Relativistic Jet Formation by Spinning Black Holes

Alexander (Sasha) Tchekhovskoy

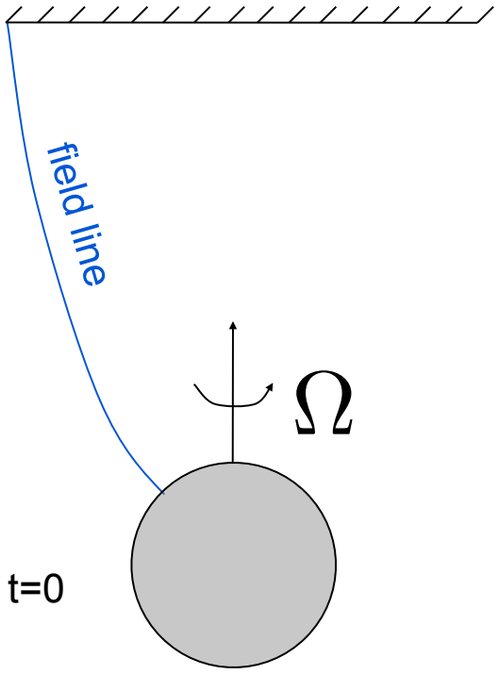
Center for Theoretical Science Fellow
Princeton University

Roger Blandford, Stanford
Jonathan McKinney, Maryland
Ramesh Narayan, Harvard

Fundamental Questions

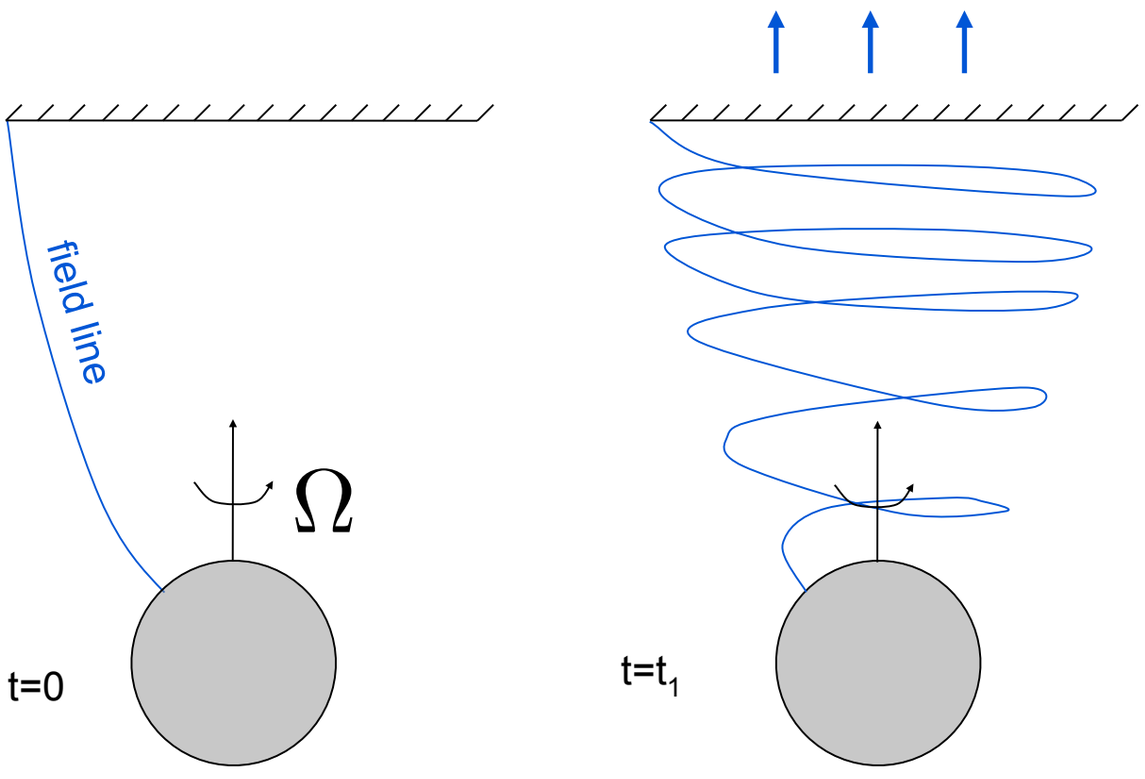
- What sets the maximum power of jets?
- Are jets powered by black holes or inner regions of accretion disks?
- How does jet power depend on BH spin?
- Does accretion always spin up BHs to high spins?
- Do black holes with tilted disks produce jets? Which way do such jets point?

How Do Jets Work?



How Do Jets Work?

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

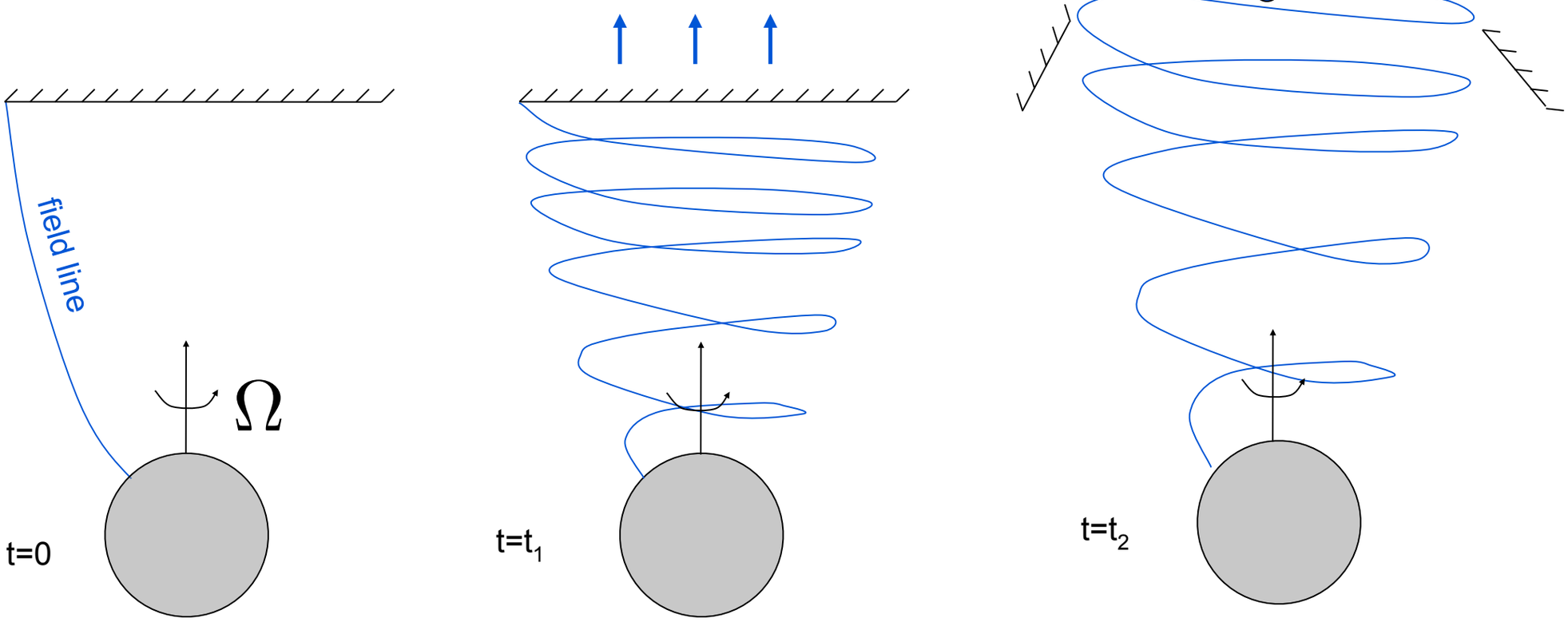


How Do Jets Work?

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

Field toroidally-dominated

$$B_\varphi \gg B_z$$



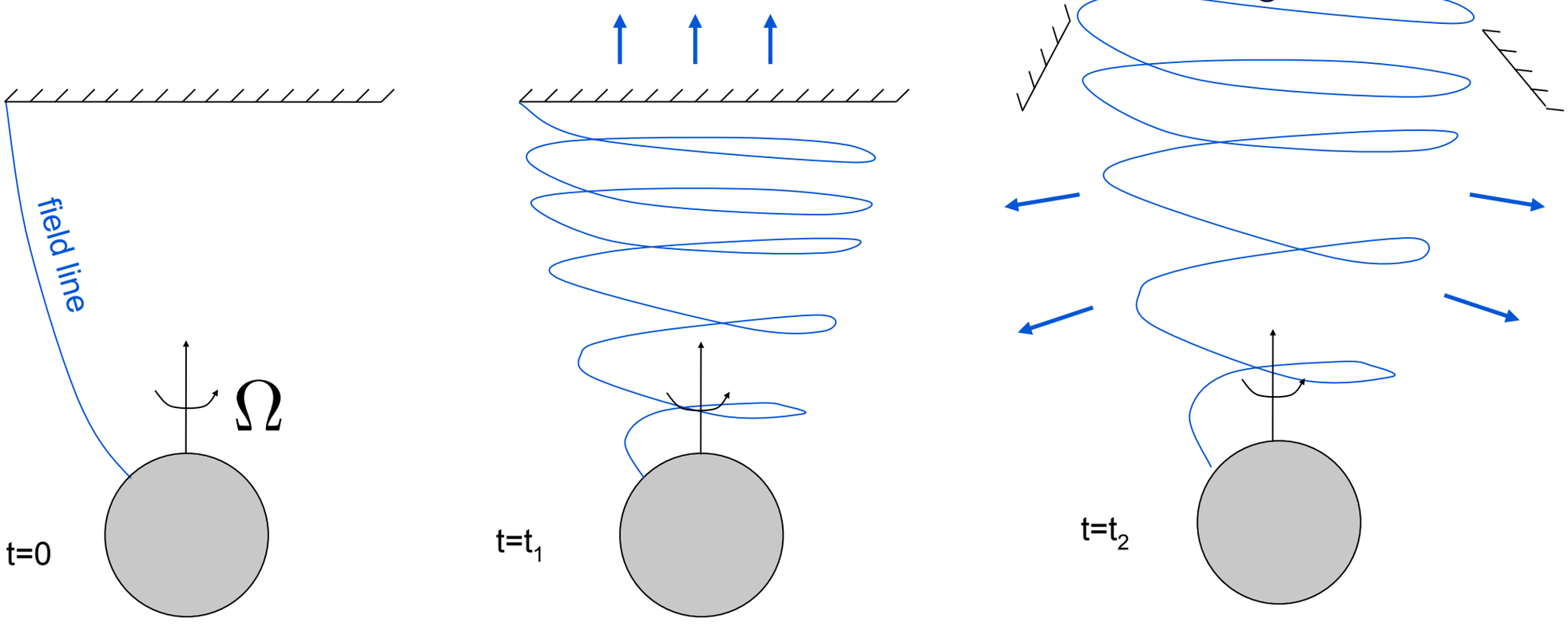
(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10)

How Do Jets Work?

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

Field toroidally-dominated

$$B_\varphi \gg B_z$$



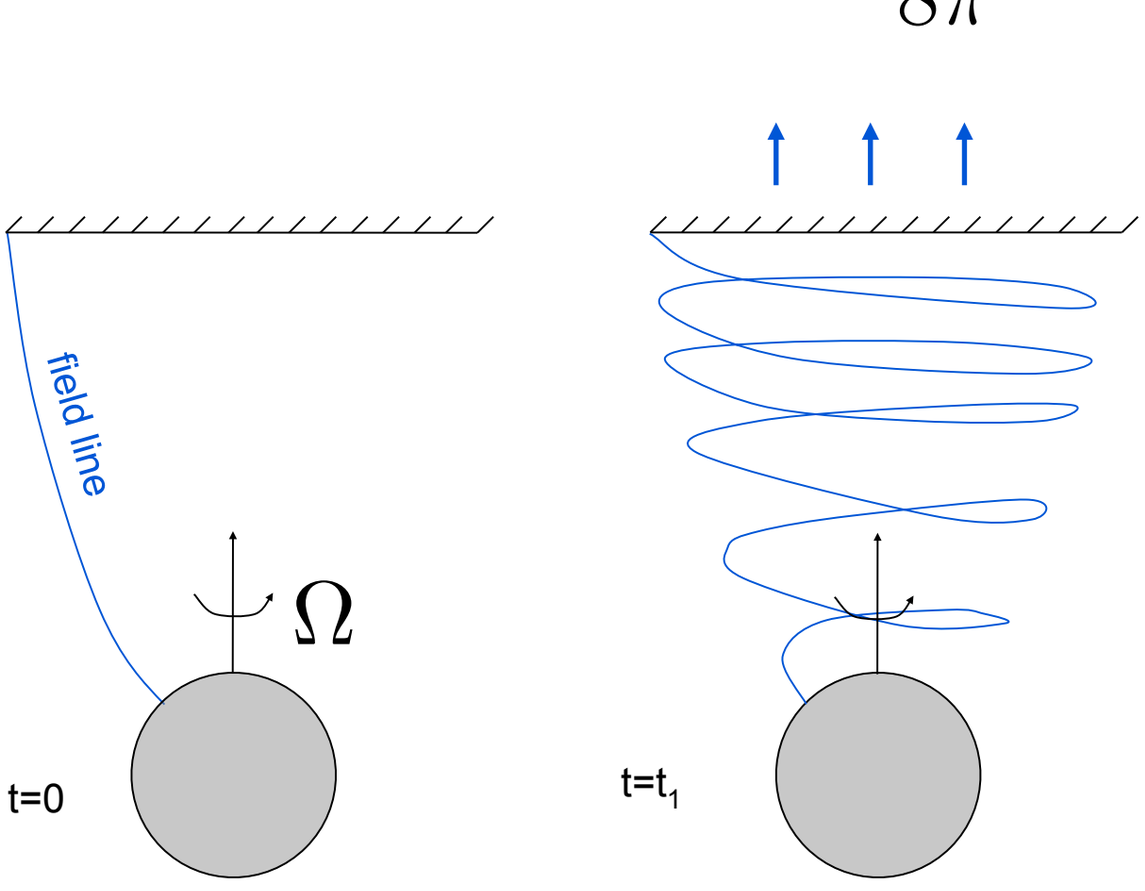
(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10)

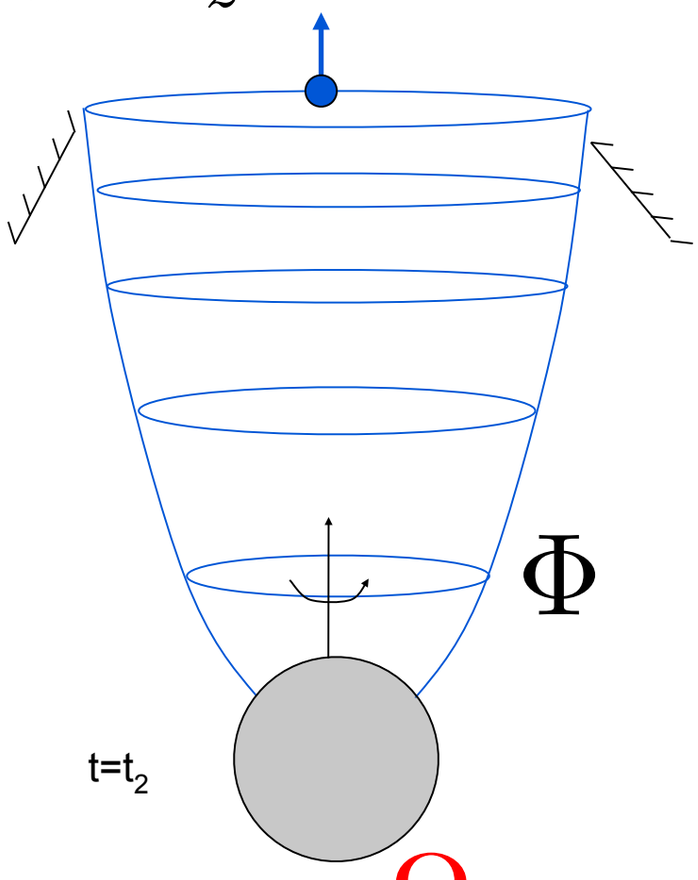
How Do Jets Work?

