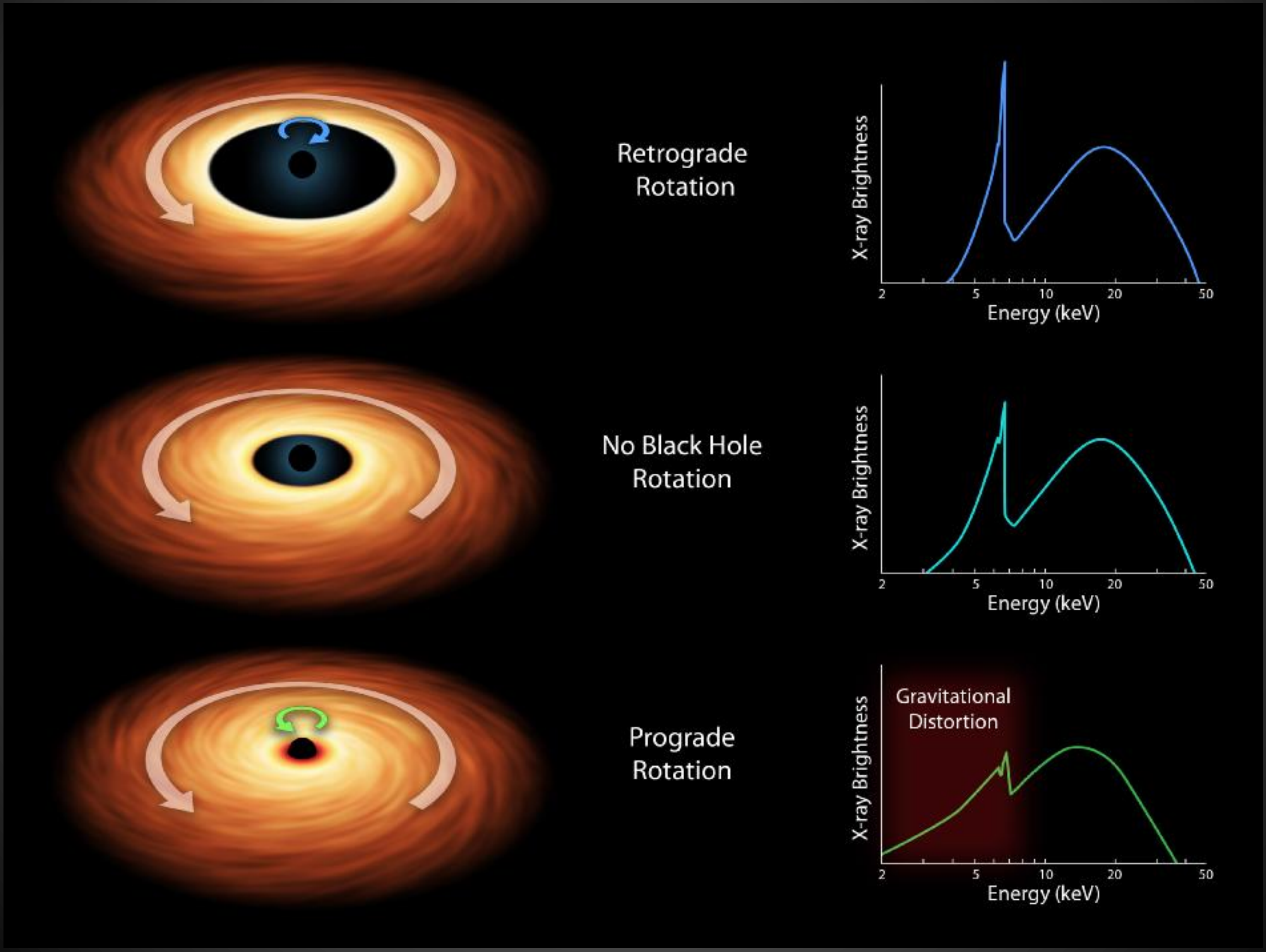
Based on RELLINE code of Dauser+ (2010)



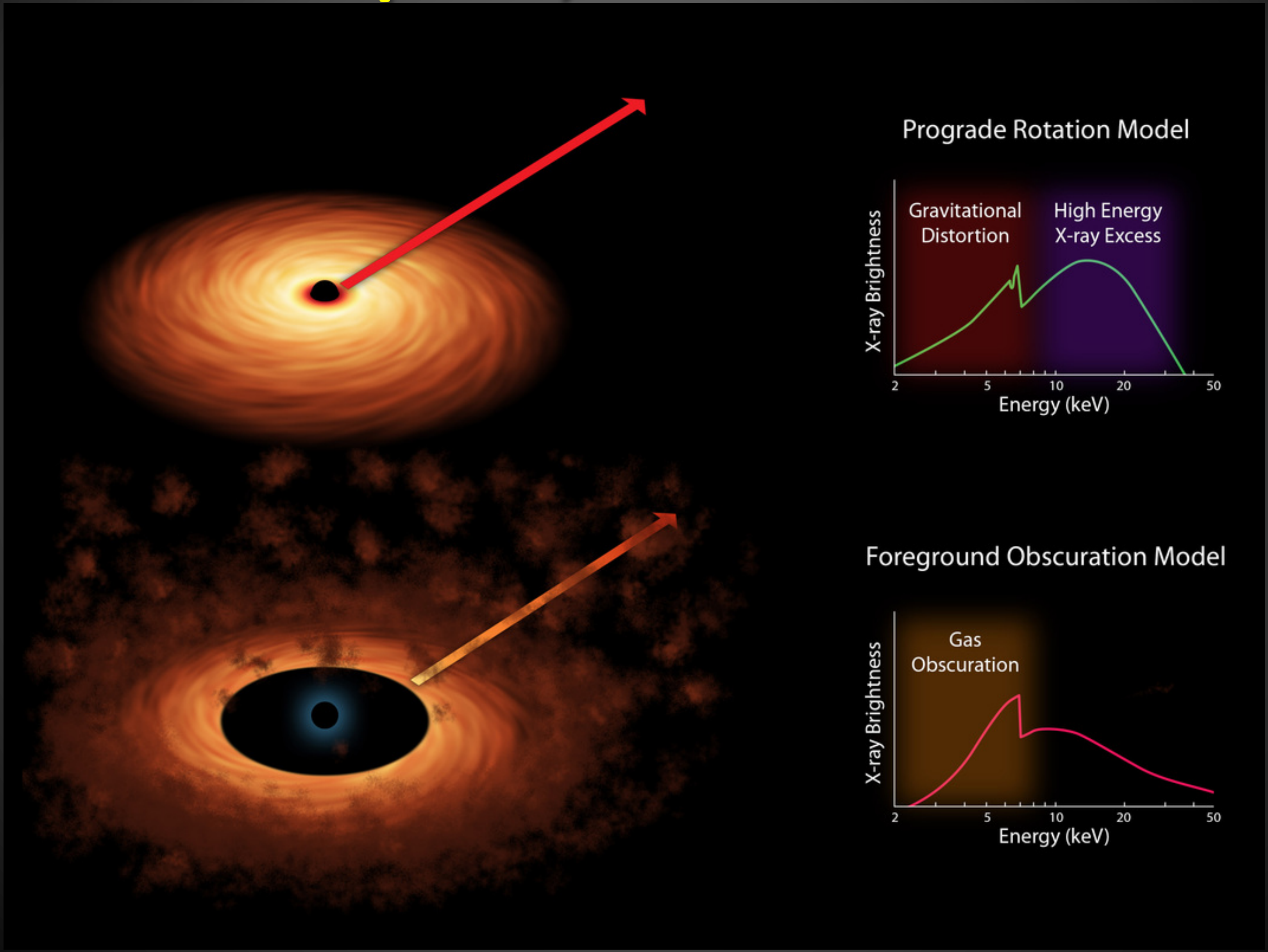
Dimensionless spin: *a* = cJ/GM²

To first order, line broadens as spin increases. Location of red wing → location of R_{ms}.

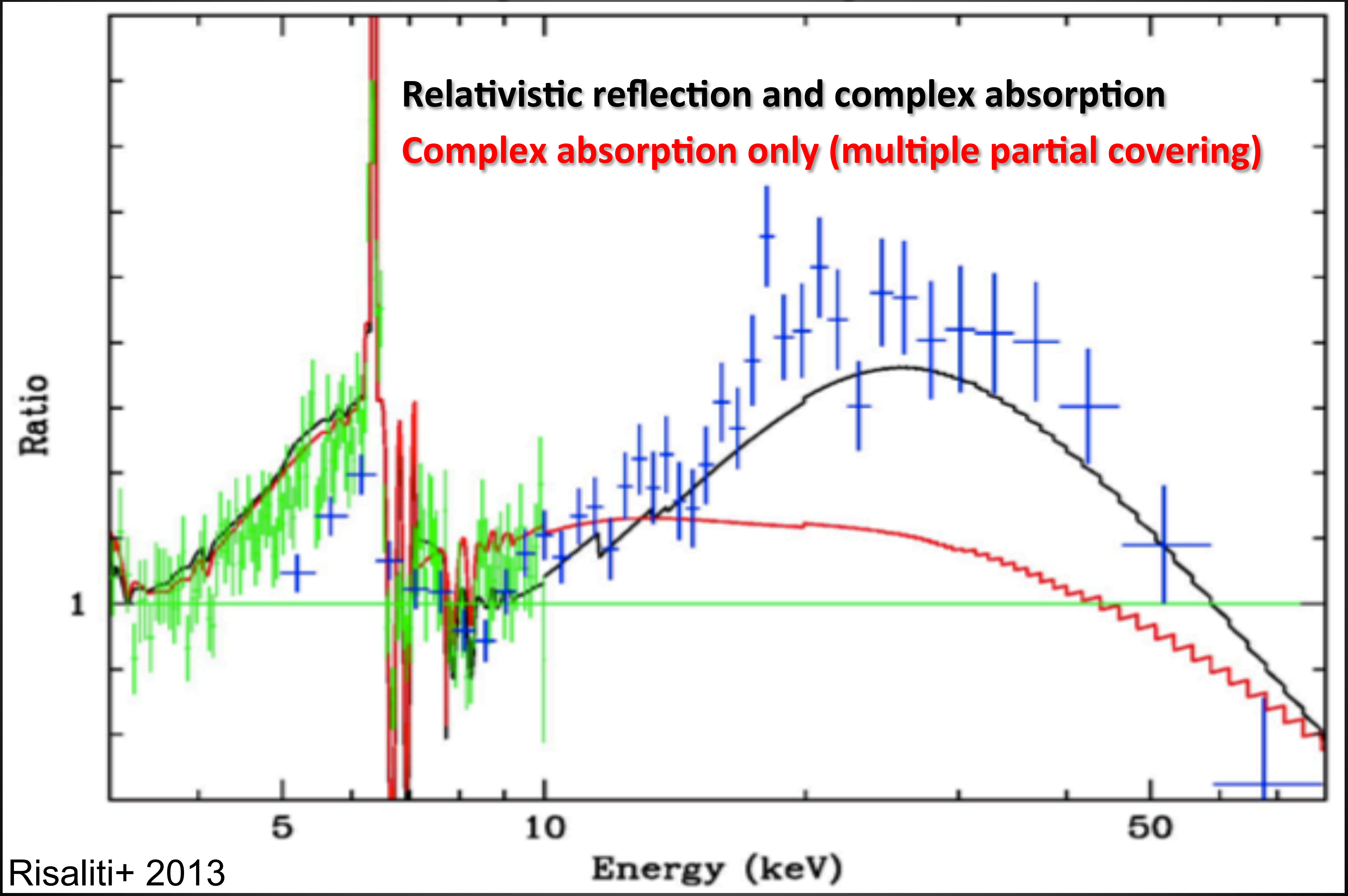
Effect of Spin on Reflection Features



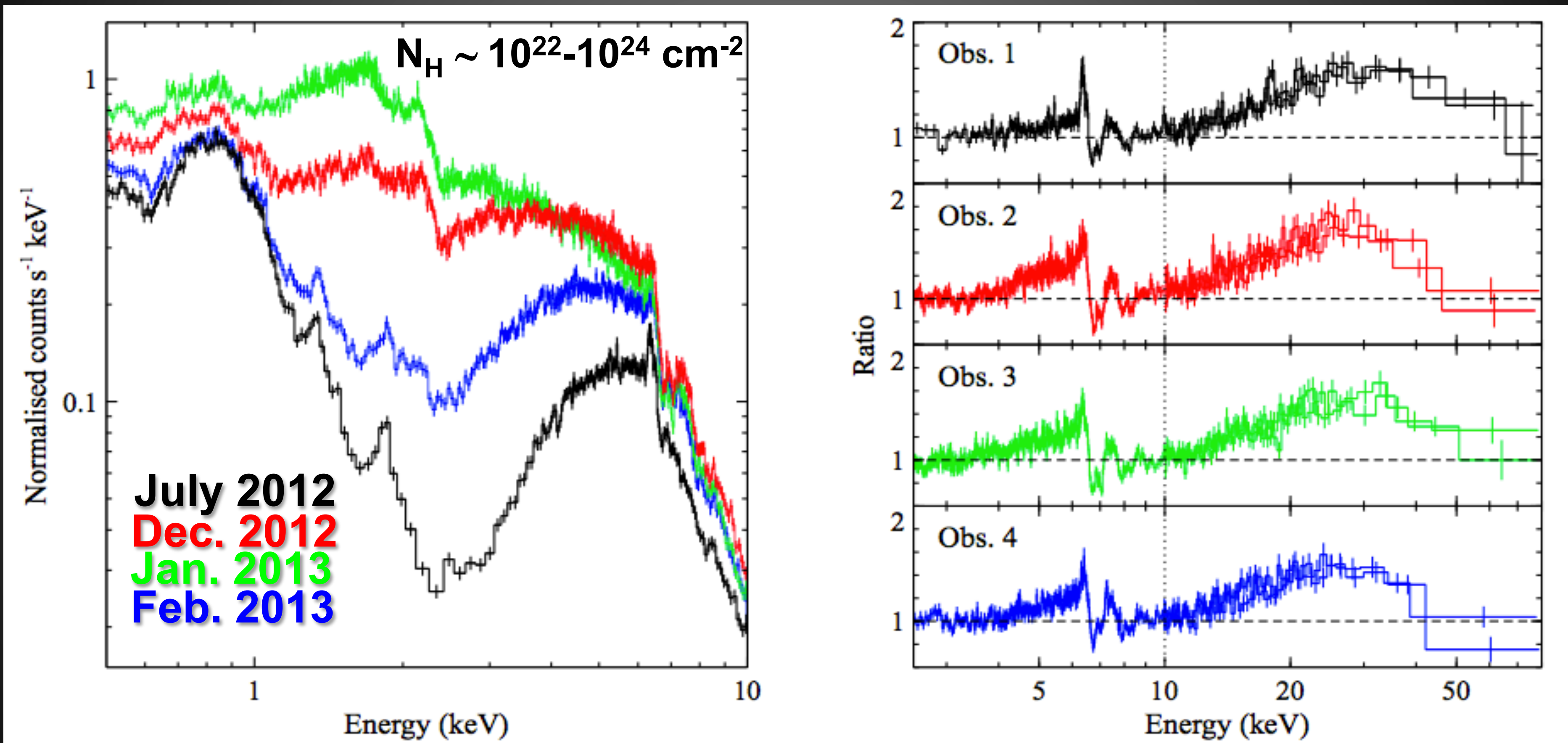
Disentangling Coronal Emission, Absorption, and Reflection



NGC 1365: reflection and variable complex absorption



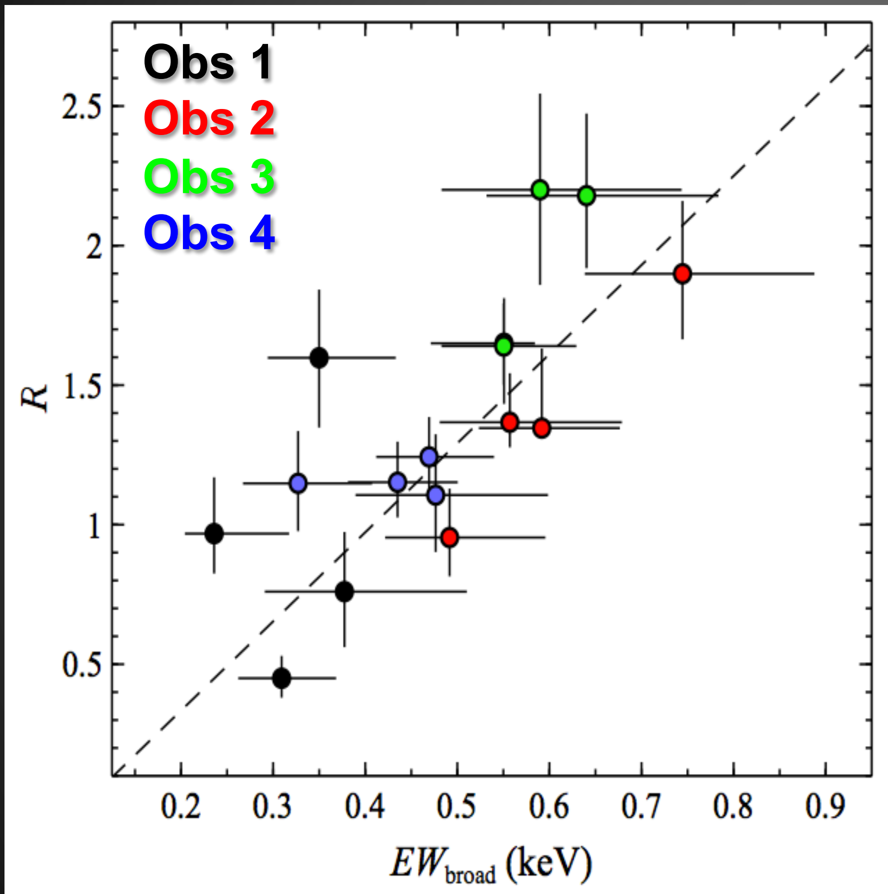
Spectral Variability

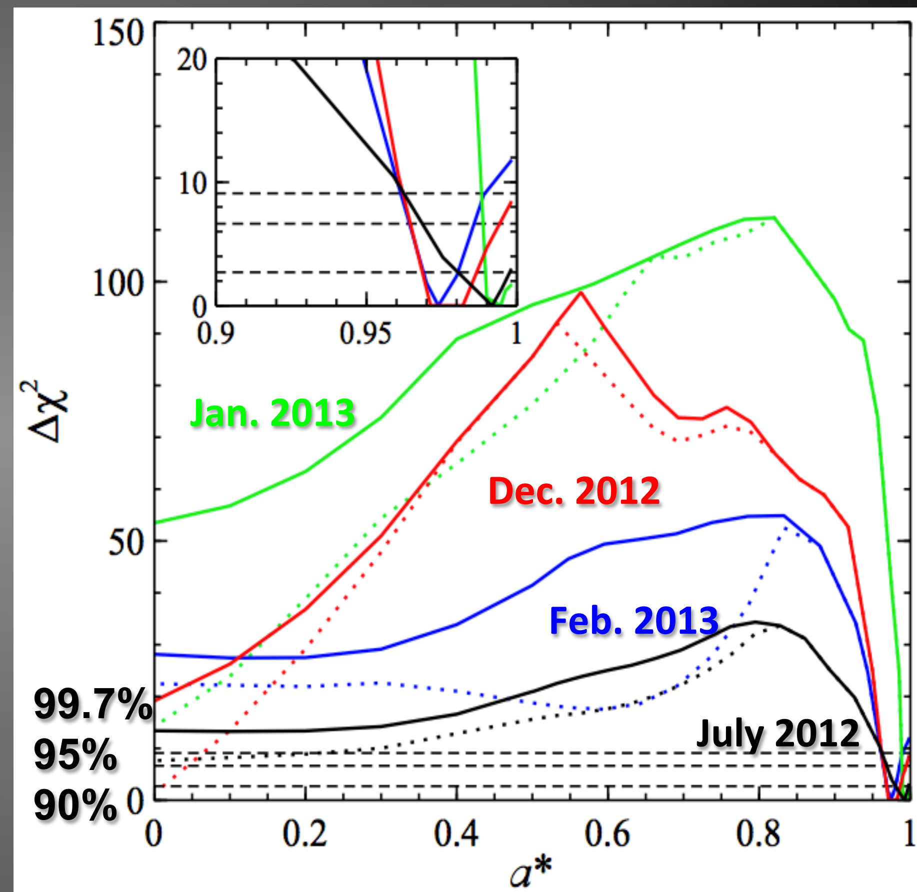


Walton+ 2014

4 *XMM/NuSTAR* ~120 ks observations

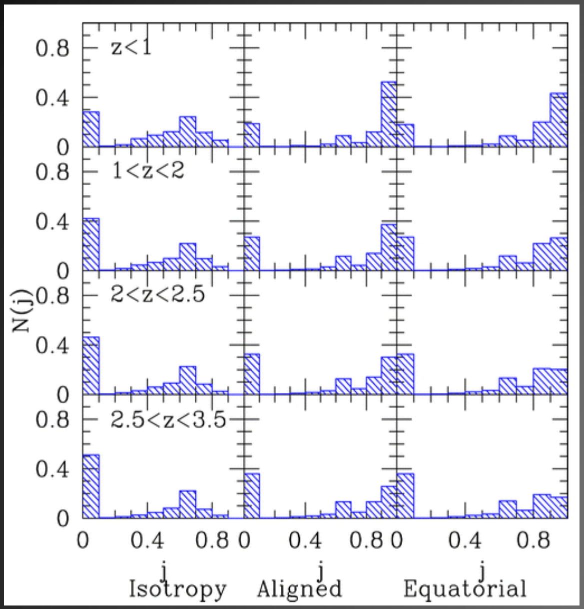
Constraining Relativistic Reflection and SMBH Spin



