Black Hole Magnetospheres (Wrap-up)

Alexander (Sasha) Tchekhovskoy

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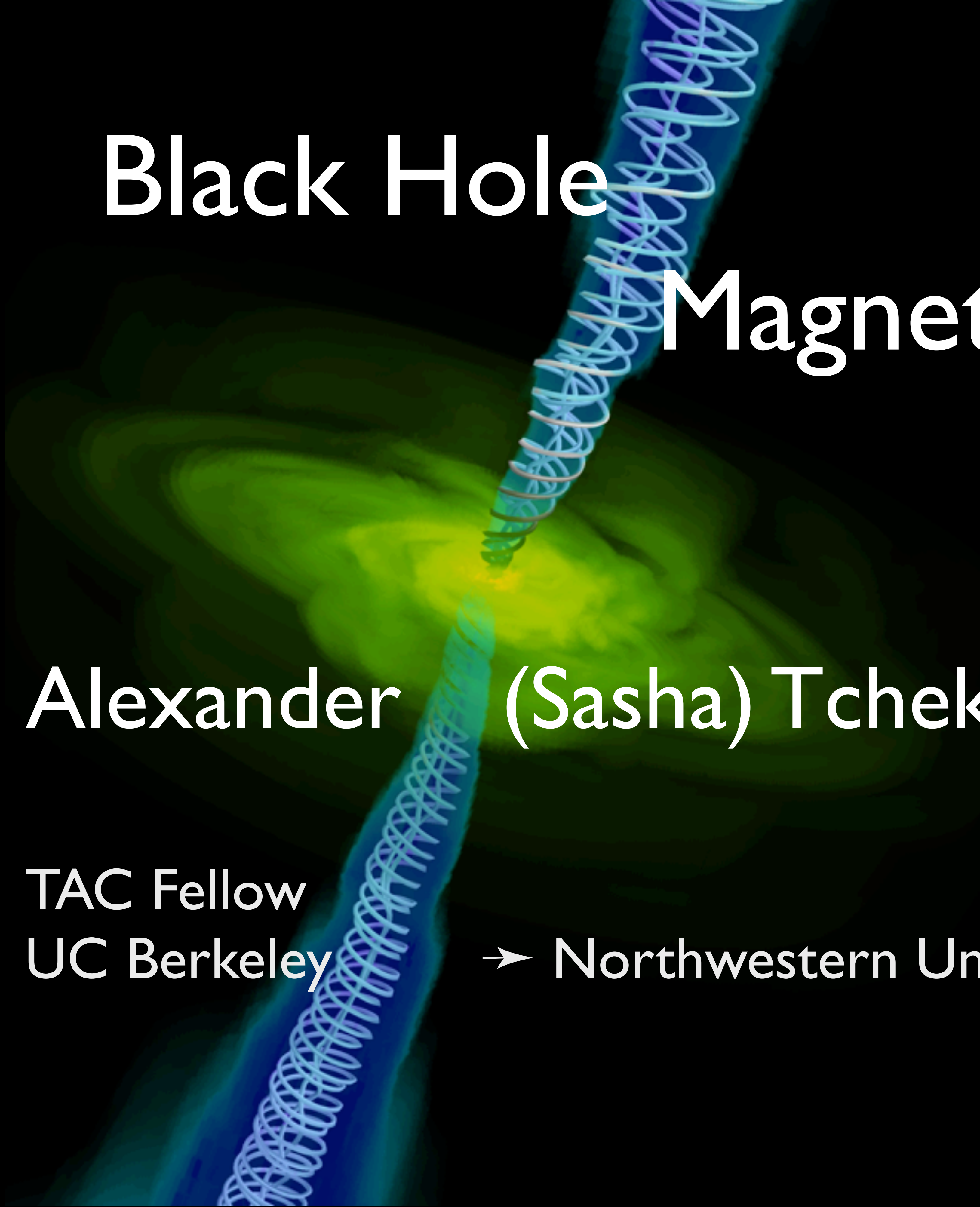
UC Berkeley ➛ Northwestern University



How do Jets Accelerate?

Conserved quantities along jets = ratios of conserved fluxes:

$$F_B = B_p$$

$$F_M = \gamma\rho v_p = \eta B_p$$

$$\Rightarrow \eta = \frac{F_M}{F_B} = \frac{\gamma\rho v_p}{B_p} = \text{const}$$

$$F_E = \underset{\displaystyle \frac{cEB_\varphi}{4\pi}}{\underset{||}{F_{EM}}} + \underset{\displaystyle \gamma F_M}{\underset{||}{F_{KE}}}$$

$$\Rightarrow \mu = \frac{F_E}{F_M} = \gamma\frac{F_{EM}}{F_{KE}} + \gamma = \gamma(\sigma + 1)$$

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$$F_{EM} = \frac{cEB_\varphi}{4\pi}, \quad F_{KE} = \gamma F_M$$

$$E = B_\varphi = \Omega R B_p / c$$

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$$\mu = \frac{\Omega^2}{4\pi^2\eta c}\pi B_p R^2 + \gamma = \frac{\mu}{\Phi}\pi B_p R^2 + \gamma$$

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$$\boxed{\frac{\gamma}{\mu} = 1 - \frac{\pi B_p R^2}{\Phi}}$$

In order to accelerate efficiently, need reduction in local field line density (Komissarov+09, AT+09)

Acceleration in a magnetic nozzle

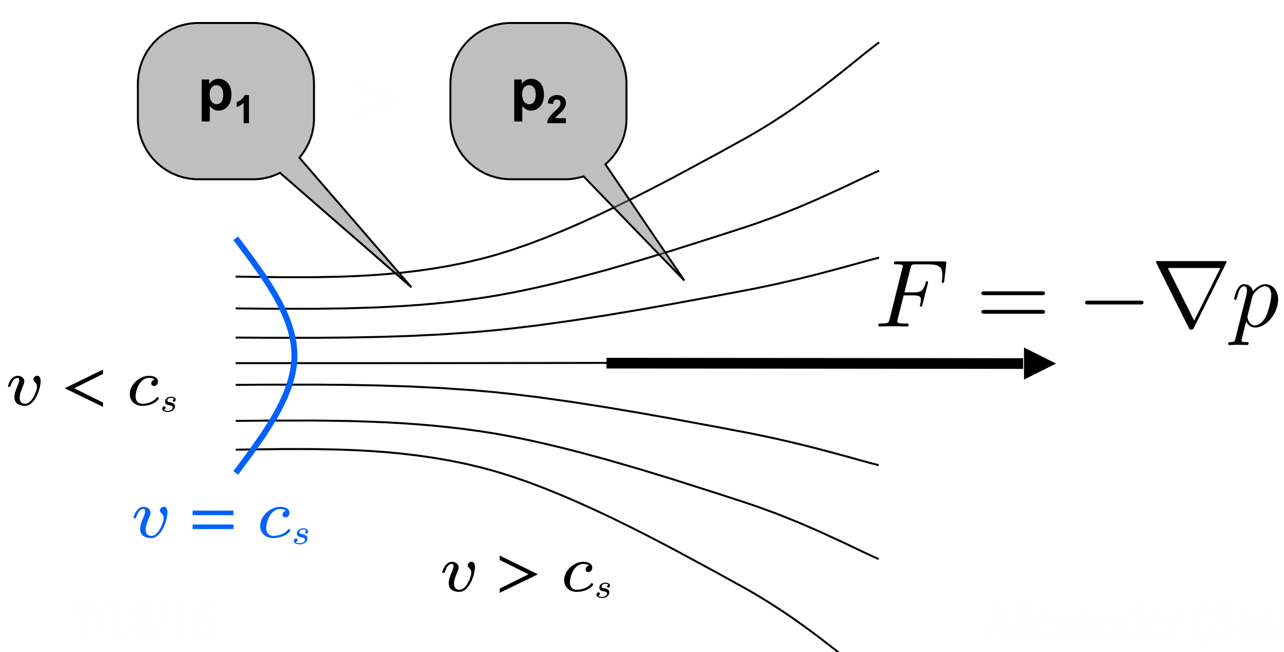
(Begelman & Li 1994,
Komissarov 2009, AT+ 2009)

$$\boxed{\frac{\gamma}{\mu} = 1 - \frac{\pi B_p R^2}{\Phi}}$$

If $B_P(R) = \mathrm{const}$, no acceleration.

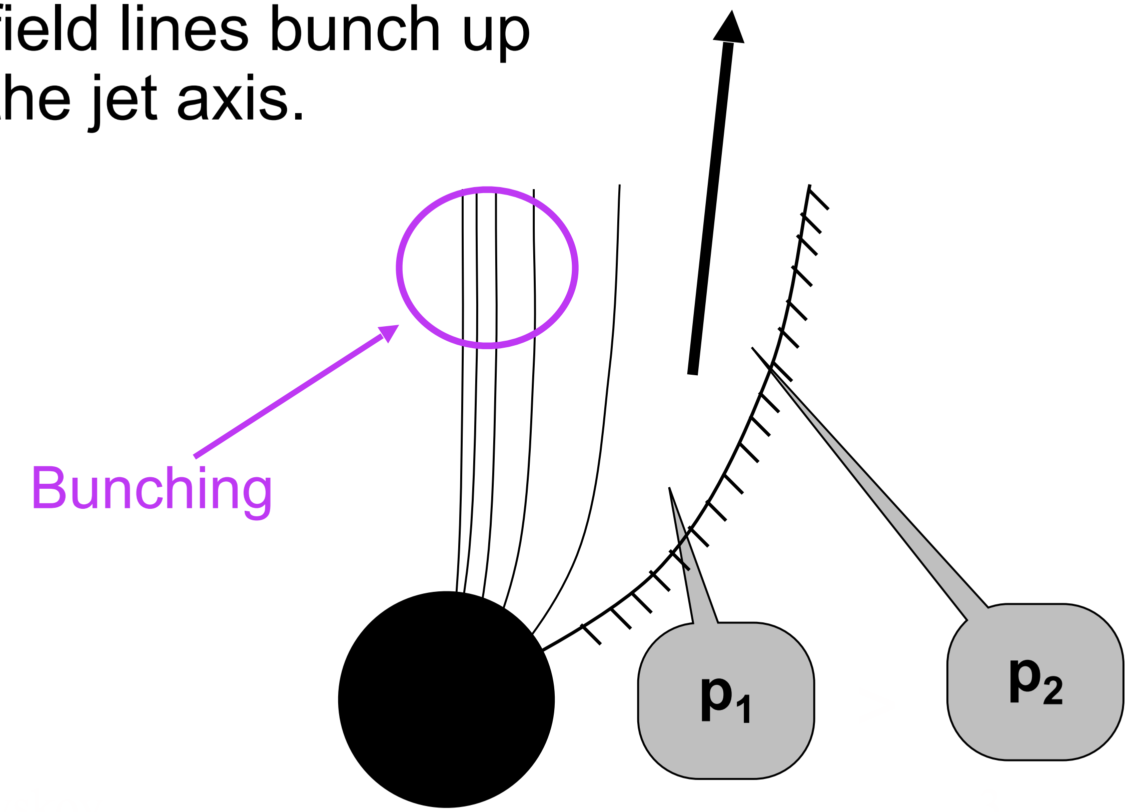
Need magnetic flux bunching toward jet axis.

Hydro: de Laval nozzle: flow opens up after sonic surface → pressure drops → ∇p accelerates flow:

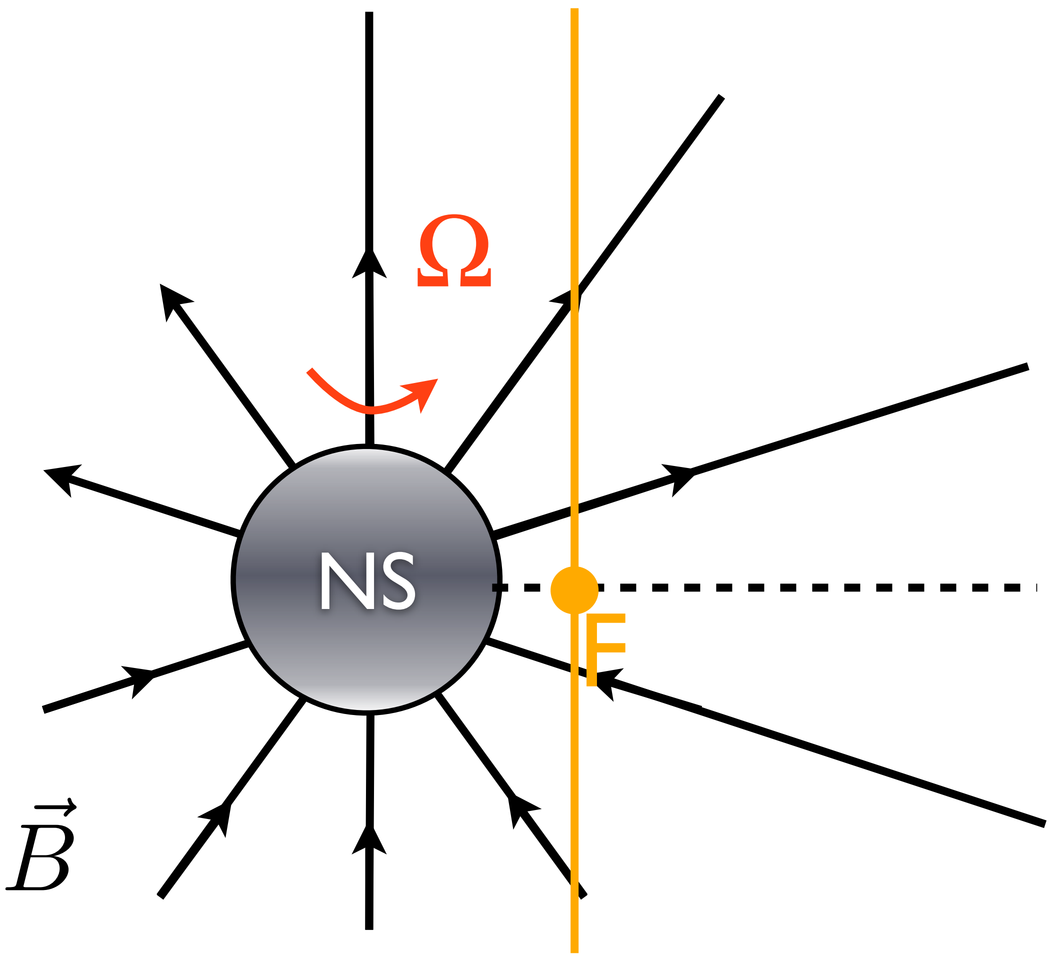


MHD: reduction in field line density as the rest of field lines bunch up at the jet axis.

$$F = -\nabla p$$



When Can Jets Accelerate?



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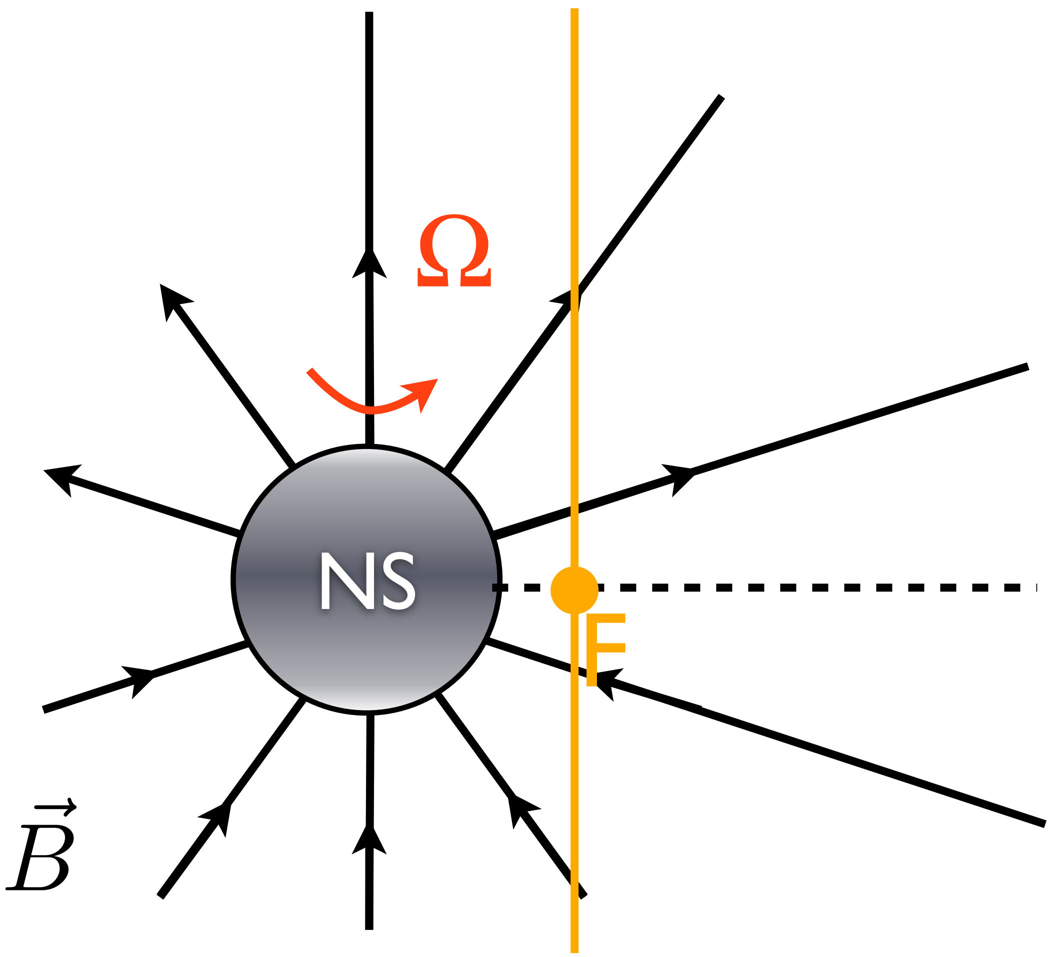

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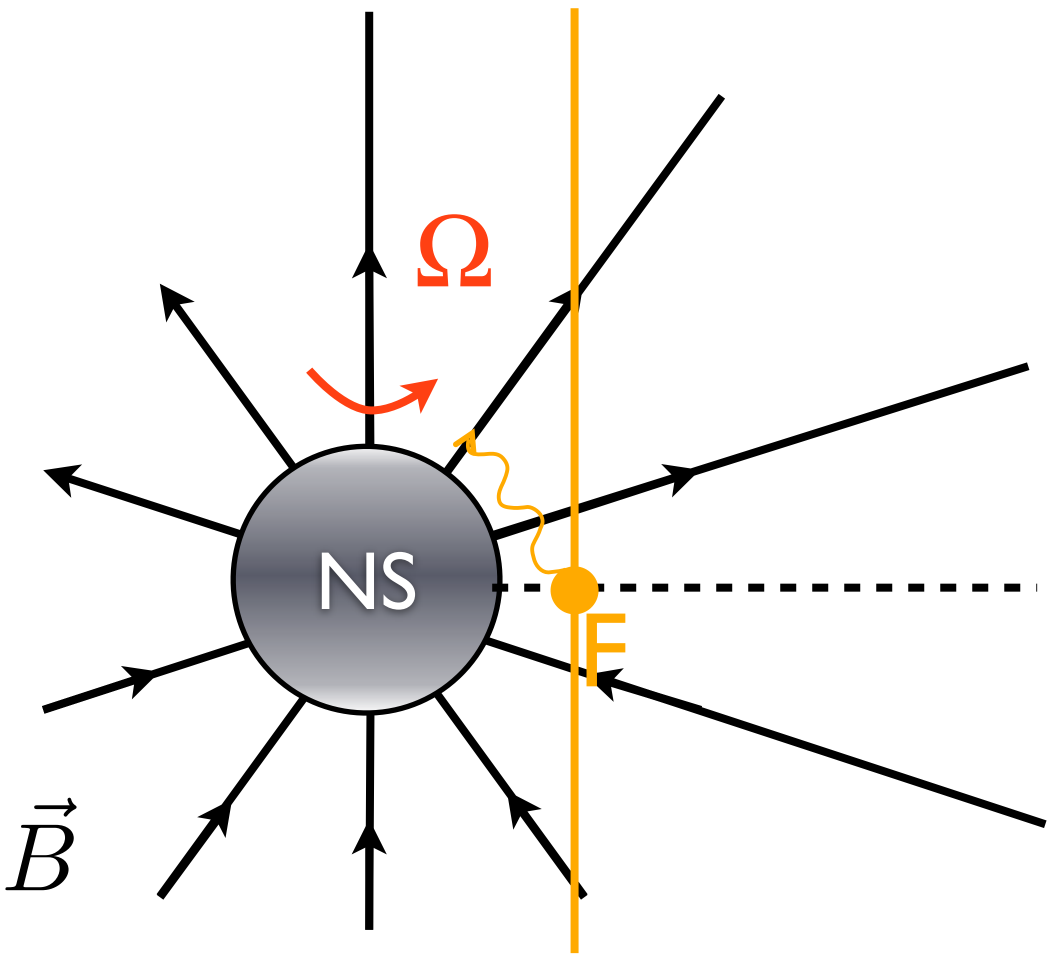

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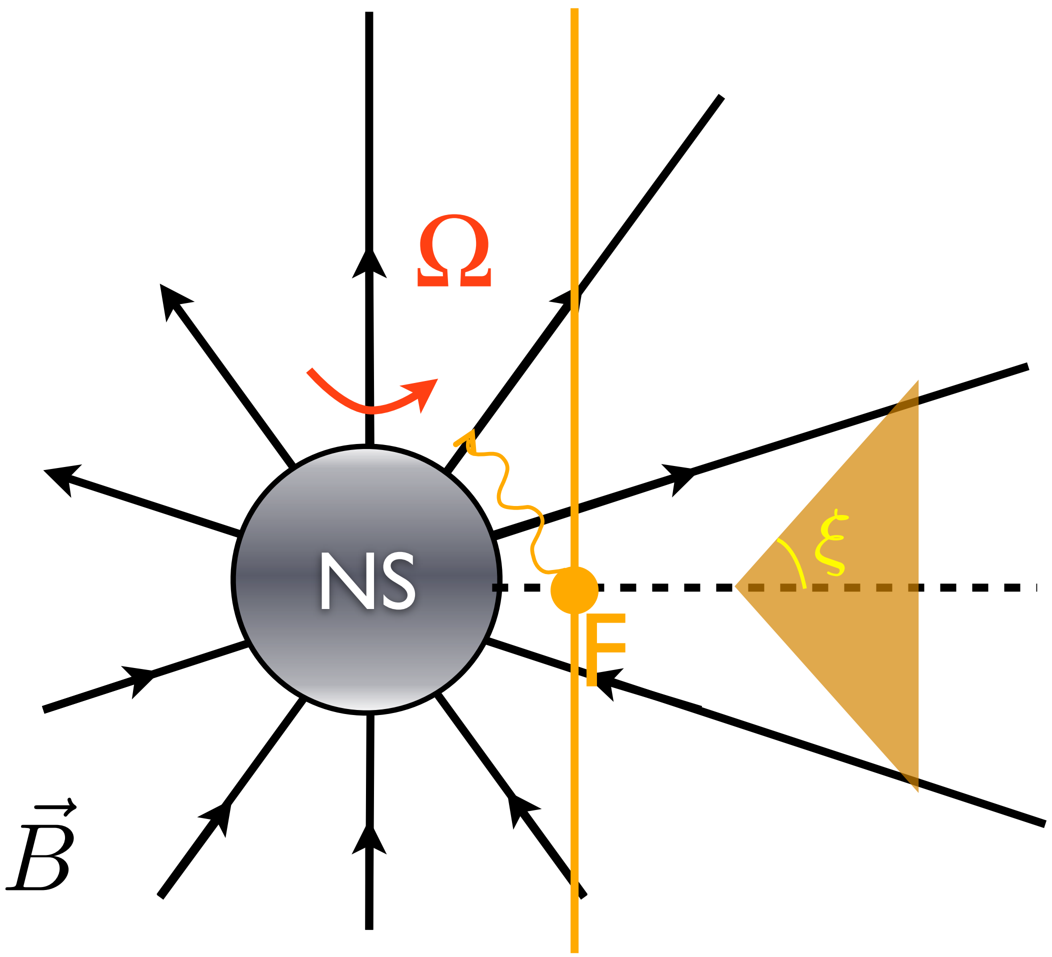

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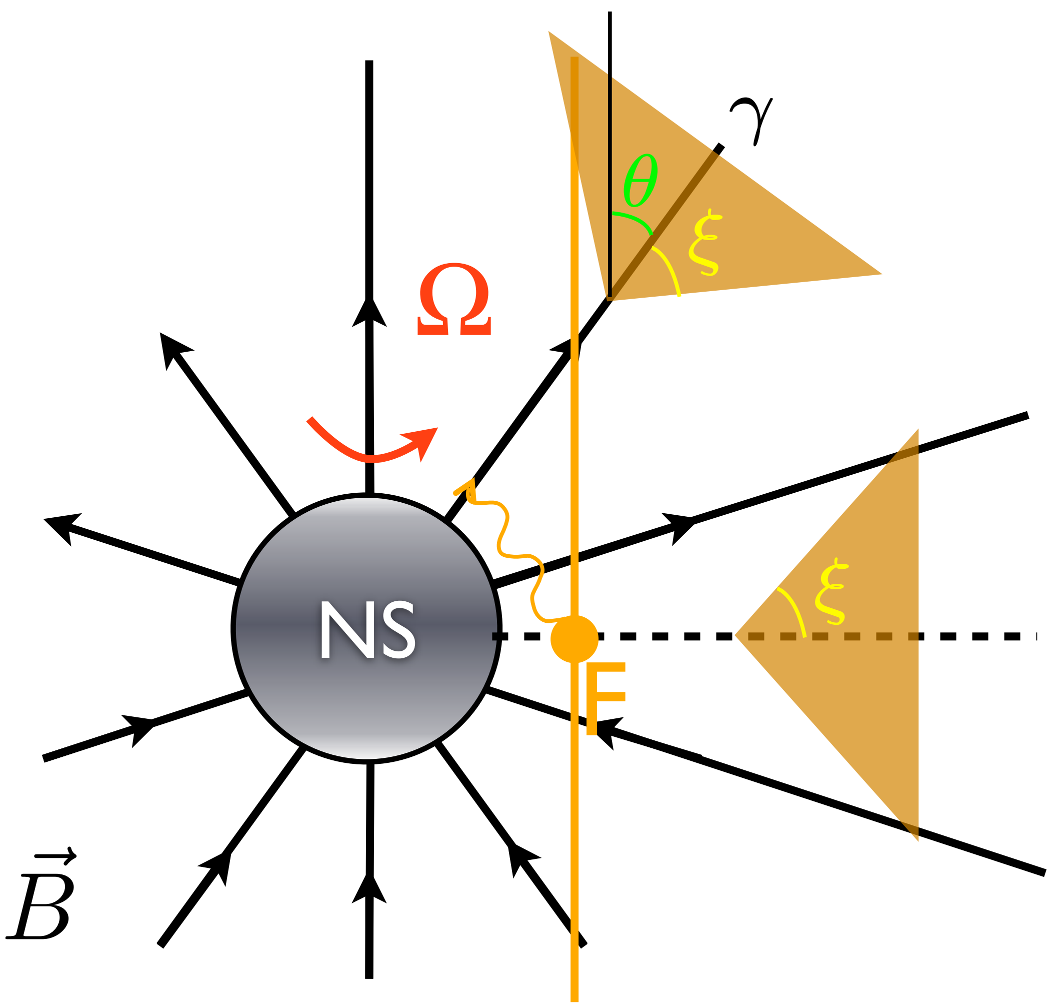

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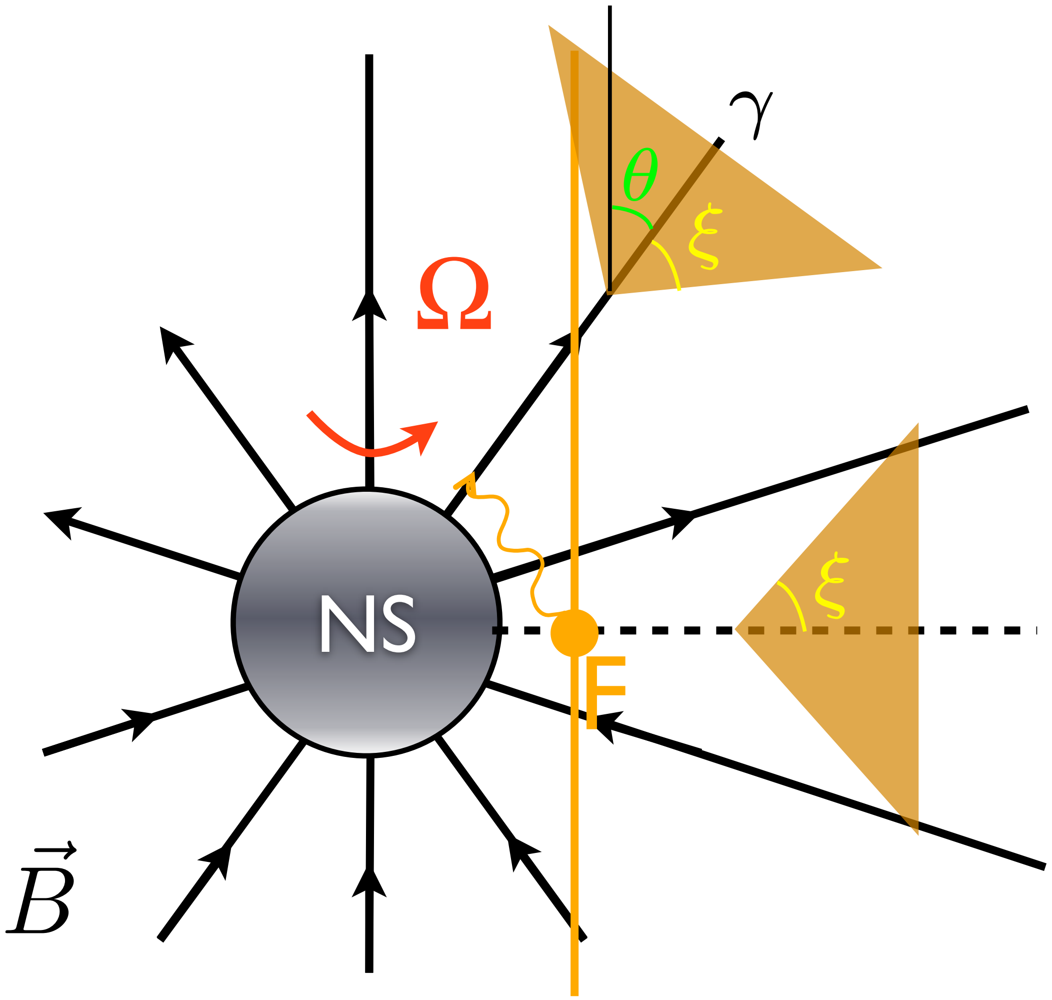

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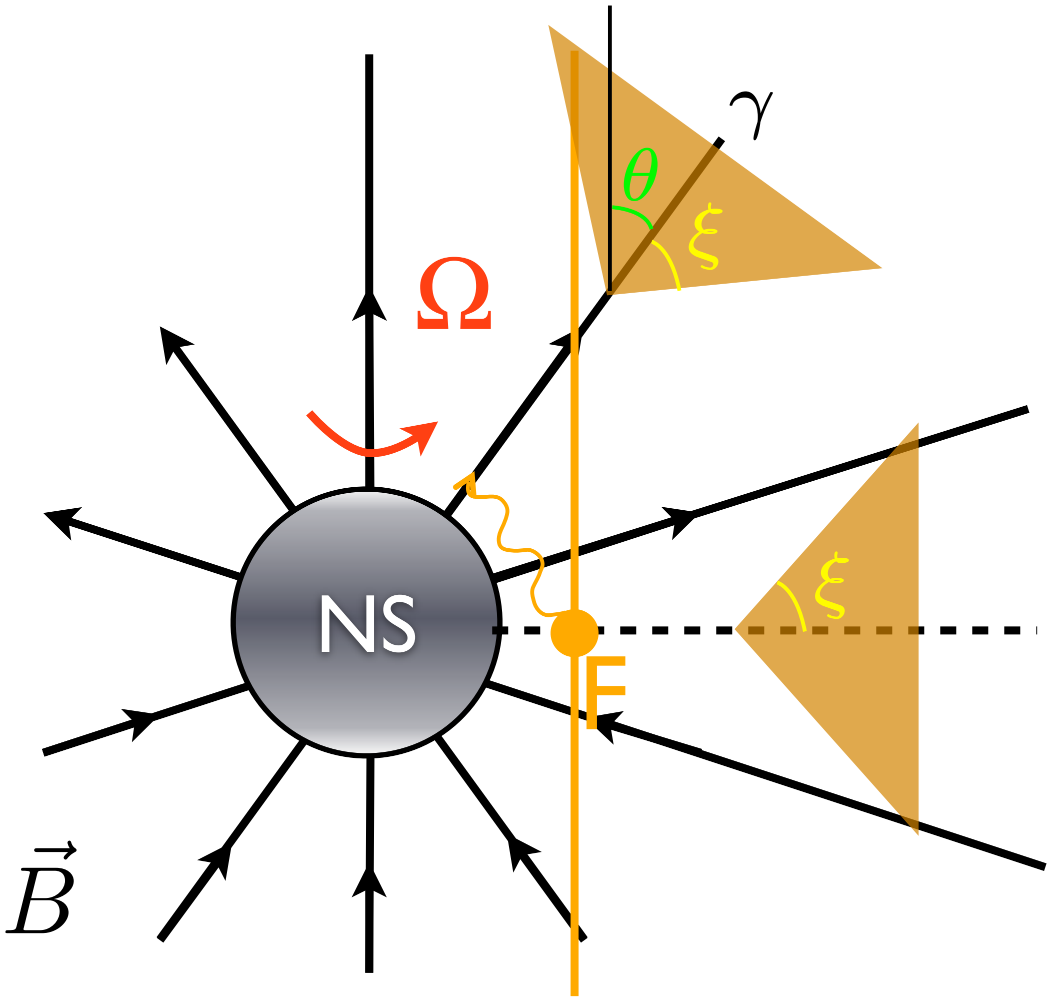

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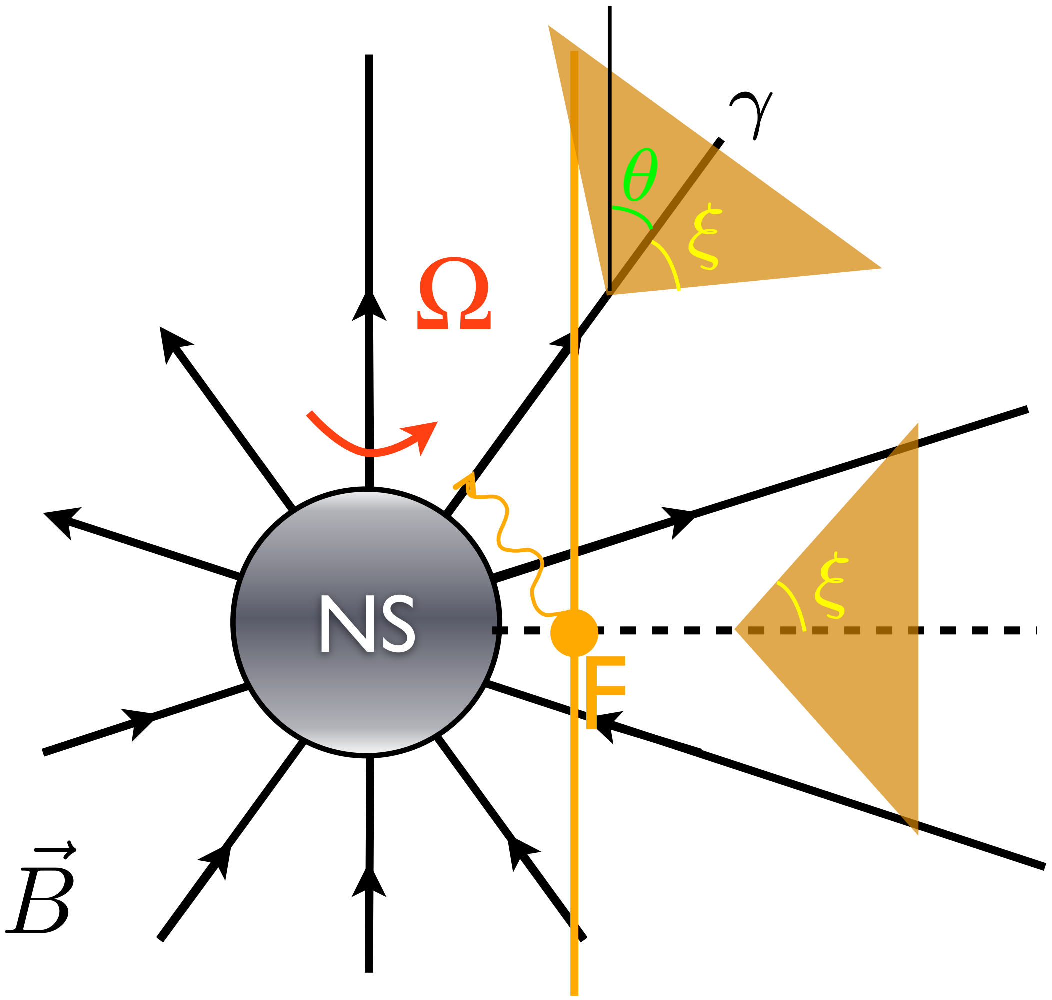
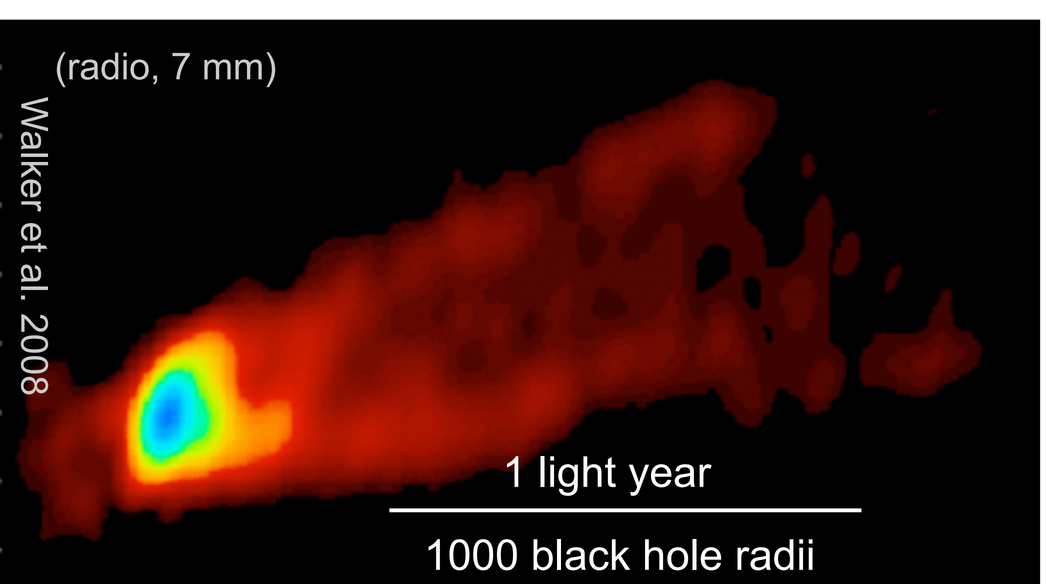


but, most jets are collimated:



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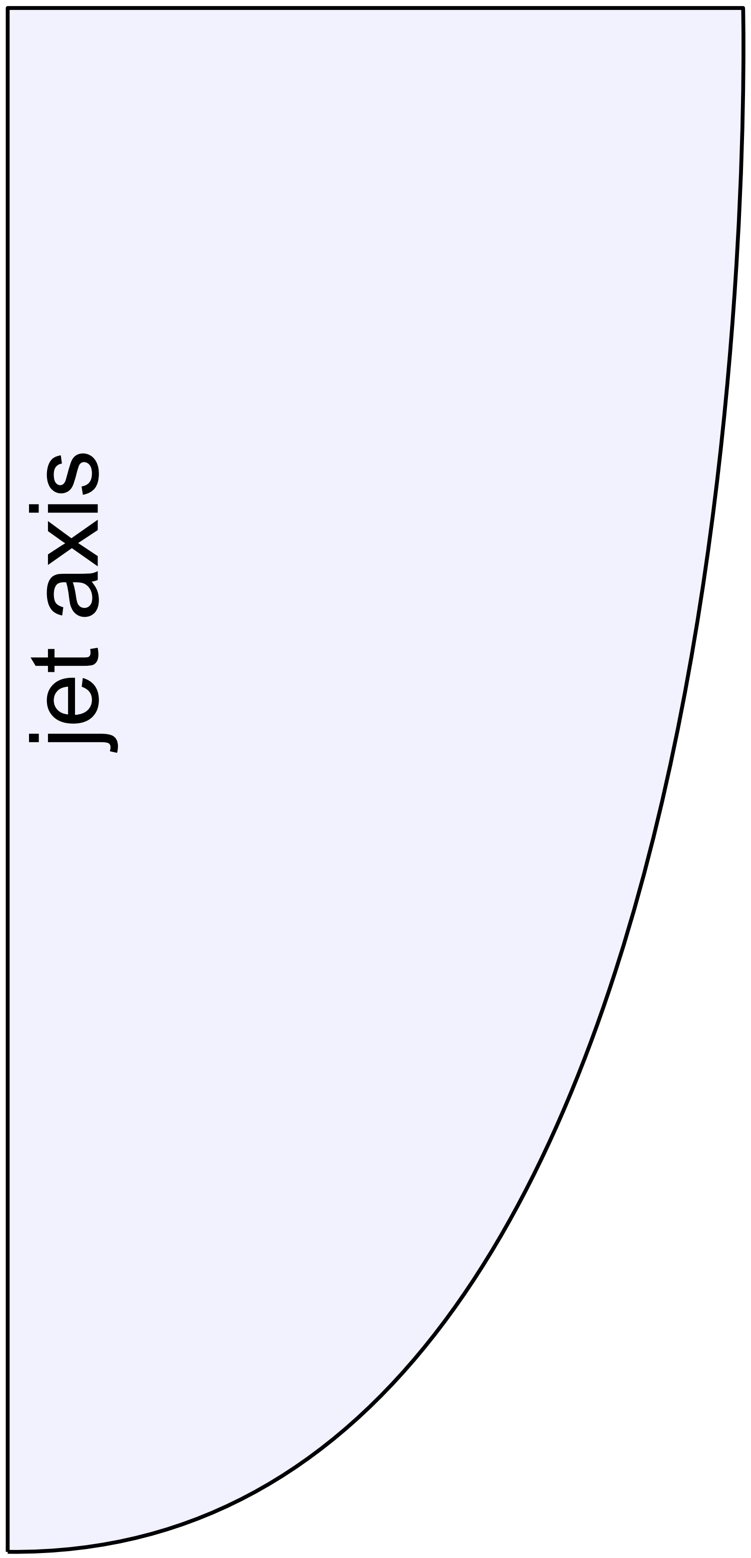

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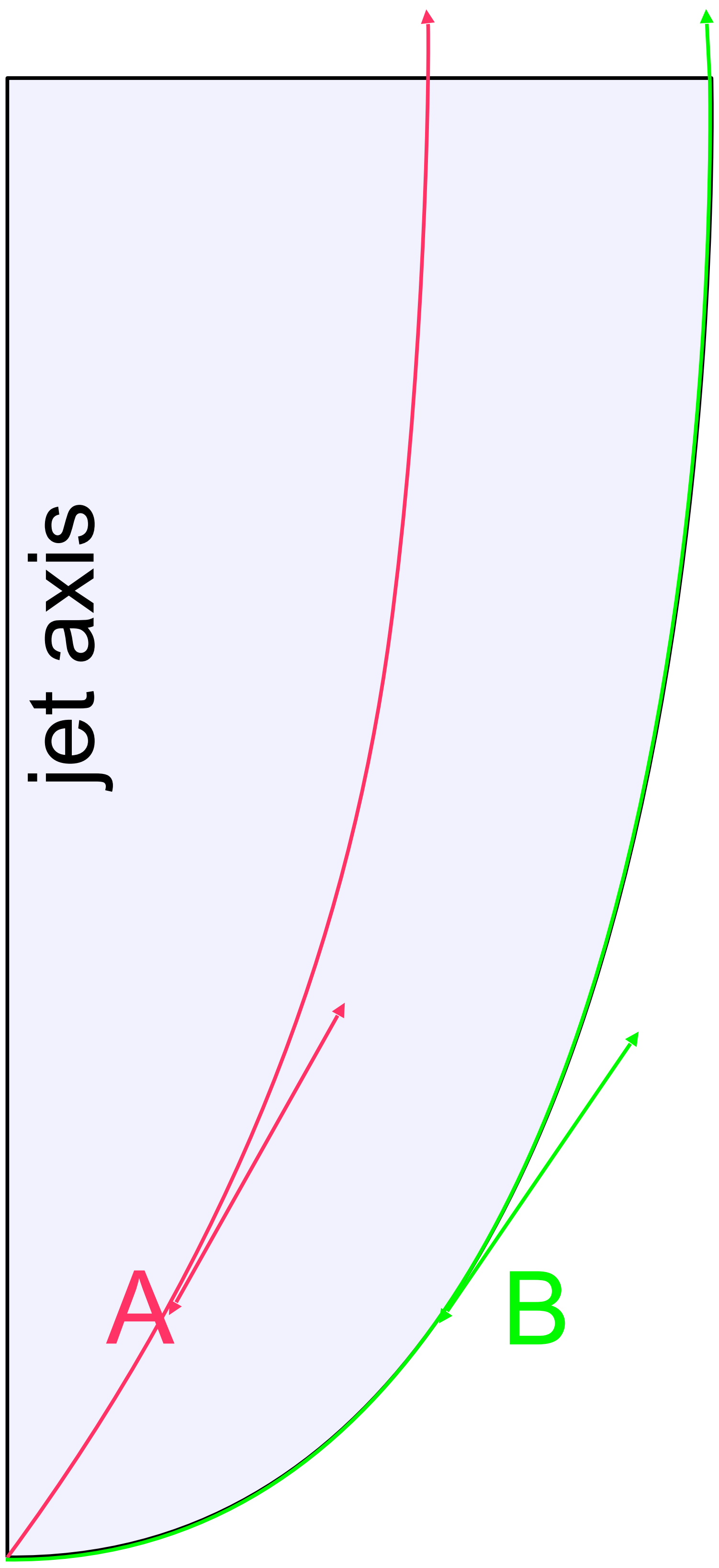

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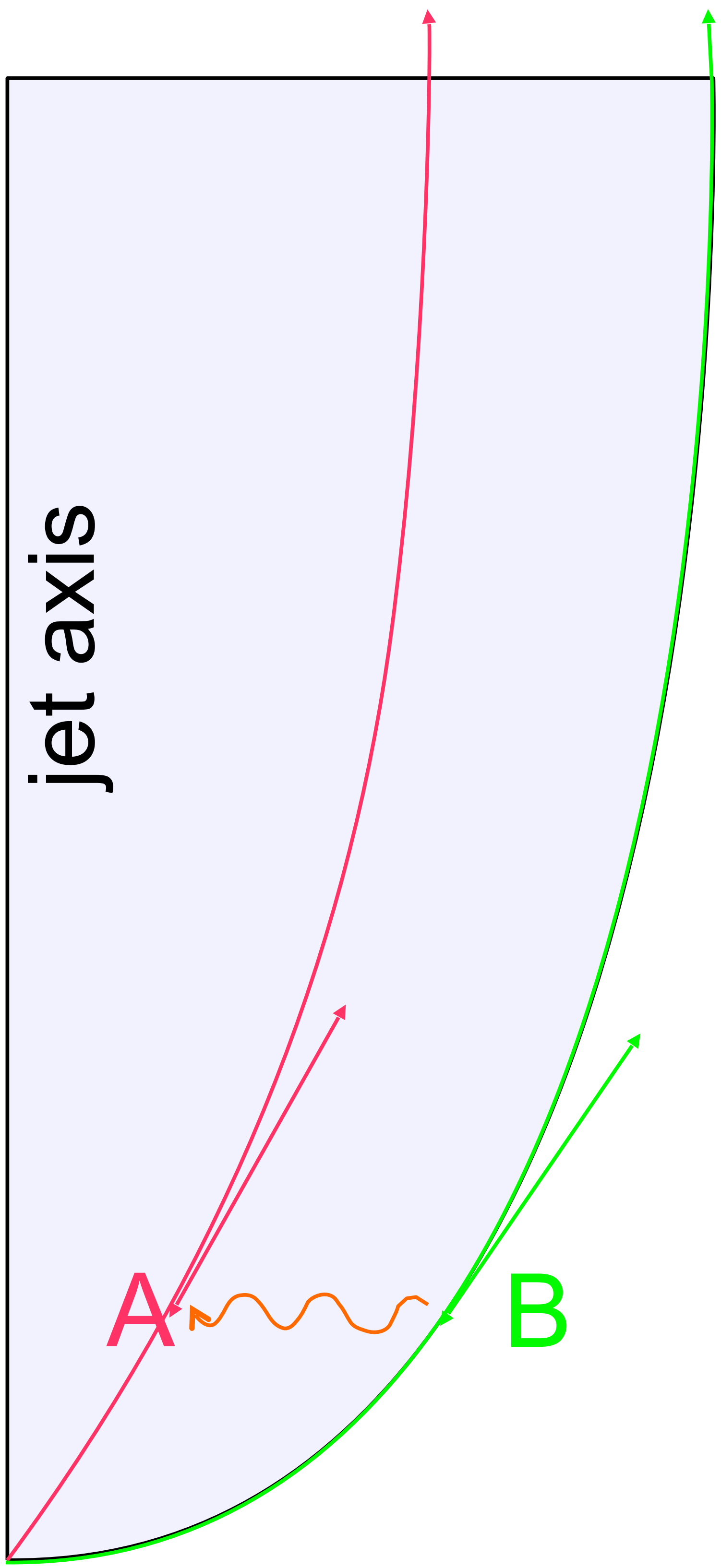

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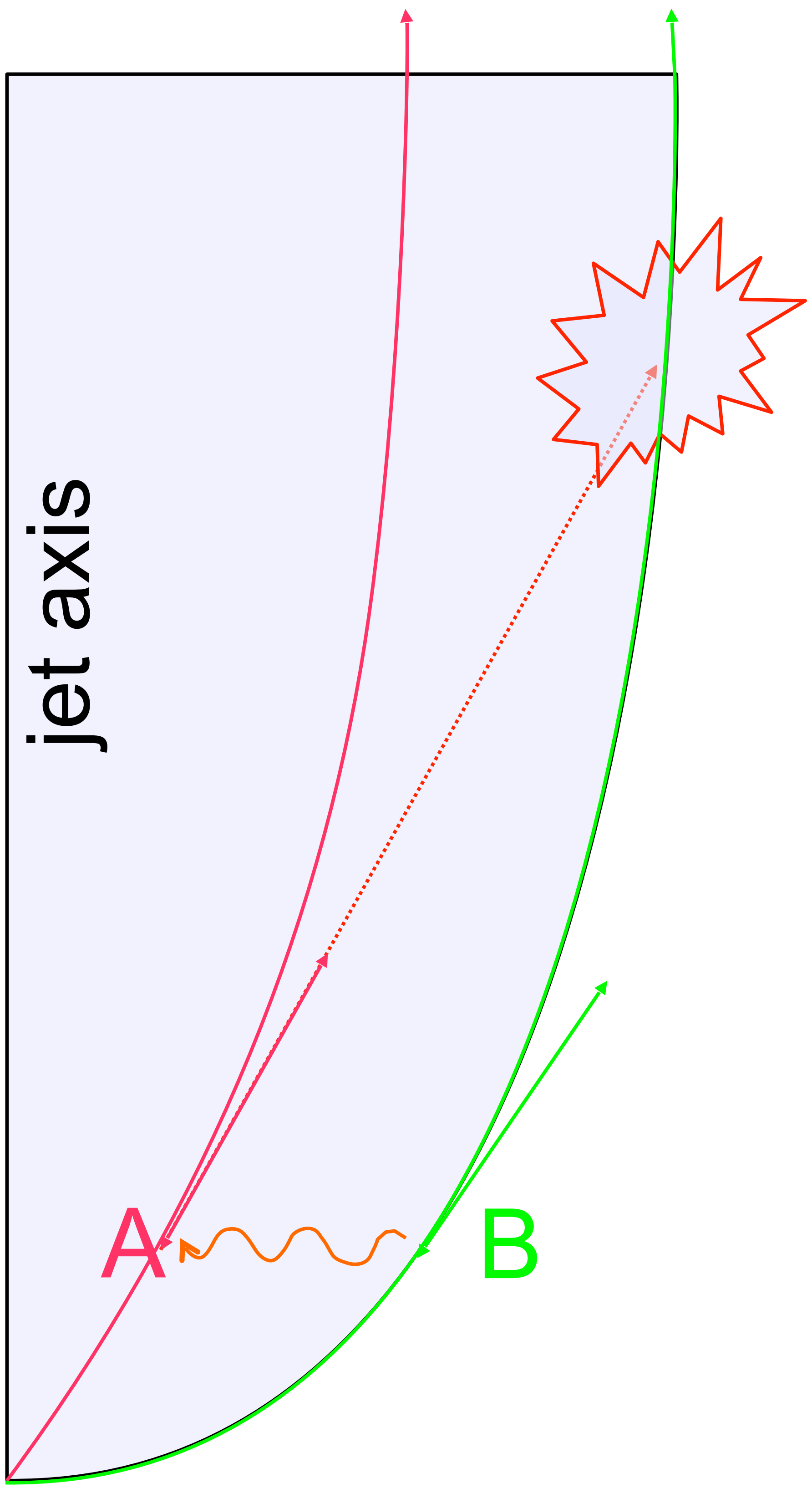

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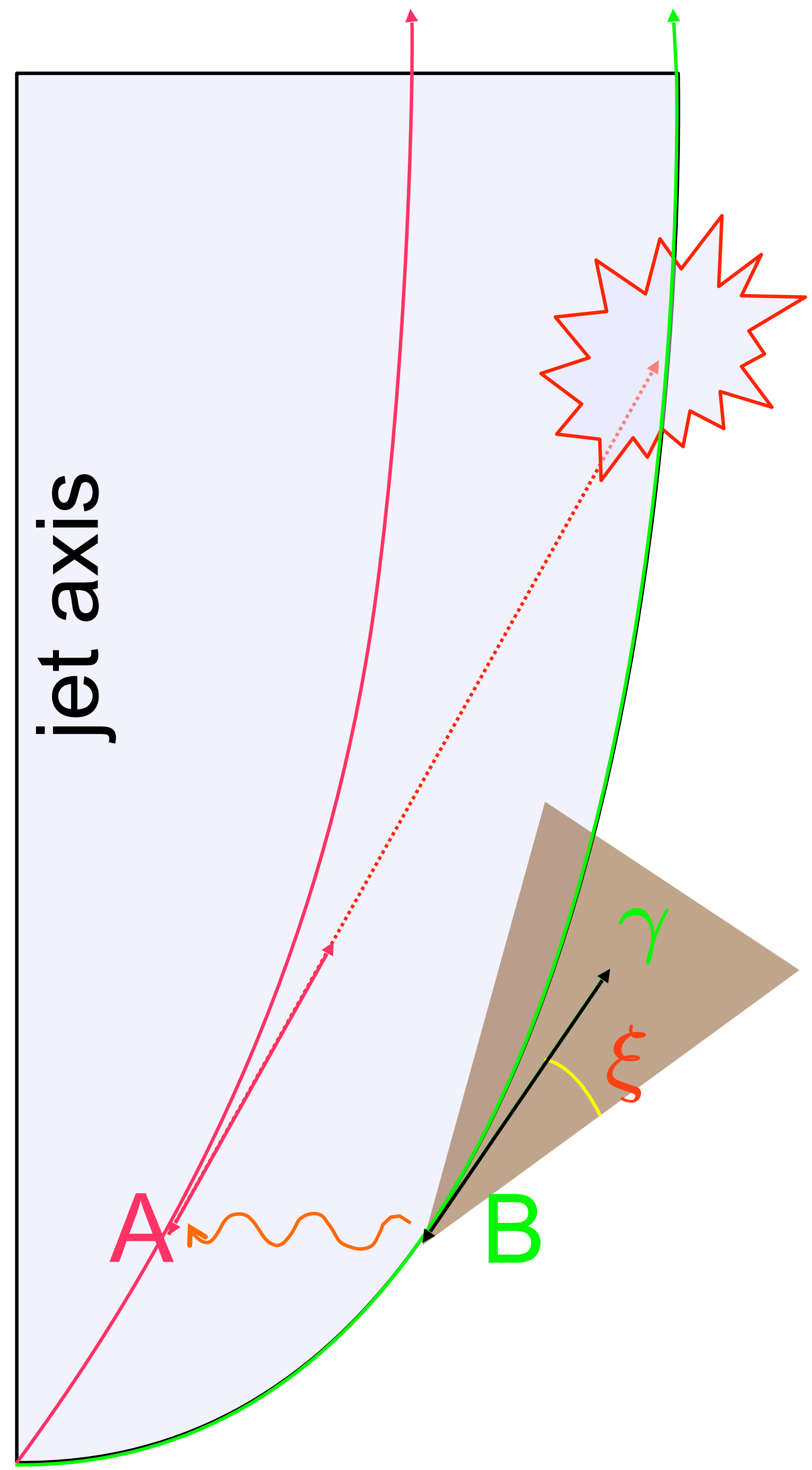

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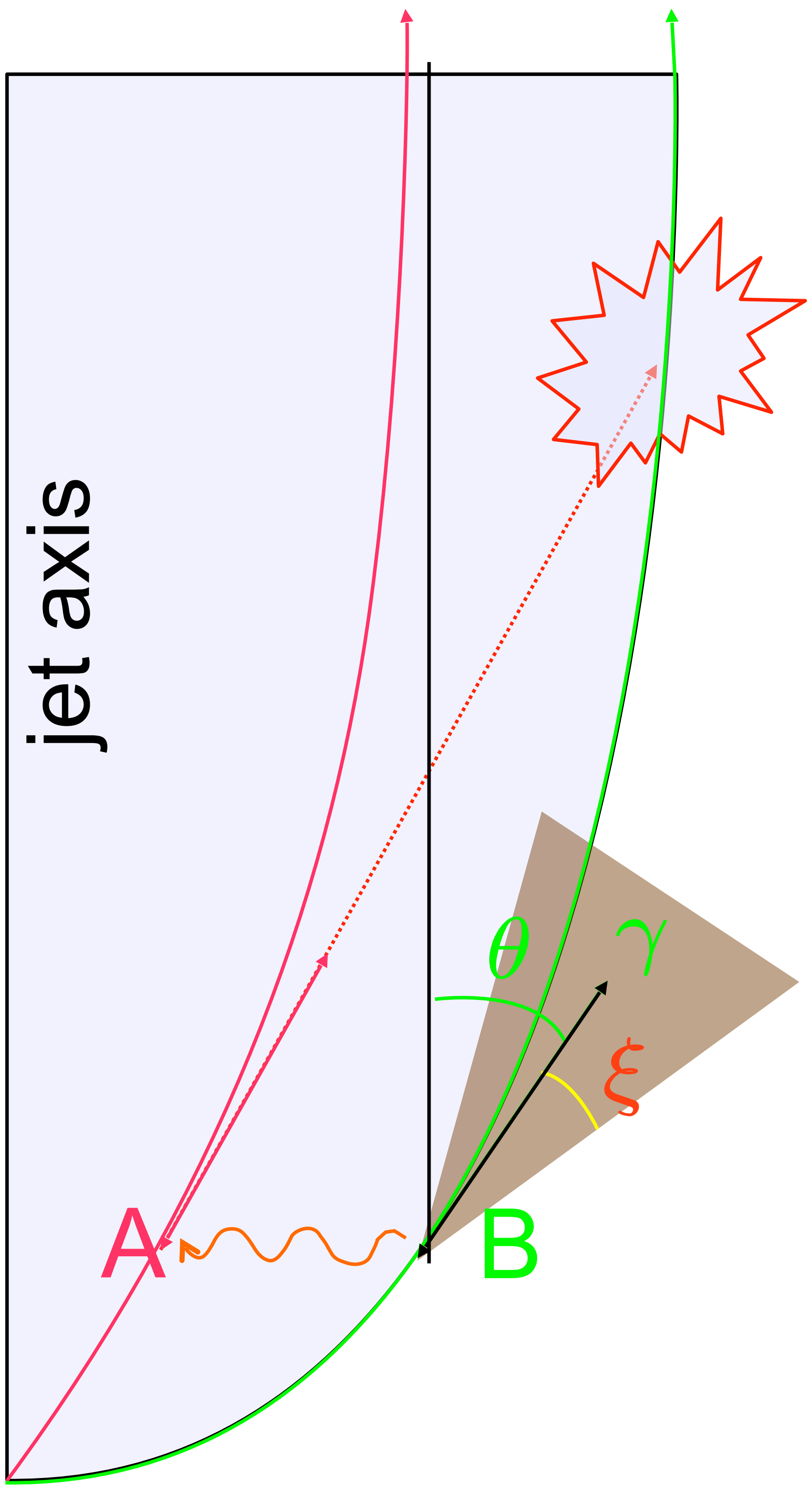

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- All signals travel inside Mach cone ξ:

$$\xi \le \frac{\gamma_F}{\gamma} = \frac{\sigma^{1/2}}{\gamma}$$

- For communication across jet need $\theta \lesssim \xi$, so $\theta \lesssim \sigma^{1/2}/\gamma$
- Robust conclusion: $\gamma\theta \lesssim \sigma^{1/2}$
- Collimated jets accelerate efficiently

What Do We Observe?

- *Expect* in collimated jets: $\gamma\theta \lesssim \sigma^{1/2} \lesssim 1$
- Observe:
  - Active Galactic Nuclei: $\gamma\theta \sim 0.1{-}0.2$
  - Gamma-ray bursts (GRBs): $\gamma\theta \sim 10{-}100$
- Does it mean that GRB jets are unmagnetized?

GRB Jets: Problem Setup

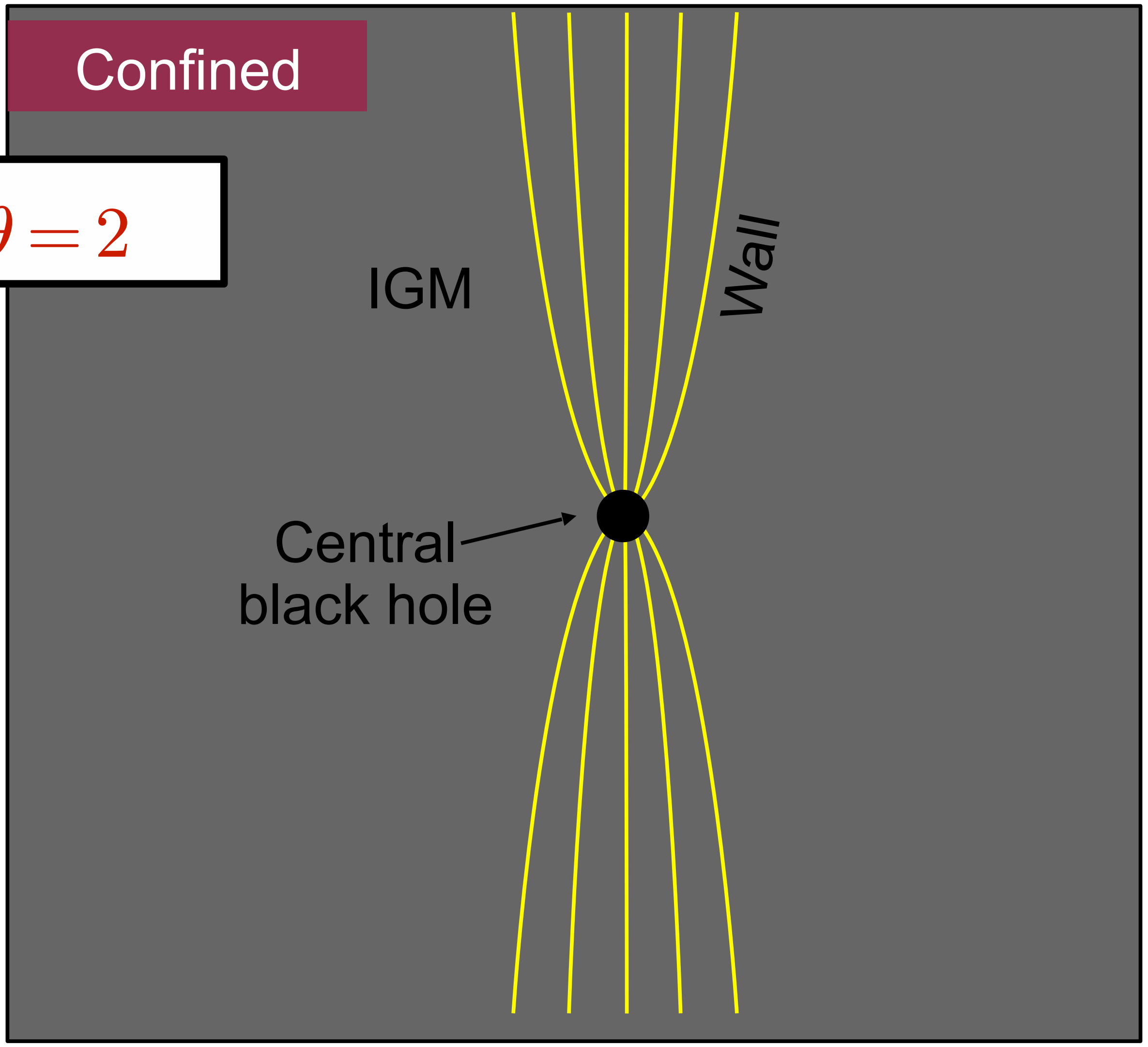
Simulations of magnetized confined jets:
$\gamma\theta \lesssim 1$

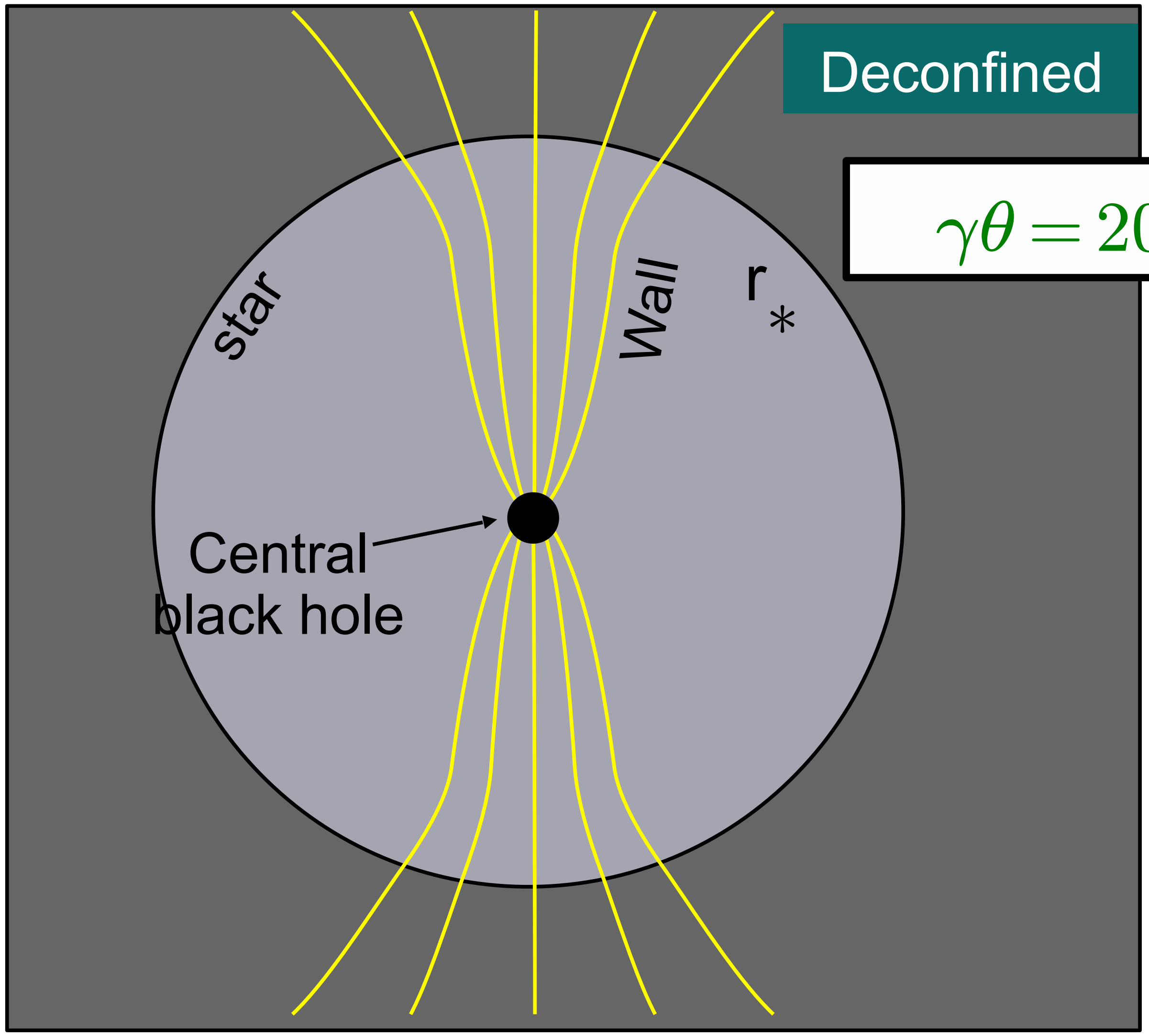
(Komissarov et al., MNRAS, 2009)

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

(Tchekhovskoy, Narayan, McKinney, New Astronomy, 2010)

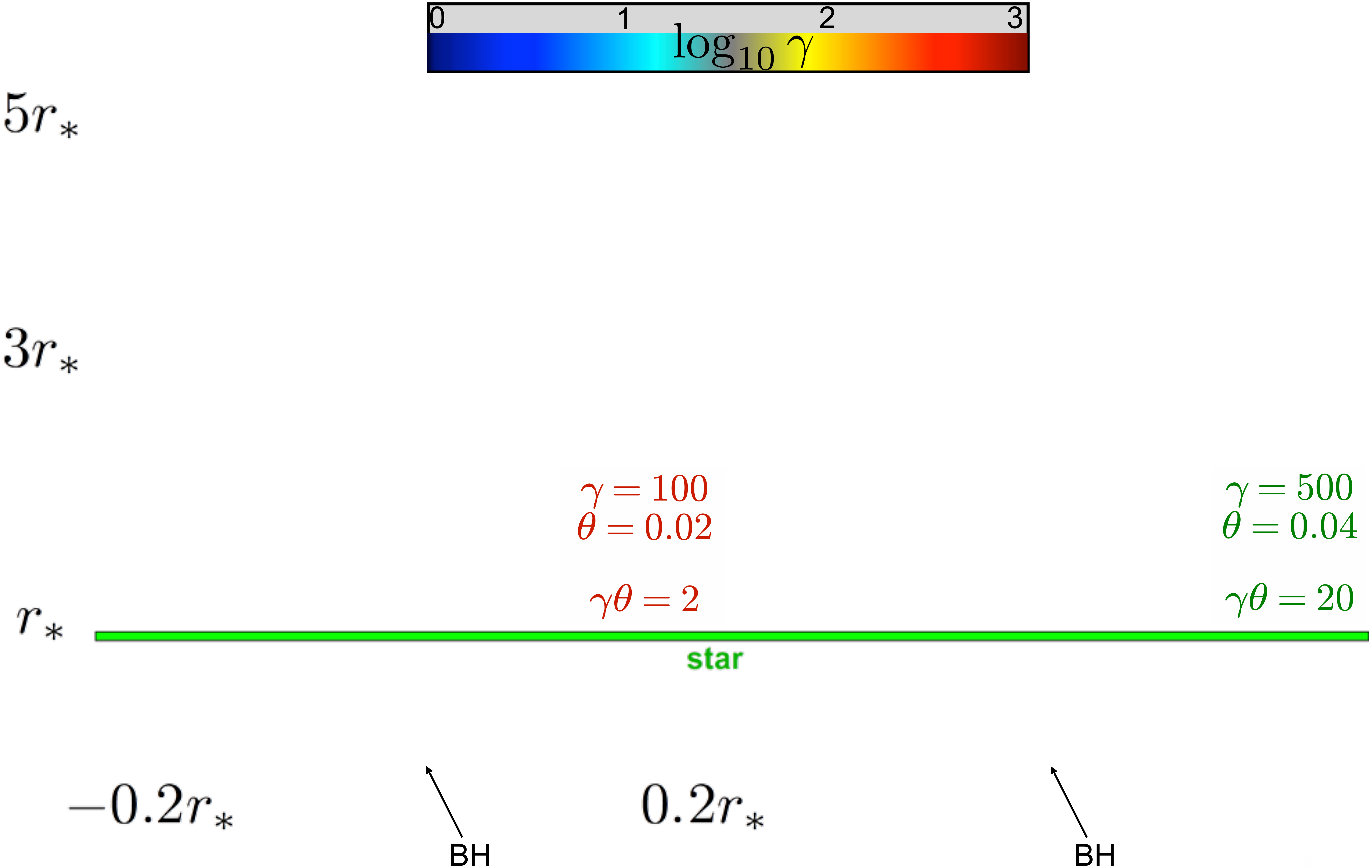
$\gamma\theta = 2$





$\gamma\theta = 20$ ✓

Confined vs. Deconfined



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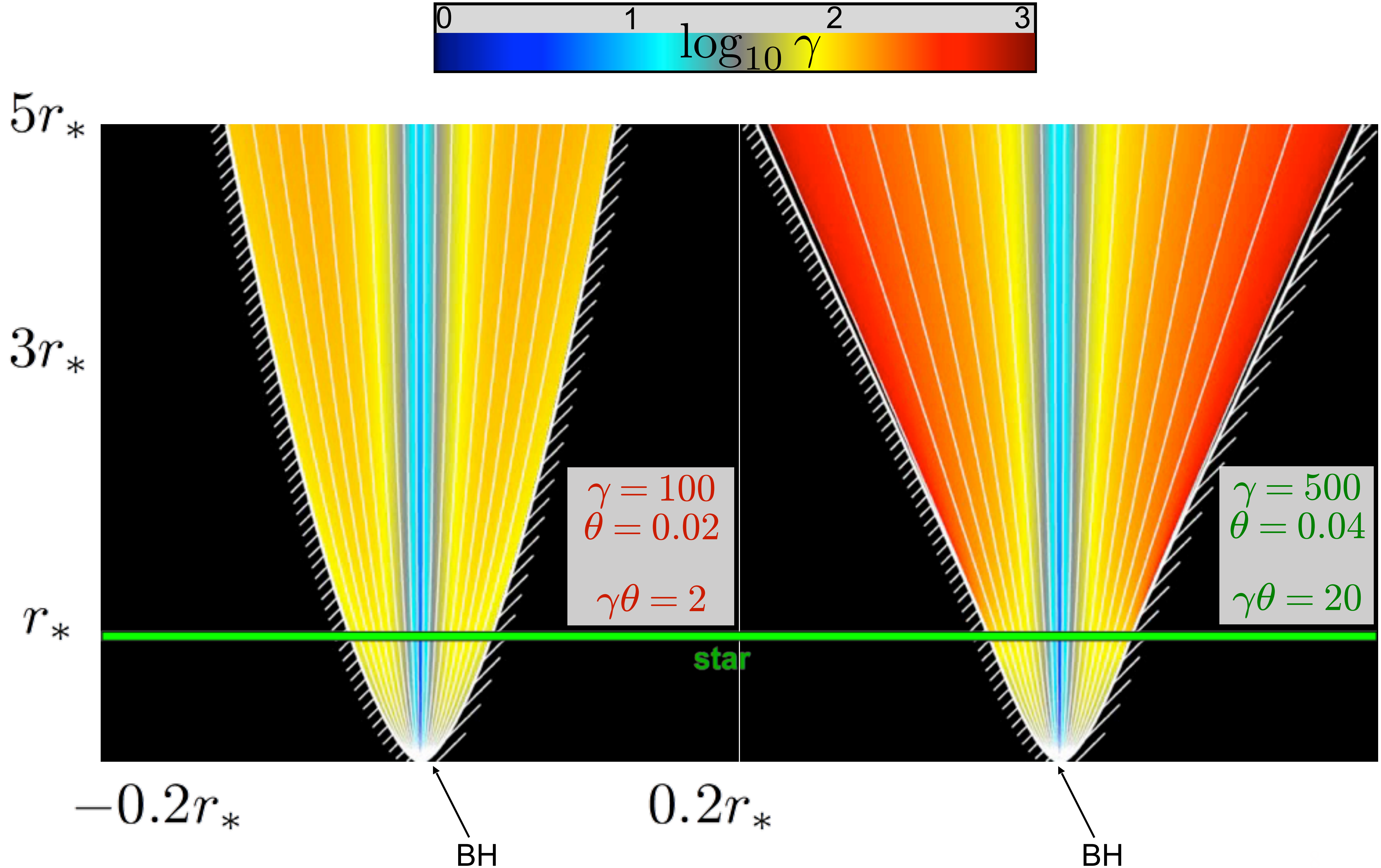
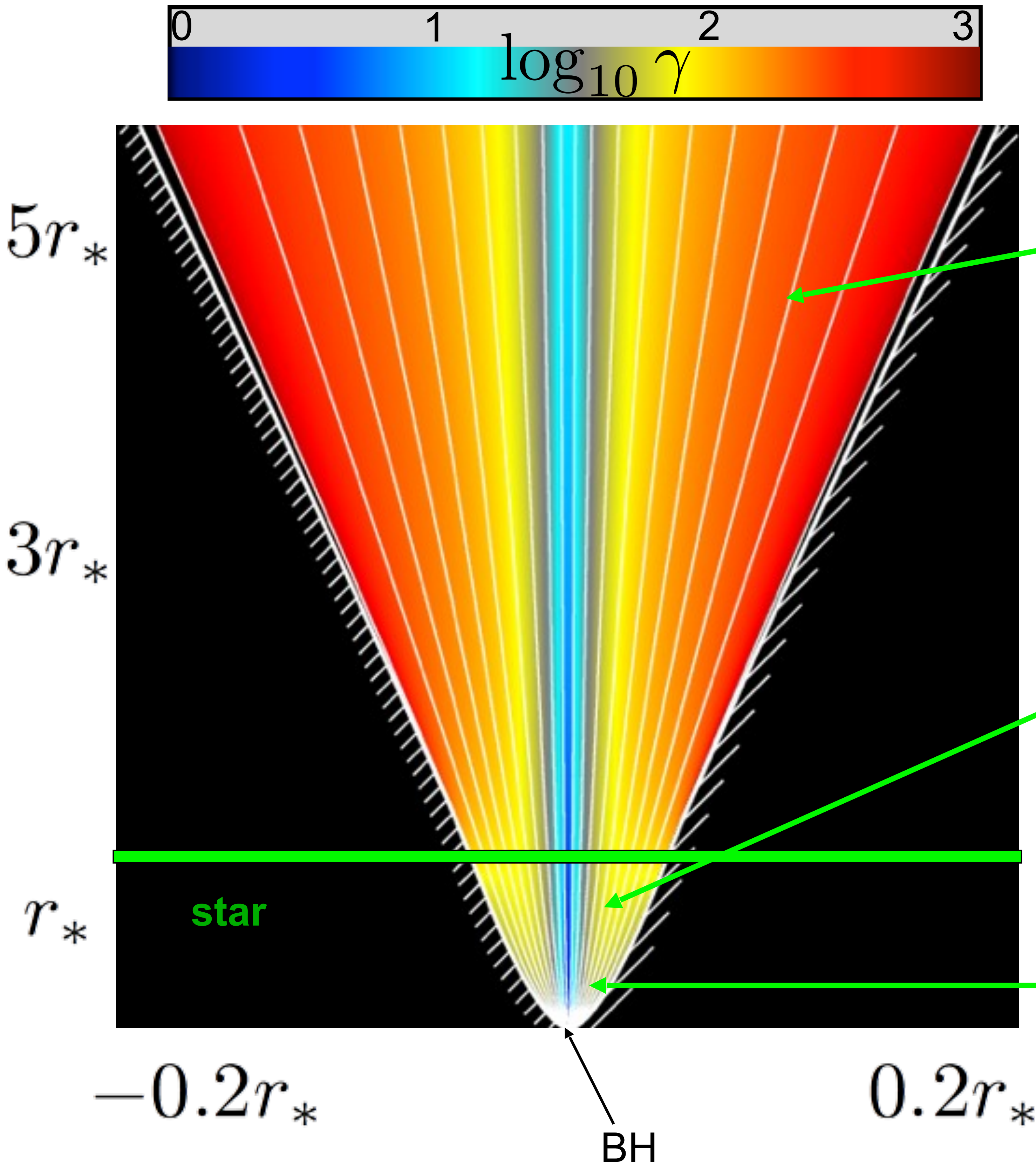


Jet Structure Recap



Fully unconfined jet:

$$\gamma\theta \simeq 20\sigma^{1/2}$$ (AT+ 2010)

Fully confined jet, large distance. Centrifugal force limits jet velocity (AT+ 2008):

$$\gamma \approx \left(\frac{R_c}{R}\right)^{1/2}$$

Fully confined jet, small distance. Linear increase:

$$\gamma \approx \Omega R/c$$ (Michel 1969)

The disk-jet connection

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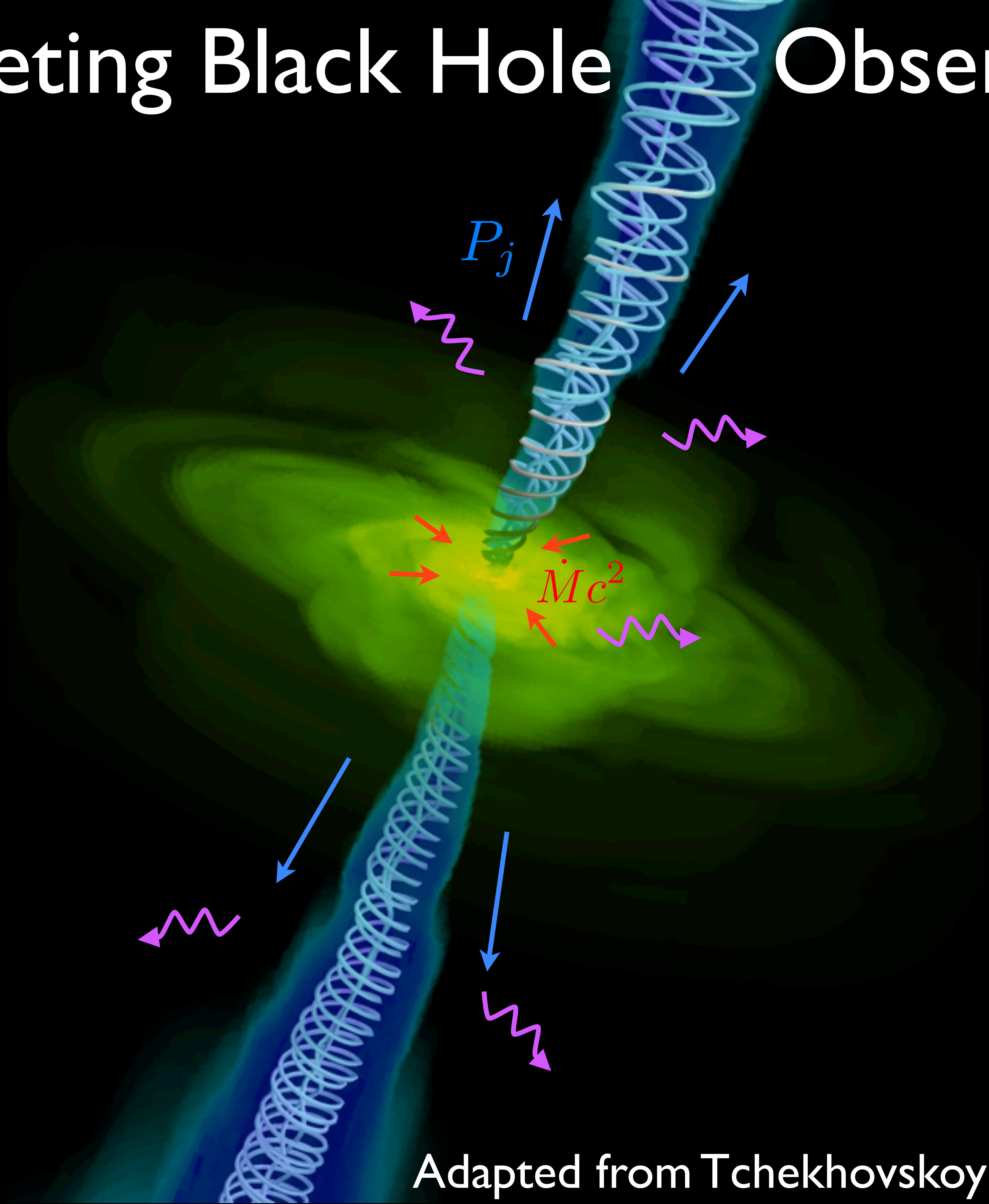
Interpreting Black Hole Observations



Adapted from Tchekhovskoy 2015

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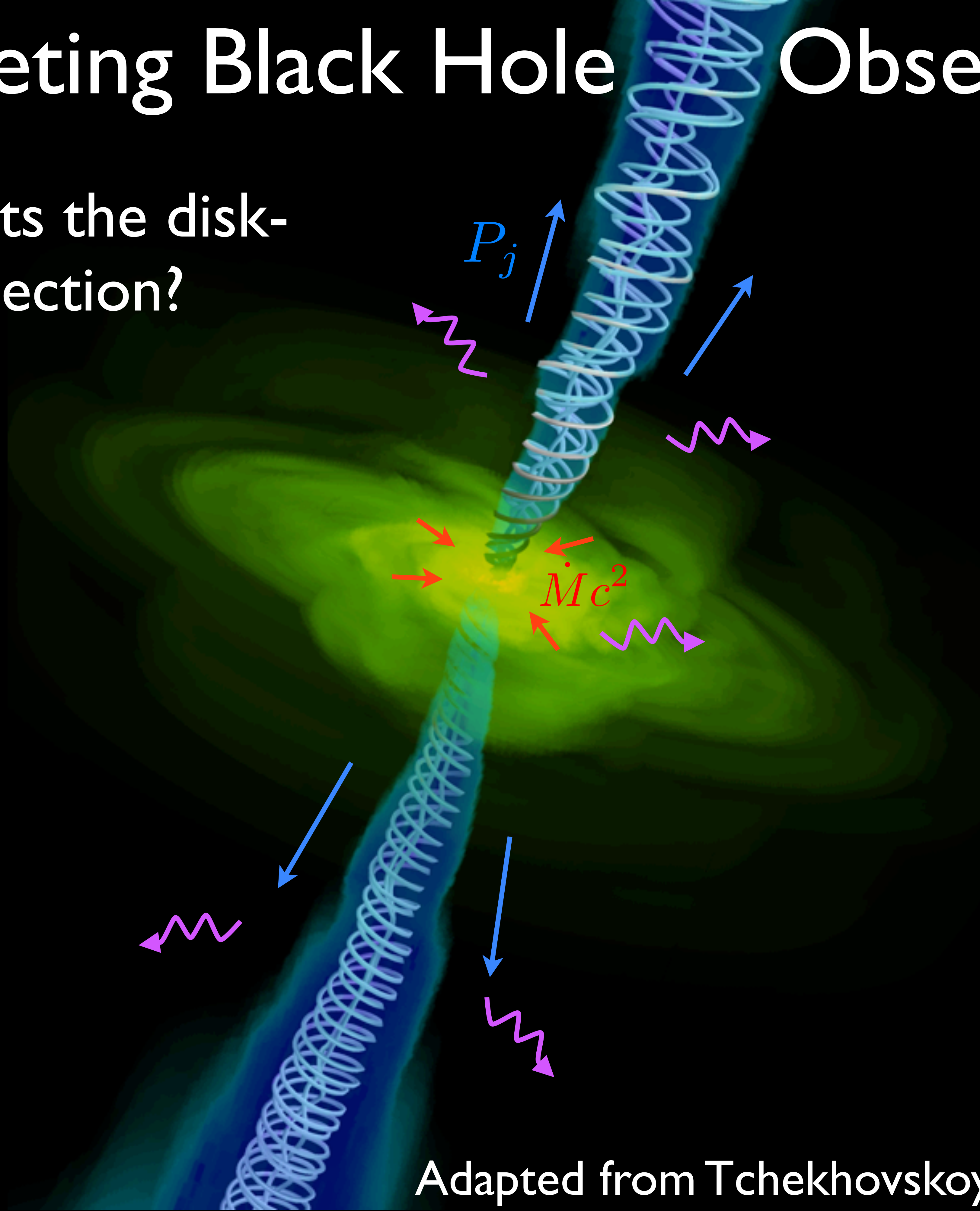

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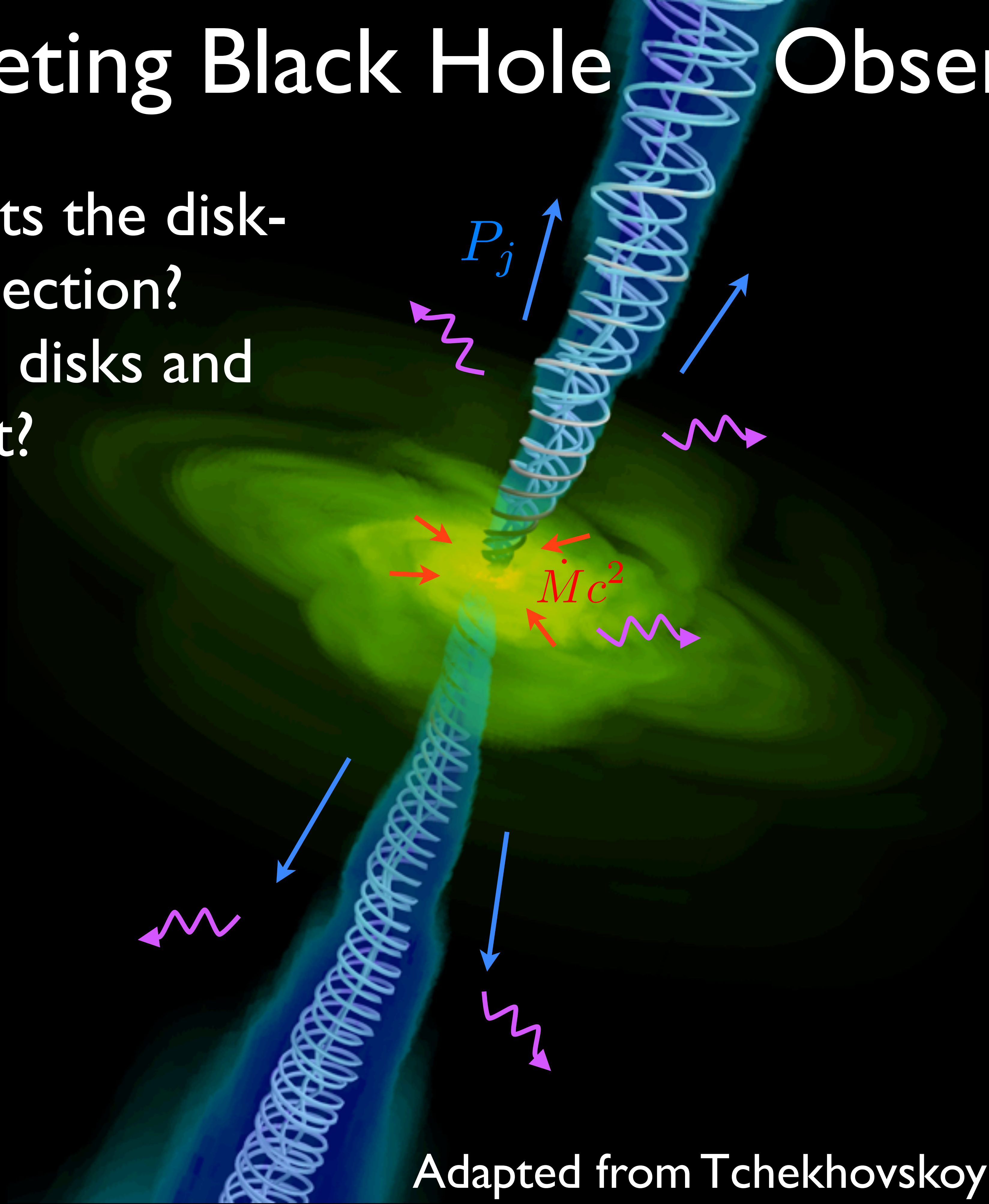

