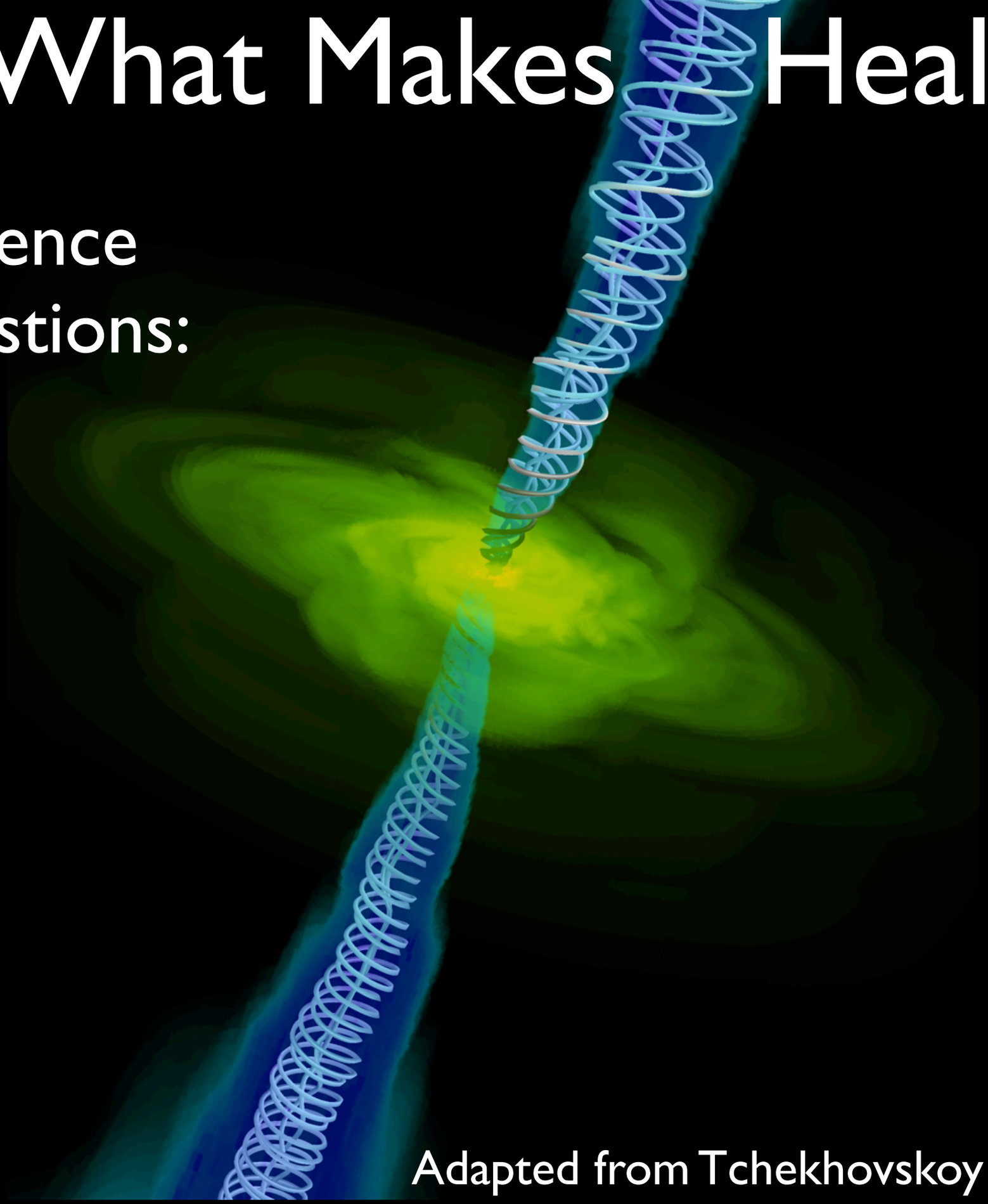
Astrophysics of Black Hole Powered Jets

Alexander (Sasha) Tchekhovskoy

TAC Fellow
UC Berkeley

What Makes Healthy Jets?

Science Questions:



Adapted from Tchekhovskoy 2015

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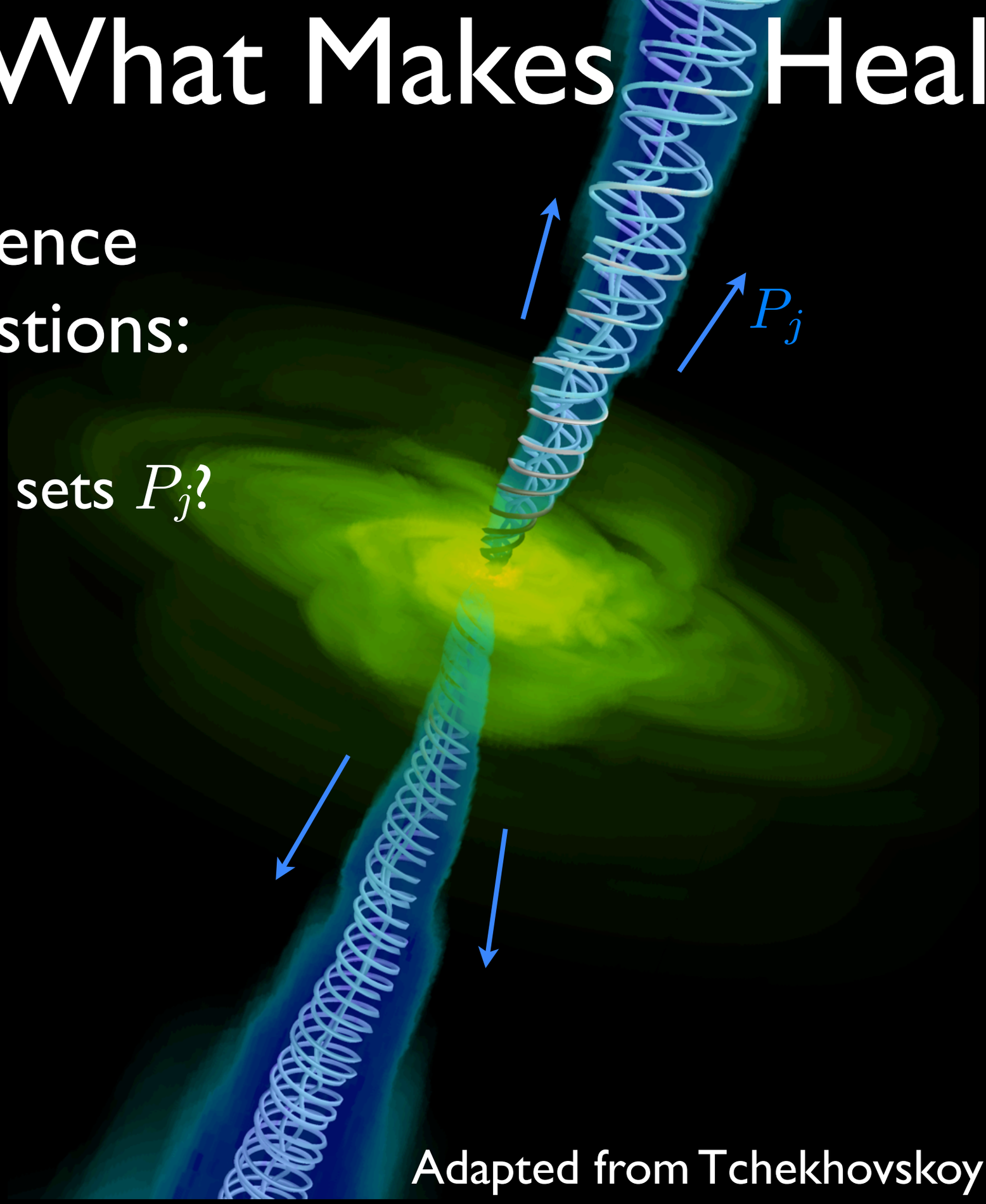
- What sets P_j?



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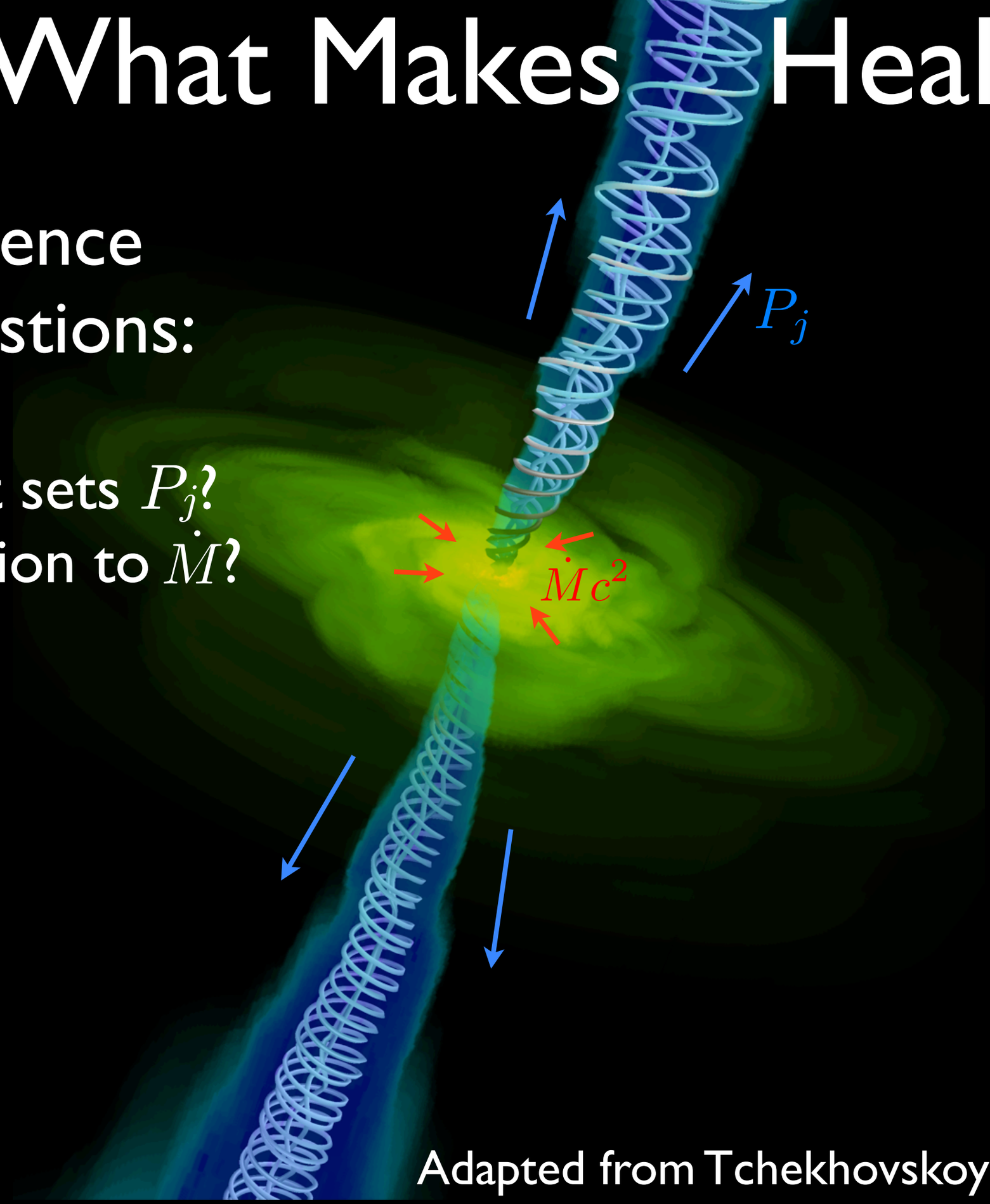
- What sets P_j?
- Relation to $\dot{M}$?



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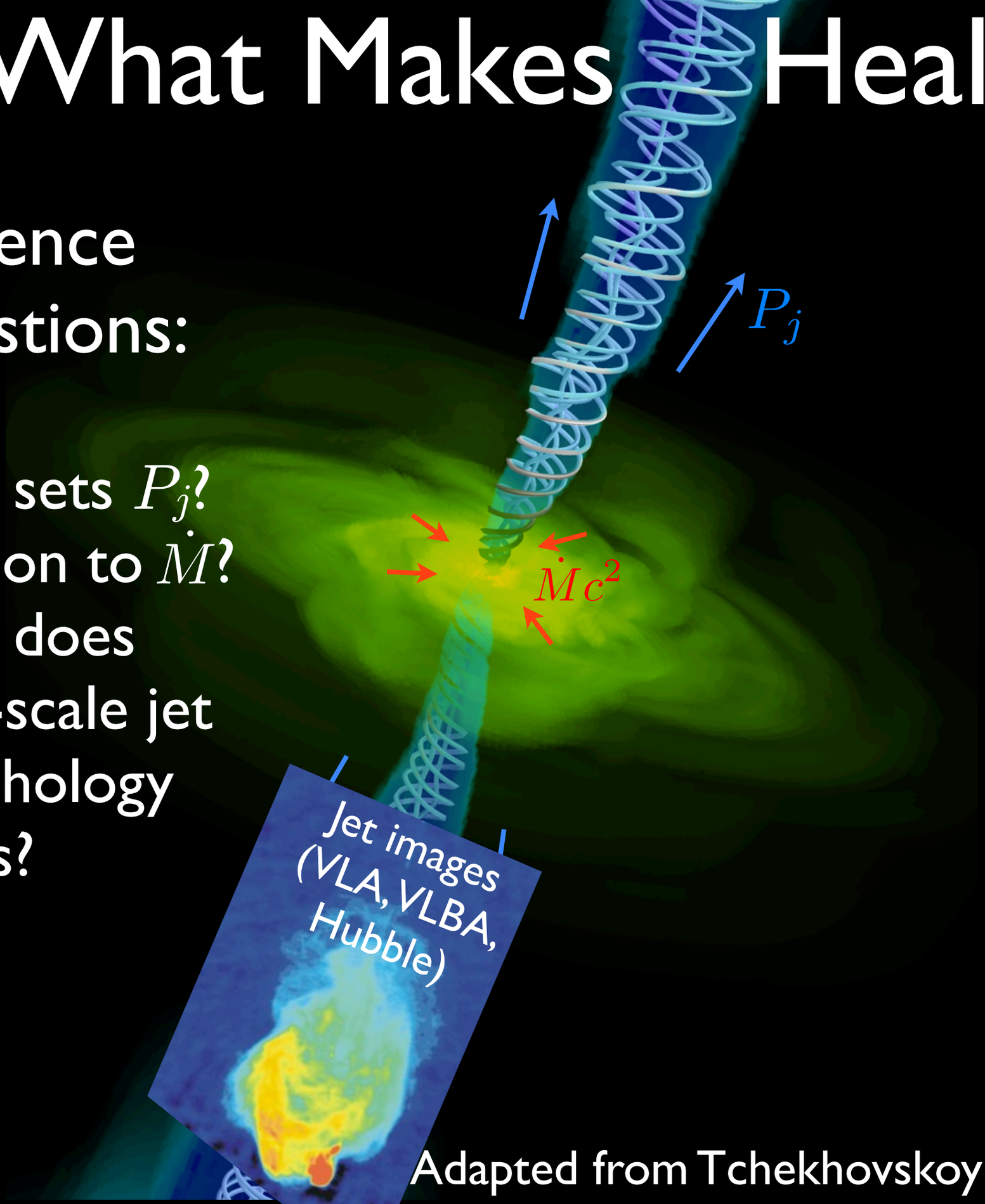
What Makes Healthy Jets?

Science Questions:

- What sets P_j?
- Relation to $\dot{M}$?
- What does large-scale jet morphology tell us?



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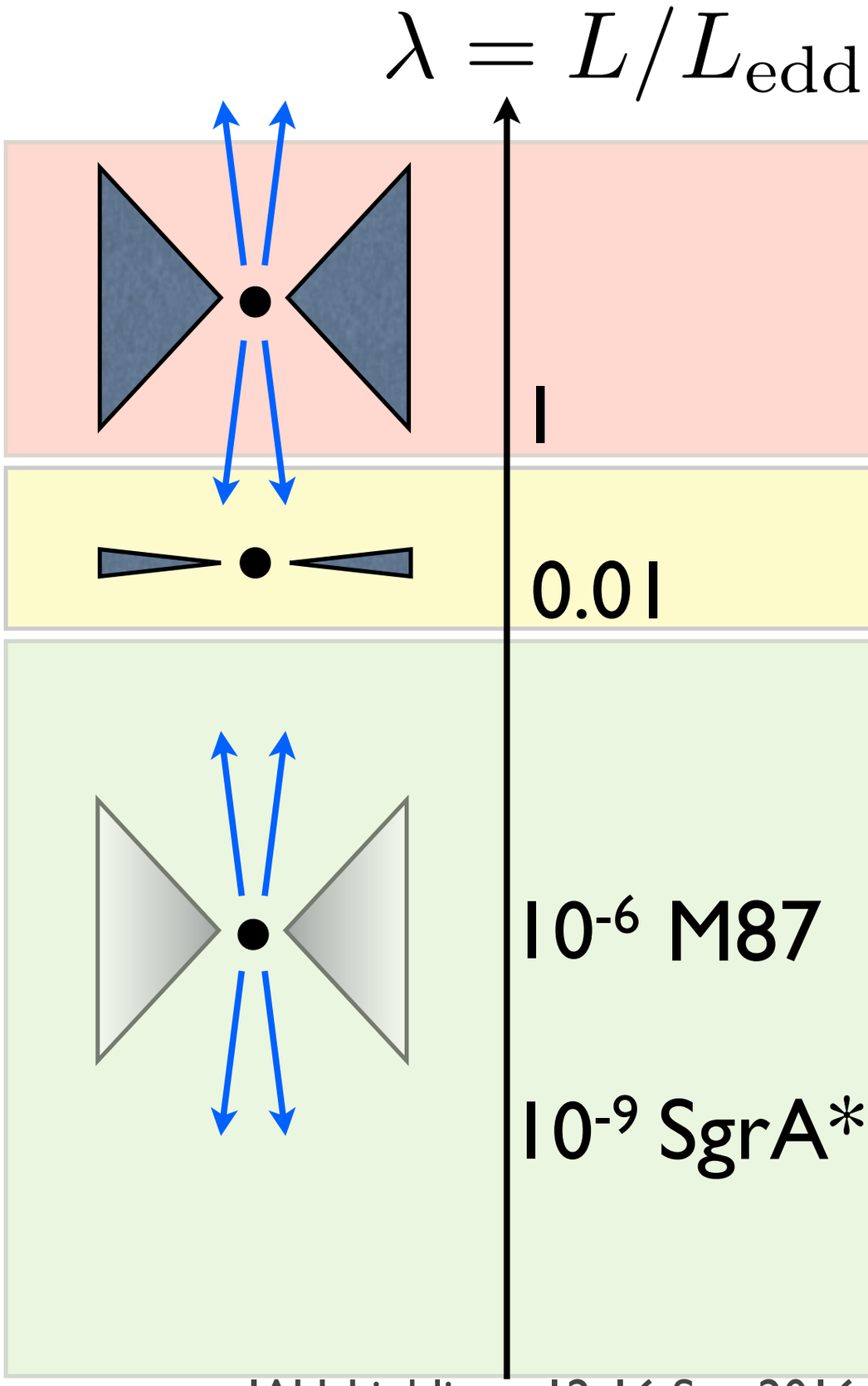
Black Hole Accretion States

Tidal disruptions (TDEs), ultra-luminous X-ray sources, gamma-ray bursts

Quasars, X-ray binaries, TDEs

Low-luminosity active galactic nuclei (LLAGN), X-ray binaries



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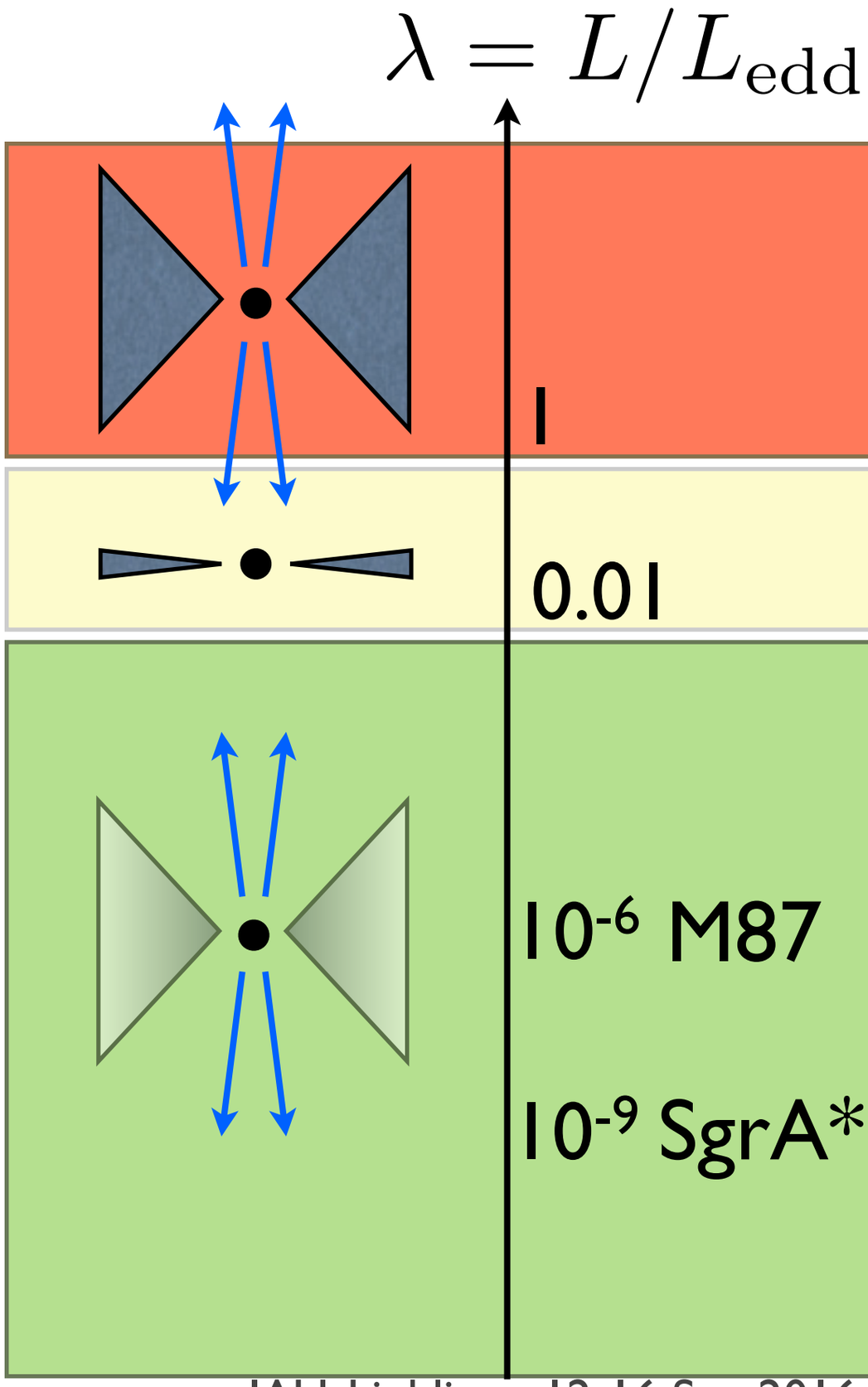

