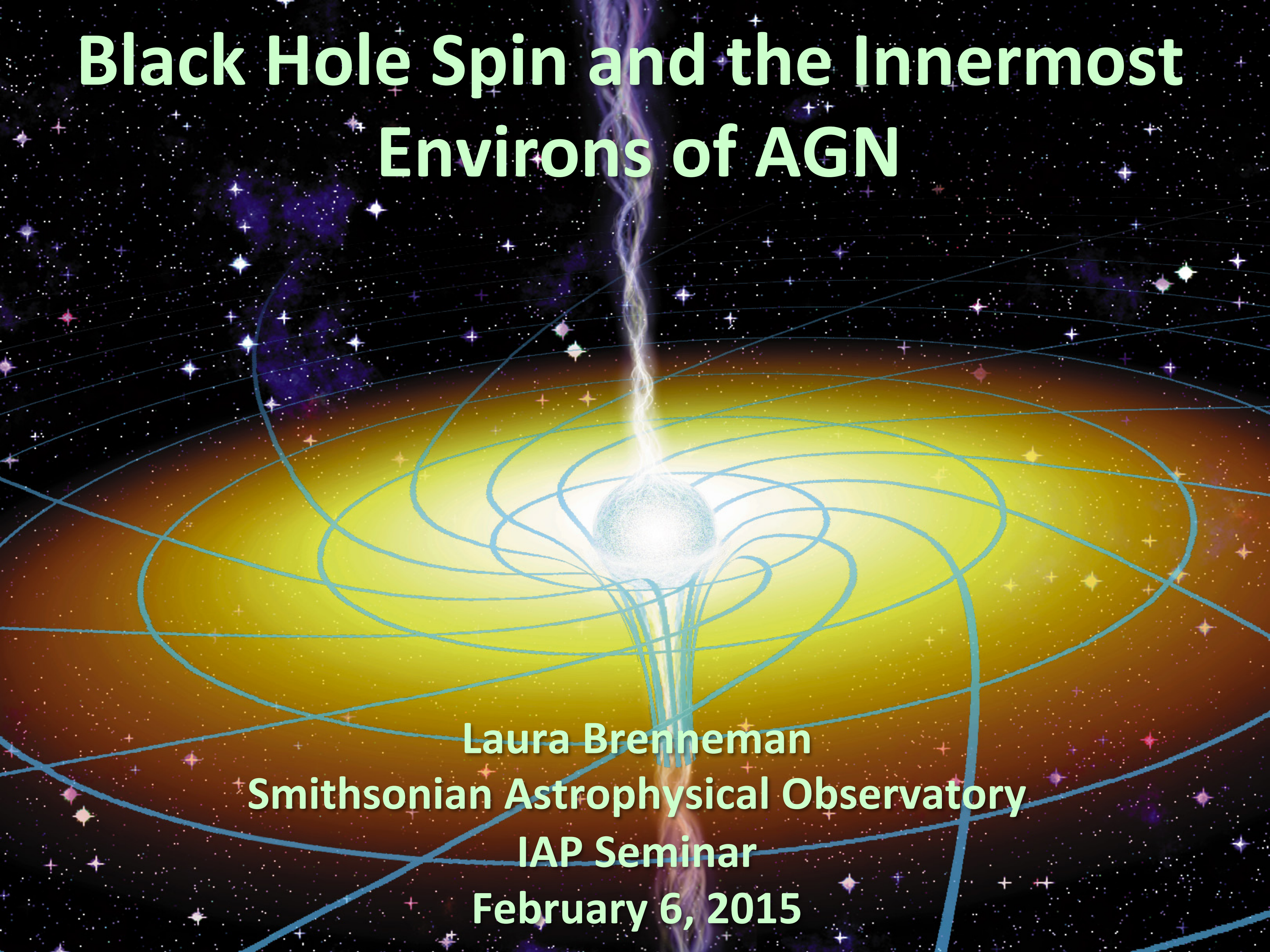


Black Hole Spin and the Innermost Environs of AGN

Laura Brenneman
Smithsonian Astrophysical Observatory

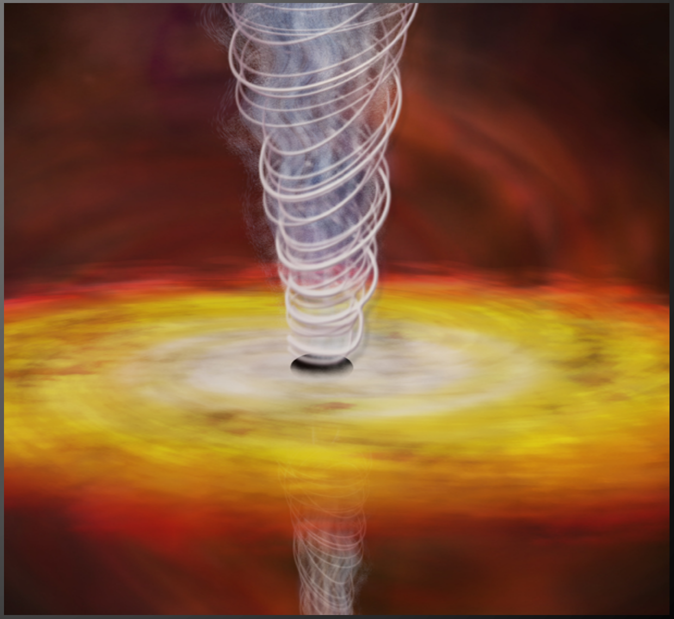
IAP Seminar

February 6, 2015

Outline

- Intro: why we care about spin in AGN
- Methods: how we measure spin
- Caveats and case studies
- The SMBH spin distribution so far and its implications and biases
- Future directions

The Importance of SMBH Spin



- Probe of **strong gravity** regime.
- Indicator of recent gas **accretion vs. merger history** of supermassive BHs.
- Thought to play a role in **jet production** and outflows in all BHs, seeding the ISM/IGM with matter and energy, possibly regulating galaxy growth and evolution.

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** (both XRBs and AGN, 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)

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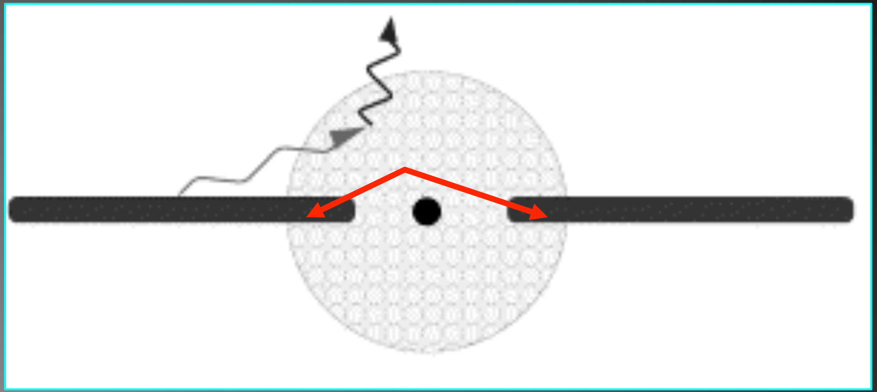
Modeling the Reflection Spectrum

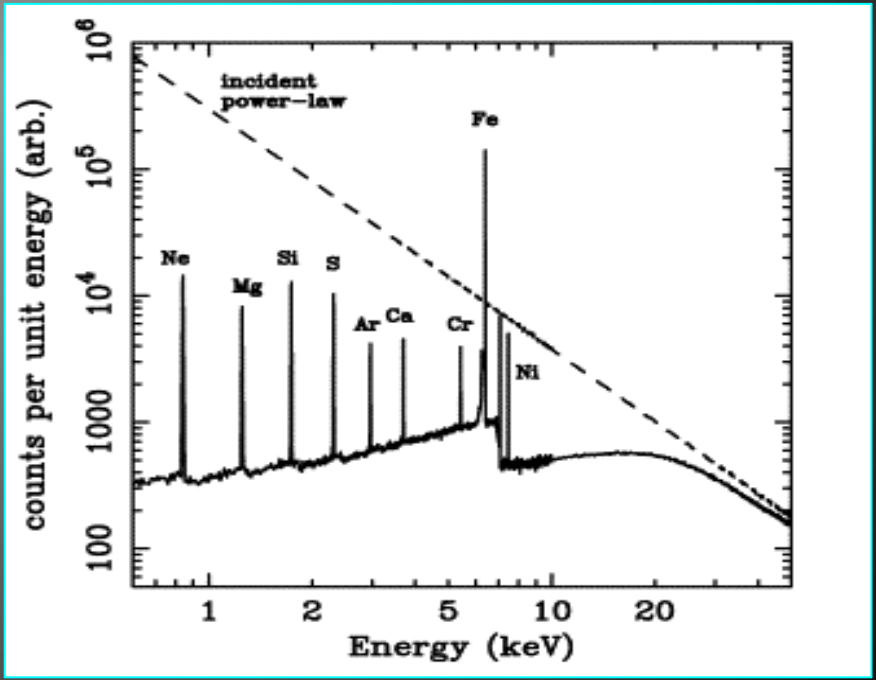
• Relativistic electrons in corona Compton scatter thermal photons (UV) from the accretion disk, producing power-law continuum spectrum in X-rays.

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

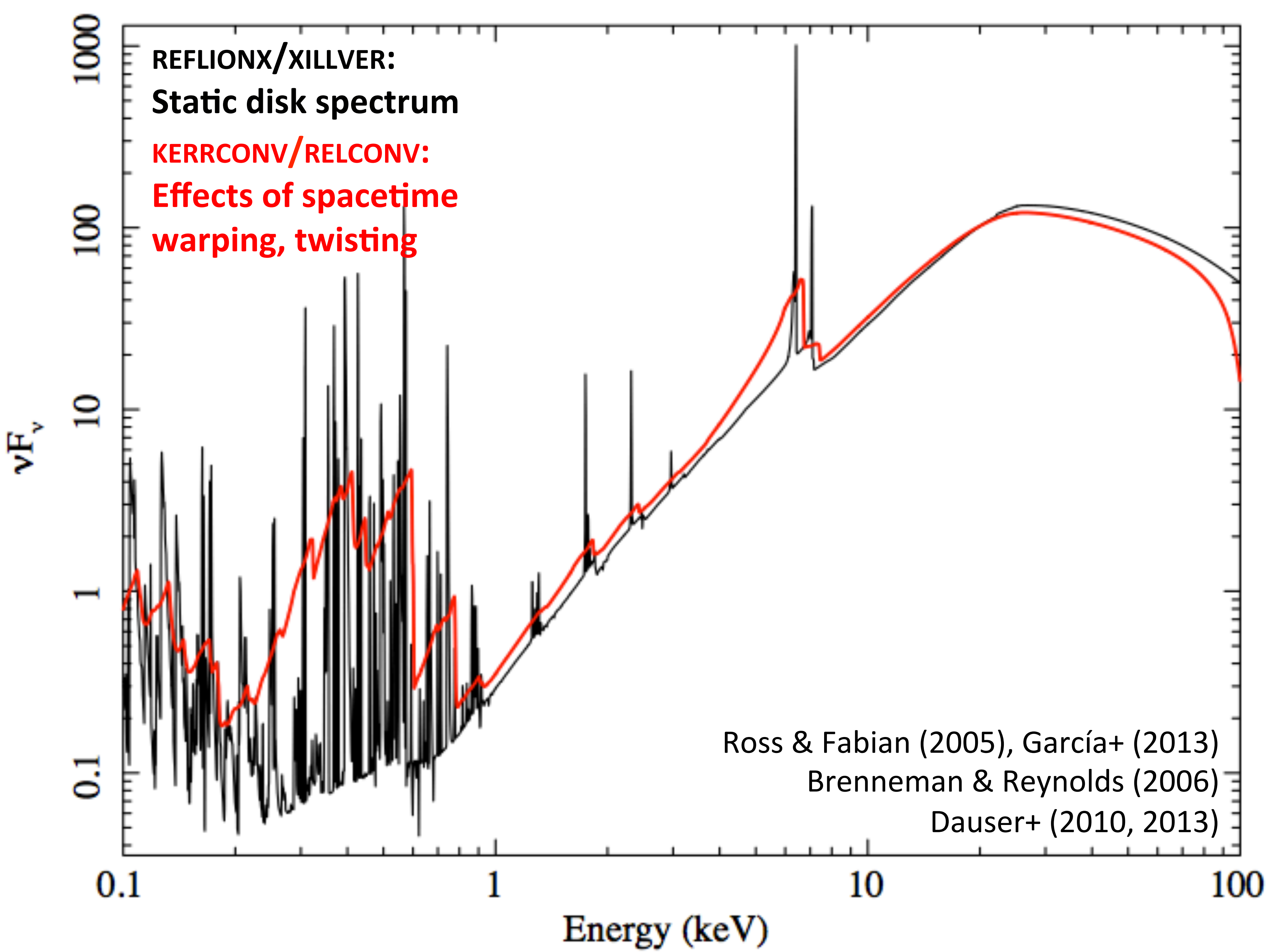
• Fluorescent lines are produced when a "cold," optically thick disk is irradiated by X-ray continuum photons, exciting a series of fluorescent emission lines.

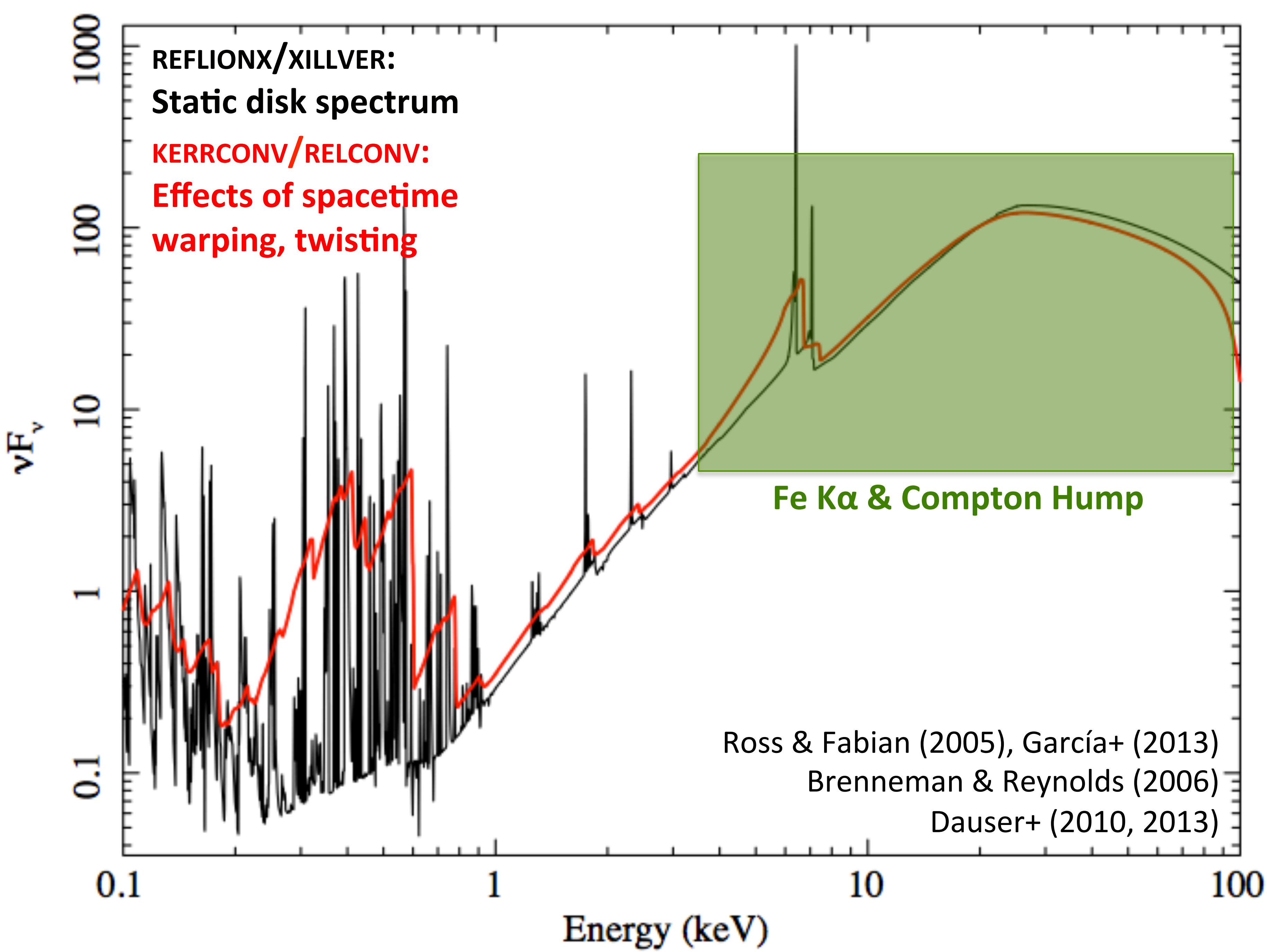
• The high energy, abundance and fluorescent yield of iron enable visibility above the power-law continuum, making it a better diagnostic feature than lines of other elements.





Reynolds & Nowak (2003)


REFLIONX/XILLVER:
Static disk spectrum
KERRCONV/RELCONV:
Effects of spacetime warping, twisting
Ross & Fabian (2005), García+ (2013)
Brenneman & Reynolds (2006)
Dauser+ (2010, 2013)
νF_ν
Energy (keV)
0.1
1
10
100
1000


REFLIONX/XILLVER:
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Effects of spacetime warping, twisting
Fe Kα & Compton Hump
Ross & Fabian (2005), García+ (2013)
Brenneman & Reynolds (2006)
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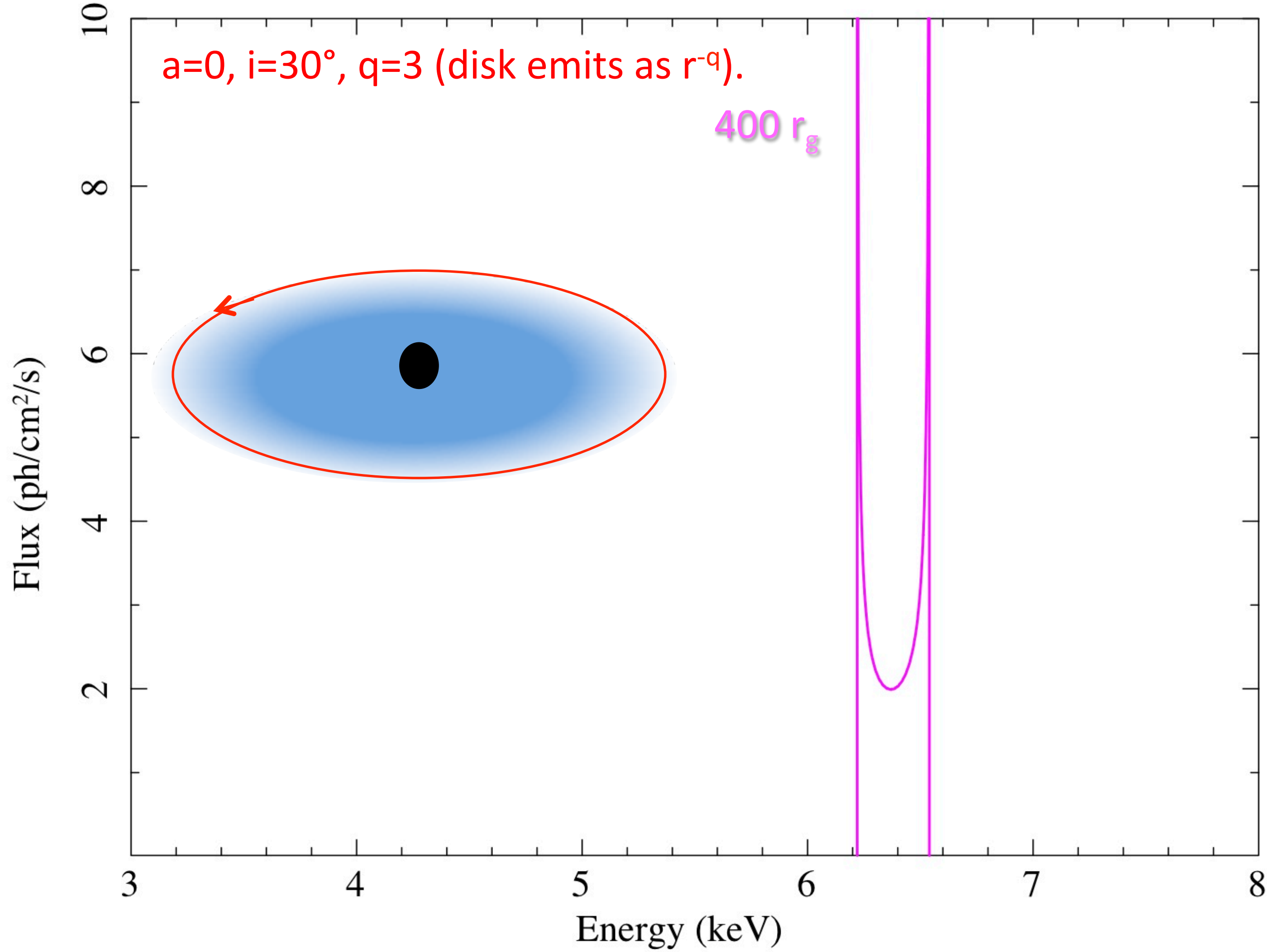
νF_ν
1000
100
10
1
0.1
0.1
1
10
100
Energy (keV)

Fe Kα emission line from different disk annuli



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

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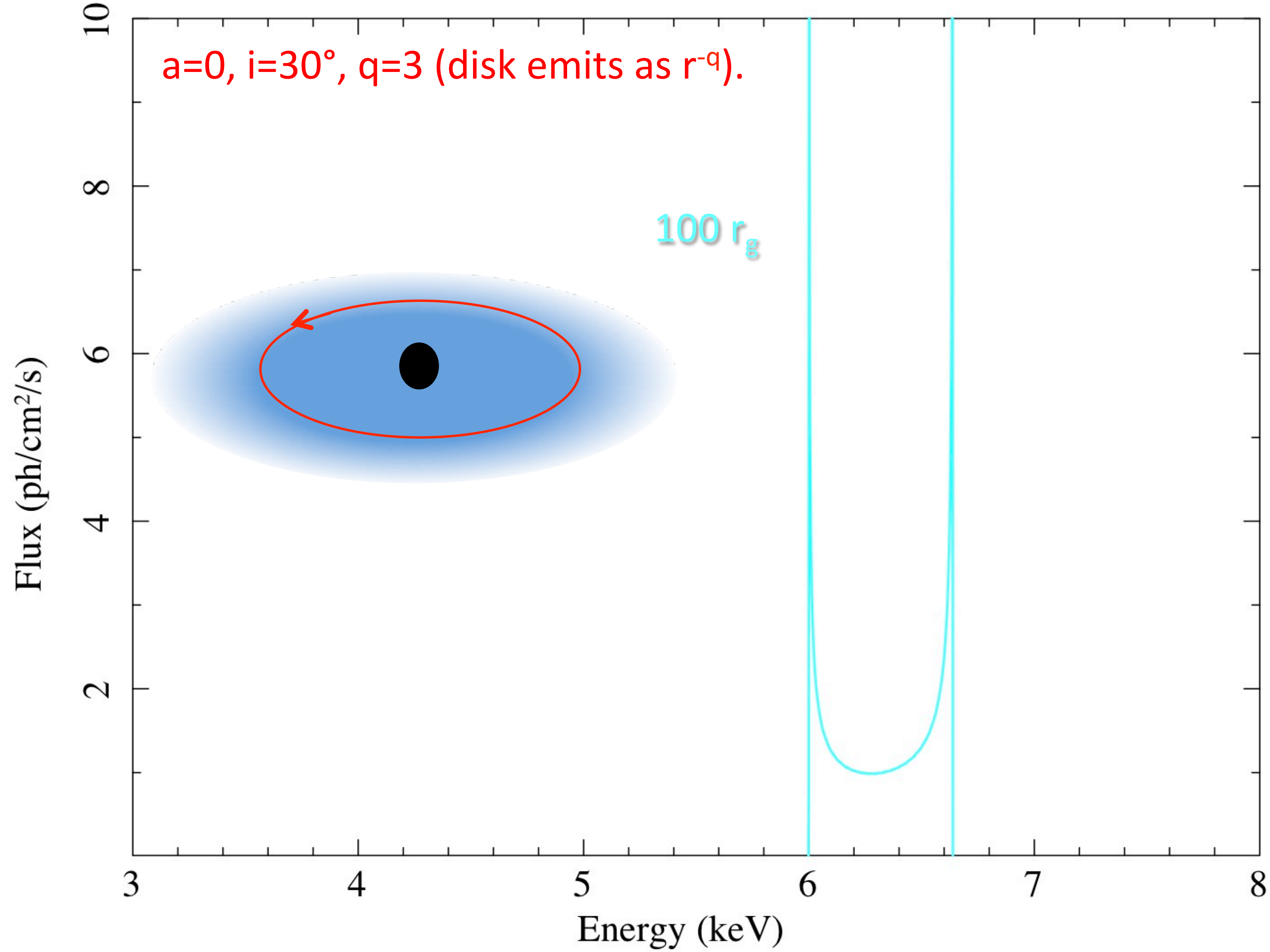

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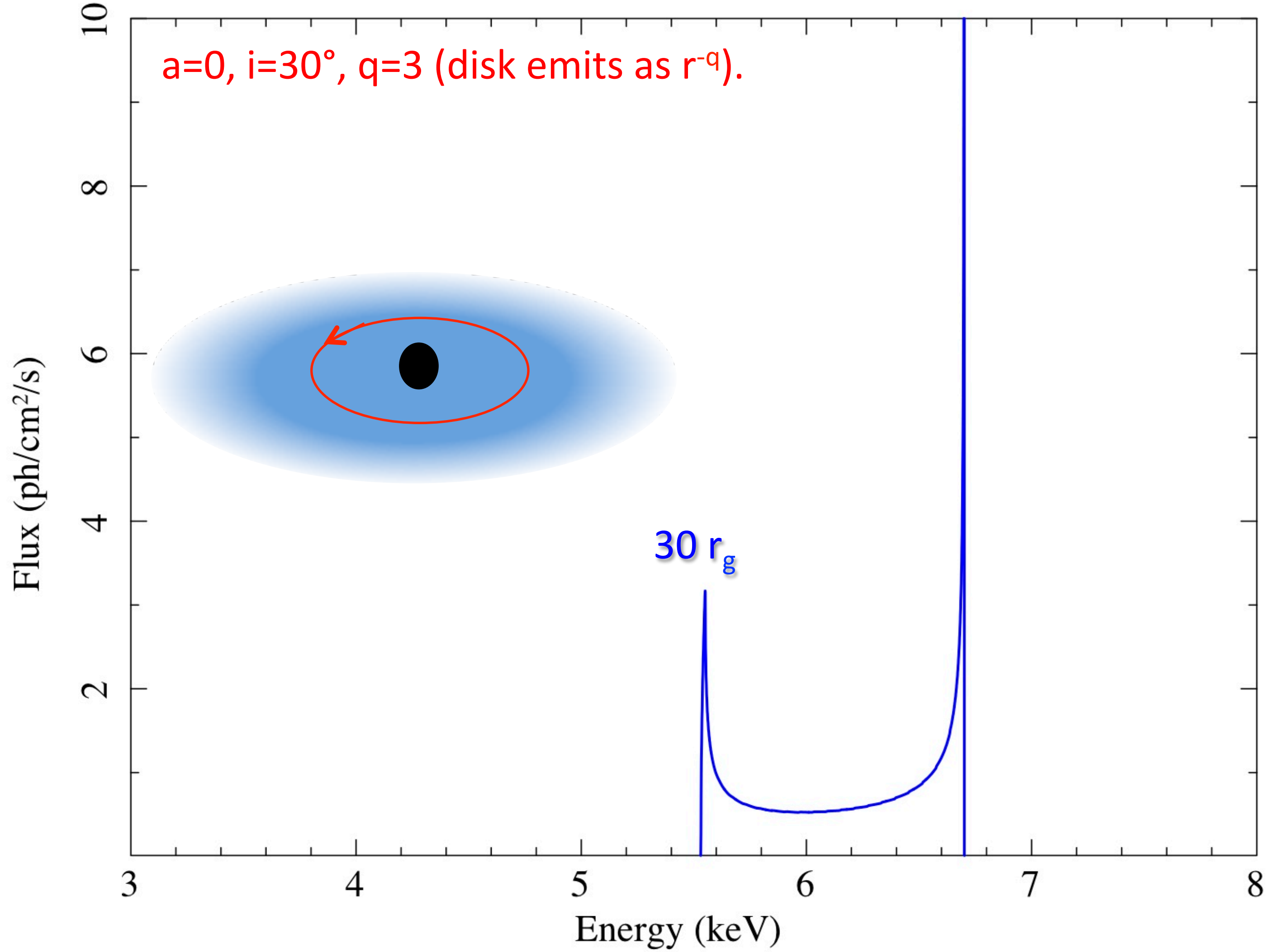

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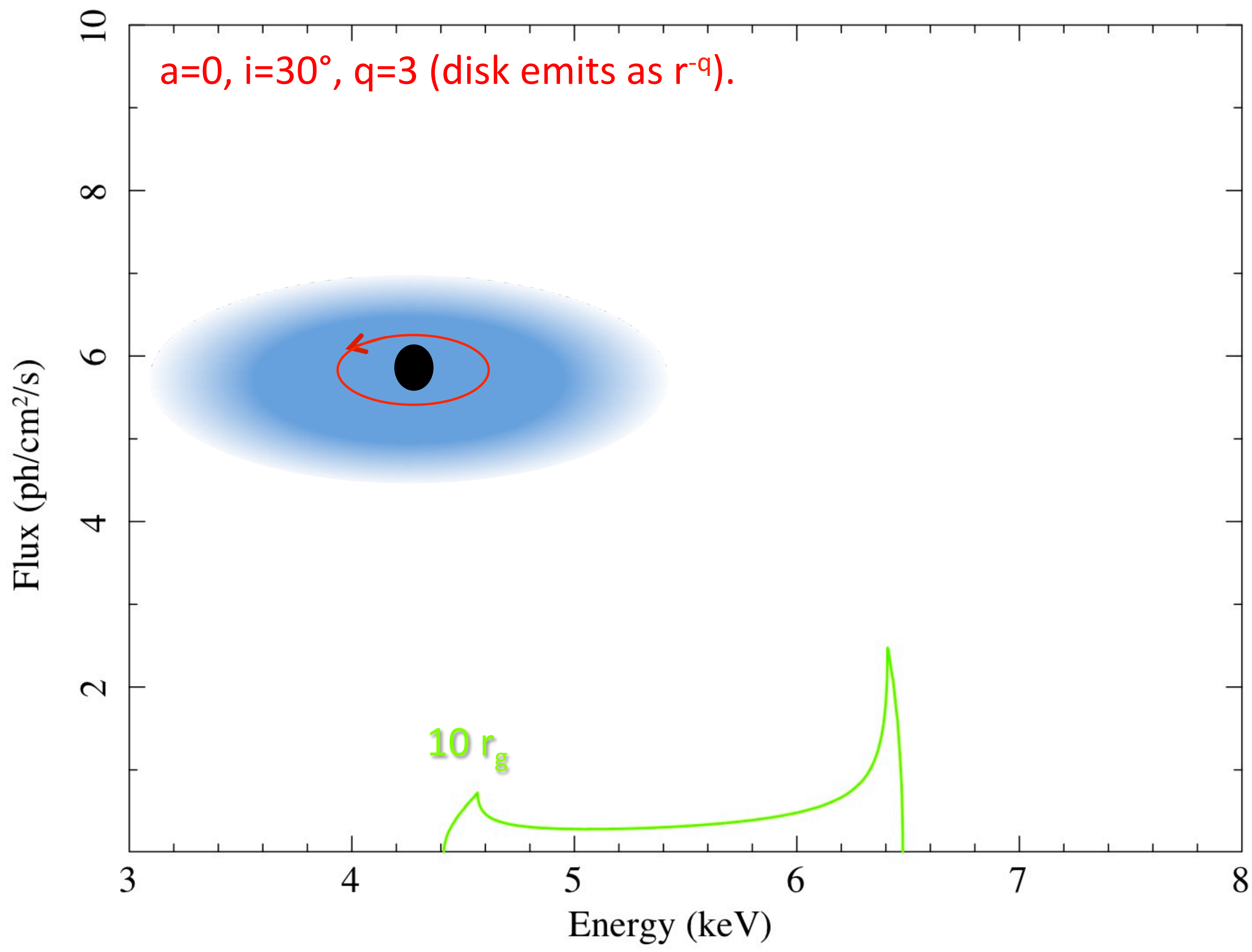

