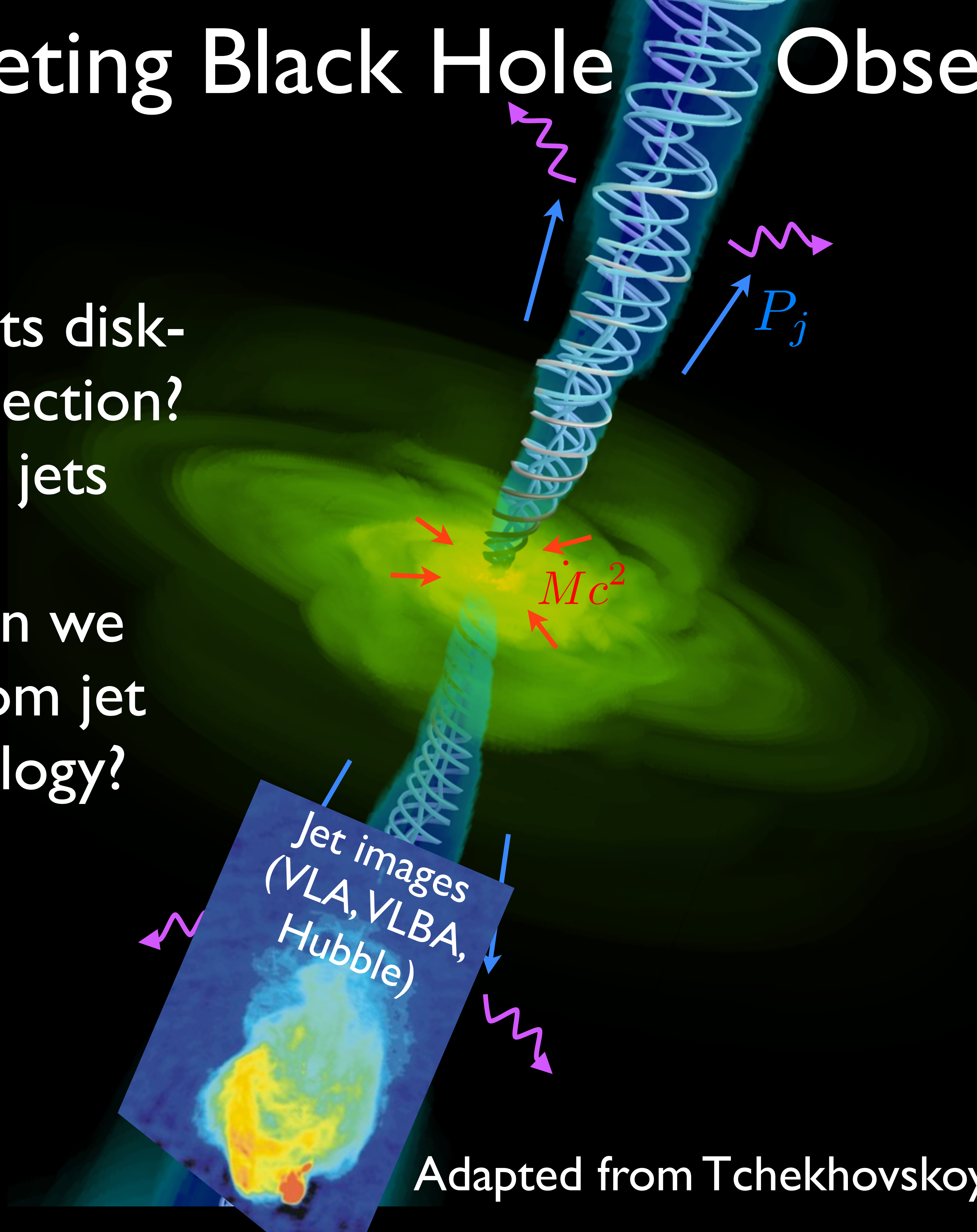
Magnetic Kink Instability and Fanaroff-Riley Dichotomy of AGN jets

Alexander (Sasha) Tchekhovskoy

Einstein Fellow
UC Berkeley

Interpreting Black Hole Observations

- What sets disk-jet connection?
- How do jets emit?
- What can we learn from jet morphology?