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

Field toroidally-dominated

$$B_\varphi \gg B_z$$





(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10)

$$\Omega_{\rm H} = \frac{ac}{2r_{\rm H}}$$

What Sets BH Power?

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

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

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

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

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977,
Komissarov 2001,
AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

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

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

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

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

- *GRMHD* simulations give $p_j \lesssim 20\%$, even for nearly maximally spinning BHs

(McKinney 05, de Villiers+ 05, Hawley & Krolik 06, Barkov & Baushev 11)

What Sets BH Power?

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

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

- *GRMHD* simulations give $p_j \lesssim 20\%$, even for nearly maximally spinning BHs

(McKinney 05, de Villiers+ 05, Hawley & Krolik 06, Barkov & Baushev 11)

- Observations: some AGN have $p_j \gtrsim 100\%$

(Rawlings & Saunders 91, Fernandes+ 10, Ghisellini+ 2010, Punsly 2011, McNamara+ 2011)

What Sets BH Power?

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

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

- *GRMHD* simulations give $p_j \lesssim 20\%$, even for nearly maximally spinning BHs

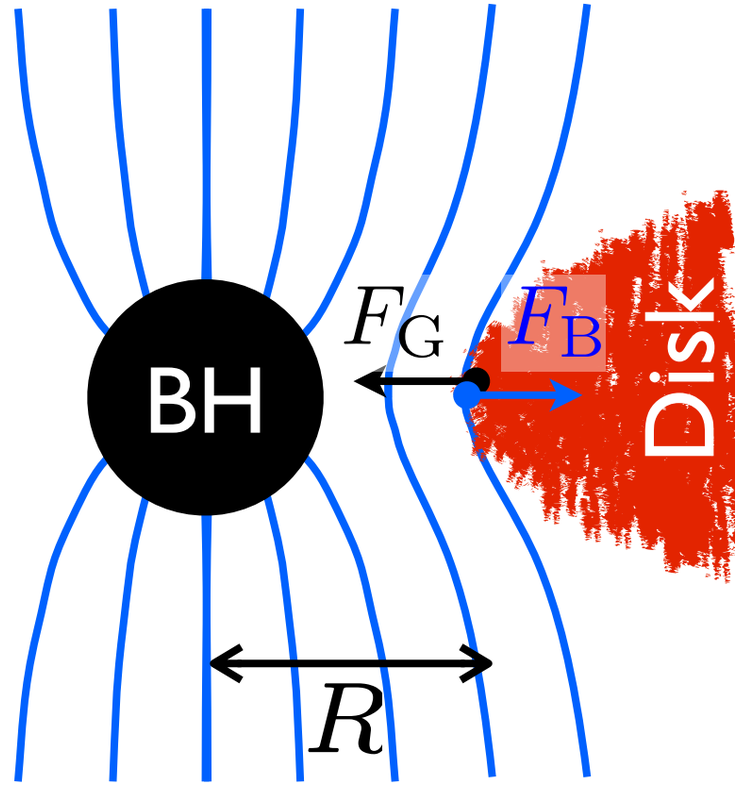
(McKinney 05, de Villiers+ 05, Hawley & Krolik 06, Barkov & Baushev 11)

- Observations: some AGN have $p_j \gtrsim 100\%$

(Rawlings & Saunders 91, Fernandes+ 10, Ghisellini+ 2010, Punsly 2011, McNamara+ 2011)

- Are larger values of p_j even possible in nature?

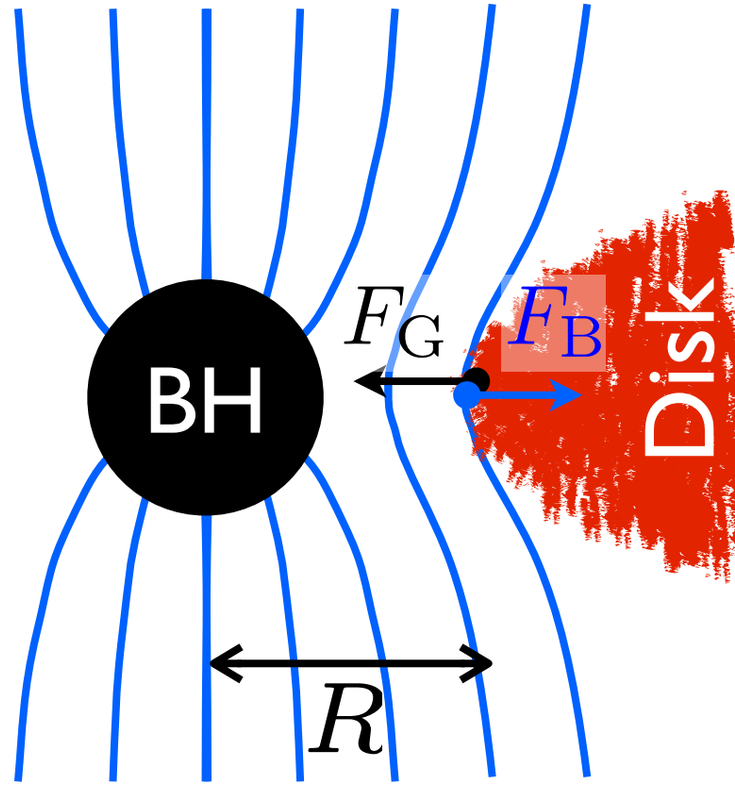
There Must be Maximum Power



There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

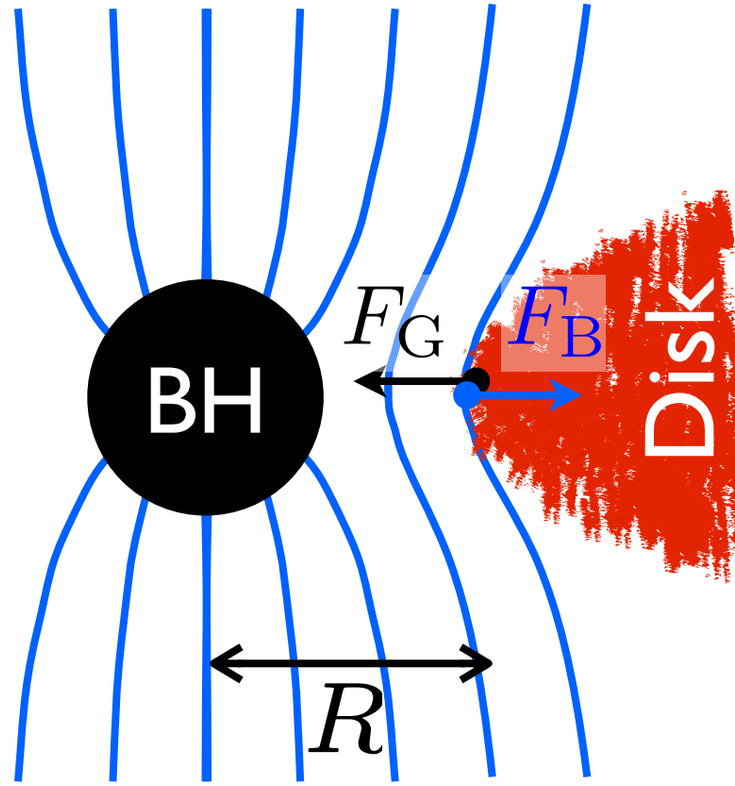


There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$



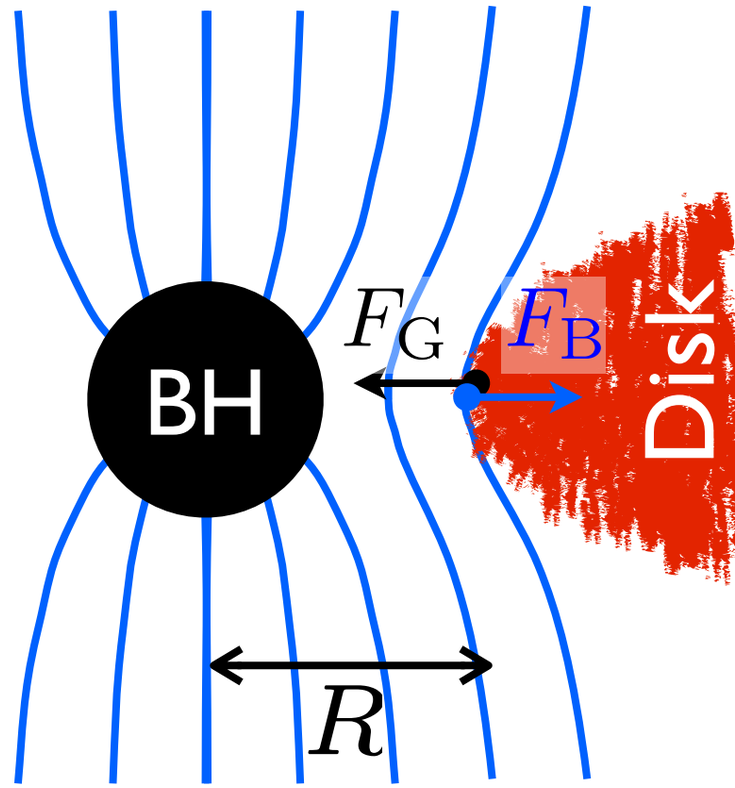
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



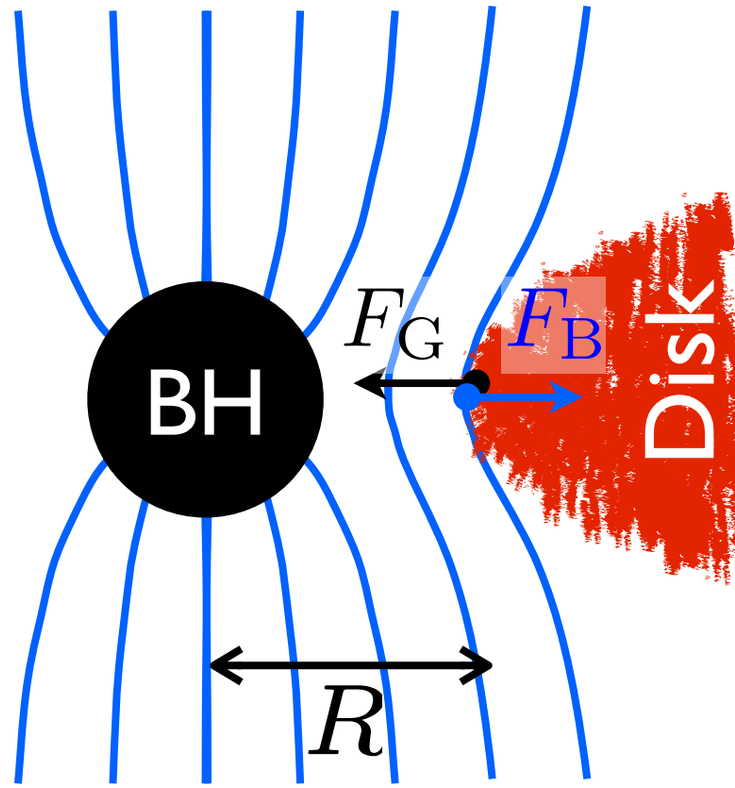
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12)

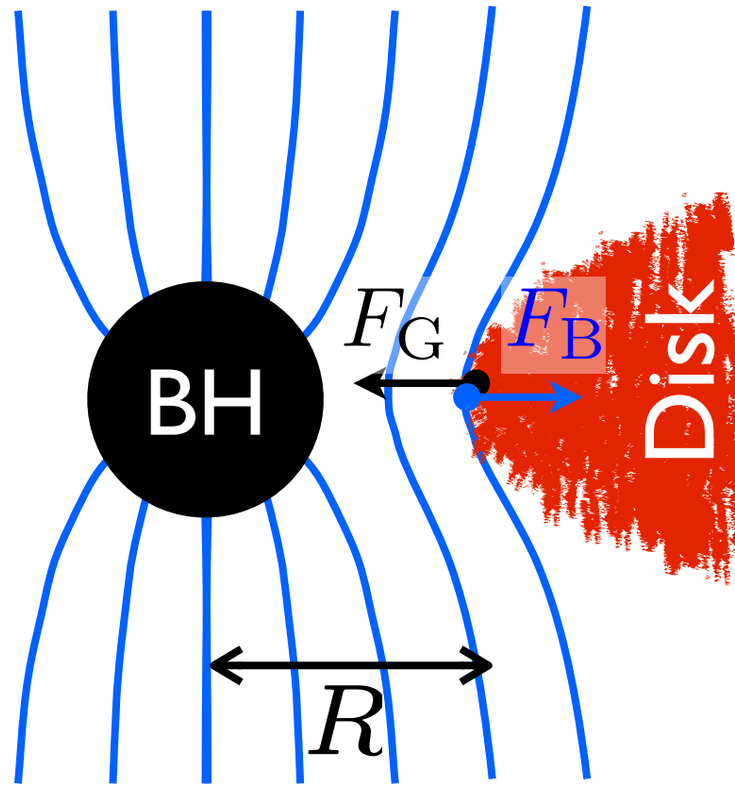
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12)

- How do we get a MAD?