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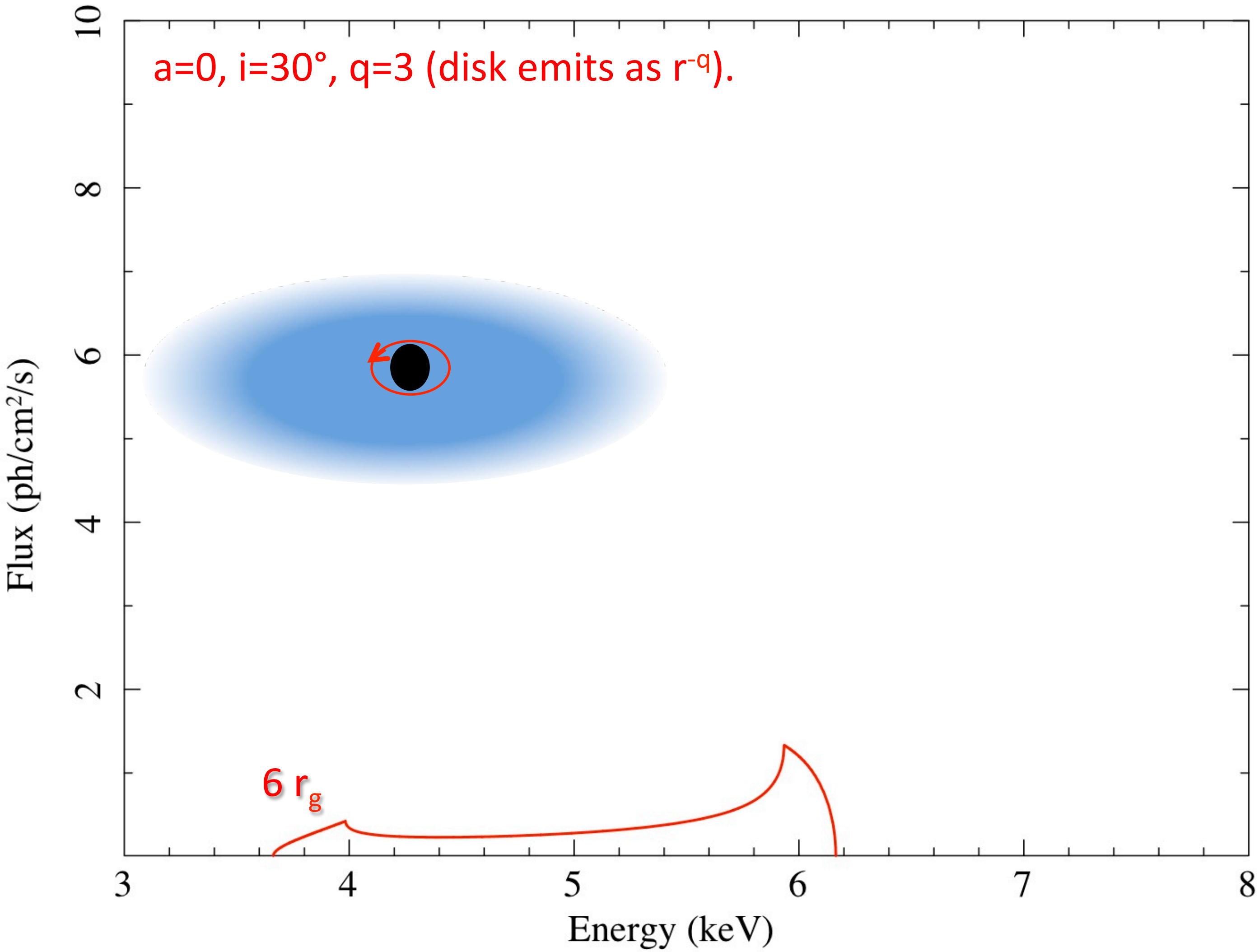

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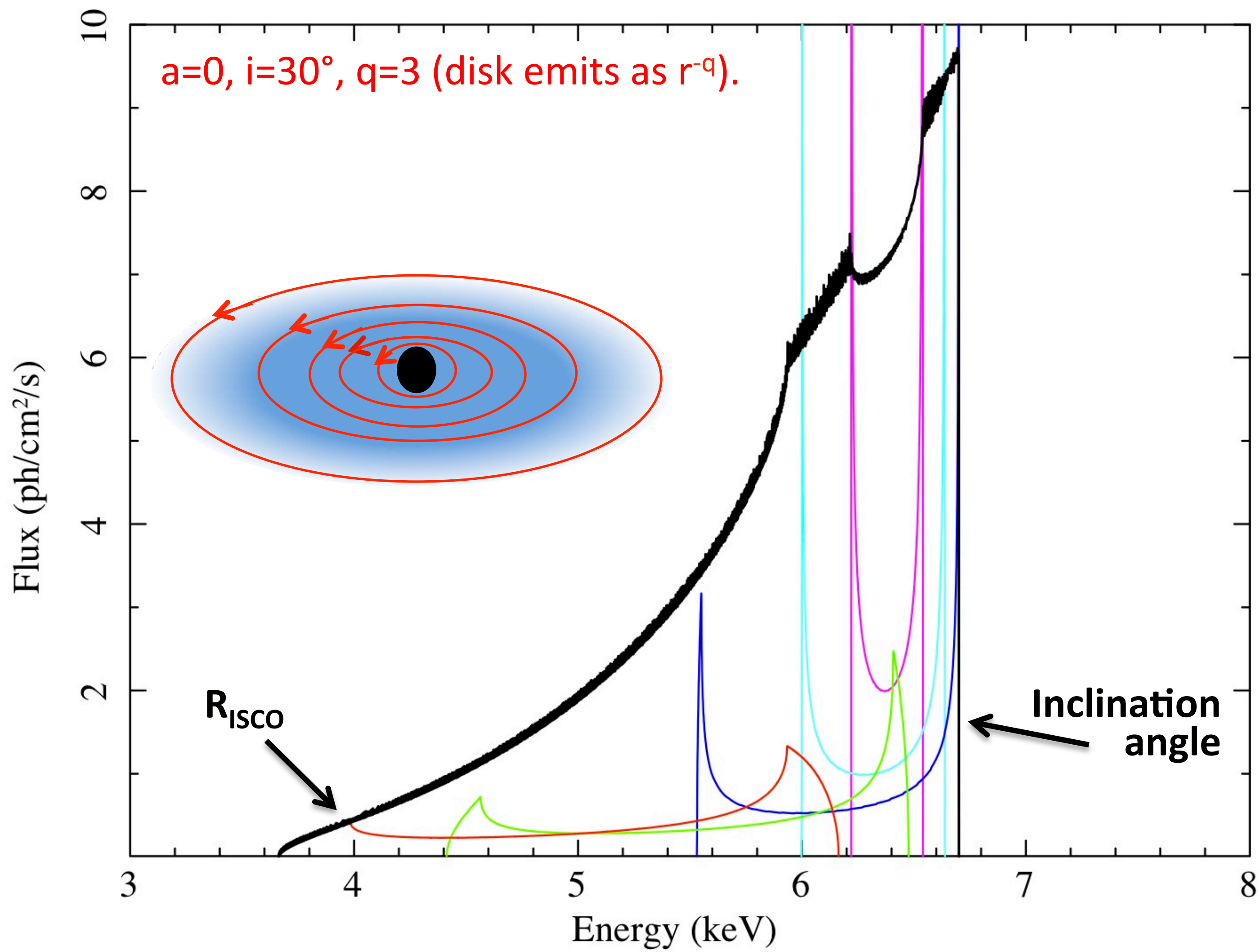

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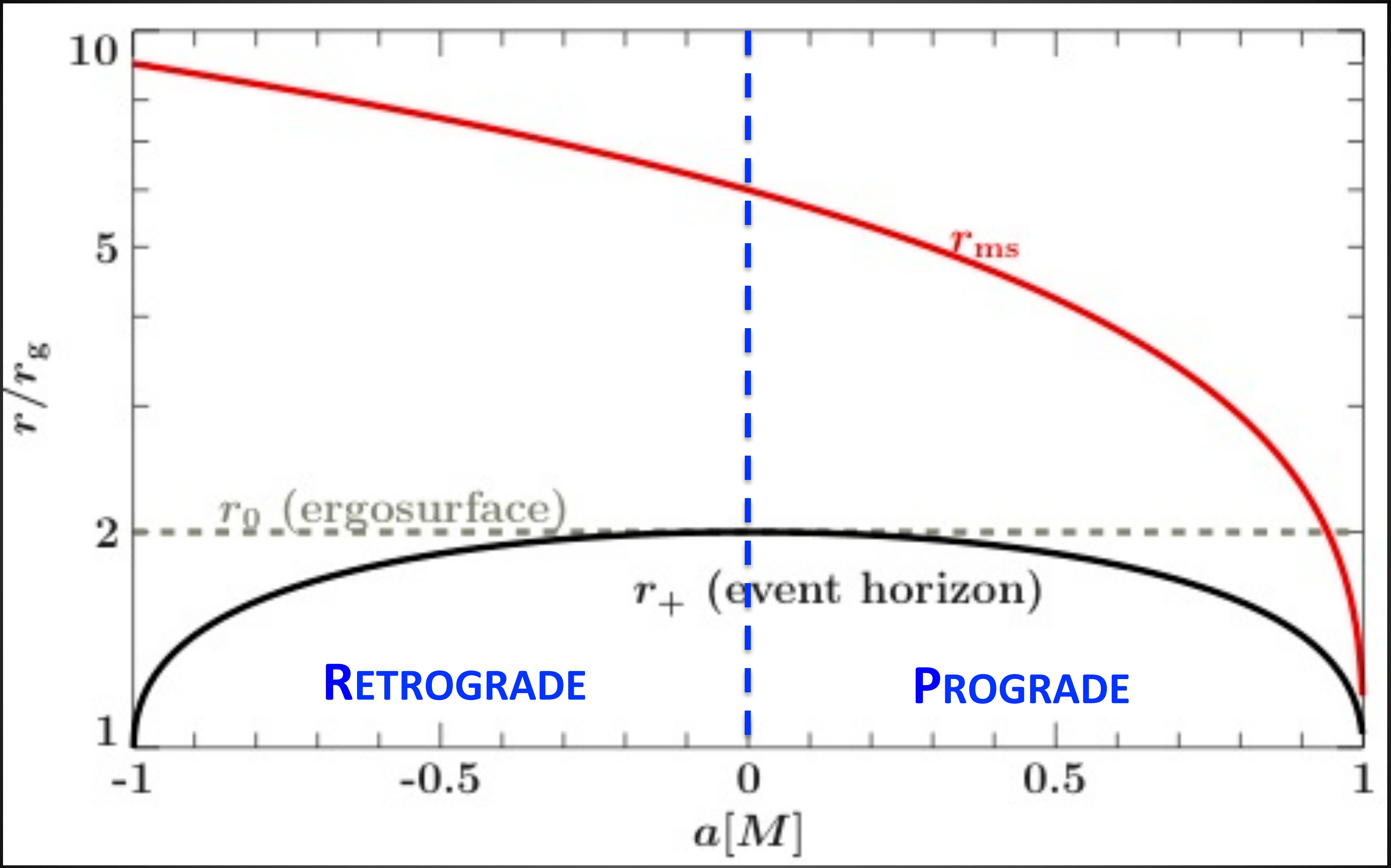
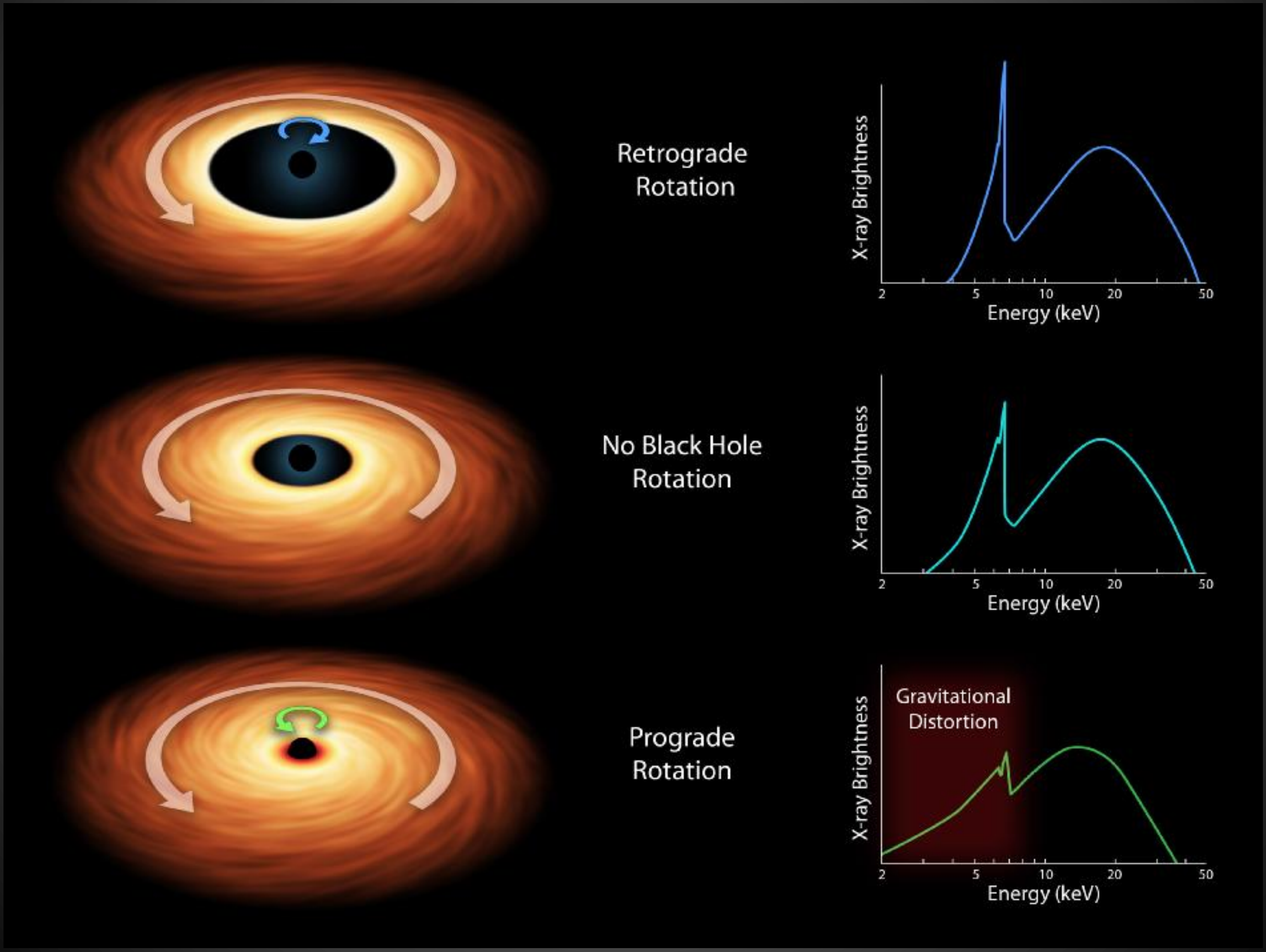

10
5
2
1
r/r_g
r_{ms}
r_0 (ergosurface)
r_+ (event horizon)
RETROGRADE
PROGRADE
-1
-0.5
0
0.5
1
$a[M]$

Dauser+ (2010)

Effect of Spin on Reflection Features



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, Reynolds 2013, Brenneman 2013).

  - Out of 10^{11-12} 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.

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

  KERRCONV, RELCONV or KYCONV × REFLIONX or XILLVER

Brenneman & Reynolds (2006) Dovčiak+ (2004) García+ (2013)

Dauser+ (2013) Ross & Fabian (2005)

CAVEATS:

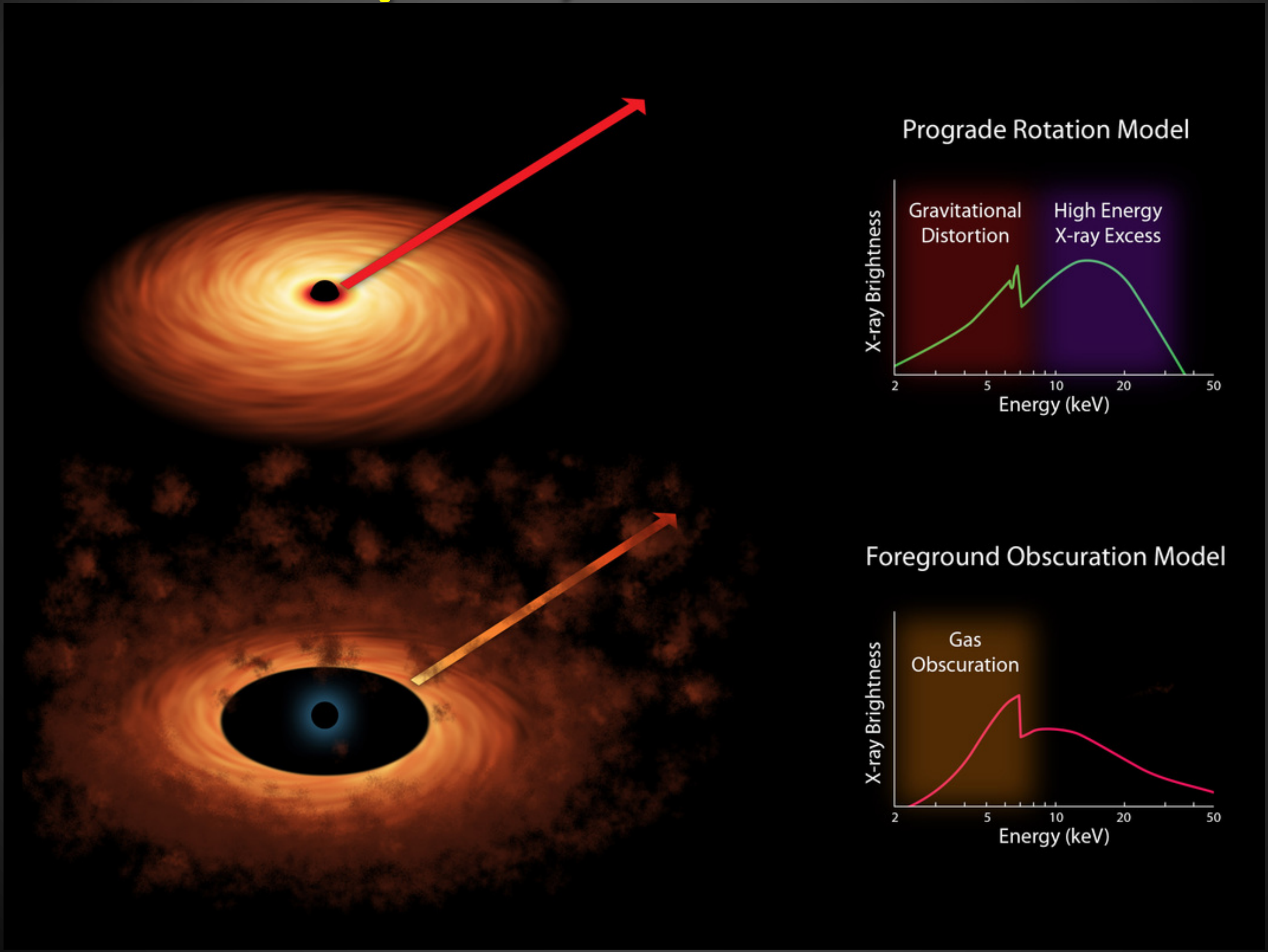
complex absorption, soft excess, coronal unknowns