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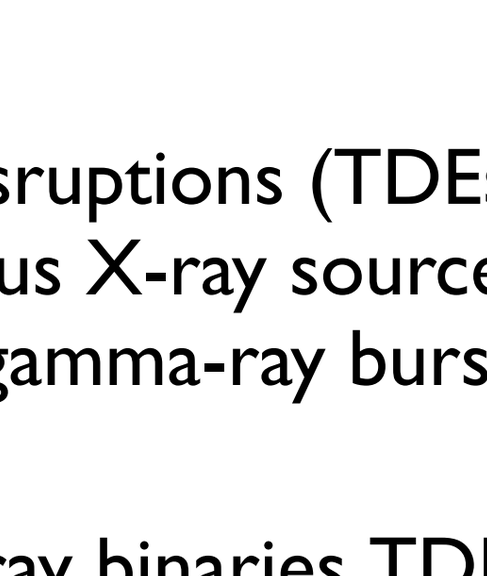
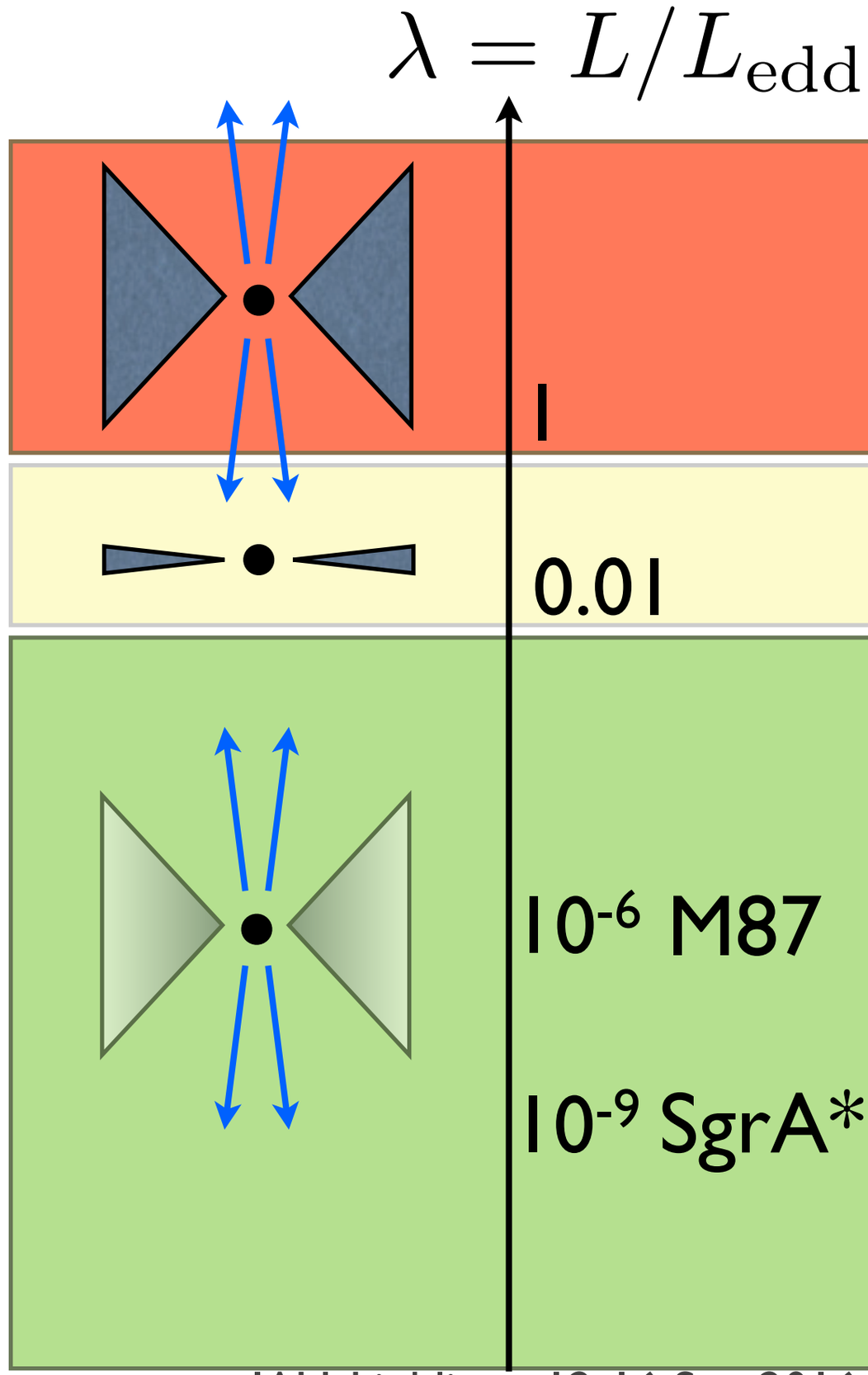
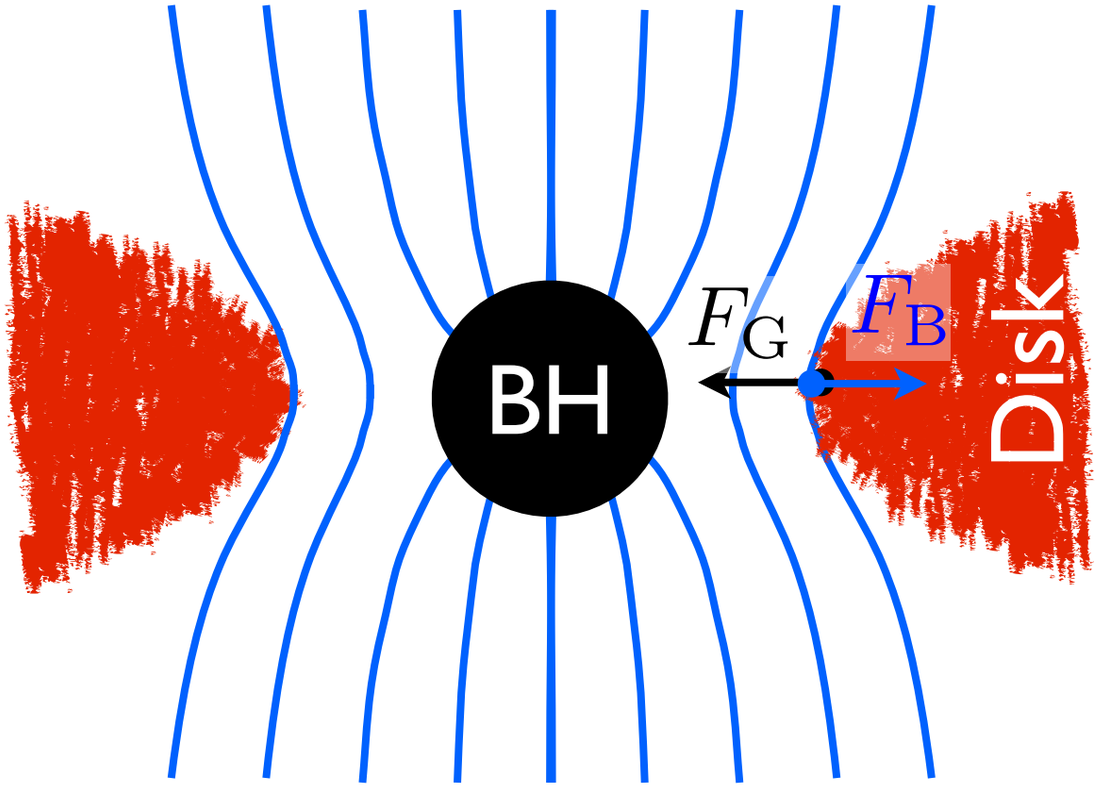
Ressler, AT+ 2016: electron thermodynamics in LLAGN to interpret upcoming *EHT* observations





What Sets Jet Power?



magnetic flux:

$$\Phi \sim B r_g^2$$

grav. radius:

$$r_g = GM/c^2$$

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

(Blandford & Znajek 77, Komissarov 01, AT+10)

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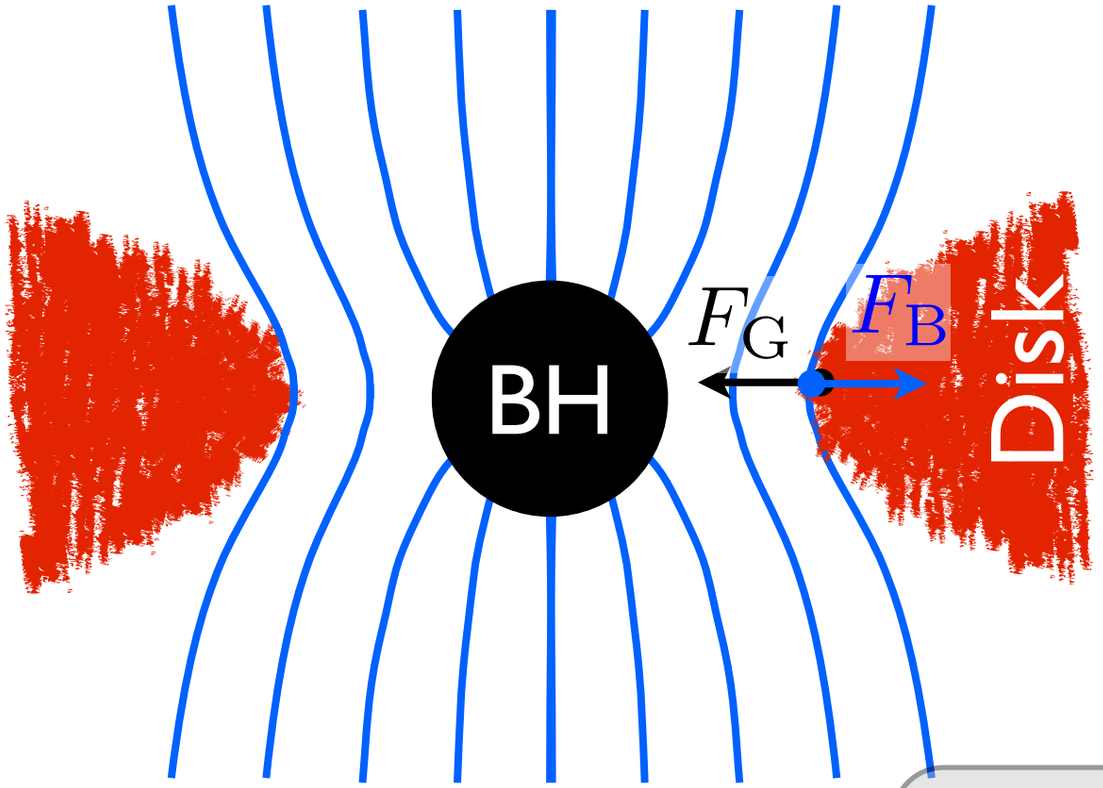

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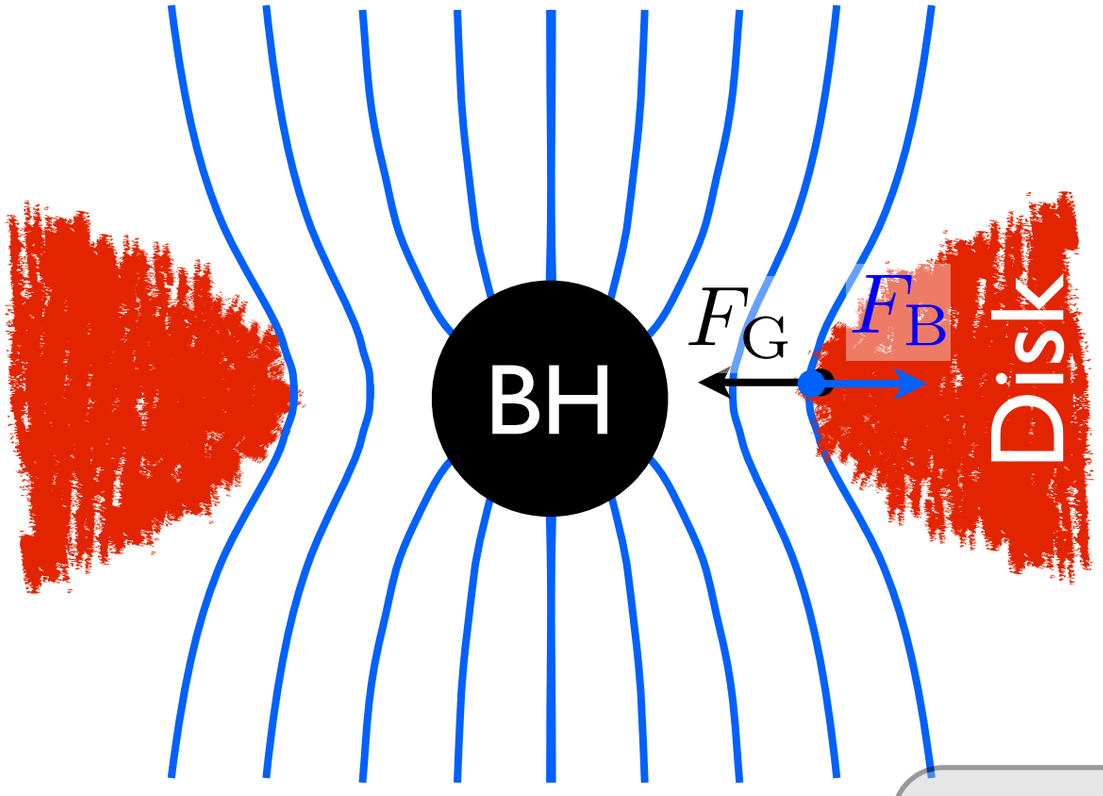

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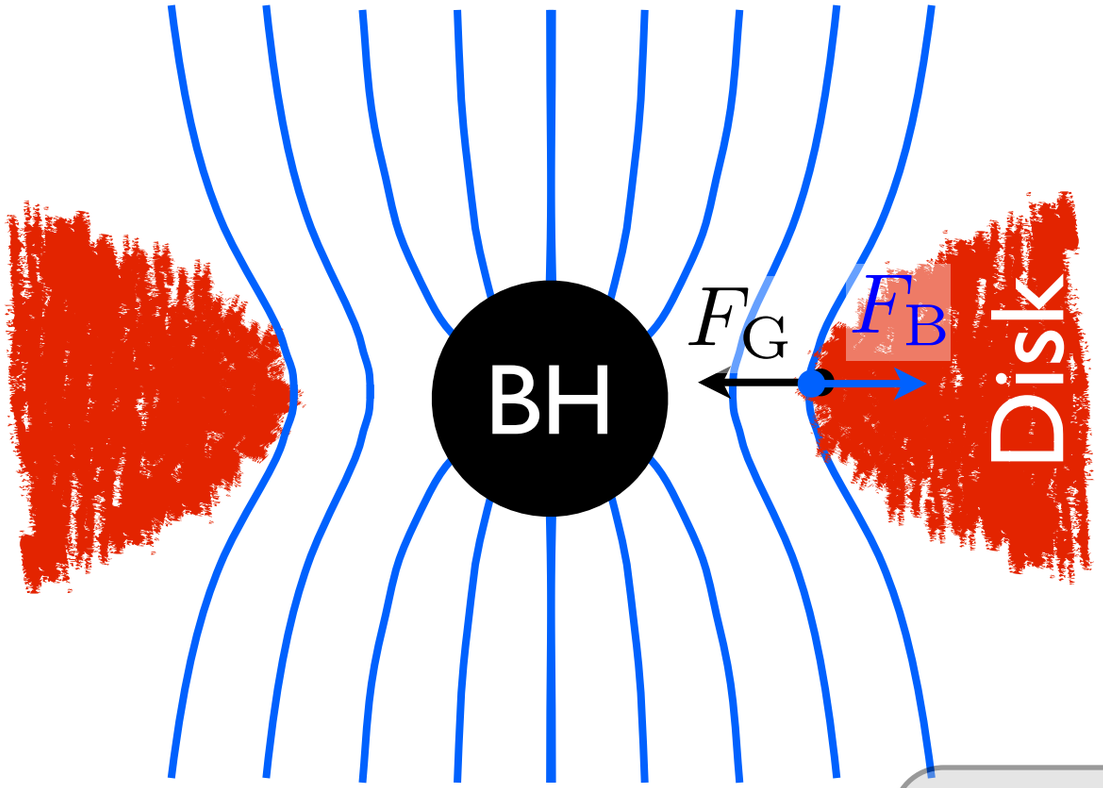

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B sub-dominant

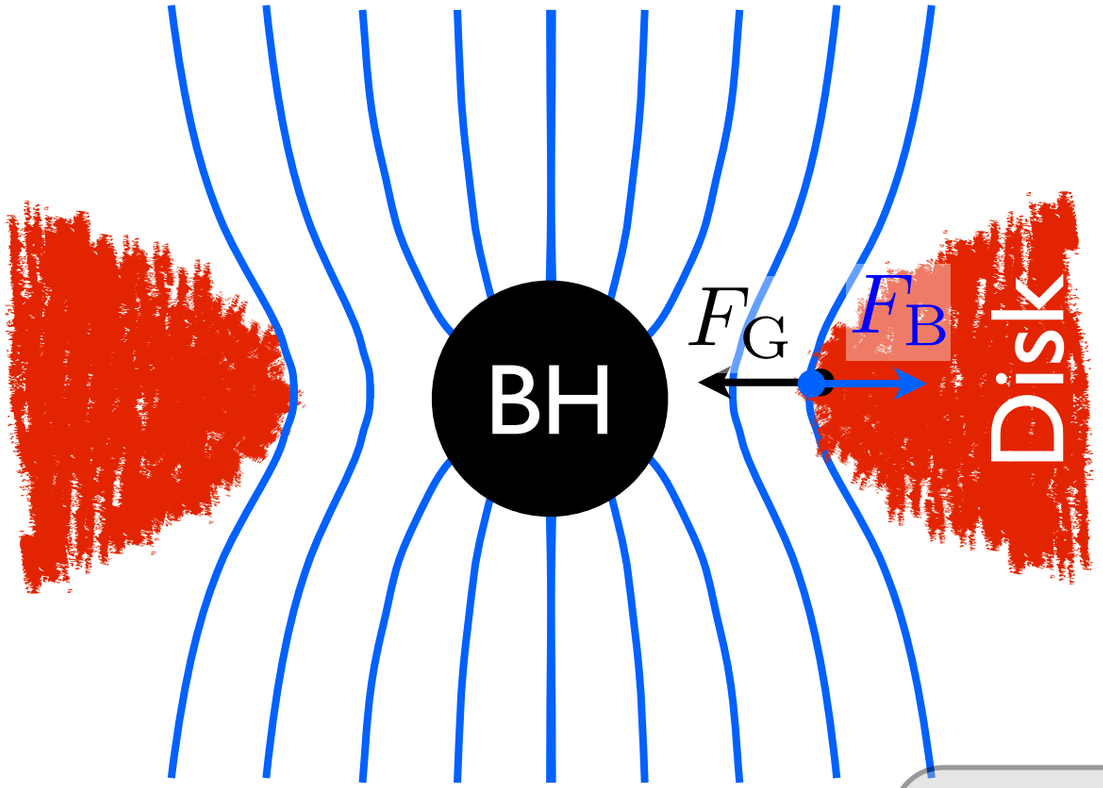
$$0 \leq P_j = k\Phi^2$$

$$\updownarrow$$

$$\Phi = 0$$

What Sets Jet Power?

Gravity limits P_j and Φ!



