Role of Black Hole Spin in Relativistic Jets

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A Fundamental Plane of Black Hole Activity

(Heinz & Sunyaev 2003; Merloni, Heinz & Di Matteo, 2003; Falcke, Kording, & Markoff, 2004)

$$\log L_R = (0.60^{+0.11}_{-0.11}) \log L_X + (0.78^{+0.11}_{-0.09}) \log M + 7.33^{+4.05}_{-4.07}$$

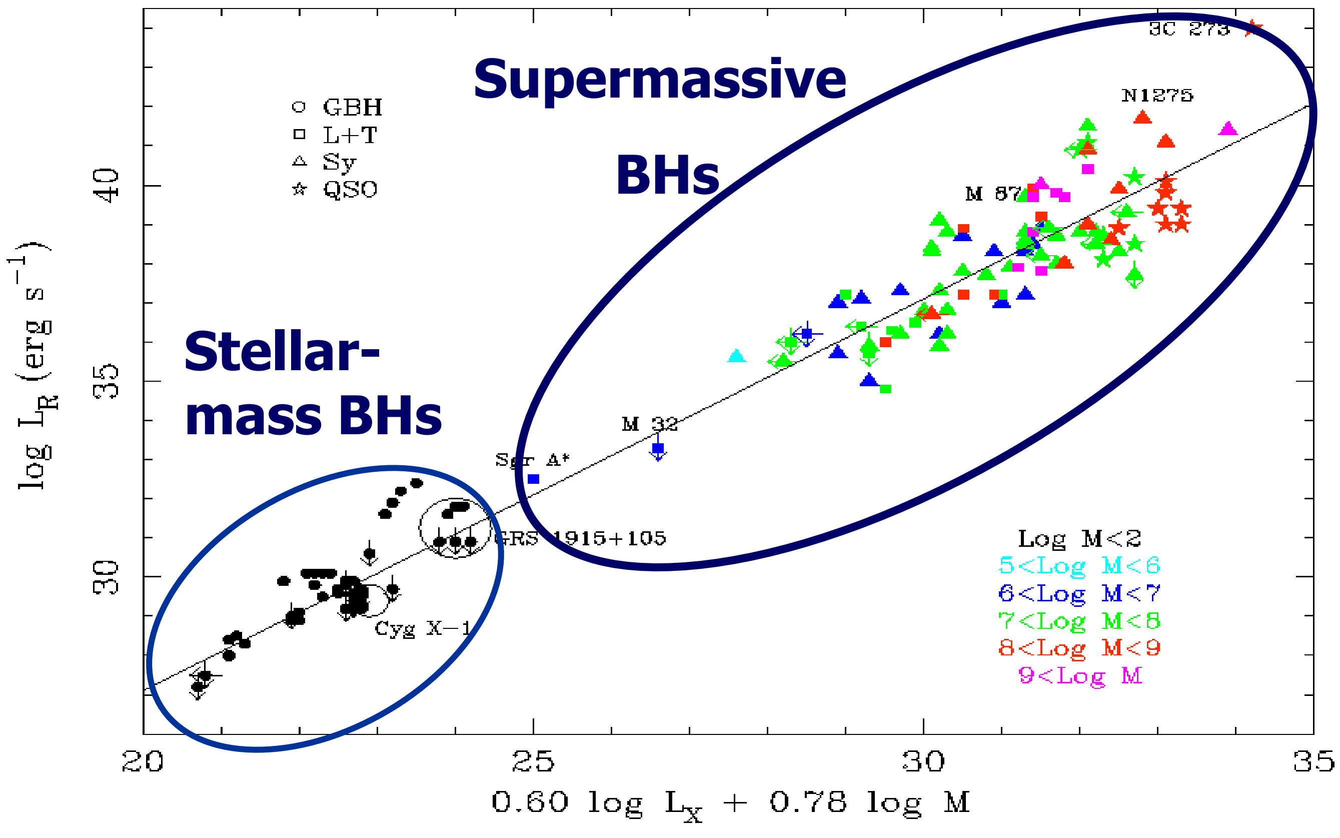


Figure 4. The edge-on view of the "fundamental plane of black hole activity". The solid line shows the best fitting function (5).

