What sets jet power in black hole accretion systems?

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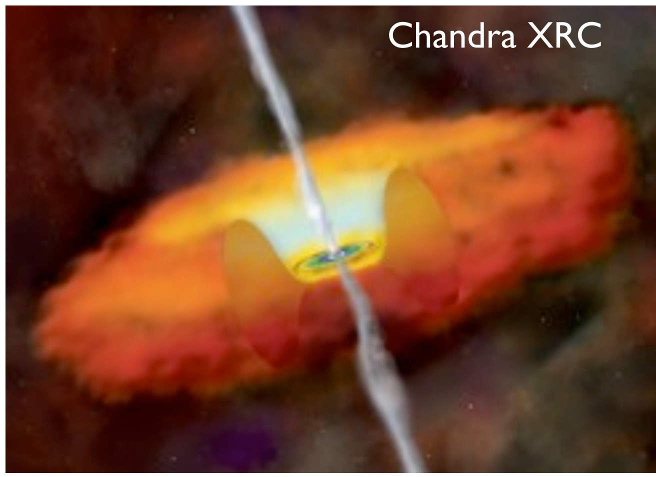
Anatoly Spitkovsky, Princeton
Mohammad Zamaninasab, MPIfR

Black Hole Jets are Everywhere

Supermassive

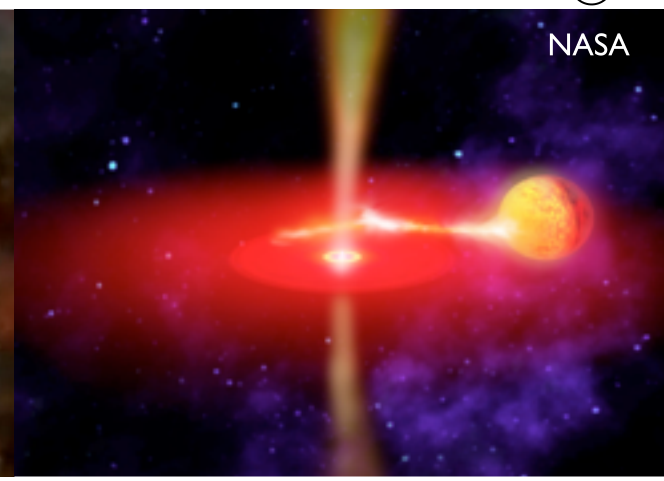
$M \sim 10^{6-10} M_\odot$



Quasars/AGN

Intermediate

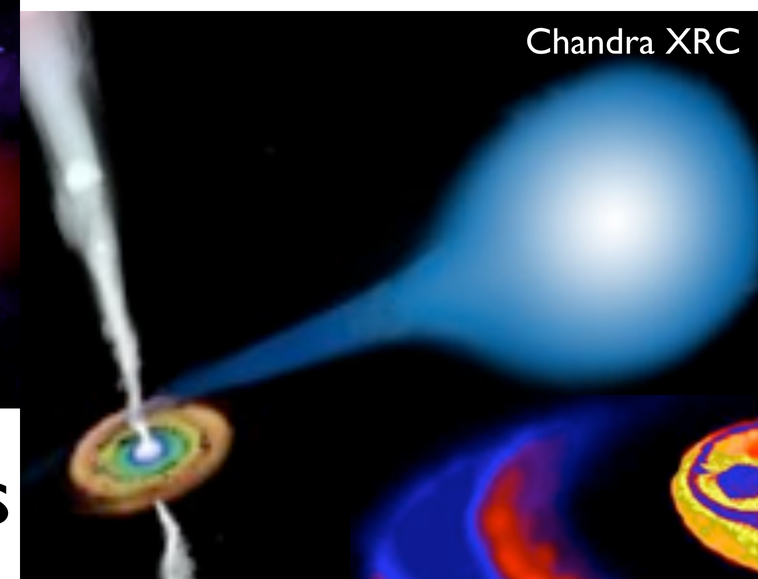
$M \sim 10^{2-5} M_\odot$



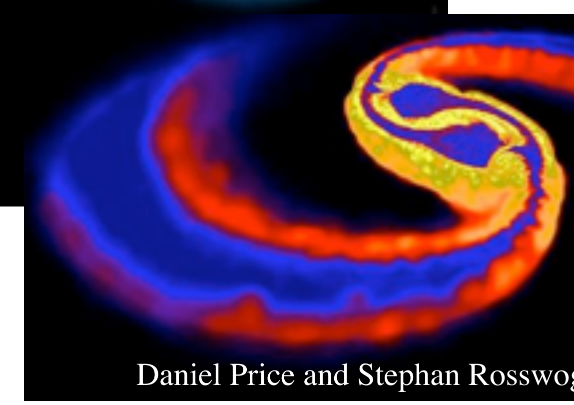
Intermediate-mass black holes/ULX?

Stellar-mass

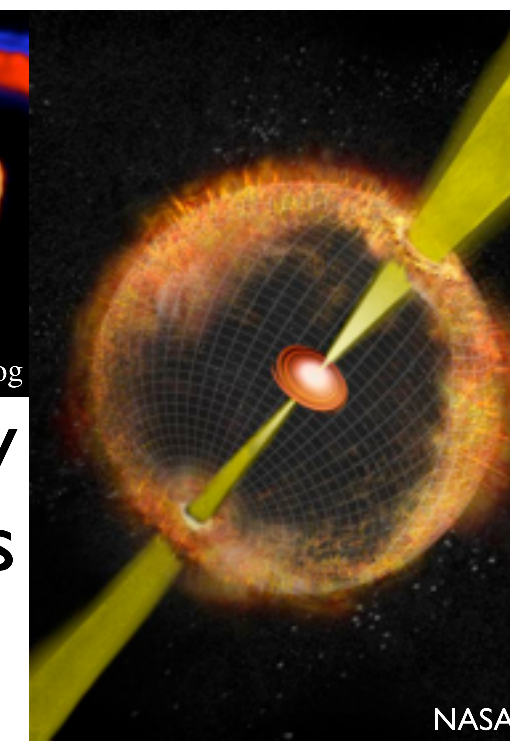
$M \sim \mathrm{few}{-}10 M_\odot$



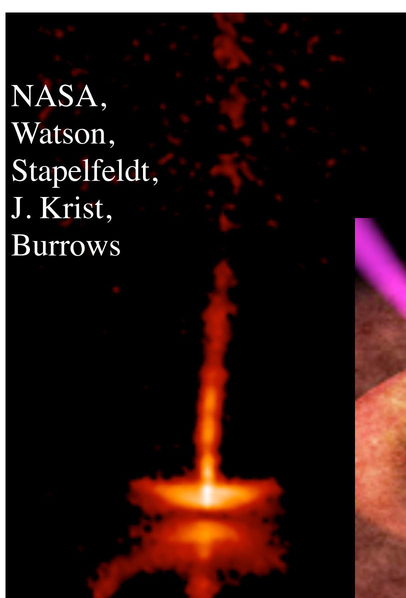
Black Hole Binaries



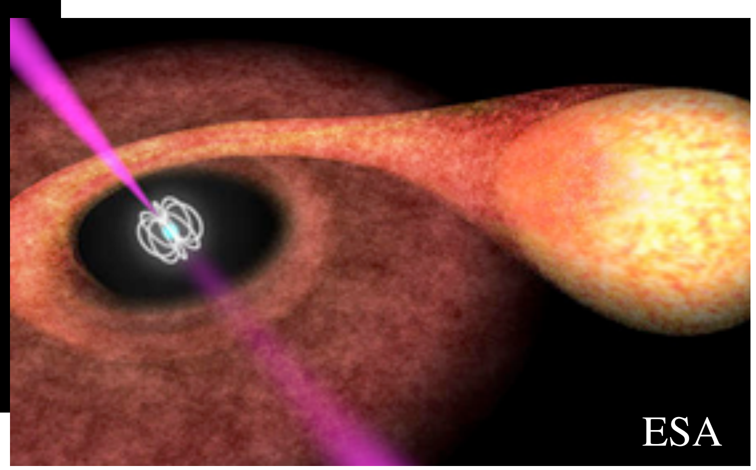
Gamma-ray bursts



Black Hole?
Neutron Star?



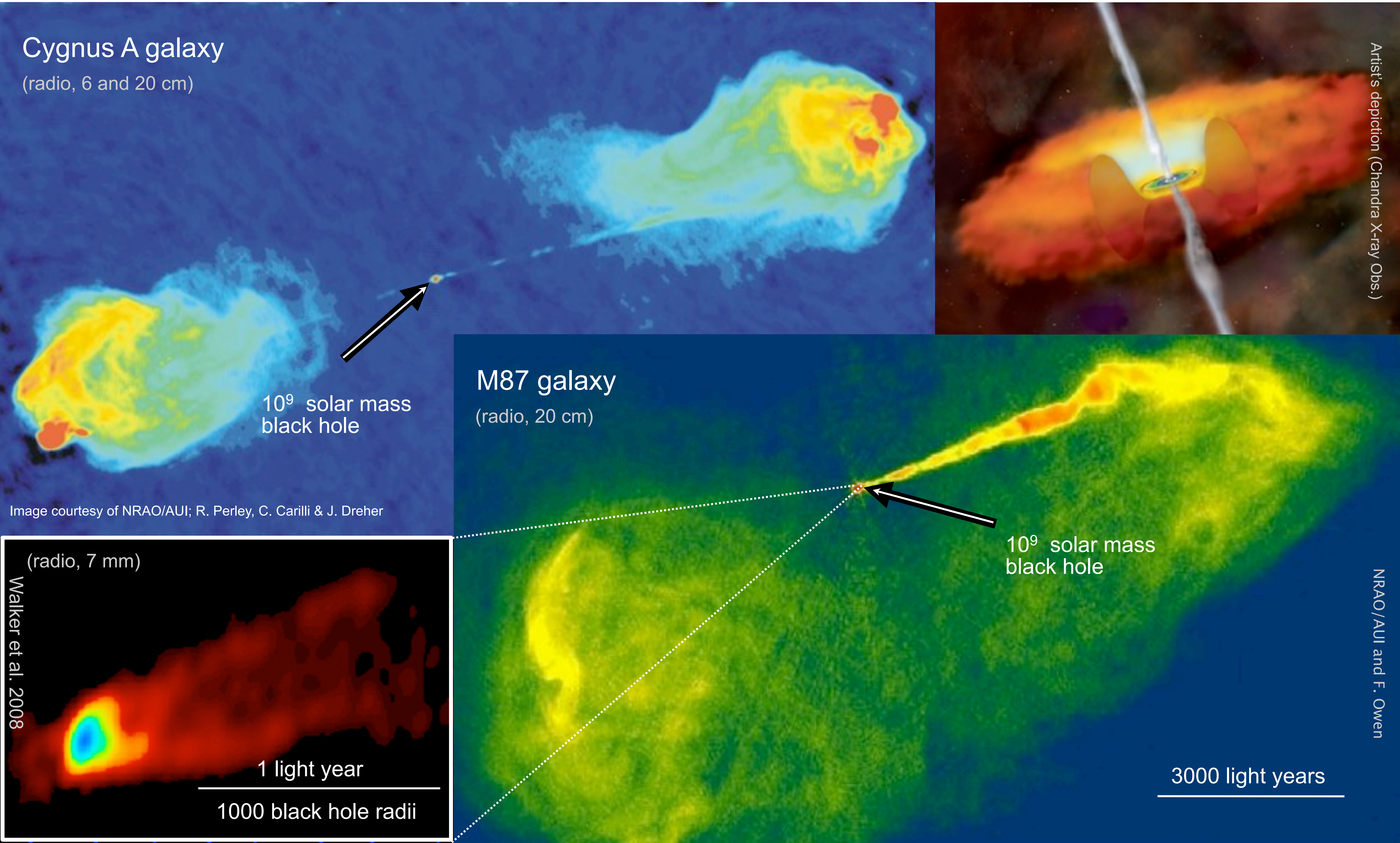
Stars



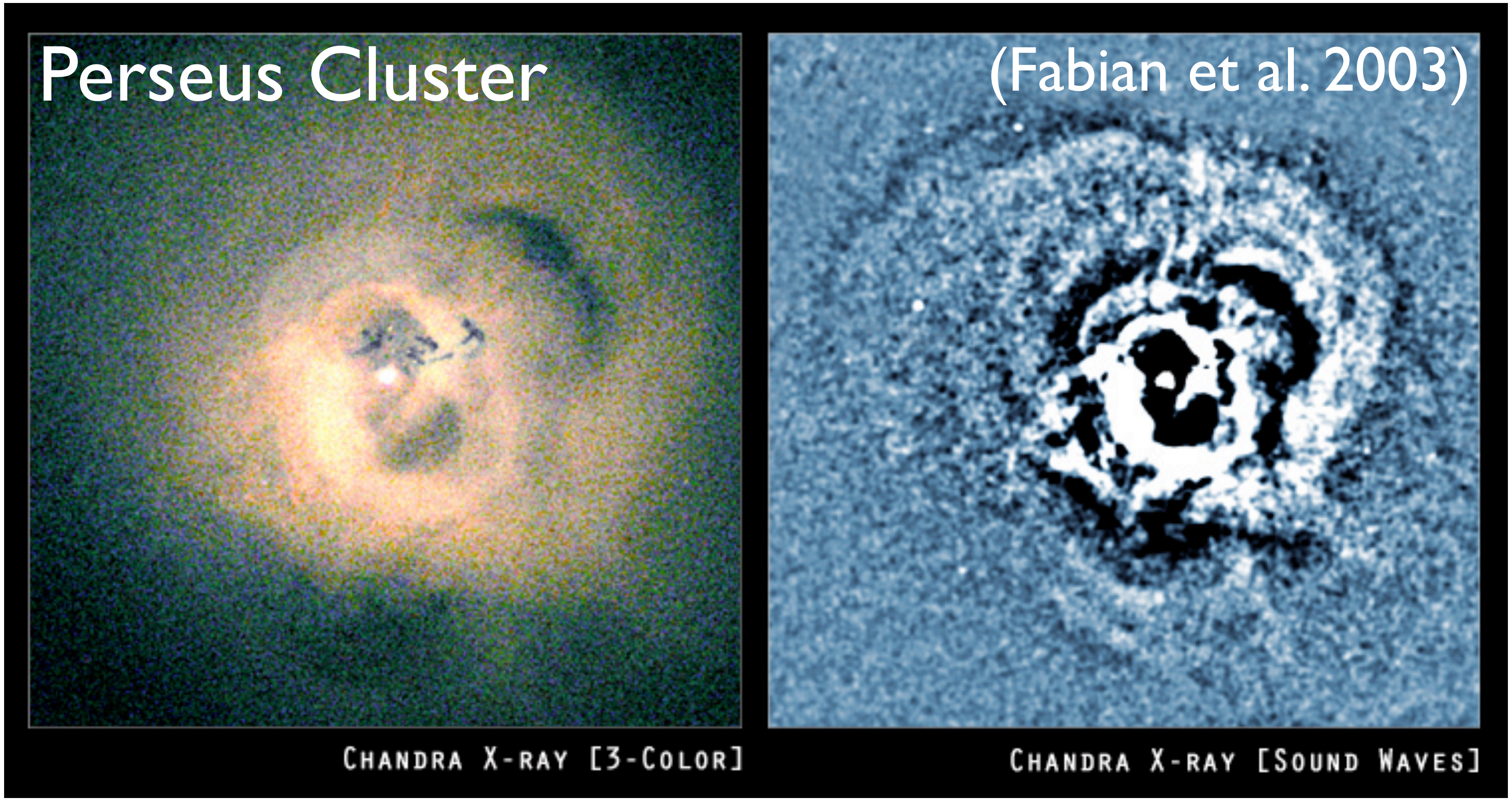
Neutron Stars, White Dwarfs

$M \sim M_\odot$

Jets: Beautiful and Challenging



Jets Affect Galaxies/Clusters



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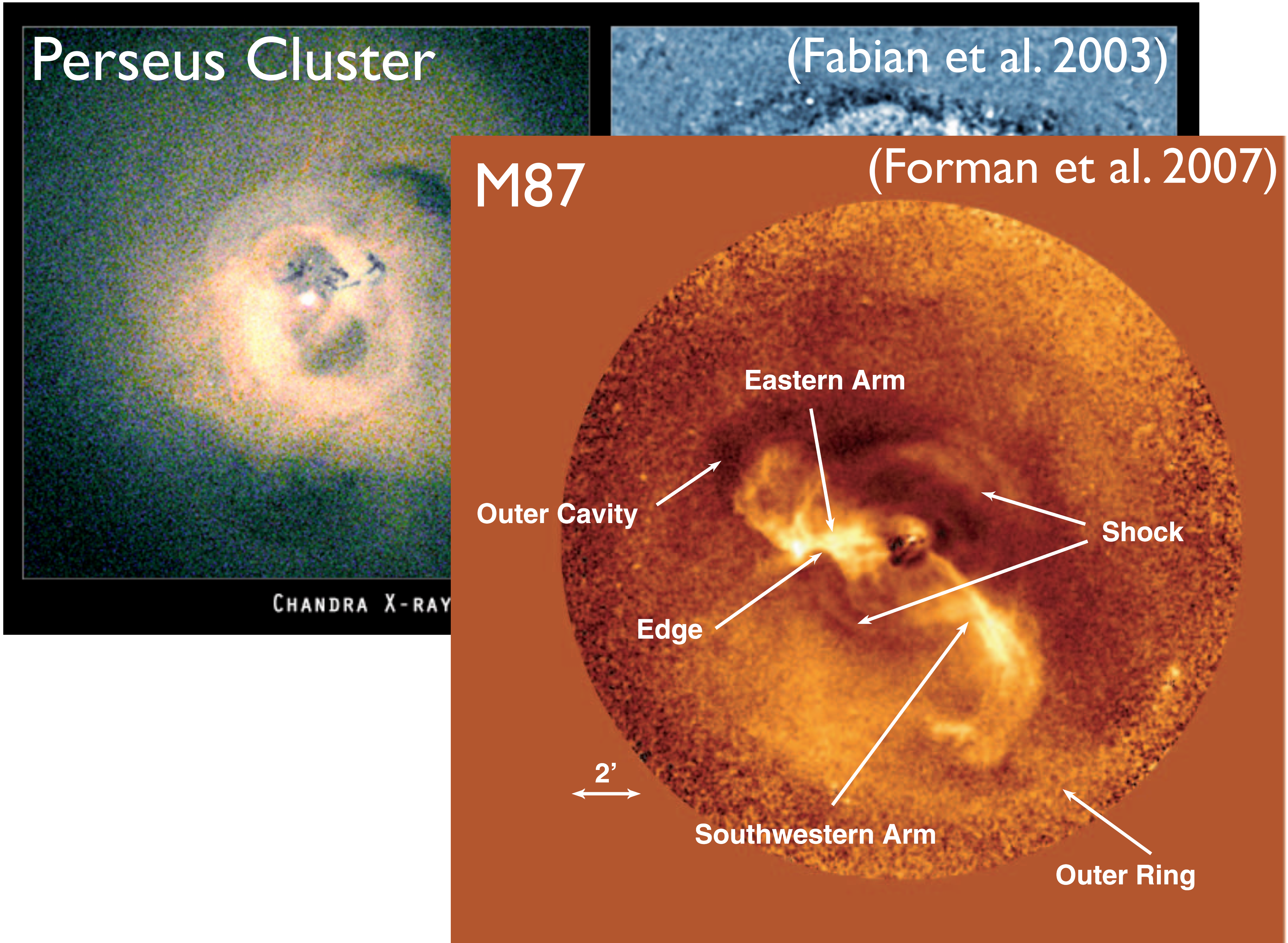