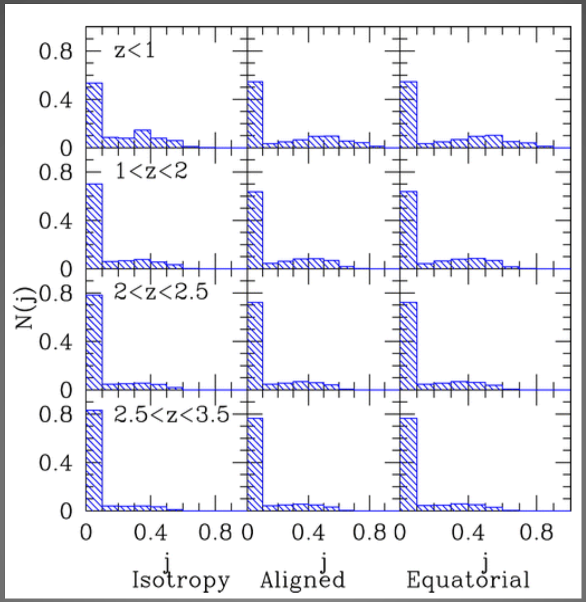


Walton+ 2014

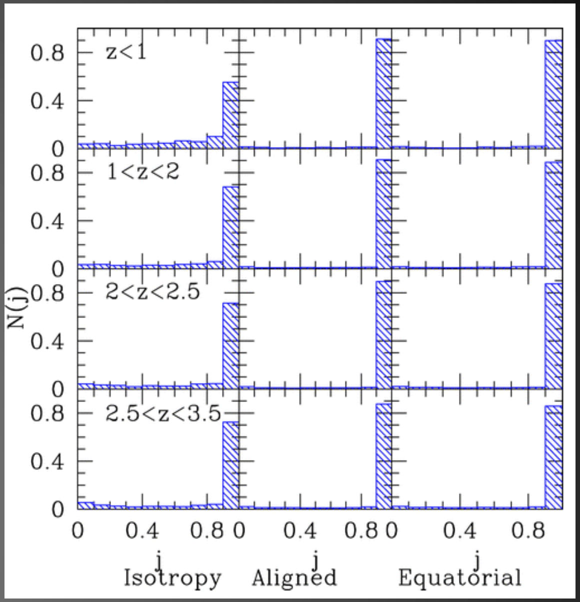
Black Hole Spin and Galaxy Evolution



Mergers only



Mergers + chaotic accretion

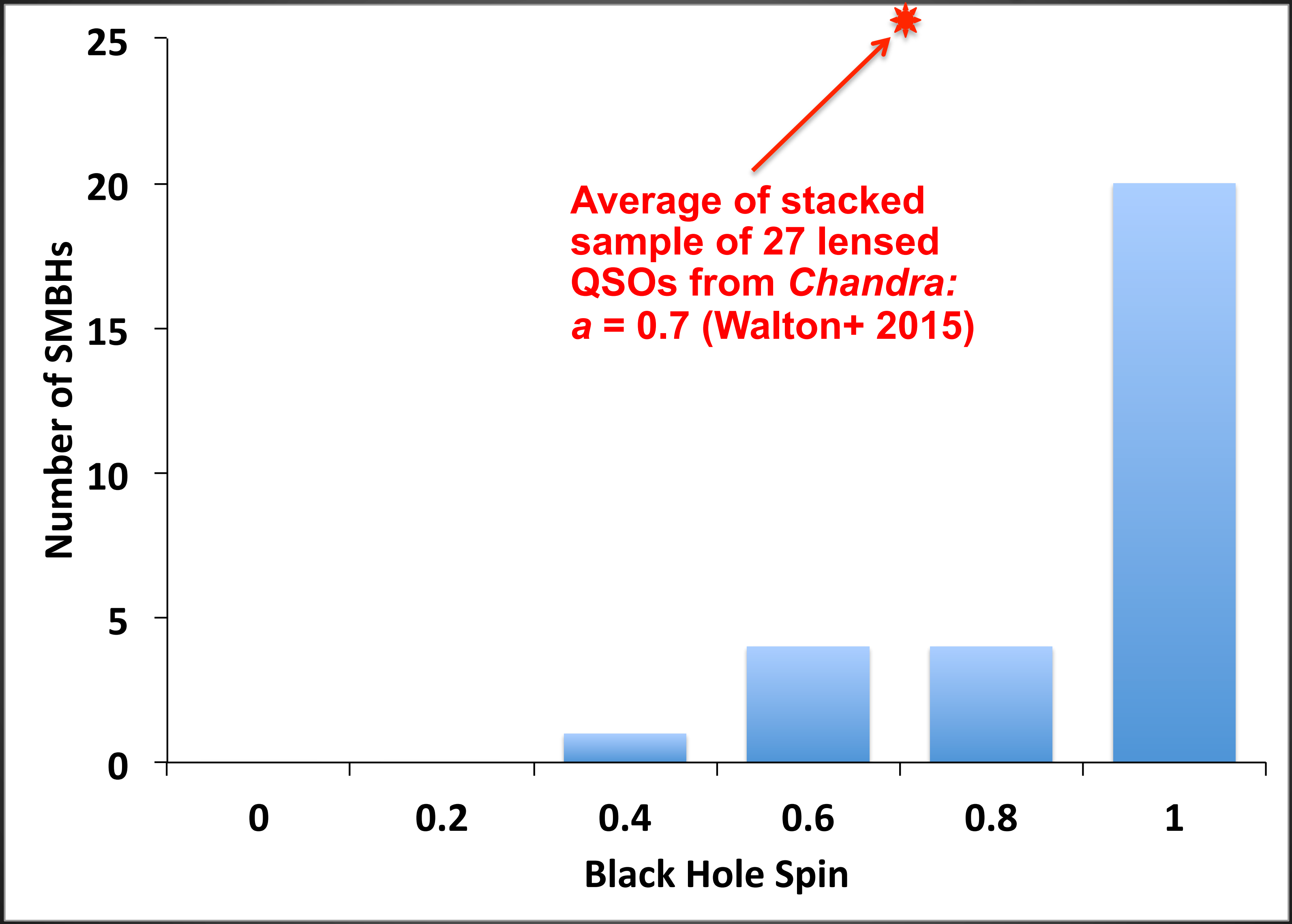


Mergers + prolonged accretion

Berti & Volonteri (2008)

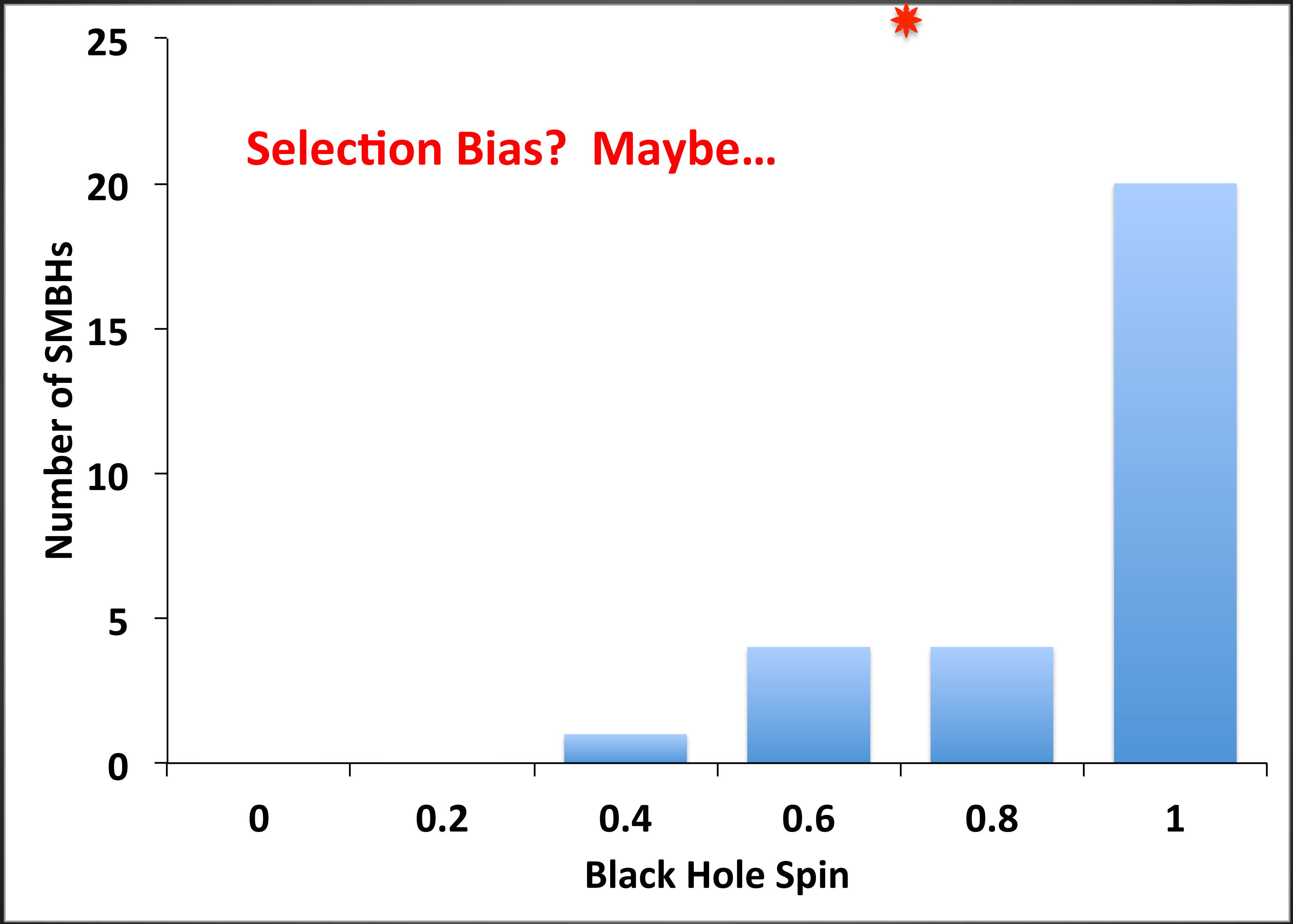
- Mergers of galaxies (and, eventually, their supermassive BHs) result in a wide spread of spins of the resulting BHs.
- Mergers and chaotic accretion (i.e., random angles) result in low BH spins.
- Mergers and prolonged, prograde accretion result in high BH spins.

The Distribution of SMBH spins (so far)



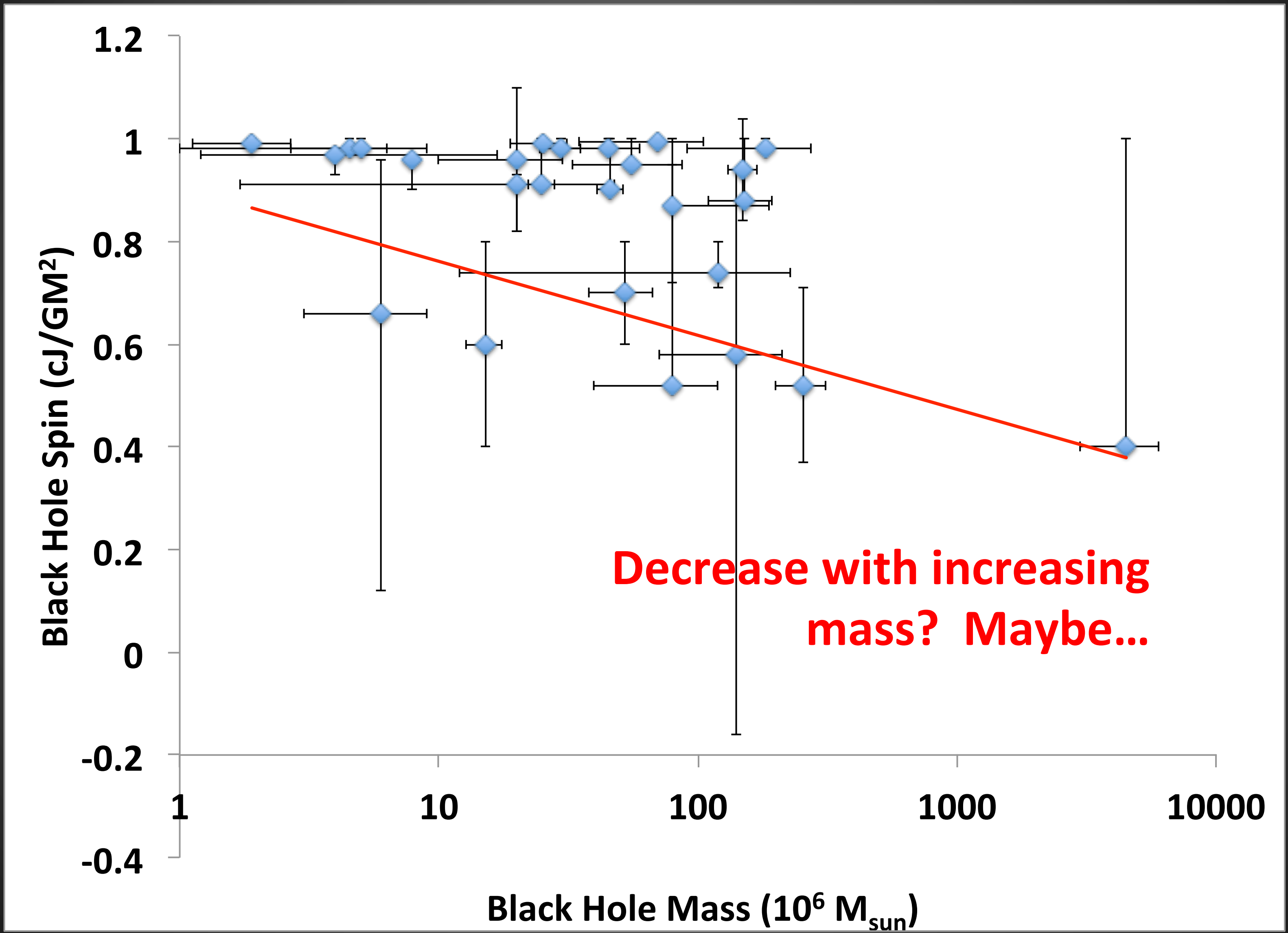
Brenneman (2013), Walton+ (2013), Reynolds (2014), Ricci+ (2014), Agis-Gonzalez+ (2014), Reynolds+ (2014), Paliya+ (2014), Gallo+ (2015), Svoboda+ (2015), Keck+ (2015)

The Distribution of SMBH spins (so far)



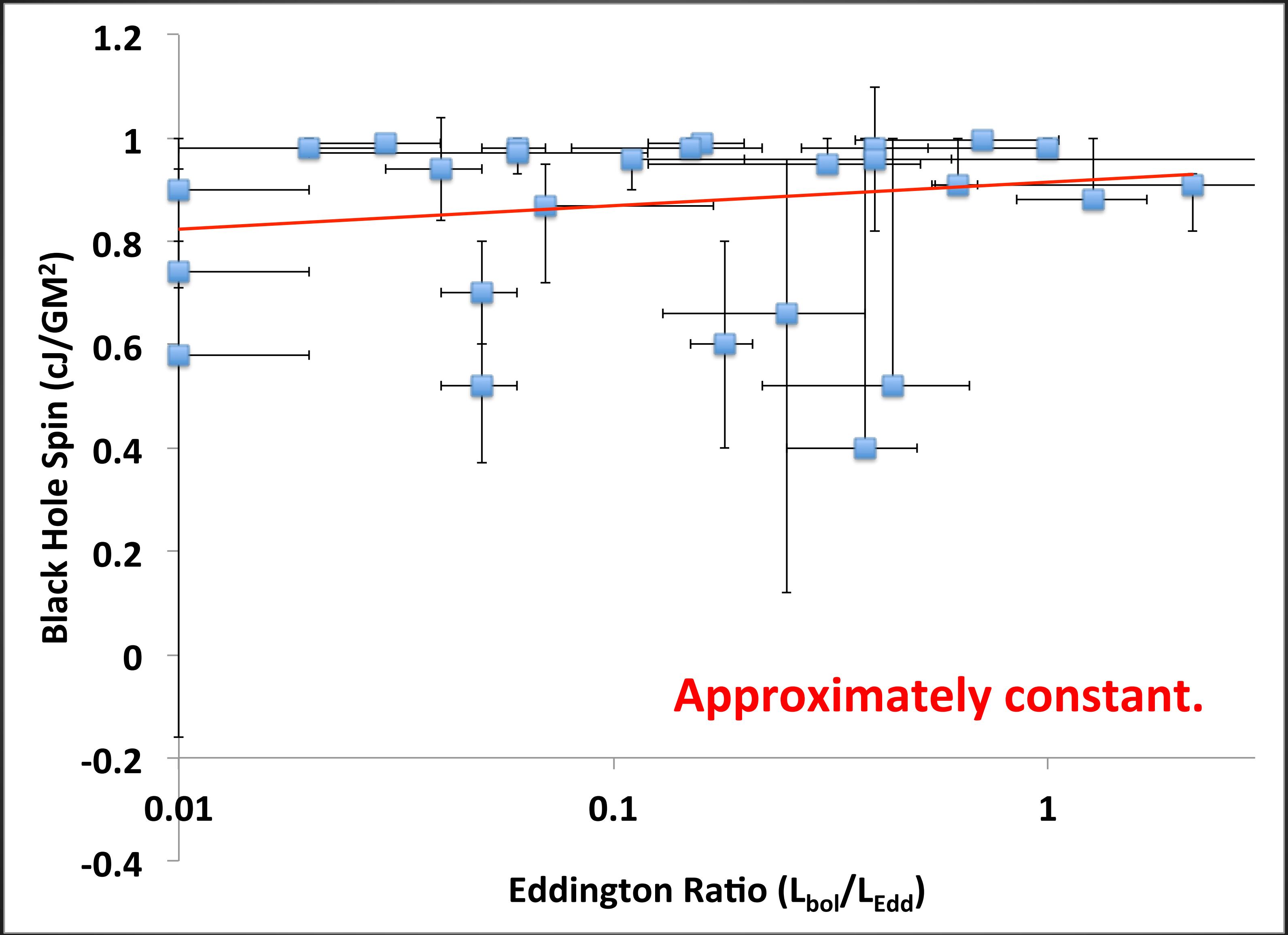
Brenneman (2013), Walton+ (2013), Reynolds (2014), Ricci+ (2014), Agis-Gonzalez+ (2014), Reynolds+ (2014), Paliya+ (2014), Gallo+ (2015), Svoboda+ (2015), Keck+ (2015)

A Trend with Black Hole Mass?



Brenneman (2013), Walton+ (2013), Reynolds (2014), Ricci+ (2014), Agis-Gonzalez+ (2014), Reynolds+ (2014), Paliya+ (2014), Gallo+ (2015), Svoboda+ (2015), Keck+ (2015)

A Trend with Accretion Rate?



Brenneman (2013), Walton+ (2013), Reynolds (2014), Ricci+ (2014), Agis-Gonzalez+ (2014), Reynolds+ (2014), Paliya+ (2014), Gallo+ (2015), Svoboda+ (2015), Keck+ (2015)

Where Do We Go From Here?

Using the study of black hole spin a a proxy for reflection science as a whole, our **goals** are:

- To **mitigate our systematic uncertainties** in spin measurements
  - assumptions about disk density, ionization structure, truncation, thickness
  - ability to isolate reflection signatures
  - degeneracies between, e.g., spin and Fe abundance
- To investigate whether spin is **correlated with other properties** of SMBH systems, e.g.:
  - Mass
  - Accretion rate
  - Host morphology
  - Host star formation rate
  - Radio loudness
- To understand **distribution of SMBH spins vs. redshift**

Mission Wish List

To explore richness of reflection science and maximize its yield, **we need a mission (or missions) with**:

- **High effective area** (science is ***VERY*** s/n dependent)
- **High spectral resolution** (≤10 keV; necessary to model absorber and separate inner disk from torus reflection)
- **Large X-ray bandpass** (≥60 keV; higher is better to disentangle reflection from primary continuum curvature and to determine coronal properties)
- **High spatial resolution** (important at higher redshifts to avoid source confusion)

Role of the X-ray Surveyor

- *Chandra*-like angular resolution with *Athena*-like effective area, plus a calorimeter and gratings.
  - Probe quasars out to z ≤ 6 without source confusion
  - Limited bandpass (0.2-10 keV) somewhat mitigated by observing higher redshift sources
  - Could measure individual hot spots in 5-10 AGN disks
  - Ability to perform X-ray microlensing to determine coronal compactness

☑ Effective area ☑ Spec Res ☑ Spatial Res ☒ Bandpass

- To get the most out of the scientific return of the mission, should ideally pair this with an observatory with high throughput and adequate spatial and spectral resolution above 10 keV.

