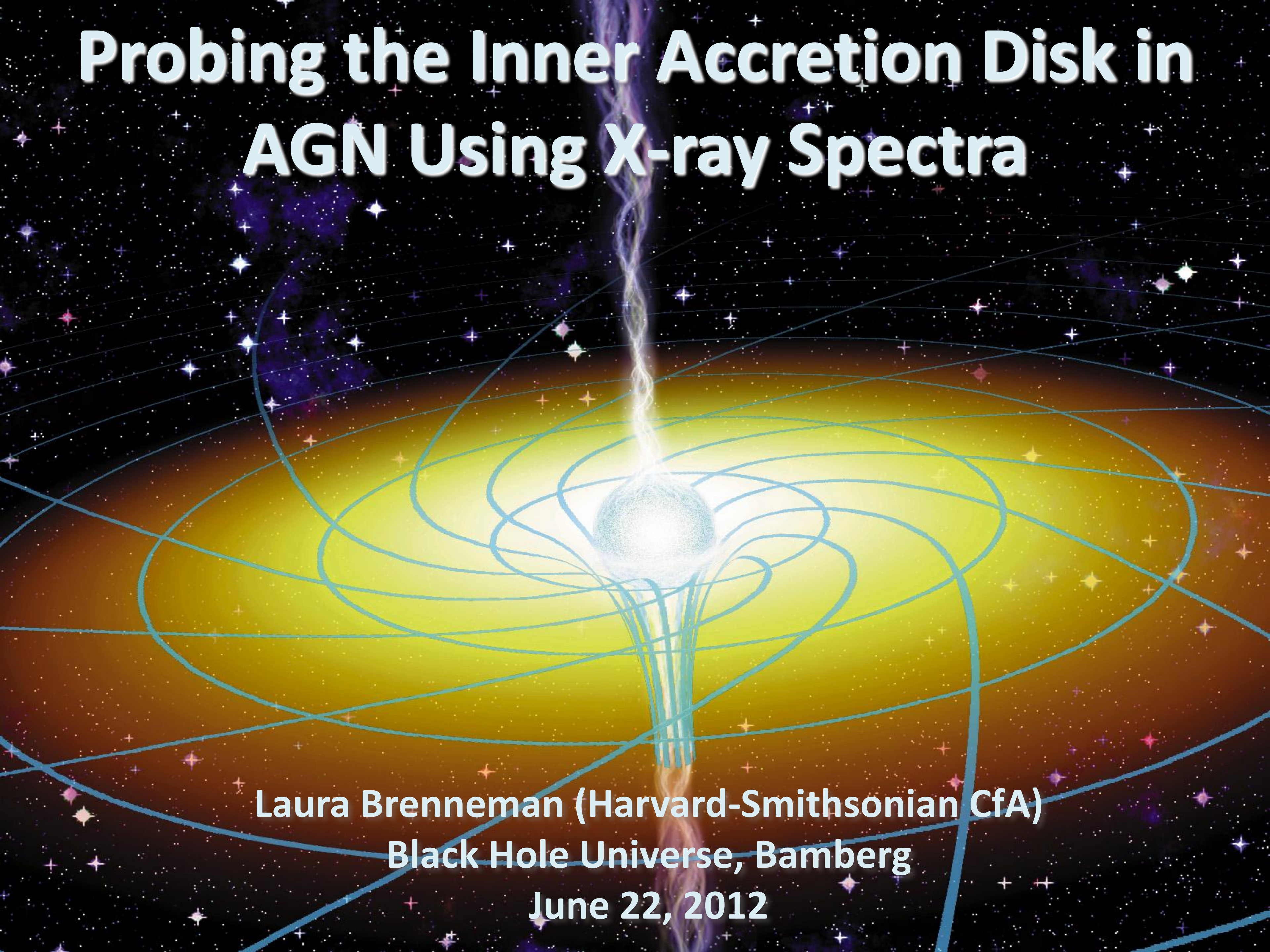
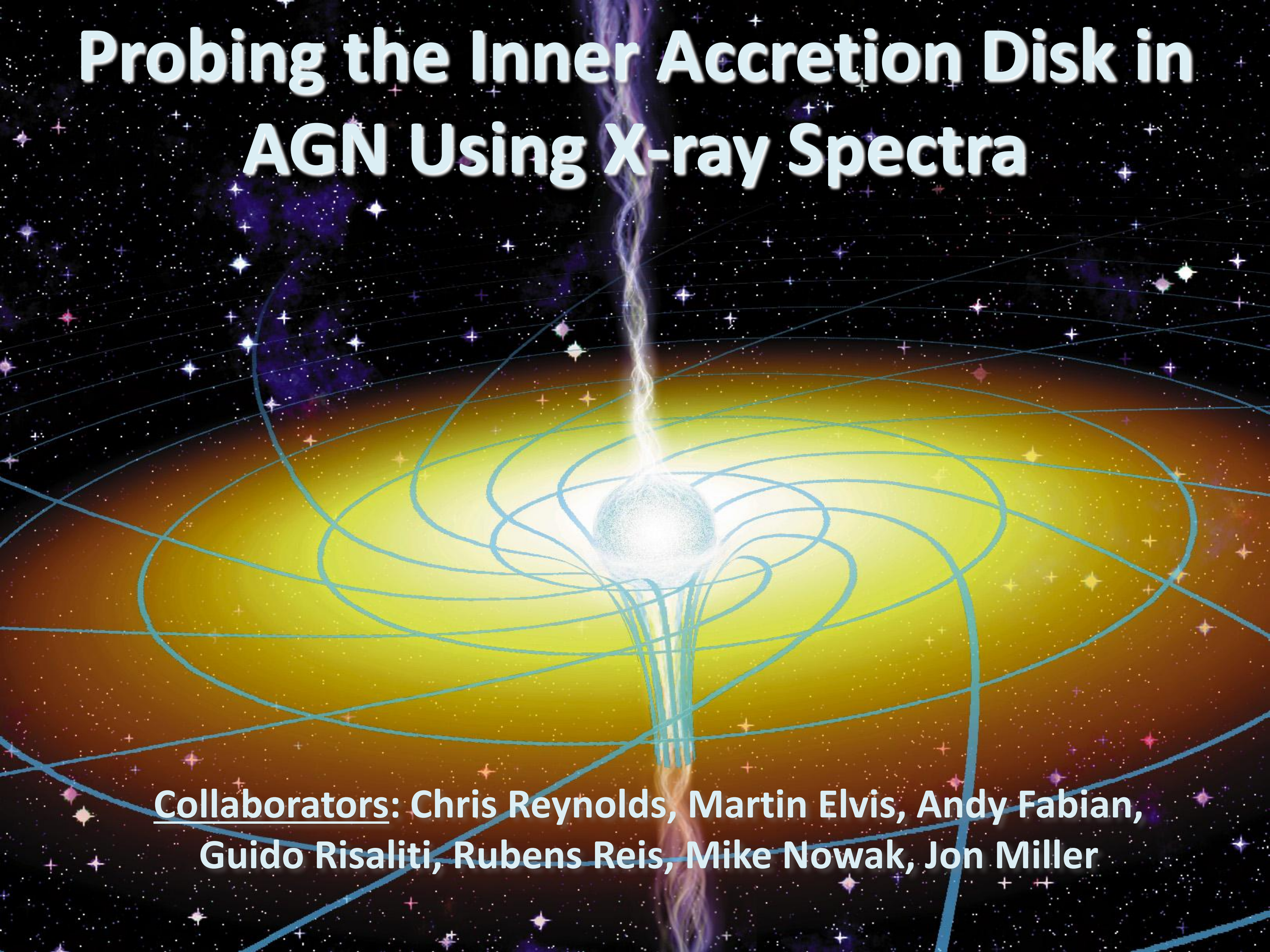
Probing the Inner Accretion Disk in AGN Using X-ray Spectra



Laura Brenneman (Harvard-Smithsonian CfA)

Black Hole Universe, Bamberg

June 22, 2012



Probing the Inner Accretion Disk in AGN Using X-ray Spectra

Collaborators: Chris Reynolds, Martin Elvis, Andy Fabian, Guido Risaliti, Rubens Reis, Mike Nowak, Jon Miller

Outline

- One motivation for studying inner accretion flow: black hole spin

- Measuring spin: methods and caveats

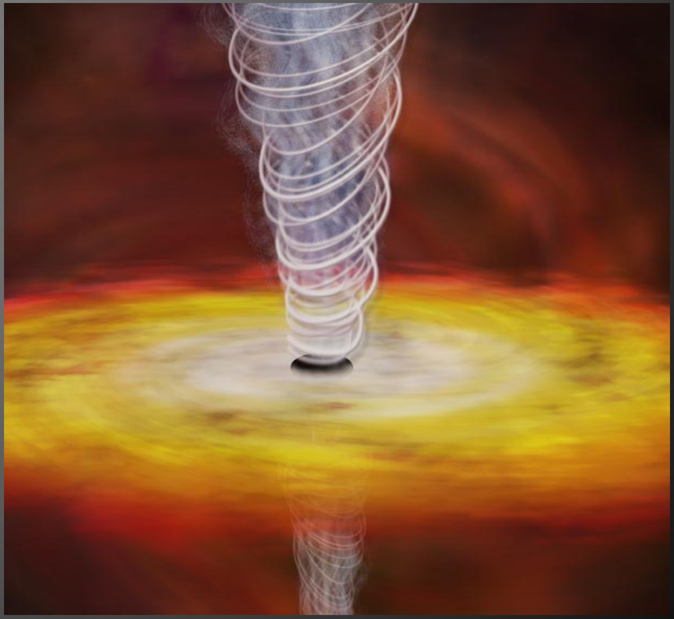
- Spin measurements in AGN so far

- Implications for BH/host galaxy evolution

- Future prospects

The Importance of Black Hole Spin

- Provides rare means of **probing strong-field gravity regime**.
- Indicator of recent gas **accretion vs. merger history** of supermassive BHs.
- Thought to drive **jet production** and outflows in all BHs, seeding the ISM/IGM with matter and energy.



How Can We Measure BH Spin?

- ***Thermal Continuum Fitting***

    - **X-ray Spectral** (XRBs only: *M, i, D* must be accurately known)

- ***Inner Disk Reflection Modeling***

    - **X-ray Spectral** (both XRBs and AGN)

- High Frequency Quasi-periodic Oscillations**

    - **X-ray Timing** (both XRBs and AGN)

- Polarization Degree & Angle vs. Energy**

    - **X-ray Spectral**, **polarimetry** (easier for XRBs)

- Imaging the Event Horizon Shadow**

    - **≤mm-VLBI Imaging** (AGN only: must be large, e.g., Sgr A*, M87)

How Can We Measure BH Spin?

