The disk-jet connection

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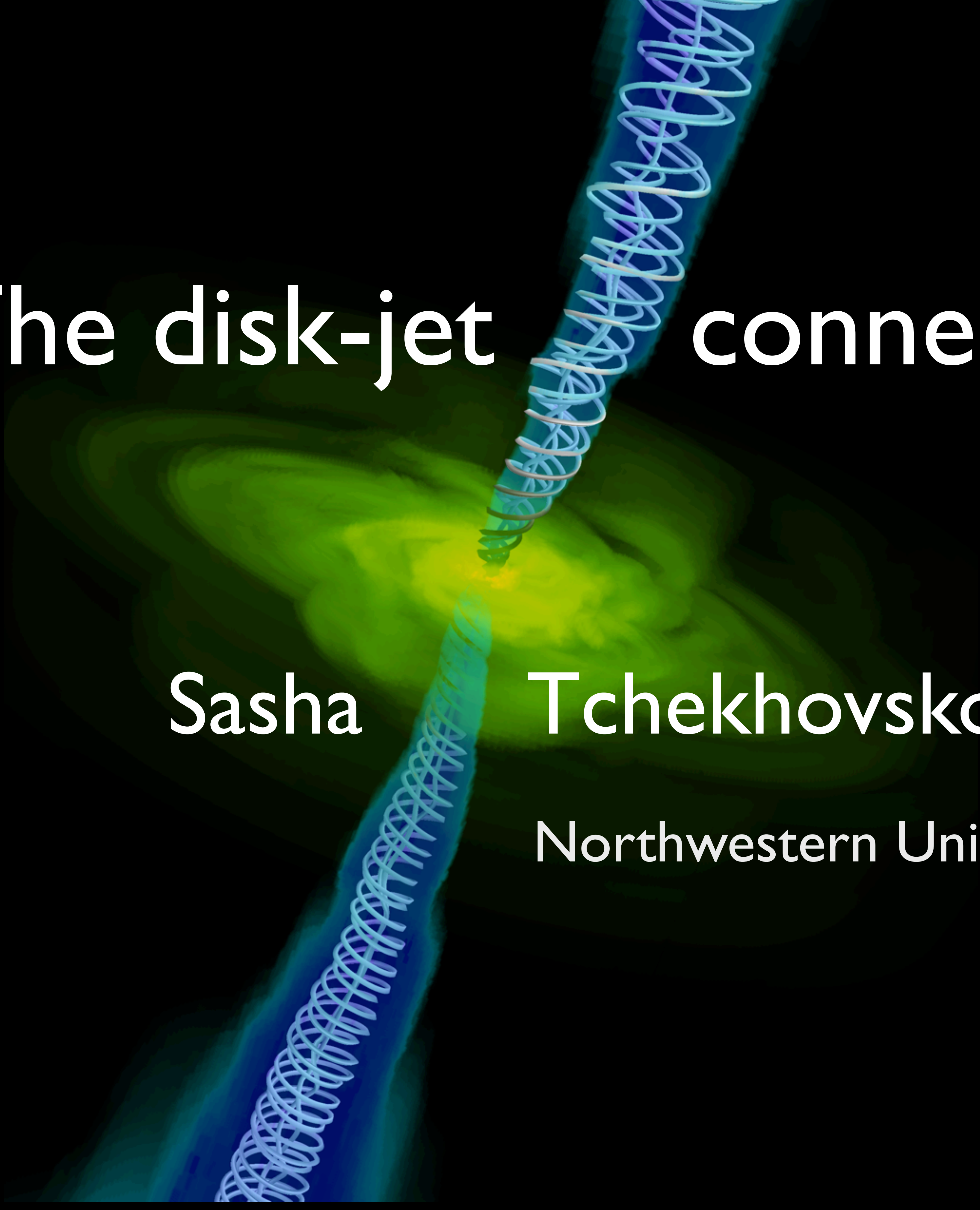
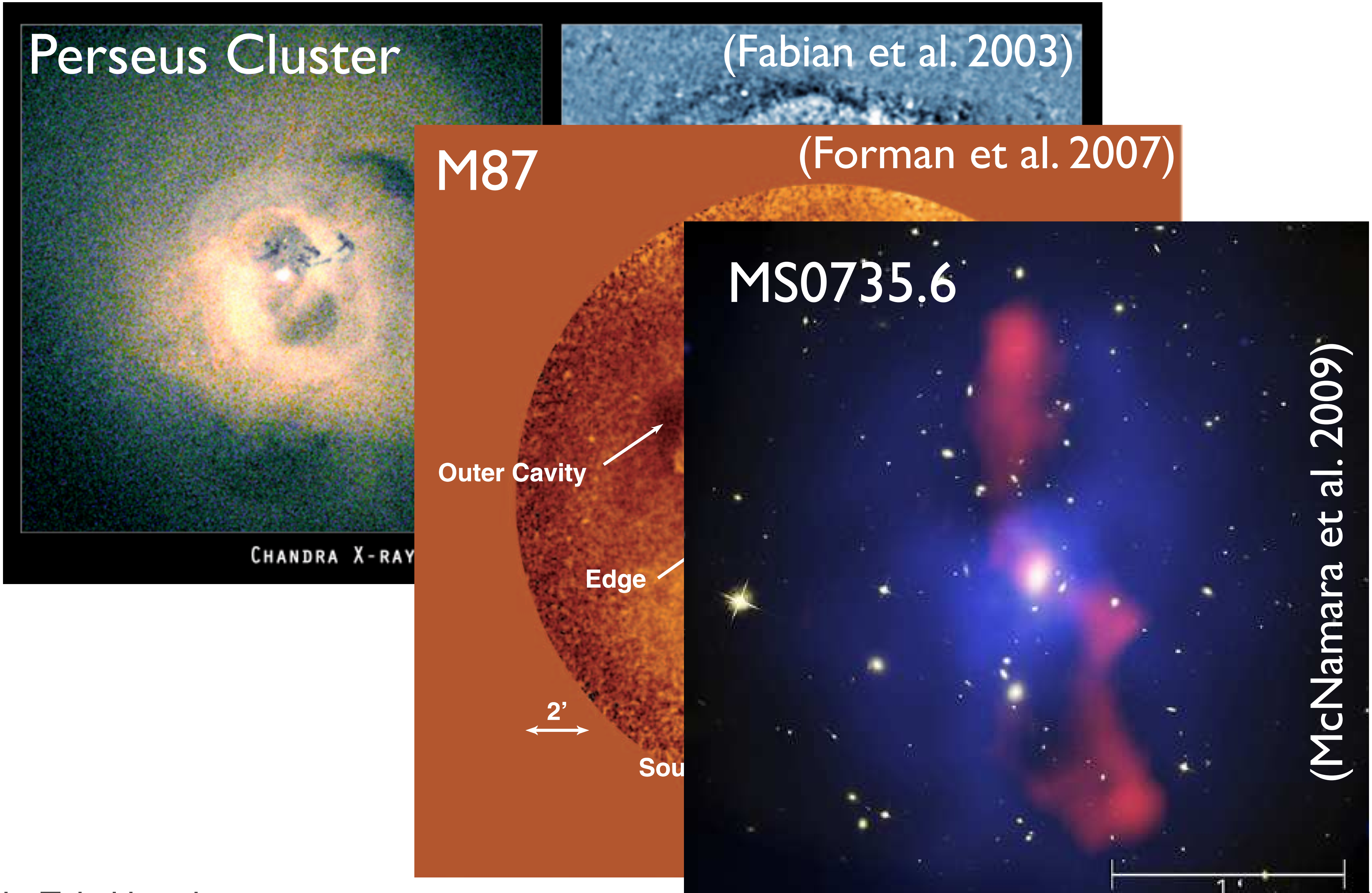
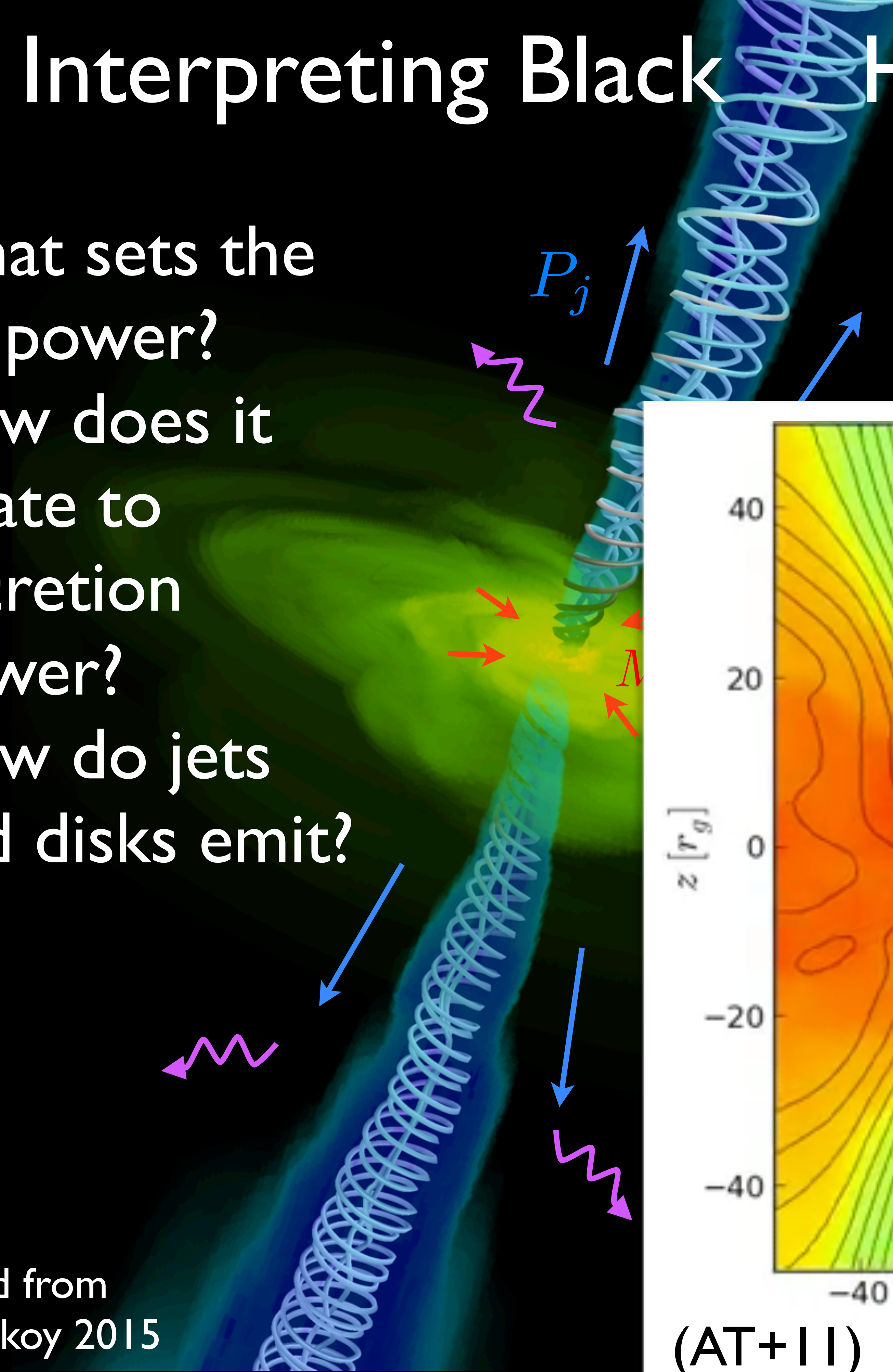


