Lecture 3: Stellar-mass Black Holes

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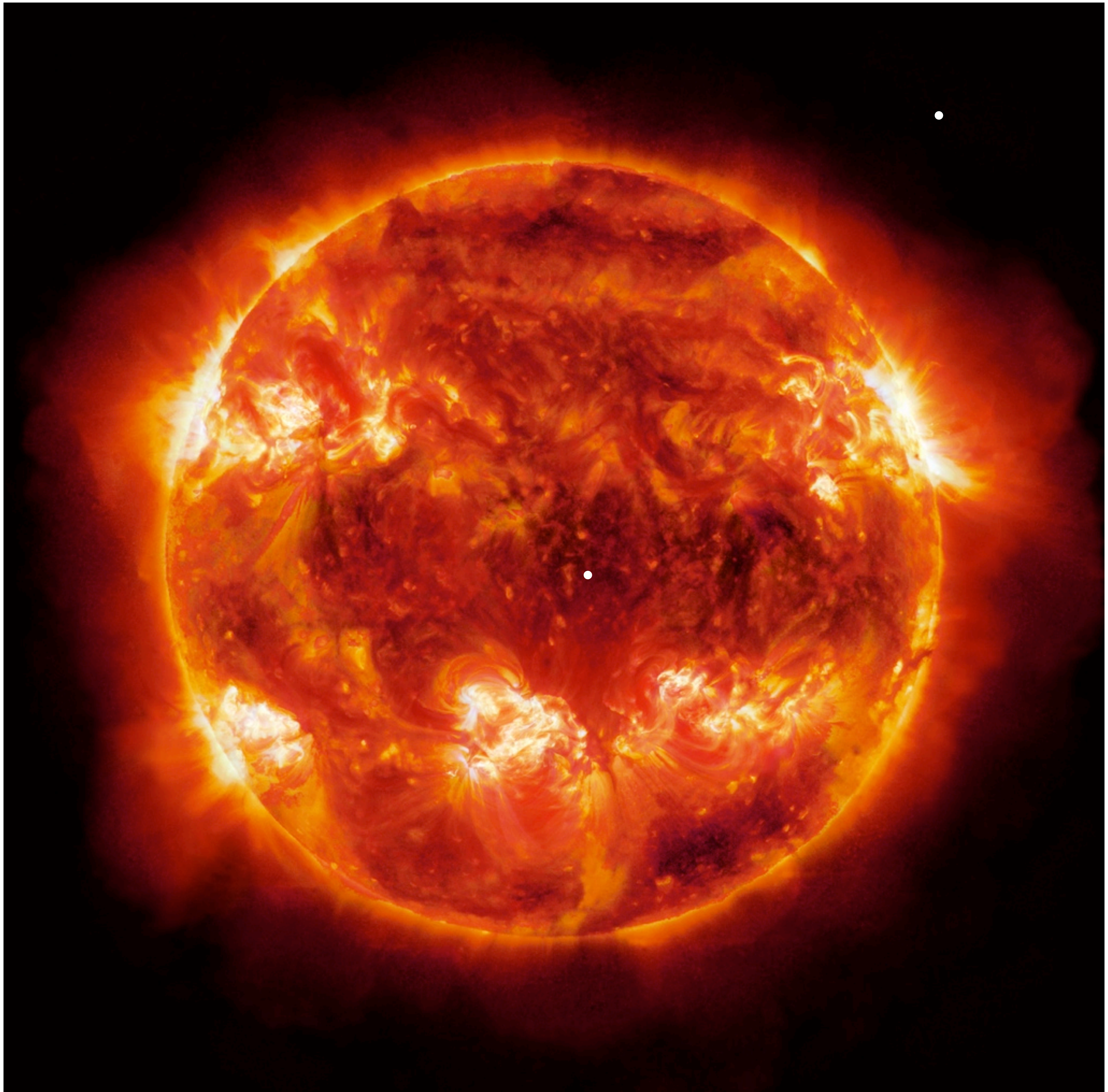
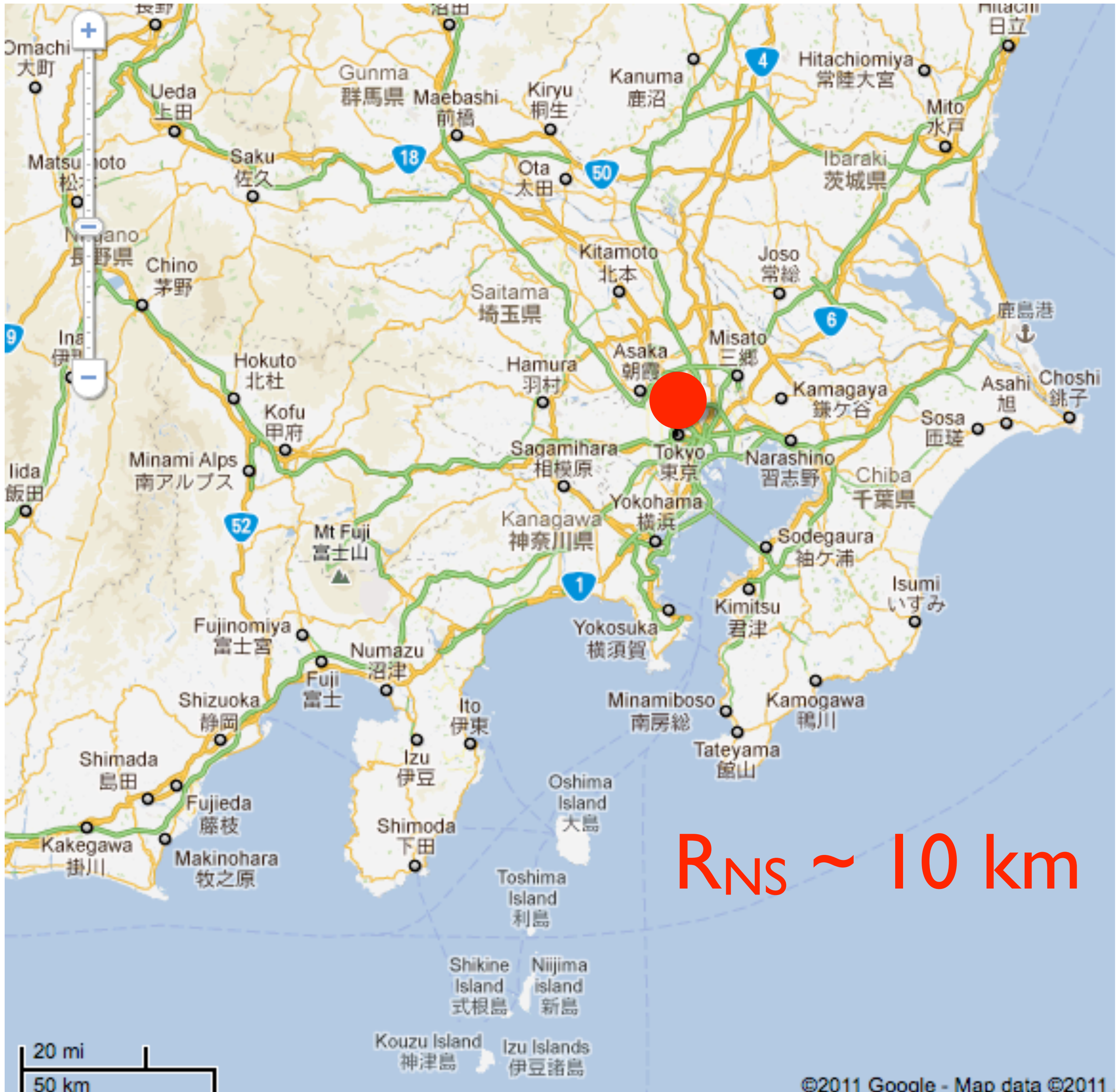
Compact Objects

Sun:WD ~ 100:1

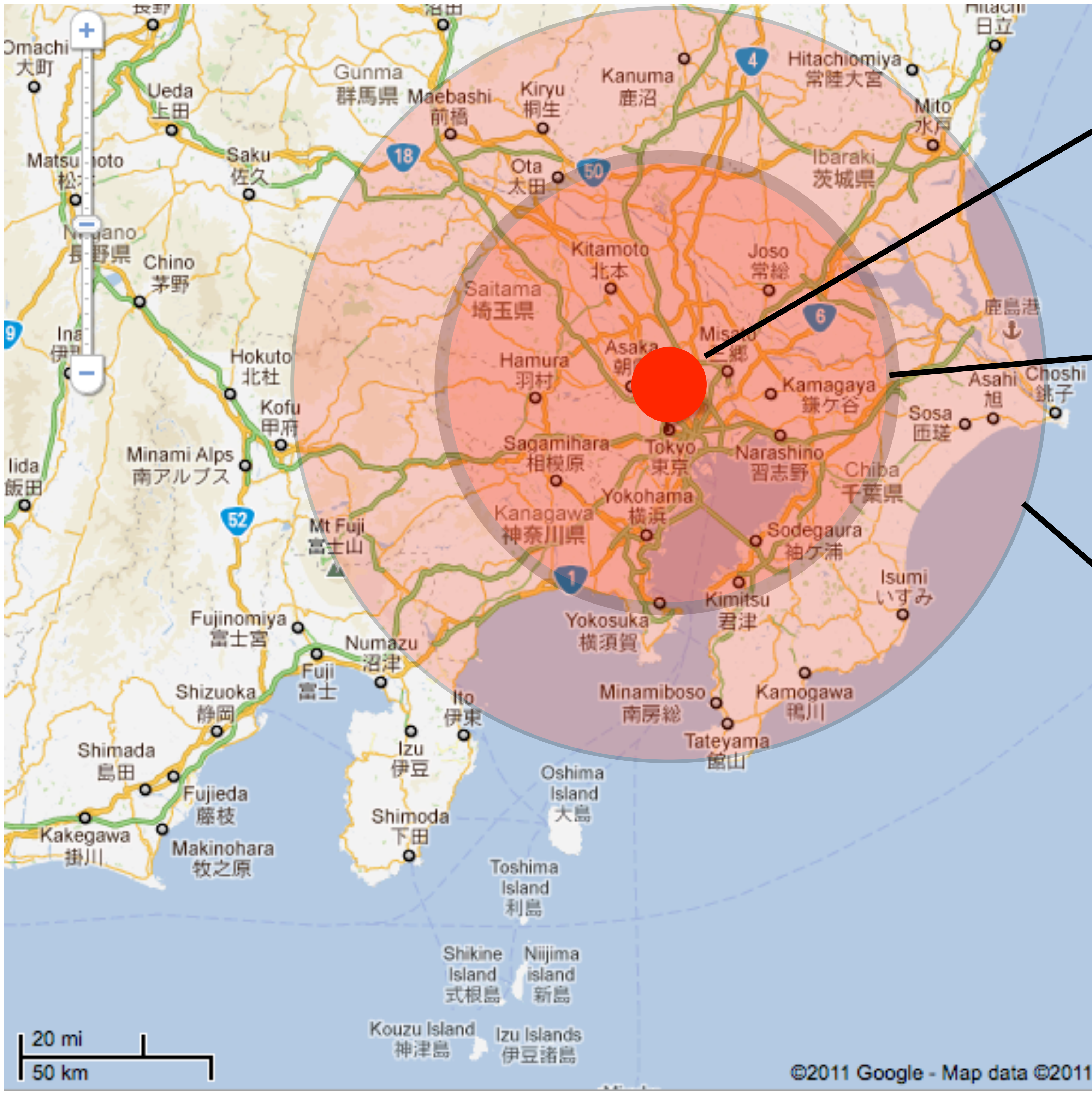


WD: NS ~ 500:1



$R_{NS} \sim 10$ km

1 R_g for 10 Msun: 15 km



- A 10 Msun BH at Eddington can be the most luminous X-ray source in the Milky Way.
- Since $D(R) \sim R^{-3}$ most of the radiation comes from a *very* small emission region.

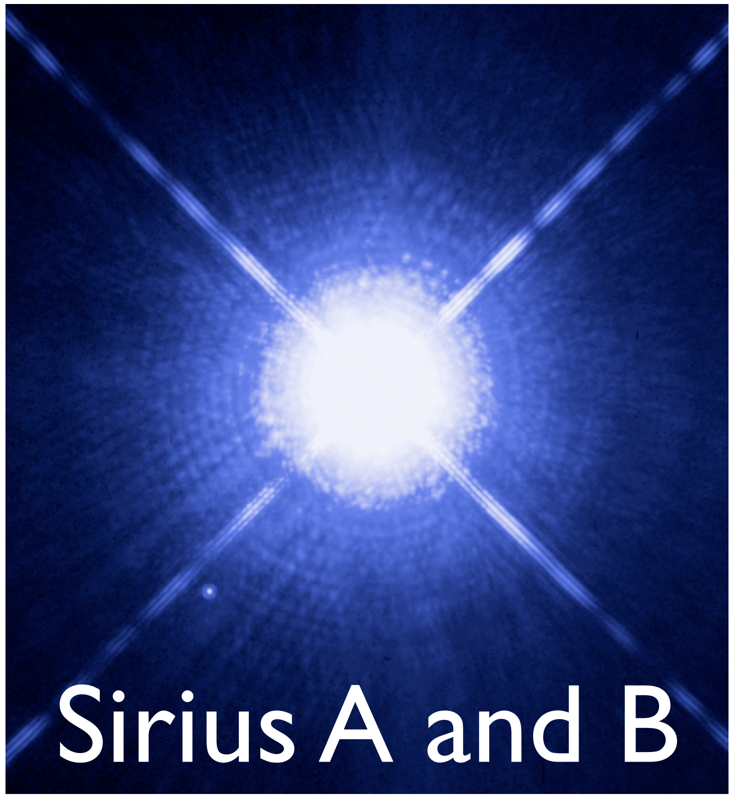
White Dwarfs

- White dwarfs are supported by electron degeneracy pressure.
- This is a simple consequence of the Pauli exclusion principle.
- If you add mass to a degenerate star, its radius gets smaller:

$P = K\rho^{5/3}$ (for a non-relativistic degenerate gas)

$P \sim M^2/R^4$ (from hydrostatic equilibrium)

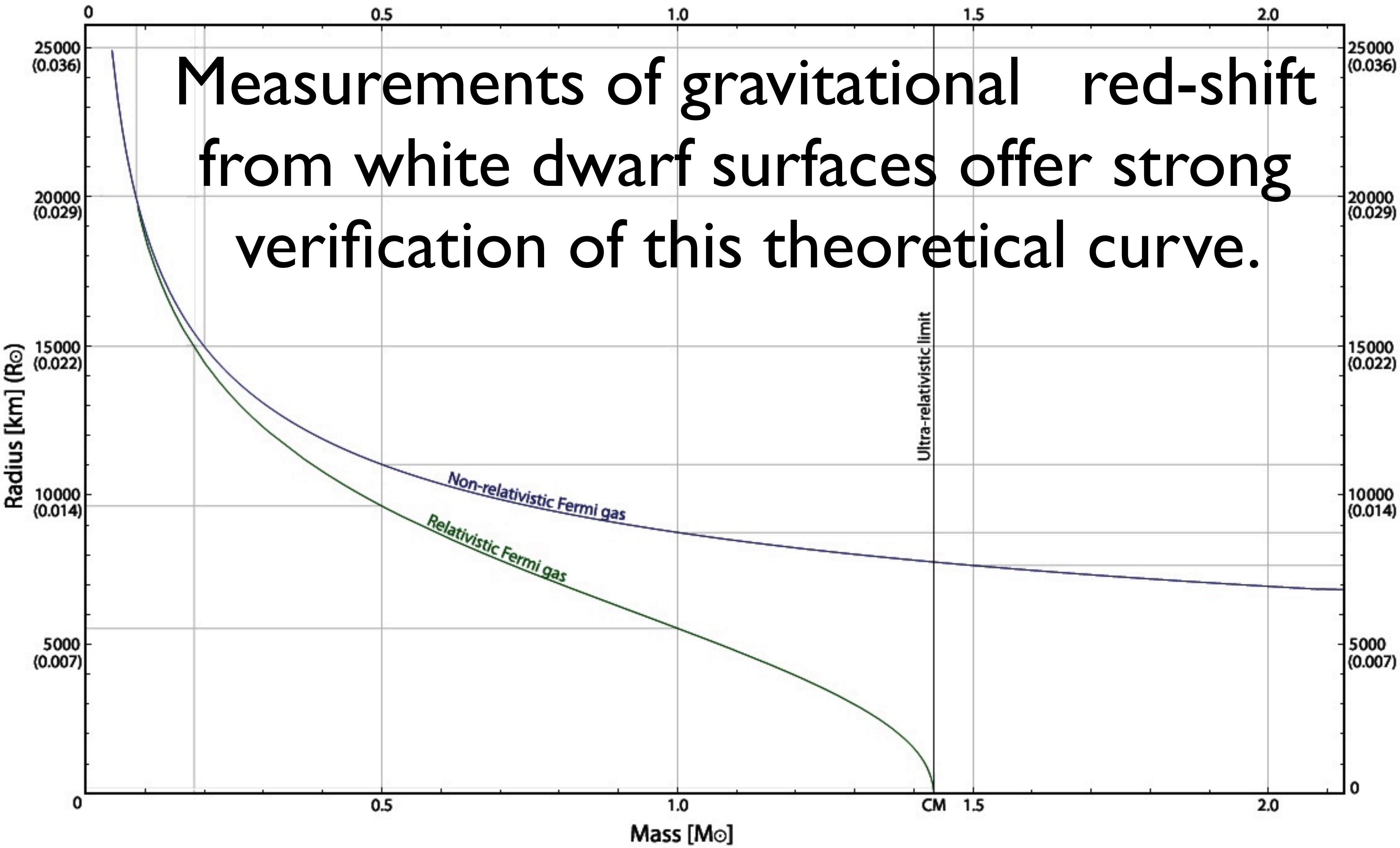
$R \sim 1/M^{1/3}$



- Chandrasekhar limit: 1.4 Msun
- Comes from relativistic case of $P = K\rho^{4/3}$

Mass-radius relation

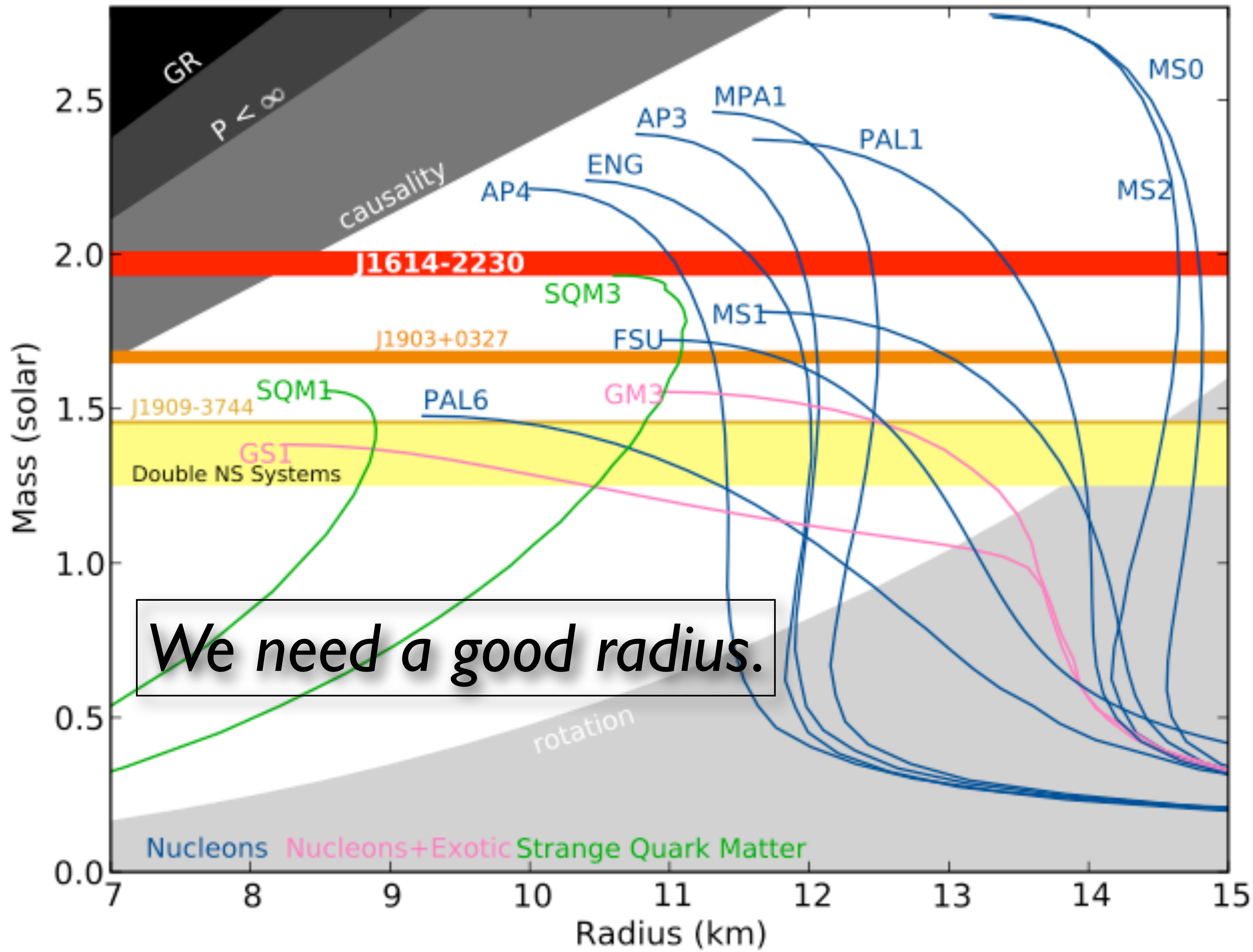
Measurements of gravitational red-shift from white dwarf surfaces offer strong verification of this theoretical curve.



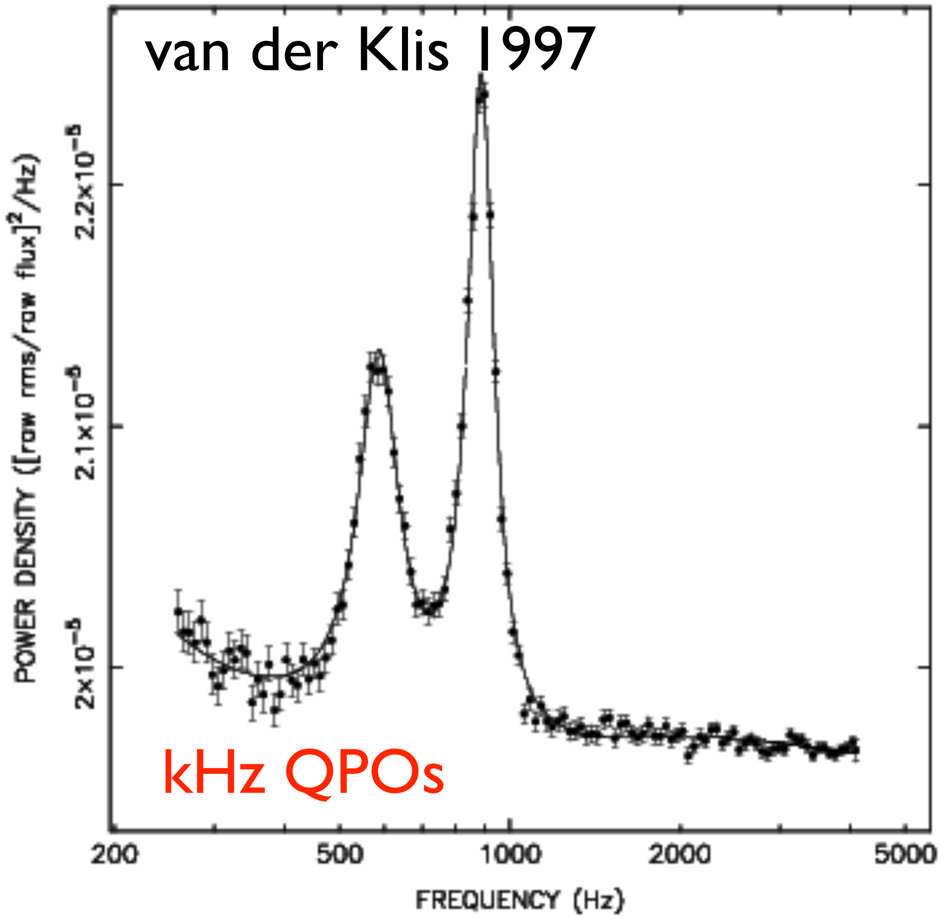
Neutron Stars

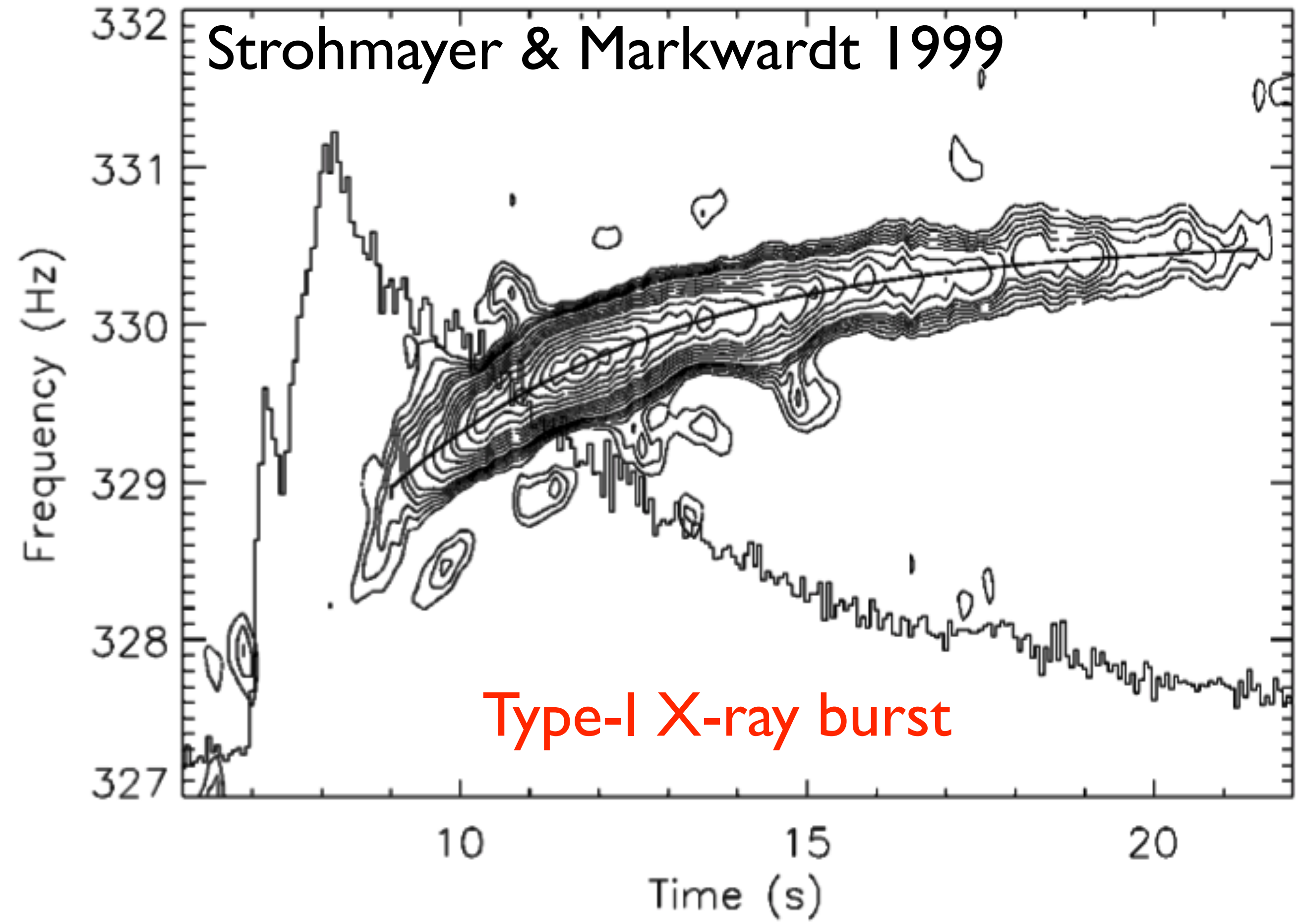
- Neutron stars are also degenerate stars, but it is neutron degeneracy pressure that holds off gravity.
- *Neutron* stars because e- and p+ have been crushed into neutrons.
- Neutron stars show a broad range of magnetic field strengths.
  Typical LMXB without pulsations: 10^{8} G
  NS in a millisecond X-ray pulsar: 10^{9-10} G
  Crab Pulsar: 10^{12} G
  Magnetars (AXPs, SGRs): 10^{14-15} G
- The mass-radius relationship for neutron stars is unknown, and exceedingly observationally challenging.
- Laboratory tests cannot test this form of matter.

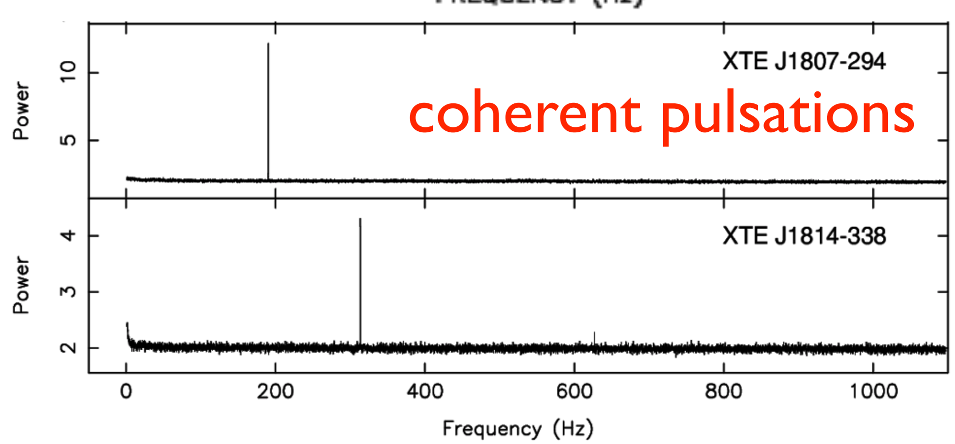
Demorest et al. 2010



Key NS Phenomena







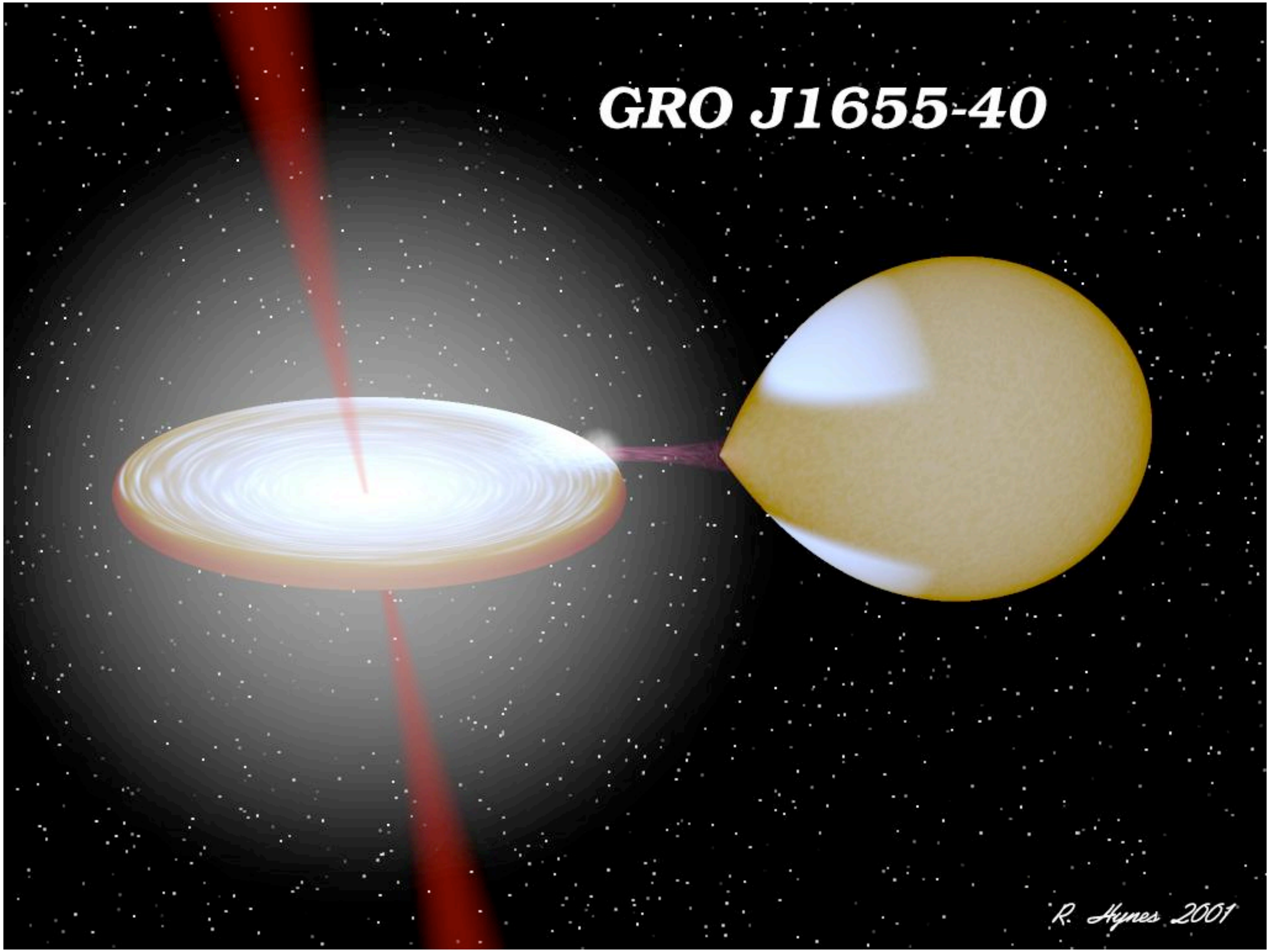
BHs do none of these things (lack of a surface).
Neutron stars are harder below 10 keV, softer above.

Gravitational red-shifts

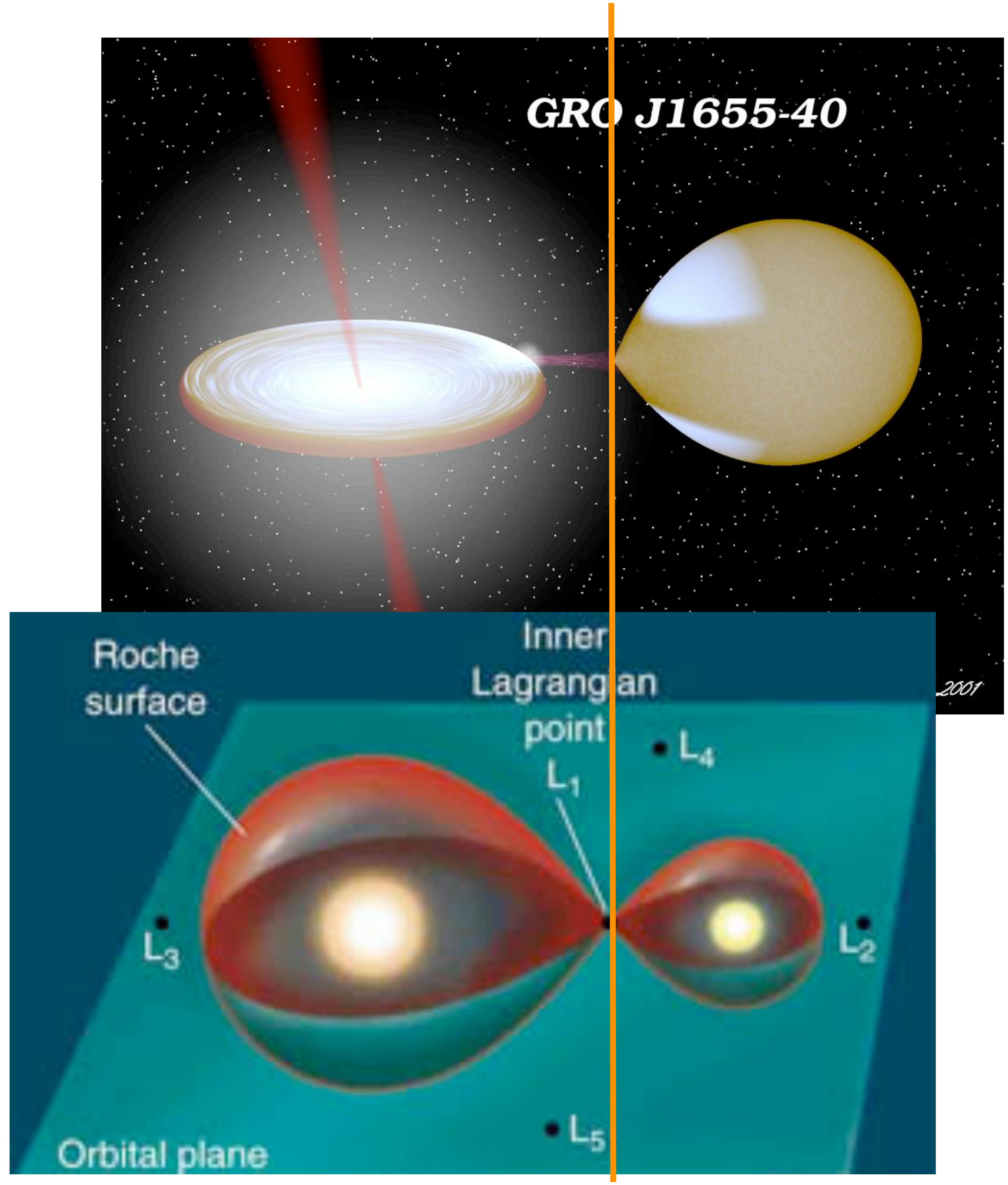
- For a white dwarf: $GM/Rc^2 \sim 2\text{-}3 \cdot 10^{-4}$
- For a neutron star: $GM/Rc^2 \sim 0.2\text{-}0.3$
- For a black hole: $\lambda_f/\lambda_i = [\ 1 - 2GM/Rc^2]^{-1/2}$
- @ISCO, a=0: ~ 0.23

Fundamentals of Binary Systems

A (good) Cartoon



Roche Potential



- Within each lobe, a test particle will fall back onto the central mass.
- Mass transfer in a low-mass X-ray binary occurs when the companion star over-flows its Roche Lobe.
- Mass is transferred through the inner Lagrange point, L1.
- The material has angular momentum, and forms a disk.

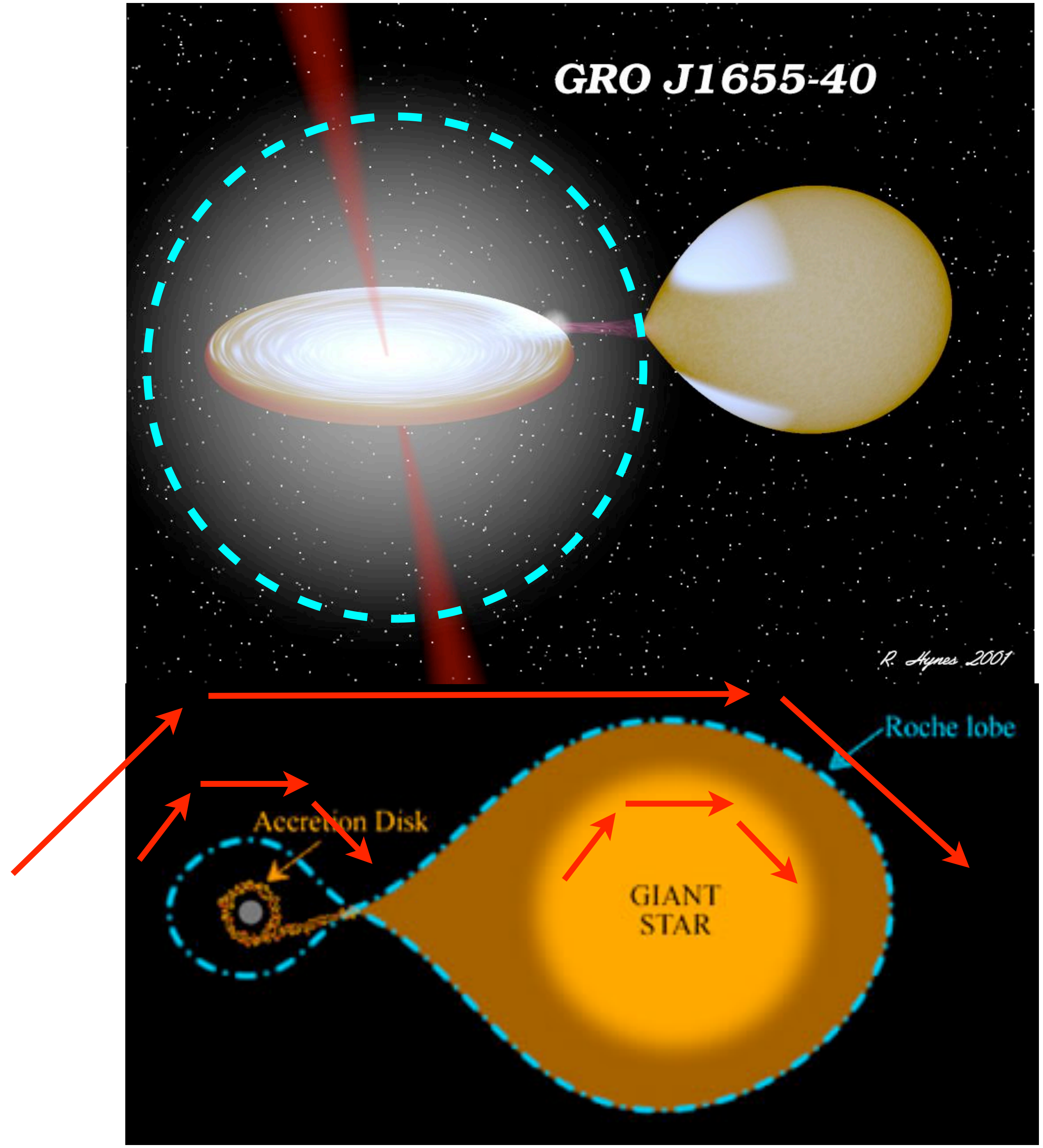
Roche Potential II

- P_{orb} ~ 1 day, sep. is ~few R_*.

- The disk does not fill-up the full Roche lobe of the black hole.

- Rather, likely about 2/3 of that. see Paczynski, B., 1977, ApJ, 216, 822

- Note also that the accretion stream comes off of the “back”.



