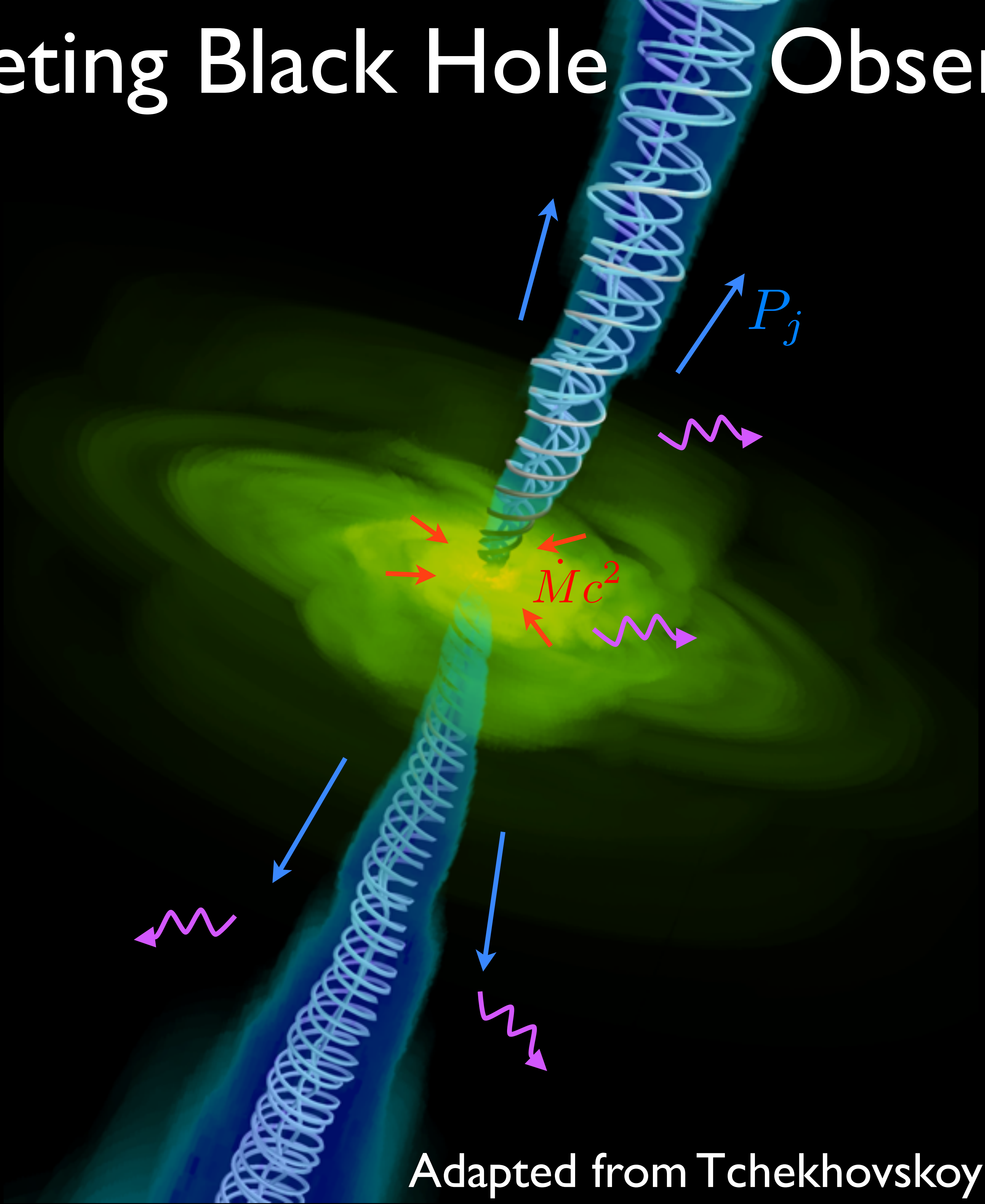
Disks and Jets

Alexander (Sasha) Tchekhovskoy

Einstein Fellow
UC Berkeley

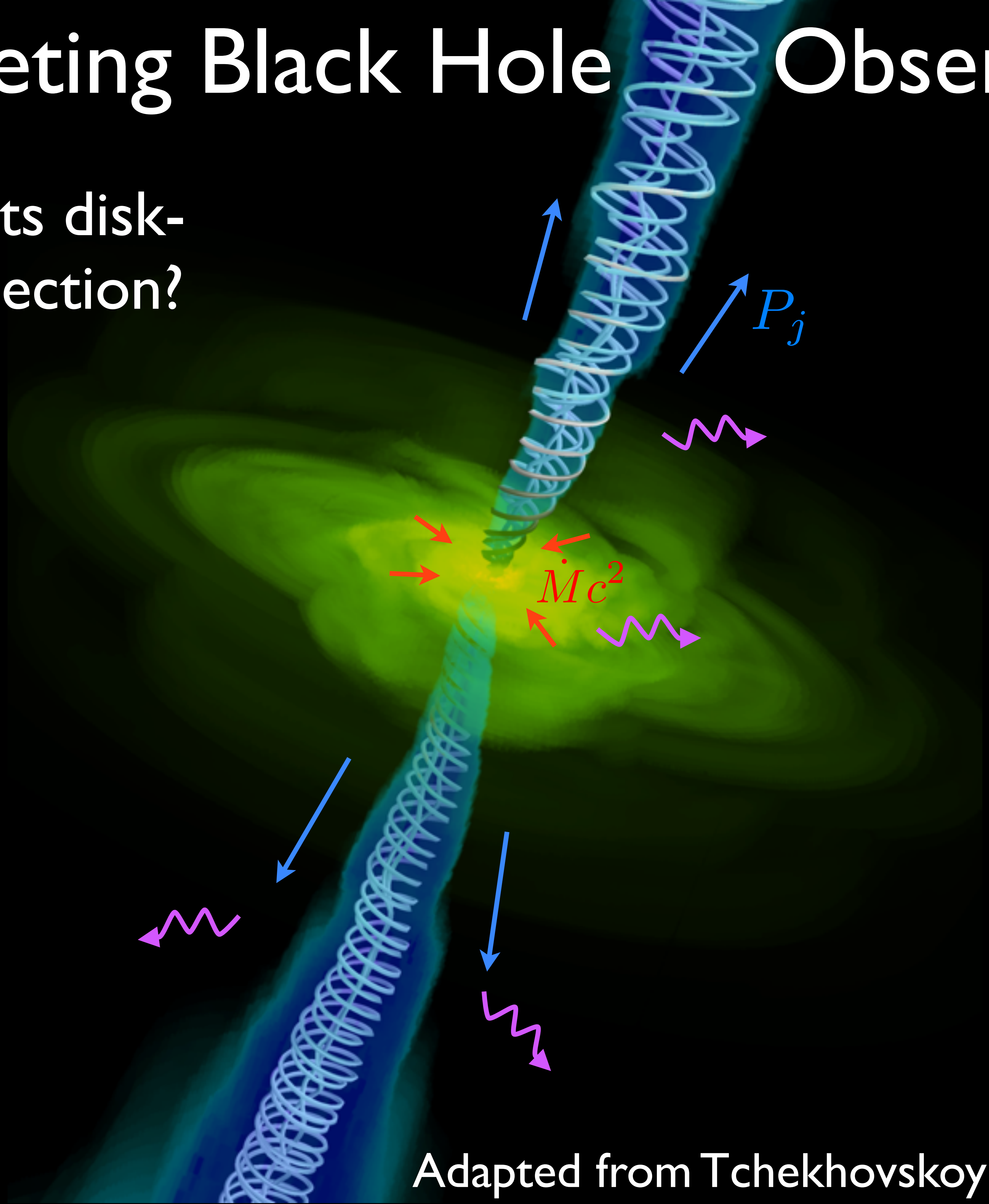
Interpreting Black Hole Observations



Adapted from Tchekhovskoy 2015

Interpreting Black Hole Observations

- What sets disk-jet connection?



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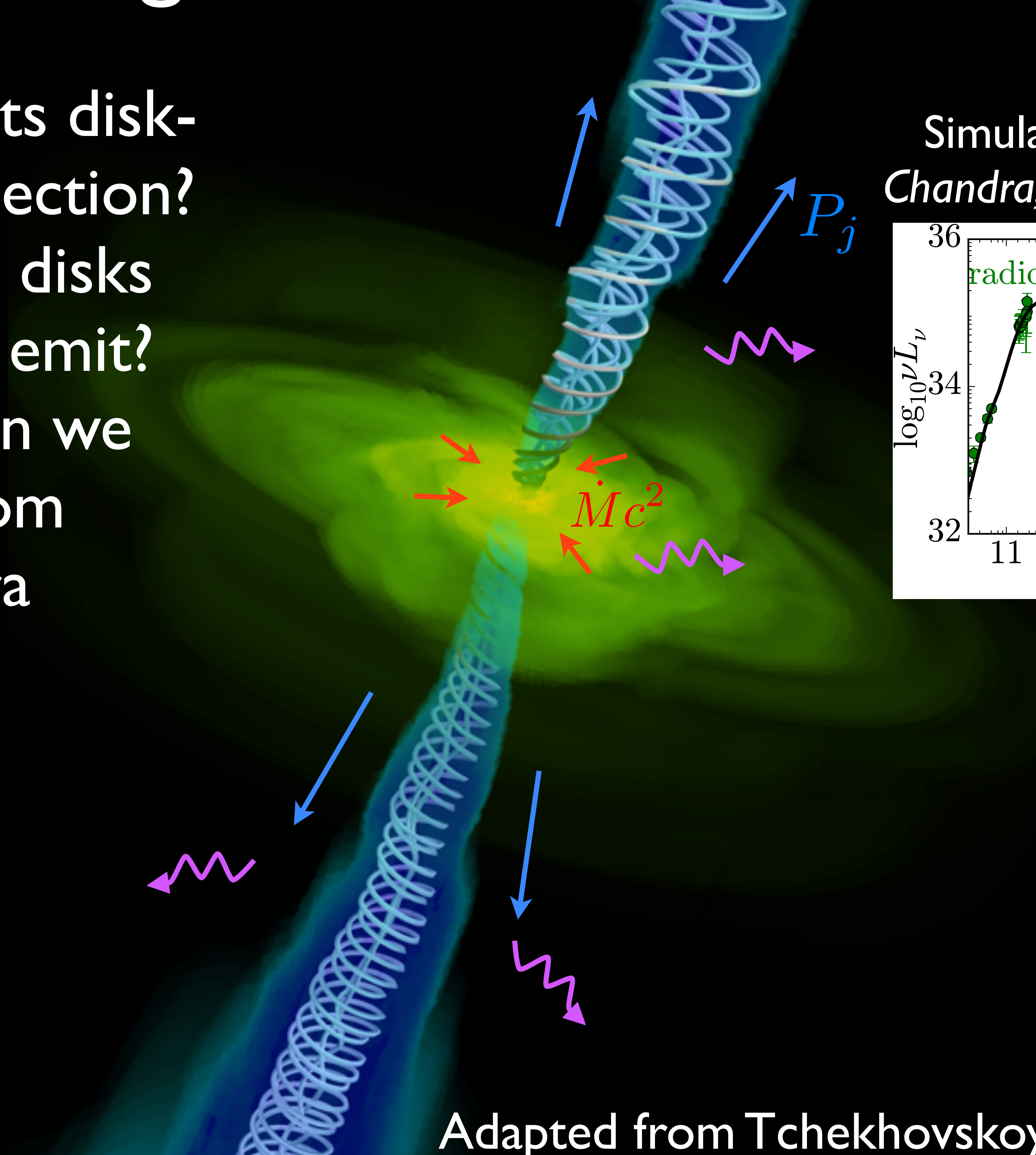
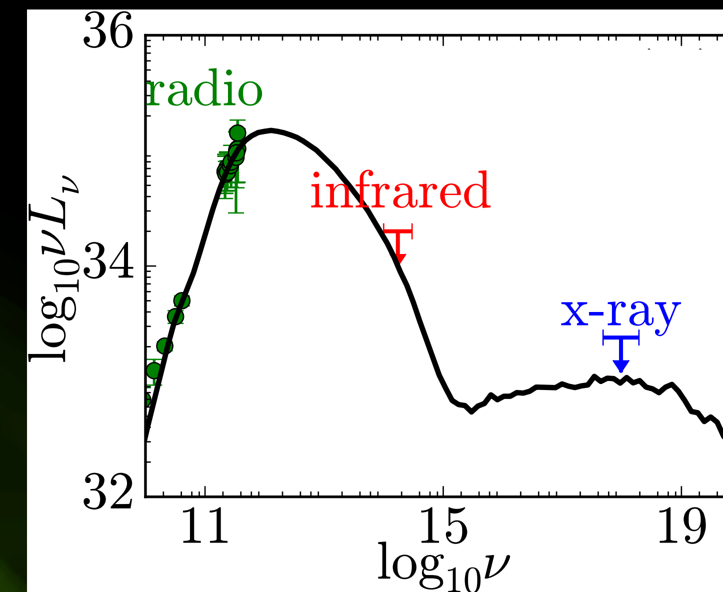
Interpreting Black Hole Observations

- What sets disk-jet connection?
- How do disks and jets emit?
- What can we learn from
  - spectra



Simulated *ALMA, VLA, Chandra, NuSTAR* spectra



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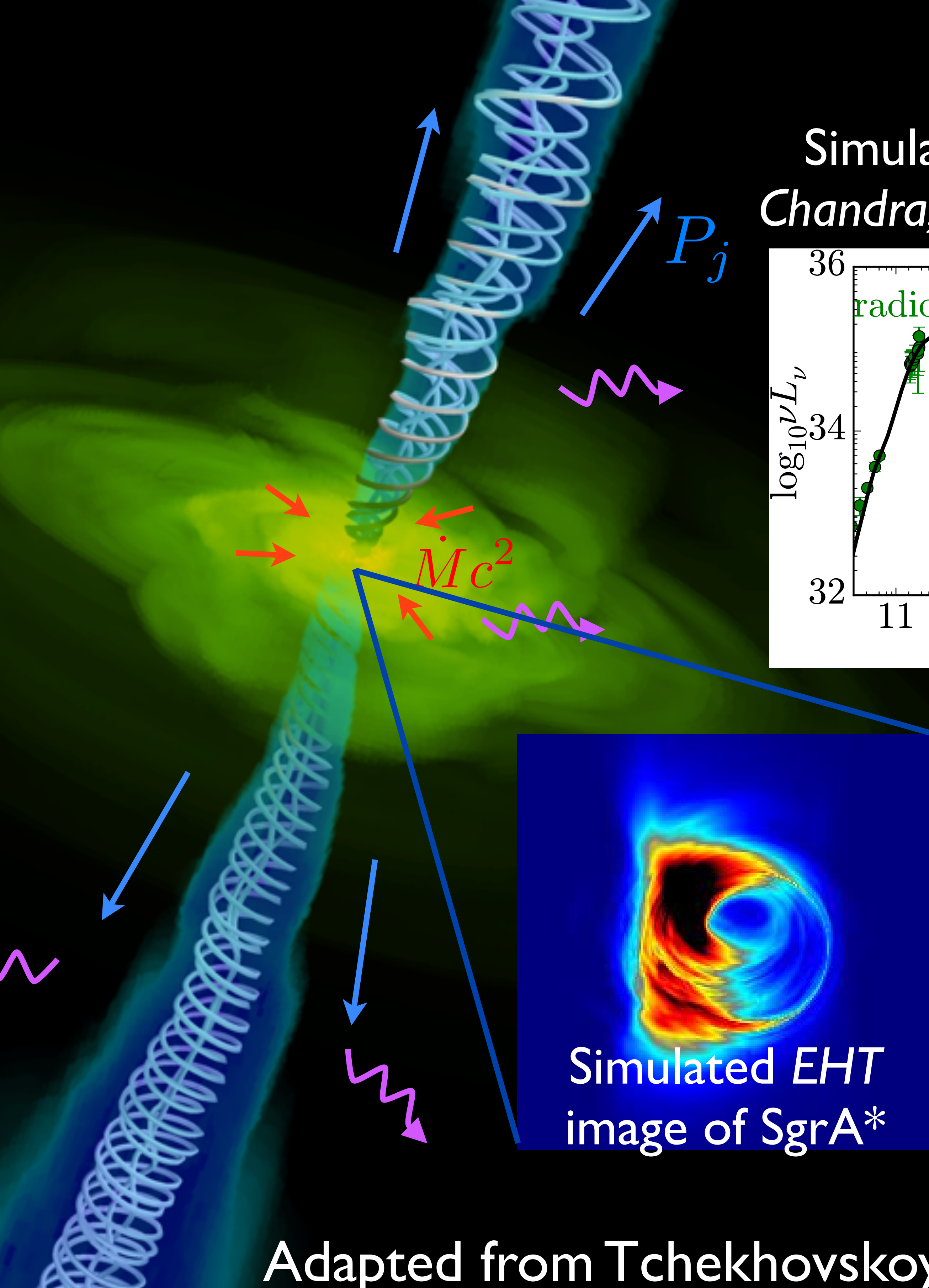

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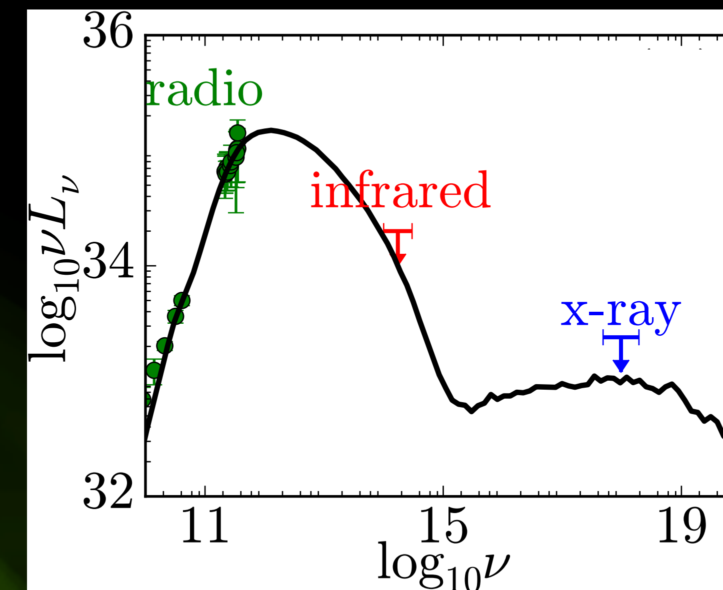

Simulated *EHT* image of SgrA*

Adapted from Tchekhovskoy 2015

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  - spectra
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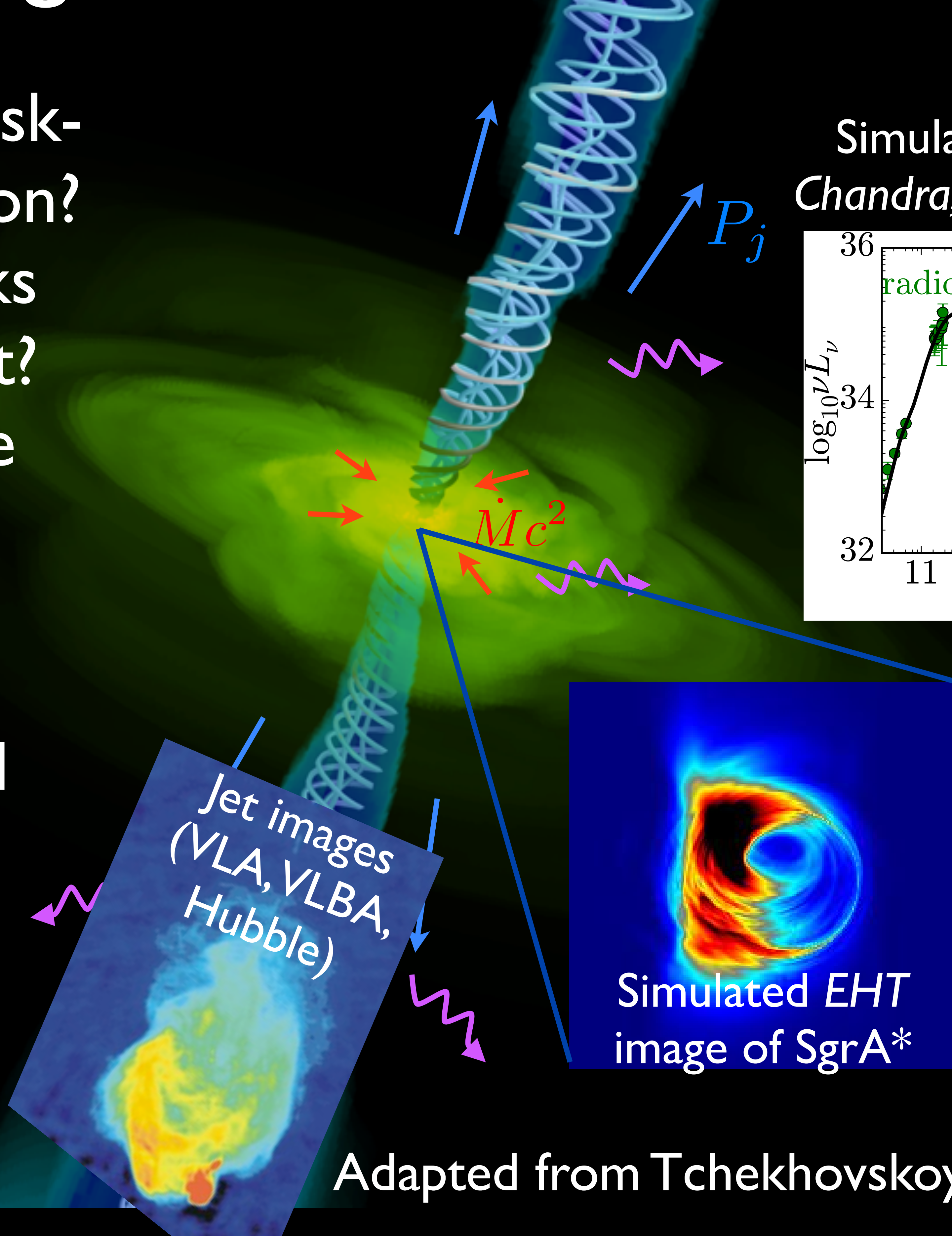
  on small and large scales?



