General Relativistic MHD Simulations of Relativistic Jets in AGN

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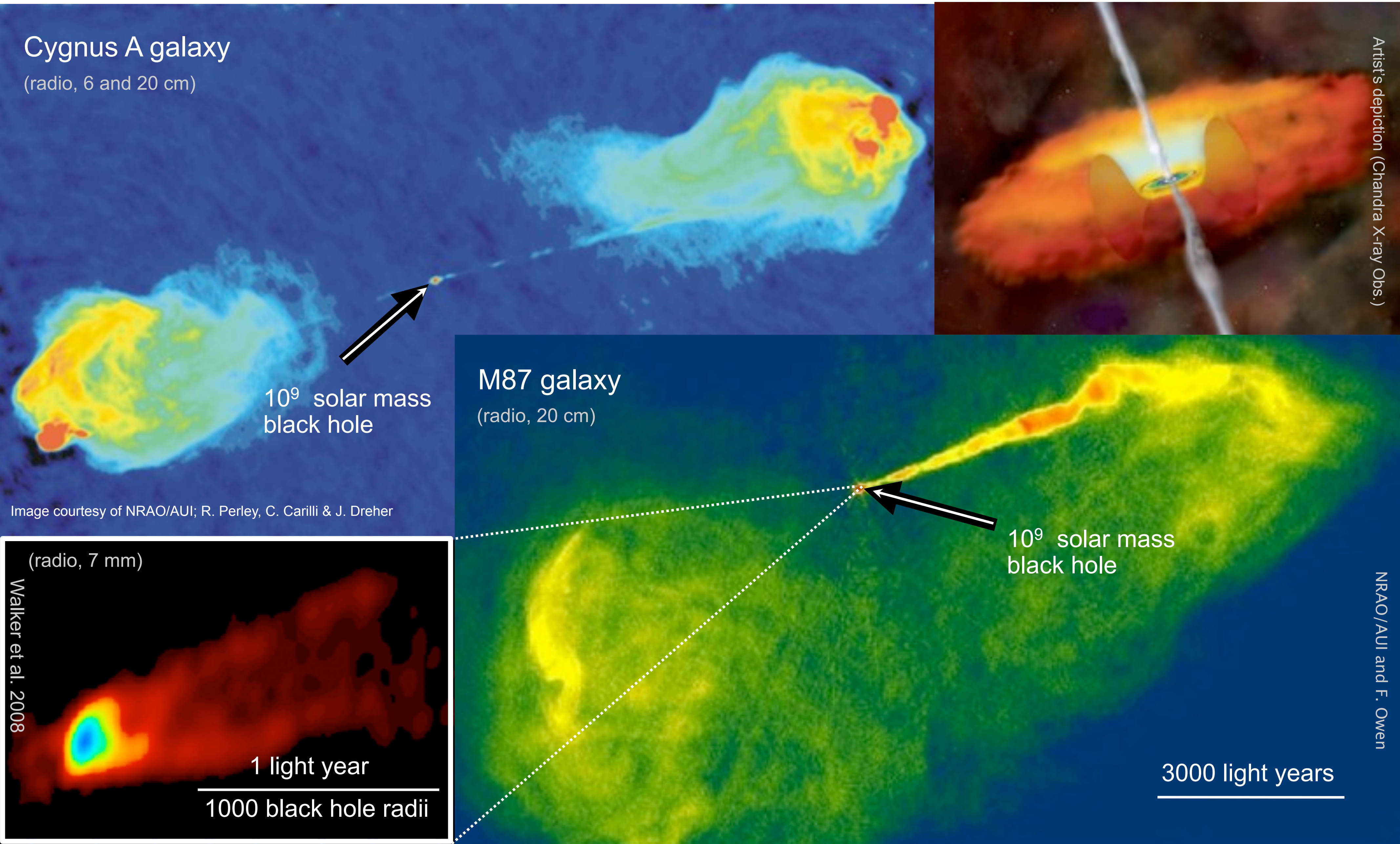
Jets: Beautiful & Challenging



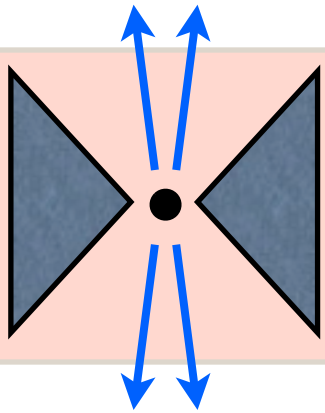
Fundamental Questions

- What sets the maximum power of jets?
- Are jets powered by black holes or inner regions of accretion disks?
- How does jet power depend on BH spin?
- Does accretion always spin up BHs to high spins?

When Do We Observe Jets?

$\lambda = L/L_{\rm edd}$

$h/r \sim 1$
$\tau \gg 1$



Radiatively-Inefficient (super-Eddington) ULX/HLX and TDEs
(see talks by Gladstone, Middleton, Roberts, Farrell)

100%

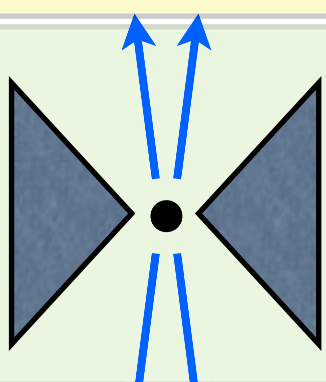
10%

$h/r \ll 1$
$\tau \gg 1$

Thin Disk
(High/Soft or Thermal state)

1%

$h/r \sim 1$
$\tau \ll 1$



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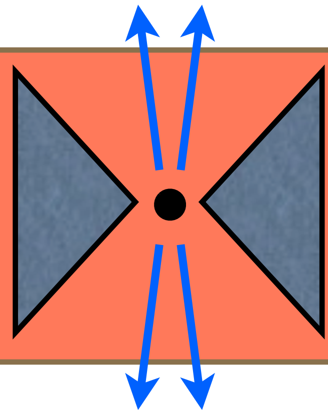

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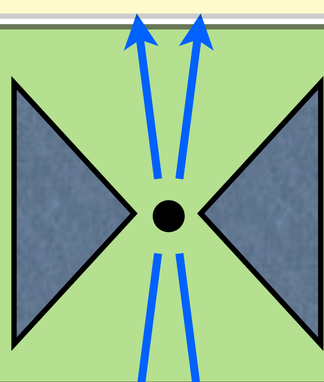

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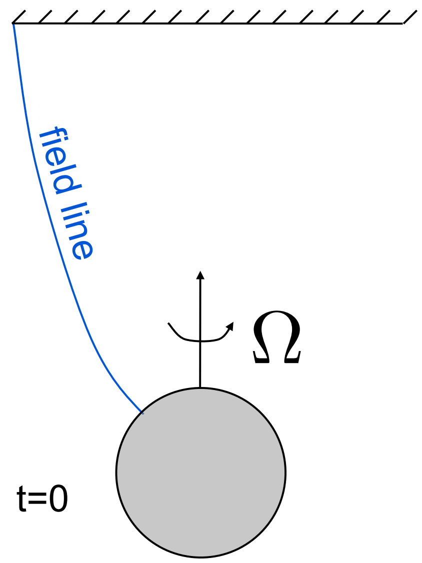
How Do Jets Work?



