Disk-jet connection in black hole accretion simulations

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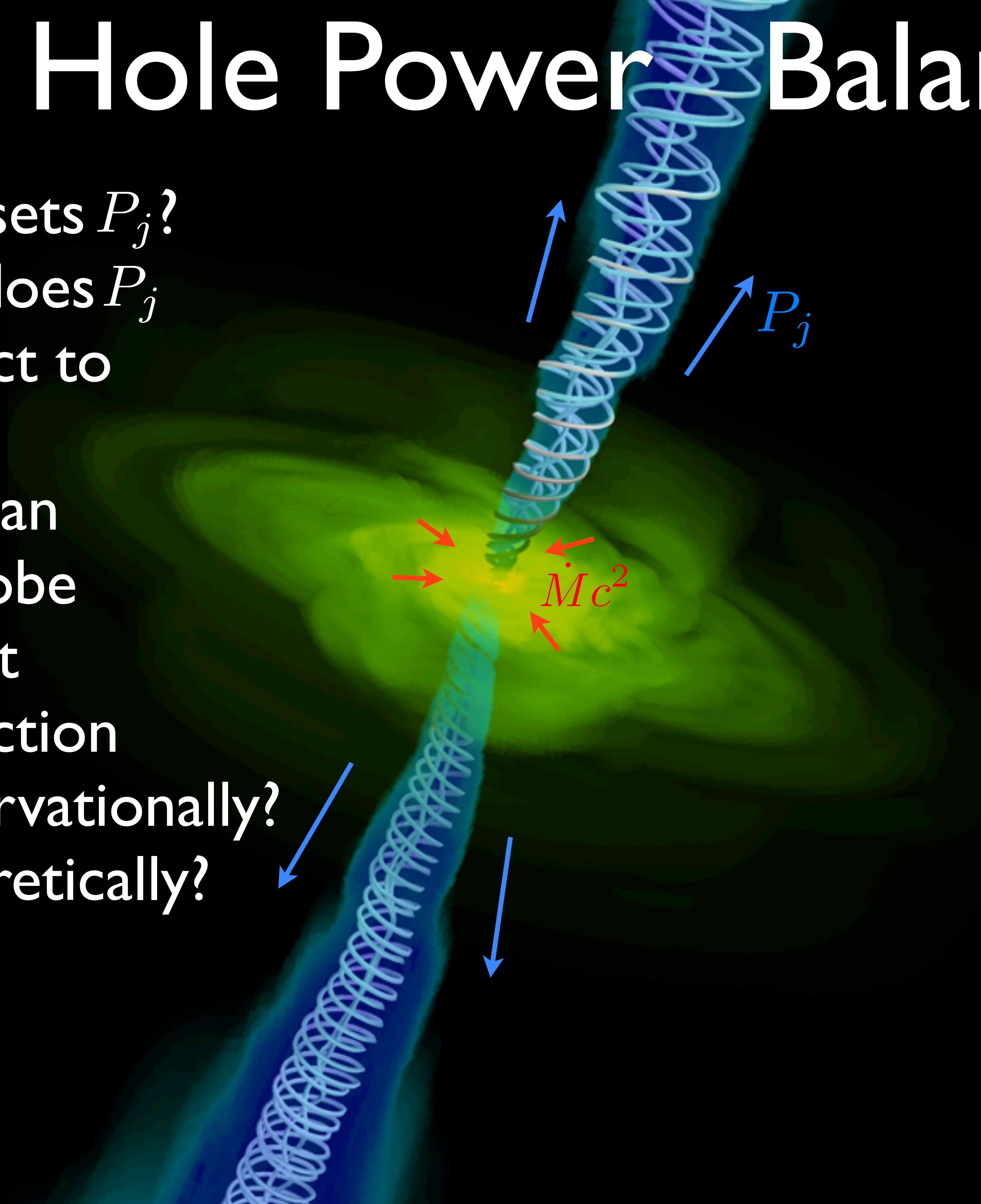
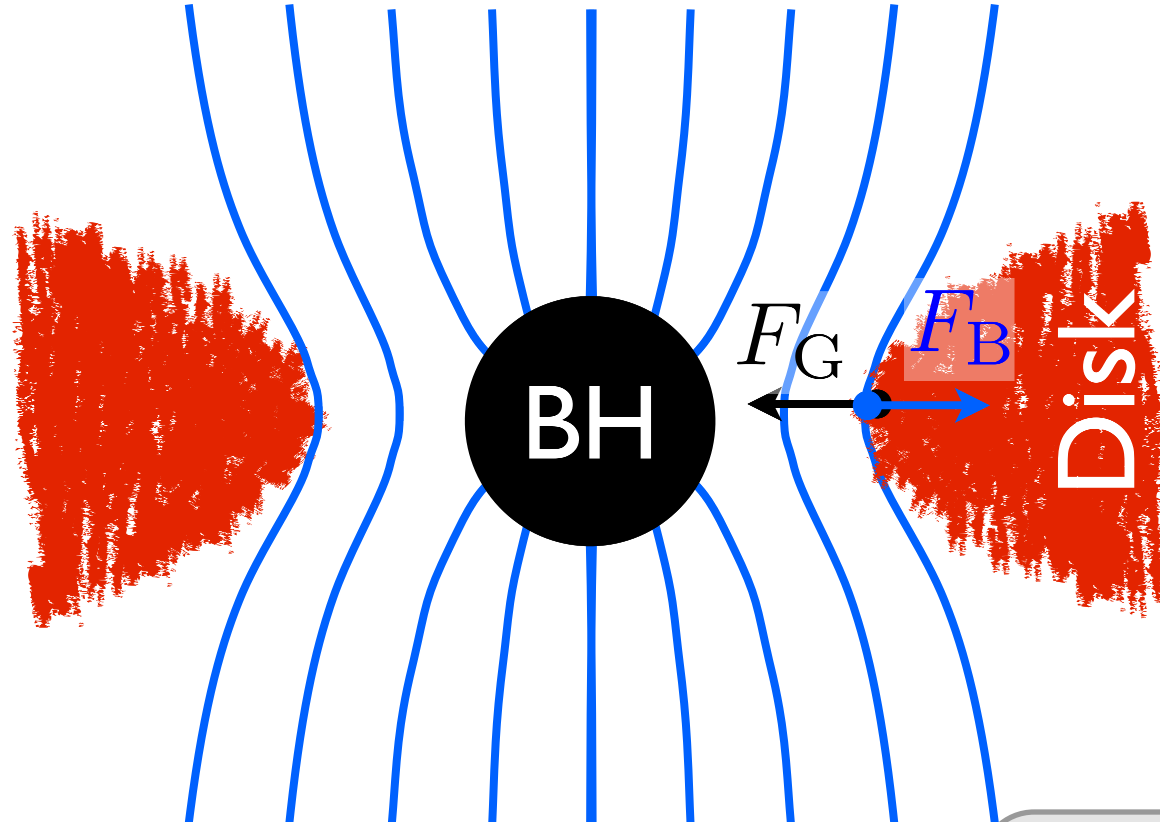
Black Hole Power Balance

- What sets P_j?
- How does P_j connect to $\dot{M}c^2$?
- How can we probe disk-jet connection
  - observationally?
  - theoretically?



What Sets Jet Power?

Gravity limits P_j and Φ!



magnetic flux:
$\Phi \sim B r_g^2$

grav. radius:
$r_g = GM/c^2$

$$P_j \sim a^2 B^2 r_g^2 c \propto \Phi^2 (a/r_g)^2$$

$(a/r_g)^2 \rightarrow k$

$$0 \le P_j = k\Phi^2 \lesssim \dot{M}c^2$$

B sub-dominant ↕ $\Phi = 0$

B dominant ↕ $\Phi = \Phi_{\rm MAX}$

*M*agnetically-*A*rrested *D*isk (MAD)

(Narayan+ 2003, Tchekhovskoy+ 2011)

How strong are the jets? $p_j = P_j/\dot{M}c^2$

What Sets Jet Power?

What sets magnetic field strength on the hole?
Is it inner disk's...