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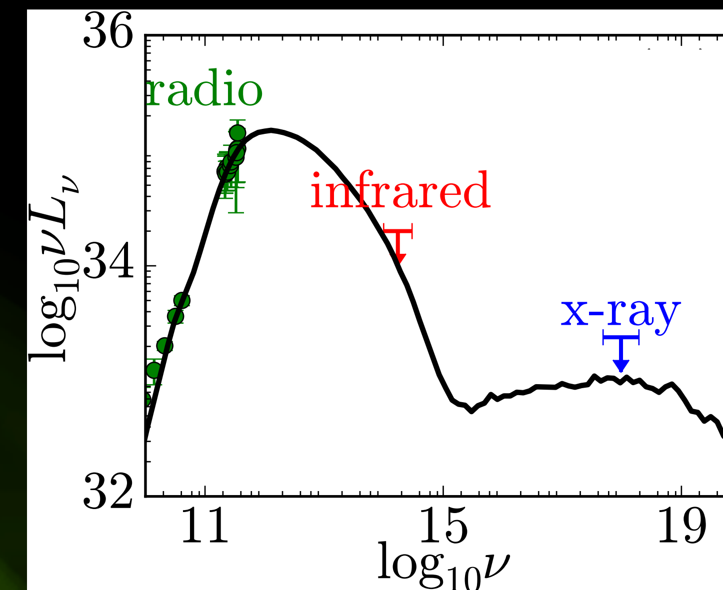

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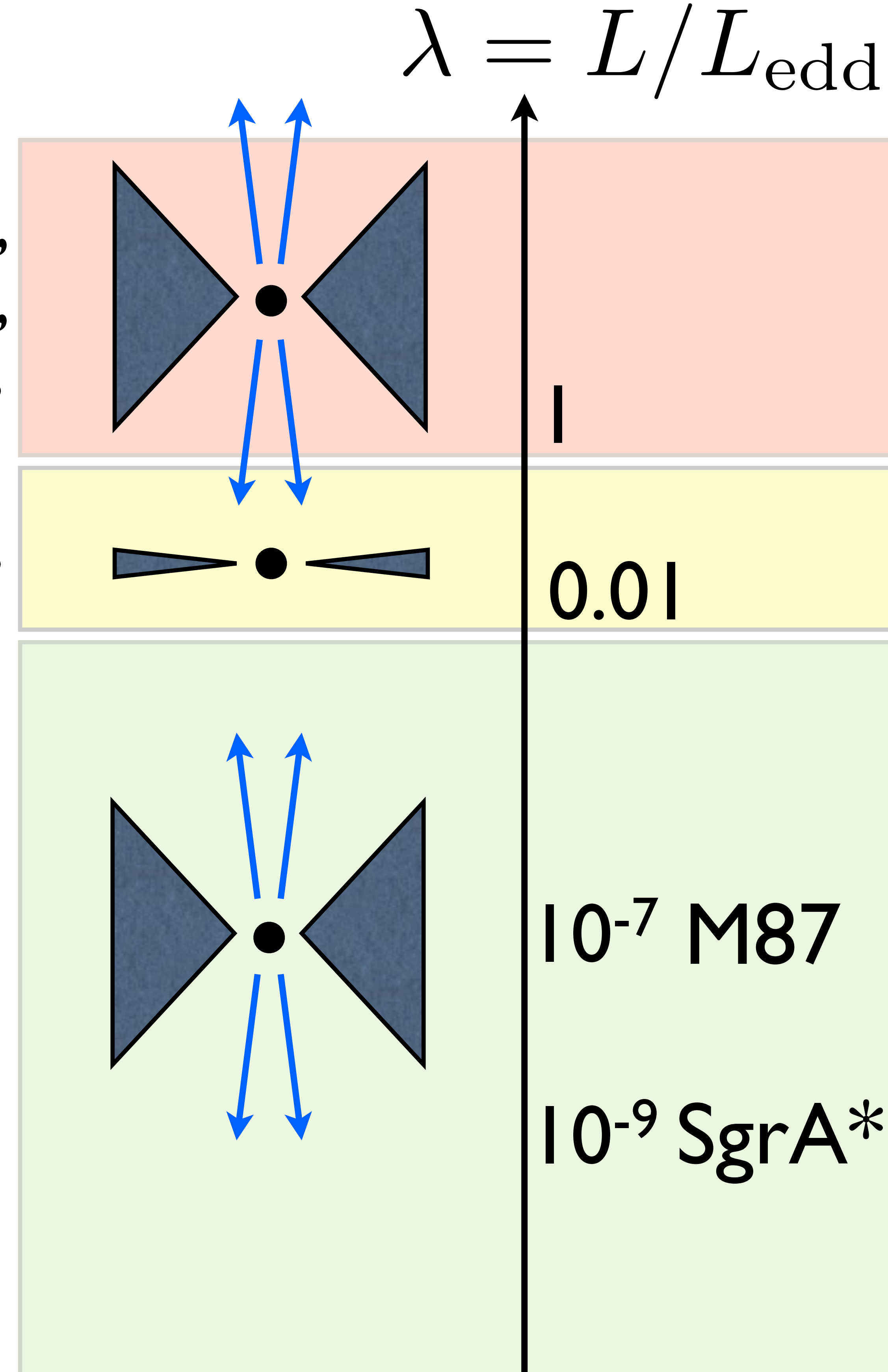
Black Hole Accretion States

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

Quasars, X-ray binaries, TDEs

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



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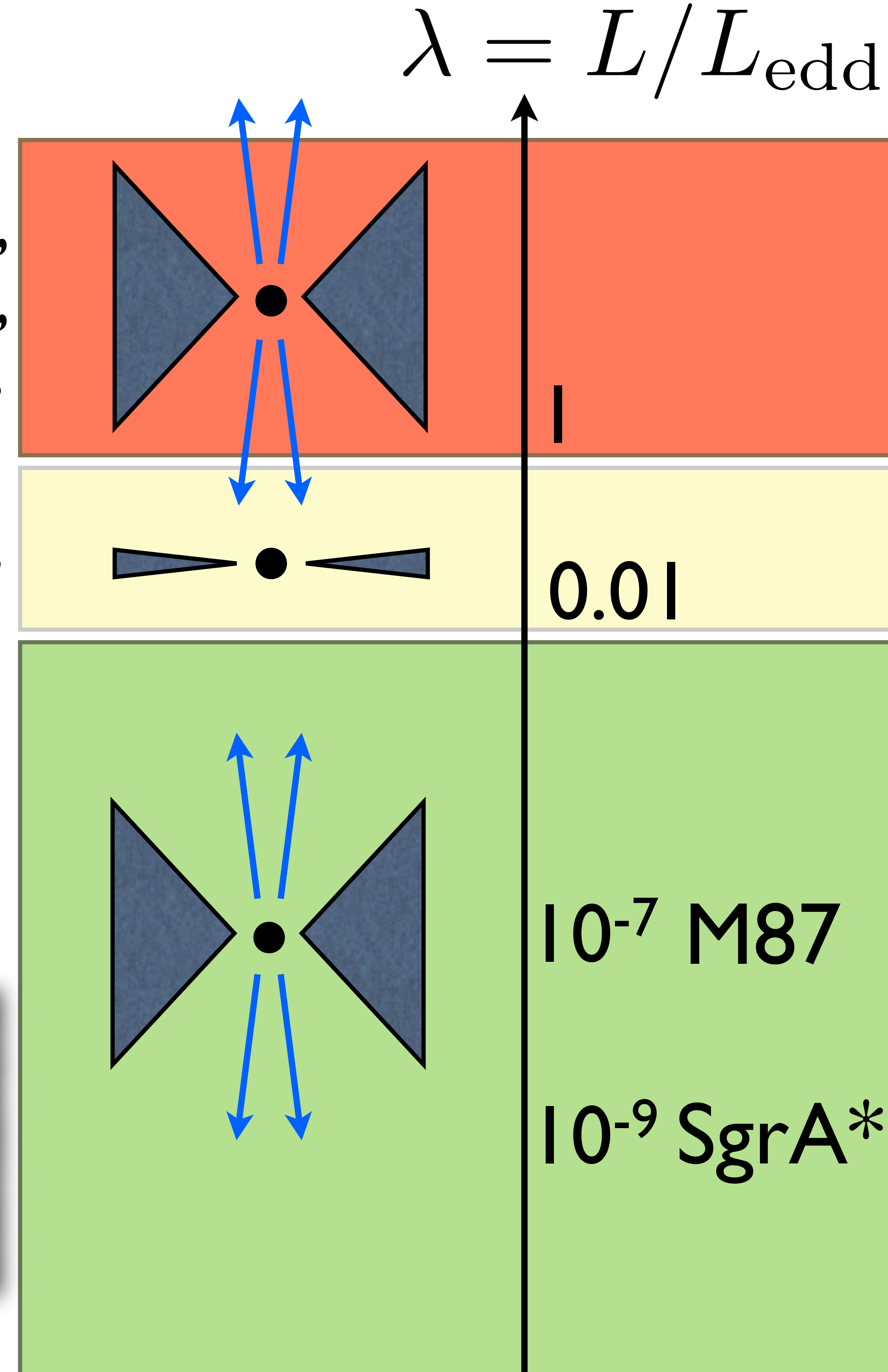
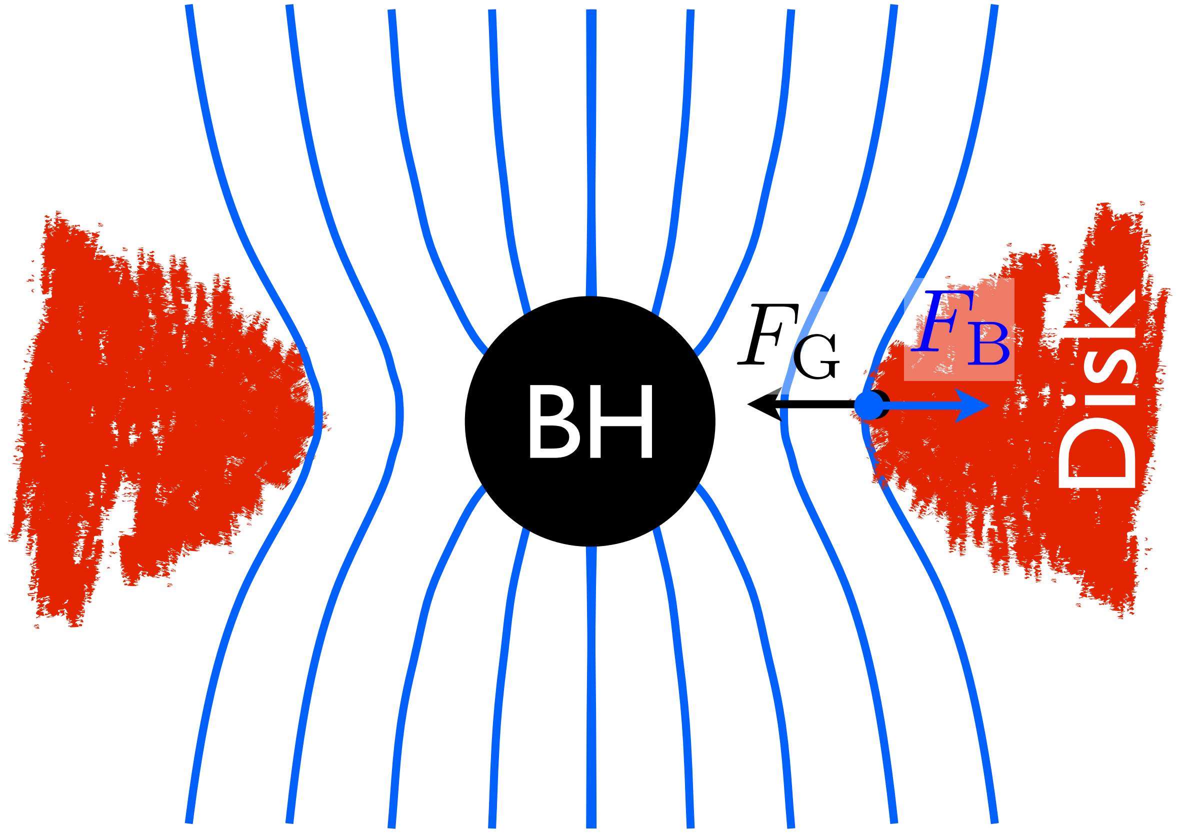


Both high- and low-luminosity disks are *radiatively inefficient*.
Neglect radiation and simulate.

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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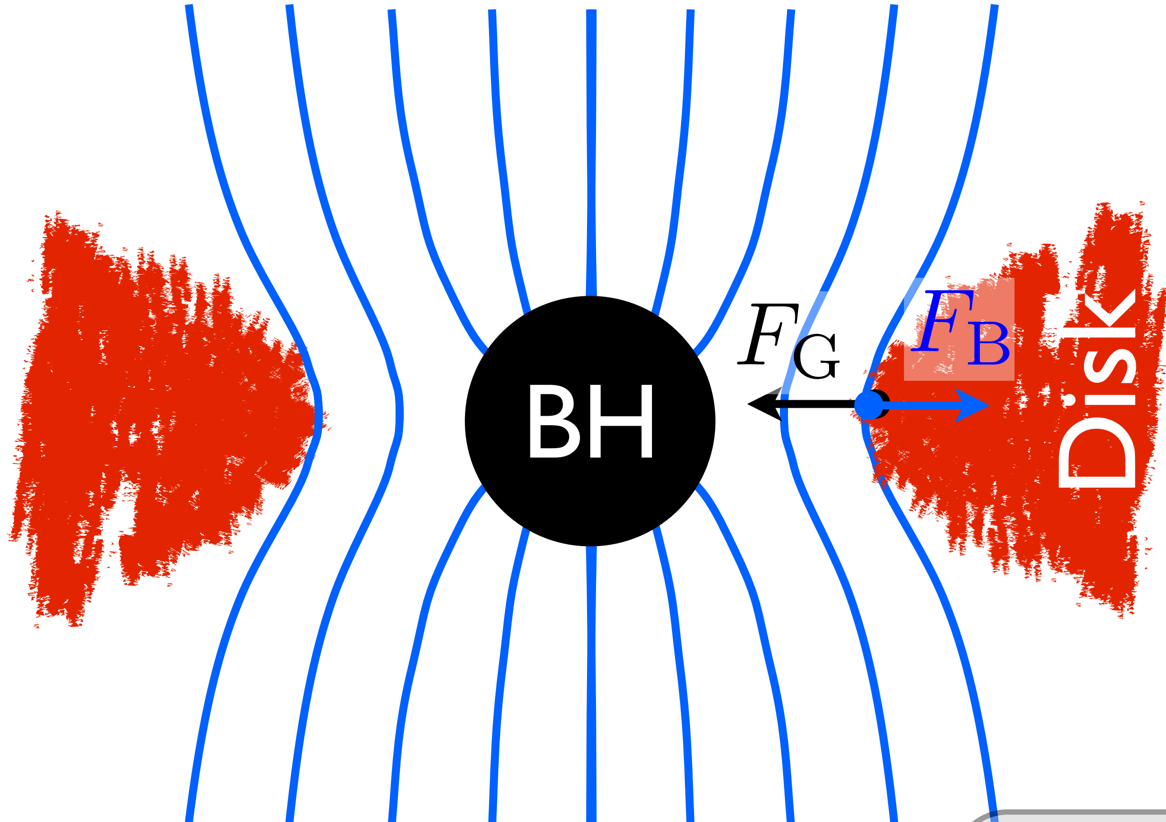

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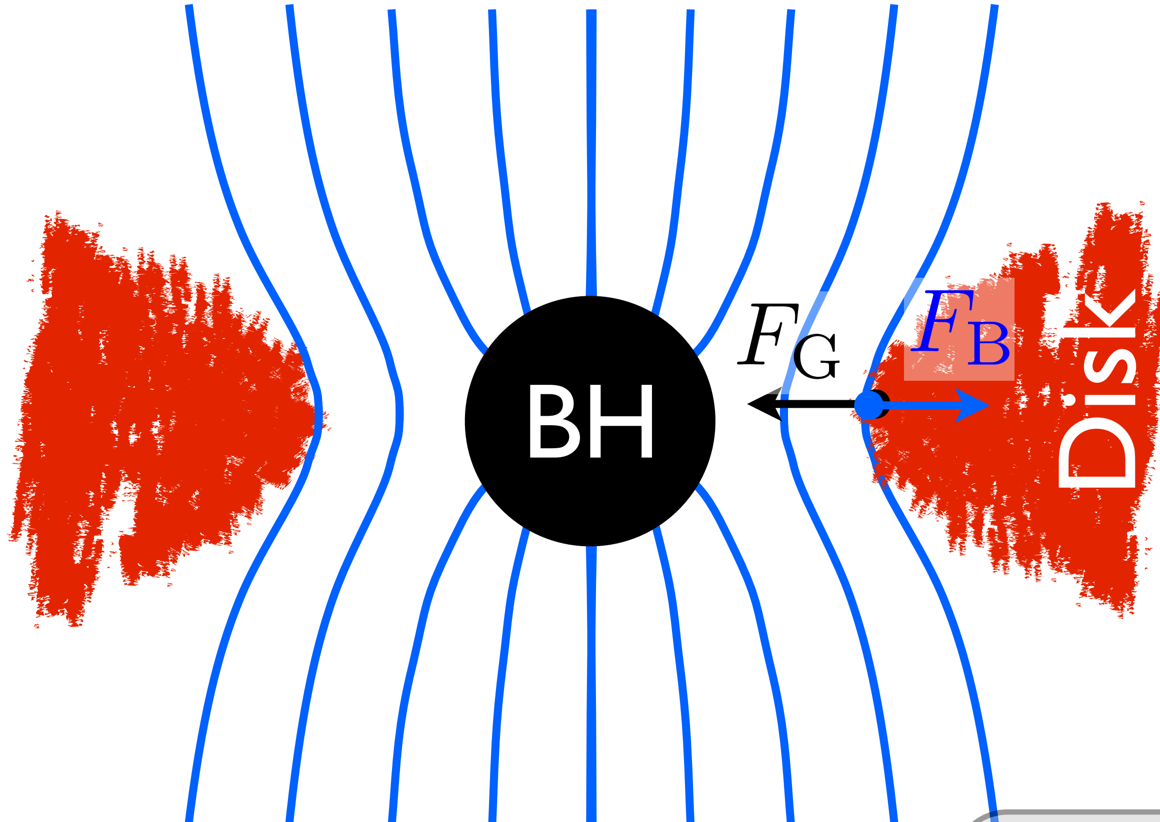

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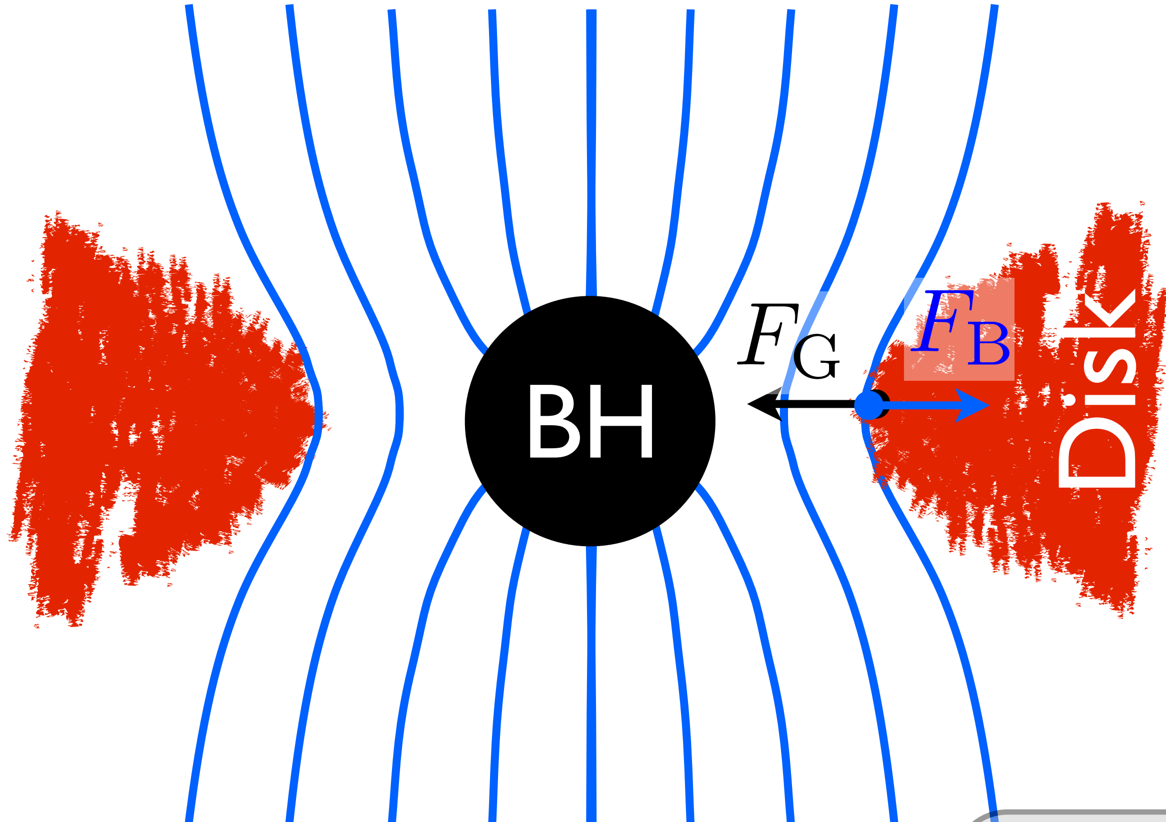

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B sub-dominant

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

$$\Phi = 0$$

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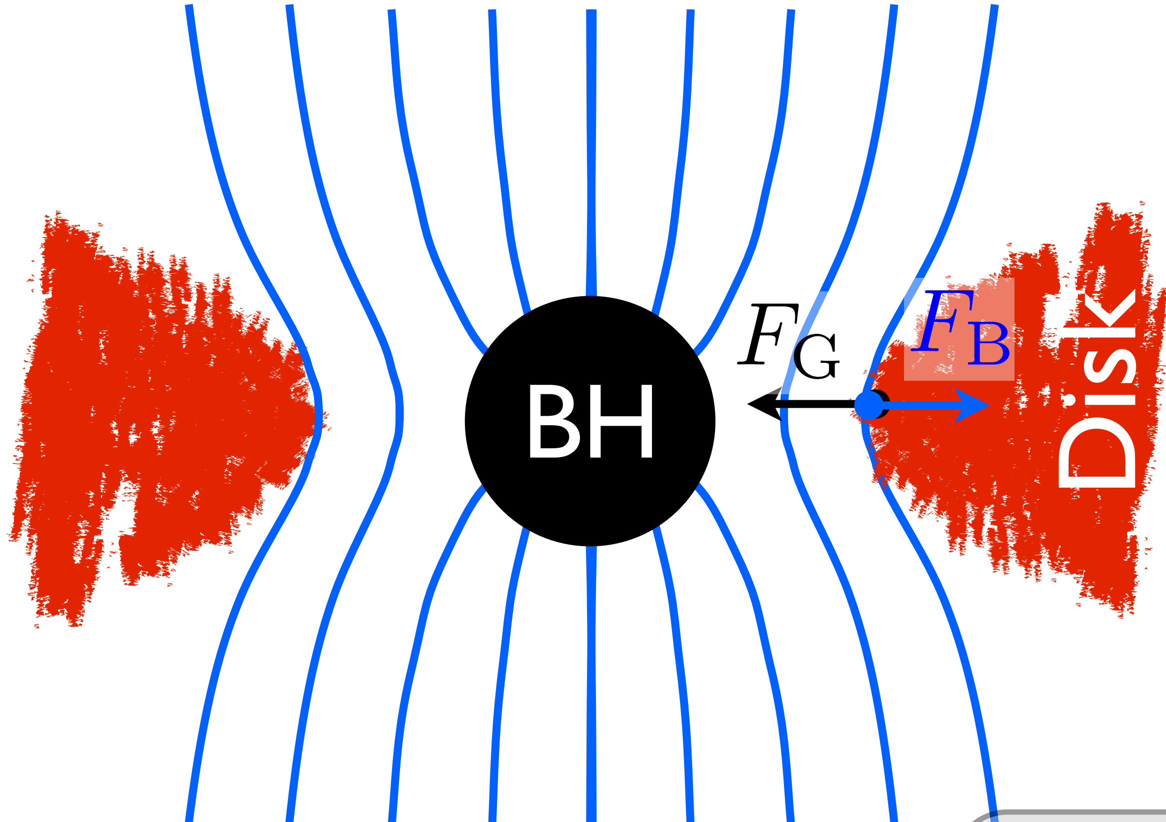

Gravity limits P_j and Φ!

