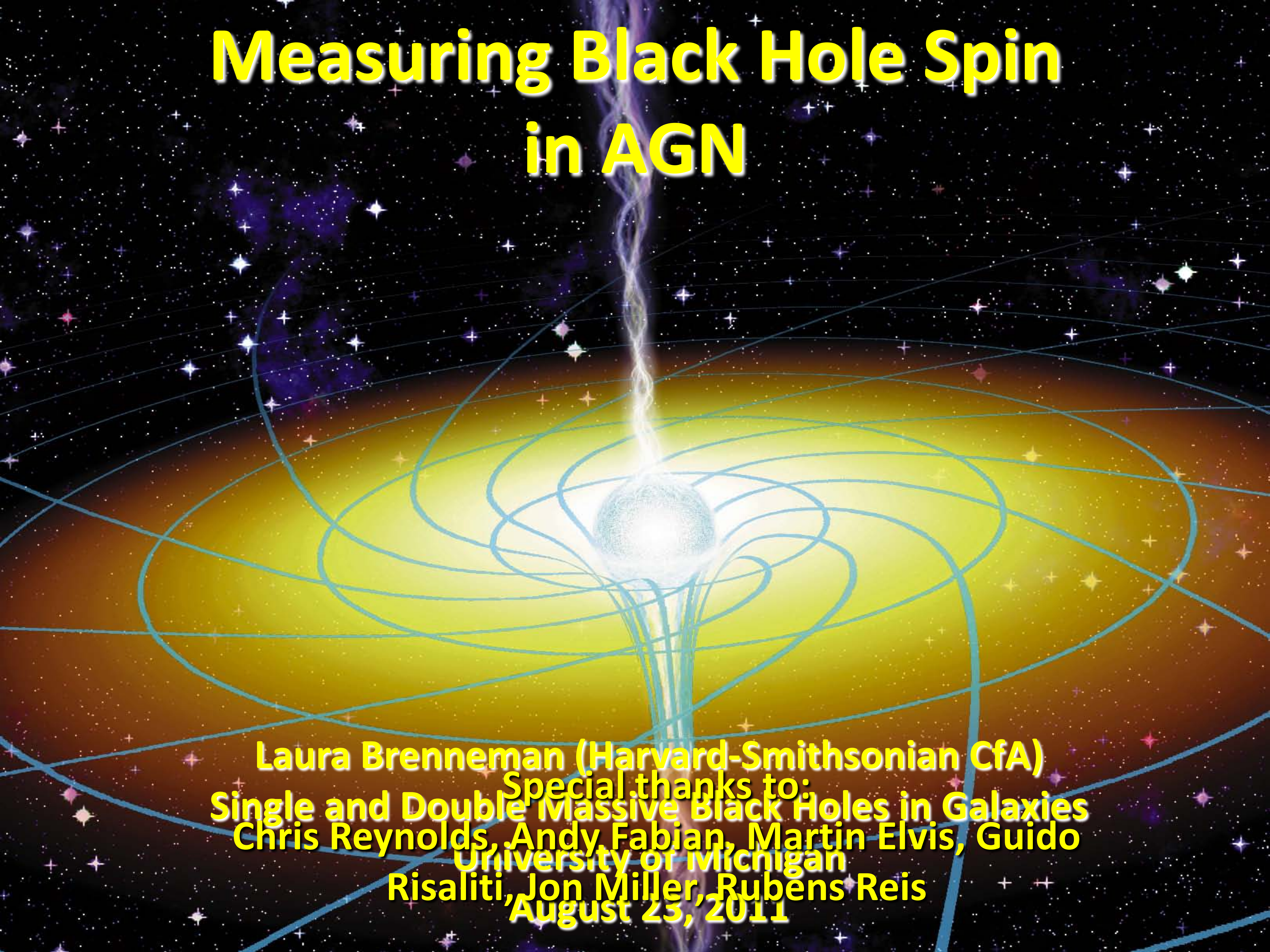


Measuring Black Hole Spin in AGN

Laura Brenneman (Harvard-Smithsonian CfA)

Single and Double Massive Black Holes in Galaxies

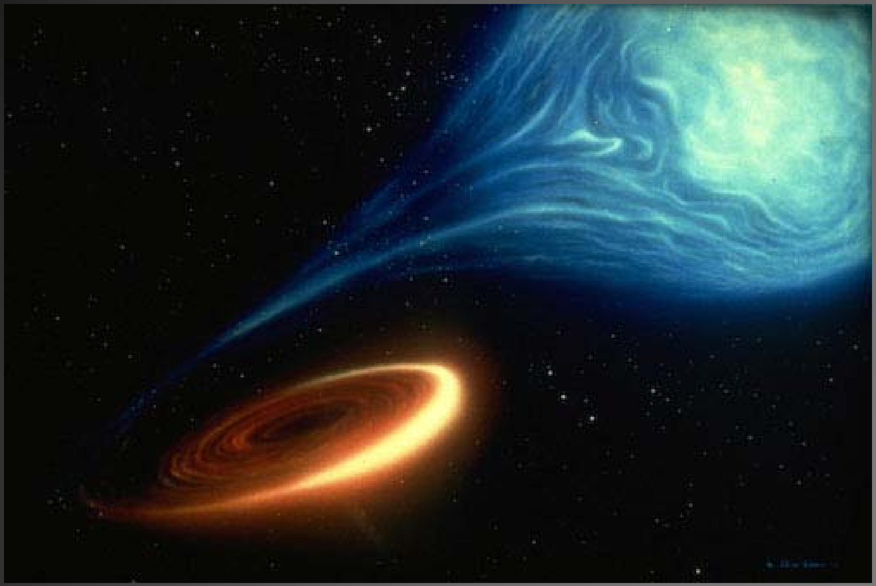
University of Michigan

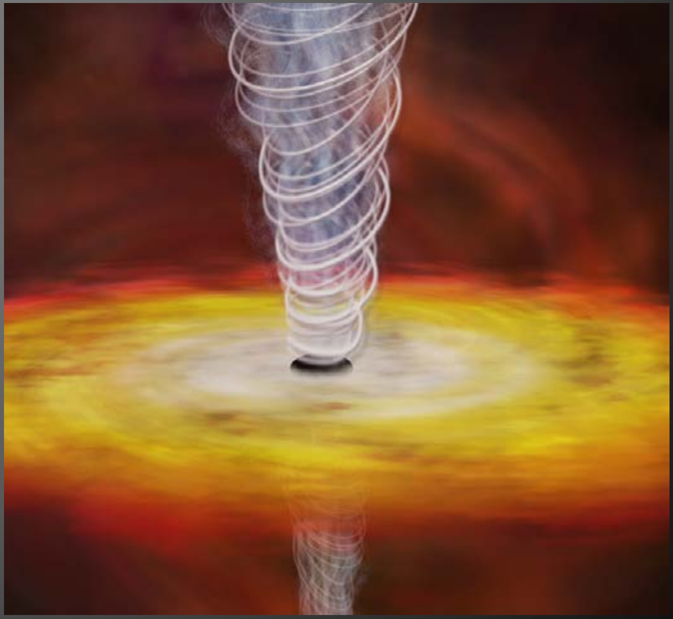
August 23, 2011

Special thanks to:

Chris Reynolds, Andy Fabian, Martin Elvis, Guido Risaliti, Jon Miller, Rubens Reis

The Importance of Black Hole Spin





- Provide rare means of testing predictions of Relativity in strong-field gravity regime.
- Natal spins in stellar-mass BHs can probe formation event (novae/supernovae).
- Indicator of recent gas accretion vs. merger history of supermassive BHs.
- Thought to drive jet production and outflows in all BHs, seeding the interstellar or intergalactic medium with matter and energy.

How Can We Measure BH Spin?

- ***Thermal Continuum Fitting***

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

- ***Inner Disk Reflection Modeling***

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

- High Frequency Quasi-periodic Oscillations**

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

- Polarization Degree & Angle vs. Energy**

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

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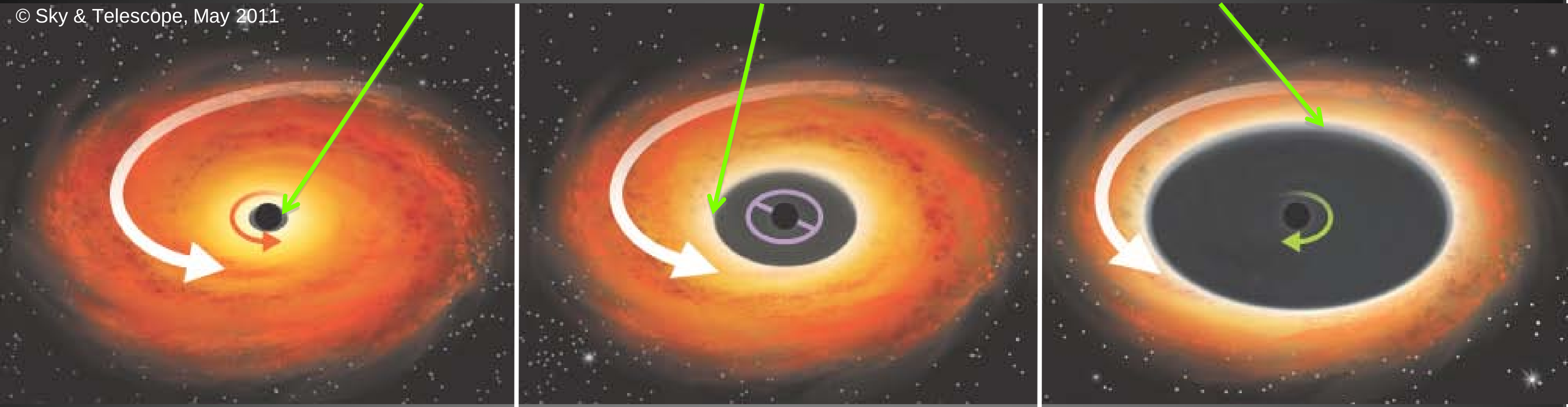
The Innermost Stable Circular Orbit



• Maximally-spinning ***prograde* BH** (spinning in same direction as disk).