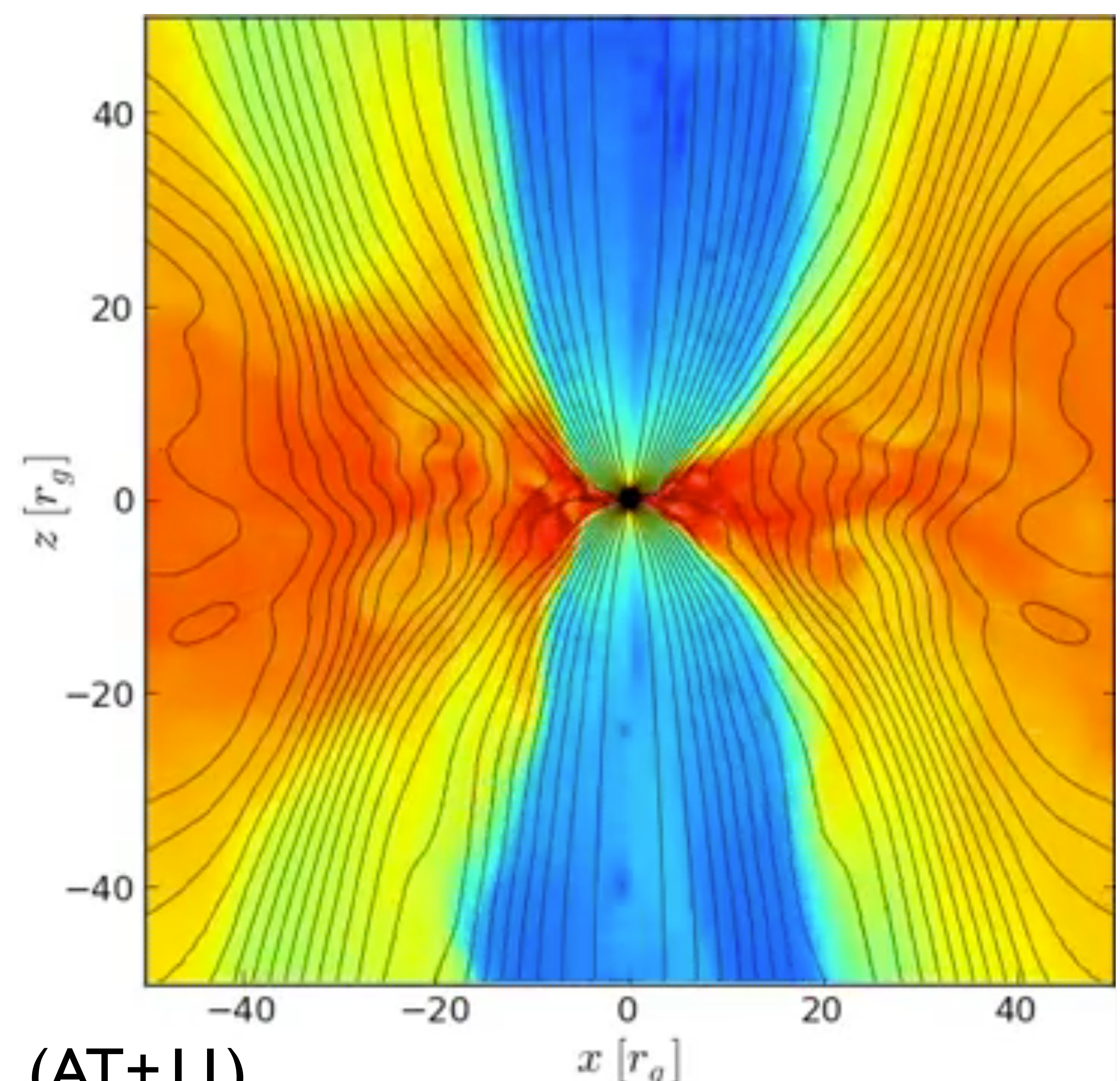
Jets Affect Galaxies/Clusters



Interpreting Black Hole Observations

- What sets the jet power?
- How does it relate to accretion power?
- How do jets and disks emit?