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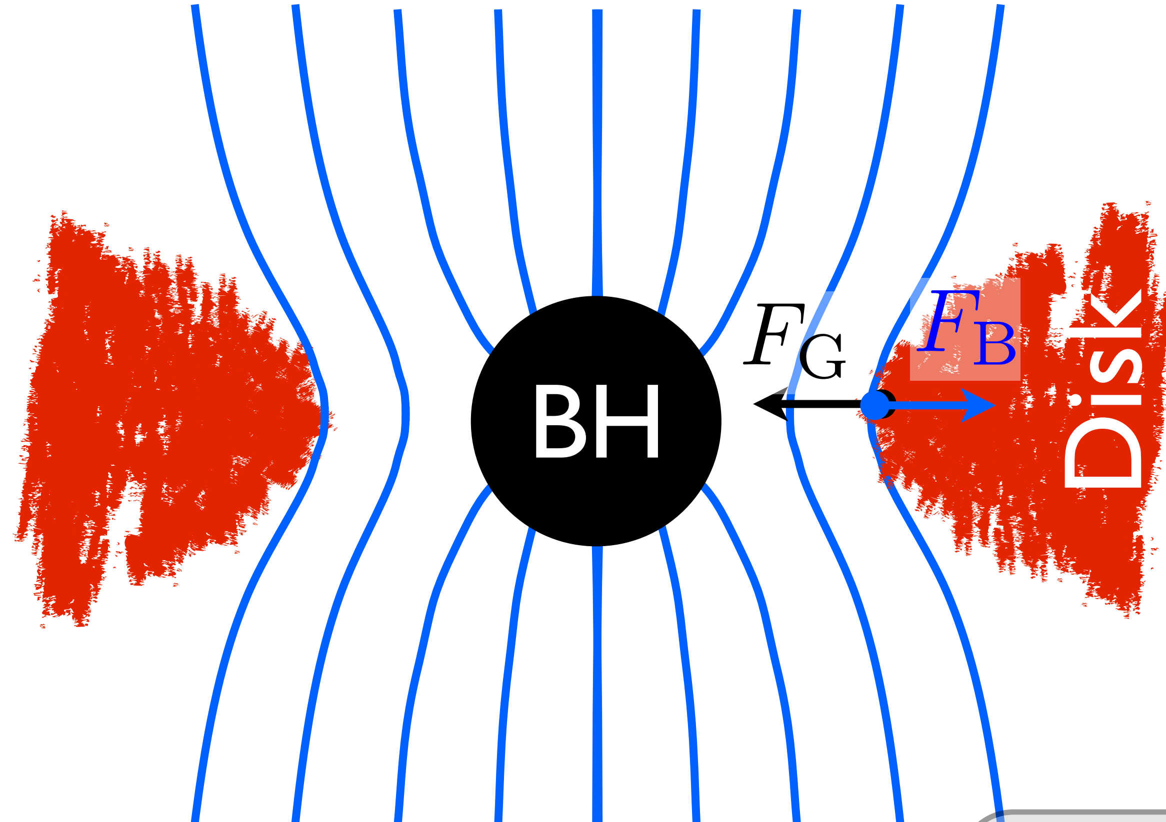

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Magnetically-Arrested Disk (MAD)

(Narayan+ 2003, AT+ 2011)

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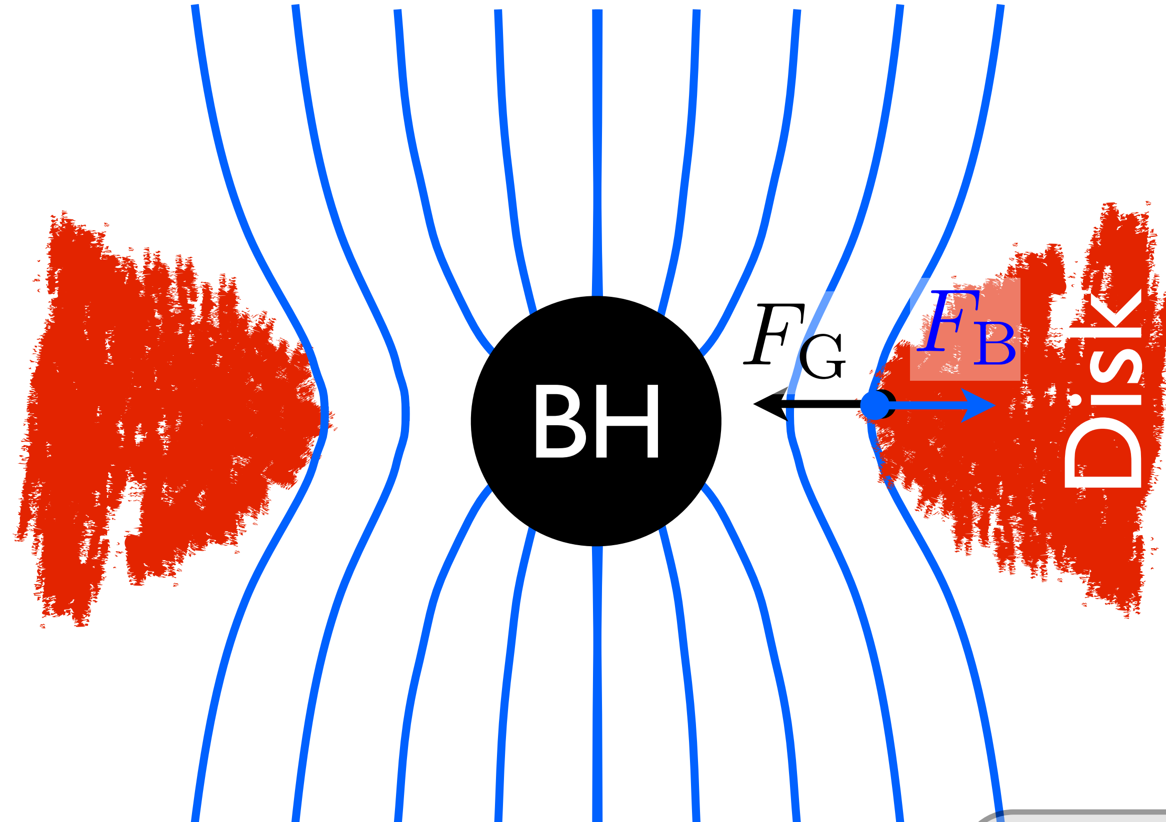

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*M*agnetically-*A*rrested *D*isk (MAD)

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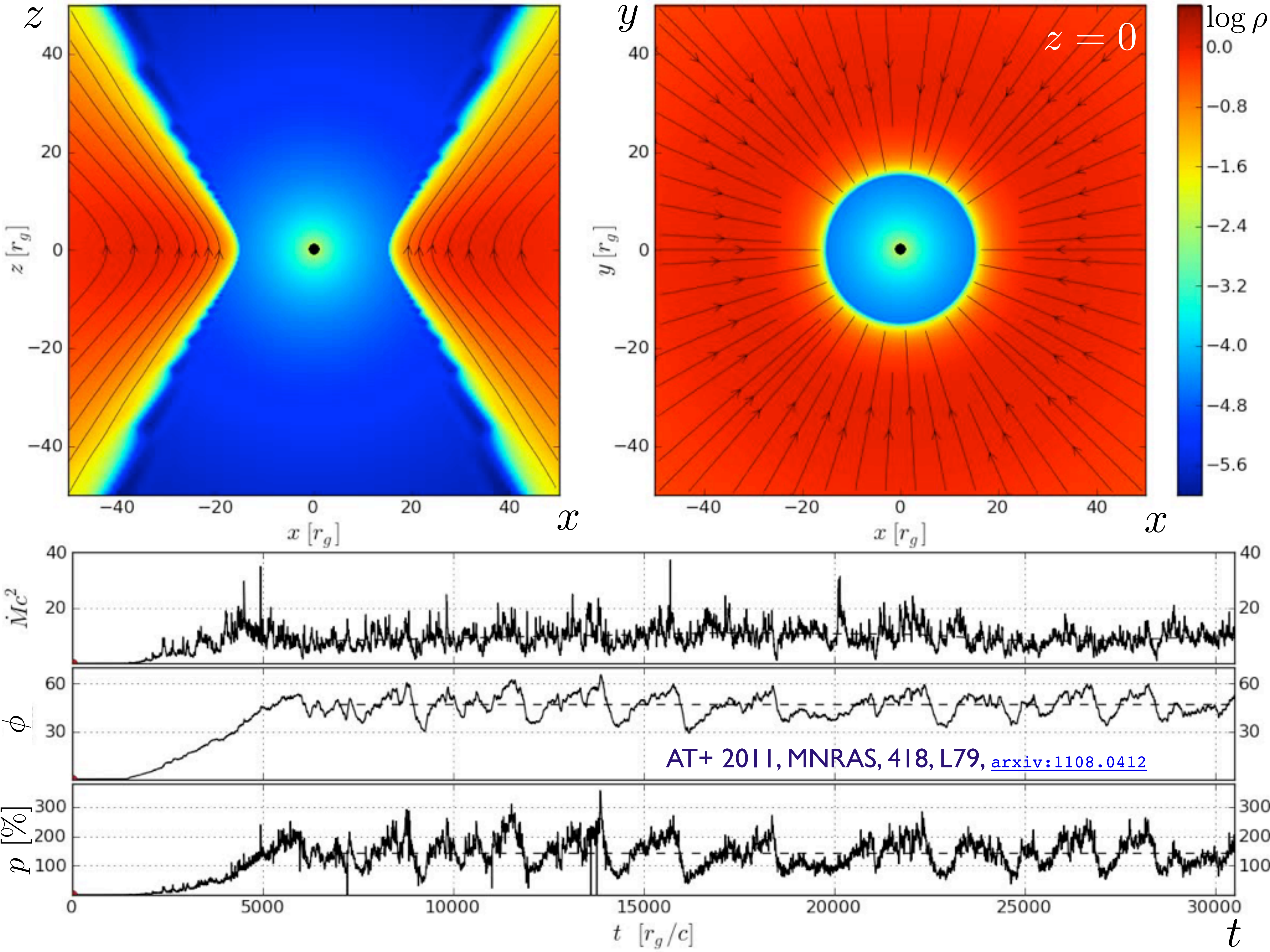
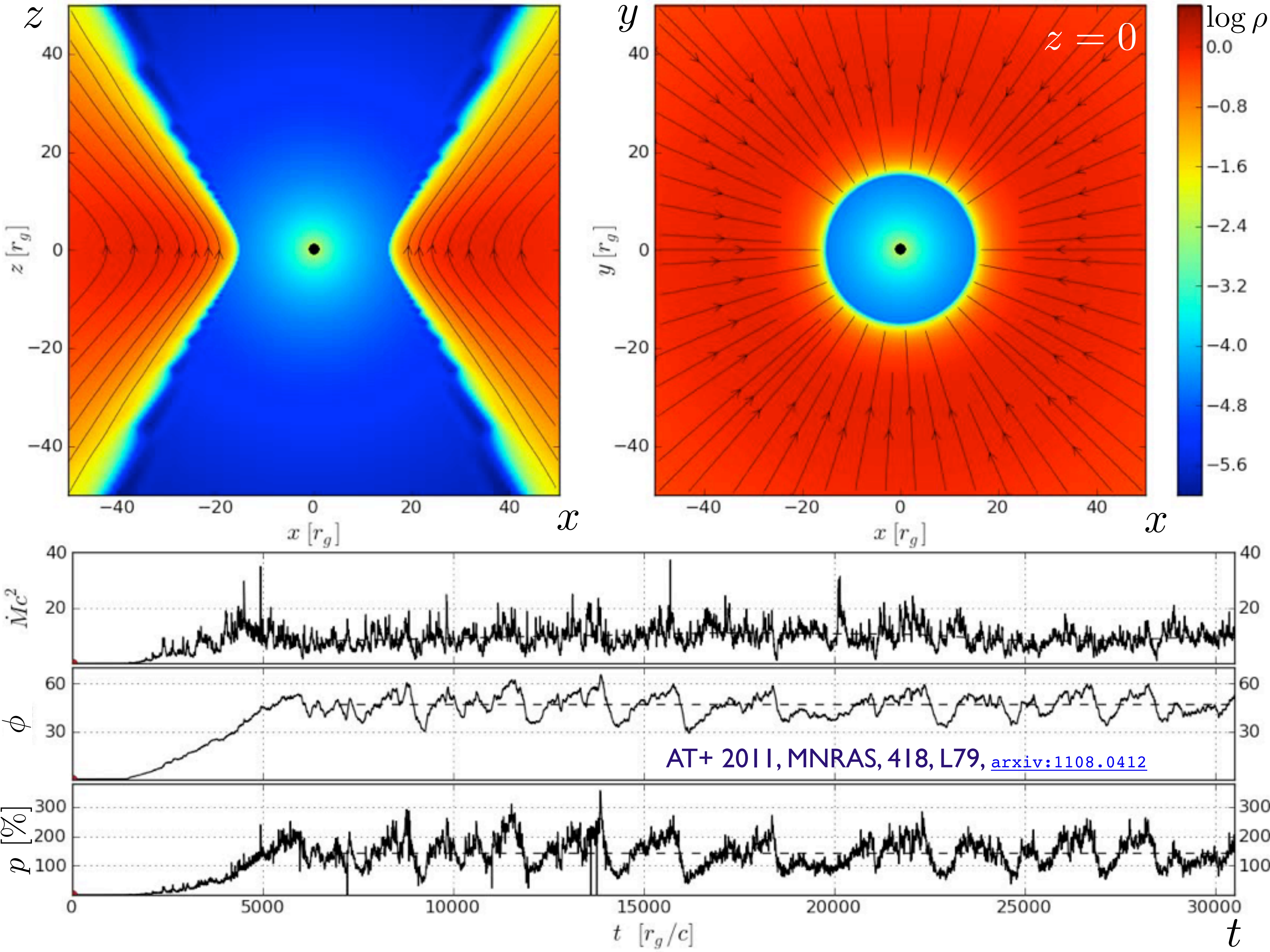
How strong are the jets?

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



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



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x
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ϕ
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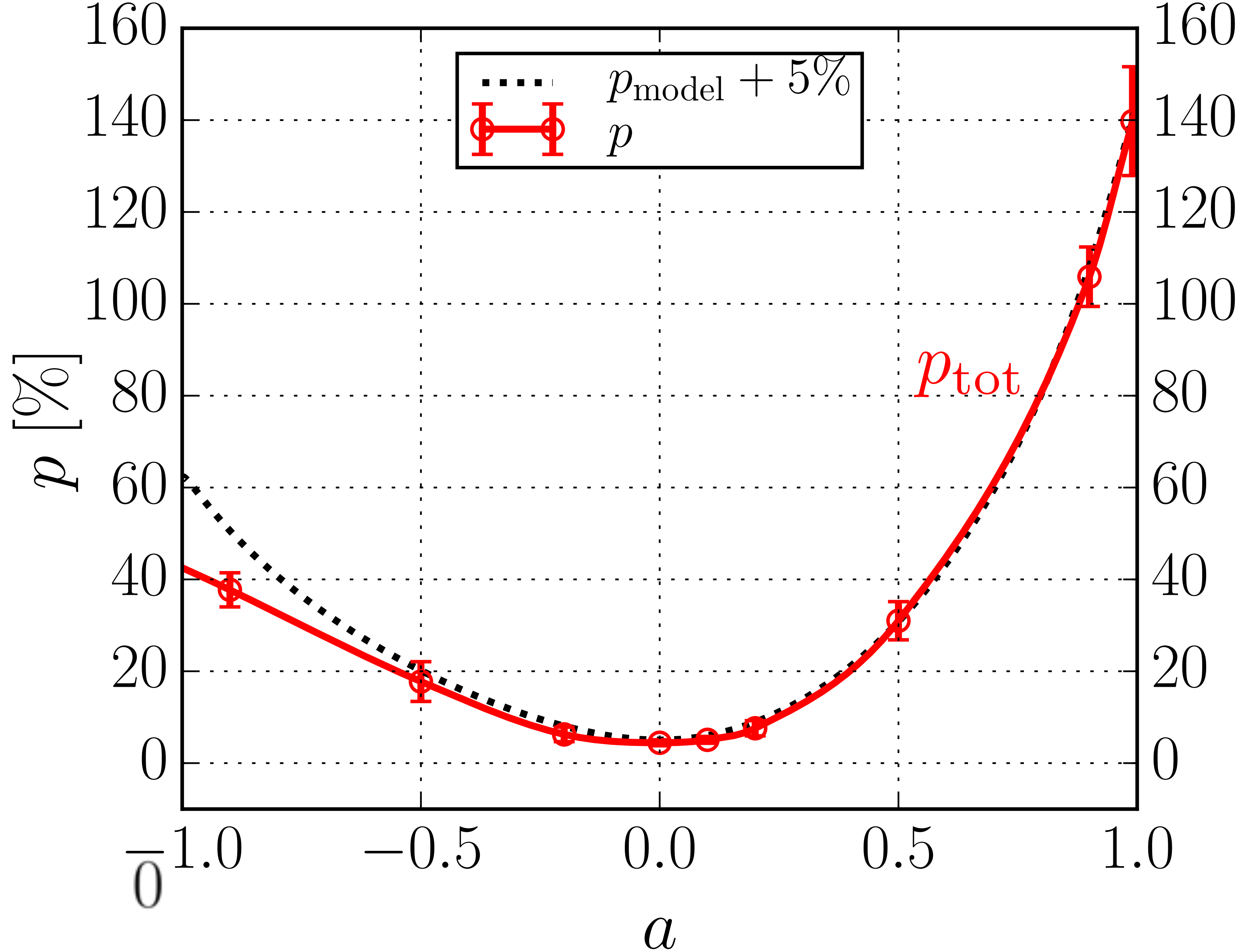
Upper Envelope of Jet Power vs. Spin

(h/r~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

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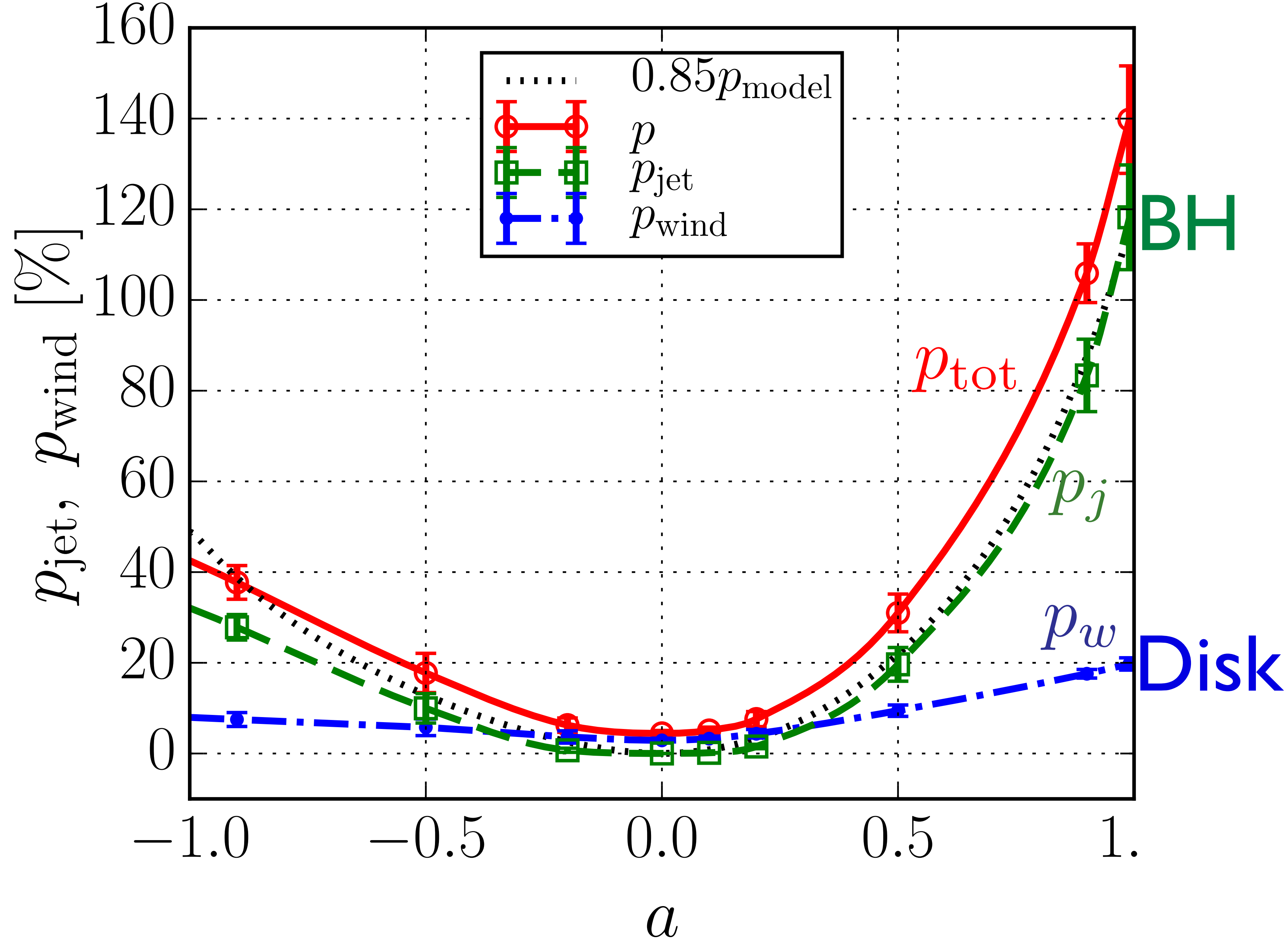