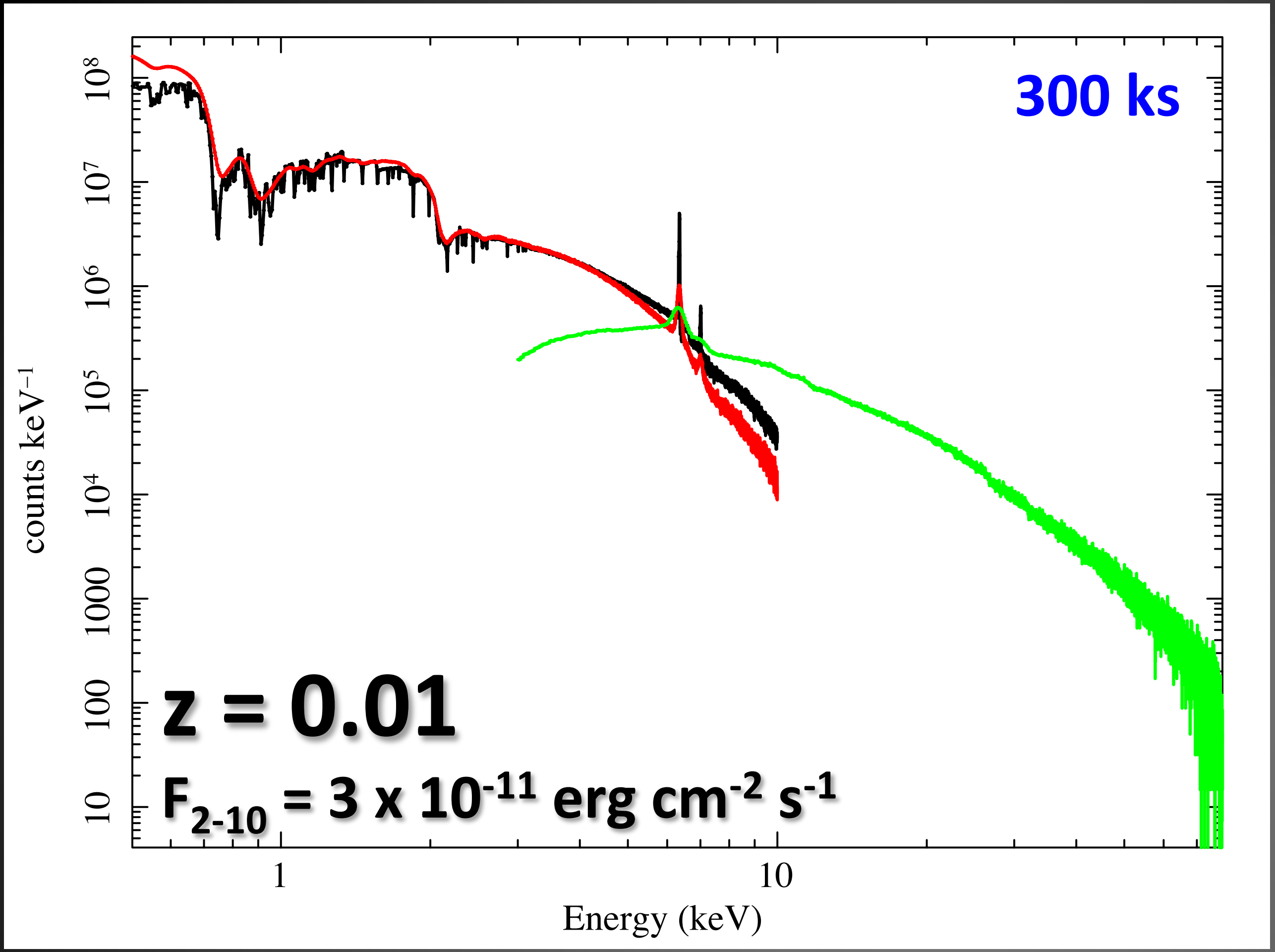
- E.g., *HEX-P* (PI: F. Harrison), proposed as the successor to *NuSTAR*.

Expanding Population of Measured SMBH Spins

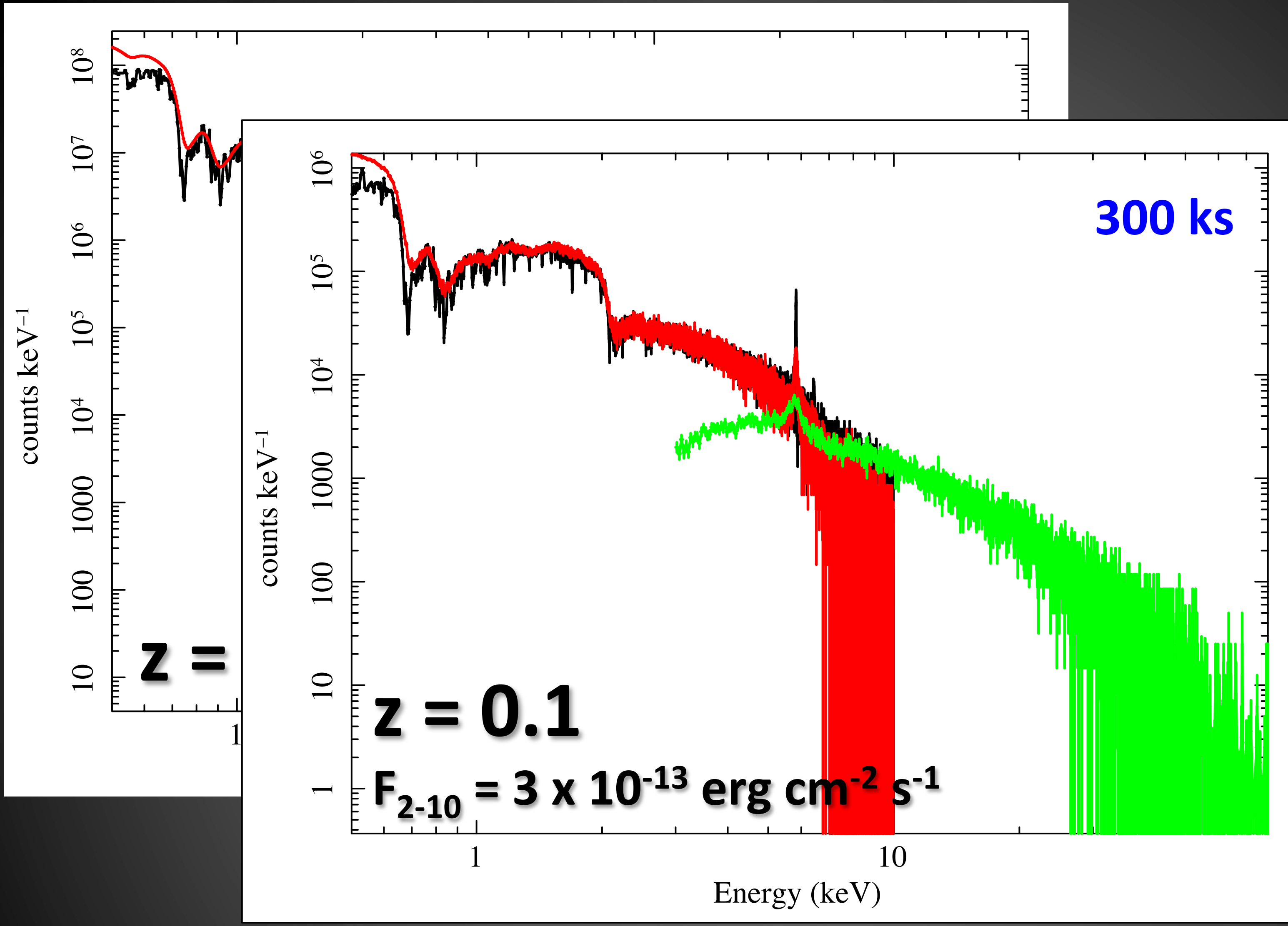
- ***IXO* would have measured spins in 200-300 AGN to z<0.2, handful out to z~1.** Its effective area was planned for 3 m^2 at 1 keV and 0.65 m^2 at 6 keV. *GRAVITAS* is/was similar.

- **Need this order of effective area to start reliably probing out to z~1 in reasonable exposure times, increase sample size of measured SMBH spins to ~100s and beyond** *if significant time is devoted to this science*. At redshifts z<2 also need high-energy detector in order to capture Compton hump, break model degeneracies.

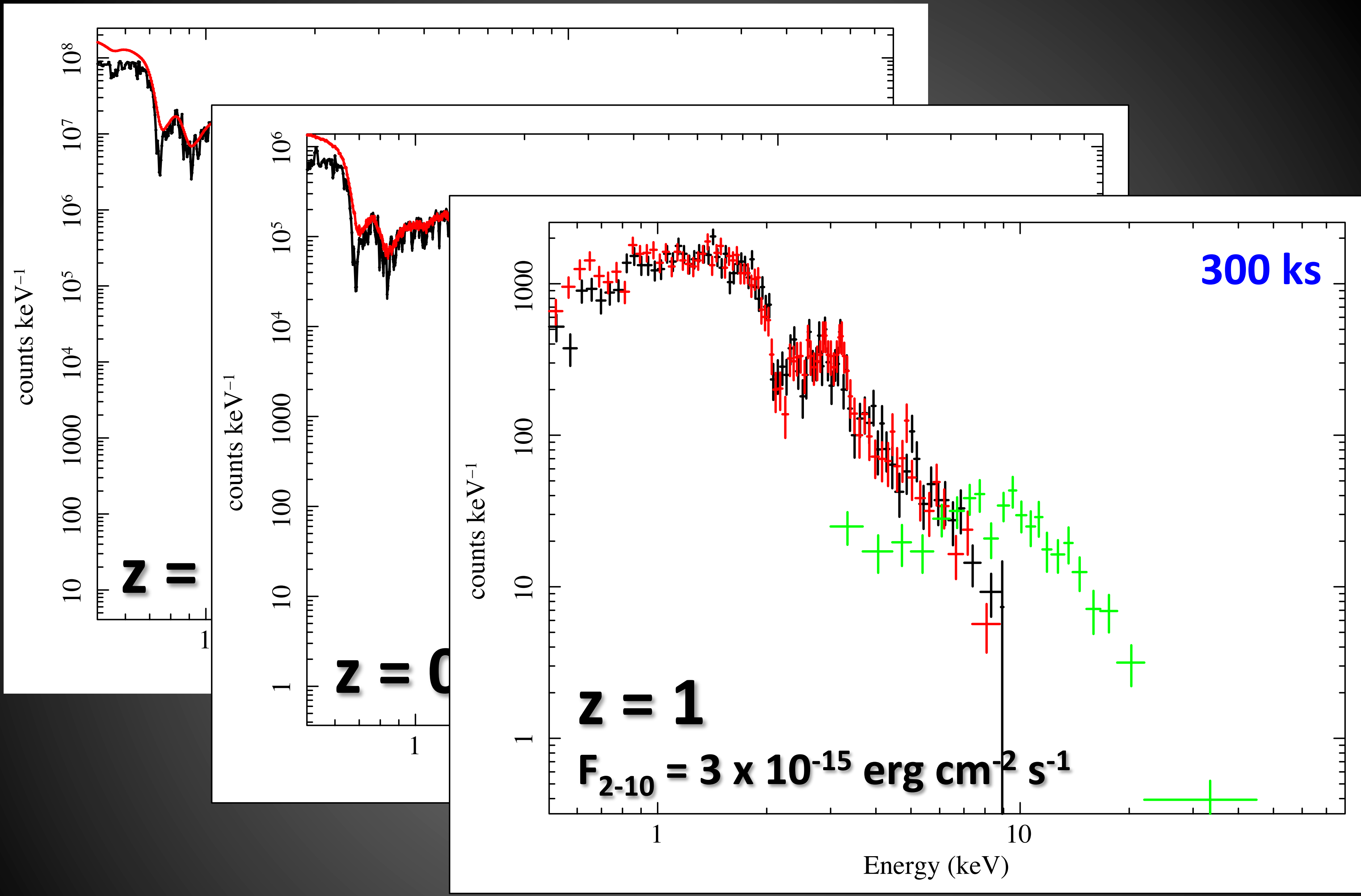
- As proof of concept, we can simulate spectrum of a good candidate AGN for making spin measurements using the X-ray Surveyor responses, **consider exposure time necessary to achieve Δa=0.1 for redshifts of z=0.01, 0.1, z=1 (diminishing flux correspondingly).**



Typical Sy 1 AGN model: N_H=5 x 10^{22} cm^{-2}, Γ=2, *a*=0.99, *i*=30°, L_{2-10}=8 x 10^{42} erg cm^{-2} s^{-1}

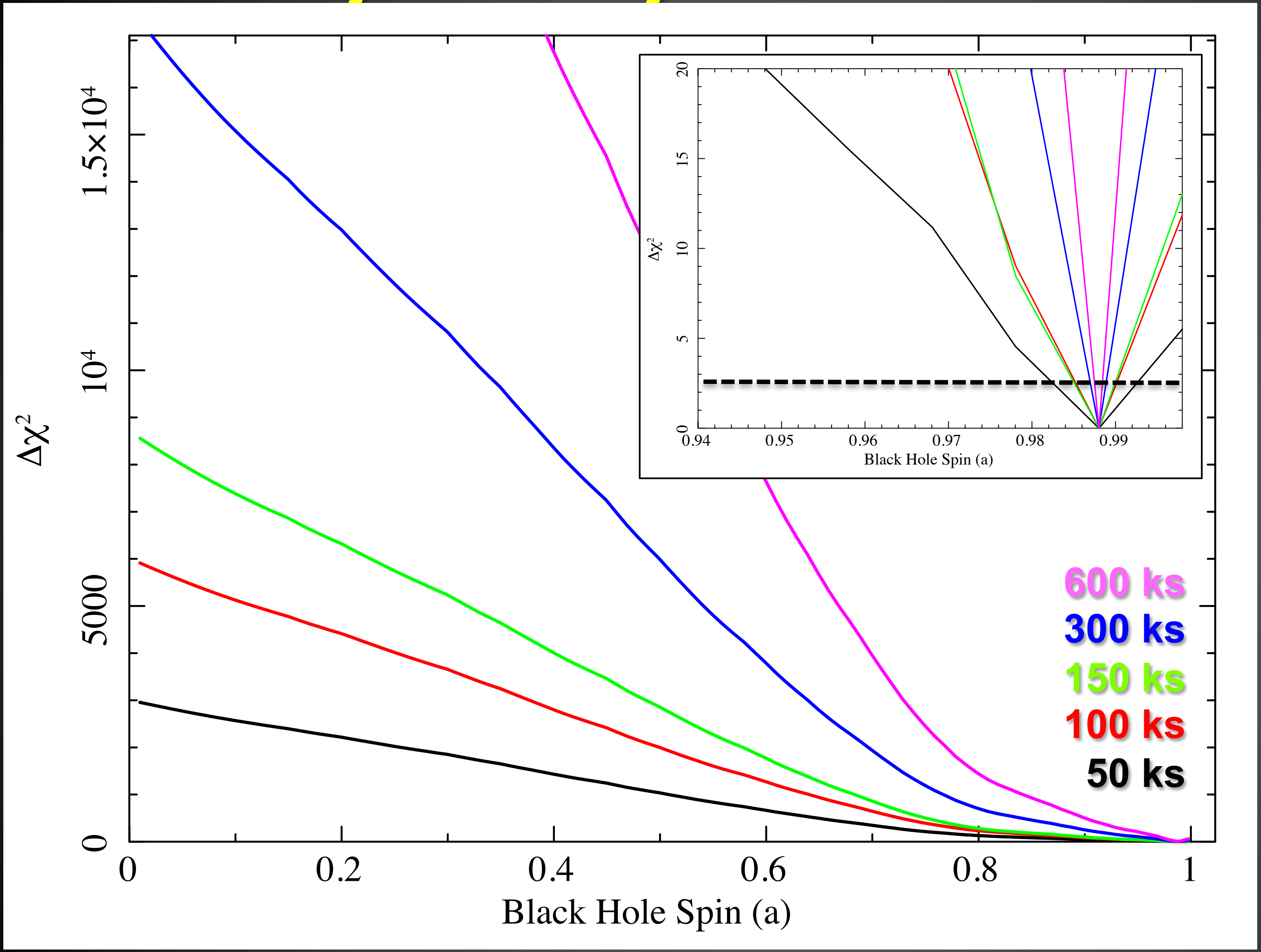


Typical Sy 1 AGN model: N_H=5 x 10^{22} cm^{-2}, Γ=2, *a*=0.99, *i*=30°, L_{2-10}=8 x 10^{42} erg cm^{-2} s^{-1}



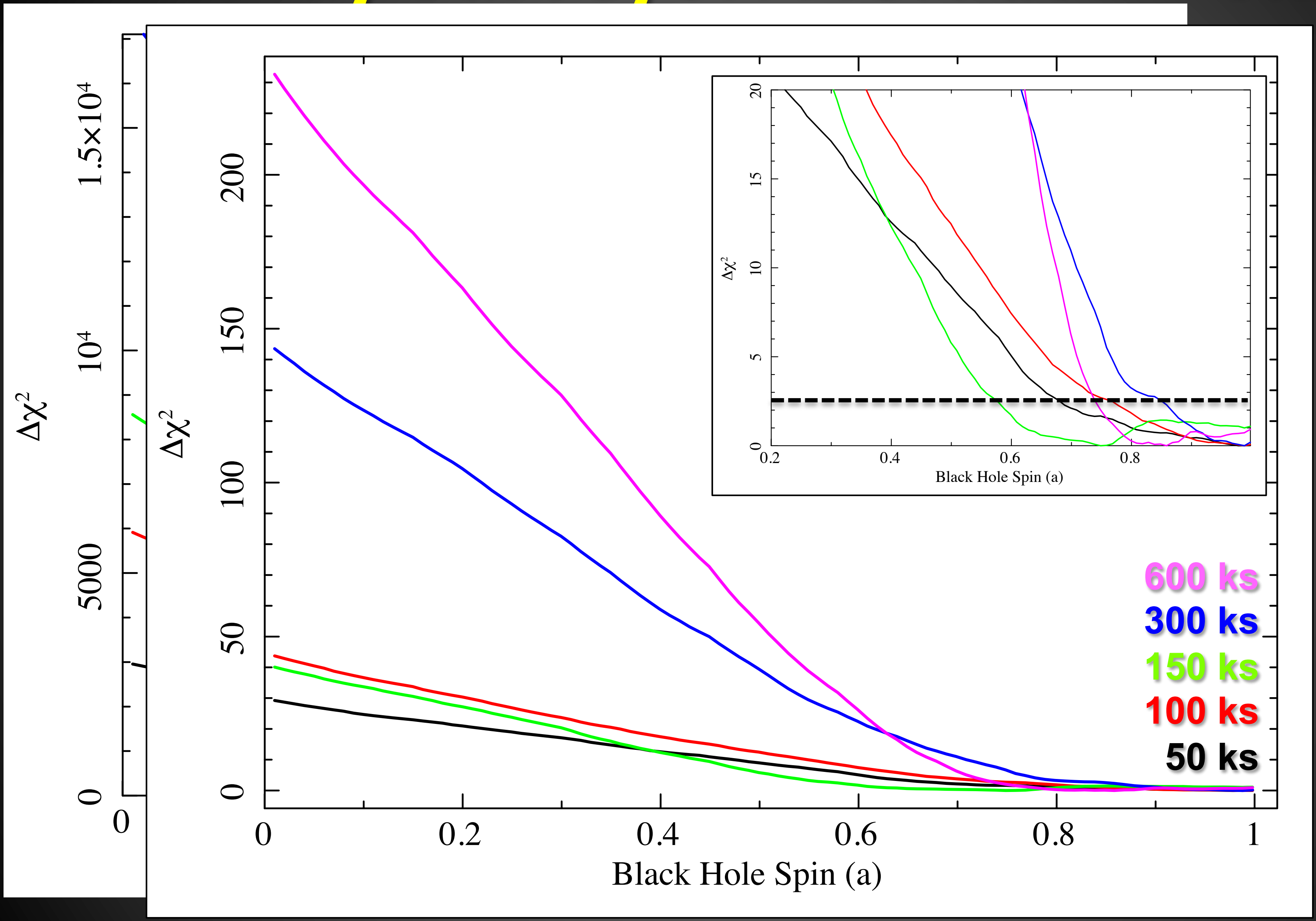
Typical Sy 1 AGN model: N_H=5 x 10^{22} cm^{-2}, Γ=2, *a*=0.99, *i*=30°, L_{2-10}=8 x 10^{42} erg cm^{-2} s^{-1}

