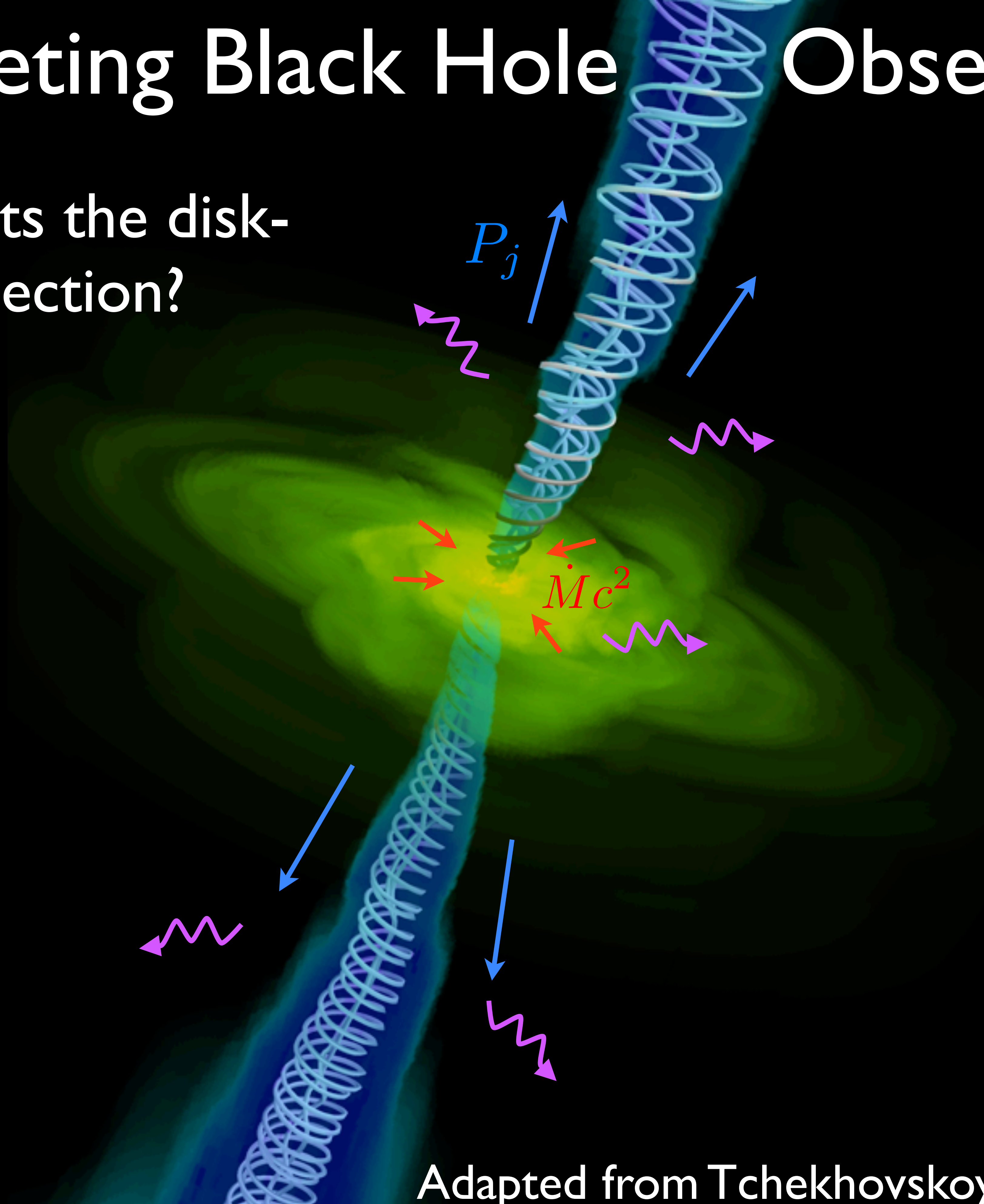
The disk-jet connection

Alexander (Sasha) Tchekhovskoy

Einstein Fellow
UC Berkeley

Interpreting Black Hole Observations

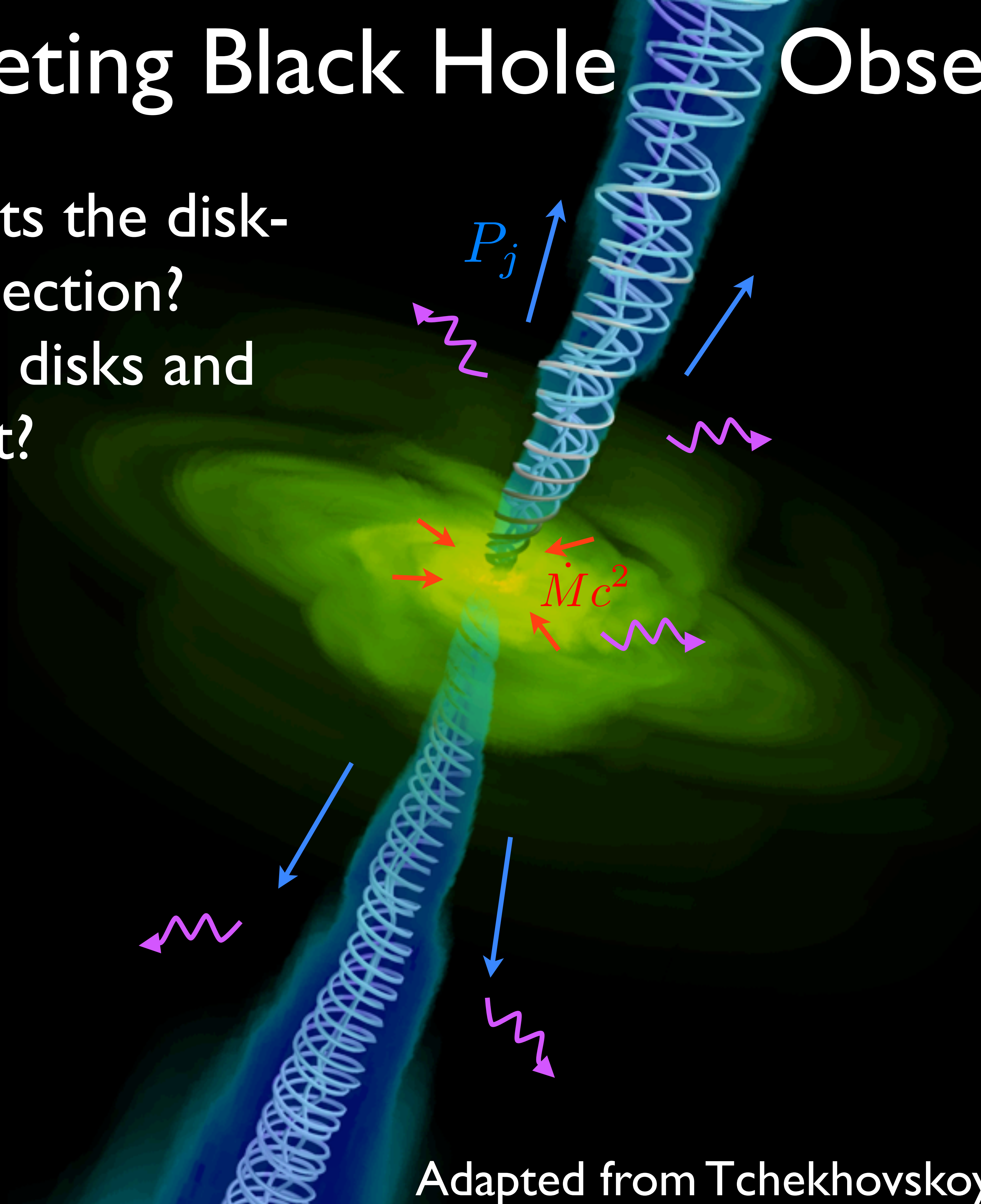
- What sets the disk-jet connection?



Adapted from Tchekhovskoy 2015

Interpreting Black Hole Observations

- What sets the disk-jet connection?
- How do disks and jets emit?



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- How do disks and jets emit?
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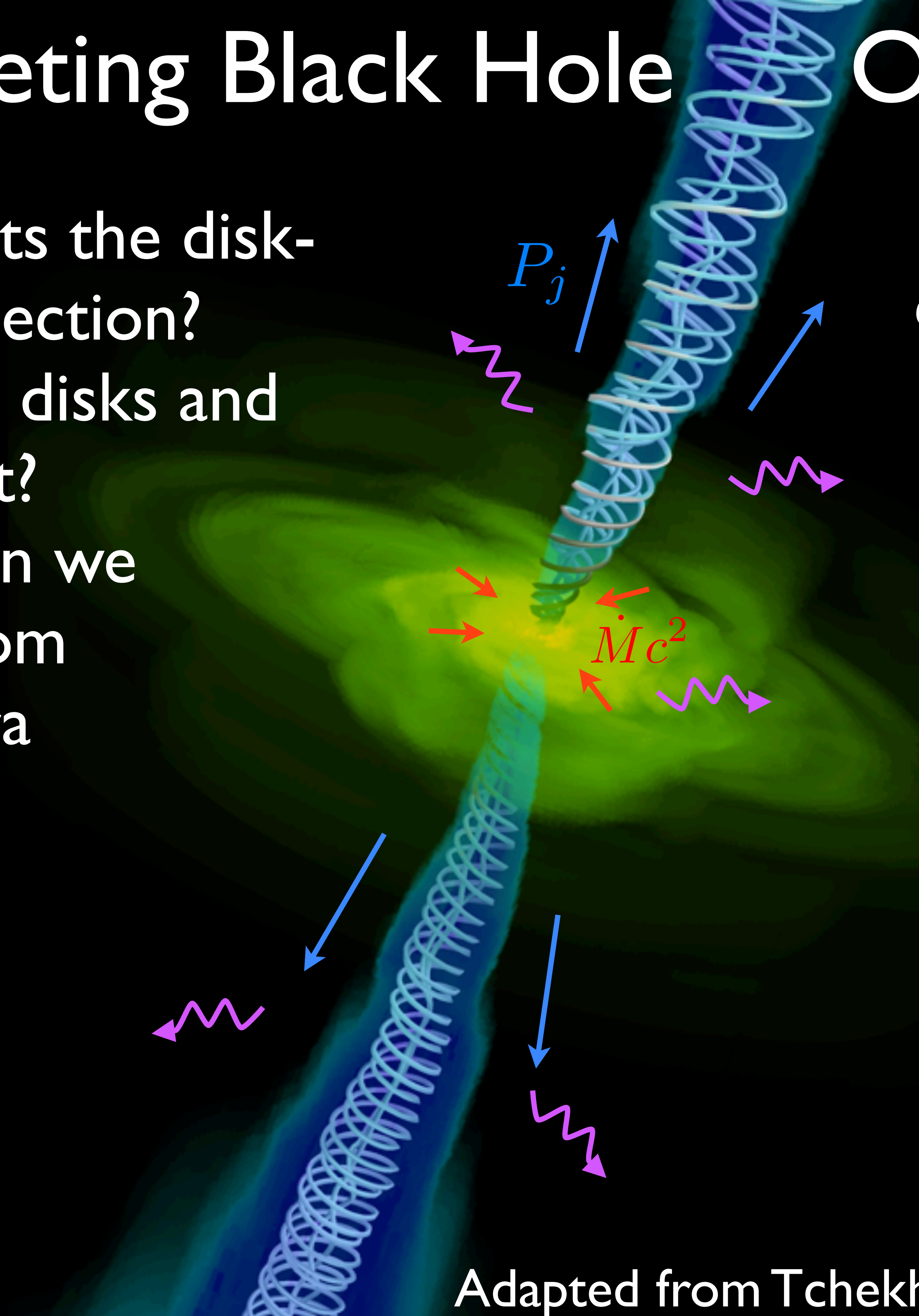
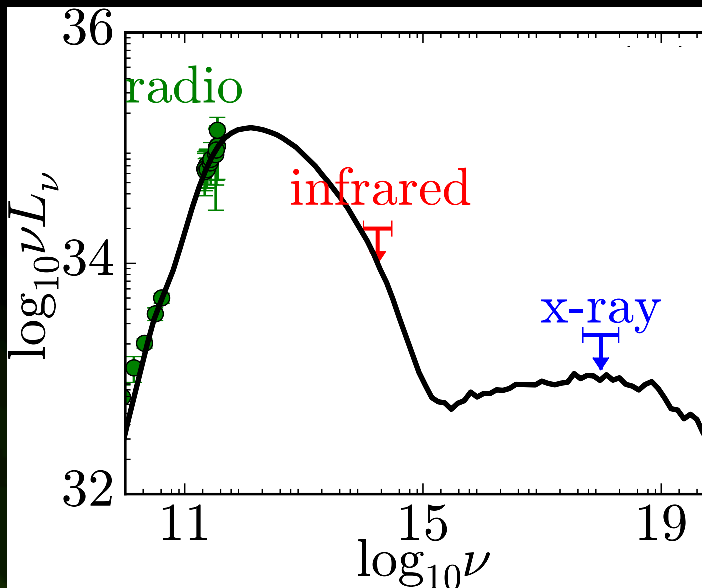


Simulated *ALMA, VLA, Chandra, NuSTAR* spectra



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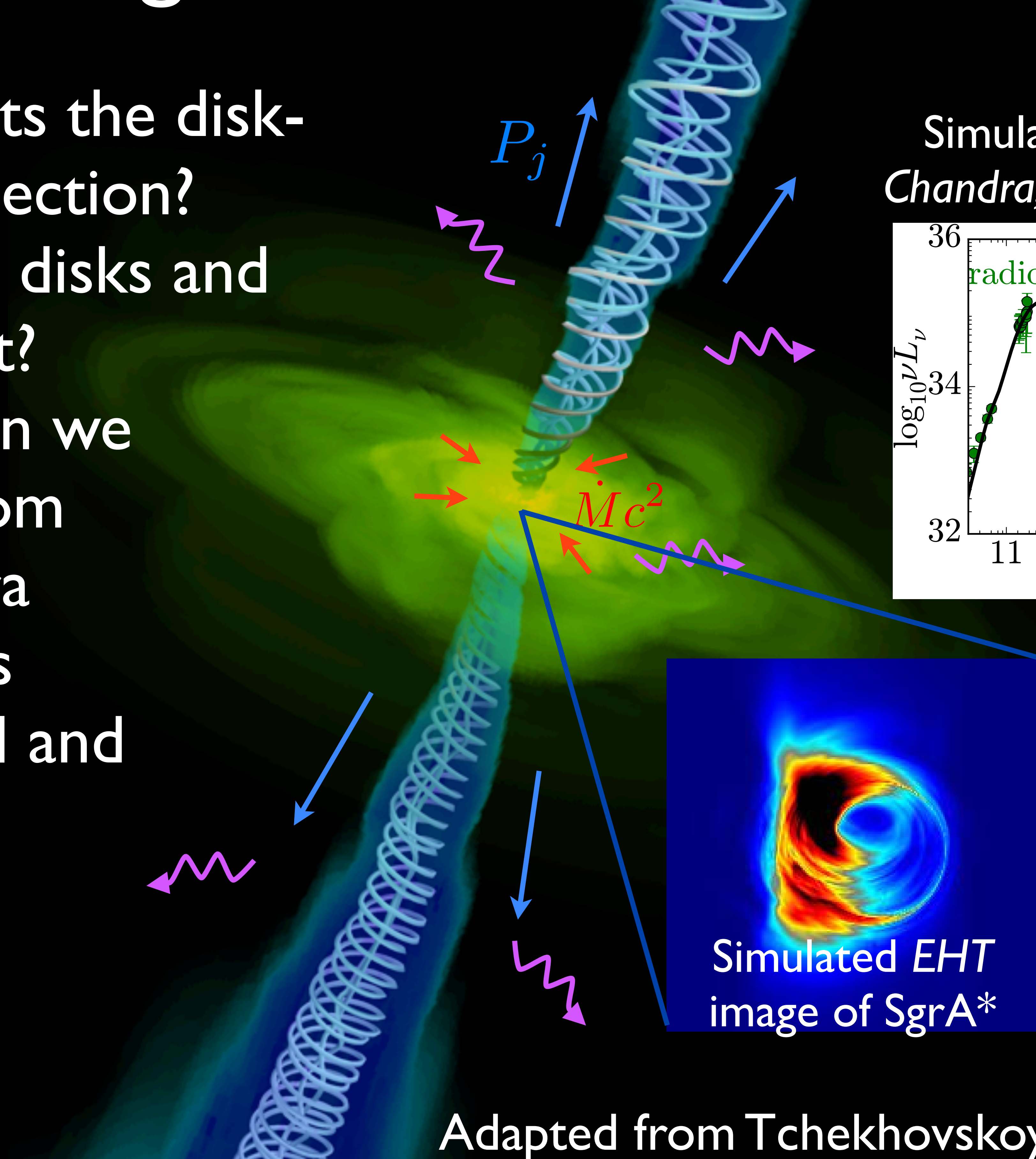
  on small and



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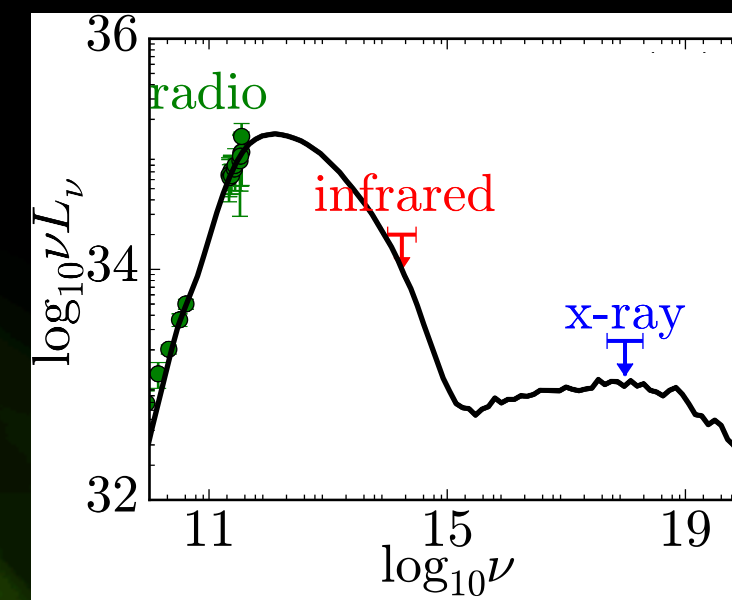

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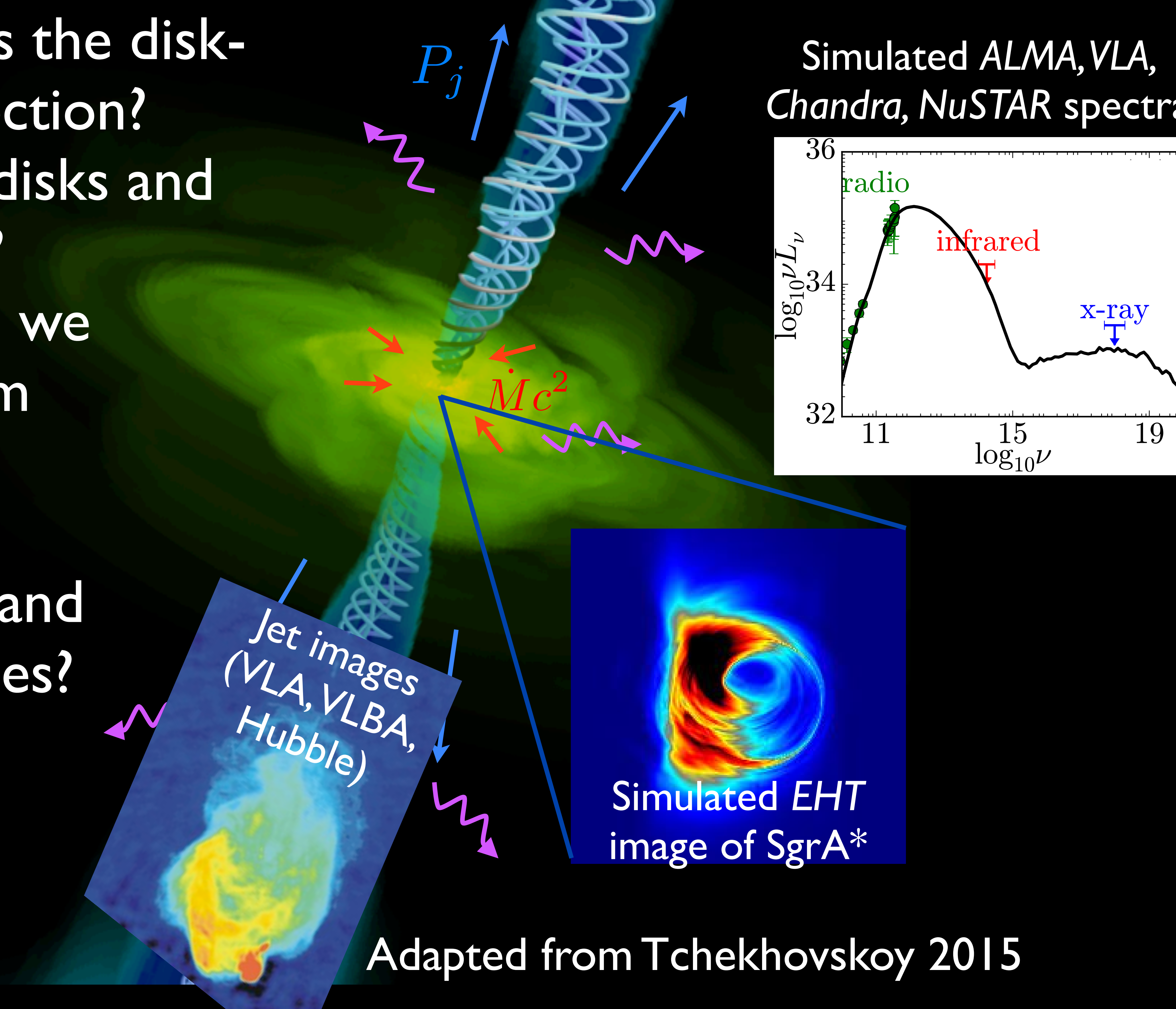

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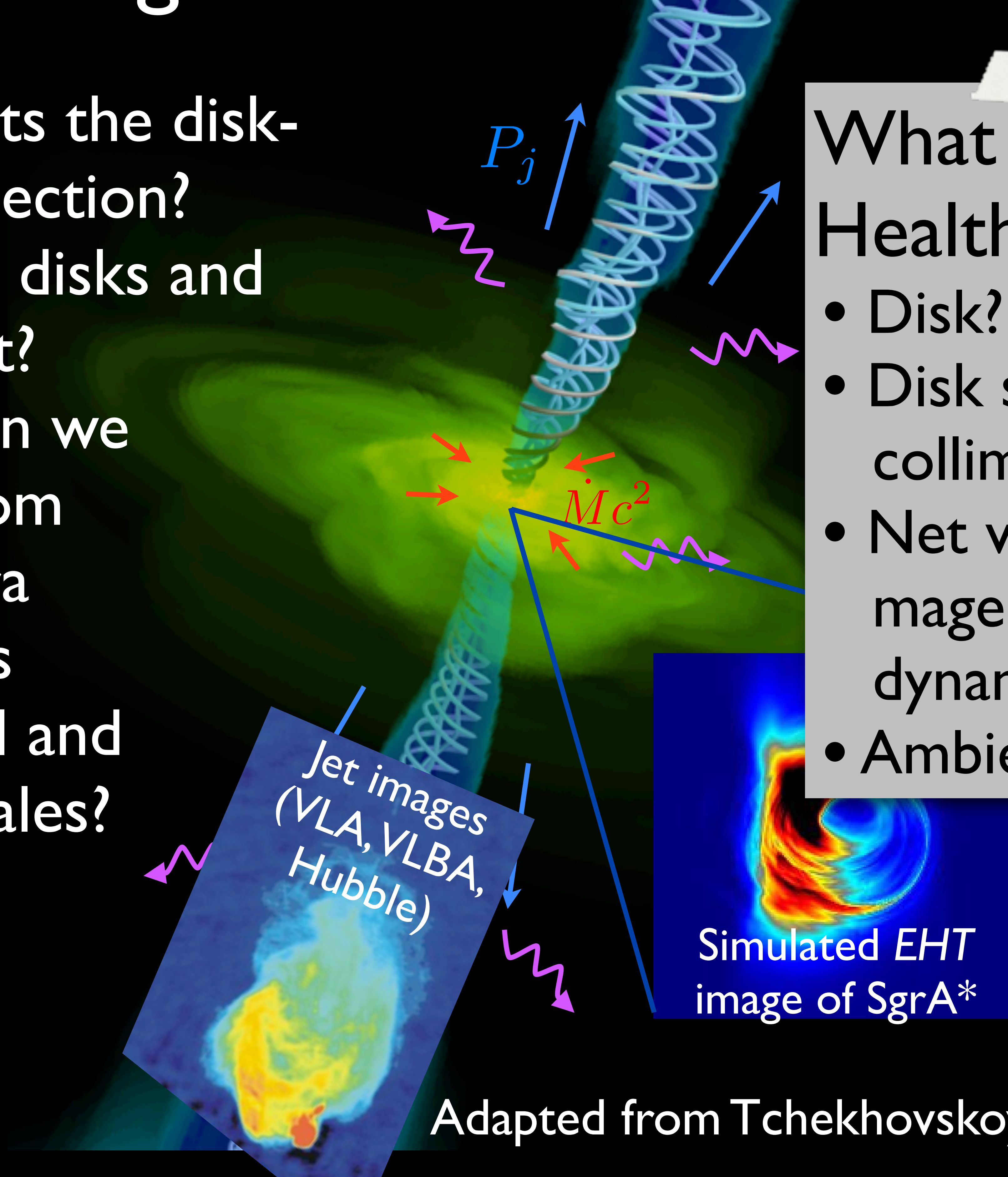


What is a Healthy Jet Diet?

- Disk?
- Disk size/thickness/collimation?
- Net vertical magentic flux/dynamo?
- Ambient medium?

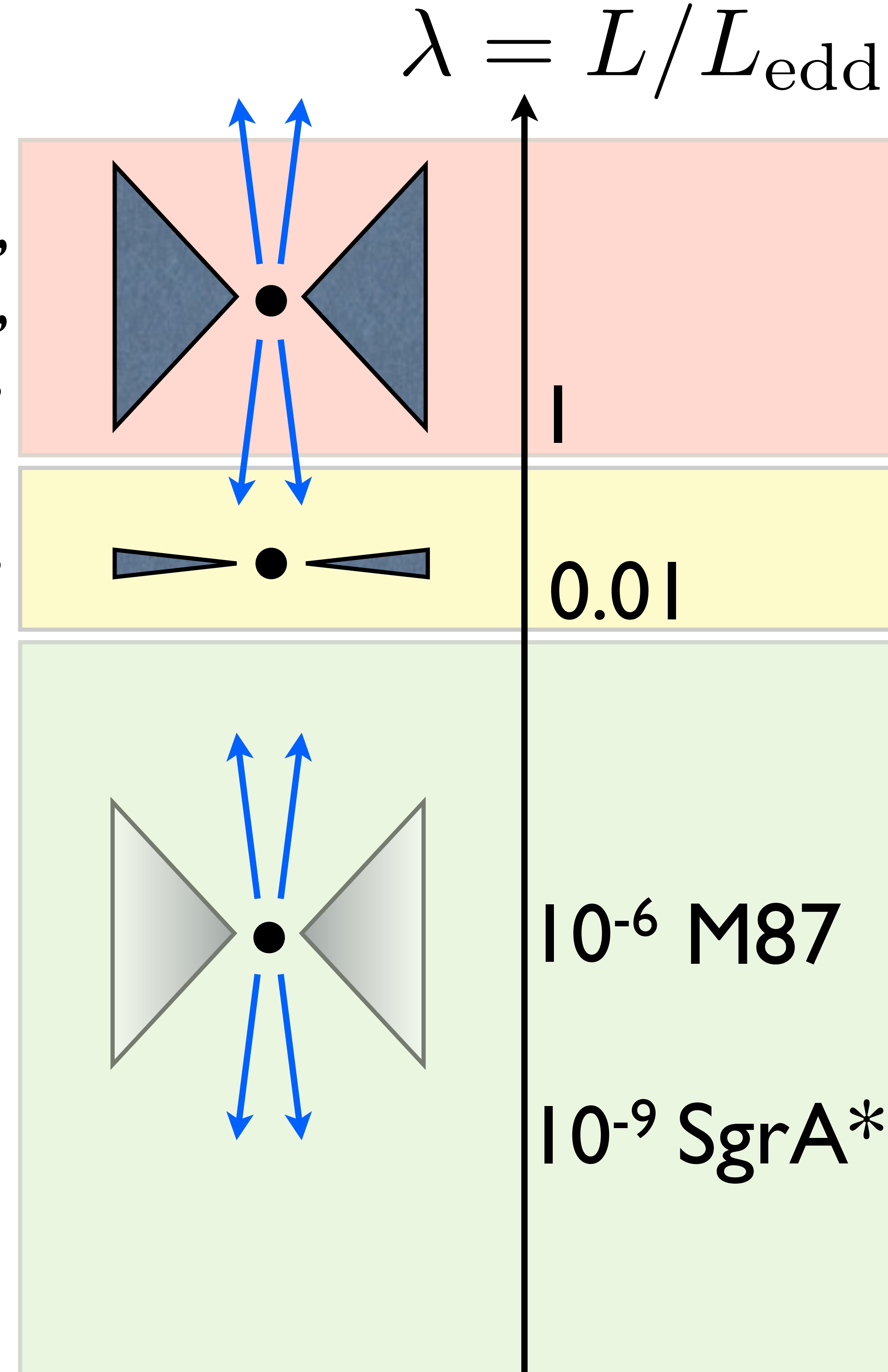
Adapted from Tchekhovskoy 2015

When are Jets Produced?

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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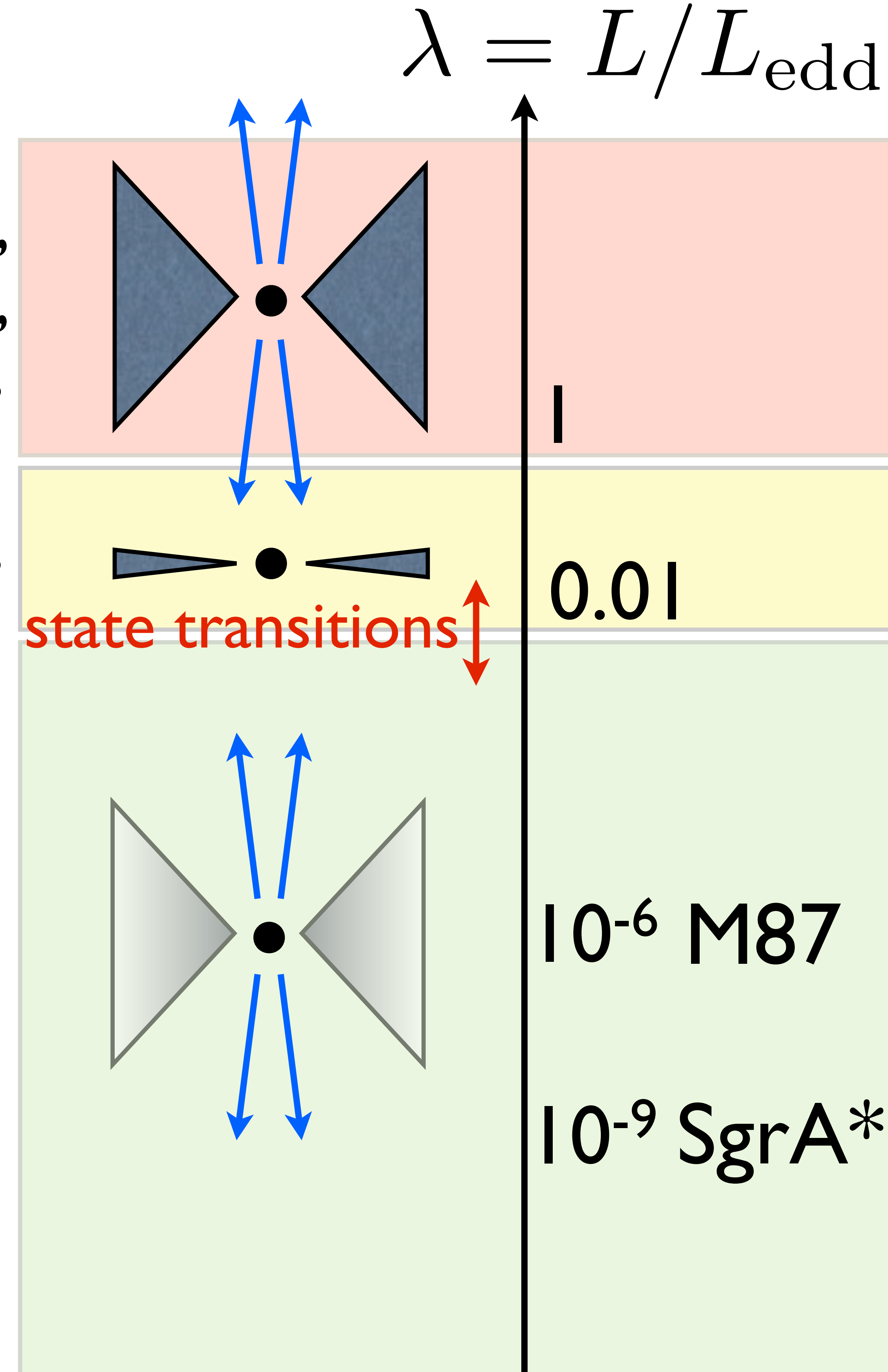
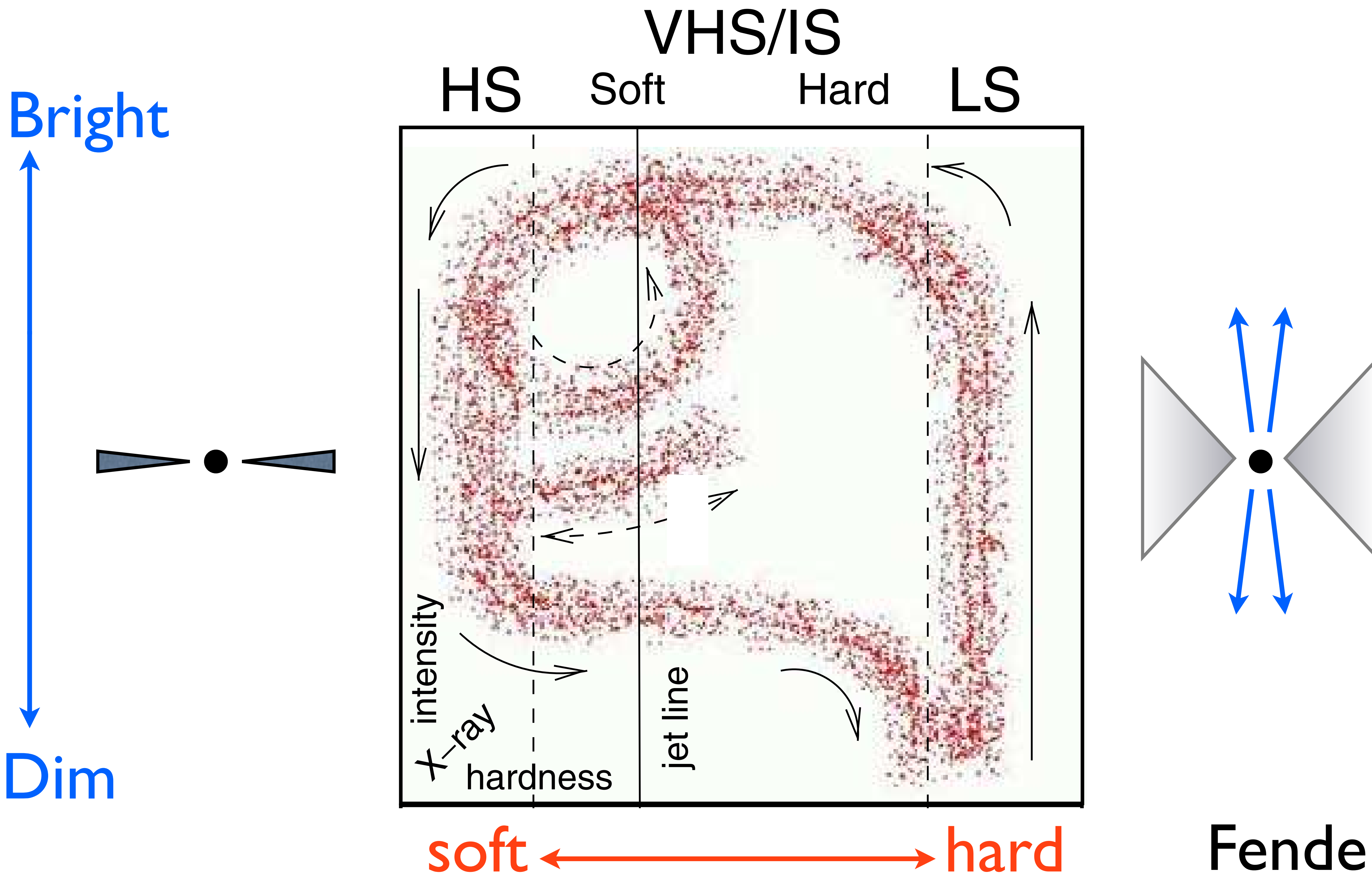


When are Jets Produced?

"q" or turtlehead diagram



Fender+2004

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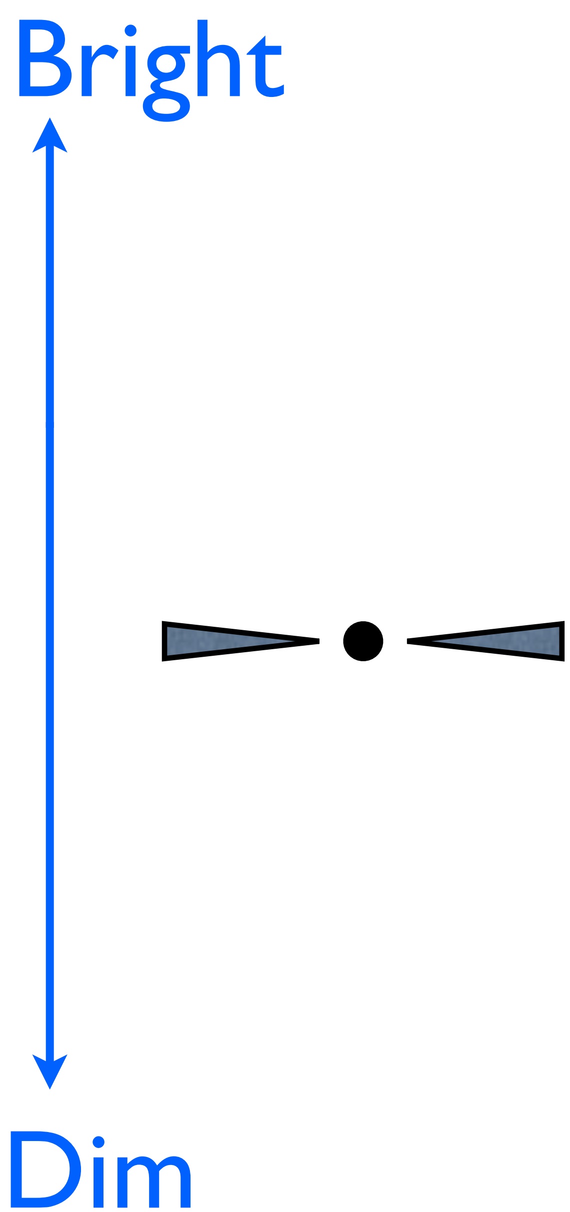

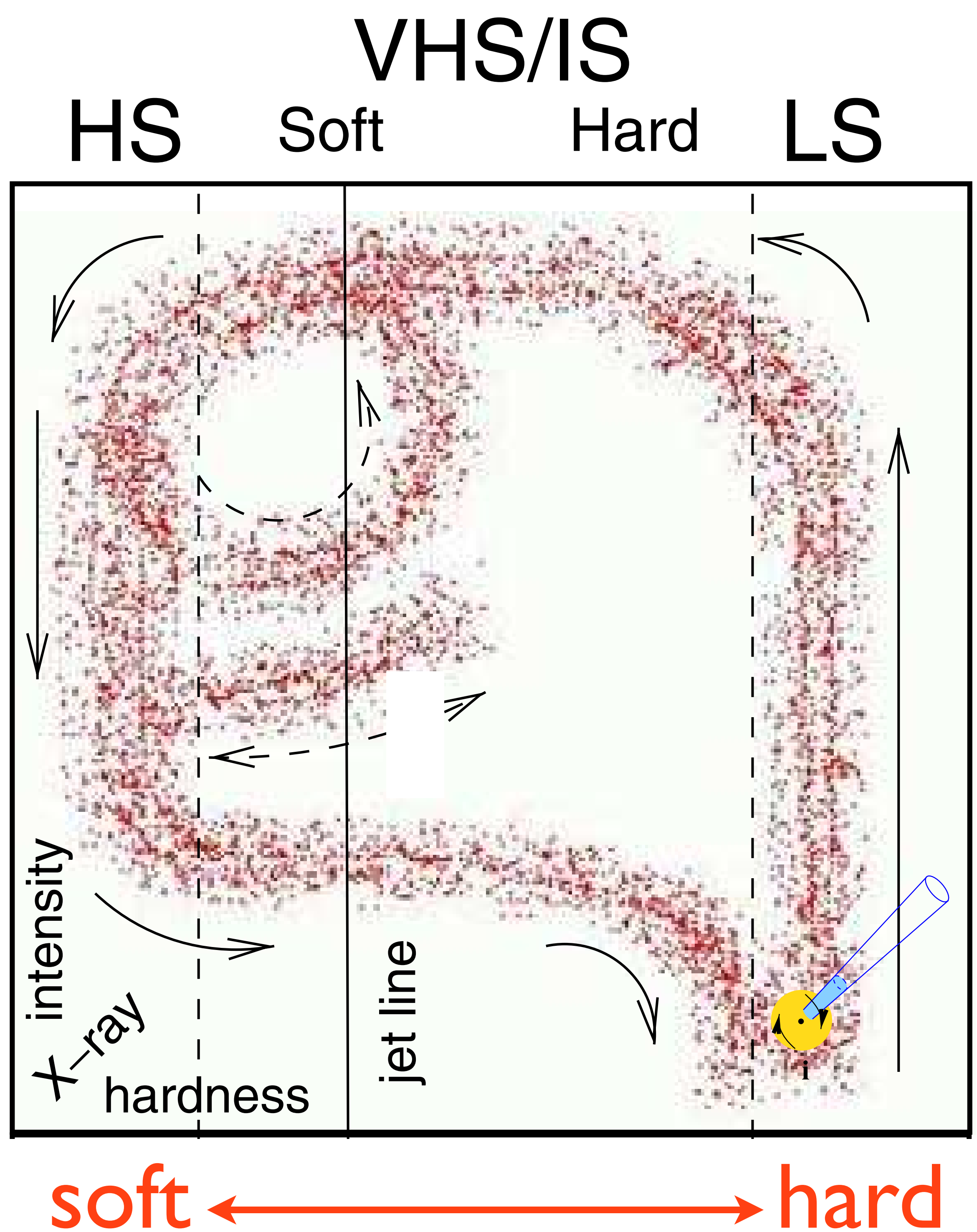

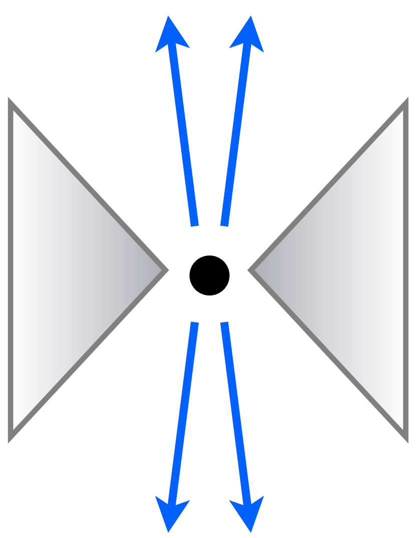

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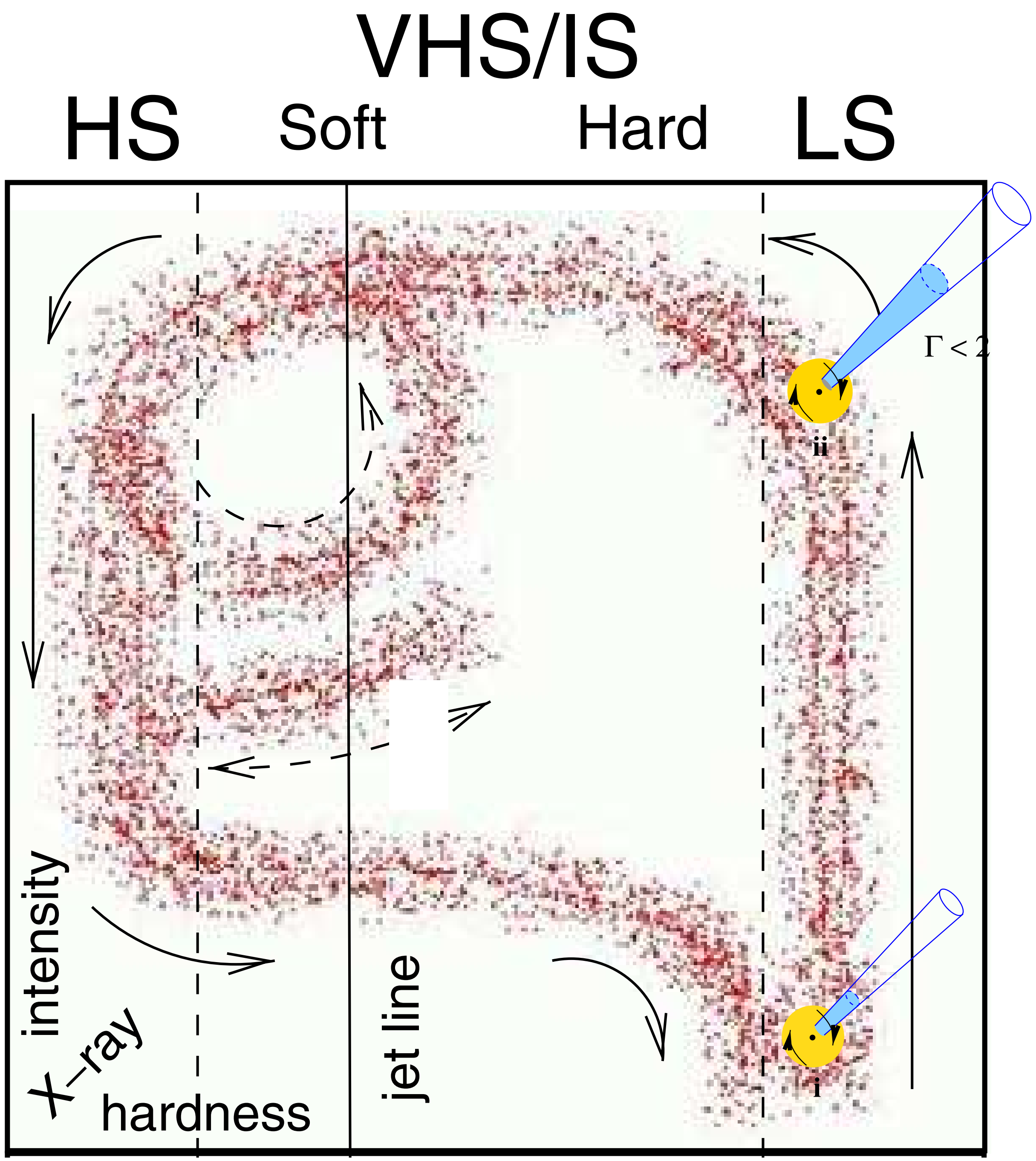
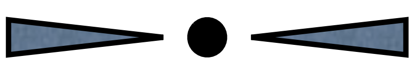
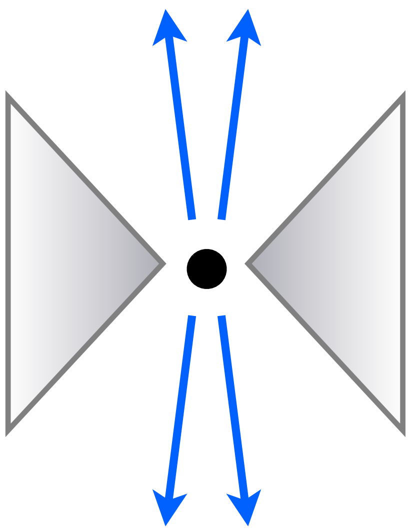


