Title: Relativistic Magnetized Jets: Power, Acceleration, and Collimation

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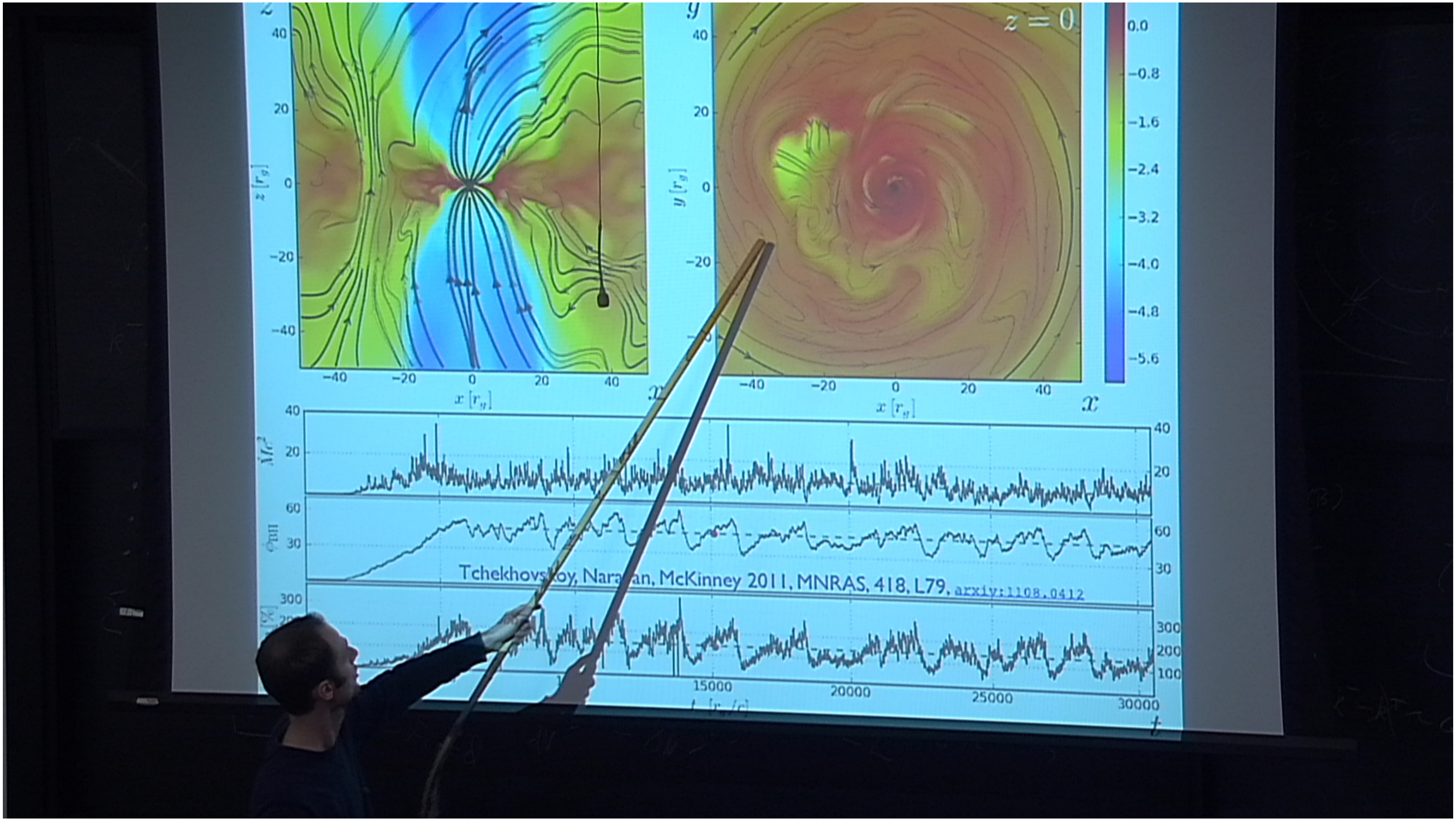
Abstract: After overviewing the fundamentals of magnetized relativistic jets production, I present the results of new global 3D general relativistic magnetohydrodynamic simulations of jet formation by black hole (BH) accretion systems. The simulations are designed to transport a large amount of magnetic flux to the center, more than the accreting gas can force into the BH. The excess magnetic flux remains outside the BH, impedes accretion, and leads to a magnetically arrested disc. We find powerful outflows. For a BH with spin parameter a = 0.5, the efficiency with which the accretion system generates outflowing energy in jets and winds is eta ~ 30%. For a = 0.99, we find eta ~ 140%, which means that more energy flows out of the BH than flows in. The only way this can happen is by extracting spin energy from the BH. Thus the a = 0.99 simulation represents an unambiguous demonstration, within an astrophysically plausible scenario, of the extraction of net energy from a spinning BH via the Penrose-Blandford-Znajek mechanism.



Tchekhovskoy, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412

Relativistic Magnetized Jets: Power, Acceleration, and Collimation

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Center for Theoretical Science Fellow
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Ramesh Narayan
Jon McKinney

Jets: Beautiful & Challenging

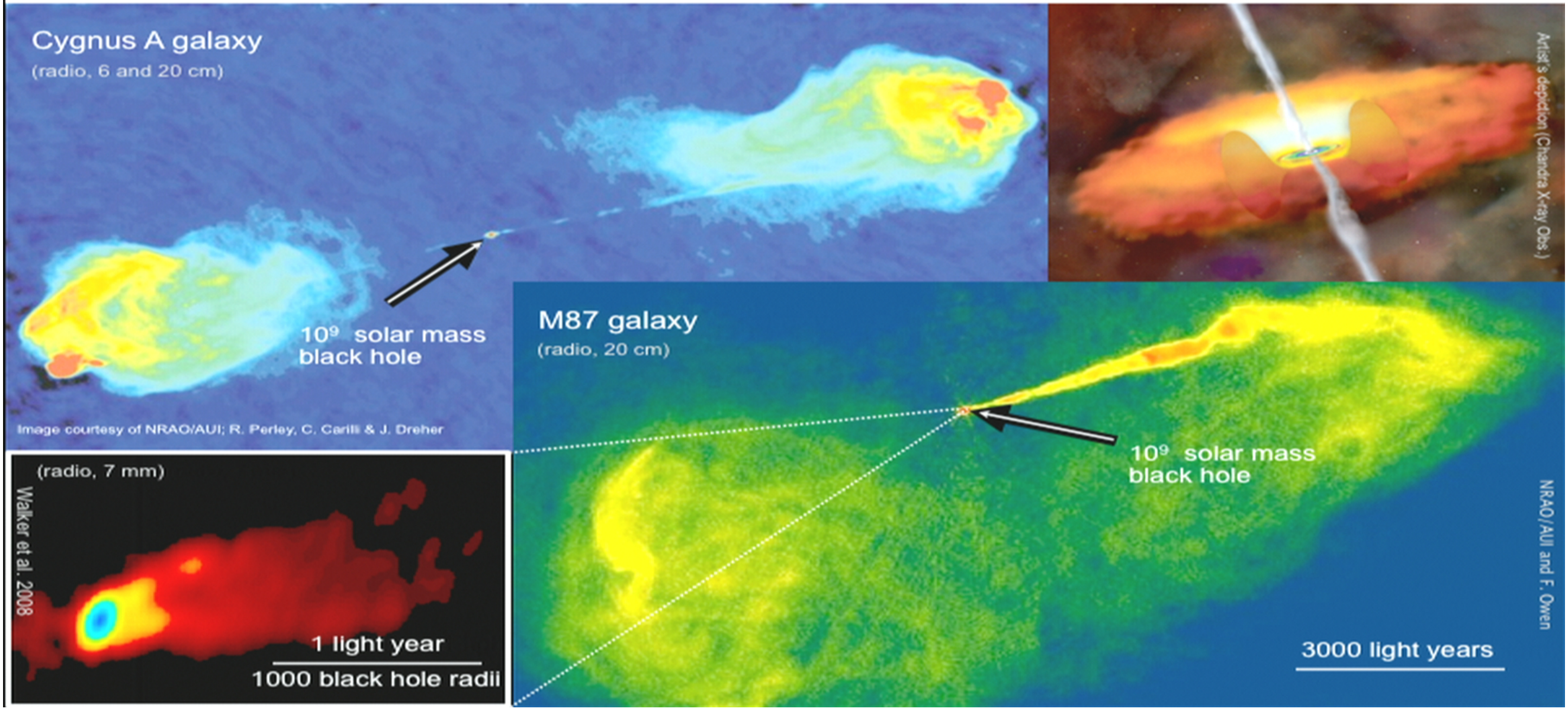


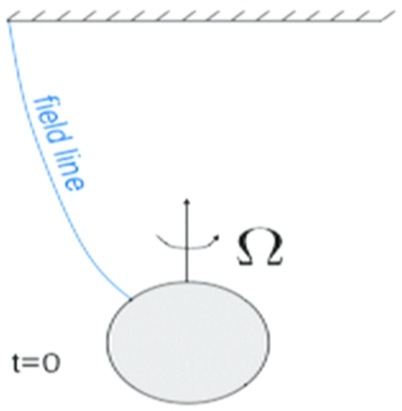
Image courtesy of NRAO/AUI; R. Perley, C. Carilli & J. Dreher

Artist's depiction (Chandra X-ray Obs.)

NRAO/AUI and F. Owen

Walker et al. 2008

How Do Magnetized Jet Work?



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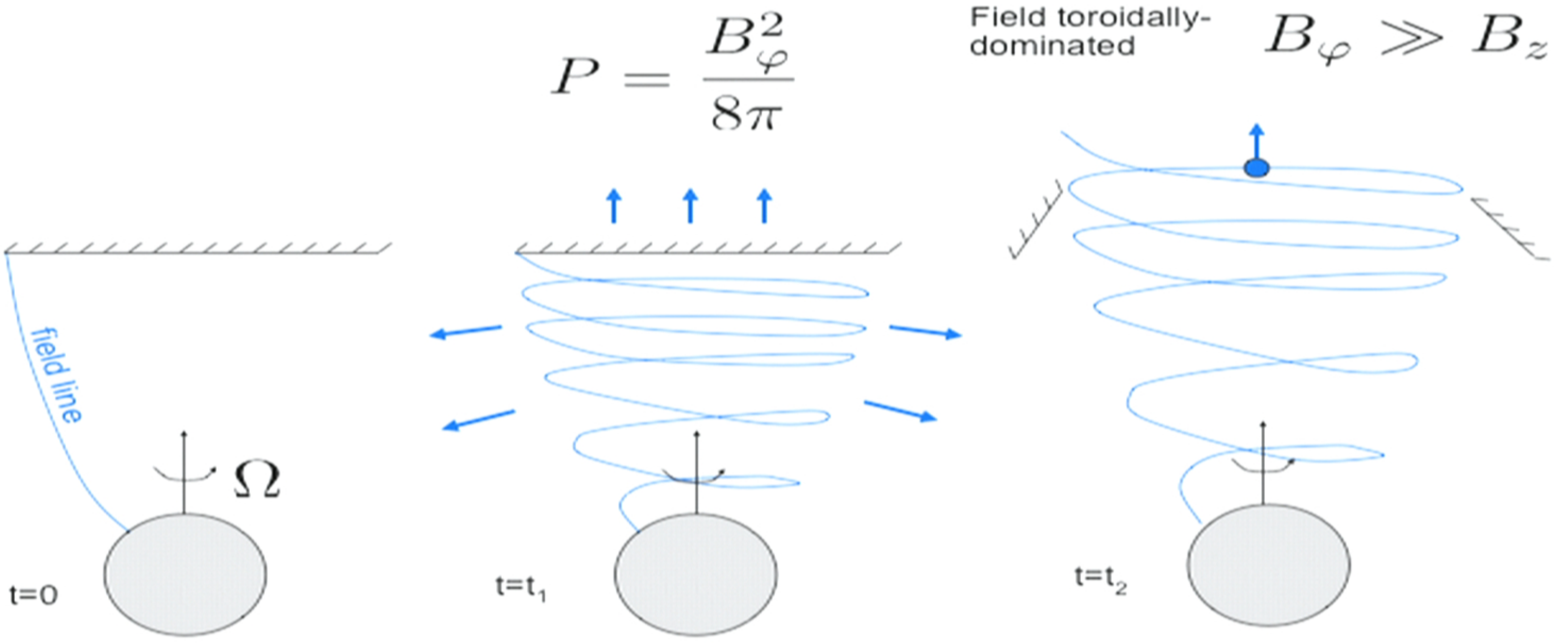


$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated $B_\varphi \gg B_z$

Jet Acceleration and Collimation

GRB:
$\gamma \gtrsim 100$
$\theta \lesssim 0.1$
$\gamma\theta \gtrsim 10$
$\sigma \lesssim 1$

$\sigma = \Gamma_m \epsilon_m / \rho c^2$

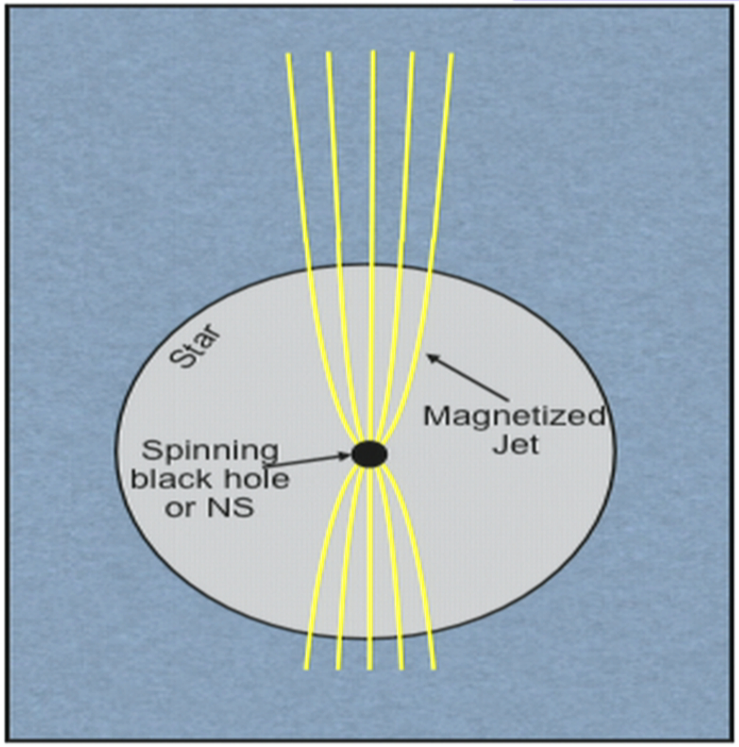
Prompt emission

- Acceleration: ultra-relativistic velocity, Lorentz factor $\gamma \gtrsim 100$
- Weak mag. field: $\Gamma_m \epsilon_m / \rho c^2 \equiv \sigma \lesssim 1$

- Collimation: opening angle $\theta \lesssim 0.1$
- Relation between acceleration collimation: $\boxed{\gamma\theta \gtrsim 10}$

Jet breaks in afterglow emission

× Recent simulations of magnetized (MHD) continuously collimated jets (Komissarov et al. 2009): $\boxed{\gamma\theta \lesssim 2}$



Tchekhovskoy et al. 2010a

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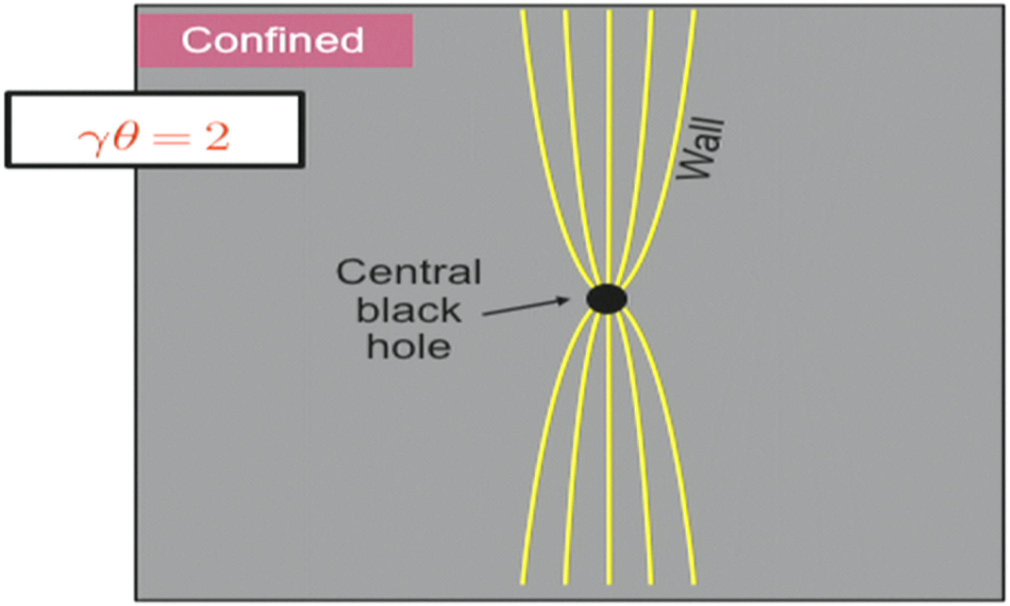
GRB Jets: Problem Setup