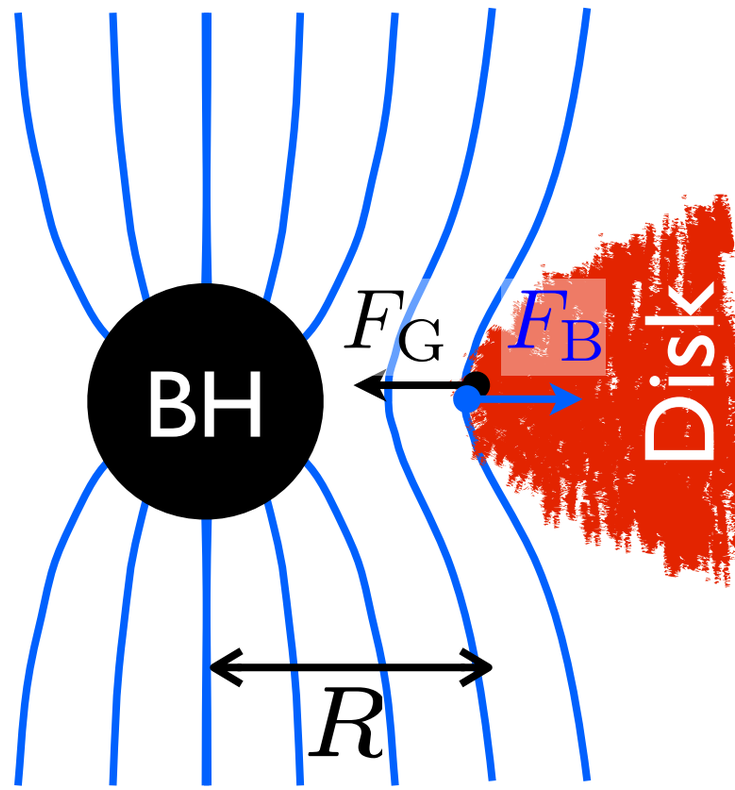
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12)

- How do we get a MAD? Flood the black hole with magnetic flux

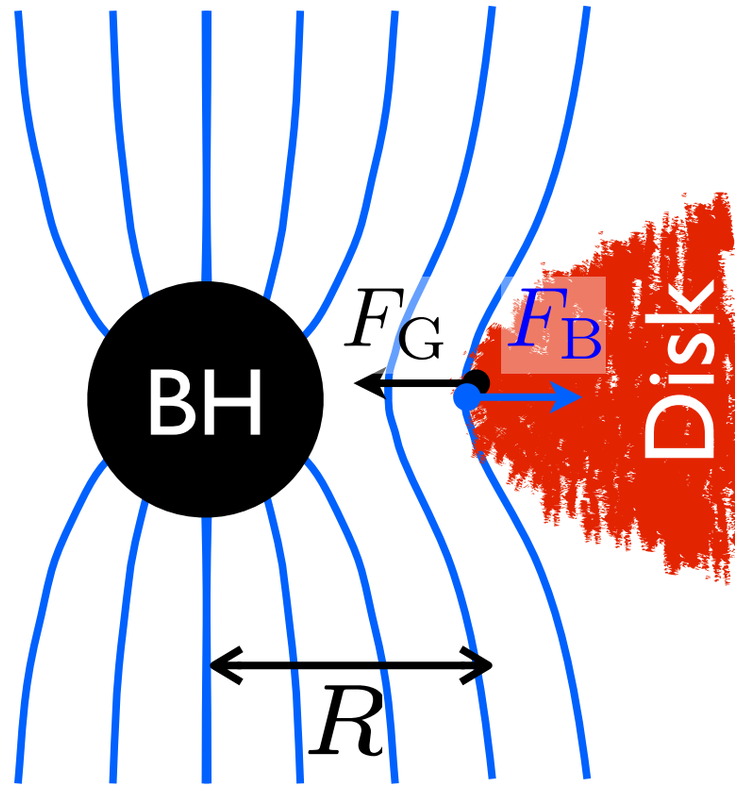
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12)

- How do we get a MAD? Flood the black hole with magnetic flux
- Numerical experiments via advanced 3D *GRMHD* simulations with the HARM code (Gammie+03, AT+07, McKinney & Blandford 09): took over 10^3 CPU-years!

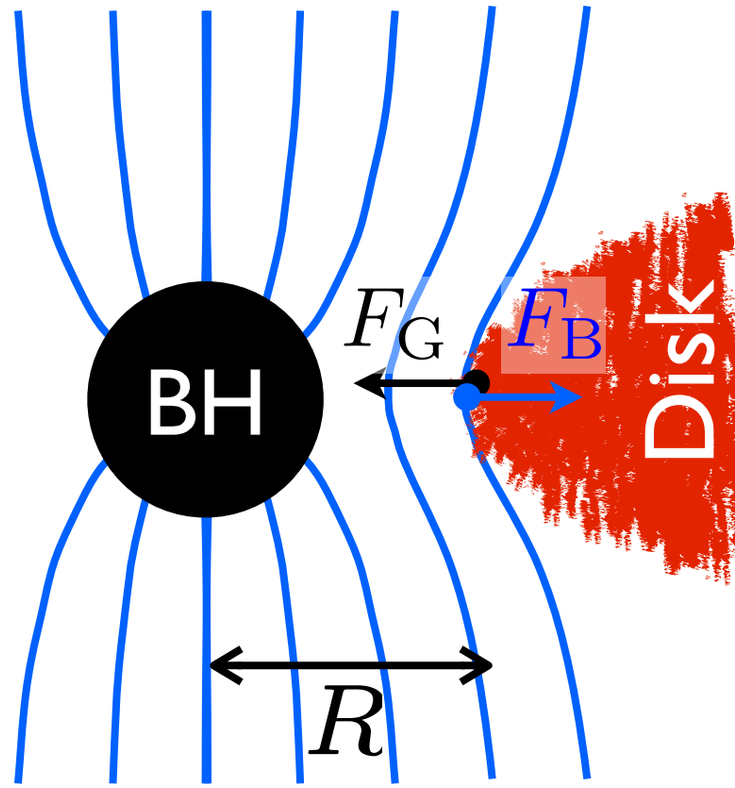
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$

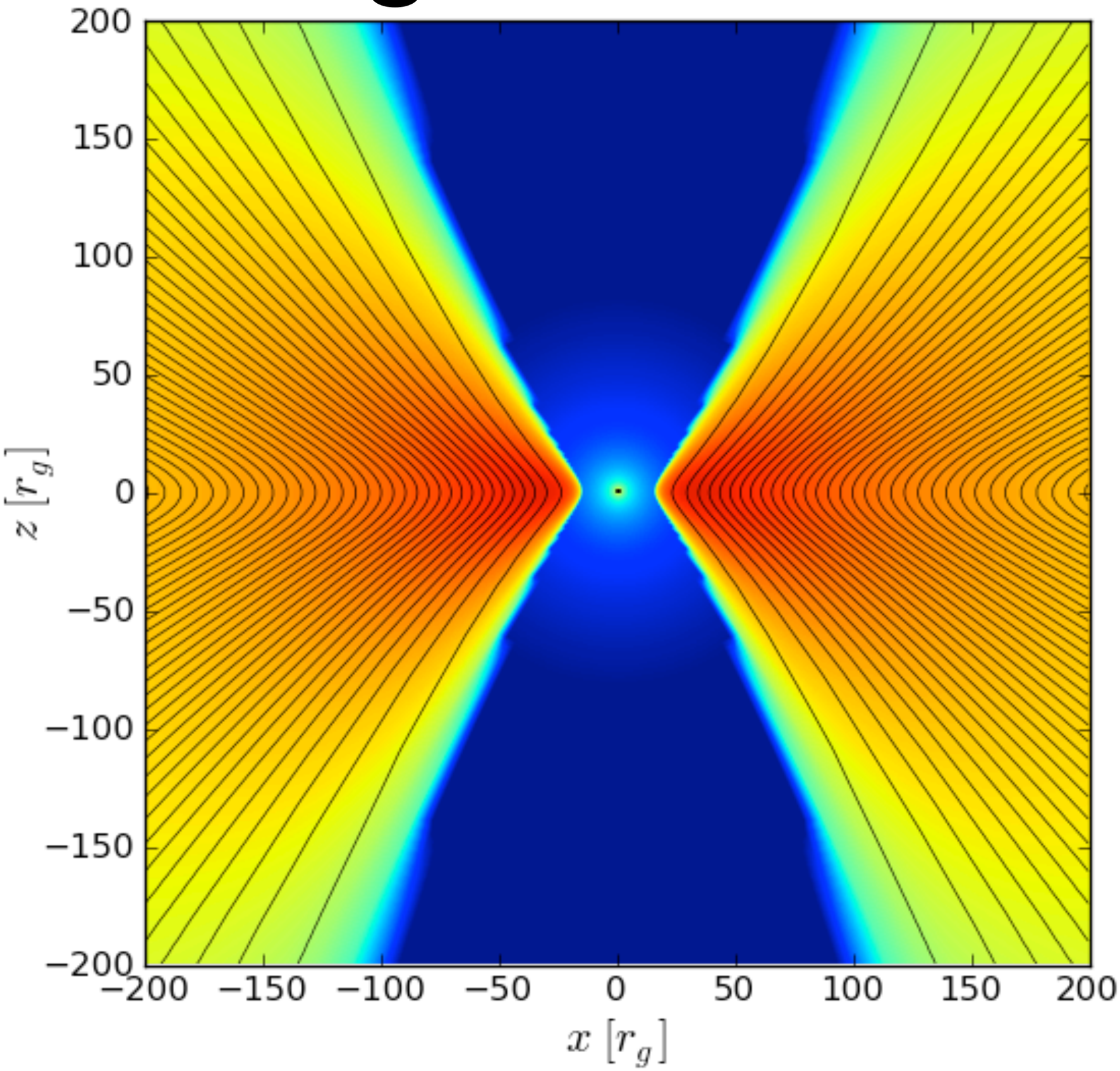


- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12)

- How do we get a MAD? Flood the black hole with magnetic flux
- Numerical experiments via advanced 3D *GRMHD* simulations with the HARM code (Gammie+03, AT+07, McKinney & Blandford 09): took over 10^3 CPU-years!
- New physics: high jet power and new MAD mode of accretion in which the magnetorotational instability (MRI, Balbus & Hawley 91) is marginally suppressed

