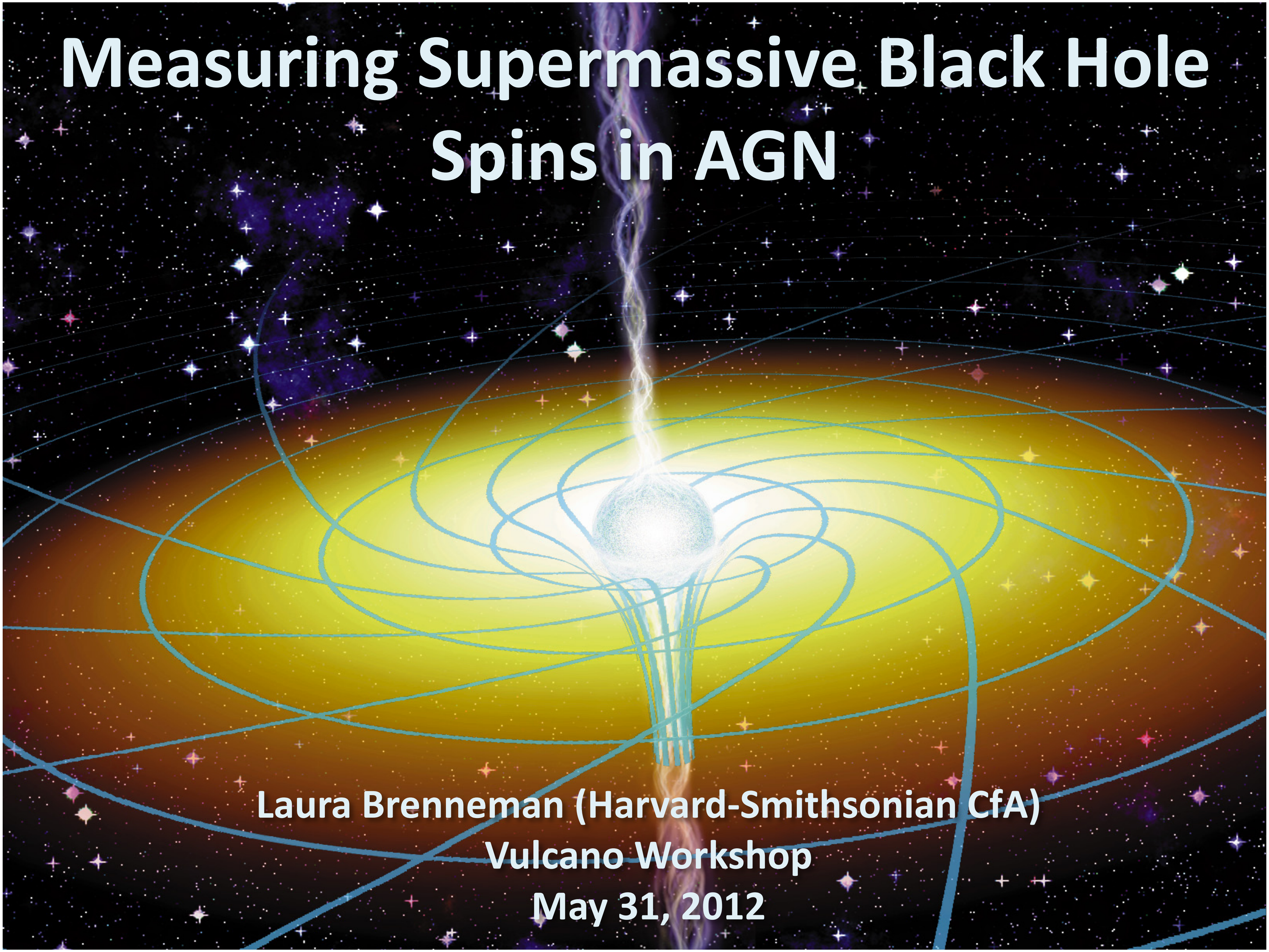
Measuring Supermassive Black Hole Spins in AGN



Laura Brenneman (Harvard-Smithsonian CfA)

Vulcano Workshop

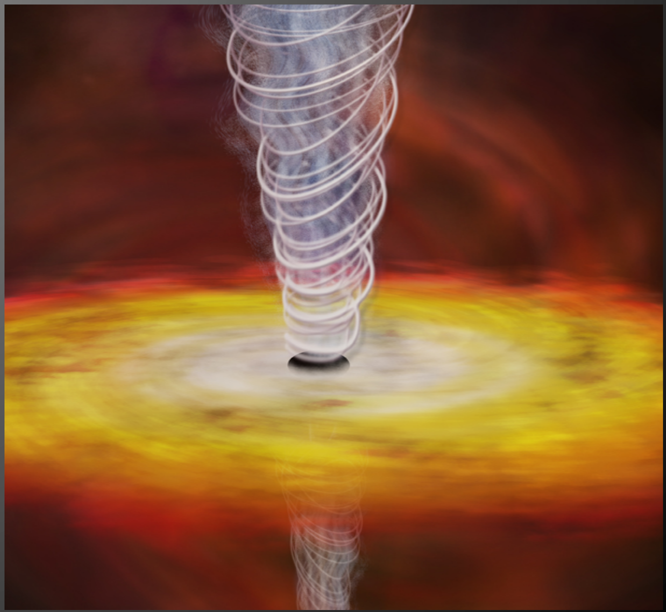
May 31, 2012


Measuring Supermassive Black Hole Spins in AGN
Collaborators: Chris Reynolds, Martin Elvis, Andy Fabian, Guido Risaliti, Rubens Reis, Mike Nowak, Jon Miller

Outline

- Motivation for studying 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** (e.g., talk by Boller).
- 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)

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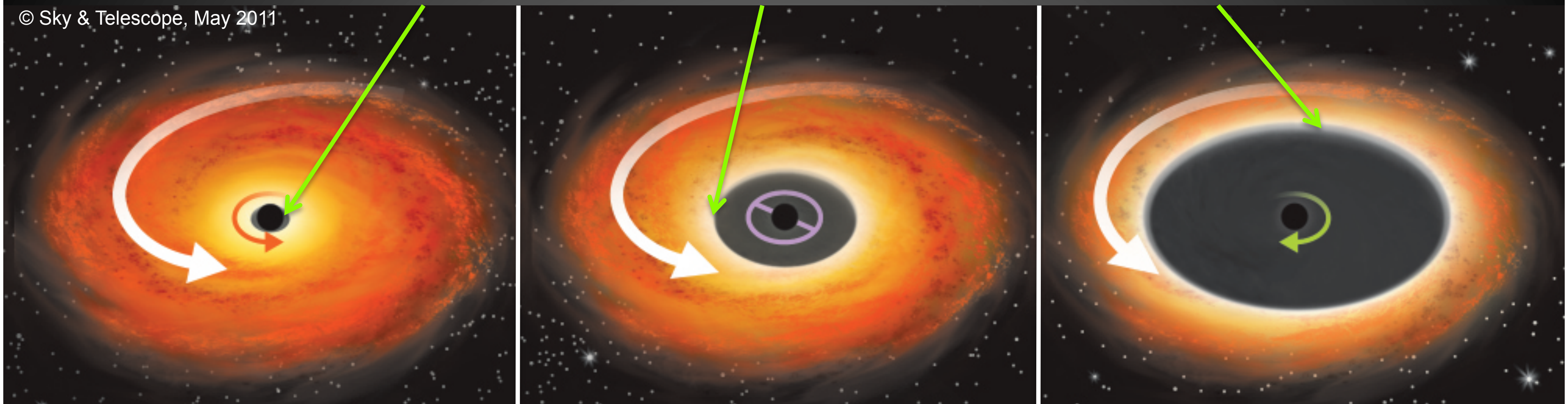
The Innermost Stable Circular Orbit

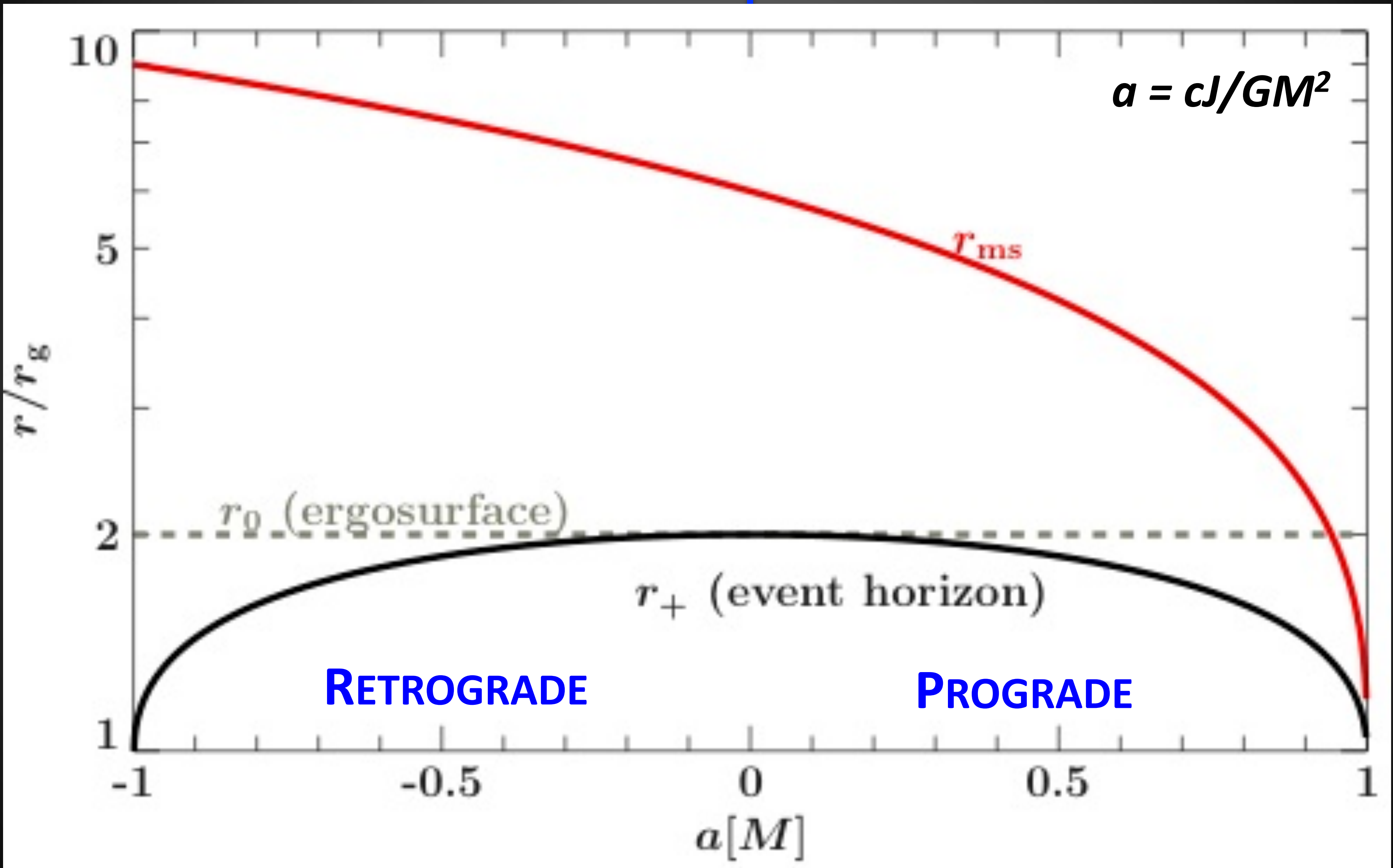


- Maximally-spinning ***prograde* BH** (spinning in same direction as disk).
- ISCO at 1 GM/c^2.
- Frame-dragging rotationally supports orbits closer to BH before plunging.