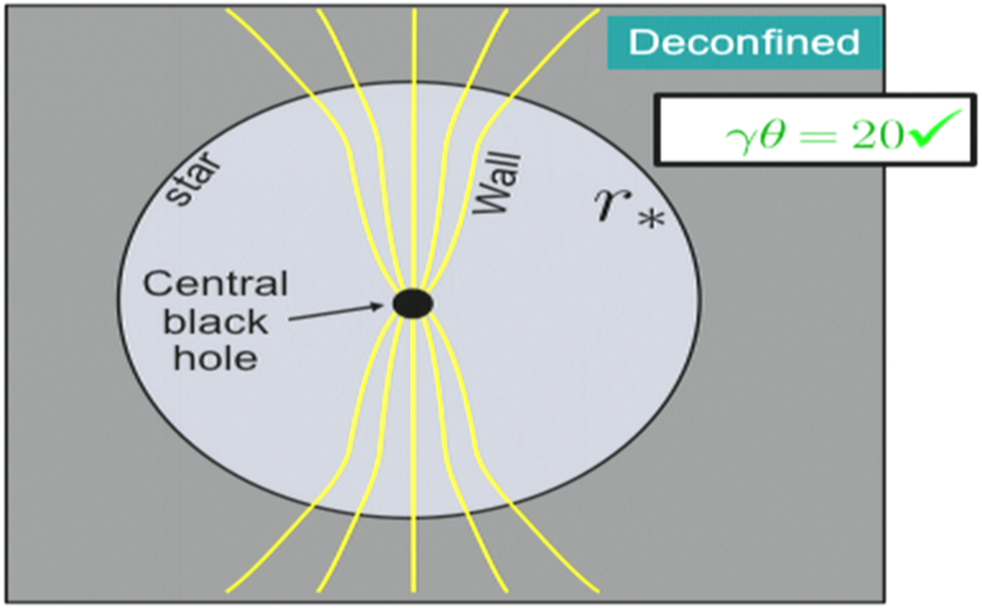
Magnetized confined jets:
$\gamma\theta \lesssim 2$

(Komissarov et al. 2009)

GRB jets are DEconfined:
$\gamma\theta \gtrsim 10$

(Tchekhovskoy et al. 2010a)





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Deconfinement Acceleration

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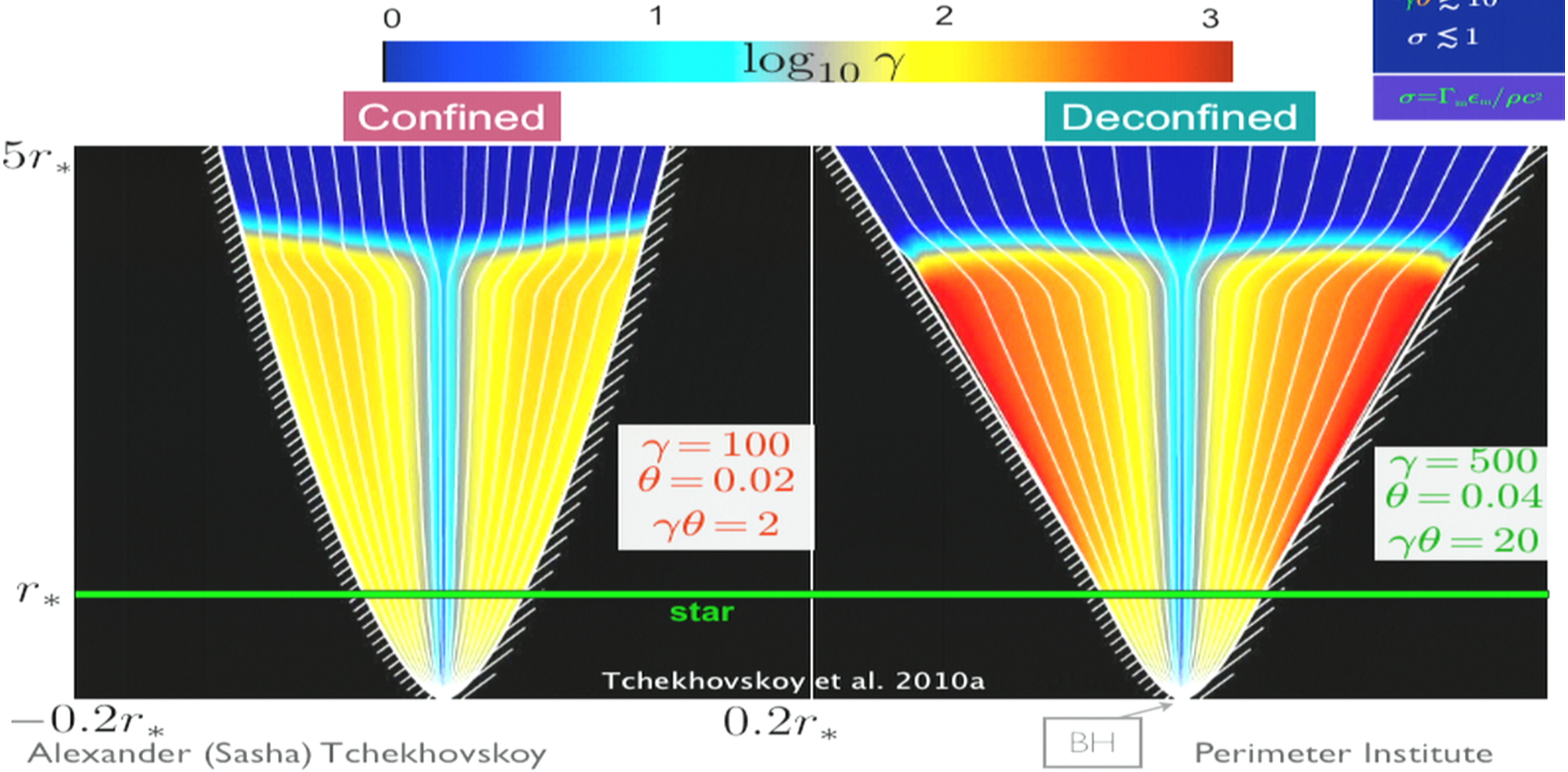

Tchekhovskoy et al. 2010a

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Deconfinement Acceleration

(see also Komissarov et al. 2010)

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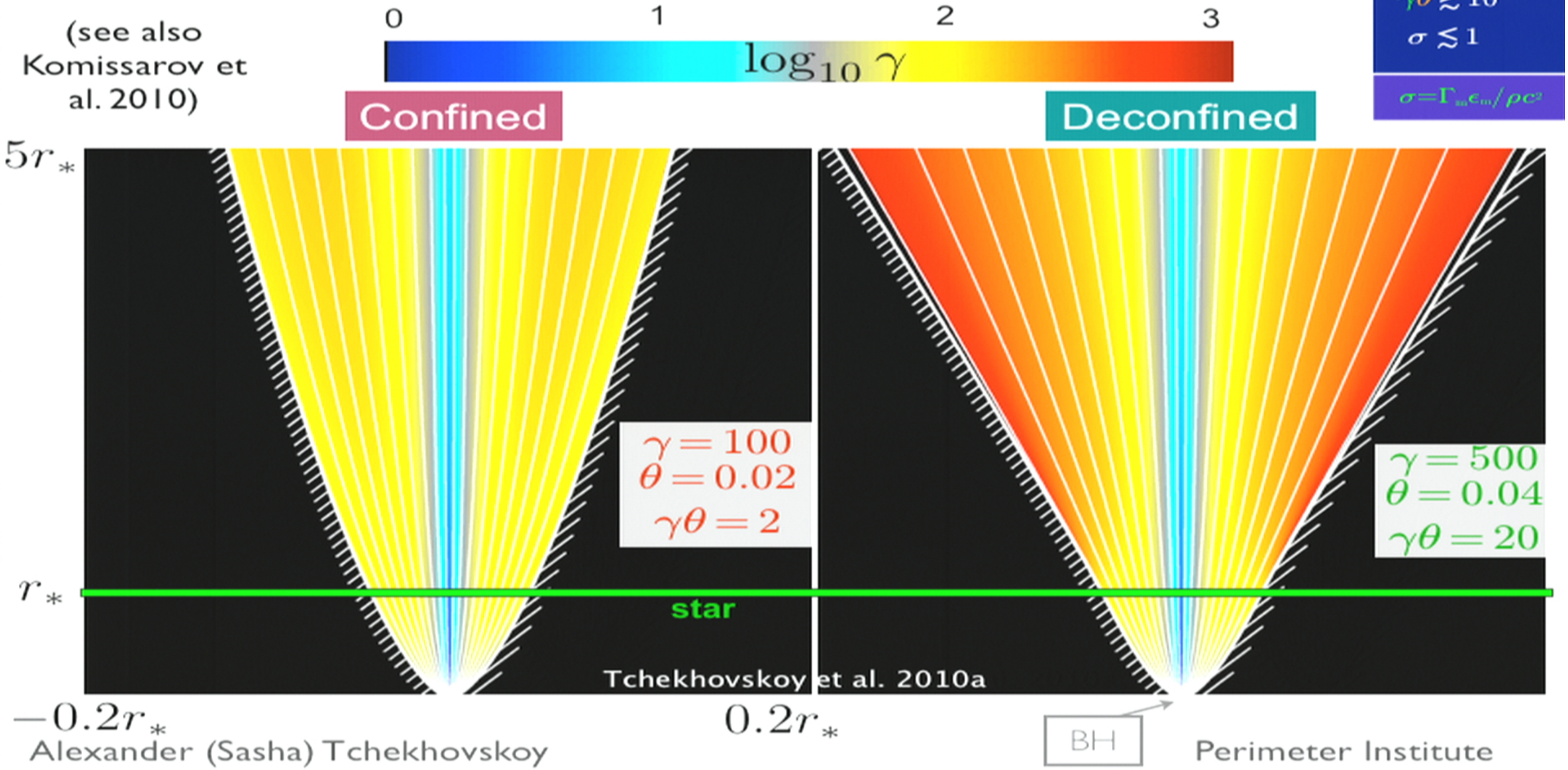

Tchekhovskoy et al. 2010a

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Understanding Deconfinement

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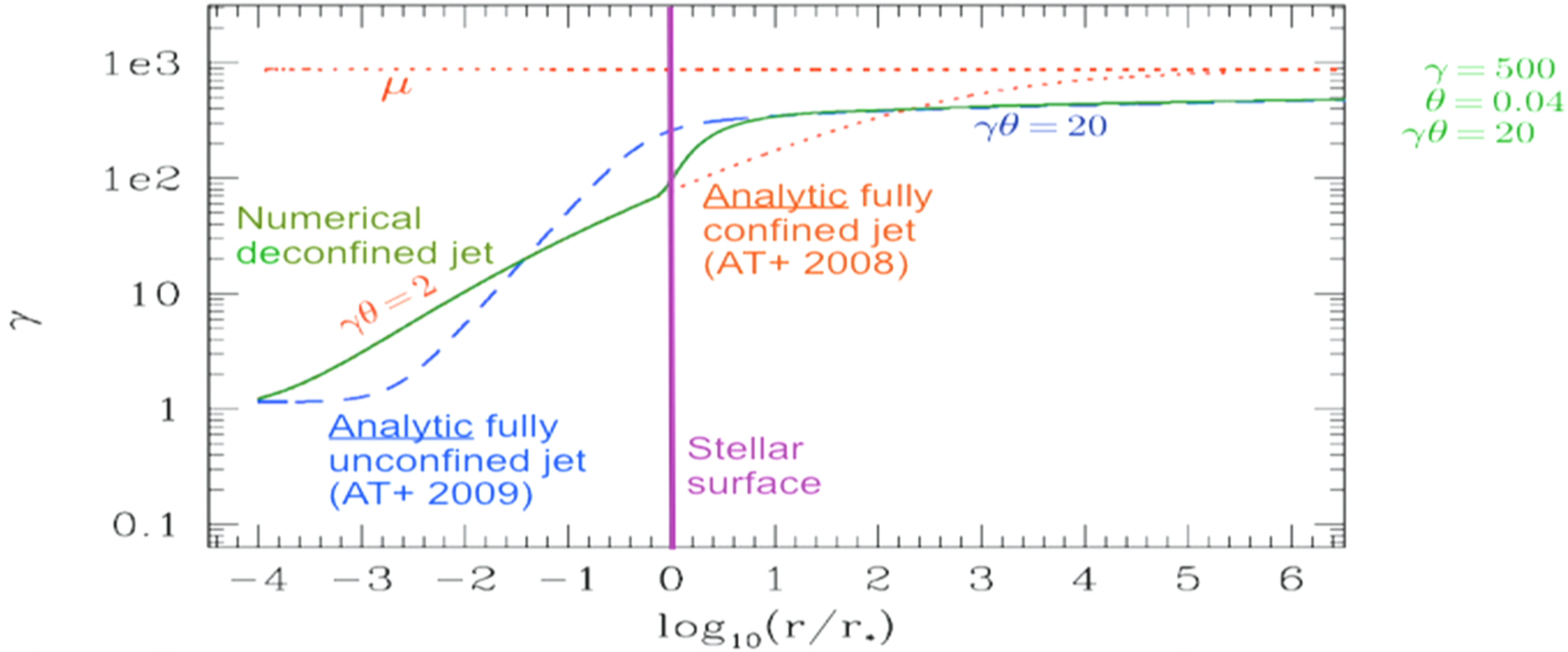
After jets lose ambient pressure support, they switch from the fully confined solution to the fully unconfined solution.



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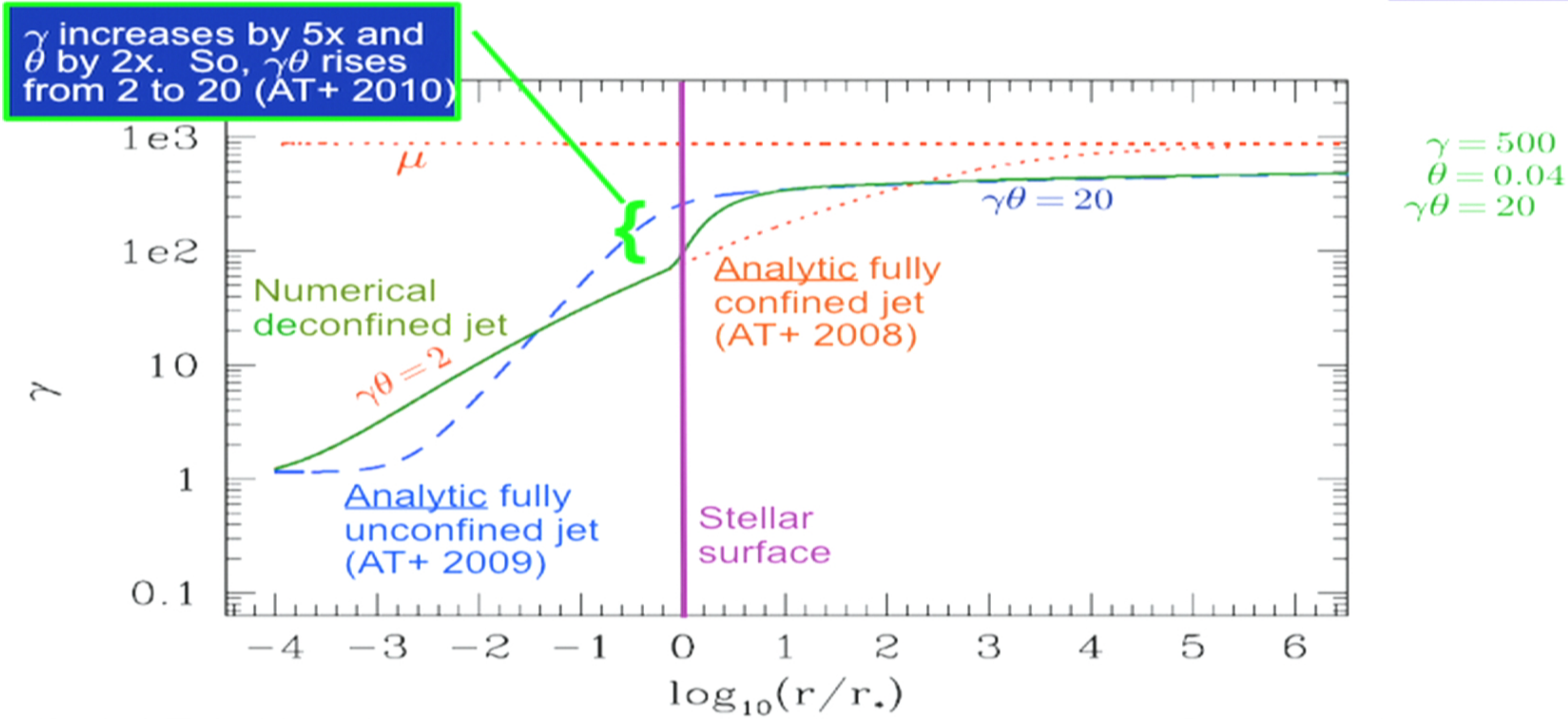
γ increases by 5x and θ by 2x. So, $\gamma\theta$ rises from 2 to 20 (AT+ 2010)