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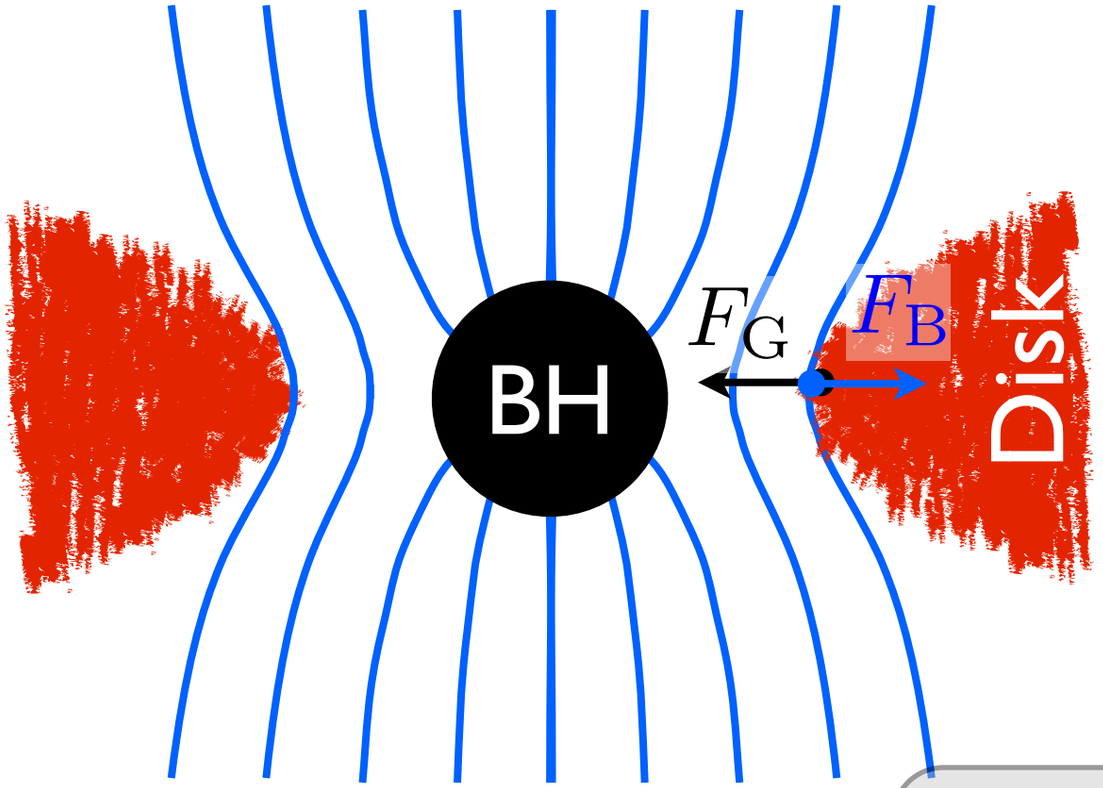

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B dominant *M*agnetically-*A*rrested *D*isk (MAD)

(Narayan+ 2003, AT+ 2011)

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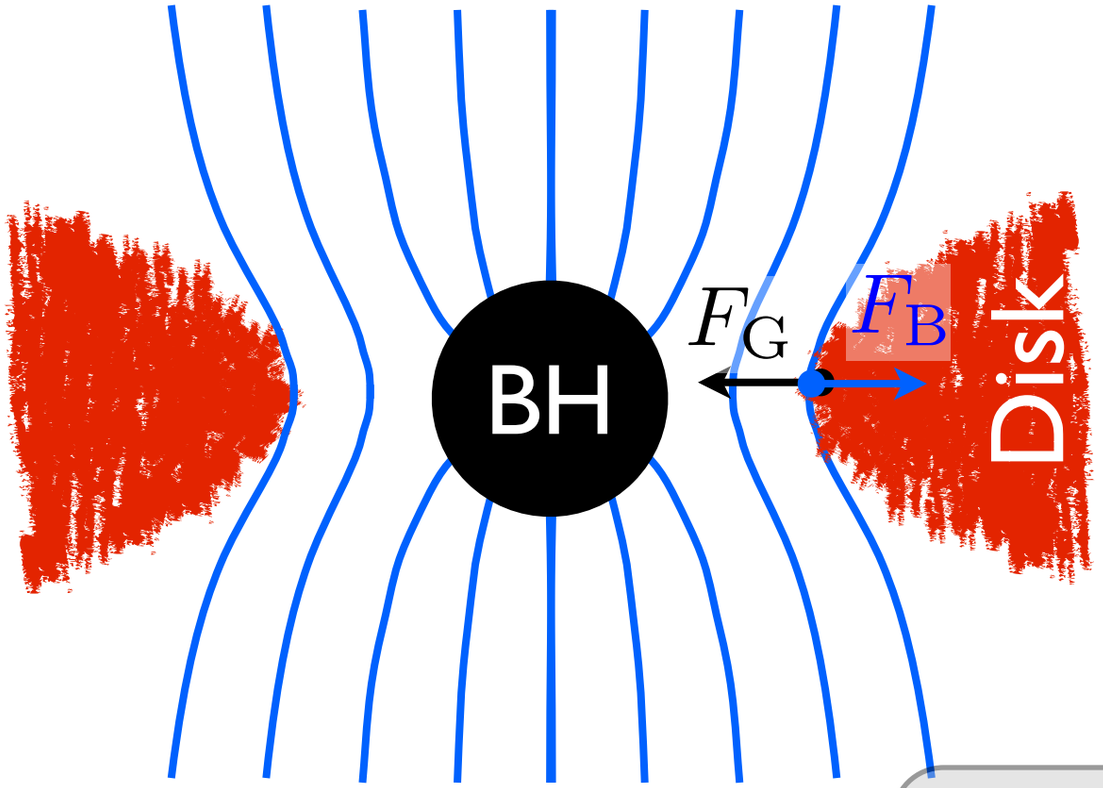

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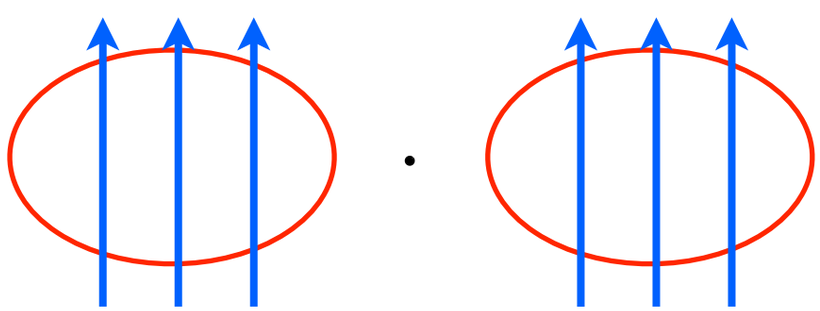
How strong are the jets?

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

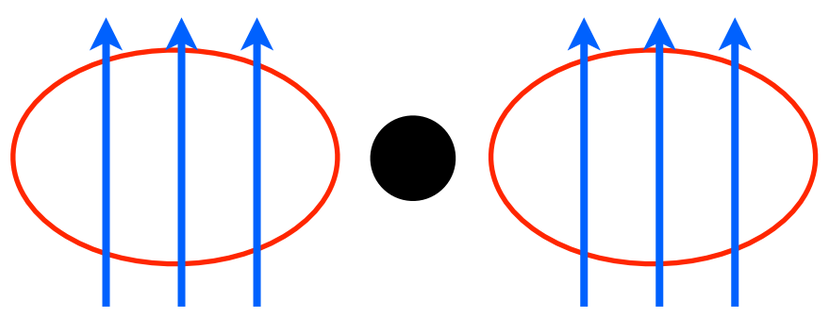
What is a Healthy Jet Diet?

BIG disk



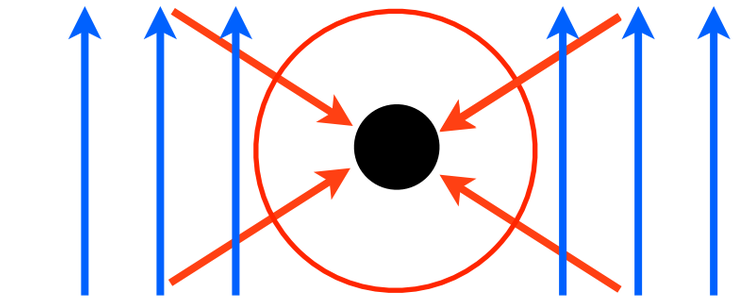
$10^5 r_g$

small disk



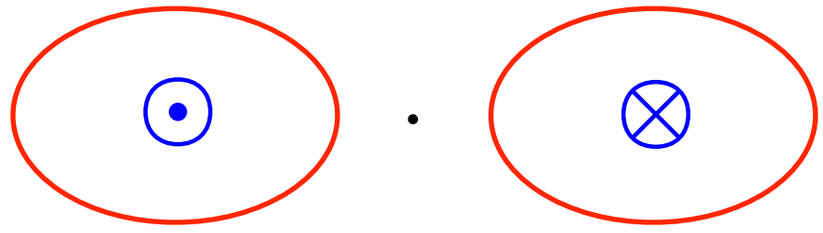
$10 r_g$

no disk



∞r_g

no poloidal field



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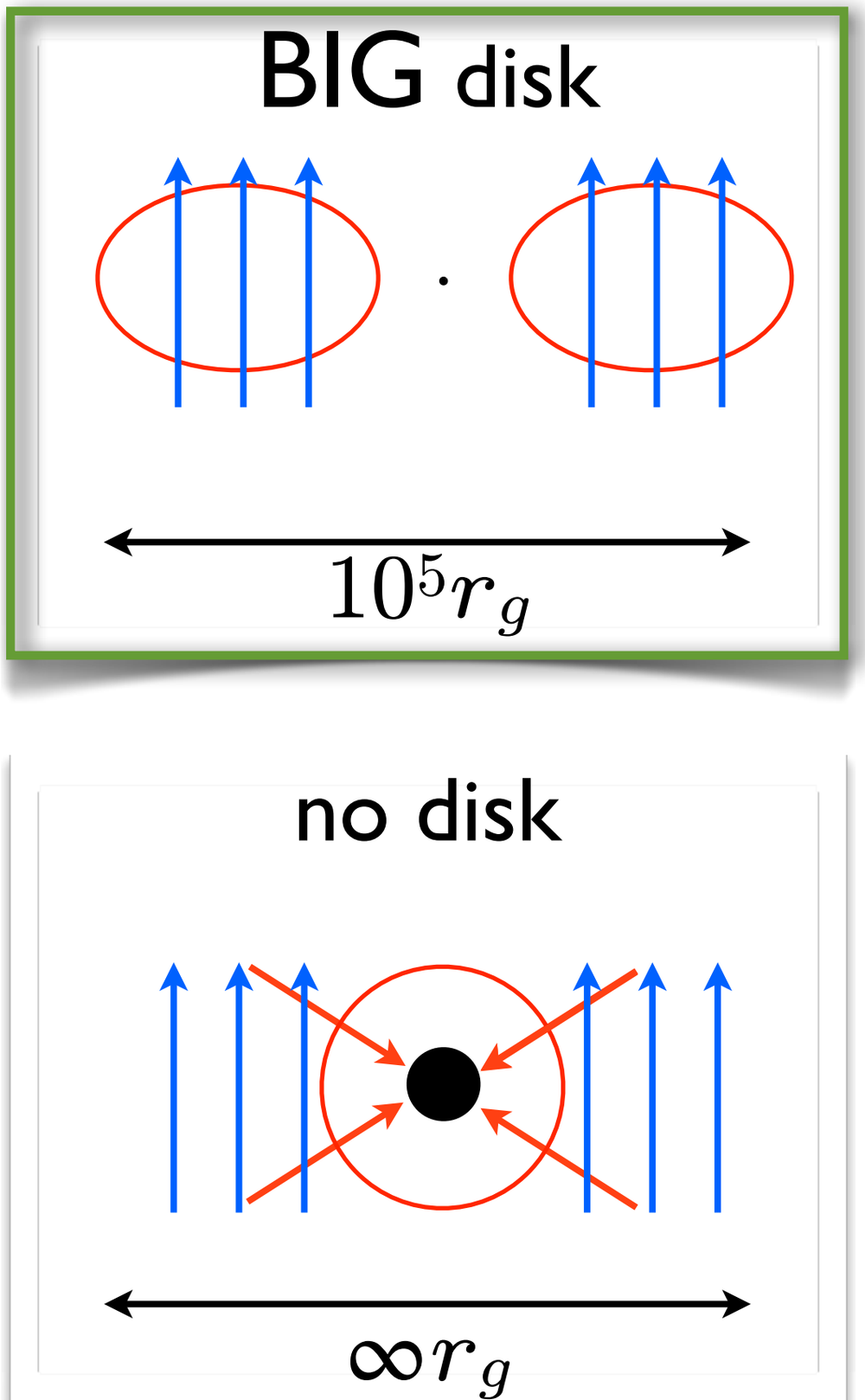
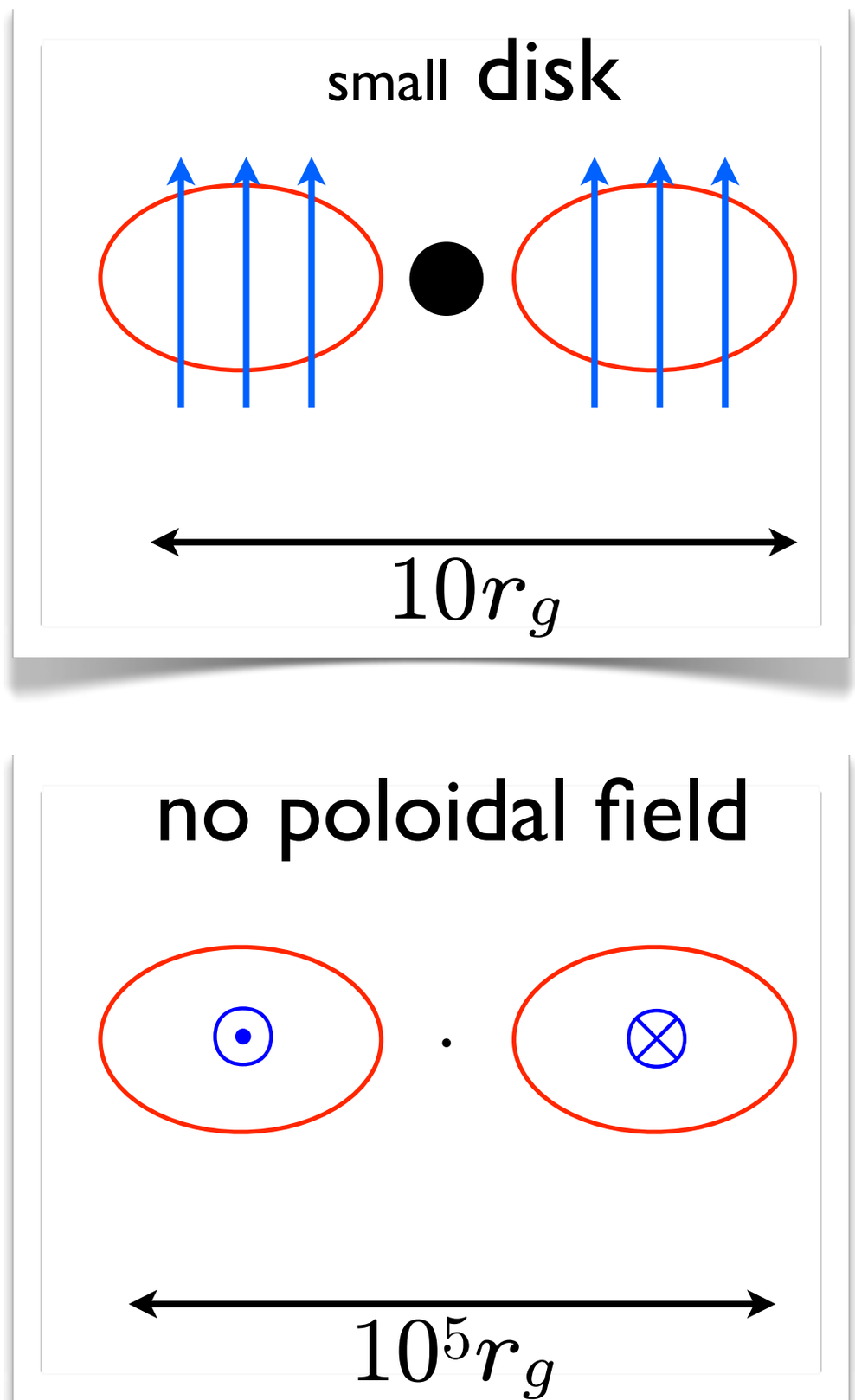




z y $\log\rho$

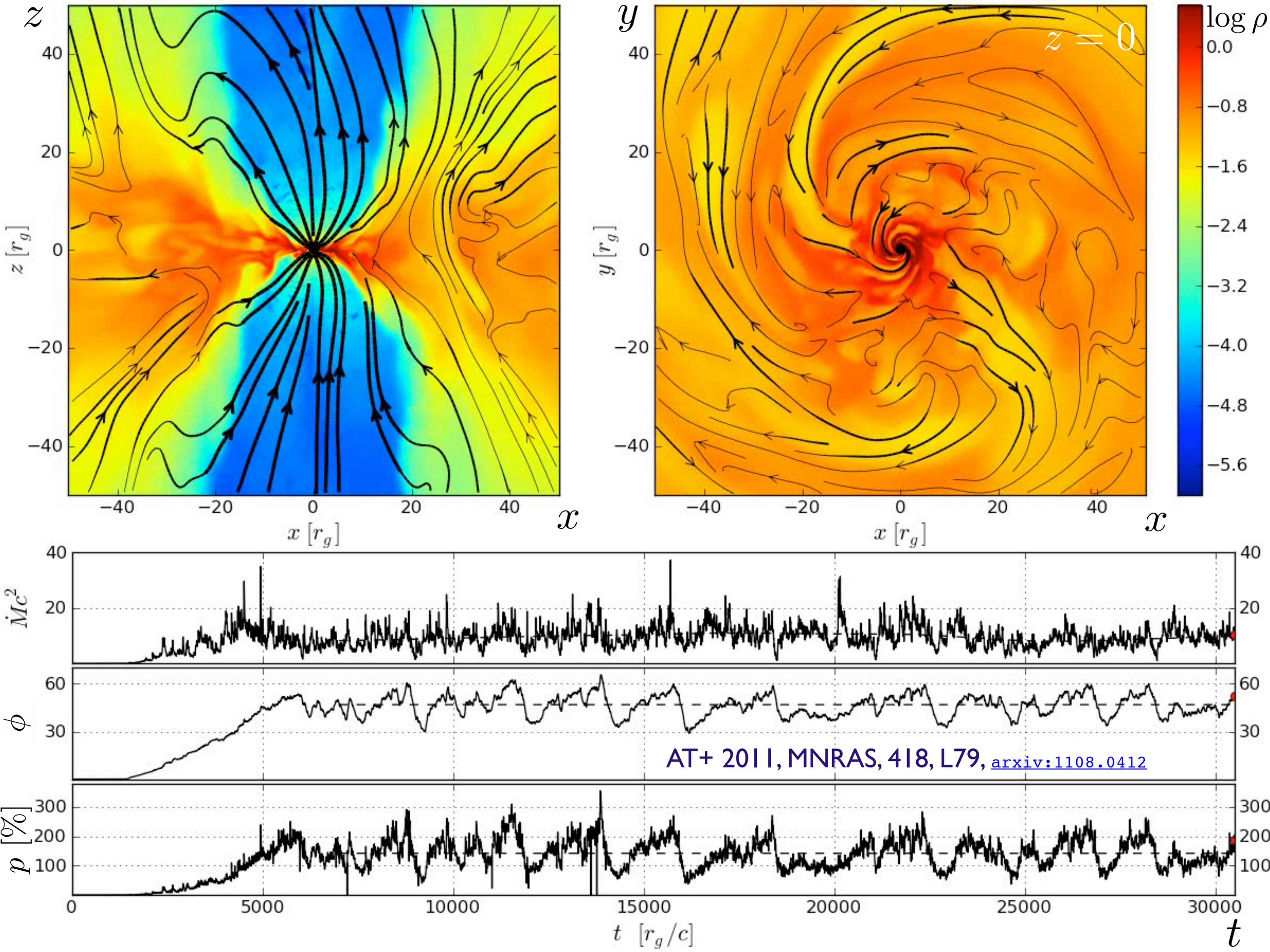
$a = 0.99$
large disk
large B-flux

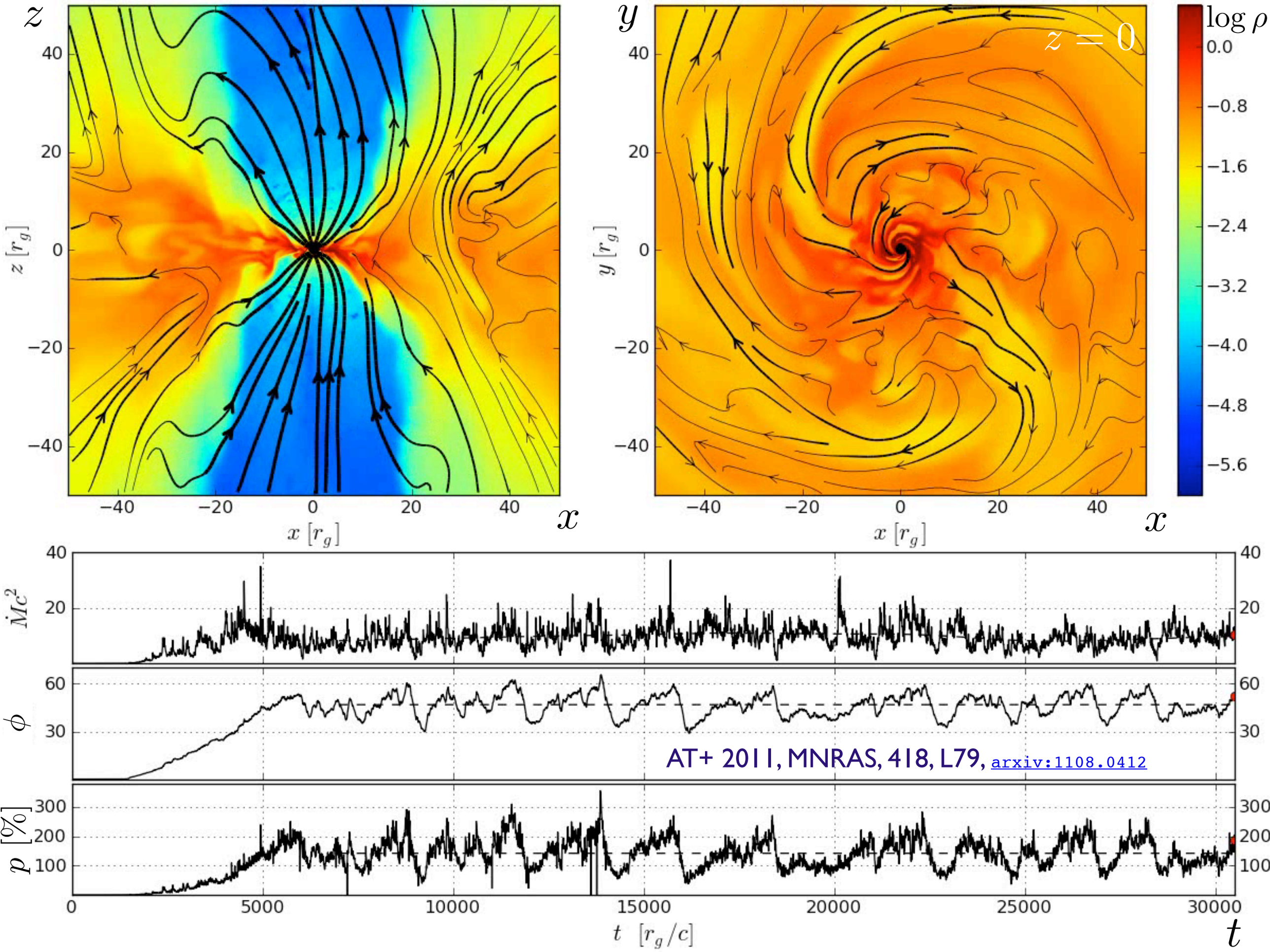
x x

ϕ

AT+ 2011, MNRAS, 418, L79, arxiv:1108.0412

p [%]


z
y
$z = 0$
$\log \rho$
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
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ \ [r_g/c]$
t
AT+ 2011, MNRAS, 418, L79, arxiv:1108.0412


z
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x
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ϕ
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MADs recycle:

rotation destroys magnetic flux bundles escaping from the black hole and mixes them back into the disk