• ISCO at 1 GM/c^2.

• Frame-dragging rotationally supports orbits close to BH.

• **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.

Modeling the Reflection Spectrum

• Relat
Comp
(UV) f
produ
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• Som
scatte
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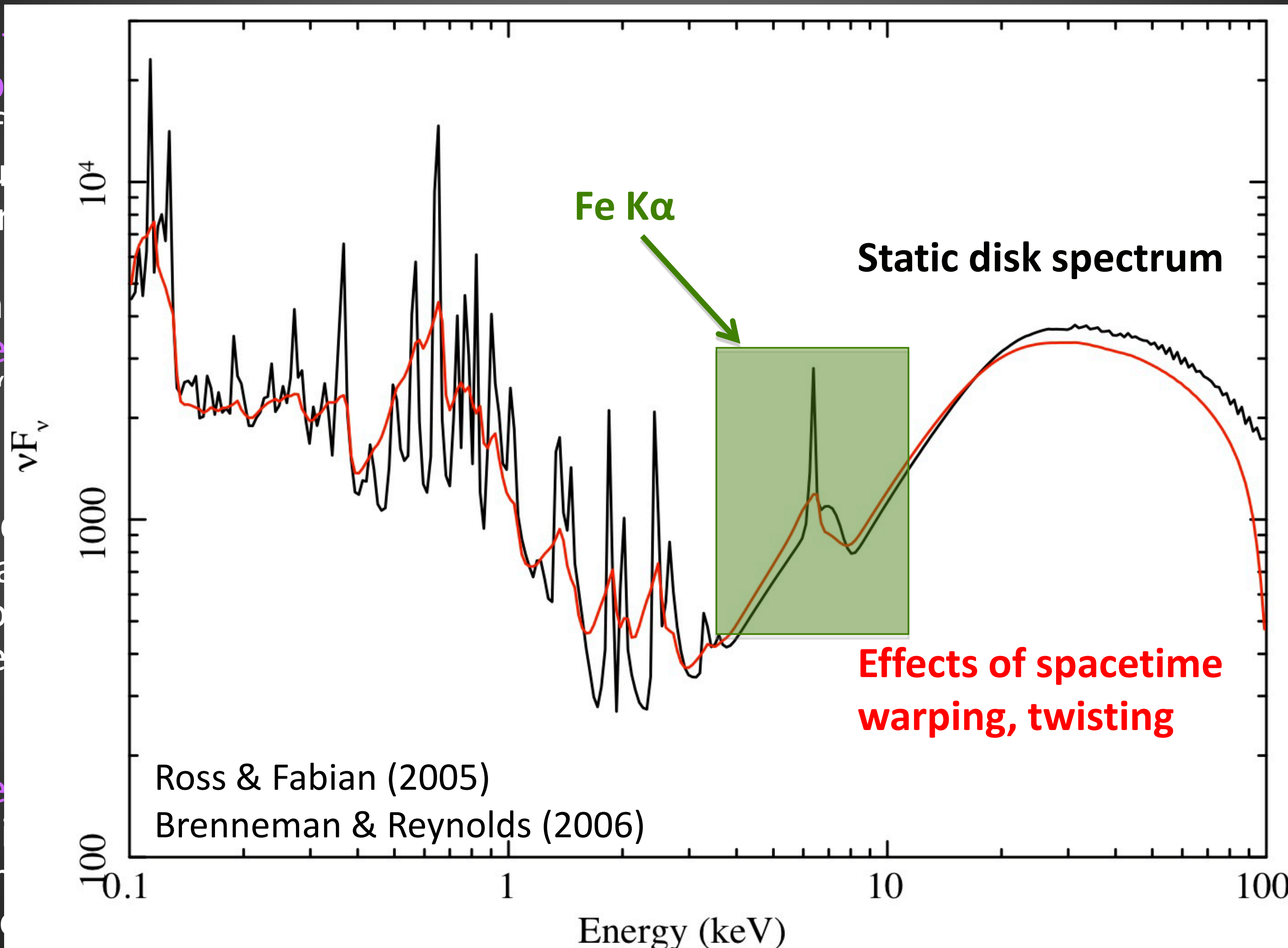
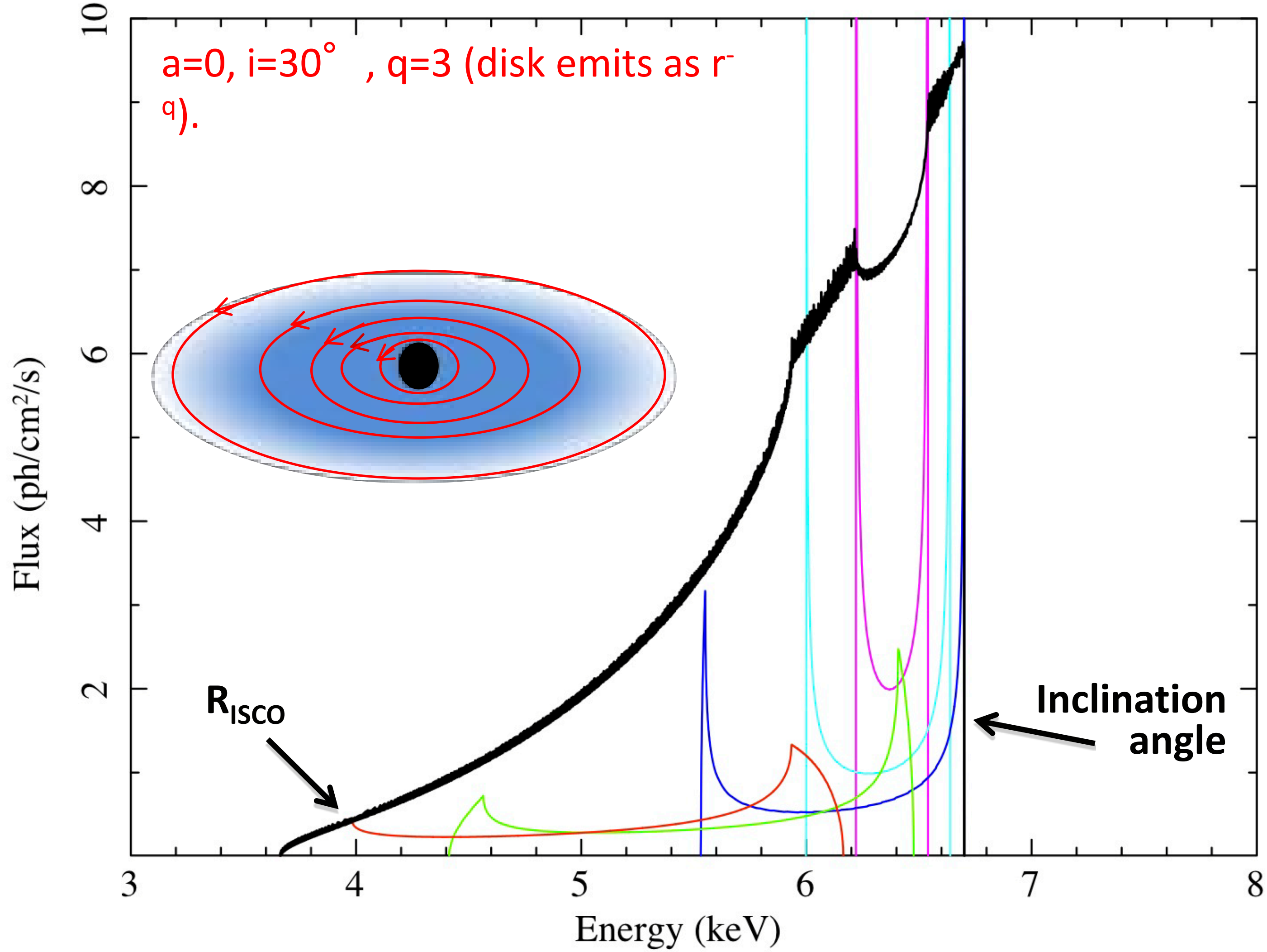
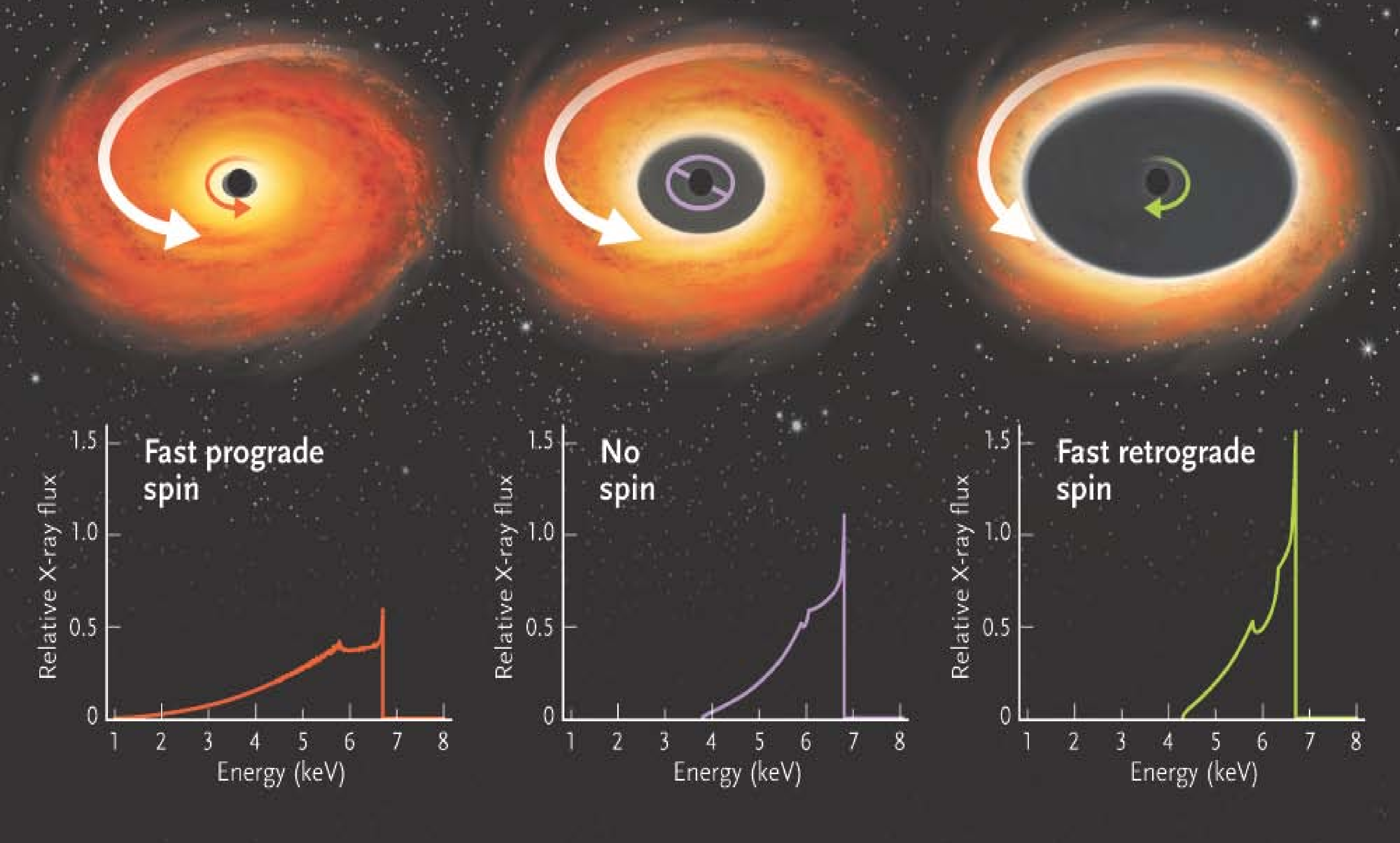