X-ray Surveyor: AGN at z = 0.01



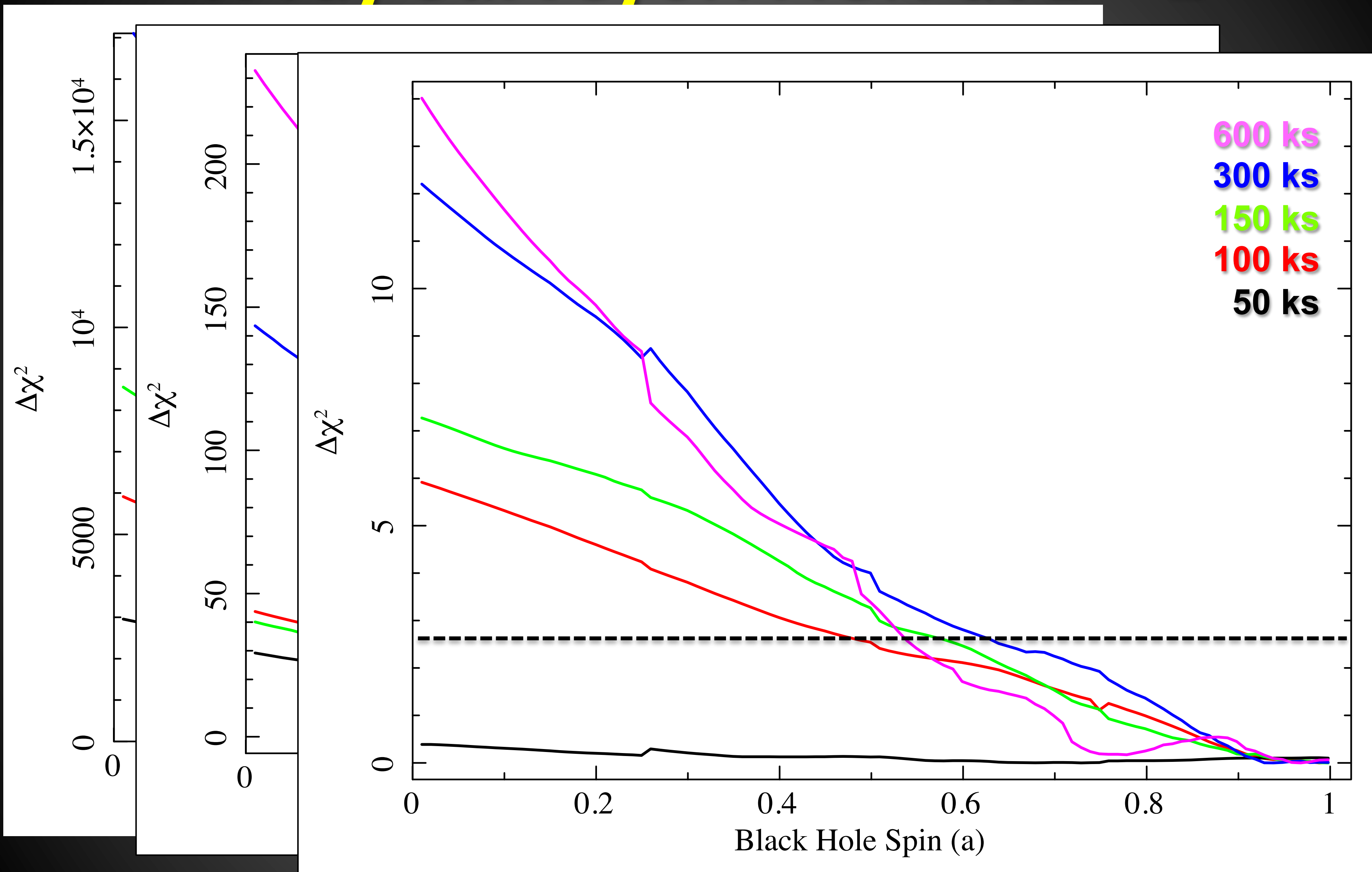
Typical Sy 1 AGN model: N_H=5x10^{22} cm^{-2}, Γ=2, *a*=0.99, *i*=30, $F_{2\text{-}10}$=3x10^{-11} erg cm^{-2} s^{-1}

X-ray Surveyor: AGN at z = 0.1



Typical Sy 1 AGN model: N_H=5x10^{22} cm^{-2}, Γ=2, *a*=0.99, *i*=30, F_{2-10}=3x10^{-13} erg cm^{-2} s^{-1}

X-ray Surveyor: AGN at z = 1



Typical Sy 1 AGN model: N_H=5x10^{22} cm^{-2}, Γ=2, *a*=0.99, *i*=30, $F_{2\text{-}10}$=3x10^{-15} erg cm^{-2} s^{-1}

Summary

- **Reflection modeling** currently gives SMBH spin constraints and coronal constraints in a modest sample of AGN, though care must be taken in model fitting, assumptions.

- **Wide range of measured spins** for AGN, but so far all spin values are consistent with $a \geq 0$ and show a tendency toward high spin values. Possible trend with BH mass… other properties?

- Great care must be taken when evaluating different models, consideration of **systematic uncertainties.** Also, **larger sample size** of AGN spins must be obtained.

- **X-ray Surveyor can make important strides** in this last respect: avoid source confusion in crowded fields, microlensing, advancing spin and coronal studies; especially true when combined with a "super-*NuSTAR*"-like mission with high effective area >10 keV.

EXTRAS

How Can We Measure BH Spin?

- ***Thermal Continuum Fitting***
  - **X-ray Spectra** (XRBs, some AGN attempts)
- ***Inner Disk Reflection Modeling***
  - **X-ray Spectra** (both XRBs and AGN)
- Quasi-periodic Oscillations**
  - **X-ray Timing** (mainly XRBs; only one seen in AGN so far)
- Fe K Reverberation Lags, Orbiting Disk Hot Spots**
  - X-ray Timing and Spectra (easier in AGN)
- Polarization Degree & Angle vs. Energy**
  - **X-ray Spectra**, **polarimetry** (easier for XRBs)
- Imaging the Inner Disk and Event Horizon**
  - **≤mm-VLBI Imaging** (AGN only: must be large, e.g., Sgr A*, M87)

Measuring SMBH Spins in AGN

- Current sample size: ~30-40 SMBHs in bright AGN with broad Fe Kα lines (Miller+ 2007, Nandra+ 2007, de La Calle Pérez+ 2010, Brenneman 2013, Reynolds 2014).

  - Out of $10^{11\text{-}12}$ estimated SMBHs in the accessible universe.

  - Must have high line EW, high X-ray s/n (≥200,000 photons from 2-10 keV), and line must be relativistically broad with $r_{in} \leq 9\ r_g$. Not all type 1 AGN have such features (e.g., NGC 5548).

- Technique used: **Inner Disk Reflection**:

  KERRCONV, RELCONV or KYCONV × REFLIONX or XILLVER

  Brenneman & Reynolds (2006) — Dauser+ (2013) — Dovčiak+ (2004) — Ross & Fabian (2005) — Garcia+ (2013)

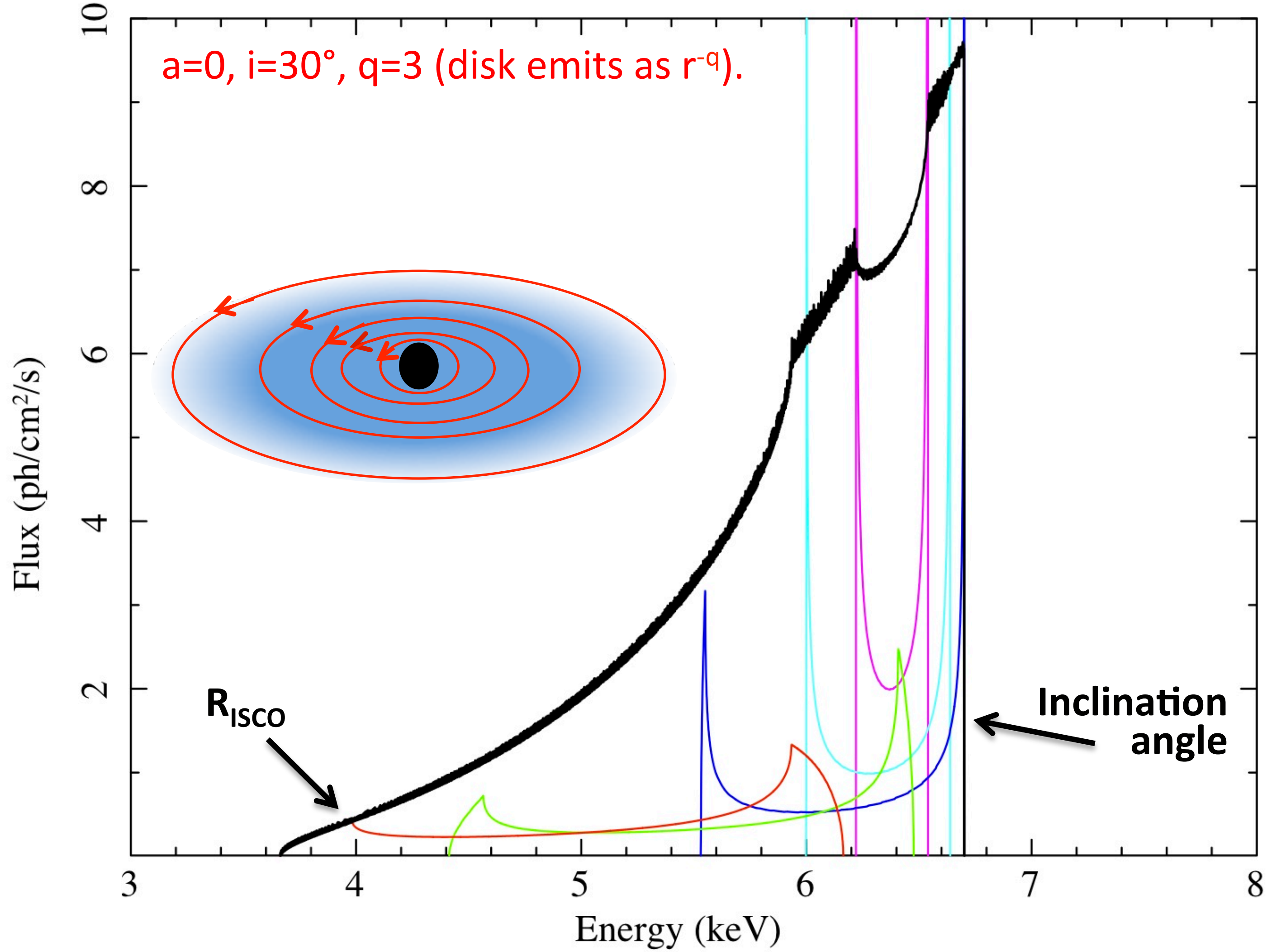
Or RELXILL (Garcia+ 2014), which convolves RELCONV and XILLVER in self-consistent way, also links with irradiating power-law.

CAVEATS: complex absorption, soft excess, coronal unknowns, disk truncation, disk ionization and density, Fe abundance.

Biggest Systematic Uncertainties in SMBH Spin Measurements

- Ability to isolate reflection from **absorption, continuum**, properly model **soft excess** (differs for each source; time-resolved spectra are key).
- Degeneracies with **Fe abundance** (worse for weaker inner disk reflection features; must carefully probe parameter space).
- **Jet contamination, disk truncation** in RLAGN (multi-wavelength analysis critical to ensure disk is not truncated > ISCO).
- Assumption of no contribution to reflection spectrum from **within the ISCO**; introduces systematic uncertainties for high spin constraints at ~2%, low spin constraints at 20% or more.

Fe Kα emission line from different disk annuli



KERRDISK or RELLINE model (Brenneman & Reynolds 2006; Dauser+ 2010)

What Missions are Being Planned?

- *Astro-H* (2016): higher E.A., better spectral resolution than *Suzaku*, simultaneous high-energy data comparable with *NuSTAR*.
  - separate absorption from emission to isolate reflection
  - probe soft excess more accurately
  - lacking in spatial resolution, effective area still small

☑ Effective area ☑ Spec Res ☑Spatial Res ☑ Bandpass

What Missions are Being Planned?

- *Astro-H* (2016)

- *Athena* (~2028): Further increase in effective area over *Astro-H*
  - slight increase in sample size of spin measurements
  - improvement in Fe K reverberation statistics
  - no high energy detector or effective area >12 keV.

☑ Effective area ☑ Spec Res ☑Spatial Res ☑ Bandpass

What Missions are Being Planned?

- *Astro-H* (2016)

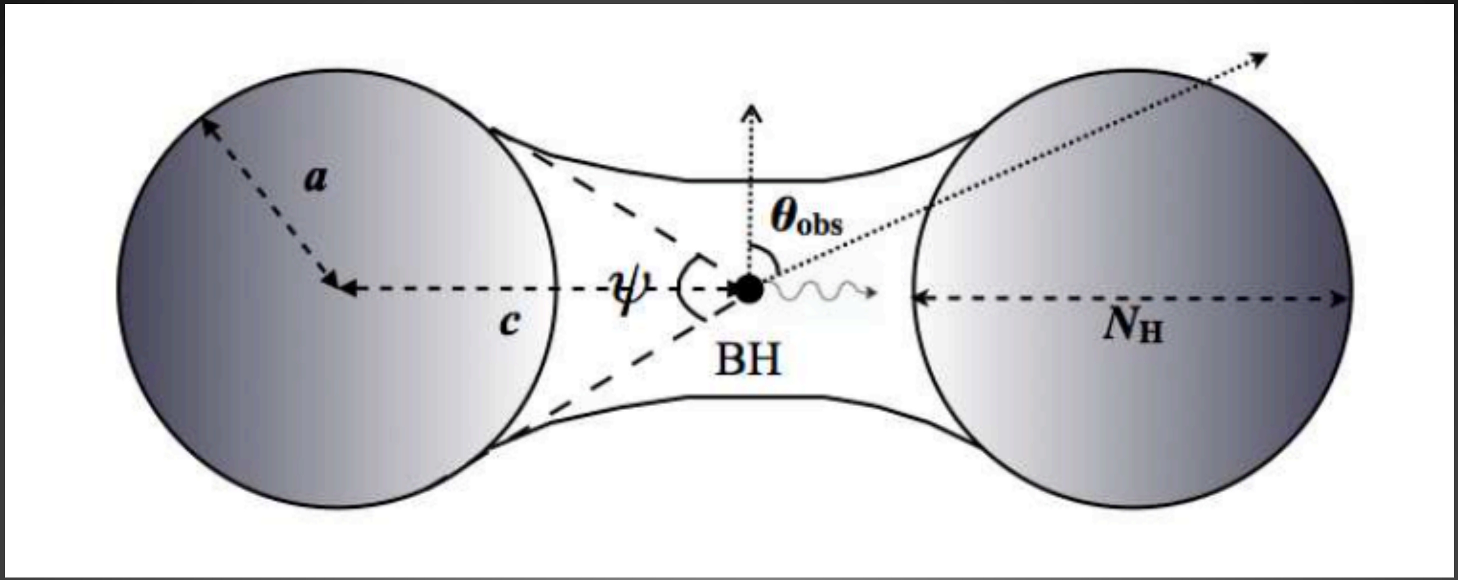
- *Athena* (~2028)

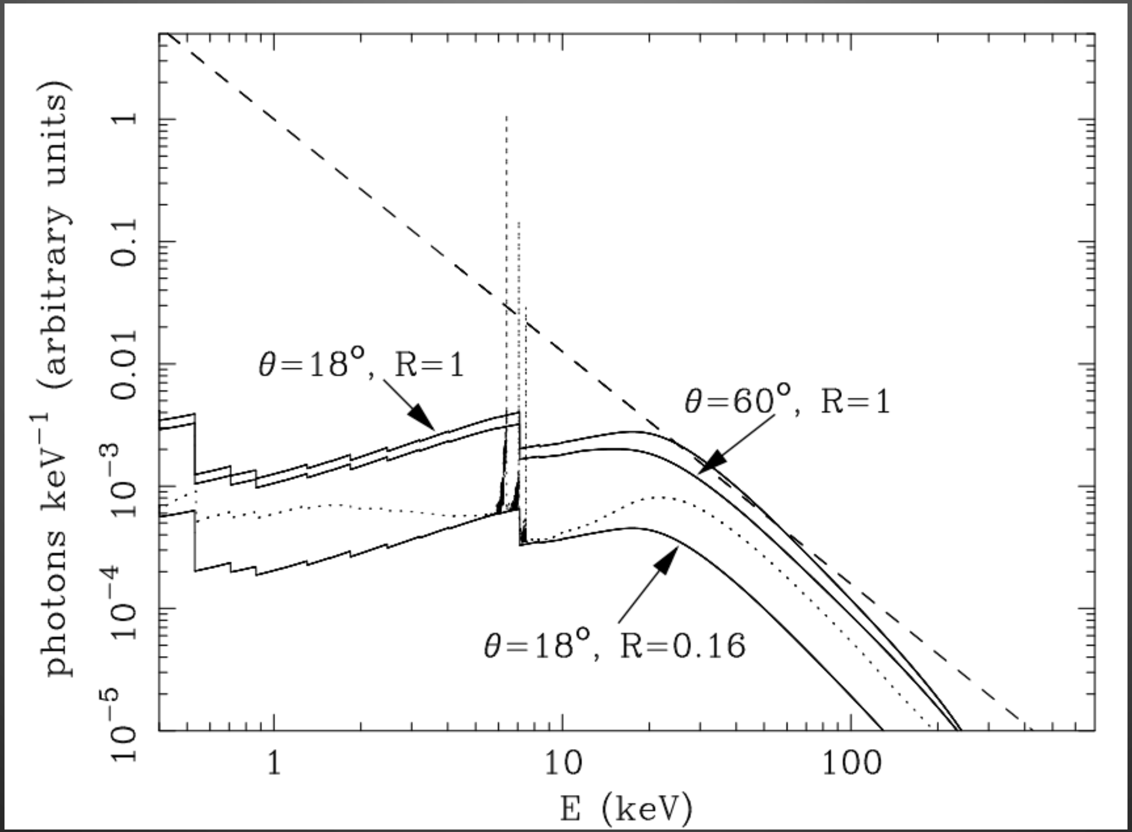
- *LOFT* (~2025?): ~5x increase in effective area over *Athena*, precise timing ability
  - probe accretion physics on orbital timescales
  - increase sample size of spin measurements by ~10x
  - trace individual hotspots in the inner disk, significant improvement in Fe K reverberation measurements
  - effective area out to ~60 keV, but lacks in spatial and spectral resolution

☑ Effective area ☑ Spec Res ☑Spatial Res ☑ Bandpass

What We Learn From Reflection

- ***Torus covering fraction***
- Fe abundance (disk, torus)
- Coronal height and geometry
- Black hole spin

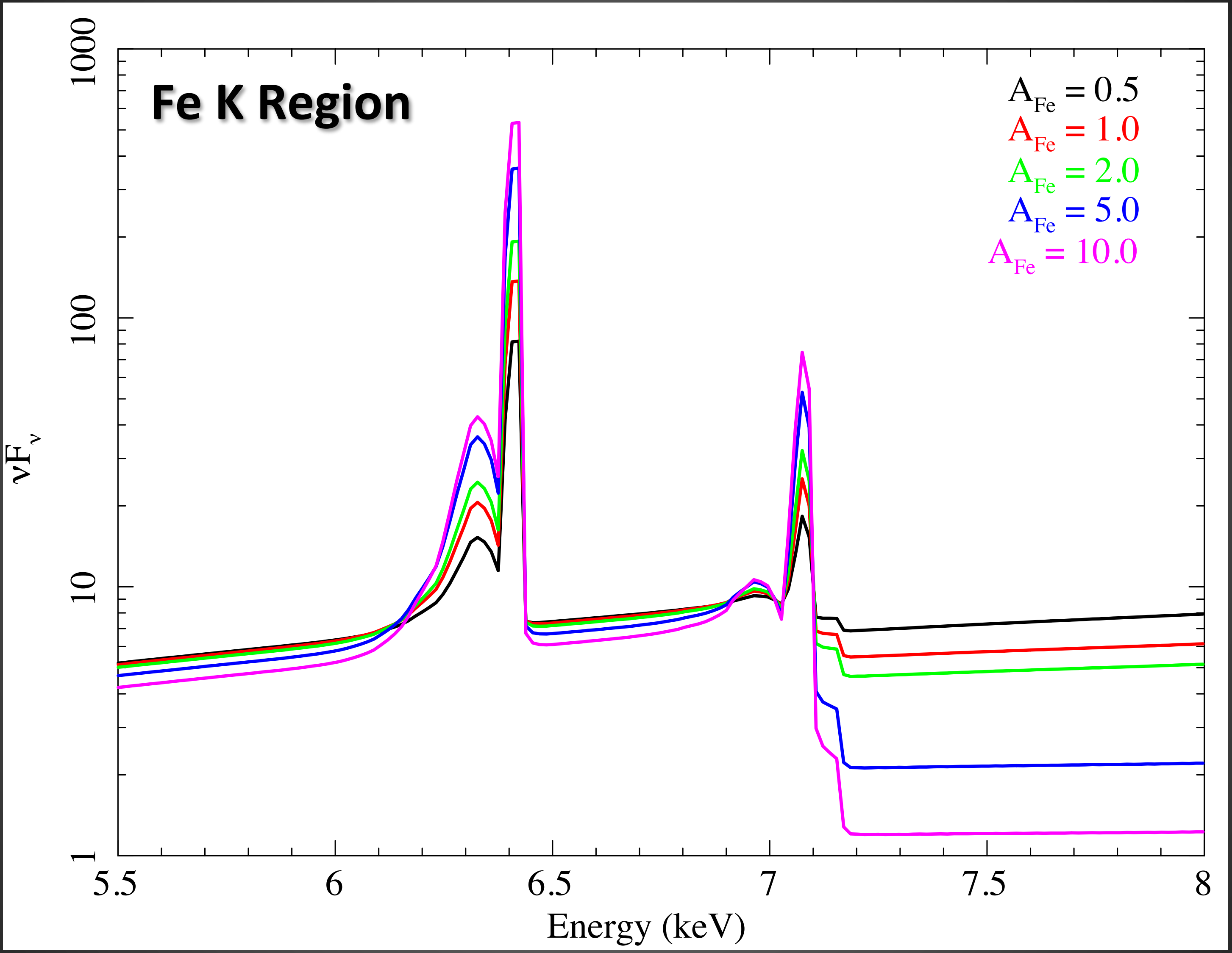




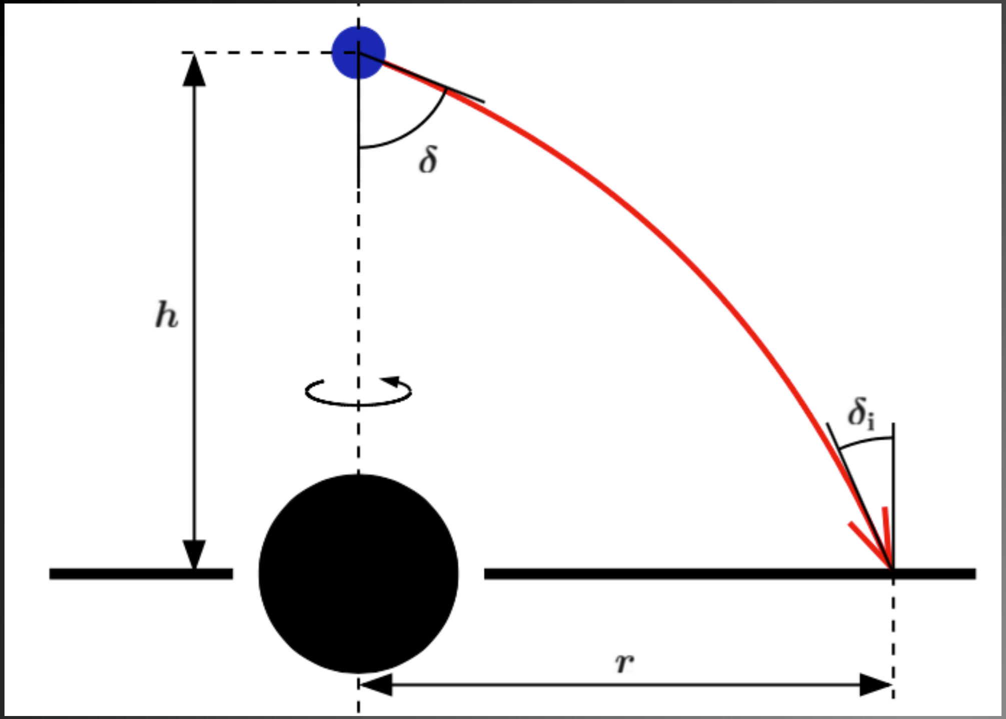
Murphy & Yaqoob (2009)