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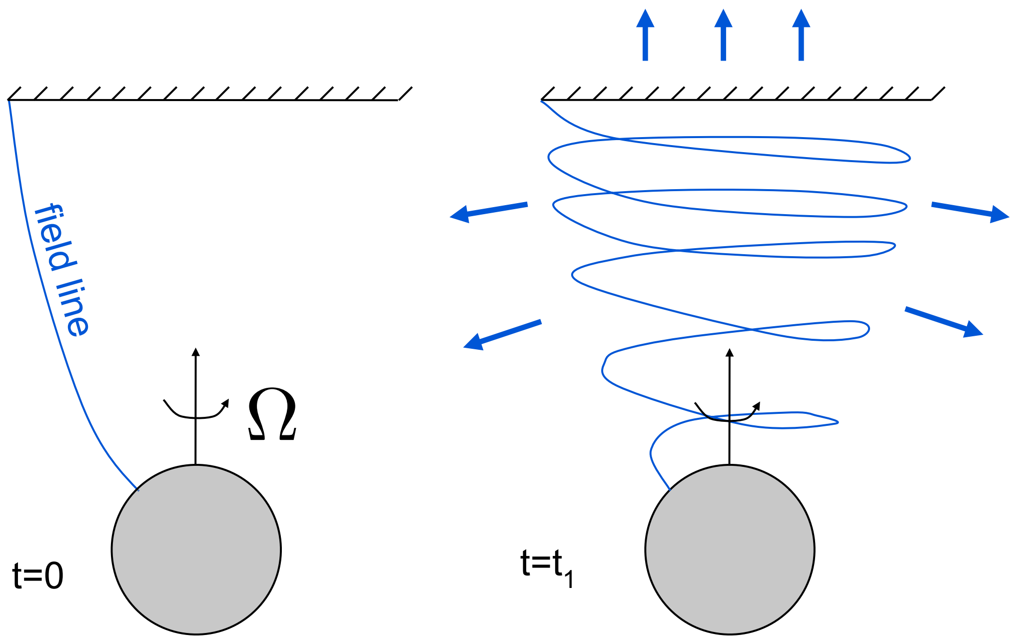
$$P = \frac{B_\varphi^2}{8\pi}$$



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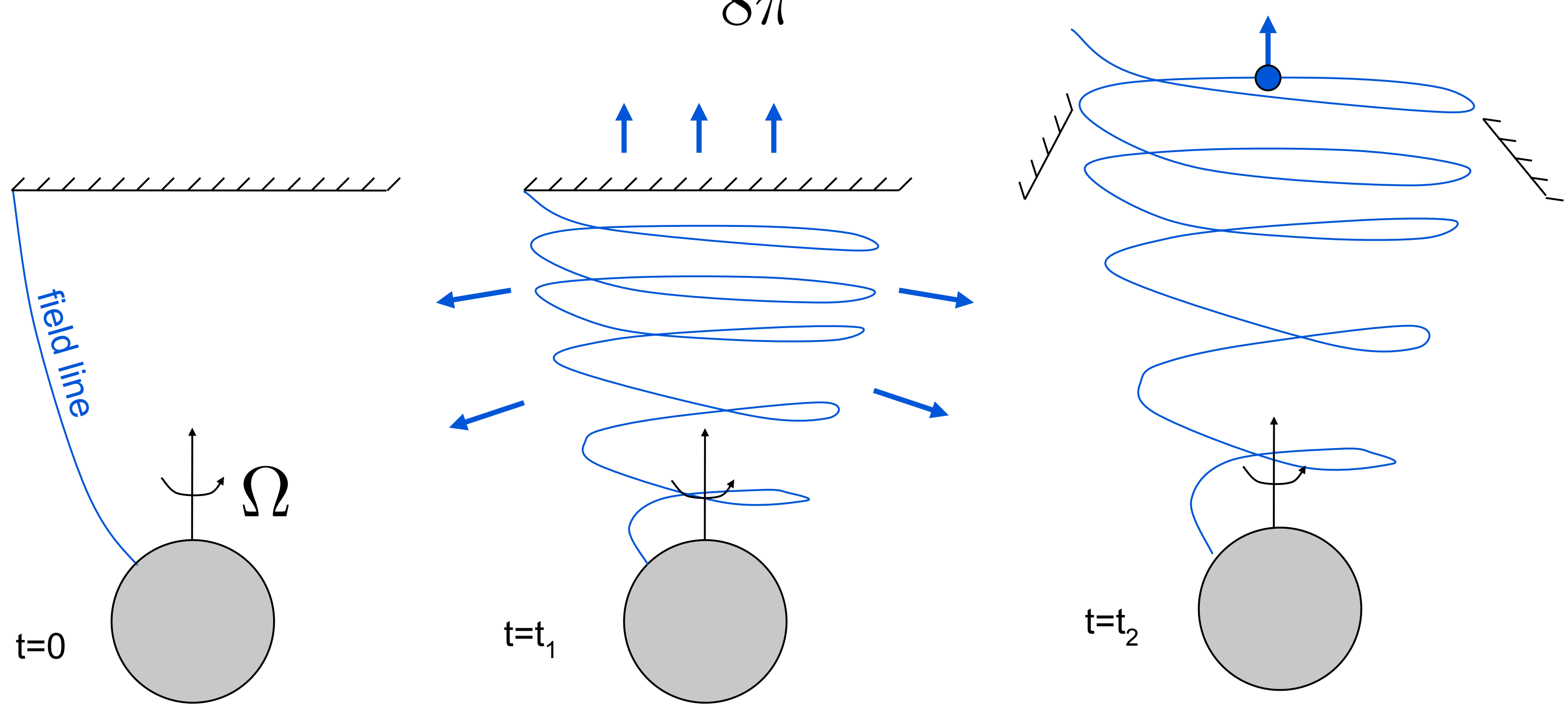
Field toroidally-dominated $B_\varphi \gg B_z$