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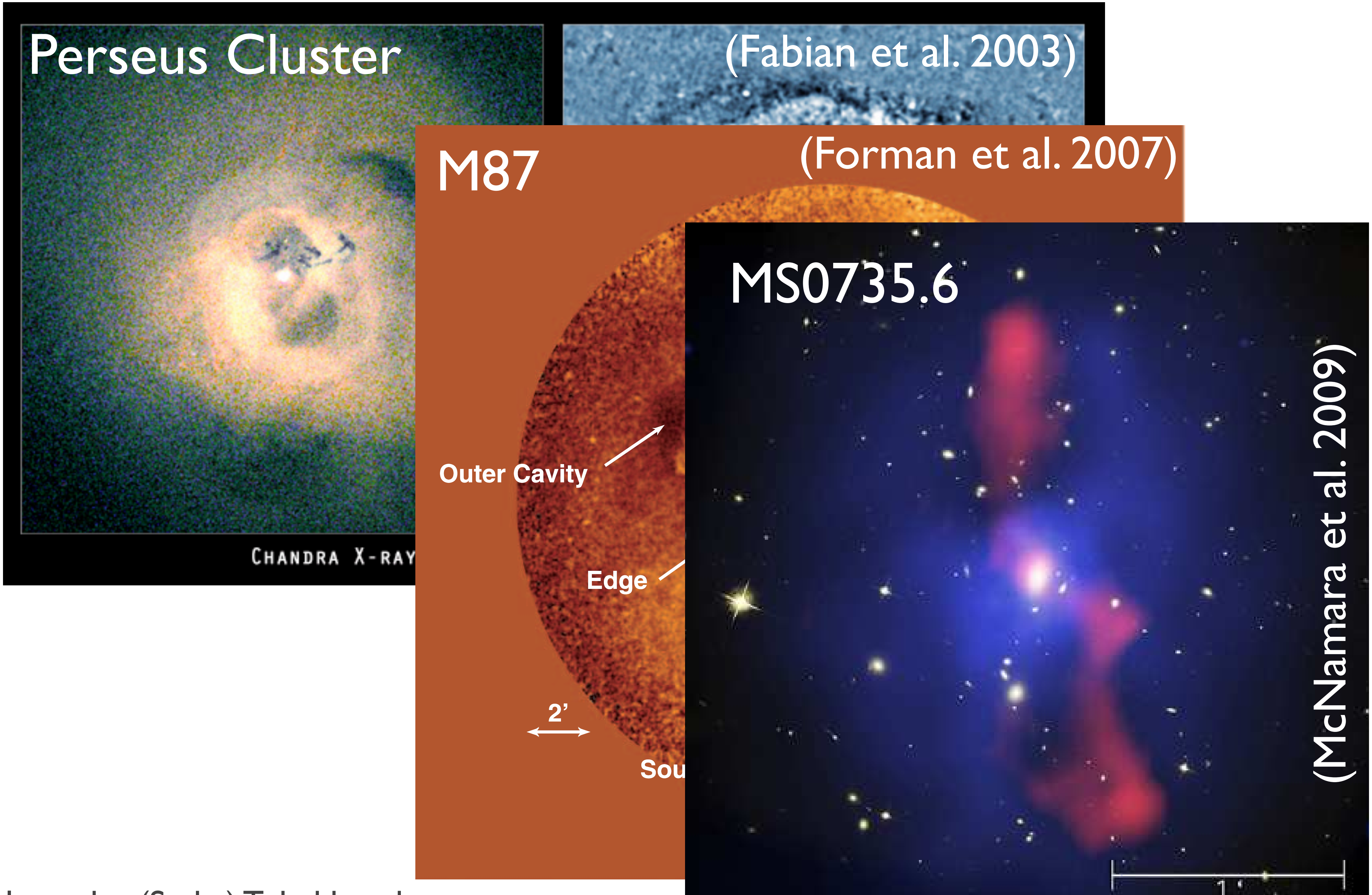
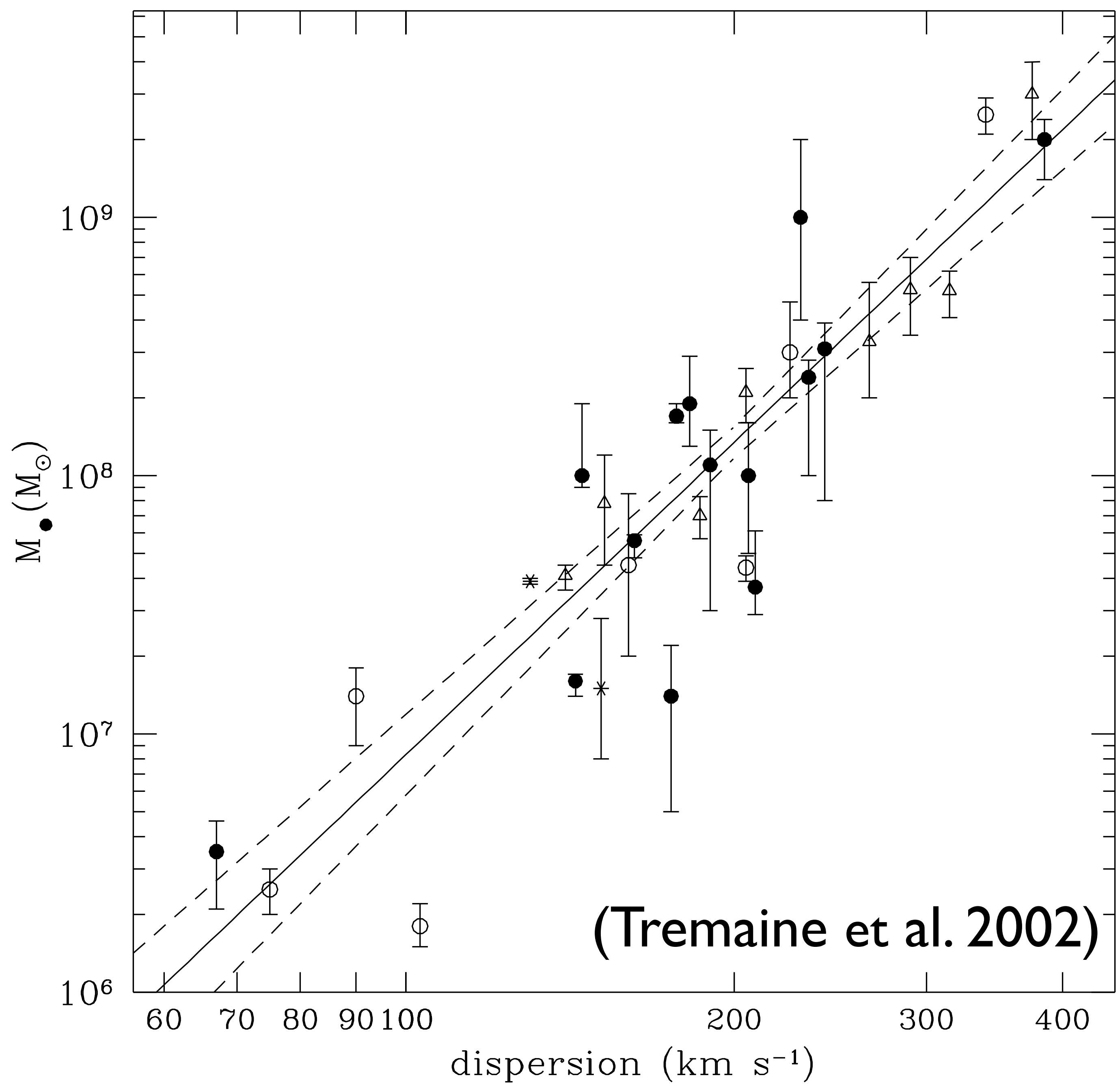


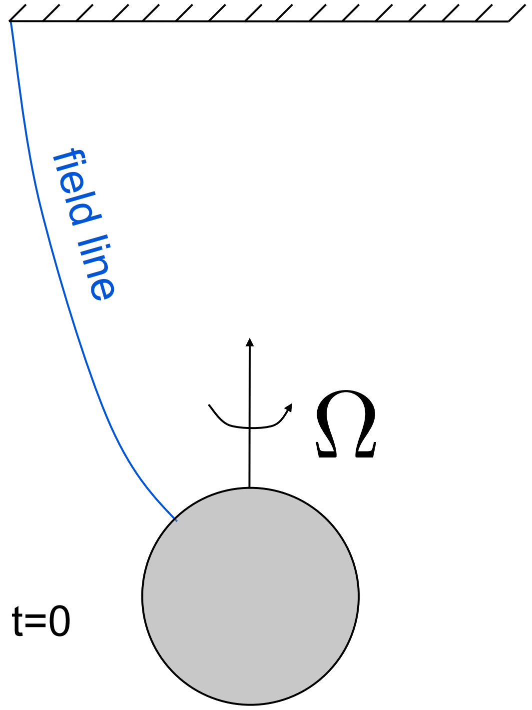
Jets Affect Galaxies/Clusters

"M-sigma" relation: BH mass and stellar velocity dispersion are correlated

- Growth of the central BHs and their host galaxies are inter-connected
- Jet feedback?
- Radiative feedback?

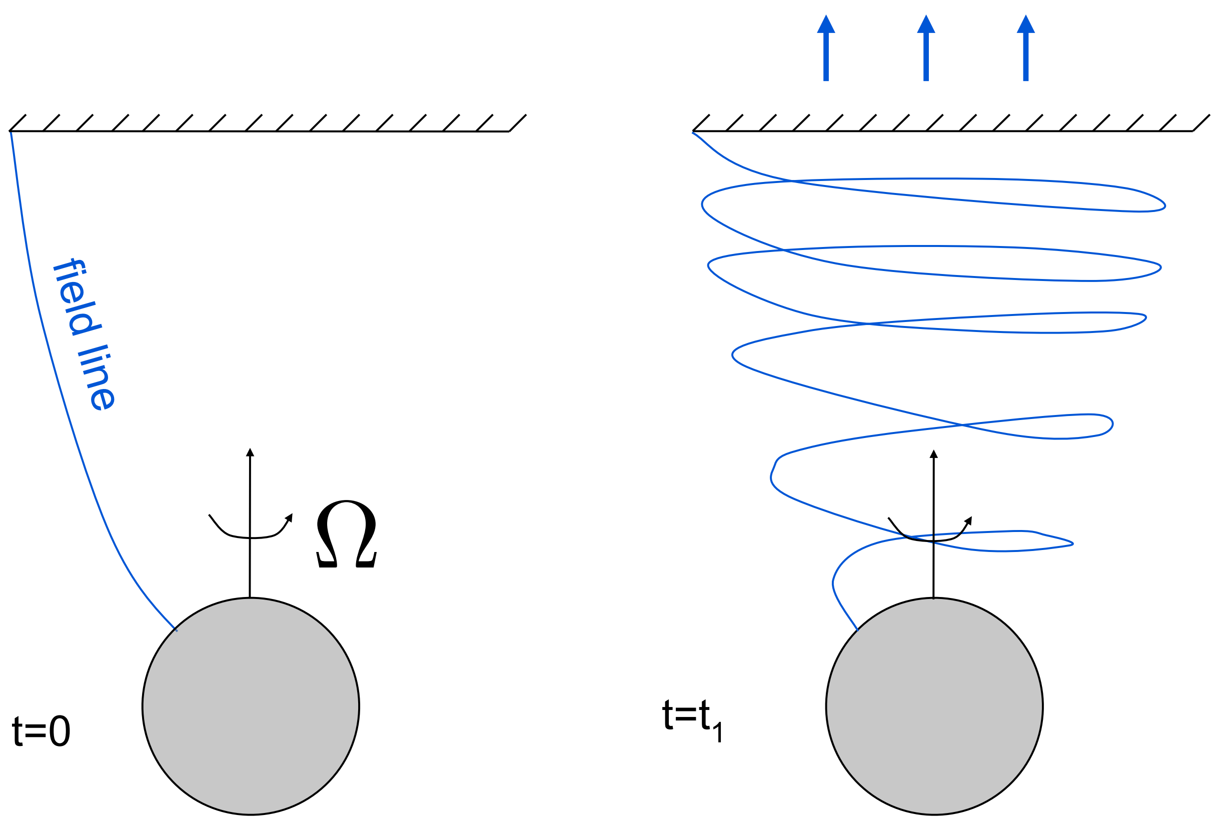


Jets 101



Jets 101

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



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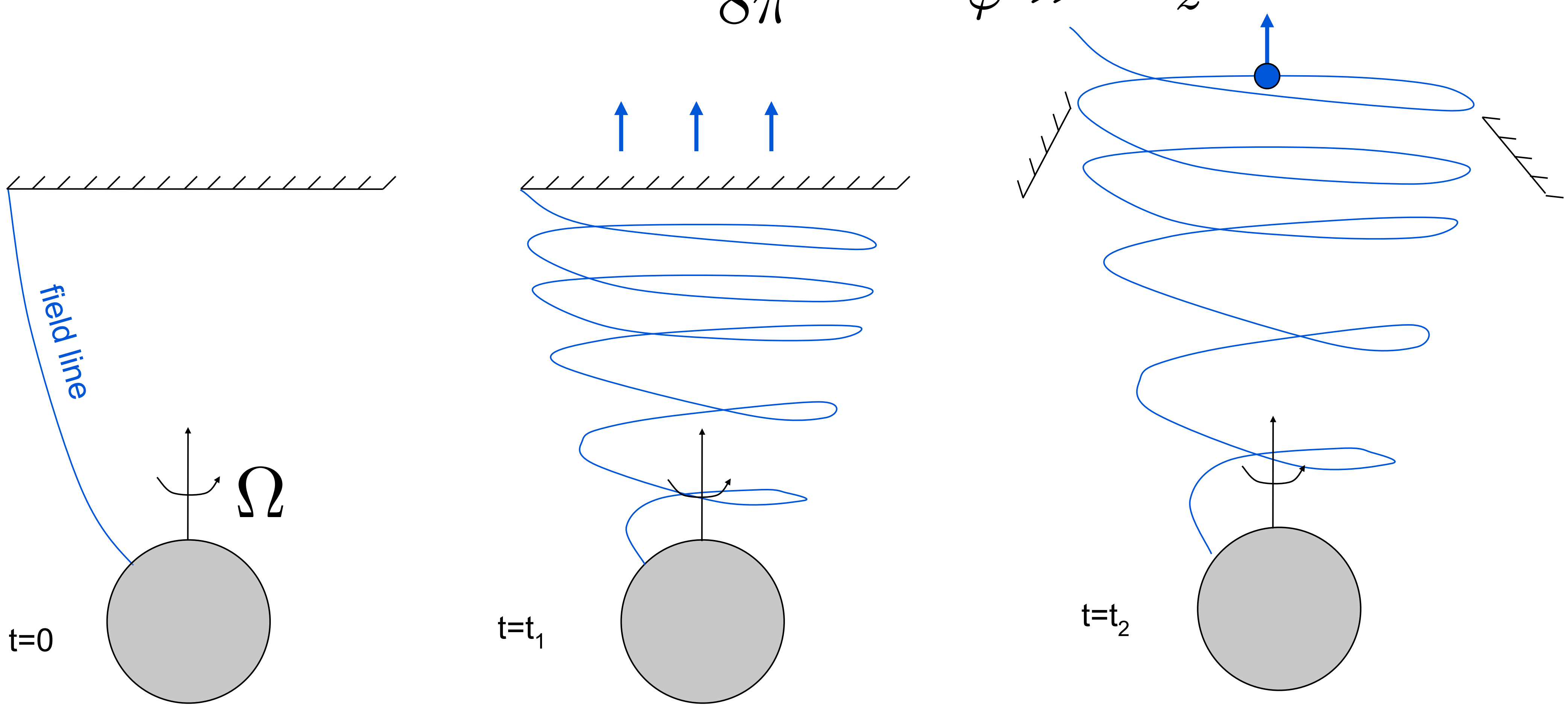
Field toroidally-dominated

$$B_\varphi \gg B_z$$



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

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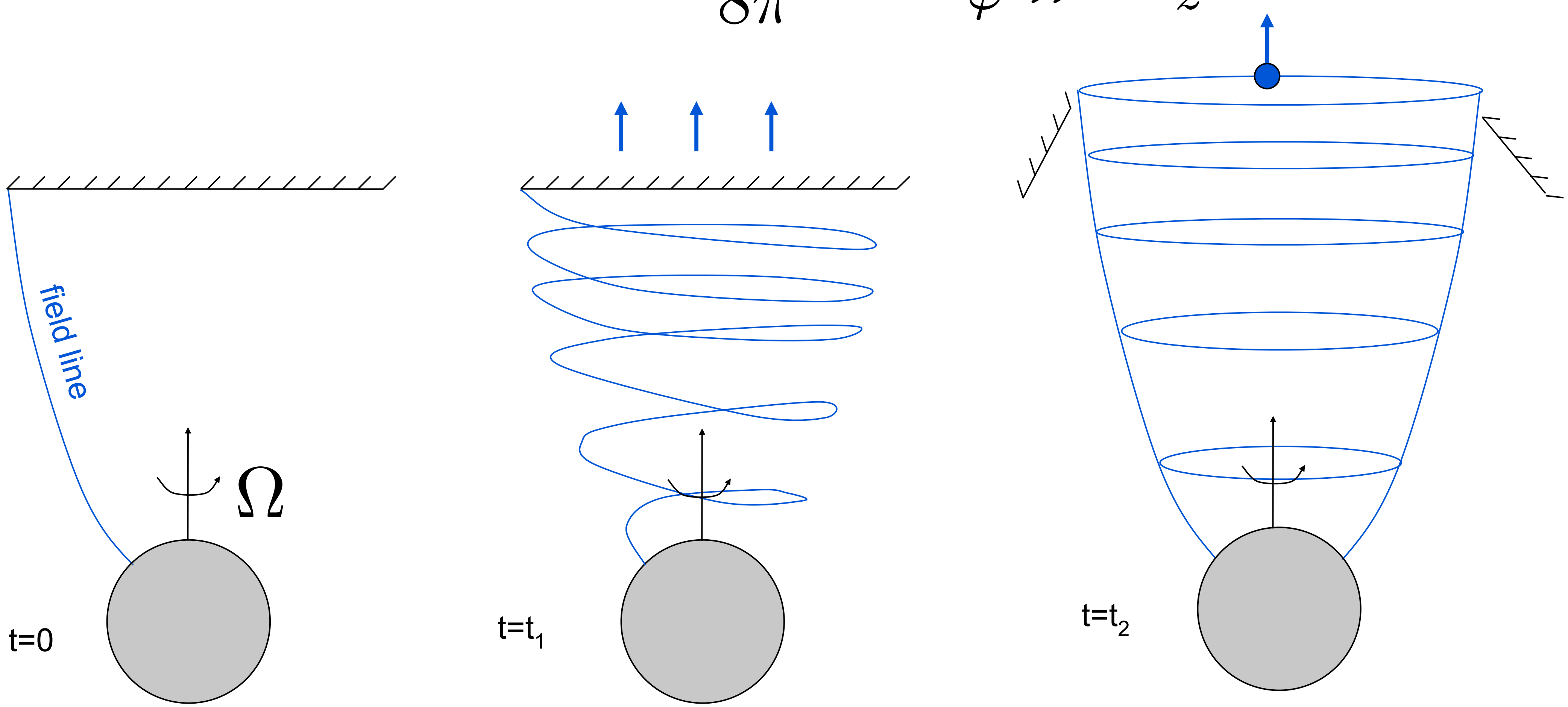

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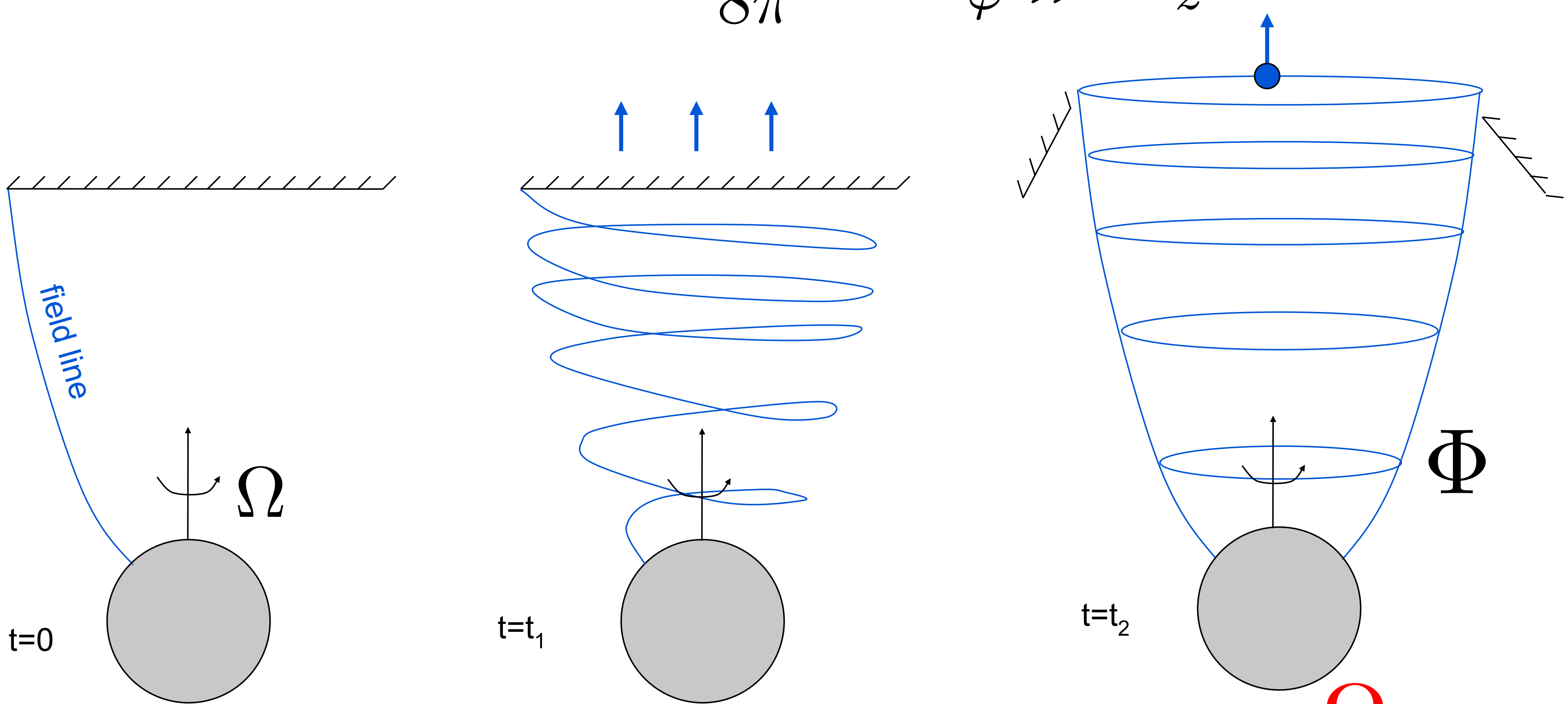