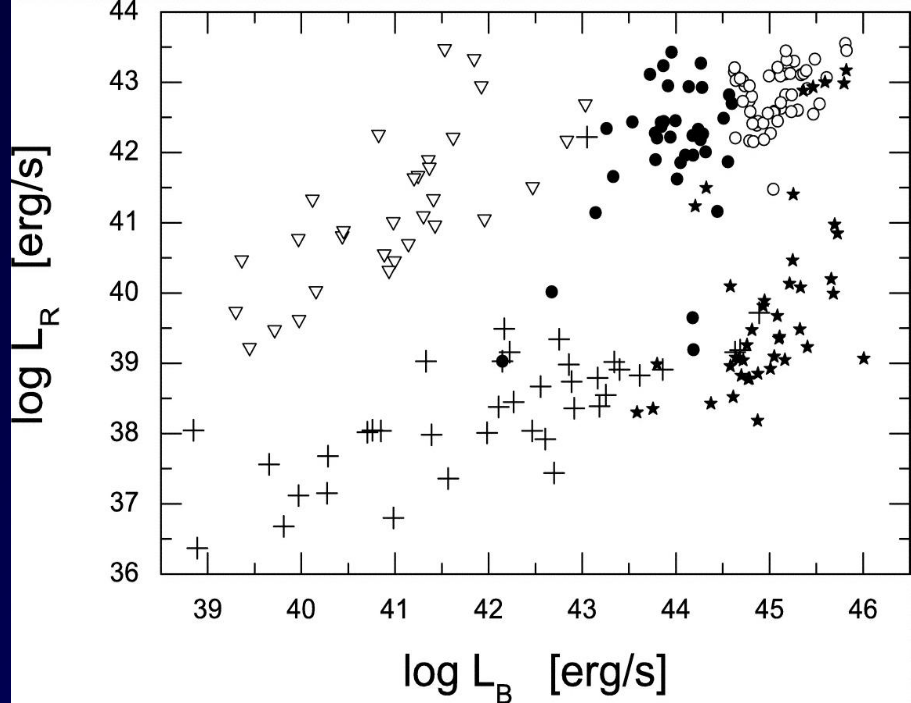
Radio Loud/Quiet Dichotomy

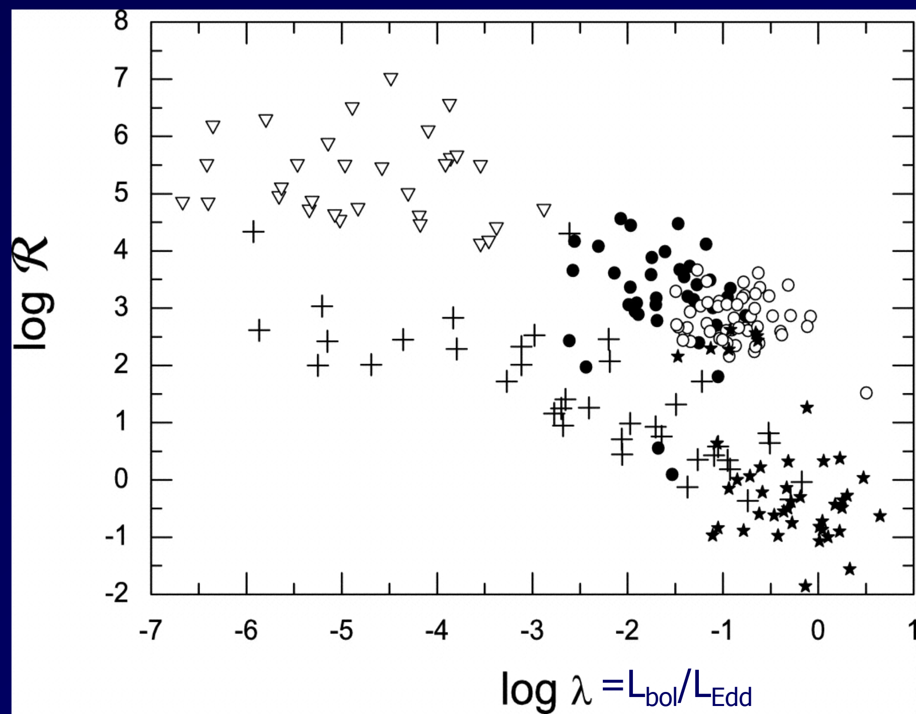
Sikora, Stawarz & Lasota 2007

Two well-separated classes of objects, with a factor **~10³** difference in radio loudness

There must be at least one other parameter in addition to M and Mdot: P_{jet}(M,Mdot,?,?)

Could it be BH spin $\mathbf{a}_*$?





Talk Outline

- Jet power vs
  - BH spin a_* (theory/simulations)
  - Accretion rate Mdot (simulations)
  - Measured values of a_* (observations)

Slowly-Spinning BH: Blandford & Znajek (1977)

For $a_* \ll 1$, BZ give

$$P_{\rm jet} = k\Phi_{\rm tot}^2 \frac{a_*^2}{16 r_g^2} c$$

$$r_g = \frac{GM}{c^2} = \text{ gravitational radius}$$

$$\Phi_{\rm tot} = \text{ magnetic flux on BH}$$

$$k = 0.054 \text{ (split monopole)}$$

$$k = 0.044 \text{ (paraboloidal)}$$

A Good Approximation at High Spins: Tchekhovskoy, Narayan & McKinney (2010)

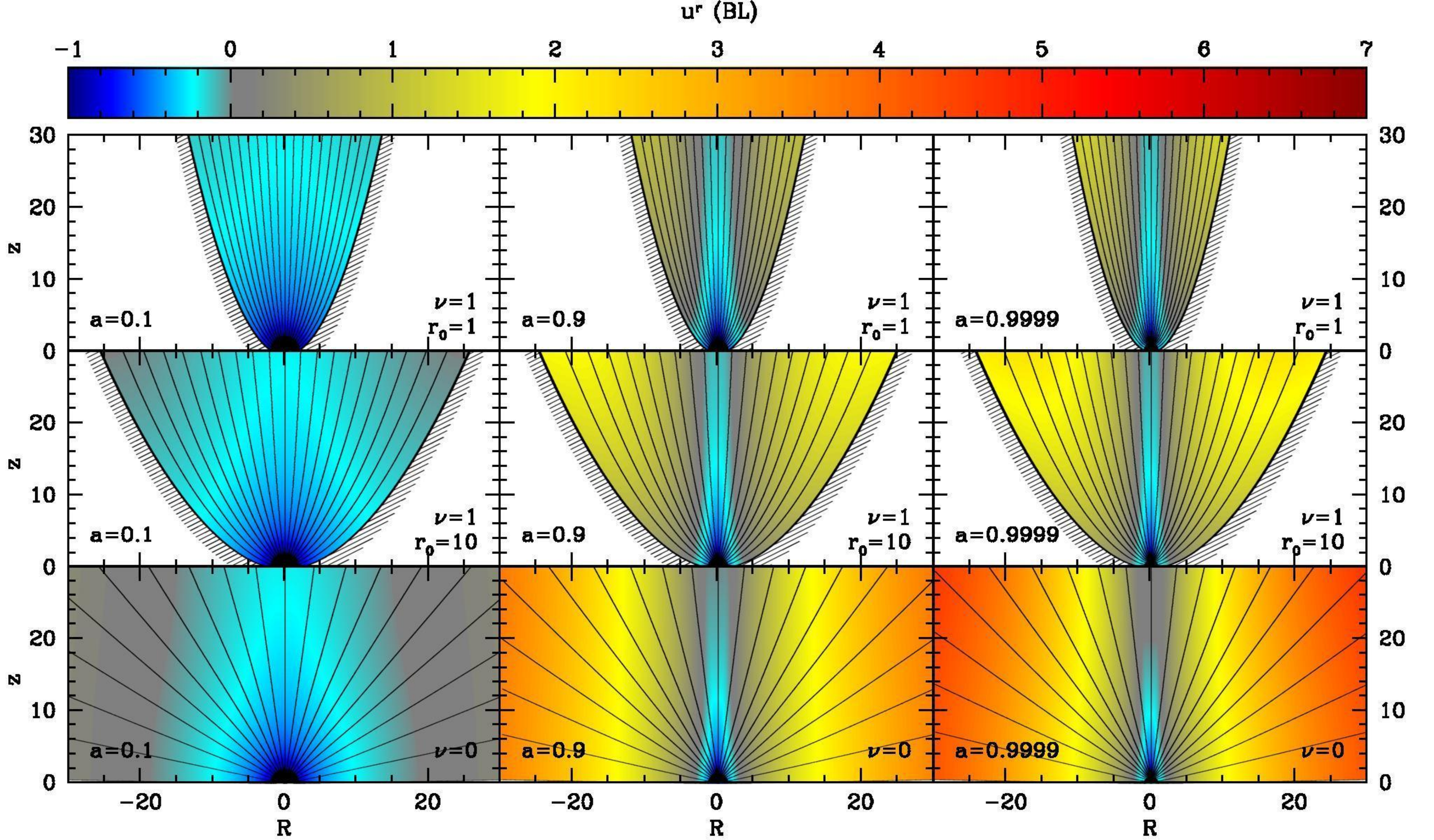
$$P_{\rm jet} = k\Phi_{\rm tot}^2 \left(\frac{\Omega_H}{c}\right)^2 c$$