- **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

• Rela
Comp
(UV)
prod
spect

• Son
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• Fluo
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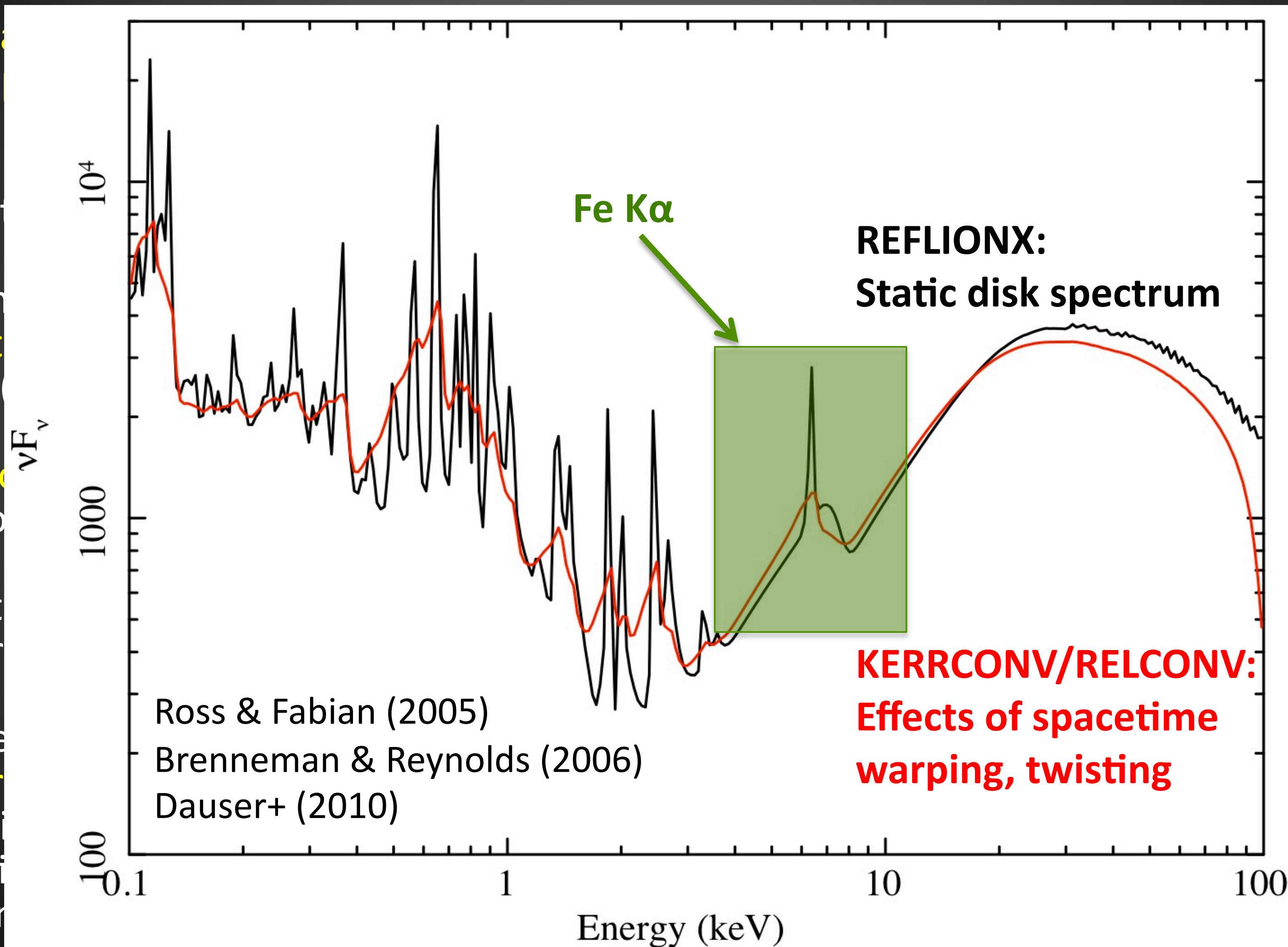
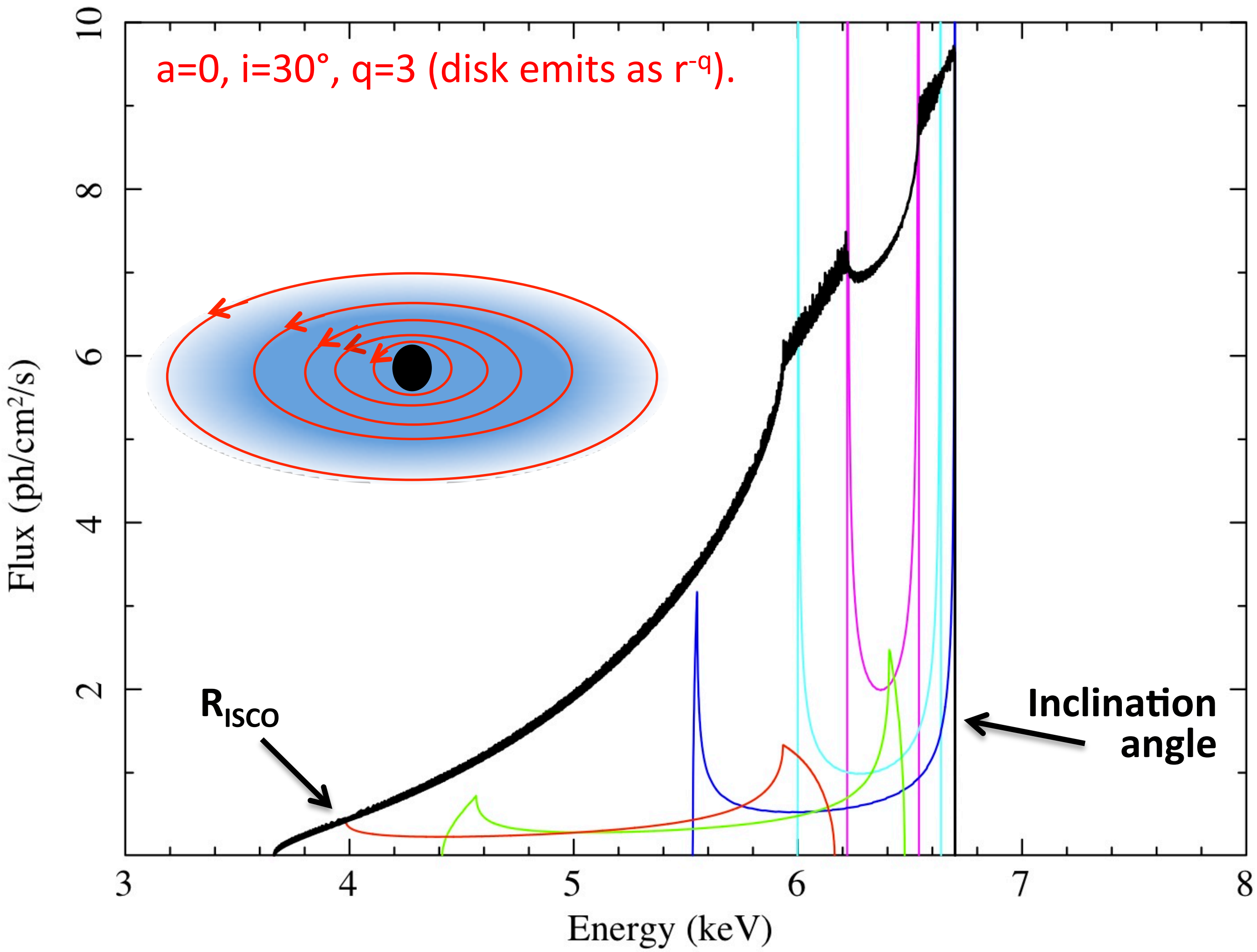
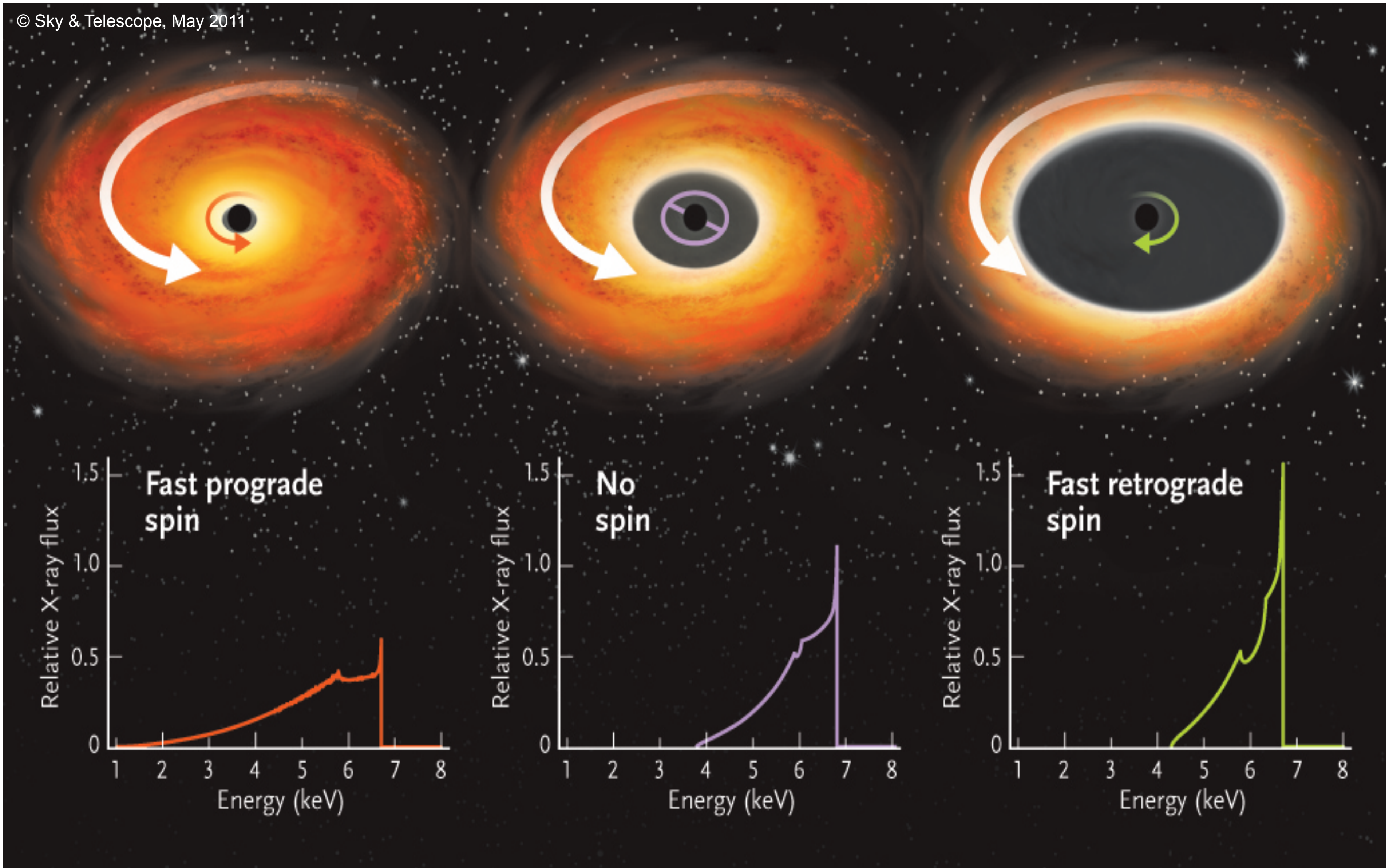


