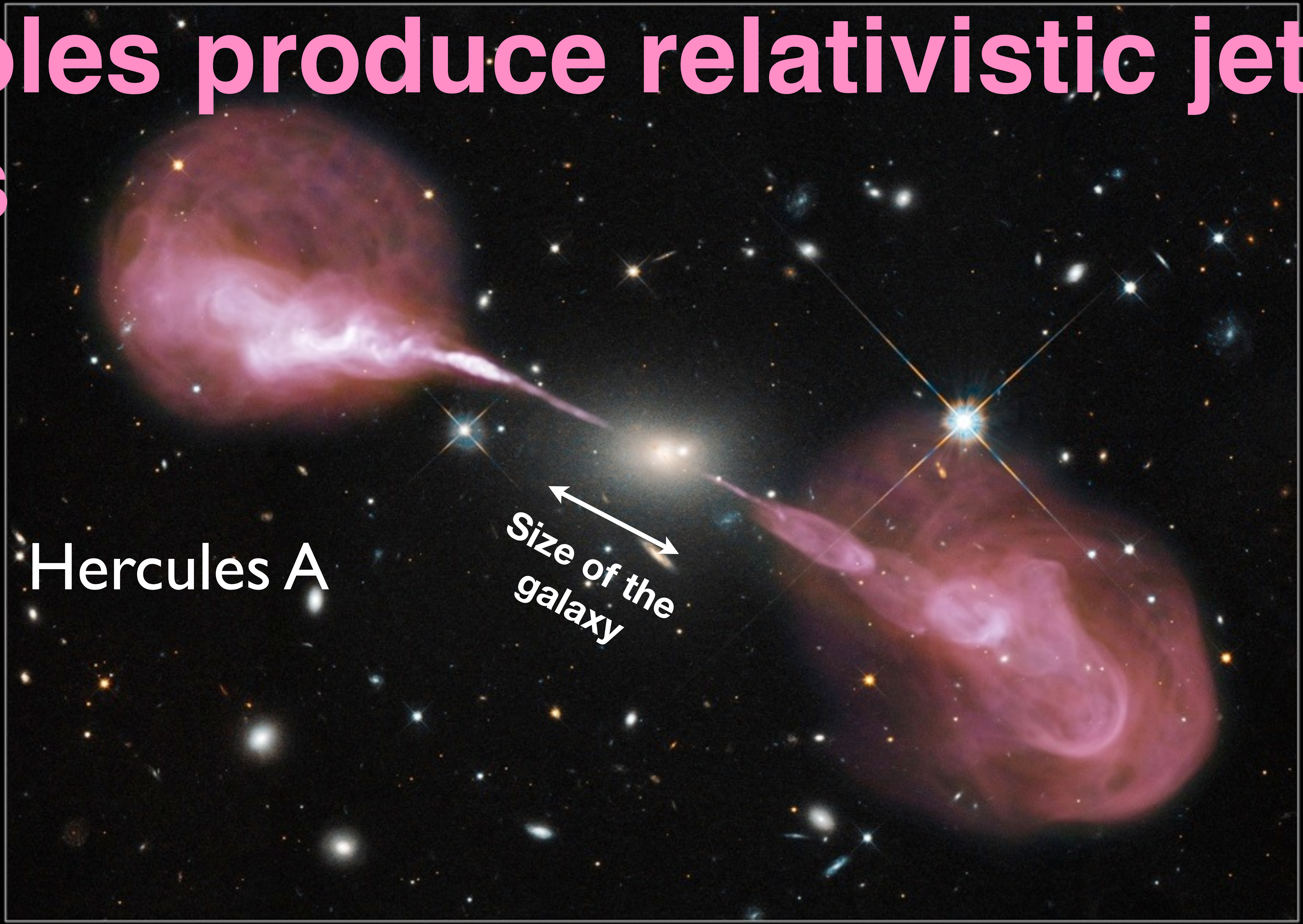
# The ins and outs of black holes: Outflows


Rodrigo Nemmen

Universidade de São Paulo

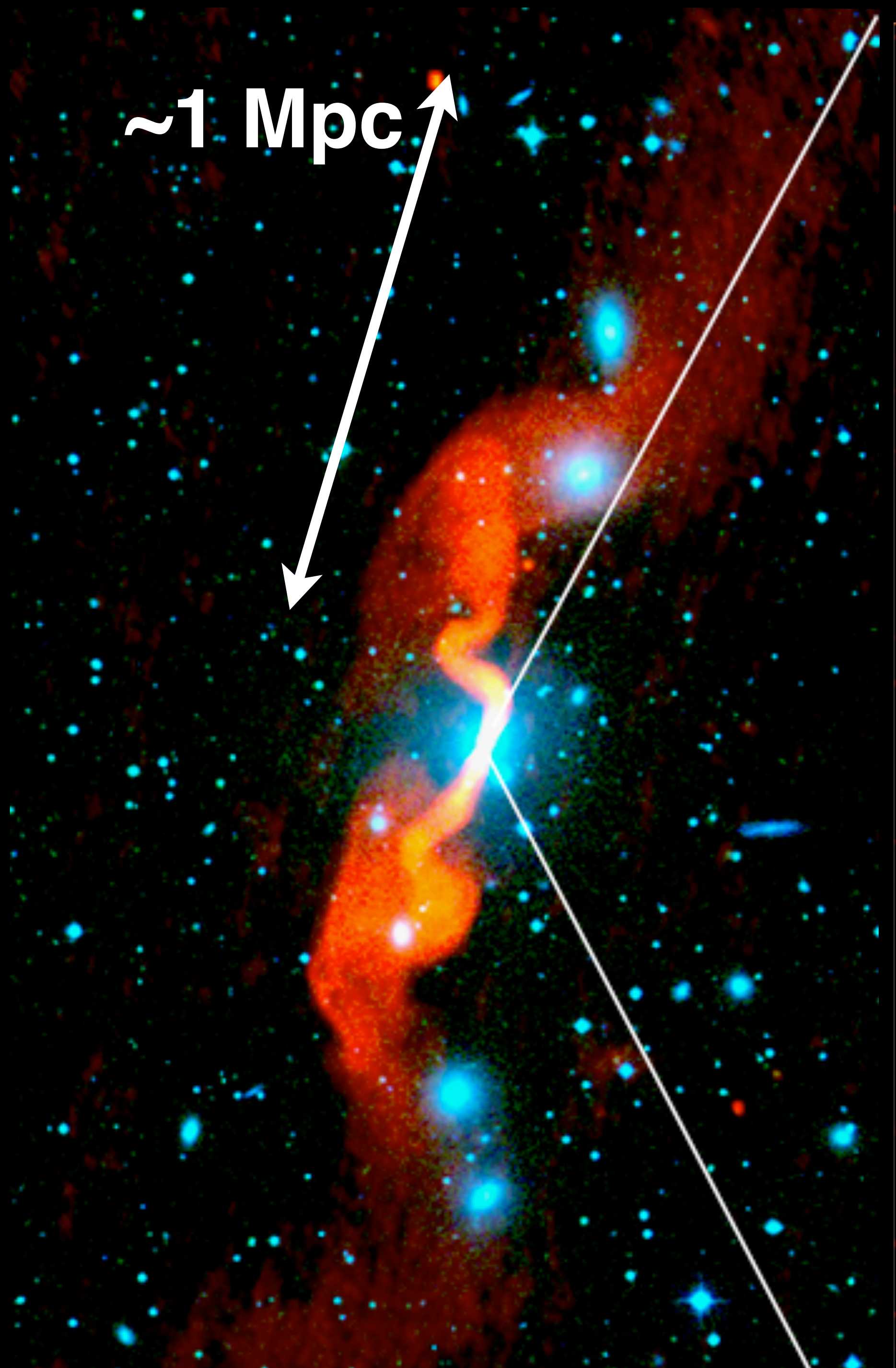
# Black holes produce relativistic jets of particles

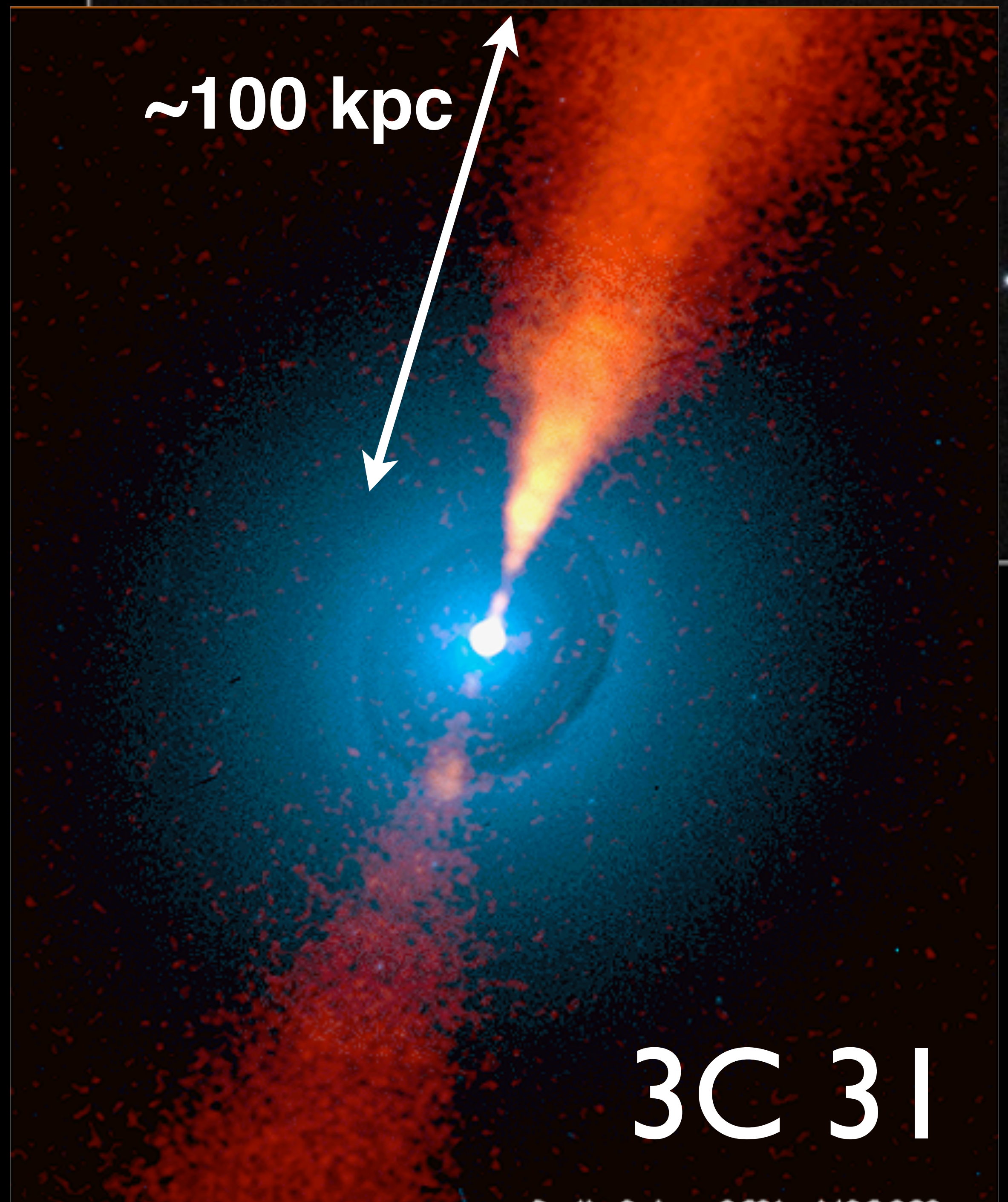


# Black holes produce relativistic jets of particles


Huge powers (enough to unbind a galaxy)

Aligned over long periods (millions of years)




Cosmic particle accelerators!