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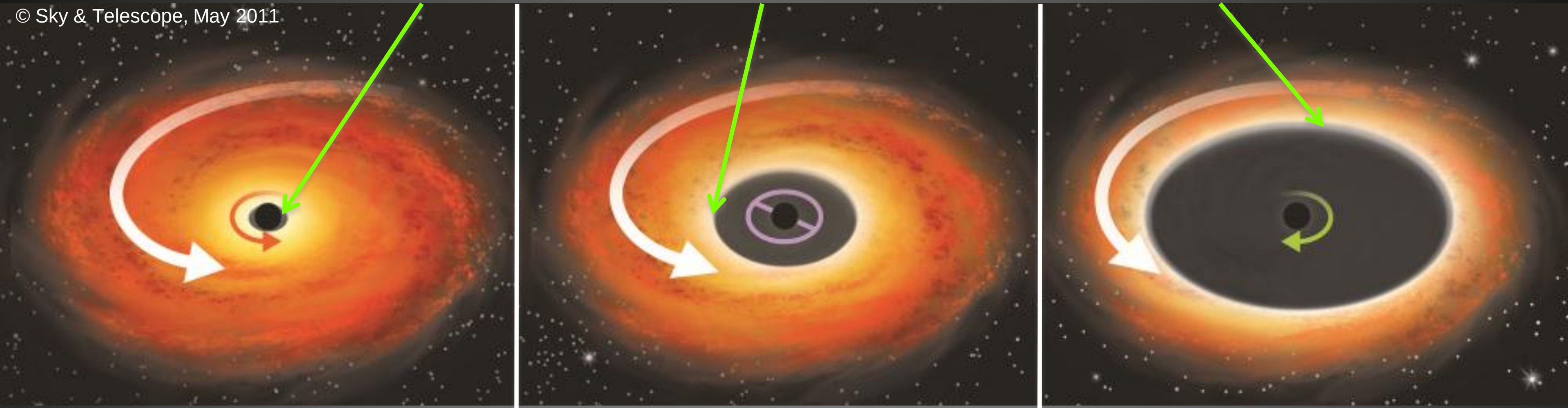
The Innermost Stable Circular Orbit

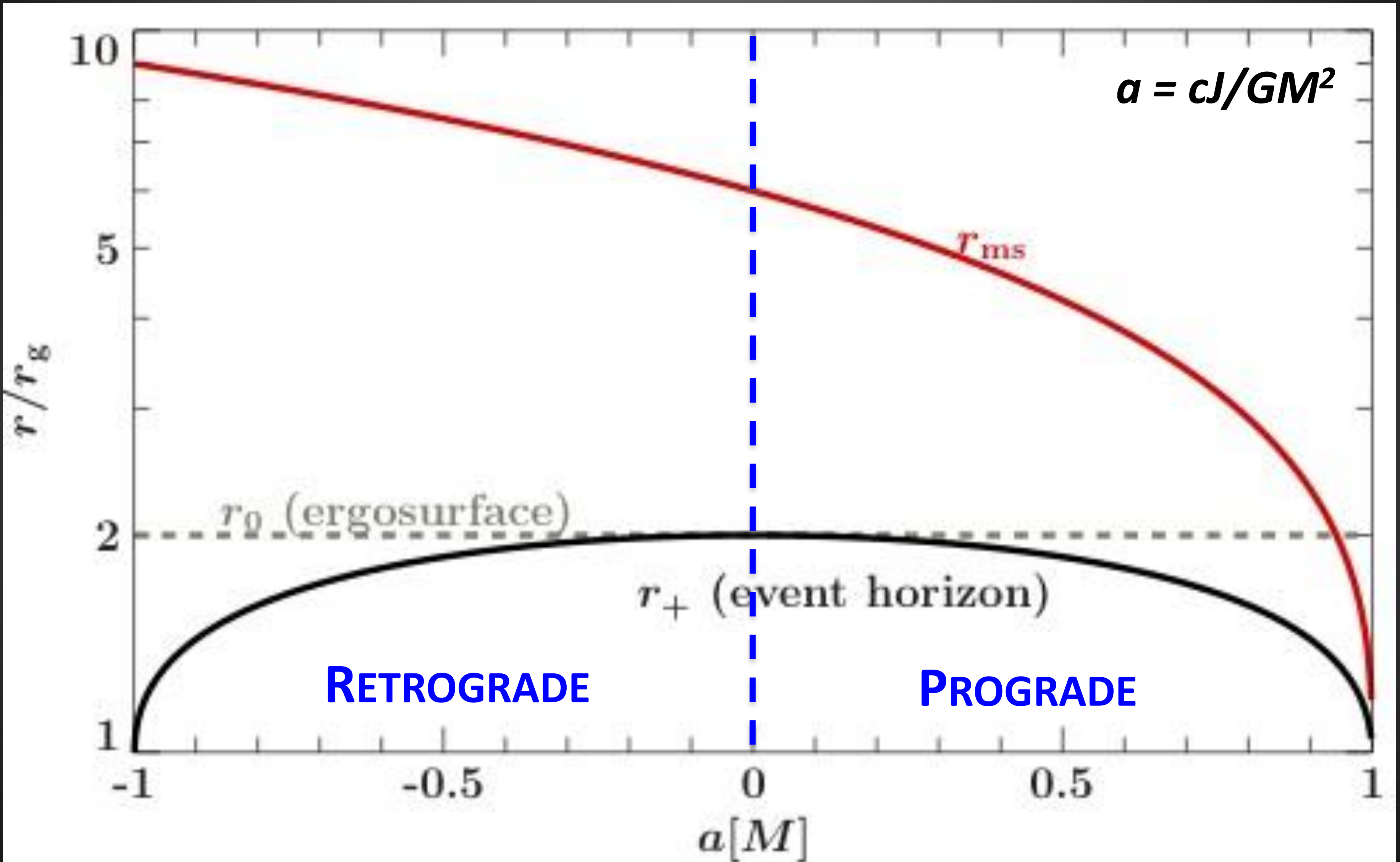


- Maximally-spinning ***prograde* BH** (spinning in same direction as disk).
- ISCO at 1 GM/c^2.
- Frame-dragging rotationally supports orbits closer to BH before plunging.

- **Non-spinning BH**.
- Accretion disk still rotates!
- ISCO at 6 GM/c^2.
- No frame-dragging: orbits cease to spiral in and instead plunge toward BH inside ISCO.

- Maximally-spinning ***retrograde* BH** (spinning in opposite direction as disk).
- ISCO at 9 GM/c^2.
- Frame-dragging acts in opposition to disk angular momentum, causing orbits to plunge farther out.

GR Predicts Monotonic Relation for a, r_{ISCO}



Dauser, Wilms, Reynolds & Brenneman (2010)