- magnetic pressure? $(B^2/8\pi)_{BH} = (B^2/8\pi)_{DISK}$ NO
- total pressure? $(B^2/8\pi)_{BH} = P_{DISK}$ NO
- ram pressure? $(B^2/8\pi)_{BH} = (\rho c^2)_{DISK}$ NO!

ux:

s:

M/c^2

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Magnetically-Arrested Disk (MAD)
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$(a/r_g)^2 \to k$

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k

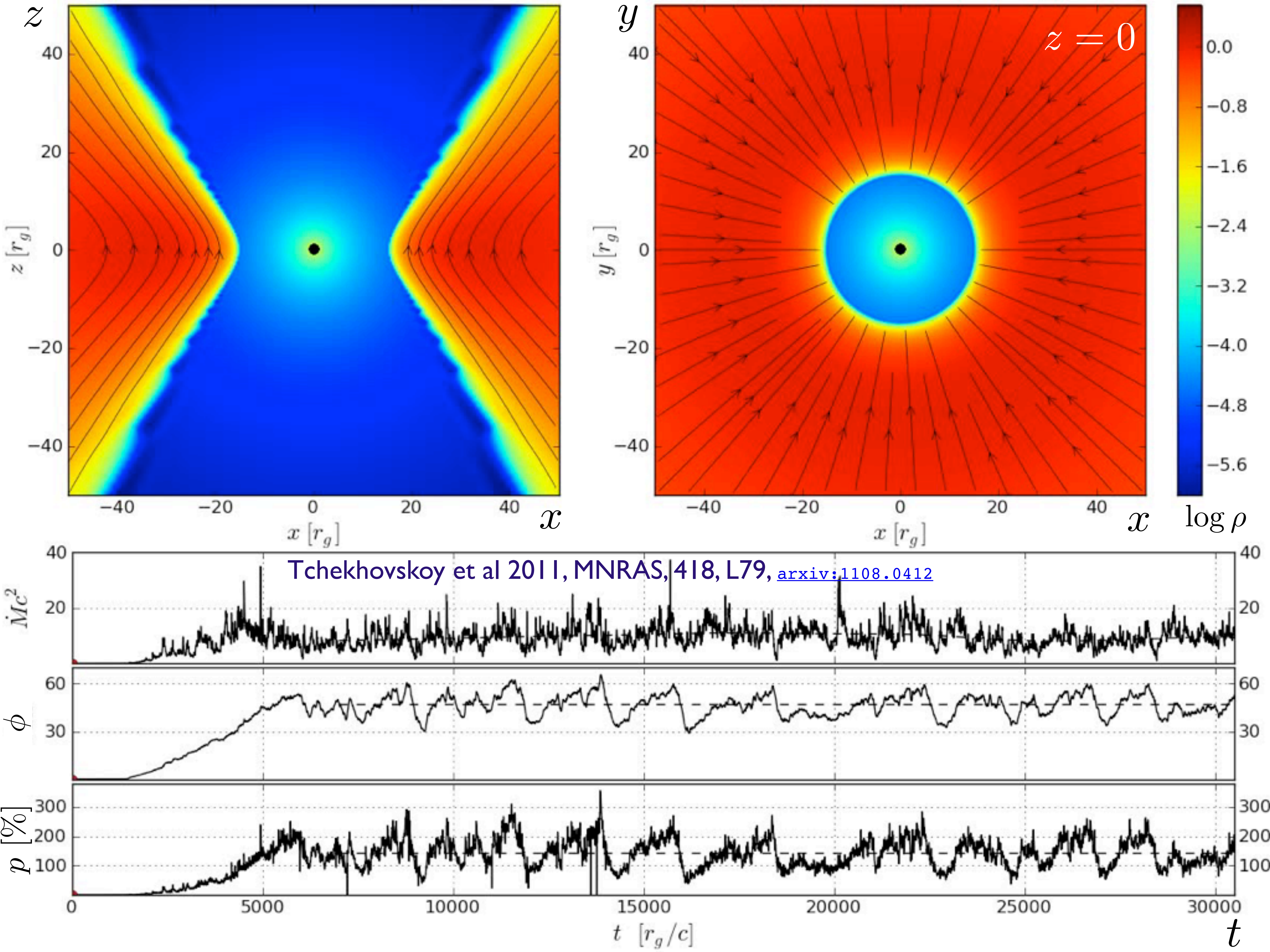
- Numerical experiments via advanced 3D *GRMHD* simulations with the HARM code (Gammie+03, McKinney & Blandford 09, Tchekhovskoy+07,11): took over 1000 CPU-years!

How strong are the jets?

$$p_j = P_j/\dot{M}c^2$$

(MAD)

(Narayan+ 2003, Tchekhovskoy+ 2011)

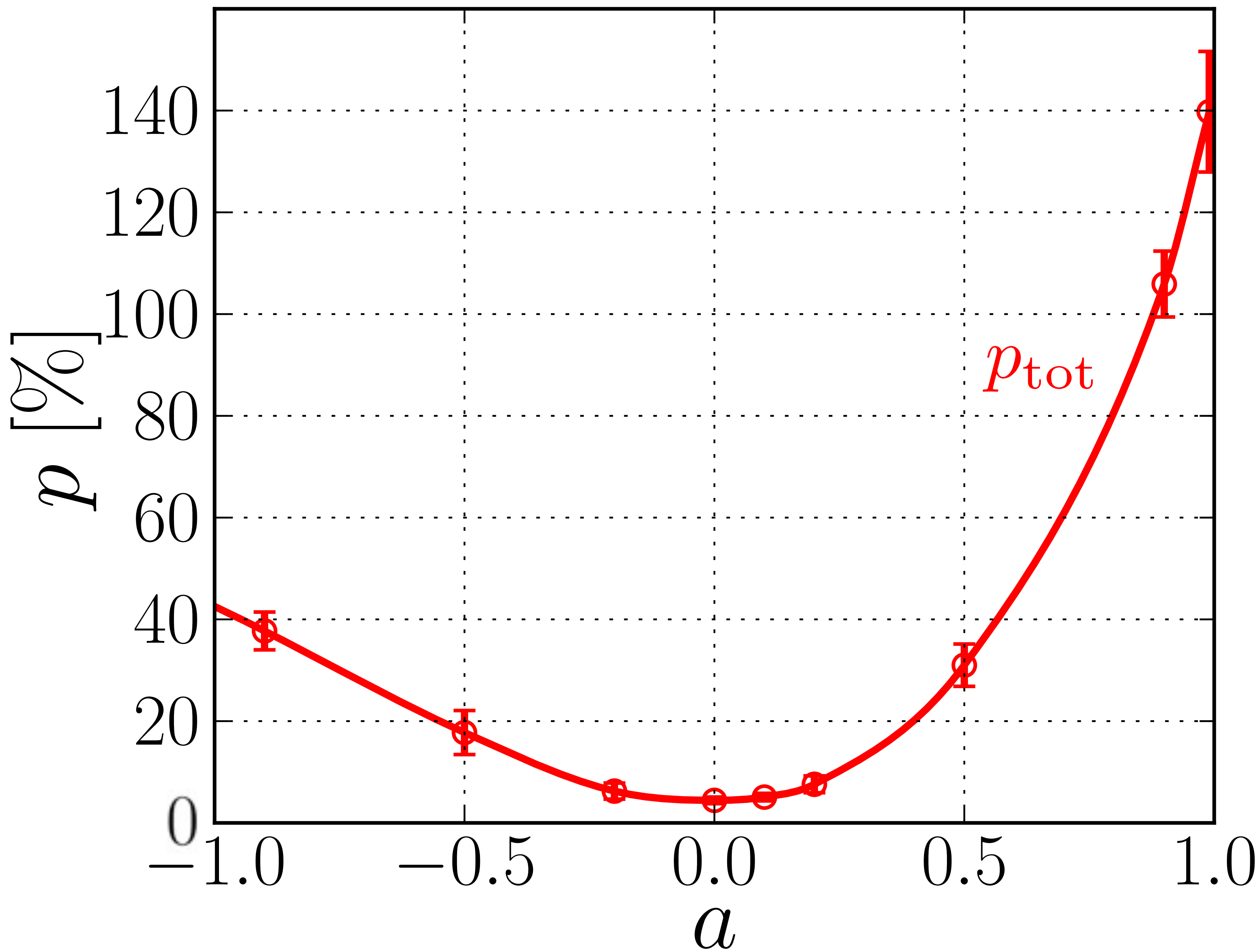


z
y
z = 0
x
x
log ρ
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
z [r_g]
y [r_g]
x [r_g]
x [r_g]
Tchekhovskoy et al 2011, MNRAS, 418, L79, arxiv:1108.0412
Ṁc²
φ
p [%]
t [r_g/c]
t