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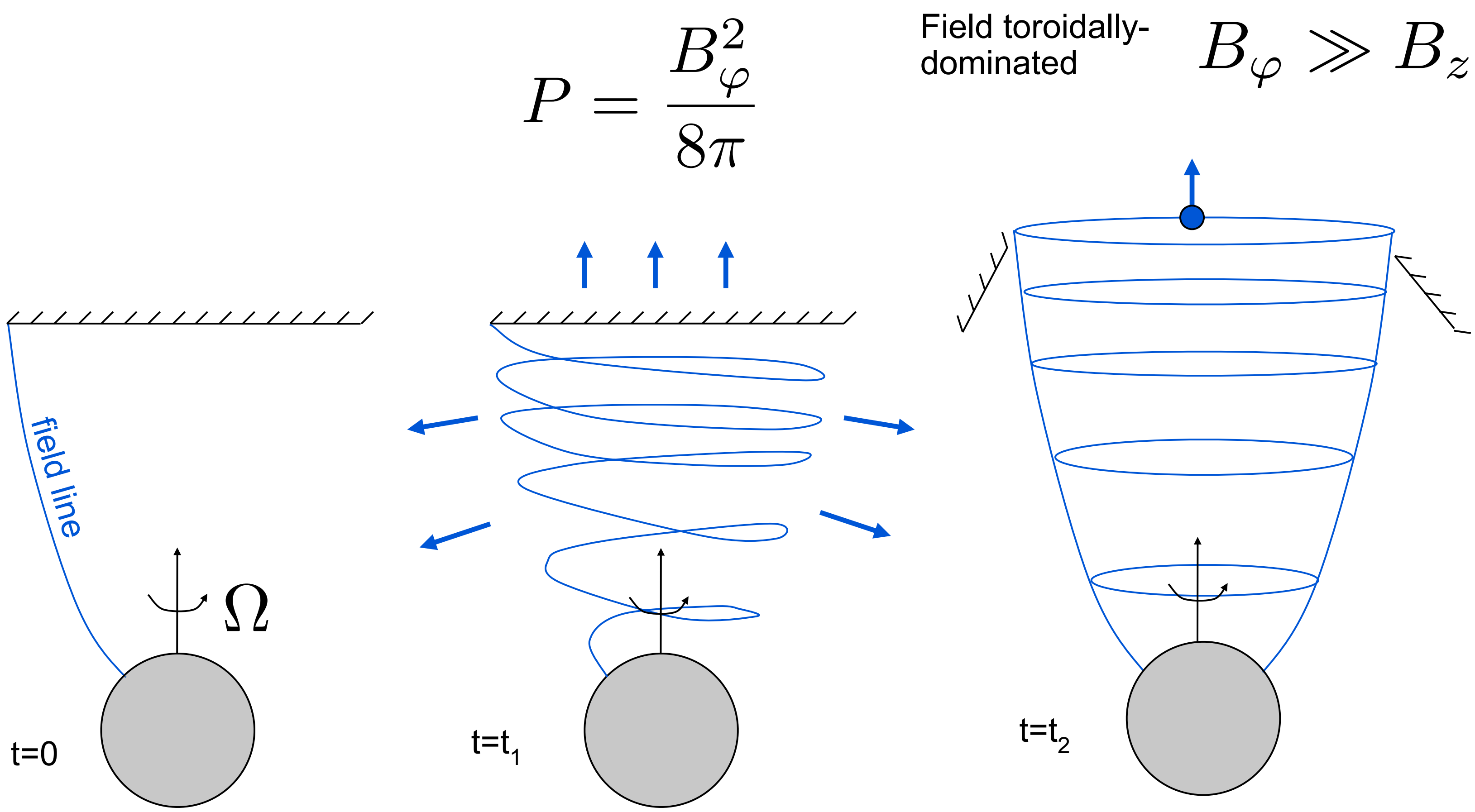

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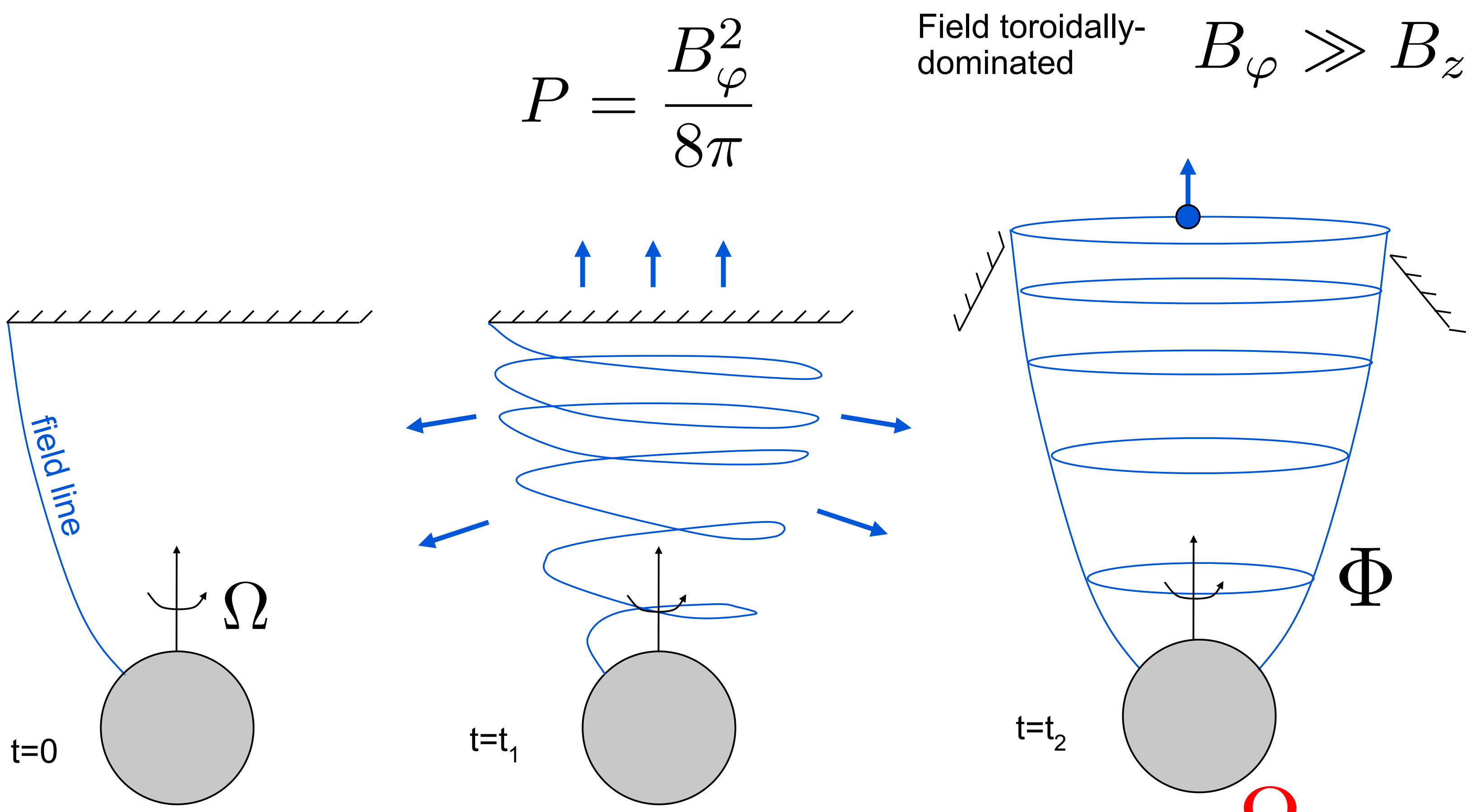

$$\Omega_H = \frac{ac}{2r_H}$$

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

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

(Blandford & Znajek 1977,
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$$1 + 1.4(\Omega_{\rm H} r_g/c)^2 - 9.2(\Omega_{\rm H} r_g/c)^4$$

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

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

(Gammie 2002, Komissarov & Barkov 2009, Penna et al. 2010)

and BH power efficiency,

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

What Sets the Flux?