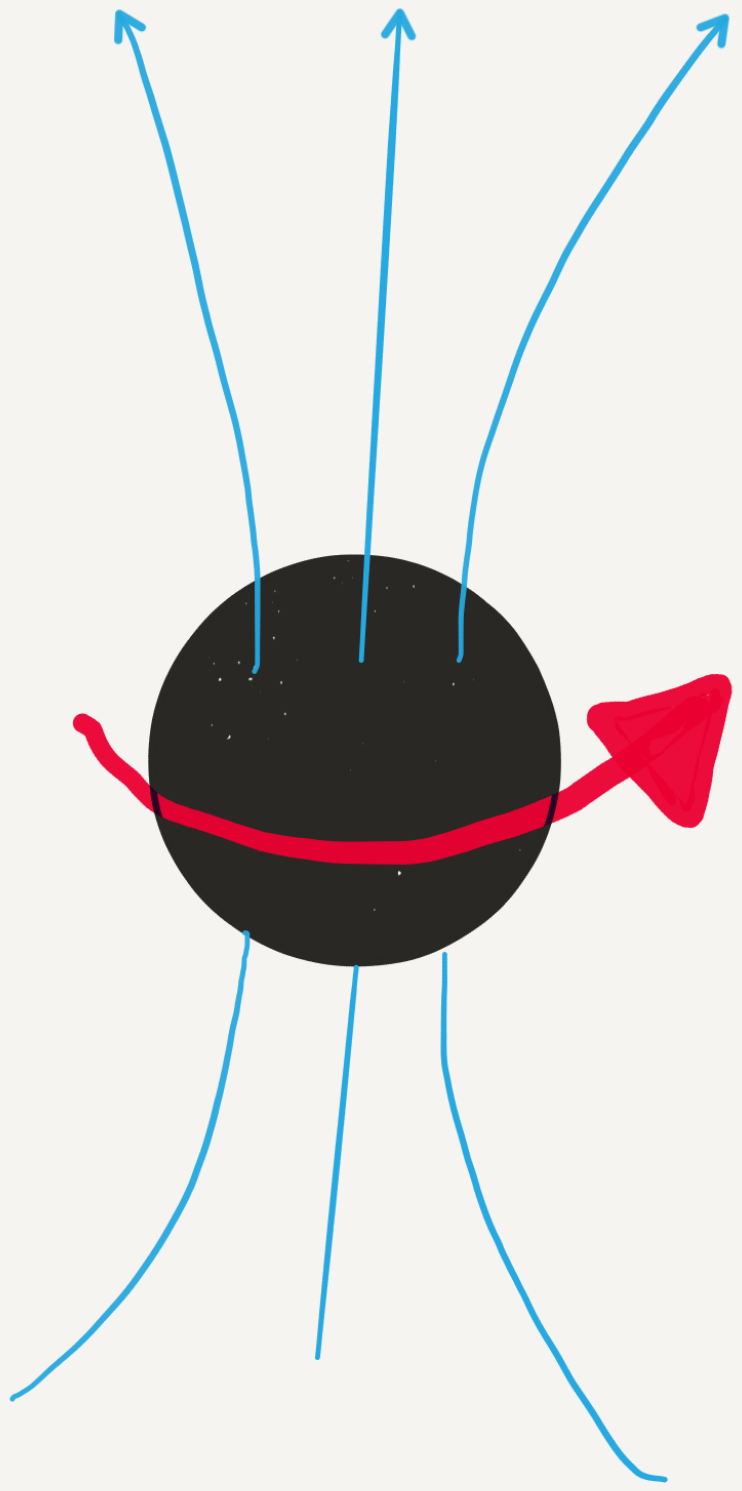
# How are relativistic jets produced by black holes?

Conjecture: from spinning black holes

- ☑ Huge free energy
- ☑ Stable gyroscopes

Growing evidence that this is correct

- ☑ Theory/simulations
- ☐ Observations (?)



# Penrose process: Spinning black hole has free energy that can be extracted

Penrose 1969

Rotational energy of spacetime (frame dragging)

Thought experiment by Penrose that demonstrates the principle, probably not important in astrophysics

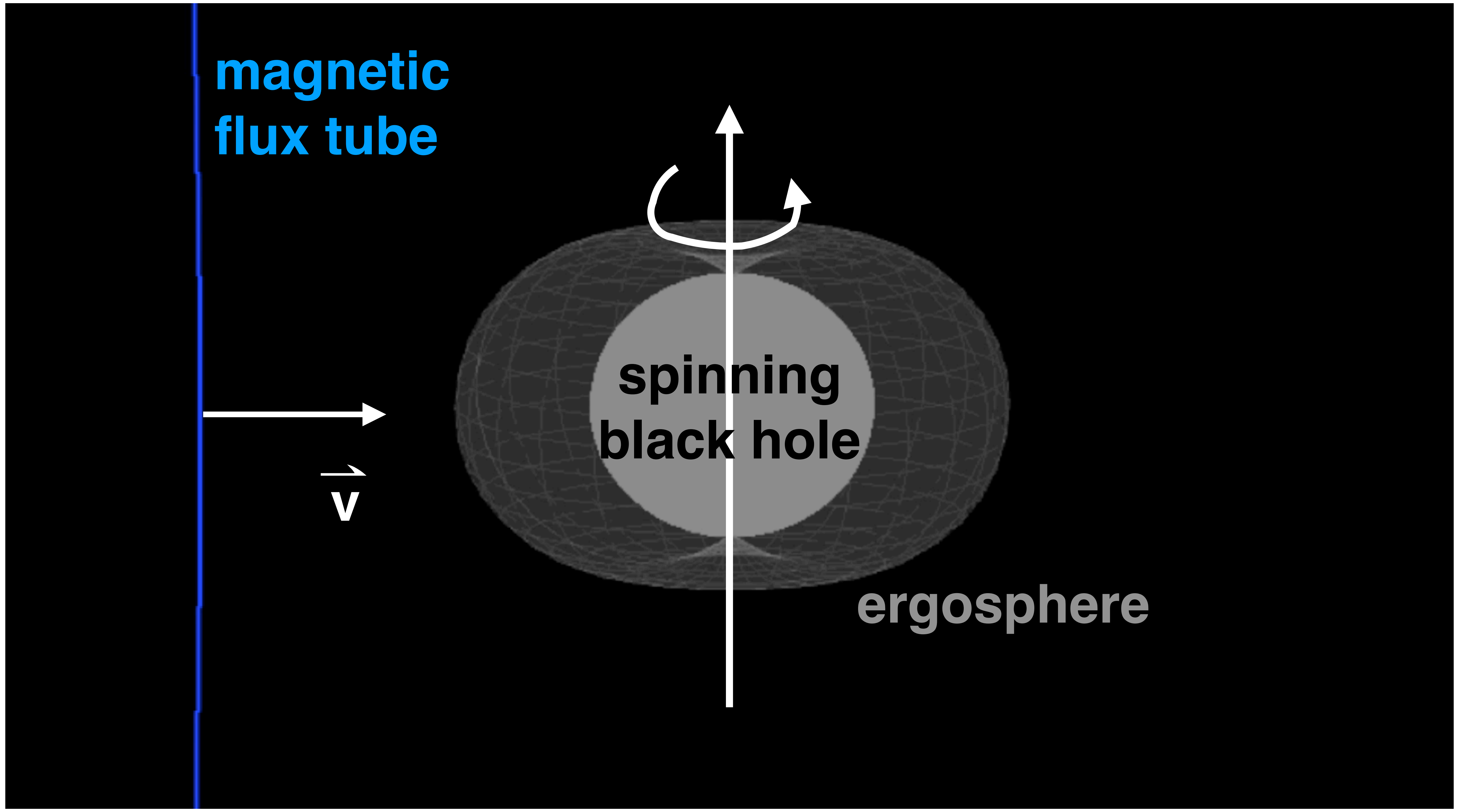
But *magnetized* accretion disks is promising