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Wind = BP = 15% of BZ power + 5%

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

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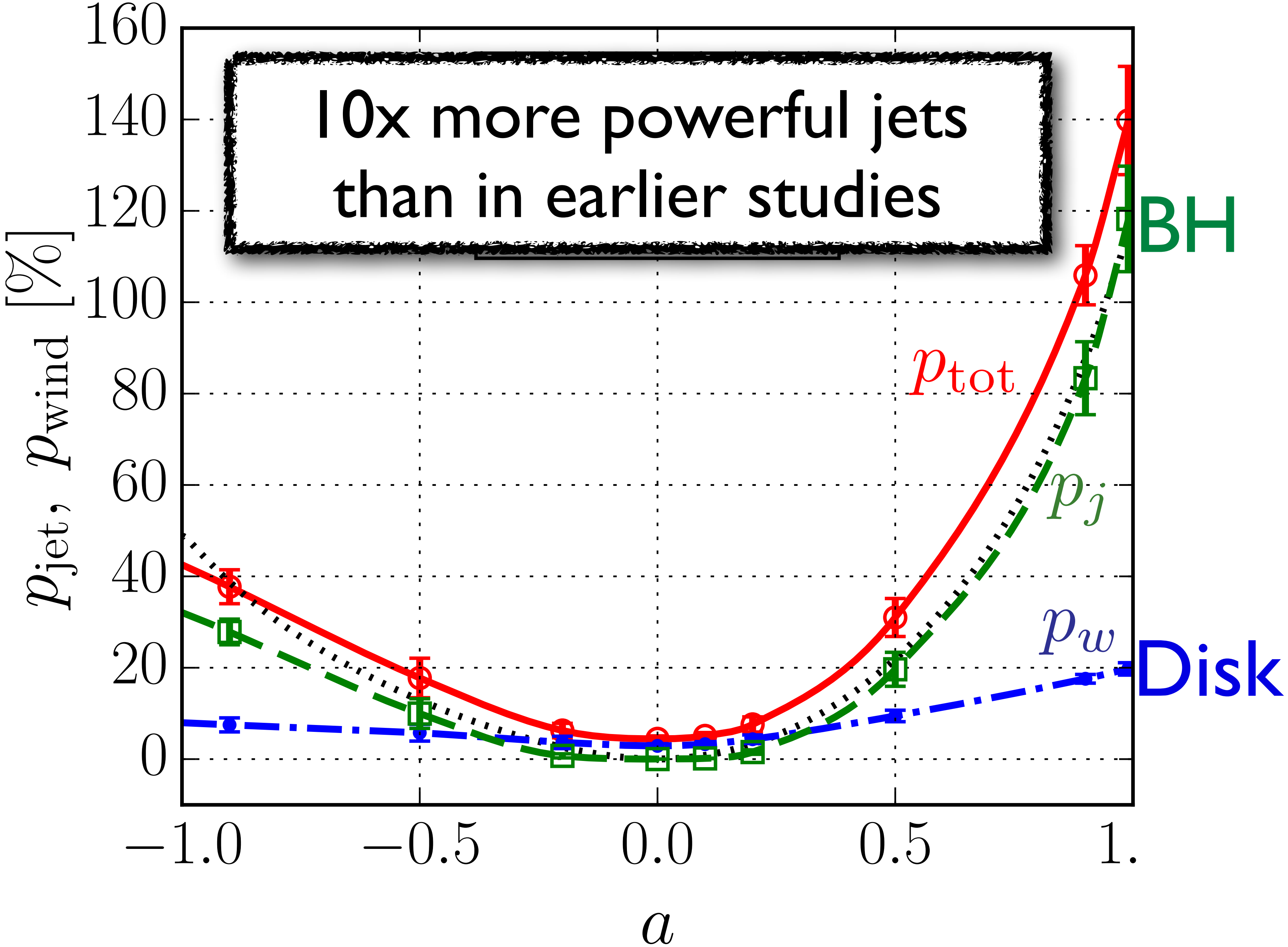

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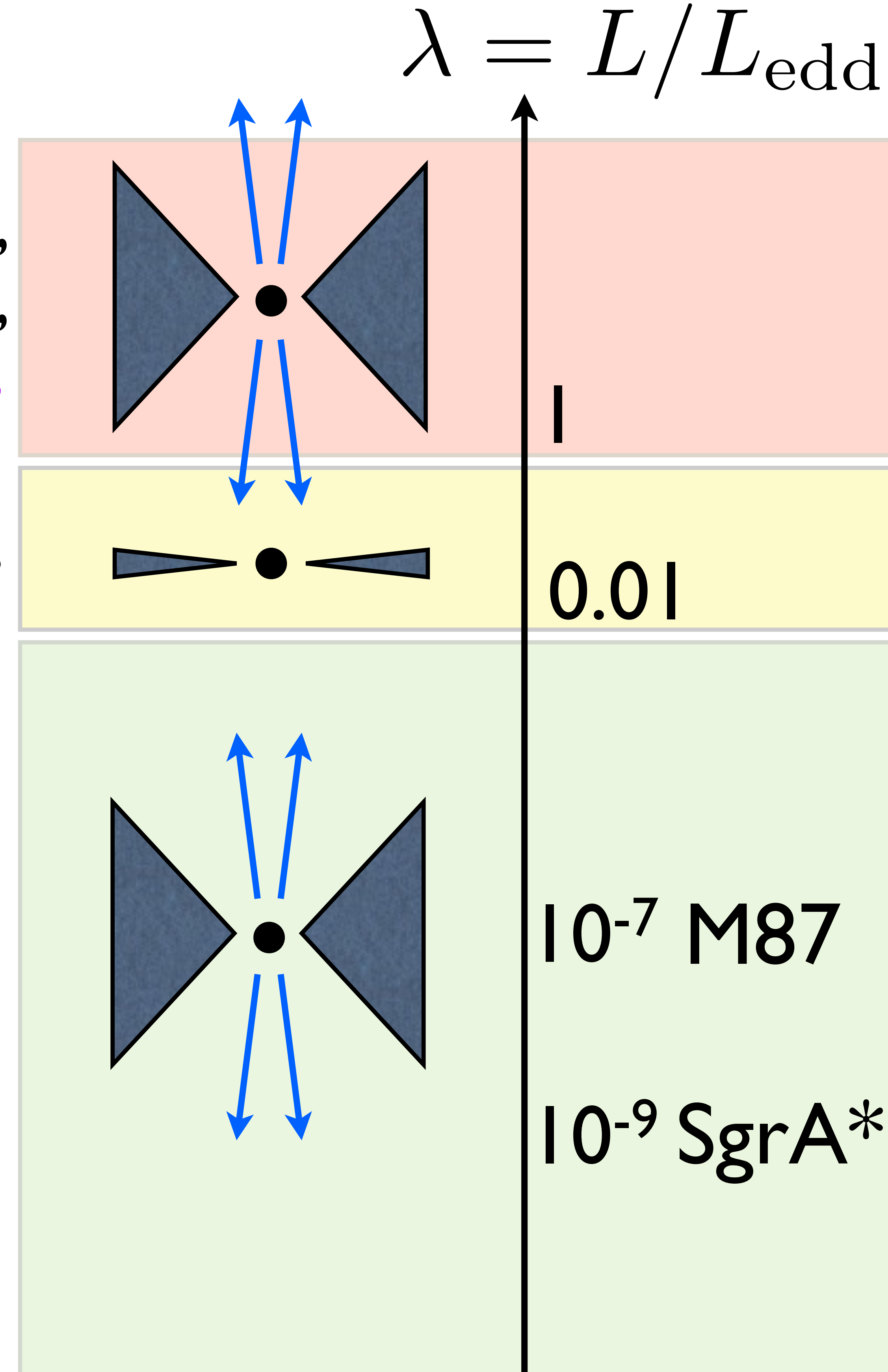

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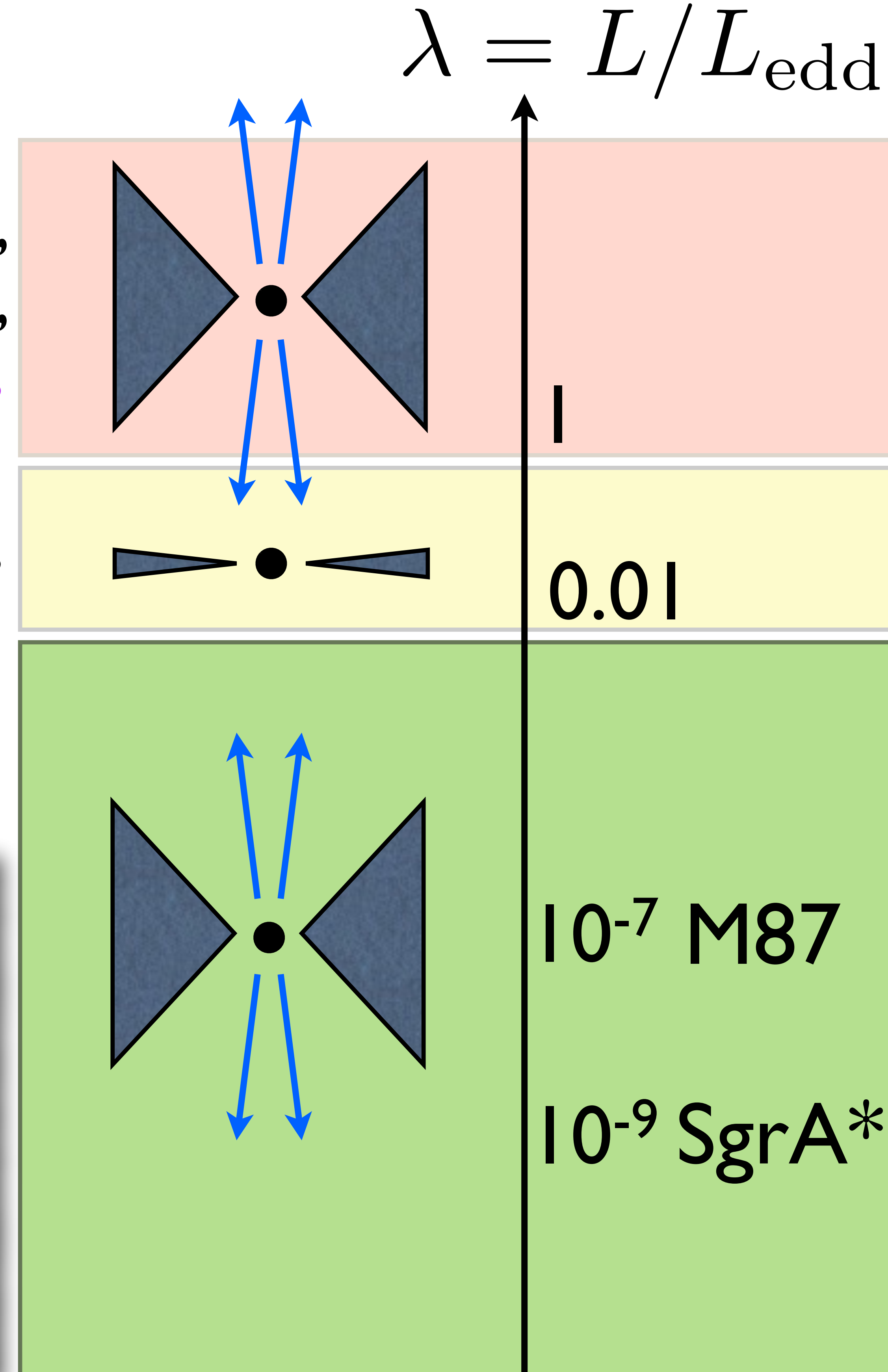
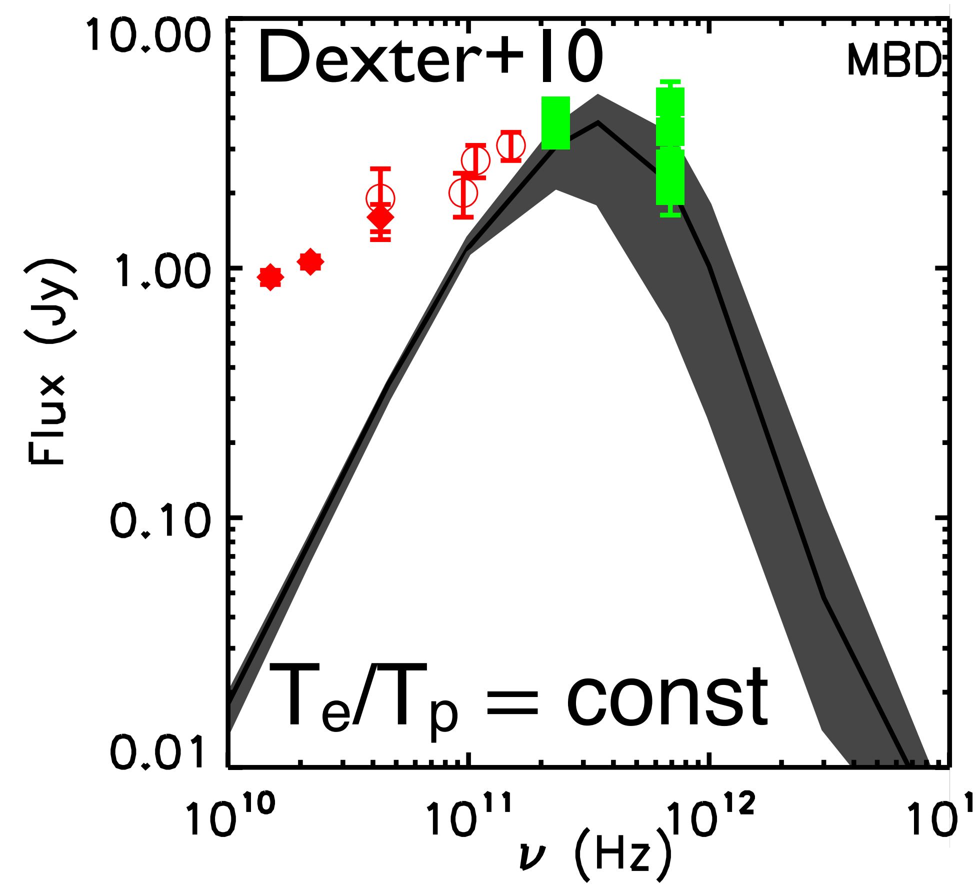


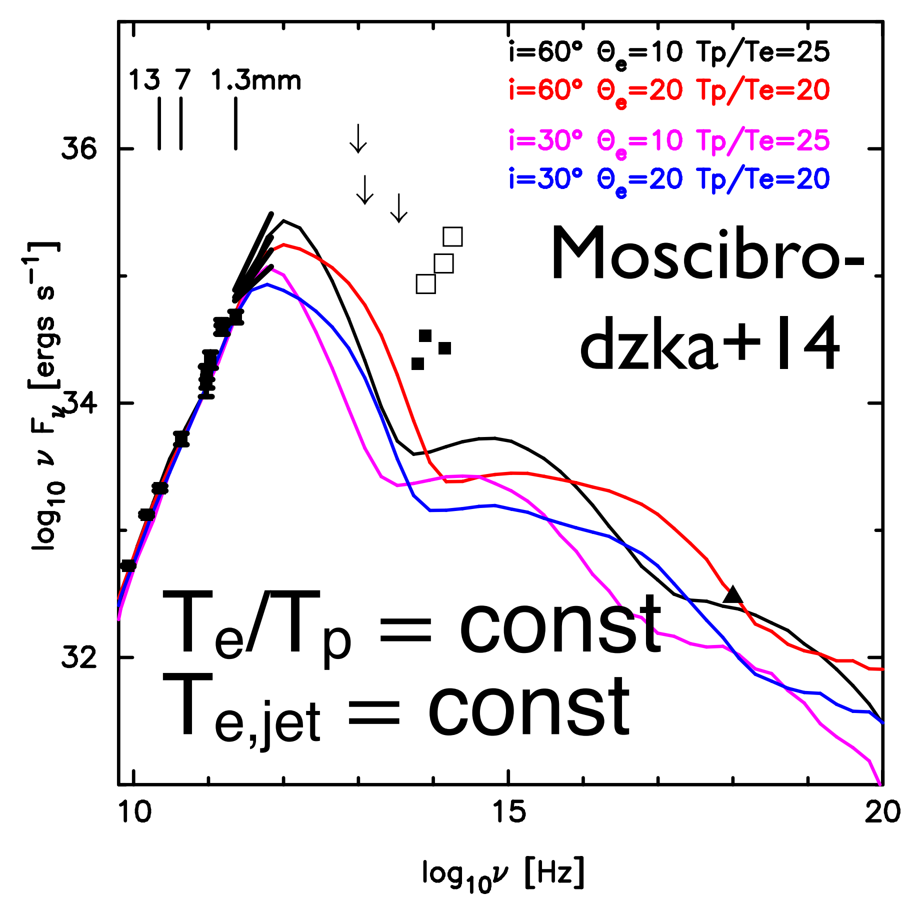
Disk radiative properties are most uncertain at low luminosities.

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): $T_e/T_p = \text{const.} < 1$
  - 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
  - Neglect back-reaction of electrons on the flow
- Simulations with *CHARMER*, new parallel, 3D general relativistic MHD code that includes electrons as a separate fluid (Ressler, AT et al., 2015, 2016)

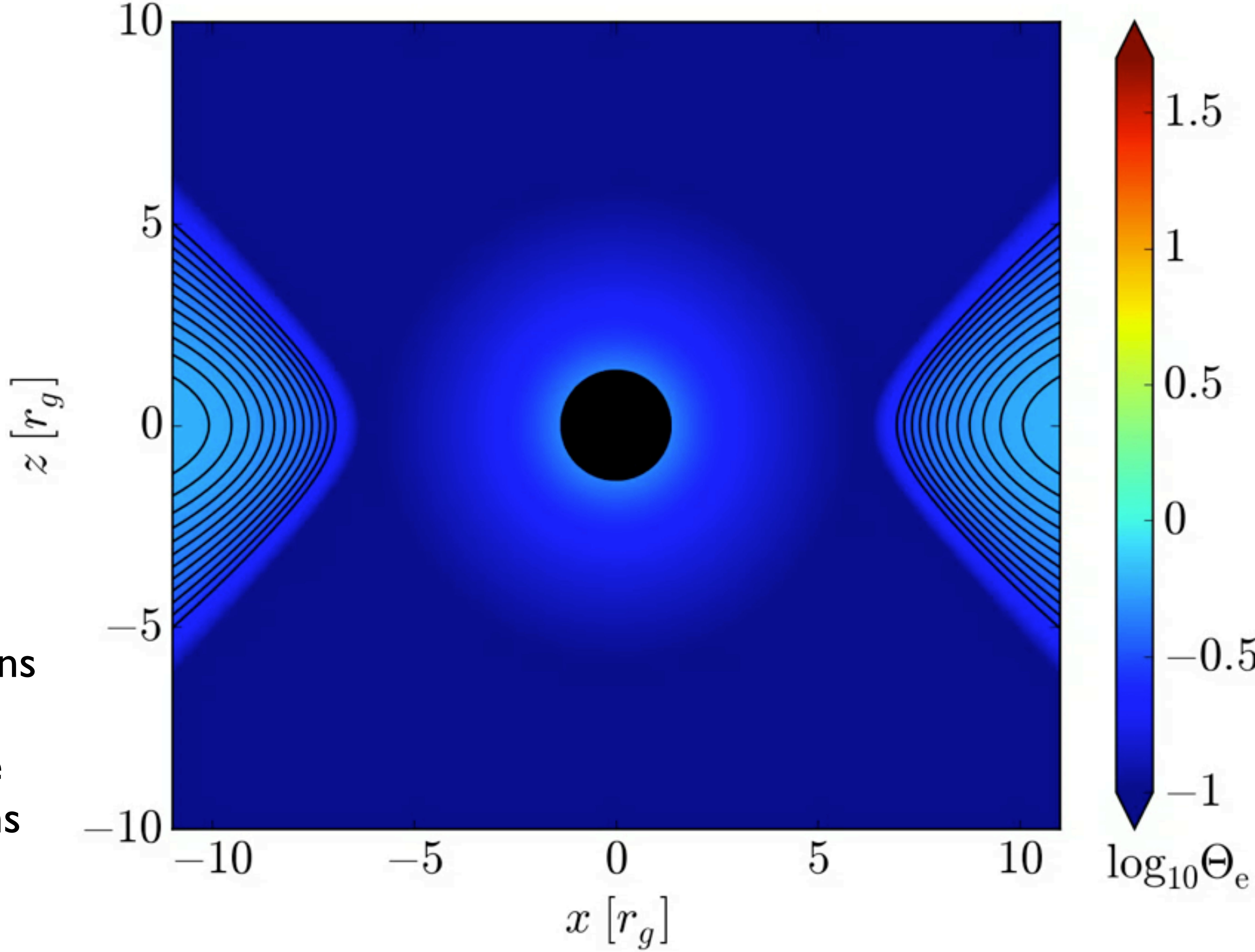
Sean Ressler
(UC Berkeley)