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$$\Omega_{\rm H} = \frac{ac}{2r_{\rm H}}$$

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j = \frac{k}{c}\Phi^2\Omega_{\rm H}^2$$

(Blandford & Znajek 1977,
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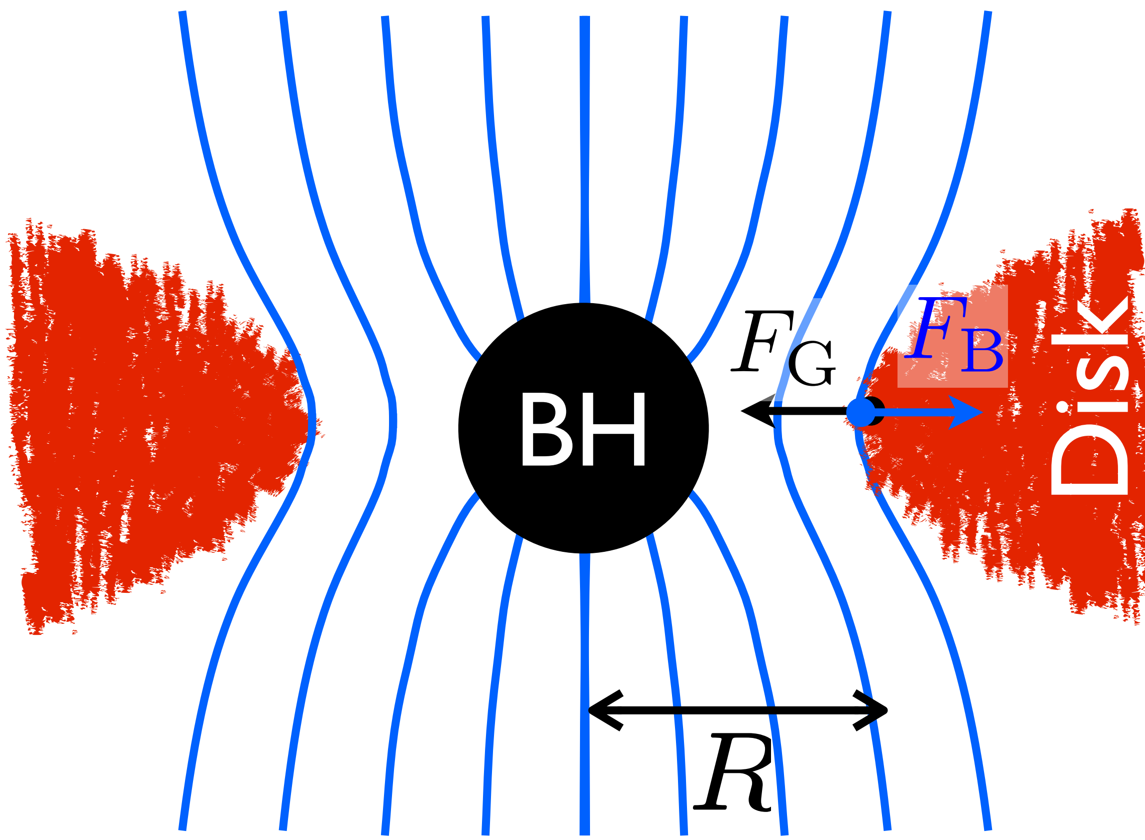
- Is $p_j = 20\%$ really the limit?
- Are larger values of p_j possible?

Gravity Sets Maximum Power

- Gravity limits BH B-field strength:

$$F_{\mathrm{B}} \lesssim F_{\mathrm{G}}$$ (Narayan+ 03)



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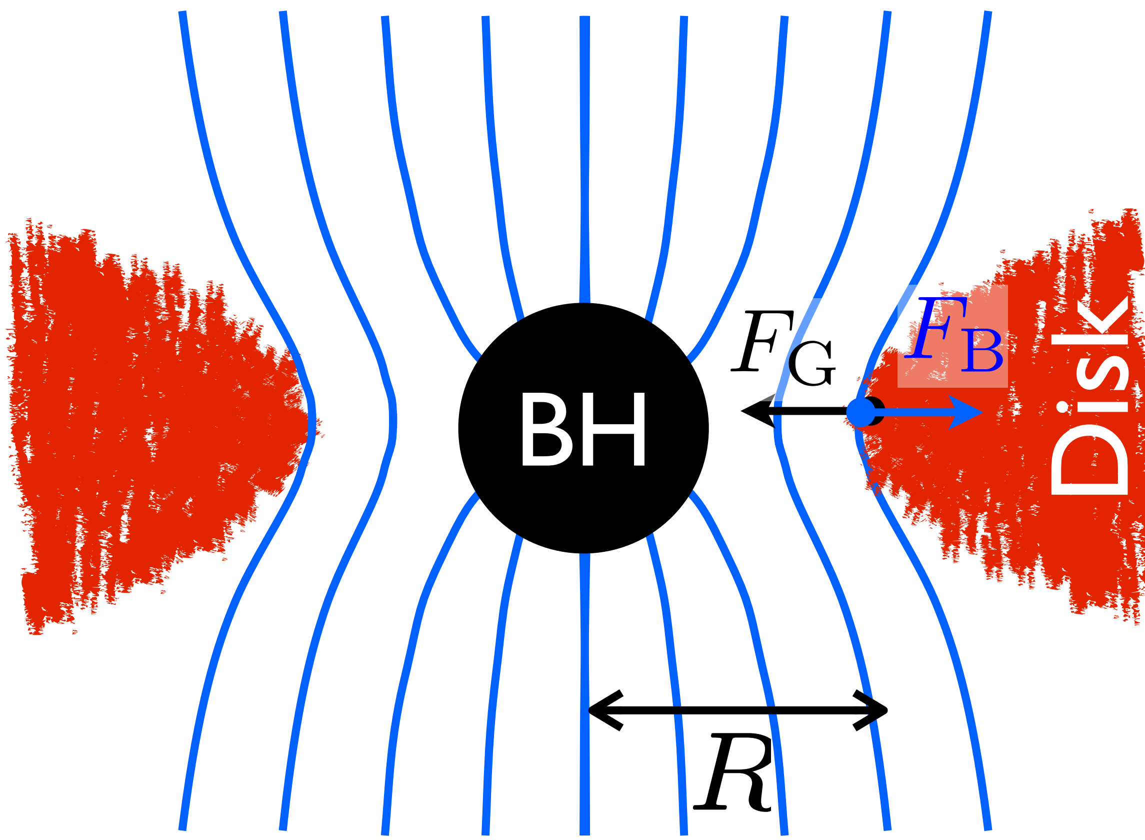

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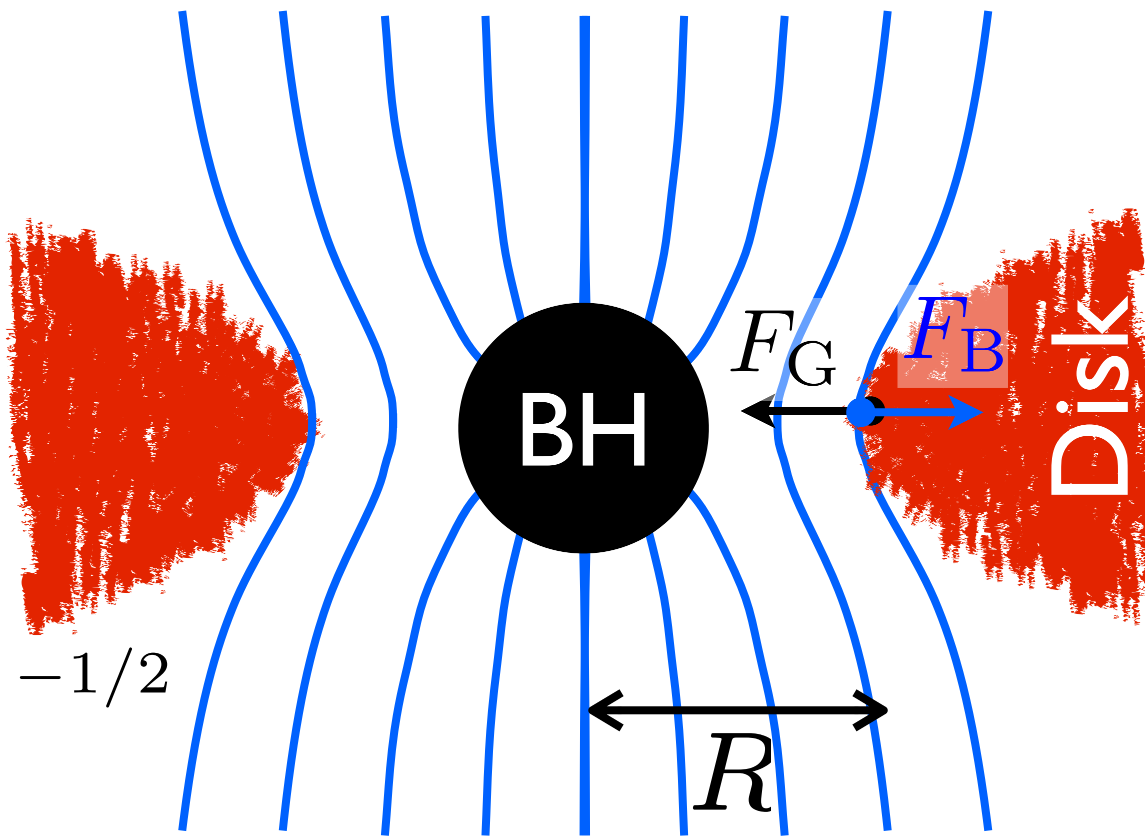

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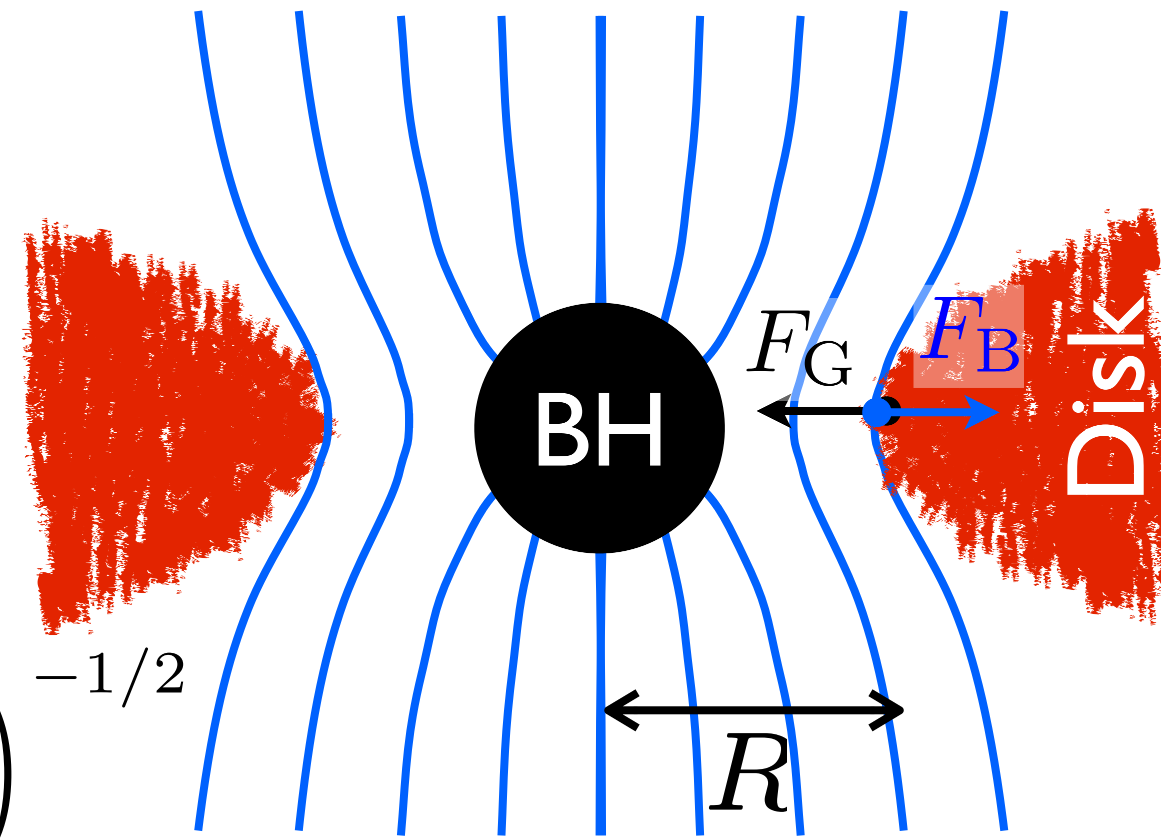

- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12,13, McKinney, AT, Blandford 12)

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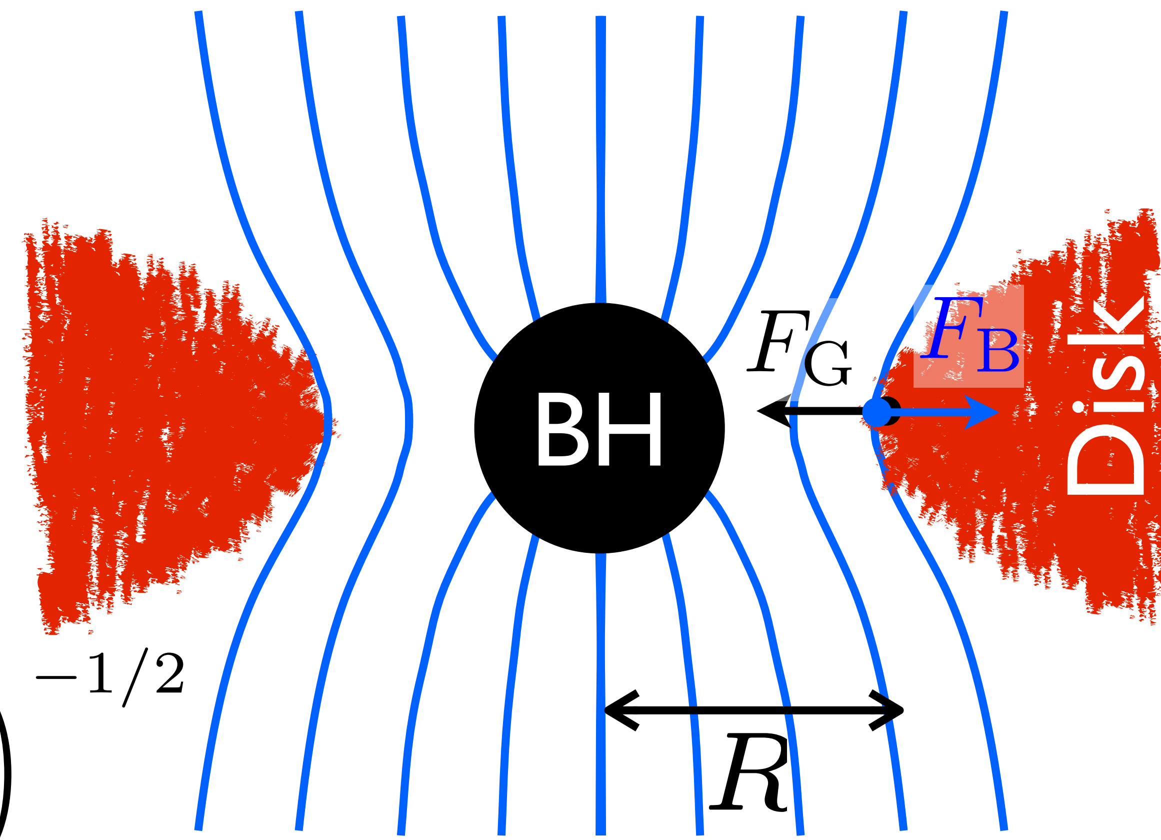

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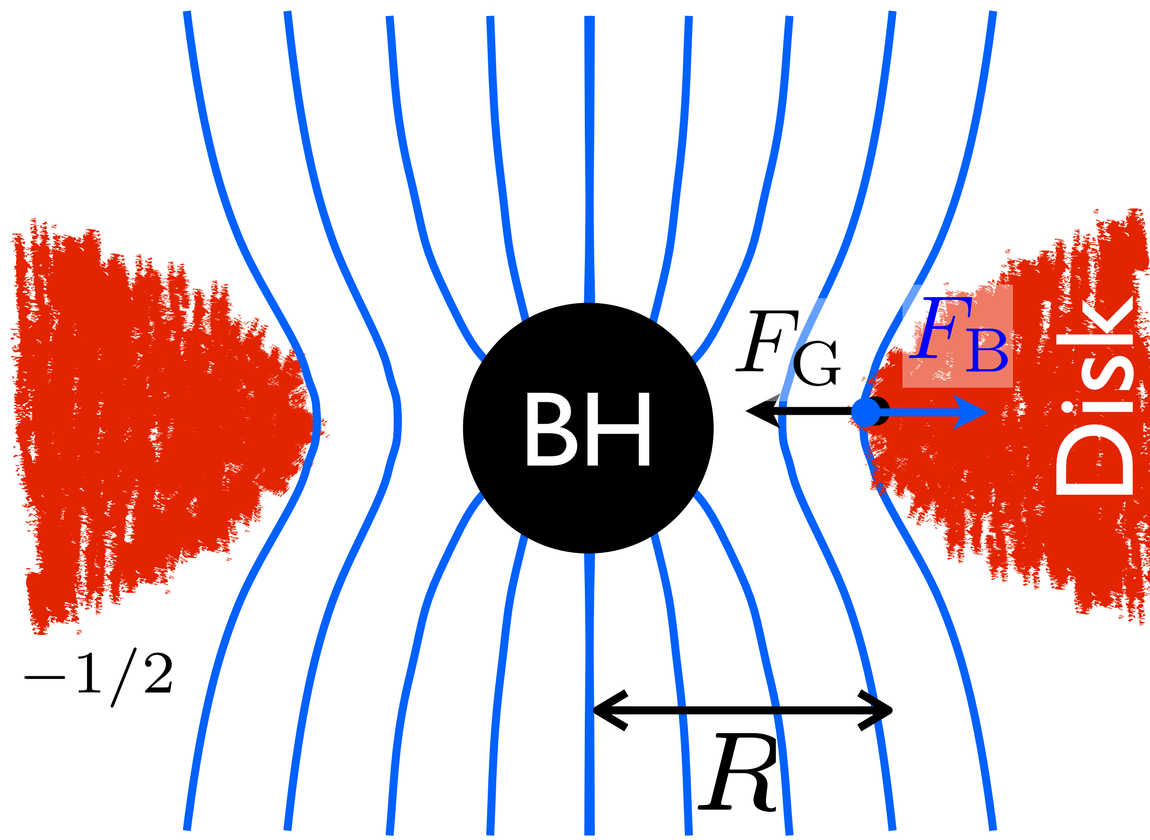

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- How do we get a MAD? Flood the black hole with magnetic flux

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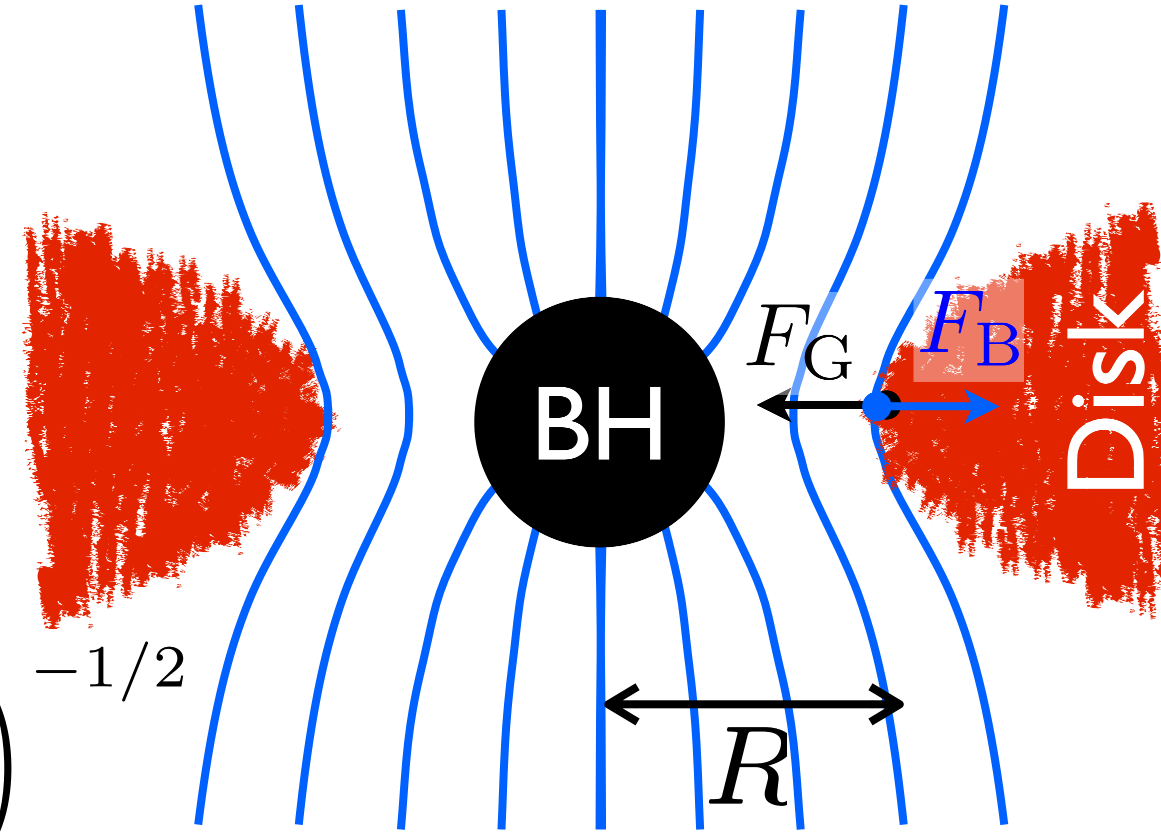