Modeling the Reflection Spectrum

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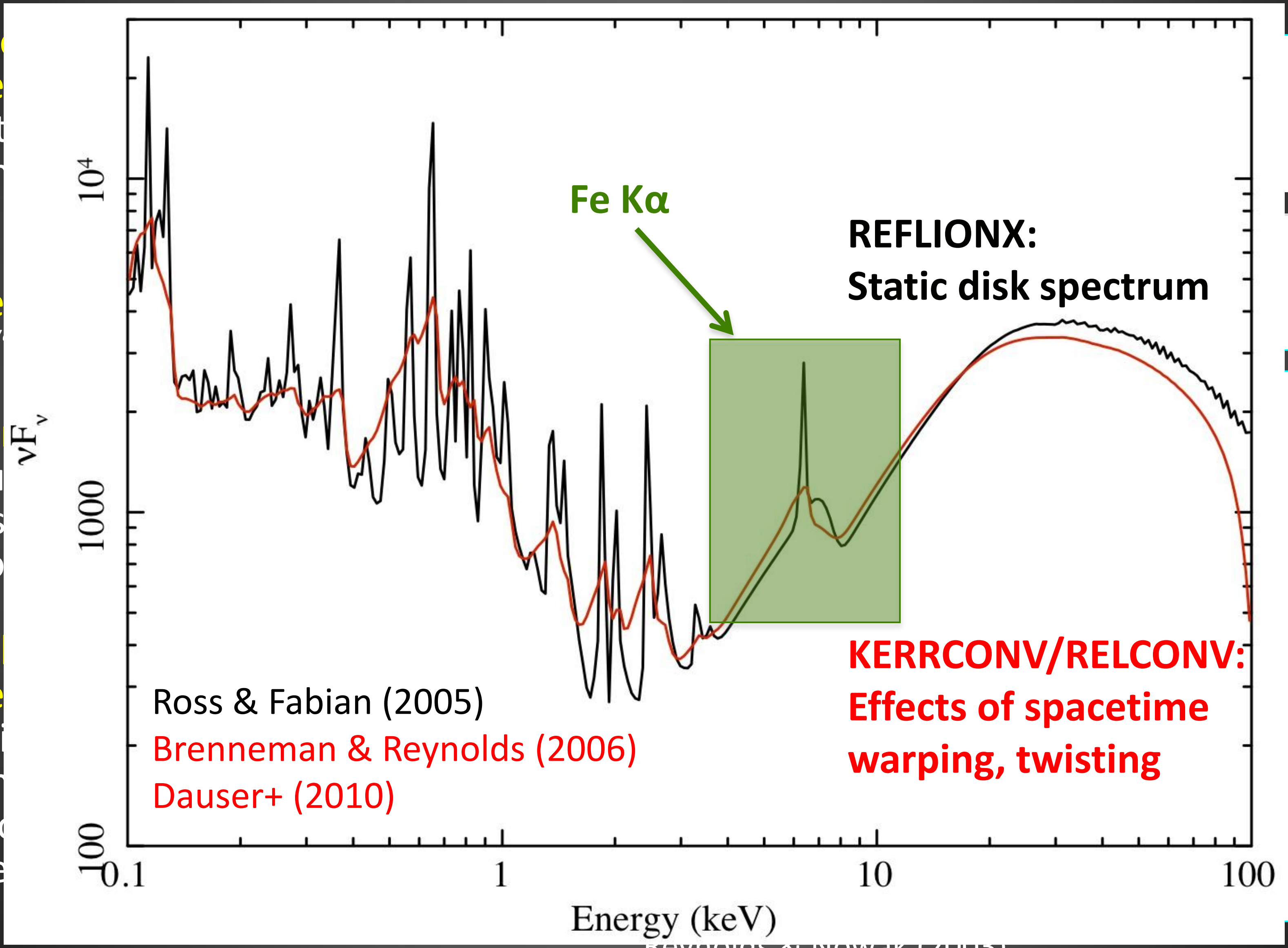
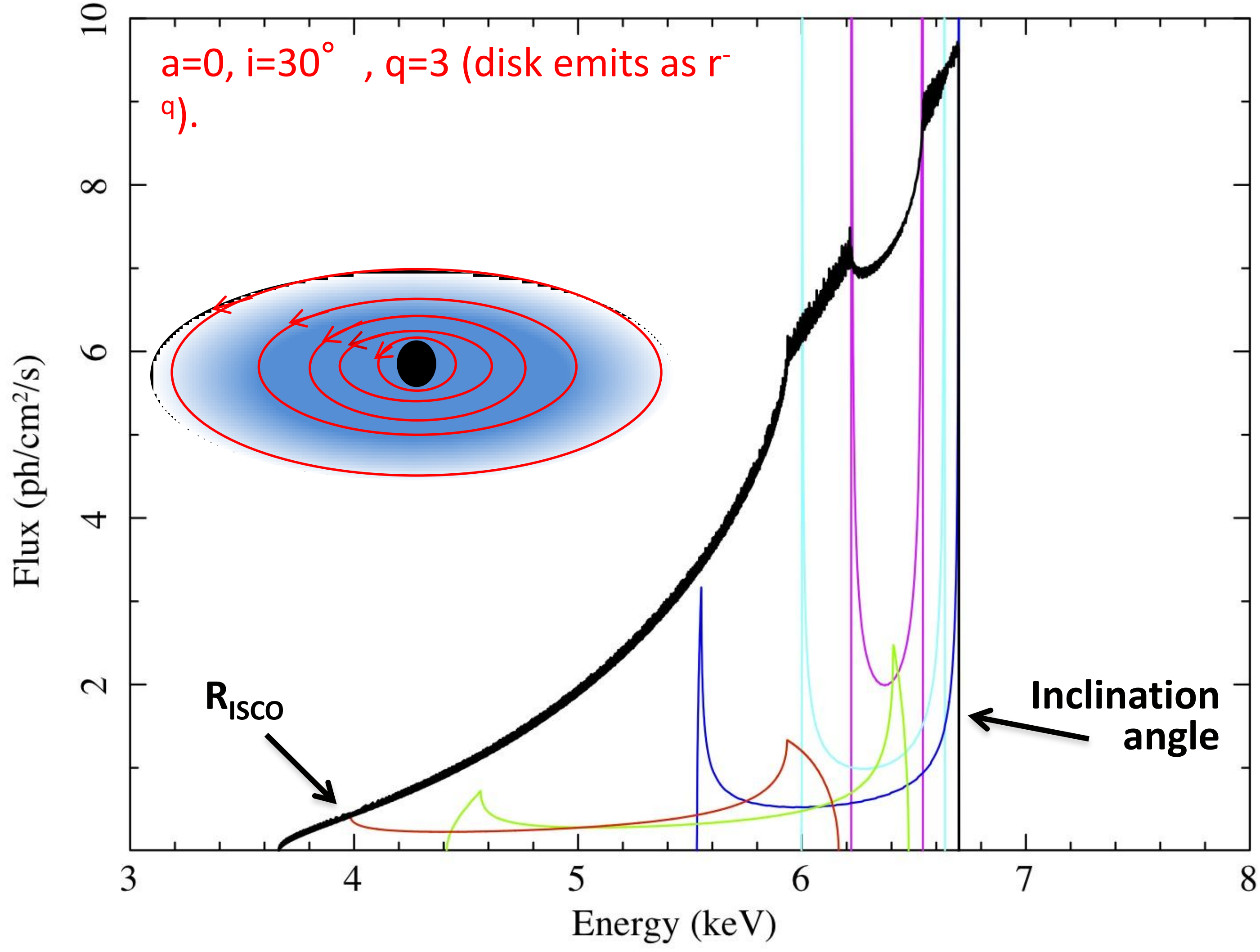
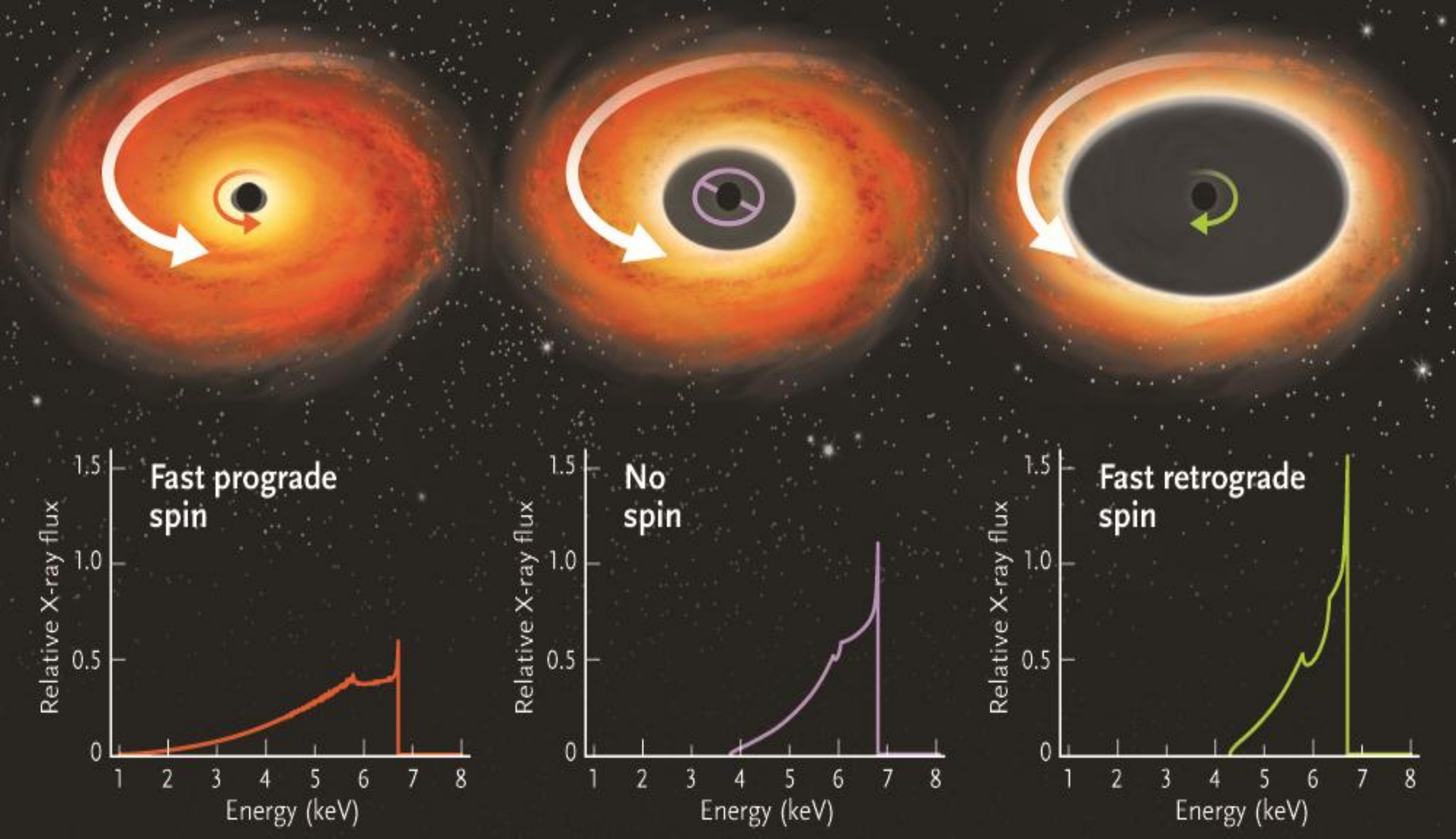


Reynolds & Nowak (2003)

Fe Kα emission line from different disk annuli



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



Shape of Fe Kα emission line allows us to measure BH spin in systems of arbitrary mass: BHXRBs and AGN.

BH Spins in AGN

- Sample Size: **~30 SMBHs** in bright, nearby AGN with broad Fe Kα lines (Miller+ 2007, Nandra+ 2007, de La Calle Perez+ 2010).
  - 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, Guainazzi+ 2006), and line must be relativistically broad with $r_{in} \leq 9\ r_g$.
- Technique used: **Inner Disk Reflection** (e.g., broad Fe Kα):

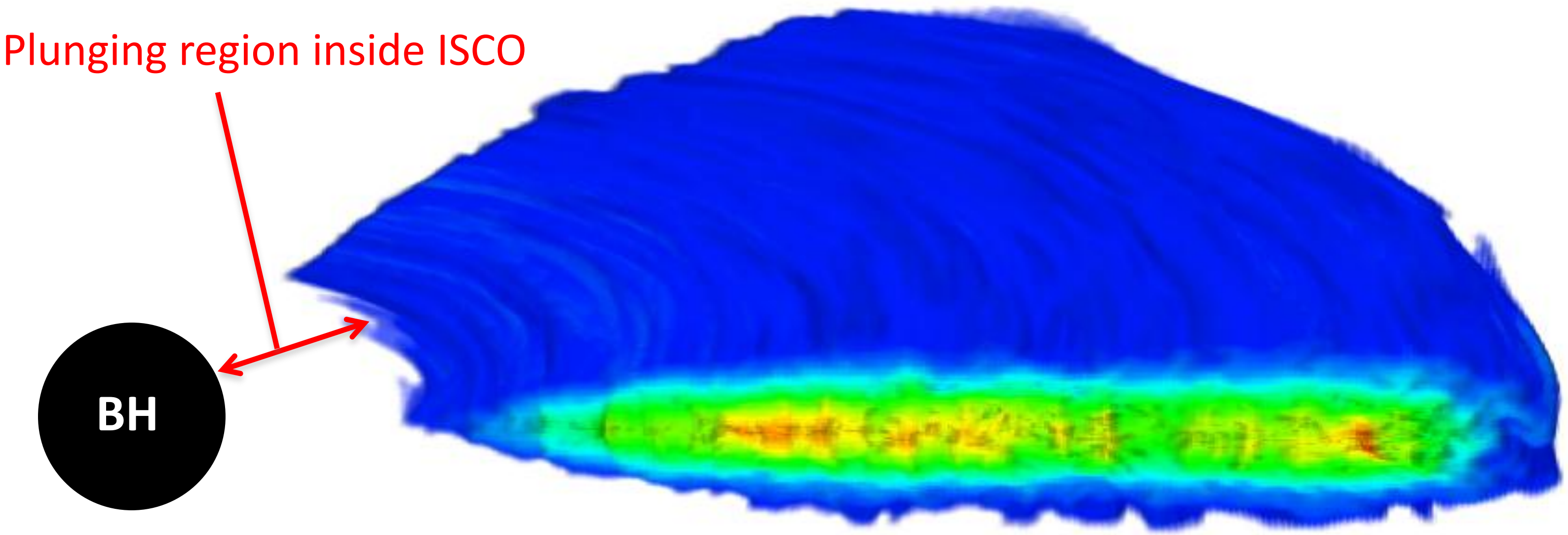
KERRCONV, RELCONV or KYCONV × REFLIONX or XILLVER