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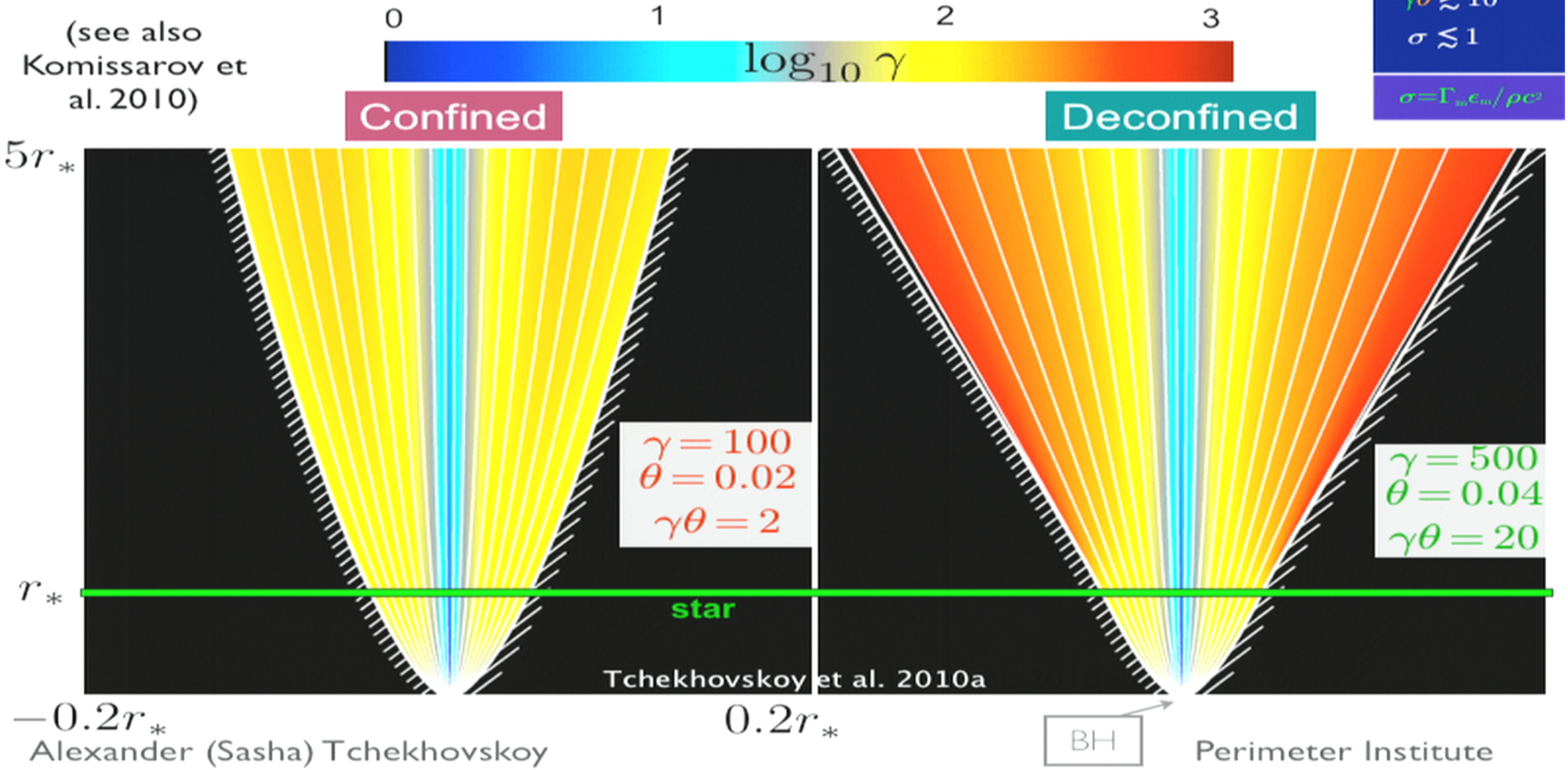
(see also Komissarov et al. 2010)



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Understanding Deconfinement

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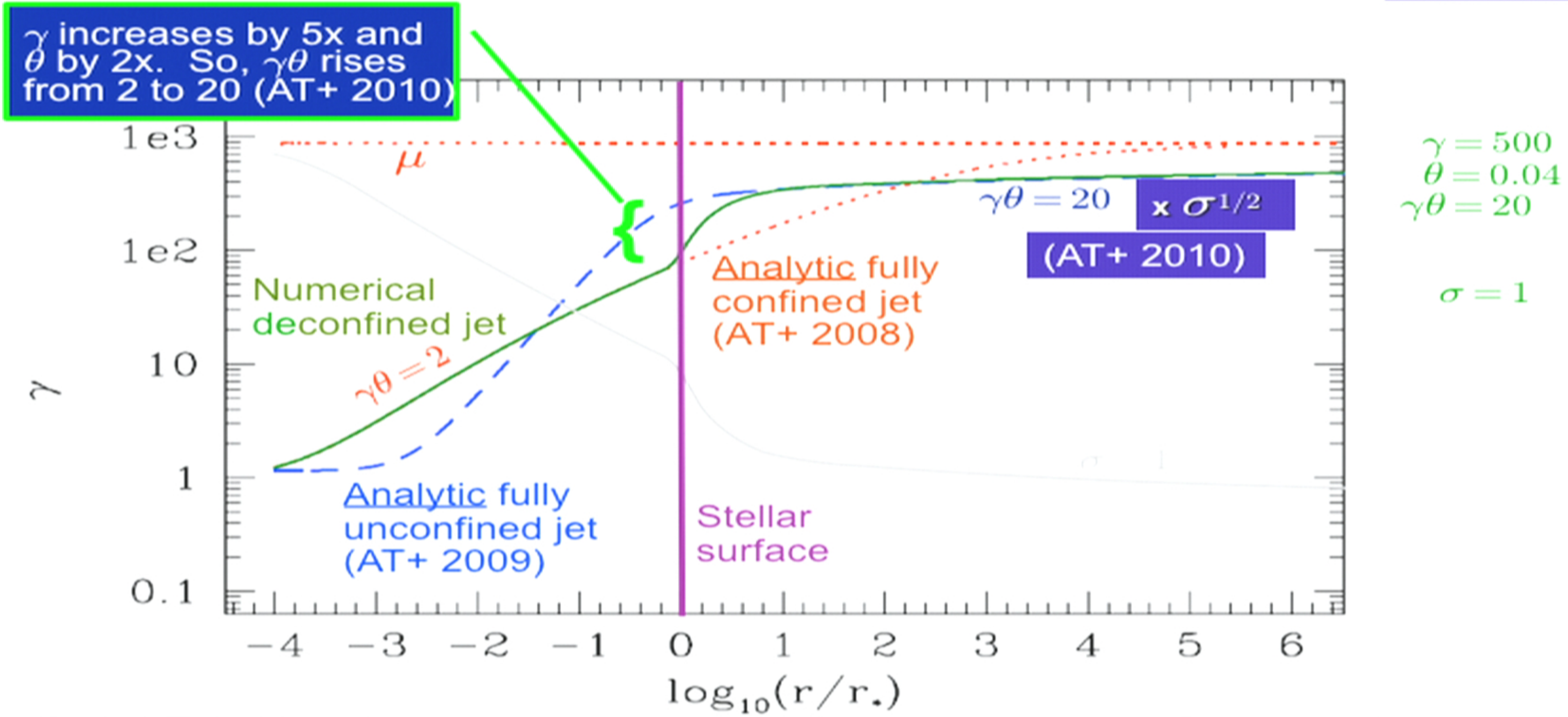

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Summary: Acceleration & Collimation

GRB:
$\gamma \gtrsim 100$
$\theta \lesssim 0.1$
$\gamma\theta \gtrsim 10$
$\sigma \lesssim 1$

$\sigma = \Gamma_m \epsilon_m / \rho c^2$

- Relation between GRB jet acceleration and collimation

$$\gamma\theta \approx 20\sigma^{1/2}$$ (Tchekhovskoy et al. 2010)

- Faster jets are more collimated
- What do observations tell us?
  - Most GRBs: $\gamma\theta \lesssim 10-30 \quad \rightarrow \quad \sigma \lesssim 1$
  - Some GRBs: $\gamma\theta \sim 100 \quad \rightarrow \quad \sigma \sim 25 \gg 1$
  - Serious challenge to standard GRB emission models that require $\sigma \lesssim 1$ (Narayan, Kumar, Tchekhovskoy, 2011)

GRB	$\gamma\theta$
970508	47
980519	10
990123	11
990510	7.8
991208	15
991216	7.0
000301c.....	38
000418	78
000926	19
010222	9.2
090323	27
090328	18
090902B	70
090926A	90

Panaitescu & Kumar 2002

Cenko+ '10

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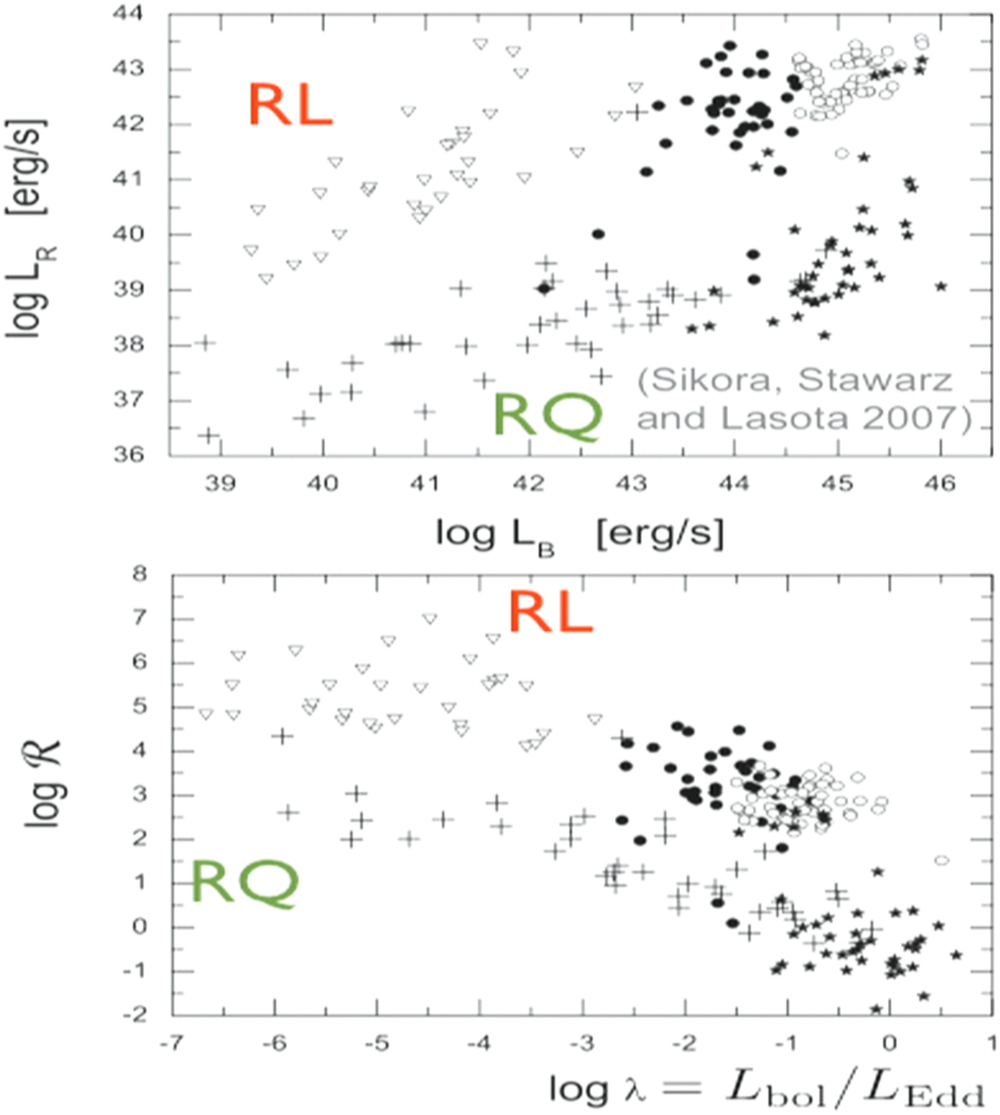
AGN Radio Loud/Quiet Dichotomy

- Factor of 1000 difference in radio luminosity.
- There must be at least one other parameter in addition to M and $\dot{M}$:

$$P_{\rm jet}(M, \dot{M}; ??)$$

- Could it be BH spin a? (Wilson and Colbert '95)



(Sikora, Stawarz and Lasota 2007)

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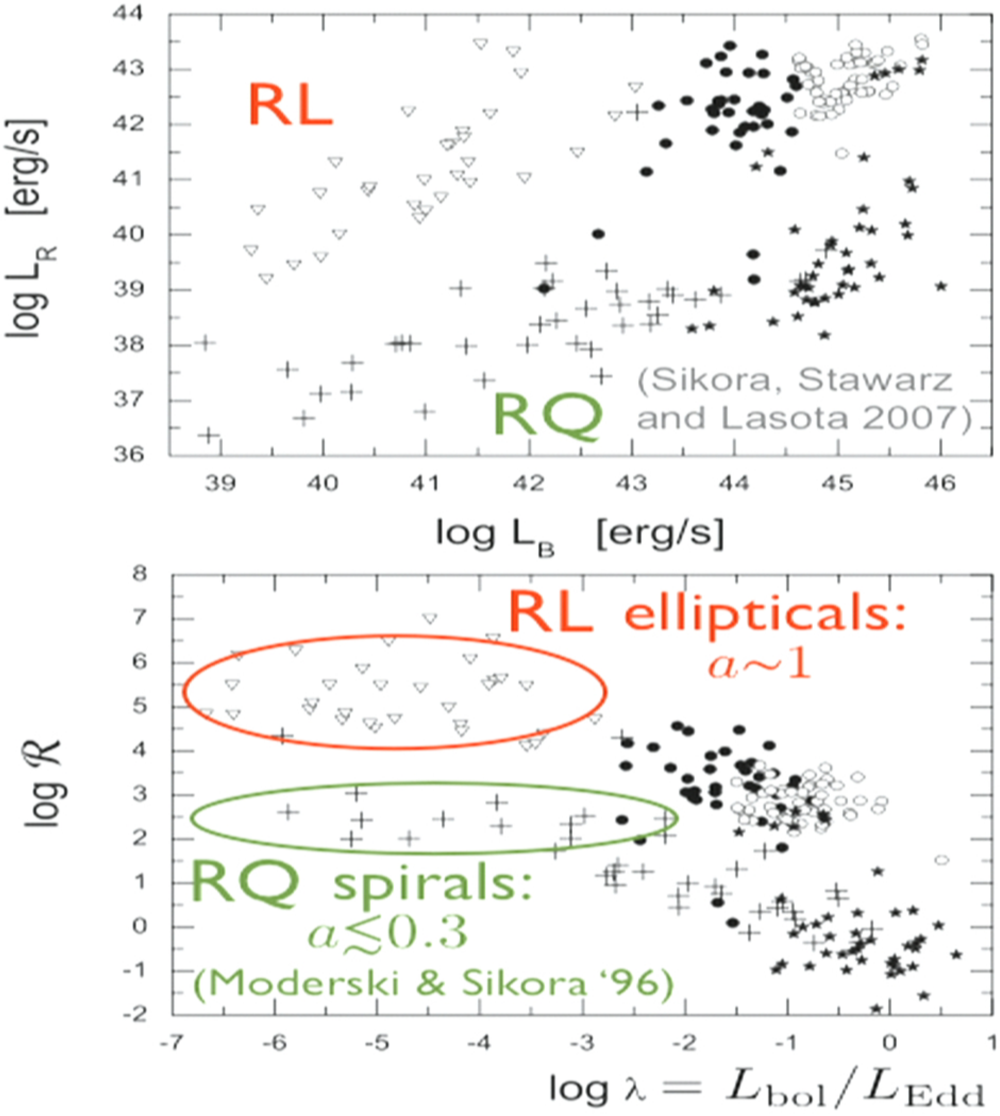

(Sikora, Stawarz and Lasota 2007)

(Moderski & Sikora '96)

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Black Hole Power

Blandford-Znajek (1977), low spin limit, $a \ll 1$:

$$P_{\rm BZ} = k\Phi^2 \frac{a^2}{16 r_g^2} c$$

- a dimensionless BH spin
- $r_g = GM/c^2$ BH gravitational radius
- Φ magnetic flux through the BH
- k = 0.054 (split monopole), k = 0.044 (paraboloidal)

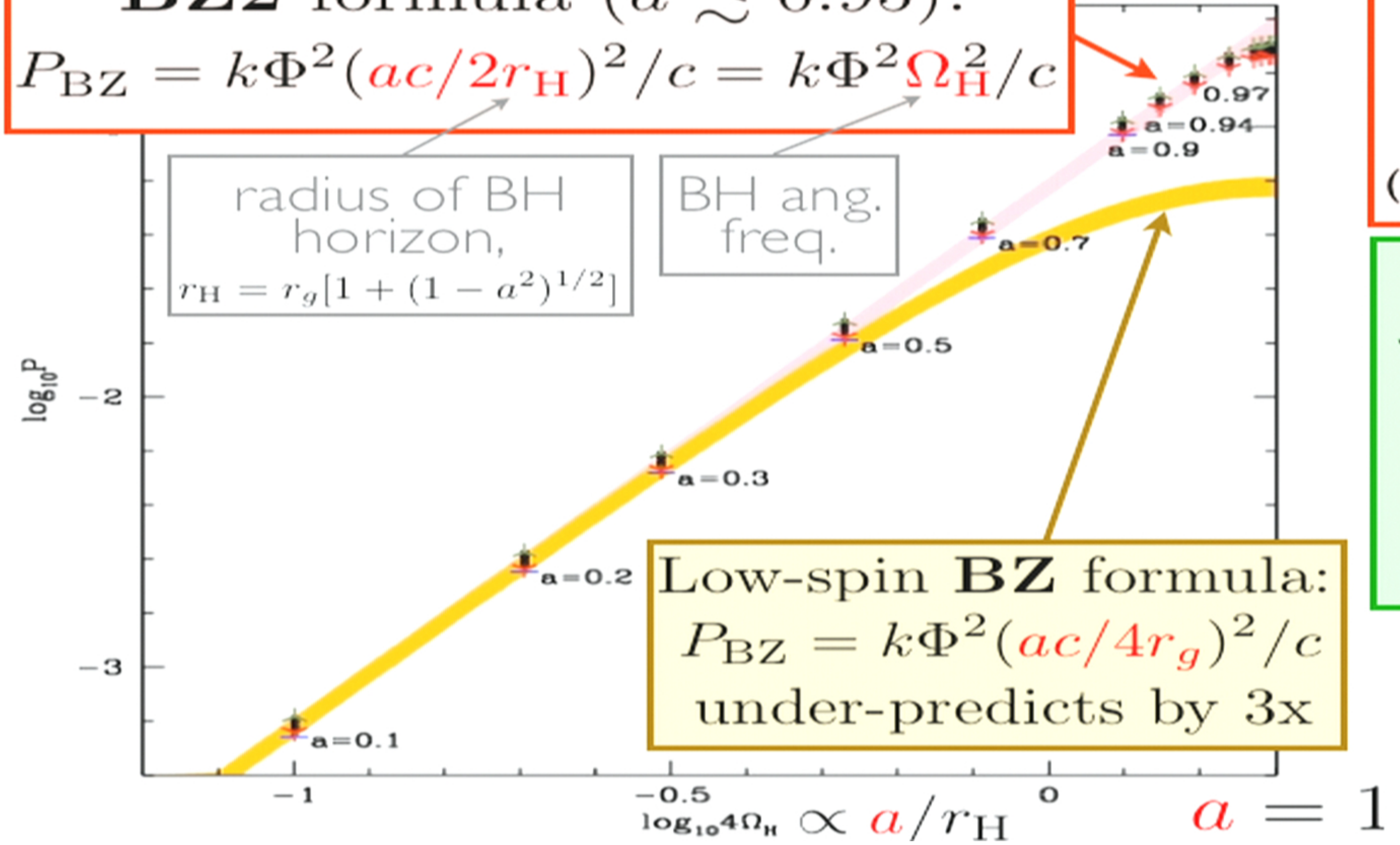
The $\propto a^2$ scaling does not appear steep enough to explain the 1000x dichotomy: BH power varies by ~10 if a varies from 0.3 to 1. Can the power scaling become steeper as $a \to 1$?

