Two Decades of Measuring Supermassive Black Hole Spins with XMM-Newton

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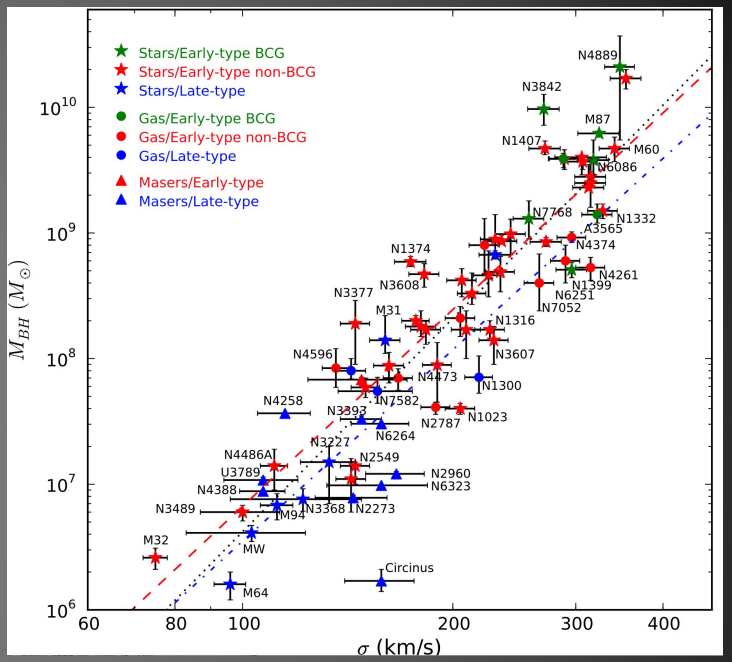
Outline

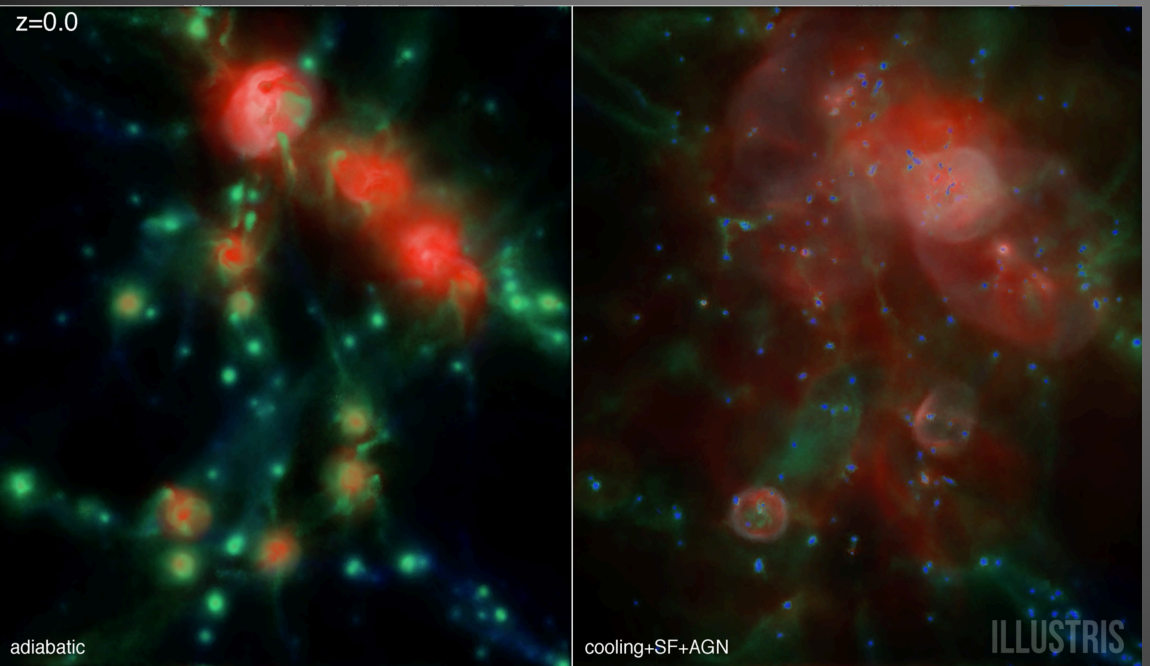
- SMBH spins in context
- A bit of history: MCG—6-30-15 and *KERRDISK*
- More data and better models: *XMM's* role in the current landscape of SMBH spin knowledge
- The SMBH spin distribution so far and its implications and biases
- Future directions

Black Hole Spin and Inner Disk, Corona/Jet

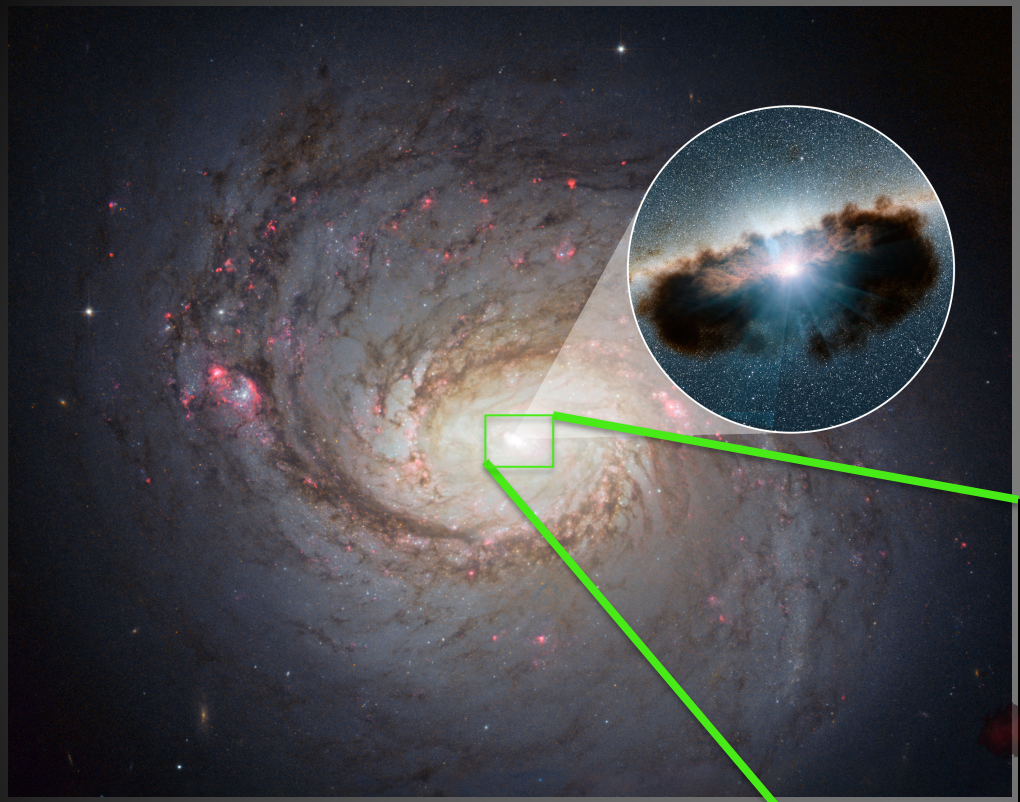
- Thought to play a role in **jet production and outflows** in all BHs, seeding the ISM/IGM with matter and energy, possibly regulating galaxy growth and evolution.
- SMBH spin is also an indicator of recent gas **accretion vs. merger history.**



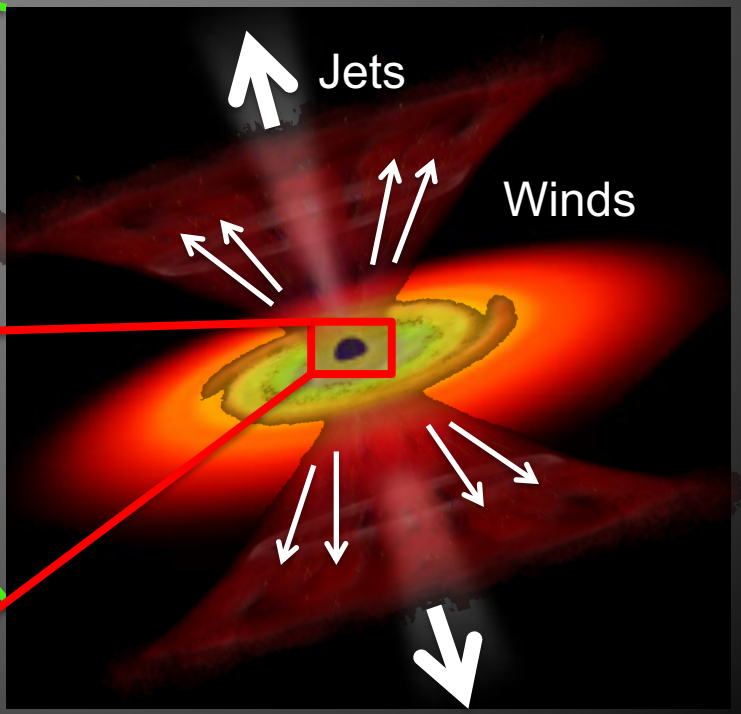
McConnell & Ma (2013)

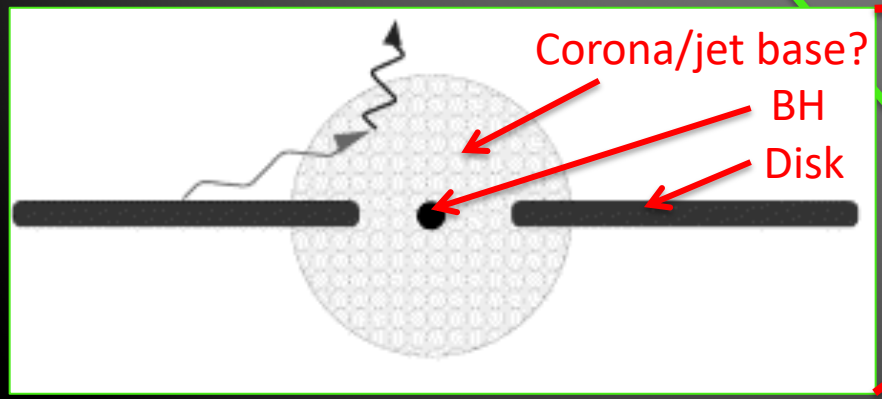


AGN Structure

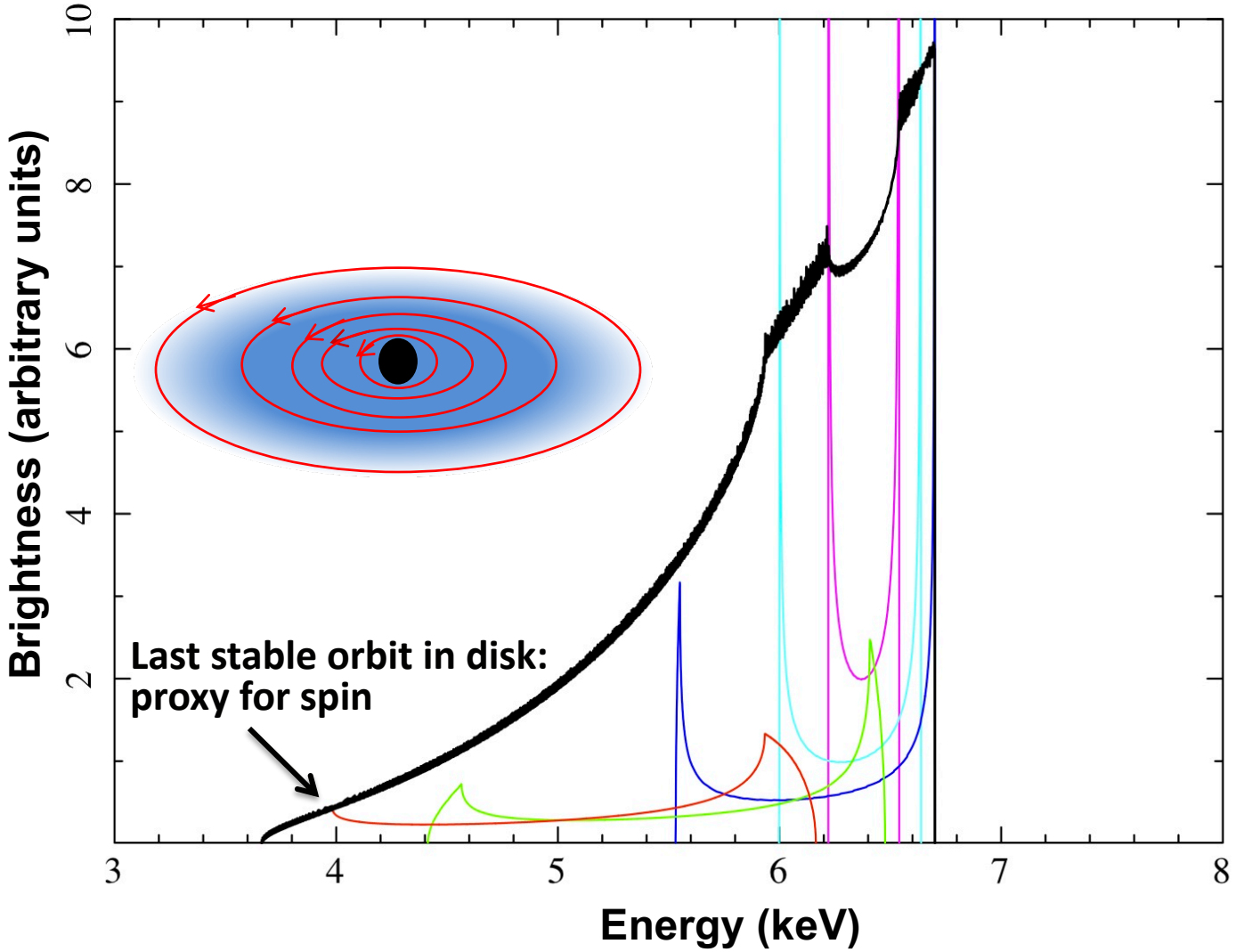


- Black hole
- Accretion disk (X-ray reflection)
- Corona (X-ray continuum)
- Jet?
- Outflowing winds (X-ray absorption)