Ruffini & Wilson 1975; Blandford & Znajek 1977

https://www.youtube.com/watch?v=9MHuhcFQsBg

Need a *natural* mechanism to accelerate particles from compact objects

# How jets are formed

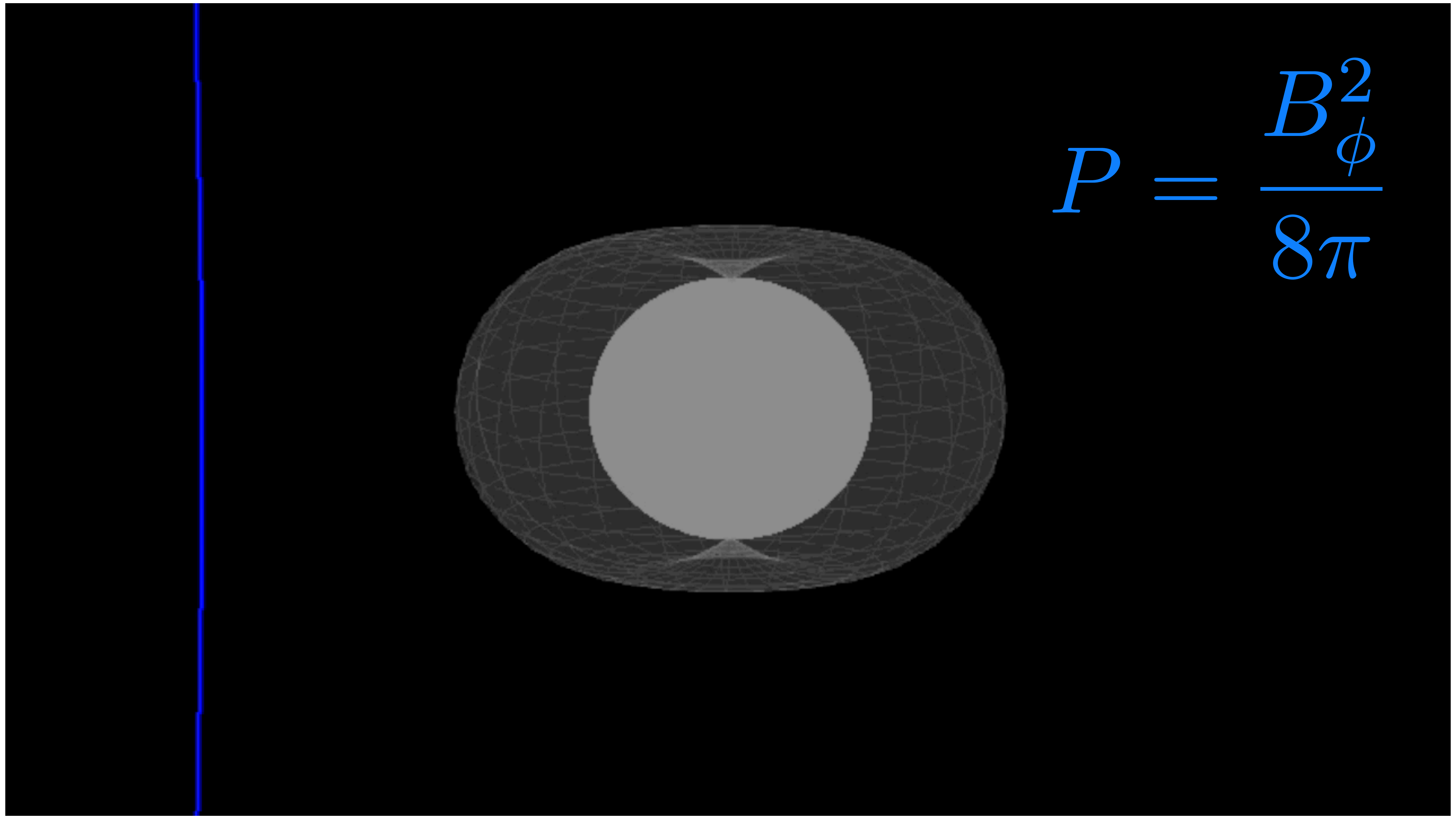


Semenov+2004, *Science*

**Requirements**

**large scale B + accretion + rotation**

# How jets are formed

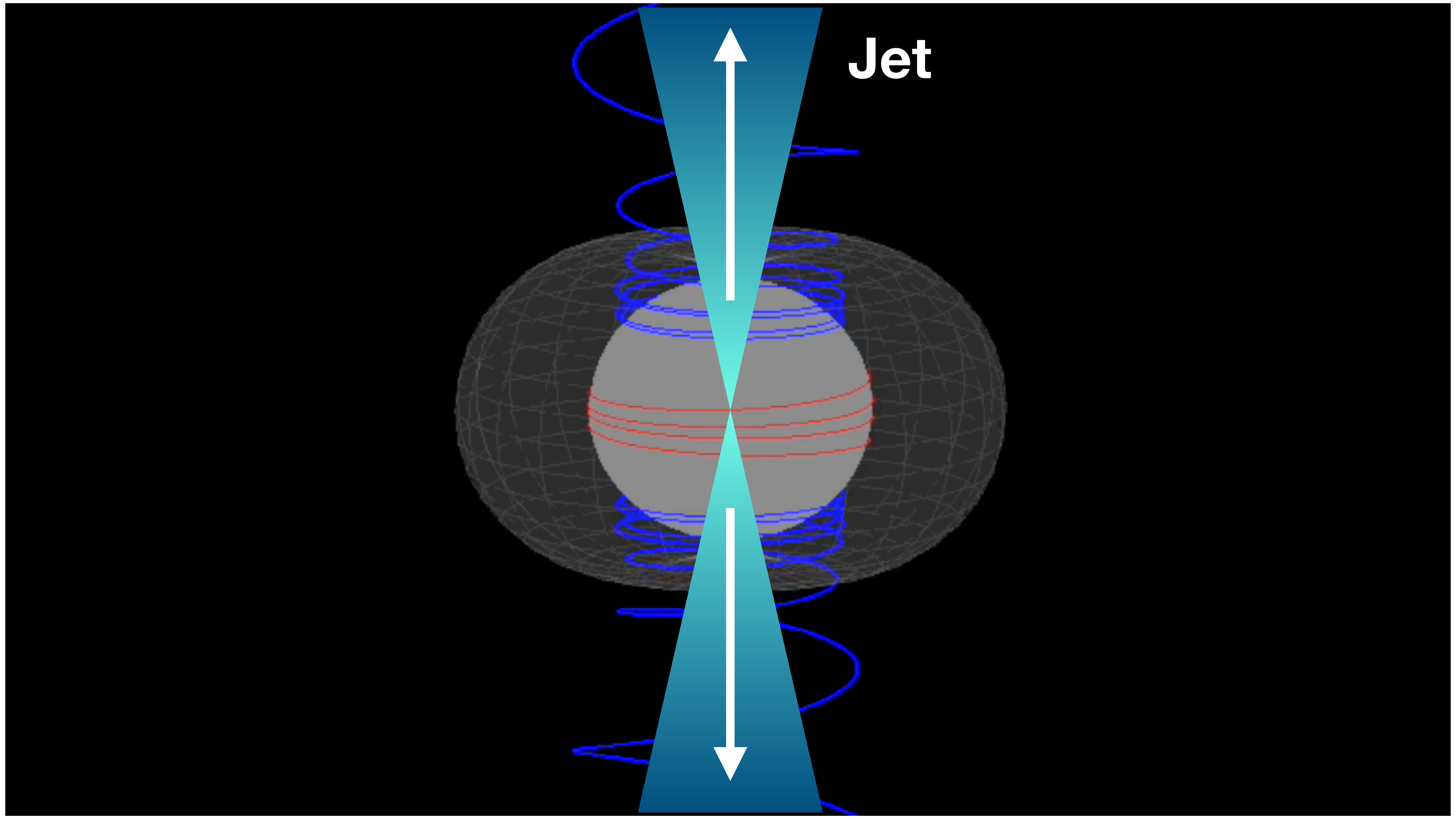



Semenov+2004, *Science*

**Requirements**

**large scale B + accretion + rotation**

# How jets are formed




Semenov+2004, *Science*

**Requirements**

**large scale B + accretion + rotation**

**Complications for theory**

- **environment**
- **radiation**
- **GR**
- **Lense-Thirring precession**

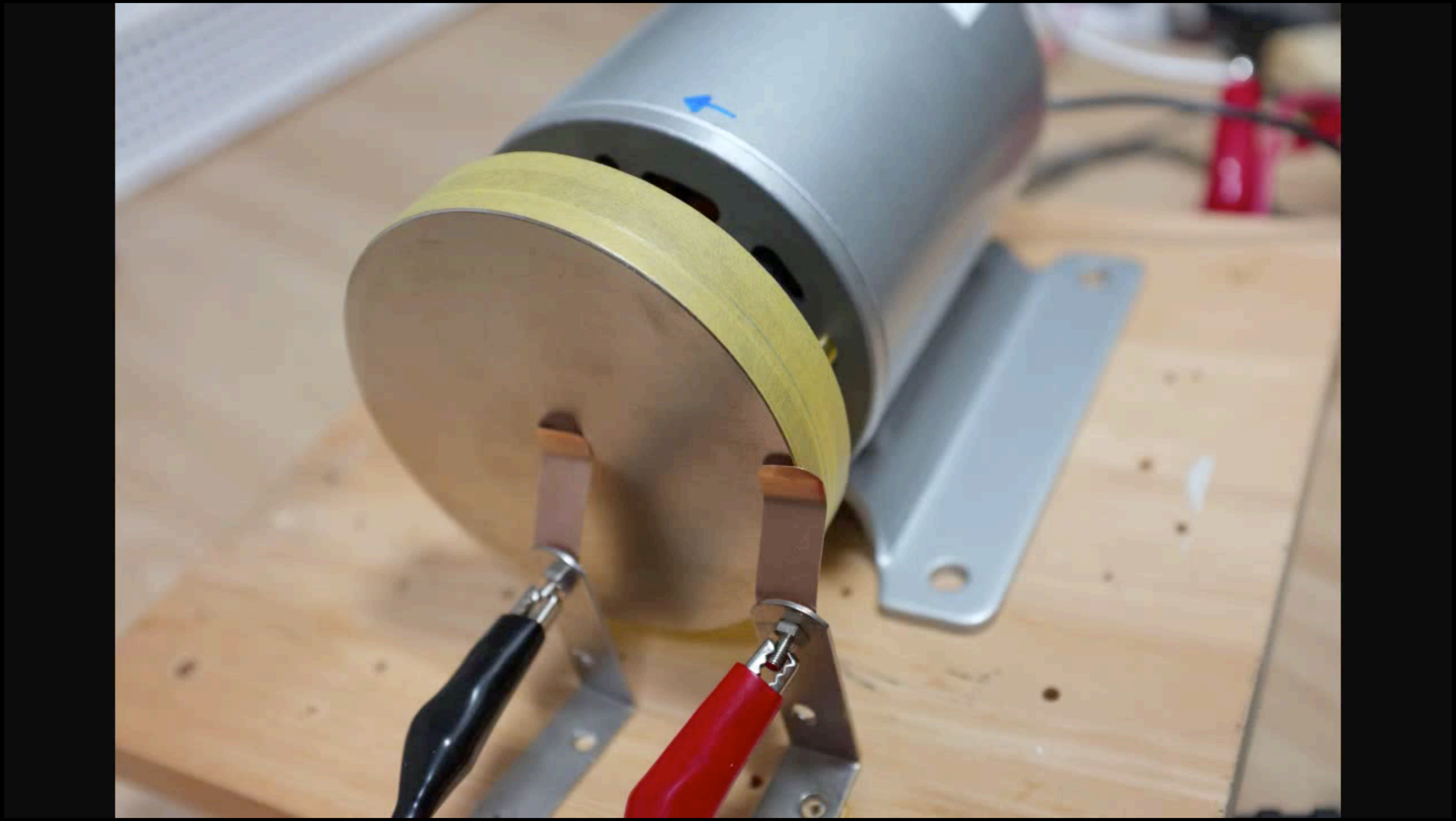
**Blandford-Znajek mechanism:**

$$\text{Jet power} \propto (\Phi\Omega)^2 \sim \left(\frac{a}{M}\Phi_{\rm BH}\right)^2 \sim a^2\dot{M}c^2$$

magnetic flux

rotation frequency

# How to make a black hole jet at home: Homopolar generator

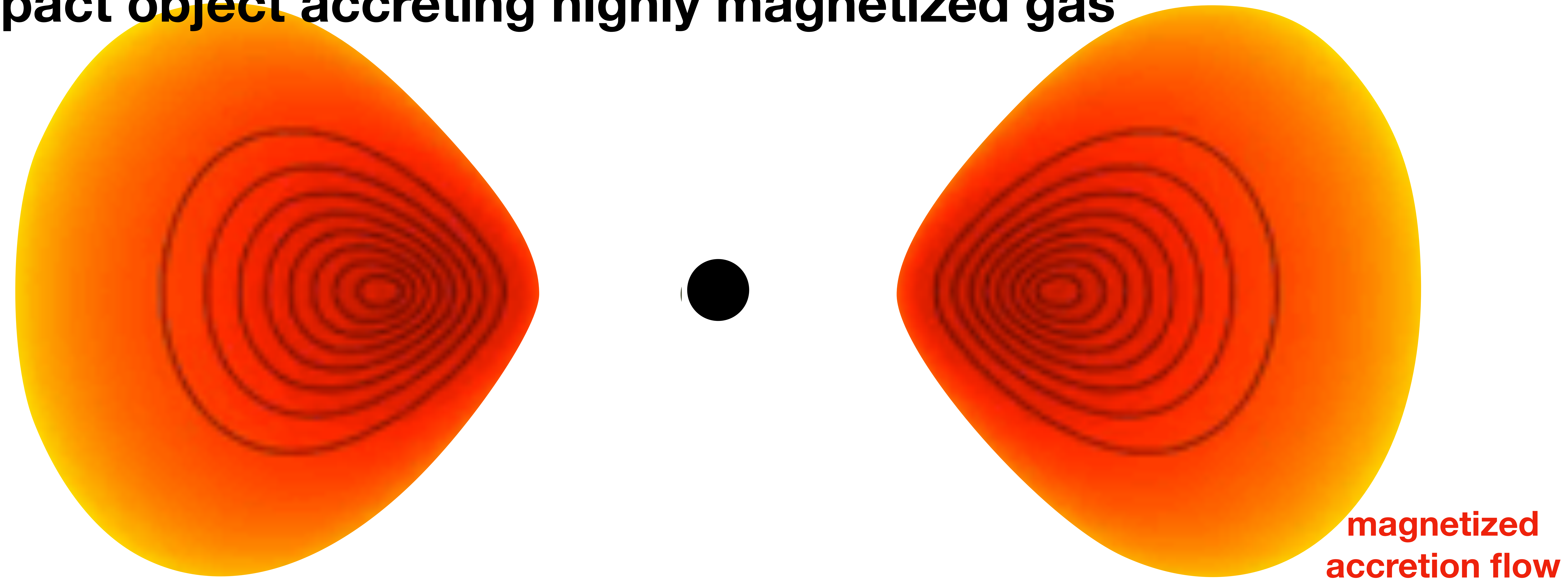


Kudos to Alice Harding (NASA GSFC)