Bright



Dim



soft ⟷ hard

Fender+2004

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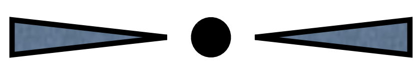

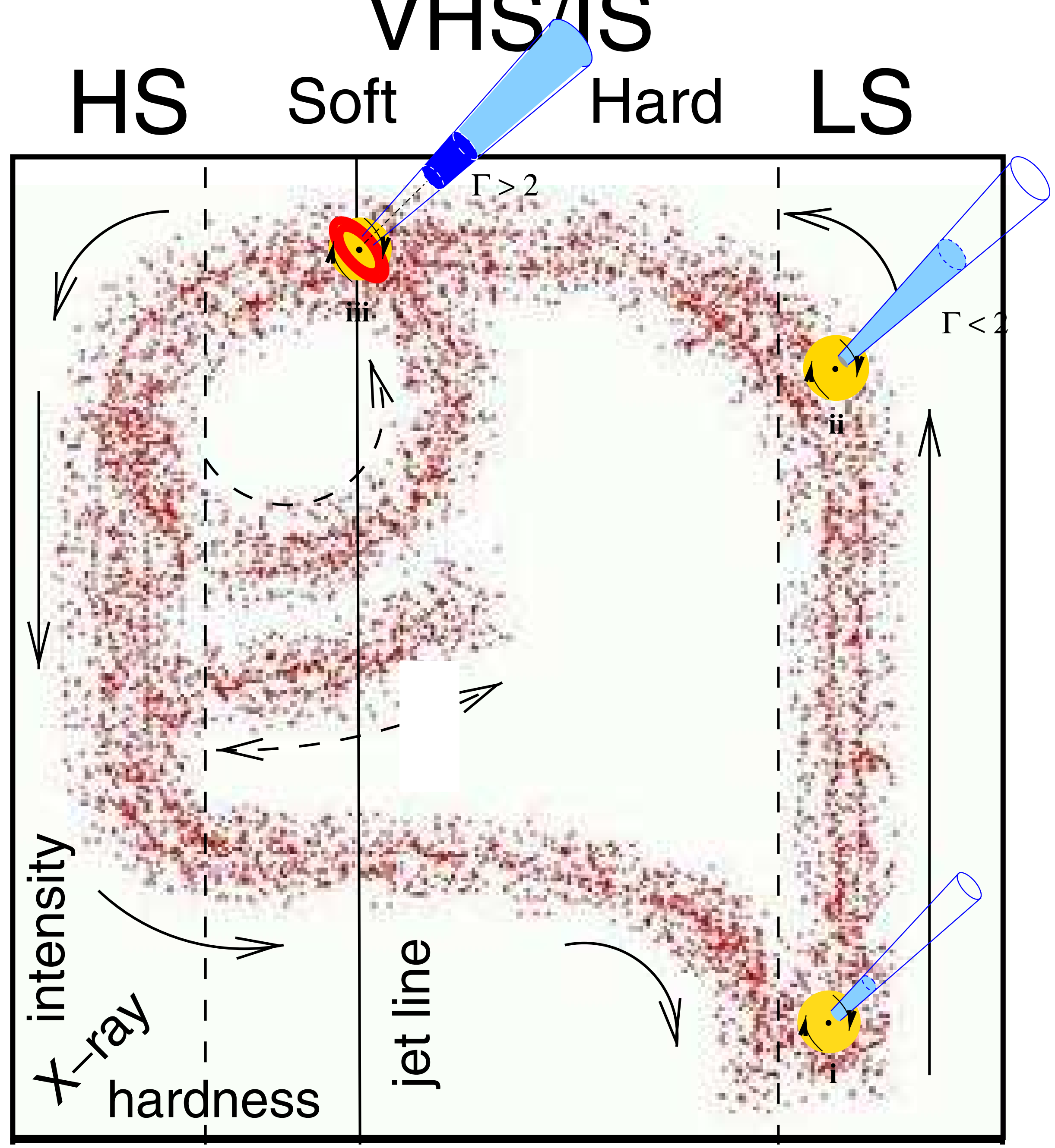

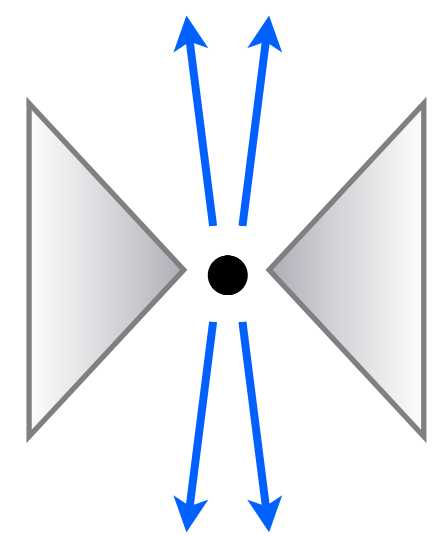

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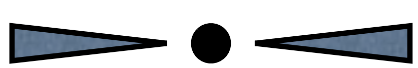

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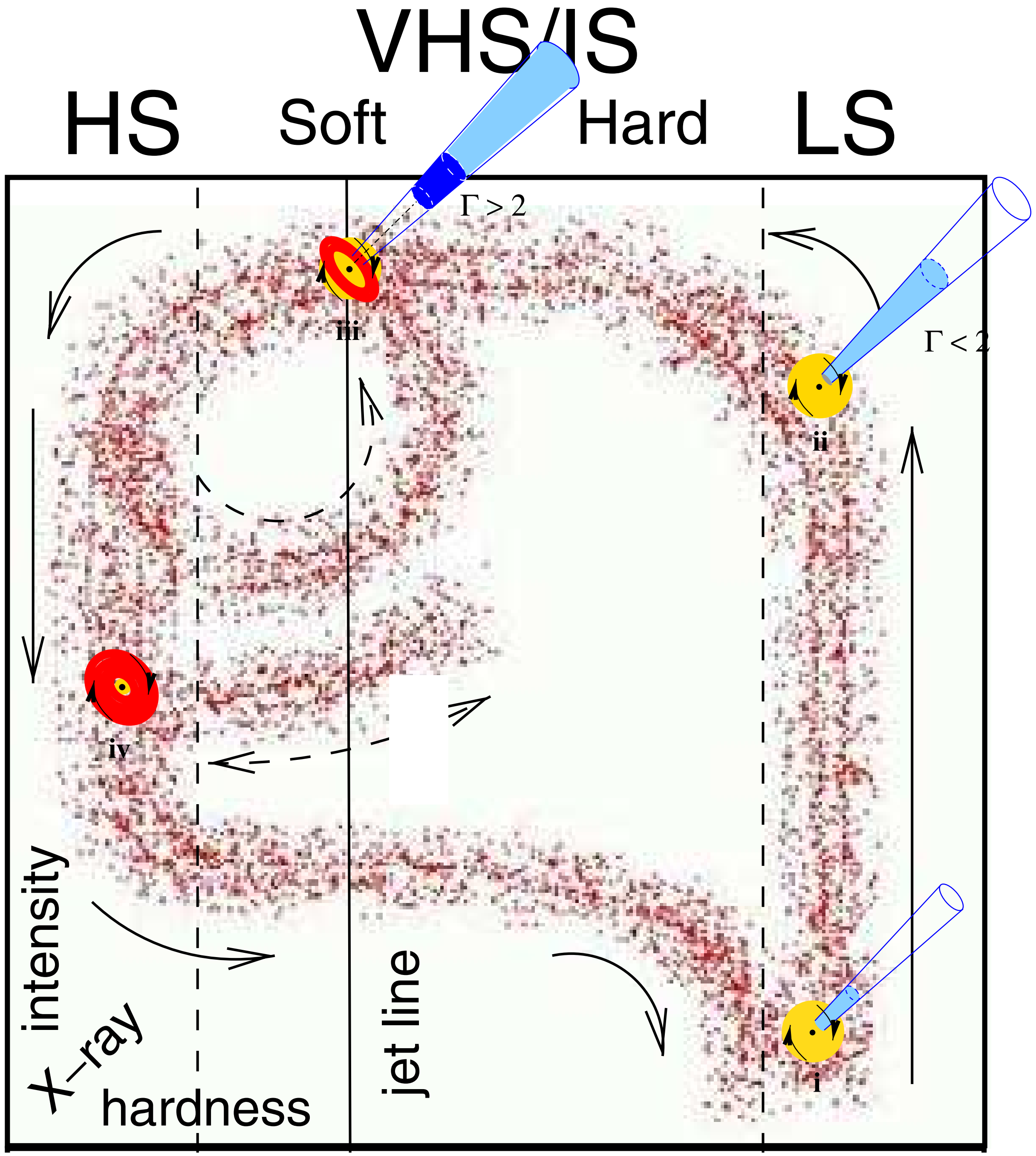

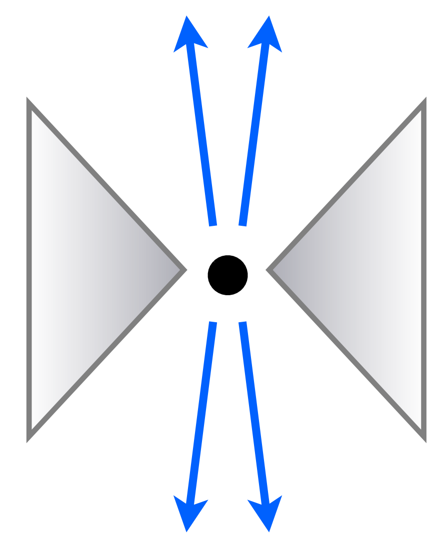

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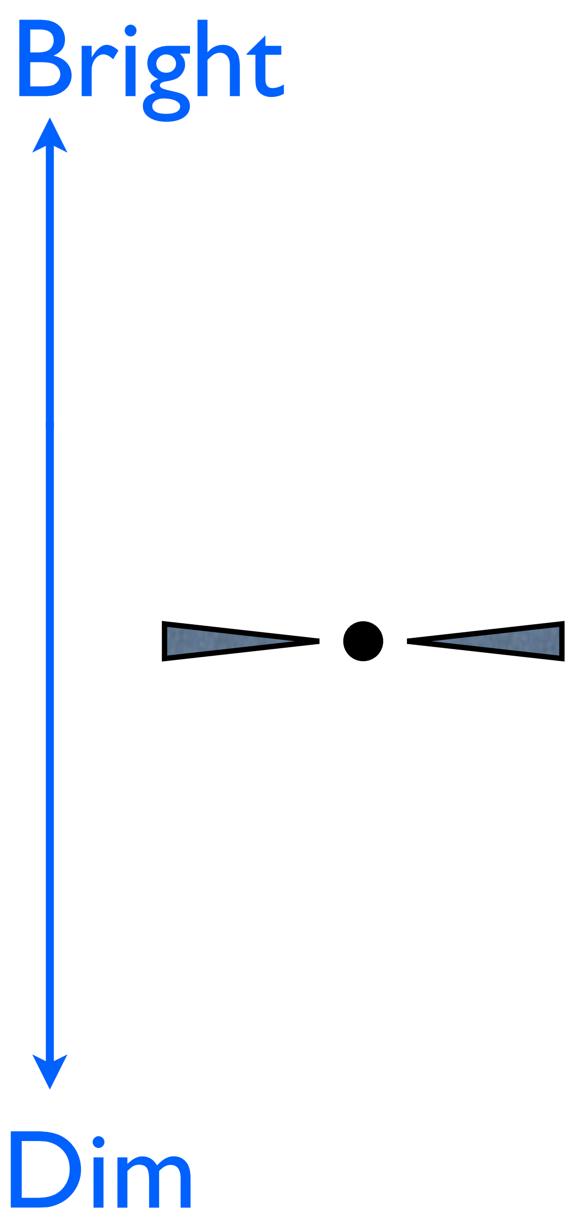
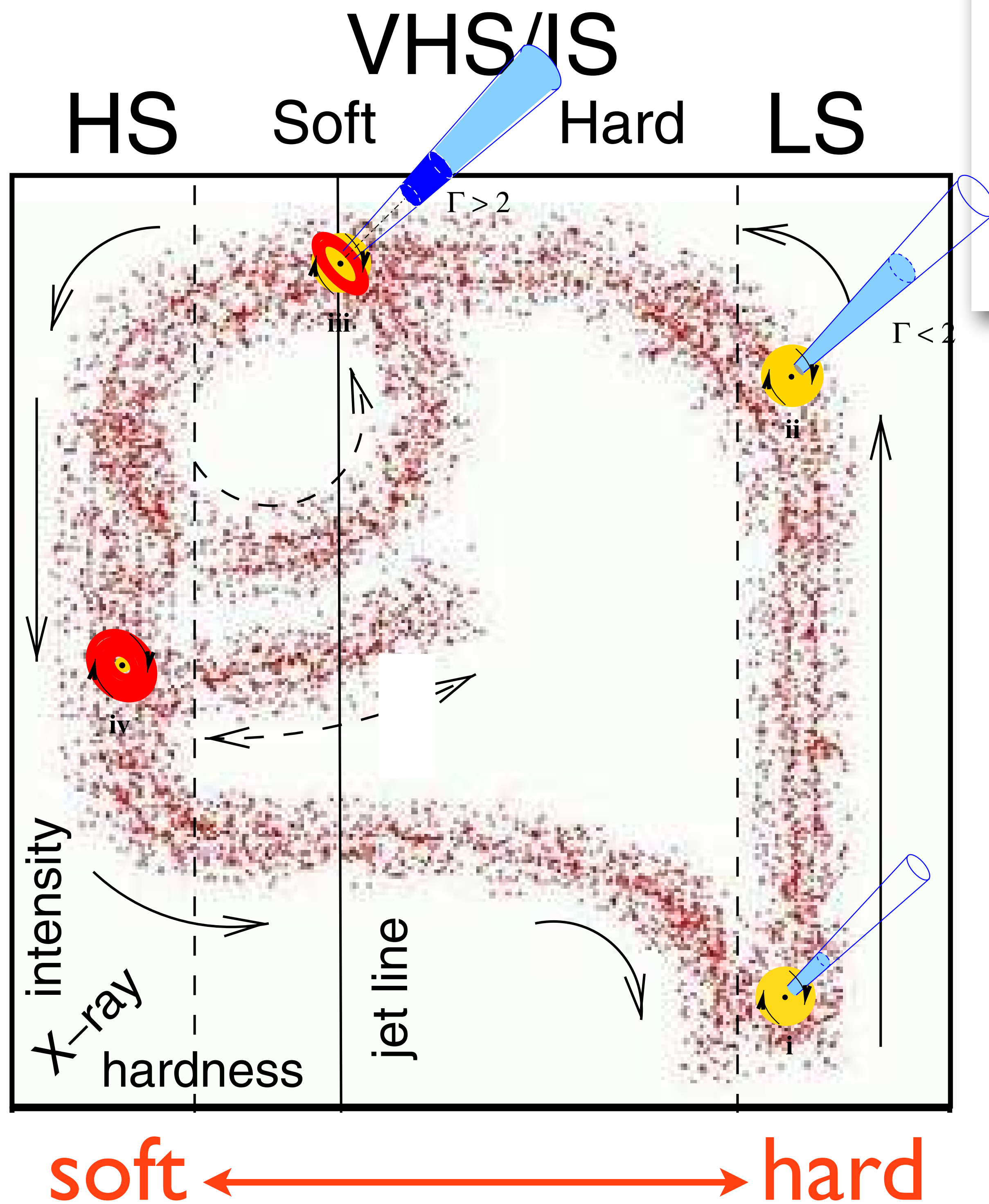
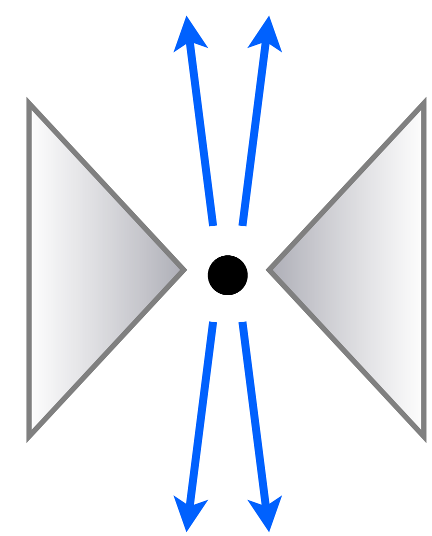




No correlation with BH spin of *persistent jets*
(Fender+10)



Fender+2004

When are Jets Produced?

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Correlation with BH spin of *transient jets*
(Narayan & McClintock '12)

No correlation with BH spin of *persistent jets*
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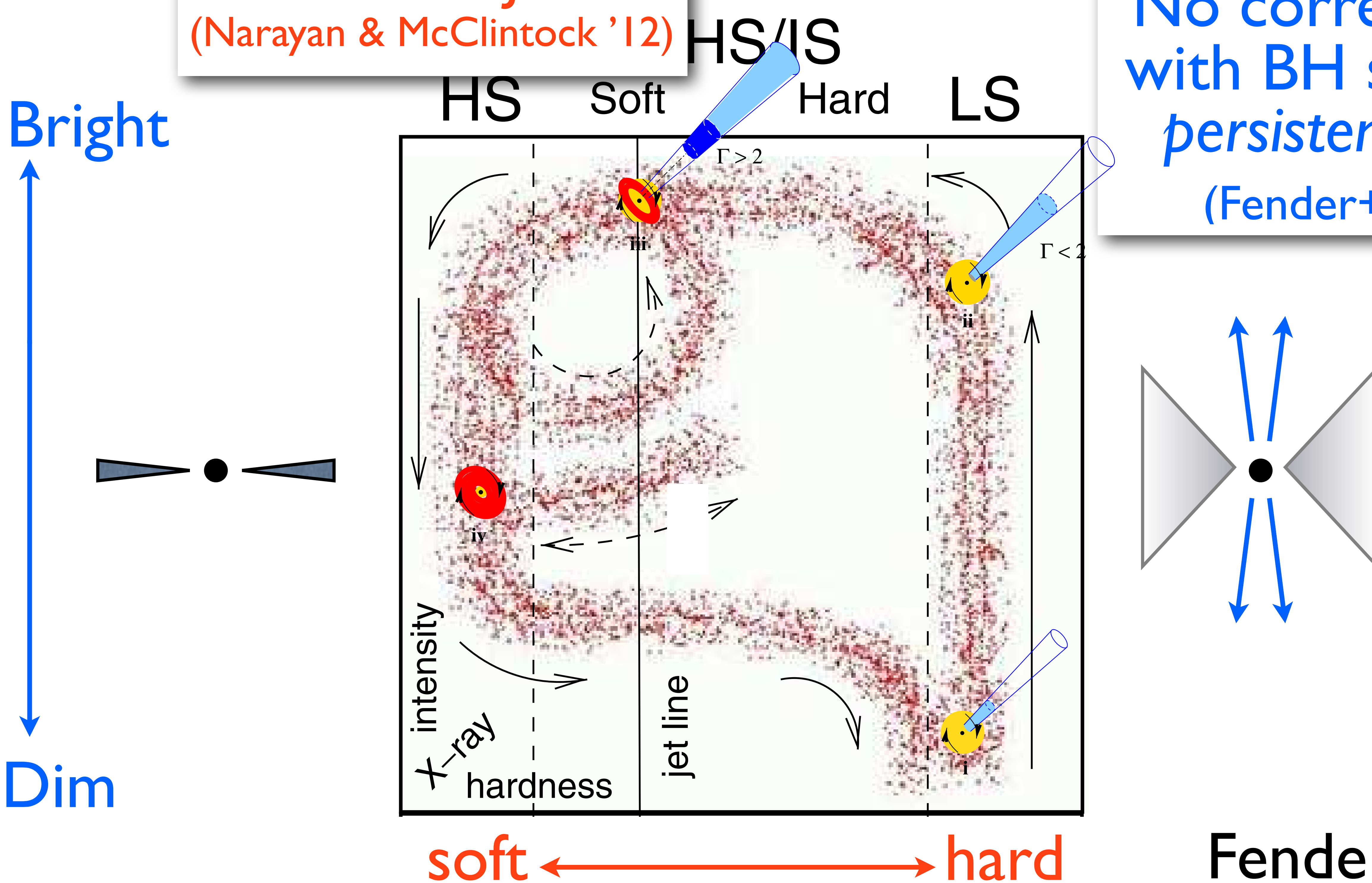
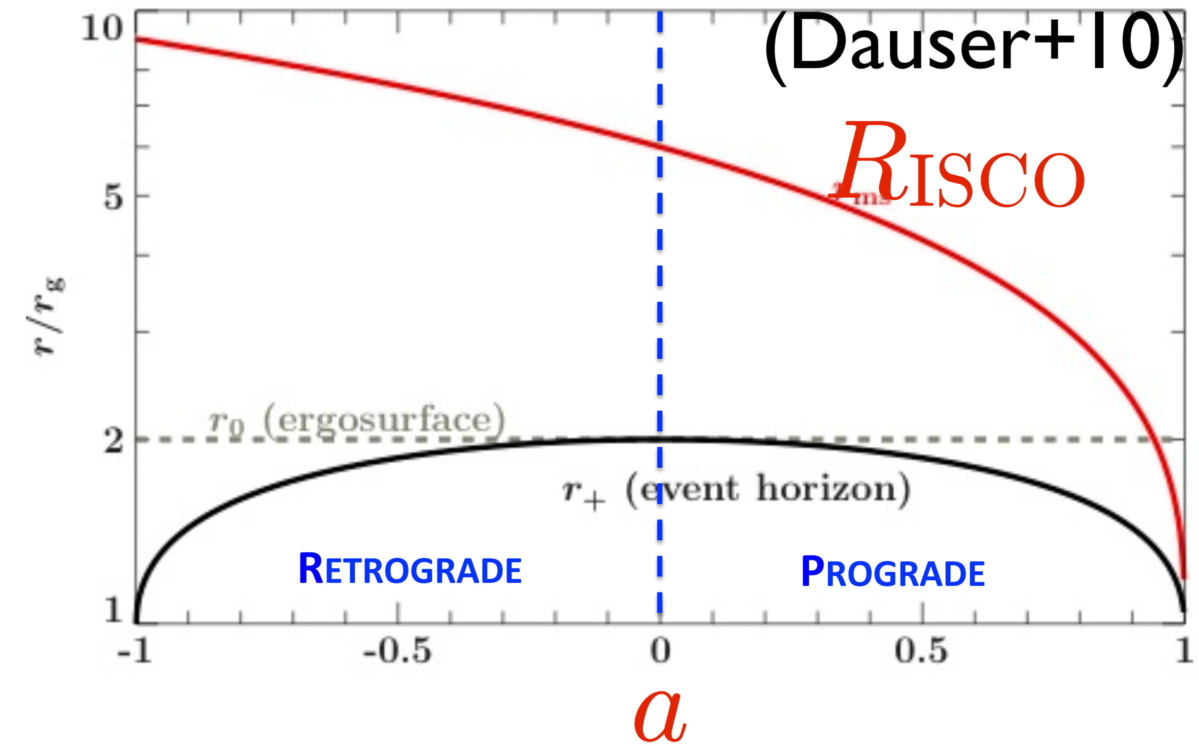
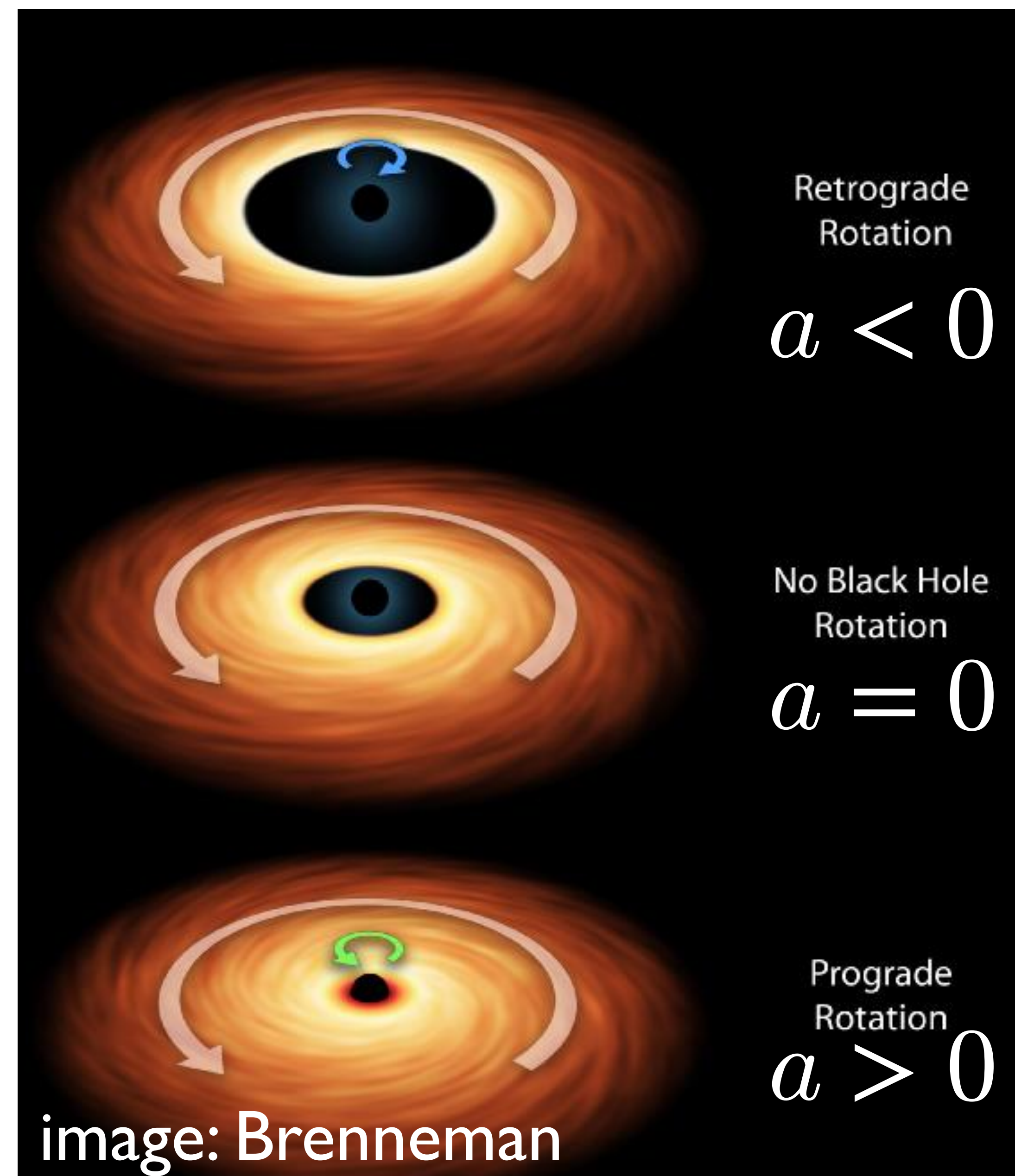


Fender+2004

Two major methods of measuring BH spin

- Both methods rely on measuring the size of the 'hole' in the disk
- 'Hole' size = Radius of Innermost Stable Circular Orbit (ISCO), $R_{\rm ISCO}$
- Continuum fitting: via blackbody-like spectrum
  (McClintock, Narayan, Steiner, ...)
- Iron line: via the shape of the Fe line
  (Brenneman, Fabian, Reynolds, Russell, ...)





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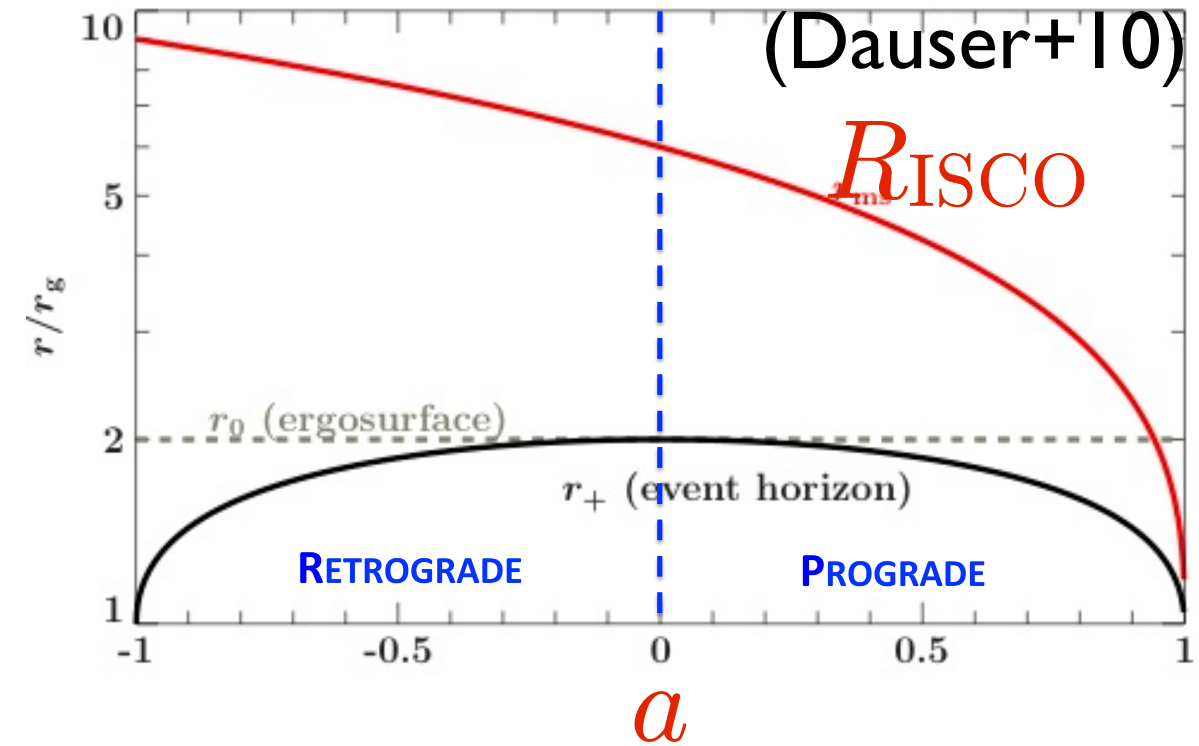
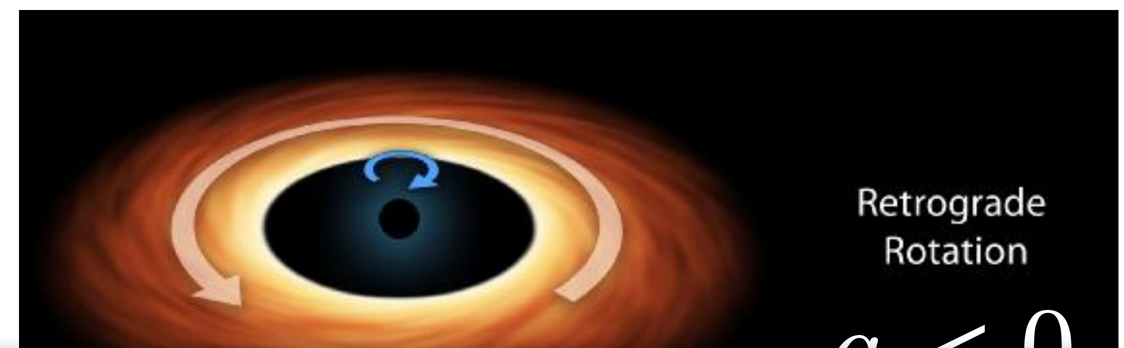
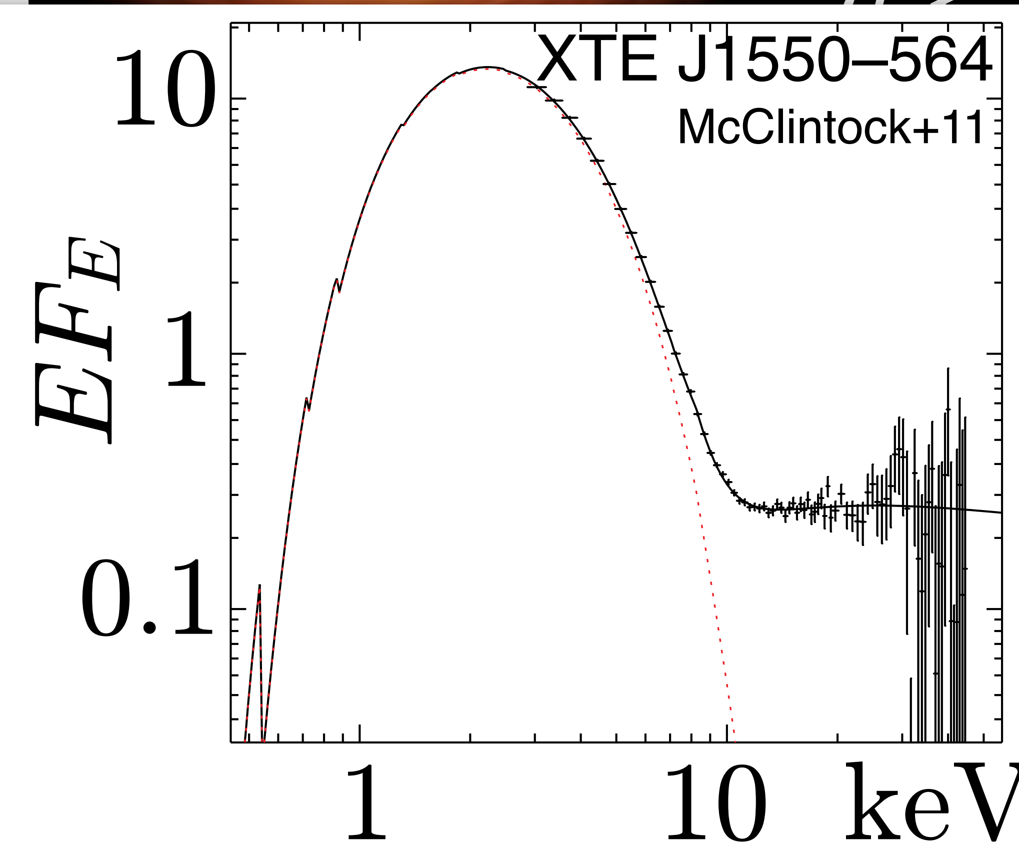




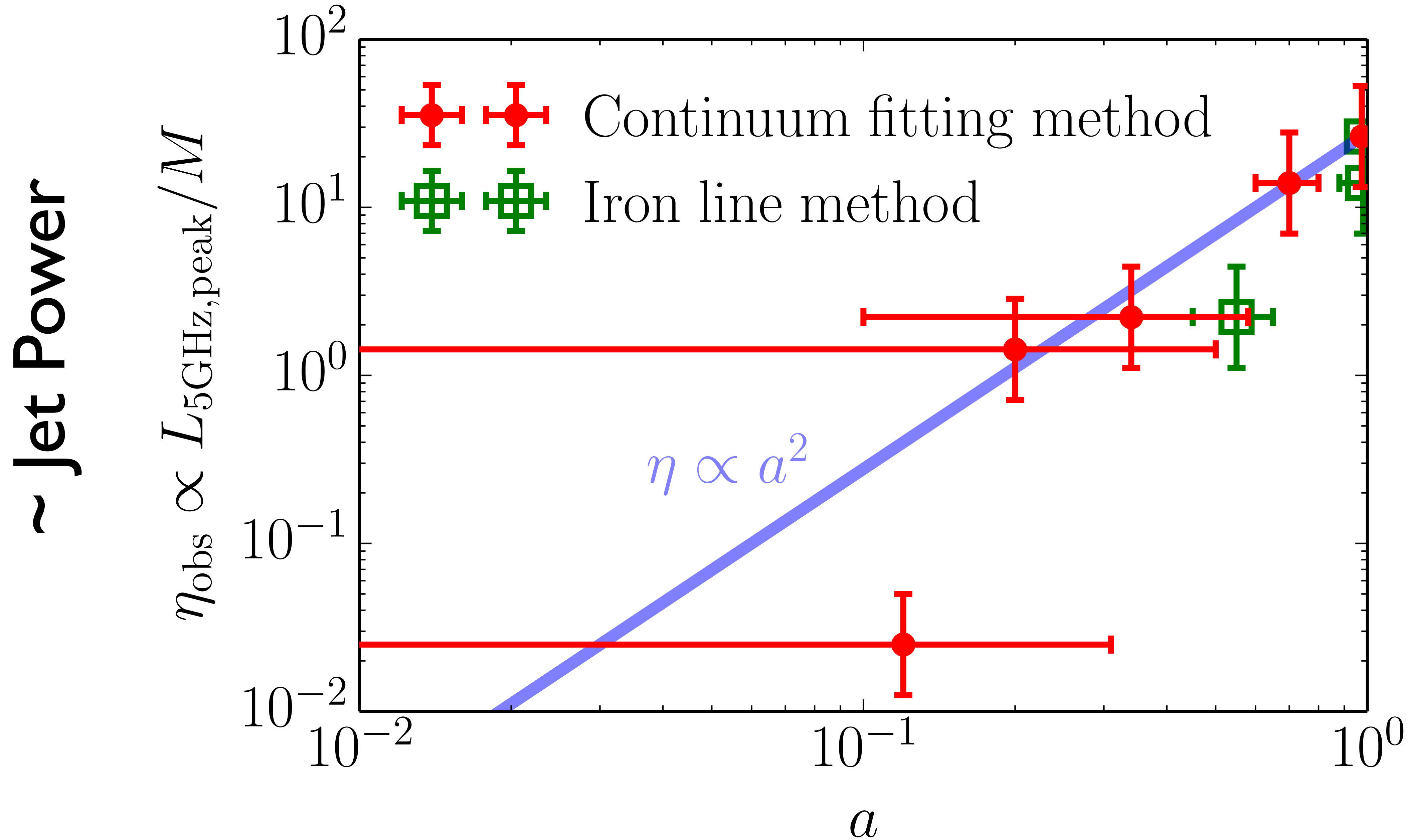
Continuum fitting method:

$$\underset{\text{normalization}}{L} \sim \pi \overset{a}{R_{\rm ISCO}}{}^2 \sigma \underset{\text{shape}}{T^4}$$

normalization shape of the spectrum



Are Transient Jets Powered by BH spin?