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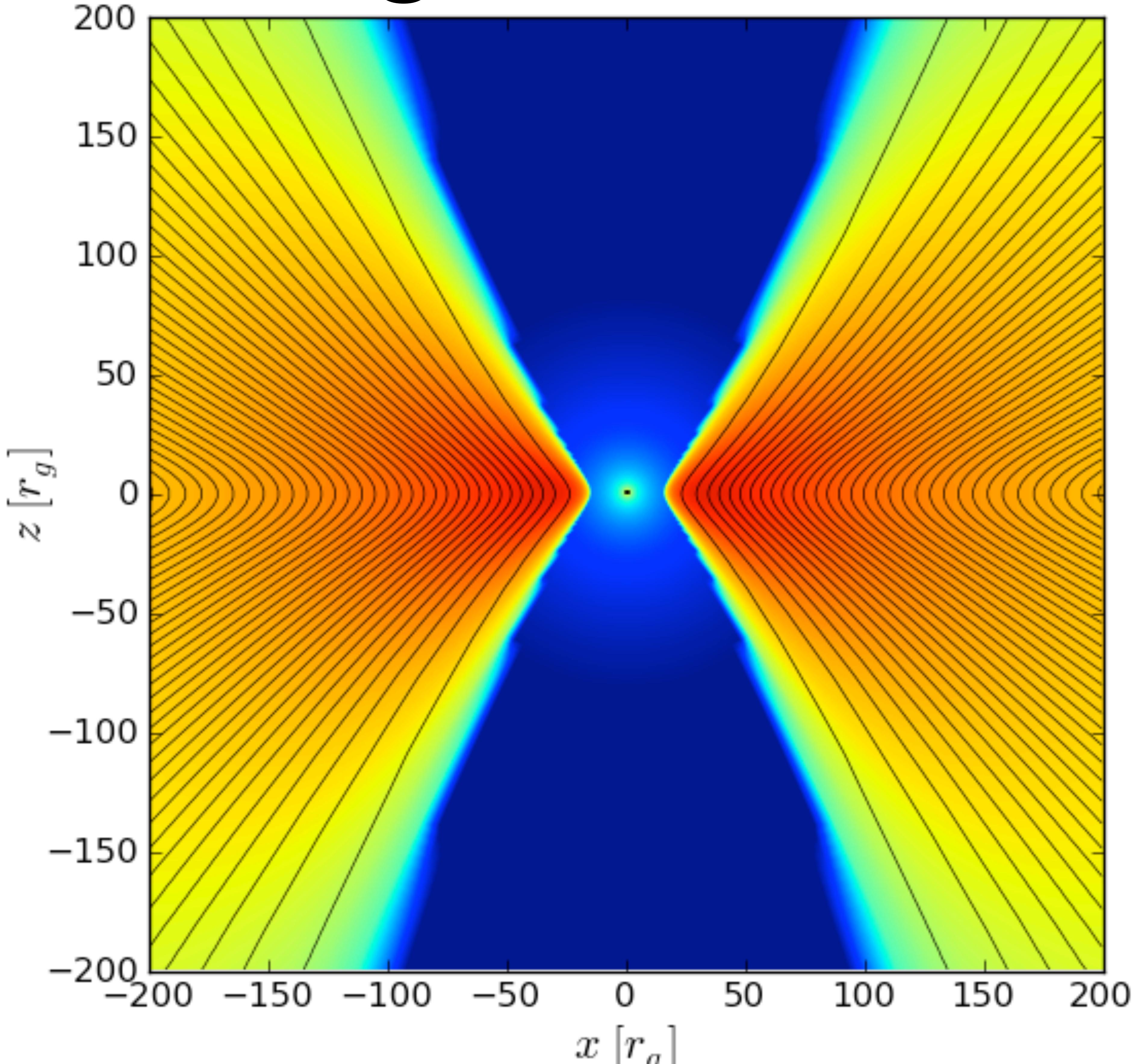
- How do we get a MAD? Flood the black hole with magnetic flux
- Numerical experiments via advanced 3D *GRMHD* simulations with the HARM code (Gammie+03, AT+07,11, McKinney & Blandford 09): took over 10^3 CPU-years!

Much Larger Flux than Before



Our grid extends out to $10^5 r_g$

AT, Narayan, McKinney 2011, MNRAS, 478, L79

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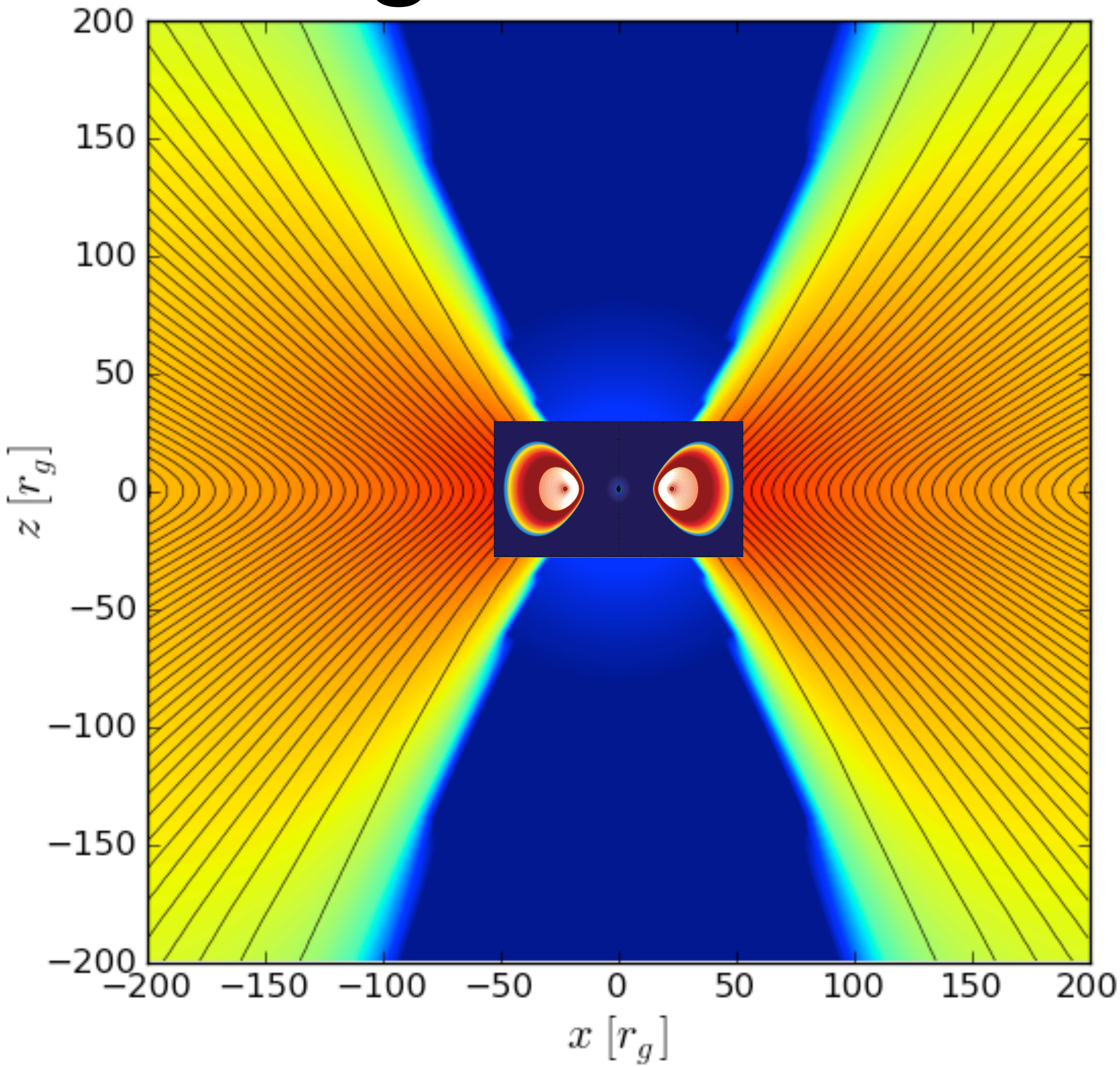

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Beckwith, Hawley, Krolik 2008

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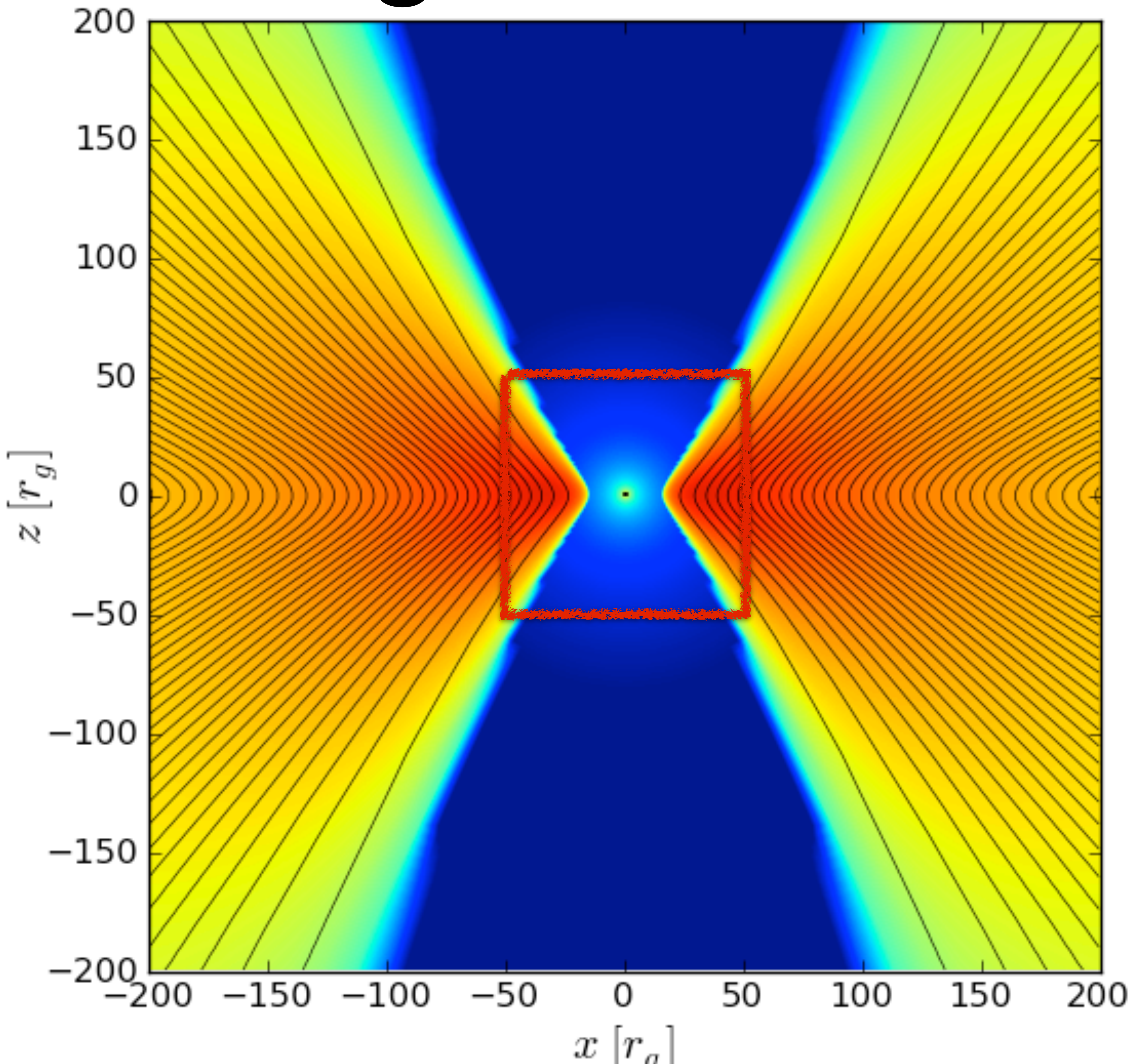

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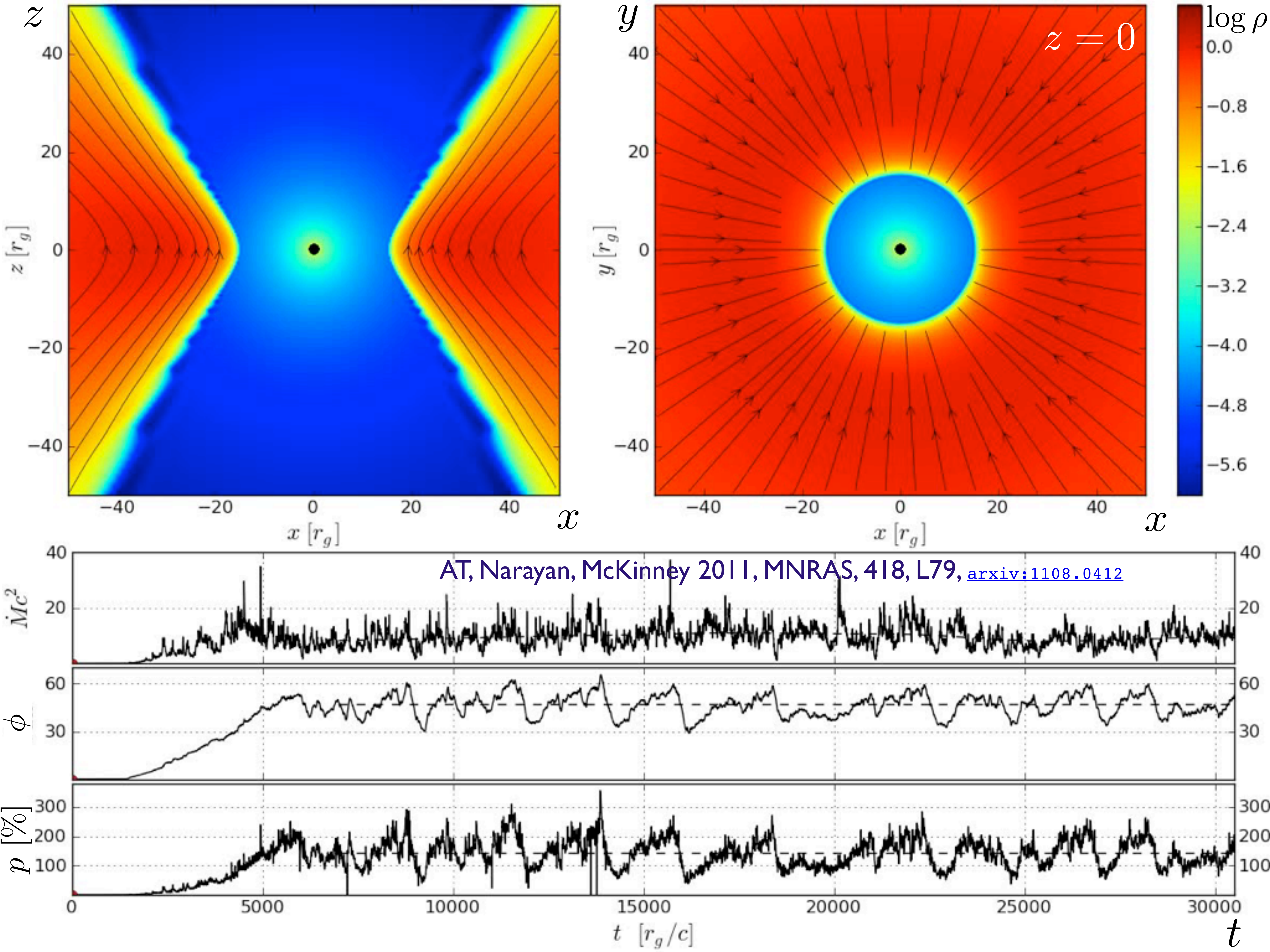


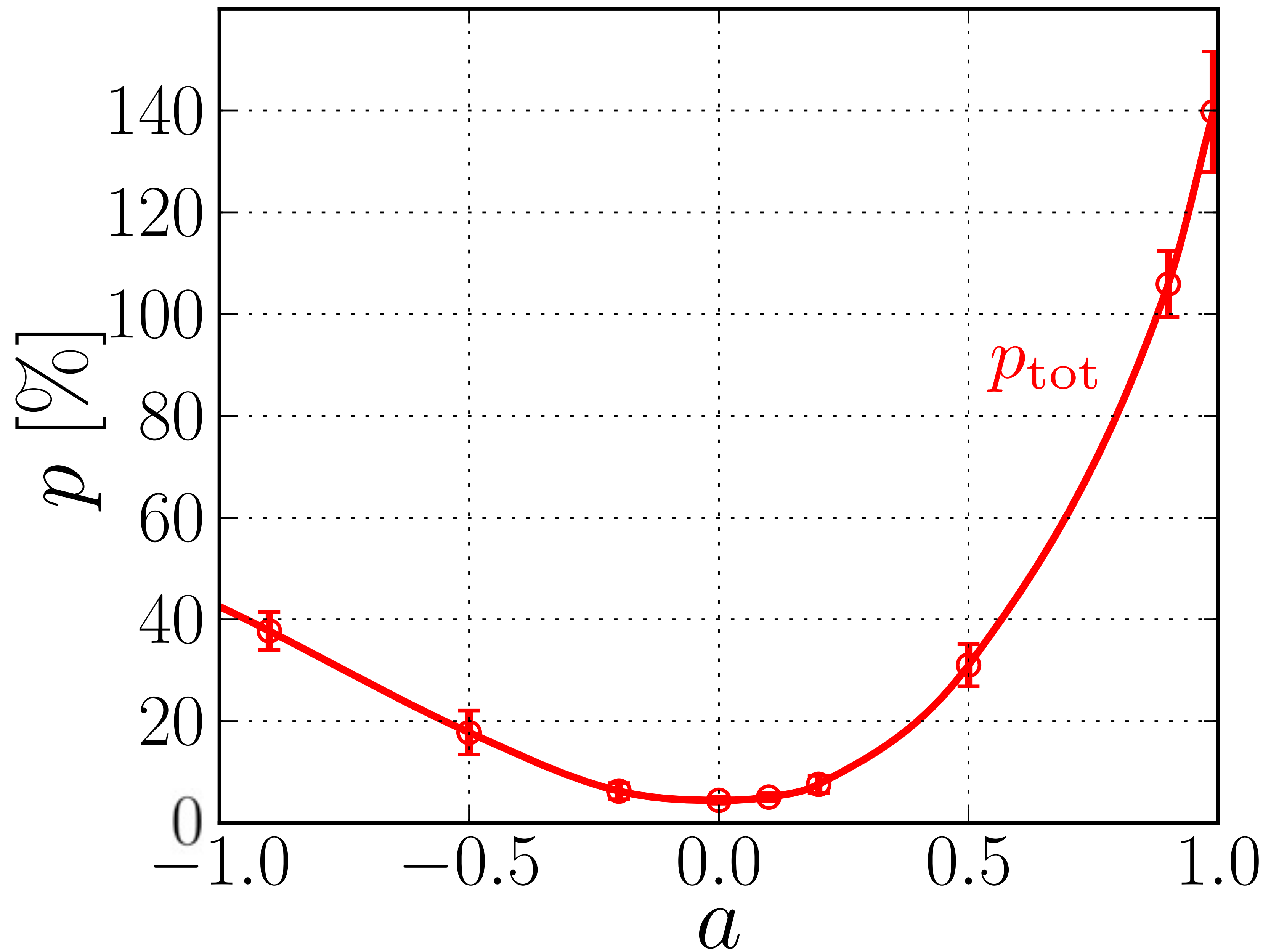
z
y
z = 0
log ρ
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
z [r_g]
y [r_g]
x [r_g]
x
AT, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412
Ṁc²
φ
p [%]
t [r_g/c]
t

Maximum Jet Power vs. Spin

$(h/r \sim 0.3)$

(AT, McKinney 2012, MNRAS, 423, 55; 2014 in prep.)

tilted1 2



$p > 100\%$ unambiguously shows that net energy is extracted from the BH

Magnetic fields are dynamically important if $P_{\rm jet} \sim \dot{M}c^2$

(for rapidly spinning black holes)