$$\frac{\Omega_H}{c} = \frac{a_*}{2r_H}$$

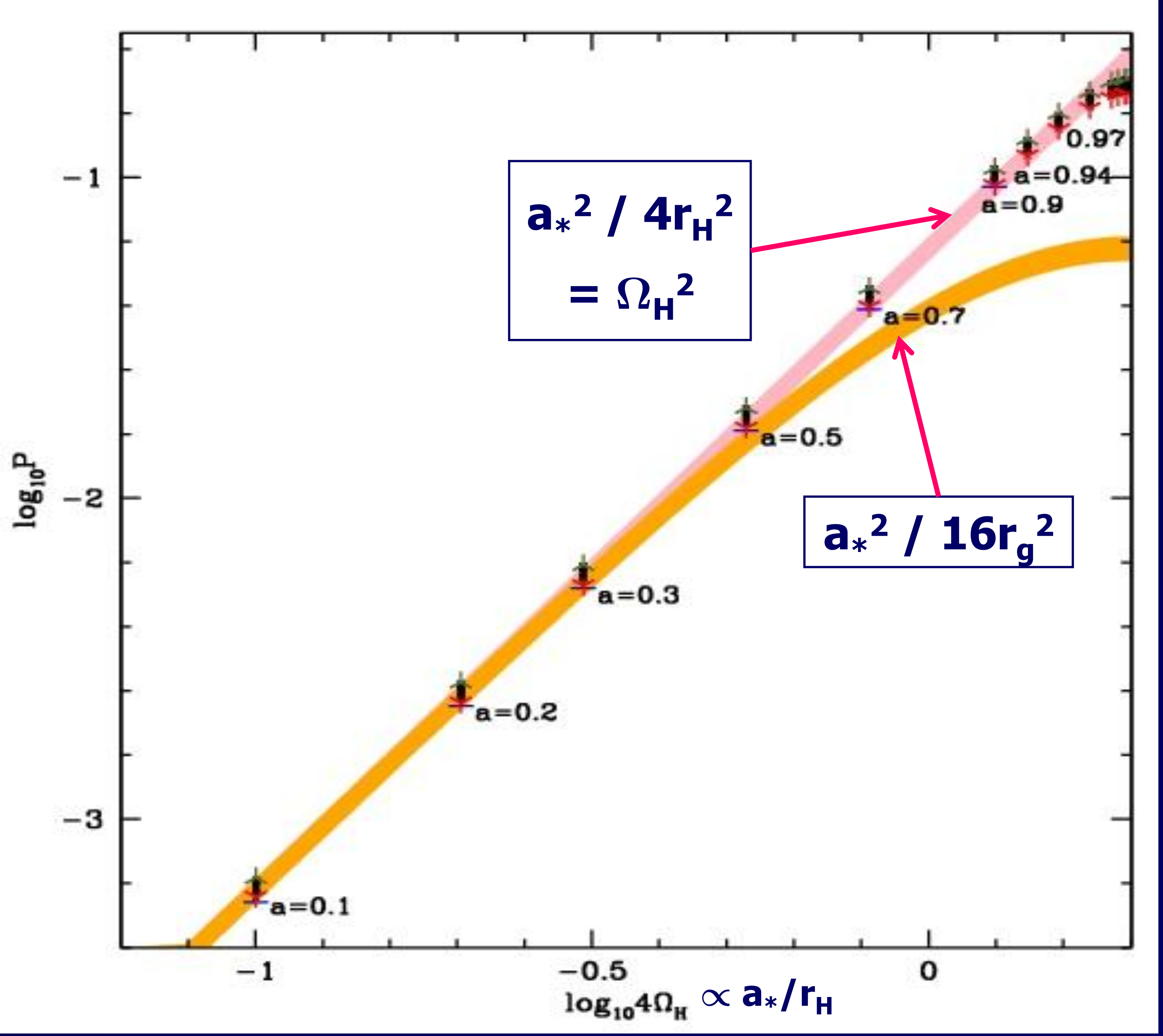
$=$ angular velocity of BH horizon

$$\mathrm{r}_H = r_g\left[1+\left(1-a_*^2\right)^{1/2}\right]$$

$=$ radius of BH horizon



Tchekhovskoy et al. (2010)



Fixed Φ_{tot}, **M**, varying **a_***, force-free simulations in the **Kerr metric:**
Jet power increases steeply with spin (Tchekhovskoy et al. 2010)

Dynamic Range of Jet Power

- The scaling $P_{jet} \propto \Omega_H^2$ gives a fairly wide range of jet power as a_* is varied
- If a_* varies from 0.1 to 1, the jet power (for fixed ϕ_{tot}) varies by $\sim 10^{2.5}$
- If a_* varies from 0.3 to 1, the jet power varies by $\sim 10^{1.5}$
- Even larger range possible if we have a thick disk (ADAF) and only the magnetic flux in the funnel contributes to the jet

What Next?

- We now have a pretty good idea of how power varies with a_*, viz., $\propto \Omega_H^2$ or steeper
- However, jet power also depends on ϕ_{tot}
- What determines the value of ϕ_{tot}?
- Clearly it is the accretion disk
- Let us define jet efficiency η_{jet} by:

$$P_{jet} = \eta_{jet}\, \mathrm{Mdot}\, c^2$$

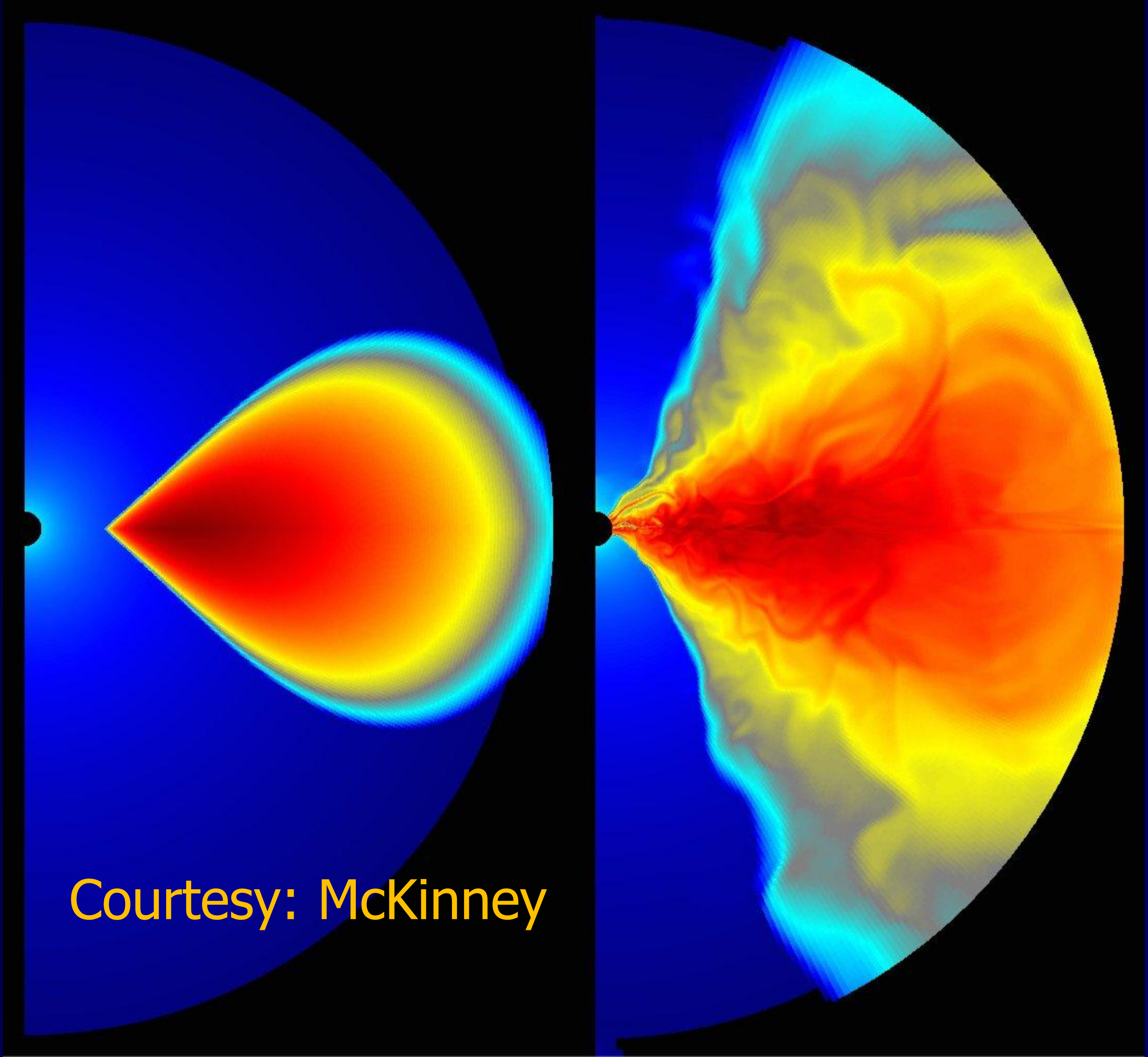
- How big can η_{jet} be?
- We can look at simulations for the answer

Jet-Disk GRMHD Simulations

2D and 3D GRMHD simulations of magnetized accretion produce relativistic jets self-consistently: Koide, Gammie, McKinney, de Villier, Hawley, Nagataki, Komissarov,Tchekhovskoy,...