AT15; data Steiner+13, Narayan & McClintock+12

But: Russell+13

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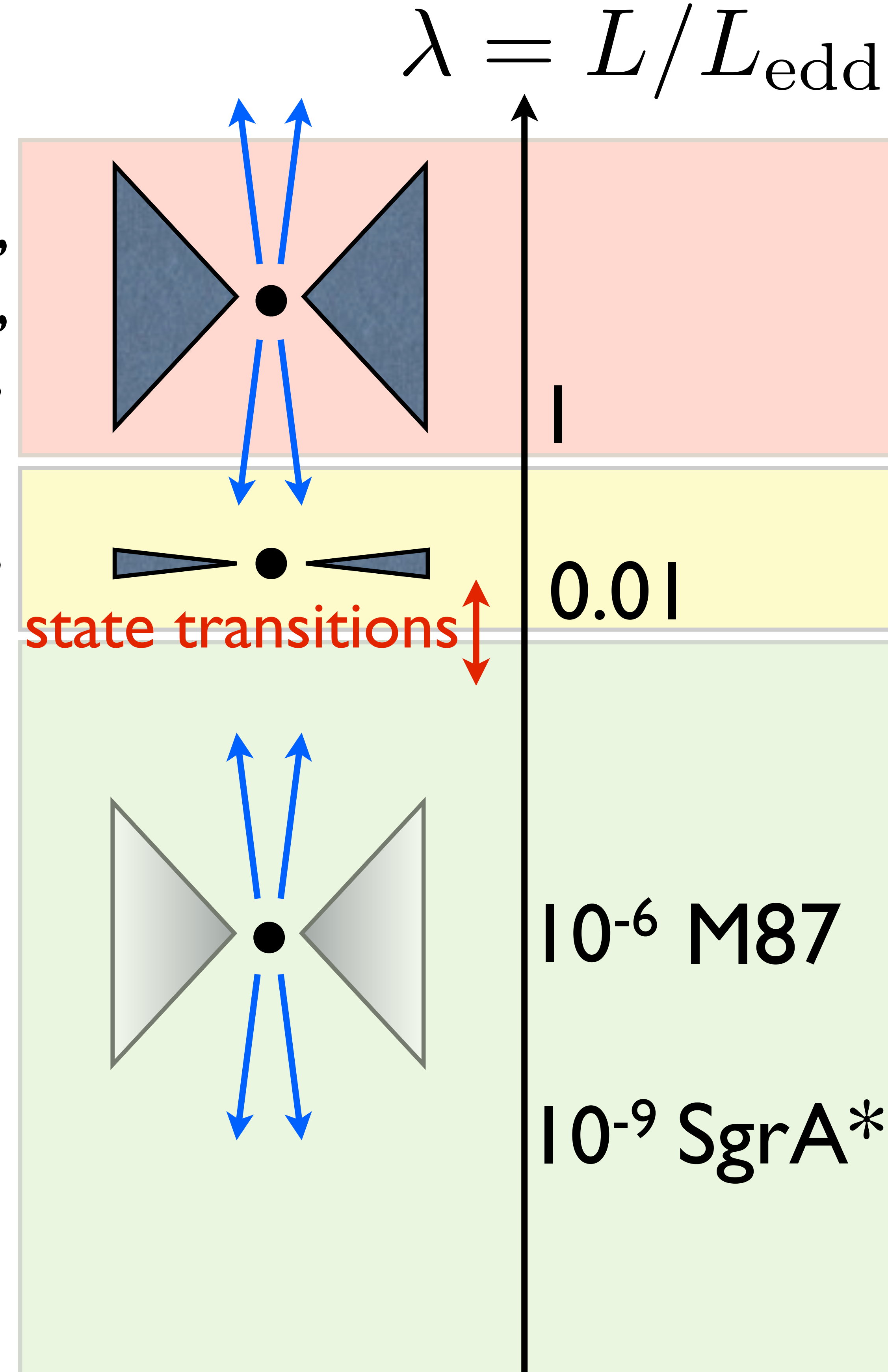

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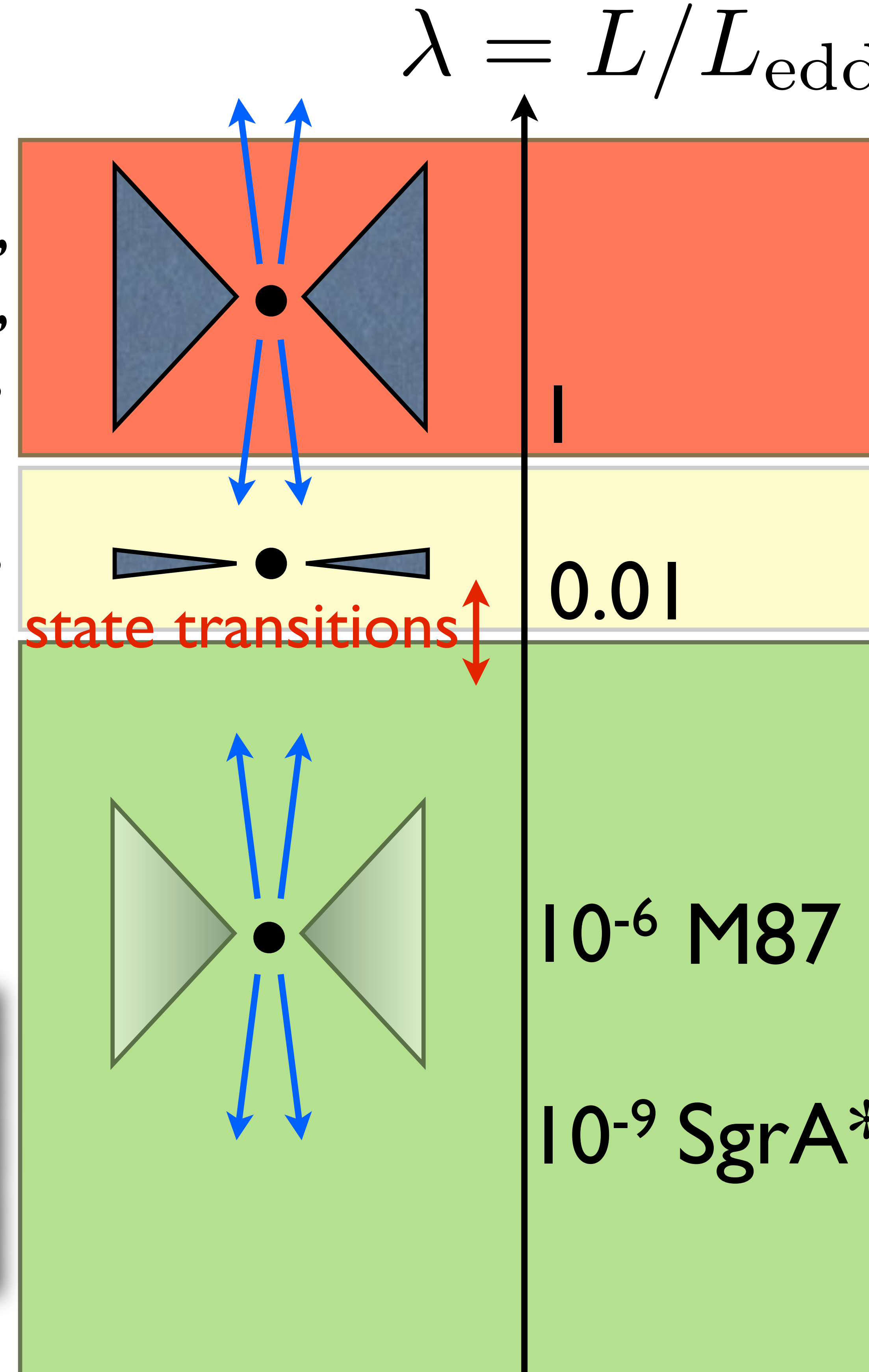
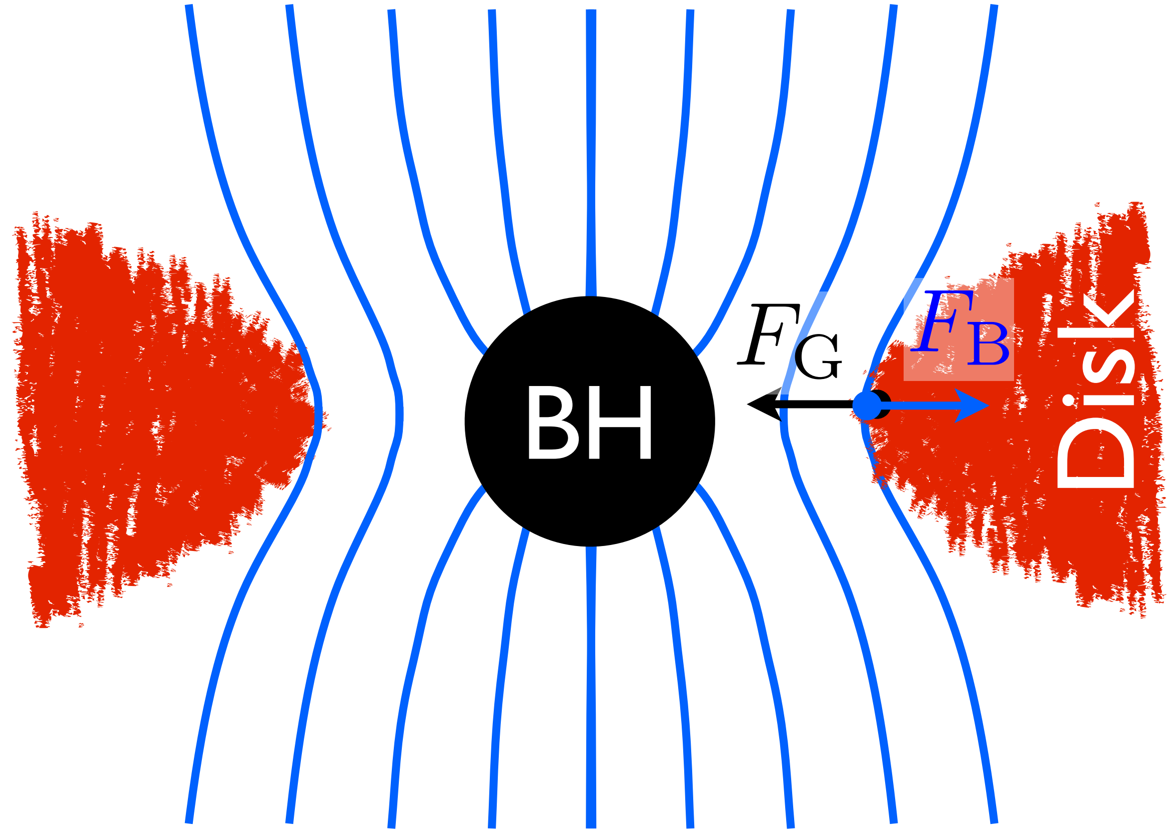


Both high- and low-luminosity disks are *radiatively inefficient*. Neglect radiation and simulate.

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, AT+10)

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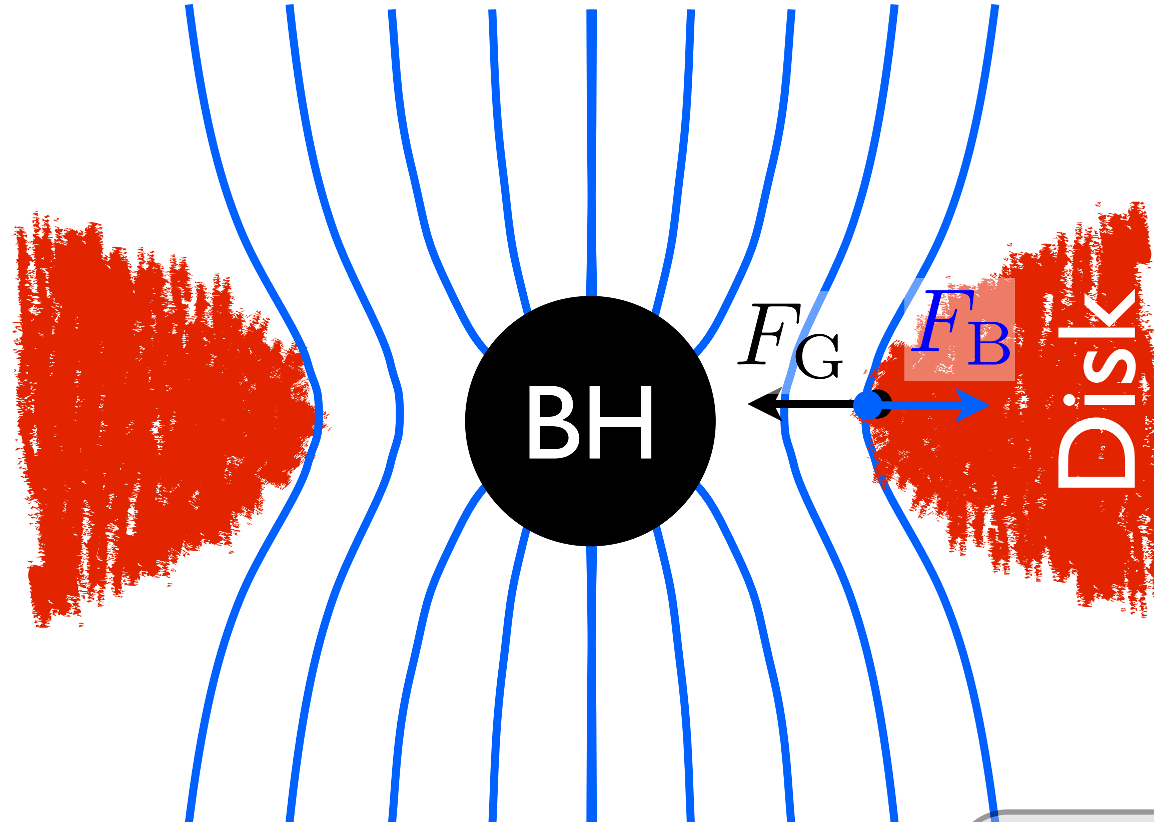

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$$P_j \sim a^2 B^2 r_g^2 c \propto \Phi^2 \overbrace{(a/r_g)^2}^{k}$$

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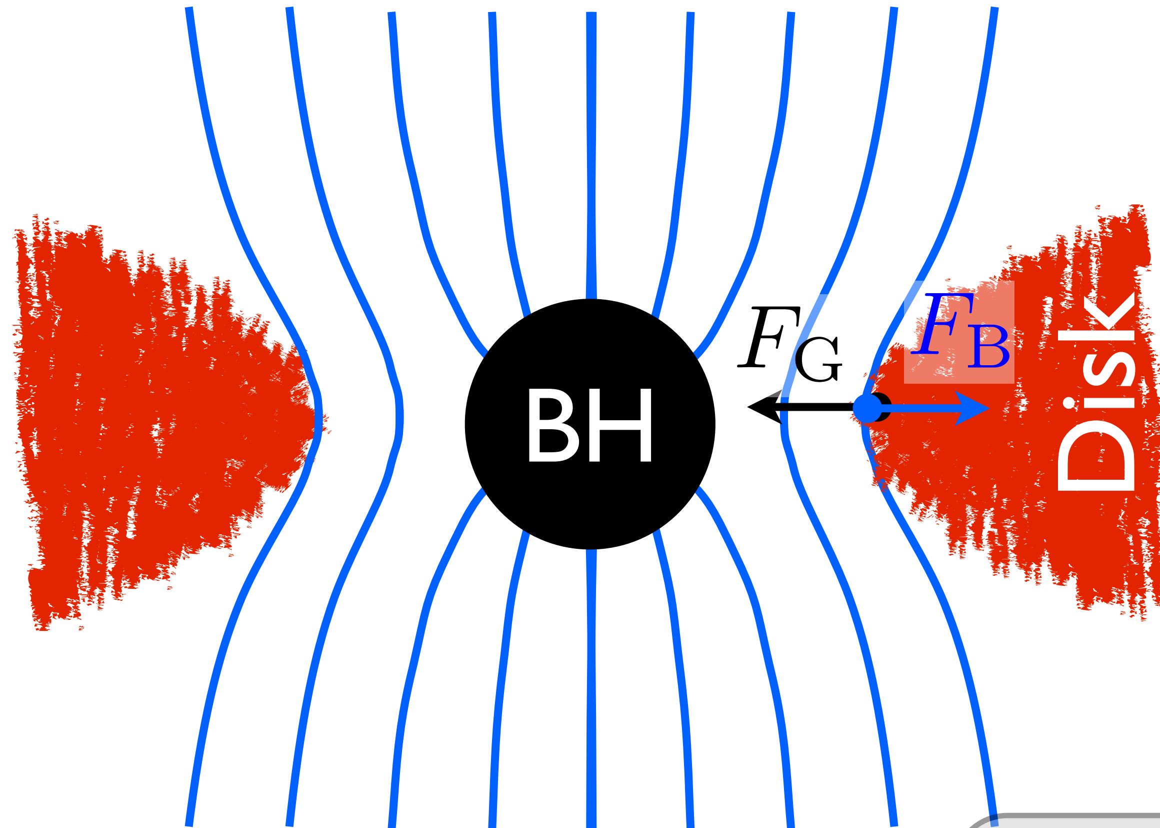

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$$P_j = k\Phi^2$$

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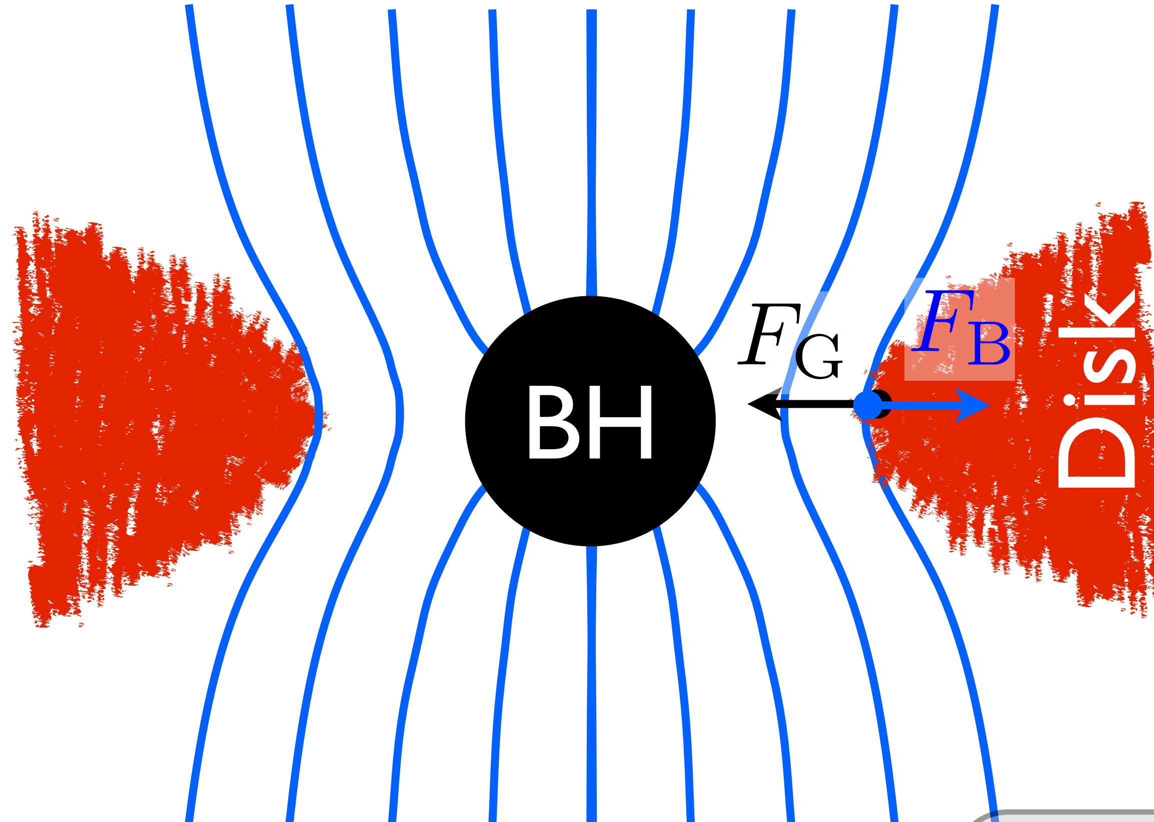

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B sub-dominant

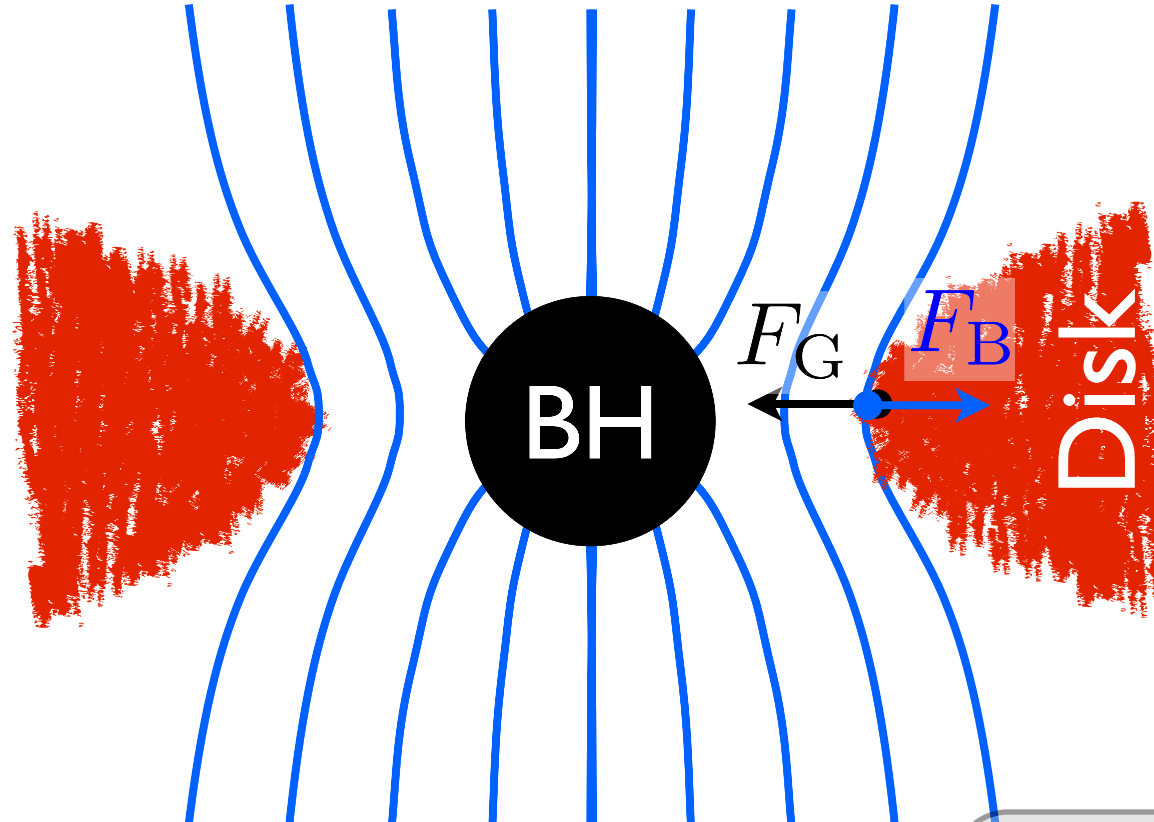
$$0 \le P_j = k\Phi^2$$

$$\Updownarrow$$

$$\Phi = 0$$

What Sets Jet Power?

Gravity limits P_j and Φ!



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B sub-dominant $\updownarrow$ $\Phi = 0$

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

B dominant $\updownarrow$ $\Phi = \Phi_{\mathrm{MAX}}$

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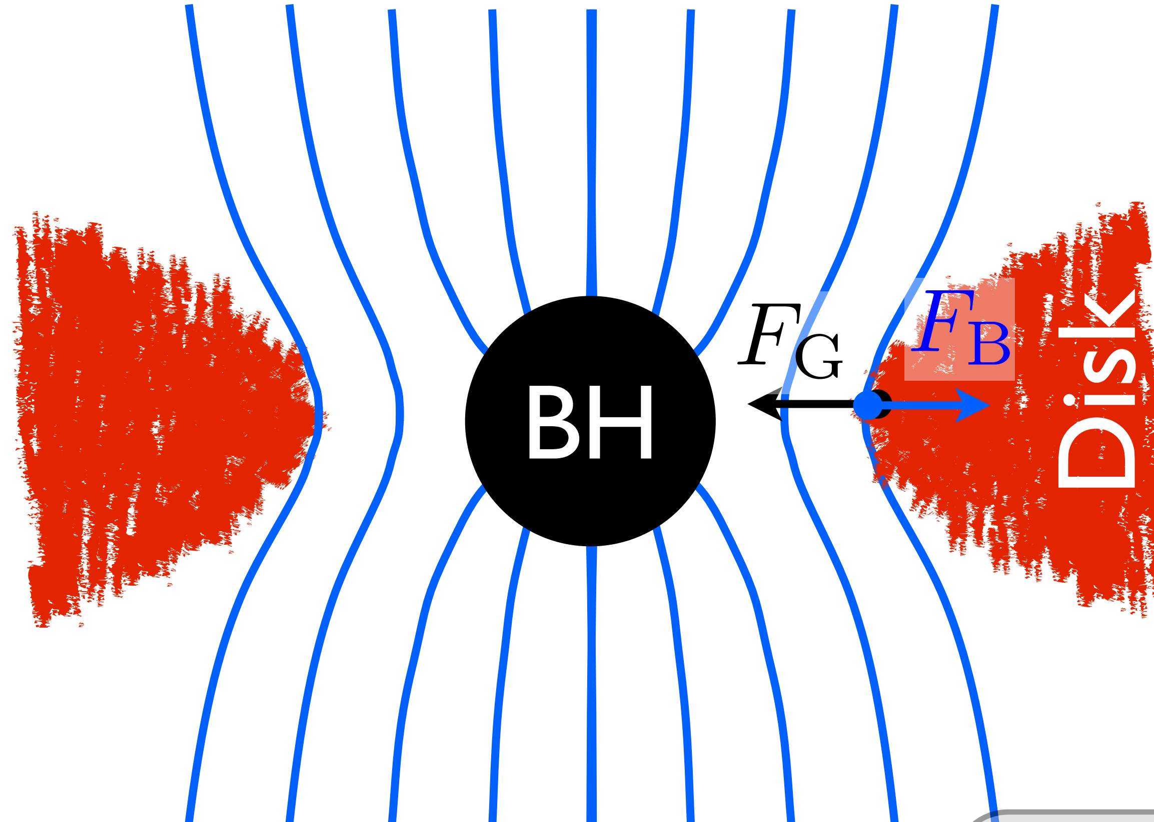
Gravity limits P_j and Φ!



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B dominant
Magnetically-Arrested Disk (MAD)

(Narayan+ 2003, AT+ 2011)

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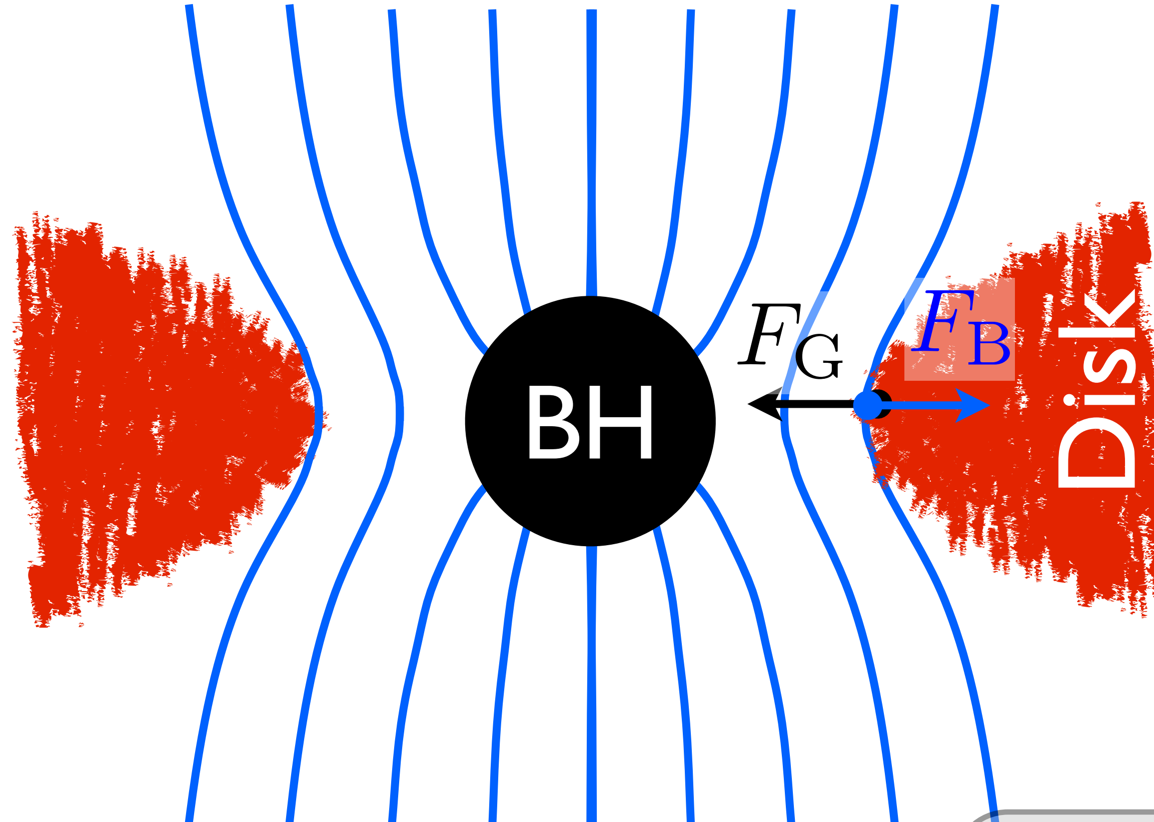

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B dominant
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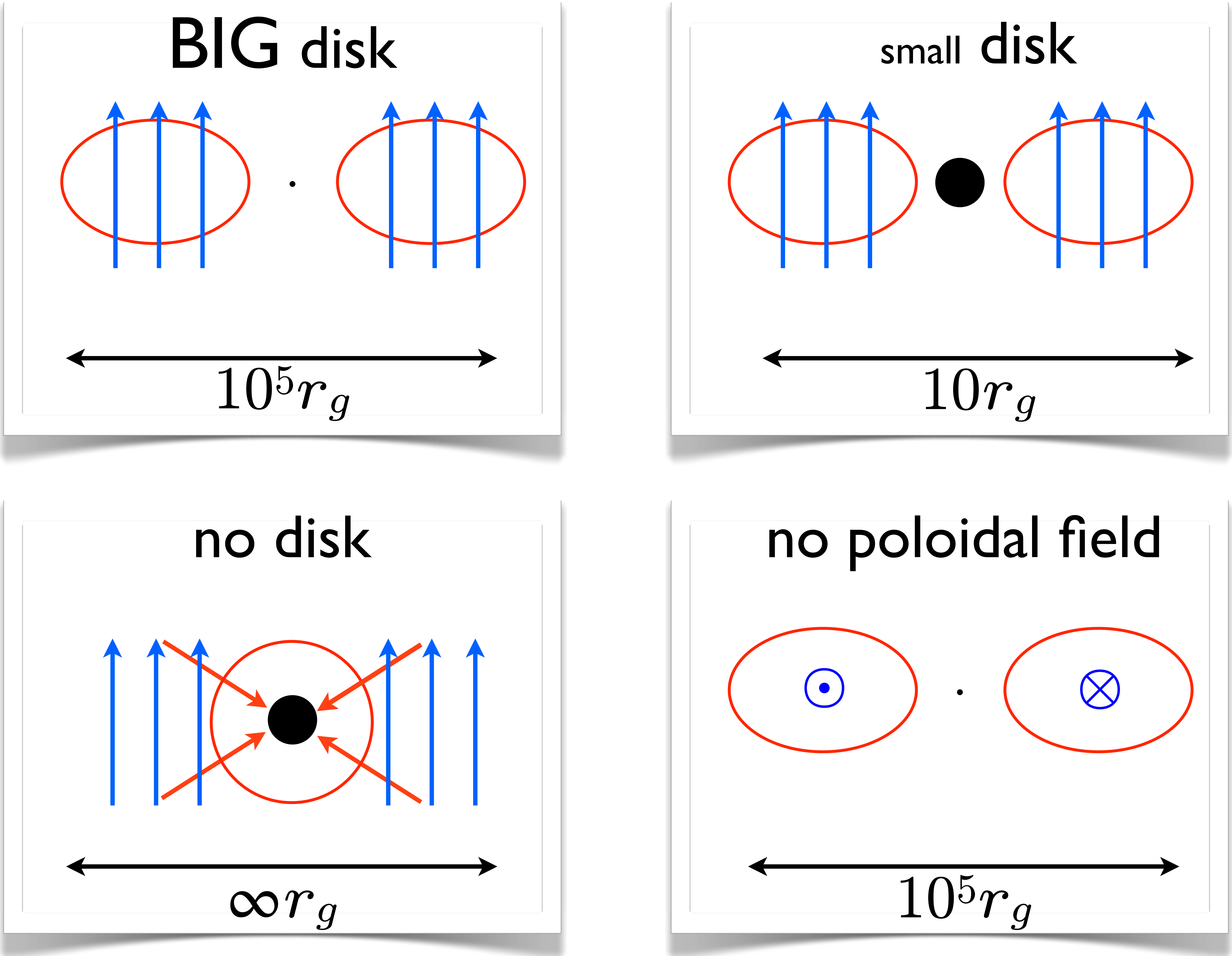
How strong are the jets?

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

What is a Healthy Jet Diet?



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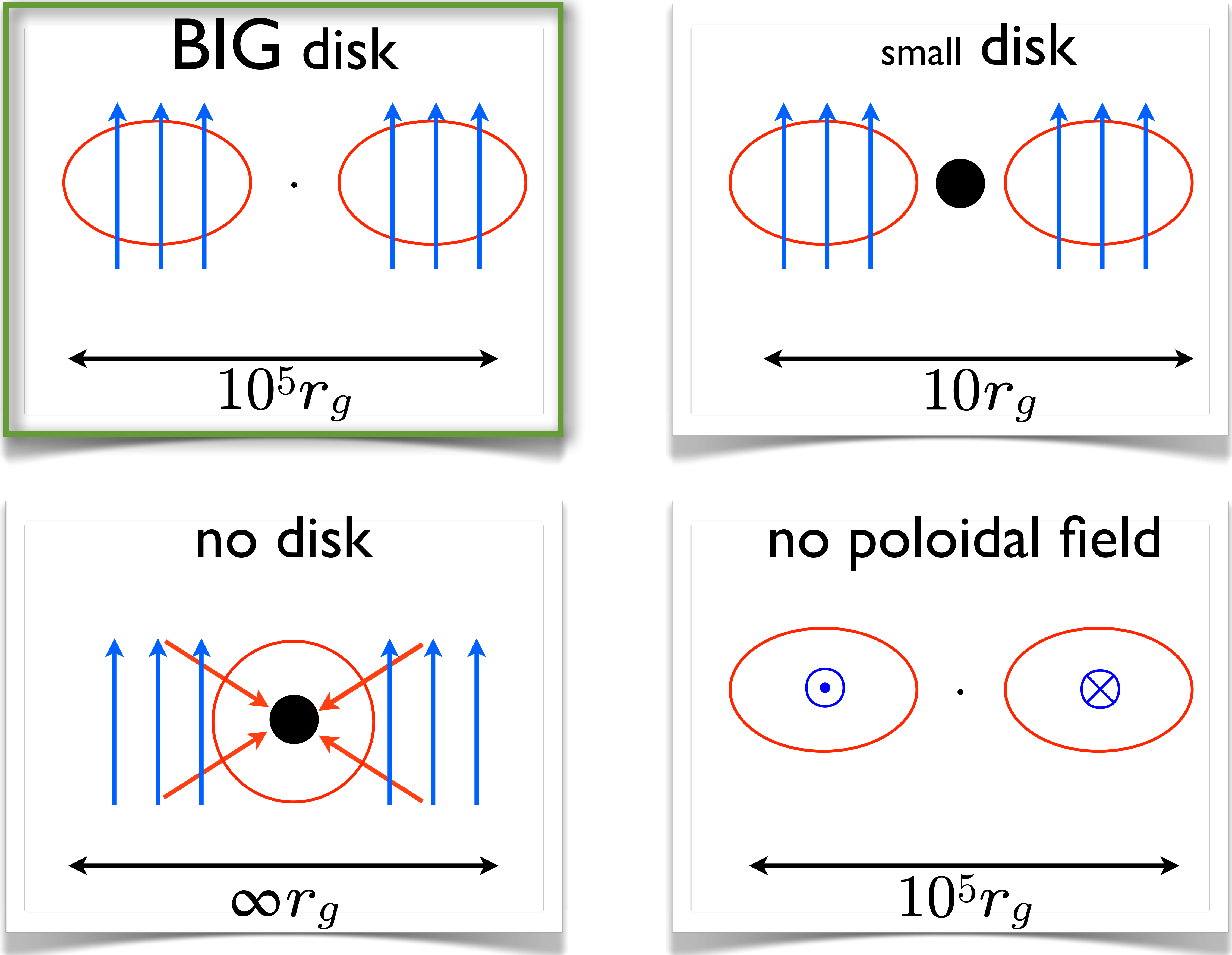
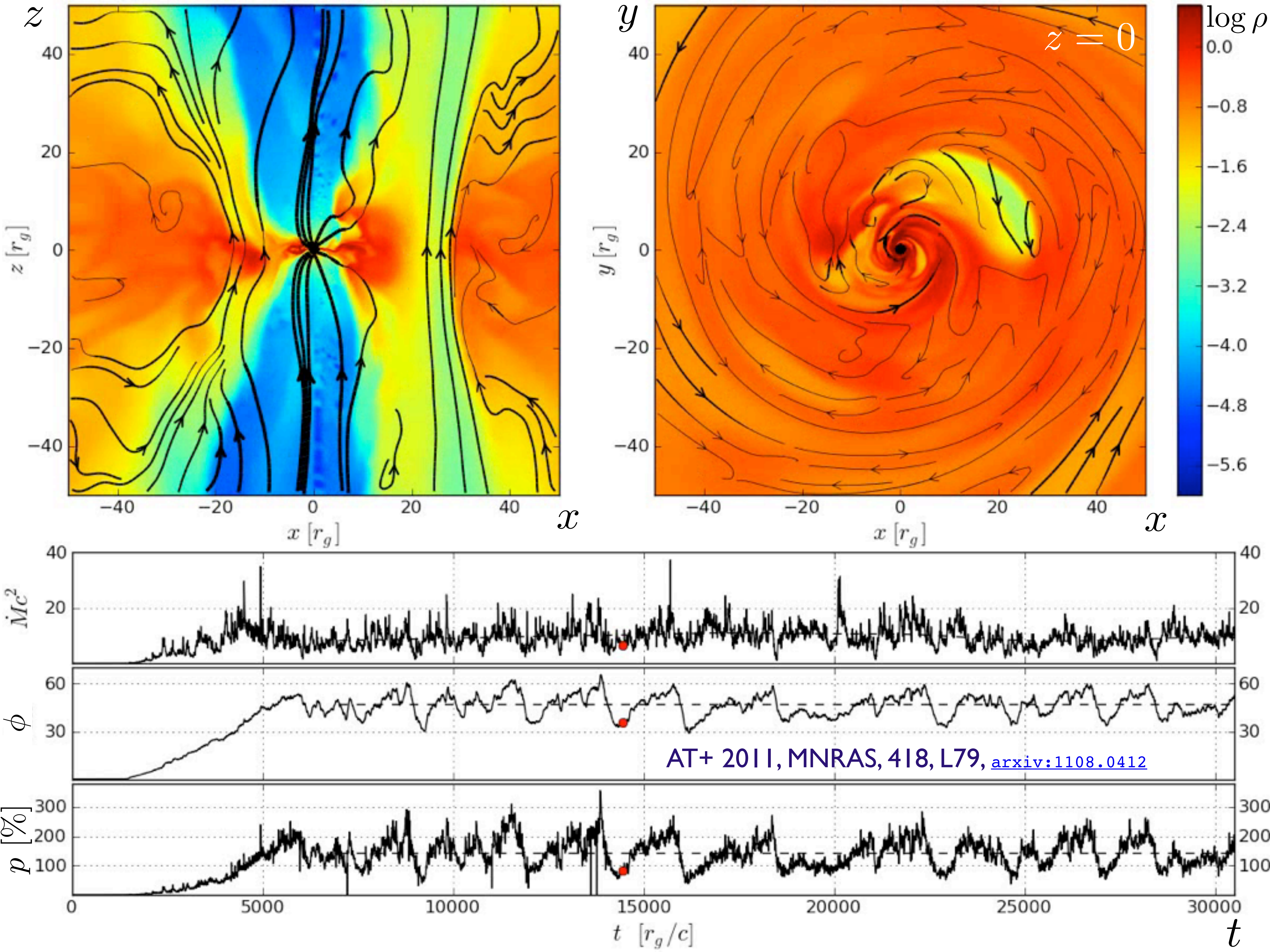
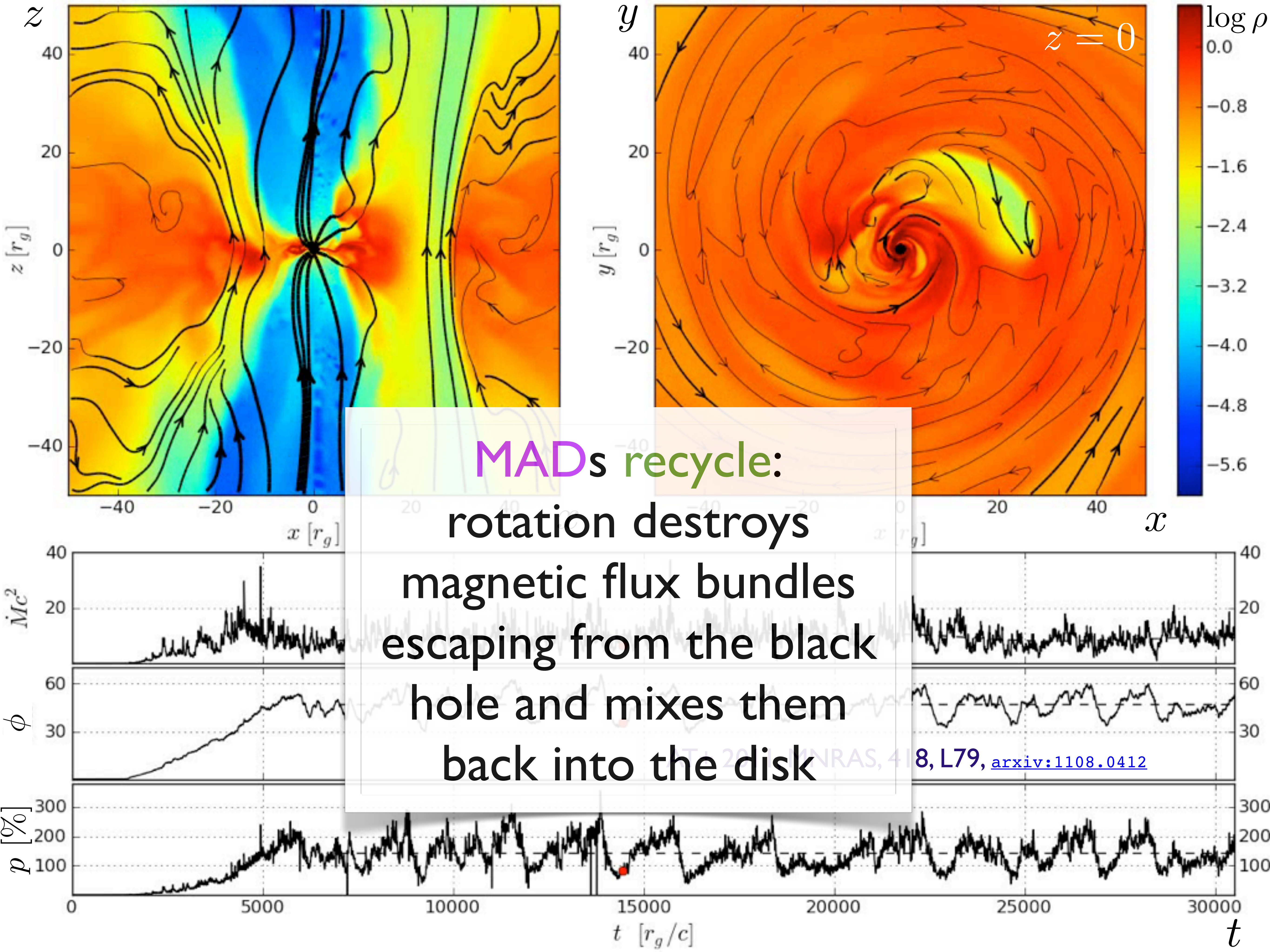




z
y
log ρ
z = 0
x [r_g]
z [r_g]
y [r_g]
x
t
Ṁc²
φ
p [%]
t [r_g/c]
AT+ 2011, MNRAS, 418, L79, arxiv:1108.0412

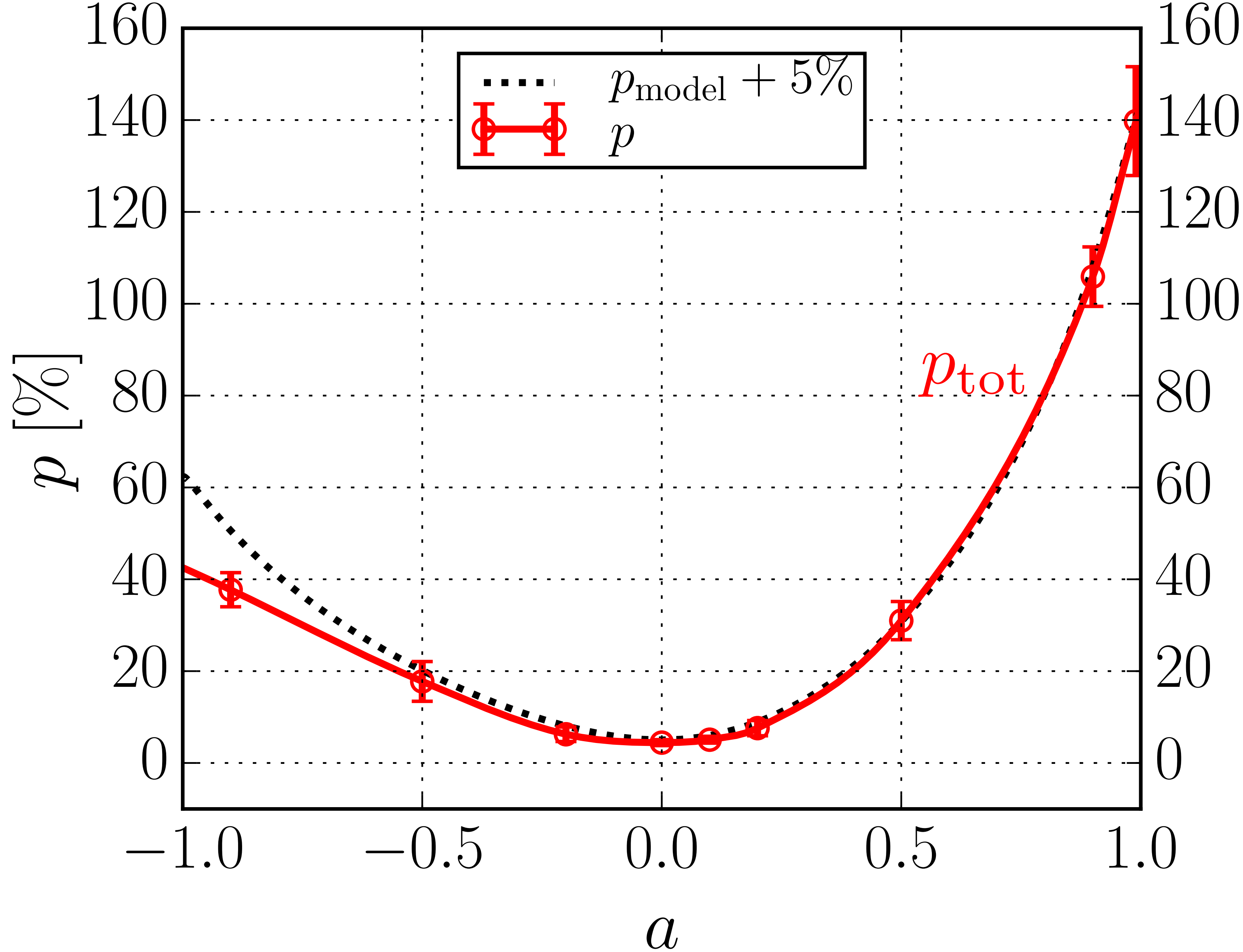


MADs recycle:
rotation destroys
magnetic flux bundles
escaping from the black
hole and mixes them
back into the disk