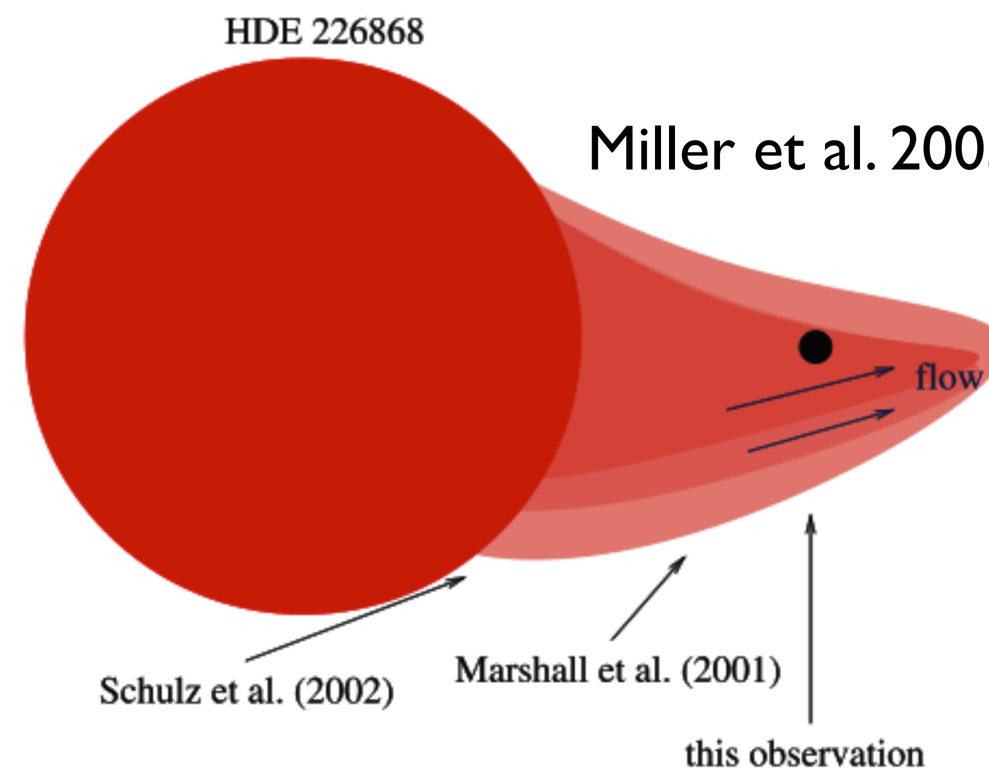
Massive Stars and Focused Winds

- In high-mass X-ray binaries, accretion likely occurs (at least partially) via a focused wind scenario.

- The focused wind may form a disk, but it will be much smaller than if it were a Roche-lobe-filling scenario.

- The case with Cygnus X-1, for instance, is unclear. It may be filling its Roche lobe.

- Other relevant cases:
LMC X-1, LMC X-3, some ULXs.



Miller et al. 2005

How do systems evolve?

$$\dot{a}/a = 2(-\dot{M}_c/M_c)\ (1-M_c/M_x)$$

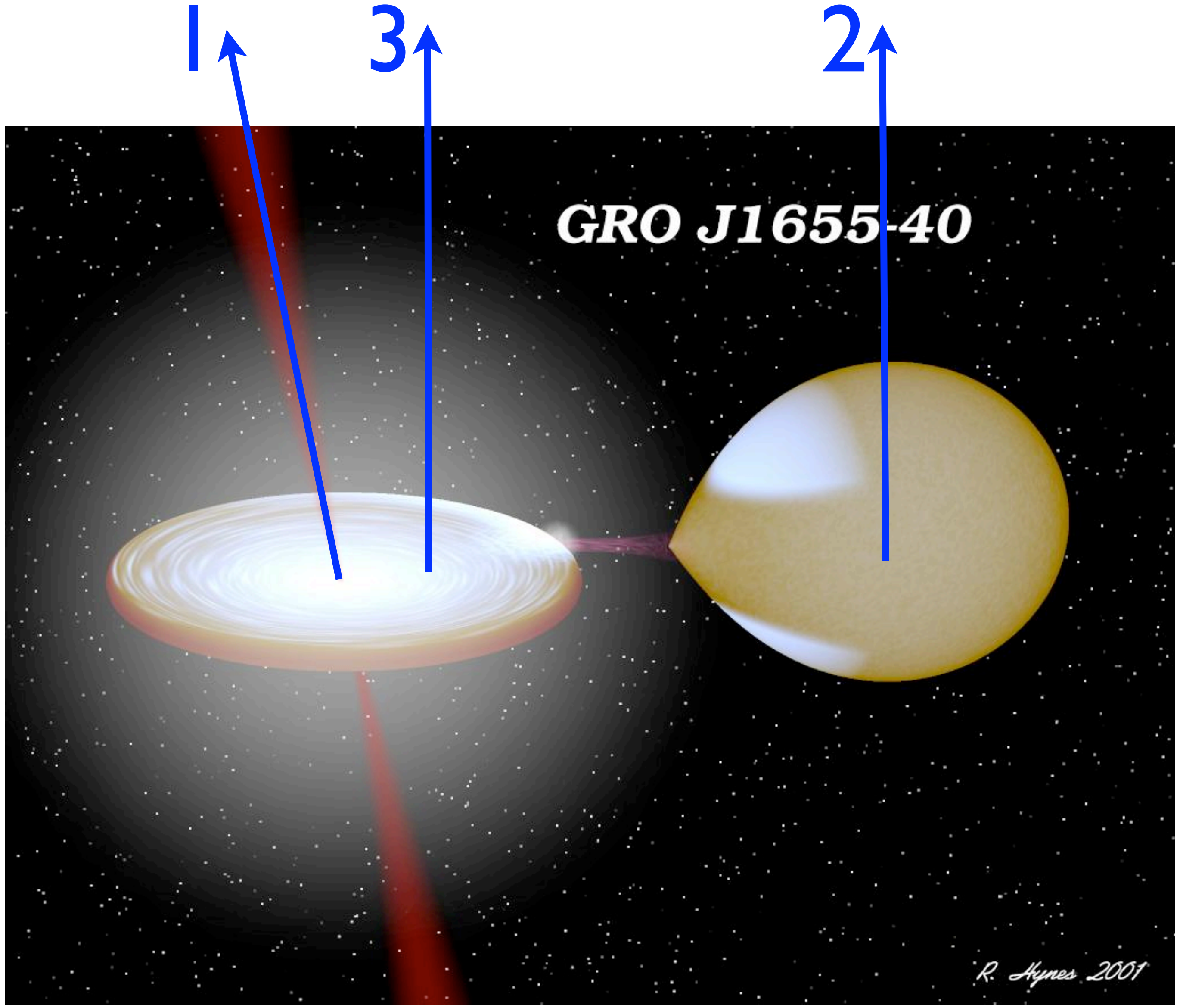
(remember: $\dot{M}_c < 0$ for mass transfer)

$M_c<M_x$ --> X: separation increases
$M_c>M_x$ --> X: separation decreases

For binary evolution, see:
Frank, King, & Raine 2003

Notes on inclinations

- There are three angular momentum vectors of importance: (1) that of the black hole, (2) that of the companion, and (3) the binary system as a whole.
- *They do not have to be aligned.*
- Indeed, depending on the particulars of the SNe/GRB, the BH vector might be fairly *mis-aligned*.
- The *inner* disk should be aligned with the BH ang. mom. vector.
- The timescale to align the BH and system vectors is the lifetime of the system (see e.g. Maccarone 2002).



Distances and Masses

Some Key References

Casares, J., Charles, P.A., Naylor, T., 1992, Nature, 355, 614

Casares, J., et al., 2004, RMexAA, 20, 21

Miller-Jones, J., et al., 2009, ApJ, 706, L230

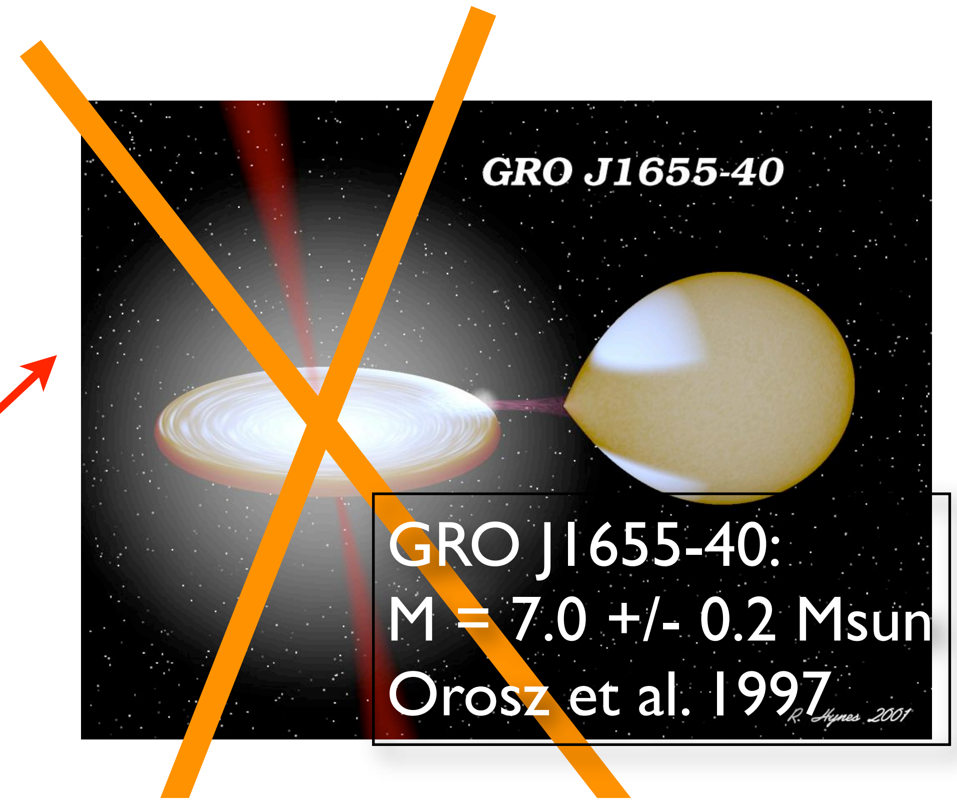
Orosz, J., & Bailyn, C., 1997, ApJ, 477, 876

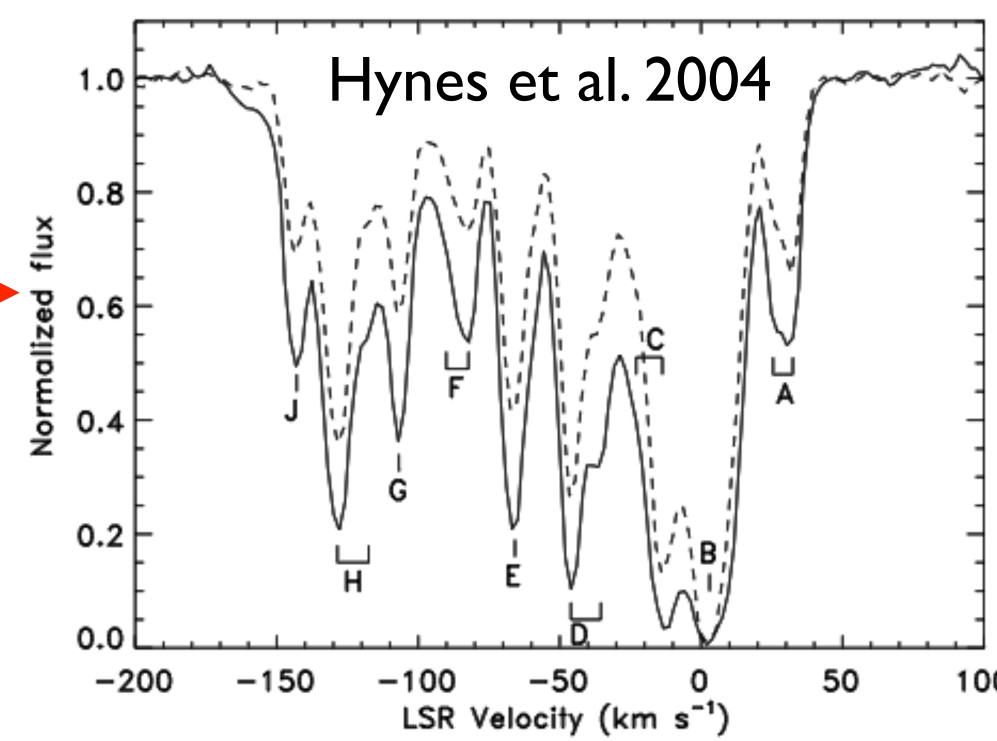
Remillard, R., McClintock, J., Bailyn, C., 1992, ApJ, 399, L145

Steeghs, D., & Casares, J., 2002, ApJ, 568, 273

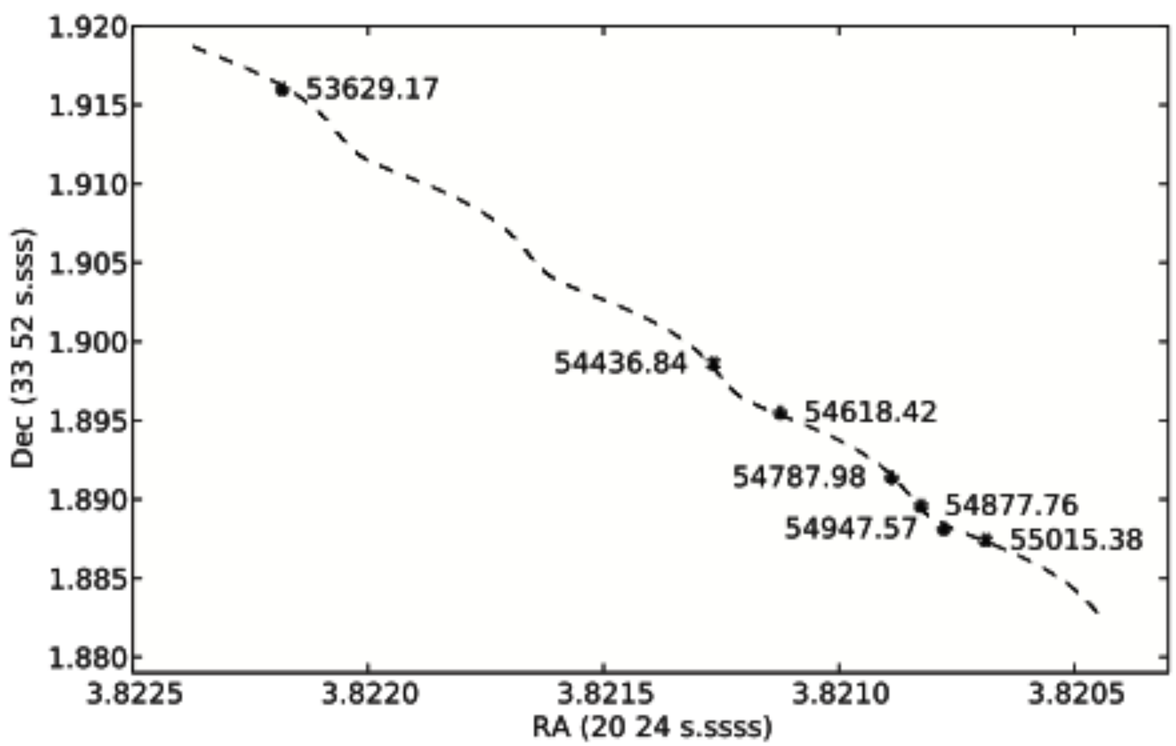
Distances

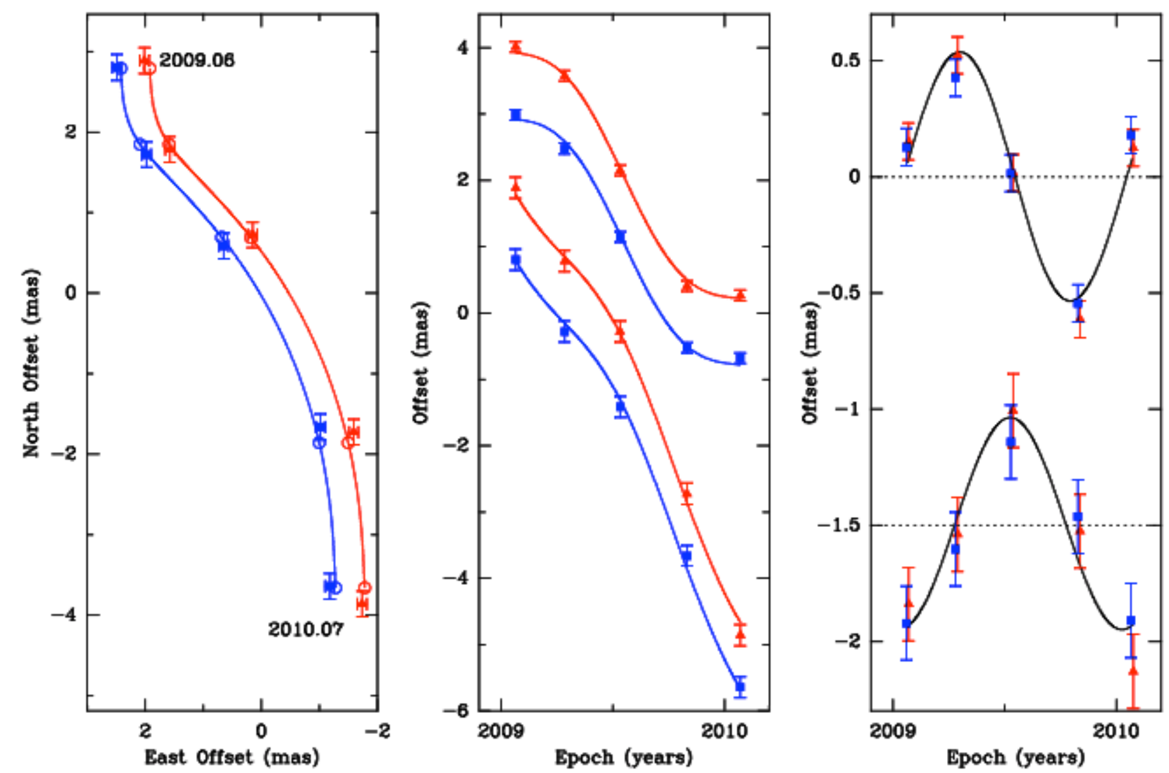
- Distance can be VERY difficult.
- Eddington limit scaling - for an assumed mass - is one bad way to get a distance. e.g. 1957+11
- Quiescent luminosity of the companion, once accretion is halted, is another means. Need stellar type.
- Velocity systems in the ISM may indicate a distance. Lines such as Na D1, Na D2. e.g. GX 339-4.





Parallax: *hard*, but good





V404 Cyg: 2.39 +/- 0.14 kpc
(Miller-Jones et al. 2009)

Cyg X-1: 1.86 +/- 0.12 kpc
(Reid et al. 2011)

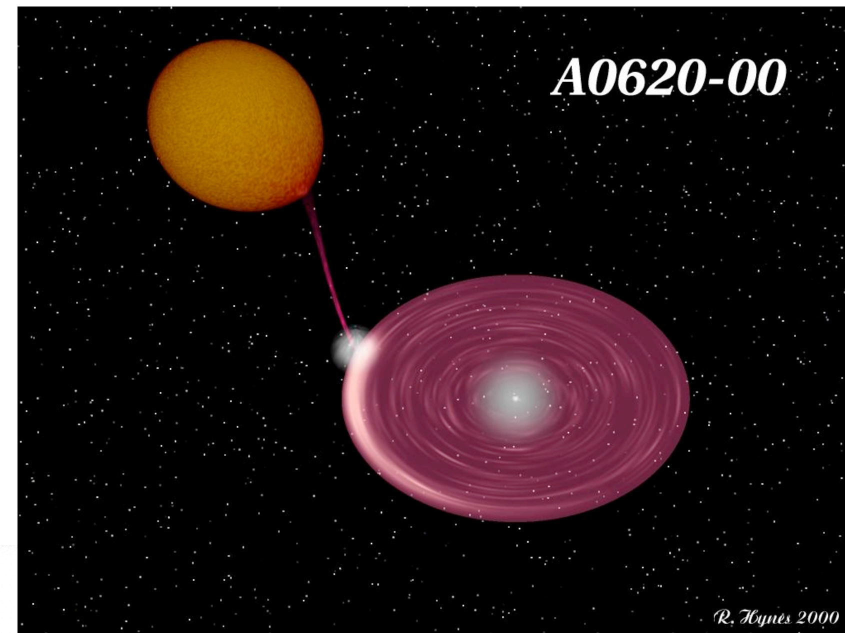
<u>But</u>: you need a persistent source, and to avoid confusion between core versus knots.

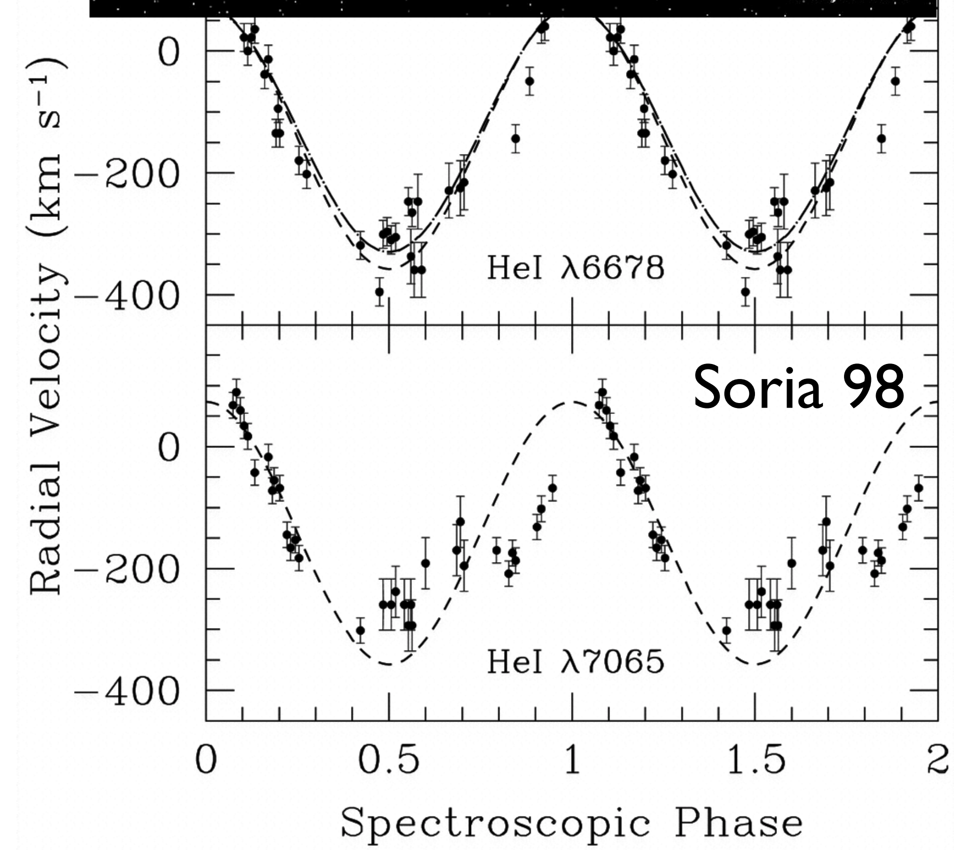
Radial Velocity Curves

- **Quiescent system**:
  Monitor Doppler shifts of absorption lines in the photosphere of the companion.

- **Active system**:
  Monitor Doppler shifts of lines in the Bowen fluorescence blend excited on the surface of the companion star. This requires a large scope & high resolution.

- Must be careful to account for: rotational broadening.

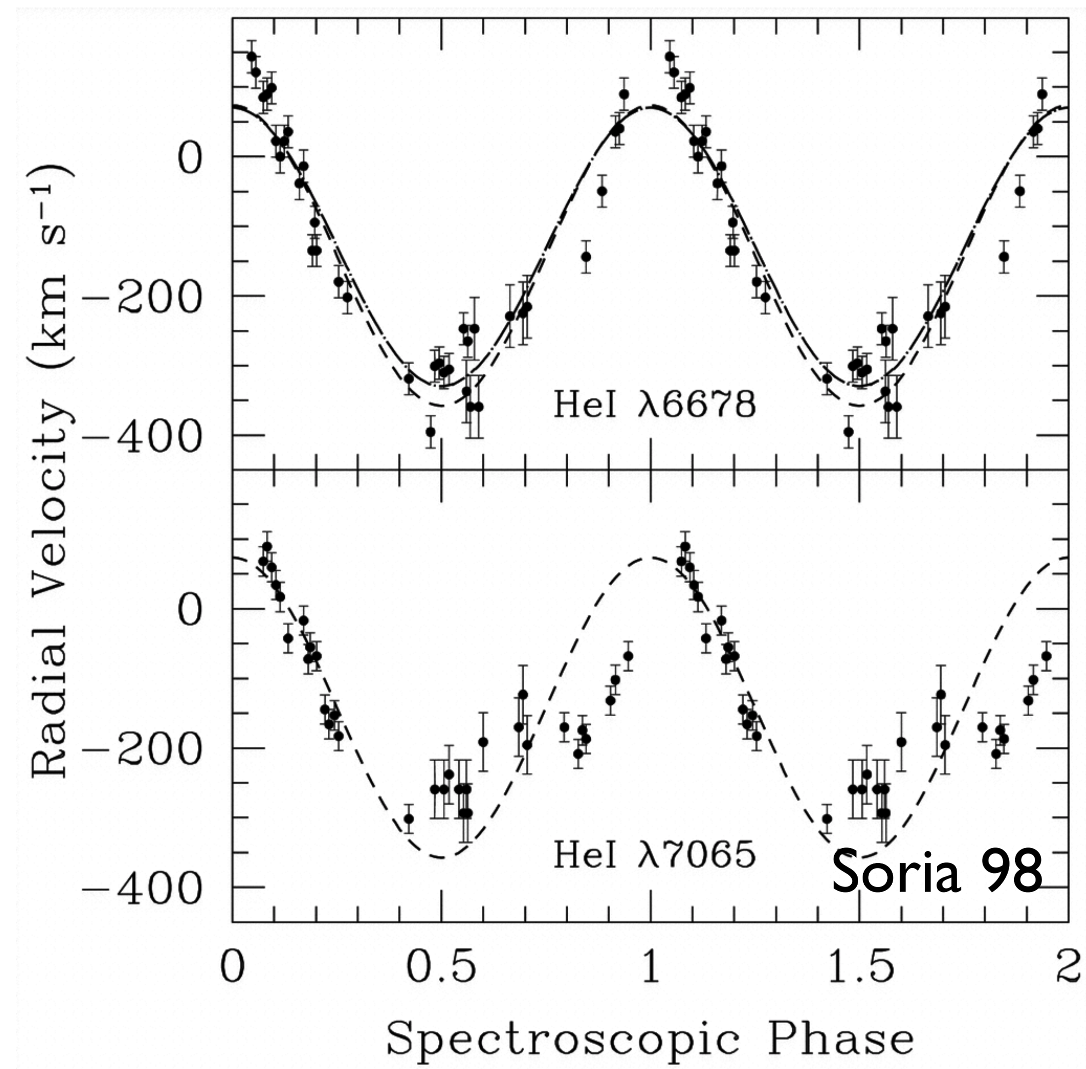




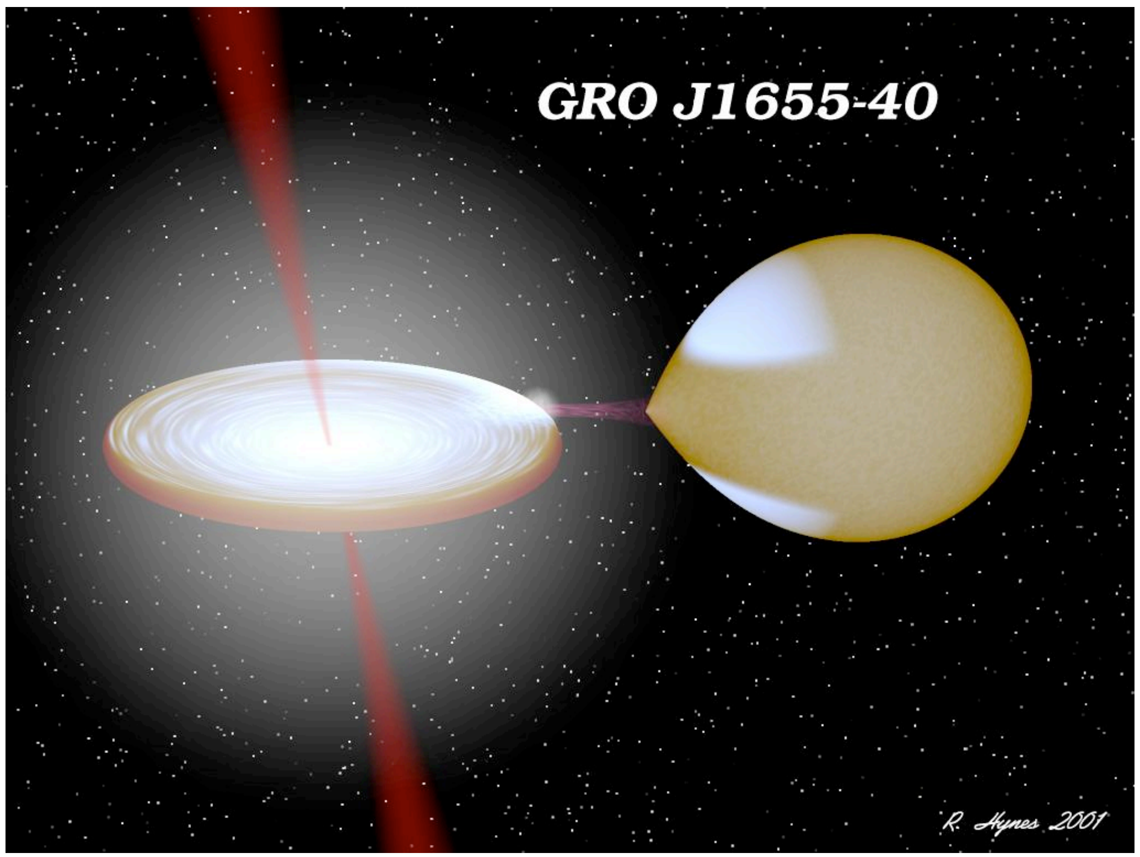
Mass function

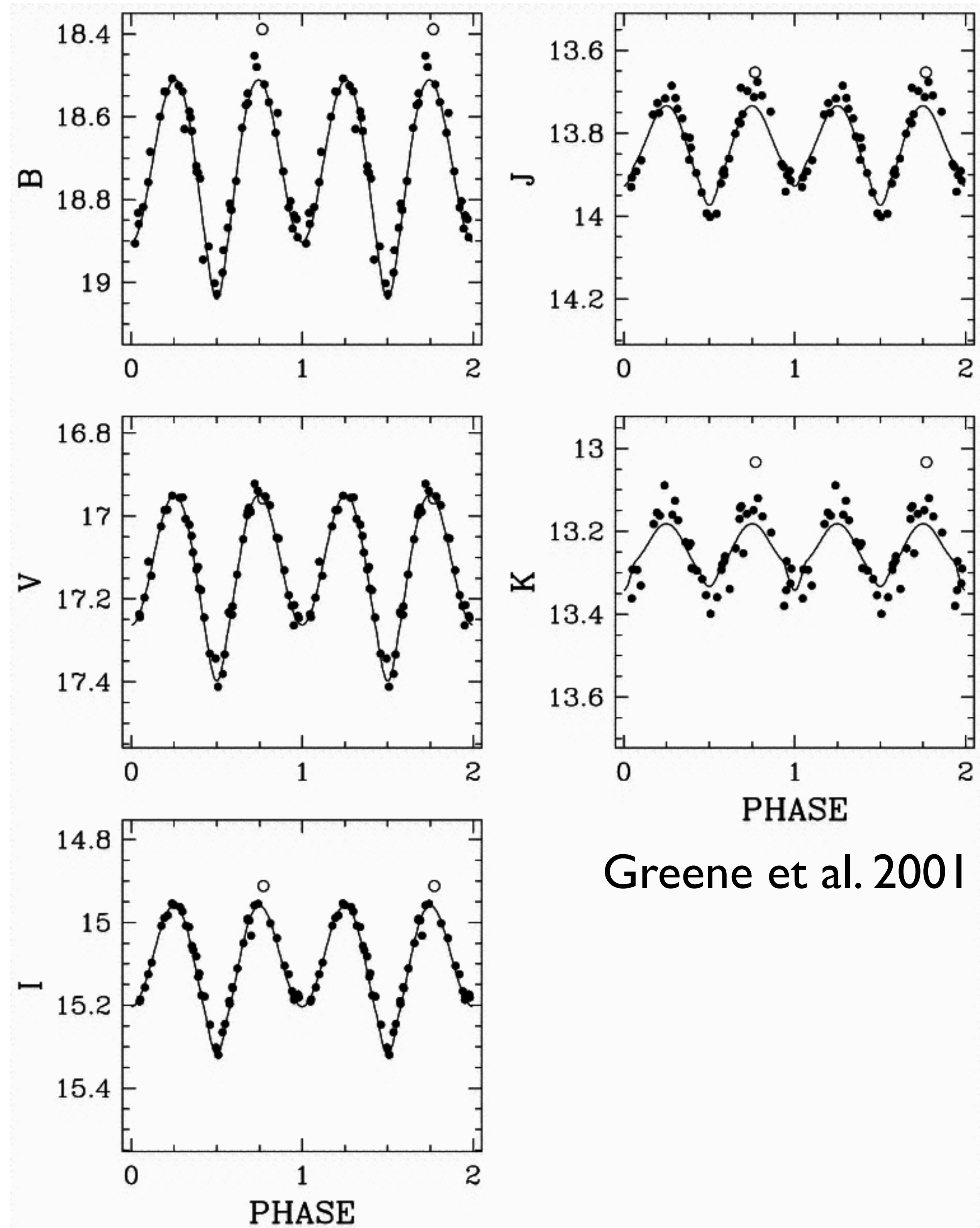
$$f(M_x) = \frac{P^2 K_c^3}{2\pi G} = \frac{M_x^3 \sin^3 i}{(M_x + M_c)^2}$$

- Work in relation to the center of mass.
- Remember conservation of momentum.
- Use Kepler's third law.
- A lower limit on the mass of the X-ray source Mx is given by measuring the velocity of the companion Mc.
- Also need inclination *i*, and companion mass, Mc.



sin(i) via ellipsoidal light curve



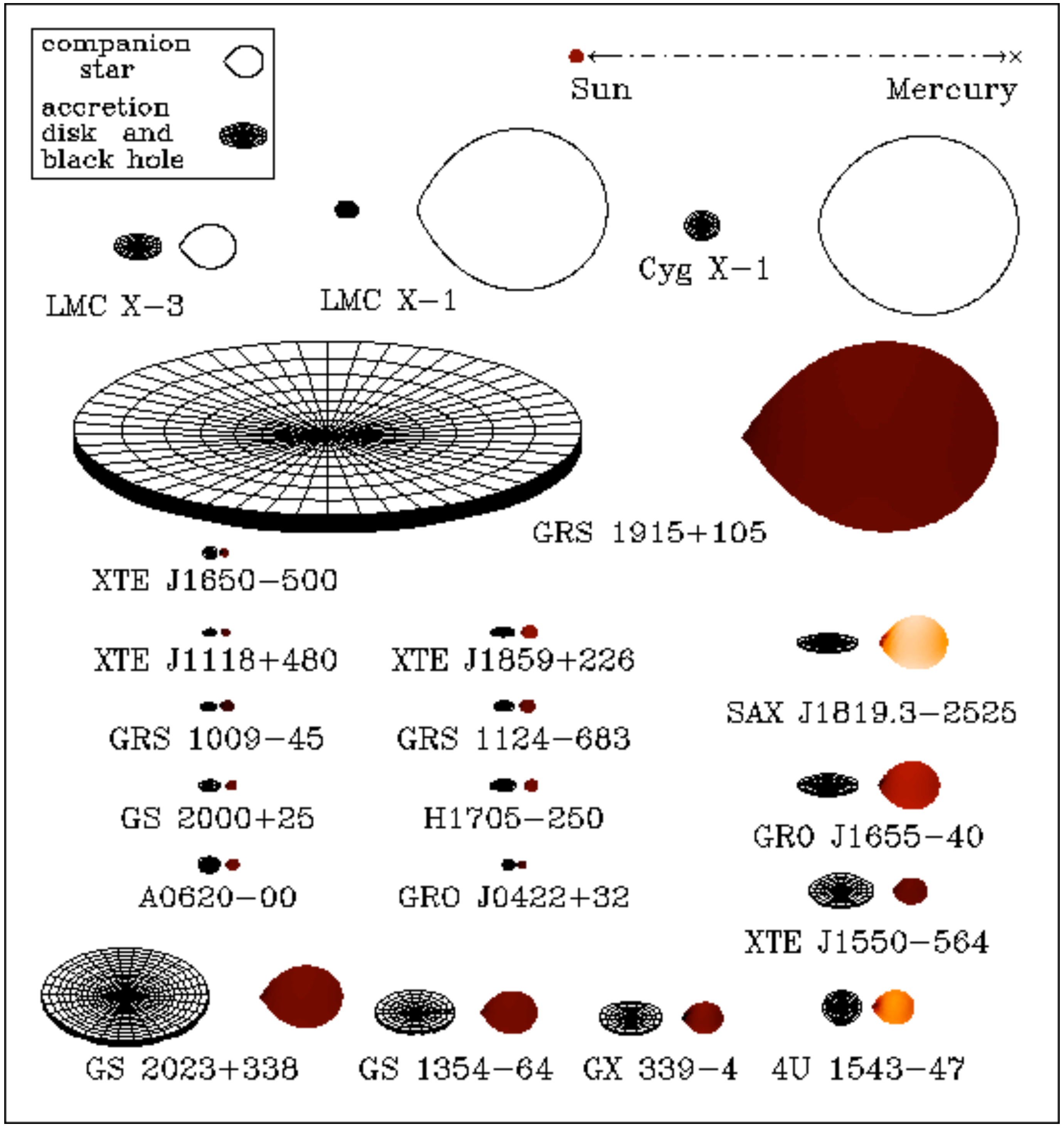


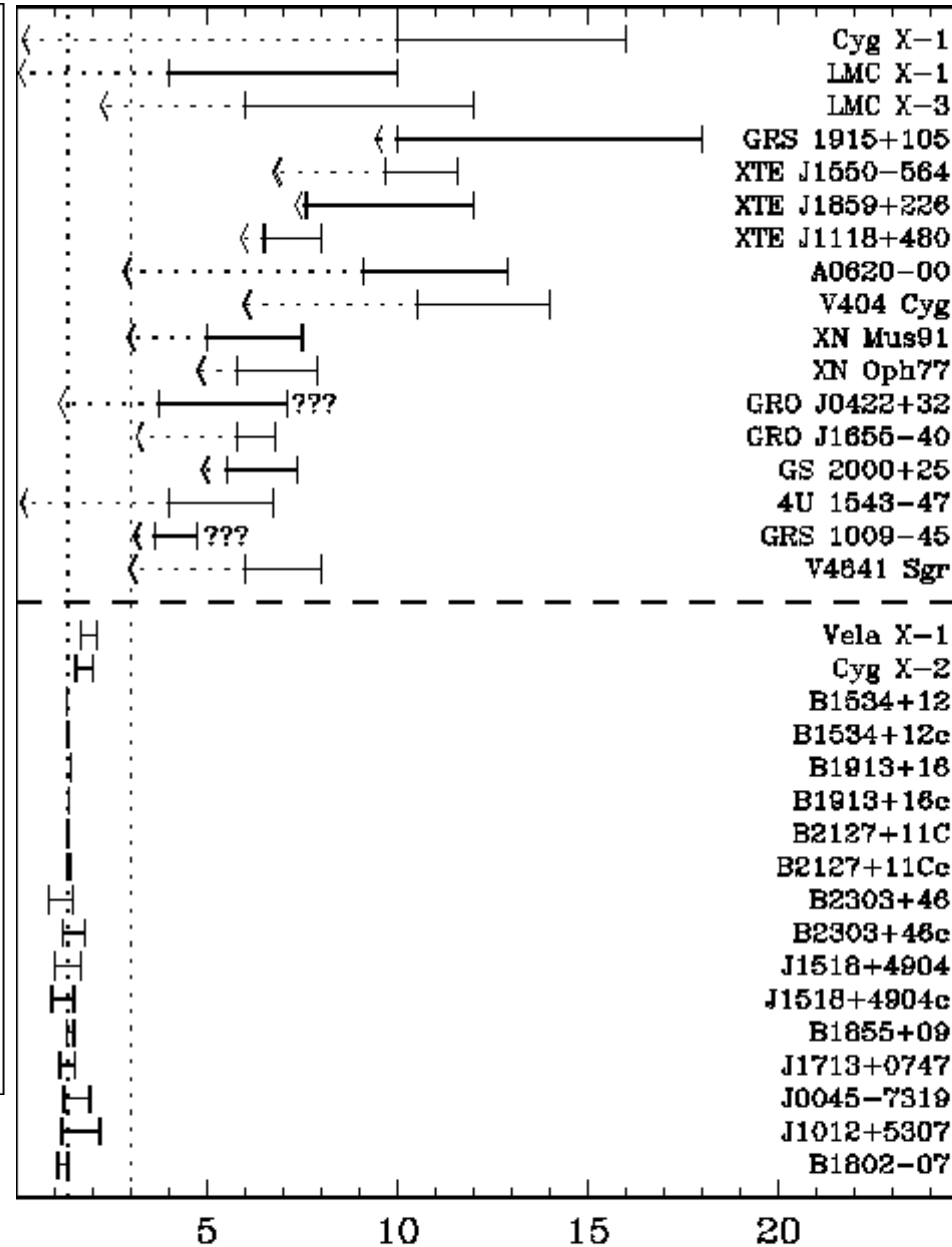
Greene et al. 2001

Neutron star mass limit

- This is important for understanding whether or not your mass function (more on this later) actually implies that your source is a black hole.
- When a white dwarf exceeds 1.4 Msun, degeneracy pressure fails.
- This is the well-known Chandrasekhar limit.
- Adapting the arguments for the case neutron degeneracy pressure, for a neutron star, actually gives a pretty loose limit (e.g. 5 Msun).
- The upper limit on the mass of a neutron star is set by *causality*:
The matter cannot be so dense that the sound speed exceeds *c*.
This sets an upper limit of 3 Msun.
see Rhoades & Ruffini 1974 PhRvL 32 324
- *If your mass function implies a primary with M > 3 Msun, it is a black hole.*