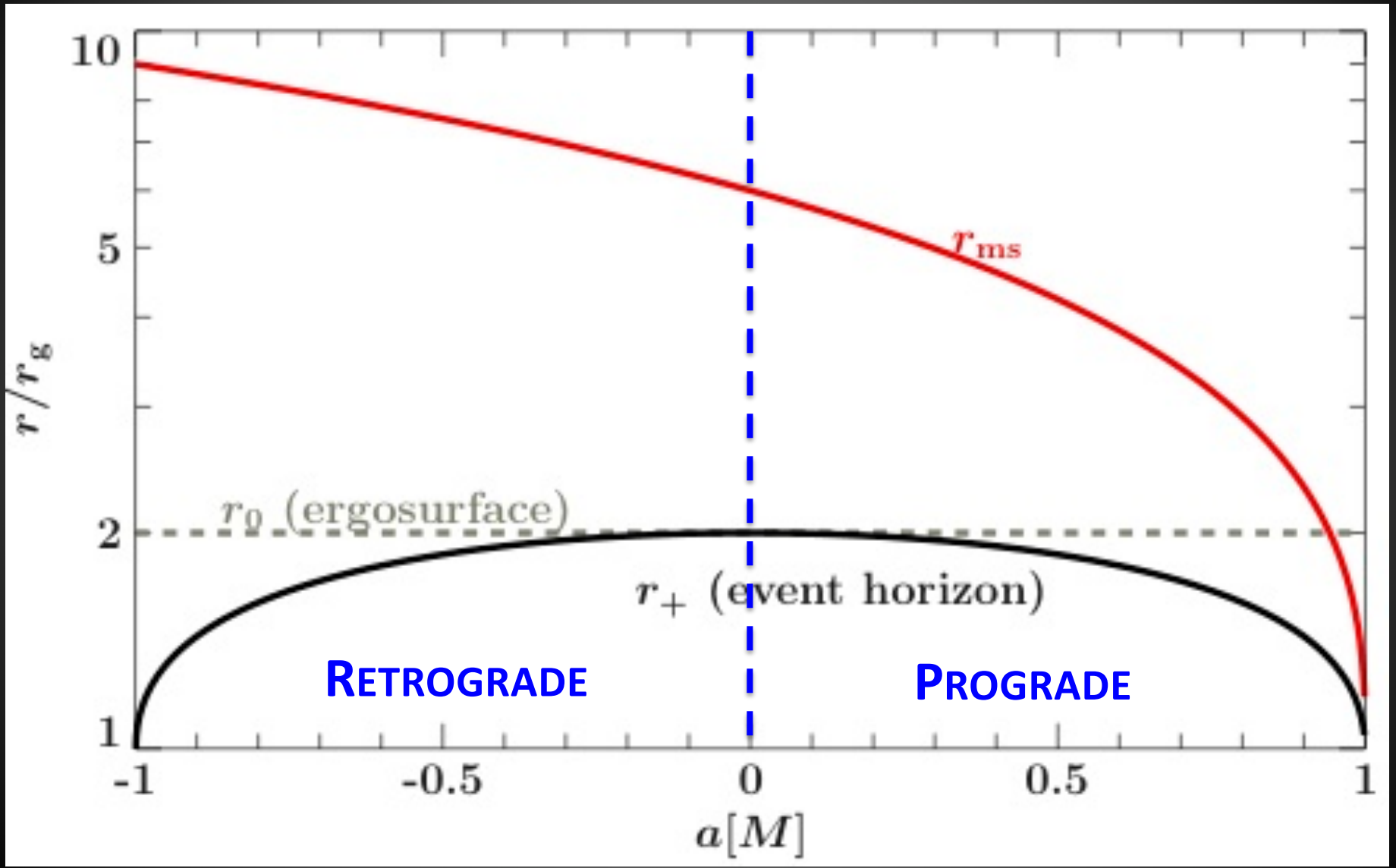




X-ray Emission Lines from the Infalling Gas in the Disk



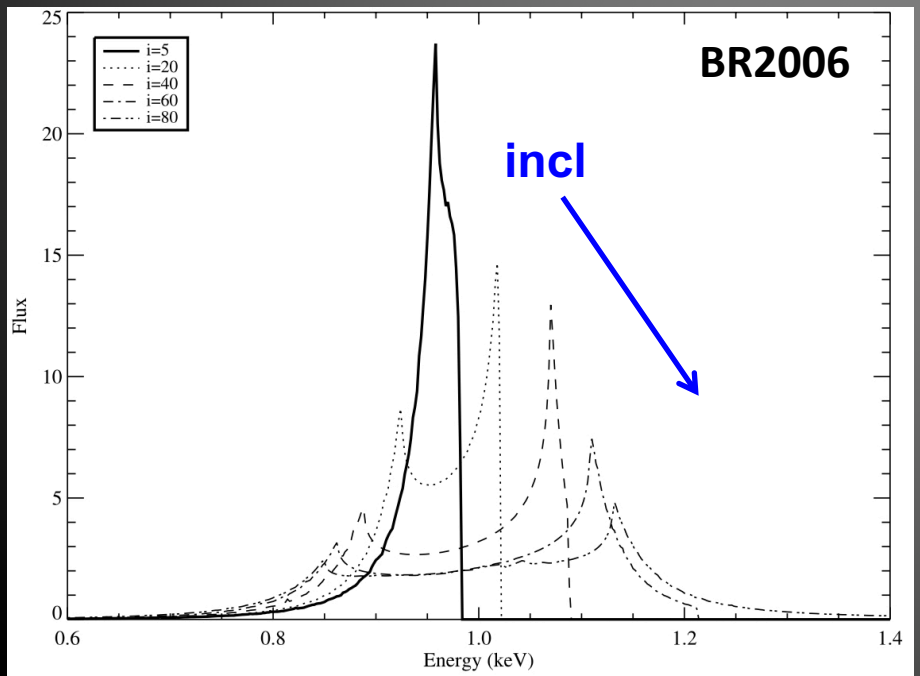
Measuring Black Hole Spin

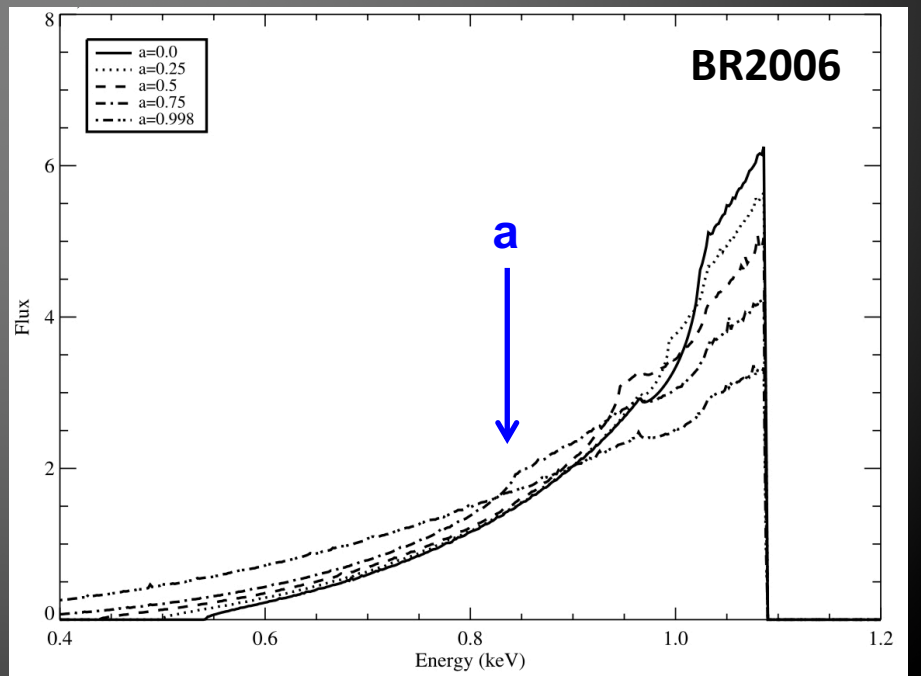


Dauser+ (2010)

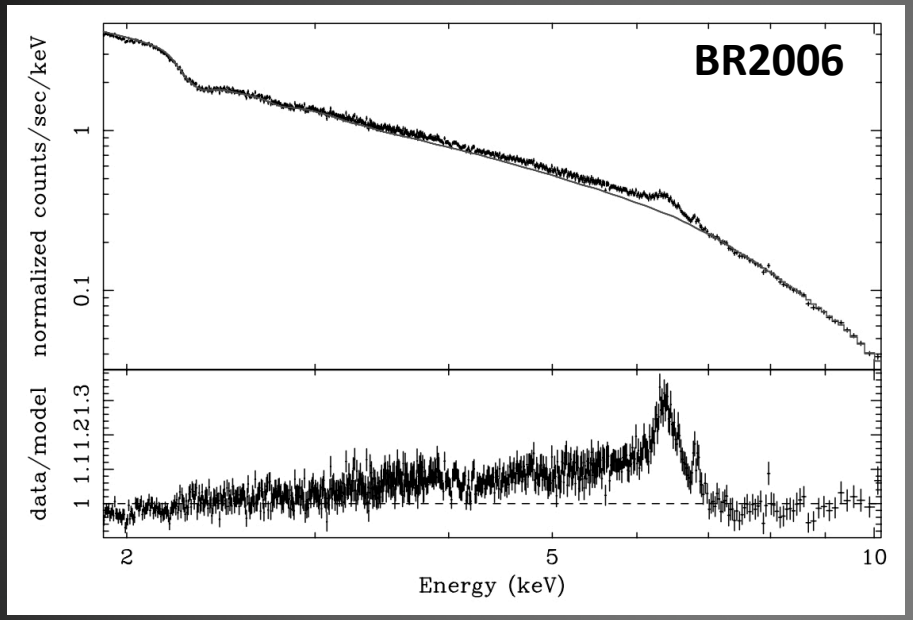
A Model for Broad Fe K Lines

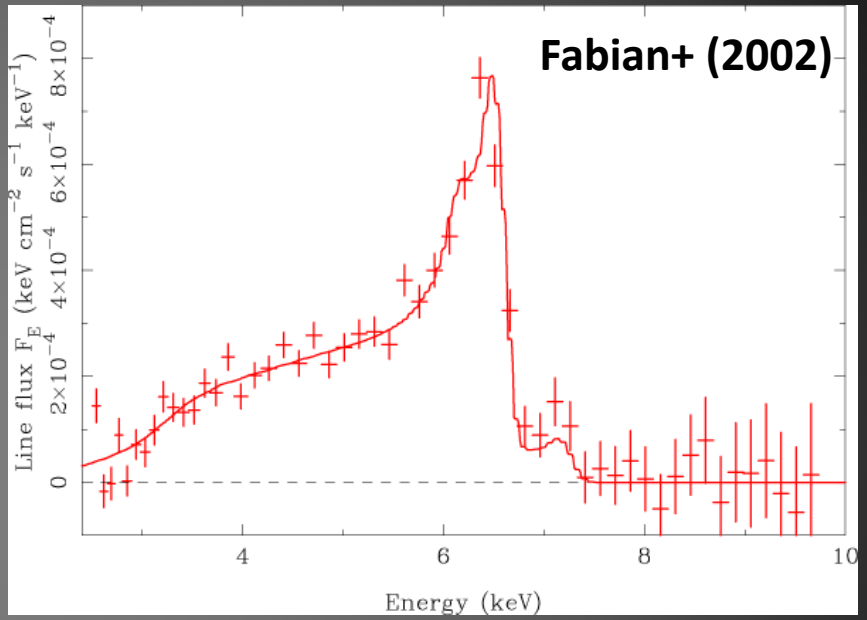
- Dimensionless black hole spin parameter: $a = cJ/GM^2$.
- Models existed with hard-wired spins: DISKLINE (Fabian+ 1989; a = 0) and LAOR (Laor 1991; a = 0.998).
- Free spin models being developed by Dovčiak+ (2004), Beckwith & Done (2004) and Cădež & Calvani (2005) relied on >GB-sized tables.
- Adapting the approaches of Cunningham (1975) and Speith (1995), Brenneman & Reynolds (2006) created KERRDISK, a much more portable free spin model that was the first to be in the standard XSPEC release.





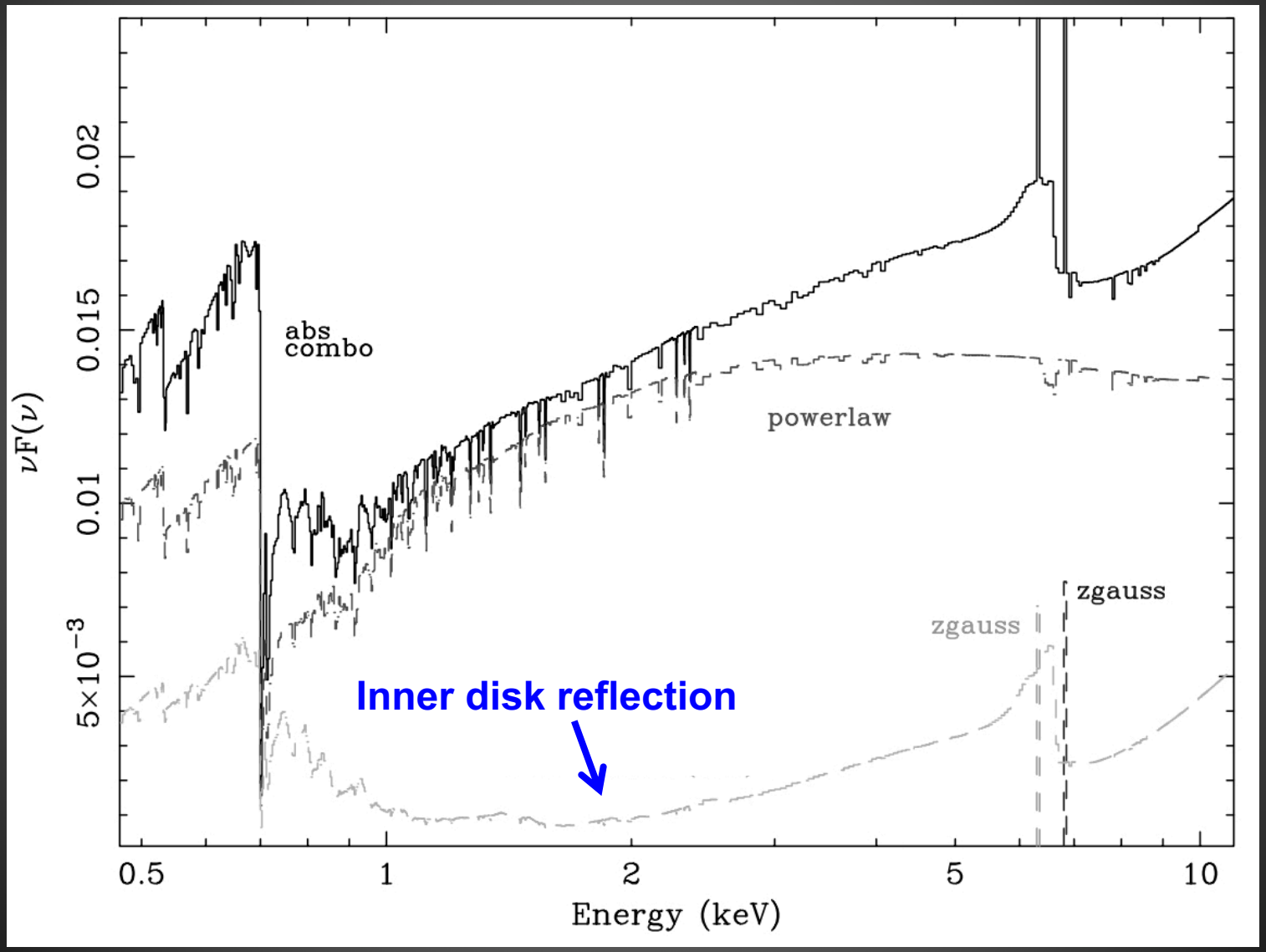
Measuring the SMBH Spin in MCG—6-30-15





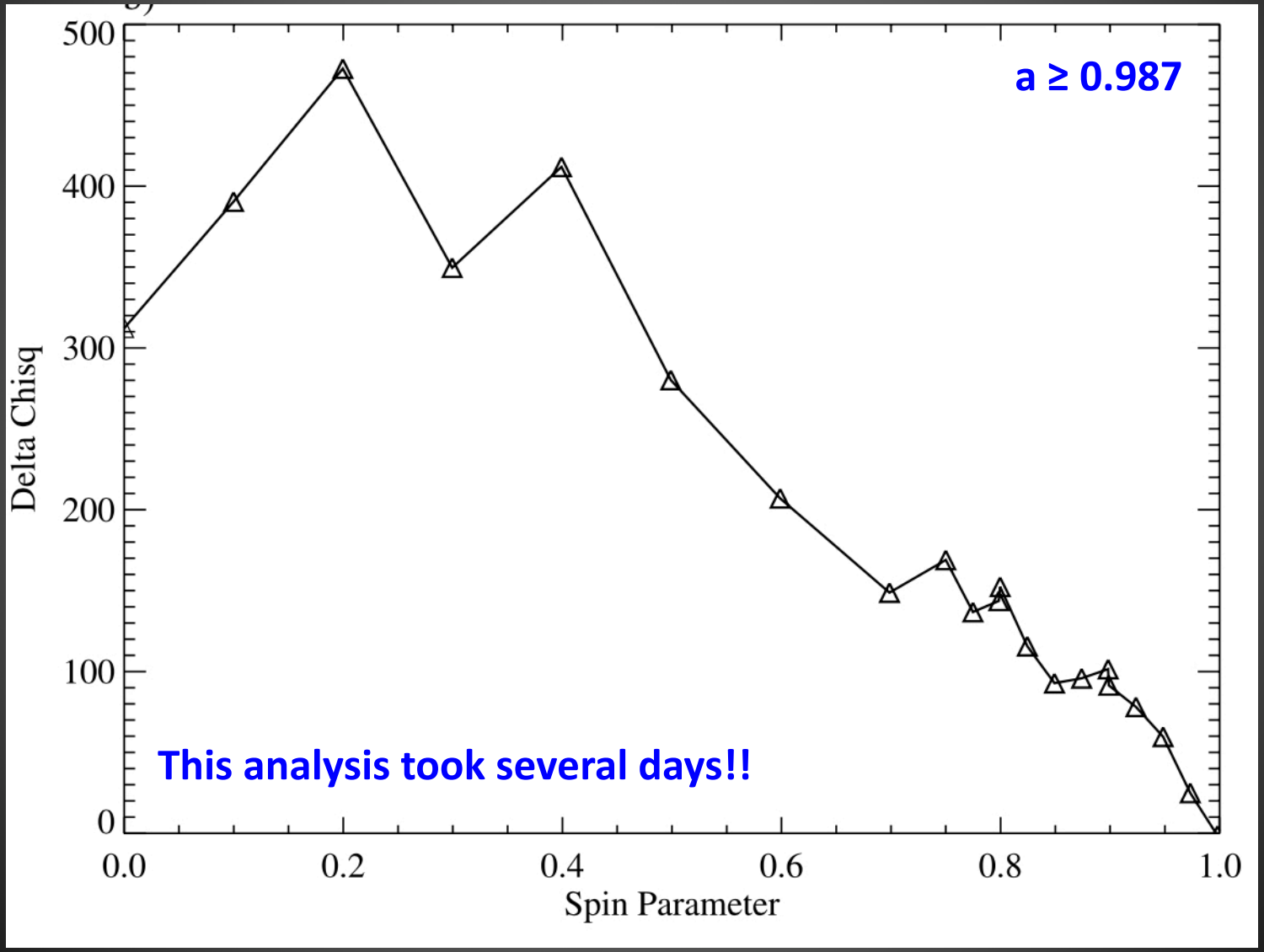
- ~350 ks XMM observation in 2001, published by Fabian+ (2002).
- Removing continuum illustrates residual reflection features left behind in EPIC/pn spectrum:
  - Narrow emission lines from outer disk/torus
  - Broad Fe Kα emission from inner disk
- Well-known ionized absorption from outflowing wind evident in RGS spectrum (Turner+ 2003).