Electron Temperature in Simulations

Spin:
a=0.5

Protons:
ɣ =5/3

Electrons:
ɣ e=4/3



Hot electrons naturally occur in the polar regions

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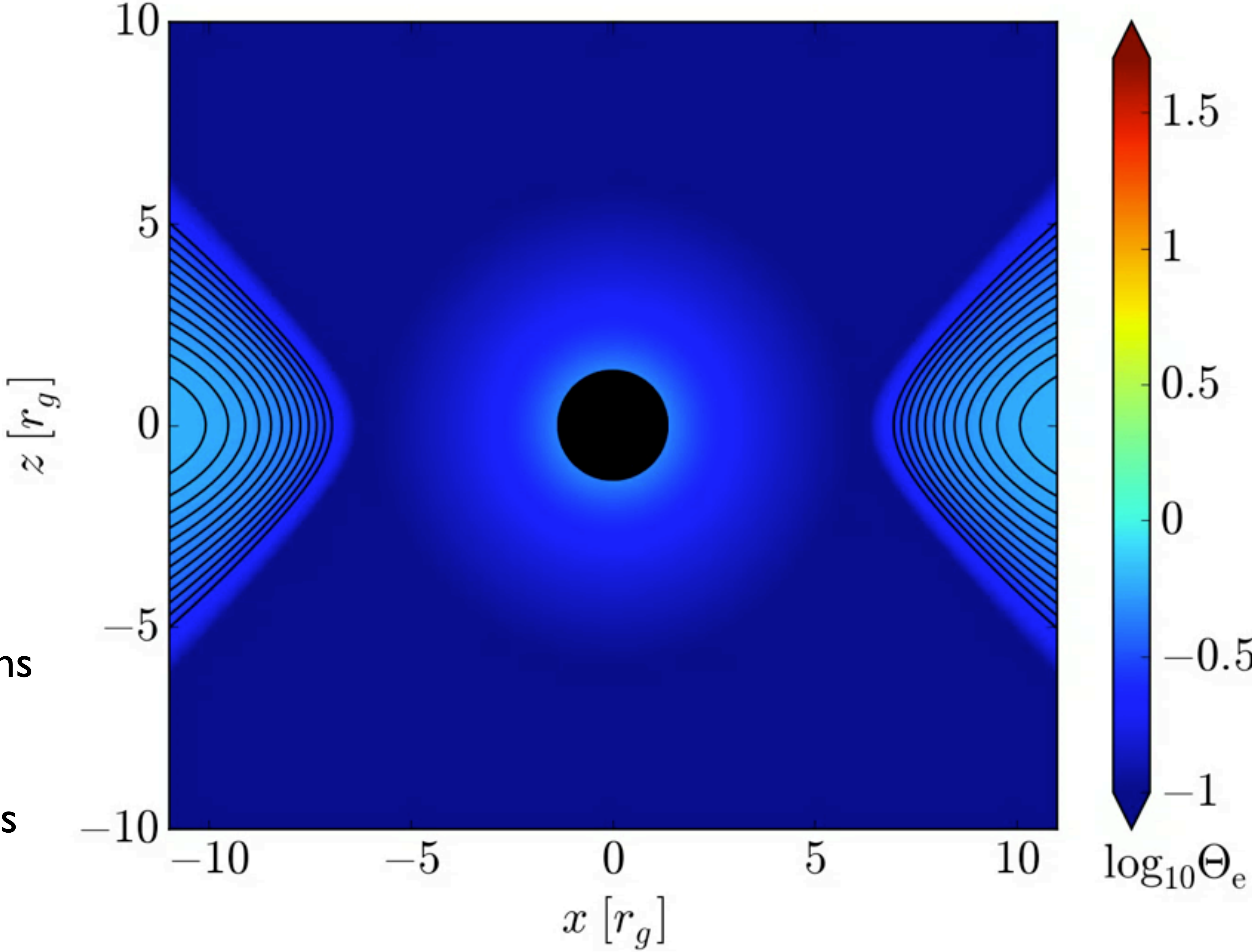

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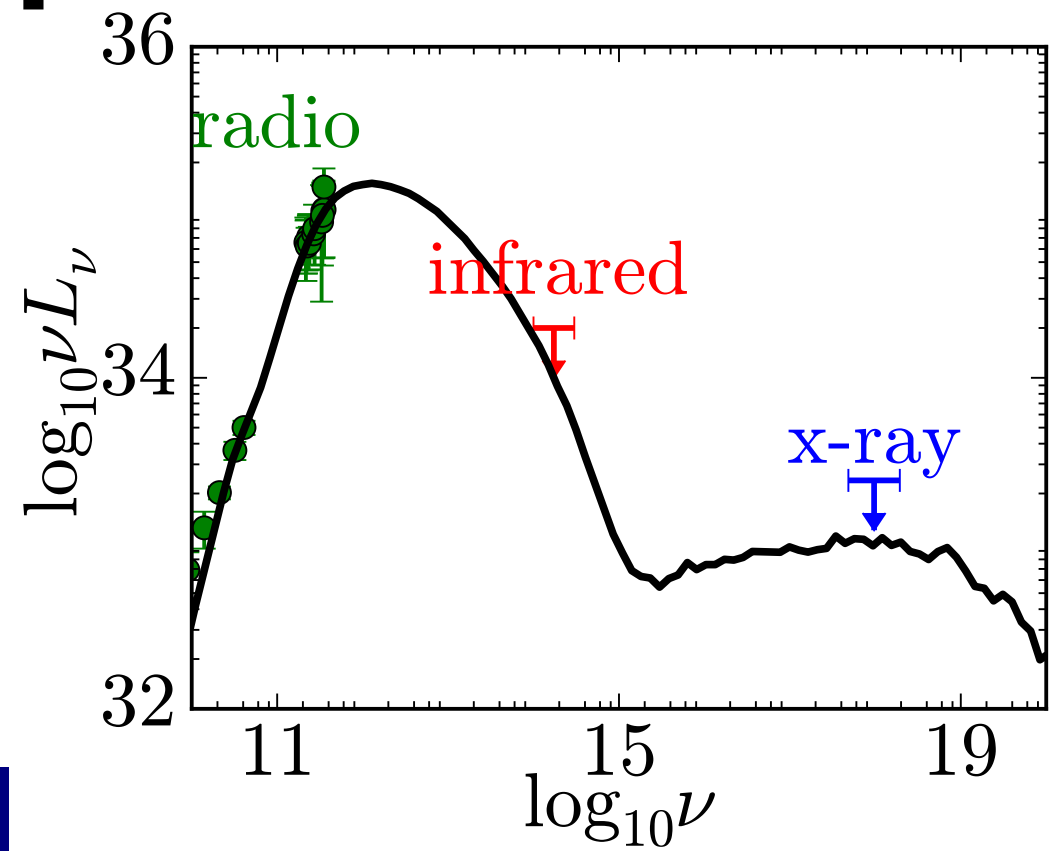

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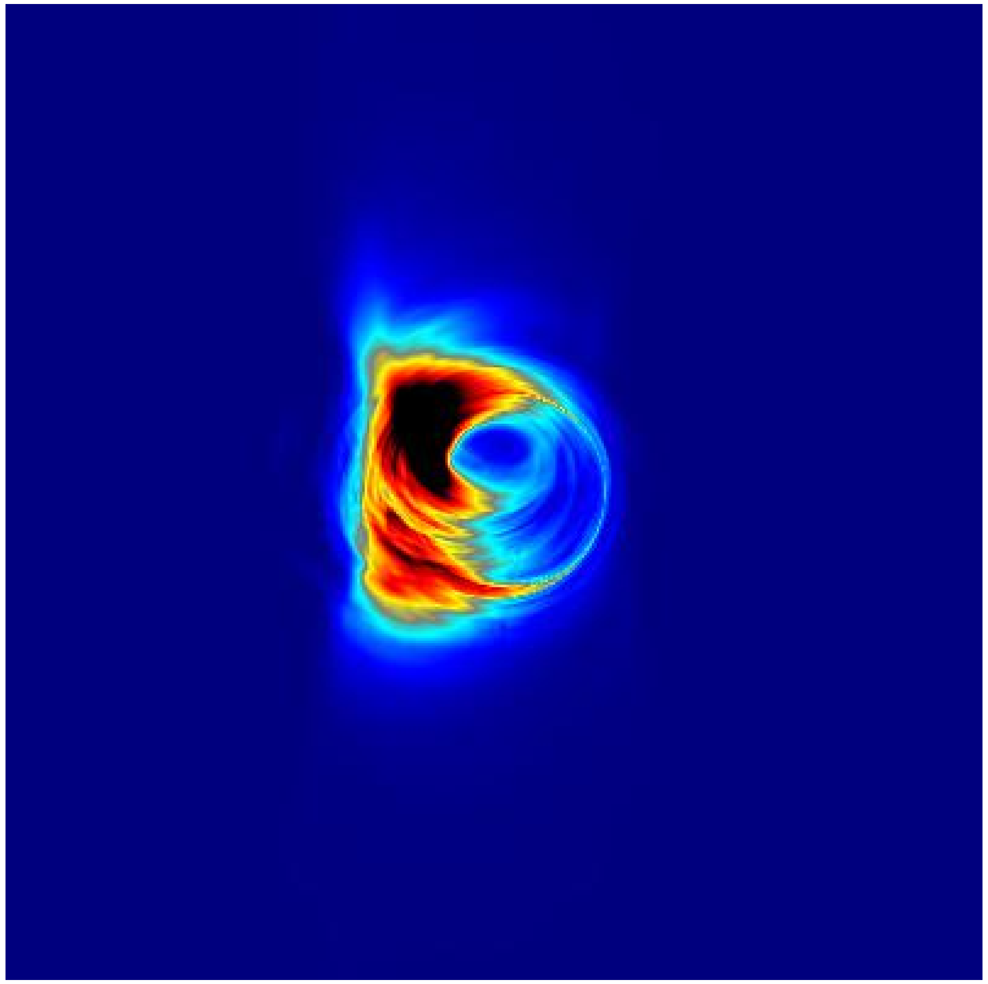

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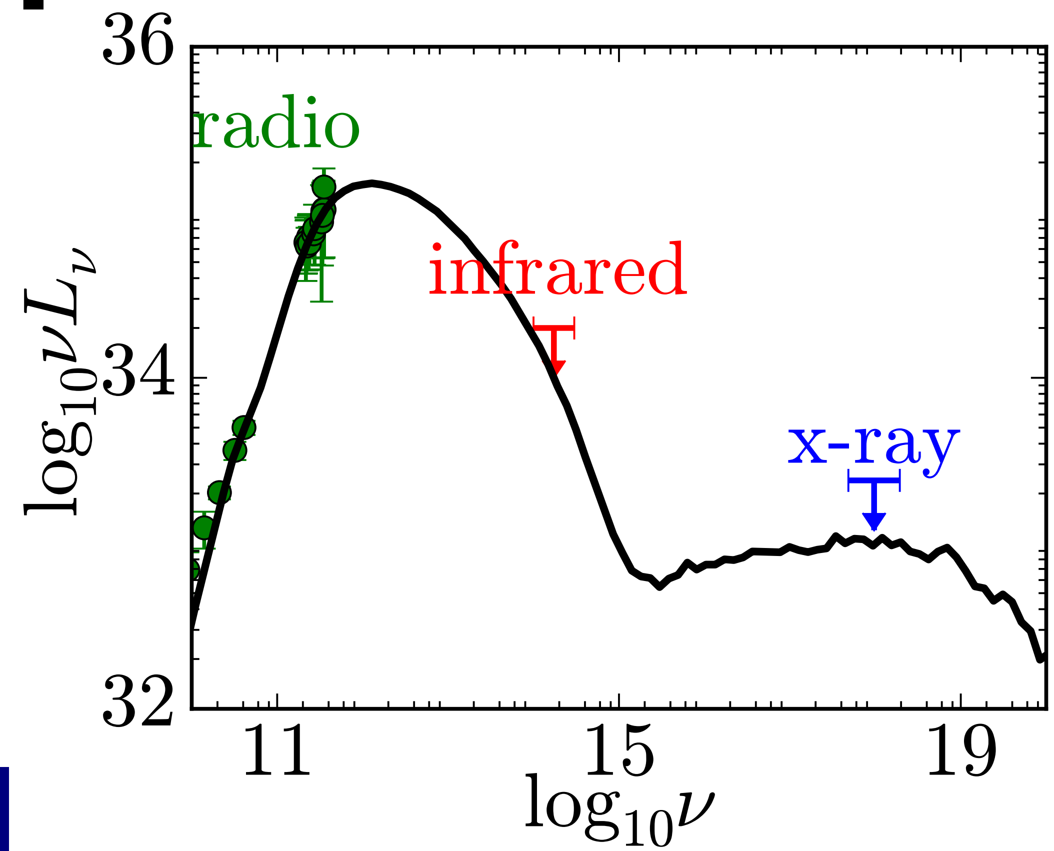
Predicted Spectra and Images

Electron micro-physics naturally leads to flat radio spectrum of SgrA* with *one* free parameter.



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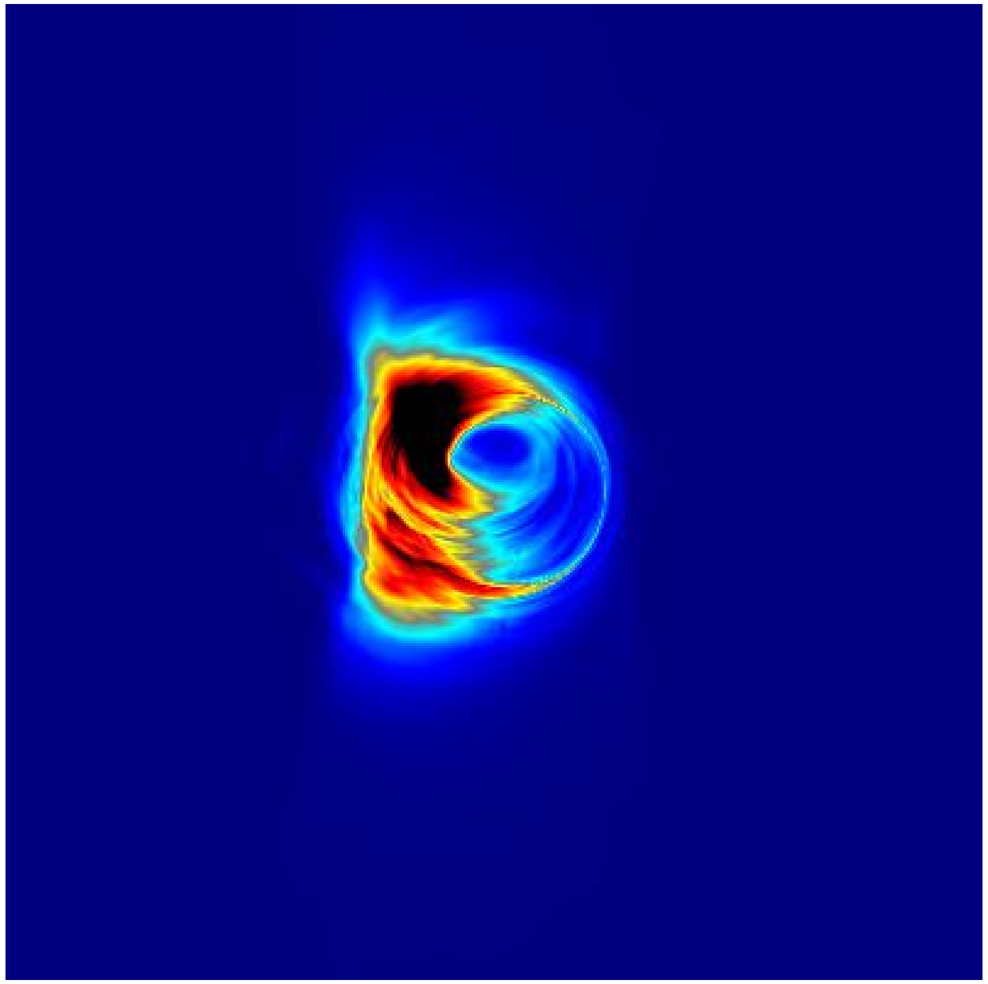
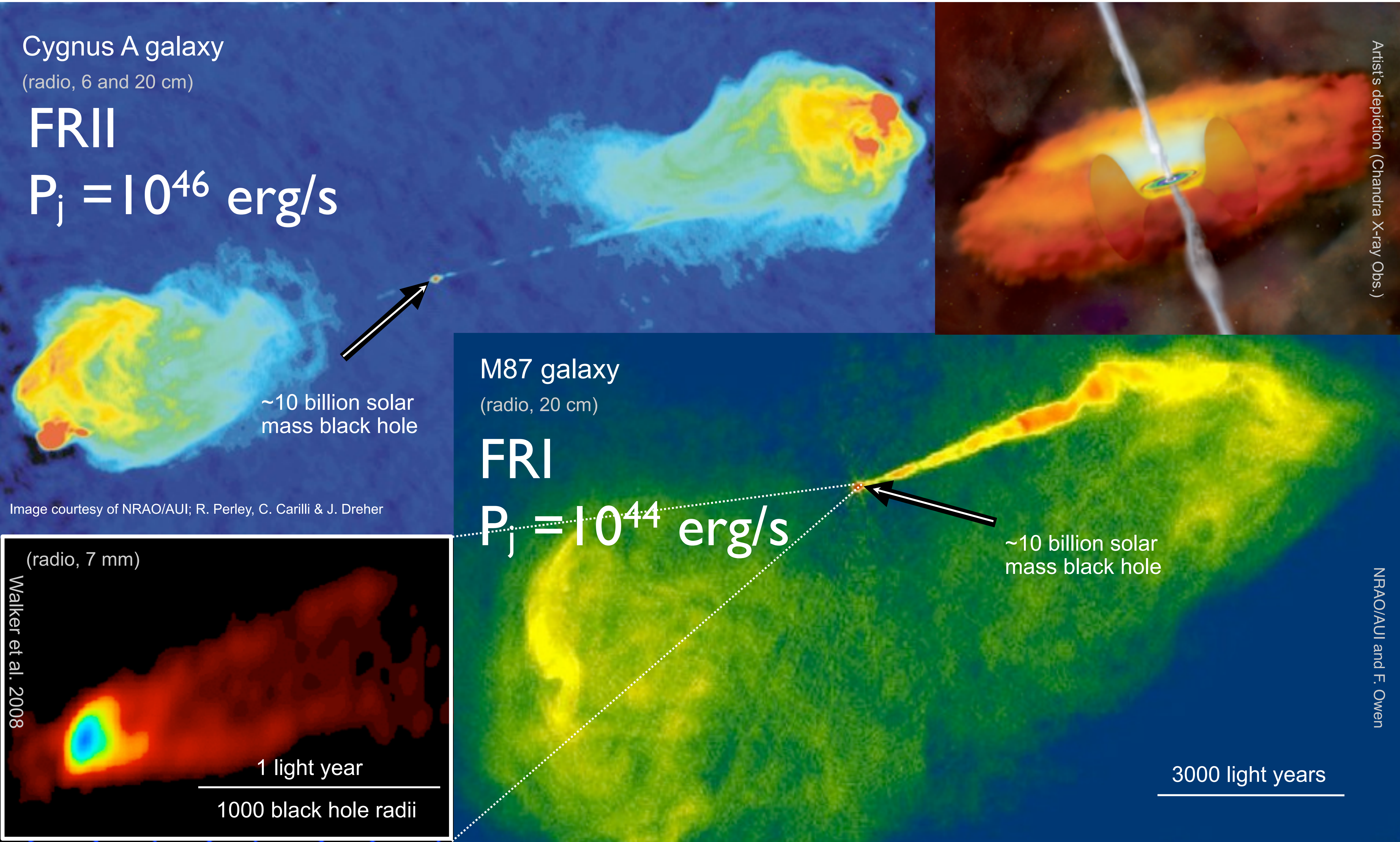


Predicted *EHT* mm-wavelength image of SgrA* black hole shadow

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

What does Jet Morphology Tell Us?

