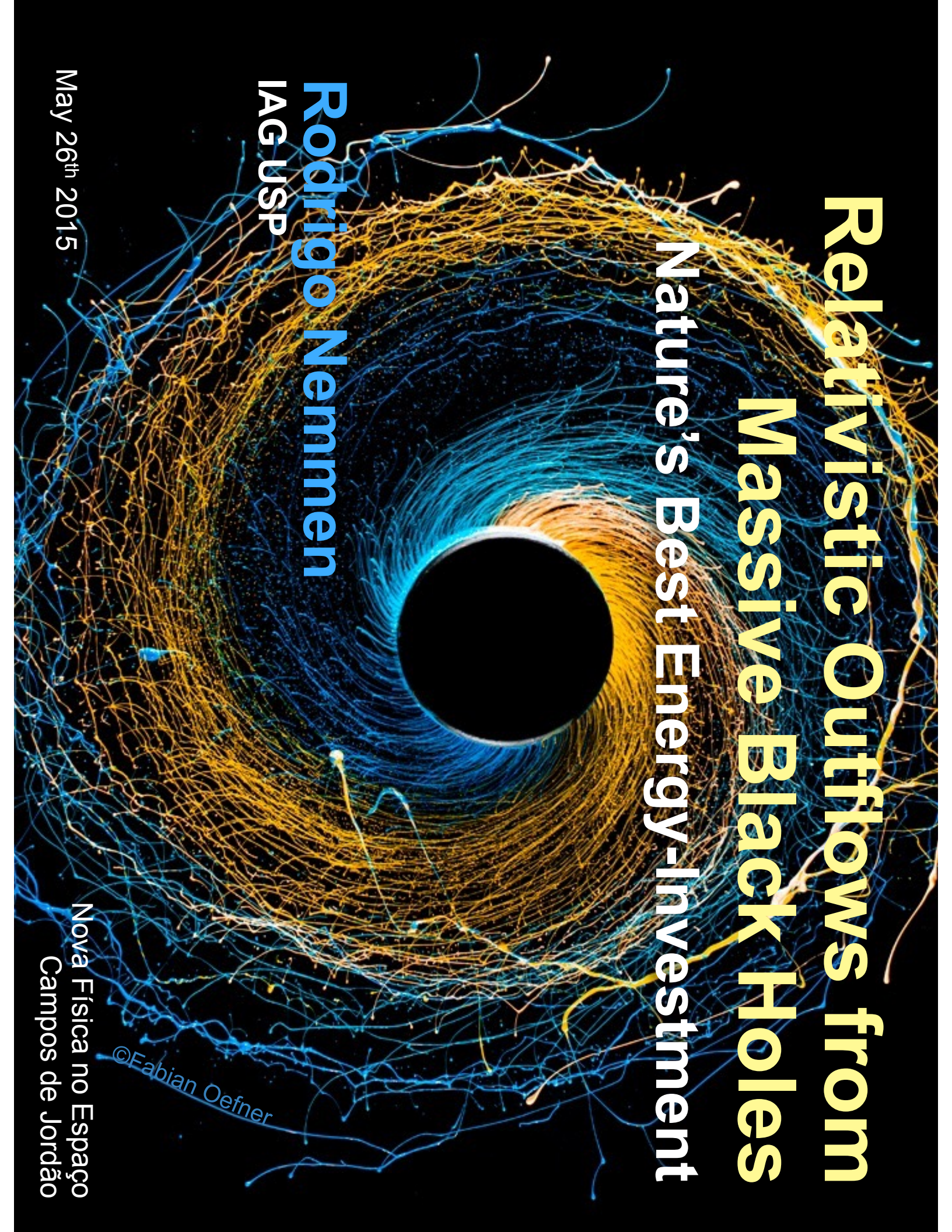


A black hole is depicted as a dark, circular center. Surrounding it is a dense, swirling structure of blue and yellow lines, representing relativistic outflows. The lines are more concentrated near the black hole and become more sparse as they move outwards. The background is black.

Relativistic Outflows from Massive Black Holes

Nature's Best Energy-Investment

Rodrigo Nemmen

IAG USP

©Fabian Oefner

May 26th 2015

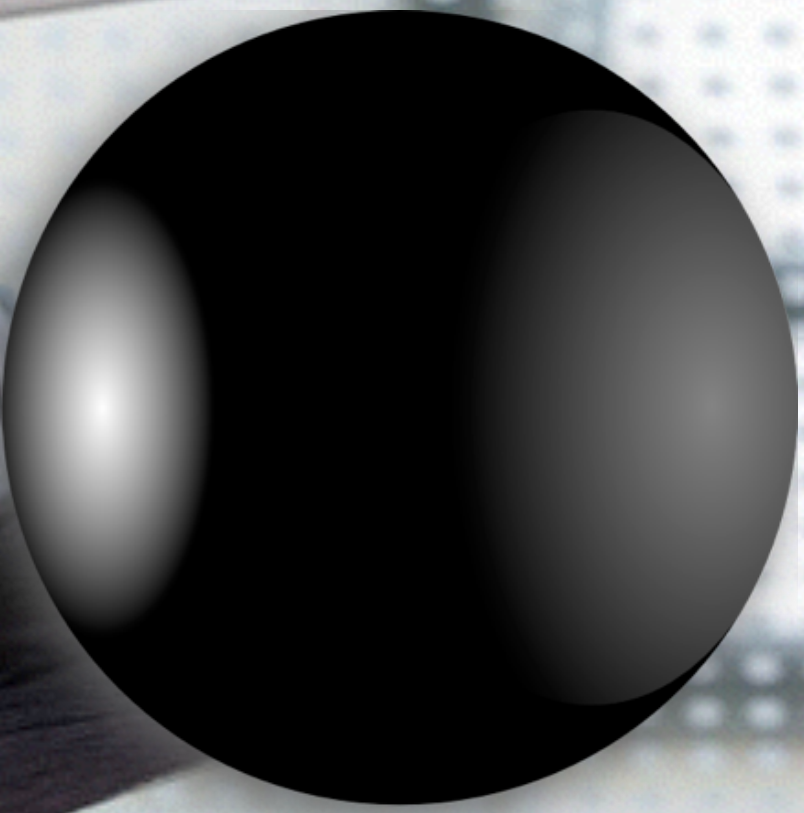
Nova Física no Espaço
Campos de Jordão

M. Volonter's talk



This talk

F. Bauer's talk



Black holes are the most perfect objects in the universe



Kerr metric $ds^2 = - \left(1 - \frac{2Mr}{\Sigma} \right) dt^2 - \frac{4Mar}{\Sigma} dt d\phi +$

Described completely by their mass and spin

$$J = a GM^2/c$$
$$0 \leq |a| \leq 1$$

Once inside, nothing escapes

Black holes are the most perfect macroscopic objects in the universe

Kerr metric ds^2

Described completely by their mass and angular momentum

$$J = a$$

$$0 \leq |a| < 1$$

Father-in-law (sogro)

Mother-in-law (sogra)

Once inside, nothing escapes

Black holes are the most perfect
objects in the universe

Kerr metric

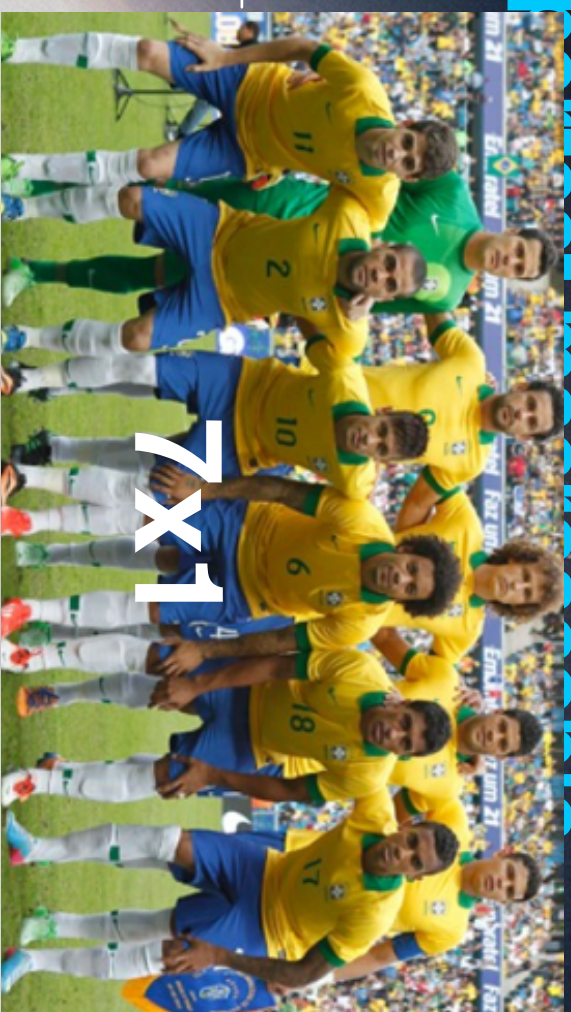
$$ds^2 = - \left(1 - \frac{2GM}{r} \right) dt^2 - \frac{4J}{r} dt d\phi + \left(r^2 + \frac{2GMJ^2}{r^2} \right) d\phi^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2$$

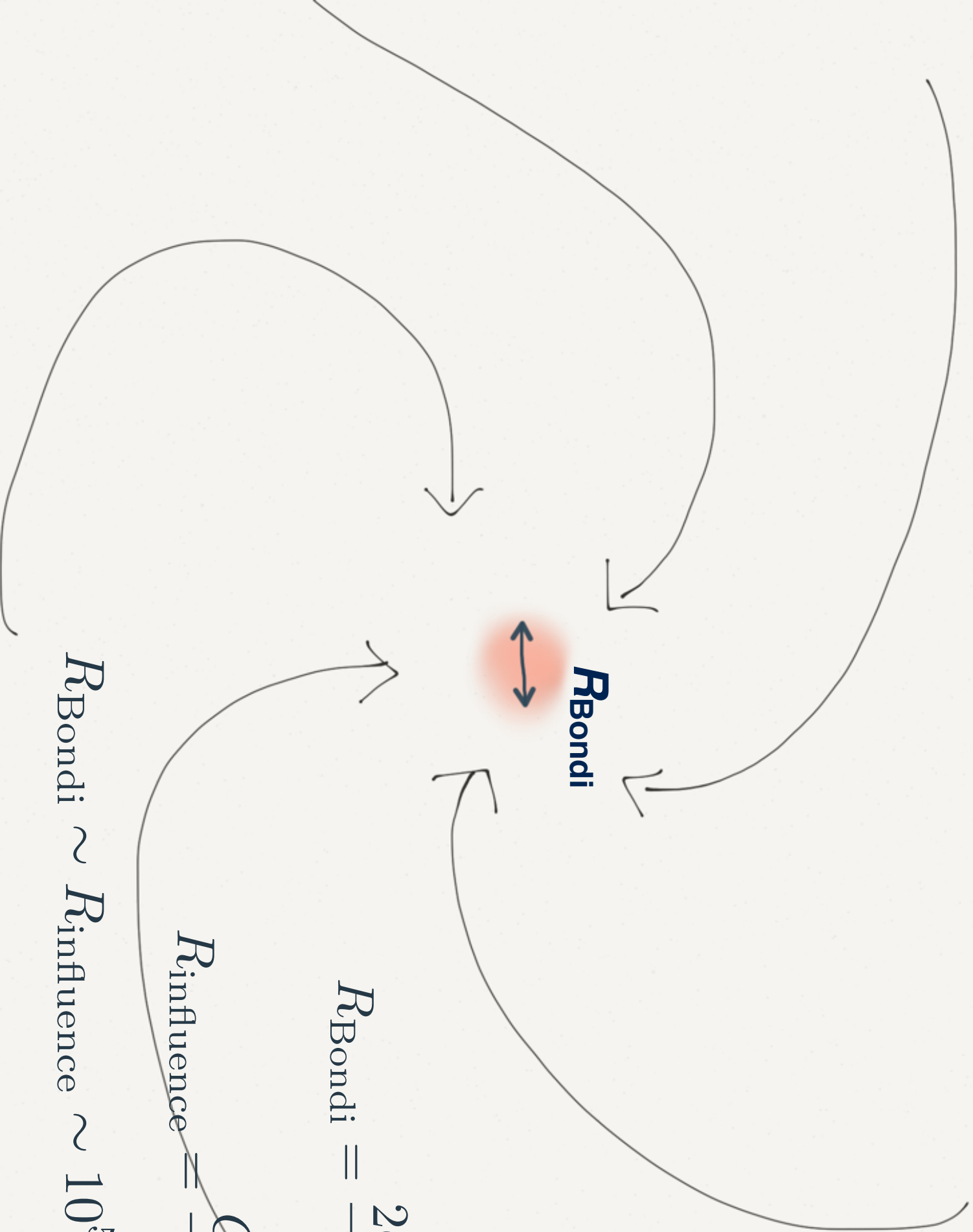
**Described completely
by their mass and spin**