(AT+11)

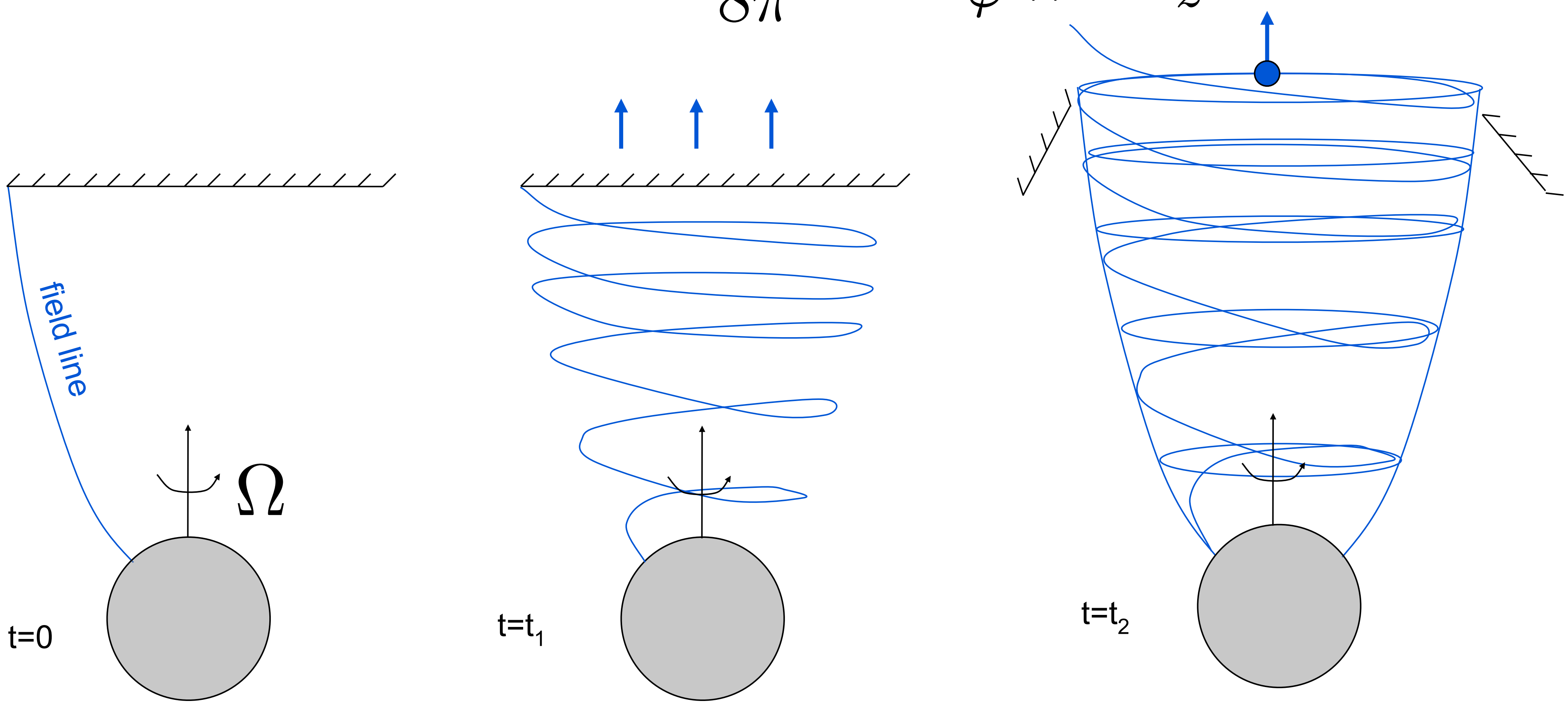
Adapted from
Tchekhovskoy 2015

Jets 101

$$P = \frac{B_\varphi^2}{8\pi}$$

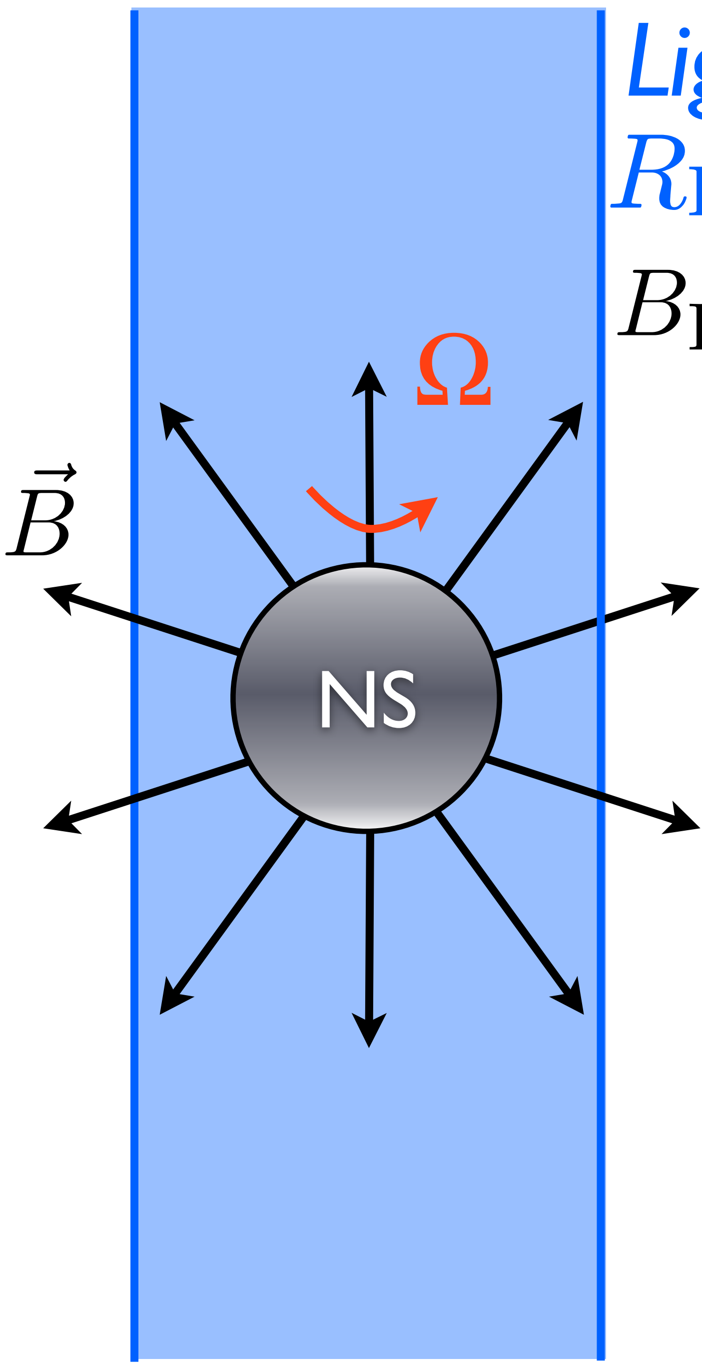
Field toroidally-dominated

$$B_\varphi \gg B_z$$



(Beskin & Nokhrina 06, Komissarov 07-10, AT+08,09,10,12, Lyubarsky 10, AT 15)

What Powers Outflow?