FRI/FRII dichotomy (Fanaroff & Riley, 1974)



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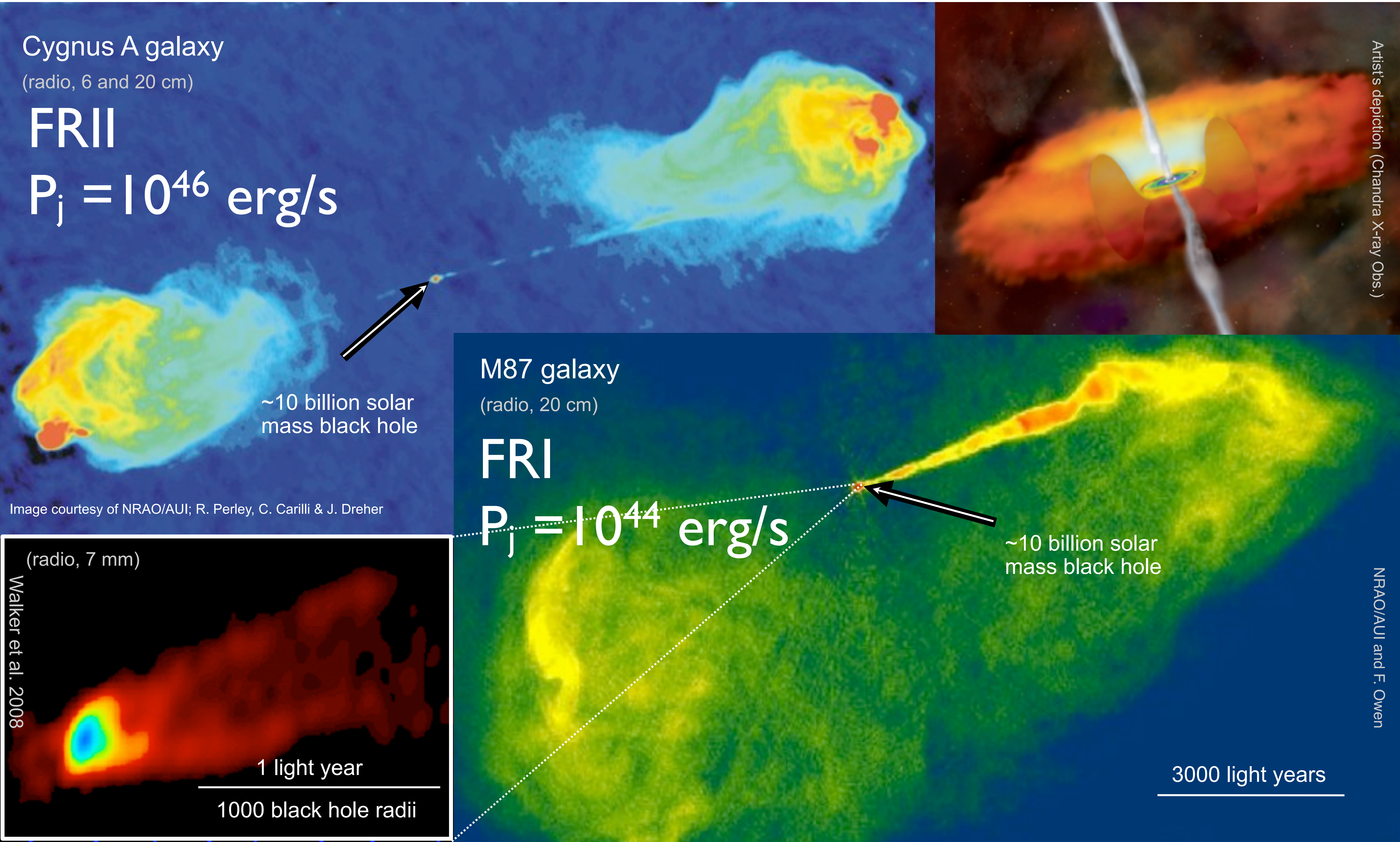

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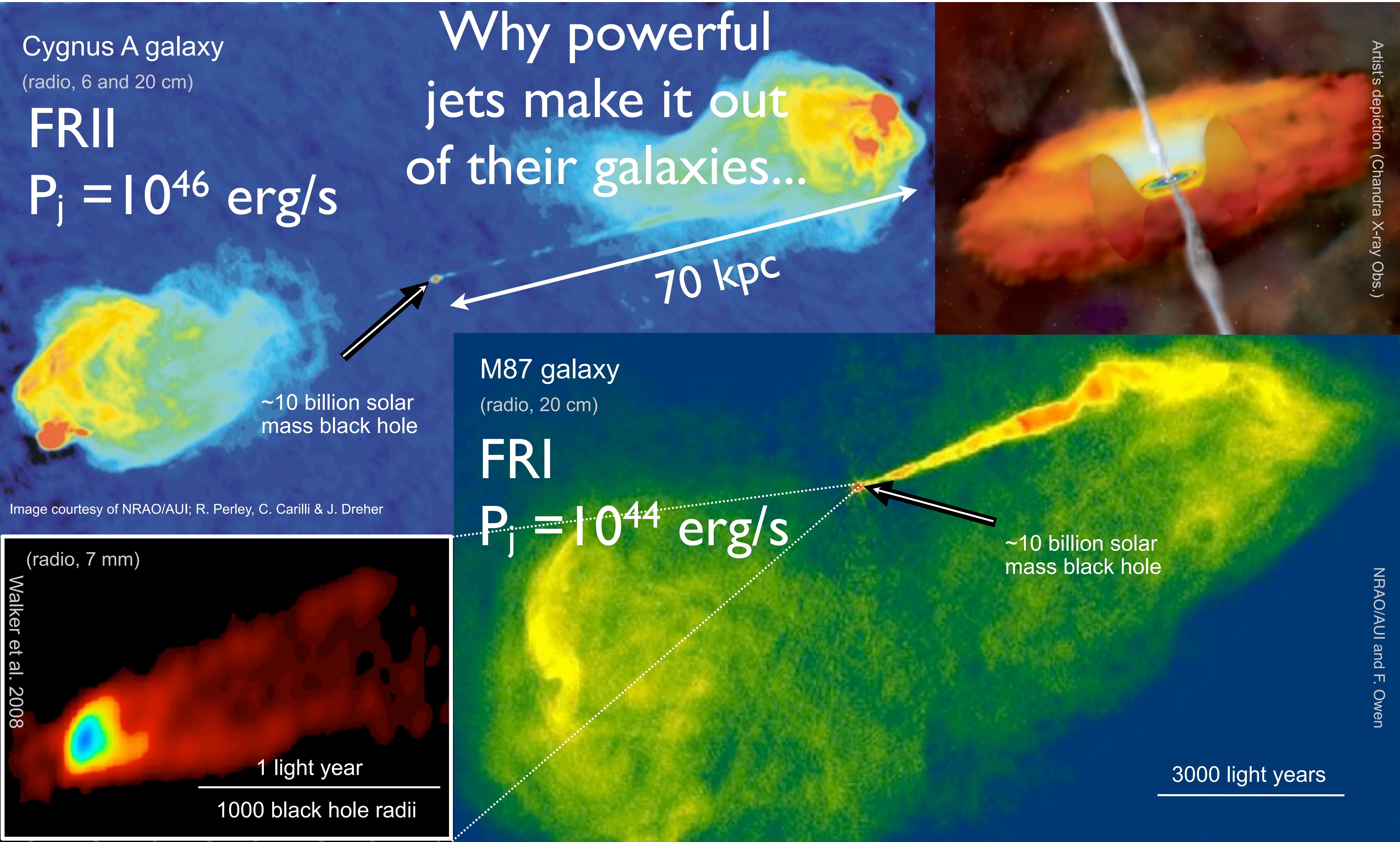

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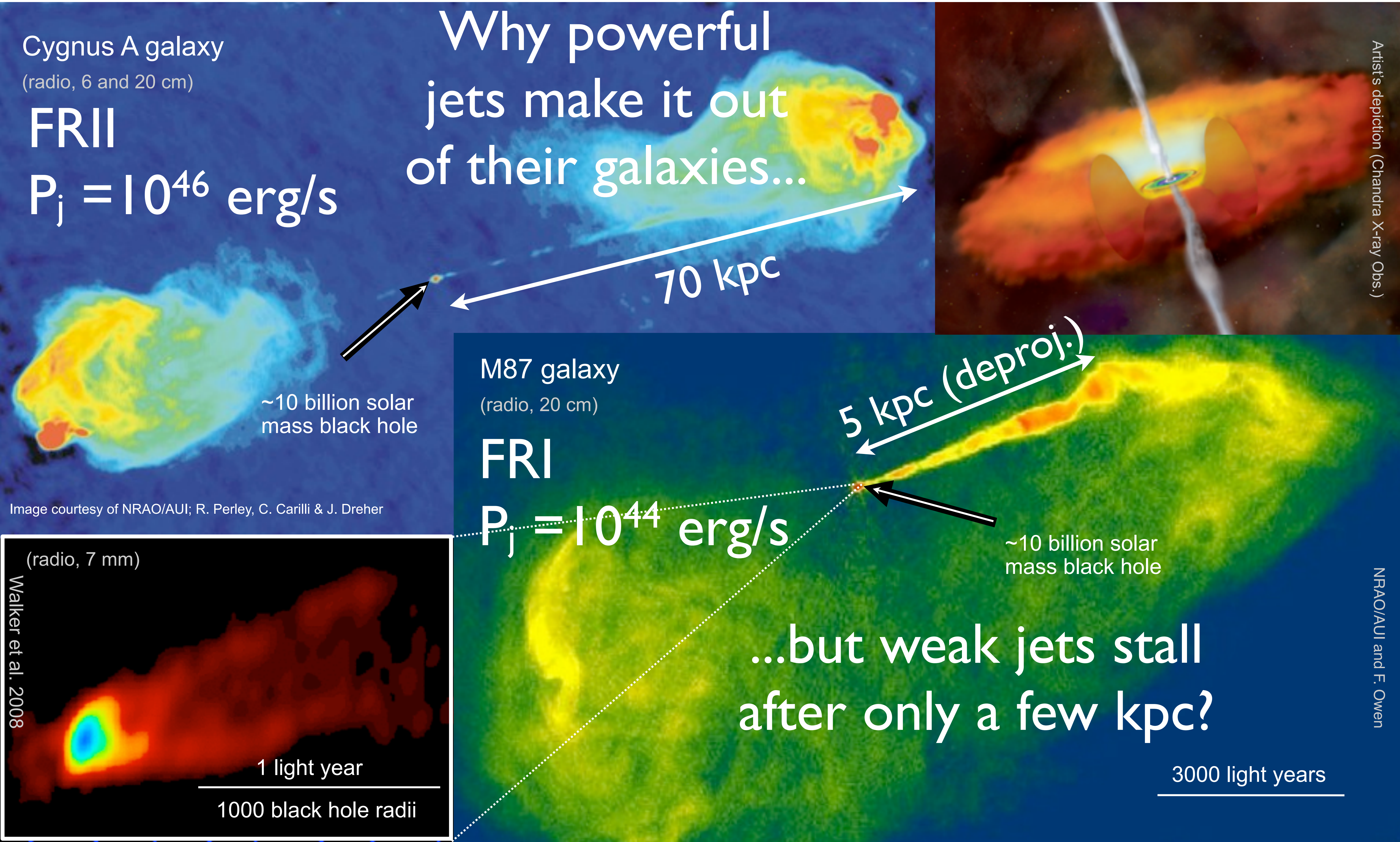

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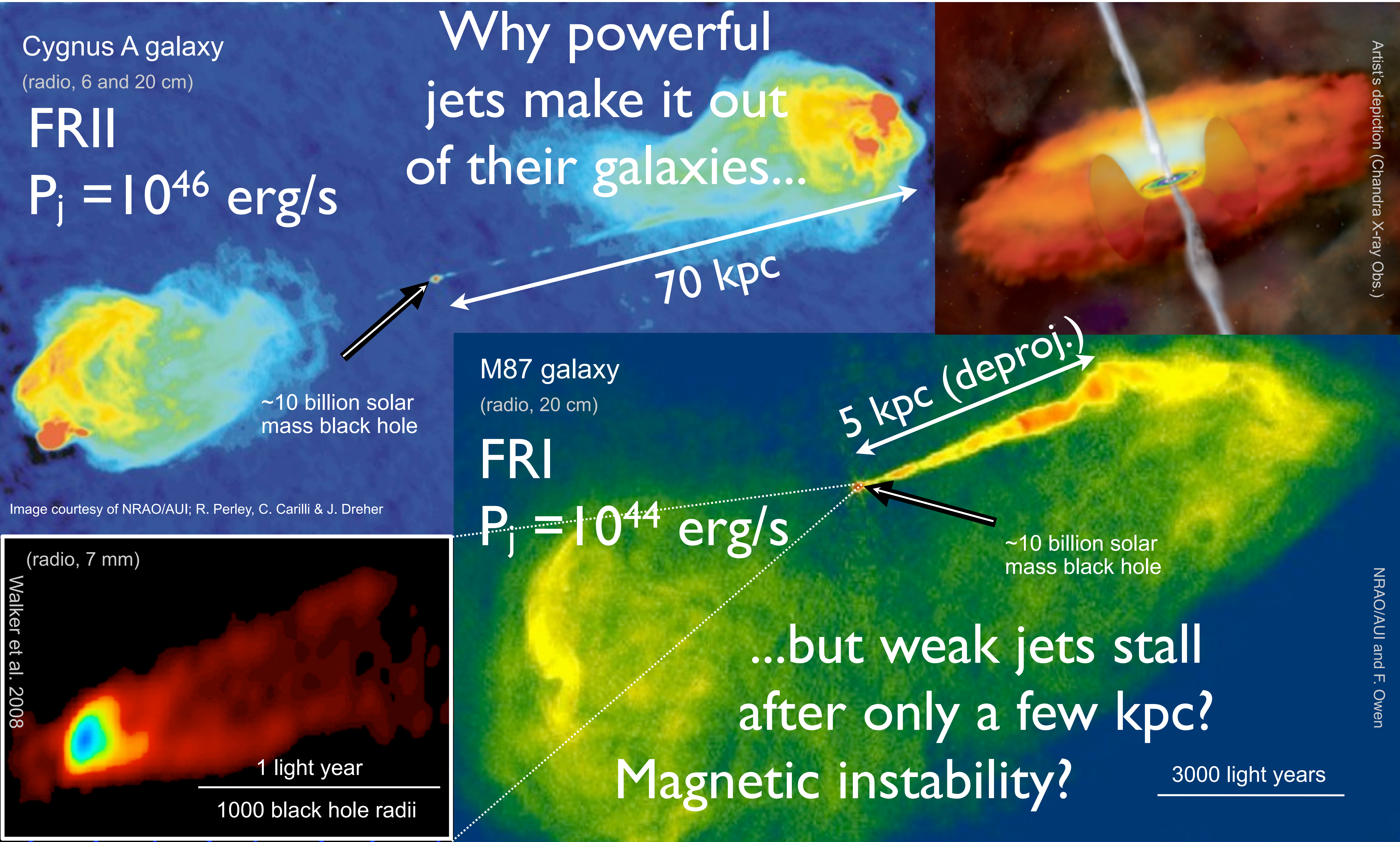


Instability of Magnetized Jets

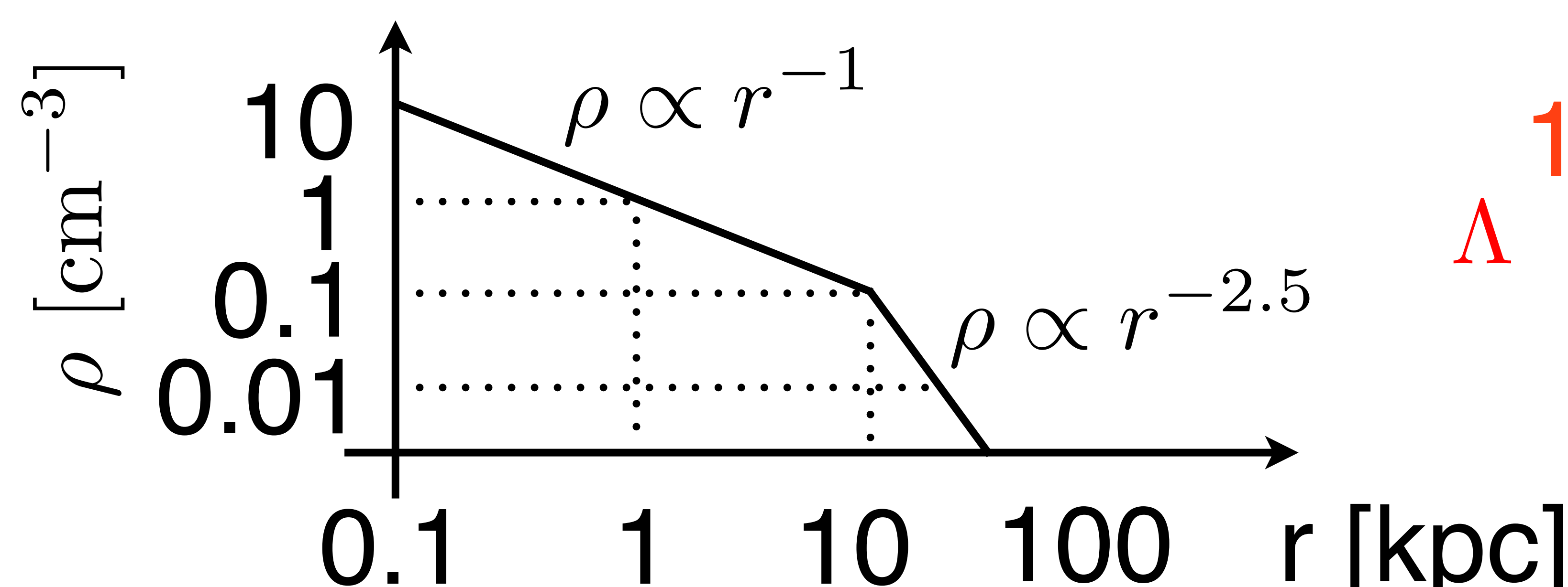
- Kink instability growth timescale controlled by the magnetic pitch (high-mag., mildly relativistic):

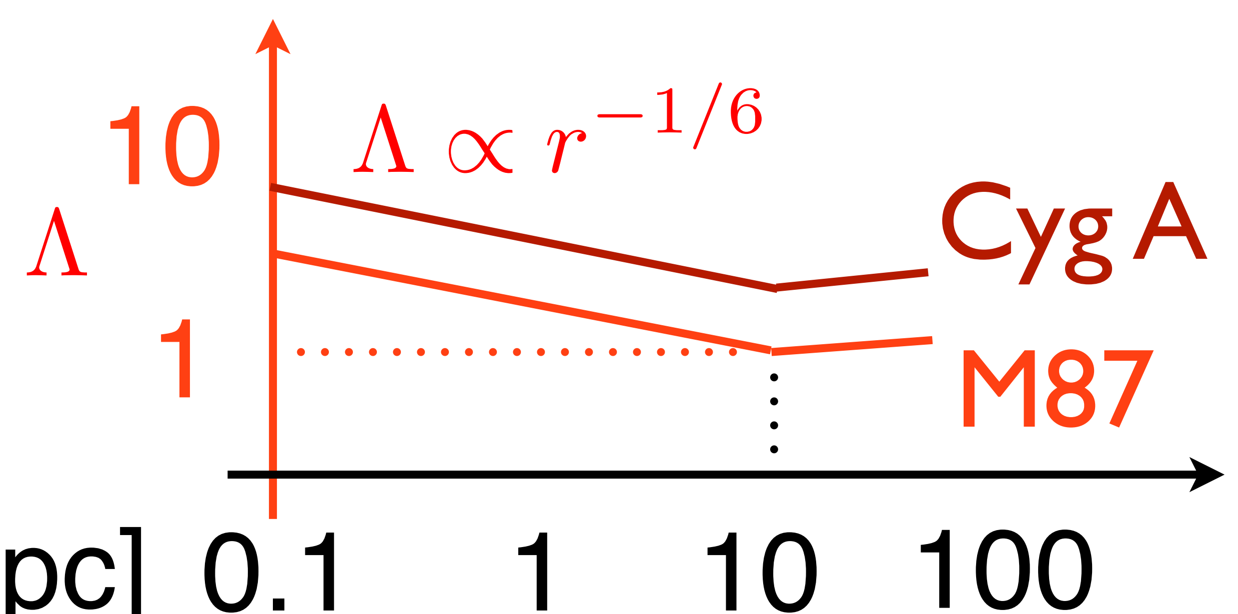
$$t_{\rm kink} \simeq \frac{2\pi R_{\rm j}}{c}\frac{B_p}{B_\phi}$$ (Appl et al. 2001)

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

$$\Lambda \simeq 10\left(\frac{L_{\rm j}}{\rho r^2 c^3}\right)^{1/6} \lesssim 1$$ (Bromberg & AT 2015)

- Cartoon galaxy density profile:



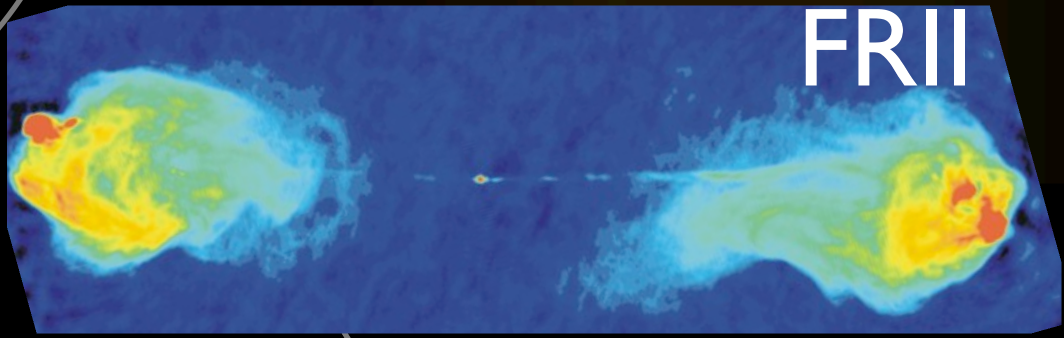


Cyg A-like

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

t =3 Myr

10 kpc



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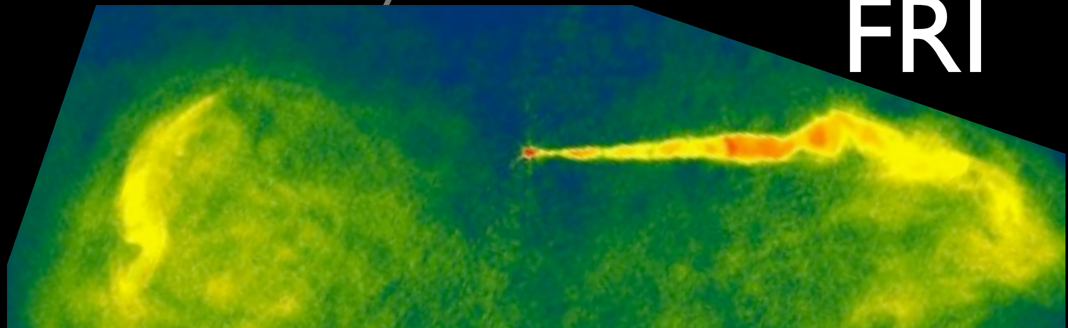