$$J = a GM^2/c$$

$$0 \leq |a| \leq 1$$

***Once inside, nothing
escapes***



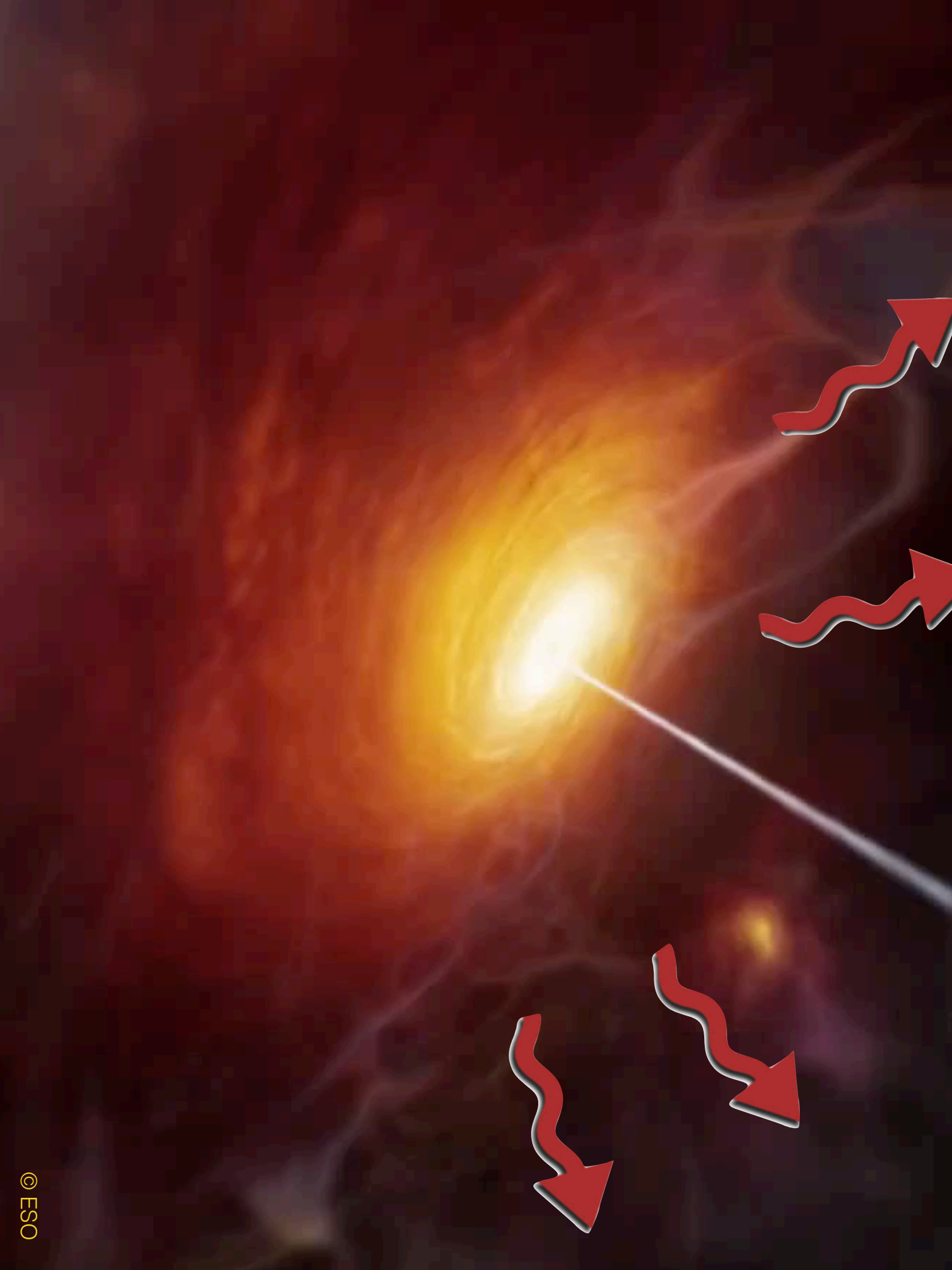


$$R_{\text{Bondi}} = \frac{2GM}{c_s^2}$$

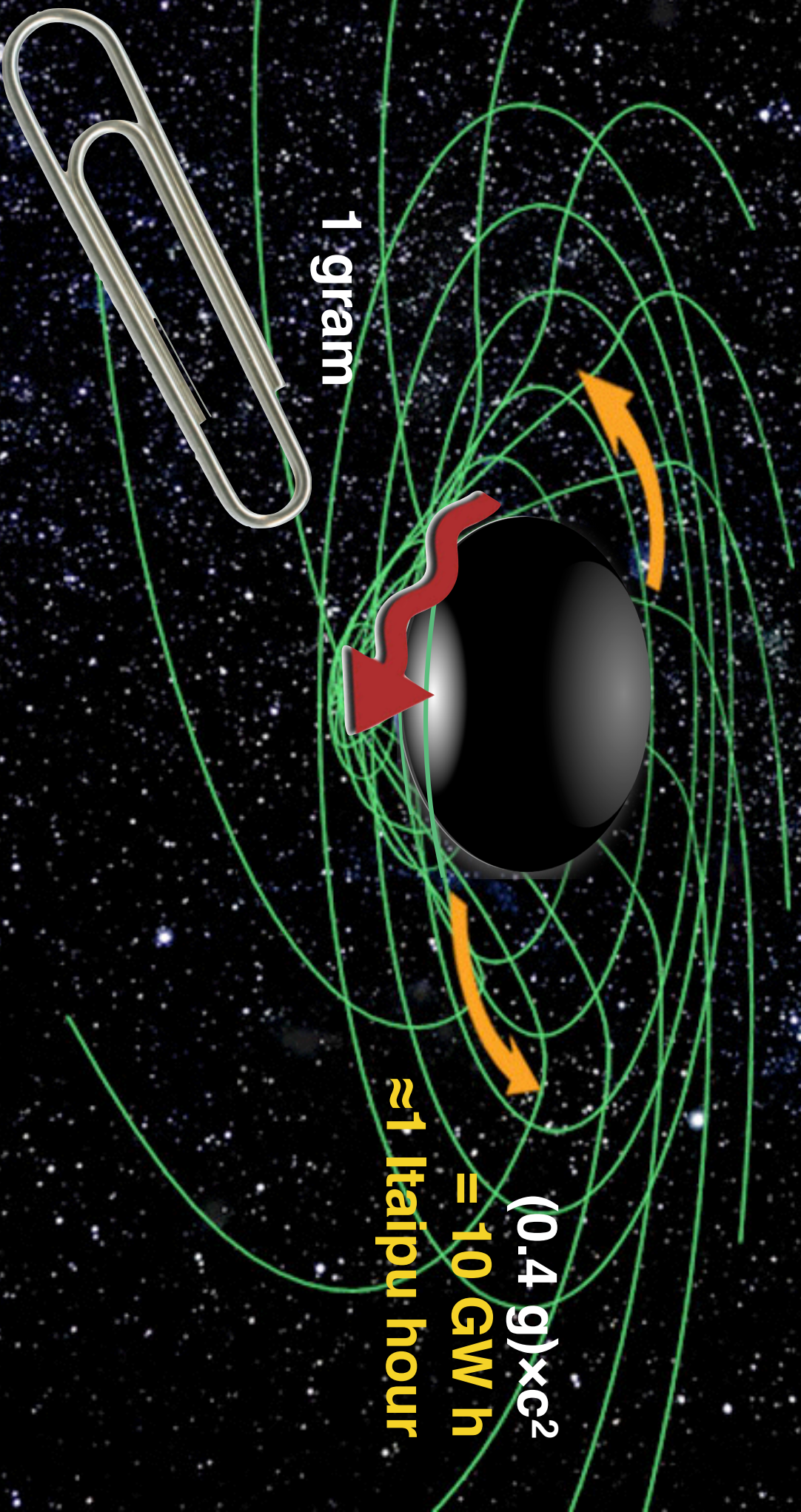
$$R_{\text{influence}} = \frac{GM}{\sigma^2}$$

$$R_{\text{Bondi}} \sim R_{\text{influence}} \sim 10^5 R_s$$

$$R_{\text{Bondi}} \sim R_{\text{influence}} \sim 10^5 R_s$$



Energy-extraction efficiency $\eta \equiv L/\dot{M}c^2$ from
Kerr black holes: η up to 40%

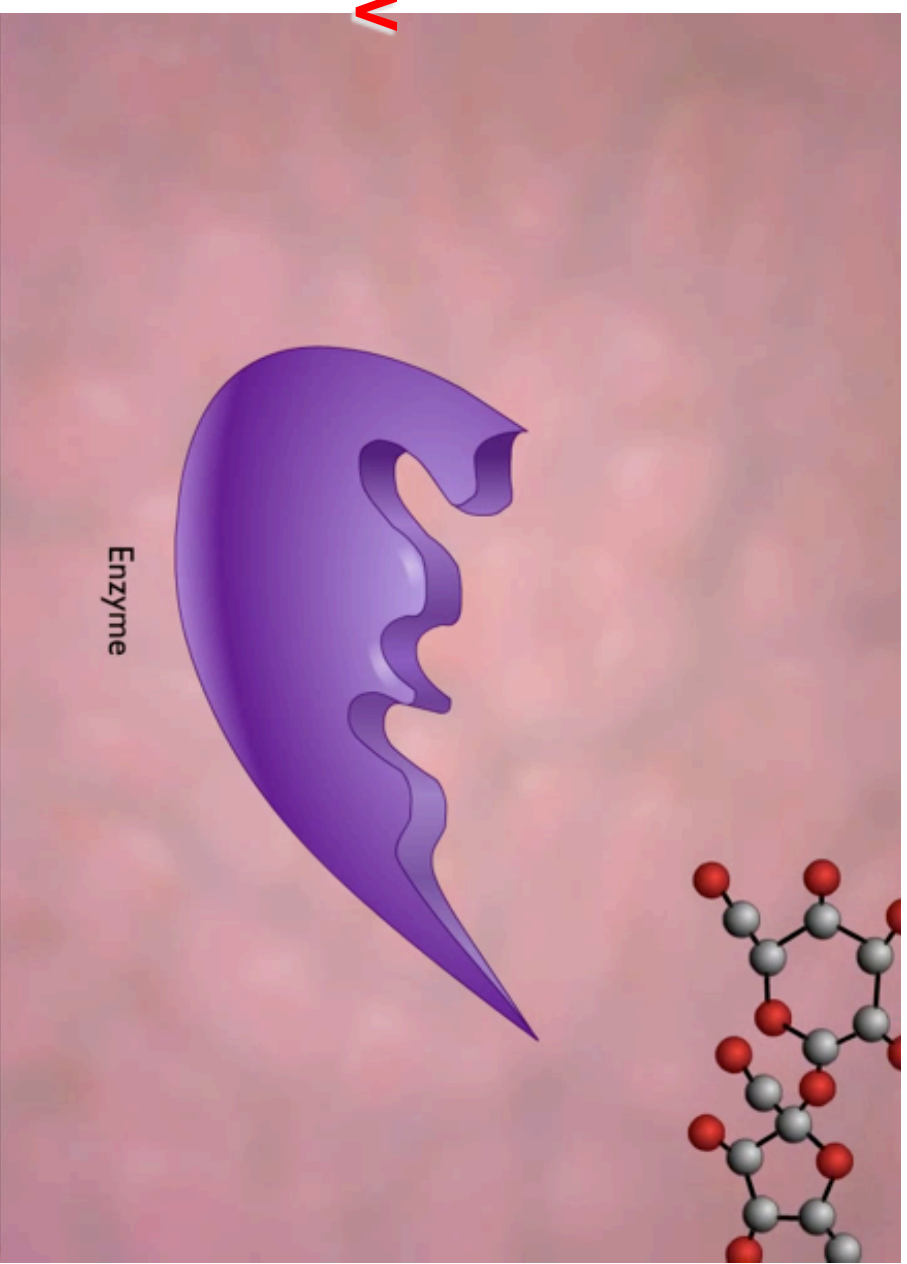


1 gram

$(0.4 \text{ g}) \times c^2$
 $= 10 \text{ GW h}$
 $\approx 1 \text{ Itaipu hour}$

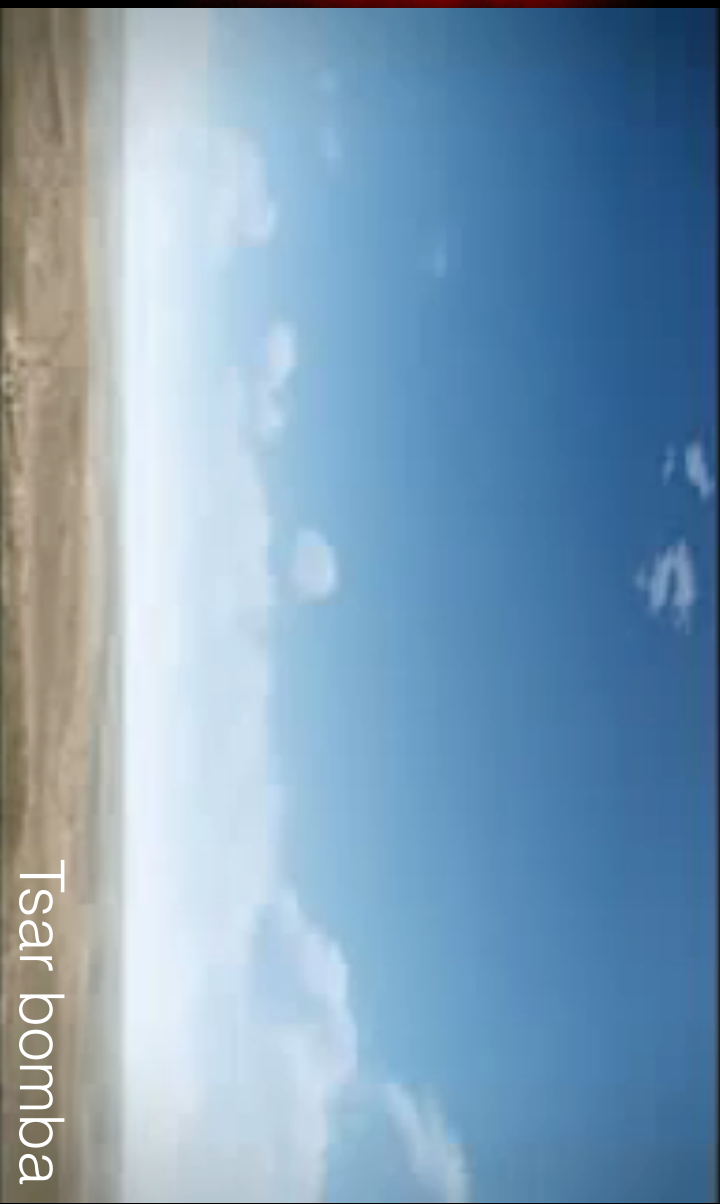
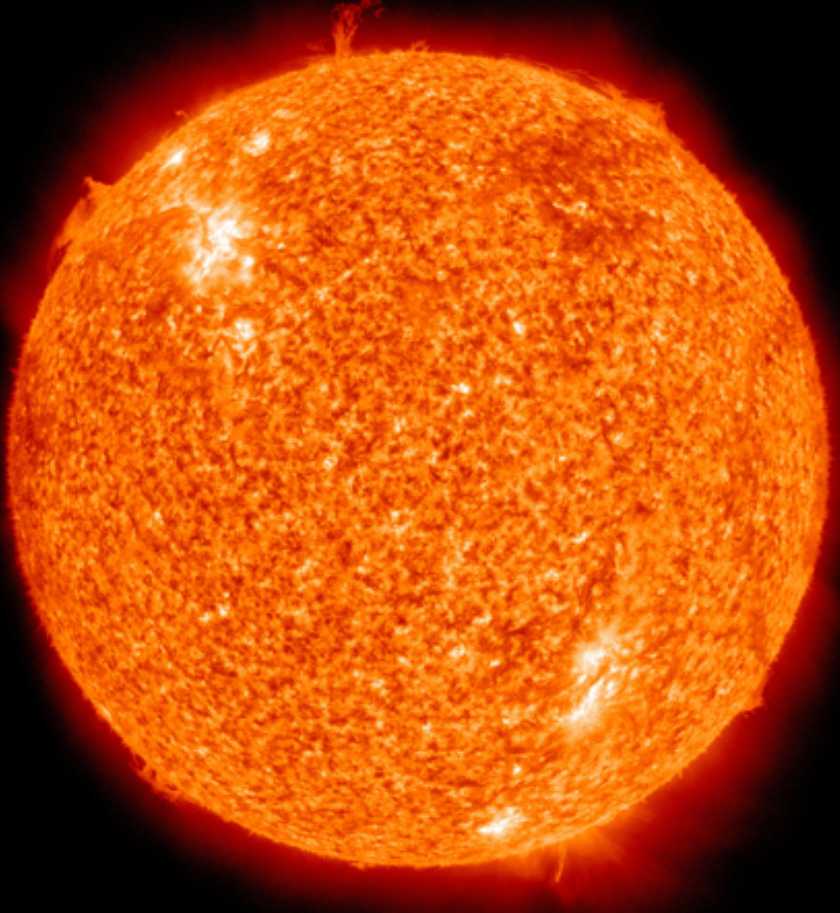
Sugar (sucrose) $\text{C}_{12}\text{H}_{22}\text{O}_{11}$