- Gravity limits BH field strength:

$$\frac{B^2}{8\pi} \lesssim \frac{GM\Sigma}{R^2}$$ (Narayan+ 2003)

- Mass conservation in a disk:

$$\dot{M} = 2\pi R \Sigma \beta_r c$$

- BH magnetic field:

$$B_r^{\rm max} \sim 2\times 10^4\ [{\rm G}]\,(0.1/\beta_r)^{1/2}$$

$$\phi^{\rm max} \simeq 50\,(0.1/\beta_r)^{1/2}$$

for $\dot{M} = 0.1\dot{M}_{\rm Edd}, M = 10^9 M_\odot$

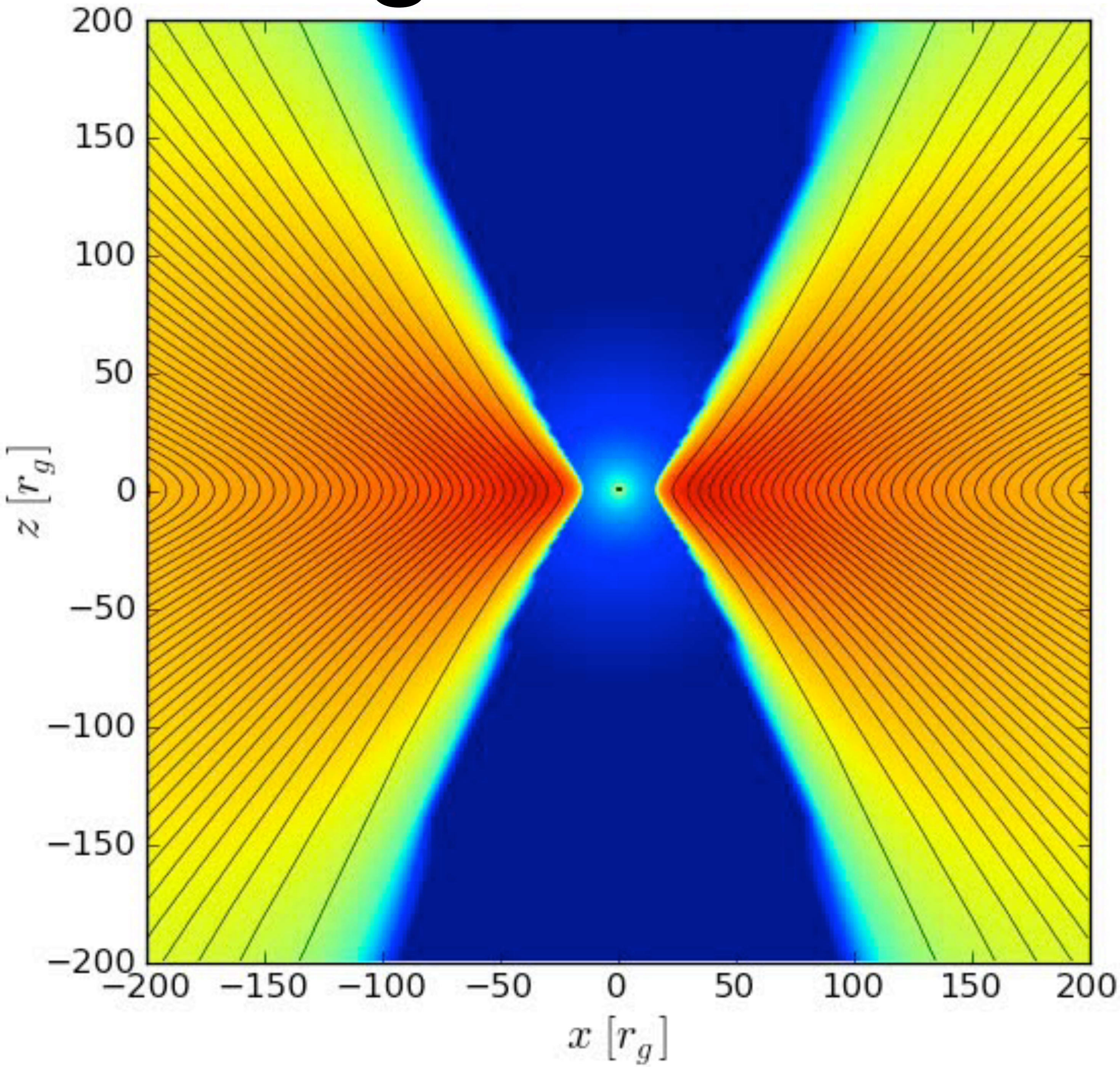
Maximum Black Hole Power = ?

- 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 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)

Maximum Black Hole Power = MAD Power

- Jet power increases with increasing BH magnetic flux, Φ.
- BH + large Φ = magnetically-arrested accretion (MAD): BH is saturated with flux, and B-field is as strong as gravity (Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev et al. 03, Narayan et al. 03, AT et al. 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12).
  - ➡ Maximum η for each spin
  - ➡ Efficiency exceeds 100%
  - ➡ First example of net energy extraction from a BH
- New physics: high jet power, QPOs, mode of accretion...
- Advanced 3D GR MHD simulations with HARM code: took over 2000 CPU-years! (Gammie et. al. 2003; AT et al. 2007)

