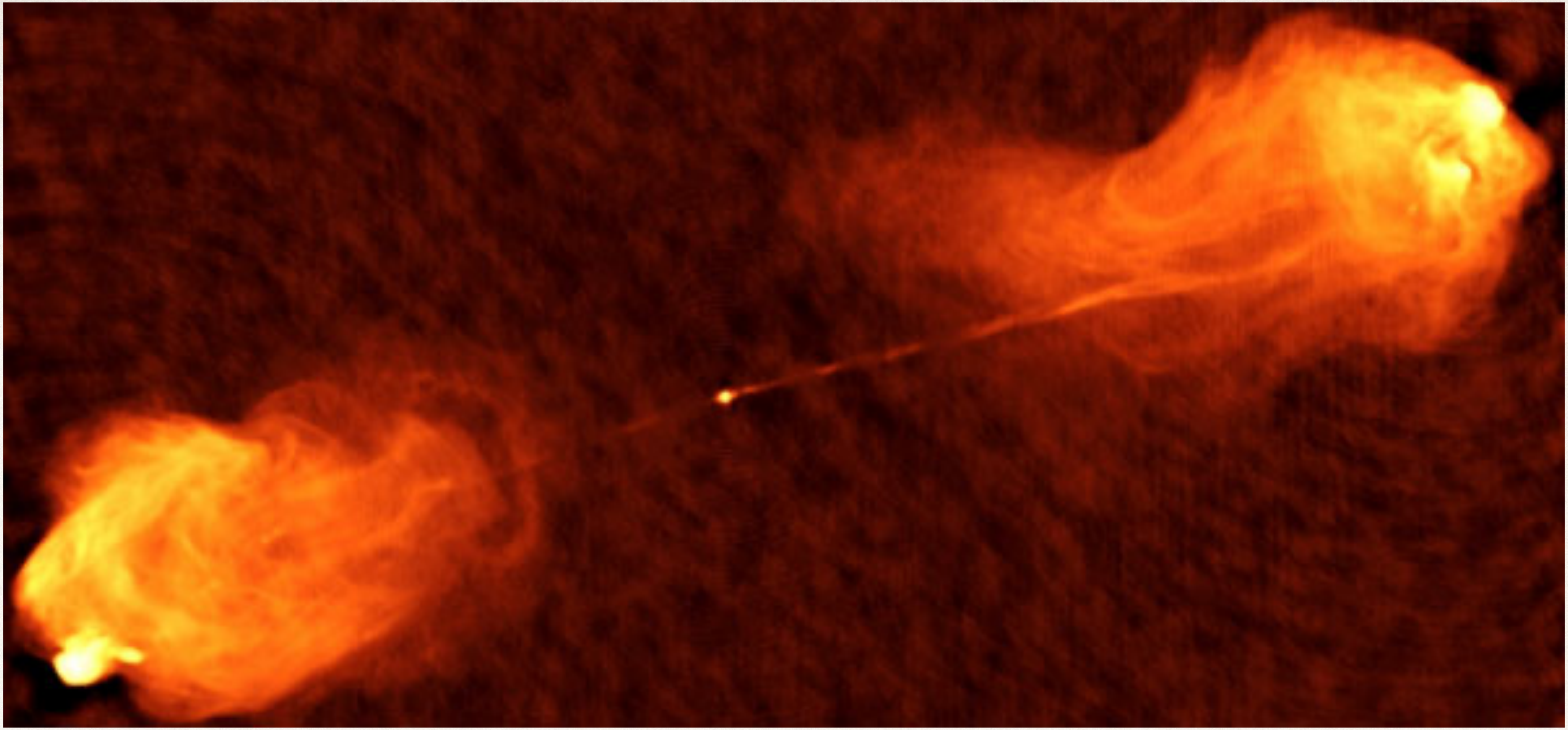
Cygnus A



Jets in the Context of Common Envelope Evolution

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2 June 2022

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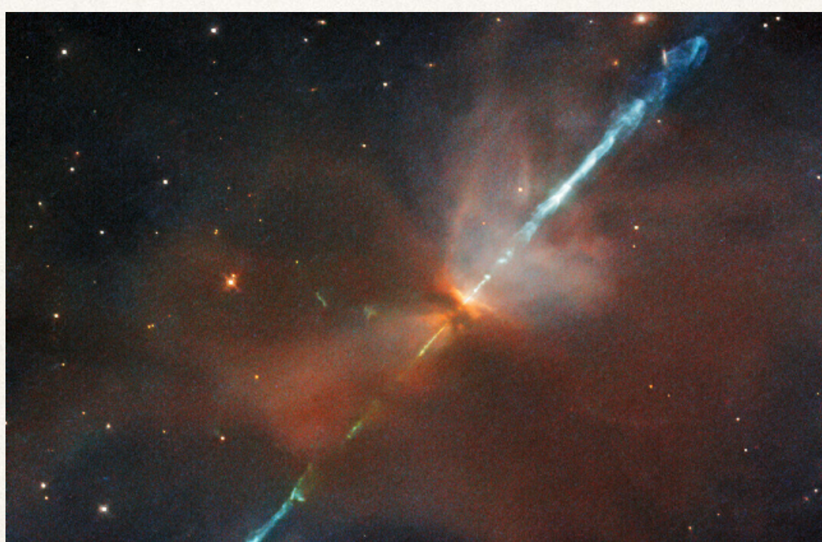
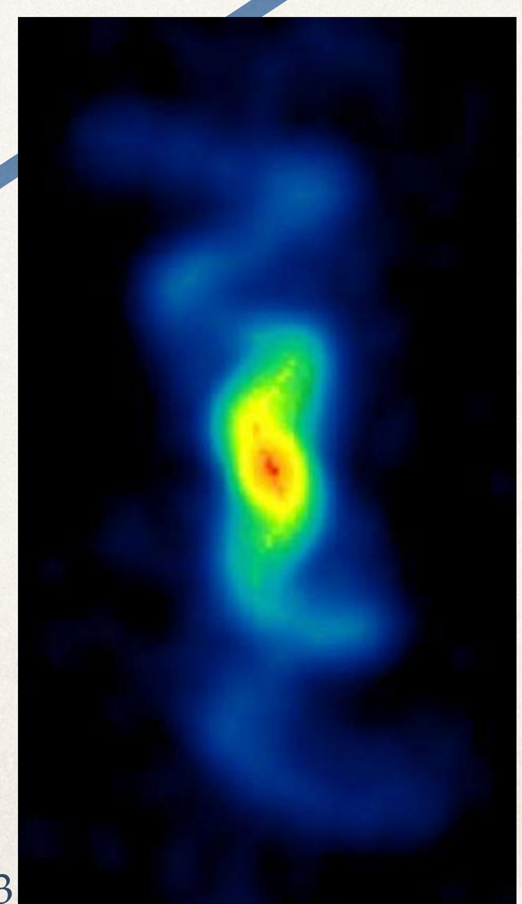
Physics and Astrophysics of Common Envelope