Light cylinder (LC):

$$R_{\rm L} = c/\Omega$$

$$B_{\rm L} = \Phi/2\pi R_{\rm L}^2$$

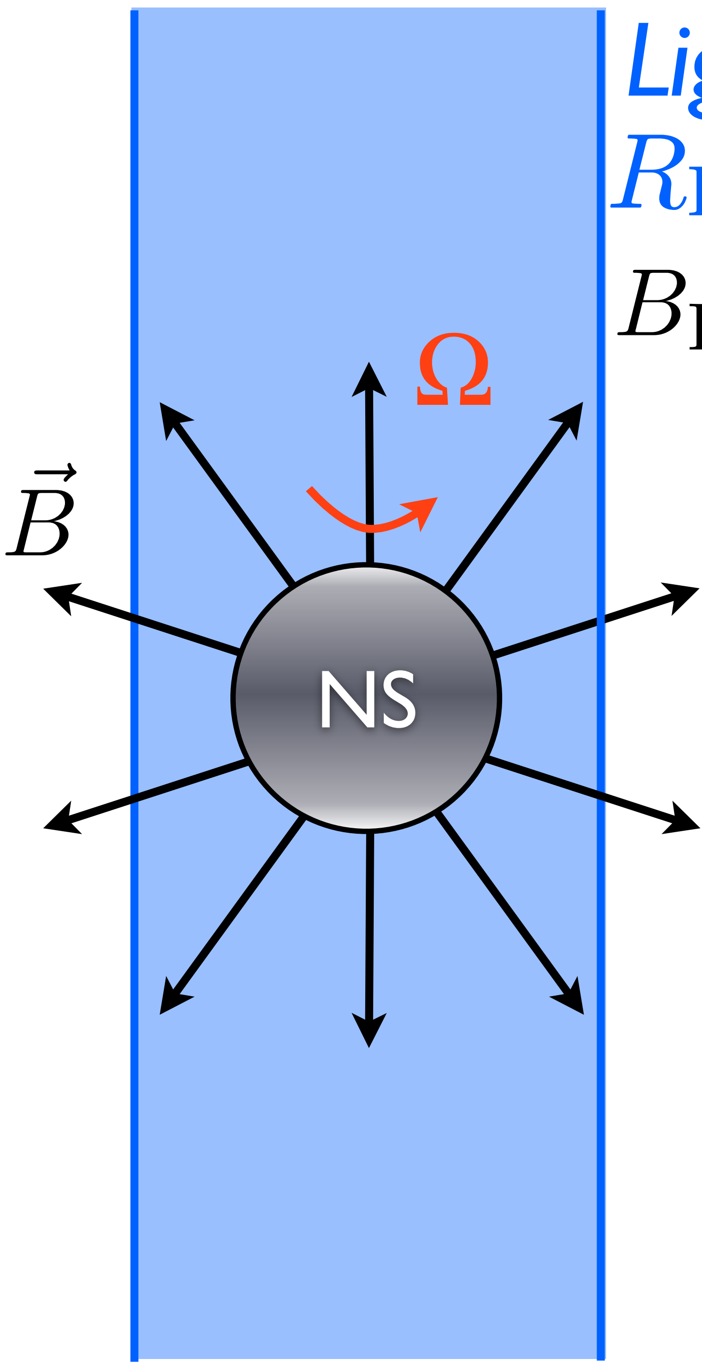
- Flow separates from NS at LC: $E_{\rm L} \sim B_{\rm L}$
- Spindown power

$$P \sim \frac{c}{4\pi}(\vec{E}\times\vec{B}) \times 4\pi R_{\rm L}^2 = cB_{\rm L}^2 R_{\rm L}^2$$

$P \sim$ as a function of Φ, Ω ?

Let's try to compute it!

What Powers Outflow?



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$$P \sim \frac{1}{6\cancel{4}\pi^2 c}\Phi^2\Omega^2$$

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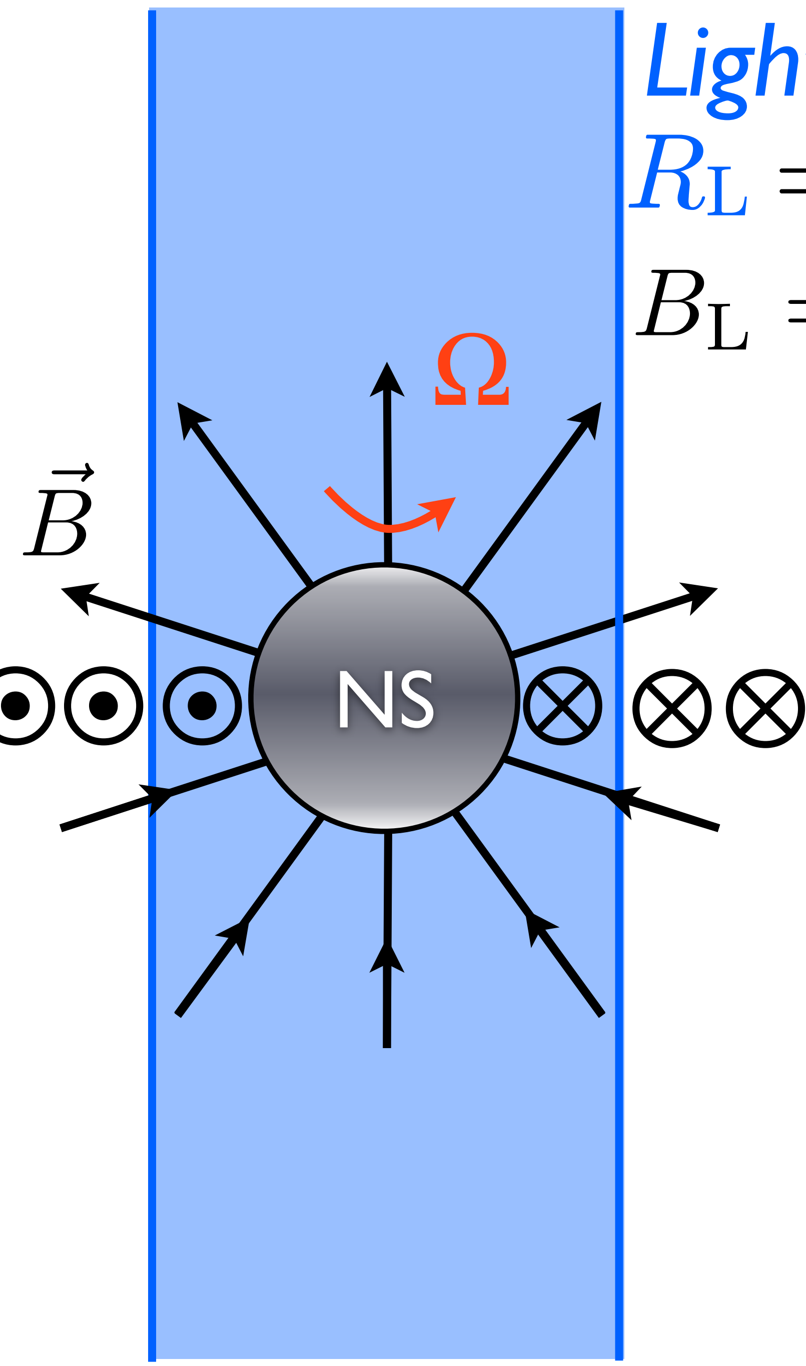

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- Split-monopole
- What about black holes?