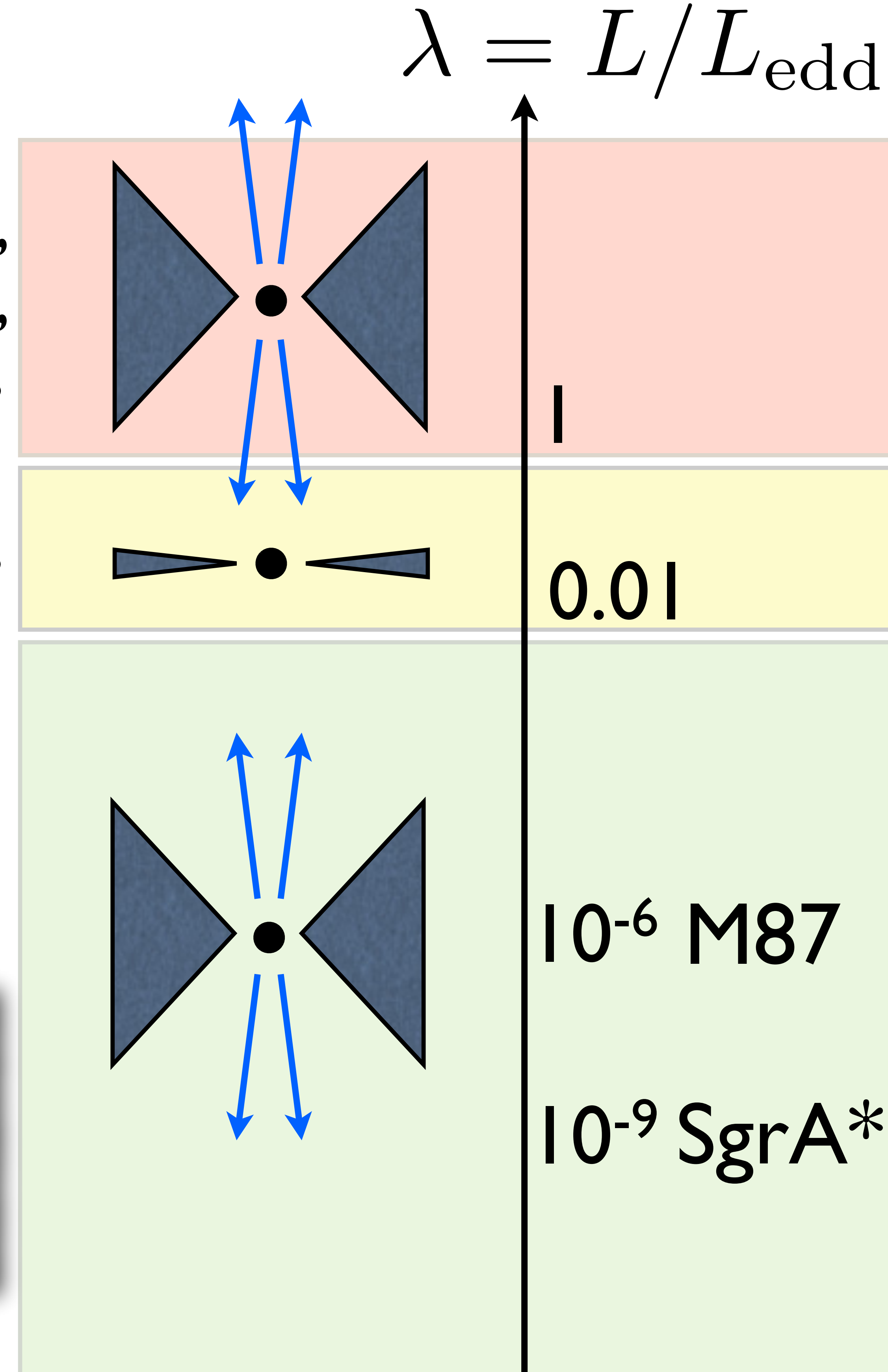
Adapted from Tchekhovskoy 2015

Black Hole Accretion States

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

Quasars, X-ray binaries, TDEs

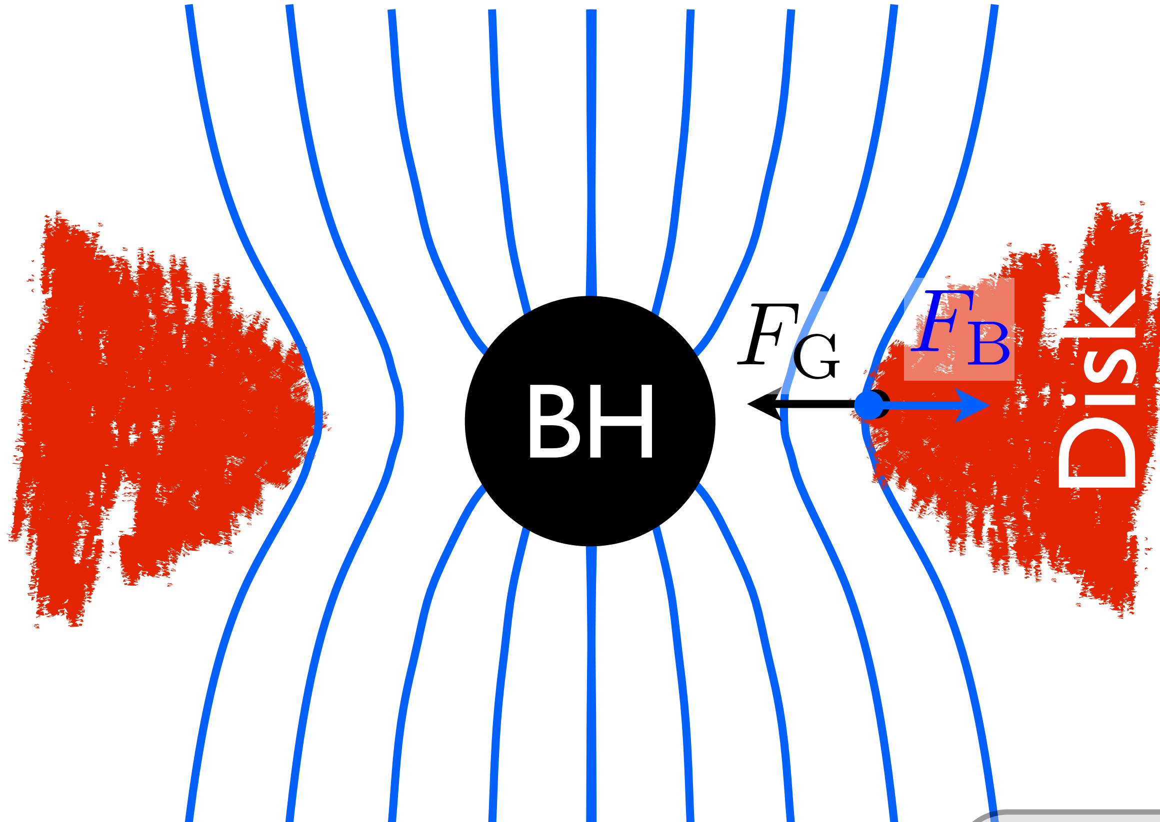
Low-luminosity active galactic nuclei (LLAGN), X-ray binaries



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

What Sets Jet Power?

Gravity limits P_j and Φ!



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

grav. radius:
$r_g = GM/c^2$

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

(Blandford & Znajek '77, AT+10)

B sub-dominant

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

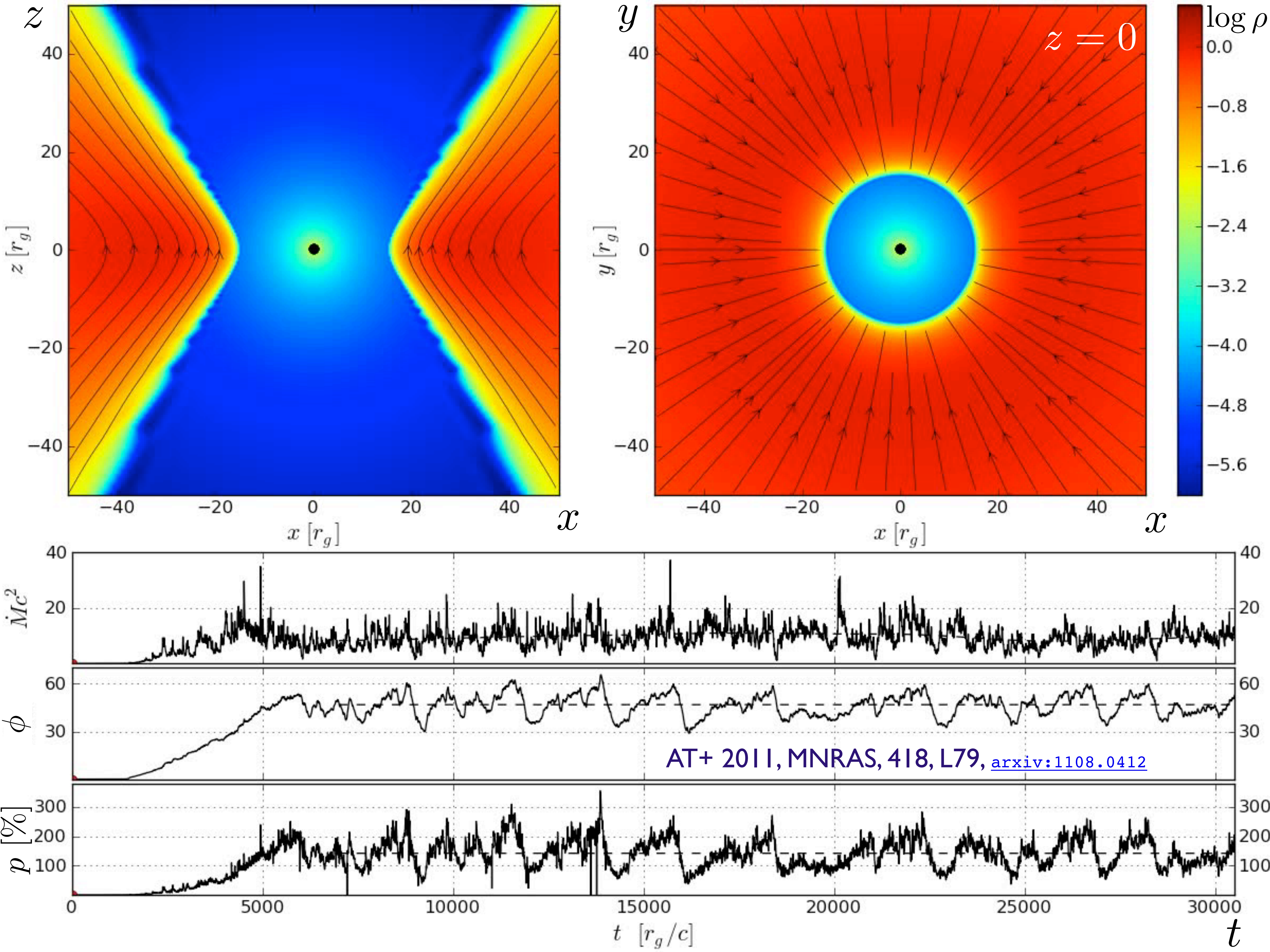
$$\Phi = 0 \qquad \Phi = \Phi_{\rm MAX}$$