Measuring the SMBH Spin in MCG—6-30-15



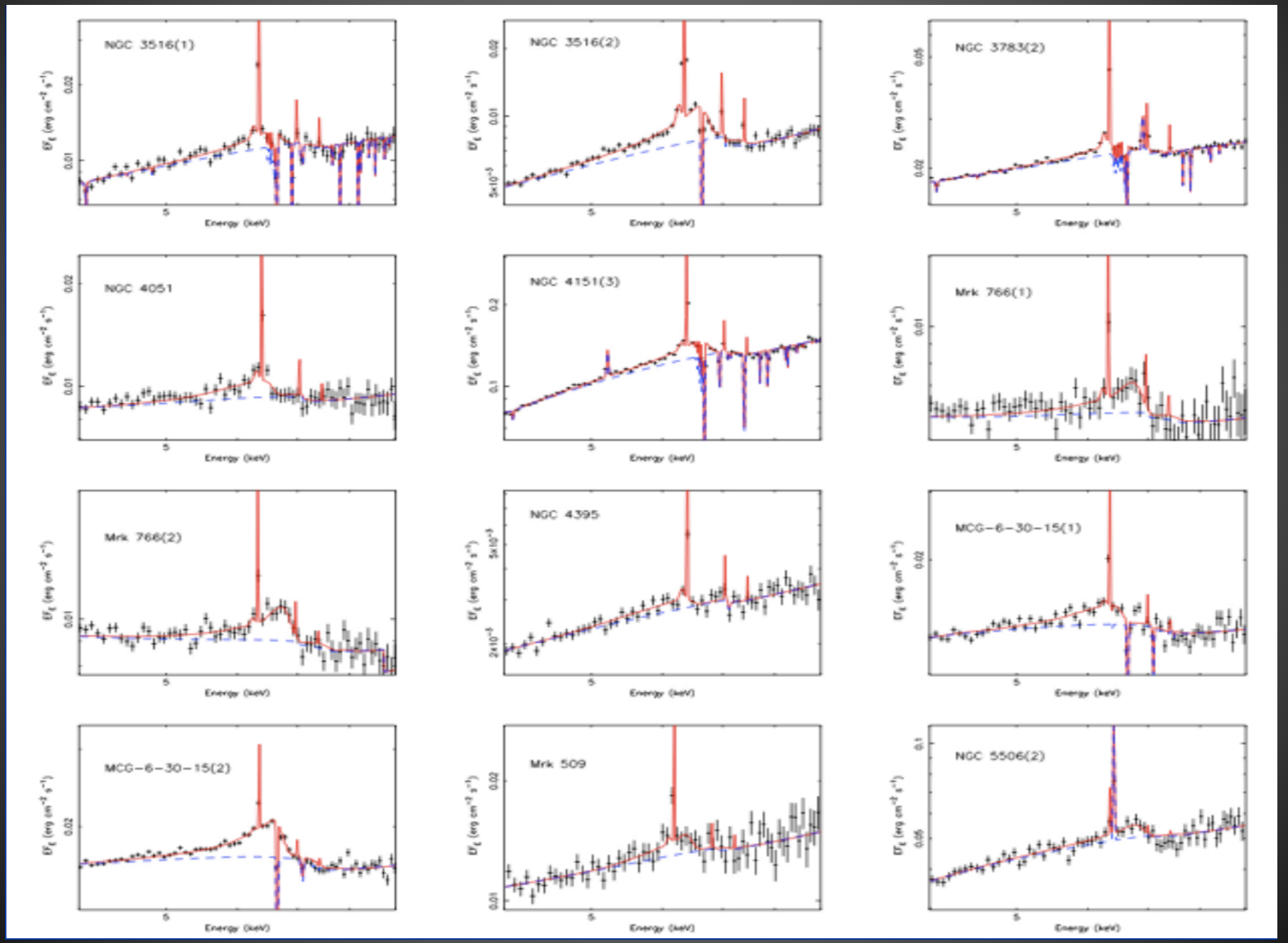
BR2006

Measuring the SMBH Spin in MCG—6-30-15



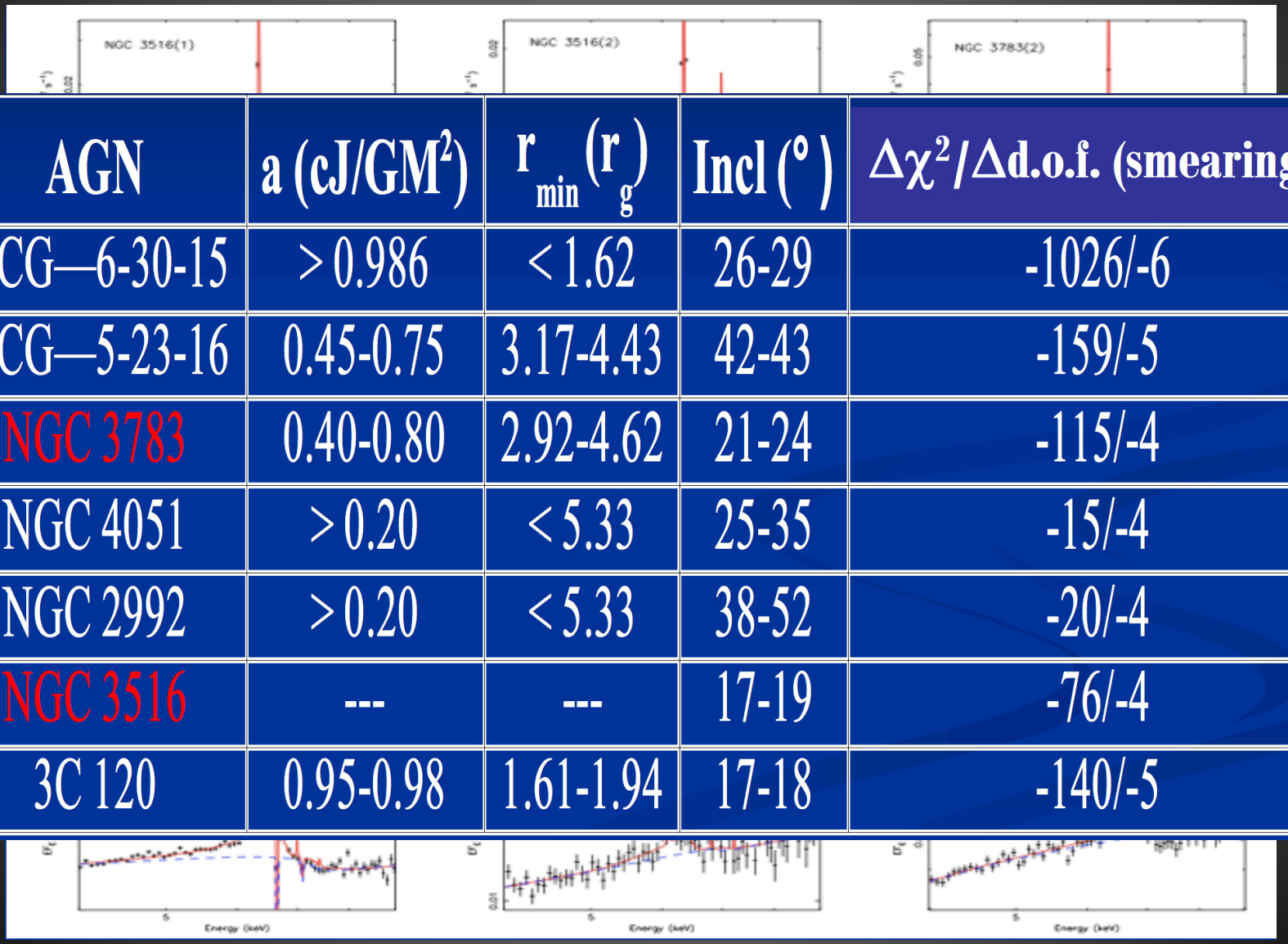
BR2006

Expanding the Catalog



Nandra+ (2007)

Expanding the Catalog



AGN	a (cJ/GM^2)	r_{min} (r_g)	Incl (°)	$\Delta\chi^2/\Delta$d.o.f. (smearing)
MCG—6-30-15	> 0.986	< 1.62	26-29	-1026/-6
MCG—5-23-16	0.45-0.75	3.17-4.43	42-43	-159/-5
NGC 3783	0.40-0.80	2.92-4.62	21-24	-115/-4
NGC 4051	> 0.20	< 5.33	25-35	-15/-4
NGC 2992	> 0.20	< 5.33	38-52	-20/-4
NGC 3516	---	---	17-19	-76/-4
3C 120	0.95-0.98	1.61-1.94	17-18	-140/-5

Brenneman+ (2009)

Model Improvement

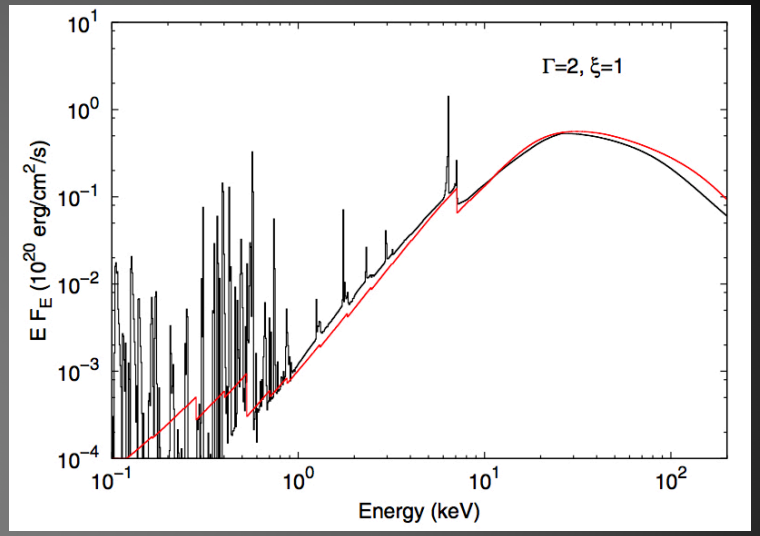
XILLVER (Garcia+ 2013)

+

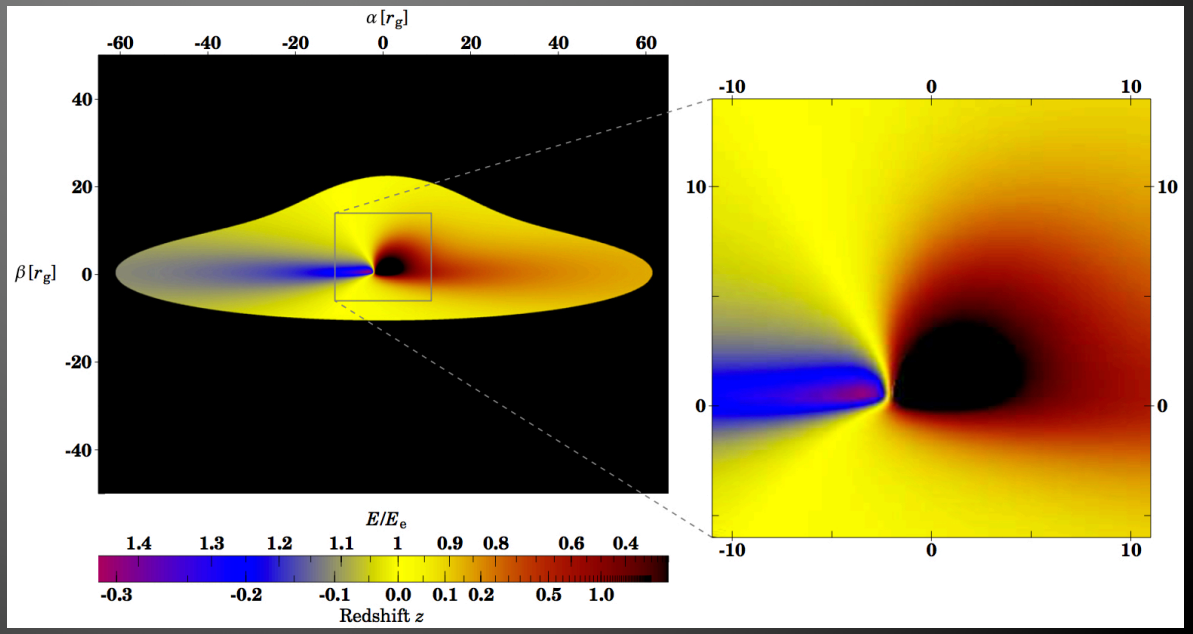
RELLINE (Dauser+ 2010)