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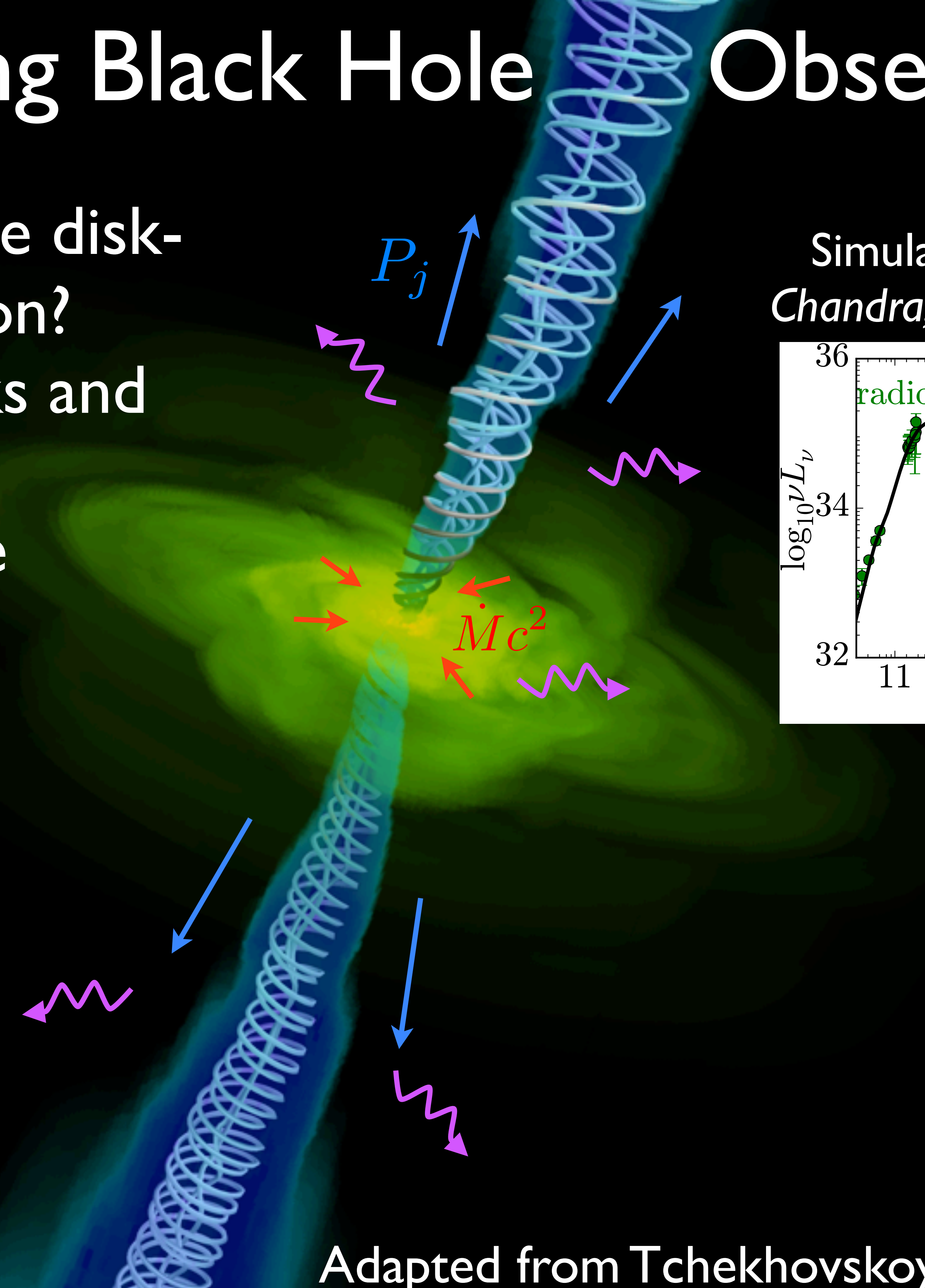
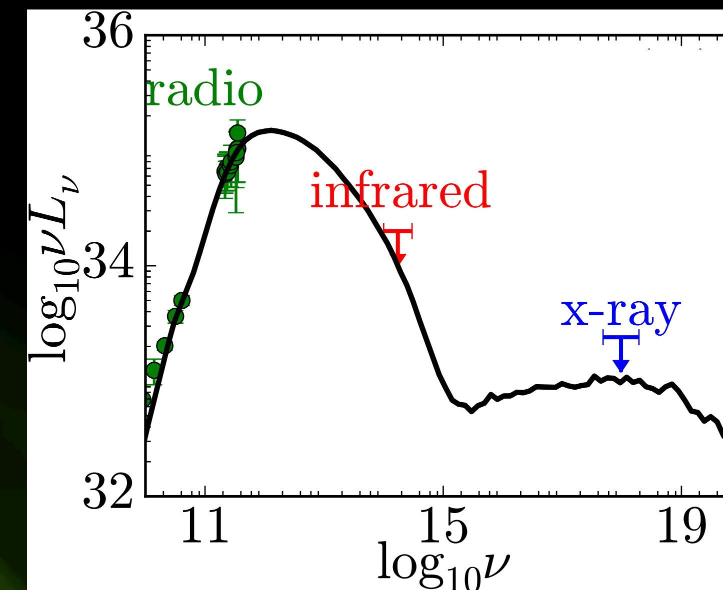


Simulated *ALMA, VLA, Chandra, NuSTAR* spectra



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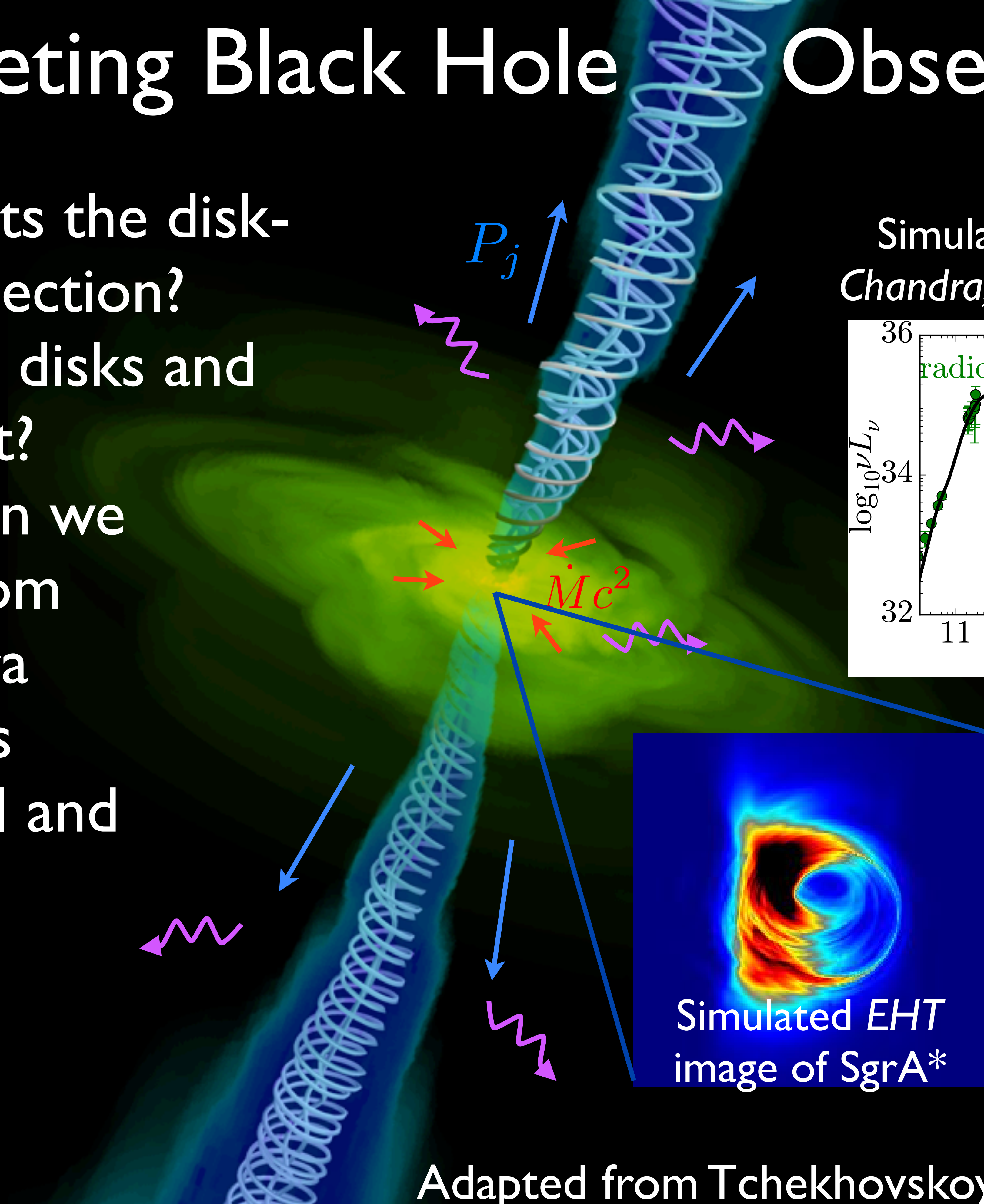

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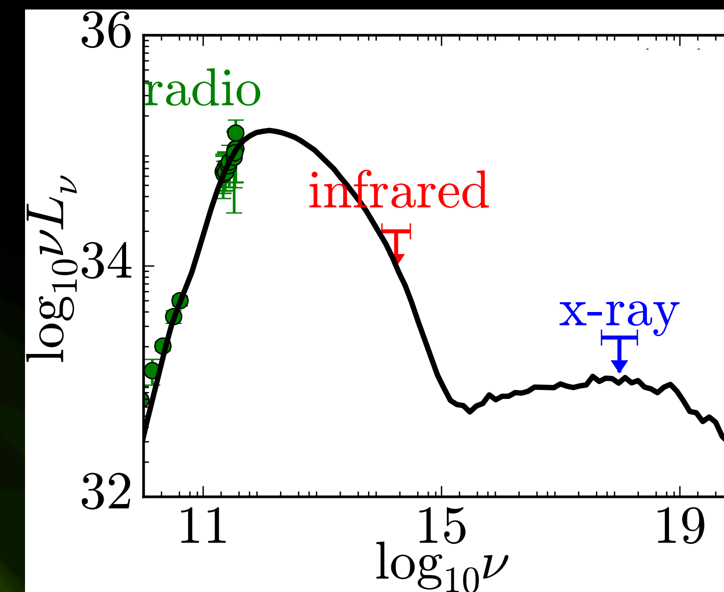

Simulated *EHT* image of SgrA*

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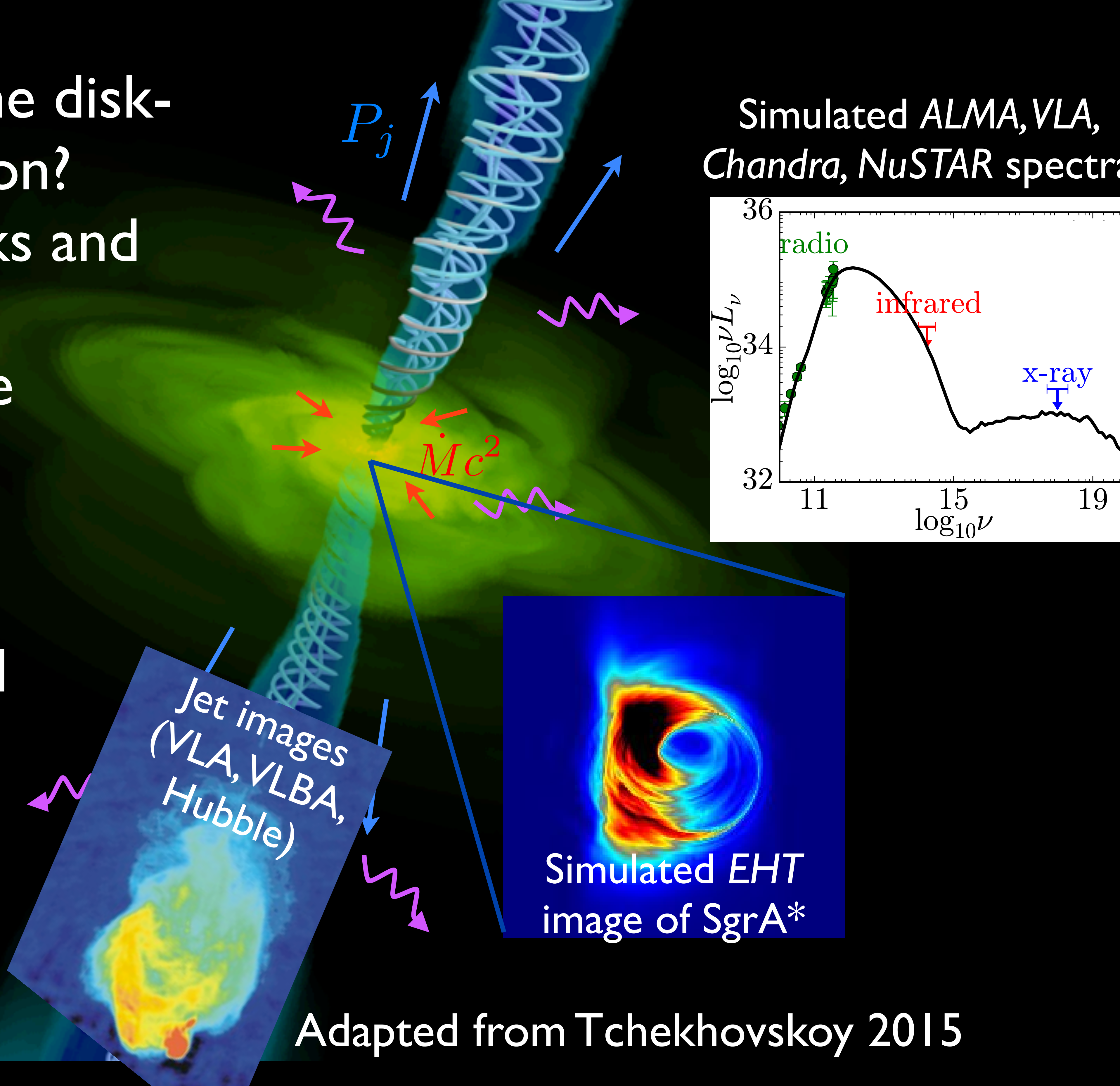

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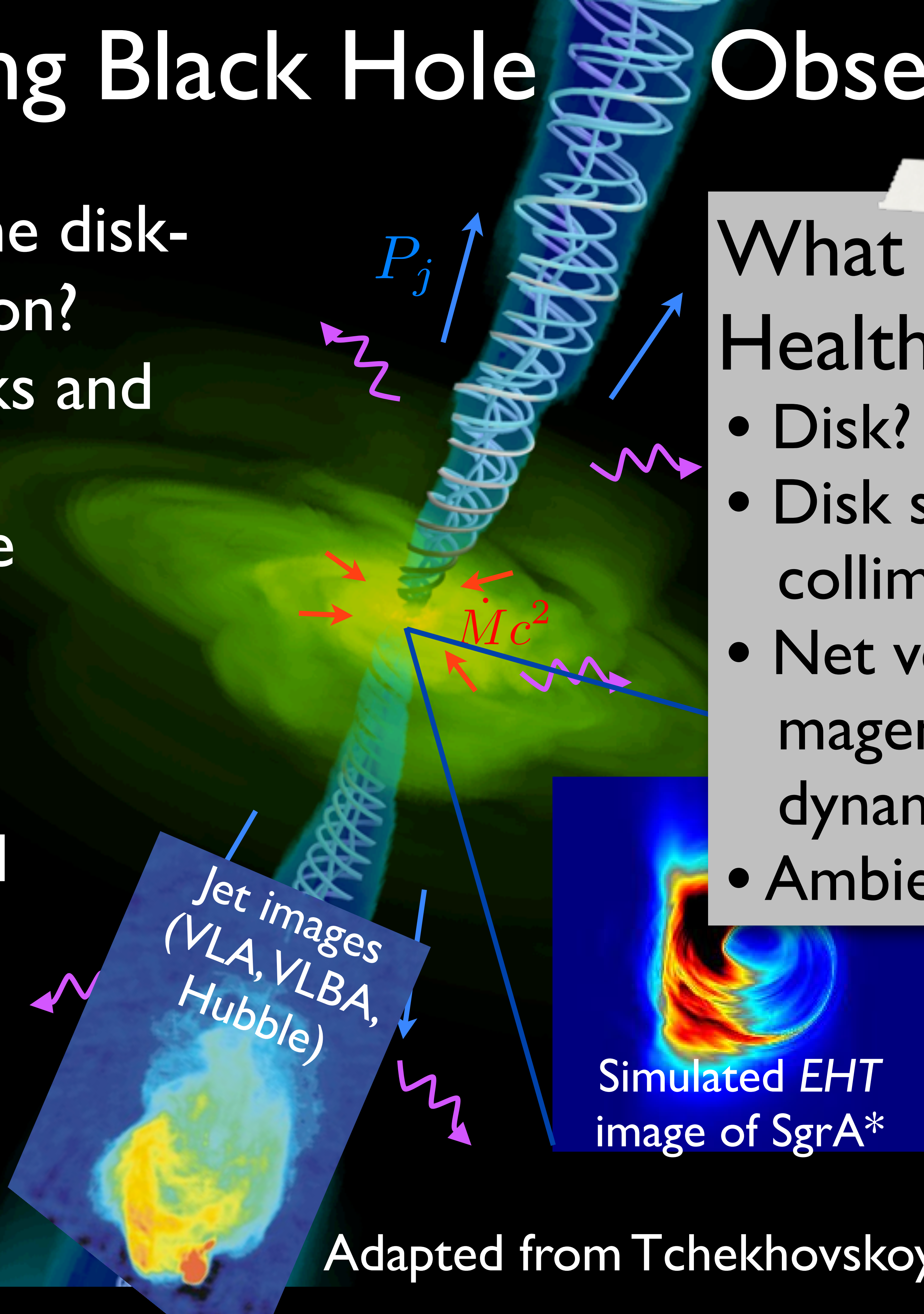
What is a Healthy Jet Diet?

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



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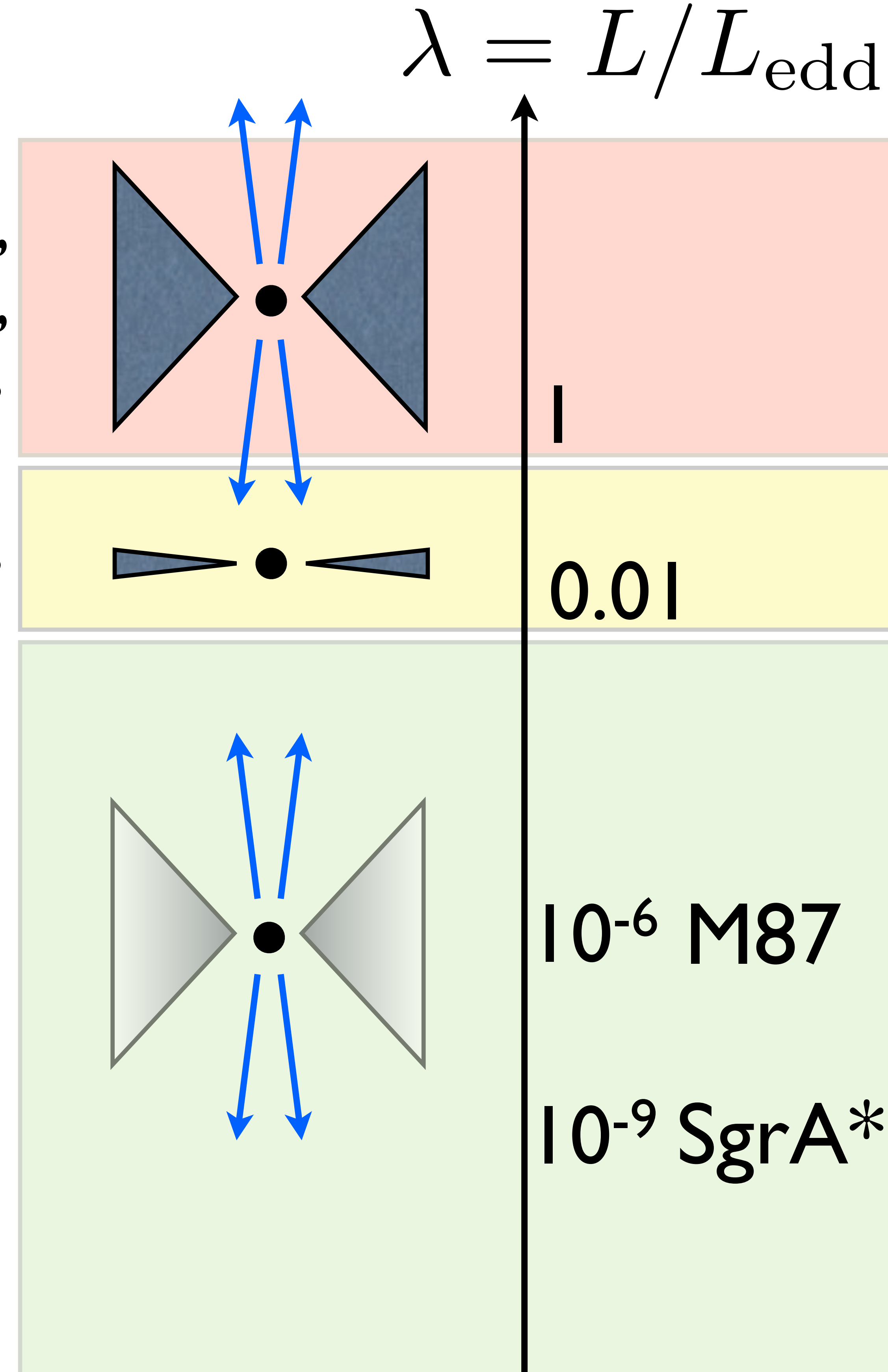
When are Jets Produced?

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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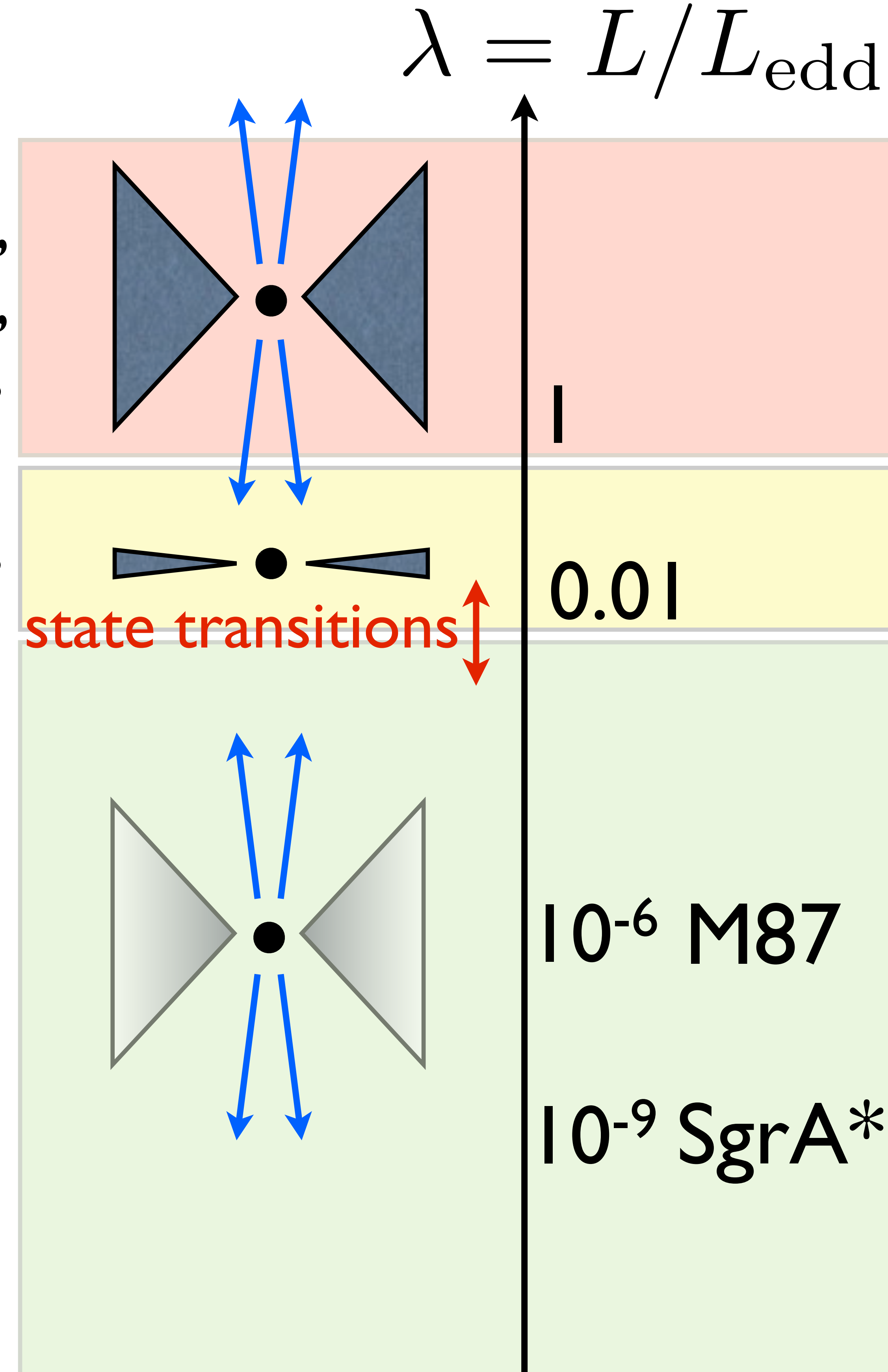

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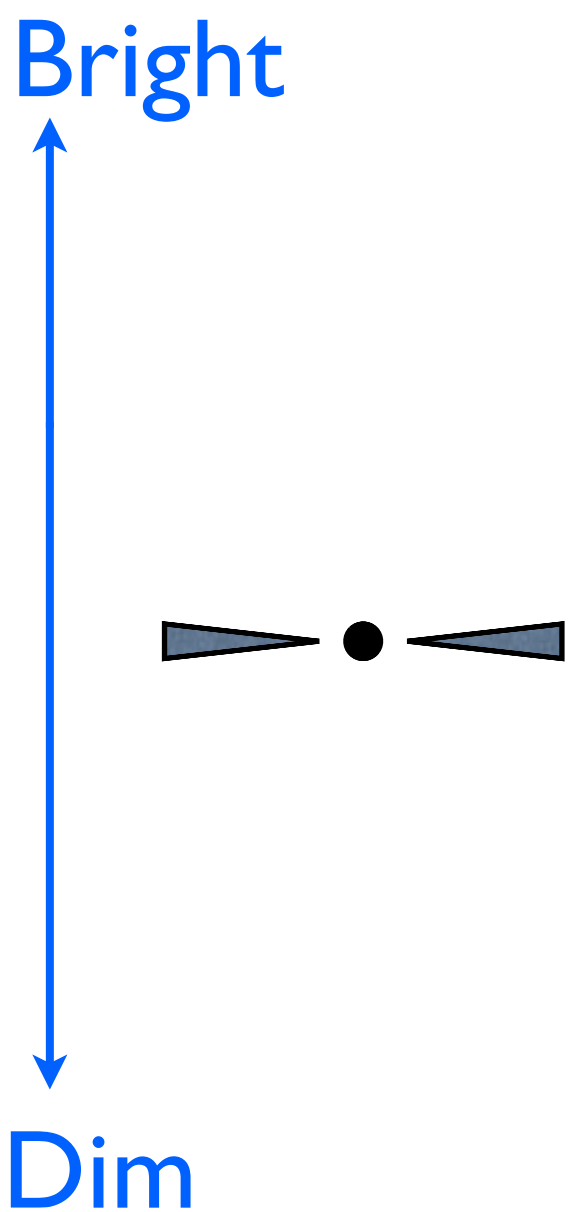
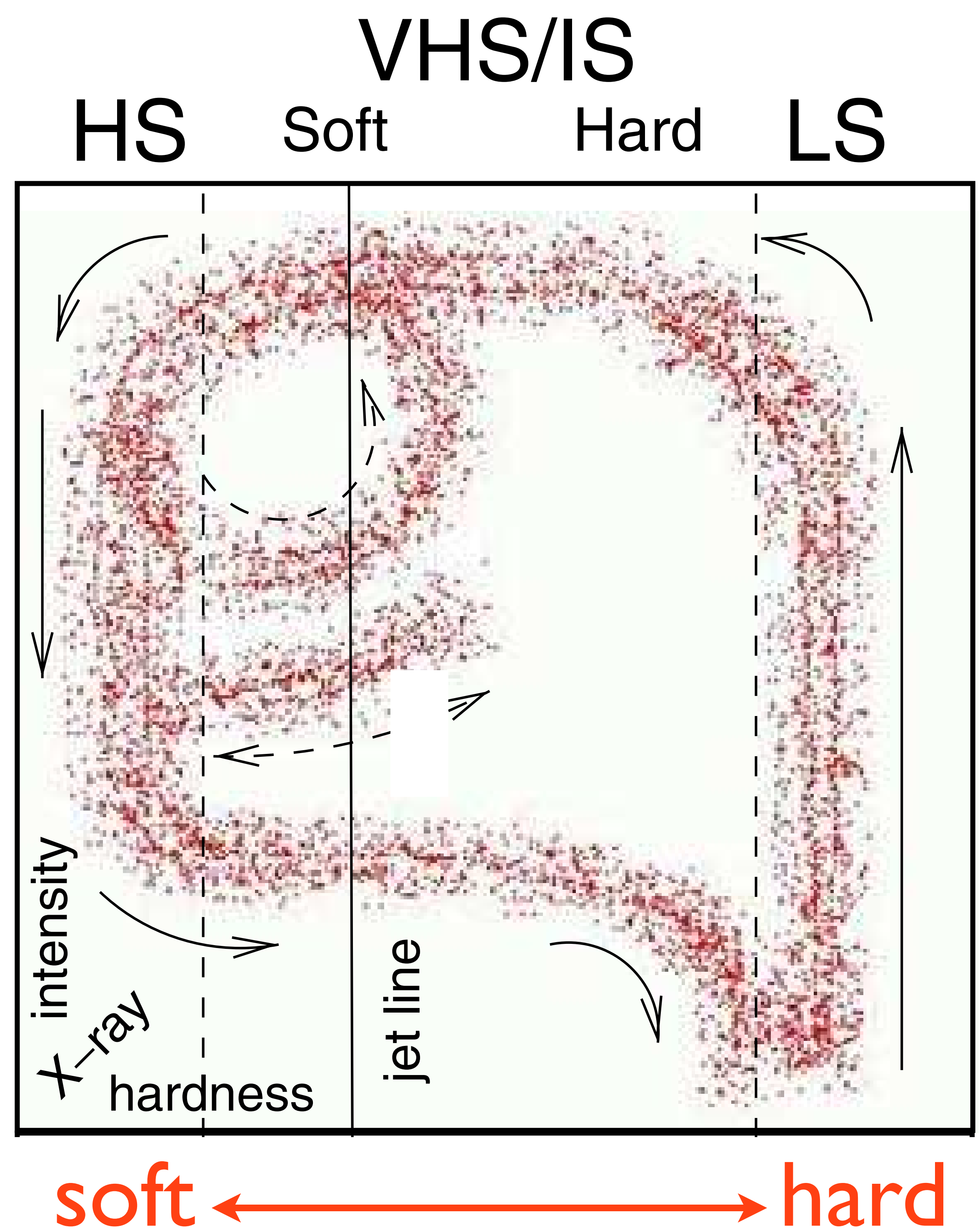
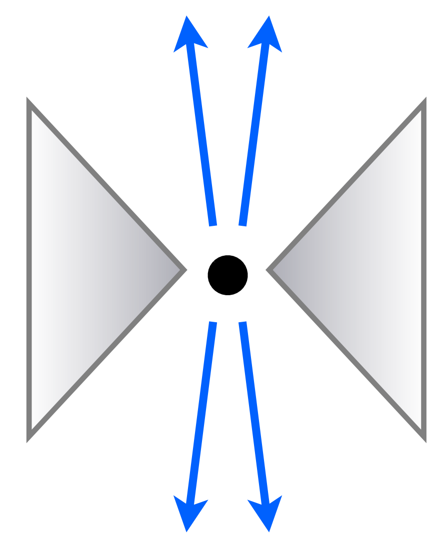
"q" or turtlehead diagram







Fender+2004

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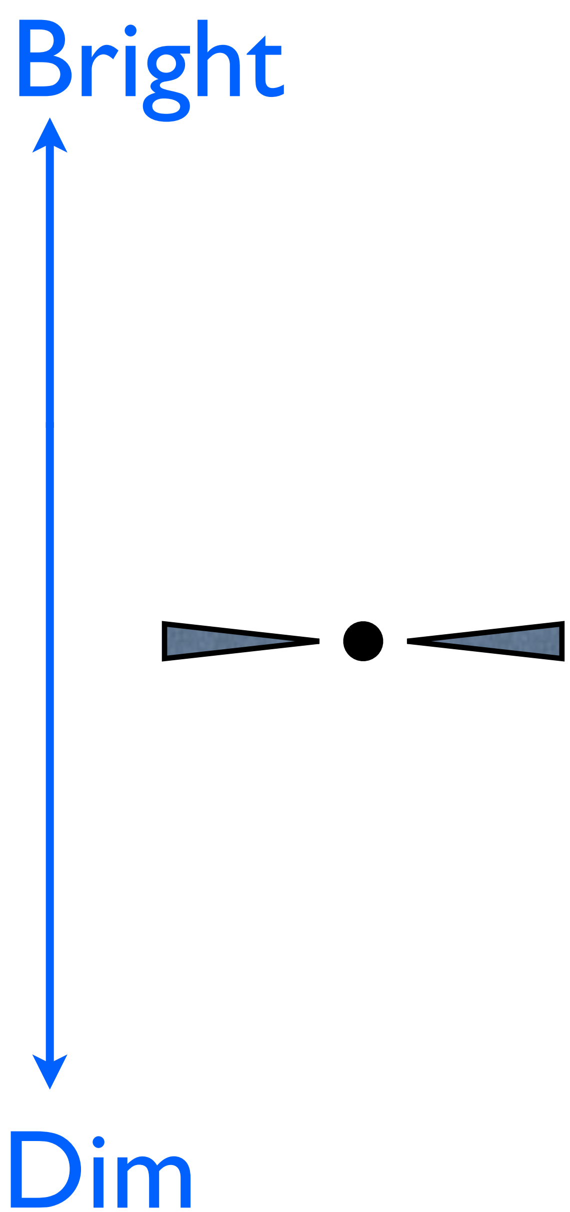

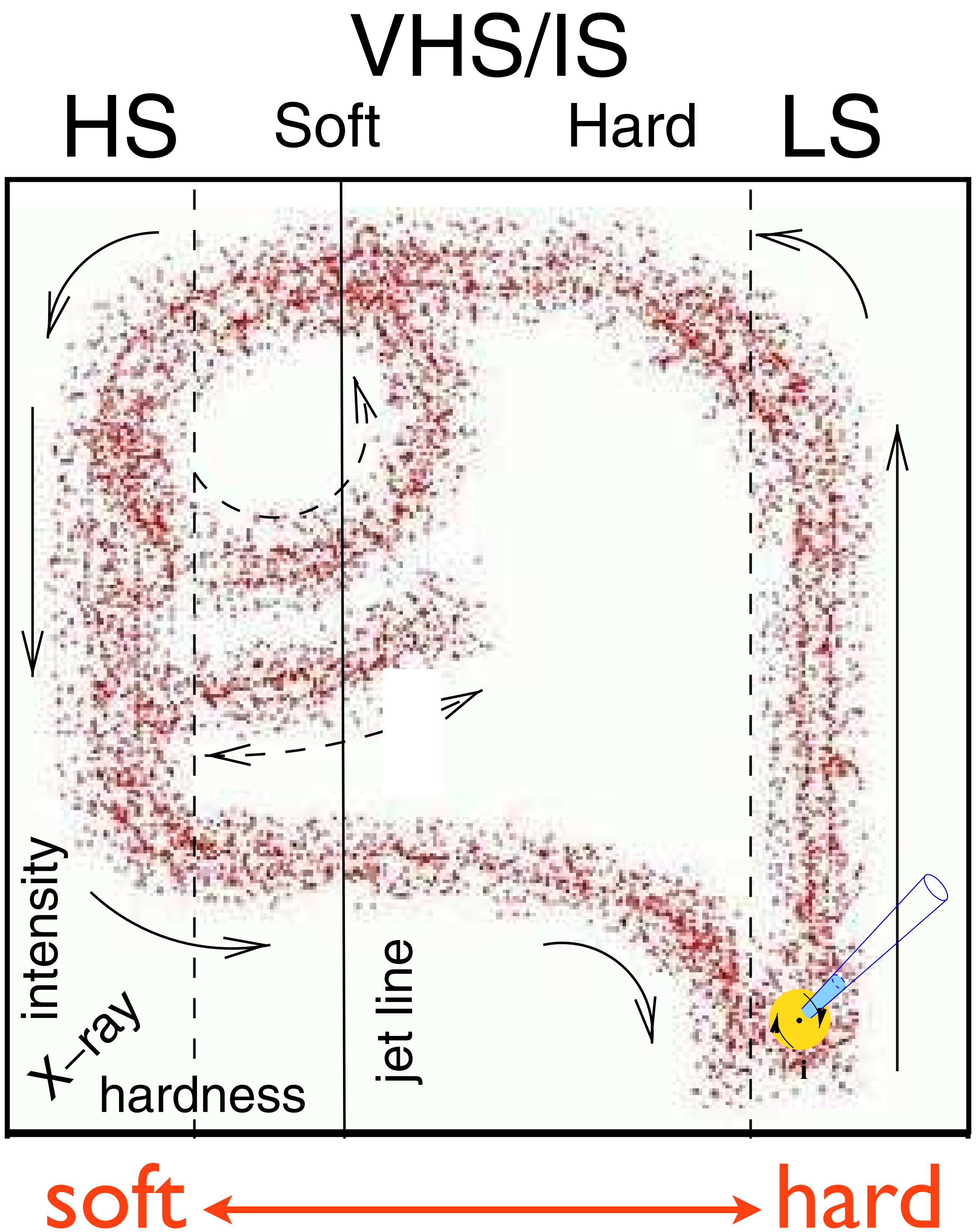

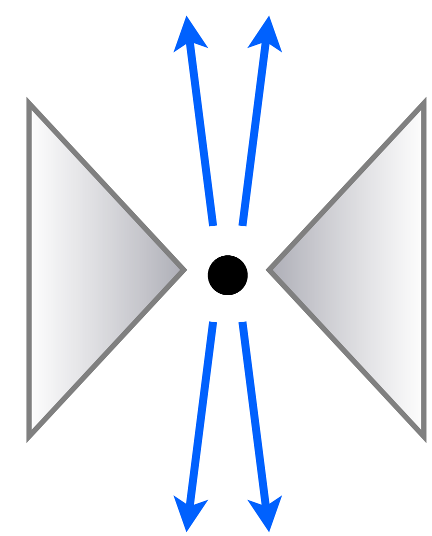

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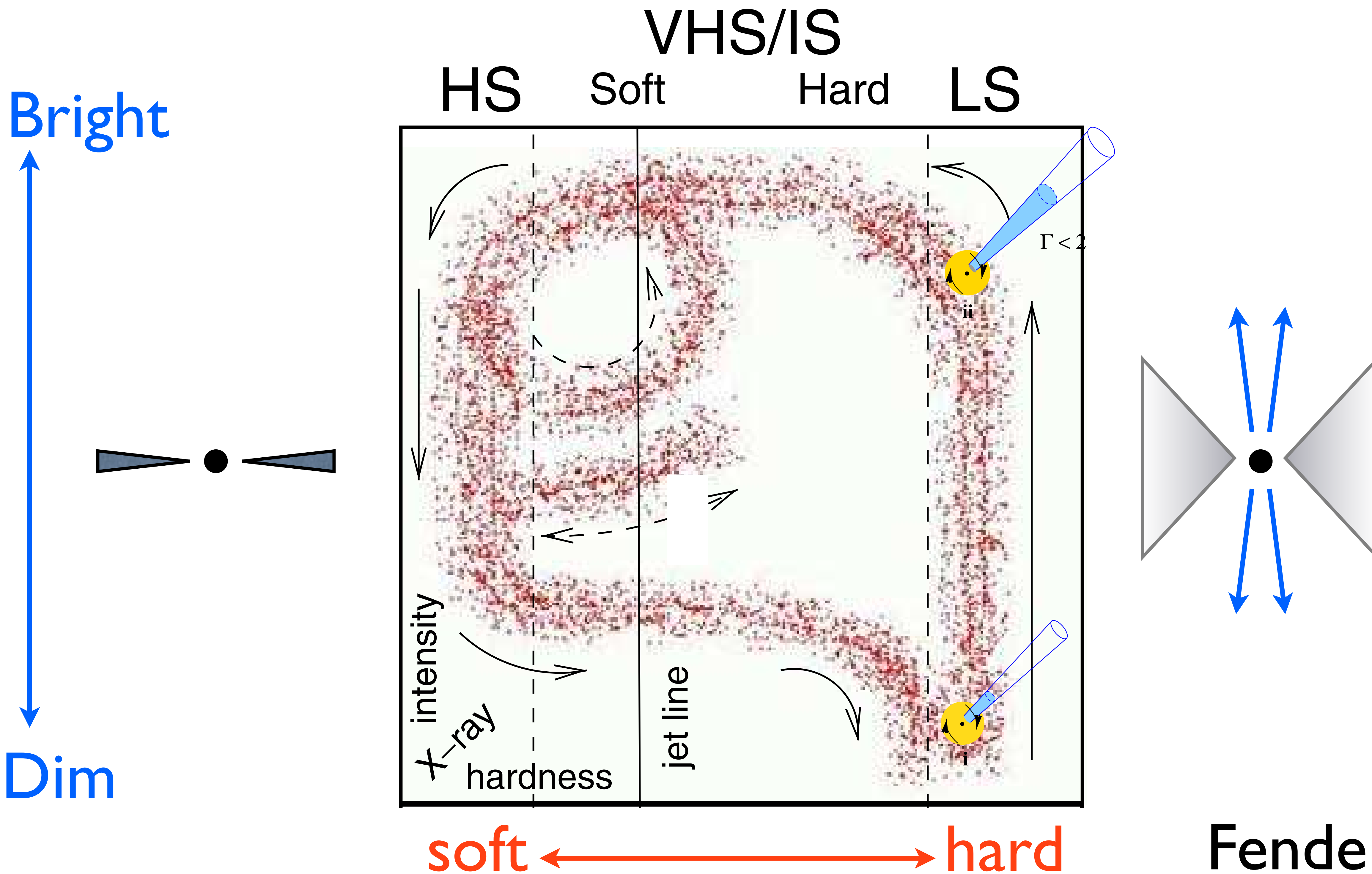

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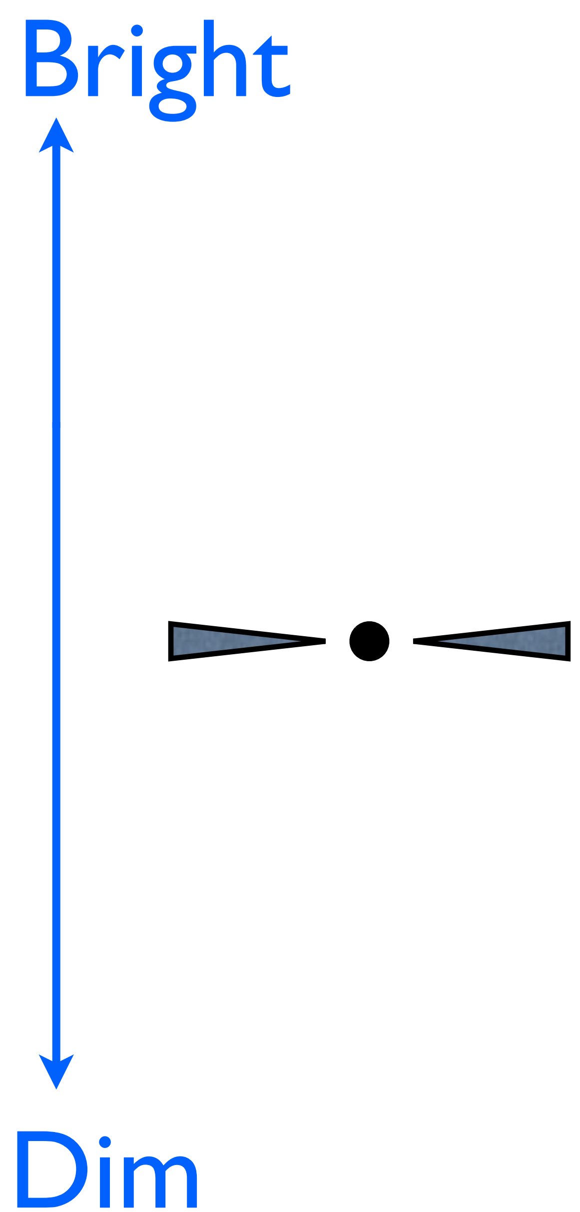
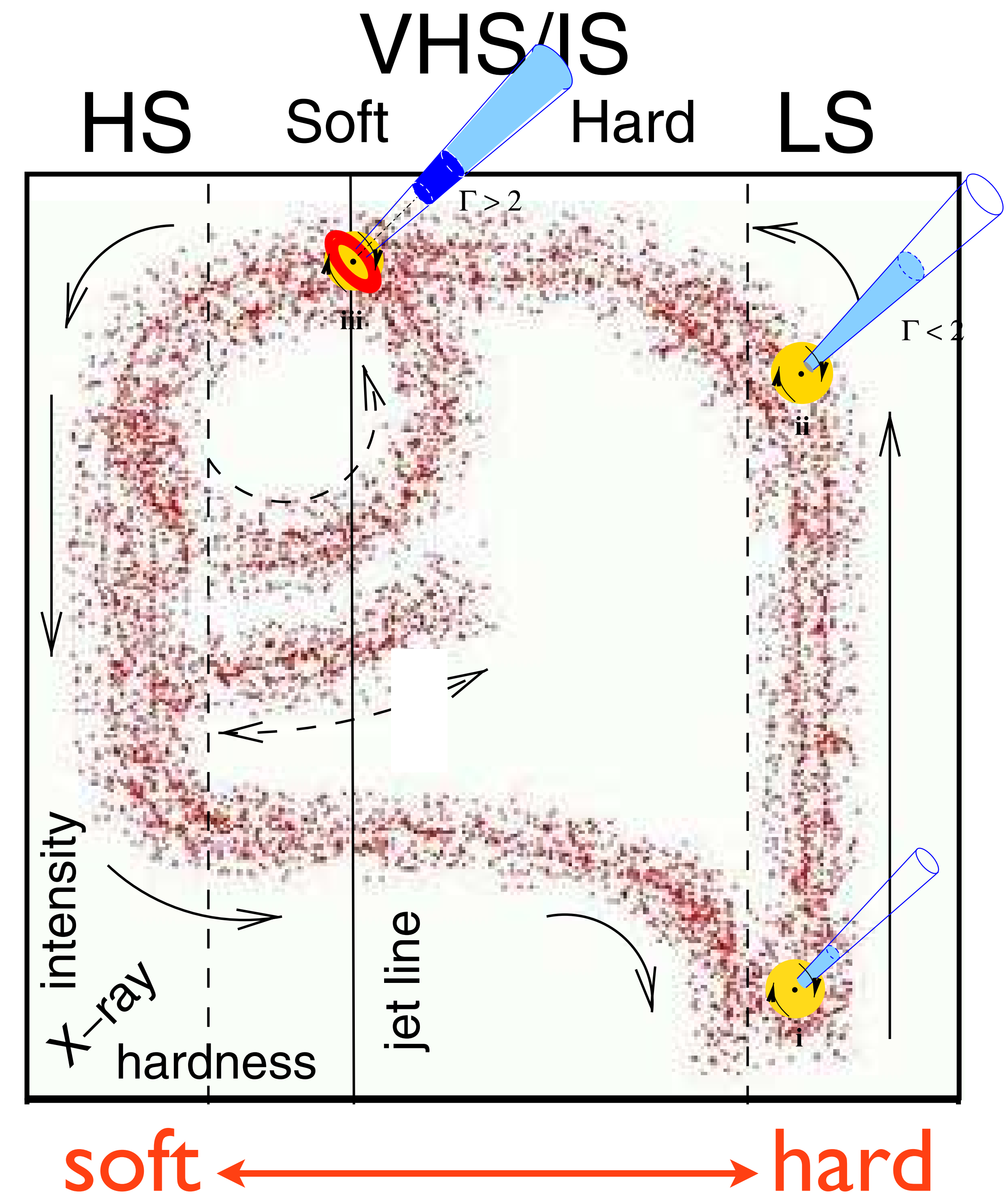
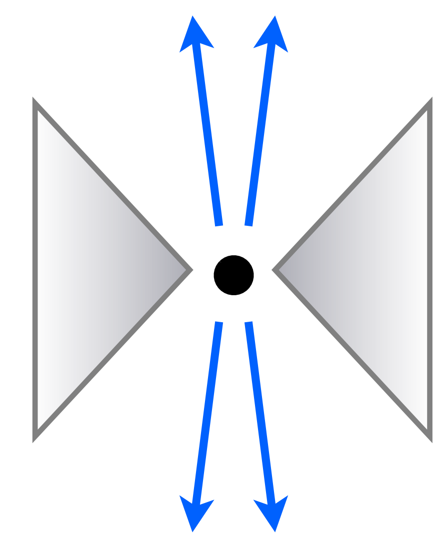


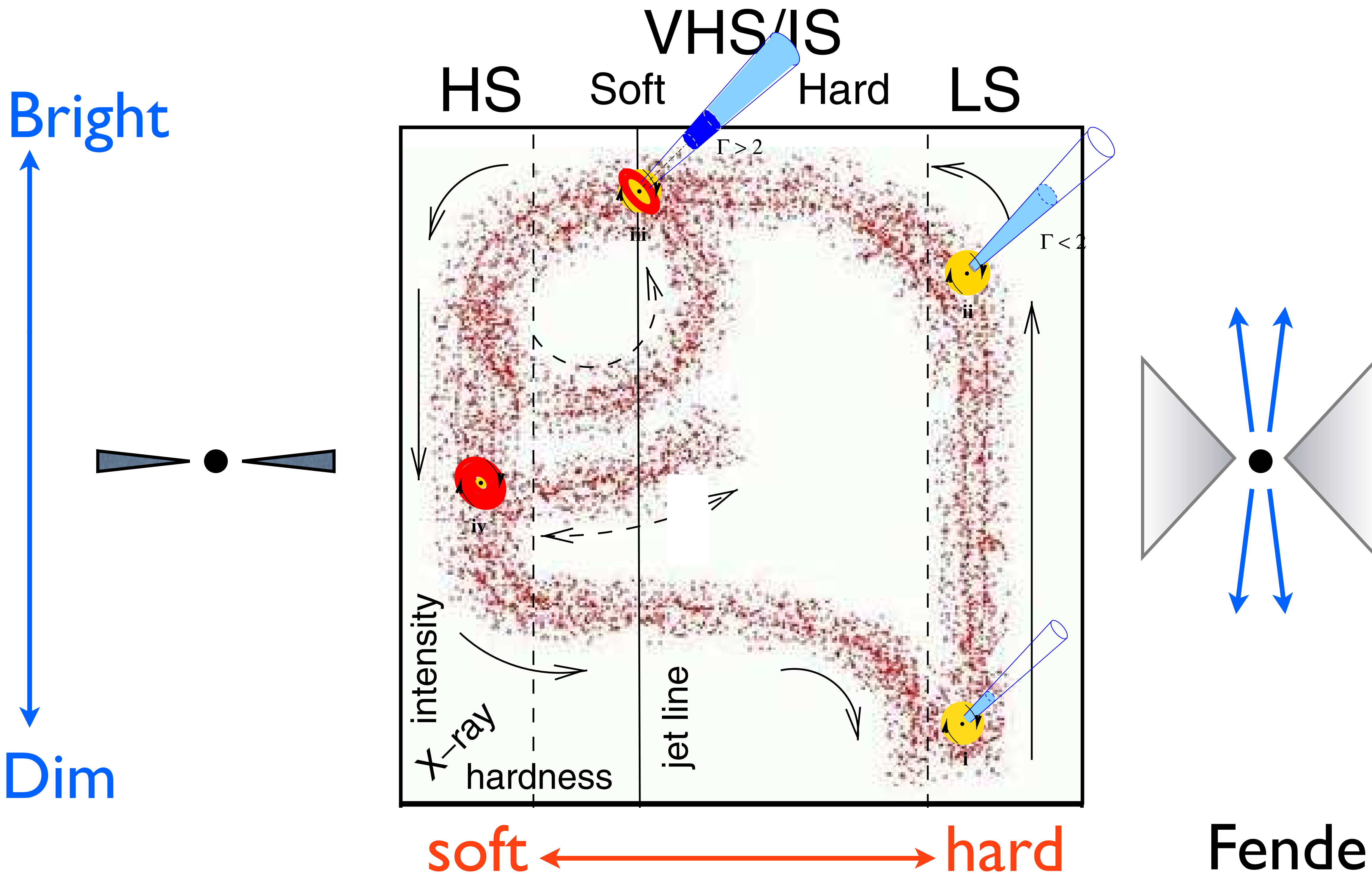




Fender+2004

When are Jets Produced?

"q" or turtlehead diagram

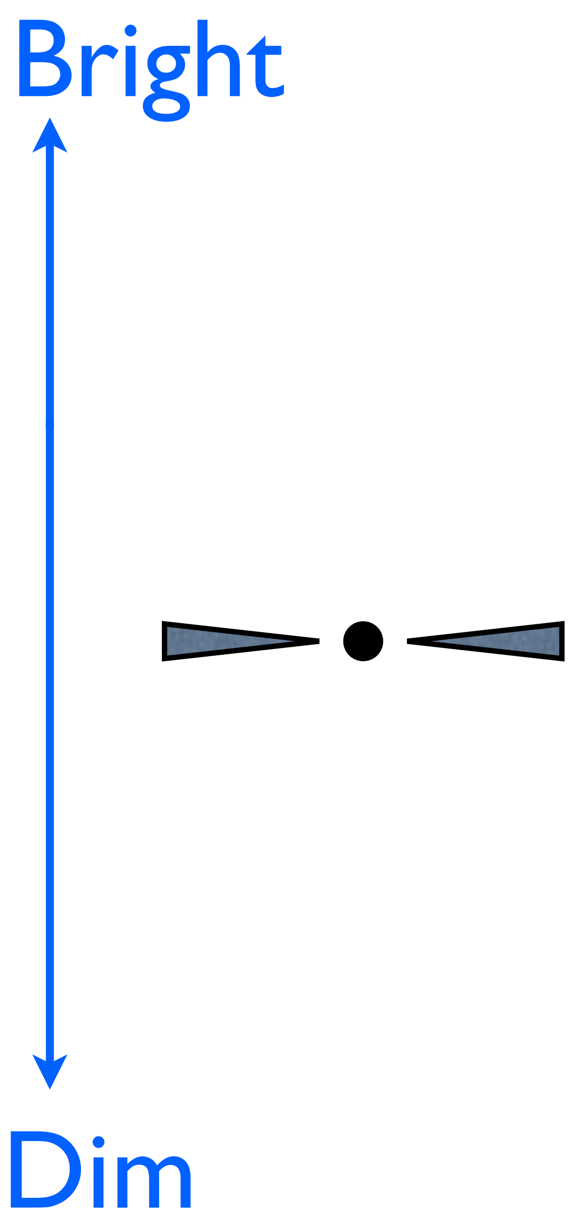


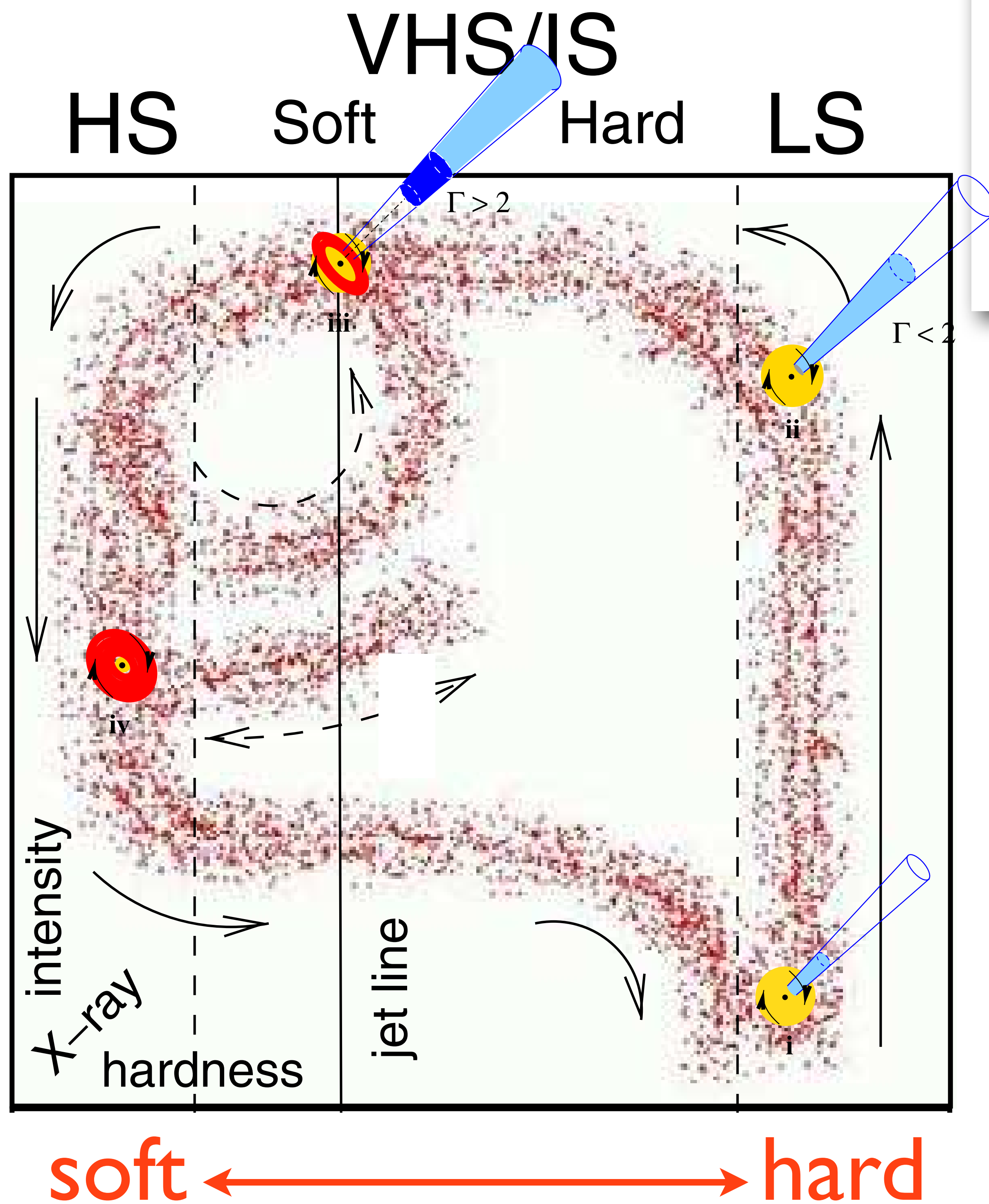
Fender+2004

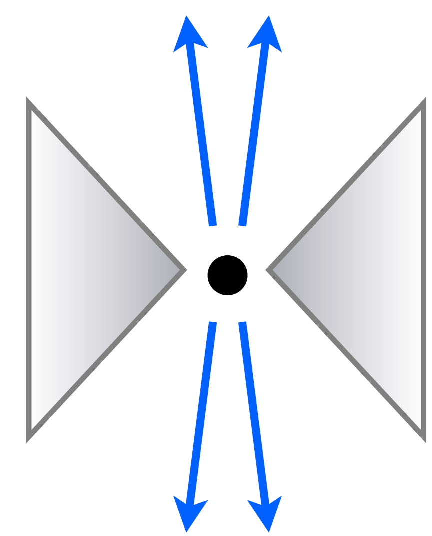
When are Jets Produced?

"q" or turtlehead diagram

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







Fender+2004

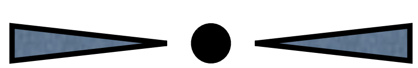
When are Jets Produced?

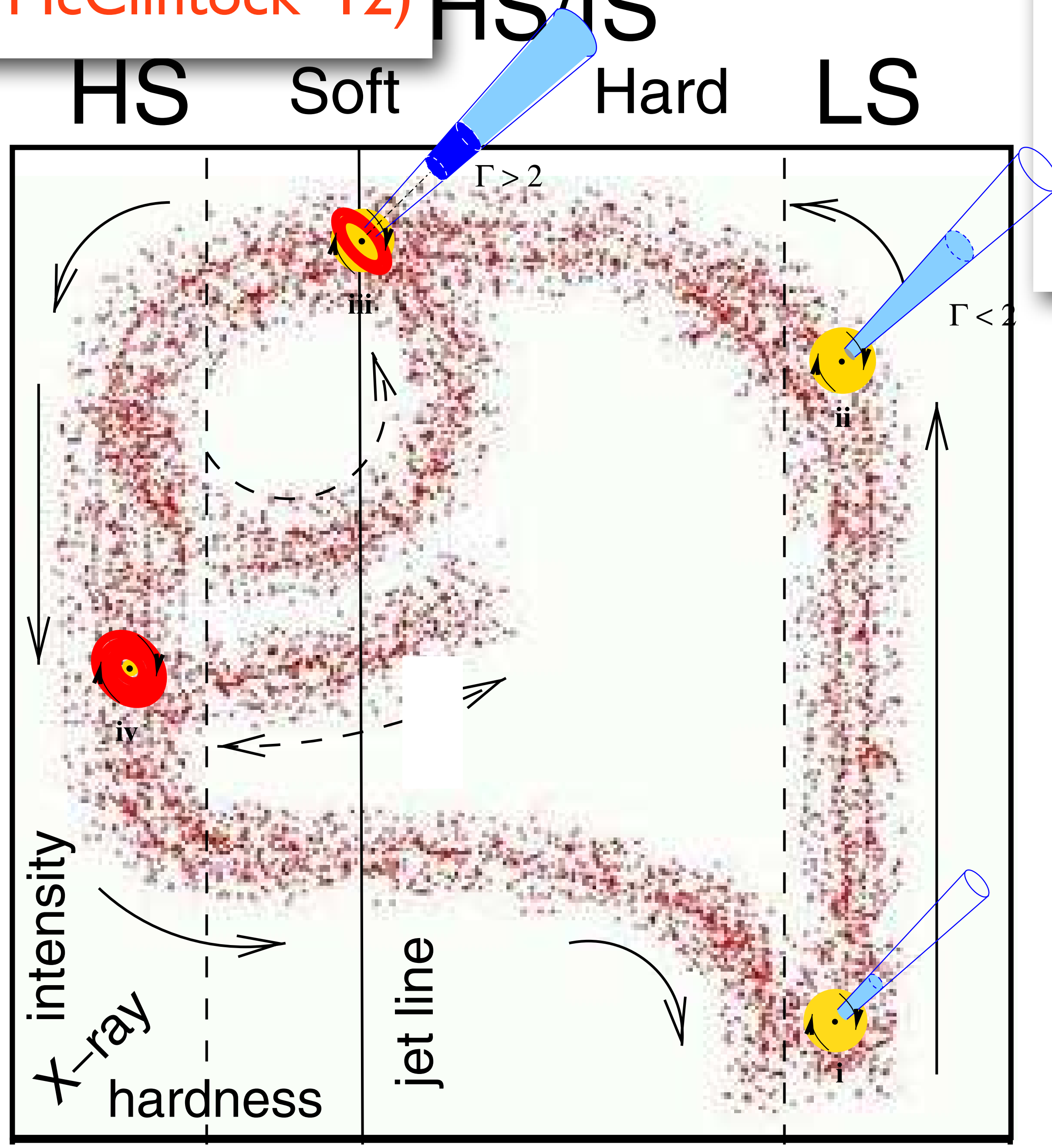
Correlation with BH spin of *transient jets* (Narayan & McClintock '12)

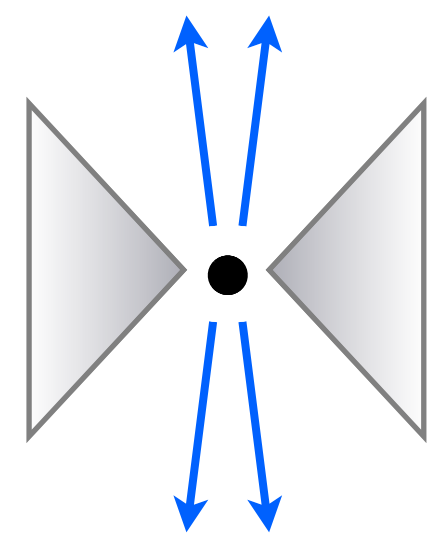
ehead diagram

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

Bright







Dim

soft ⟷ hard

Fender+2004

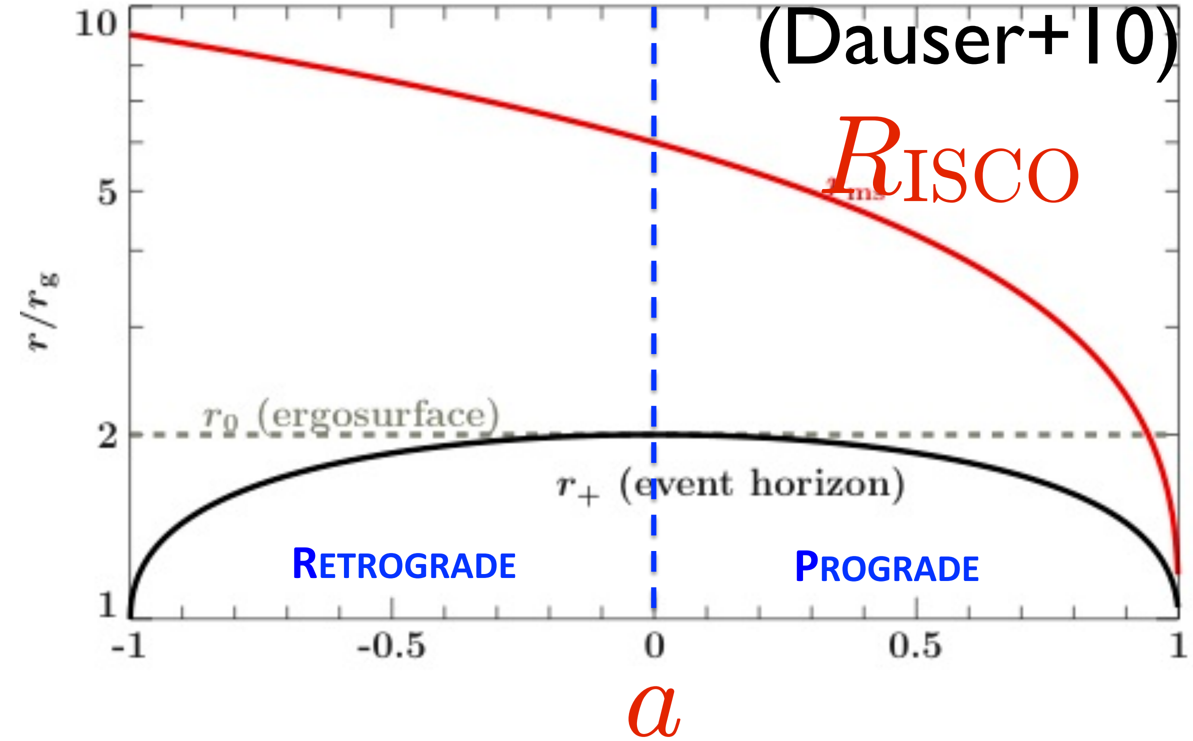
Two major methods of measuring BH spin

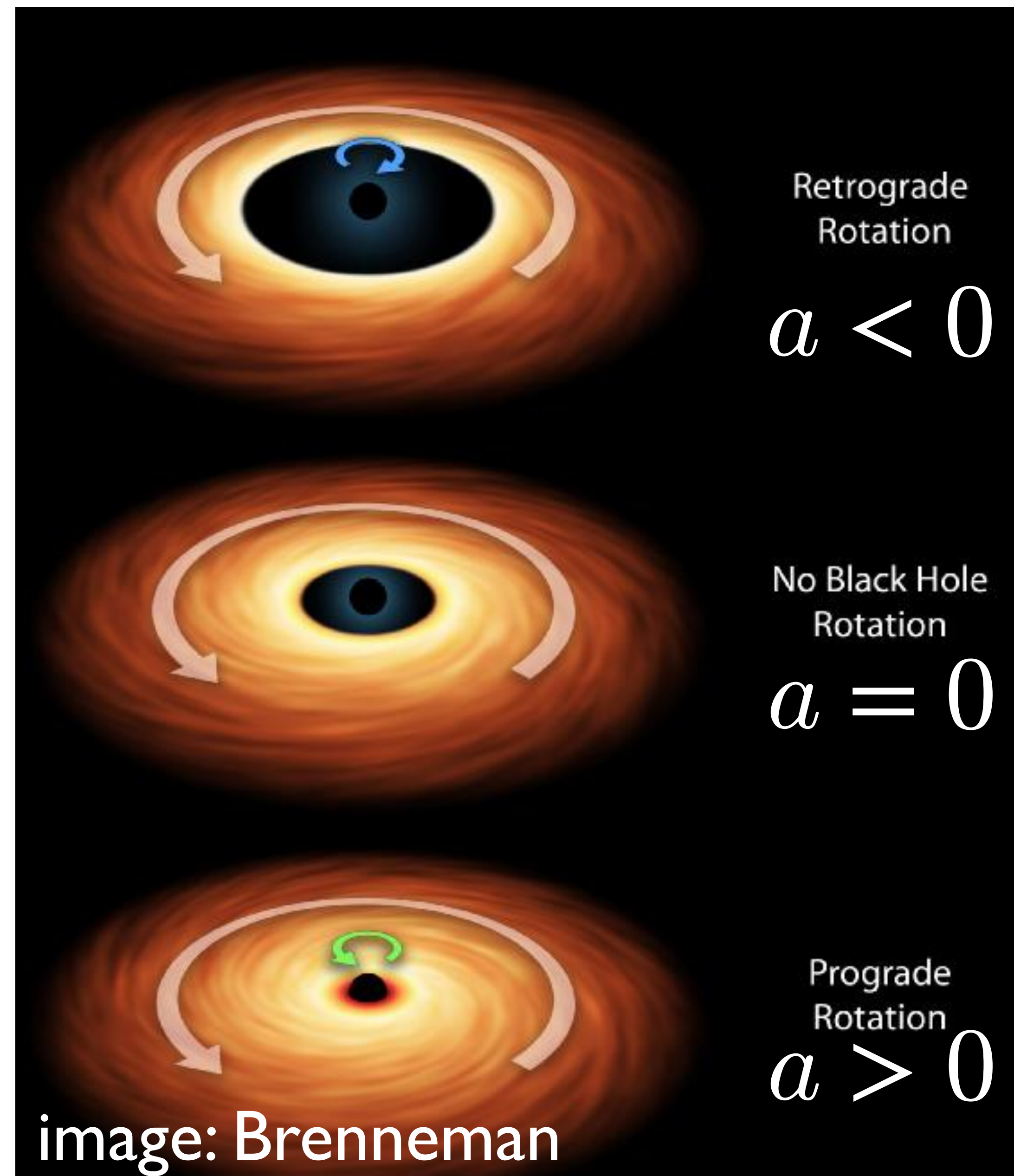
- Both methods rely on measuring the size of the 'hole' in the disk

- '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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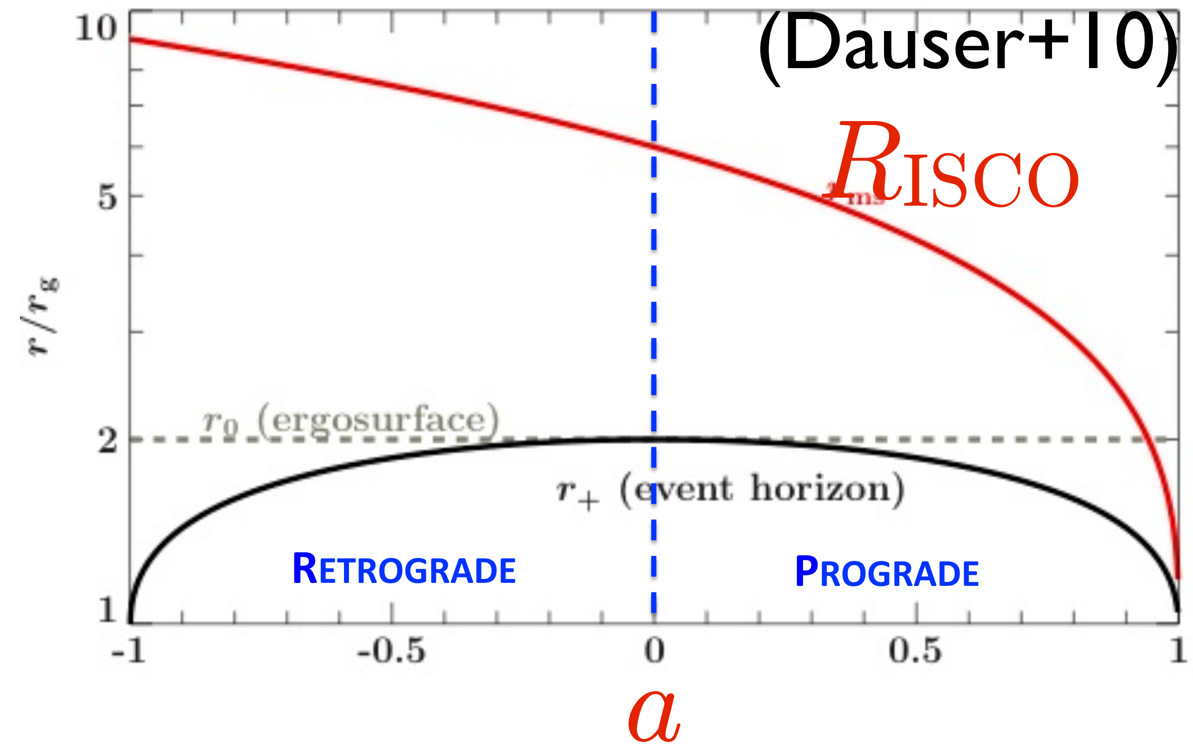
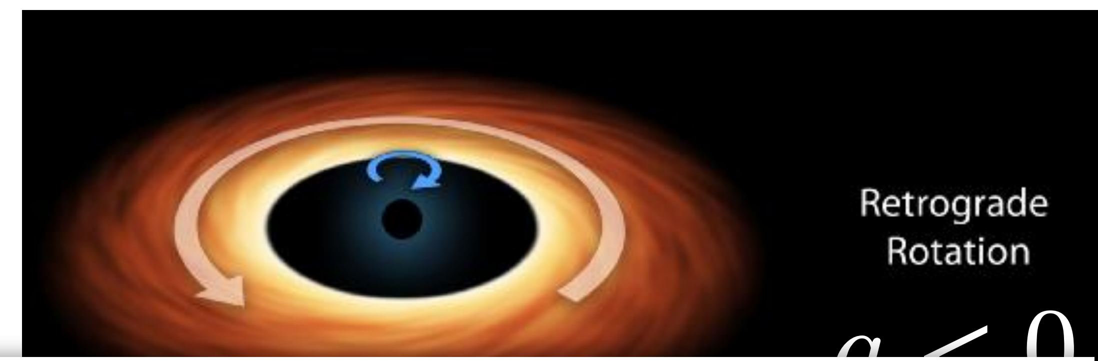


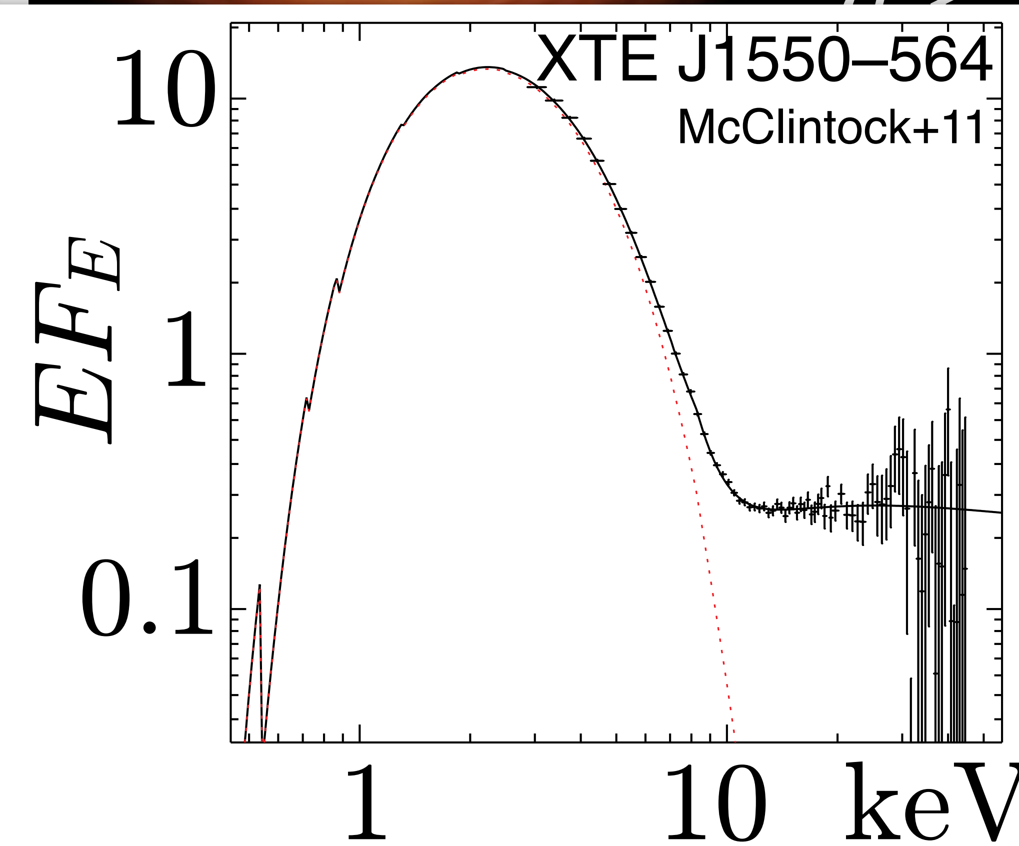


Continuum fitting method:

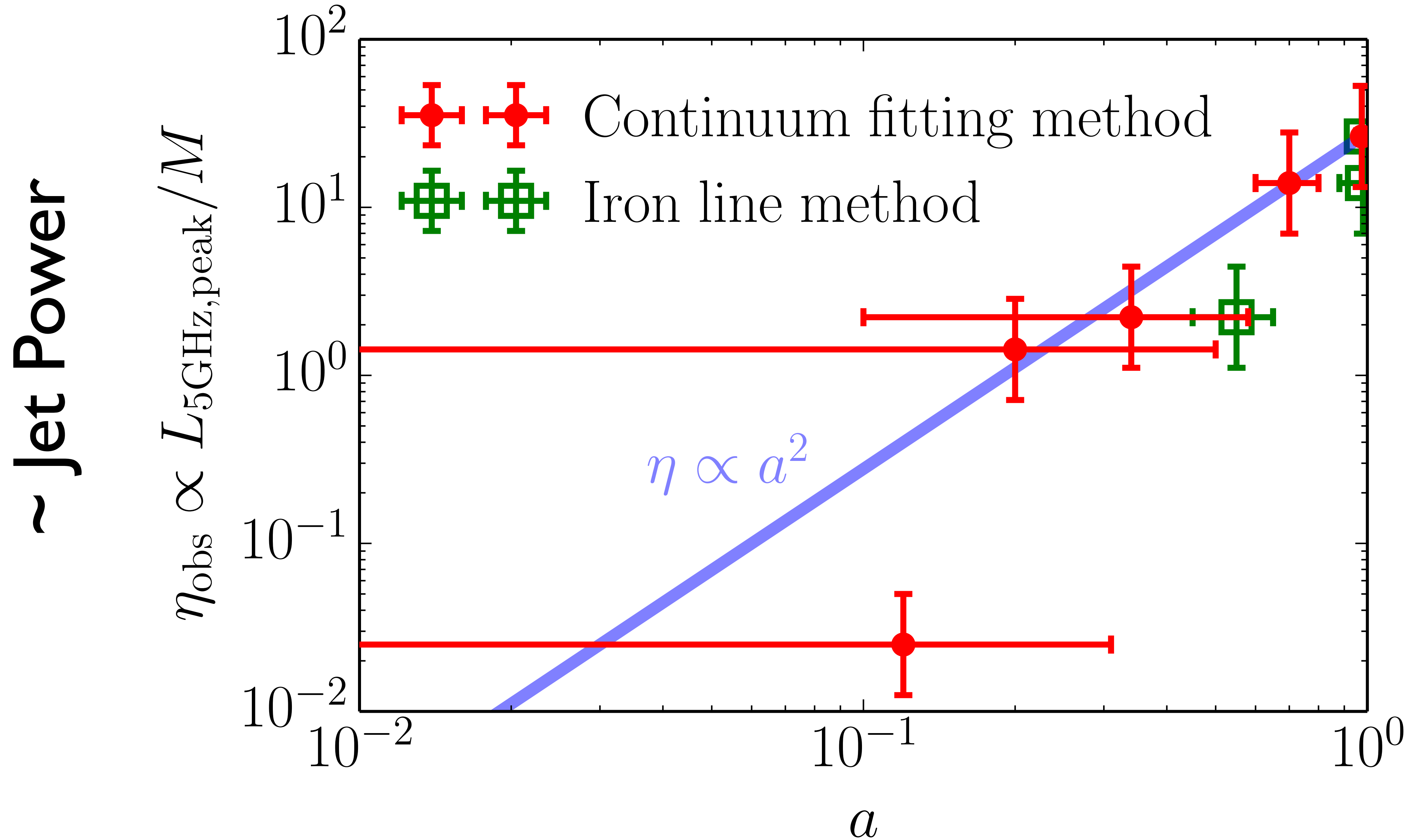
$$\begin{array}{c} a \\ \uparrow \\ L \sim \pi R_{\rm ISCO}{}^2 \sigma T^4 \end{array}$$

↑ normalization ↑ shape

of the spectrum



Are Transient Jets Powered by BH spin?



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

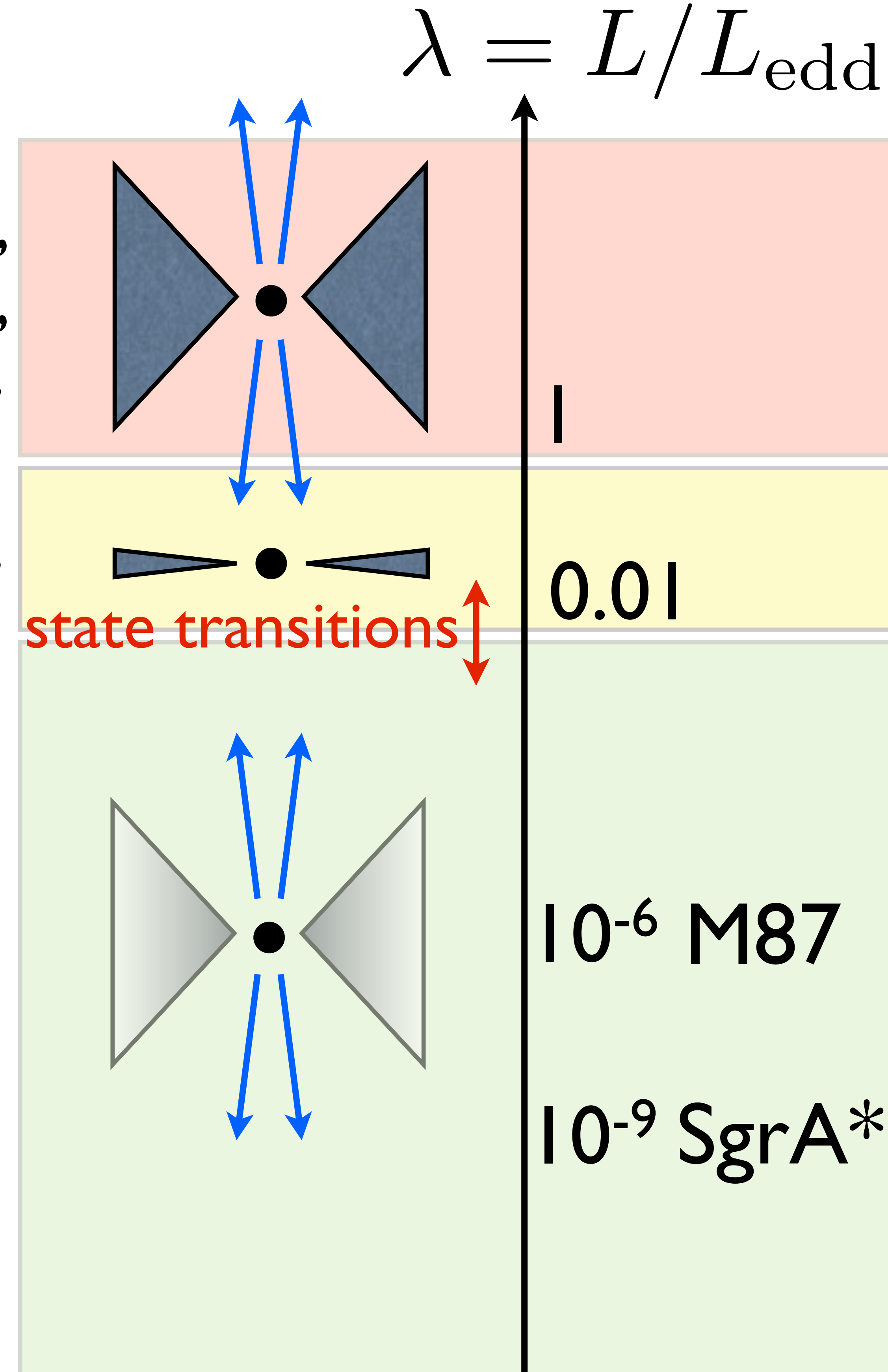
But: Russell+13

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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Low-luminosity active galactic nuclei
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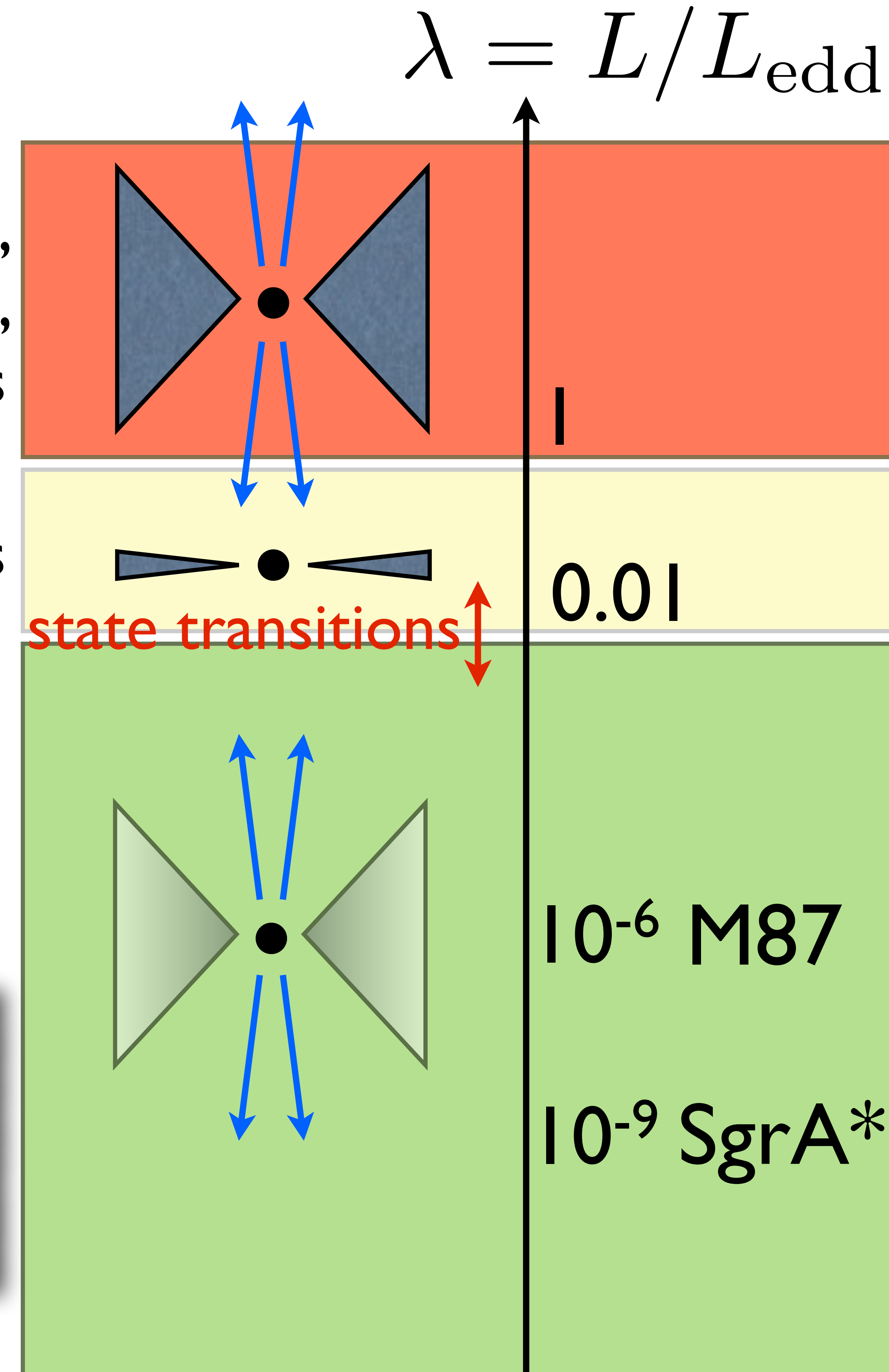
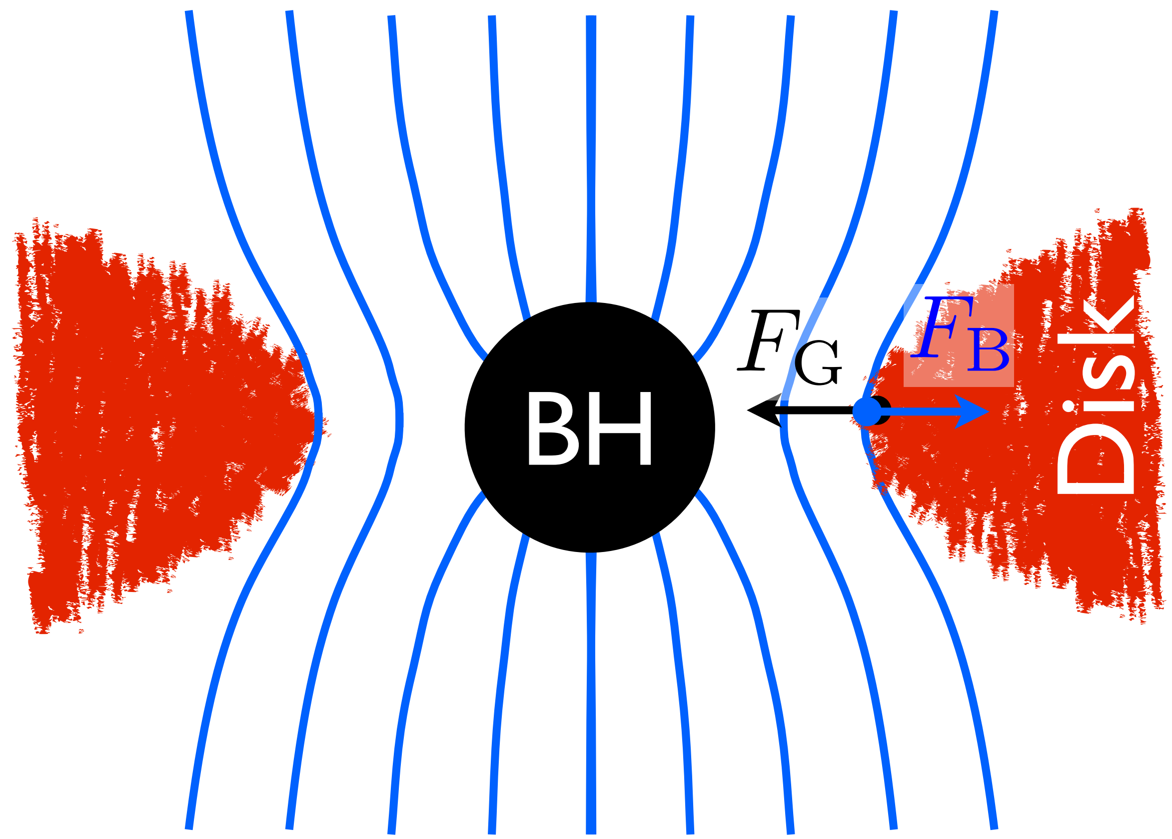


Both high- and low-luminosity disks
are *radiatively inefficient*.
Neglect radiation and simulate.