Upper Envelope of Jet Power vs. Spin

($h/r \sim 0.3$)

(Tchekhovskoy+ 11; Tchekhovskoy, McKinney 12; McKinney, Tchekhovskoy, Blandford 12; Tchekhovskoy 15)



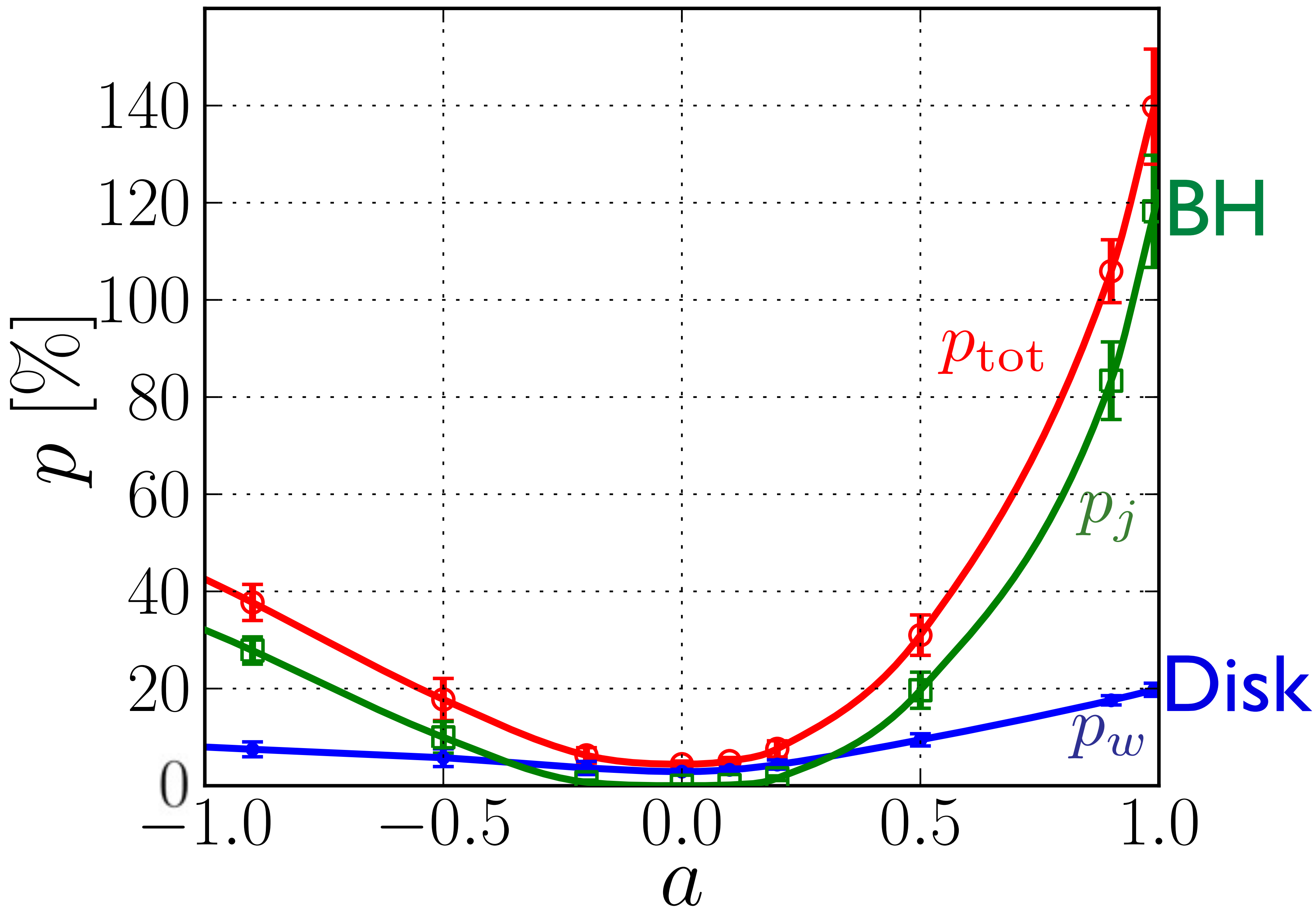
Can *quantify* feedback due to black hole jet, disk wind from *first principles*

That $p > 100\%$ unambiguously shows that net energy is extracted from the BH

Upper Envelope of Jet Power vs. Spin

$(h/r \sim 0.3)$

(Tchekhovskoy+ 11; Tchekhovskoy, McKinney 12; McKinney, Tchekhovskoy, Blandford 12; Tchekhovskoy 15)



Can *quantify* feedback due to black hole jet, disk wind from *first principles*

High spin: most power is from black hole spin (Blandford-Znajek)

Low spin: most power is from disk spin (Blandford-Payne)

(see also Meier 1999)

Upper Envelope of Jet Power vs. Spin

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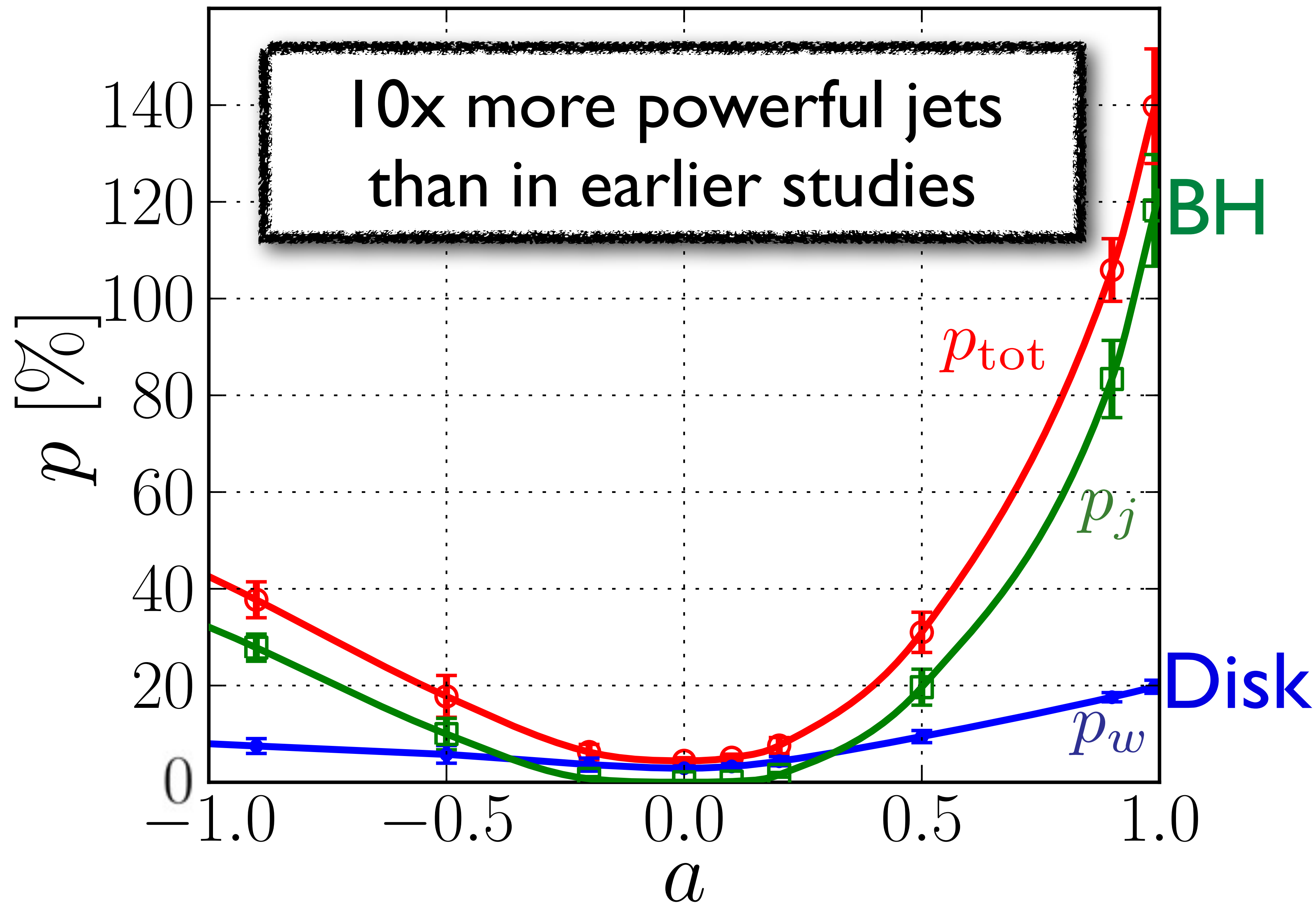