=

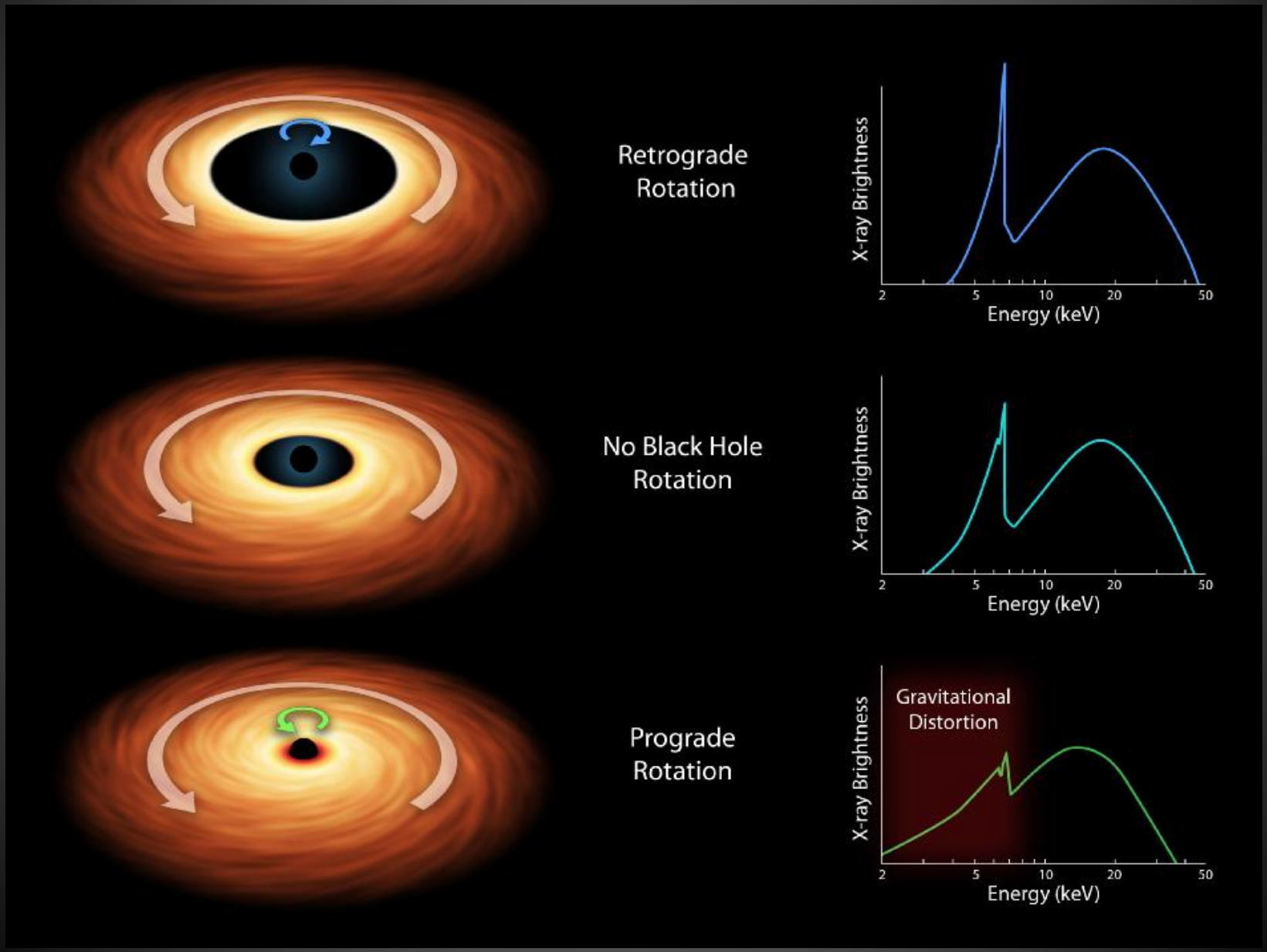
RELXILL (Garcia, Dauser+ 2014)



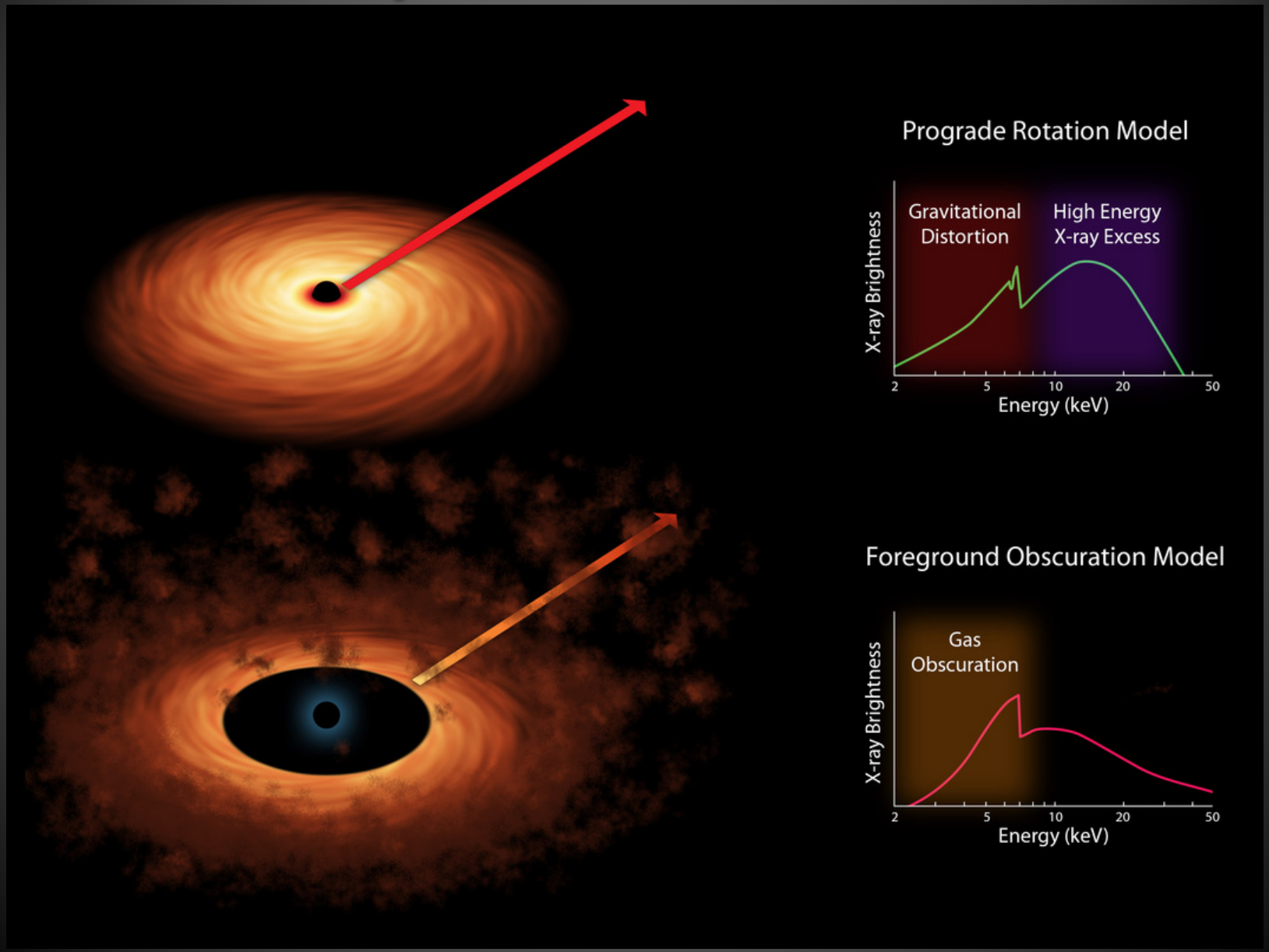
- Faster, cleaner integration
- Retrograde spins
- Lamppost/jet options for coronal geometry
- Comptonization option for continuum emission
- More accurate atomic physics for reflected emission



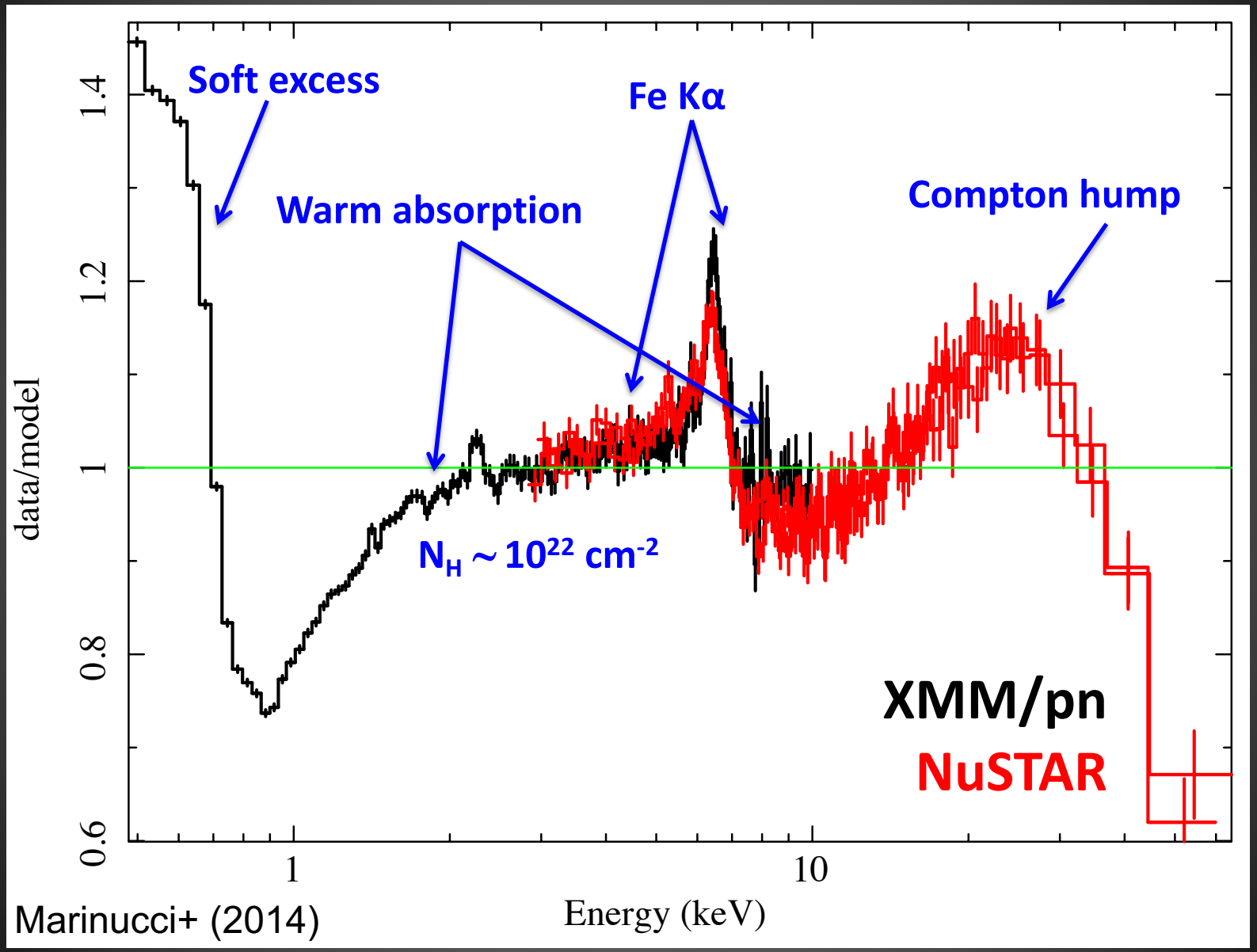
Effect of Spin on Reflection Features



Disentangling Coronal Emission, Absorption and Reflection

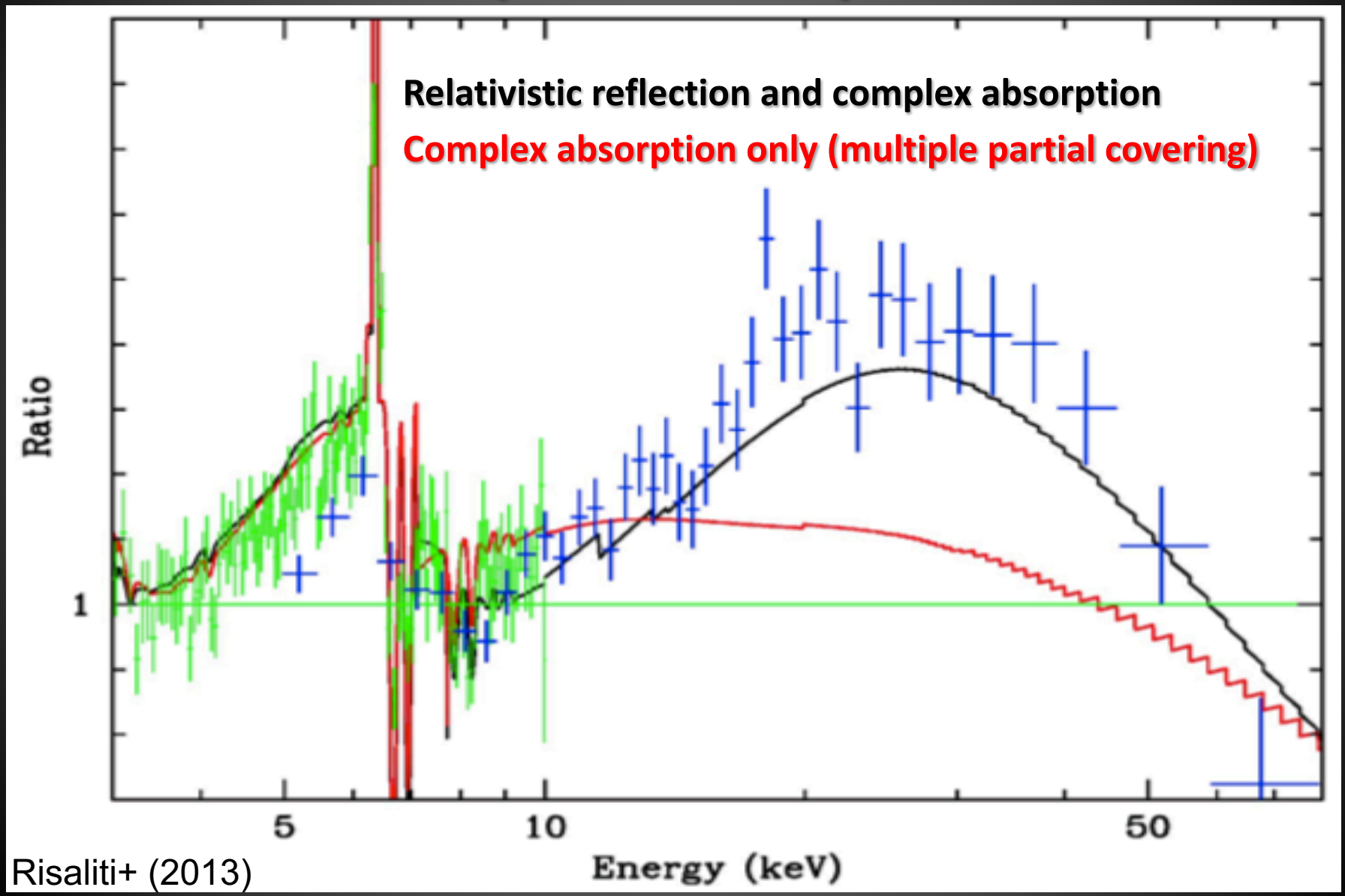


The Power of a Broader Bandpass



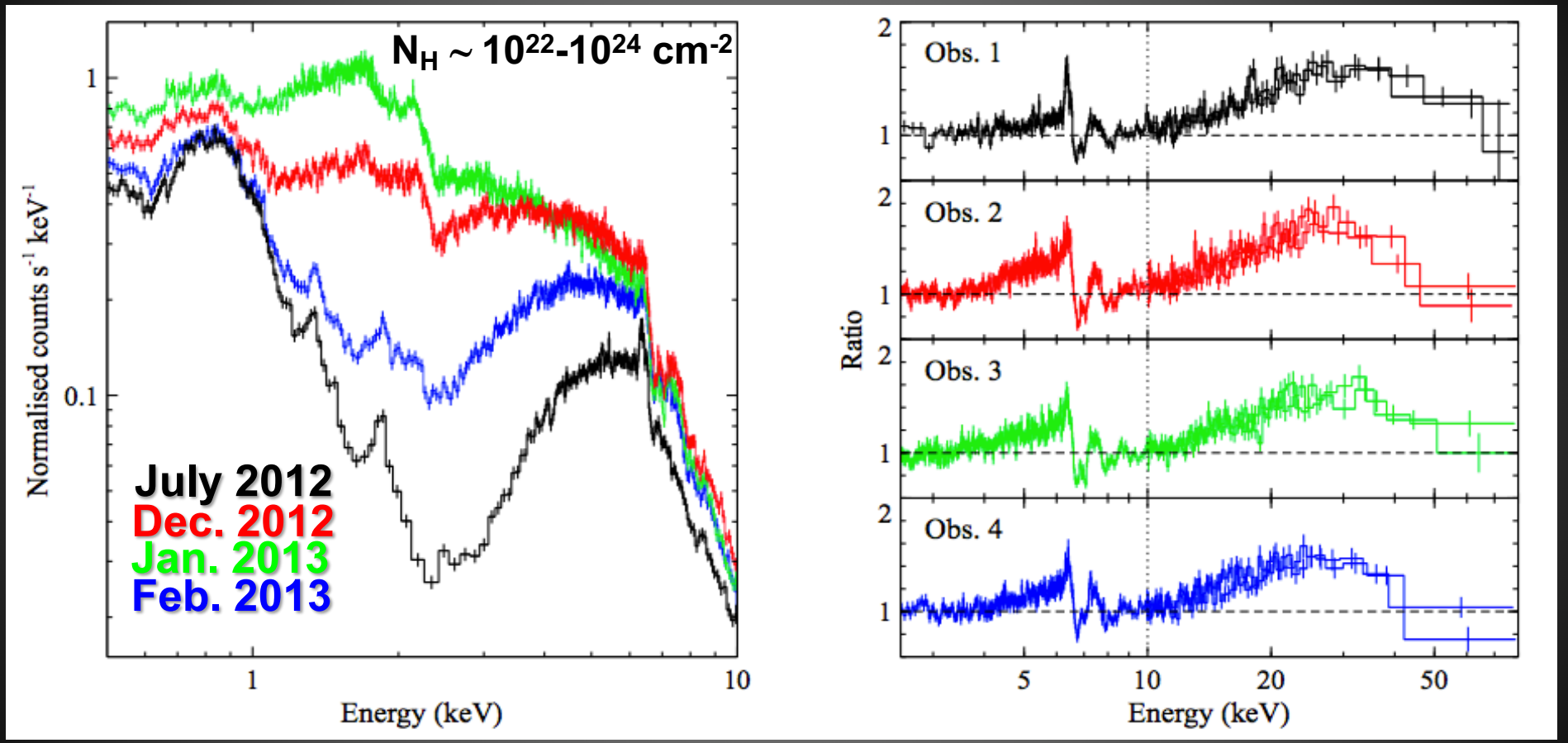
MCG6 spectral components with continuum taken out