Jets and ADAFs

- Most GRMHD simulations deal with radiatively inefficient systems (ADAFs) – and these invariably produce winds and/or jets
- Suggests a strong jet-ADAF connection (Narayan & Yi 1994, 1995) – **collimation**
- Also, ADAF simulations generally produce **organized magnetic field**
- So the coherent dipolar field needed for a strong jet seems to occur fairly naturally


Courtesy: McKinney

Jet Efficiency in GRMHD Simulations

- Jet power is found to depend on magnetic topology (Beckwith, Hawley & Krolik 2008; McKinney…)
  - Dipolar geometry gives high power
  - Quadrupolar or toroidal, almost no power
- Dipolar geometry is expected if large-scale field is advected to the center (from ISM/companion star)
- GRMHD simulations so far give only $\eta_{jet} \sim 0.2$ even for very rapidly spinning BHs (McKinney 2005; de Villiers et al. 2005; Hawley & Krolik 2006;…)
- Not too impressive
- Can we obtain larger values of η_{jet}?

Accretion Power or Black Hole Spin Power?

- An isolated spinning BH has no jet
- Accretion disk needed to make a jet
- Question: Is the jet powered by the accretion disk or the BH?
- Not easy to answer this simple question
- Jet power increases with a_*. But this could just be due to accretion power increasing in the deeper potential well
- How do we know it is Penrose/BZ?

Clean Demonstration of BH Spin Power

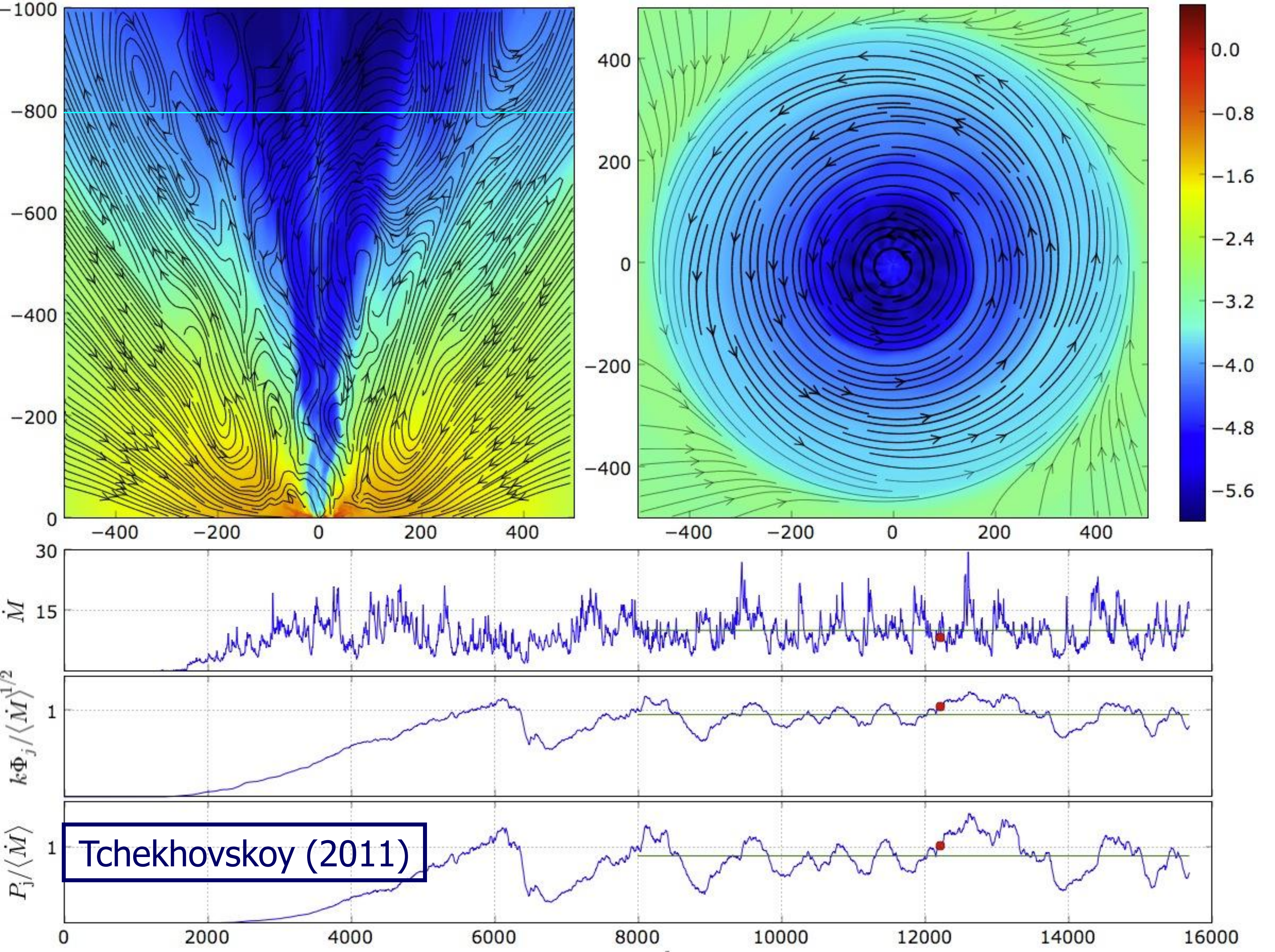
If we can show via a GRMHD simulation that the kinetic+thermal+magnetic energy coming out in the jet exceeds the total rest mass energy accreted by the BH, then we can confidently state that the BH is the source of the jet power:

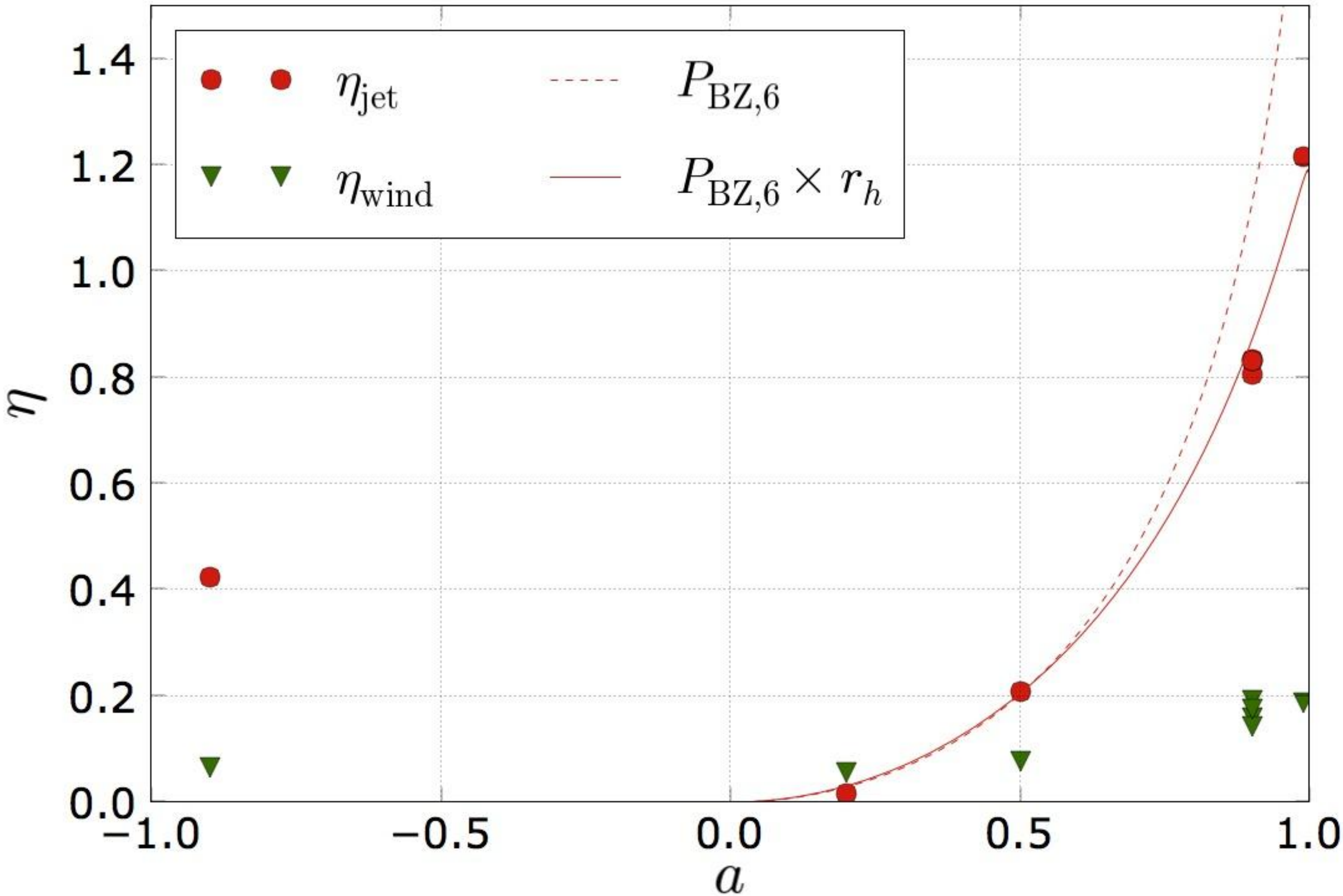
$$\eta_{\rm jet} = \frac{P_{\rm jet}}{\dot{M}\, c^2} > 1$$

Tchekhovskoy (2011)

- 3D GRMHD (**2π**) simulations using HARM with high accuracy STAGgered representation of field (McKinney) (superior to previous TOTH scheme)
- Novel coordinates that follow the jet
- Well-defined jet forms; flops a lot, but is stable (McKinney & Blandford 2009; Narayan, Li & Tchekhovskoy 2009)
- **>100% efficiency seen!!**

Movie Based on Tchekhovskoy's Simulation with $a_*=0.9$


−1000
−800
−600
−400
−200
0
−400 −200 0 200 400
400
200
0
−200
−400
−400 −200 0 200 400
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$\dot{M}$
30
15
$k\Phi_j/\langle\dot{M}\rangle^{1/2}$
1
$P_j/\langle\dot{M}\rangle$
1
0 2000 4000 6000 8000 10000 12000 14000 16000
Tchekhovskoy (2011)



Tchekhovskoy (2011)

Summary of Simulations

- Jet power depends on how strong the field is – which is determined by initial torus
- Tchekhovskoy's simulations are designed to maximize the magnetic flux $\phi_{\mathbf{tot}}$ on the BH
- $\phi_{\mathbf{tot}}$ seen to saturate after some time (MAD)
- $\eta_{jet} > 1$ for $a_* \gtrsim 0.9$ (wind power uncertain)
- **Clear demonstration that the system is tapping the spin energy of the BH!!** (Penrose 1969; Blandford & Znajek 1977)
- Counter-rotating disk has less efficient jet

Flux Saturation

- For a given Mdot, the BH can accept only a certain maximum ϕ_{tot}
- If the disk brings in more flux, the steady accretion flow is arrested and gas accretes in bursts via reconnection
- This is a magnetically arrested disk (MAD, Narayan, Igumenshchev & Abramowicz 2003; Proga…)

Testing the Jet-BH Spin Connection via Observations

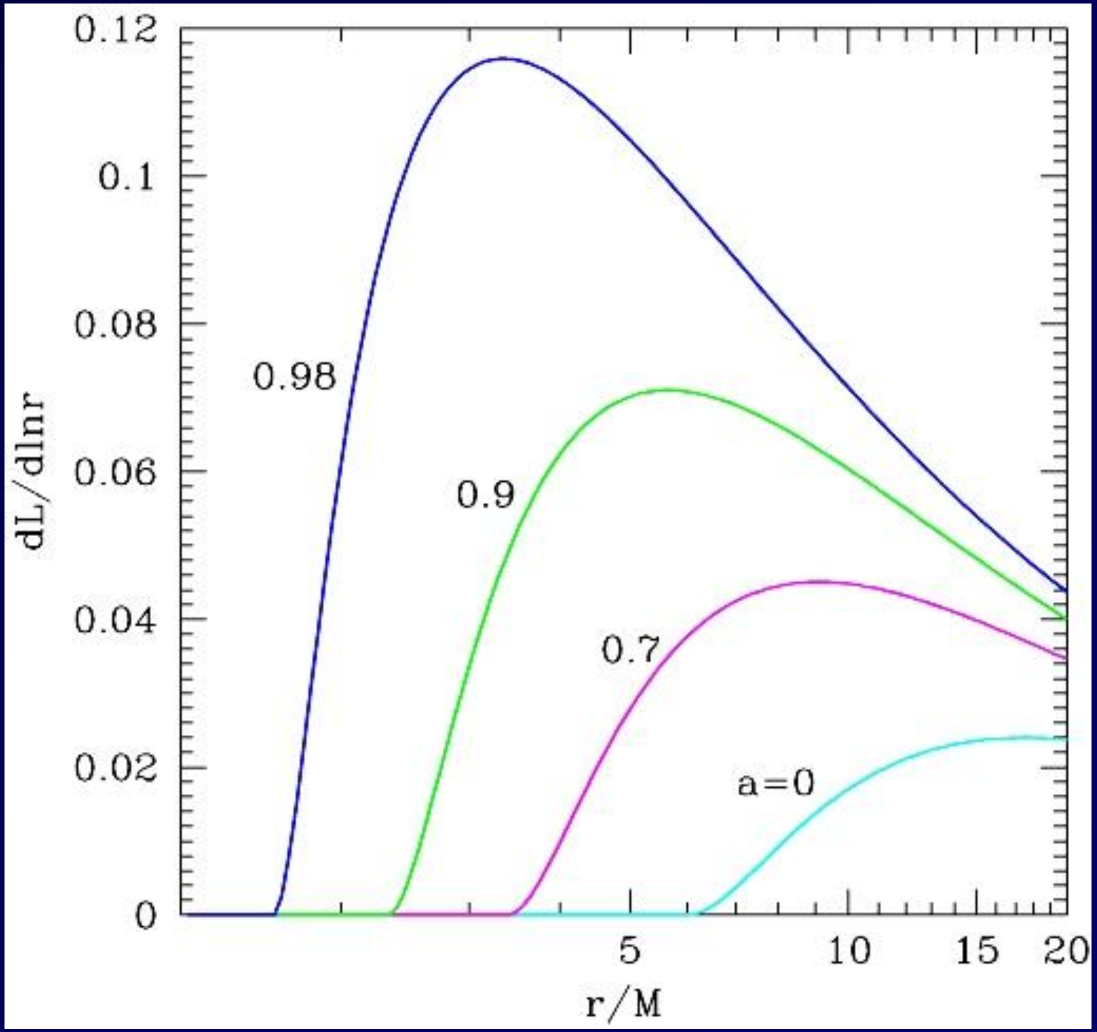
- We now have reasonably robust estimates of BH spin for a handful of stellar-mass BHs (BH XRBs)
- We (McClintock, Narayan, et al.) measure $\mathbf{a}_*$ by fitting the X-ray continuum spectrum of the disk in the Thermal (High Soft) spectral state
- Use the Novikov & Thorne (1973) model