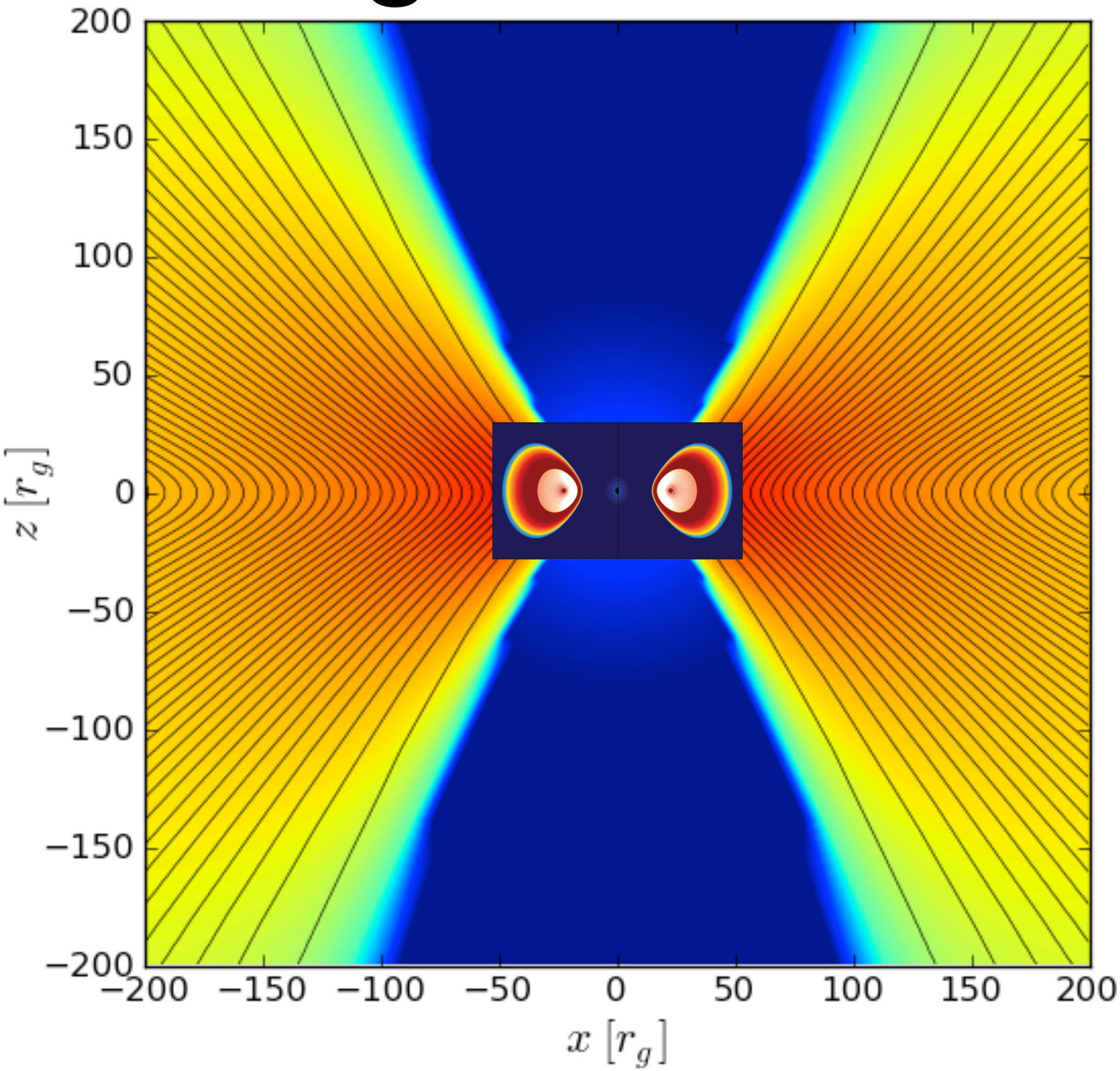
Much Larger Flux than Before



Our grid extends out to $10^5 r_g$

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

Much Larger Flux than Before

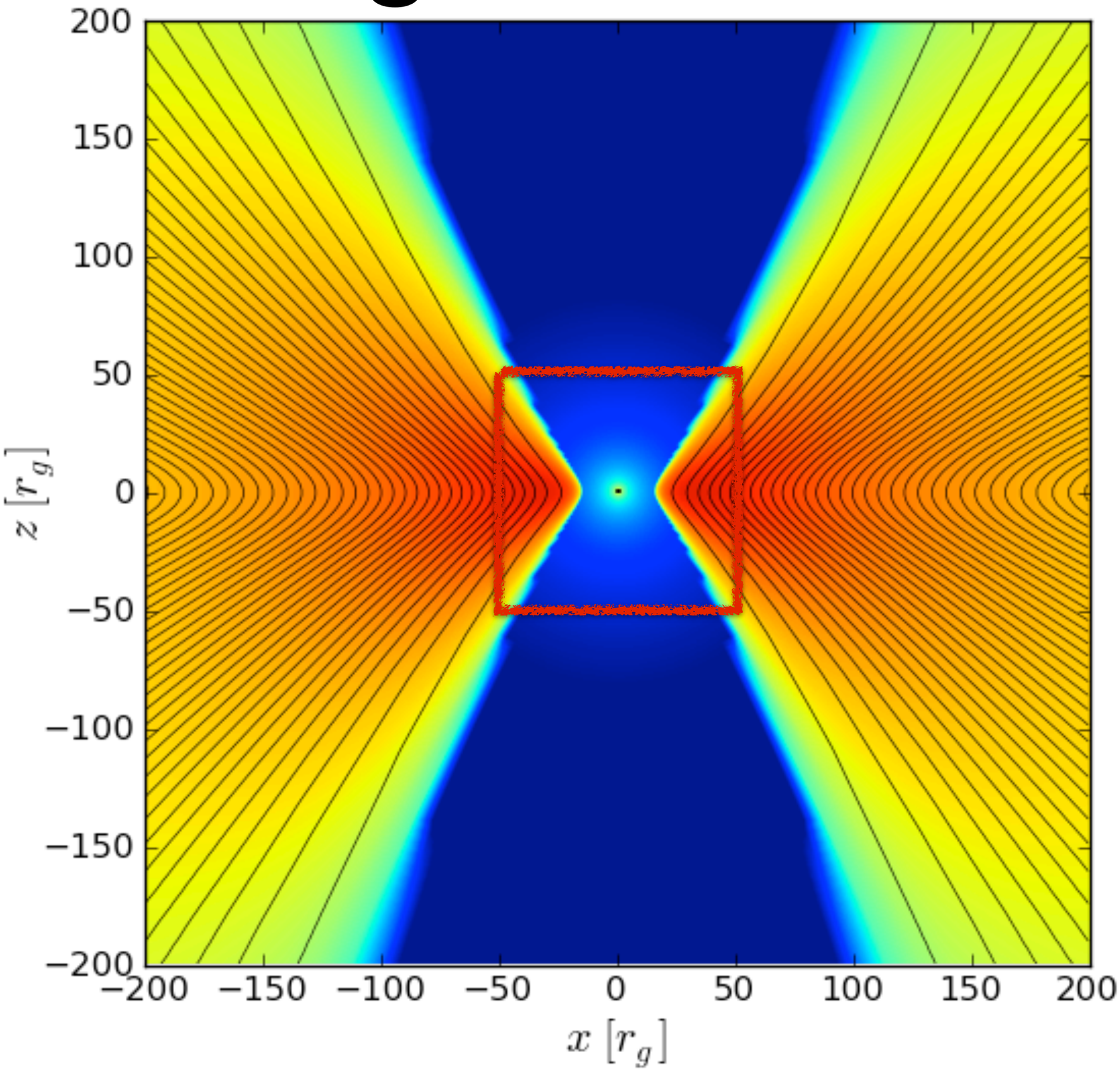


Our grid extends out to $10^5 r_g$

Beckwith, Hawley, Krolik 2008

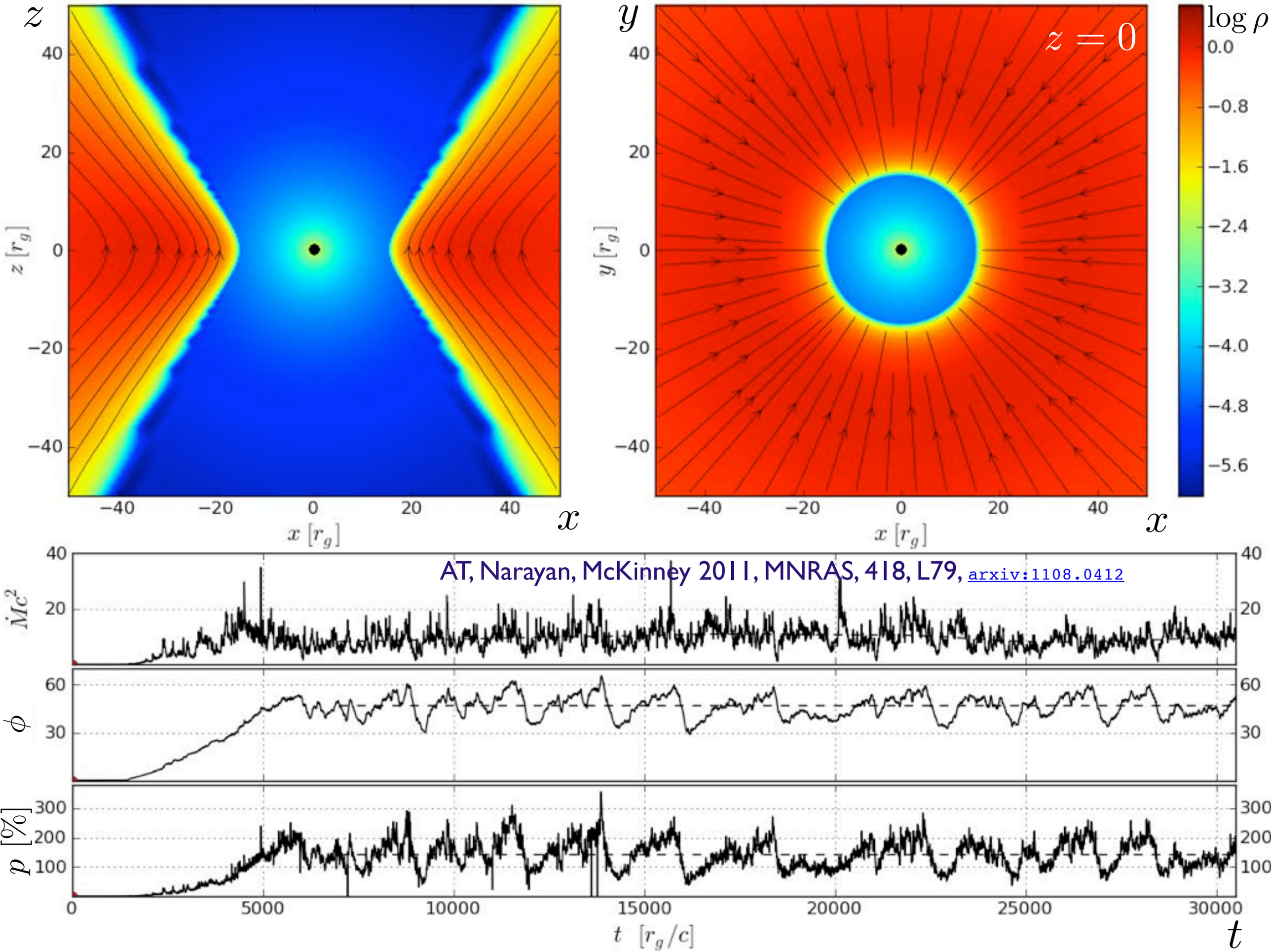
AT, Narayan, McKinney 2011, MNRAS, 478, L79

Much Larger Flux than Before

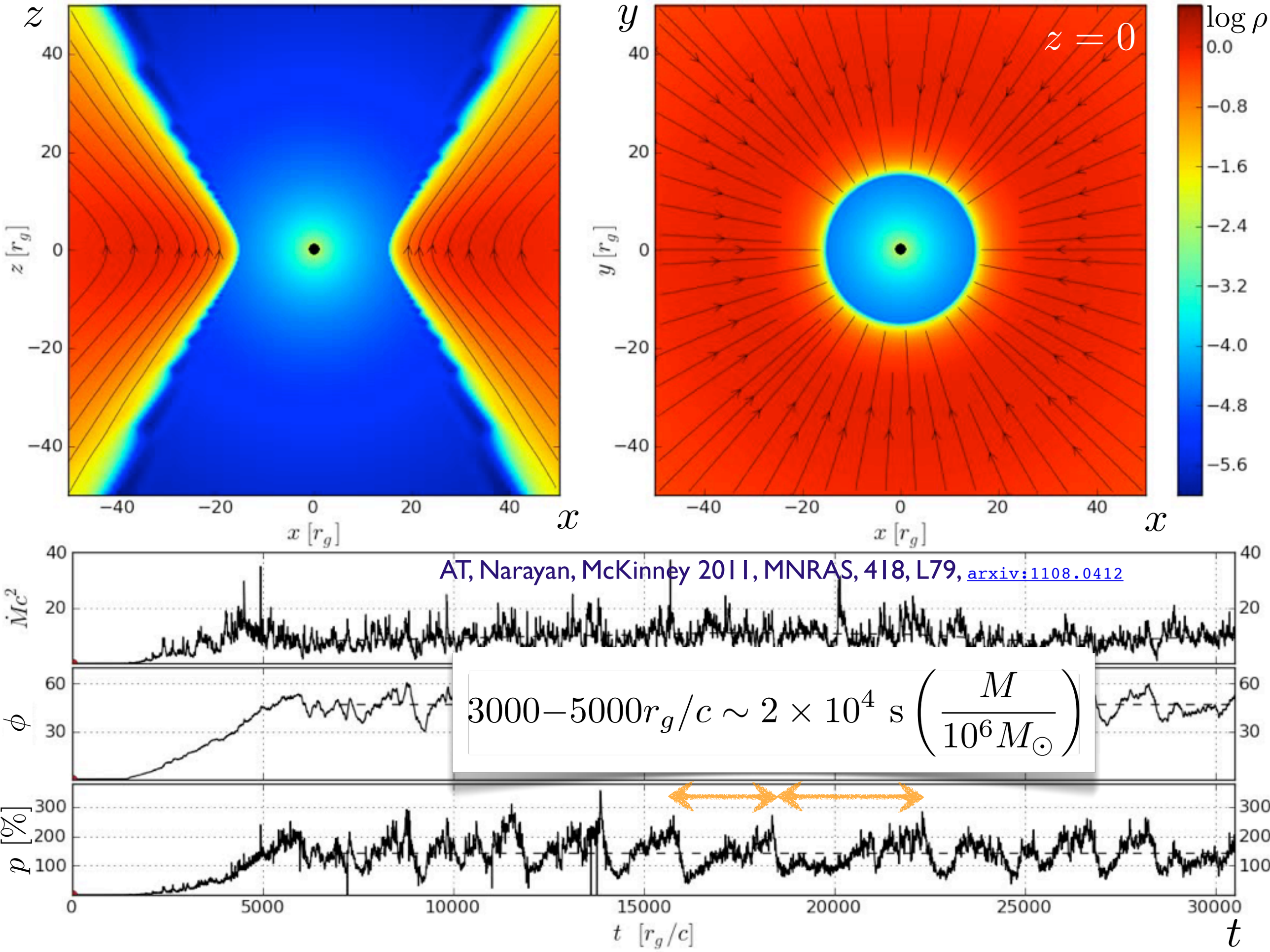


Our grid extends out to $10^5 r_g$

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



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



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

$$3000{-}5000 r_g/c \sim 2 \times 10^4 \text{ s} \left(\frac{M}{10^6 M_\odot} \right)$$