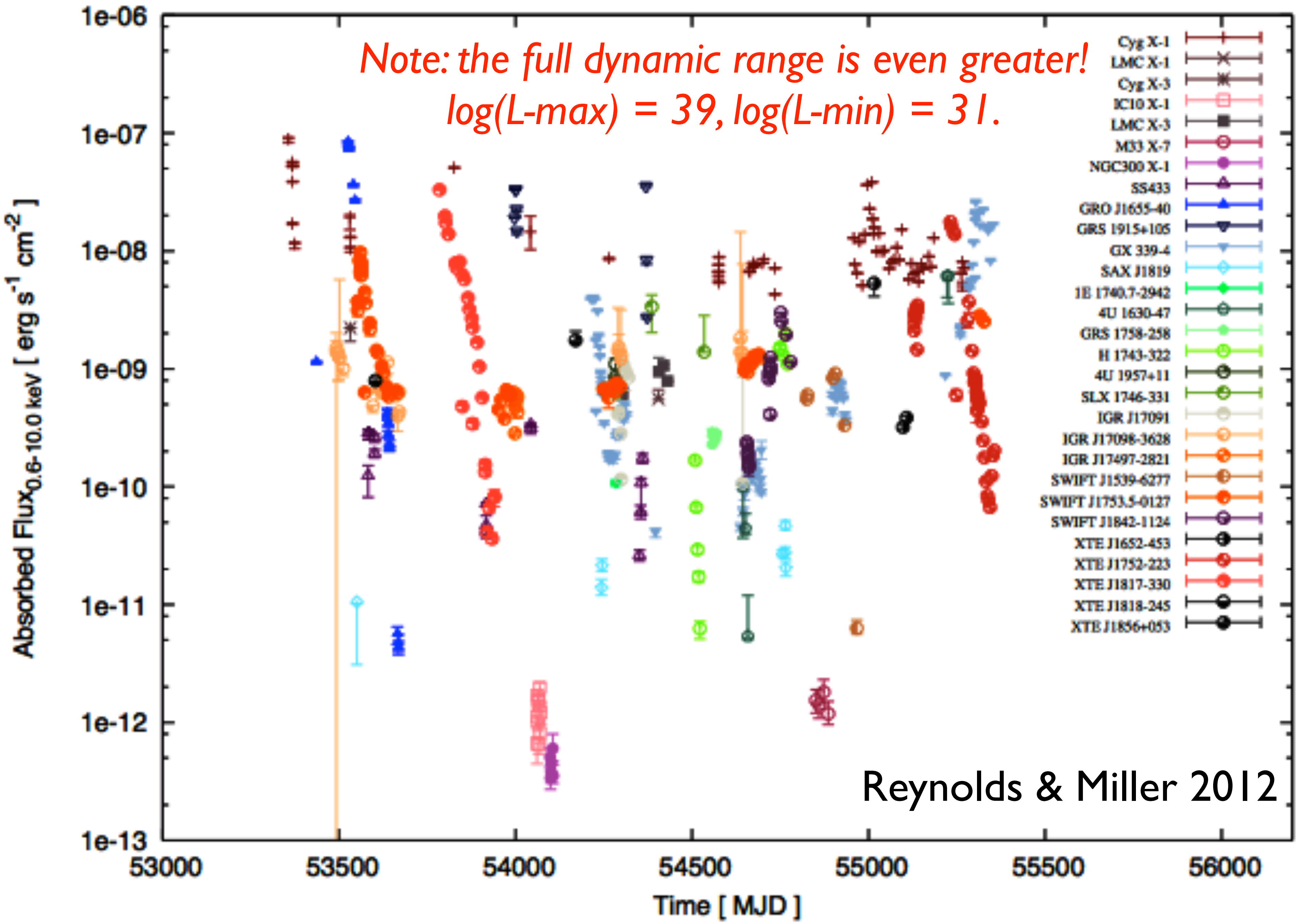
Stellar-mass BHs





Outbursts

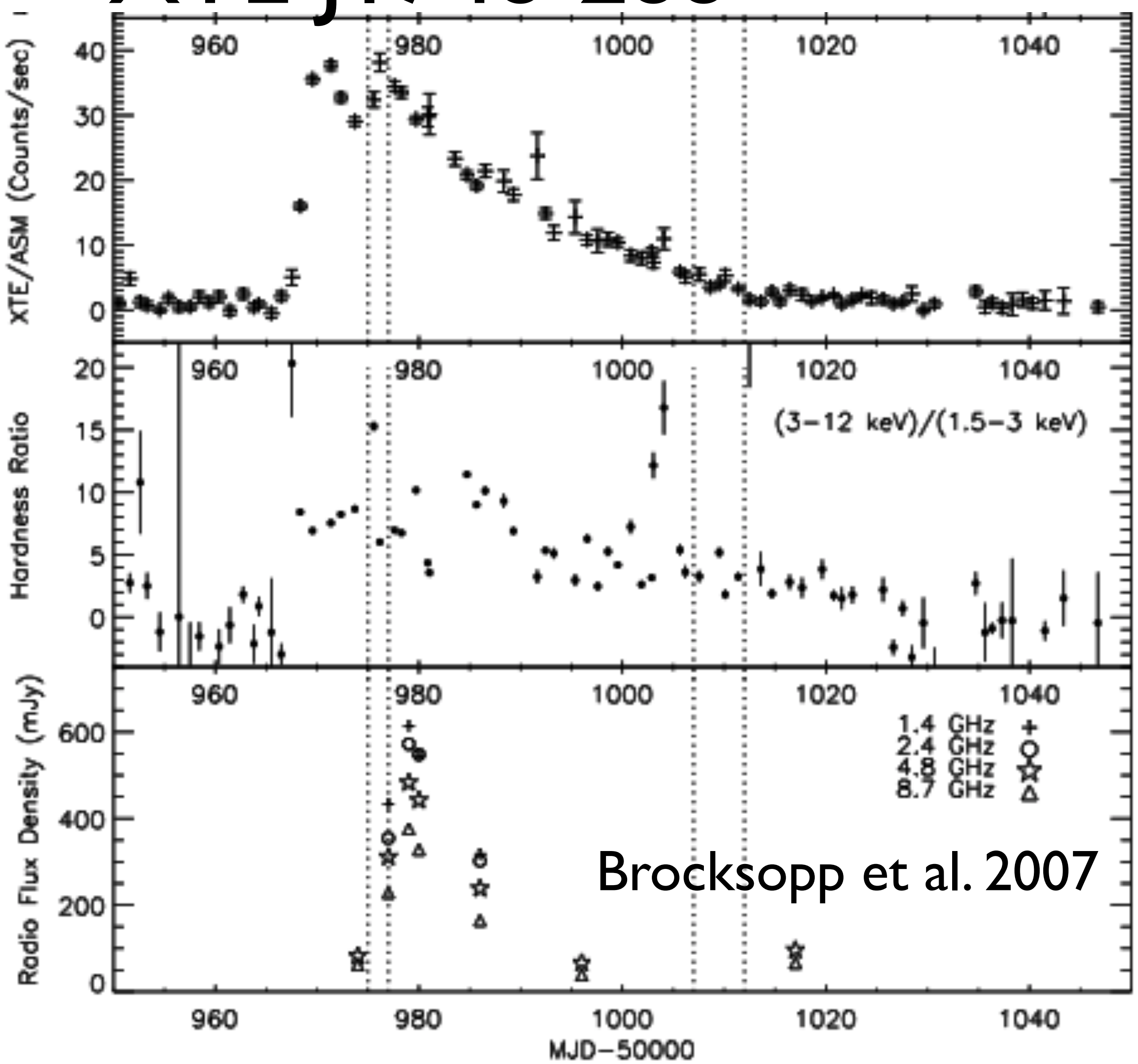
Outbursts



Note: the full dynamic range is even greater!
log(L-max) = 39, log(L-min) = 31.
Reynolds & Miller 2012
Absorbed Flux$_{0.6-10.0\ keV}$ [erg s^{-1} cm^{-2}]
Time [MJD]
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
1e-13
53000
53500
54000
54500
55000
55500
56000
Cyg X-1
LMC X-1
Cyg X-3
IC10 X-1
LMC X-3
M33 X-7
NGC300 X-1
SS433
GRO J1655-40
GRS 1915+105
GX 339-4
SAX J1819
1E 1740.7-2942
4U 1630-47
GRS 1758-258
H 1743-322
4U 1957+11
SLX 1746-331
IGR J17091
IGR J17098-3628
IGR J17497-2821
SWIFT J1539-6277
SWIFT J1753.5-0127
SWIFT J1842-1124
XTE J1652-453
XTE J1752-223
XTE J1817-330
XTE J1818-245
XTE J1856+053

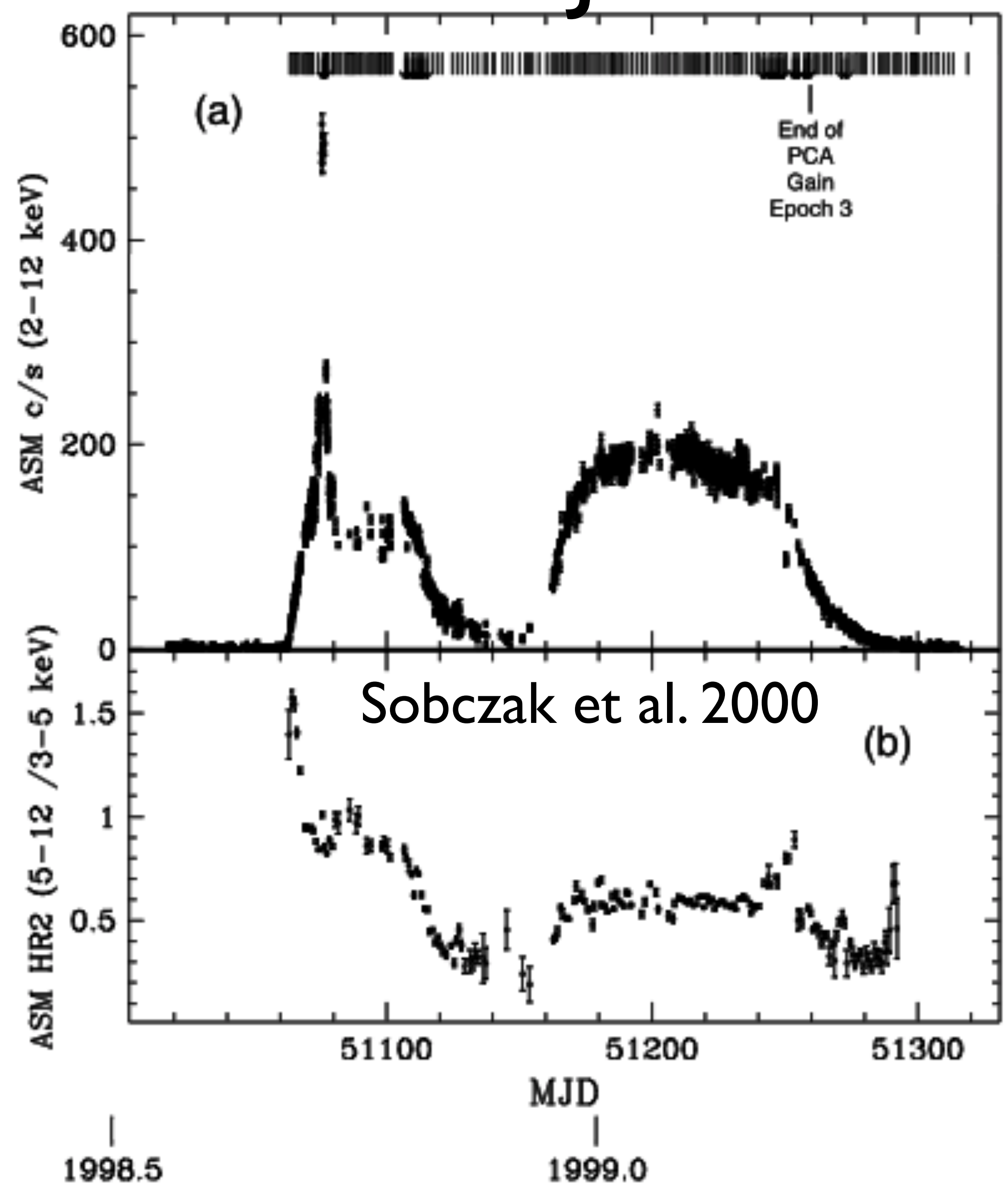
Two general flavors

XTE J1748-288



"FRED"

XTE J1550-564



Not FRED

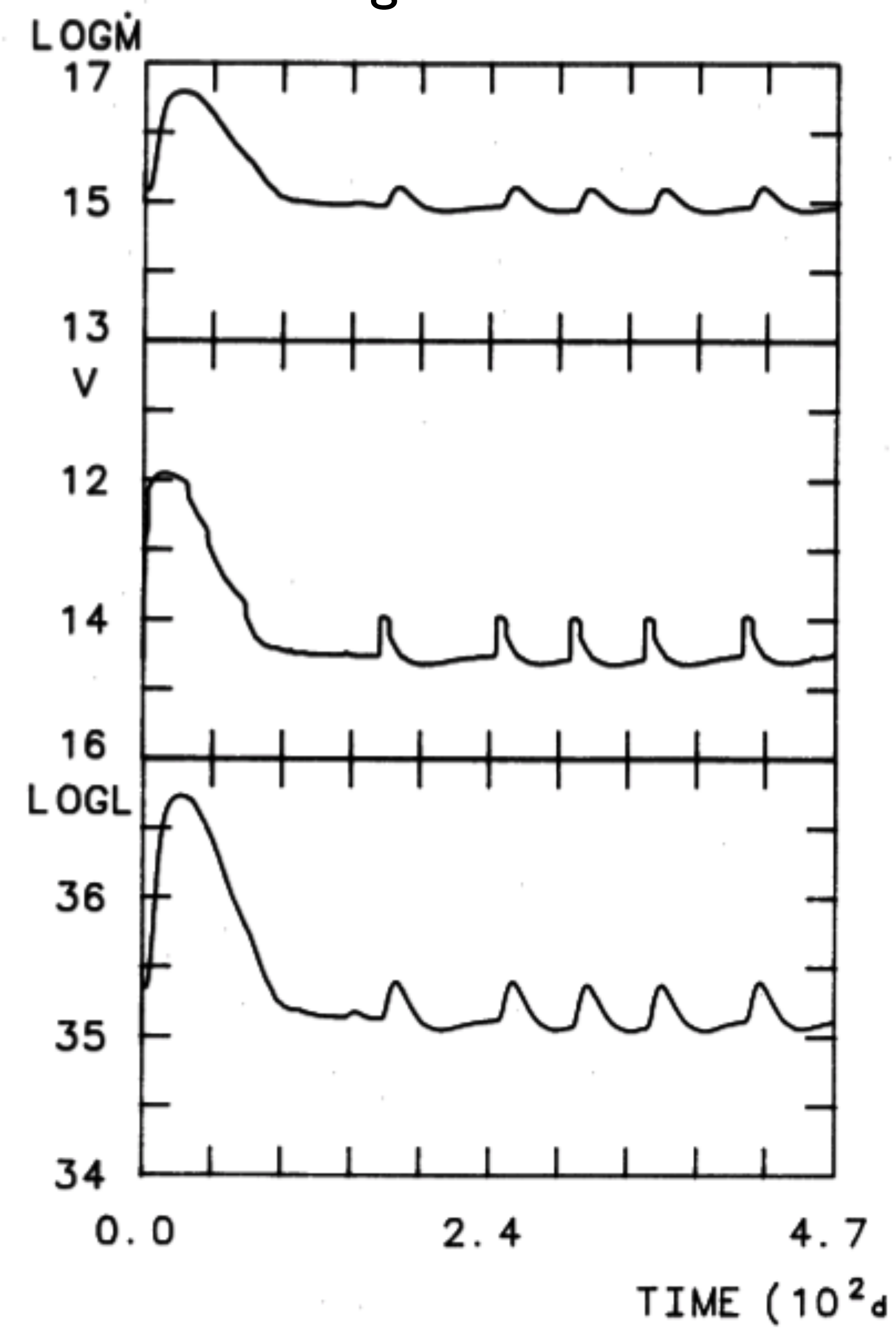
Outburst profiles

- Spread of FRED vs OTHER is about 50/50.
- The same source can show both types.
- The viscous timescale through the entire disk in a P = 1 day binary is about 20 days.
- Outbursts do evolve on that timescale.
- Some outbursts show less evolution, but they are typically short and weak.

Disk Instability Model

- Such models are partly based on those for dwarf novae.
- A quiescent, truncated disk experiences a thermal instability.
- Accretion becomes possible, and matter begins to accrete, filling in the inner accretion disk.
- There are many many details, including irradiation, but the basic picture endures.

Mineshige & Wheeler 1989



States

some good references:

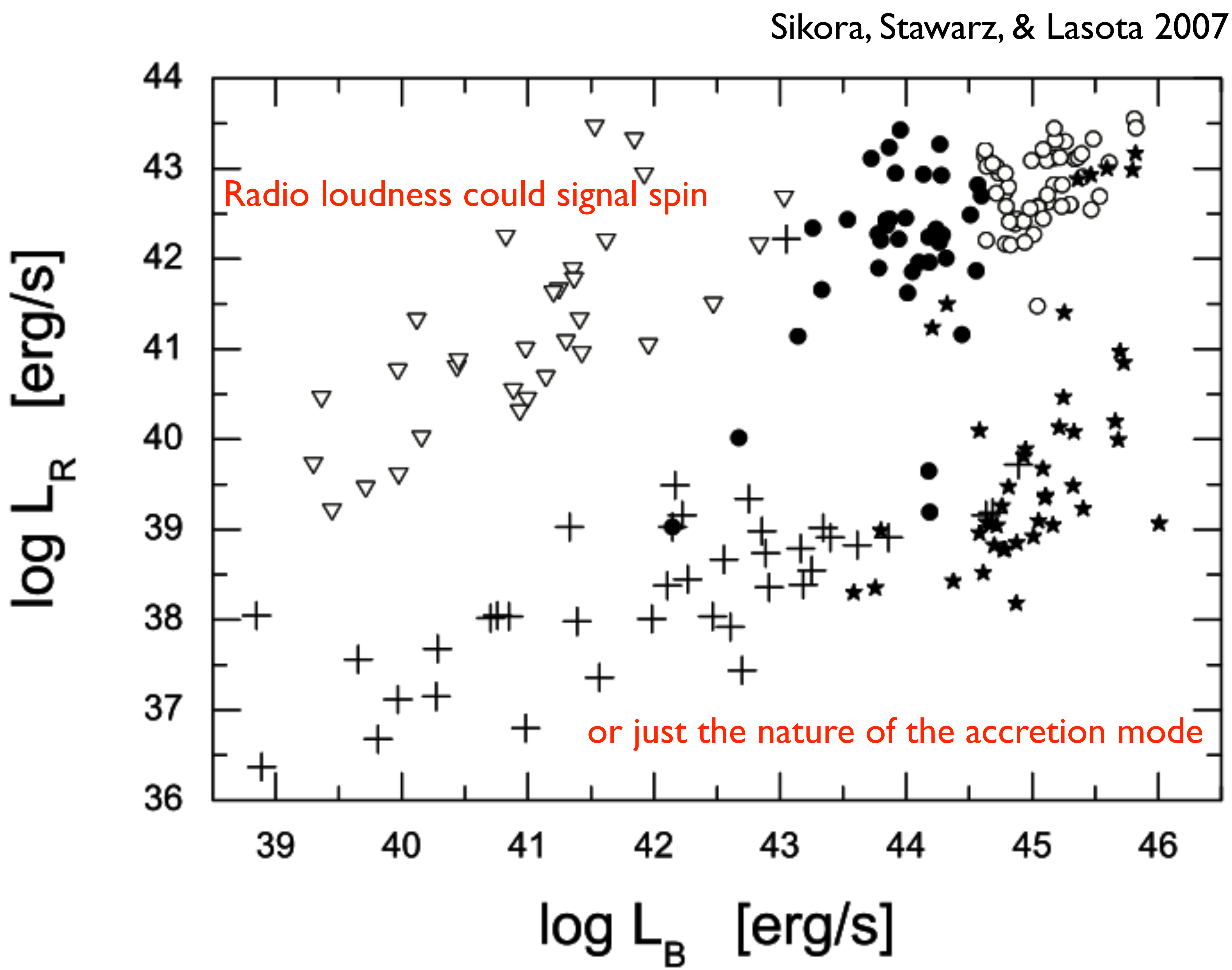
Esin, A. , McClintock, Narayan, 1997, ApJ, 489, 865
Gallo, E., Fender, Pooley, 2003, MNRAS, 344, 60
Homan, J., et al., 2000, ApJS, 132, 377
Markoff, S., Falcke, Fender, 2001, A&A, 372, L25
Remillard, R., McClintock, 2006, ARA&A, 44, 49
Zdziarski, A., et al., 2004, MNRAS, 351, 791

Black Hole States:

- States are, at some level, a hold-over from the early days of X-ray astronomy.

- But, states might be fundamental:

- They may signal different accretion flows.
- States may tell us about AGN modes.


Sikora, Stawarz, & Lasota 2007
Radio loudness could signal spin
or just the nature of the accretion mode
log L_R [erg/s]
log L_B [erg/s]
44
43
42
41
40
39
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37
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42
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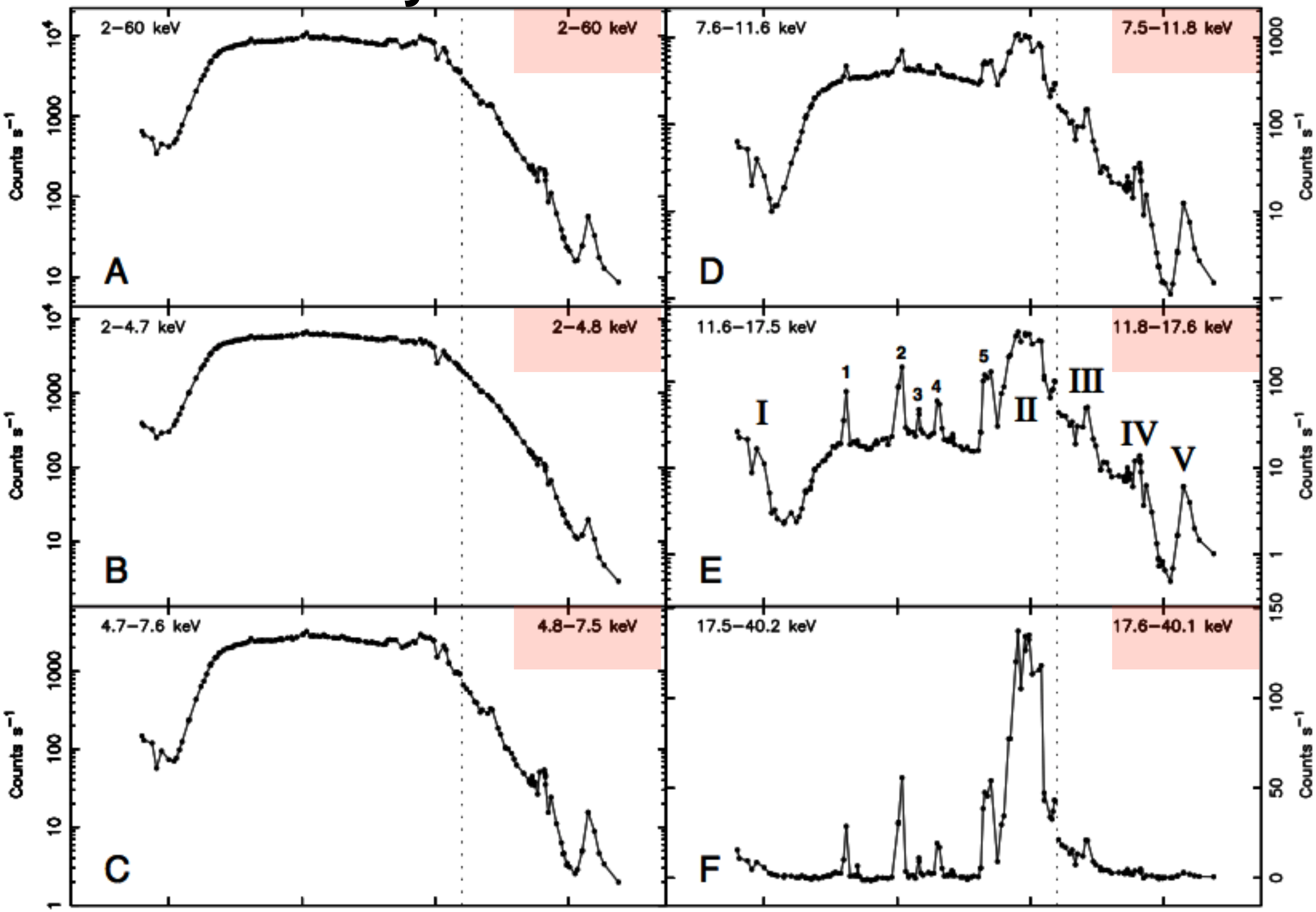
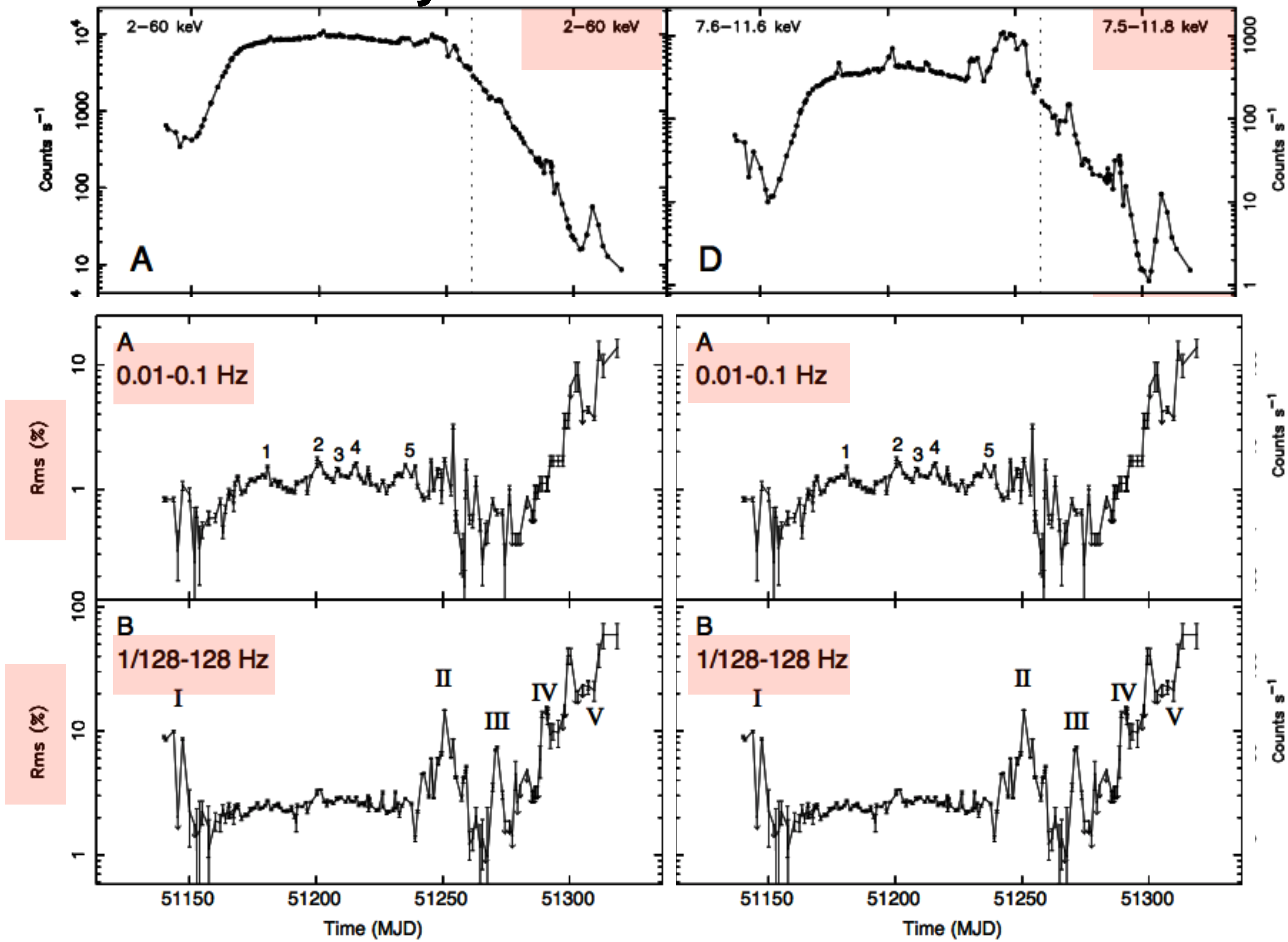
44
45
46

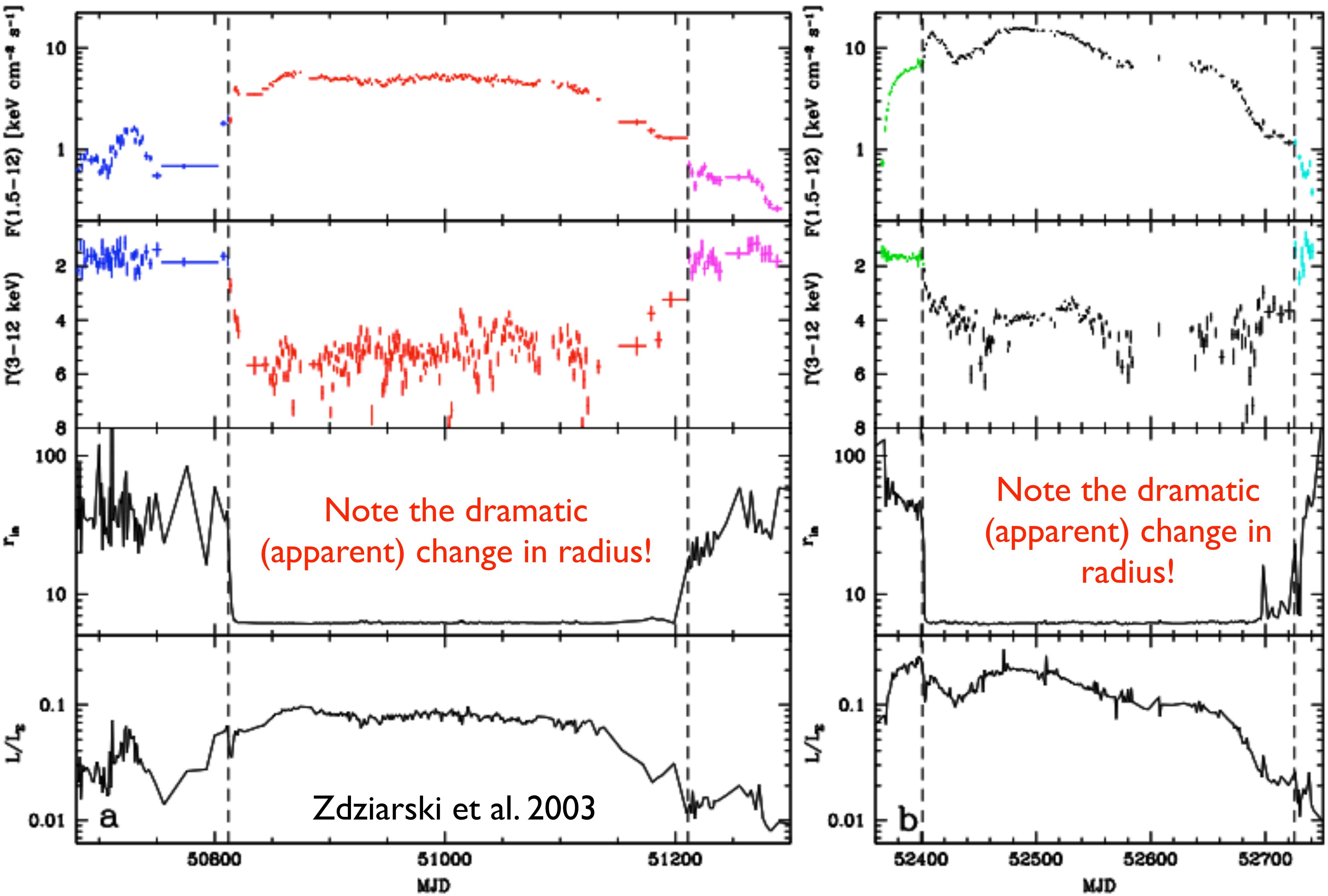
XTE J1550-564 in 1998/1999



XTE J1550-564 in 1998/1999

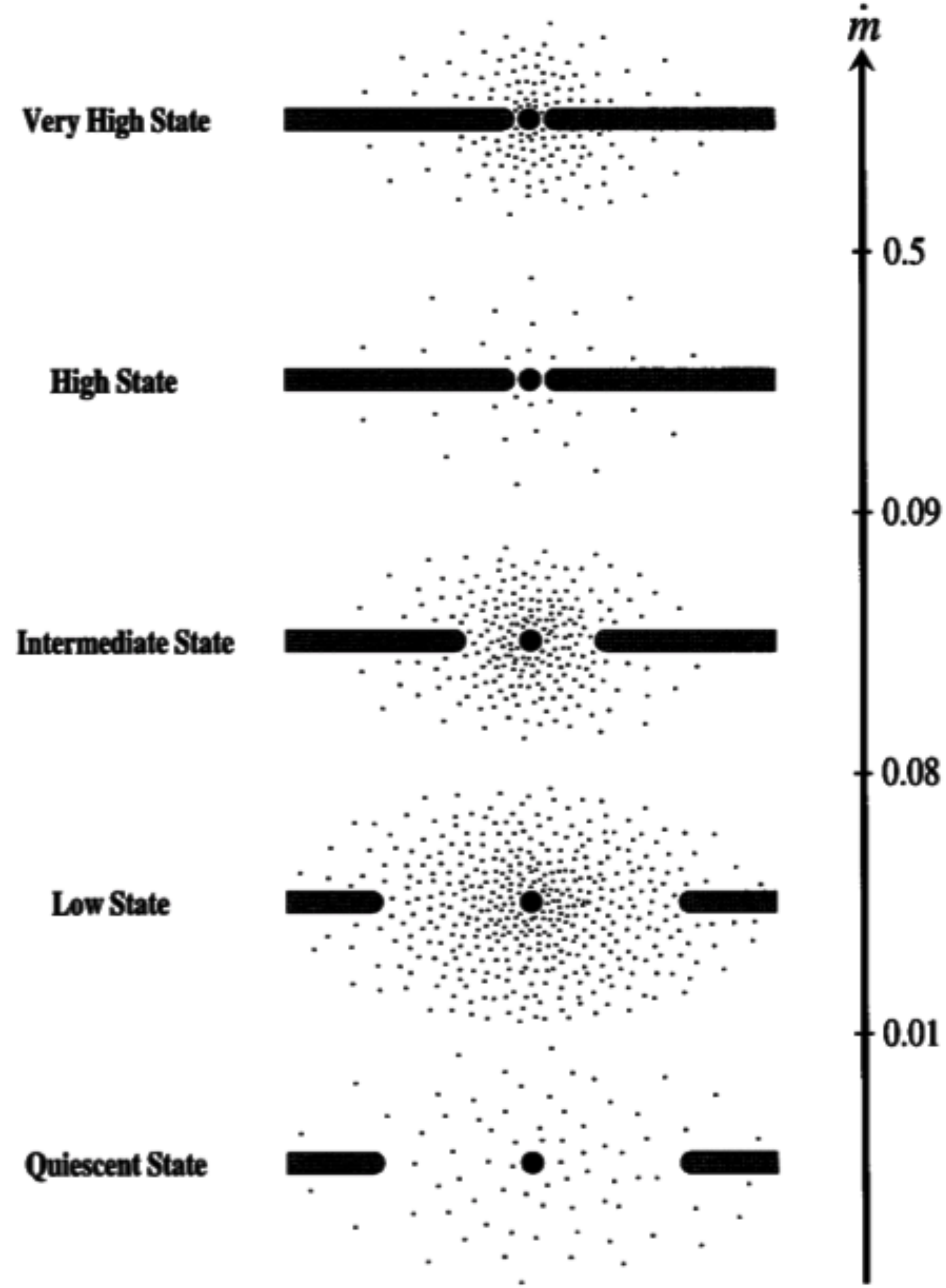


GX 339-4 (2 outbursts)



- States represent changes in flux, spectral, *and* timing properties (but, detector bias).
- These quantities are not a set of orthogonal basis vectors.
- Fractional variability is positively correlated with hard flux. (RMS-flux relationship.)
- Disks are cooler at high flux levels; Comptonizing coronae are cooler.

Something of a paradigm (Esin++ 97).



Some problems:

- Homan et al. 2001, & others since:
  states do not depend only on m-dot.
- *Jets* are also important, and appear to be dependent on the black hole state.
- Perhaps - *perhaps* - jet production (or some aspect thereof) is another parameter that drives state transitions.

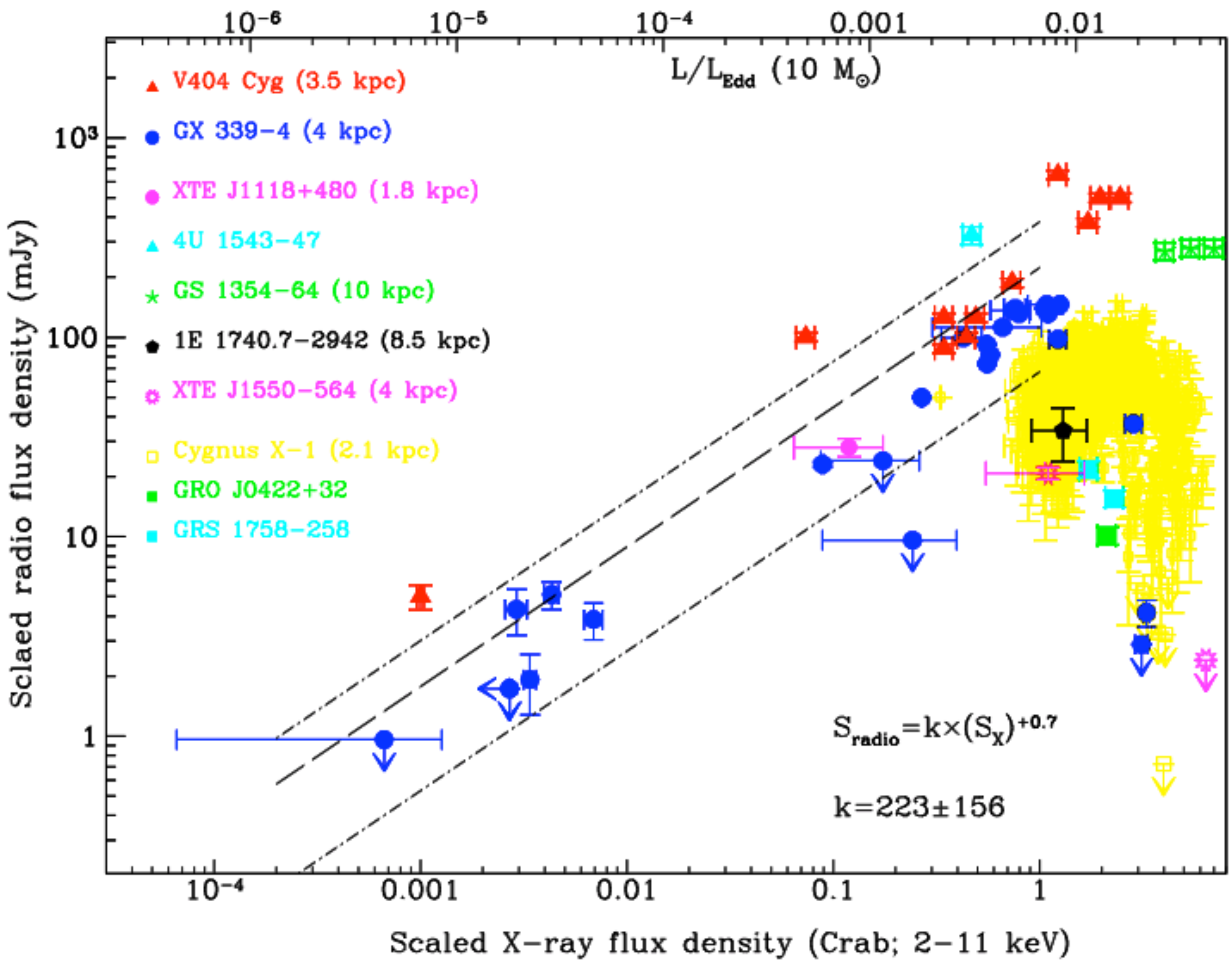
On the role of jets:

In what states to jets operate?

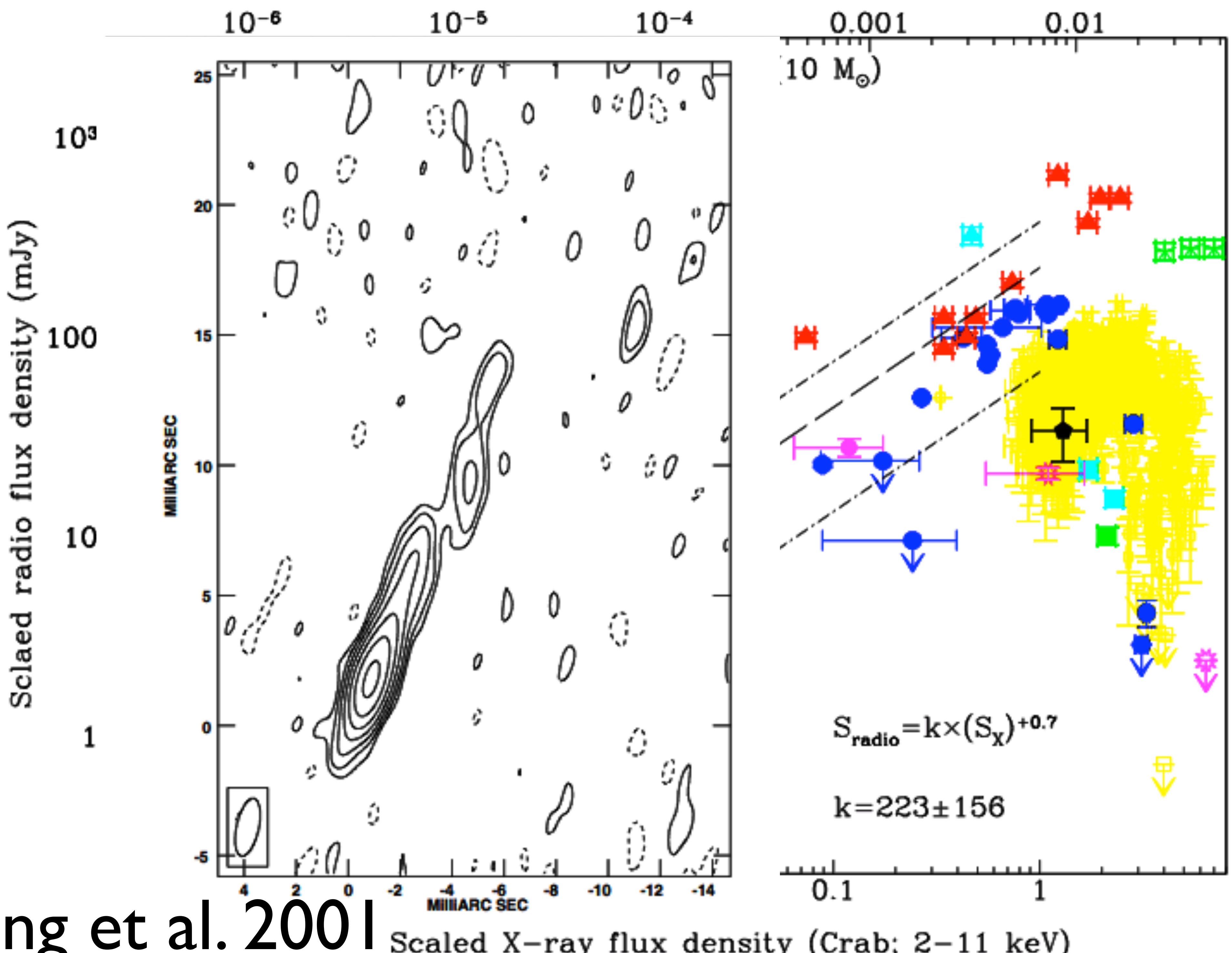
What is their contribution to SEDs?

What is required of the disk?