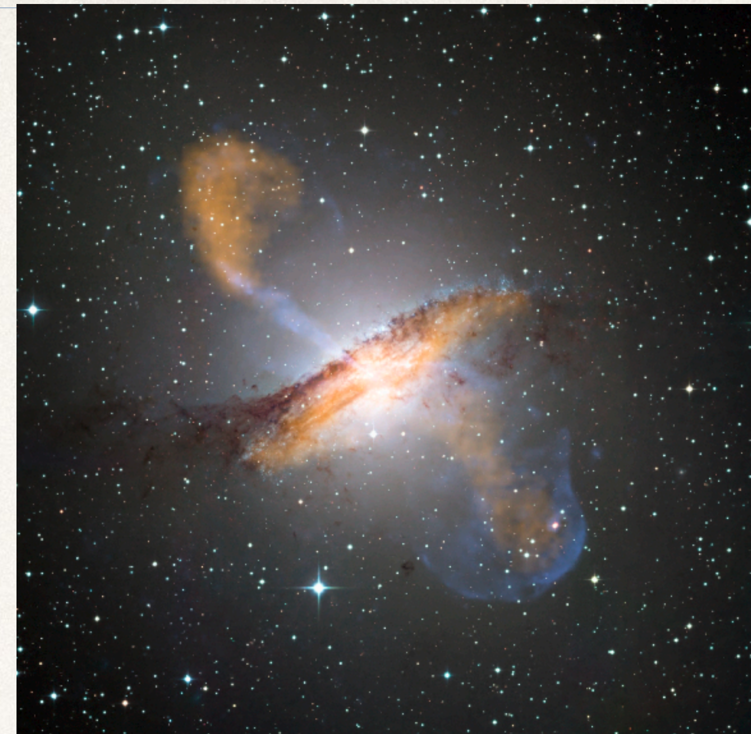
Jets exist across a huge range of physical scales