Brenneman & Reynolds (2006) Dovčiak+ (2004) Garcia & Kallman (2010)

Dauser+ (2010) Ross & Fabian (2005)

CAVEATS:
disk truncation radius
disk ionization, density, Fe abundance
disk irradiation profile
complex absorption, soft excess

Assumption of ISCO Truncation



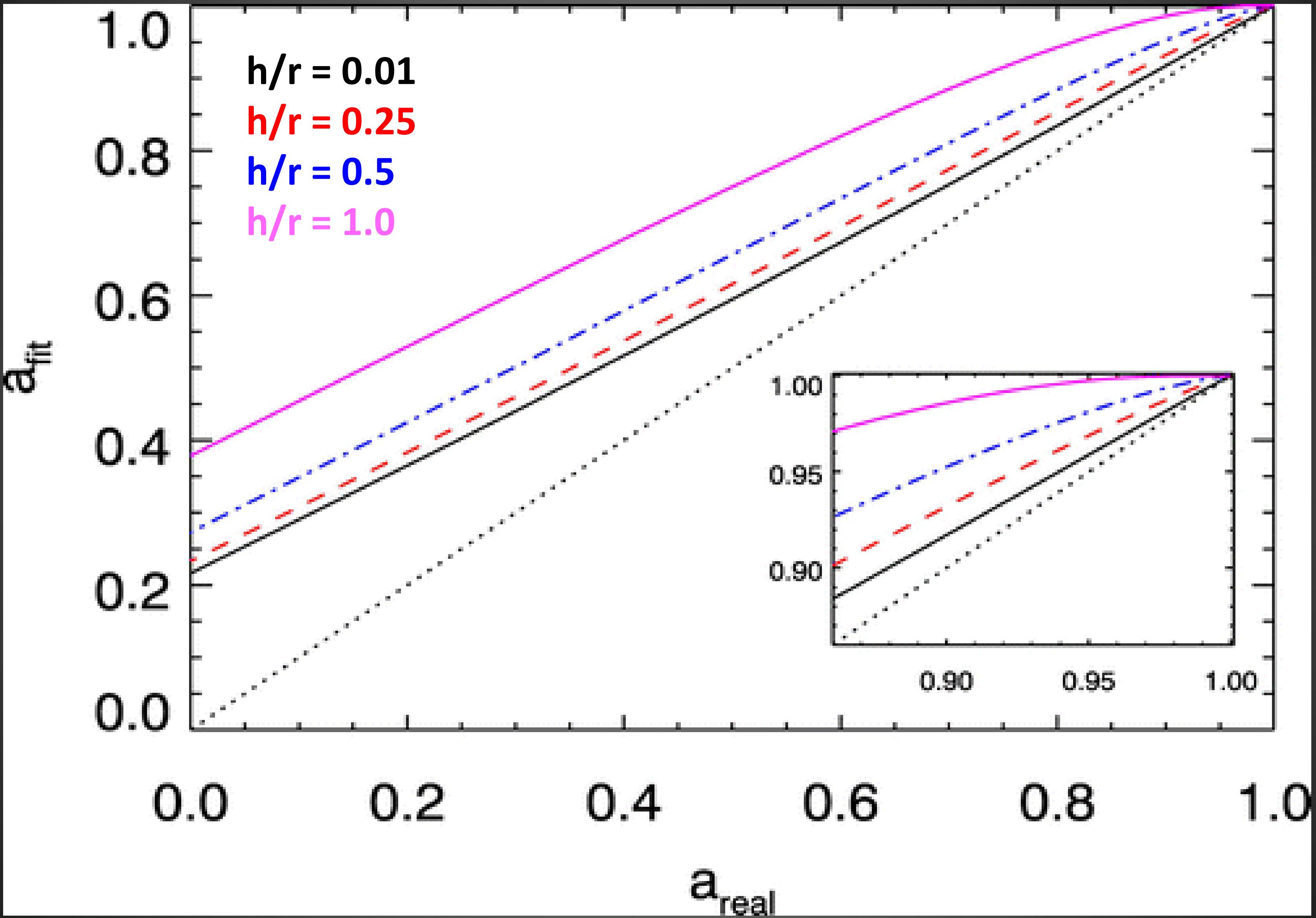
3-D MHD simulation of a geometrically-thin accretion disk.

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

Rapid drop in τ, rise in ξ within ISCO.

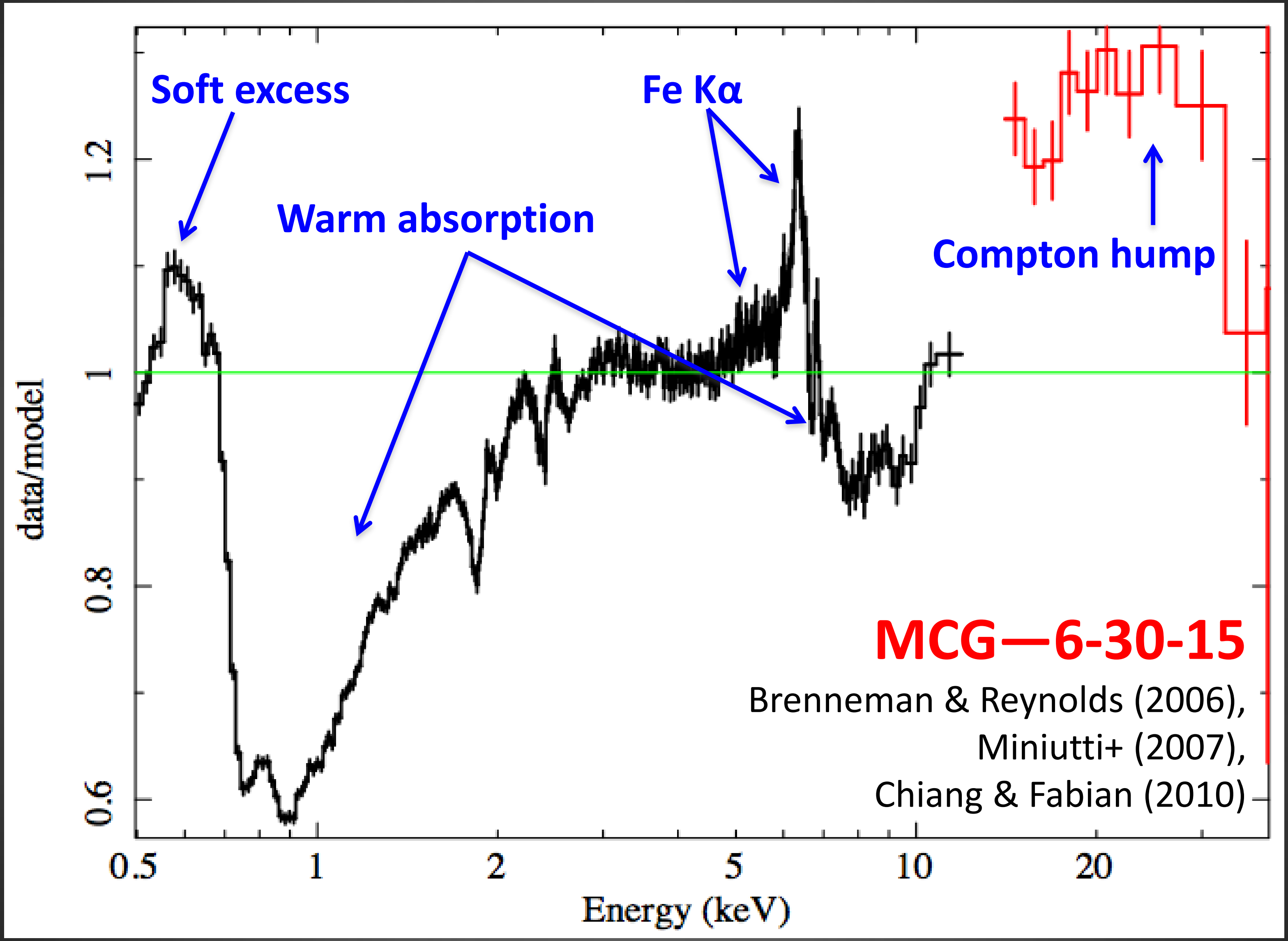
Reynolds & Fabian (2008)