https://www.youtube.com/watch?v=R173dLIktsw

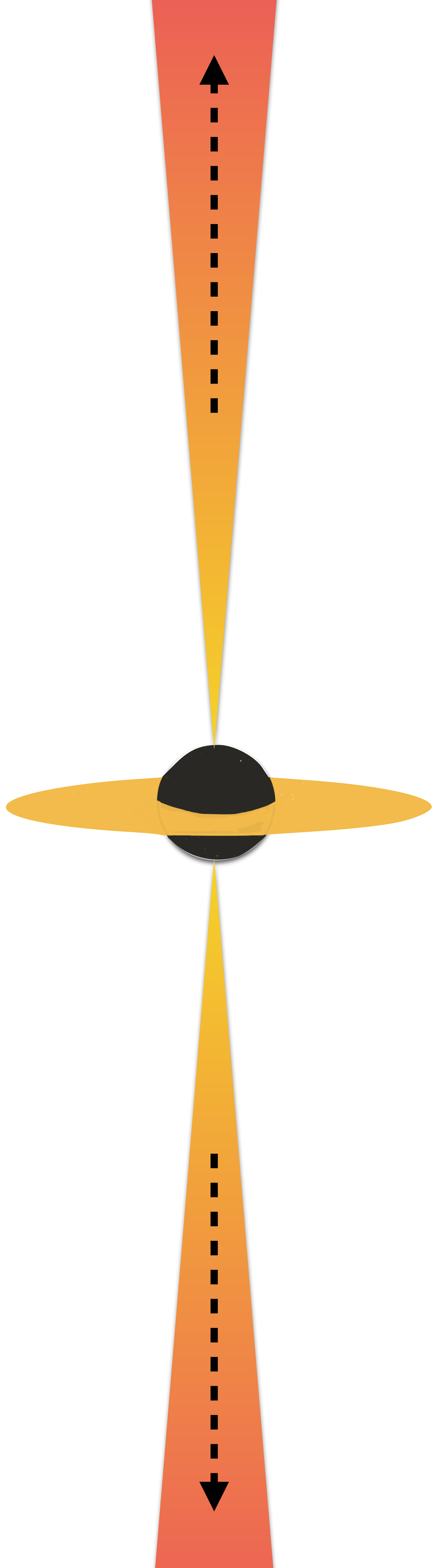
# Best way of producing relativistic jets

**Compact object accreting highly magnetized gas**




**Such conditions are natural outcomes of stellar deaths and easily produced around black holes**

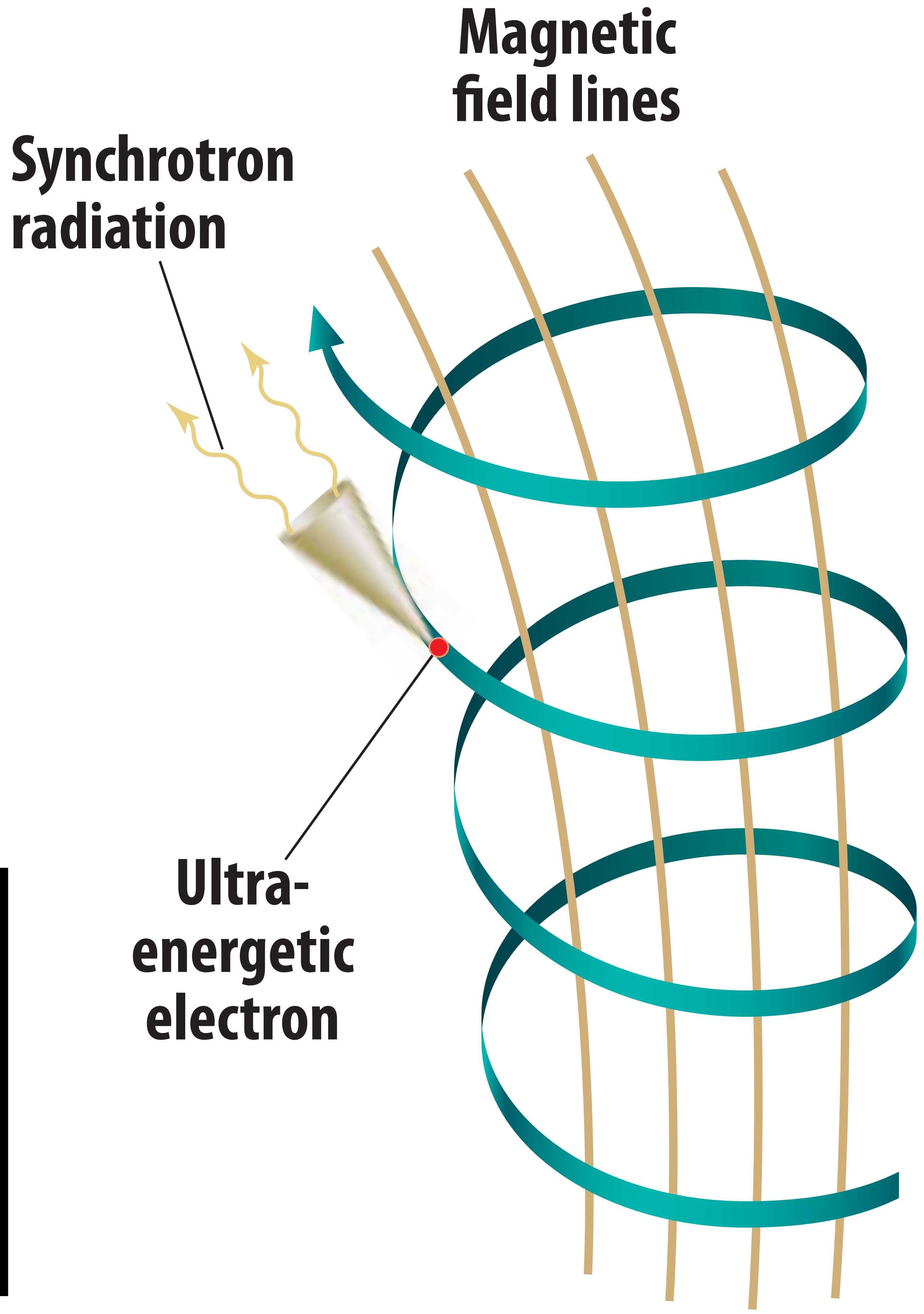
# Basic facts about jets



**Highly magnetized**

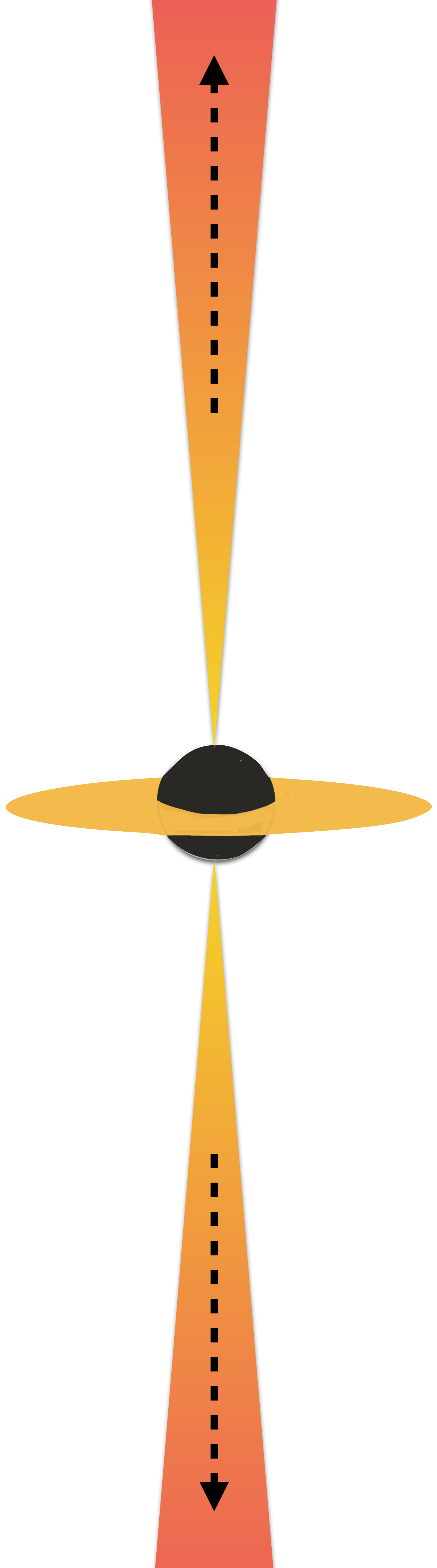
$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}} < 0.1$$