(Komissarov 2001; Krasnopolsky; Tanabe & Nagataki 2009; Tchekhovskoy et al. 2010b)

Good Approximation at High Spin: Tchekhovskoy, Narayan, & McKinney (2010b)

BZ2 formula ($a \lesssim 0.95$):

$P_{\rm BZ} = k\Phi^2(ac/2r_{\rm H})^2/c = k\Phi^2\Omega_{\rm H}^2/c$



radius of BH horizon,
$r_{\rm H} = r_g[1+(1-a^2)^{1/2}]$

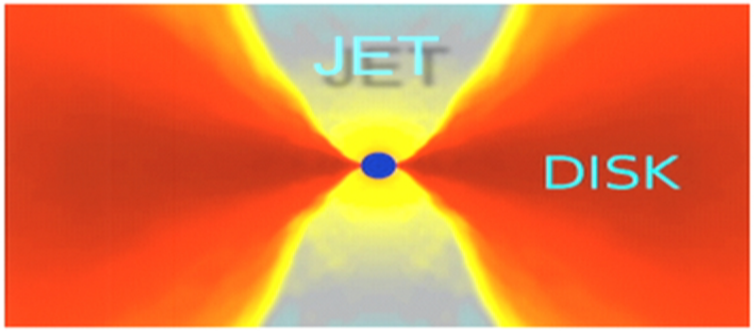
BH ang. freq.

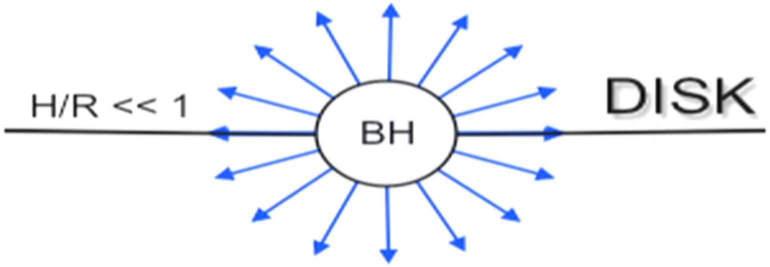
Low-spin **BZ** formula:
$P_{\rm BZ} = k\Phi^2(ac/4r_g)^2/c$
under-predicts by 3x

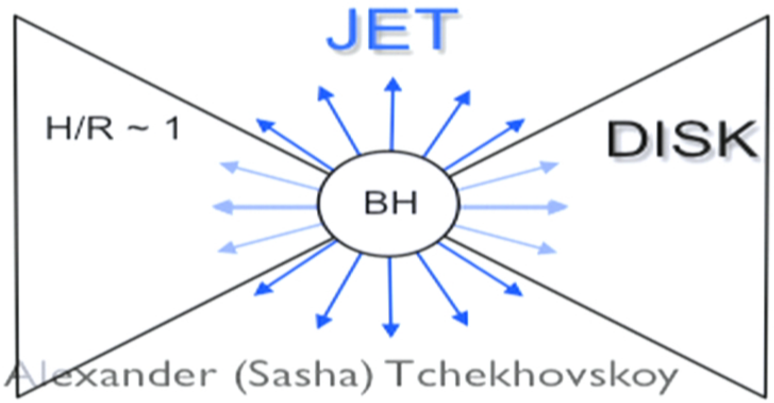
BZ6 formula works for all spins
(Tchekhovskoy et al.'10b)

Fixed Φ, M, varying a. Force-free simulations in Kerr metric.
(Tchekhovskoy et al. 2010b)

Effect of Disk Thickness

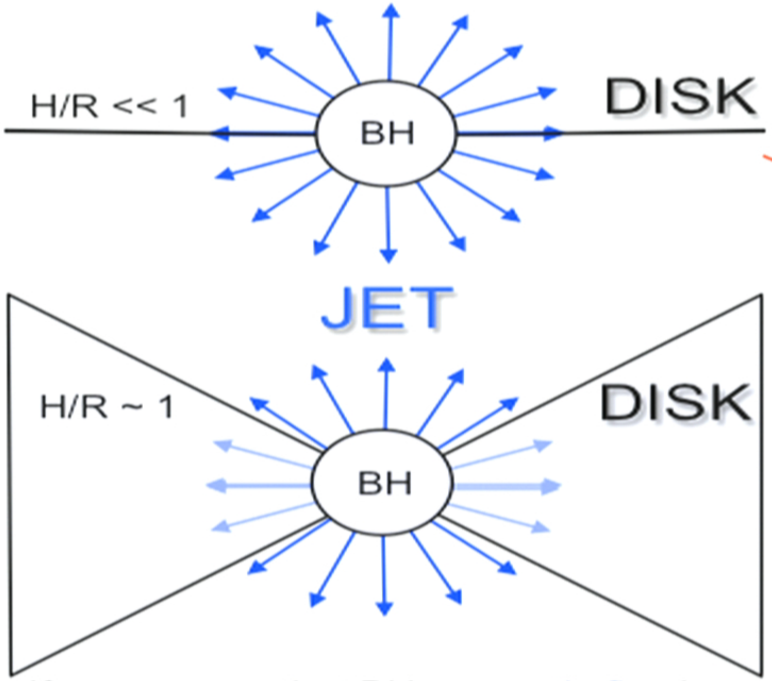






- Low-luminosity AGN are powered by thick advection-dominated flows (ADAF, Narayan & Yi 1994, 1995).
- In the standard BZ picture, the disk is razor-thin, so all field lines power the jet.
- If the disk is thick, some field lines become part of matter wind and the rest power the jet.
- How does this modify the scaling of jet power?

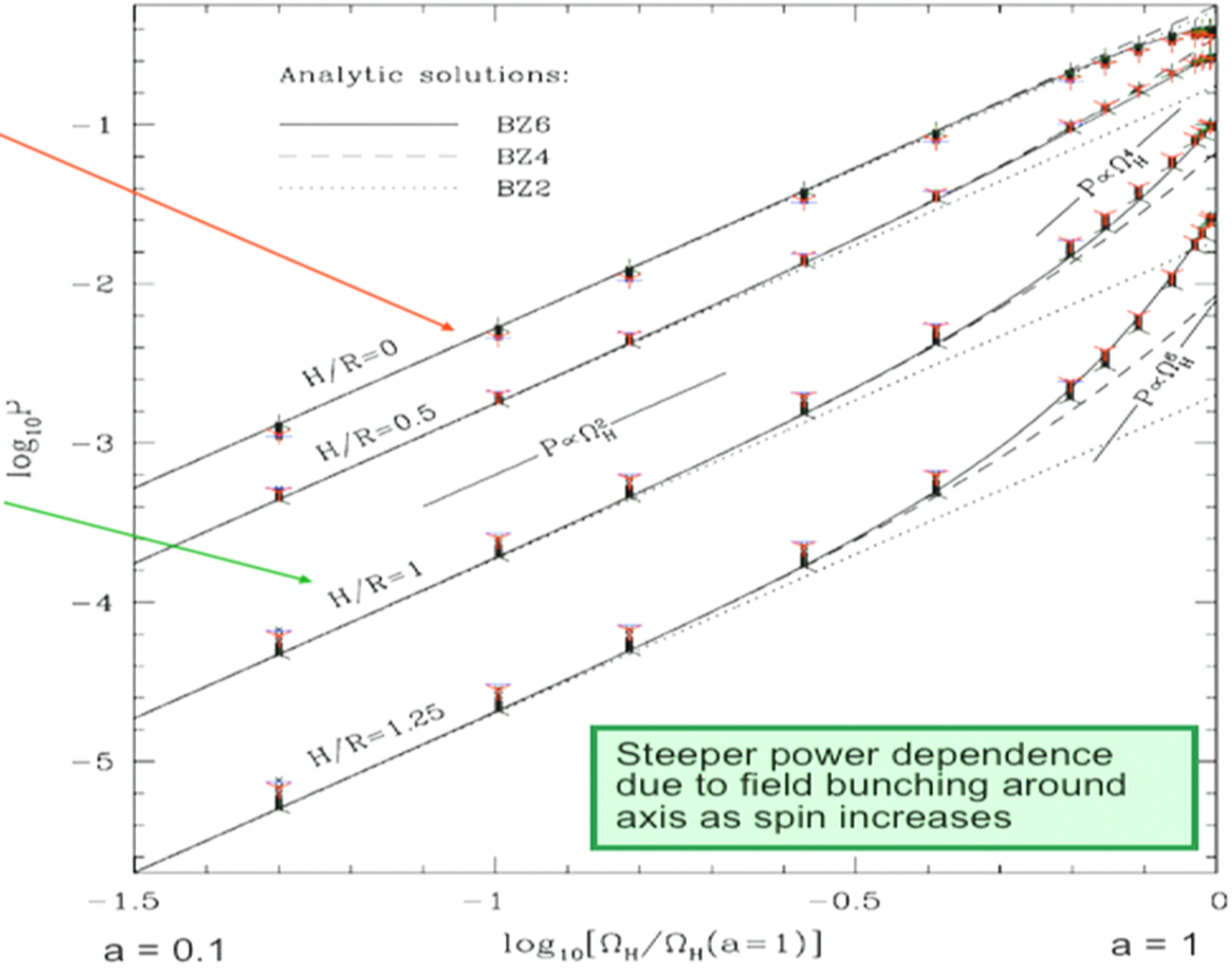
Thick Disks: Steep Jet Power Scaling



If we assume that BH magnetic flux is the same for all spins, then we find that the power in the Poynting-dominated jet increases rapidly with spin:

$$P_j \propto \Omega_{\rm H}^4$$

(Tchekhovskoy et al. 2010b; see also McKinney 2005)



Steeper power dependence due to field bunching around axis as spin increases

Steep Jet Power Can Explain Radio Loud/Quiet Dichotomy

- The factor of 1000 in radio luminosity can be explained by having two galaxy populations with different spins (assuming disk with H/R = 1):
  - Radio-loud population: $a \approx 1$
  - Radio-quiet population: $a \approx 0.15$
  - This is much more comfortable than the previous requirement for razor-thin disks that the radio-quiet population has $a \approx 0.03$

Summary:
Jet Power vs. Spin

- The scaling $P_{\rm BZ} = k\Phi^2\Omega_{\rm H}^2/c$ gives a rather wide range of power as a is varied
- BH power (for fixed Φ) varies by ~$10^{1.5}$ if a varies from 0.3 to 1.
- If the disk is thick (ADAF, H/R~1), and only the magnetic flux in the funnel contributes to the jet,

$$P_{\rm jet} \propto \Omega_{\rm H}^4,$$

and power variation by ~10^3 is possible (Tchekhovskoy et al. 2010b).

What Sets BH Magnetic Flux?

- We understand now how BH power depends on Φ and a:

$$P_{\rm BZ} = k\Phi^2\Omega_{\rm H}^2/c$$

- Clearly, $\Phi^2 \propto \dot{M}c^2$
- But, what sets value of the proportionality factor,

$$\phi = \frac{\Phi}{\sqrt{\dot{M}r_g^2c}},$$

and BH power efficiency,

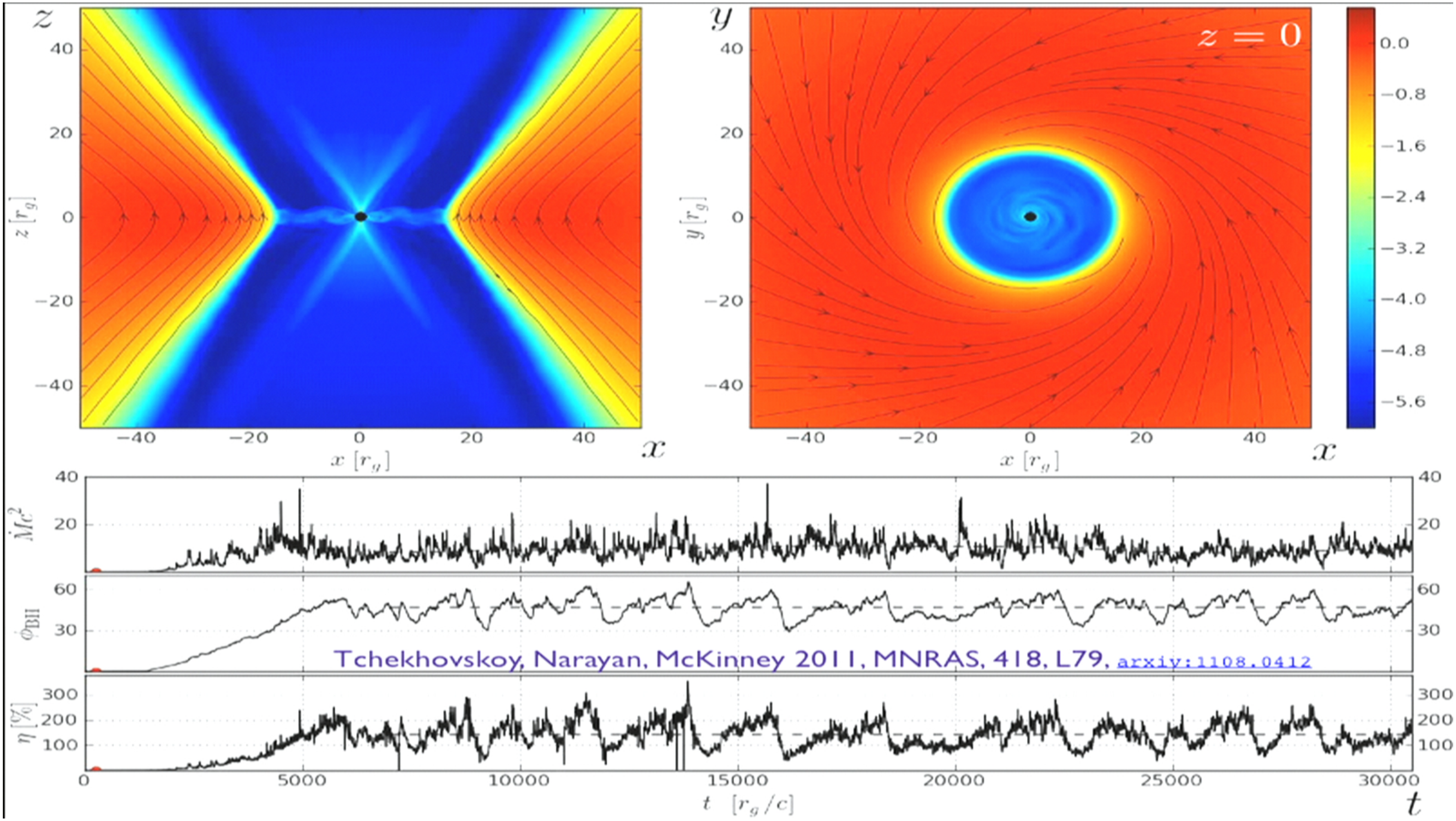
$$\eta_{\rm BZ} = \frac{P_{\rm BZ}}{\dot{M}c^2} = k\,\phi^2\left(\frac{\Omega_{\rm H}r_g}{c}\right)^2?$$