tilted

$z\,[r_g]$

$y\,[r_g]$

$x\,[r_g]$

$x\,[r_g]$

$\dot{M}_{\rm H}c^2$
$\dot{M}_{\rm j}c^2$
$\dot{M}_{\rm mw,o}c^2$
$\dot{M}c^2$

$\Upsilon_{\rm H}$
$\Upsilon_{\rm j}$
$\Upsilon_{\rm mw,o}$
Υ

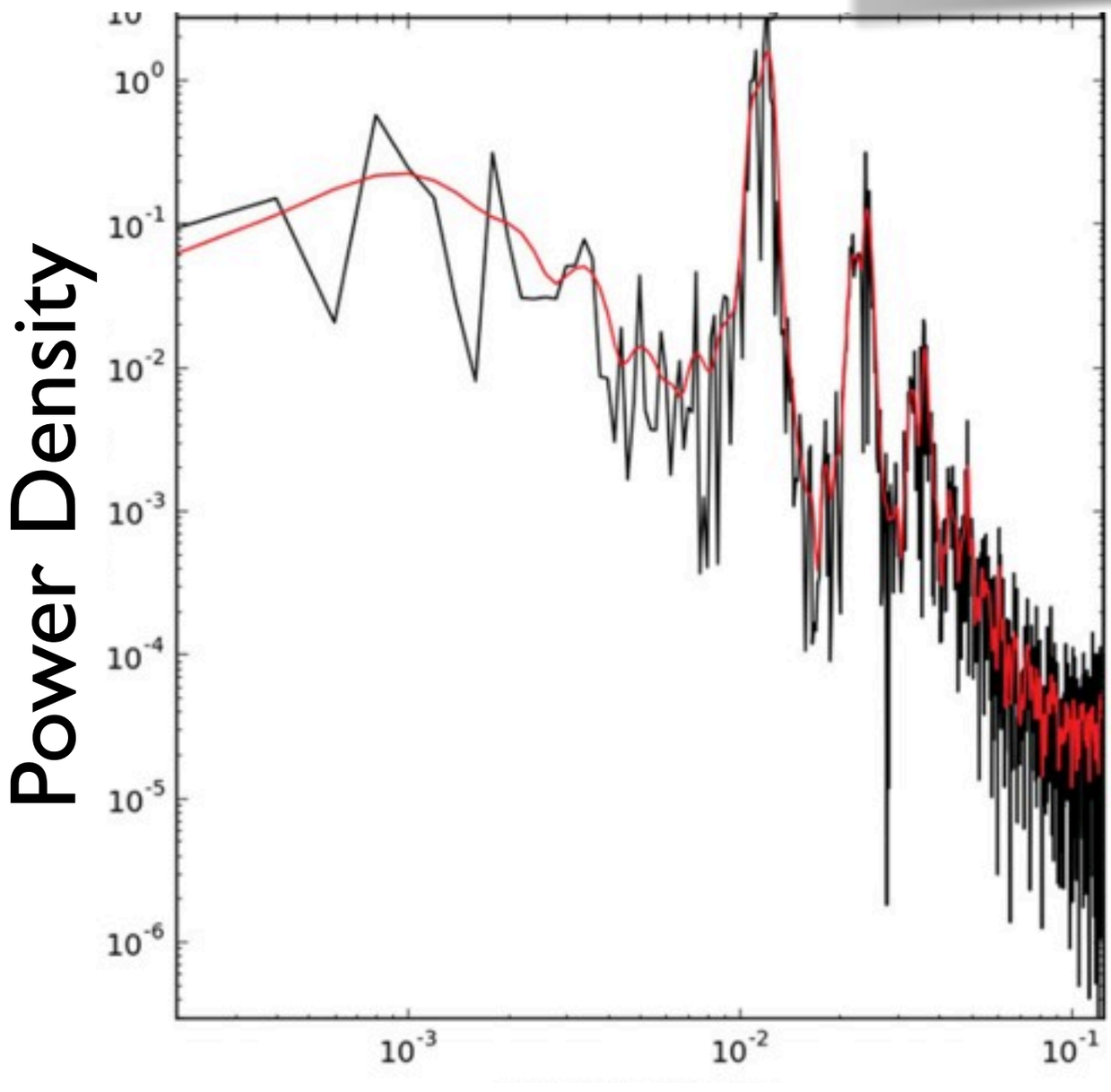
$\eta_{\rm H}$
$\eta_{\rm j}$
$\eta_{\rm mw,o}$
$p\ [\%]$

$t\ \ [r_g/c]$

McKinney, AT, Blandford 2012, MNRAS, 423, 3083

MADs Give Quasi-Periodic Oscillations

$$\tau_{\rm QPO} \sim 250\ {\rm s} \left(\frac{1}{a}\right) \left(\frac{M}{10^6 M_\odot}\right)$$



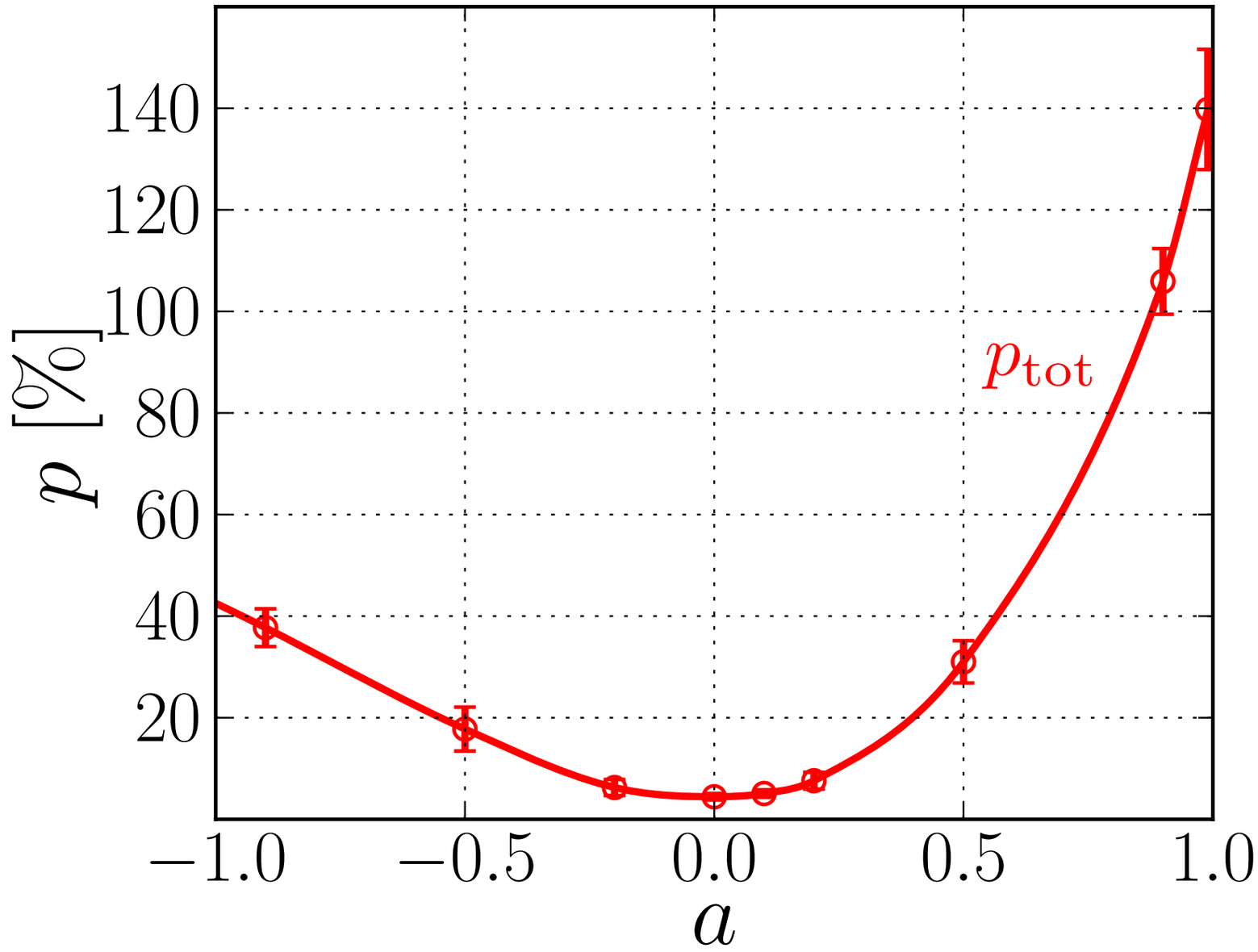
Jet-Disk Oscillation (JDO):

- QPO period equals BH jet field bundle rotation period
- Period directly tied to BH mass and spin

McKinney, AT, Blandford (2012)

see also Shcherbakov and McKinney (2013)

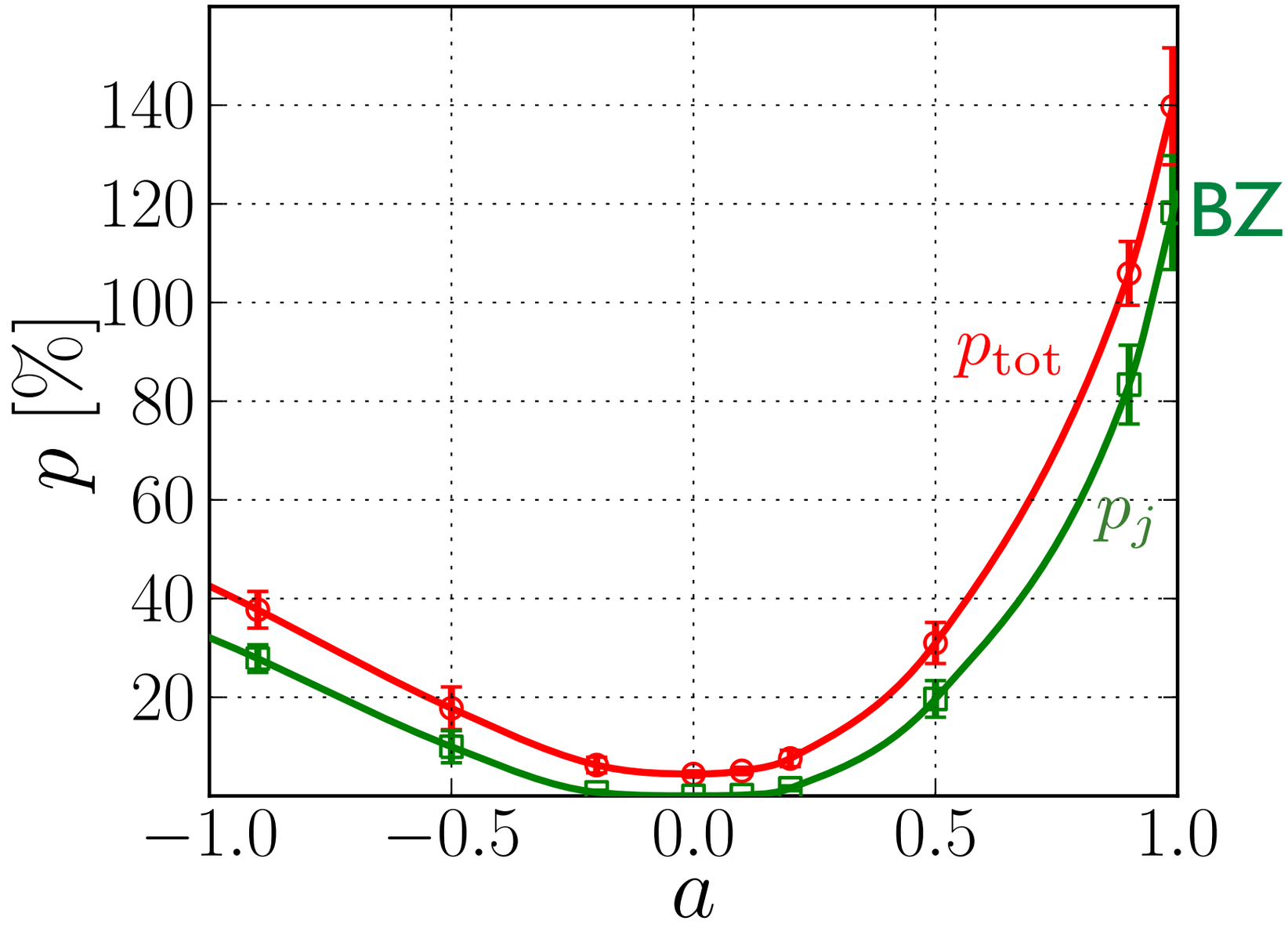
Maximum Jet Power vs. Spin ($h/r \sim 0.3$)



(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

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

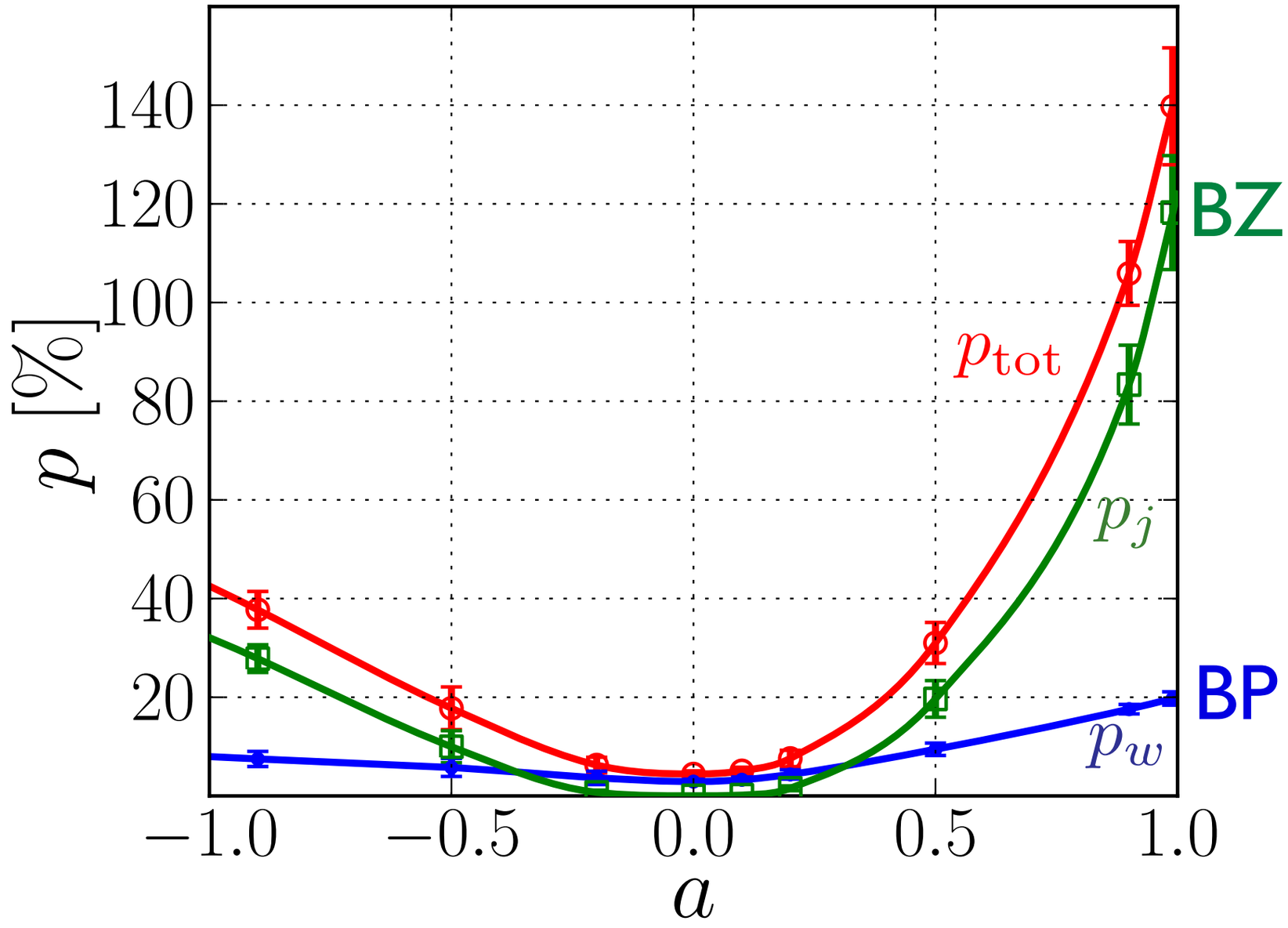
Maximum Jet Power vs. Spin ($h/r \sim 0.3$)