Upper Envelope of Jet Power vs. Spin

$(h/r \sim 0.3)$

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



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

$p > 100\%$ means net energy is extracted from the BH

Upper Envelope of Jet Power vs. Spin

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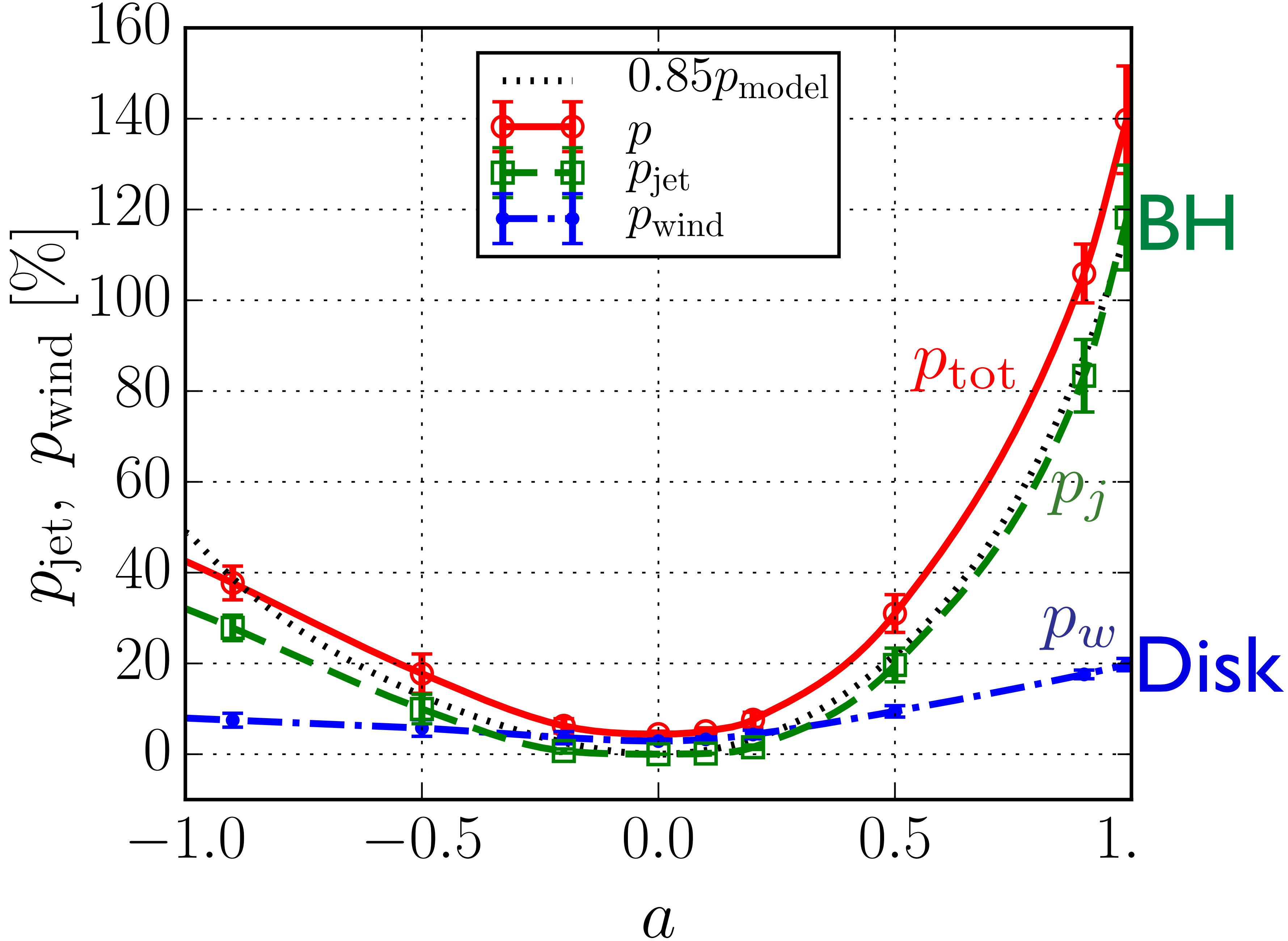

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Jet = 85% of Blandford-Znajek power

Wind = BP = 15% of BZ power + 5%

Disk wind is powered by a combination of BH spin and disk rotation

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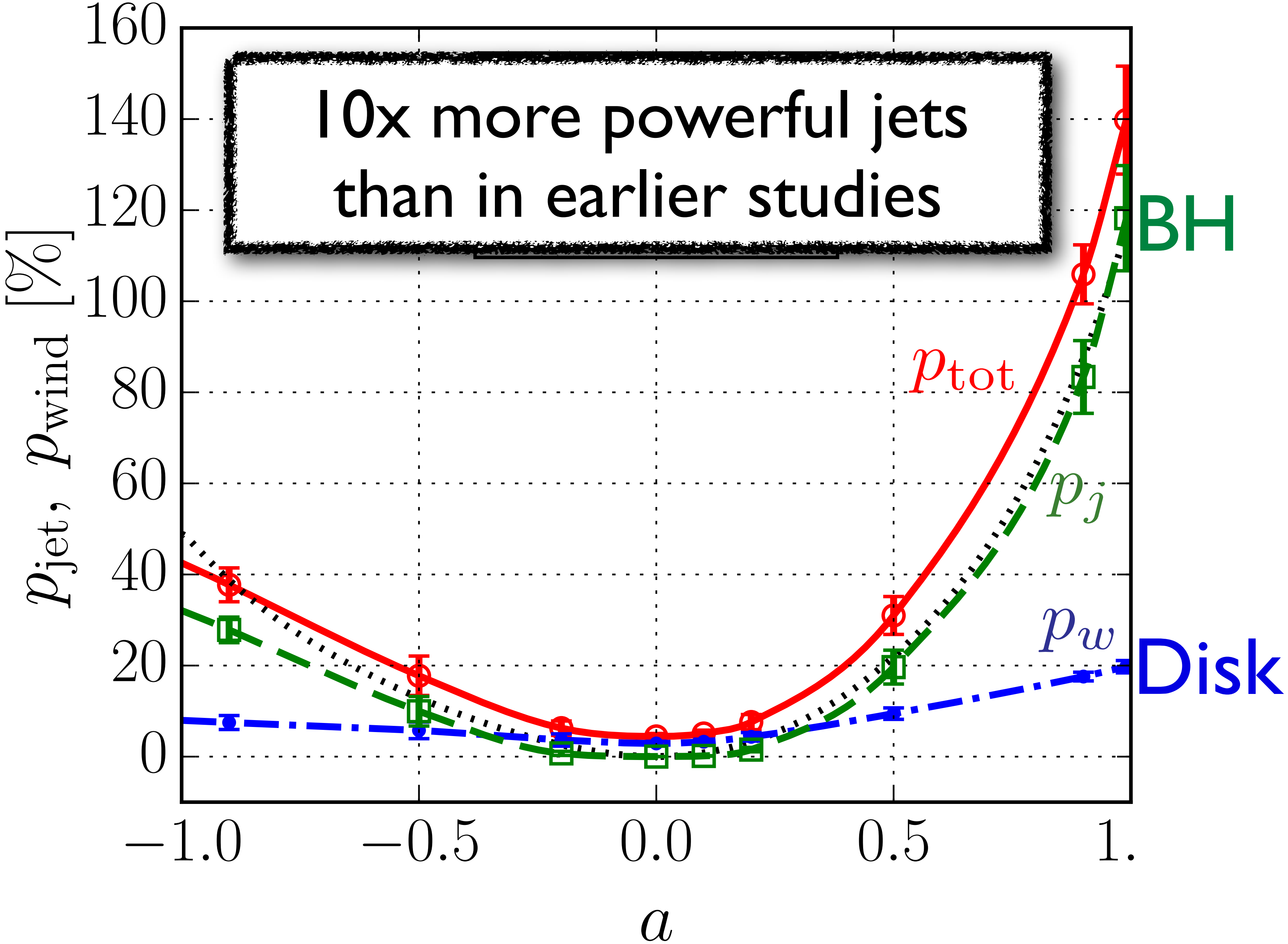

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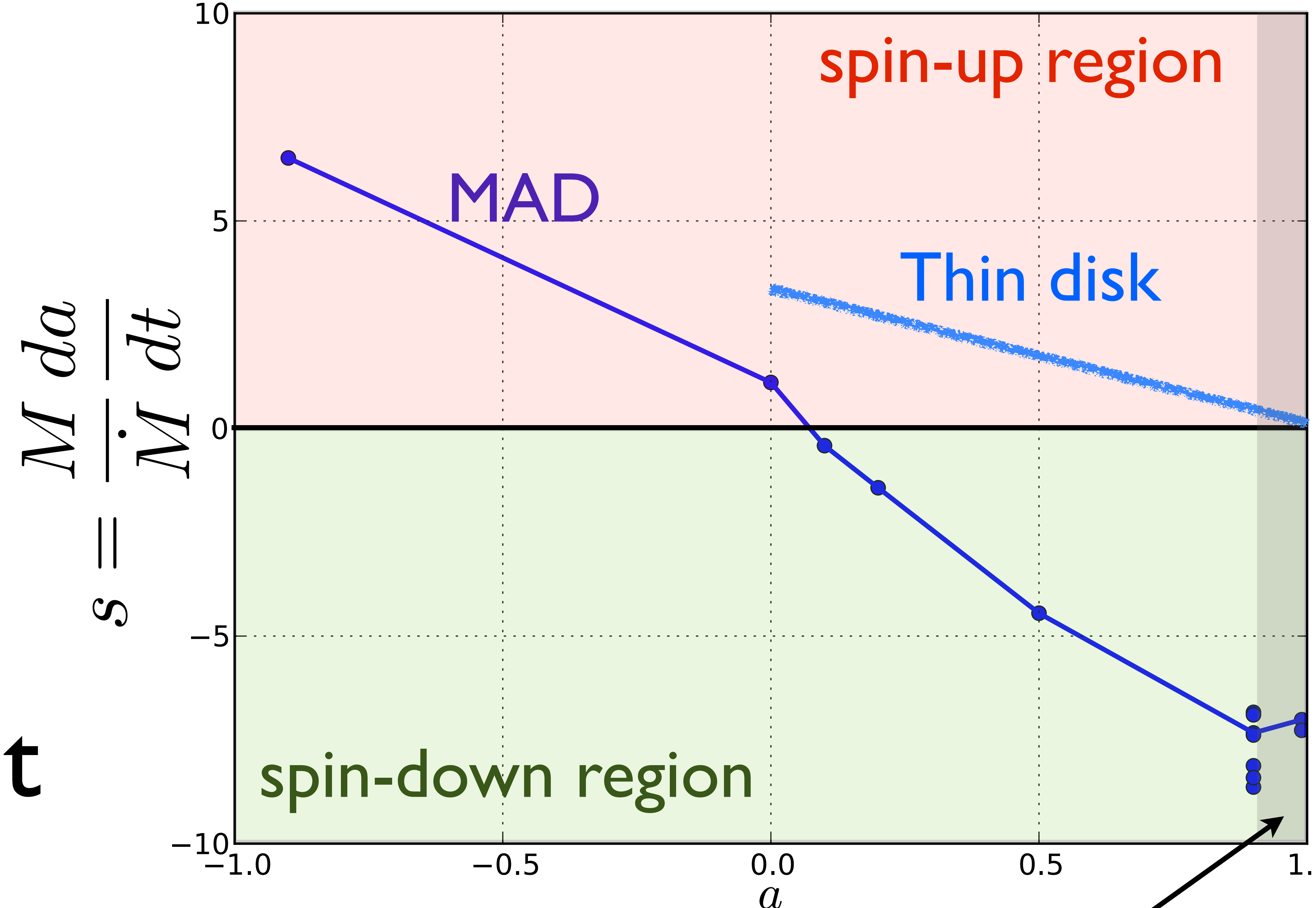
Our MADs slow down BHs to a halt

(Tchekhovskoy, McKinney 2012a, MNRAS, 423, 55; Tchekhovskoy 2015)



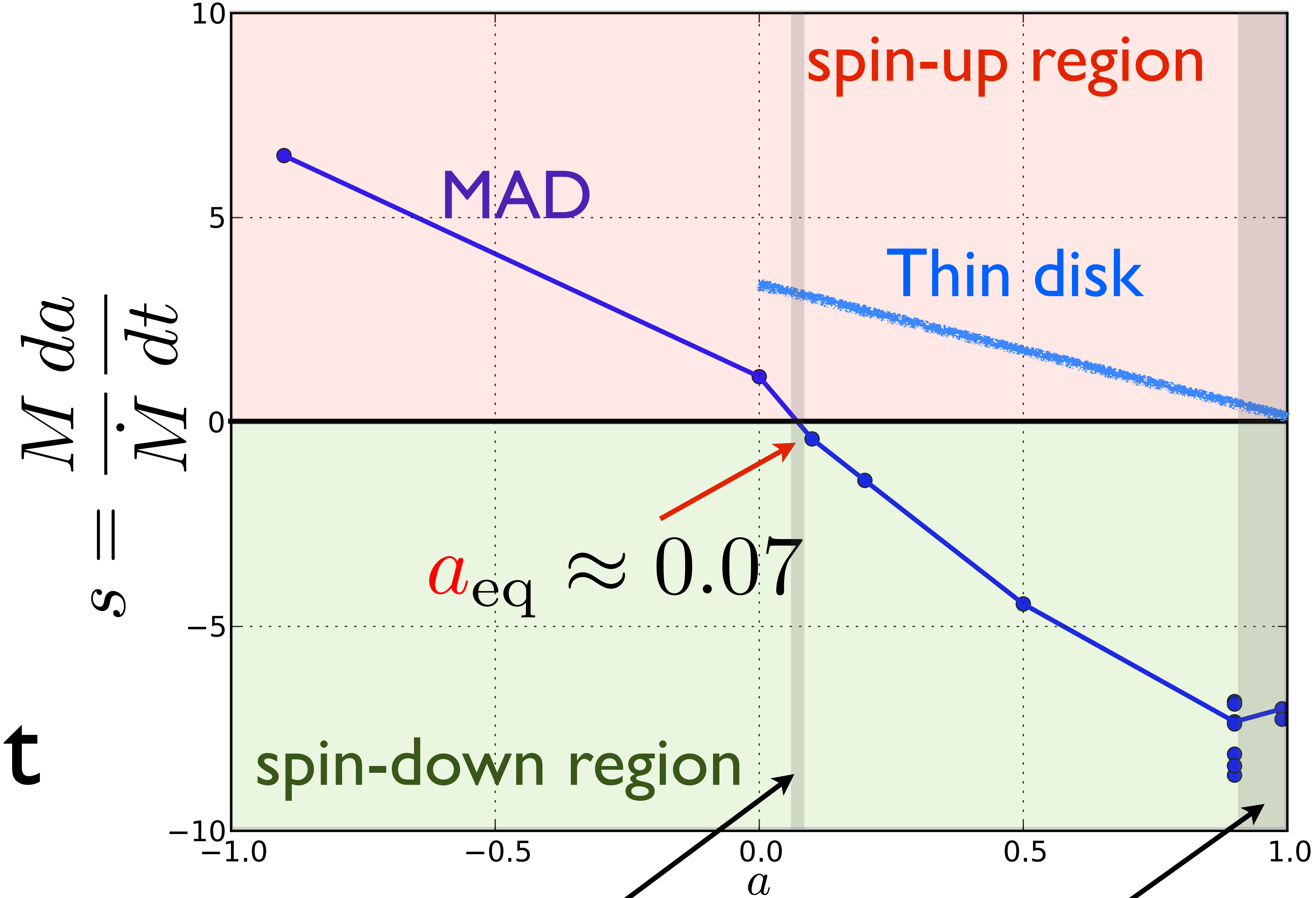
Conventional spin equilibrium region, $a \gtrsim 0.9$

(see also Thorne 1974, Gammie et al. 2005, Shapiro et al. 2005, Benson & Babul 2009)

tilted1 2

Our MADs slow BHs down to a halt

(Tchekhovskoy, McKinney 2012a, MNRAS, 423, 55; Tchekhovskoy 2015)



MAD spin equilibrium

Conventional spin equilibrium region, $a \gtrsim 0.9$

(see also Thorne 1974, Gammie et al. 2005, Shapiro et al. 2005, Benson & Babul 2009)

tilted12

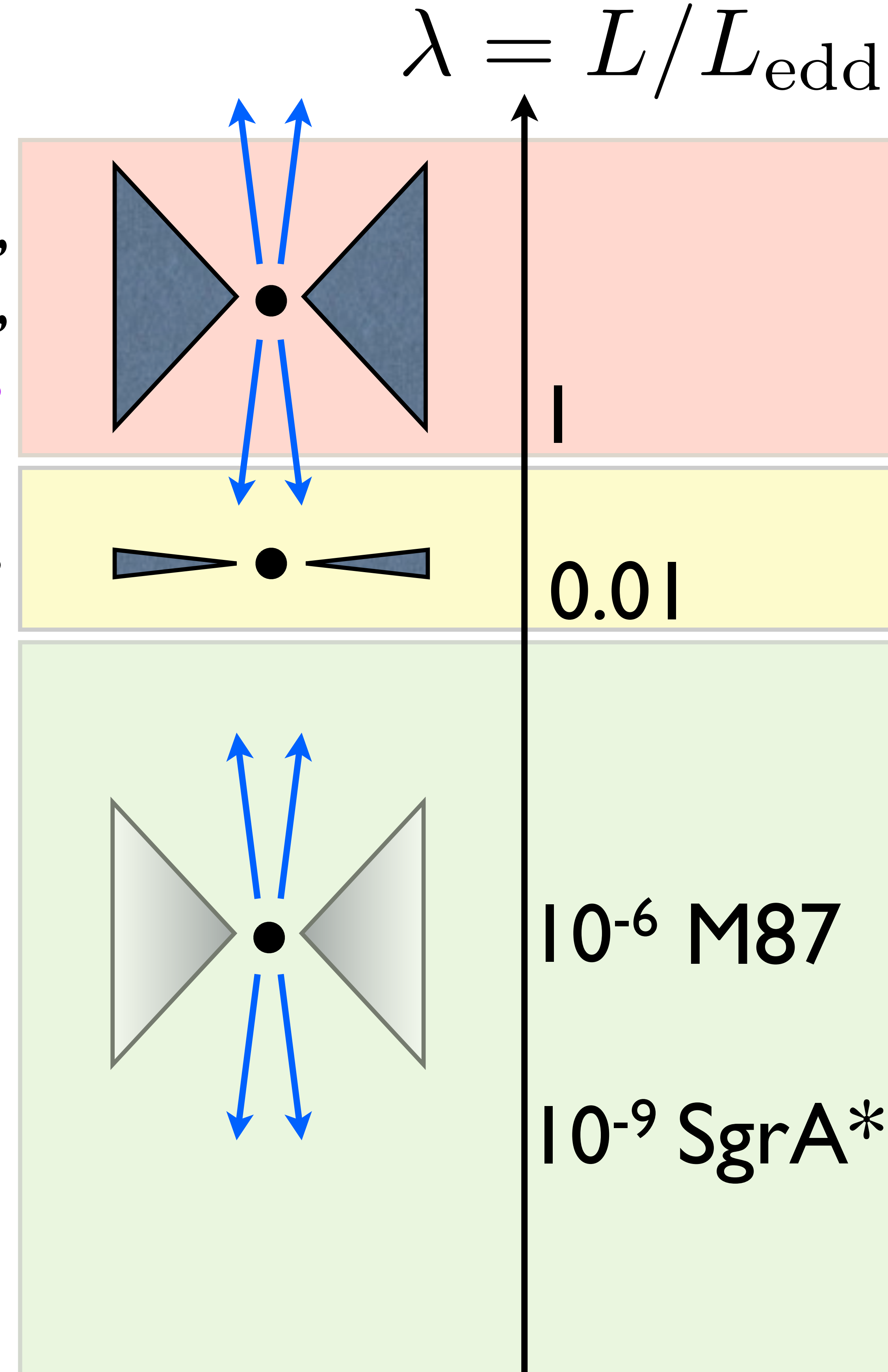
When are Jets Produced?

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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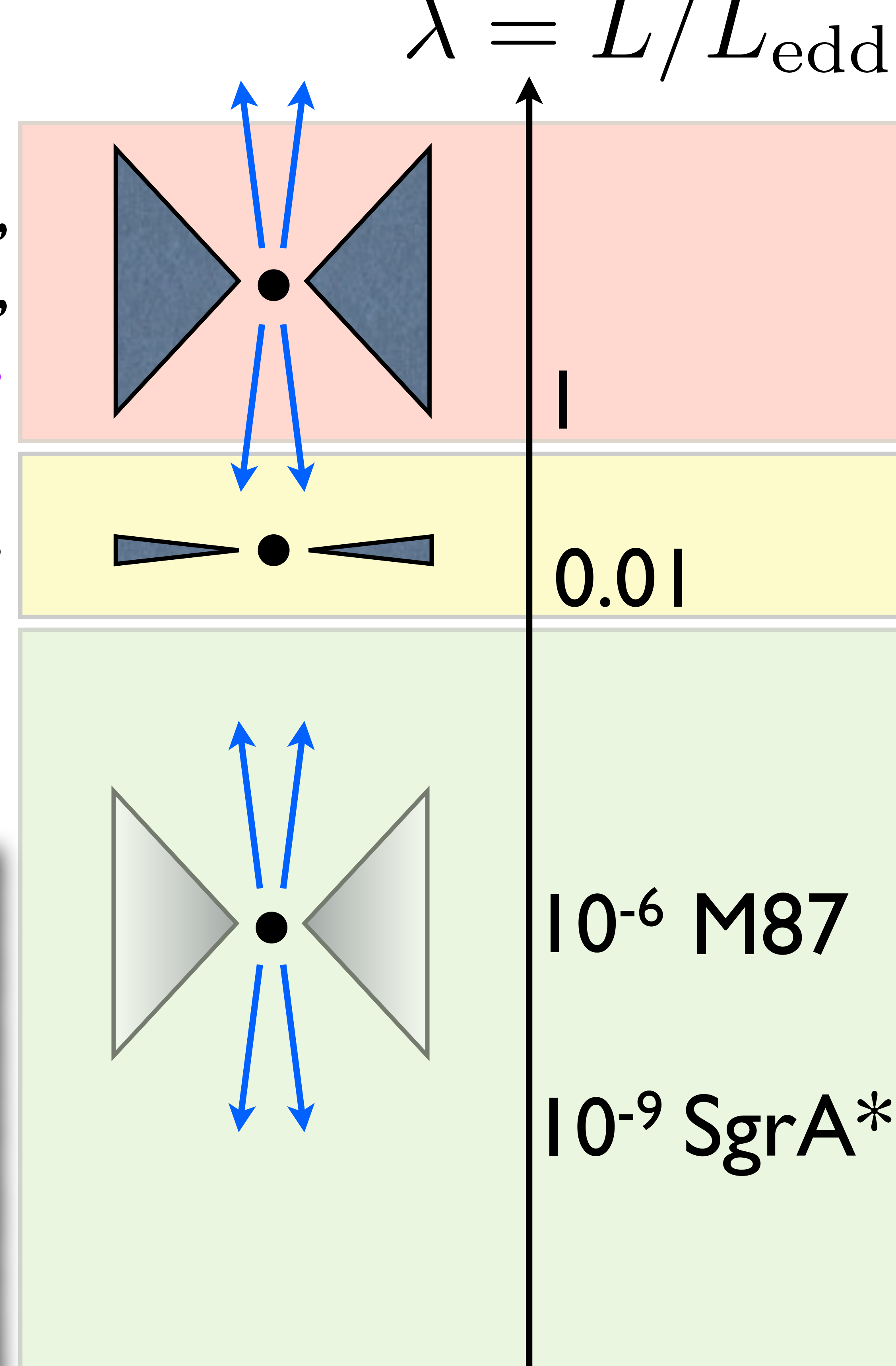
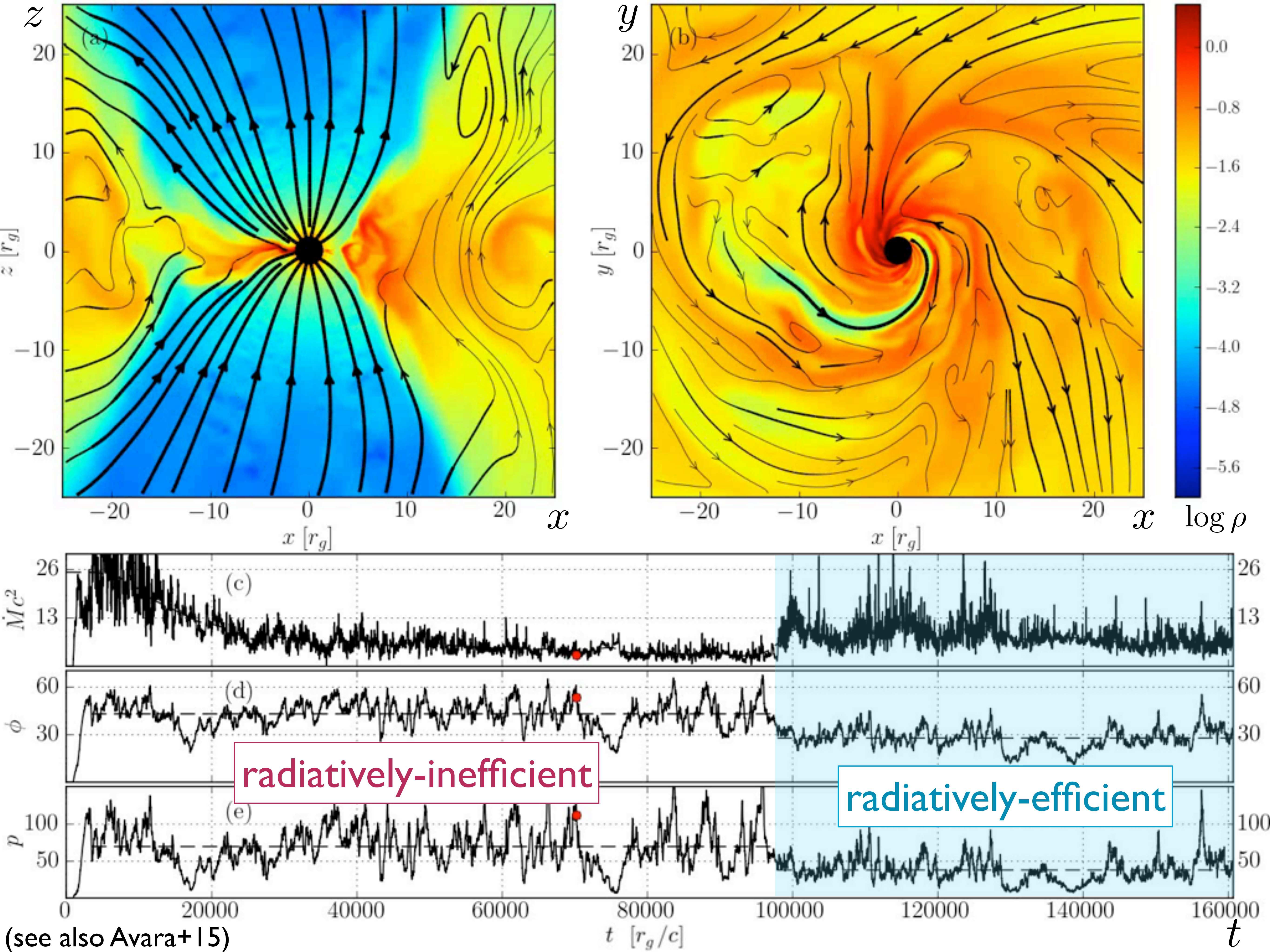
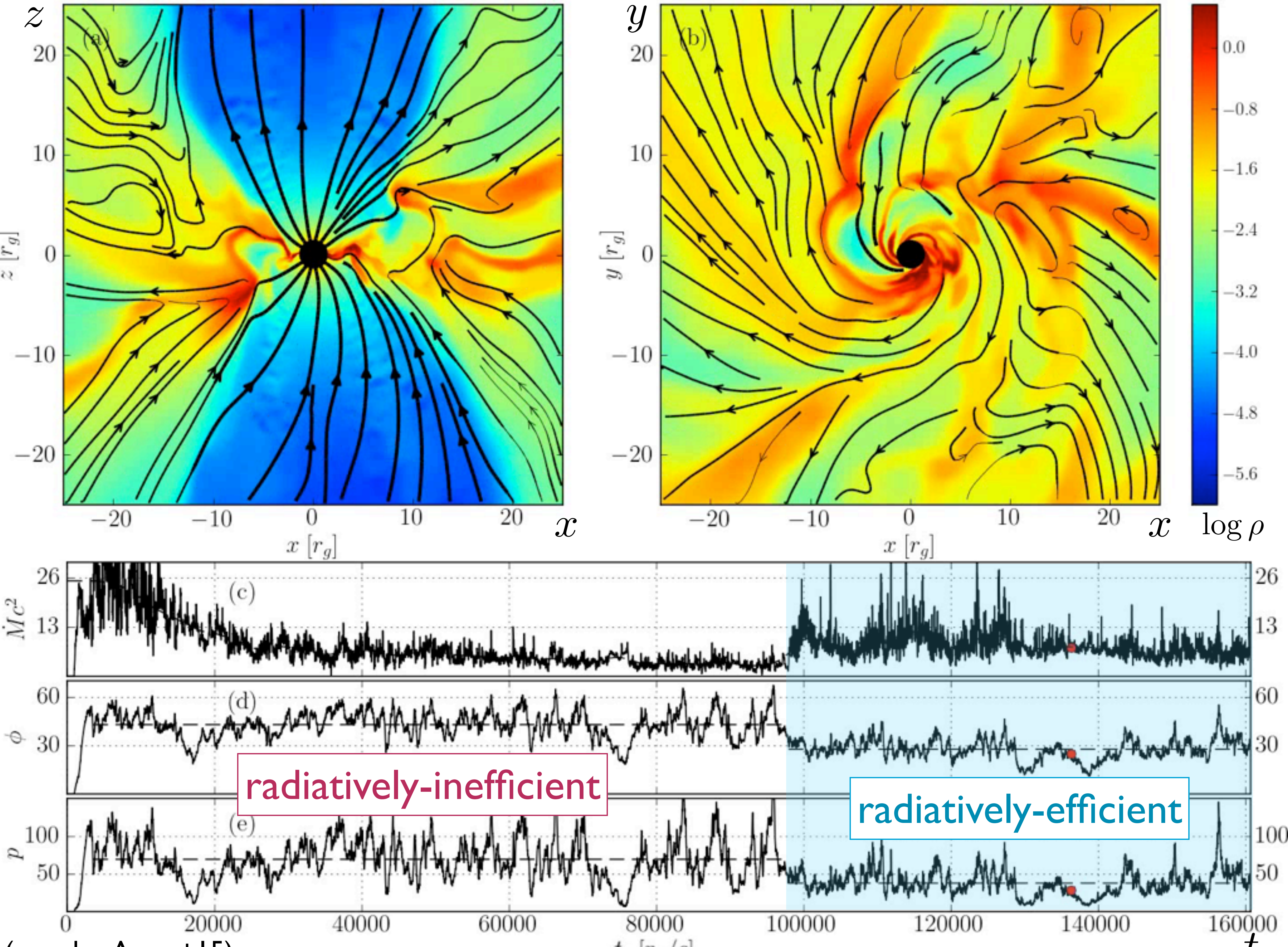


- Can radiatively-efficient disks drag large-scale magnetic flux in and make powerful jets?
- Analytical studies: does not seem so! (Lubow et al 1994, Guilet & Oglivie 2013a,b)
- But then, how do quasars make jets?



(see also Avara+15)



(see also Avara+15)

How strong is B in Blazars?

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

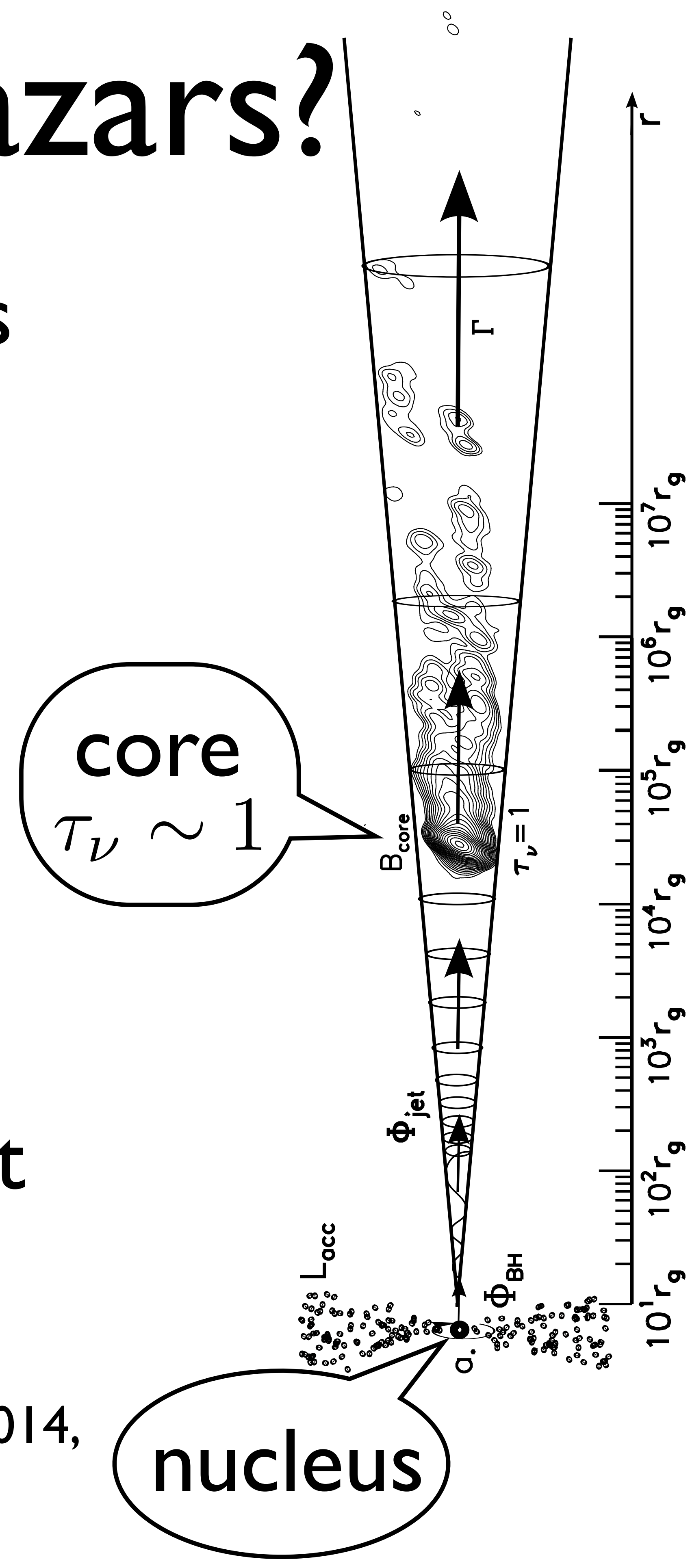
$$\tau_\nu \sim 1$$

- At higher ν, the core shifts inward

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

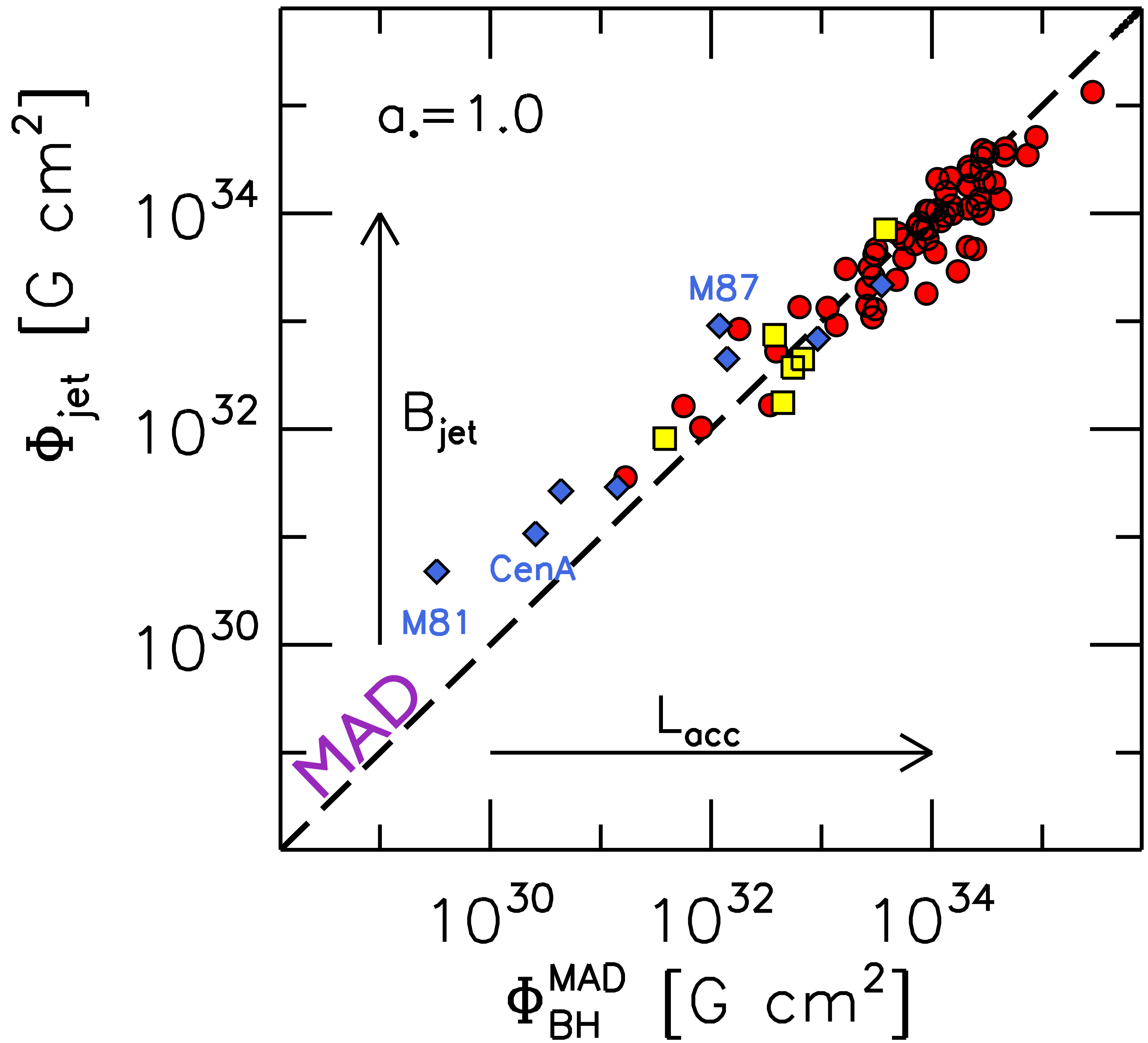
- Can use this to measure B in the jet
- Magnetic flux $\Phi \approx B\pi r_{\rm core}^2 \theta_j^2$

(Zamaninasab, Clausen-Brown, Savolainen, Tchekhovskoy, Nature, 2014, Zdziarski, Sikora, Pjanka, Tchekhovskoy, MNRAS, 2015)



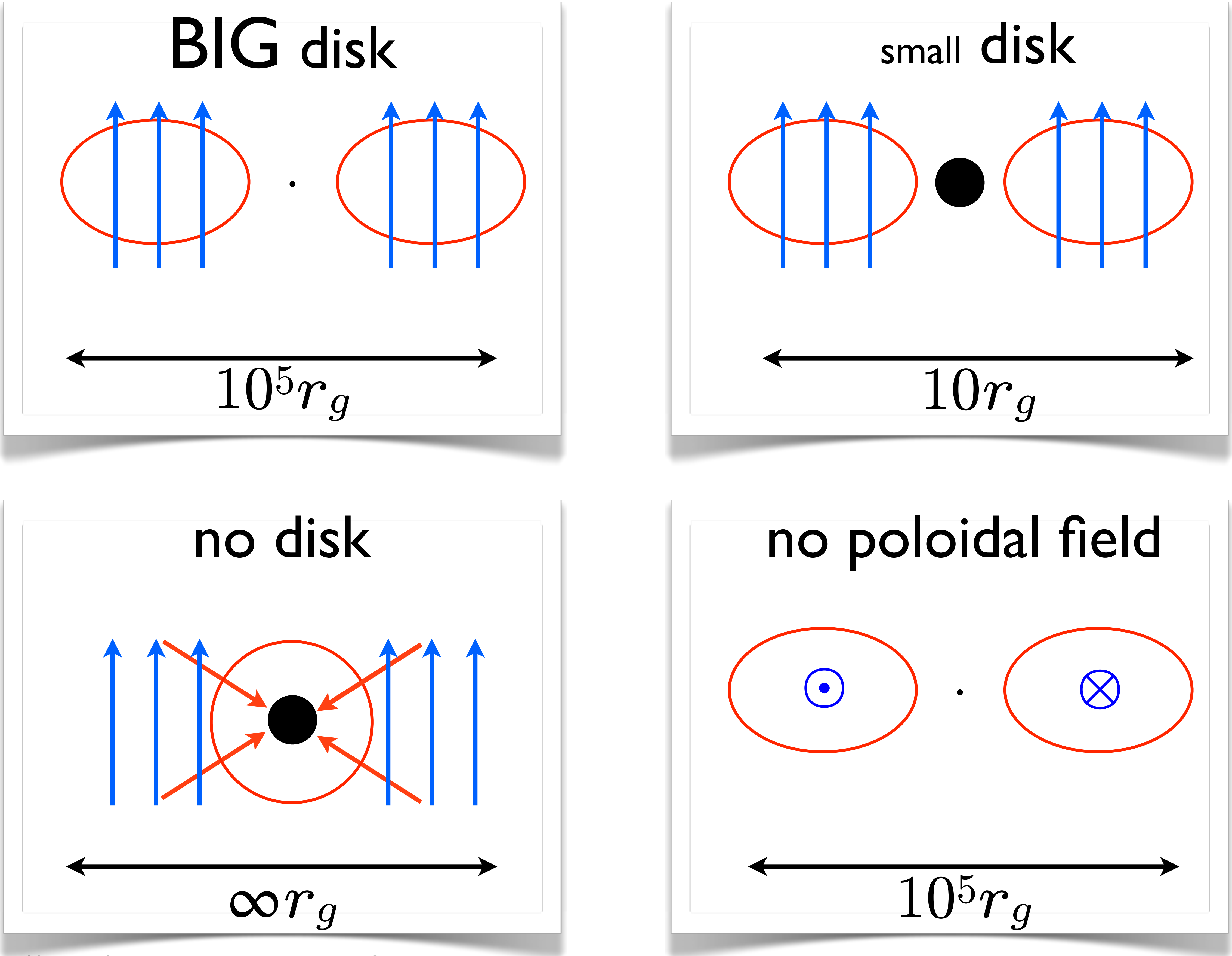
MADs in Blazars?

- Observed scaling:
  $$B_{\rm jet} \propto L_{\rm acc}^{1/2}$$
- Magnitude of magnetic flux in *radio-loud* AGN is consistent with MAD expectation (Tchekhovskoy, McKinney, Narayan, MNRAS, 2011)
- Many AGN are MAD
  - their central BHs are surrounded by *dynamically important magnetic field*



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

What is a Healthy Jet Diet?