Gallo, Fender, & Pooley 2003

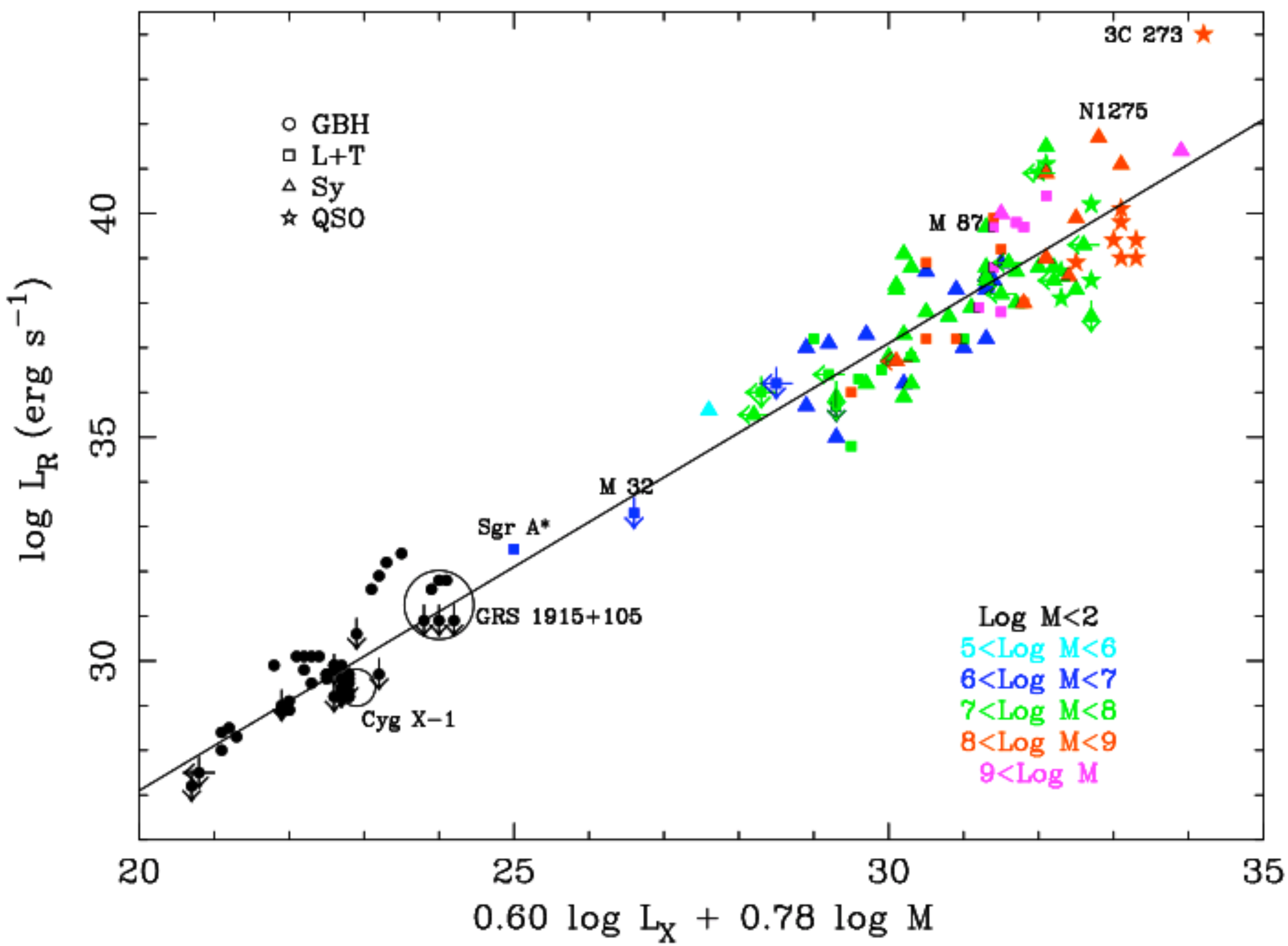


Gallo, Fender, & Pooley 2003

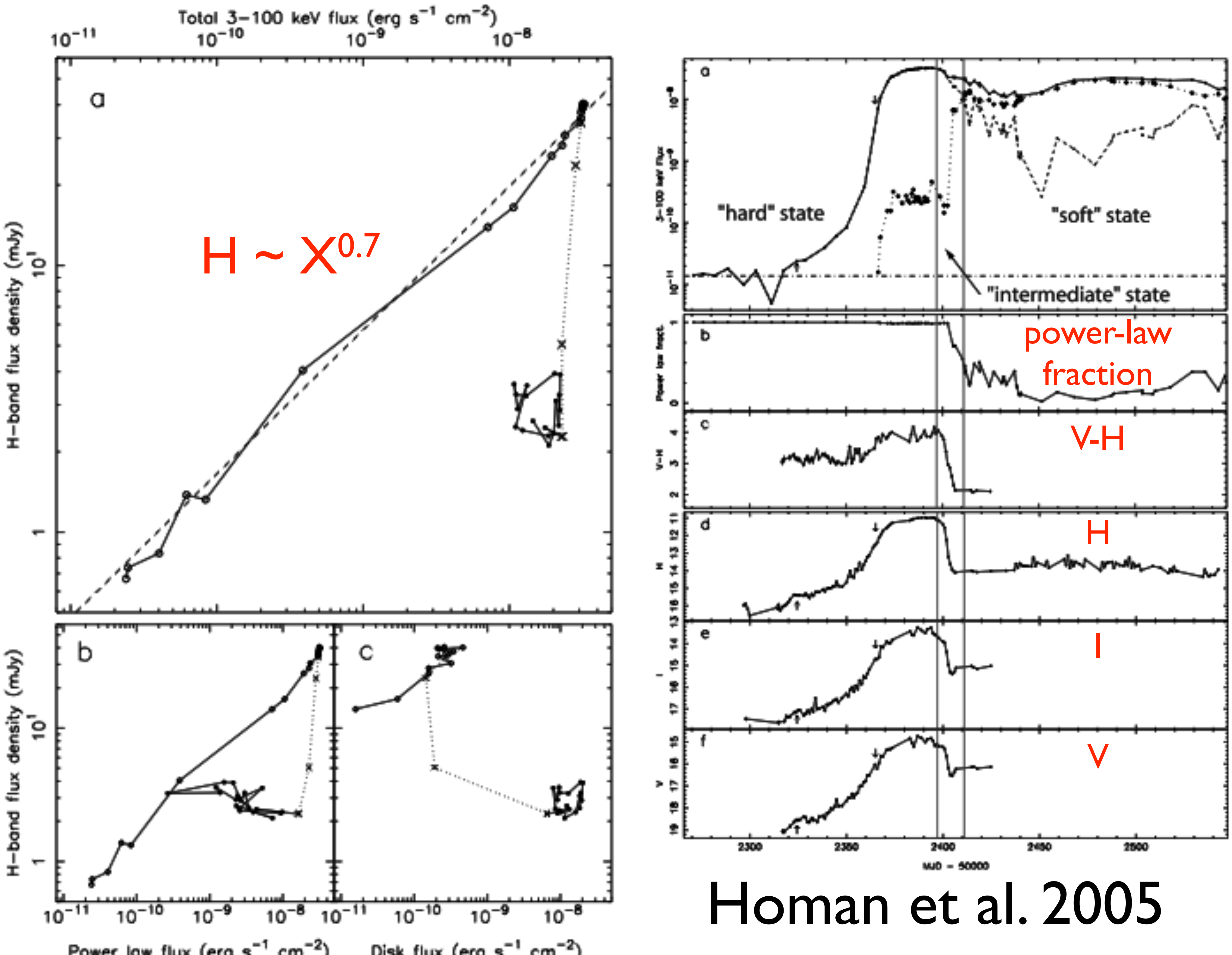


Stirling et al. 2001

Merloni, Heinz, & Di Matteo 2003

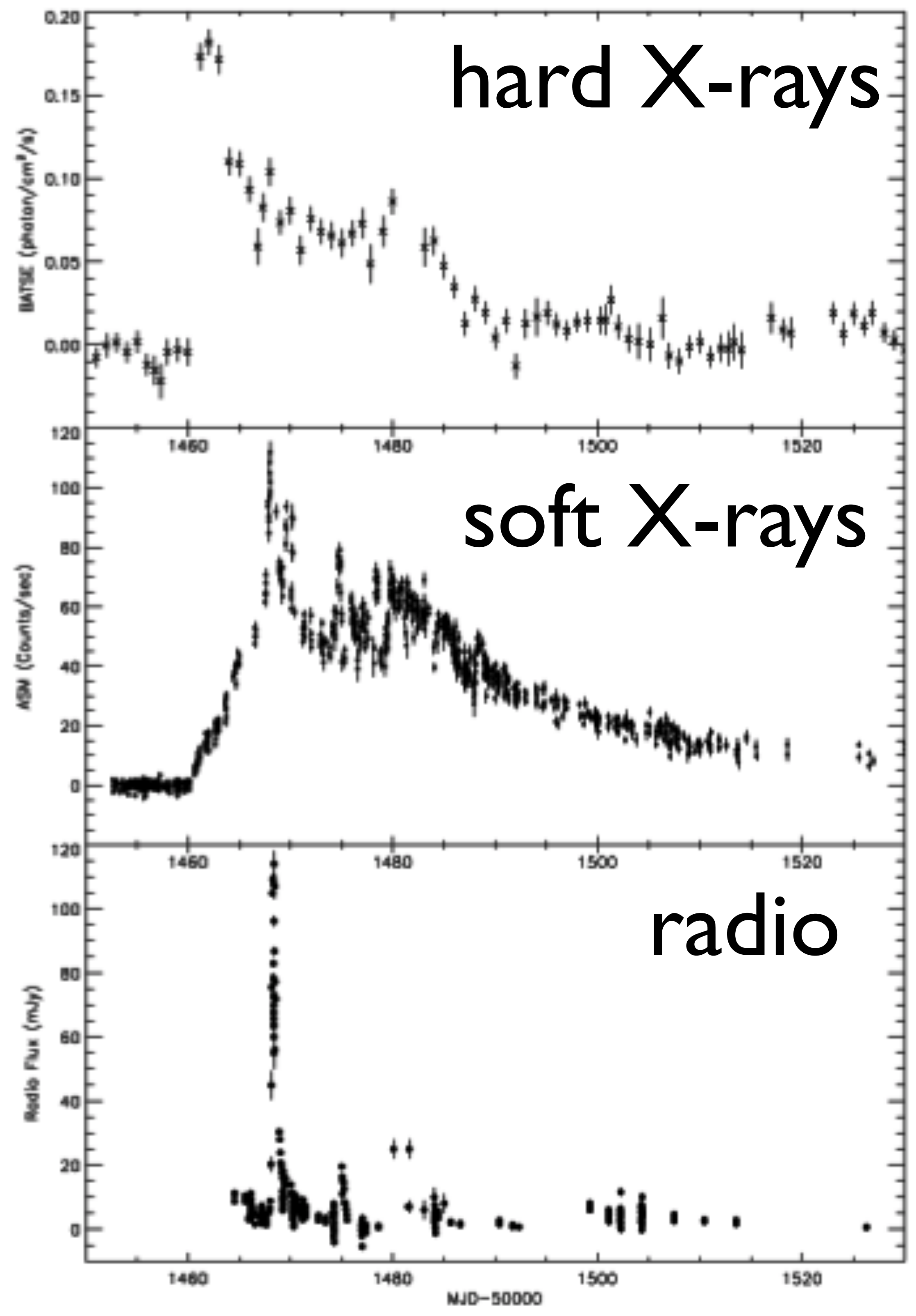


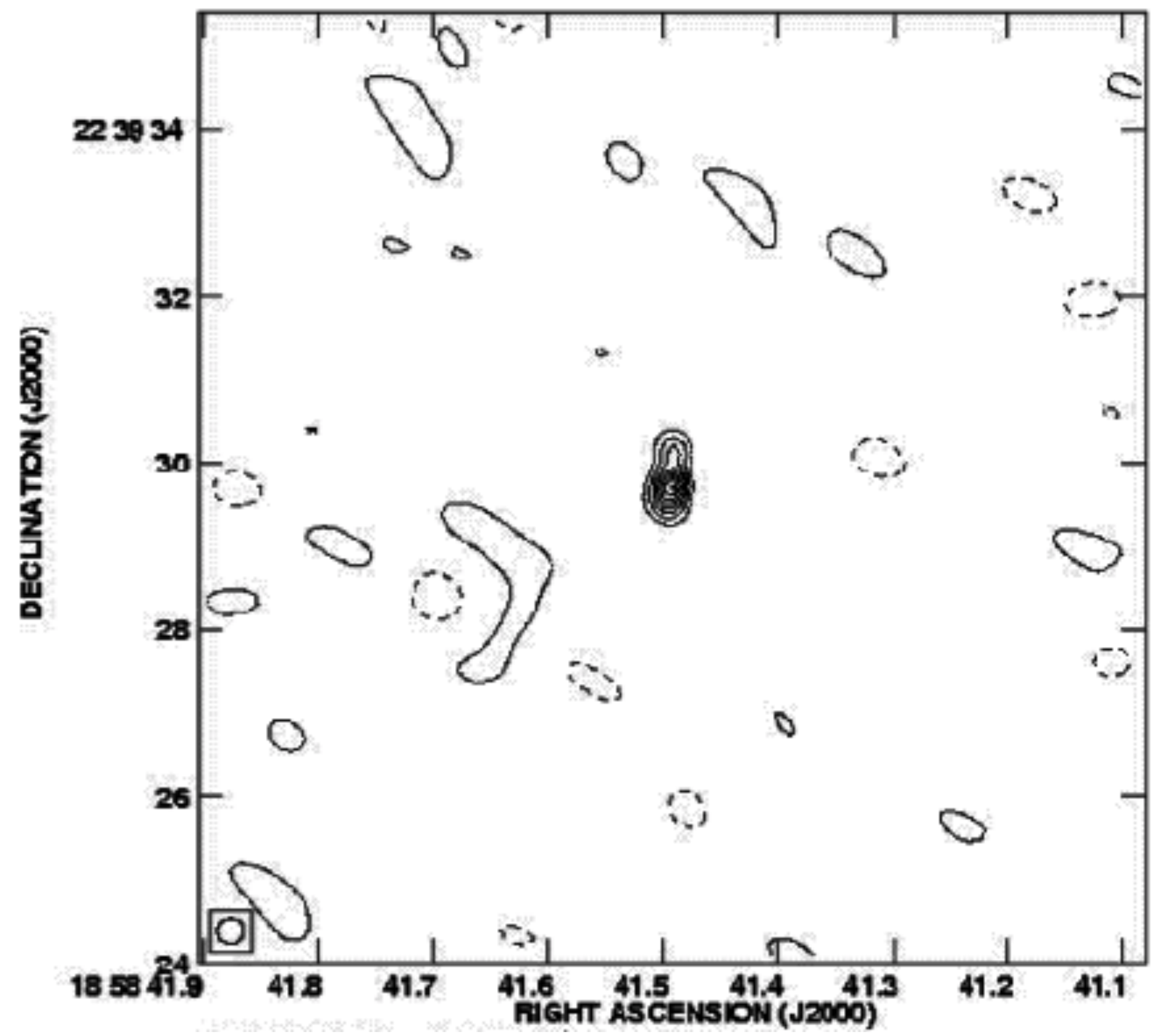
IR from jet synchrotron



Homan et al. 2005

Cannonballs & transitions?





XTE J1859+226
Brocksopp et al. 2002

On disk evolution

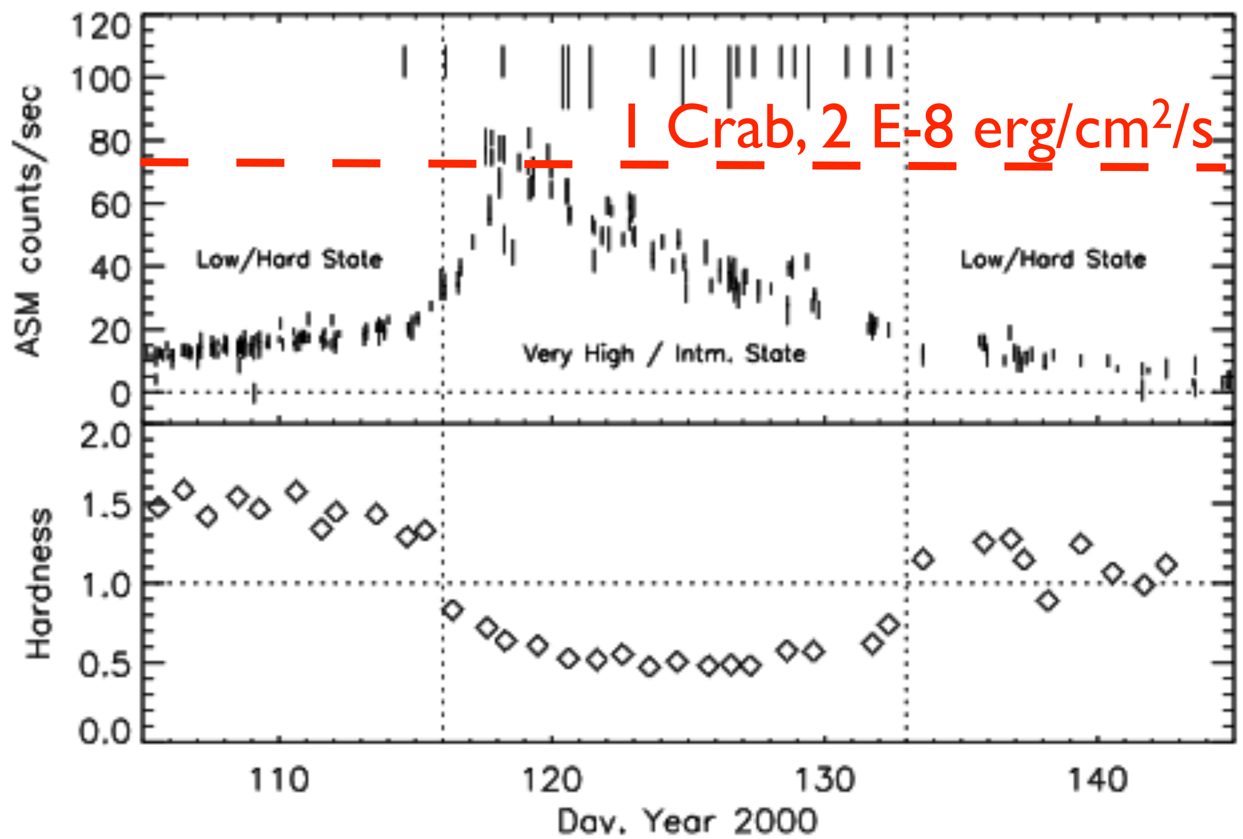
Over what range can thin disks operate?
--> Timing, continuum spectra, line spectra.

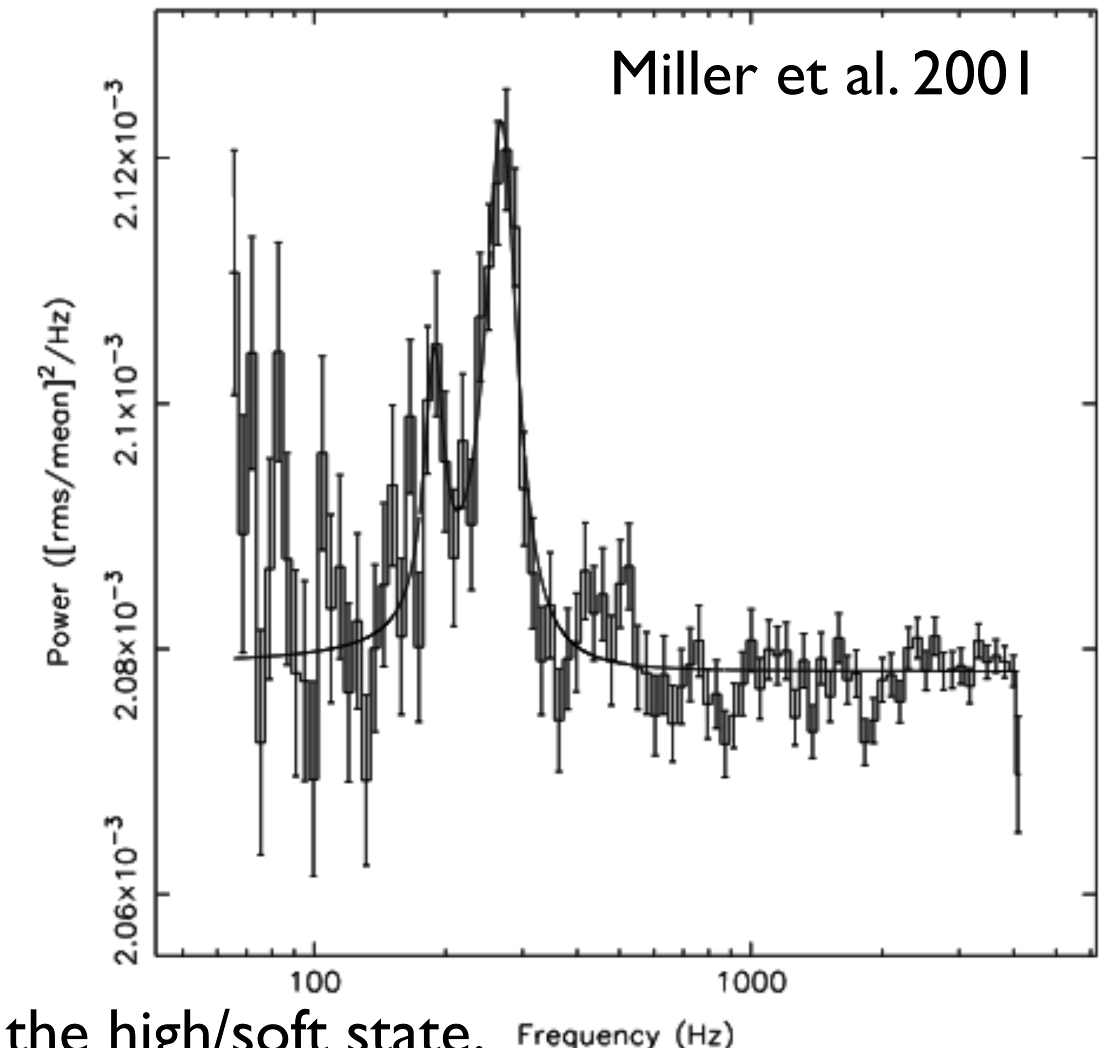
At what Eddington fraction do they truncate?

How do disks and jets relate?

Timing

XTE J1550-564

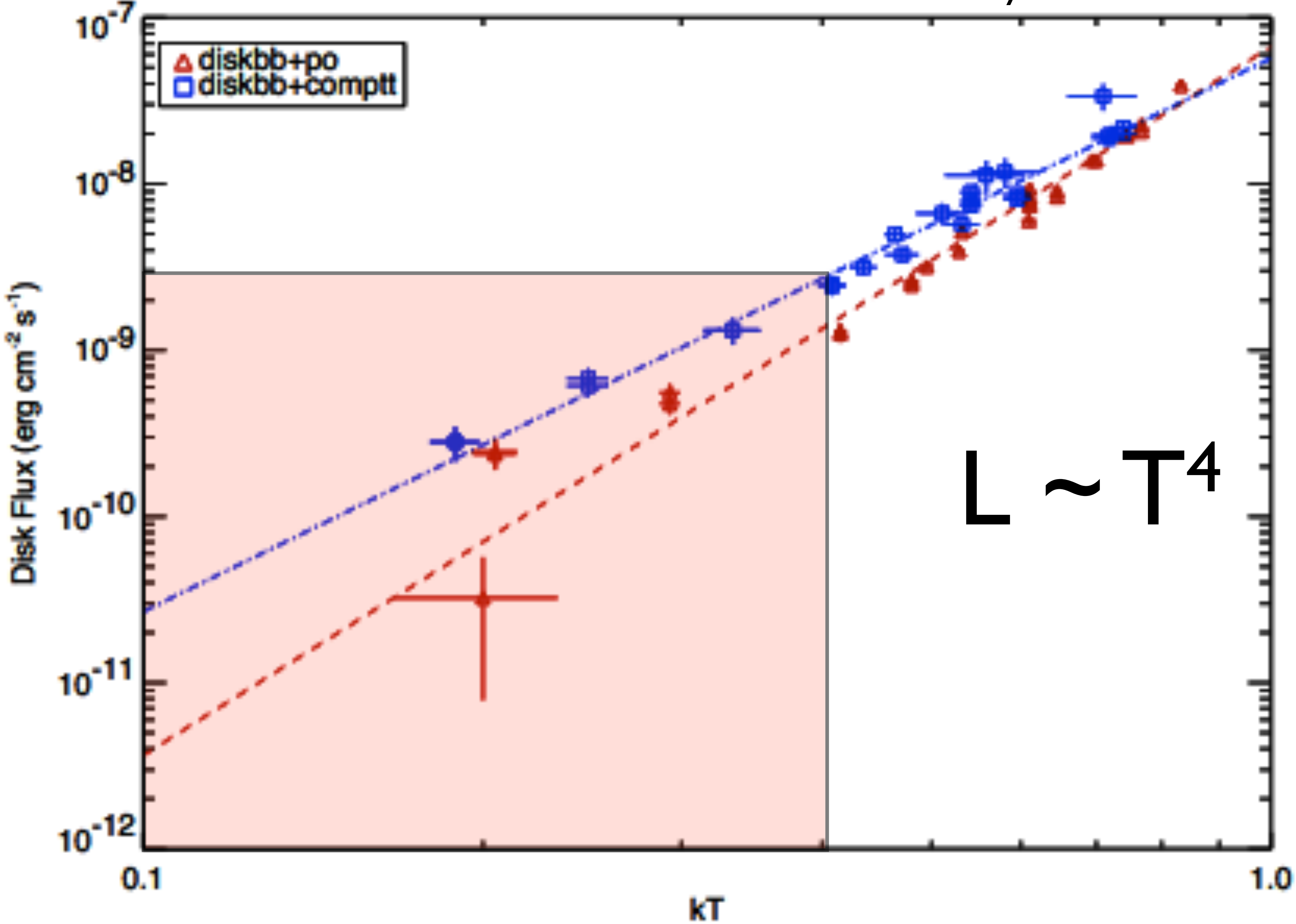




- Band-limited noise is only seen outside of the high/soft state.
- The high/soft state is strictly 1/f noise, if present at all.
- High frequency (ISCO-like) QPOs: only in very high and intermediate states. This could be a S/N issue.
- QPOs are spectrally hard. A very non-disk-like energy dependence.

Swift Obs. of XTE J1817

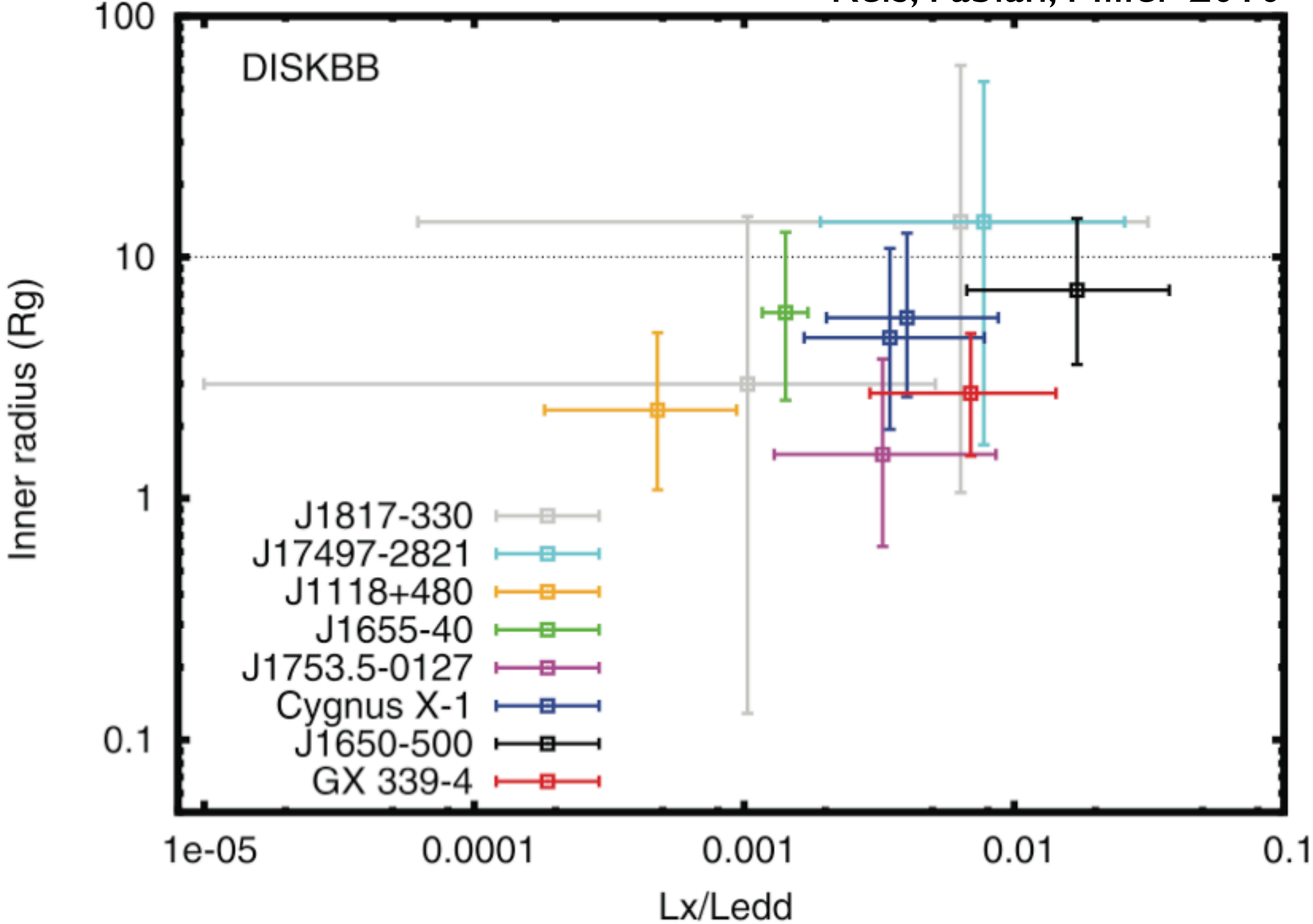
Rykoff et al. 2007



No strong evidence of disk truncation.

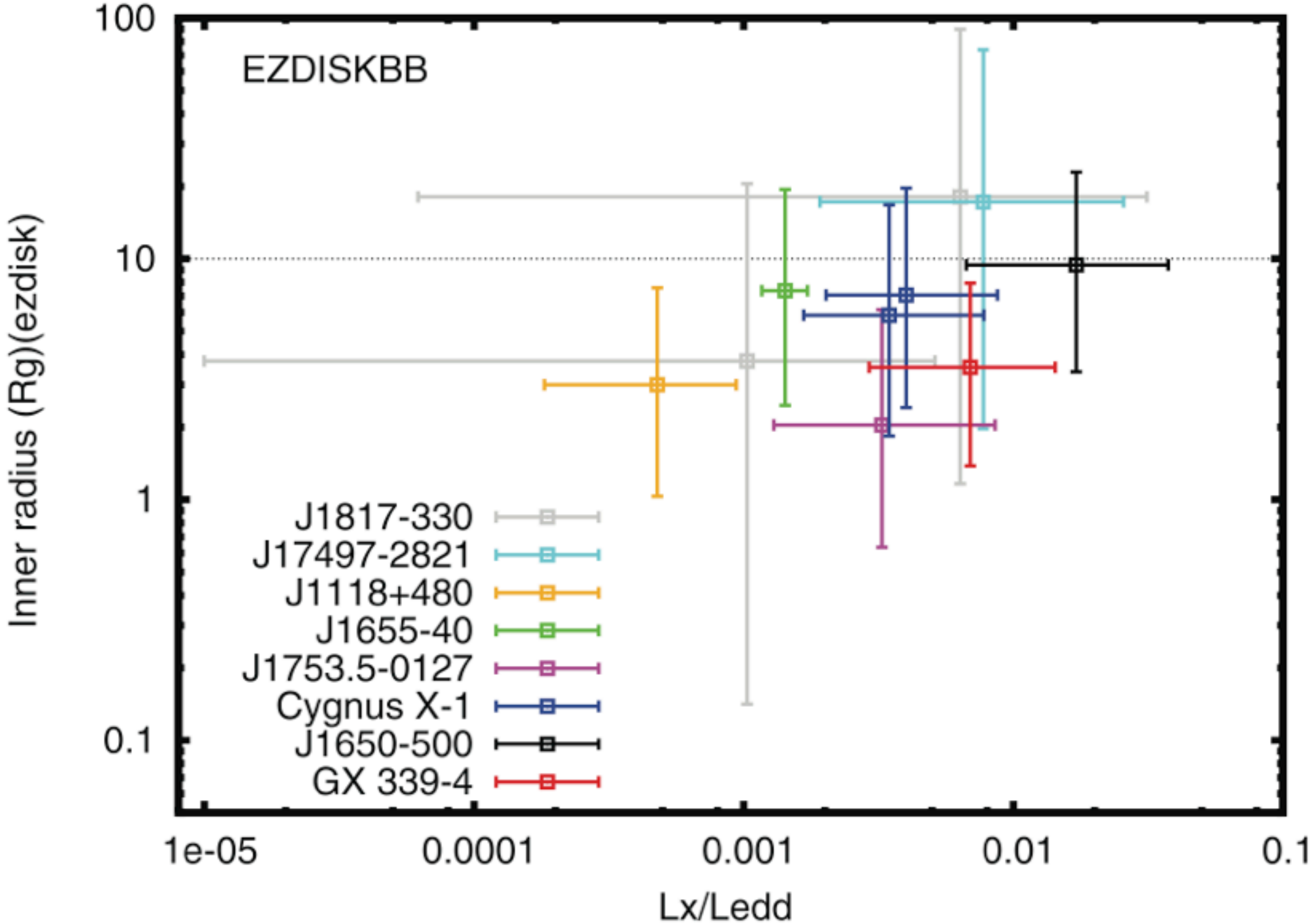
Disks at Low L/L_{Edd}

Reis, Fabian, Miller 2010

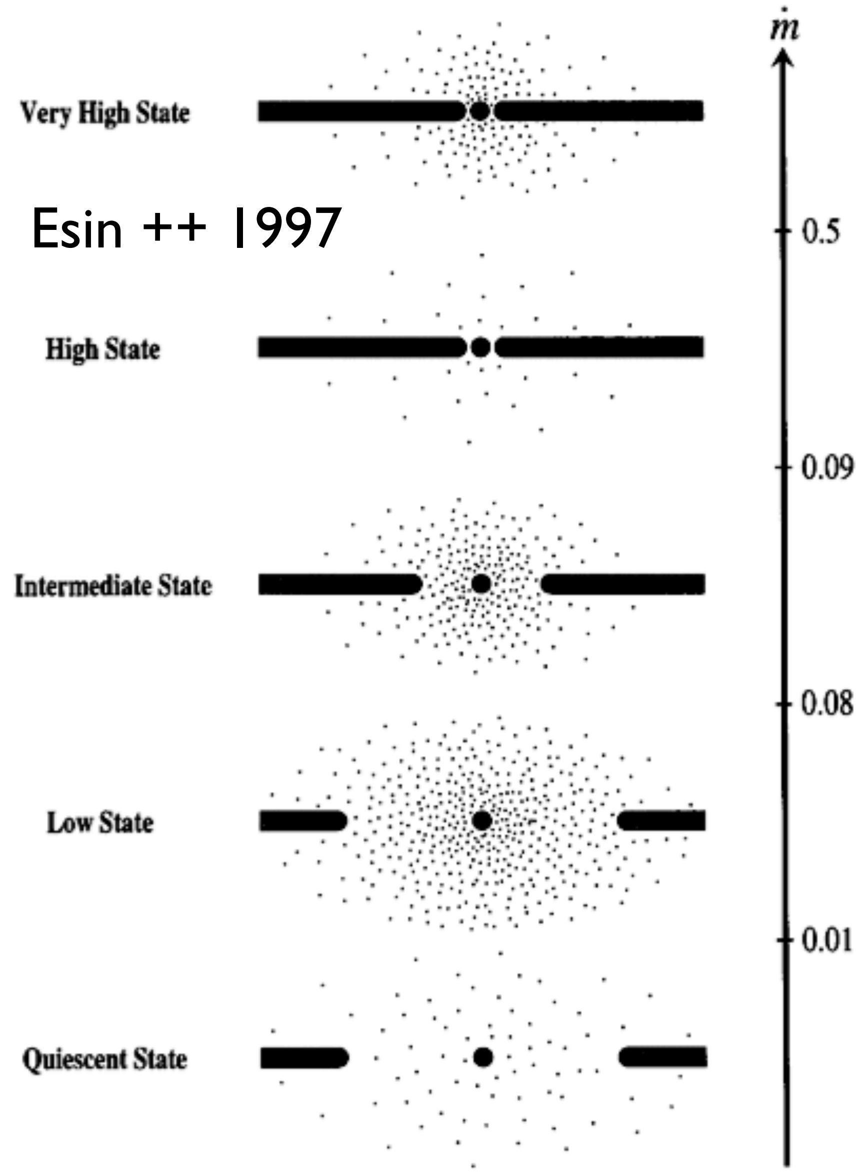


Systematic Study

Reis, Fabian, Miller 2010

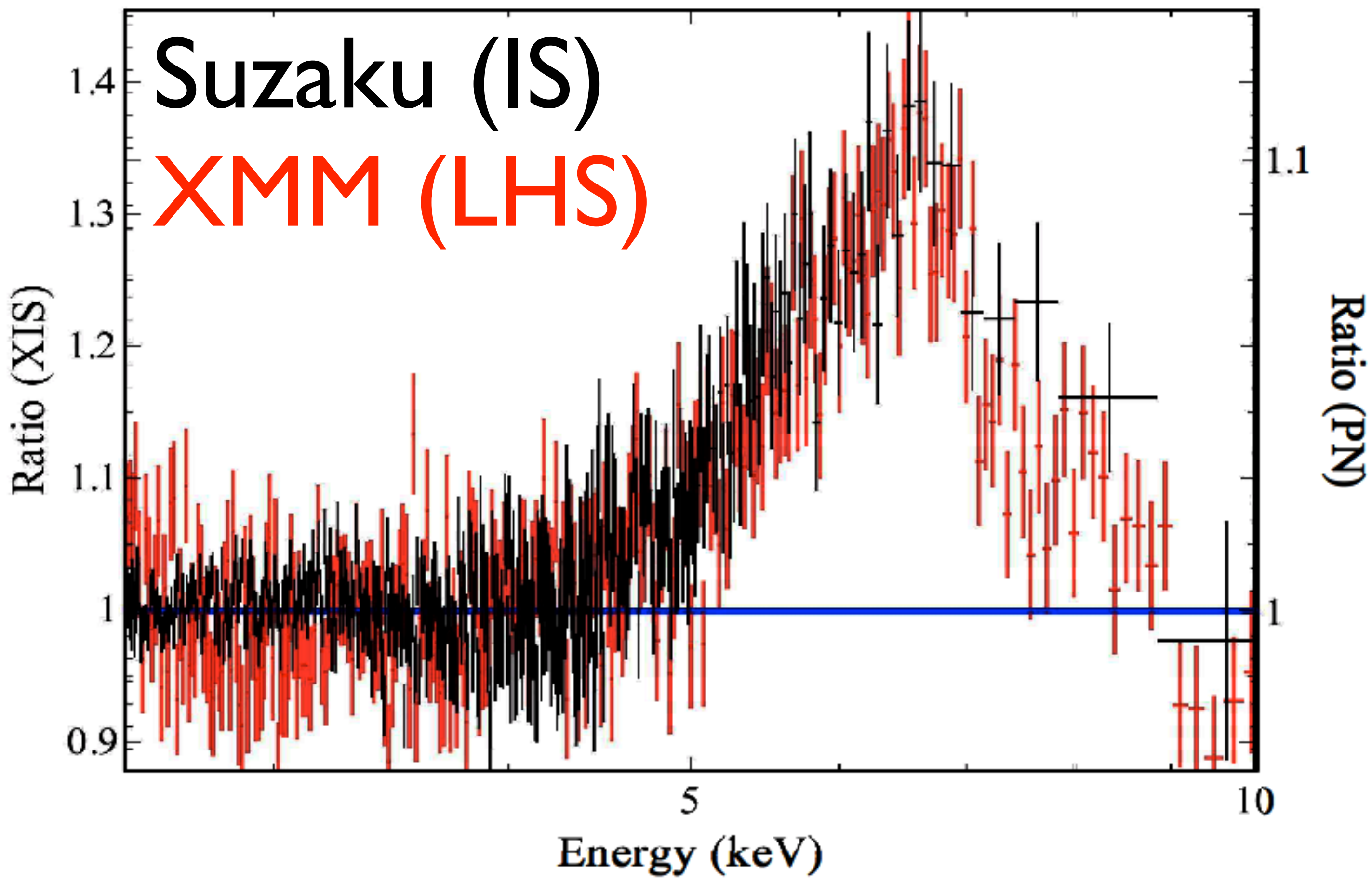


Spin in XTE J1752-223



Esin ++ 1997

Reis et al. 2011

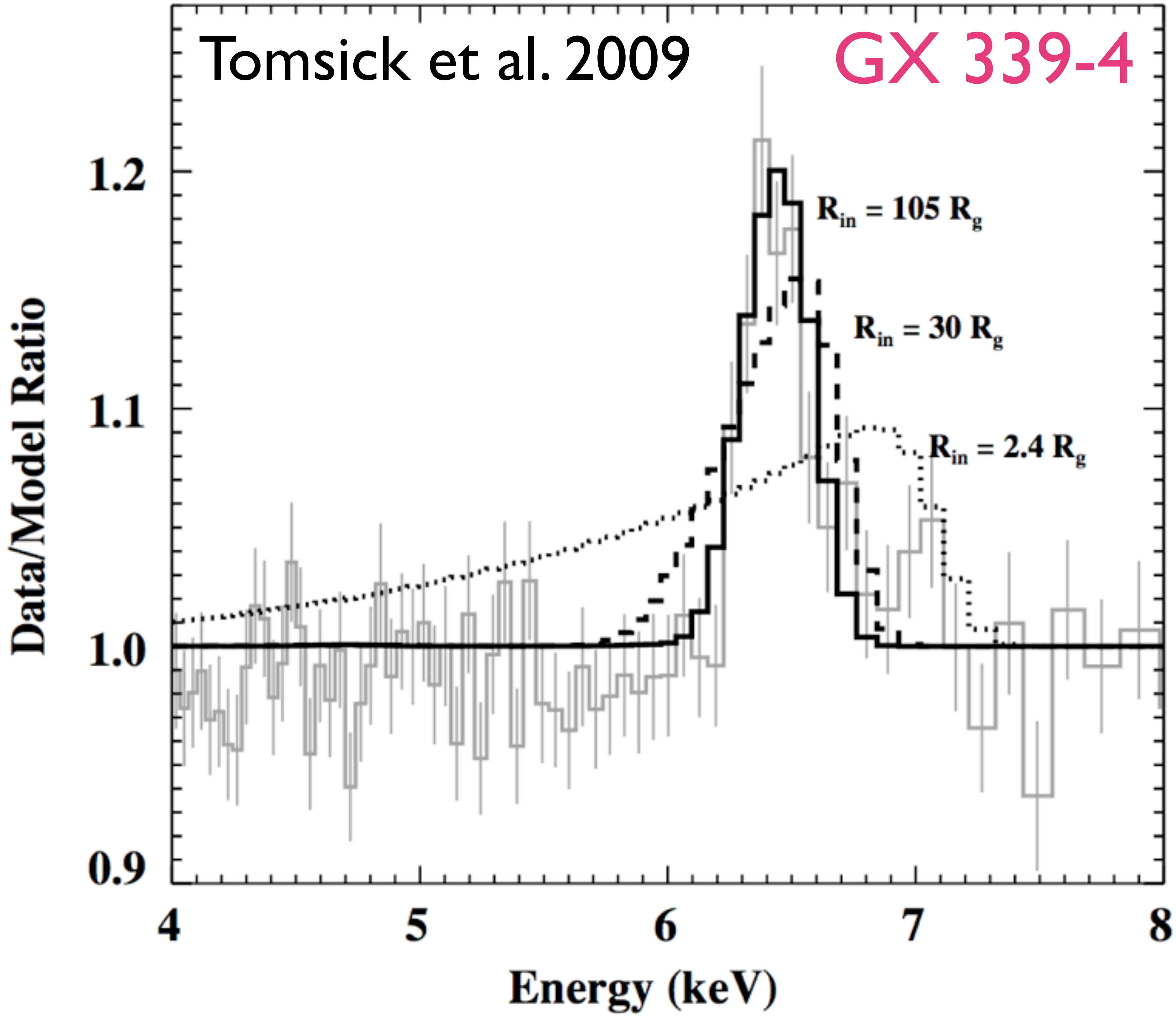


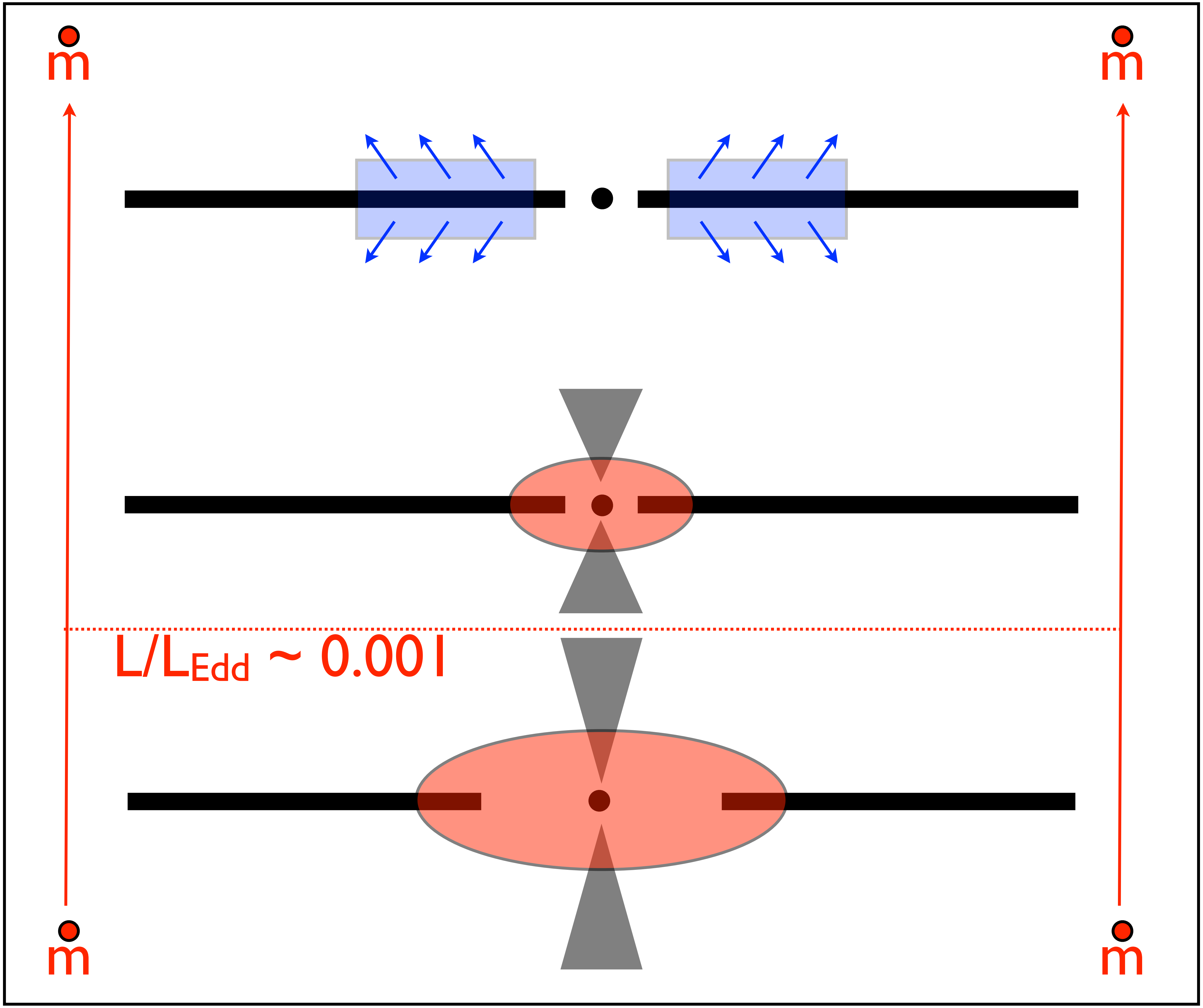
Intermediate State (Suzaku), low/hard state (XMM).