(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

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

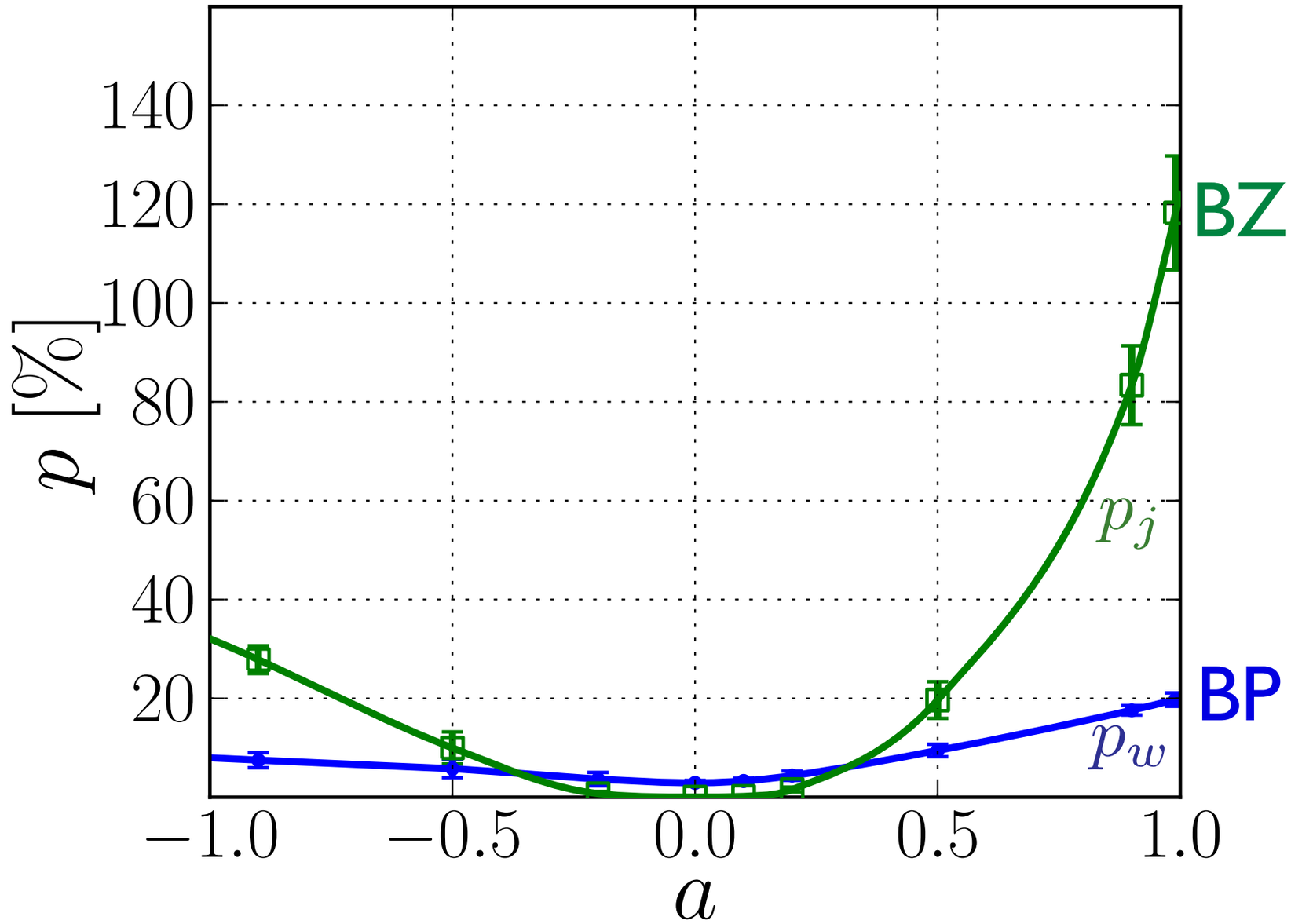
Maximum Jet Power vs. Spin (h/r~0.3)



(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

At high spin, most of the power comes from black hole spin (BZ effect).

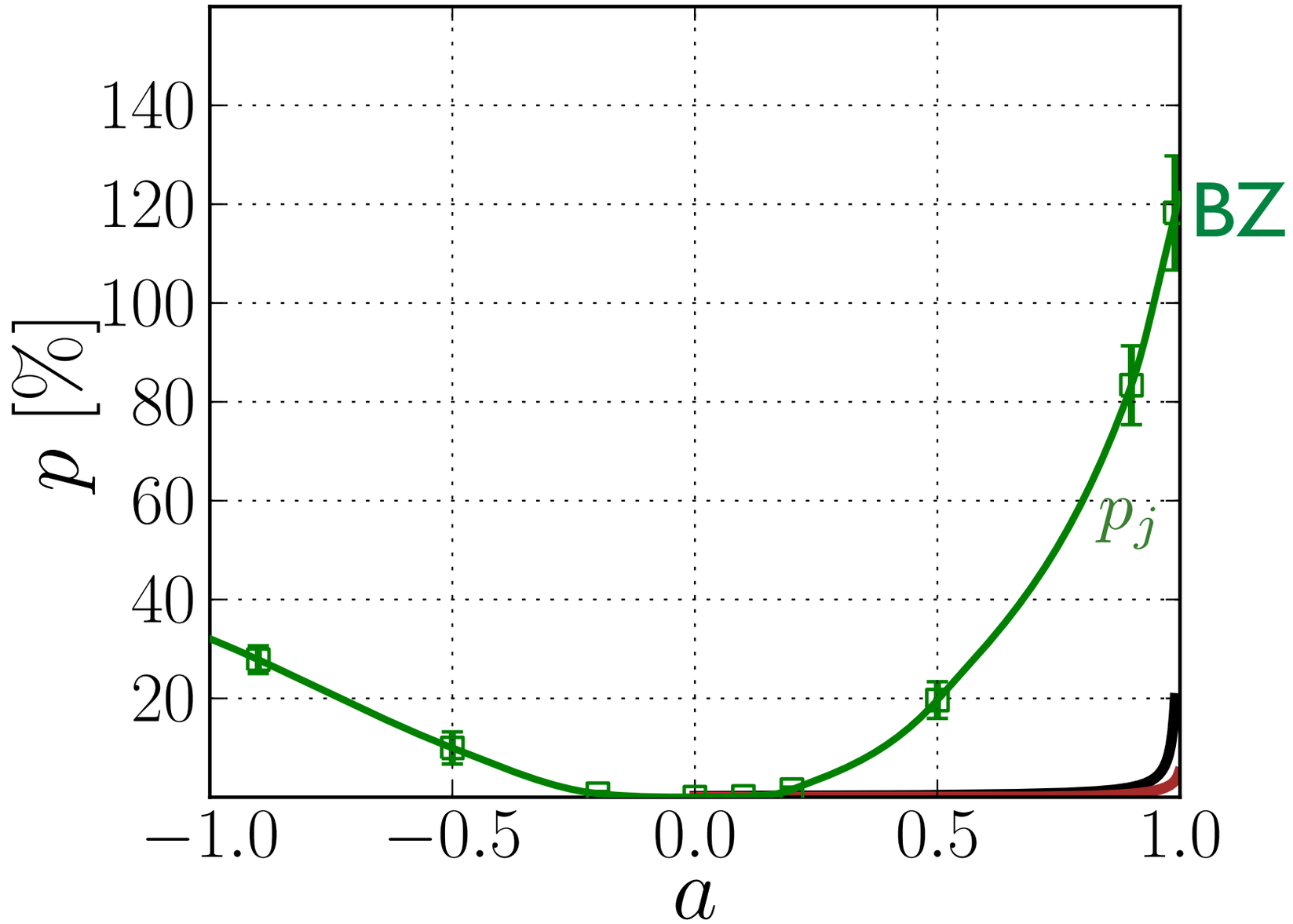
Maximum Jet Power vs. Spin (h/r~0.3)



(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

At high spin, most of the power comes from black hole spin (BZ effect).

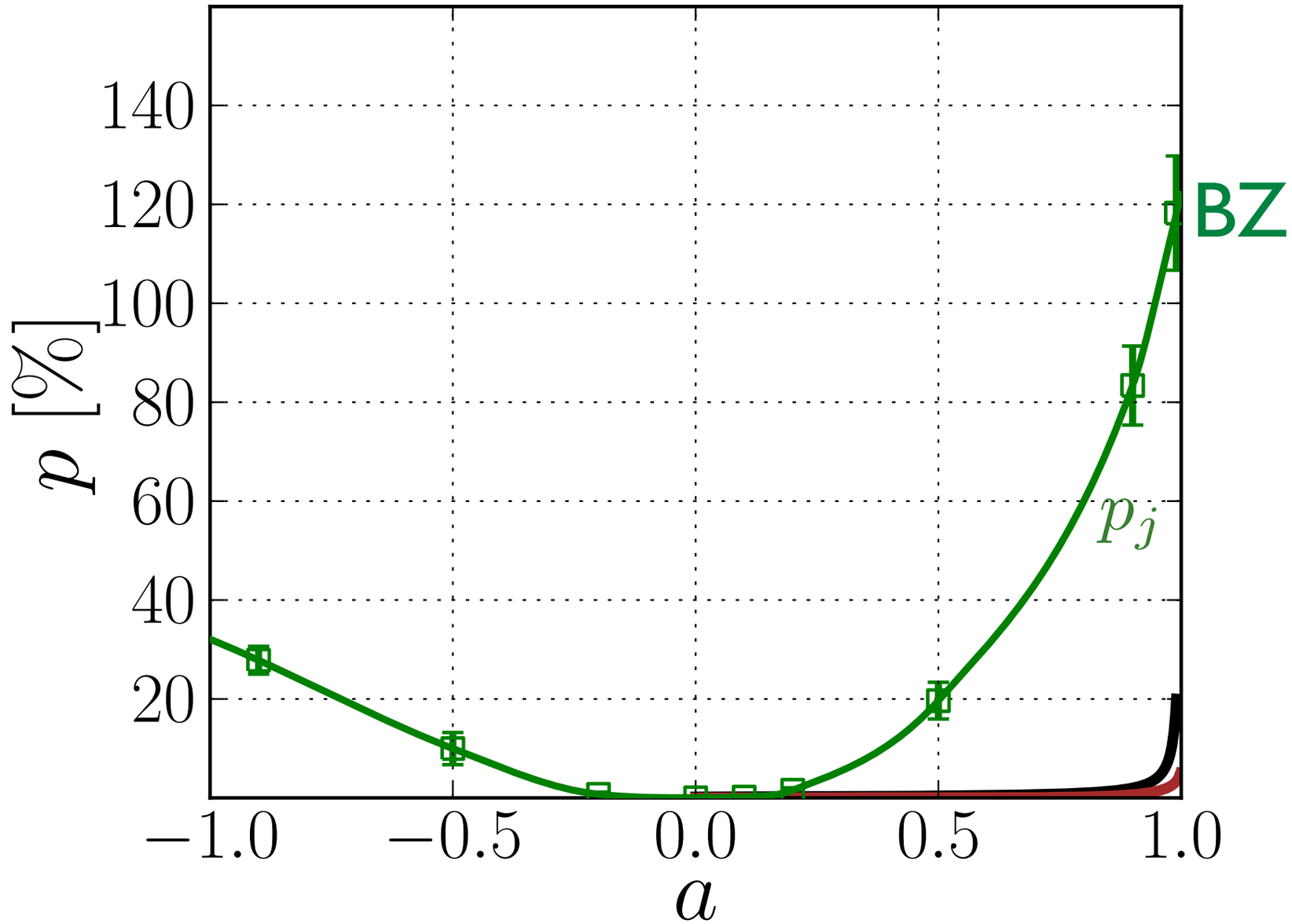
Maximum Jet Power vs. Spin (h/r~0.3)



(AT, McKinney 2012a, MNRAS, 423, 55; 2013, in prep.)

Jets from MADs can be much more powerful than in limited-flux simulations.
Thicker MADs -> more powerful jets.