AT and Bromberg 2015, arXiv:1512.04526

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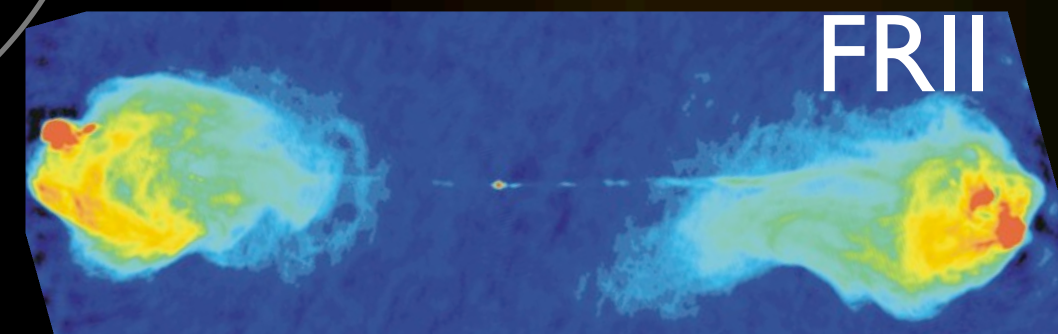

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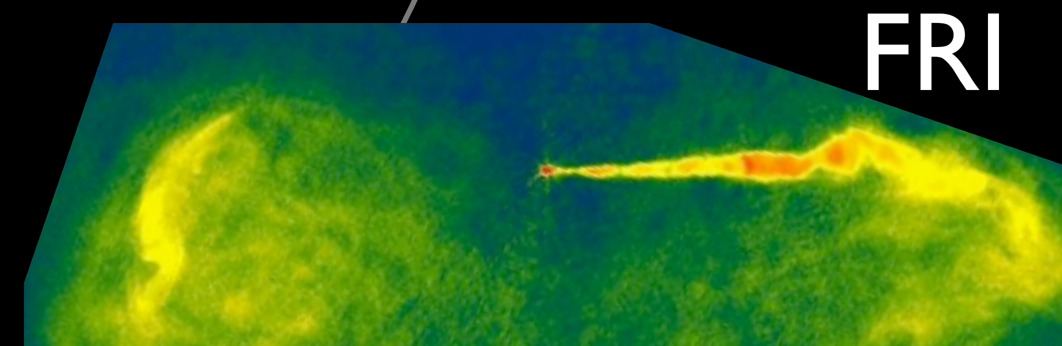

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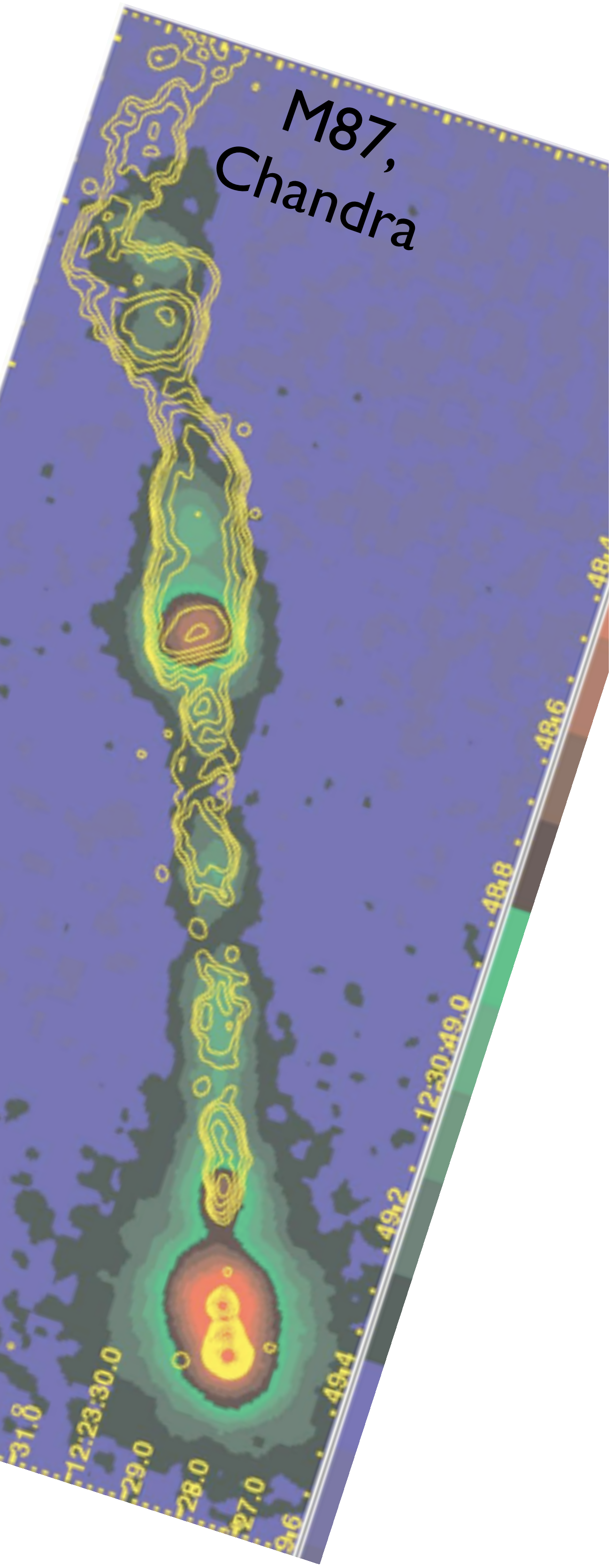
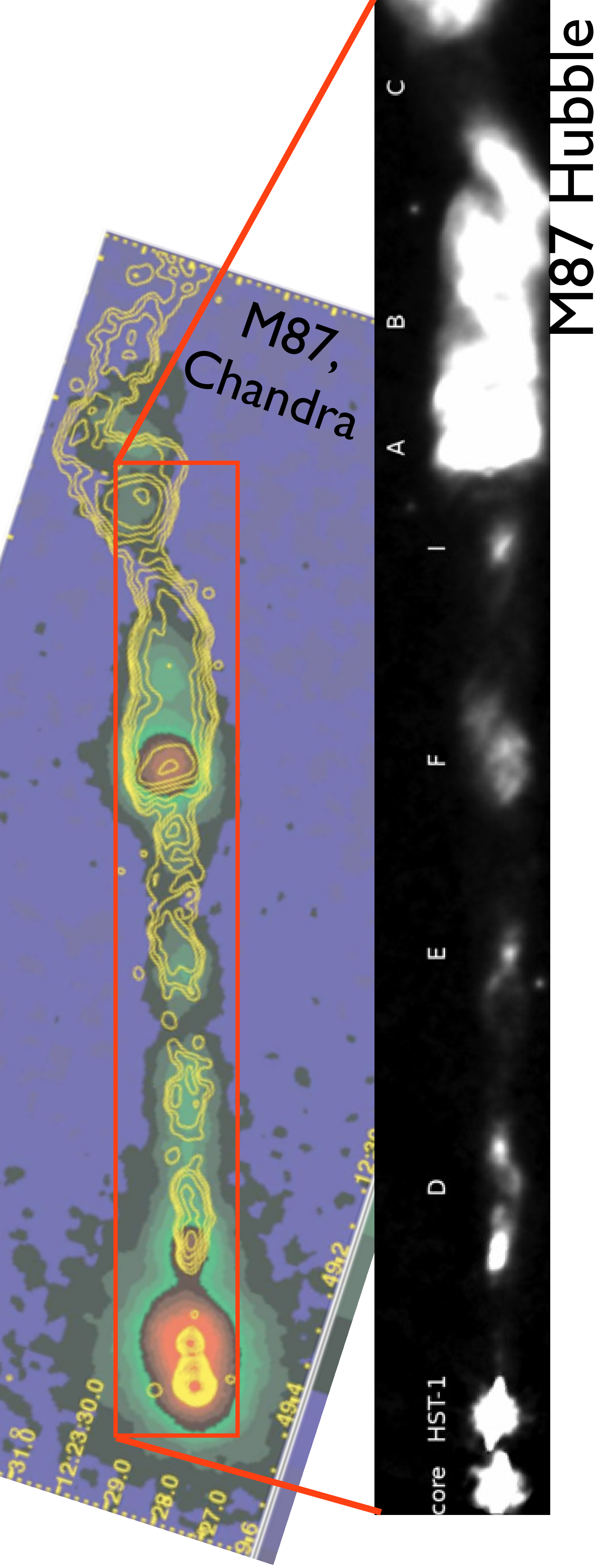
What Lights Up Jet Blobs and High-E Flares?



What Lights Up Jet Blobs and High-E Flares?



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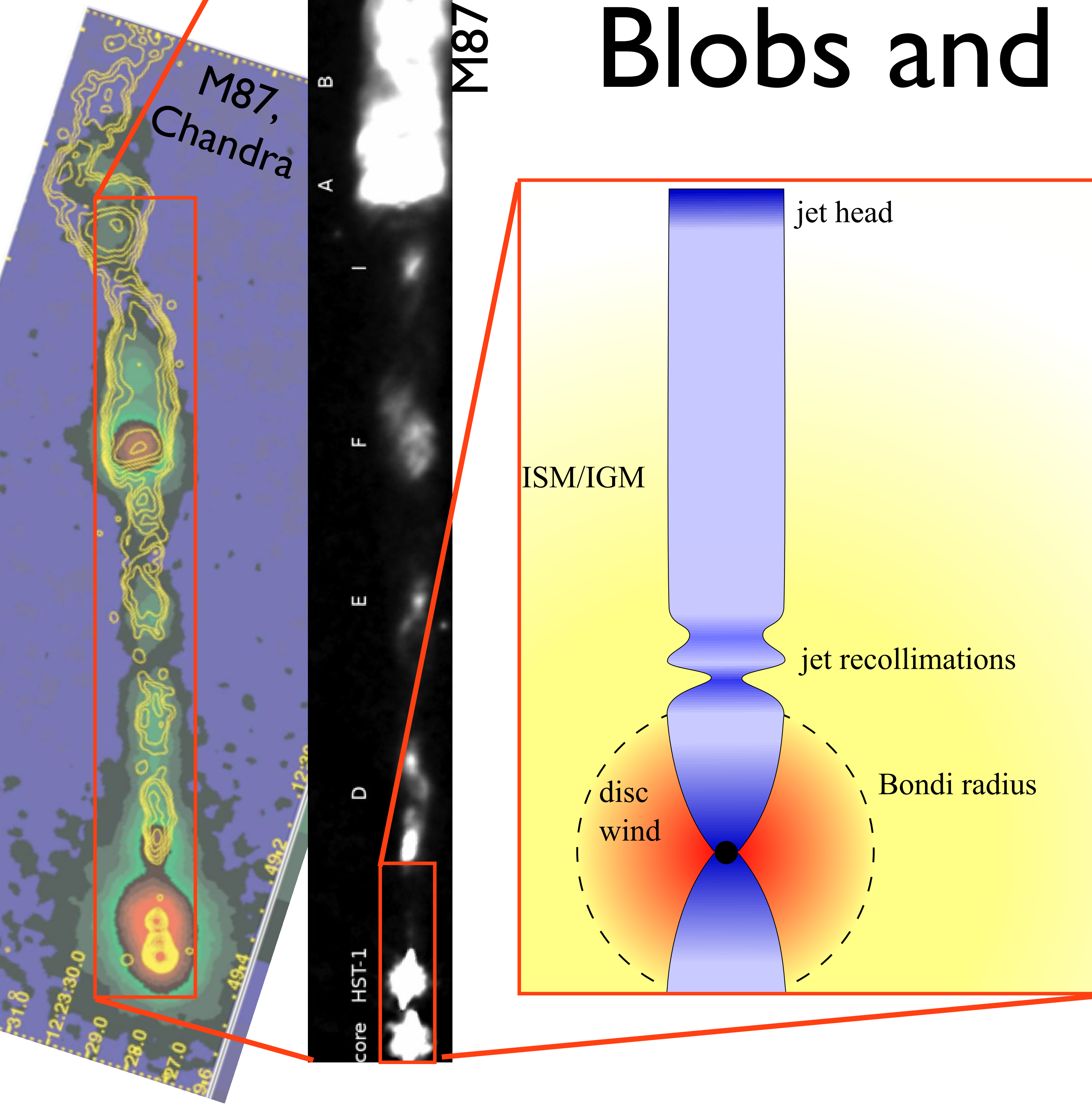

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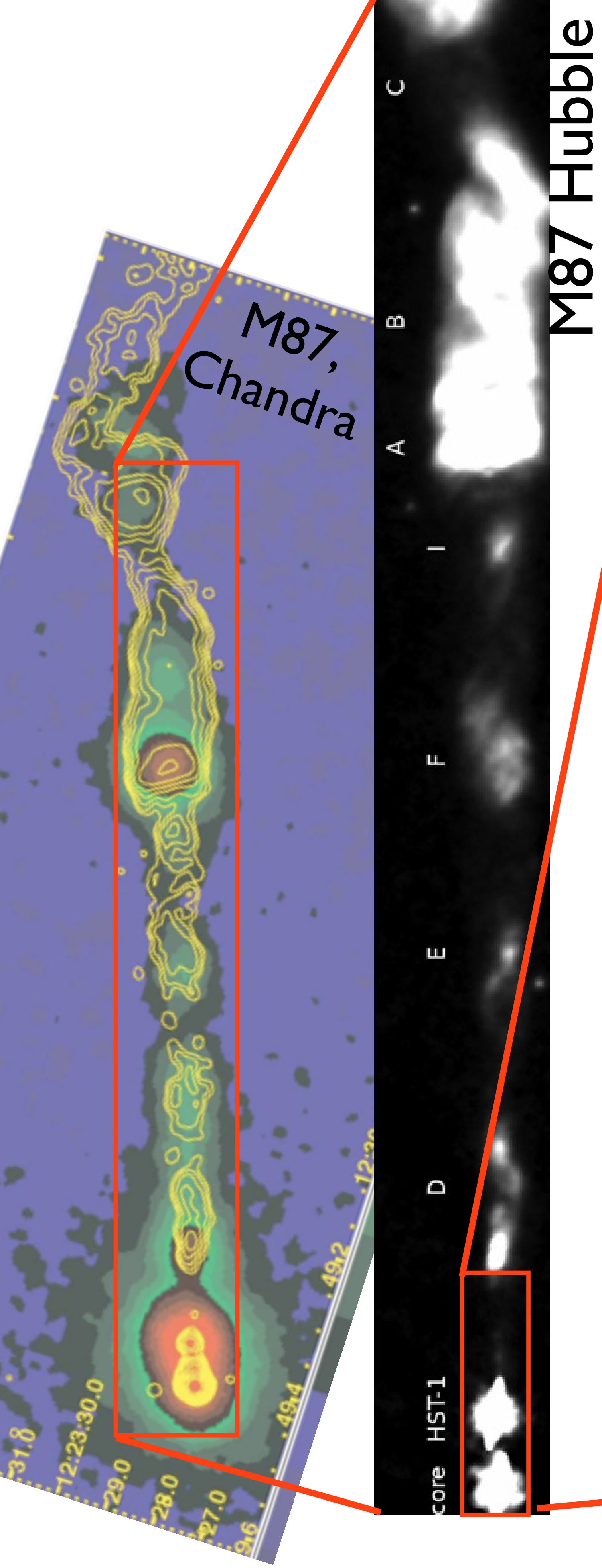
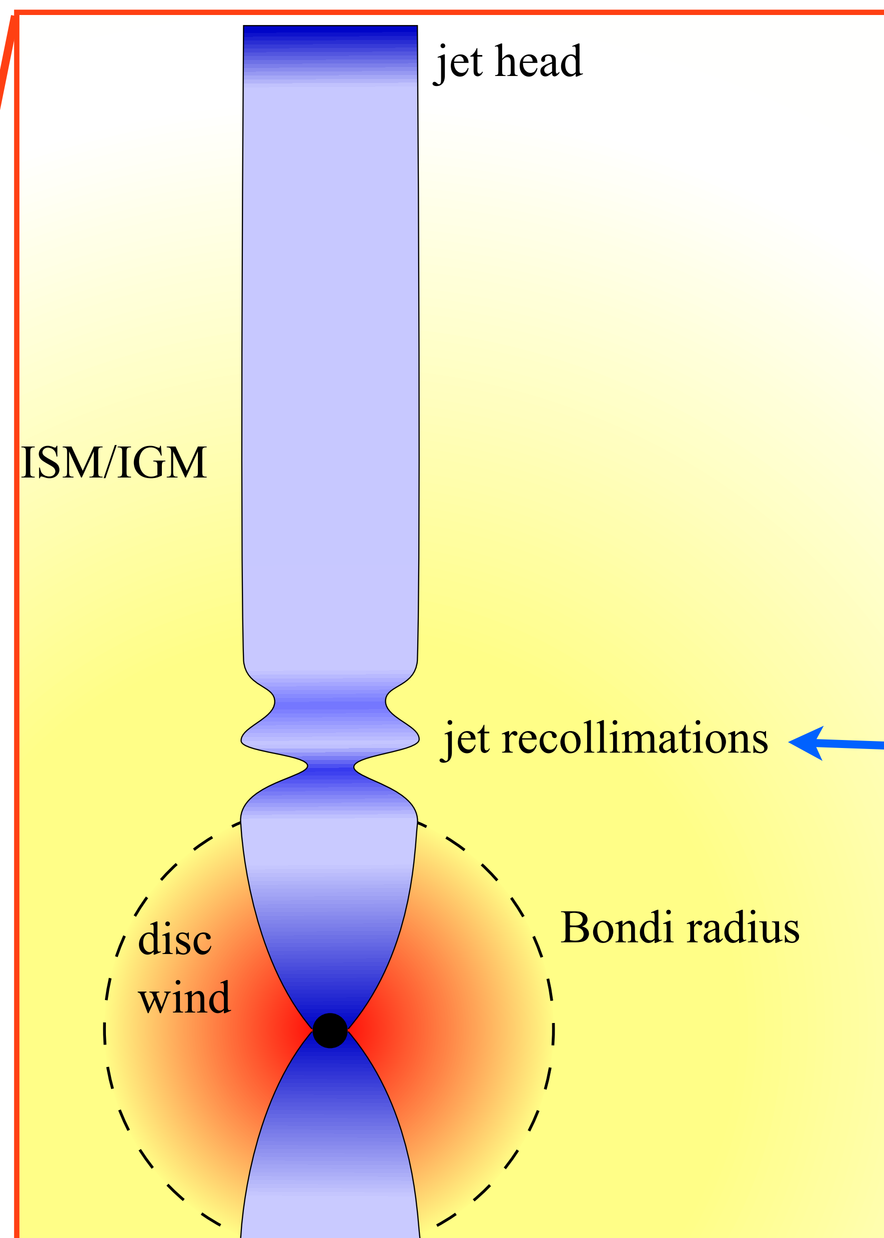
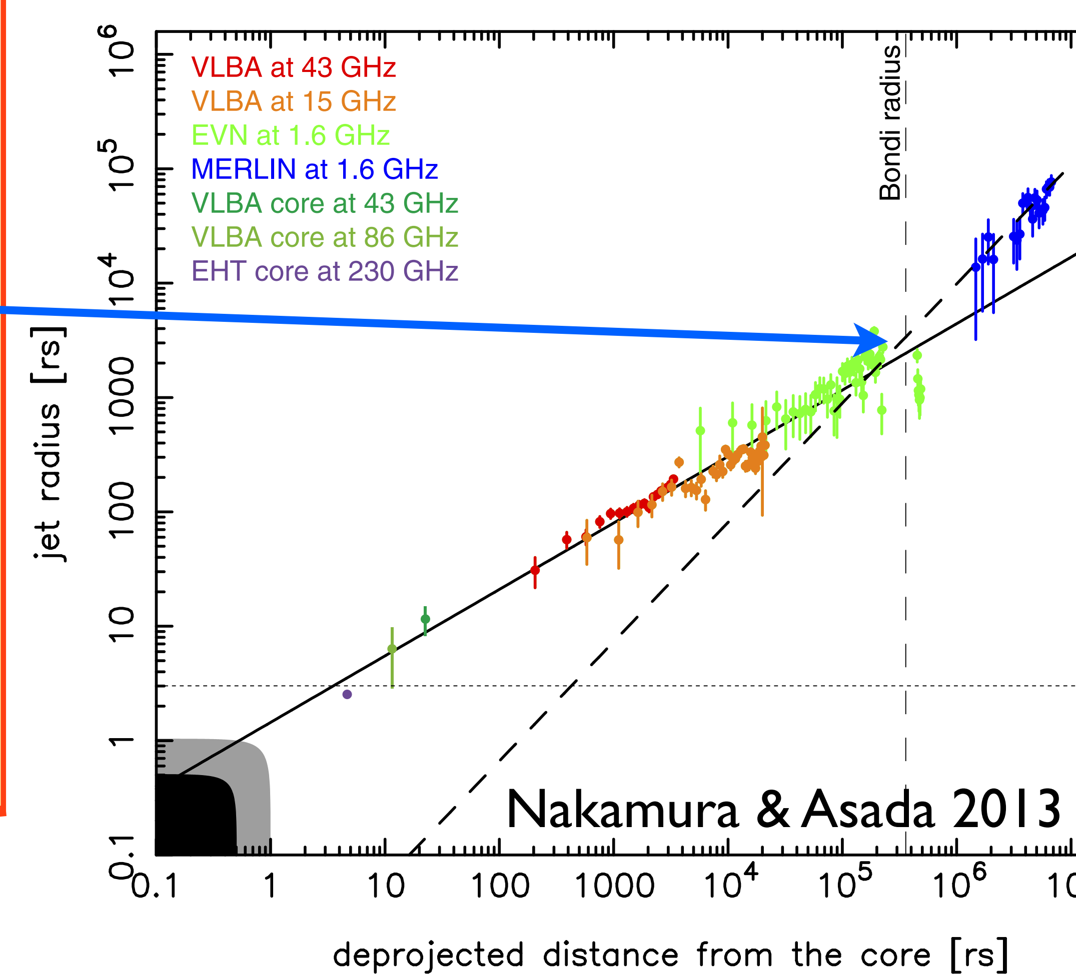


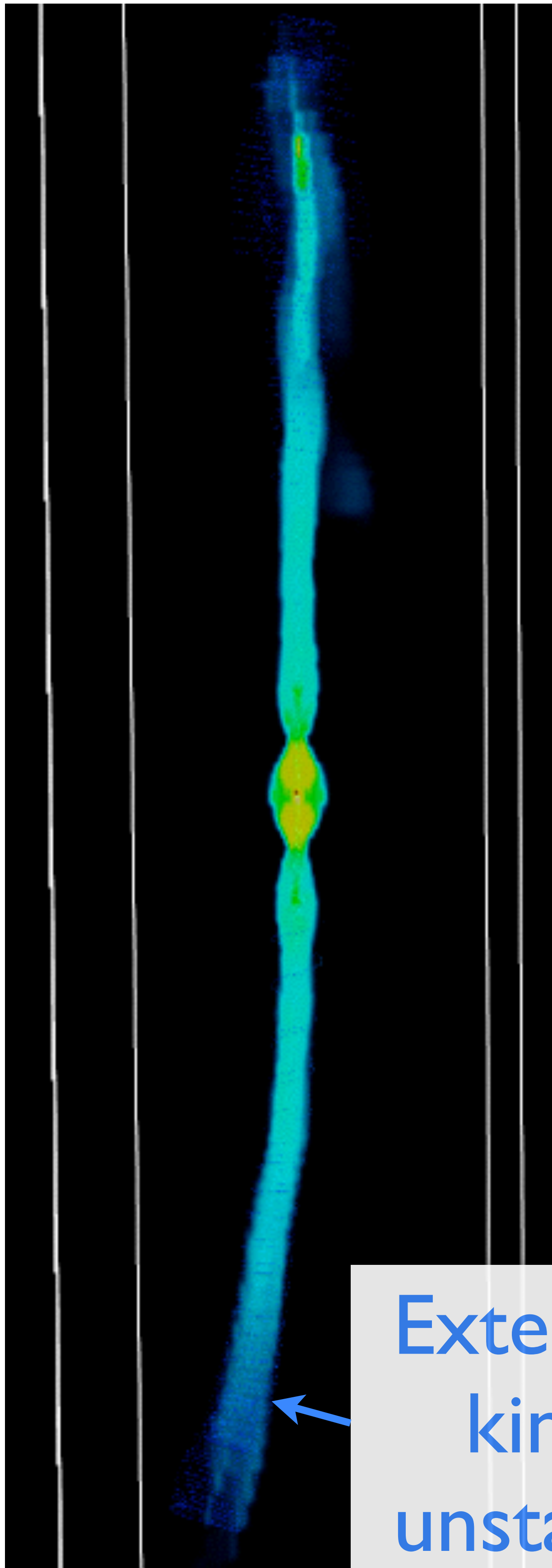


Are we seeing jet-ISM interaction?