Much Larger Flux than Before



Our grid extends out to $10^5 r_g$

AT, Narayan, McKinney 2011, MNRAS, 478, L79

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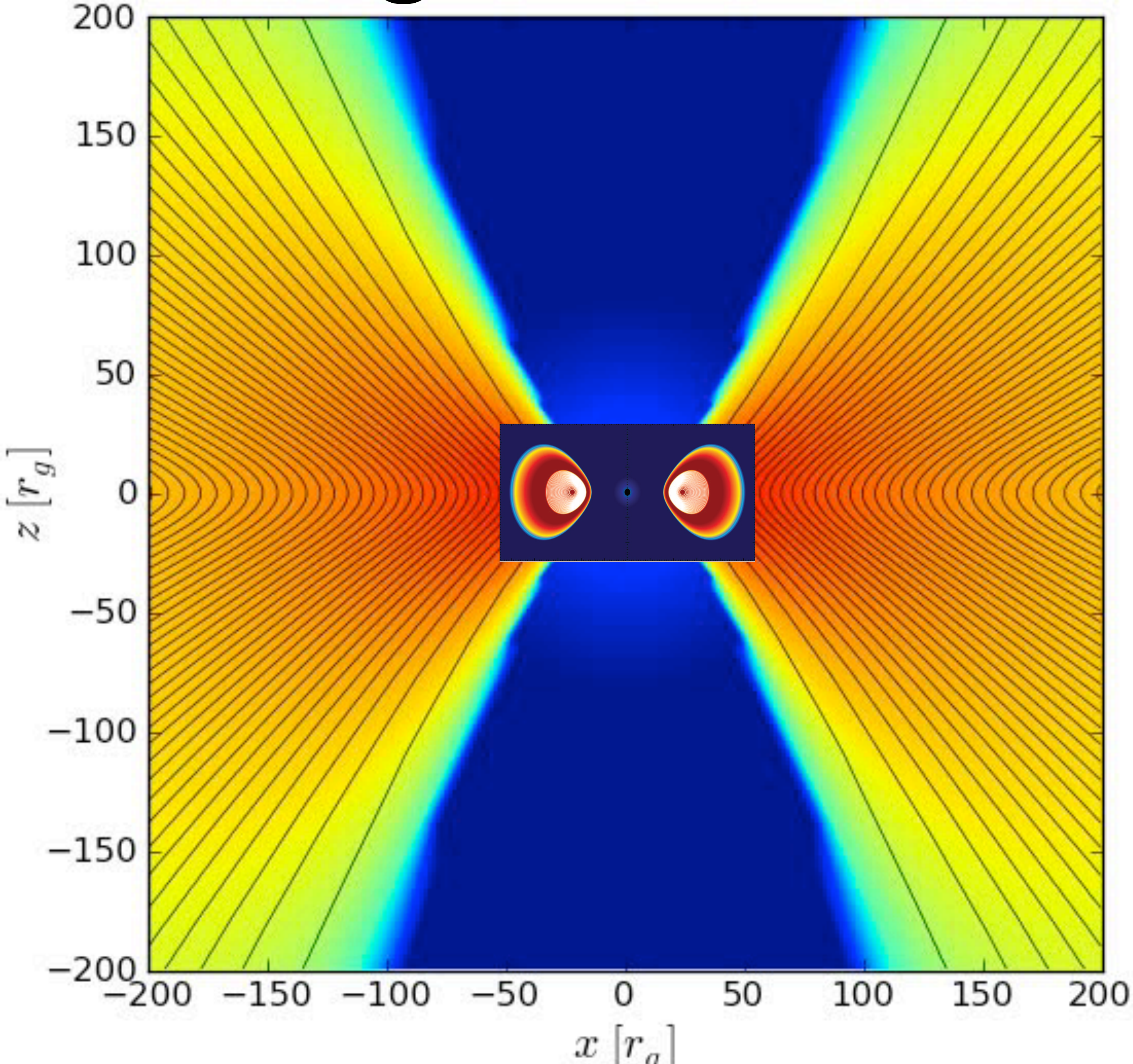