Systematic Error from Emission ≤ISCO

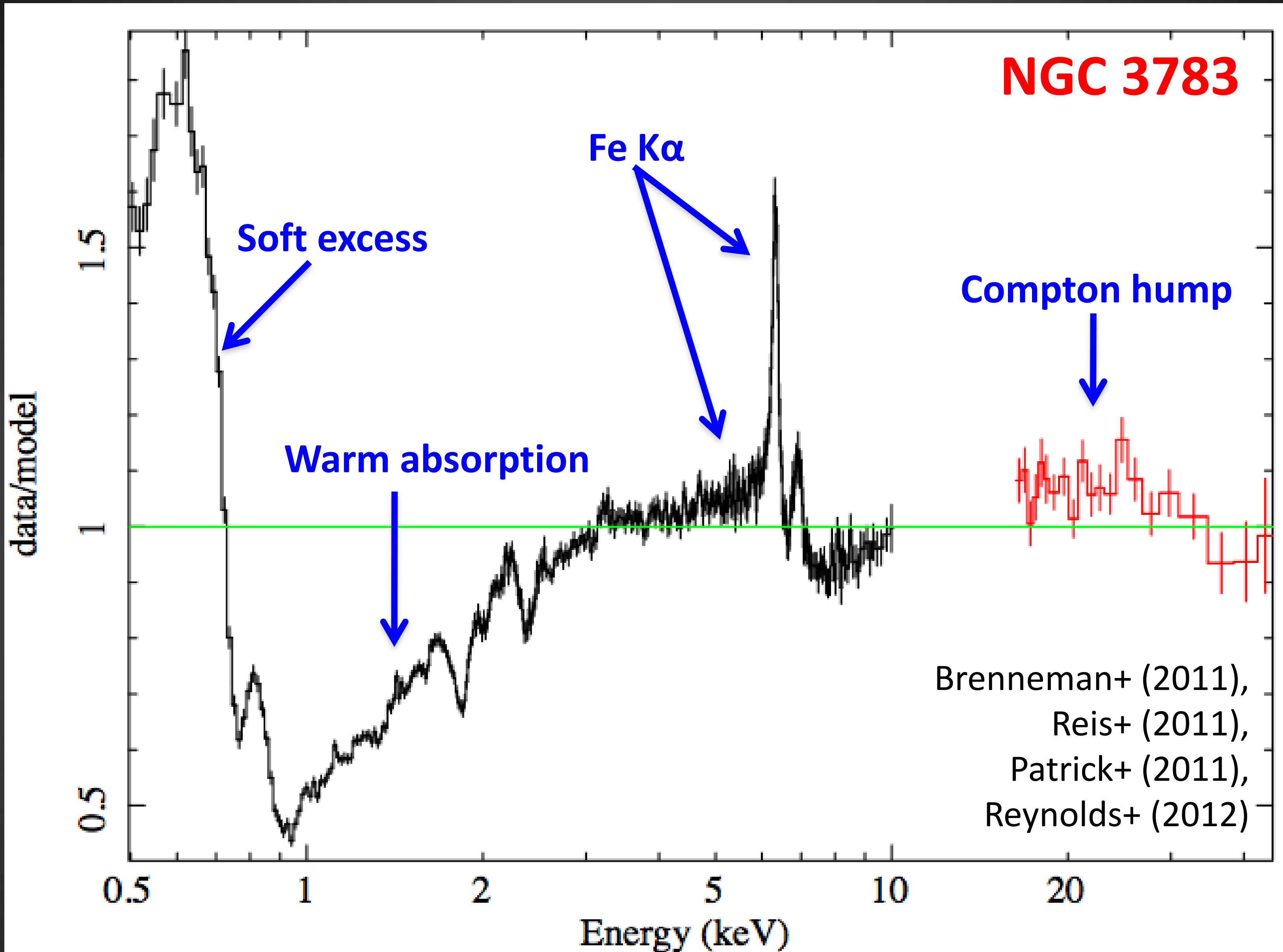


Reynolds & Fabian (2008)

Spectral Complexity



Spectral components with continuum power-law modeled out



Spectral components with continuum power-law modeled out

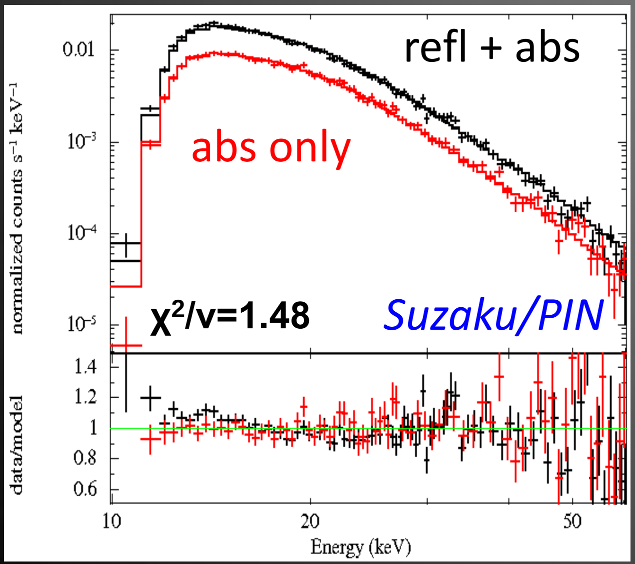
Separating Reflection from Absorption

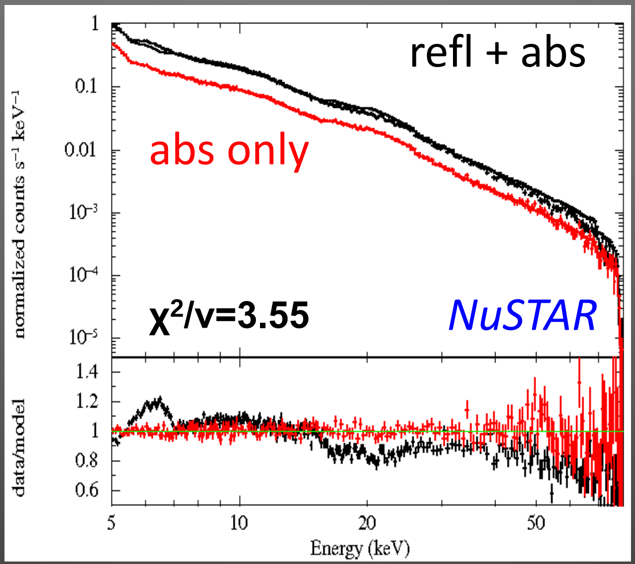
- **Multi-epoch & time-resolved spectral analysis** assesses variability of three spectral components: continuum, reflection, absorption.

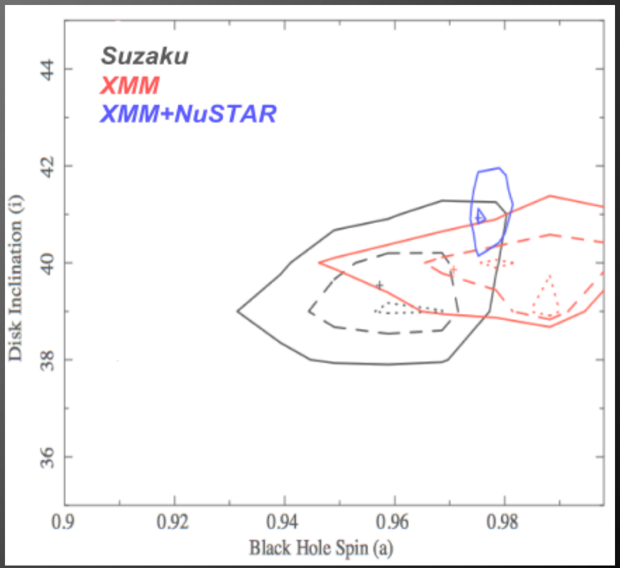
- A **physically consistent model** should be able to explain ALL the data: spin, disk inclination, abundances shouldn't change.

- ***NuSTAR* (June 2012)** will also have high enough collecting area and low enough background >10 keV to differentiate between reflection and absorption (e.g., MCG—6: Miller, Turner & Reeves 2007 vs. Brenneman & Reynolds 2006).

- When used **simultaneously with *XMM* and/or *Suzaku***, will achieve best-ever constraints on BH spin in terms of **accuracy** and **precision**.







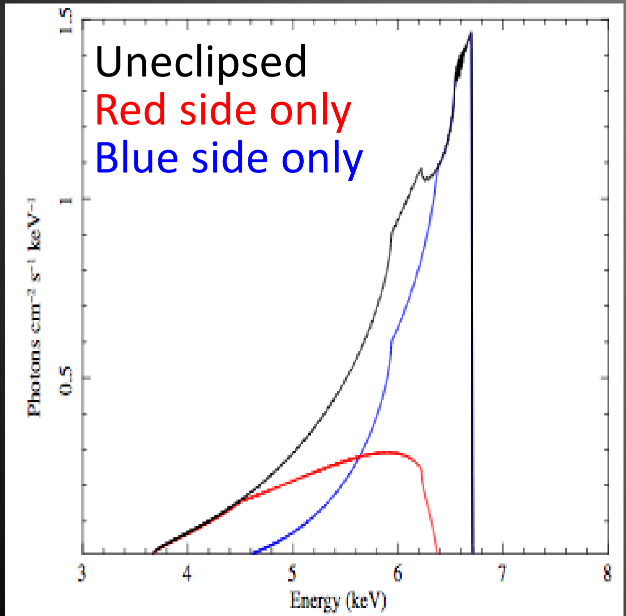
Are Broad Fe K Lines Real??

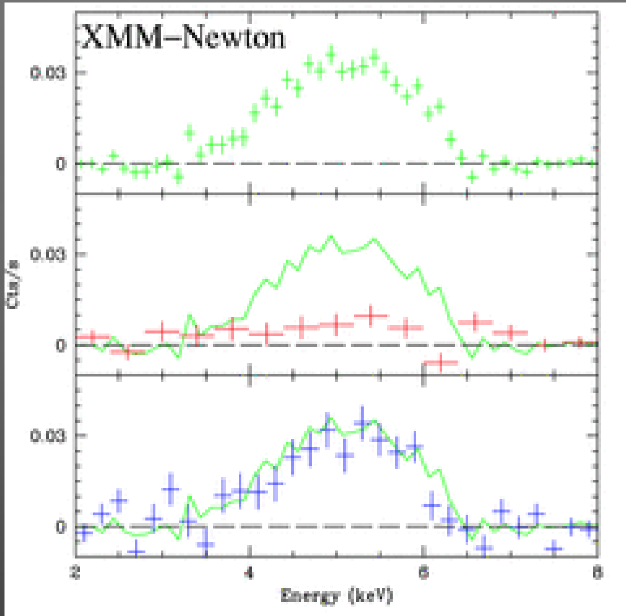
- **X-ray eclipses of the inner disk** by BLR clouds cited in NGC 1365 (e.g., Risaliti+ 2011, Brenneman+, in prep.) can also differentiate between the reflection and absorption-only spectral modeling interpretations.

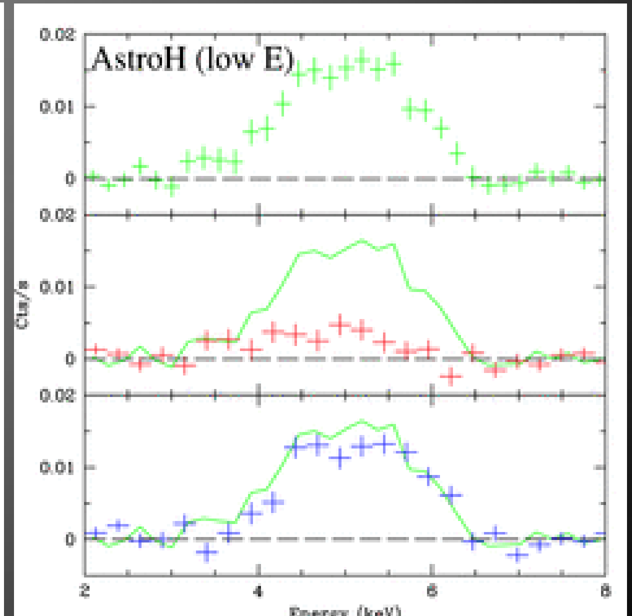
- Can **verify the existence of relativistic emission** features from the inner accretion disk by examining change in morphology of putative Fe K line as the eclipse progresses… *absorber-only model can't mimic such changes*.

- Must have Compton-thick eclipse producing a **change in column density of factor ~10** to demonstrate such an effect.