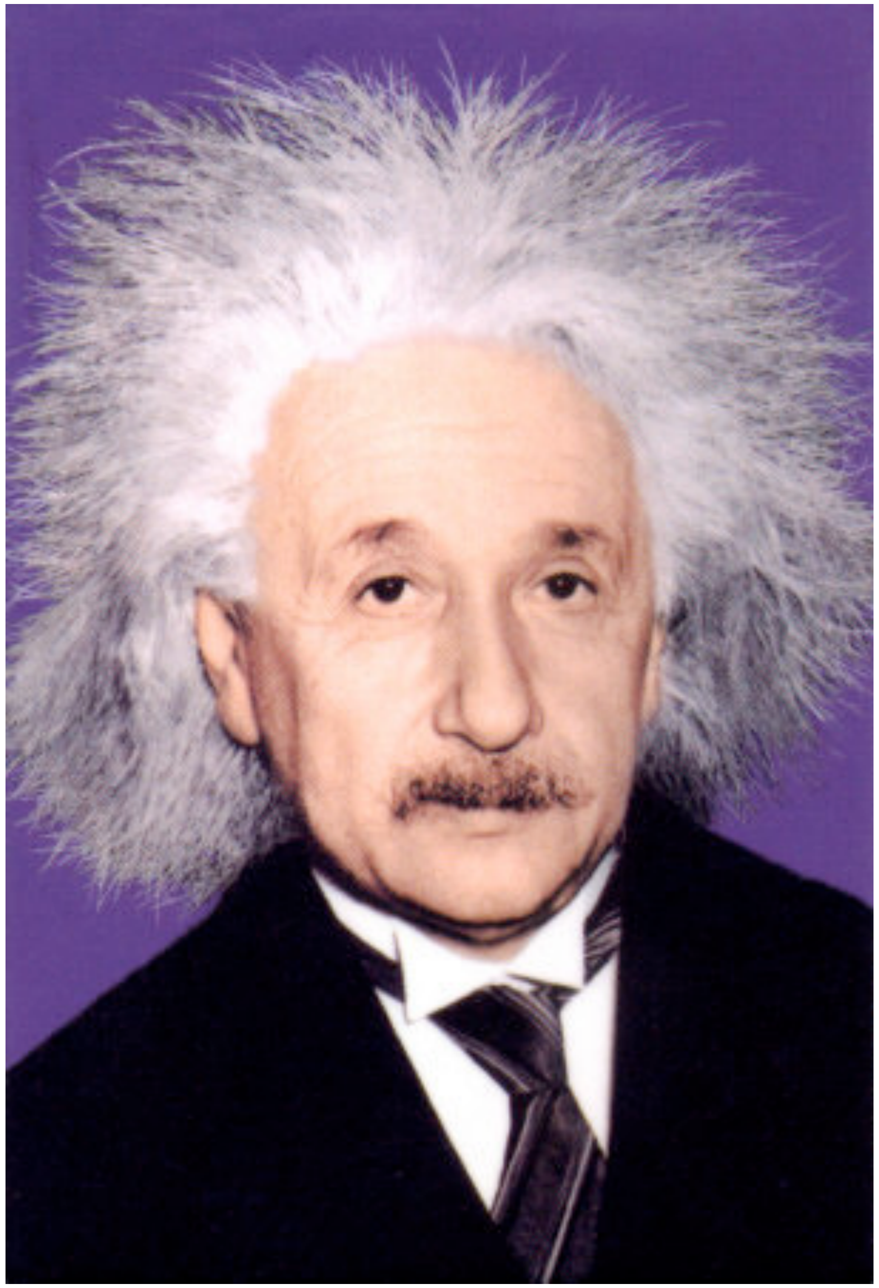
Slide: R. Narayan

A Black Hole is VERY Simple

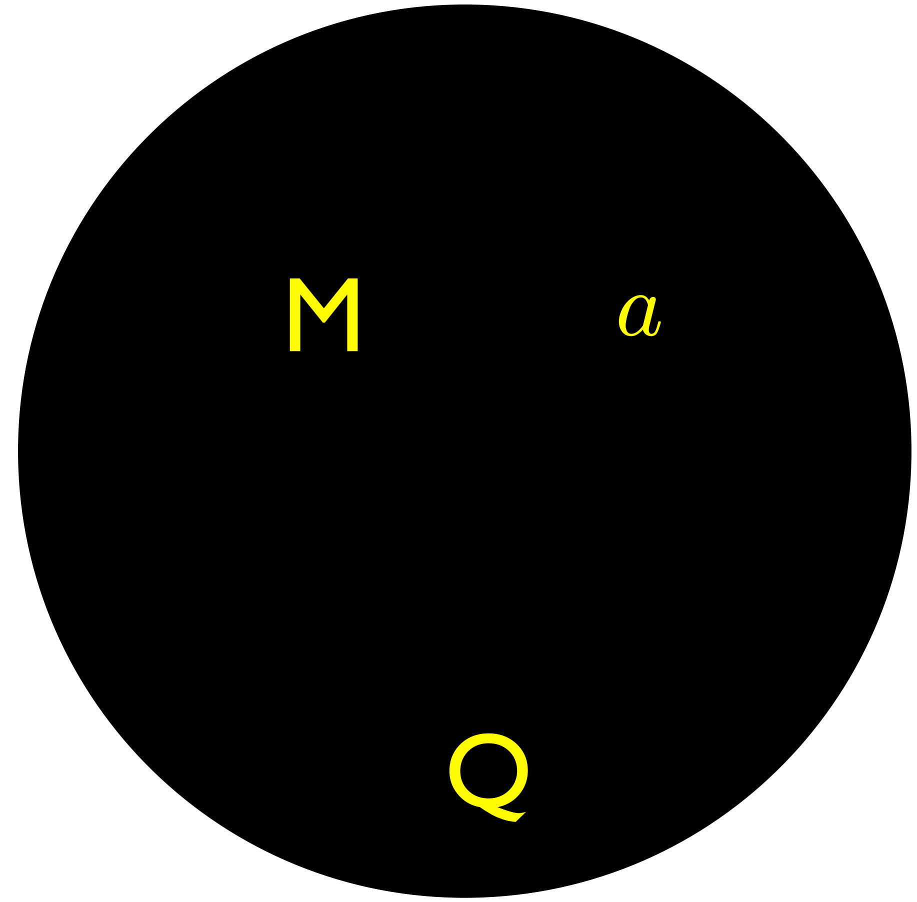
- Mass: **M**
- Spin: a **(J=a GM²/c)**
- ~~Charge: Q~~

A Black Hole has no Hair! (No Hair Theorem)
To be precise, a BH has 2 (at most 3) hairs