B dominant
Magnetically-Arrested Disk (MAD)

(Narayan+ 2003, AT+ 2011)

How strong are the jets?

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

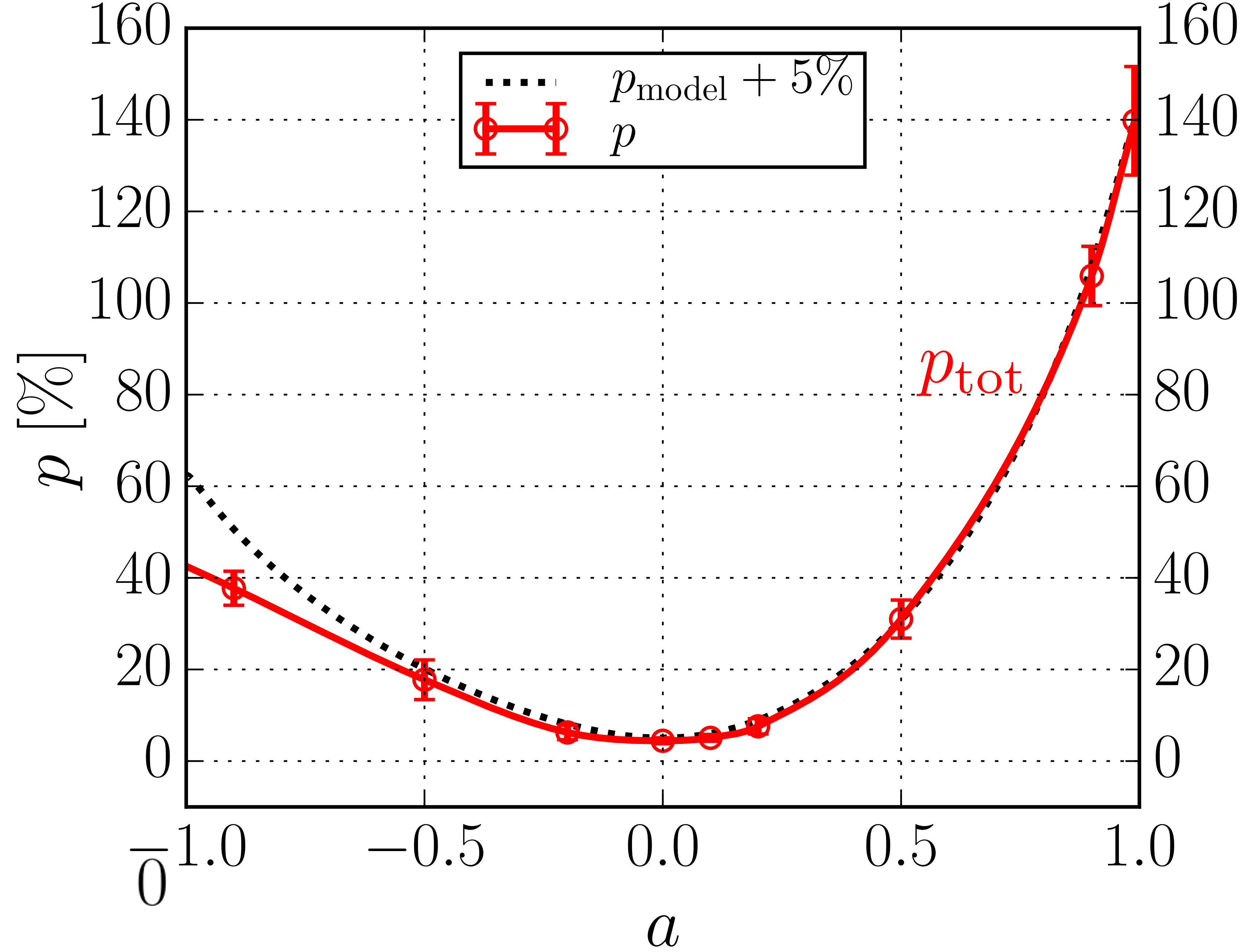


z
$x\ [r_g]$
$z\ [r_g]$
x
y
$z = 0$
$y\ [r_g]$
x
$\log \rho$
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ [r_g/c]$
t
AT+ 2011, MNRAS, 418, L79, arxiv:1108.0412

Upper Envelope of Jet Power vs. Spin

(h/r~0.3)