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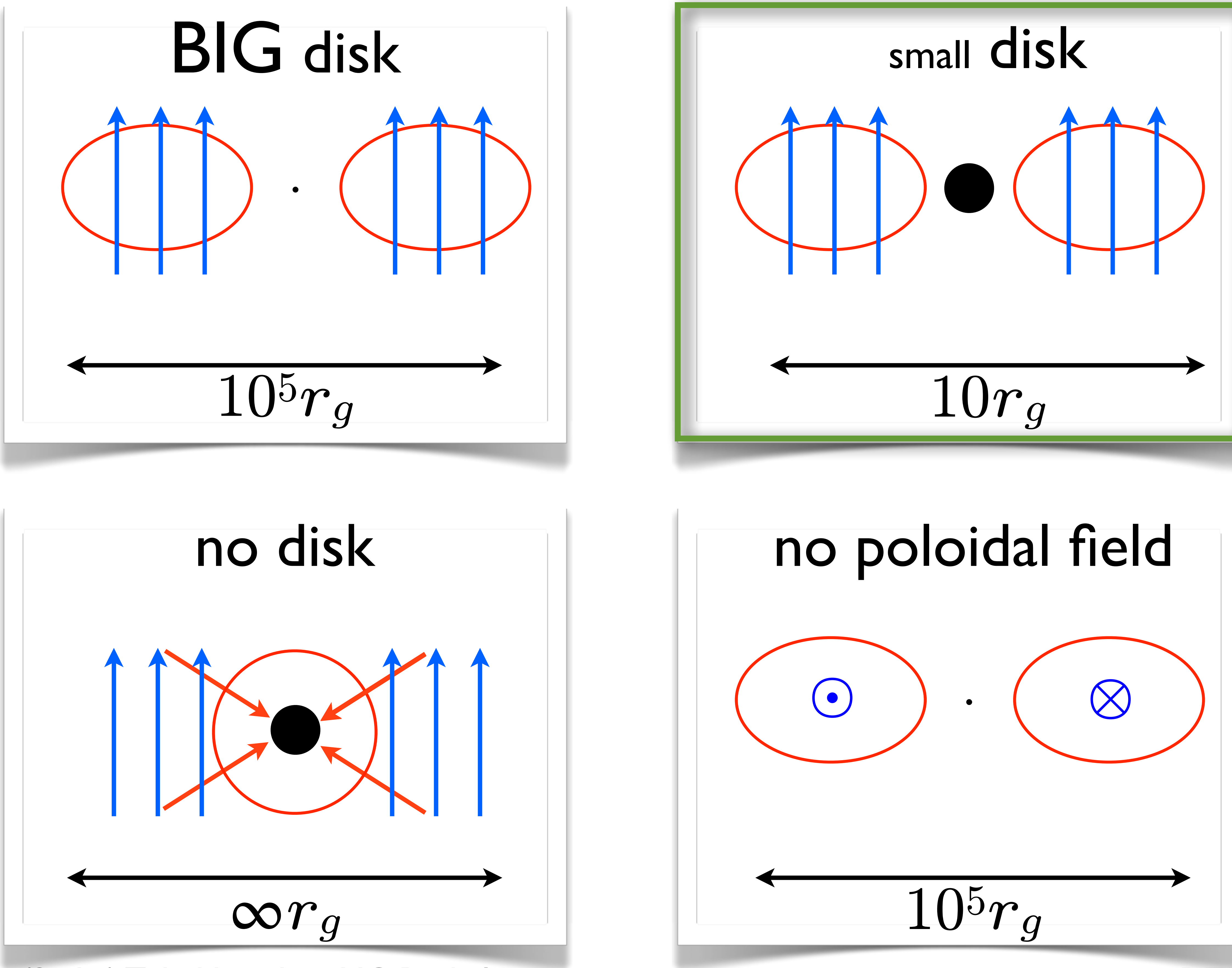
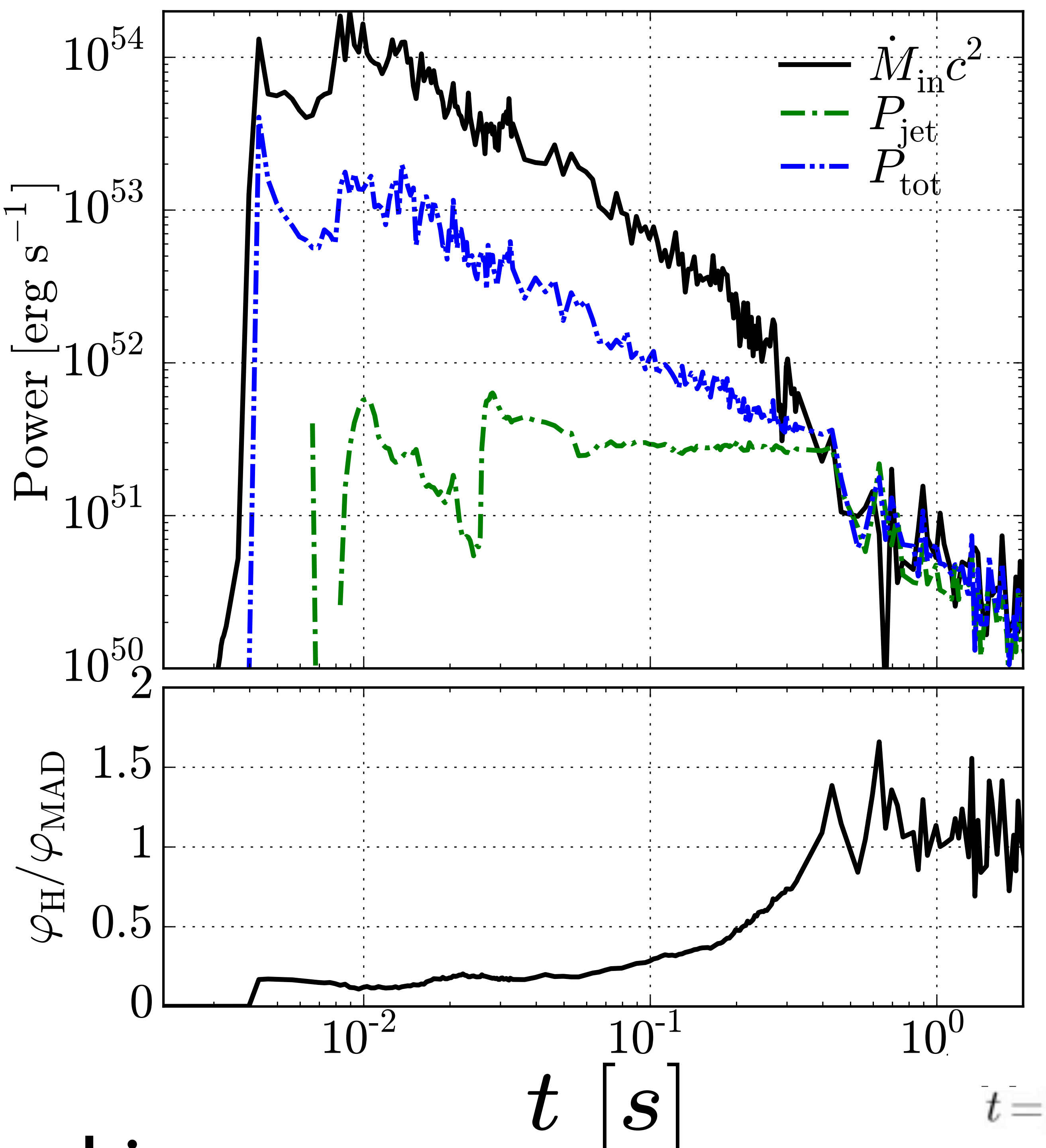
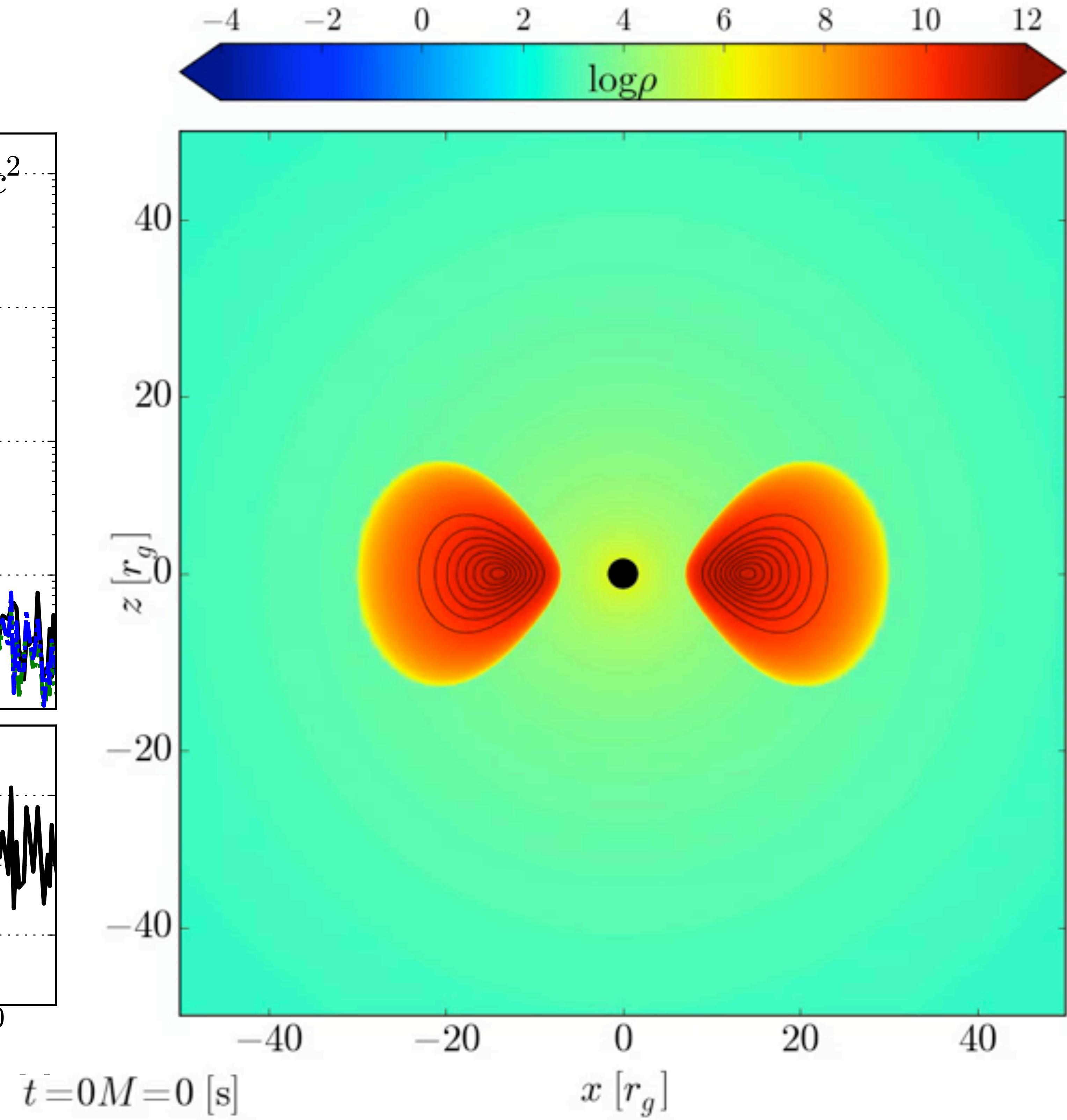


Binary Merger Disks Gone MAD

(AT, Fernandez, Foucart+, in prep)





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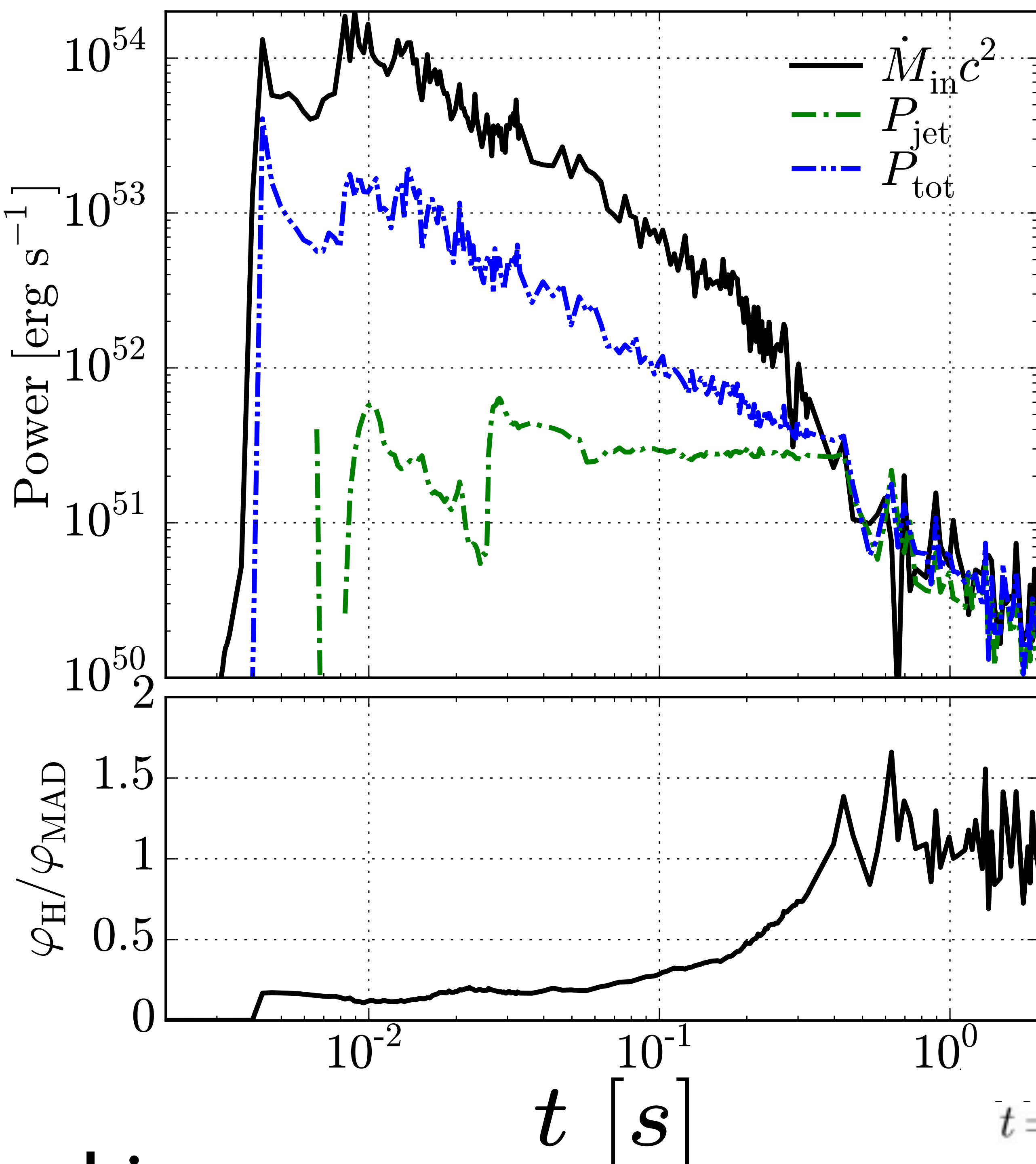

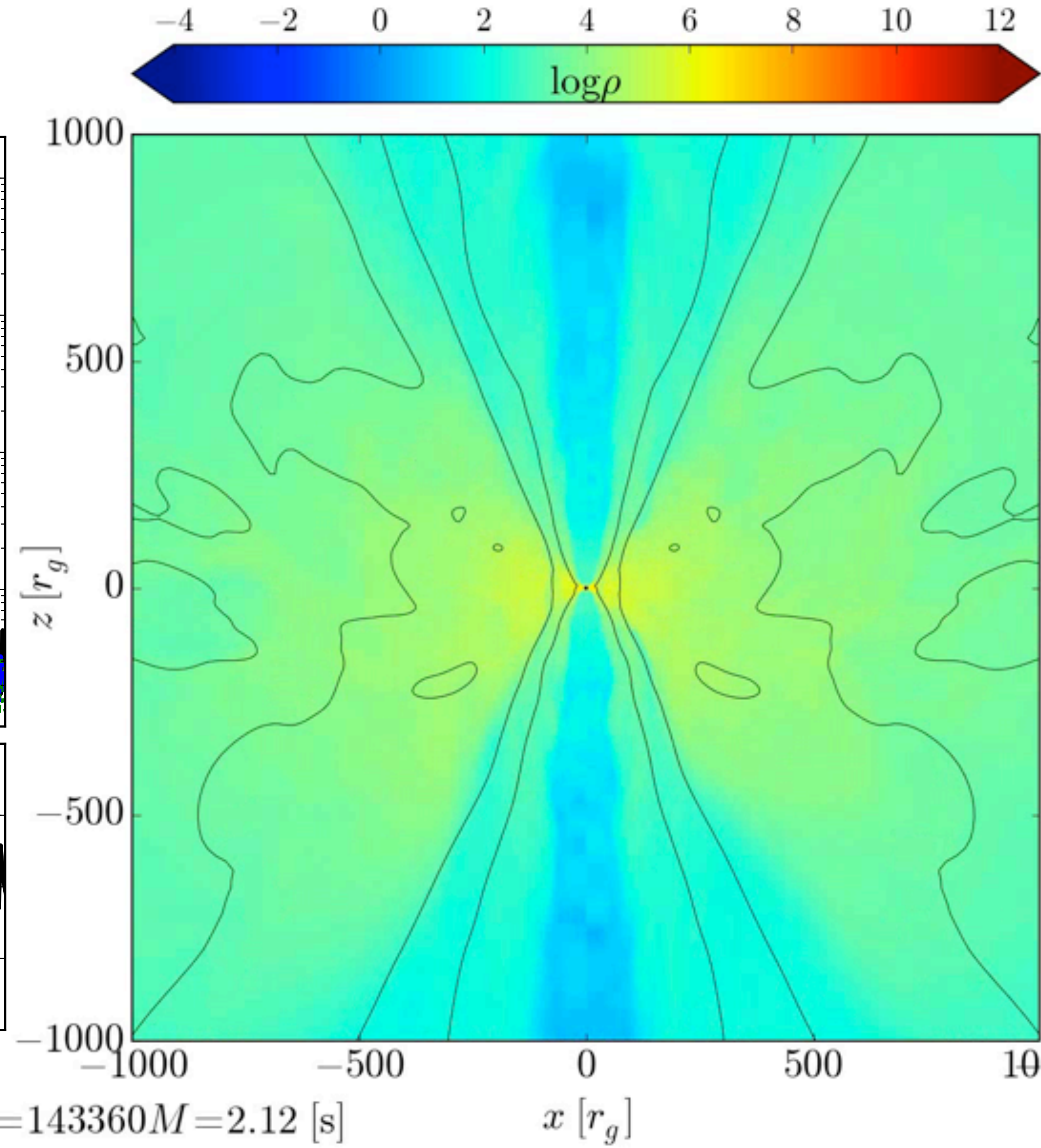

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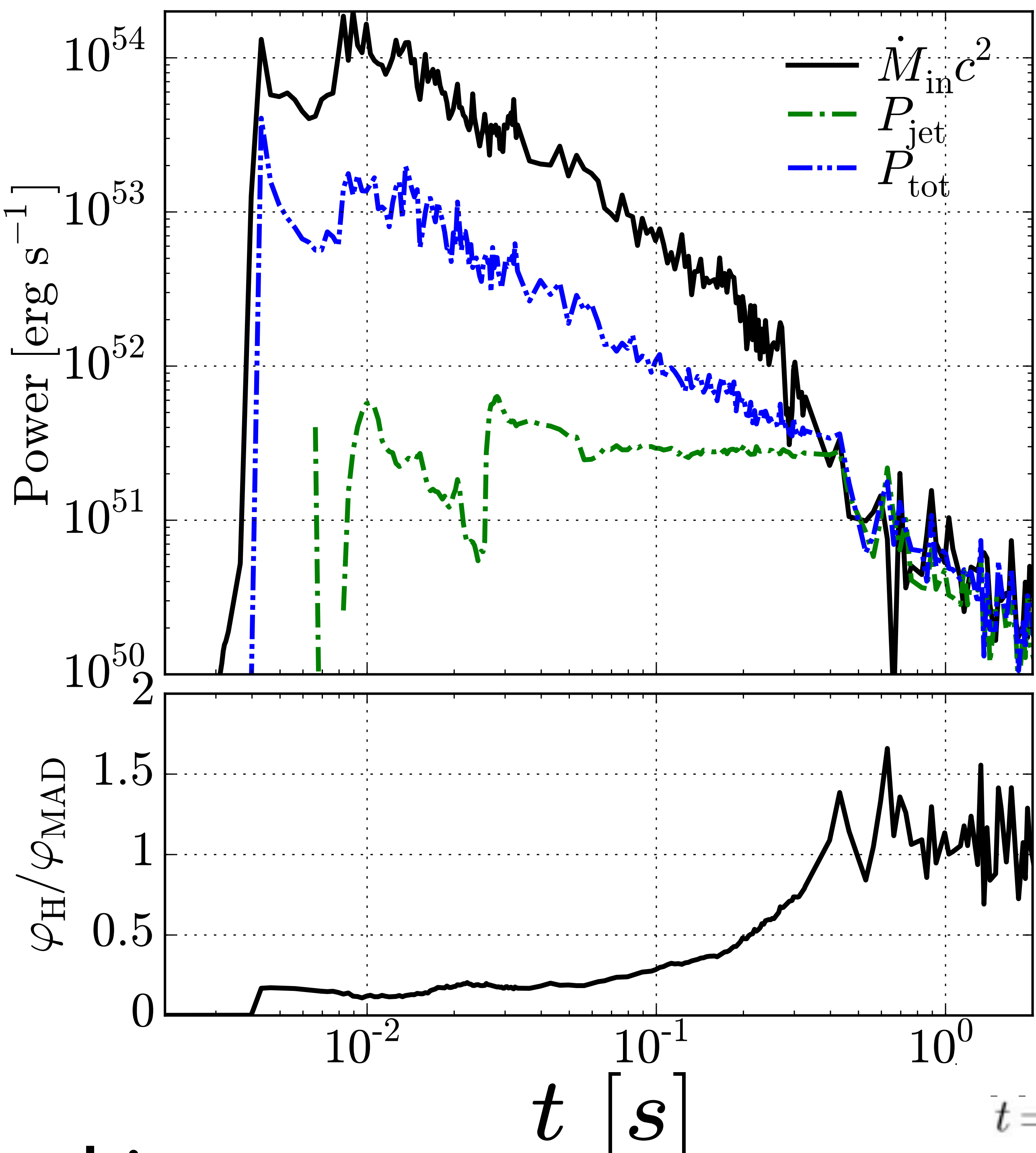
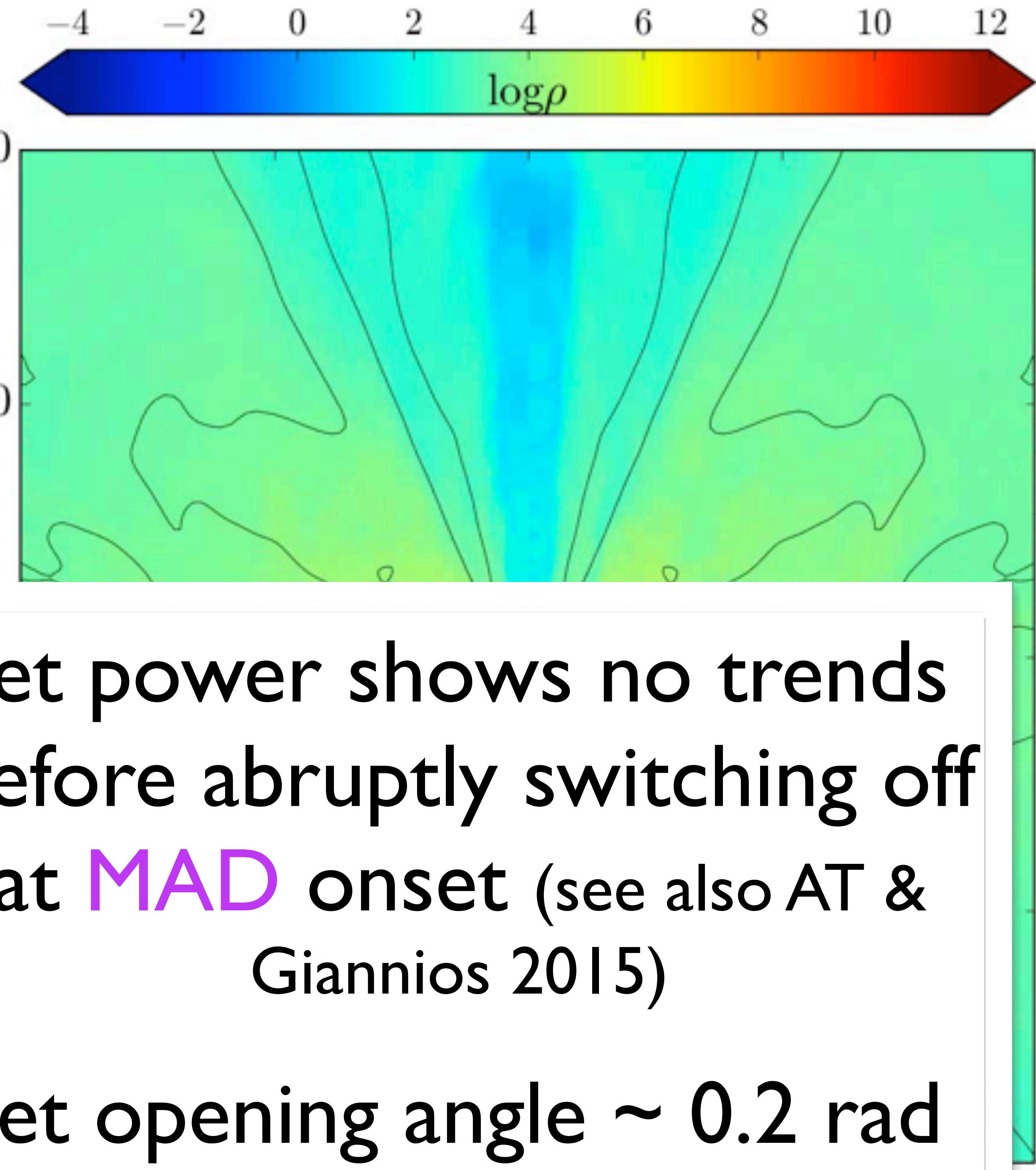


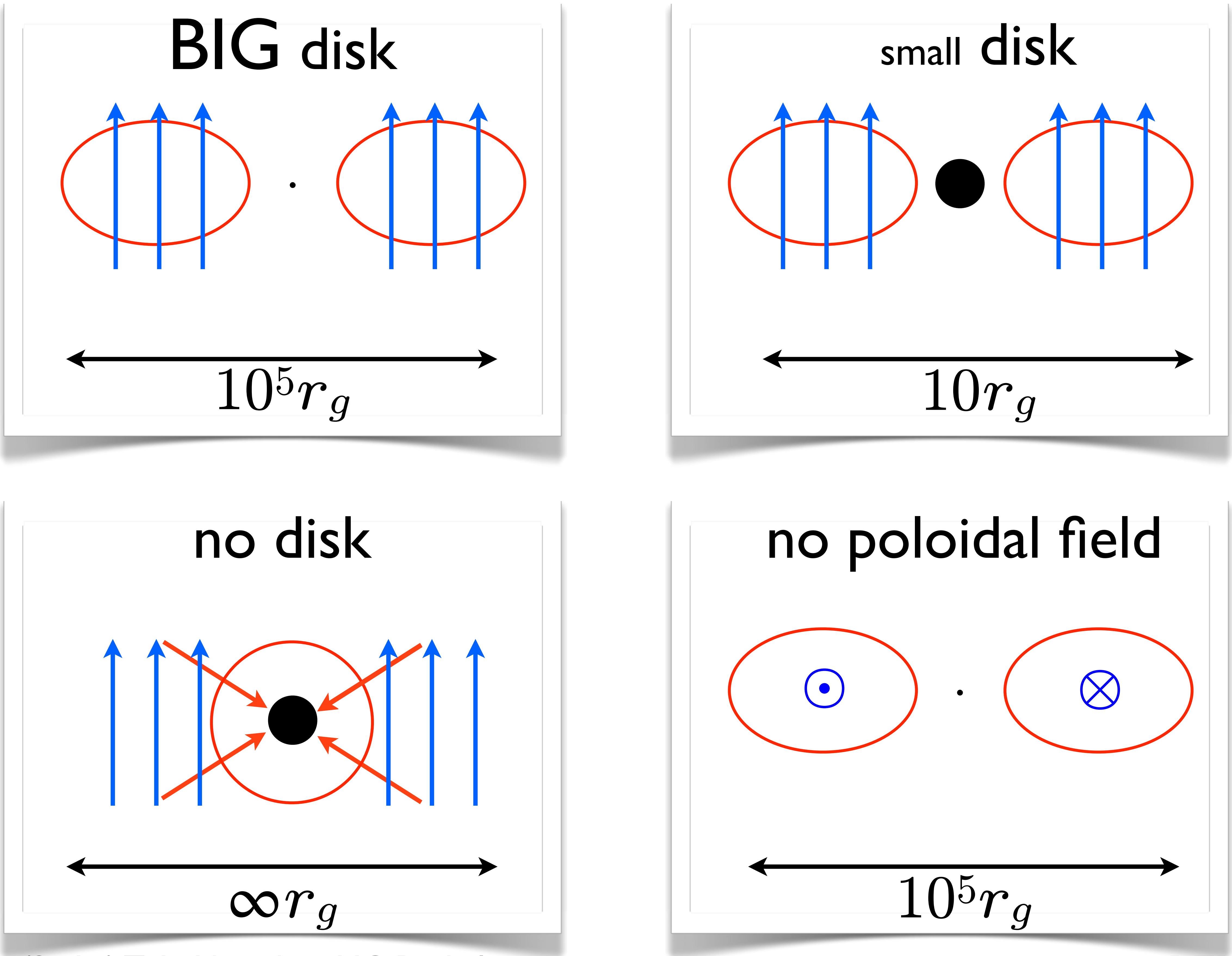


Jet power shows no trends before abruptly switching off at MAD onset (see also AT & Giannios 2015)

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

skip

What is a Healthy Jet Diet?



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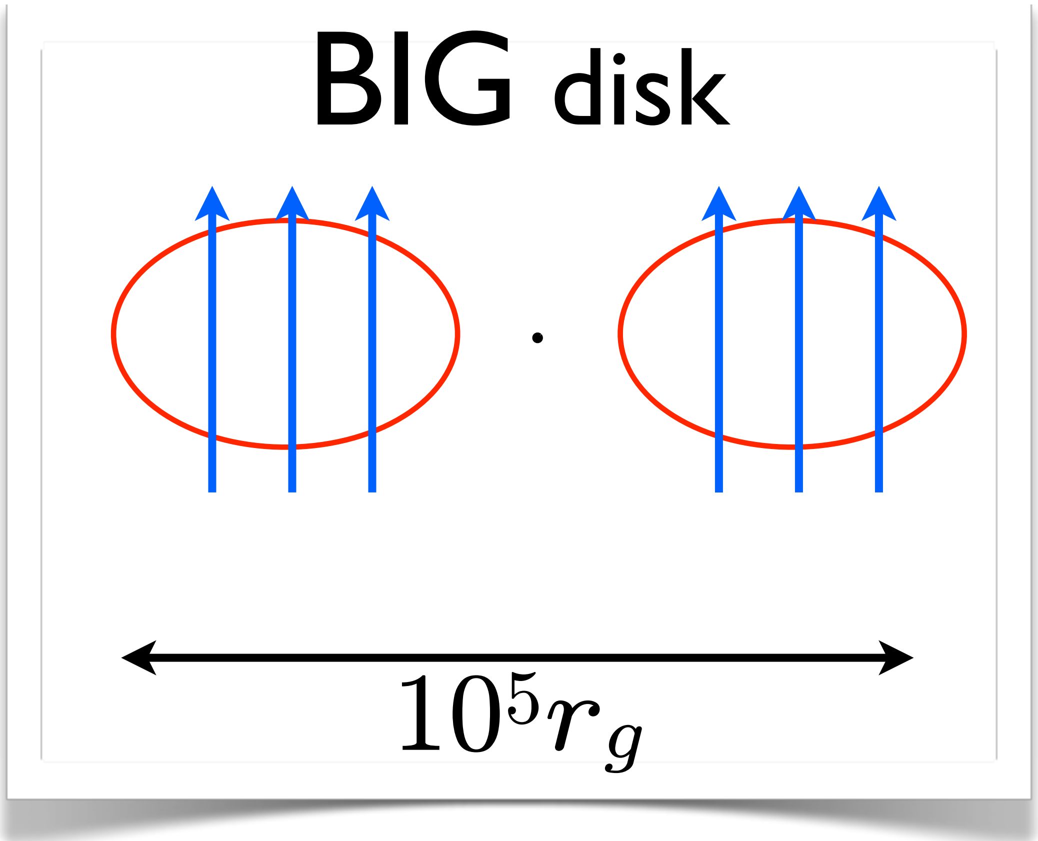
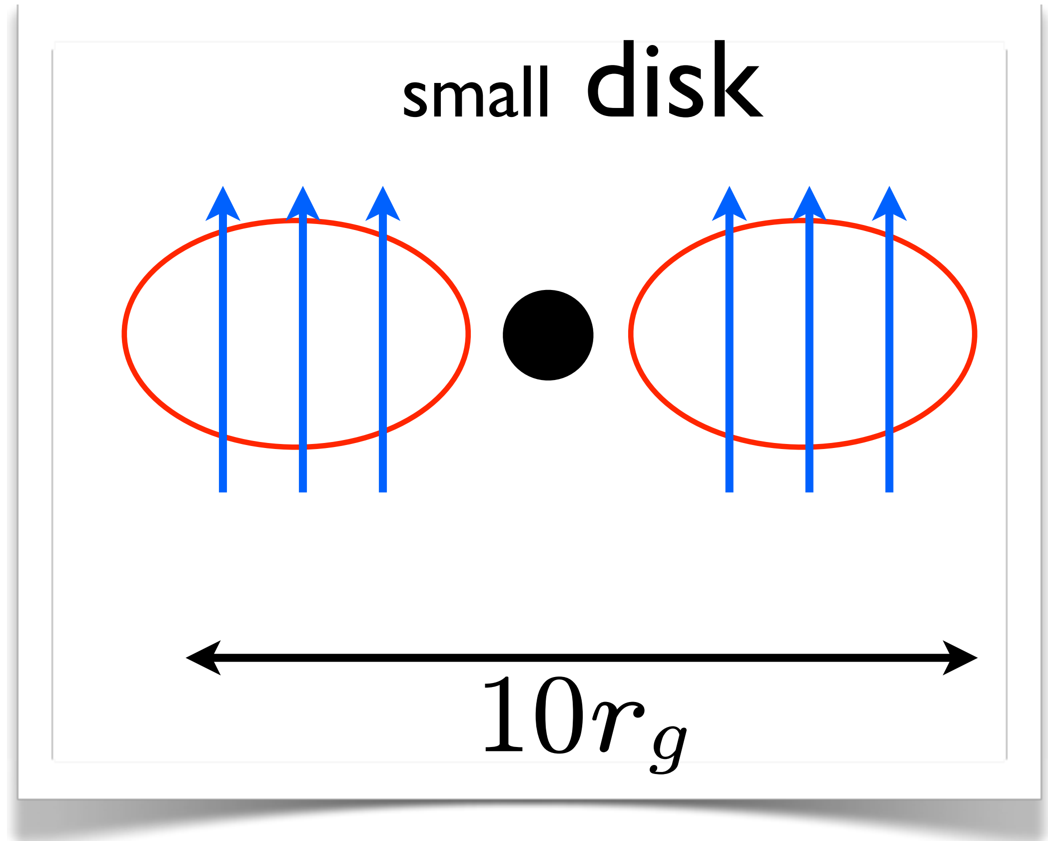
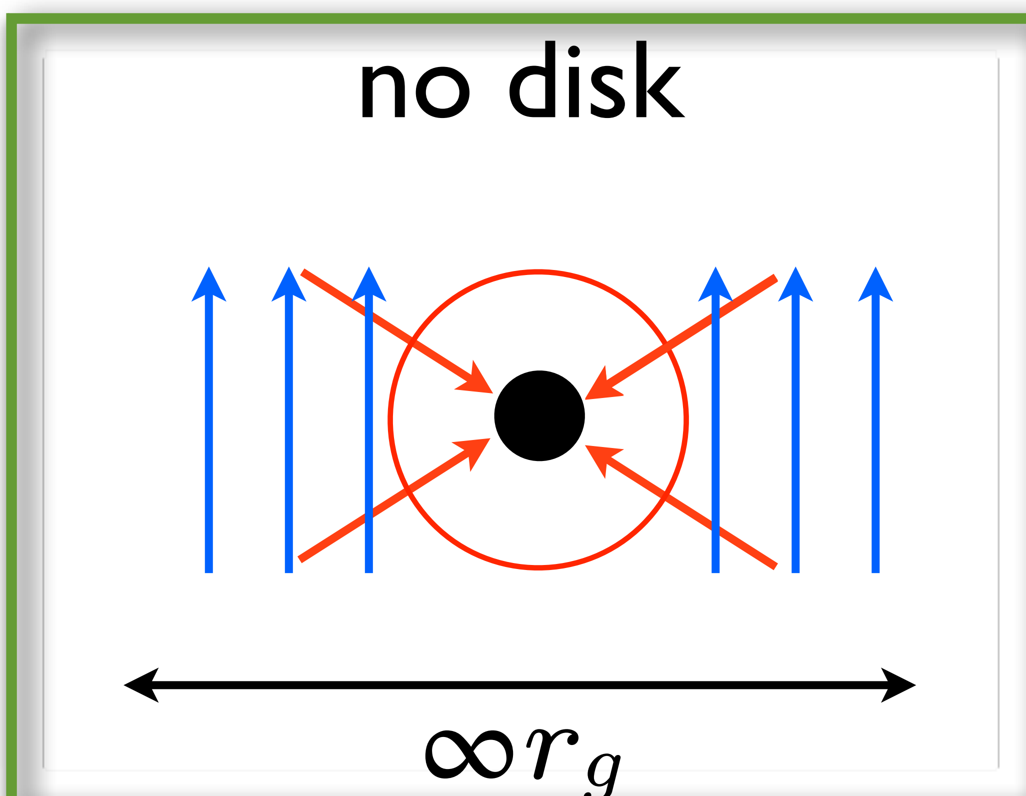
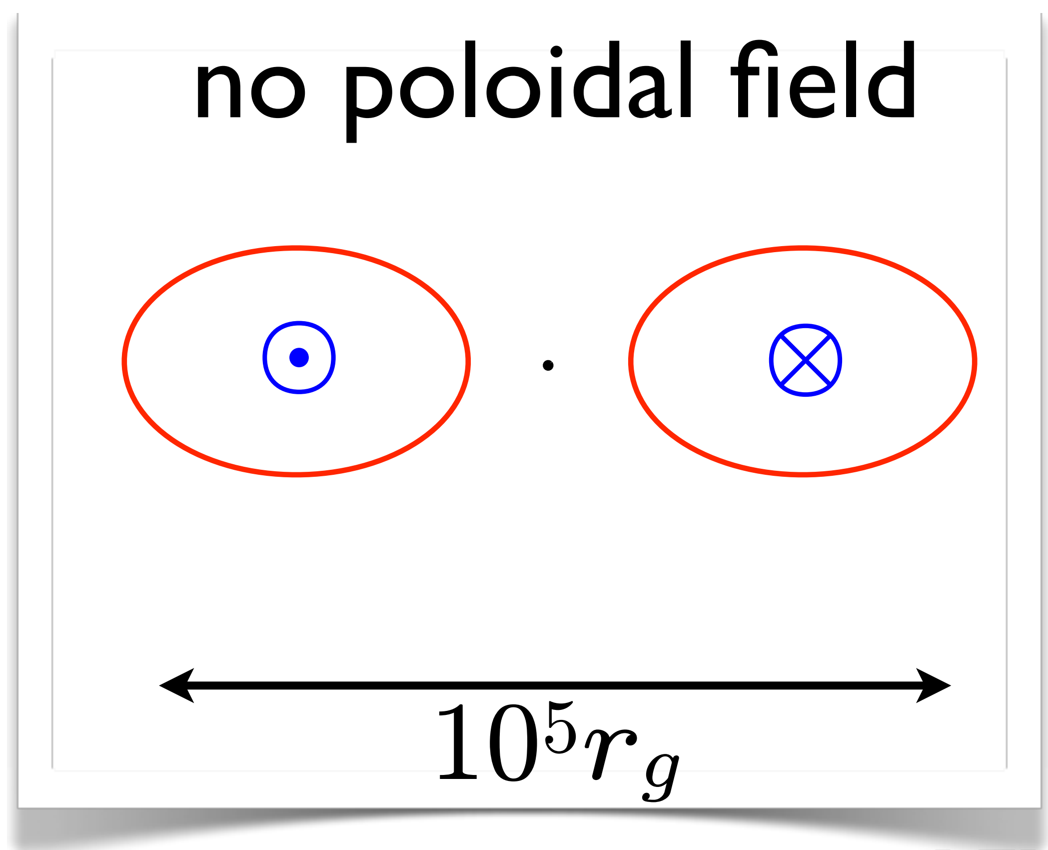




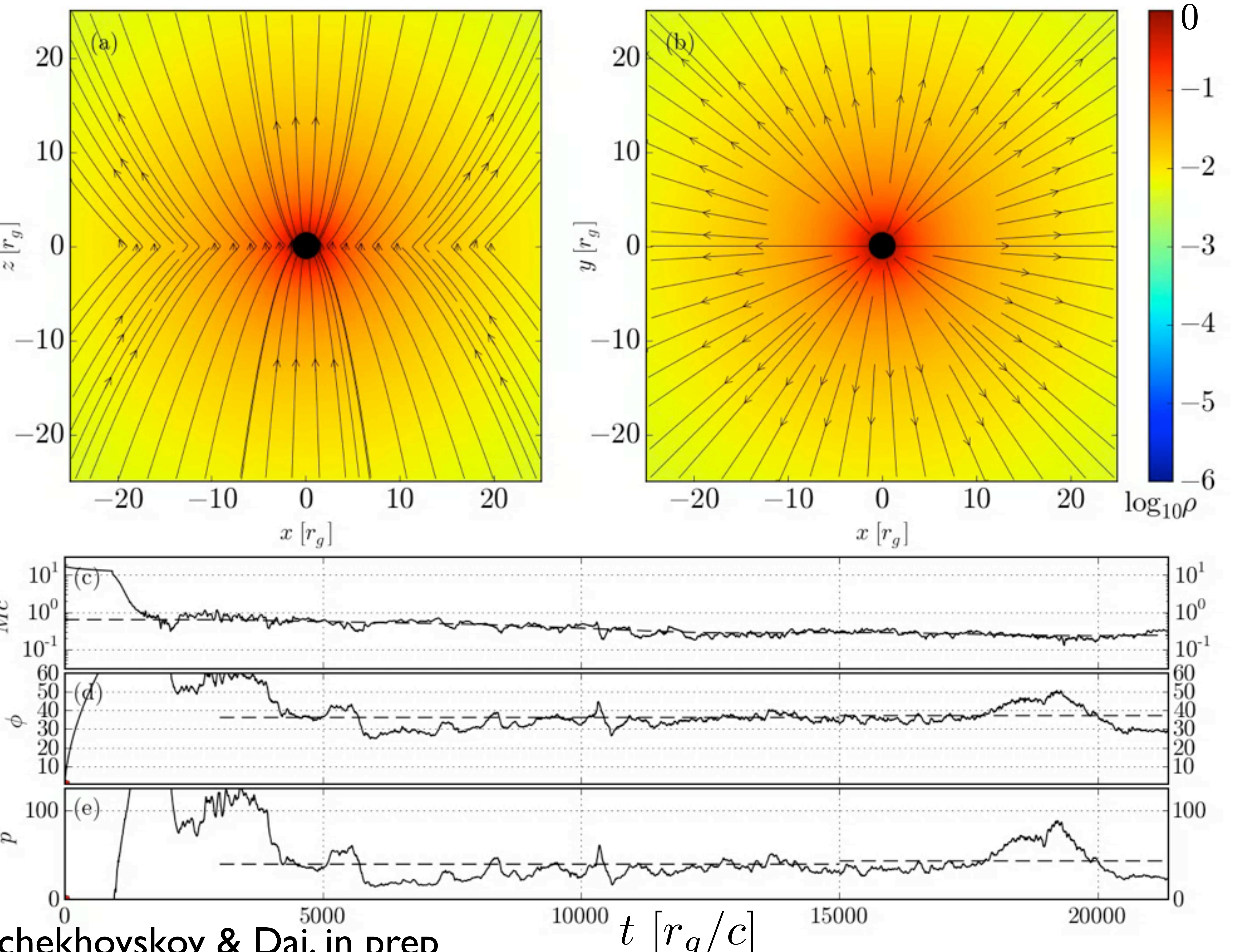




$a = 0.9$
spherical accretion
no rotation

Tchekhovskoy & Dai, in prep

$t\ [r_g/c]$



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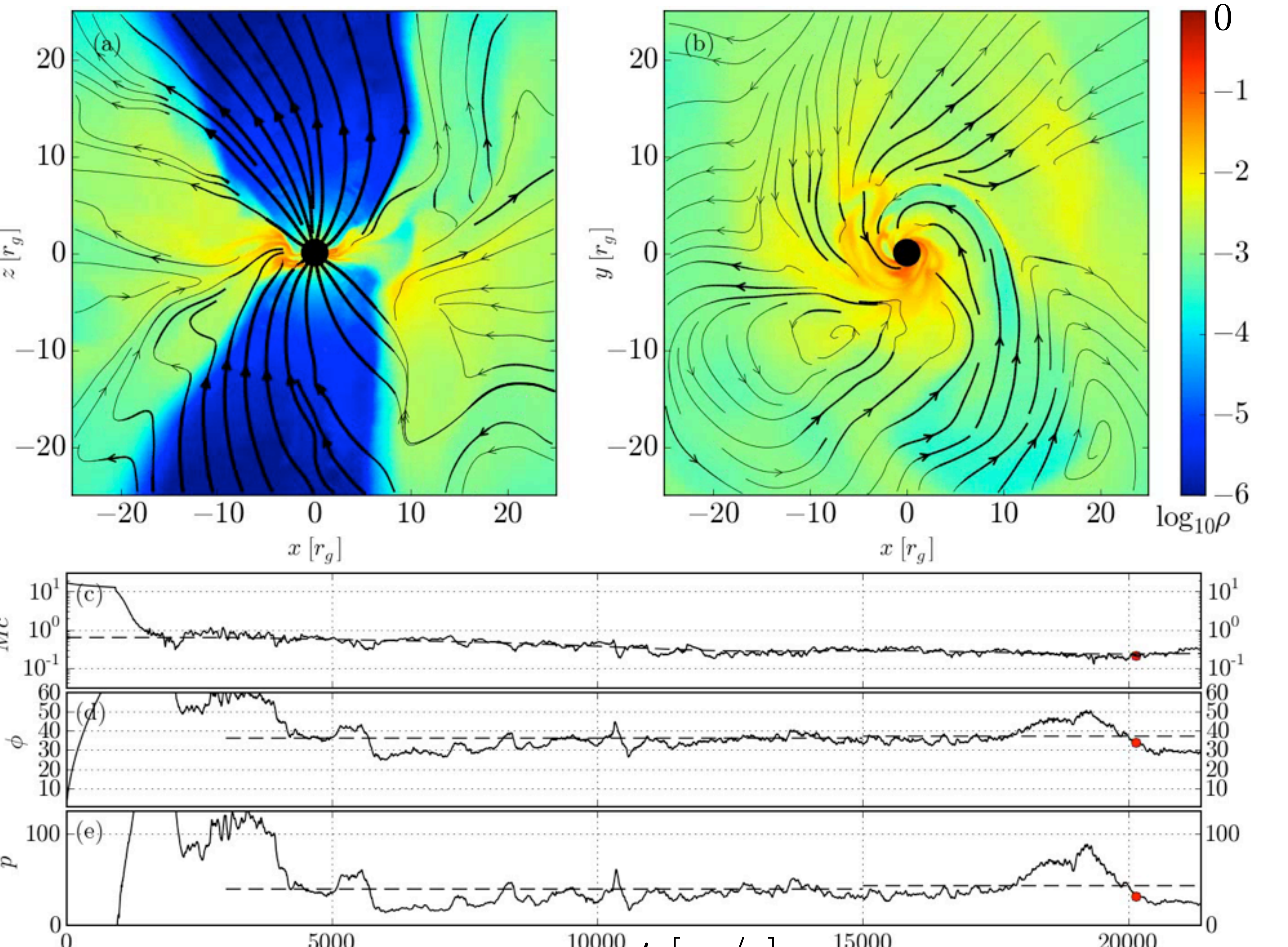