Turn to Simulations

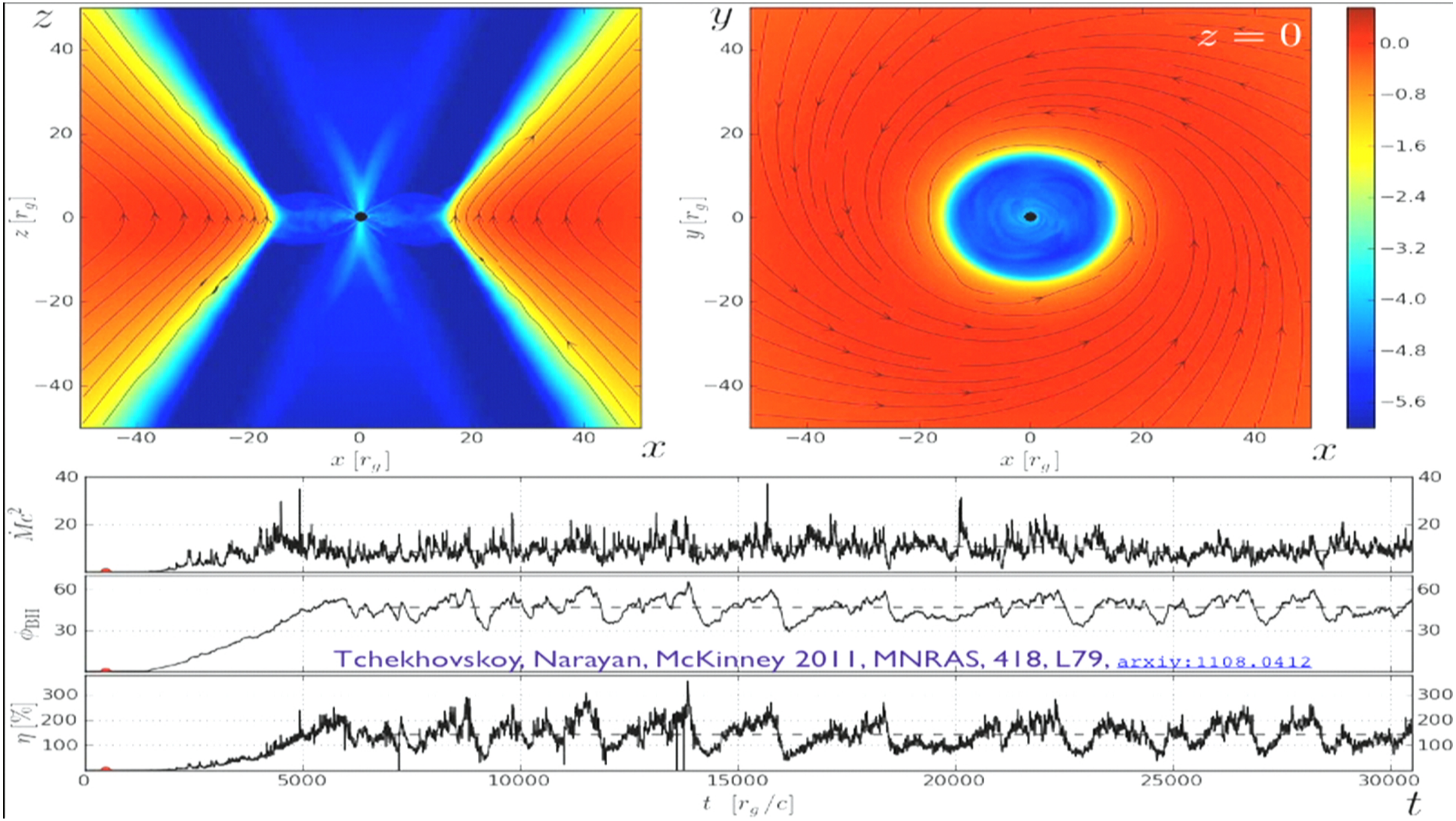
- Jet power depends on magnetic field topology (McKinney 2005, Beckwith, Hawley & Krolik 2008, McKinney & Blandford 2009)
  - ➡ Dipolar geometry gives powerful jet
  - ➡ Quadrupolar or toroidal gives weak or no jet
- GR MHD simulations give $\eta_{\rm BZ} \lesssim 20\%$, even for nearly maximally spinning BHs (McKinney & Gammie 2004, McKinney 2005, de Villiers et al. 2005, Hawley & Krolik 2006, Barkov & Baushev 2011)
- Can we obtain larger values of η?
- Observations: some AGN have $\eta \gtrsim 100\%$ (Rawlings & Saunders 1991, Fernandes et al. 2010, Ghisellini et al. 2010, Punsly 2011, McNamara et al. 2011)

Jets from Magnetically-Arrested Disks

- Jet power increases with increasing BH magnetic flux, Φ.
- Our simulations contain enough magnetic flux to magnetically "overwhelm" the BH:
  - BH receives more flux than the inner disk can push into the BH, which maximizes Φ and leads to $\eta > 100\%$.
- Outcome is magnetically-arrested accretion (MAD): matter has to fight its way through the field to get to BH (Igumenshchev et al. 2003, Narayan et al. 2003).



Tchekhovskoy, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412



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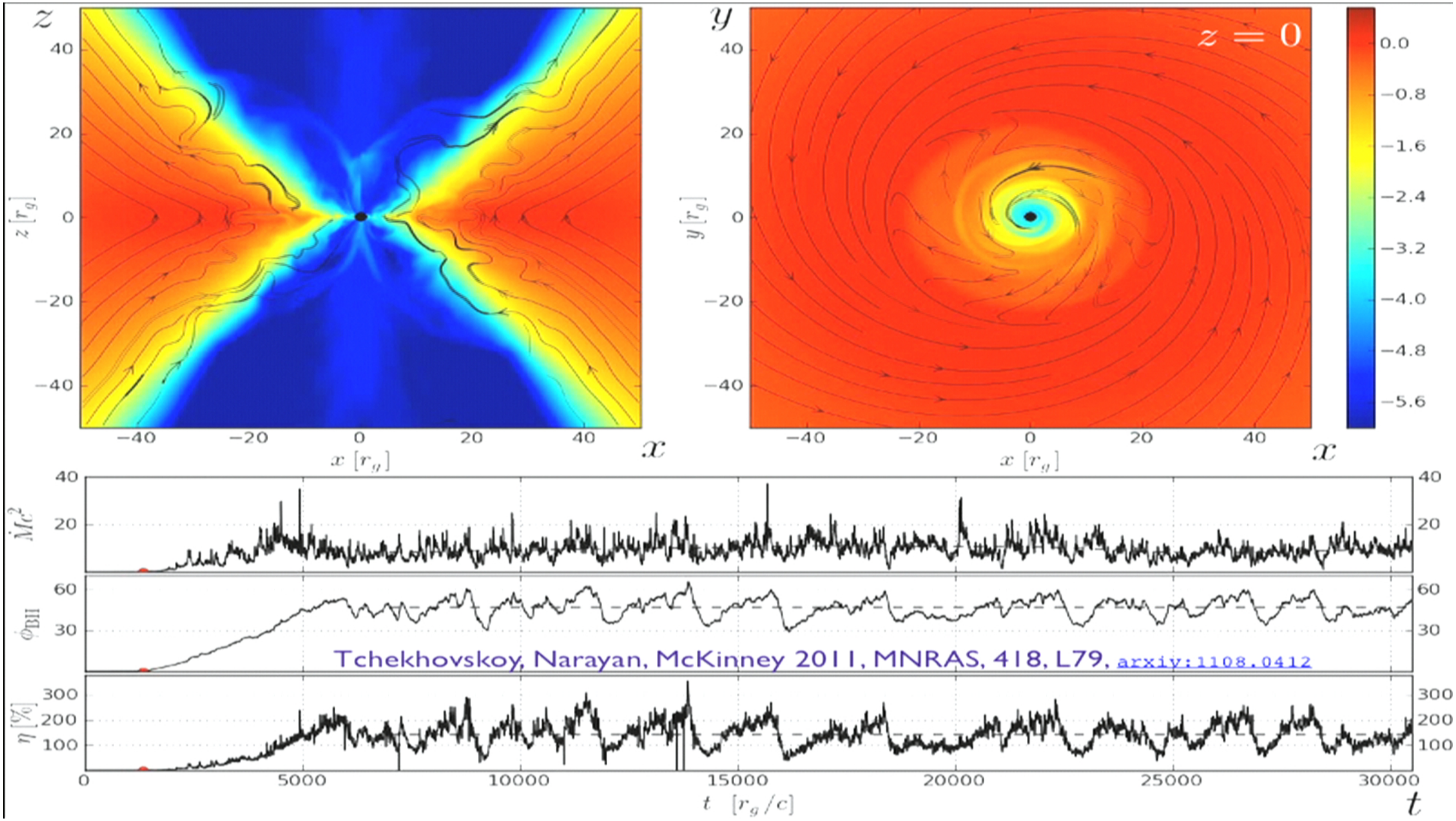

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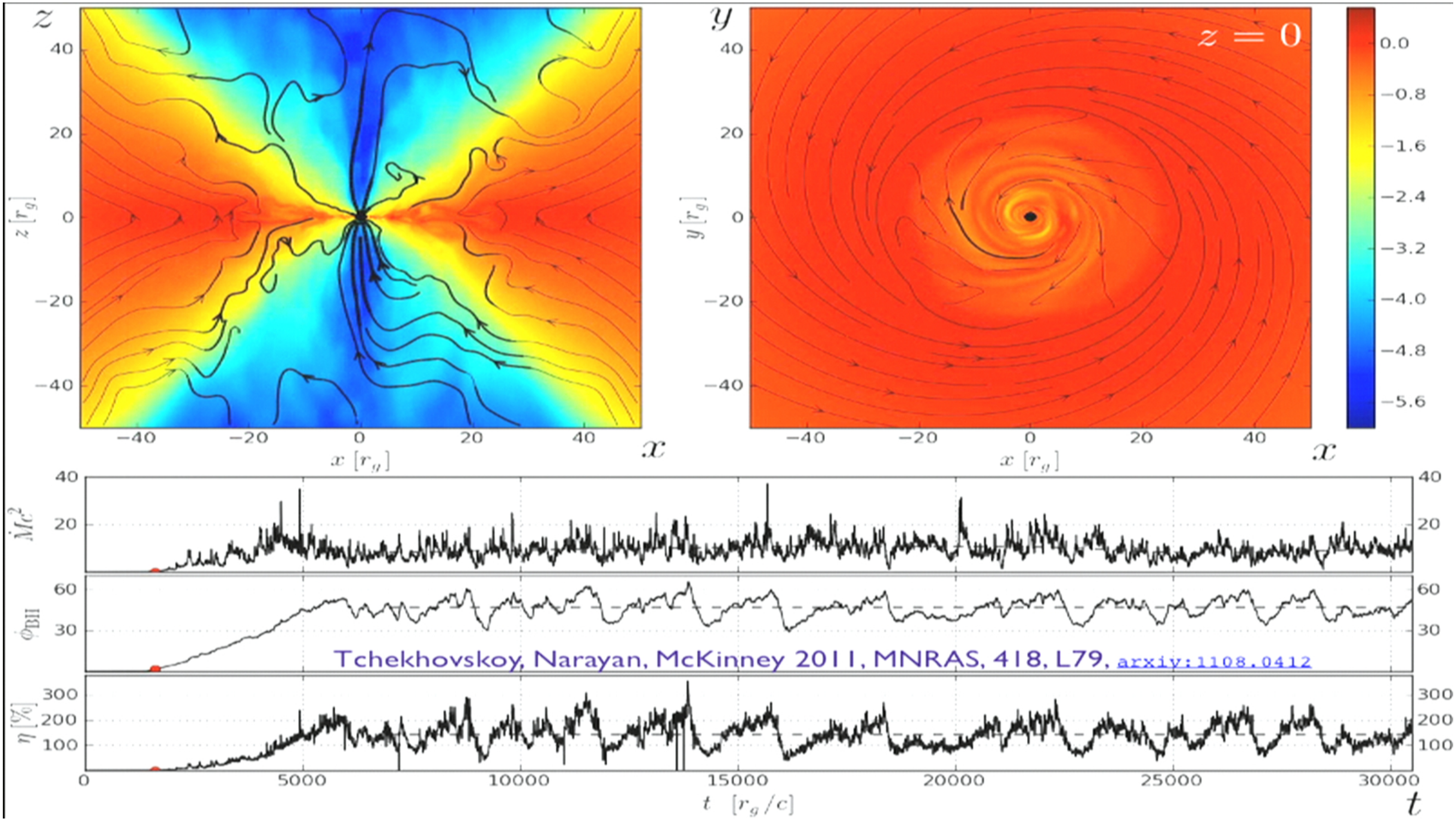

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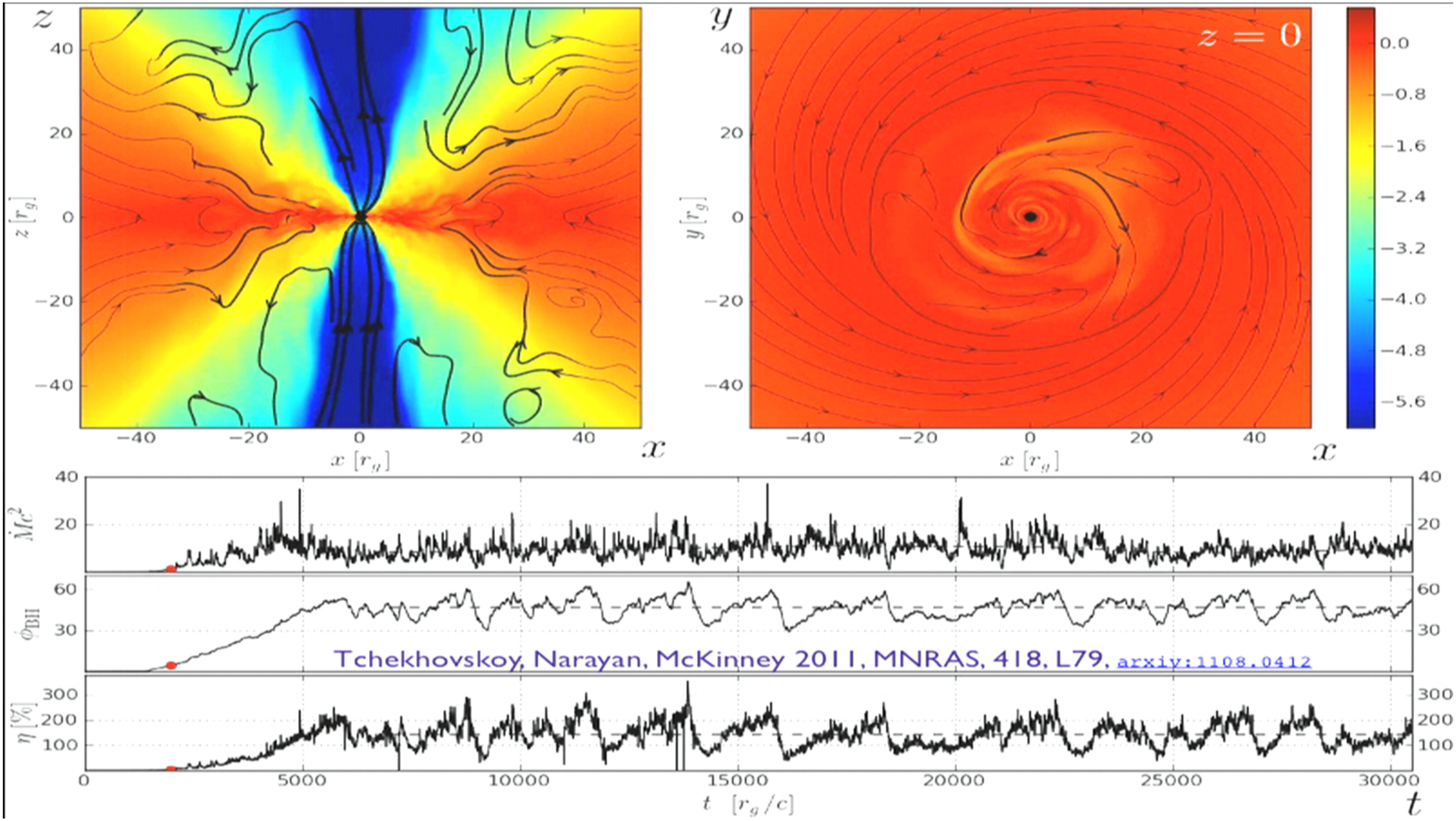