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



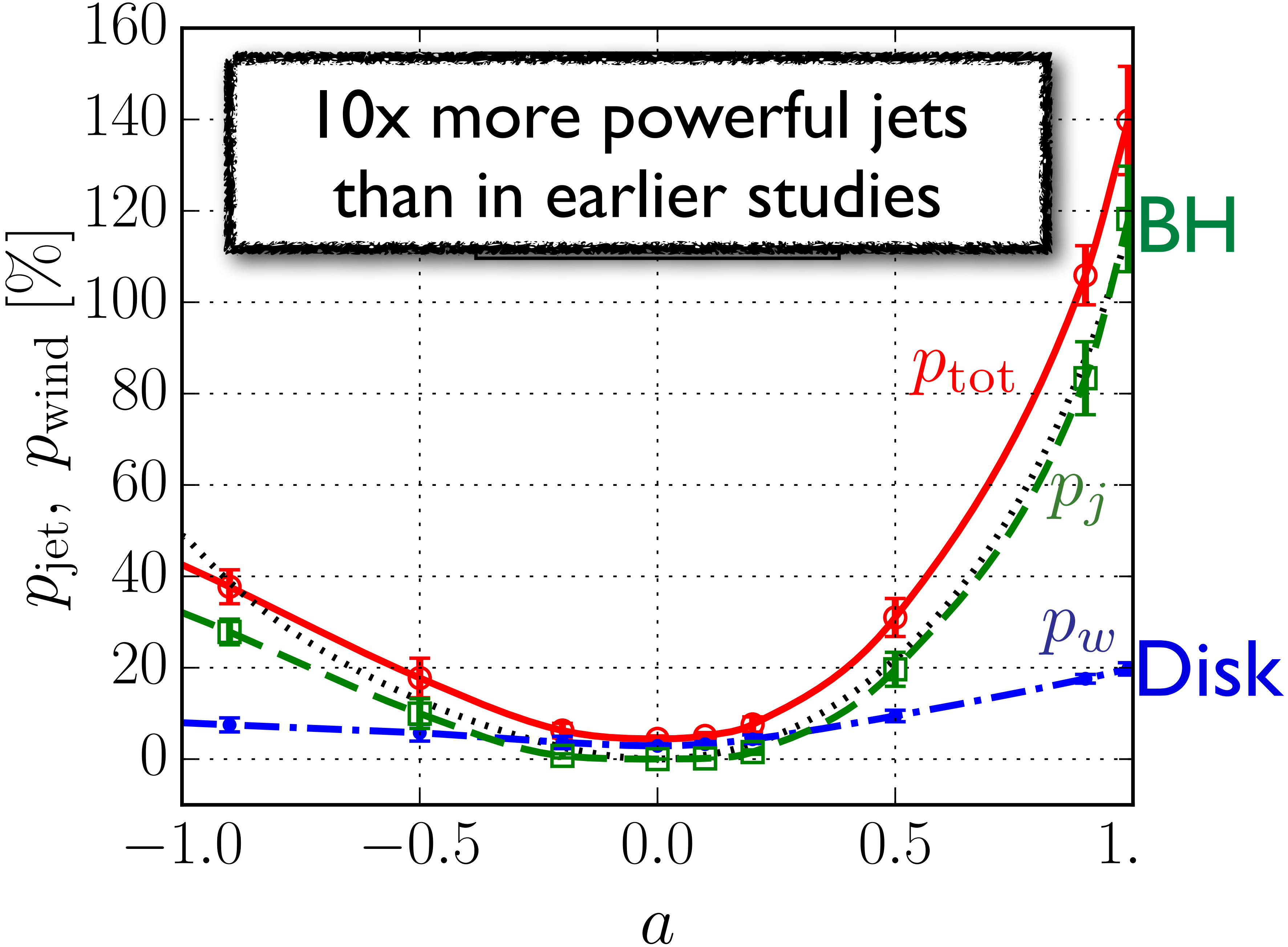
Quantify feedback due to black hole jet, disk wind from *first principles*

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

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*

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

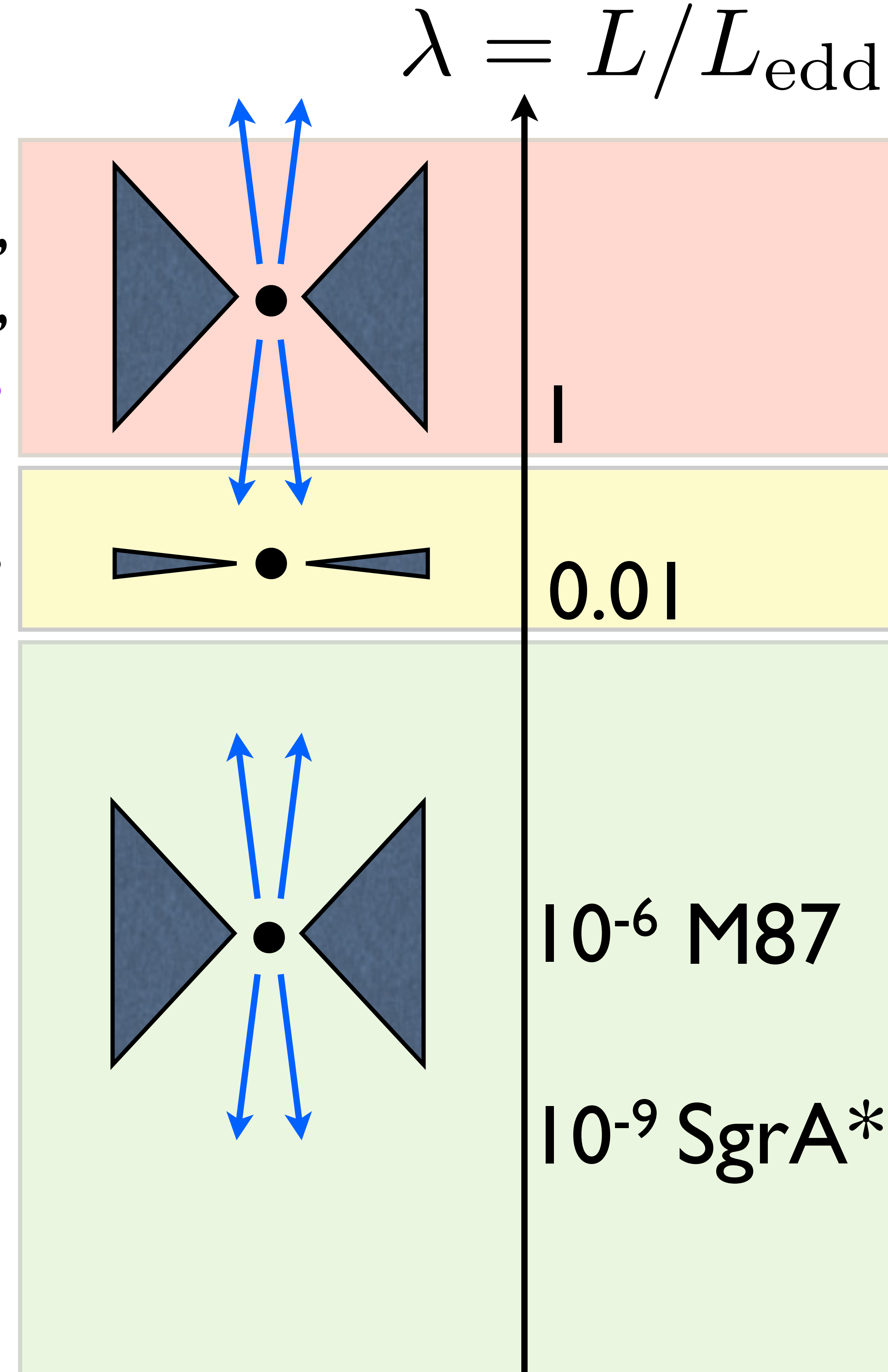
Black Hole Accretion States

MADs:

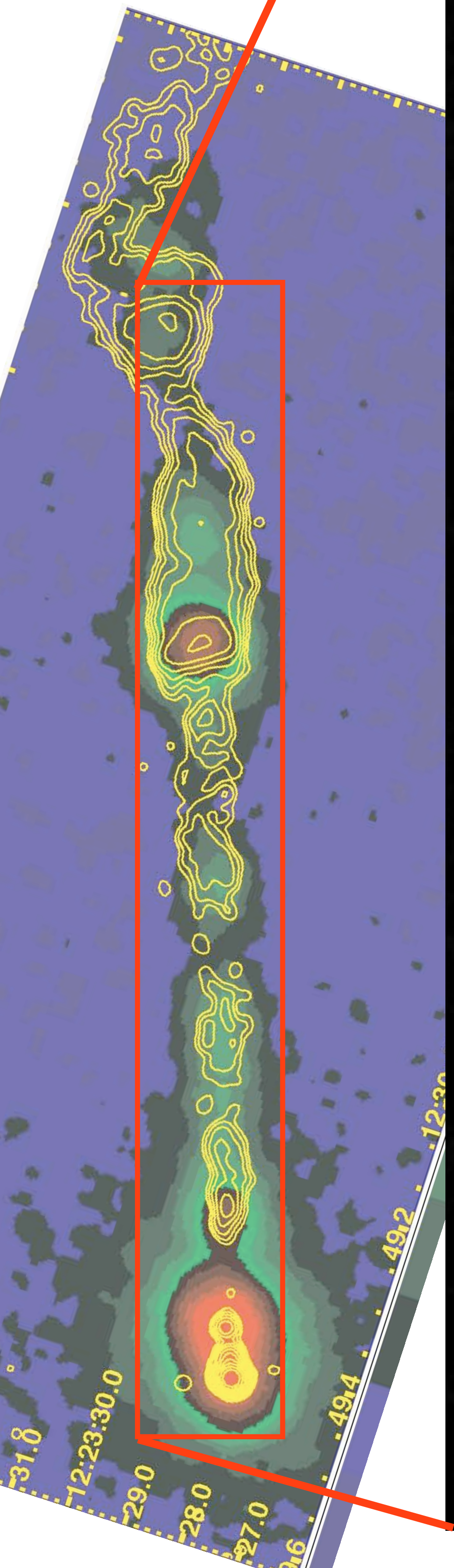
(AT+13, AT & Giannios 15) — Tidal disruptions (TDEs), ultra-luminous X-ray sources, gamma-ray bursts

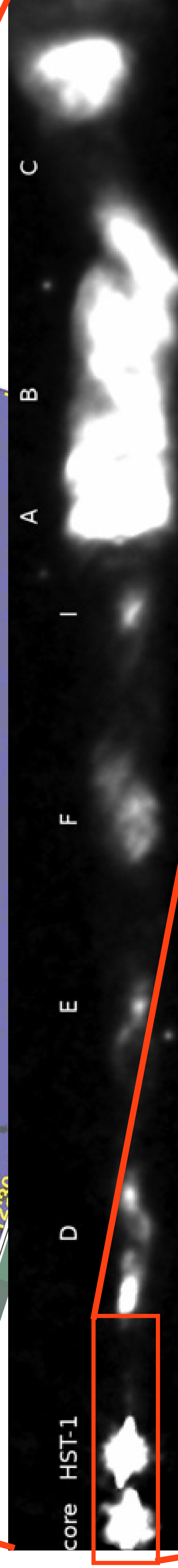
(Zamaninasab ++AT 14, Ghisellini+14) — Quasars, X-ray binaries, TDEs