General Relativistic Disk Model: Novikov & Thorne (1973)

L(r) peaks at a different radius for each value of the dimensionless BH spin parameter a_*

Therefore, the observed spectrum depends on a_*

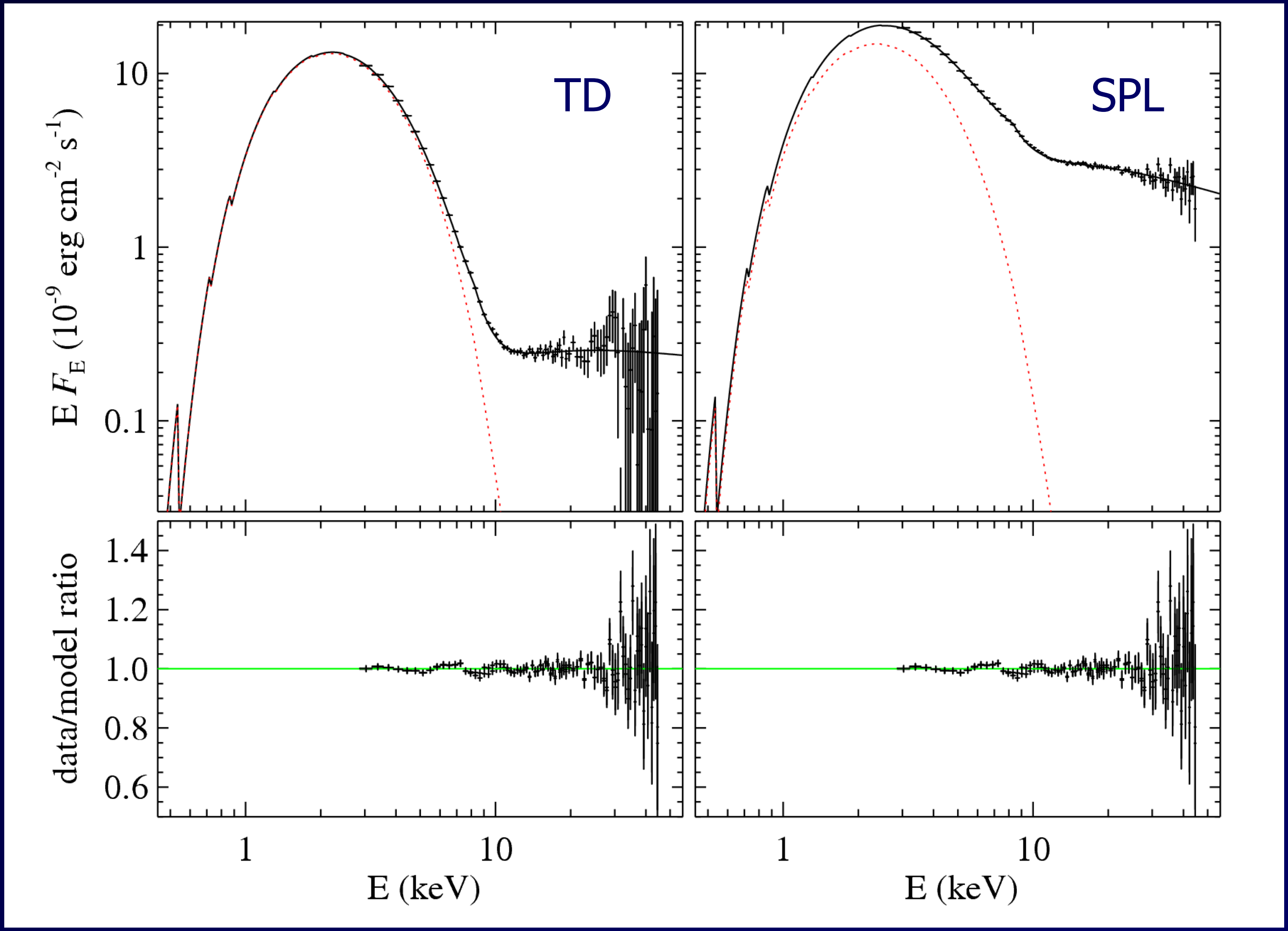
This is what enables us to estimate a_* from observations



Can We Achieve Necessary Accuracy to Measure a_*?

- The model predictions are quantitatively robust – very few uncertainties (no α)
- In Thermal Dominant (TD) spectral state radiation processes are simple
  - Optically thick, blackbody-like emission
  - Easier than a stellar atmosphere
  - Spectral hardening is under control (**Davis**)
- Boundary condition at the ISCO is okay