HH 111

$\sim 1 M_\odot$

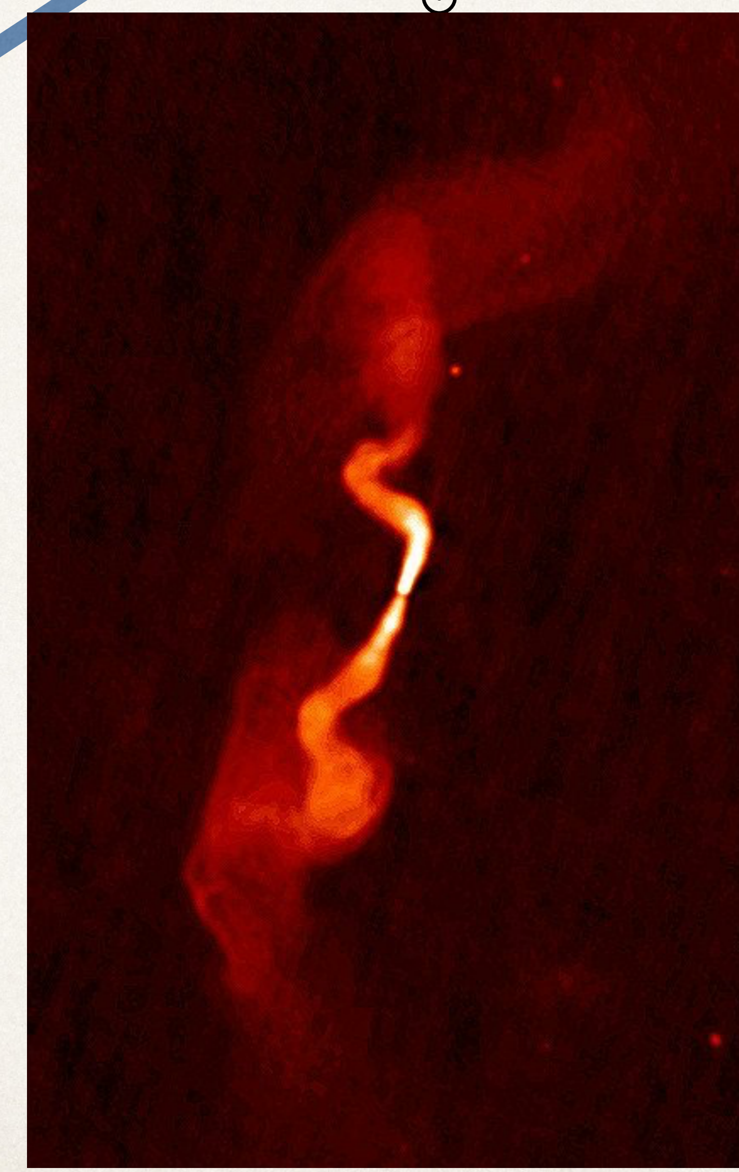

SS433

$\sim 10 M_\odot$


Centaurus A

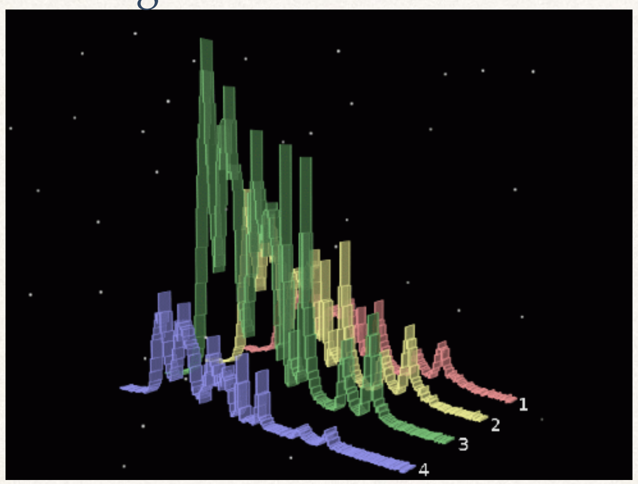
$\sim 10^6 M_\odot$

$\sim 10^9 M_\odot$

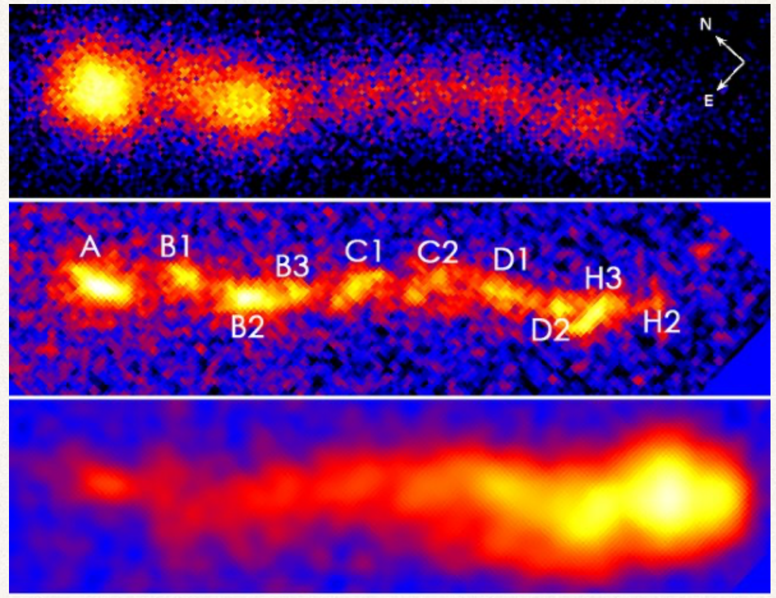

3C31

Jets are observed across the EM spectrum

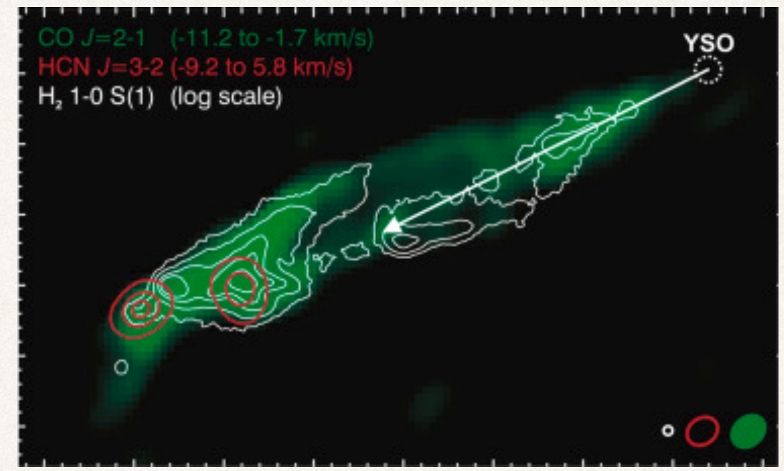
GRB light curve



3C 273



HH 211



γ-ray

UV

IR

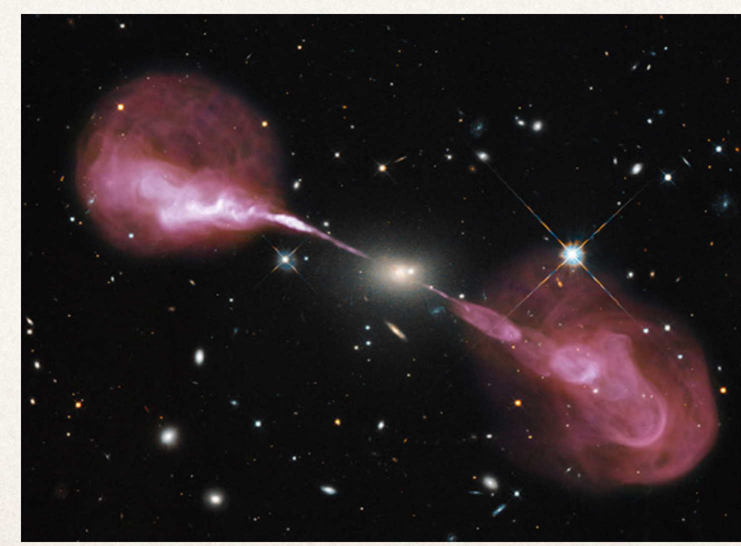
X-ray

Optical

Radio

Crab Pulsar

M87



Hercules A

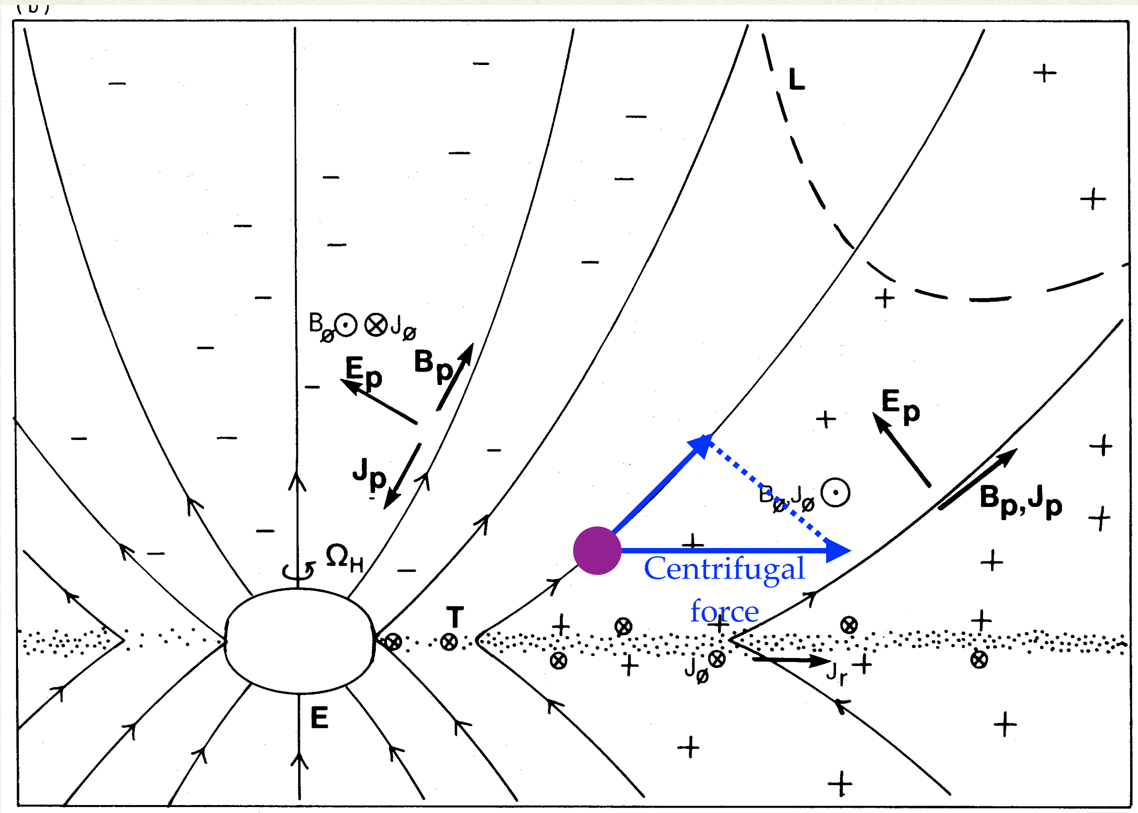
Ingredients for a jet

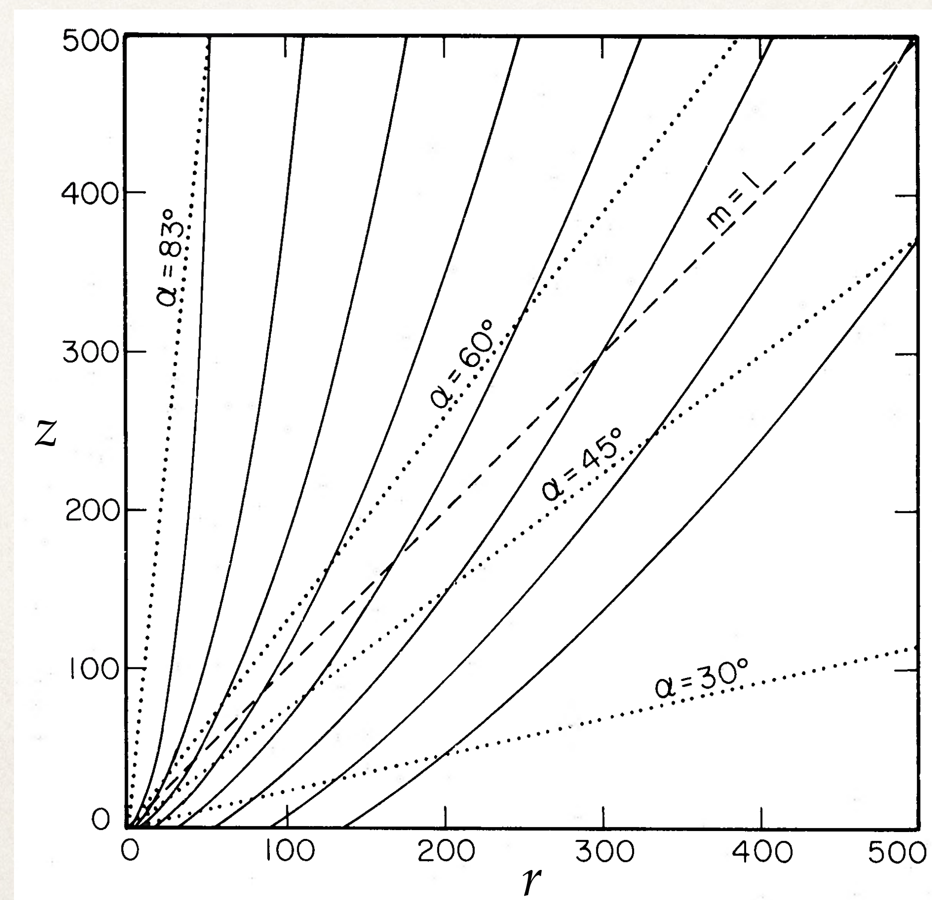
- Rotation
- Open magnetic field lines

Open question #1: Are the jet ingredients provided by the central object or a surrounding accretion disk?