Blurred reflection fits: a/M = 0.52 +/- 0.11.

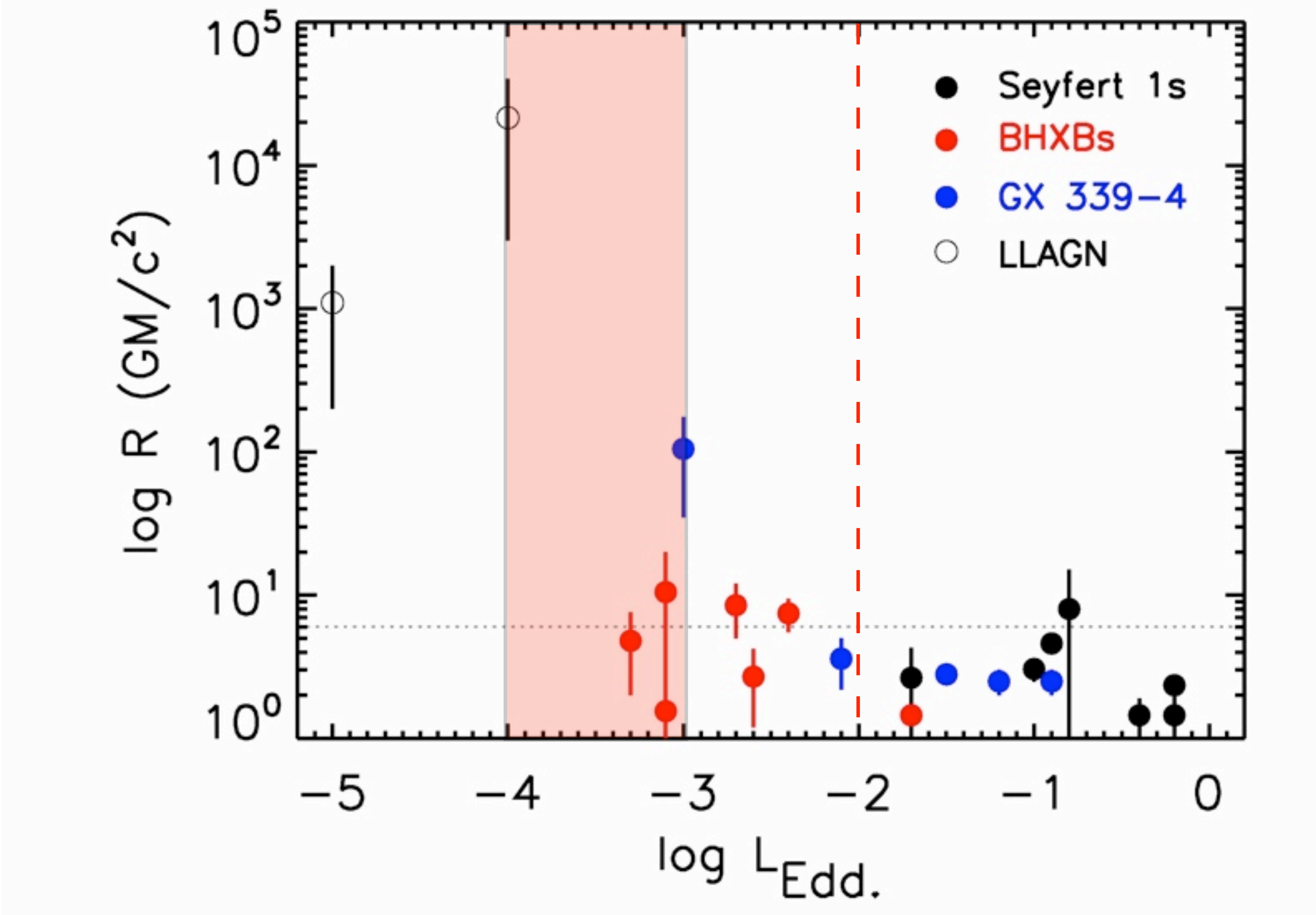
Strong implications for accretion flow models.

Truncation ... at last




ṁ
ṁ
L/LEdd ~ 0.001
ṁ
ṁ

Where the disk-->ADAF transition occurs?



– -

Summary

- There are periods of correlated multi-wavelength behavior in every stellar-mass black hole system.
- These do appear to be distinctive accretion modes, very relevant to AGN.
- Compact, steady jets are ubiquitous in the low/hard state.
- Jets are quenched in the high/soft state, where the corona is minimal.
- Jets can contribute at least into the IR; perhaps higher.
- The accretion disk is likely at, or near to, the innermost stable circular orbit in all phases where log(Edd) > -3, regardless of the state label.
- Below that, a standard thin disk likely gives way to an advective disk.
- Jet production does not require a truncated disk.

X-ray Spectra

- Disk Continua
- Disk Reflection
- Disk Winds
- Coronae

QPOs: [orbital?] flux modulations.

Blackbody disk continuum.

Relativistic line spectroscopy.

Thermal disk continua

- Model the disk as a series of blackbody annuli

$$F \sim \sigma T^4 r^2$$

- For any internal viscosity prescription, including MRI, the dissipation with radius will be:

$$D(R) = \frac{3GM\dot{M}}{8\pi R^3}$$

- Correct for the fact that torques must vanish at the ISCO:

$$D(R) = \frac{3GM\dot{M}}{8\pi R^3}\left[1 - \left(\frac{R_{\rm in}}{R}\right)^{1/2}\right]$$

- So, for a standard thin disk, far from the ISCO,

$$T \sim R^{-3/4}$$

- And working in R_g one can also show that:

$$T \sim M^{-1/4}$$

Problems, corrections

The disk model that is most widely used ("diskbb"; Mitsuda et al. 1984) does not include the inner torque condition.

$$D(R) = \frac{3GM\dot{M}}{8\pi R^3}\left[1 - \left(\frac{R_{\rm in}}{R}\right)^{1/2}\right]$$

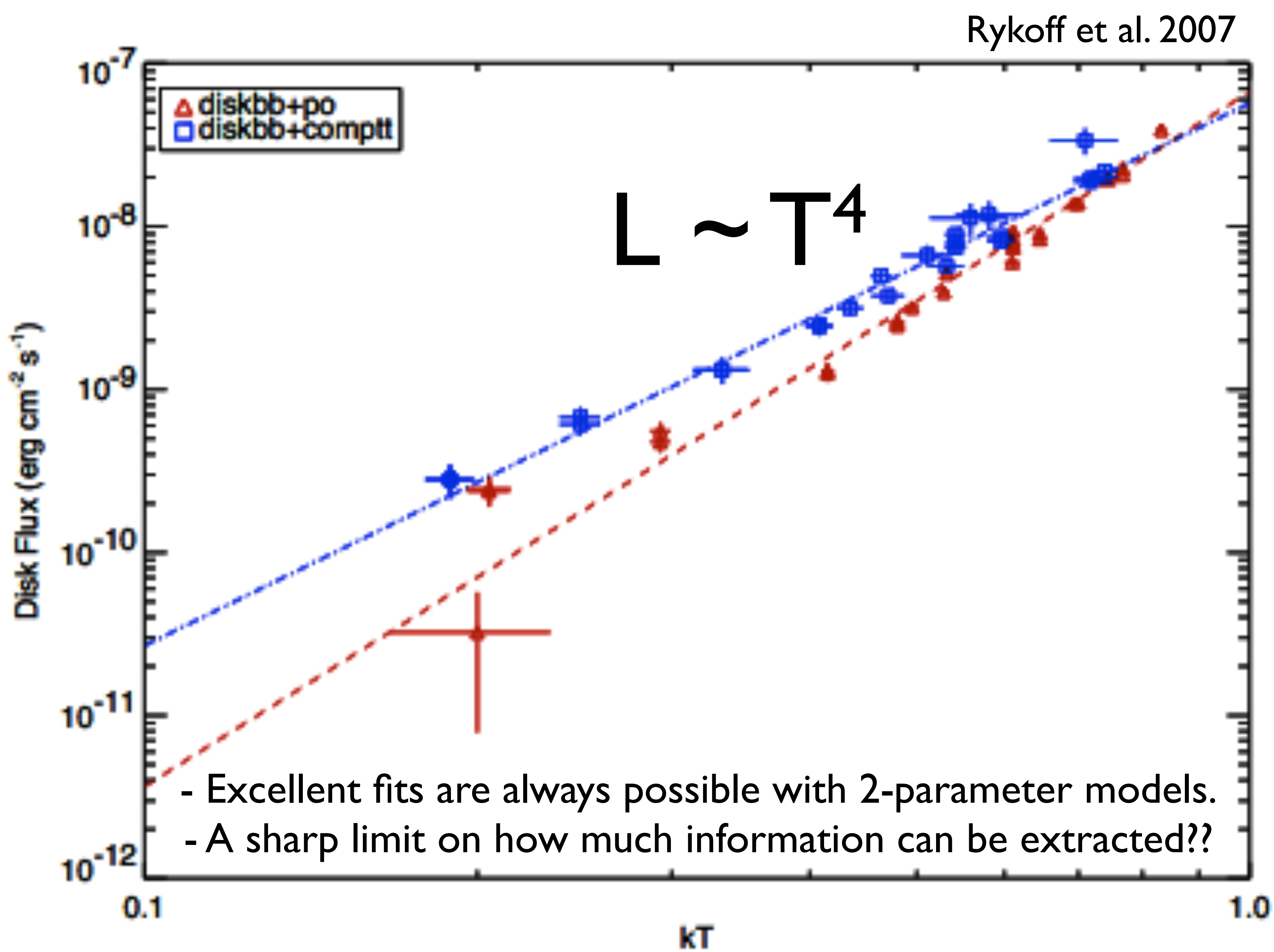
And, it was realized that radiative transfer through a disk atmosphere hardens spectra. kT too high, R too small (e.g. Shimura & Takahara 1995; Merloni, Fabian, Ross 2000).

And there are other corrections needed to get a "true" inner disk radius:

$$r_{in} = \eta g(i) f^2_{col} r_{col}$$

r_{in} is the "true" disk radius.
η ~ 0.65, corrects for real peak of disk emissivity.
$g(i)$ ~ 0.75, accounts for relativistic effects.
f_{col} ~ 1.7-3.0++, corrects for radiative transfer.
r_{col} is the color radius, related to sqrt(norm).

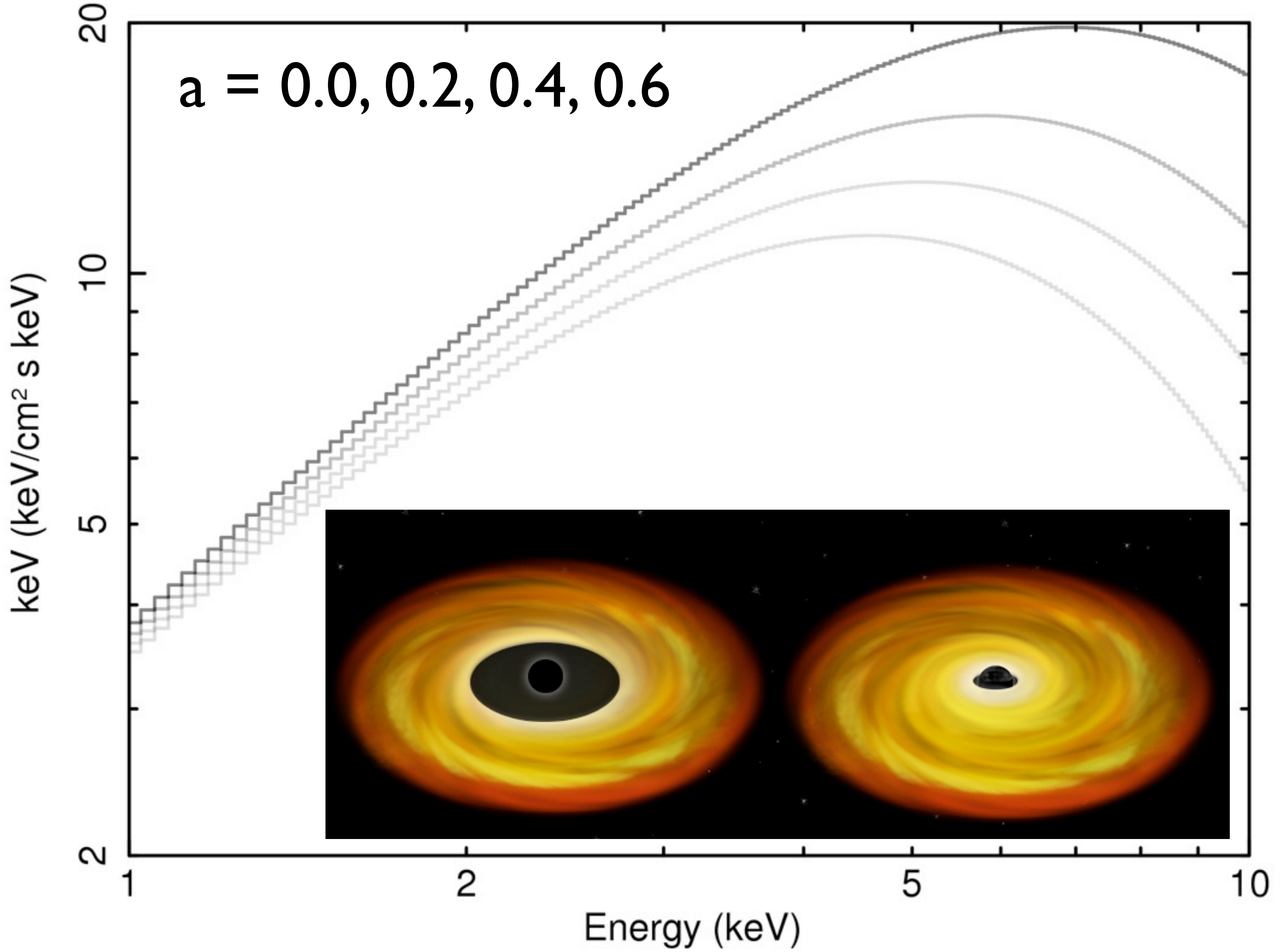
Swift Obs. of XTE J1817

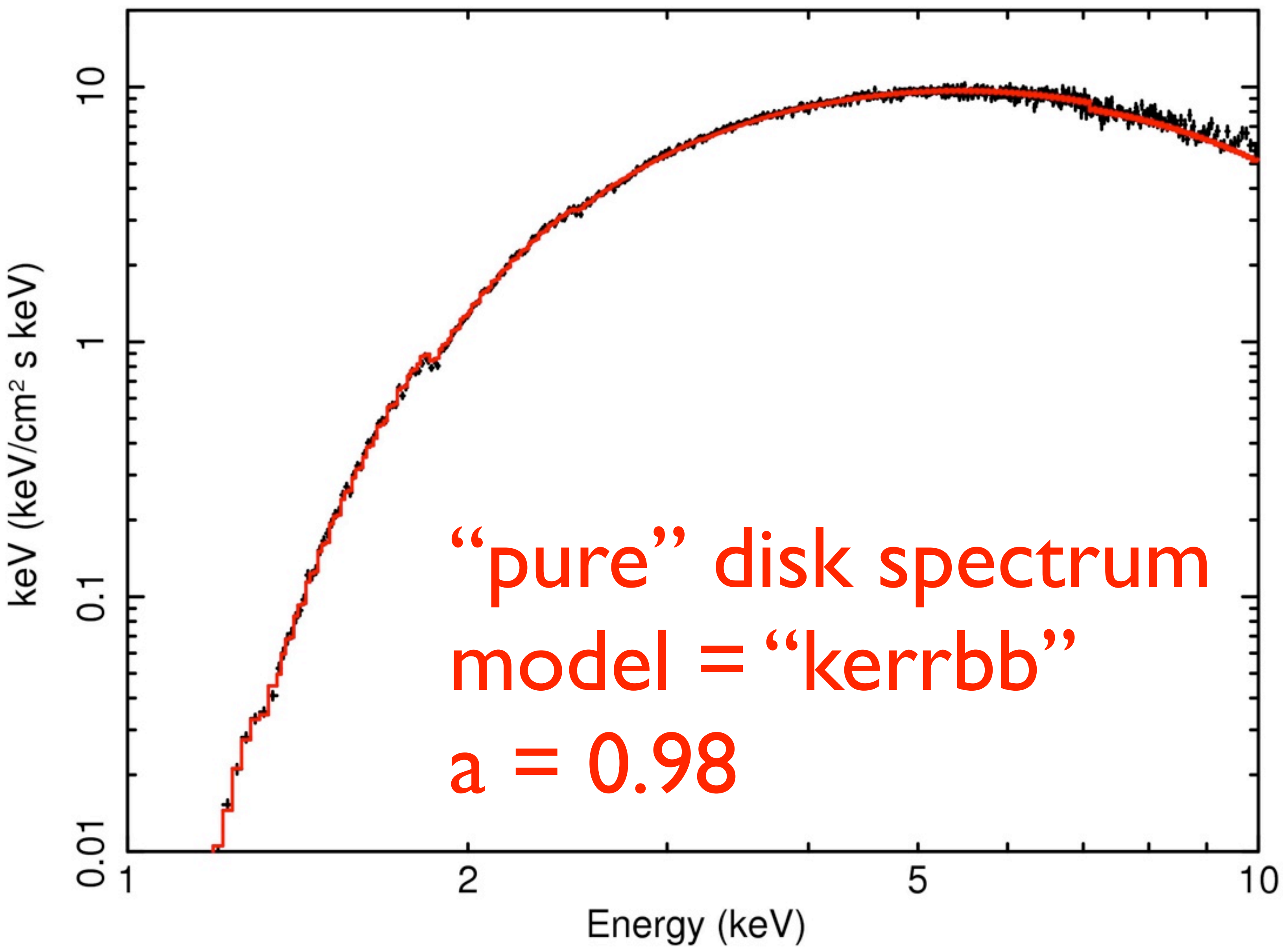


Spin via the continuum

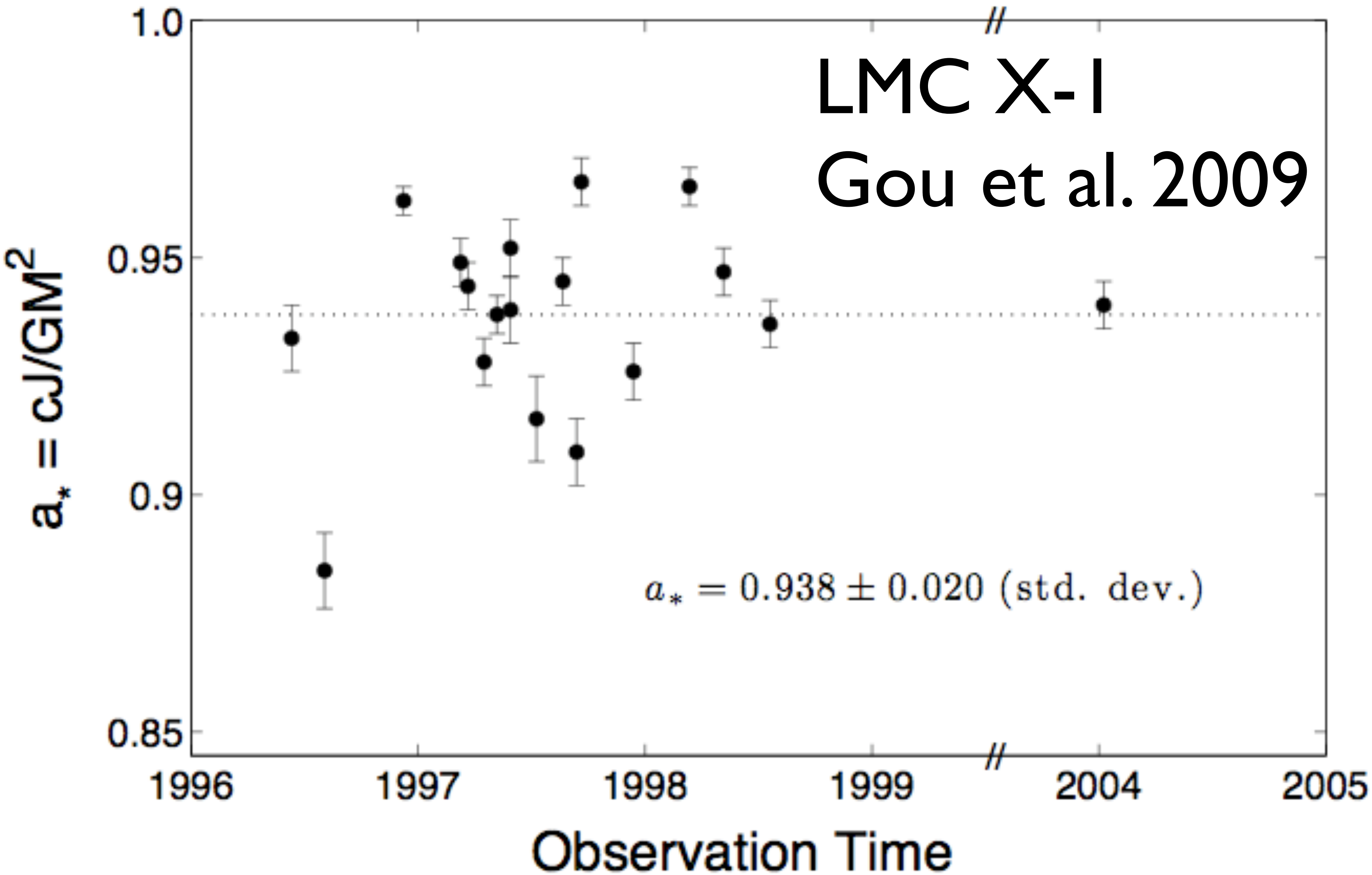
- New models include the spin as a fitting parameter (e.g. Davis et al. 2005).
- Need a value for f_{col}, and to measure or fix a value of m-dot.
- m-dot is exceedingly hard to measure or estimate.
- How much luminosity you infer from the disk depends on the viscosity parameter, alpha, as well as mass, distance, inclination.
- The flux in the disk also depends on the nature of the hard component (power-law, broken power-law, thermal Comptonization, hybrid Compt.).
- And then there is the issue of disk winds, which carry away mass, and are observed to operate in disk-dominated states.

Spin effects



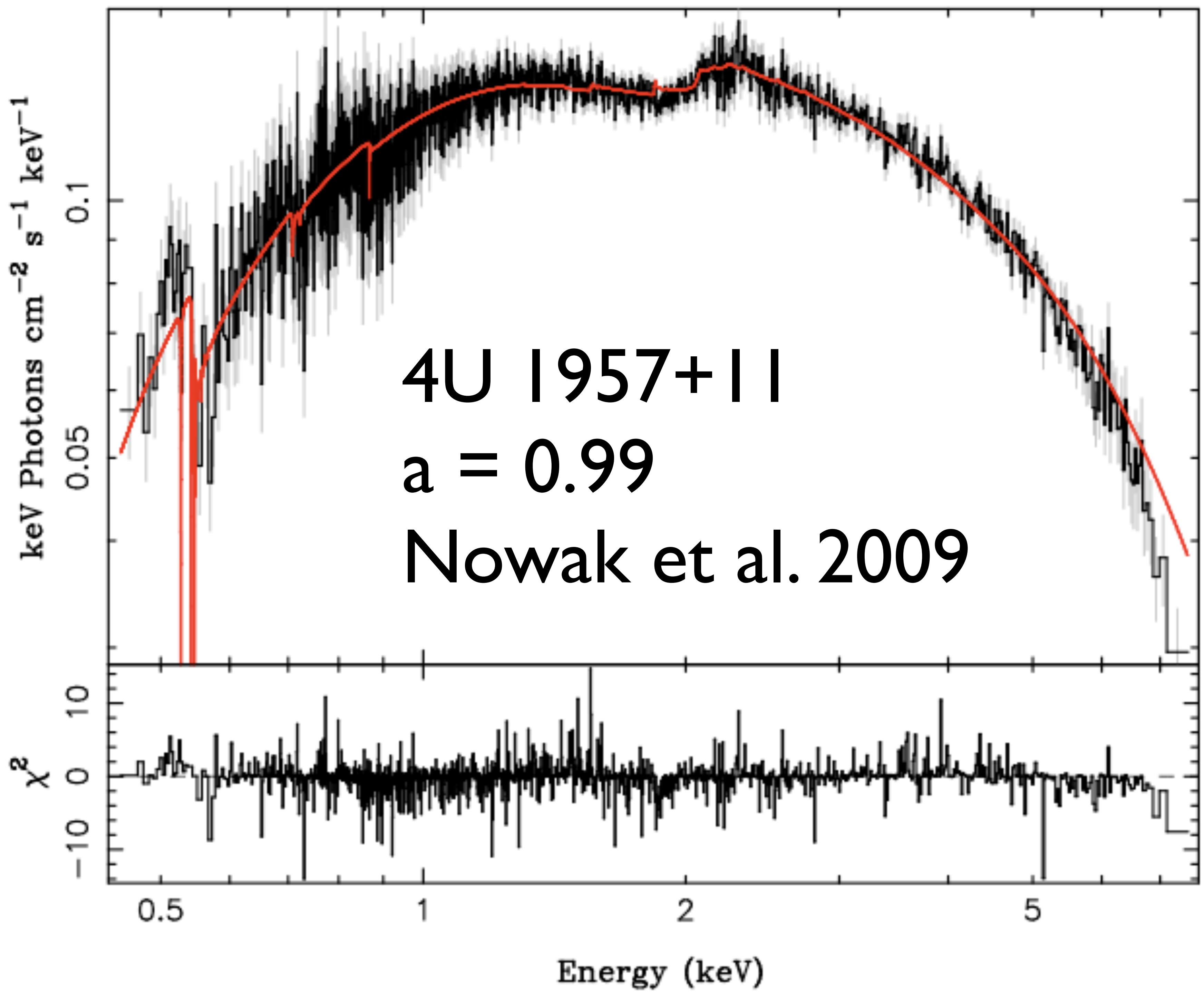


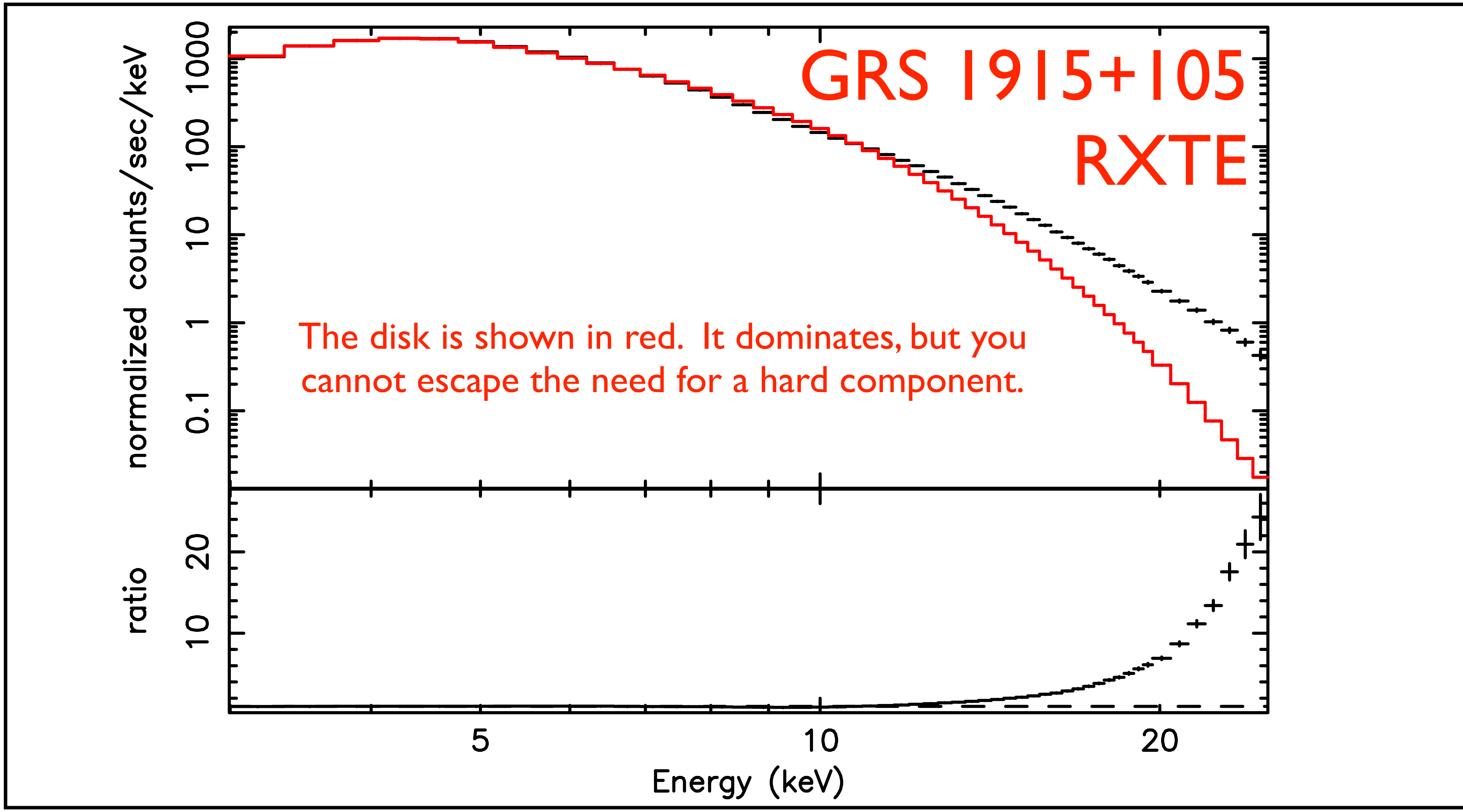
McClintock et al. (2006): a > 0.98.



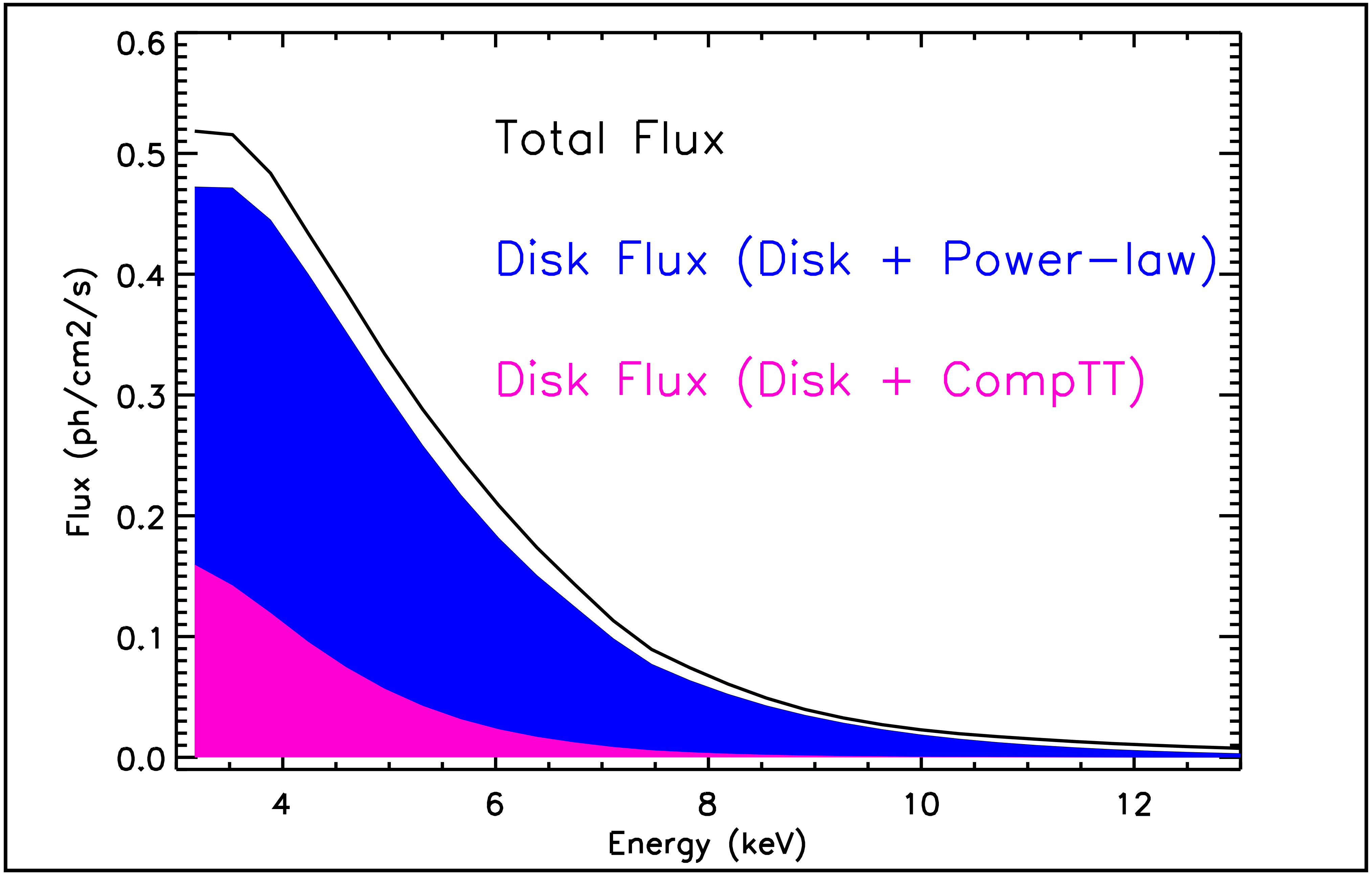
LMC X-1
Gou et al. 2009
$a_* = 0.938 \pm 0.020$ (std. dev.)
$a_* = cJ/GM^2$
1.0
0.95
0.9
0.85
1996
1997
1998
1999
2004
2005
Observation Time

Models vs data



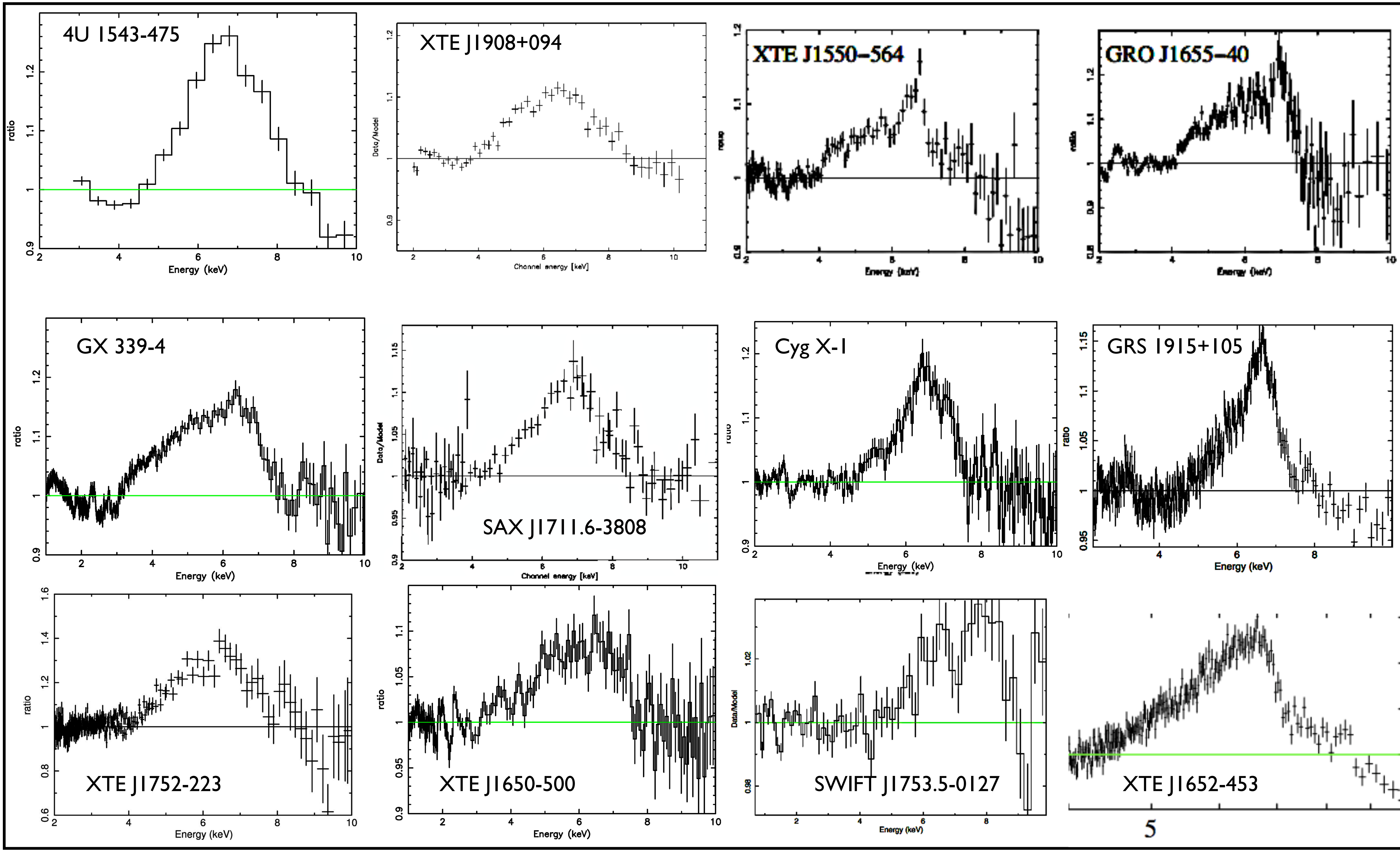


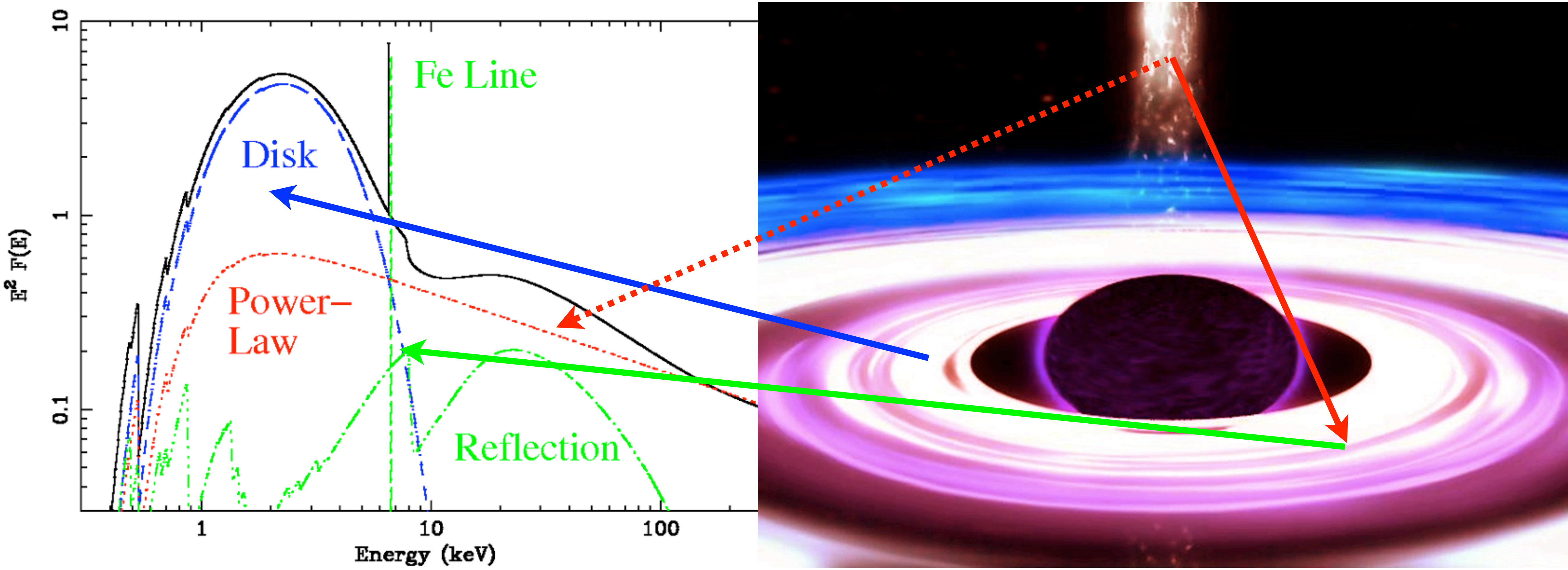
McClintock et al. 2006 fit this very spectrum and found a = 0.98 through disk modeling.