NGC 1365: reflection and variable complex absorption



Risaliti+ (2013)

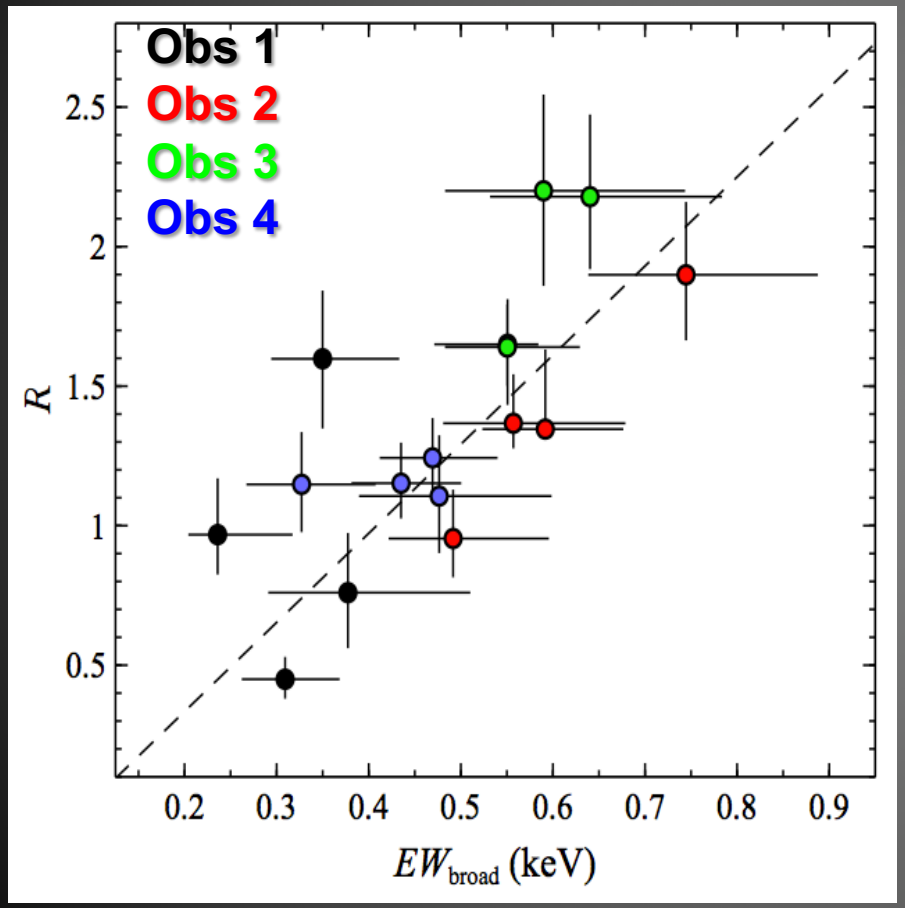
Spectral Variability

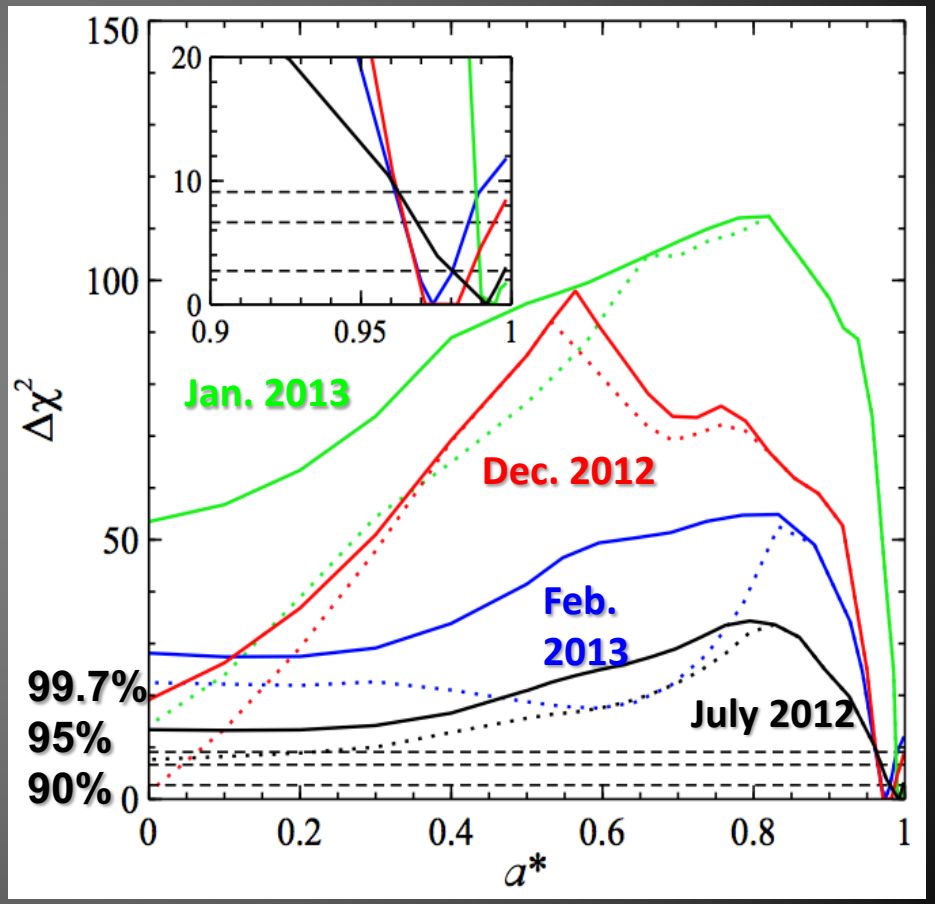


Walton+ (2014)

4 XMM/NuSTAR ~120 ks observations

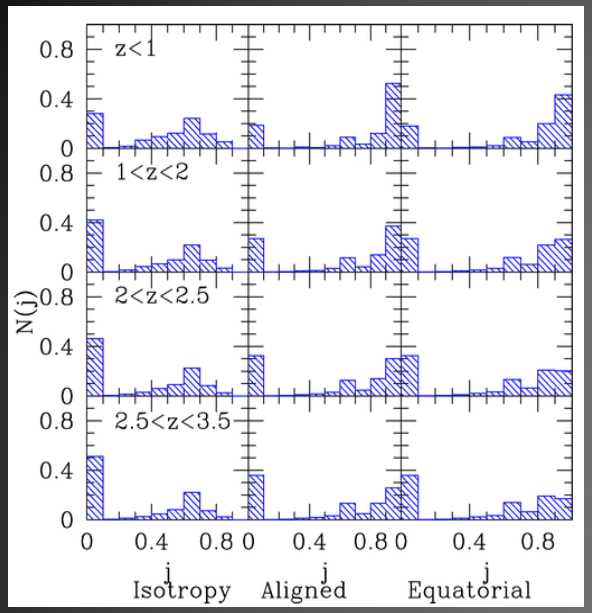
Constraining Relativistic Reflection and Spin





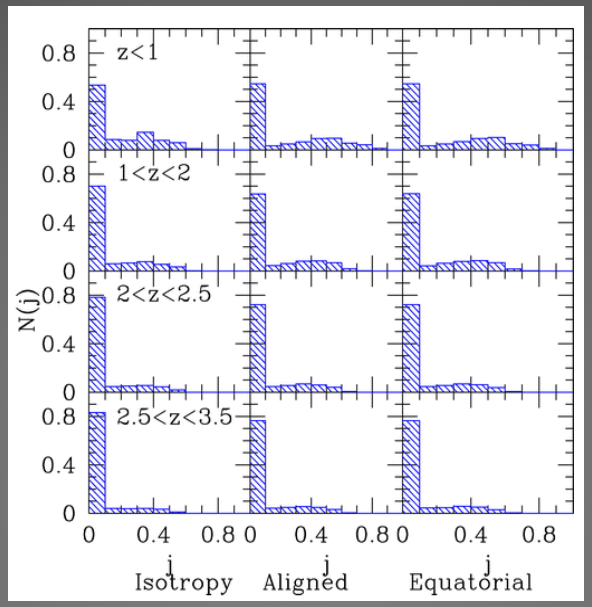
Walton+ (2014)

Black Hole Spin and Galaxy Evolution

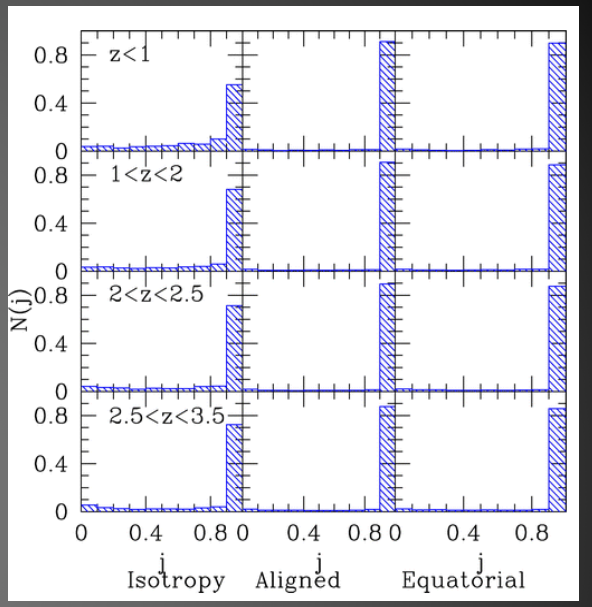


Mergers only

Berti & Volonteri (2008)



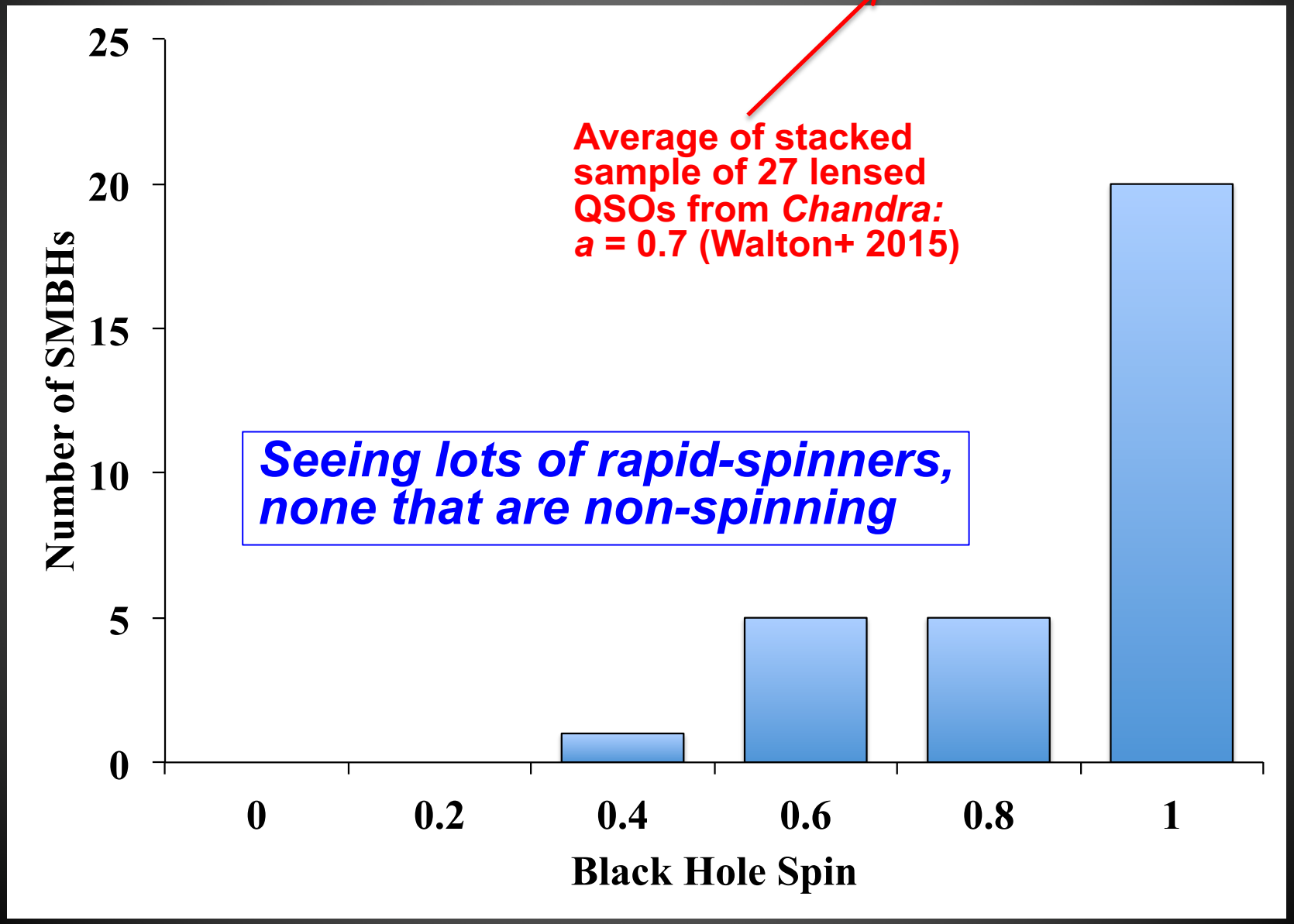
Mergers + chaotic accretion



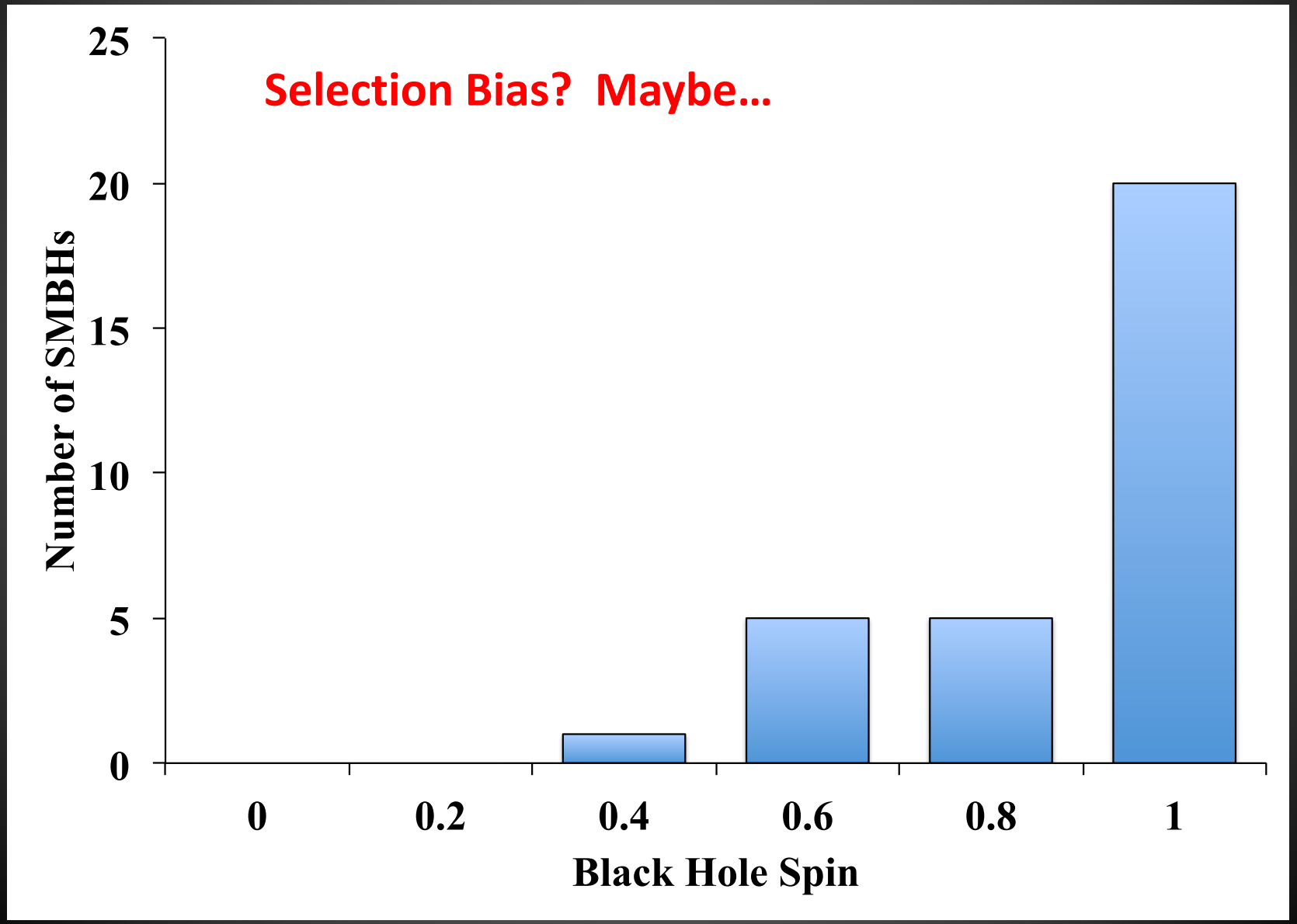
Mergers + prolonged accretion

- 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.