$1\text{g} \rightarrow 4\text{ kcal} = 16.2\text{ kJ} = 1\text{e}23\text{ eV}$



$$\eta = \frac{E}{mc^2} = \frac{1.6 \times 10^{11} \text{erg}}{9 \times 10^{20} \text{erg}} = 2 \times 10^{-10}$$

Nuclear fusion

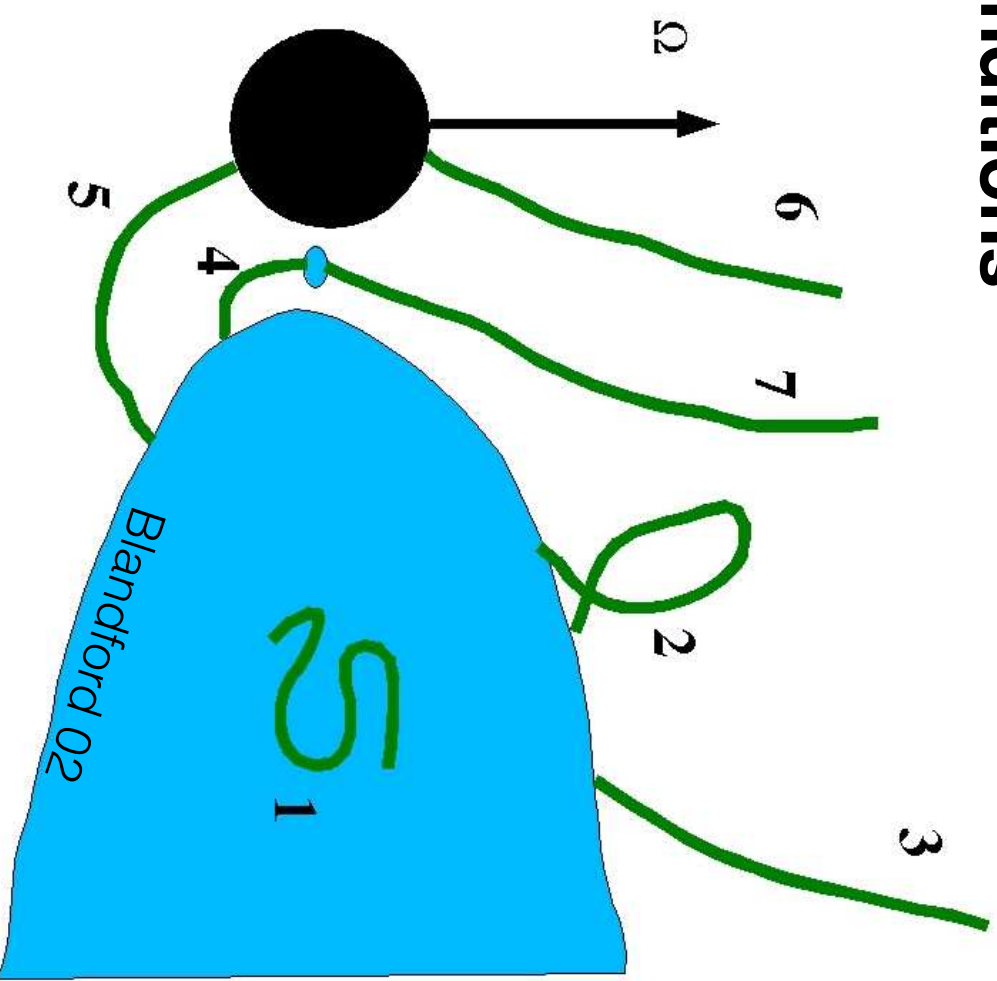
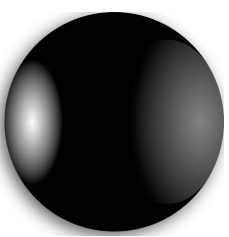


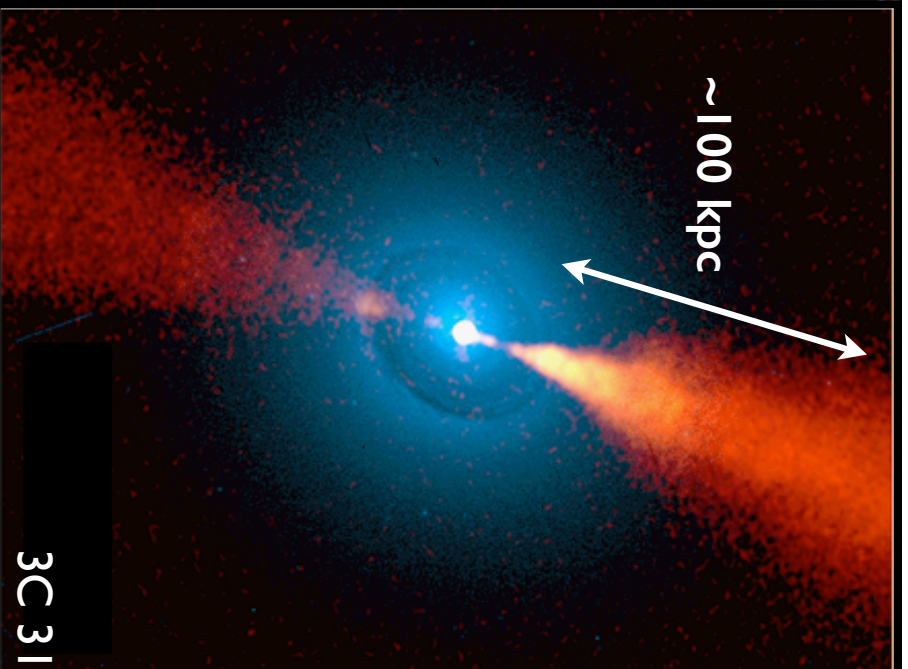
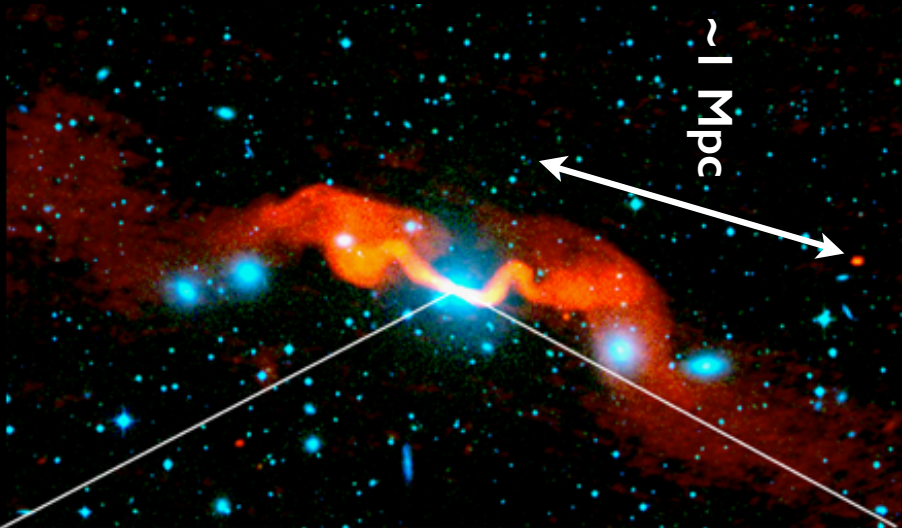
Tsar bomba

$$\eta = 0.008 \times 0.1 \sim 8 \times 10^{-4}$$

Black hole accretion is messy: lack of knowledge about

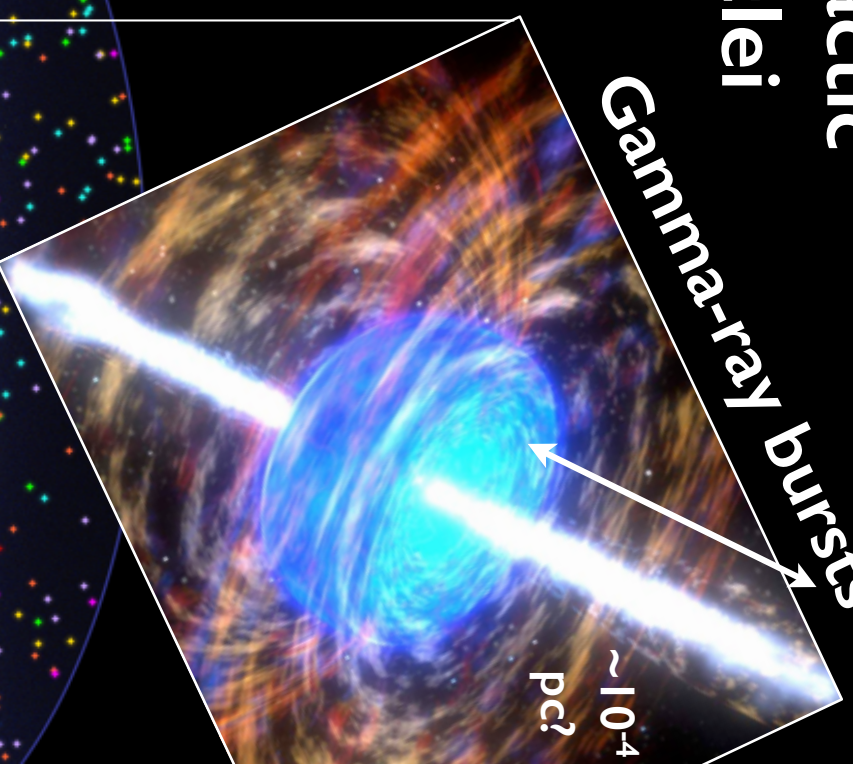
- Plasma physics
- (Outer boundary / Initial) conditions
- Magnetic field geometry





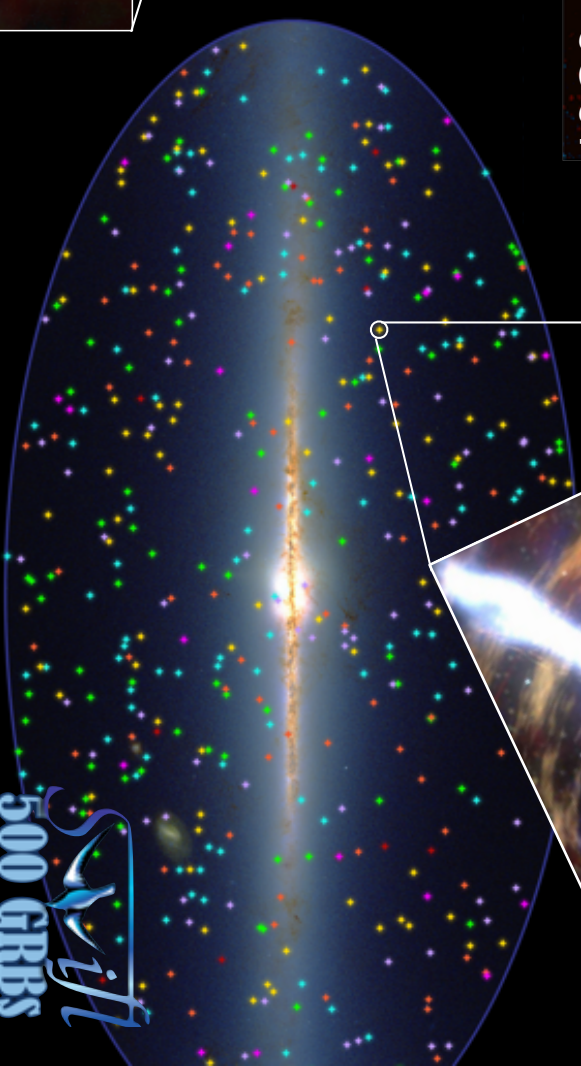
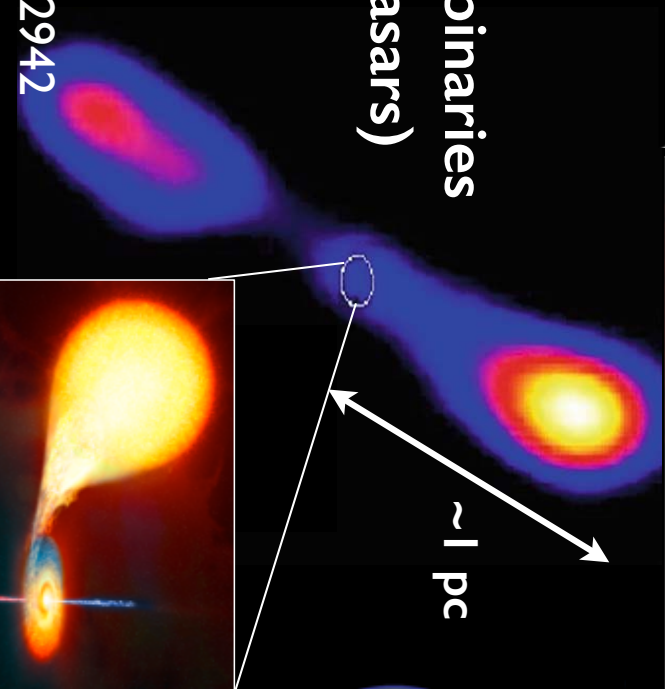
**Active
galactic
nuclei**