Fe Kα emission line from different disk annuli



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 $r_{in} \leq 9\ r_g$.

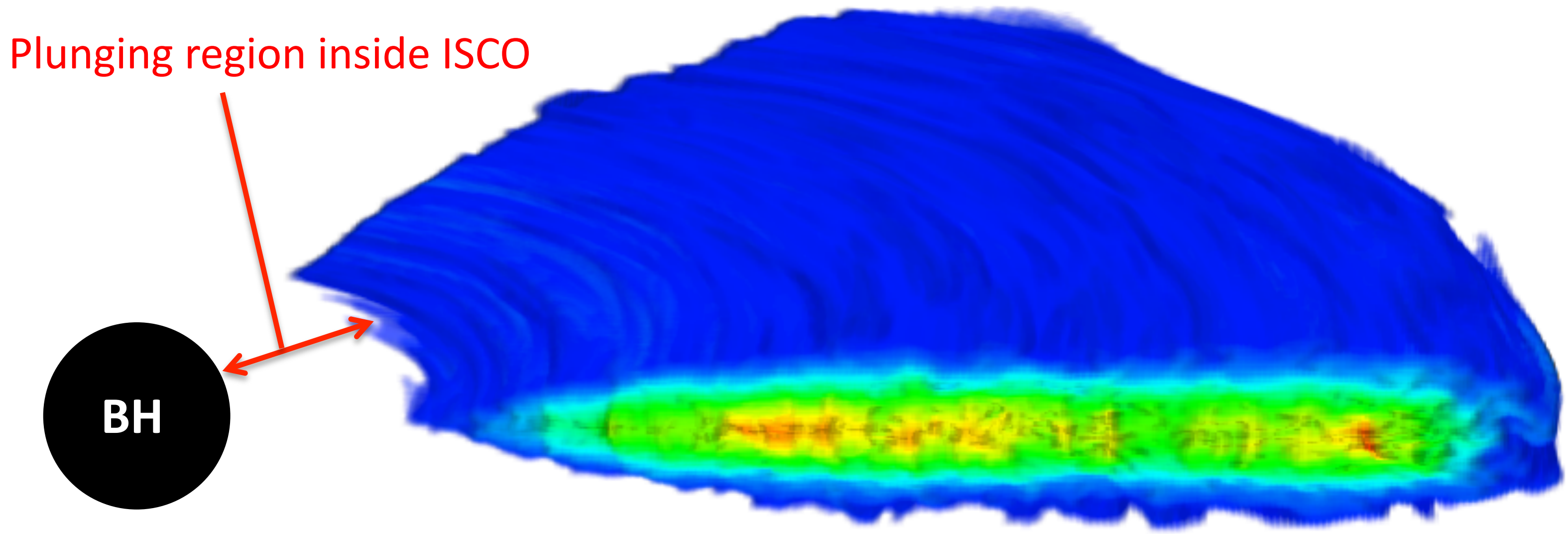
- Technique used: **Inner Disk Reflection** (e.g., broad Fe Kα):

KERRCONV, RELCONV or KYCONV × REFLIONX or XILLVER

Brenneman & Reynolds (2006) — Dauser+ (2010) — Dovčiak+ (2004) — Ross & Fabian (2005) — Garcia & Kallman (2010)

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

Assumption of ISCO Truncation



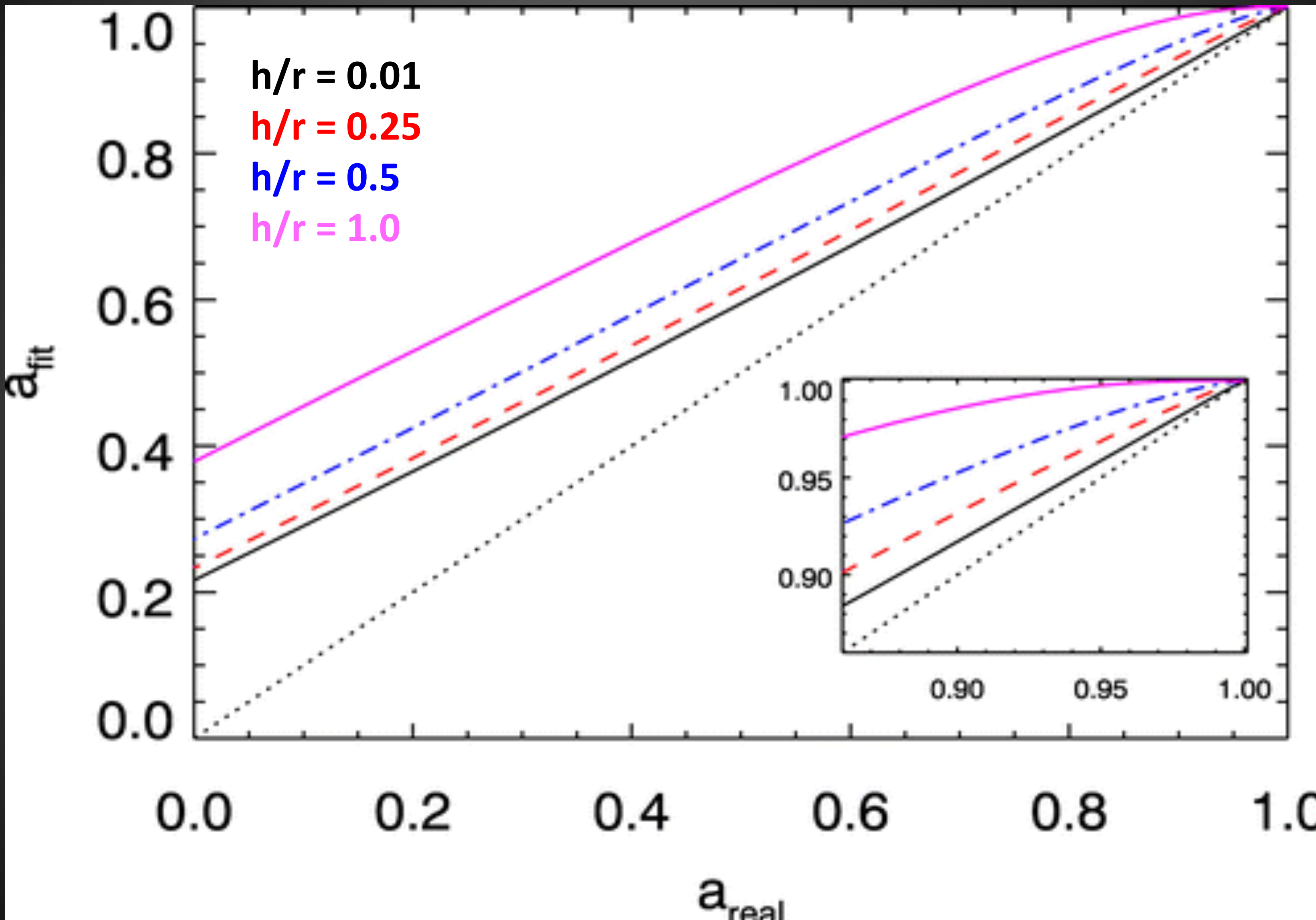
3-D MHD simulation of a geometrically-thin accretion disk.

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

Rapid drop in τ, rise in ξ within ISCO.