What We Learn From Reflection

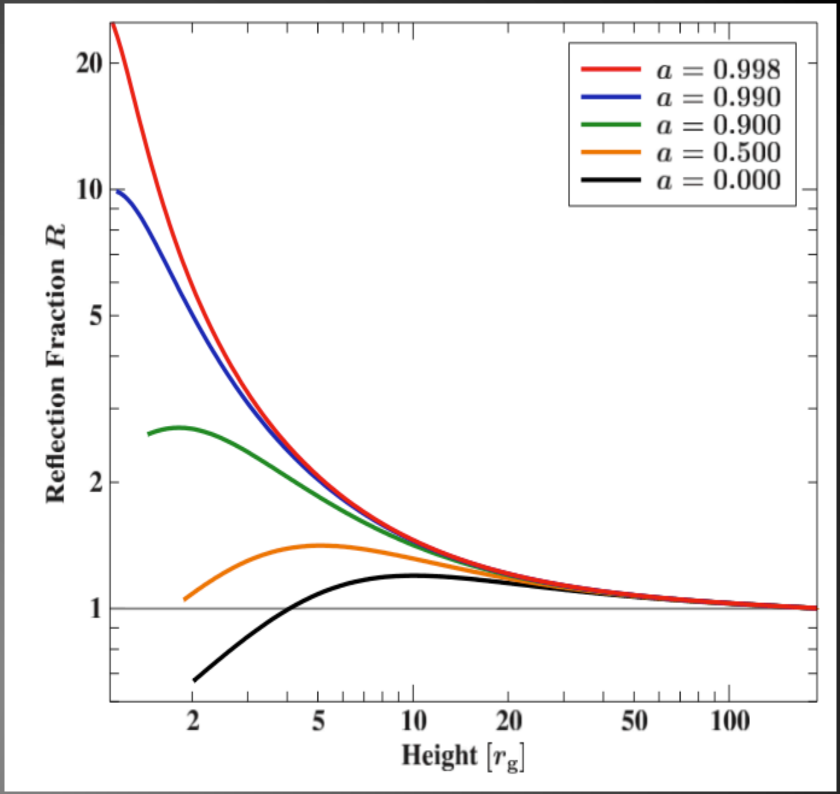
- Torus covering fraction
- ***Fe abundance (disk, torus)***
- Coronal height and geometry
- Black hole spin



Based on the XILLVER model of Garcia+ (2013)

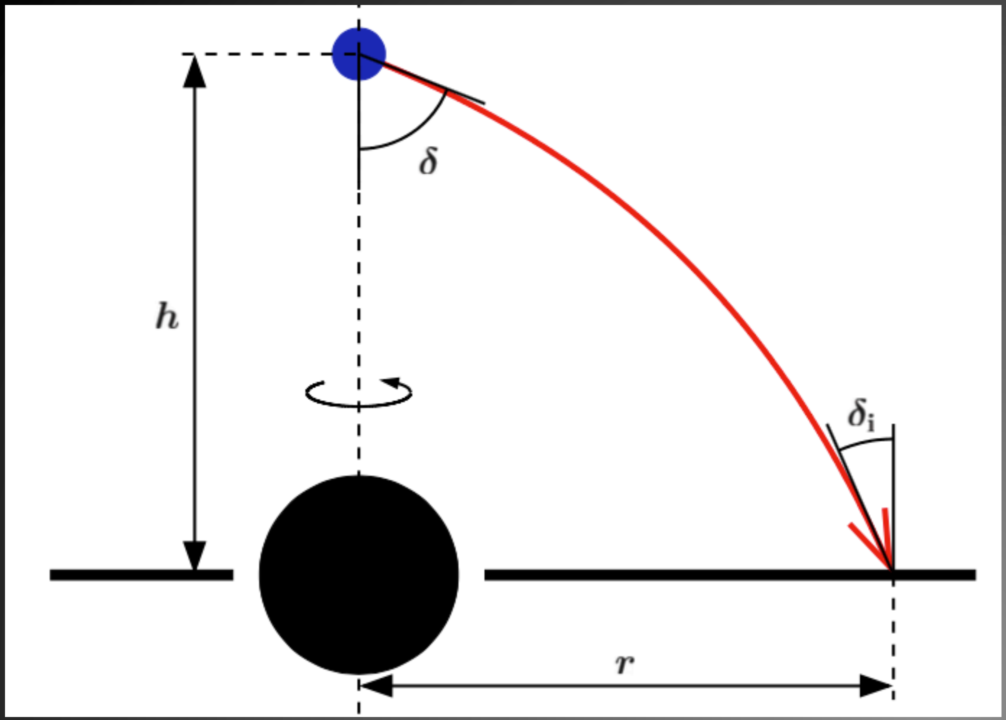


Dauser+ (2013)

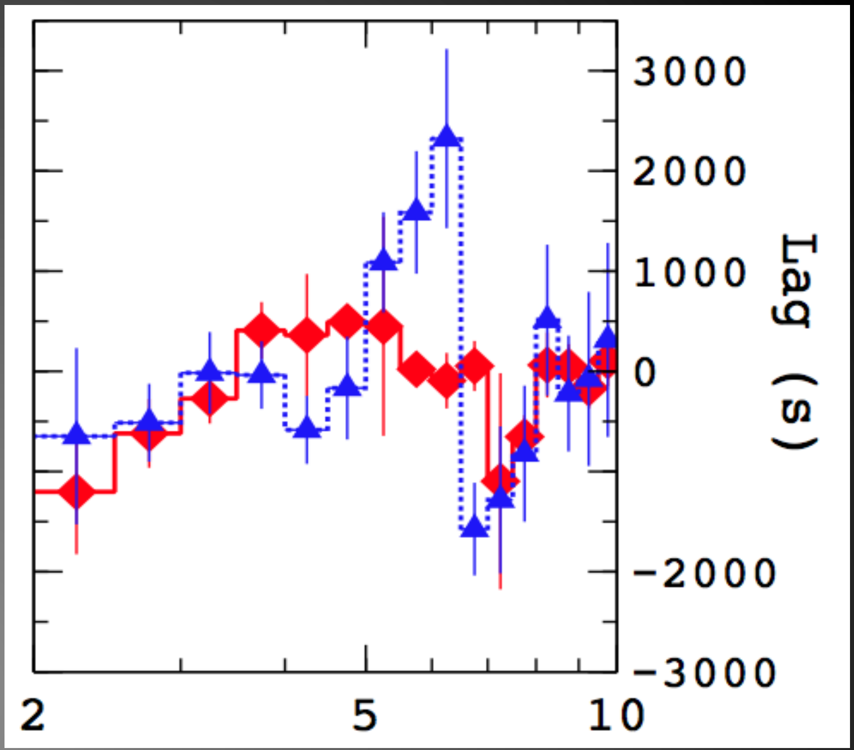


Garcia+ (2014)

- Latest **lamp-post models** (e.g., RELXILL) tie together primary irradiating power-law, reflection off of inner disk.
- Assumption is that **corona is point-like** and on spin axis of BH at a given height.
- **Height determines irradiation** pattern on disk and subsequent reflection fraction.



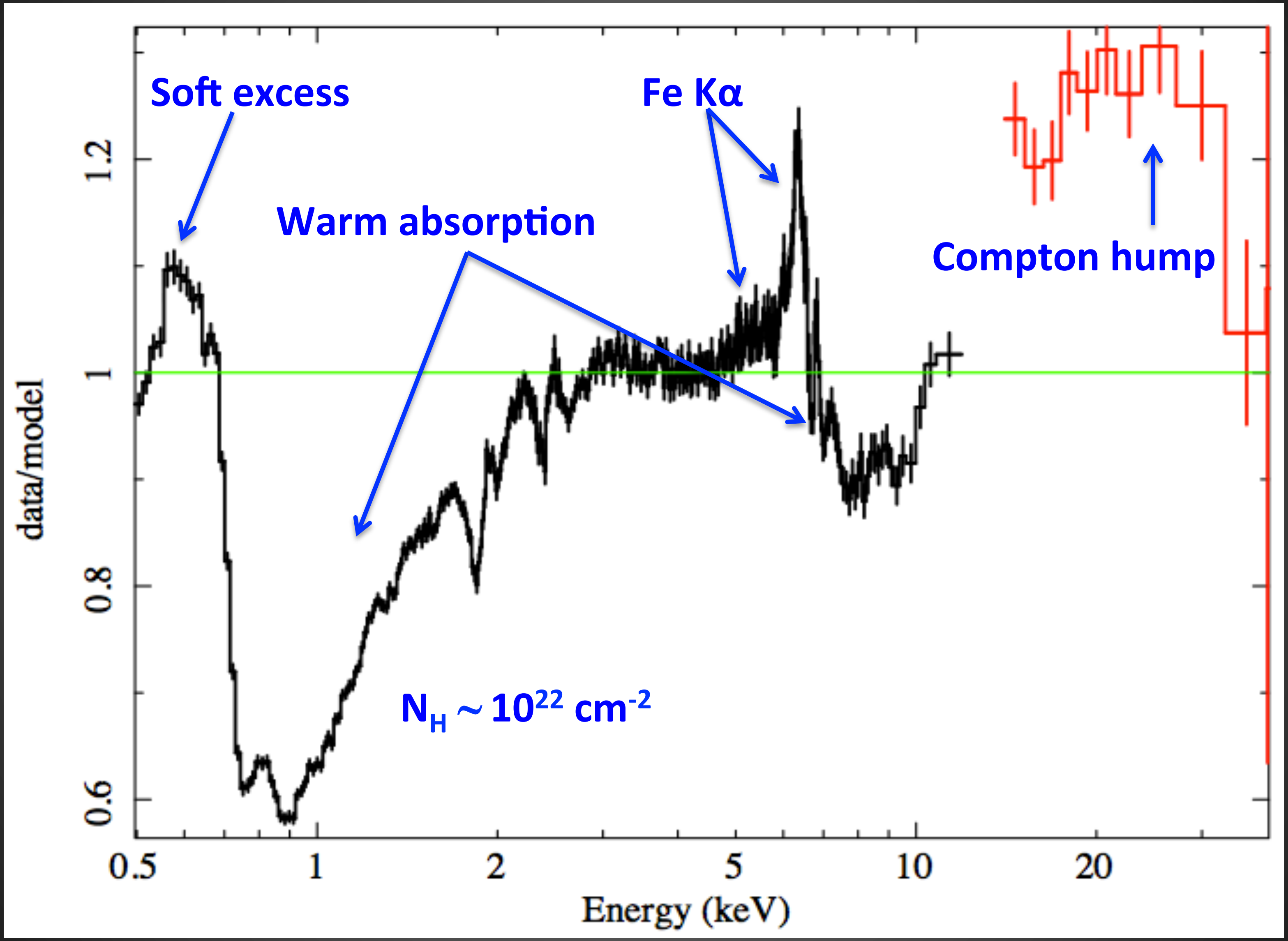
Dauser+ (2013)



Zoghbi+ (2012)

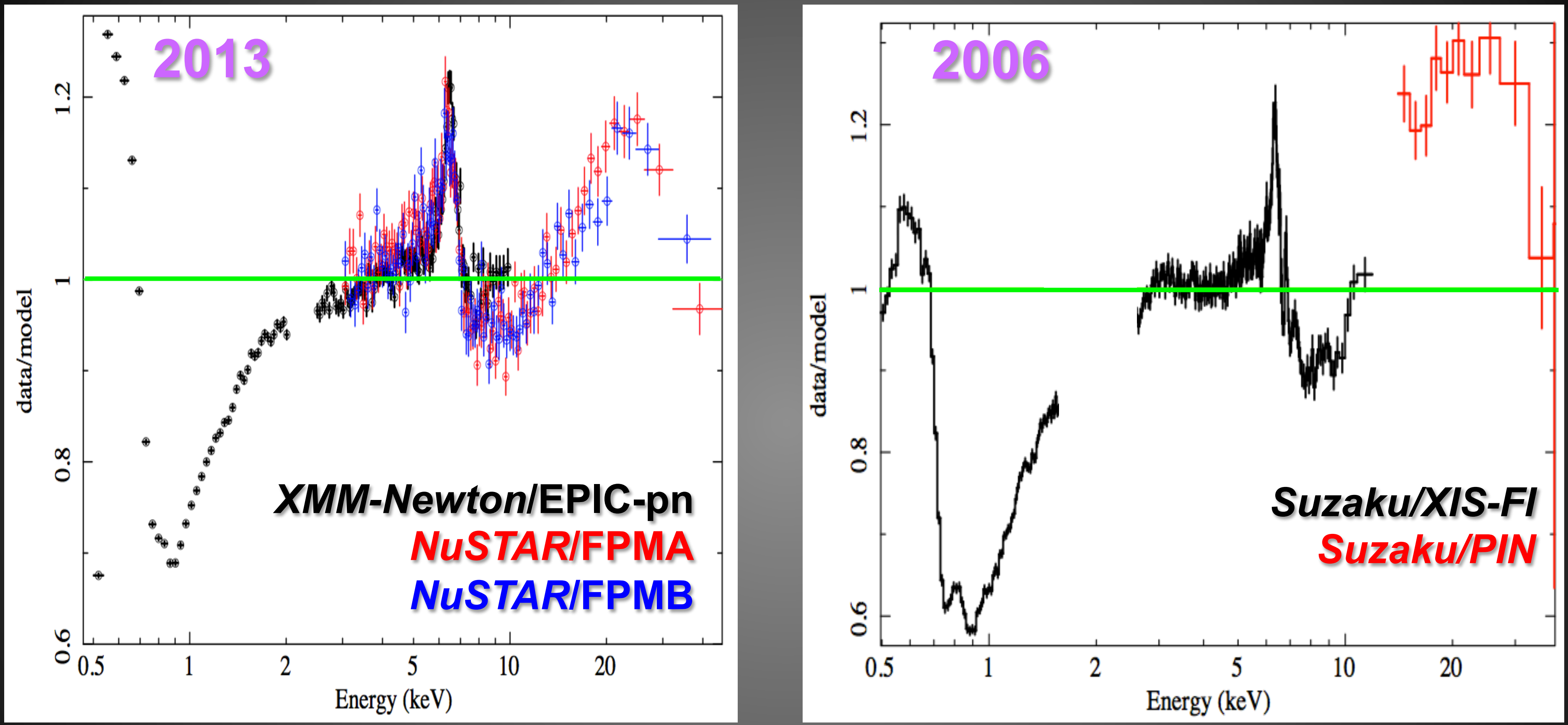
- Latest **lamp-post models** (e.g., RELXILL) tie together primary irradiating power-law, reflection off of inner disk.
- Assumption is that **corona is point-like** and on spin axis of BH at a given height.
- **Height determines irradiation** pattern on disk and subsequent reflection fraction.
- **Time delay** measured between coronal flare and reprocessed disk flare yields information about height and compactness of corona.

Spectral Complexity



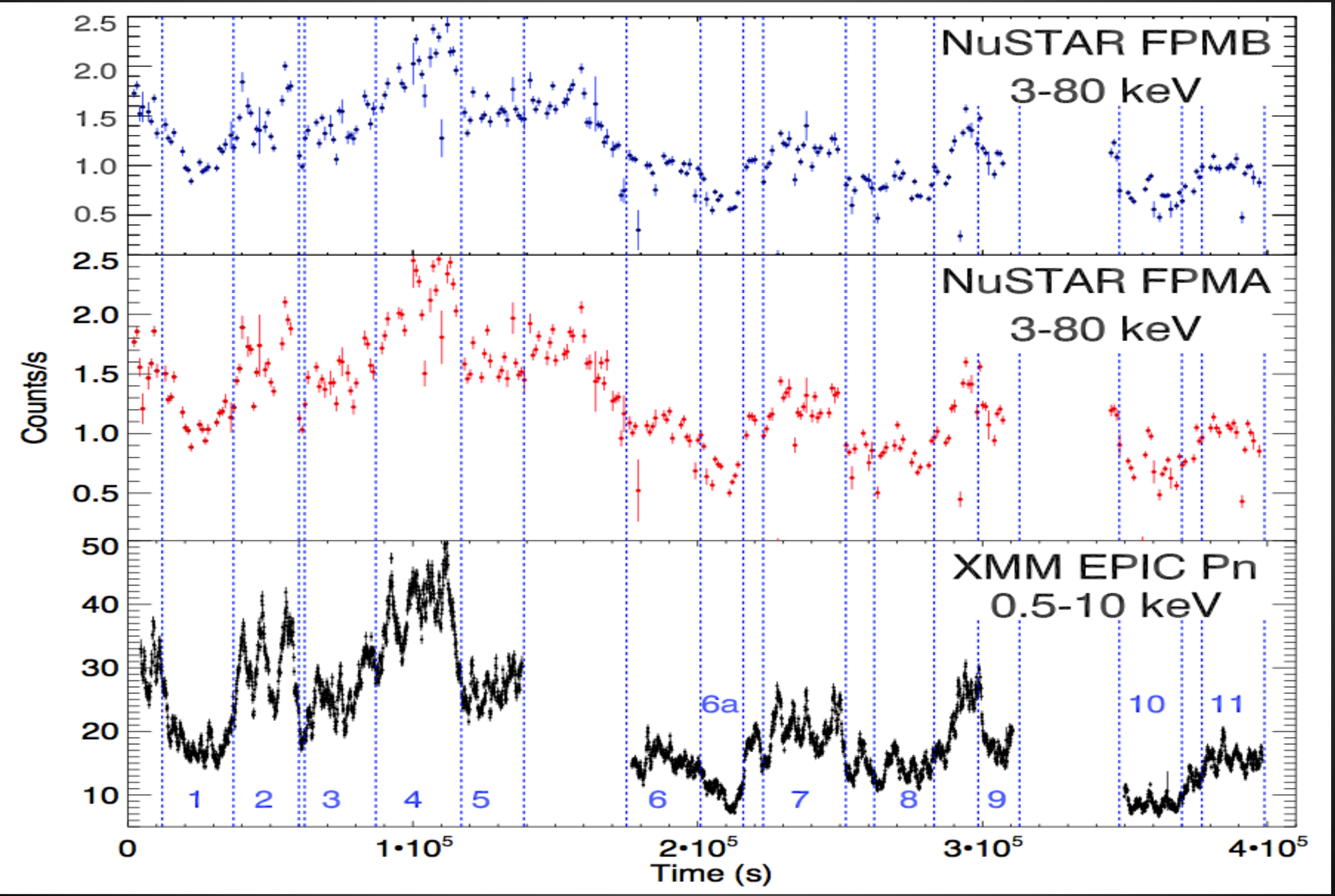
Spectral components with continuum power-law modeled out

Time-averaged Spectra



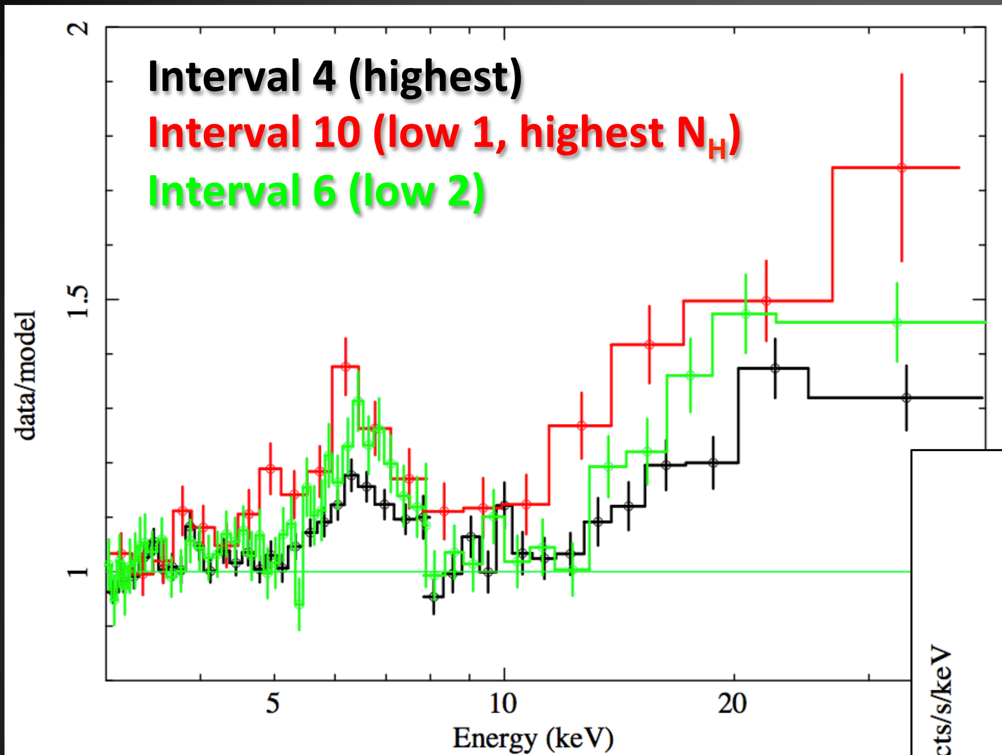
- Residuals to a power-law are qualitatively similar to those seen in most previous epochs, as is overall flux state ($F_{2\text{-}10}$ = 4e-11 ergs/cm^2/s).
- Average broad Fe Kα Line EW = 312 ± 183 eV in 2013 vs. 305 ± 20 eV in 2006.