strong synchrotron radiation




$$\boxed{\nu_c \sim \gamma^2 B \text{ MHz}}$$

expect to see in radio



# Basic facts about jets

***Highly magnetized***

$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}} < 0.1$$

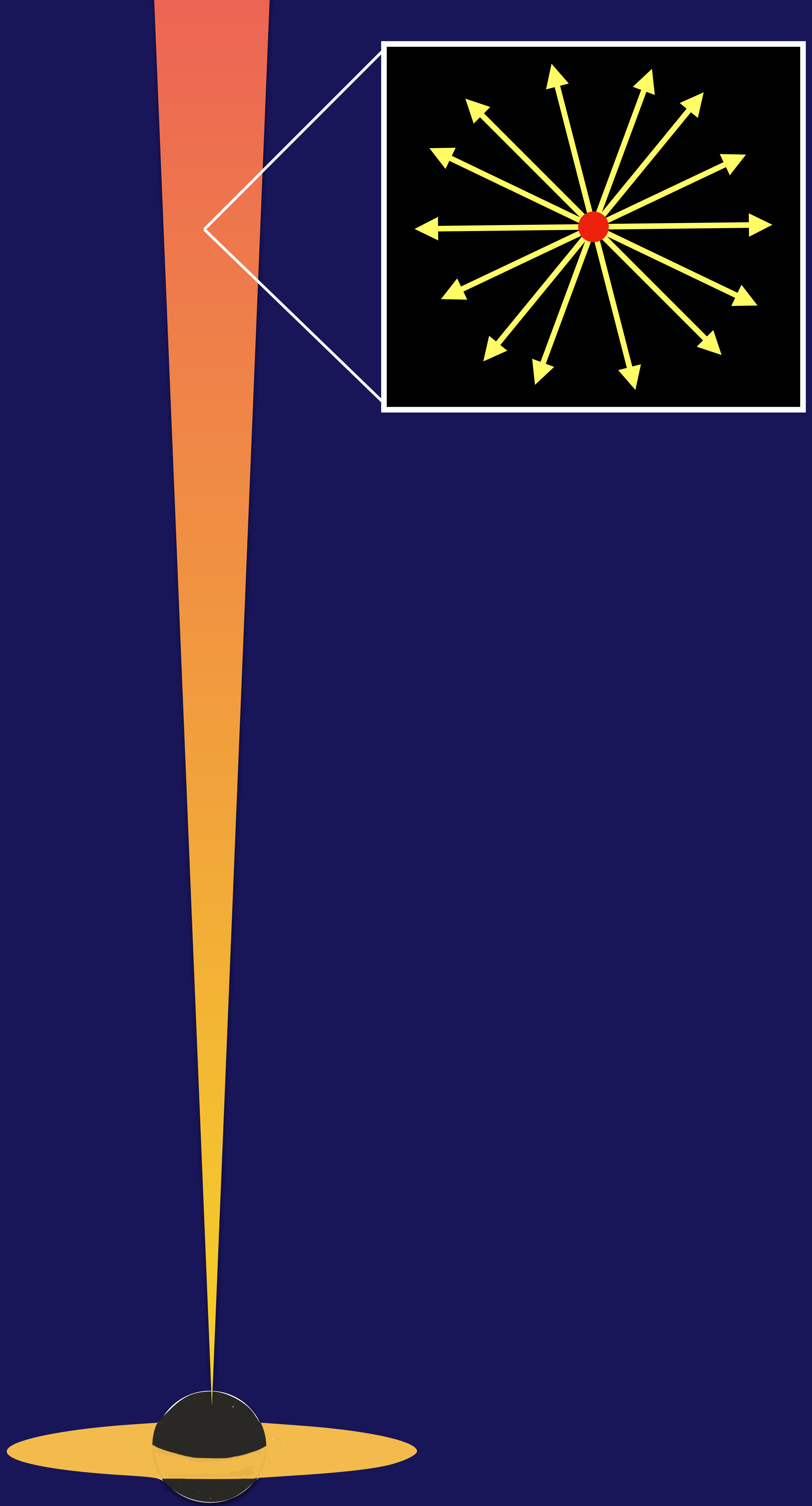
***Relativistic***

$$\Gamma \sim \text{a few} - 100 \qquad v > 0.9c$$

bulk Lorentz factor

AGNs

GRBs

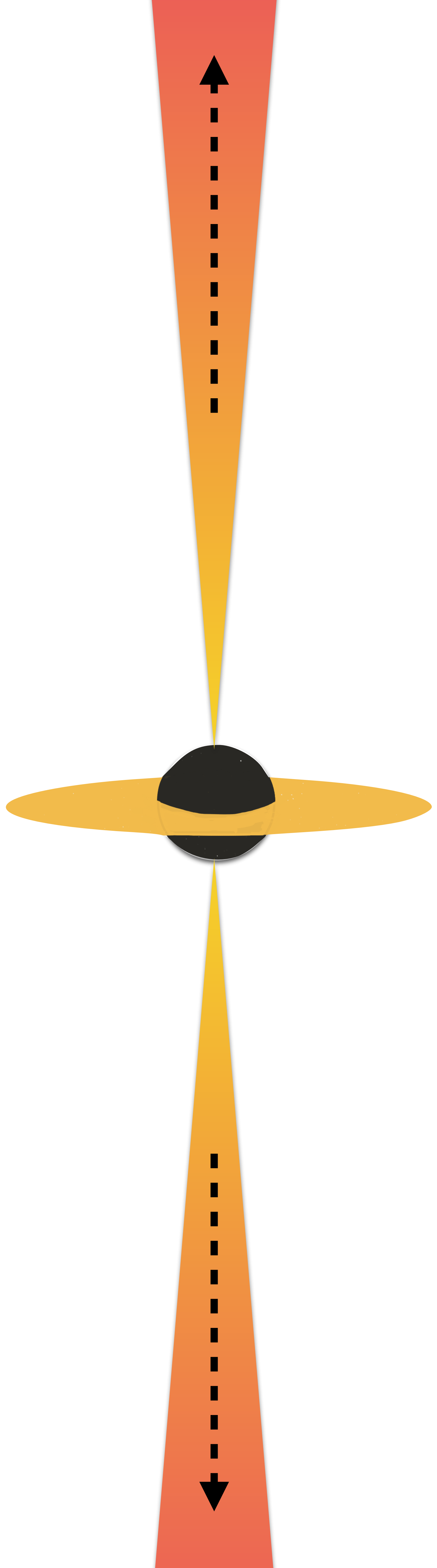


synchrotron emitting electron

in the comoving frame of the plasma


comoving
frame
observer's frame
v= 0.5c
v= 0.75c
v= 0.94c
v= 0.98c

# Basic facts about jets



***Highly magnetized*** $\beta = \dfrac{P_{\rm gas}}{P_{\rm mag}} < 0.1$

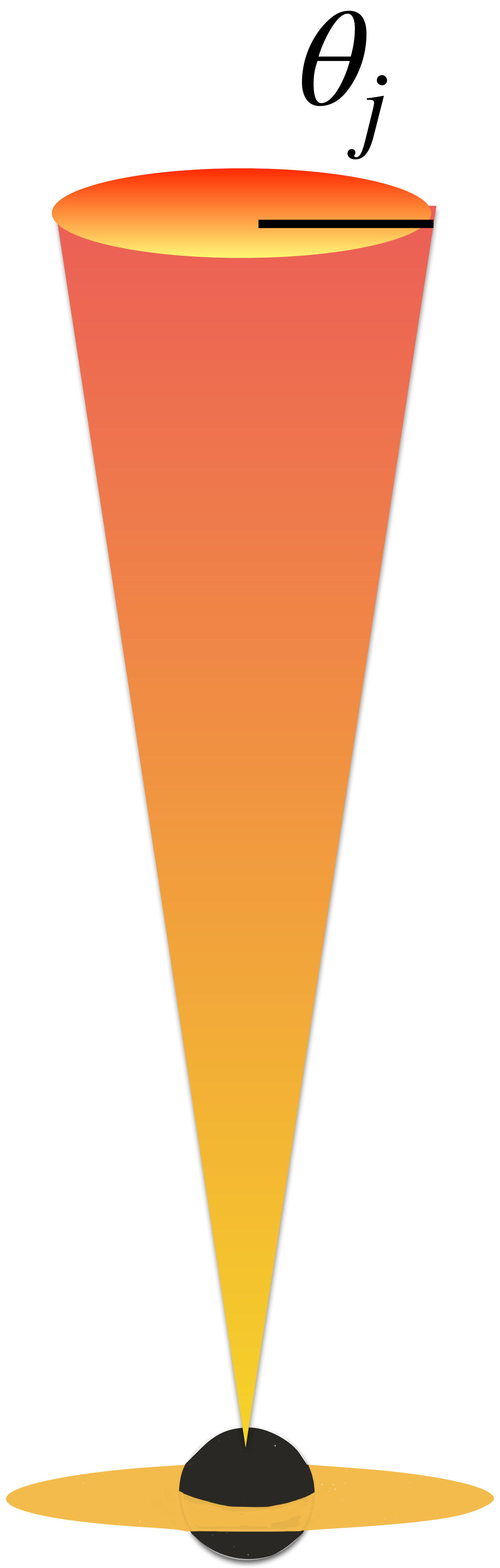
***Relativistic*** $\Gamma \sim \text{a few} - 100$ $v > 0.9c$