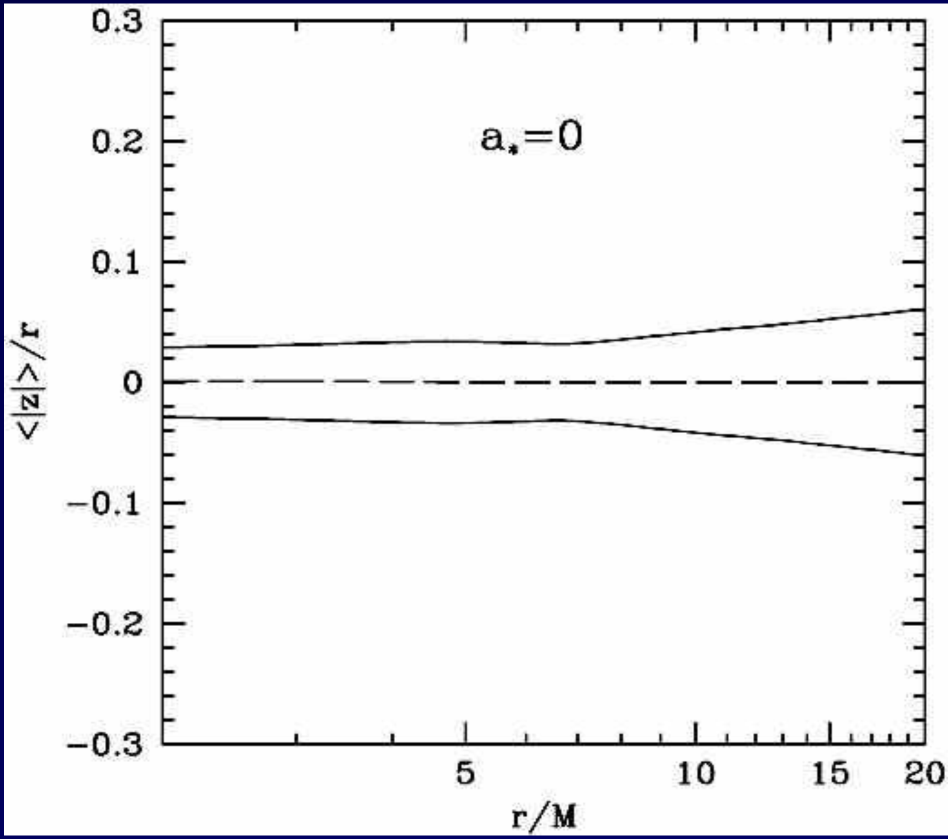
XTE J1550-564



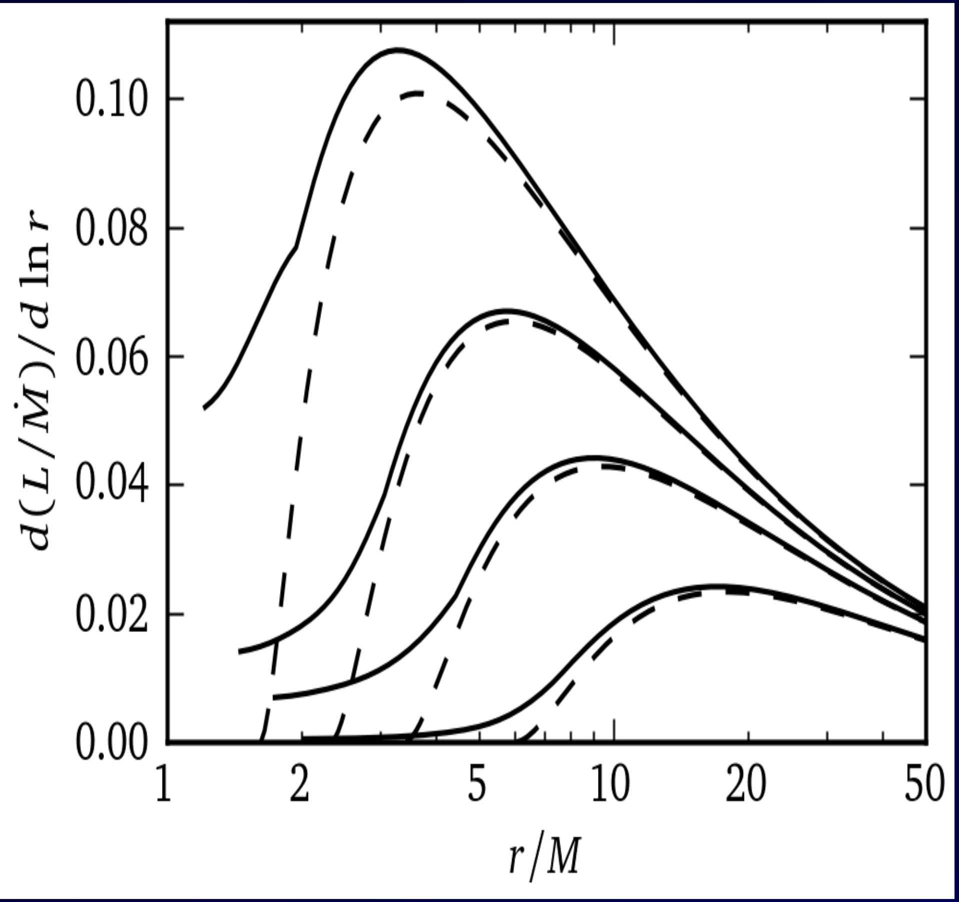
X-ray continuum spectral fits and residuals for a TD and an SPL observation of XTE J1550-564 (Steiner et al. 2010)

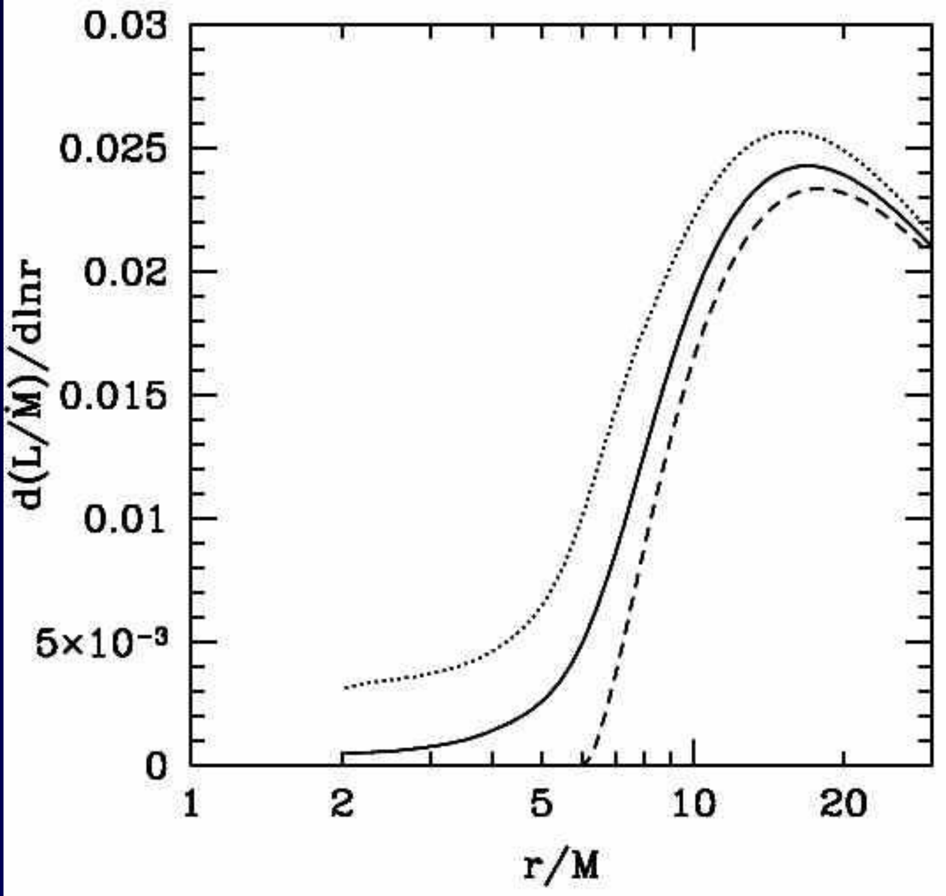
3D GRMHD Simulations of Thin Accretion Disks

- Shafee et al. (2008), Penna et al. (2010)
- Self-consistent MHD simulations (HARM: Gammie, McKinney & Toth 2003)
- All GR effects included
- $h/r \lesssim 0.05$ (thin!!)
- Very few other thin disk simulations: Reynolds & Fabian (2008); Noble, Krolik & Hawley (2009, 2010)