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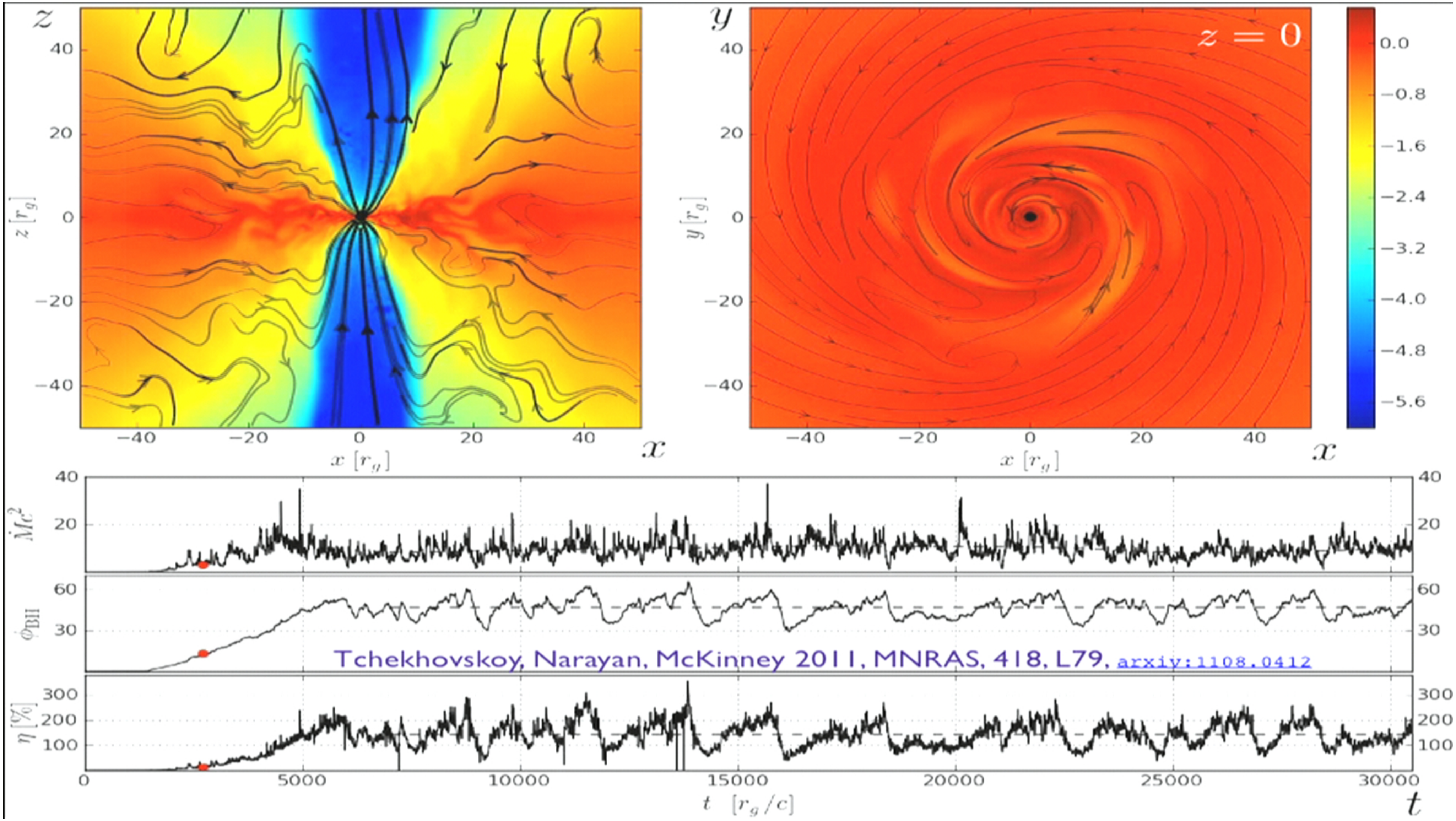

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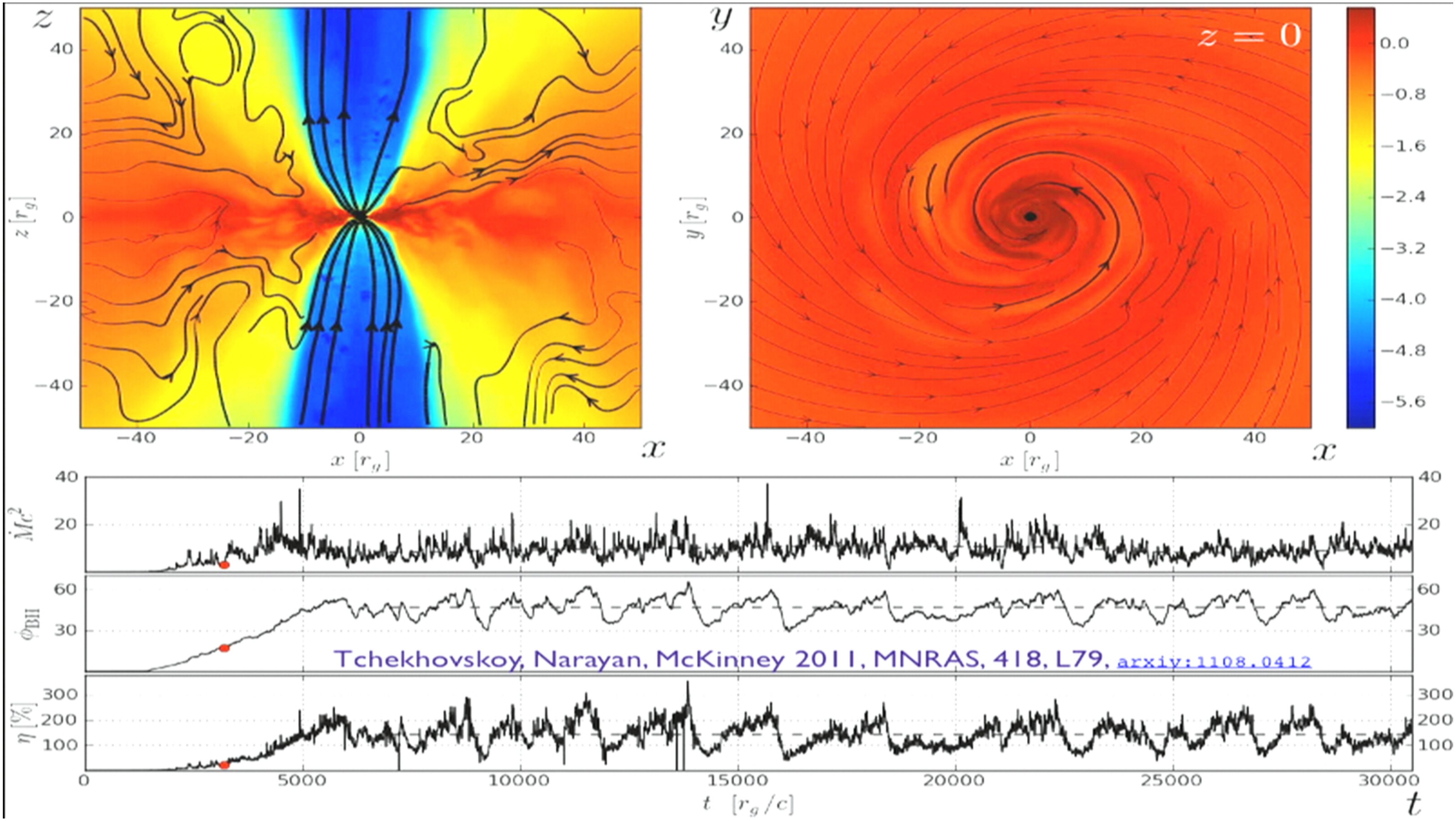

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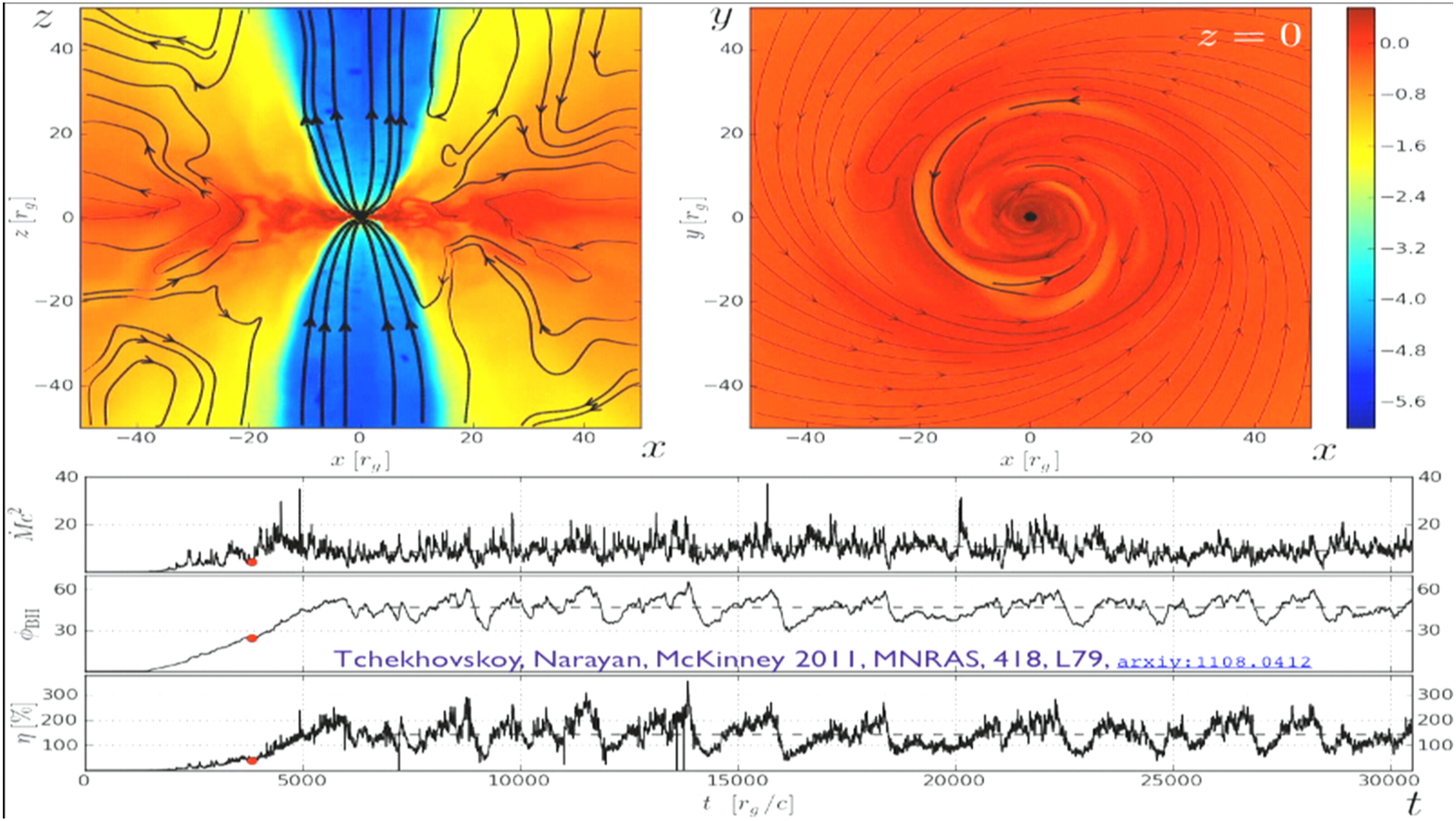

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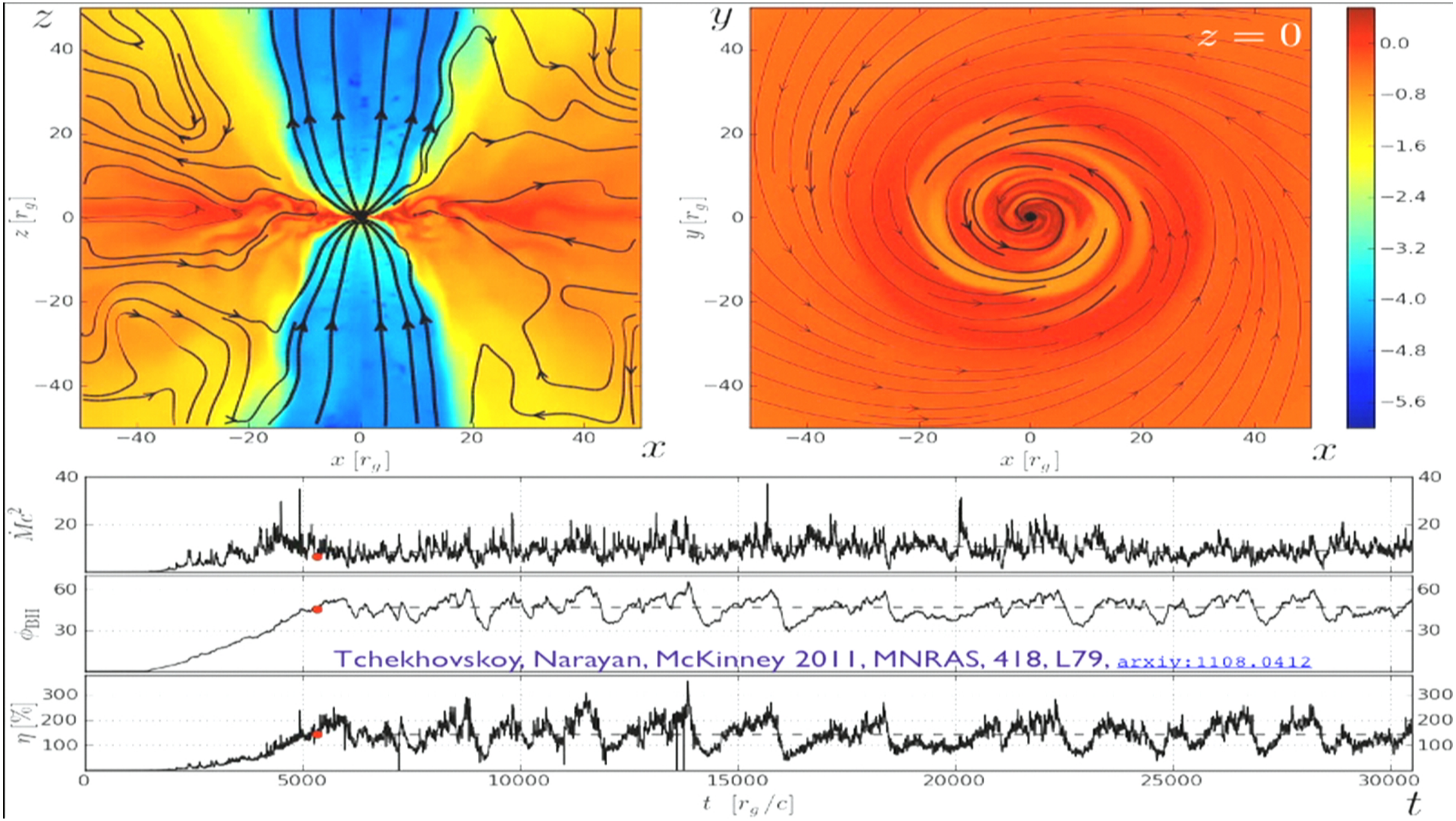

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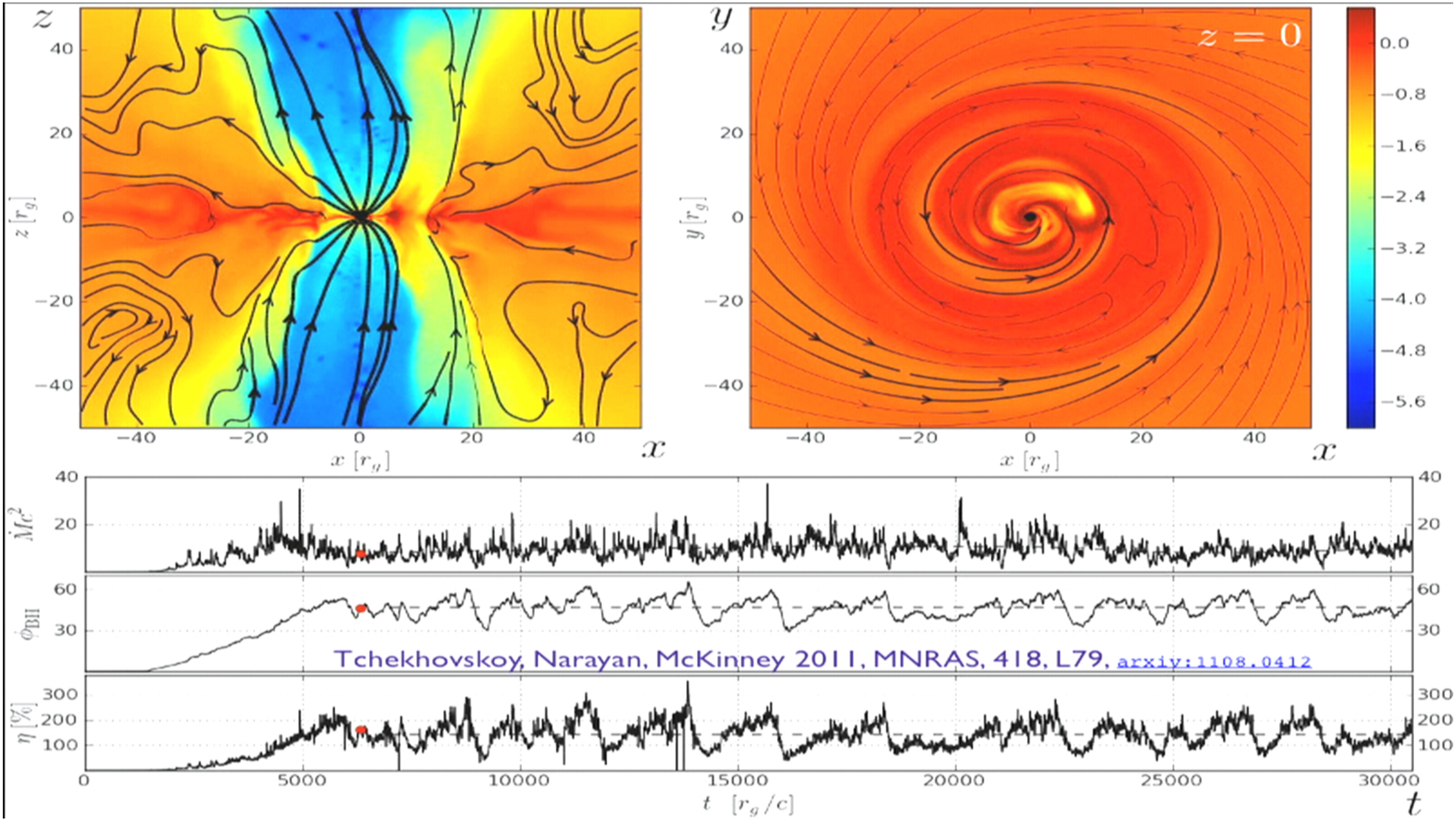