Ingredients for a jet

- Rotation
- Magnetic fields
  - Play multiple roles:
    - Launching jets



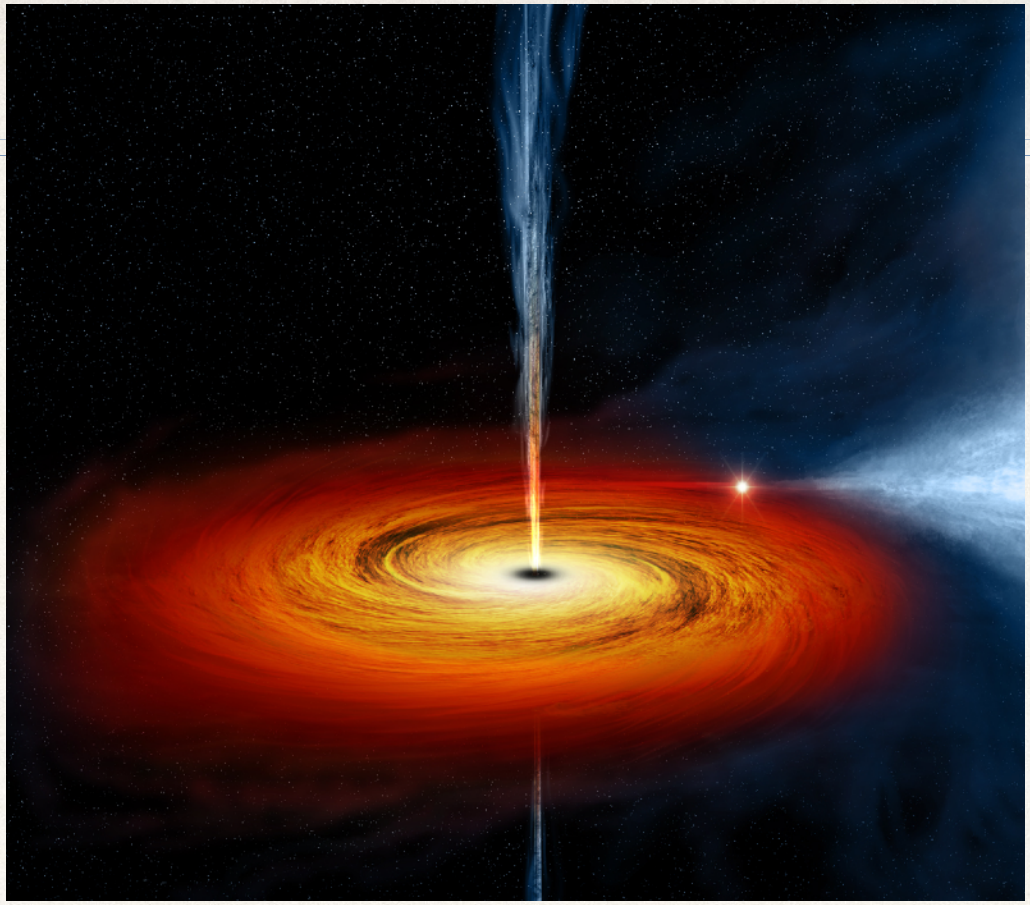


Reference: Blandford & Znajek 1977; Blandford & Payne 1982

Ingredients for a jet

- Rotation
- Accretion disk
- Magnetic fields
  - Play multiple roles:
    - Launching jets
    - Driving accretion

Necessary, though maybe not sufficient



$$\dot{M}_{\rm wind} = \frac{1}{2}\left(\frac{r}{r_A}\right)^2 \dot{M}$$

$$B \approx 0.2 \left(\frac{\dot{M}}{10^{-7} M_\odot \ {\rm yr}^{-1}}\right)^{1/2} \left(\frac{R_{\rm disk}}{1 \ {\rm AU}}\right)^{-5/4} \left(\frac{M}{M_\odot}\right)^{1/4} \ {\rm G}$$

Magnetic field strength required if the field is entirely responsible for angular momentum transport.

Reference: Livio 1999; Wardle 2007; Tocknell et al. 2014

A bit about accretion

- Gravitational binding energy released by accretion

$$L_{\rm acc} \simeq \frac{1}{2}\frac{GM_2\dot{M}_{\rm acc}}{R_2} \qquad\qquad E_{\rm acc} \simeq \frac{1}{2}\frac{GM_2M_{\rm acc}}{R_2} \lesssim 10^{49}\ {\rm erg}$$

  - In the extreme case, this is comparable to the binding energy of the envelope.

A bit about accretion

- Gravitational binding energy released by accretion

$$L_{\rm acc} \simeq \frac{1}{2}\frac{GM_2\dot{M}_{\rm acc}}{R_2} \qquad E_{\rm acc} \simeq \frac{1}{2}\frac{GM_2 M_{\rm acc}}{R_2} \lesssim 10^{49}\ {\rm erg}$$

- This energy can be partitioned between radiation, winds, and jets

Table 1. Summary of the main properties of the five $\dot{m}$ regimes sketched in Fig. 1 and described in Sects. 2.2–2.6.

$\dot{m}$ range (1)	Accretion/ejection flow (2)	Feedback (3)	Examples (4)
Very low $\dot{m} \approx 10^{-8}$ ($\ll 10^{-6}$)	Non-radiative hot accretion flow relativistic polar jet	$L_{\rm kin}$	Quiescent/inactive, Sgr A*
Low $\dot{m} \approx 10^{-4}$ ($10^{-6} \lesssim \dot{m} \lesssim 10^{-3}$)	Outer cold disk at ~1000 s $R_{\rm g}$, inner hot flow relativistic polar jet	$L_{\rm kin} \gg L_{\rm rad}$	LLAGN M 81*, M 87
Moderate $\dot{m} \approx 10^{-2}$ ($10^{-3} \lesssim \dot{m} \lesssim 10^{-1}$)	Outer cold disk at ~10 s $R_{\rm g}$, extended hot corona weak/moderate LD wind depending on small/large $M_{\rm BH}$	$L_{\rm kin} \ll L_{\rm rad}$	Seyfert/mini-BAL QSO NGC 5548/PG 1126−041
High $\dot{m} \gtrsim 0.25$ ($0.1 \lesssim \dot{m} \lesssim 1$)	Cold accretion disk down to ISCO, compact hot corona moderate/strong LD wind depending on small/large $M_{\rm BH}$	$L_{\rm kin} < L_{\rm rad}$	NLS1/BAL QSO I Zw 1/PDS 456
Very high $\dot{m} \gg 1$ ($1 \lesssim \dot{m} \lesssim 100$)	Outer thin disk, inner slim disk, very compact hot corona strong outflows, both polar and equatorial	$L_{\rm kin} \lesssim L_{\rm rad}$	Super-Eddington RX J0439.6−531

Notes. (1) Nomenclature for the Eddington ratio ranges used in this work, with an indicative order of magnitude, and an indicative range of values in parentheses. (2) Accretion and ejection flow main physical characteristics. (3) Type of energy feedback between the AGN and the environment: kin = kinetic, rad = radiative. (4) Classes of objects or individual examples of well-studied local AGN.