Temporal Variability

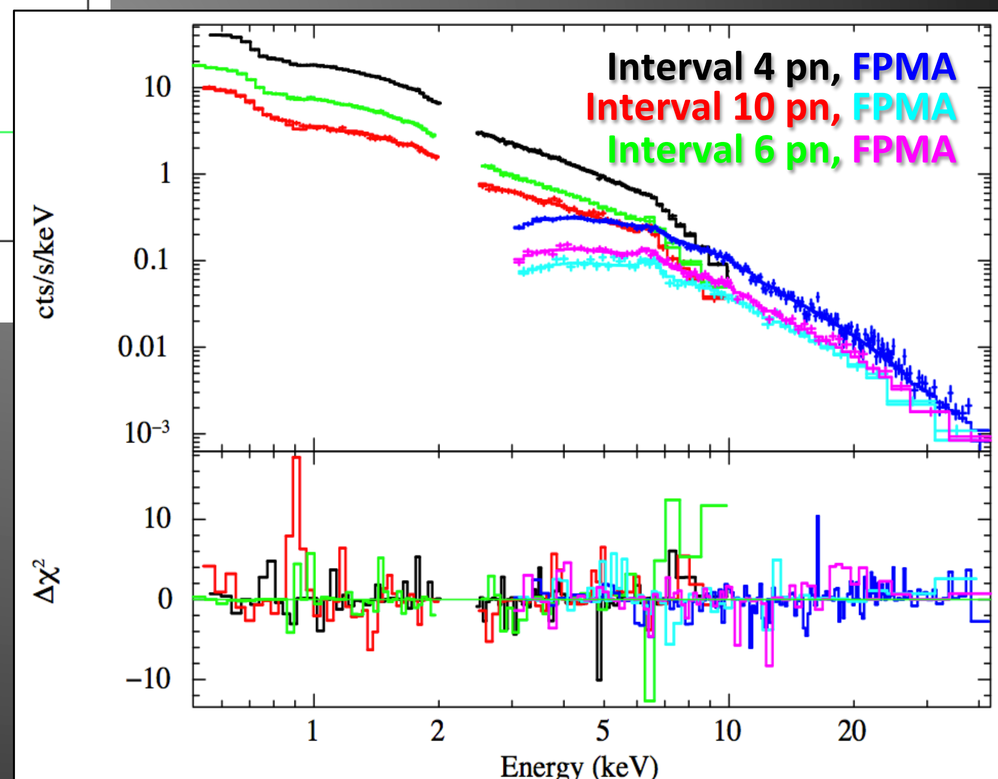


Marinucci+ 2014

Spectral Variability

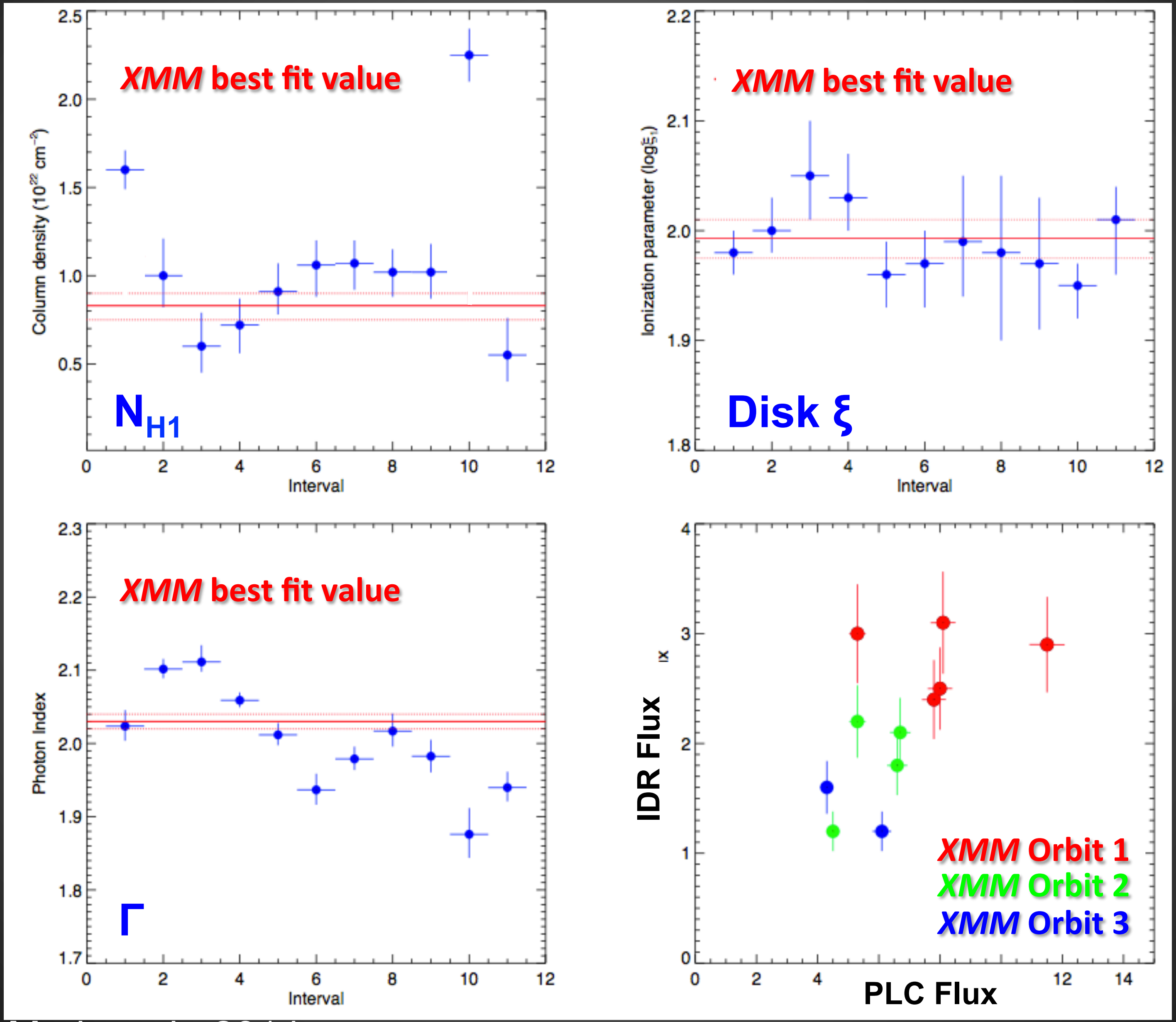


- Highest, two lowest flux time intervals analyzed jointly with simultaneous *XMM* and *NuSTAR* data.
- Left plot shows data ratioed against a power-law with $\Gamma = 2$ (ignoring 4 - 7.5 keV).



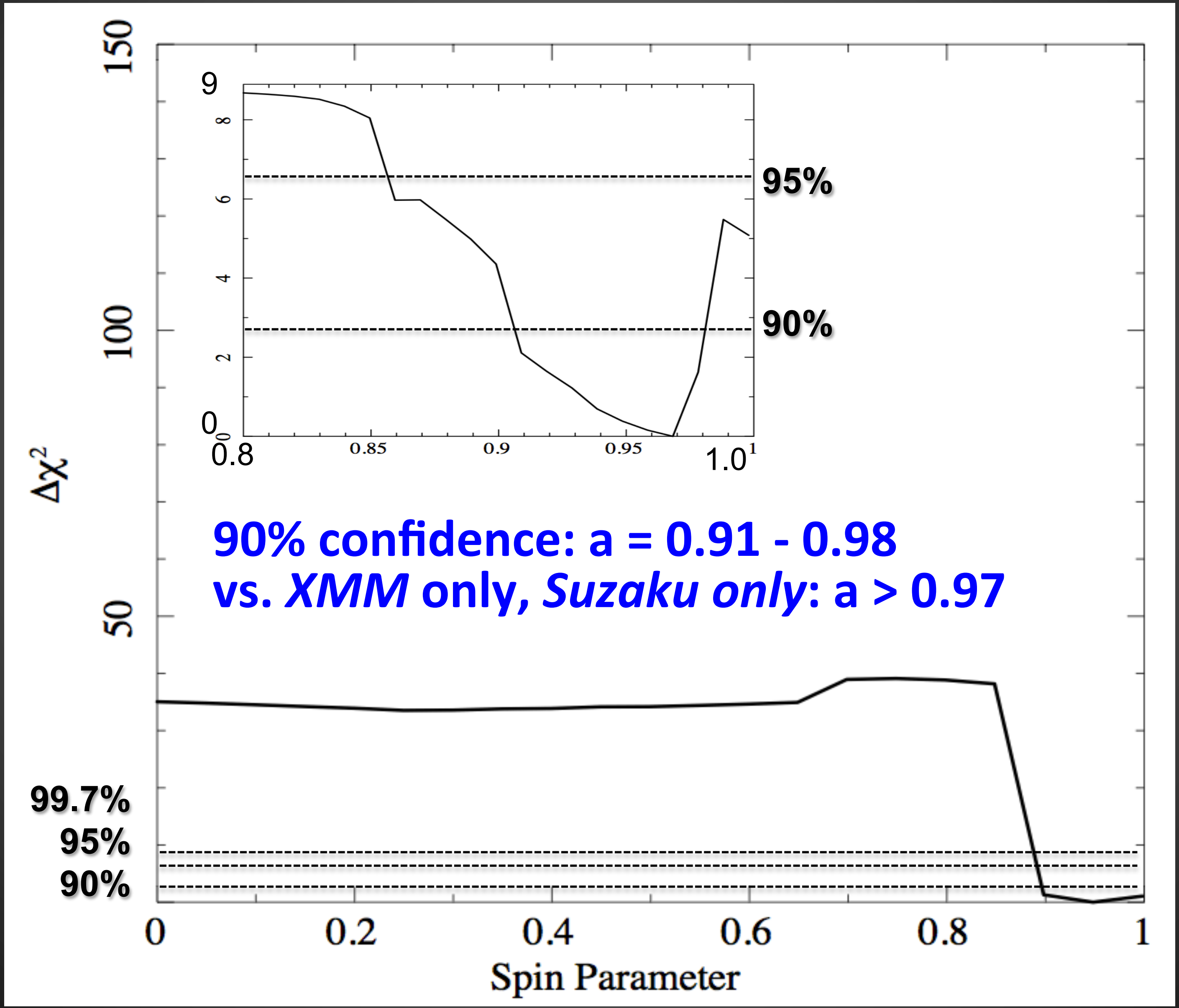
- Right plot shows data fit with model including power-law continuum (no constrained E_{cut}); 2 ionized absorbers; 1 cold, dusty absorber; distant (neutral); inner disk (ionized) reflection.
- Without inner disk: $\Delta\chi^2/\Delta\nu = +191/+11$.

Time-resolved Spectral Fitting



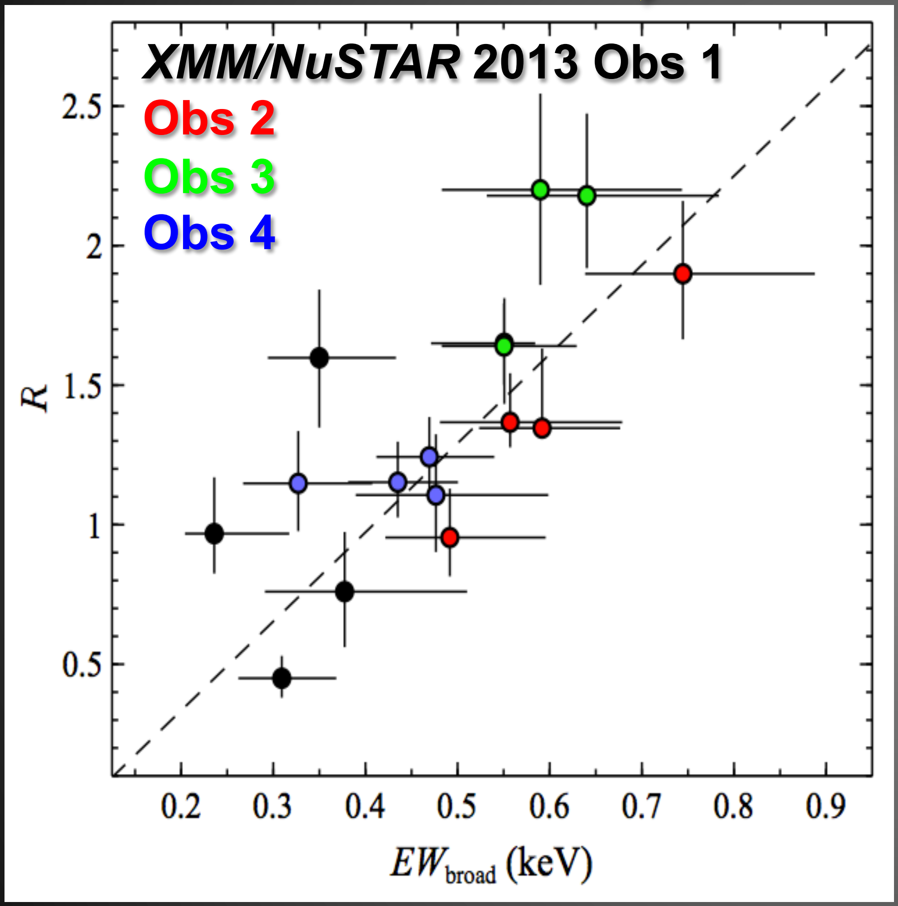
Marinucci+ 2014

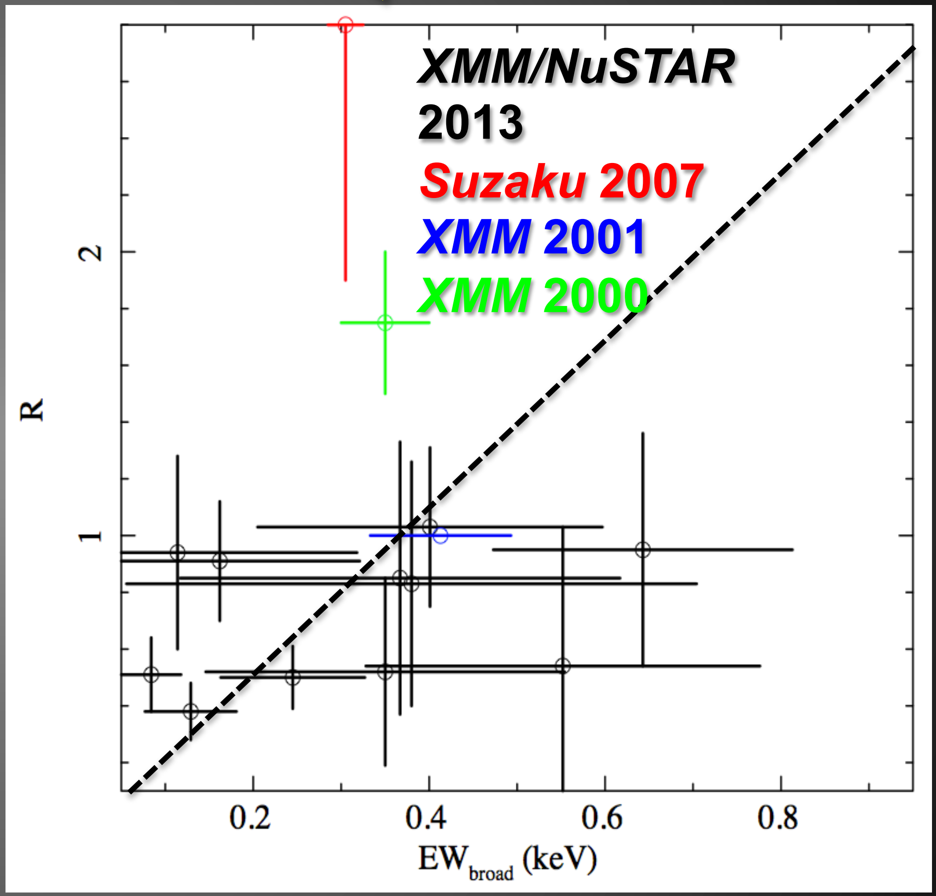
Spin Constraint



90% confidence: a = 0.91 - 0.98
vs. *XMM* only, *Suzaku only*: a > 0.97

NGC 1365 vs. MCG6



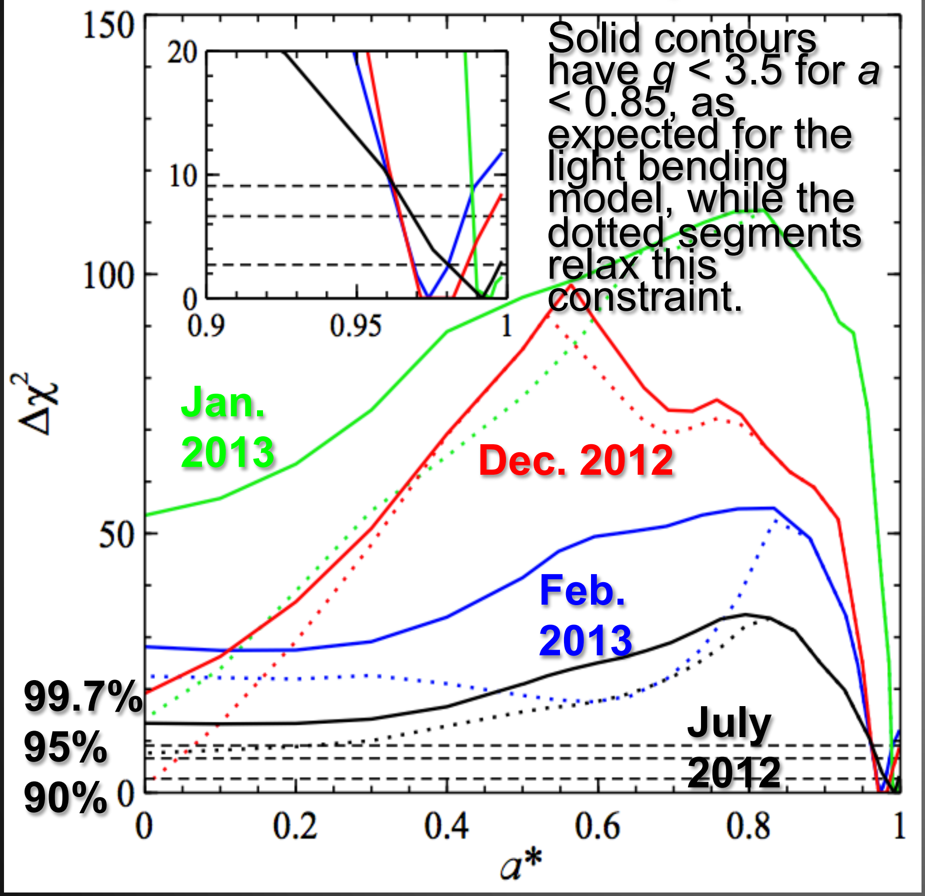


Walton+ 2014 → **106.03**

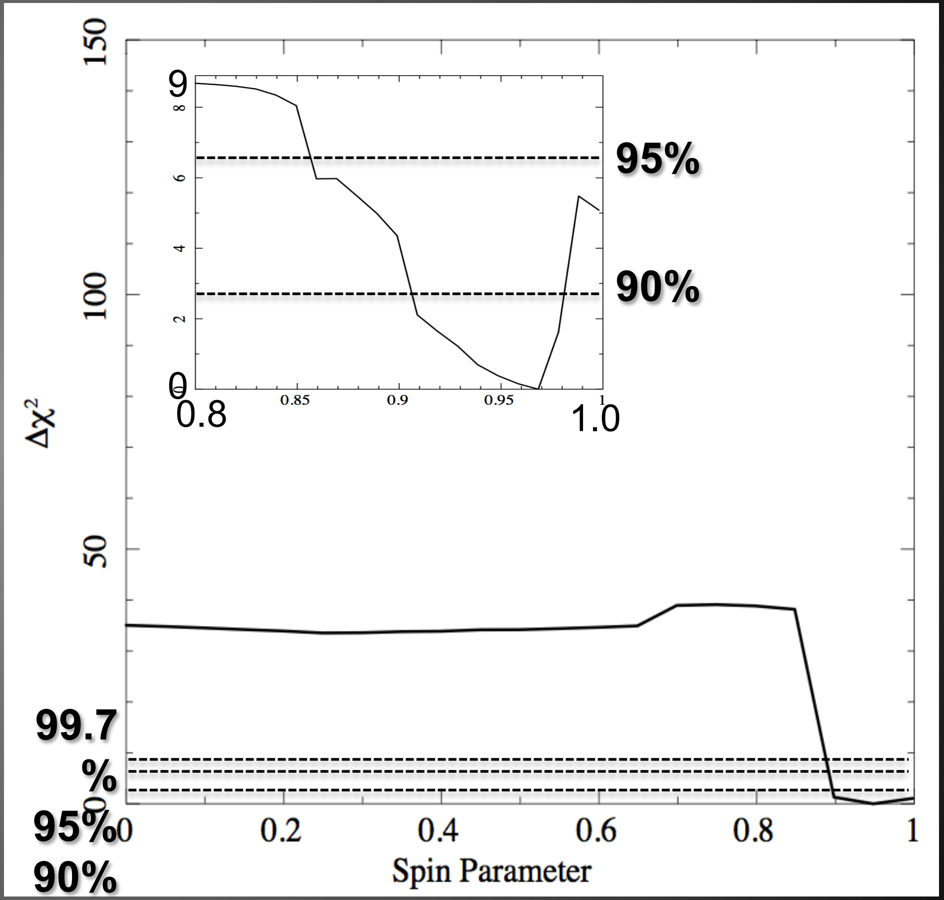
Brenneman+ (in prep.)