8, L79, arxiv:1108.0412

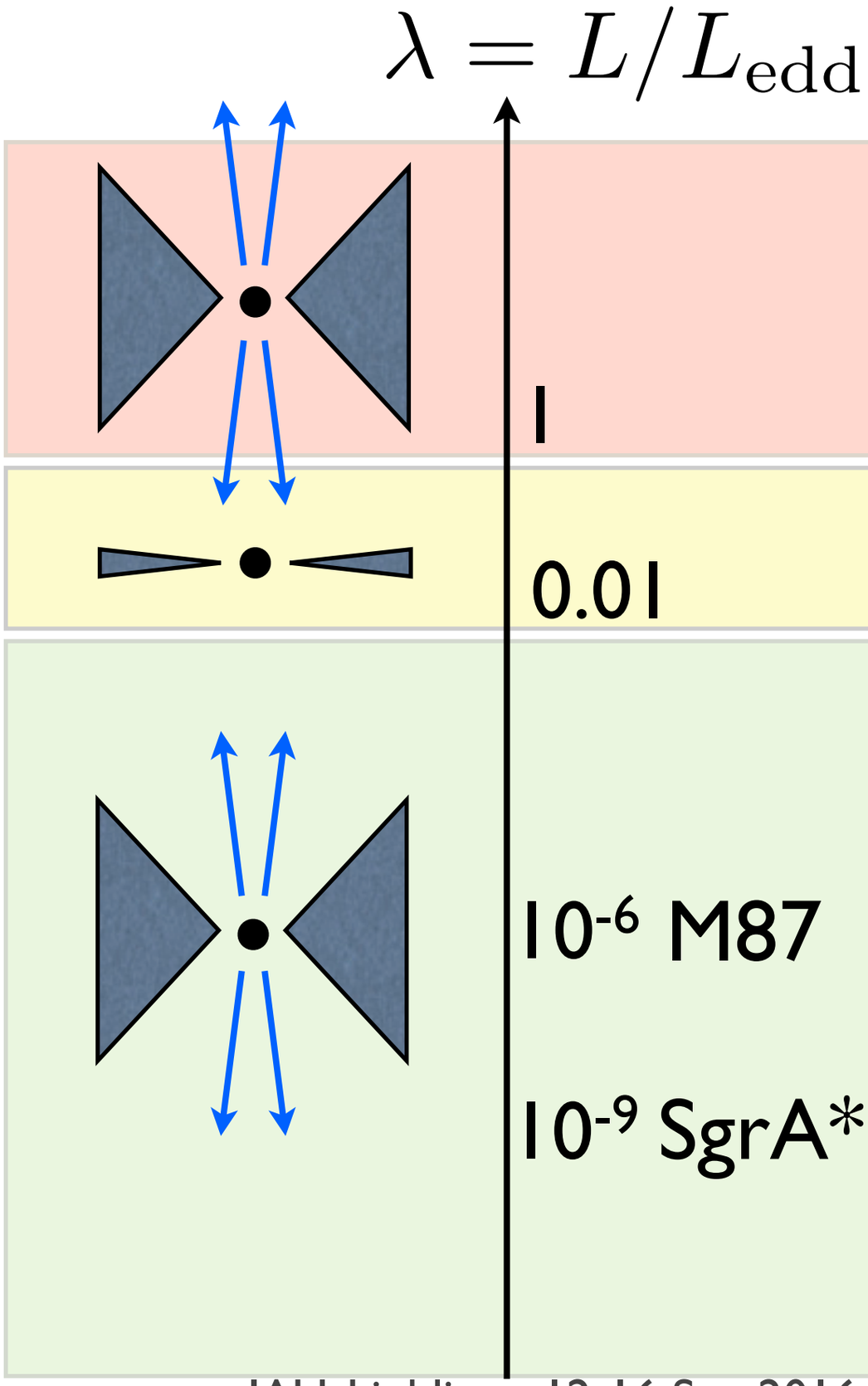
Black Hole Accretion States

Dynamically important magnetic fields:

(AT+13, AT & Giannios 15) Tidal disruptions (TDEs), ultra-luminous X-ray sources, gamma-ray bursts

(Zamaninasab ++AT 14, Ghisellini+14) Blazars, X-ray binaries, TDEs

(Nemmen & AT 14) Low-luminosity active galactic nuclei (LLAGN), X-ray binaries



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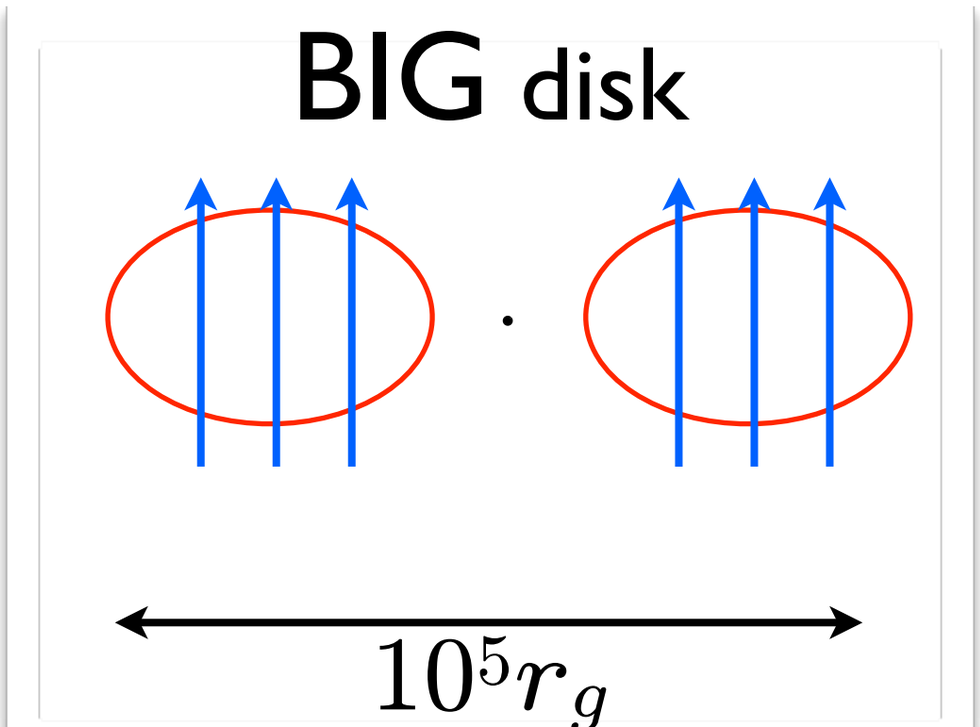

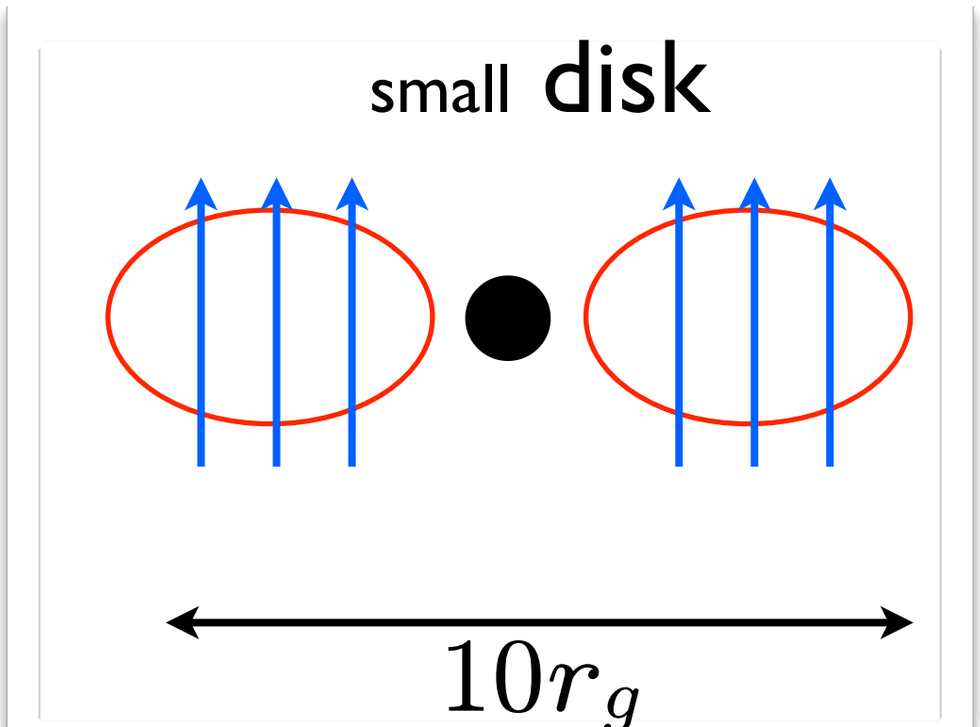

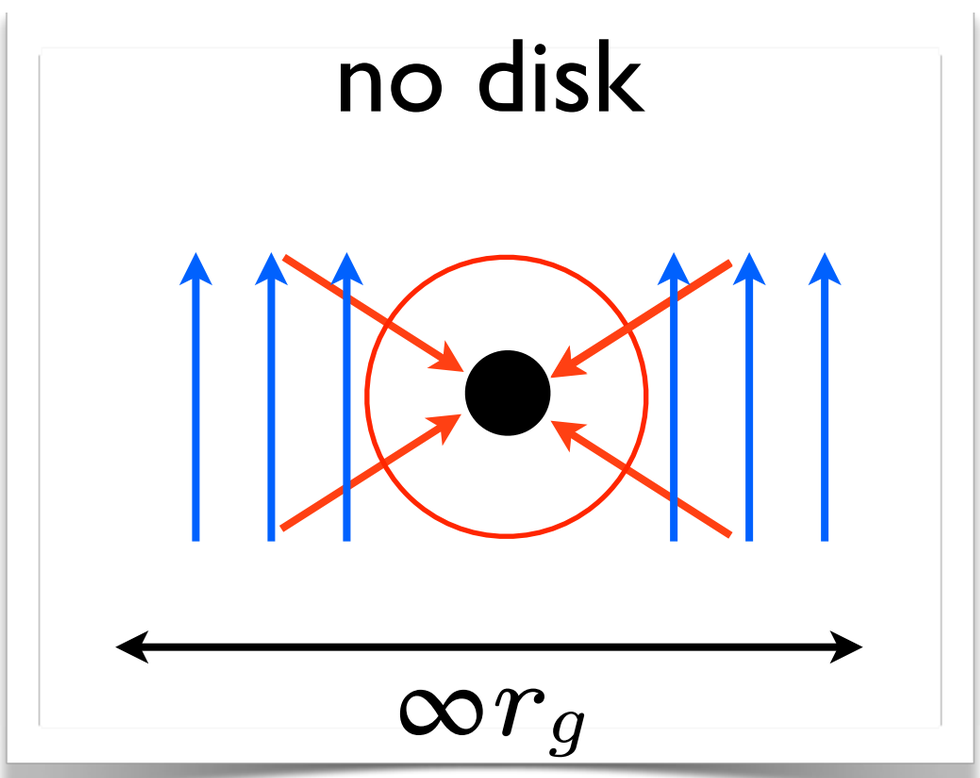

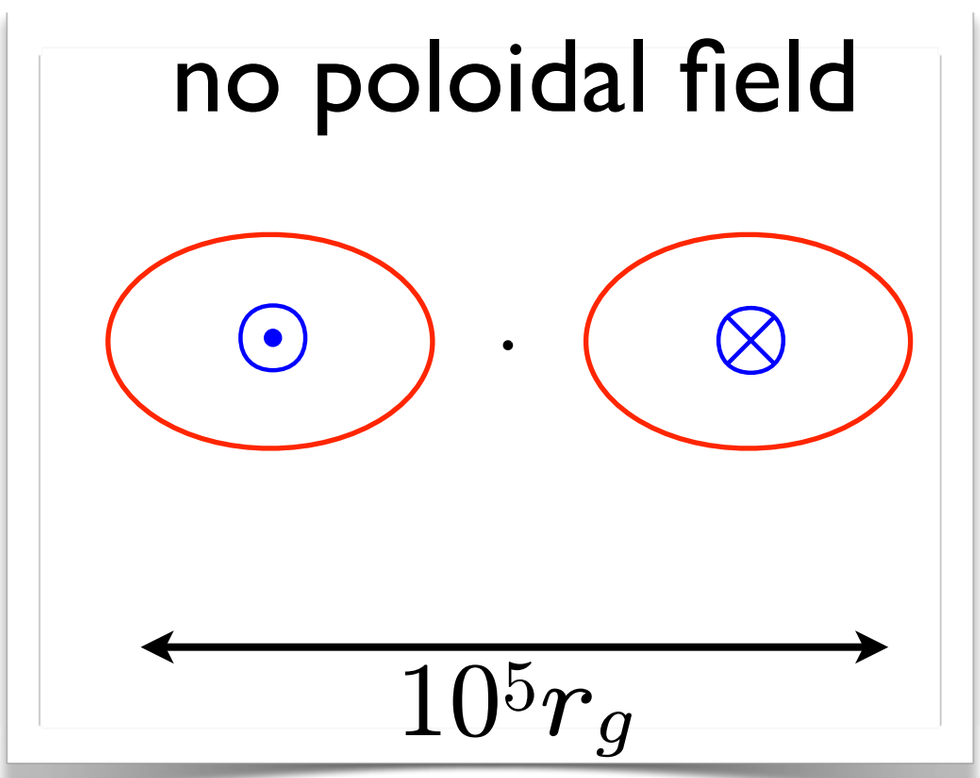

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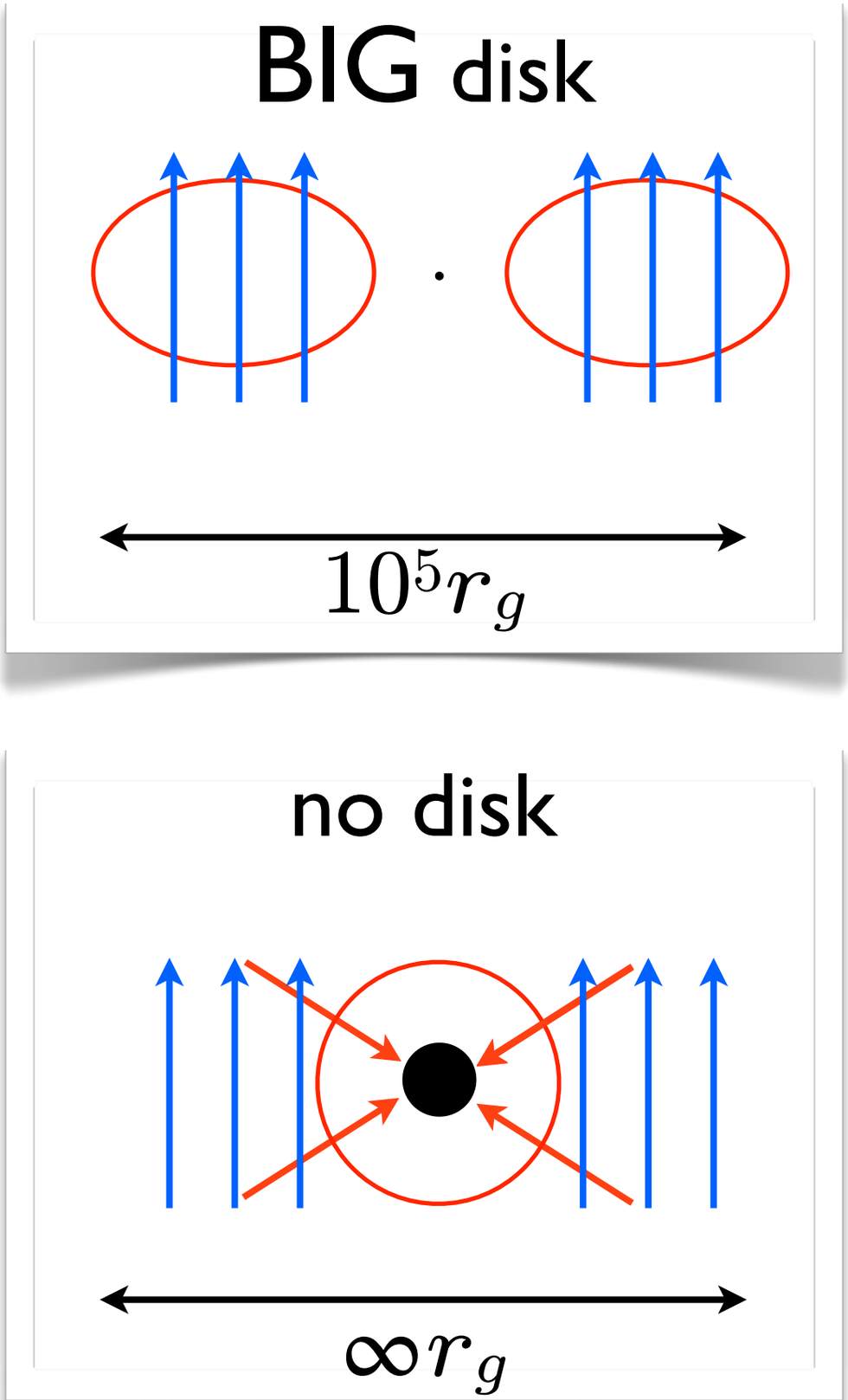

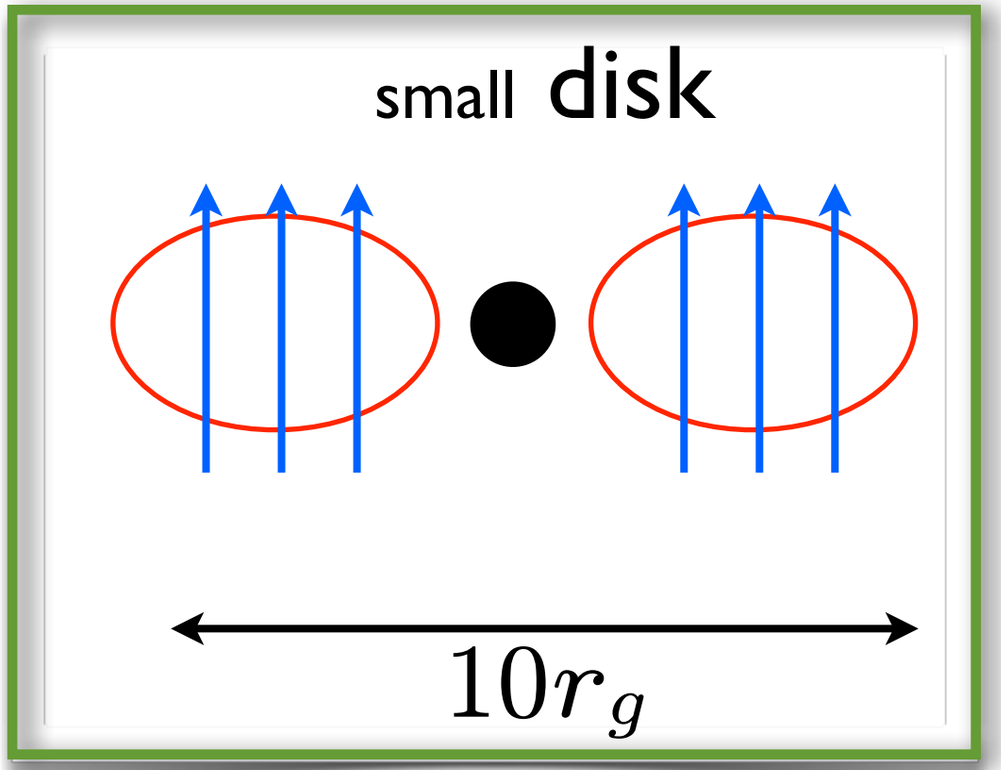

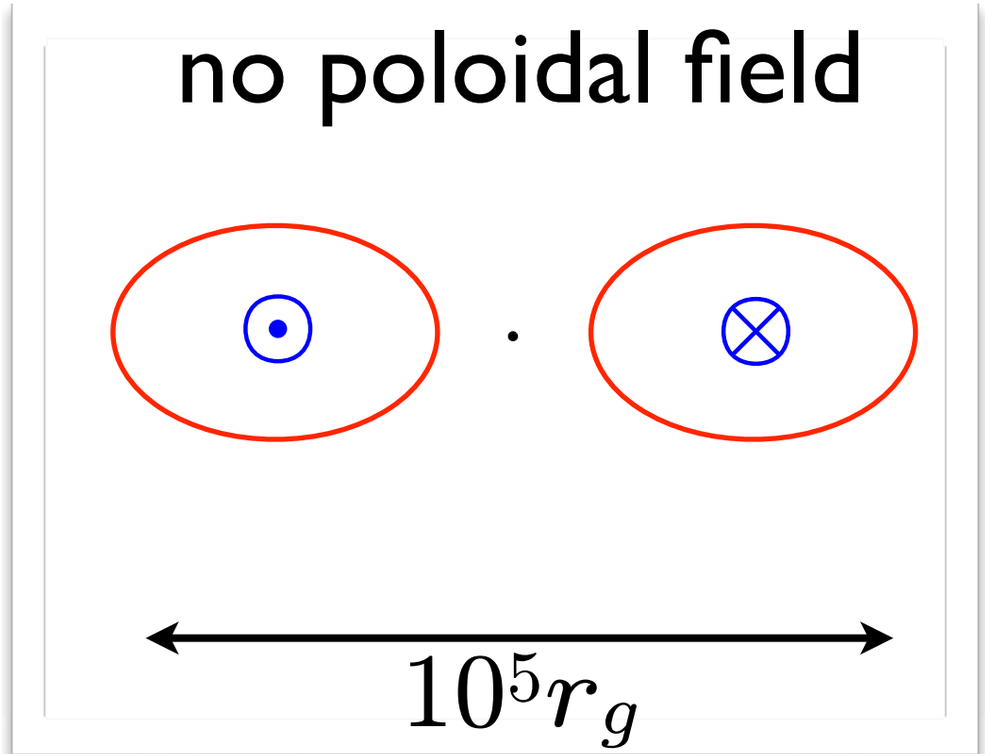

Binary Merger Disks Gone MAD

(AT, Fernandez, Foucart+, in prep)

$$M_{\rm BH} = 3\ M_{\rm sun}$$
$$M_{\rm disk} = 0.03\ M_{\rm sun}$$
$$a = 0.8$$
$$B_p = 10^{15}\ G$$

skip

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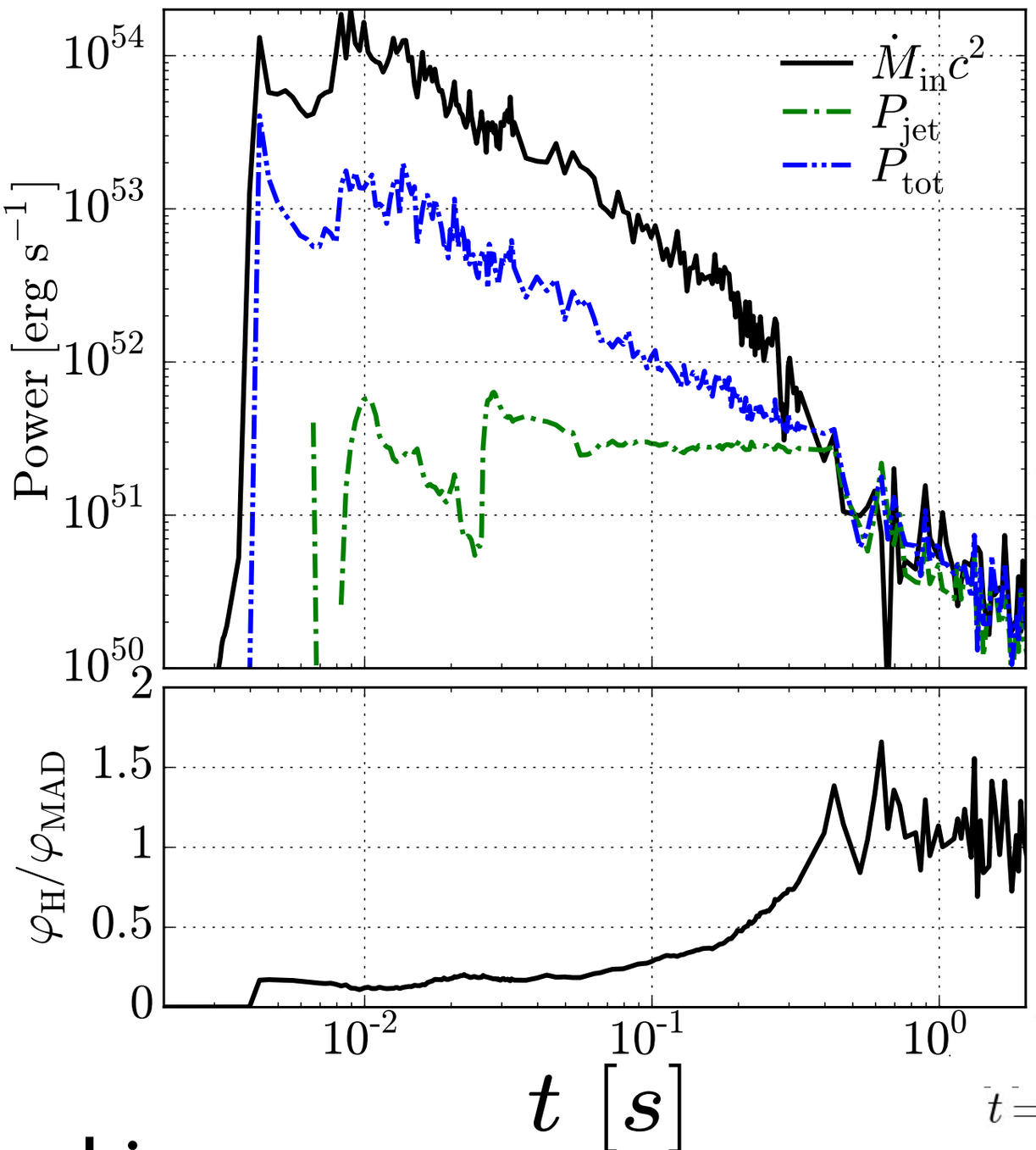