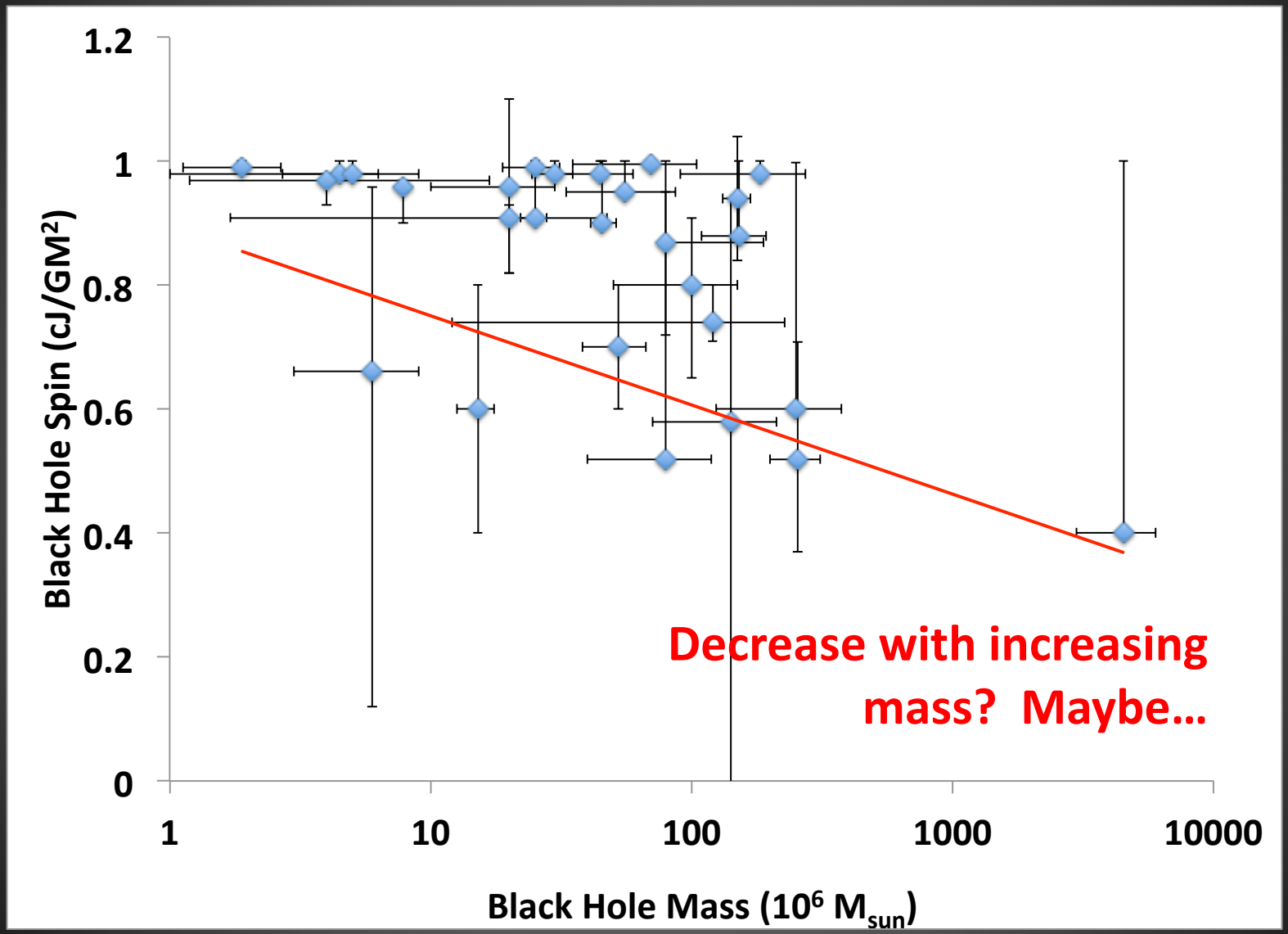
Measured Supermassive Black Hole Spins (so far)



Measured Supermassive Black Hole Spins (so far)

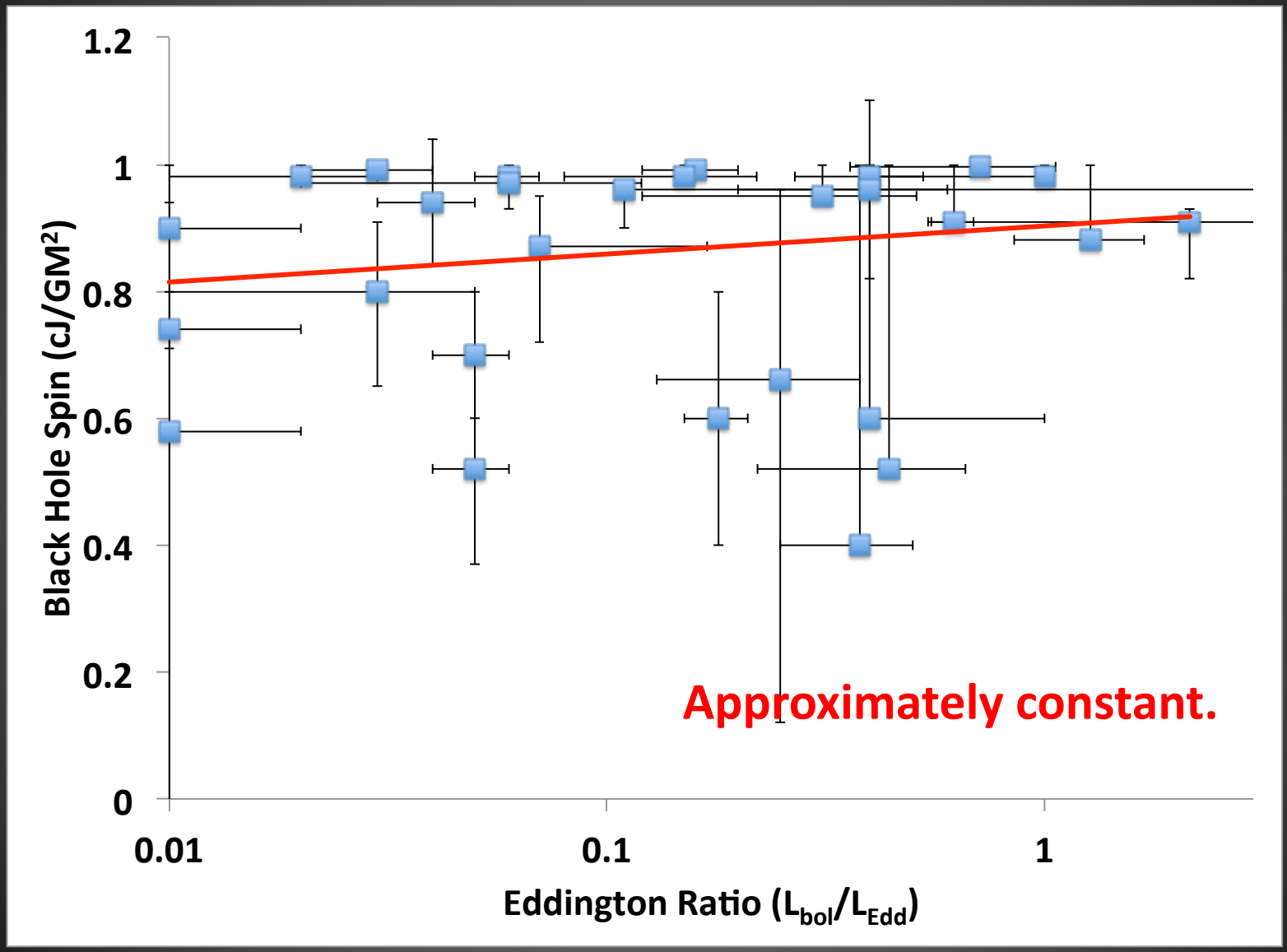


A Trend with Black Hole Mass?



Brenneman (2013), Walton+ (2013), Reynolds (2014), Ricci+ (2014), Agis-Gonzalez+ (2014), Reynolds+ (2014), Paliya+ (2014), Gallo+ (2015), Svoboda+ (2015), Keck+ (2015), Walton+ (2018)

A Trend with Accretion Rate?

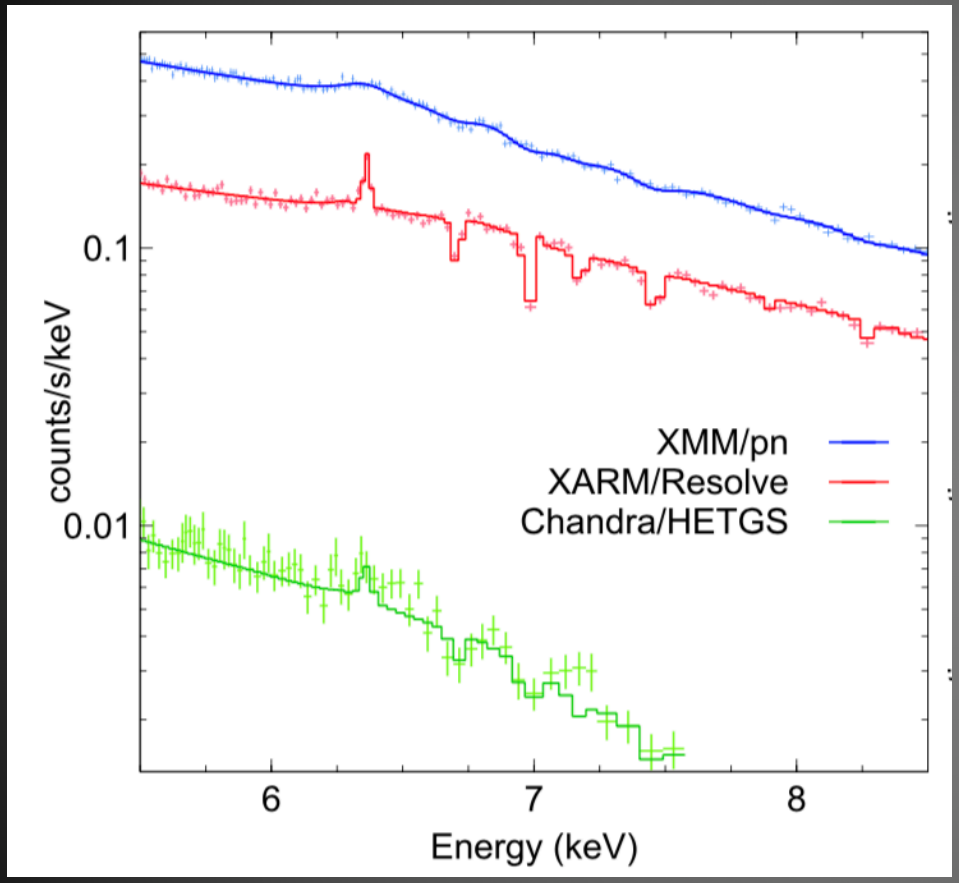


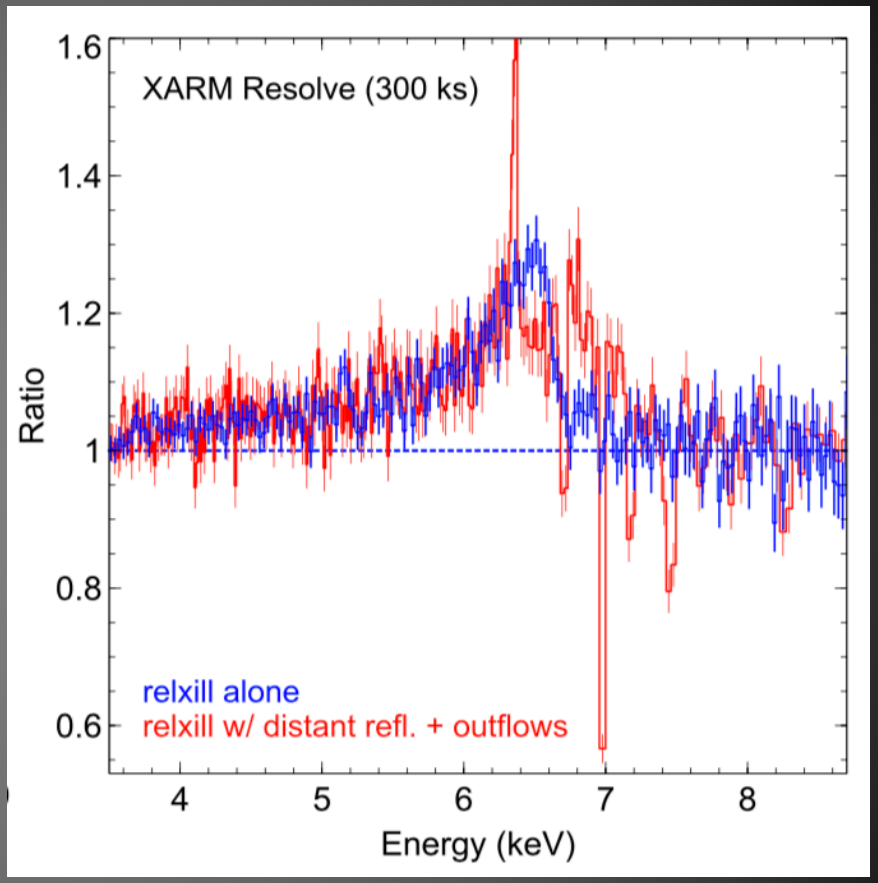
Brenneman (2013), Walton+ (2013), Reynolds (2014), Ricci+ (2014), Agis-Gonzalez+ (2014), Reynolds+ (2014), Paliya+ (2014), Gallo+ (2015), Svoboda+ (2015), Keck+ (2015), Walton+ (2018)

Future Prospects

- XRISM (~2022): μ-calorimeter successor to Hitomi
  - resolve absorption and emission lines
- Athena (~2030): μ-cal with significant increase in effective area
  - increase sample size of spin measurements
- STROBE-X Probe (~2031)
  - probe accretion physics on orbital timescales
- Lynx (~2035): Athena-like A_{eff} with *Chandra*-like spatial resolution
  - microlensing in more distant AGN

Future Prospects





MCG6 XRISM simulations courtesy of Erin Kara

Summary

• Broadband X-ray spectra provide the ability to disentangle reflection from continuum, absorption gives SMBH spin constraints in a sample of local AGN.