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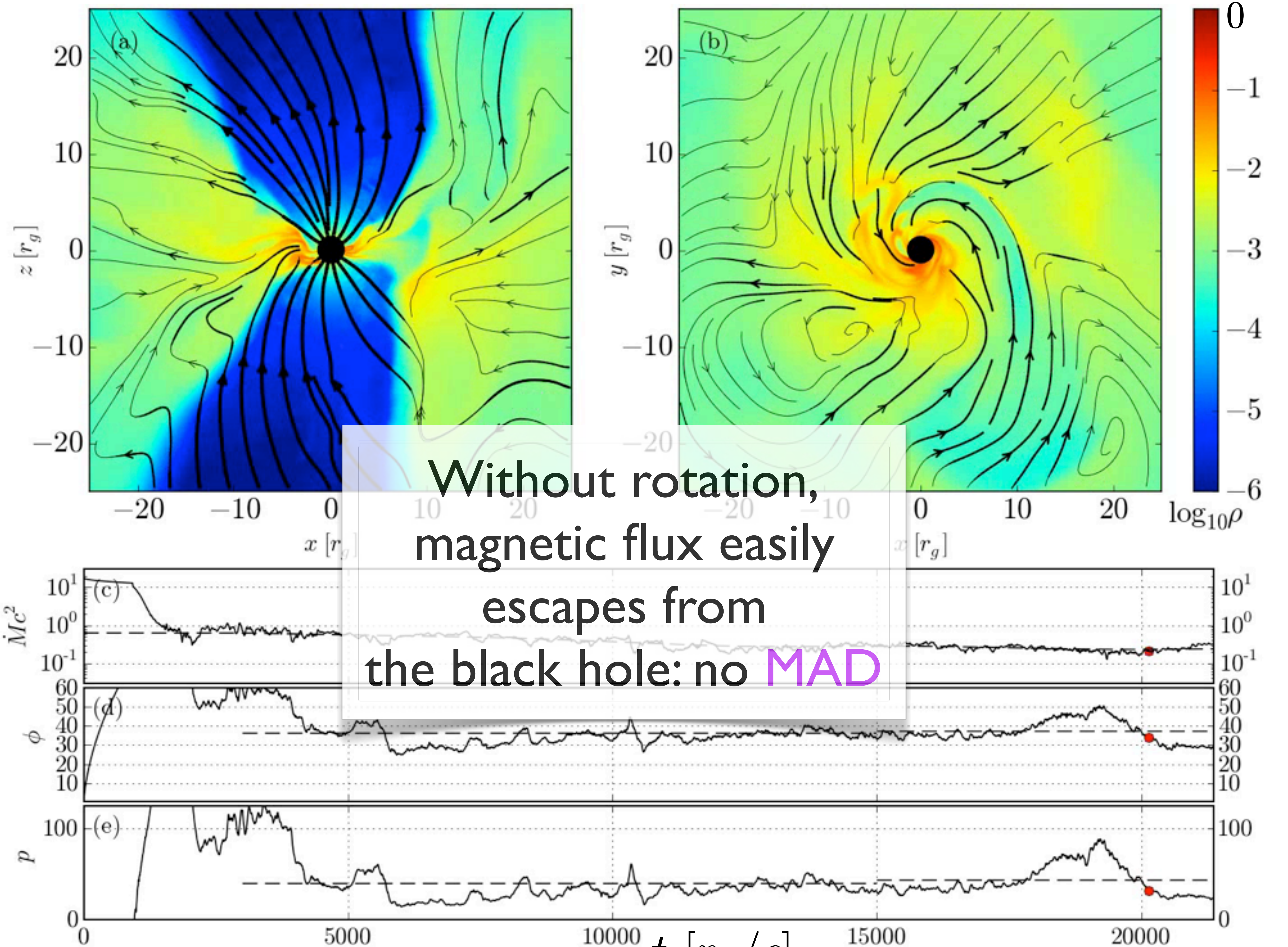


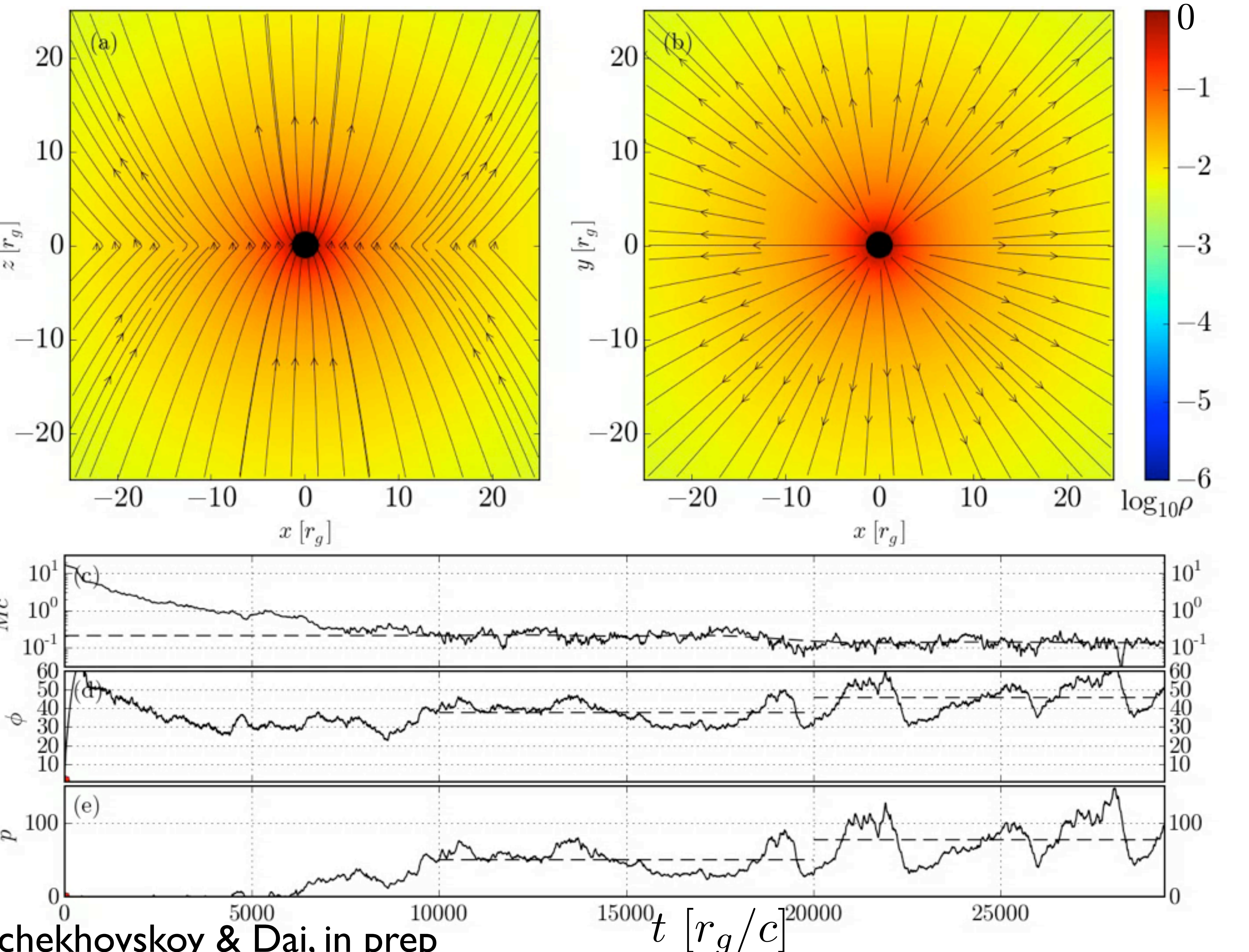
Without rotation, magnetic flux easily escapes from the black hole: no MAD

Tchekhovskoy & Dai, in prep

$a = 0.9$
spherical accretion
rotation: $R_{\rm circ} = 50 r_g$

Tchekhovskoy & Dai, in prep

$\boldsymbol{t}\ [\boldsymbol{r_g/c}]$



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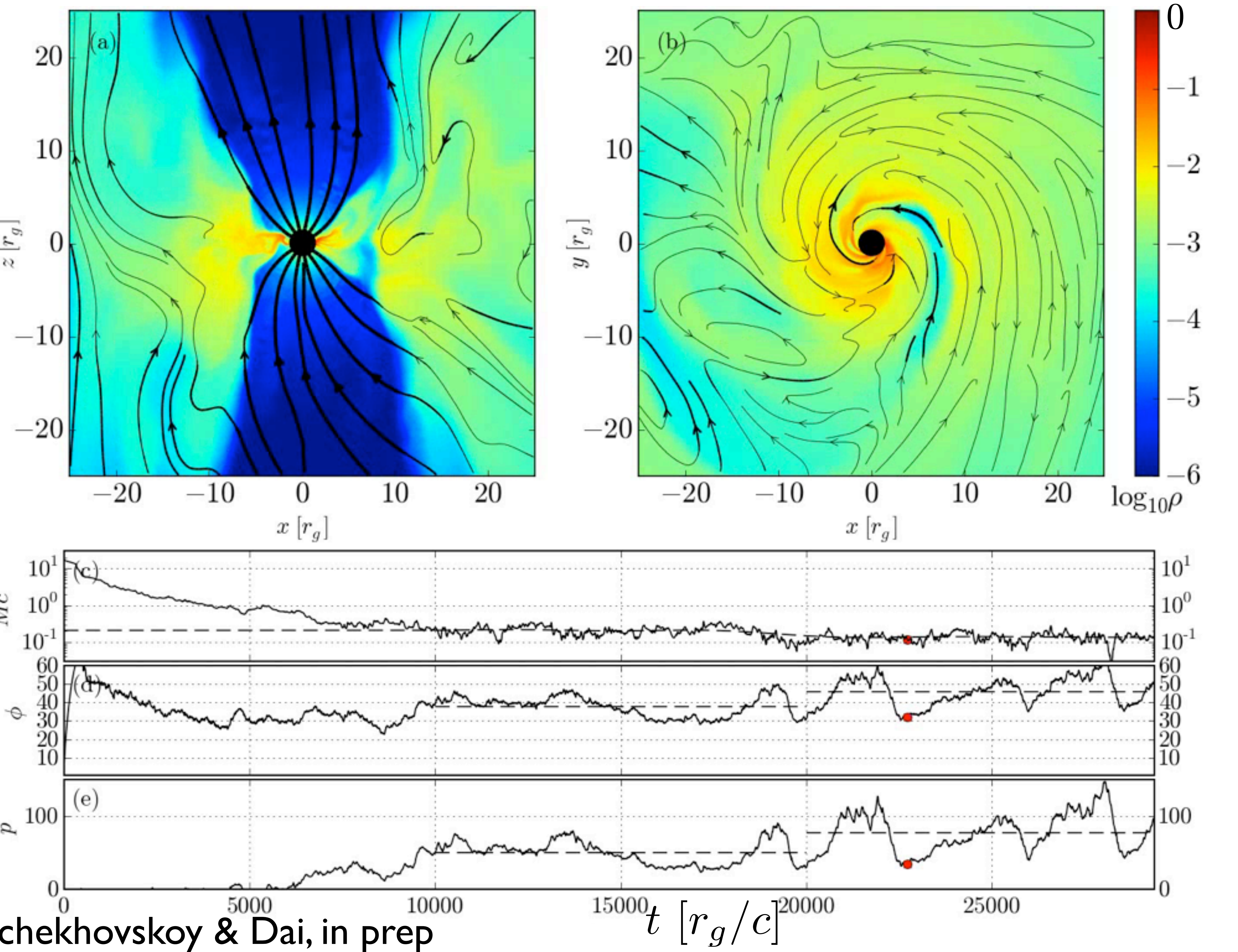

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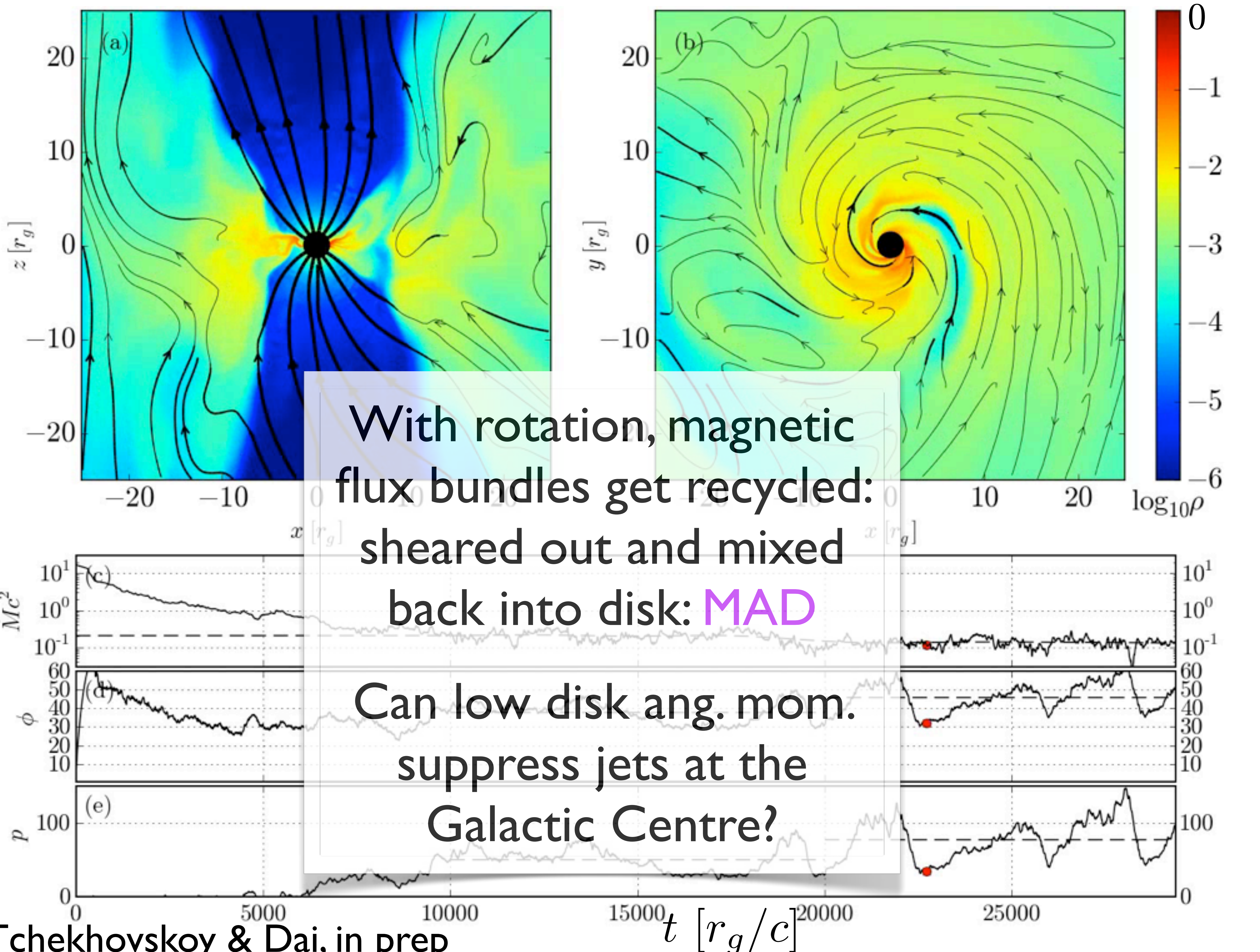
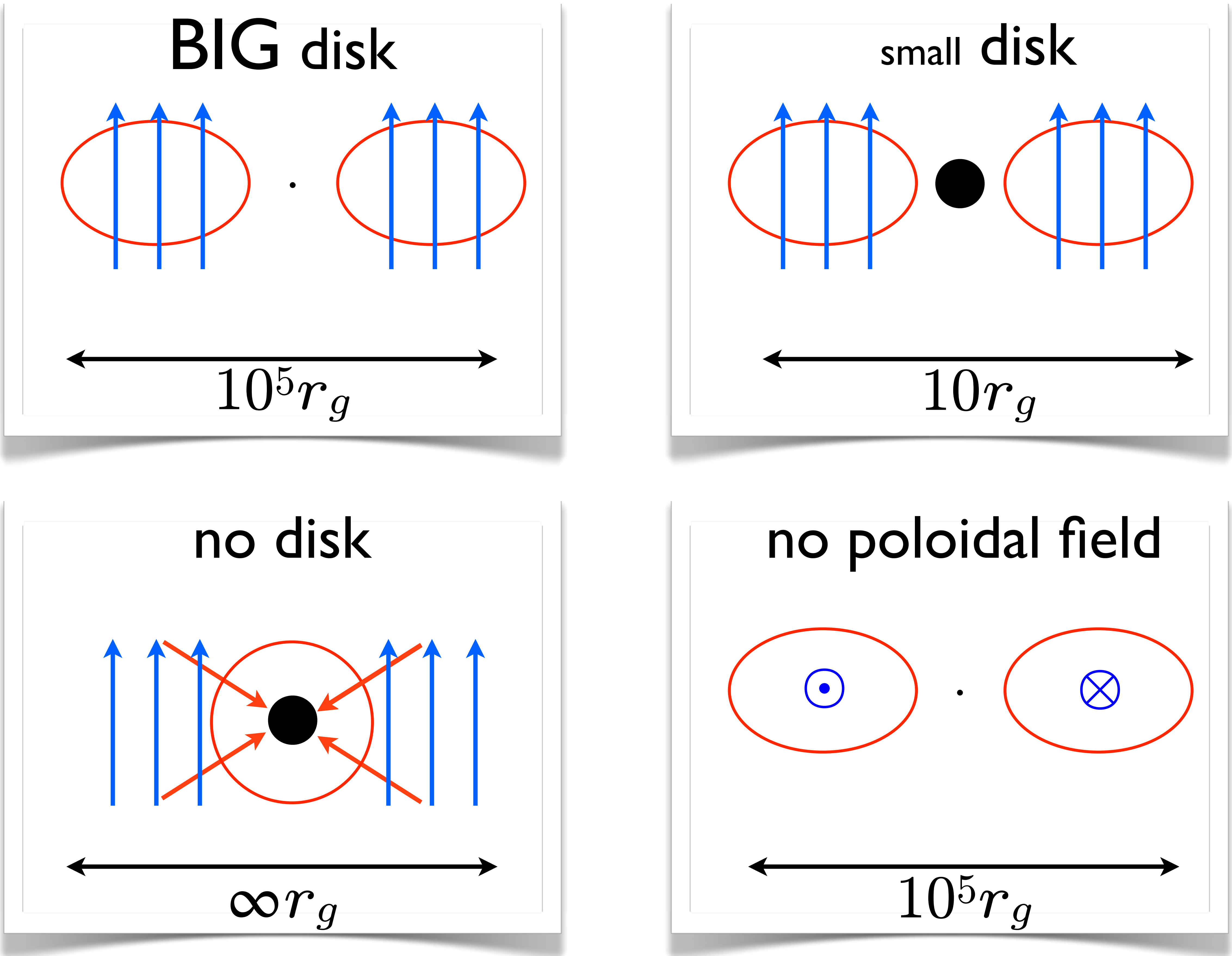


With rotation, magnetic flux bundles get recycled: sheared out and mixed back into disk: MAD

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

Tchekhovskoy & Dai, in prep

What is a Healthy Jet Diet?



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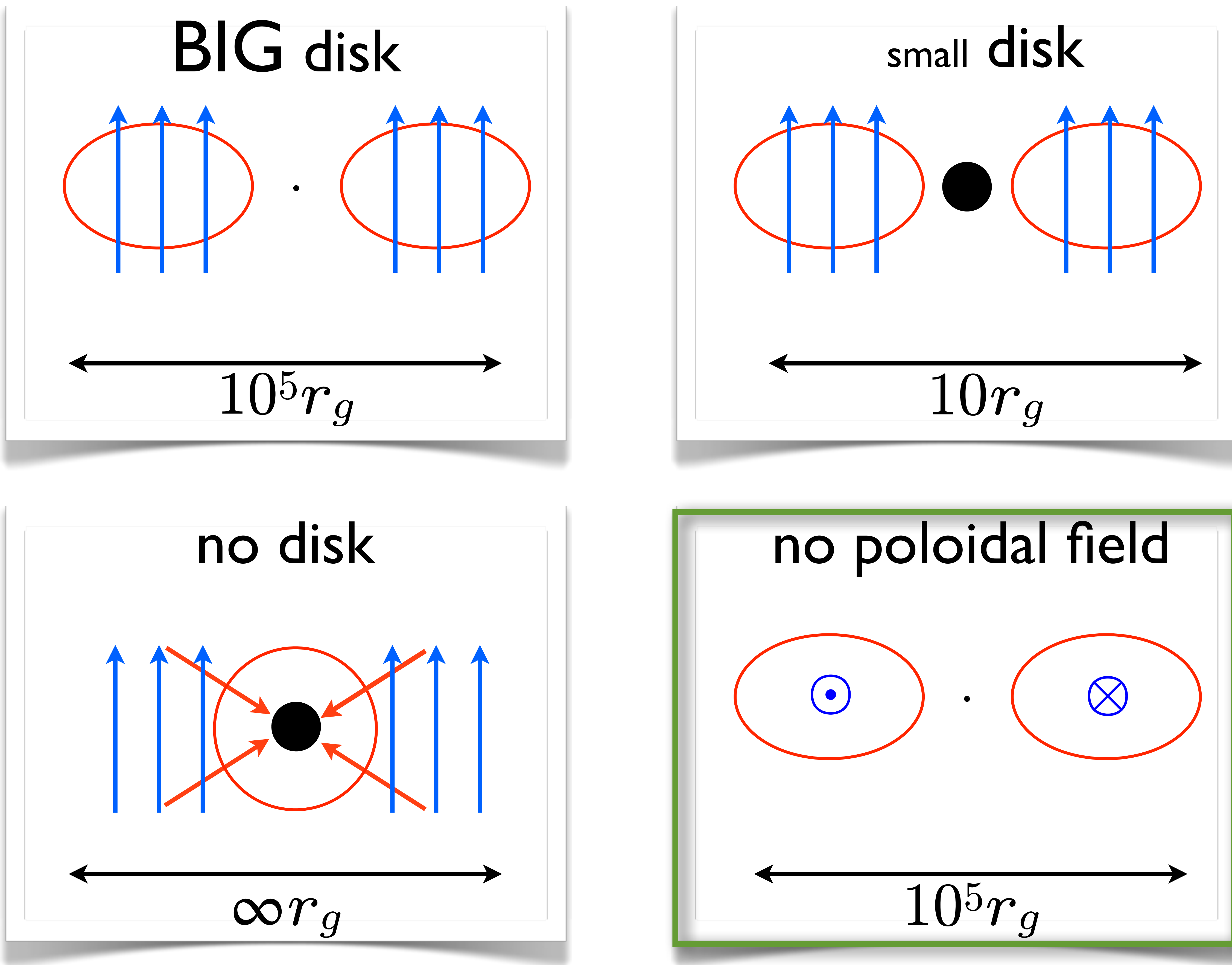

Can Toroidal Fields Make Jets?

- Unlikely: healthy jets need poloidal field (e.g., Beckwith, Hawley, Krolik+08, McKinney, AT, Blandford '12)
- Possible mechanism for jets without B_{p}?
  - Large-scale α-ω dynamo (Moffatt '78; Parker '79)
  - BUT: not seen in global simulations

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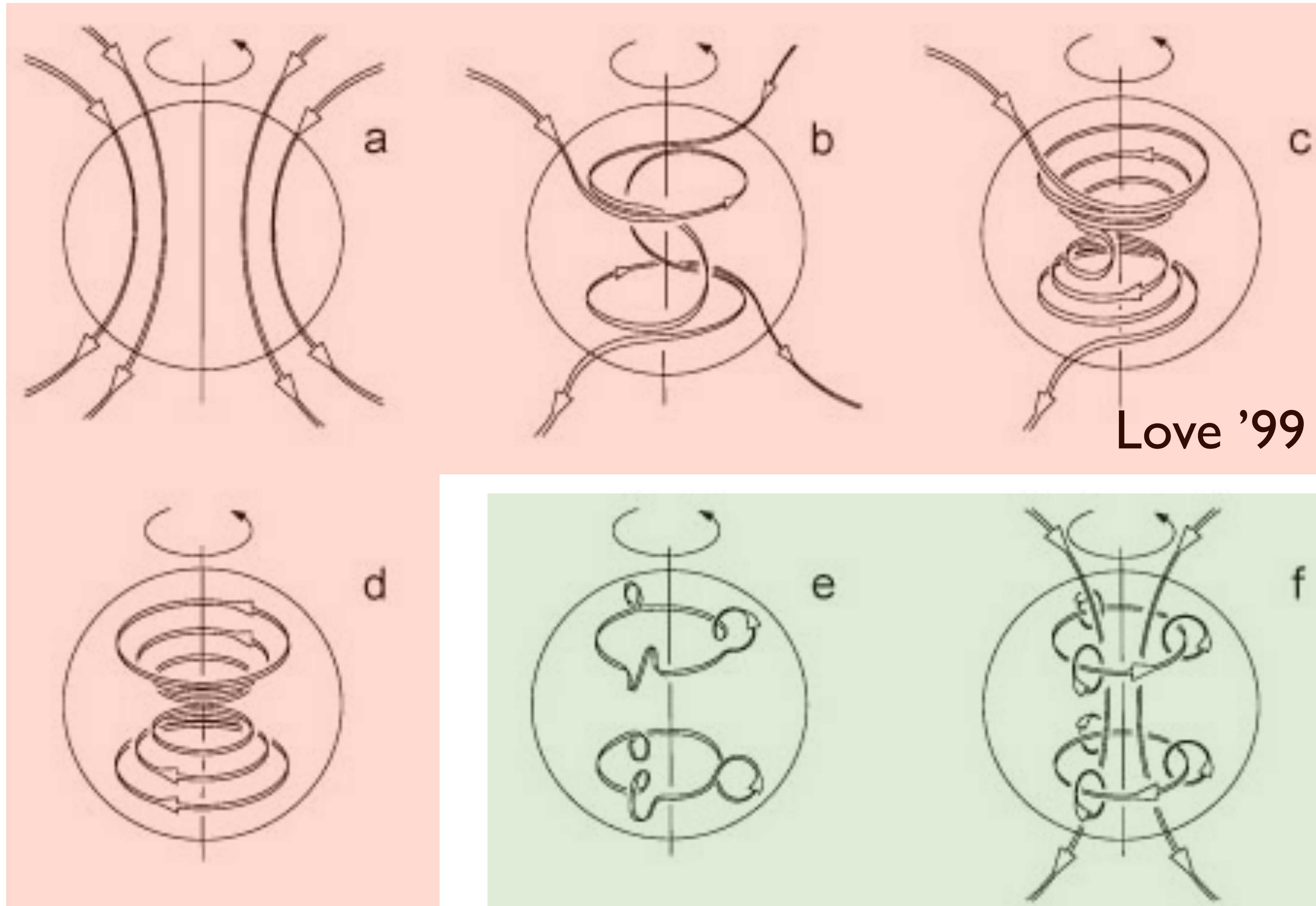
α-ω dynamo:



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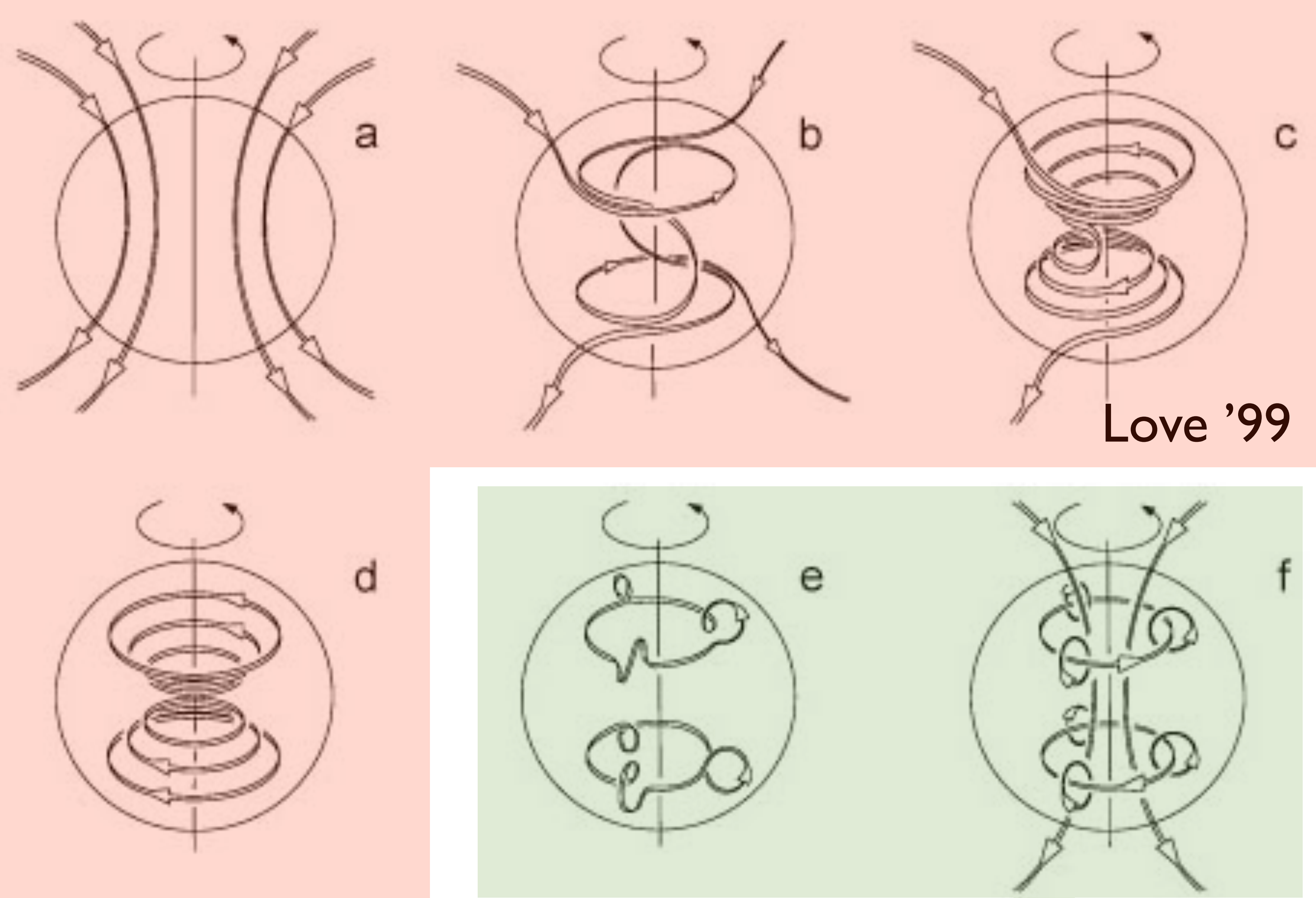


$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times [(\vec{\omega} \times \vec{r}) \times \vec{B} + \alpha \vec{B}]$$

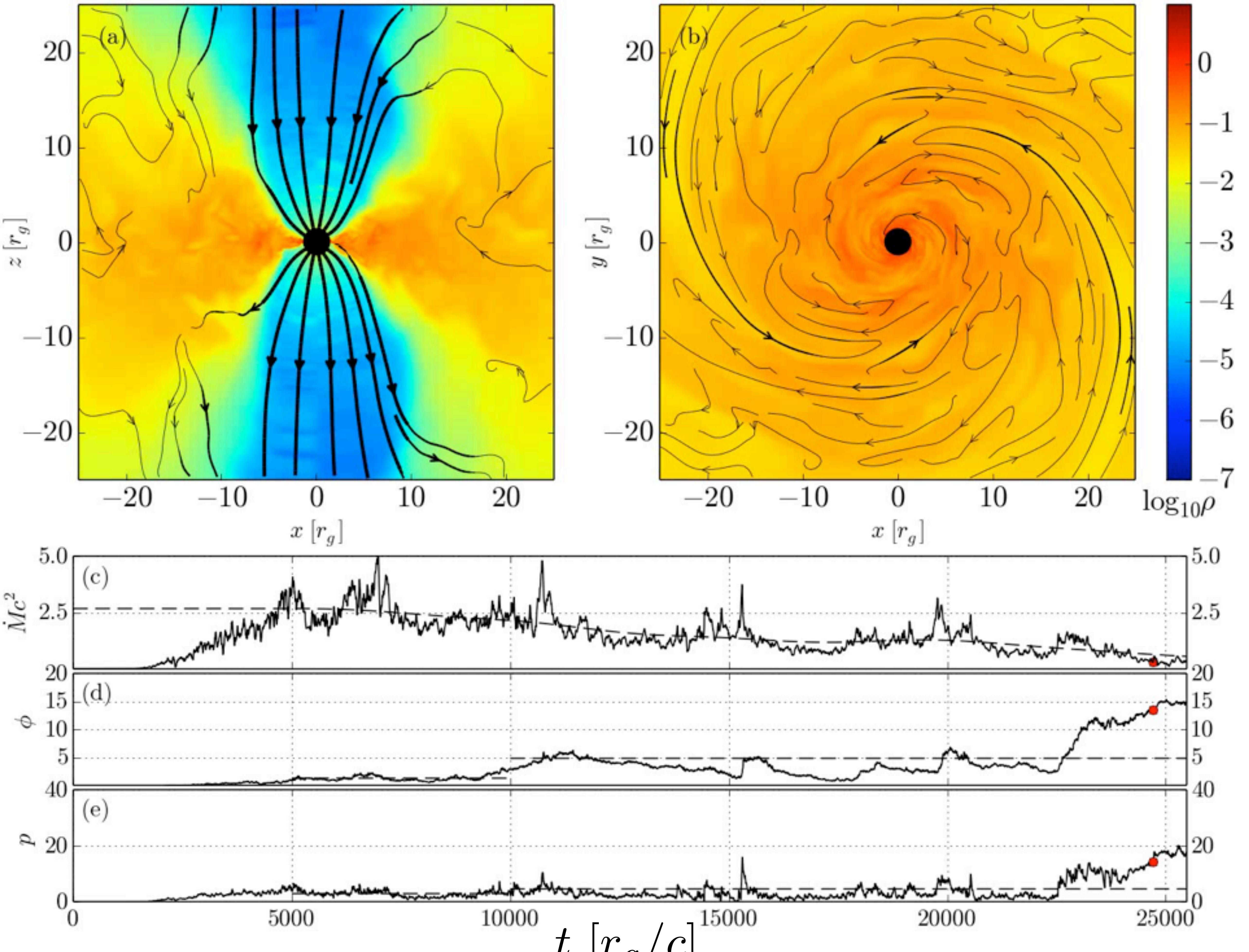
Moffatt '78

Tchekhovskoy & Quataert, in prep.

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

$t\ [r_g/c]$

Tchekhovskoy & Quataert, in prep.



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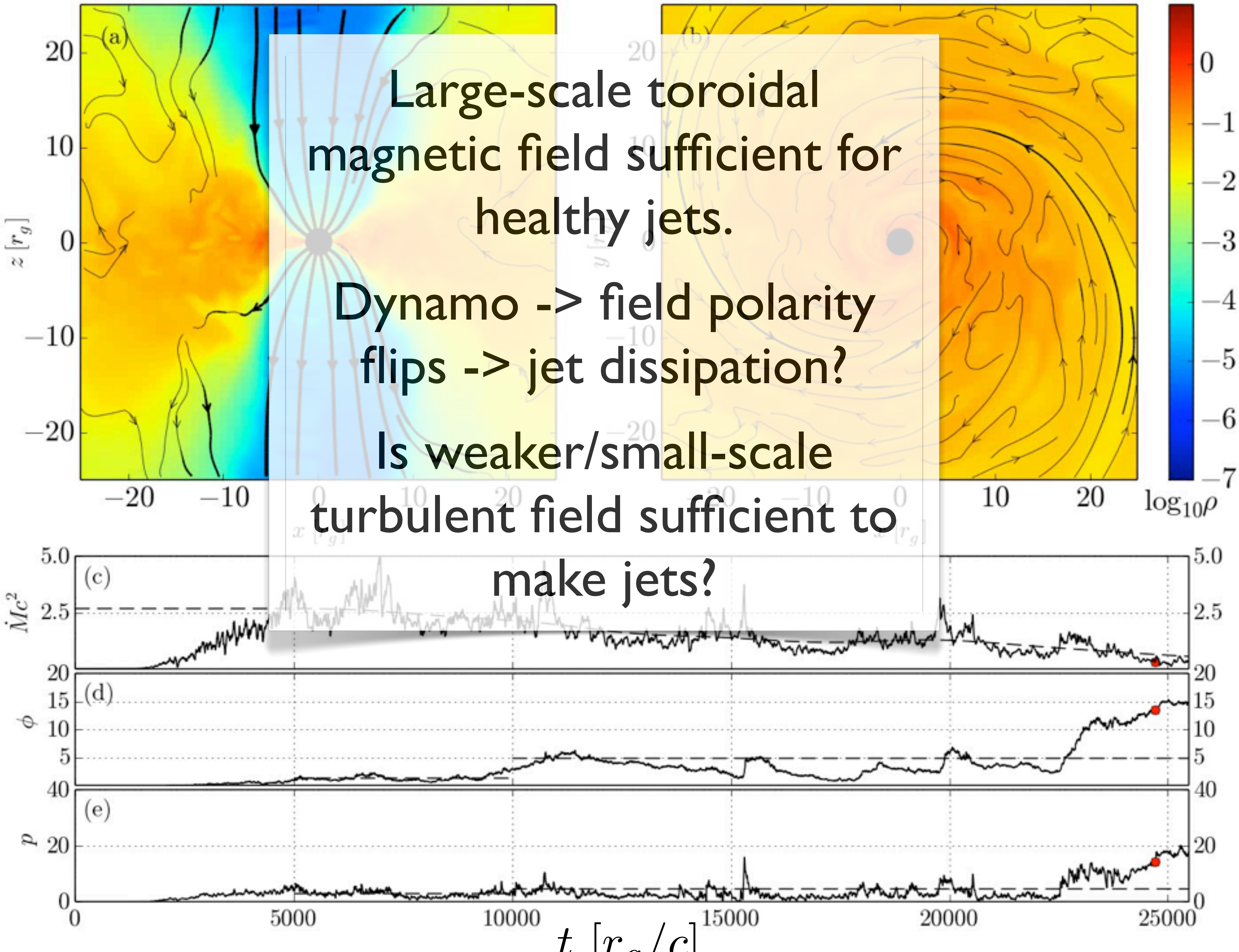
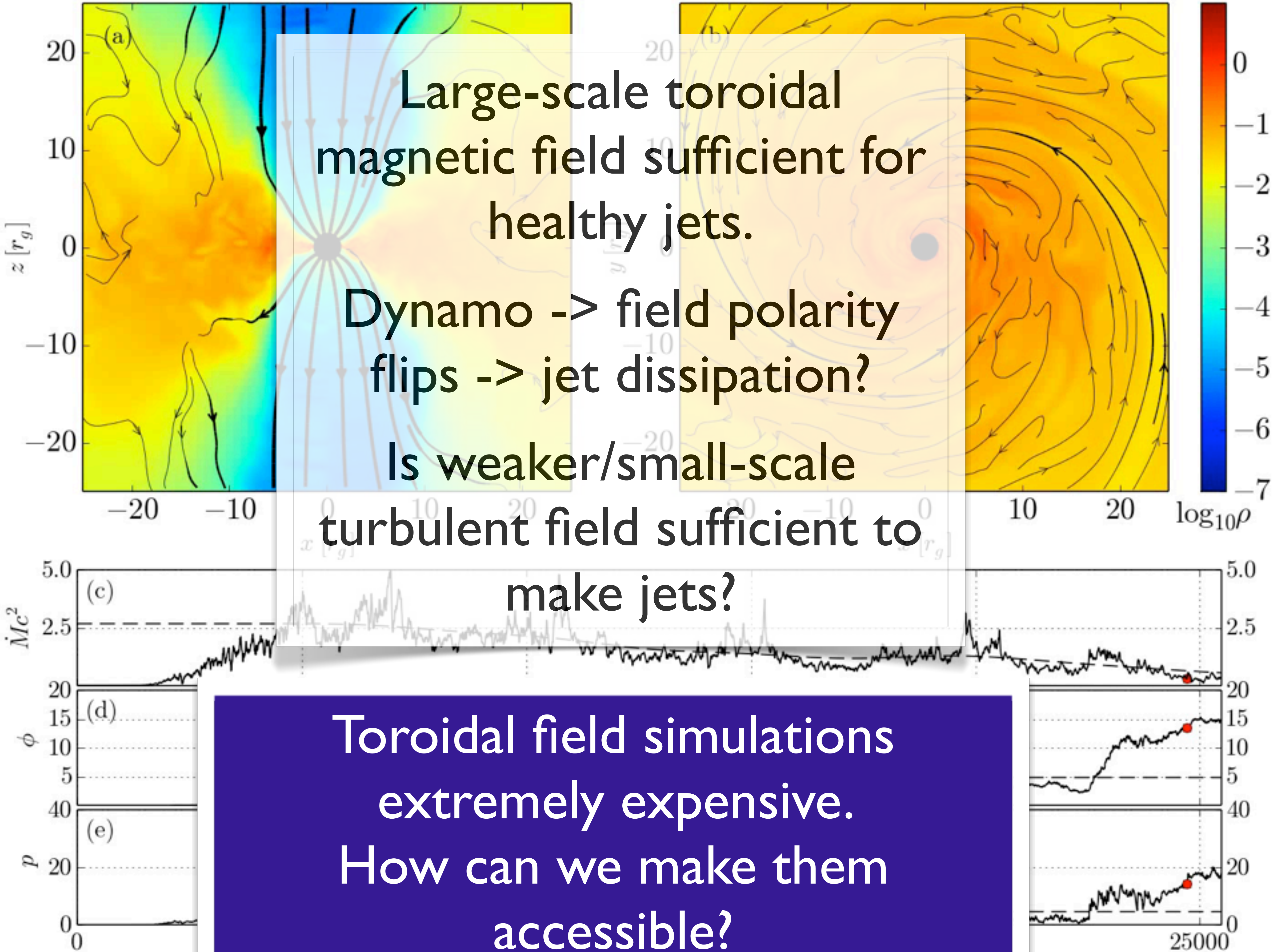


Large-scale toroidal magnetic field sufficient for healthy jets.