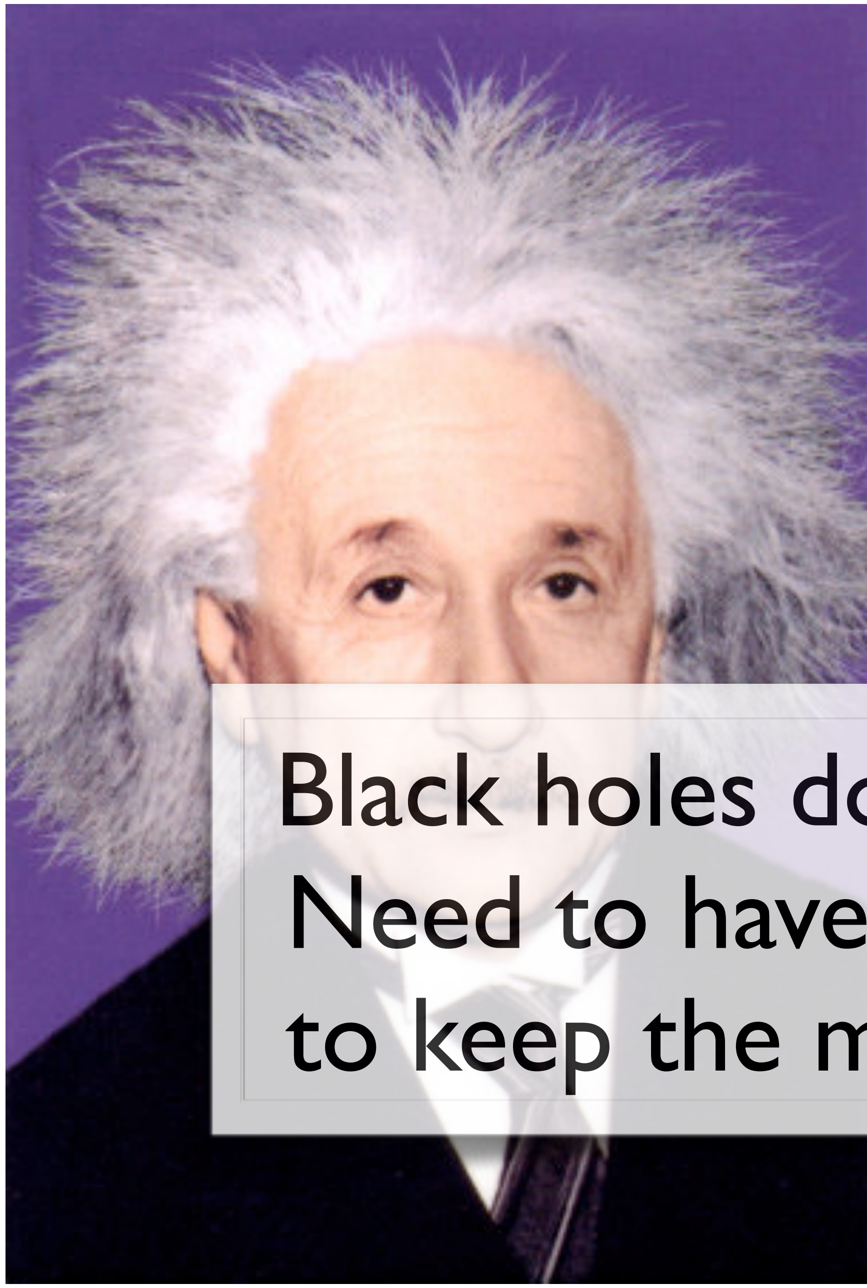
Slide: R. Narayan



Einstein had a lot of hair!



Black Hole has **3** hairs!

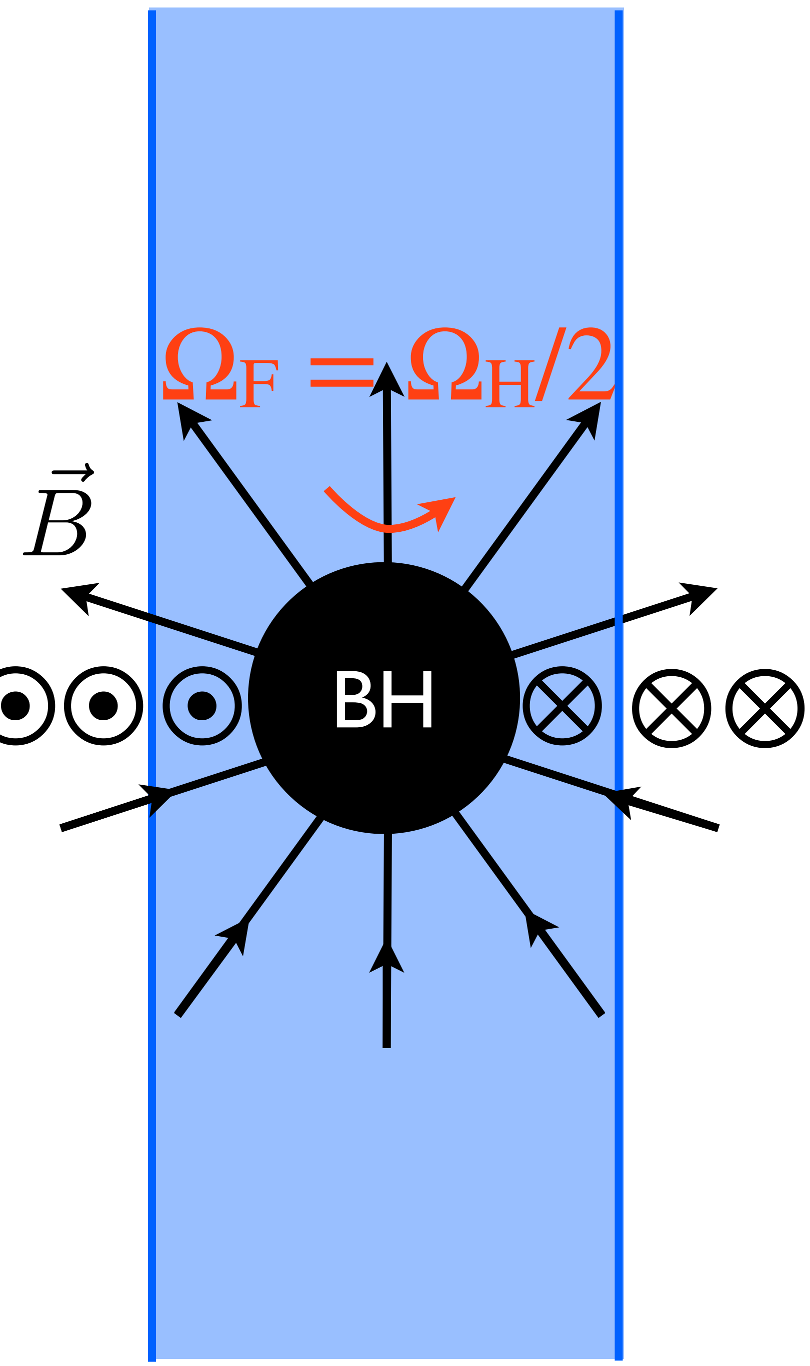


Black holes do not have magnetic hair. Need to have currents *outside* the BH to keep the magnetic field on the BH.

Einstein had a lot of hair!

A **Black Hole** has only **2** hairs

What about Black Holes?