Reynolds & Nowak (2003)

Fe Kα emission line from different disk annuli



KERRDISK model (Brenneman & Reynolds 2006)



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^{11-12} 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 $r_{in} \leq 9\ r_g$.

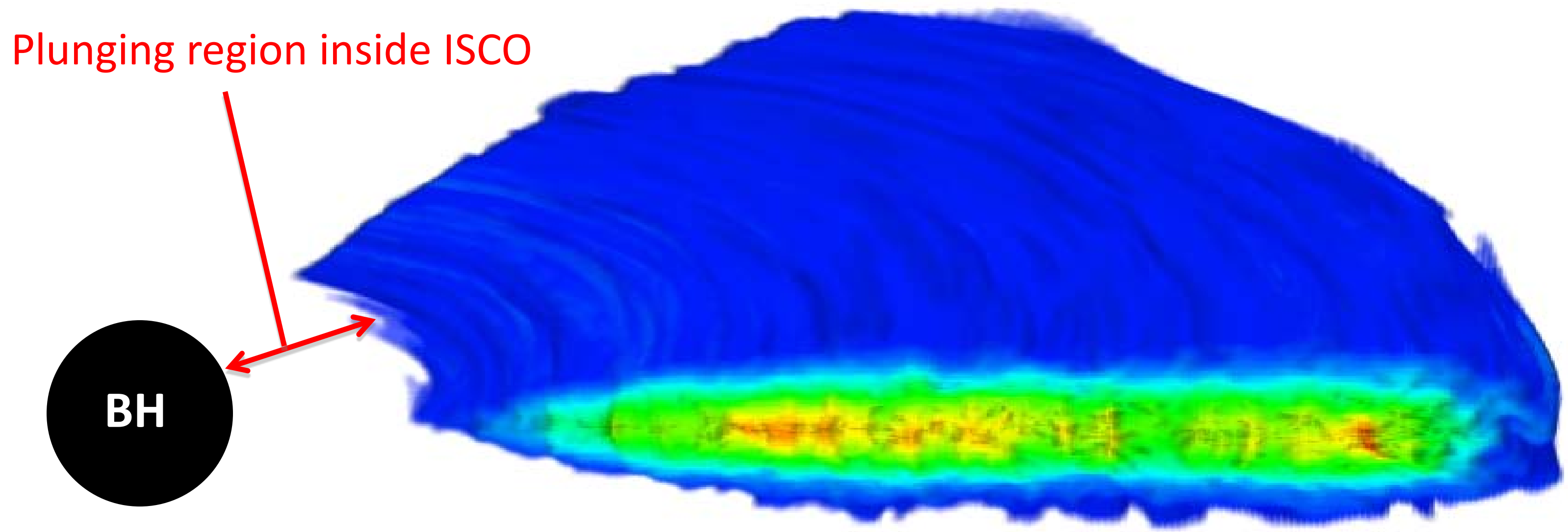
- Technique used: **Inner Disk Reflection** (broad Fe Kα):

  KERRCONV, RELCONV or KYCONV × REFLIONX

CAVEATS:

disk truncation radius
disk ionization, density
disk irradiation
spectral state (??)
complex absorption, soft excess