Maximum Jet Power vs. Spin

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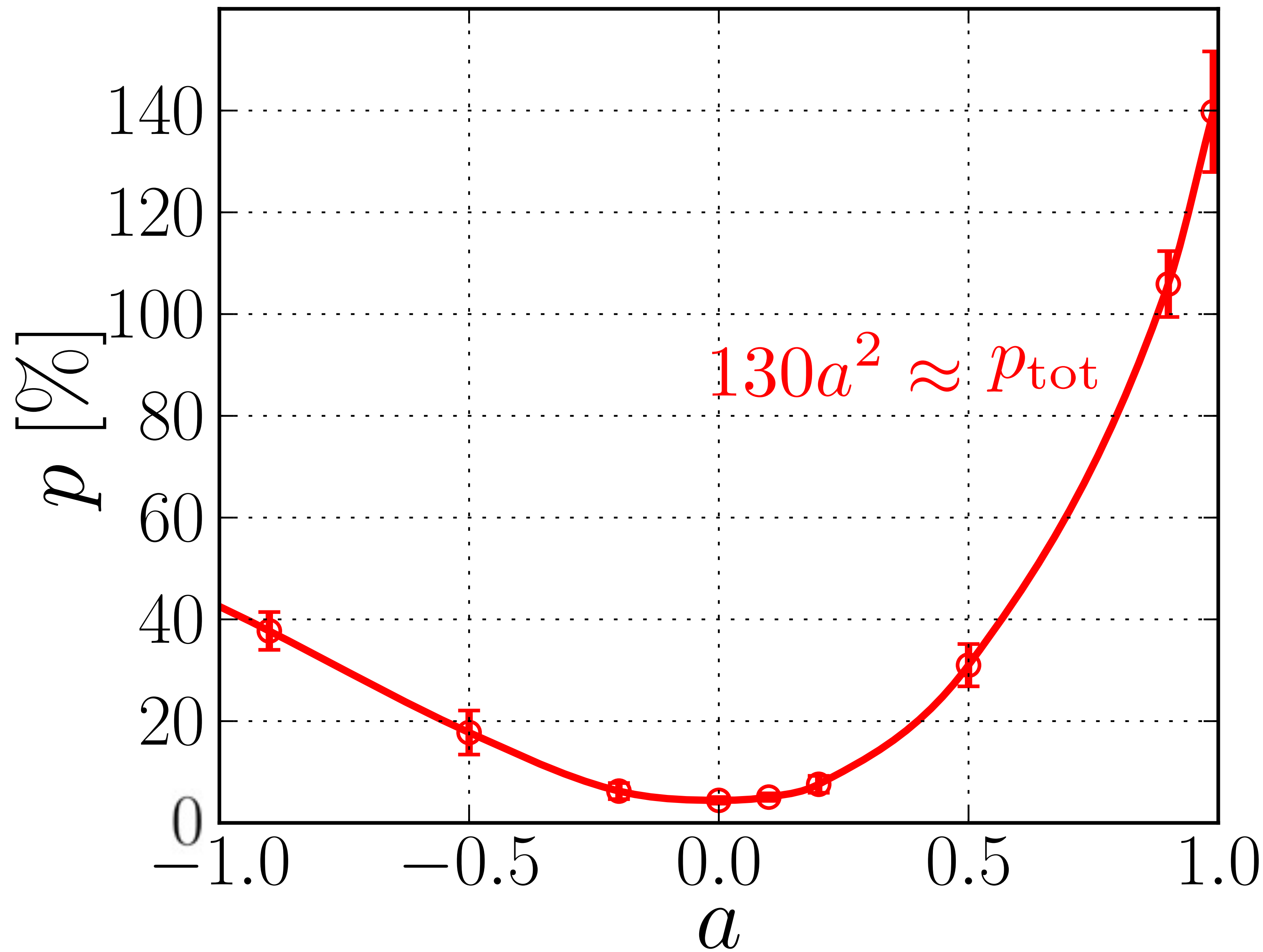

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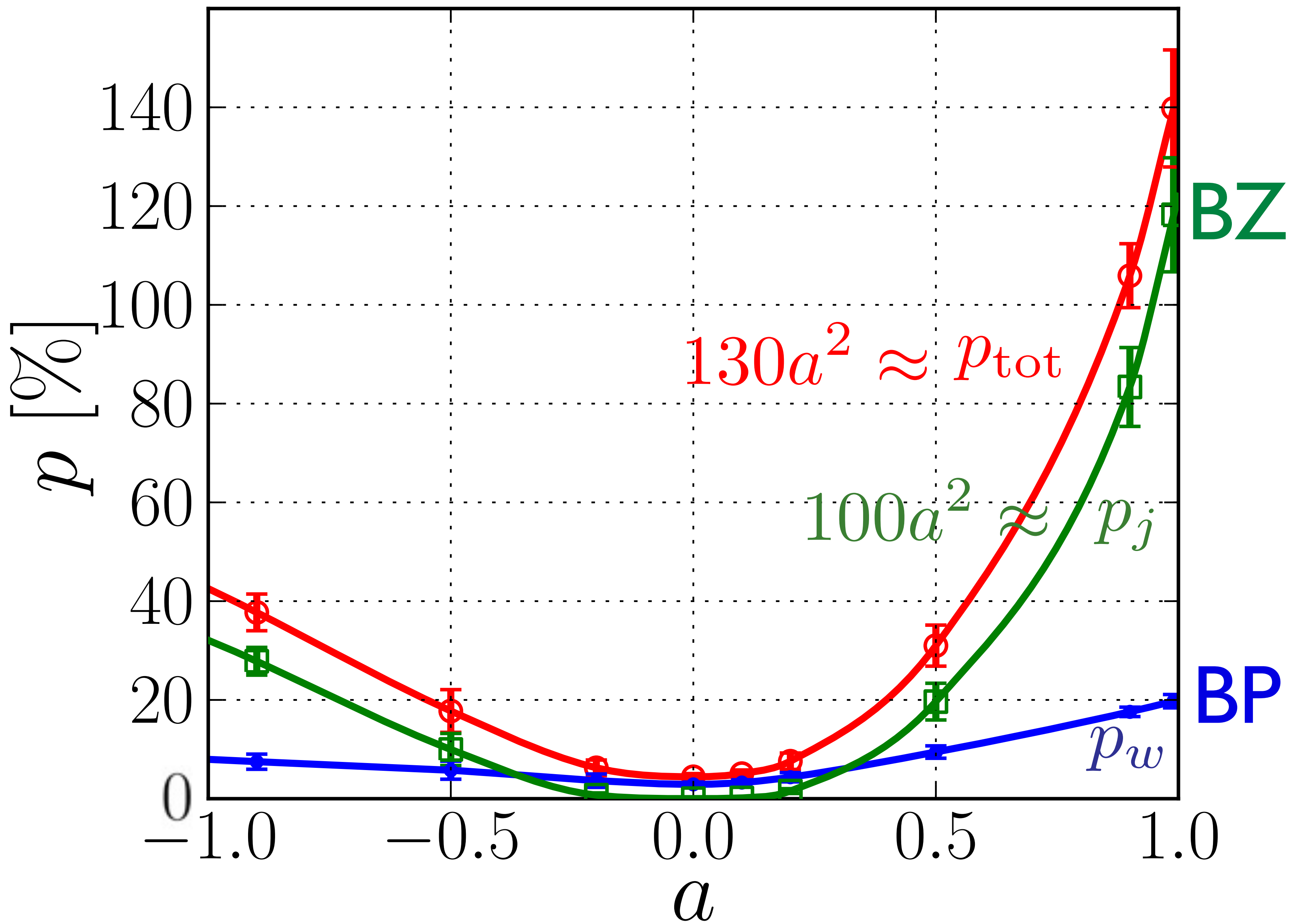
Maximum Jet Power vs. Spin

($h/r \sim 0.3$)

(AT, McKinney 2012, MNRAS, 423, 55; 2014 in prep.)

tilted12

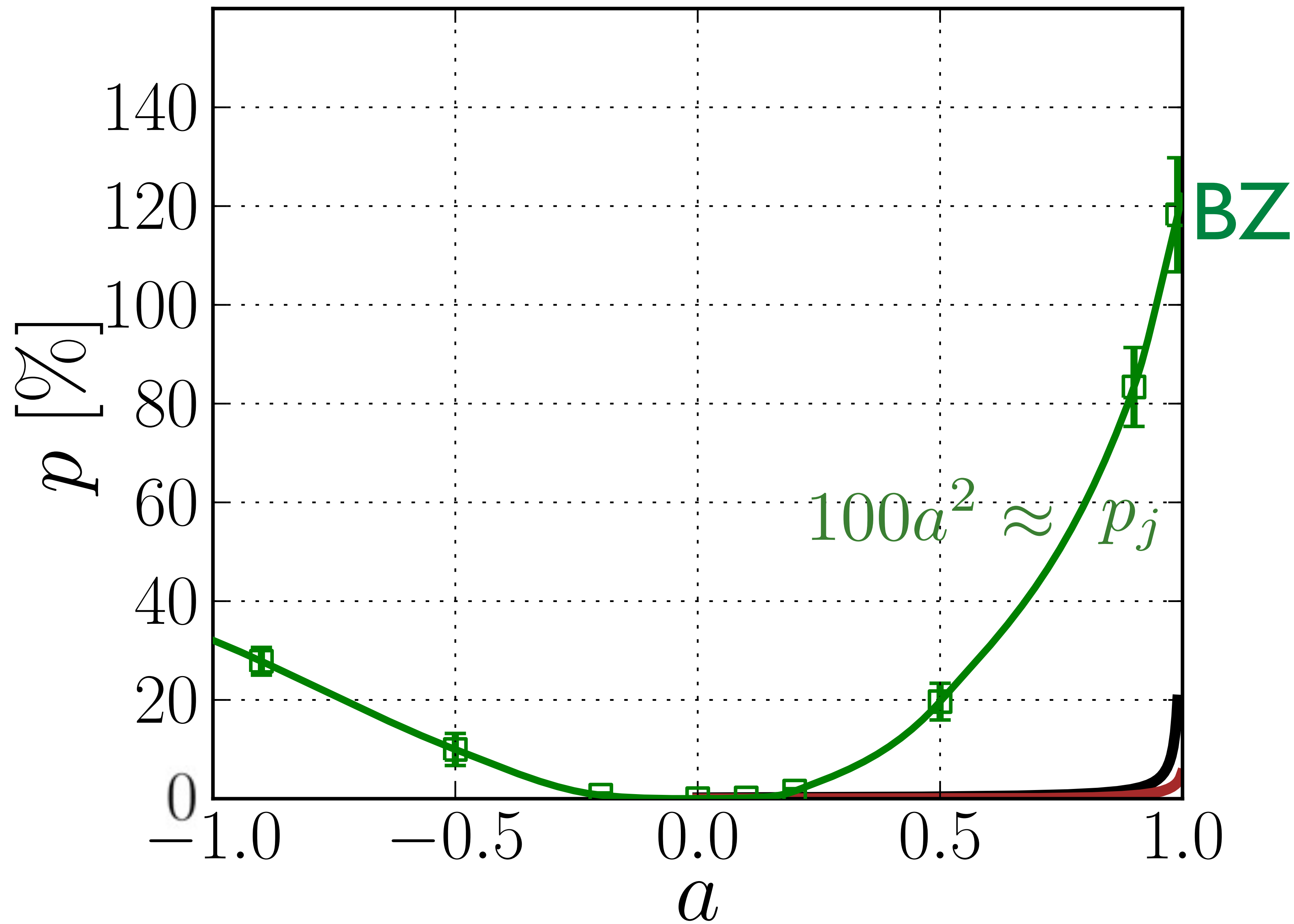


Most of the power comes from black hole spin due to BZ effect (for rapidly spinning black holes).

Maximum Jet Power vs. Spin

$(h/r \sim 0.3)$

(AT, McKinney 2012a, MNRAS, 423, 55; 2014, in prep.)



(McKinney 05, Hawley & Krolik 06)

Jets from MADs can be much more powerful than in previous simulations with fine-tuned initial conditions.

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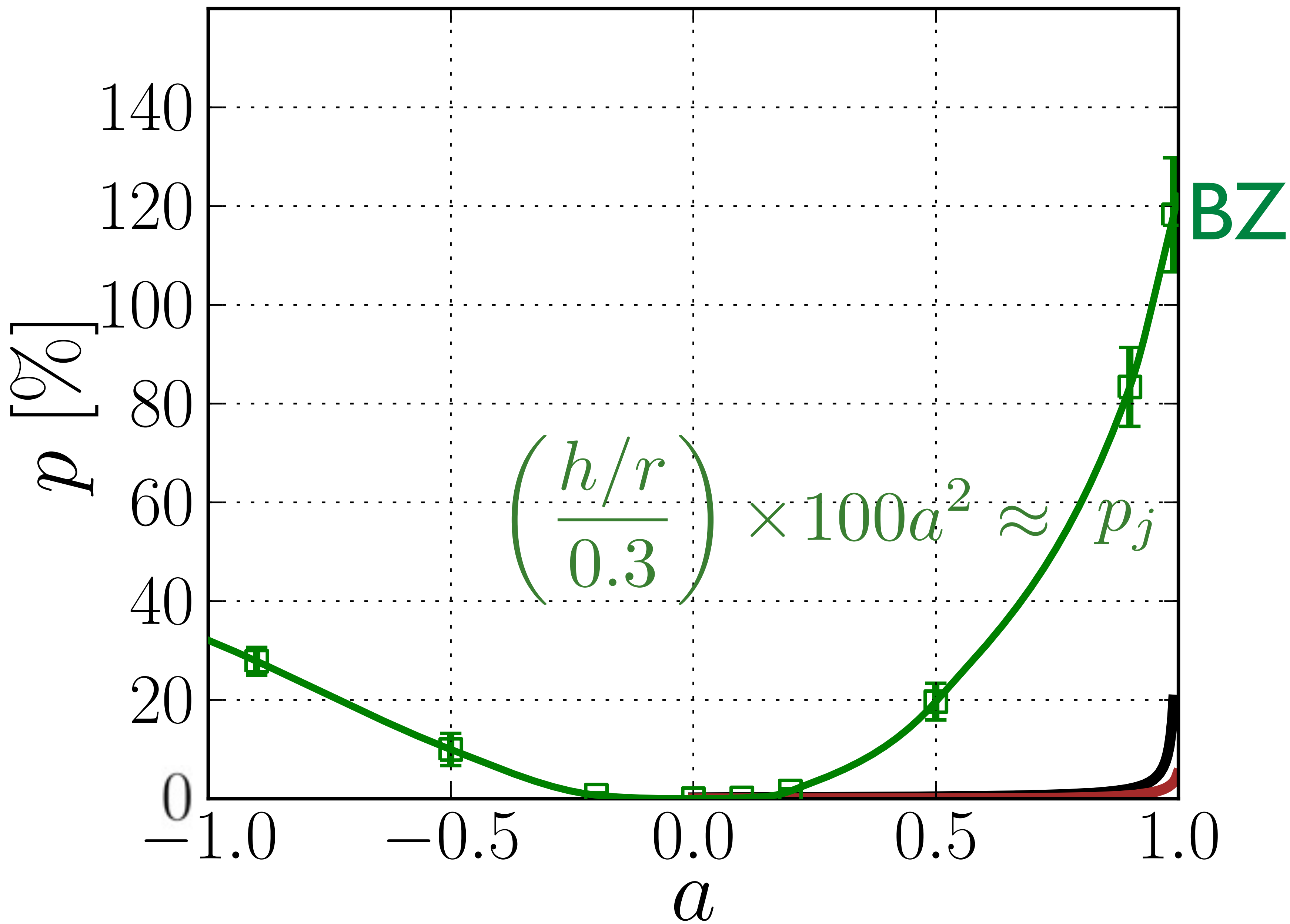

(McKinney 05, Hawley & Krolik 06)

Thicker disks produce more powerful jets

(McKinney, Tchekhovskoy, Blandford, 2012, MNRAS, 423, 3083)

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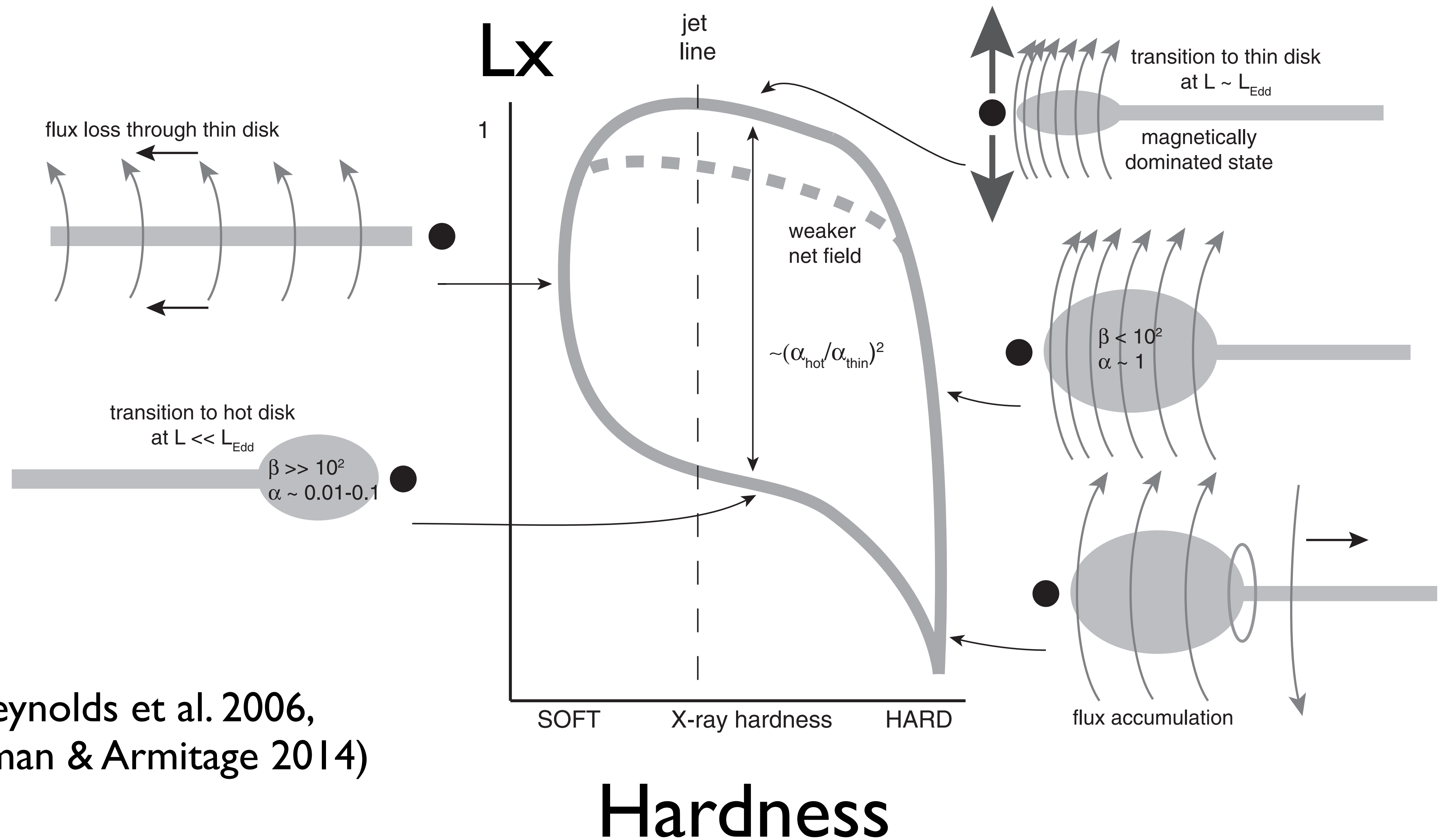
Mystery of Transient Jets

- Global disk instability -> increase in mass accretion rate (Potter and Balbus 2014) -> increase in $\dot{M}$ and jet power
- Disk can become thermally unstable and catastrophically cool
- This is believed to cause magnetic flux to leave the black hole and switch off the jets. Does it?