What Sets Jet Power?



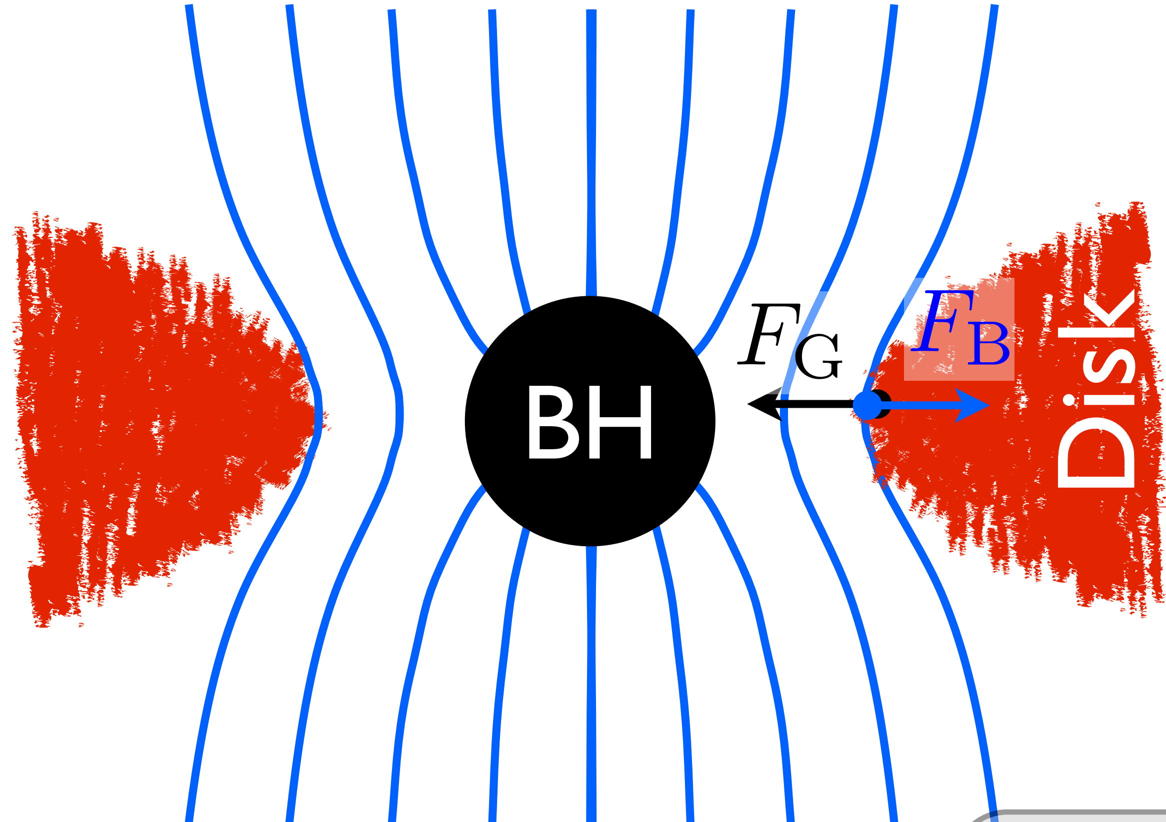
magnetic flux:
$\Phi \sim B r_g^2$

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)

What Sets Jet Power?



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k

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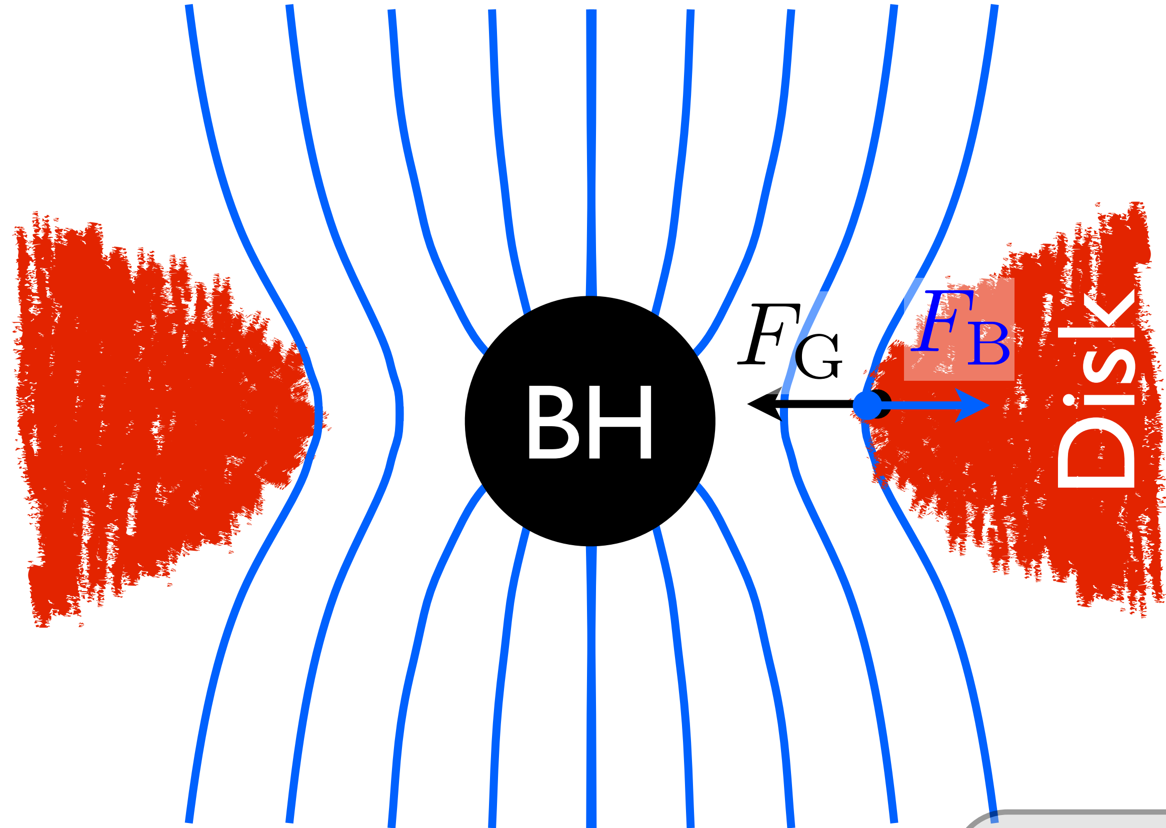

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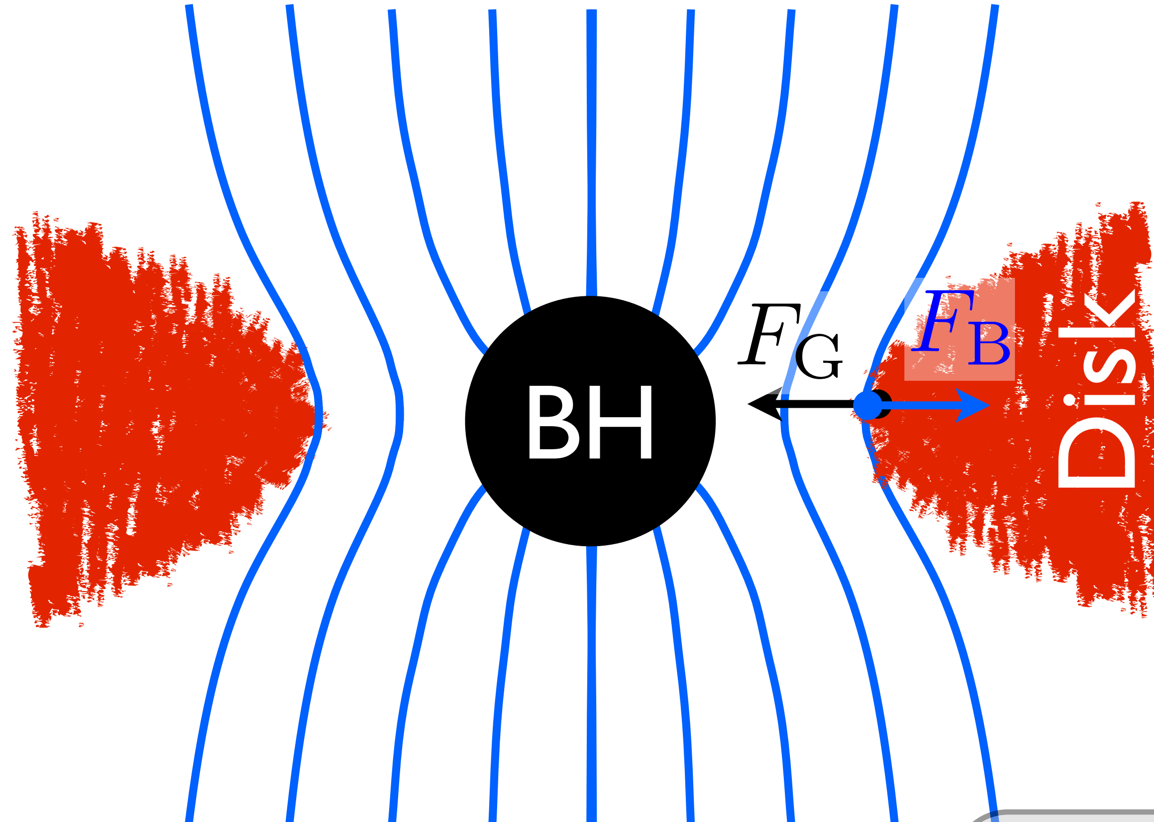
(Blandford & Znajek '77, AT+10)

$$P_j = k\Phi^2$$

What Sets Jet Power?



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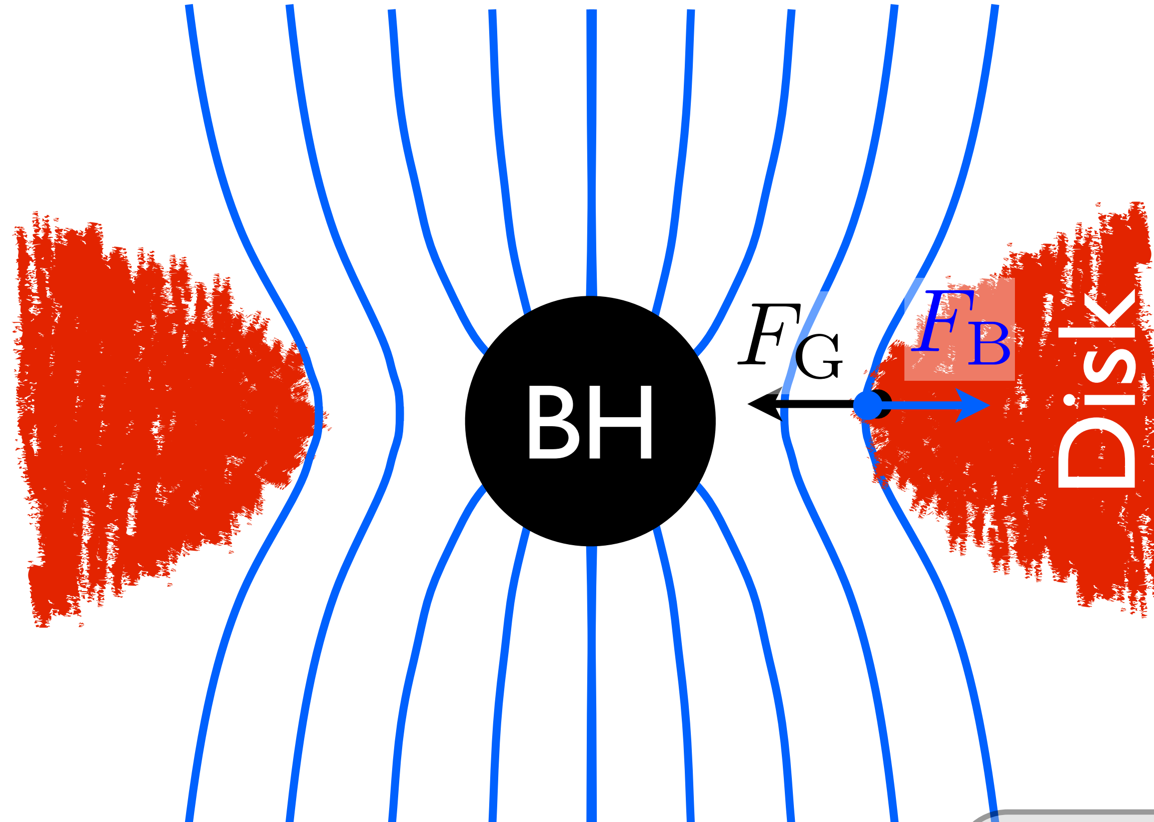
(Blandford & Znajek '77, AT+10)

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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$$\Phi = 0 \qquad \Phi = \Phi_{\mathrm{MAX}}$$

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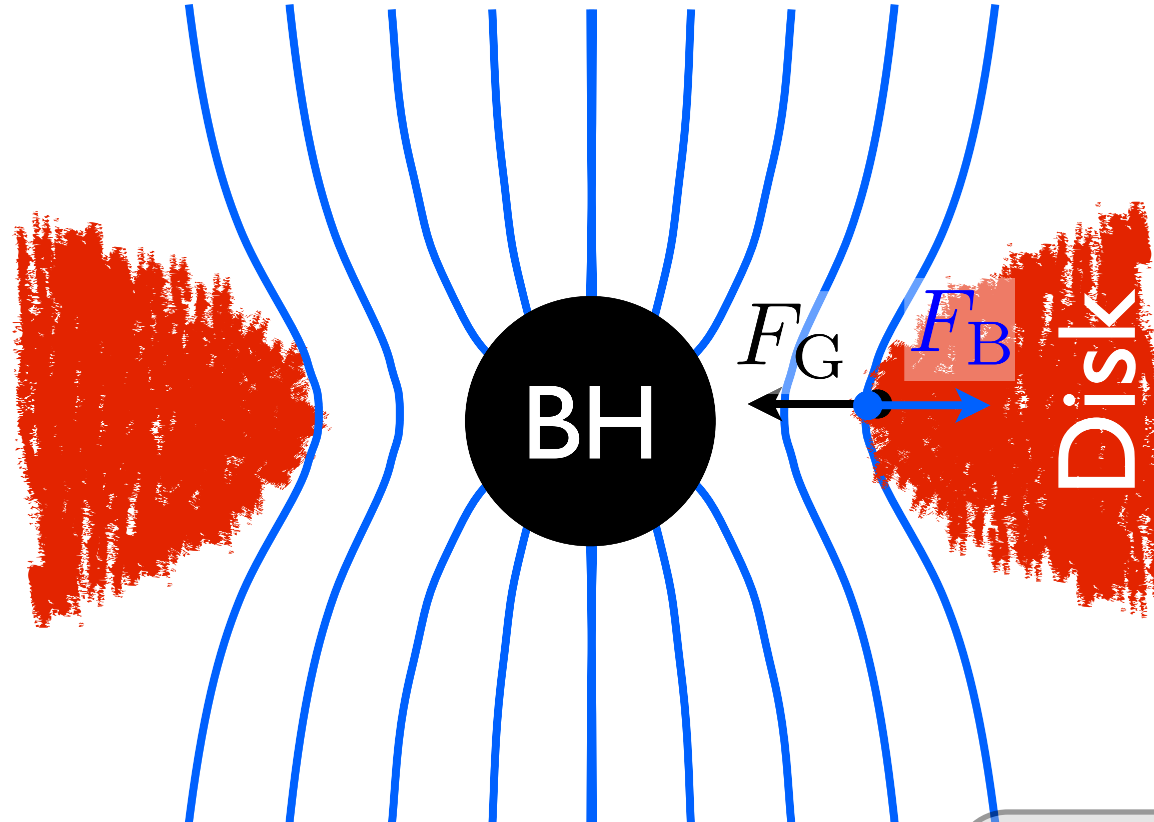

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Magnetically-Arrested Disk (MAD)

(Narayan+ 2003, AT+ 2011)

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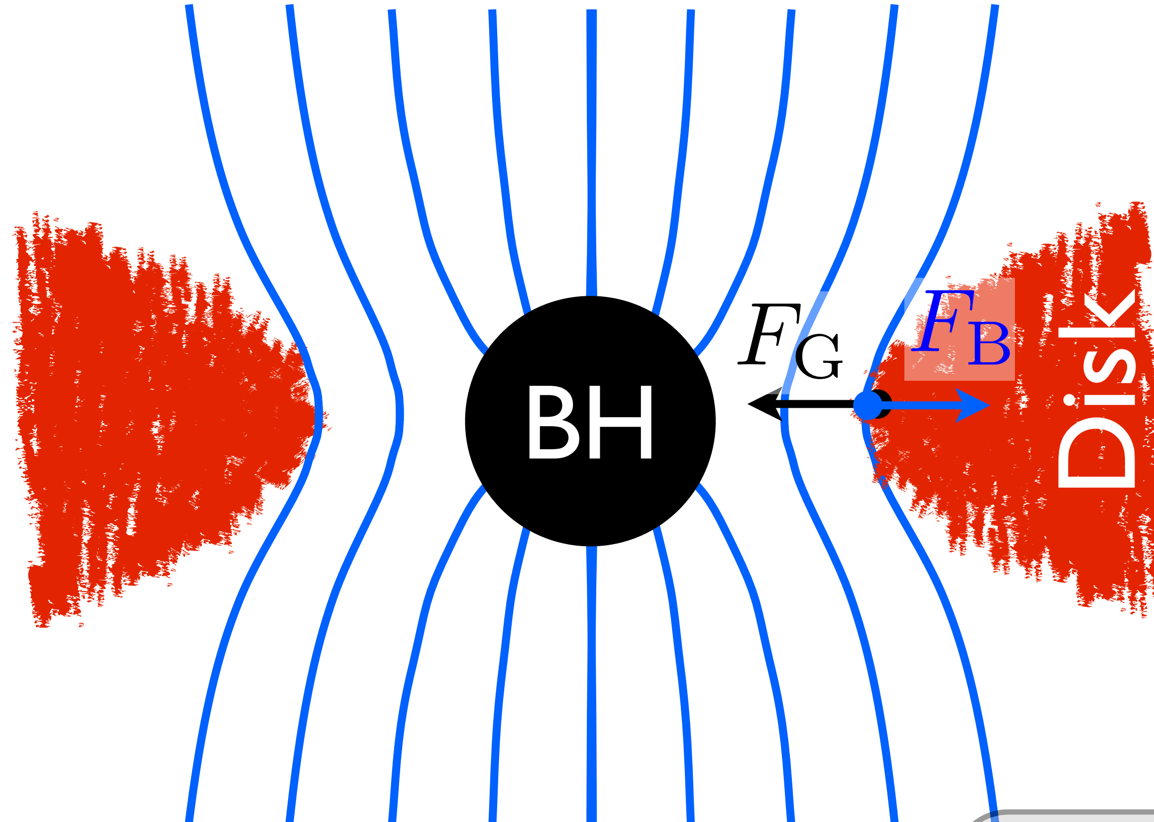

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k

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

(Narayan+ 2003, AT+ 2011)

What Sets Jet Power?

What sets magnetic field strength on the hole?
Is it inner disk's...

- magnetic pressure? $(B^2/8\pi)_{BH} = (B^2/8\pi)_{DISK}$

ux:

s:

I/c^2

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(Blandford & Znajek '77, AT+10)

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

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ux:

s:

$/c^2$

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- total pressure? $(B^2/8\pi)_{BH} = P_{DISK}$

ux:

s:

$/c^2$

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- ram pressure? $(B^2/8\pi)_{BH} = (\rho c^2)_{DISK}$

ux:

s:

$/c^2$

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(Narayan+ 2003, AT+ 2011)

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ux:

s:

$/c^2$

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ux:

s:

$/c^2$

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(Narayan+ 2003, AT+ 2011)

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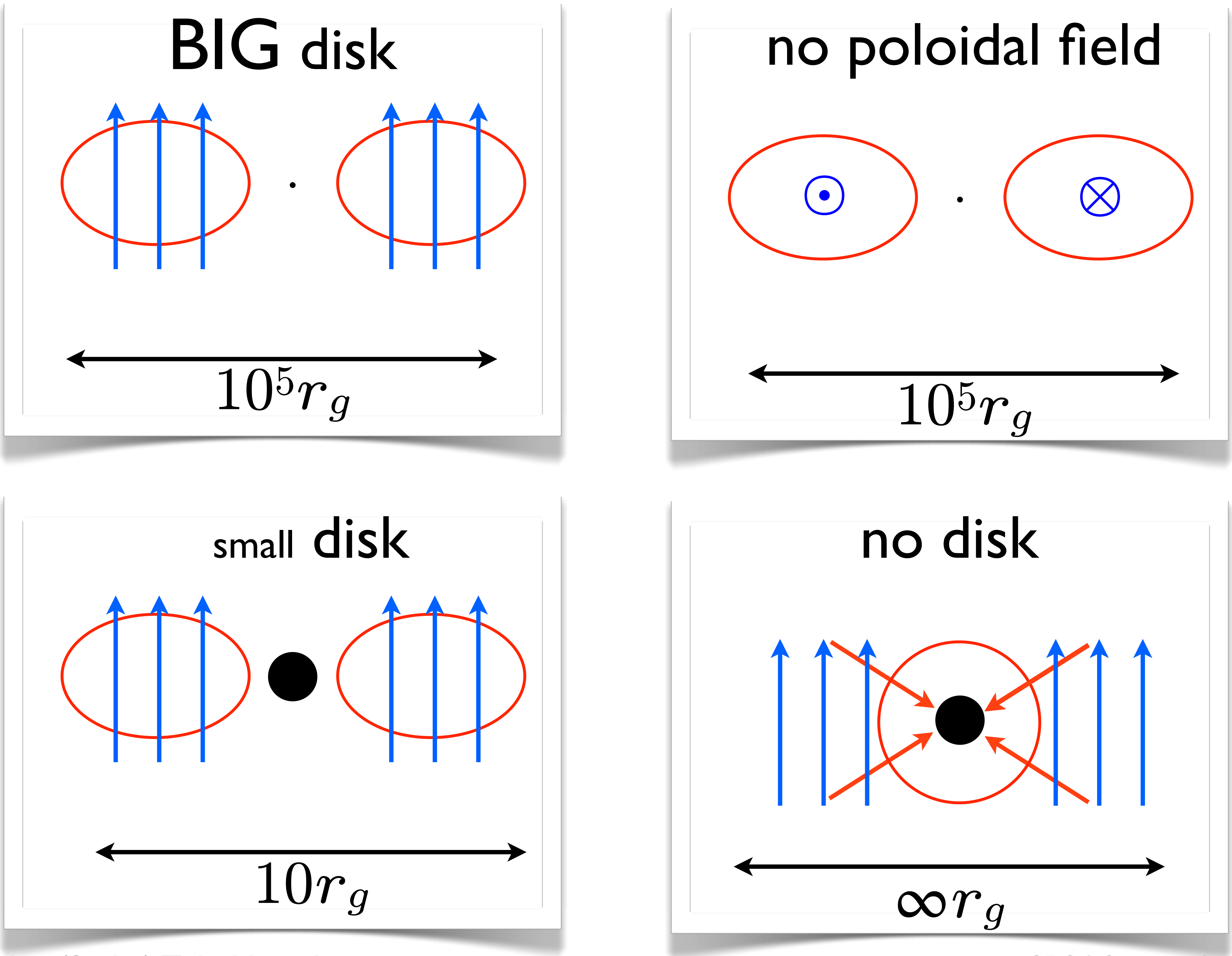
What is a Healthy Jet Diet?



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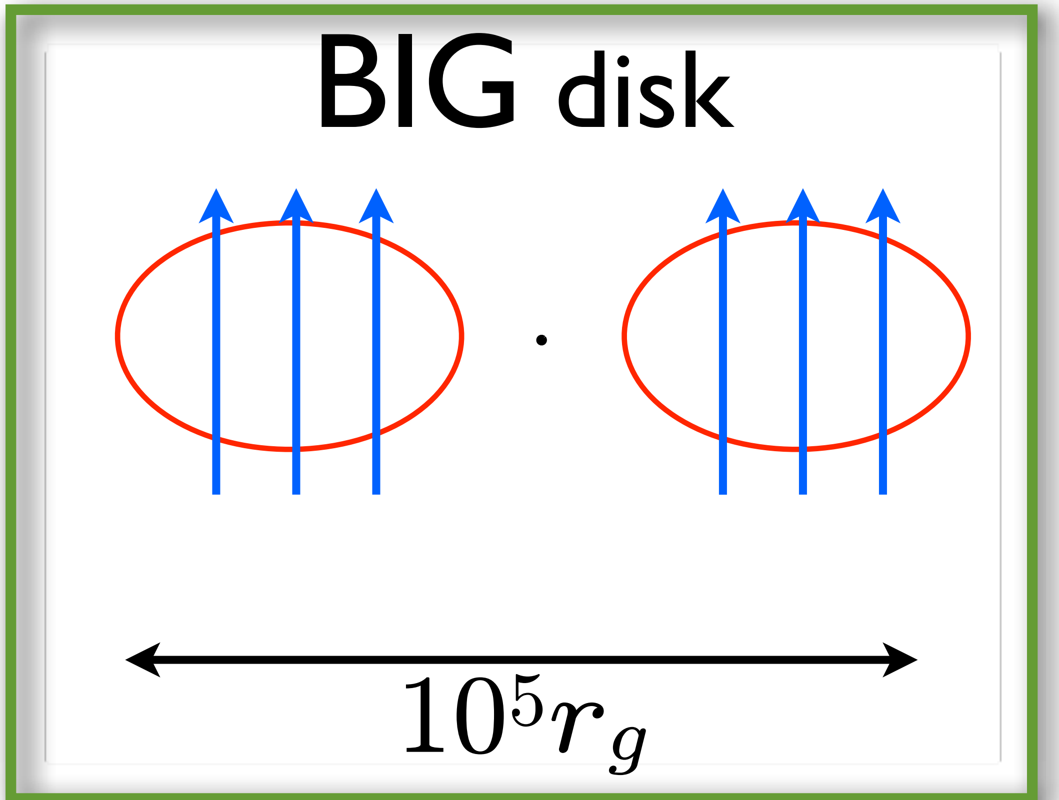
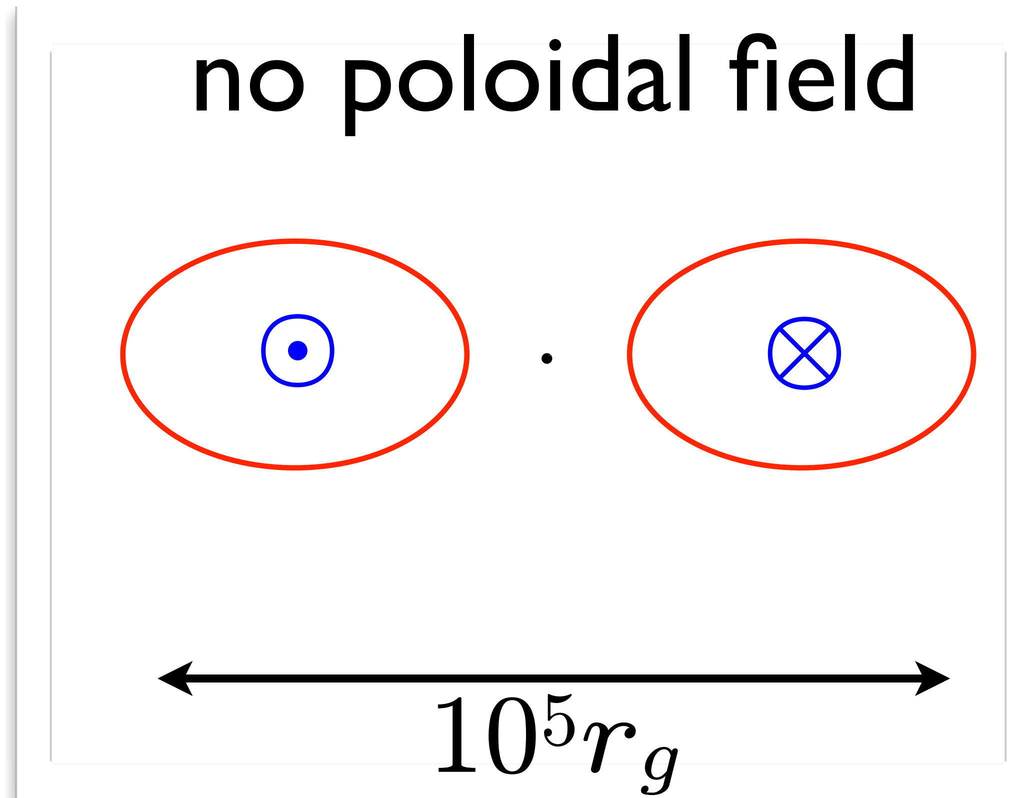
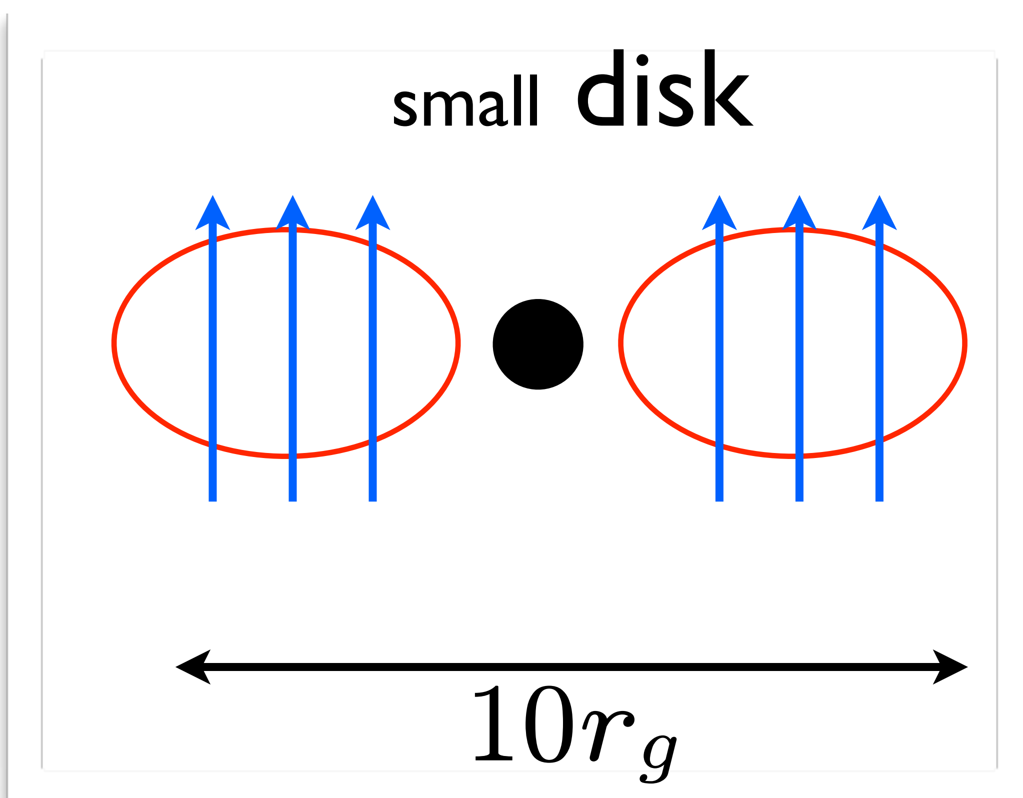
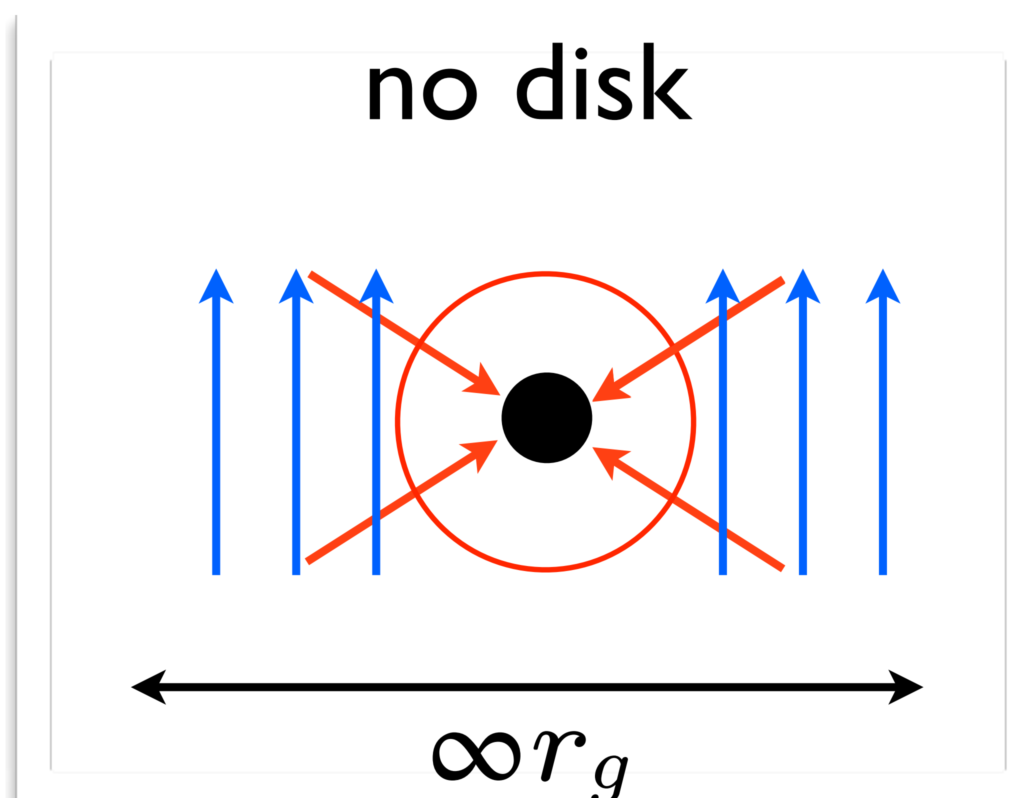
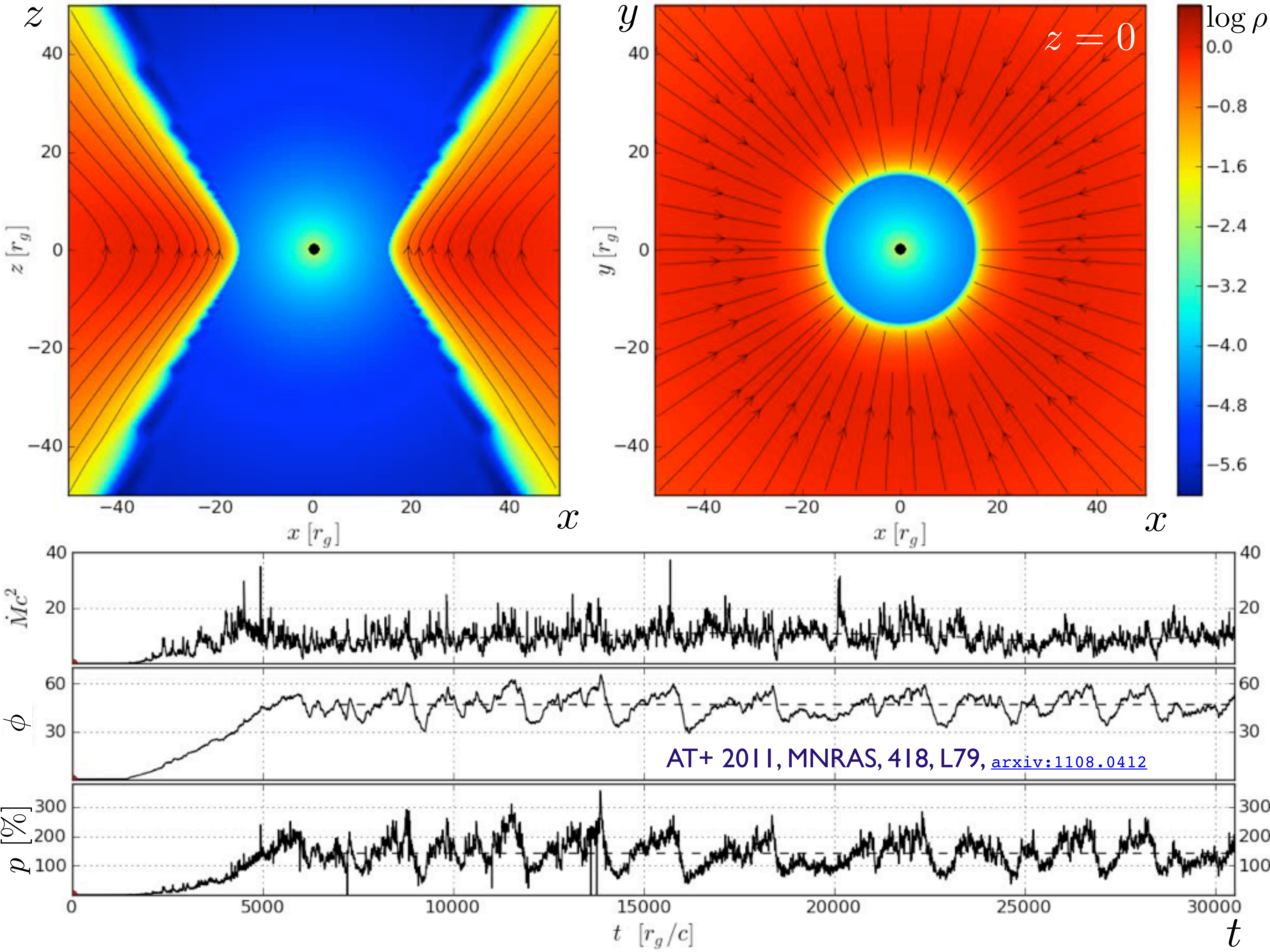


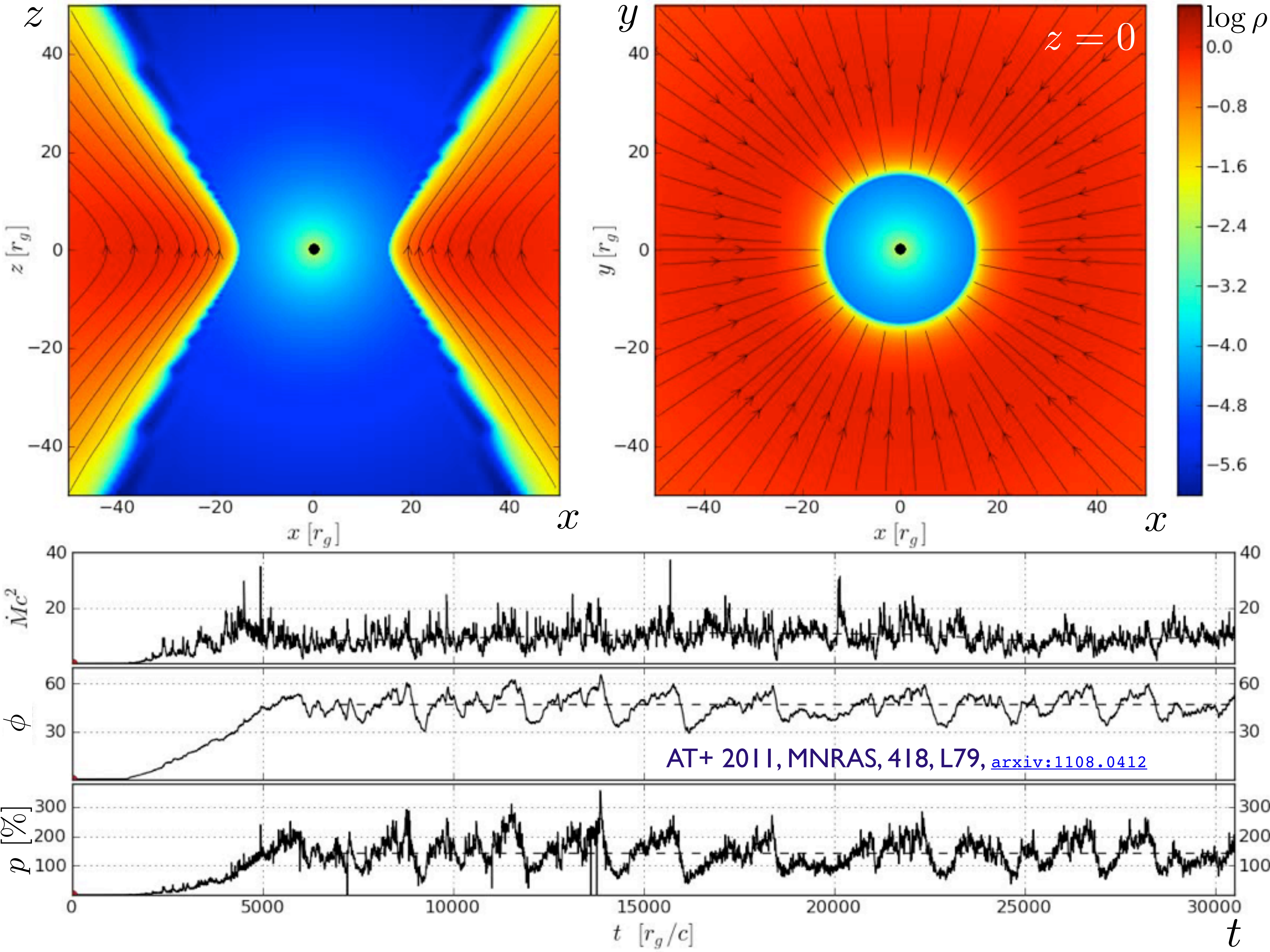




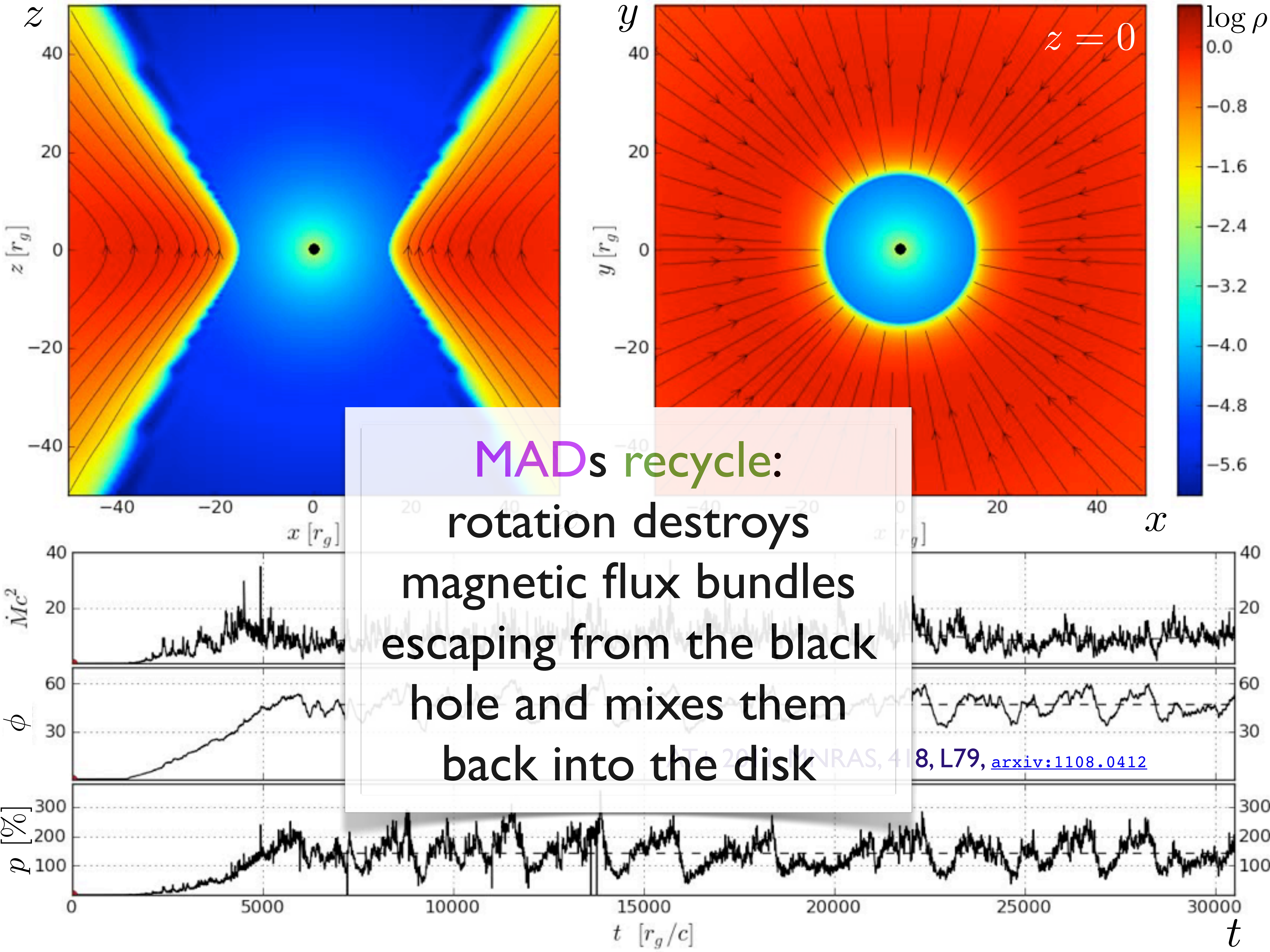




z
y
$z = 0$
$\log \rho$
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
x
$\dot{M}c^2$
ϕ
$p\ [\%]$
AT+ 2011, MNRAS, 418, L79, arxiv:1108.0412
$t\ \ [r_g/c]$
t



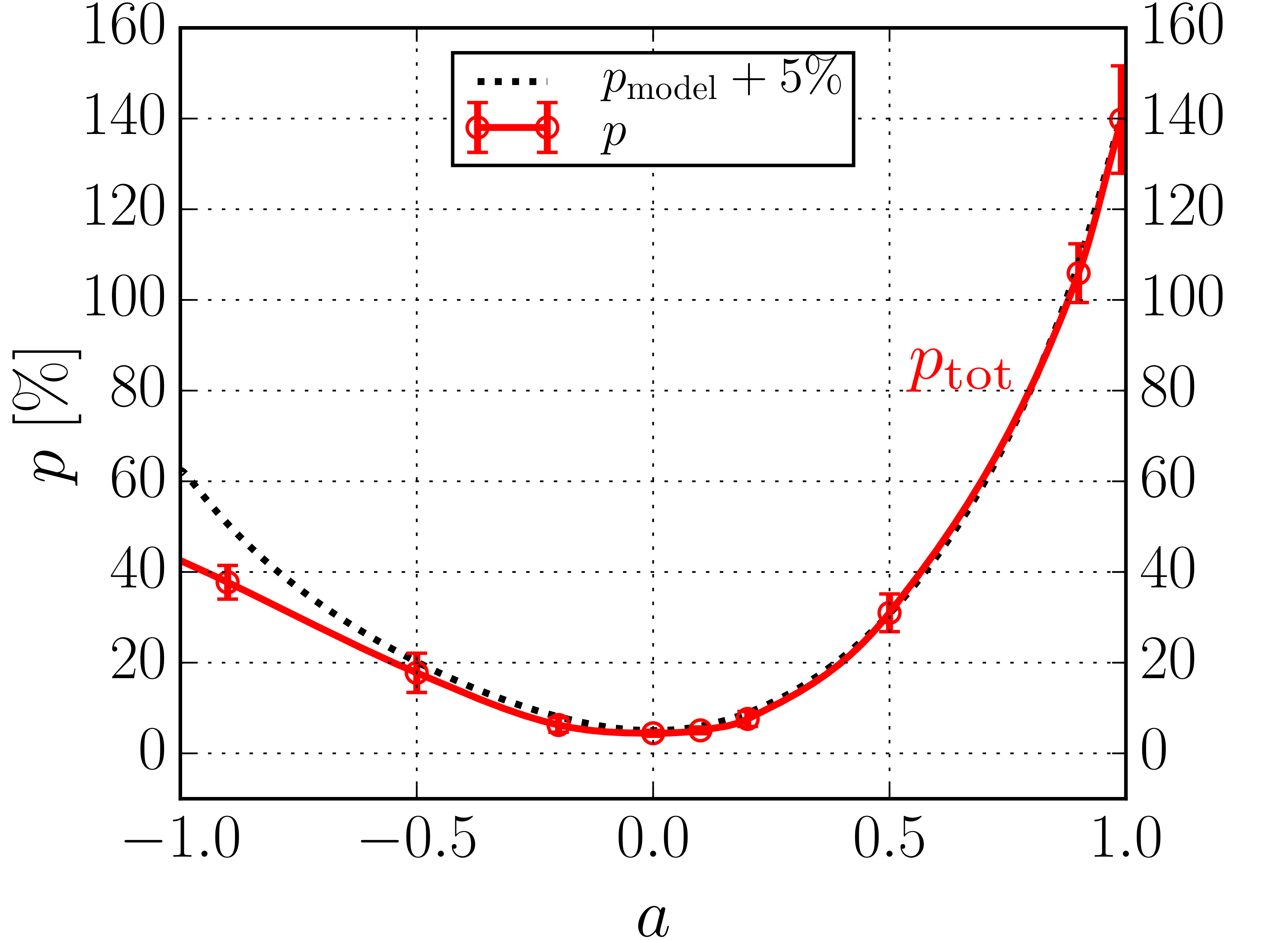
z
y
$z = 0$
$\log \rho$
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
x
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ \ [r_g/c]$
t
AT+ 2011, MNRAS, 418, L79, arxiv:1108.0412


MADs recycle:
rotation destroys
magnetic flux bundles
escaping from the black
hole and mixes them
back into the disk
8, L79, arxiv:1108.0412
z
y
z = 0
log ρ
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
40
20
0
−20
−40
z [r_g]
y [r_g]
x [r_g]
x
Ṁc²
φ
p [%]
300
200
100
60
30
0
5000
10000
15000
20000
25000
30000
t [r_g/c]
t

Upper Envelope of Jet Power vs. Spin

$(h/r \sim 0.3)$

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



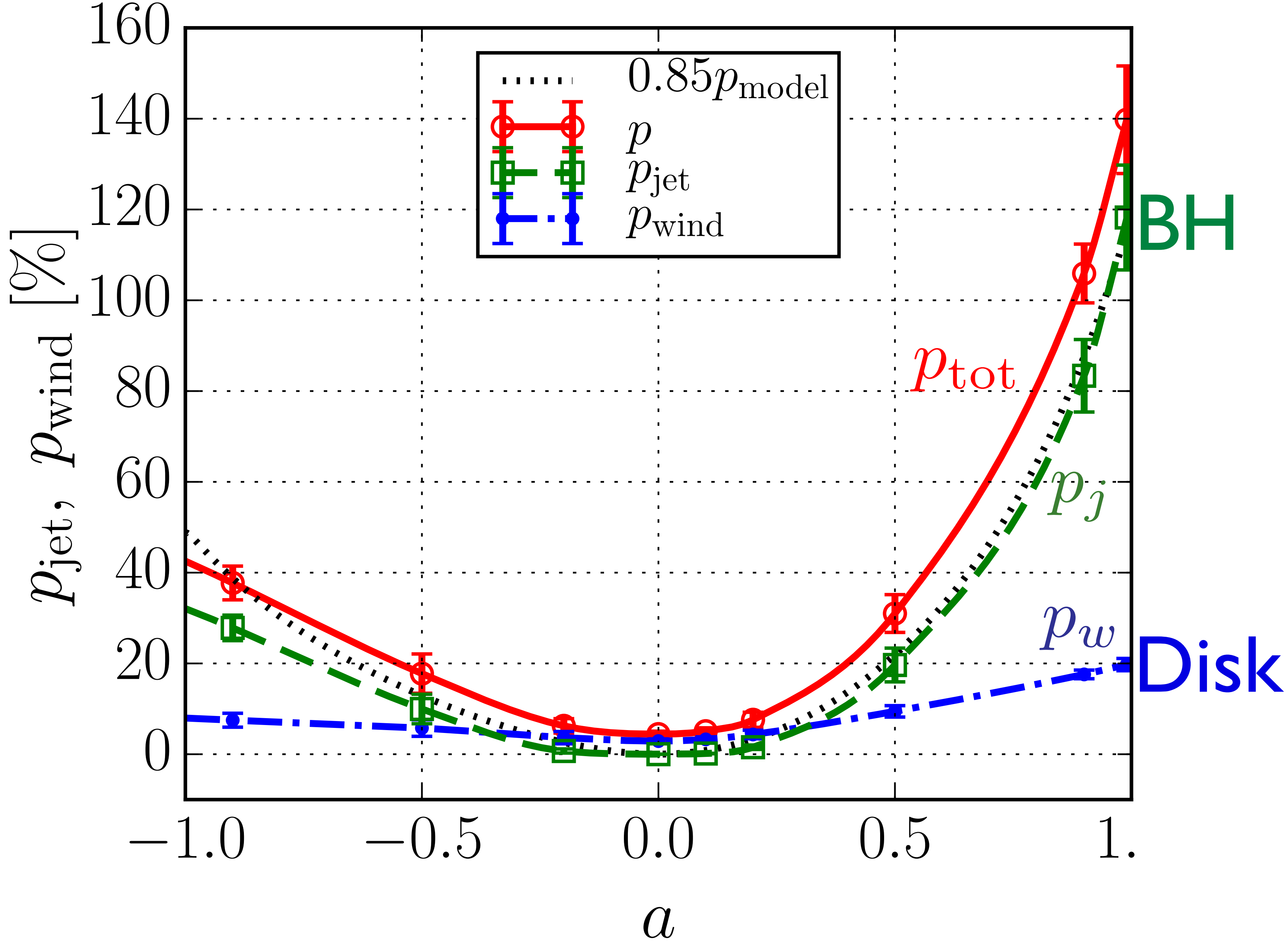
Quantify feedback due to black hole jet, disk wind from *first principles*

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

Upper Envelope of Jet Power vs. Spin

$(h/r \sim 0.3)$

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



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

Jet = 85% of Blandford-Znajek power

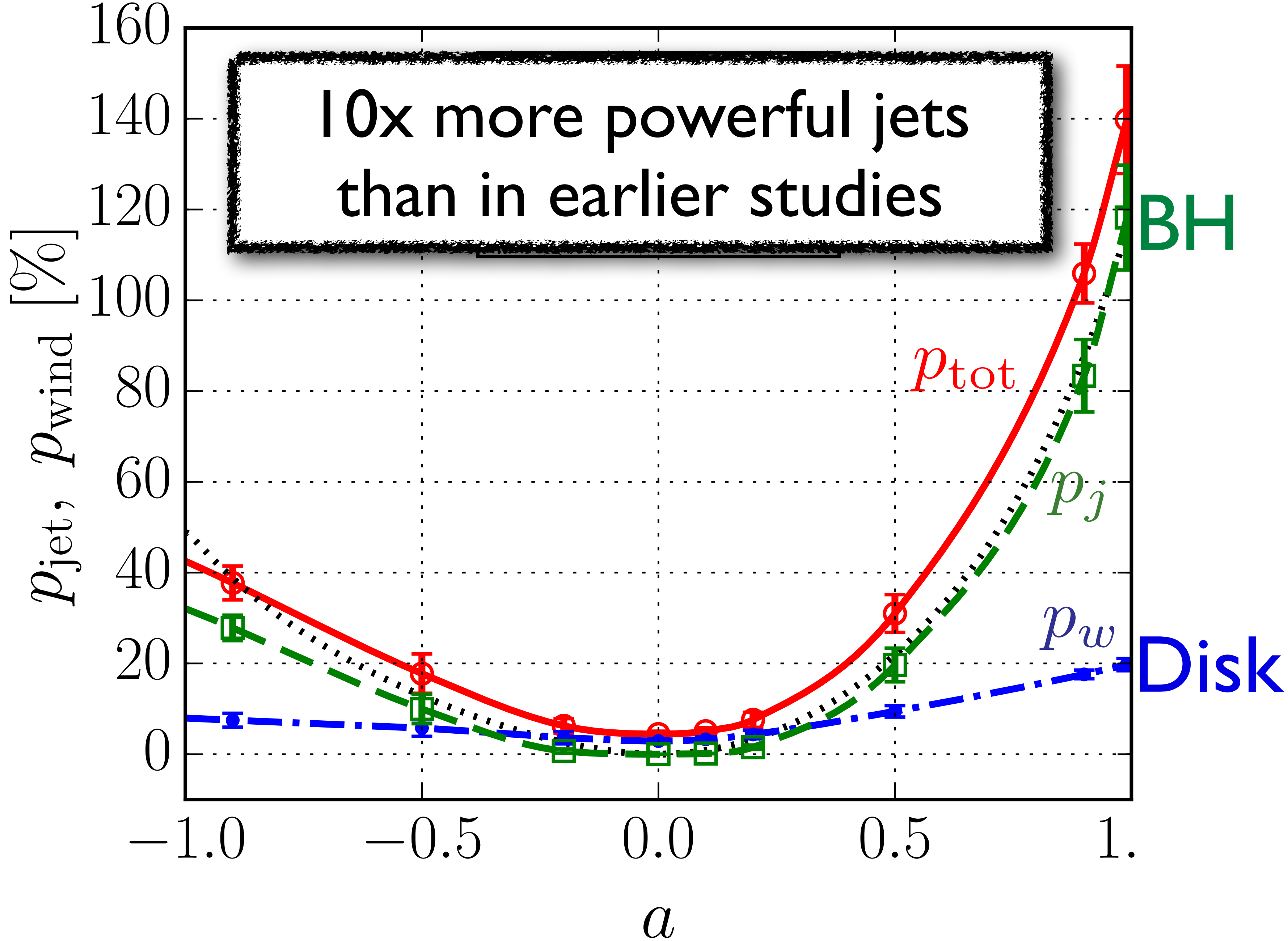
Wind = BP = 15% of BZ power + 5%

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

Upper Envelope of Jet Power vs. Spin

$(h/r \sim 0.3)$

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



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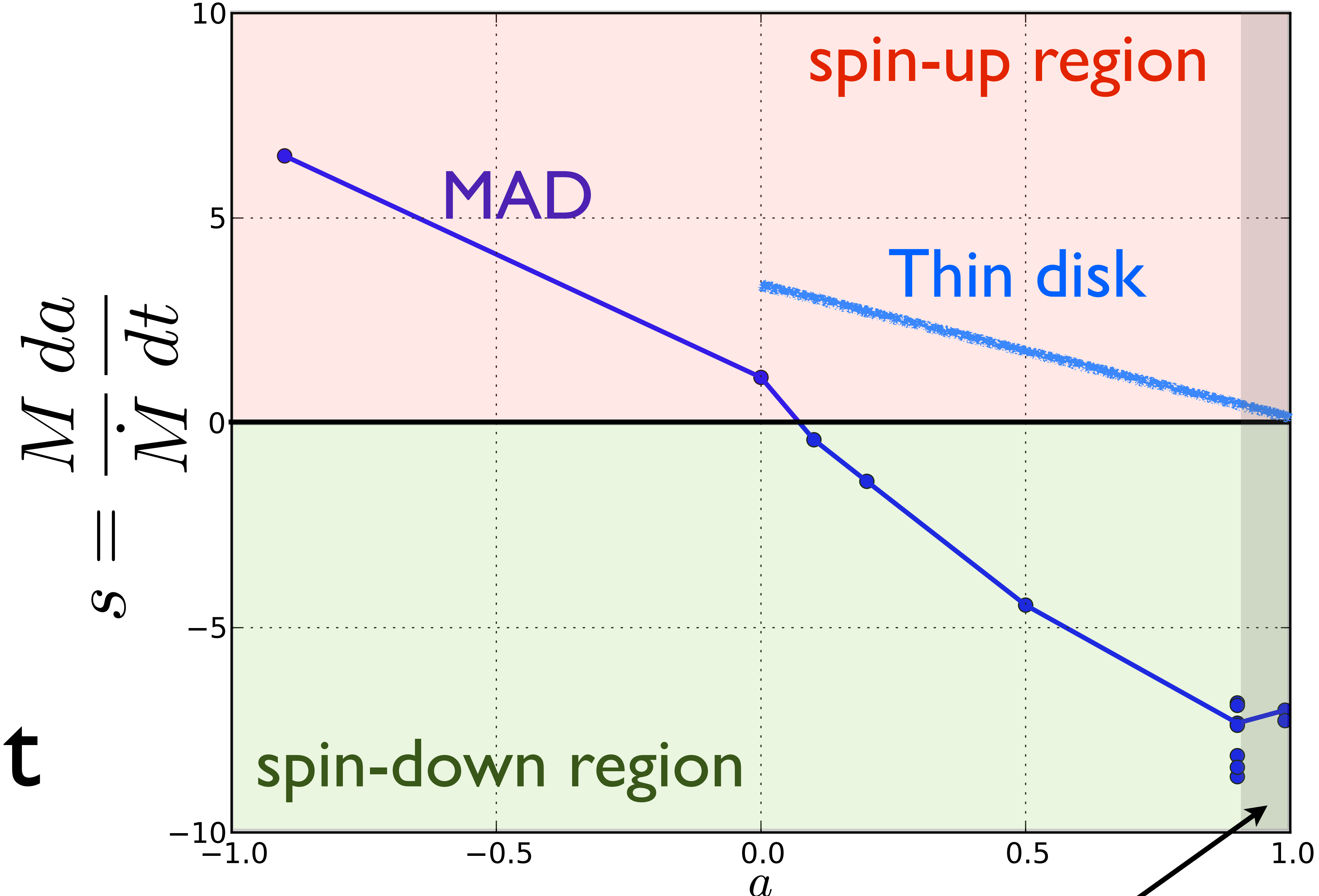
Disk wind is powered by a combination of BH spin and disk rotation tilted12

Our MADs slow BHs down to a halt



Conventional spin equilibrium region, $a \gtrsim 0.9$

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

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

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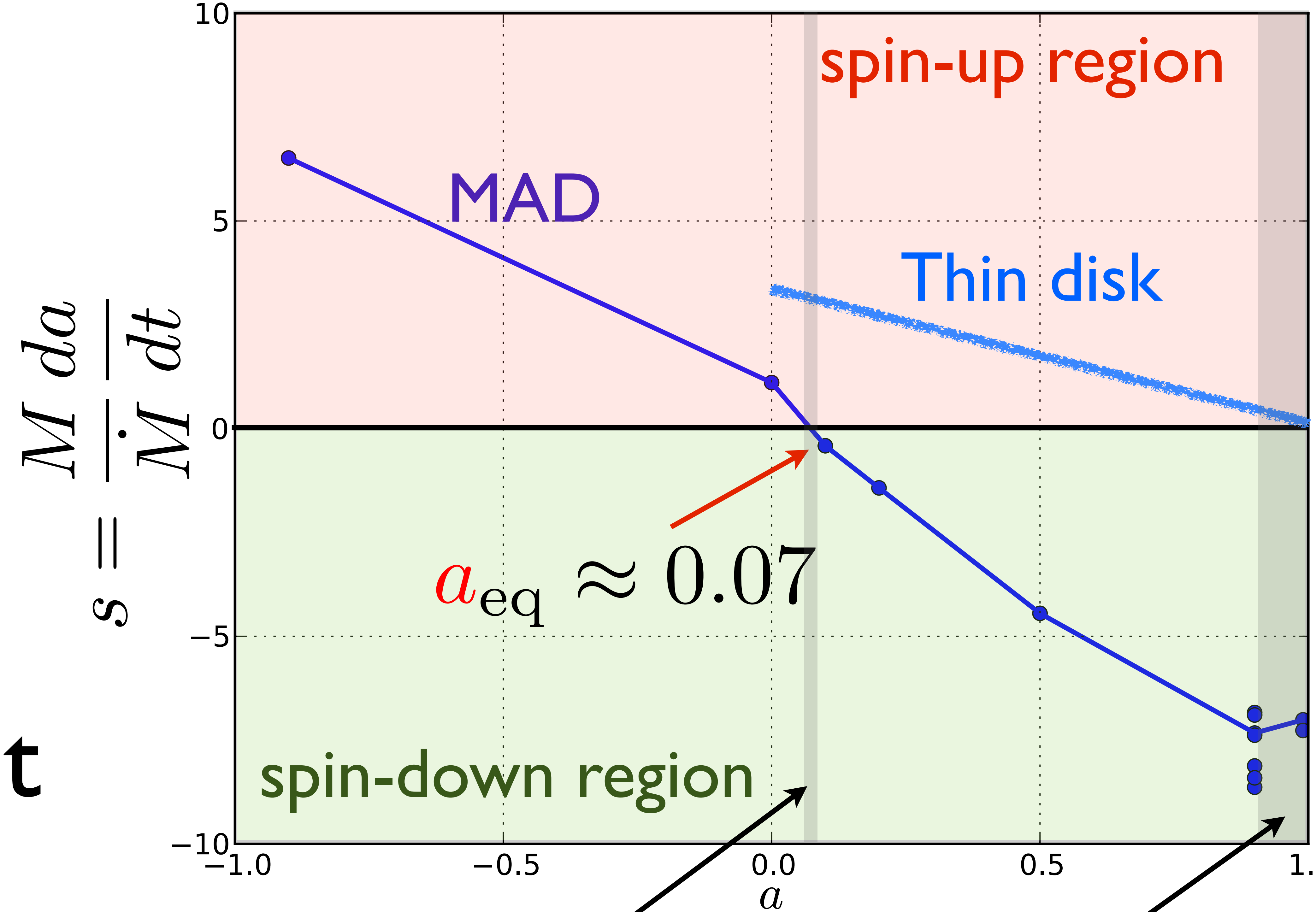

MAD spin equilibrium

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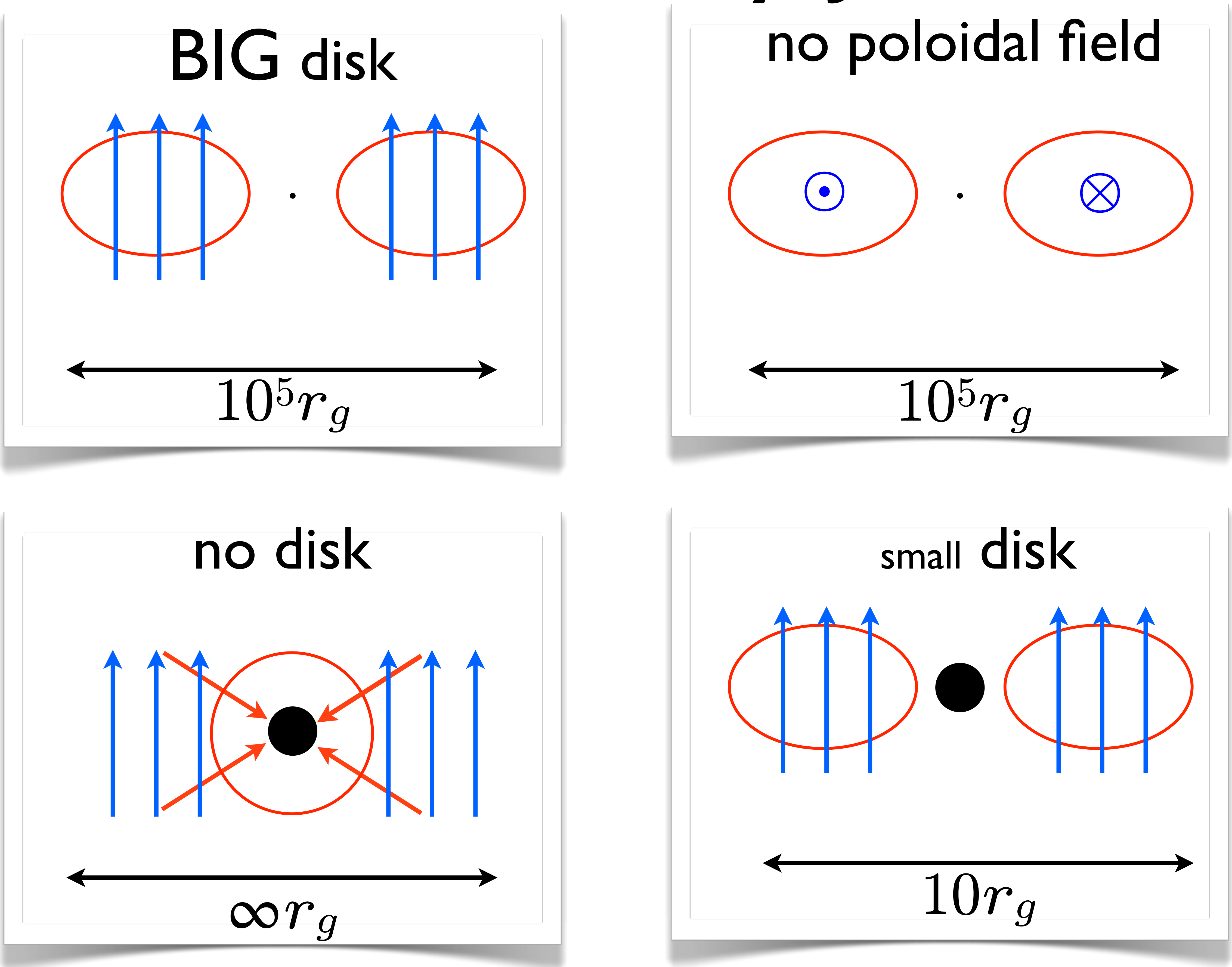
tilted1 2

What is a Healthy Jet Diet?



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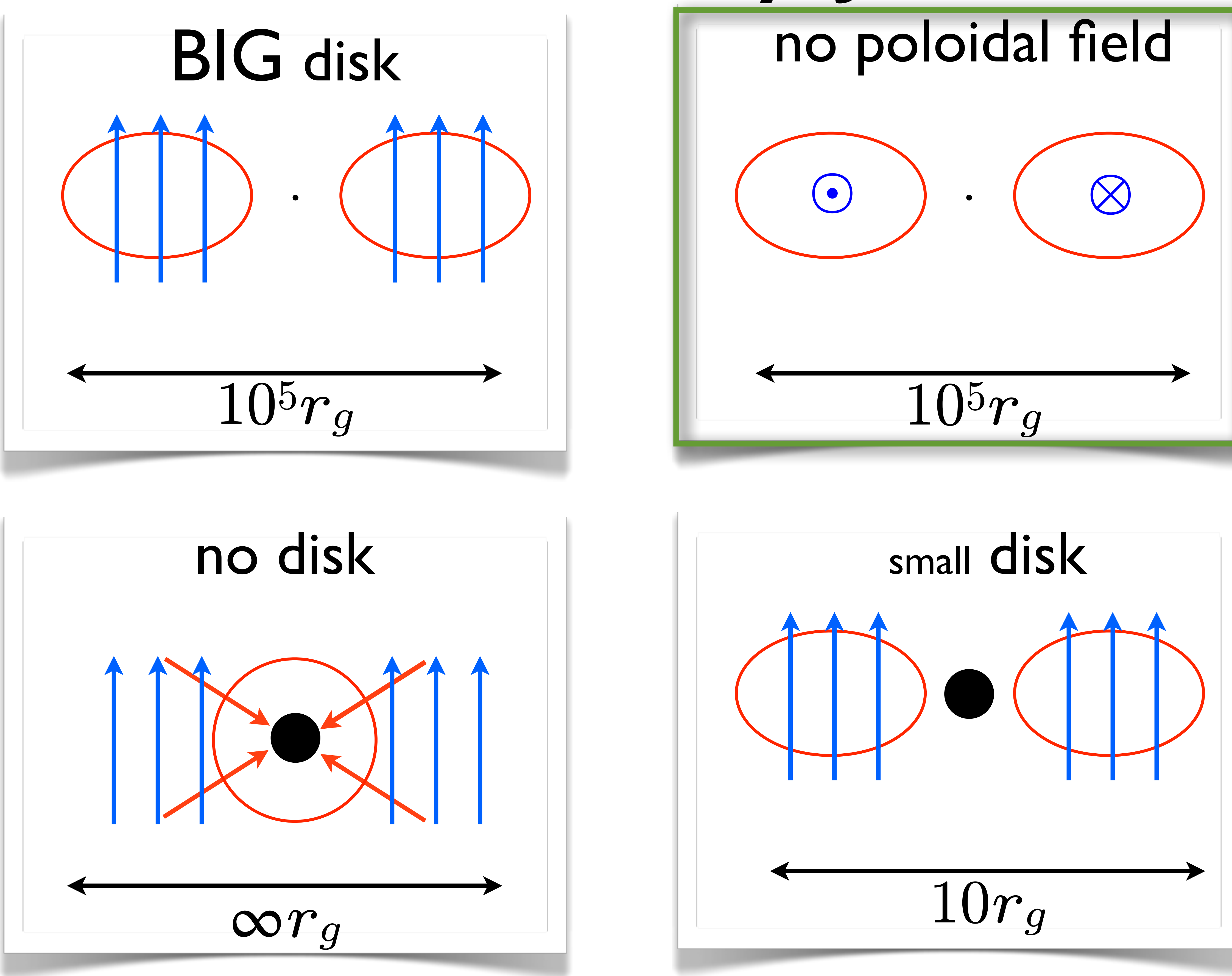
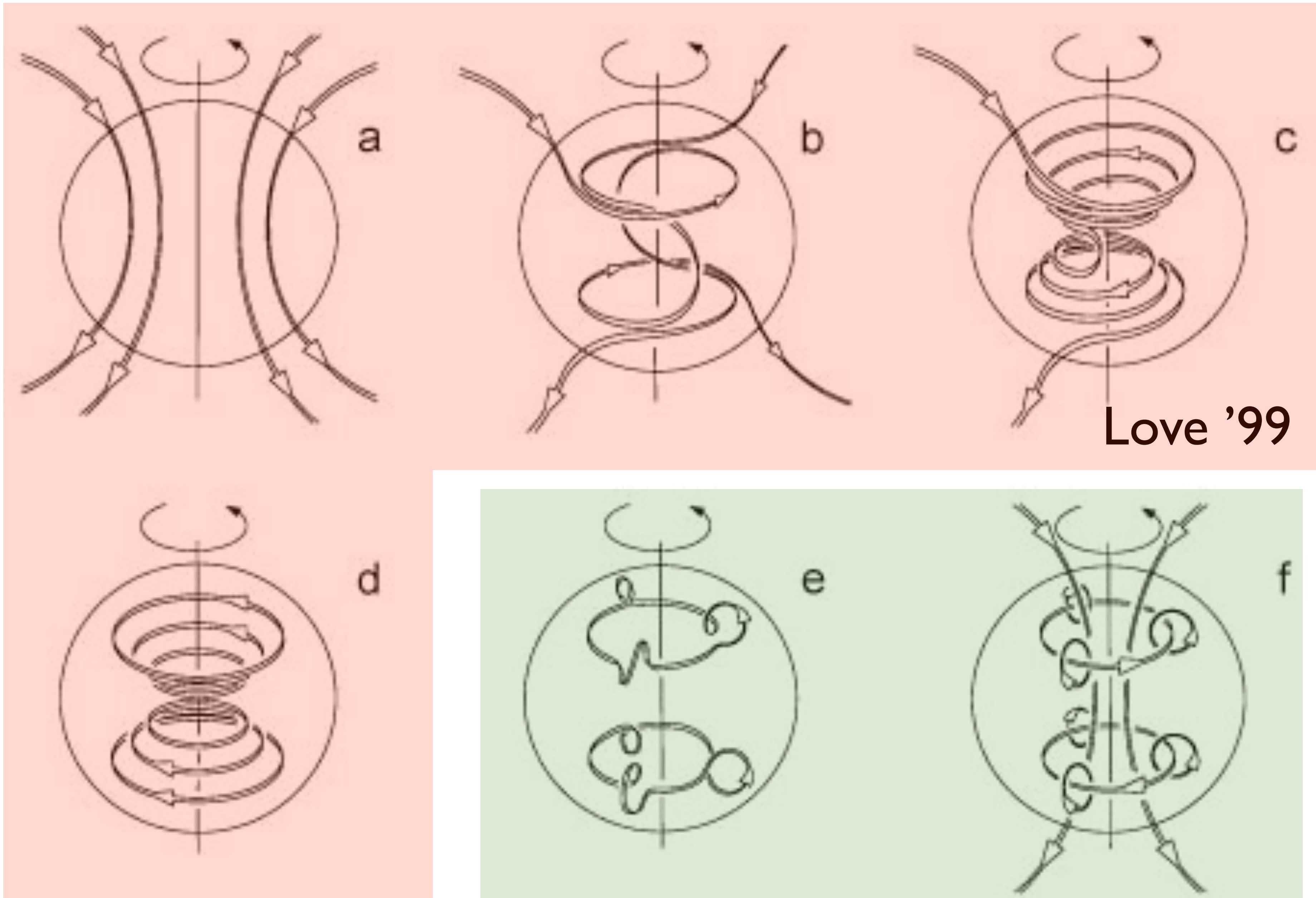


Can Toroidal Fields Make Jets?

- 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

α-ω dynamo:



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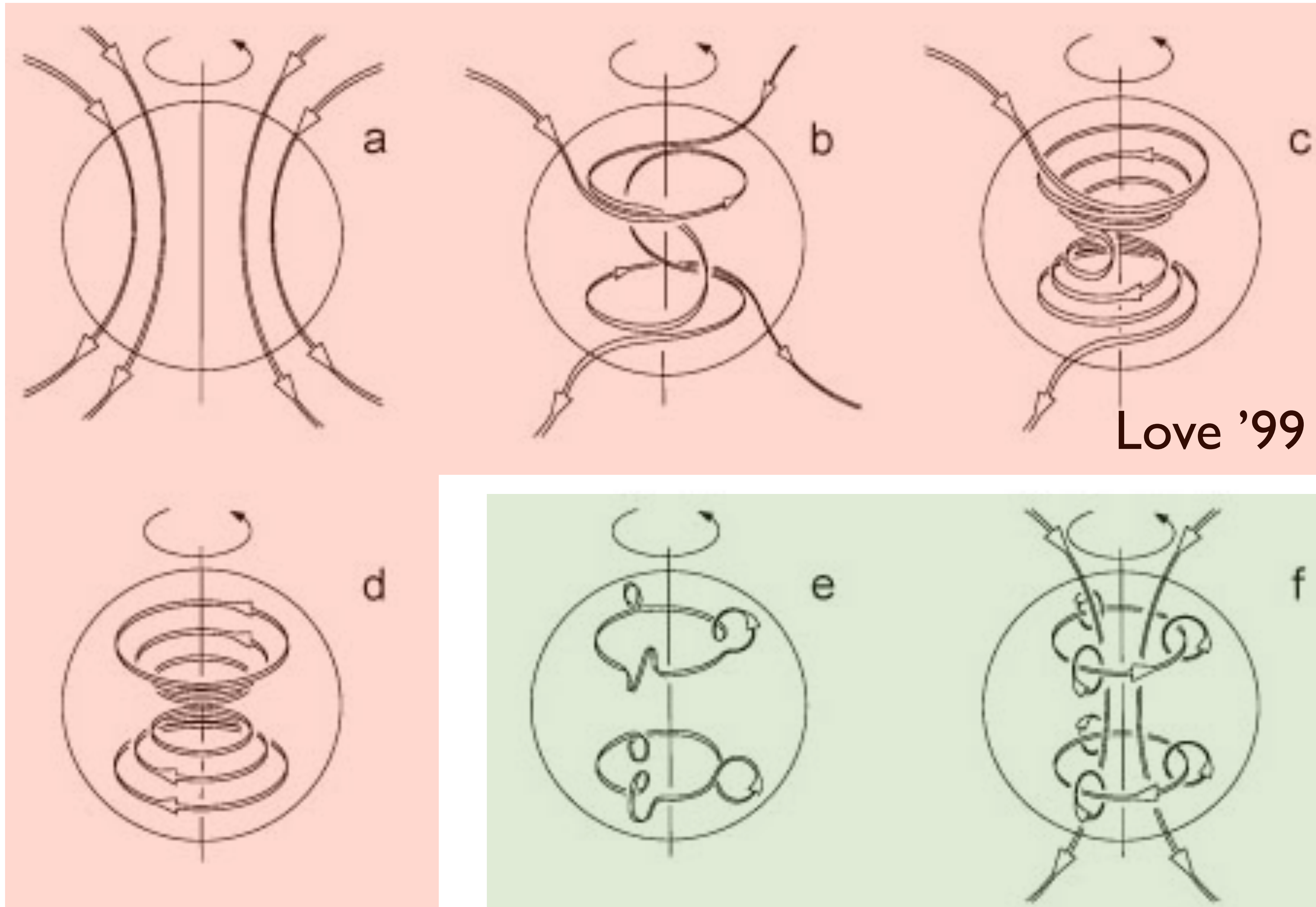
α-ω dynamo:



Love '99

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

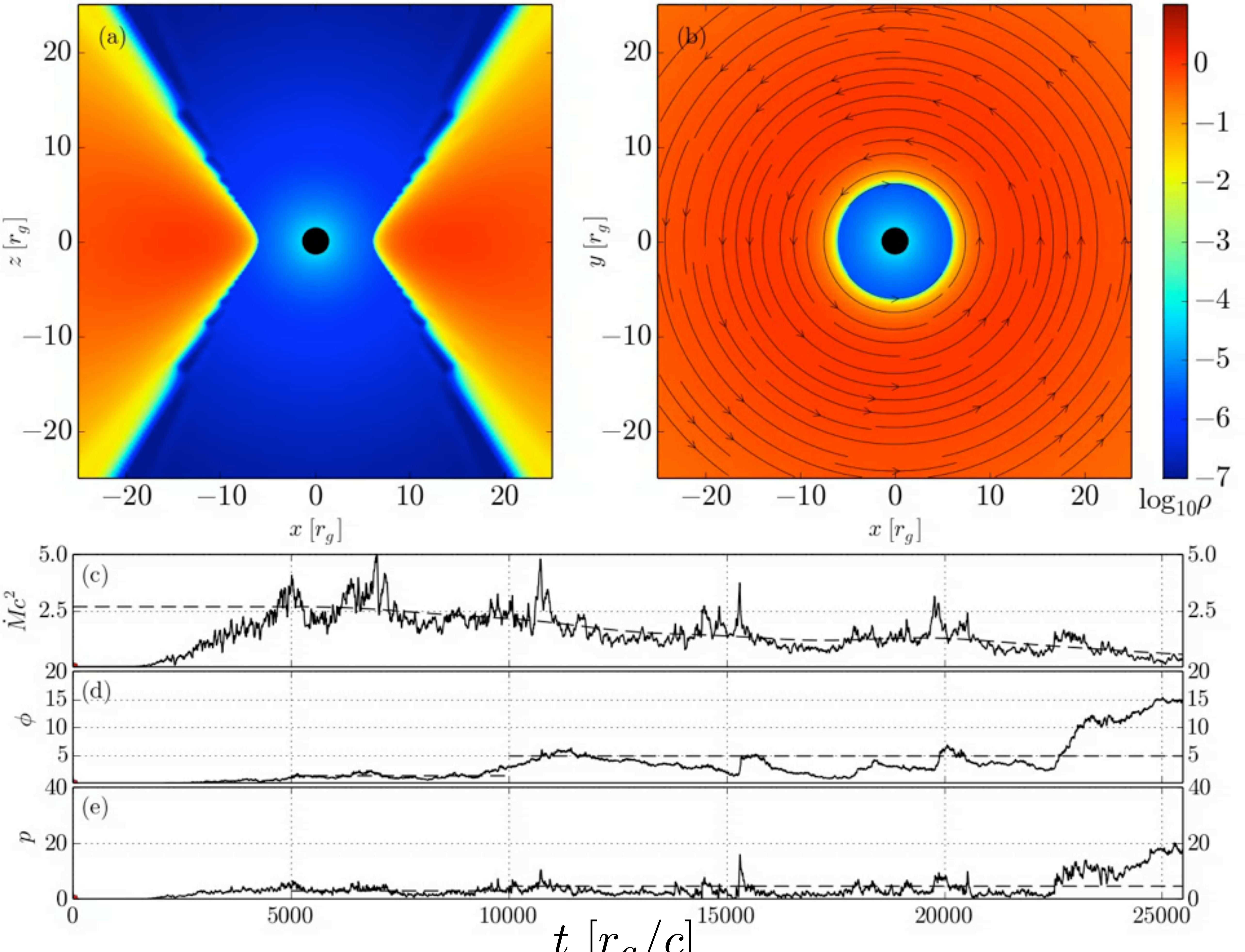
Moffatt '78

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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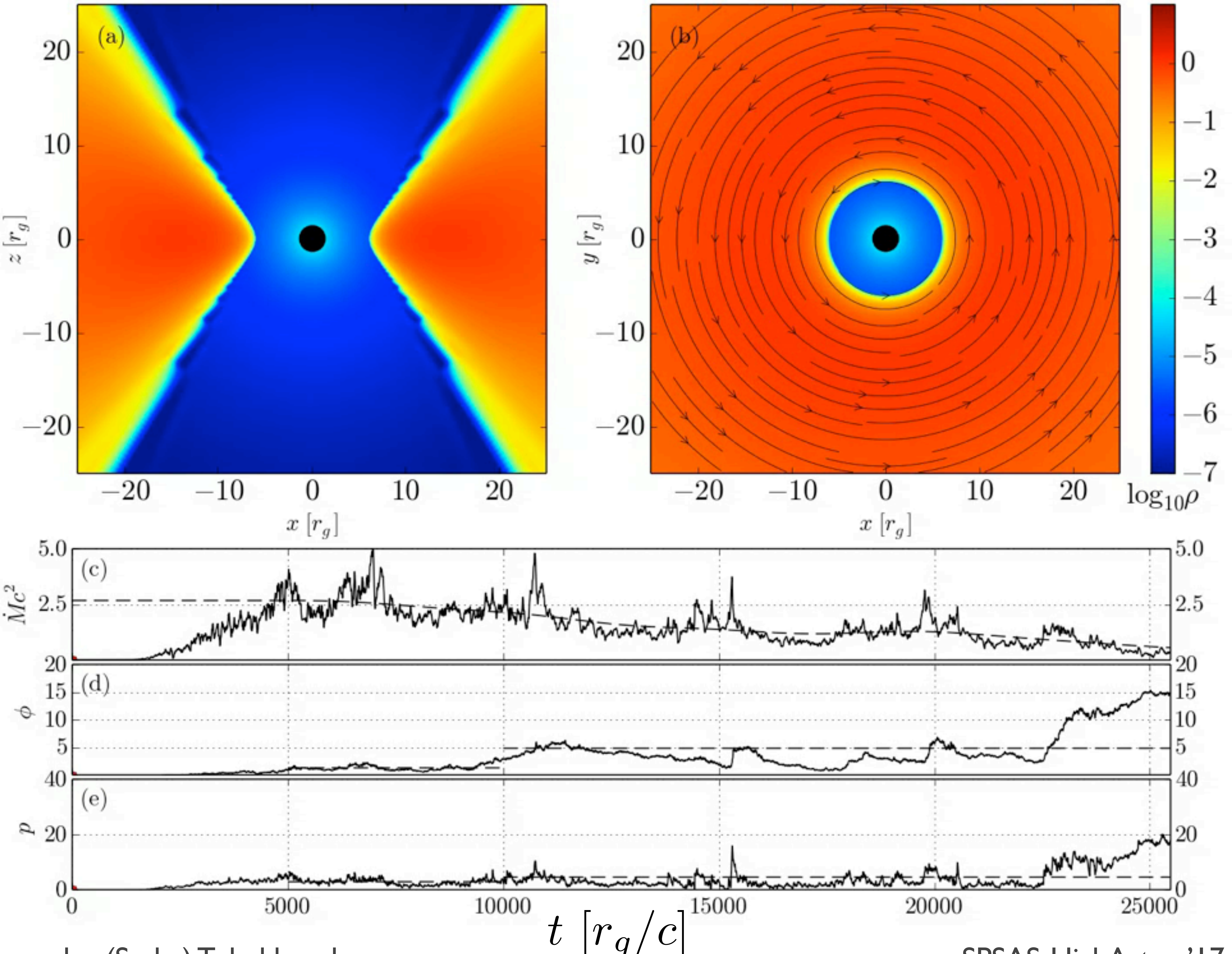

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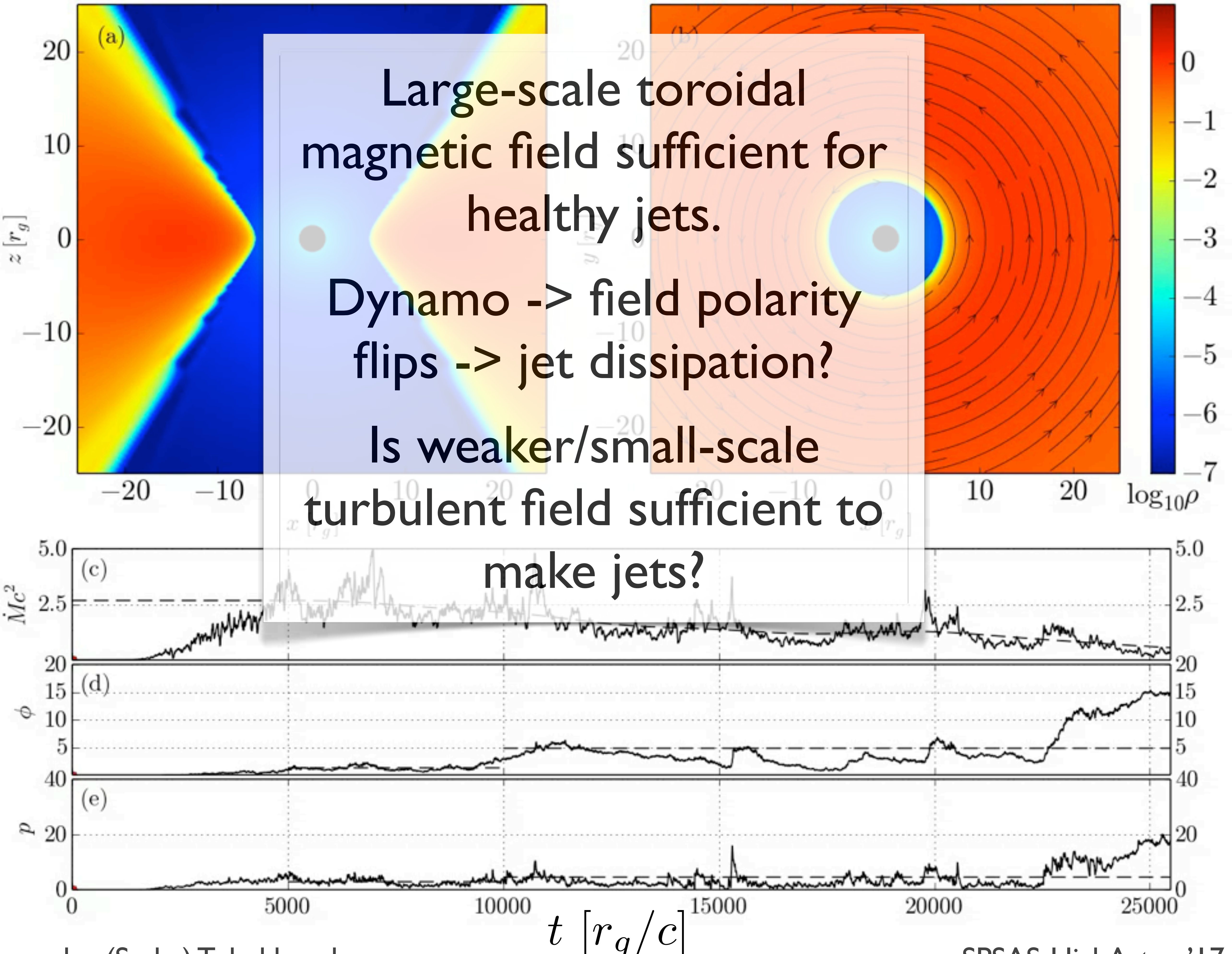

Large-scale toroidal magnetic field sufficient for healthy jets.