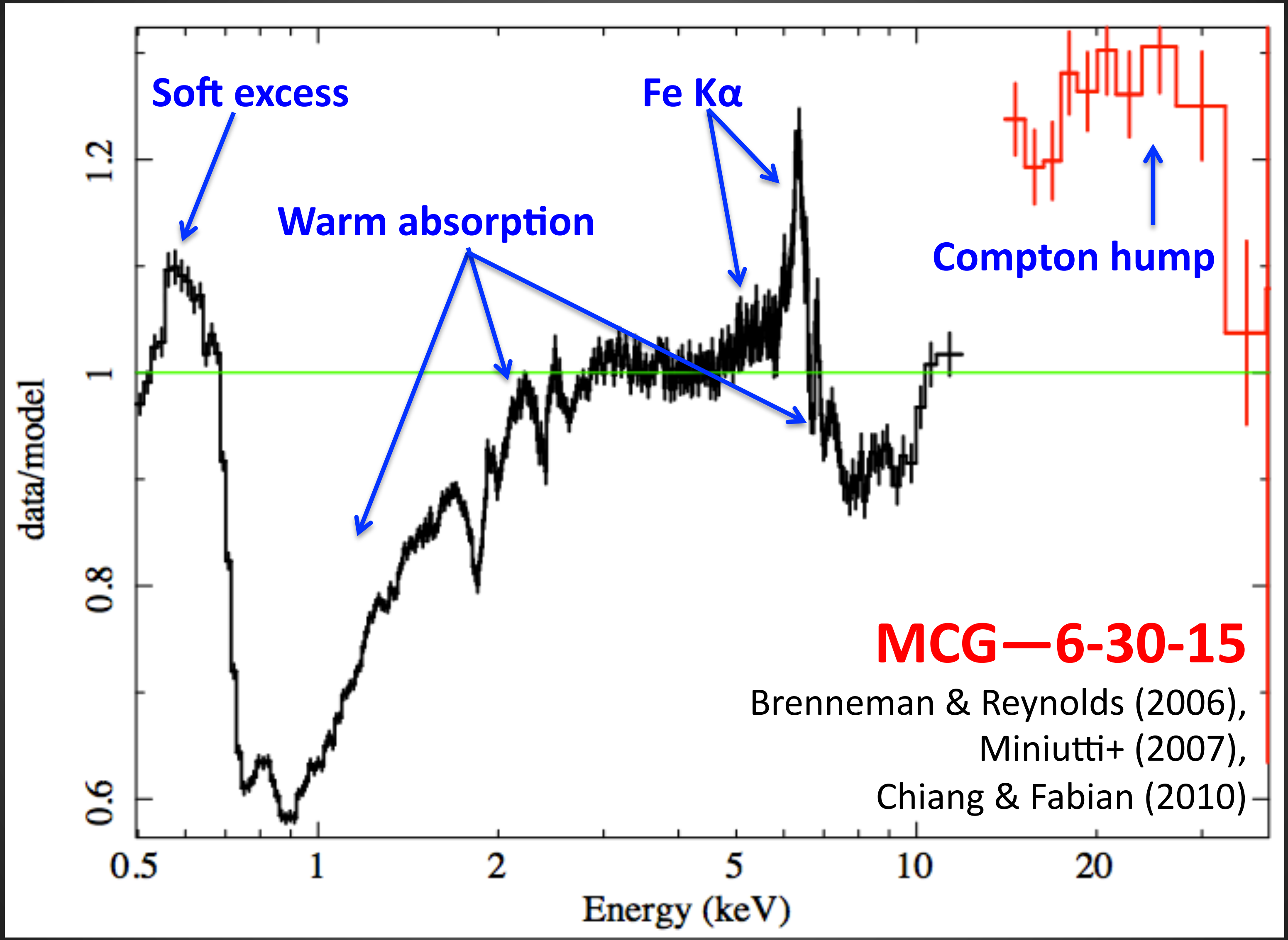
Reynolds & Fabian (2008)

Systematic Error from Emission ≤ISCO

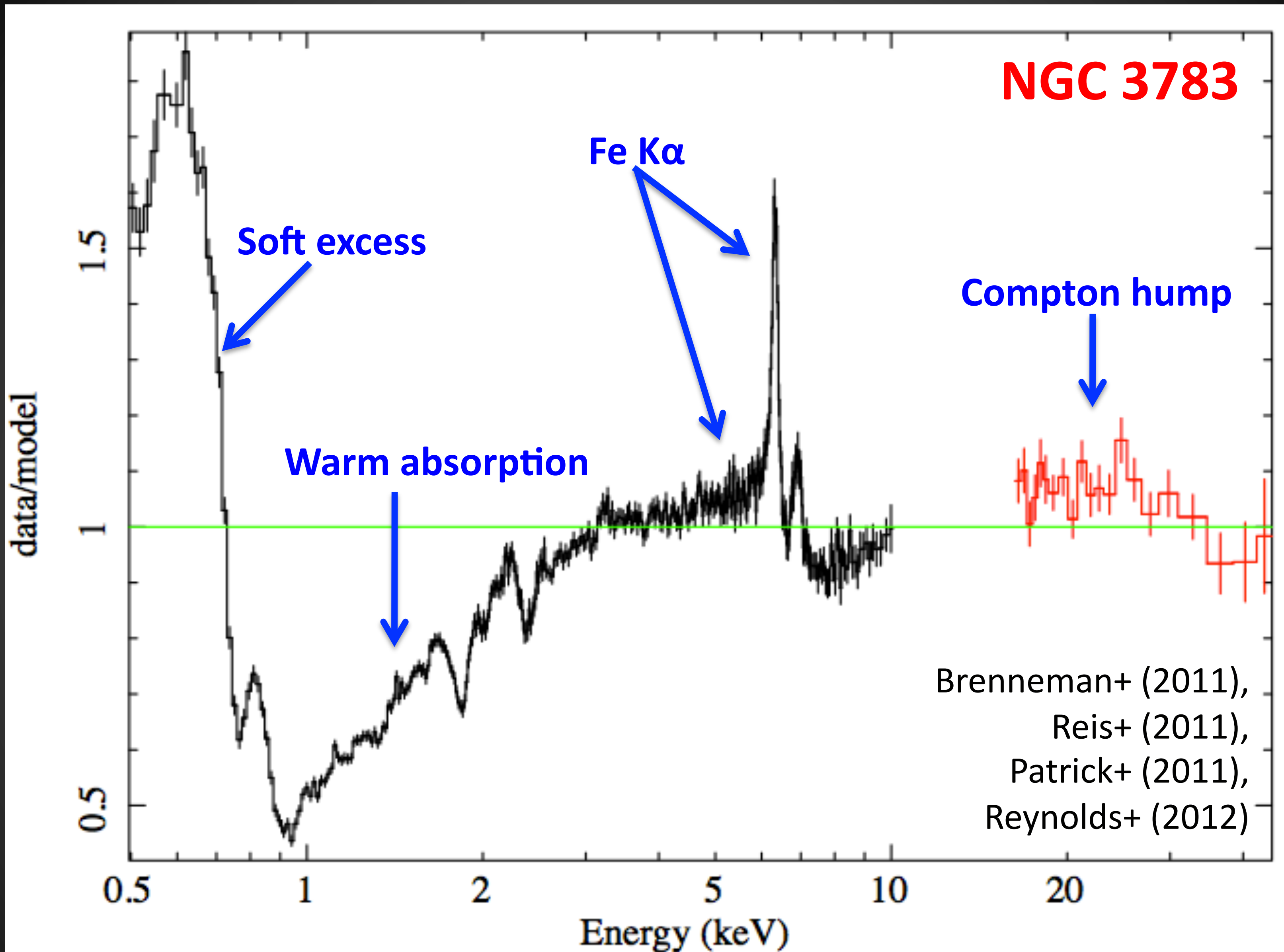


Reynolds & Fabian (2008)

Spectral Complexity



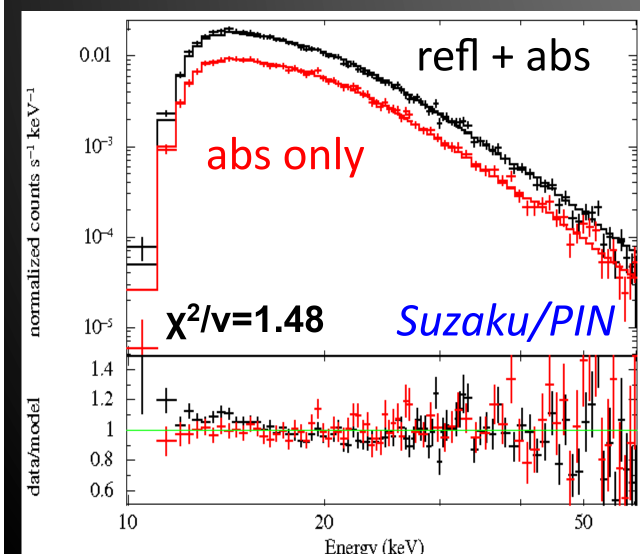
Spectral components with continuum power-law modeled out

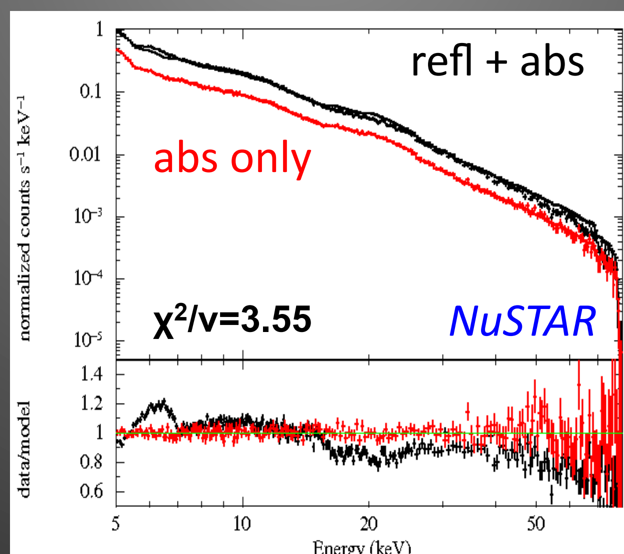


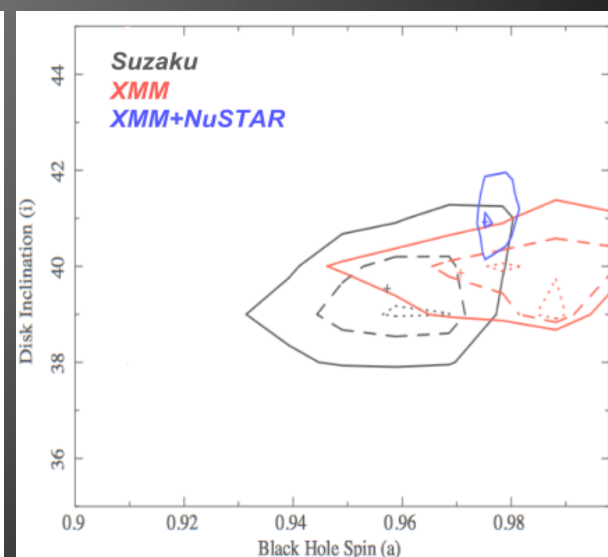
Spectral components with continuum power-law modeled out

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, spectral resolution 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**.