Gamma-ray bursts

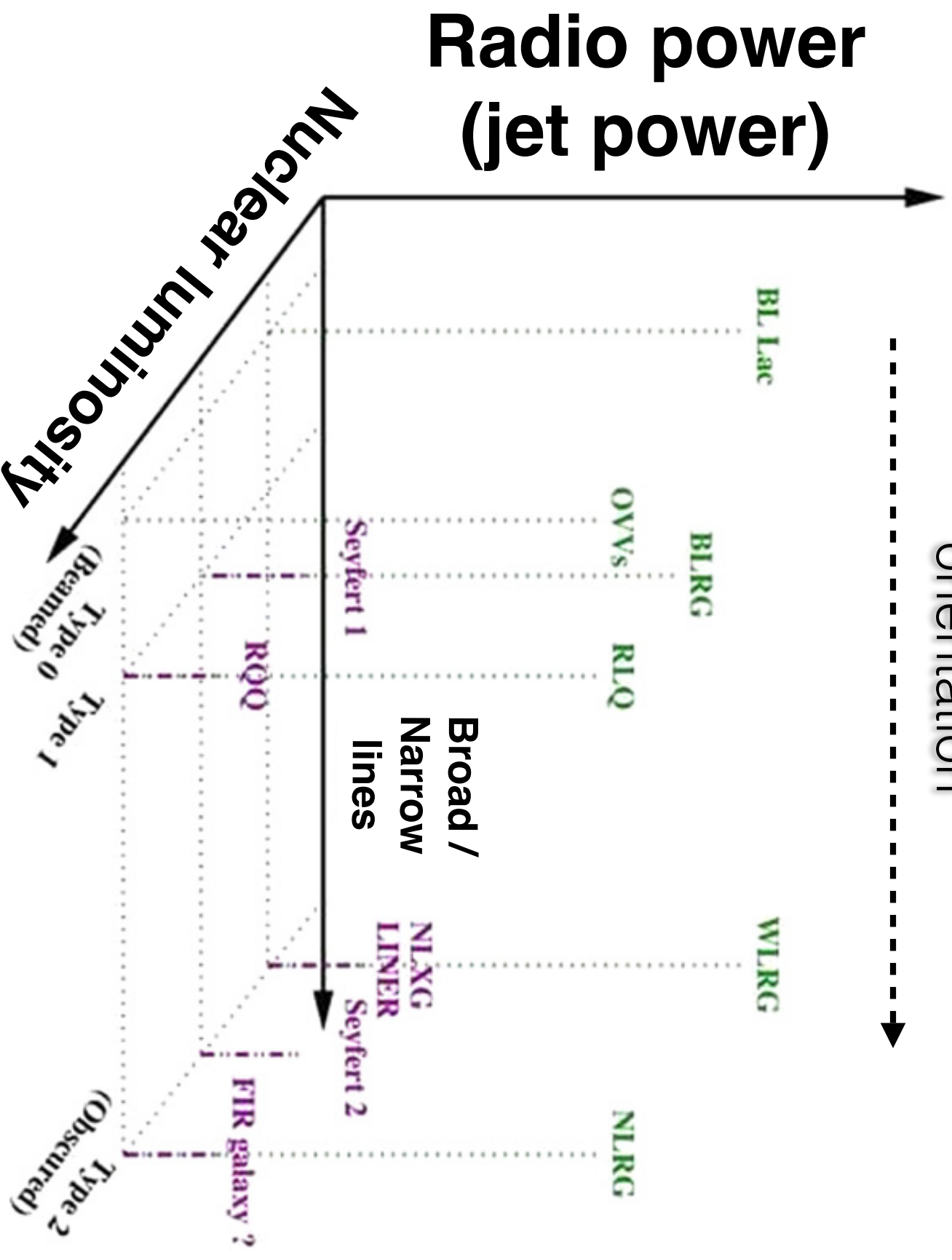


**Black hole binaries
(microquasars)**

1E1740.7-2942



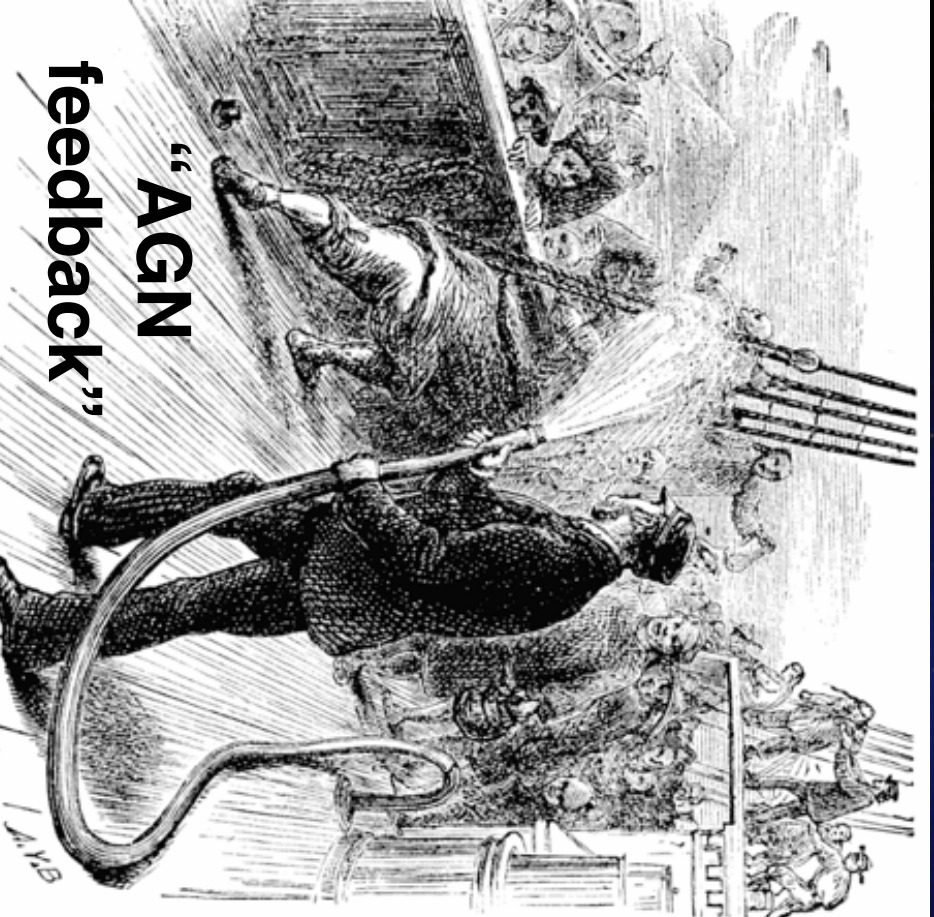
Black hole accretion $\Rightarrow$ Active galactic nuclei (AGN) $\Rightarrow$ Very complex phenomenology
 orientation



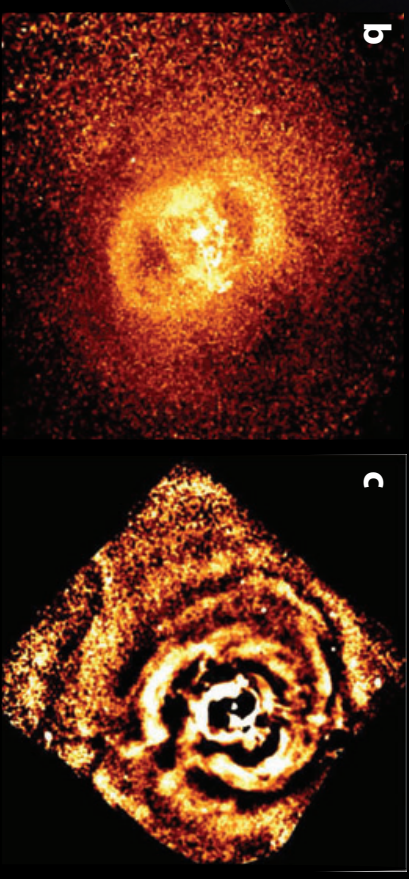
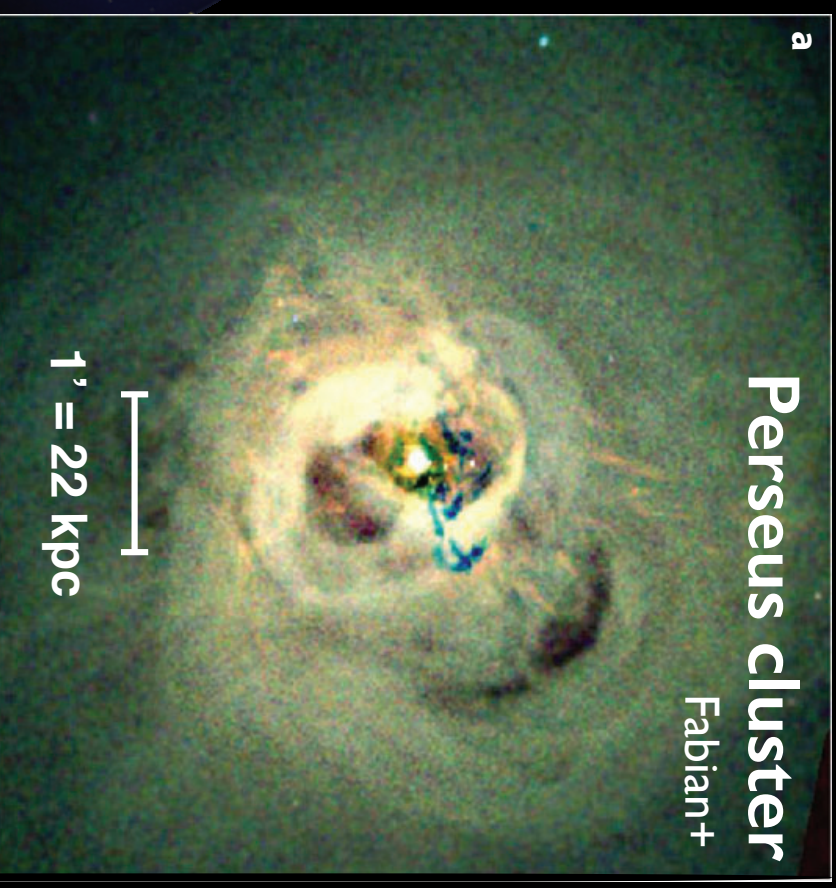
AGN feedback: Supermassive black hole outflows affect the evolution of galaxies and galaxy clusters

MS0735

McNamara+05 *Nature*,
McNamara+ 09



“AGN
feedback”





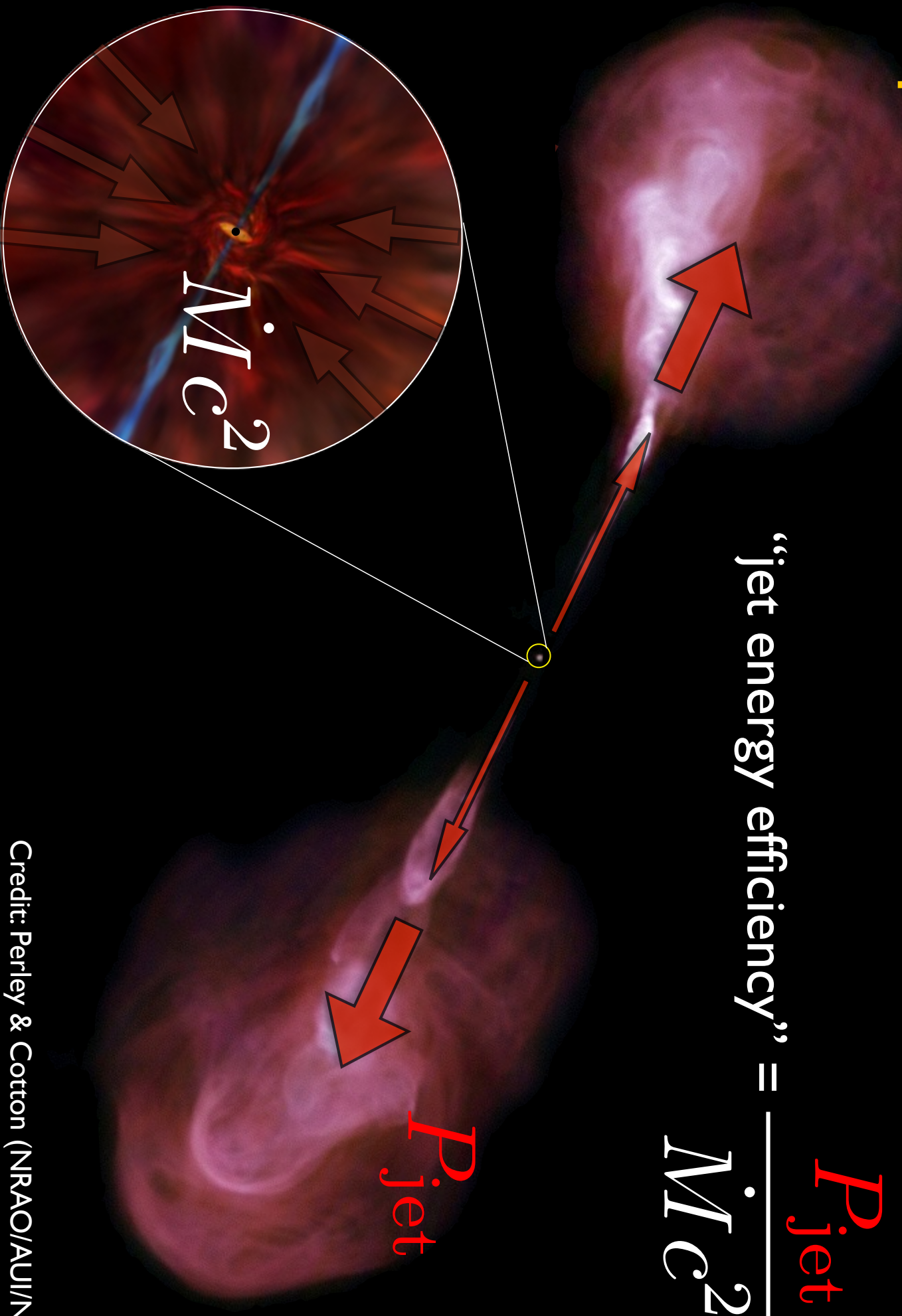
Outstanding questions:

How do you get jets from black holes?