(Reynolds et al. 2006, Begelman & Armitage 2014)

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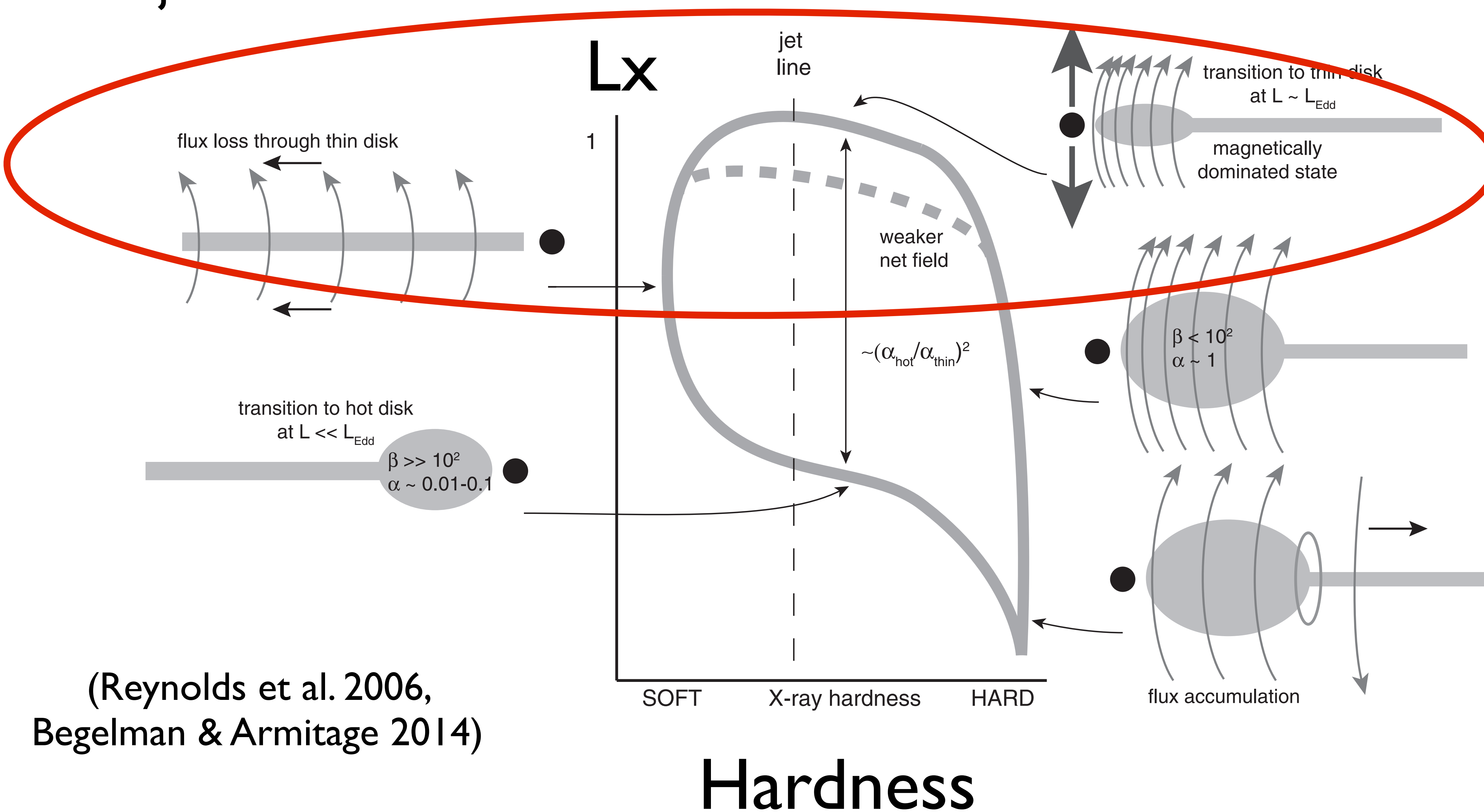

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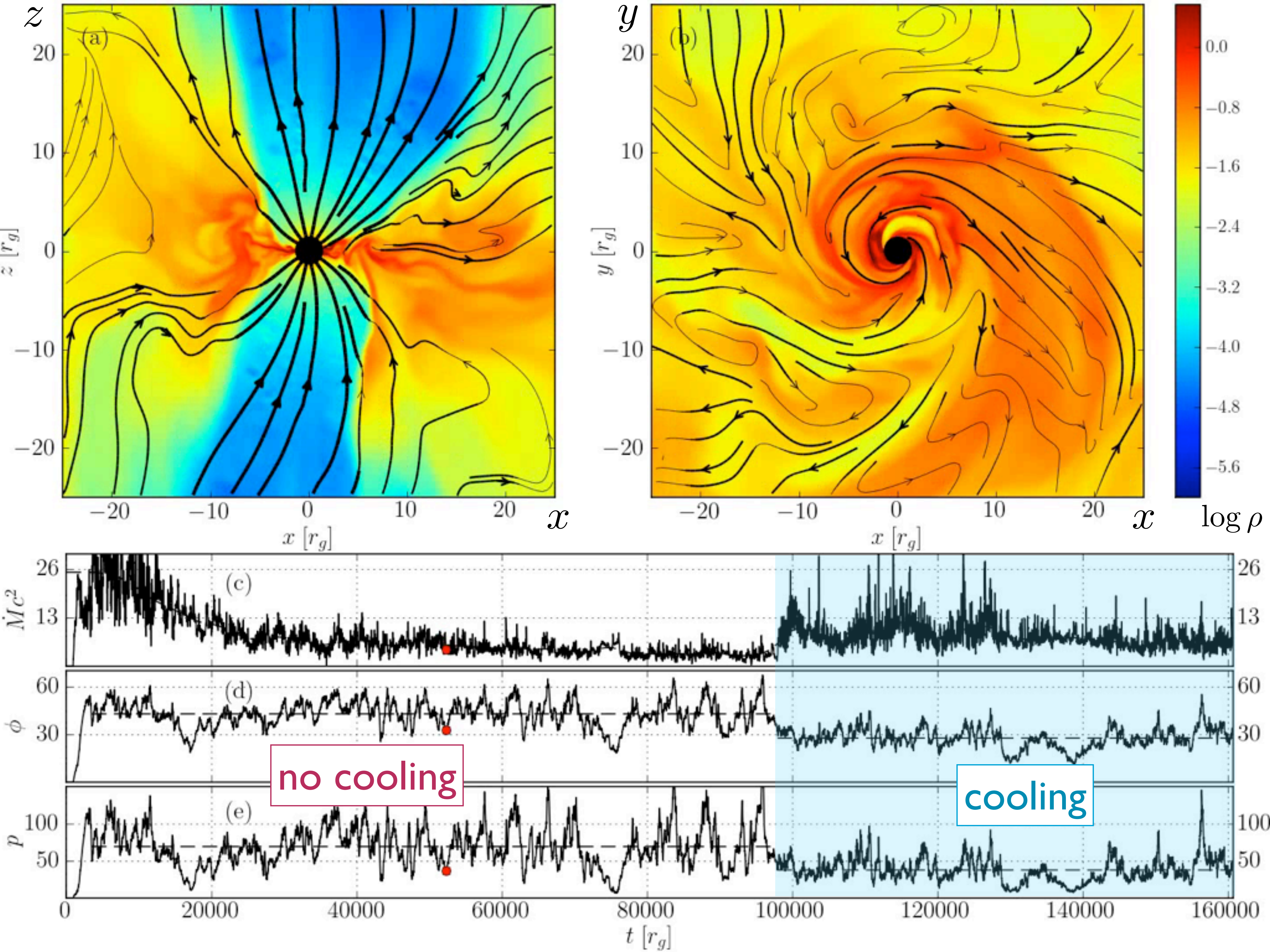


z
(a)
x
y
(b)
x
log ρ
(c)
(d)
(e)
no cooling
cooling

MAD connection to observations

- This model has been fleshed out in the last year or two
- Many connections to observations of microquasars, AGN, GRBs, tidal disruption events
- We are only getting started!

MADs in AGN?

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

$$\tau_\nu \sim 1$$

- At higher ν, the core shifts inward

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

core
$\tau_\nu \sim 1$

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

nucleus

MADs in AGN?

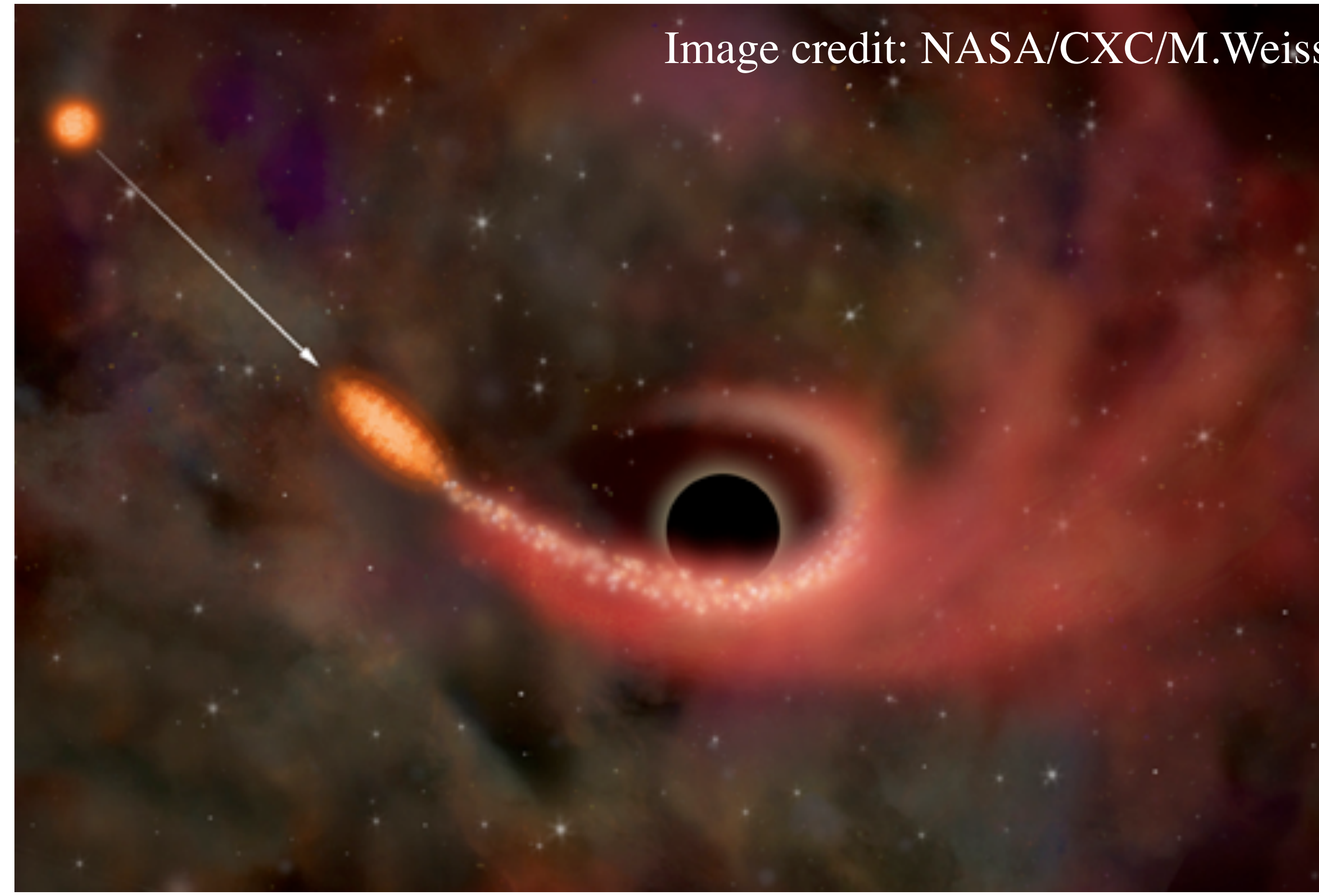
- Observed scaling:

  $$B_{\rm jet} \propto L_{\rm acc}^{1/2}$$

- Magnitude of magnetic flux in *radio-loud* AGN is consistent with MAD expectation
- Many AGN are MAD
  - their central BHs are surrounded by *dynamically important magnetic field*

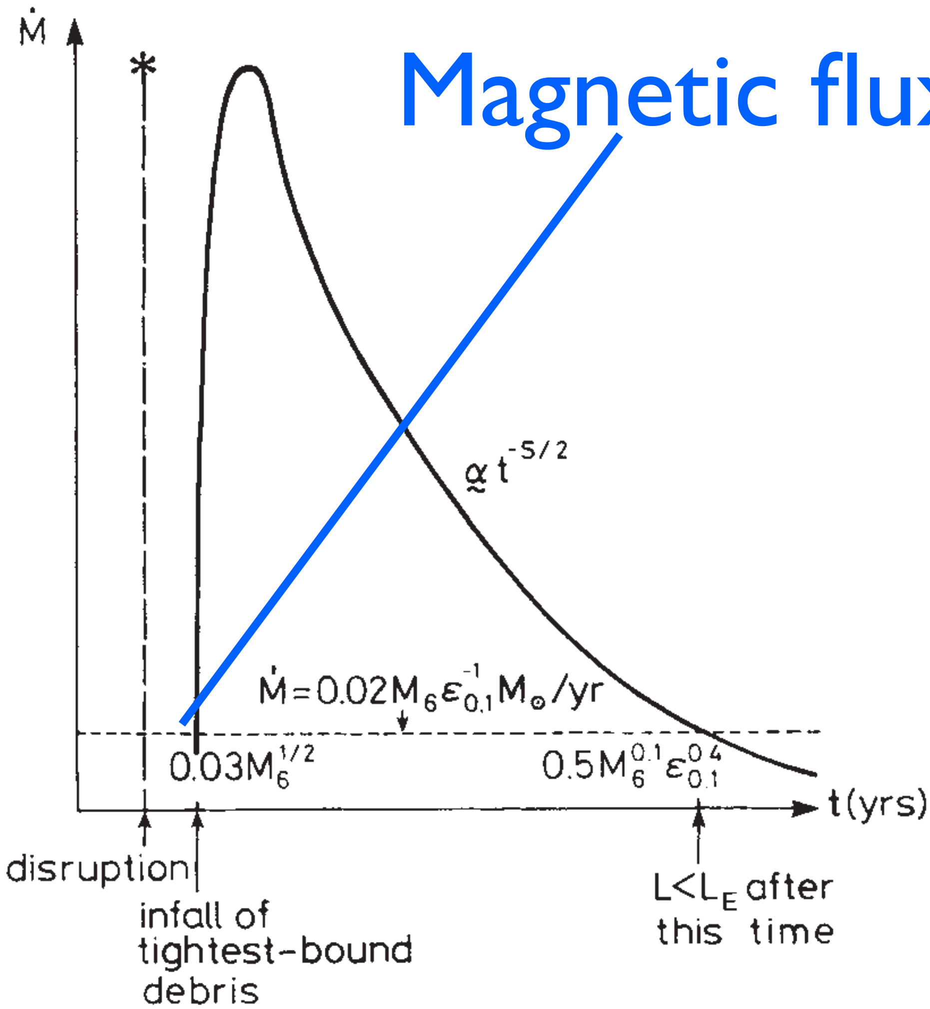
MADs in tidal disruption events? Yes!

- Unlucky star that wanders too close is torn apart by BH tidal forces



- Mass accretion rate peaks, then decreases as mass reservoir depletes

(Rees 1988, Phinney 1989)



- However, B^2 keeps increasing as accretion brings magnetic flux in (either stellar flux or flux picked up from the "fossil" disk, Tchekhovskoy et al. 2014)
- Inevitably, MAD forms (Tchekhovskoy, Metzger, Giannios, Kelley 2014)

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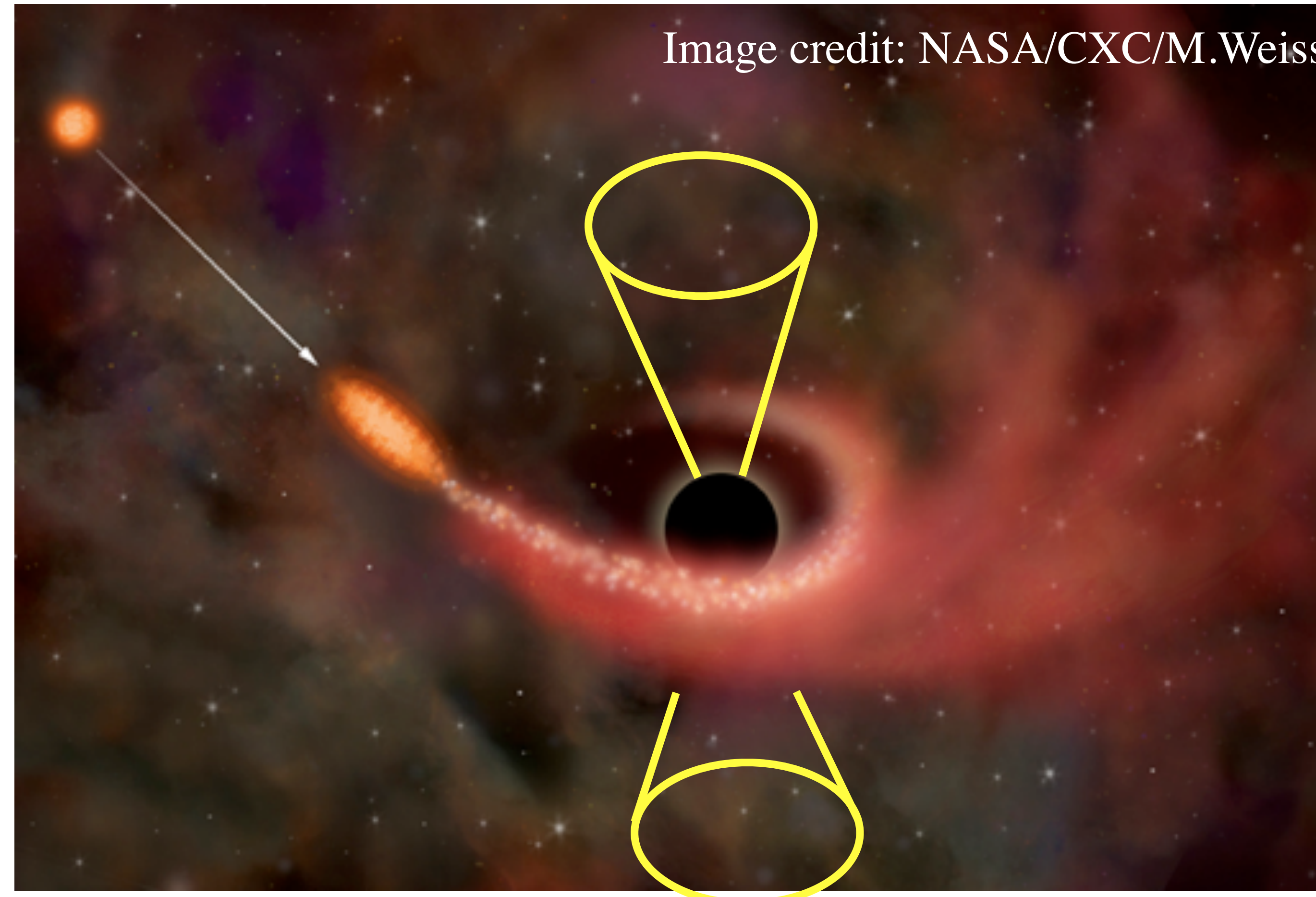