Maximum Jet Power vs. Spin (h/r~0.3)

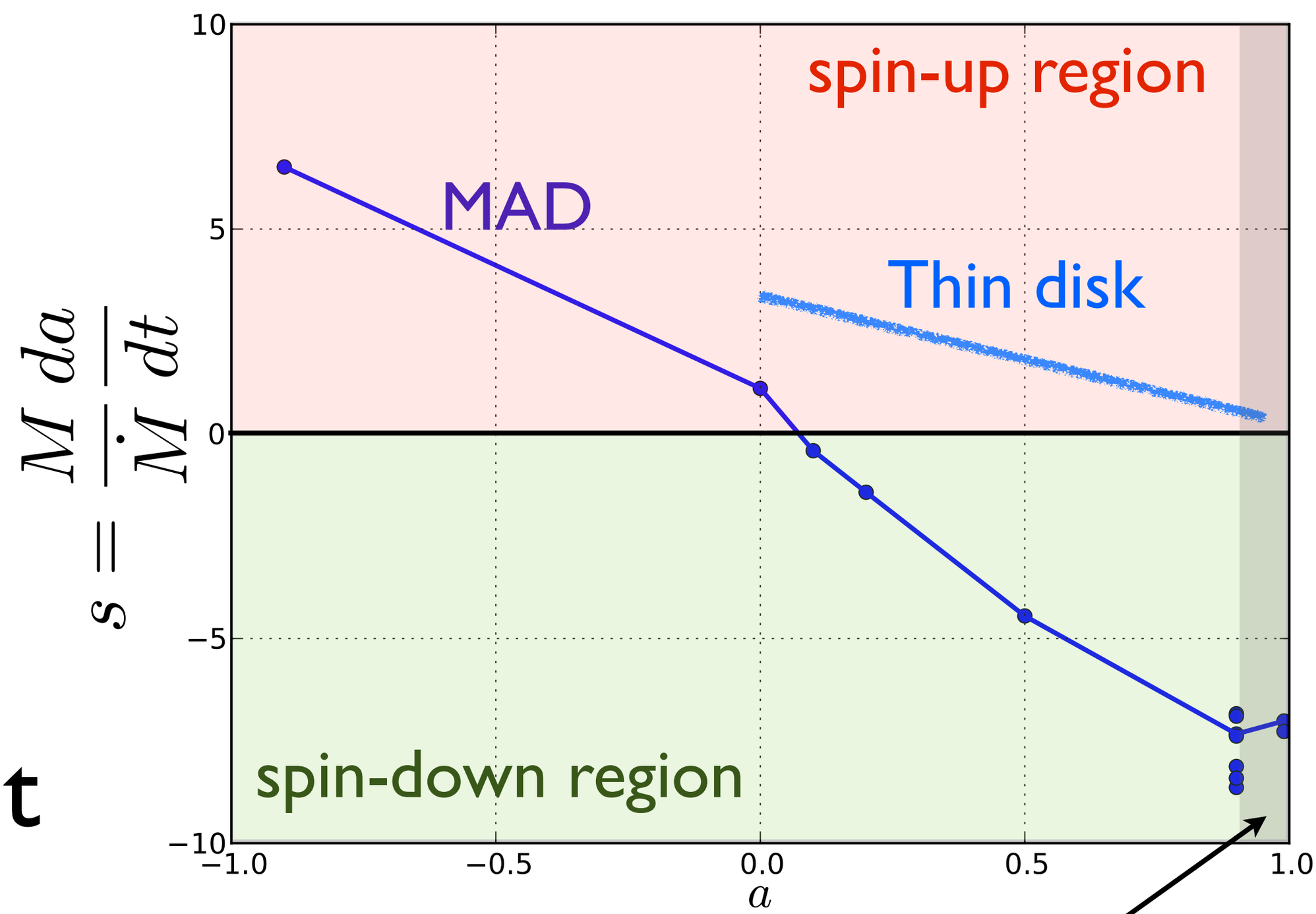


(McKinney 05, Hawley & Krolik 06)

(AT, McKinney 2012a, MNRAS, 423, 55; 2013, in prep.)

Jets from MADs can be much more powerful than in limited-flux simulations. Thicker MADs -> more powerful jets.

Our MADs slow BHs down to a halt



(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

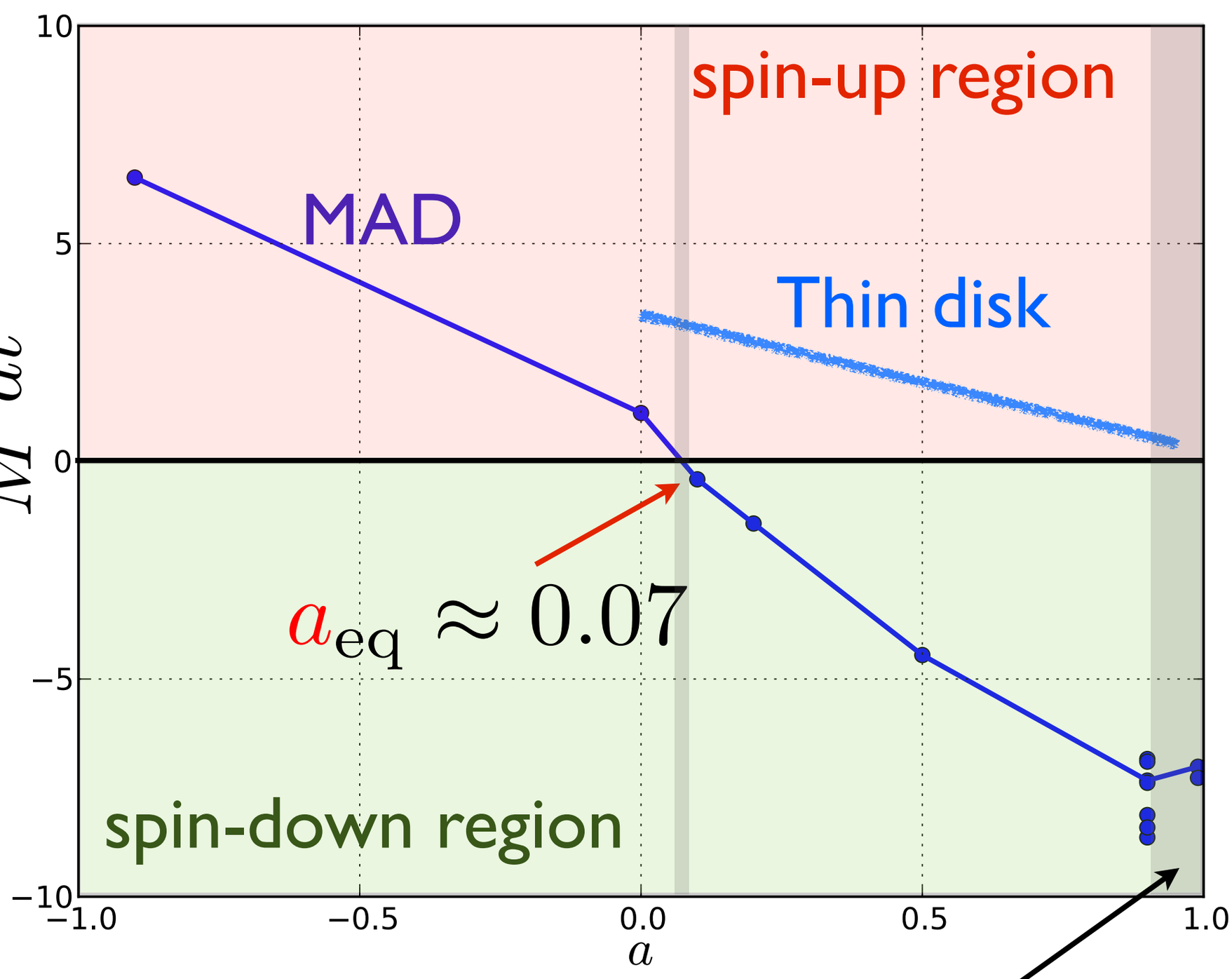
Conventional spin equilibrium region, $a \gtrsim 0.9$

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

tilted | 2

Our MADs slow BHs down to a halt

$$s = \left| \frac{M}{\dot{M}} \frac{da}{dt} \right|$$



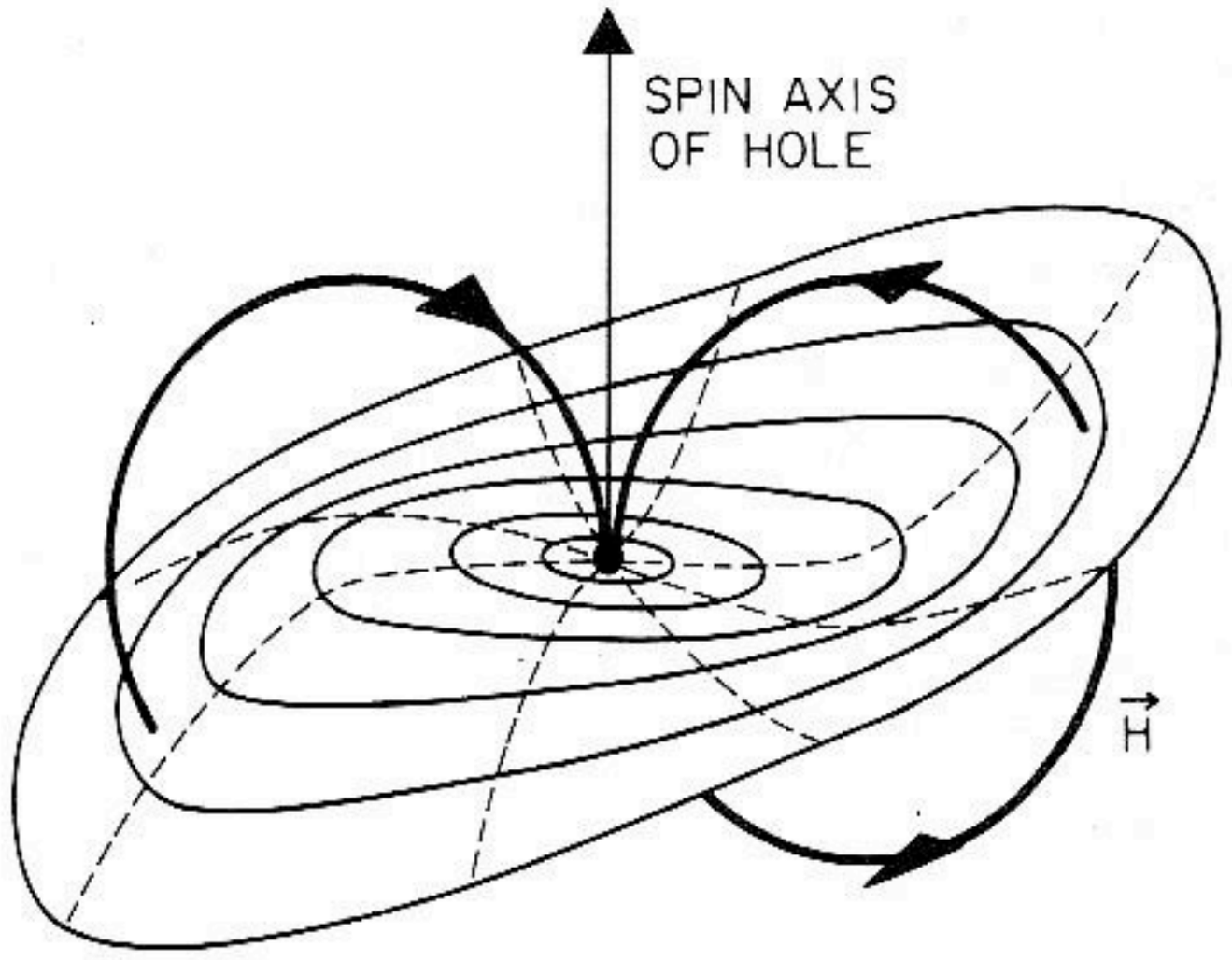
(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

Conventional spin equilibrium region, $a \gtrsim 0.9$

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

What if a Disk Is Tilted?

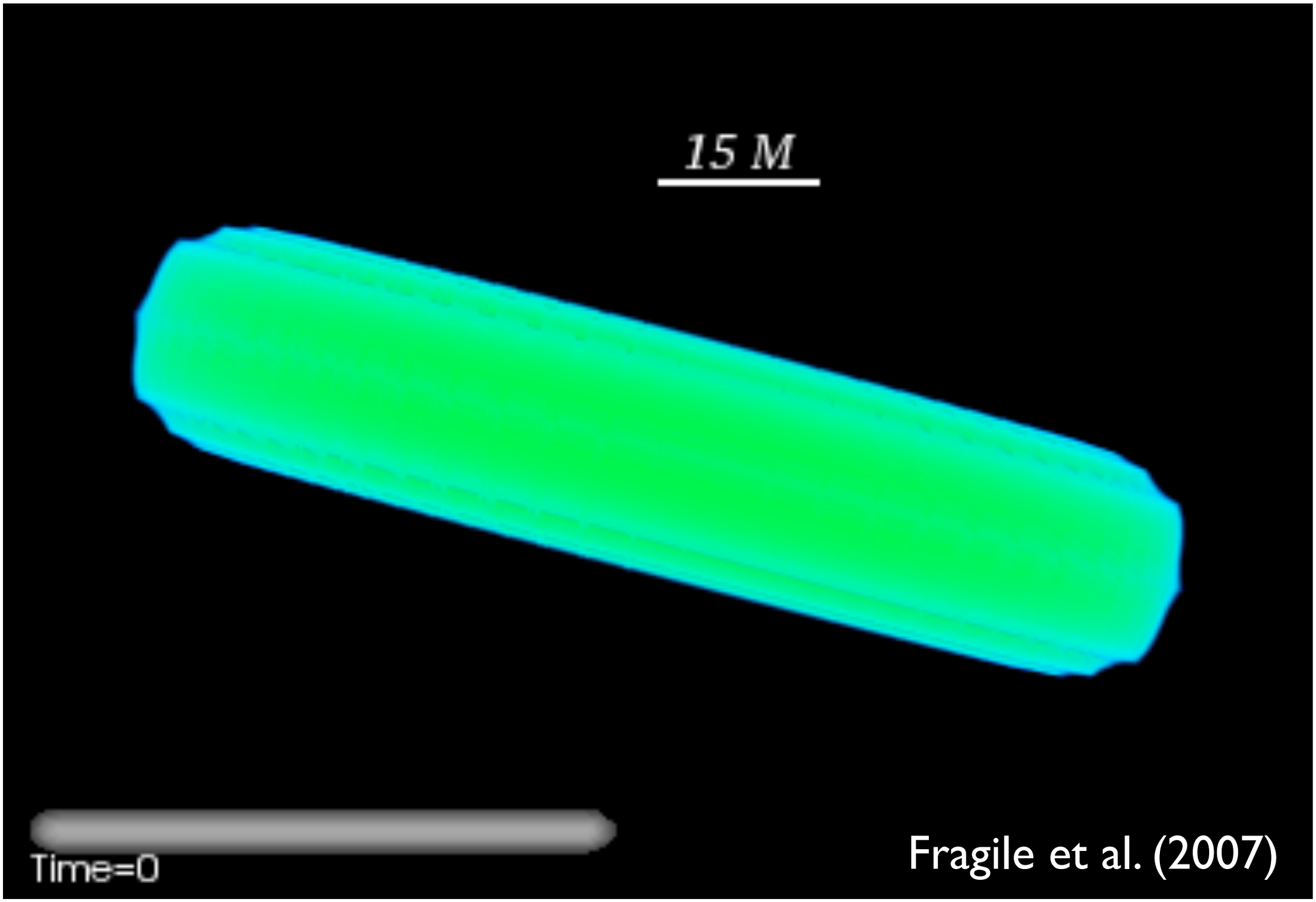
Thin disks align with black hole spin via Bardeen-Petterson Effect



Thorne et al.