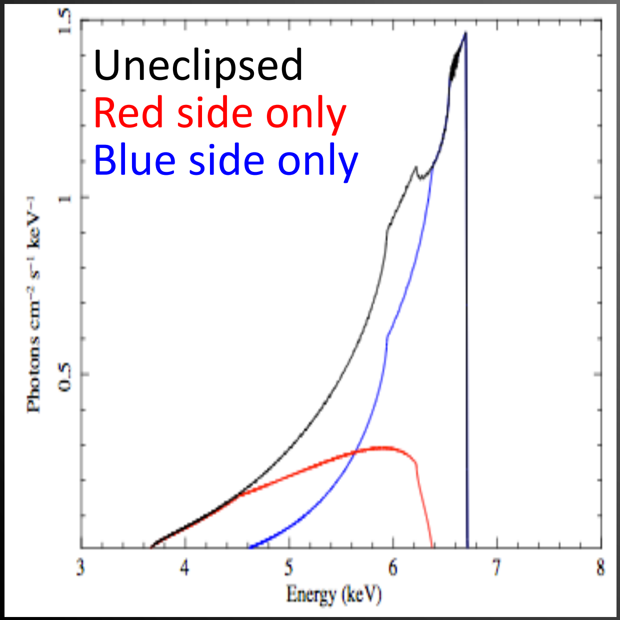
Separating Reflection from Absorption

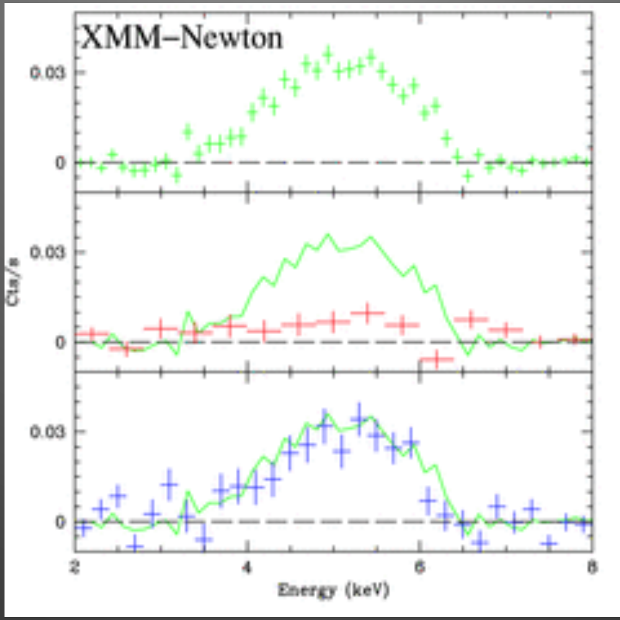
- **X-ray eclipses of the inner disk** by BLR clouds cited in NGC 1365 (e.g., Risaliti+ 2011, Brenneman+, in prep.) can also differentiate between the reflection and absorption-only spectral modeling interpretations.

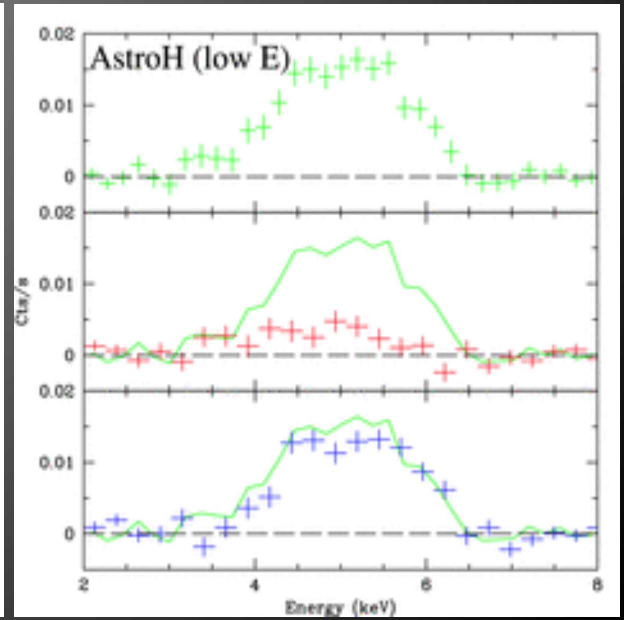
- Can **verify the existence of relativistic emission** features from the inner accretion disk by examining change in morphology of putative Fe K line as the eclipse progresses.

- Eclipse must produce a **change in column density of factor ~10** to demonstrate such an effect.

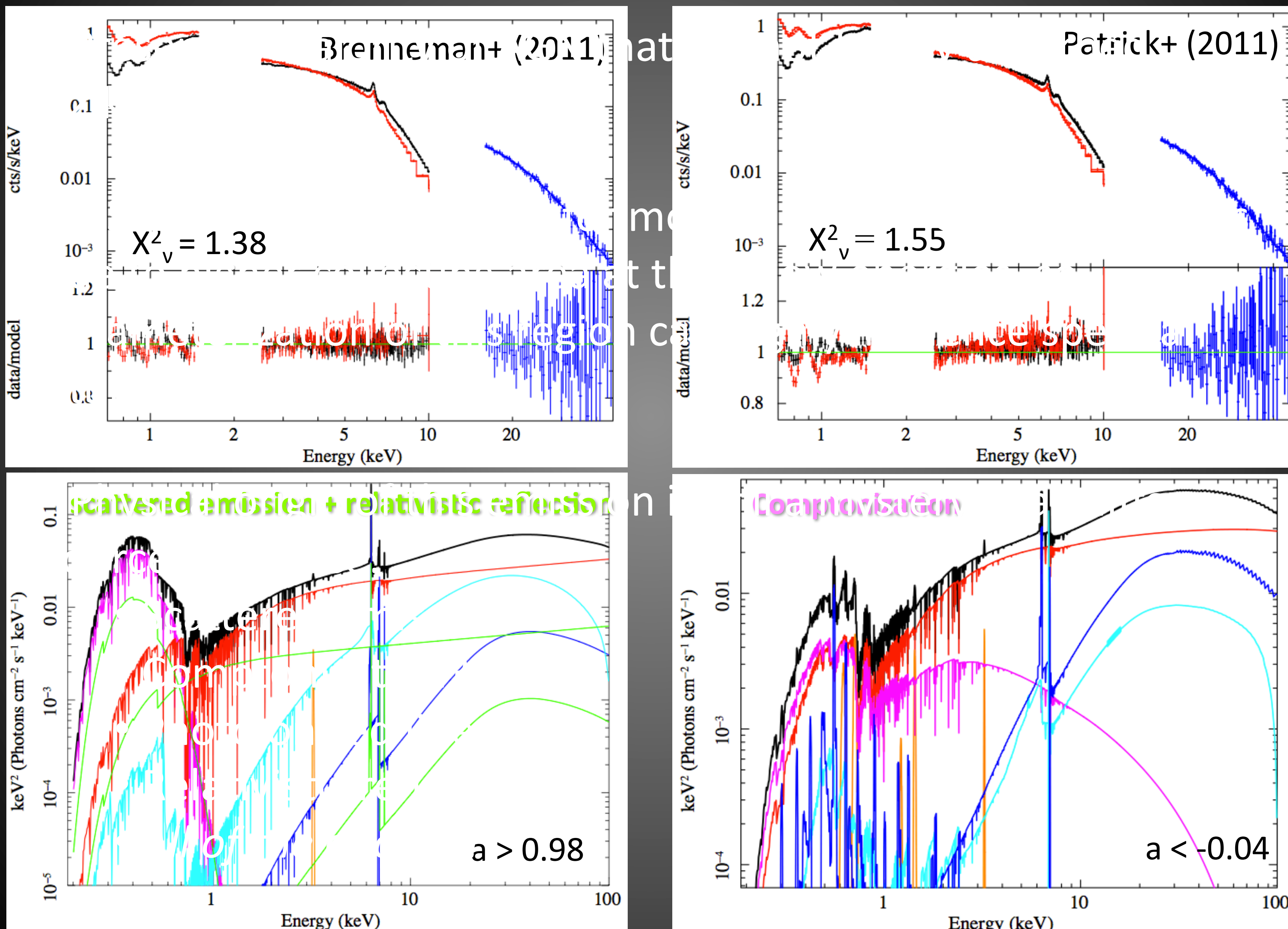
- NGC 1365 subject of ***XMM/NuSTAR* observing campaign** (PI: Risaliti); **theoretical modeling** of light curves and spectra from inner disk during eclipses is also ongoing (PI: Brenneman).





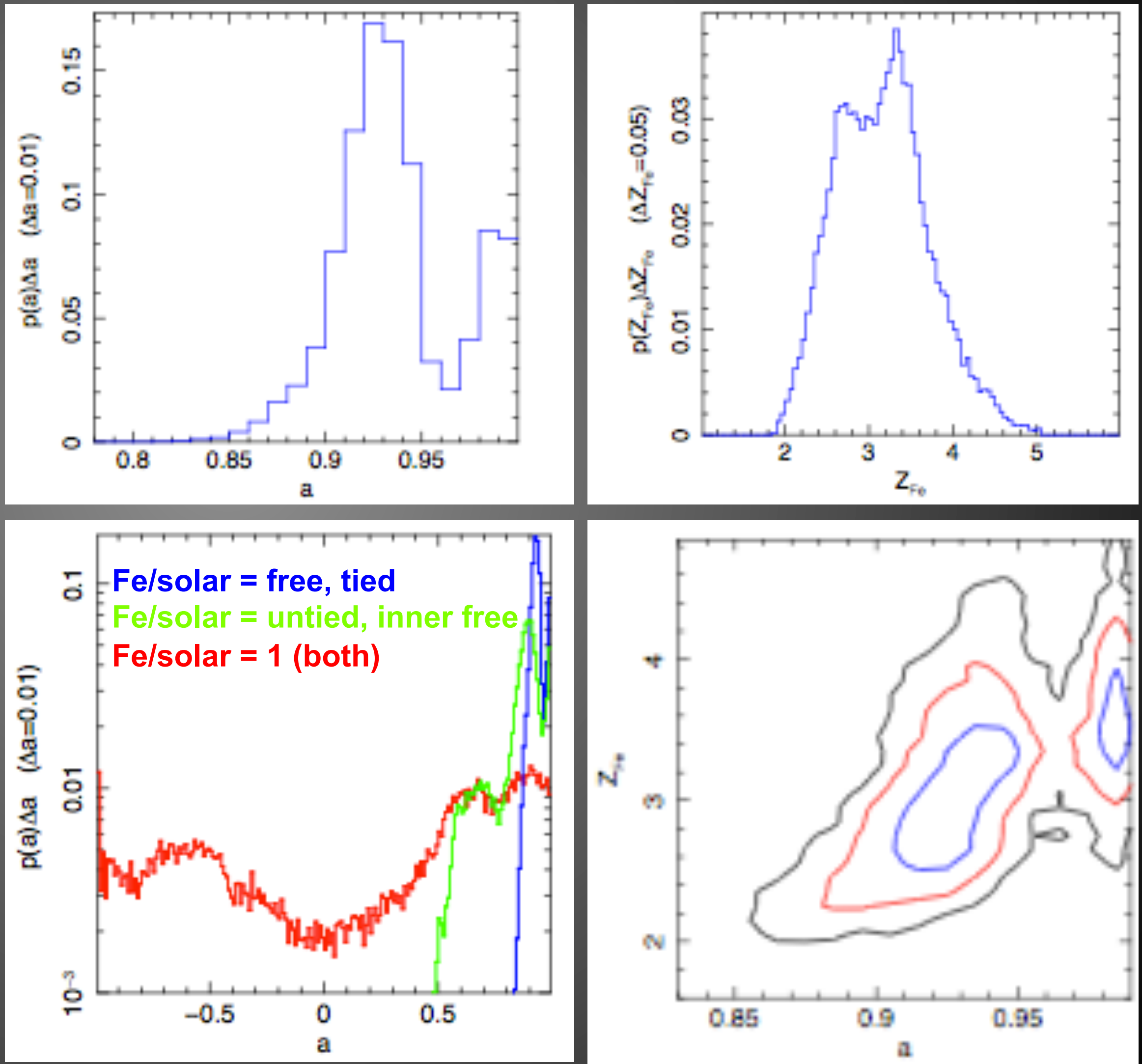


What about the Soft Excess (e.g., NGC 3783)?