Total Flux
Disk Flux (Disk + Power-law)
Disk Flux (Disk + CompTT)
Flux (ph/cm2/s)
Energy (keV)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
4
6
8
10
12

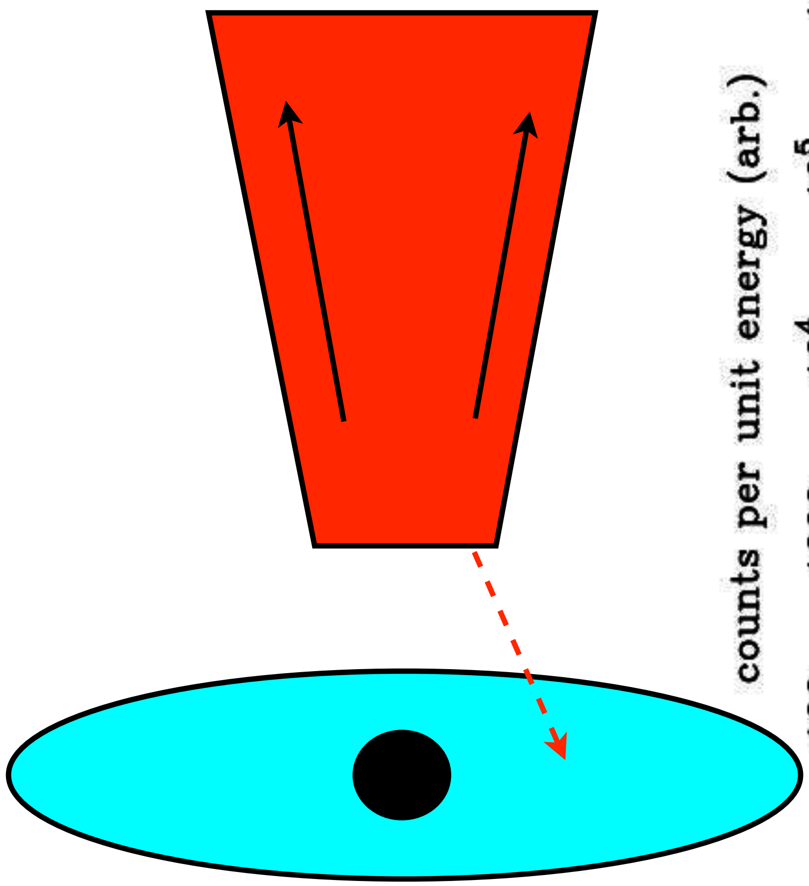
Disk Reflection. And Spin.

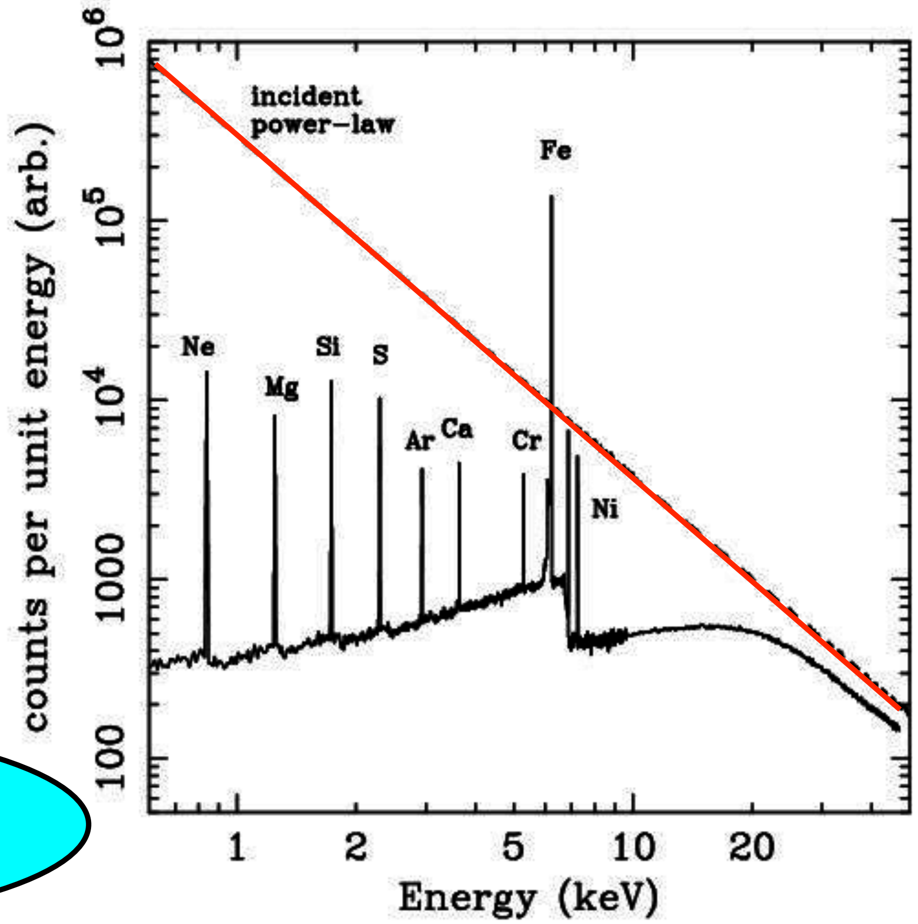

4U 1543-475
XTE J1908+094
XTE J1550-564
GRO J1655-40
GX 339-4
SAX J1711.6-3808
Cyg X-1
GRS 1915+105
XTE J1752-223
XTE J1650-500
SWIFT J1753.5-0127
XTE J1652-453
ratio
Data/Model
Energy (keV)
Channel energy [keV]
5

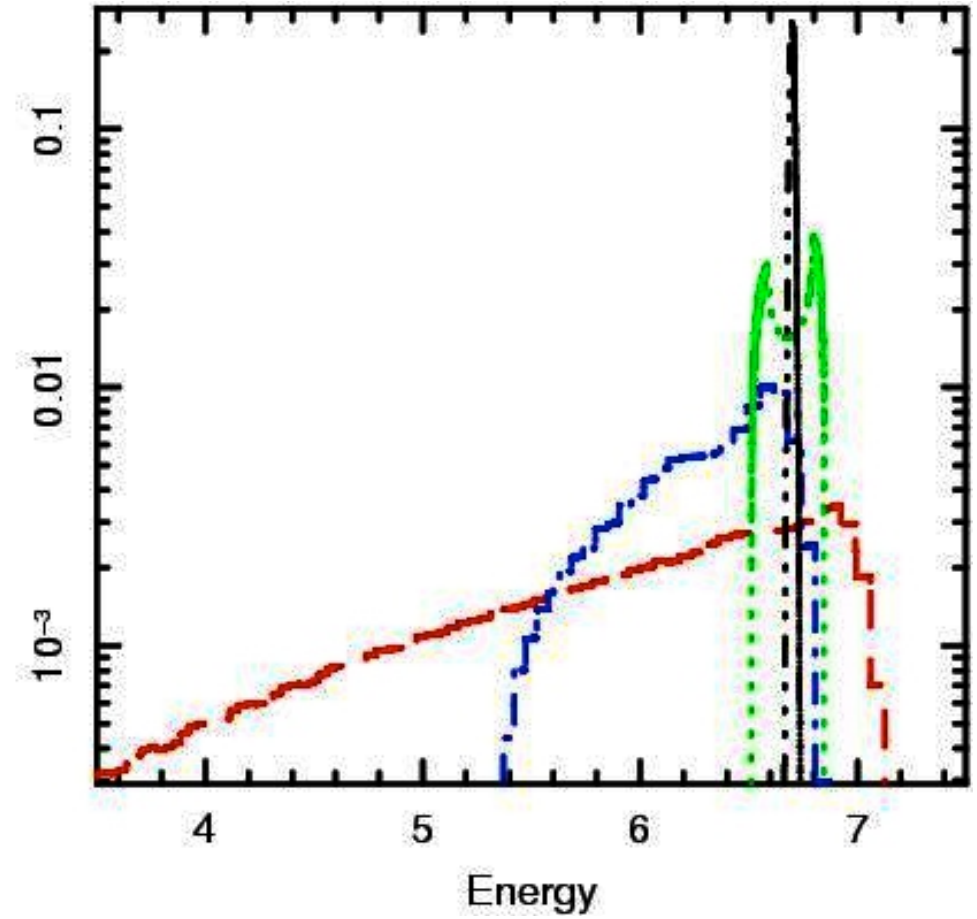


10
1
0.1
E^2 F(E)
1
10
100
Energy (keV)
Fe Line
Disk
Power–
Law
Reflection

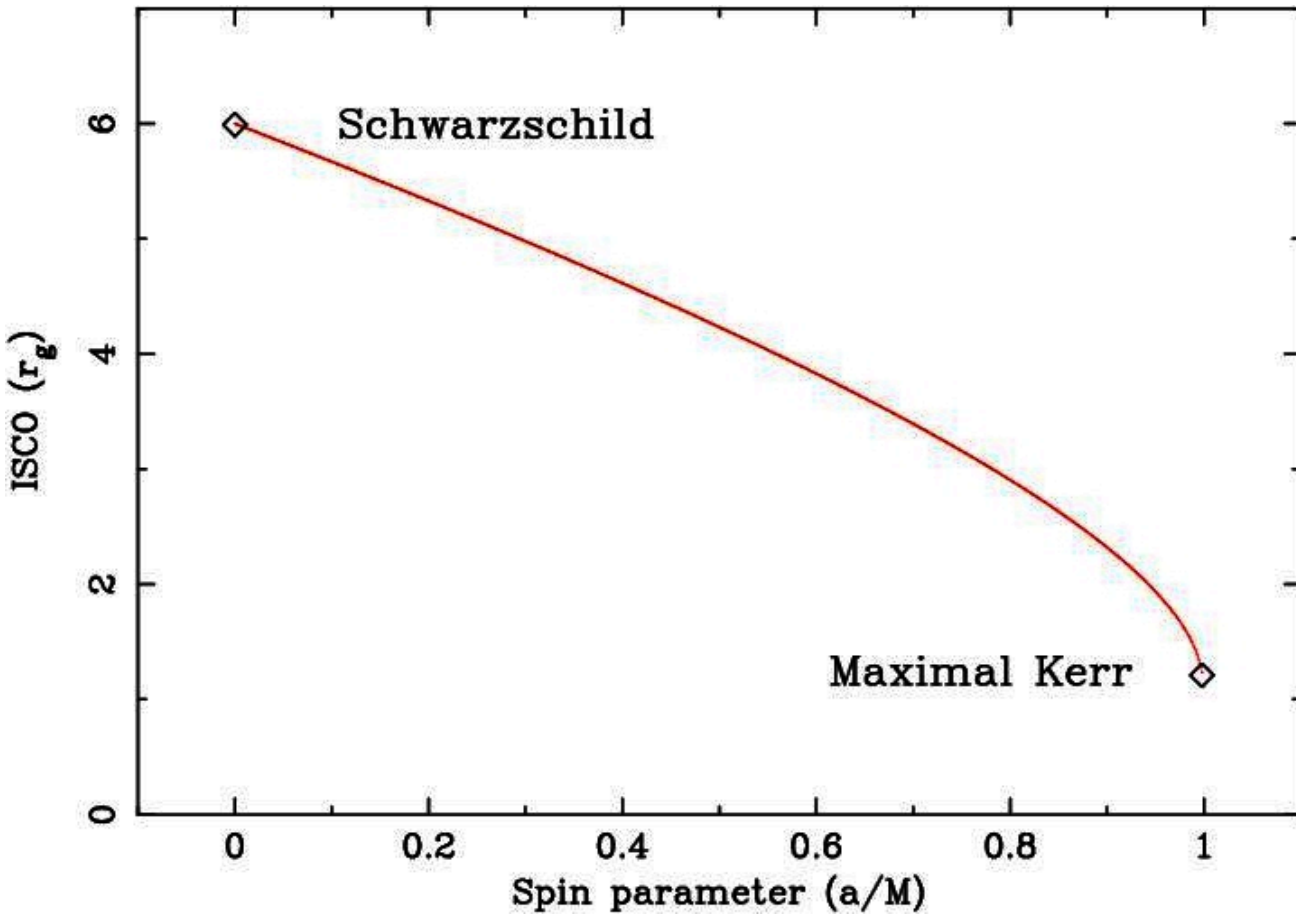
X-ray Disk Lines

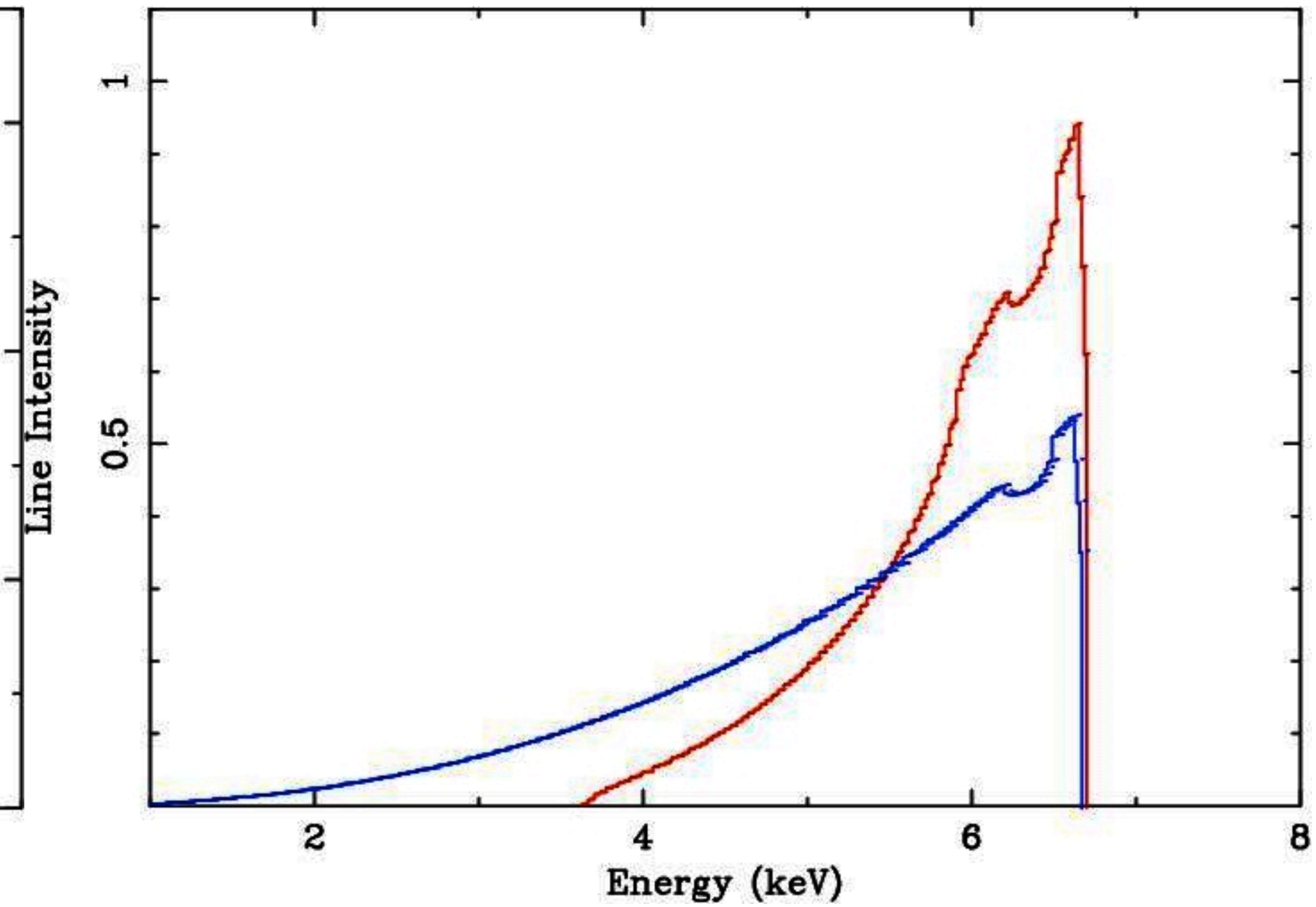






Lines and the ISCO

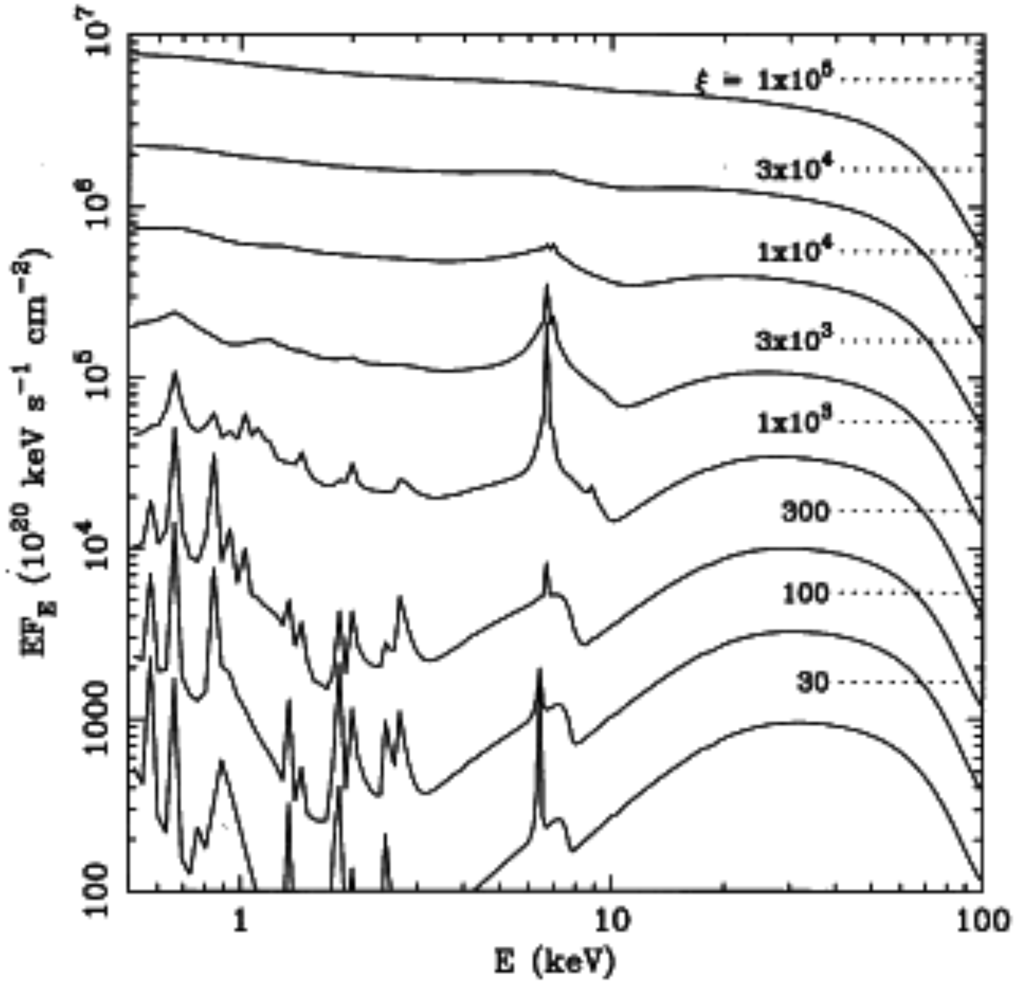




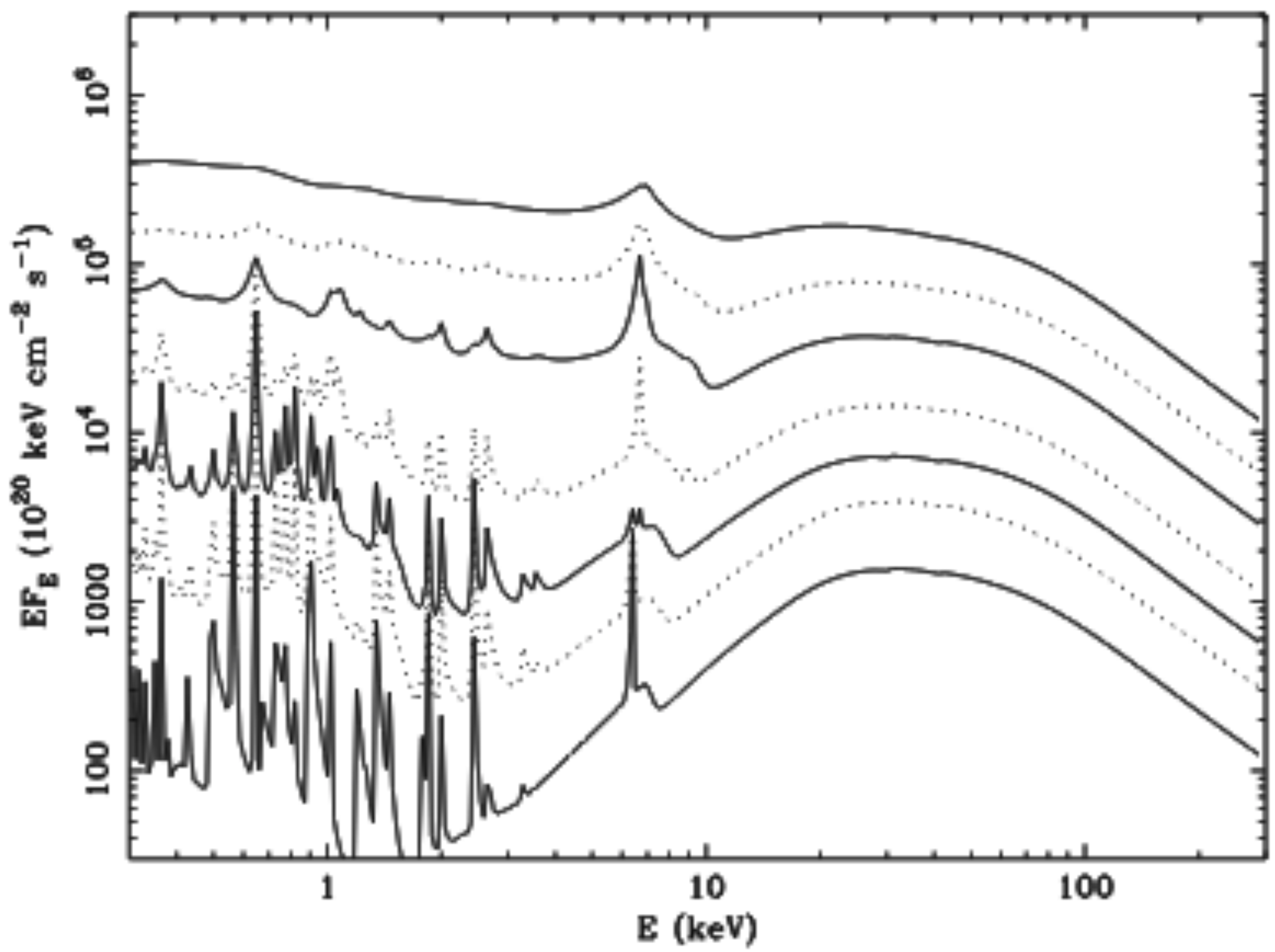
Ray tracing --> line profiles.
Diskline (a=0), Laor (a=0.998).
4 models where spin is variable

X-ray Disk Reflection

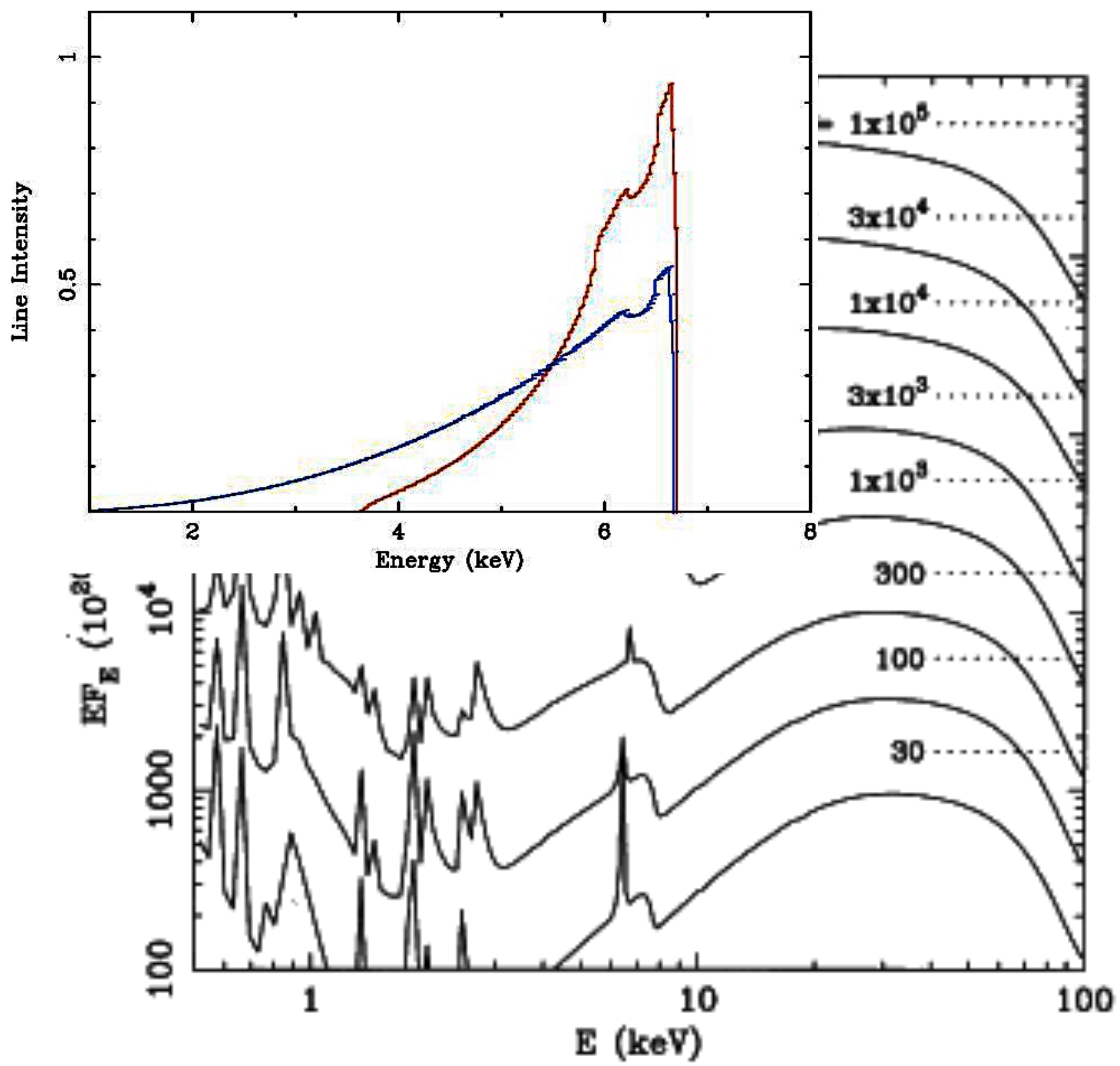
Ross & Fabian 93



Ross & Fabian 07



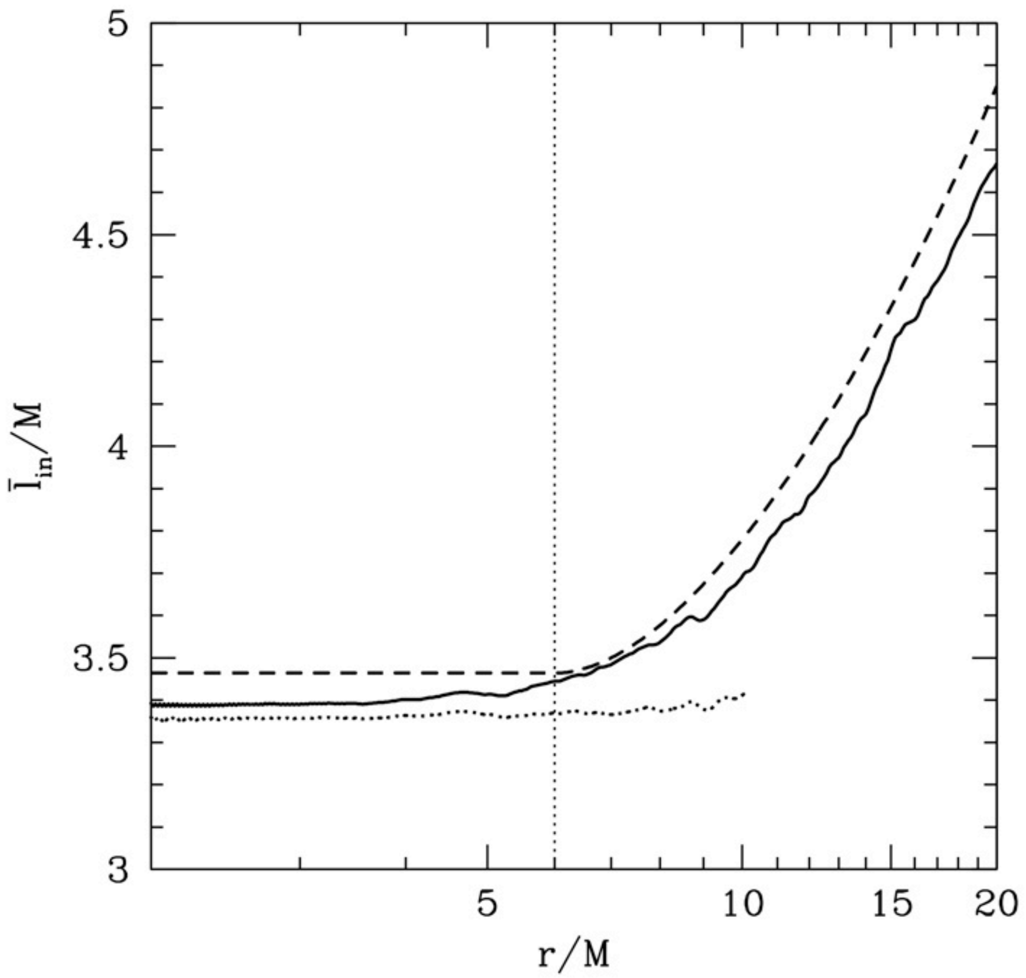
Reflection must be *blurred*



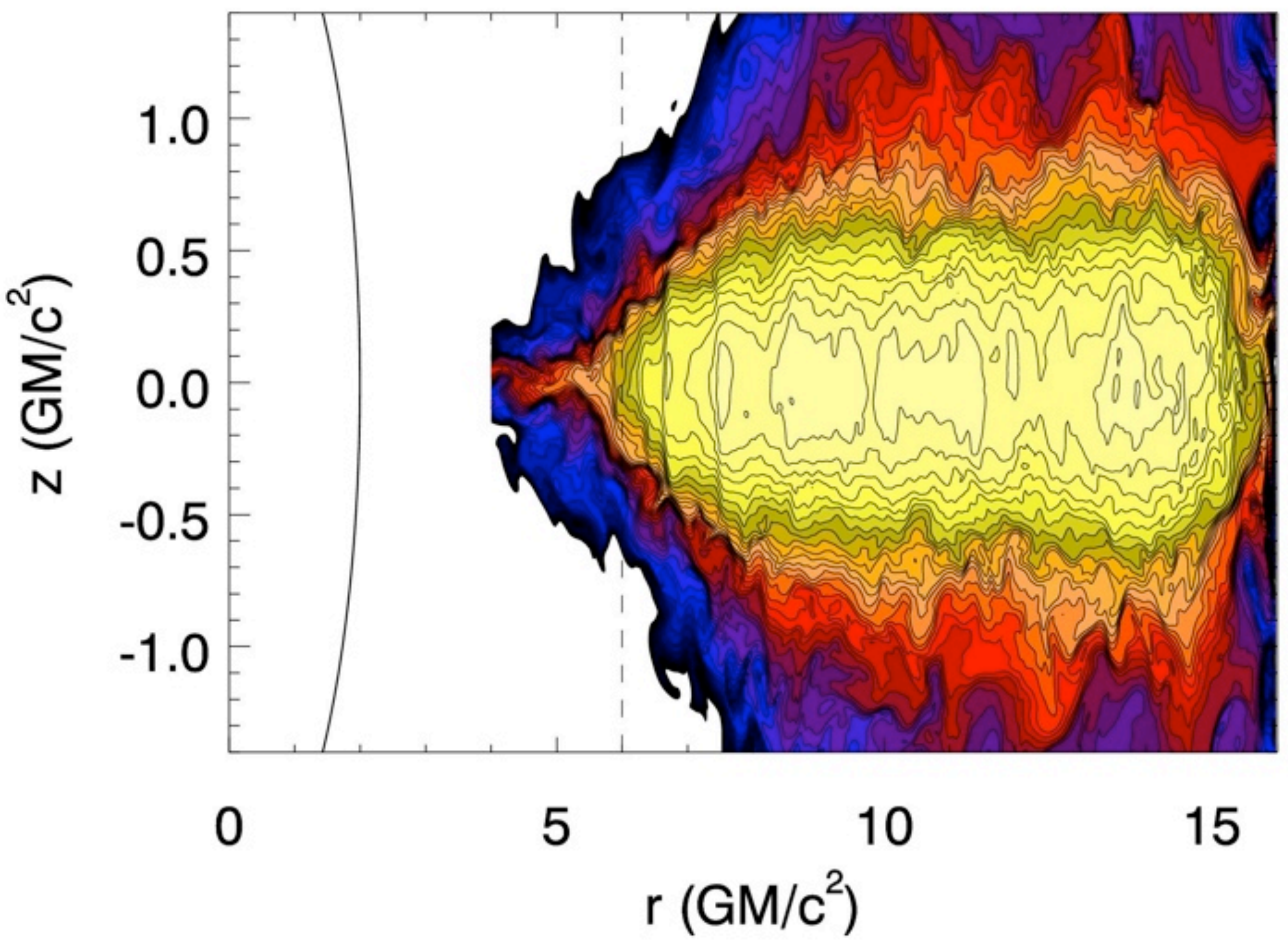
- Fe K lines & disk reflection *are one and the same.*
- Reflection spectra are calculated in the disk frame.
- Must change frames to see what it looks like at infinity. -> *convolve with line function.*
- Ross, Fabian, Brandt 1996; Zycki & Done 1999

Simulations on the Edge

Shafee et al. 2008

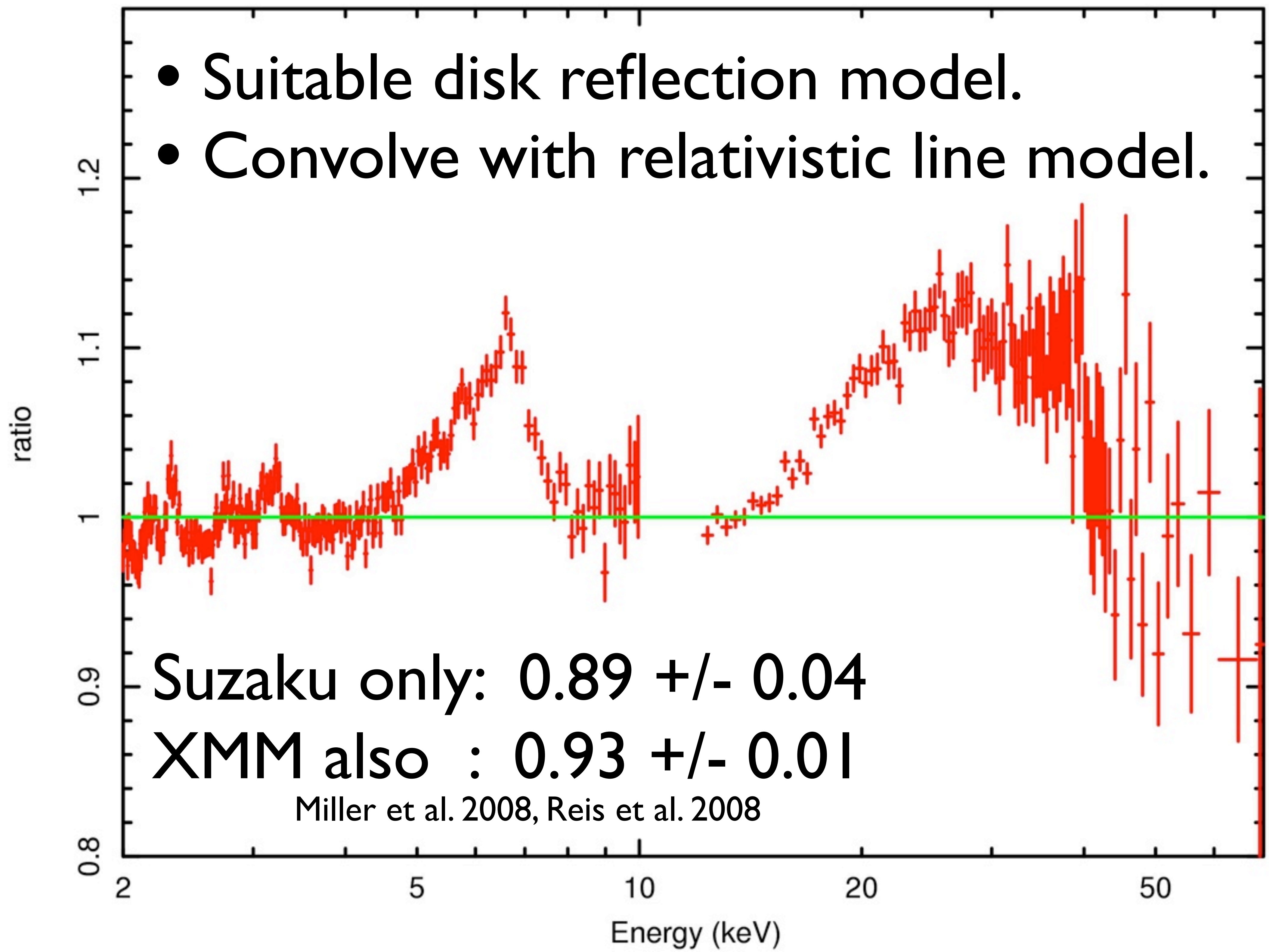


Reynolds & Fabian 2008



Spin in GX 339-4

- Suitable disk reflection model.
- Convolve with relativistic line model.