disk truncation radius

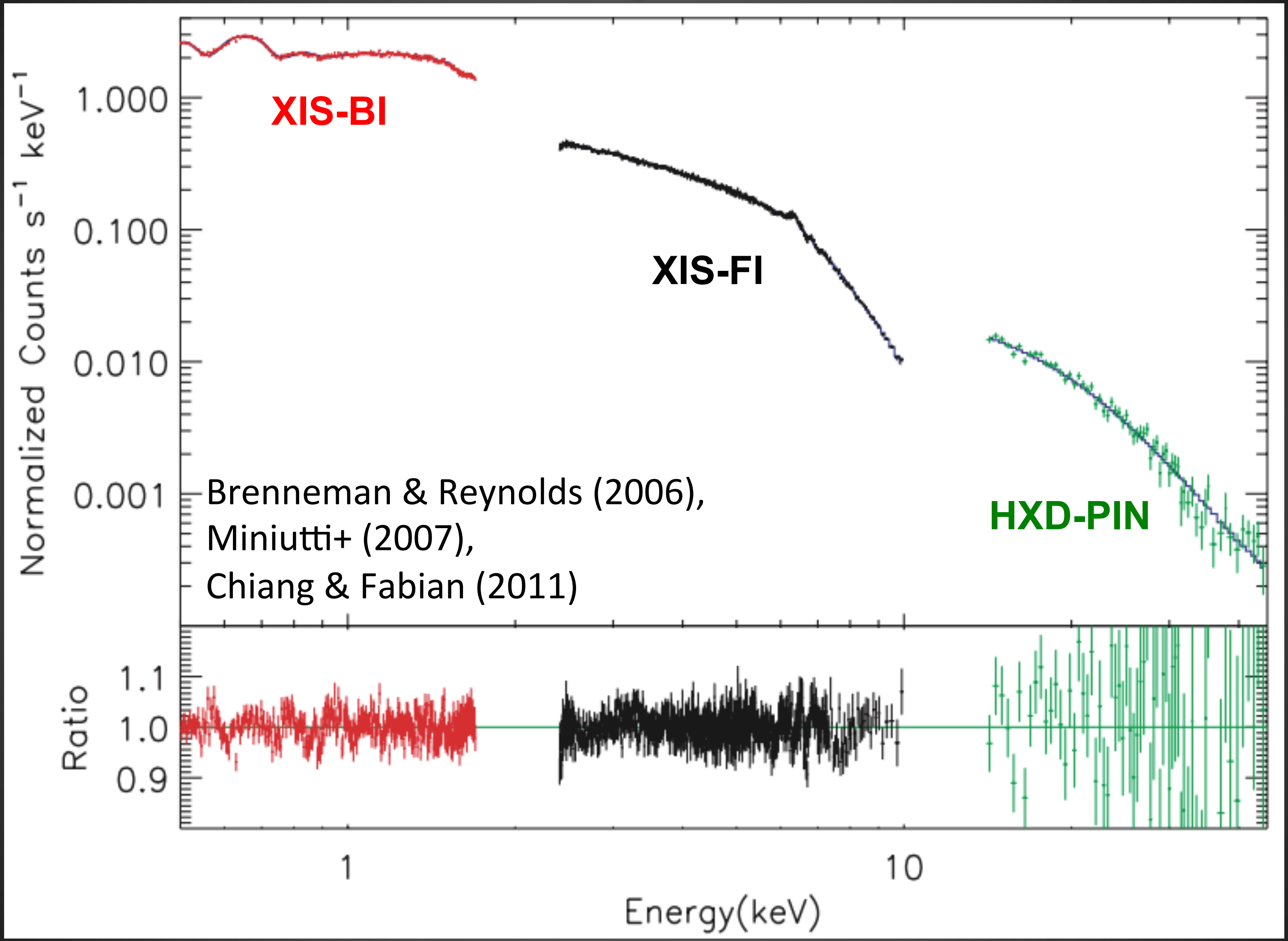
disk ionization, density, Fe abundance

disk irradiation profile

Disentangling Coronal Emission, Absorption, and Reflection

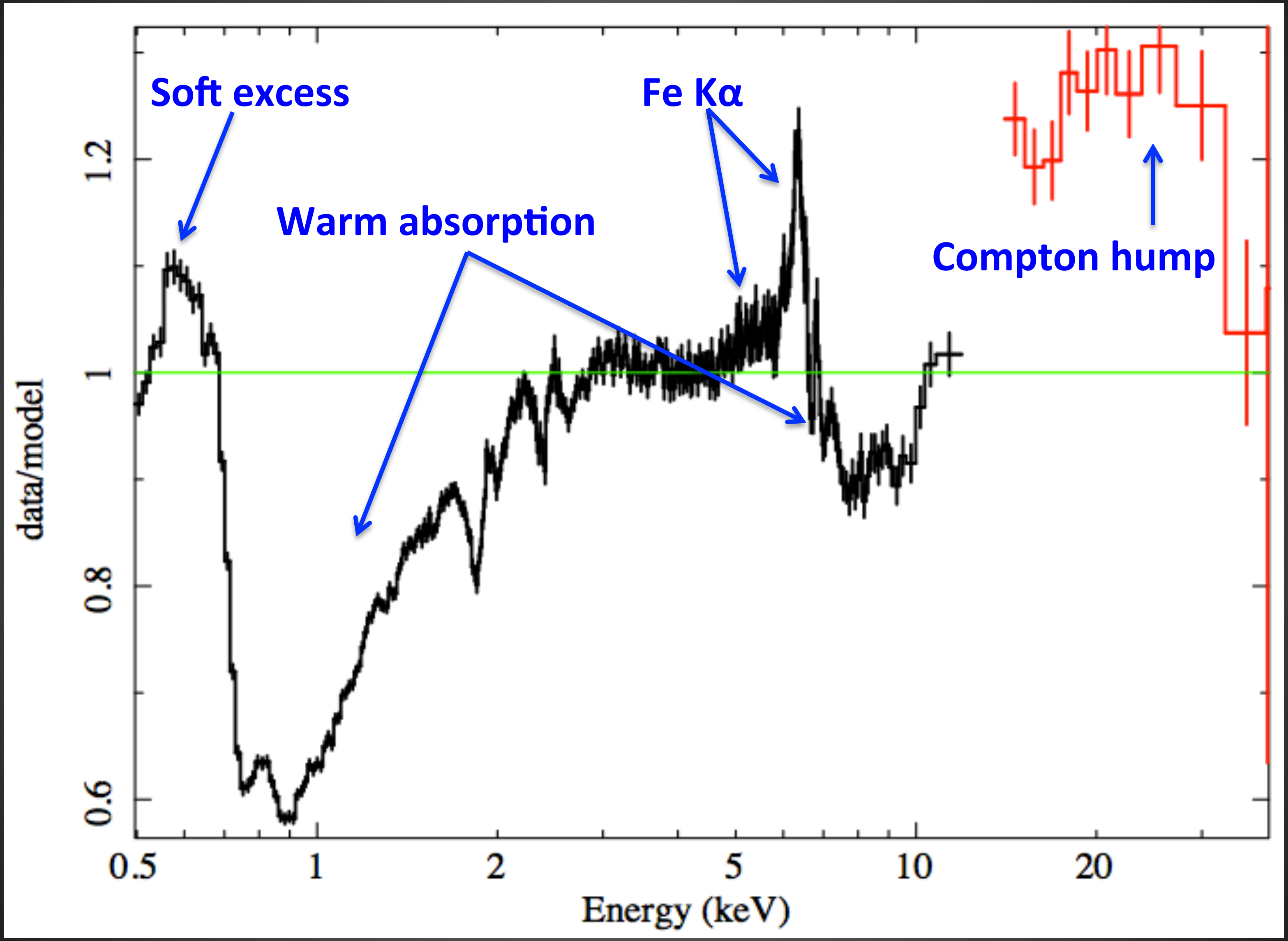


MCG—6-30-15: Spectral Complexity



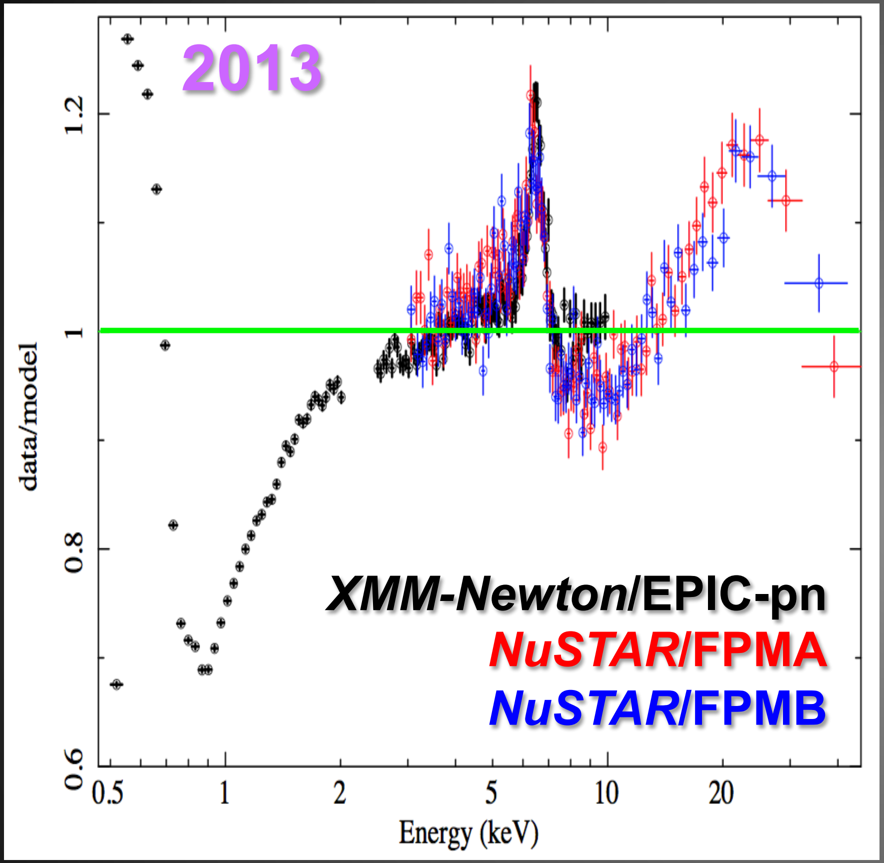
2006 *Suzaku* ~330 ks Observation

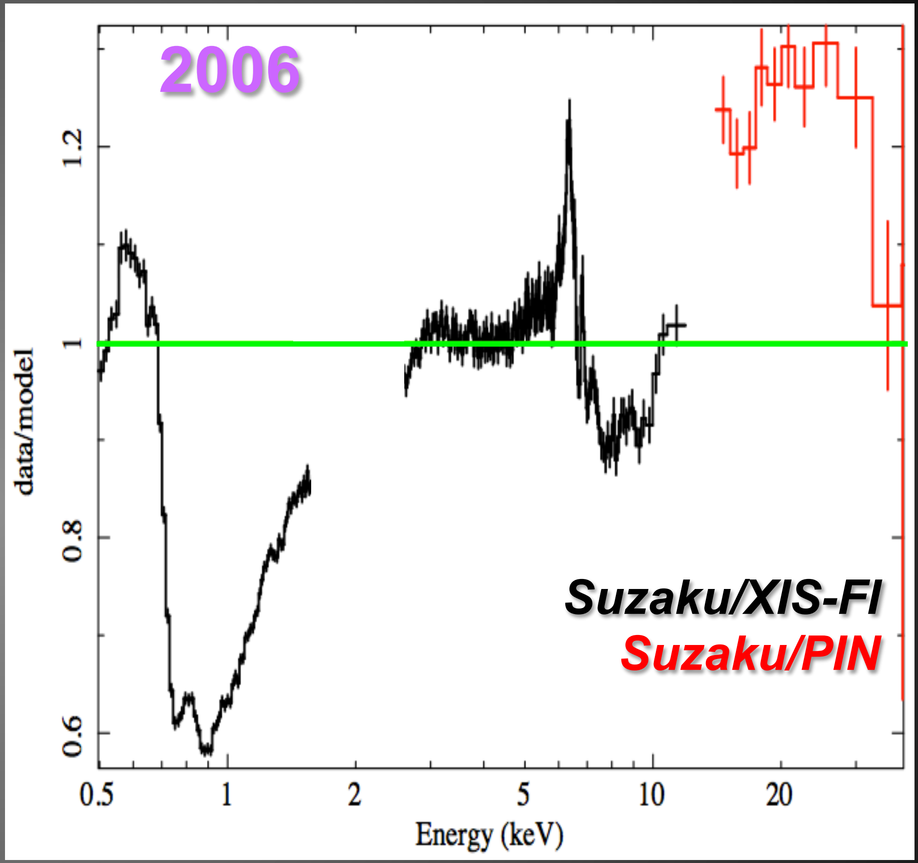
Spectral Complexity



Spectral components with continuum power-law modeled out

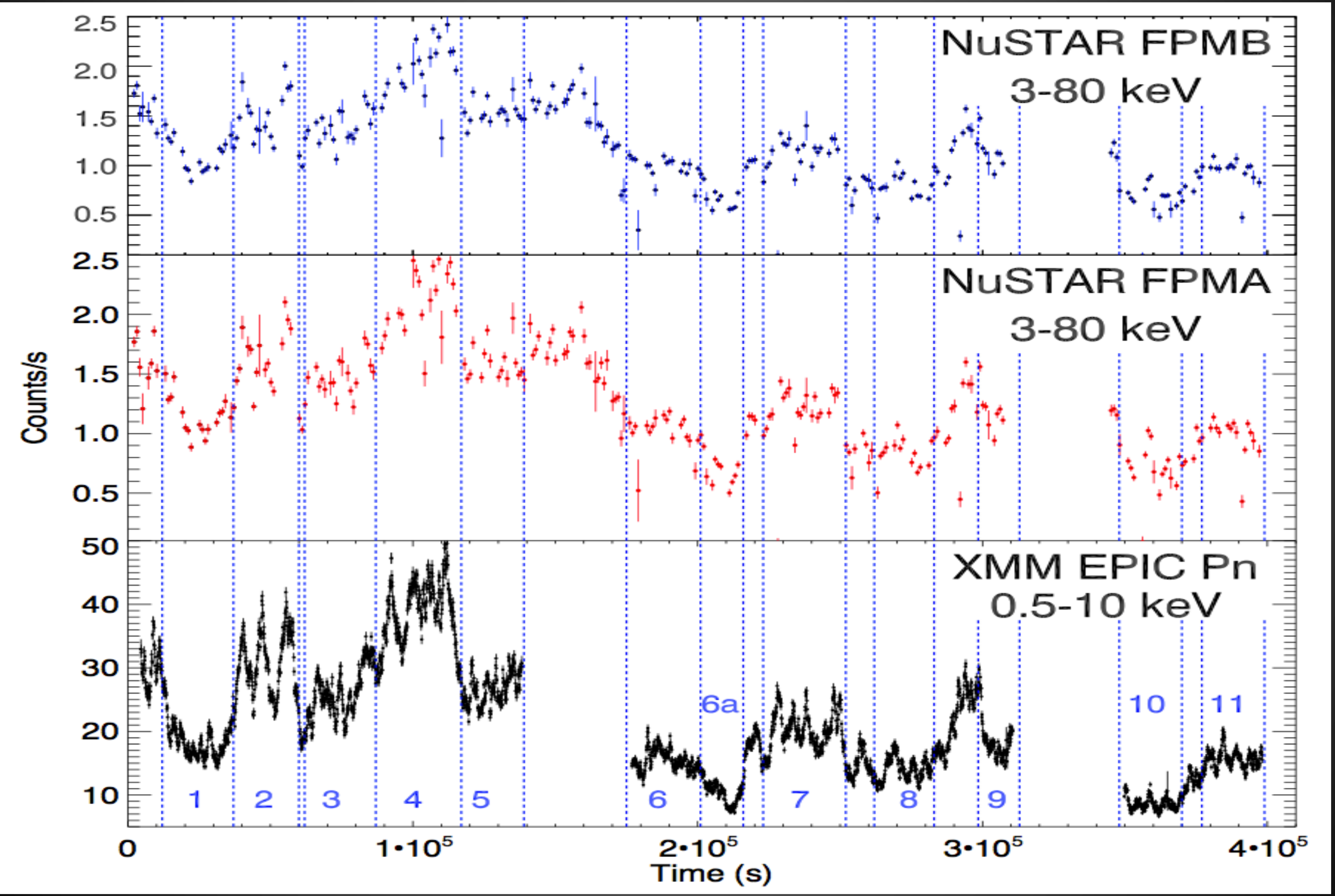
Time-averaged Spectra





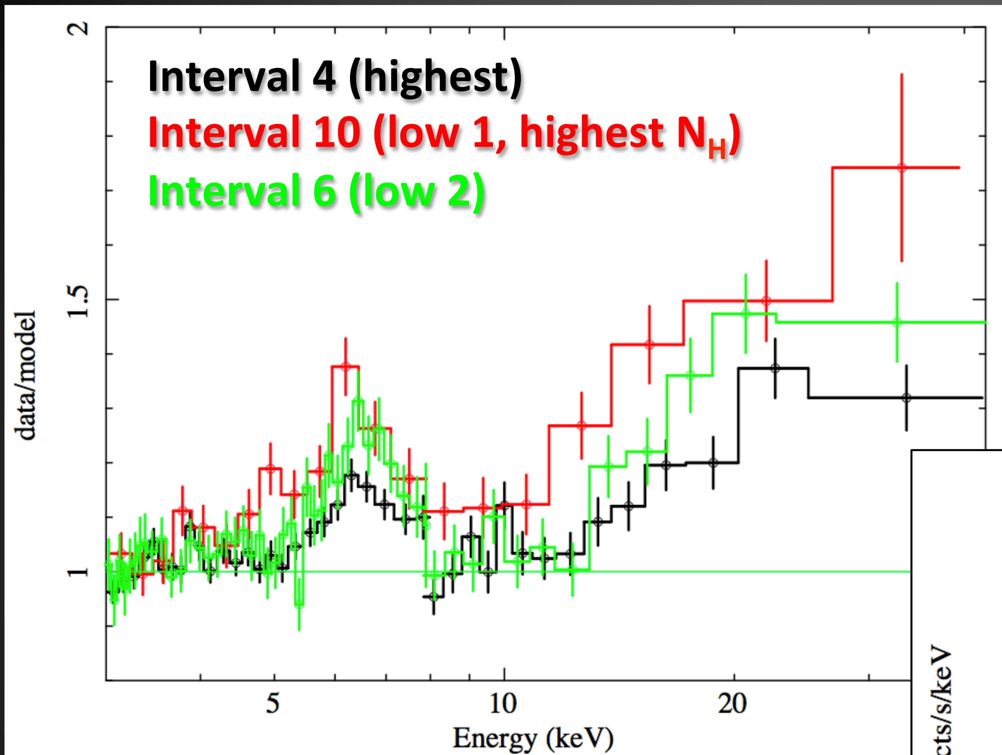
- Residuals to a power-law are qualitatively similar to those seen in most previous epochs, as is overall flux state ($F_{2\text{-}10}$ = 4e-11 ergs/cm^2/s).
- Average broad Fe Kα Line EW = 312 ± 183 eV in 2013 vs. 305 ± 20 eV in 2006.

Temporal Variability

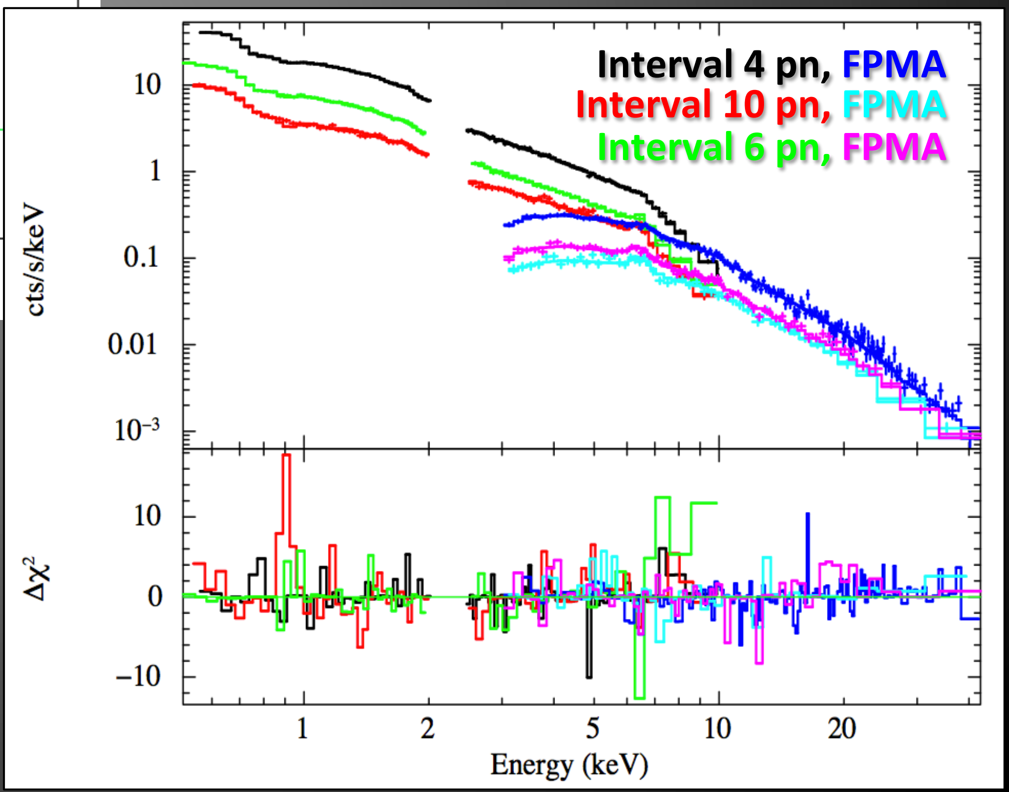


Marinucci+ 2014

Spectral Variability

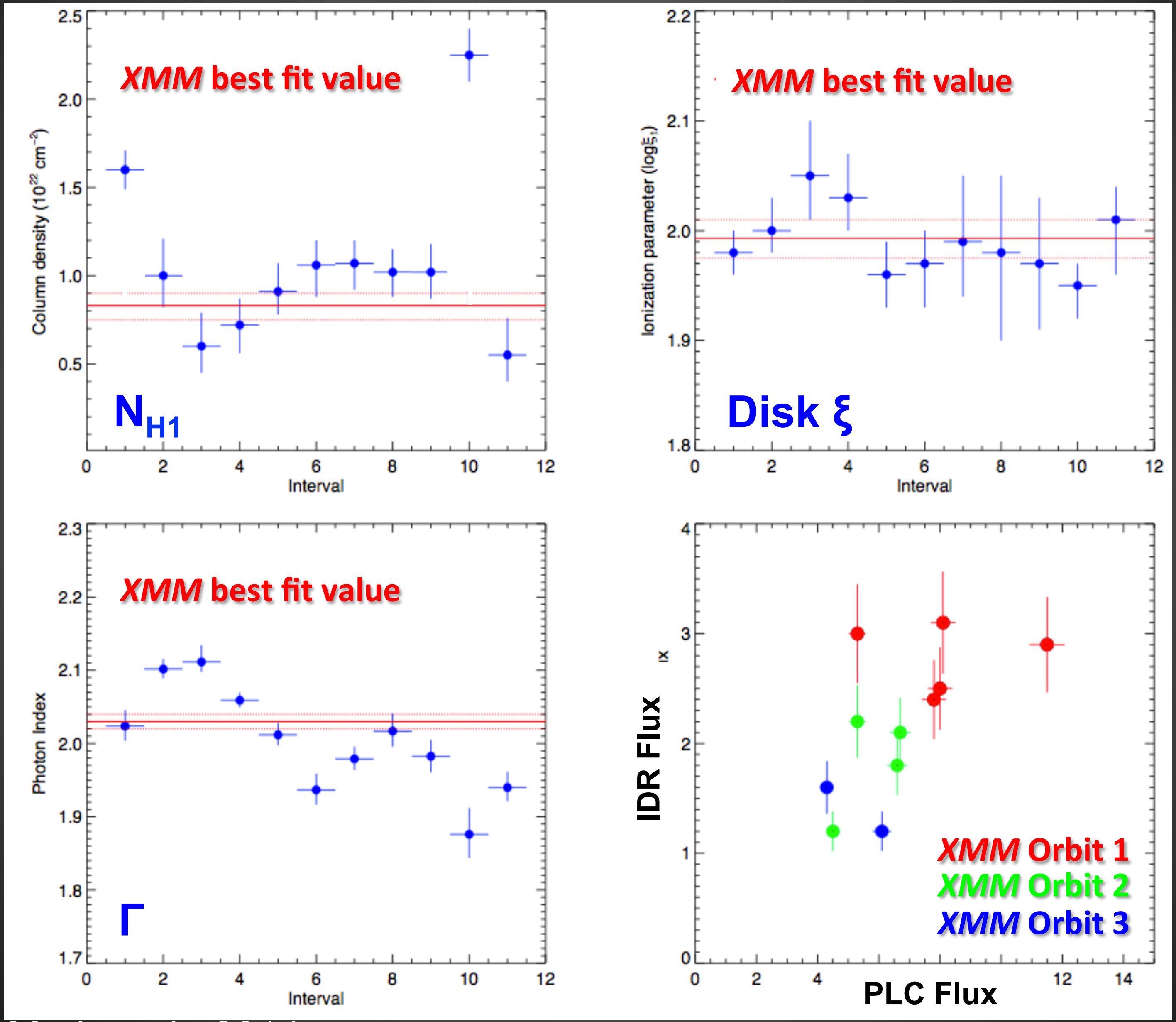


- Highest, two lowest flux time intervals analyzed jointly with simultaneous *XMM* and *NuSTAR* data.
- Left plot shows data ratioed against a power-law with $\Gamma = 2$ (ignoring 4 - 7.5 keV).



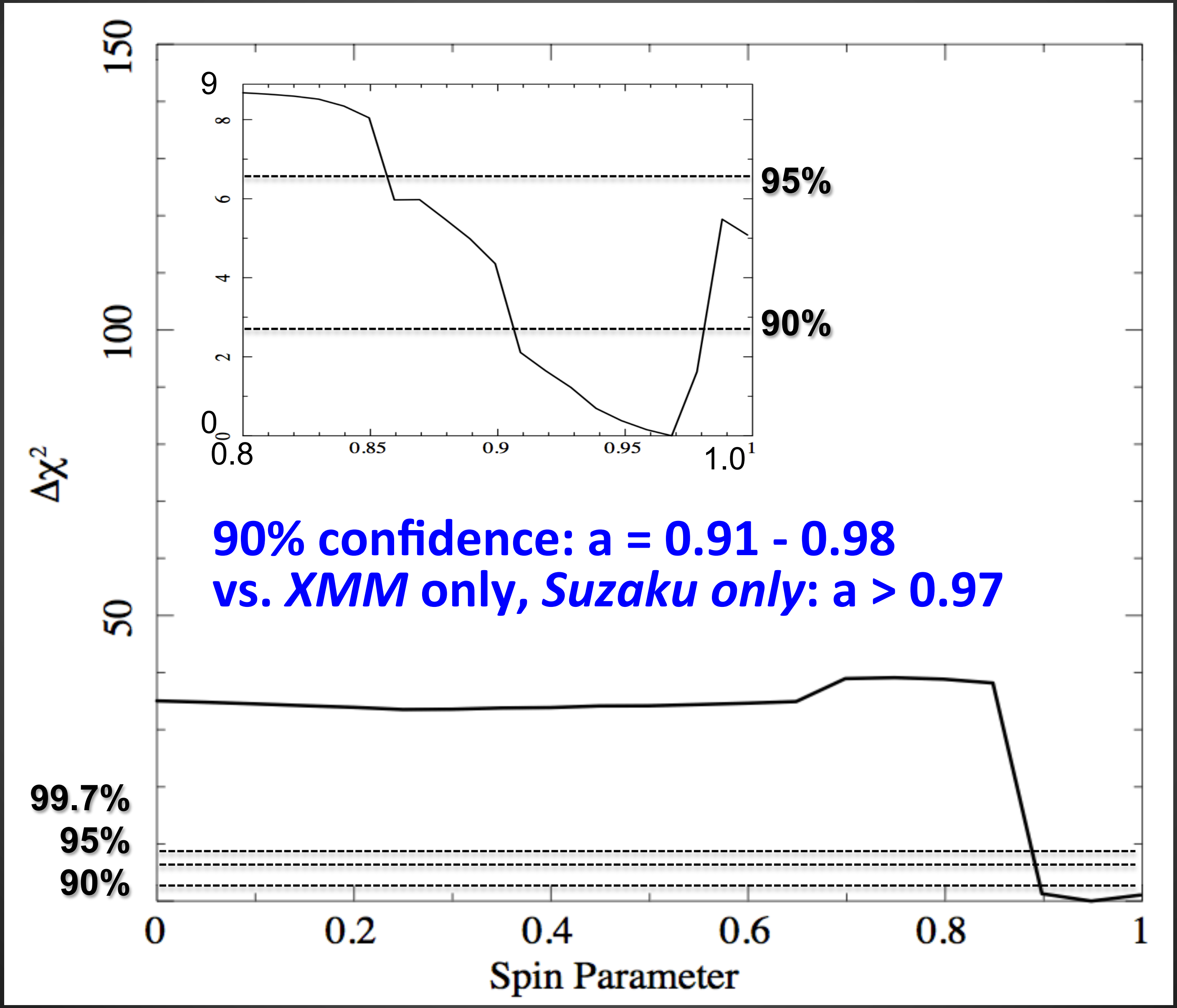
- Right plot shows data fit with model including power-law continuum (no constrained E_{cut}); 2 ionized absorbers; 1 cold, dusty absorber; distant (neutral); inner disk (ionized) reflection.
- Without inner disk: $\Delta\chi^2/\Delta\nu = +191/+11$.