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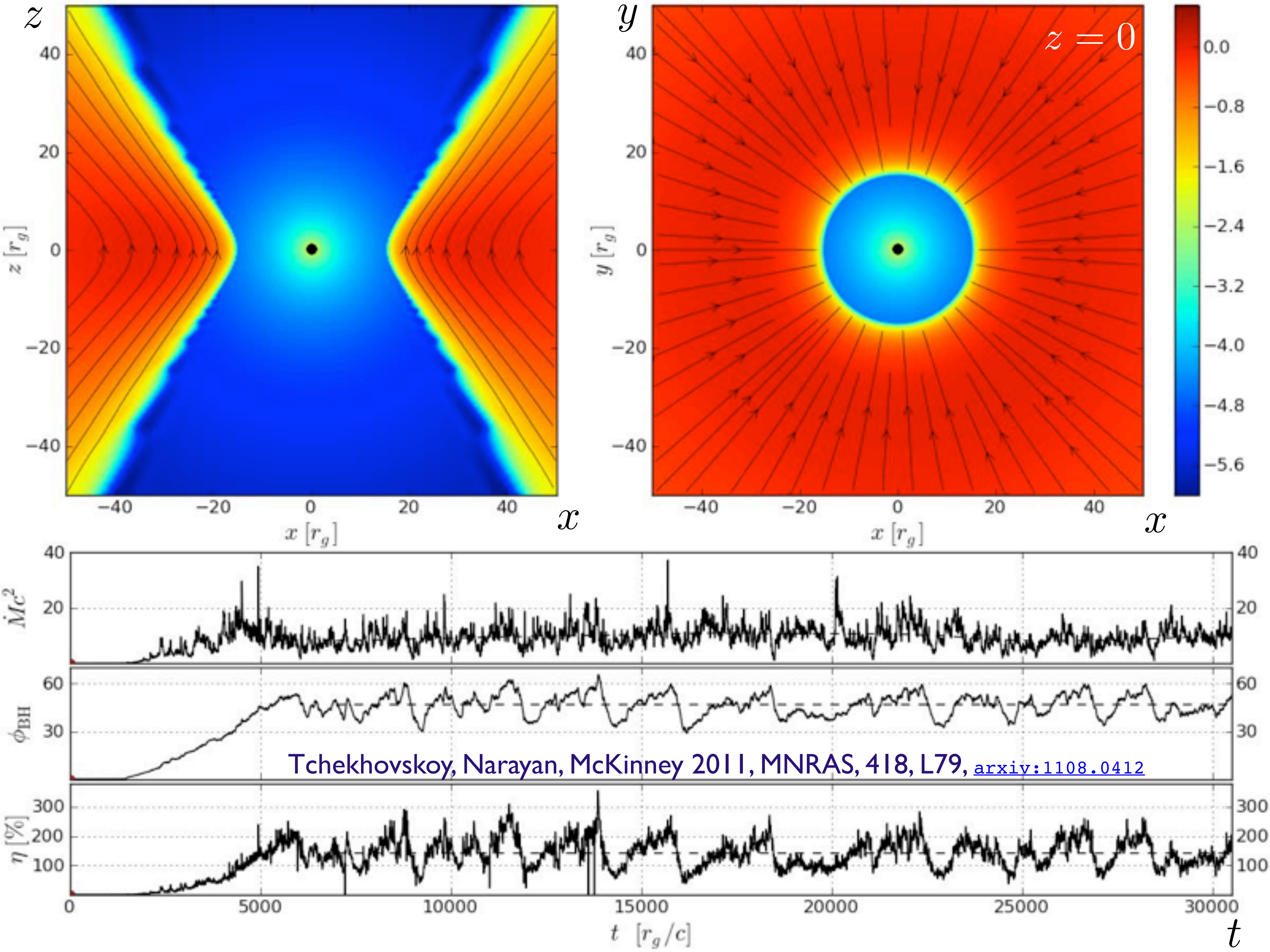
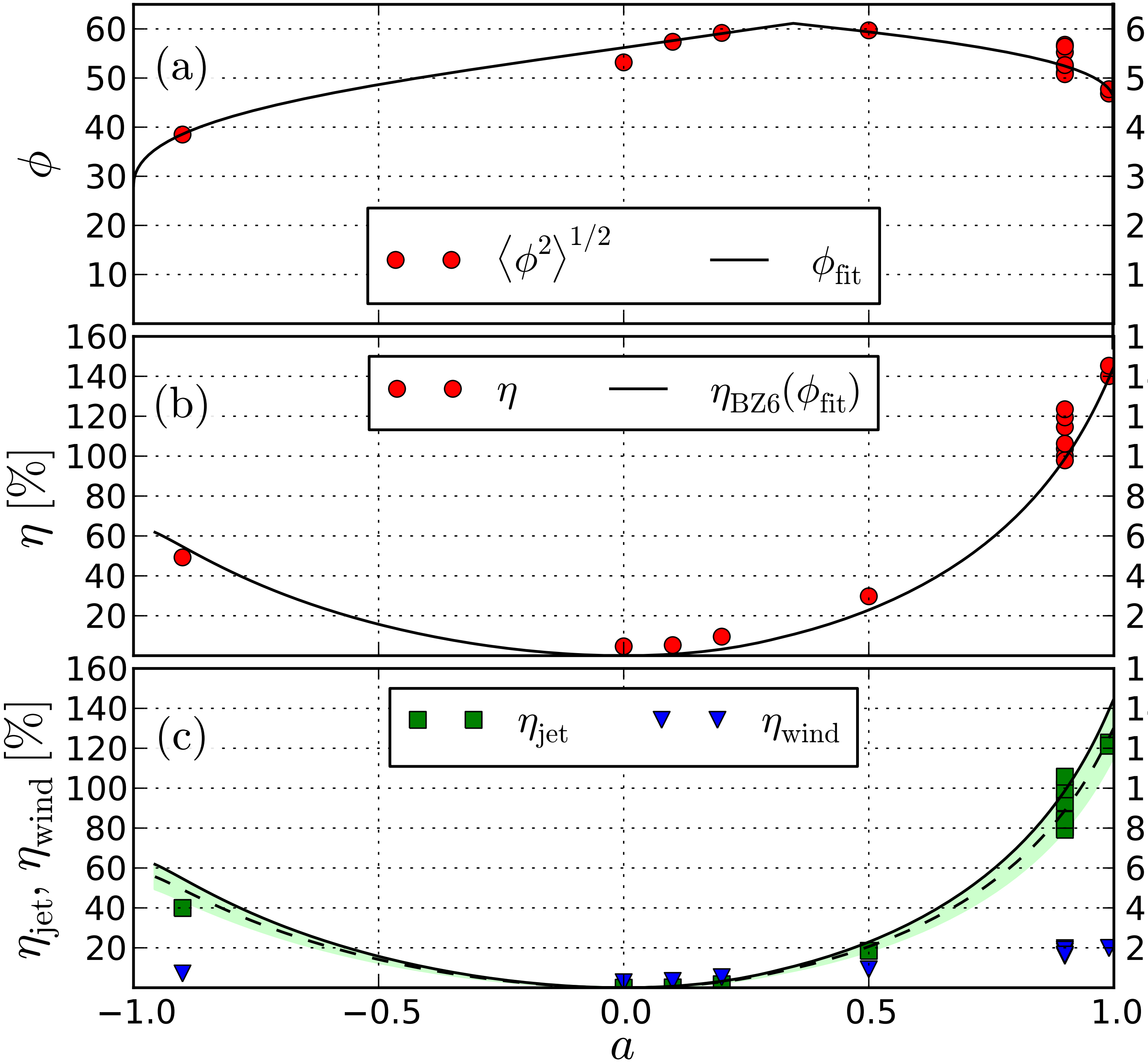
Beckwith, Hawley, Krolik 2008

AT, Narayan, McKinney 2011, MNRAS, 478, L79



z
y
z = 0
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
x
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$\dot{M}c^2$
$\phi_{\rm BH}$
$\eta\ [\%]$
$t\ \ [r_g/c]$
t
Tchekhovskoy, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412

Maximum jet power vs. spin (h/r~0.3)



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

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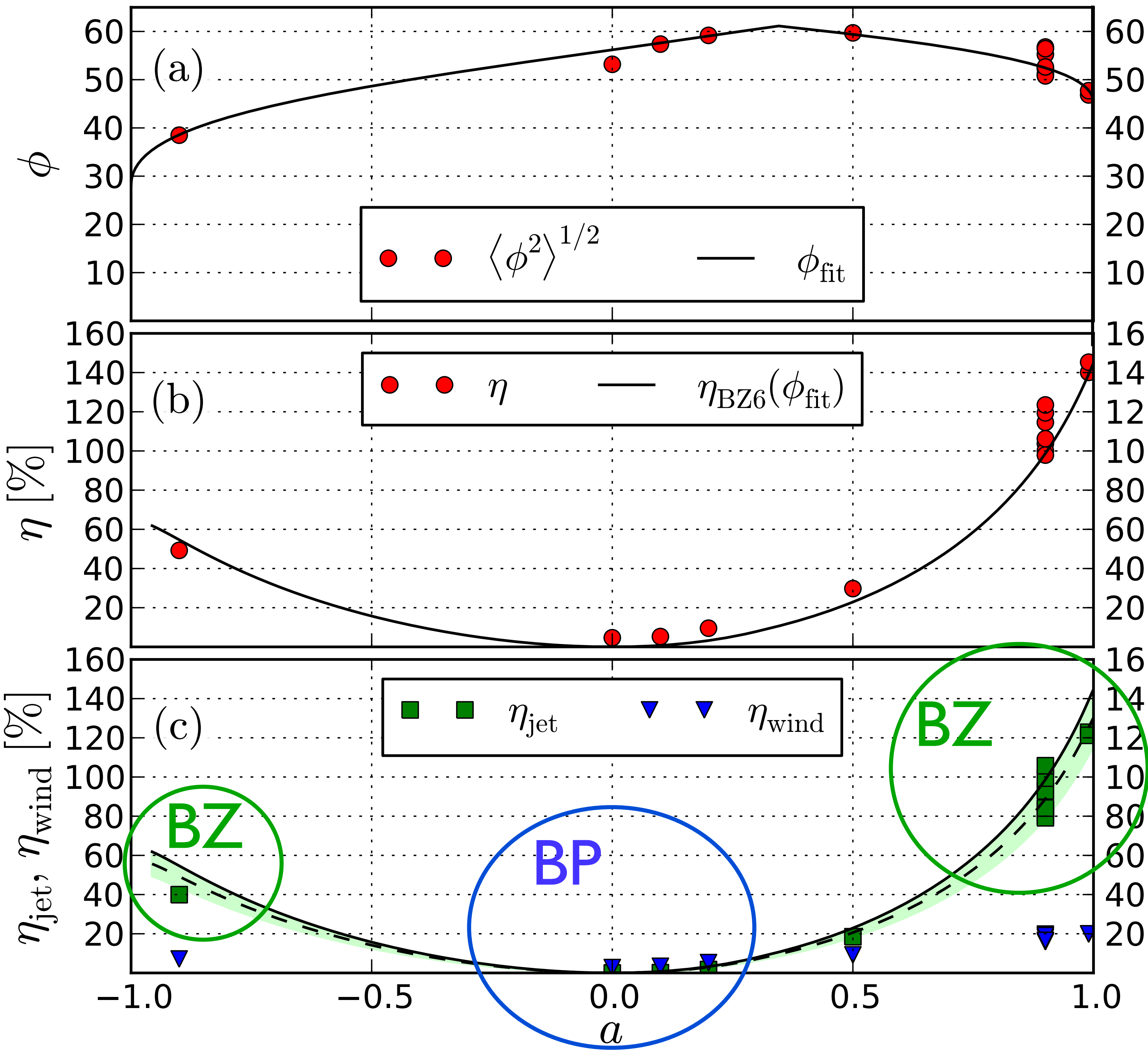