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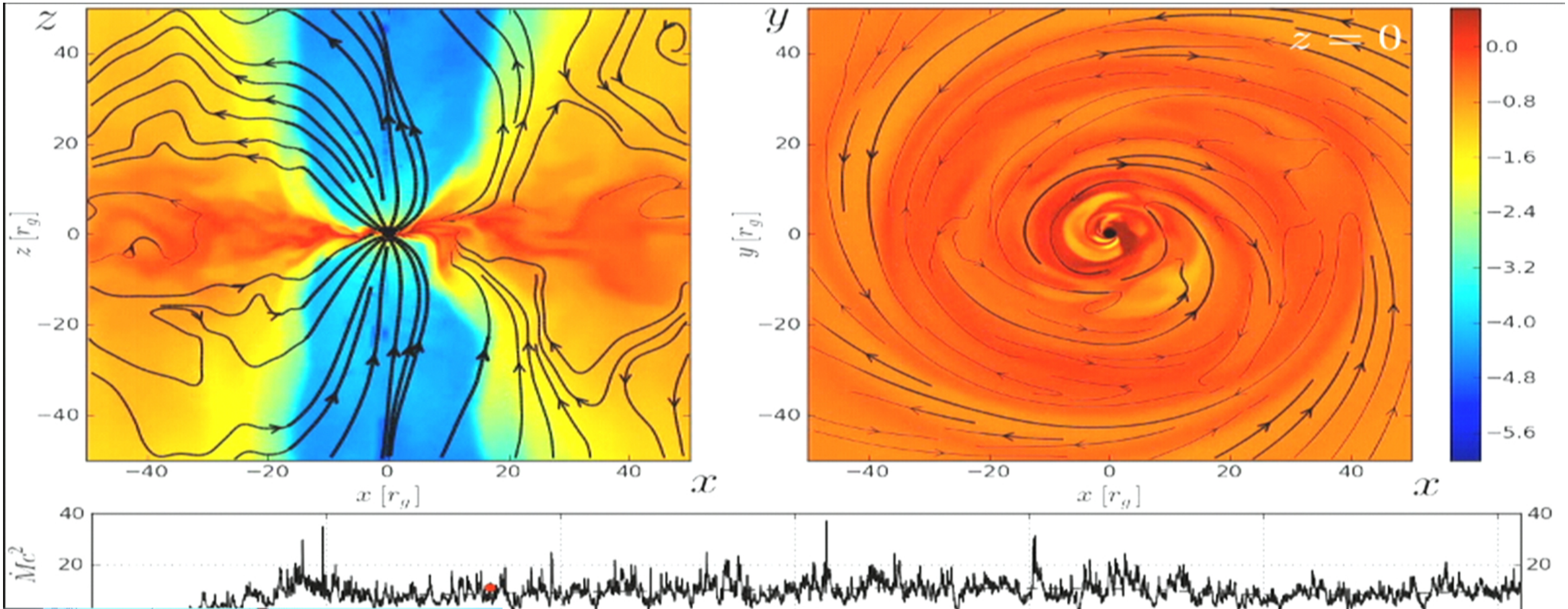

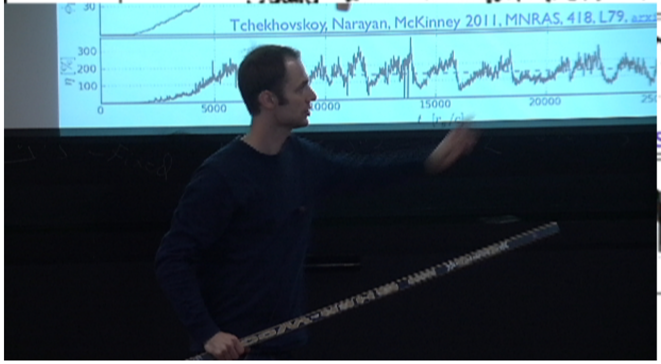

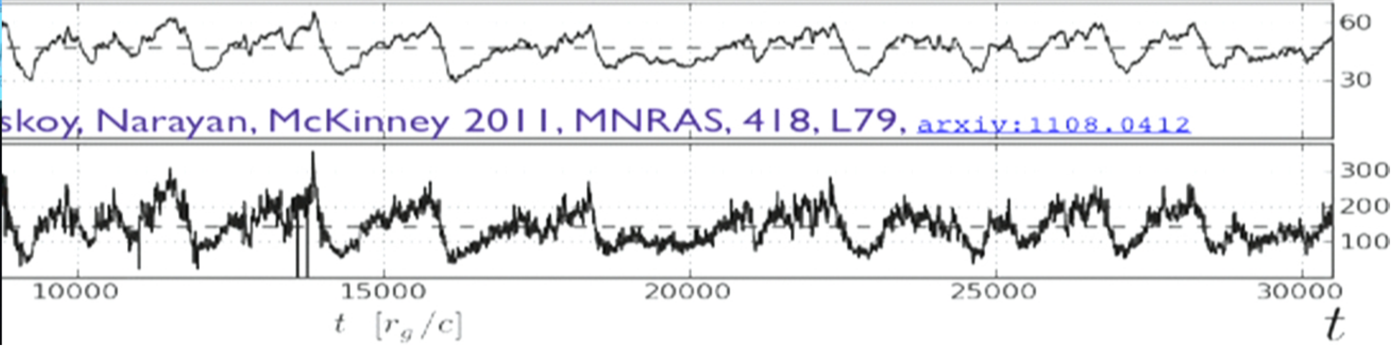

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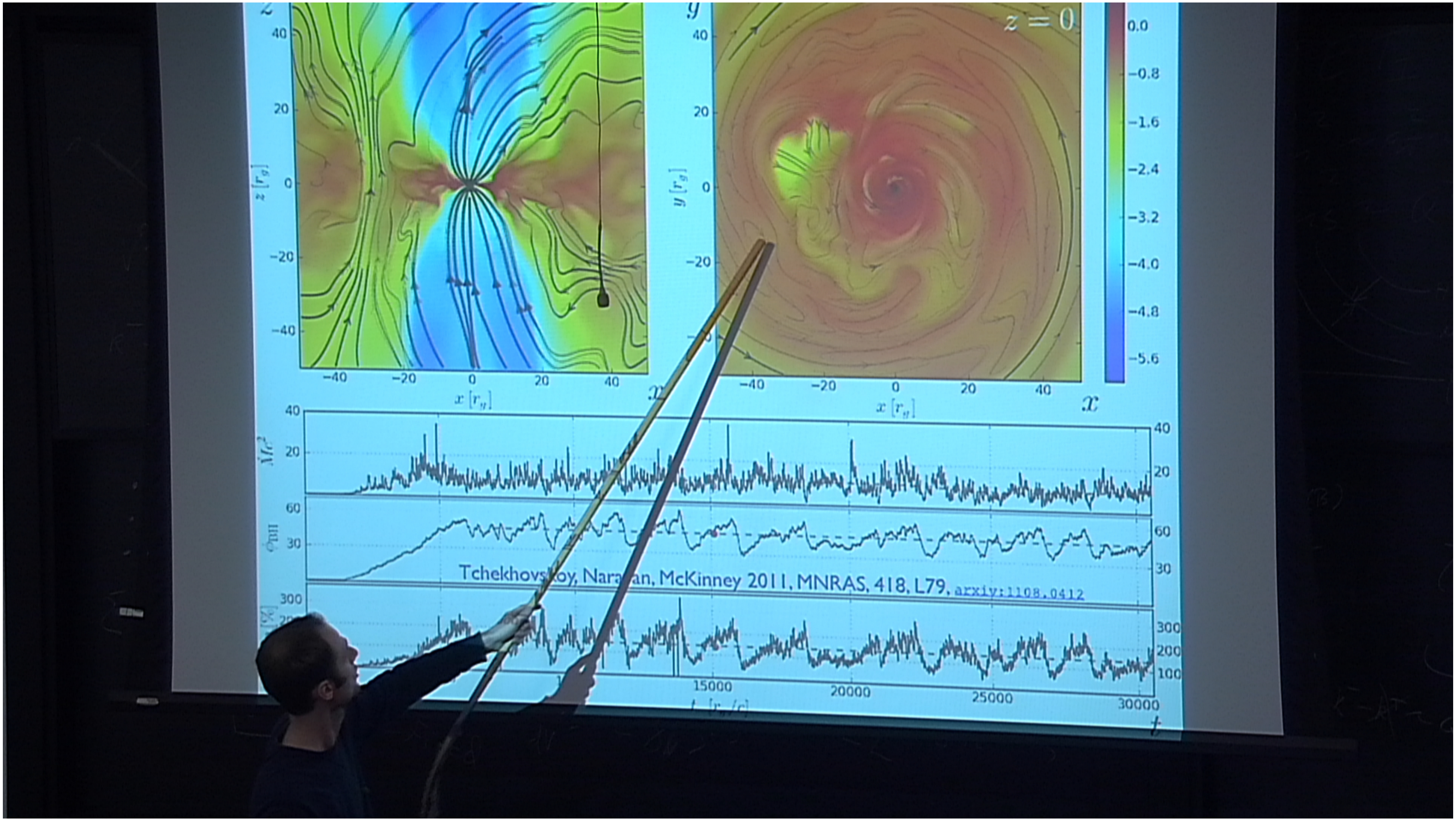

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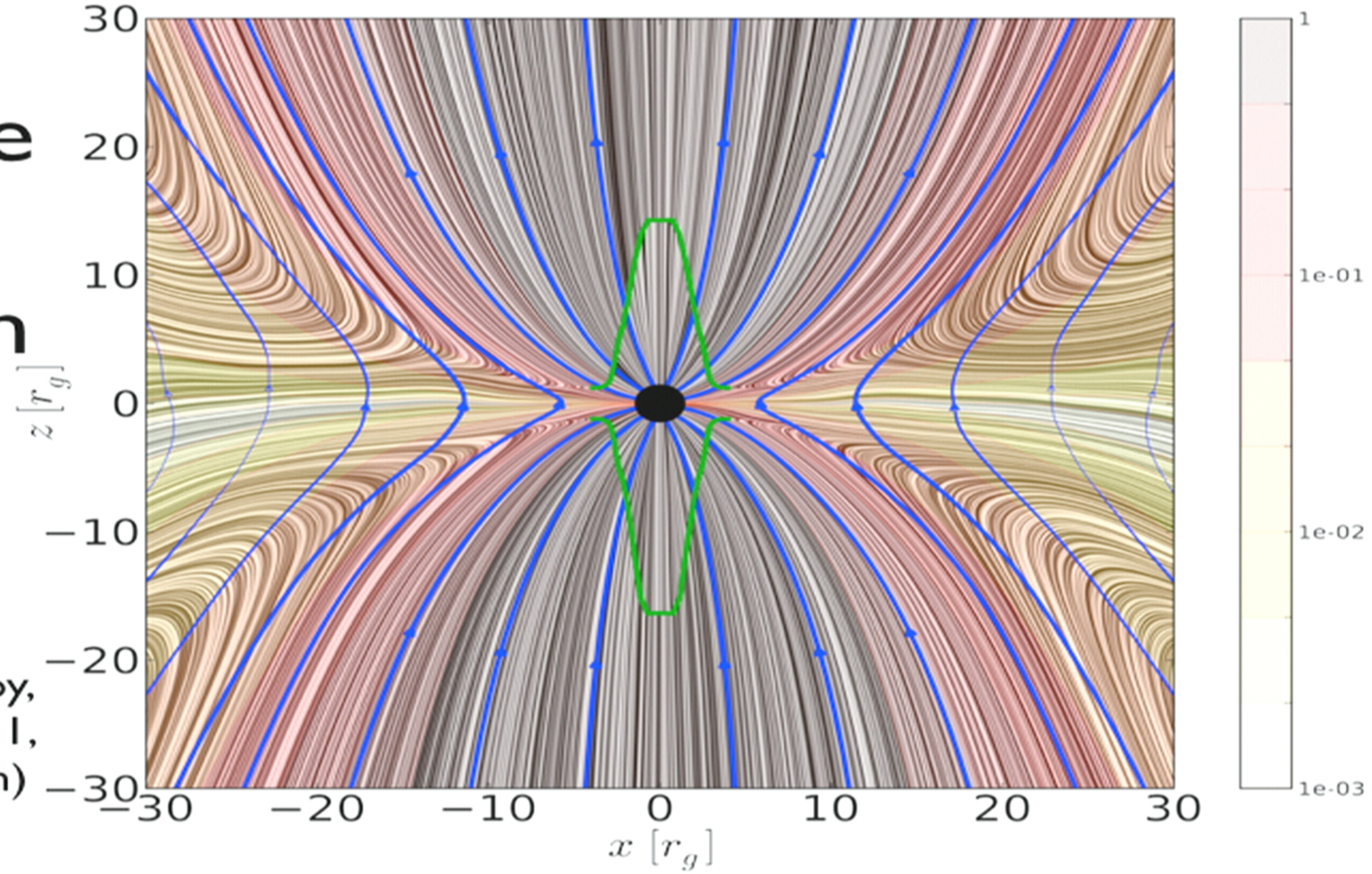
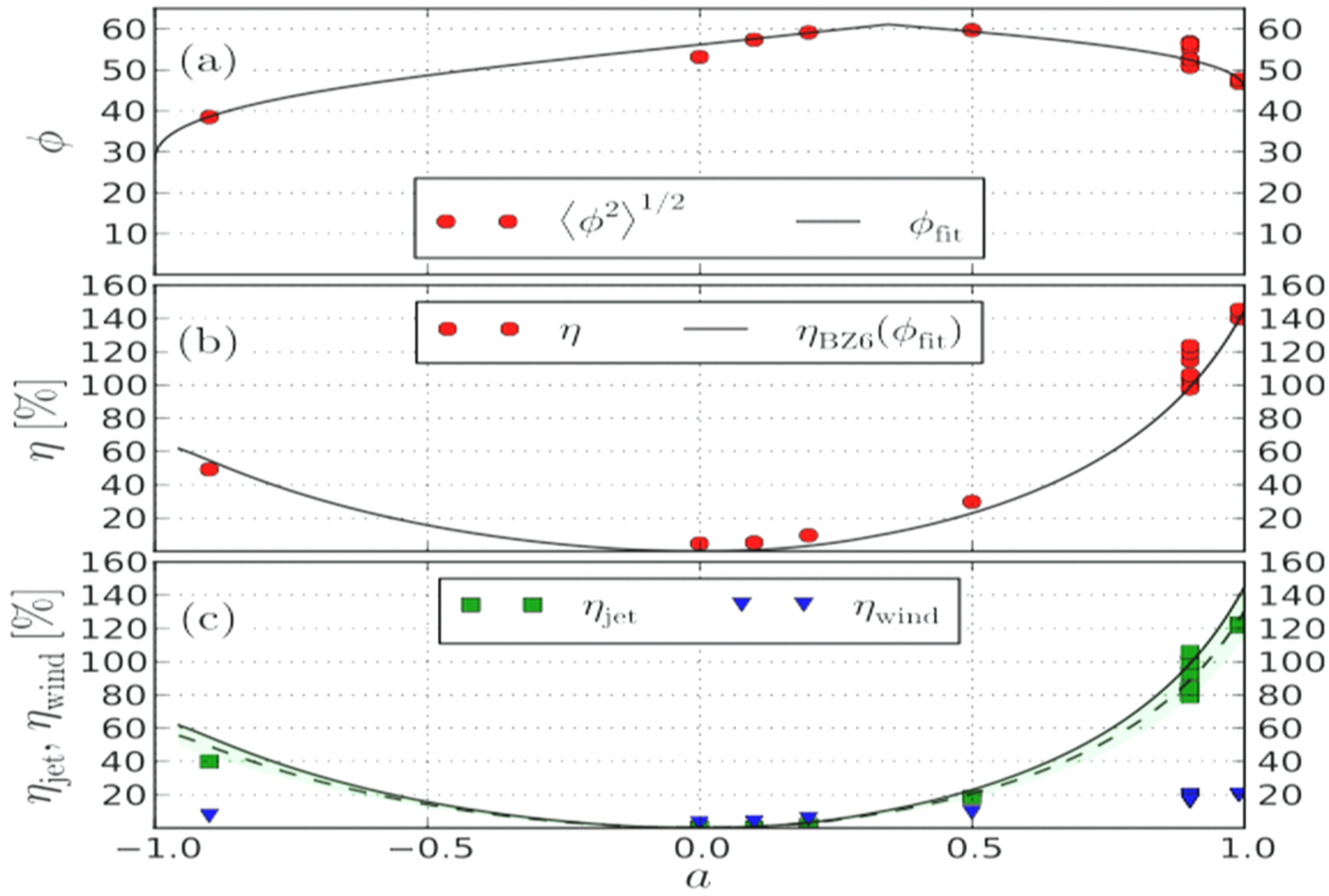
Time-average flow pattern