Time-resolved Spectral Fitting

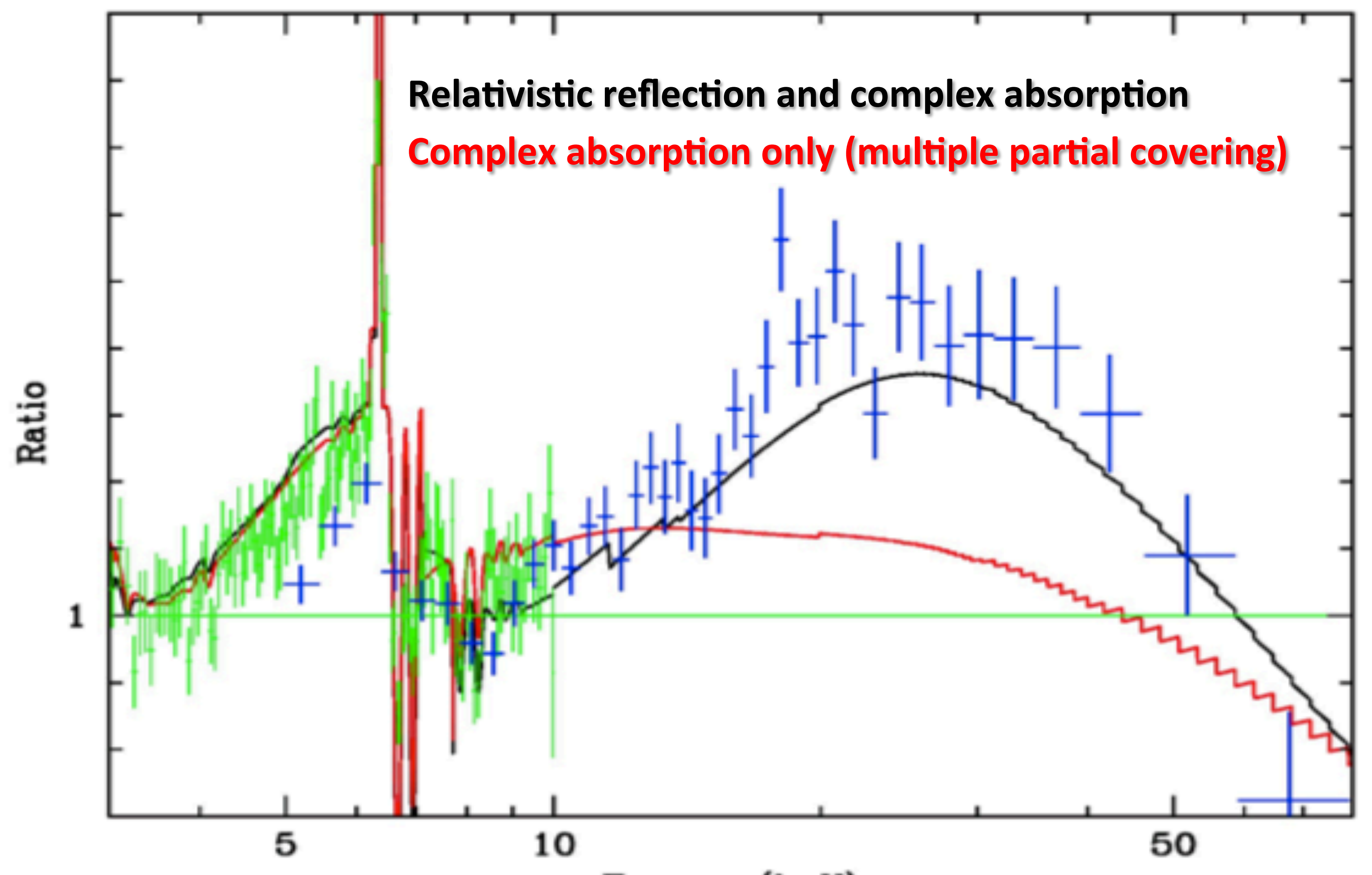


Marinucci+ 2014

Spin Constraint

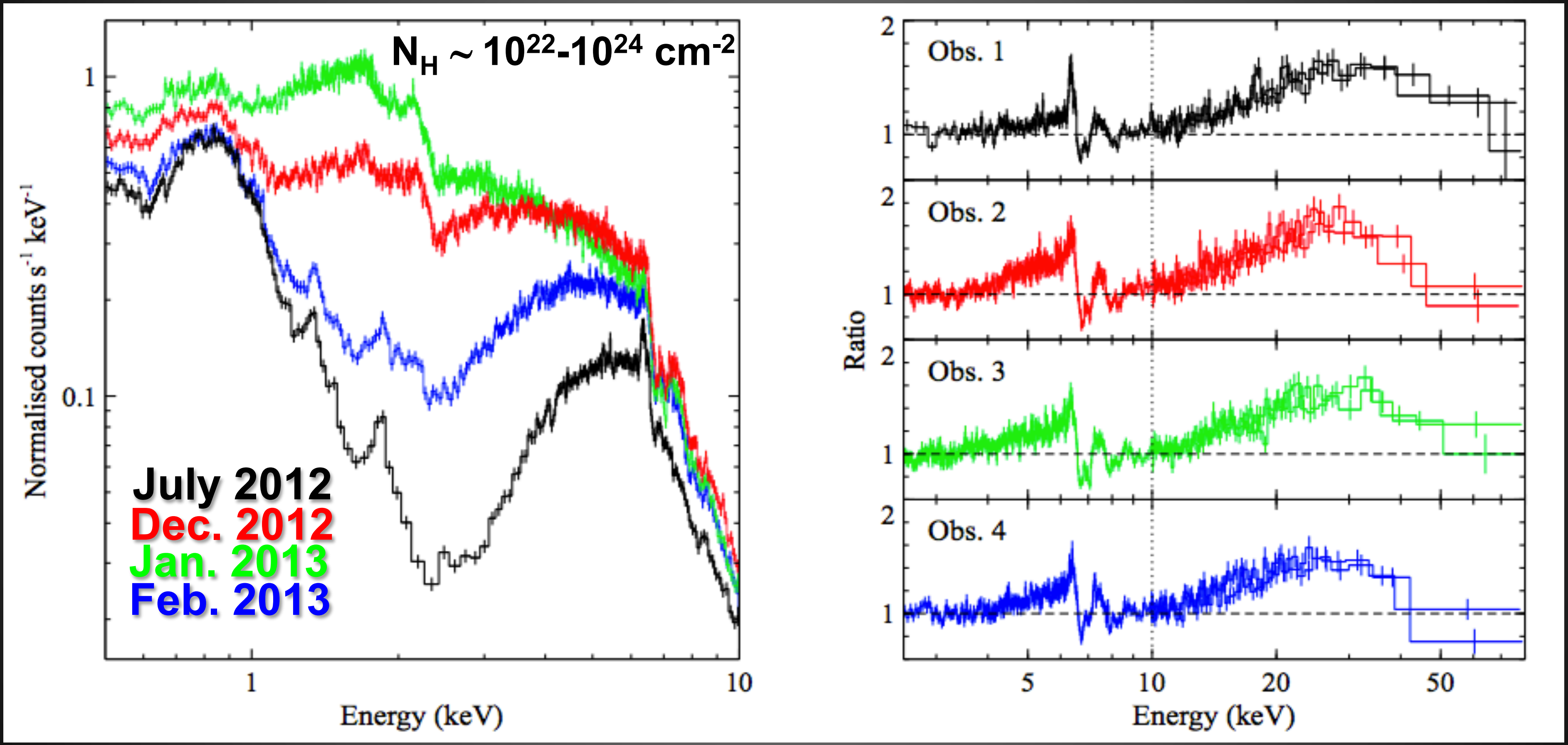


NGC 1365: reflection and variable complex absorption



Risaliti+ 2013

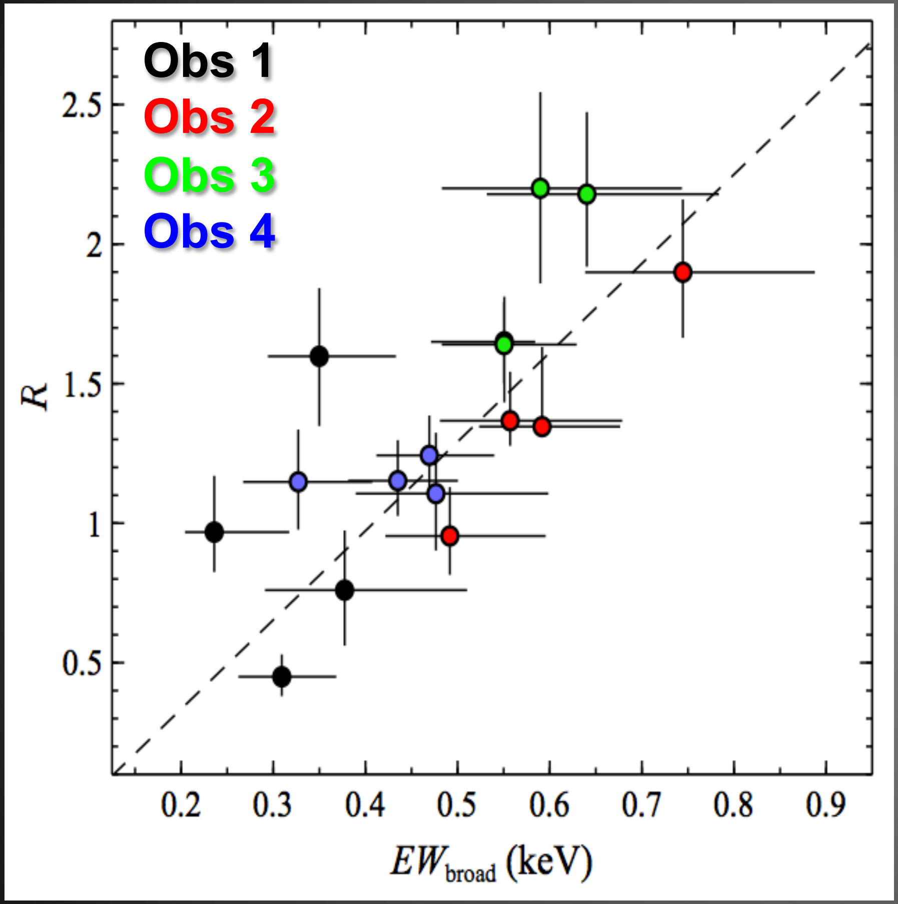
Spectral Variability

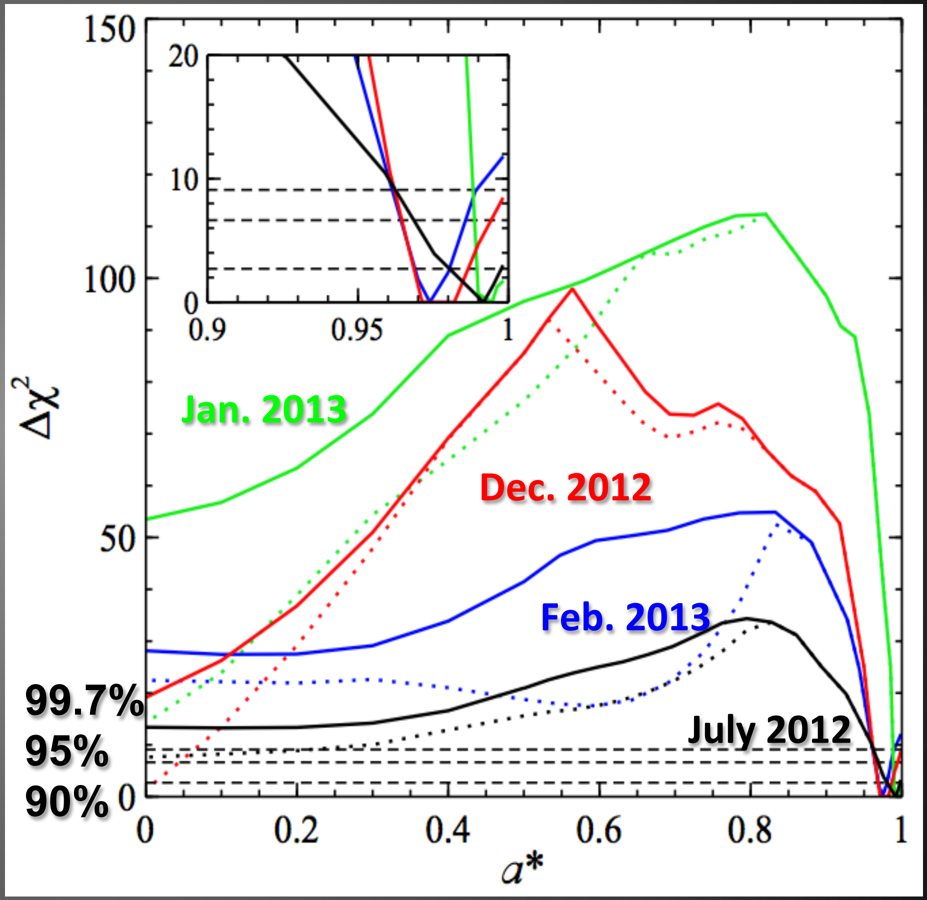


Walton+ 2014

4 *XMM/NuSTAR* ~120 ks observations

Constraining Relativistic Reflection

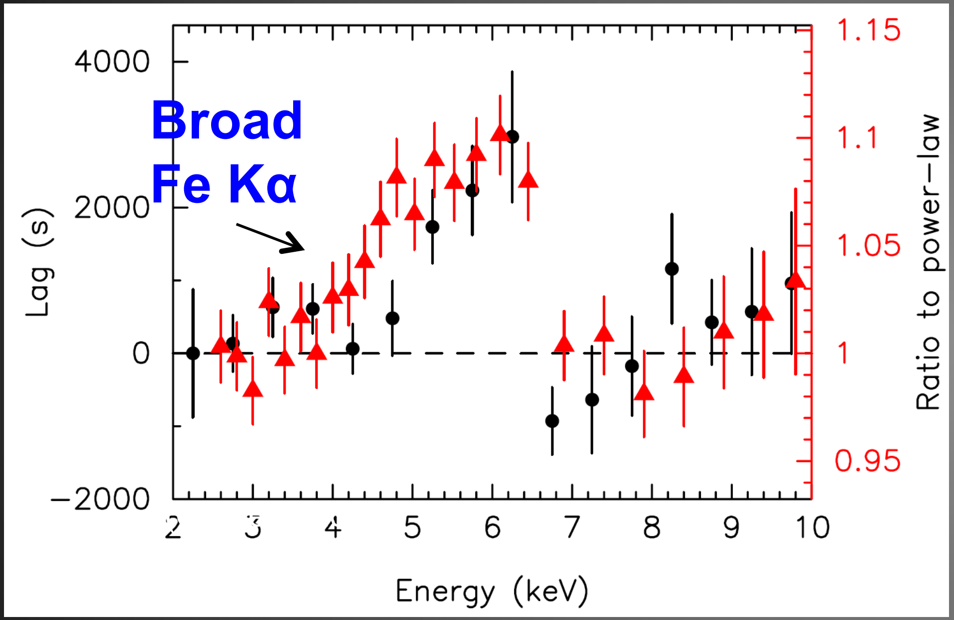




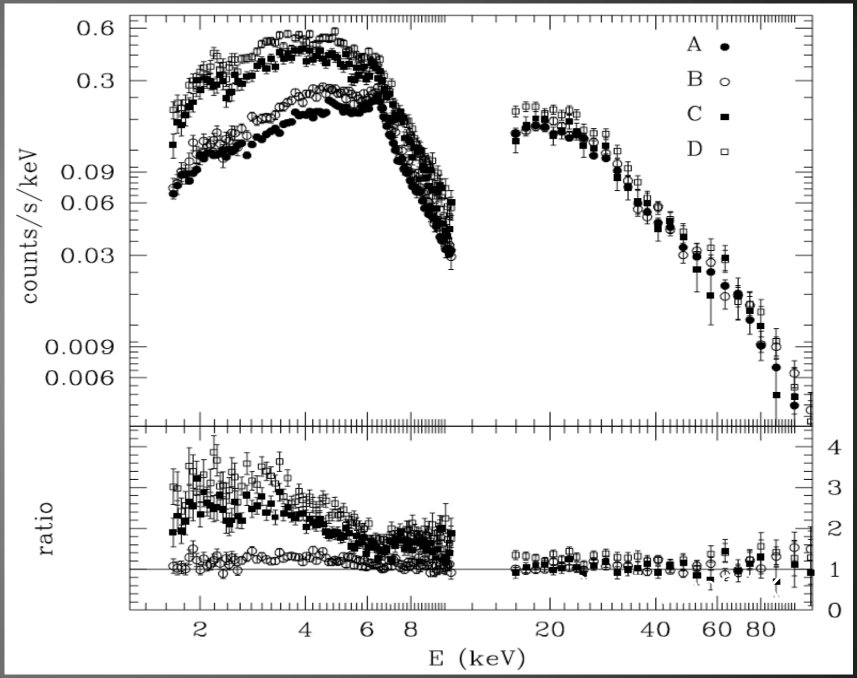
Walton+ 2014

NGC 4151: Variable Absorption and Nature of the Corona

Strong evidence for relativistic reflection

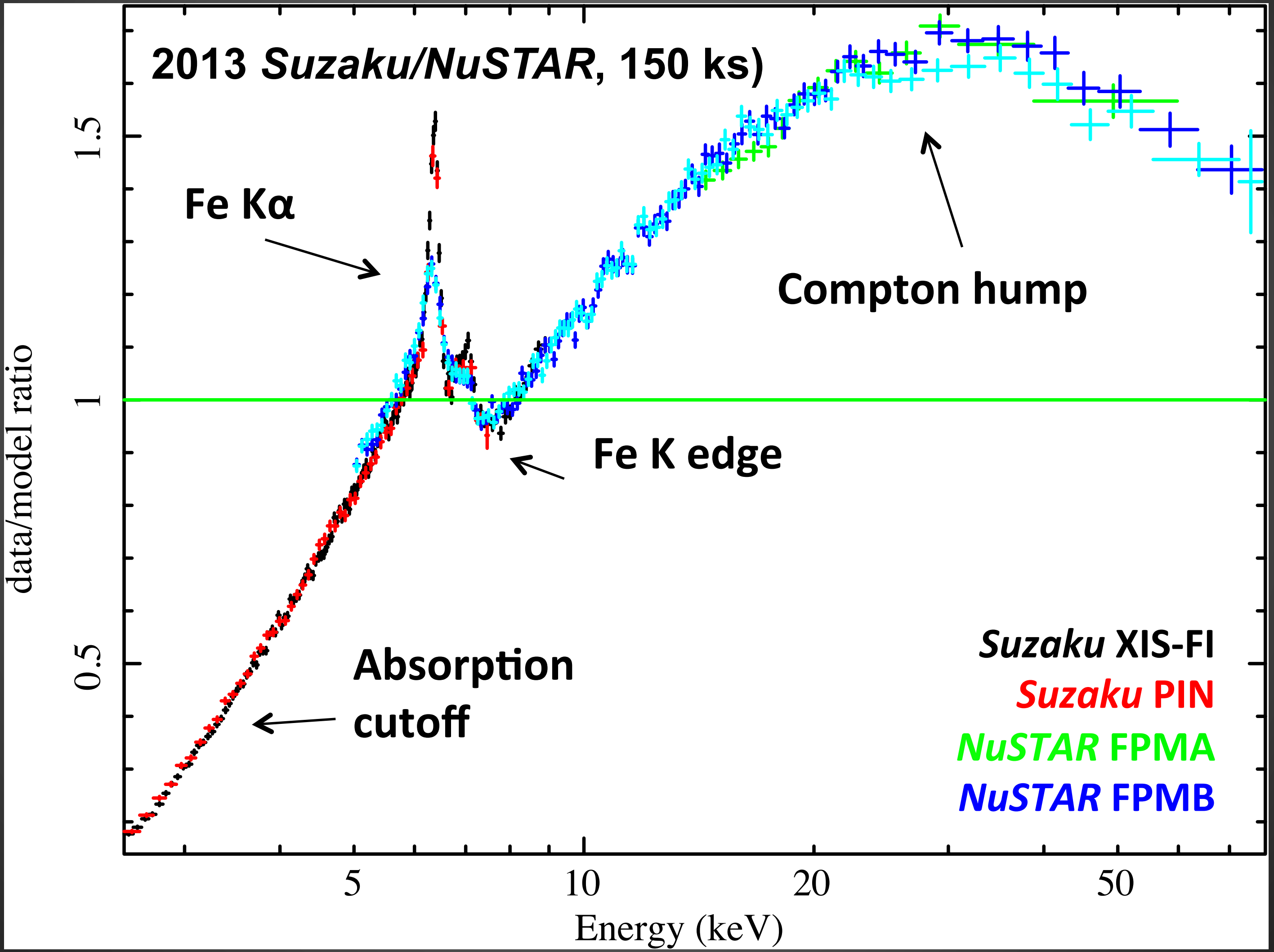


Strong evidence for variable absorption



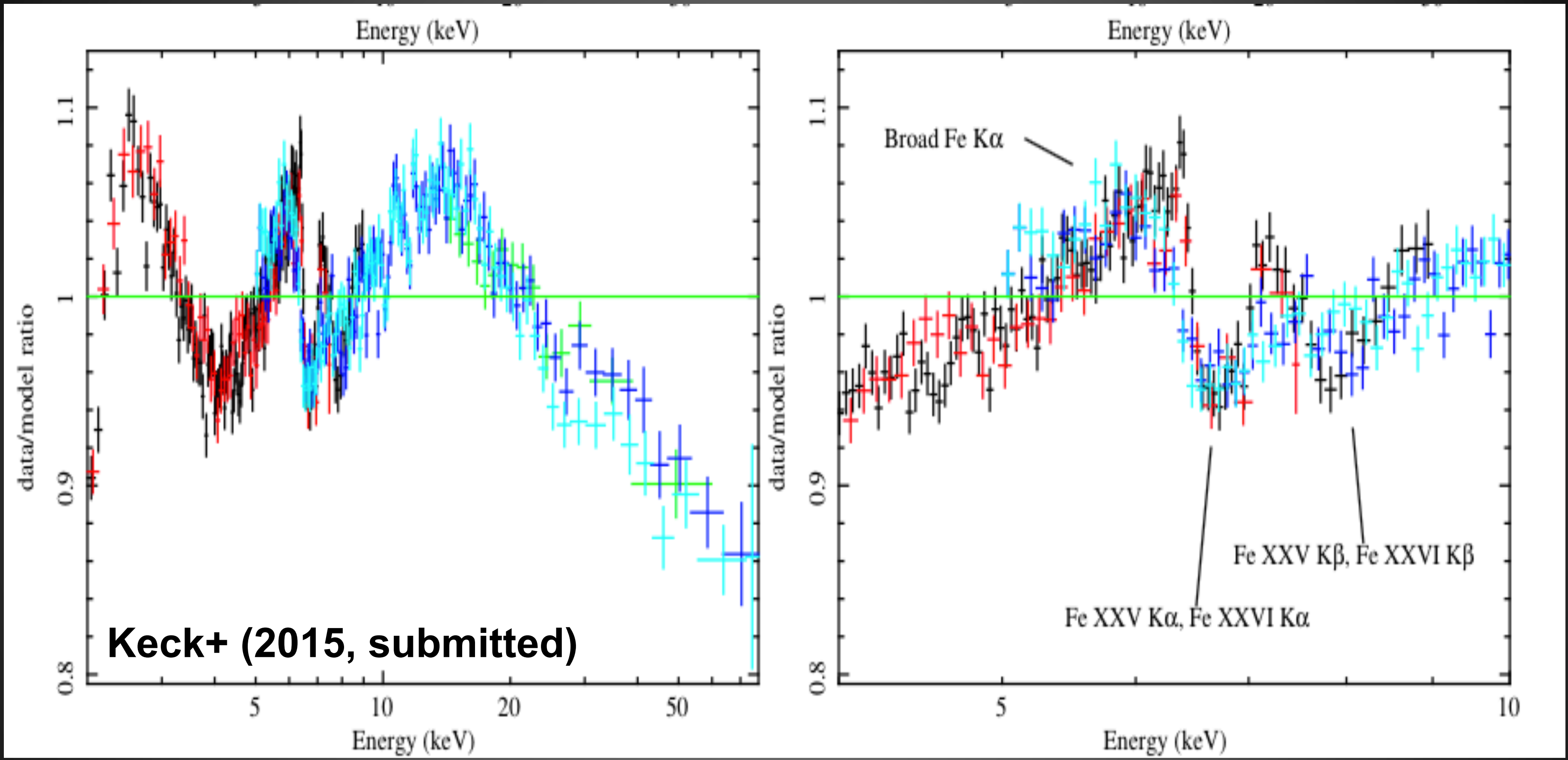
- X-ray spectroscopy has indicated the presence and absence of relativistic reflection (Nandra+2007; Schurch+2003).
- Fe K-reverberation measurements have revealed relativistic reflection in this source (Zoghbi+2012; Cackett+2014).
- Complex absorption structure has shown N_H variability on two-day timescales (Puccetti+ 2007).

Time-Averaged Spectrum w/o PLC



Keck+ (2015, submitted)

Evidence for Relativistic Reflection



- Accounting for the prominent AGN features reveals Fe XXV and XXVI absorption lines and evidence for relativistic reflection from the inner accretion disk.
- Also evidence for both distant and inner disk reflection.

Model 1: inner disk reflection model

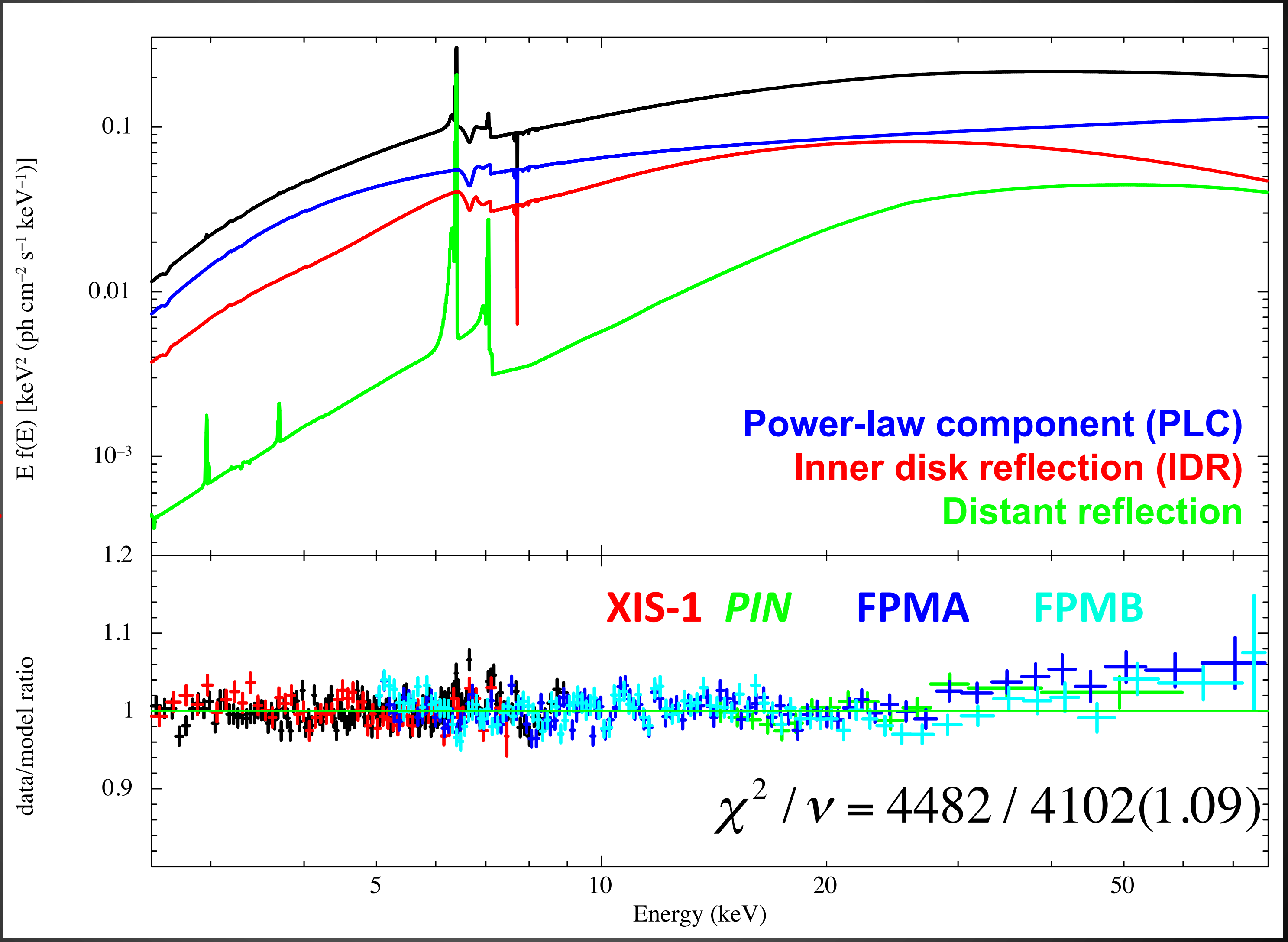
Cut-off power-law
- $\Gamma=1.74\pm0.02$
- $E_{cut} > 1000$ keV

Black hole
- $a=0.97\pm0.02$

Accretion disk
- $\xi\sim 1100$ erg cm s^{-1}
- $i=24\pm3$ deg
- $q_1>9.6$ $q_2=3.0\pm0.1$
- $r_{br}=3.1\pm0.3$ r_g
- $A_{fe}\sim2.7$

Warm absorber
- $\xi\sim1000$ erg cm s^{-1}

Cold absorber
- $N_H\sim10^{23}$ cm^{-2}
- $f_{cov}=0.92\pm0.01$



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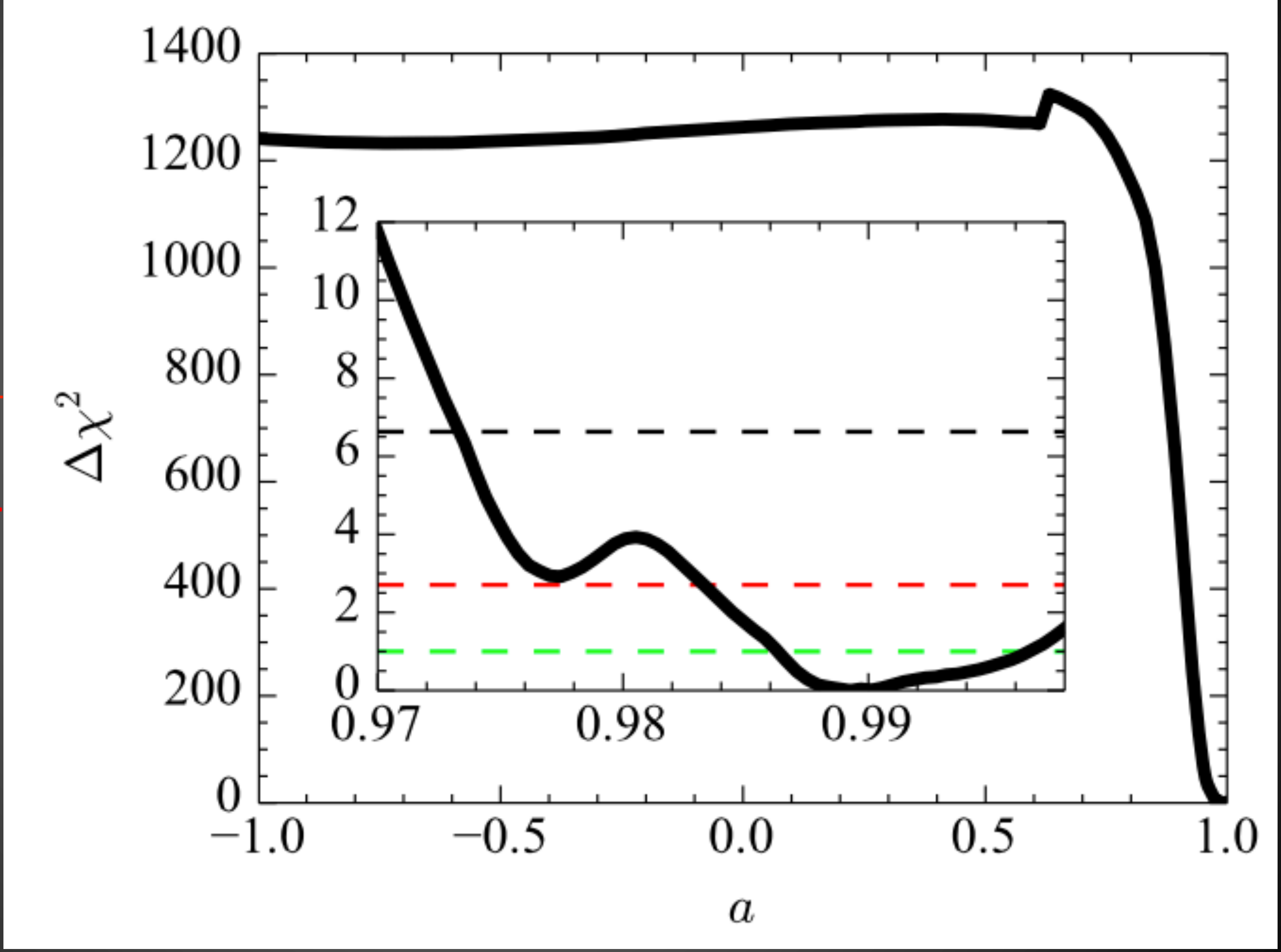


Keck+ (2015, submitted)

Model 2: absorption-dominated model

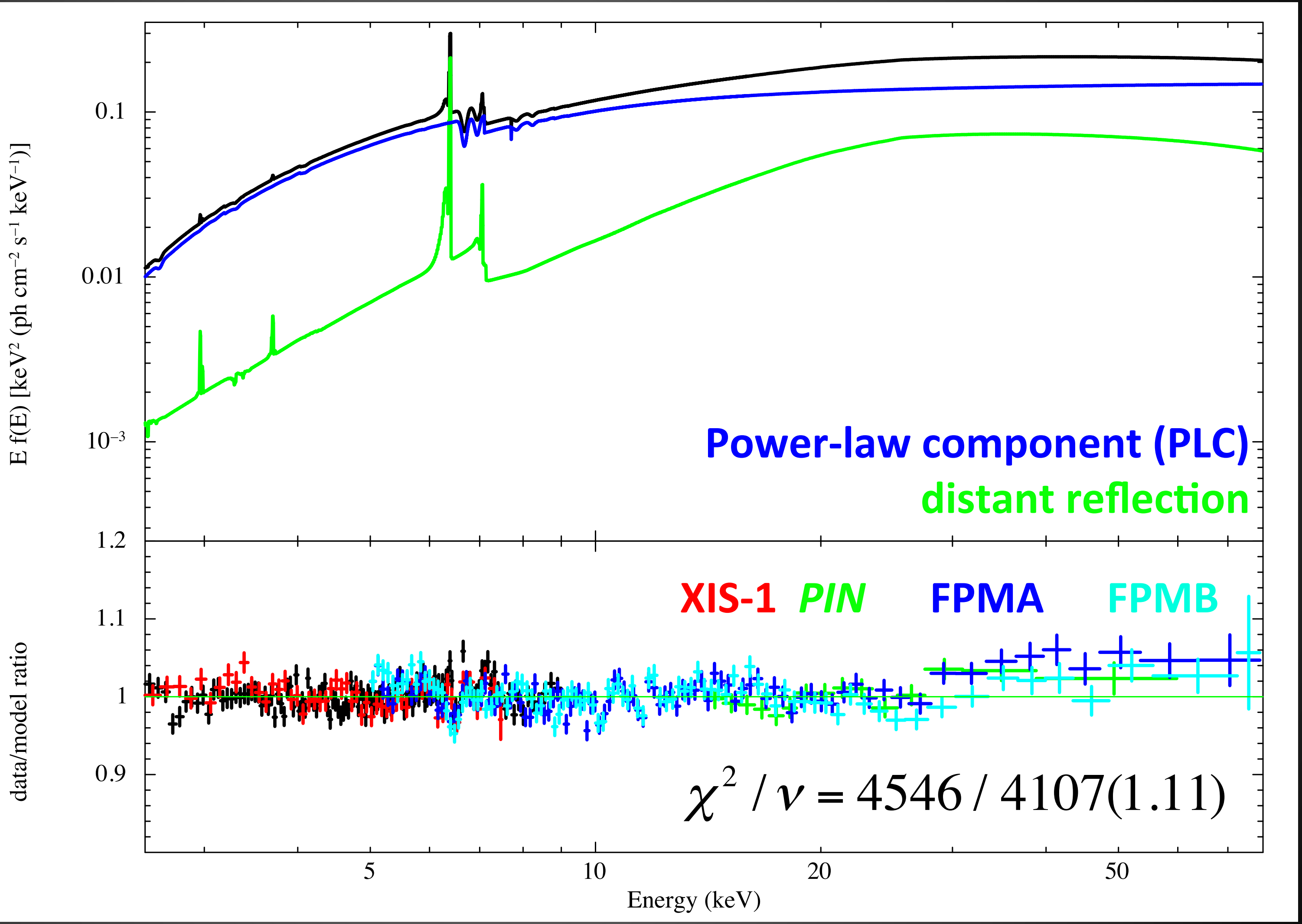
Cut-off power-law
- $\Gamma=1.90 \pm 0.01$
- $E_{cut} > 1000$ keV

Distant reflector
- $A_{Fe}=1.4\pm0.1$

Cold absorber 1
- $N_H \sim 13\times10^{23}$ cm^{-2}
- $f_{cov}=0.95\pm0.01$

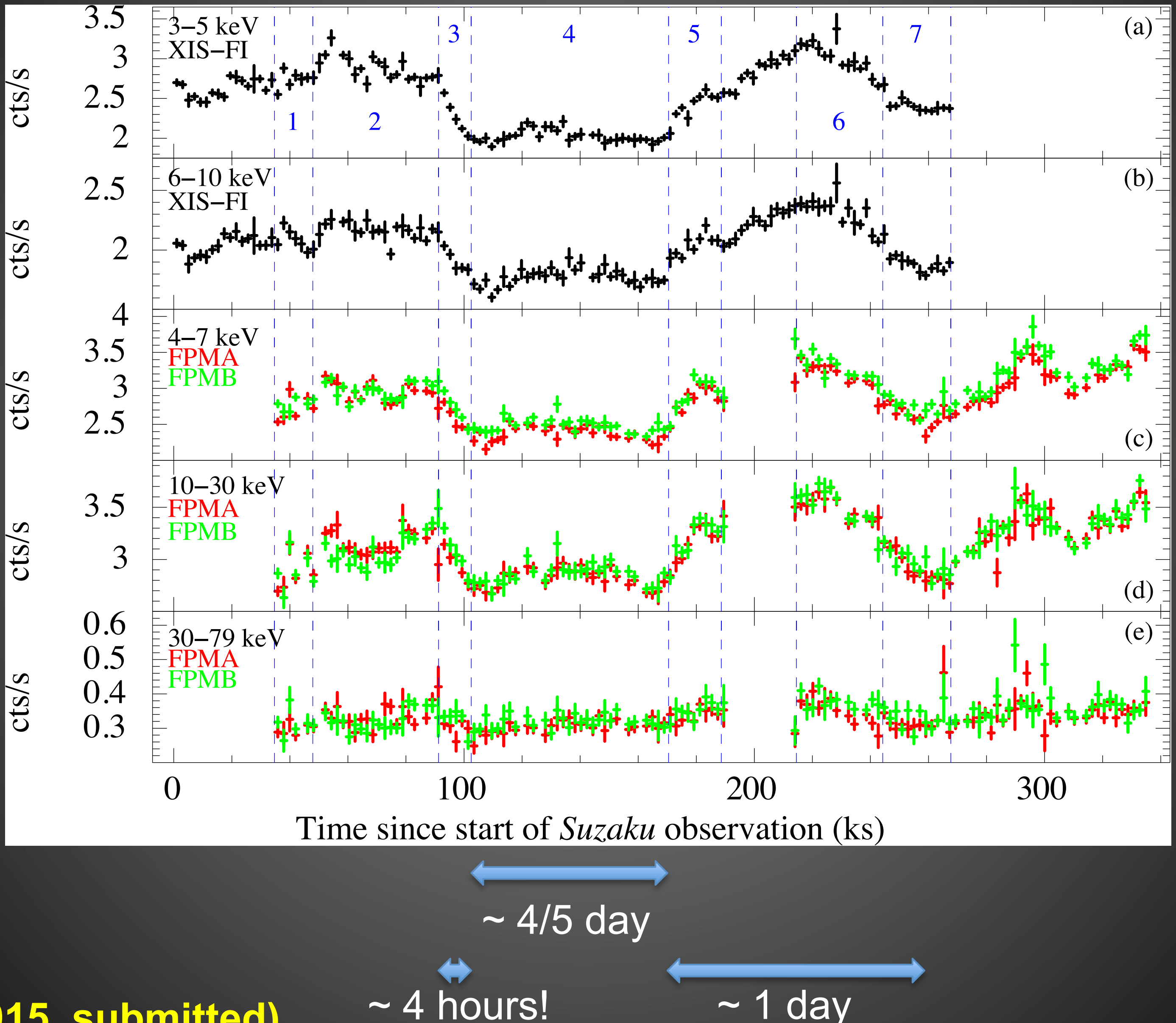
Cold absorber 2
- $N_H \sim 53\times10^{23}$ cm^{-2}
- $f_{cov}=0.41\pm0.03$

Warm absorber
- $\xi \sim 2750$ erg cm s^{-1}



Keck+ (2015, submitted)

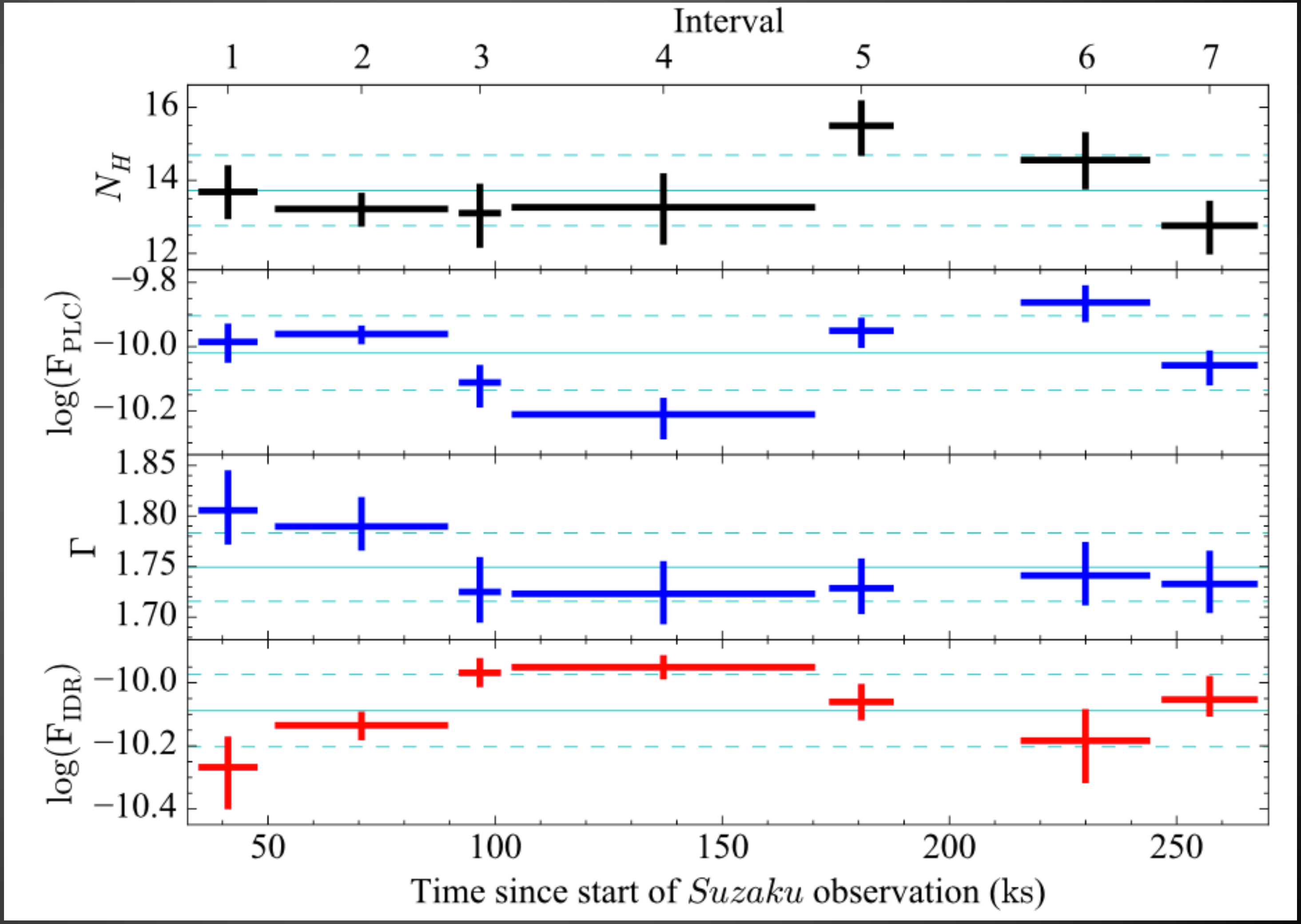
Time-Resolved Analysis



Keck+ (2015, submitted)

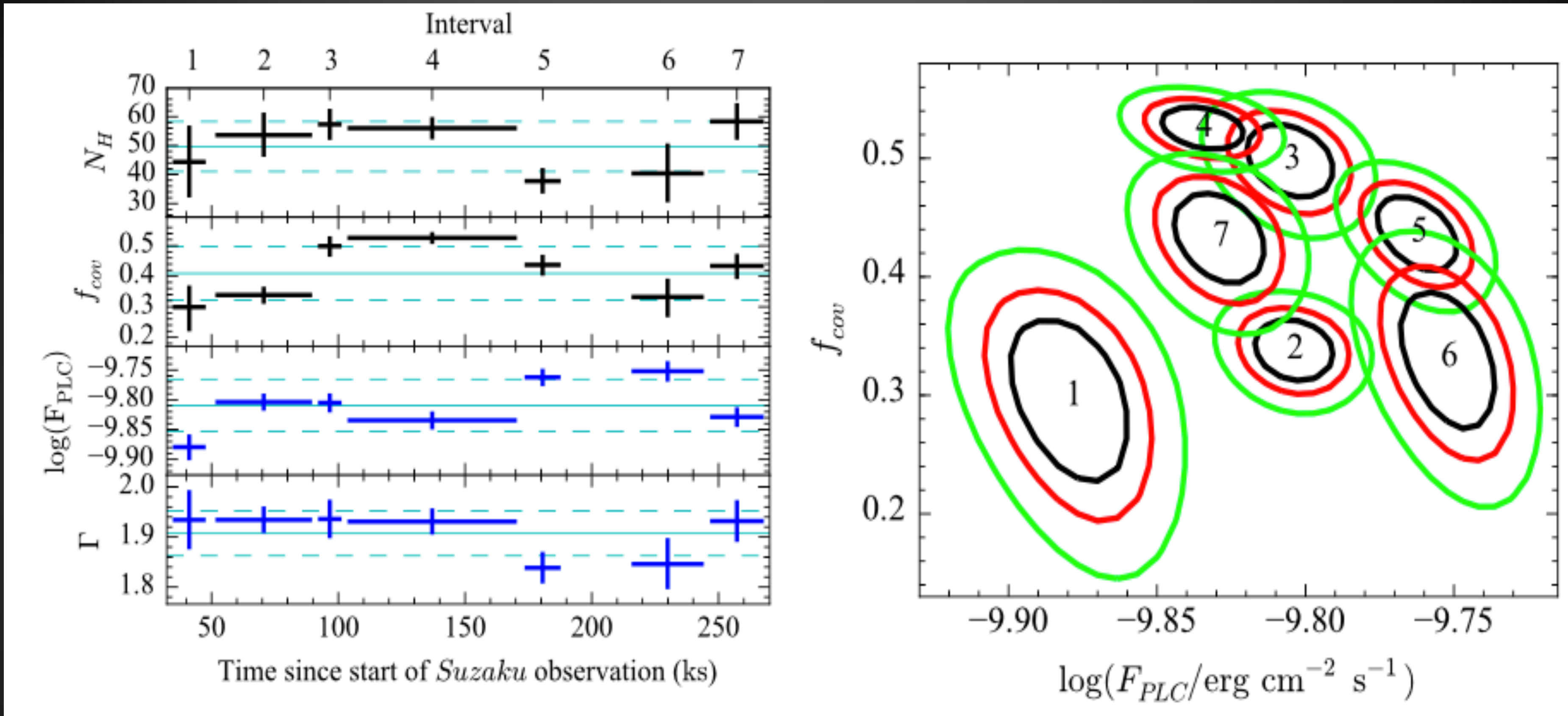
Model 1: inner disk reflection model

- Time-resolved analysis reveals that change in cold N_H and PLC flux dominate variability.
- Anti-correlation between PLC slope and flux of IDR seen, as expected for the light-bending model.