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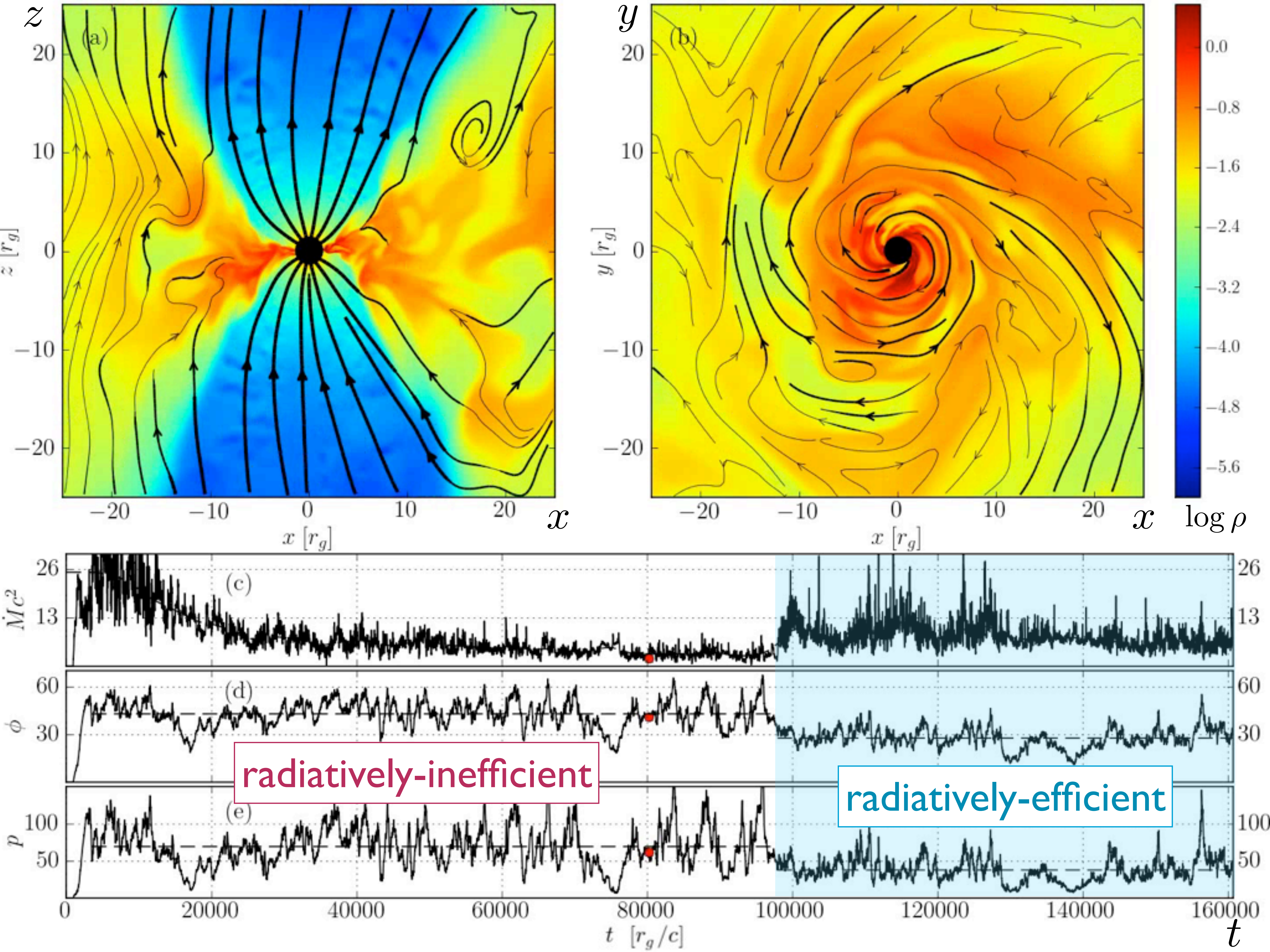
Disks shine, jets die?

- Quasar disks are bright and geometrically-thin
- Our simulated disks are non-radiative and thick
- Can radiatively-efficient disks drag large-scale magnetic flux in and make powerful jets?
- Analytical studies: does not seem so!
  (Lubow et al 1994, Guilet & Oglivie 2013a,b)
- But then, how do quasars make jets?



z
(a)
$z\ [r_g]$
$x\ [r_g]$
x
y
(b)
$y\ [r_g]$
$x\ [r_g]$
x
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
log ρ
(c)
$\dot{M}c^2$
(d)
ϕ
(e)
p
radiatively-inefficient
radiatively-efficient
$t\ [r_g/c]$
t

MAD connection to observations

- This model has been fleshed out in the last year or two
- Many connections to observations of active galactic nuclei, gamma-ray bursts, tidal disruption events, microquasars
- Magnetic flux pinned: need to determine only $M_{\rm BH}, a, \dot{M}$
- We are only getting started!

MADs in AGN

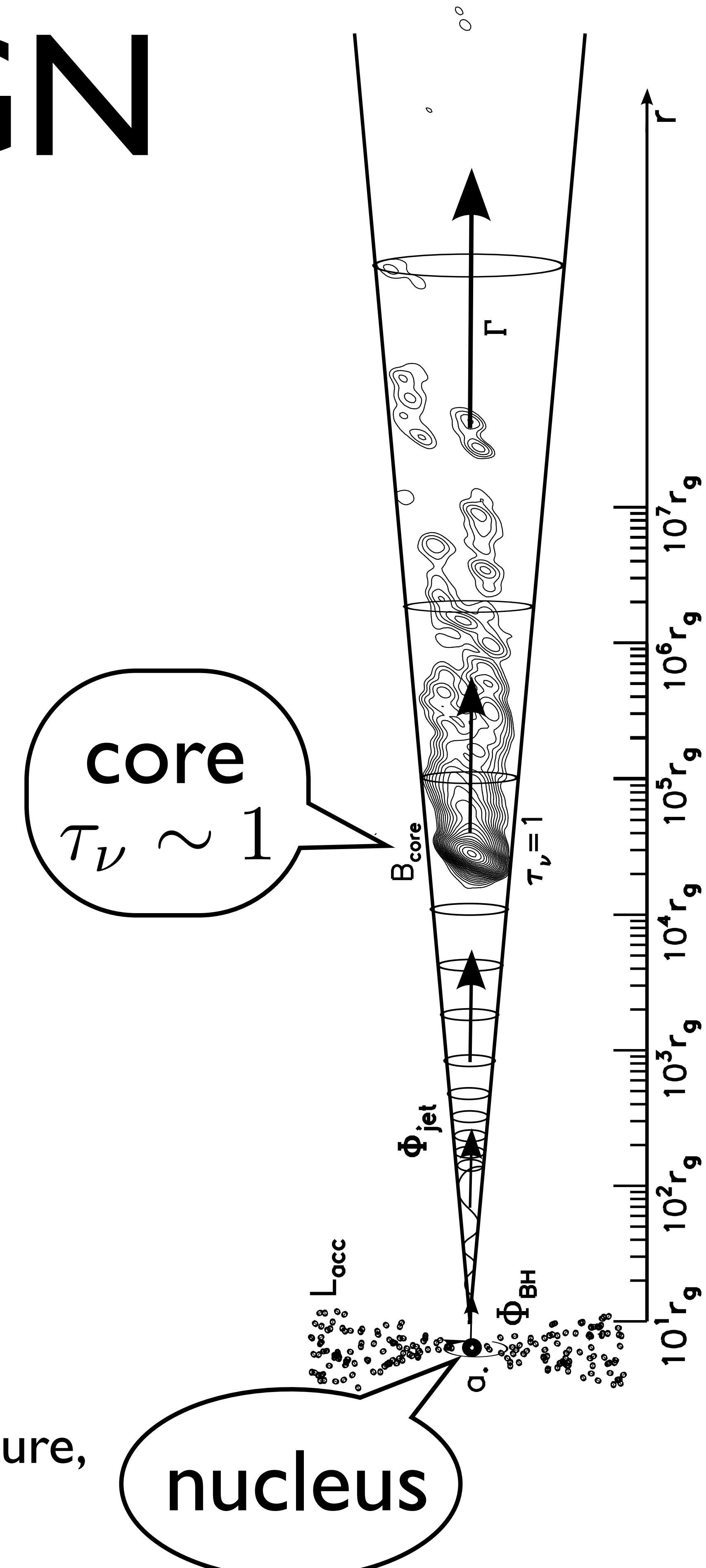
- Radio jet core is where jet becomes transparent to its own synchrotron radiation:

$$\tau_\nu \sim 1$$

- At higher ν, the core shifts inward

$$B \propto (dr_{\rm core})^{3/4}$$

- Can use this to measure B in the jet
- Magnetic flux $\Phi \approx B\pi r_{\rm core}^2\theta_j^2$



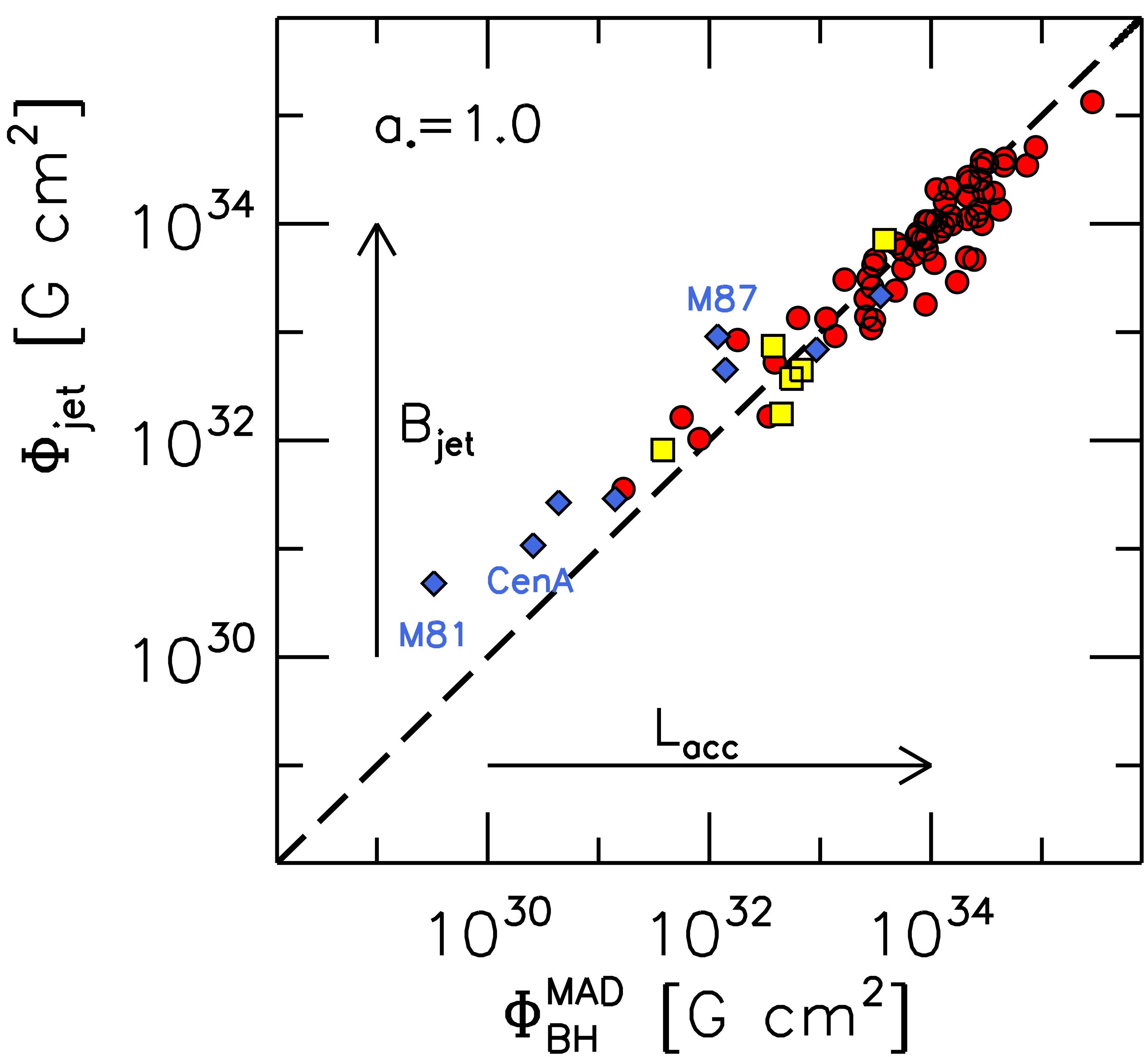
(Zamaninasab, Clausen-Brown, Savolainen, Tchekhovskoy, 2014, Nature, Zdziarski, Sikora, Pjanka, Tchekhovskoy, MNRAS, submitted)

MADs in AGN?

- Observed scaling:

$$B_{\rm jet} \propto L_{\rm acc}^{1/2}$$

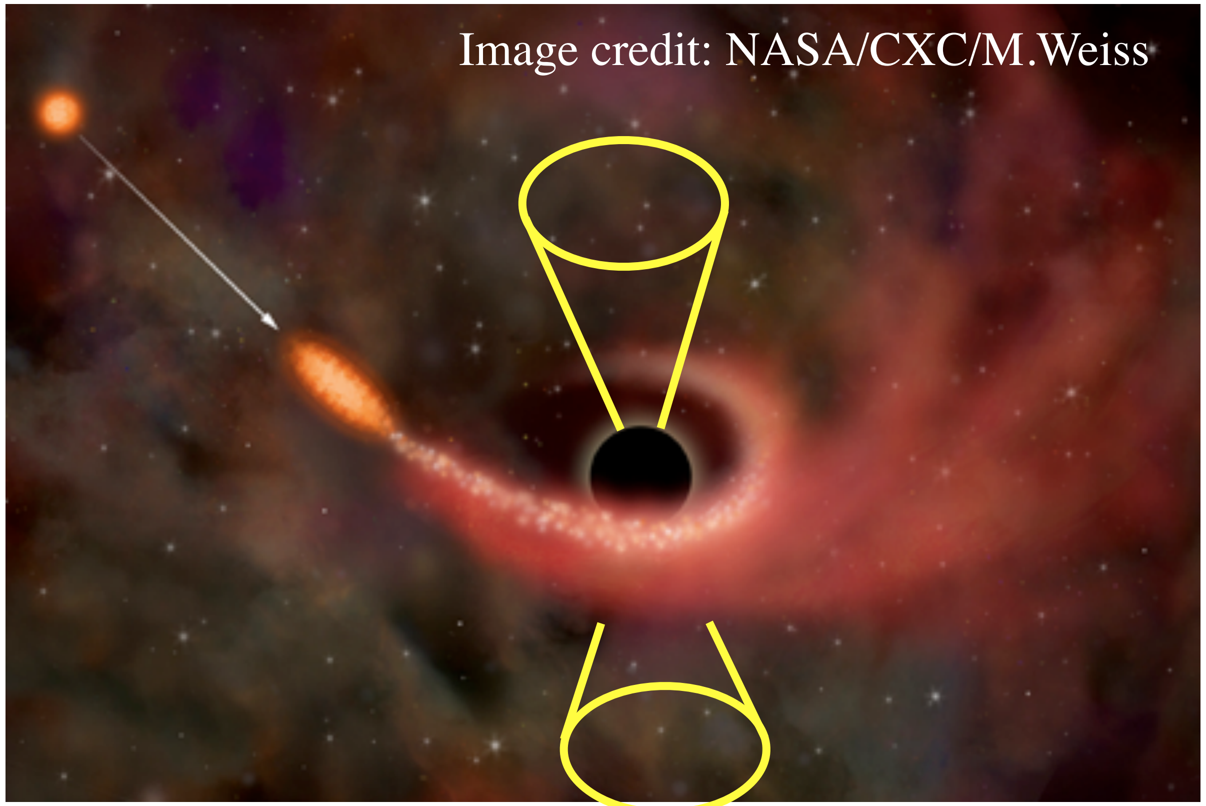
- Strength of magnetic flux in *radio-loud* AGN is consistent with MAD expectation
- Many AGN are MAD
  - their central BHs are surrounded by *dynamically important magnetic field*
- Evidence for MADs in Fermi blazars (Ghisellini et al. 2014, Nature) and nearby low-luminosity AGN (Nemmen & Tchekhovskoy 2015, MNRAS)