Dynamo -> field polarity flips -> jet dissipation?

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

Tchekhovskoy & Quataert, in prep.



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

What's next? GPUs

- Graphical Processing Units (GPUs) is a new disruptive technology
  - cutting edge of modern supercomputing

Matthew Liska
(U of Amsterdam)

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  - Based on an open-source HARM2D
  - 100x speedup: 1 GPU = 100 cores
    - Excellent scaling to >= 4096 GPUs.
    - 3D, staggered fields, AMR
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- Whole slew of important applications:
  - Long-term disk evolution
  - Tilted thin disks
  - Etc.

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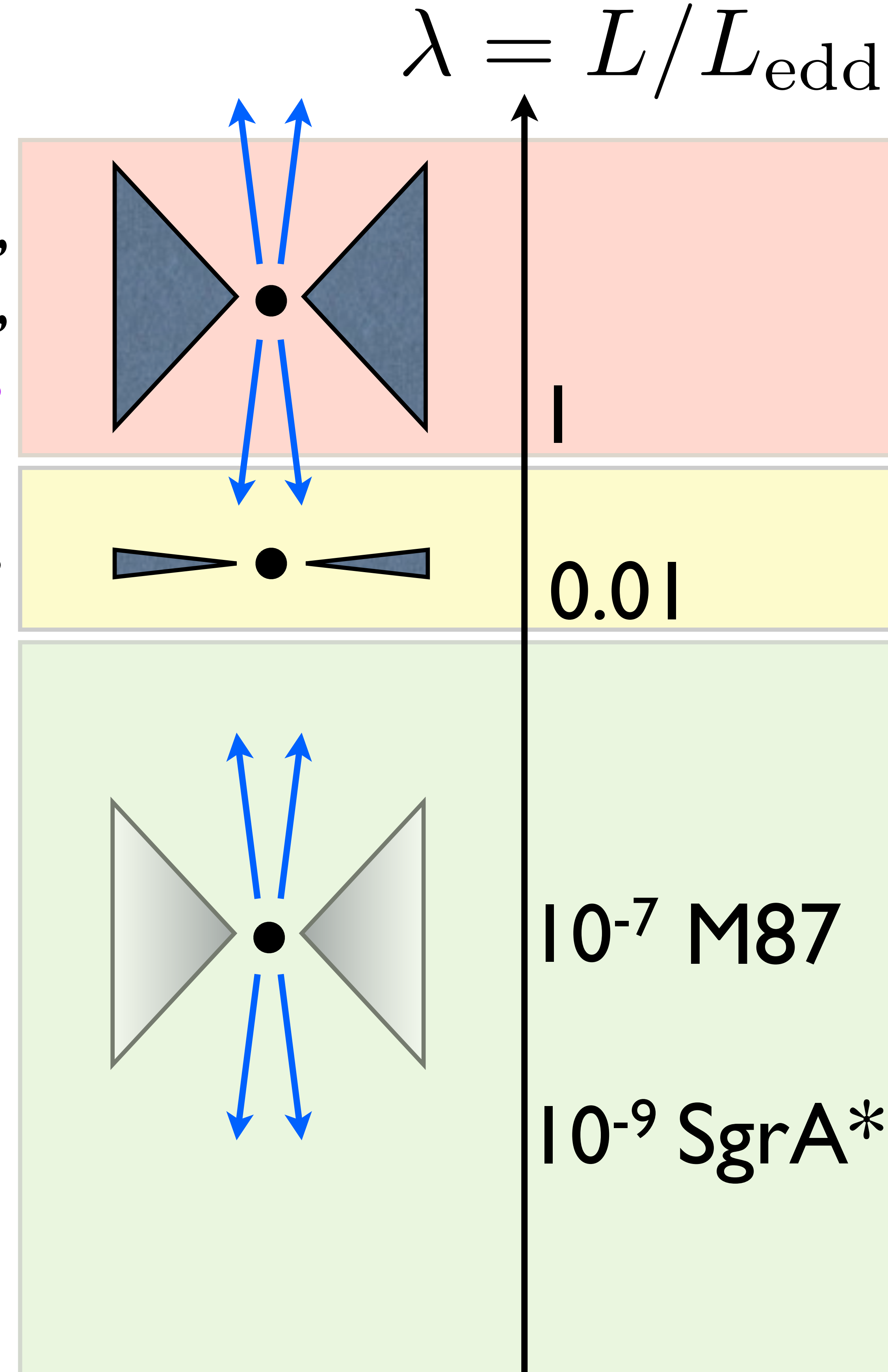

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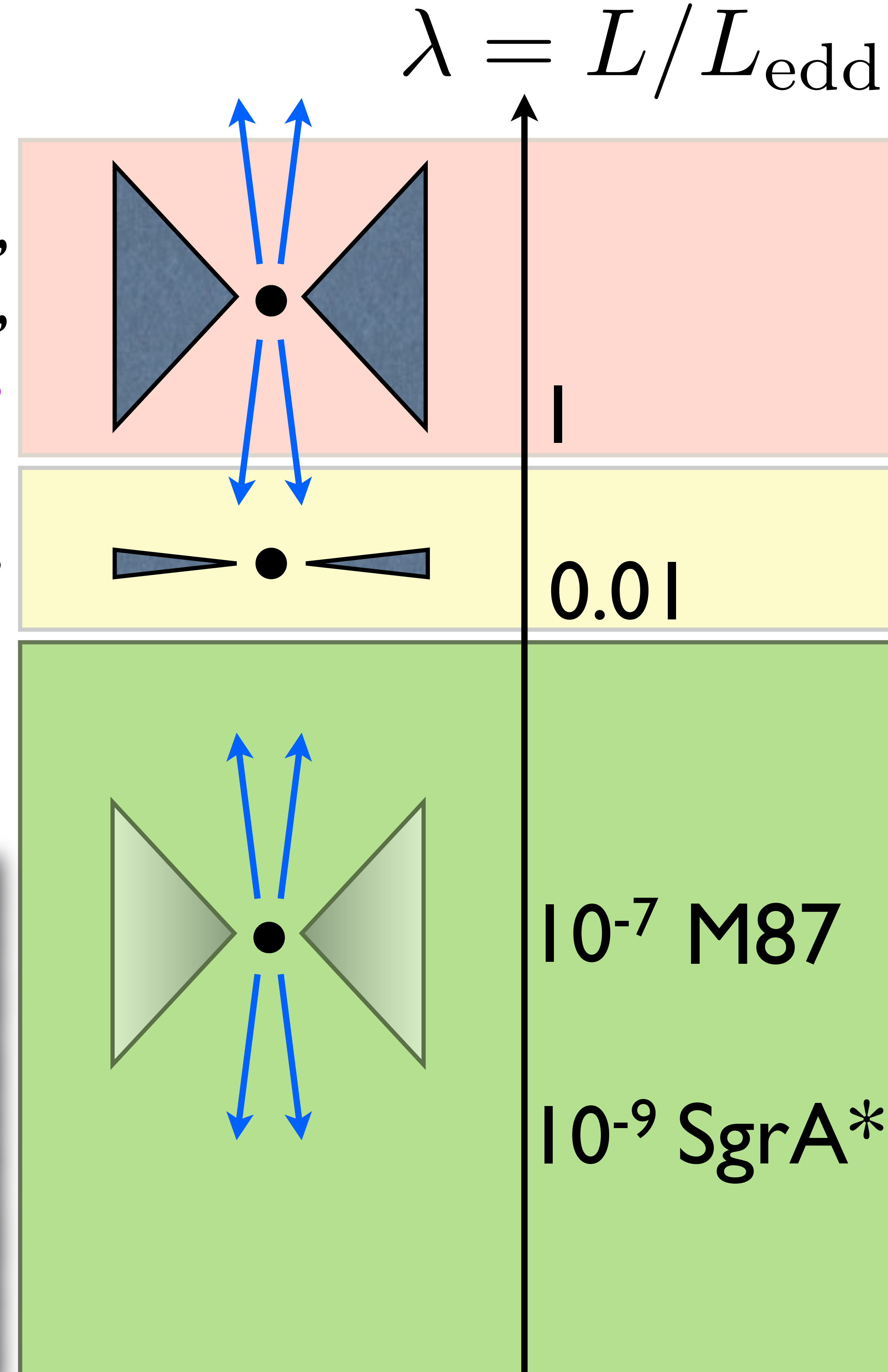
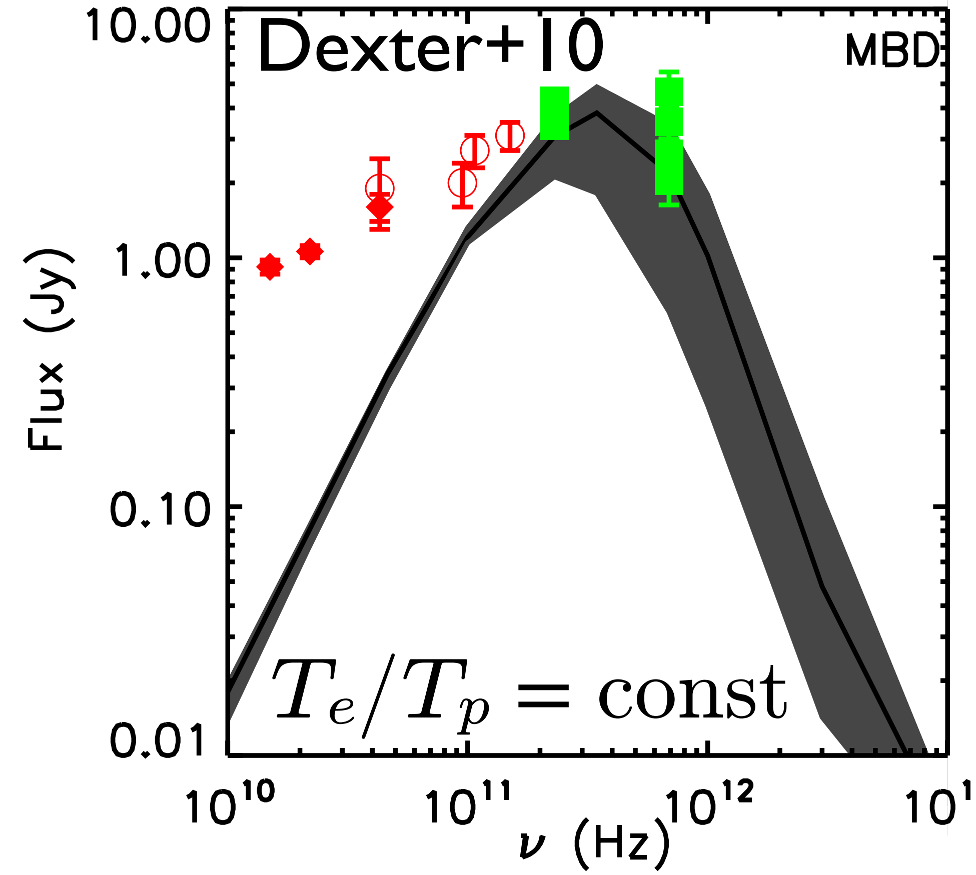


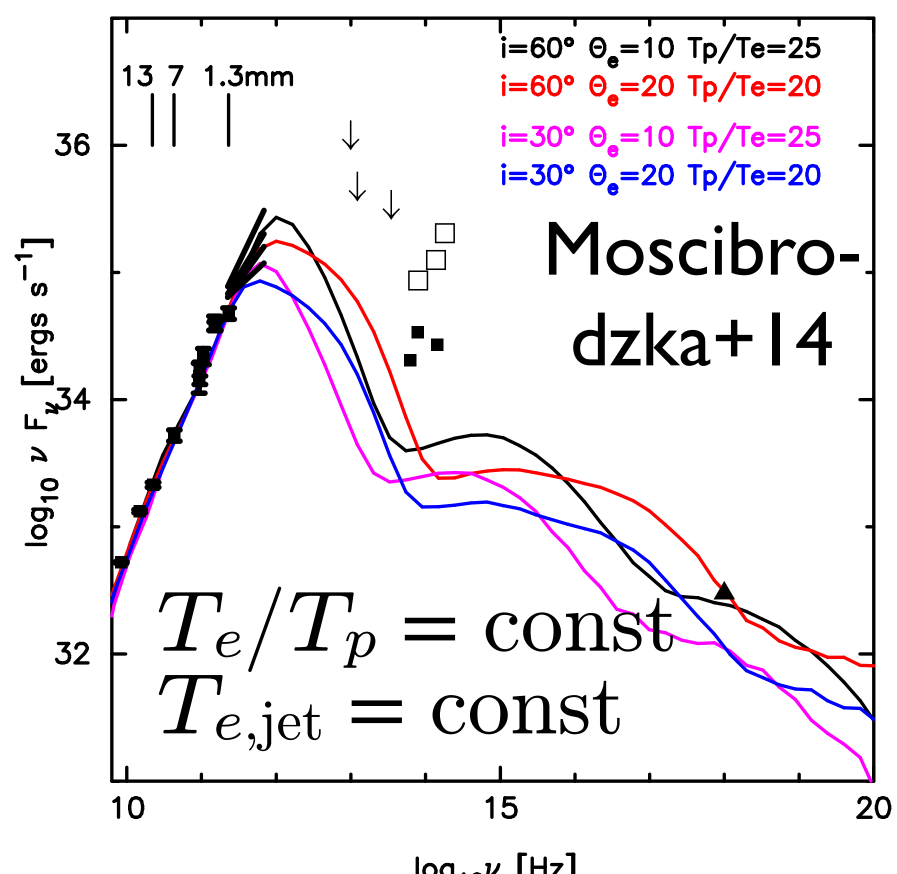
Disk radiative properties are most uncertain at low luminosities.

In the next several years, *EHT* will resolve the shadows of two black holes that accrete in this regime.

Electron Micro-physics is Key to SgrA* Observations

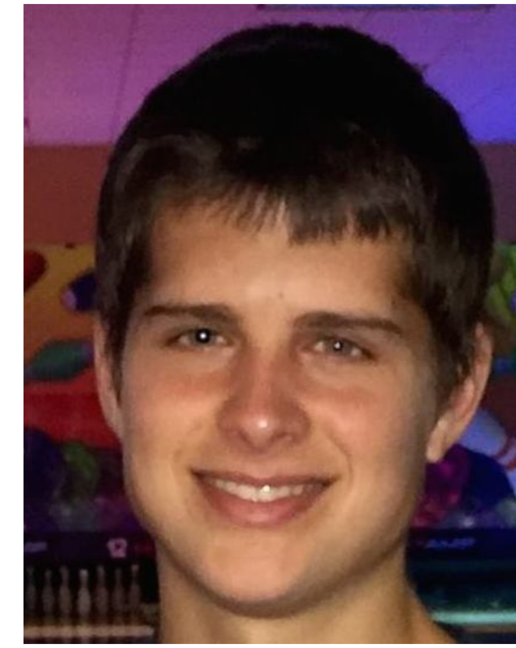
- Plasma is *collisionless*, so electron and proton temperatures decouple
  - but, T_e ($\neq T_p$) is poorly known!
- Dissipation predominantly heats protons, whereas electrons radiate
- So, T_e is usually "painted" on top of simulations:
  - Usual assumption (eg Dexter+10): $T_e/T_p = \mathrm{const.} < 1$
  - To reproduce flat radio spectrum, need to "paint" polar regions with hot $T_e{=}10^{11}$ K electrons (Moscibrodzka et al. 2014)
- Is there a way to eliminate the free function, $T_e(T_p, \ldots)$?





Electron Micro-physics is Key to SgrA* Observations

- Our improved approach:
  - Evolve electrons as a second fluid
  - Electrons receive a fraction $f_e(T_e, T_p, \beta)$ of dissipated heat (Howes 2010)
    - stronger heating in highly magnetized regions
  - Include thermal conduction *along* field lines (Chandra et al. 2015)
  - Neglect back-reaction of electrons on the flow
- Simulations with e-*HARMPI*, new parallel, 3D general relativistic MHD code that includes electrons as a separate fluid (Ressler, AT et al., 2015, 2016)



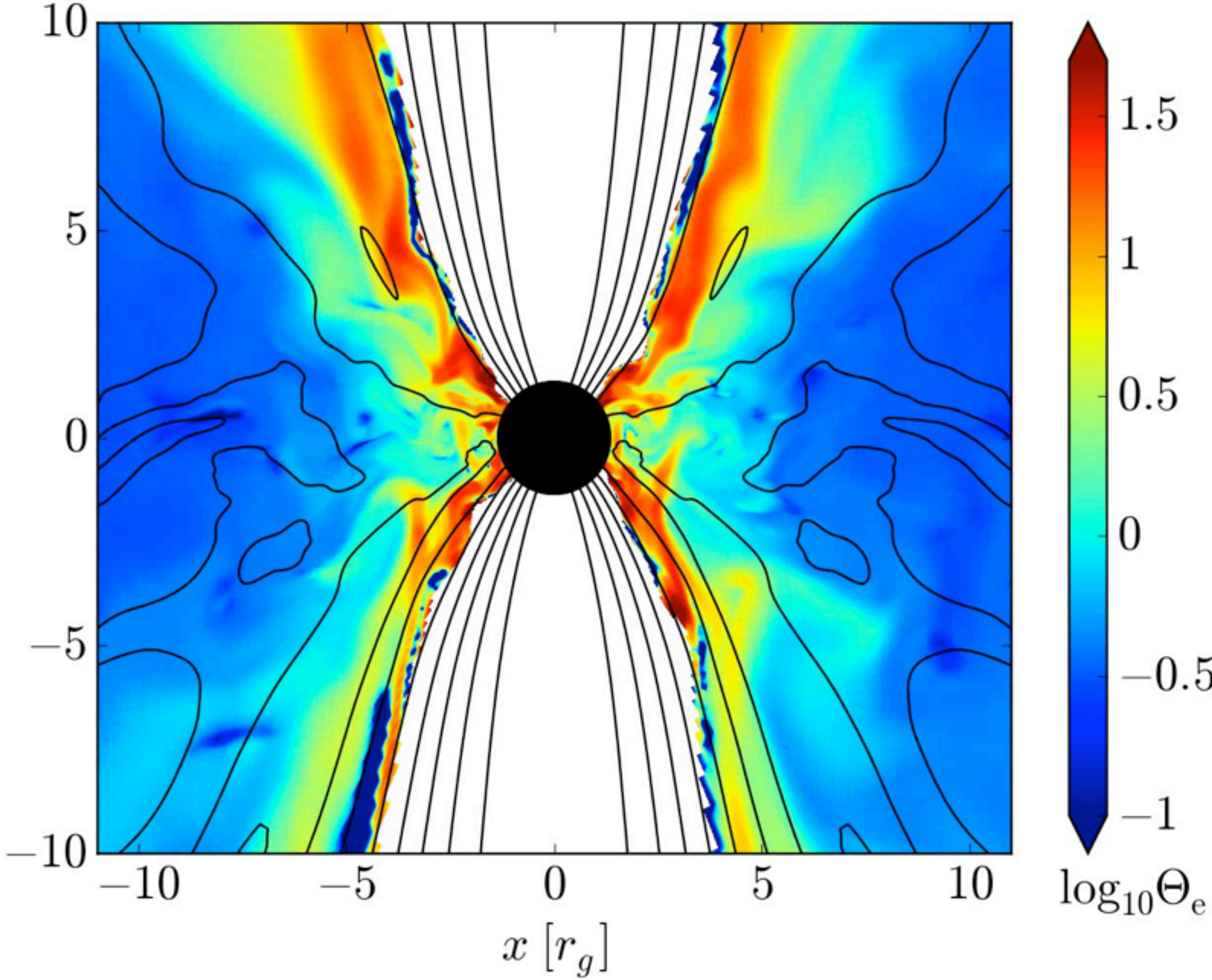
Sean Ressler
(UC Berkeley)

Electron Temperature in Simulations

Spin:
a=0.5

Protons:
$\gamma=5/3$

Electrons:
$\gamma_e=4/3$

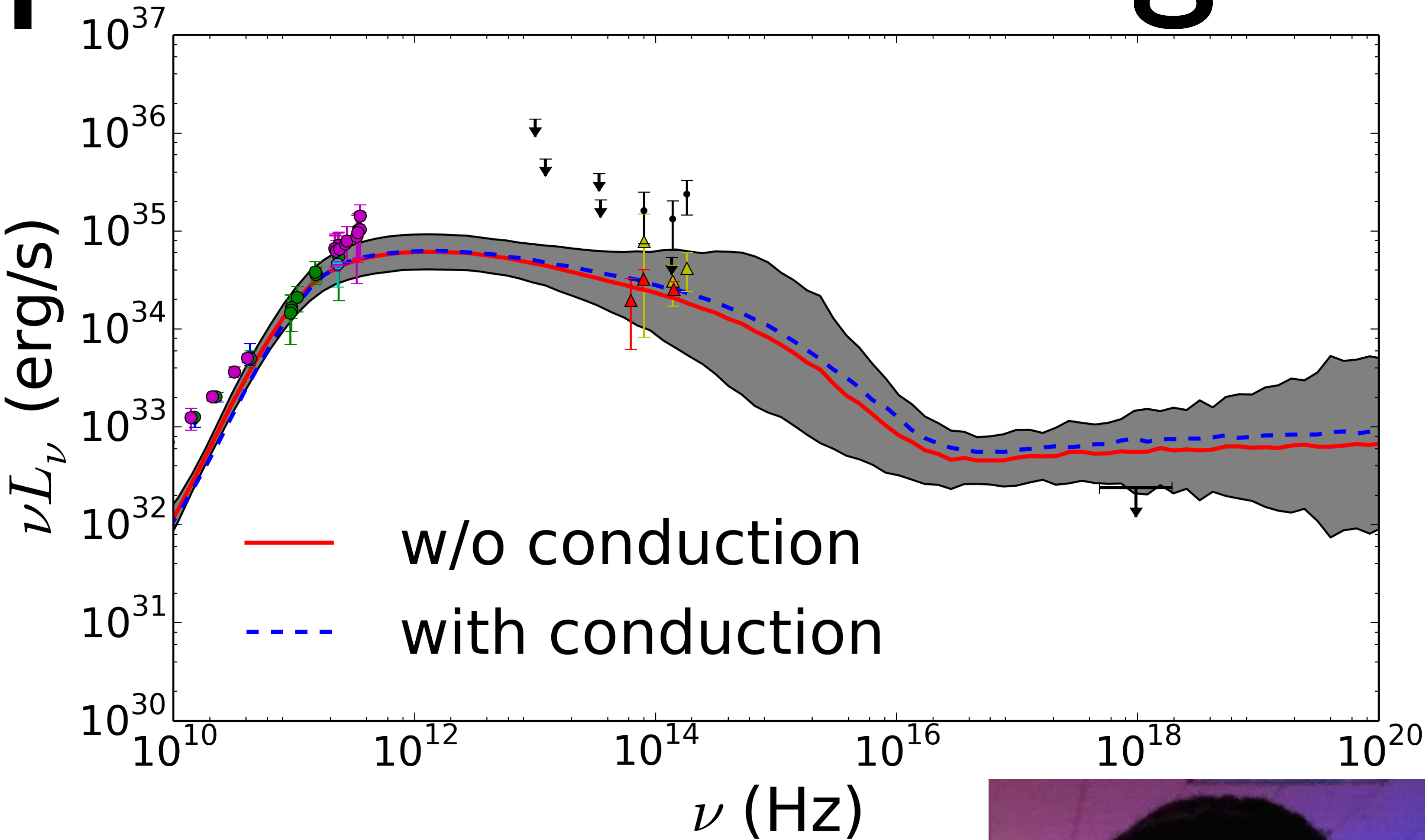


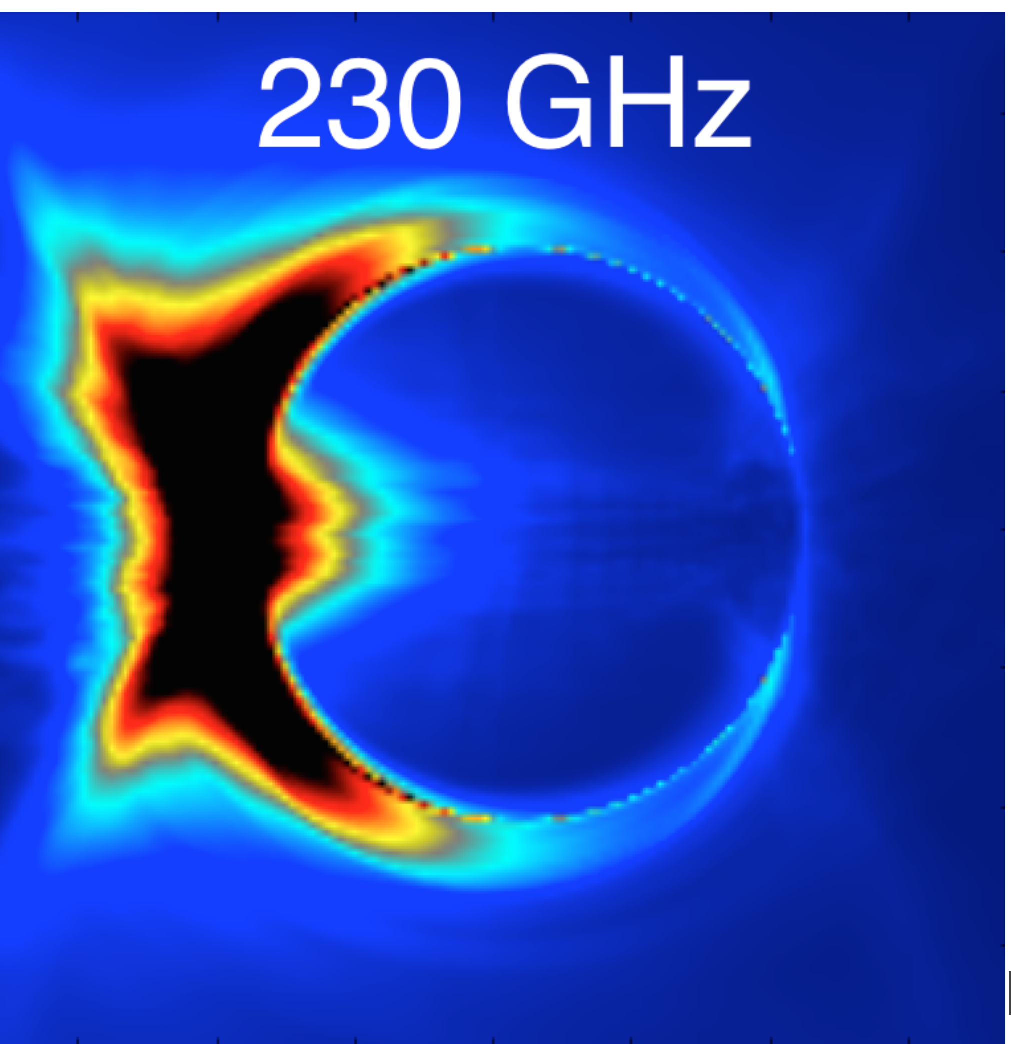
Hot electrons naturally occur in the polar regions

(Ressler, AT et al, 2016, in prep)

Predicted Spectra and Images

Electron micro-physics naturally reproduces broadband spectrum and high-E variability but falls short at very low frequencies. More to come!



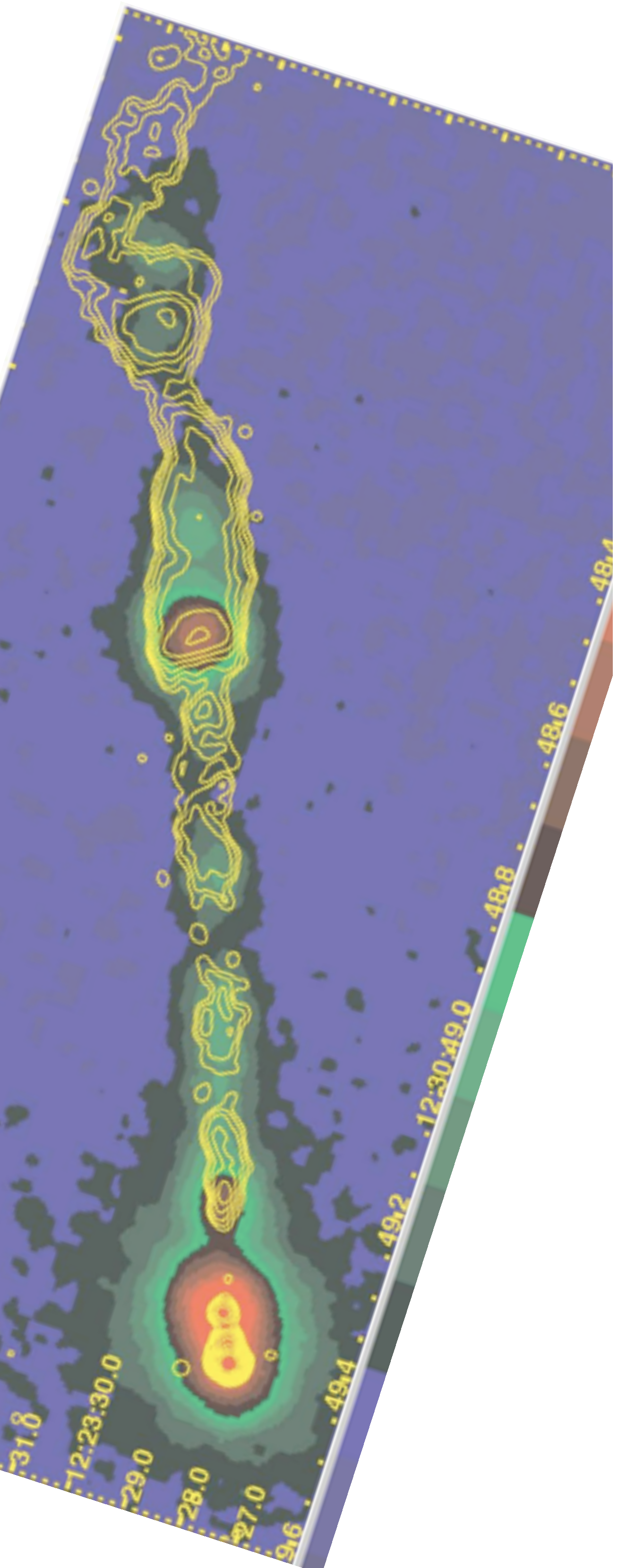


Predicted *EHT* mm-wavelength image of SgrA* black hole shadow

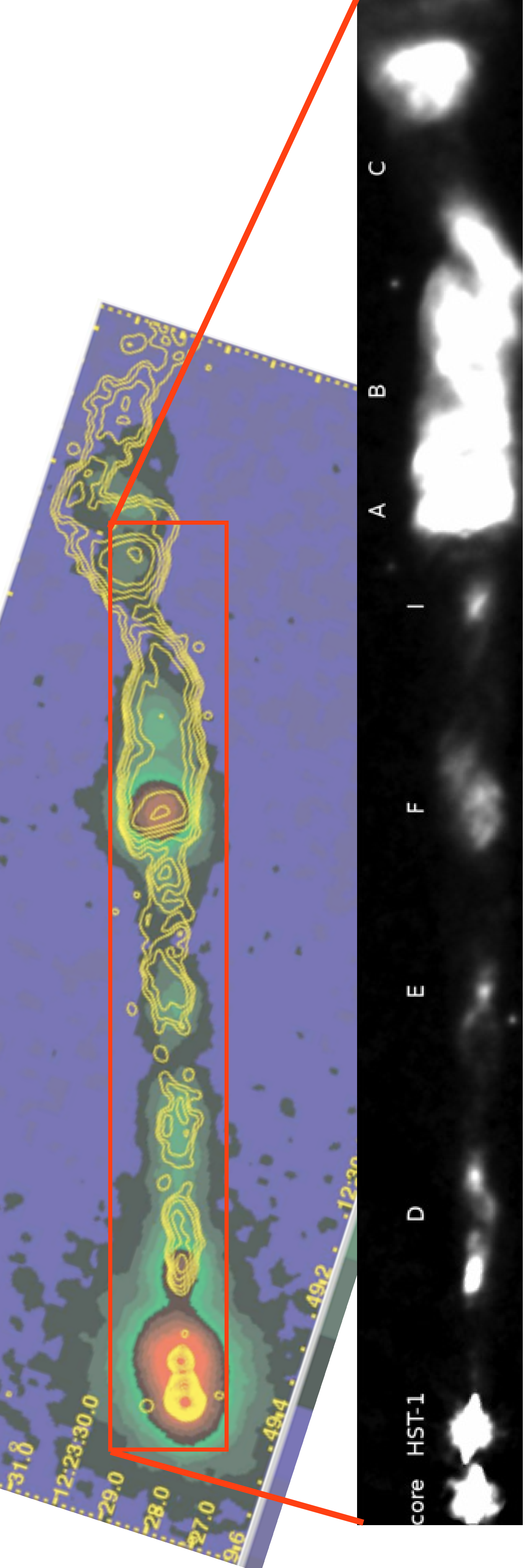
(Ressler, AT et al, 2016, in prep)

Sean Ressler (UC Berkeley)

Magnetic Instabilities and Jet Emission

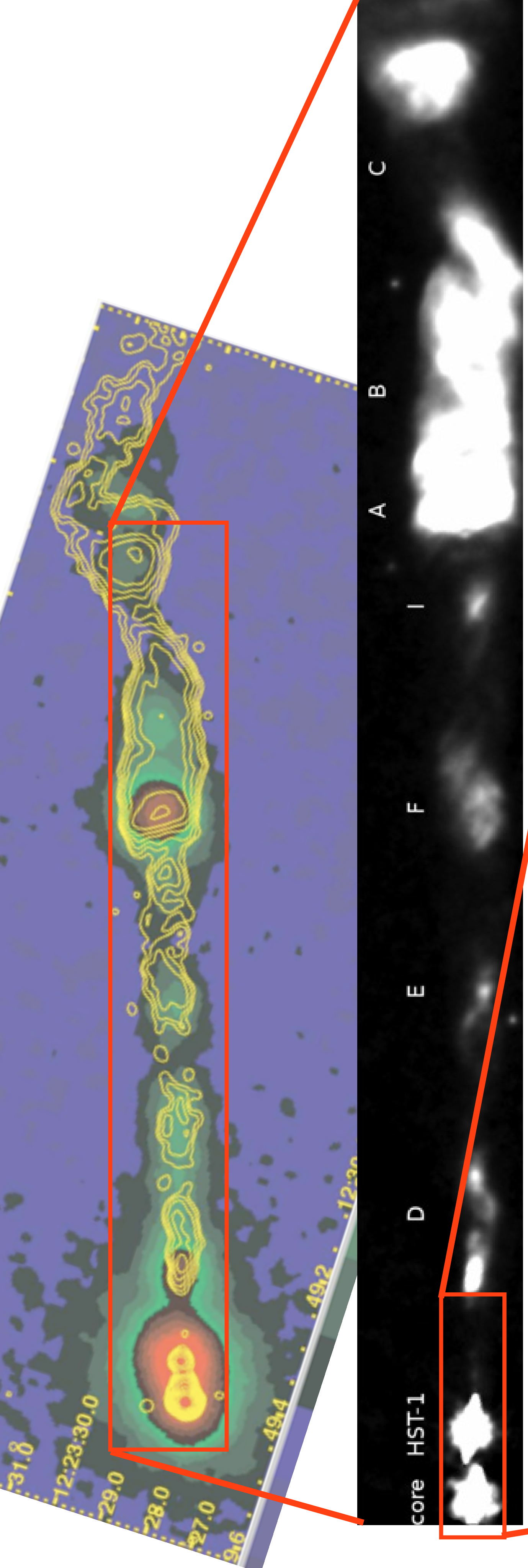


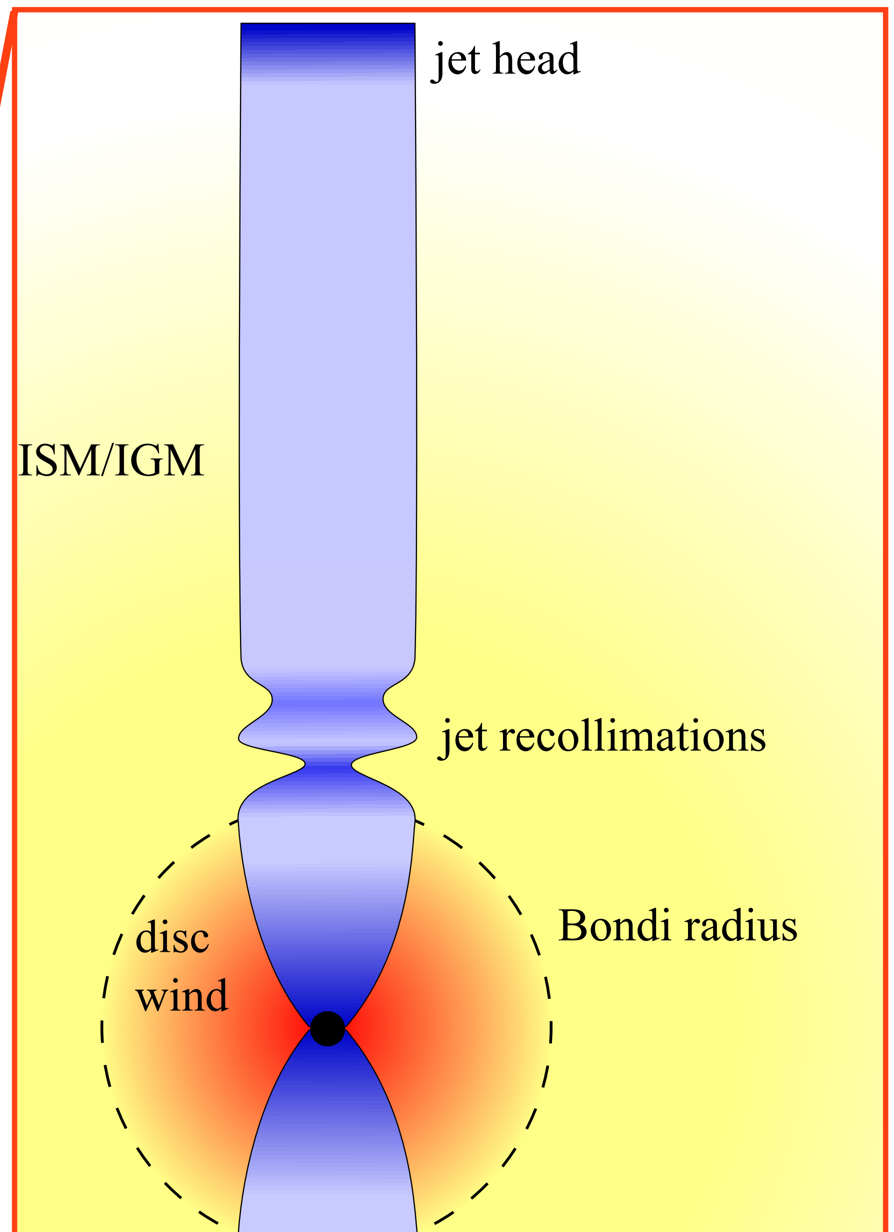
Magnetic Instabilities and Jet Emission



(Meyer+13)

Magnetic Instabilities and Jet Emission





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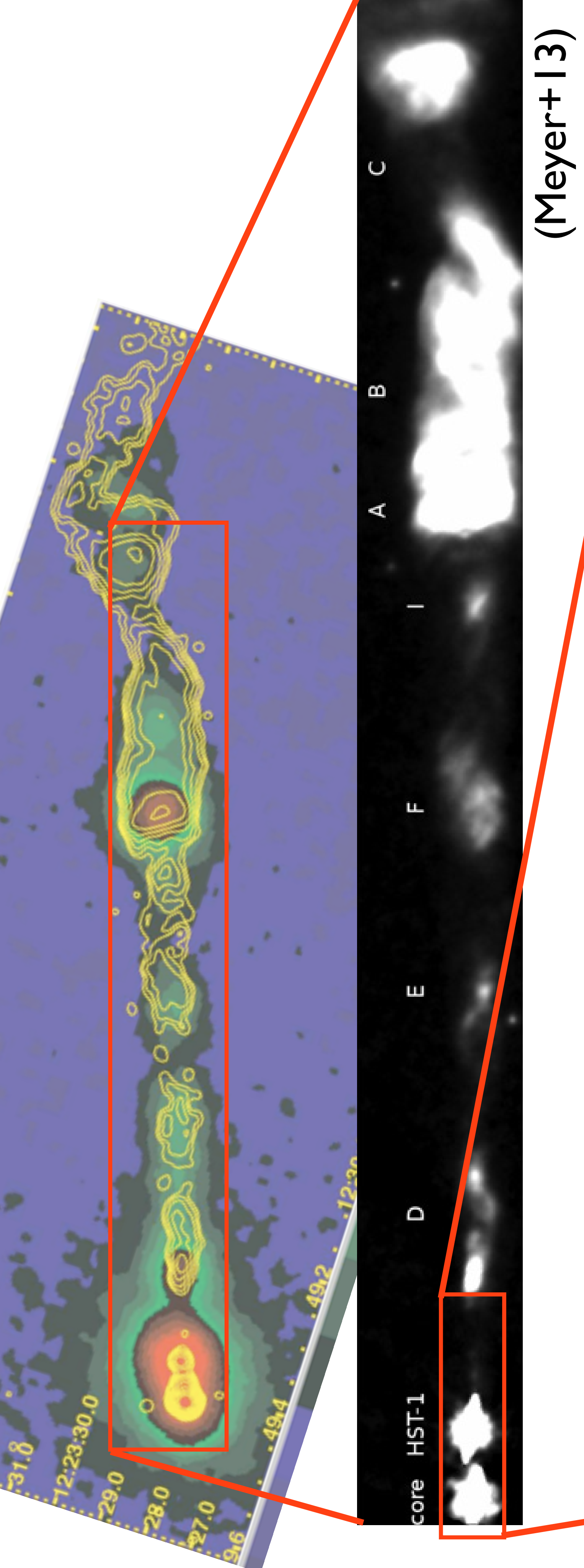
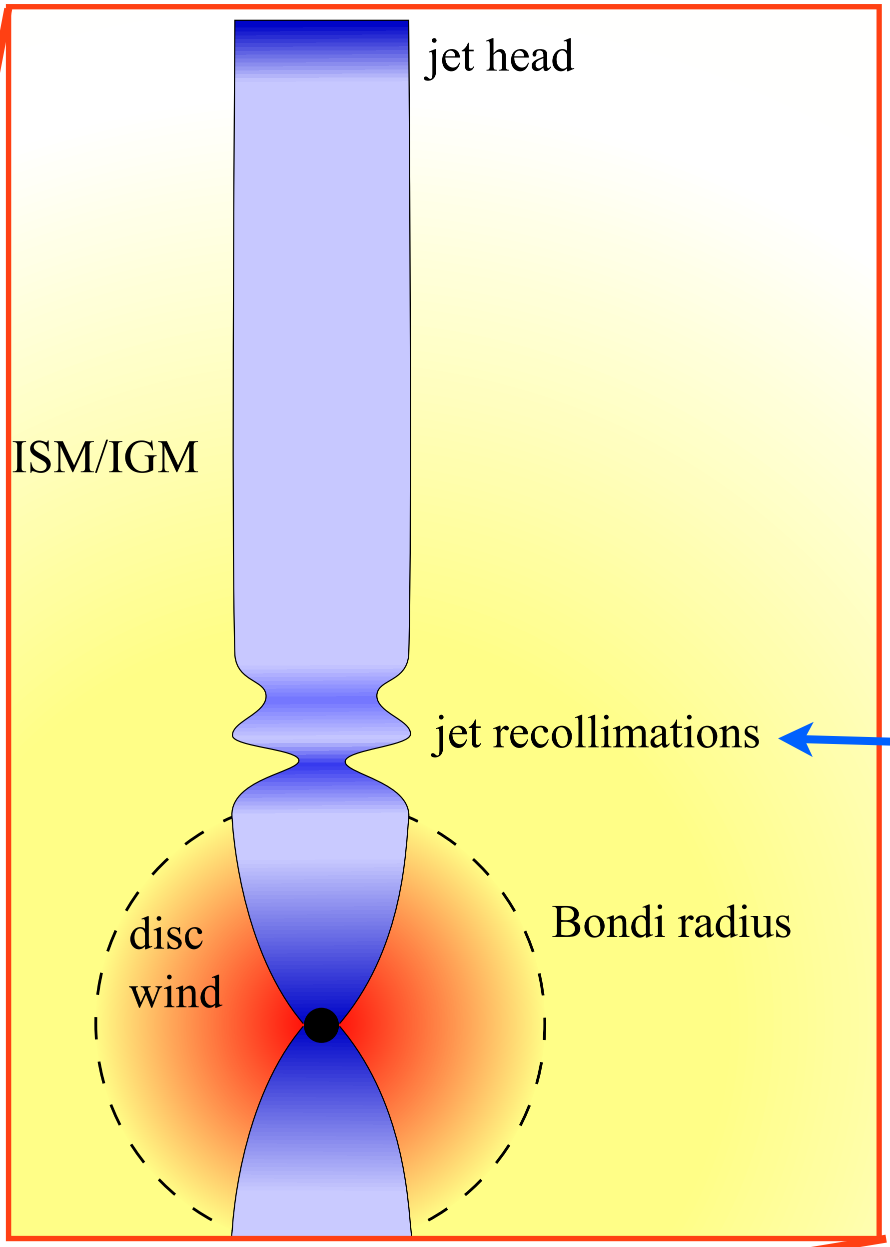
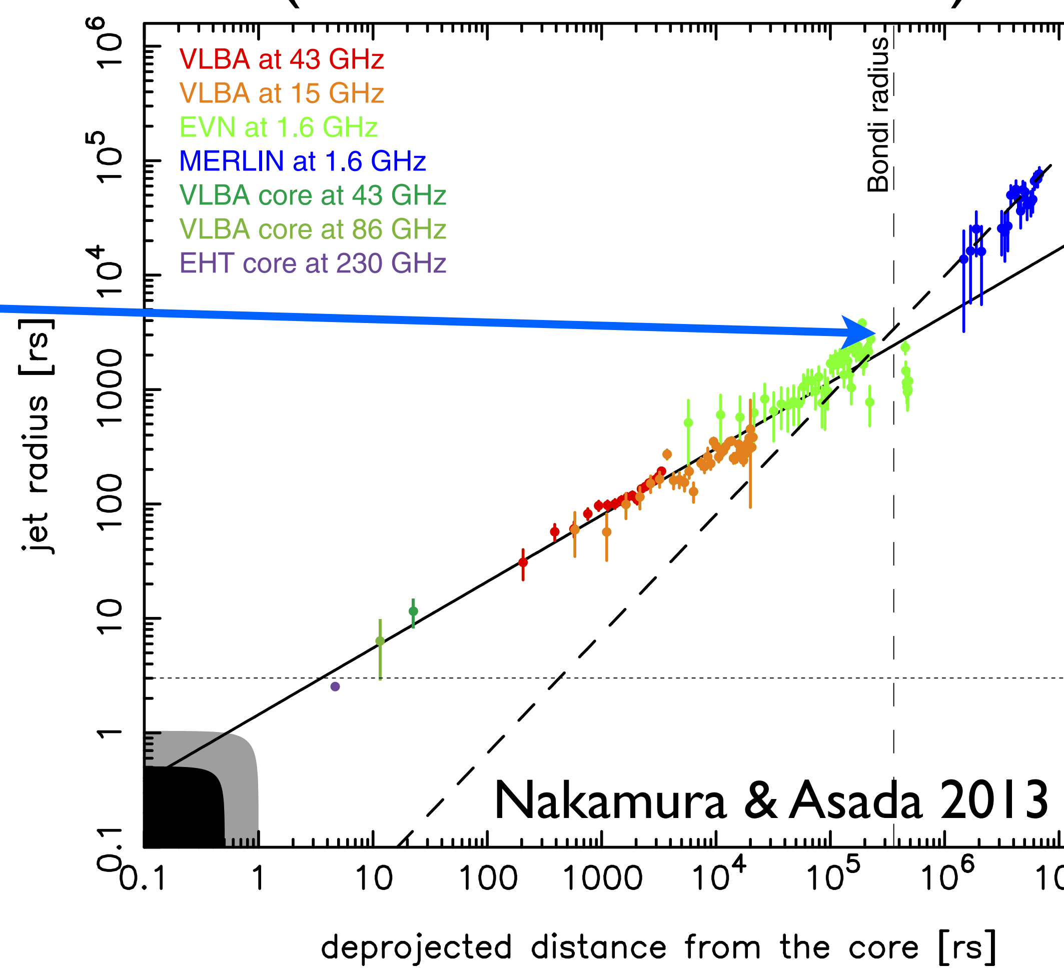