Keck+ (2015, submitted)

Model 2: absorption-dominated model



Keck+ (2015, submitted)

- Change in covering fraction of partial-covering absorber dominates variability.
- Cut-off power-law shows significant variability, though this seems unphysically anti-correlated with that of the partial-coverer.

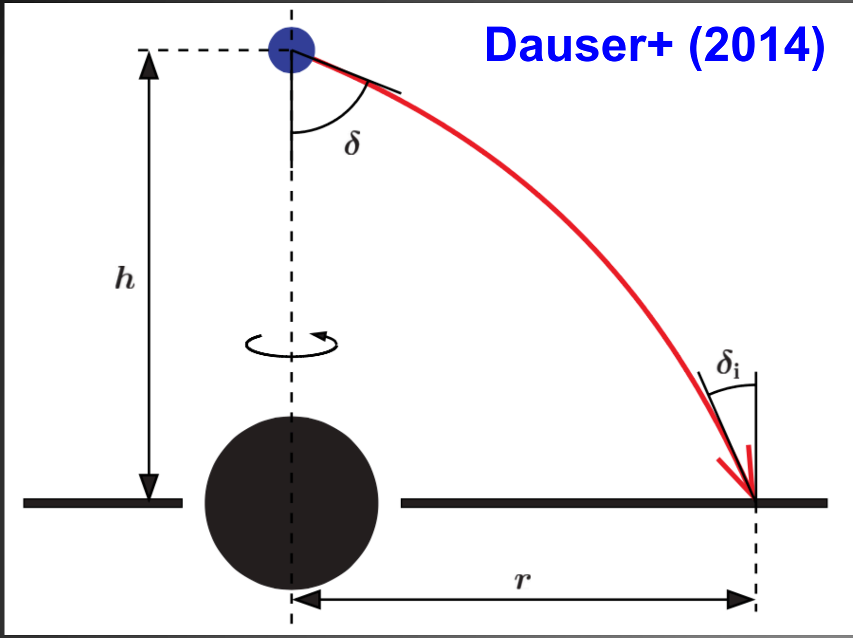
Absorption Variability

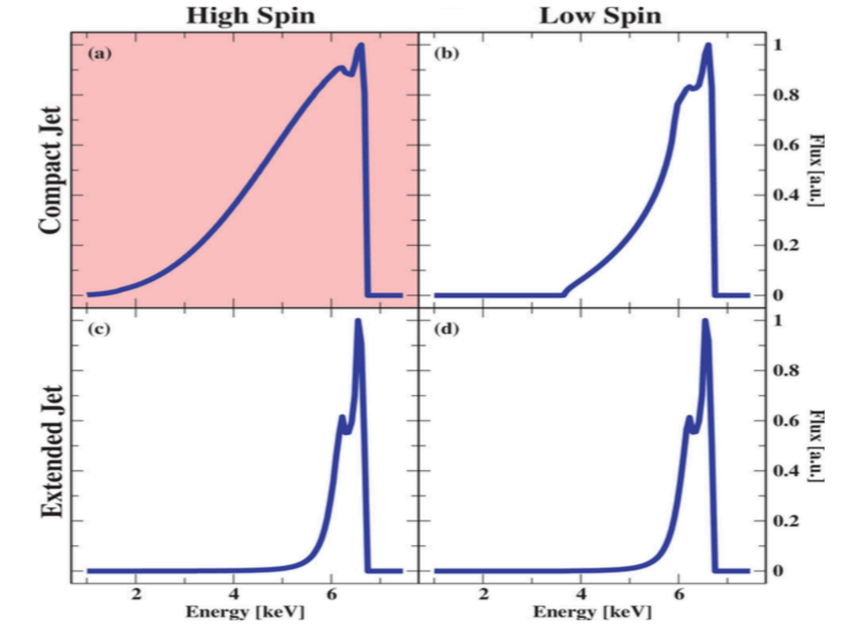
- ~4 hour crossing time of absorber from the light curve suggests location of eclipsing cloud at a distance $d<15000\ r_g$ following the same methods of Puccetti+ (2007). This firmly **rules out the absorber at the location of a parsec-scale torus** (1 pc ~ $5\times10^5\ r_g$).

- In absorption-dominated model (no inner disk reflection), we see a strong and unphysical anti-correlation between F_{PLC} and N_H of the cold, partial-covering absorber. This **favors the reflection+absorption model on physical grounds**.

- Unlike NGC 1365, pairs thick ($N_H > 10^{23}$ cm^{-2}), variable absorbing column with **<u>modest</u> inner disk reflection** signatures, which makes spin constraints more challenging.

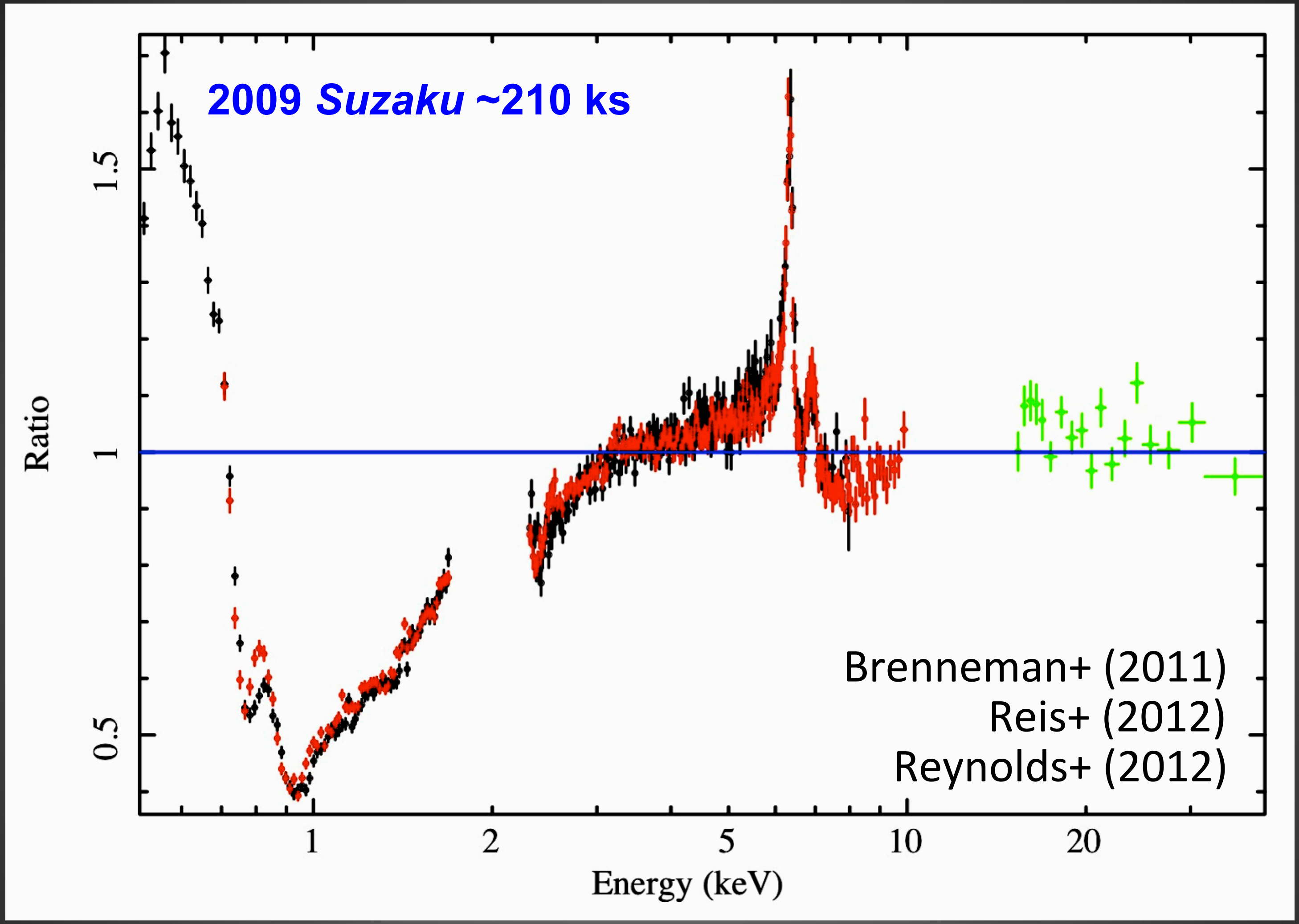
Implications for Coronal Properties



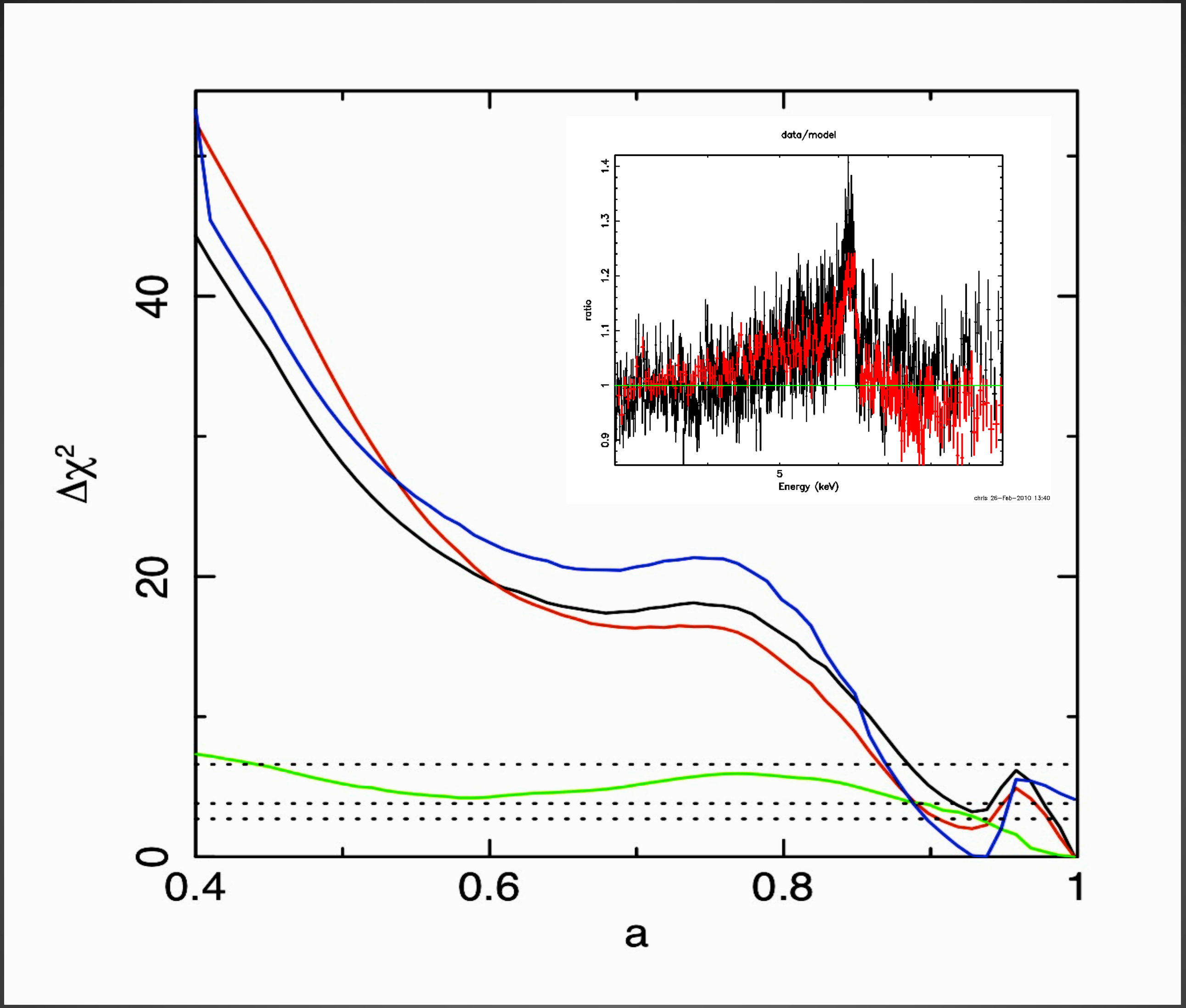


- Reflection model (light bending) assumes corona is a point on the spin axis of the BH. Oversimplification: **radial and vertical extent? Active regions?**
- If it's the **base of a jet**, plasma may have some extension and/or **outflow**.
- This is broadly consistent with **relative weakness of IDR 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?**

NGC 3783: Fe abundance and soft excess



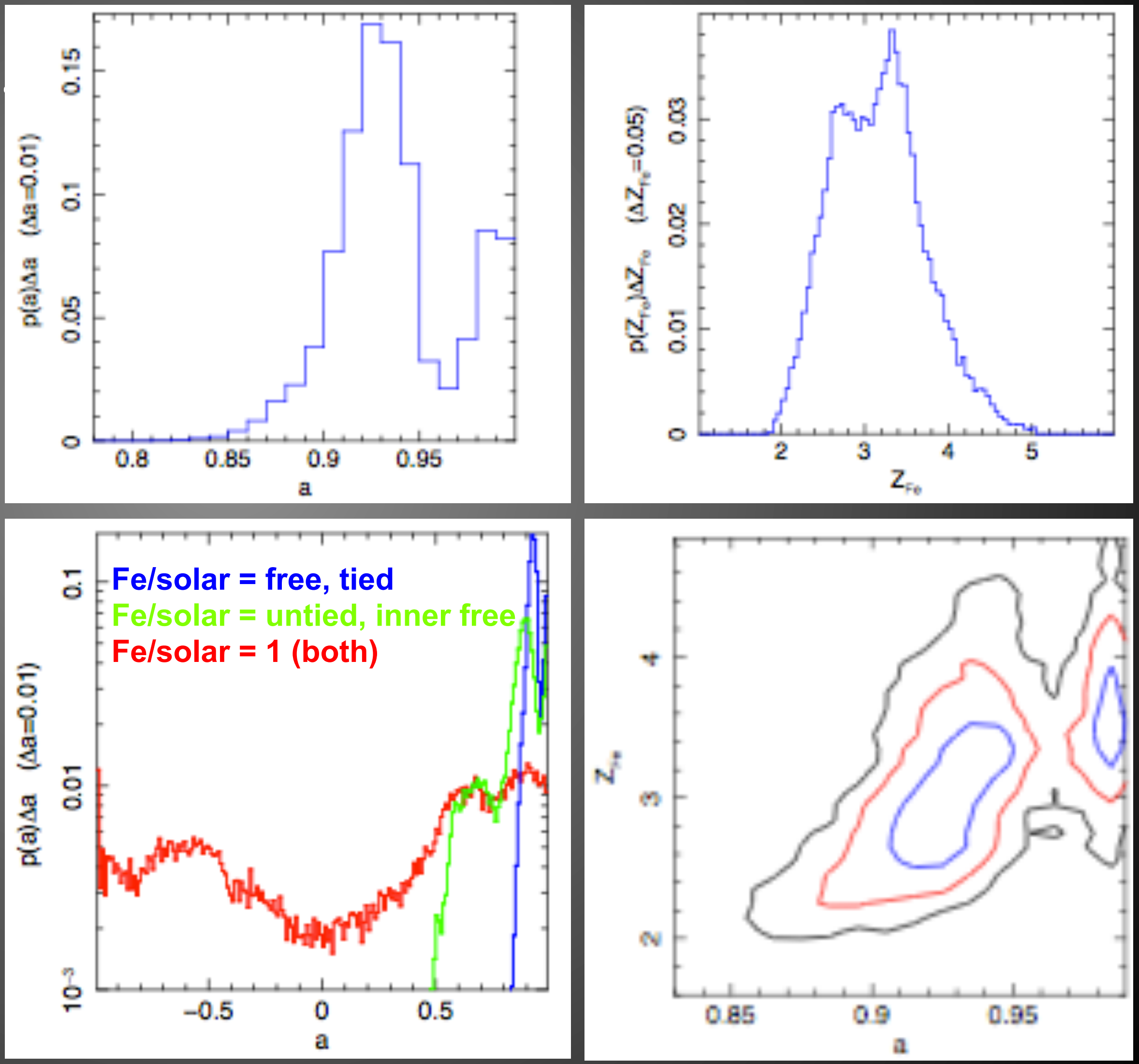
Suzaku/XIS+PIN spectrum ratioed against simple power-law. A global model of this spectrum **requires** multi-zone ionized absorption, reflection from distant matter, reflection from inner accretion disk, and a scattered component.



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)

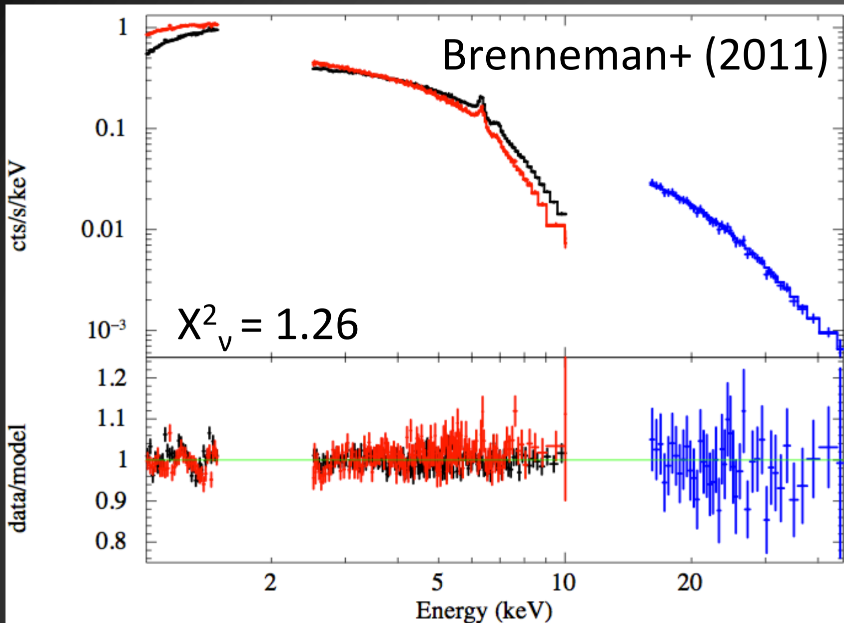
What about the Soft X-ray Excess?

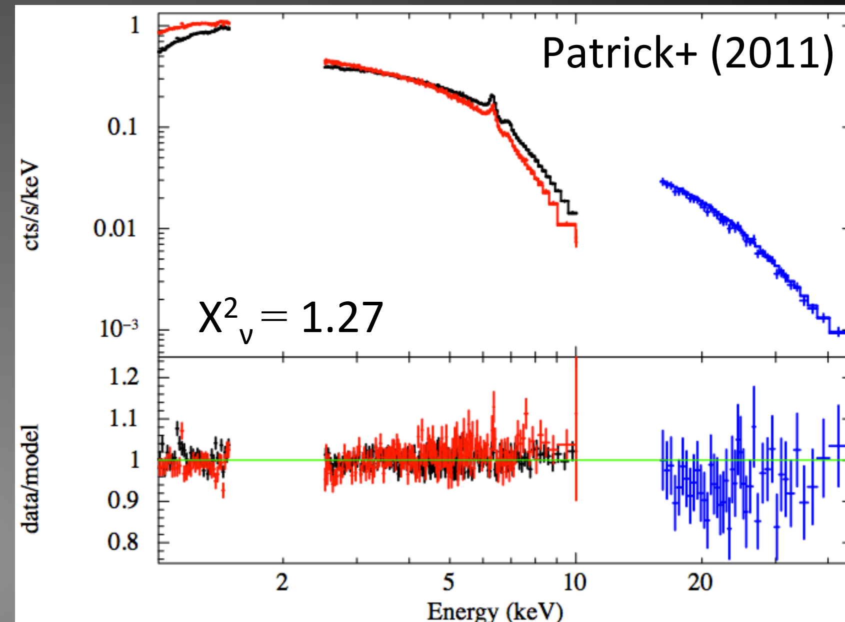
- **Present in majority of AGN** that are not totally absorbed <2 keV.

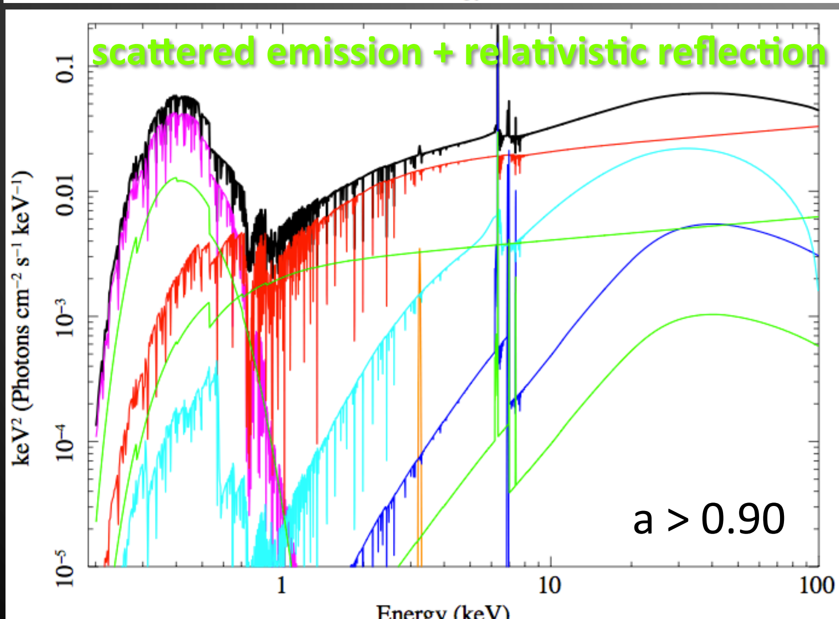
- 0.5-2 keV range **accounts for most of S/N in AGN observations** due to higher collecting area at these low energies, so parameterization of this region can highly influence spectral fitting!

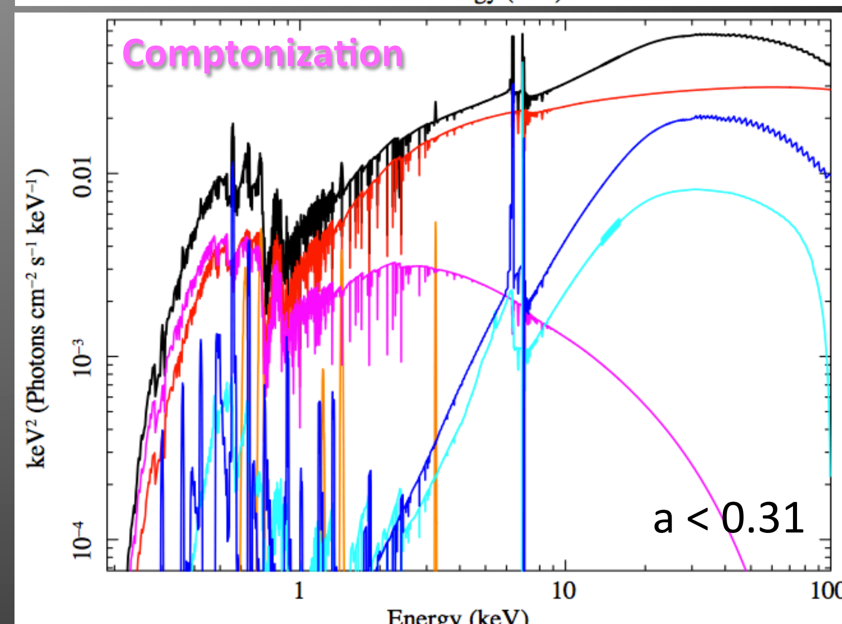
- **Physical origin of this emission is still a mystery**, may differ source-to-source (e.g., Crummy+ 2006, Done+ 2012, Lohfink+ 2013a):
    - Scattered continuum?
    - Comptonization?
    - Thermal disk?
    - Blurred relativistic reflection?
    - *Combination? Something else??*

Soft Excess Modeling in NGC 3783

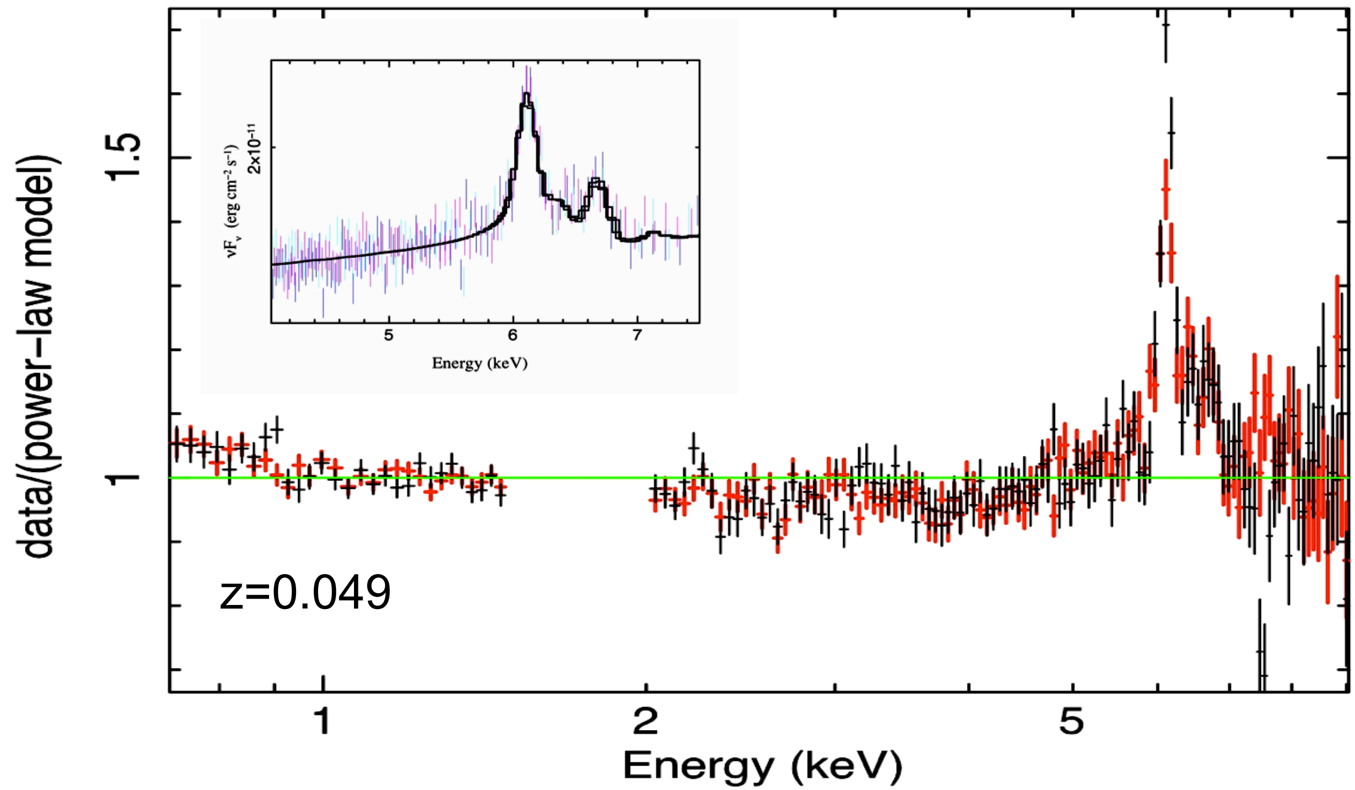






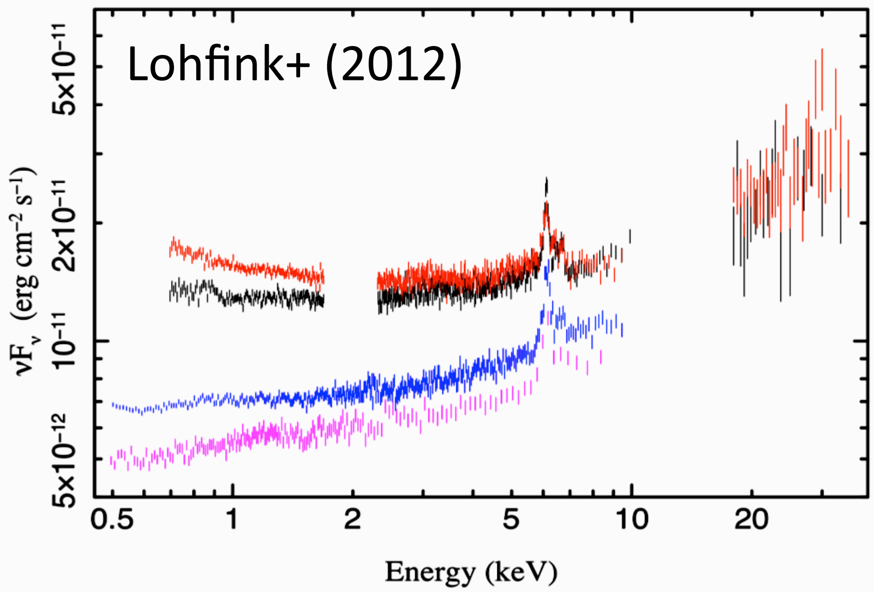


Fairall 9: soft excess in a “bare” AGN



Lohfink+ (2012)

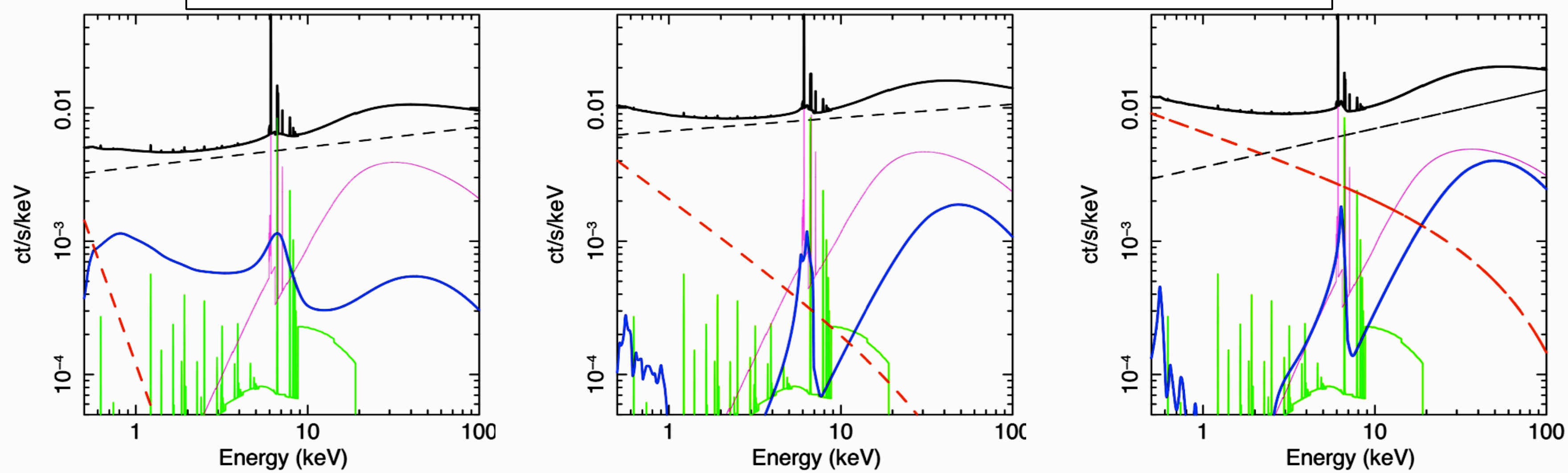
2011 *Suzaku* ~ ks data ratioed against simple power-law. Very “clean” object – no evidence for any intrinsic absorption. Broad iron line is weak but clearly seen to low-energy side of strong narrow iron line.