What is the source of the outflow power: disk or hole?

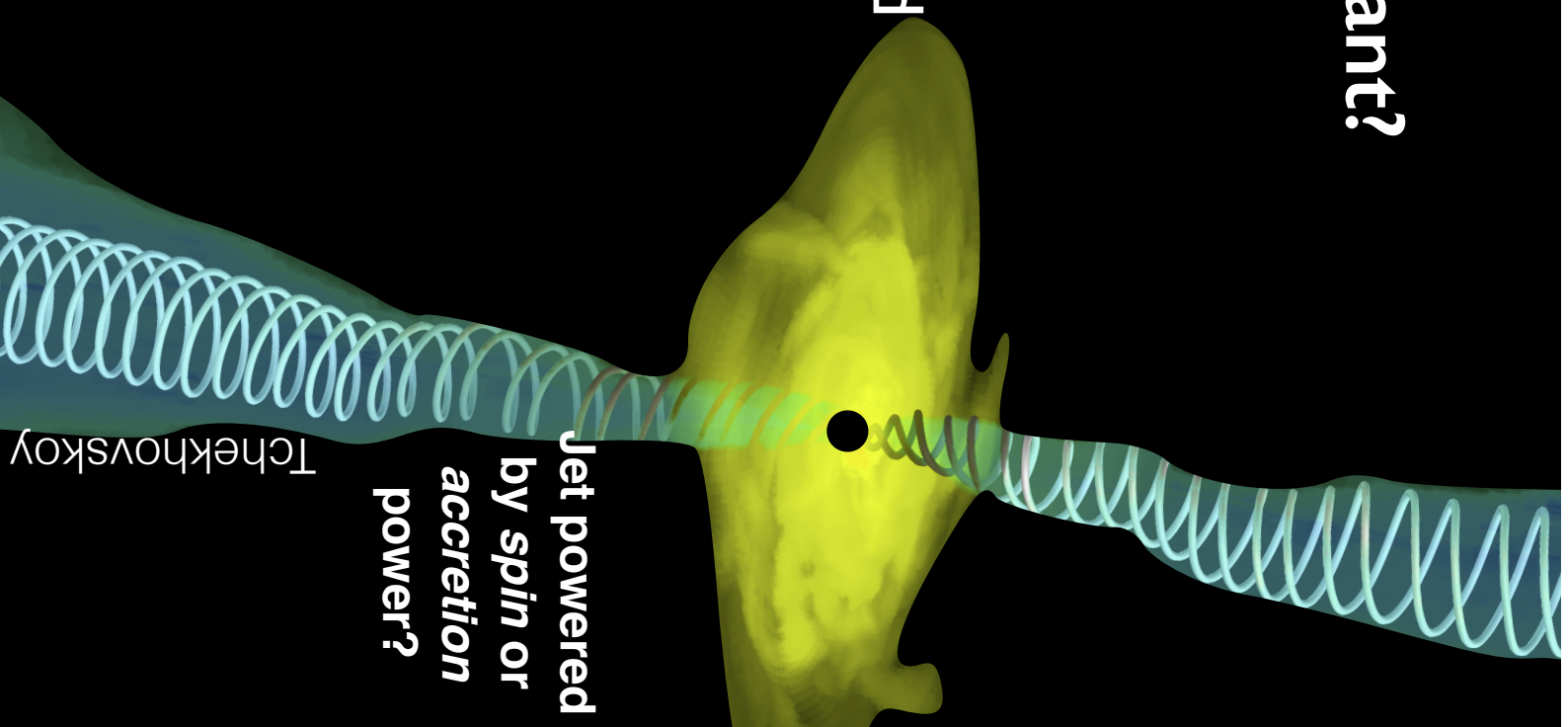
Driving goal: Obtain jet production efficiency from supermassive black holes

$$\text{“jet energy efficiency”} = \frac{P_{\text{jet}}}{\dot{M}c^2}$$

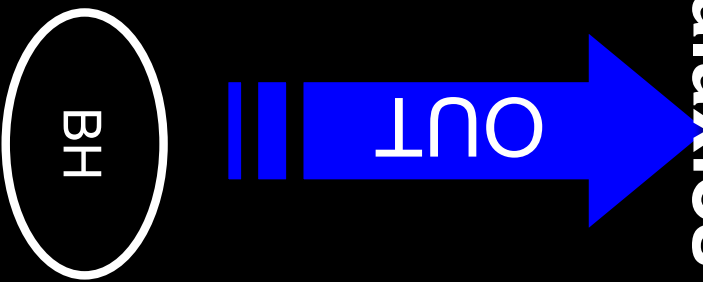


Why is $\eta_{\text{jet}} \equiv \frac{P_{\text{jet}}}{\dot{M}c^2}$ important?

- Diagnostic of jet formation process and accretion physics
- AGN feedback scenarios
- Growth rate of massive black holes

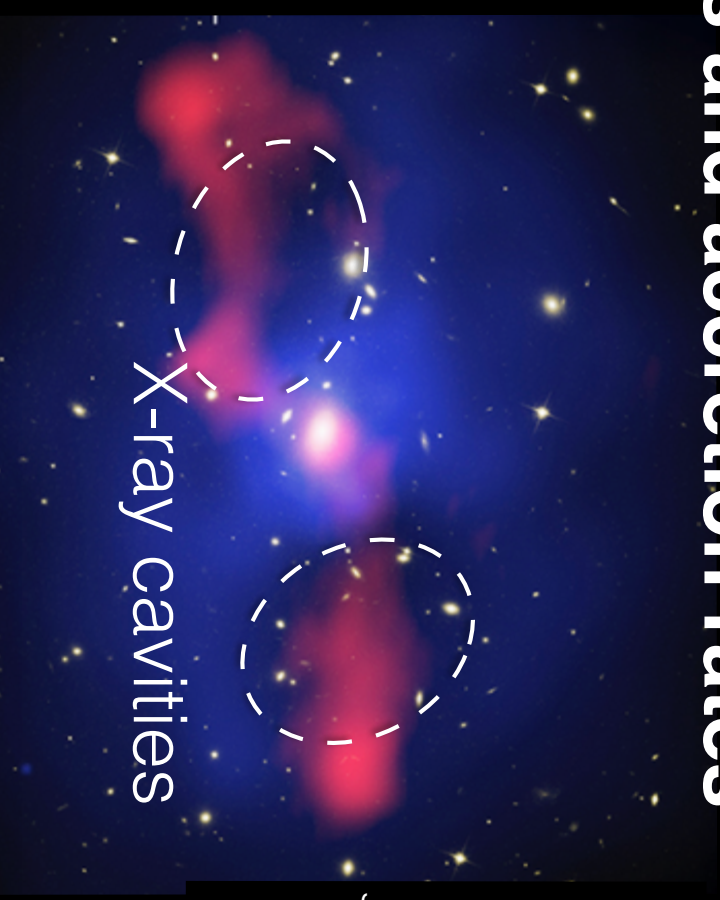


Chandra observations of 27 nearby radio galaxies provide jet powers and accretion rates



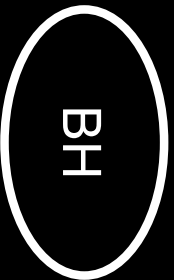
Jet power

$$P_{\text{jet}} = E_{\text{bubble}} / t_{\text{age}} \\ (4P_{\text{bub}}) (R_{\text{bub}} / c_s)$$



McNamara+05, Nature

Chandra observations of 27 nearby radio galaxies provide jet powers and accretion rates

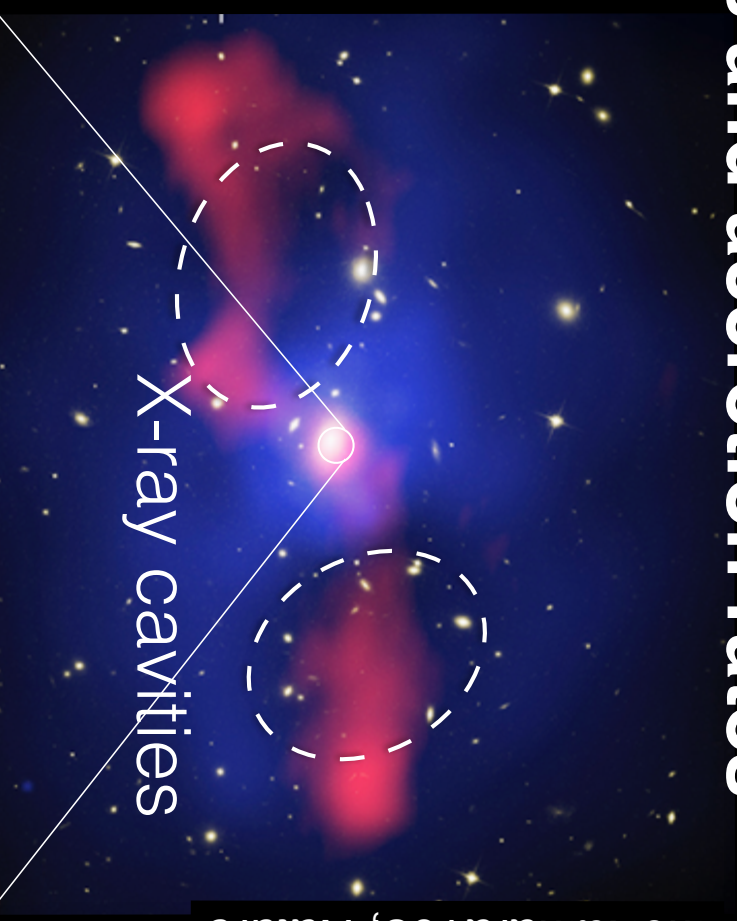


Jet power

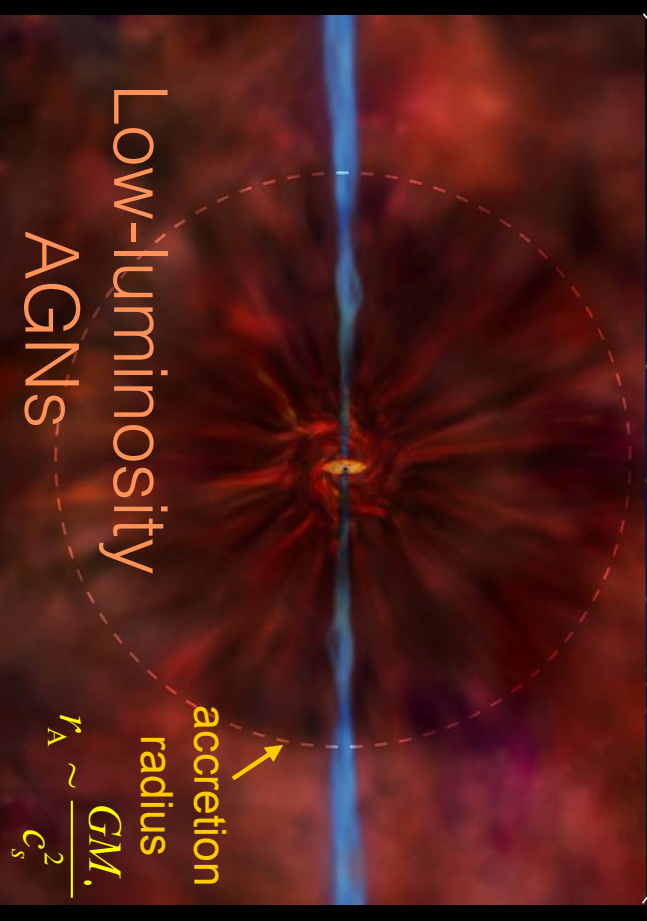
$$P_{\text{jet}} = E_{\text{bubble}} / t_{\text{age}} \\ (4PV_{\text{bub}}) \quad (R_{\text{bub}} / c_s)$$