- Black hole drags space-time at

$$\omega \simeq \Omega_{\rm H}(r/r_{\rm H})^{-3}, \quad \Omega_{\rm H} = ac/2r_{\rm H}$$

- At the event horizon $\omega = \Omega_{\rm H}$
- At infinity $\omega = 0$
- Field line tries to please both:

$$\Omega_{\rm F} = \Omega_{\rm H}/2$$

- Black hole behaves almost like a NS!

$$P \sim \frac{1}{6\,\cancel{4}\pi^2 c}\Phi^2\Omega_{\rm F}^2 \sim \frac{1}{24\,\cancel{16}\pi^2 c}\Phi^2\Omega_{\rm H}^2$$

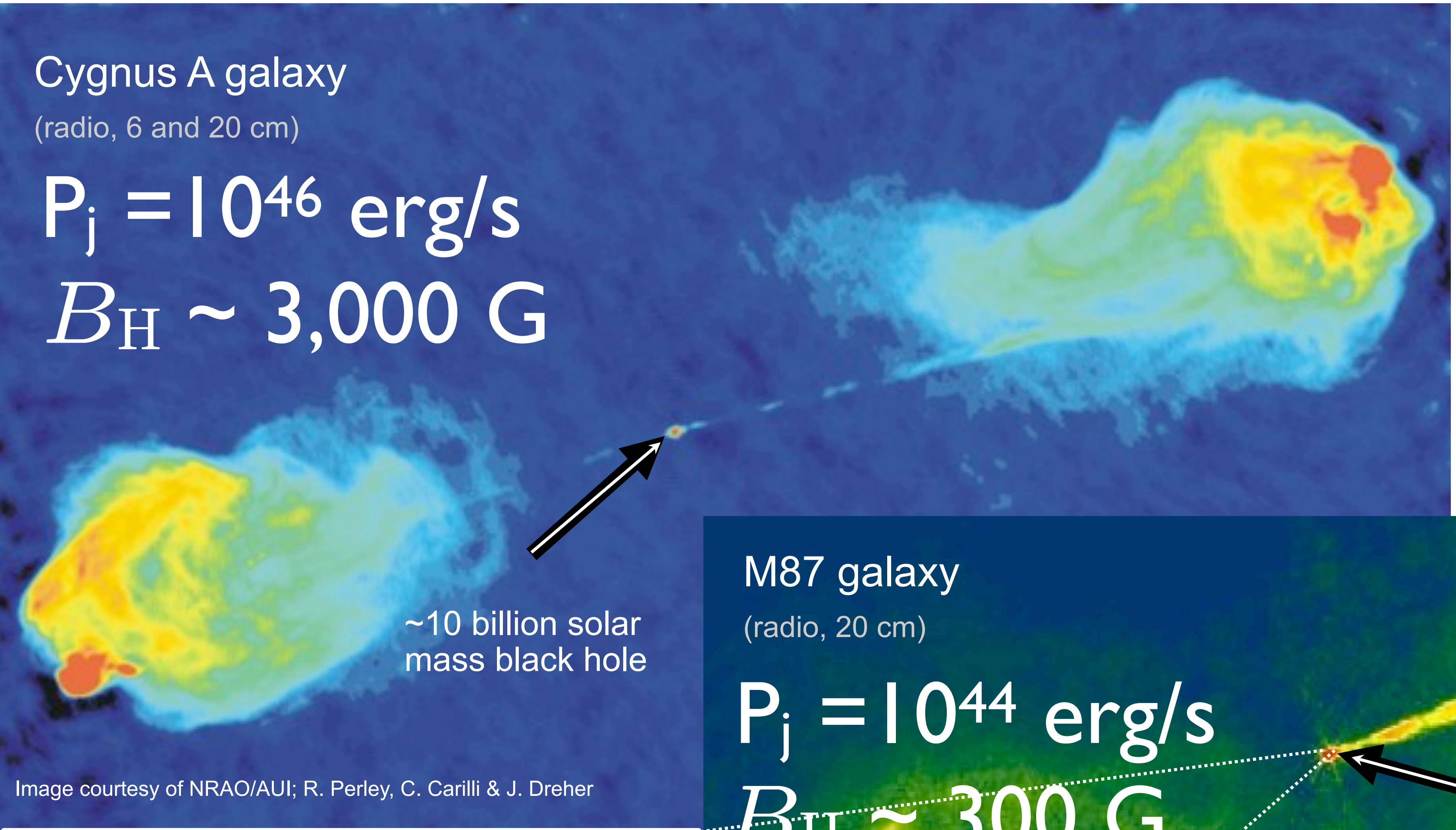
- Blandford-Znajek (1977) process!

(~10% corrections for other field geometries, AT+10, AT15)

Sasha Tchekhovskoy

Magnetic Field Sets Jet Power

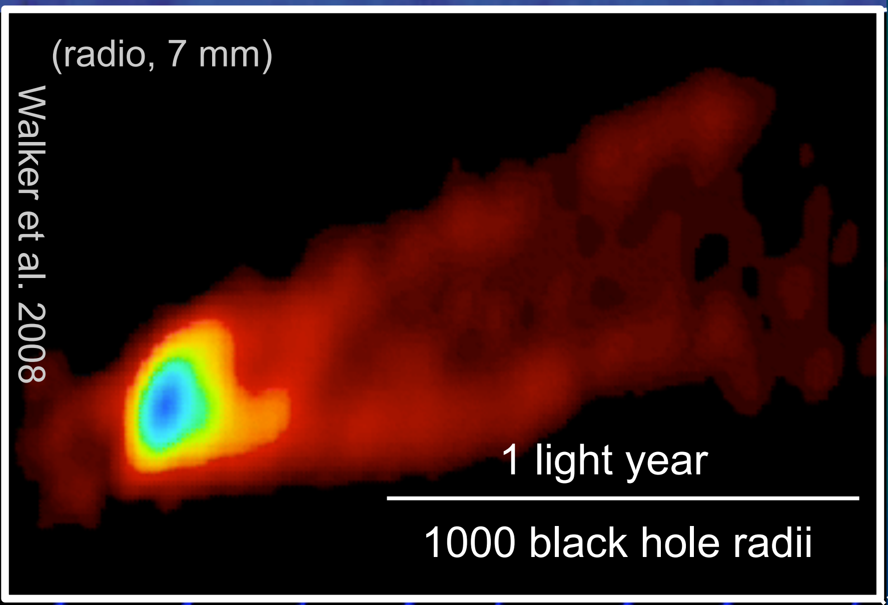
Let's Estimate the B field at the Event Horizon, $B_{\rm H}$!