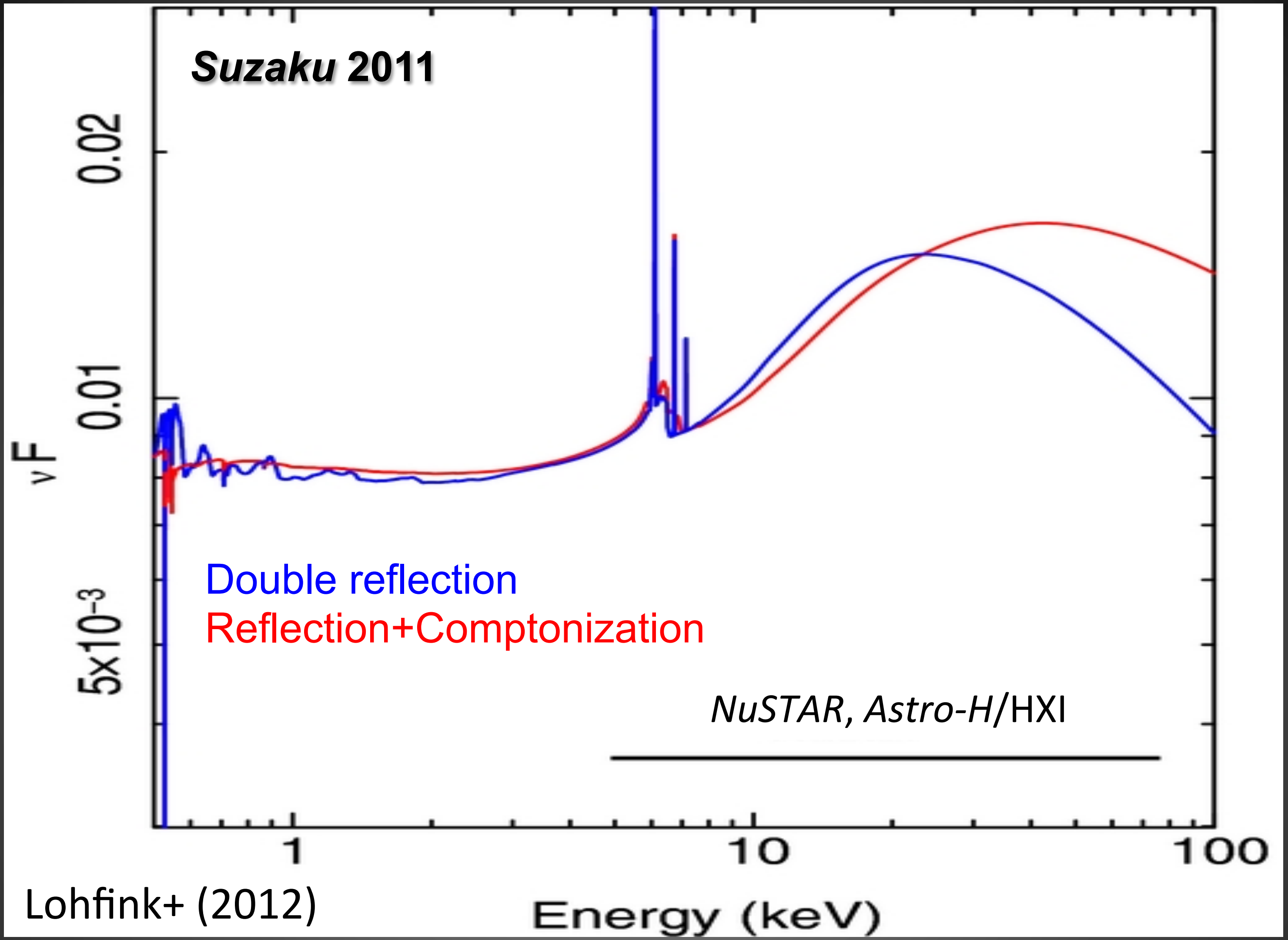


Strong flux and spectral variability seen between *XMM* and *Suzaku* observations (from bottom to top: 2001-*XMM*, 2010-*XMM*, 2007-*Suzaku*, 2010-*Suzaku*).

Need to employ a **multi-epoch analysis** to break degeneracies introduced by photoionized emission line complexes and soft excess.

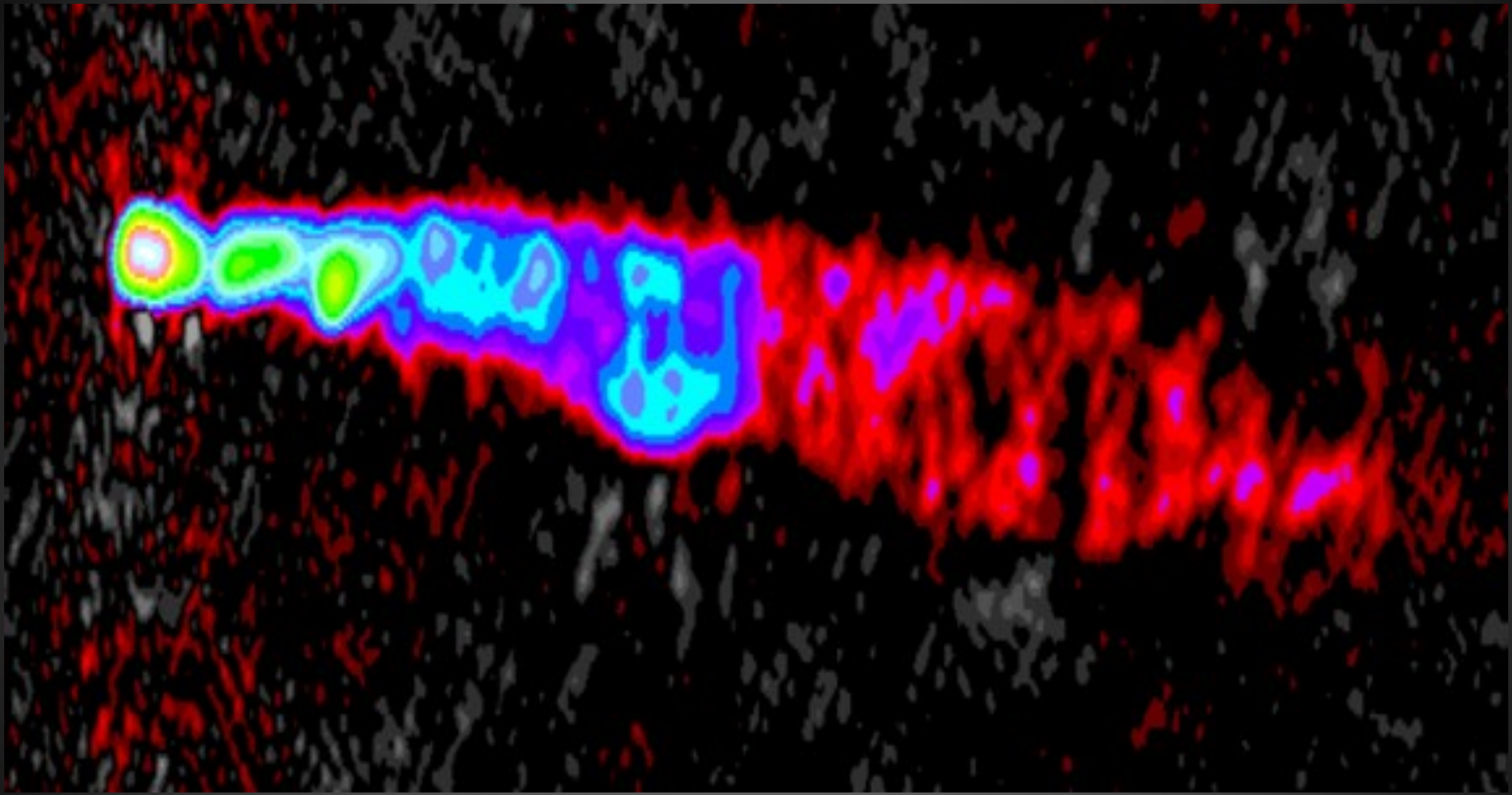
$$a = 0.52^{+0.19}_{-0.15} \qquad i = 48^{+6}_{-2}\,\mathrm{deg}$$





Double reflection model can be distinguished from reflection+ Comptonization model with a broad energy range, e.g., *XMM*+ *NuSTAR* or *Astro-H.*

3C120: Measuring spin in RLAGN



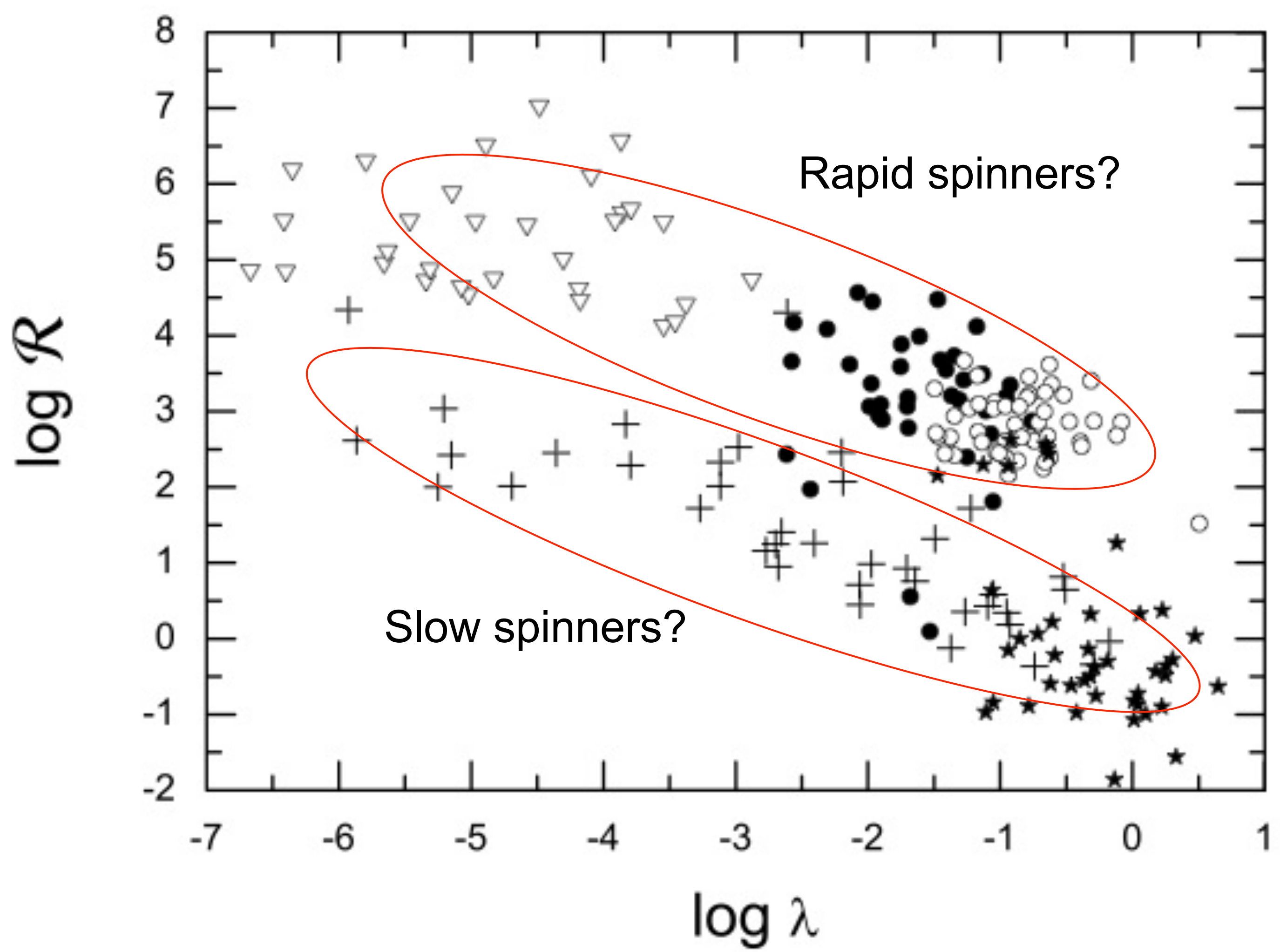
VLA (1.66GHz)

Credit: R.C.Walker

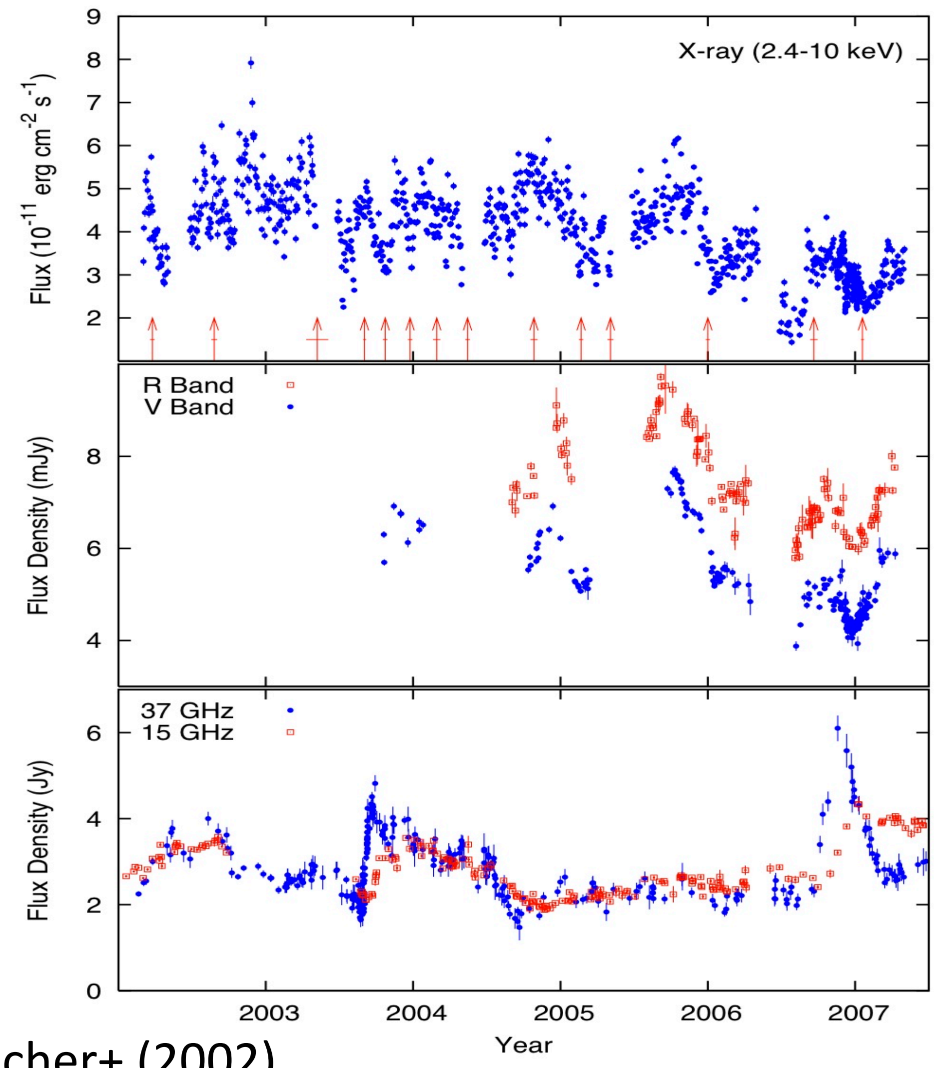
The Spin-Jet Paradigm

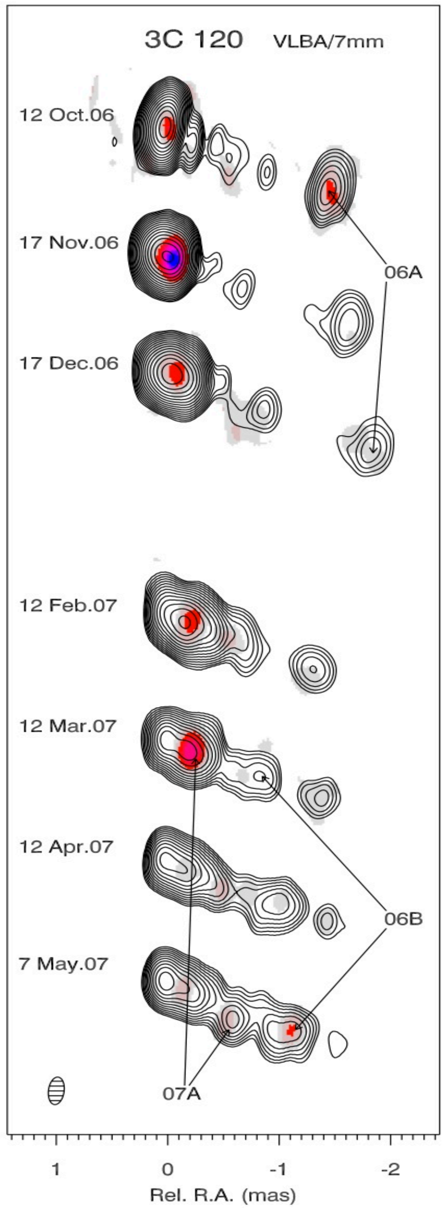
Spin as an energy source?

Spin paradigm for radio-quiet/radio-loud AGN

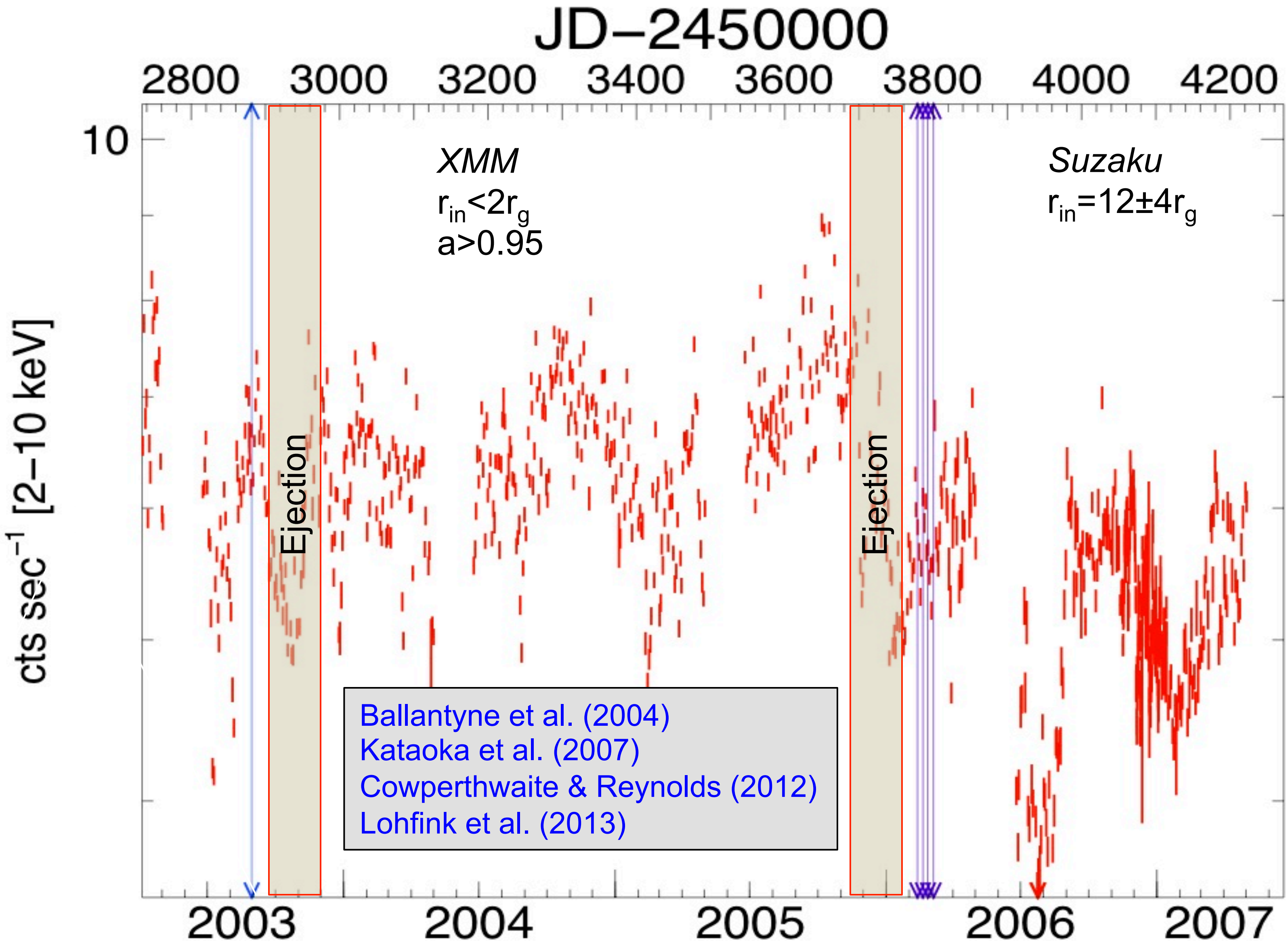


Sikora et al. (2007)

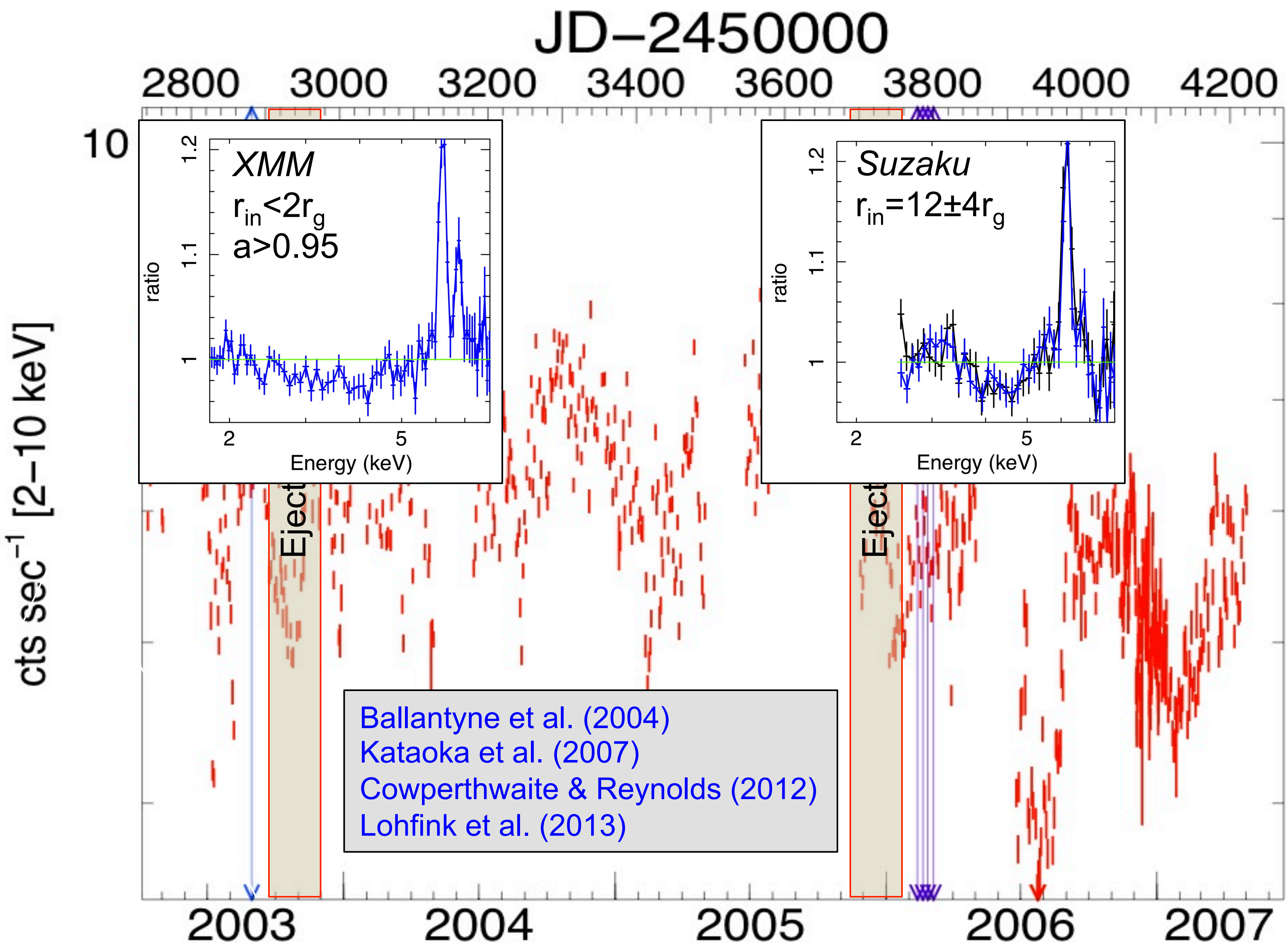




Marscher+ (2002)
Chatterjee+ (2009)



JD−2450000
2800
3000
3200
3400
3600
3800
4000
4200
10
cts sec^{-1} [2–10 keV]
XMM
$r_{in}<2r_g$
a>0.95
Suzaku
$r_{in}=12\pm4r_g$
Ejection
Ejection
Ballantyne et al. (2004)
Kataoka et al. (2007)
Cowperthwaite & Reynolds (2012)
Lohfink et al. (2013)
2003
2004
2005
2006
2007