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

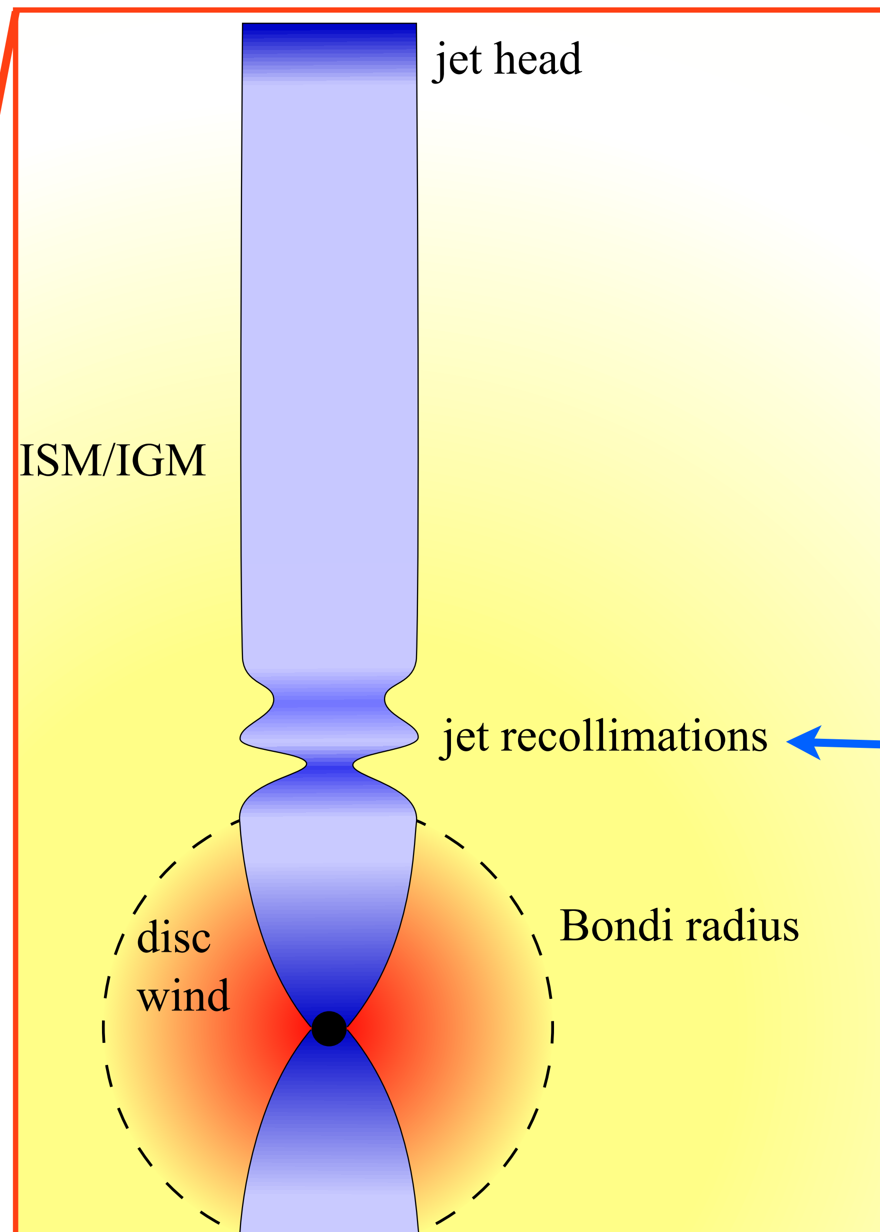


Magnetic Instabilities and Jet Emission



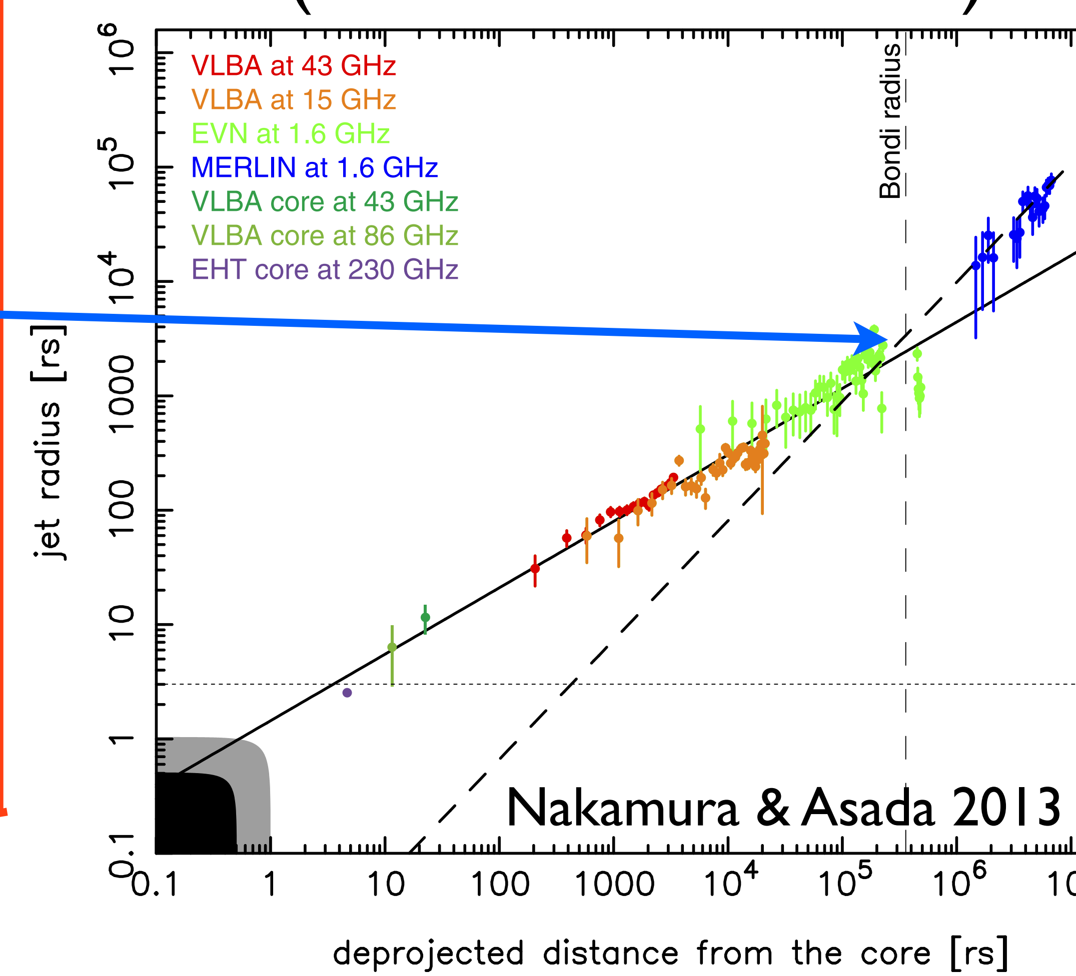


(Meyer+13)



Are we seeing jet-ISM interaction?

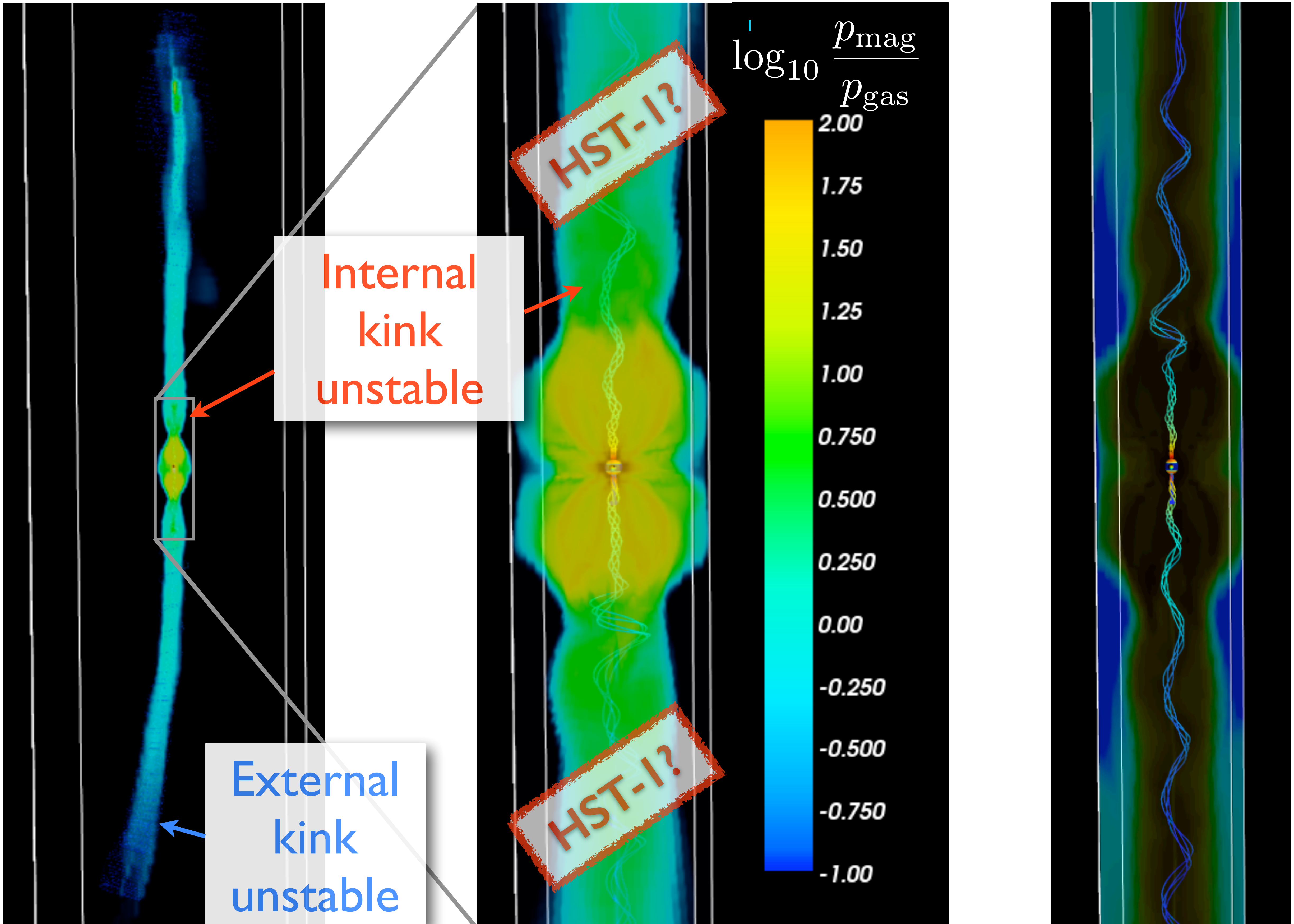
(see also Meier 2012)