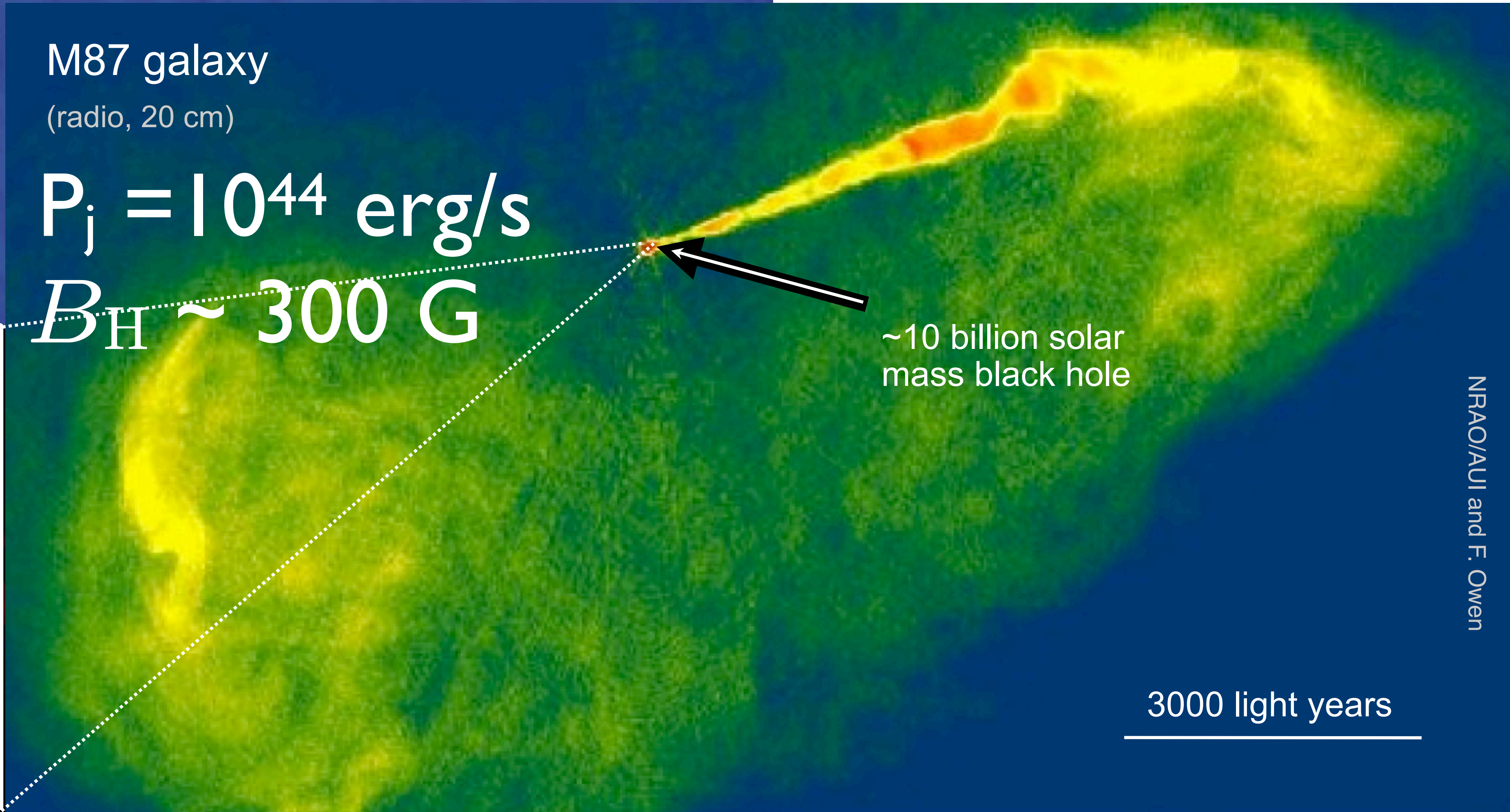


$$P \sim \frac{1}{24\pi^2 c}\Phi^2\Omega_{\rm H}^2$$

$$\Omega_{\rm H} = \frac{ac}{2r_{\rm H}}$$

$$\Phi \sim 2\pi r_{\rm H}^2 B_{\rm H}$$





Give Me the Power! Differently.

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

- magnetic pressure? $(B^2/8\pi)_{BH} = (B^2/8\pi)_{DISK}$ NO
- total pressure? $(B^2/8\pi)_{BH} = P_{DISK}$ NO
- ram pressure? $(B^2/8\pi)_{BH} = \sim 10 \, (\rho c^2)_{DISK}$ YES

ux:

s:

$/c^2$

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

(Blandford & Znajek '77, AT+10)

B sub-

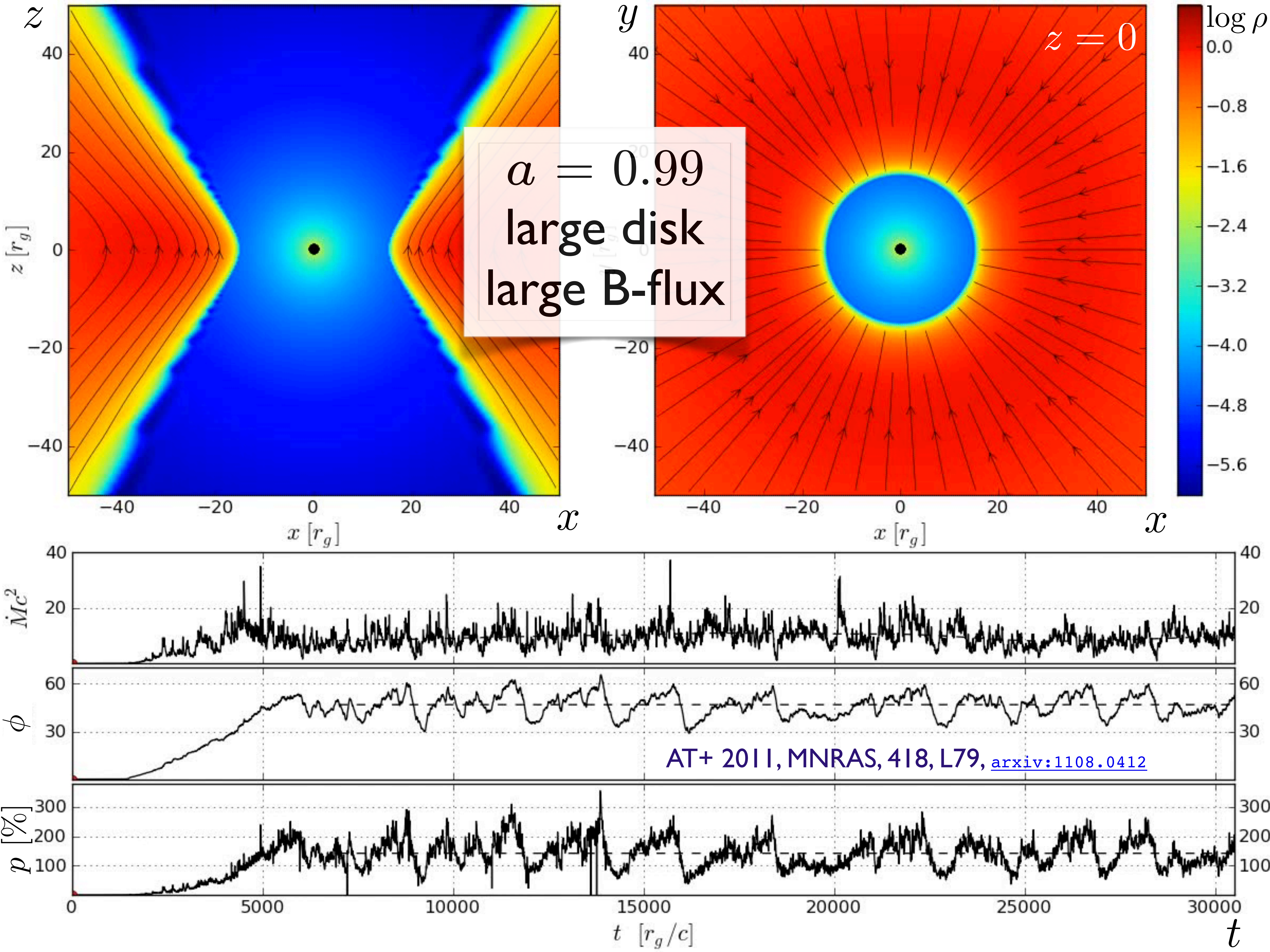
$$0 \le P_j = k\Phi^2 \lesssim \dot{M}c^2$$

B dominant
Magnetically-Arrested Disk (MAD)

(Narayan+ 2003, AT+ 2011)

What $\dot{M}$ is needed to keep M87's 300G field on the hole?

- $\dot{M}c^2 \sim 4\pi r_H^2 \times \rho c^2 \times c \sim 10^{44}$ erg/s $\sim P_j$!
- How does $\dot{M}$ compare to $P_j \sim 10^{44}$ erg/s?



$a = 0.99$
large disk
large B-flux
$z = 0$
$\log \rho$
z
y
x
t
$x\ [r_g]$
$z\ [r_g]$
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ \ [r_g/c]$
AT+ 2011, MNRAS, 418, L79, arxiv:1108.0412

Summary

- Black hole + magnetic fields = jets
- Jet power set by B-field strength
  - We computed B from P_j
- B is limited by disk weight
  - We computed $\dot{M}$ from B
- We found $P_j \sim \dot{M}c^2$ if disk is MAD and $a \sim 1$
  - more power can come out of the black hole than come in!
- How do jets accelerate?