- In need of consistent analytical approach to the phenomenological modeling!

NGC 1365 vs. MCG6

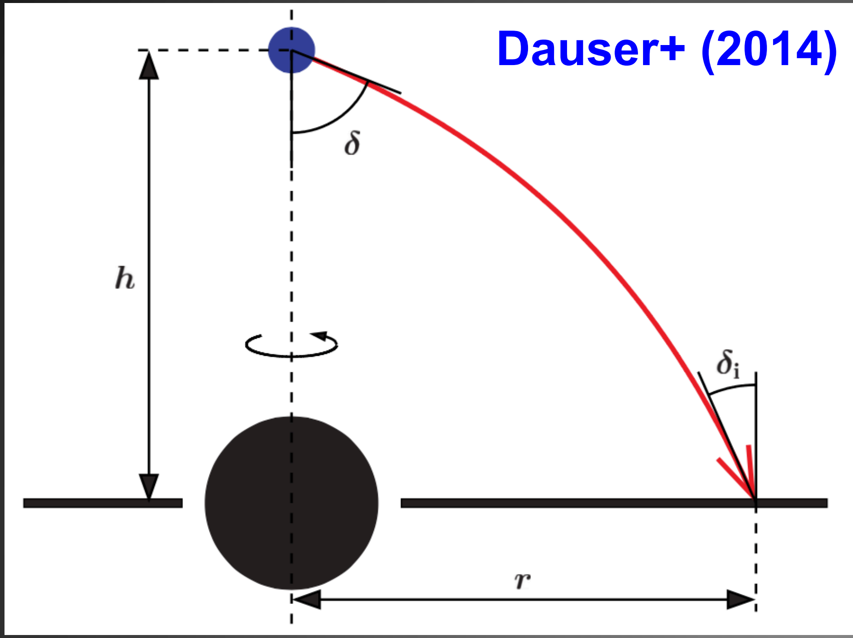


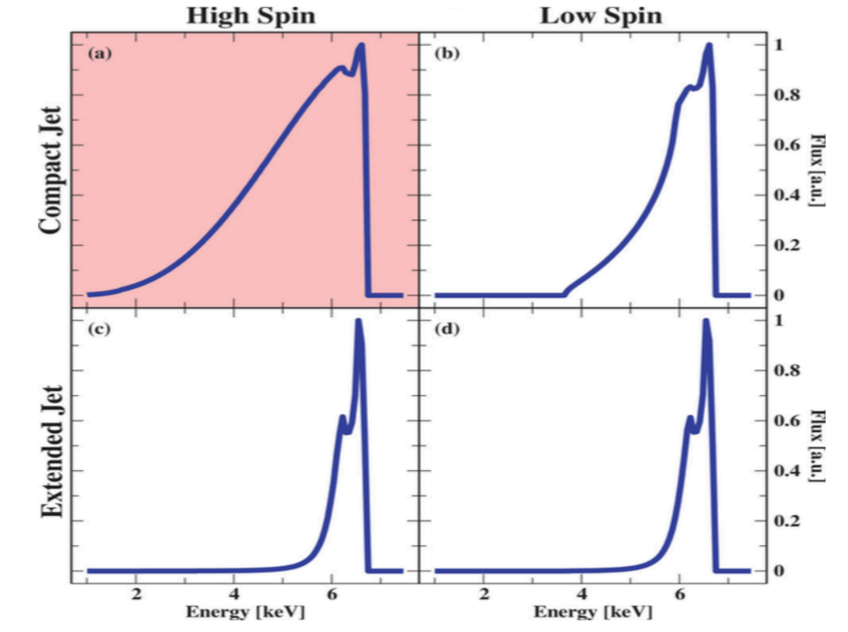
Walton+ 2014 → **106.03**



Brenneman+ (in prep.)

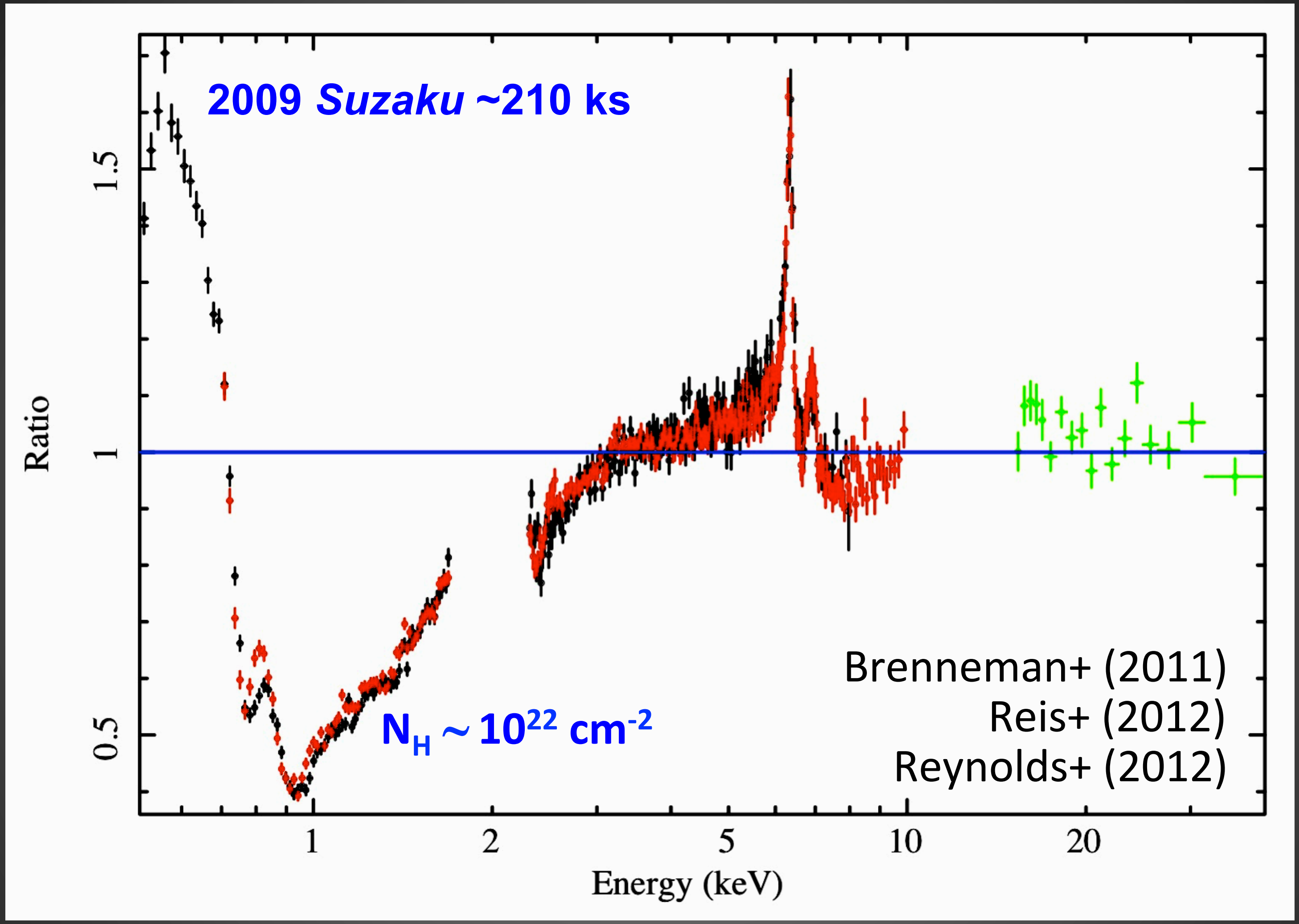
Implications for Coronal Properties



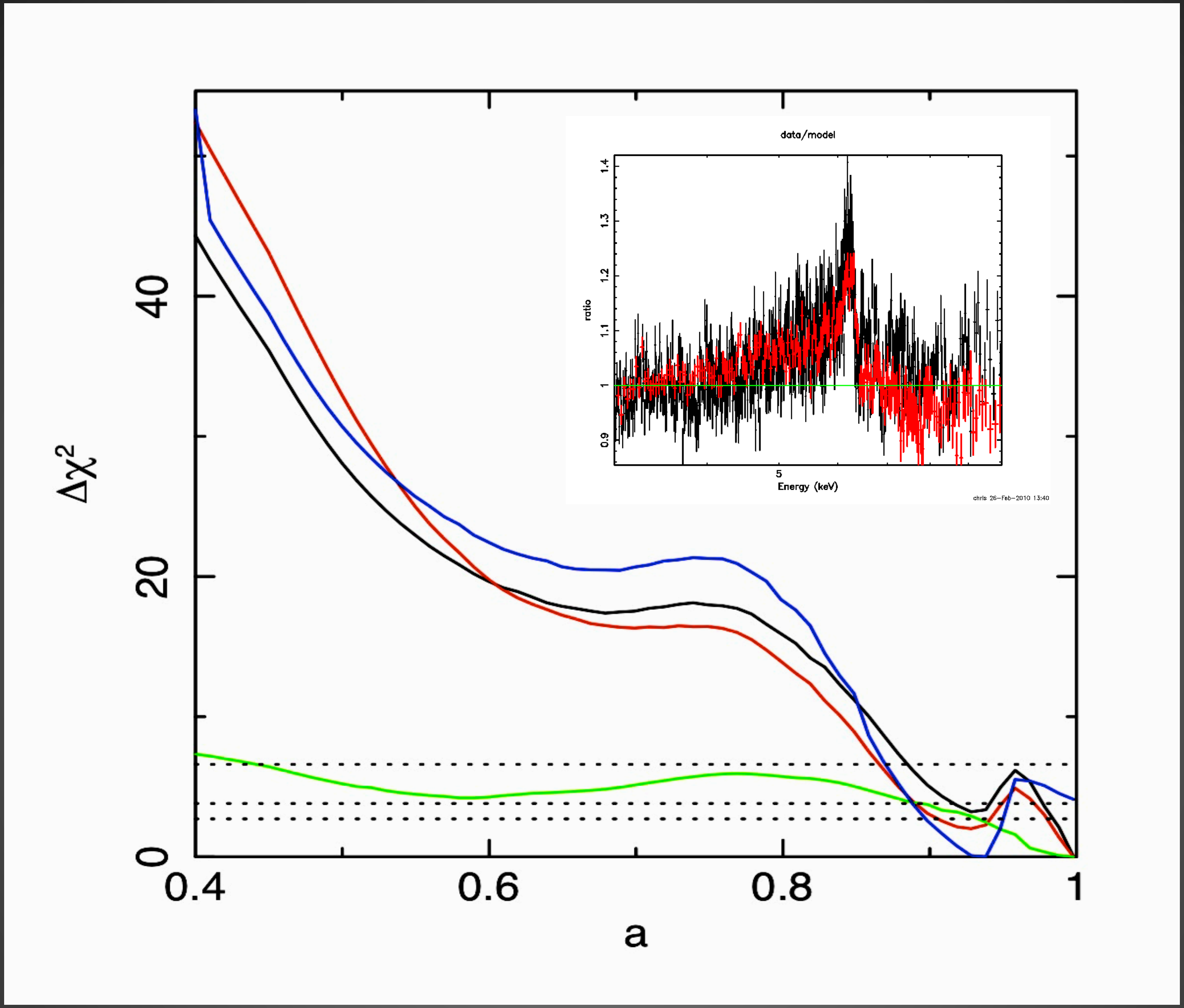


- "Lamp-post" model (light bending) assumes corona is a point on the spin axis of the BH. Over-simplification: **radial and vertical extent? Active regions?**
- If it's the **base of a jet**, plasma may have some extension and/or **outflow**.
- This is broadly consistent with **relative weakness of IDR flux vs. PLC flux** in NGC 4151: factor of ~3 lower than is expected for compact corona.
- Self-consistent model (RELXILL) still does not fit as well as phenomenological model (relaxed dependence of emissivity on coronal height). **Complex geometry? Outflow?**

NGC 3783: Fe abundance and soft excess



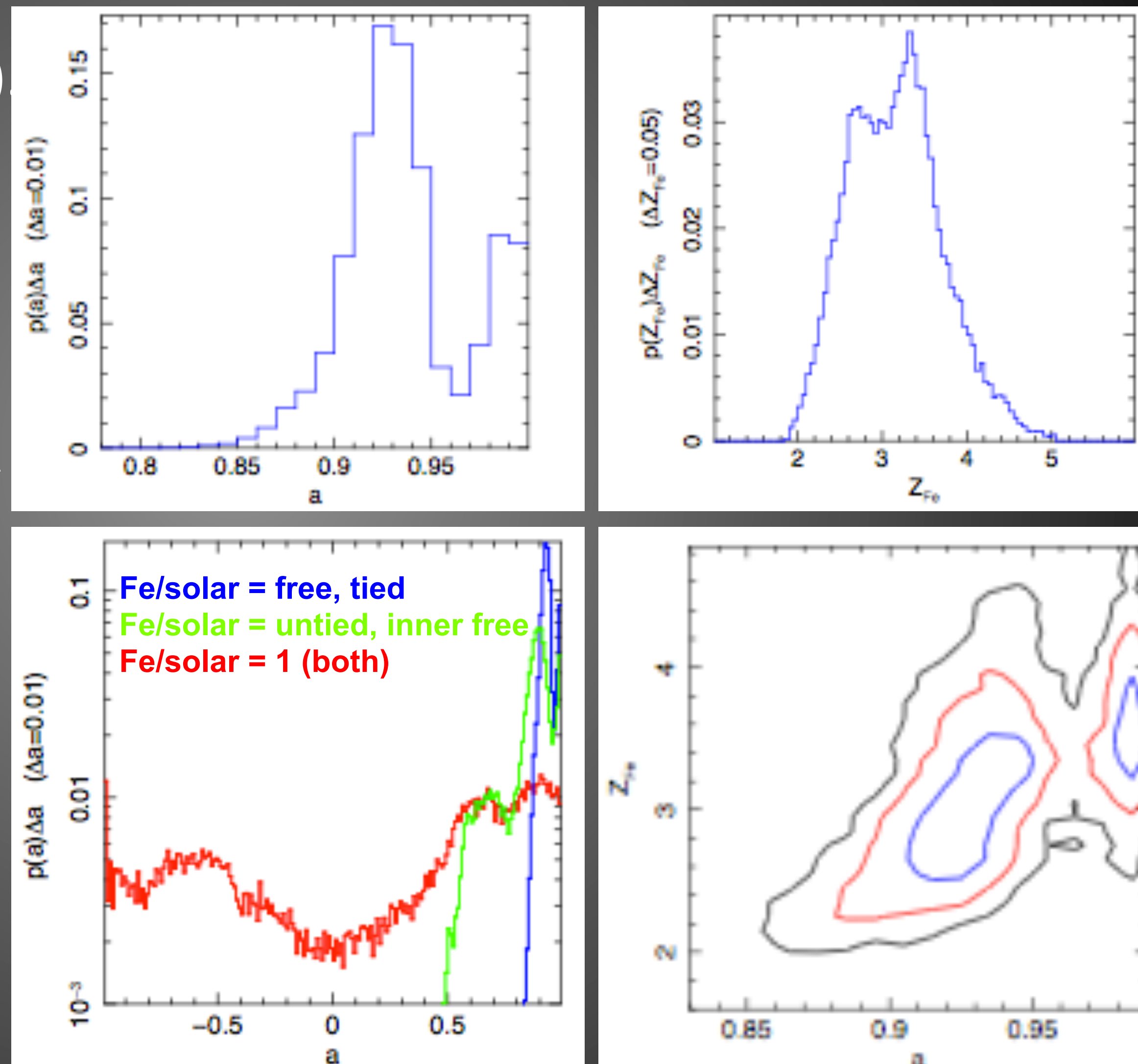
Suzaku/XIS+PIN spectrum ratioed against simple power-law. A global model of this spectrum **requires** multi-zone ionized absorption, reflection from distant matter, reflection from inner accretion disk, and a scattered component.



Requires high spin **(a > 0.90 at 90% CL)**. This includes all uncertainties associated with ionized absorption, irradiation profile of inner disk, iron abundance, and treatment of PIN background.

Iron Abundance

- Fit drives **a > 0.90** (90% conf.), **Fe/solar = 2-4** (MCMC).
- Strict assumption of **Fe/solar = 1 worsens fit significantly**, allows for low spin.
- Supersolar Fe consistent with measurements from BLR in other AGN (e.g., Warner+ 2004, Nagao+ 2006).
- Caveat: **Fe abundance and spin clearly correlated!**
- More Fe → stronger reflection→ more blurring required to fit data → higher spin values.
- Illustrates importance of exploring wide range of modeling assumptions.



Reynolds+ (2012)

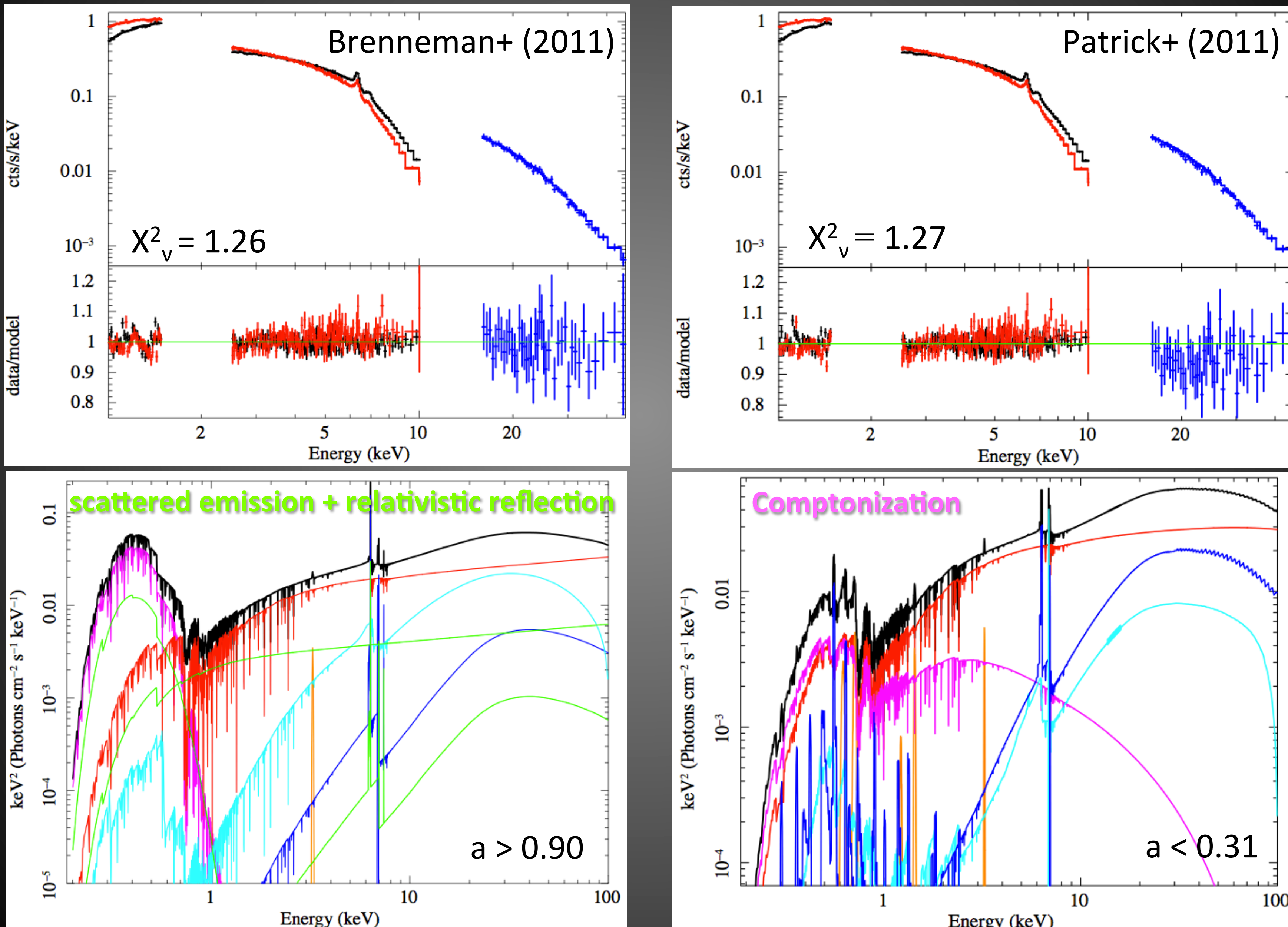
What about the Soft X-ray Excess?