Other Factors: Iron Abundance in NGC 3783

- Fit drives a > 0.88, 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 (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.



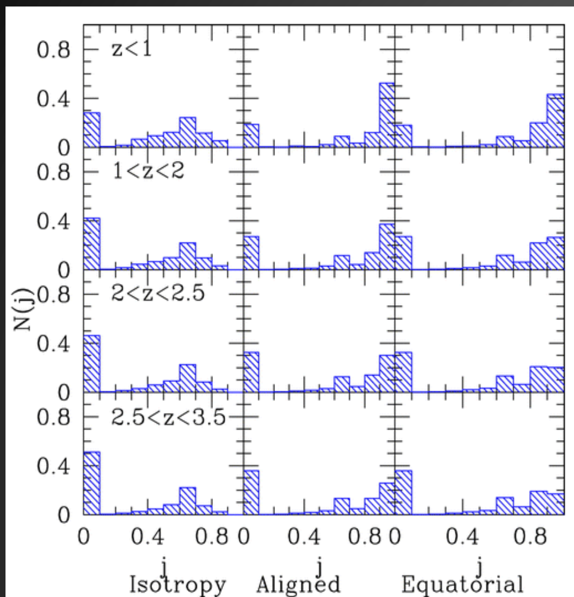
Reynolds, Brenneman+ (2012)

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	≥0.98	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
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

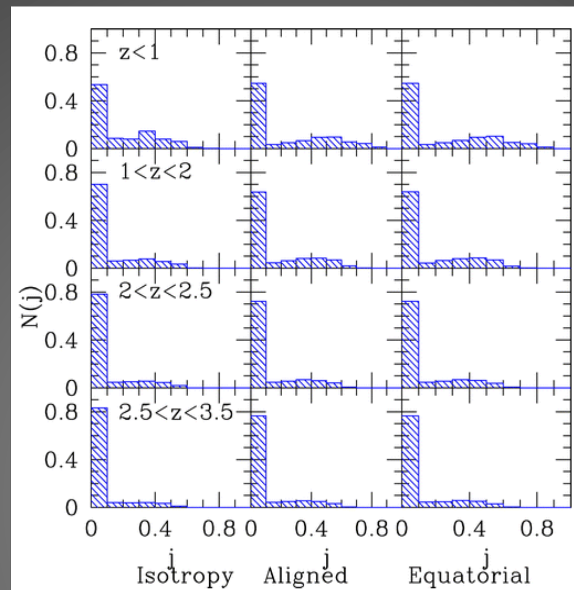
N.B.: Patrick+ (2011) have published disparate spin constraints: NGC 3783 ($a < -0.04$) and MCG—6-30-15 ($a \sim 0.44$) based on different modeling of soft excess emission.

Black Hole Spin and Galaxy Evolution

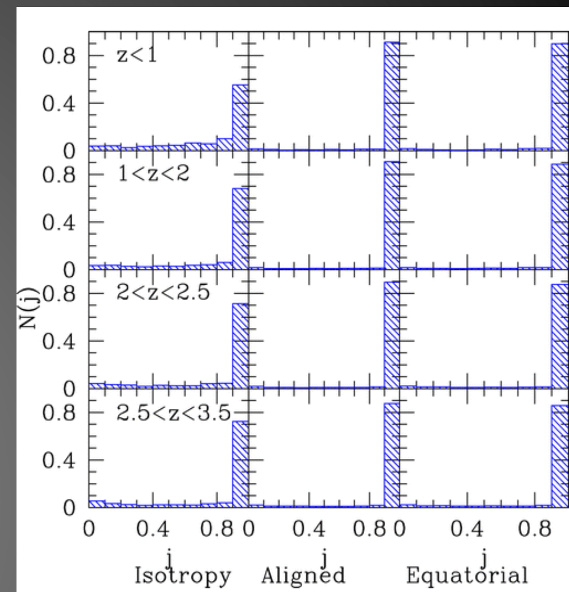


Mergers only

Berti & Volonteri (2008)

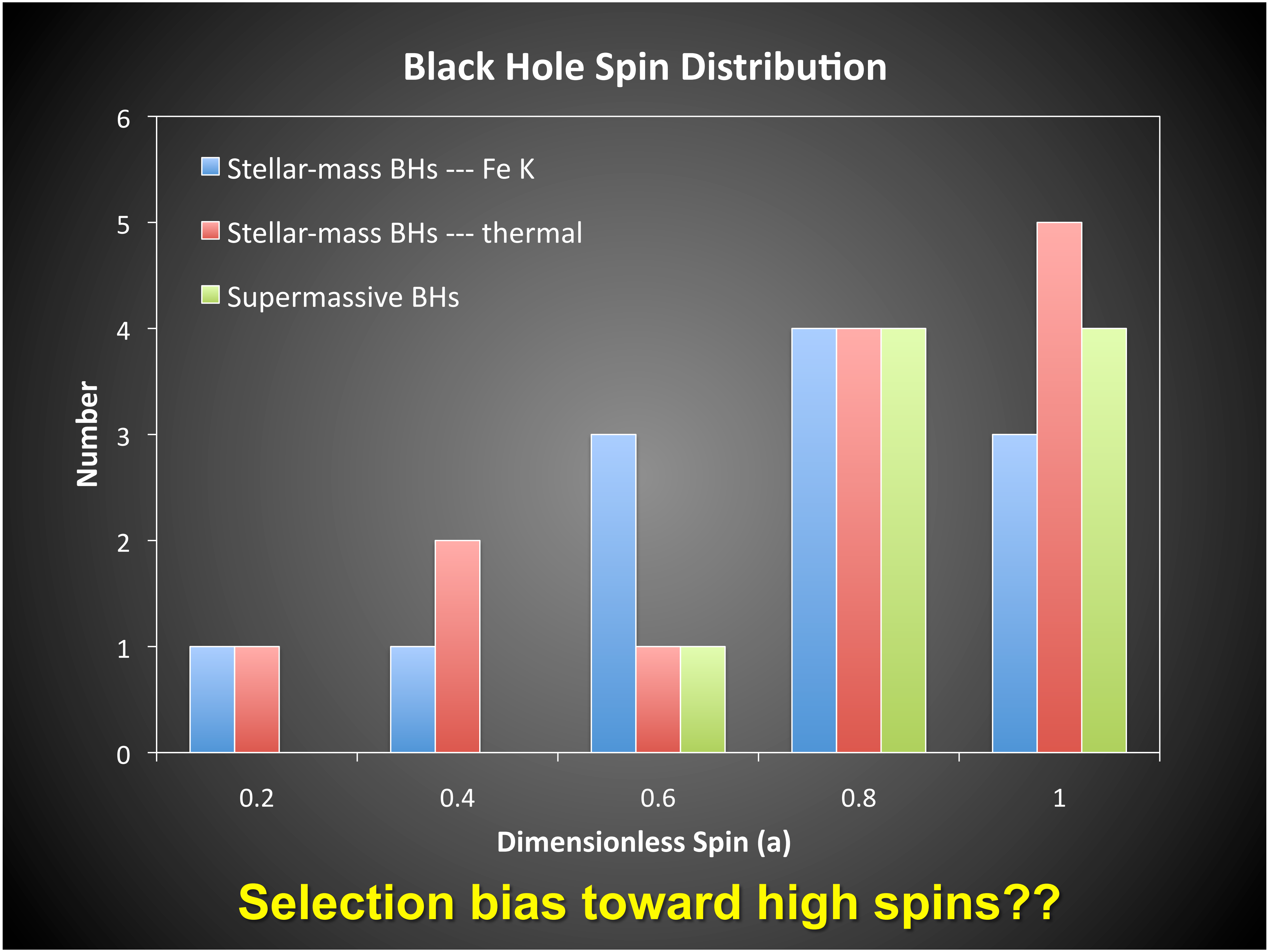


Mergers + chaotic accretion



Mergers + prolonged accretion

- 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 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)
Selection bias toward high spins??

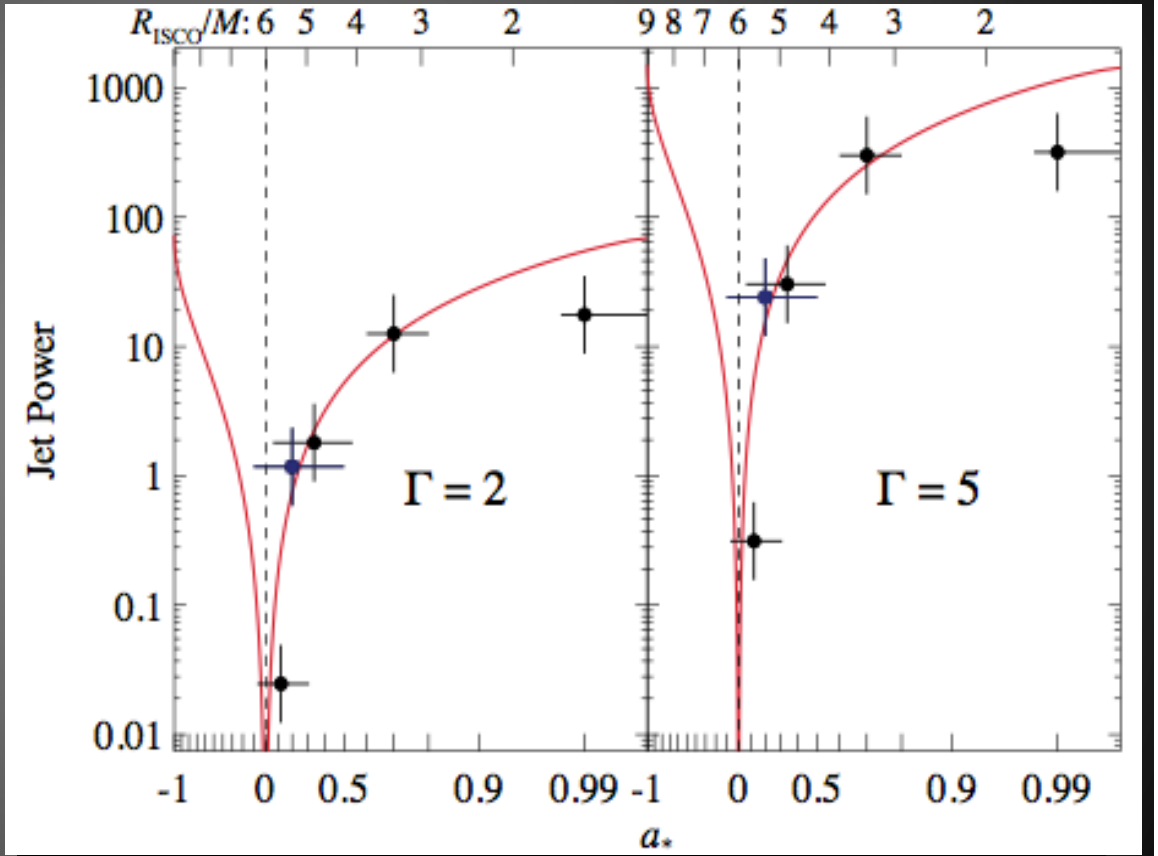
Black Hole Spin and Jet Production

- 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.