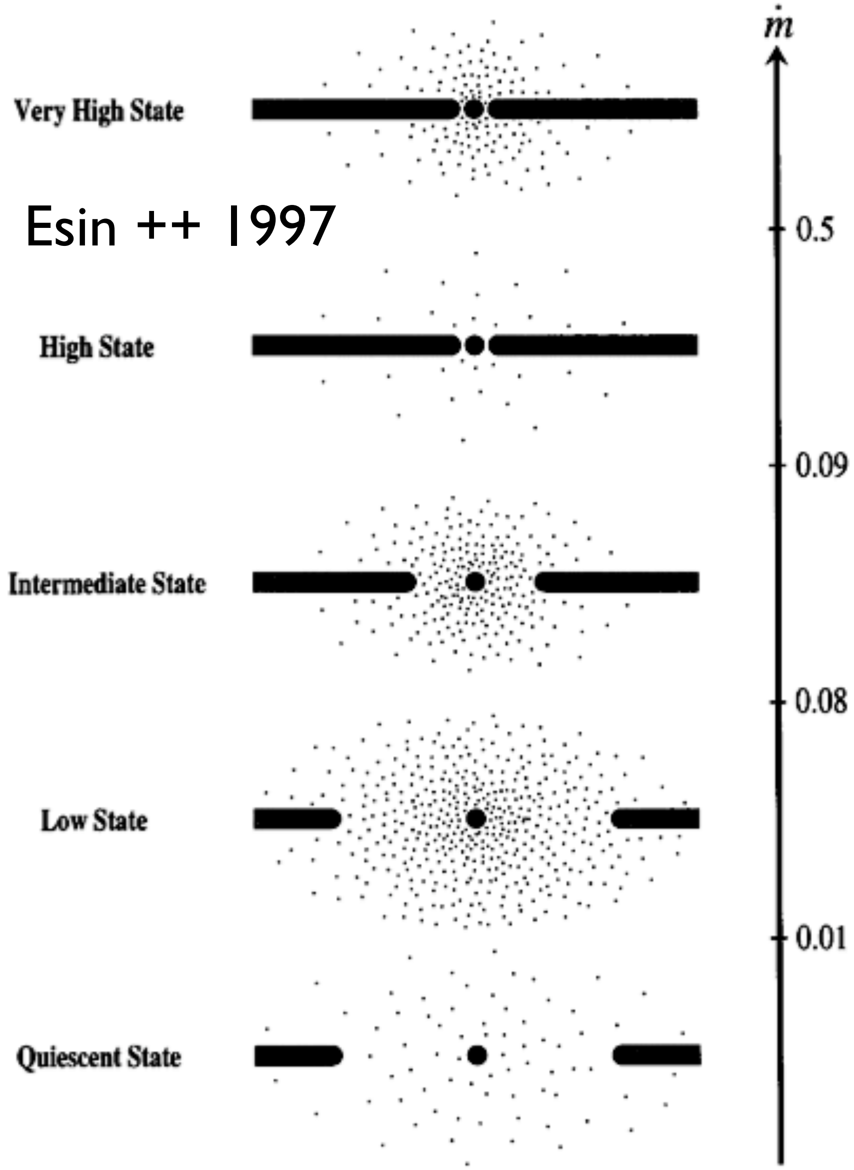


Suzaku only: 0.89 +/- 0.04

XMM also : 0.93 +/- 0.01

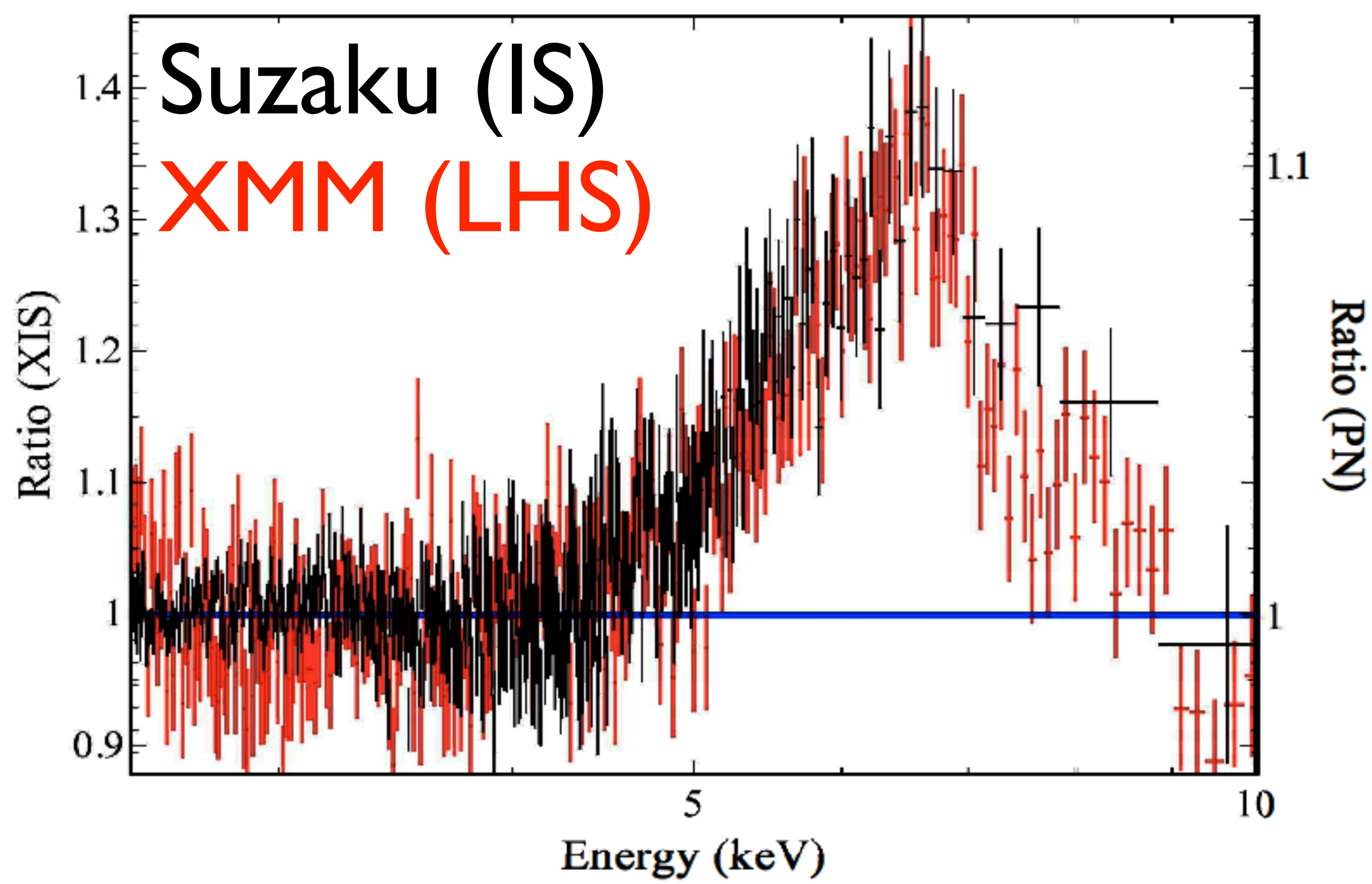
Miller et al. 2008, Reis et al. 2008

Spin in XTE J1752-223



Esin ++ 1997

Reis et al. 2011



Intermediate State (Suzaku), low/hard state (XMM).

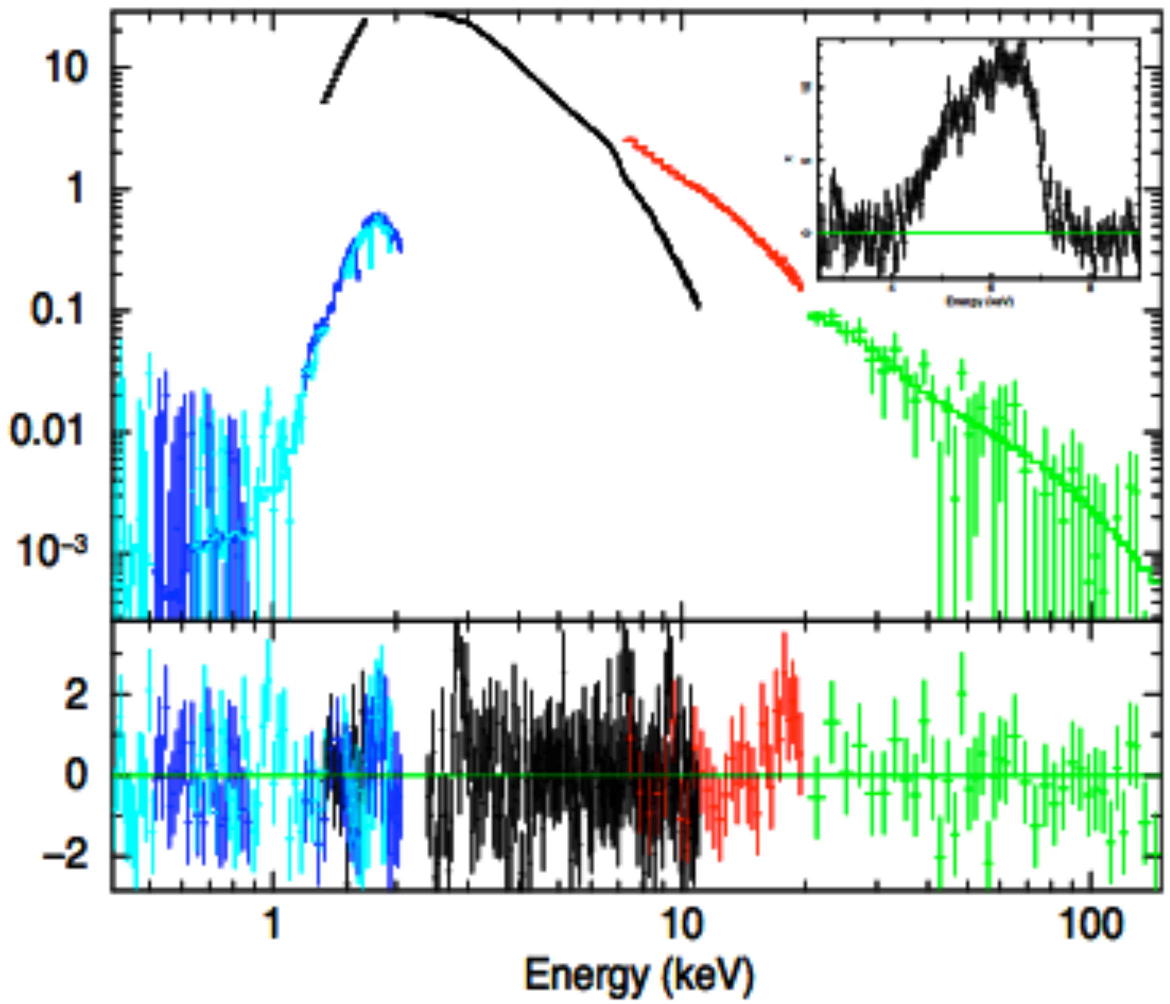
Blurred reflection fits: a/M = 0.52 +/- 0.11.

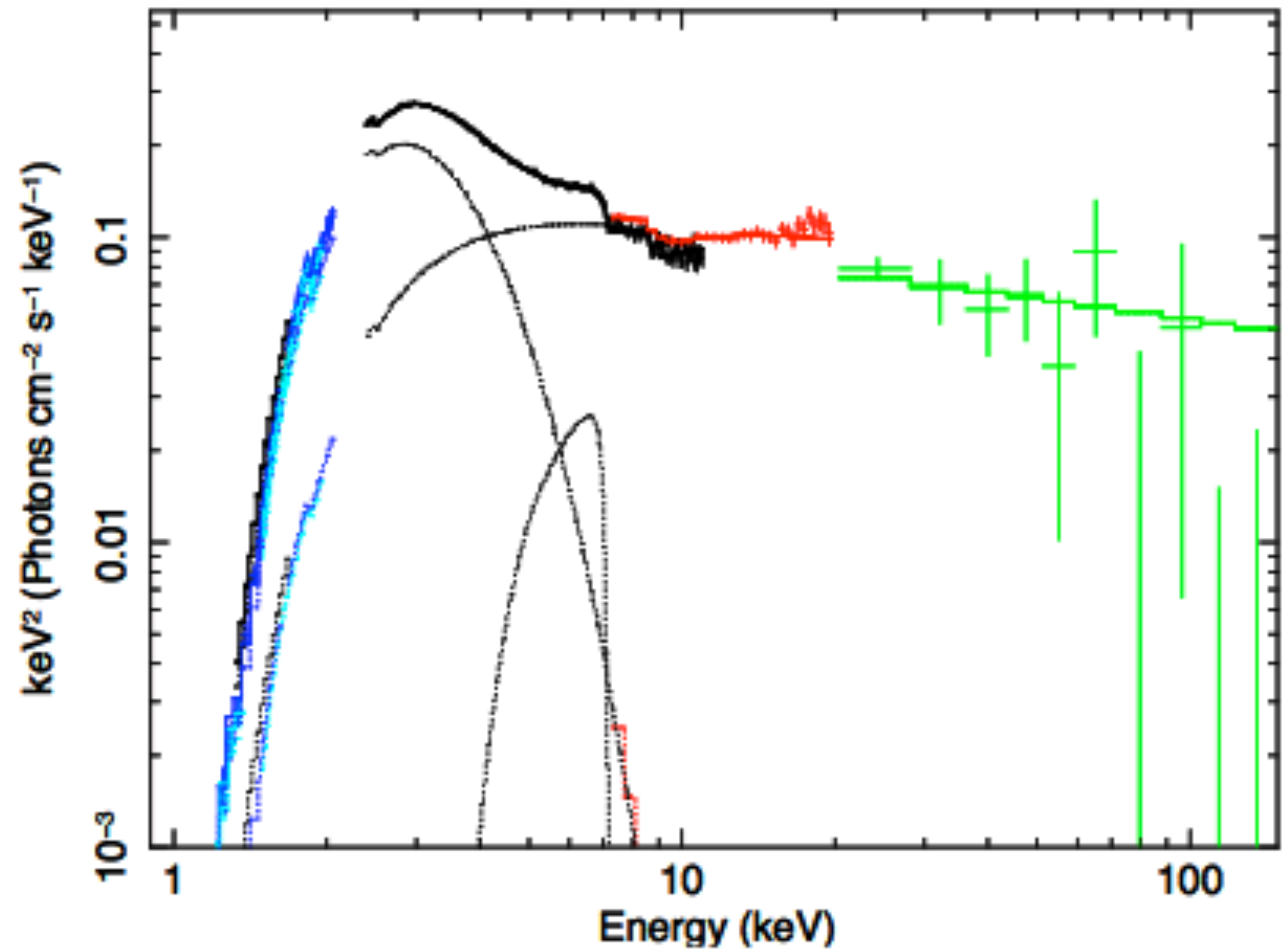
Strong implications for accretion flow models.

Spin in XTE J1652-453

XMM-Newton

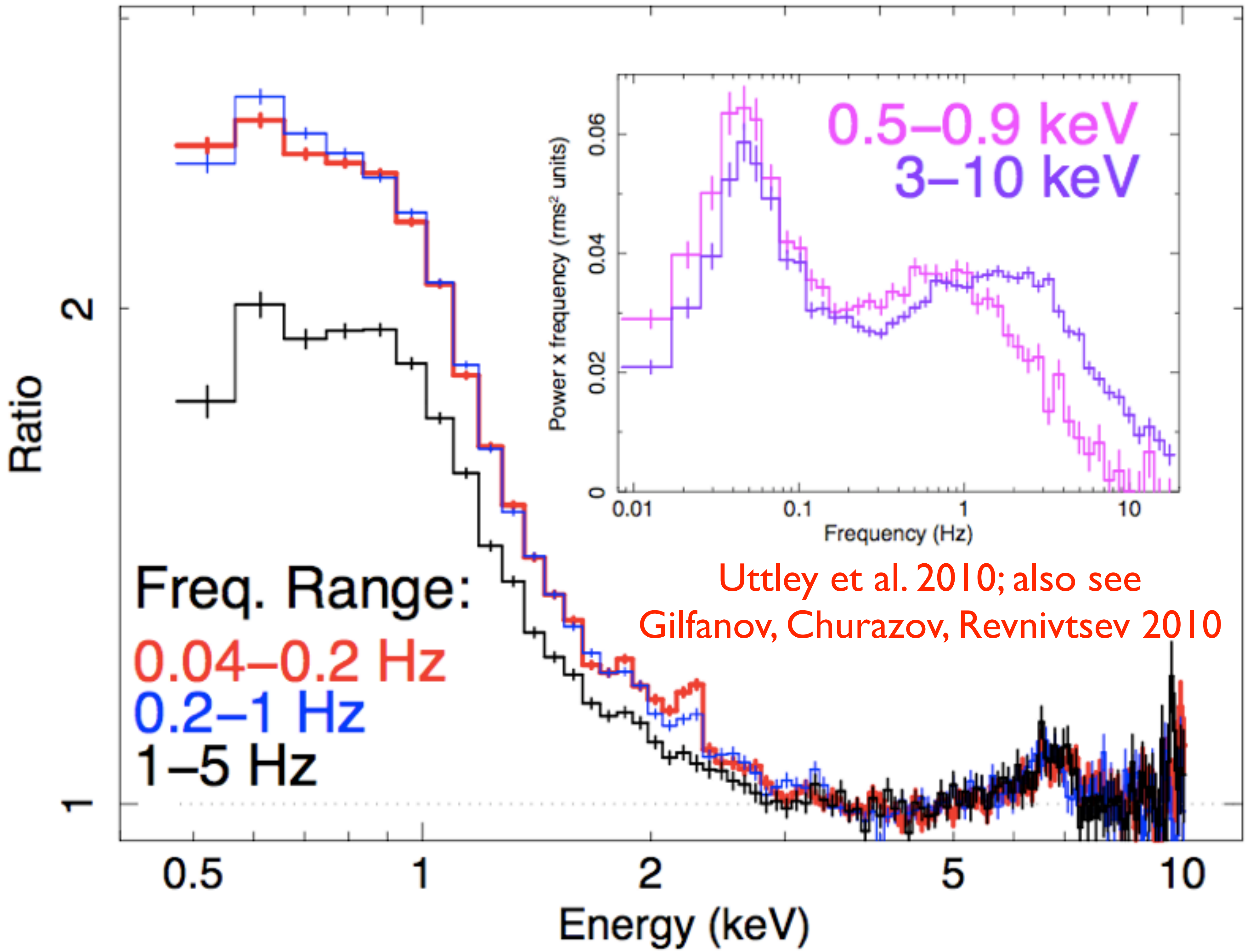
Hiemstra et al. 2010





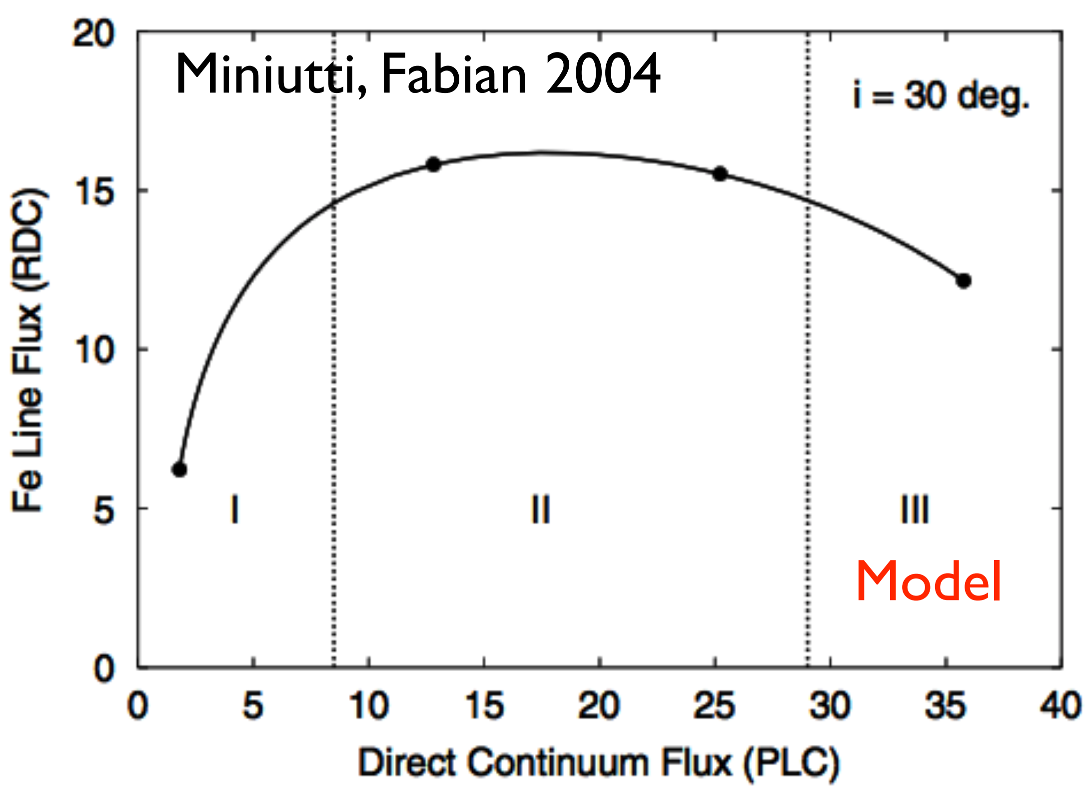
XTE J1652-453 observed in an Intermediate State.
Blurred reflection fits: a/M = 0.45 +/- 0.02.

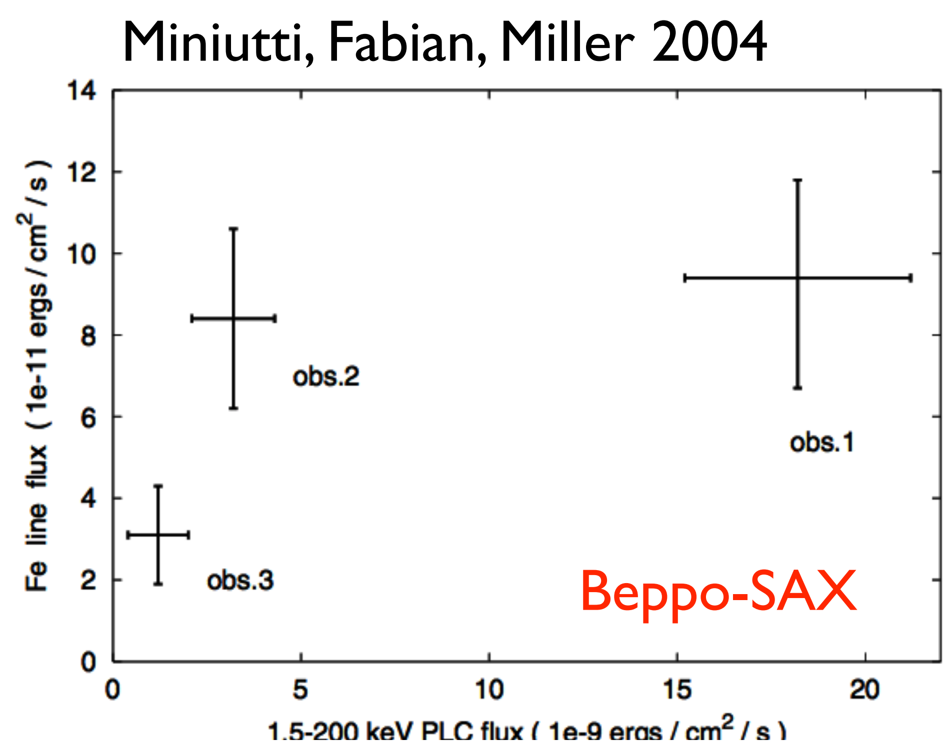
Lags in FCS of GX 339-4

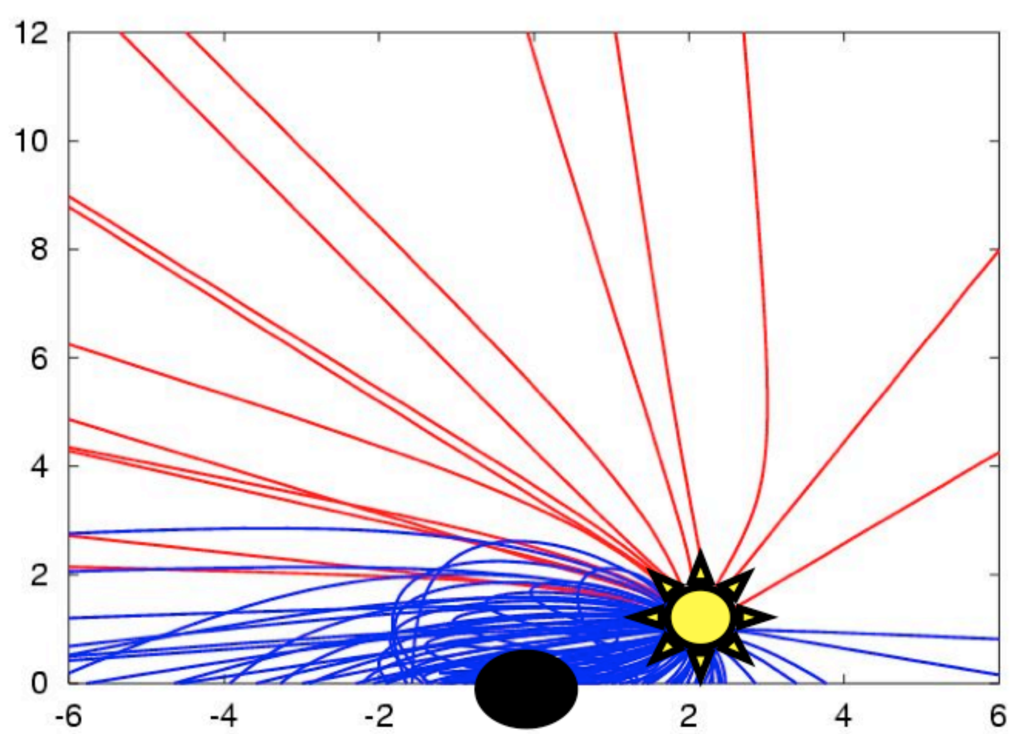


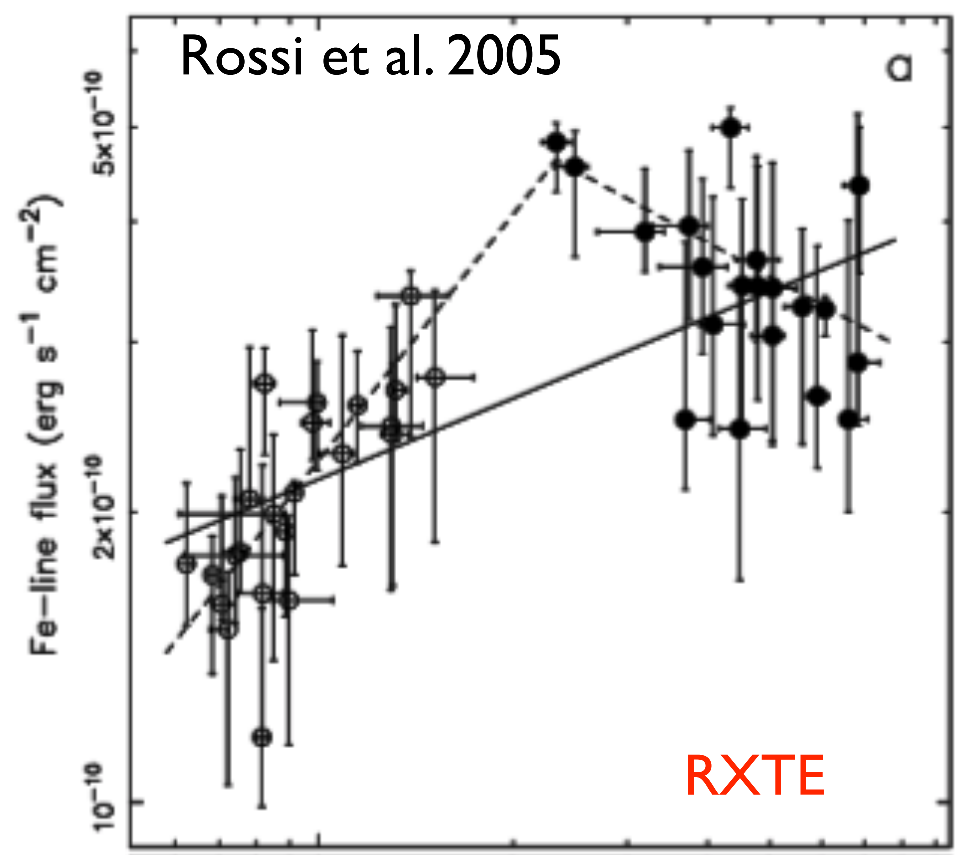
Uttley et al. 2010; also see
Gilfanov, Churazov, Revnivtsev 2010

XTE J1650: Light Bending?

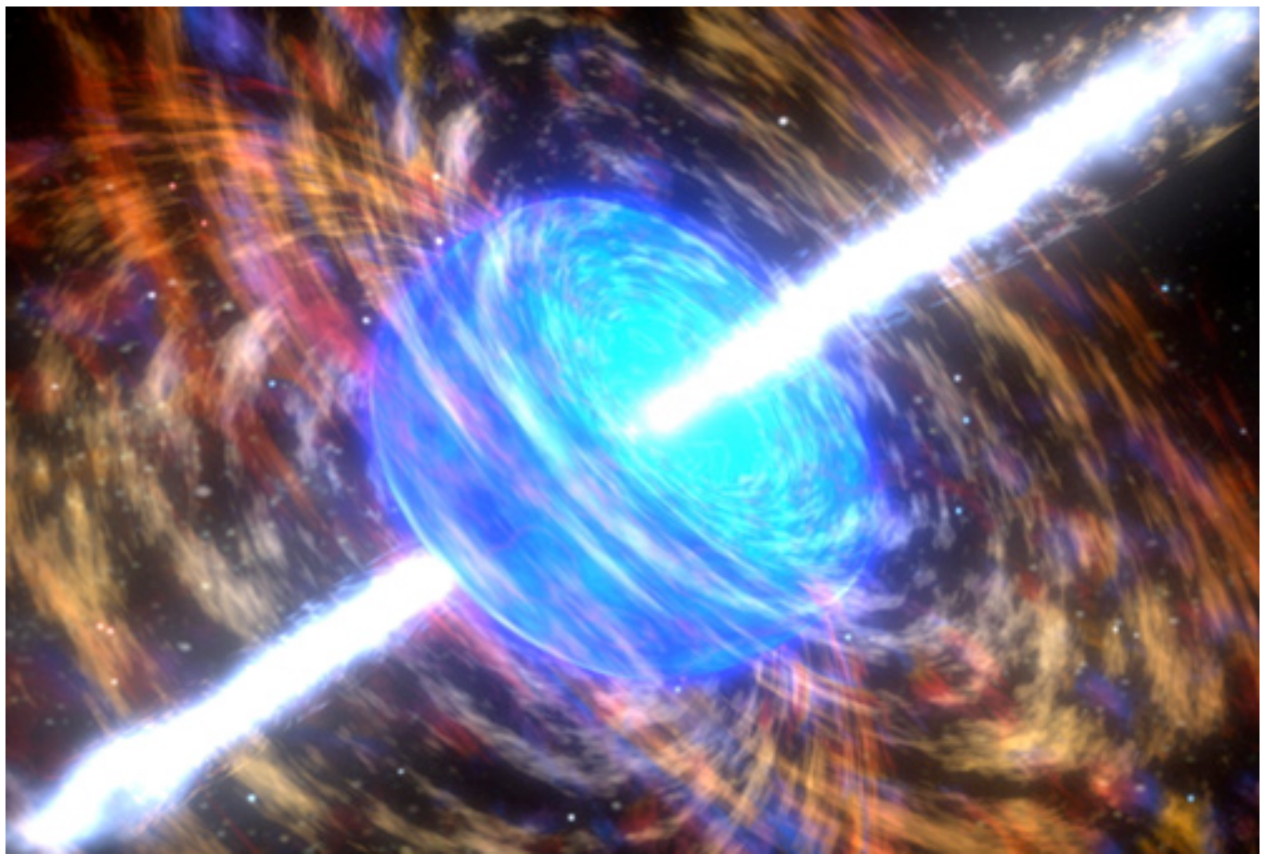






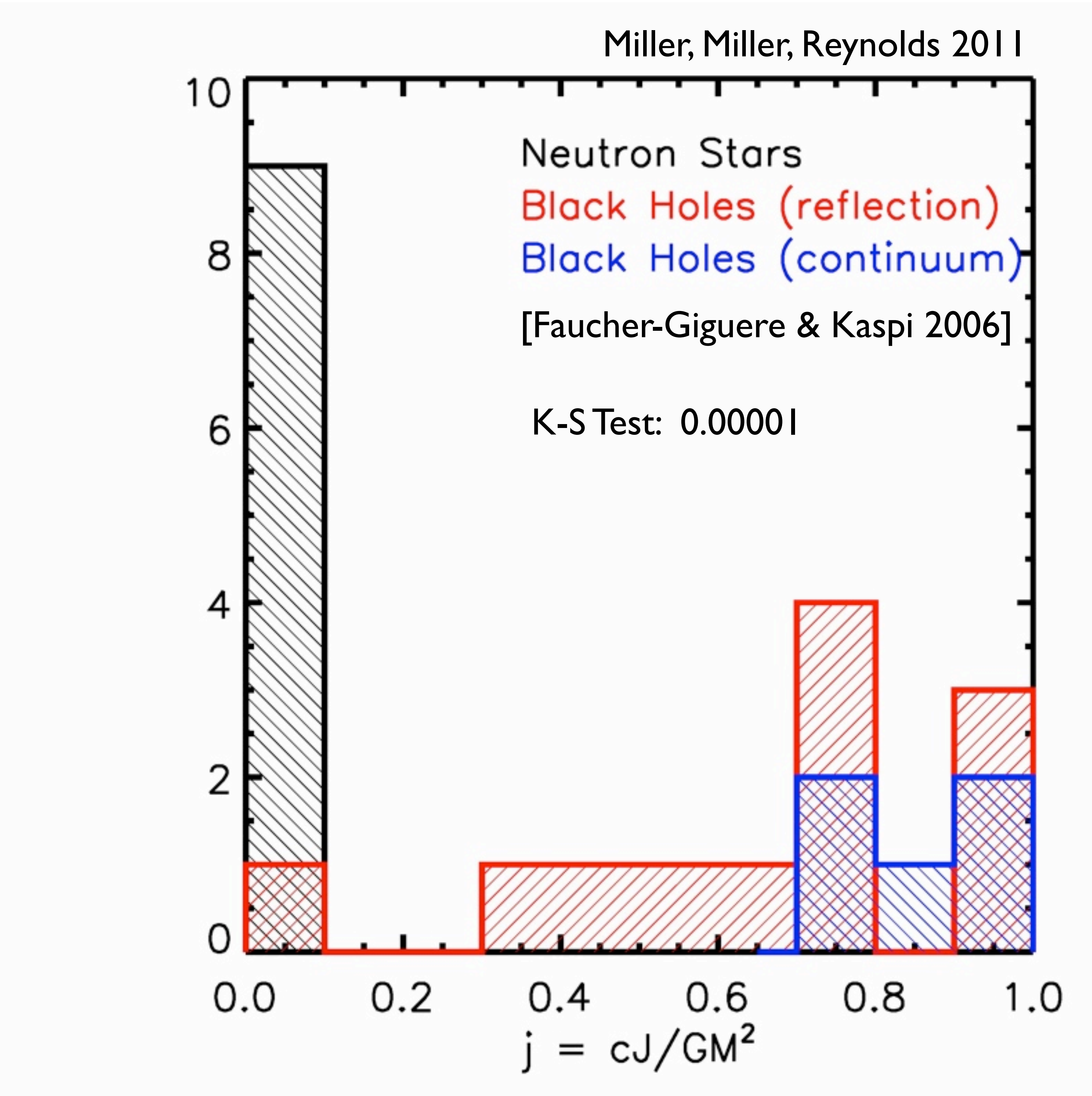


Spin, SNe, GRBs



Gamma-ray burst

- Black holes must double their mass to change their spin. (Bardeen 70, Thorne 74)
- Impossible in stellar binaries. Stellar-mass black hole spins are set in the creation event.
- Spin is a unique view into the nature and energetics of GRBs and SNe.


Miller, Miller, Reynolds 2011
10
8
6
4
2
0
Neutron Stars
Black Holes (reflection)
Black Holes (continuum)
[Faucher-Giguere & Kaspi 2006]
K-S Test: 0.00001
0.0
0.2
0.4
0.6
0.8
1.0
j = cJ/GM^2

“Collapsar” model, Woosley 93; MacFadyen & Woosley 99:

- Core with sufficient M, J collapses to BH, remaining “disk” spins-up hole to a = 0.9 and drives MHD jets (GRB).
- Core with low M, J collapses to NS or BH with low spin. No jet, standard SNe.
- Processes could rapidly spin-down a neutron star created with a = 0.7, e.g. gravitational radiation (Andersson 98).
- Internal B field of the progenitor is very important: could lead to NS with low spin (Heger, Woosley, Spruit 2005).

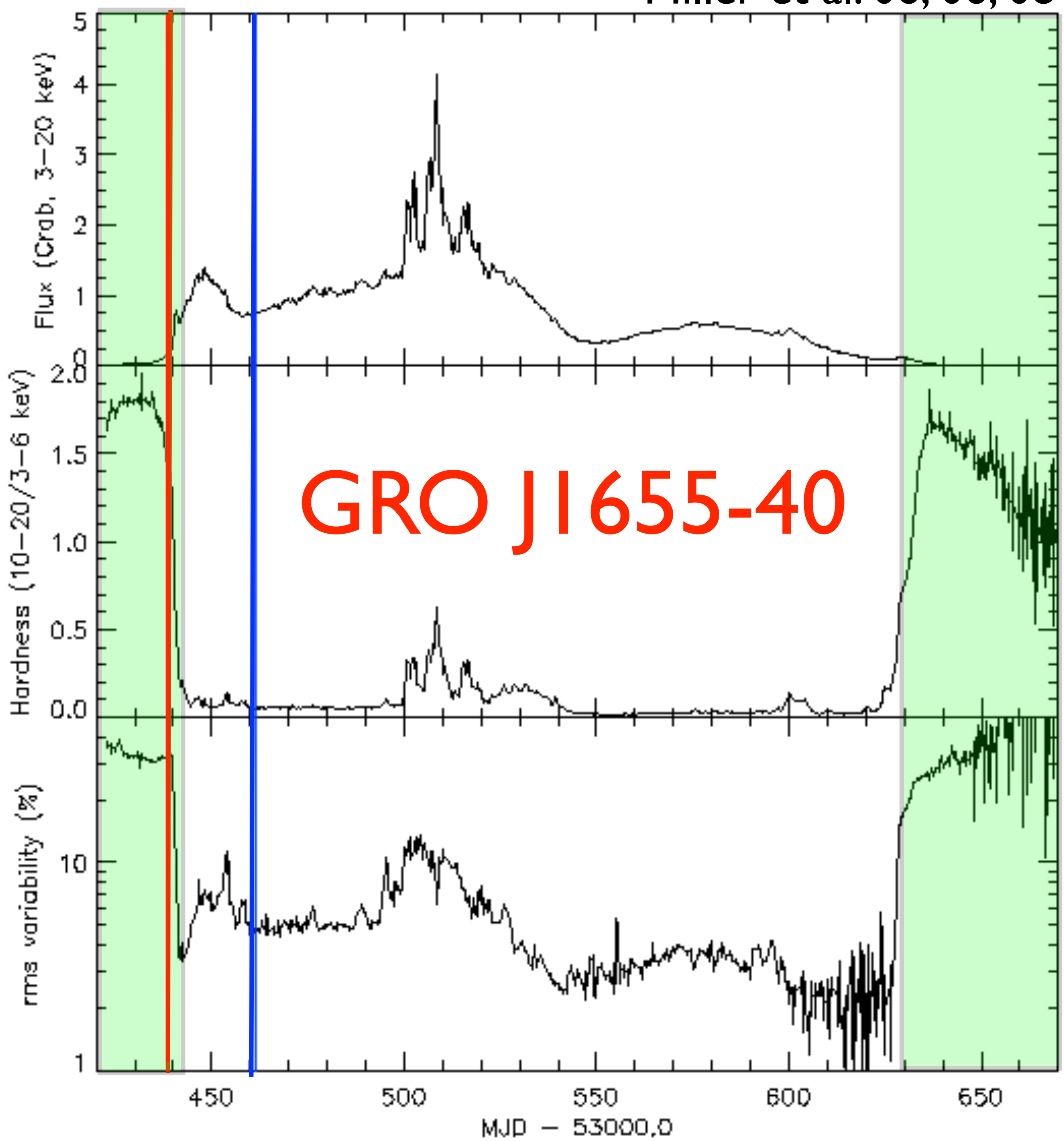
Disk Winds

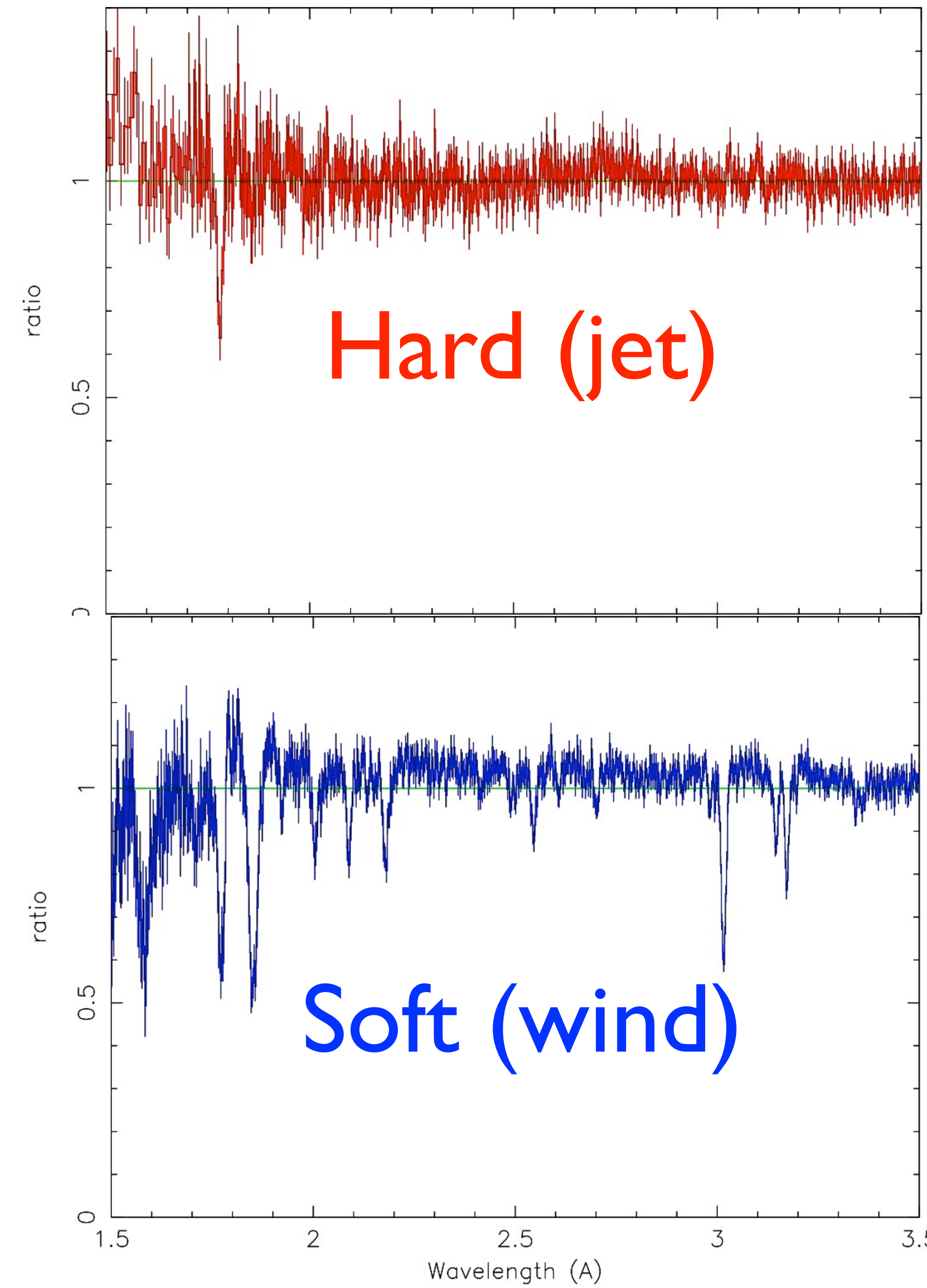
Why study winds?

- Disk winds can carry away at least as much mass as actually accretes.
- Winds also carry away angular momentum ... required for disk accretion!
- Winds may offer more information on disk physics than the continuum.
- We may need to understand winds to understand jets.