- NGC 1365 subject of ***XMM/NuSTAR* observing campaign** (PI: Risaliti); **theoretical modeling** of light curves and spectra from inner disk during eclipses is also ongoing (PI: Brenneman).

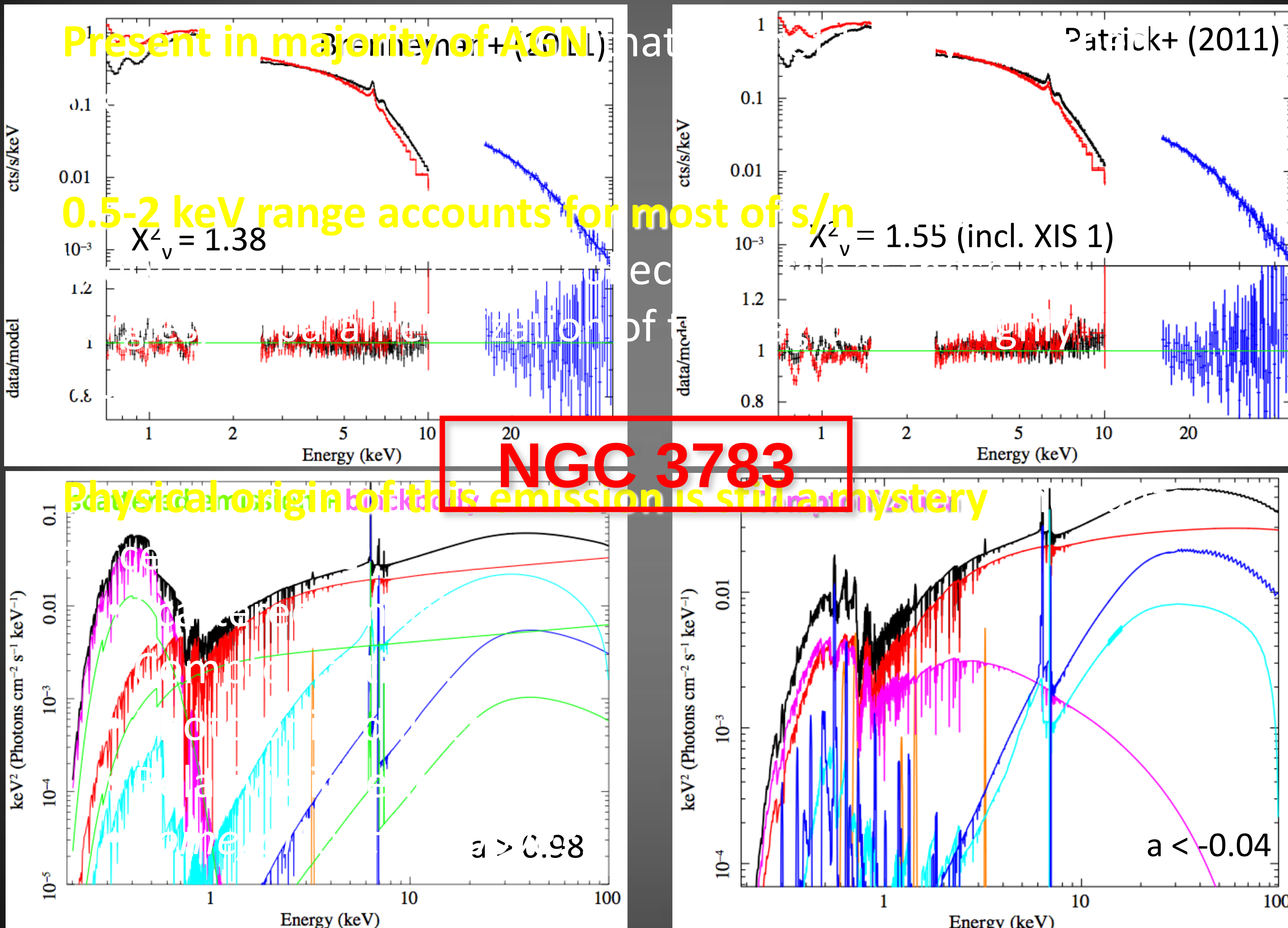






What about the Soft Excess?

- Present in majority of AGN
- 0.5-2 keV range accounts for most of s/n
- Physical origin of this emission is still a mystery



Iron Abundance in NGC 3783

- Fit drives **$a > 0.88$**, **Fe/solar = 2-4** (MCMC).

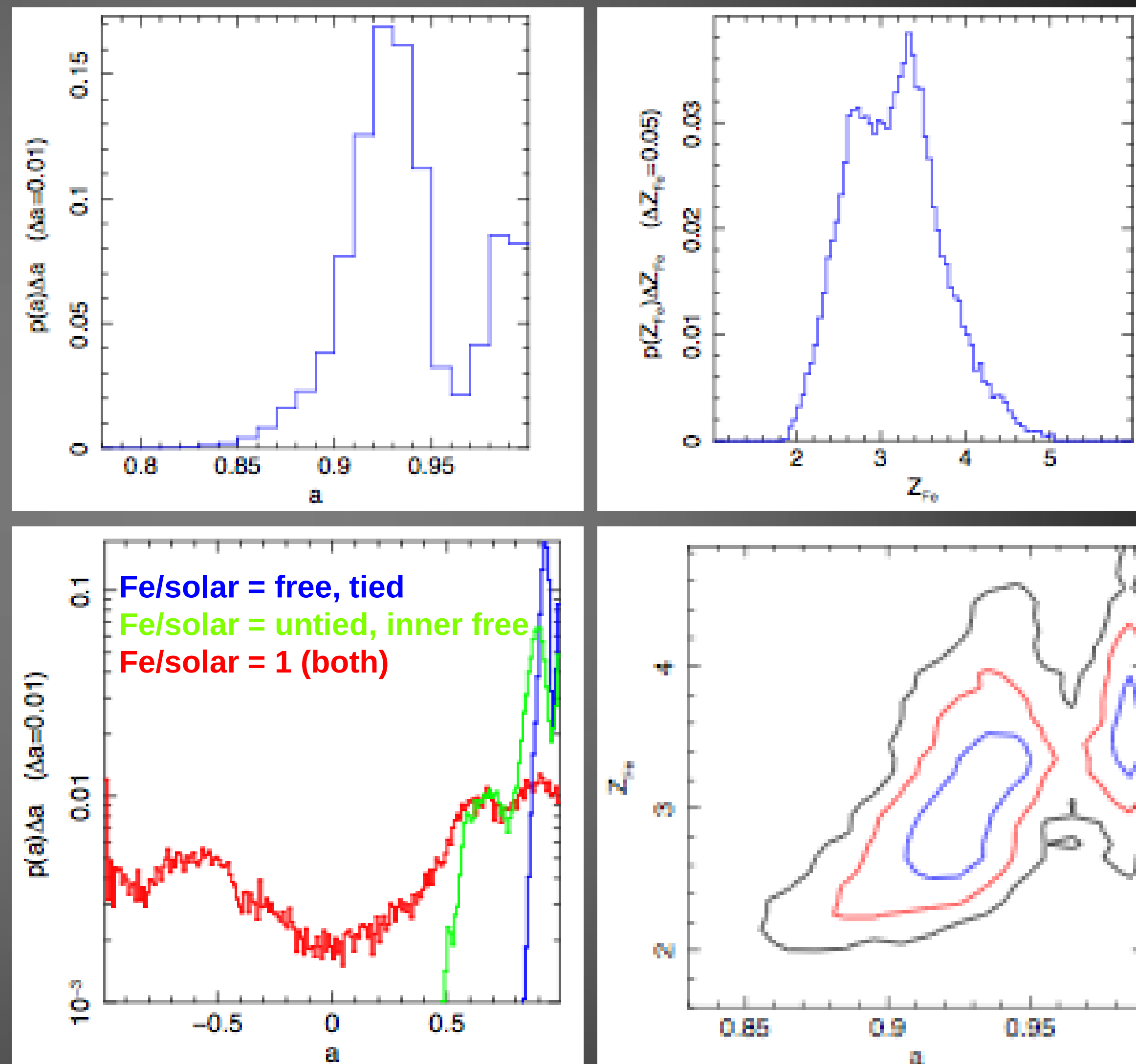
- **Fe/solar = 1 worsens fit** significantly, **allows for low spin.**

- Supersolar Fe consistent with measurements from BLR (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.



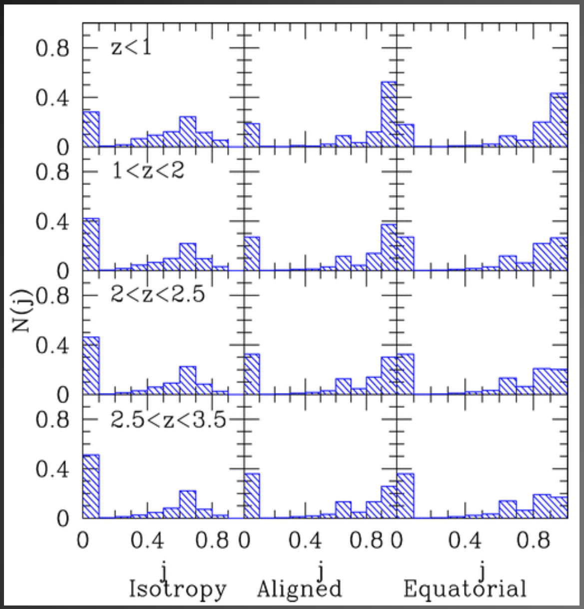
Reynolds, Brenneman+ (2012)