“Bondi”
inflow rate

$$\dot{M}_B \propto M^2 T^{-3/2} n \\ \dot{M}_B < 0.01 \dot{M}_{\text{Edd}}$$



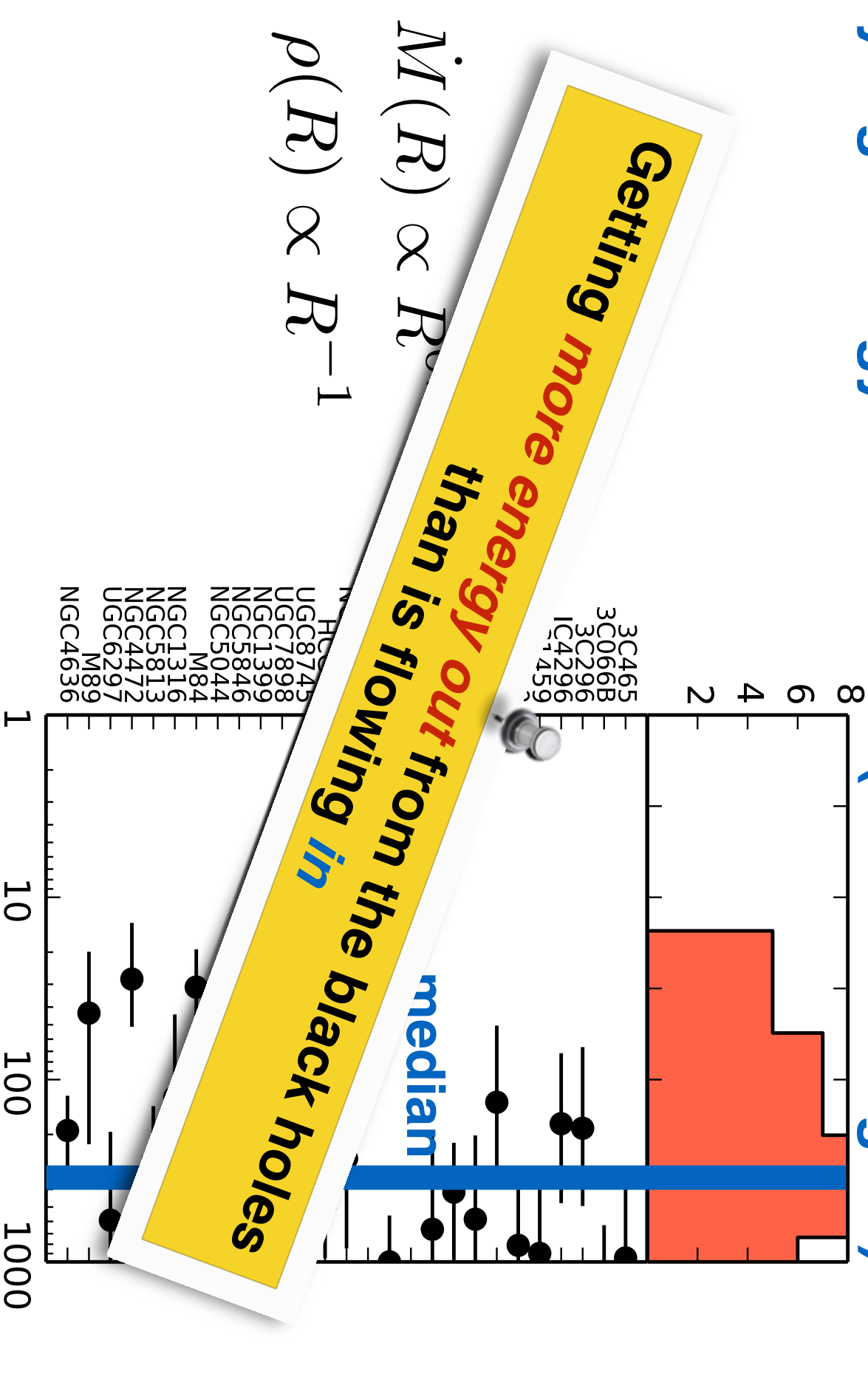
McNamara+05, Nature



Low-luminosity
AGNs

accretion
radius
 $r_A \sim \frac{GM}{c_s^2}$

X-ray observations of nearby AGNs with jets imply very high energy efficiencies (~100% or higher)

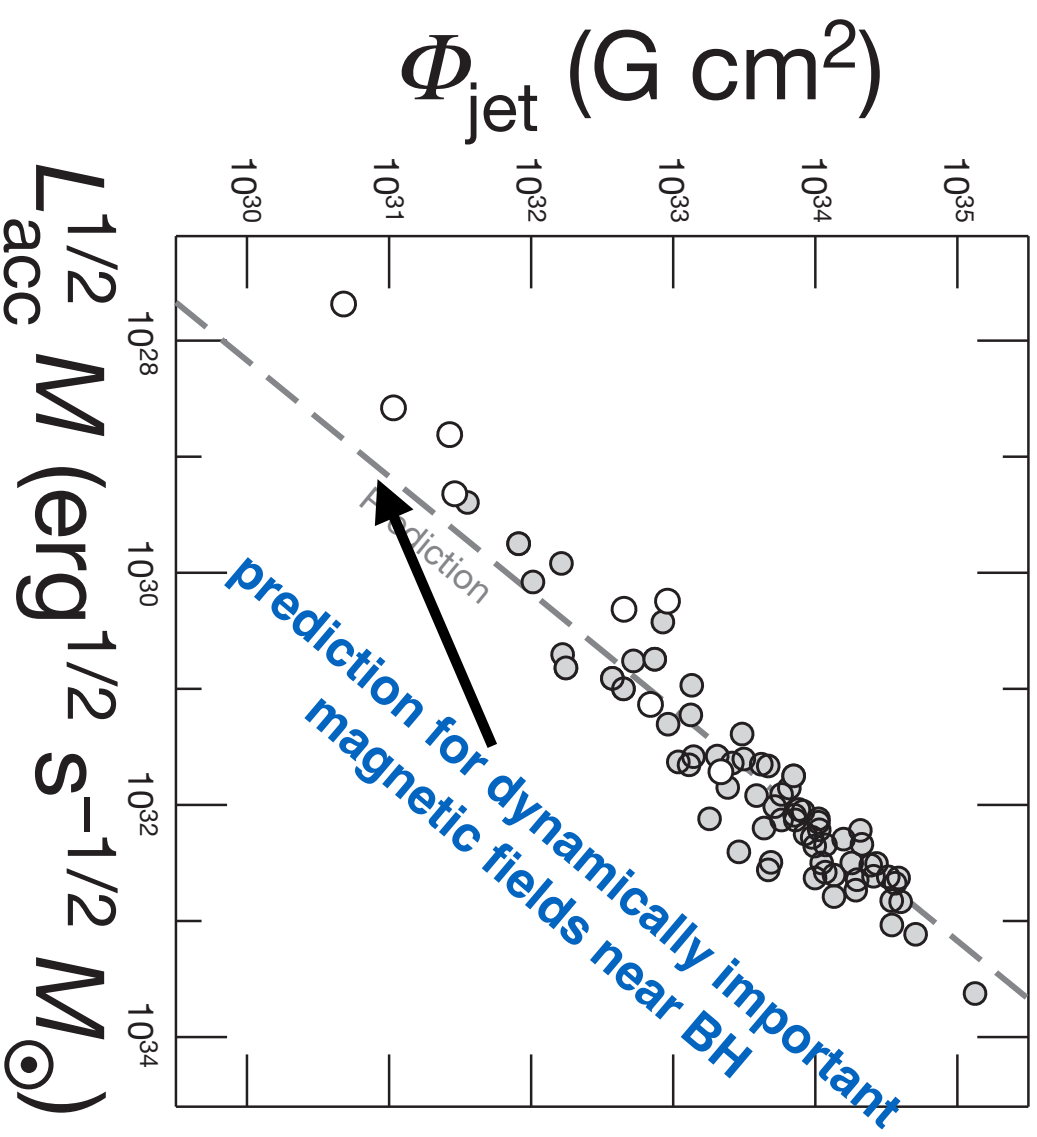
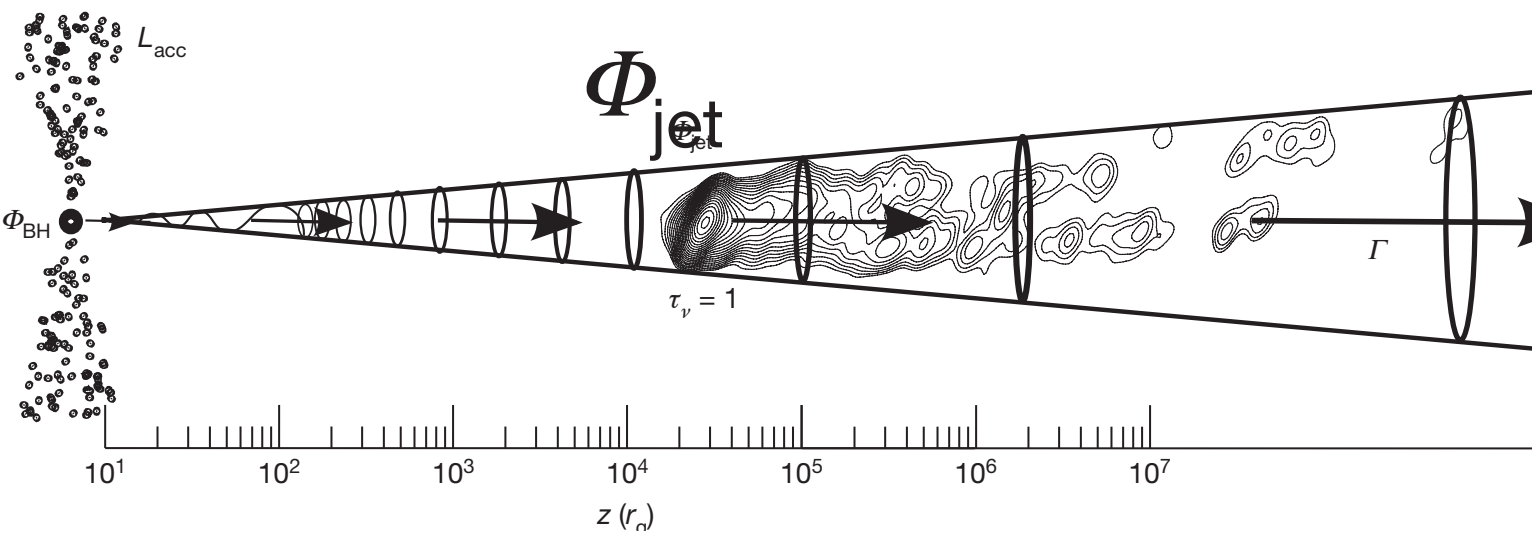


Three more puzzling observations load more radio-

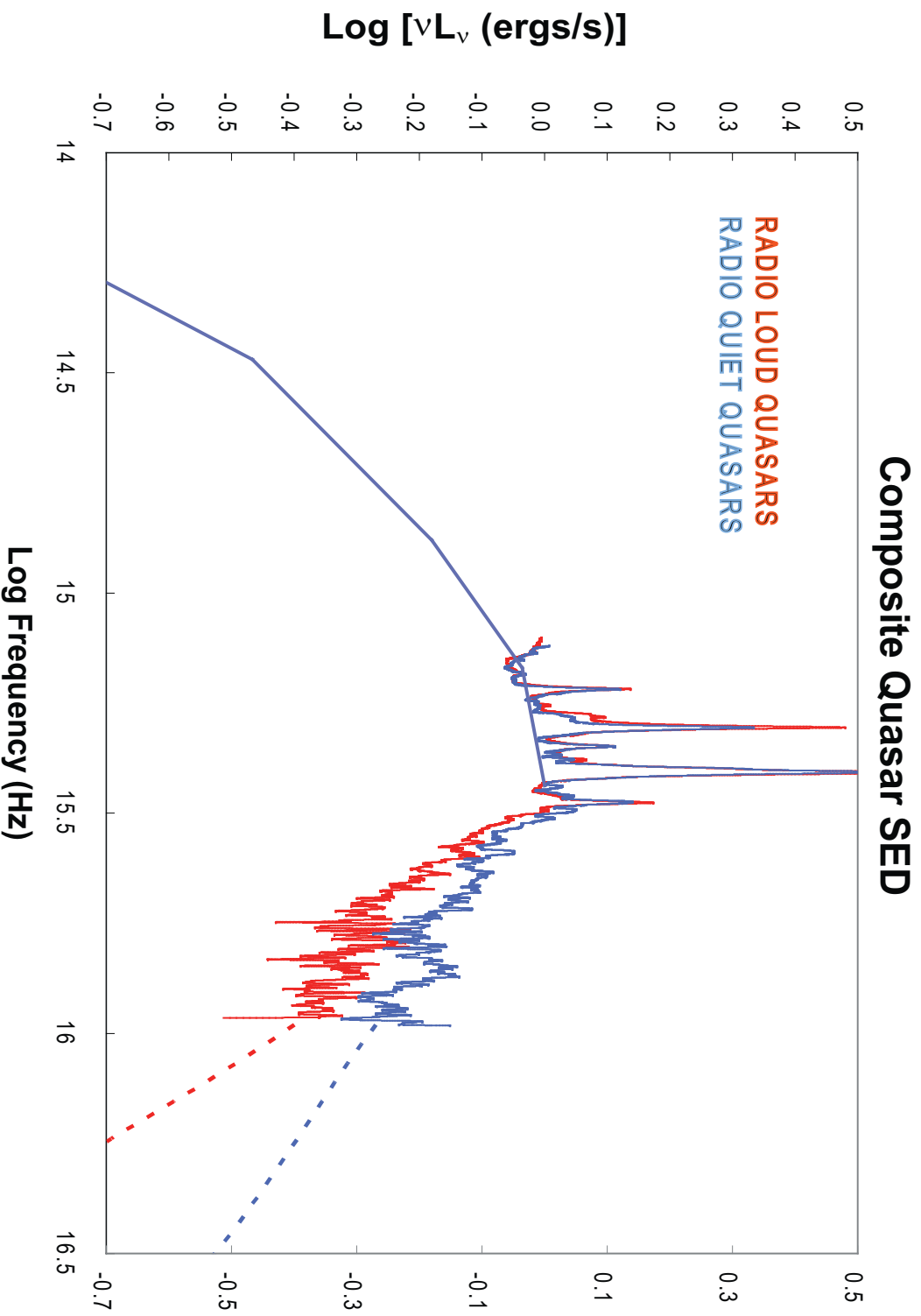
SKIP THESE FOR THIS TALK

Dynamically important magnetic fields near accreting supermassive black holes

M. Zamaninasab¹, E. Clausen-Brown¹, T. Savolainen¹ & A. Tchekhovskoy^{2,3}



UV deficit in radio-loud quasars compared to radio-quiet: destruction of inner accretion flow?



Oh my, how to explain?