Nakamura & Asada 2013

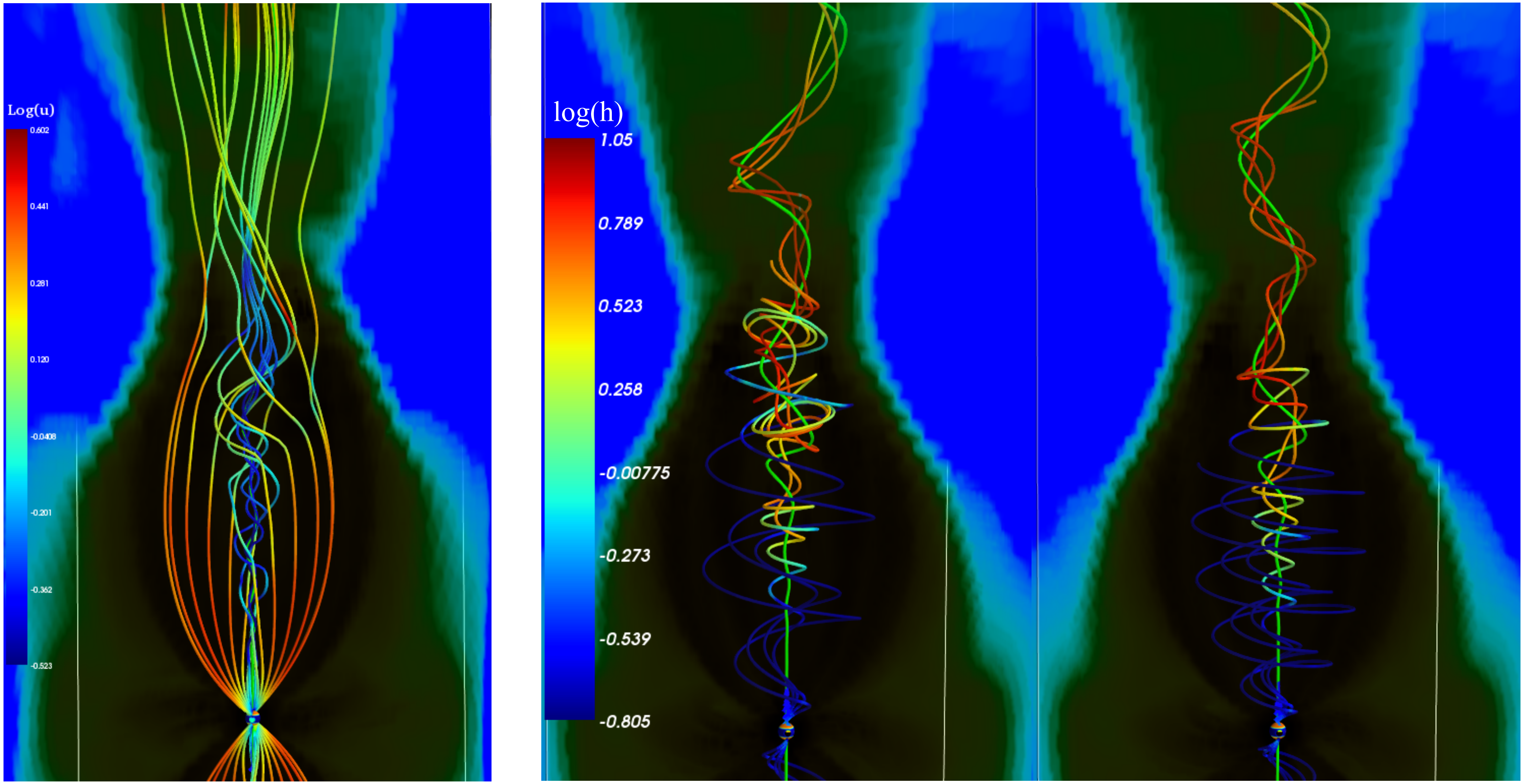
Internal Kink Makes Jets Hot

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



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

How does Jet Heating Work?