SMBH Spin Constraints from Reflection

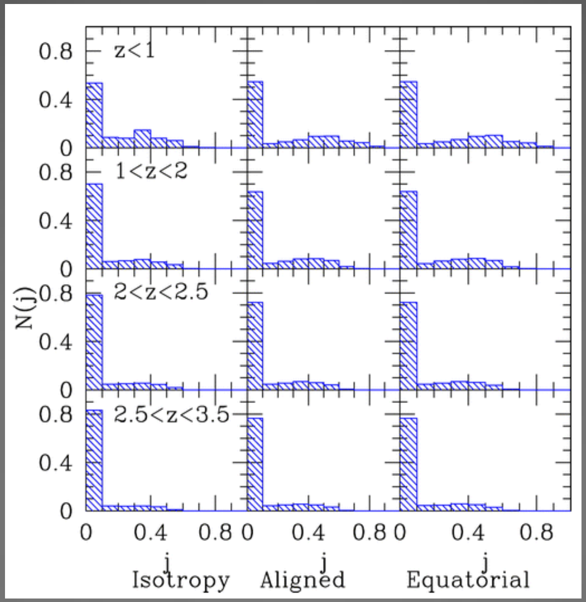
AGN	EW (eV)	a	Log M_{BH}	L_{bol}/L_{Edd}	host
MCG—6-30-15 (Brenneman & Reynolds 2006; Miniutti+ 2007)	~400	≥0.98	6.19	0.42	S0
Fairall 9 (Schmoll+ 2009, Patrick+ 2011)	~130	0.65 ± 0.05	7.91	0.05	Sc
SWIFT J2127.4+5654 (Miniutti+ 2009)	~220	0.6 ± 0.2	7.18	0.18	??
1H 0707-495 (Fabian+ 2009; Zoghbi+ 2010)	~1200	≥0.98	6.70	~1.00	IrS
Mrk 79 (Gallo+ 2010)	~380	0.7 ± 0.1	7.72	0.05	SBb
NGC 3783 (Brenneman+ 2011)	~260	≥0.88	6.94	0.19	SB(r)a
Mrk 335 (Patrick+ 2011)	~145	0.70 ± 0.12	7.15	0.25	S0/a
NGC 7469 (Patrick+ 2011)	~90	0.69 ± 0.09	7.09	1.12	SAB(rs)bc
Ark 120 (Patrick+ 2011; Nardini+ 2011; Tu & Brenneman in prep.)	~120	0.94 ± 0.10	8.18	0.03	Sb/pec
3C 120 (Cowperthwaite & Reynolds 2012)	~50	≤-0.1	7.74	0.23	S0

N.B.: Patrick+ (2011) have published disparate spin constraints: NGC 3783 (*a* < -0.04) and MCG—6-30-15 (*a* ~ 0.44) based partly on different modeling of soft excess emission.

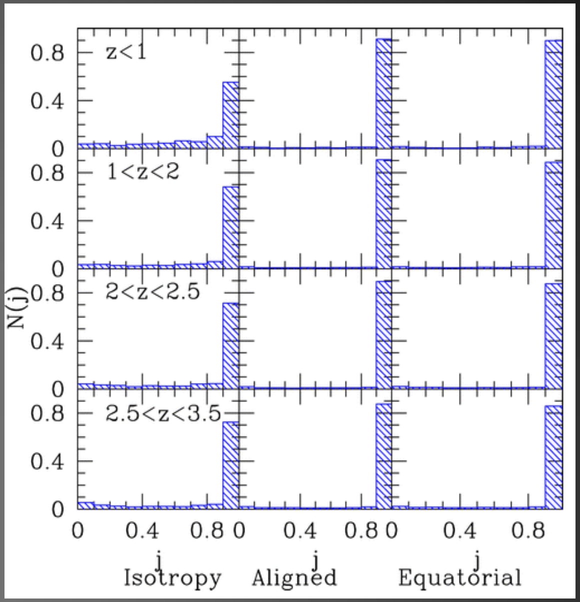
Black Hole Spin and Galaxy Evolution



Mergers only



Mergers + chaotic accretion



Mergers + prolonged accretion

Berti & Volonteri (2008)

- Mergers of galaxies (and, eventually, their SMBHs) 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.

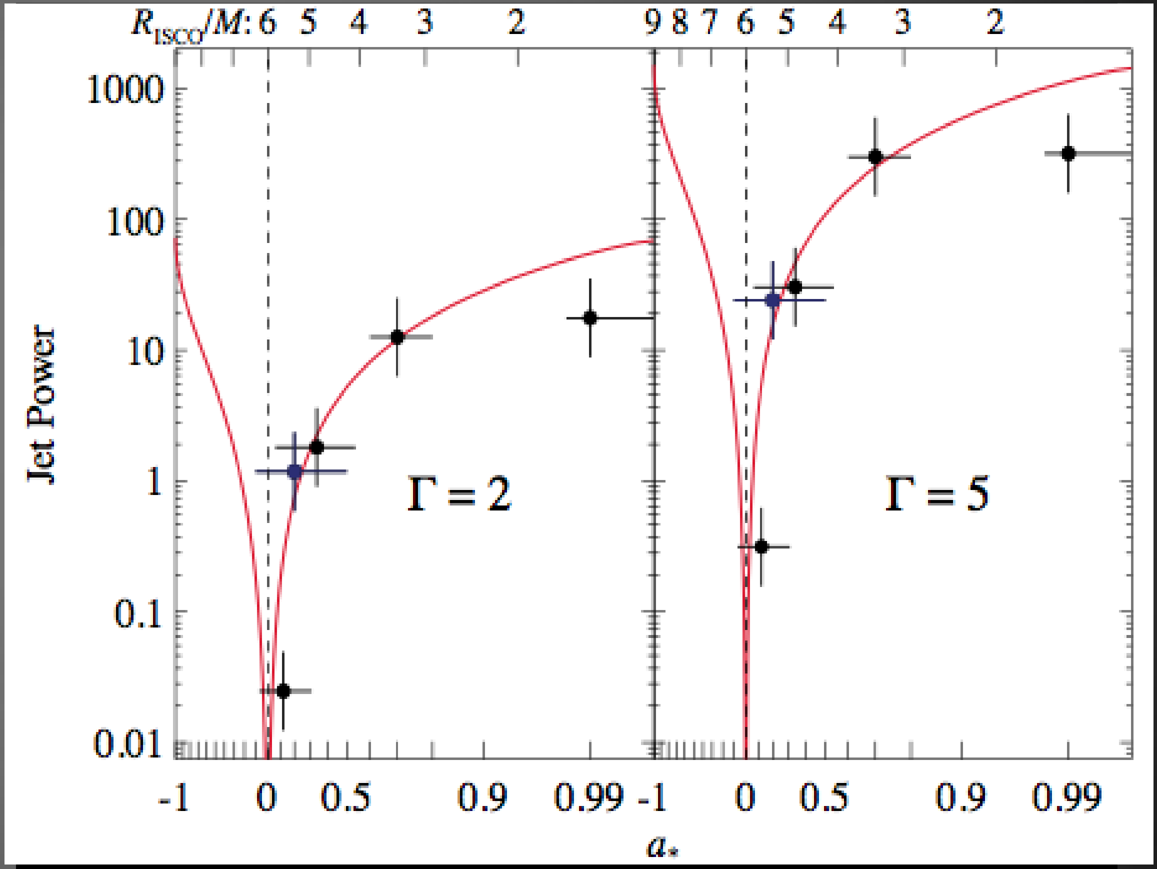
Black Hole Spin and Jet Production

- 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.

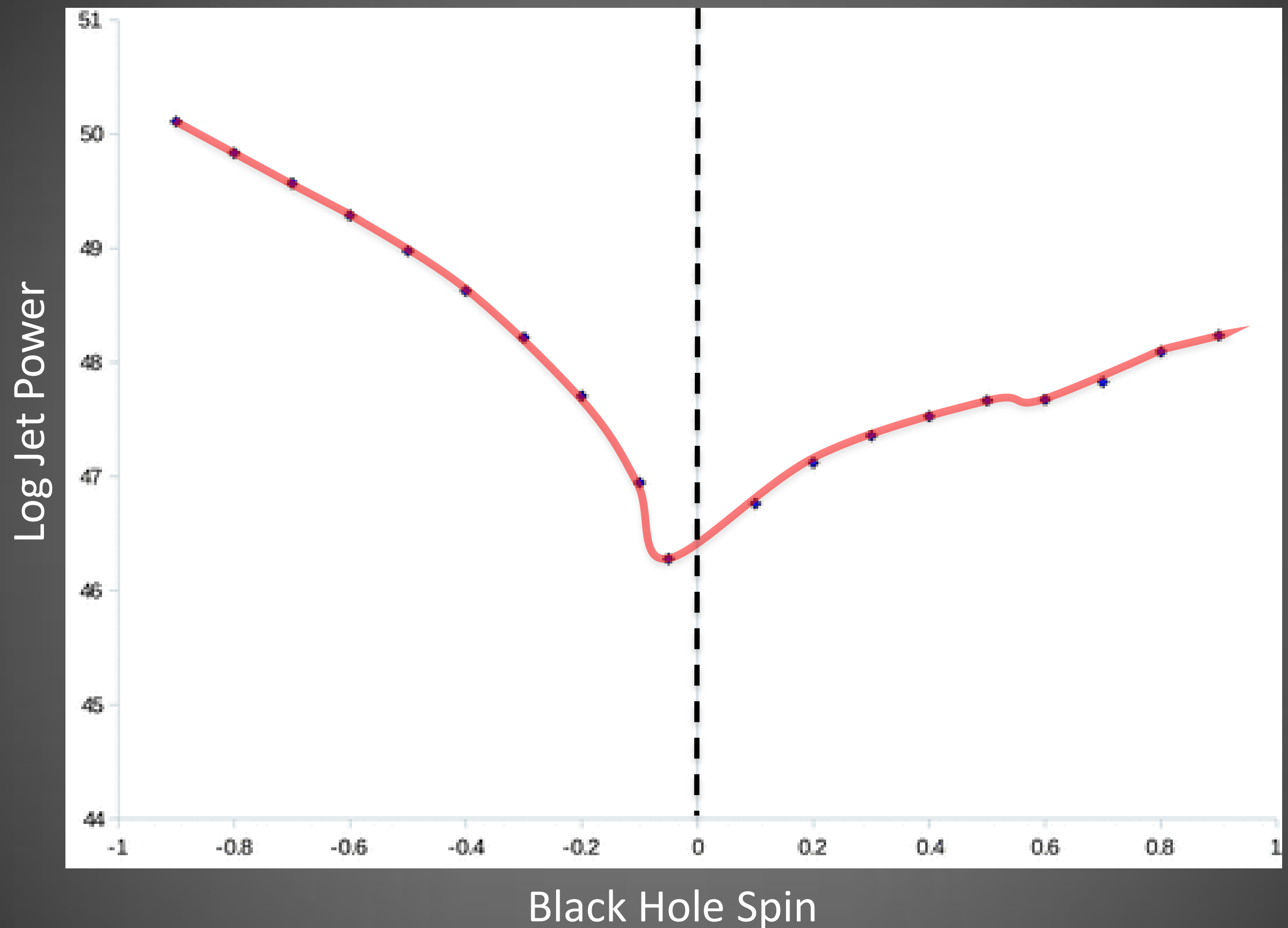
- Results in a powerful outflow, though **many specifics are still unknown**, including how/why jets launch, dependence on spin, magnetic field, accretion rate.

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



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

Powerful Jets = Retrograde Spin?



- Based on numerical simulations of Garofalo (2009), jet power is maximized for large, retrograde BH spins (though see Tchekhovskoy & McKinney 2012).
- Present *Suzaku* and forthcoming *XMM/NuSTAR/Swift* campaign on 3C 120.