Internal Kink Makes Jets Hot

Bromberg and Tchekhovskoy, in prep;
figures/movies courtesy Bromberg



External kink unstable

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

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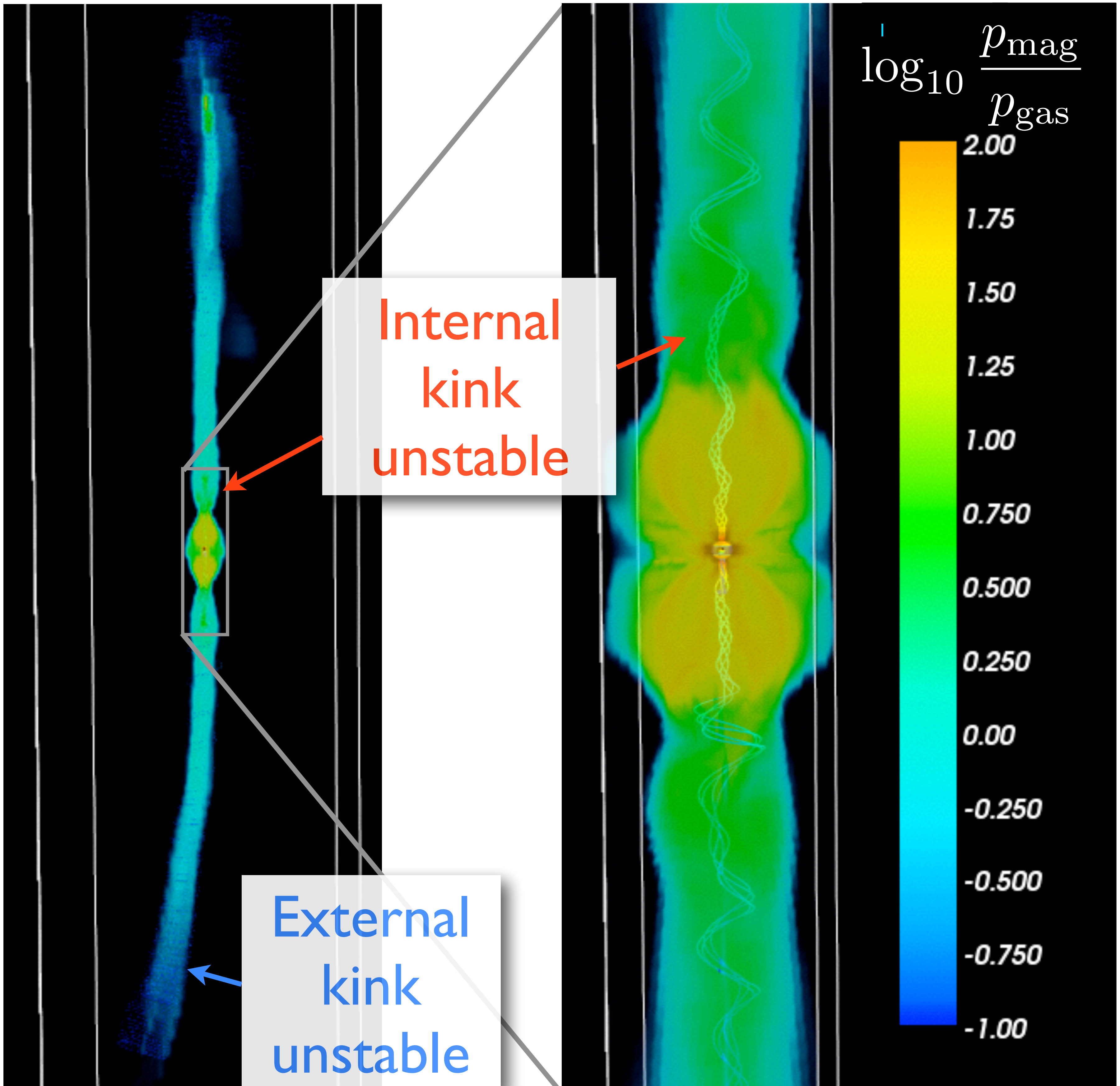

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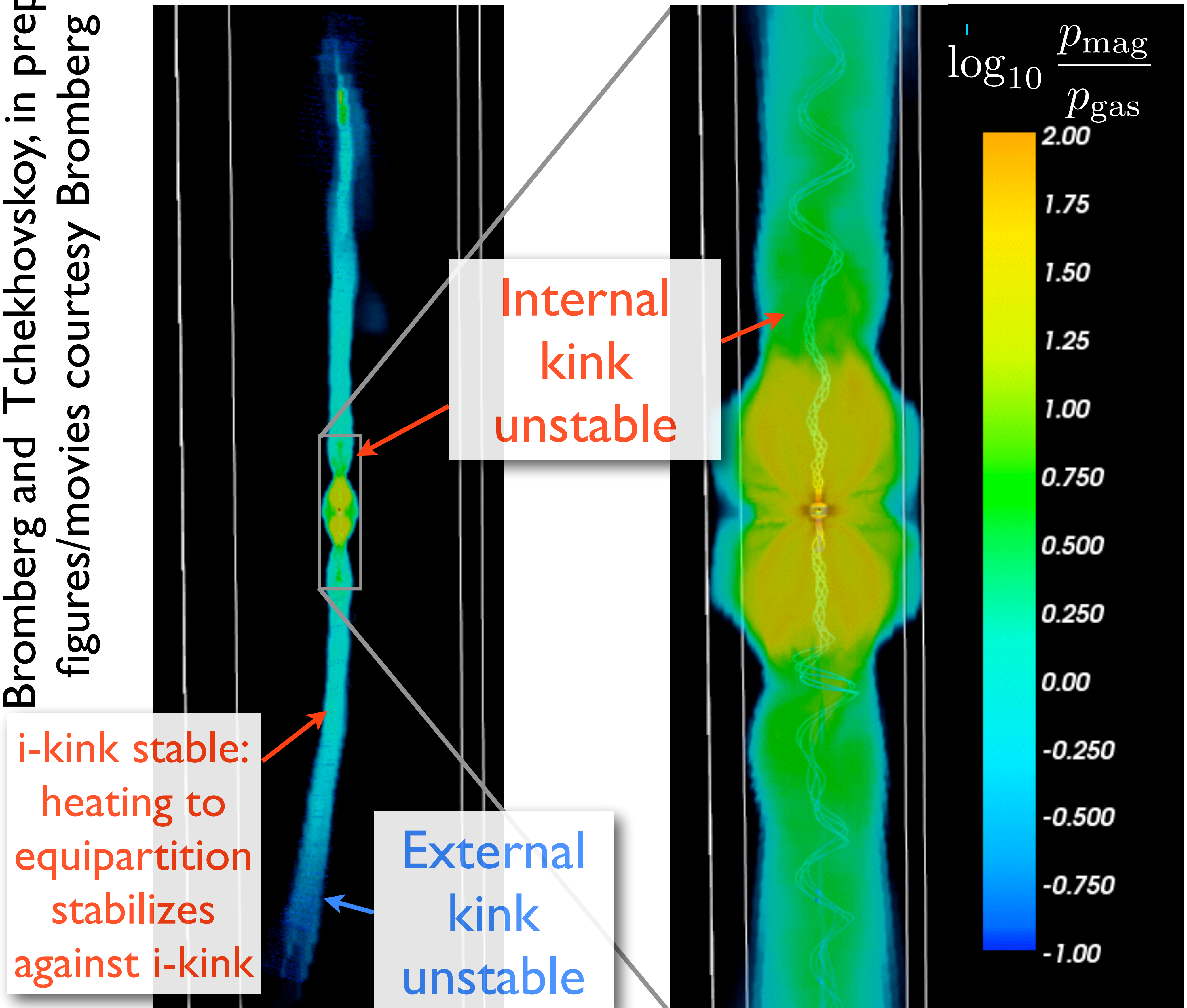

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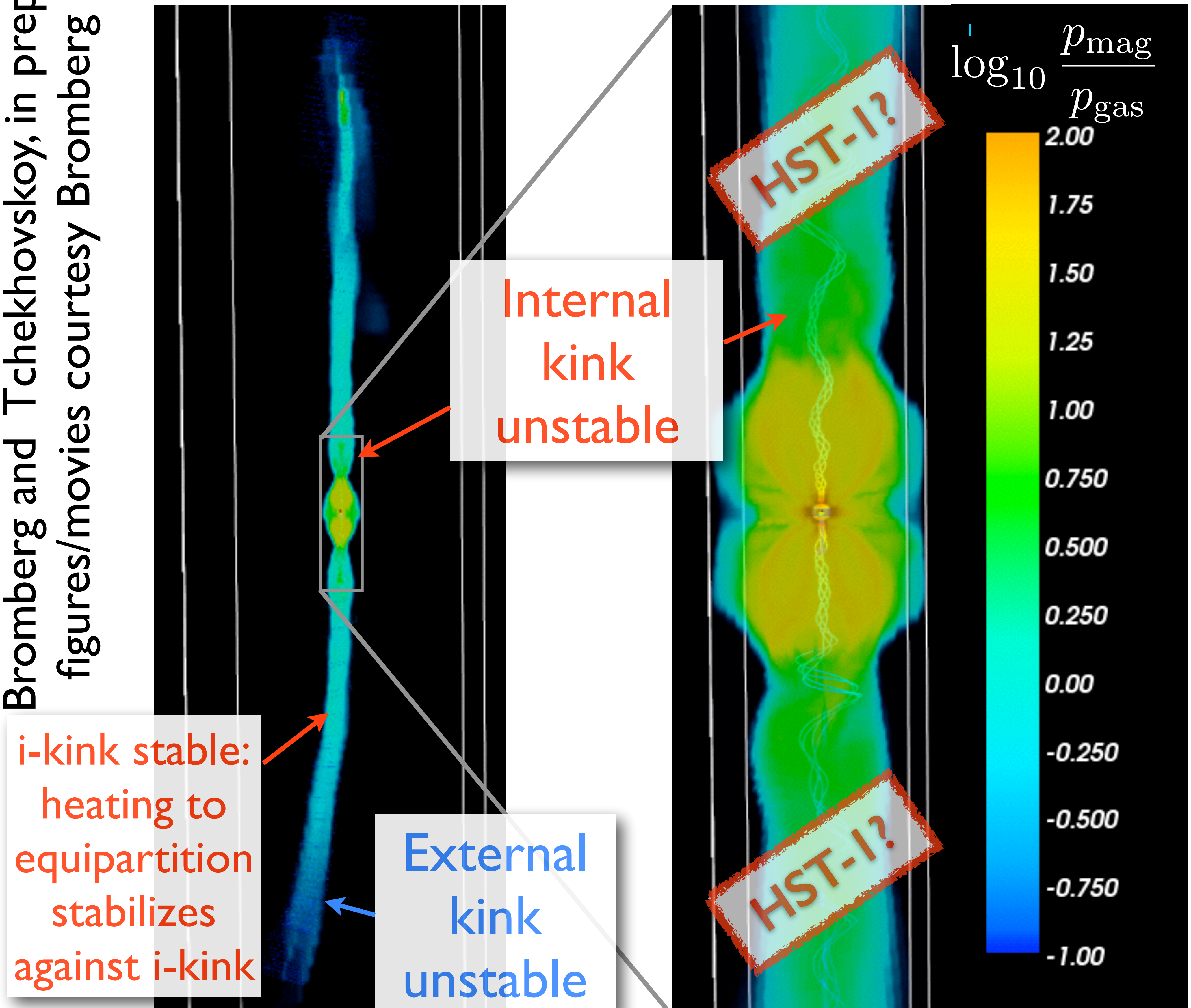

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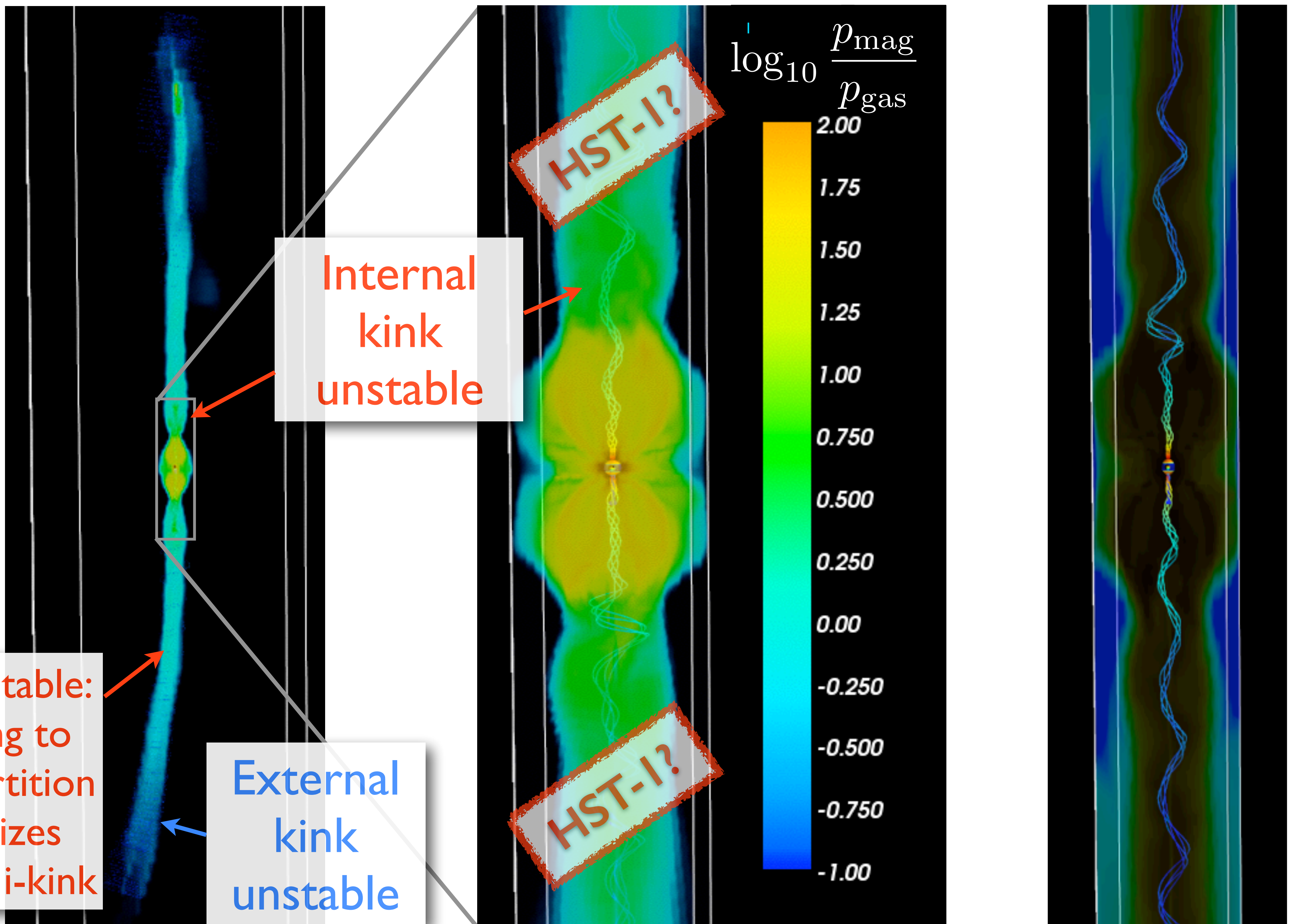

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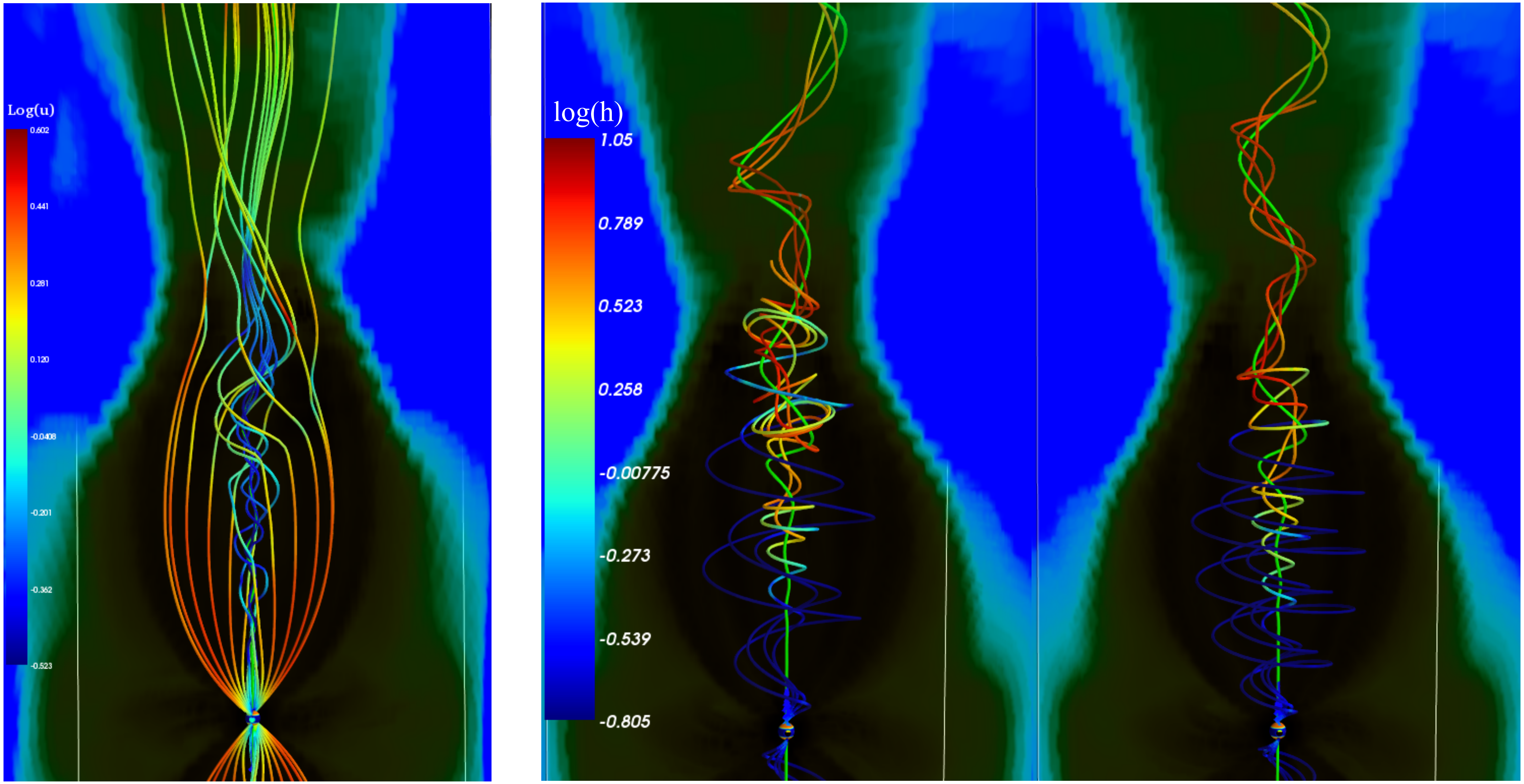
How does Jet Heating Work?



Velocity lines | Fluid B lines | Lab B lines

Recollimation → internal kink →
→ turbulence → dissipation

Summary

- MADs give us the upper envelope of disk-jet connection: galaxy feedback from first principles

- Electron physics in simulations to *directly* interpret:
  - black hole shadow images
  - spectra and variability

- Jet morphology is controlled by 3D external kink:
  - low-power jets are unstable and get stalled inside galaxy
  - FRI/FRII dichotomy likely mediated by magnetic instabilities

- Jet heating caused by 3D internal kink. Power behind
  - HST-1
  - blazar flares
  - gamma-ray burst prompt emission?

What's next?
Solve LARGE Problems Using GPUs

- Graphical Processing Units (GPUs) is a new disruptive technology
  - cutting edge of modern supercomputing
- Multi-GPU 3D HARM:
  - based on open-source HARM2D
  - 100x speedup compared to CPU version
- Applications:
  - Long-term accretion-jet simulations
  - Tidal disruption events simulations
  - Long-term accretion in GRBs and kilonovae
  - Accretion disks with full radiation transport

Matthew Liska
(U of Amsterdam)