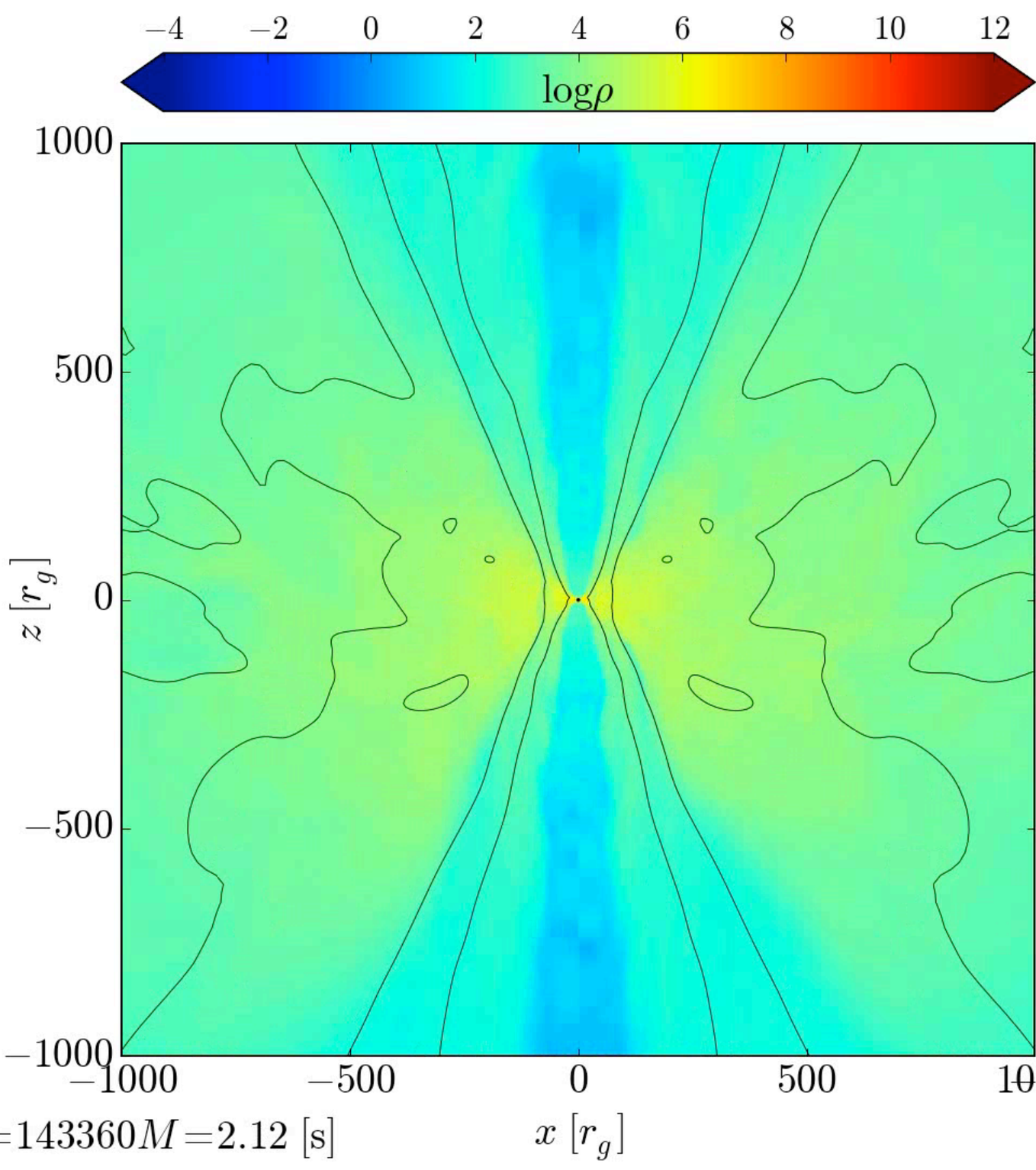

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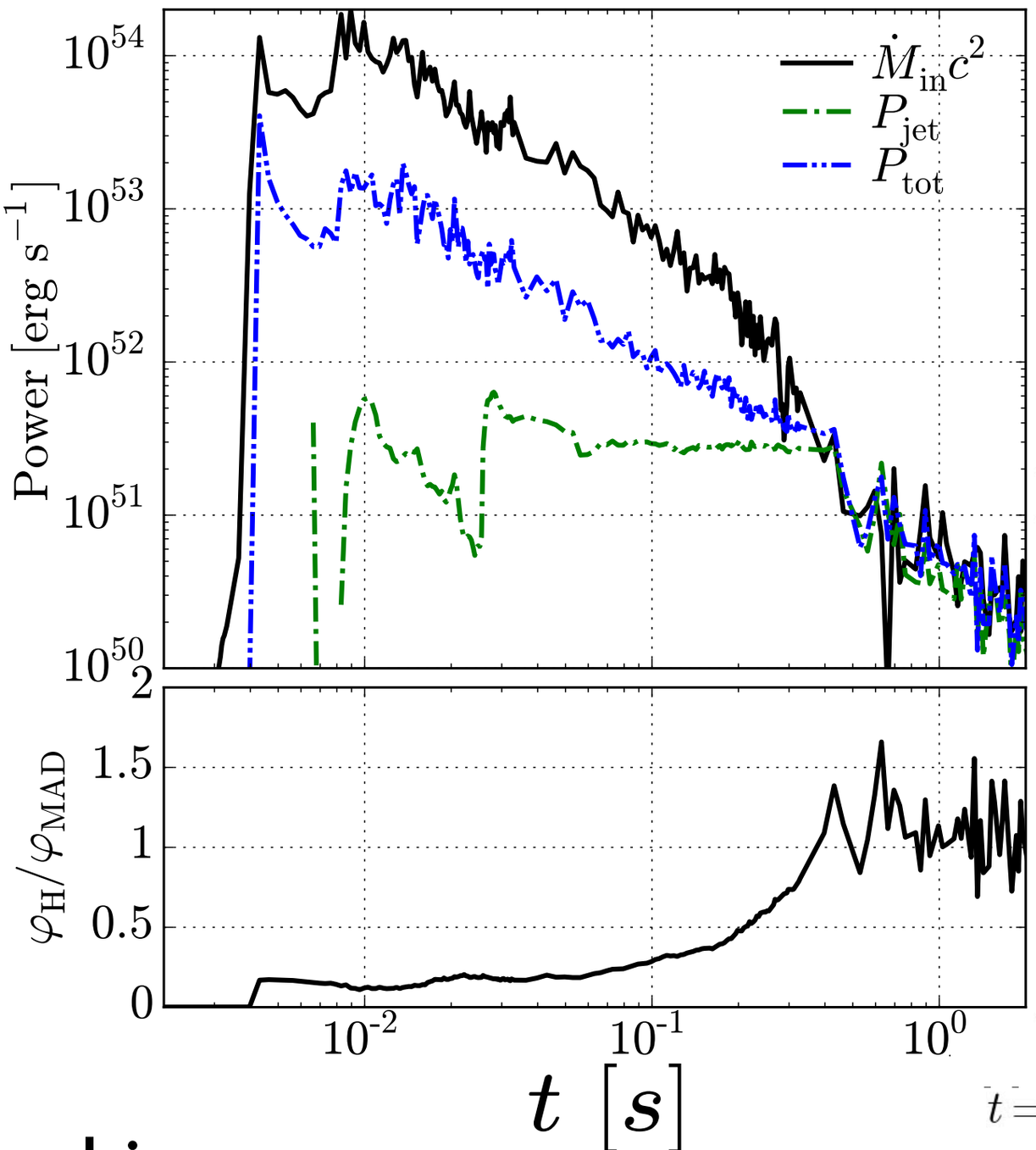

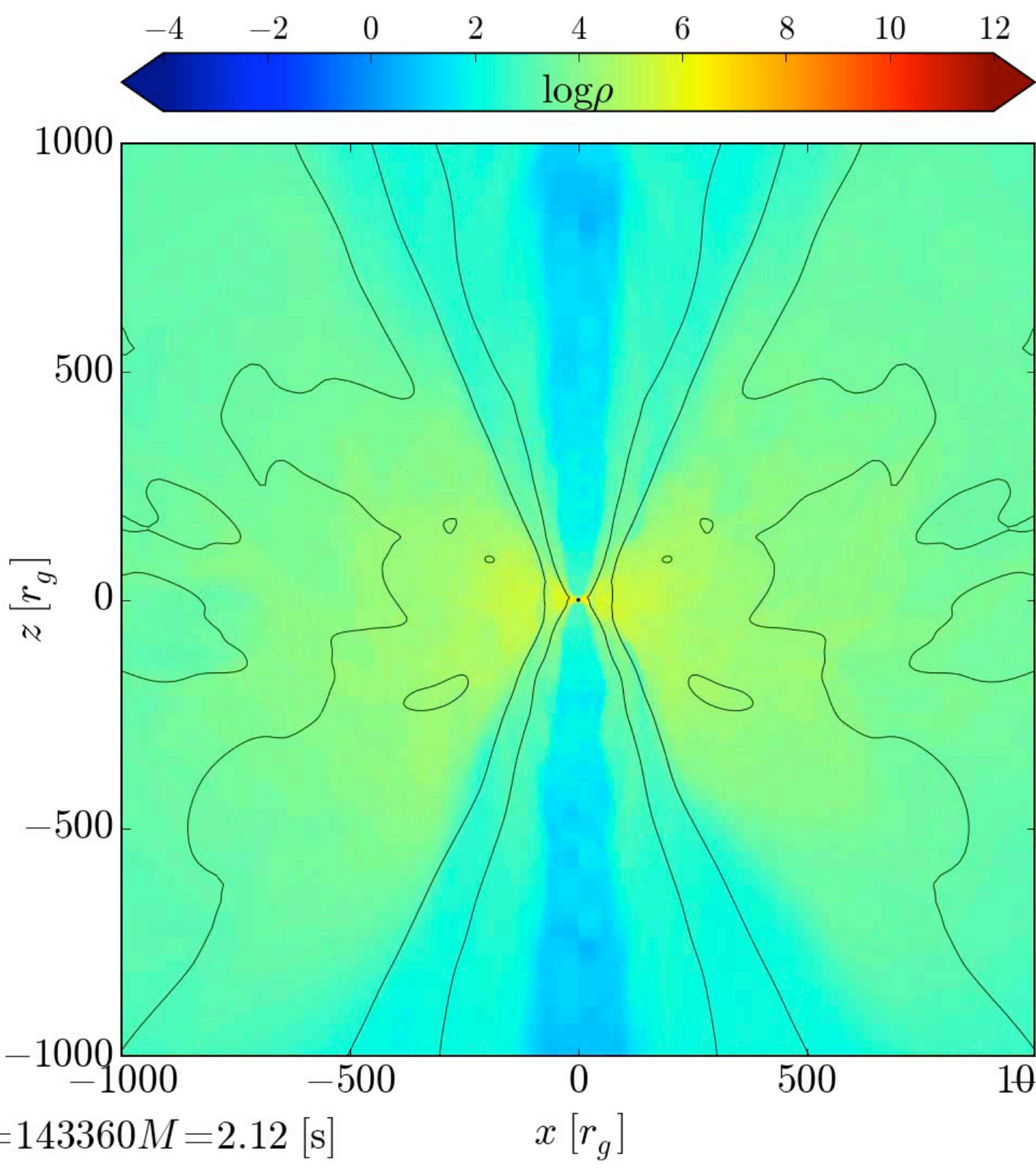

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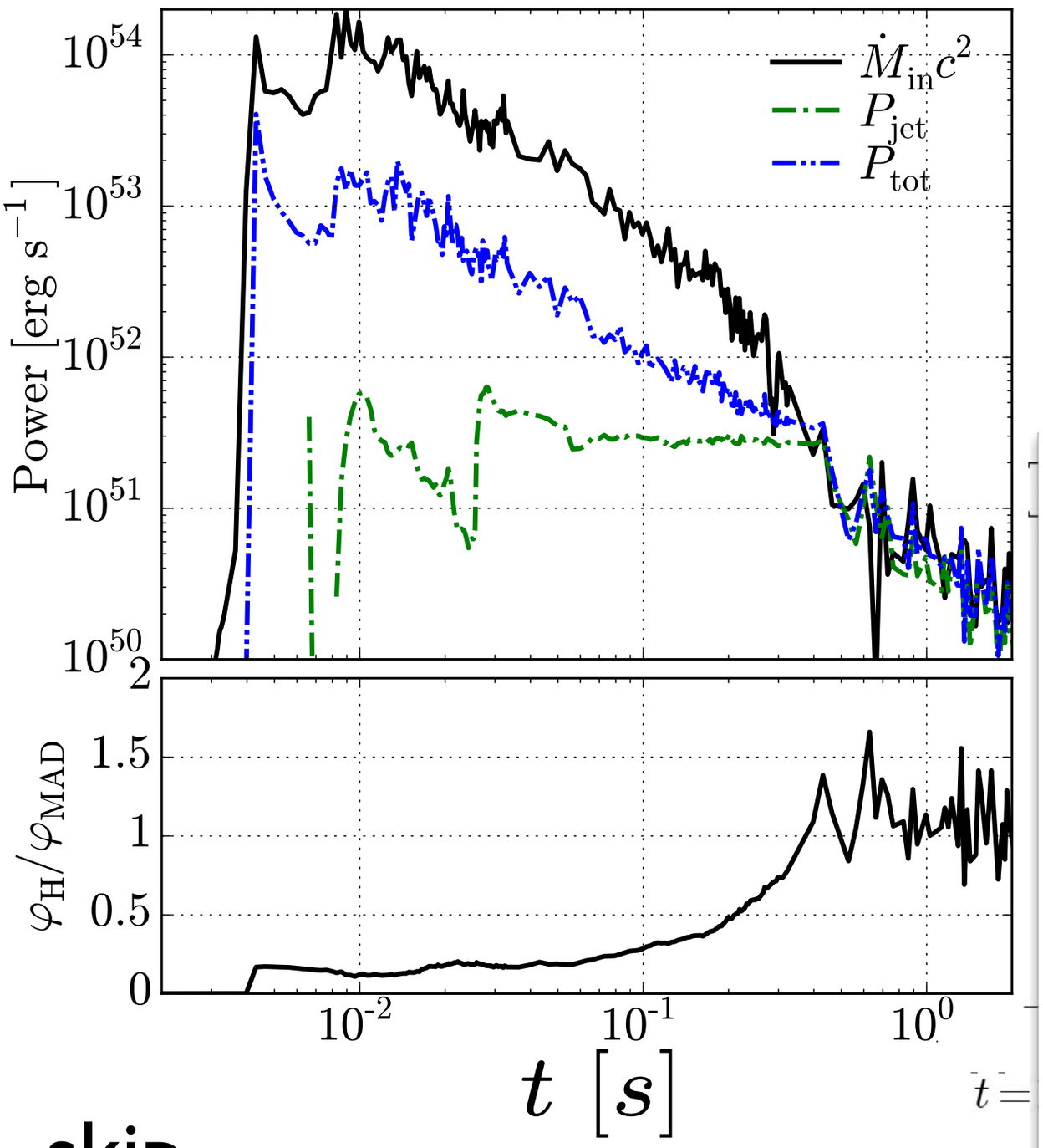
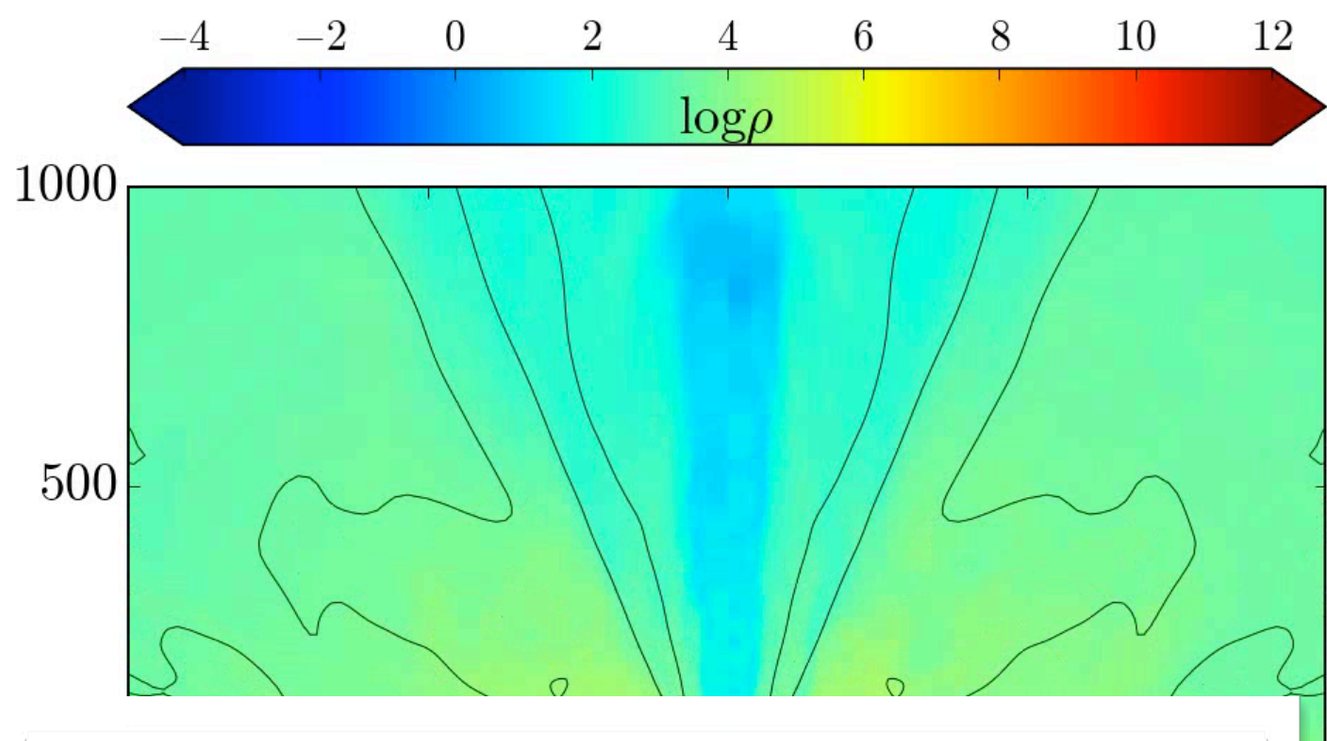


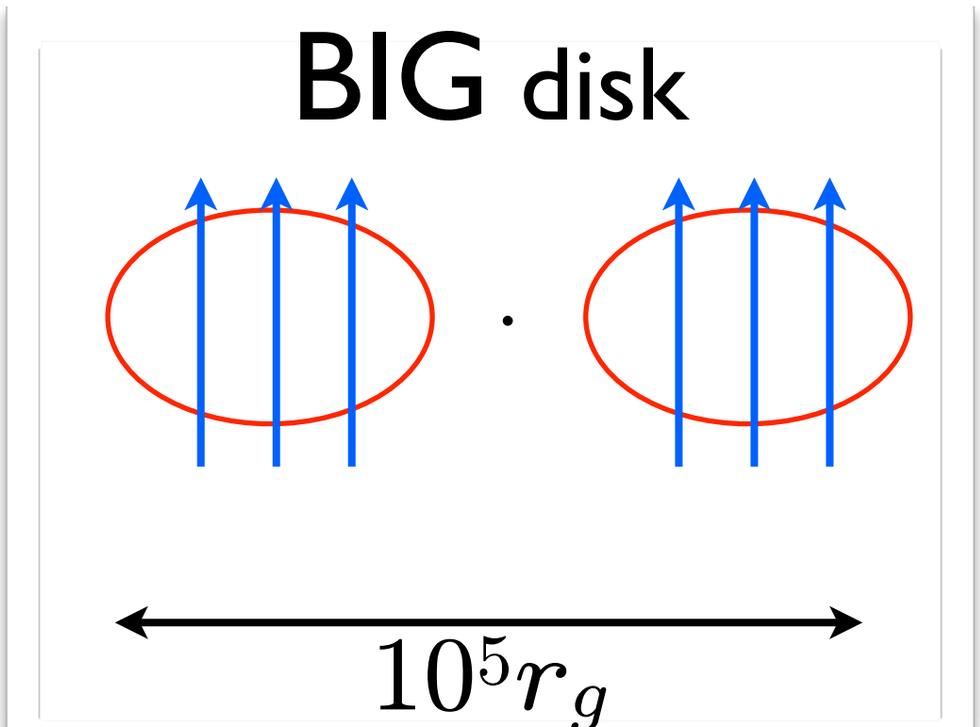


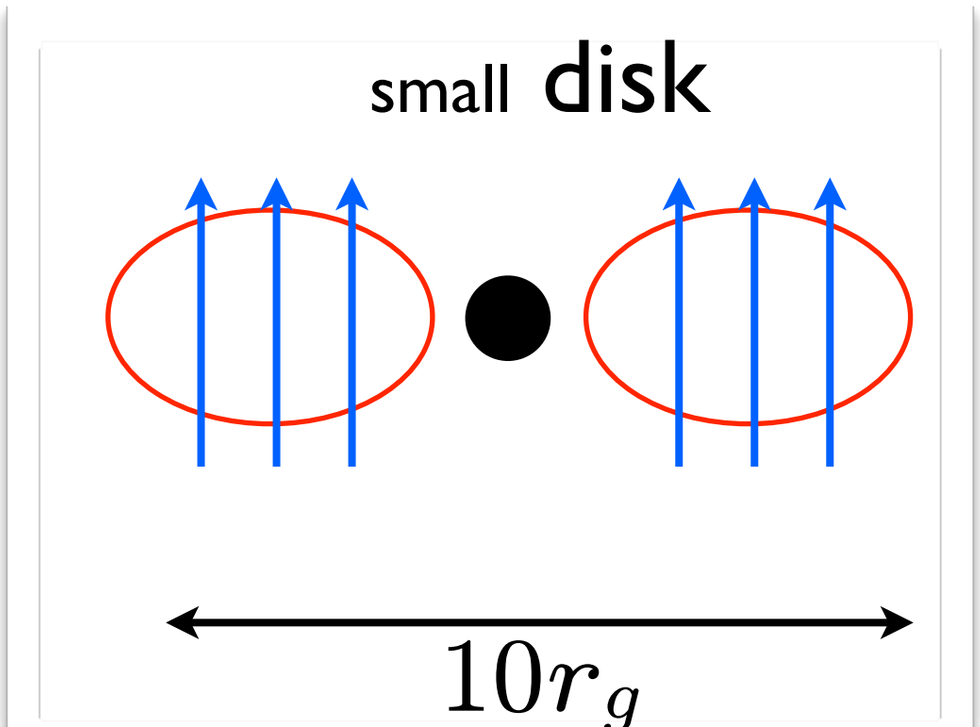
Jet power shows no trends before abruptly switching off at MAD onset (TDEs: AT+2014, GRBs: AT & Giannios 2015)