Assumption of ISCO Truncation

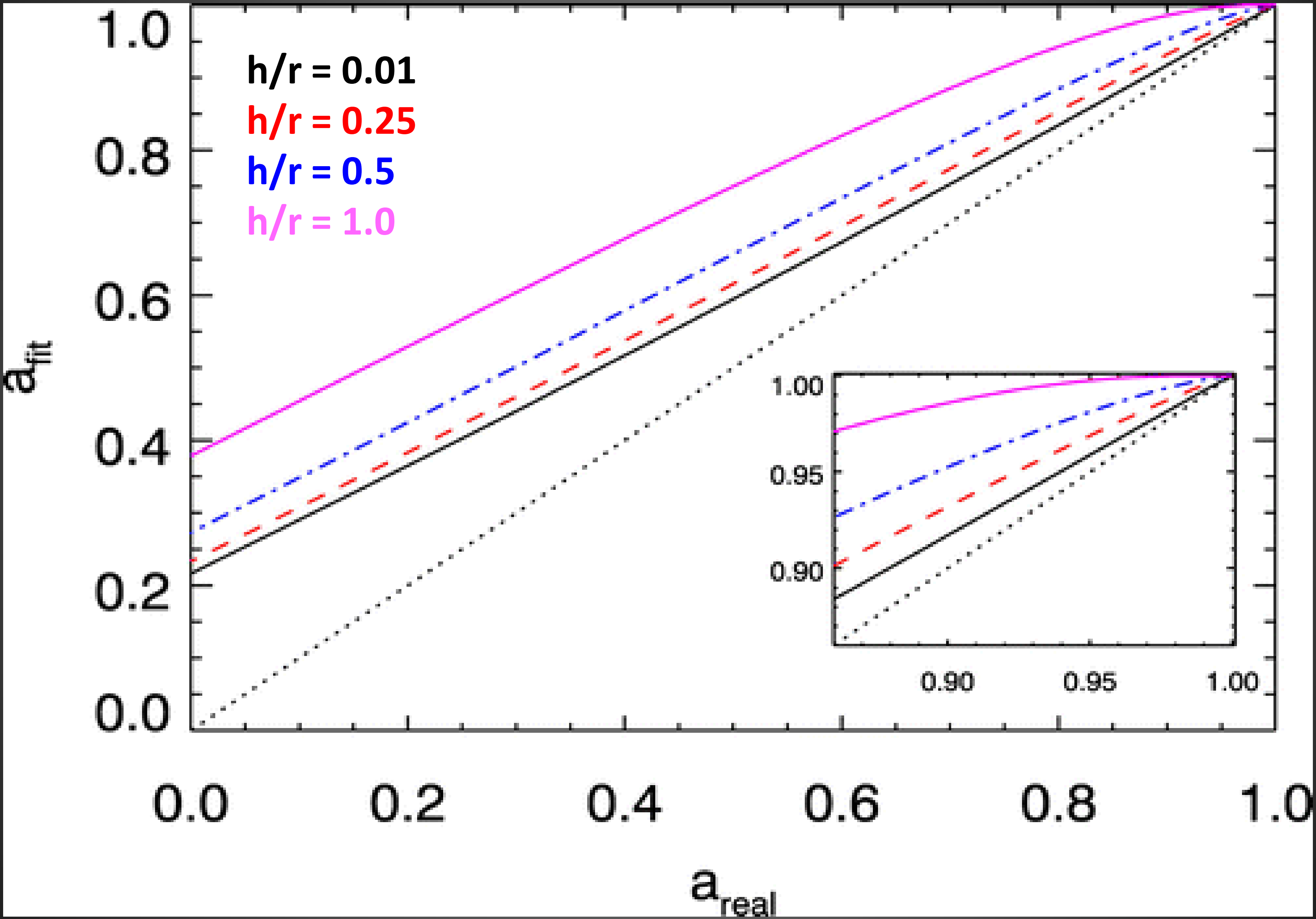


3-D MHD simulation of a geometrically-thin accretion disk

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

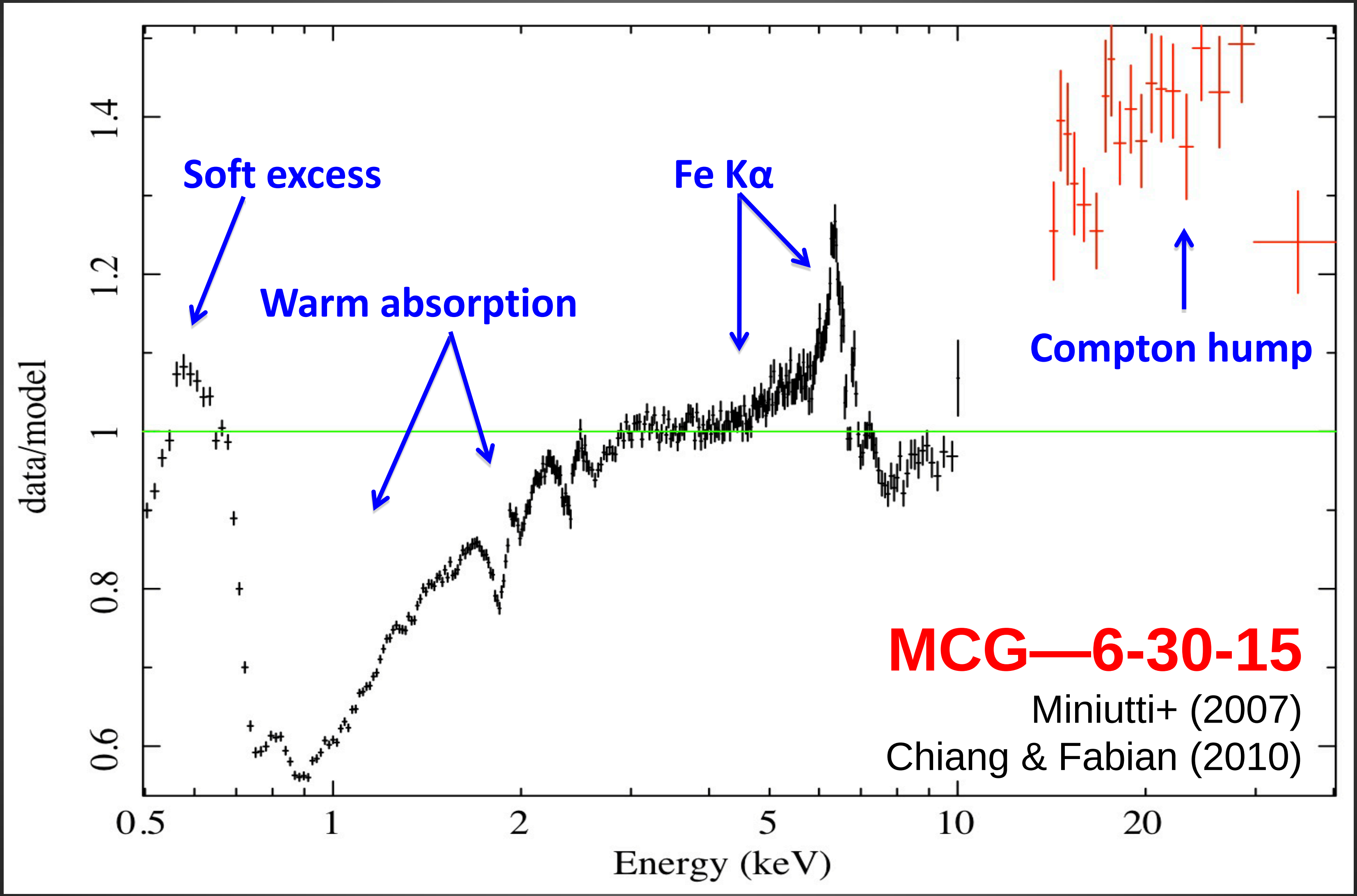
Reynolds & Fabian (2008)

Systematic Error on Spin

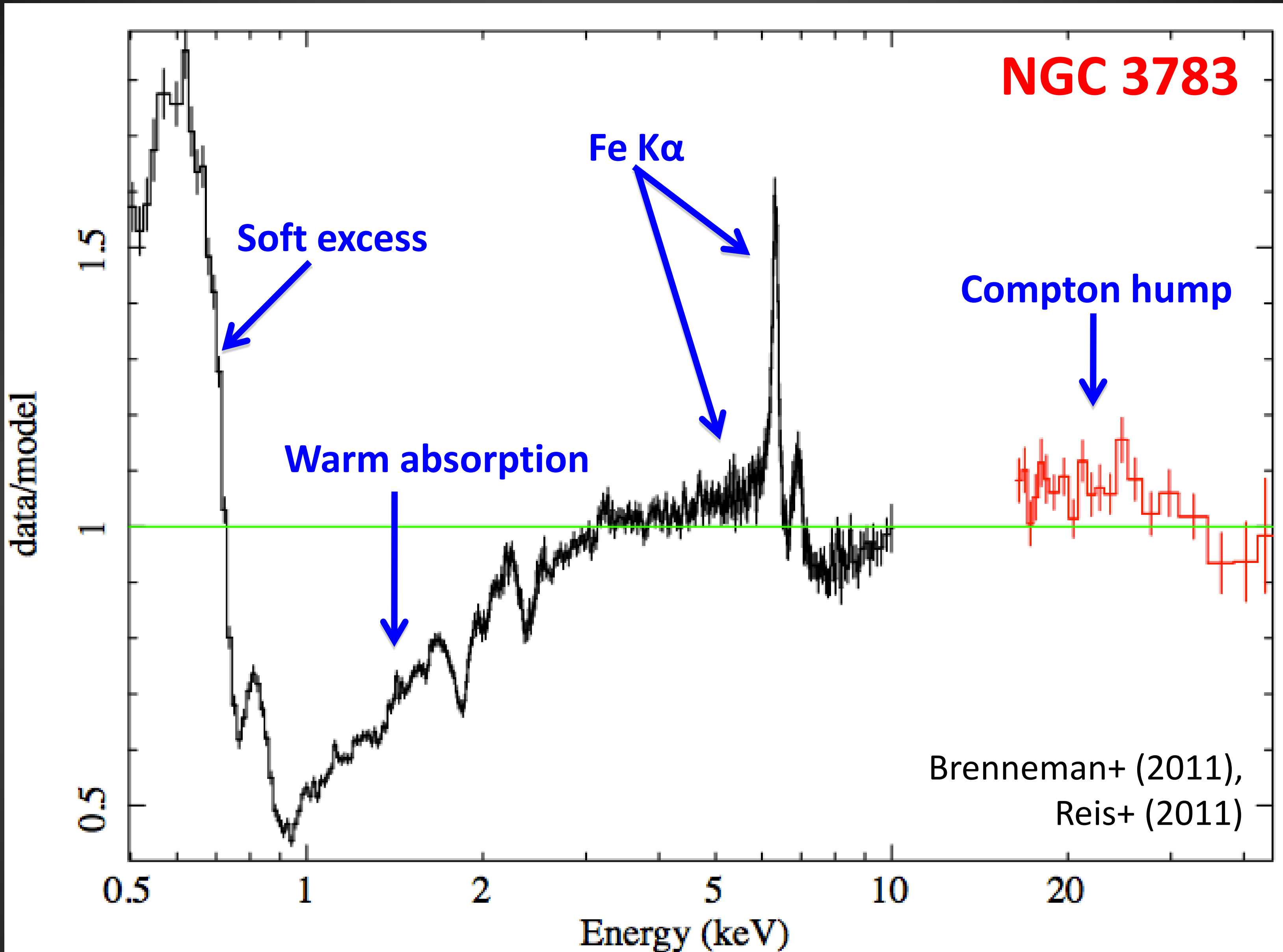


Reynolds & Fabian (2008)