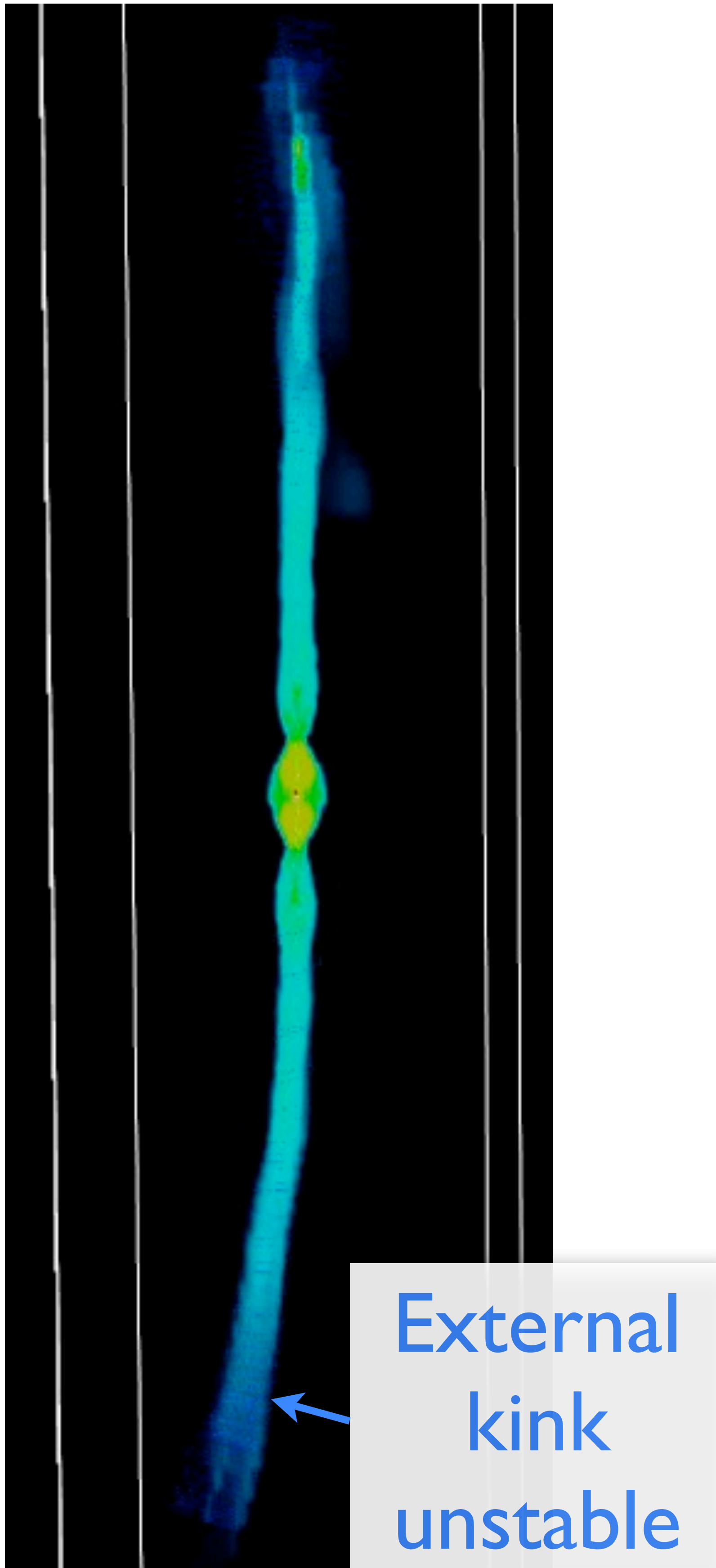
Are we seeing jet-ISM interaction?

(see also Meier 2012)



Internal Kink Makes Jets Hot

Bromberg and Tchekhovskoy, 2016, MNRAS, 456, 1739; figures/movies courtesy Bromberg



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

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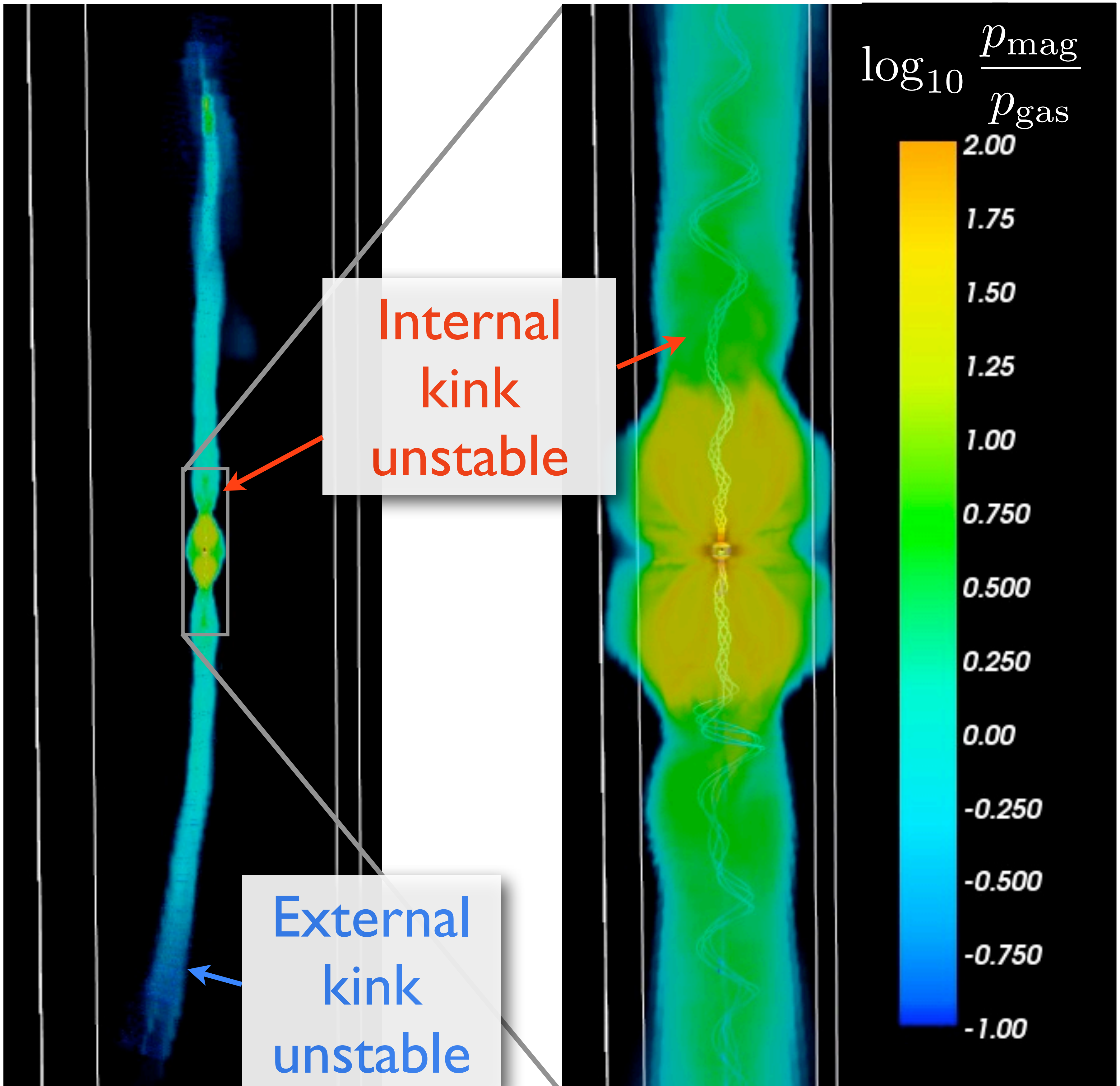

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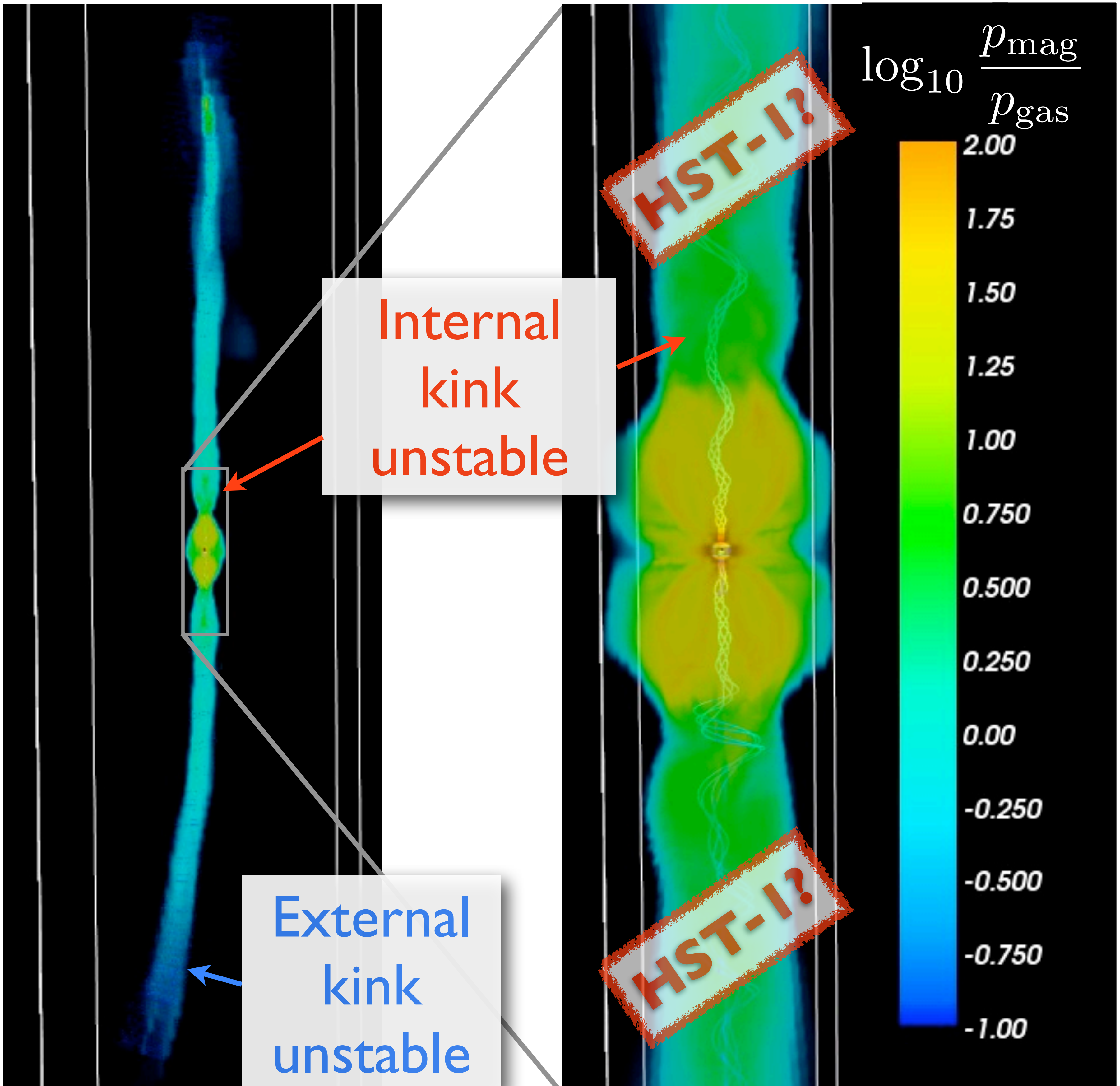

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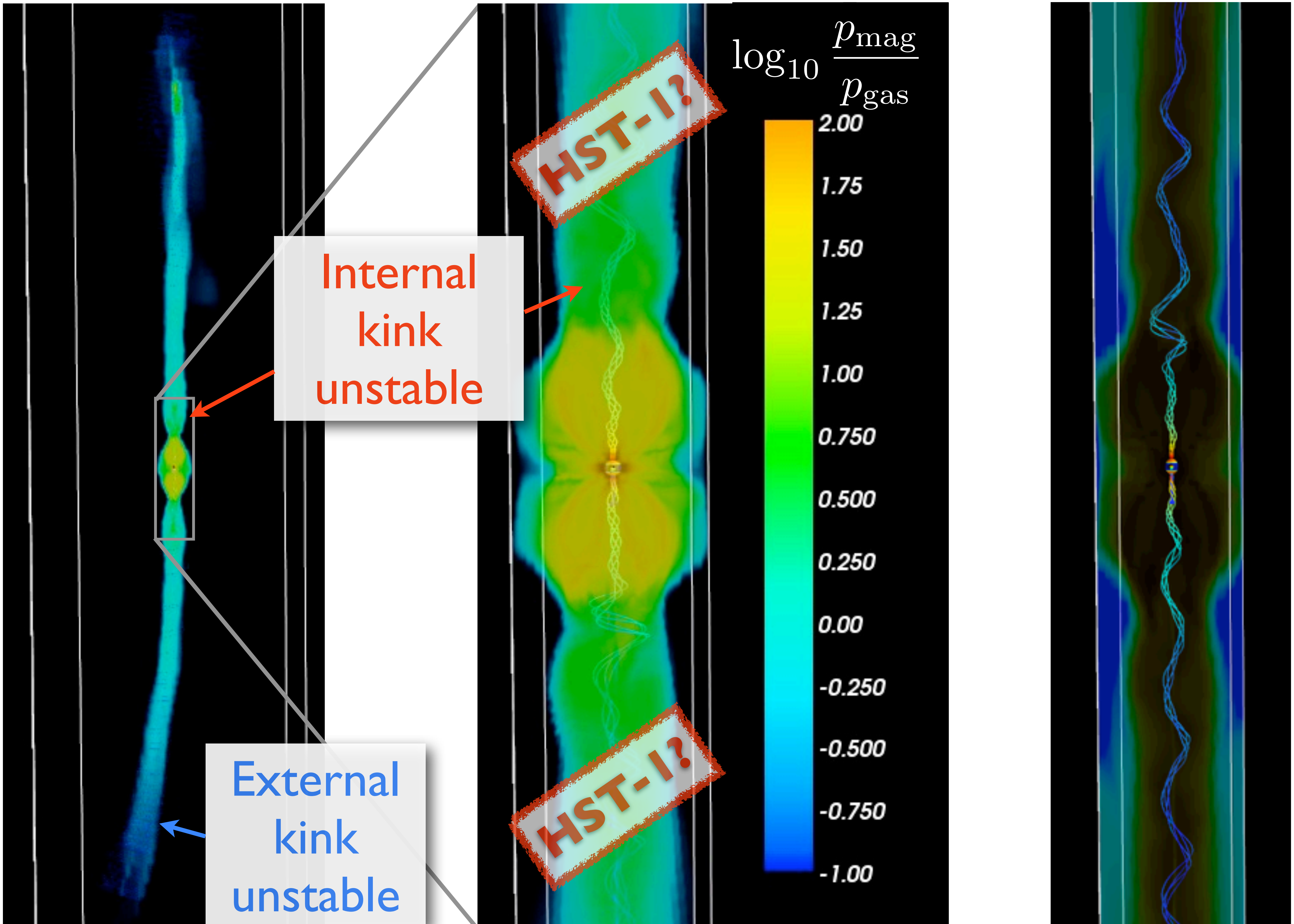

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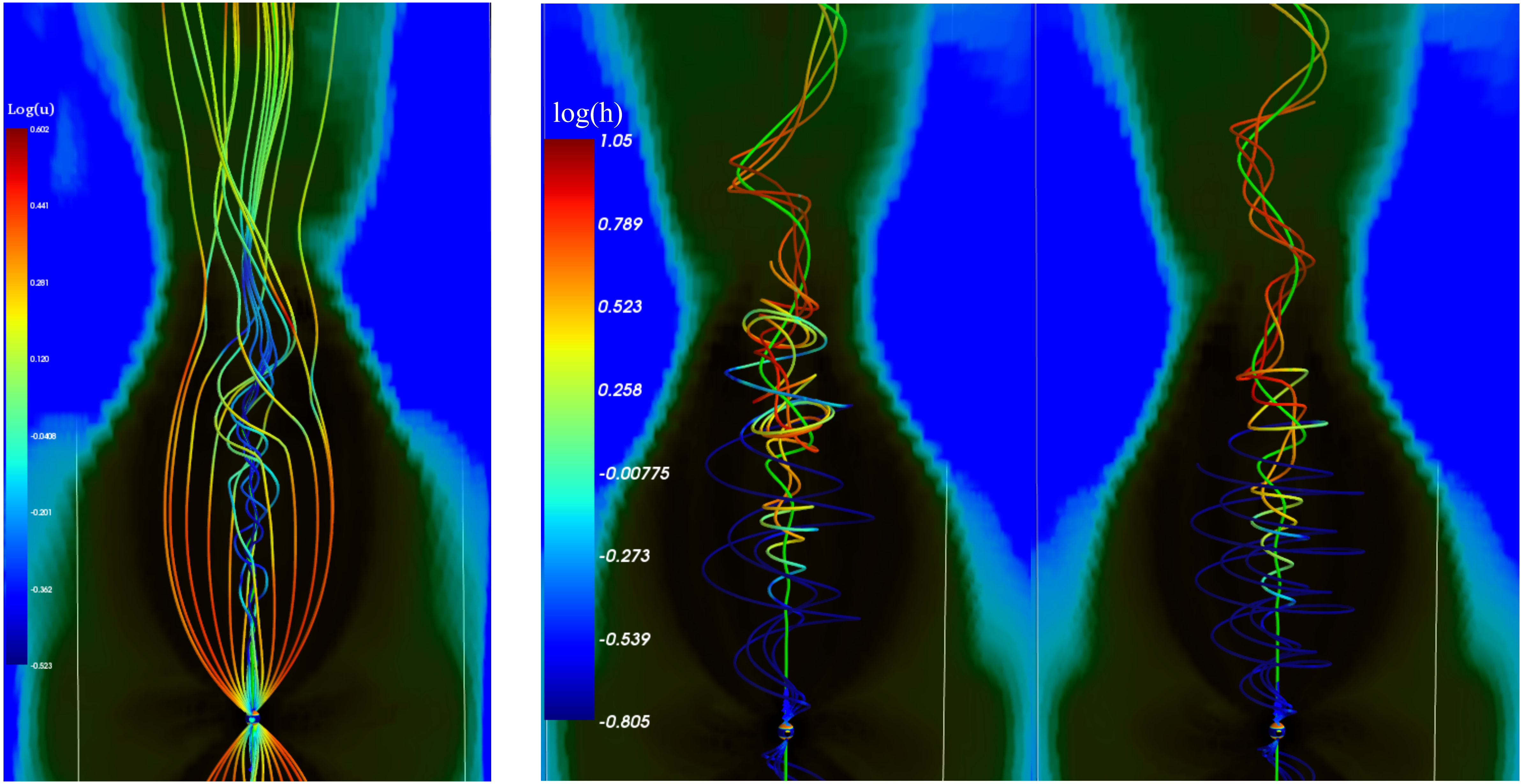
How does Jet Heating Work?

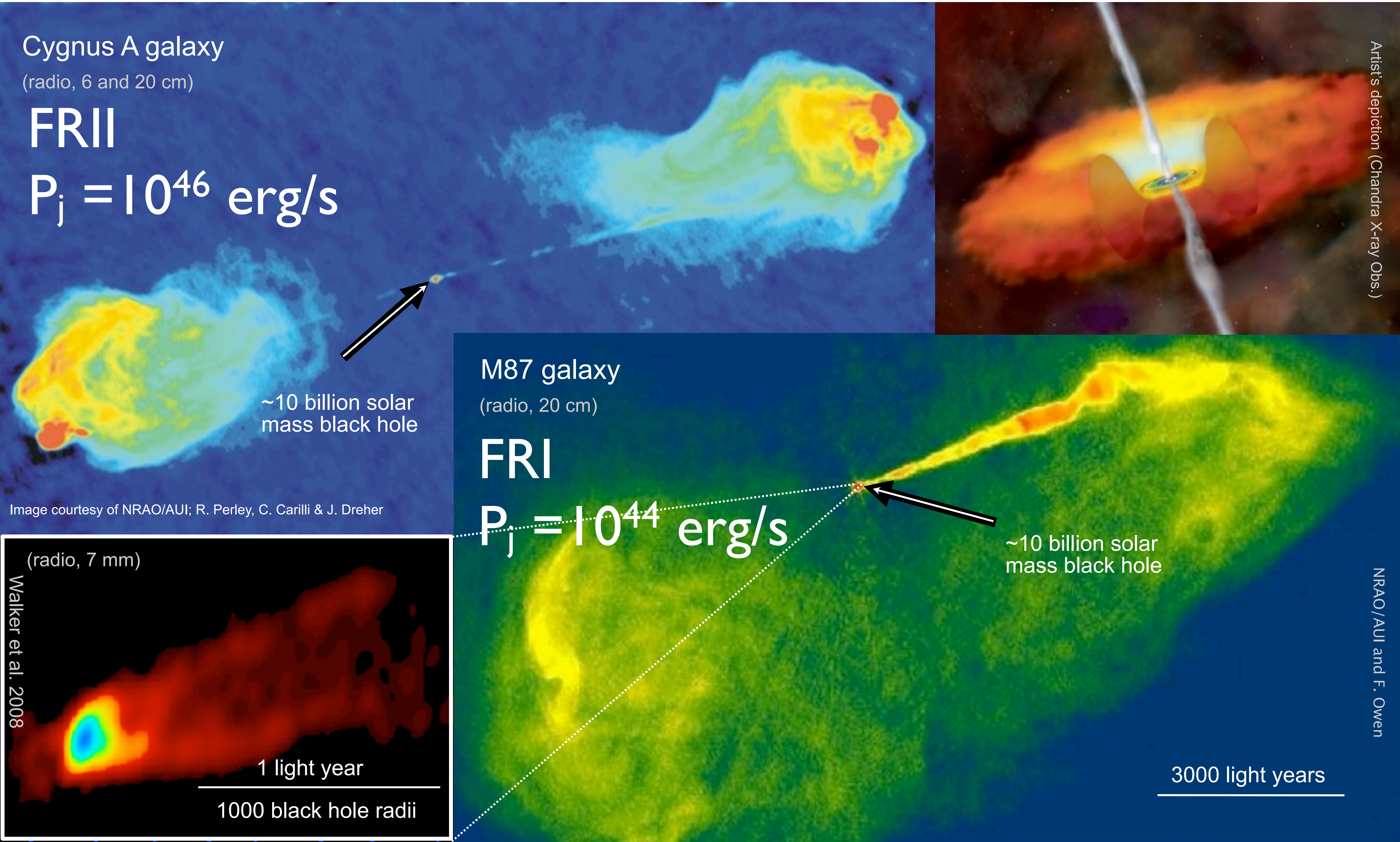


Velocity lines | Fluid B lines | Lab B lines

Recollimation → internal kink →
→ turbulence → reconnection → emission

What does Jet Morphology Tell Us?

FRI/FRII dichotomy (Fanaroff & Riley, 1974)



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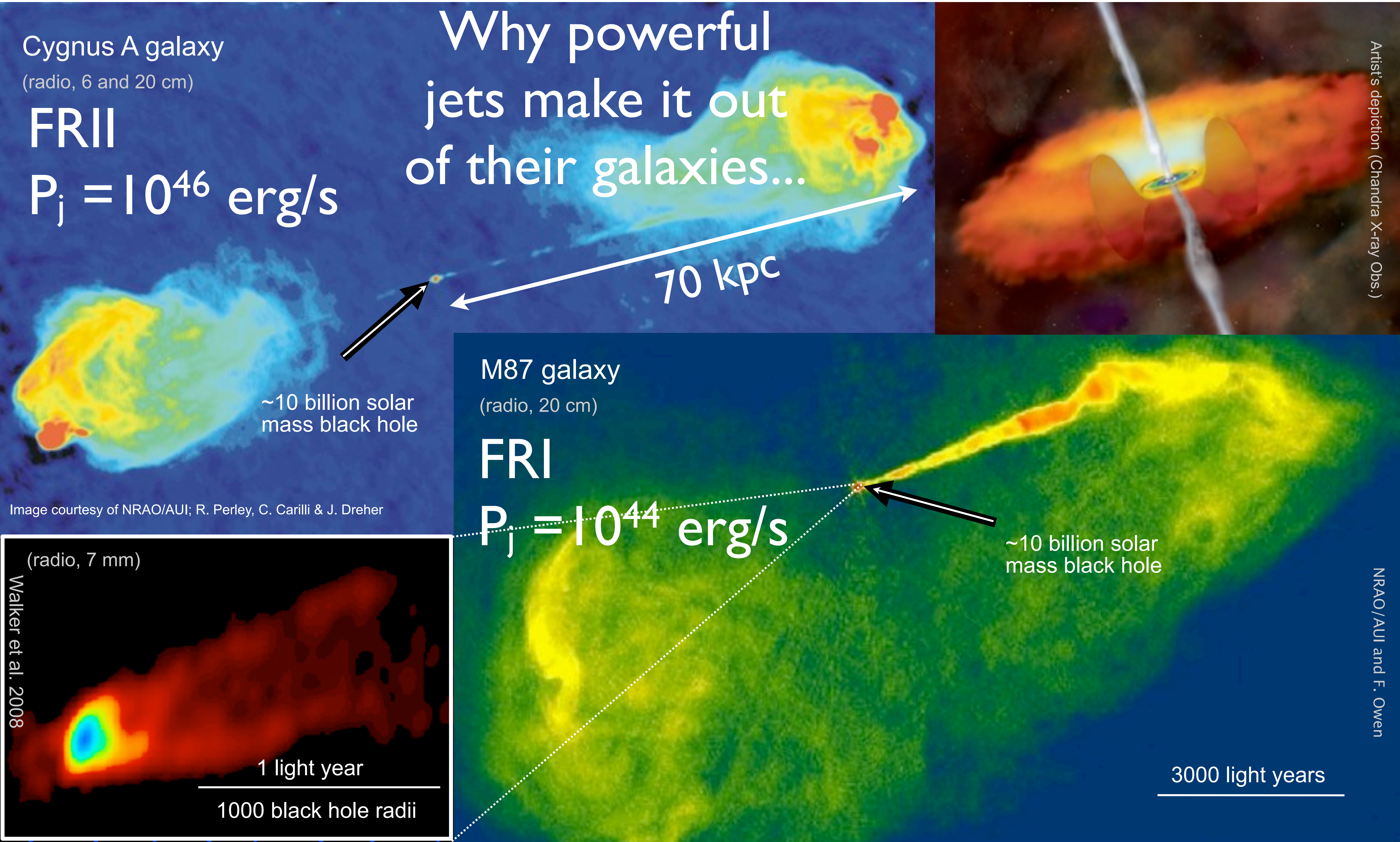

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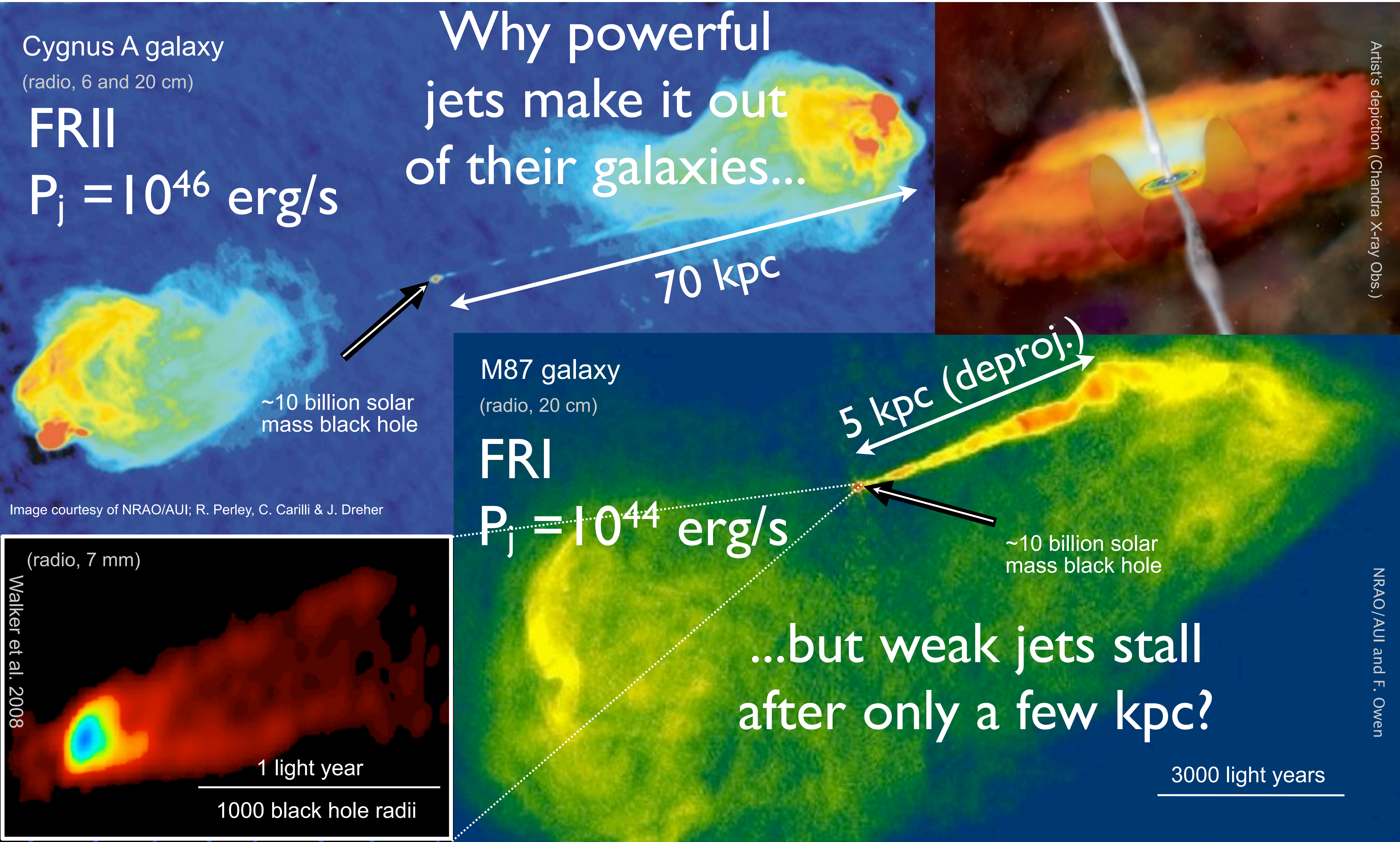

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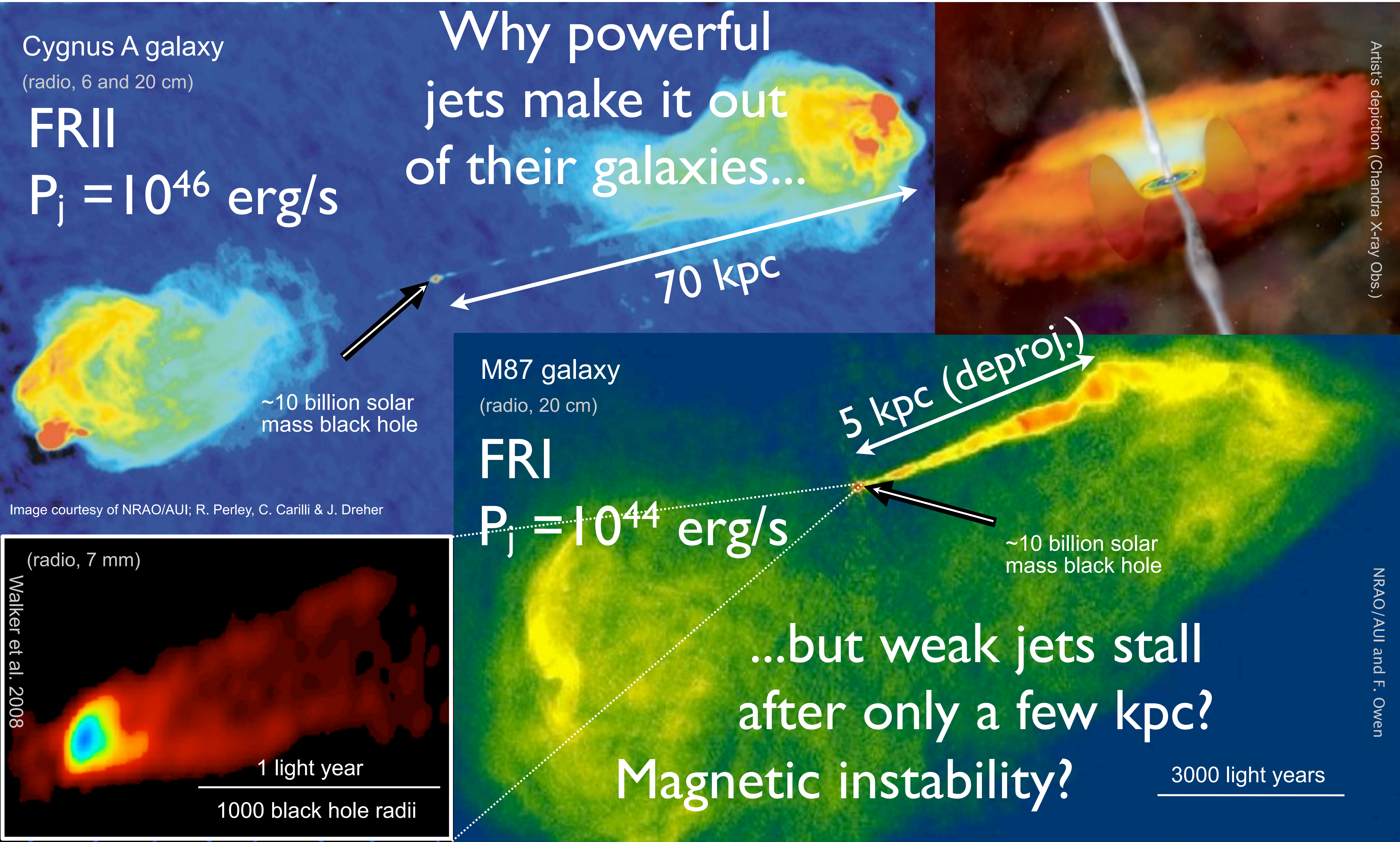


Instability of Magnetized Jets

- Kink instability growth timescale controlled by the magnetic pitch (high-mag., mildly relativistic):

$$t_{\rm kink} \simeq \frac{2\pi R_{\rm j}}{c}\frac{B_p}{B_\phi}$$

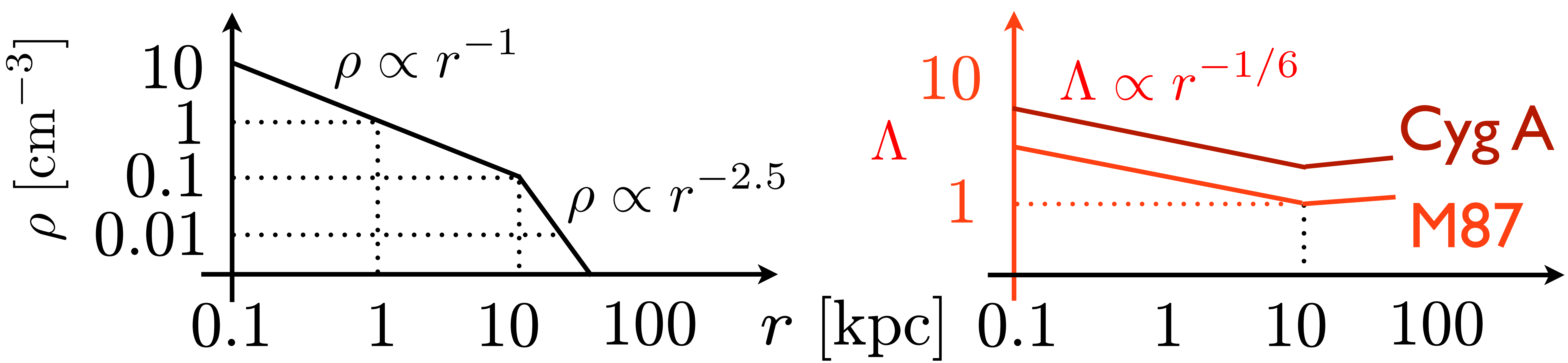
(Appl et al. 2001)

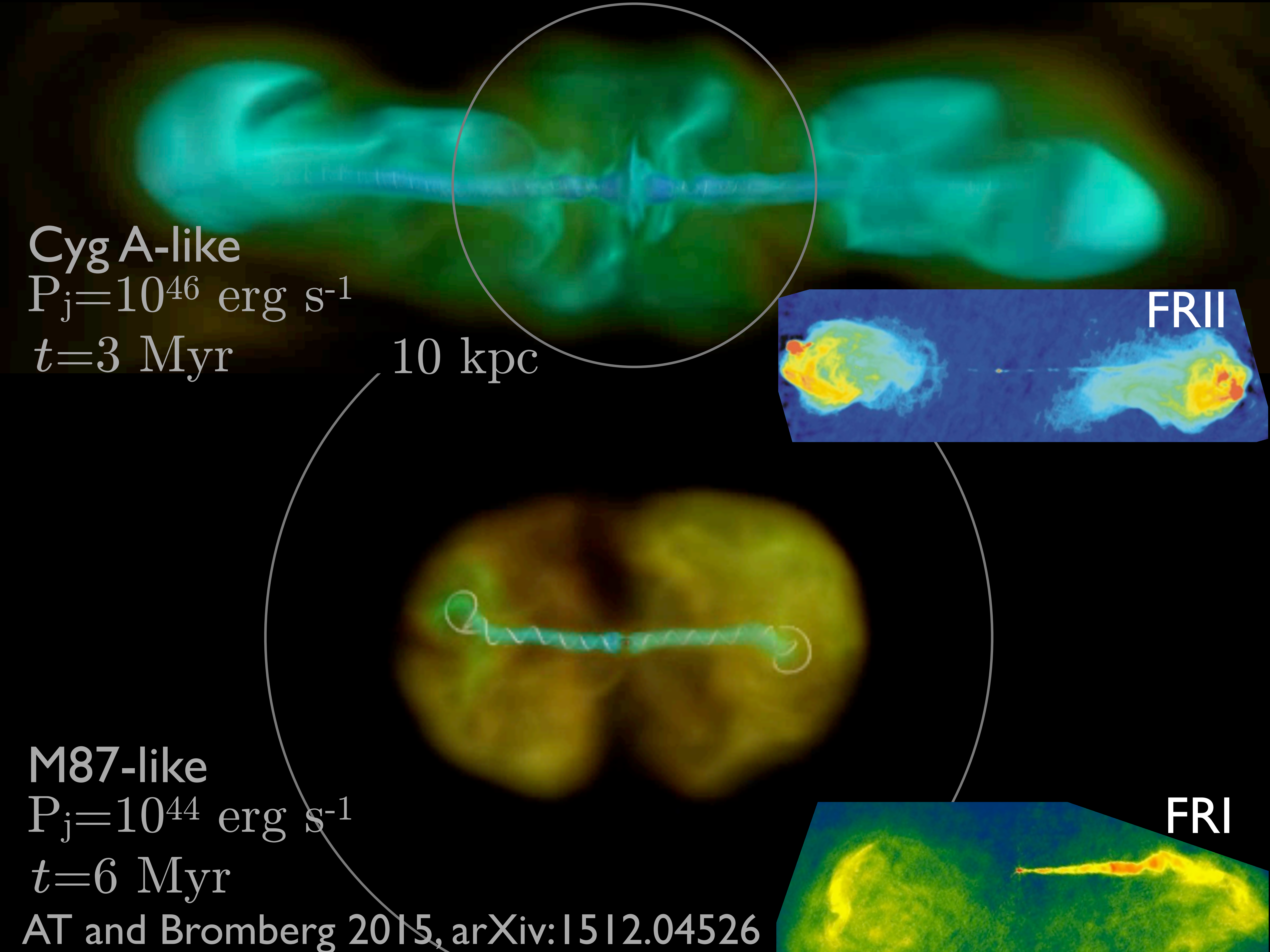
- Jets are *unstable* if $5t_{\rm kink} \lesssim t_{\rm travel}$, or

$$\Lambda \simeq 10\left(\frac{L_{\rm j}}{\rho r^2 c^3}\right)^{1/6} \lesssim 1$$

(Bromberg & AT 2016)

- Cartoon galaxy density profile:




Cyg A-like
$P_j = 10^{46}$ erg s^{-1}
$t = 3$ Myr
10 kpc
FRII
M87-like
$P_j = 10^{44}$ erg s^{-1}
$t = 6$ Myr
FRI
AT and Bromberg 2015, arXiv:1512.04526

Summary

- Dynamically important magnetic fields wide spread:
  - Jets are robust and happy to feed on anything
  - MADs give the upper envelope of jet power for given $\dot{M}$
  - BUT: strong jets benefit from disk rotation
  - Problem: How do you get rid of large-scale magnetic flux?
- Large-scale poloidal field dynamo is now a reality
  - No need for large-scale poloidal flux: toroidal would do too
- Jet morphology is set by 3D external kink and controlled by jet power and ambient density:
  - low-power jets are unstable and get stalled inside galaxies
  - FRI/FRII dichotomy likely mediated by magnetic instabilities