N & Tchekhovskoy 2015

1. $>100\%$ jet energy-efficiency in LLAGNs
2. $P_{\text{jet}} \propto M$ & $P_{\text{jet}} > L_{\text{acc}}$ e.g., Ghisellini+10, 14
3. Dynamically important magnetic fields near BH Zamaninasab+14
4. UV deficit in radio-loud quasars Punsly 15

Field equations

$$(\rho u^\mu)_{;\mu} = 0$$

$$T^\mu_{\nu;\mu} = 0$$

$$F_{\mu\nu,\lambda} + F_{\lambda\mu,\nu} + F_{\nu\lambda,\mu} = 0$$

$$J^\mu = F^{\mu\nu}{}_{;\nu}$$

$$u_\mu F^{\mu\nu} = 0 \text{ (MHD)}$$

Kerr metric

$$ds^2 = - \left(1 - \frac{2r}{\rho^2} \right) dt^2 + \left(\frac{4r}{\rho^2} \right) dr dt$$

$$+ \left(1 + \frac{2r}{\rho^2} \right) dr^2 + \rho^2 d\theta^2$$

$$+ \sin^2 \theta \left[\rho^2 + a^2 \left(1 + \frac{2r}{\rho^2} \right) \sin^2 \theta \right] d\phi^2$$

Mass/energy/momentum

$$T^{\mu\nu}_{\text{fluid}} = (\rho + u + p) u^\mu u^\nu + p g^{\mu\nu}$$

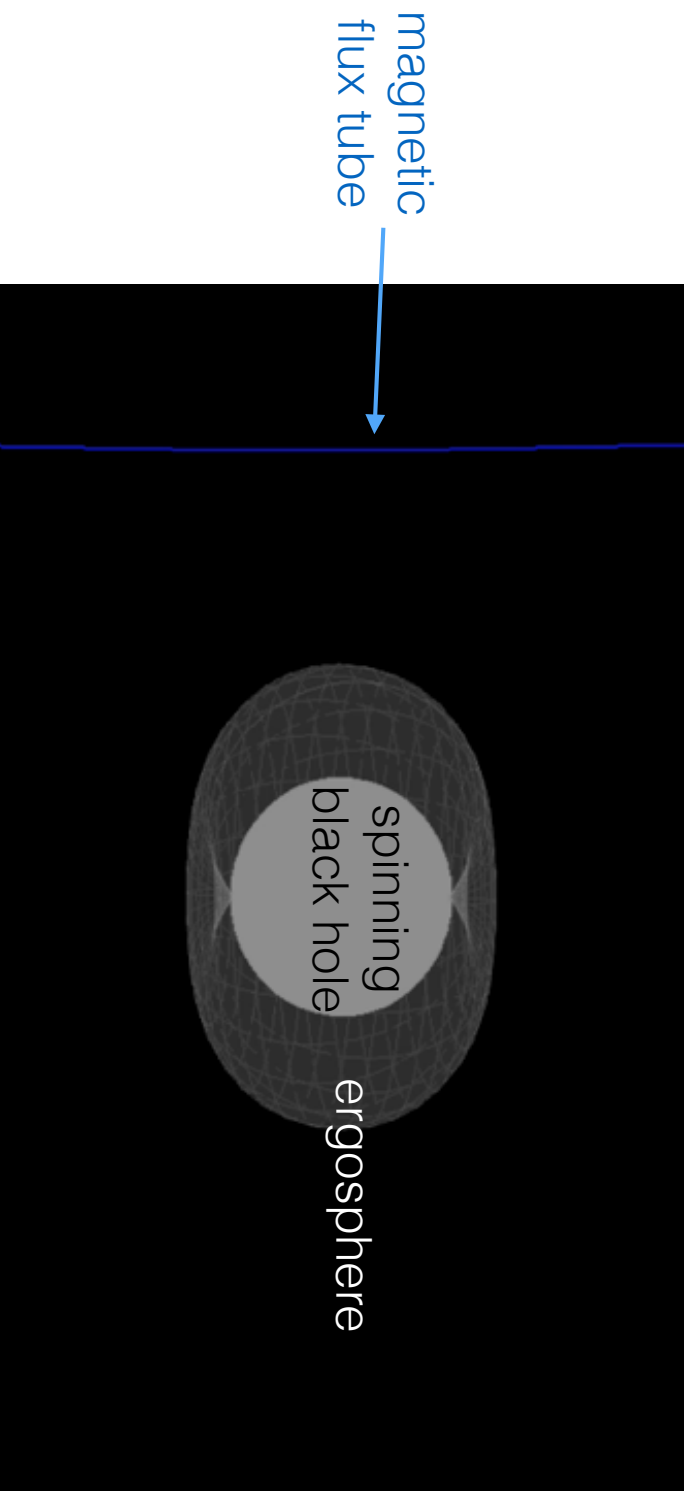
E and B fields

$$b^\mu \equiv \frac{1}{2} \epsilon^{\mu\nu\kappa\lambda} u_\nu F_{\lambda\kappa}$$

$$F^{\mu\nu} = \epsilon^{\mu\nu\kappa\lambda} u_\kappa b_\lambda$$

$$T^{\mu\nu}_{\text{EM}} = F^{\mu\alpha} F^\nu_\alpha - \frac{1}{4} g^{\mu\nu} F_{\alpha\beta} F^{\alpha\beta}$$

Jet production from black holes: depends strongly on black hole spin + magnetic fields near the BH



Semenov+04, *Science*

Blandford-Znajek mechanism:

$$\text{Jet power} \propto \left(\frac{a\Phi_h}{M} \right)^2 \sim a^2 \dot{M} c^2$$

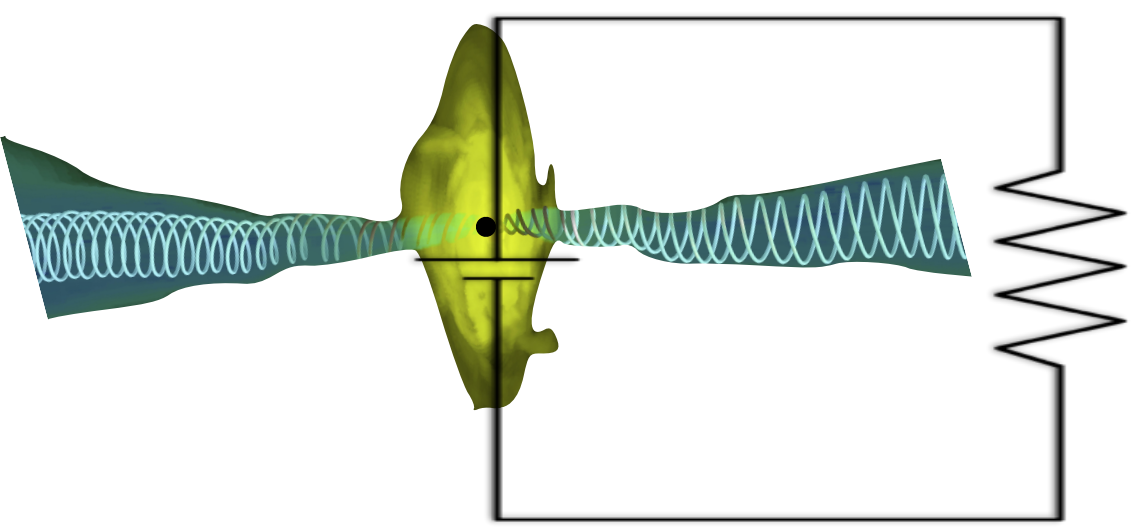
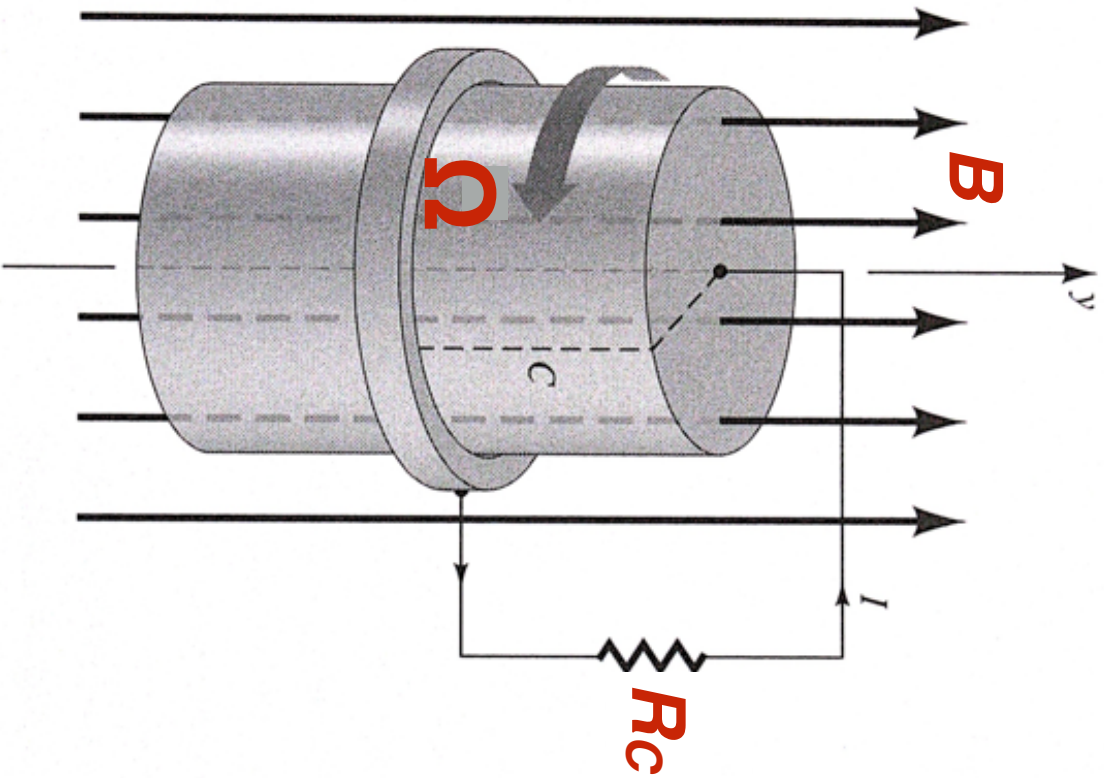
spin points to a
magnetic flux points to Φ_h

Blandford &
Znajek 77;

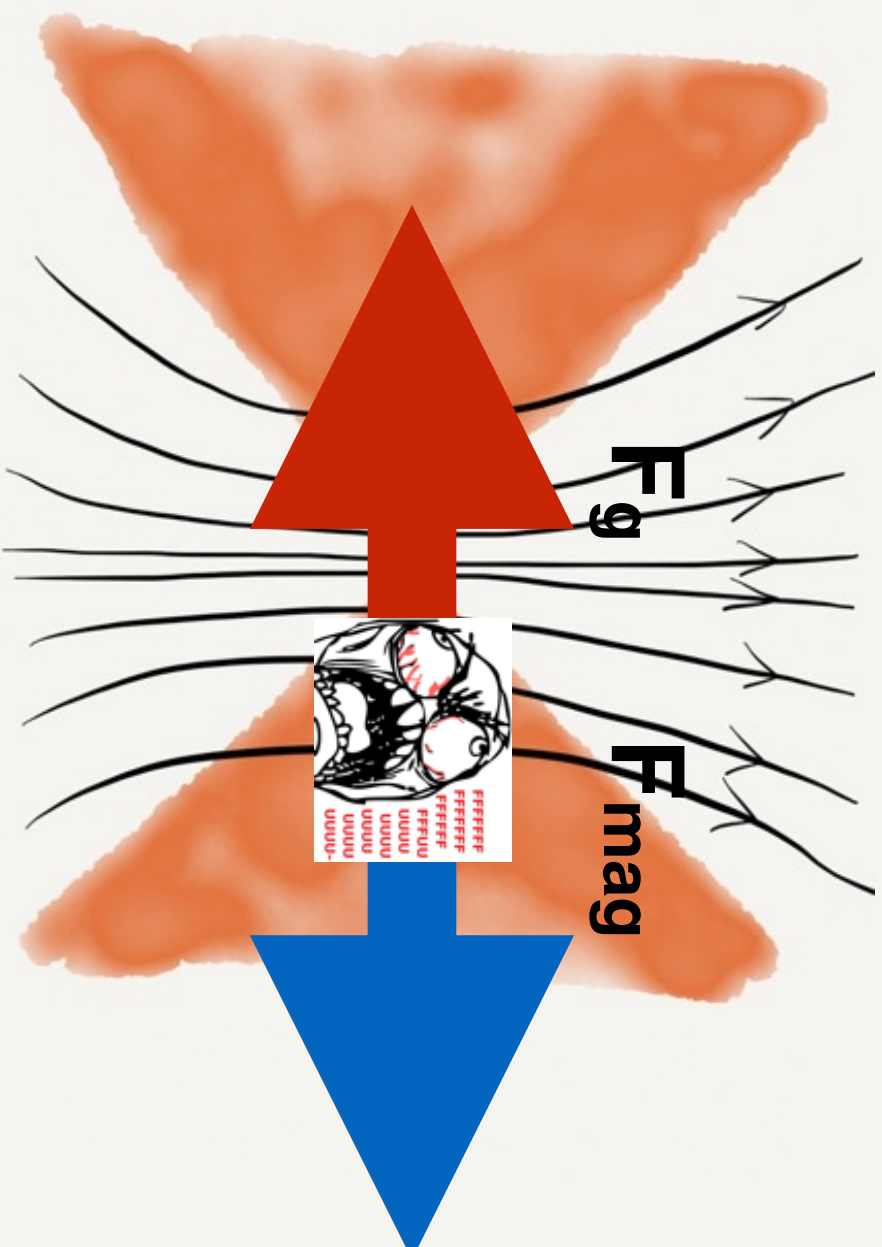
Komissarov+;
Nemmen+07;

Tchekhovskoy+

How to make a radio galaxy at home: Homopolar generator → “black hole battery”



Dynamically important magnetic fields + Kerr black holes → Magnetically arrested disks → **Powerful jets**



$$B_{\text{max}} \sim 10^4 \text{ [G]} \left(\frac{L}{0.1 L_{\text{Edd}}} \right)^{1/2} \left(\frac{M_{\text{BH}}}{10^9 M_{\odot}} \right)^{-1/2}$$

Bisnovatyi-Kogan & Ruzmaikin 74, 76; Igumenshchev+ 03;
Narayan+03; Tchekhovskoy+11; McKinney+12