Spectral Complexity



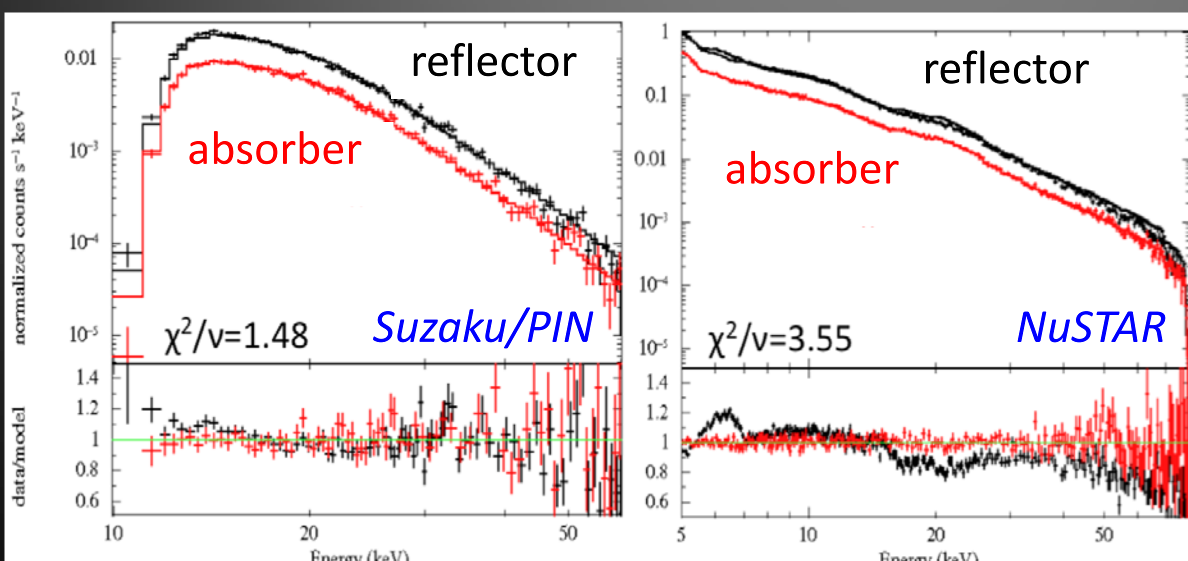
Spectral components with continuum power-law modeled out

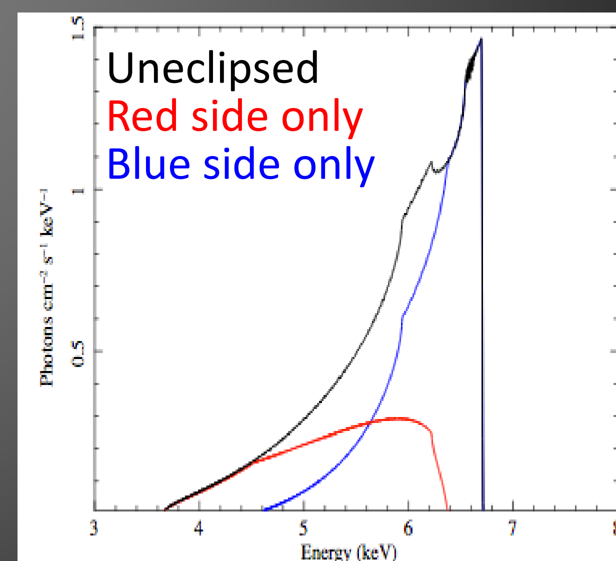


Spectral components with continuum power-law modeled out

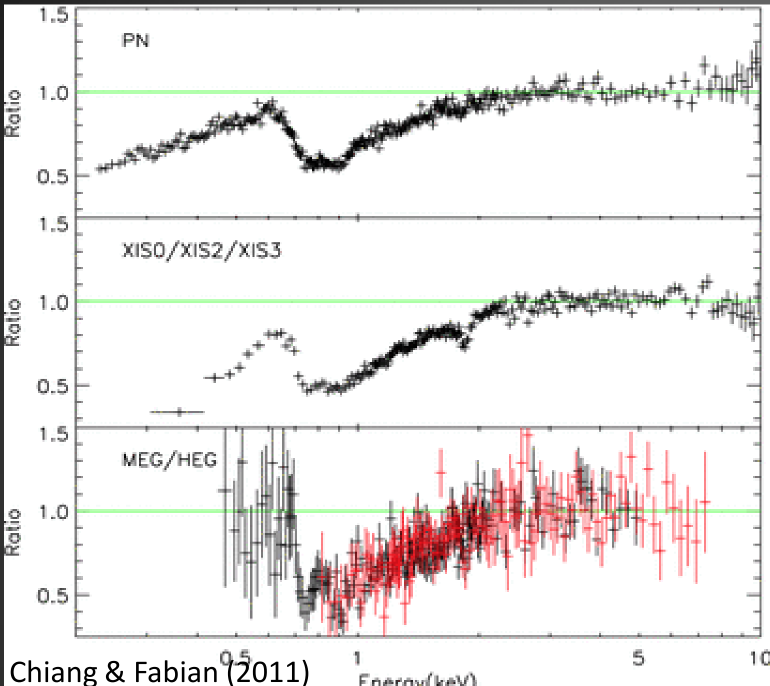
Separating Reflection from Absorption

- **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* (2012)** will also have high enough collecting area, spectral resolution and low enough background >10 keV to differentiate between reflection and absorption.
- **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 two.





Spectral Variability in MCG—6-30-15



Chiang & Fabian (2011)

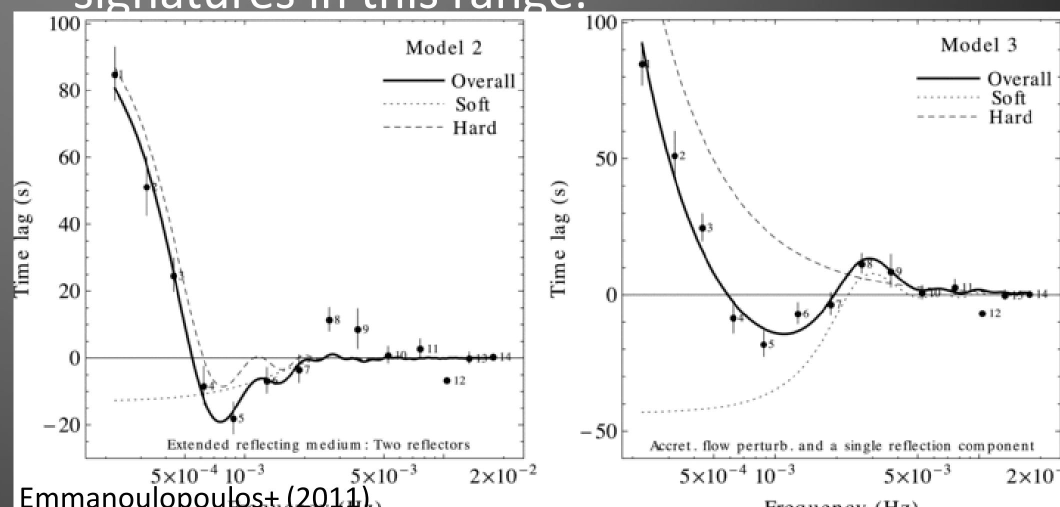
- Negative time-lag (~20 s) seen between hard and soft bands (soft trails hard), like 1H0707.

- 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.