JD−2450000
2800
3000
3200
3400
3600
3800
4000
4200
10
cts sec^{-1} [2–10 keV]
XMM
$r_{in}<2r_g$
$a>0.95$
ratio
1.2
1.1
1
2
5
Energy (keV)
Suzaku
$r_{in}=12\pm4r_g$
Eject
Eject
Ballantyne et al. (2004)
Kataoka et al. (2007)
Cowperthwaite & Reynolds (2012)
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2003
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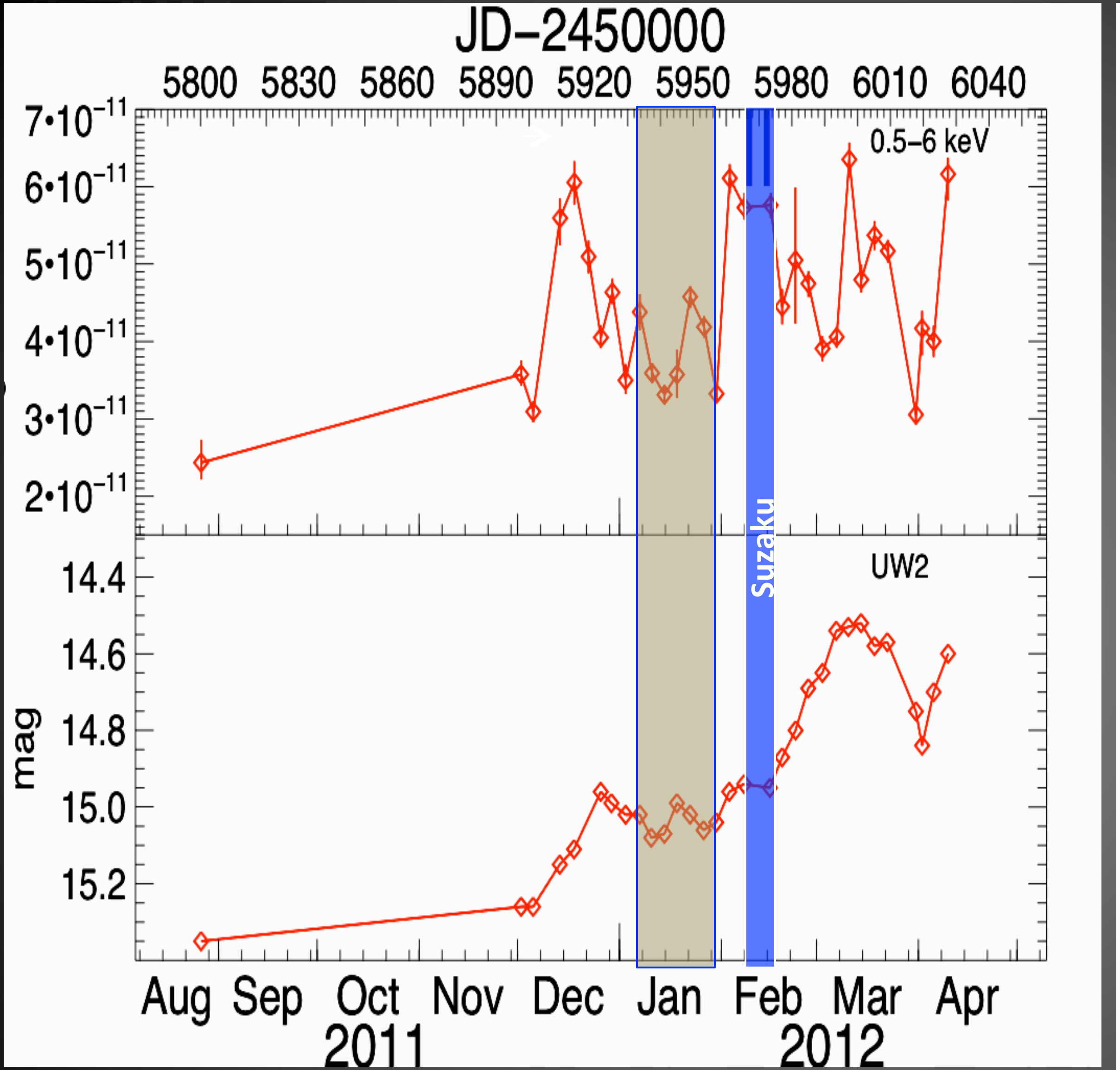
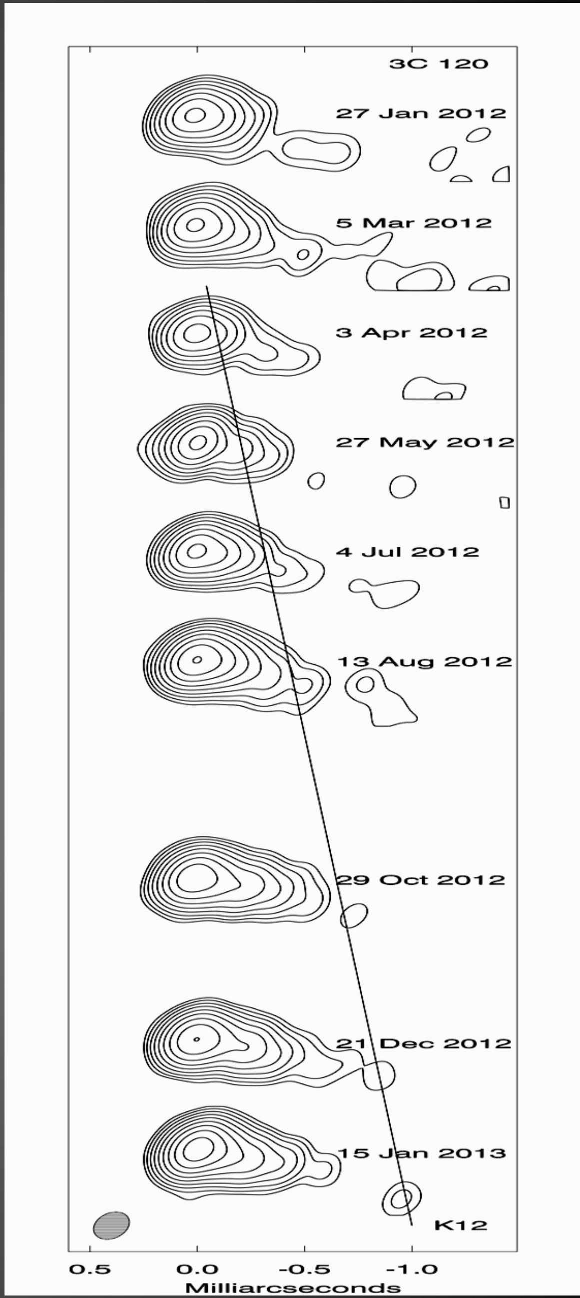
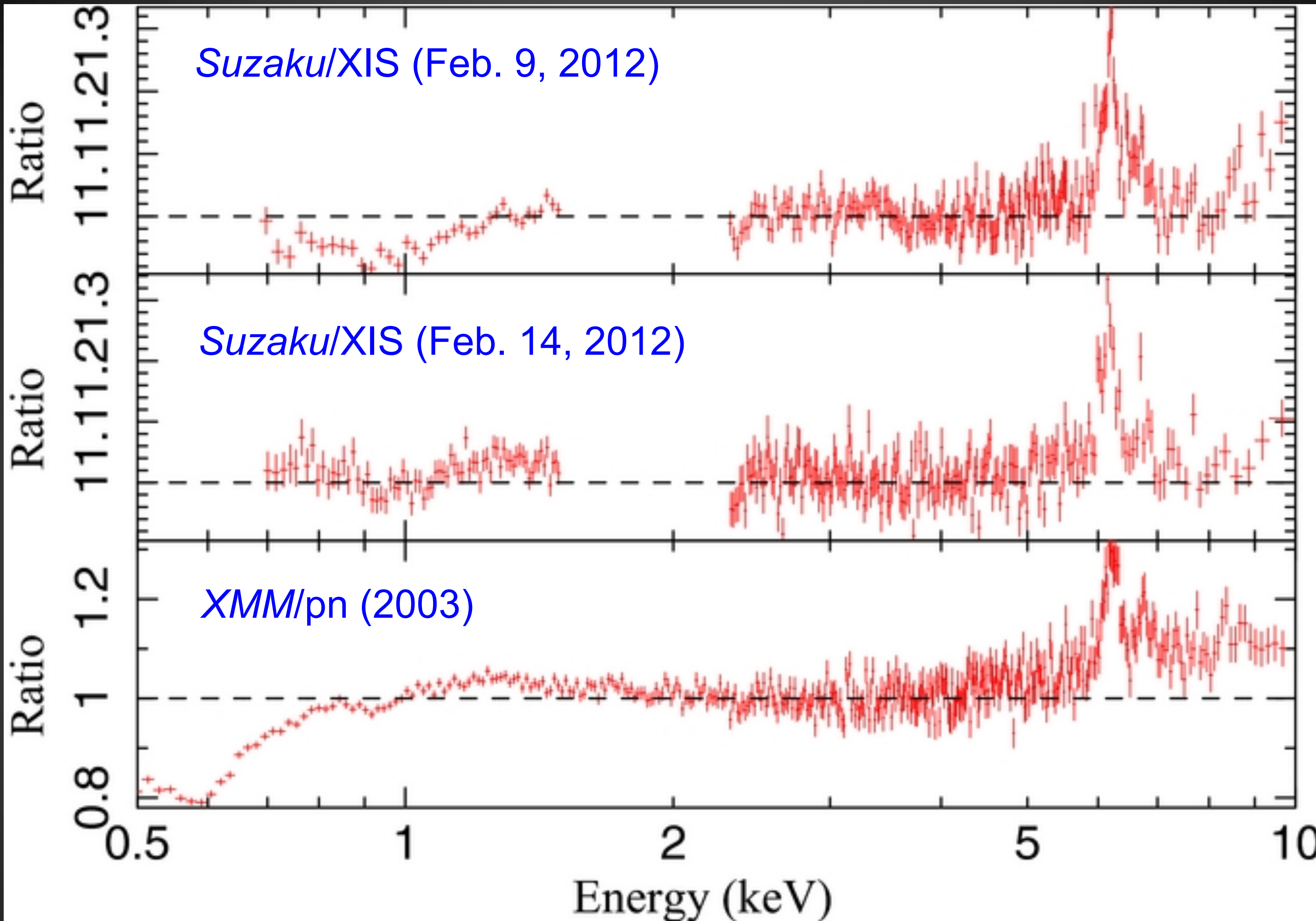




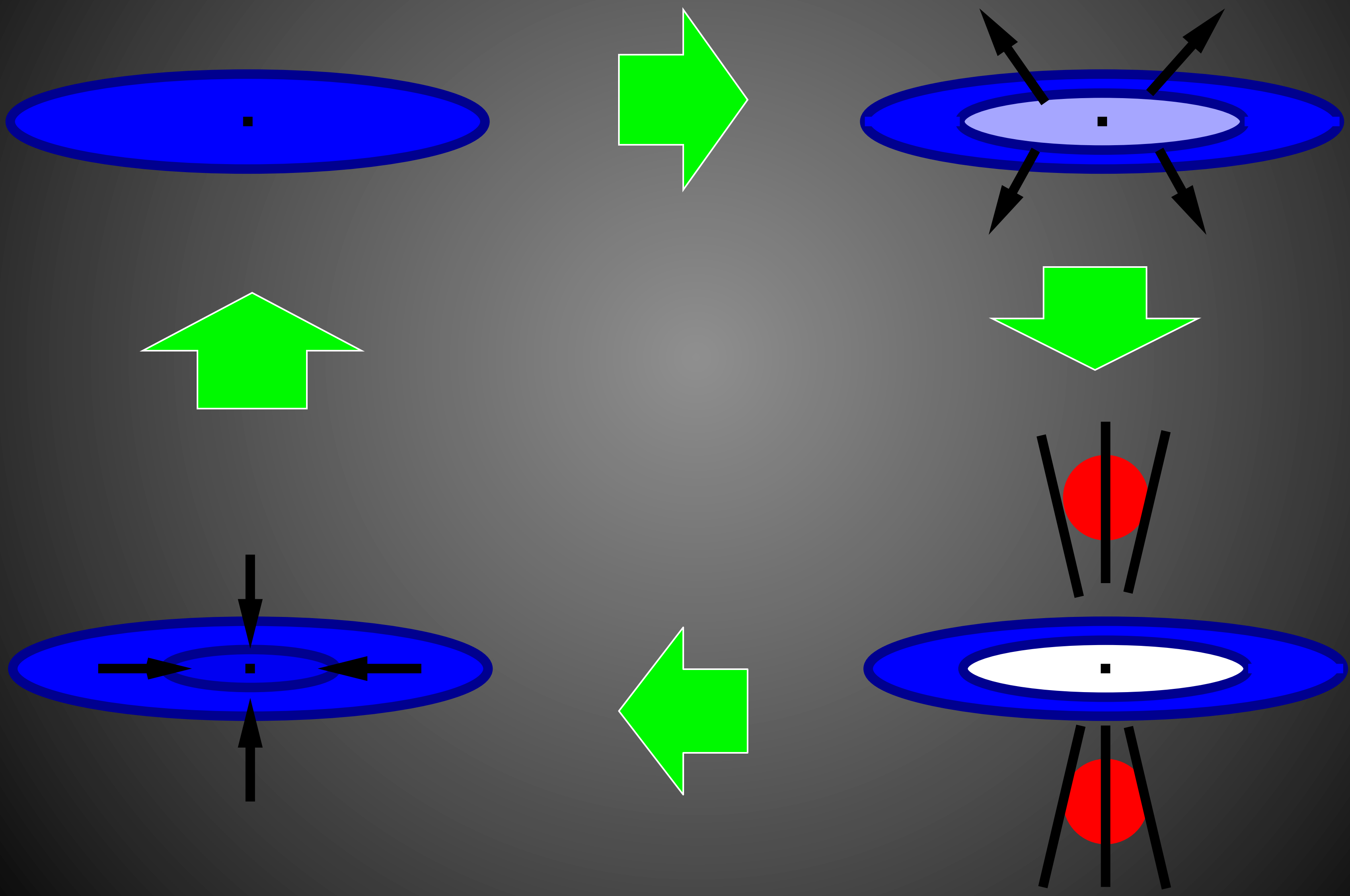
Lohfink+ (2013b)



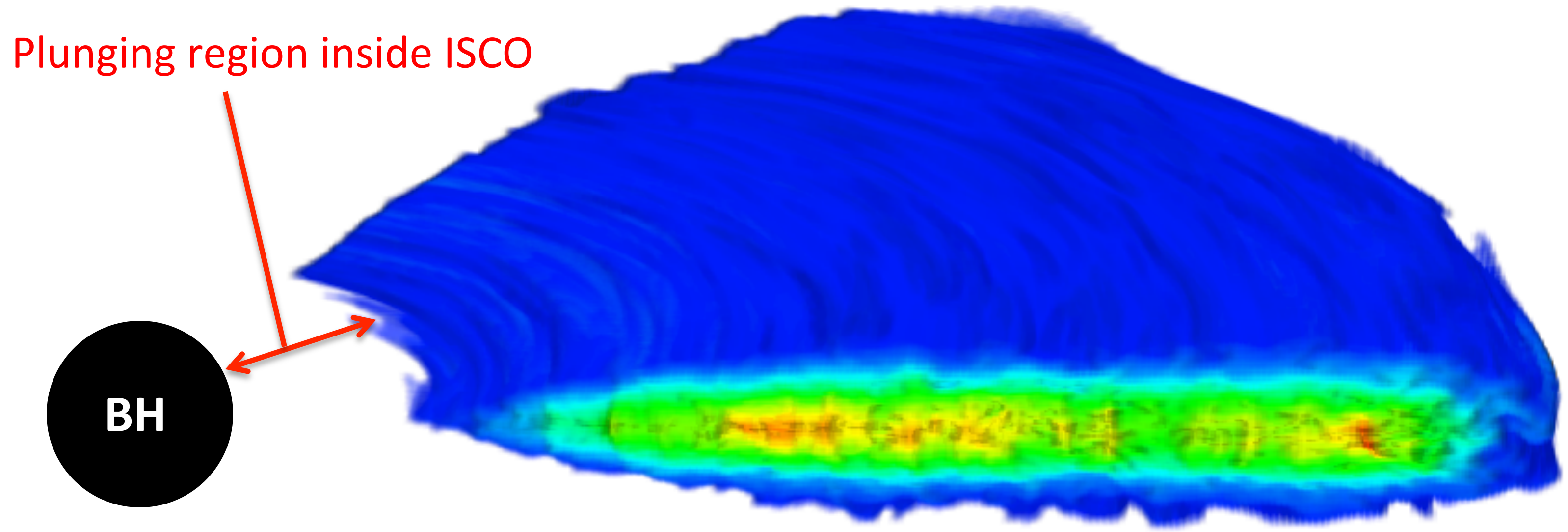
Lohfink+ (2013b)

Multi-epoch analysis yields a > 0.95, r_{in} ranging from <2 to 60 r_g (90% CL).

The Jet Cycle



Assumption of ISCO Truncation



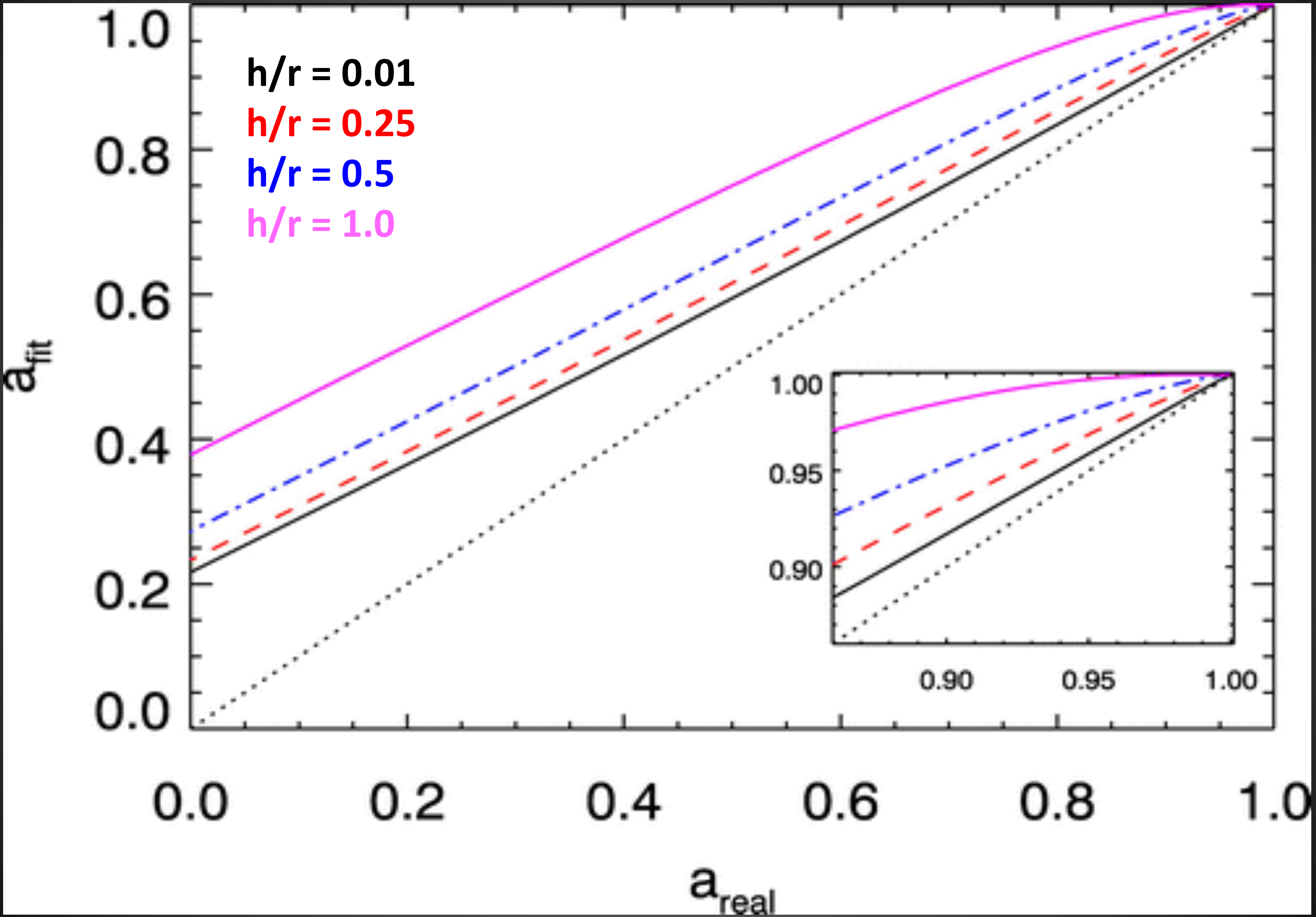
3D MHD simulation of a geometrically-thin accretion disk.

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

Rapid drop in τ, rise in ξ within ISCO.

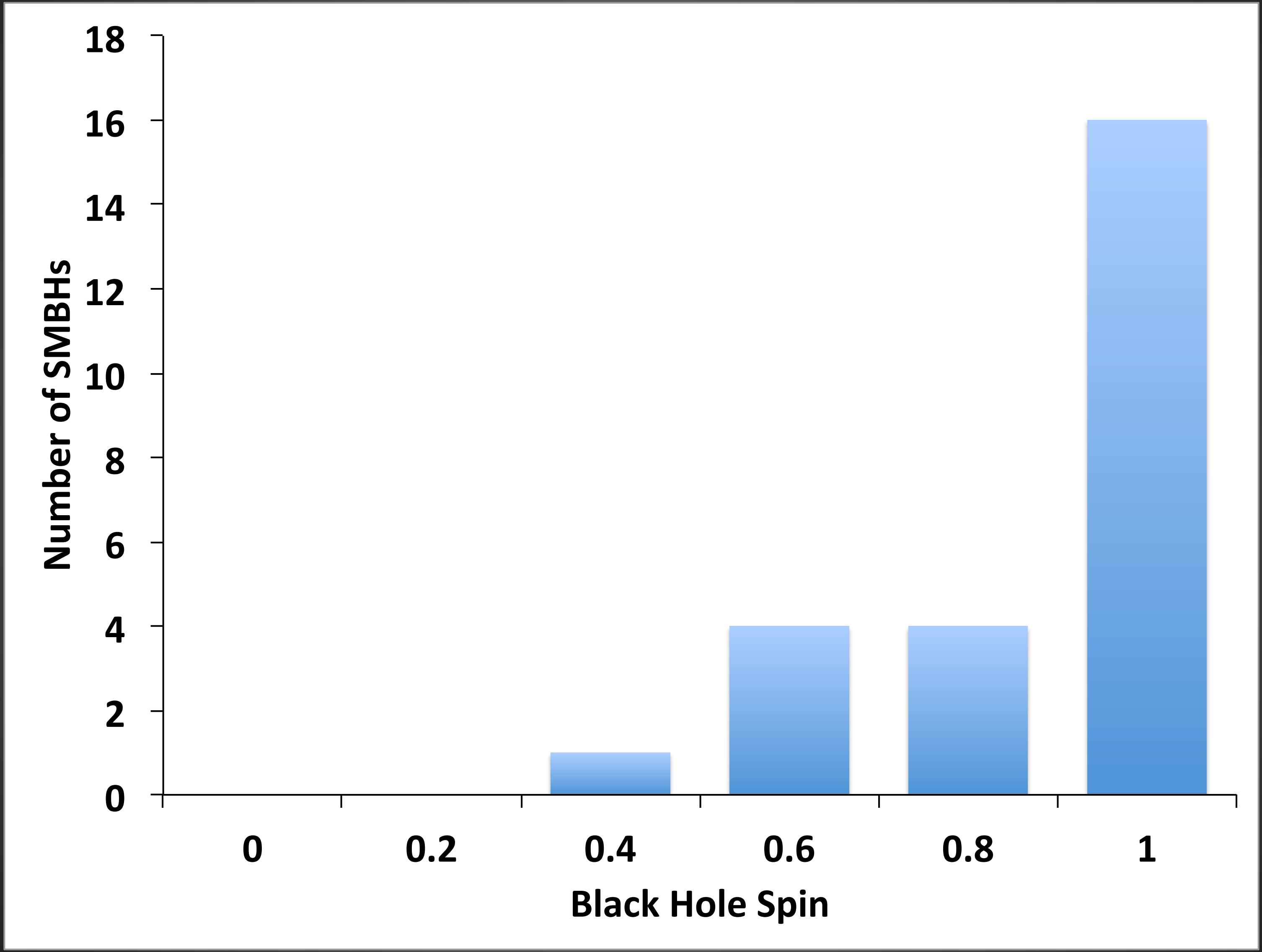
Reynolds & Fabian (2008)

Systematic Error from Emission ≤ISCO



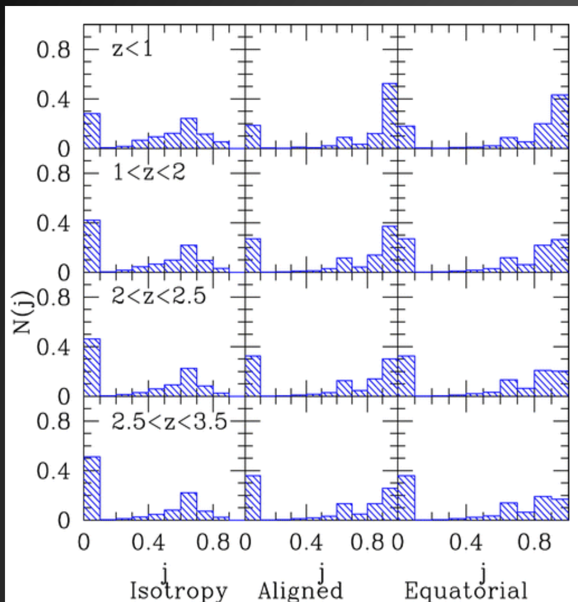
Reynolds & Fabian (2008)

The Distribution of SMBH spins (so far)

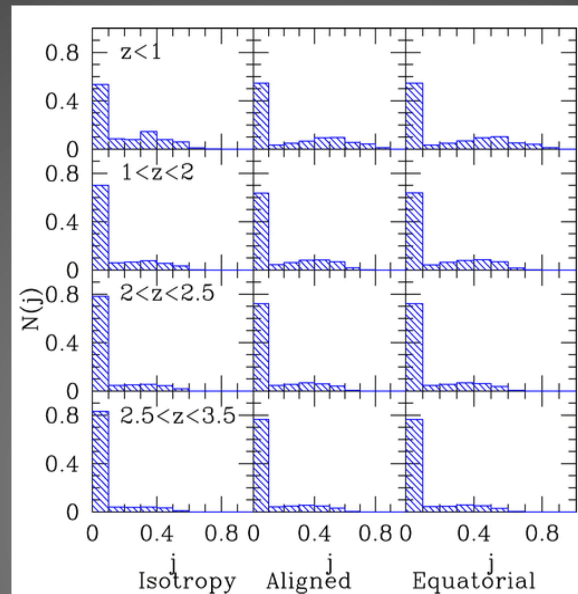


Brenneman (*SpringerBrief* 2013); Reynolds (2014); Walton+ (2013)

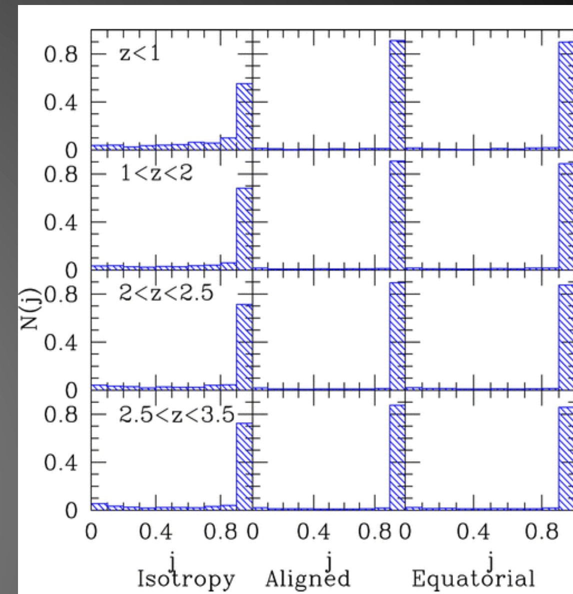
Black Hole Spin and Galaxy Evolution



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.

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** 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.

Summary

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

- **Wide range of measured spins** for AGN, but so far all are consistent with $a \geq 0$, tendency toward high spin values.

- **Larger sample size** of AGN spins (**esp. RLAGN**) must be obtained with combination of **broad-band X-ray time-resolved spectroscopy, multi-epoch spectroscopy and timing analysis** with various instruments to begin understanding spin demographics, AGN structure, relation to jets.

- Great care must be taken when evaluating different models, consideration of **systematic uncertainties.**

Future Work

- Further **self-consistent model fitting** using RELXILL (Garcia+ 2014)
  - exploration of **systematic errors on spin constraints**

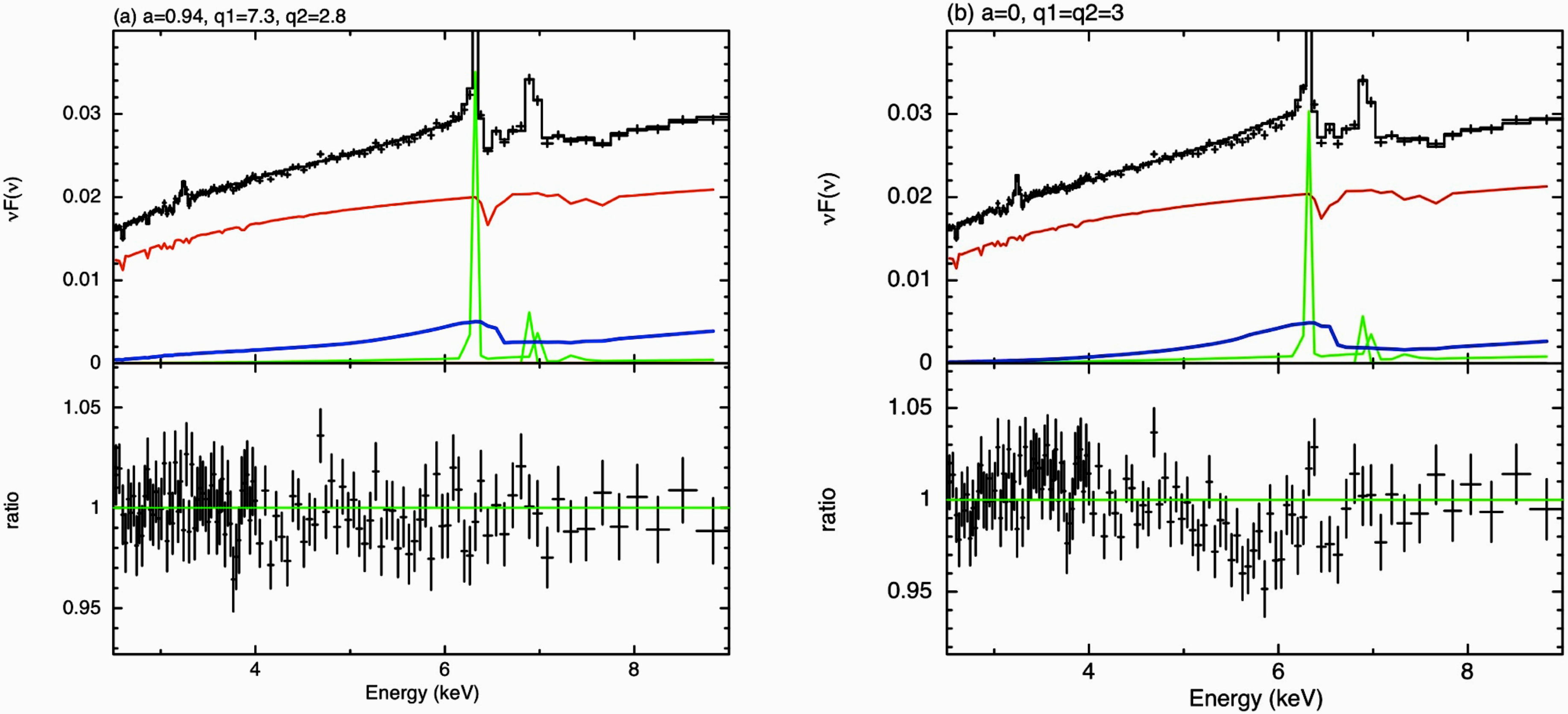
- *Astro-H* (2016): higher E.A., better spectral resolution than *Suzaku*, simultaneous high-energy data superior to *NuSTAR*.
  - separate absorption from emission
  - probe soft excess more accurately

- *ASTROSAT* (?): Simultaneous UV & X-ray spectroscopy
  - tighter constraints on disk thermal emission, warm absorption over wider kinematic scale

- *Athena/LOFT* (~2028): Further large increase in effective area
  - probe accretion physics on orbital timescales
  - increase sample size of spin measurements by ~10x
  - trace individual hotspots in the disk, Fe K reverberation measurements much more robust

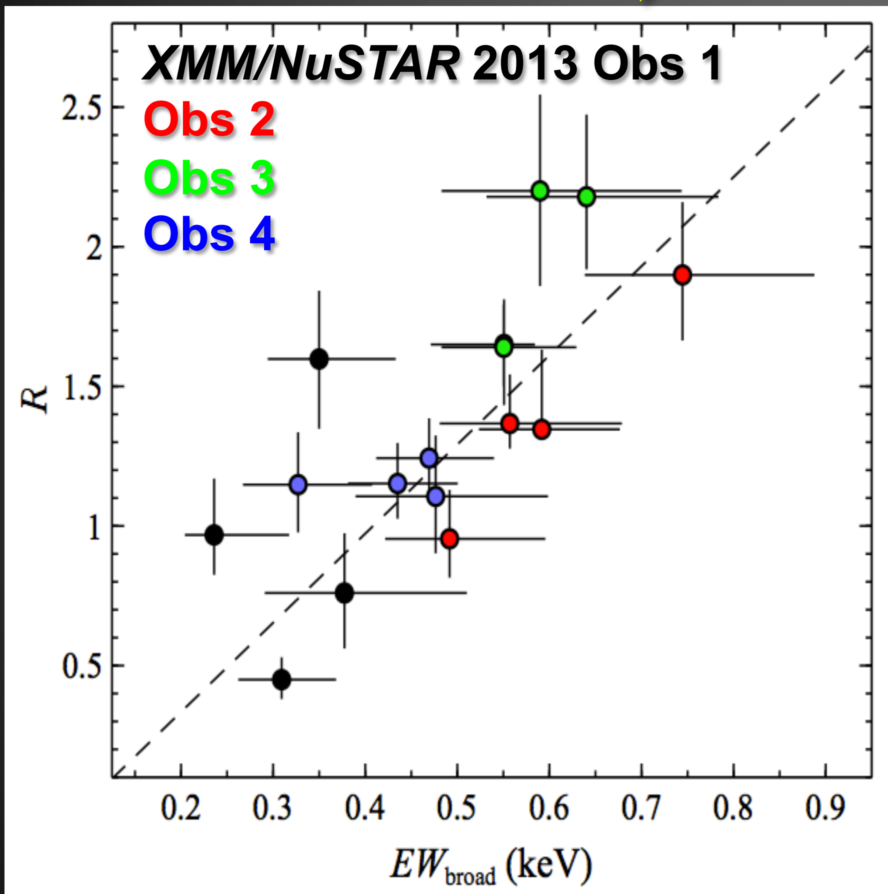
EXTRAS

Effects of Spin on Spectrum Are Subtle…

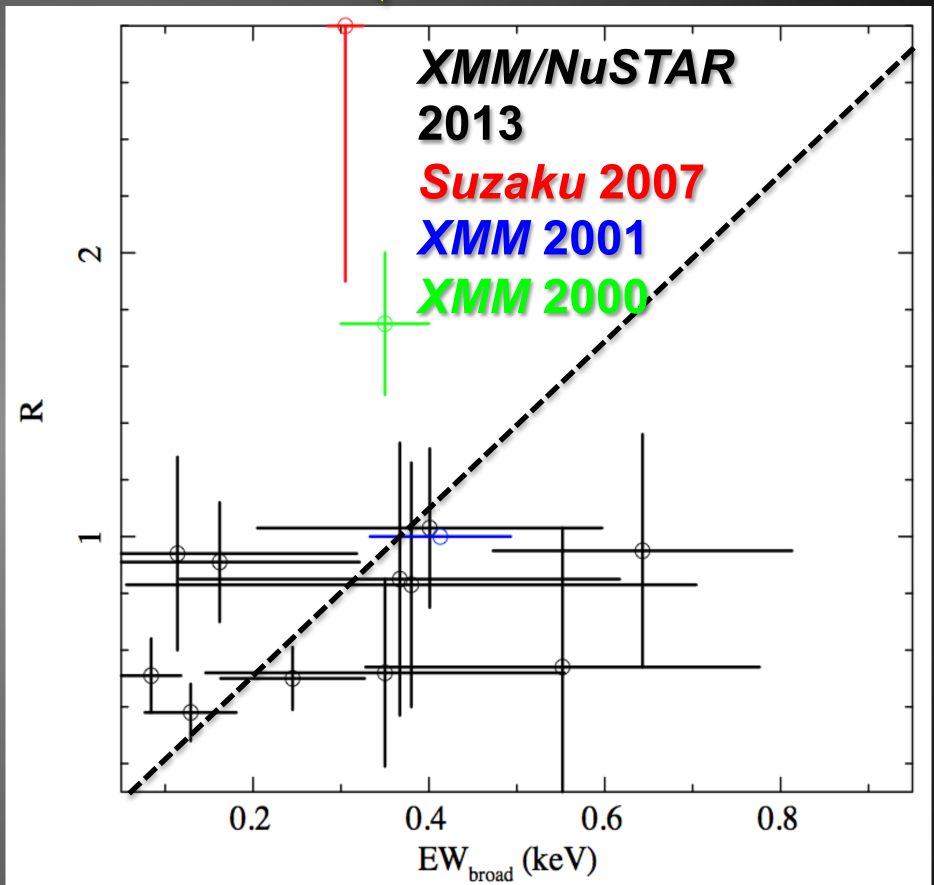


Reynolds+ (2012)