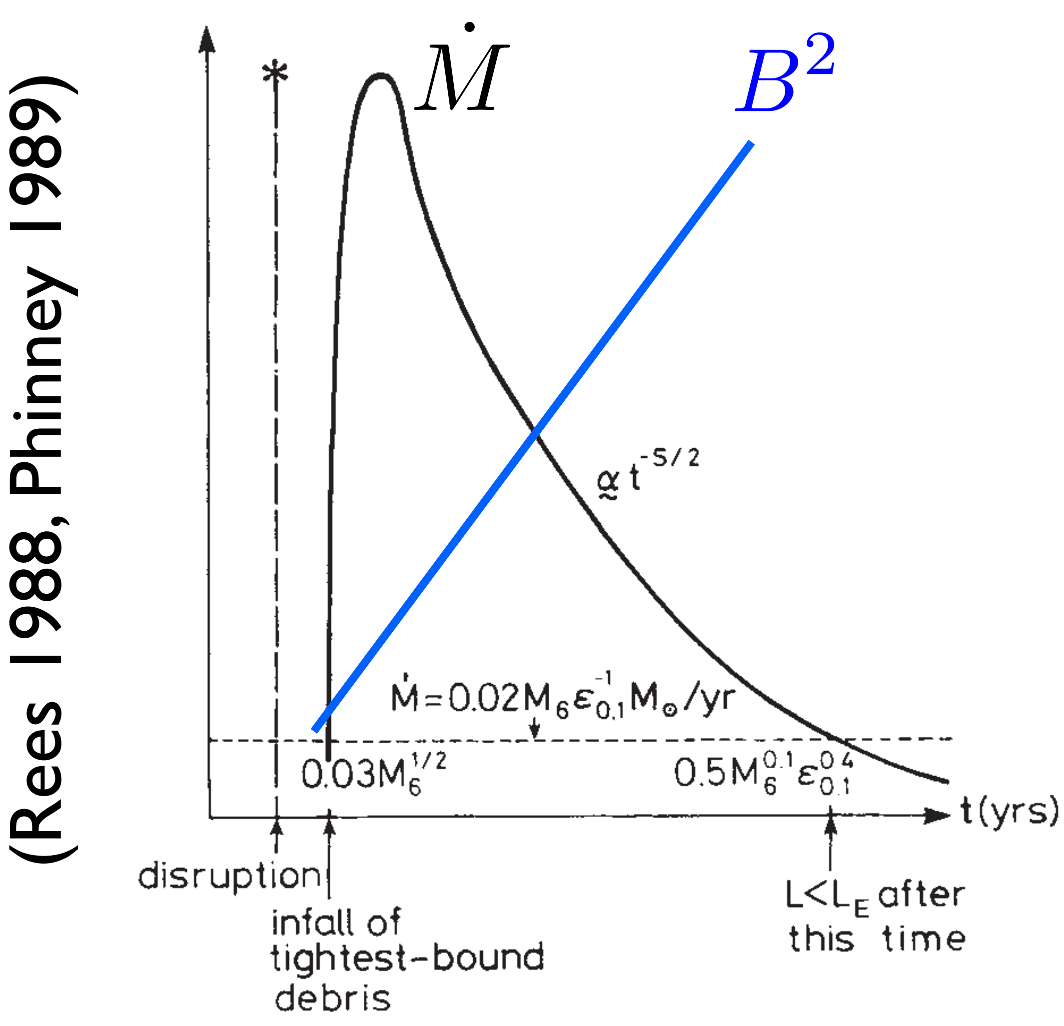


(Zamaninasab, Clausen-Brown, Savolainen, Tchekhovskoy, 2014, Nature)

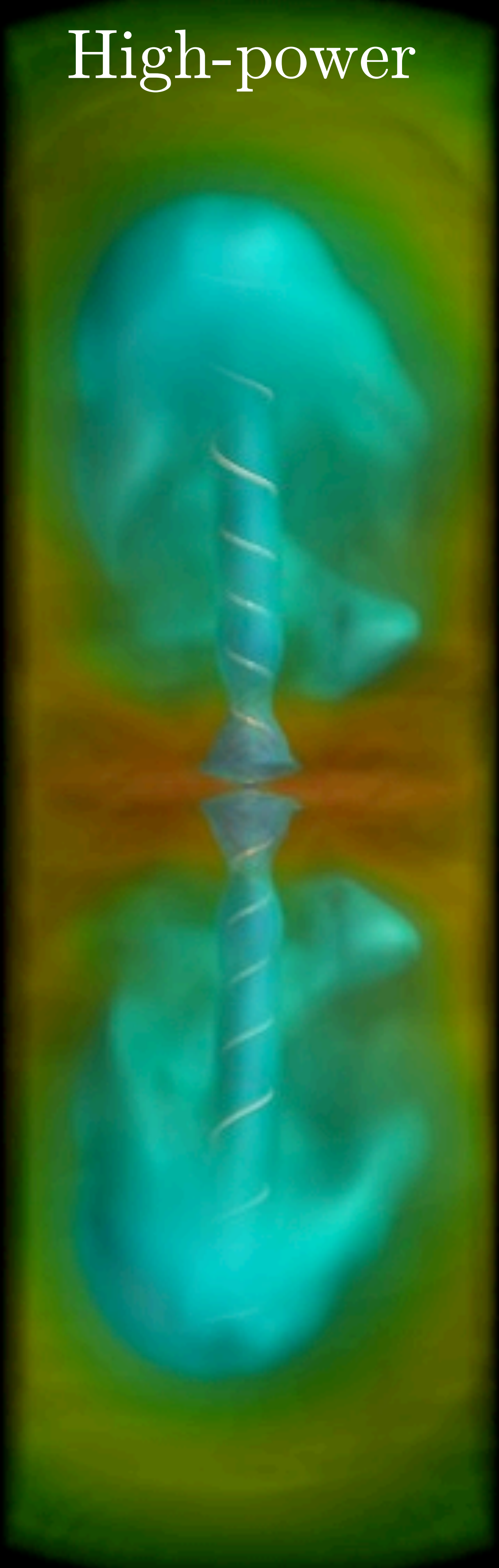
$\color{purple}{\text{MADs}}$ in tidal disruptions? Swift J1644

- Unlucky star torn apart by BH gravity
- $\dot{M}$ peaks, then decreases as mass reservoir depletes
- However, B^2 keeps increasing as more stellar magnetic flux falls in
- Inevitably, MAD forms and launches jets