Dynamo -> field polarity flips -> jet dissipation?

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

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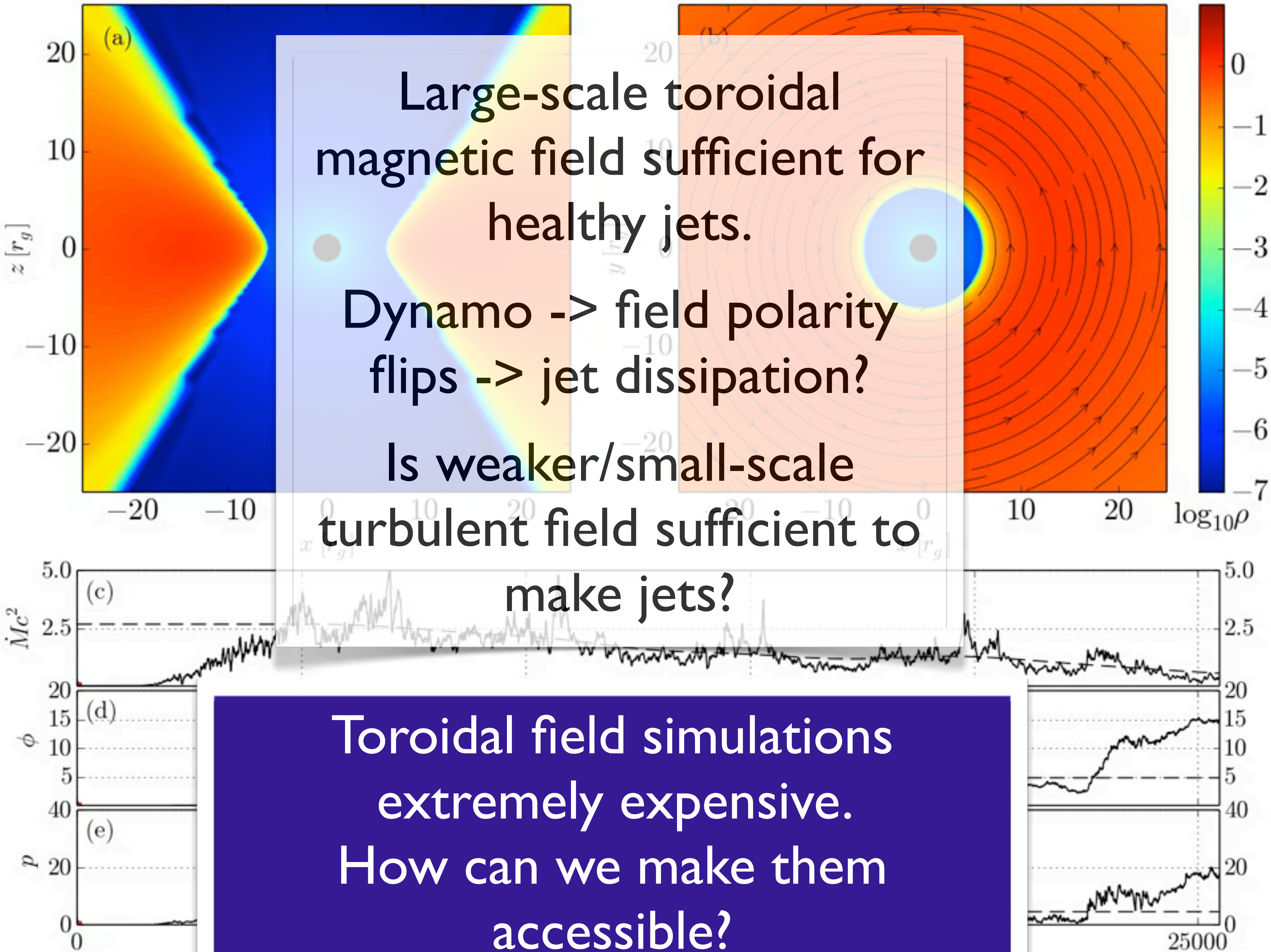

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Toroidal field simulations extremely expensive.
How can we make them accessible?

Practical Tutorial

Why is Simulating Jets Hard?

- Typical AGN jet has $\gamma \sim 10$
- How do you get something to move that fast?
- You need energy! $$\frac{B^2}{8\pi} = \epsilon = \gamma \rho c^2$$
- Set $\frac{B^2}{8\pi} = 10$, then $\rho c^2 = 1$
- 10% error in B^2 means $\Delta\epsilon = 1$, or 100% error in ρc^2!
- This is a *stiff* problem
- We need to minimize errors. How?

Equations of Motion in Conservative Form

Non-relativistic: $$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} = S$$

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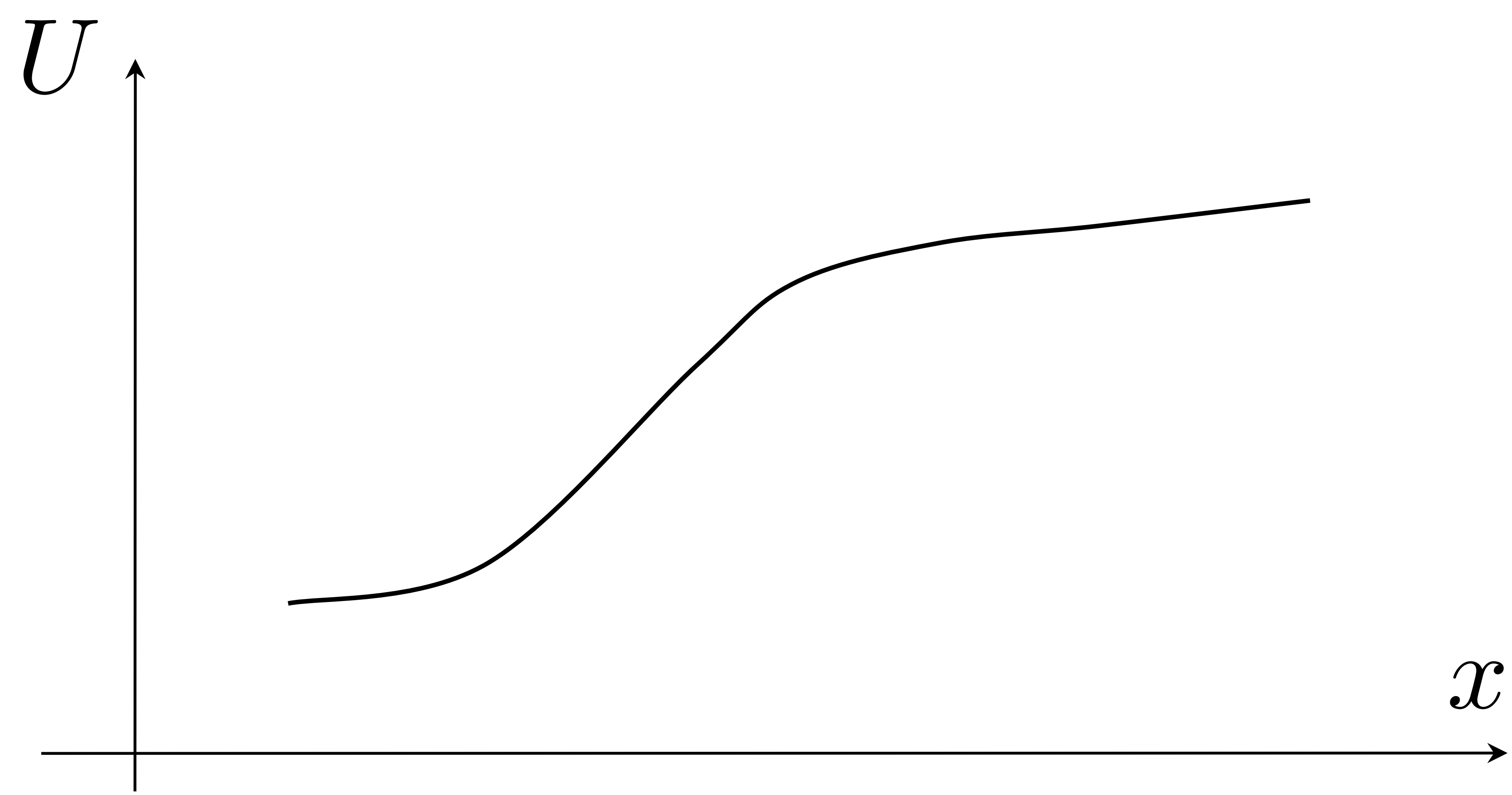
The rest of equations of motion reduce to this form of conservation law as well.

How Do We Put Equations on the Grid?

Conservation law: $$\frac{\partial U}{\partial t} + \frac{\partial F^x}{\partial x} = S$$



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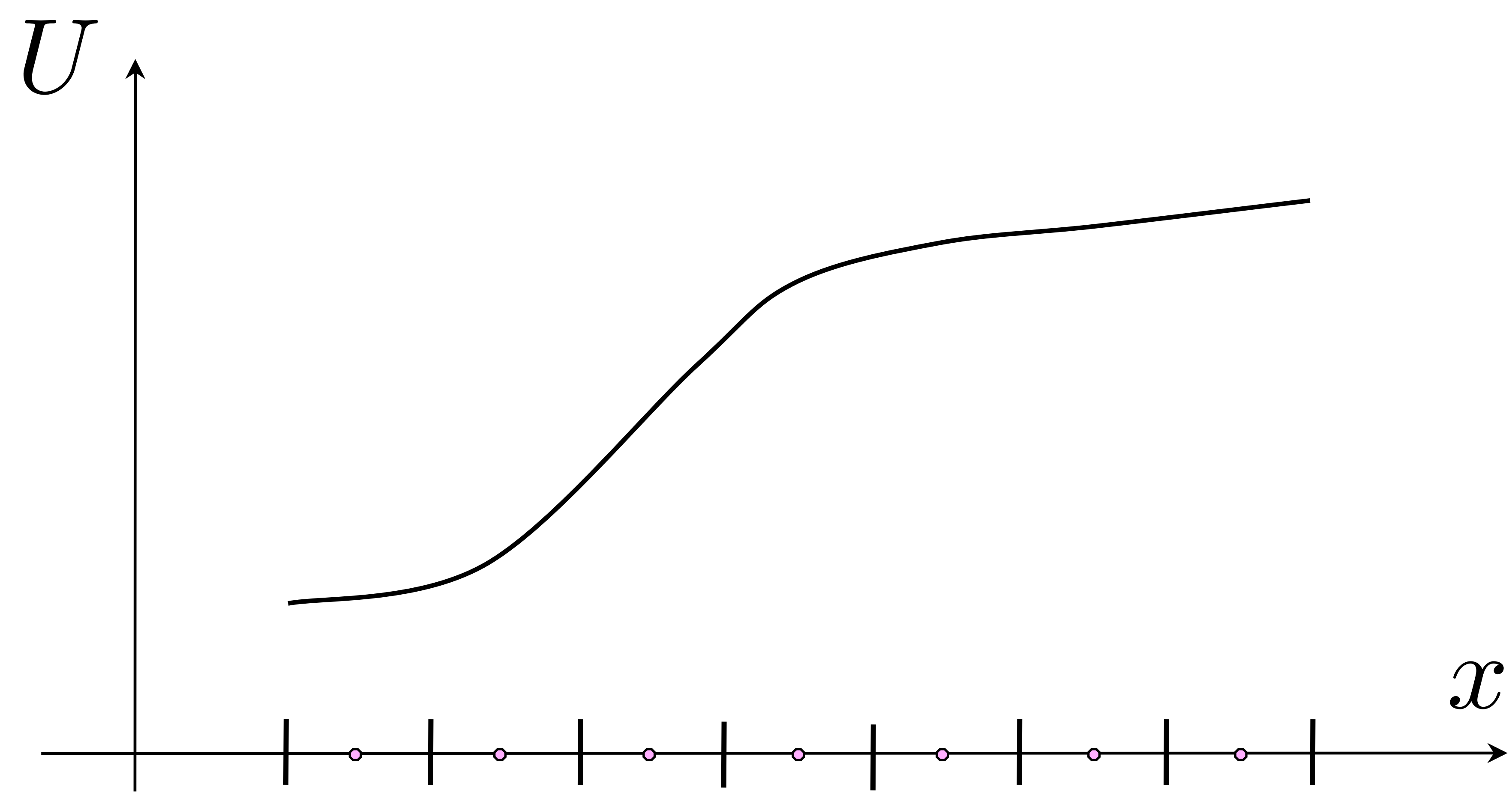

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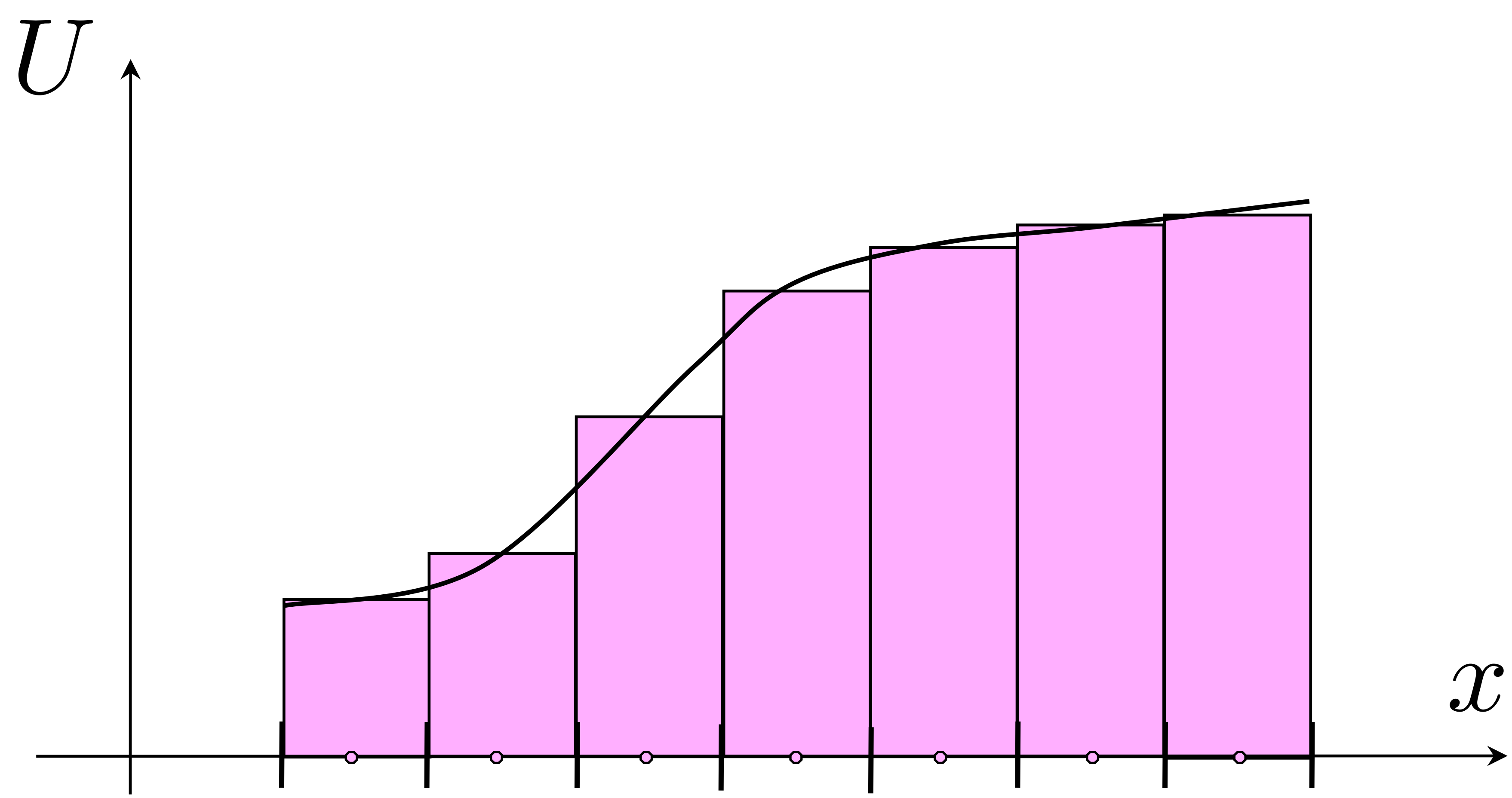

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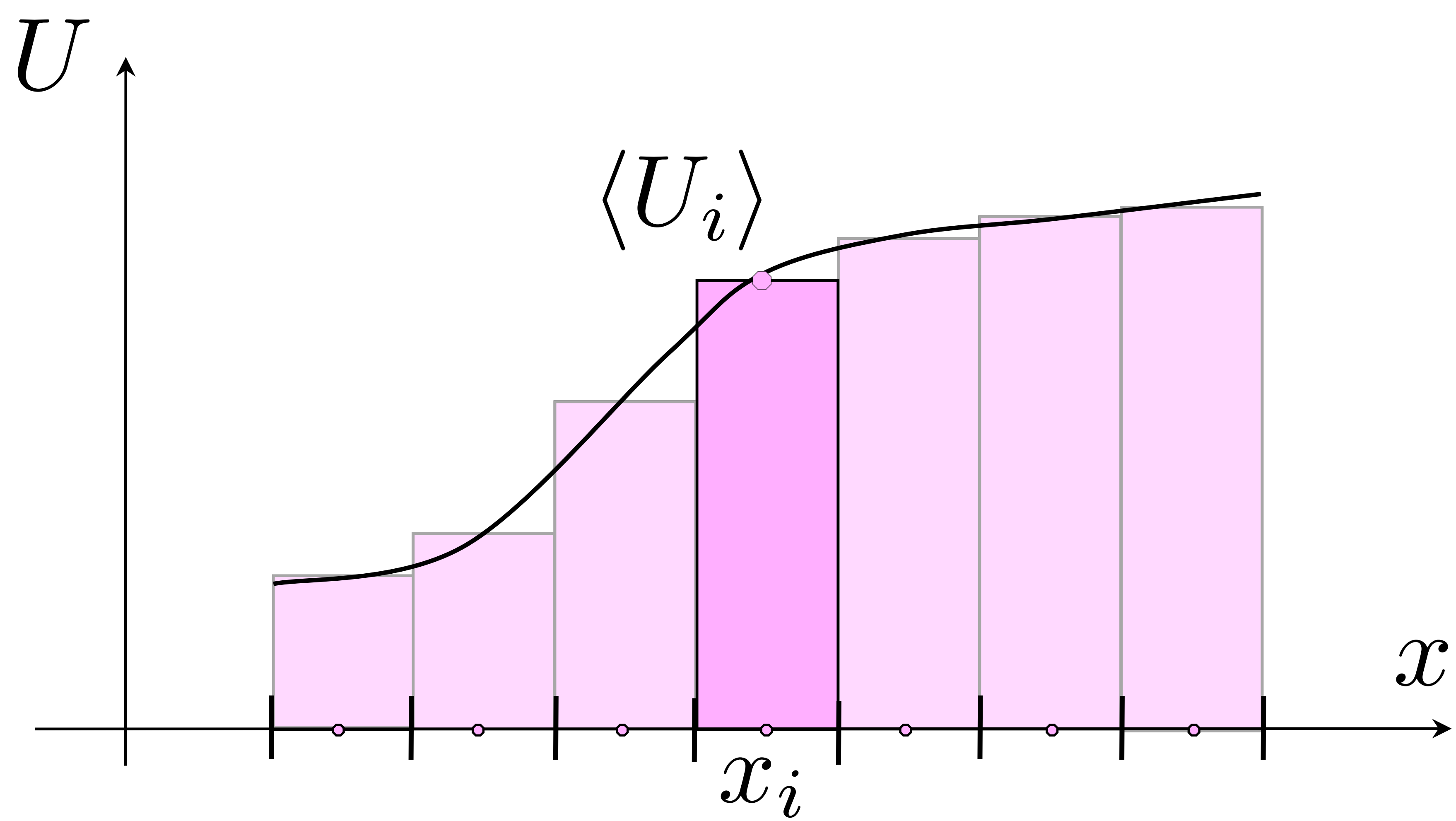

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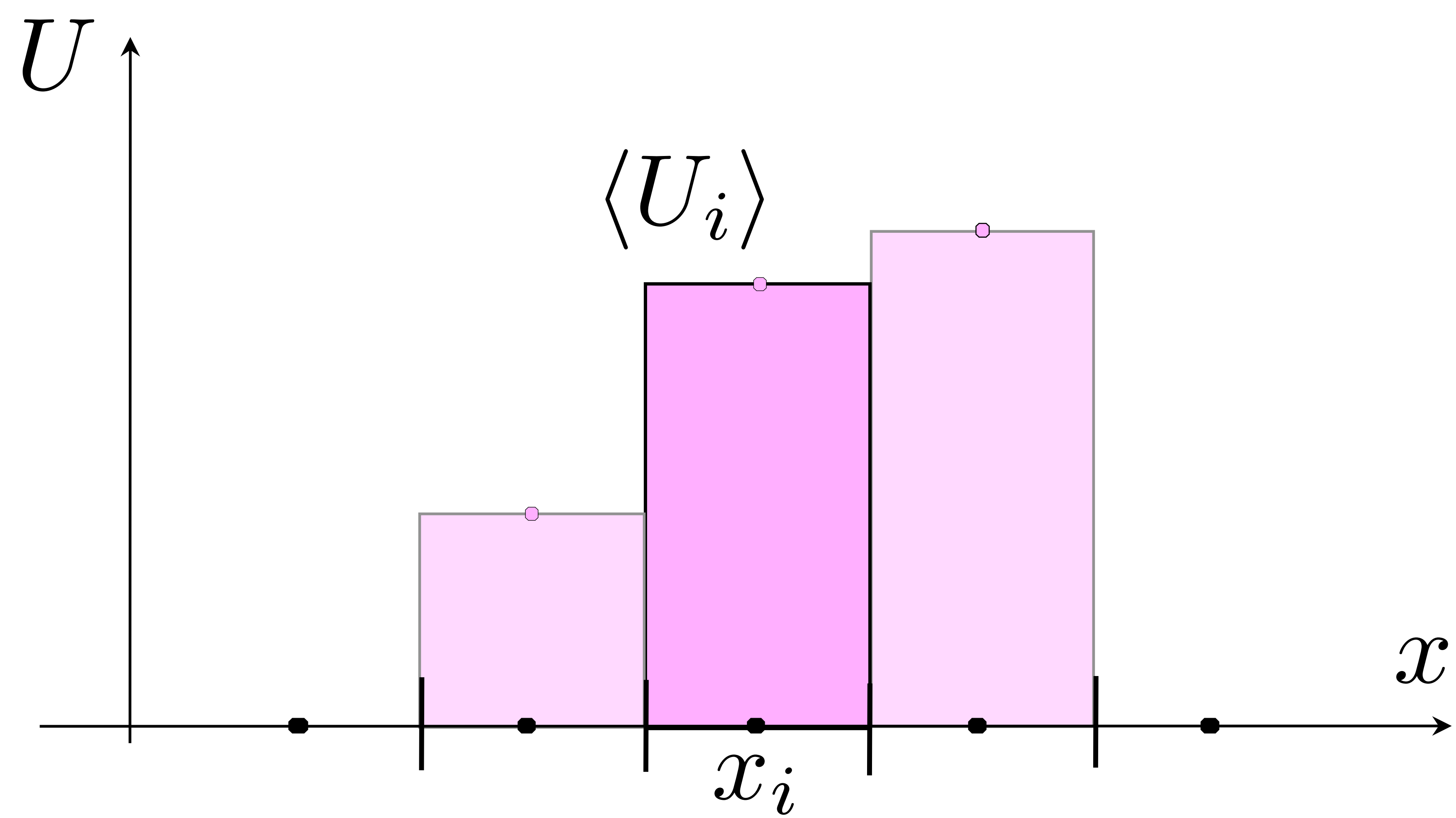

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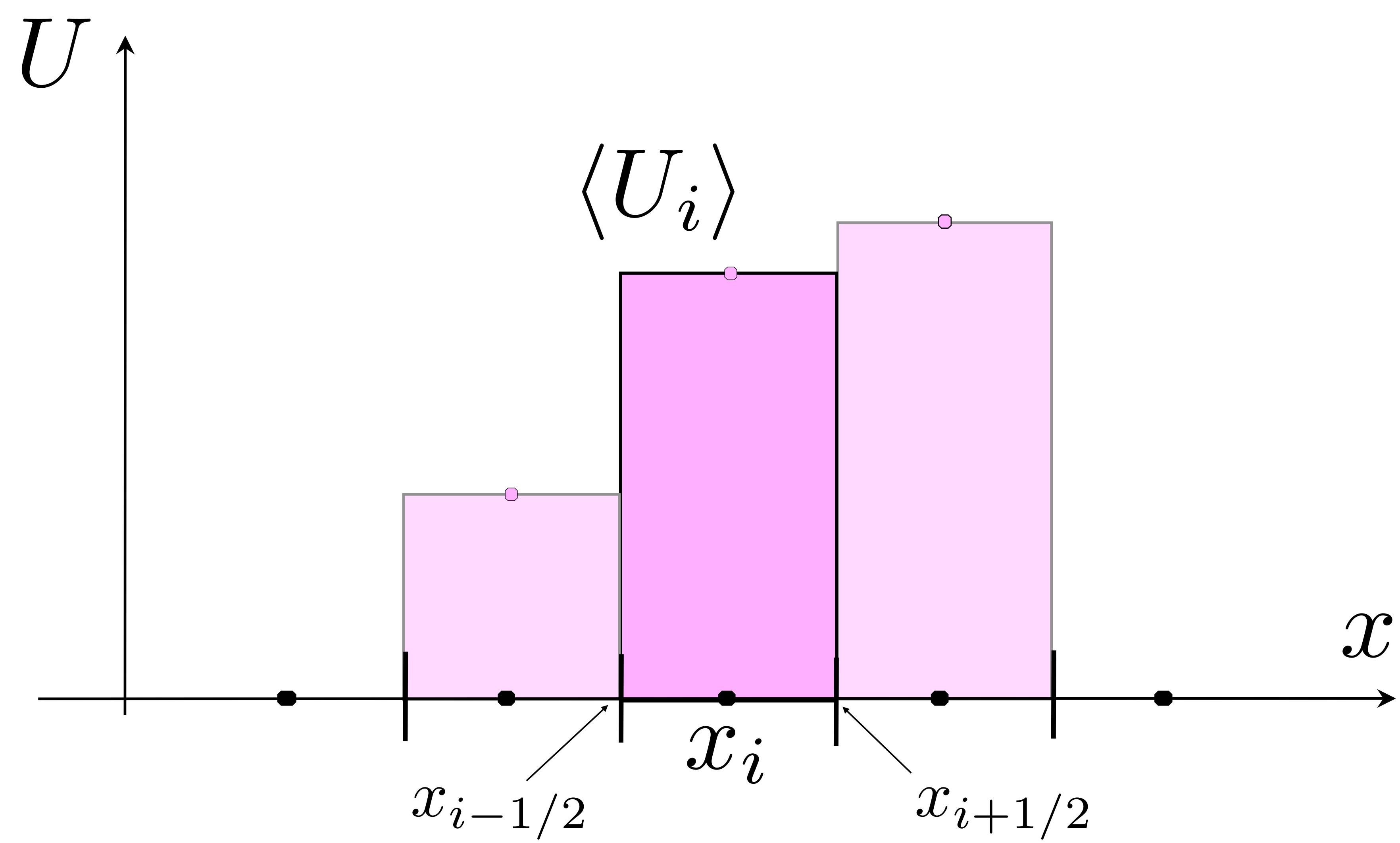

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Conservation law:

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Integrate over the volume of a grid cell:

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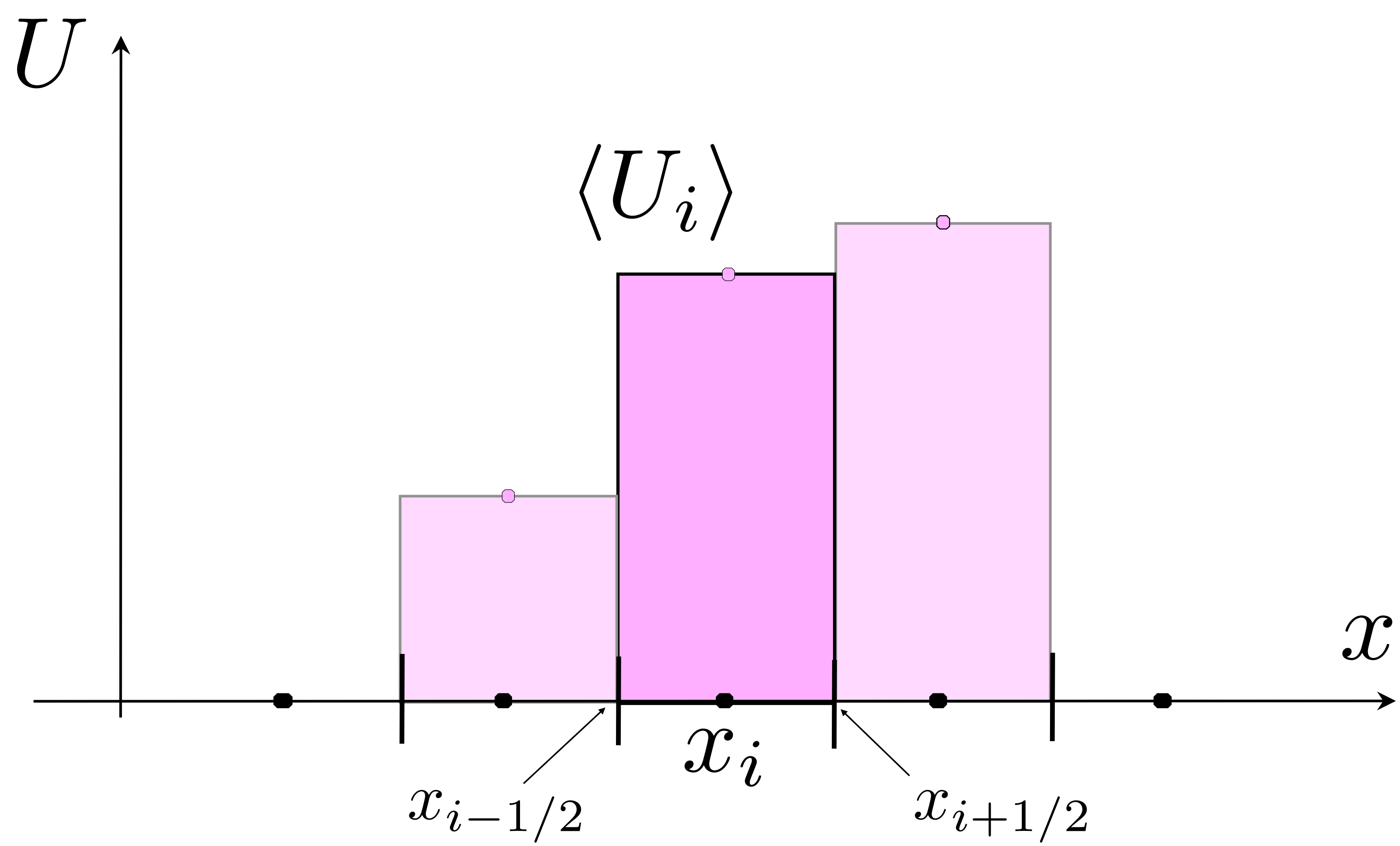

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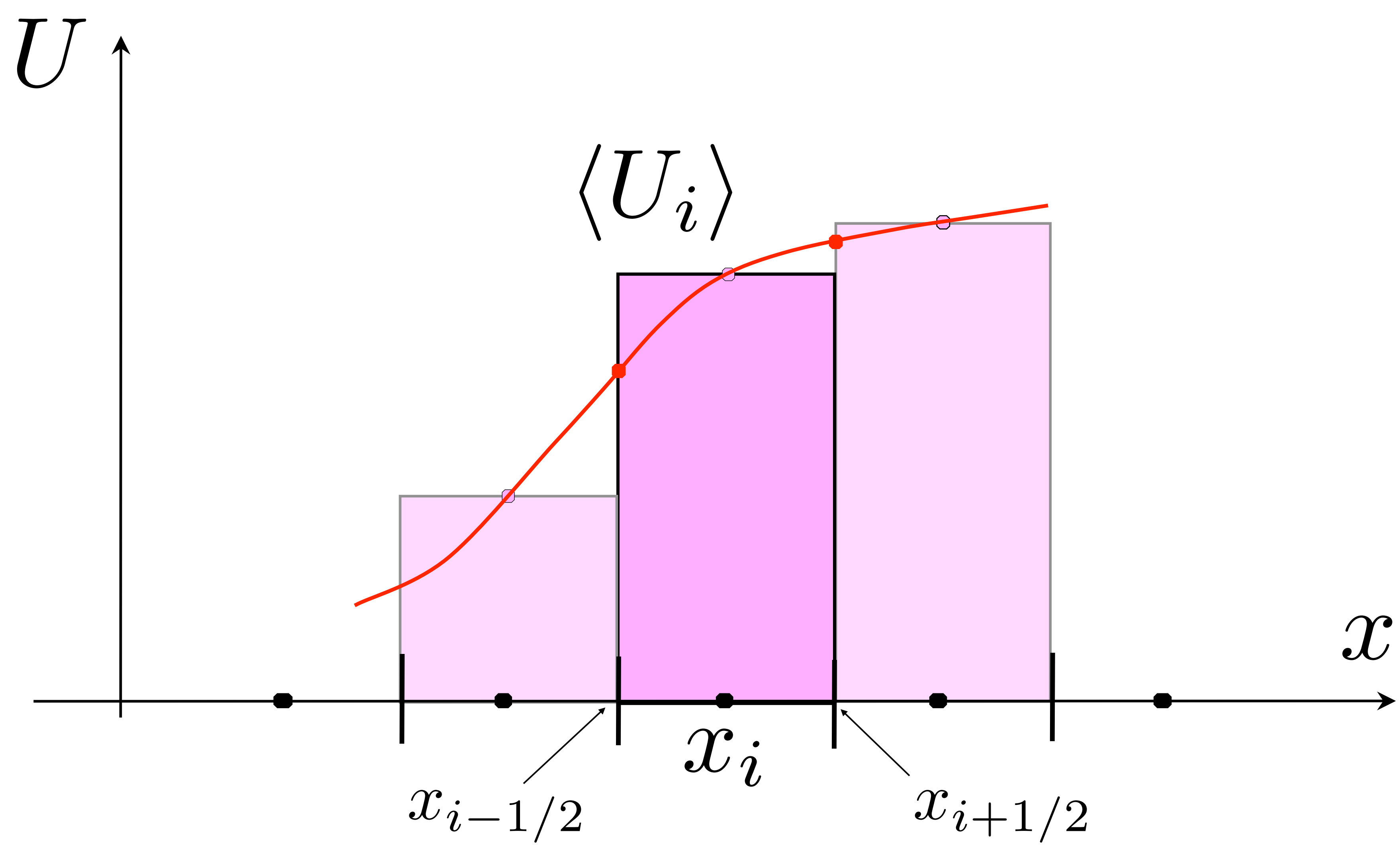
Fit a high-order non-oscillatory polynomial

(e.g., high order schemes possible in GR, e.g., AT+2007)



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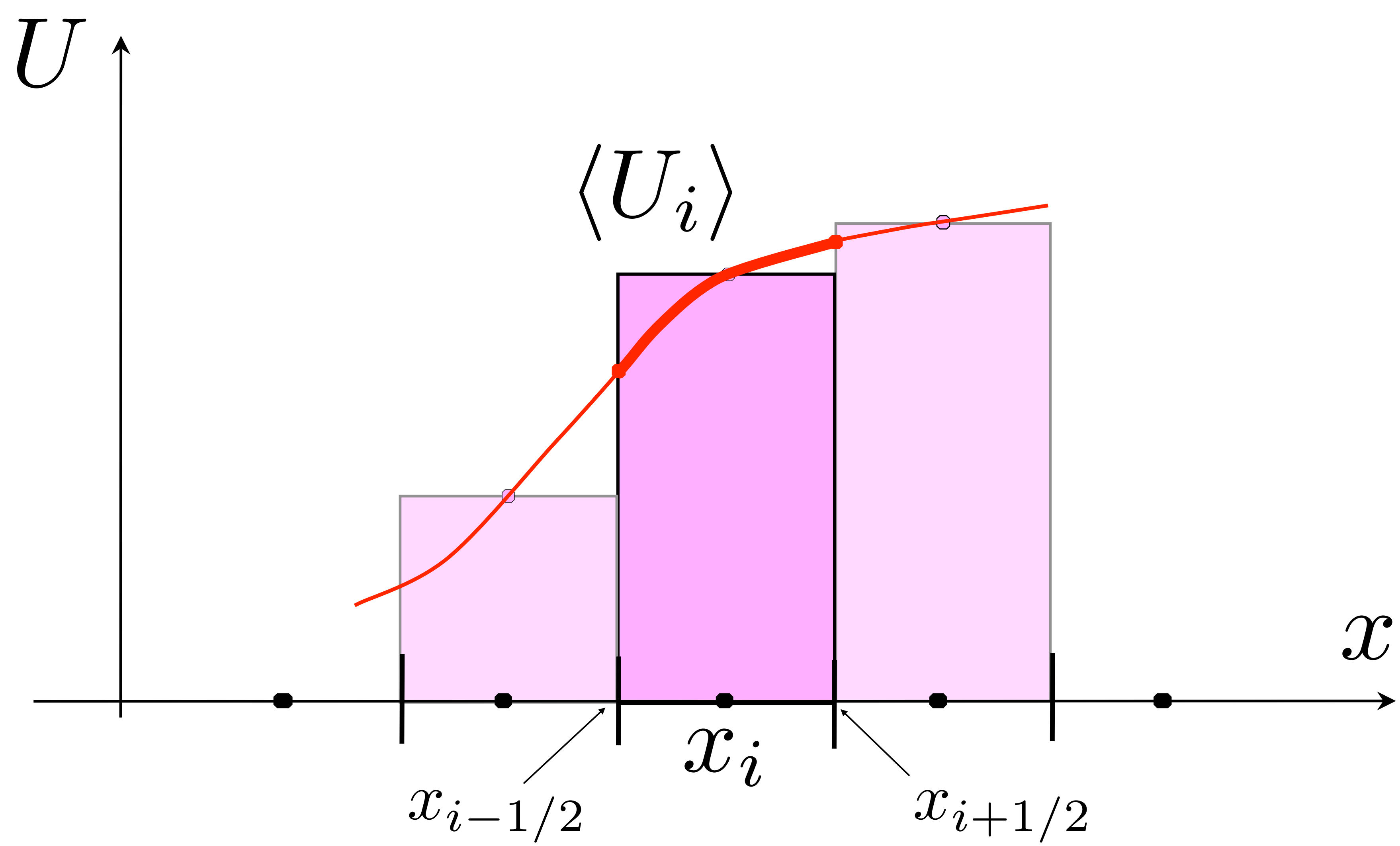

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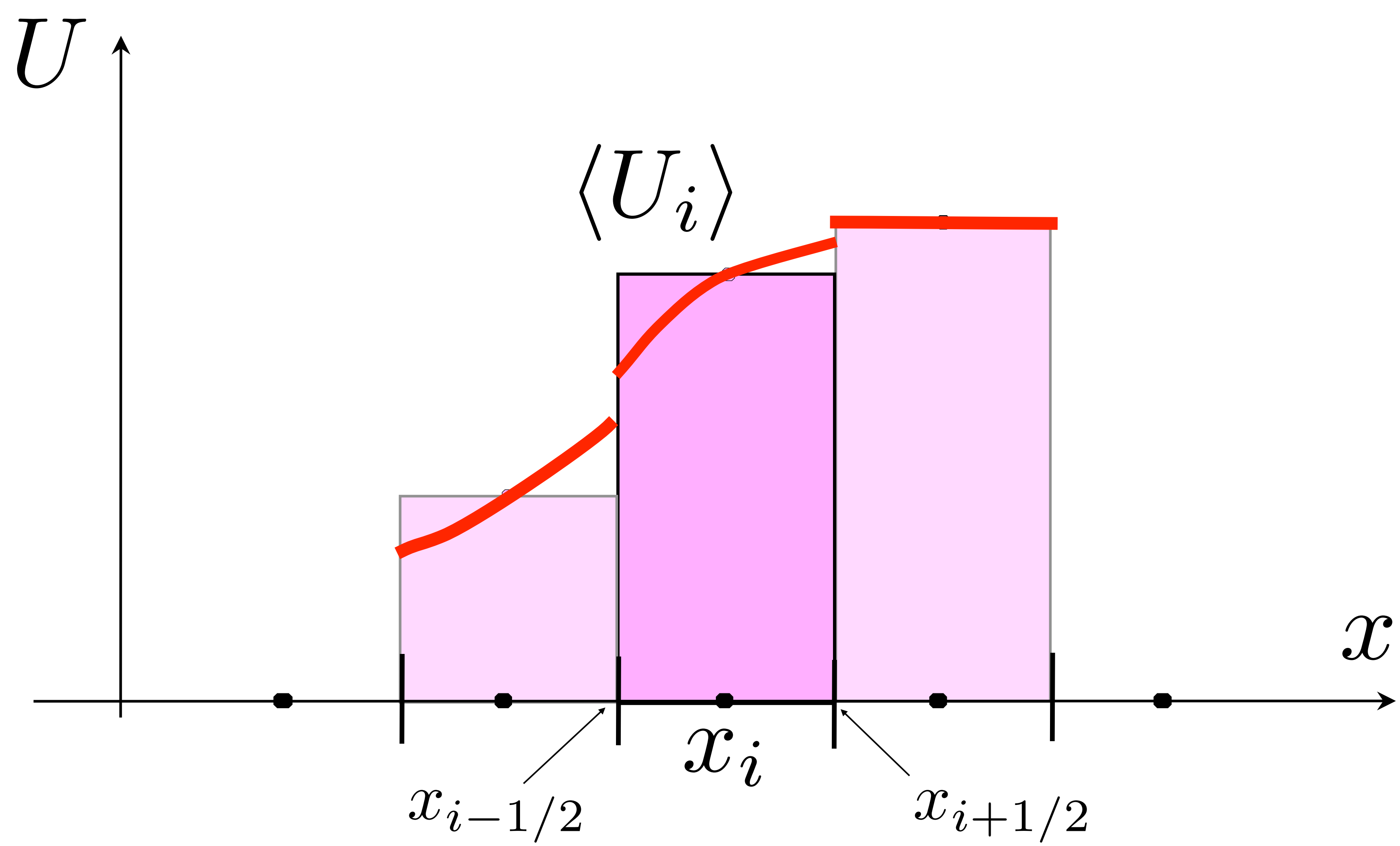

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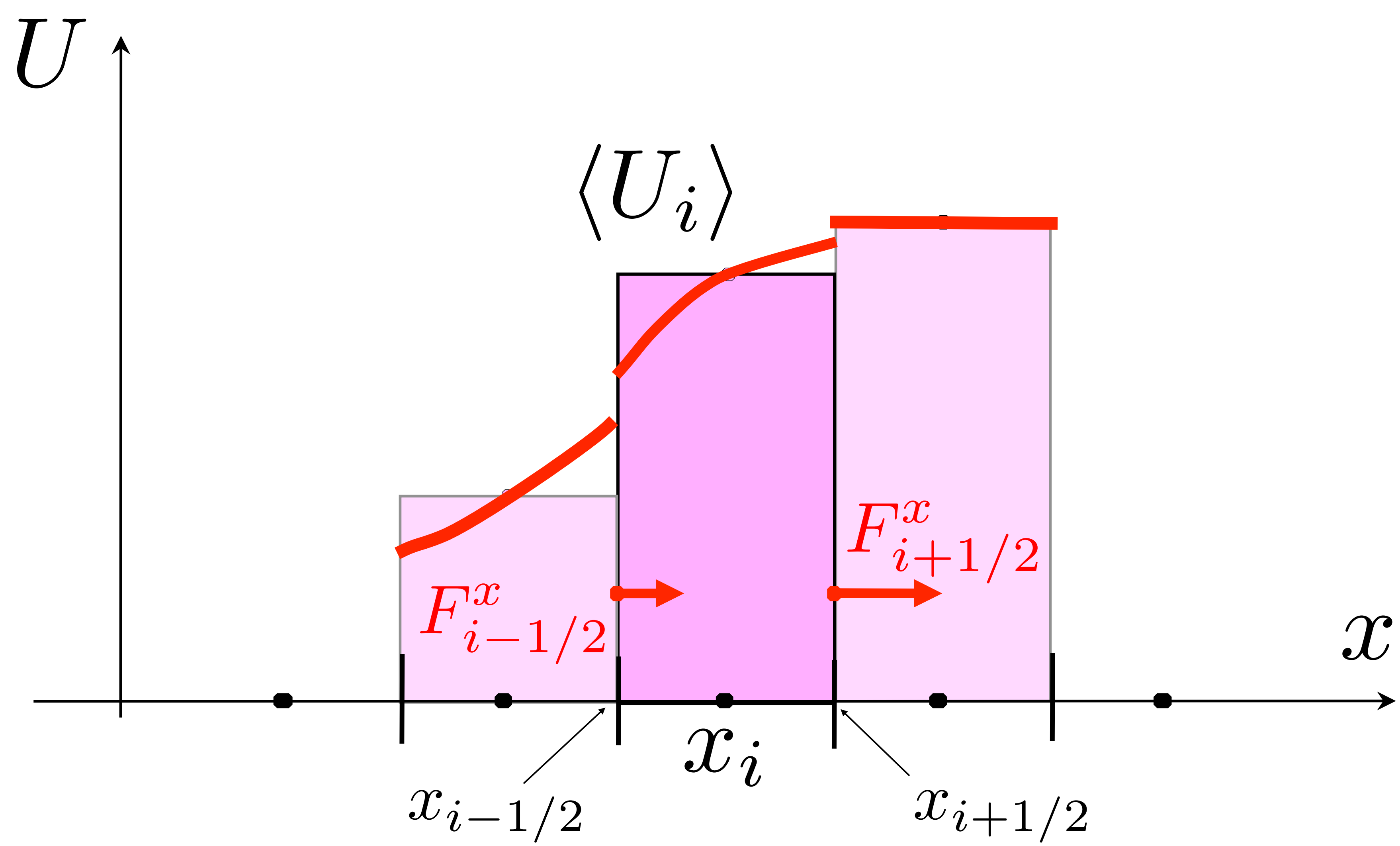

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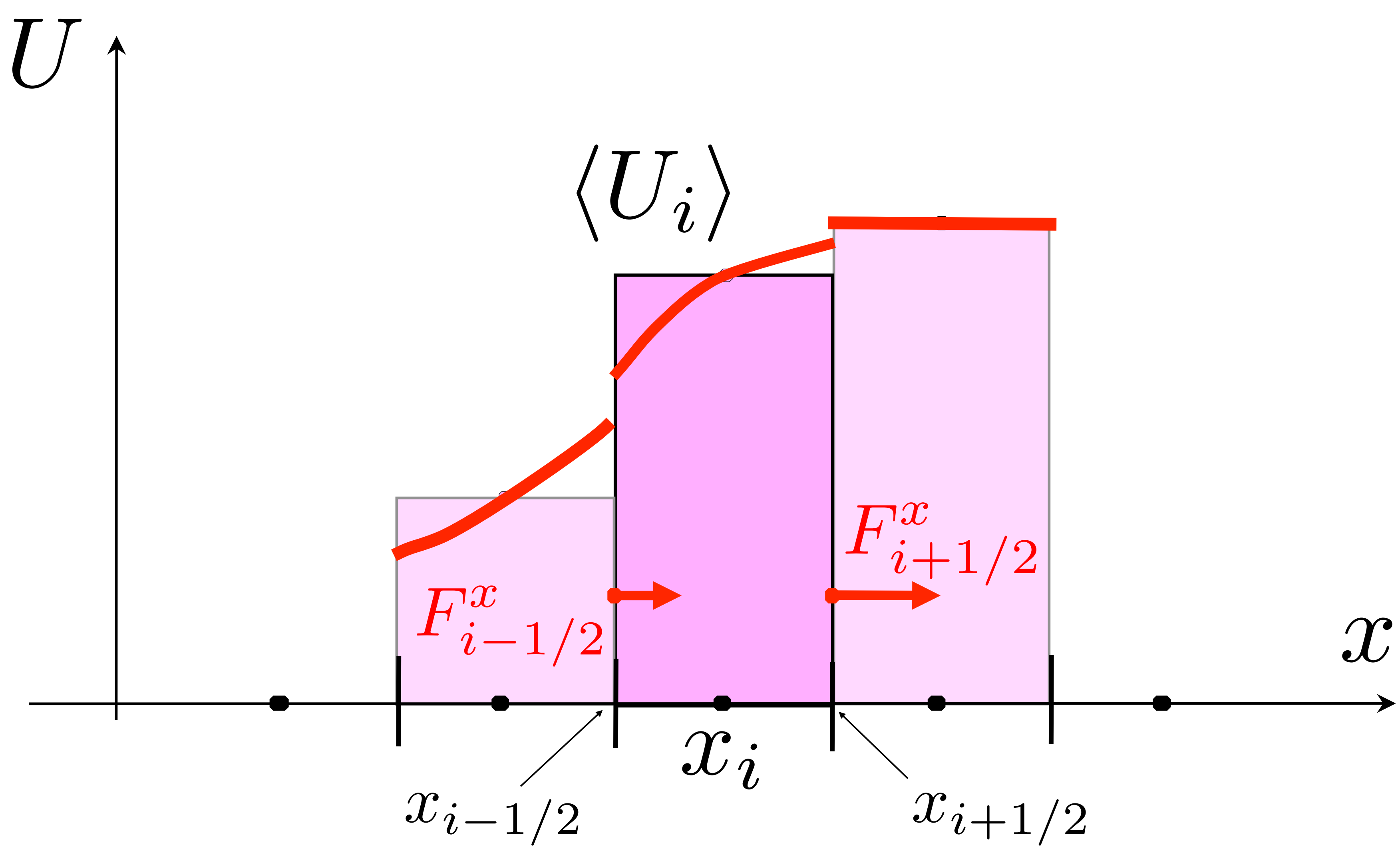
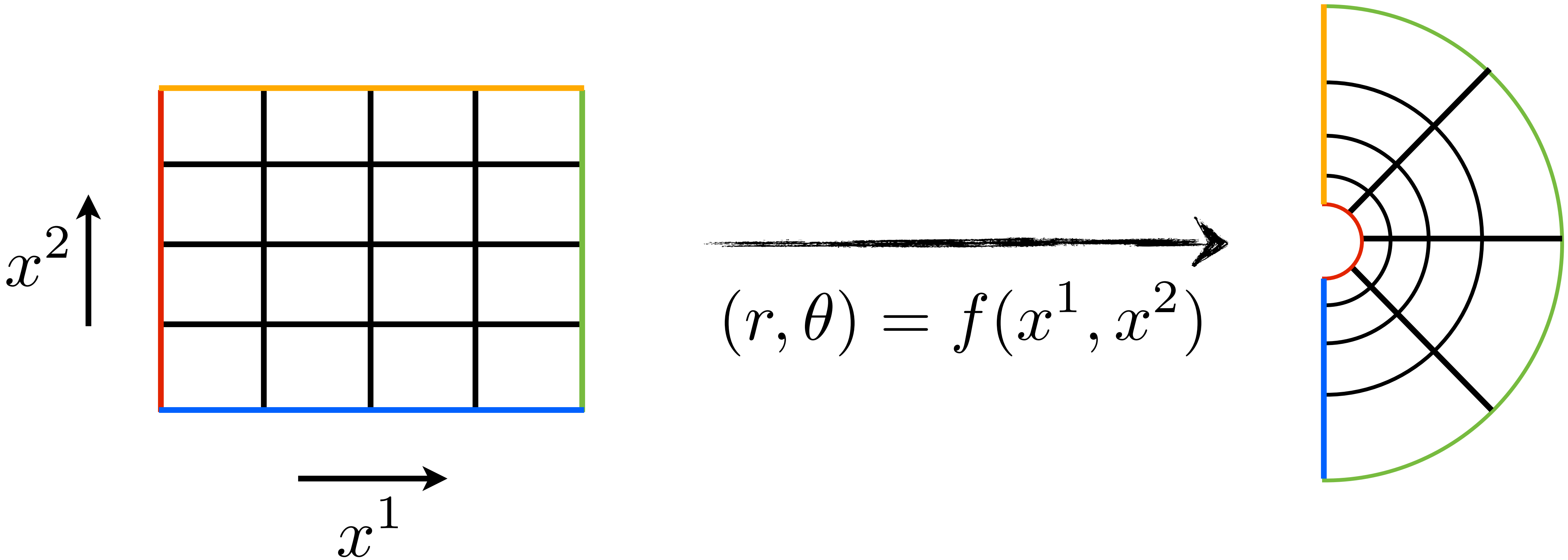
Compute $\Delta \langle U_i \rangle$



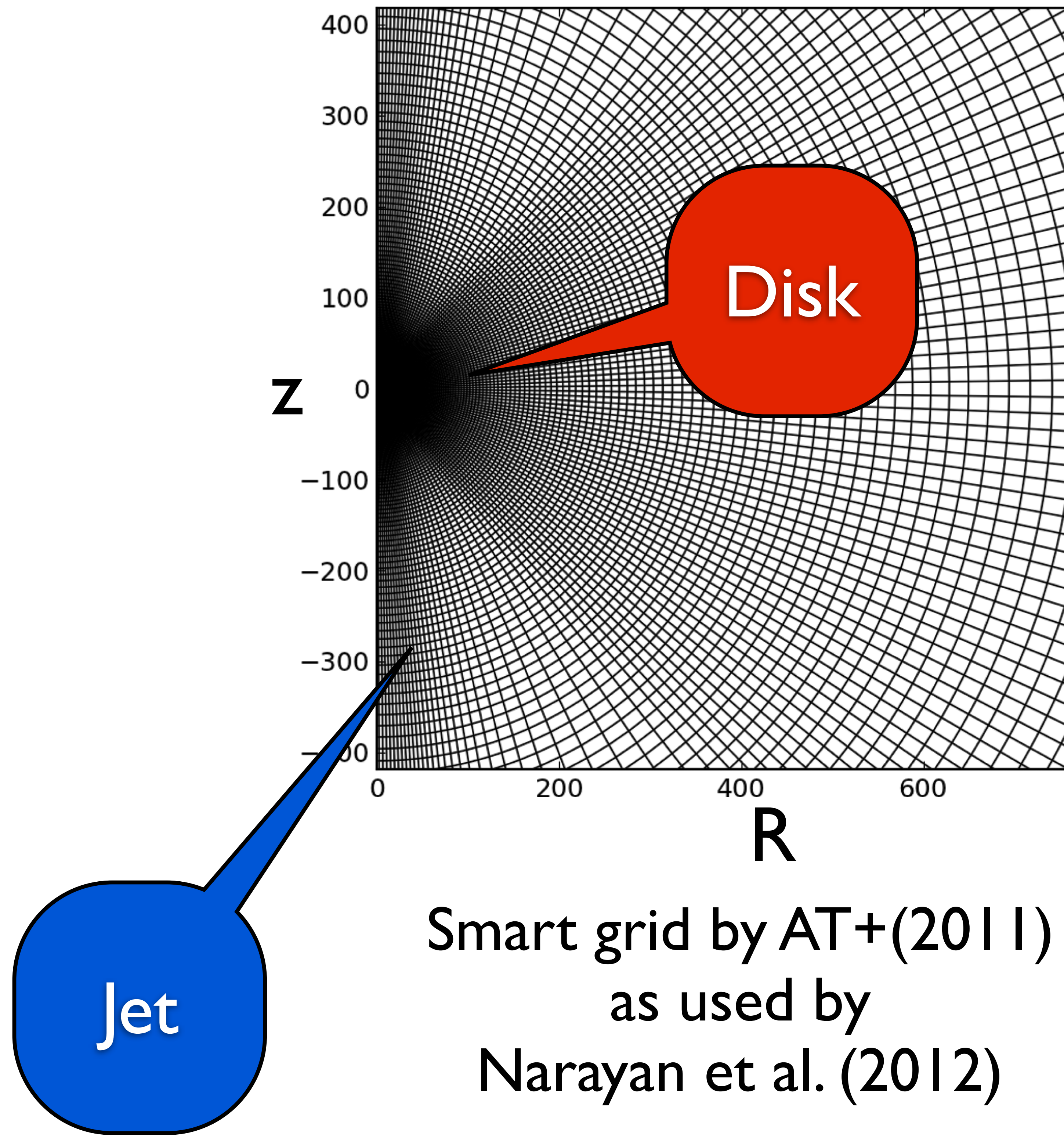
Flexible Grid: Concentrate Resolution where Needed



We can concentrate resolution in regions of interest by choosing an appropriate mapping f.

Literally flexible: grid can be curved or non-uniform, to conform to the shape of the boundary or geometry of the problem.

Smart Grid that Focuses Resolution on Disk and Jet



Smart grid by AT+(2011)
as used by
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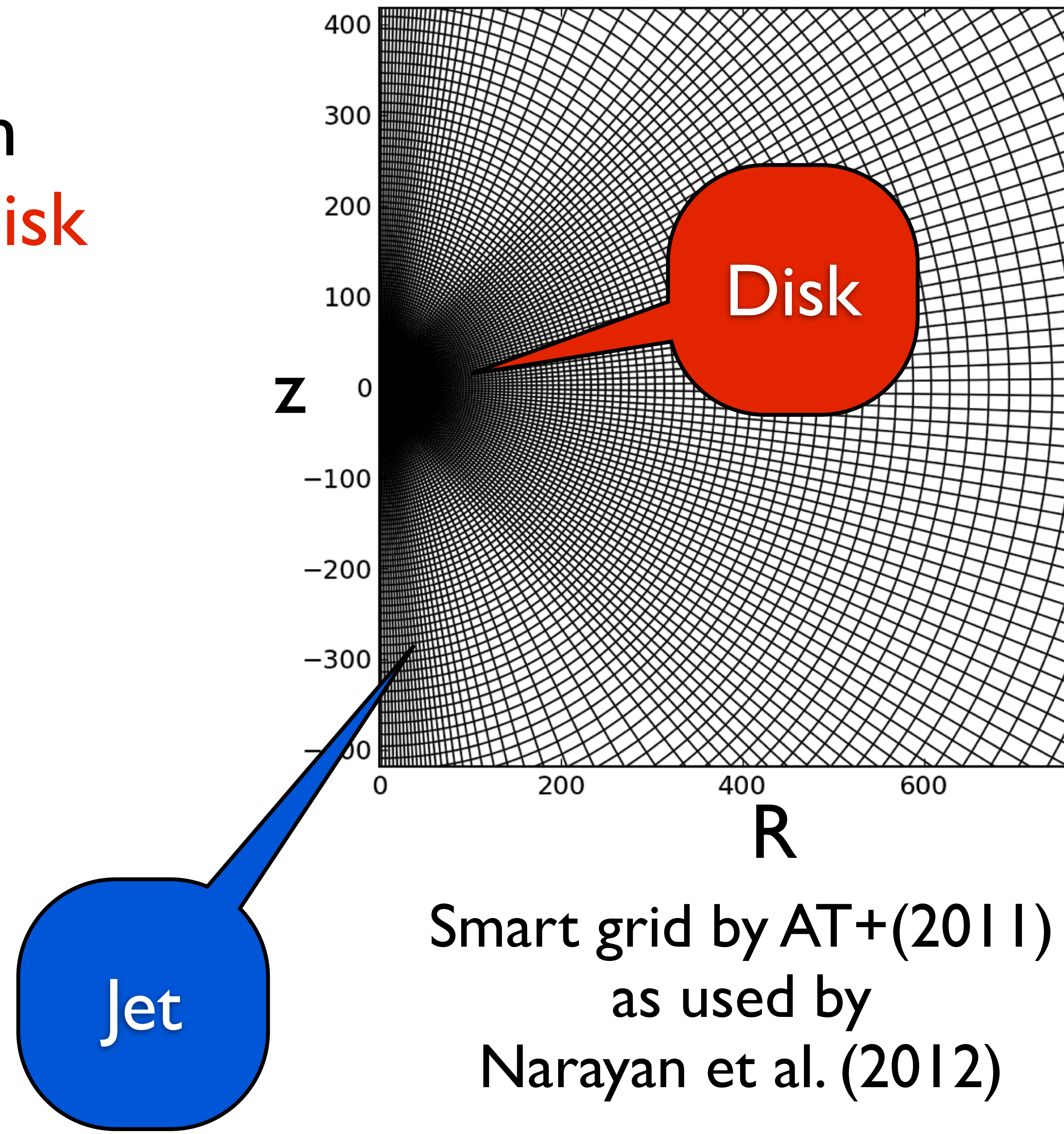

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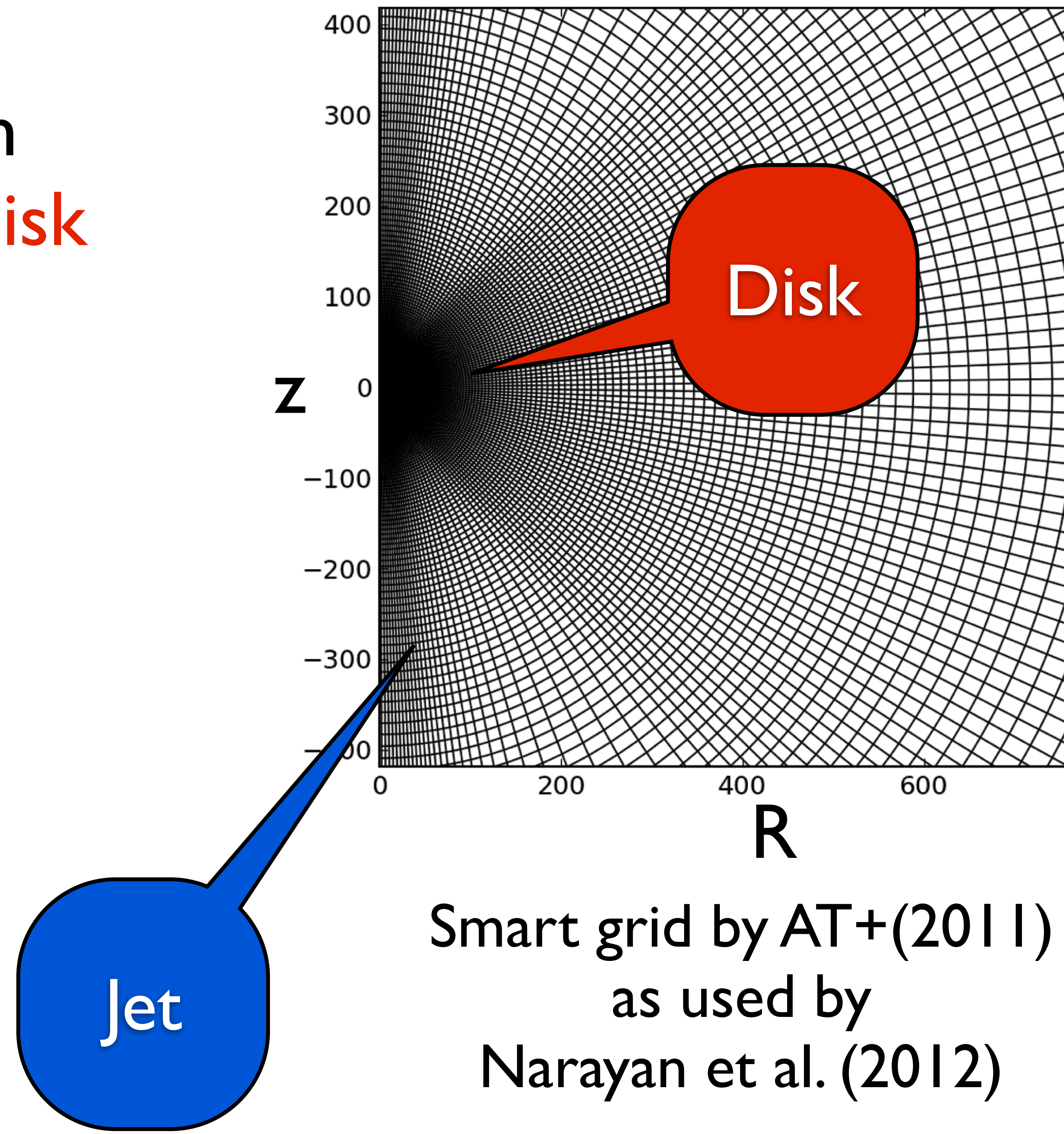

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Smart Grid that Focuses Resolution on Disk and Jet

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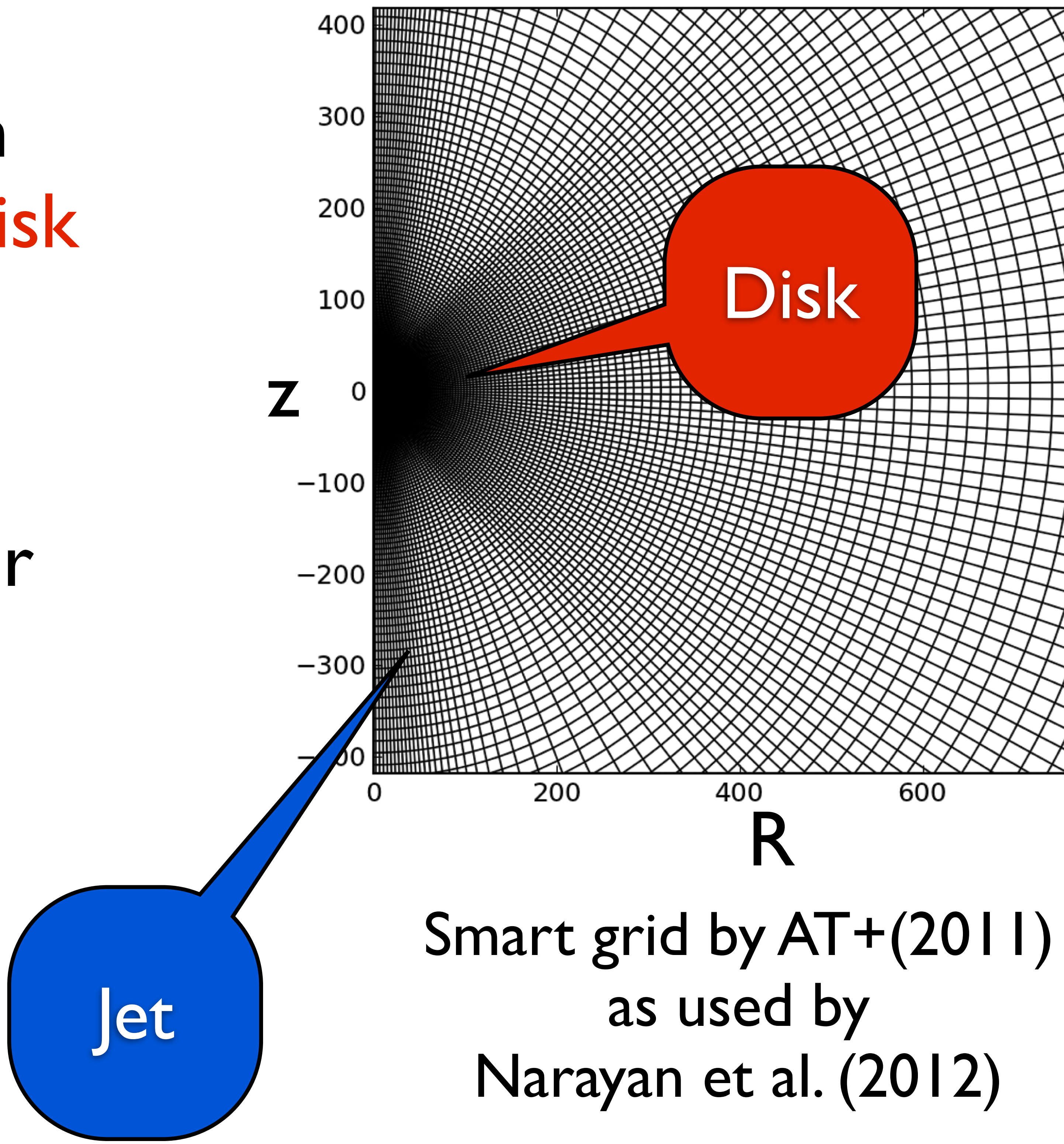
- Allows the use of smaller resolutions



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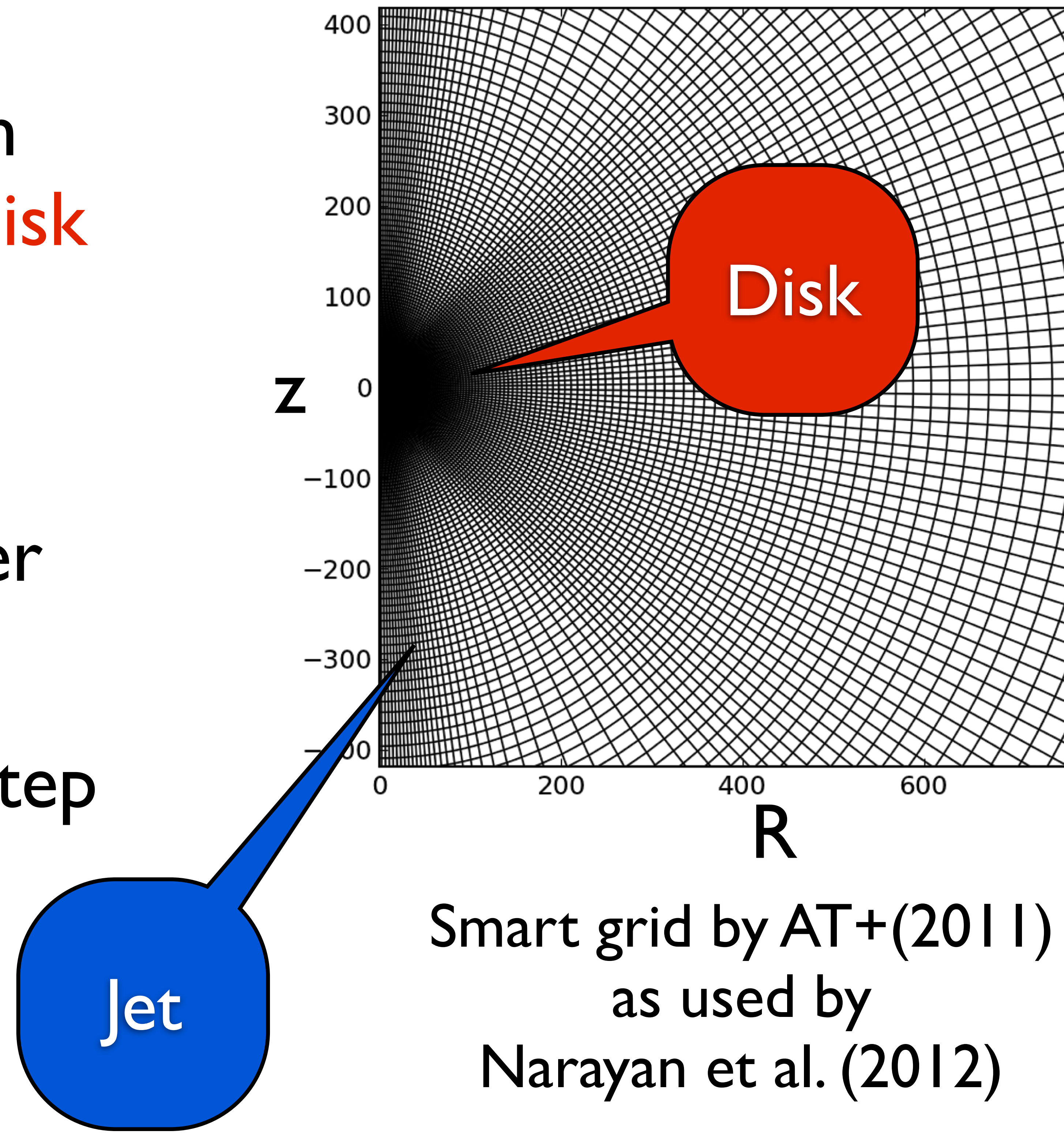

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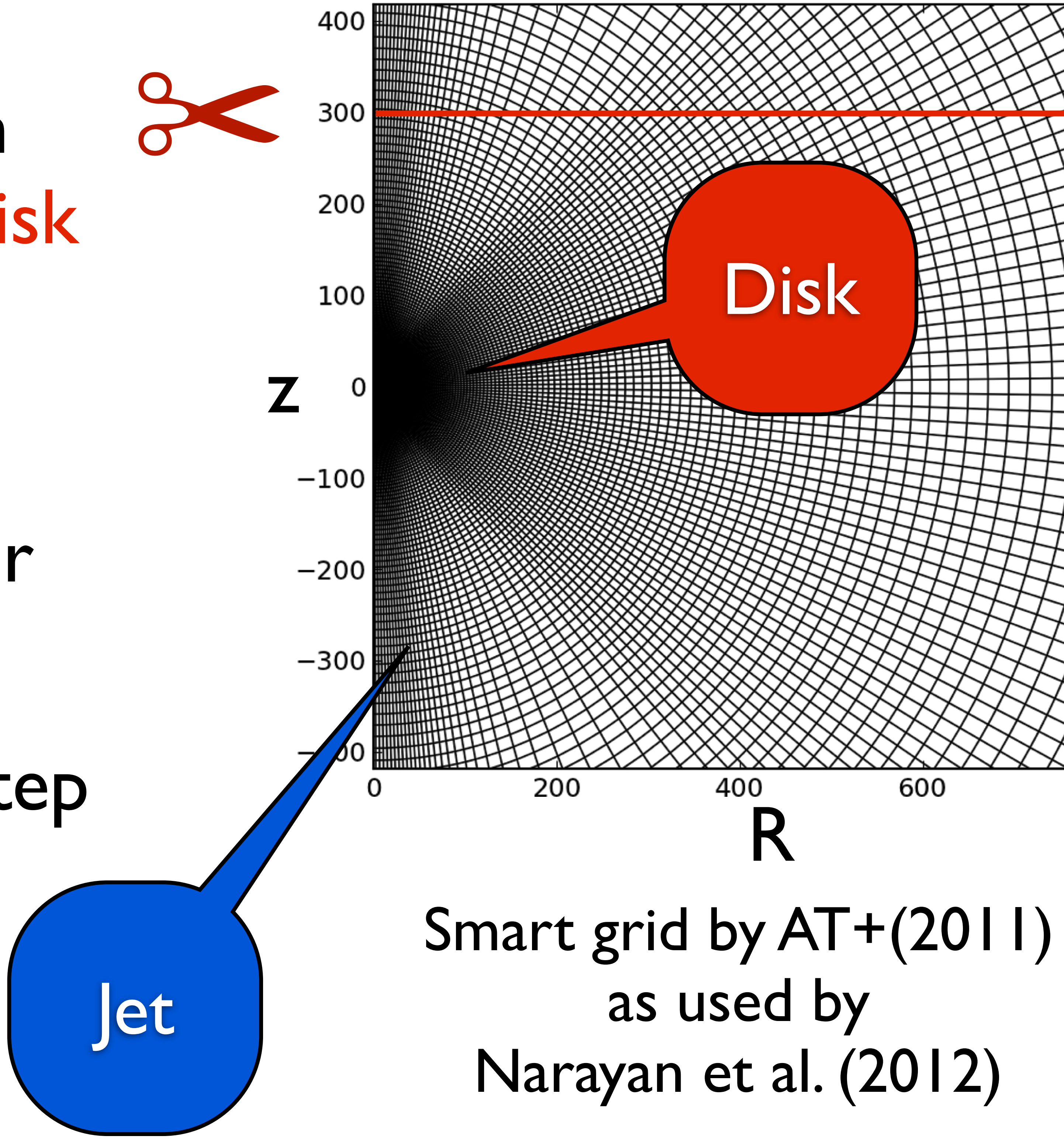

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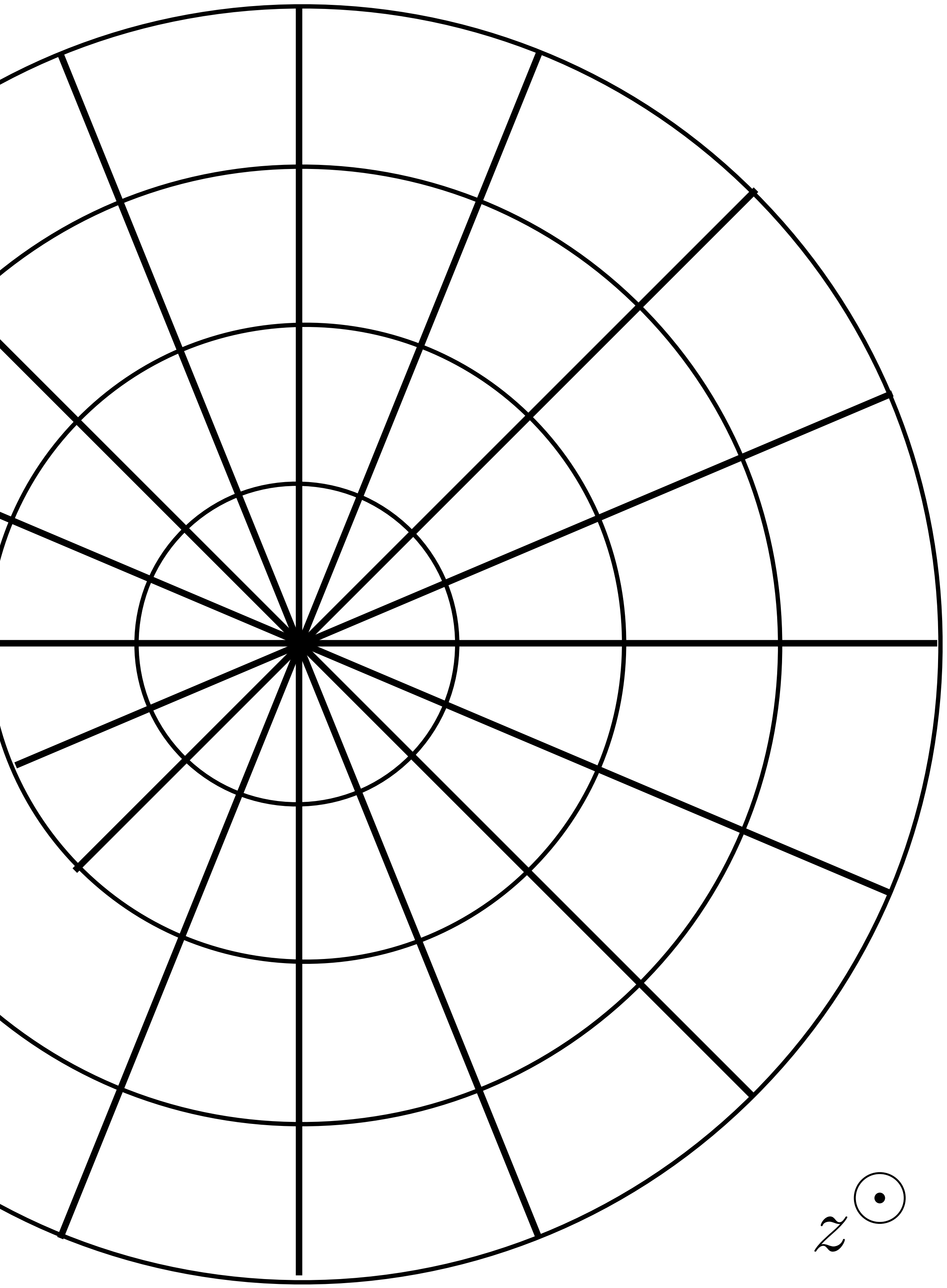
Advanced Approach to Polar Axis



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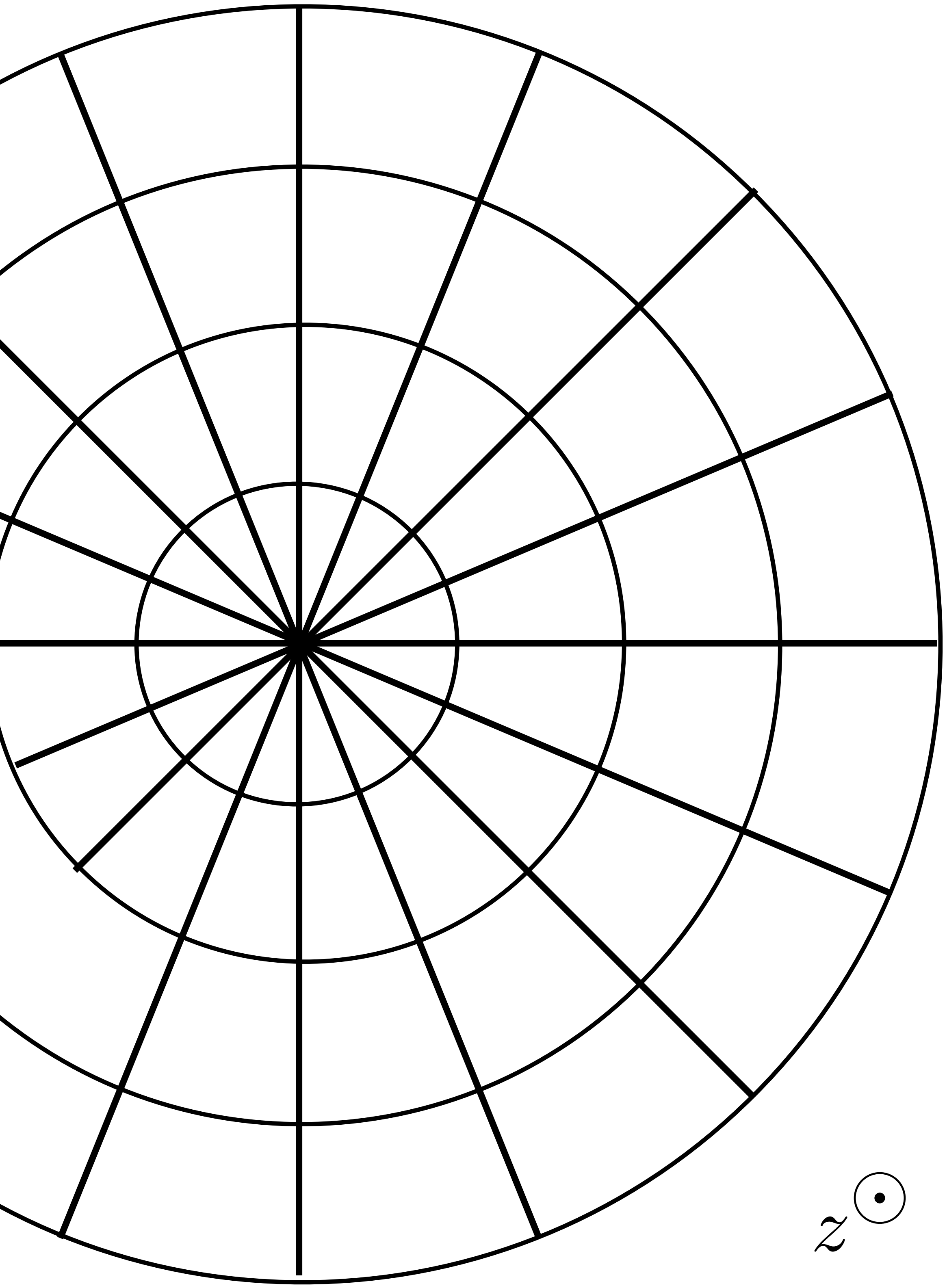

- Time step is the *smallest* light crossing time among all cells

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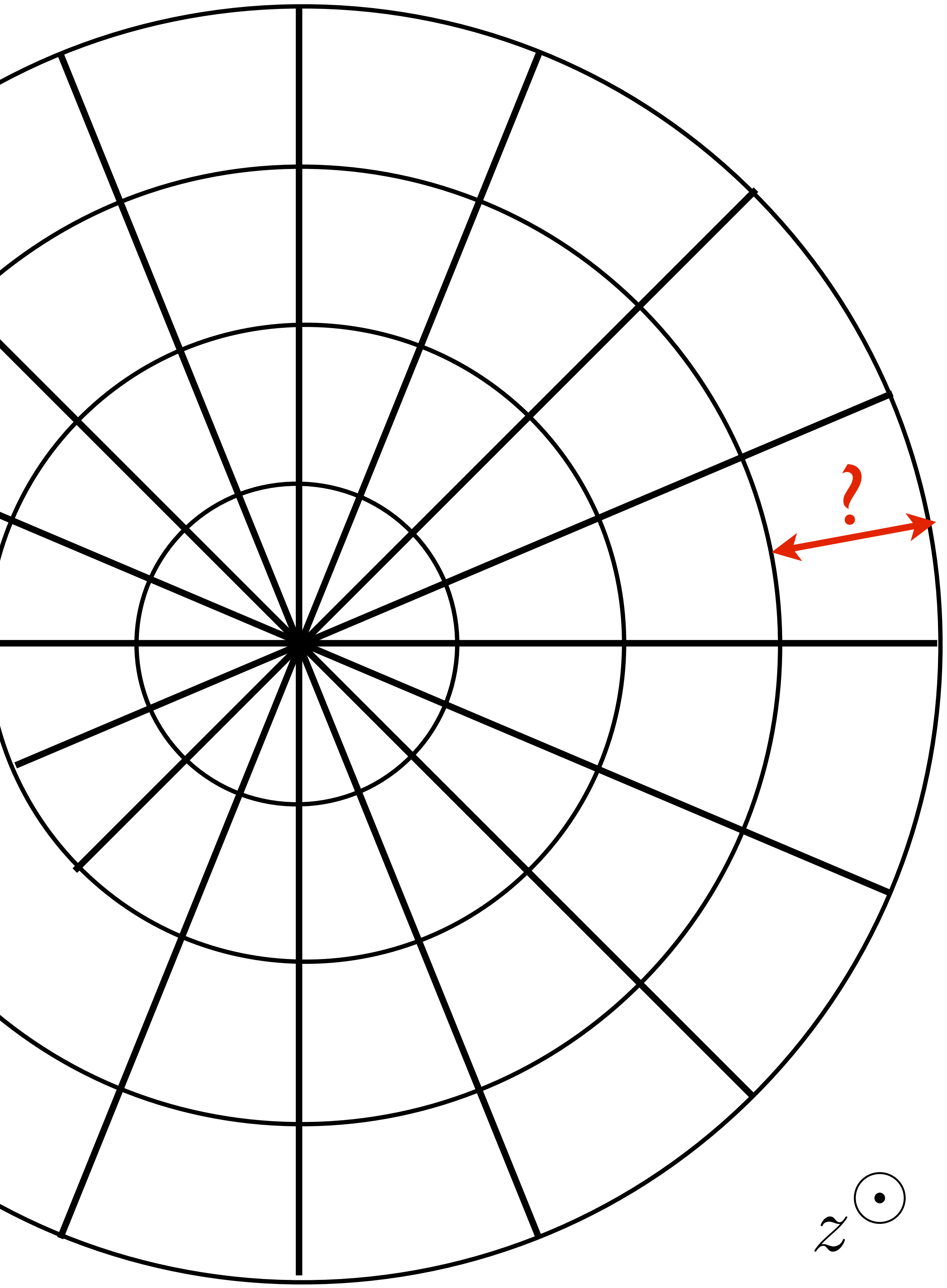

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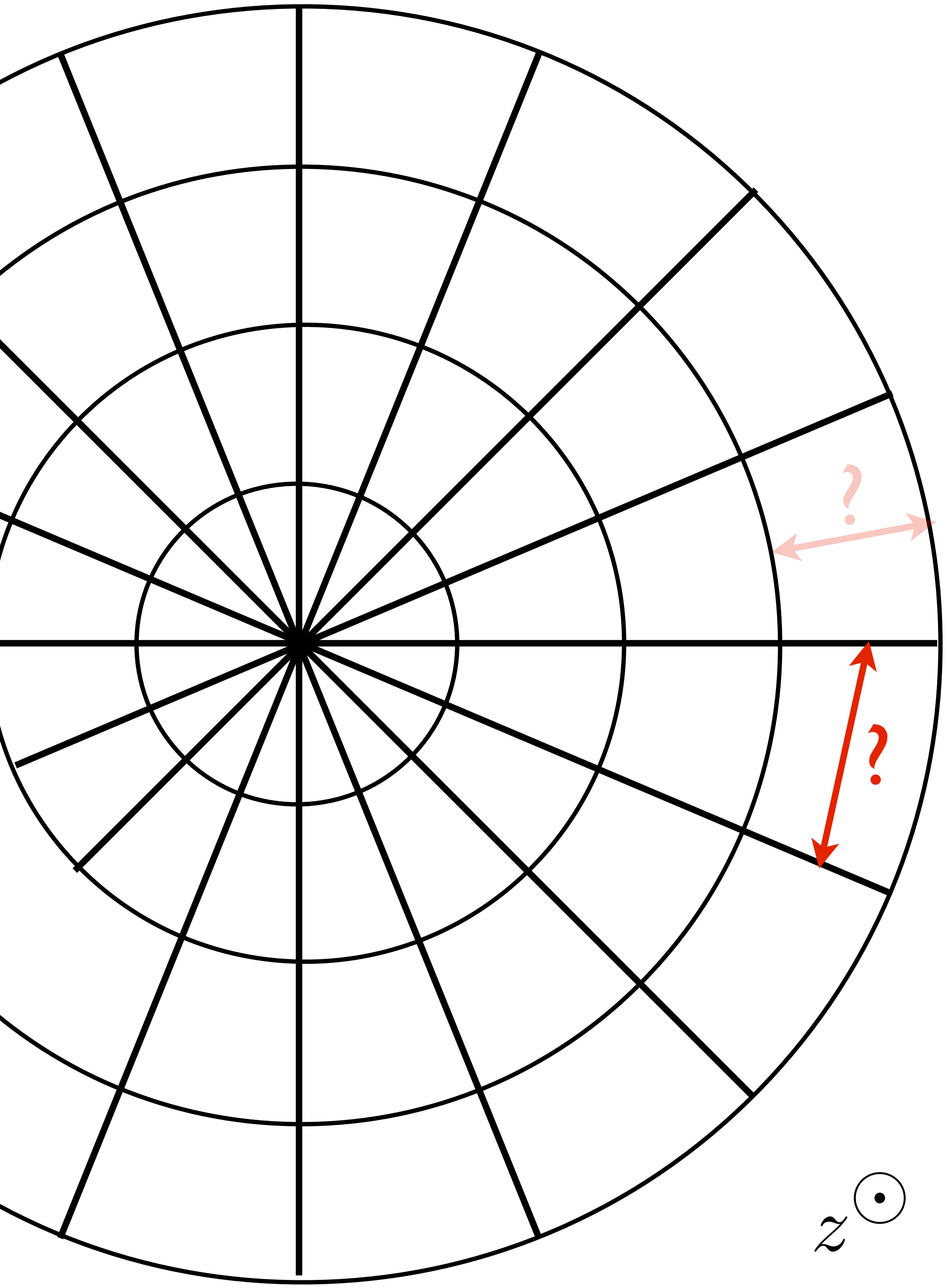