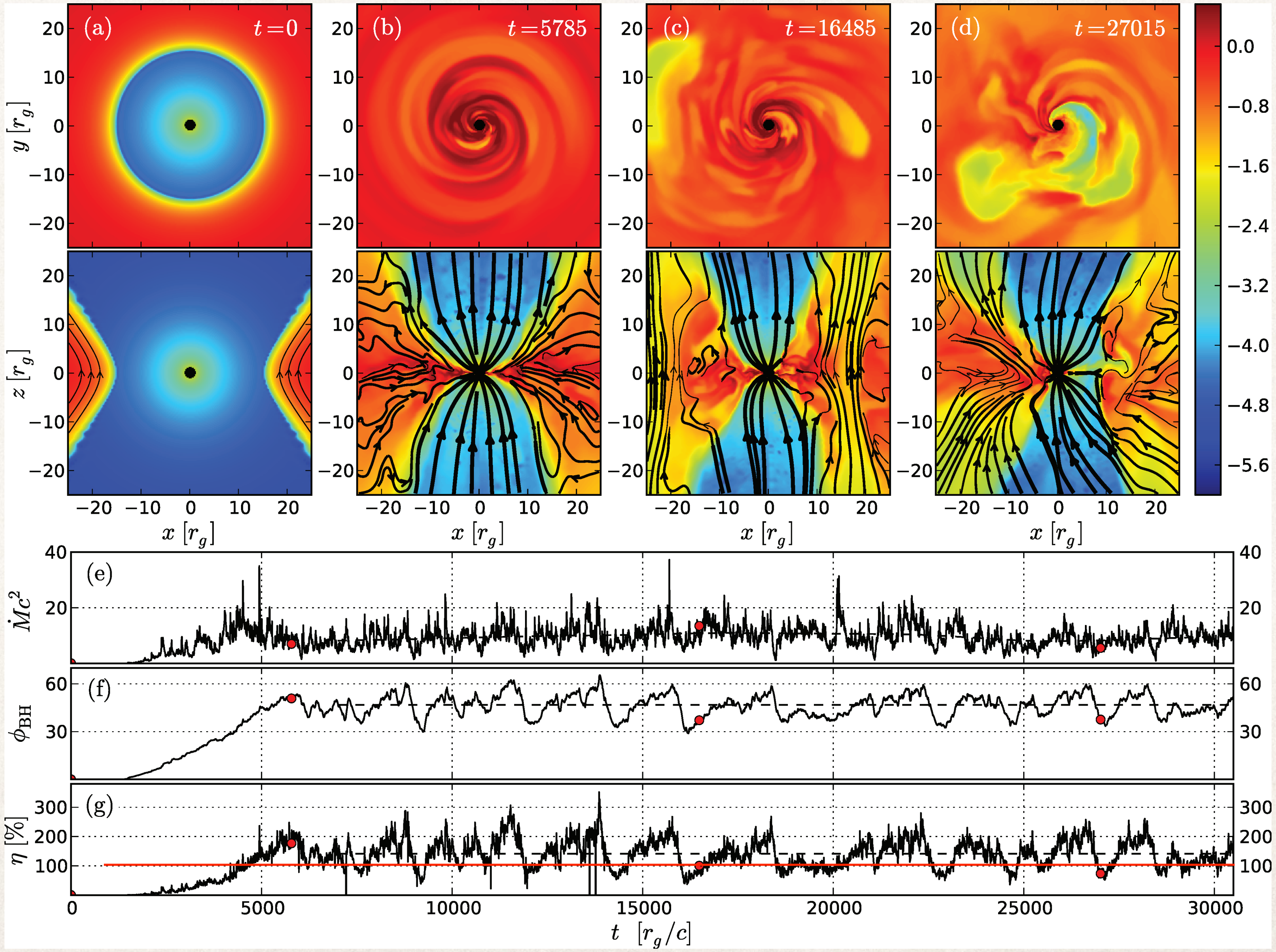
Reference: Giustini & Proga 2019

A bit about accretion

- Gravitational binding energy released by accretion

$$L_{\rm acc} \simeq \frac{1}{2}\frac{GM_2\dot{M}_{\rm acc}}{R_2} \qquad E_{\rm acc} \simeq \frac{1}{2}\frac{GM_2M_{\rm acc}}{R_2} \lesssim 10^{49}\ {\rm erg}$$

- This energy can be partitioned between radiation, winds, and jets



More energy coming out in jets than radiation!

Reference: Tchekhovskoy, Narayan & McKinney 2011

Roles of jets

- Extract/transport mass

$$\dot{M}_{\rm jet} \overset{?}{\sim} \dot{M}_{\rm Edd} \sim 10^{-3} \left(\frac{R_2}{R_\odot} \right) M_\odot \ {\rm yr}^{-1}$$

Reference: Tocknell et al. 2014

Roles of jets

- Extract / transport mass

$$\dot{M}_{\rm jet} \overset{?}{\sim} \dot{M}_{\rm Edd} \sim 10^{-3} \left(\frac{R_2}{R_\odot} \right) M_\odot \ {\rm yr}^{-1}$$

- Extract / transport energy

$$\dot{E}_{\rm jet} \gtrsim 10^{37} \ {\rm erg} \ {\rm s}^{-1}$$

Reference: Fragile et al. 2012

Roles of jets

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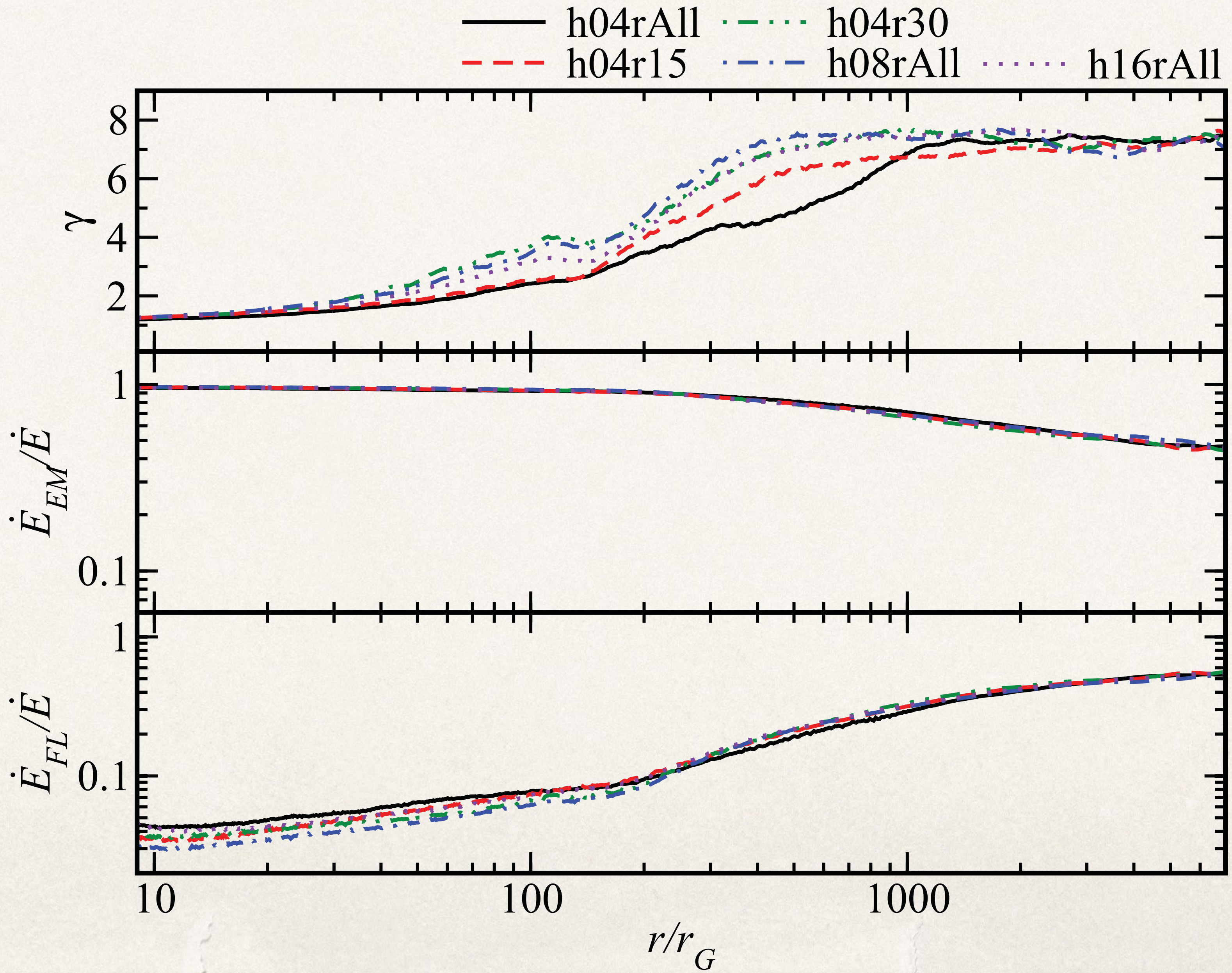
$$\dot{M}_{\rm jet} \overset{?}{\sim} \dot{M}_{\rm Edd} \sim 10^{-3} \left(\frac{R_2}{R_\odot} \right) M_\odot \ {\rm yr}^{-1}$$

- Extract / transport energy

$$\dot{E}_{\rm jet} \gtrsim 10^{37} \ {\rm erg \ s^{-1}}$$

Poynting flux

Kinetic flux



Reference: Fragile et al. 2012

Roles of jets

- Extract / transport mass

$$\dot{M}_{\rm jet} \overset{?}{\sim} \dot{M}_{\rm Edd} \sim 10^{-3} \left(\frac{R_2}{R_\odot}\right) M_\odot \ {\rm yr}^{-1}$$

- Extract / transport energy

$$\dot{E}_{\rm jet} \gtrsim 10^{37} \ {\rm erg} \ {\rm s}^{-1}$$

- Extract / transport angular momentum?