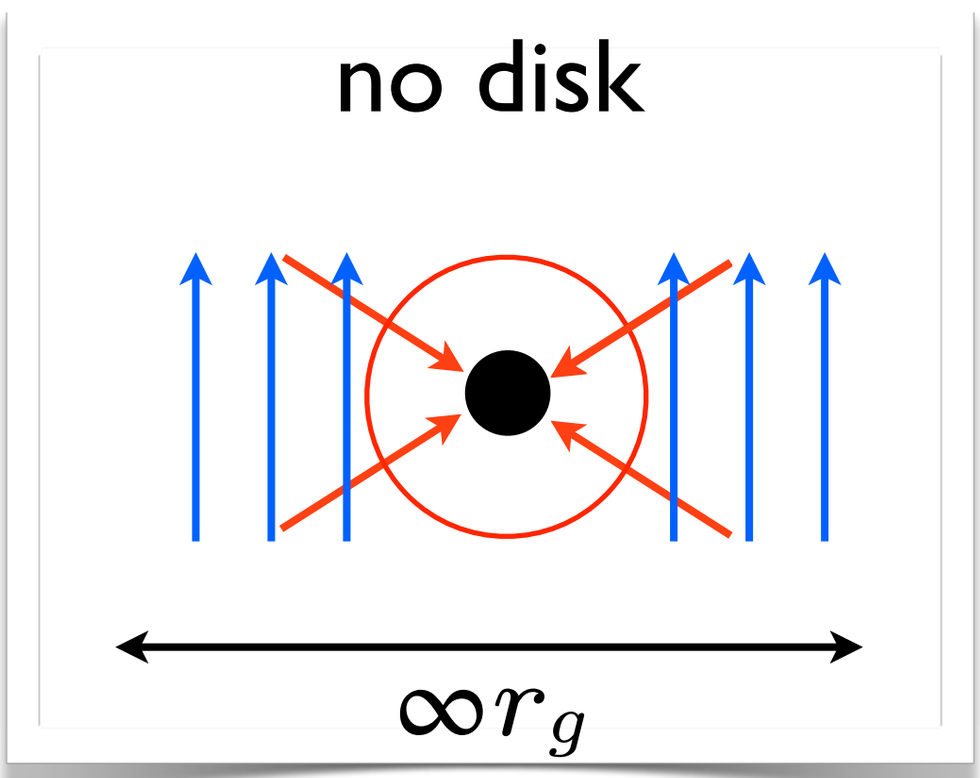
Jet opening angle ~ 0.2 rad agrees with observations (Fong+2015)

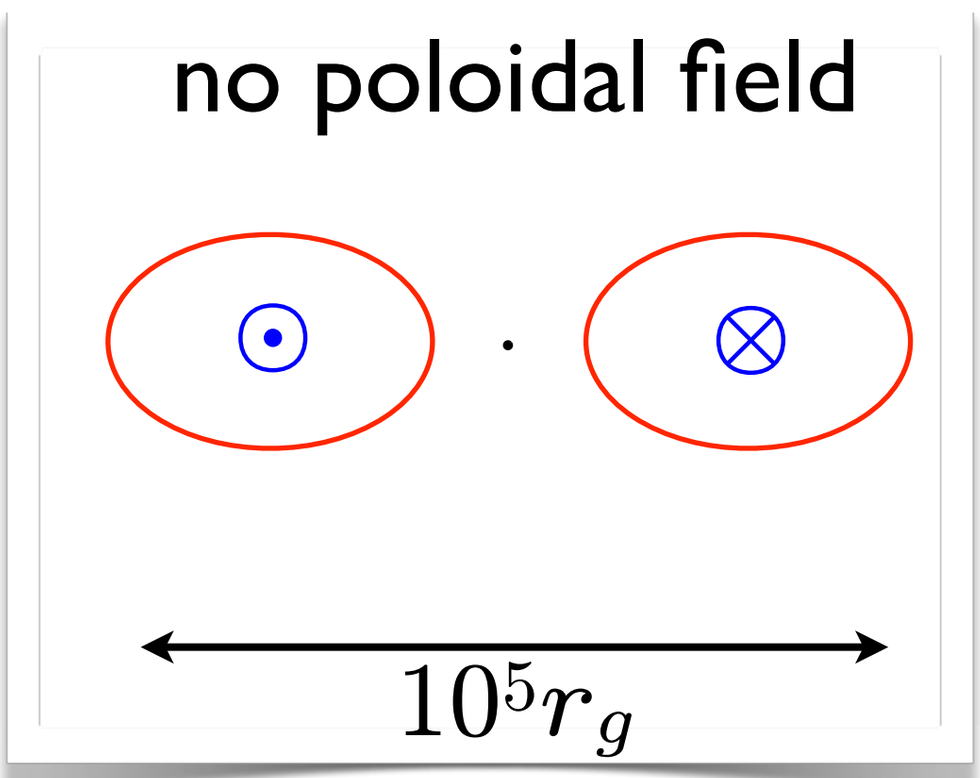
skip

What is a Healthy Jet Diet?









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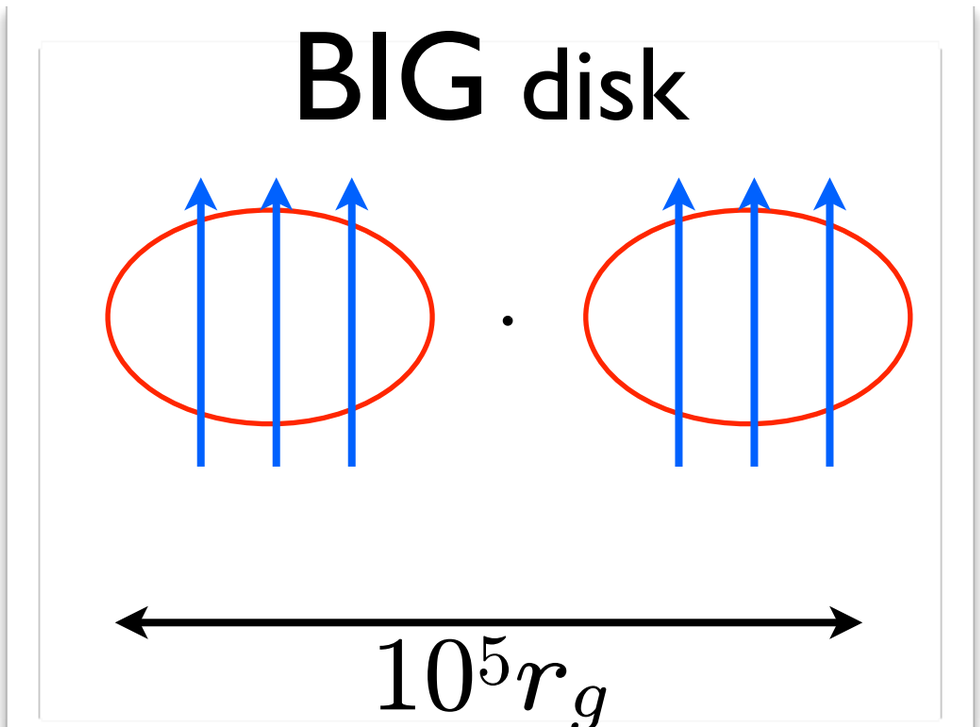
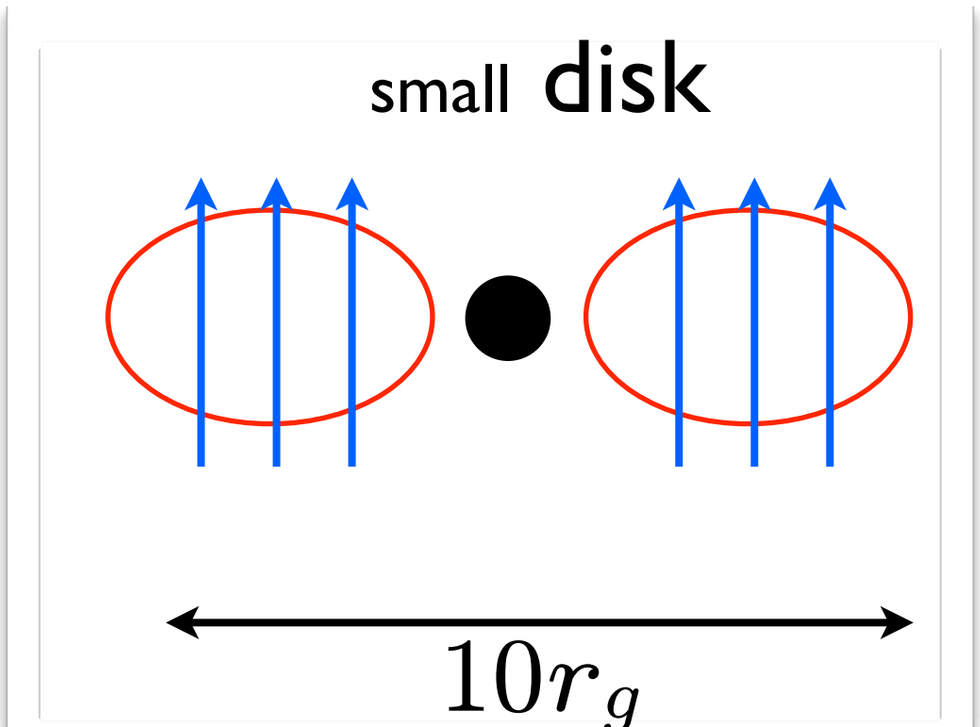
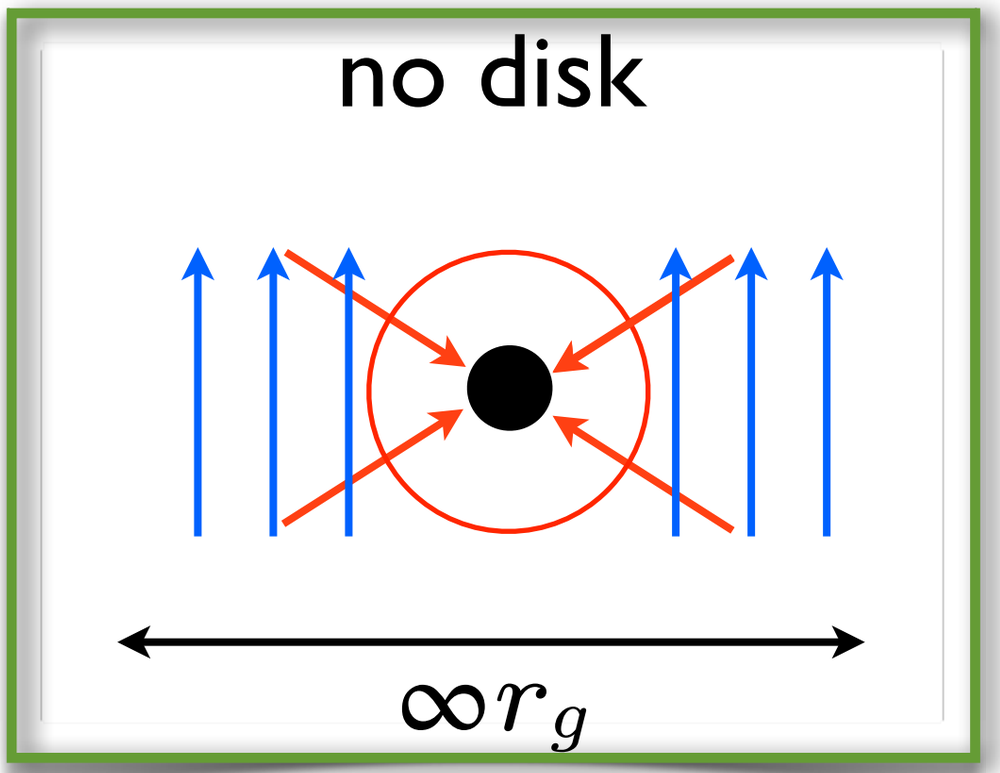
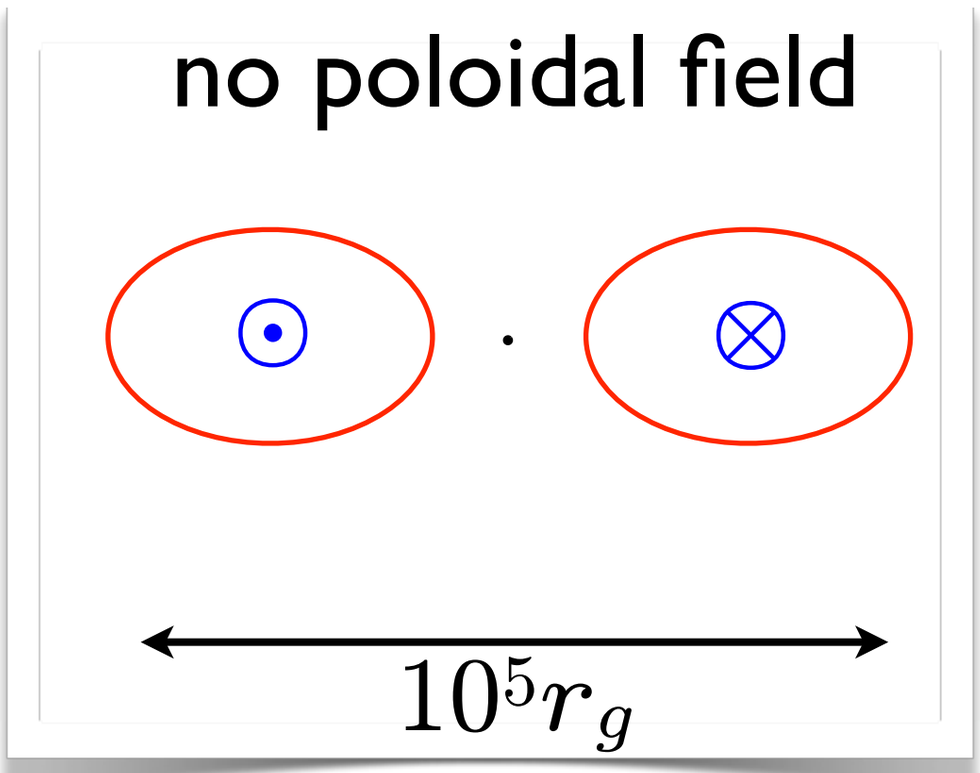






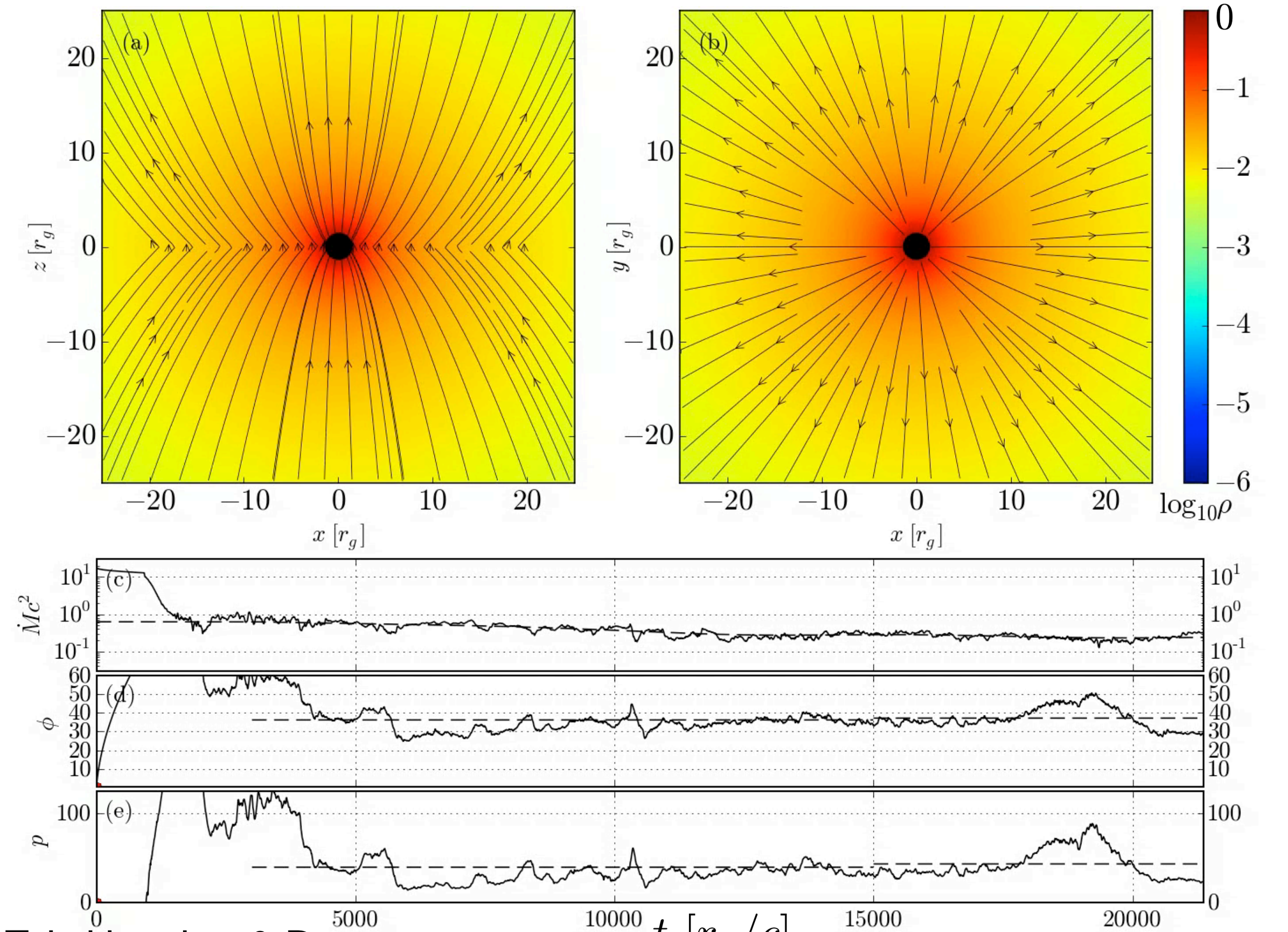


0

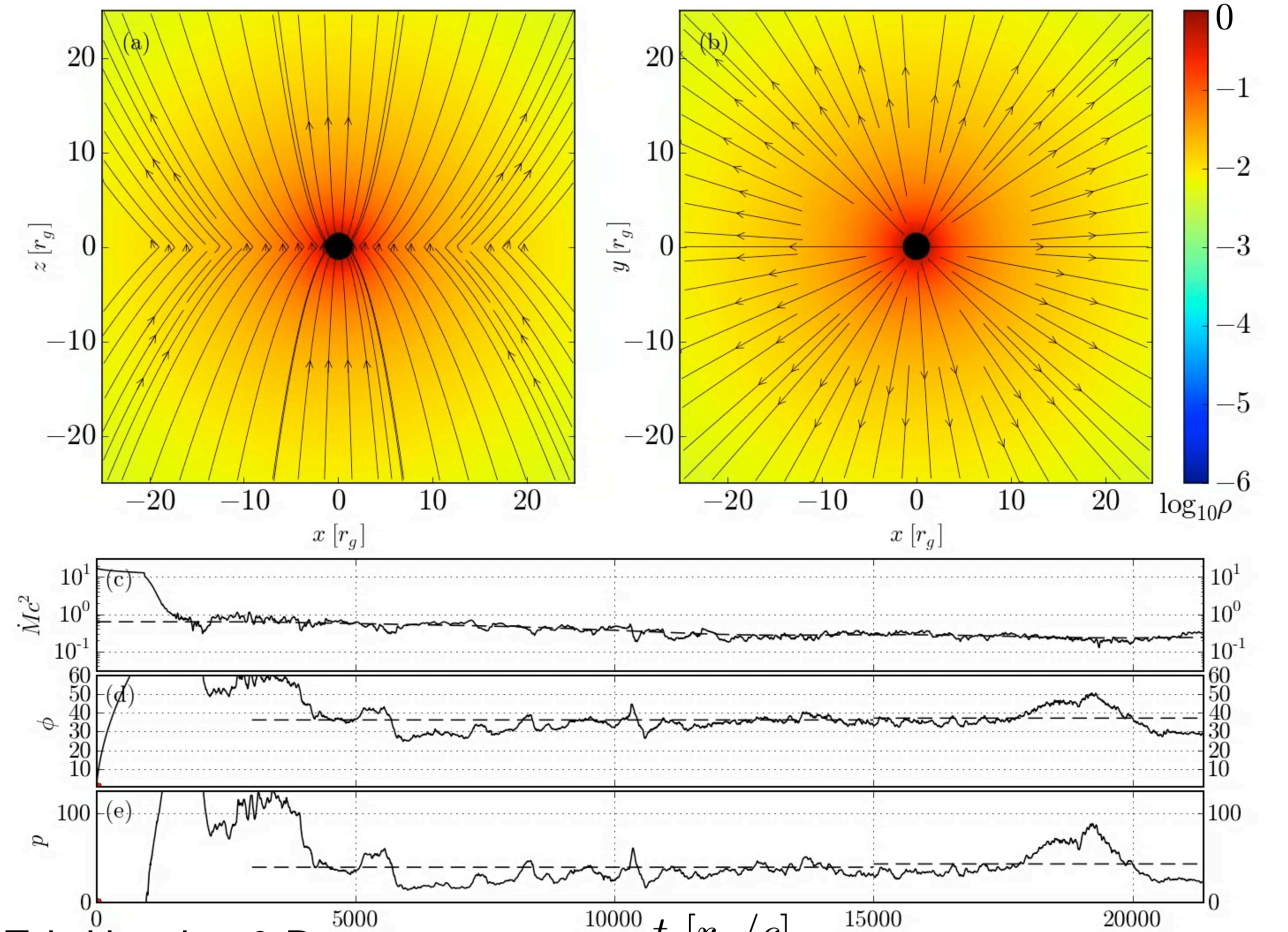
$a = 0.9$
spherical accretion
no rotation