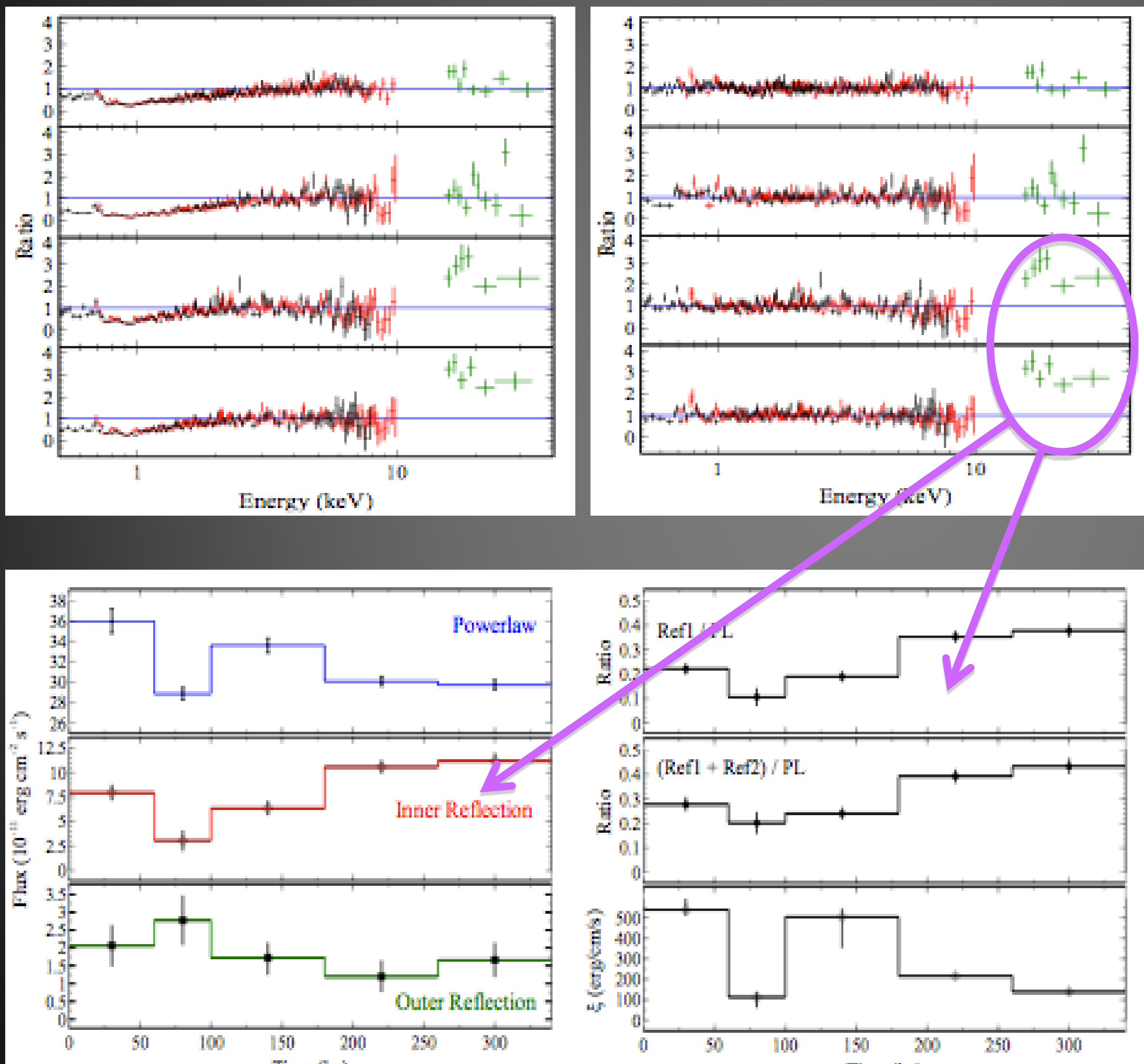
- Difference spectra (high flux - low flux) best fit by absorbed power-law <2 keV, unabsorbed power-law >2 keV in *XMM, Suzaku, Chandra* data.

- Best-fit model to all three has constant, three-zone warm absorber: $N_H = 10^{20-23}$, $\xi = 0.03$-6300, <u>no partial covering</u>.



Emmanoulopoulos+ (2011)

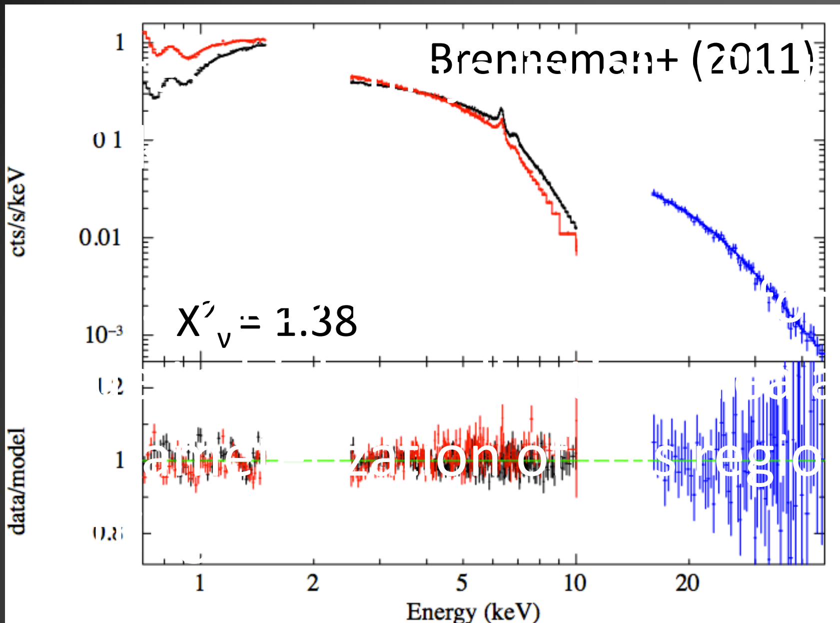
Spectral Variability in NGC 3783

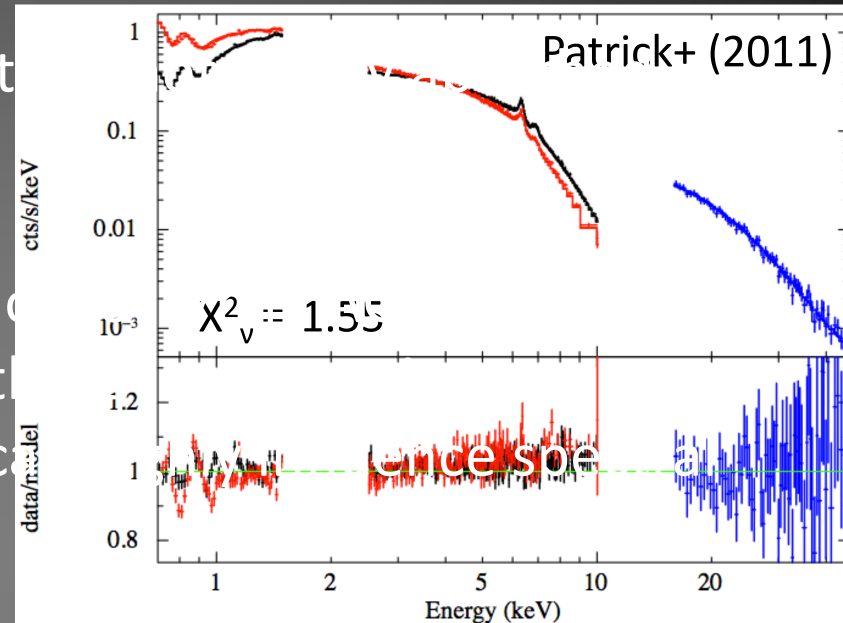


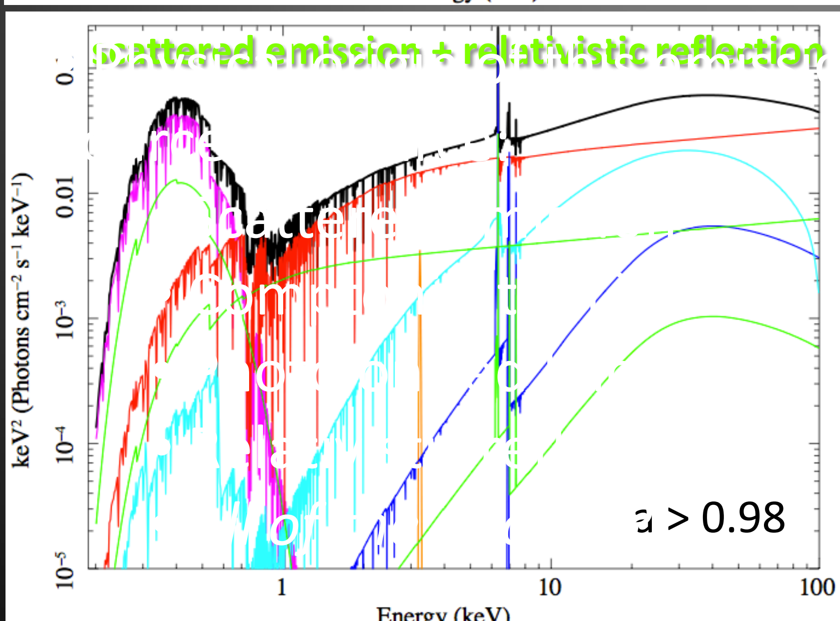
Reis+ (2011)

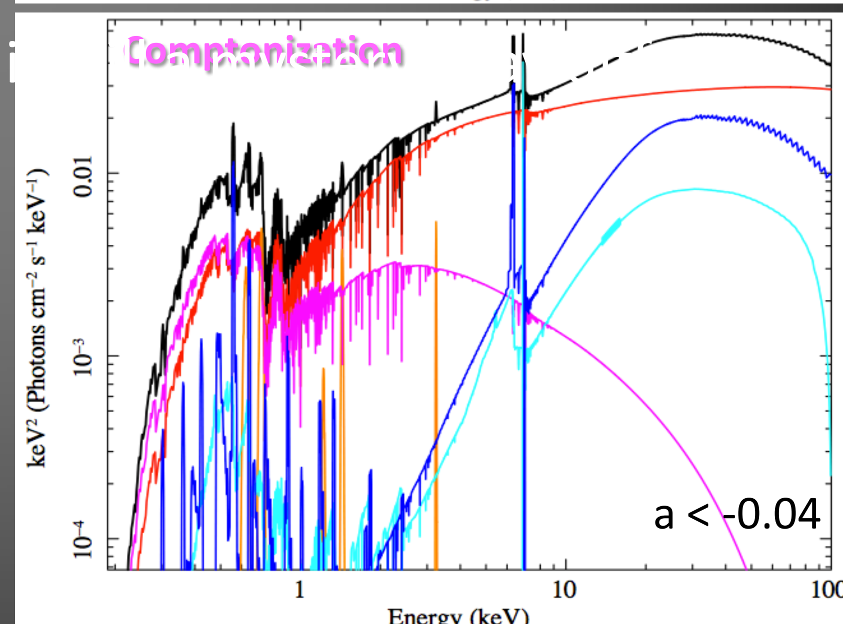
- *Suzaku* difference spectra in NGC 3783 also well-modeled by absorbed power-law <2 keV, power-law only >2 keV.
- Once constant warm absorber is included for each time interval, difference spectra are fit very well <10 keV.
- Excess hard emission remains in intervals 4-5; best fit with model that allows for changing reflection fraction, inner disk ionization (ξ) as inner disk flux changes.
- Broadly consistent with light bending interpretation.