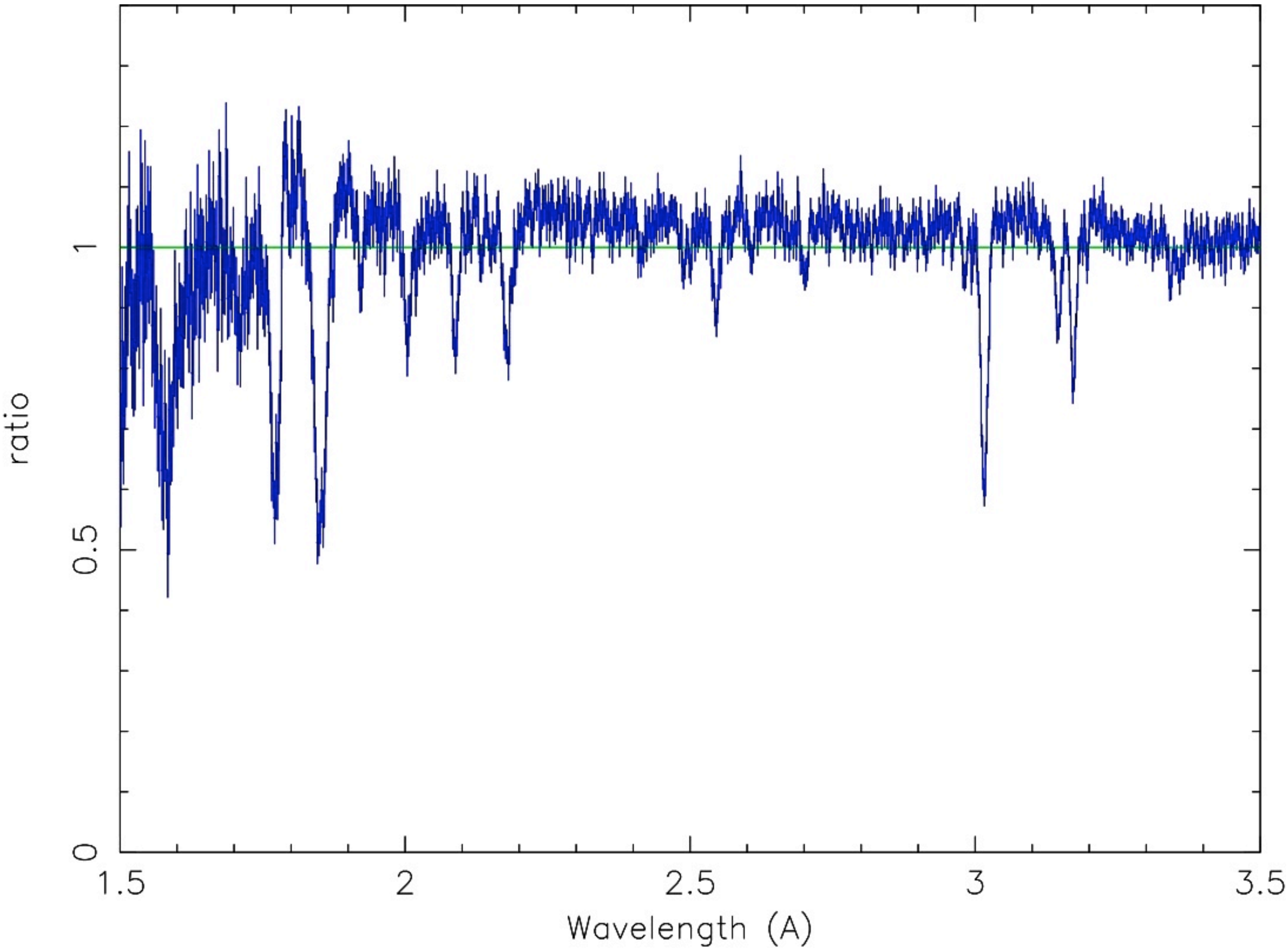
Winds, Jets vs State

Miller et al. 06, 06, 08





(also see Neilsen & Lee 2009)

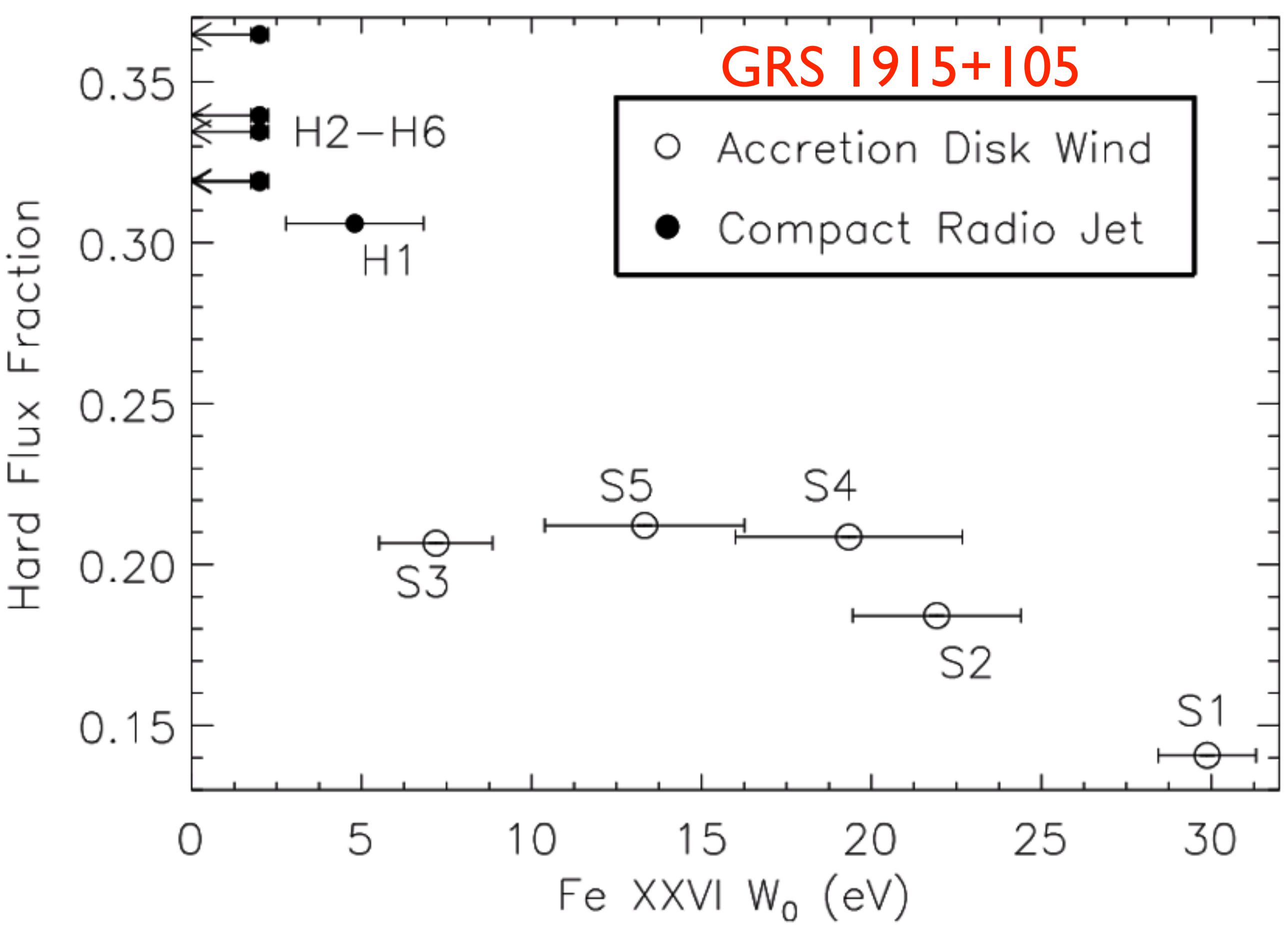


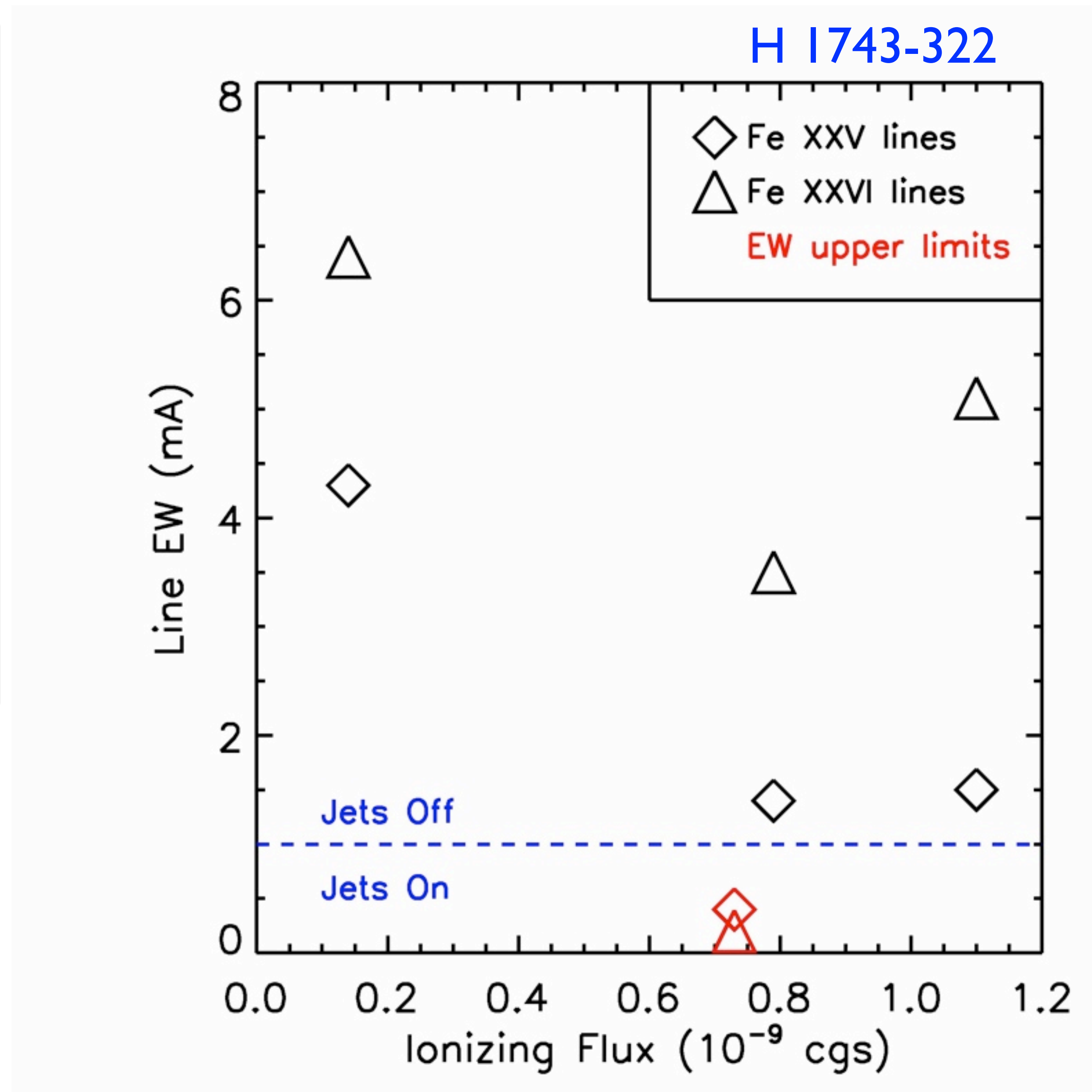
ratio
0
0.5
1
1.5
2
2.5
3
3.5
Wavelength (A)

Winds variations

Neilsen & Lee 2009

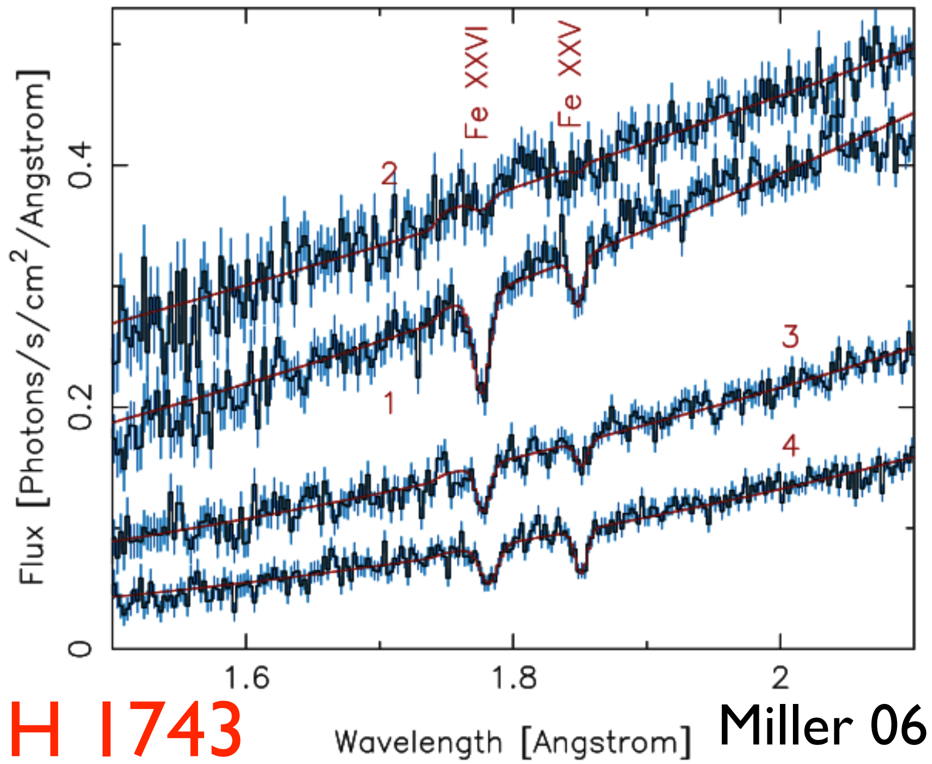
Miller et al. 2011

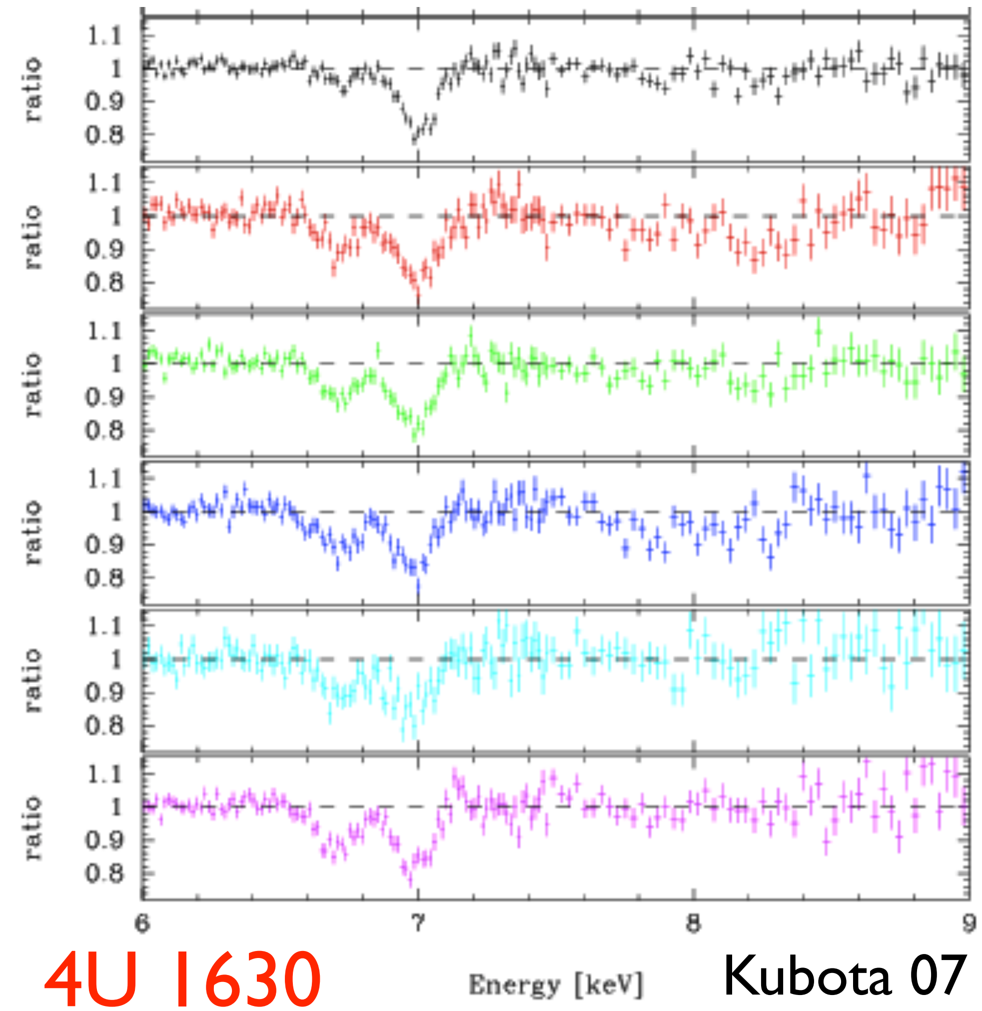


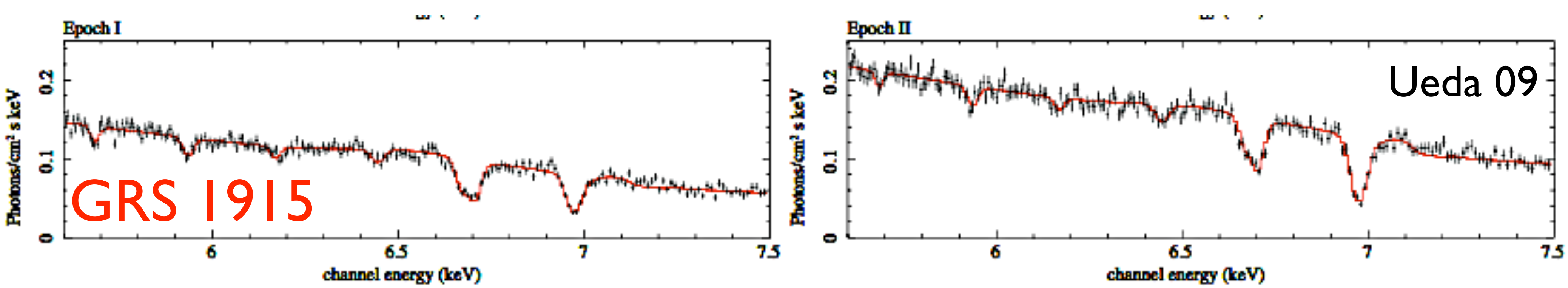


Winds really shut off,
not an ionization effect.

1655 is not alone ...







Driving winds

- Radiation pressure works well for $\log(\xi) < 3$.
  There, there is a force multiplier effect for UV resonance lines.

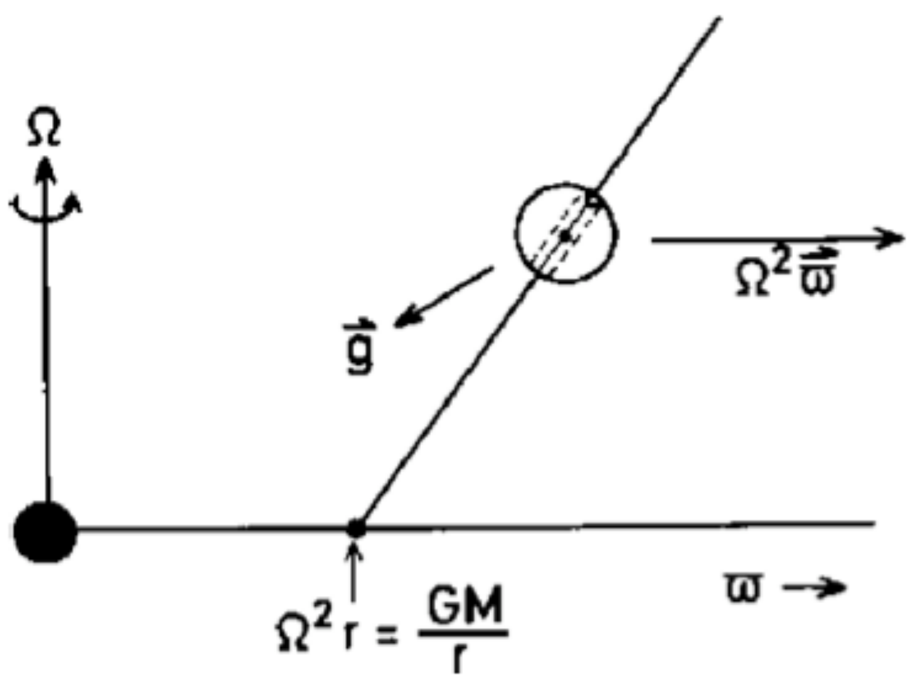
- Thermal pressure is also likely in many instances.
  $kT_{gas} > kT_{escape}$.

- For $\log(\xi) < 3$ and $kT_{gas} < kT_{escape}$ something else is needed.
  Magnetic driving is the only viable option remaining.

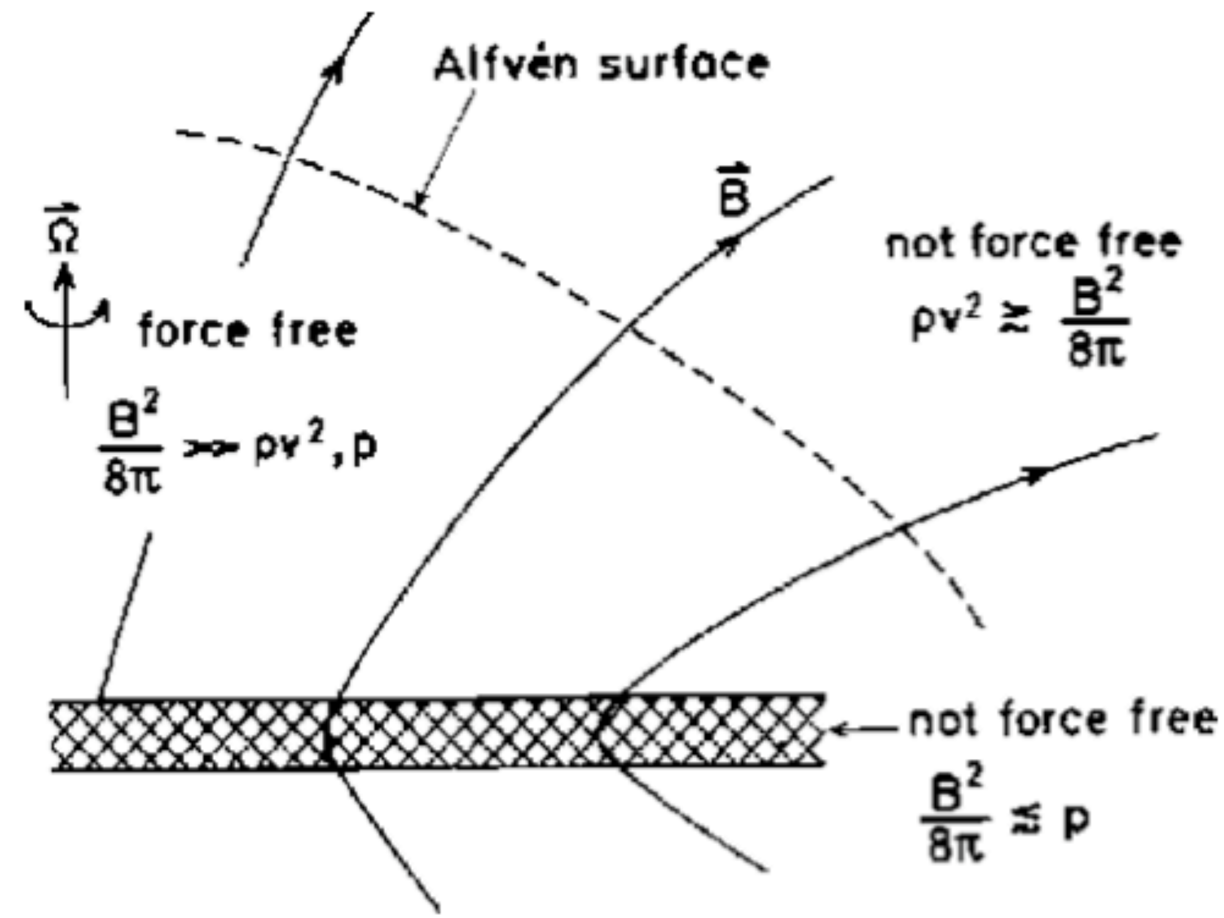
- In all of this, it is vital to have an estimate of density:
  $\xi = L/nr^2$ (Assuming that N = nr is only an upper limit.)

- He-like triplets are common density diagnostics.
  Winds are often seen in absorption, however, and Fe XXII may be good.
  (Mauche & Raymond 2000, Miller et al. 2008).

Paradigm



Spruit 1996

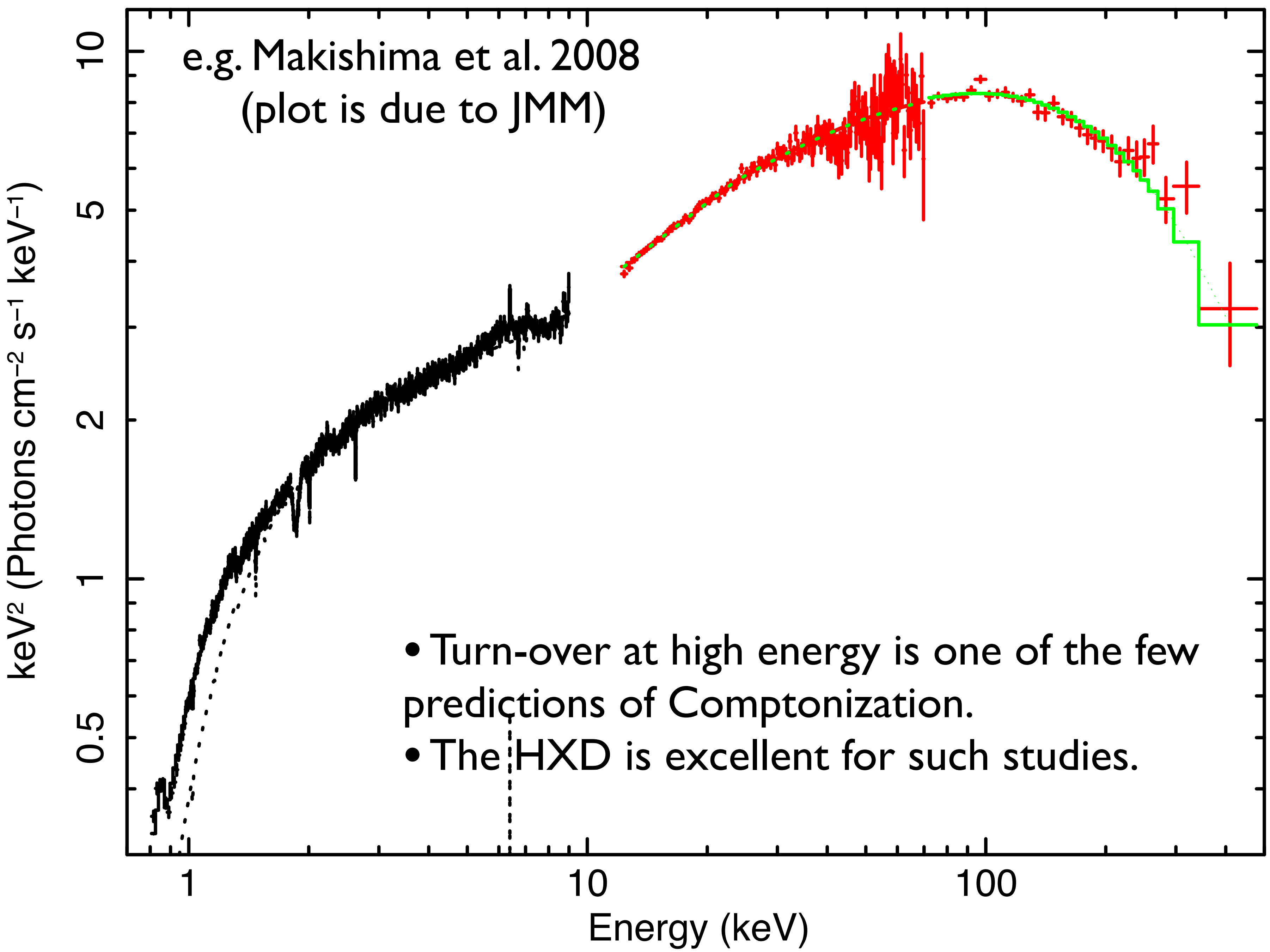


Blandford & Payne 1982

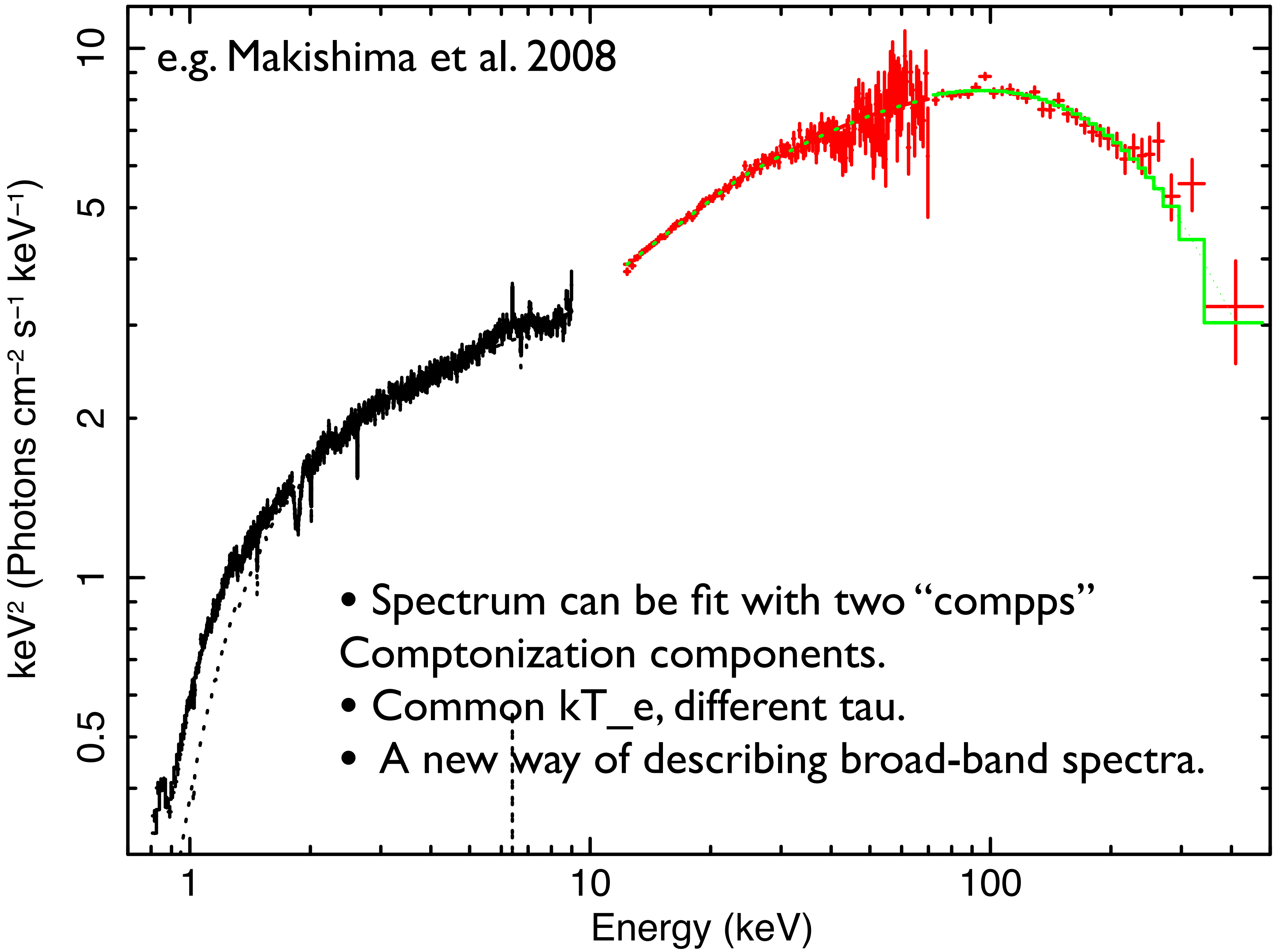
Hard X-ray Emission

- Thermal Comptonization?
- Non-thermal Comptonization?
- Both?!
- Synchrotron?
- Synchrotron self-Comptonization?

Turn-over in Cyg X-1

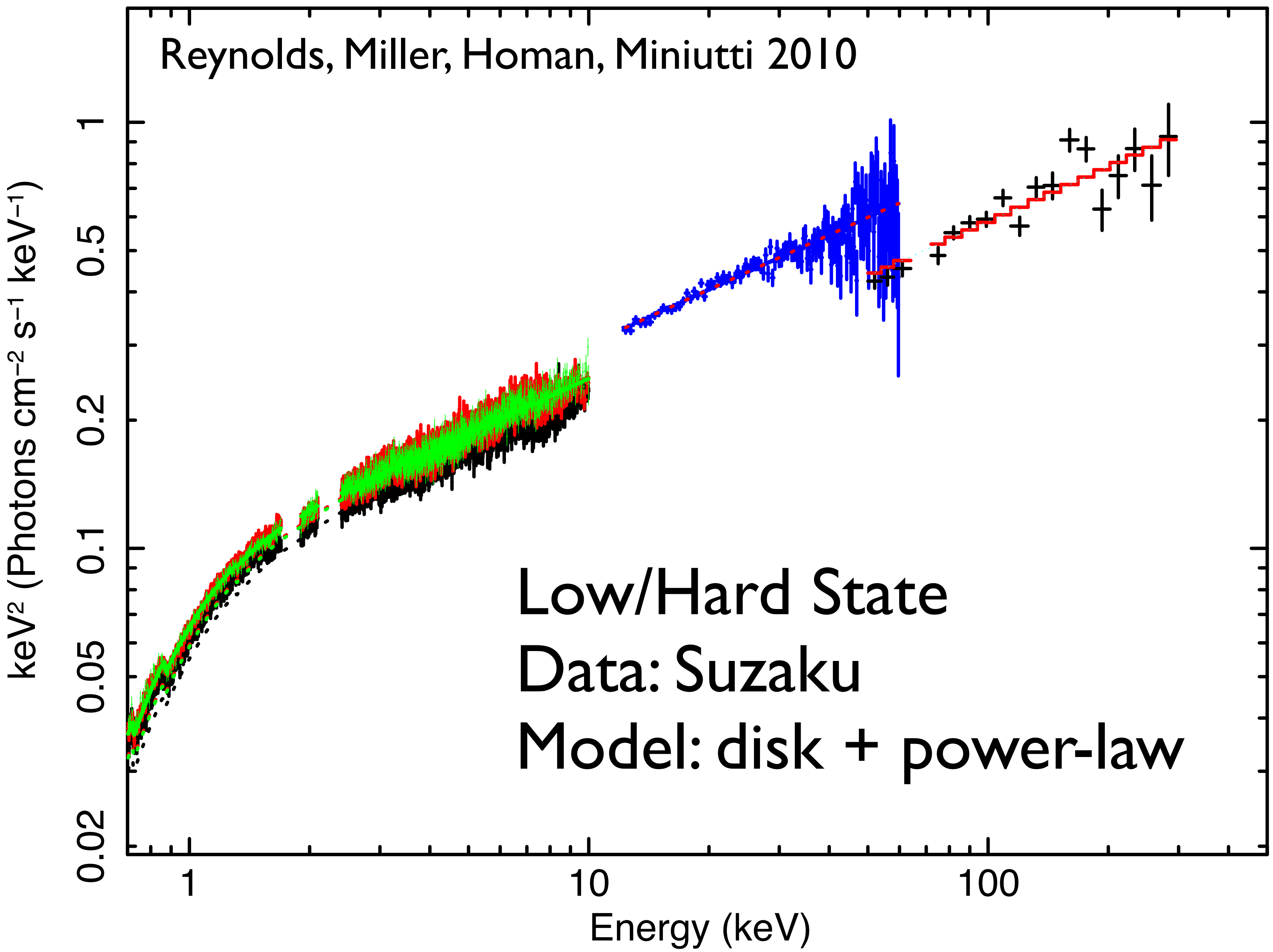


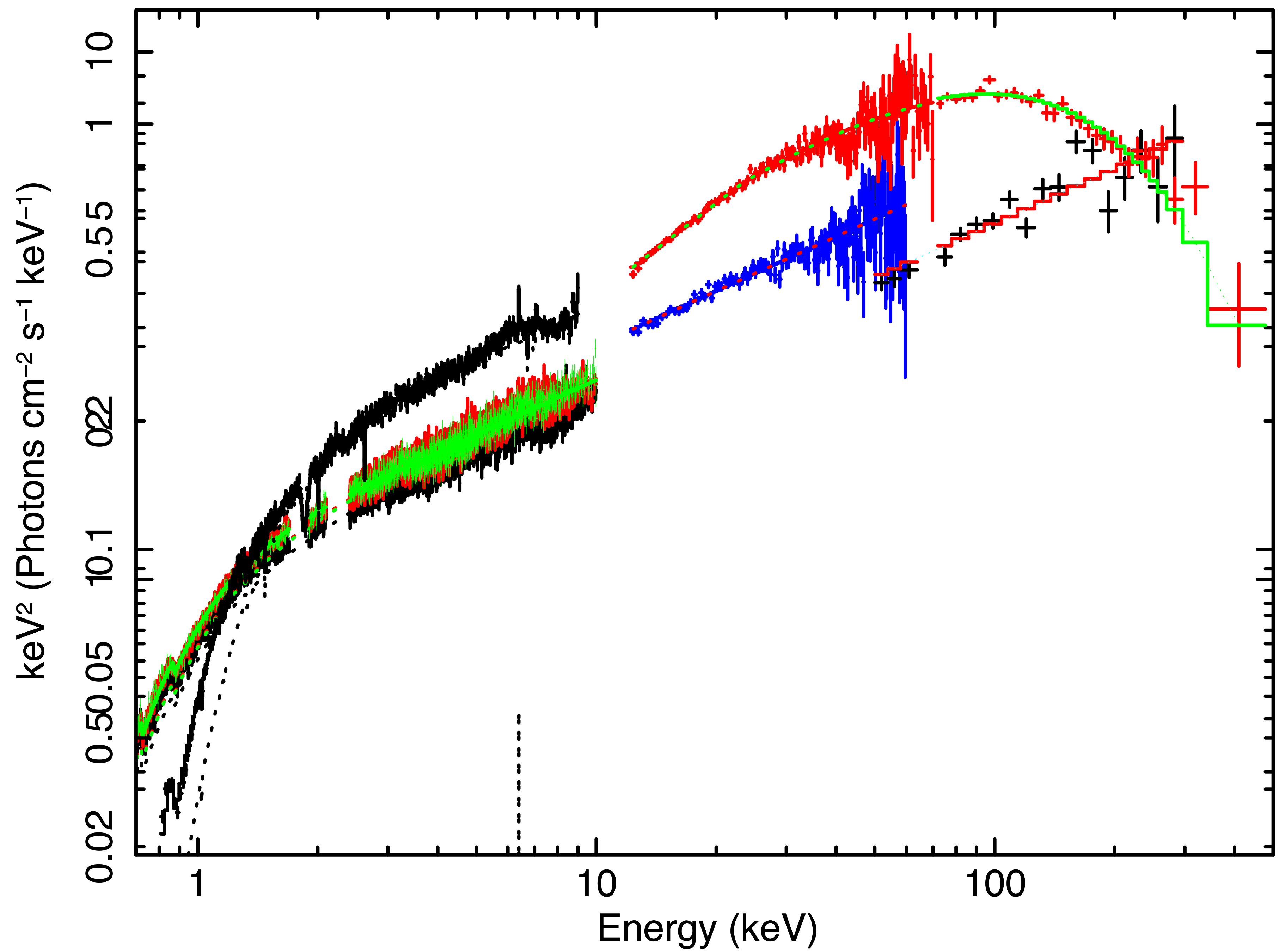
Cyg X-1: complex?



- Spectrum can be fit with two "compps" Comptonization components.
- Common kT_e, different tau.
- A new way of describing broad-band spectra.

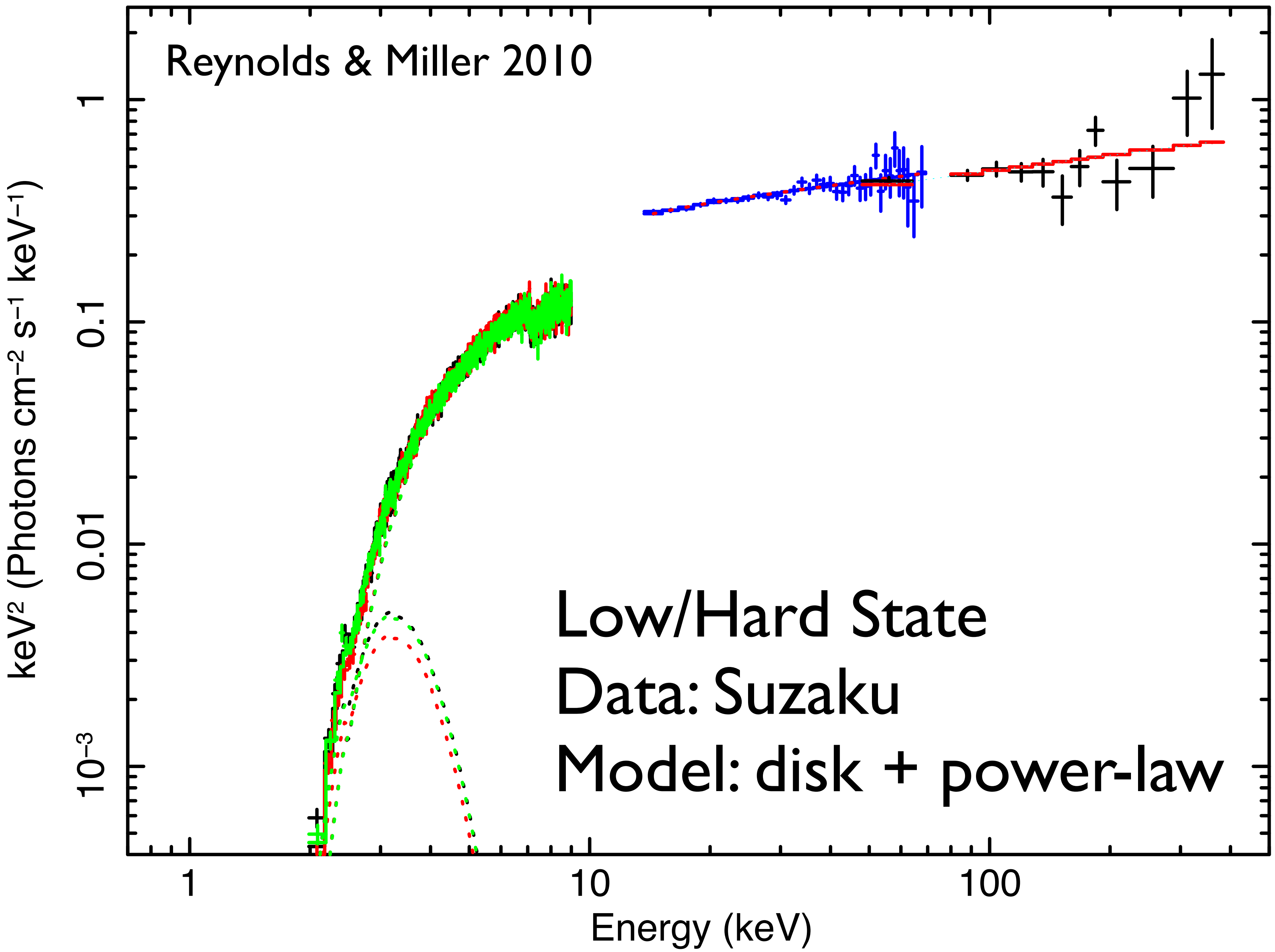
Swift J1753.5





keV² (Photons cm⁻² s⁻¹ keV⁻¹)
10
1
0.55
0.22
10.1
0.50.05
0.50.05
0.02
1
10
100
Energy (keV)

IE 1740.7-2942



Hard X-ray Production

- Thermal or hybrid Comptonization is at work in some sources, e.g. Cygnus X-1.
- Other sources do not show the same signatures. They may require different or additional mechanisms.
- Different sorts of hard states hinted at by Coriat et al. based on X+R observations.

Extra slides