***Beamed*****: most radiated power along the propagation direction, skewed towards high frequency**

relativistic aberration

Doppler shift

# Basic facts about jets




***Highly magnetized*** $\beta = \frac{P_{\text{gas}}}{P_{\text{mag}}} < 0.1$

***Relativistic*** $\Gamma \sim \text{a few} - 100$ $v > 0.9c$

***Beamed*: most radiated power along the propagation direction**

**neutrinos, cosmic rays**
**maybe show Feynman diagrams**

**Collimated** $\theta_j < 10^\circ$ **collimation half-angle**

# Where in the universe do we find jets?

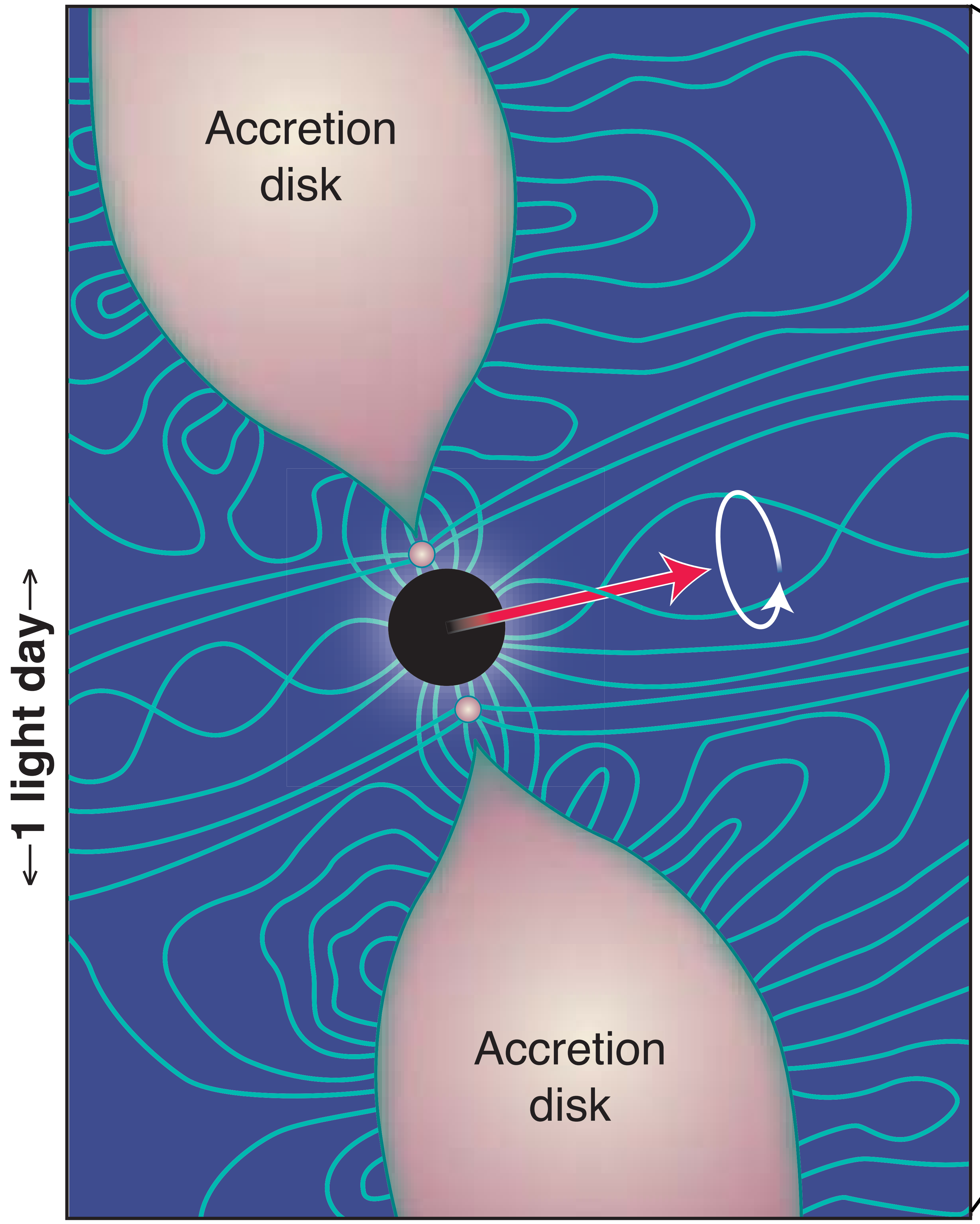
Wherever there is accretion

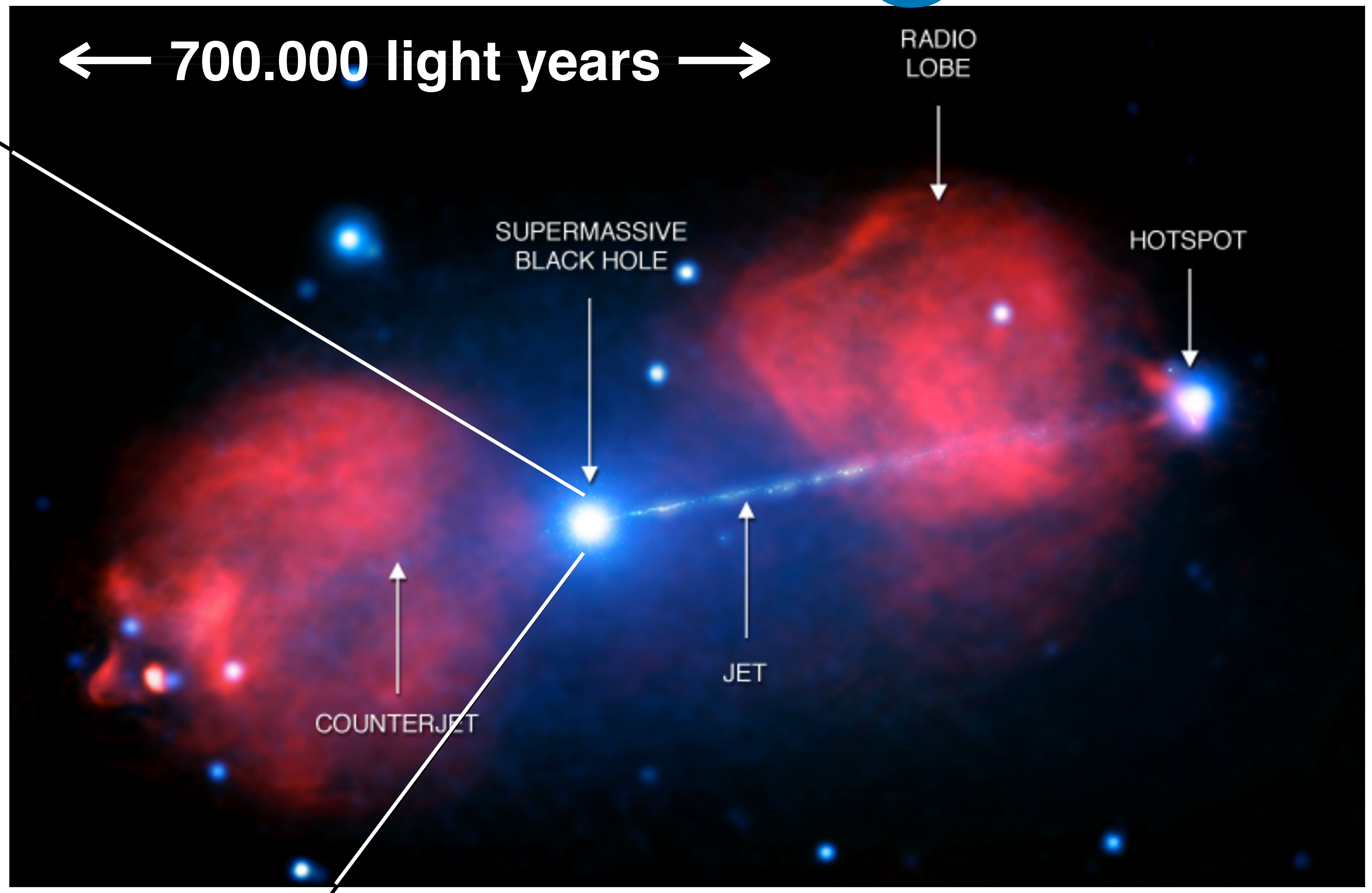

~1 Mpc
~100 kpc
3C 31
Active galactic nuclei
$10^6$-$10^{10}$ $M_\odot$
Tidal disruption events
$10^6$-$10^7$ $M_\odot$
slides from “jets from stellar deaths”, GMT 2018
pc?
Short GRBs
Black hole binaries (μquasars)
few-10 $M_\odot$
~1 pc
1E1740.7-2942
Young stellar objects
few $M_\odot$
1000 AU
HH 30
500 GRBs
Gamma-ray bursts
few-100 $M_\odot$
Swift
500 GRBs


~1 Mpc
~100 kpc
Tidal disruption events
Active galactic nuclei
3C 31
parei aqui
Black hole binaries (µquasars)
~1 pc
1E1740.7-2942
stellar objects
HH 30
kilonovas
rt GRBs
GWs ✅
supernovae
Long GRBs
~$10^{-4}$ pc?
GWs ?
Gamma-ray bursts
Swift
500 GRBs

# Jets from BHs at galactic nuclei and binary systems

# Good conditions for producing jets naturally found at centers of galaxies




**Zooming in on black holes. Right:** X-ray image (blue) of the jet associated with the radio galaxy Pictor A superimposed on the radio image (red)

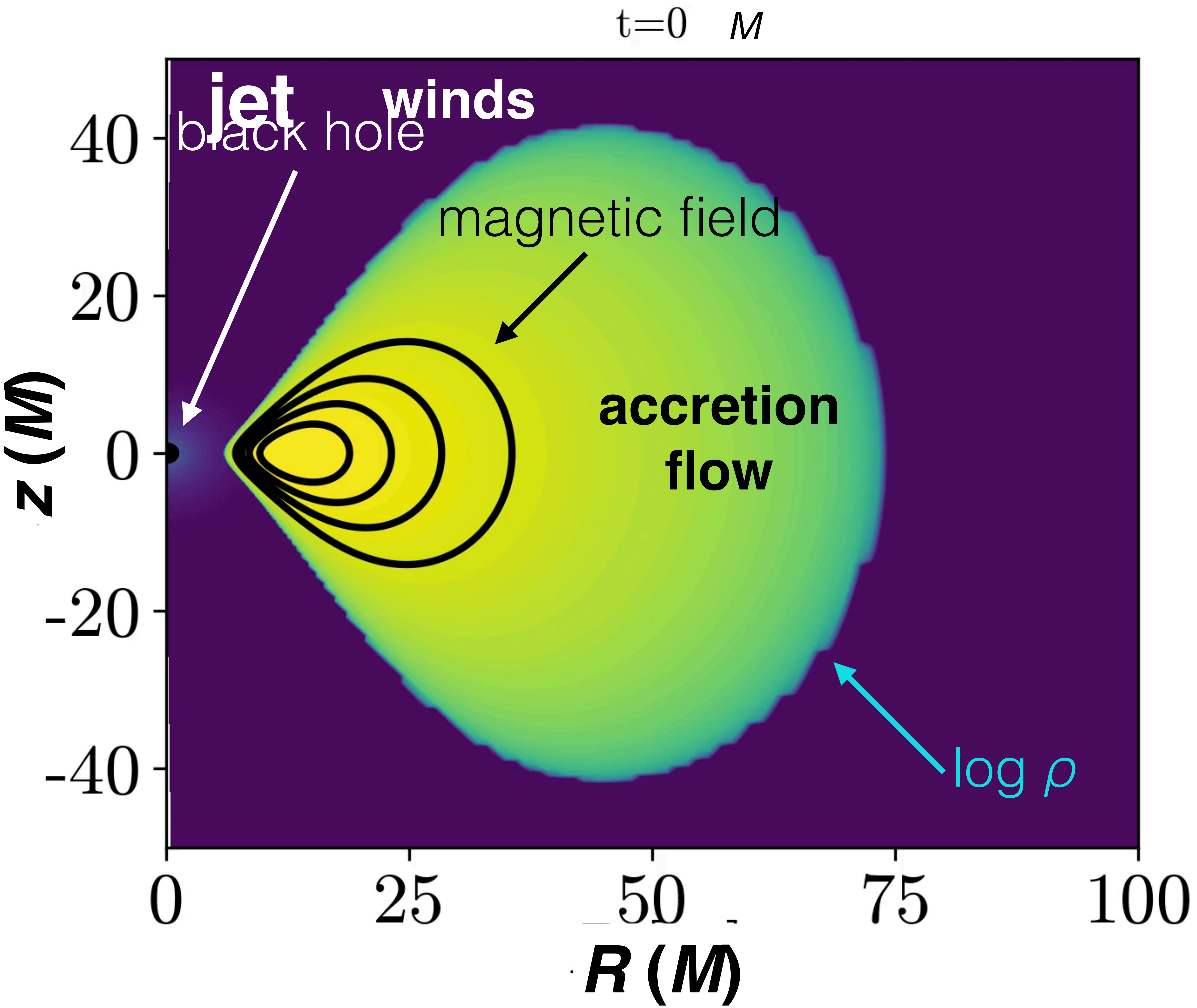
# Also in binary systems in Our Galaxy (BH + star)