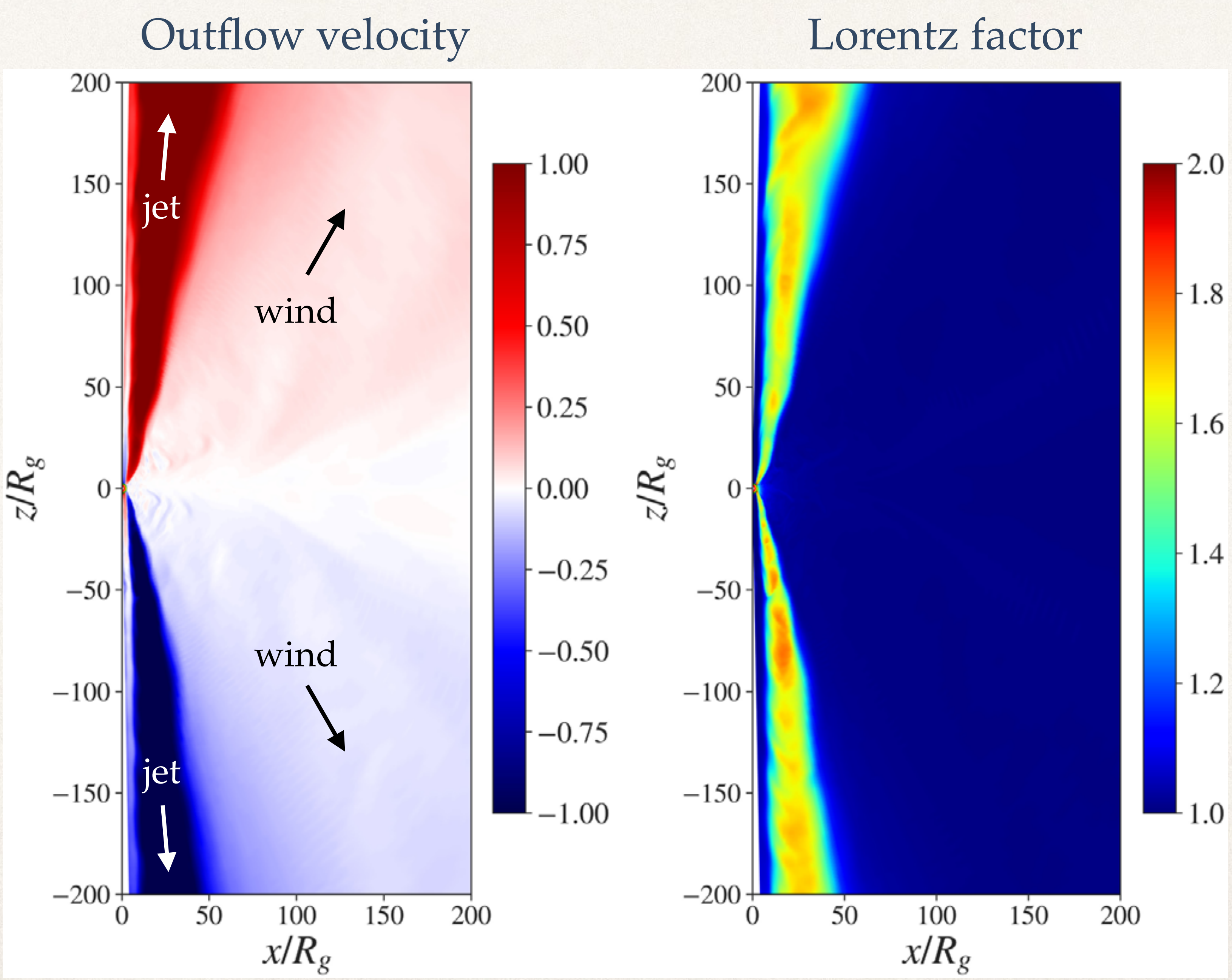
$$\dot{J} = \frac{1}{2}\dot{M}_{\rm acc} R_{\rm disk}^2 \Omega$$

Open question #2: How much of a disk's angular momentum is carried away by the jet?

Reference: Tocknell et al. 2014

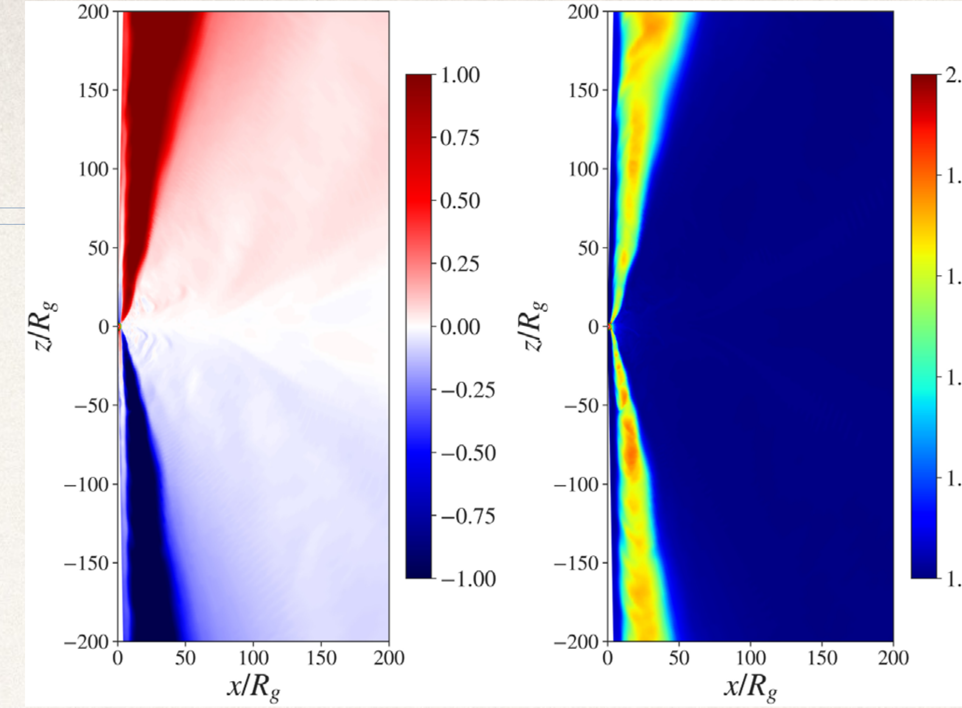
Jets vs. winds

- Outflows can come in
  - narrow, high velocity components (jets)
  - wider, slower components (winds)