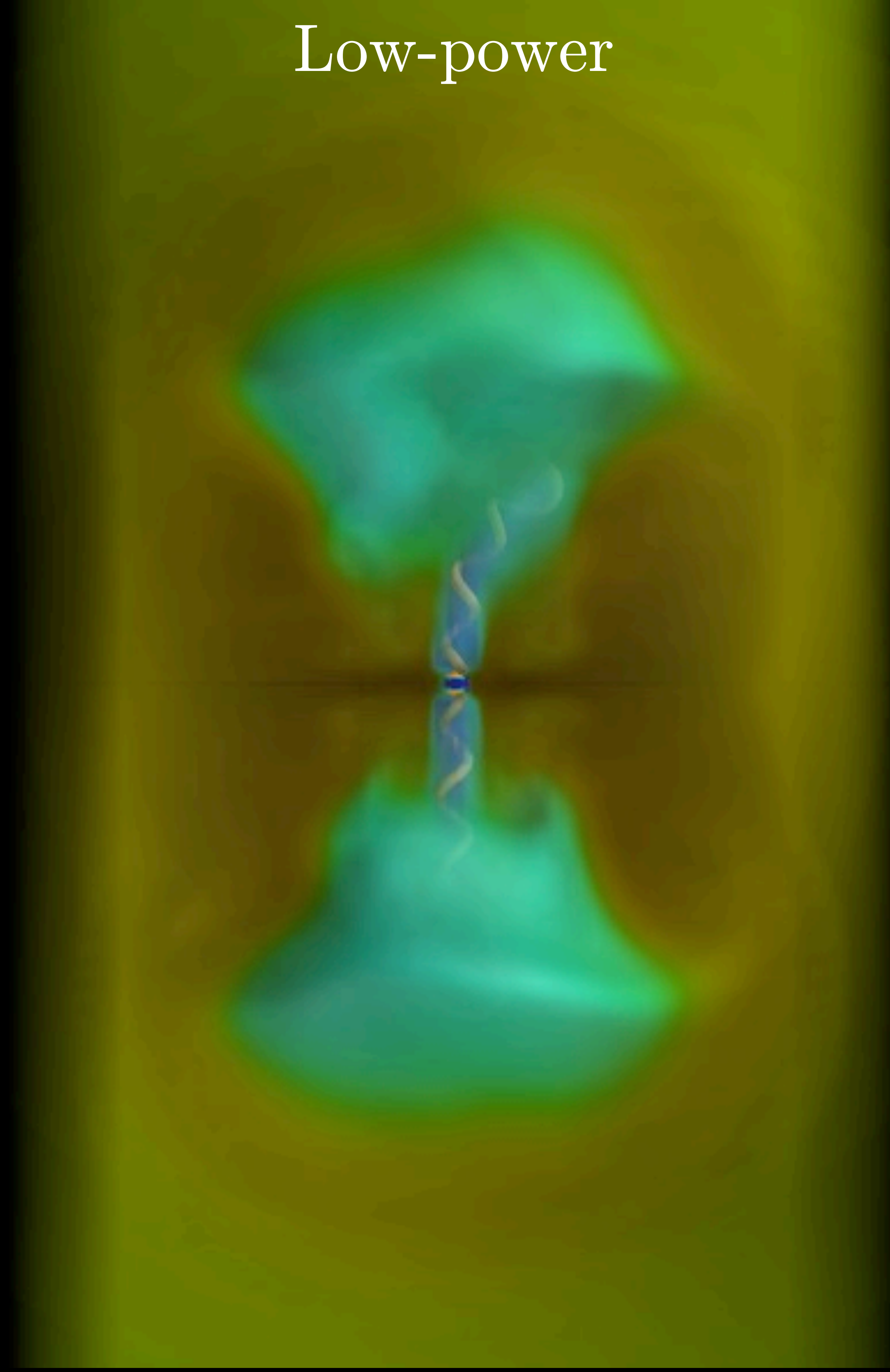




- Prime example: Swift J1644 (Tchekhovskoy et al. 2014, MNRAS, 437, 2744)
- Stellar flux insufficient: flux can be dragged from ambient medium (Tchekhovskoy+ 2014).
- Did numerical experiments to check this (Kelley, Tchekhovskoy, Narayan, 2014, MNRAS)
- Similarly, MADs form in *core-collapse GRBs*: gas drags stellar flux into BH (Tchekhovskoy & Giannios 2015)



Jets far out

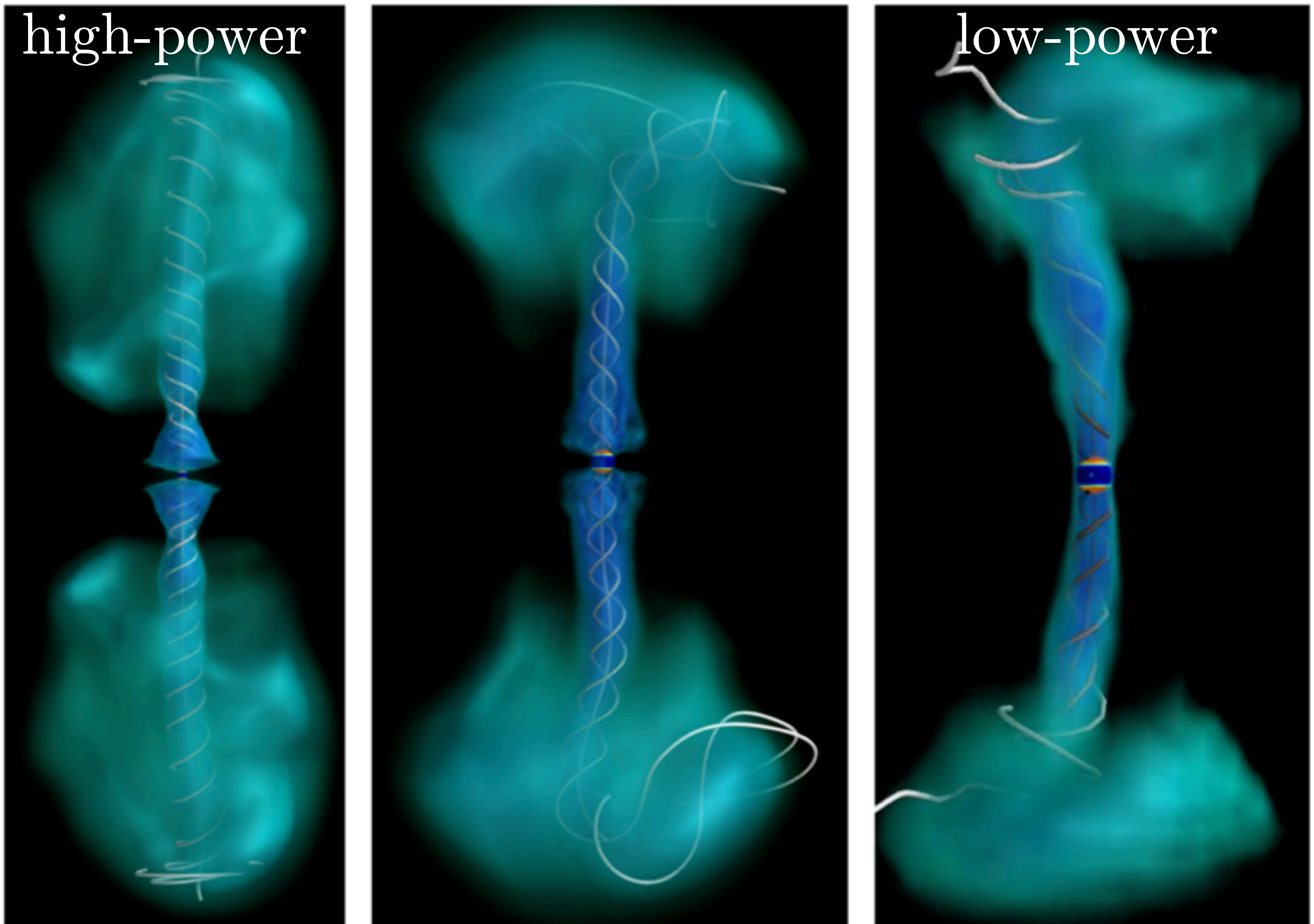


Same spherically symmetric density distribution.

Jet power different by 100x.