(Tchekhovskoy, McKinney 2011, in preparation)

Time-average outflow properties



(Tchekhovskoy, McKinney 2011, in preparation)

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

Prograde BHs are twice as efficient as retrograde BHs

see also Hawley & Krolik '06

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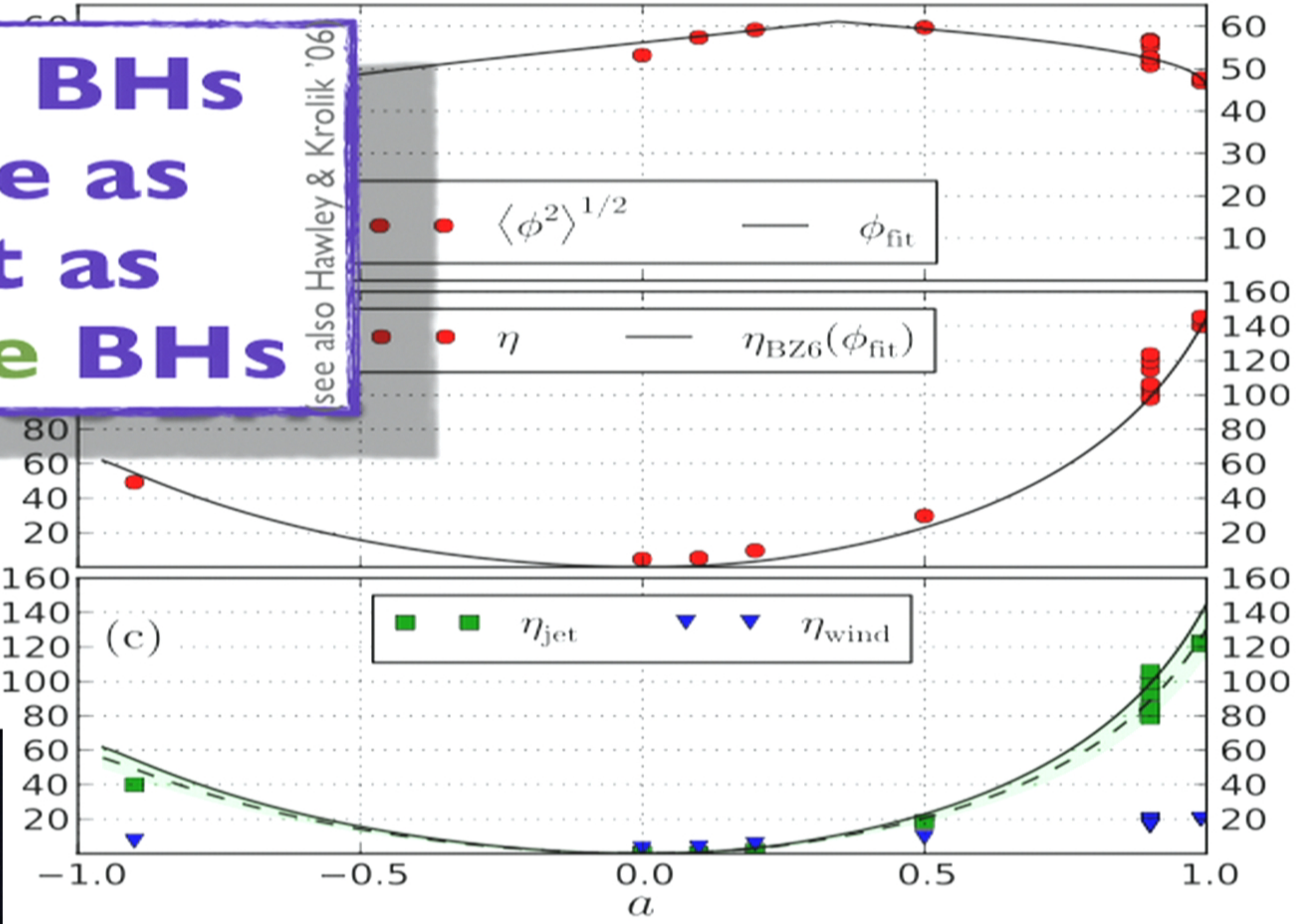

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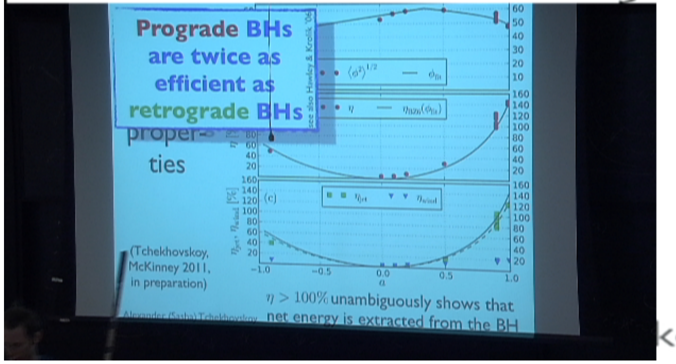
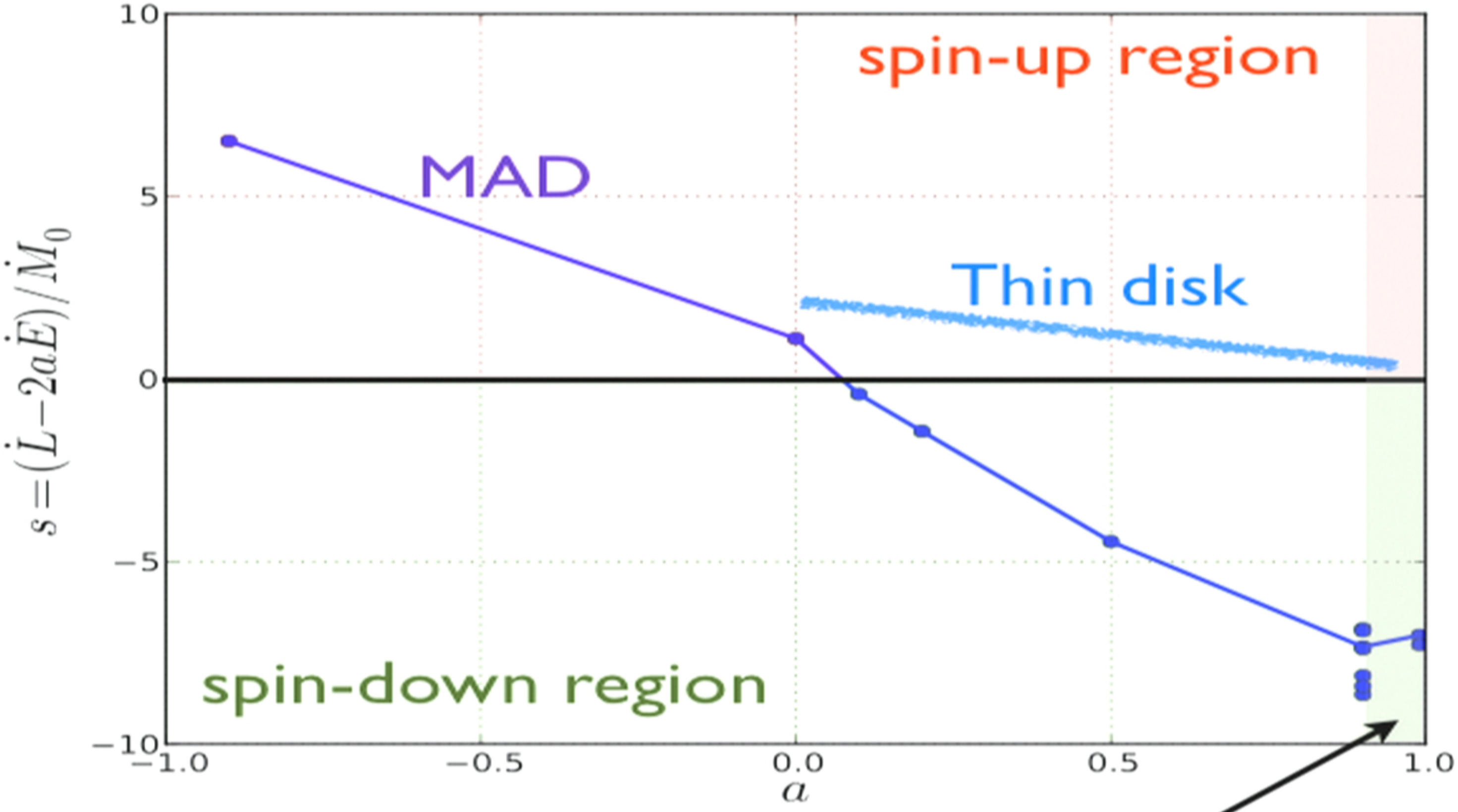


(Tchekhovskoy, McKinney 2011, in preparation)

Our MADs slow BHs down to a near halt



Conventional spin equilibrium region, $a \gtrsim 0.9$

(Tchekhovskoy, McKinney 2011, in preparation)

(see also Gammie et al. 2005, Shapiro et al. 2005, Benson & Babul 2009)

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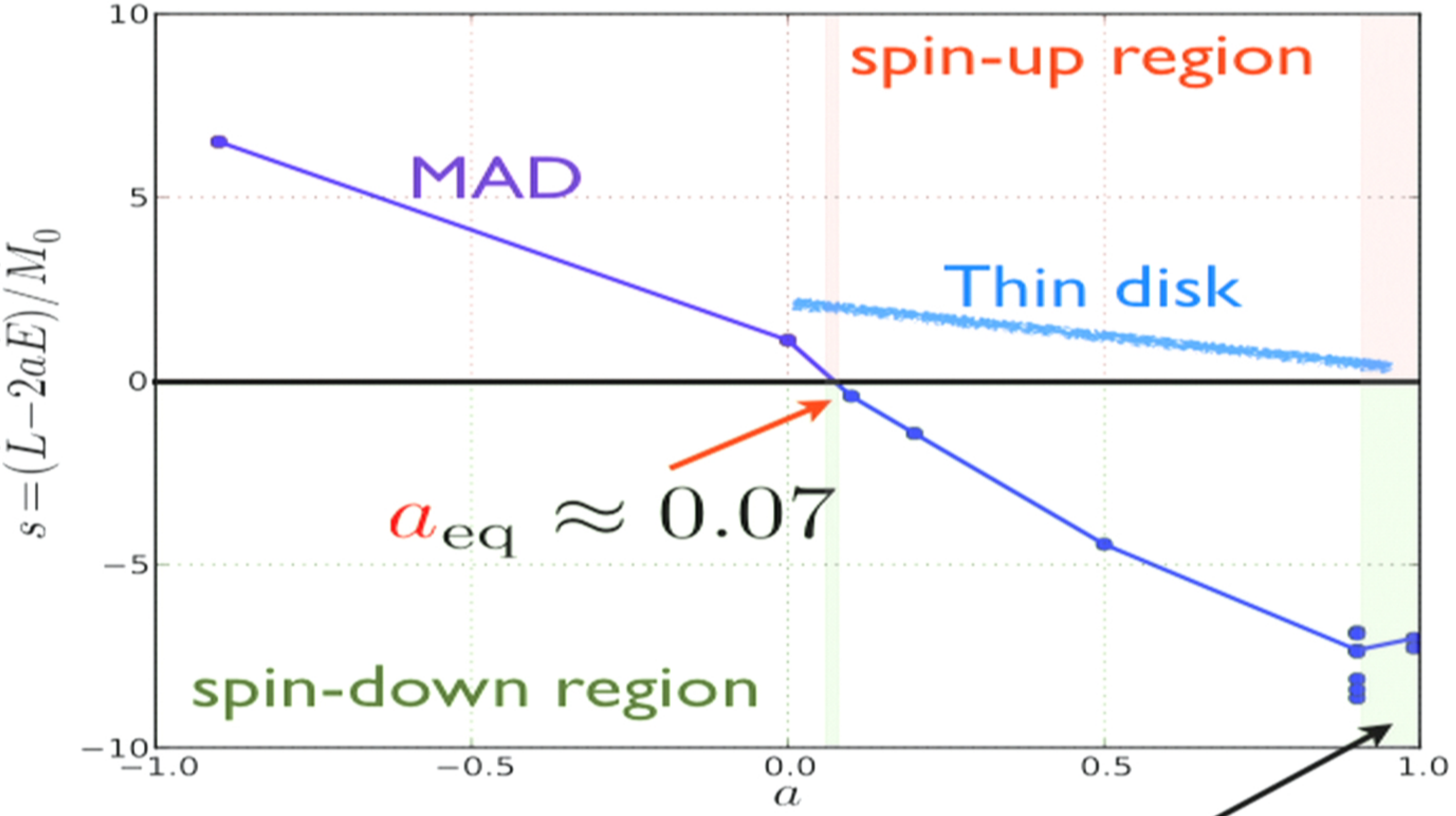


(Tchekhovskoy, McKinney 2011, in preparation)

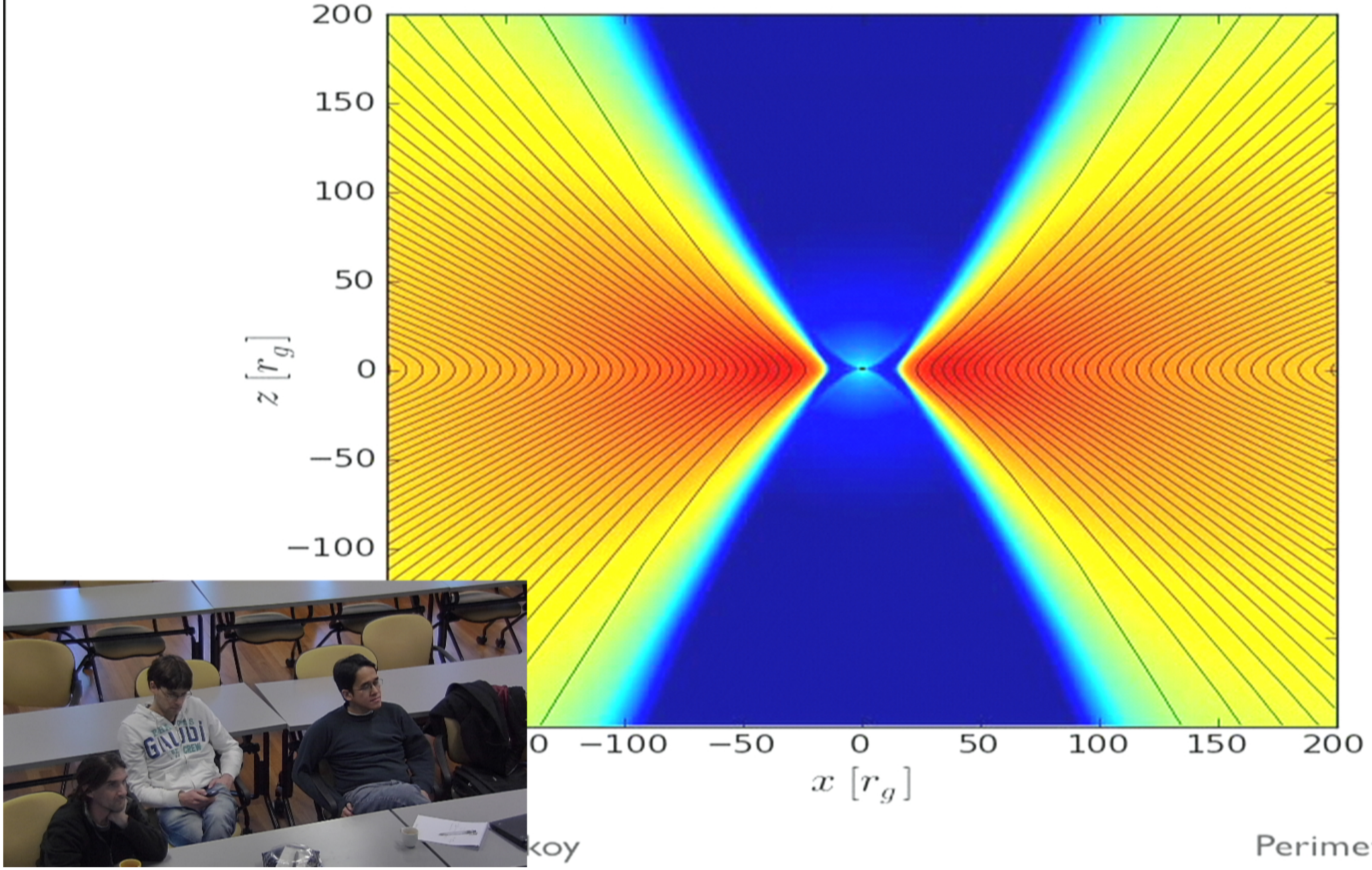
Jet power varies by >1000x if a varies from 0.07 to 1.

Conventional spin equilibrium region, $a \gtrsim 0.9$

(see also Gammie et al. 2005, Shapiro et al. 2005, Benson & Babul 2009)

Summary of Magnetically-Arrested Disks

- Simulations attempt to maximize Φ
- Φ saturates in quasi-steady state
- $\eta > 100\%$ for $a \gtrsim 0.9$
  - First demonstration of net energy extraction from a spinning BH in a realistic astrophysical setting
- Retrograde disks have 50% less efficient jets than prograde disks
- MADs quickly spin down BHs to a near-halt, which can explain the radio-quiet AGN population



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AGN Radio Loud/Quiet Dichotomy

- Factor of 1000 difference in radio luminosity.
- There must be at least one other parameter in

and $\dot{M}$:

$M; ??)$

spin a?

rt '95)

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