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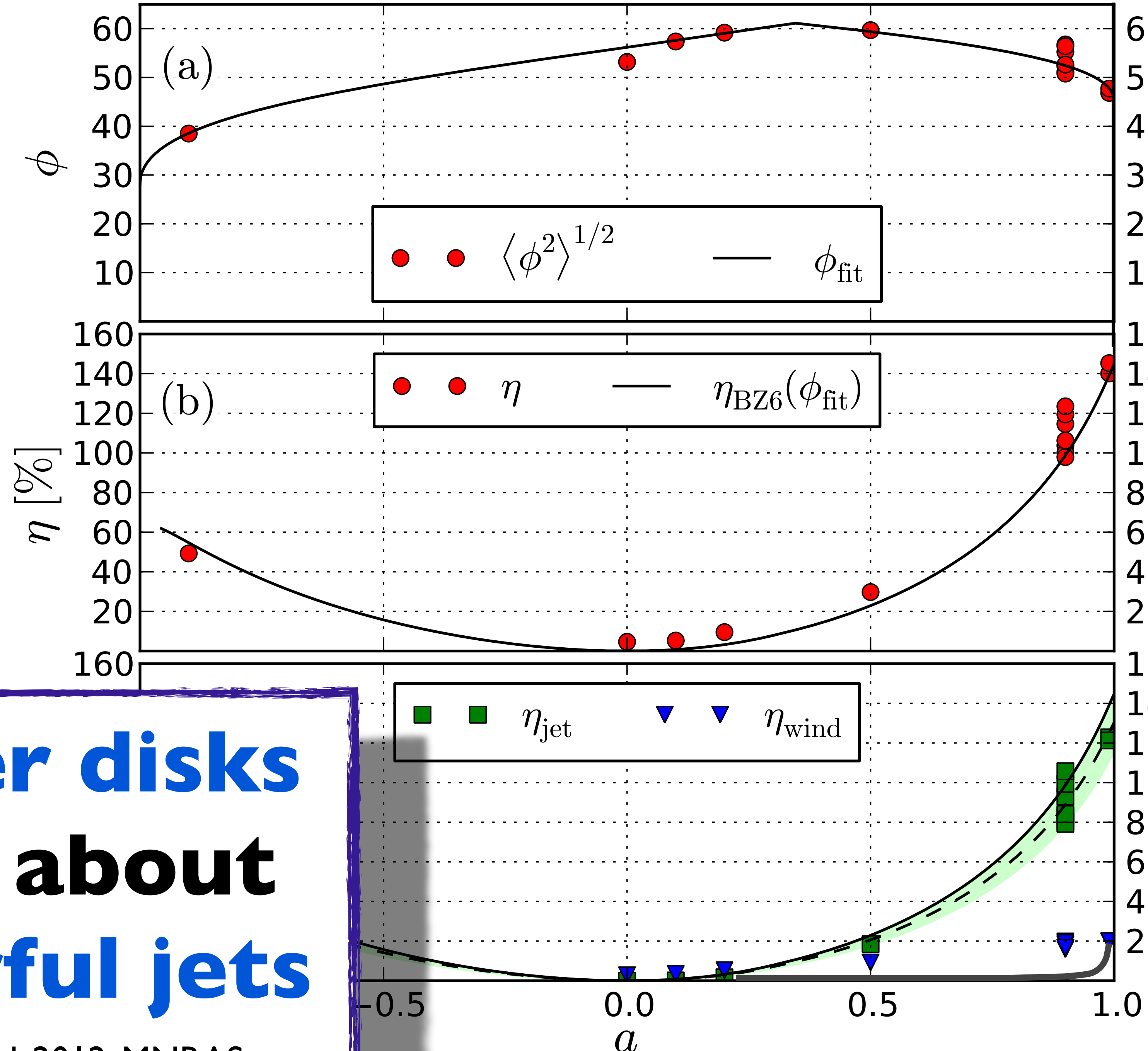

2x thicker disks produce about 2x powerful jets

(McKinney, AT, Blandford, 2012, MNRAS, submitted, arXiv:1201.4163)