# Numerical simulation of BH accretion

**Solves conservation eqs of GR magnetohydrodynamics**

**Code:** `HARMPI`

**Performed by Gustavo Soares**



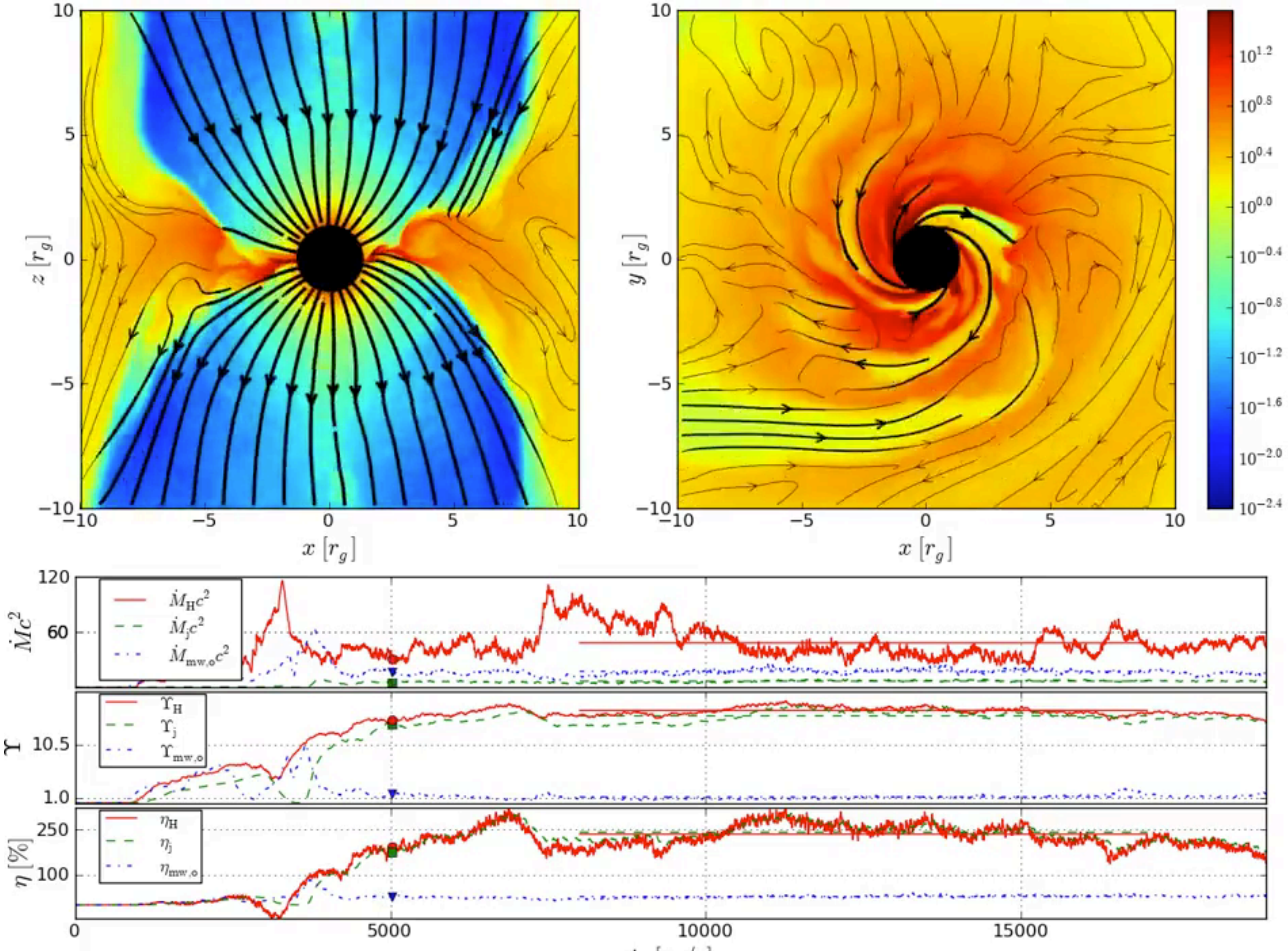
# Zooming-in closer to the BH

**GRMHD simulation**

**Code:** HARM

3D, private, heavily customized

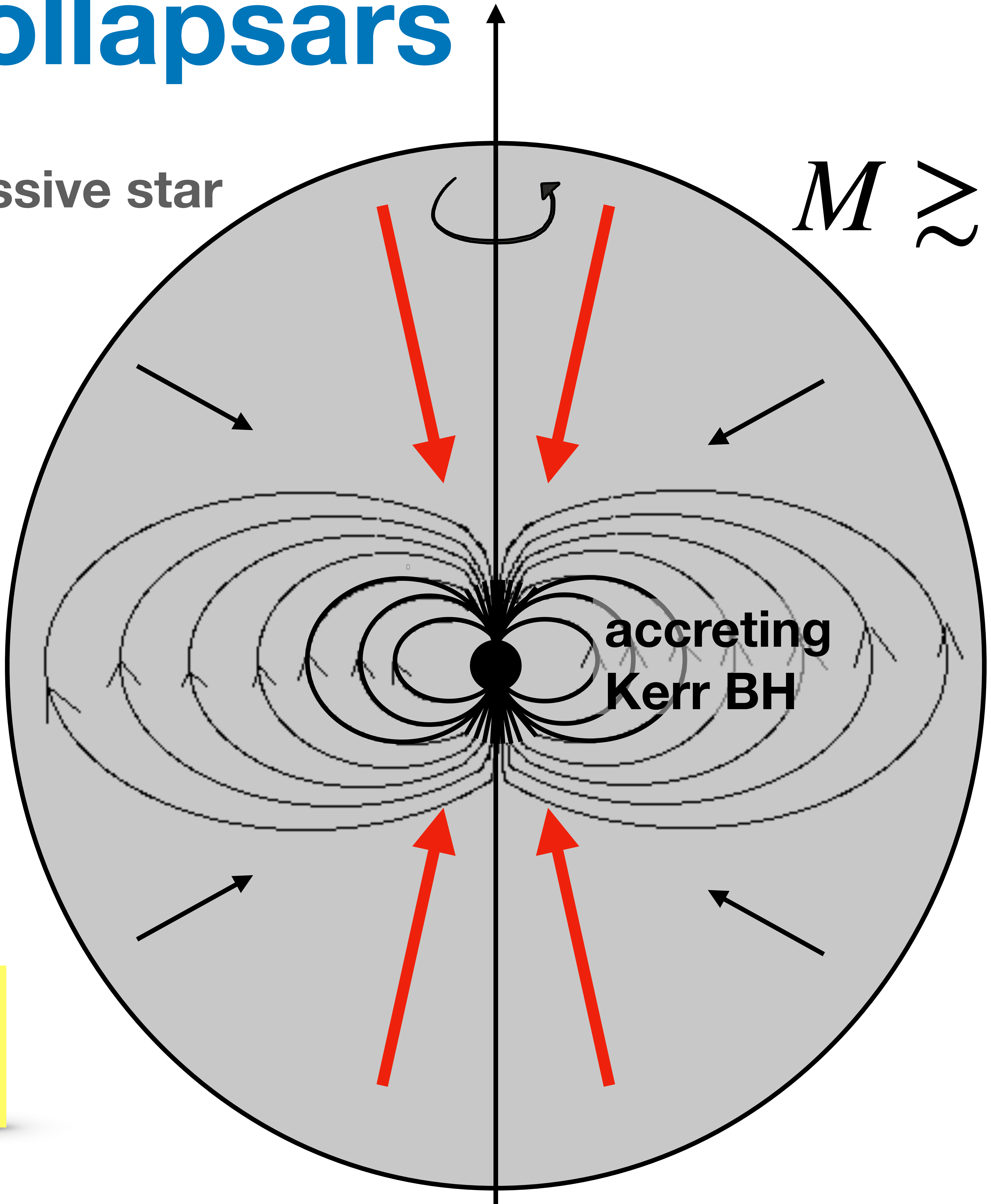
**Performed by J. McKinney**




McKinney, Tchekhovskoy & Blandford 2012

# Jets from *dying* stars

# Jets from collapsars




$M \gtrsim 30 M_\odot$

$\dot{M} \gg \dot{M}_{\rm Edd}$

BH accretion rate

conditions for jet production ✓

MacFadyen & Woosley 1999;
Woosley & Heger 2006;
Woosley & Bloom 2006

# Jets from collapsars

**Relativistic jet w/:**

$\gamma \gg 1$ Lorentz factor

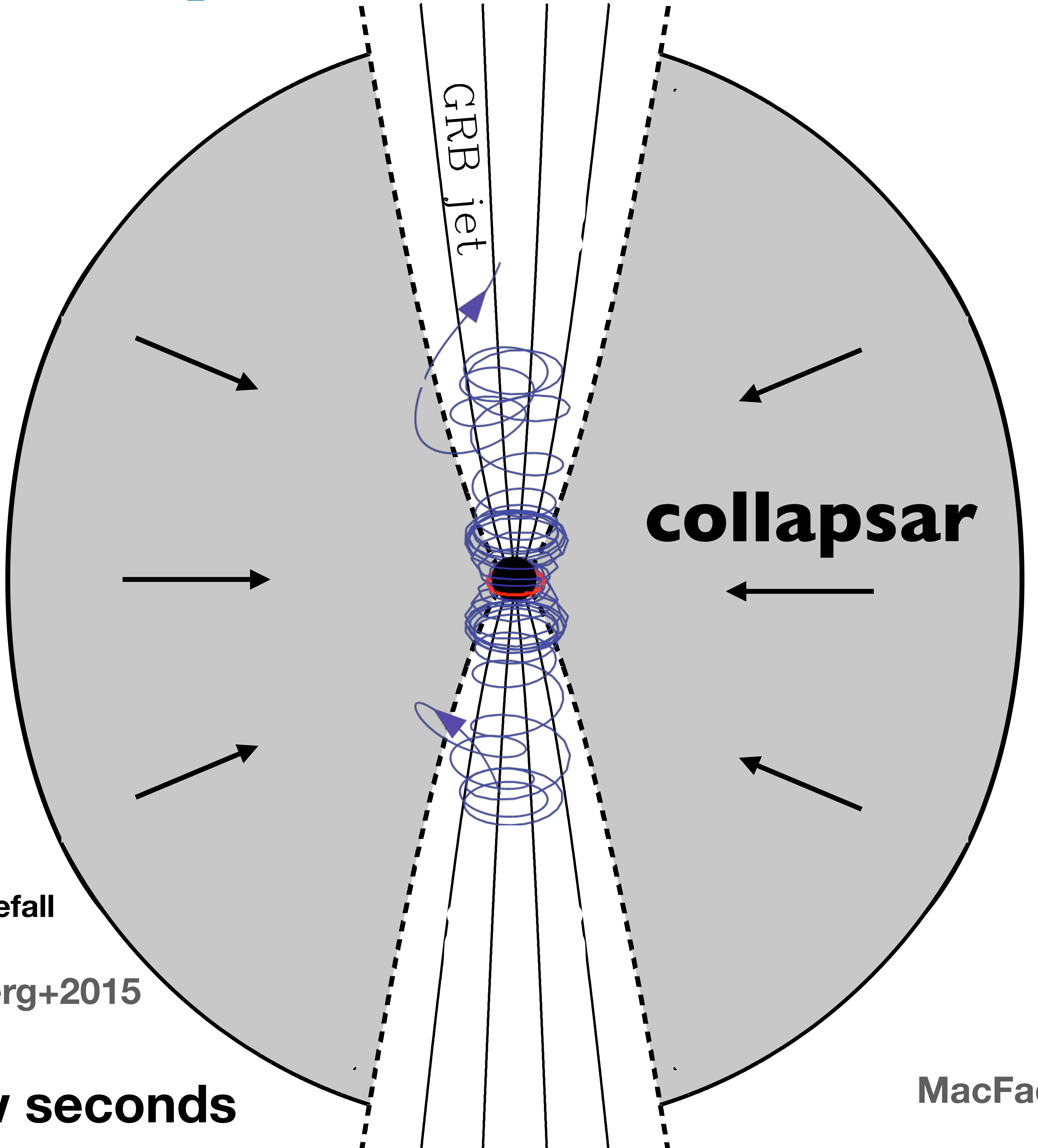
$E_{\rm jet}^{\rm iso} \sim 10^{50} - 10^{54}$ erg

jet punctures stellar envelope → GRB along jet axis (beaming)