NGC 1365 vs. MCG6



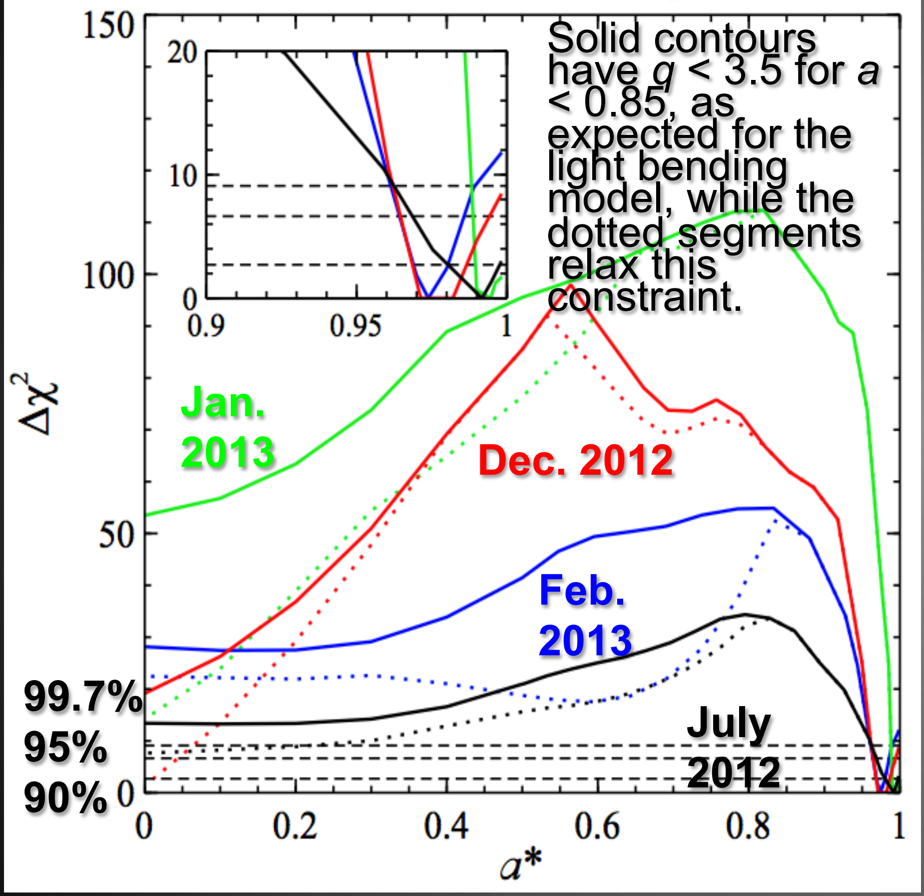
Walton+ 2014 → 106.03



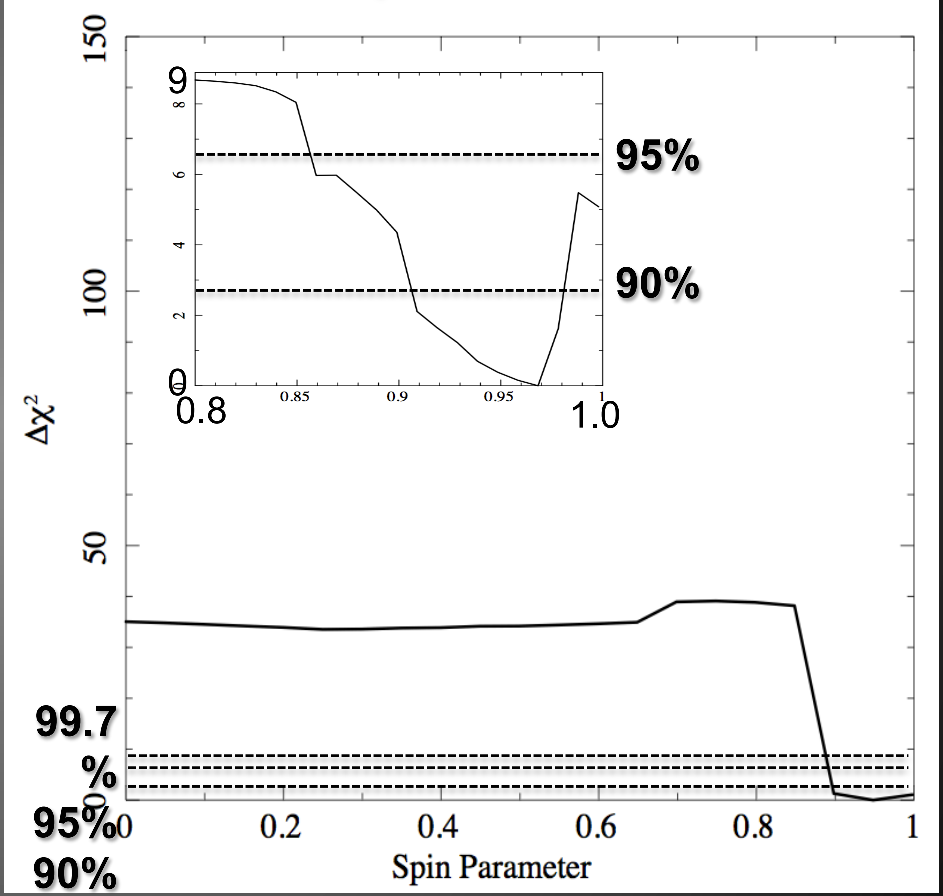
Brenneman+ (in prep.)

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

NGC 1365 vs. MCG6

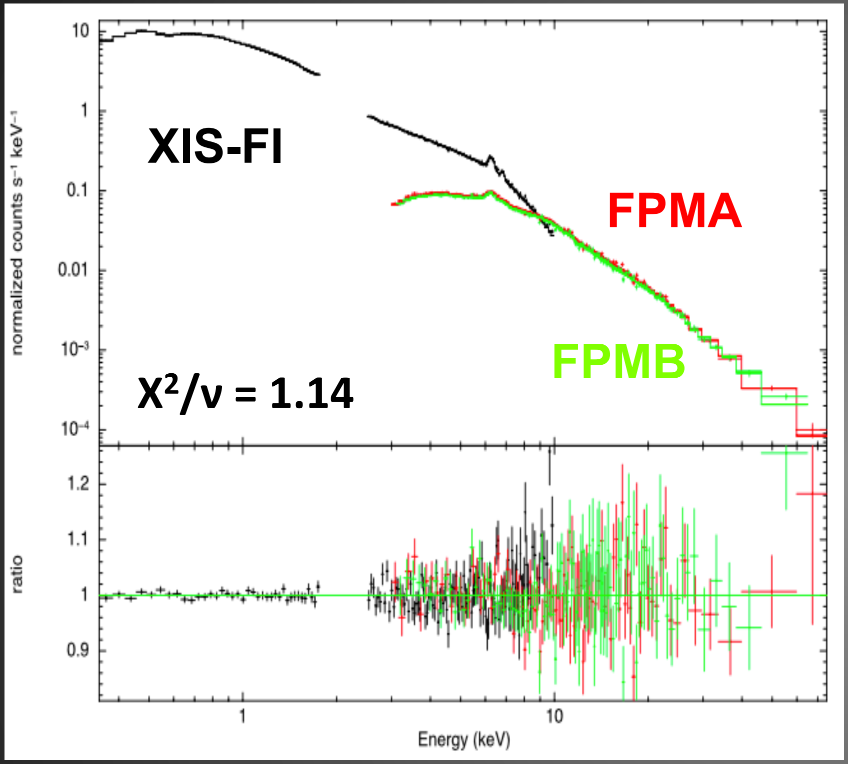


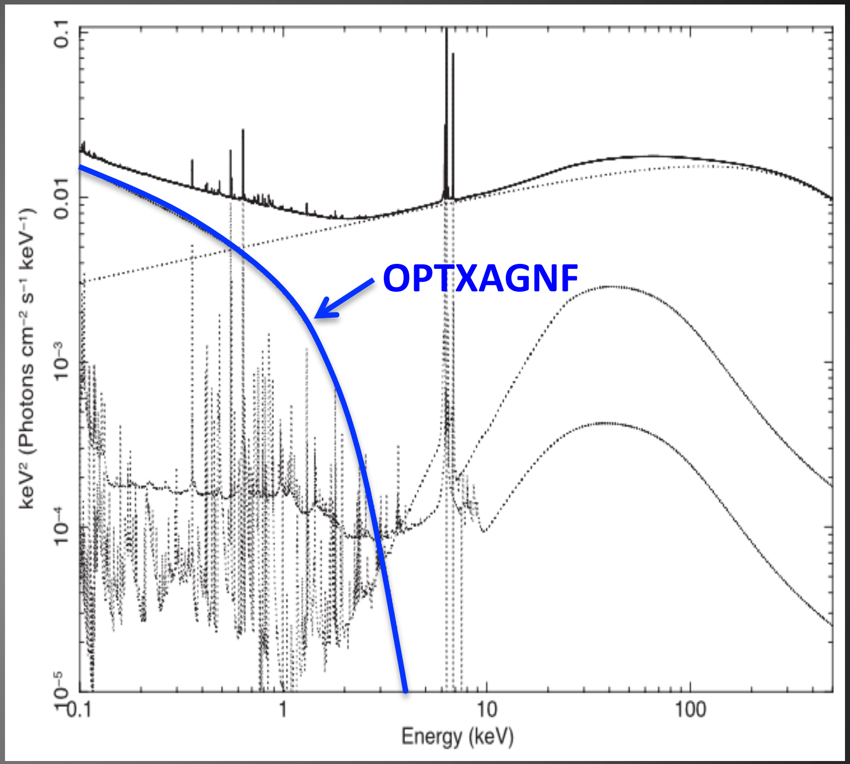
Walton+ 2014 → **106.03**



Brenneman+ (in prep.)

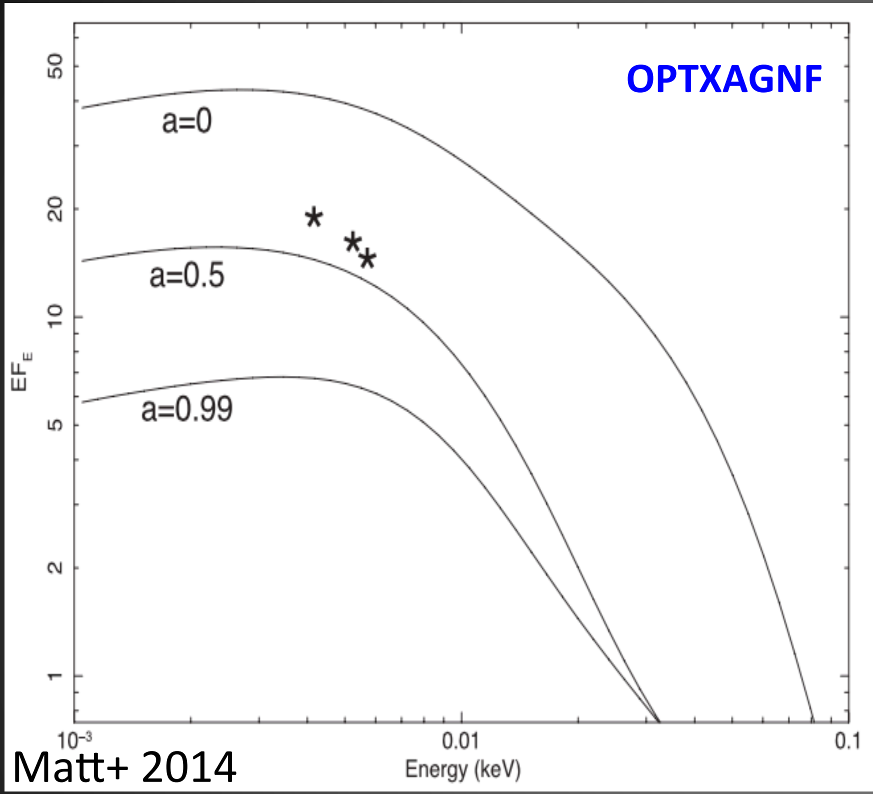
Ark 120: Alternatives for Modeling the Soft X-ray Excess

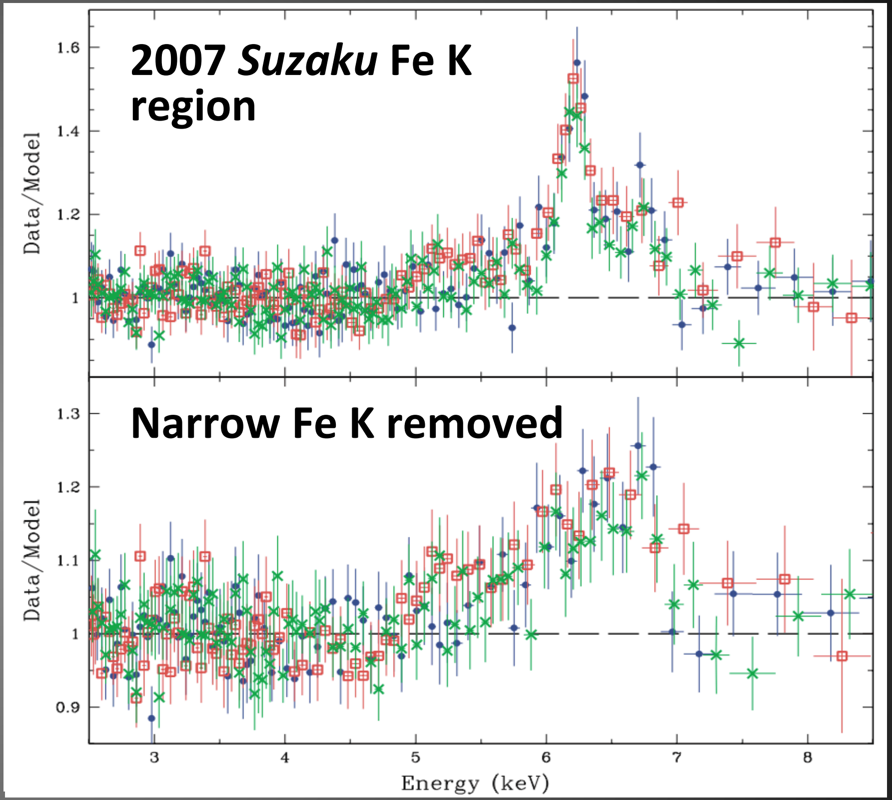




- 2013 joint *Suzaku/NuSTAR* ~80 ks observation shows strong soft X-ray excess visible above power-law continuum in another massive, bare Sy1 AGN (Matt+ 2014).
- Well fit with continuum power-law, distant and inner disk reflection, soft excess with OPTXAGNF component (Done+ 2012).
- Hot corona (hard X-rays) is optically-thick and extended here, whereas in the 2009 *Suzaku* observation it was more compact. The spectrum in the *Suzaku* observation was significantly steeper, suggesting an optically-thin corona.

Ark 120: Alternatives for Modeling the Soft X-ray Excess





- The 2007 *Suzaku* ~100 ks spectrum of Ark 120 was well fit with a continuum power-law plus distant and inner disk reflection. The latter completely accounted for the observed excess in hard and soft energies.

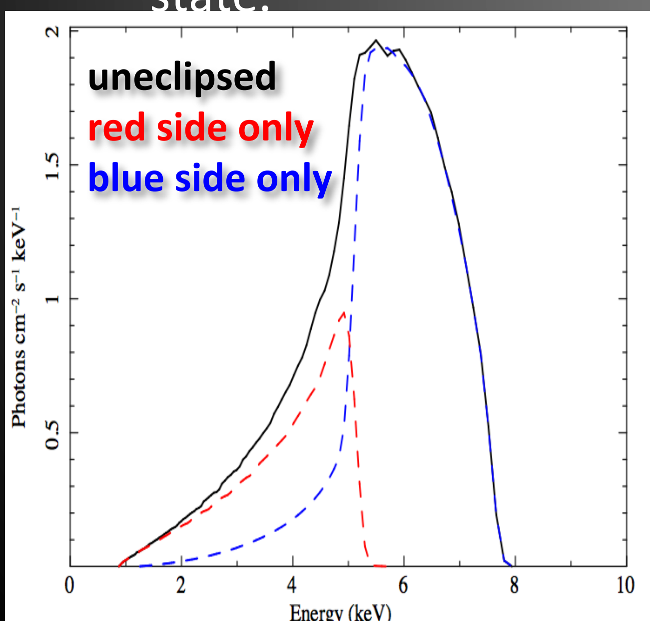
- The 2013 joint *Suzaku/NuSTAR* ~80 ks spectrum showed no evidence for inner disk reflection, though it still showed a strong soft-excess.

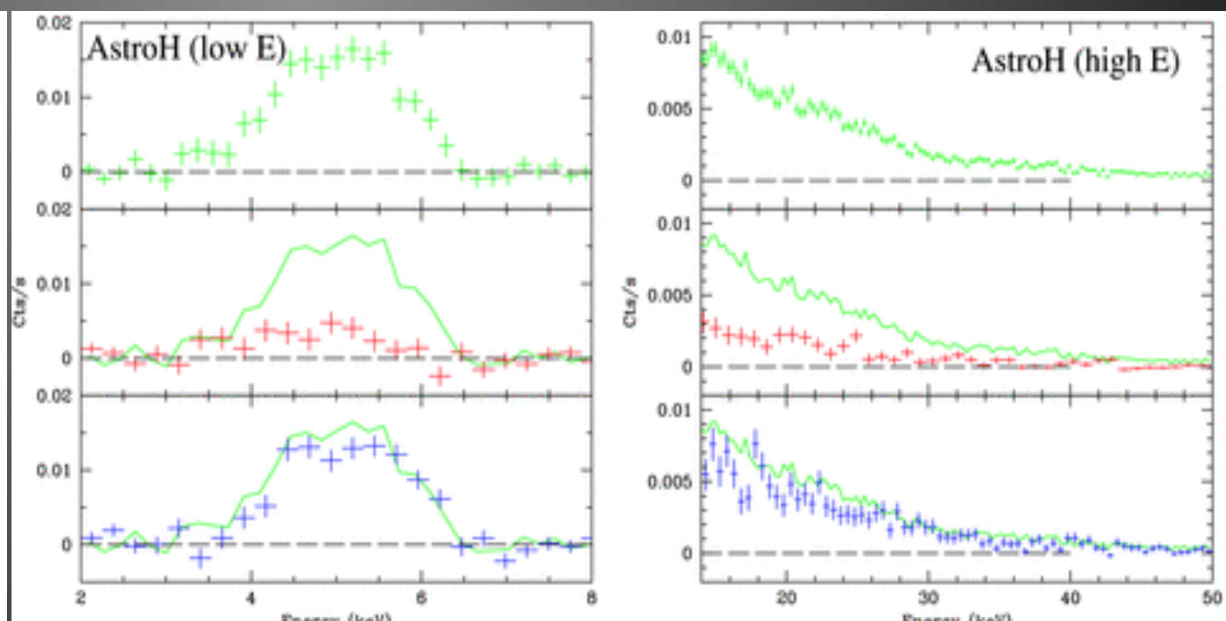
Accretion Disk Tomography

- **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.

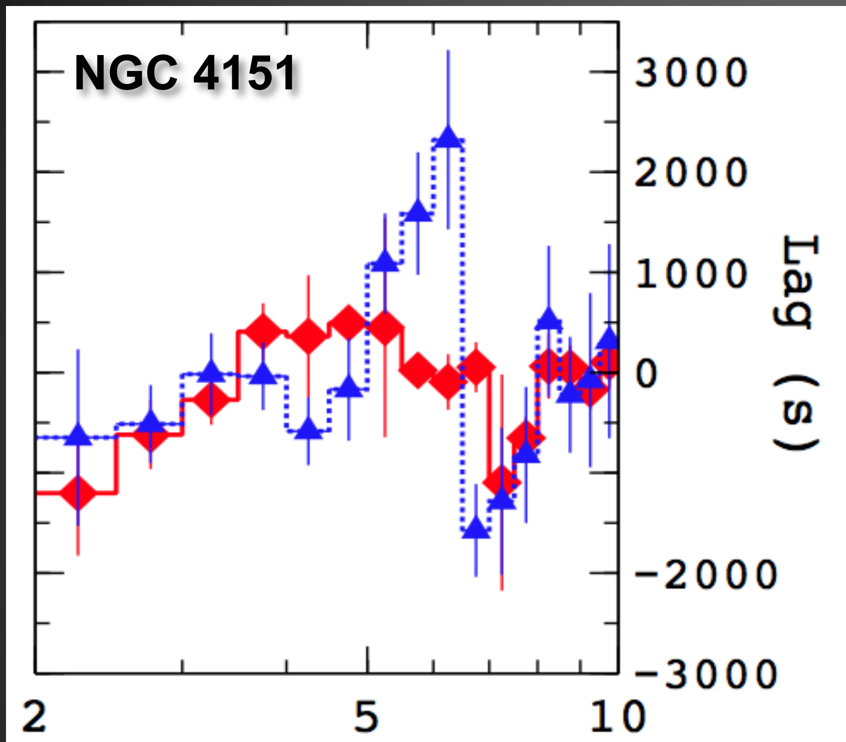
- This type of **accretion disk tomography** possible for high-contrast eclipses: e.g., factor ~10 increase in column density during high flux state.



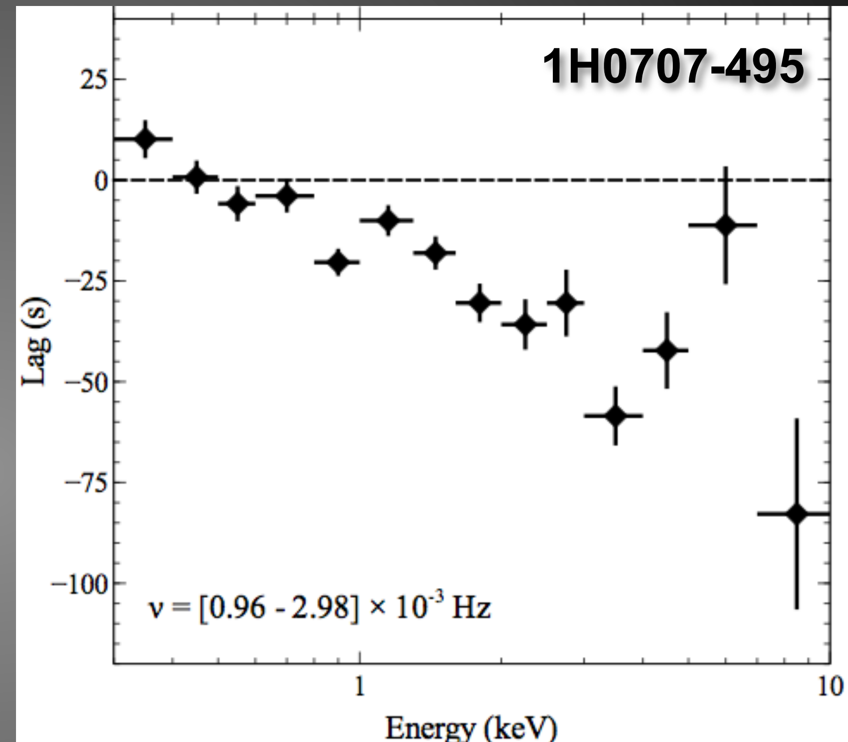


Risaliti+ (2011)

Fe Kα Reverberation Mapping



Zoghbi+ (2012)



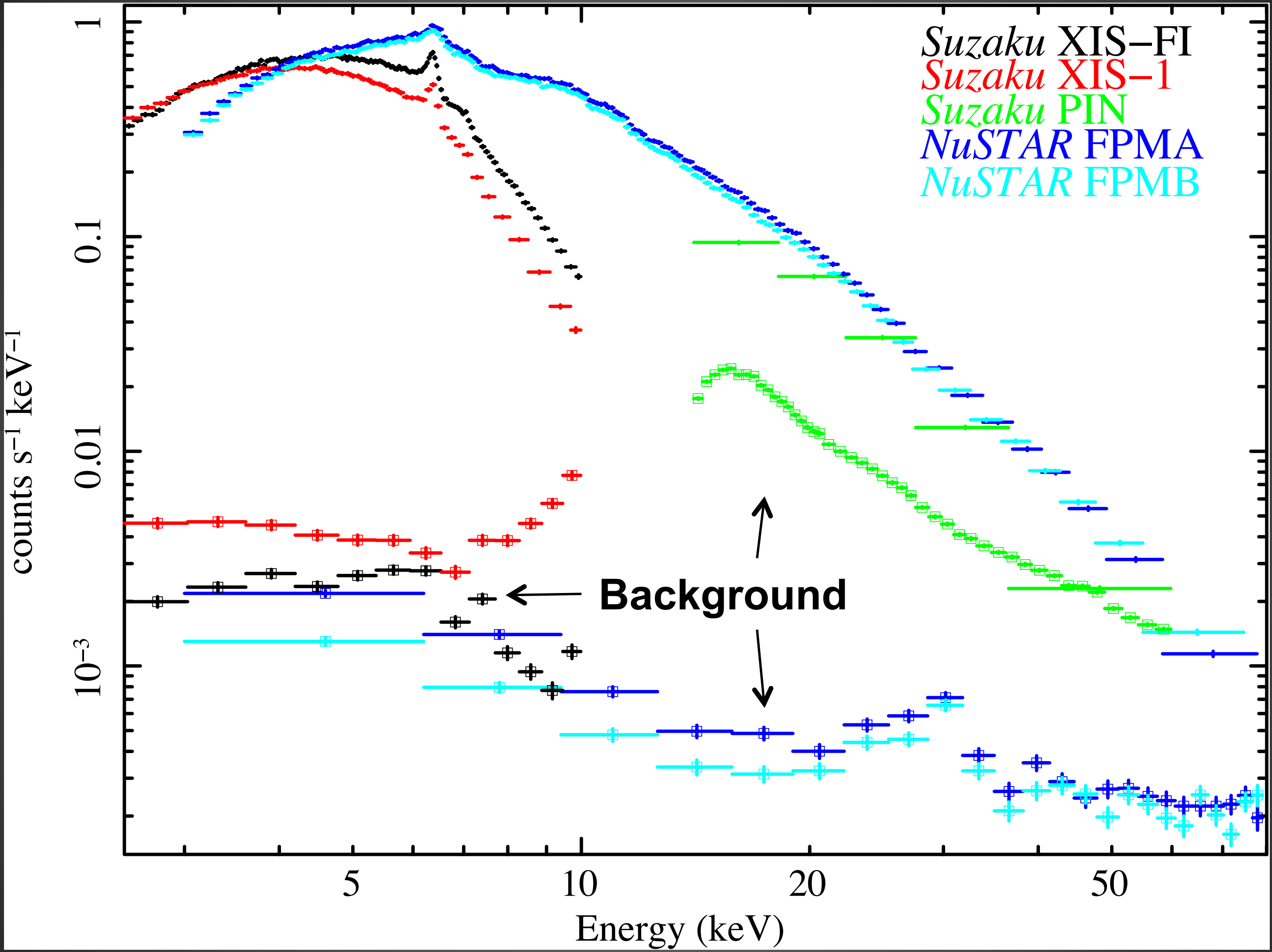
Kara+ (2013)

- 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.

Why *NuSTAR/Suzaku* or *XMM*?



Yields highest S/N achievable to date over 0.5-79 keV band; ~100x improvement over previous data >10 keV with *NuSTAR*. Allows definitive deconvolution of continuum, reflection, absorption spectral components.

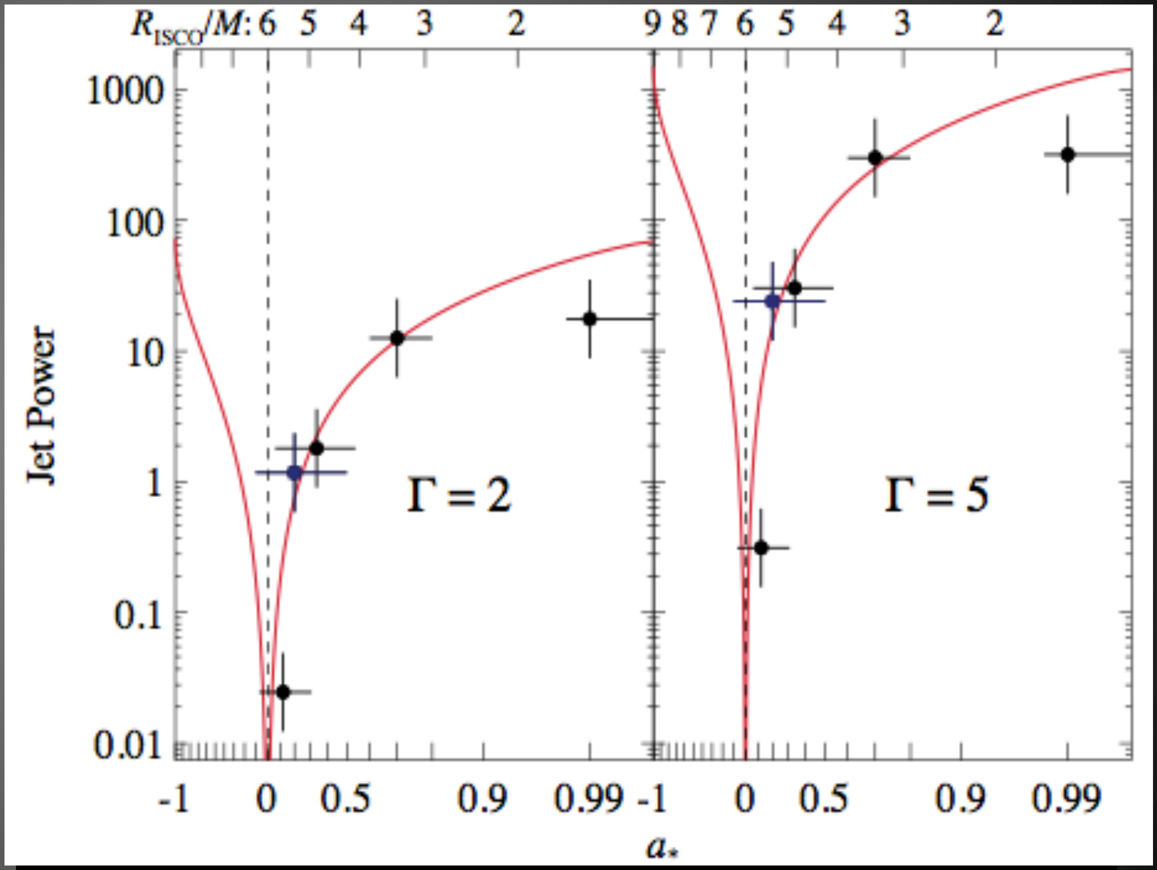
Black Hole Spin and Jet Production

• 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)