% unambiguously shows that net energy is extracted from the BH

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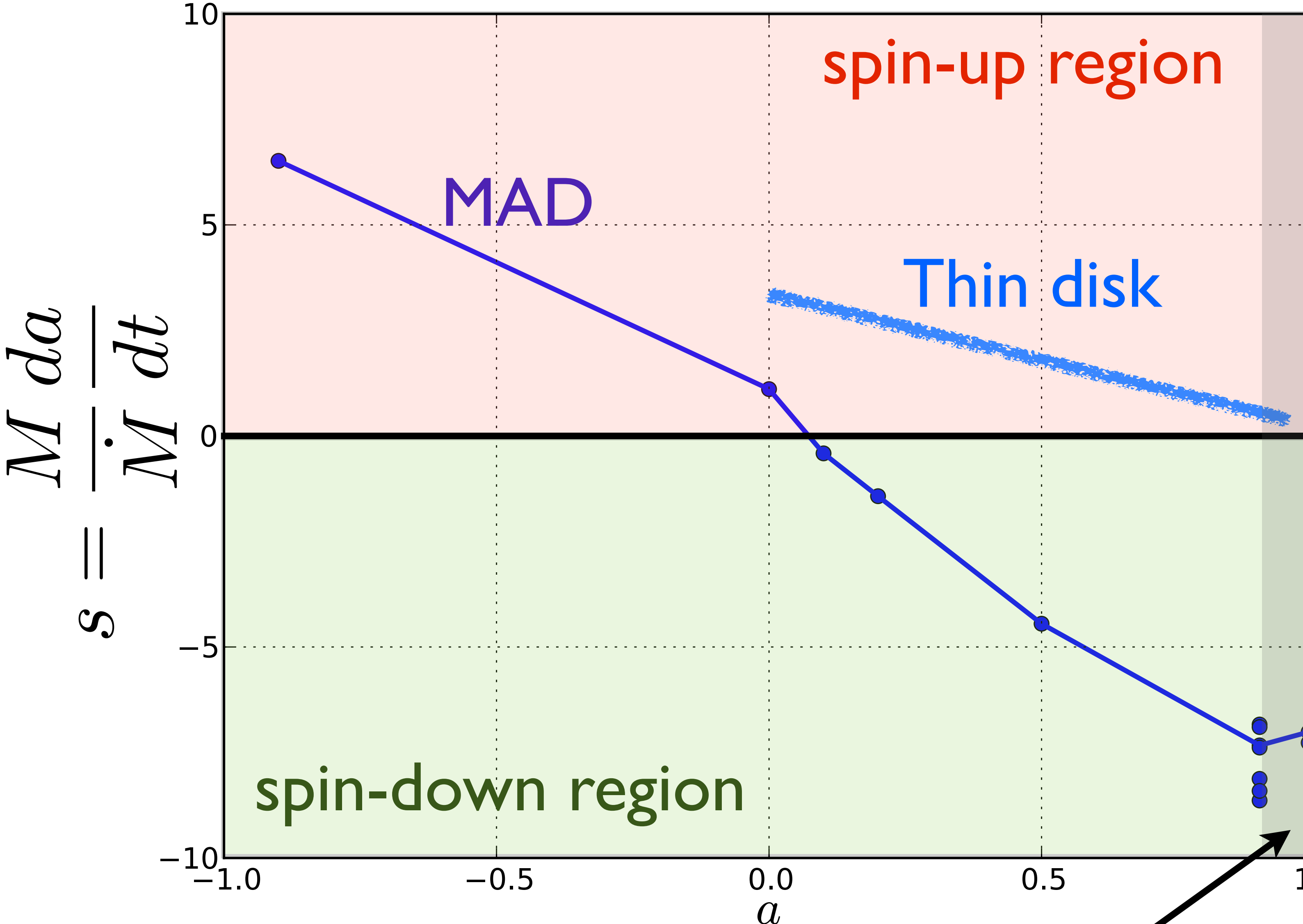
Our MADs slow BHs down to a halt



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Conventional spin equilibrium region, $a \gtrsim 0.9$

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

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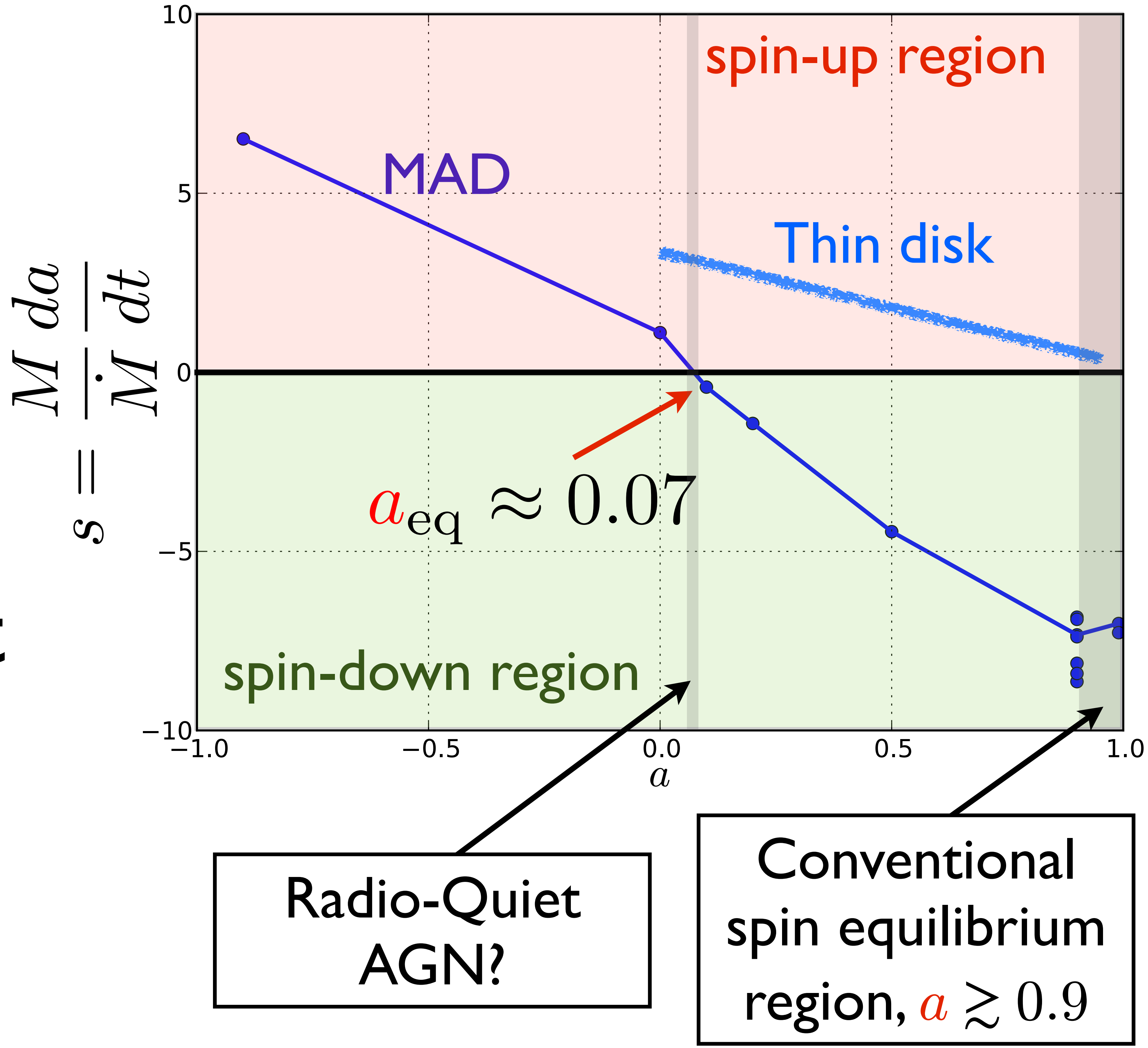

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Summary

- Simulations maximize $\Phi \rightarrow$ MAD state:
  - $\eta > 100\%$ for $a \gtrsim 0.9$
  - MADs slow BHs down to a "halt", $a \lesssim 0.1$
- Relativistic jets can provide highly efficient feedback, efficiency up to ~ few x 100%
- Slower, mass-loaded disk winds can carry up to ~ few x 10% -> UFOs? (Tombesi +2010,2011,2012; see talk by Cappi)