Tchekhovskoy & Bromberg, in prep

Jet Power Controls the Morphology



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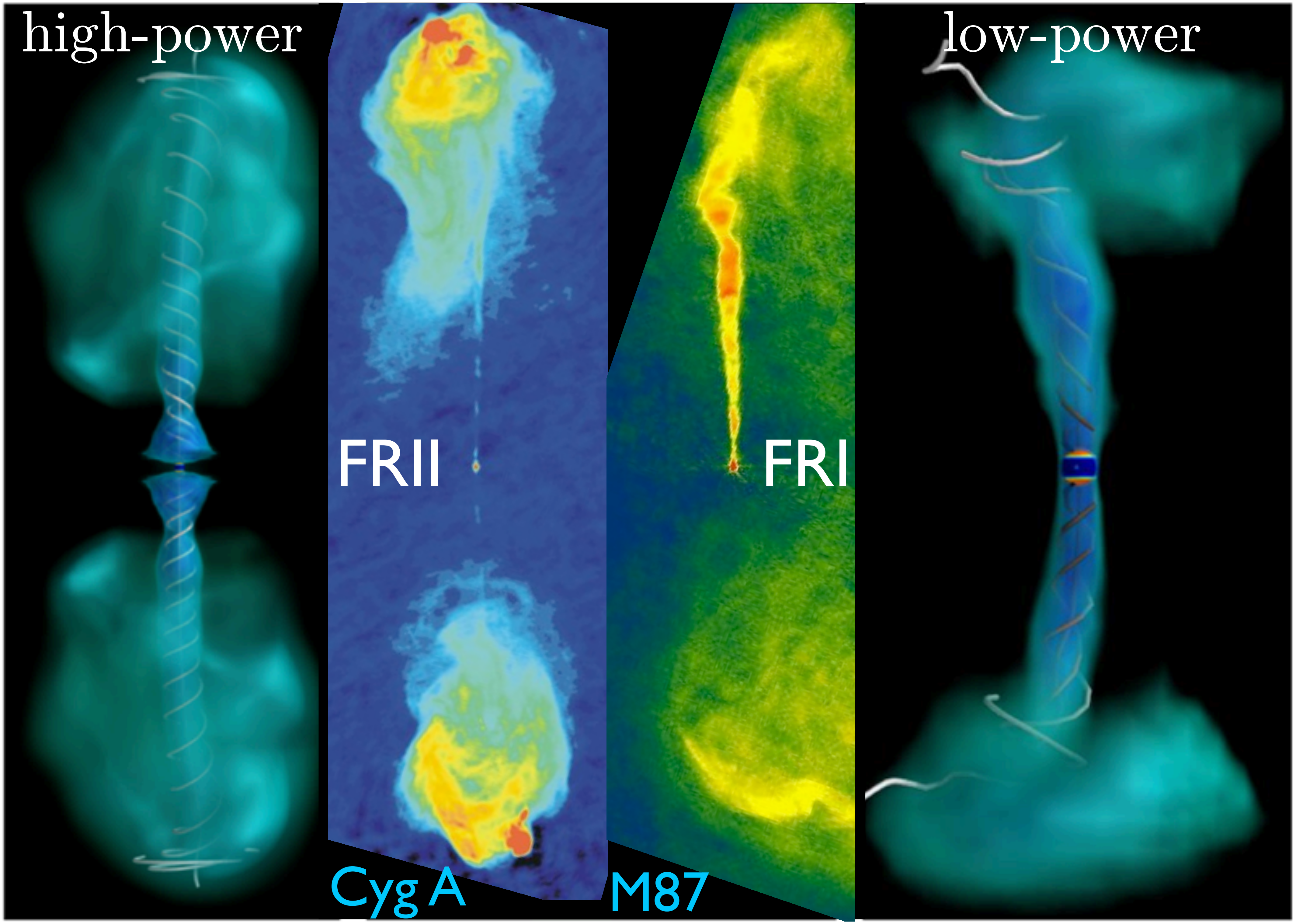
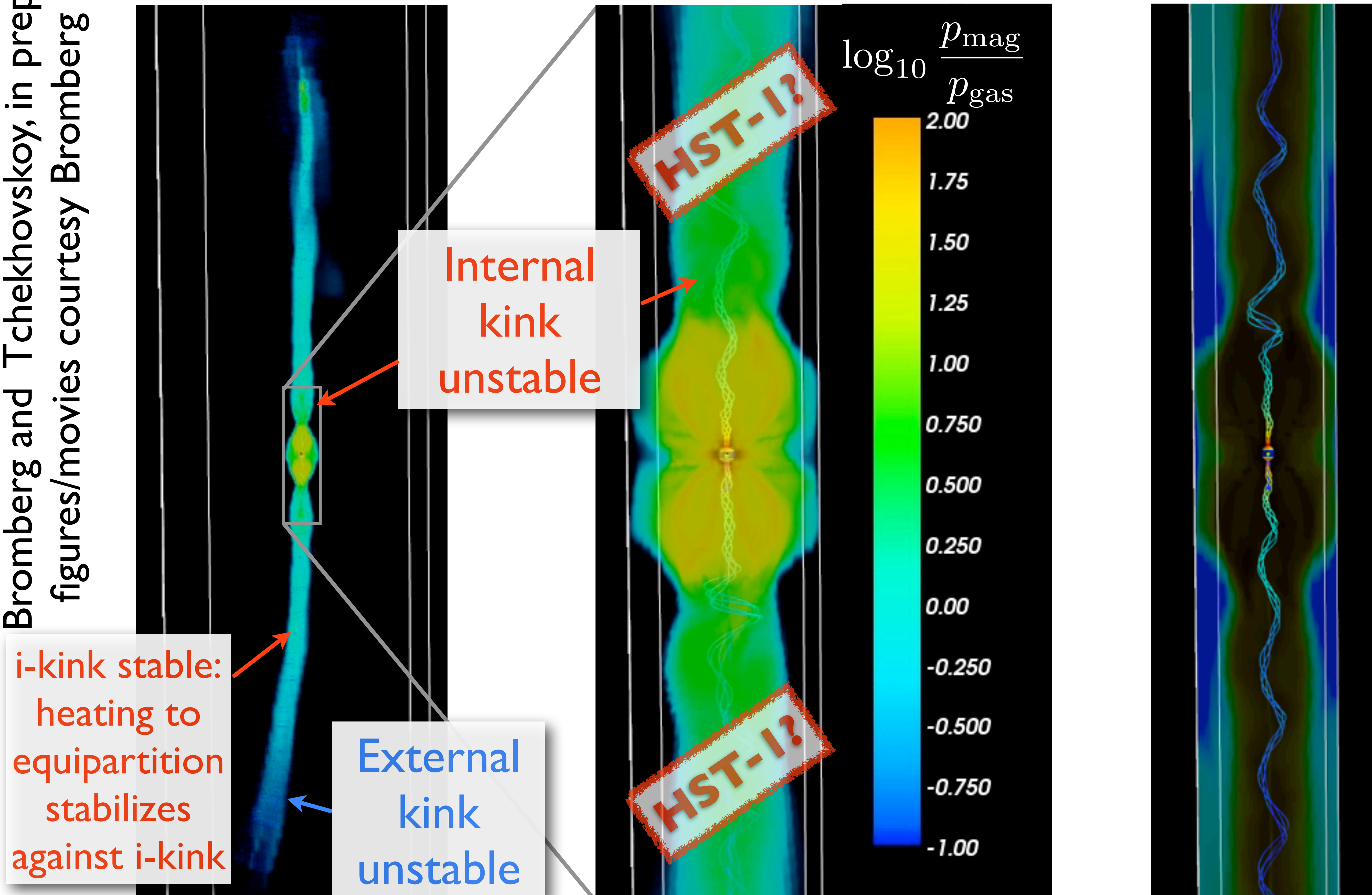


Tchekhovskoy & Bromberg, in prep

Internal Kink Makes Jets Hot

Bromberg and Tchekhovskoy, in prep;
figures/movies courtesy Bromberg



(see also Nakamura+07,08; O'Neill+12; Porth & Komissarov 14)

Summary

- Jet power is set by the *weaker* of:
  - large-scale magnetic flux Φ
  - mass accretion rate $\dot{M}$ $\longrightarrow$ MAD
- How to go MAD?
  - either centrally accumulate a lot of Φ
  - or decrease $\dot{M}$
- MADs give us the upper envelope of disk-jet connection:
  - galaxy feedback from first principles
  - slow down black hole rotation to a halt over quasar lifetime
- MADs are around us:
  - radio-loud active galactic nuclei
  - tidal disruption events
  - core-collapse gamma-ray bursts
- FRI vs FRII jet morphology is controlled by jet power
- Jets are unstable to internal kink that heats them up to *equipartition*:
  - is HST-1 internal kink-powered?