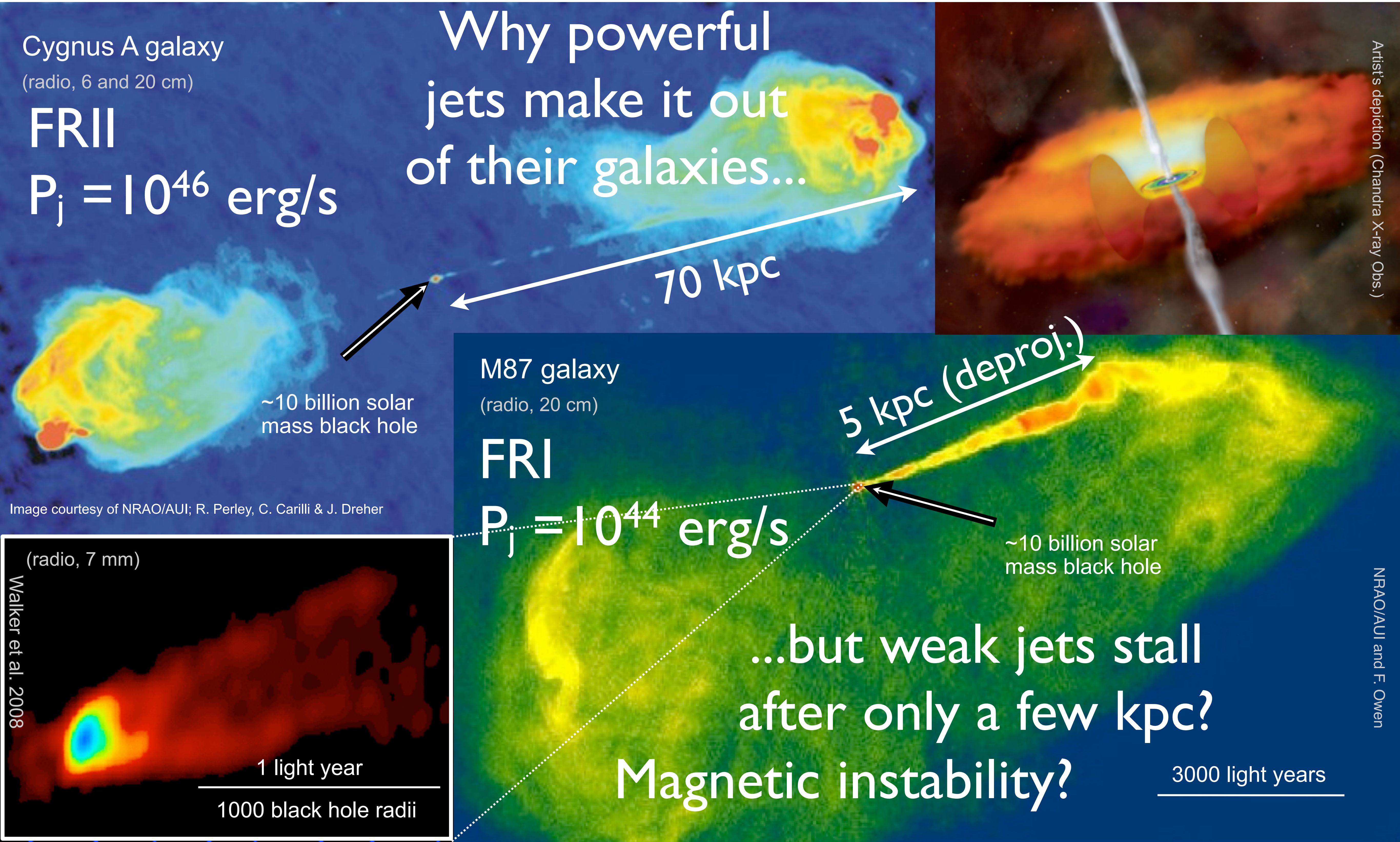


Velocity lines | Fluid B lines | Lab B lines

Recollimation → internal kink →
→ turbulence → reconnection → emission

What does Jet Morphology Tell Us?

FRI/FRII dichotomy (Fanaroff & Riley, 1974)



Instability of Magnetized Jets

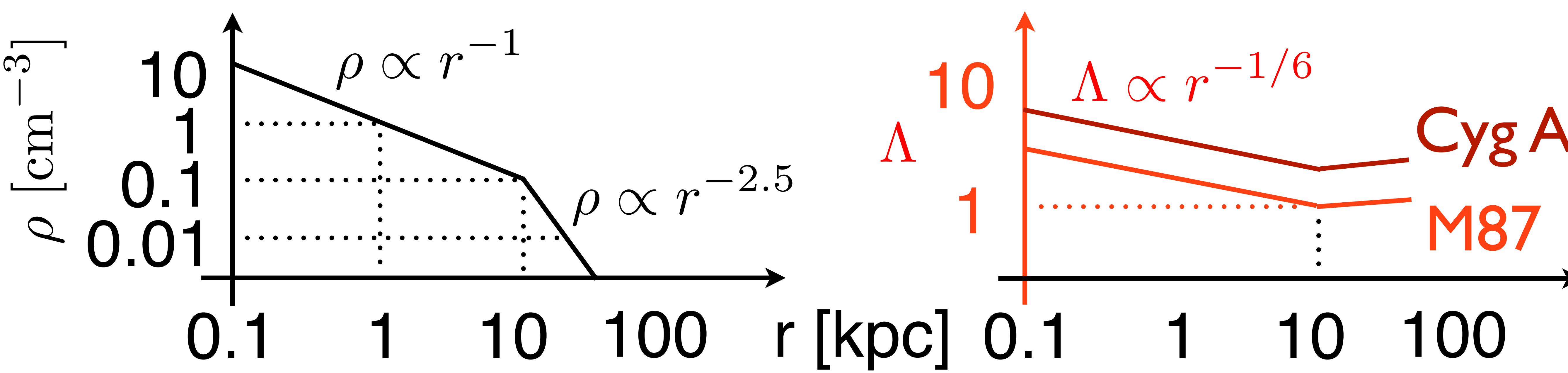
- Kink instability growth timescale controlled by the magnetic pitch (high-mag., mildly relativistic):

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

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

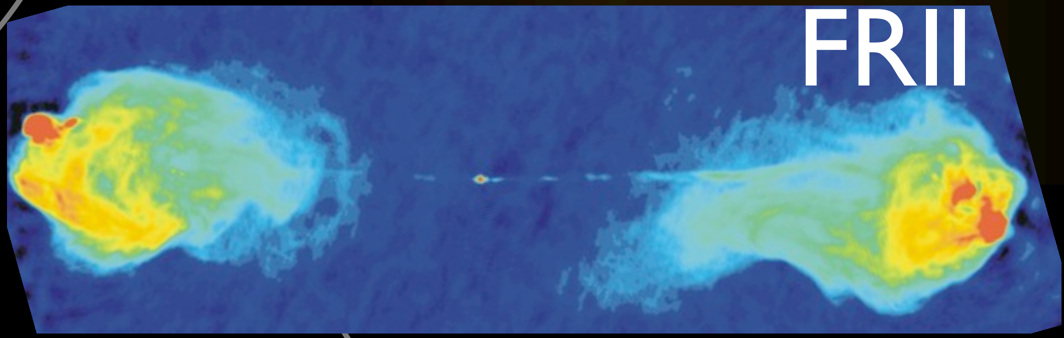
$$\Lambda \simeq 10\left(\frac{L_{\mathrm{j}}}{\rho r^2 c^3}\right)^{1/6} \lesssim 1$$ (Bromberg & AT 2016)

- Cartoon galaxy density profile:



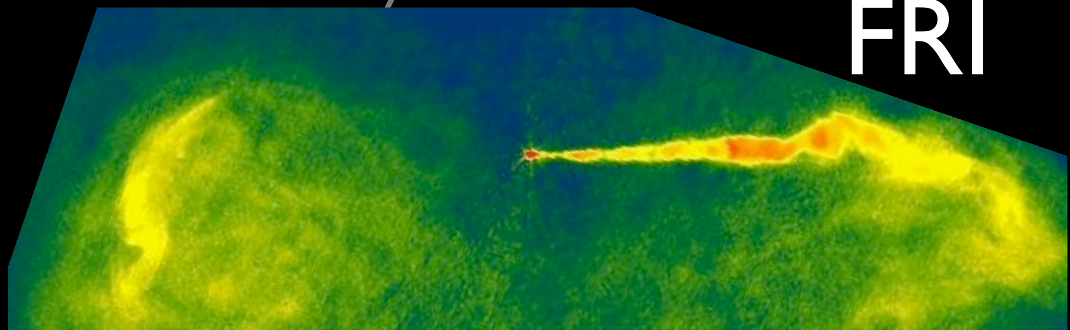
Cyg A-like
$P_j = 10^{46}$ erg s^{-1}
t =3 Myr

10 kpc



M87-like
$P_j = 10^{44}$ erg s^{-1}
t =6 Myr

AT and Bromberg 2015, arXiv:1512.04526



Summary

- MADs give us the upper envelope of disk-jet connection. MADs in blazars! (and not only)

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

- 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

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)