What about the Soft Excess?









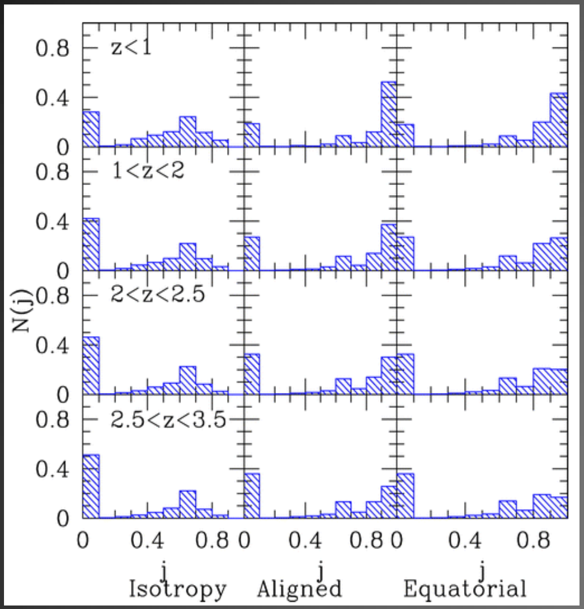
SMBH Spin Constraints from Reflection

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	>0.98	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

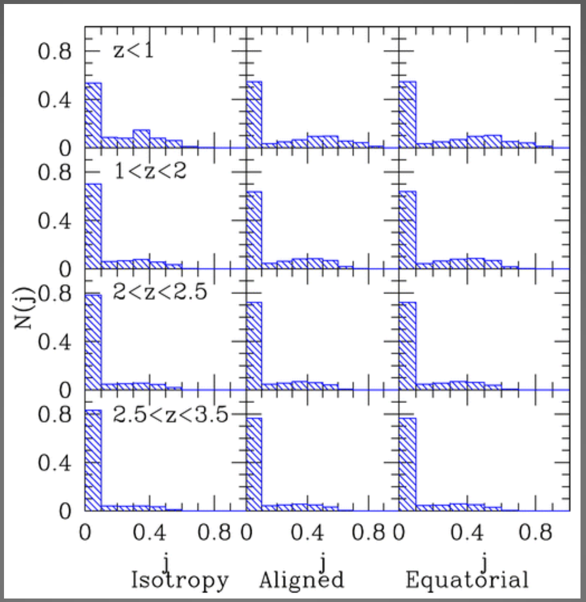
L. Miller+ (2008, 2009) have argued that multi-component, partial-covering absorber negates need for inner-disk reflection in, e.g., MCG—6-30-15, so no spin constraints possible. Also argue that distant reflection alone reproduces 1H0707 spectrum.

Patrick+ (2011) have published disparate spin constraints: NGC 3783 ($a < -0.04$) and MCG—6-30-15 ($a \sim 0.44$).

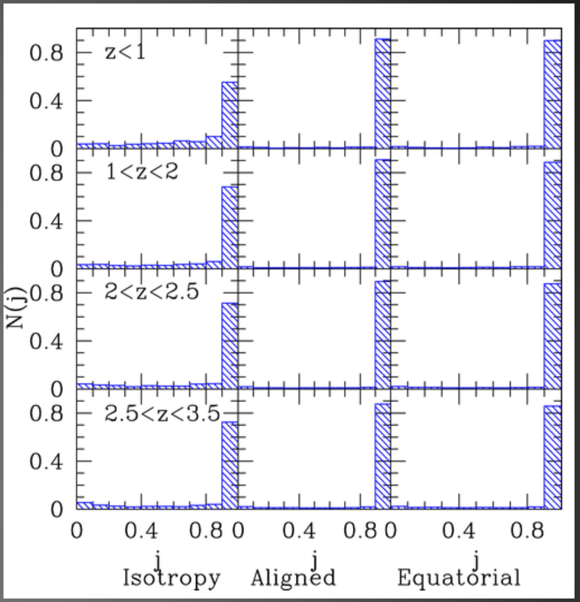
Black Hole Spin and Galaxy Evolution



Mergers only



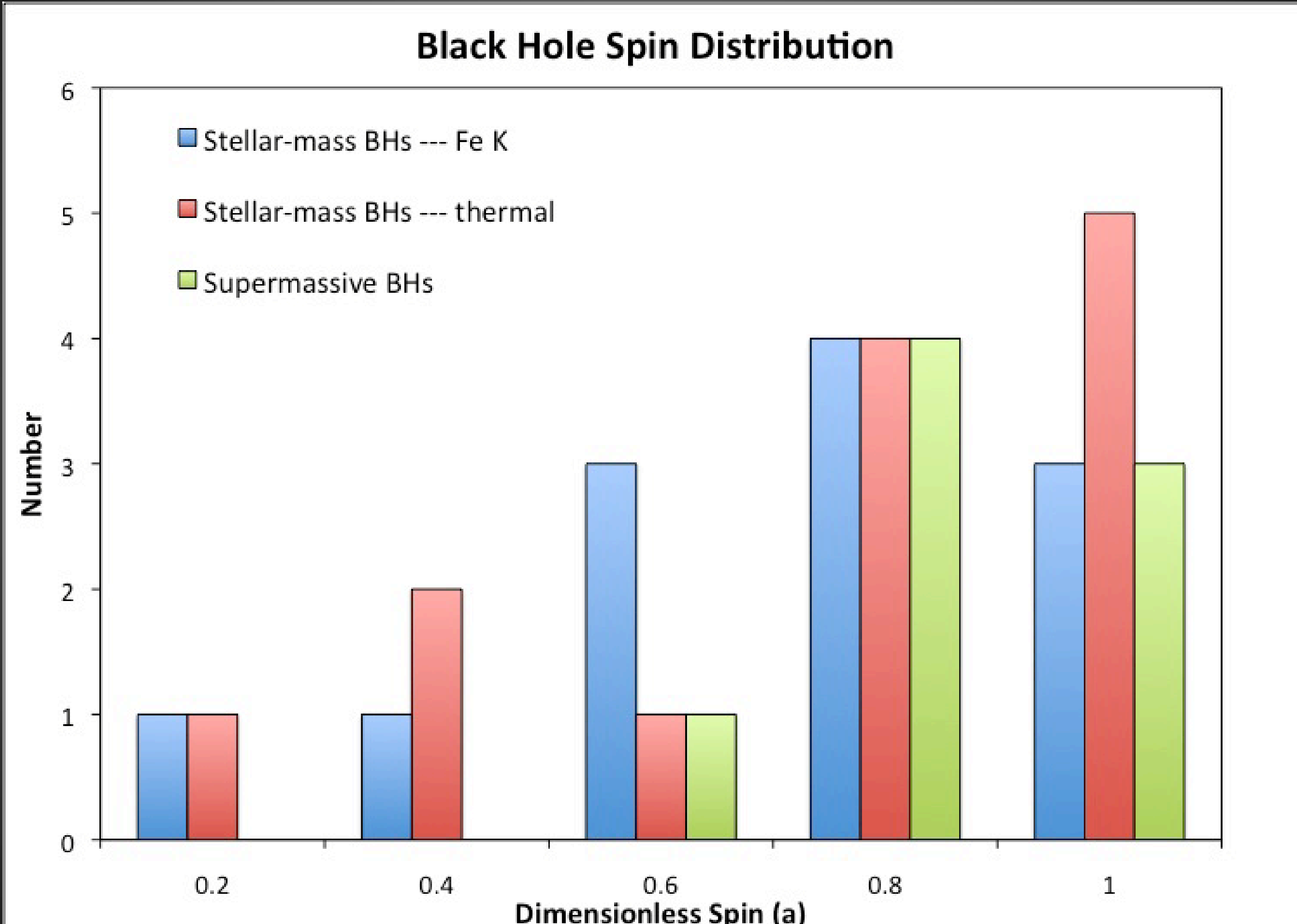
Mergers + chaotic accretion



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.