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

• Larger sample size of SMBH spins (esp. in 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.

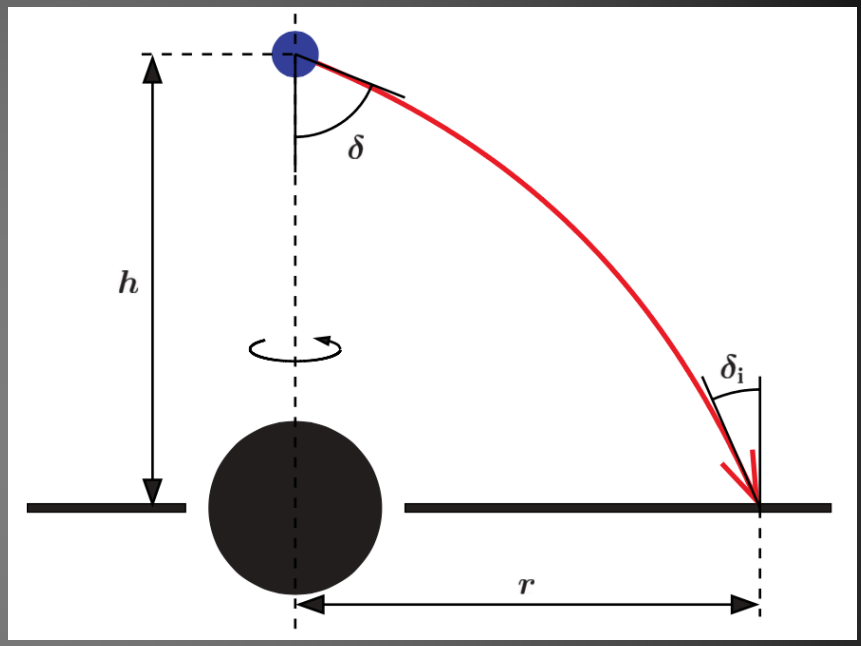
• Improved modeling is also necessary: more accurate representation of astrophysical accretion disks and coronae, improved atomic data and radiative transfer.

• Future looks bright for X-ray instrumentation!

EXTRAS

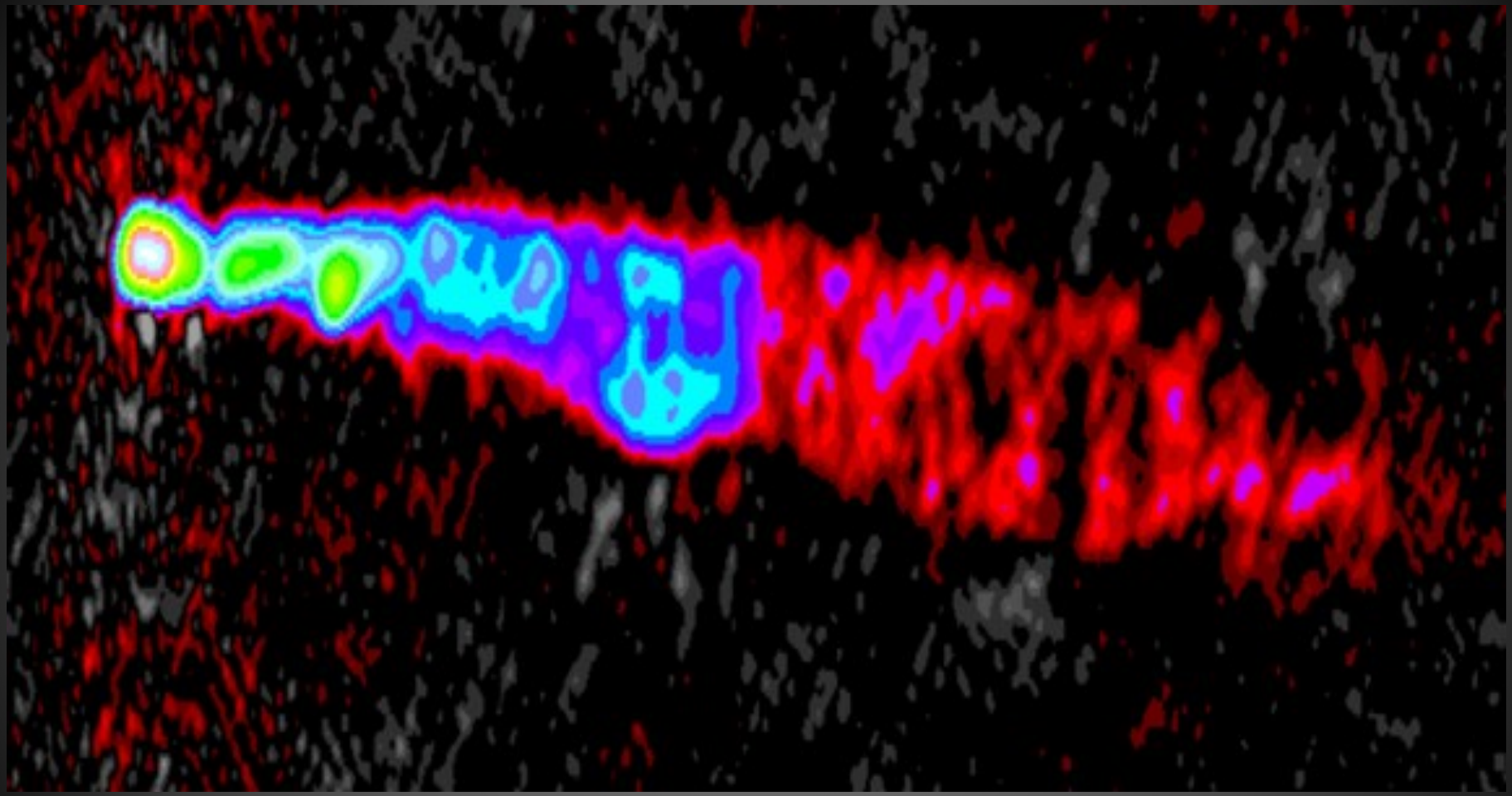
Systematic Uncertainties

- Very limited knowledge of corona
  - Radial, vertical extent (Wilkins+ 2015)
  - Kinematics (Dauser+ 2013)
- Assumption of disk r_{in} = ISCO
  - No significant radiation inside ISCO (Reynolds & Fabian 2008)
  - Truncation outside ISCO (Laor 1991)
- Disk models are over-simplified
  - Constant density (Garcia+ 2016)
  - Constant ionization (Ballantyne 2018)
  - Geometrically razor-thin (Taylor & Reynolds 2018)
  - Aligned perpendicular to black hole spin axis (Dexter & Fragile 2013)



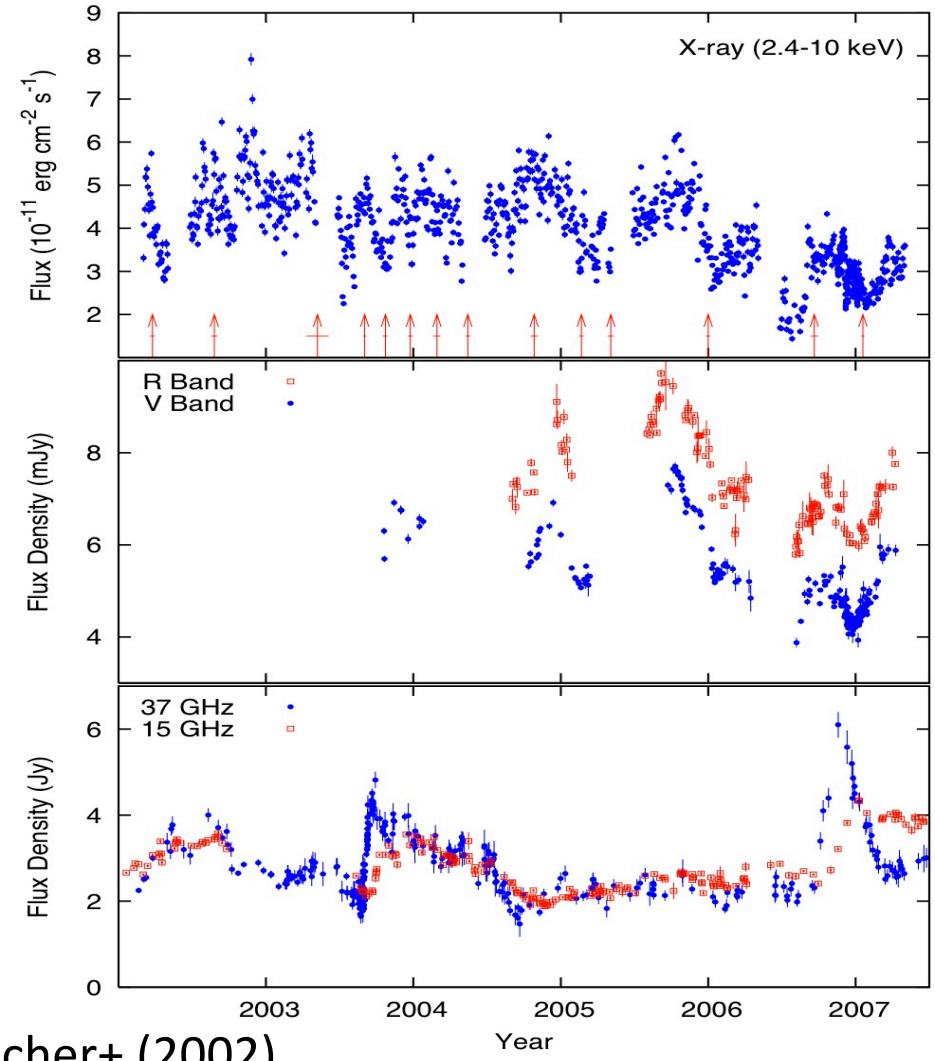
Dauser+ (2013)

3C120: Measuring spin in RLAGN



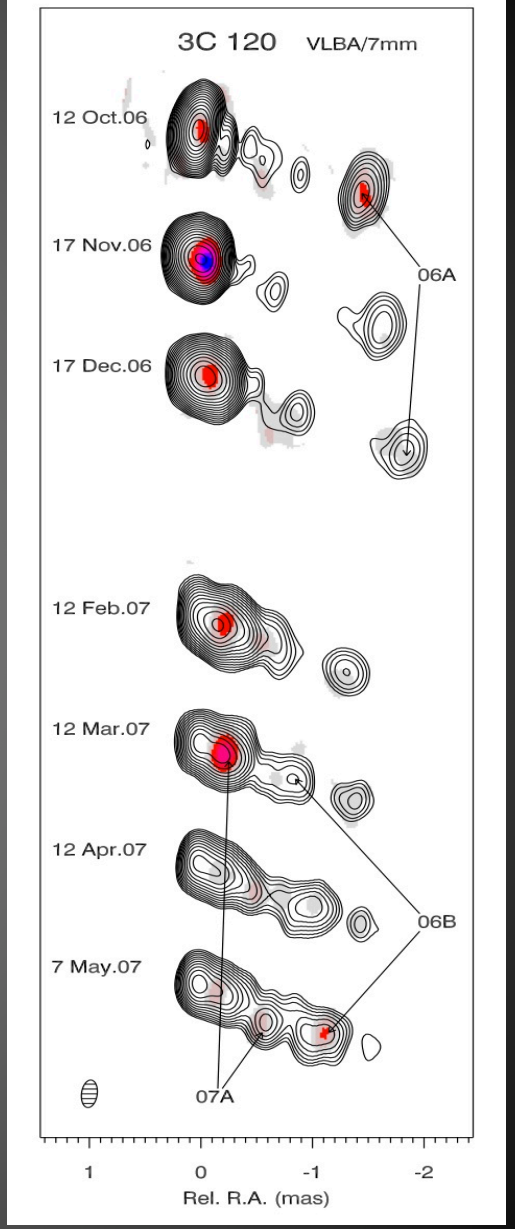
VLA (1.66GHz)