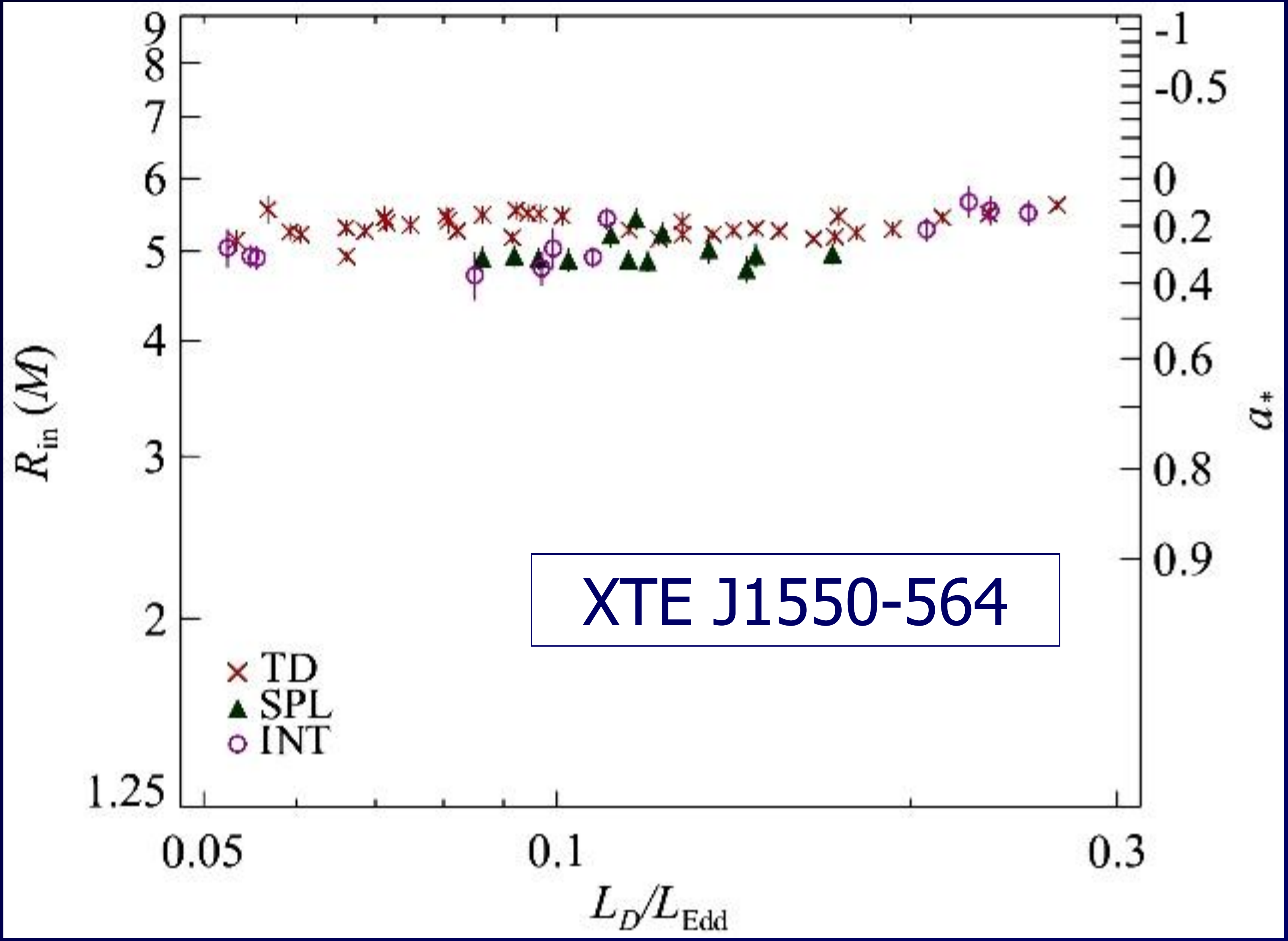
Disk thickness profile ($a_*=0$)
Penna et al. (2010)





Luminosity profile
Simulation vs NT model
a_* = 0, 0.7, 0.9, 0.98
Kulkarni et al. (2011)

Luminosity profile
Thin disk vs Thicker disk
a_* = 0
Kulkarni et al. (2011)



Estimates of disk inner edge R_{in} and BH spin parameter a_* from **35** TD and **25** SPL/Intermediate data (**Steiner et al. 2011**)

BH Spin Values

Source Name	BH Mass ($M_\odot$)	BH Spin (a_*)
A0620-00	6.3—6.9	0.12 ± 0.19
LMC X-3	5.9—9.2	~0.25
XTE J1550-564	8.5—9.7	0.34±0.24
GRO J1655-40	6.0—6.6	0.70 ± 0.05
4U1543-47	8.4—10.4	0.80 ± 0.05
M33 X-7	14.2—17.1	0.84 ± 0.05
LMC X-1	9.4—12.4	0.92 ± 0.06
Cyg X-1	13.8—15.8	> 0.95
GRS 1915+105	10—18	> 0.98

Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007,2009); Gou et al. (2009,2010,2011); Steiner et al. (2010)

With Apologies to Fender, Gallo & Russell (2010)

- Fender et al. (2010) compared jet power with BH spin estimates and concluded that there is no correlation
- However, they used all claimed spin estimates (no quality control), whereas many of the measurements are spurious
- It is like correlating jet power against random numbers → no correlation

A Better Approach

- Focus only on the most believable spin estimates
- Use a homogeneous sample, so that systematics are similar
- Here we restrict our attention to spin estimates via X-ray continuum-fitting

BH Spin Values vs Relativistic Jets

Source Name	BH Mass ($M_\odot$)	BH Spin (a_*)
A0620-00 (J)	6.3—6.9	0.12 ± 0.19
LMC X-3 ⇐	5.9—9.2	~0.25
XTE J1550-564 (J)	8.5—9.7	0.34±0.24
GRO J1655-40 (J)	6.0—6.6	0.70 ± 0.05
4U1543-47 (J)	8.4—10.4	0.80 ± 0.05
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Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007,2009); Gou et al. (2009,2010,2011); Steiner et al. (2010)

Two Significant Measurements

- A0620-00
  - Low spin: $a_* = 0.12 \pm 0.19$ (Gou et al. 2010)
  - 200 mJy radio flare during outburst (Kuulkers)
  - Steady 0.05 mJy radio emission in quiescence (Gallo)
- XTE J1550-564
  - Lowish spin: $a_* = 0.34 \pm 0.24$ (Steiner et al. 2011)
  - Relativistic blobs: radio (Hannikainen), X-ray (Corbel)
  - Genuine microquasar
- If the above two spin estimates are reliable, then we can make a strong case that jets are not powered by BH spin

How Confidently Can We Say that BH Spin has no Effect on Jets?

- Spin estimates of both A0620-00 and XTE J1550-564 have fairly large errors: ~ ± 0.2 (1-σ)
- There might also be systematic errors that we have (inclination, radiation transfer) or have not thought of
- Thus, we cannot state with certainty (e.g., 3-σ) that these two BHs have spin less than 0.5
- Given this situation, it is premature to claim that BH spin has nothing to do with relativistic jets

How to Resolve this Issue?

- More hard work!
- Reduce the statistical uncertainties further with better observations/analysis
- More GRMHD work to tackle systematics
- Find and study more low-spin BHs
- Get other spin methods, especially Fe line, to the same level (repeatability, systematics) as continuum-fitting

A Theorist's Perspective

- Considerable theoretical support for a connection between BH spin and jets
- Lovely idea – hard to resist!
- If not BH spin, what else could cause radio loud/quiet dichotomy?
  - Magnetic field strength or topology?
  - Something else in the accretion disk?
  - Jet collimation in external ISM?

Summary

- Major new tools are now available for cracking the jet problem
  - 3D GRMHD Simulations
  - Observational Advances: BH spin
- The situation is still a little murky, e.g., jet-spin connection is not yet clear
- The good news is that progress is likely in the next few years