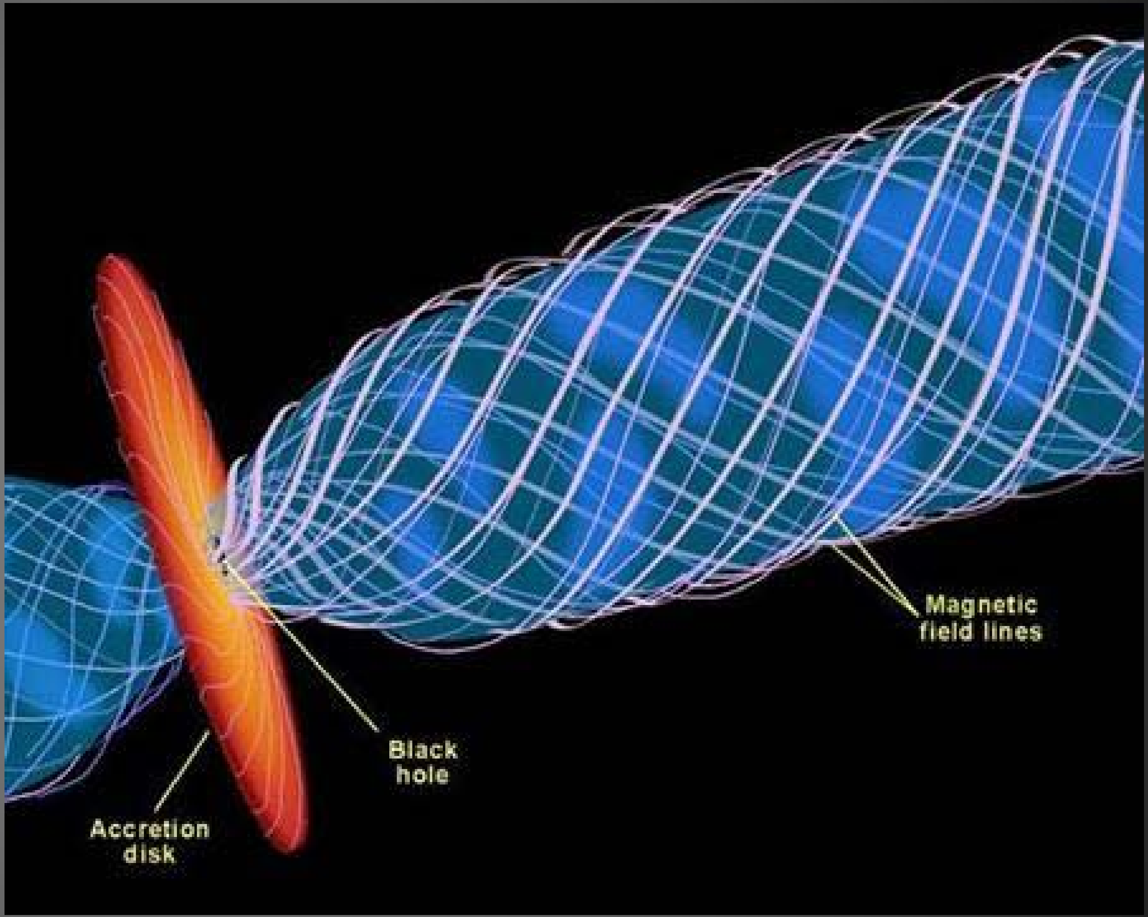

Black Hole Spin Distribution
Stellar-mass BHs --- Fe K
Stellar-mass BHs --- thermal
Supermassive BHs
Number
0
1
2
3
4
5
6
0.2
0.4
0.6
0.8
1
Dimensionless Spin (a)

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.

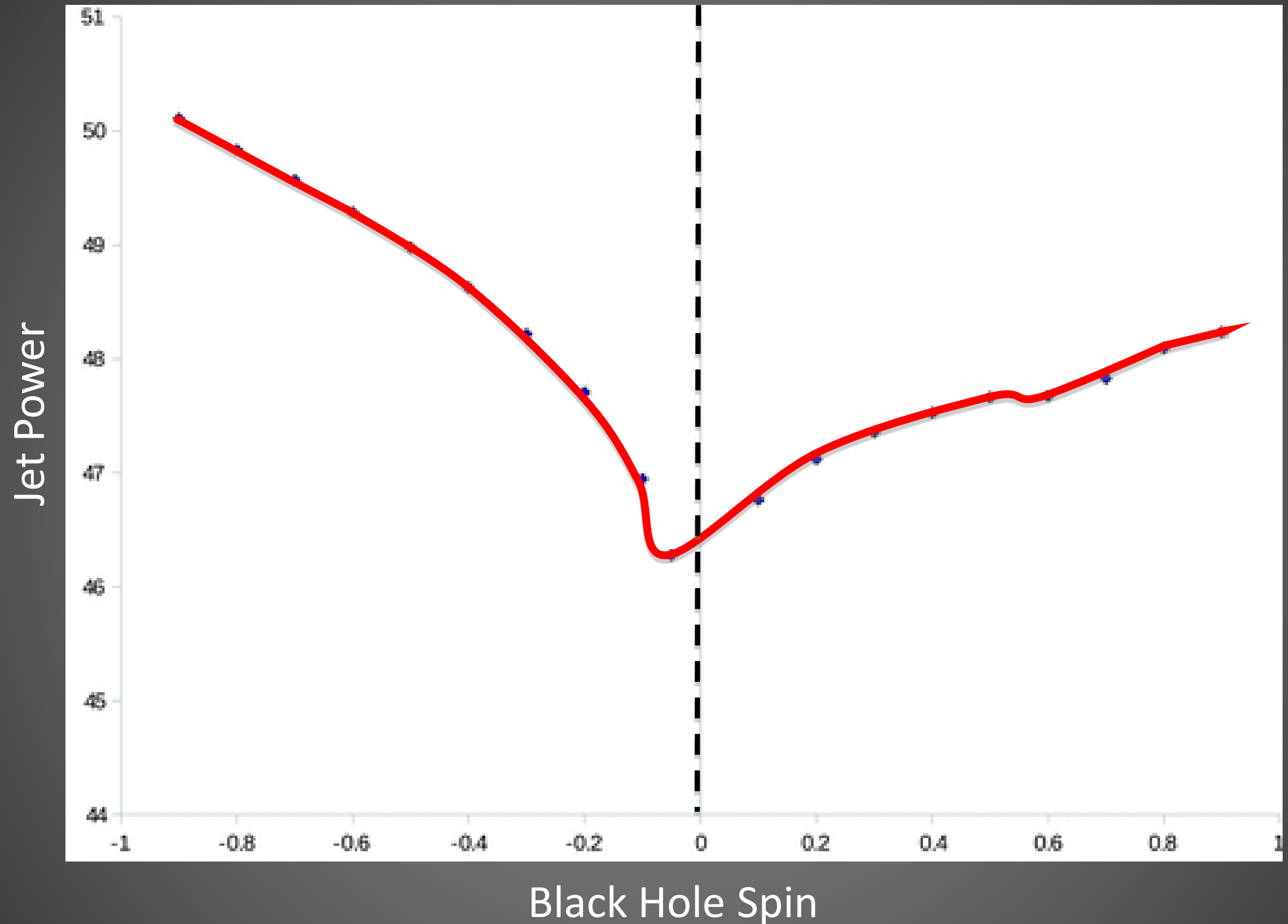
- Magnetic field lines thread disk, get twisted by differential rotation and frame-dragging.

- Results in a powerful outflow, though many specifics are still unknown, including how/why jets launch.



- Exact dependence of jet power on spin, accretion rate, magnetic field strength is as yet unknown.

Powerful Jets = Retrograde Spin?



- Based on numerical simulations of Garofalo+ (2009), jet power is maximized for large, retrograde BH spins.

Consequences for Galaxy Evolution

- **Expect to measure large, retrograde BH spins in galaxies with brightest, most powerful jets (Garofalo+ 2010).**

- But ***retrograde spin is an unstable condition…*** BH and disk want to align, and accretion will force this to happen.

- So phase of galaxy's life with powerful jets should be relatively short, perhaps following a **major merger** with another galaxy.

- Translates to relatively **few powerful, radio-loud galaxies** and lots more galaxies that are radio-quiet.

- Also expect to see more **RL galaxies that are elliptical and/or disturbed** vs. spiral if a "spin-flip" is triggered by a merger.

- **Observations back this up**, but larger sample size is needed, also need to probe to larger redshift to see how the fractions of RQ vs. RL galaxies change over time. Also need spin measurements (e.g., Daly 2011… measurement of magnetic field is a complicating factor).

Summary

• **Reflection modeling** gives SMBH spin constraints now; **polarimetry** may provide independent check in the future, perhaps eventually **HFQPOs** as well.

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

• Not yet a large enough sample size to probe accretion vs. mergers.

• Lack of retrograde spins for AGN may be **selection bias**, as may preferential finding of high spins, on average (bright, nearby sources).

• **Larger sample size** of AGN spins must be obtained with combination of **time-resolved spectroscopy, multi-epoch spectroscopy and timing analysis** with various instruments to get good spin constraints.

Future Directions

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

- *ASTROSAT* (2012): Simultaneous UV & X-ray spectroscopy
  - tighter constraints on disk thermal emission, warm absorption

- *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

- *ATHENA/EPE* (??): Further large increase in E.A. over these missions
  - probe accretion physics on orbital timescales

Open Questions

1. How much of the soft excess in AGN is due to relativistic reflection from the inner disk?

2. What is the distribution of BH spins in the universe? How does this change with time/redshift?

3. What does this distribution tell us about the recent accretion vs. merger histories of AGN?

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

5. Do retrograde spins produce the most powerful jets?