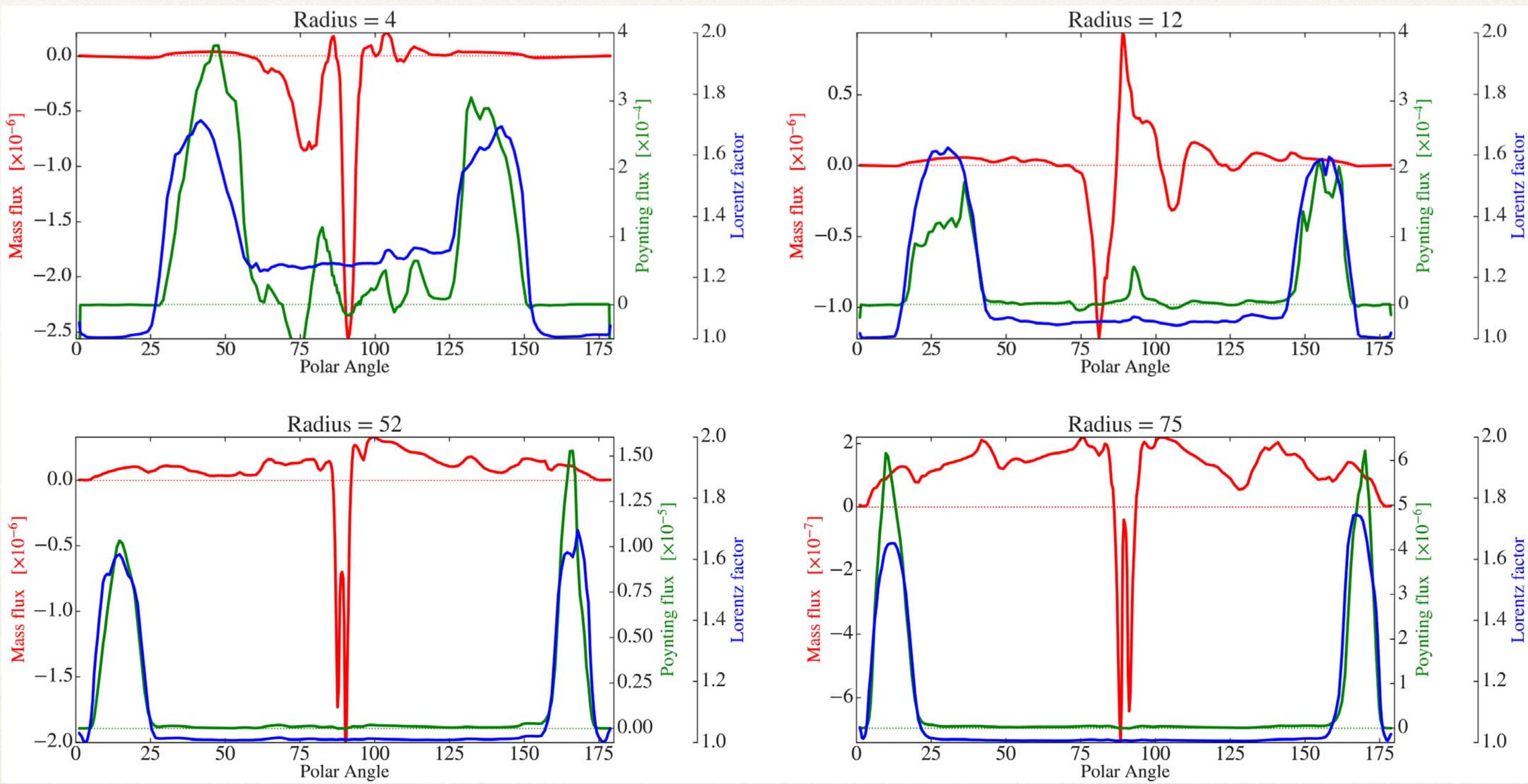


Reference: Vourellis et al. 2019

Jets vs. winds

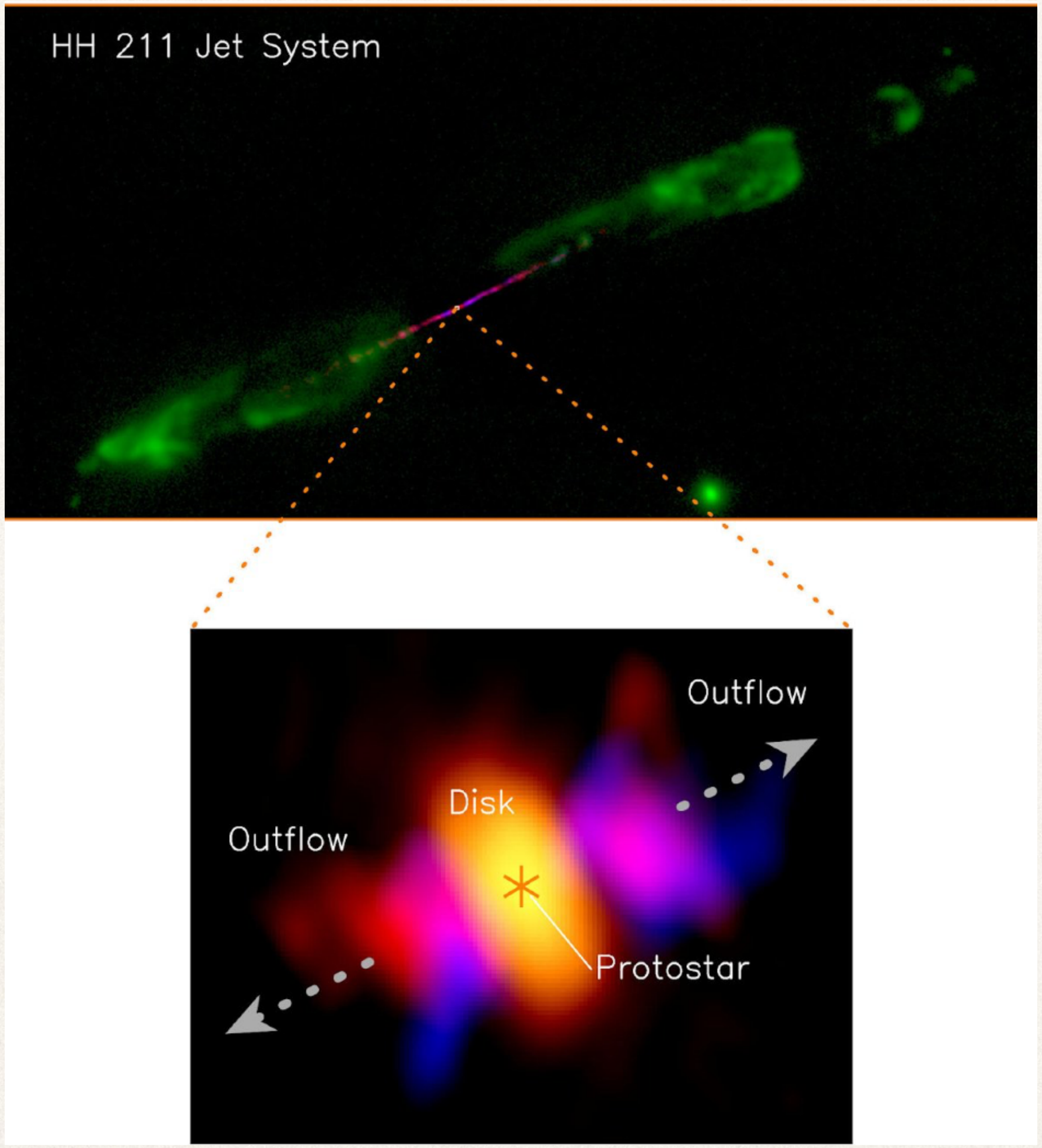


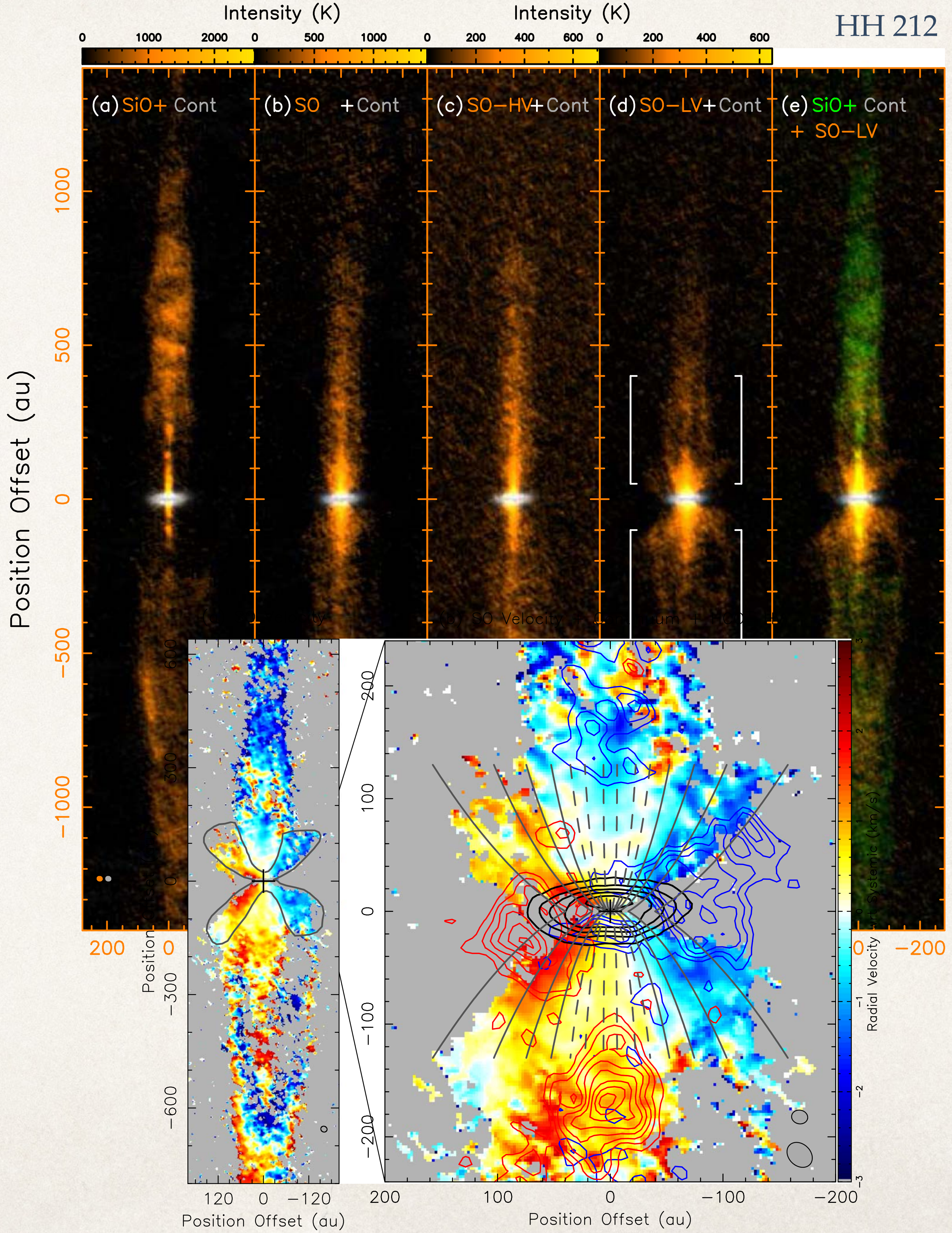
- $\dot{M}$ dominated by wind
- $\dot{J}$ dominated by wind
- $\dot{E}$ dominated by ???



Reference: Vourellis et al. 2019

Jets vs. winds





Reference: Lee et al. 2018; Lee et al. 2021

Jets vs. winds

- For those simulating "jets" in CEE
  - The jets and winds are likely originating at scales below what you can resolve -> subgrid models