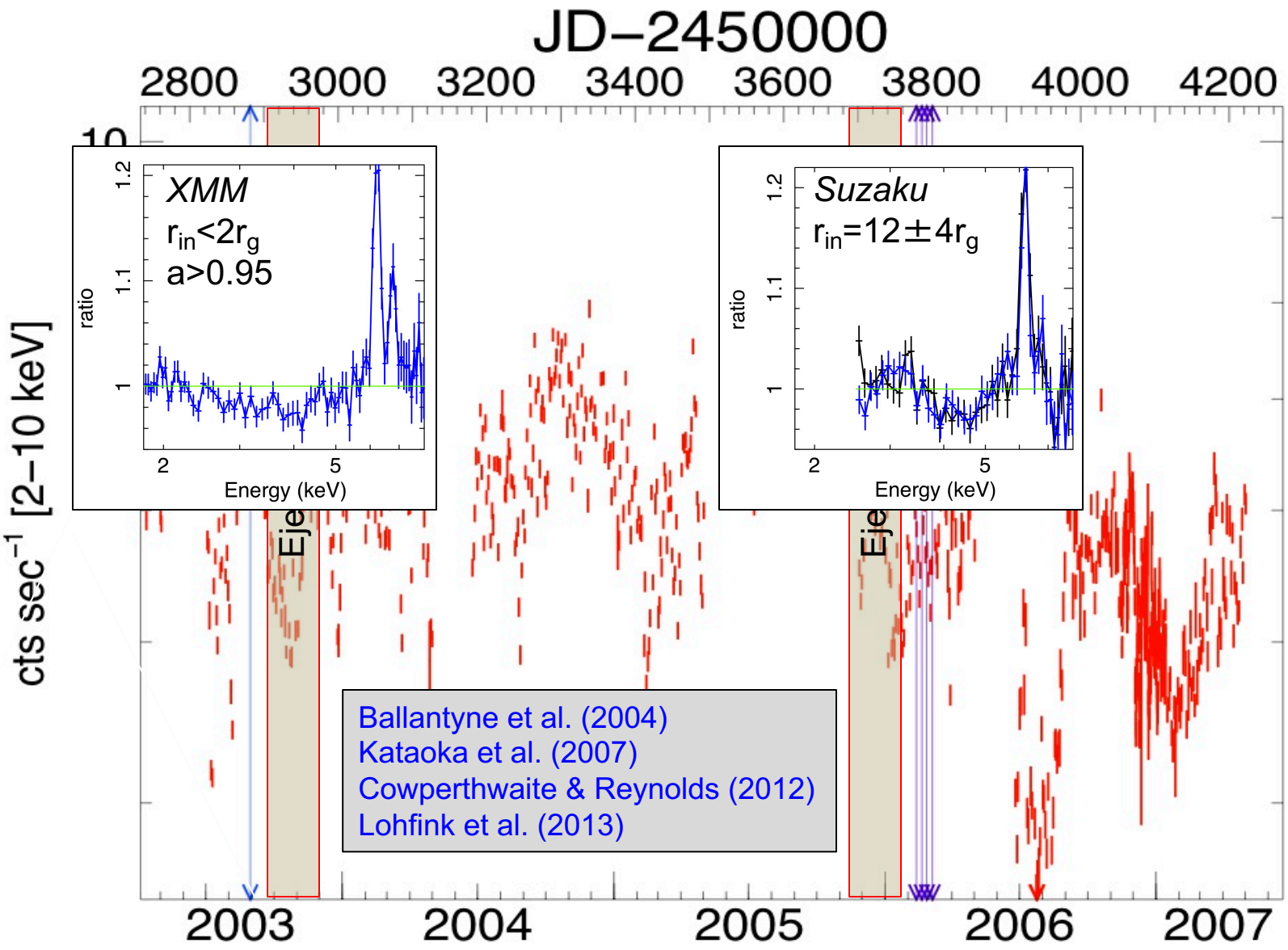
Credit: R.C.Walker



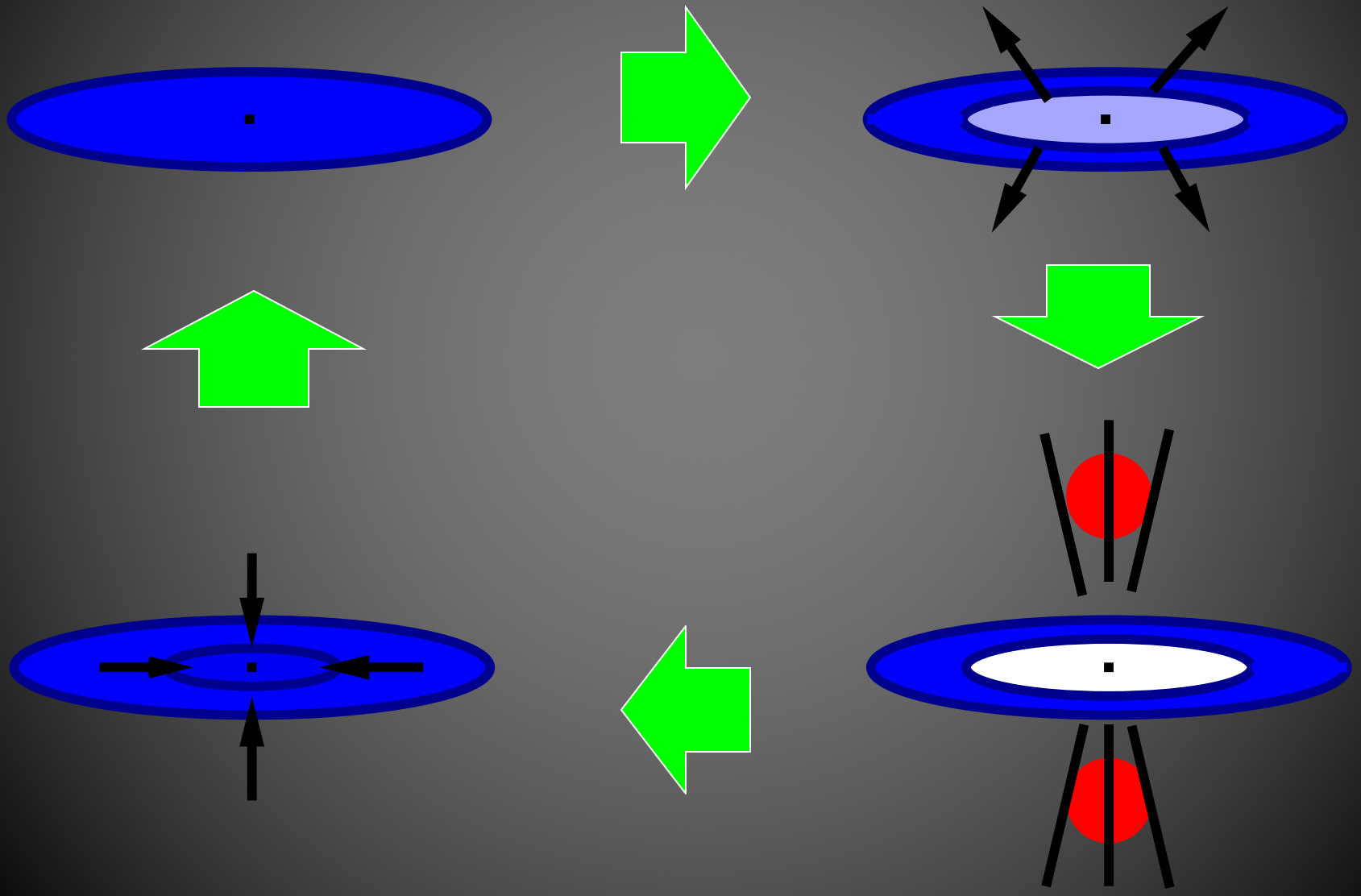
Marscher+ (2002)

Chatterjee+ (2009)




JD−2450000
2800
3000
3200
3400
3600
3800
4000
4200
cts sec^{-1} [2−10 keV]
XMM
r_{in}<2r_g
a>0.95
ratio
Energy (keV)
Suzaku
r_{in}=12±4r_g
ratio
Energy (keV)
Eje
Eje
Ballantyne et al. (2004)
Kataoka et al. (2007)
Cowperthwaite & Reynolds (2012)
Lohfink et al. (2013)
2003
2004
2005
2006
2007

The Jet Cycle



Black Hole Spin and Jet Production

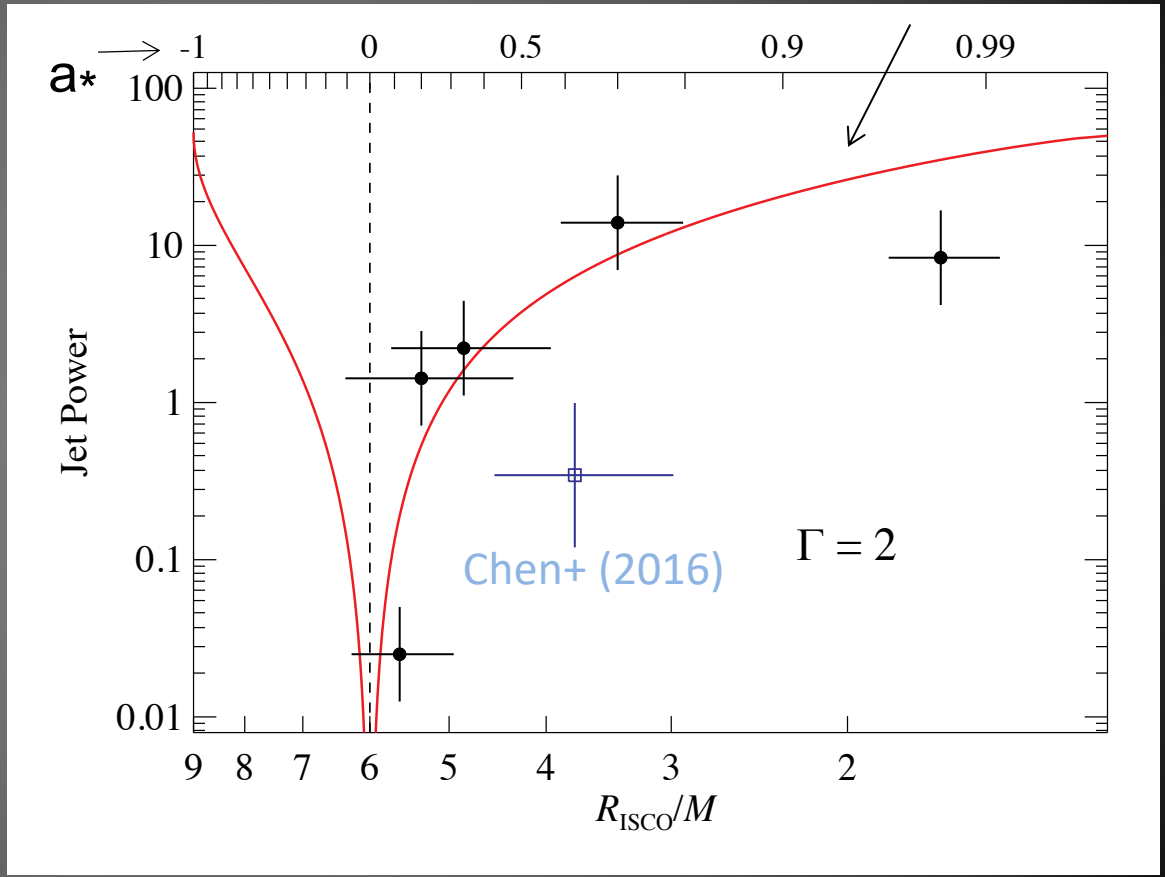
- Blandford & Znajek (1977): **rotating black hole + magnetic field from accretion disk = energetic jets** of particles along the BH spin axis.

- 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.

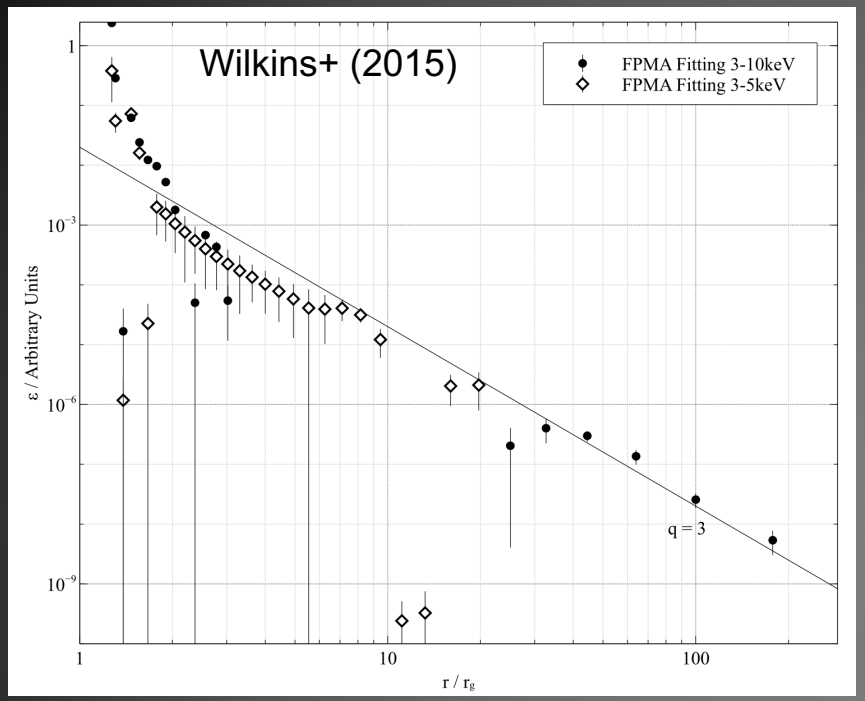
- Some observational indication of **spin correlation with jet power in microquasars**... can we extend to AGN?

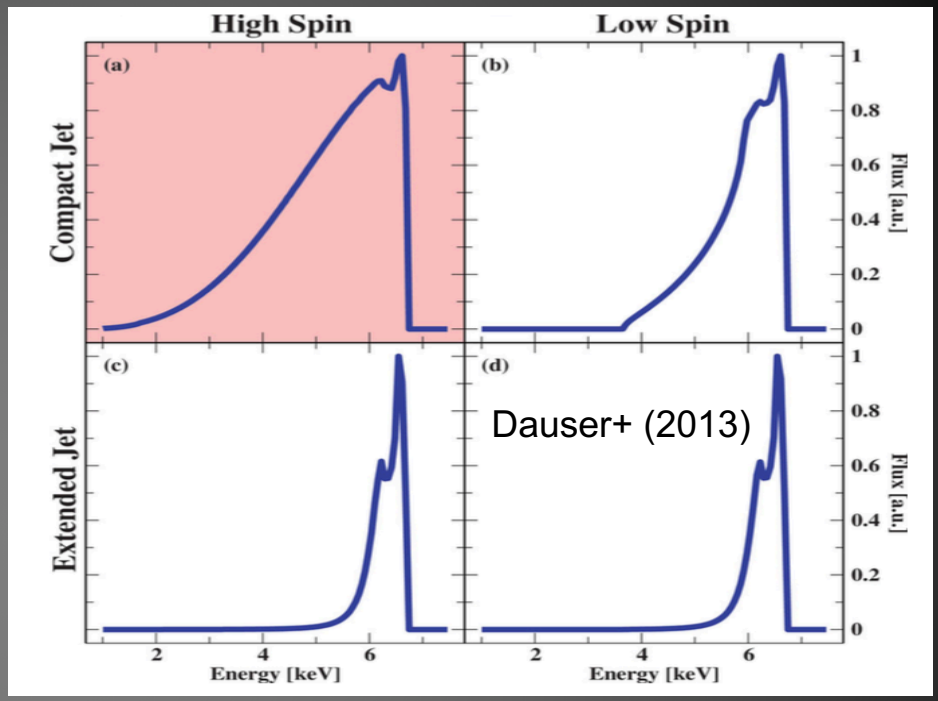
Jet power ~ Ω_H^2



Narayan & McClintock (2012)
Steiner, McClintock & Narayan (2013)
but see Russell+ (2013)

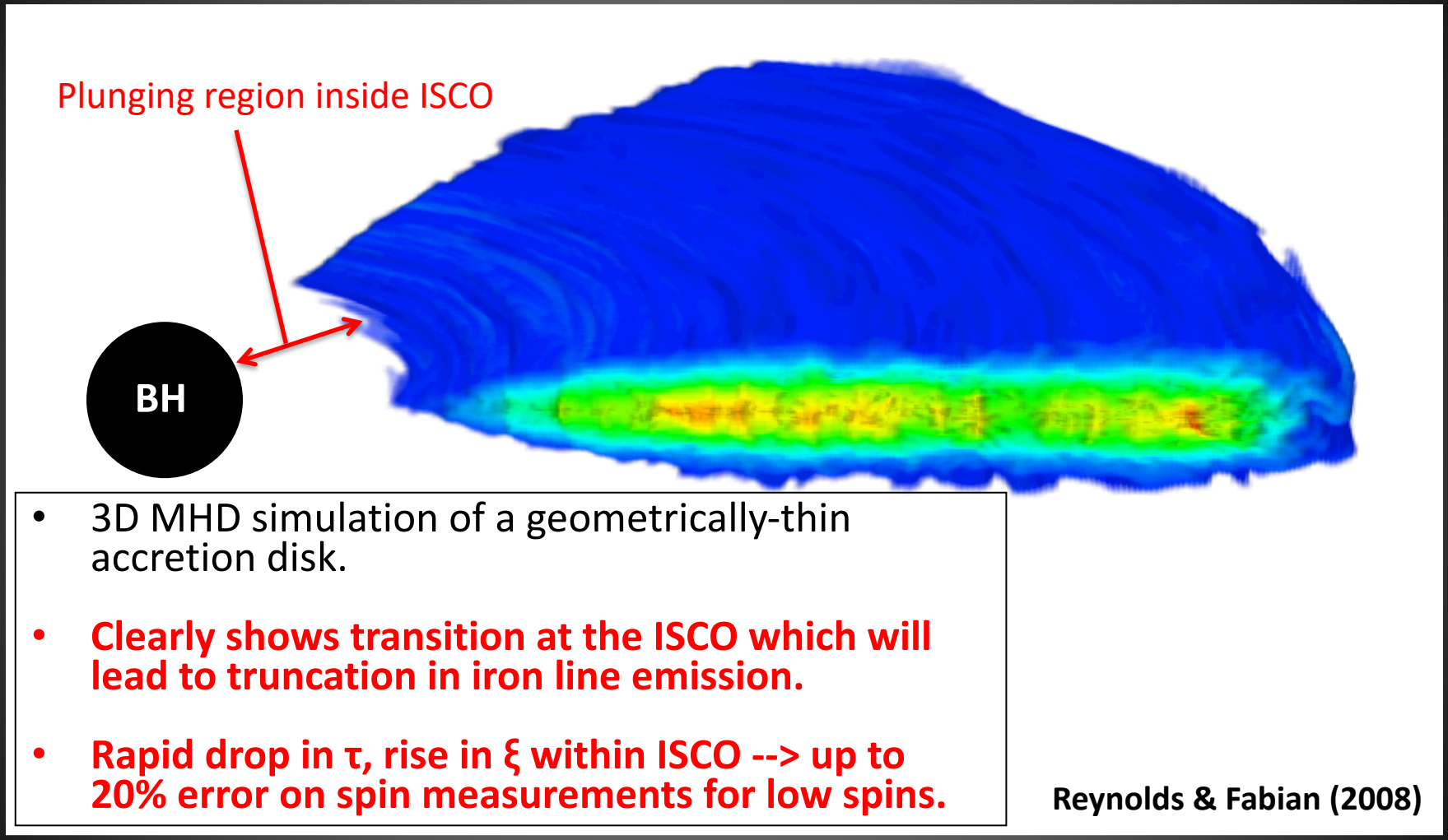
Coronal Properties





- "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.
- Broadly consistent with observed weakness of IDR flux vs. PLC flux in several sources, e.g., NGC 4151: Keck+ (2015), Beuchert+ (2017) find ~3x lower than expected reflection fraction for such a compact corona.

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 --> up to 20% error on spin measurements for low spins.**

Reynolds & Fabian (2008)

By contrast, if disk is truncated at r_{in} > ISCO, then measured spin will be a lower limit.