Tchekhovskoy & Dai, in prep

$t\ [r_g/c]$



Tchekhovskoy & Dai, in prep



Tchekhovskoy & Dai, in prep

Without rotation, magnetic flux easily escapes from the black hole: no MAD

Tchekhovskoy & Dai, in prep

0

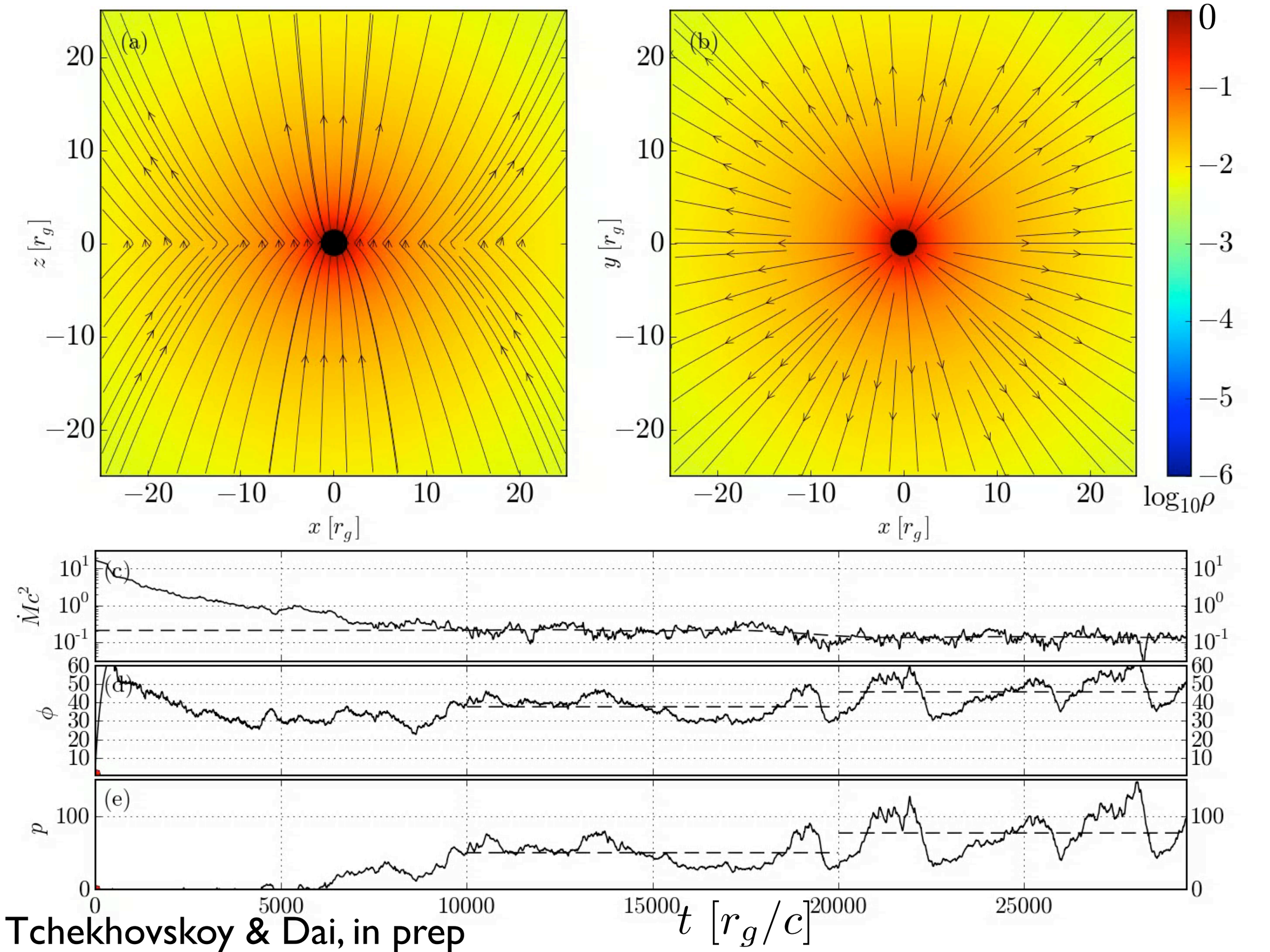
$a = 0.9$

spherical accretion

rotation: $R_{\rm circ} = 50 r_g$

Tchekhovskoy & Dai, in prep

$t\ [r_g/c]$



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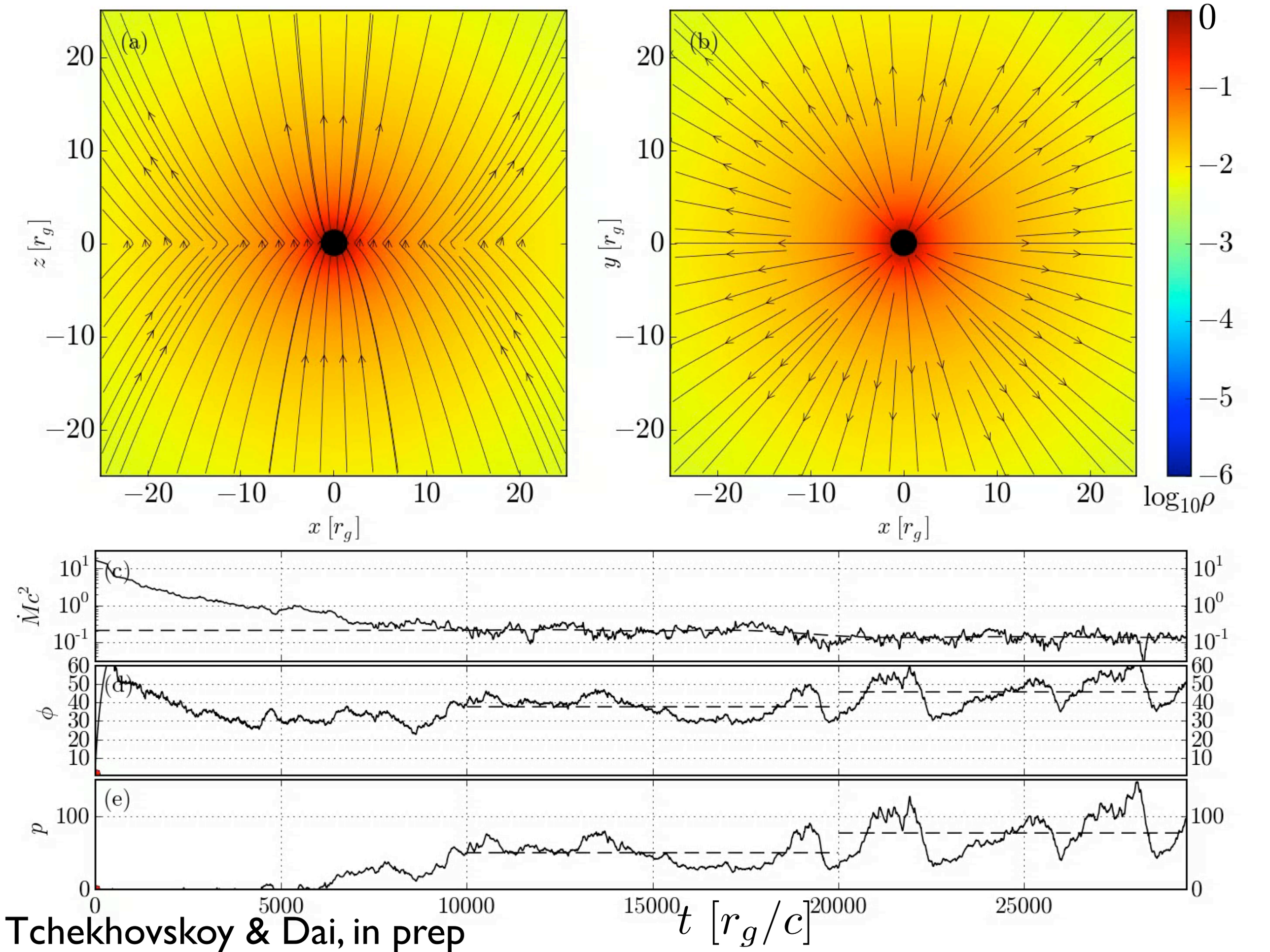


Tchekhovskoy & Dai, in prep

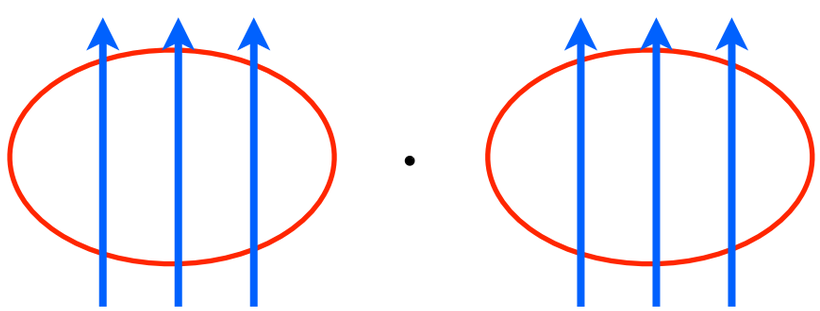
With rotation, magnetic flux bundles get recycled: sheared out and mixed back into disk: MAD

Can low disk ang. mom. suppress jets in TDEs and at the Galactic Centre?

Tchekhovskoy & Dai, in prep

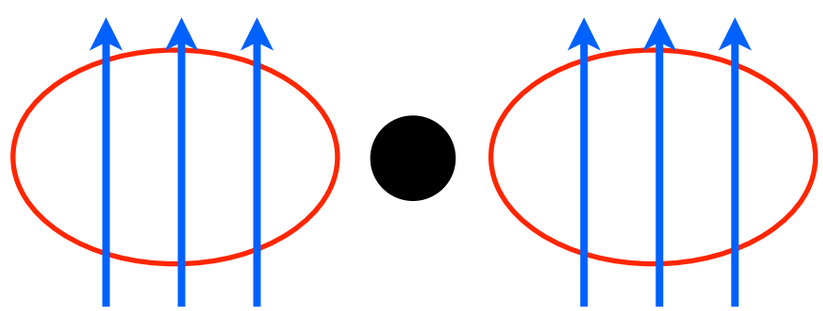
What is a Healthy Jet Diet?

BIG disk



$10^5 r_g$

small disk



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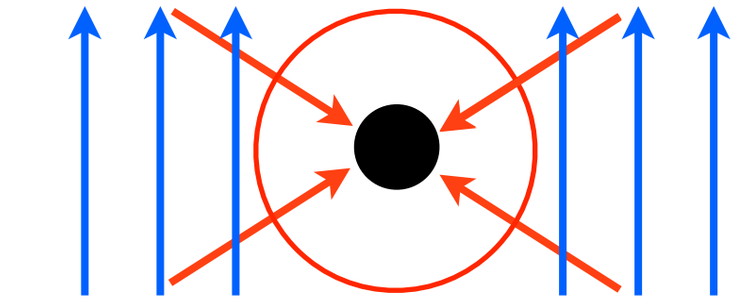
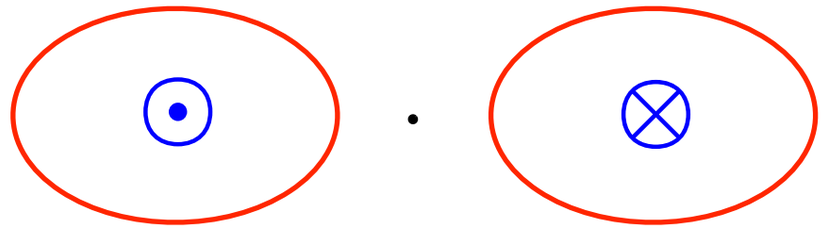


∞r_g

no poloidal field



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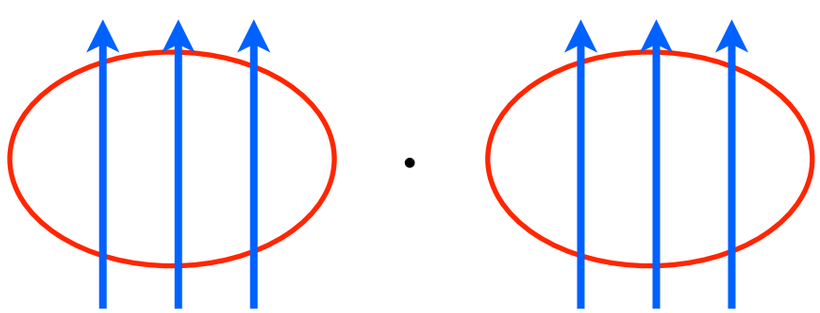

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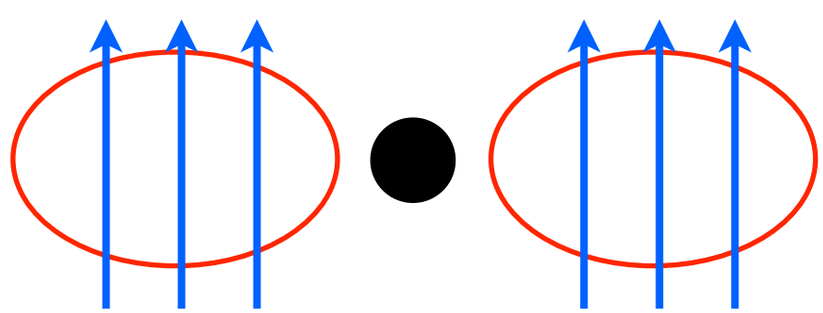

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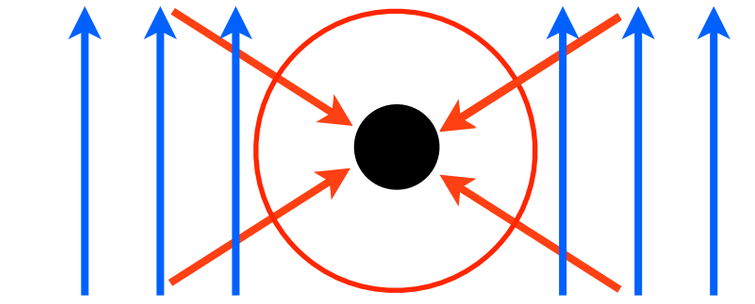

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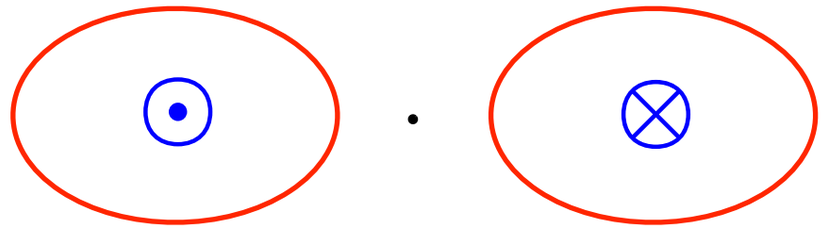

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Can Toroidal Fields Make Jets?

- Unlikely: healthy jets need poloidal field (e.g., Beckwith, Hawley, Krolik+08, McKinney, AT, Blandford '12)

- Possible mechanism for jets without $B_{\rm p}$?
  - Large-scale α-ω dynamo
    (Moffatt '78; Parker '79)
  - BUT: not seen in global simulations

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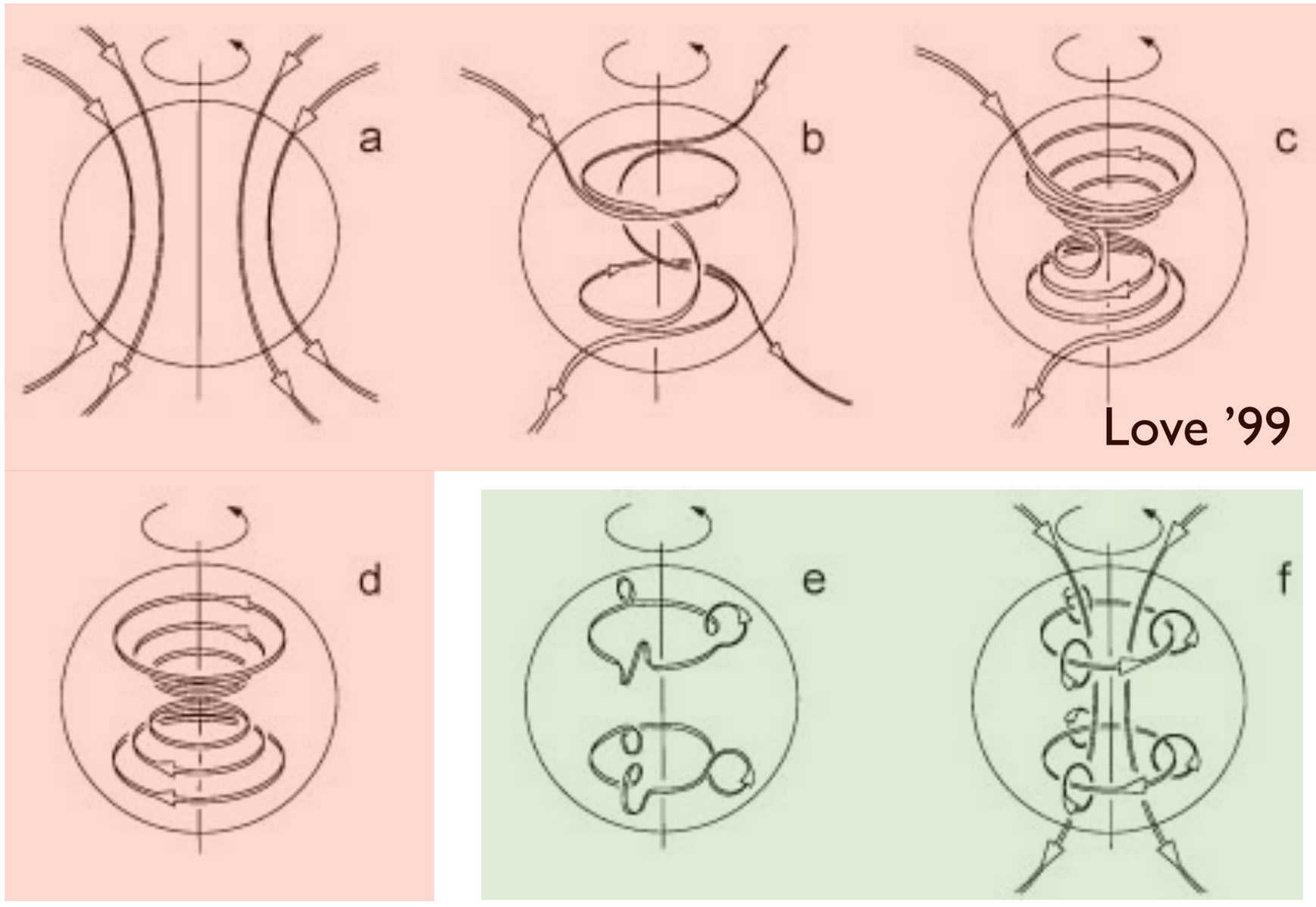
α-ω dynamo:



Love '99

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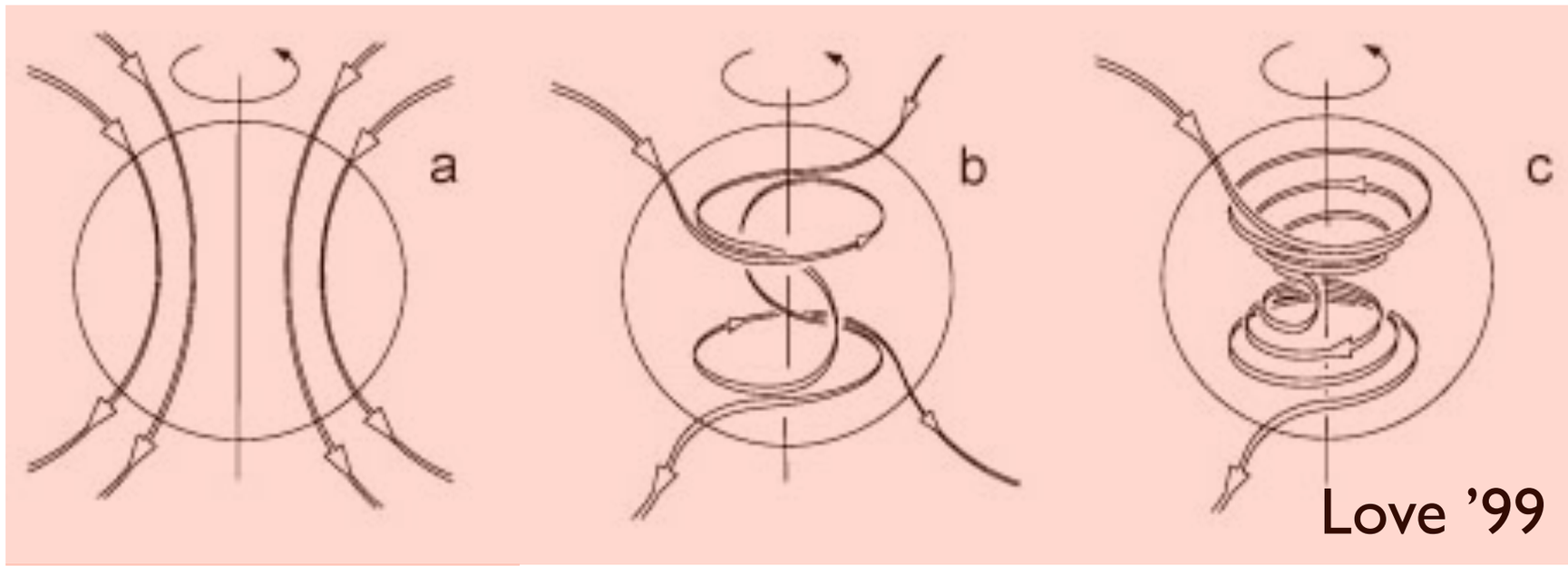


Love '99

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times [(\vec{\omega} \times \vec{r}) \times \vec{B} + \alpha \vec{B}]$$

Moffatt '78

Quataert, in prep.