central engine operation ~ $t_{\rm freefall}$

jet breakout ~ seconds Bromberg+2015

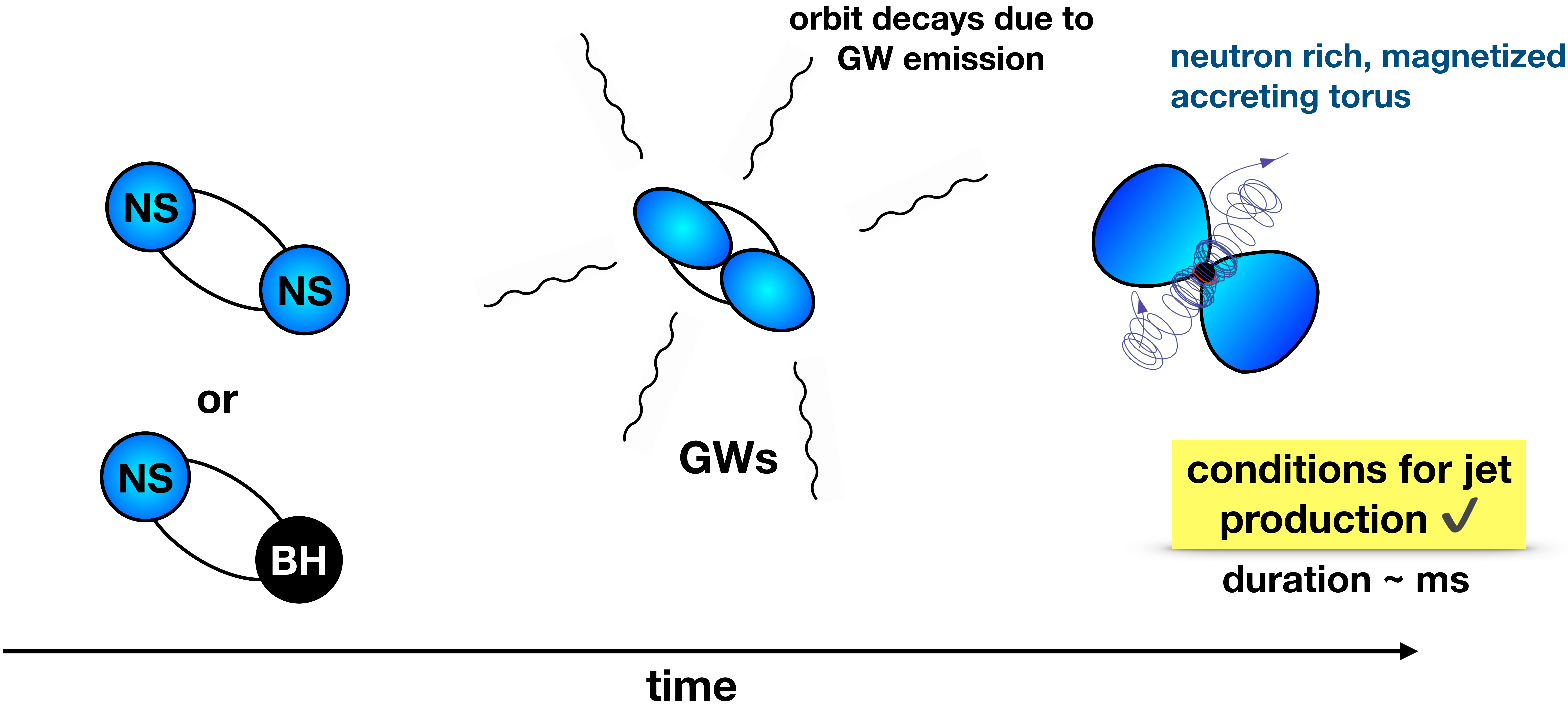
∴ duration > few seconds




GRB followed by isotropic explosion: *superluminous supernovae (type Ic SNe)*

MacFadyen 2001; Woosley & Bloom 2006

# Mergers of binary neutron stars




Paczynski 1986; Eichler et al. 1989; Narayan et al. 1992

# Numerical relativity simulation of NS merger: Short GRB emerges naturally

gas density

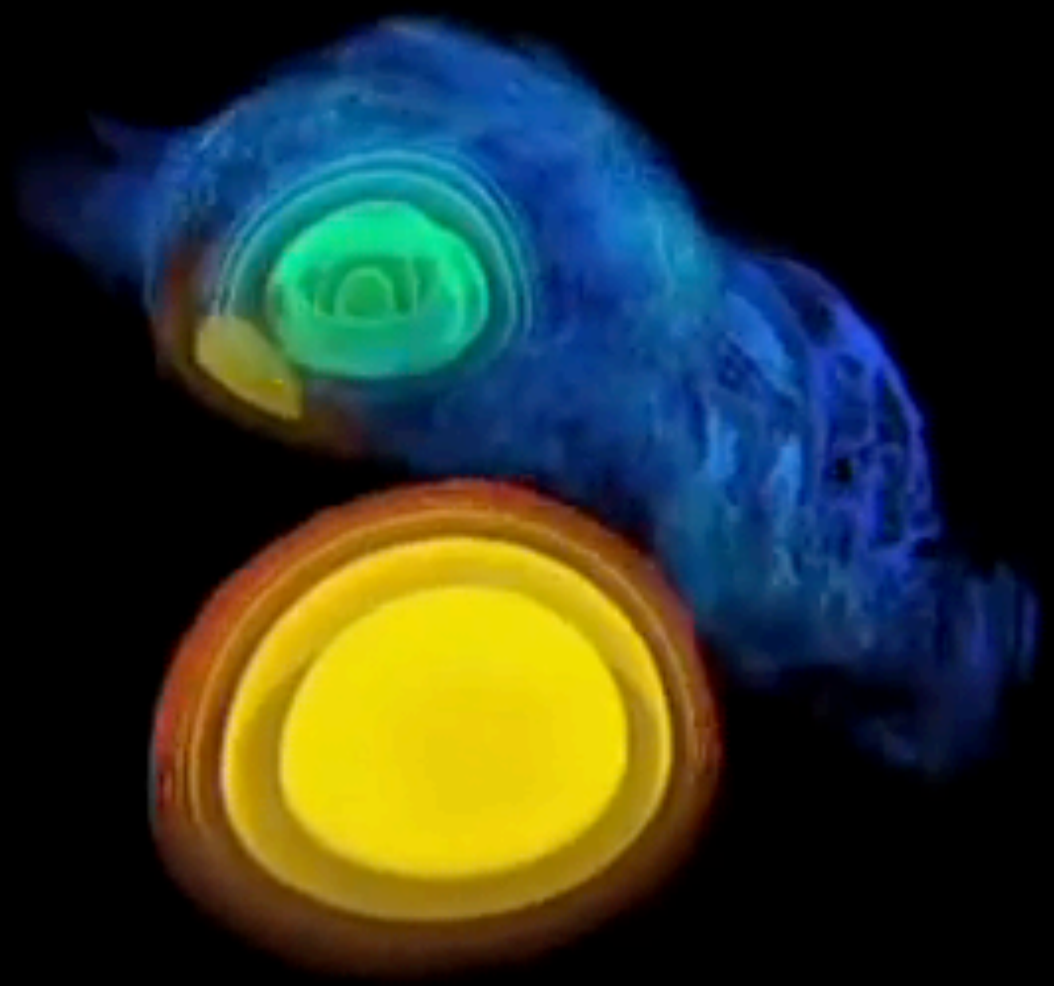
magnetic fields

Rezzolla, Giacomazzo et al. 2011

Cactus/Carpet/Whisky codes
(solves Einstein eqs. + ideal MHD)

Initial condition:

- NS binary a few orbits before its coalescence
- 2 NSs
- each NS with $M=1.5M_{sun}$
- $B_{max}=10^{12}$ G (each star)



Results in:

- accreting BH, $M$ = 2.91 $M_{sun}$
- short GRB jet, $\Delta t$ = 30 ms
- opening angle 30 deg
- amplifies $B$ to $10^{15}$ G
- $E_{iso}$ = $10^{49}$ erg

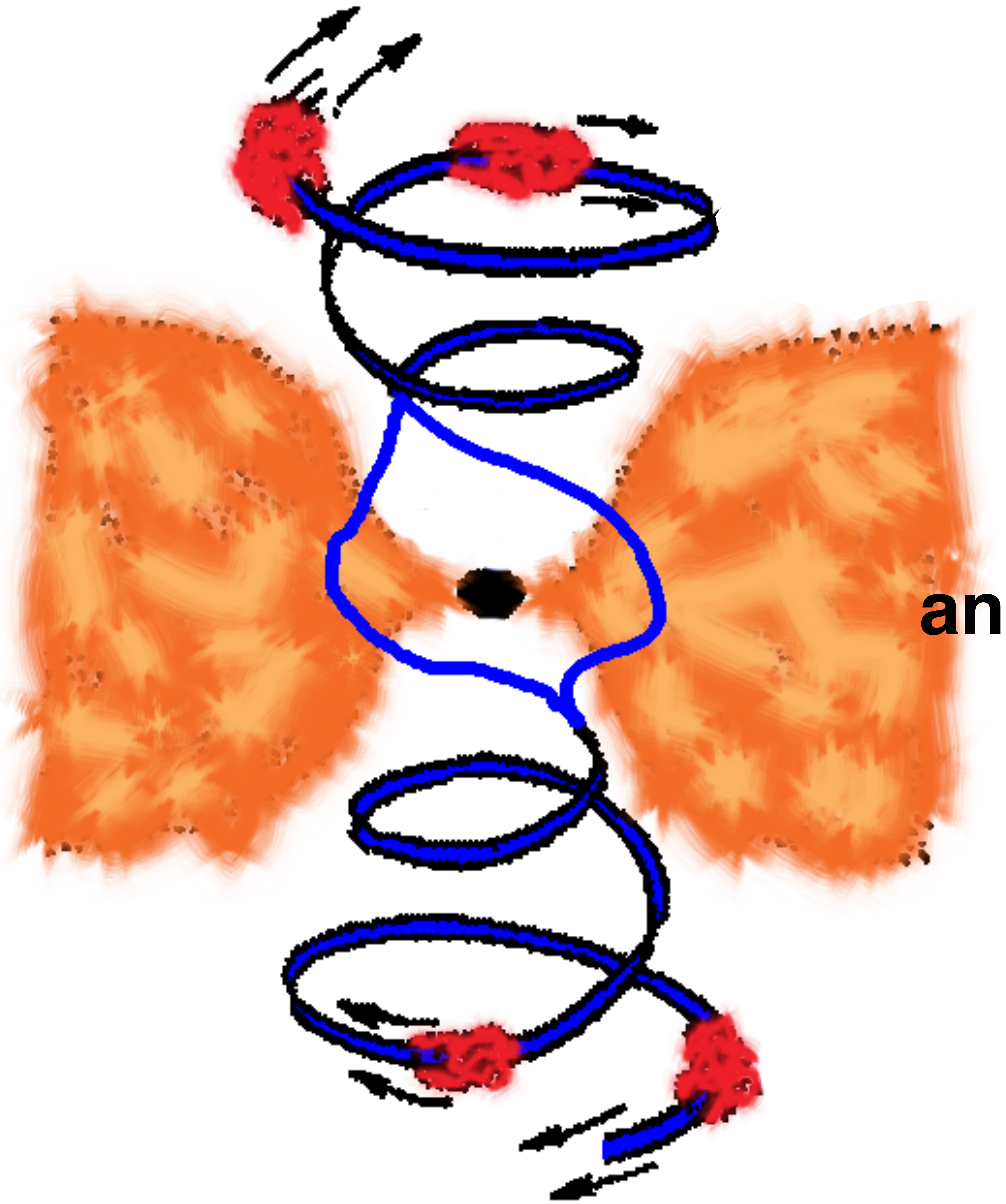
Rezzolla+2011

cf. also Ruiz+2016

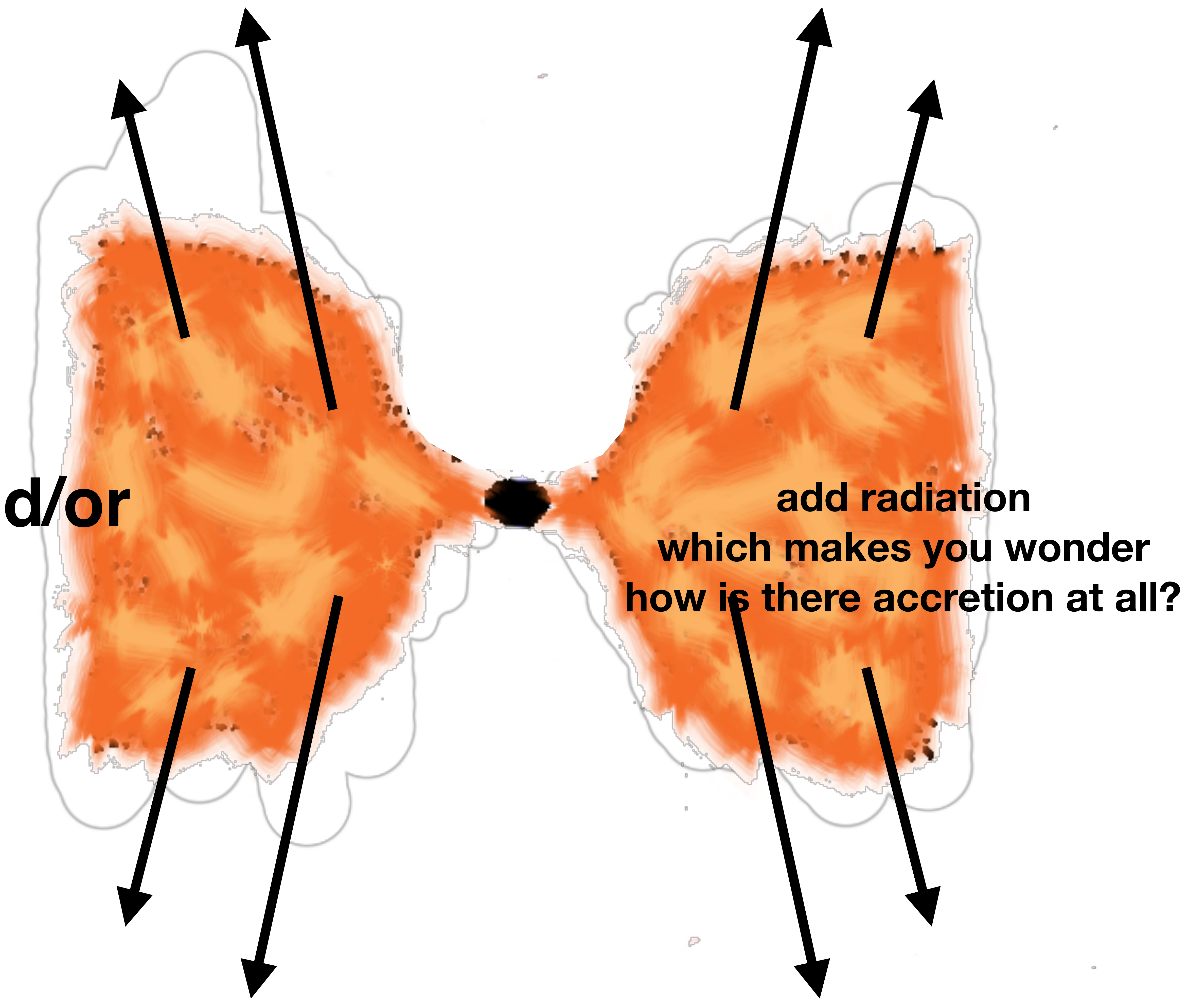
# Director’s cut

# Winds

# Two origins for LLAGN winds



and/or




**Magnetic expulsion**

Blandford-Payne

**Thermal expansion / buoyancy**

**putting it all together**

**numerical simulations of accretion and jet production**
**radiation**

**GPUs**

**winds: Ivan**

**work by Ivan**