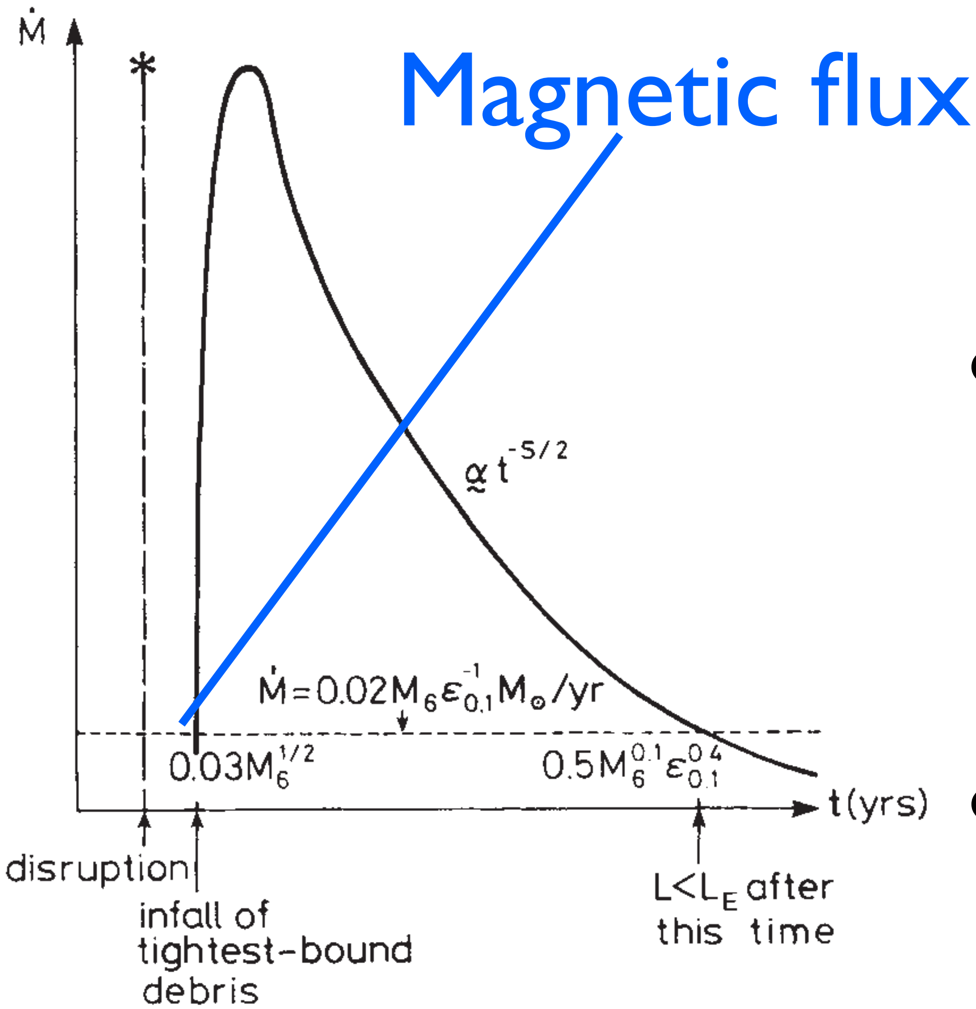

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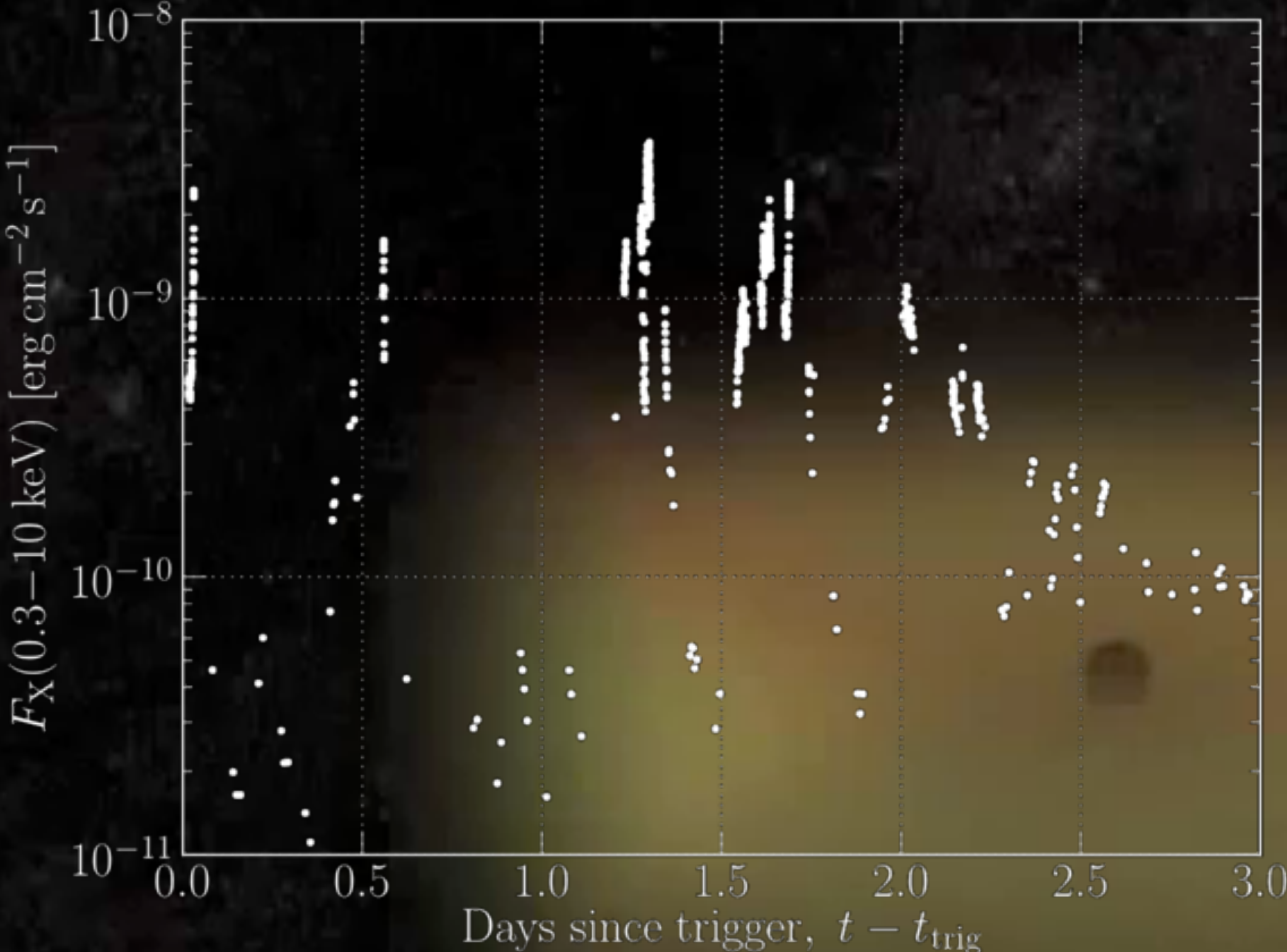
Jetted tidal disruption
Swift J1644+57



(Bloom+11, Burrows+11, Levan+11, Zauderer+11)

Large variability due to jet moving past us

(Tchekhovskoy et al 2014, MNRAS, 437, 2744)

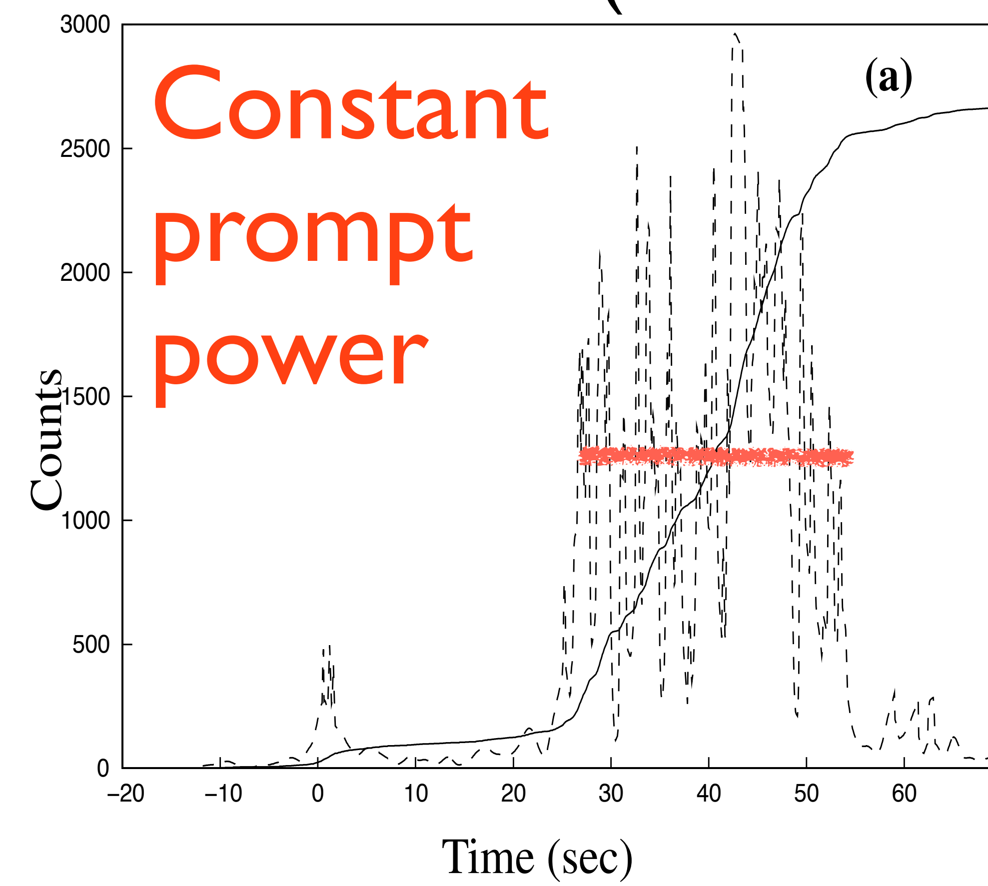
concl

Vis. by Ralf Kaehler (SLAC) and Jon McKinney

McKinney, Tchekhovskoy, Blandford, 2013, Science, 339, 49

MADs in GRBs

(McBreen+2002)



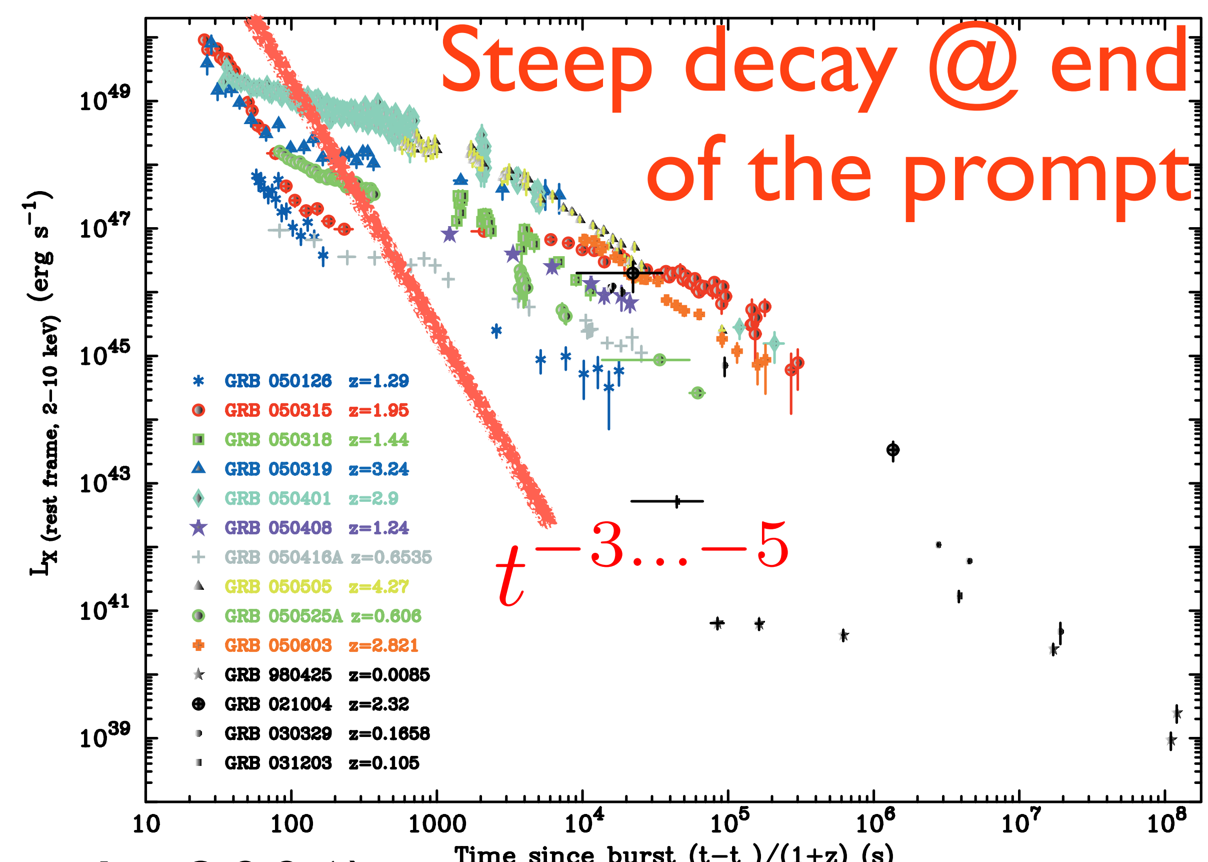
- GRB prompt emission is variable on short time scales
- But on average:

  $$L \sim \mathrm{const}$$

- However, at the end, GRBs steeply decay:

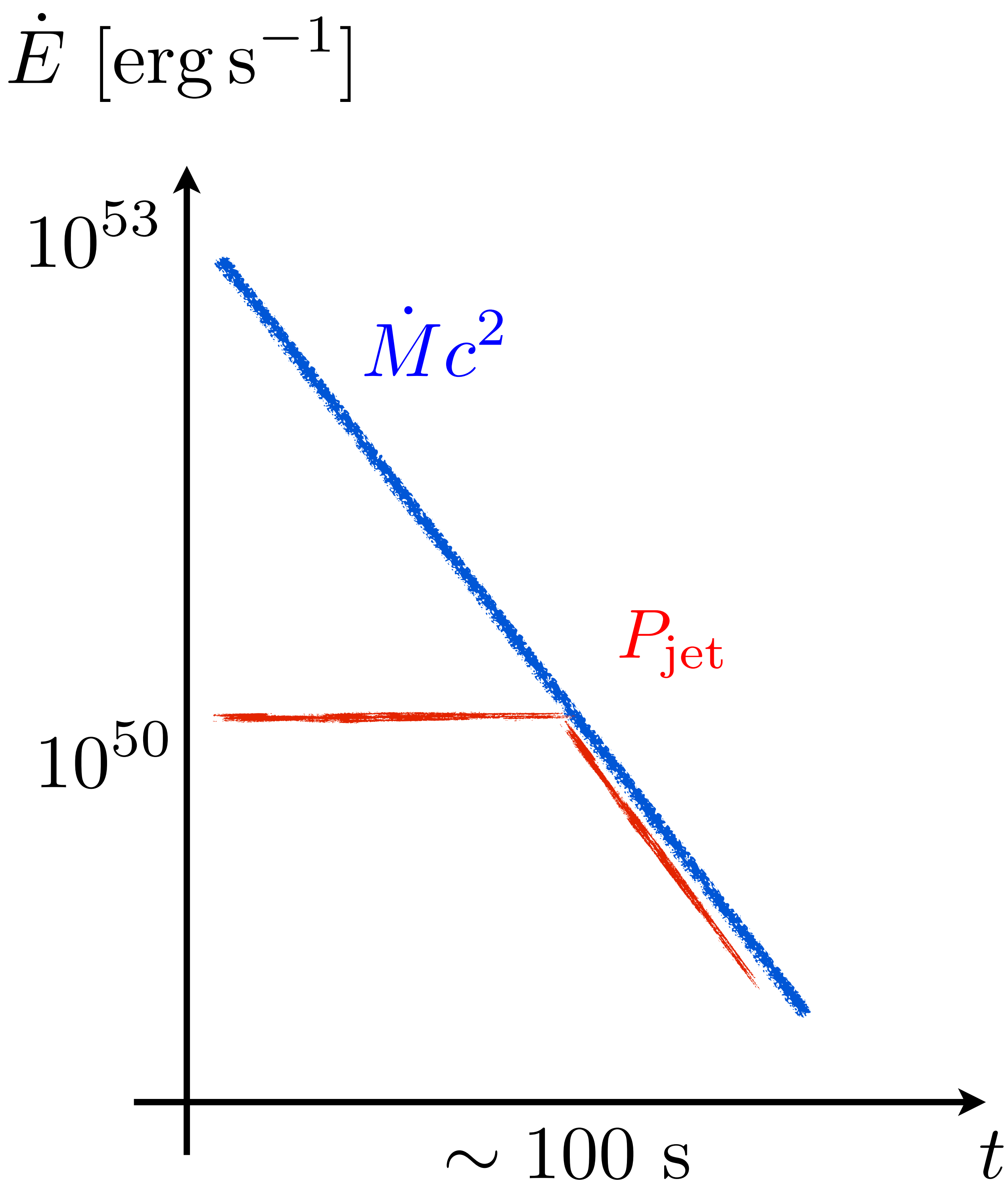
  $$L \propto t^{-3\ldots-5}$$

- What causes such an abrupt change of behavior?



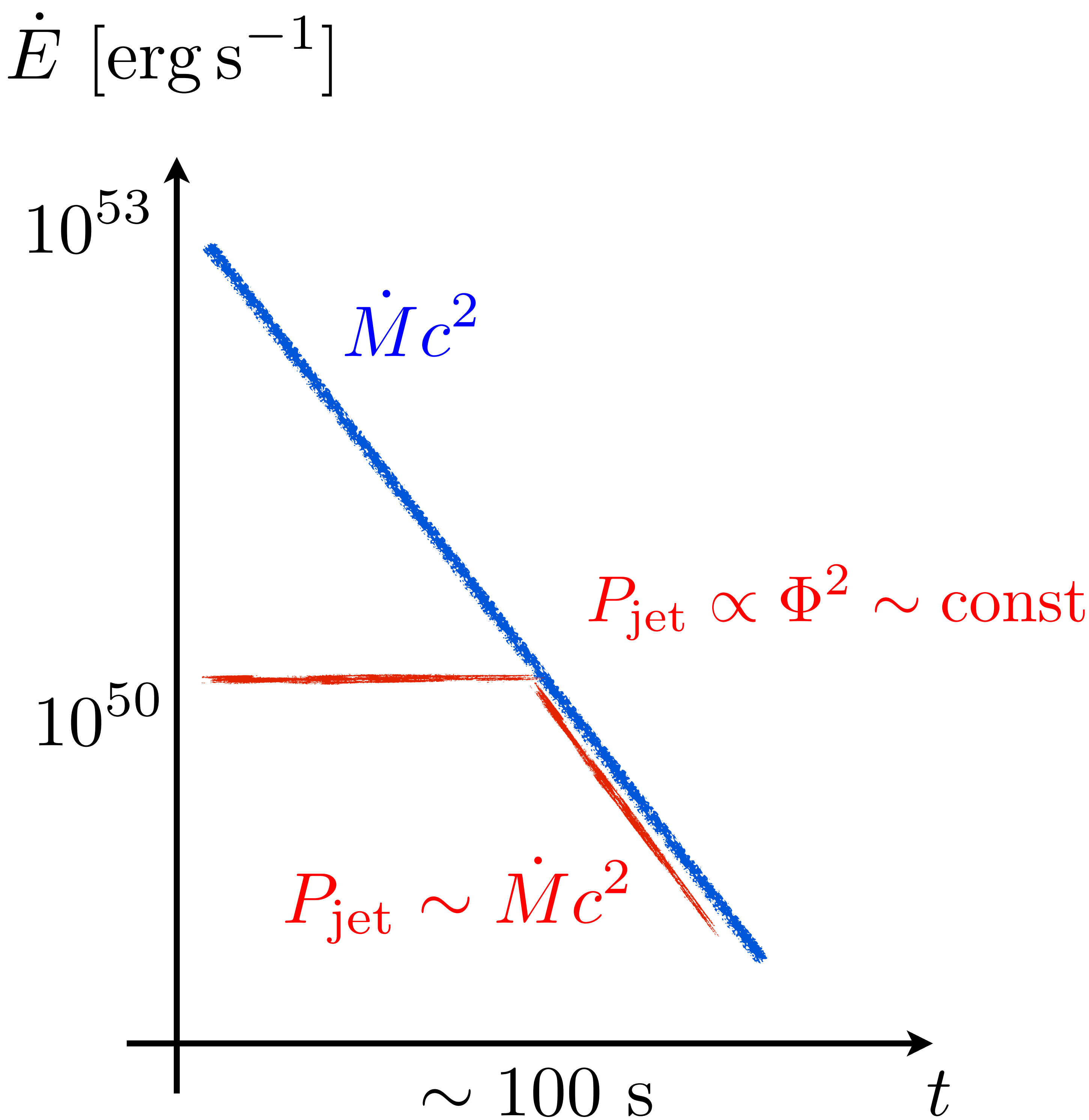
(Nousek+2006)

MADs in GRBs



- After core collapse, accretion power >> jet power → B subdominant:
  - ➡ jet power ~ constant
- As Mdot falls, B becomes dynamically important:
  - ➡ jet emission shuts off abruptly
- Naturally accounts for the observed constancy of prompt emission and steep decay power-law phase

MADs in GRBs



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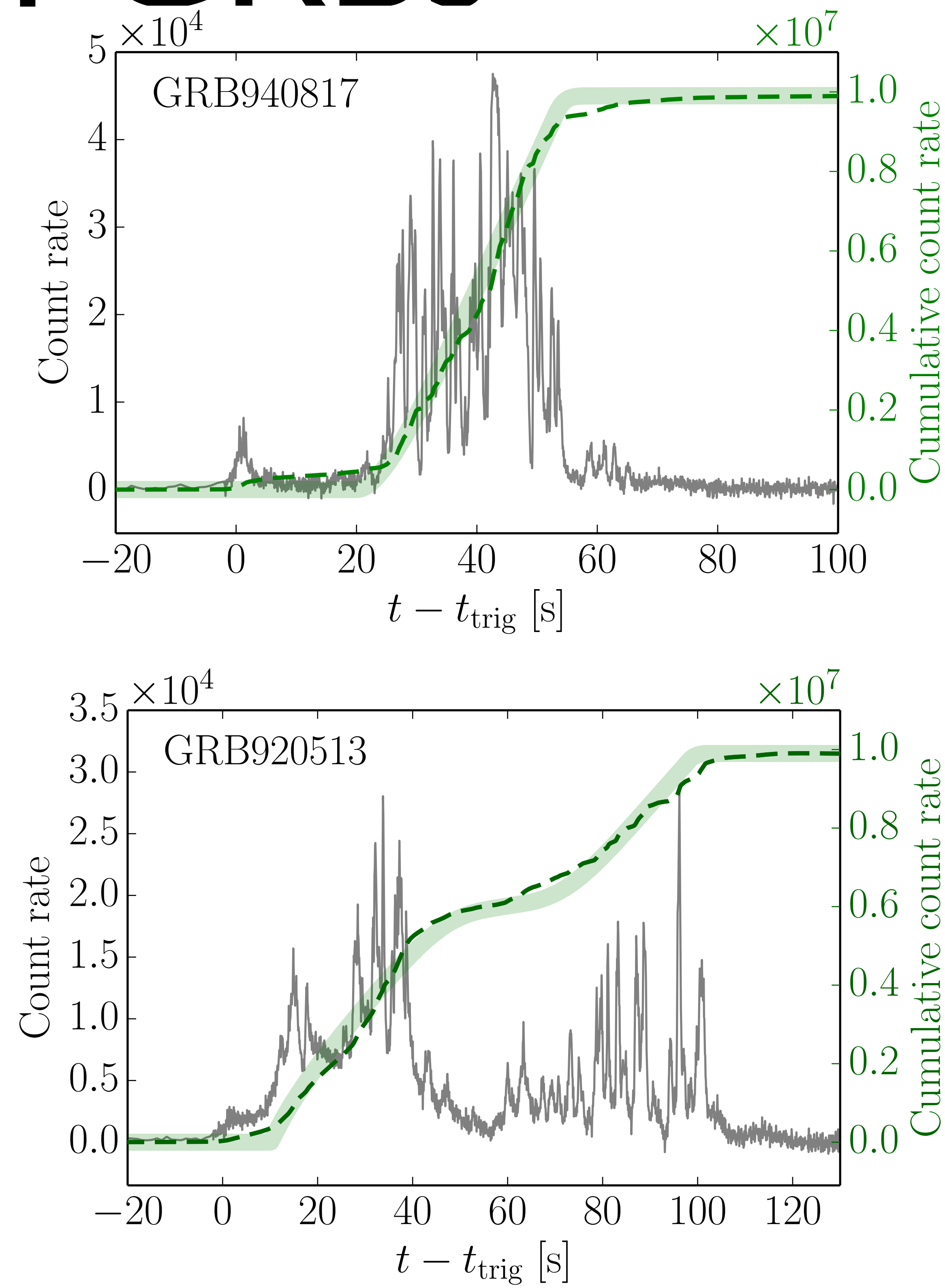
MADs in GRBs

- Magnetic flux accumulation naturally accounts for:
  - constancy of prompt GRB luminosity
  - abrupt shutoff at the end of GRB emission
- Can be used for "magnetic tomography" progenitor stars!