- **Present in majority of AGN** that are not totally absorbed <2 keV.

- 0.5-2 keV range **accounts for most of S/N in AGN observations** due to higher collecting area at these low energies, so parameterization of this region can highly influence spectral fitting!

- **Physical origin of this emission is still a mystery**, may differ source-to-source (e.g., Crummy+ 2006, Done+ 2012, Lohfink+ 2013a):
  - Scattered continuum?
  - Comptonization?
  - Thermal disk?
  - Blurred relativistic reflection?
  - *Combination? Something else??*

Soft Excess Modeling in NGC 3783

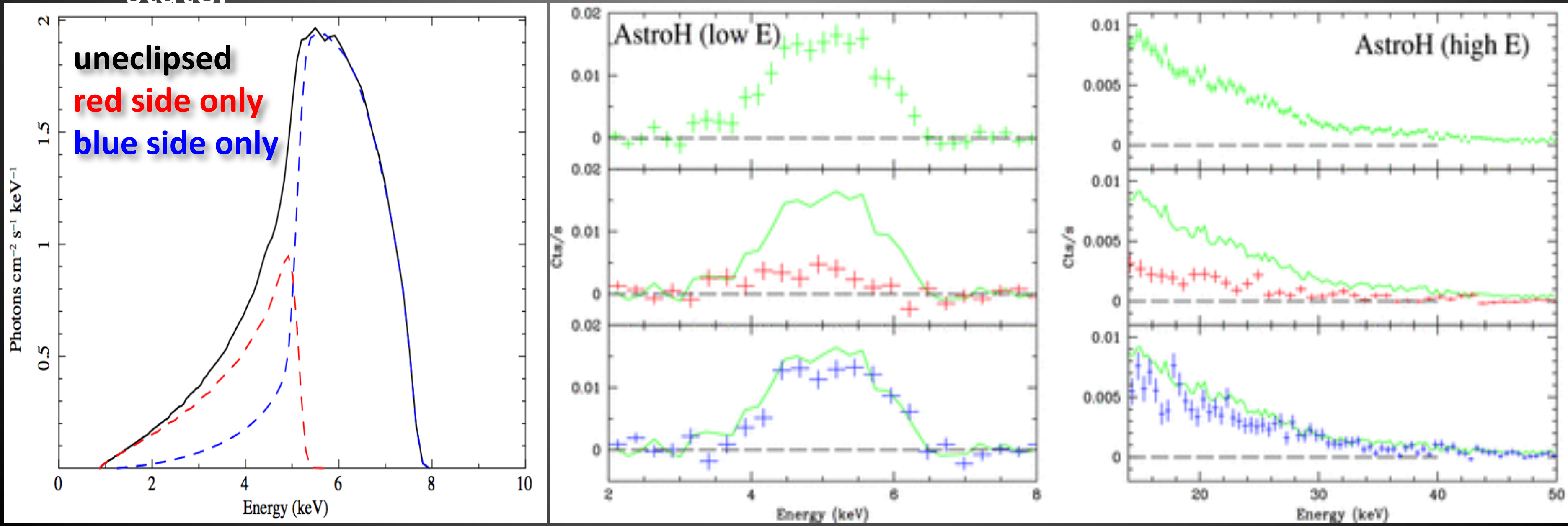


Accretion Disk Tomography

- **X-ray eclipses of the inner disk** by BLR clouds cited in NGC 1365 (e.g., Risaliti+ 2011, Brenneman+ 2013) can also differentiate between the reflection and absorption-only spectral modeling interpretations.

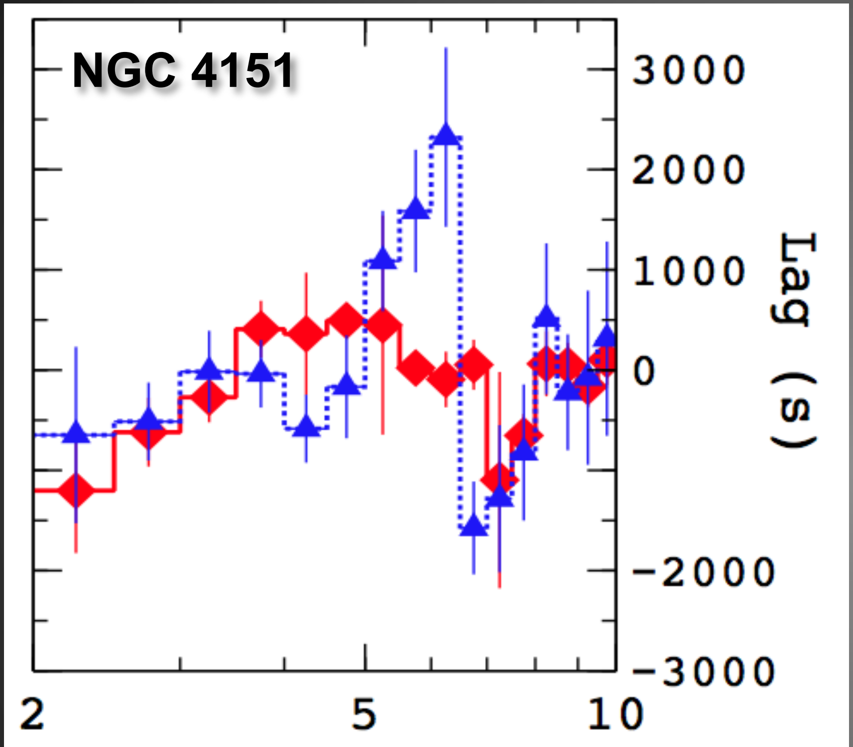
- Can **verify the existence of relativistic emission** features from the inner accretion disk by examining change in morphology of putative Fe K line as the eclipse progresses.

- This type of **accretion disk tomography** possible for high-contrast eclipses: e.g., factor ~10 increase in column density during high flux state.

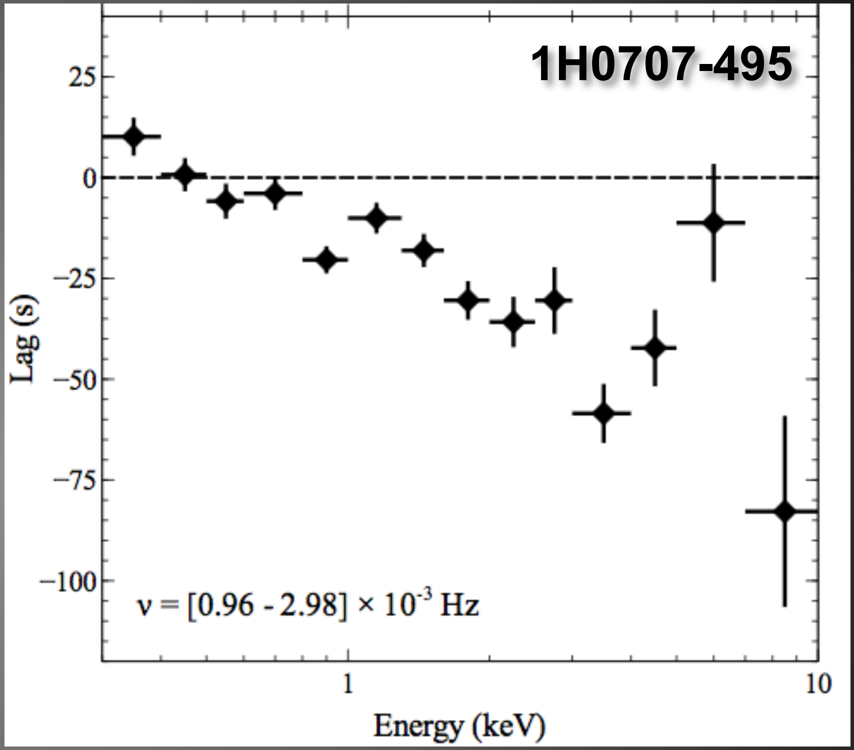


Risaliti+ (2011)

Fe Kα Reverberation Mapping



Zoghbi+ (2012)



Kara+ (2013)

• Time lags in frequency space → **time-lag spectrum** over energy in a given source, probes the **location of the emitting regions** for relativistically broadened Fe Kα.

• ***NuSTAR*** will allow **Fe Kα, Compton hump lags** to be measured simultaneously!

• Next generation X-ray telescopes (e.g., ***LOFT***) will further improve upon this science.

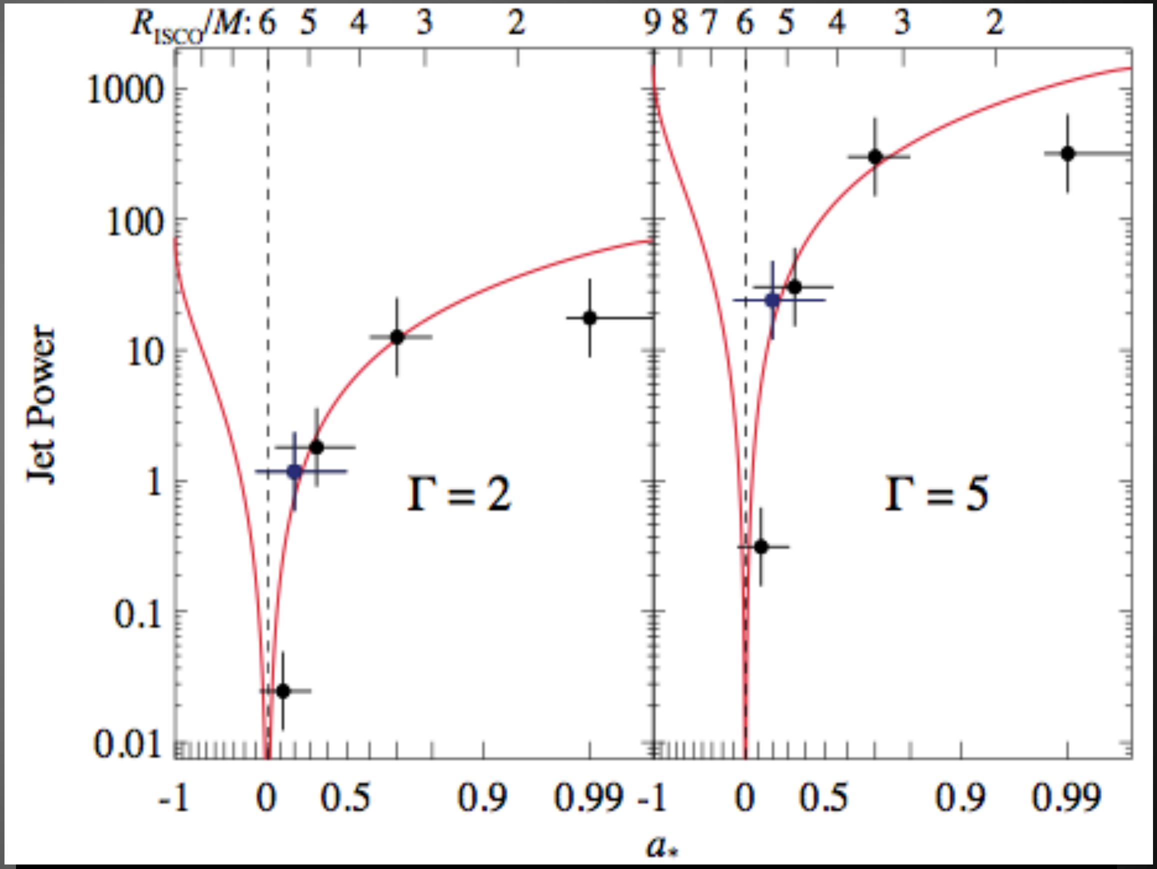
Black Hole Spin and Jet Production

- Blandford & Znajek (1977): **rotating black hole + magnetic field from accretion disk = energetic jets** of particles along the BH spin axis.

- Magnetic **field lines thread disk, get twisted** by differential rotation and frame-dragging.

- Results in a powerful outflow, though **many specifics are still unknown**, including how/why jets launch, dependence on spin, magnetic field, accretion rate.

- Some observational indication of **spin correlation with jet power in microquasars**… can we extend to AGN?



Narayan & McClintock (2012), Steiner+ (2012)

Questions

1) How can we be sure that we are measuring SMBH spins accurately?

- What are sources of systematic error on spin measurements (e.g., intrinsic absorption, presence of a radio jet, modeling of the soft excess, role of emission from within ISCO) (Steiner, Dotti)
- What are the necessary conditions that need to be met to get accurate spin constraints (e.g., energy coverage, spectral resolution, exposure time, source flux/spectral state) (me)

2) How can we increase our sample size of measured SMBH spins?

- Will *Astro-H* and *Athena* help with this? (me)
- If not, what requirements would a mission need to have to improve our sample size by 1-2 orders of magnitude? (me)
- What about pushing out to higher redshifts via gravitational lensing? (Dotti, Dubois)

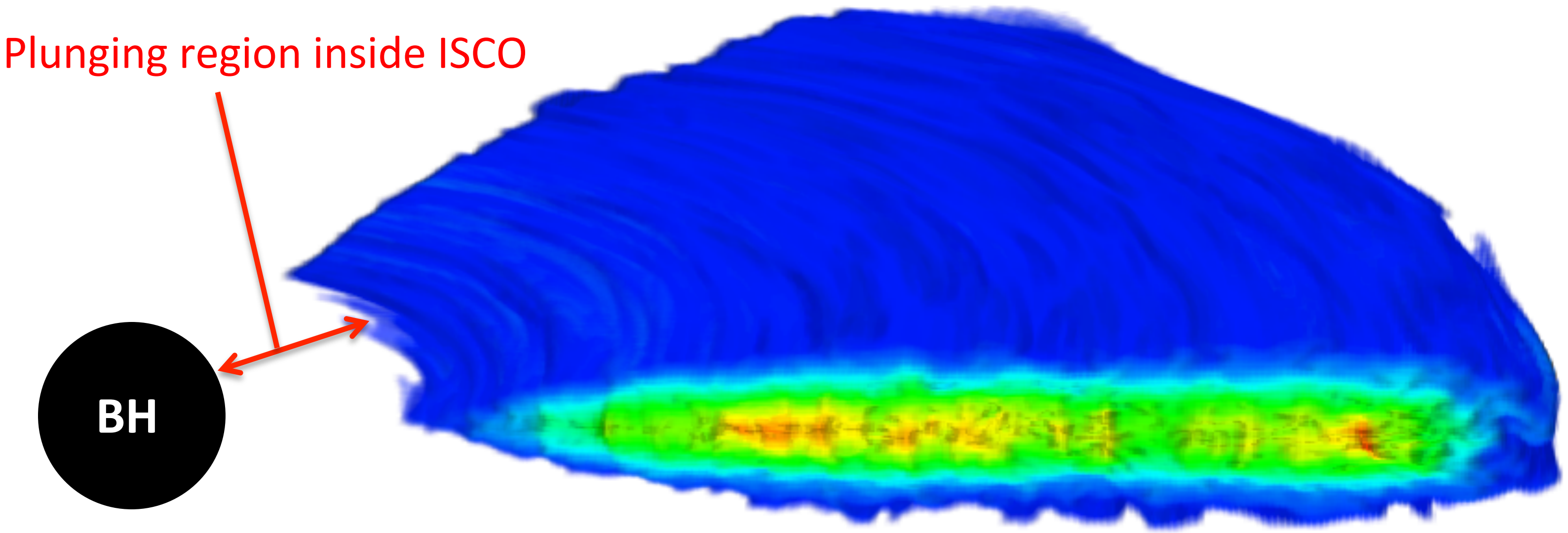
3) What can the current distribution of SMBH spins tell us about how these BHs have grown and evolved?

- Comparisons to theory (Dotti)
- Comparisons to GBHs (Steiner)

4) What is the role of BH spin in jet production?

- How can we figure this out? (Steiner, Dotti, Dubois)
- Does it differ between GBHs and SMBHs? (Steiner)
- Can jet power be used as (at least one component in) a predictive indicator for spin measurements? (Steiner)

Assumption of ISCO Truncation



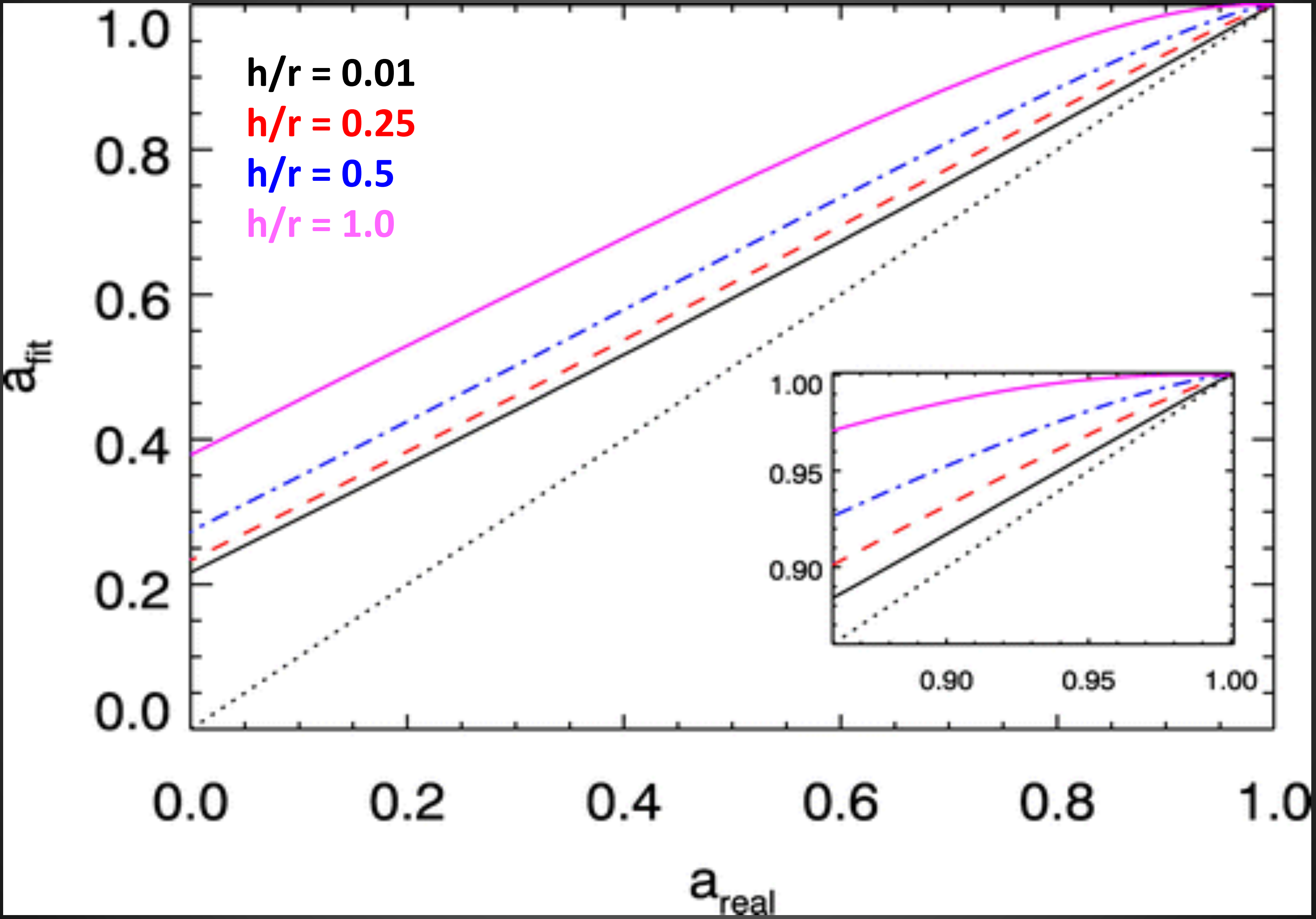
3D MHD simulation of a geometrically-thin accretion disk.

Clearly shows transition at the ISCO which will lead to truncation in iron line emission.

Rapid drop in τ, rise in ξ within ISCO.

Reynolds & Fabian (2008)

Systematic Error from Emission ≤ISCO



Reynolds & Fabian (2008)