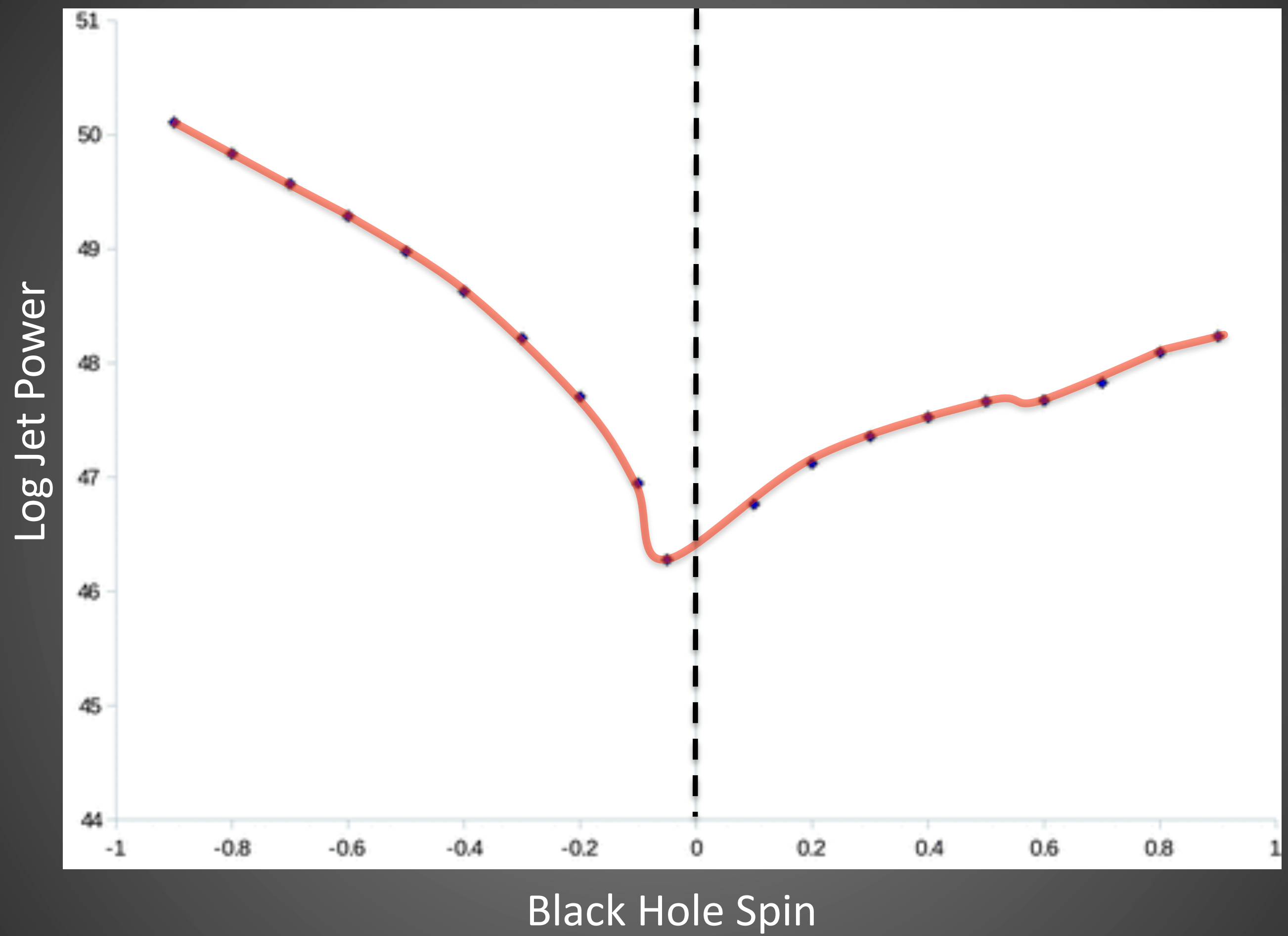
- Results in a powerful outflow, though **many specifics are still unknown**, including how/why jets launch, dependence on spin, magnetic field, accretion rate.

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



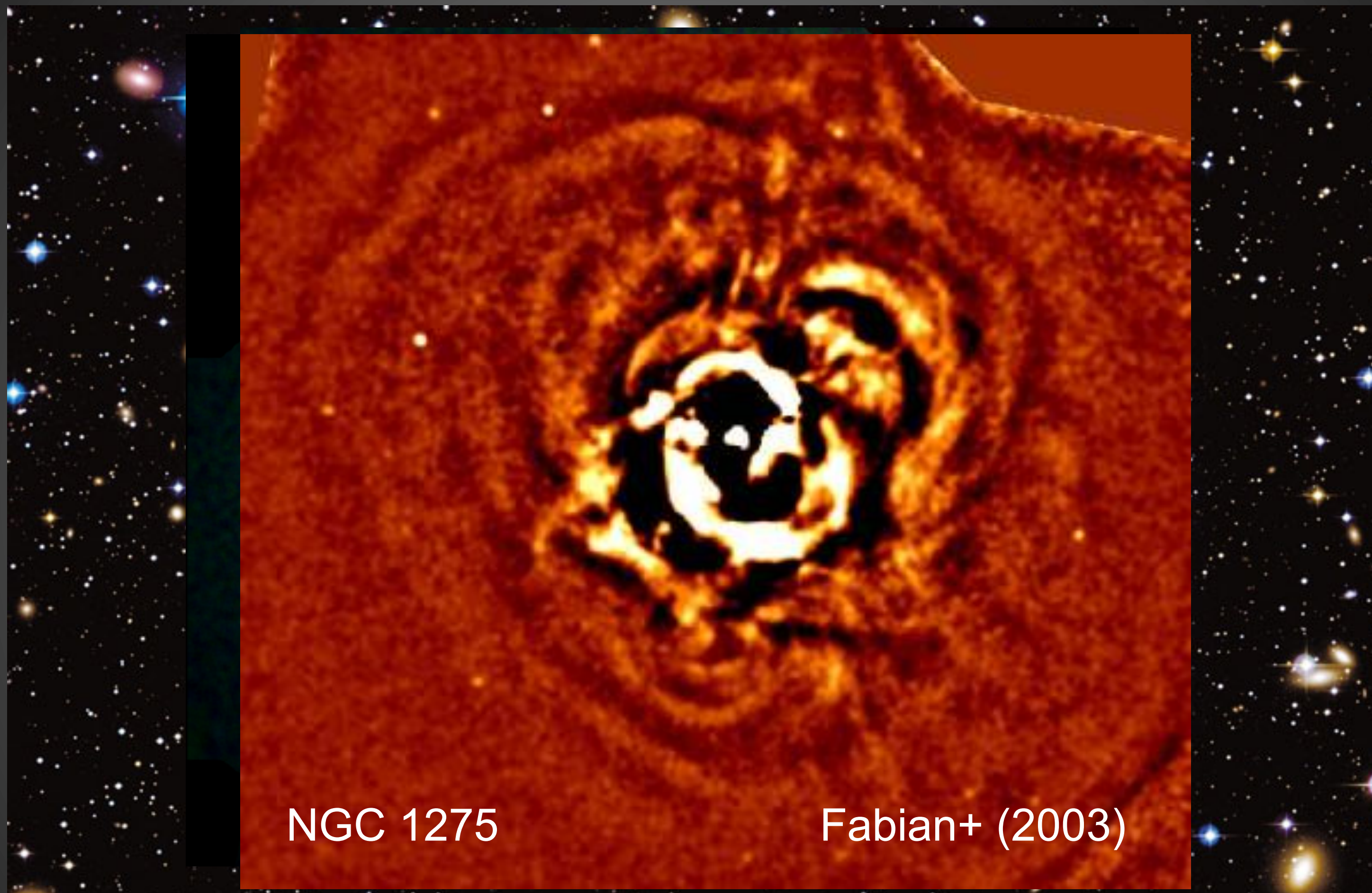
Narayan & McClintock (2012), Steiner+ (2012)

Powerful Jets = Retrograde Spin?



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

Jets and AGN Feedback



Central galaxy of the Perseus cluster, housing a BH billions of times the mass of our Sun. Likely the result of many galaxy mergers, its jets throw energy out into the intracluster medium, keeping it hot and thus regulating star formation.

Perseus Cluster of galaxies: one of the most massive objects in the universe. Thousands of galaxies, gravitationally bound together.

Consequences for Galaxy Evolution

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

- But ***how common/stable is retrograde spin?*** (Nixon+ 2012).

- Phase of galaxy's life with powerful jets may be relatively short or uncommon, perhaps following a **major merger** with another galaxy.