Tchekhovskoy &

$a = 0.9$
toroidal field, $\beta = 5$
large torus

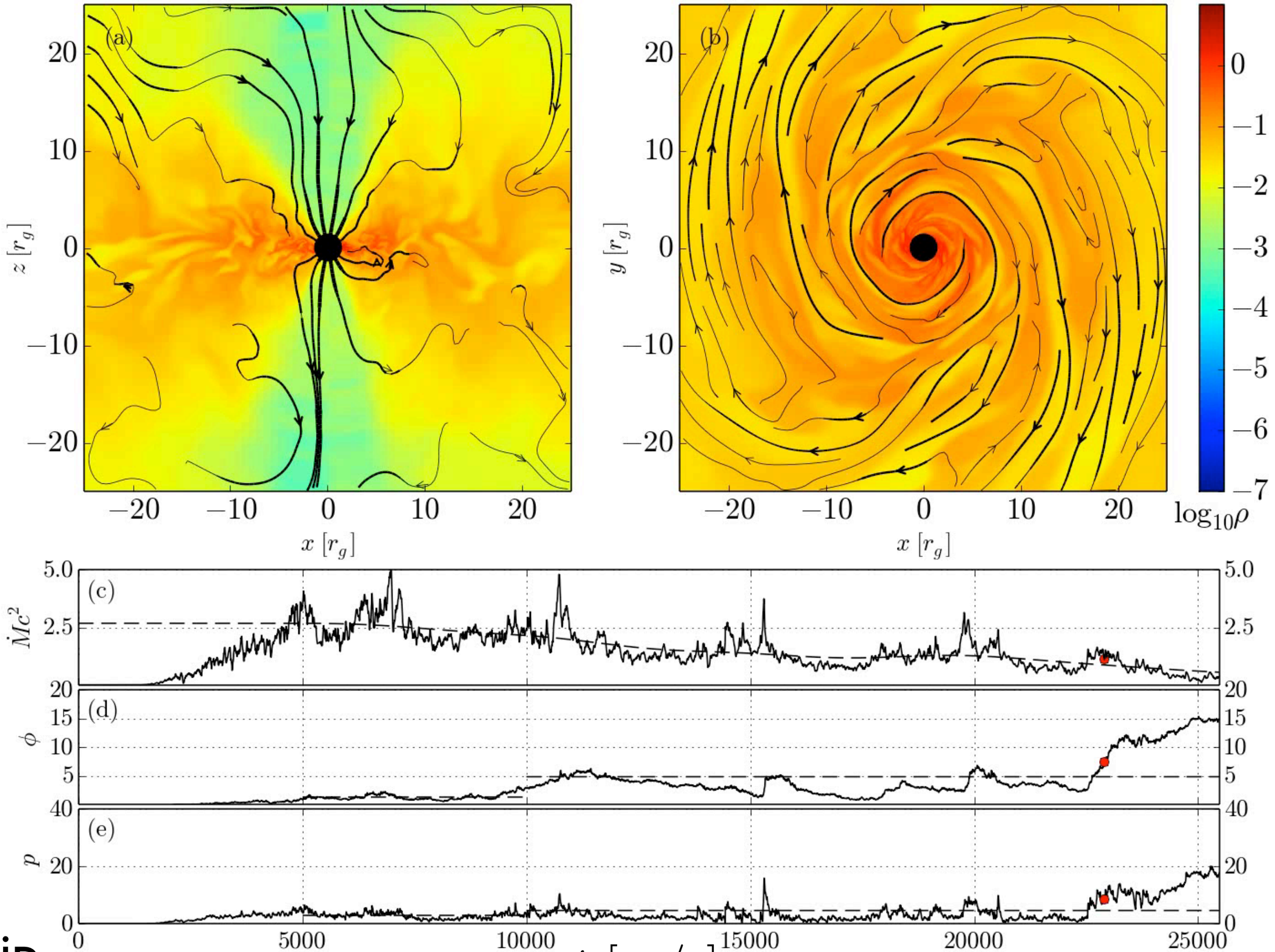
skip

$t\ [r_g/c]$

Quataert, in prep.

Tchekhovskoy &

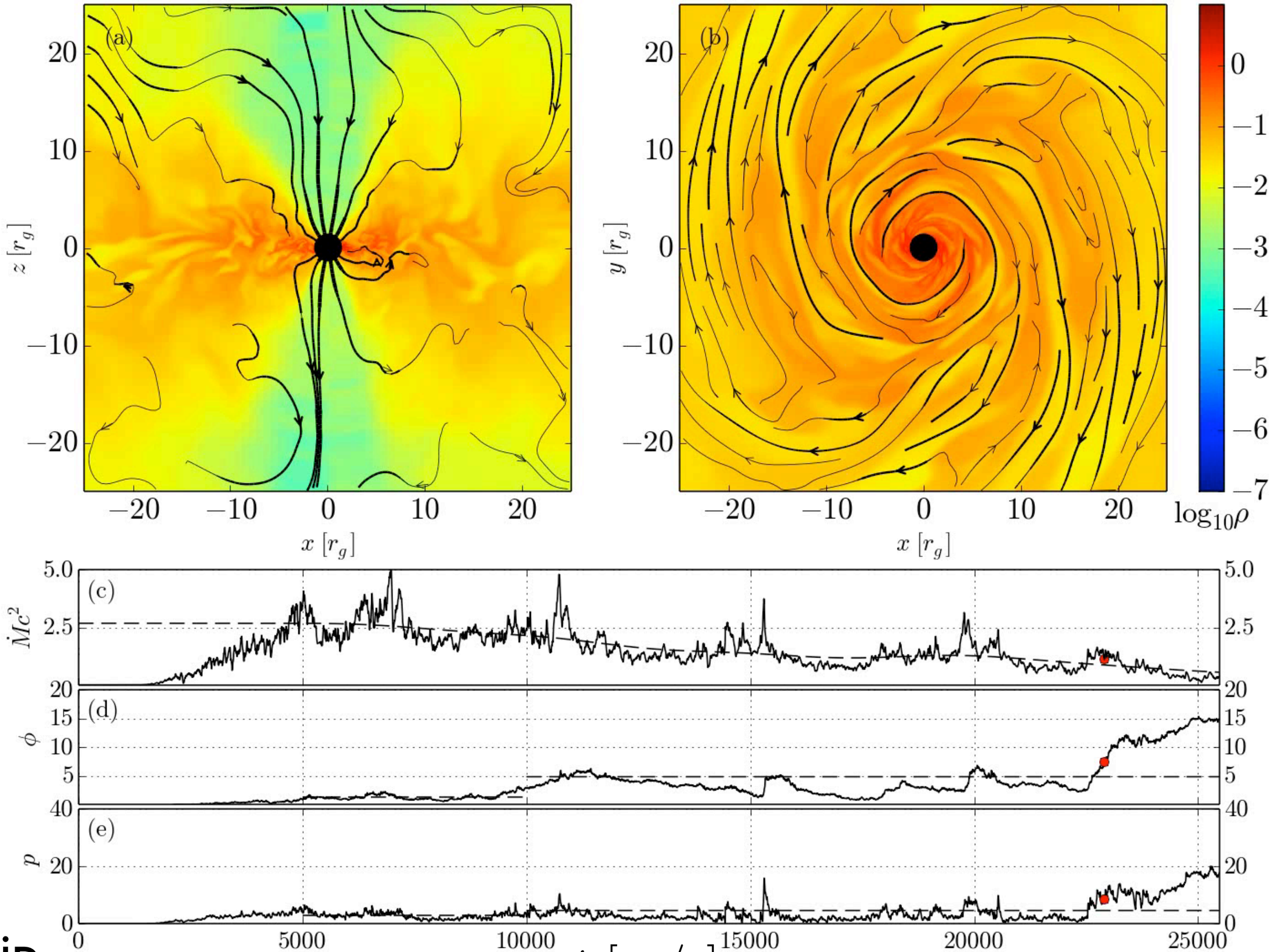
skip



Quataert, in prep.

Tchekhovskoy &

skip



Tchekhovskoy & Quataert, in prep.

Large-scale toroidal magnetic field sufficient for healthy jets.

Dynamo -> field polarity flips -> jet dissipation?

Is weaker/small-scale turbulent field sufficient to make jets?

skip

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Toroidal field simulations extremely expensive. How can we make them accessible?

skip

GPUs Open Entirely New Possibilities

- Graphical Processing Units (GPUs) is a new disruptive technology
  - cutting edge of modern supercomputing
- Multi-GPU 3D H-AMR ("hammer", Liska, AT+'16):
  - 3D, staggered fields, AMR
  - 100x speedup: 1 GPU = 100 cores
  - Excellent scaling to >= 4096 GPUs.
  - based on an open-source HARM2D
  - new GPU-based systems have 16 GPUs/node:
    - Stanford XStream (production now)
    - ORNL Summit (production in '18)
- Whole slew of important applications:
  - Long-term disk evolution
  - Tilted thin disks
  - Etc.

Matthew Liska
(U of Amsterdam)

skip

What does Jet Morphology Tell Us?

FRI/FRII dichotomy (Fanaroff & Riley, 1974)

Cygnus A galaxy

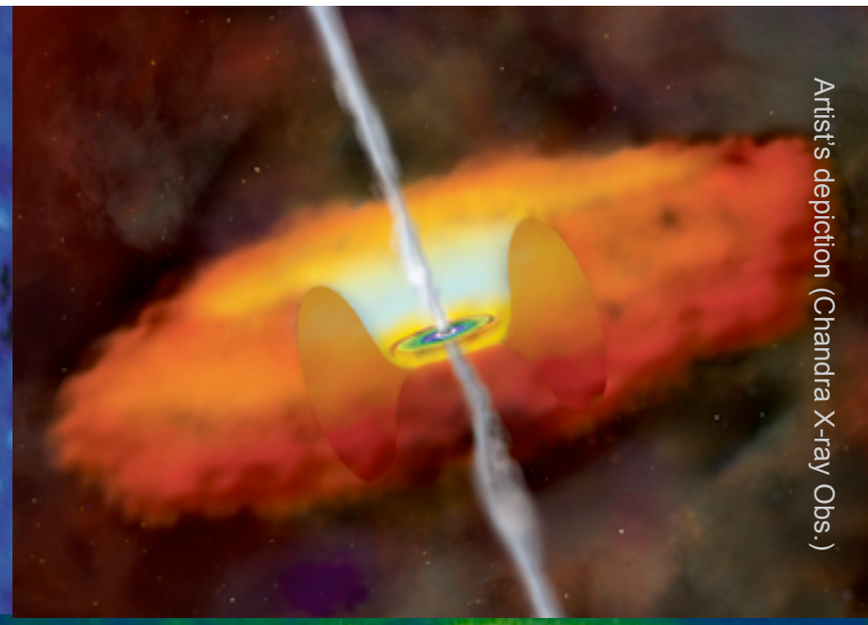
(radio, 6 and 20 cm)

FRII

$P_j = 10^{46}$ erg/s

~10 billion solar mass black hole

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



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

M87 galaxy

(radio, 20 cm)

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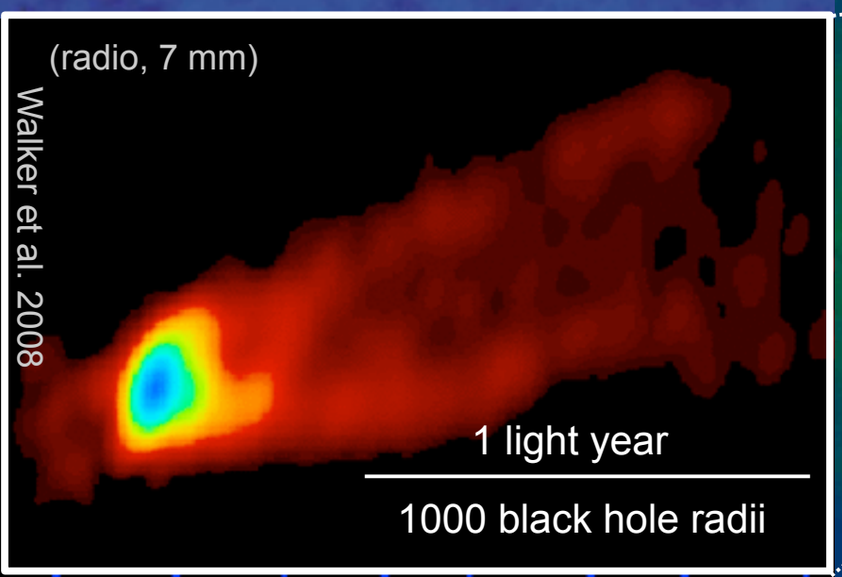
3000 light years

NRAO/AUI and F. Owen



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Why powerful jets make it out of their galaxies...

70 kpc

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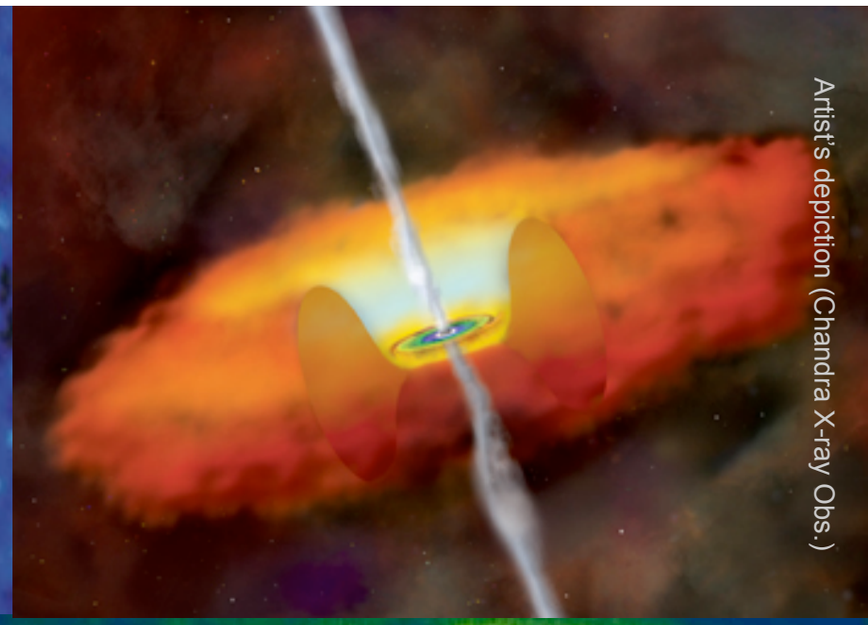

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Walker et al. 2008

1 light year

1000 black hole radii

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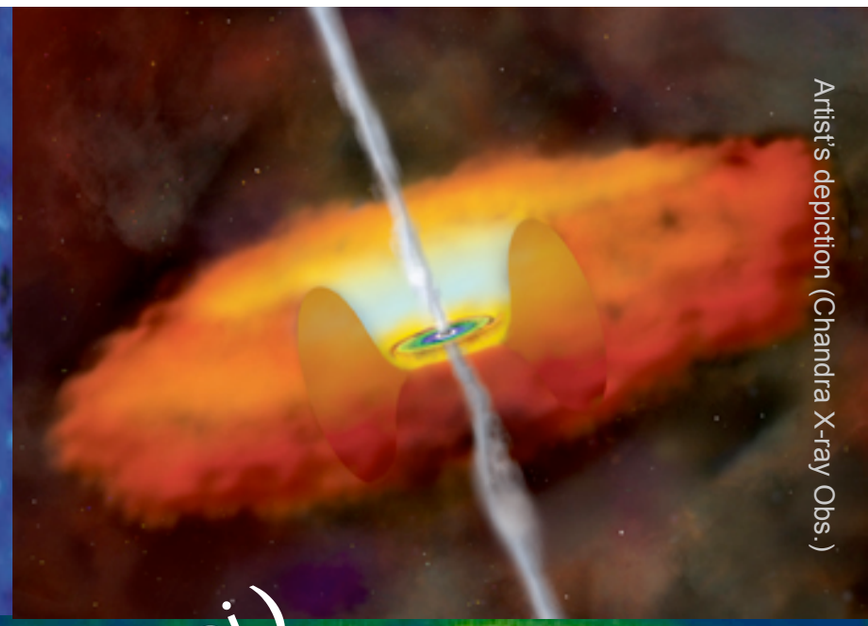

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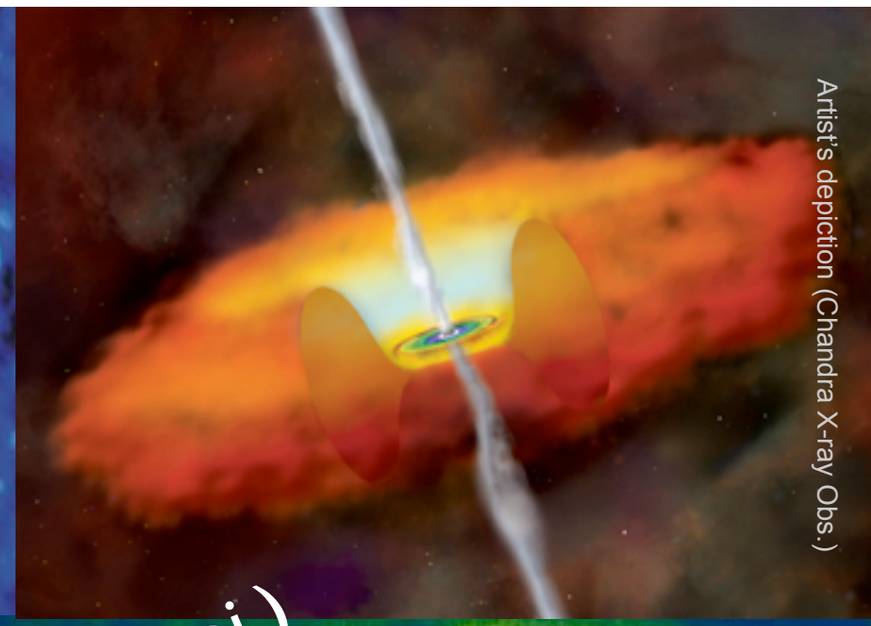

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Magnetic instability?

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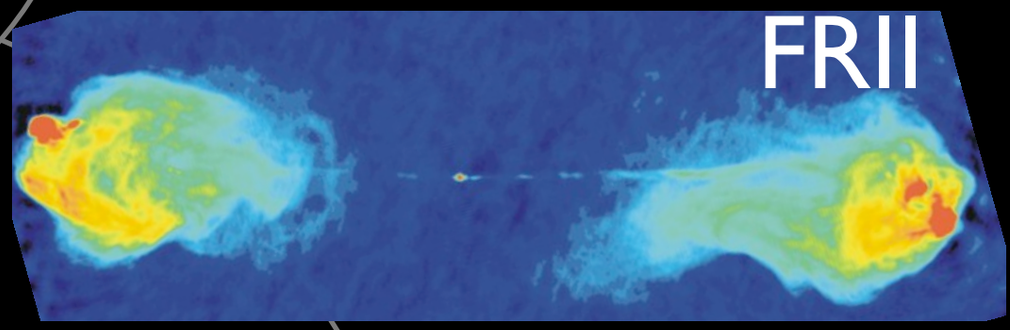
Cyg A-like
$P_j = 10^{46}$ erg s^{-1}
$t = 3$ Myr

10 kpc



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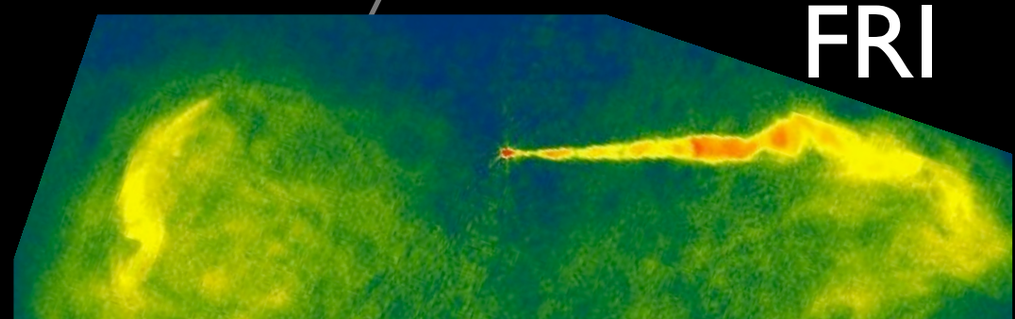

AT and Bromberg 2015, arXiv:1512.04526

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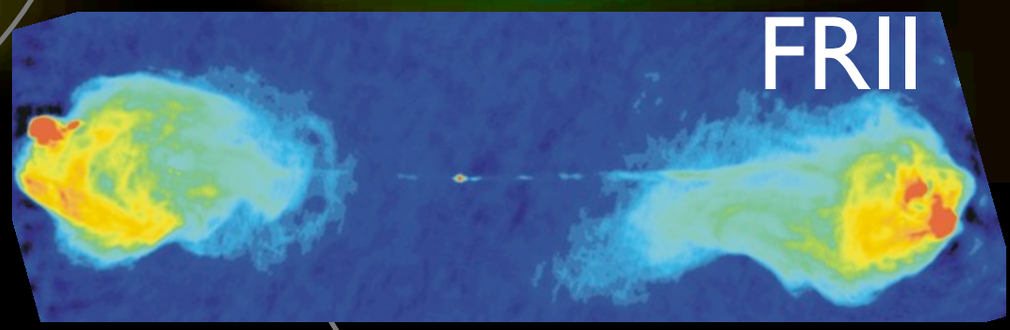

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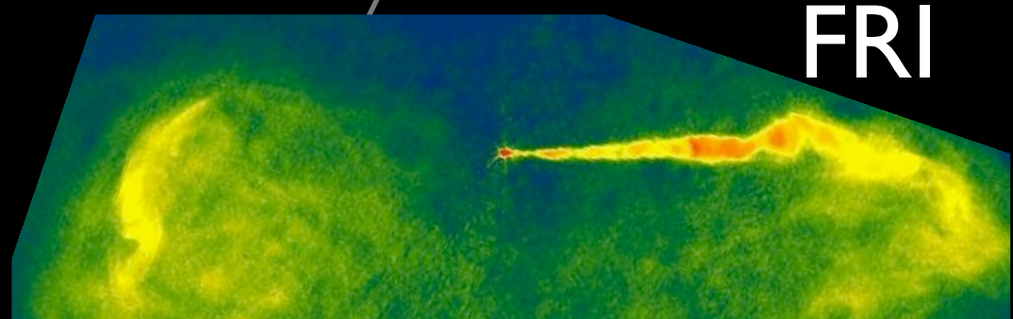

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Summary

- Dynamically important magnetic fields everywhere:
  - Jets are robust and happy to feed on anything
  - BUT: strong jets benefit from disk rotation
- Large-scale poloidal field dynamo is now a reality
  - No need for large-scale poloidal flux: toroidal would do too
  - Can small-scale turbulent magnetic field produce jets?
- Jet morphology is controlled by 3D external kink:
  - low-power jets are unstable and get stalled inside galaxies
  - FRI/FRII dichotomy likely
    - mediated by 3D magnetic kink instability
    - controlled by ratio of jet power to ambient density