Dynamically important magnetic fields + Kerr black holes → Magnetically arrested disks → **Powerful jets**

magnetically
arrested disk

MAD

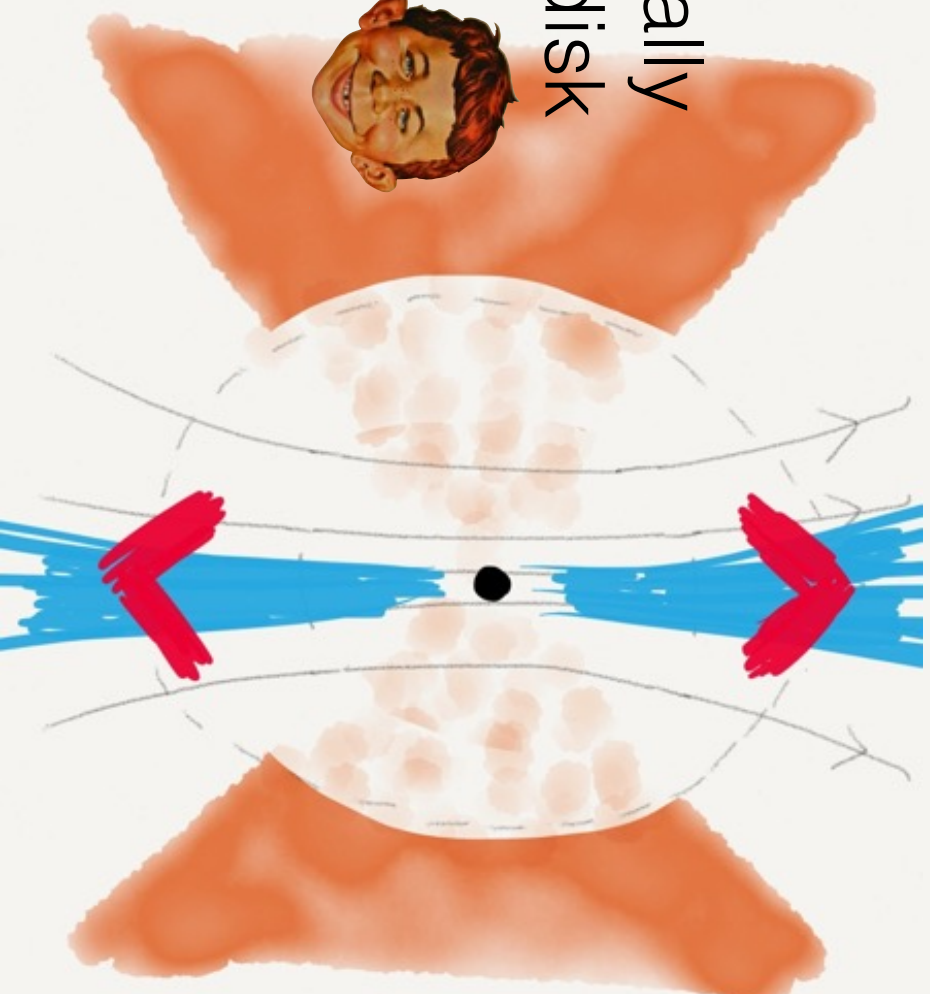


Bisnovatyi-Kogan & Ruzmaikin 74, 76; Igumenshchev+ 03;
Narayan+03; Tchekhovskoy+11; McKinney+12

Dynamically important magnetic fields + Kerr black holes → Magnetically arrested disks → **Powerful jets**

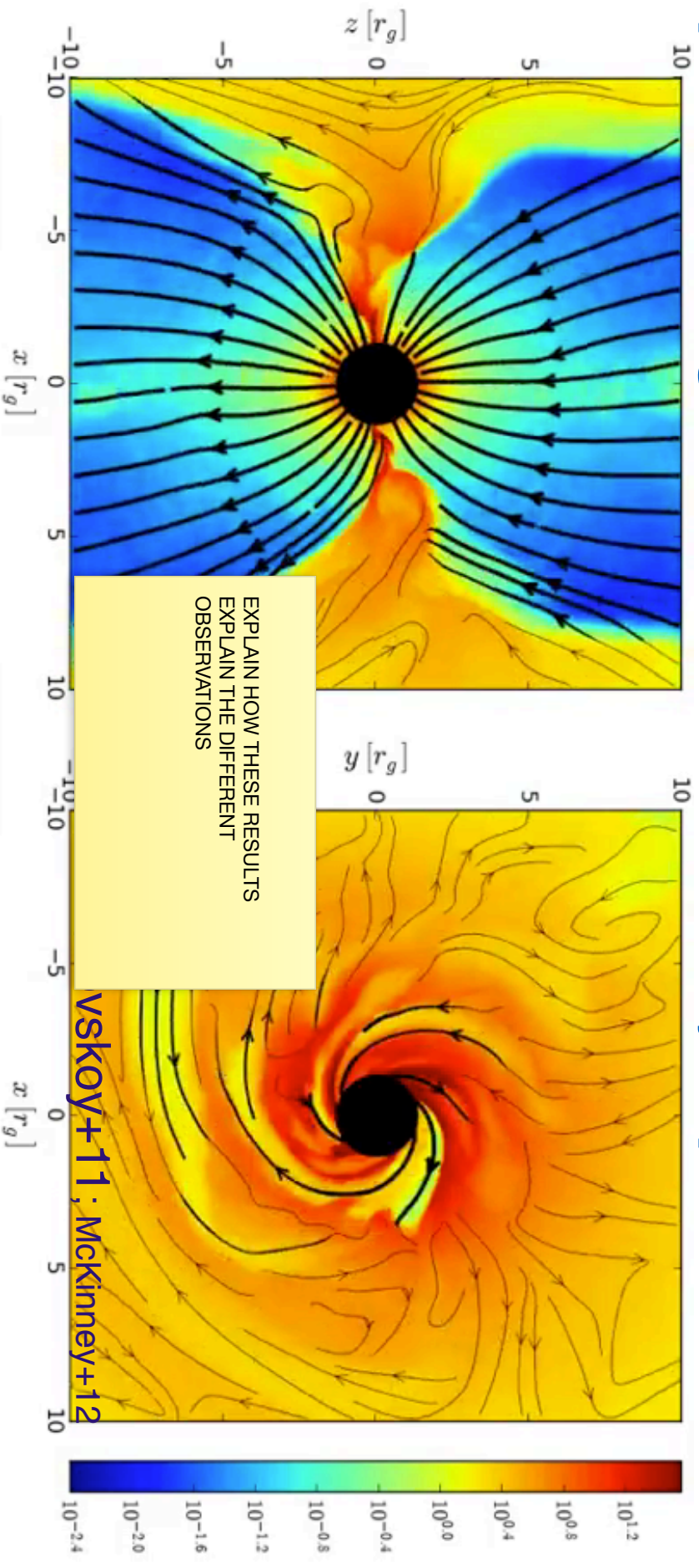
magnetically
arrested disk

MAD



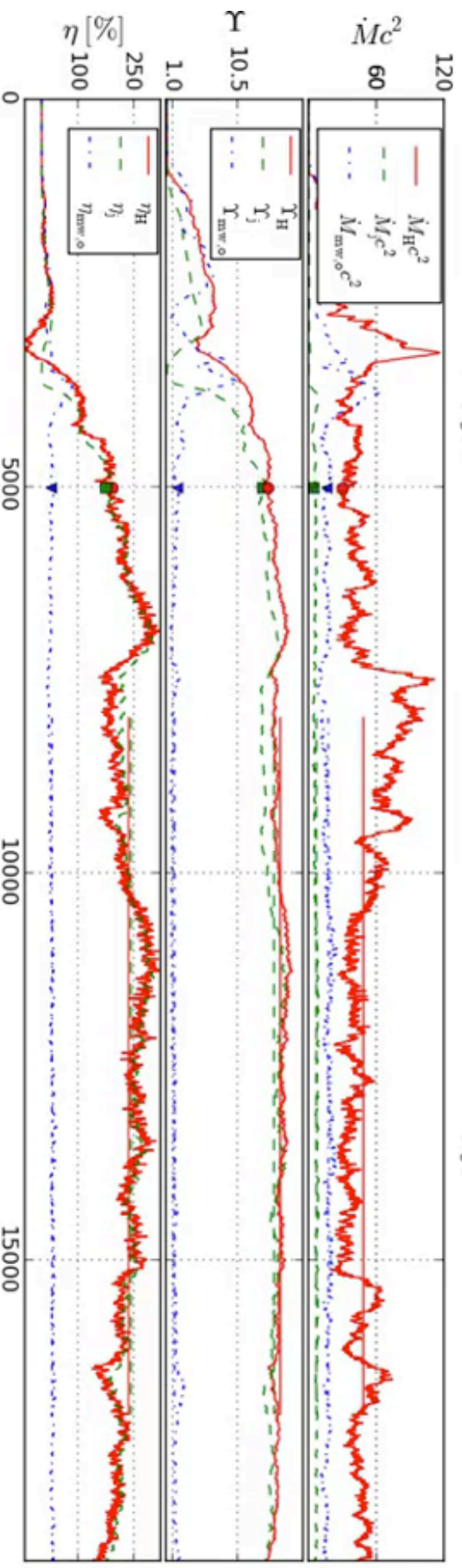
- applicability:
- RL AGNs
 - black hole binaries
 - GRBs?

Magnetically arrested disks (MADs): dynamically important magnetic fields lead to η_{jet} up to 300%



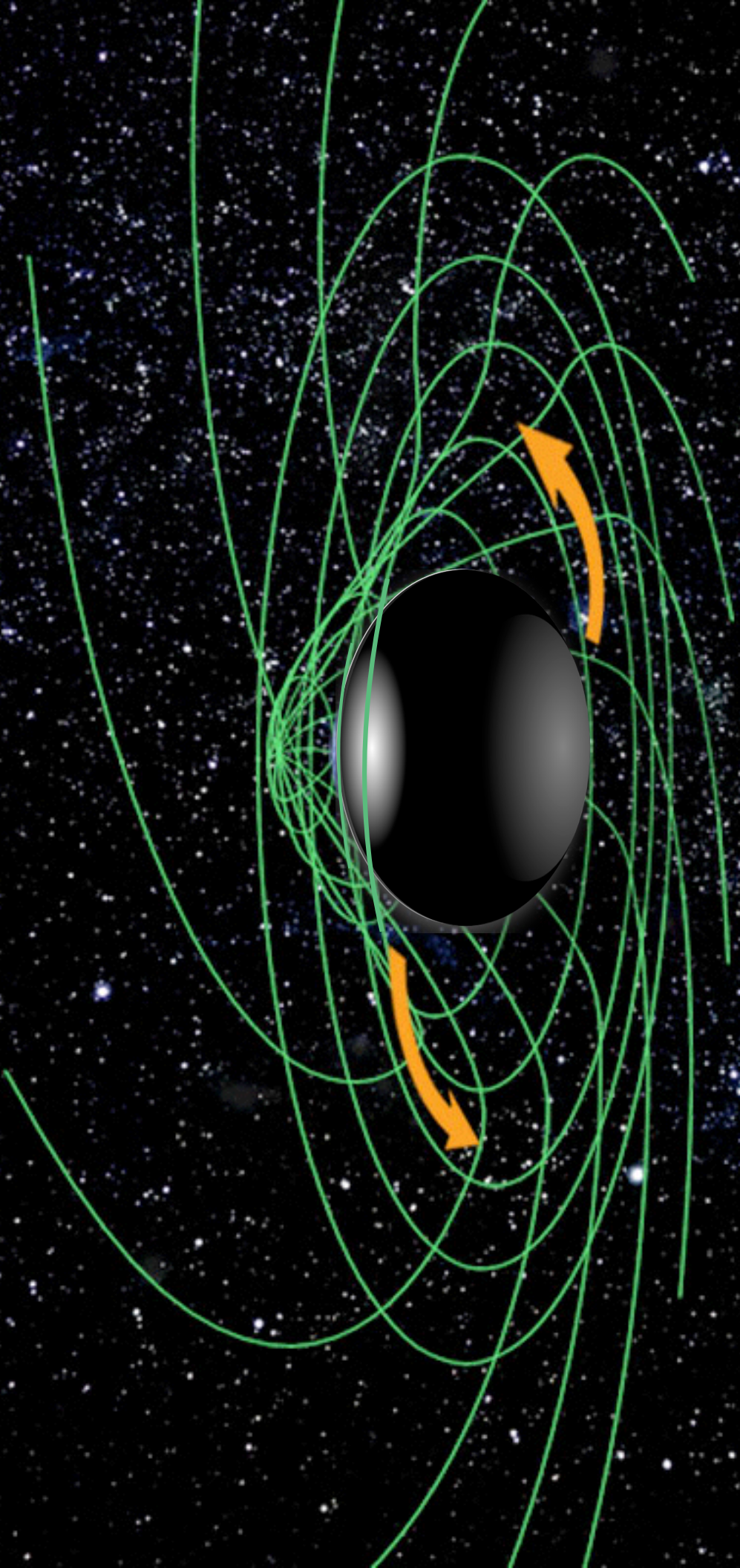
EXPLAIN HOW THESE RESULTS
EXPLAIN THE DIFFERENT
OBSERVATIONS

vskoy+11; McKinney+12



**Jet creation efficiencies $>100\%$ are possible if
black hole spin energy is extracted via BZ effect**

Nemmen & Tchekhovskoy 15; Blandford & Znajek 77



Kerr black holes surrounded by thin accretion disks: η up to 40%



**Kerr black holes threaded by dynamically
important magnetic fields (MADs):**

η up to 300%



Summary

Nemmen & Tchekhovskoy 2015, MNRAS

Relativistic outflows from black holes: most powerful and efficient machines out there

Affect:

- galaxy/clusters formation & evolution
- several important open questions about launching, powering, composition

Radio galaxies: More energy flowing out in jets than going in

(i) evidence for *spin energy extraction*

(ii) *dynamically-important magnetic fields is the new standard in accretion: magnetically arrested disks (MADs)*



Black hole astrophysics @ USP: theory / observations

Opportunities for graduate students and postdocs

Connection between accretion, outflows and black hole spin



Black hole activity across the mass scale

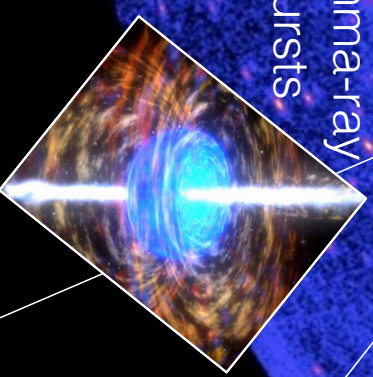


+ 4 other students

High energy astrophysics



Gamma-ray bursts



R. Nemmen
rodrigo.nemmen [[AT]] iag usp br

quasars