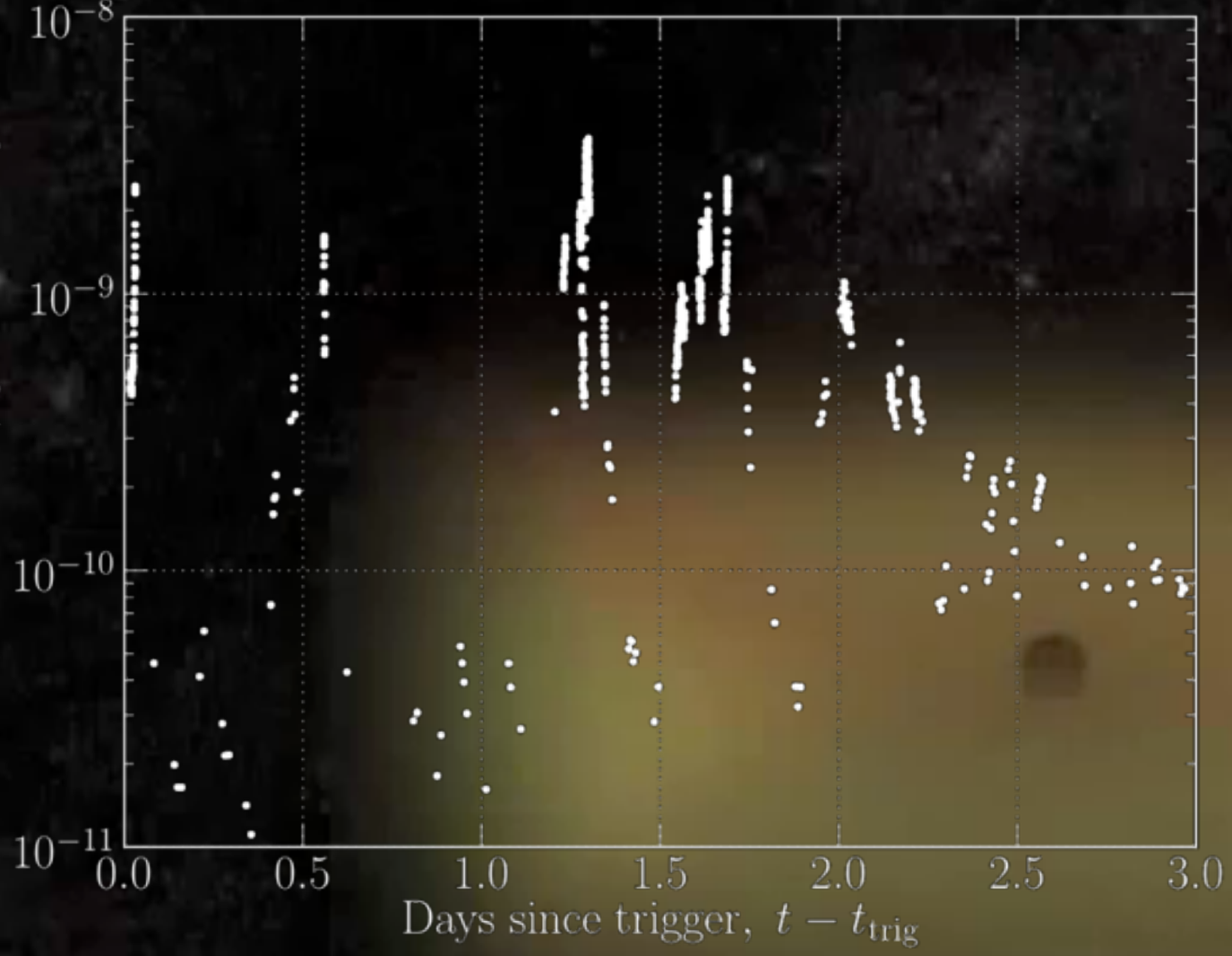
Jet-producing disks are *thick*.
What happens to them and their jets?

Thick Disks: Do Not Align But Precess



Vis. by Jon McKiney and Ralf Kaehler (SLAC)

McKinney, AT, Blandford, 2013, Science

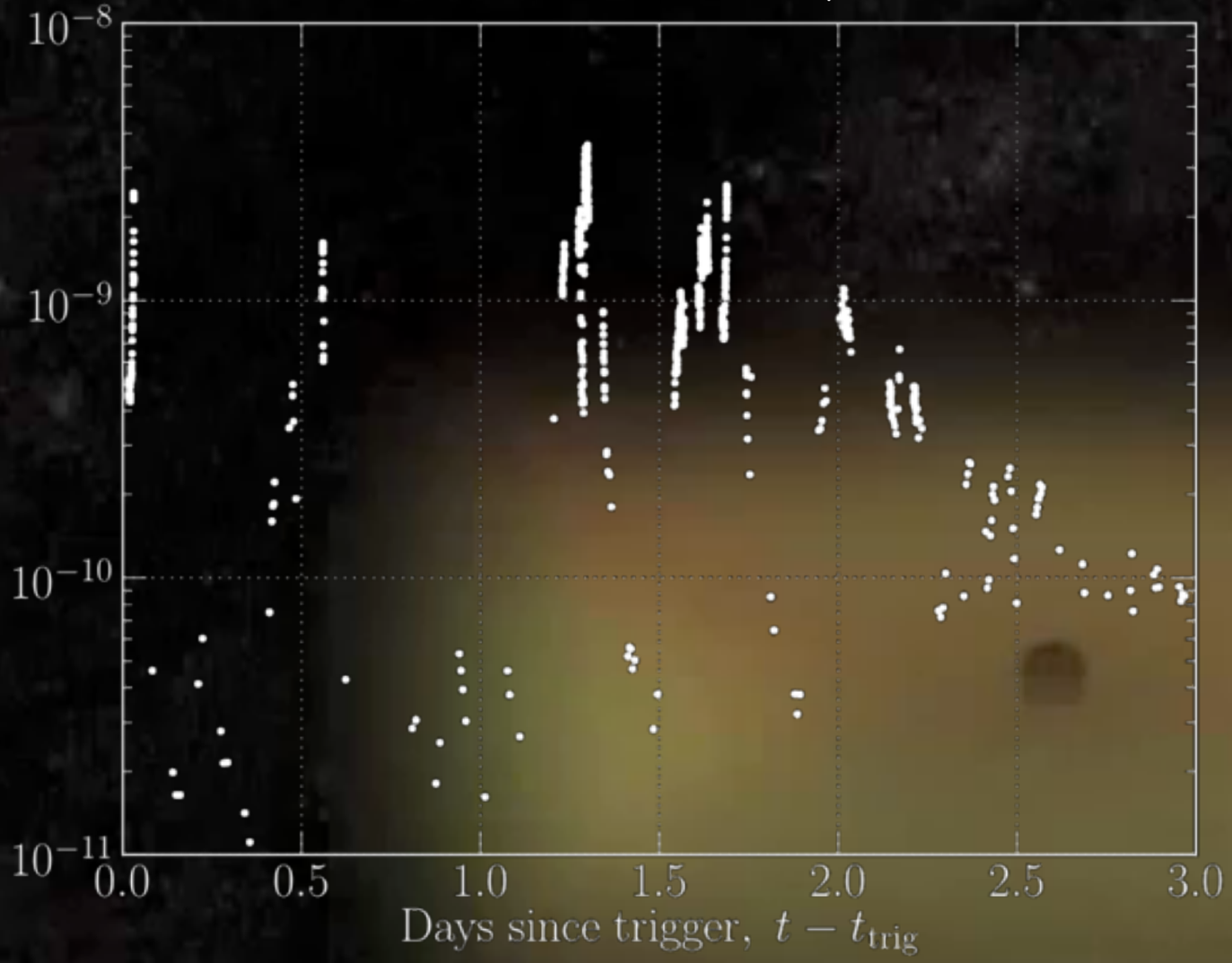


concl

Vis. by Jon McKiney and Ralf Kaehler (SLAC)

McKinney, AT, Blandford, 2013, Science

Jetted tidal disruption Swift J1644+57



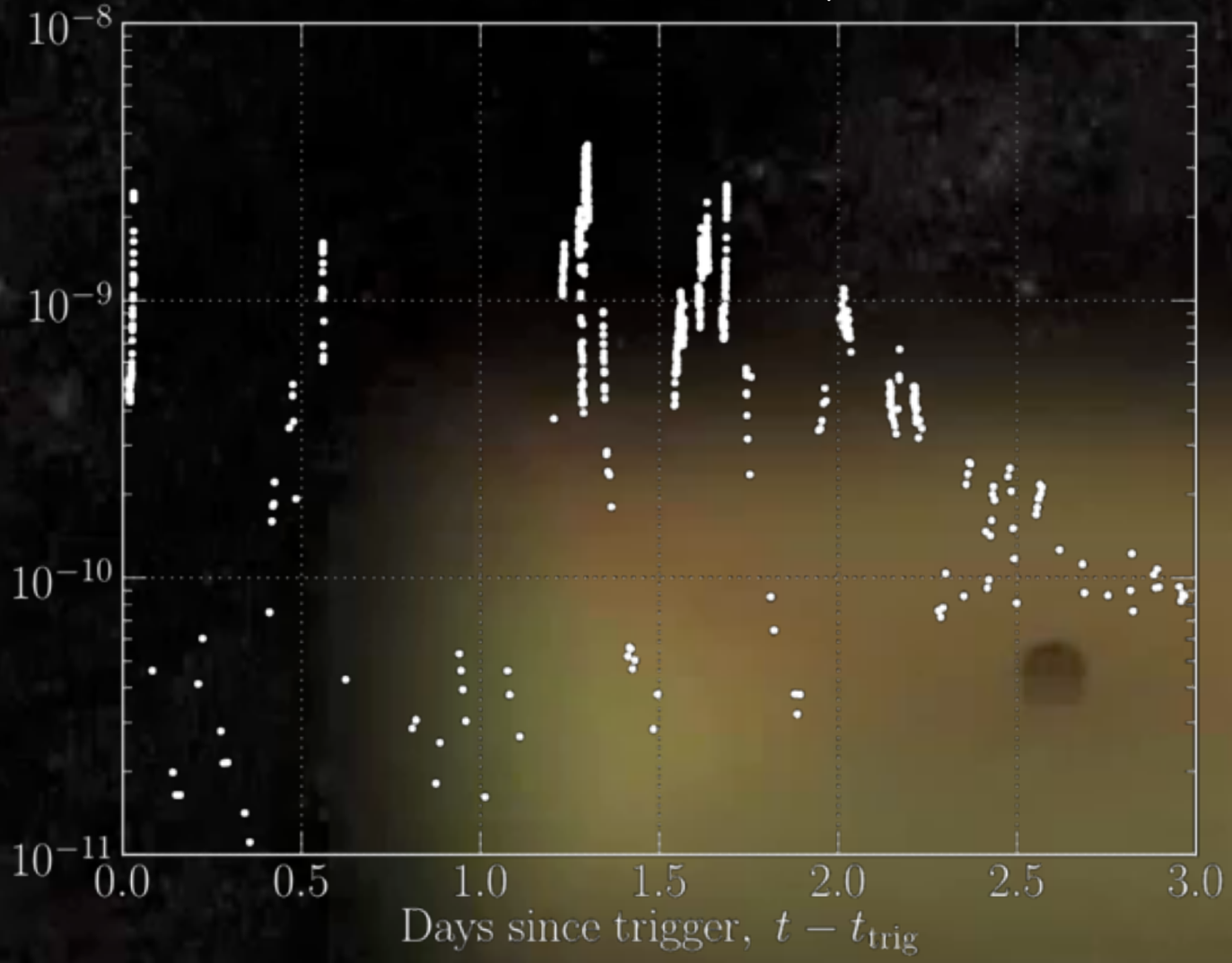
(Bloom+11, Burrows+11, Levan+11, Zauderer+11)

concl

Vis. by Jon McKiney and Ralf Kaehler (SLAC)

McKinney, AT, Blandford, 2013, Science

Jetted tidal disruption Swift J1644+57



(Bloom+11, Burrows+11, Levan+11, Zauderer+11)

Large variability due to jet moving past us and its emission beaming in and out of our line of sight

(AT, Metzger, Giannios, Kelley, 2013b, MNRAS)

Vis. by Jon McKiney and Ralf Kaehler (SLAC)

McKinney, AT, Blandford, 2013, Science

concl

MAD Summary

- Central accumulation of large-scale magnetic flux saturates black holes with flux and leads to MADs
  - Even a small amount of magnetic flux is sufficient to lead to a MAD
  - MADs *are* out there
- Jets from MADs attain the maximum outflow efficiency that can exceed 100%
  - *Net* energy can be extracted from a black hole in a realistic astrophysical setting, for the first time
  - MAD solution only depends on $M, a, \dot{M}, h/r$
  - MADs can explain the most powerful jets in the Universe
  - MADs slow black holes down to a halt
  - MADs display QPOs that potentially allow to directly probe black hole spin
  - MADs align jet and disk axes with the BH spin axis near the BH
  - The alignment process is violent and can account for the strong flaring in the lightcurve of jetted TDE Swift J1644+57

Future Outlook

- Why only thick disks produce jets?
- What produces transient jets during spectral state transitions in accretion flows?
- How do jets from tidal disruption events form?
- How does radiation change accretion flow, jets, and outflows in the most luminous systems?