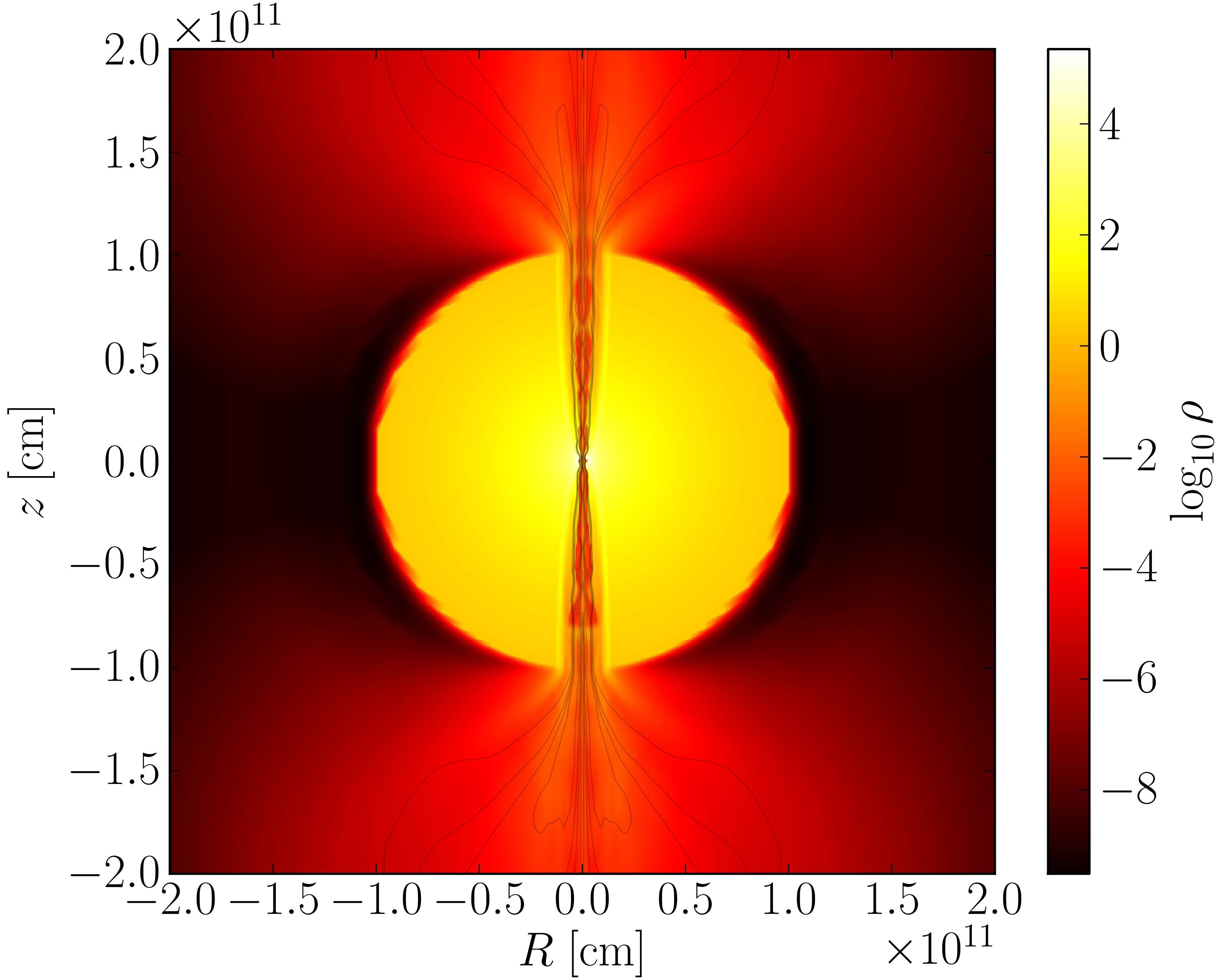
(w/D. Giannios, in preparation)

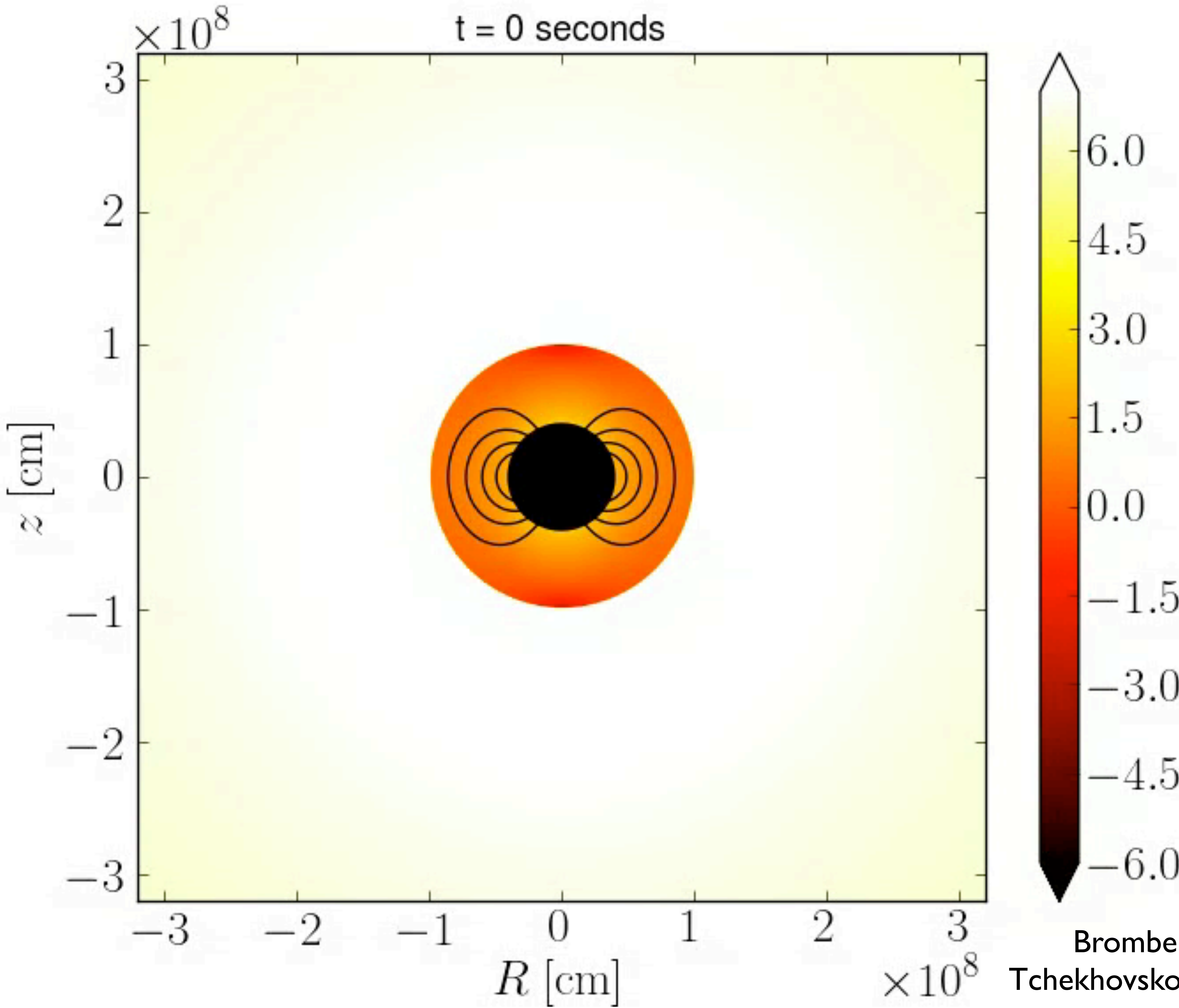
How do GRBs dissipate and radiate energy?

Insert magnetar into the middle of the star.

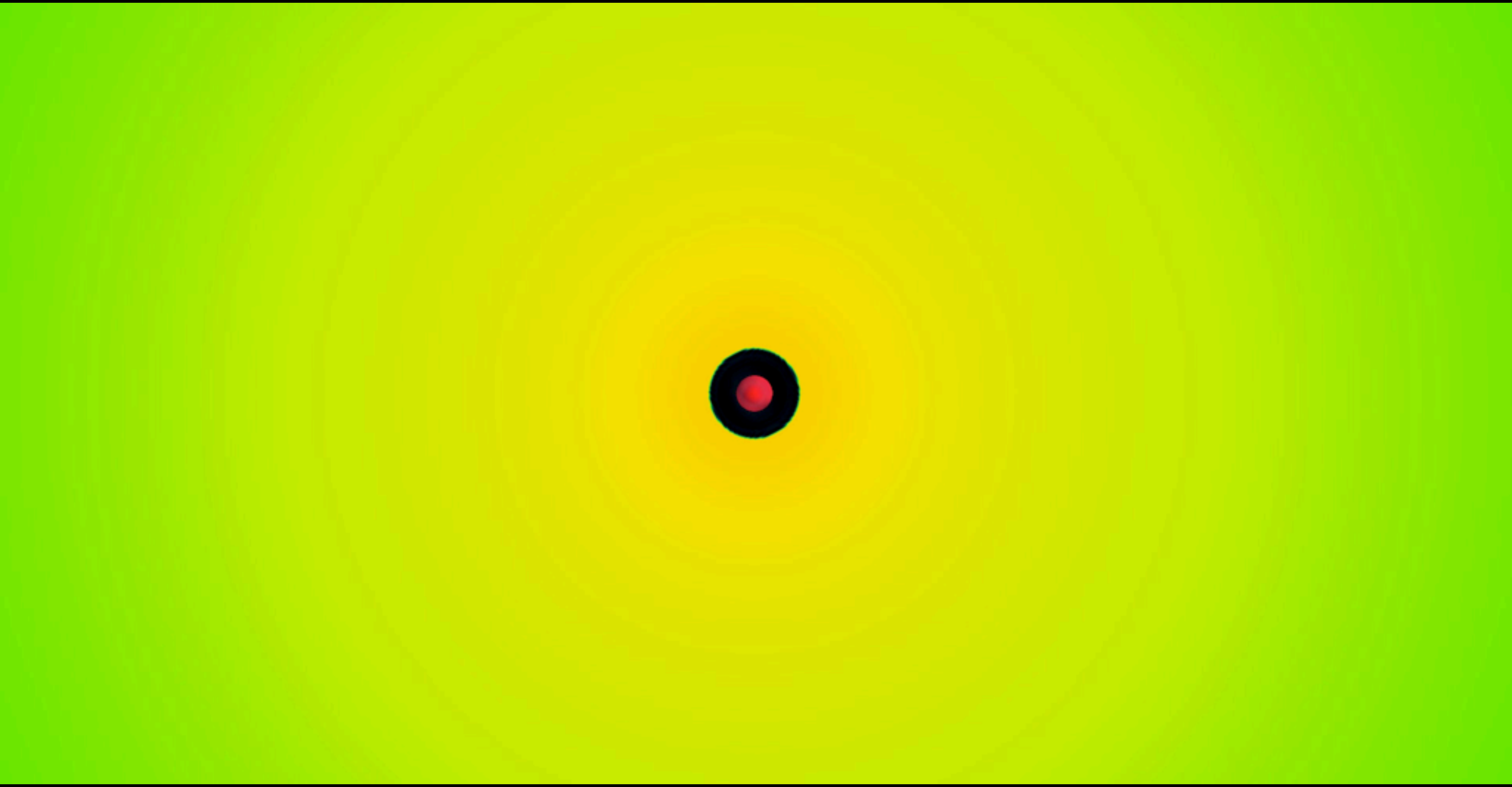
Does this produce a GRB?

Bromberg & Tchekhovskoy, in prep





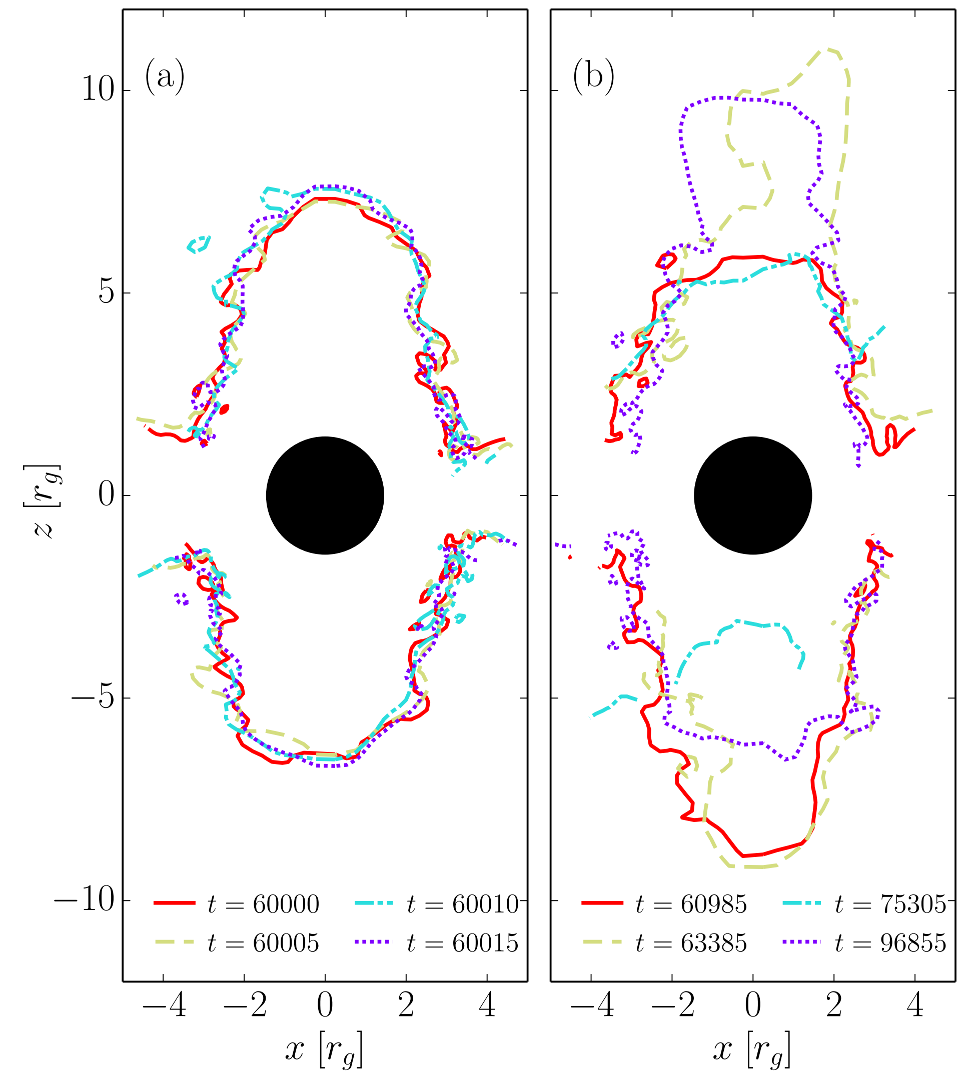
Bromberg & Tchekhovskoy, in prep



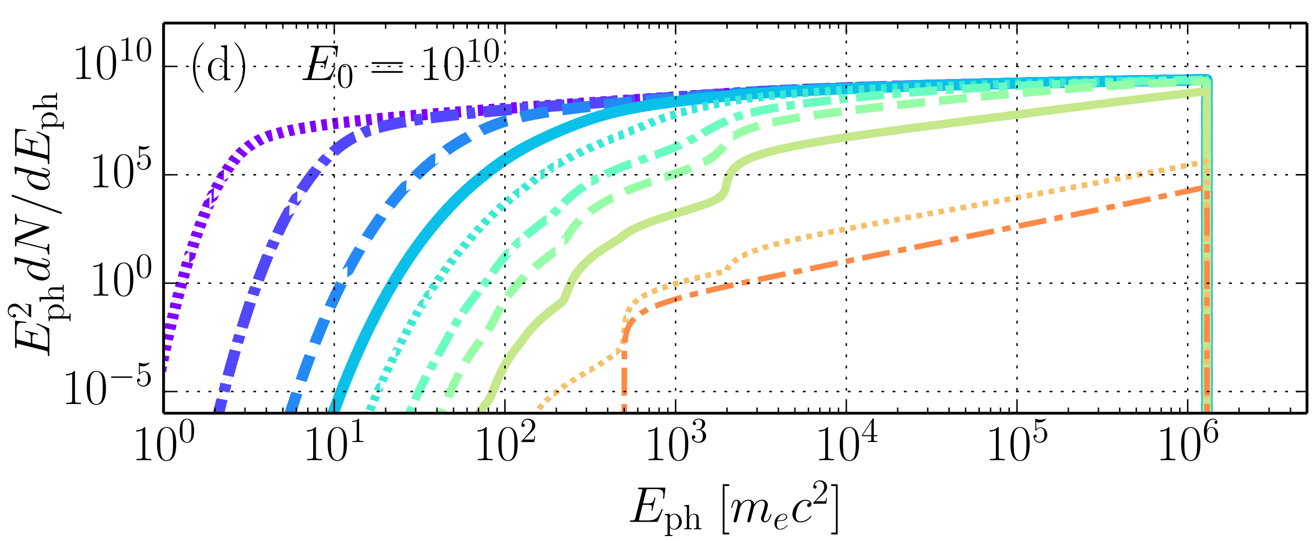
Bromberg &
Tchekhovskoy, in prep

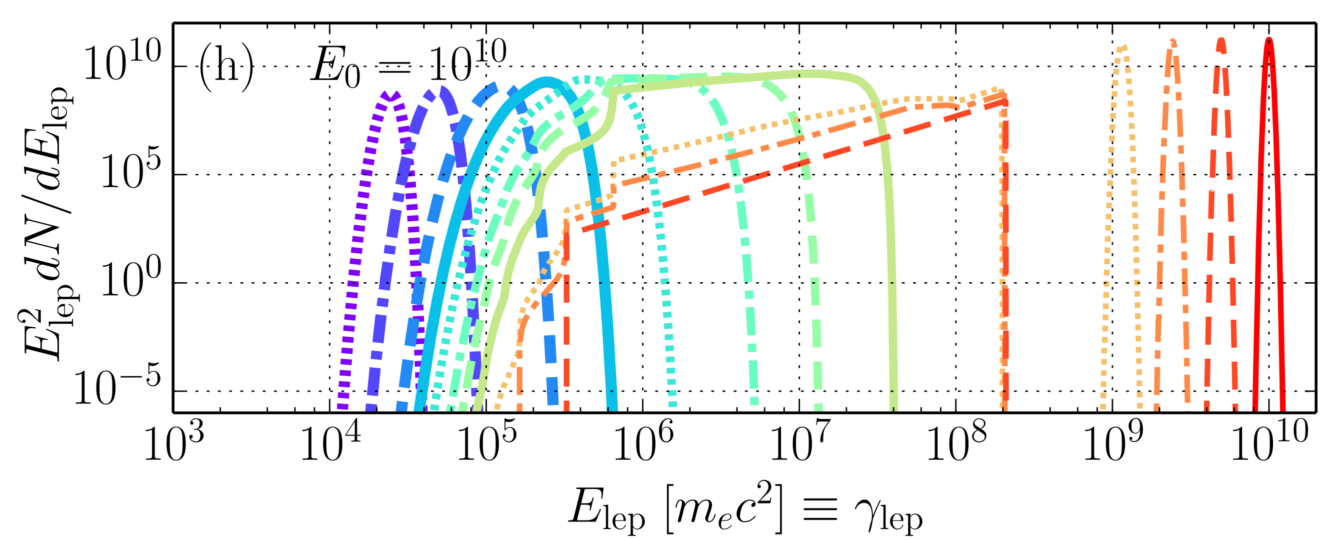
Making jets shine

- Stagnation surface is analogous to neutron star surface
- Can produce a vacuum gap that accelerates particles!
- Our detailed cascade calculations show that this produces sufficient multiplicity to make jets, such as in M87, which shine in radio and gamma-rays



(Broderick and Tchekhovskoy, submitted)





Summary

- Central accumulation of large-scale magnetic flux saturates black holes with flux and leads to MADs
- MADs give us the upper envelope of the elusive disk-jet connection:
  - MADs likely power the most powerful jets in the Universe
  - *Net* energy can be extracted from a black hole in a realistic astrophysical setting, for the first time
- Observational evidence for MADs in tidal disruption events, GRBs, and active galactic nuclei
- Cooling of the disk decreases jet power -> state transitions!
- Core-collapse GRB jets are stable in 3D! (preliminary)