Summary

- **Reflection modeling** gives SMBH spin constraints now, though care must be taken in model fitting, assumptions.

- **Wide range of measured spins** for AGN, but so far all but one are consistent with $a \geq 0$, with average $a = 0.6\text{-}0.7$.

- Not yet a large enough sample size to probe role of accretion vs. mergers in SMBH/host growth.

- Preferential finding of high spins for RQAGN may be **selection bias** since they are bright, nearby sources.

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

Future Directions

• *NuSTAR* (2012): higher E.A., lower background than Suzaku >10 keV
- with XMM/Suzaku/Astro-H, significant decrease on spin error
- differentiate between complex absorption, reflection in AGN

• *Astro-H* (2014): higher E.A., better spectral resolution than Suzaku
- separate absorption from emission in Fe K band
- break degeneracy between truncated disk and lower spin(?)

• ~~*GEMS* (2014): Most sensitive X-ray polarimeter flown~~
~~- independent check on spin, but likely only for XRBs~~

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

• *ATHENA/EPE* (??): Further large increase in E.A. over these missions
- probe accretion physics on orbital timescales
- increase sample size by $\sim$10x

Keep an Eye Out For…

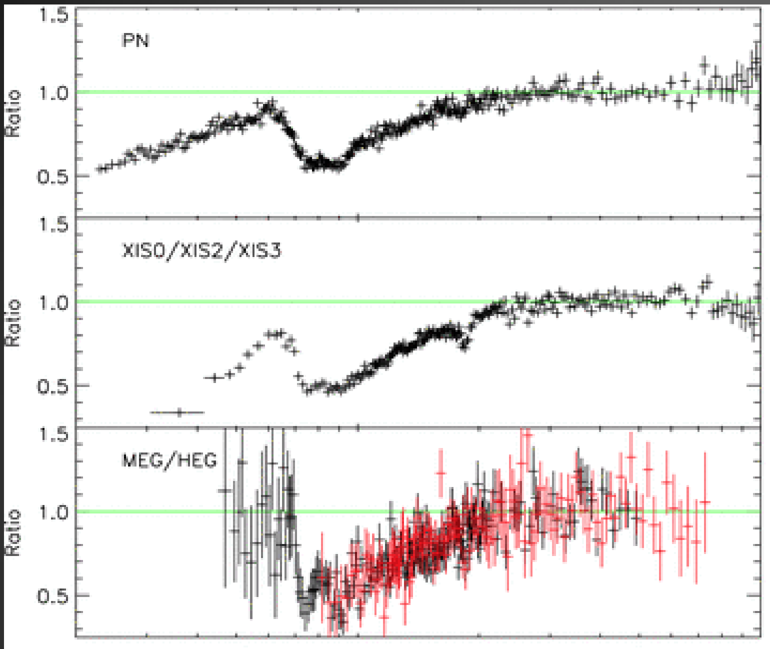
- **Results of *Suzaku* AGN spin survey (PI: Reynolds, lead Co-I: Brenneman)**
  - NGC 3783 (Brenneman+ 2011, Reynolds+ 2012)
  - NGC 3516 (Trippe+, in prep.)
  - Fairall 9 (Lohfink+ 2012)
  - 3C 120 (Cowperthwaite+, in prep.)
  - Mrk 841 (forthcoming)

- **Upcoming simultaneous *NuSTAR/XMM* AGN campaign (PI: Matt, lead Co-I: Brenneman)**
  - MCG—6-30-15
  - Ark 120
  - SWIFT J2127.4+5654
  - 3C 120 (incl. *Swift*)

- **Upcoming simultaneous *NuSTAR/Suzaku* campaign (PI: Brenneman)**
  - NGC 4151
  - 1C 4329A

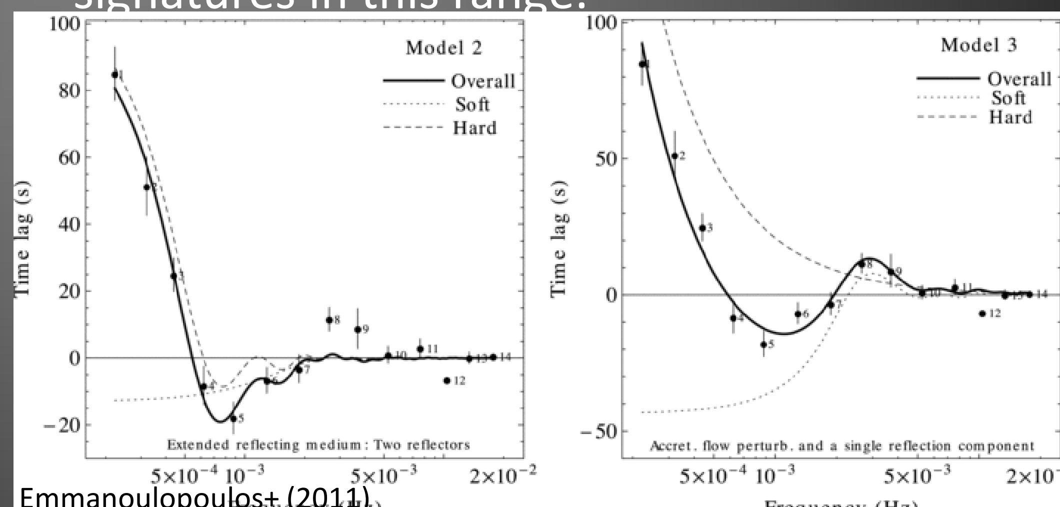
EXTRAS

Spectral Variability in MCG—6-30-15



Chiang & Fabian (2011)

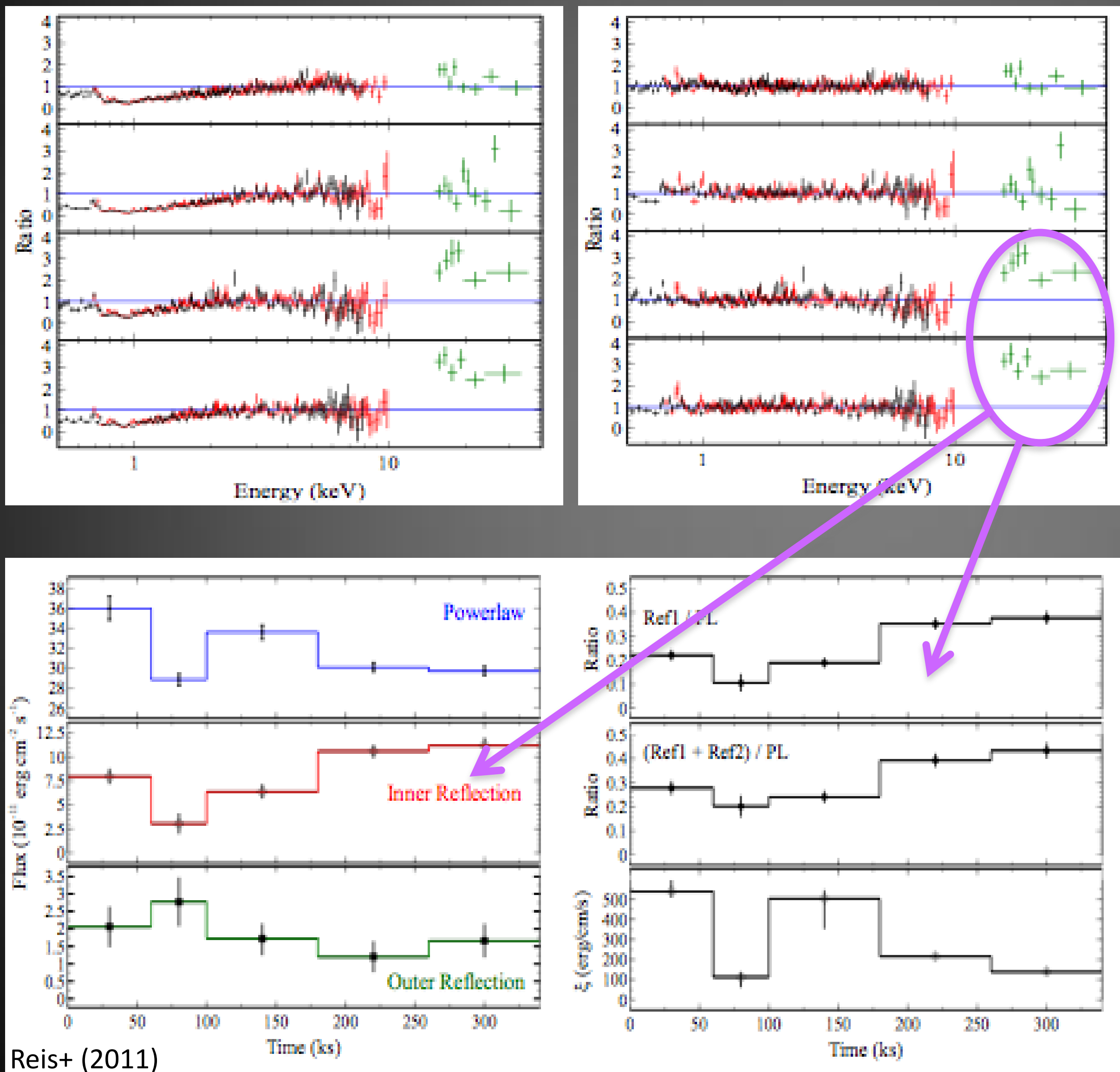
- Negative time-lag (~20 s) seen between hard and soft bands (soft trails hard), like 1H0707.
- Best modeled by reflection close to SMBH (<6 r_g), not extended reflector or PC clouds along l.o.s.
- Even if modeled by scattering from circumnuclear material, must be scattered within ~7 r_g. Expect relativistic reflection signatures in this range.



Emmanoulopoulos+ (2011)

- Difference spectra (high flux - low flux) best fit by absorbed power-law <2 keV, unabsorbed power-law >2 keV in *XMM, Suzaku, Chandra* data.
- Best-fit model to all three has constant, three-zone warm absorber: $N_H = 10^{20-23}$, ξ = 0.03-6300, no partial covering.

Spectral Variability in NGC 3783



Reis+ (2011)

- *Suzaku* difference spectra in NGC 3783 also well-modeled by absorbed power-law <2 keV, power-law only >2 keV.

- Once constant warm absorber is included for each time interval, difference spectra are fit very well <10 keV.

- Excess hard emission remains in intervals 4-5; best fit with model that allows for changing reflection fraction, inner disk ionization (ξ) as inner disk flux changes.

- Broadly consistent with light bending interpretation.