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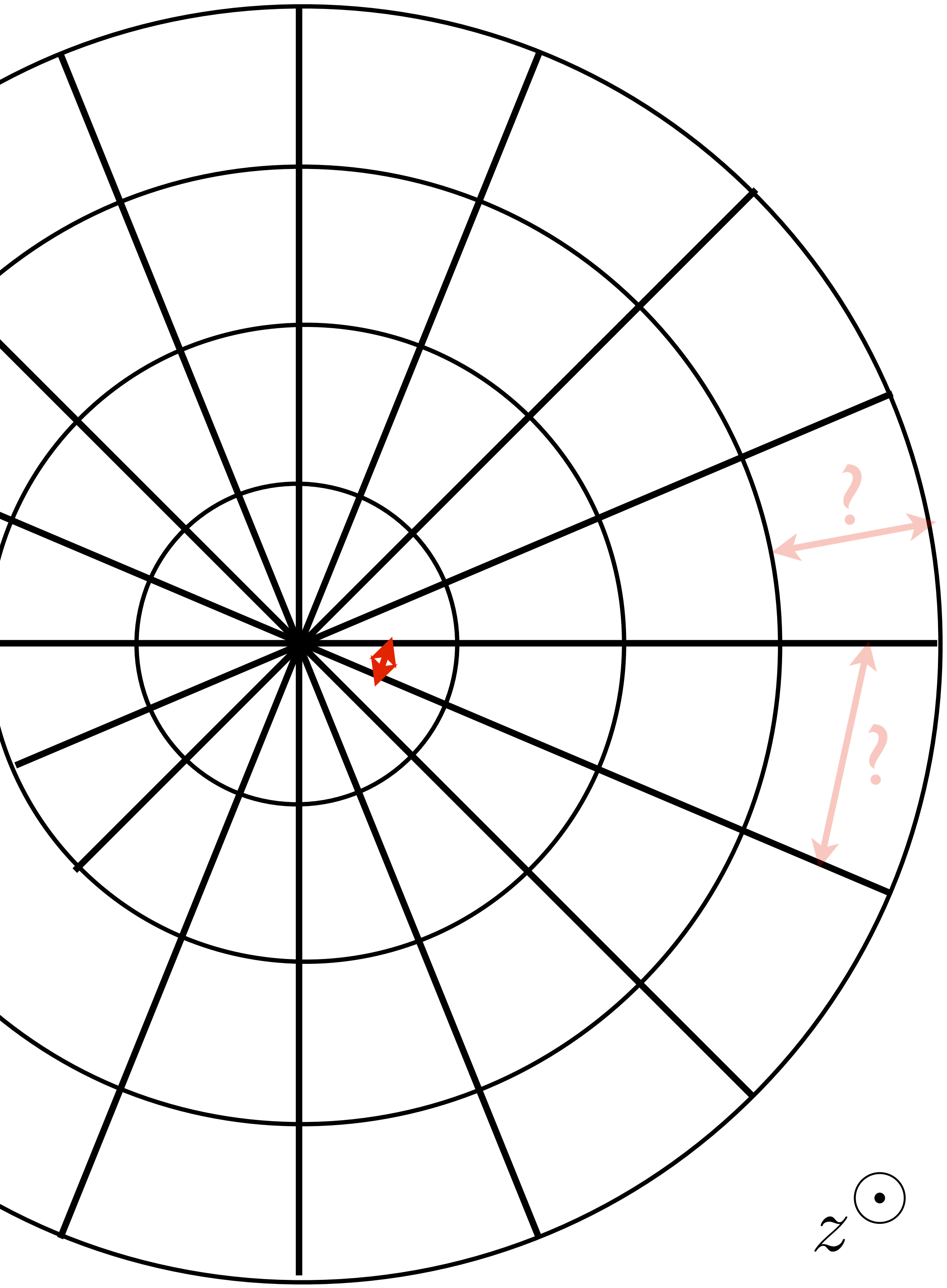

- Time step is the *smallest* light crossing time among all cells
- Small cell azimuthal extent can slow down a run by 10x

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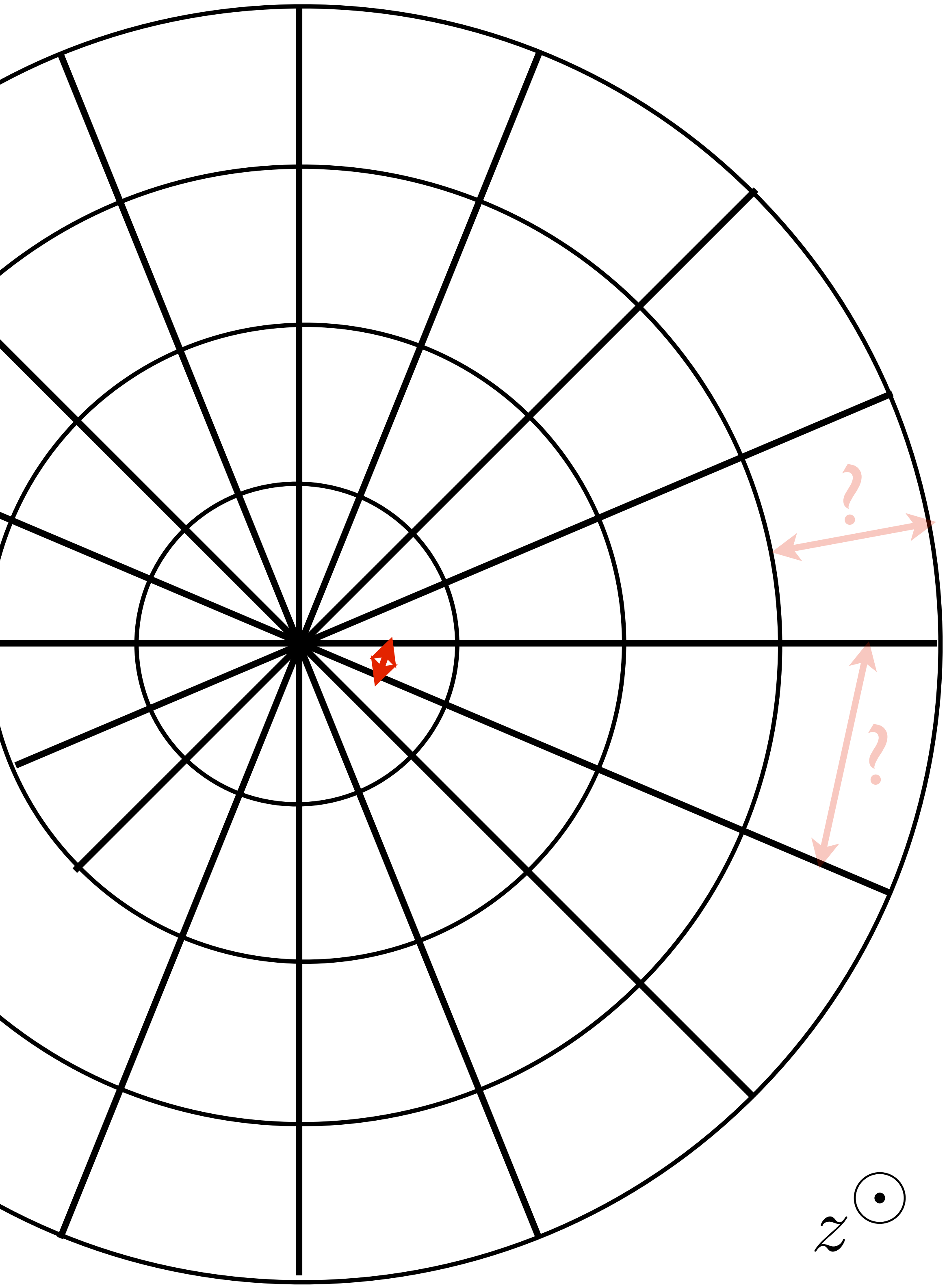
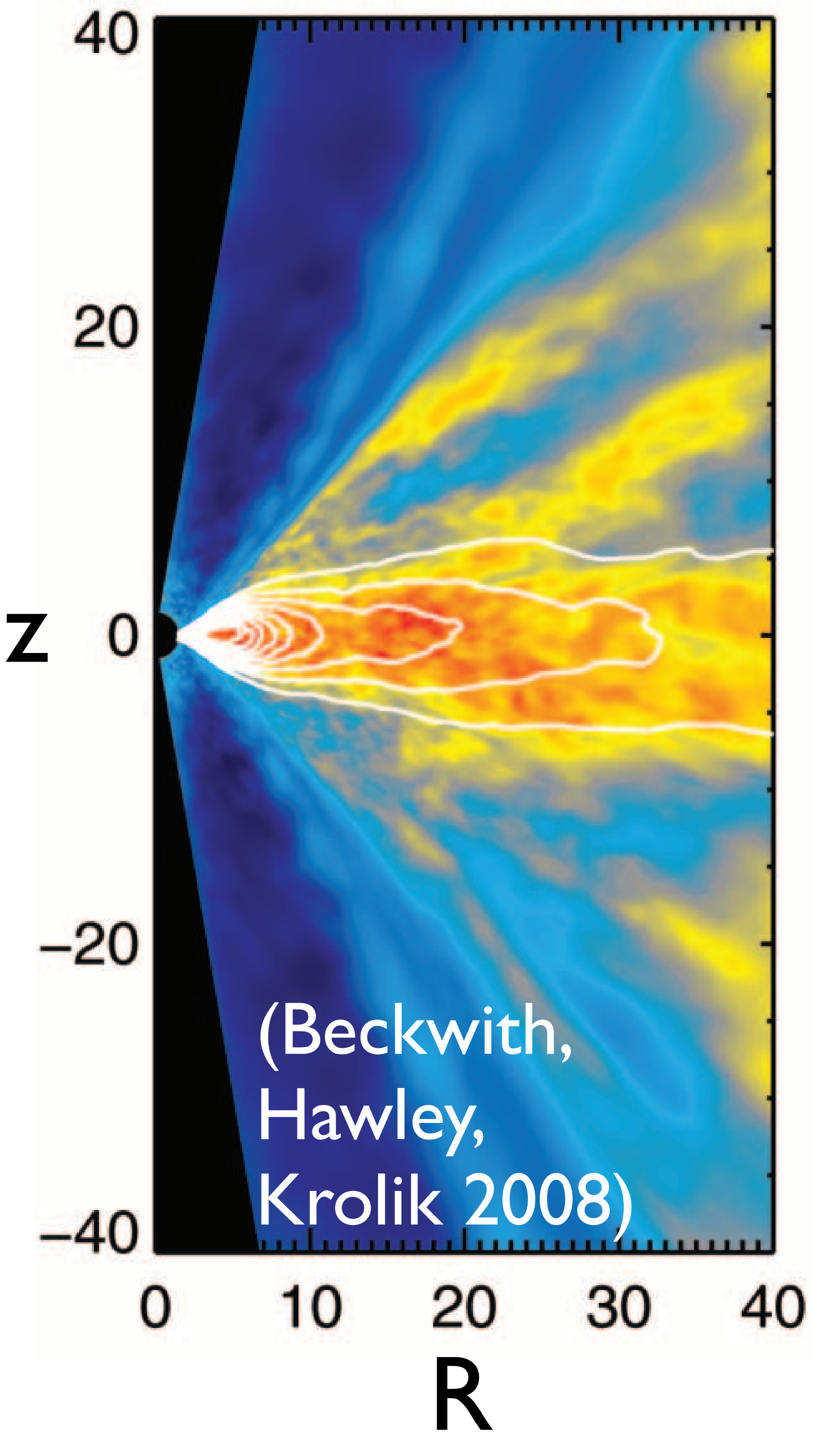


- Time step is the *smallest* light crossing time among all cells
- Small cell azimuthal extent can slow down a run by 10x
- This issue is of great importance for 3D performance

Advanced Approach to Polar Axis

1) Remove offending cells



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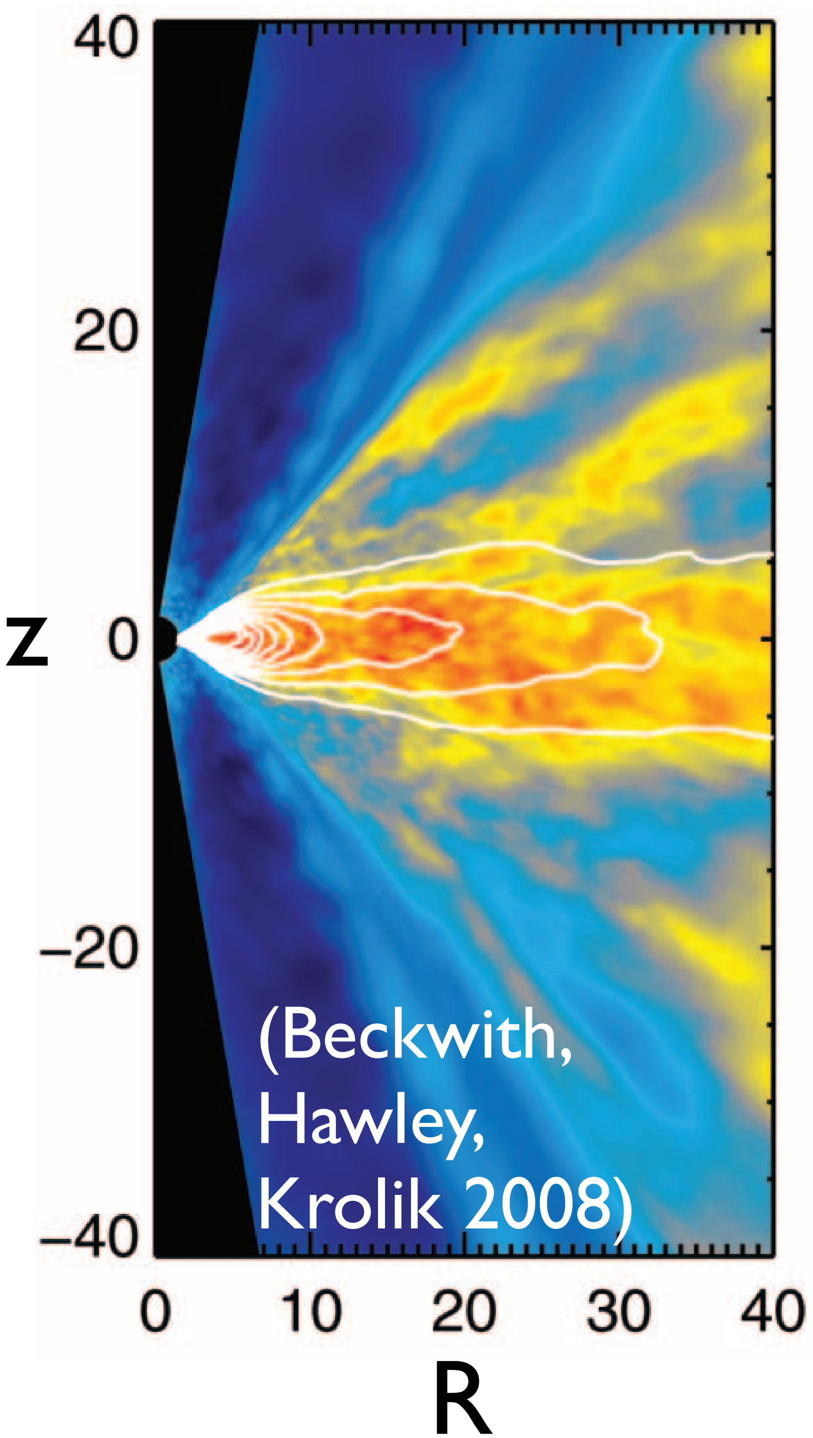
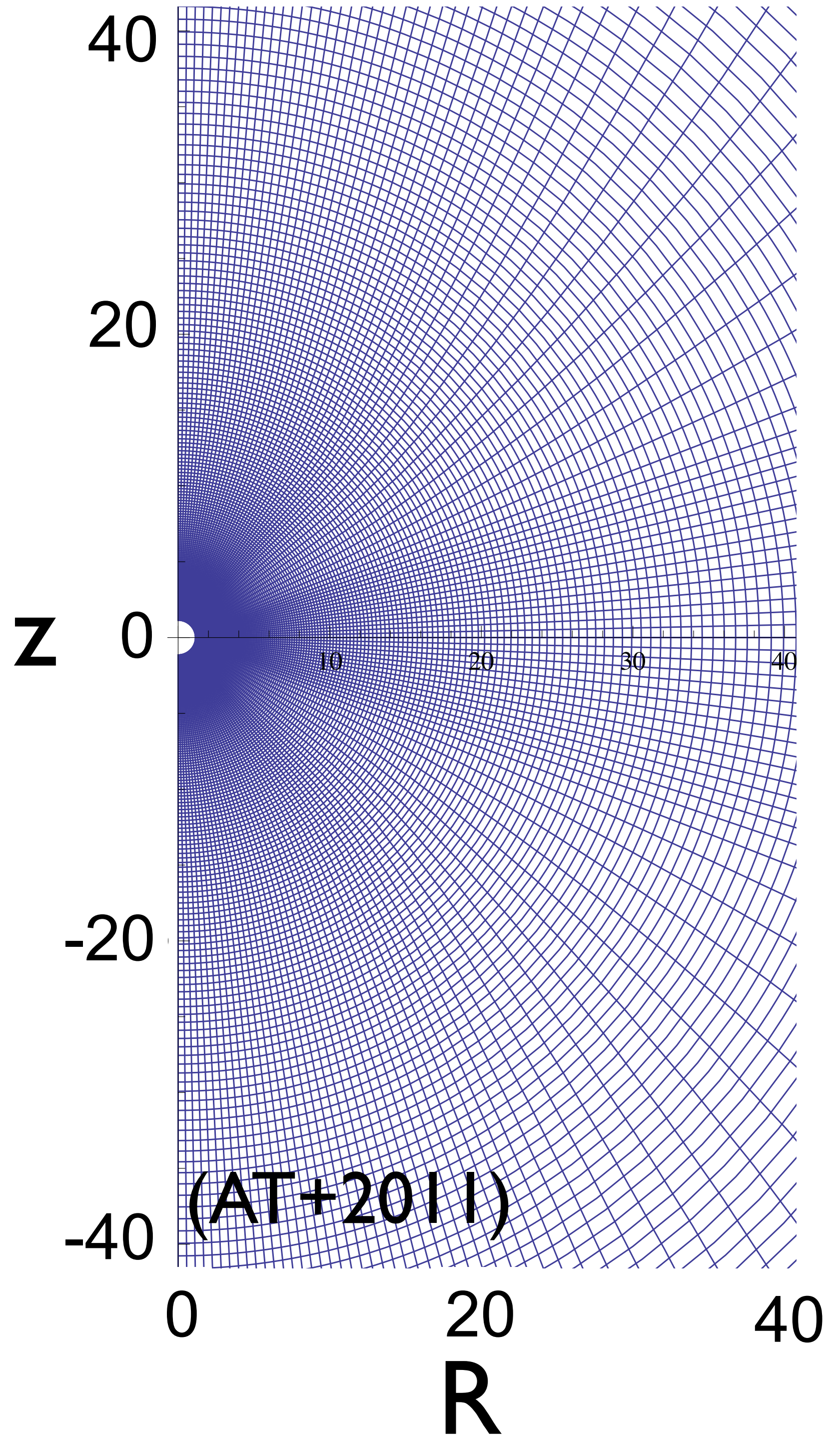


2) *Deform* offending cells



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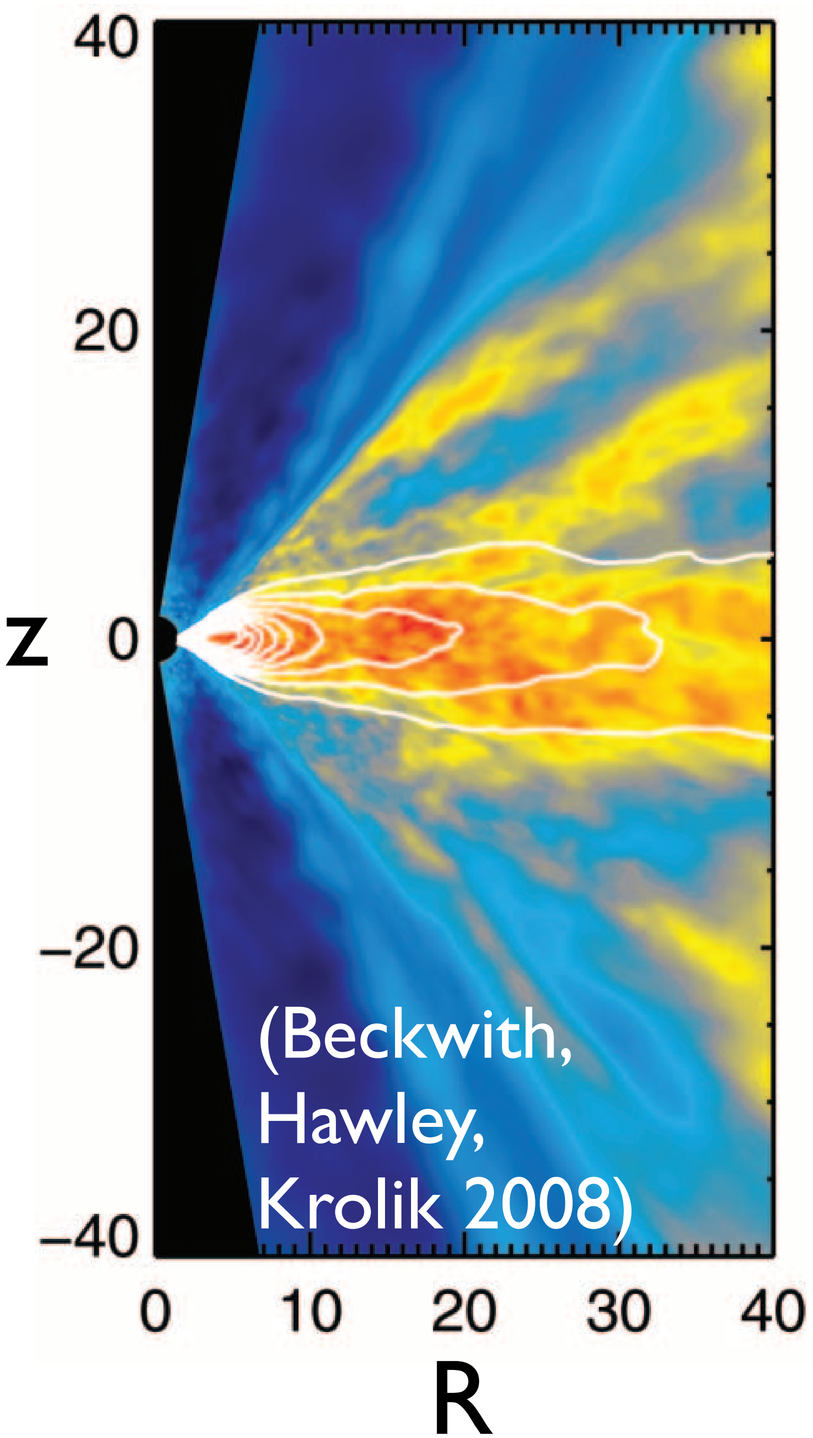

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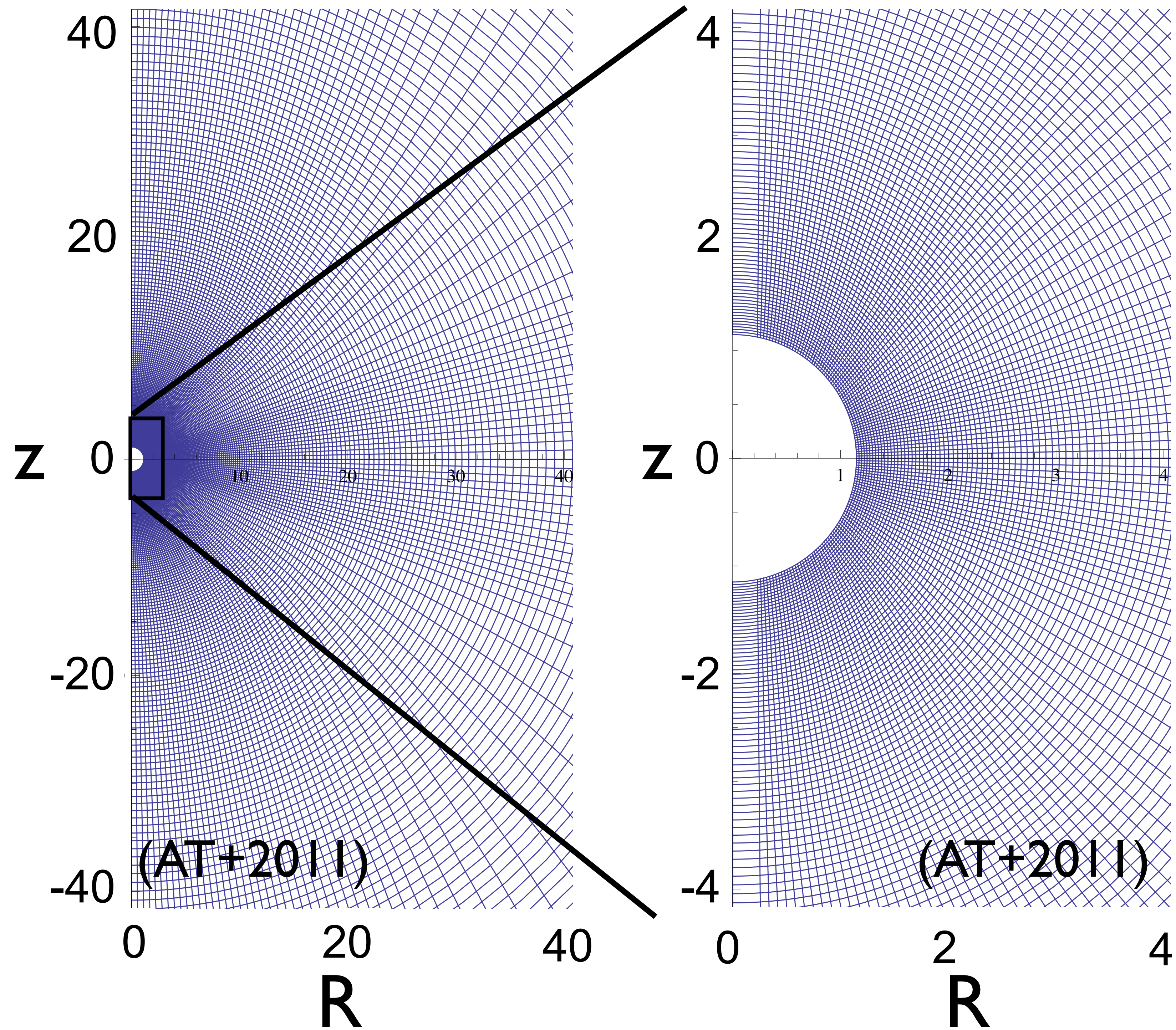
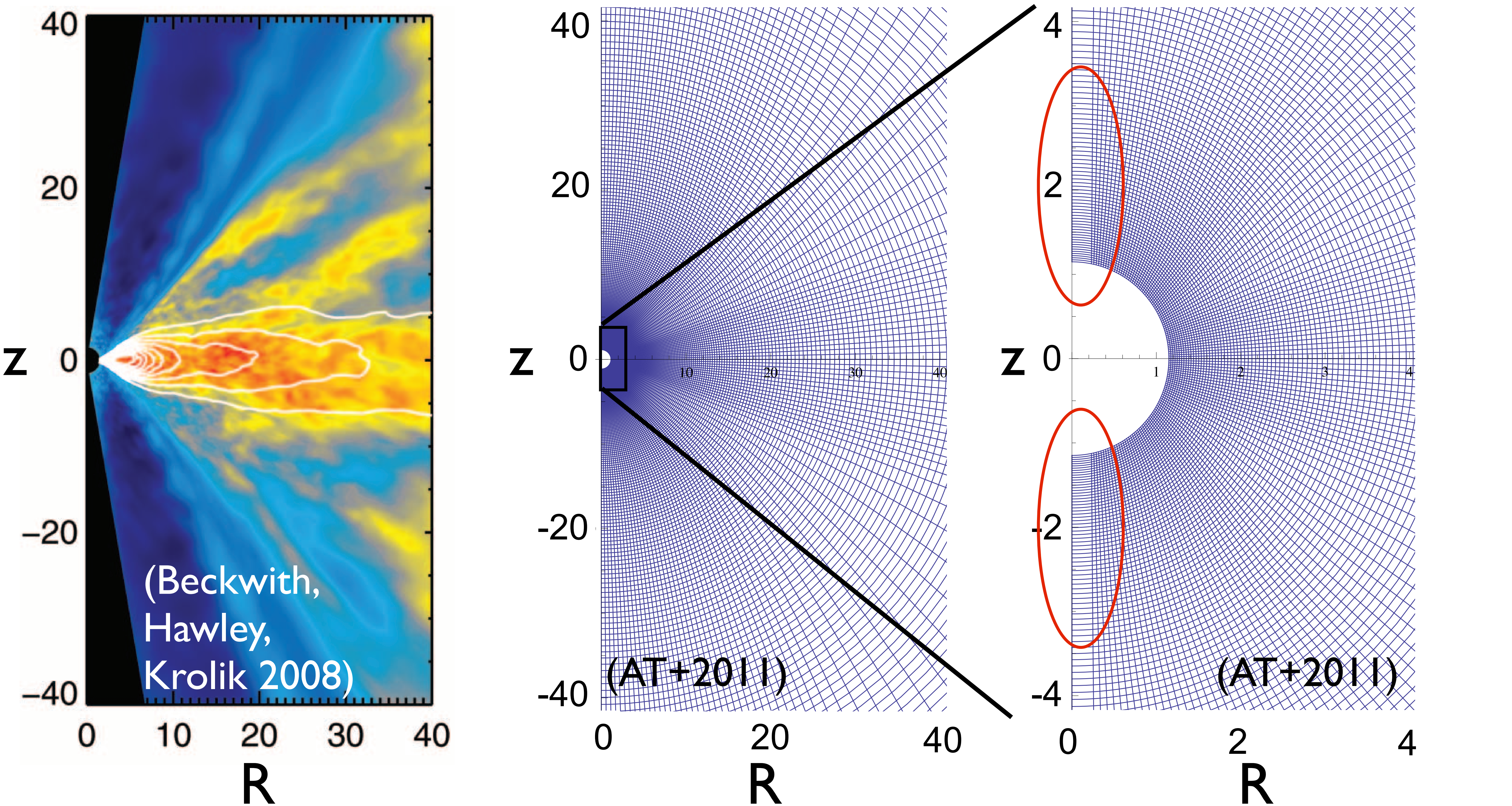


Advanced Approach to Polar Axis

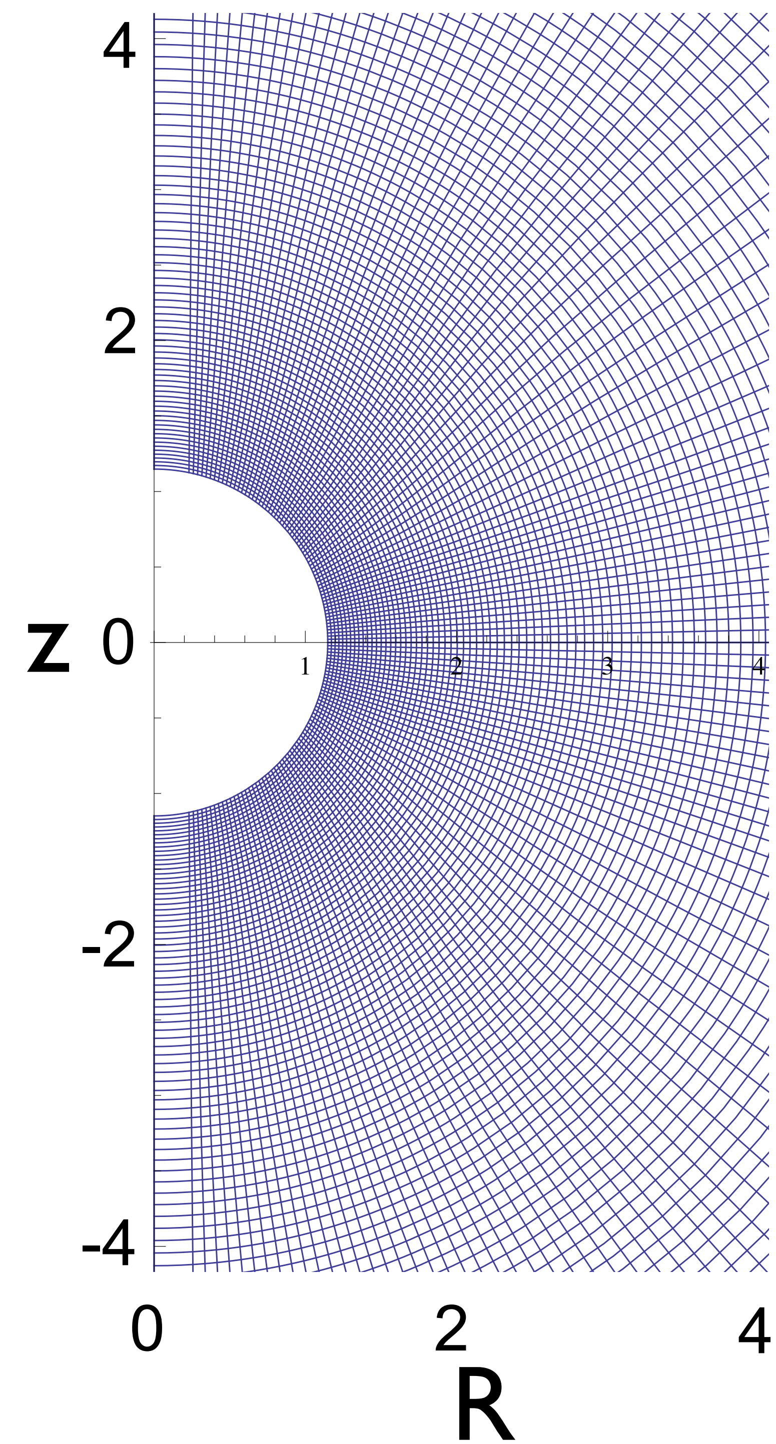
1) Remove offending cells

2) *Deform* offending cells

Speedup of 10x!

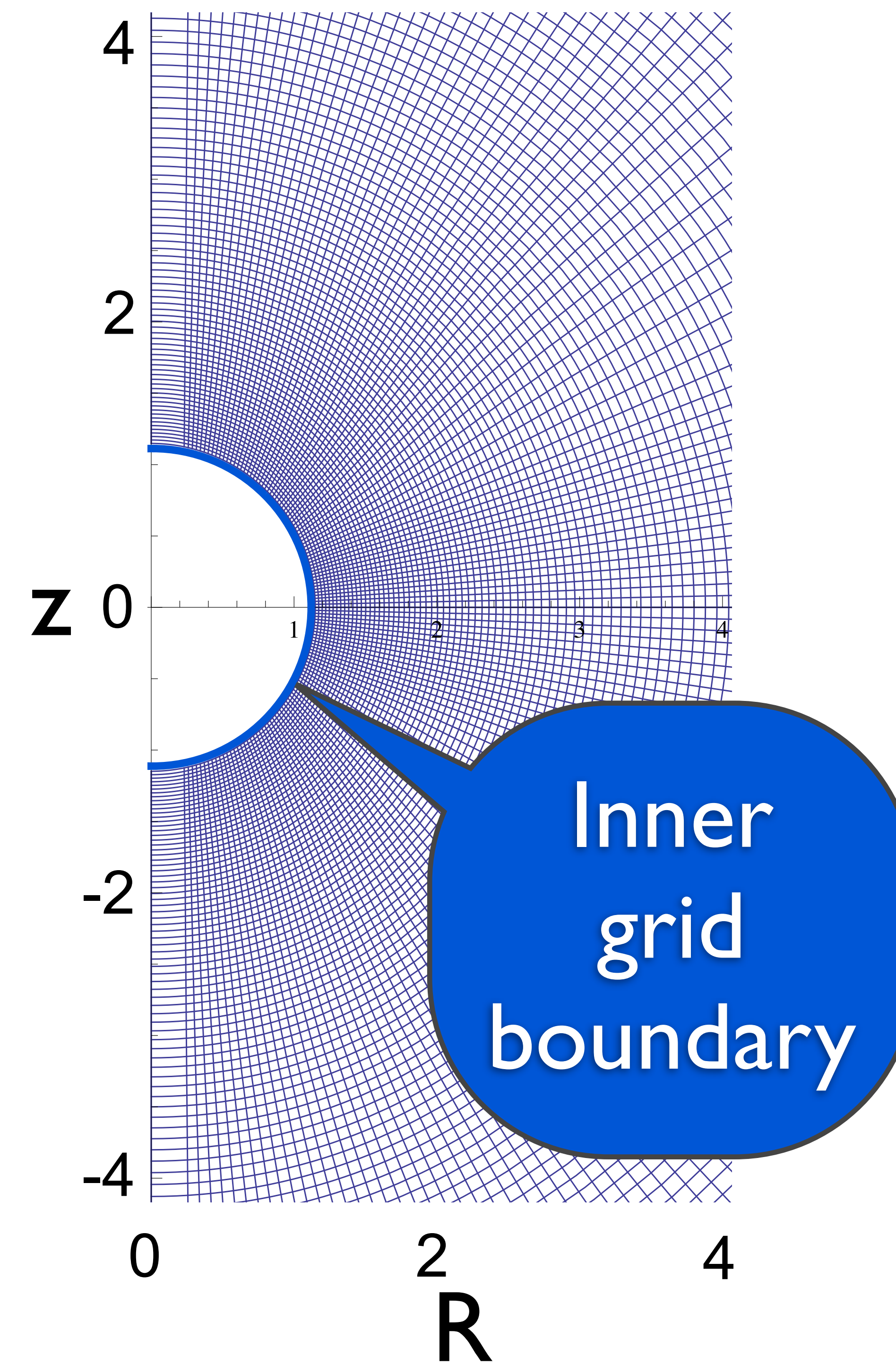


“Event Horizon” Boundary Condition



“Event Horizon” Boundary Condition

- Need to ensure that *numerically* no signals escape from the inner grid boundary



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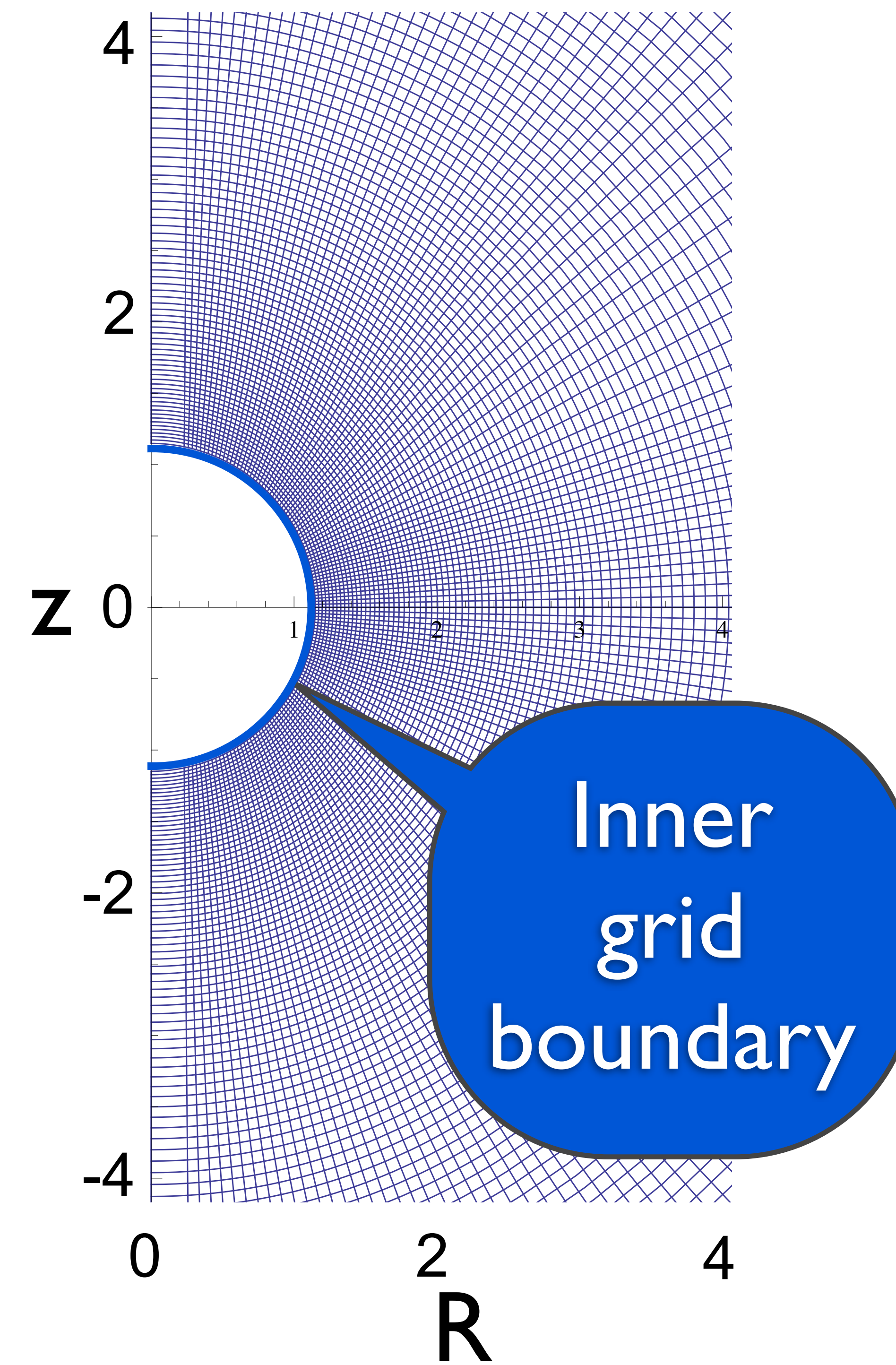

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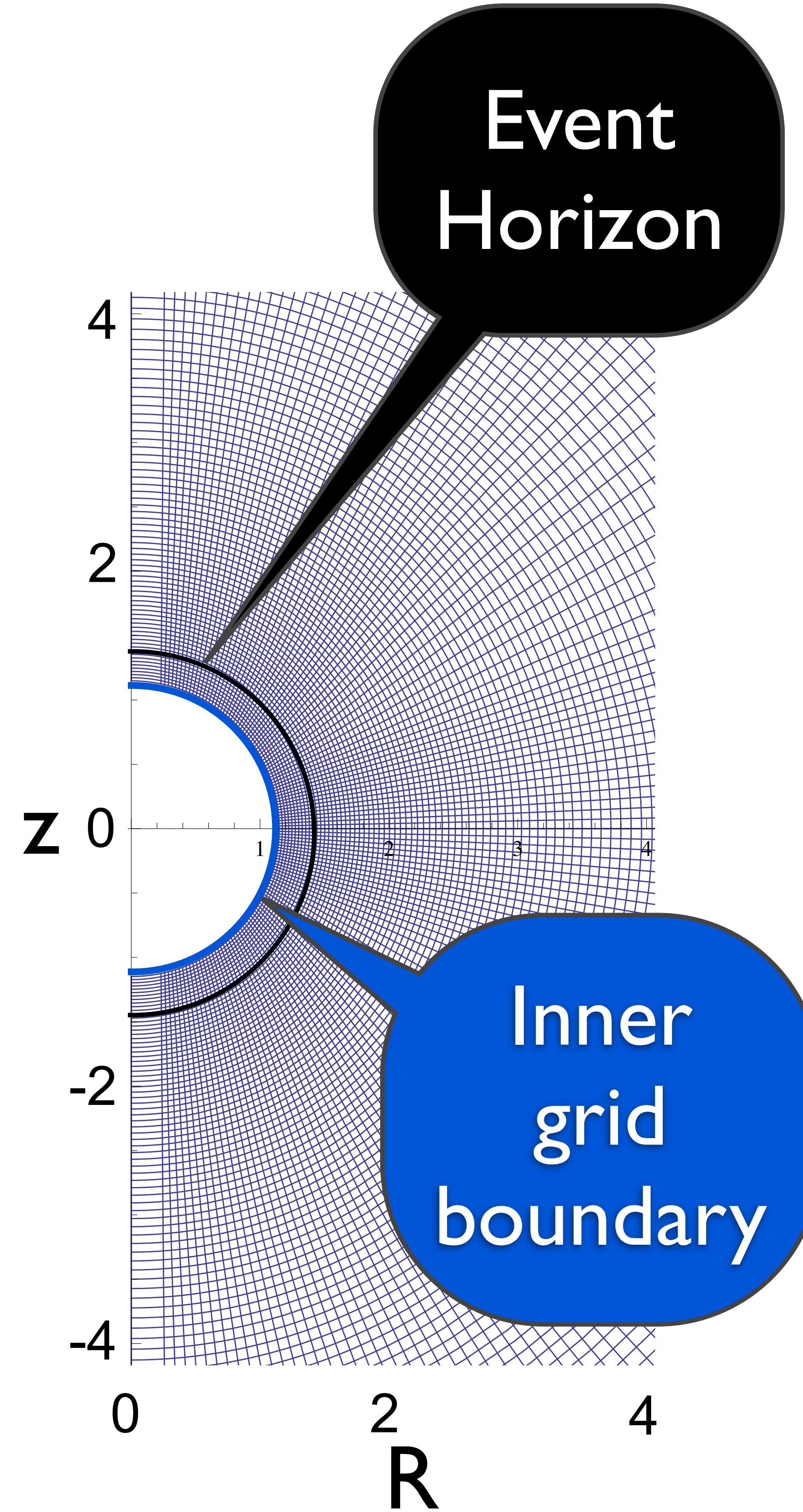
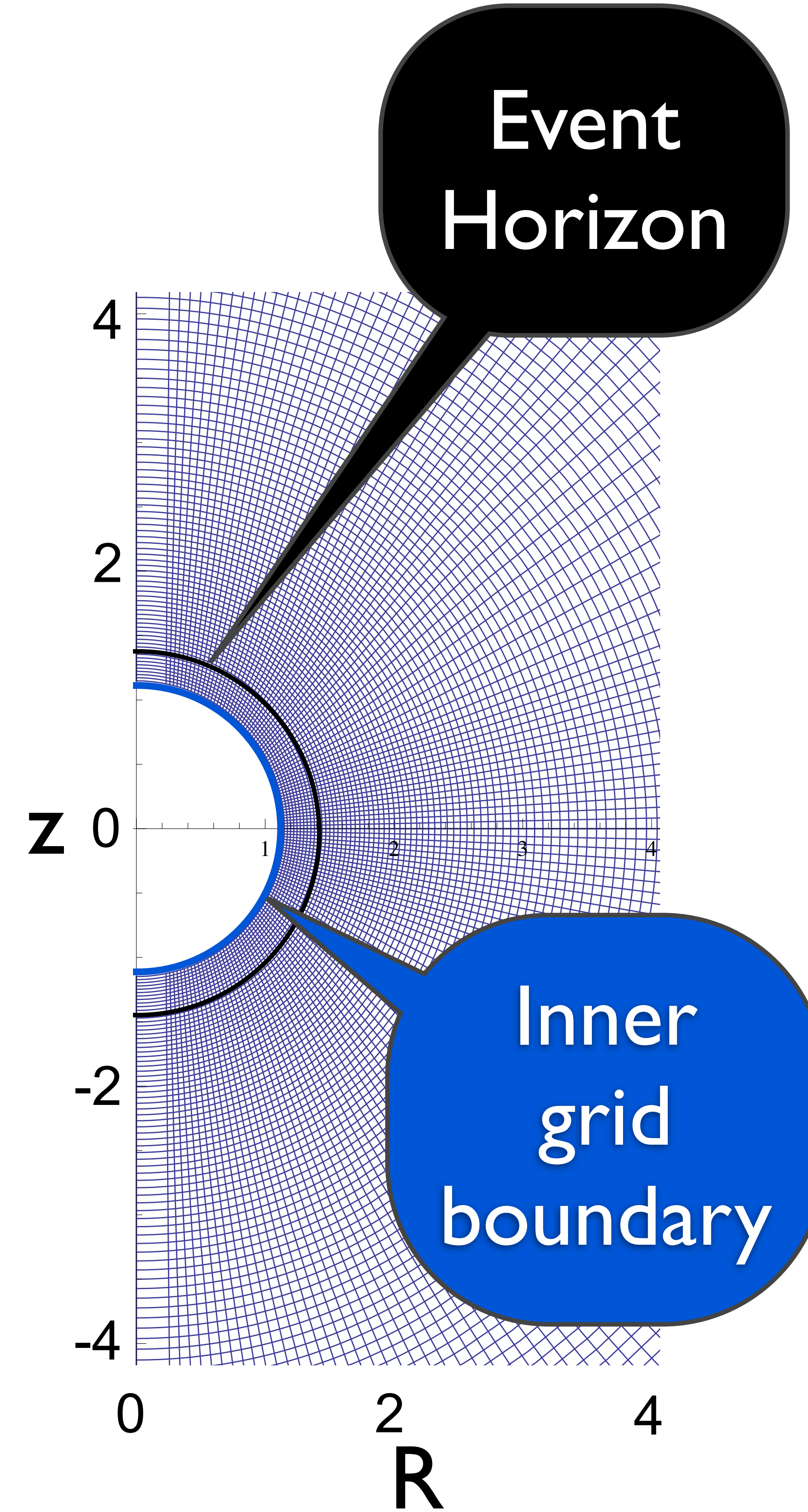


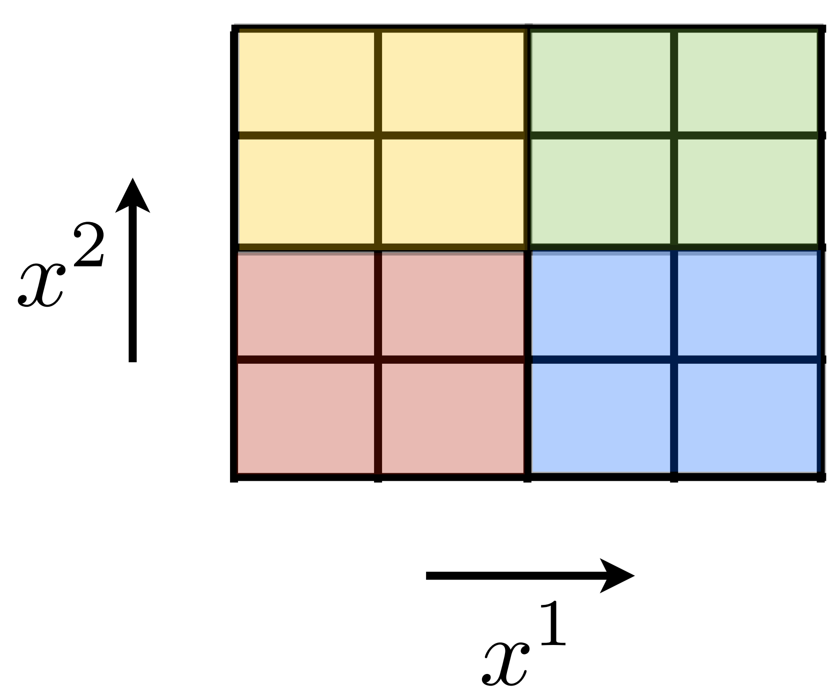
"Event Horizon" Boundary Condition

- Need to ensure that *numerically* no signals escape from the inner grid boundary
- We use horizon-penetrating (Kerr-Schild) coordinates
- Grid extends to the *interior* of the event horizon
- This ensures causal disconnect of the inner radial boundary from the rest of the grid

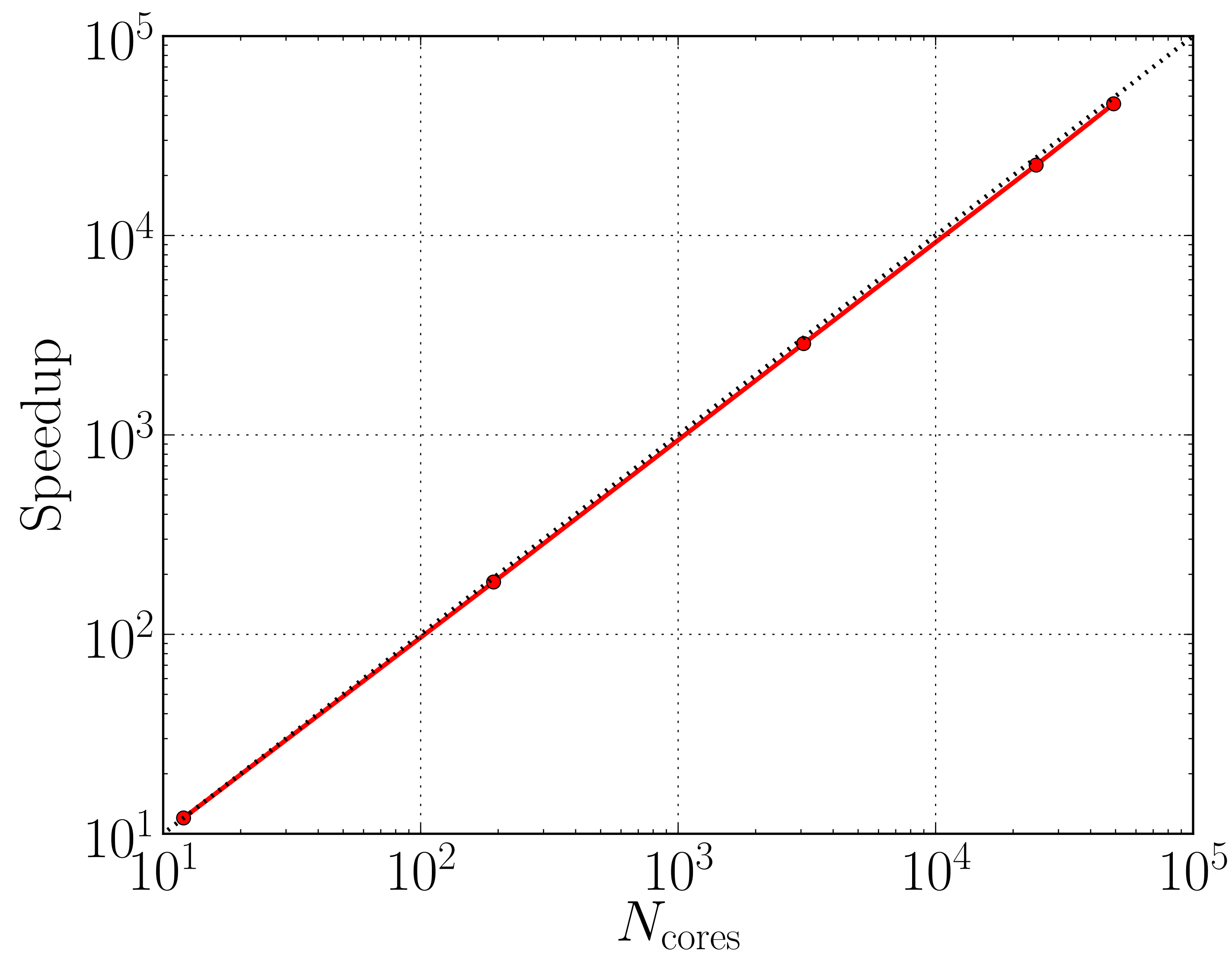


Code Parallelization and Scaling

- Both HARM and Athena Fully parallelized via domain decomposition (hybrid MPI+OpenMP)



- Near-ideal scaling up to 50,000 cores (weak scaling, 32^3 tile, NICS Kraken, Cray XT5)



New Code HARMPI

- General Relativistic MHD code
- Based on serial, 2D code HARM2D (Gammie et al. 2003)
- Parallelized it via MPI
- Extended to 3D
- Kept it simple (graduate student startup time = hours)
- Made it open-source: github.com/atchekho/harmpi
- Added extra physics

Alexander (Sasha) Tchekhovskoy

https://github.com/atchekho/harmpi/blob/master/tutorial.md

HARMPI Tutorial by Sasha Tchek

Please also see useful exercises that give you an idea of scientifi

How to set up HARMPI: choose the probler

- To install the code, you do:

```
git clone git@github.com:atchekho/harmpi.git
cd harmpi
make clean
make
```

https://github.com/atchekho/harmpi/blob/master/exercises.md

HARMPI exercises by Sasha Tchek

Please also see the tutorial that explains basic code use.

Hydro problems

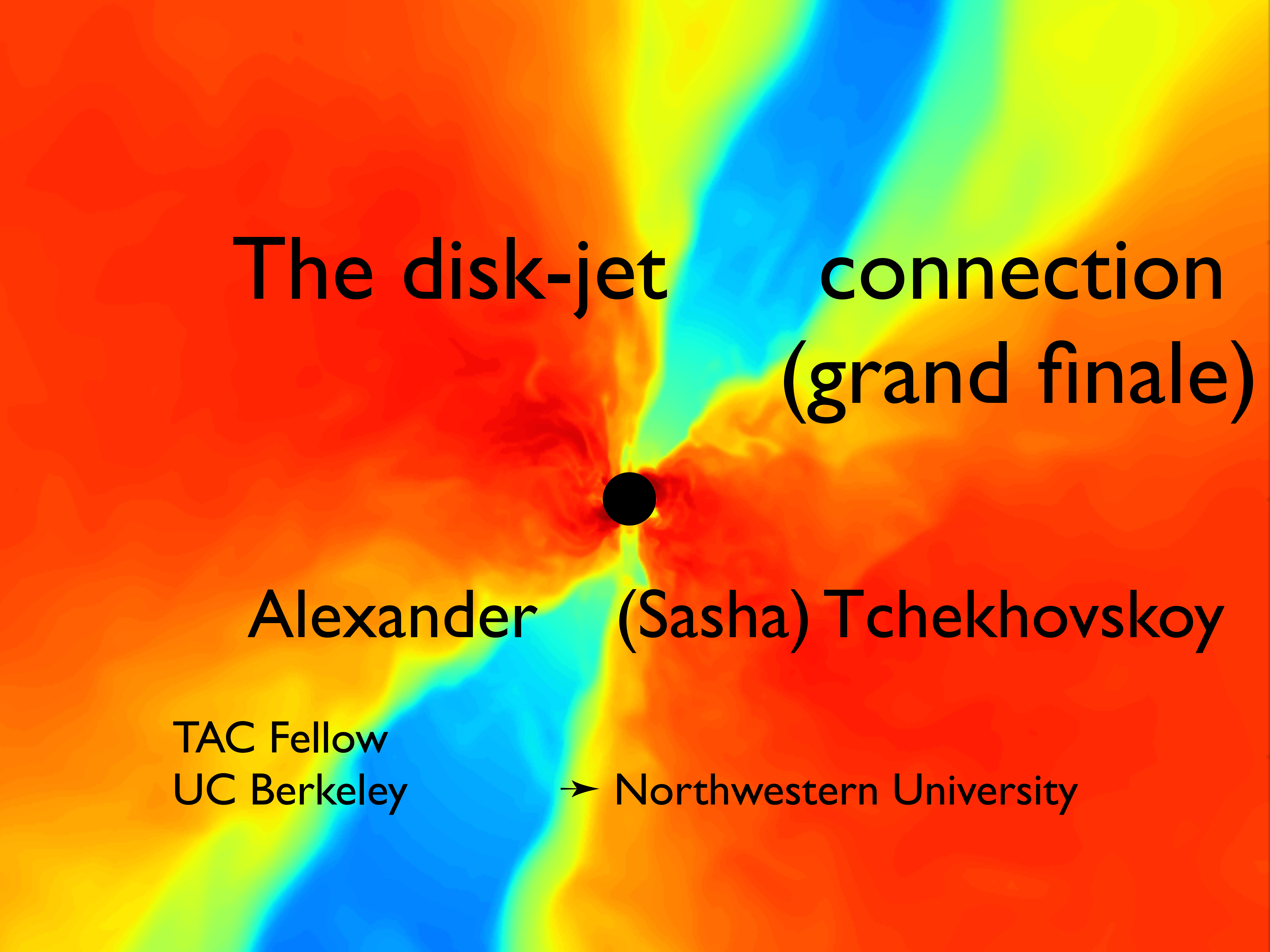
To run problems with HARMPI and to analyze the results, please fo

1D hydro problems

- Bondi accretion

  Set `WHICHPROBLEM` to `BONDI_PROBLEM_1D` in decs.h. Note: a goo

  - Plot the profiles of density at a few times in a simulation. Hint: look at where `v1p` variable changes sign. Ordinarily fast wave (in this problem there is no magnetic field, so fa flow barely falls inward, so it will be `> 0` but at small rad speed of light, so it will be `< 0`.

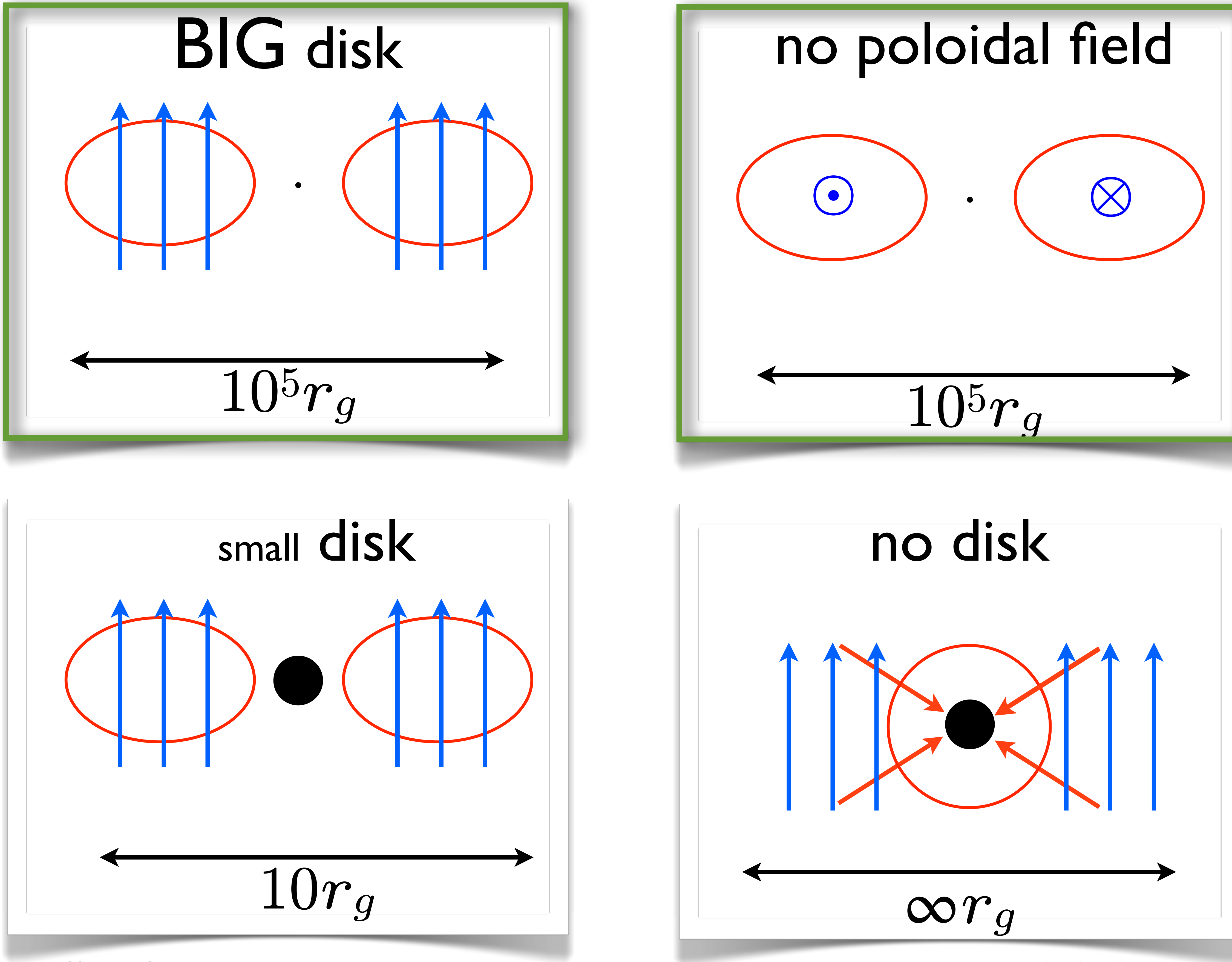


The disk-jet connection (grand finale)

Alexander (Sasha) Tchekhovskoy

TAC Fellow
UC Berkeley ➛ Northwestern University

What is a Healthy Jet Diet?



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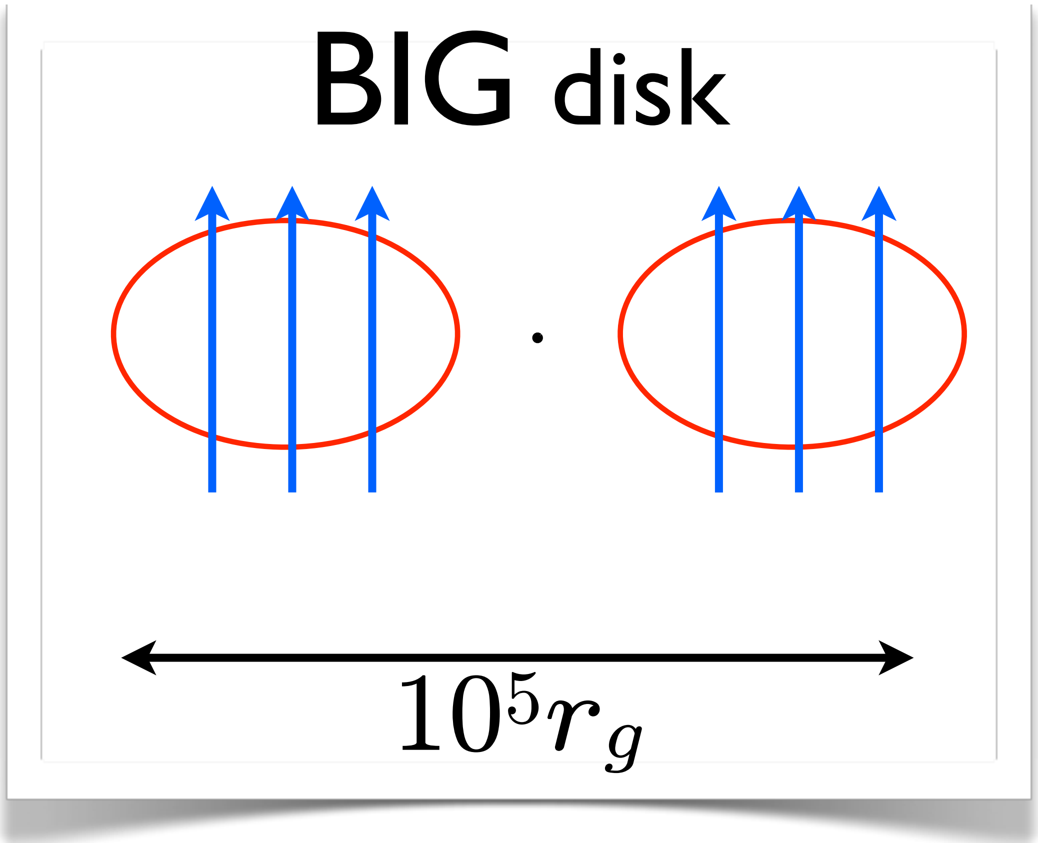

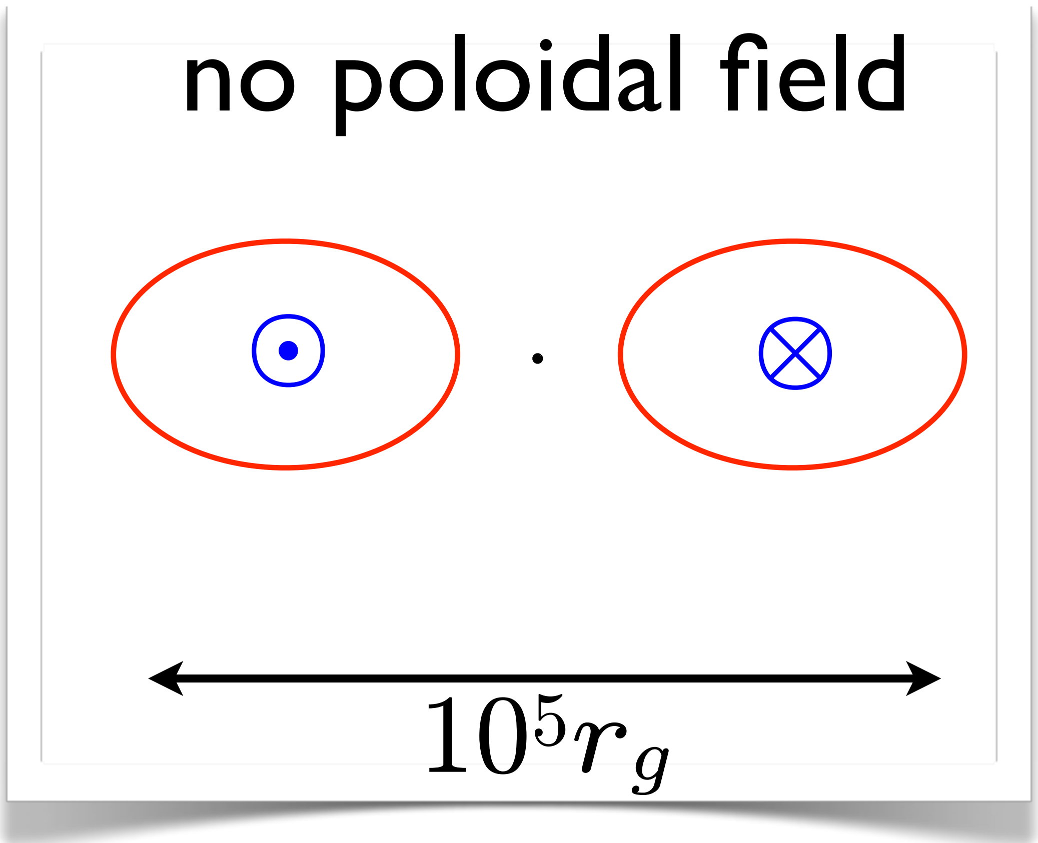

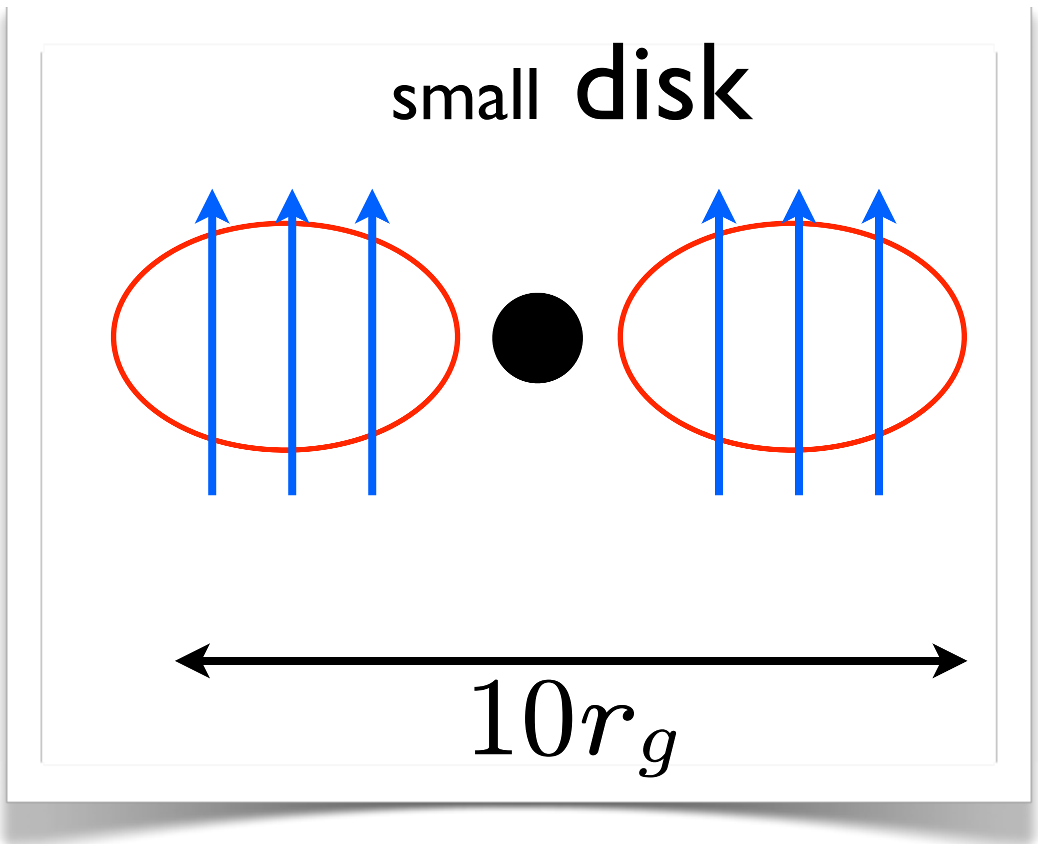

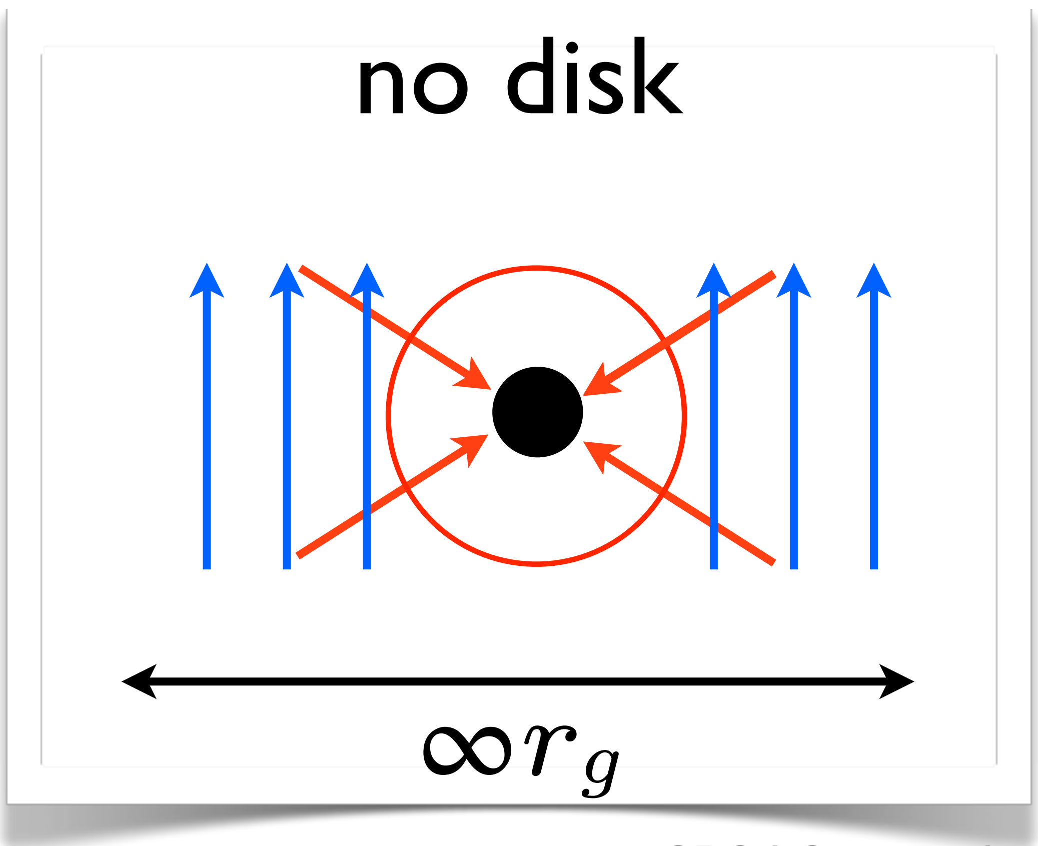

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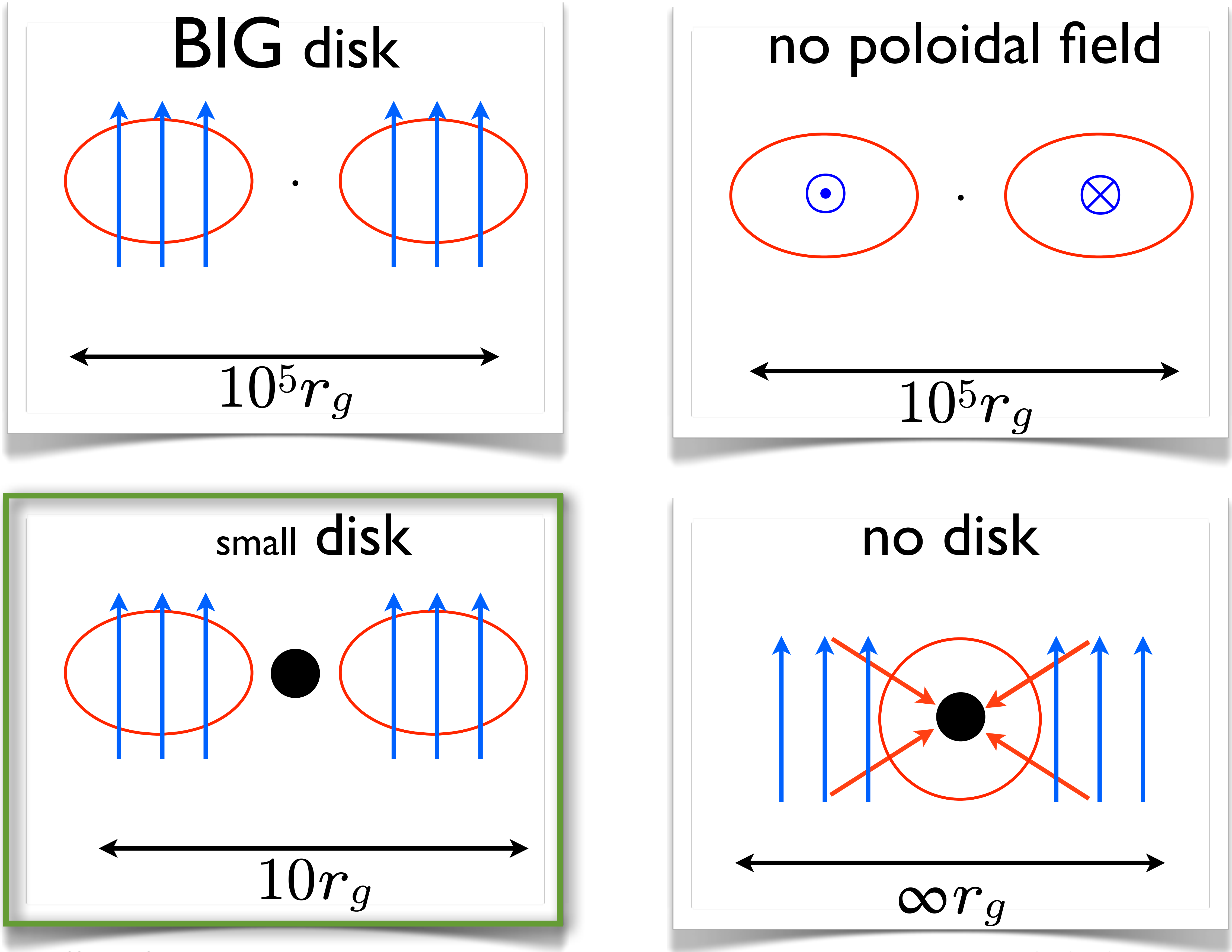
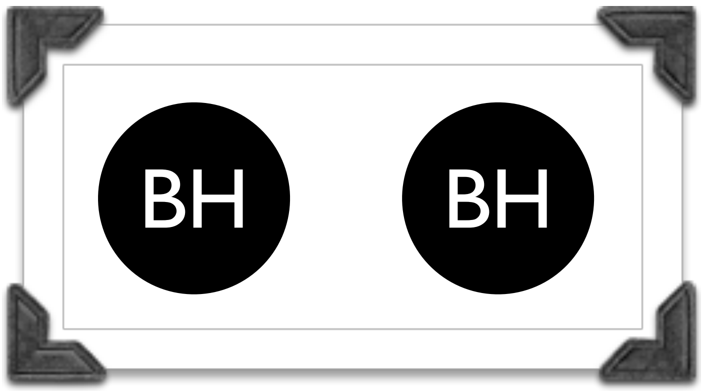
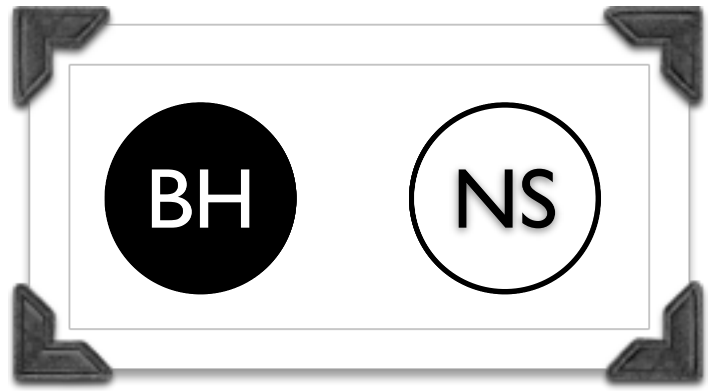
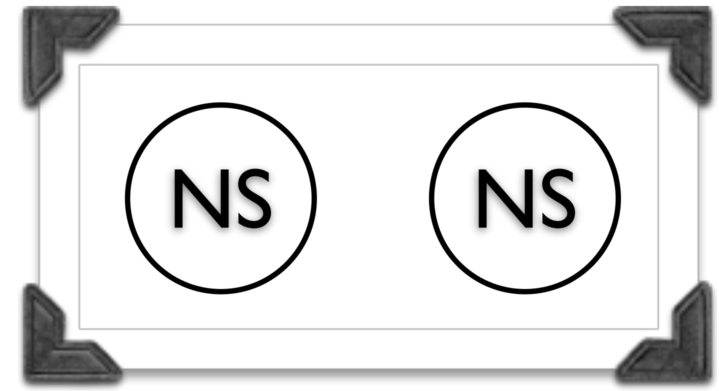


EM Counterparts to Binary Mergers



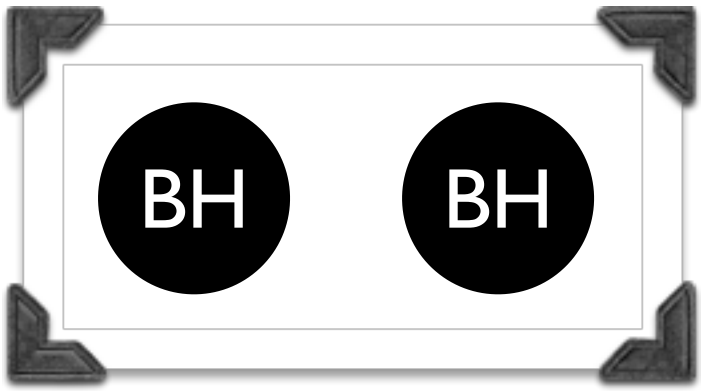


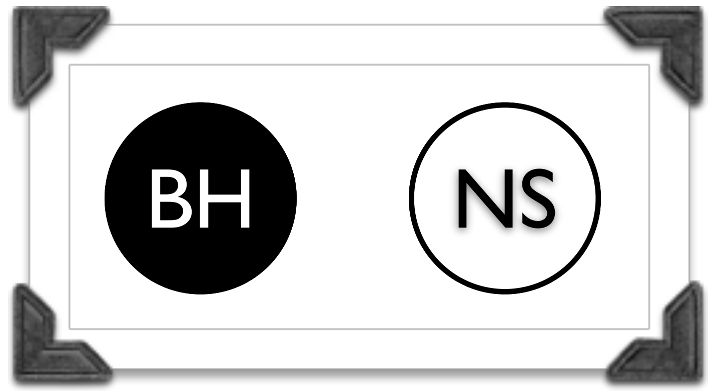


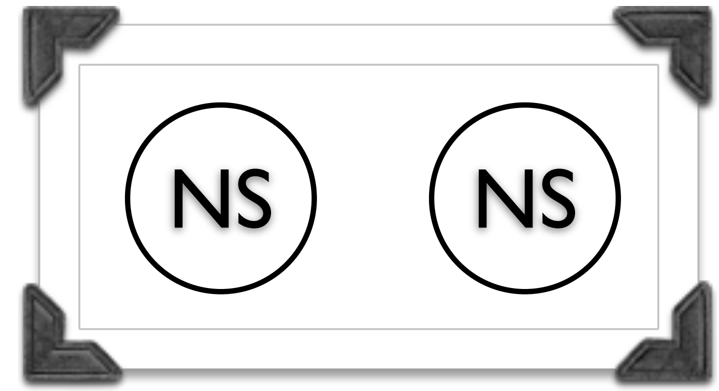
— detected! —

— detection might be imminent —

EM Counterparts to Binary Mergers







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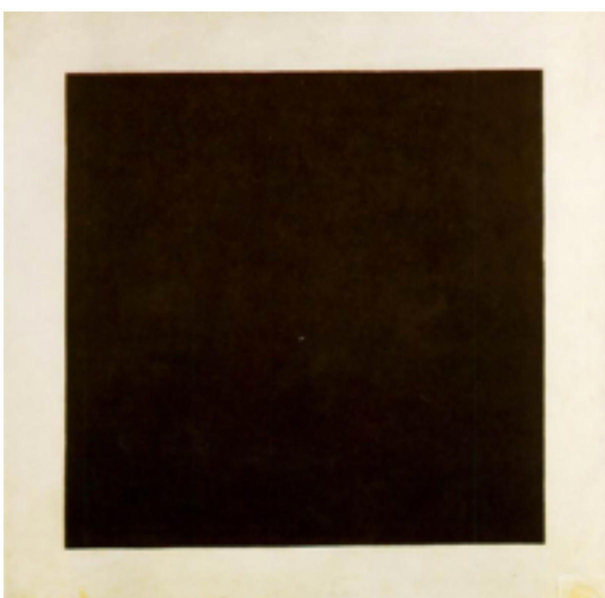
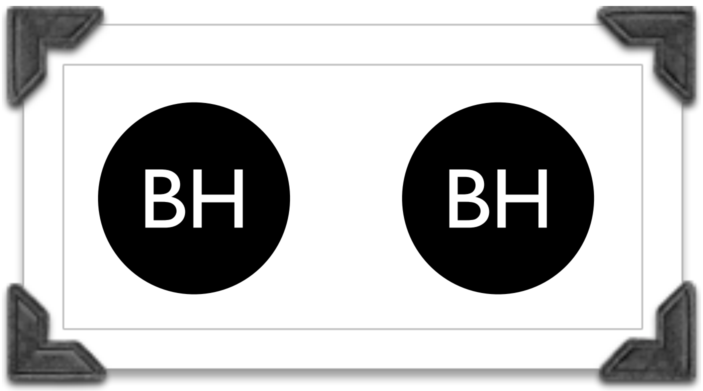
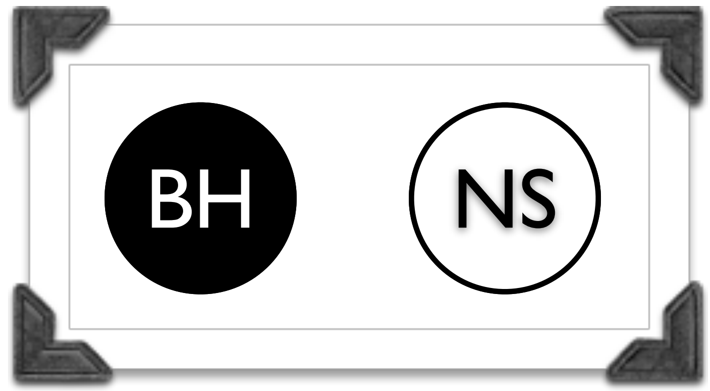
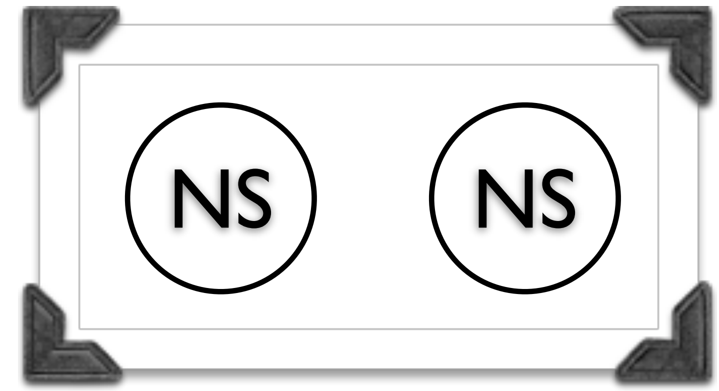


see also Perna+16

EM Counterparts to Binary Mergers







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but:

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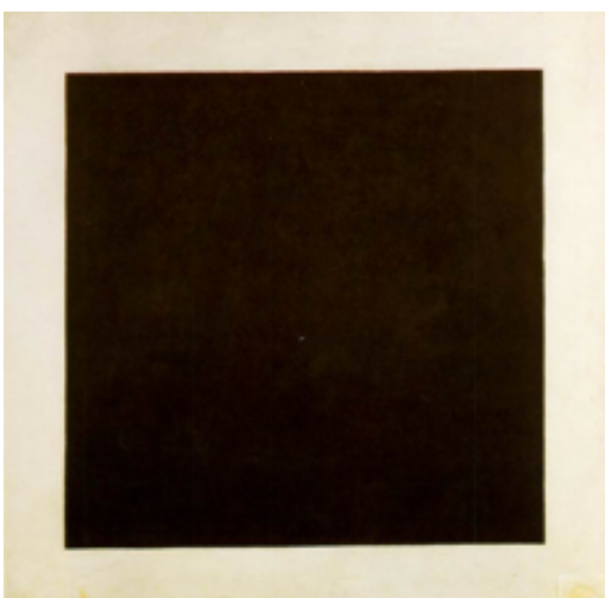
and can have EM counterparts:



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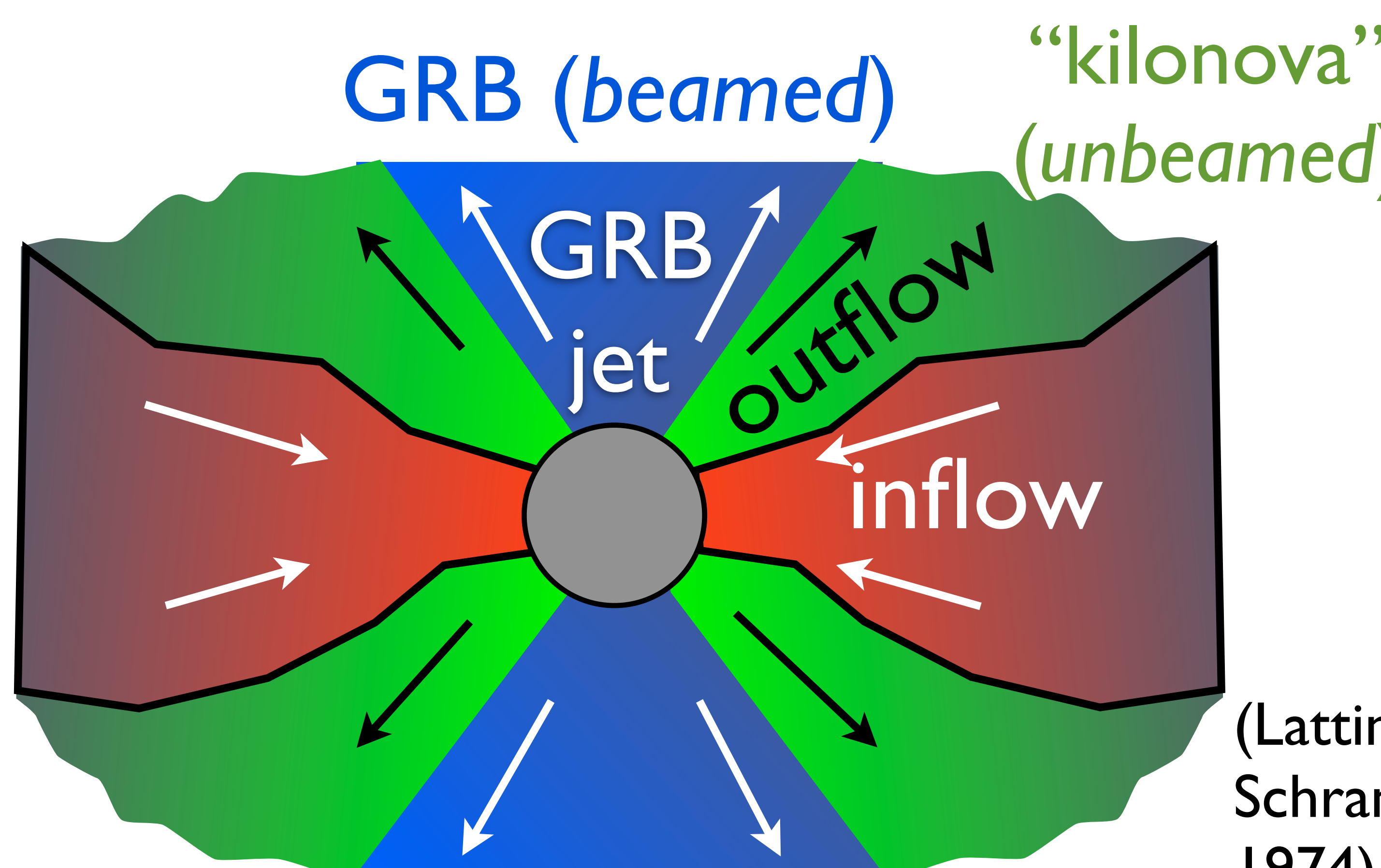
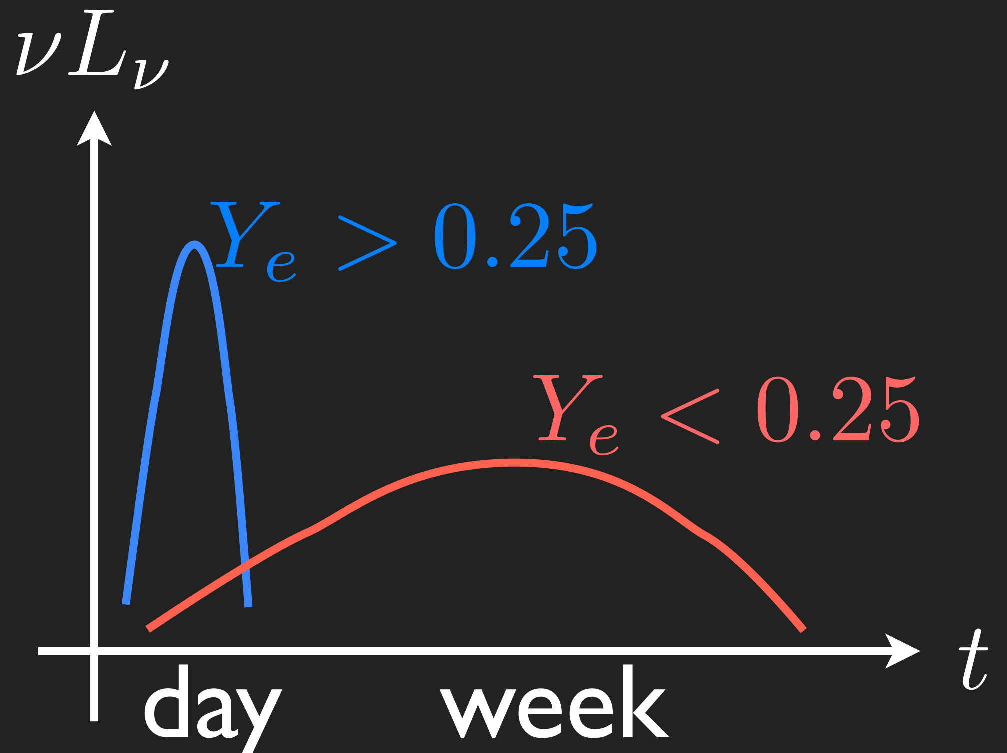


(Lattimer & Schramm 1974)

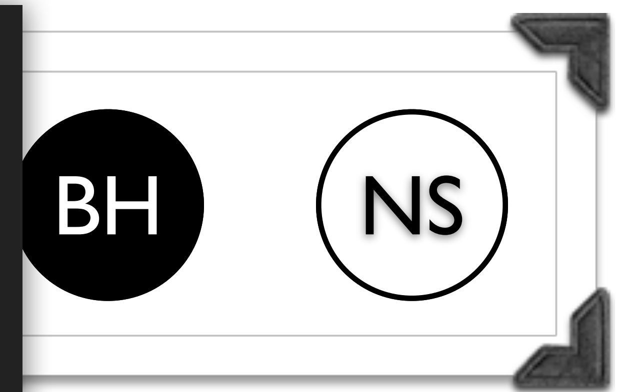
EM Counterparts to Binary Mergers

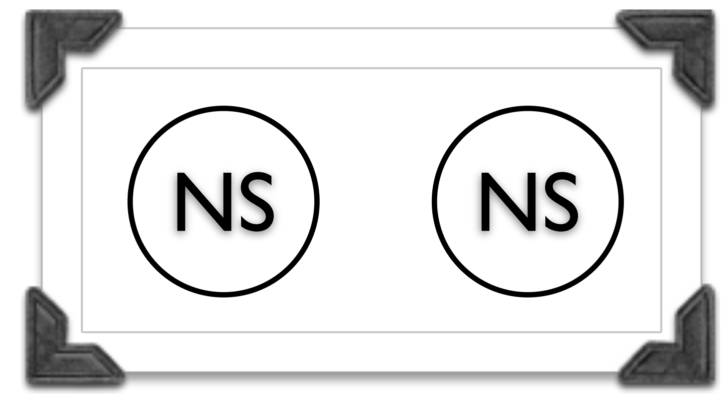
Effect of composition on kilonova light curves

Electron fraction $Y_e = \dfrac{n_e}{n_B}$



high Y_e = short blue luminous transient



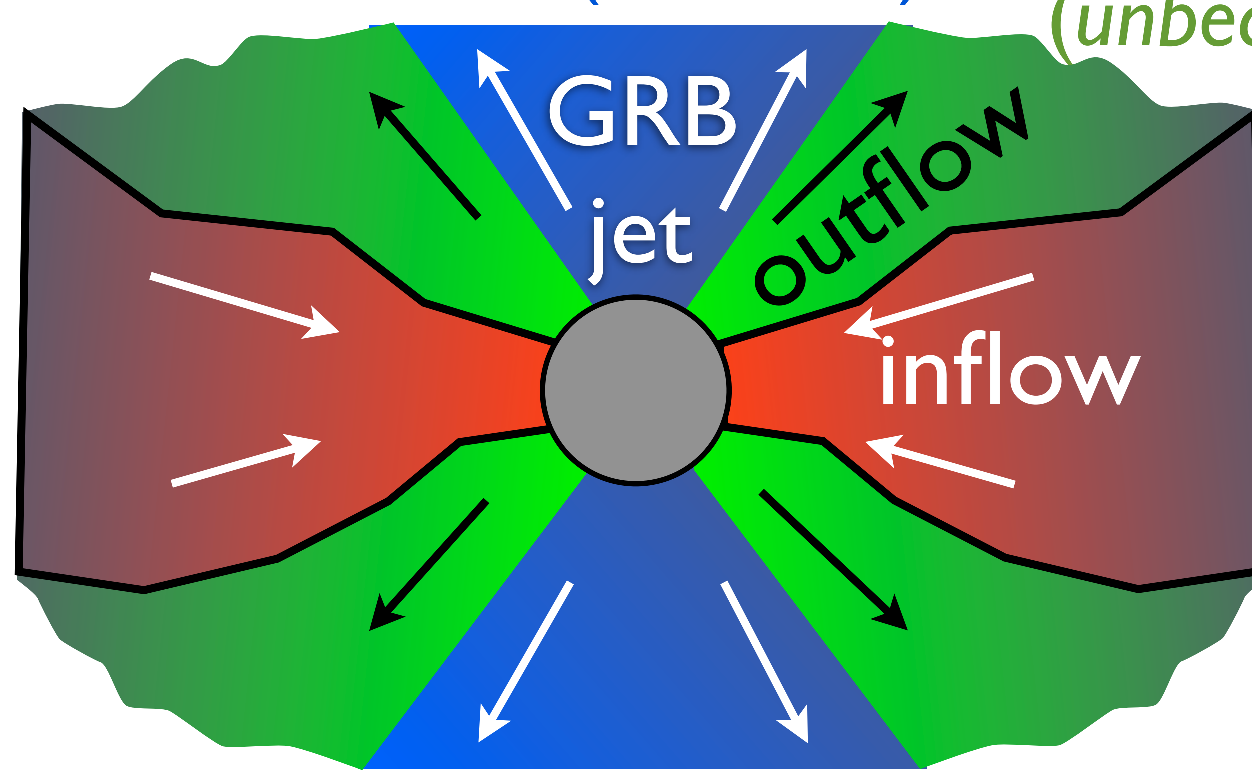


– detection might be imminent —

and can have EM counterparts:

GRB (*beamed*)

“kilonova” (*unbeamed*)



(Lattimer & Schramm 1974)

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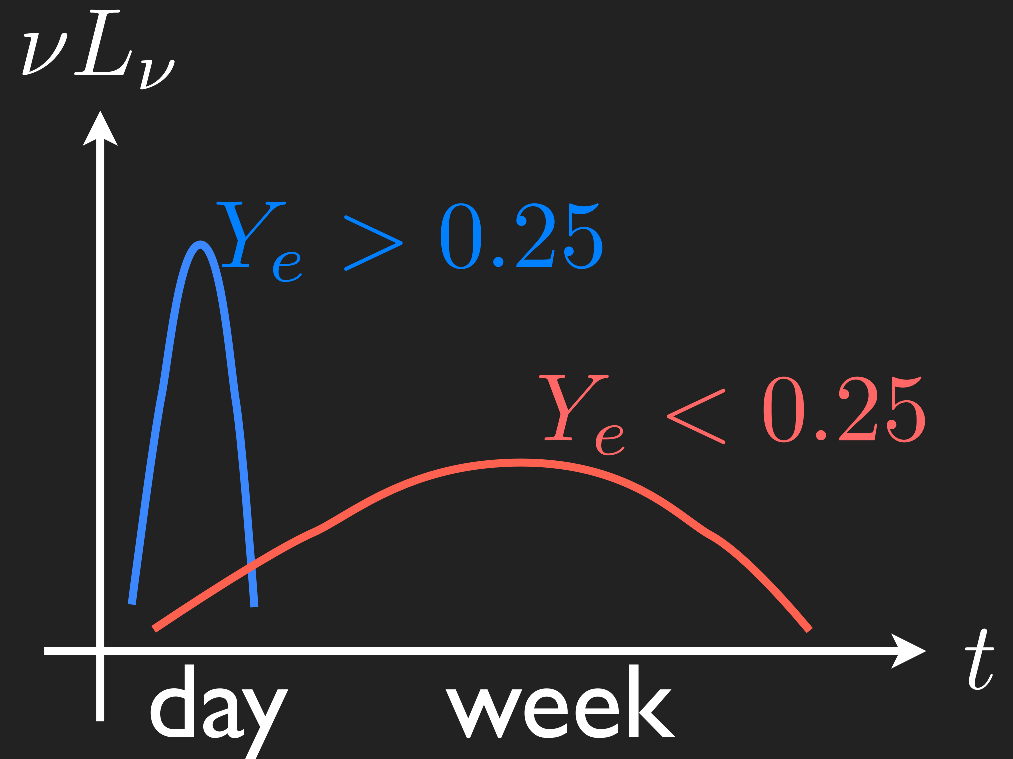
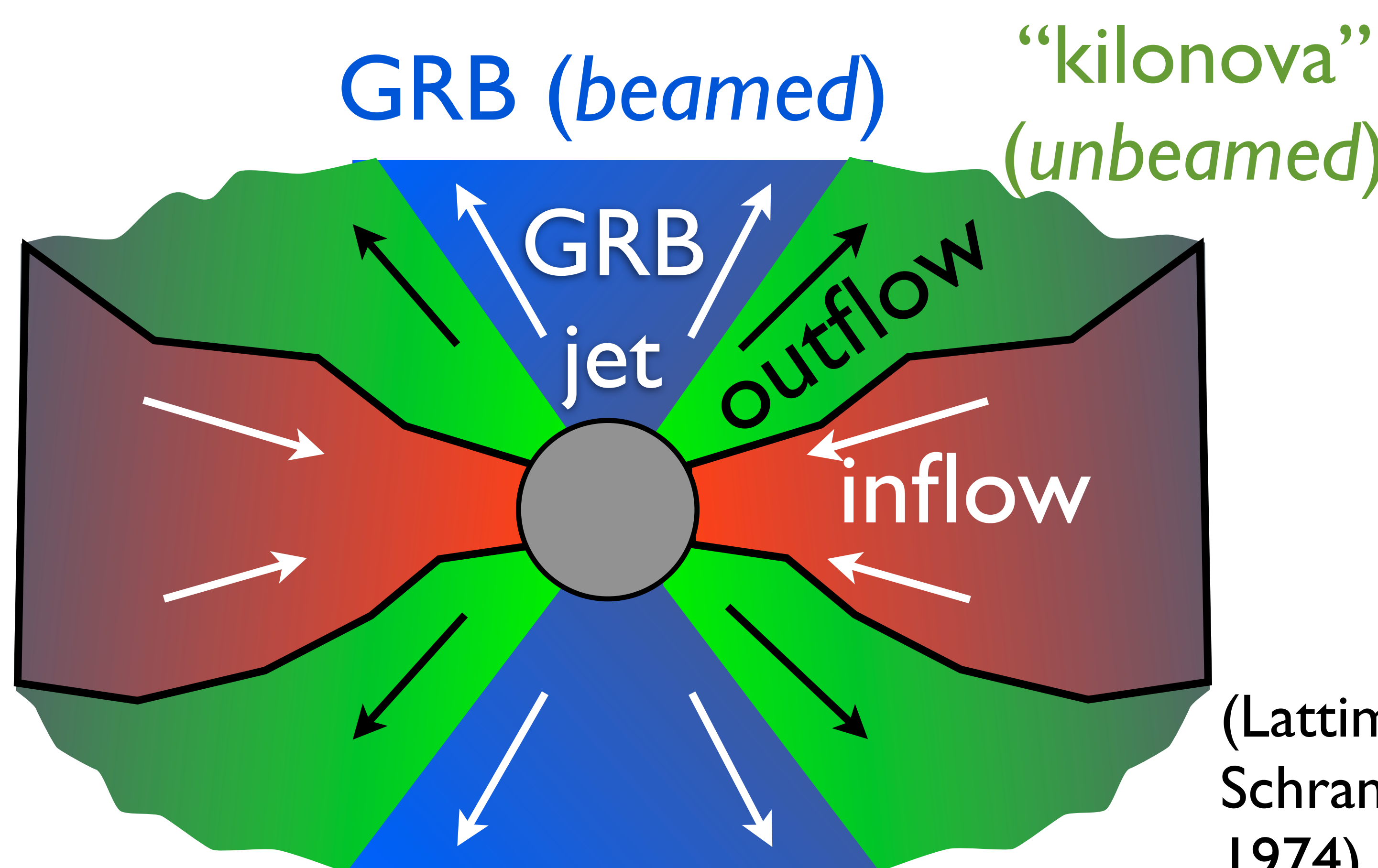


high Y_e = short blue luminous transient

- *Merger disk mass outflow*:
  - fully forms in ~5 seconds
  - only studied in 2D, neglecting GR and magnetic fields (Fernandez+15)
- Crucial to include both in 3D



(Lattimer & Schramm 1974)

Magnetic Fields Double Mass Outflow

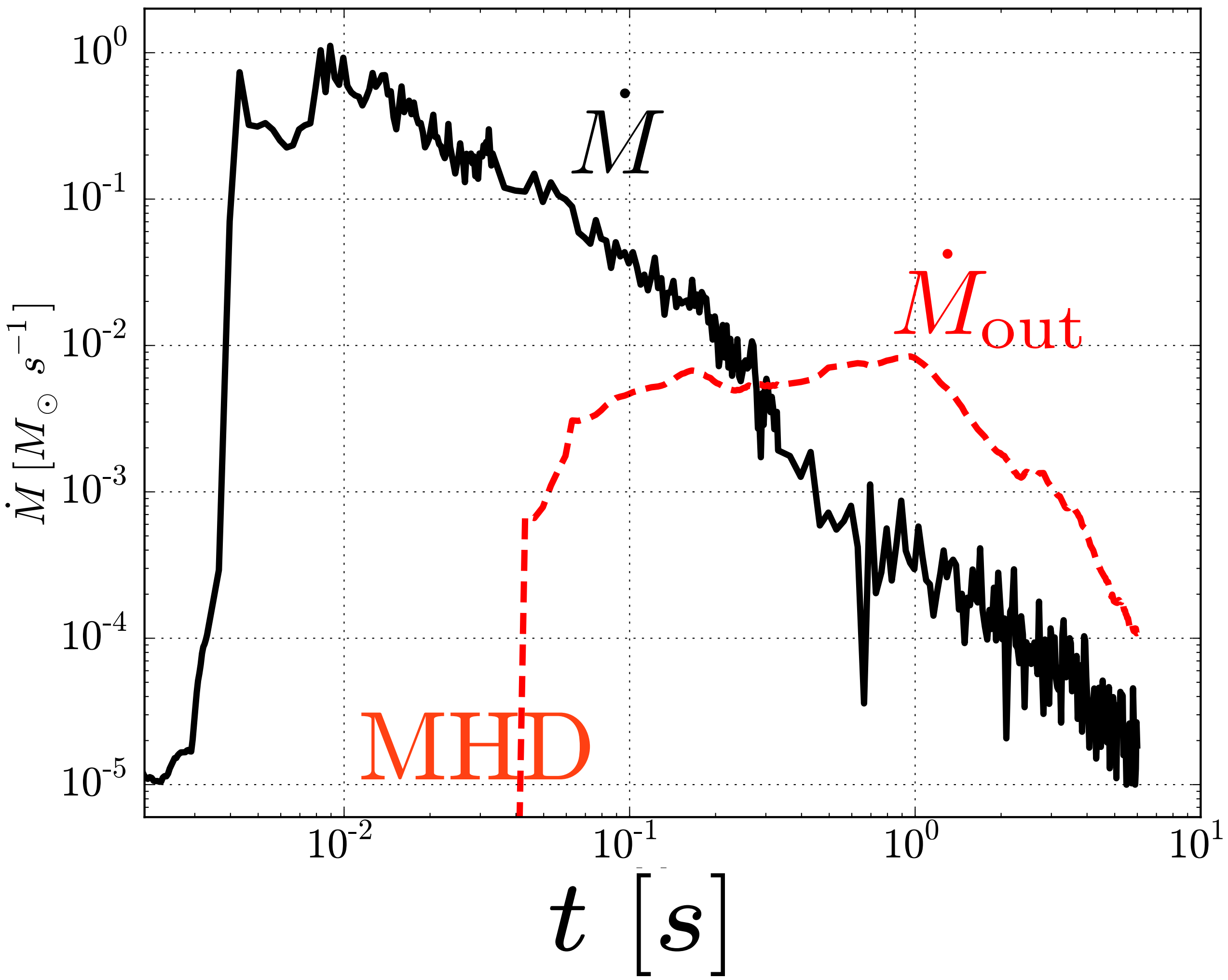
(AT, Fernandez+ 2016, in prep)

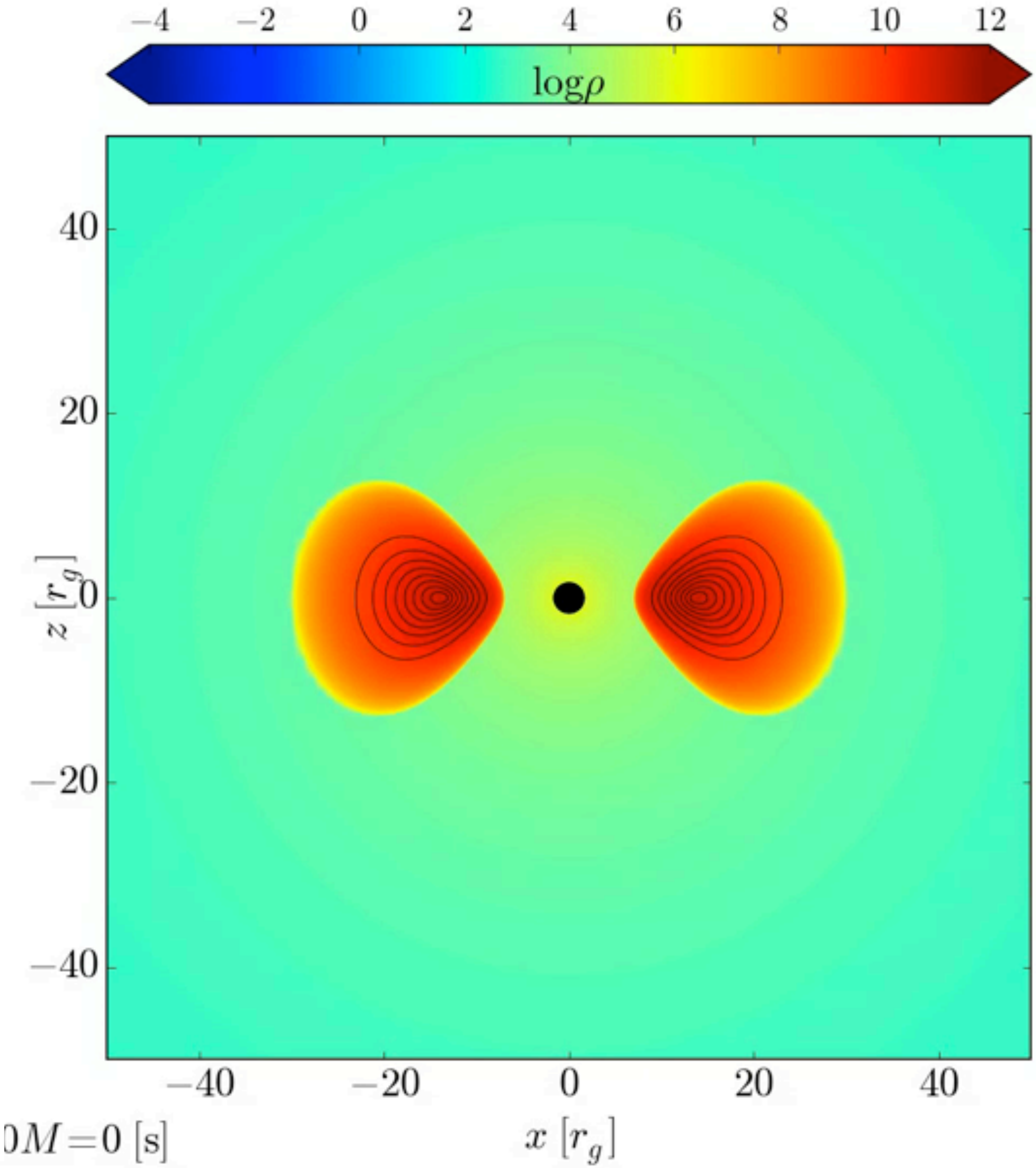
$$M_{\rm BH} = 3\ M_{\rm sun}$$
$$M_{\rm disk} = 0.03\ M_{\rm sun}$$
$$a = 0.8$$
$$B_p = 10^{15}\ G$$

- Implemented into HARMPI:
  - neutrino emission
  - nuclear recombination

Magnetic Fields Double Mass Outflow

(AT, Fernandez+ 2016, in prep)





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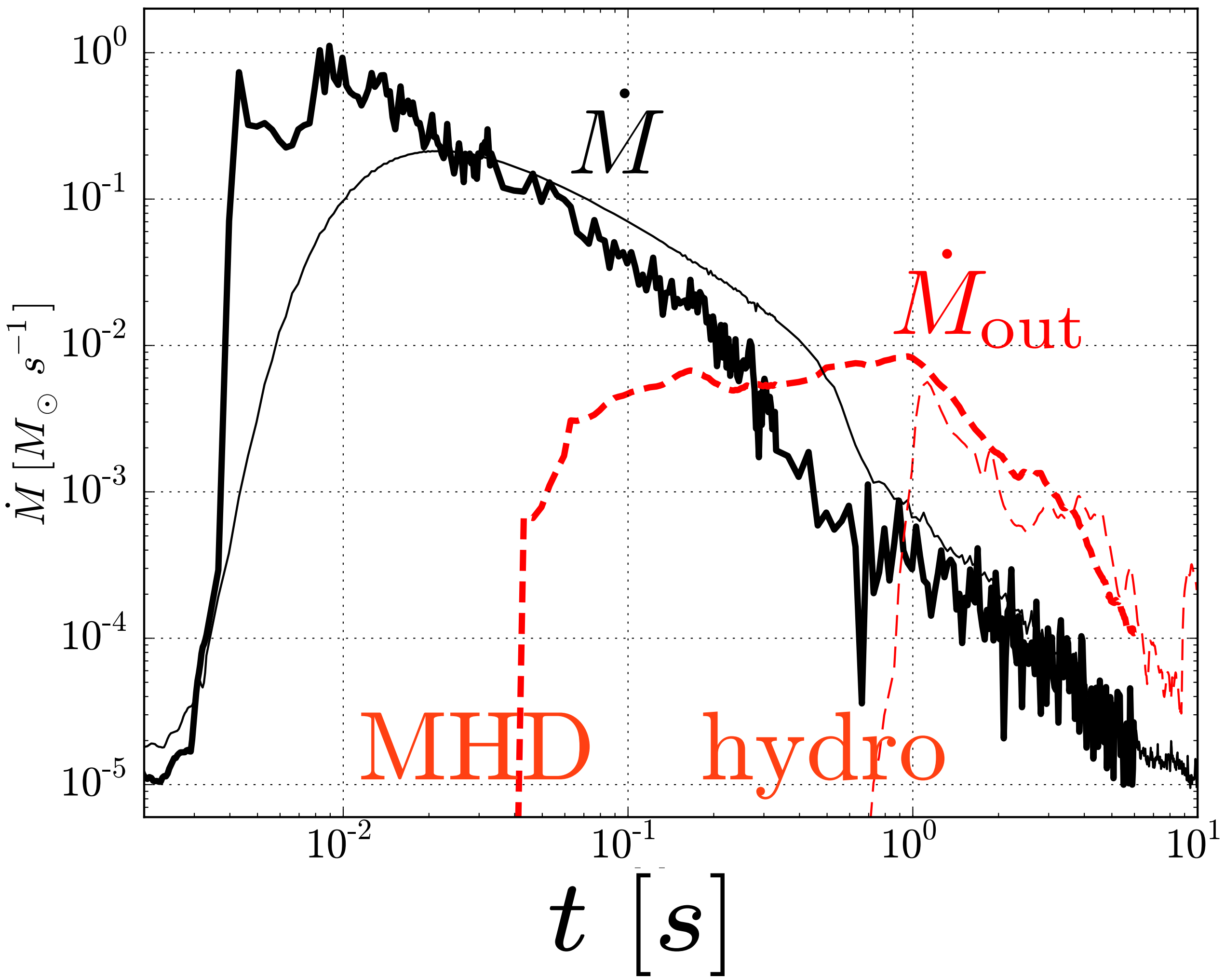

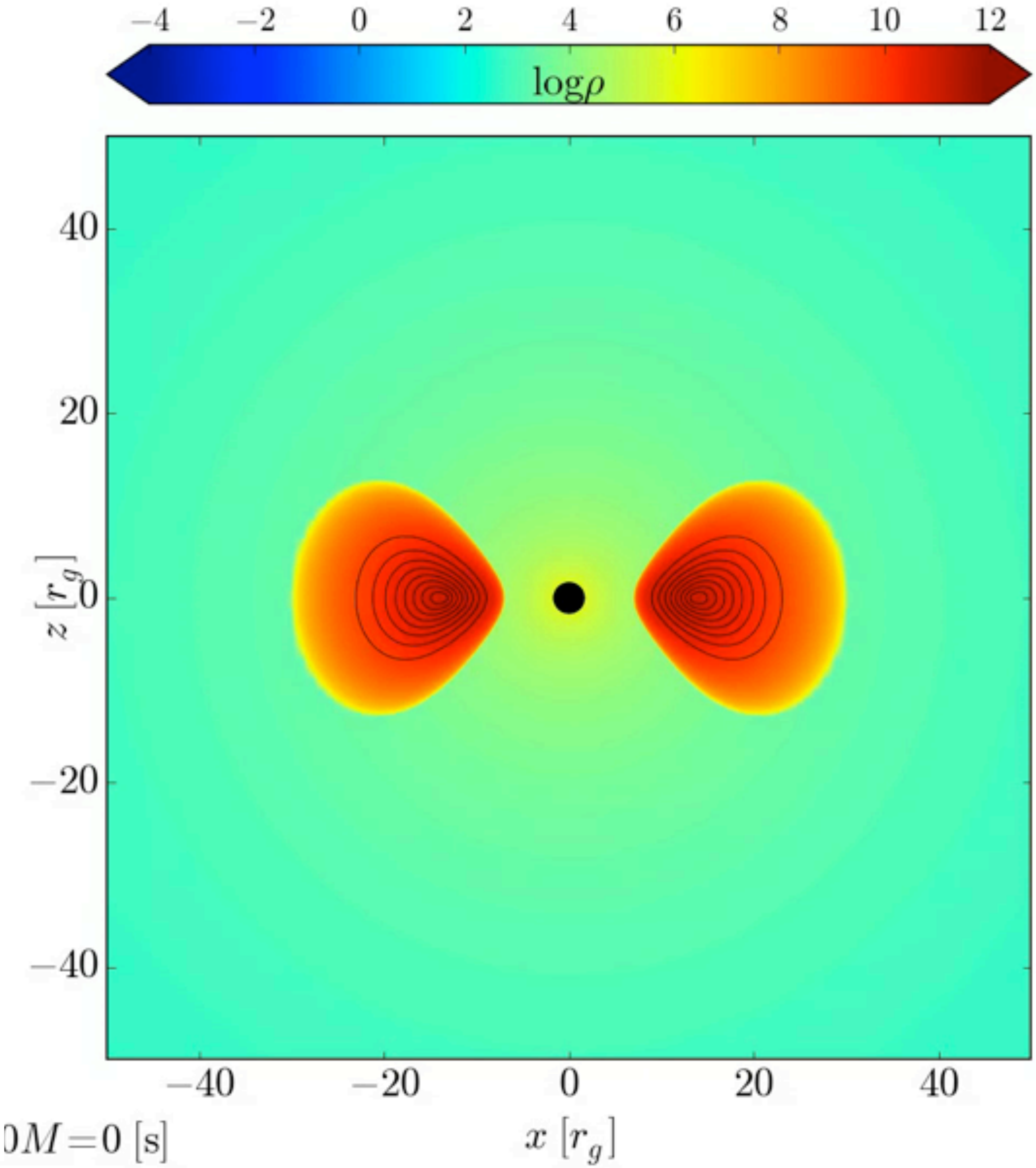

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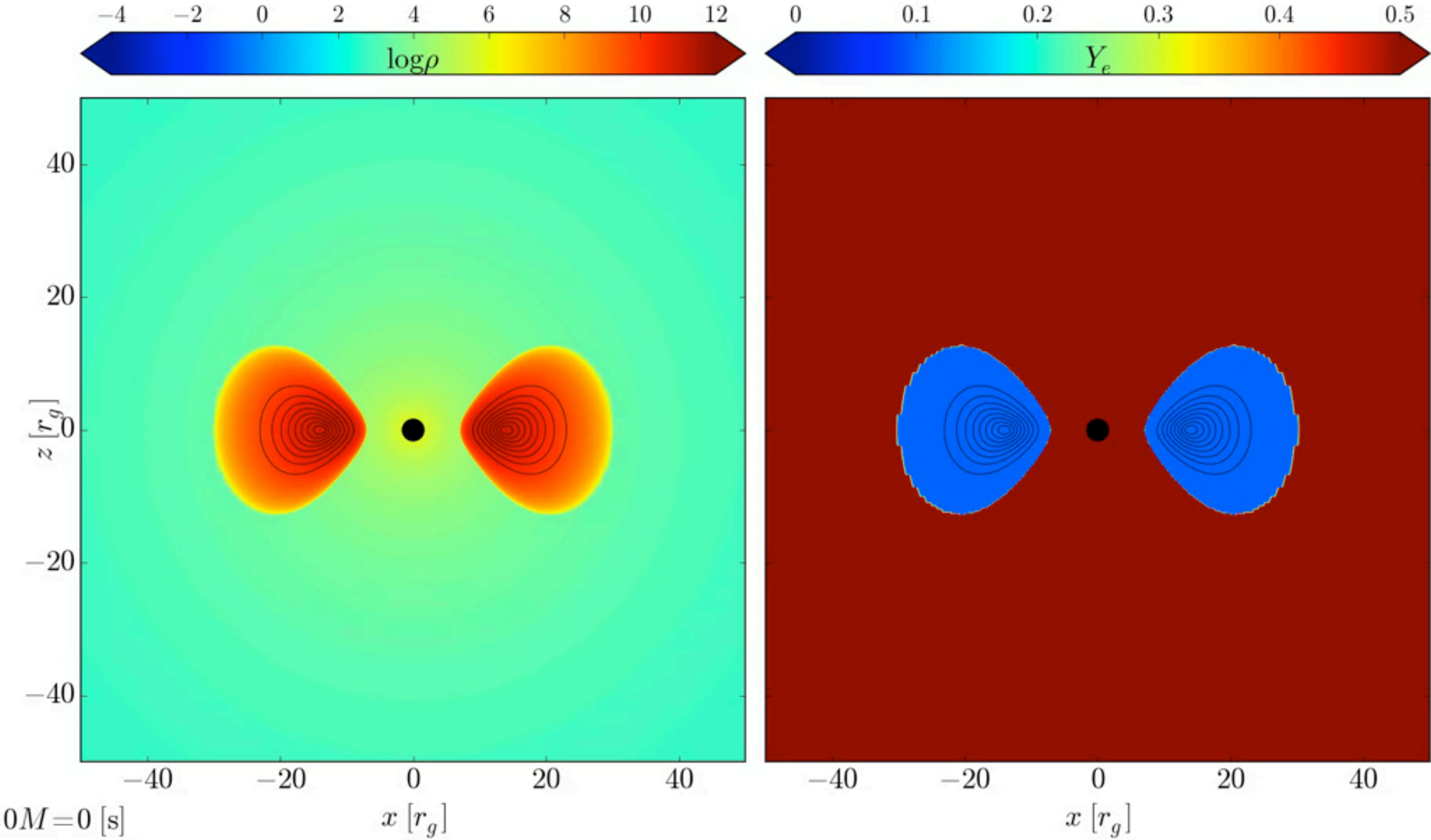
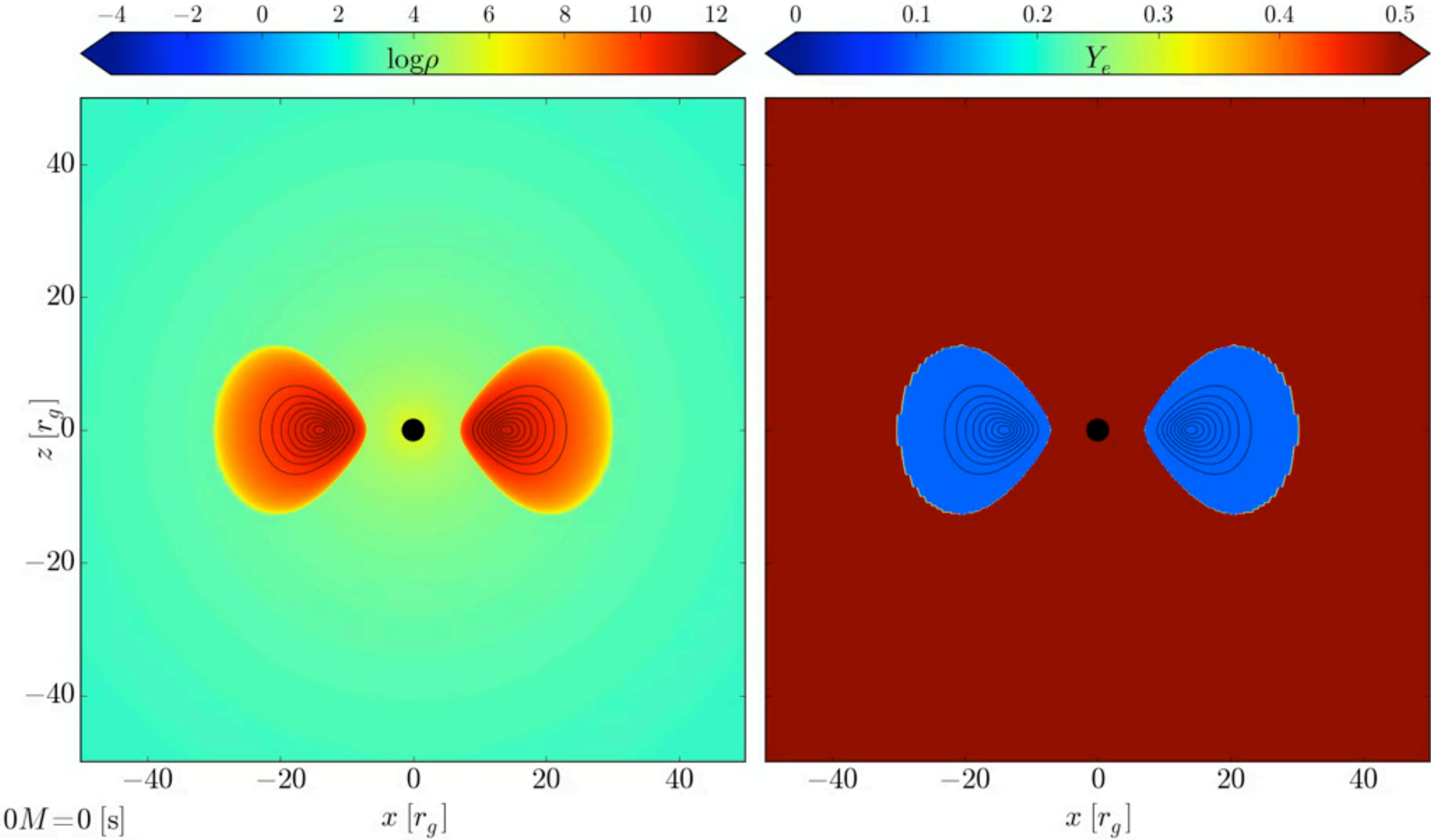


The longest 3D GRMHD simulation ever: cost ~5M CPU-hours

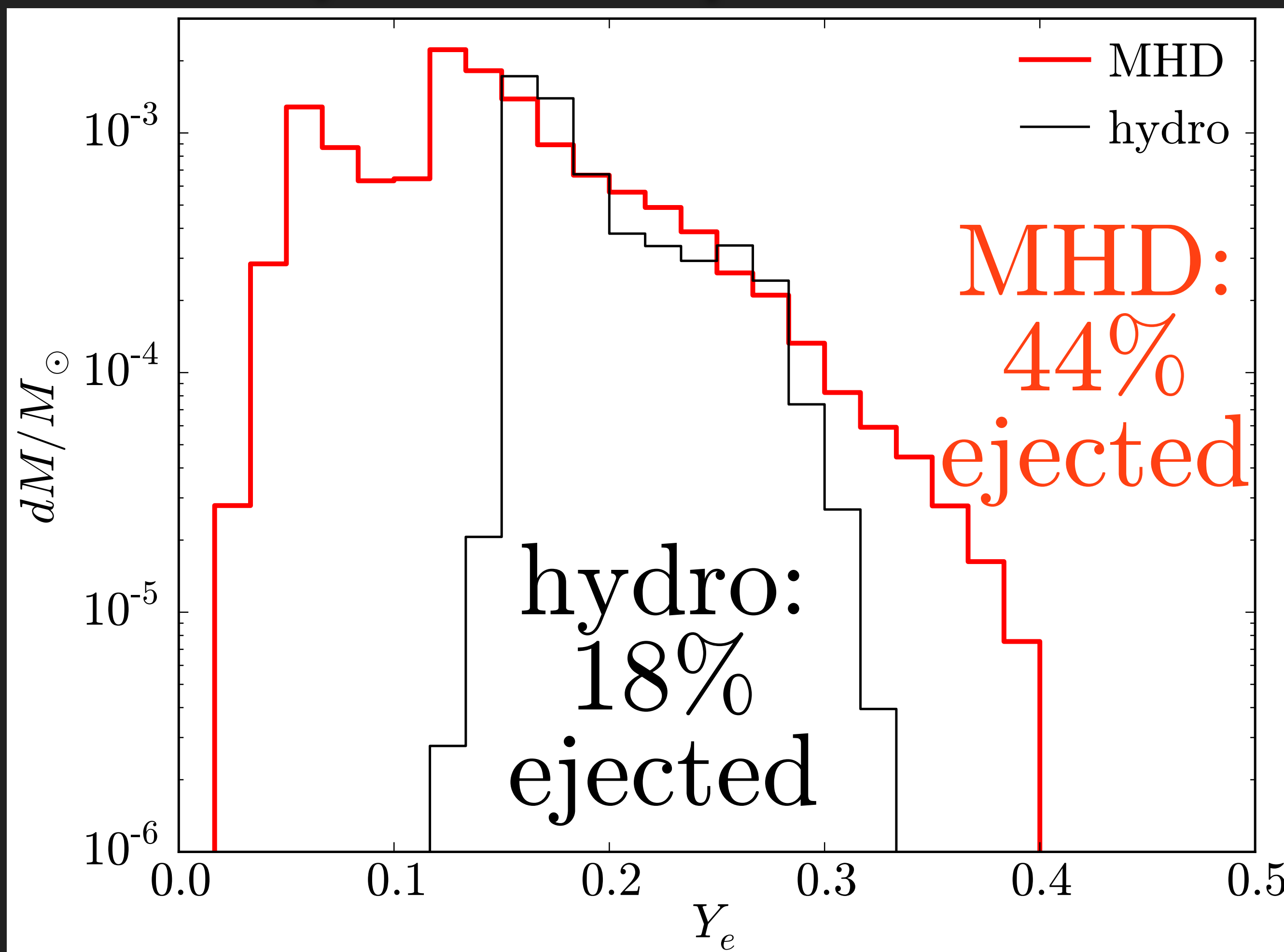
Magnetic Fields Double Mass Outflow



The longest 3D GRMHD simulation ever: cost ~5M CPU-hours

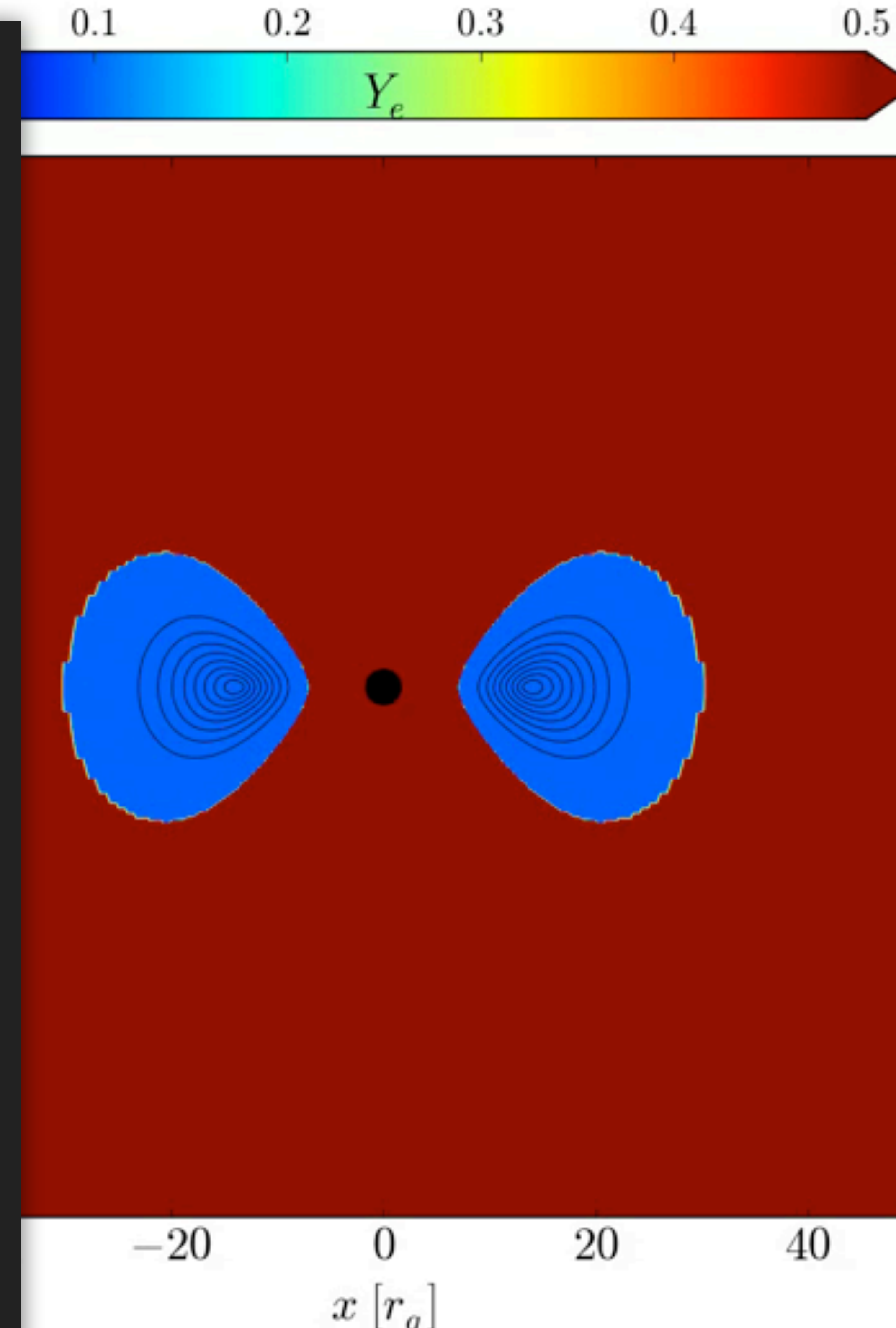
Magnetic Fields Double Mass Outflow

Ejecta composition



Magnetic effects lead to:

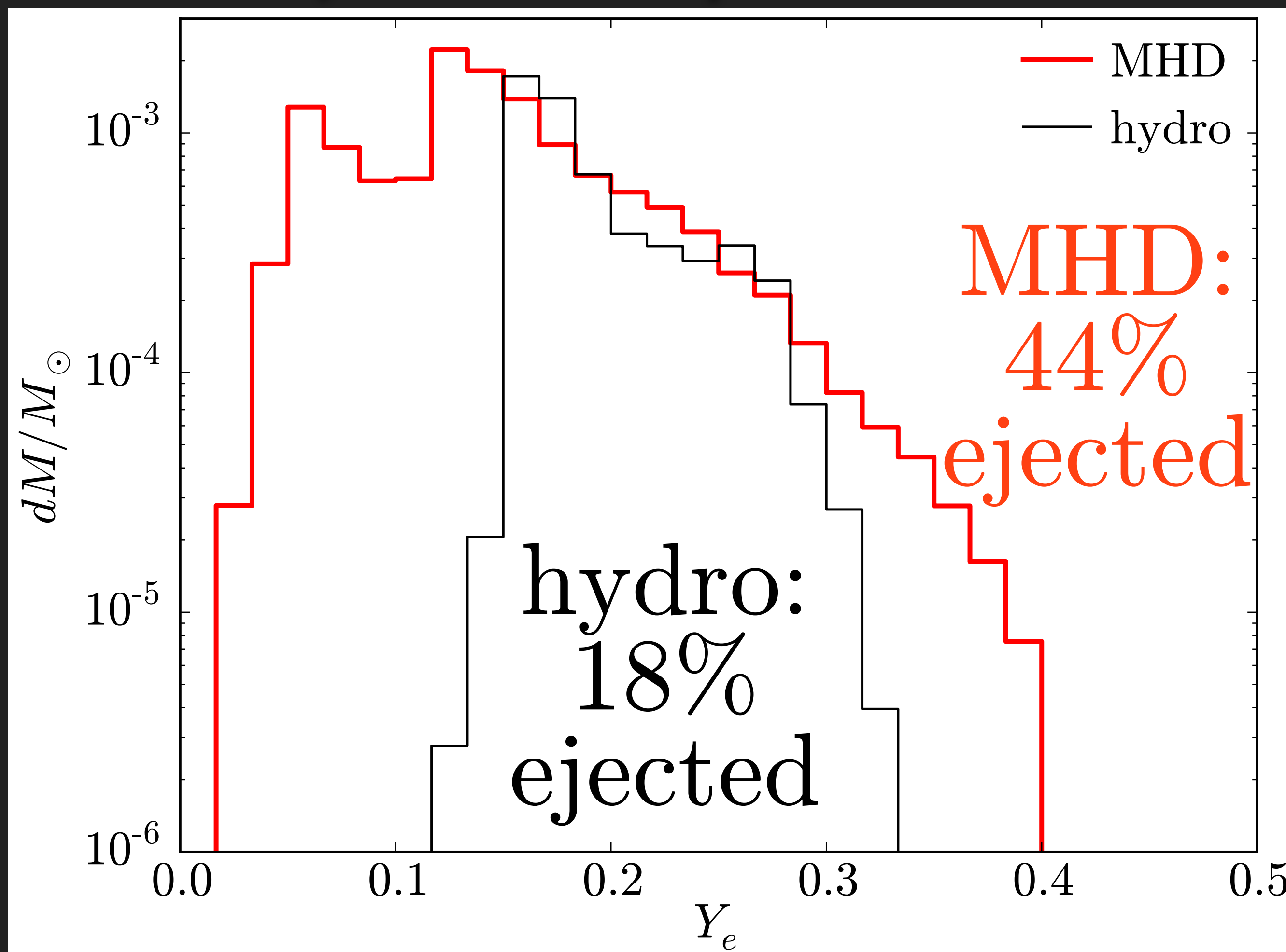
- 2.5x increase in ejecta mass
  - *brighter kilonova*
- broader ejecta composition
  - *more heavy element enrichment*



ver: cost ~5M CPU-hours

Magnetic Fields Double Mass Outflow

Ejecta composition



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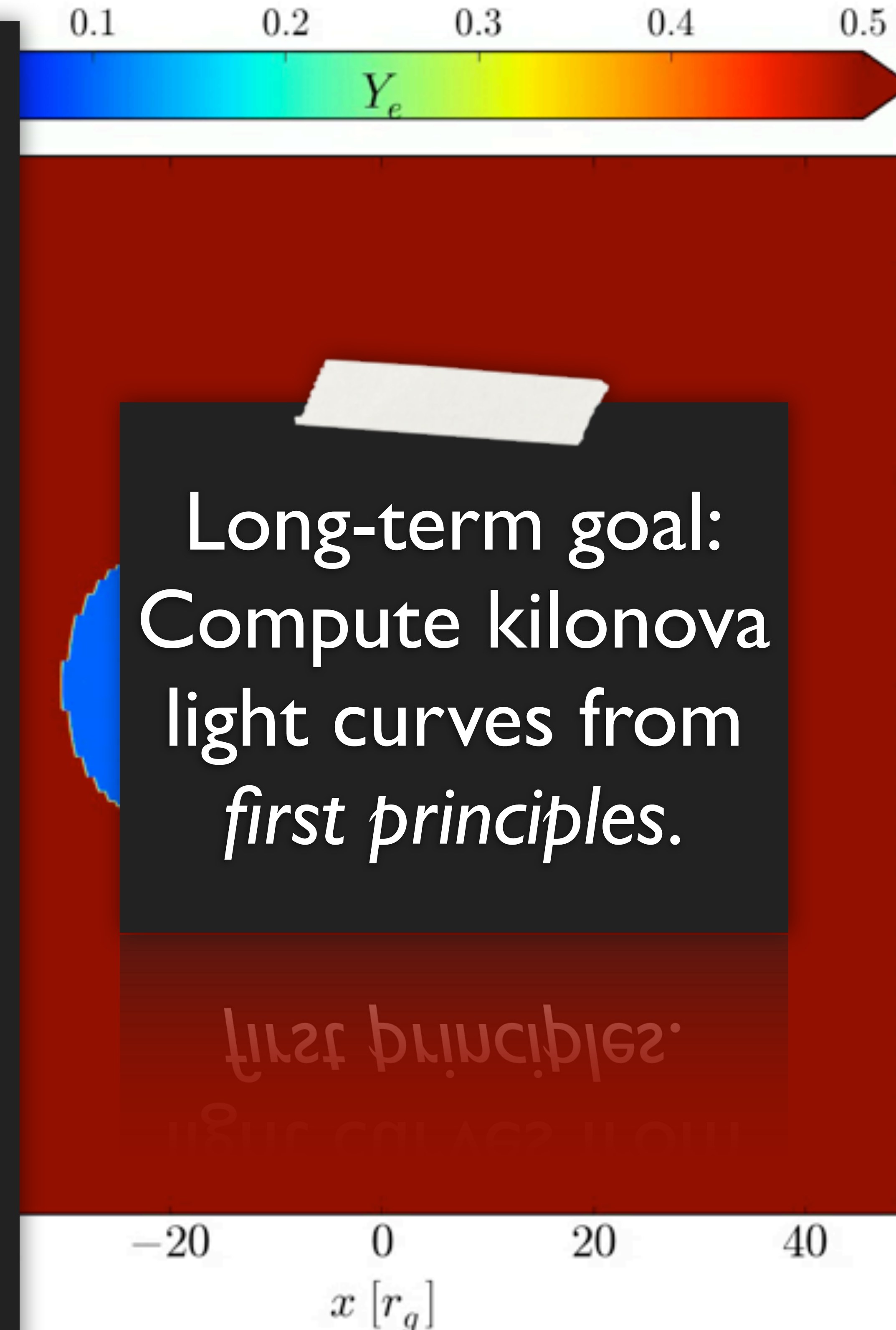
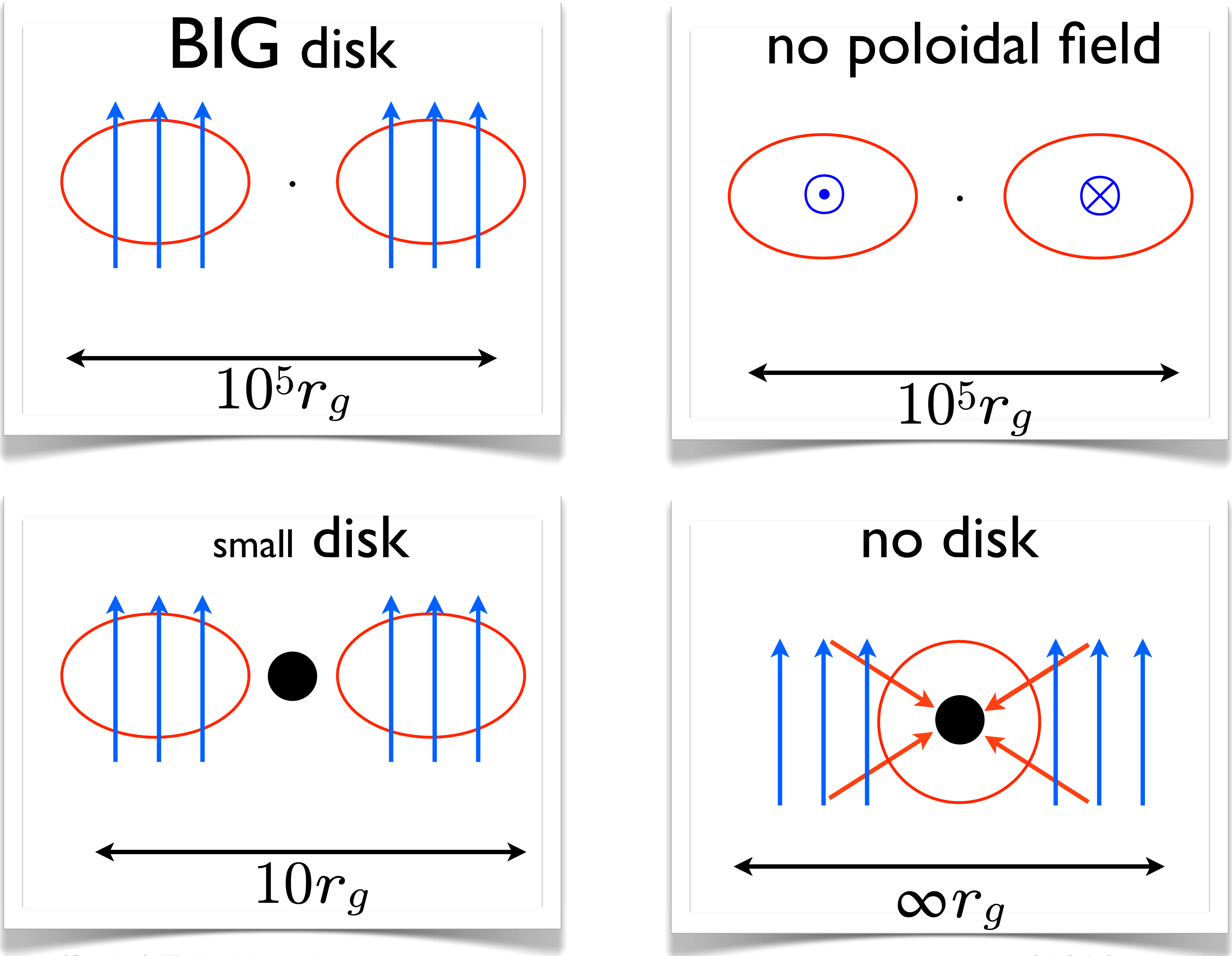


Long-term goal: Compute kilonova light curves from *first principles.*

ver: cost ~5M CPU-hours

What is a Healthy Jet Diet?



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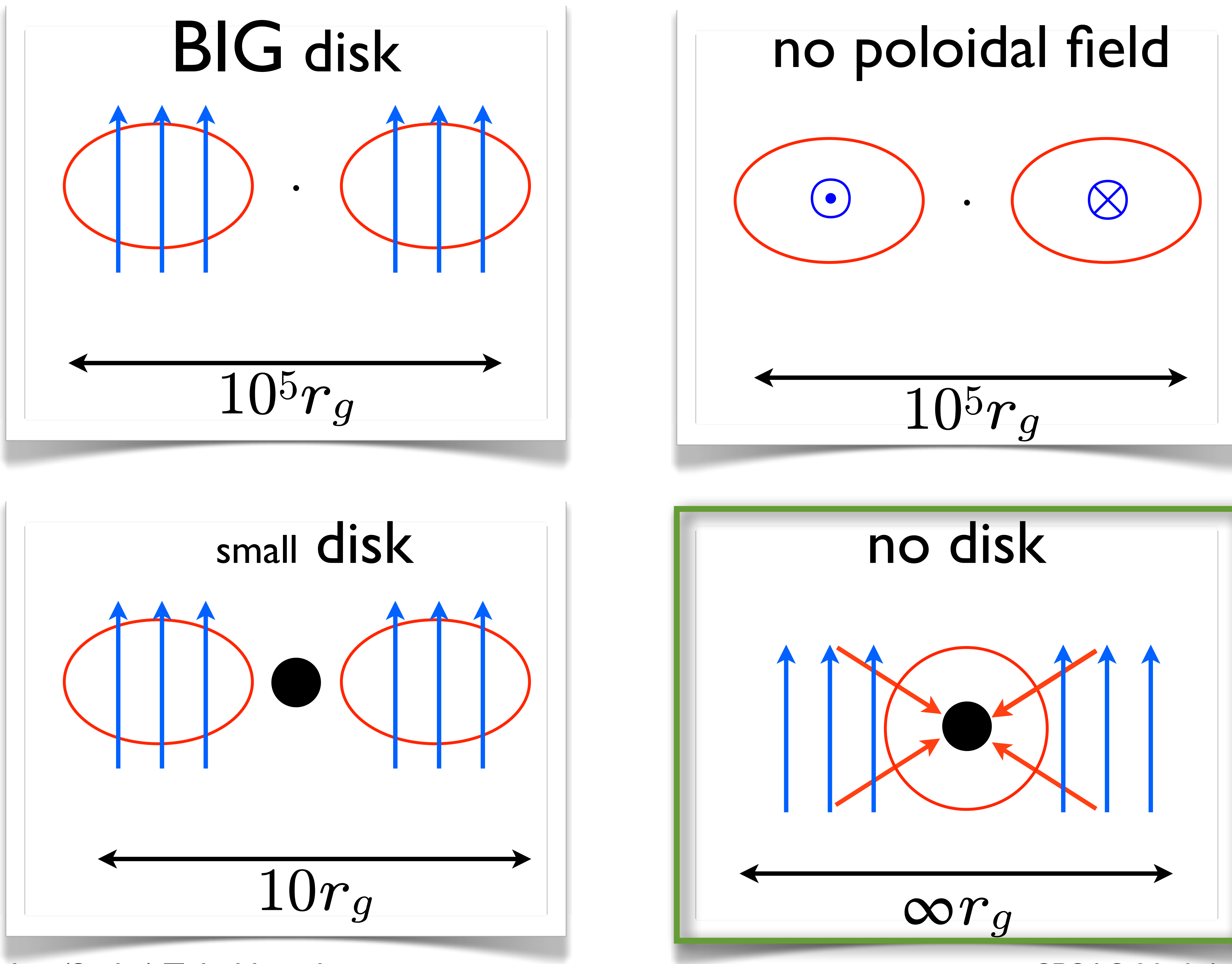
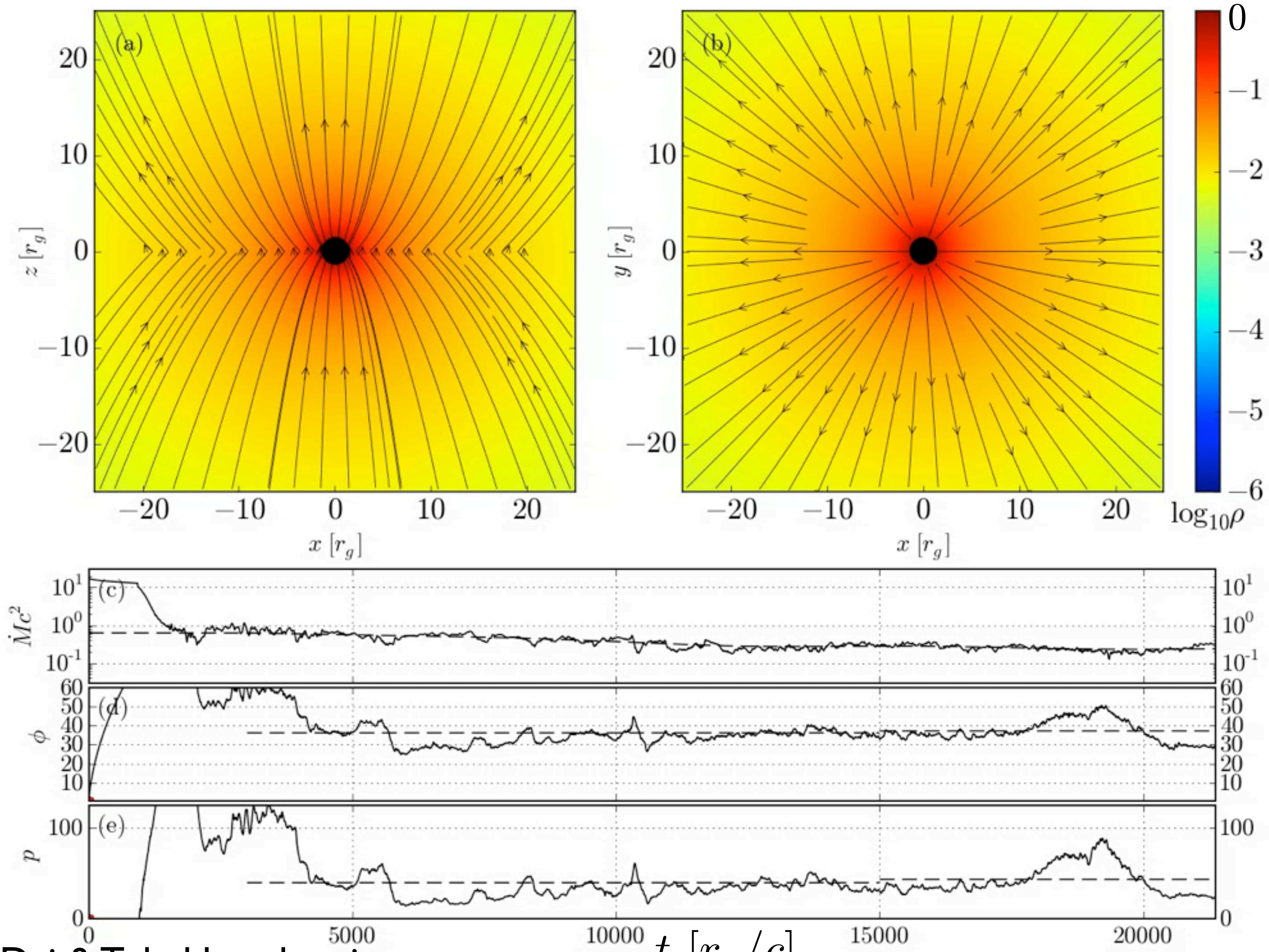


$a = 0.9$
spherical accretion
no rotation

Dai & Tchekhovskoy, in prep

$t\ [r_g/c]$



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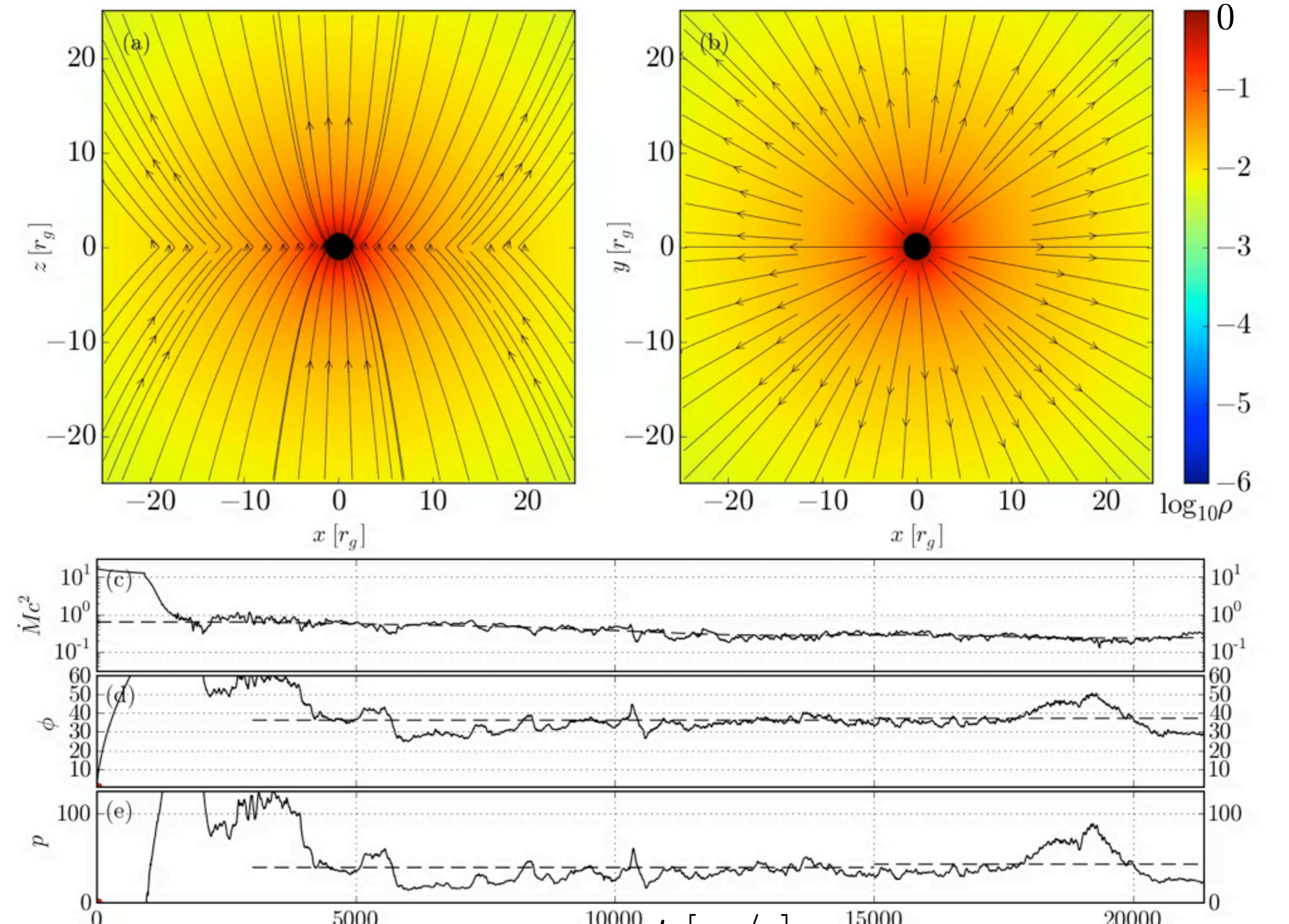

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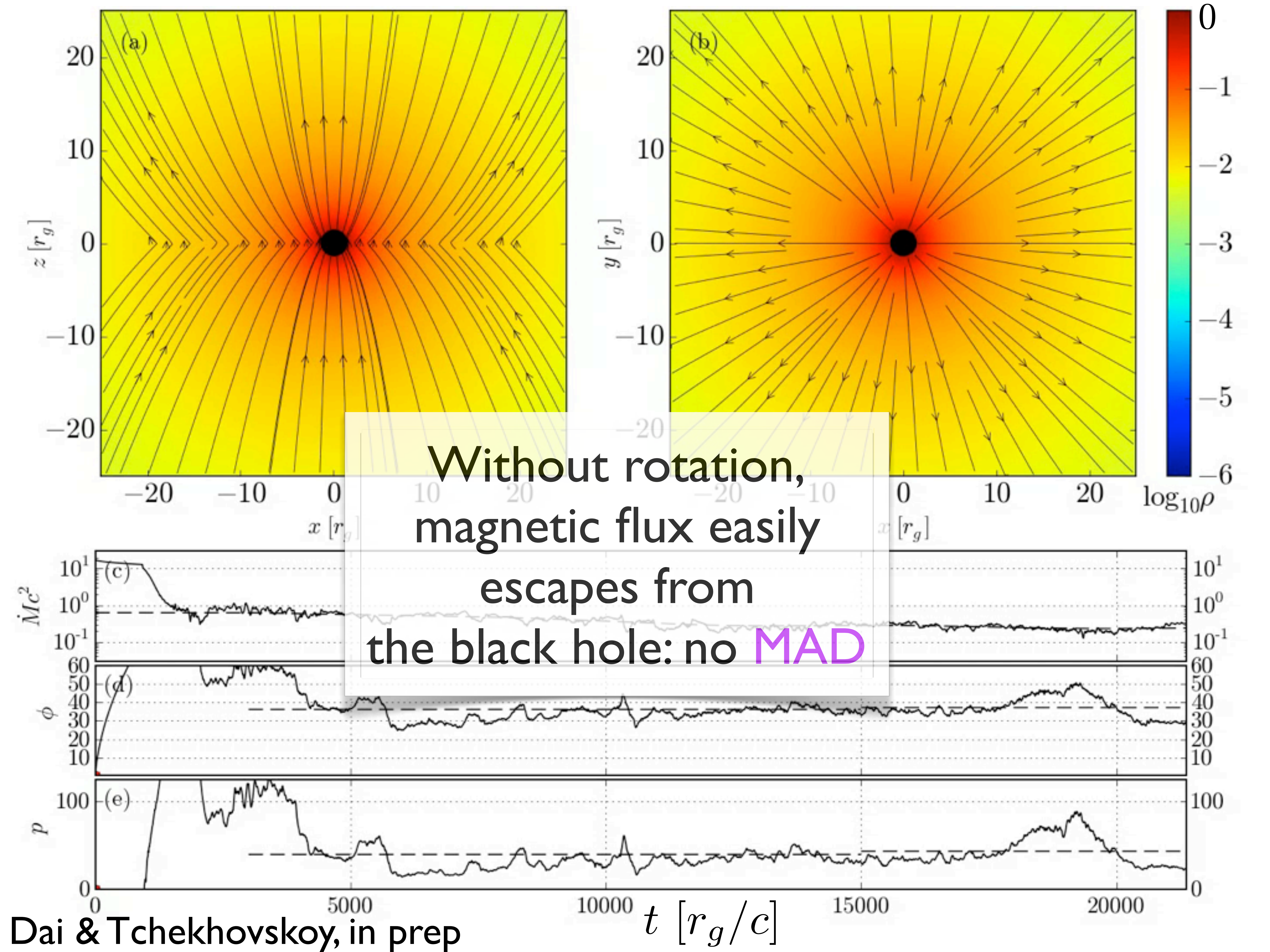


(a)
(b)
(c)
(d)
(e)
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
$\log_{10}\rho$
$\dot{M}c^2$
ϕ
p
$t\ [r_g/c]$
Without rotation, magnetic flux easily escapes from the black hole: no MAD
Dai & Tchekhovskoy, in prep

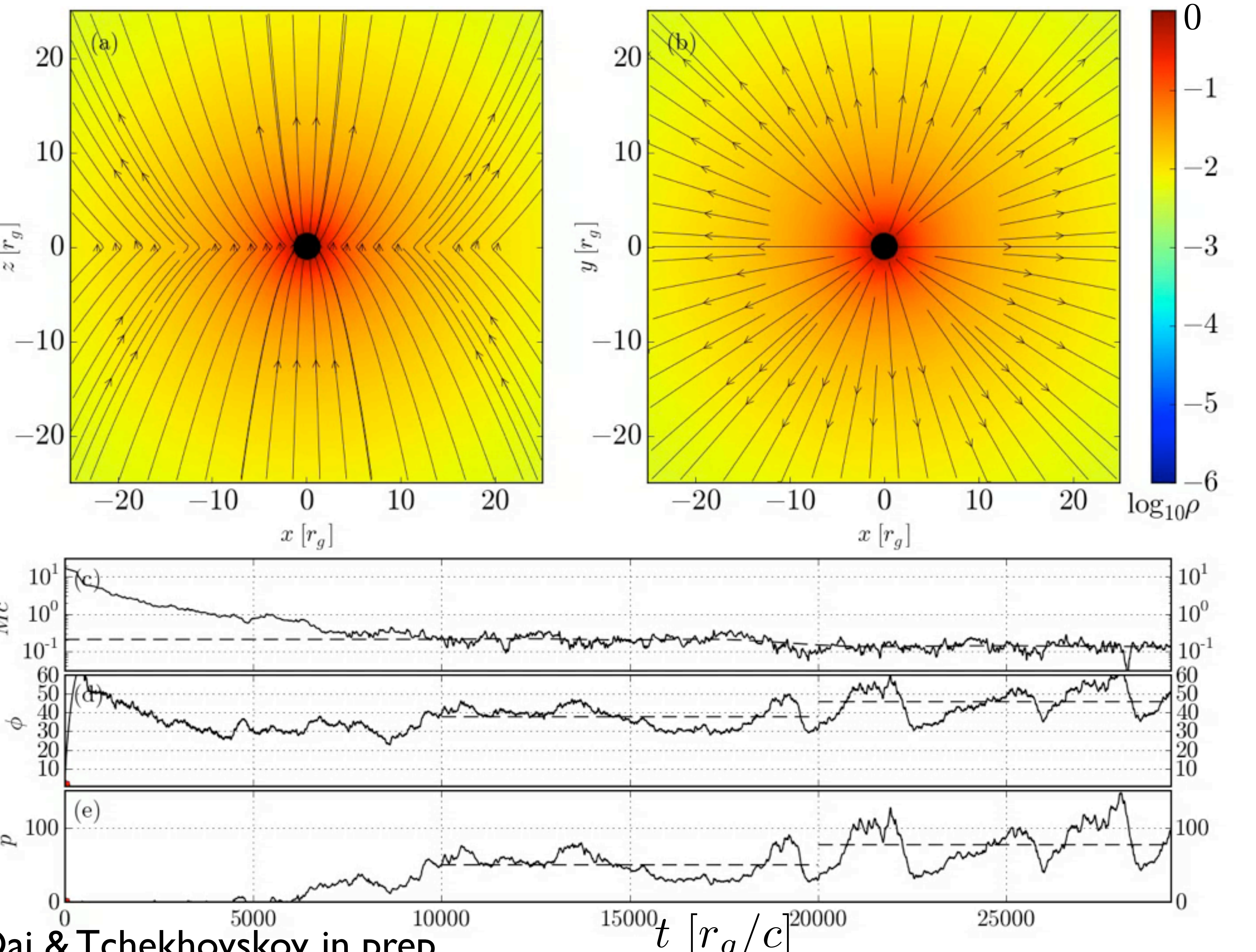
$a = 0.9$

spherical accretion

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

Dai & Tchekhovskoy, in prep

$t\ [r_g/c]$



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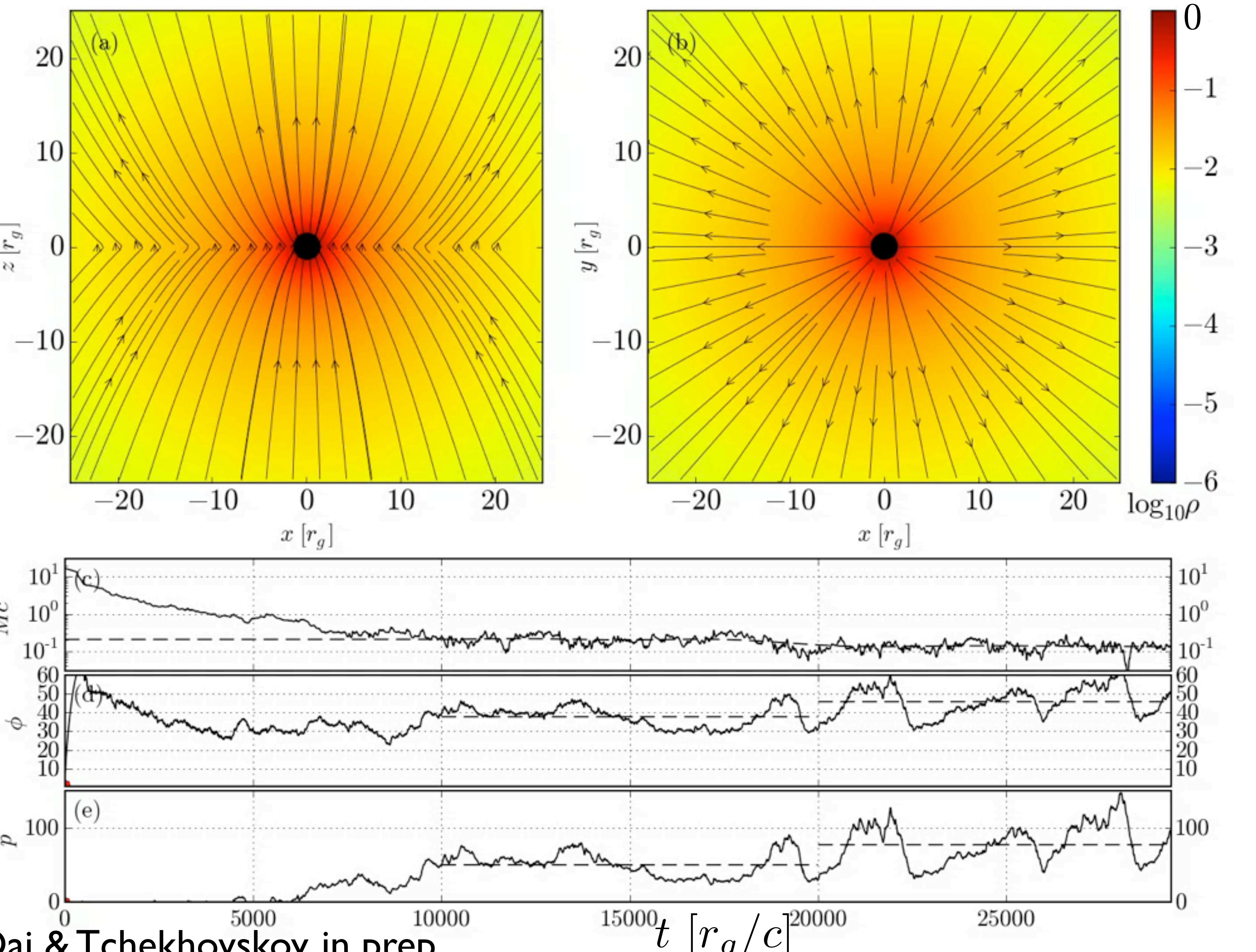

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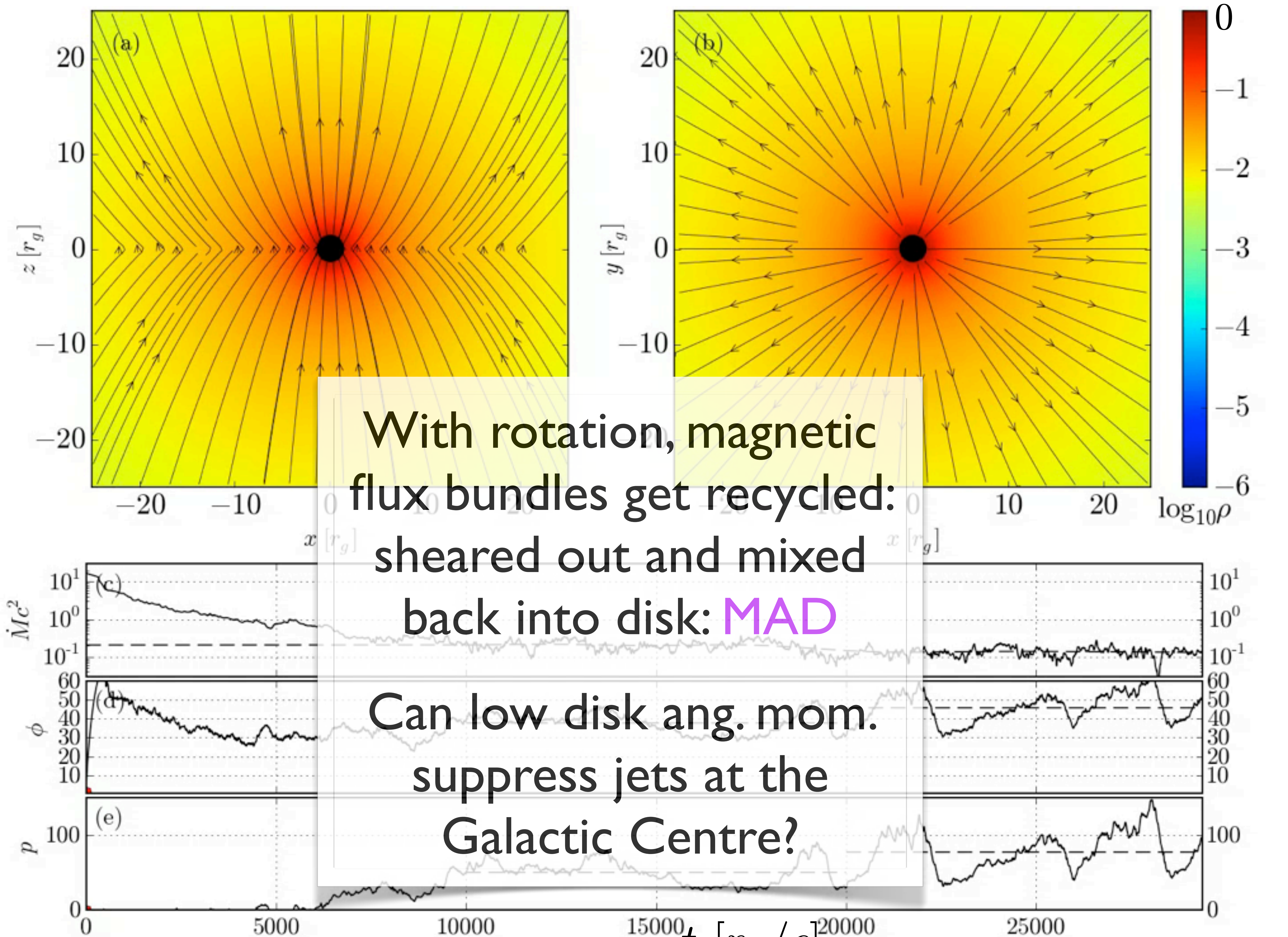

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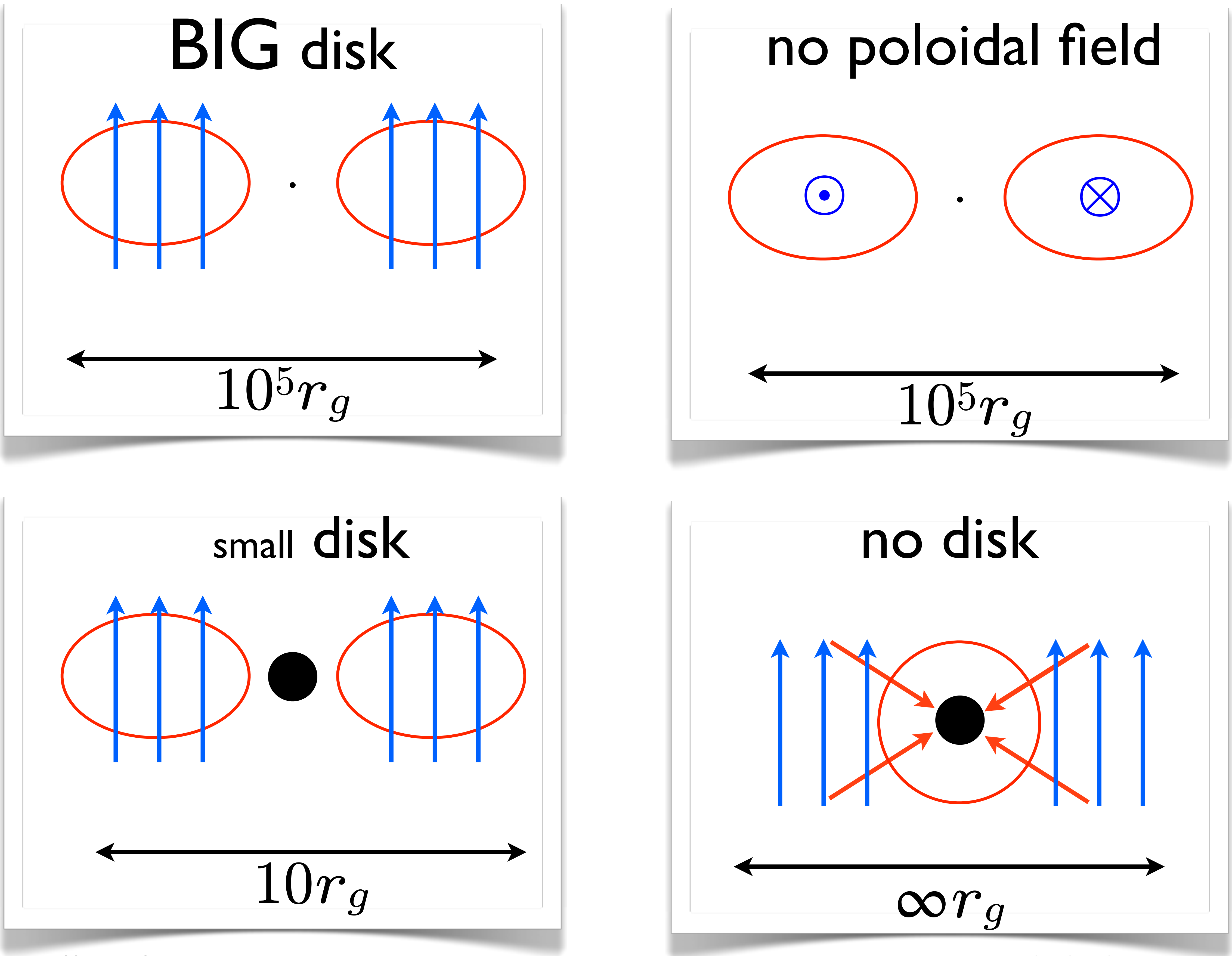

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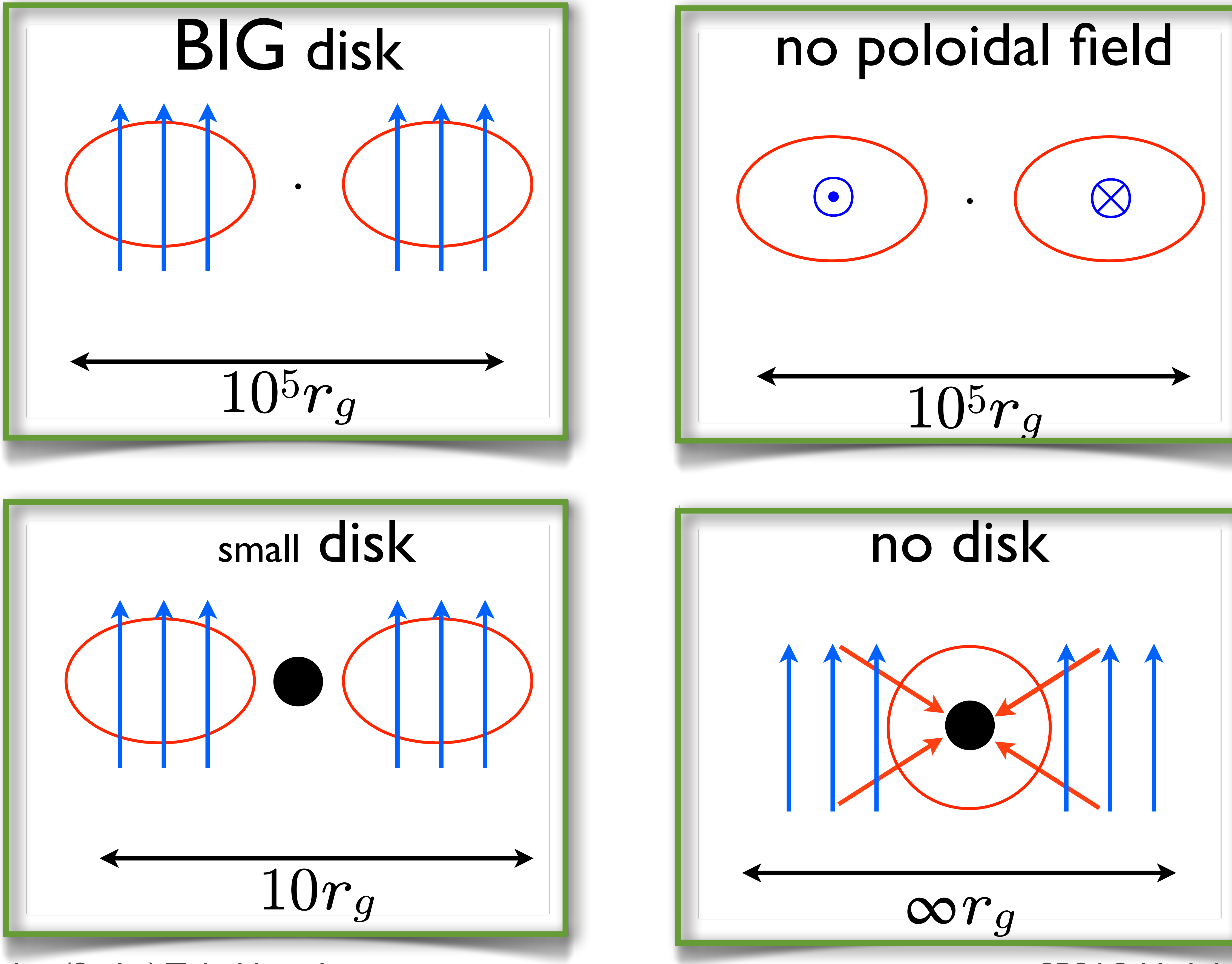

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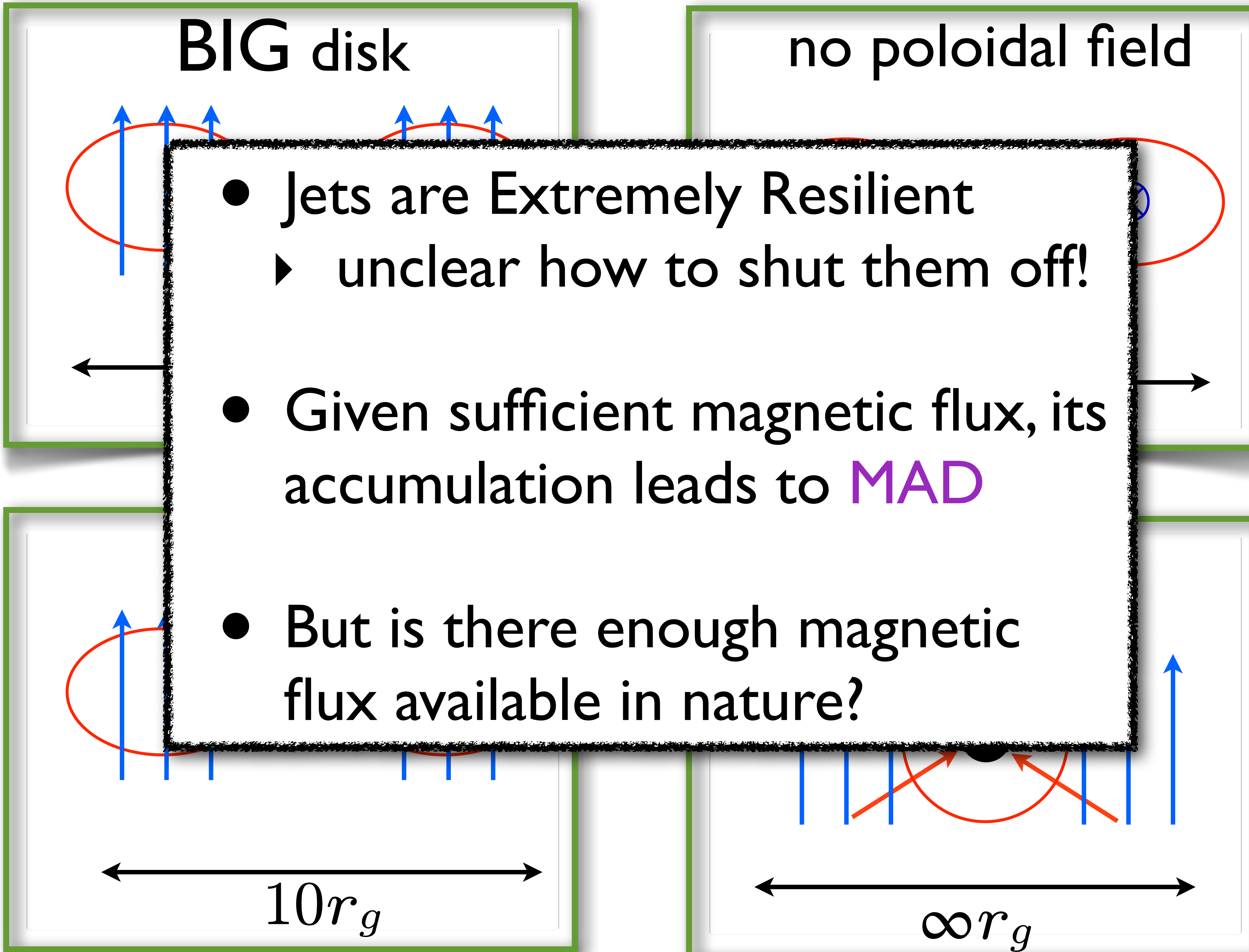


- Jets are Extremely Resilient
  - unclear how to shut them off!
- Given sufficient magnetic flux, its accumulation leads to MAD
- But is there enough magnetic flux available in nature?