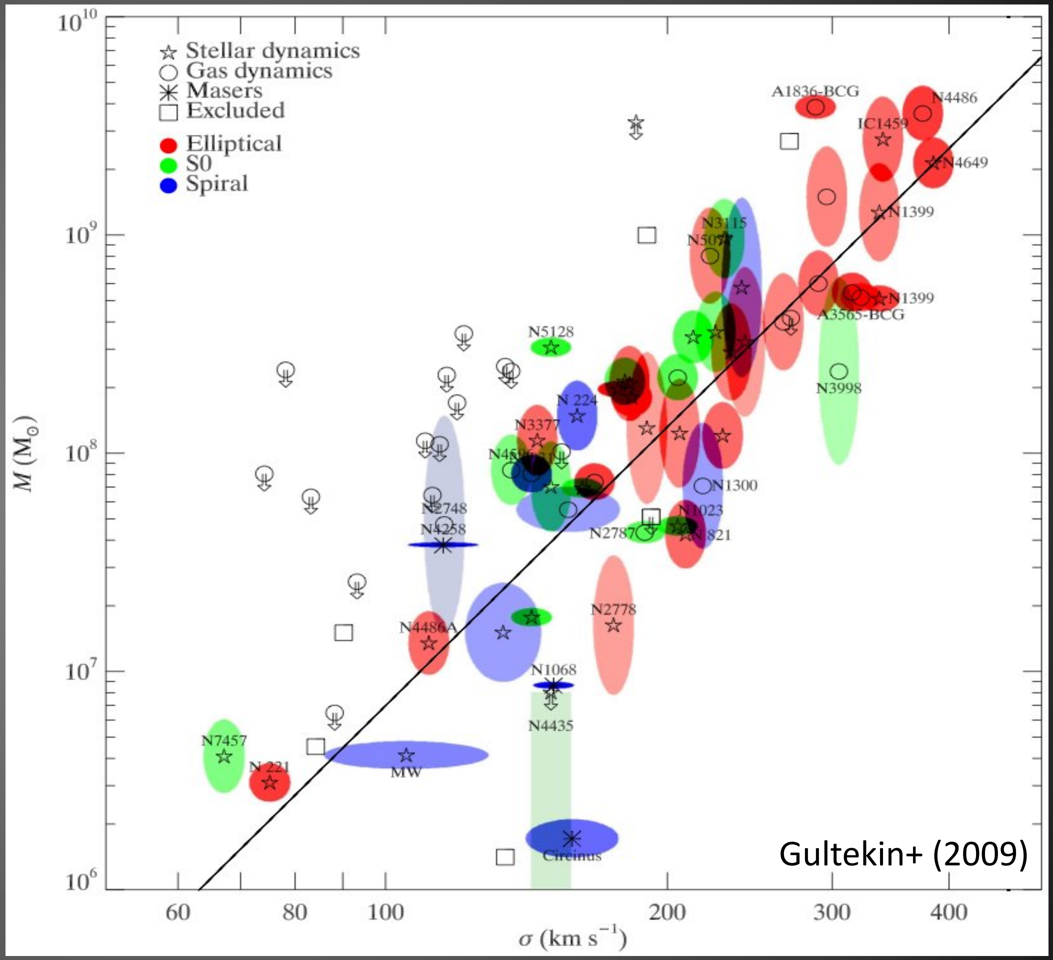
- Translates to relatively **few powerful, radio-loud galaxies** and lots more galaxies that are radio-quiet.

- 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).

Regulating Galaxy Growth

- **Feedback occurs on all mass scales,** from stellar-mass BHs to supermassive BHs in clusters of galaxies.
- **Distributes matter and energy** throughout the interstellar, intergalactic or intracluster medium.
- Effects of feedback most evident in galaxies and clusters of galaxies: **star formation halted** as ambient medium heated.



****BH spin's role in producing jets makes it a key player in feedback and galaxy evolution.****

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 = 0.6-0.7.

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

- 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 get good spin constraints.

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(?)

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

- ~~*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
  - increase sample size by ~10x

Big Open Questions

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

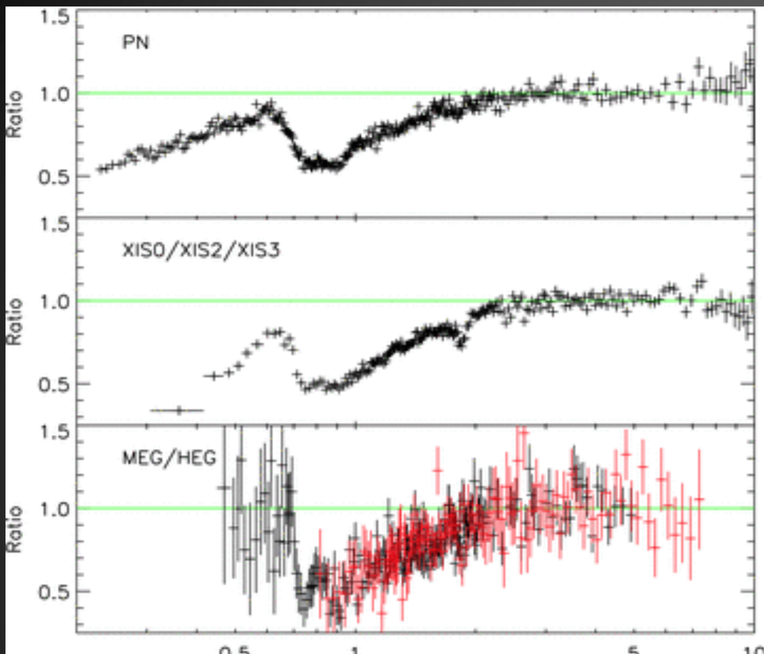
2. What does this distribution tell us about the recent accretion vs. merger histories of AGN?

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

4. Do retrograde spins produce the most powerful jets?

EXTRAS

Spectral Variability in MCG—6-30-15



Chiang & Fabian (2011)

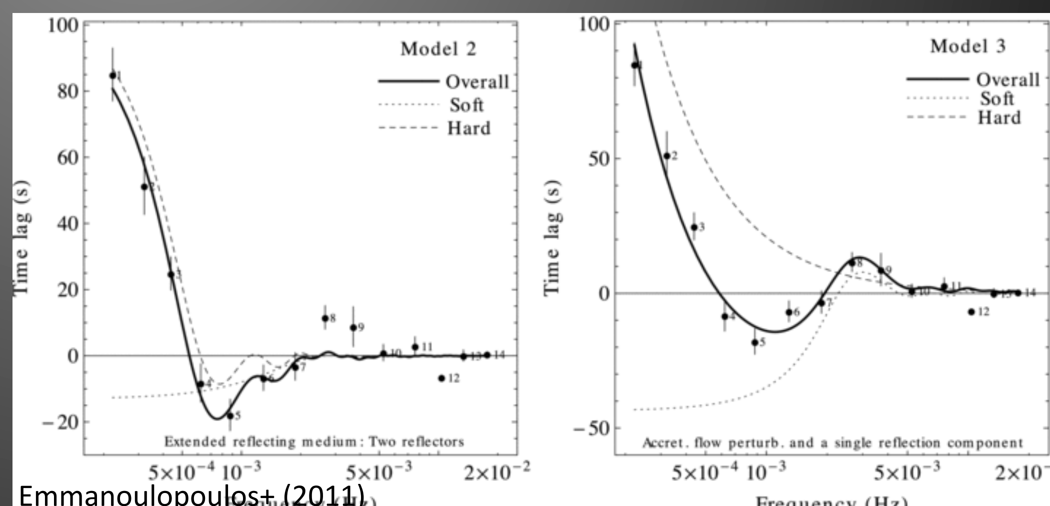
• Negative time-lag (~20 s) seen between hard and soft bands (soft trails hard), like 1H0707.

• 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.

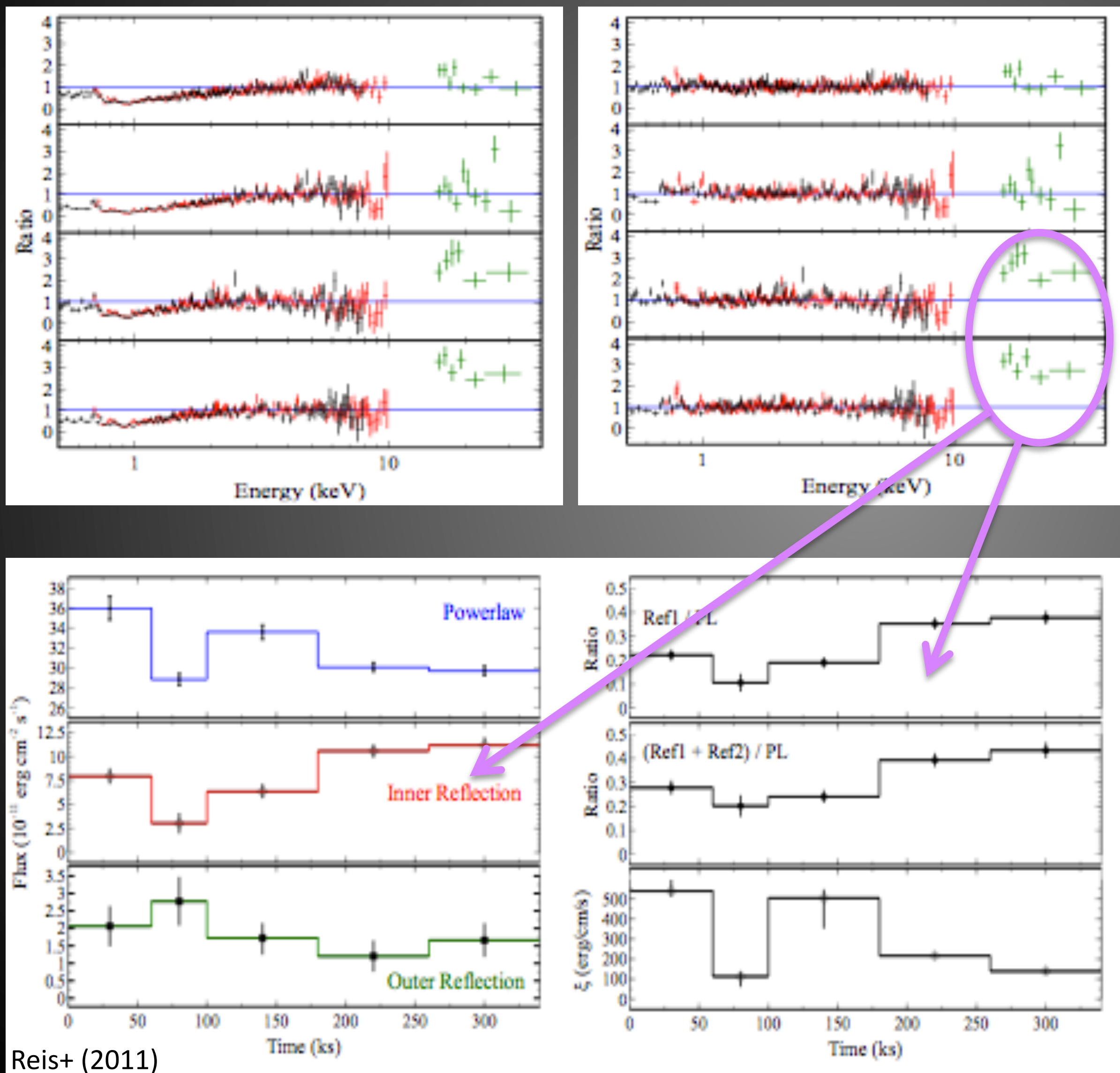
• Difference spectra (high flux - low flux) best fit by absorbed power-law <2 keV, unabsorbed power-law >2 keV in *XMM, Suzaku, Chandra* data.

• Best-fit model to all three has constant, three-zone warm absorber: $N_H = 10^{20\text{-}23}$, ξ = 0.03-6300, no partial covering.



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.