When are Jets Produced?

MADs:

(AT+13, 17
AT & Giannios 15)

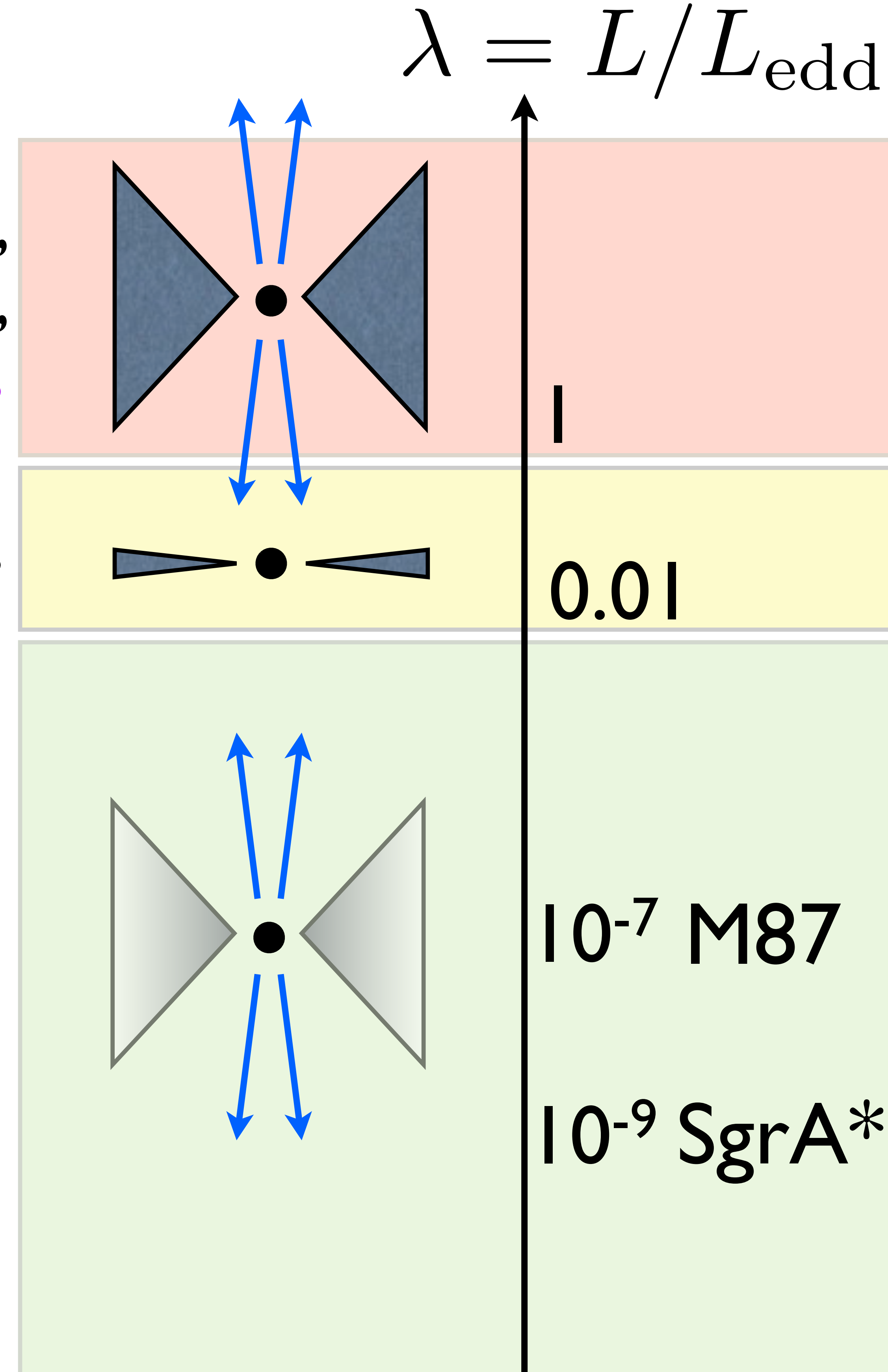
Tidal disruptions (TDEs),
ultra-luminous X-ray sources,
gamma-ray bursts

(Zamaninasab
++AT 14,
Ghisellini+14)

Quasars, X-ray binaries, TDEs

(Nemmen
& AT 15)

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



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(Nemmen & AT 15)

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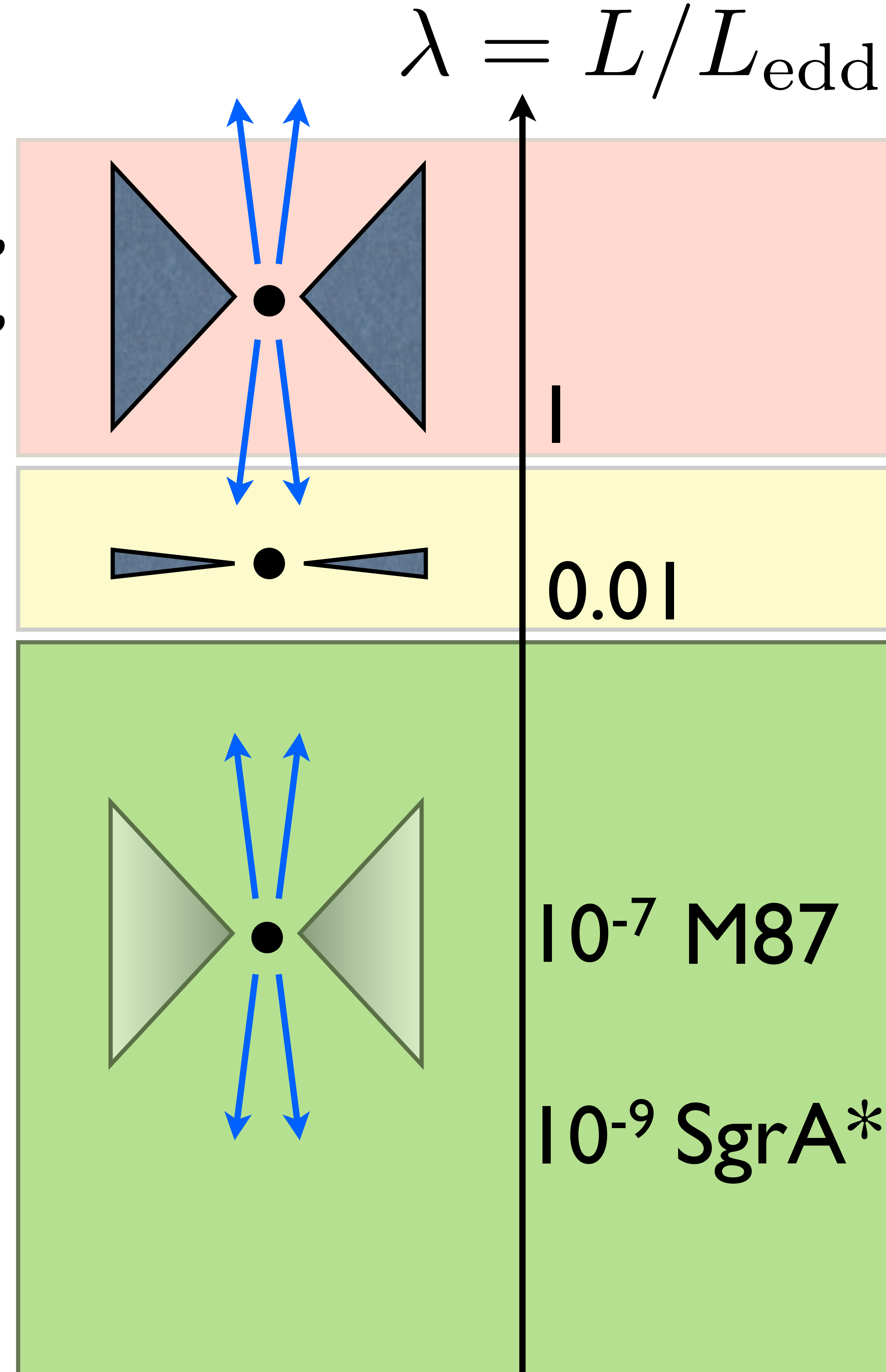
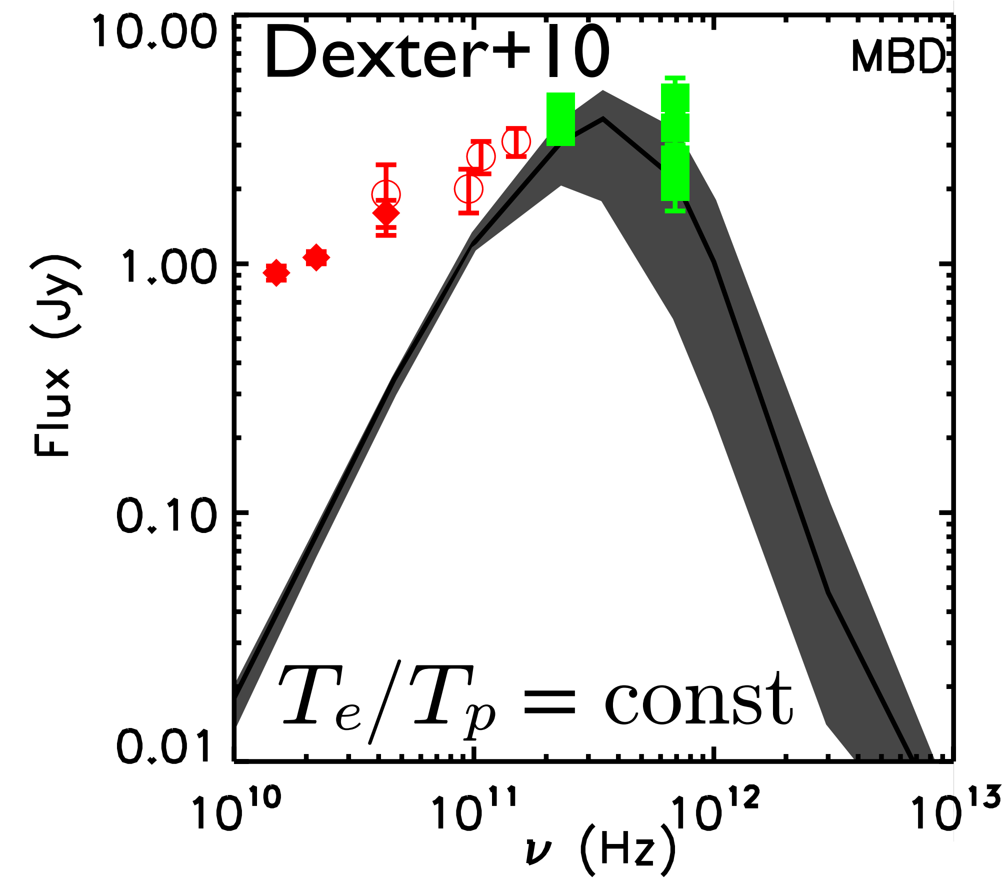


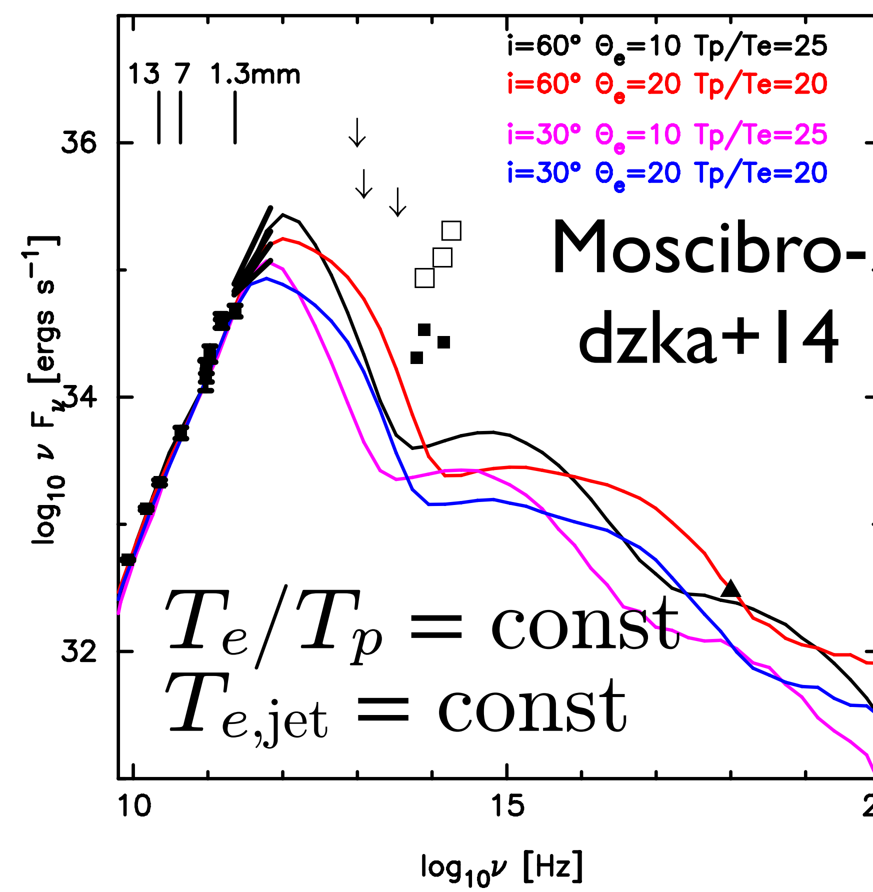
Disk radiative properties are most uncertain at low luminosities.

Recent *Event Horizon Telescope (EHT)* observations might have already resolved the shadows of 2 black holes accreting in this regime

Electron Micro-physics is Key to SgrA* Observations

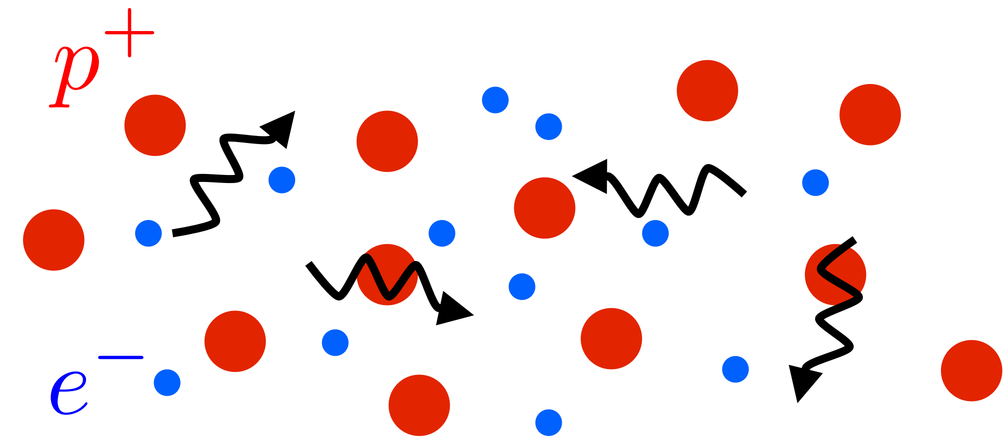
- Plasma is *collisionless*, so electron and proton temperatures decouple
  - but, T_e ($\neq T_p$) is poorly known!
- Dissipation predominantly heats protons, whereas electrons radiate
- So, T_e is usually "painted" on top of simulations:
  - Usual assumption (eg Dexter+10): $T_e/T_p = \mathrm{const.} < 1$
  - 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 *calculate* the free function, $T_e(T_p, \ldots)$?



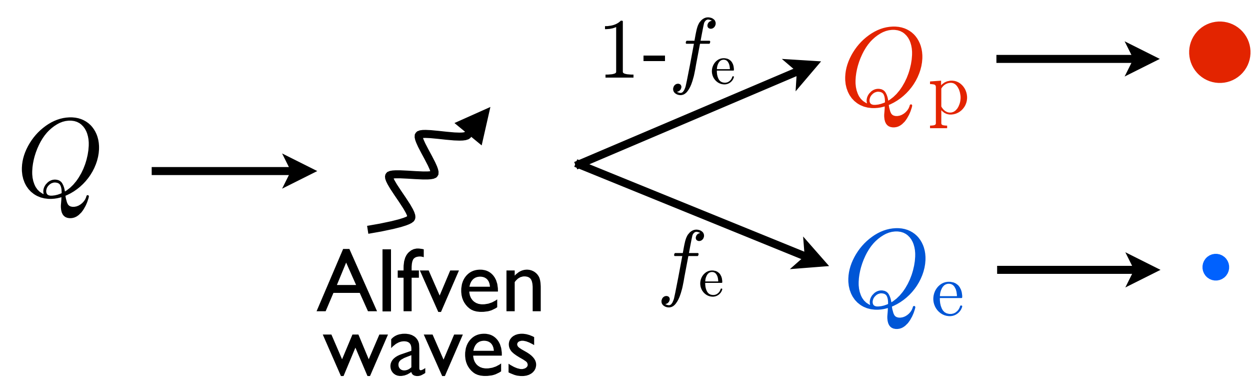


Collisionless Electron Heating in a Nutshell

- Plasma is collisionless:
  - Electrons do not know protons exist
  - But, both feel Alfven waves

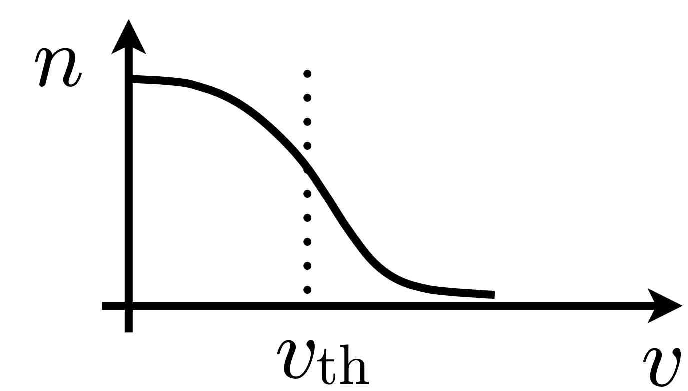


- Alfven waves couple to protons if $v_{\rm A} \lesssim v_{\rm th}$:
  - if $v_{\rm A} \gg v_{\rm th}$, electrons get all the heat



- Stronger electron heating in magnetized regions:

$$\frac{Q_p}{Q_e} \propto \exp\left(-\frac{v_{\rm A}^2}{v_{\rm th}^2}\right) = \exp\left(-\frac{1}{\beta}\right)$$



$$\beta = \frac{p_{\rm th}}{p_{\rm mag}}$$

$$f_e \equiv \frac{Q_e}{Q_e + Q_p} = f_e(T_e/T_p, \beta)$$

(Howes 2010)

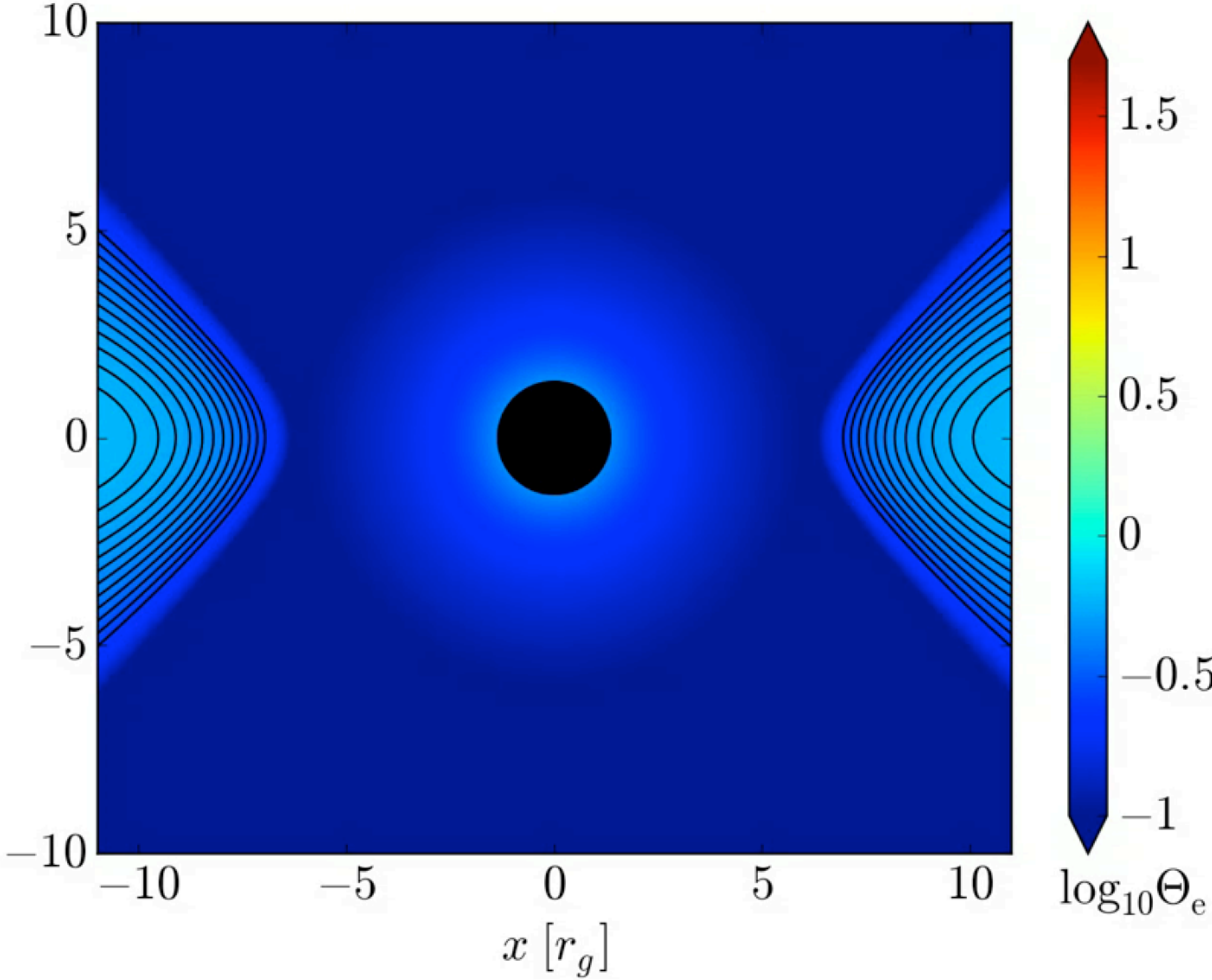
Electron Microphysics is Key to SgrA* Observations

- Our predictive approach:
  - Evolve electrons as a second fluid
  - Electrons receive a fraction $f_e(T_e/T_p,\beta)$ of dissipated heat, Q (Howes 2010)
    - stronger electron heating in highly magnetized regions
  - Include thermal conduction *along* field lines
  - Neglect back-reaction of electrons on the flow
- Simulations with *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:
γ=5/3
Electrons:
γ_e=4/3



Hot electrons naturally occur in the polar regions

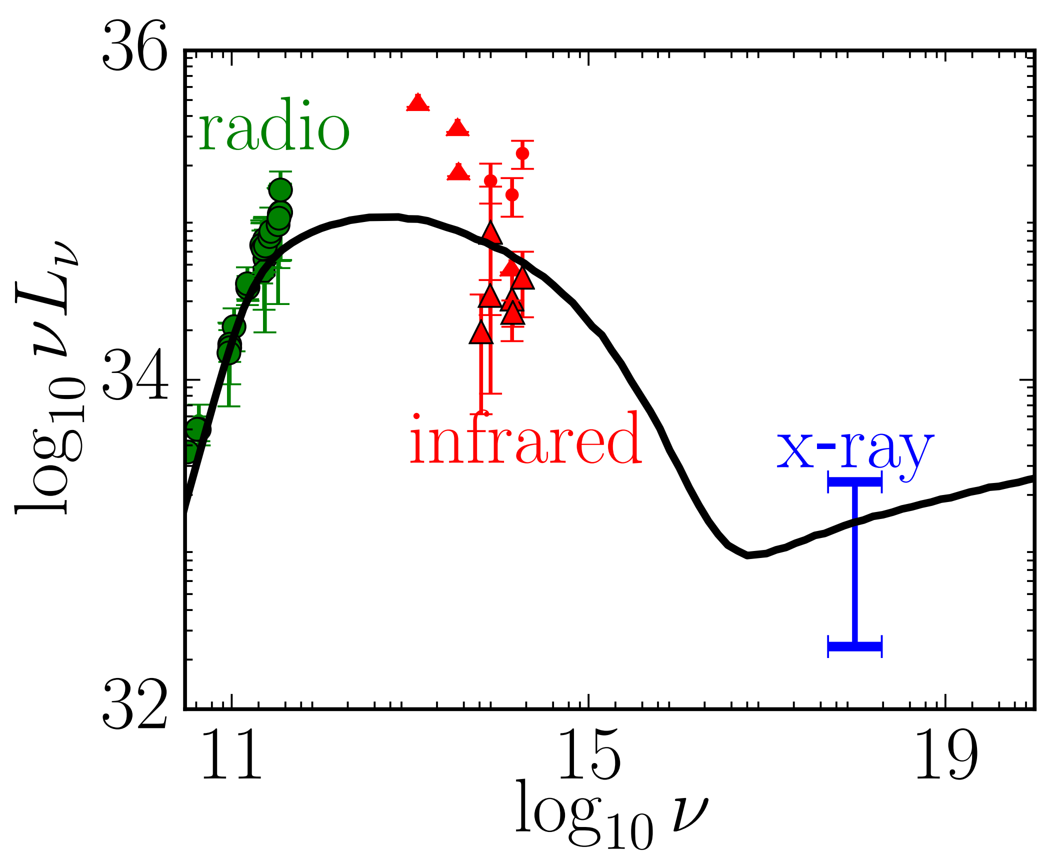
Simulation cost ~0.5M CPU-hours

(Ressler, AT et al, 2017, MNRAS, arXiv:1611.09365)

Jet-Disk Symbiosis in SgrA*

Our new simulations are:

- *predictive:* $\dot{M}$ is the only free parameter
- *naturally reproduce the spectrum* at $\gtrsim$ 30GHz



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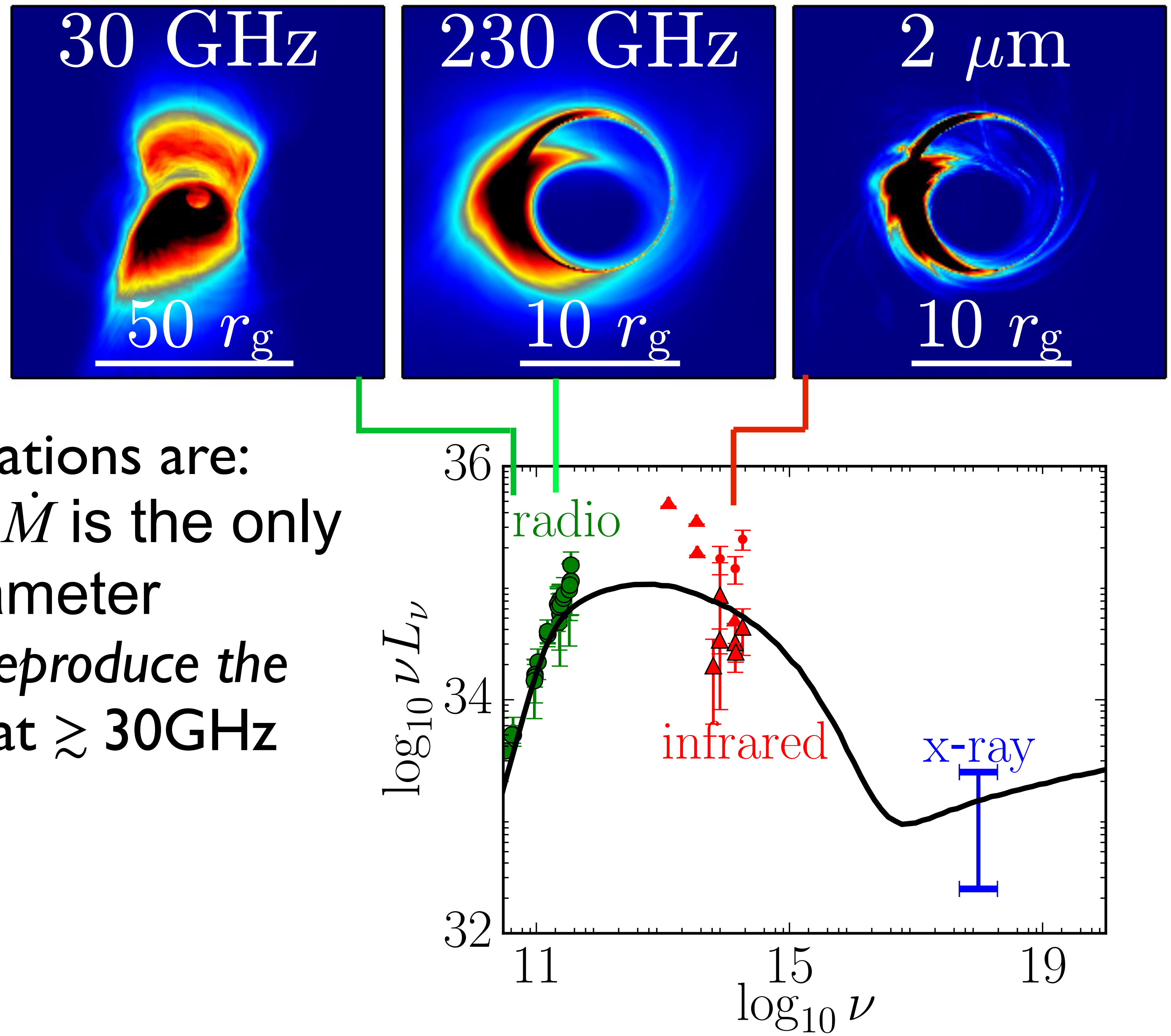

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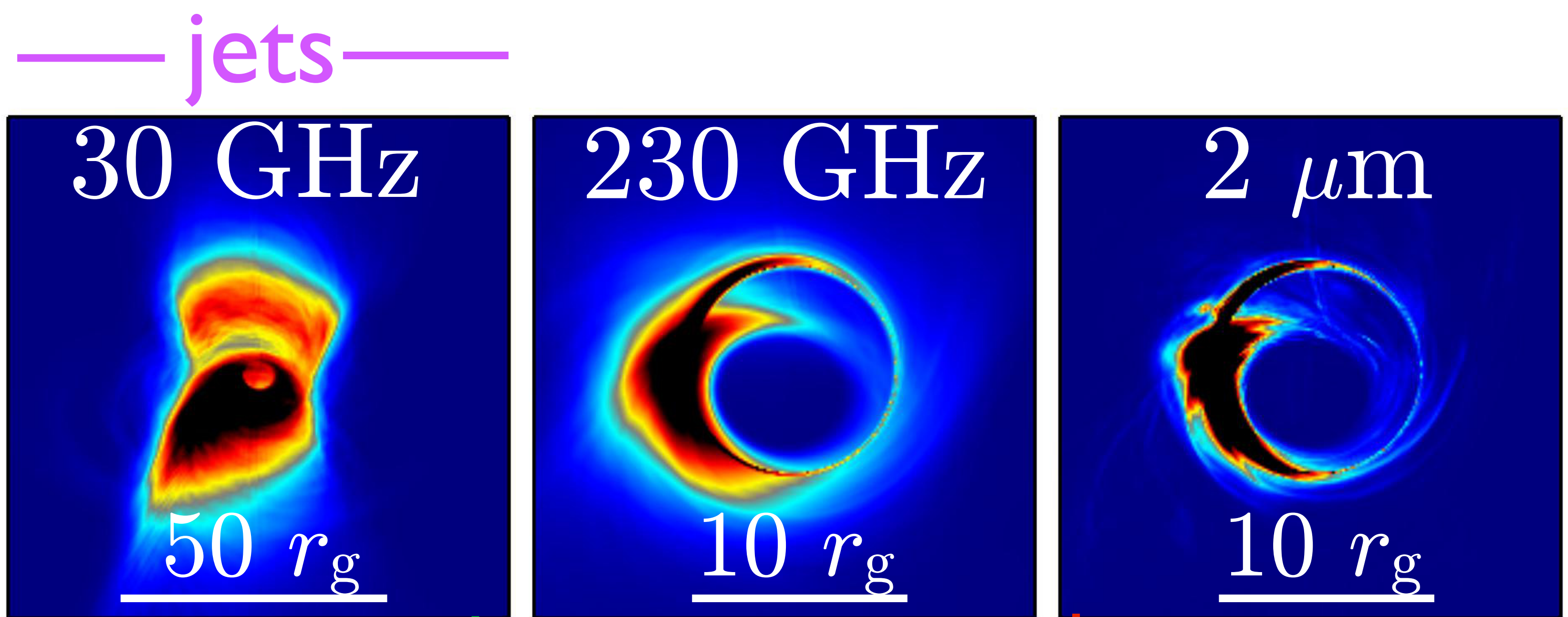

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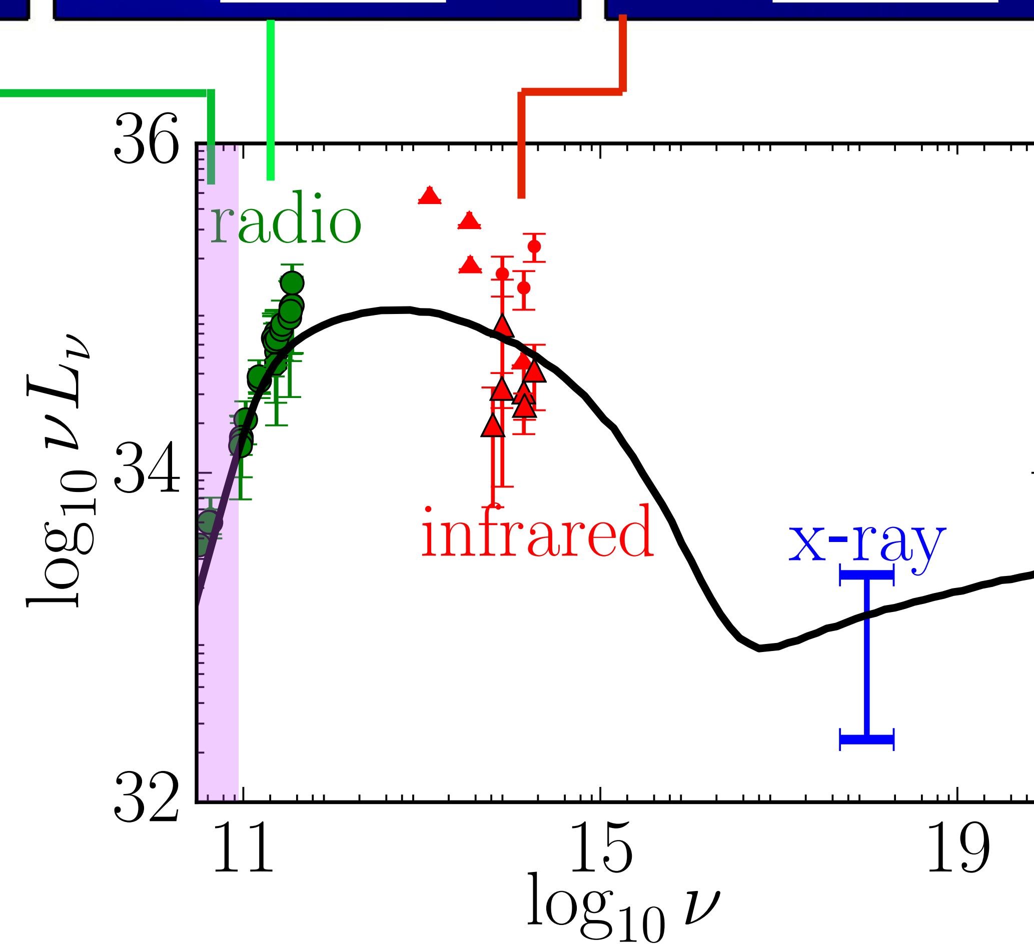

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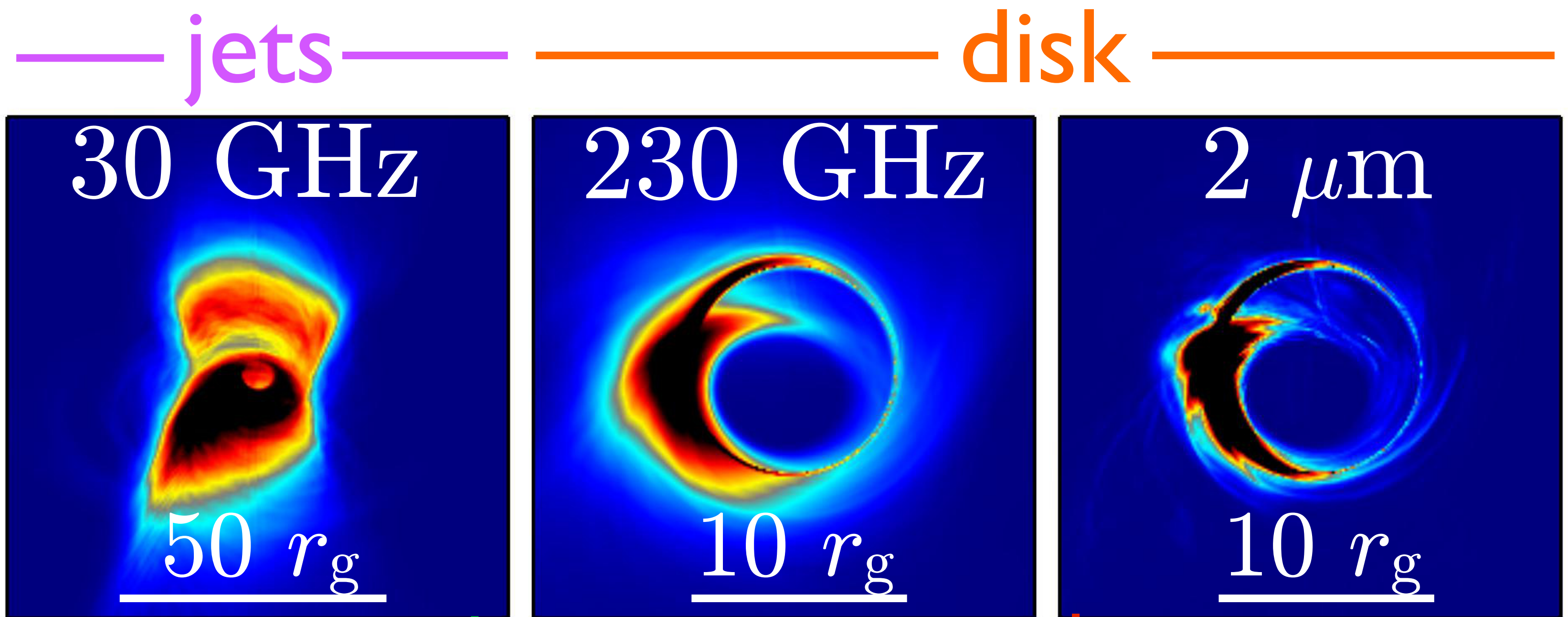

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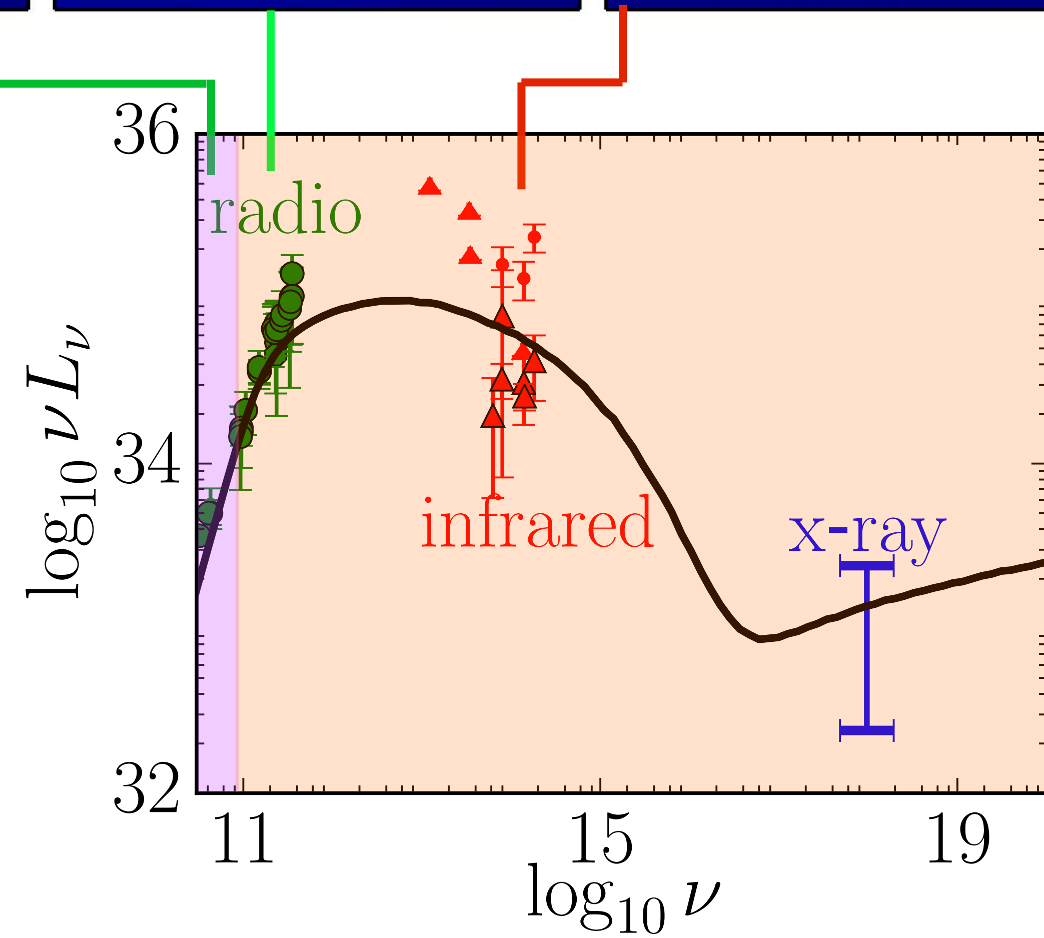

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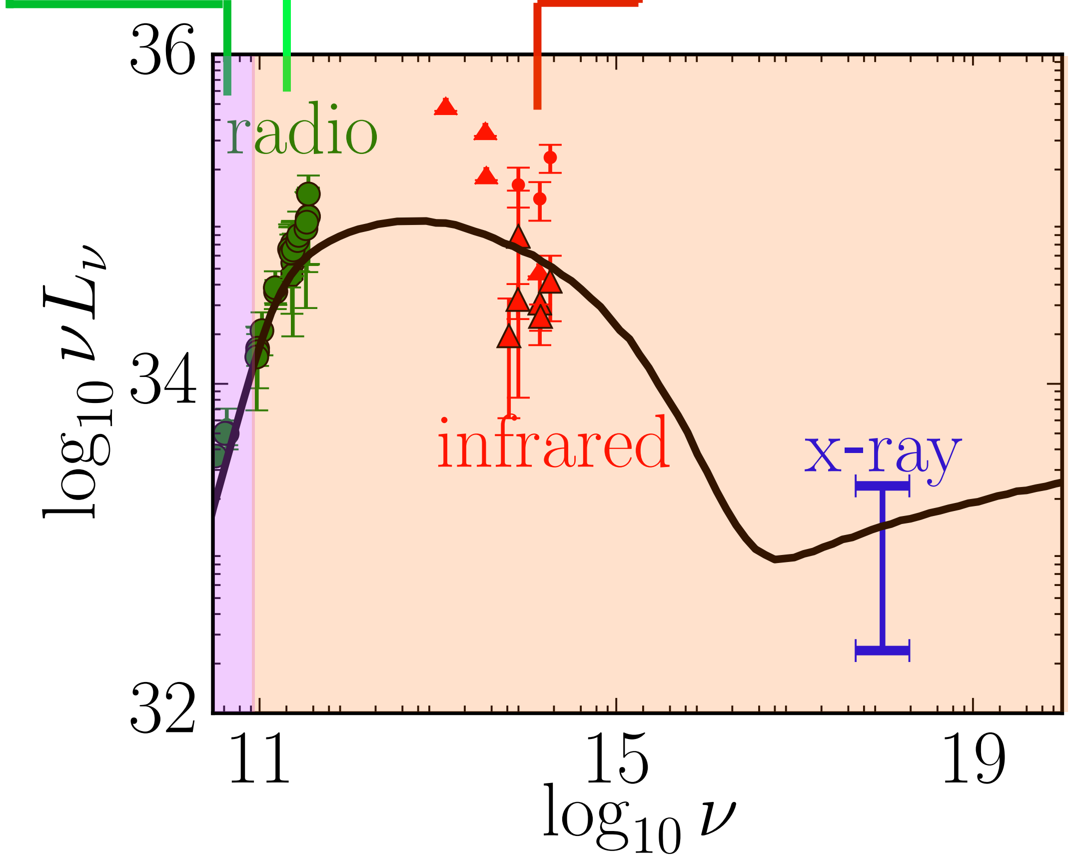

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Jet-Disk Symbiosis in SgrA*

jets — disk

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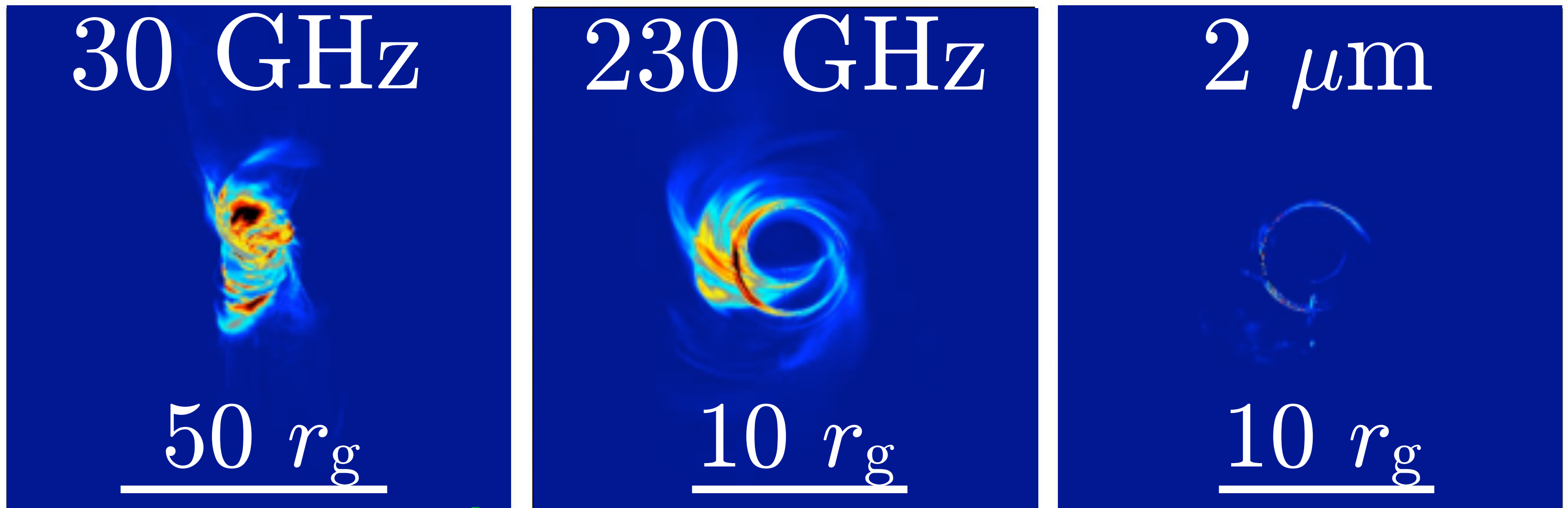

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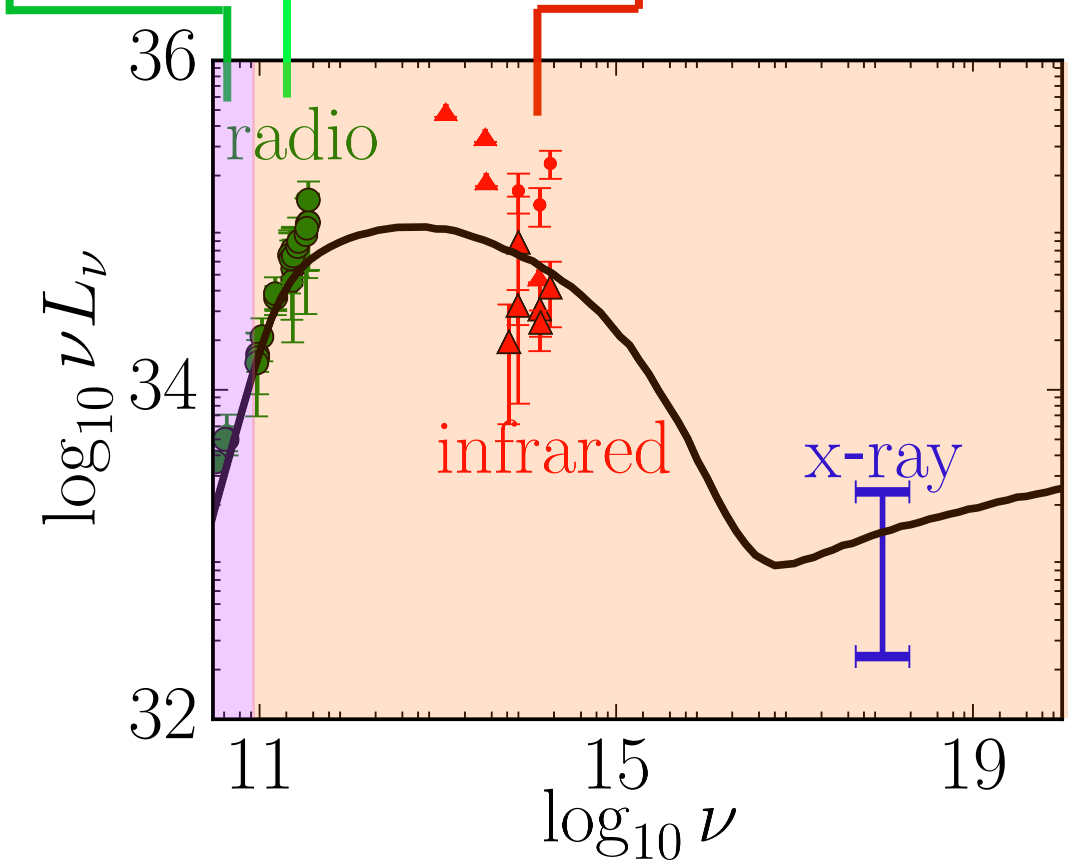


Current and future work:

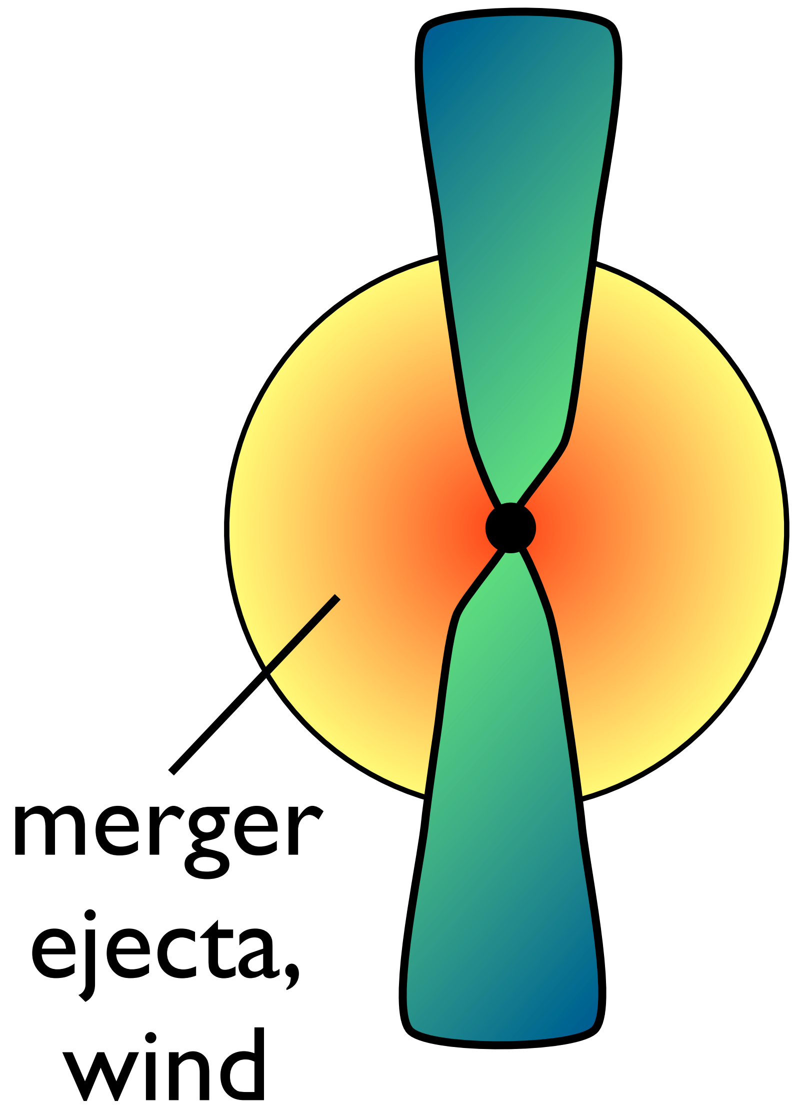
- time-variability, <u>flares</u>
- tell apart different e^- heating models
- emission at $\lesssim$ 30GHz

Sean Ressler (UC Berkeley)

(Ressler, AT et al, 2017, MNRAS, arXiv:1611.09365)

Explaining Jet High-Energy Emission

Binary Merger GRB



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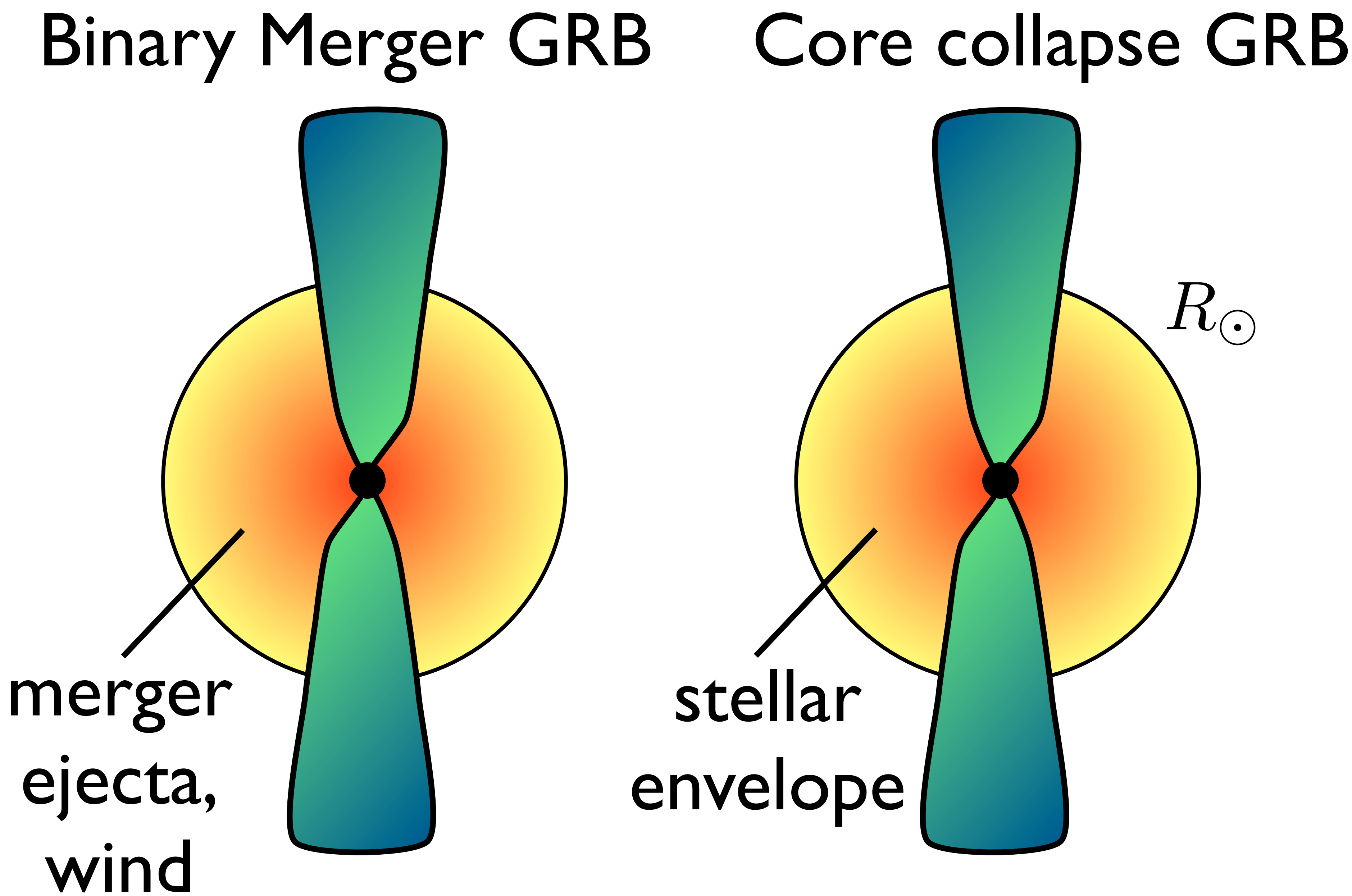

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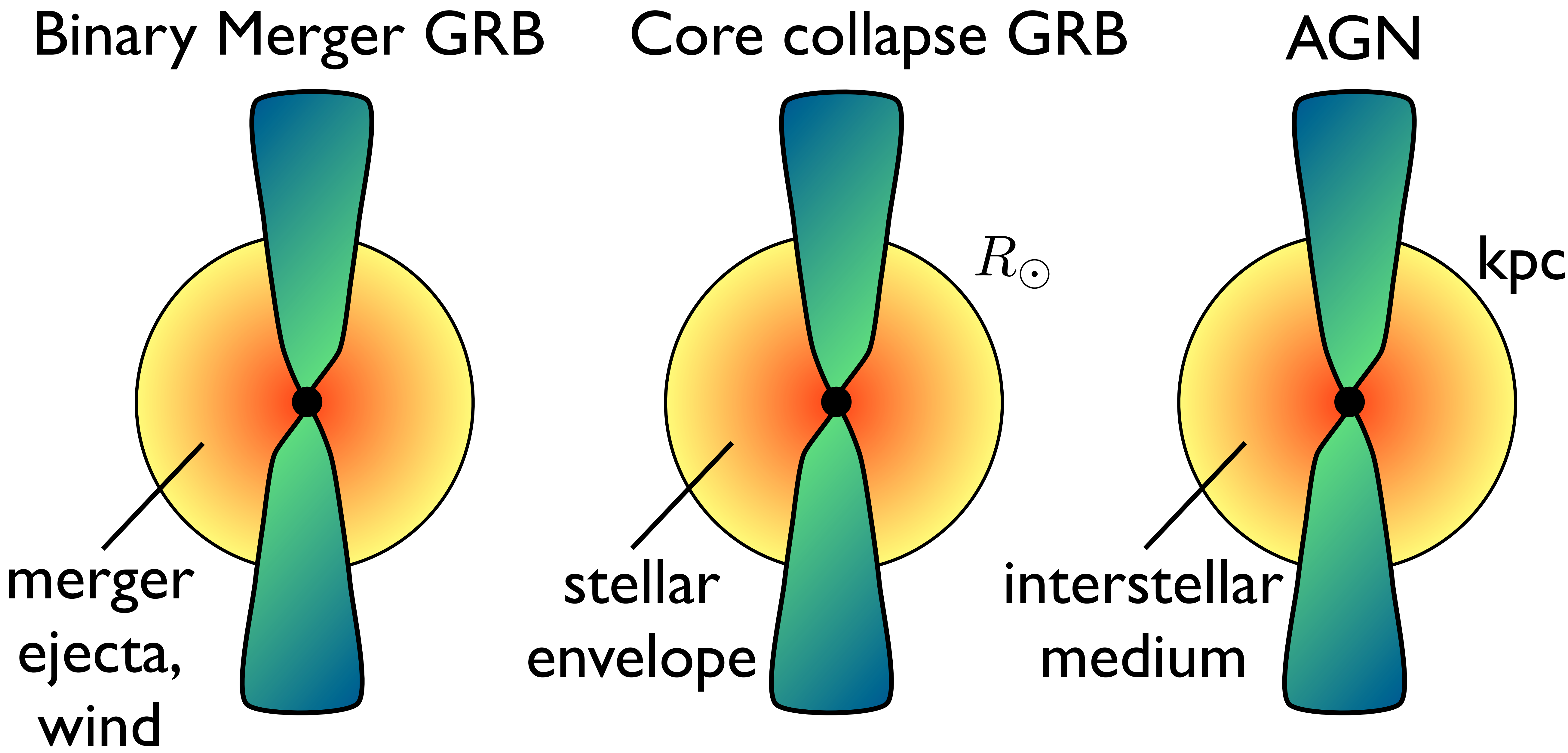

Universal mechanism to convert 10-50% of jet energy into heat?

(Panaitescu and Kumar 03, Nemmen+2013)

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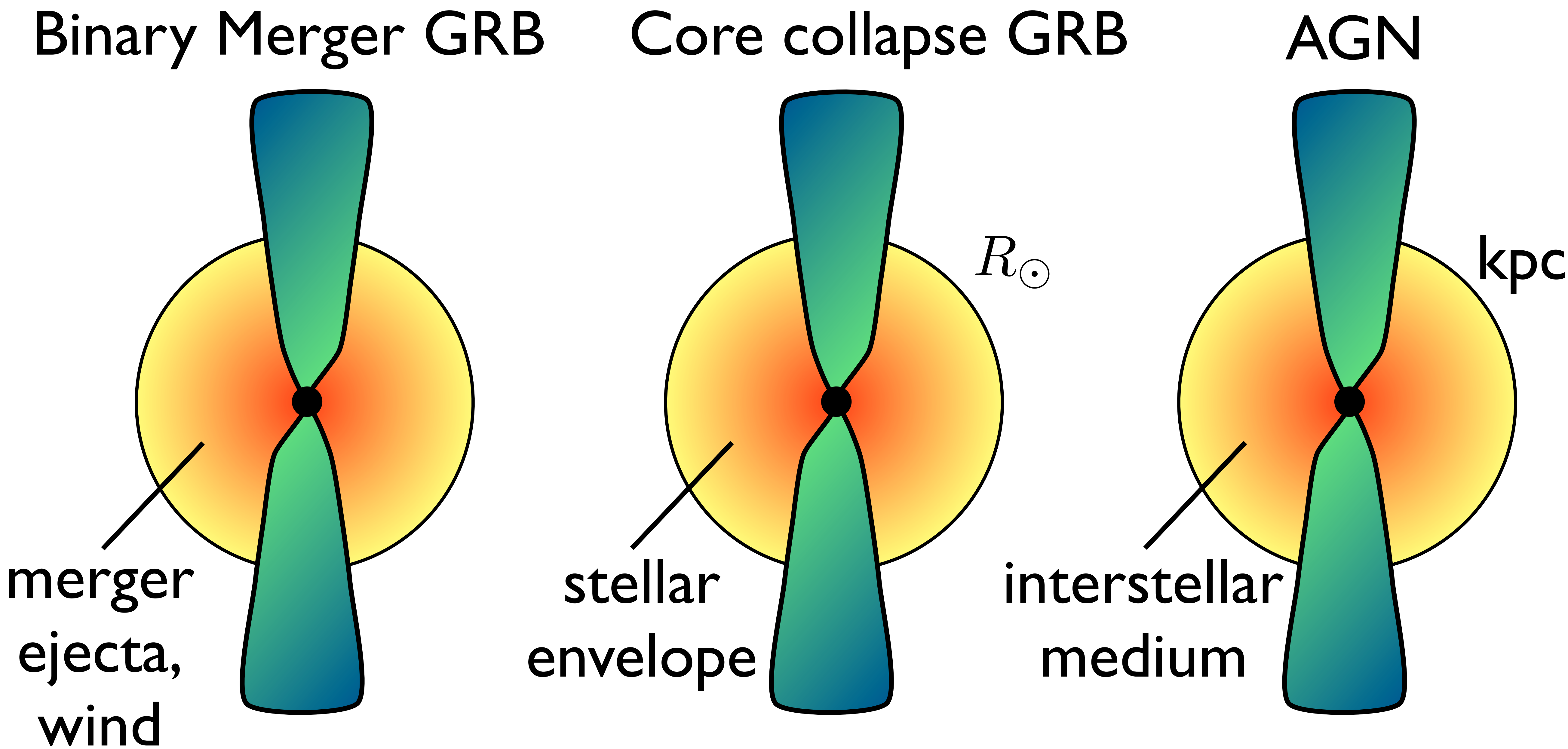

Universal mechanism to convert 10-50% of jet energy into heat?
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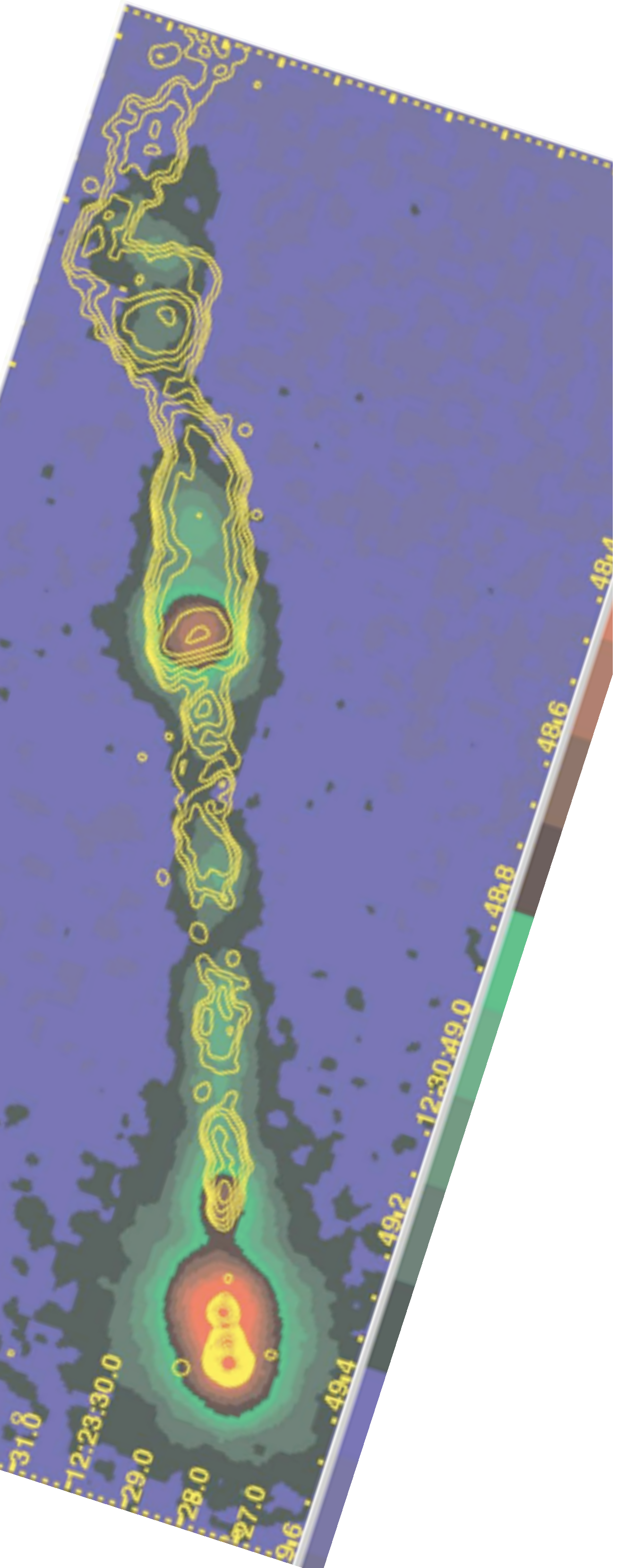
Magnetic reconnection is promising (Sironi+2015)
but how to get it to work generically in a smooth jet?

Magnetic Instabilities and Jet Emission



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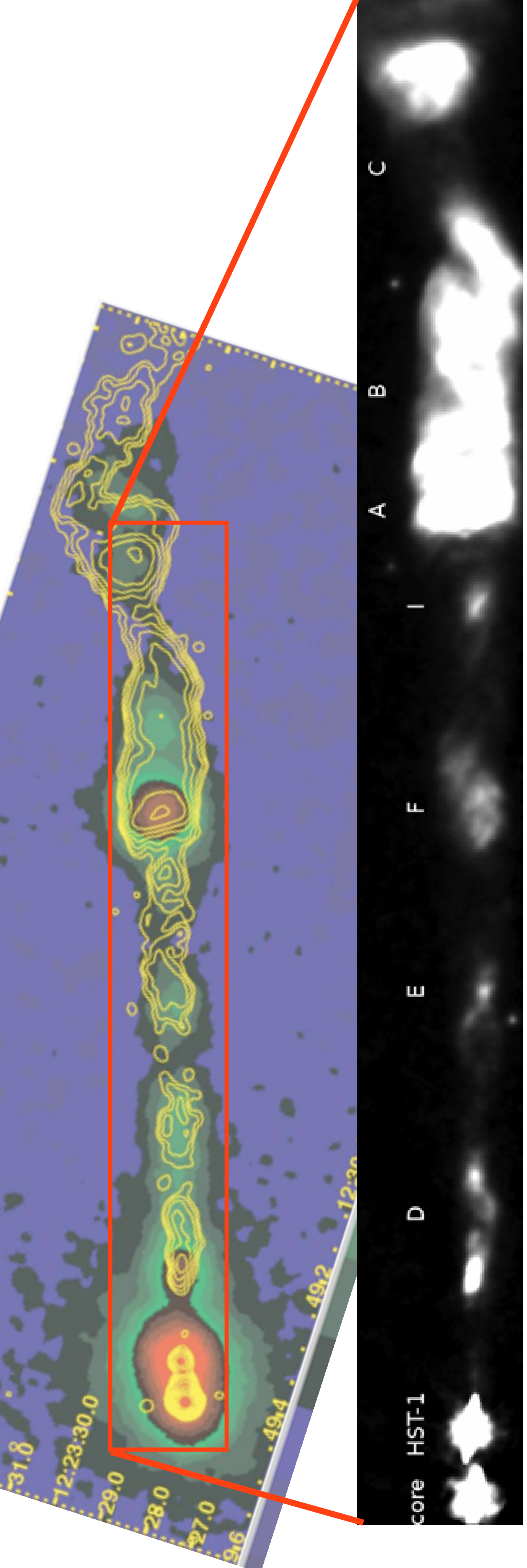

(Meyer+13)

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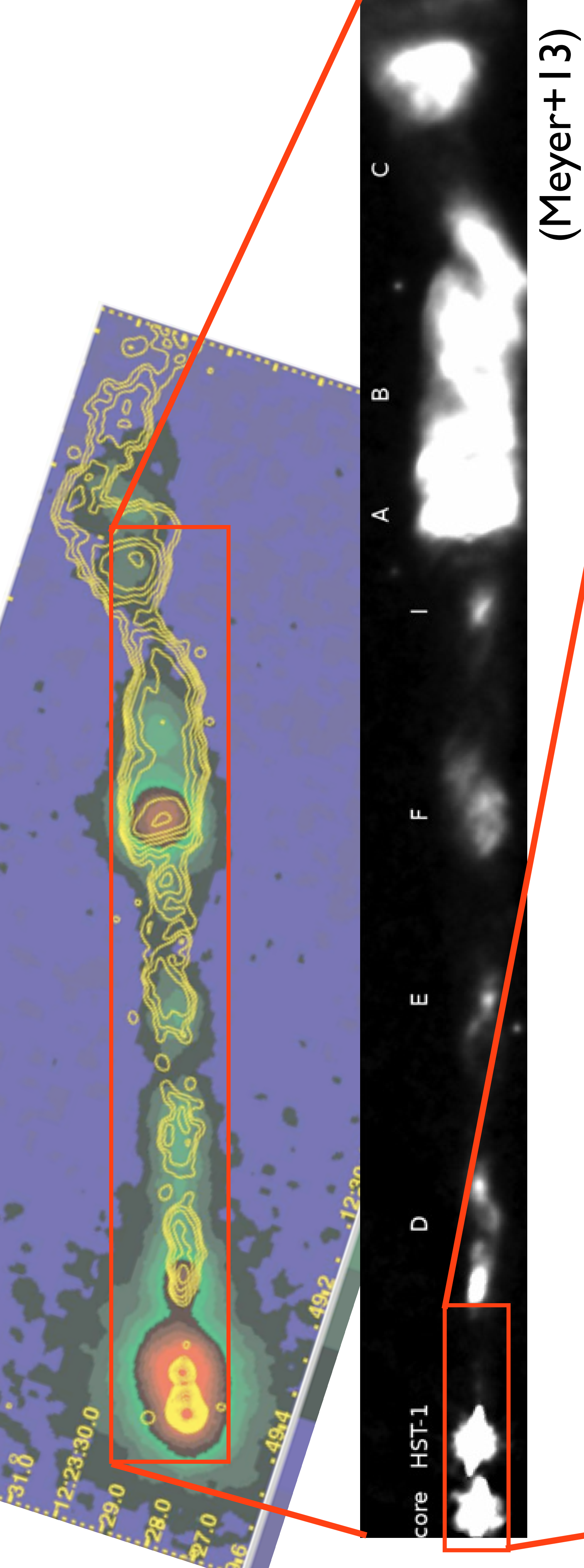

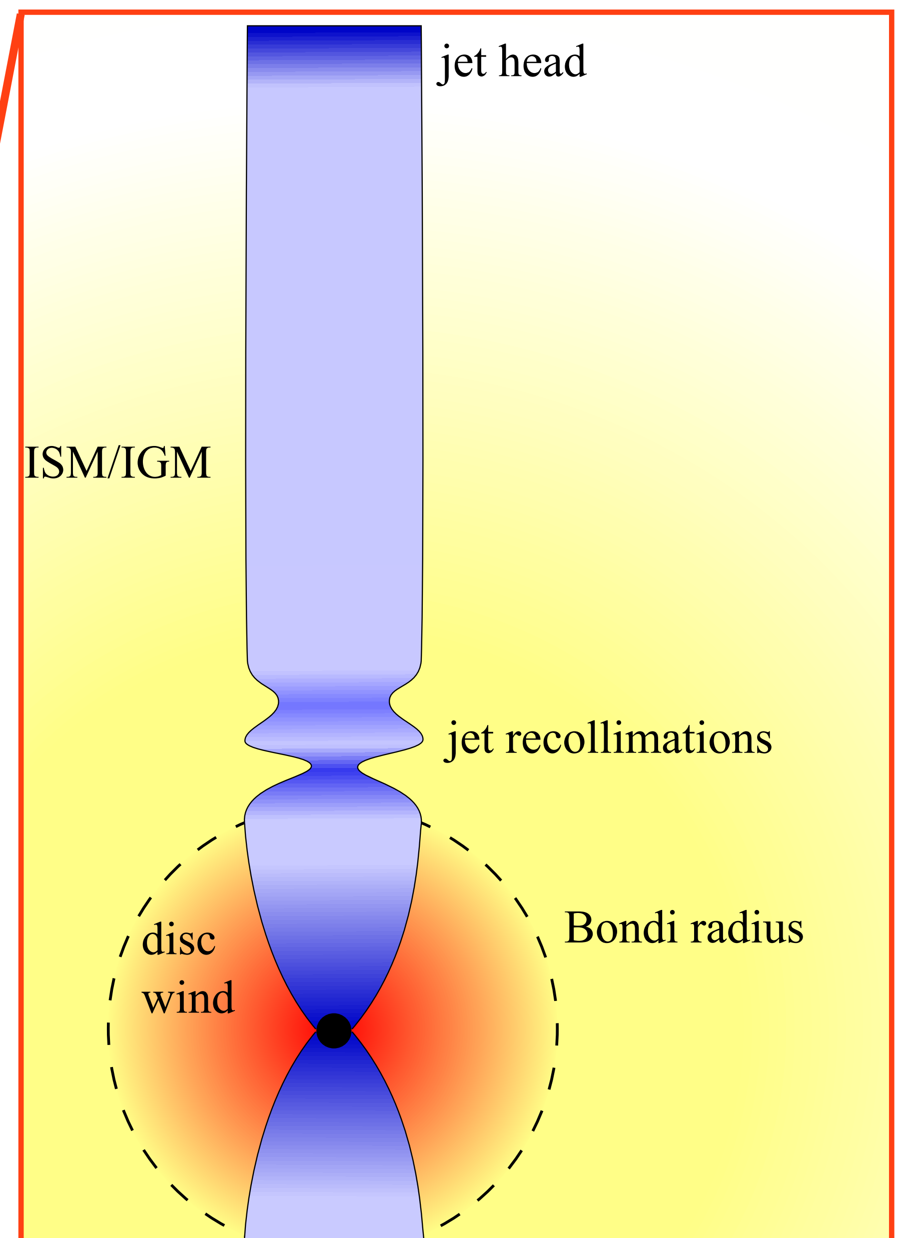

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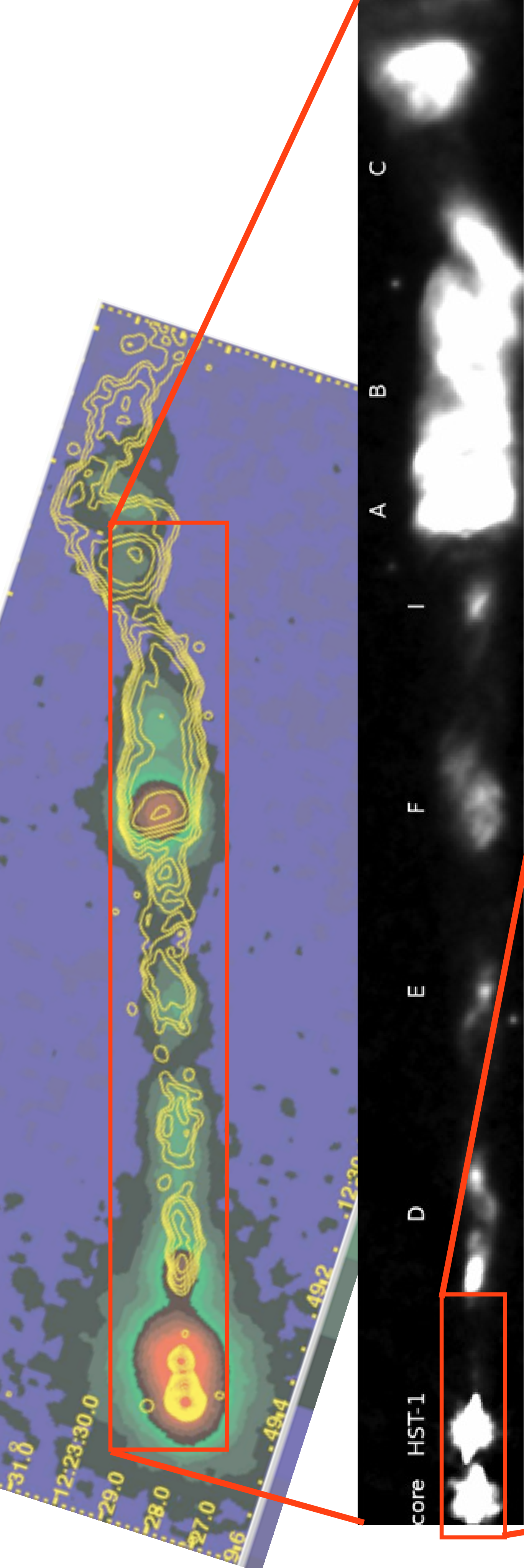

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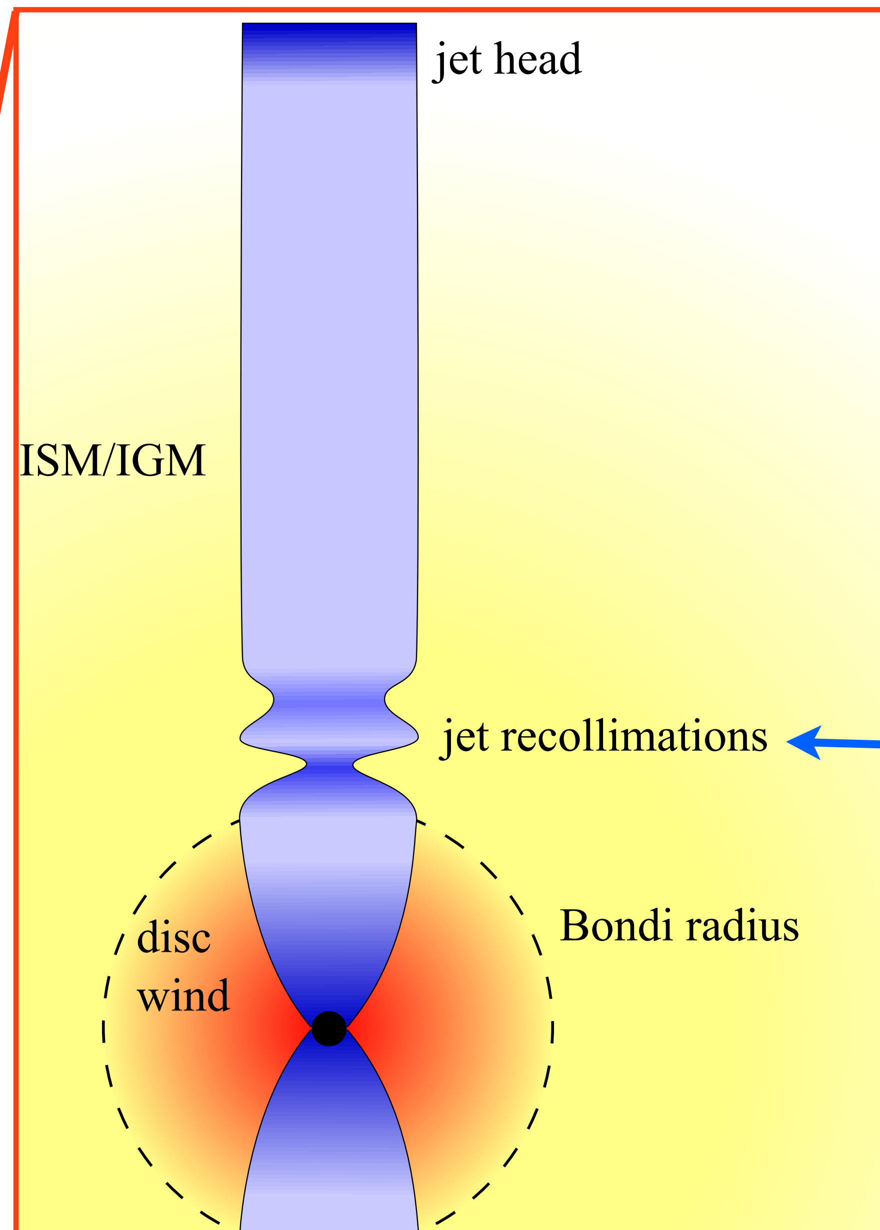
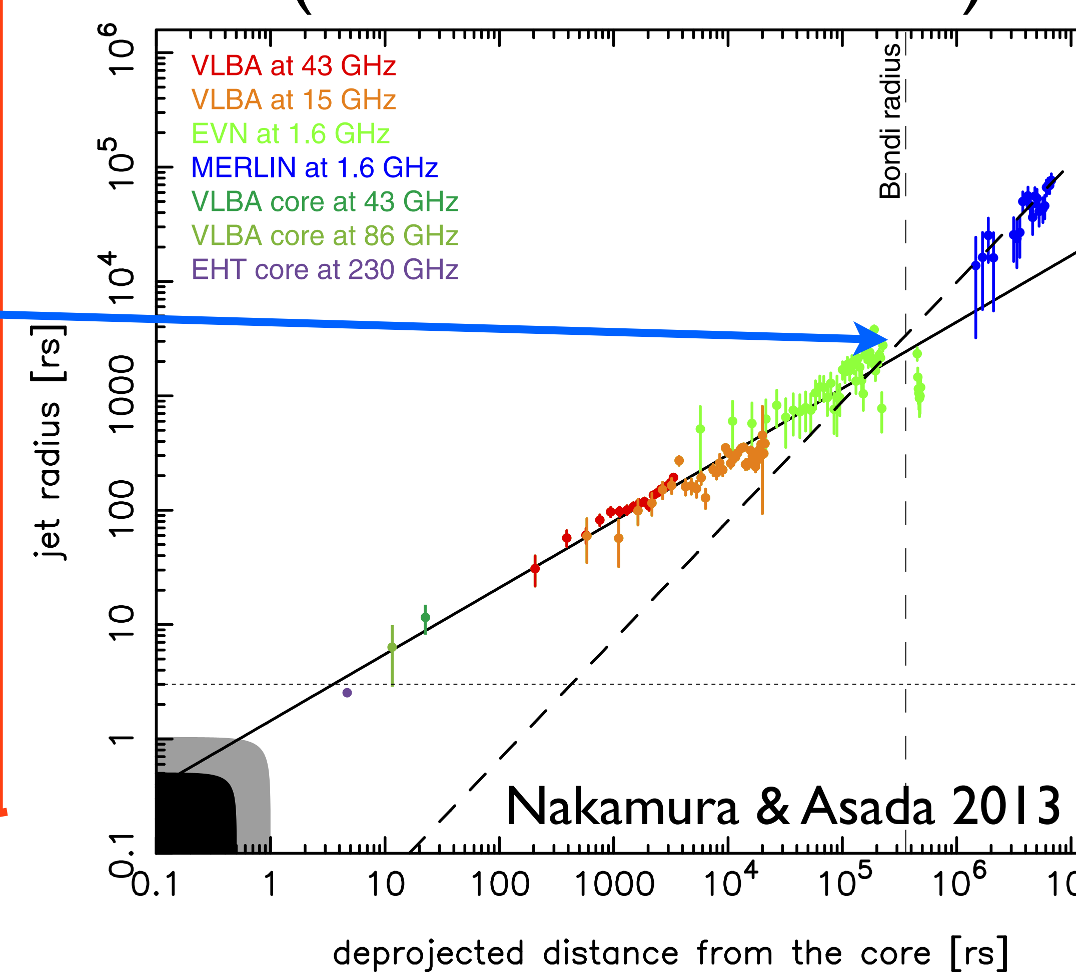


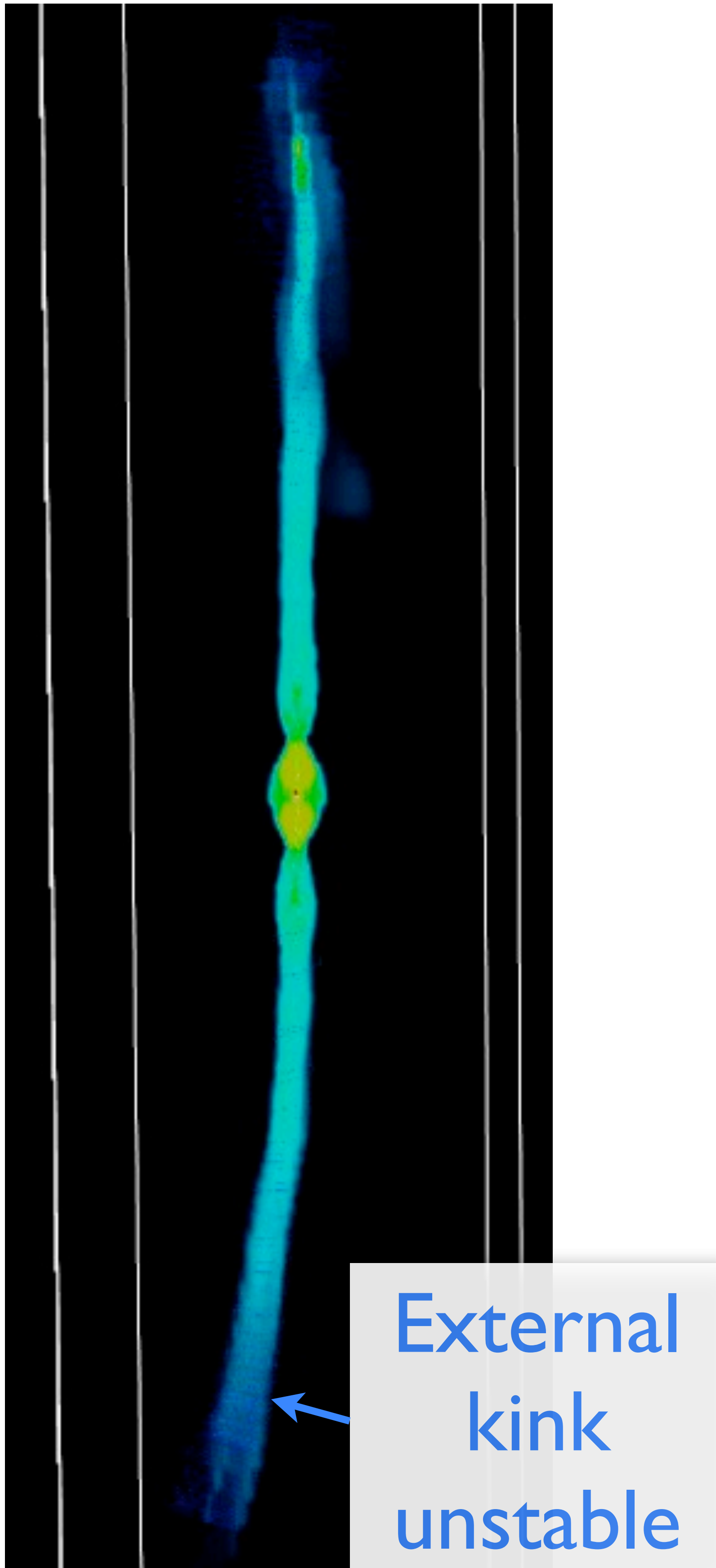
Are we seeing jet-ISM interaction?

(see also Meier 2012)



Internal Kink Makes Jets Hot

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



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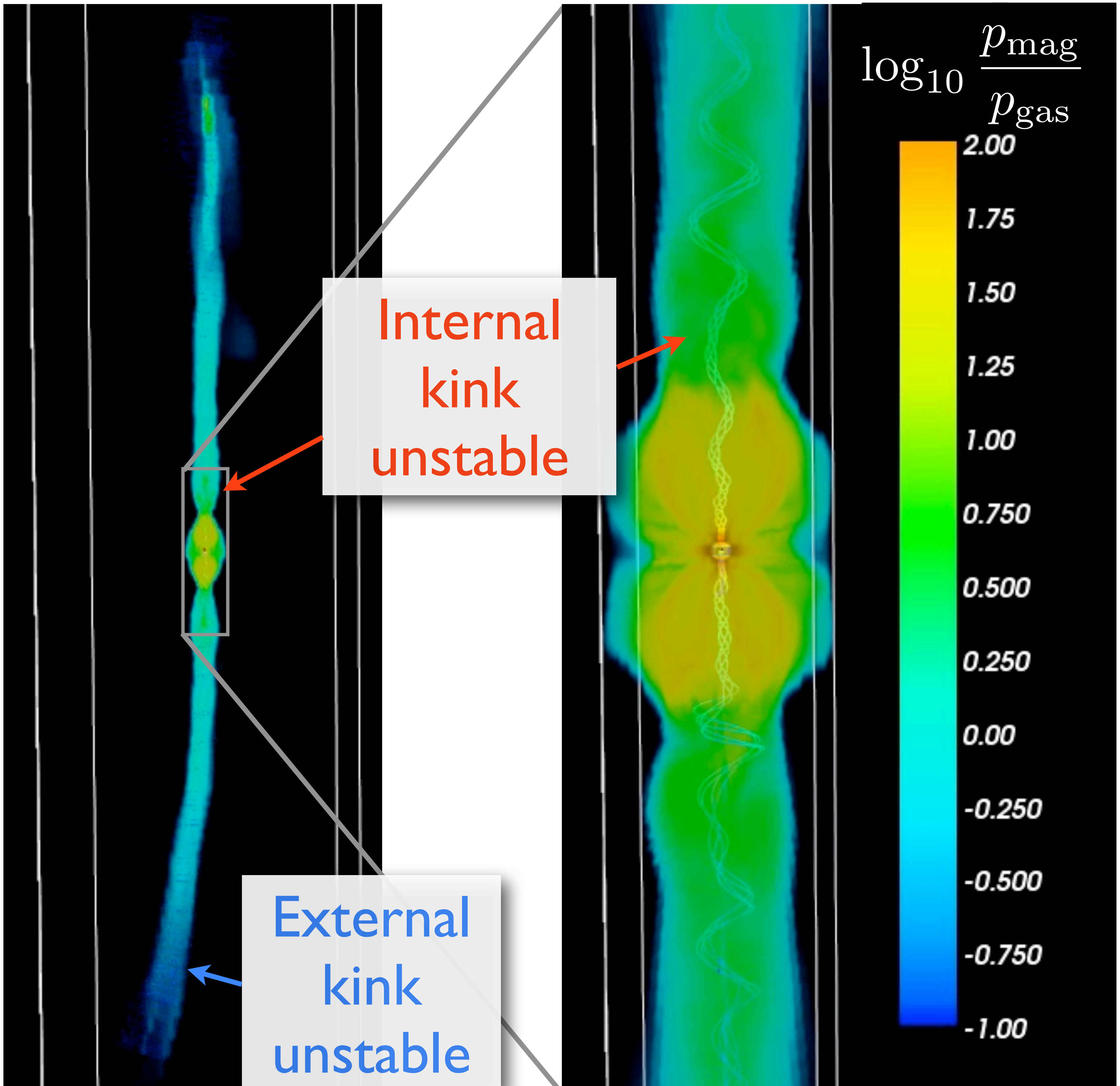

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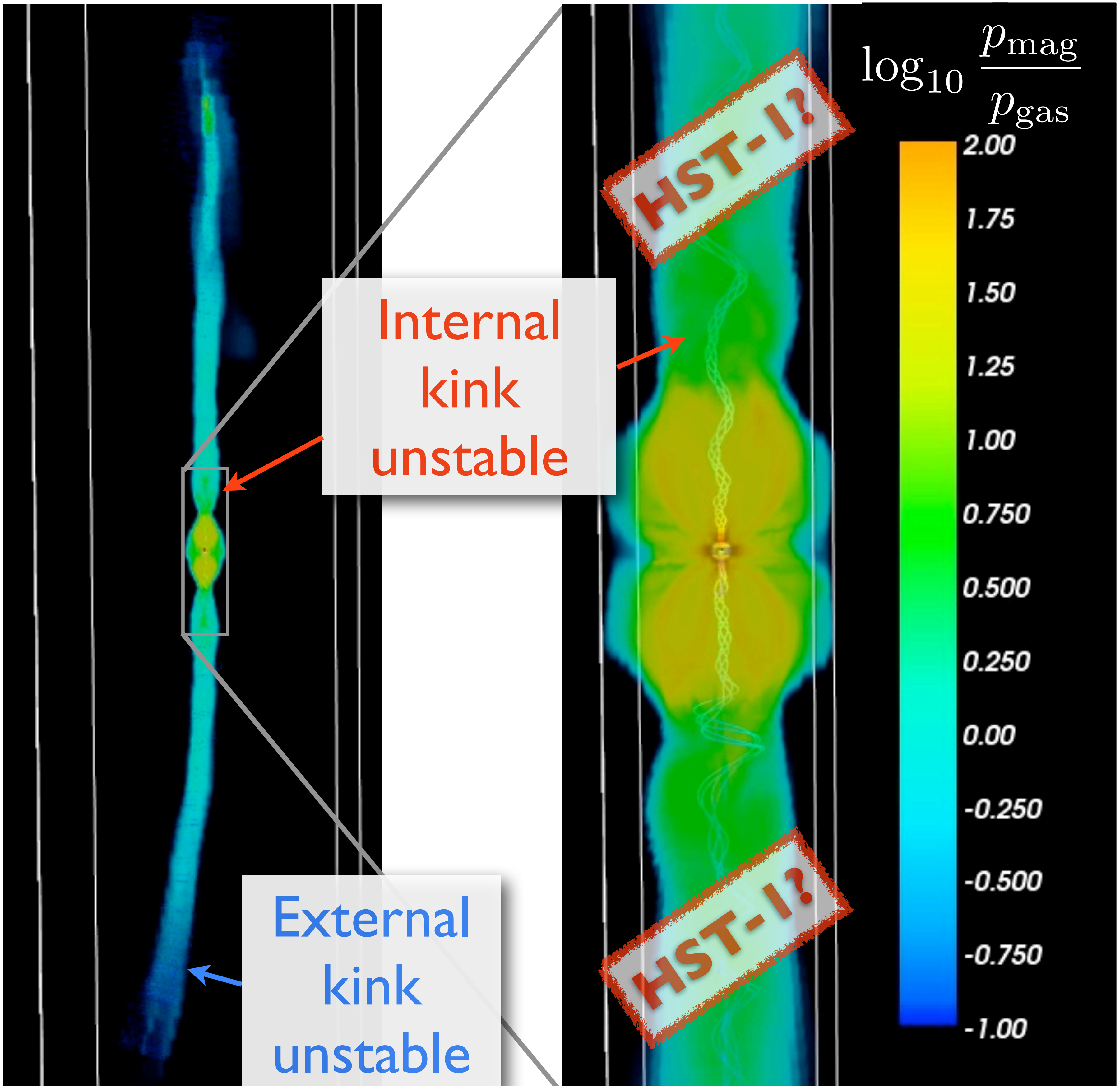

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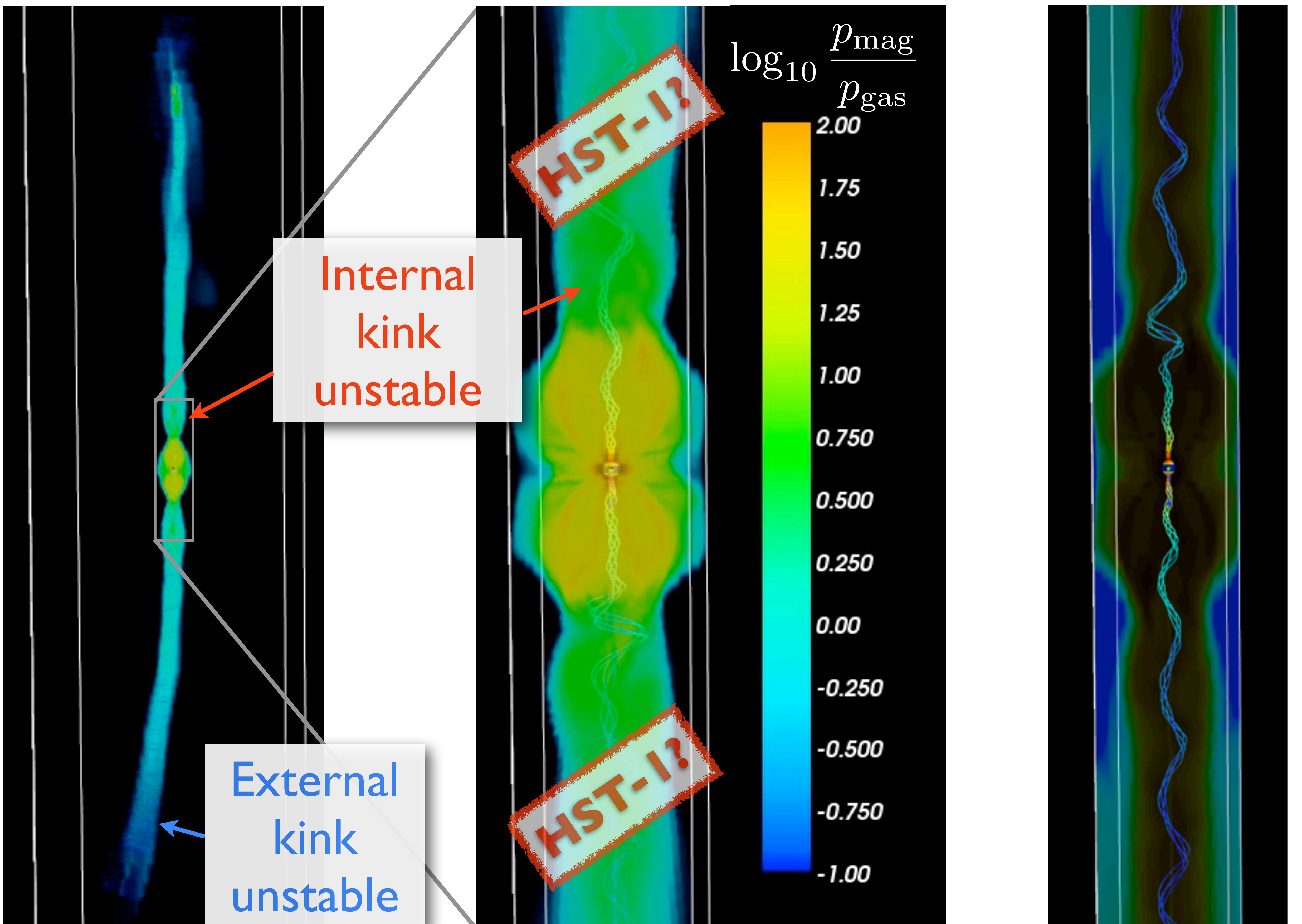

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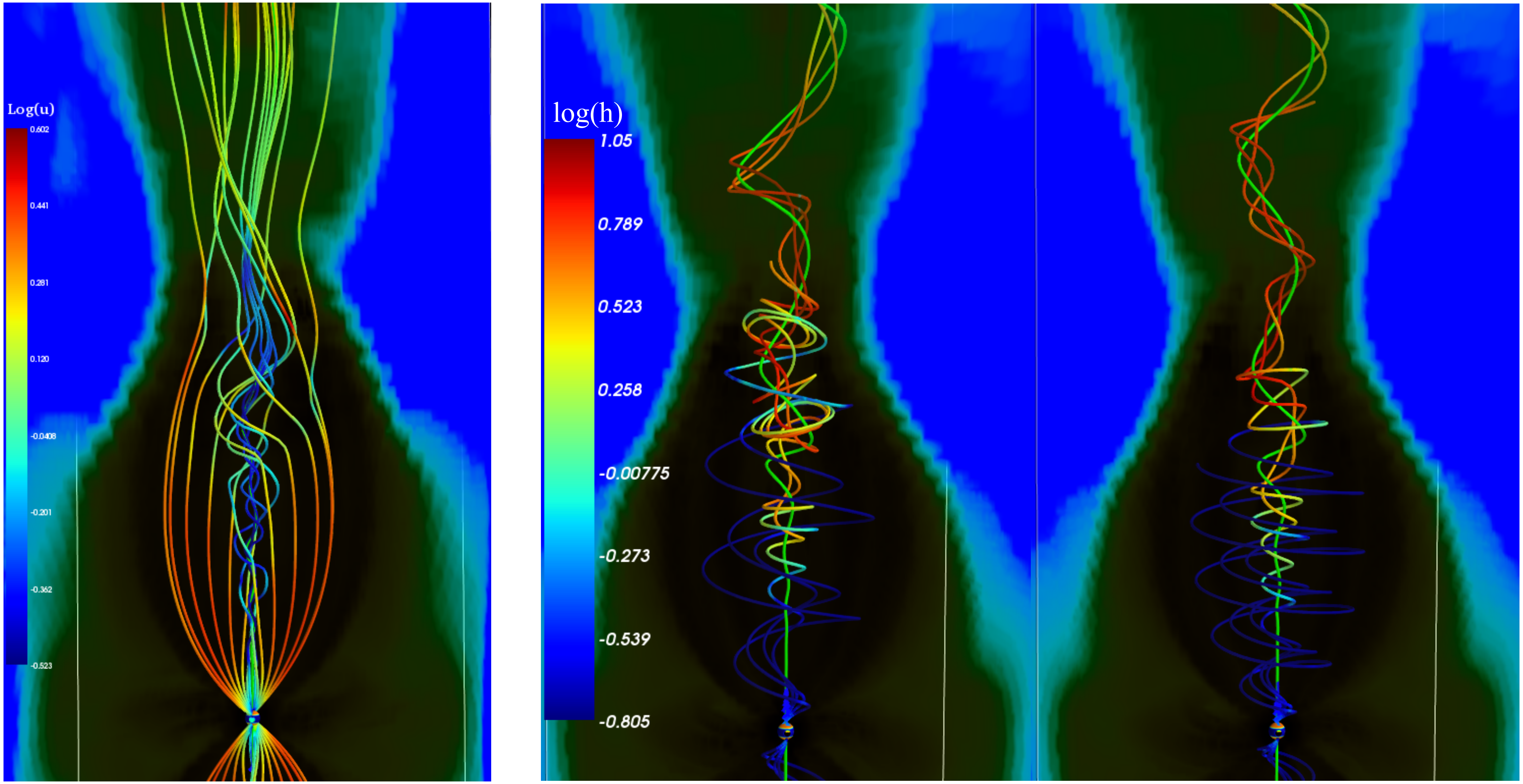
How does Jet Heating Work?

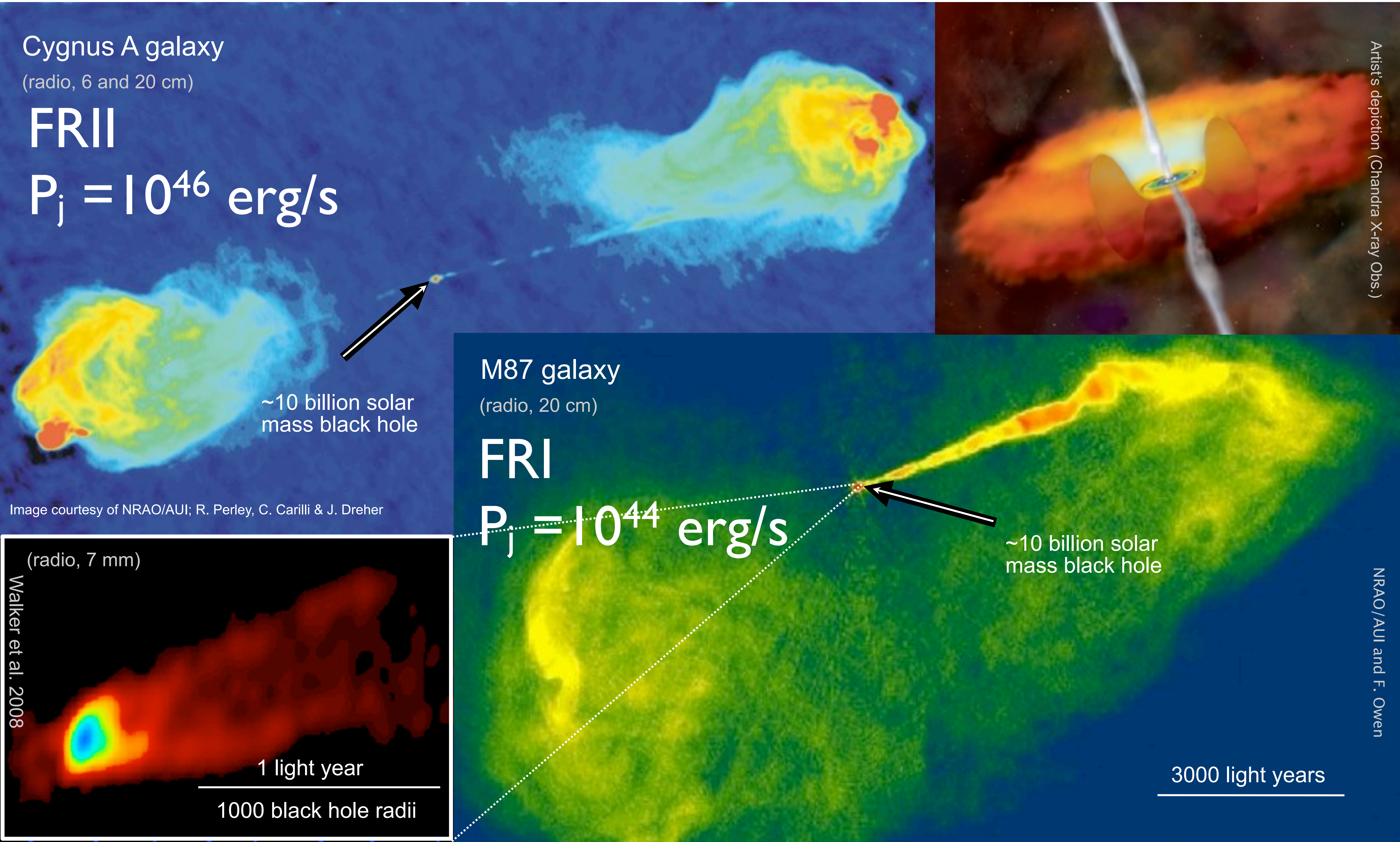


Velocity lines | Fluid B lines | Lab B lines

Recollimation → internal kink →
→ turbulence → reconnection → VHE emission

What does Jet Morphology Tell Us?

FRI/FRII dichotomy (Fanaroff & Riley, 1974)



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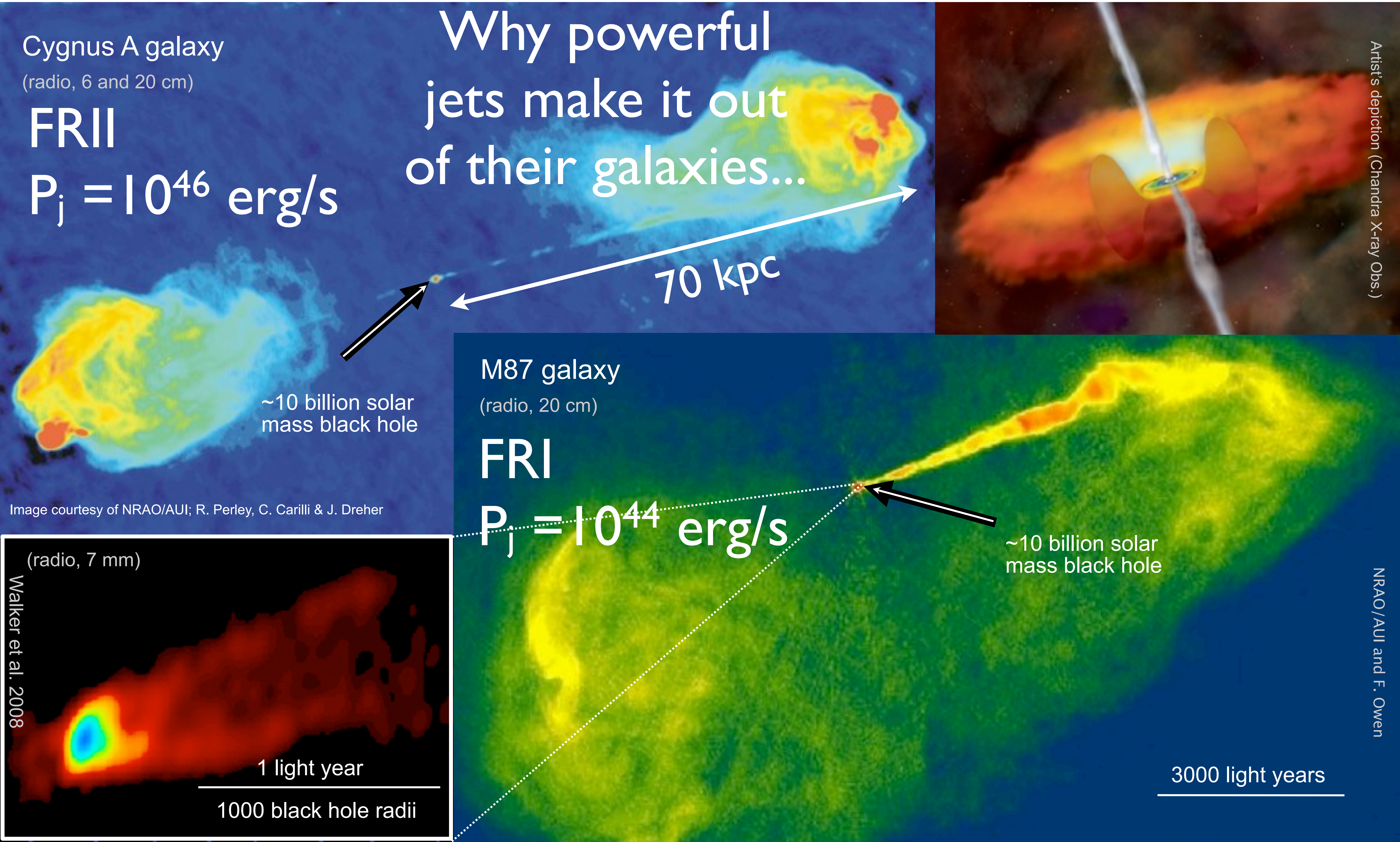

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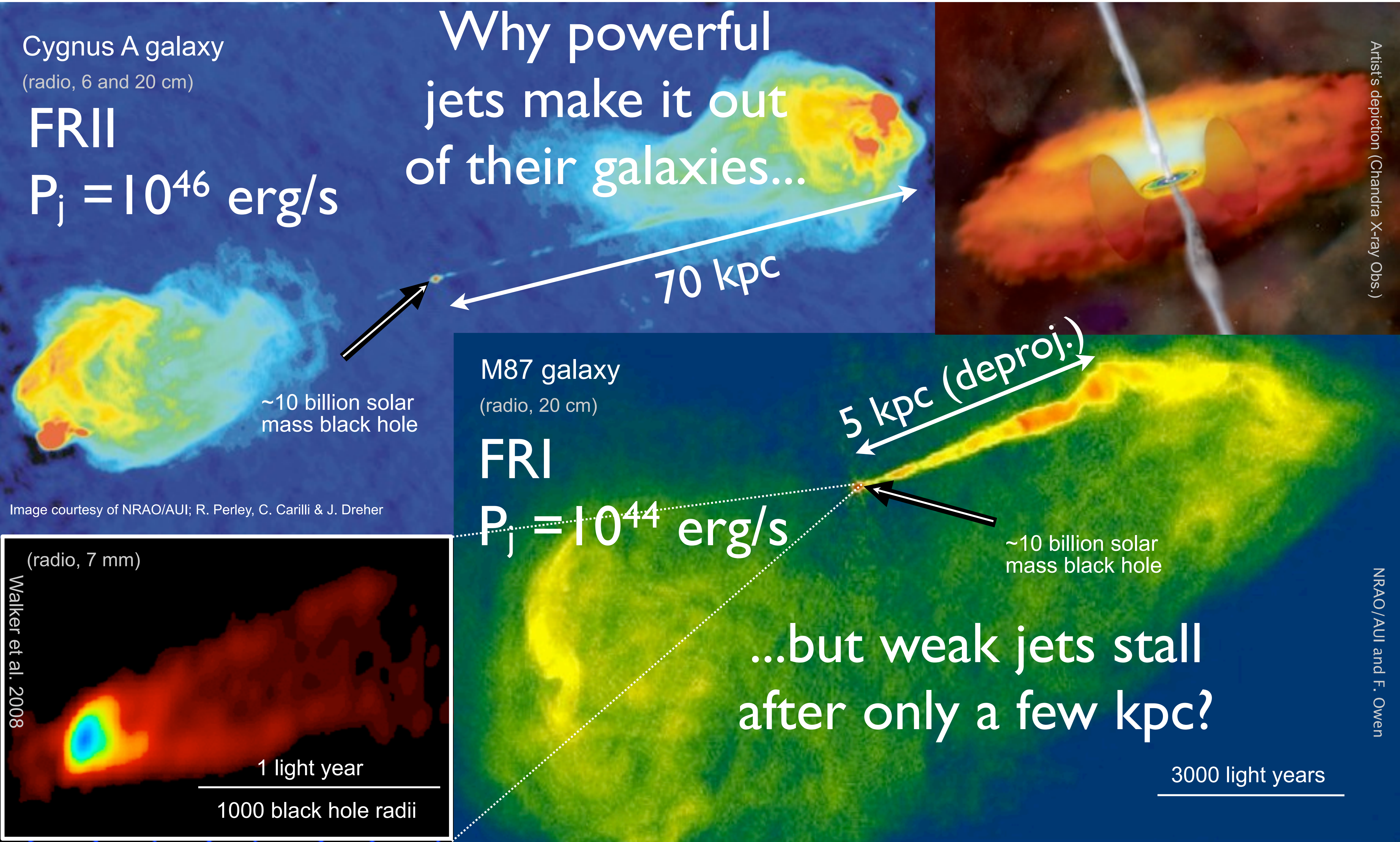

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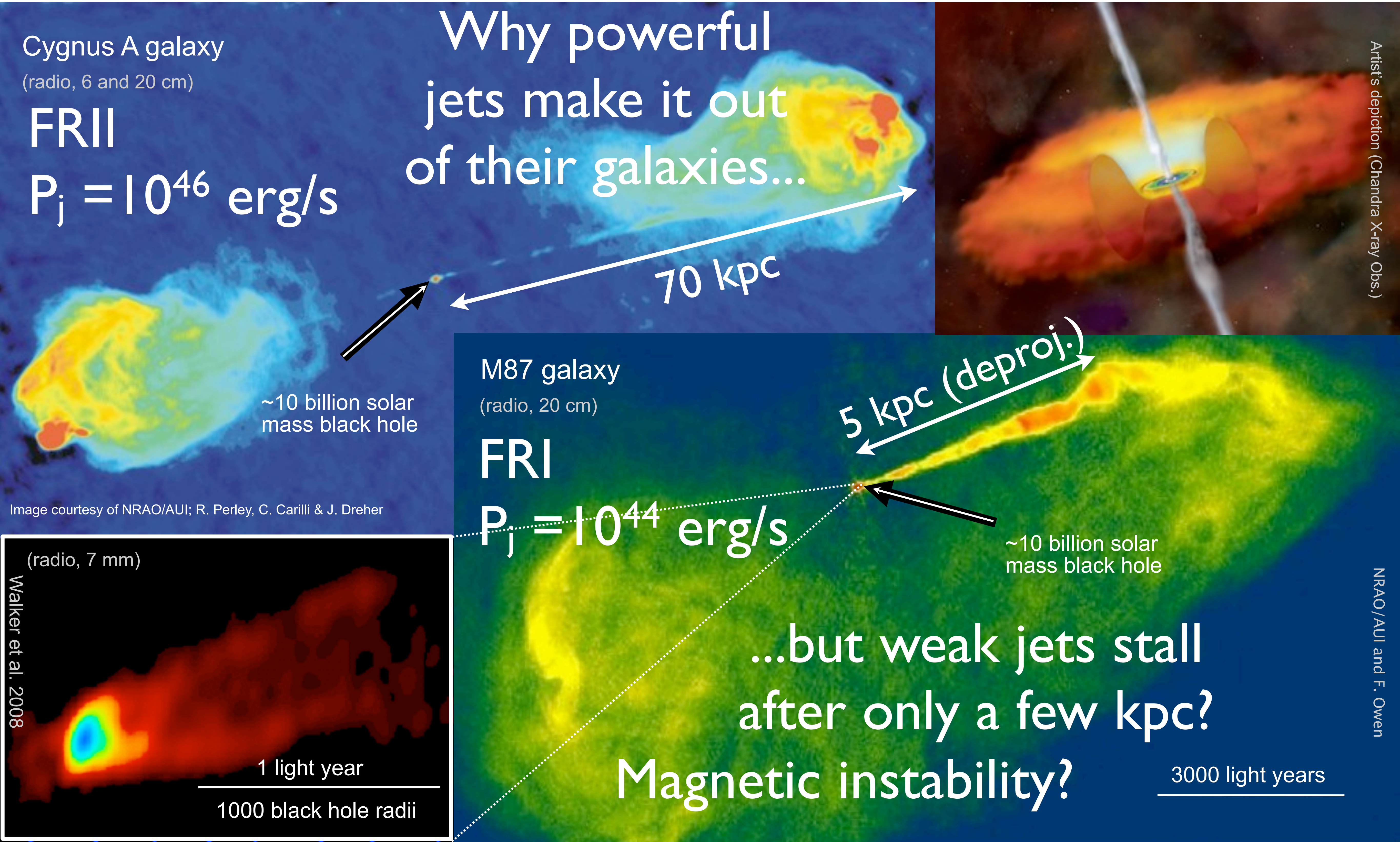


Instability of Magnetized Jets

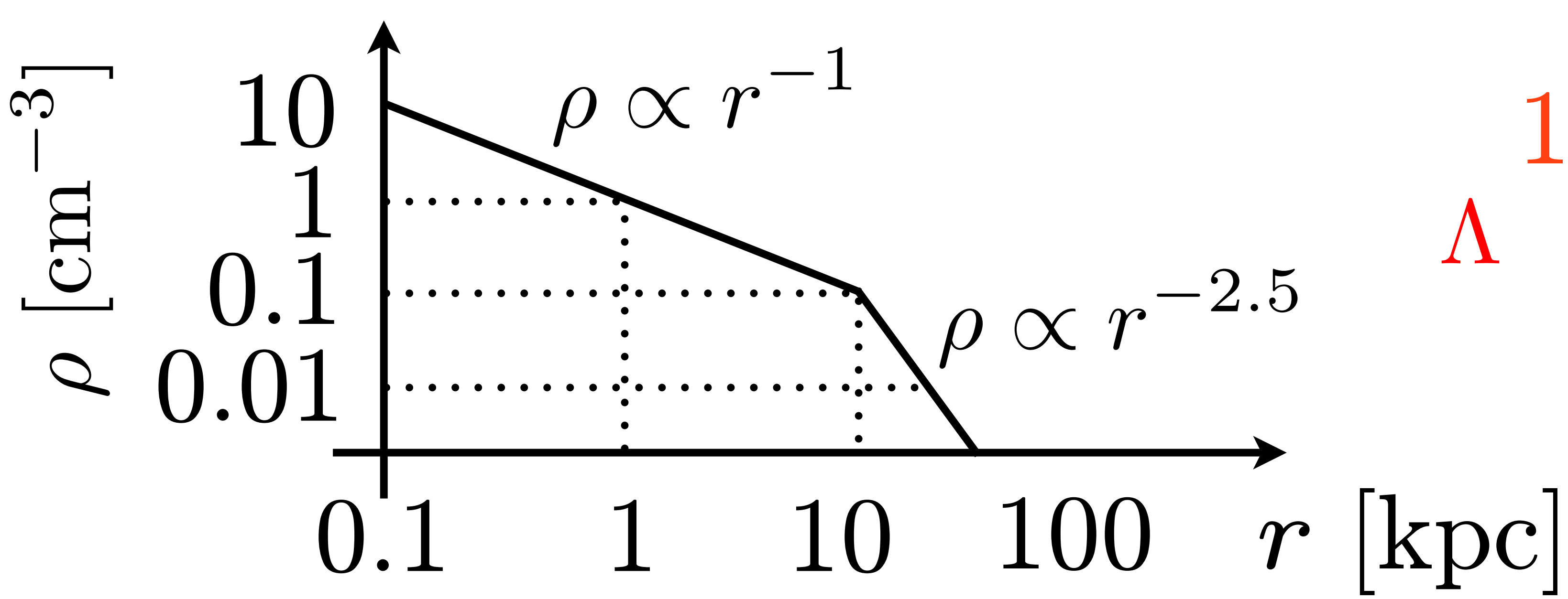
- Kink instability growth timescale controlled by the magnetic pitch (high-mag., mildly relativistic):

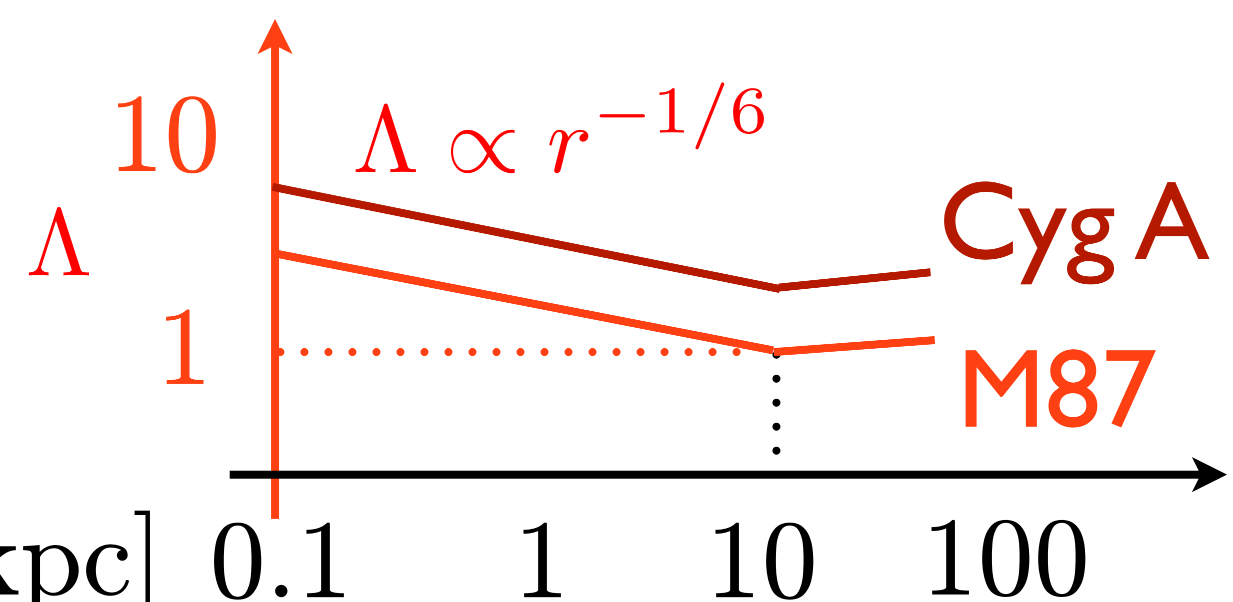
$$t_{\rm kink} \simeq \frac{2\pi R_{\rm j}}{c}\frac{B_p}{B_\phi}$$ (Appl et al. 2001)

- 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:



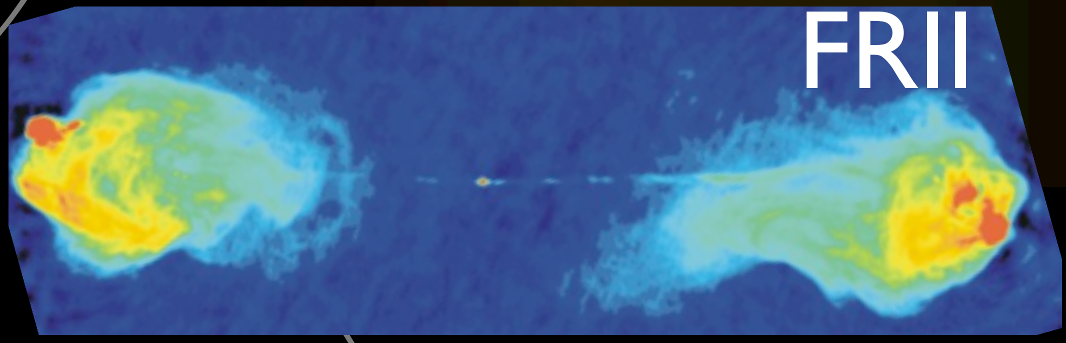


Cyg A-like

$P_j = 10^{46}$ erg s^{-1}

$t = 3$ Myr

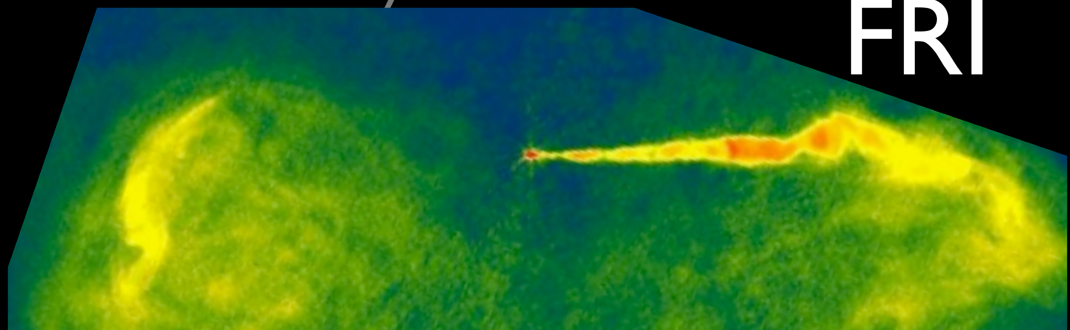
10 kpc



M87-like

$P_j = 10^{44}$ erg s^{-1}

$t = 6$ Myr



AT and Bromberg 2015, arXiv:1512.04526

H-AMR = BH Revolution

- Graphical Processing Units (GPUs), the cutting edge of modern supercomputing

Matthew Liska
(U of Amsterdam)

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- Multi-GPU 3D H-AMR ("hammer", Liska, AT, et al. 2017):
  - Based on Godunov-type code HARM2D (Gammie et al. '03)
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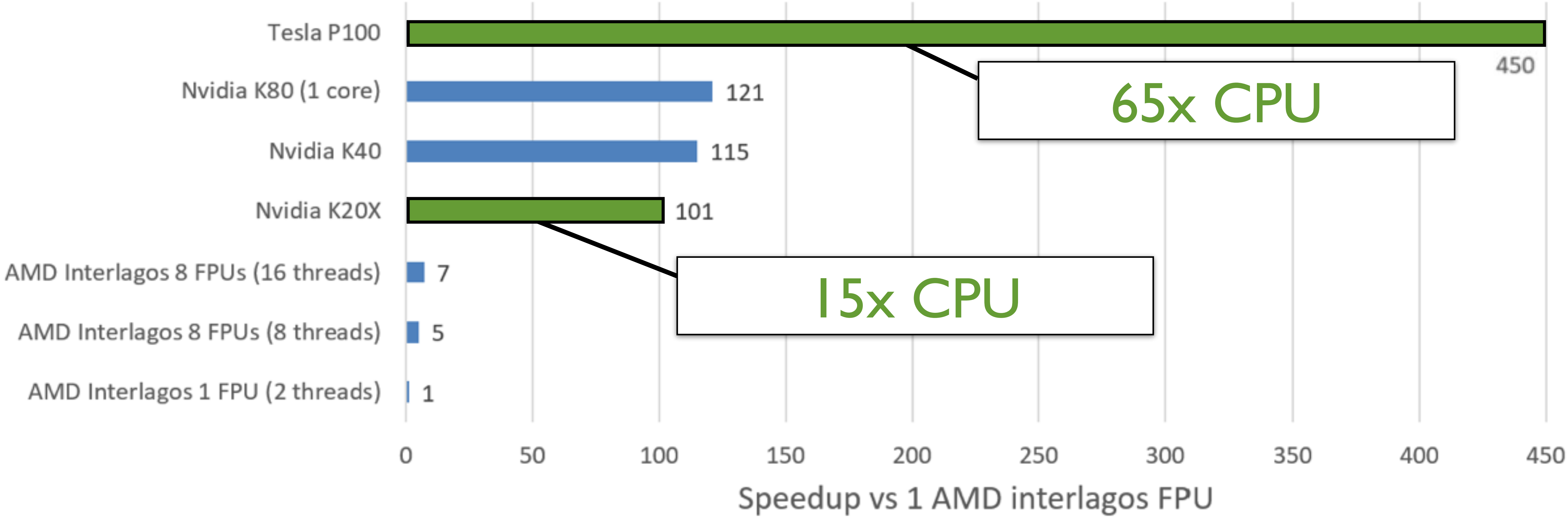

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  - features developed in the past year on BW
  - ideal for studying *typical, tilted systems*
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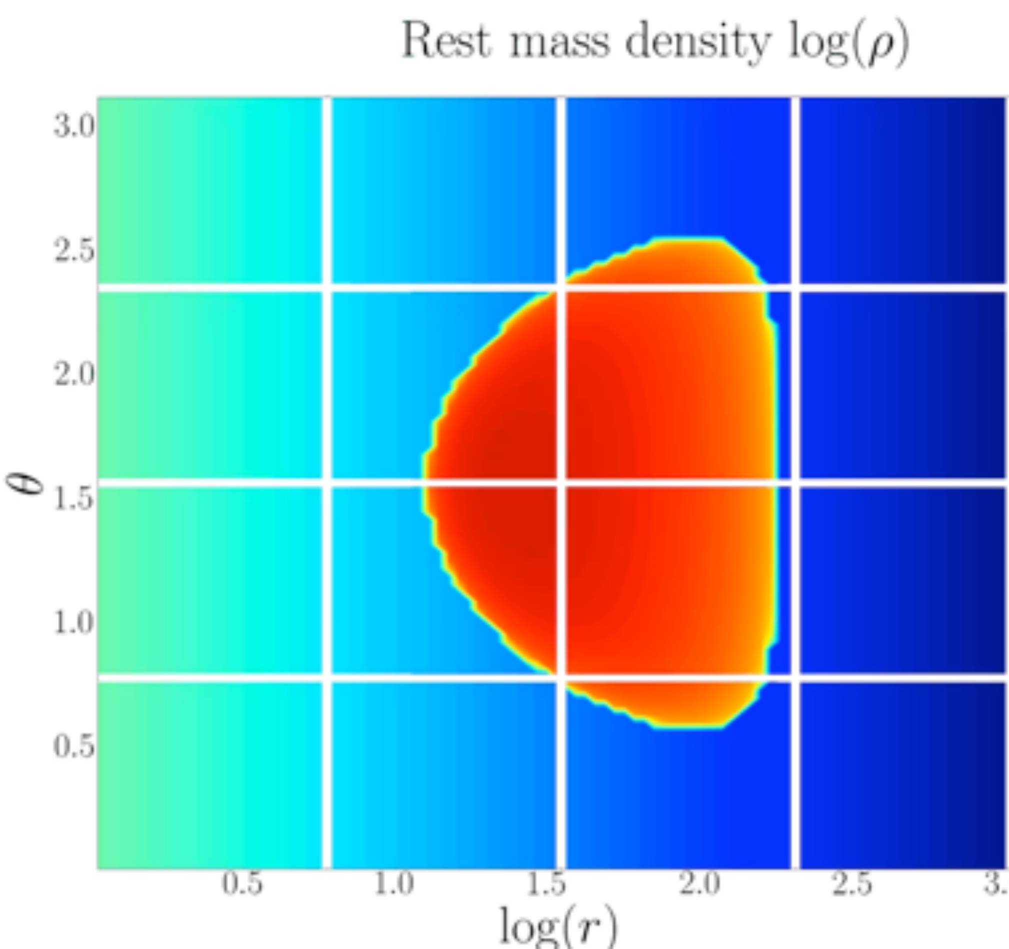

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- Ideal for getting computational time
  - 9M GPU-hours ≳ 9B CPU core-hour allocation on Blue Waters supercomputer
  - Science is no *longer limited by computational resources*!

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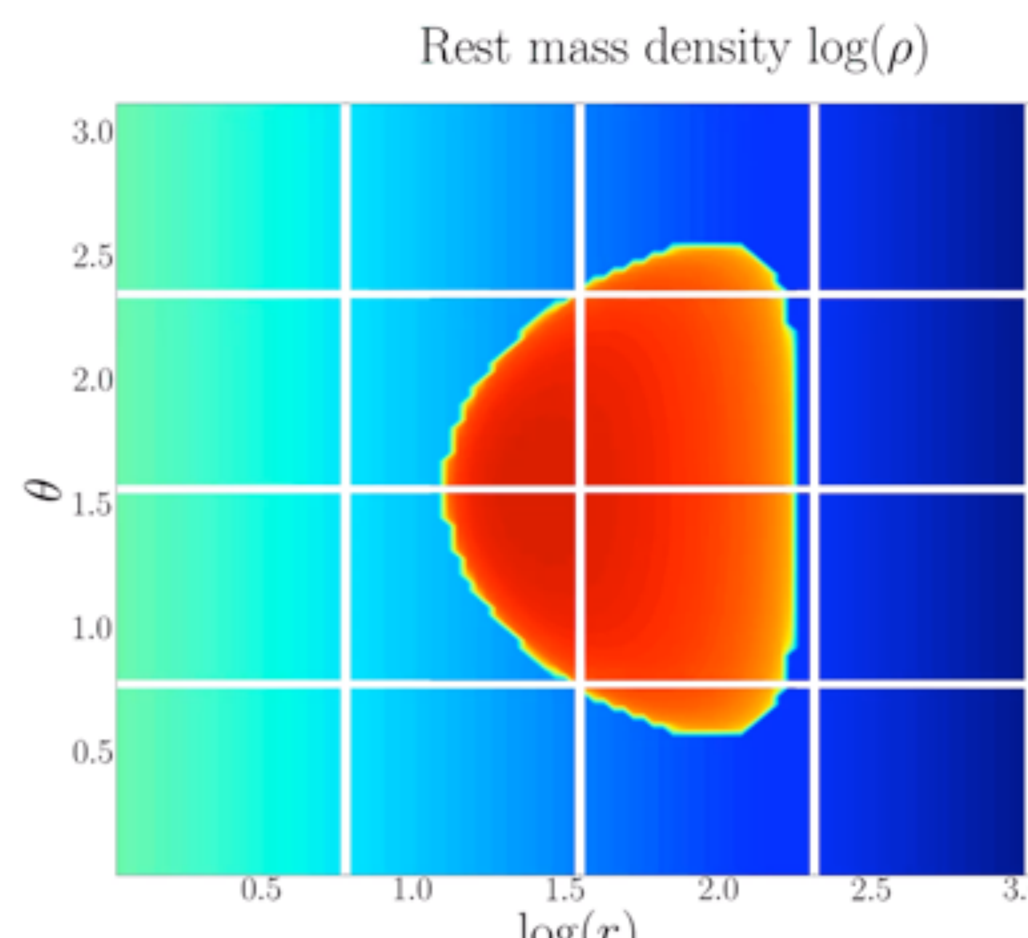
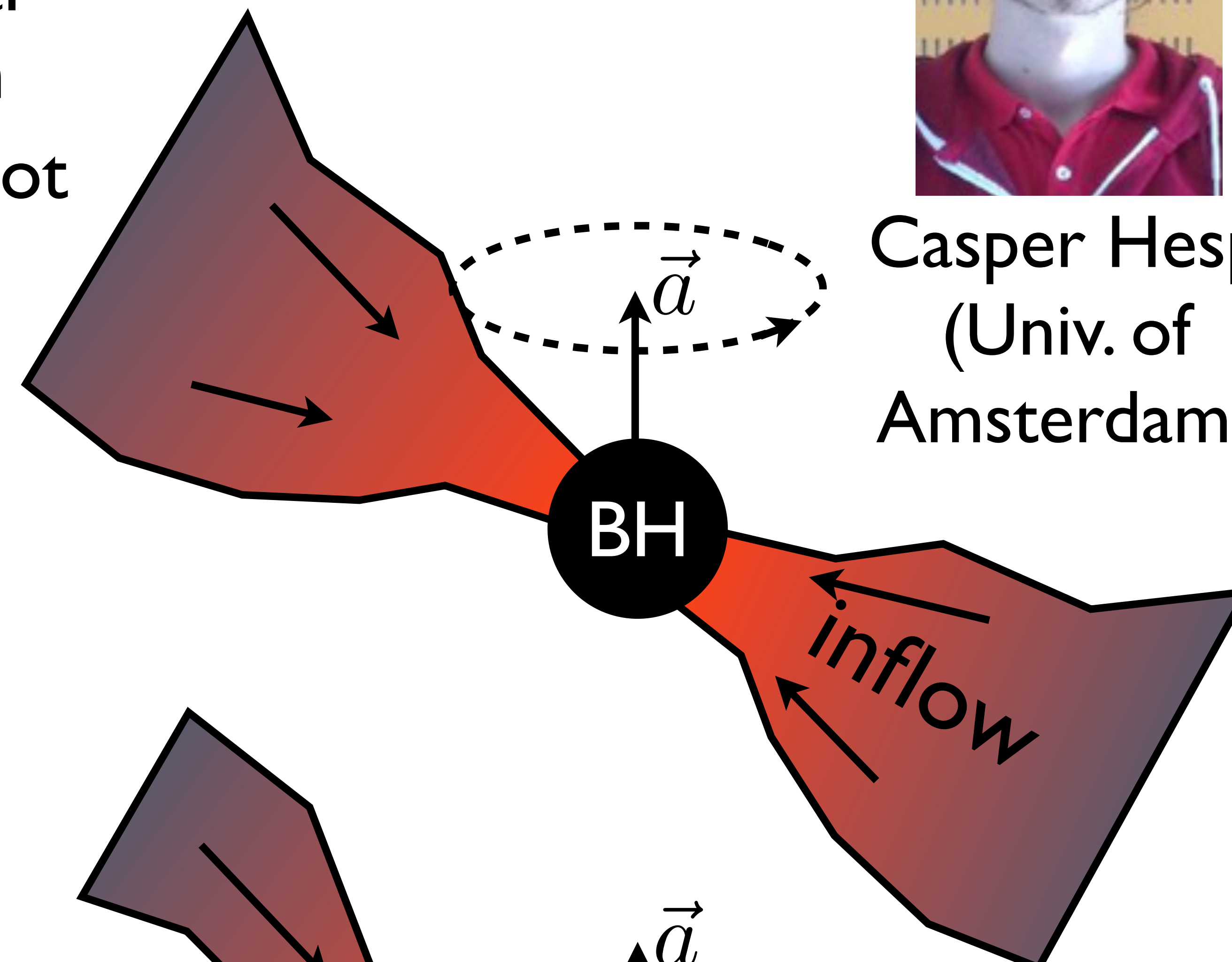
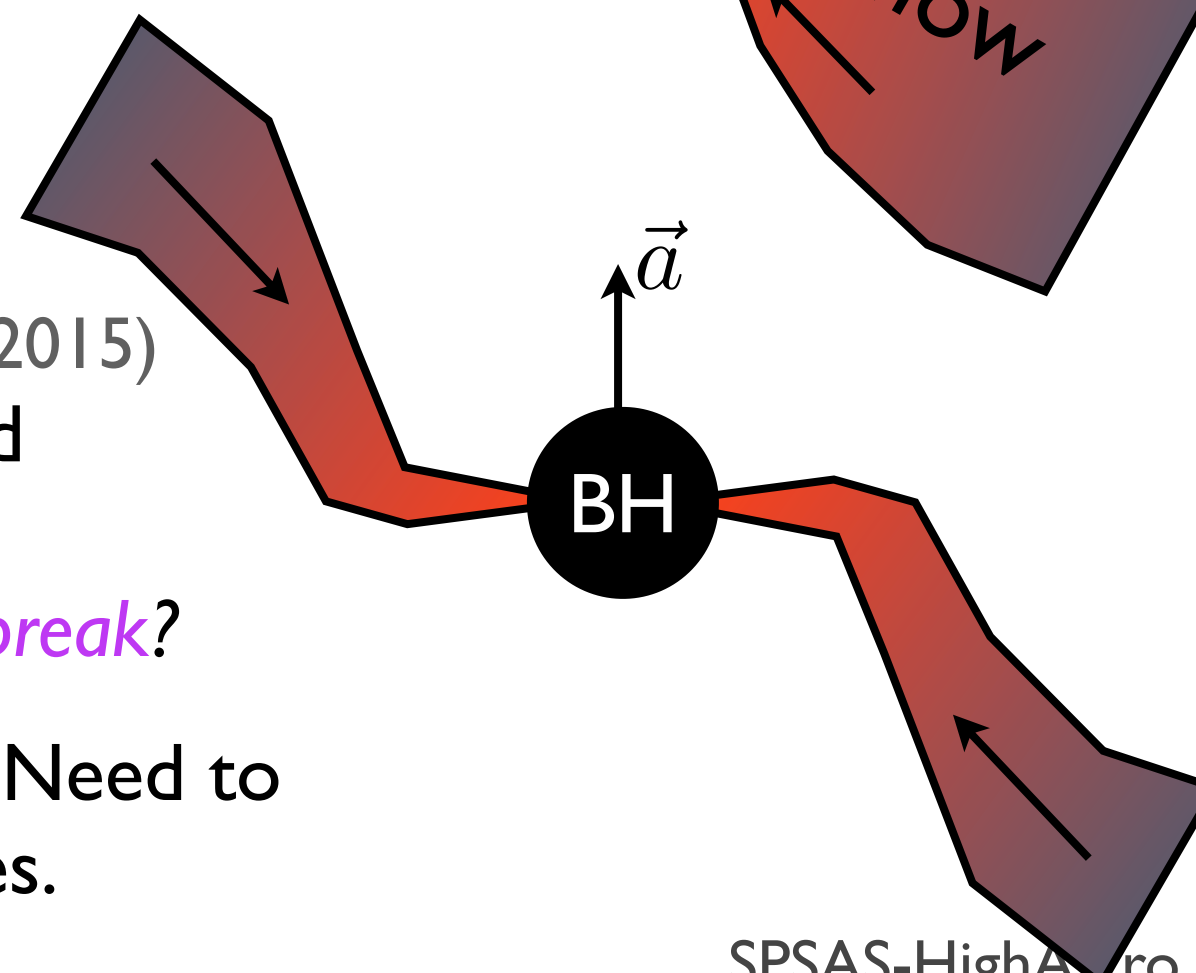


Tilted Disk Physics

- **Thick disks** precess due to general relativistic frame dragging by BH spin
  - precessing tilted disk sims could not handle jets (Fragile et al. 2005, 2007)
  - *Do tilted disks produce jets at all? Do jets precess or point along BH spin?* (McKinney, AT+2013)
- **Thin disks** can align due to Bardeen-Petterson (1975) effect
  - Seen only in pseudo-Newtonian simulations and at small inclinations (Hawley and Krolik 2015)
  - At larger inclinations disks predicted to break (Nixon et al. 2012)
  - *Do thin disks align in GR? Or do they break?*
- Challenge: enormous dynamical range. Need to resolve thin streams *over* long run times.

Casper Hesp (Univ. of Amsterdam)





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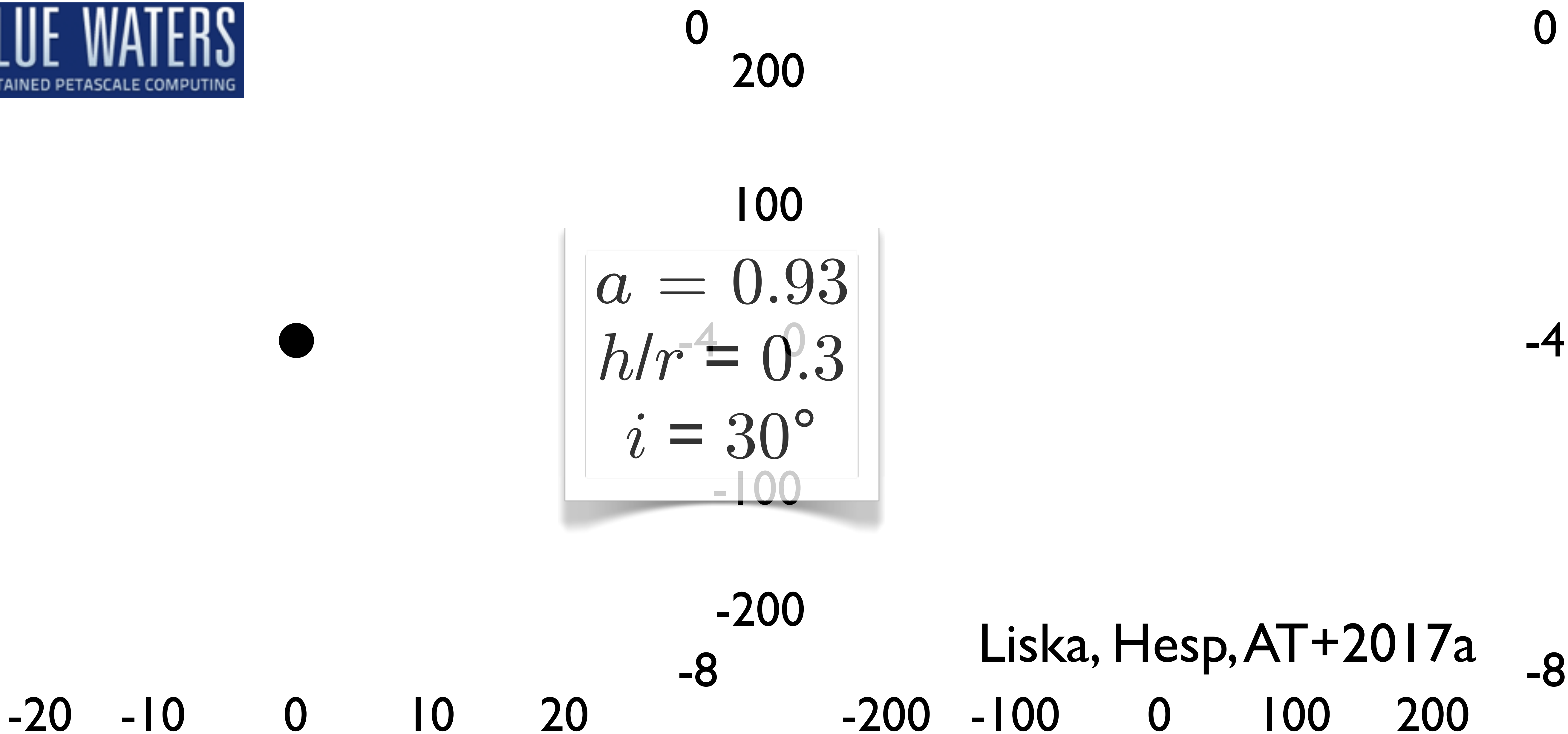

Liska, Hesp, AT+2017a

- BW enabled the first demonstration that
  - tilted thick disks produce tilted jets • tilted jets precess
- Longest GRMHD tilted disk simulation, $120{,}000\ r_g/c$
- Highest resolution GRMHD simulations: $896{\times}288{\times}480$
  - convergence verified at $1792{\times}576{\times}960$: *first ever billion cell run*

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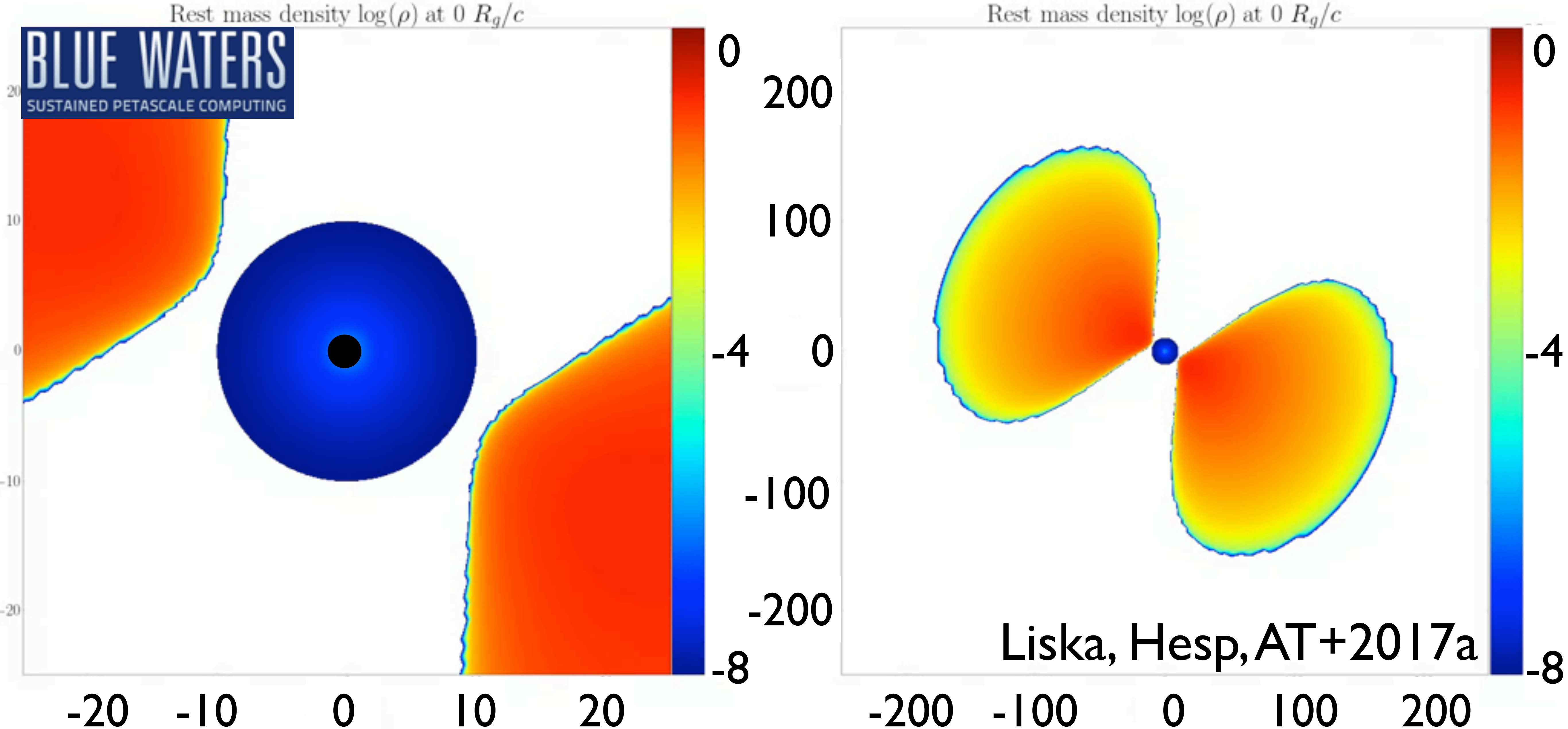

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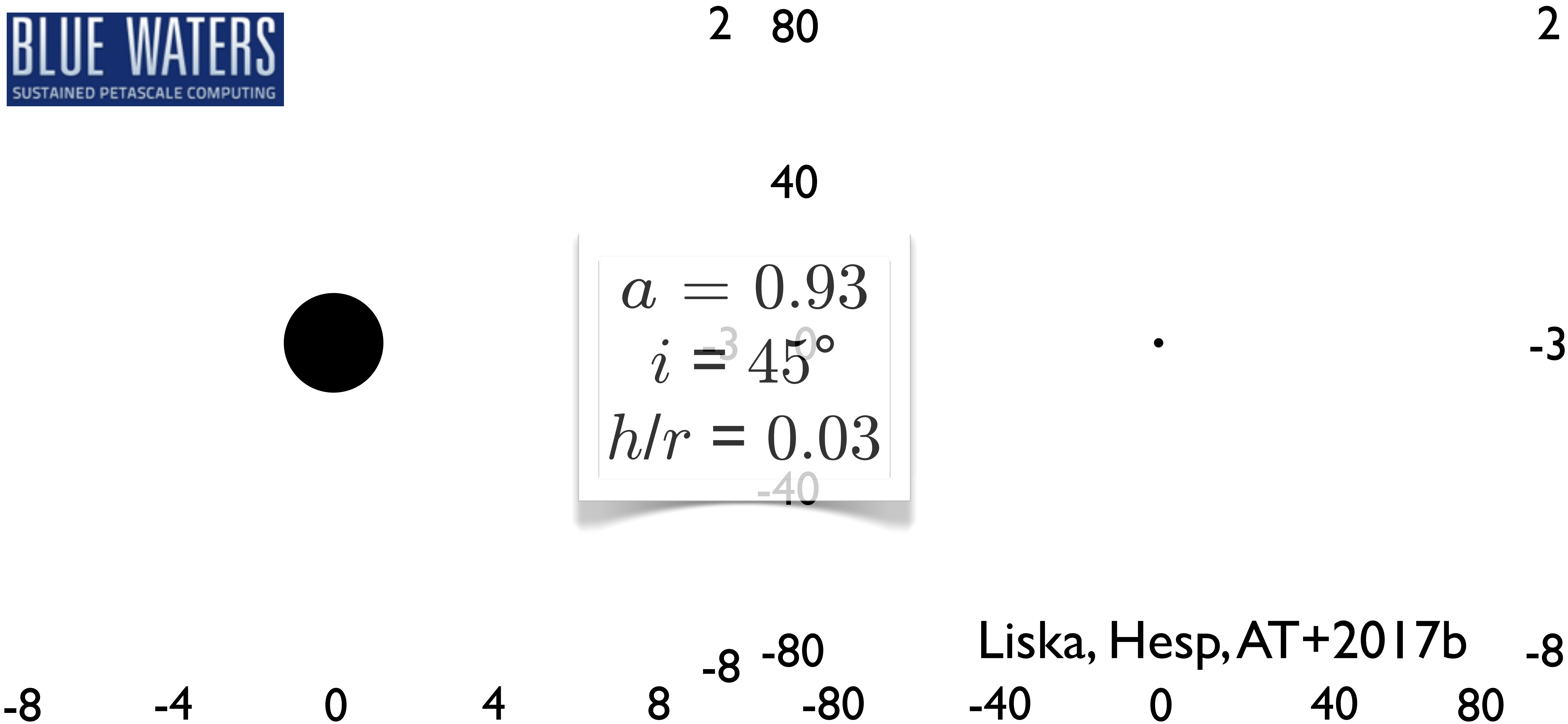
Thin Strongly Misaligned Disks Do NOT Align



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  - effective resolution $1792{\times}860{\times}1200$, 3 AMR levels
  - *preliminary*: even thinner disk, $h/r = 0.015$, does not appear to align either

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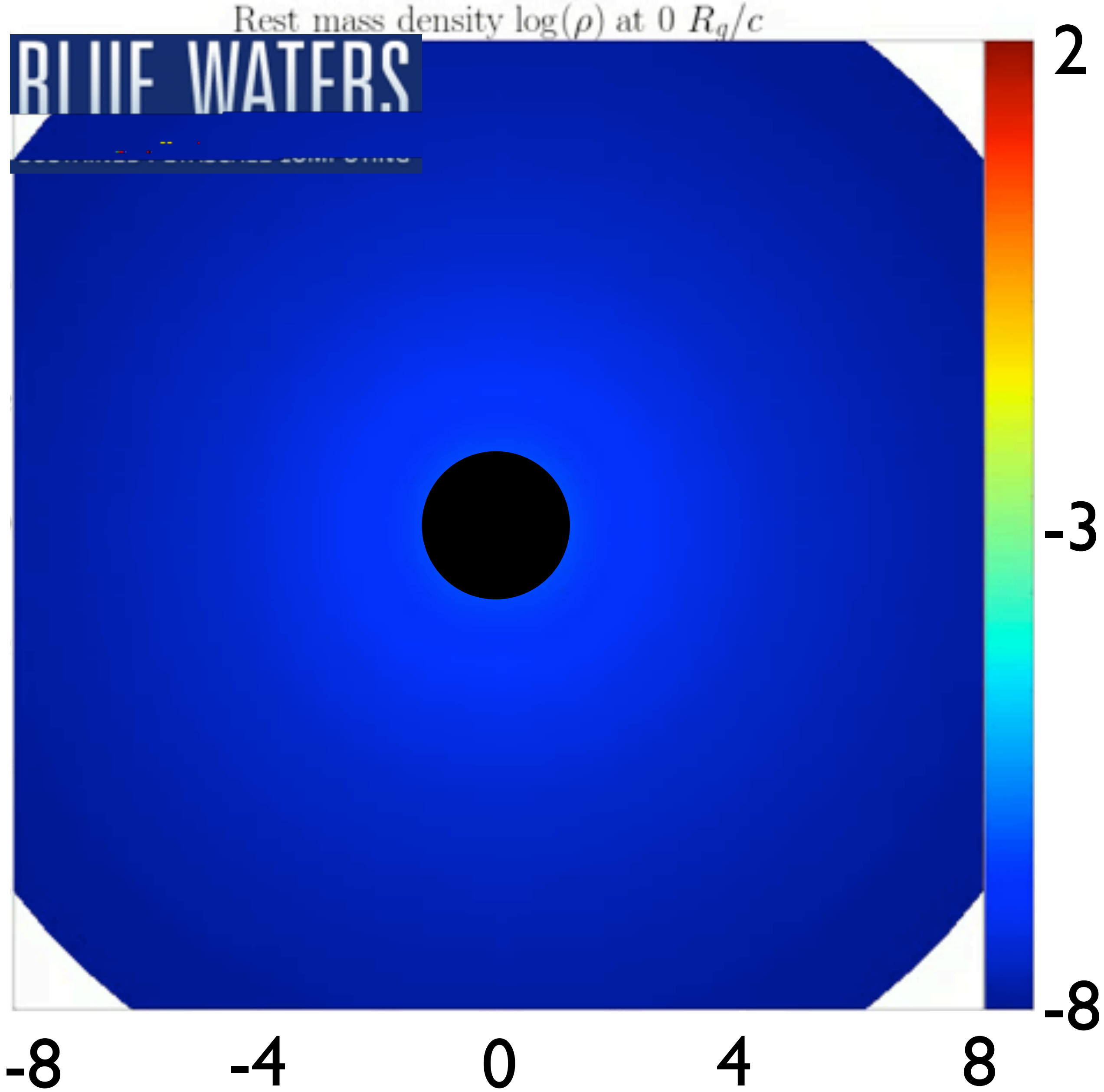

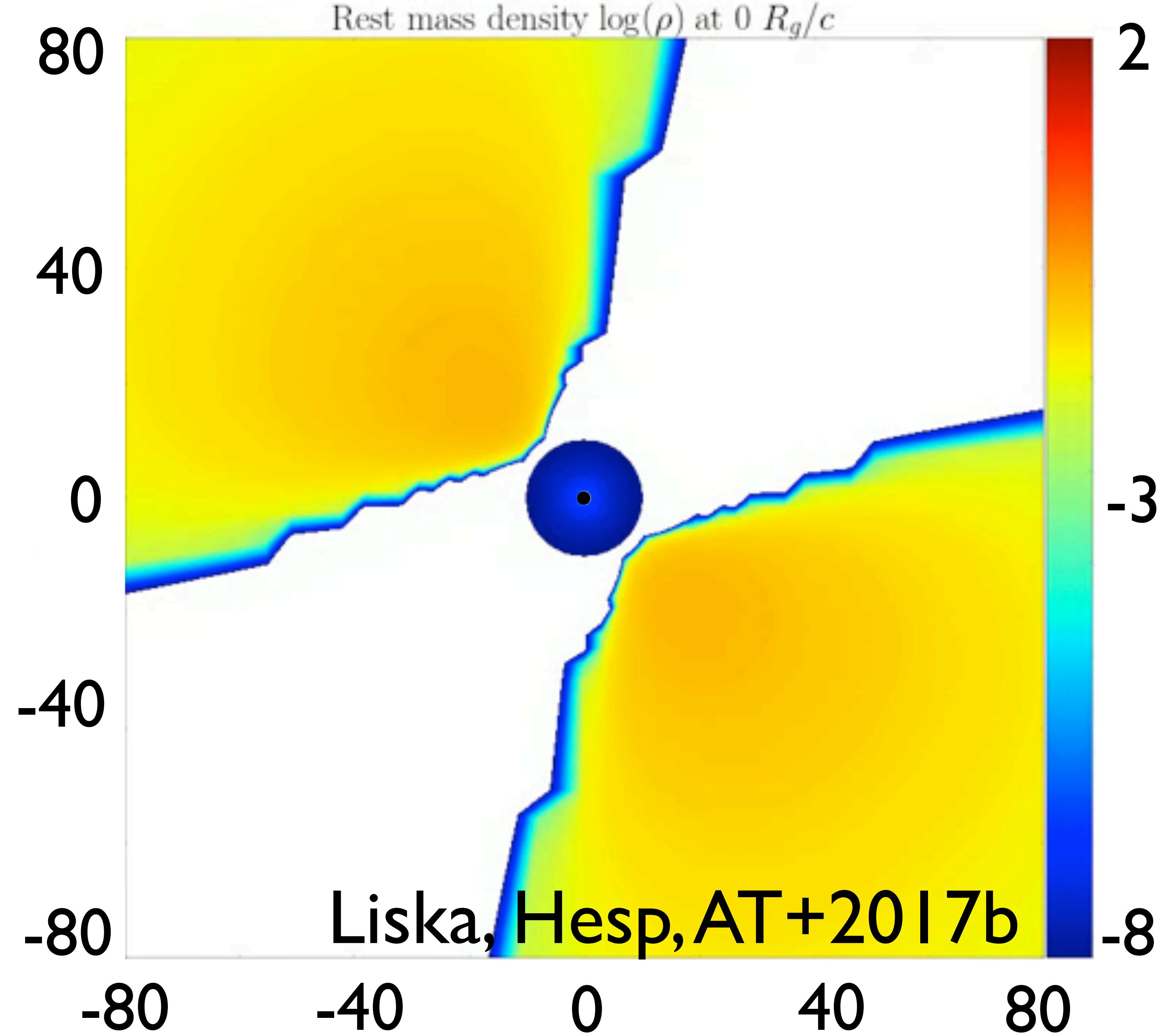

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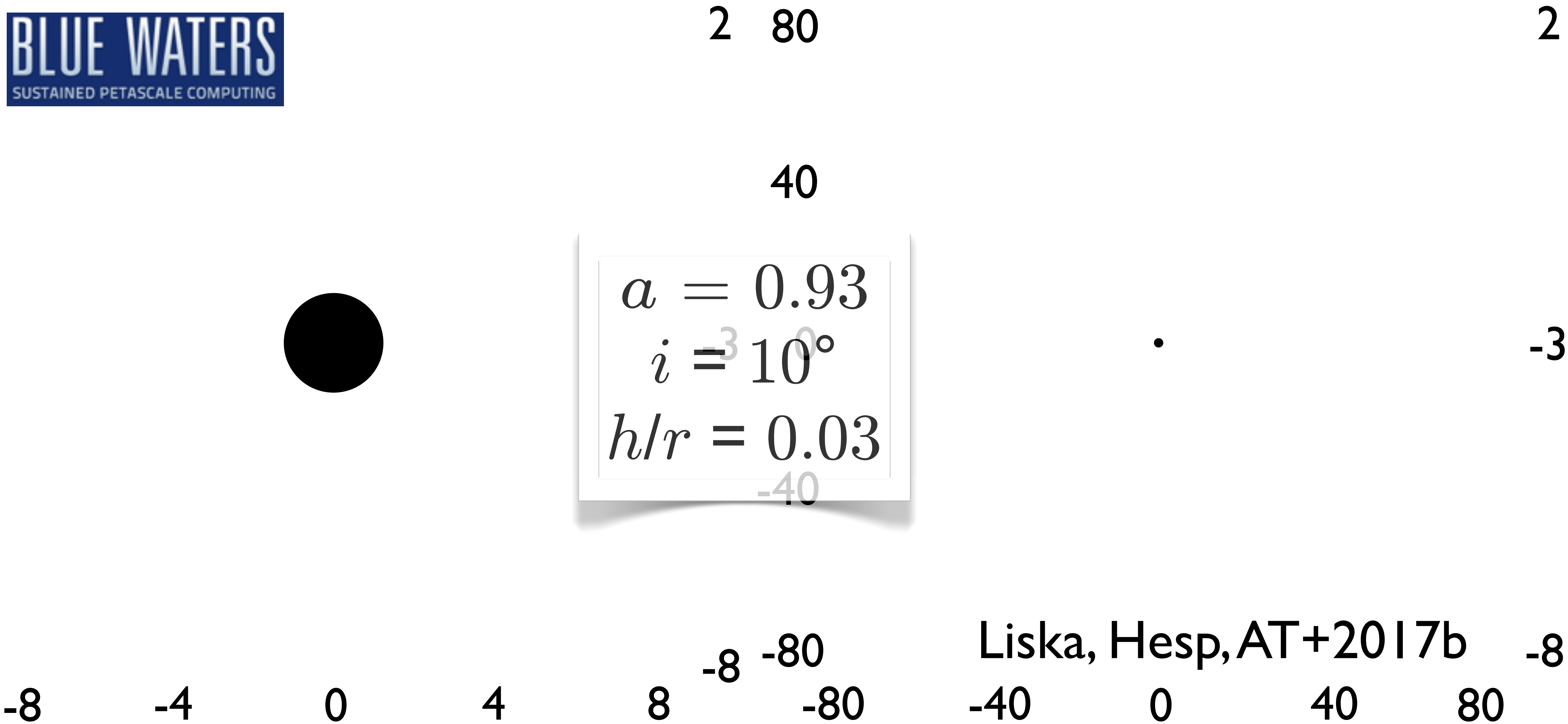
Thin **Weakly** Misaligned Disks Align



Liska, Hesp, AT+2017b

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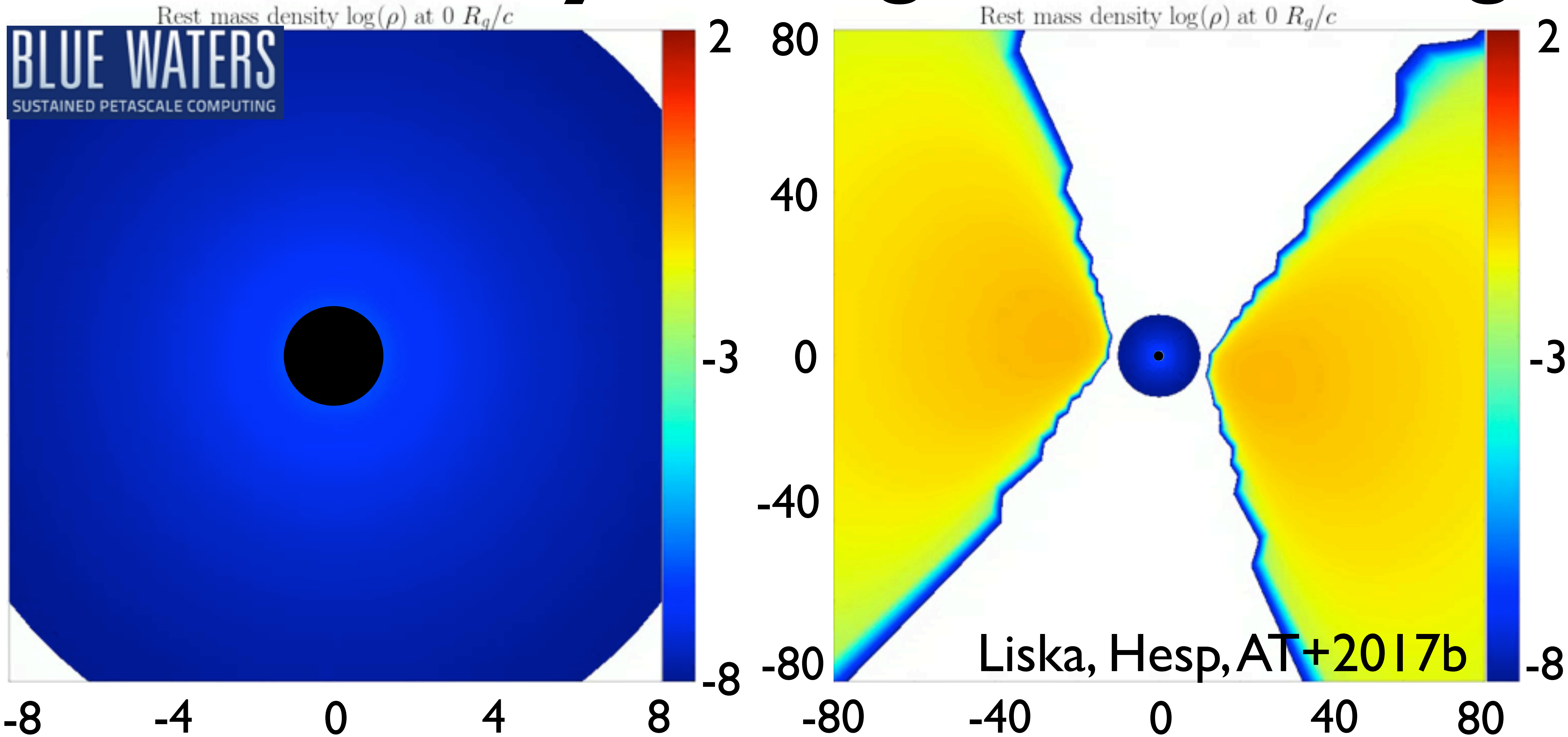

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Making the Disk from Scratch

-5

-5

SUSTAINED PETASCALE COMPUTING

400

$$a = 0.93$$

200

$$i = 0^\circ$$

parabolic orbit

0

$$R_p = 7 R_g$$

$$M_{\rm BH} = 10^6\, M_*$$

-200

-400

-12

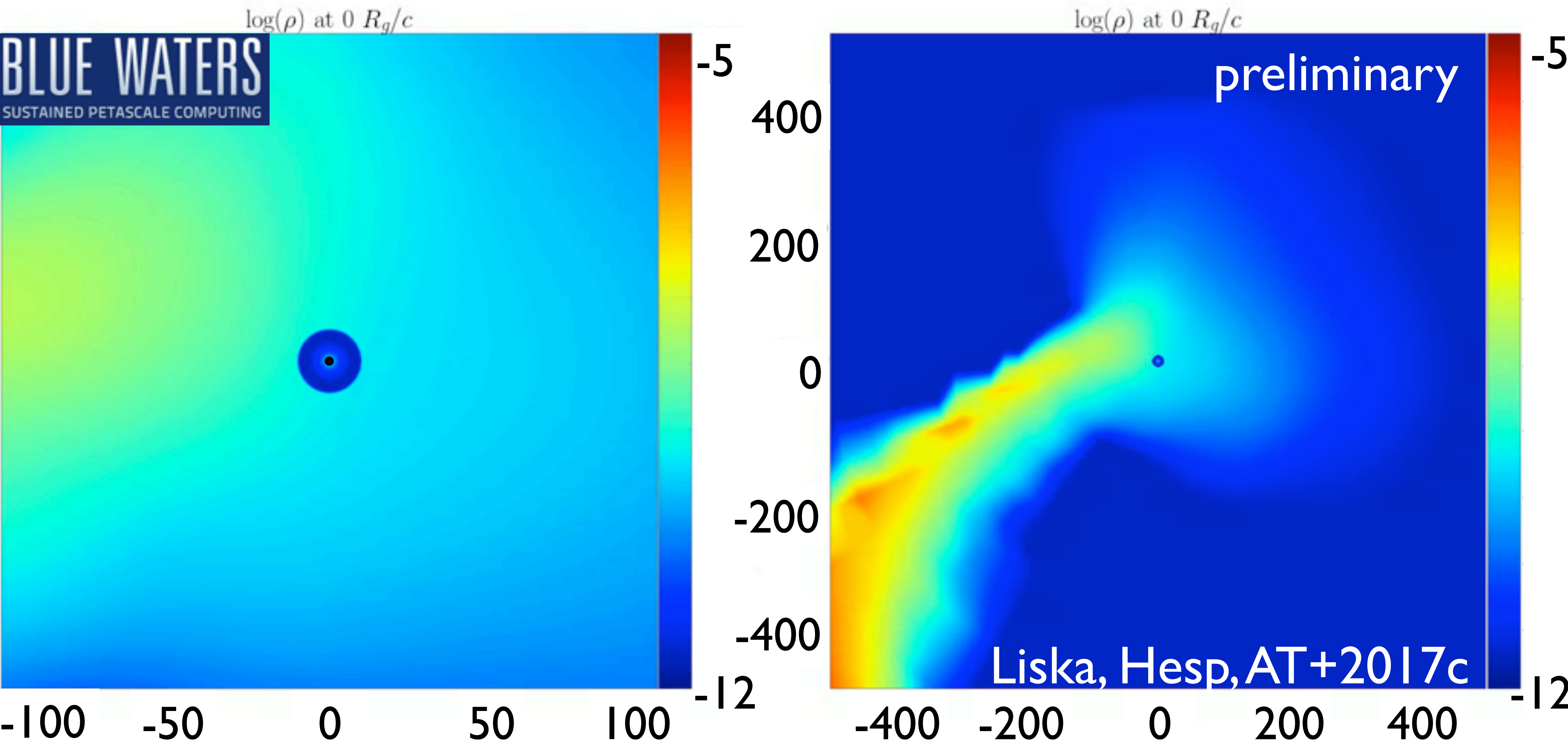
-12

-100 -50 0 50 100

-400 -200 0 200 400

- Initial conditions computed by the phantom code by Eric Coughlin
- First GR simulation of star on parabolic orbit tidally disrupted by supermassive BH, $M_{\rm BH} = 10^6\, M_*$ ($\gg 500 M_*$, Shiokawa+15)
- effective resolution $1792{\times}860{\times}1200$, 3 AMR levels

Making the Disk from Scratch



- Initial conditions computed by the $\mathrm{phantom}$ code by Eric Coughlin
- First GR simulation of star on parabolic orbit tidally disrupted by supermassive BH, $M_{\mathrm{BH}} = 10^6\, M_*$ ($\gg 500 M_*$, Shiokawa+15)
- effective resolution $1792{\times}860{\times}1200$, 3 AMR levels

Summary

- Dynamically important magnetic fields wide spread
- 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

  Jets are resilient: how to shut them off?
- GPUs + H-AMR = qualitative breakthrough in black hole simulations
  - Multi-scale physics at the new level of complexity
  - Tilted accretion studies are now routine
- I soon move to Northwestern University: please apply to join my group