- What you know

$$\dot{E}_{\rm acc} \simeq \frac{1}{2}\frac{GM_2\dot{M}_{\rm acc}}{R_2}$$

- What you need to know

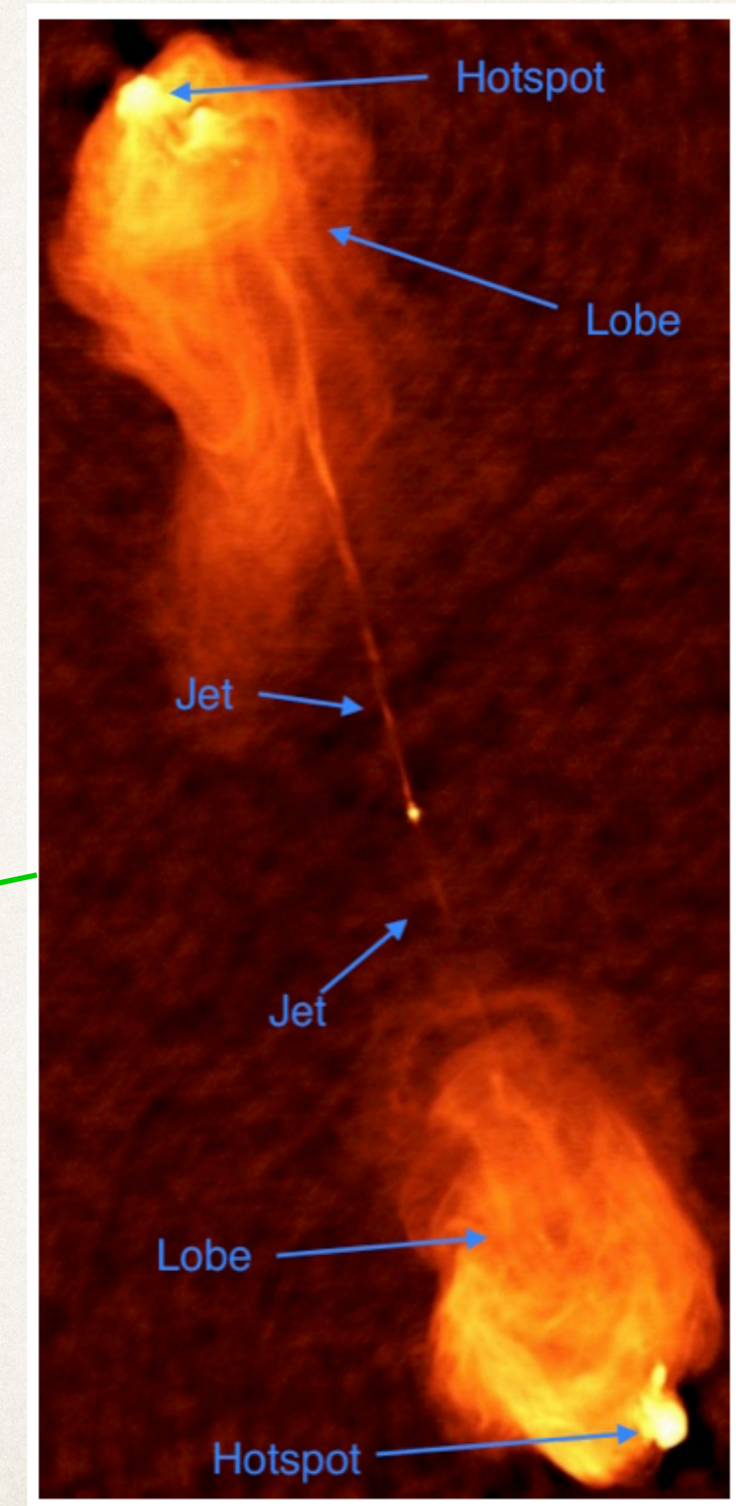
$$\dot{M}_{\rm out},\ v_{\rm out},\ \theta_{\rm out}$$

Takeaway point #1: Make sure what you inject is consistent with your energy budget.

Where do jets deposit their energy?

- In some systems, jets deposit their energy very far from the source
  - This would be bad for CE ejection

More than a million times the scale of the emitting region



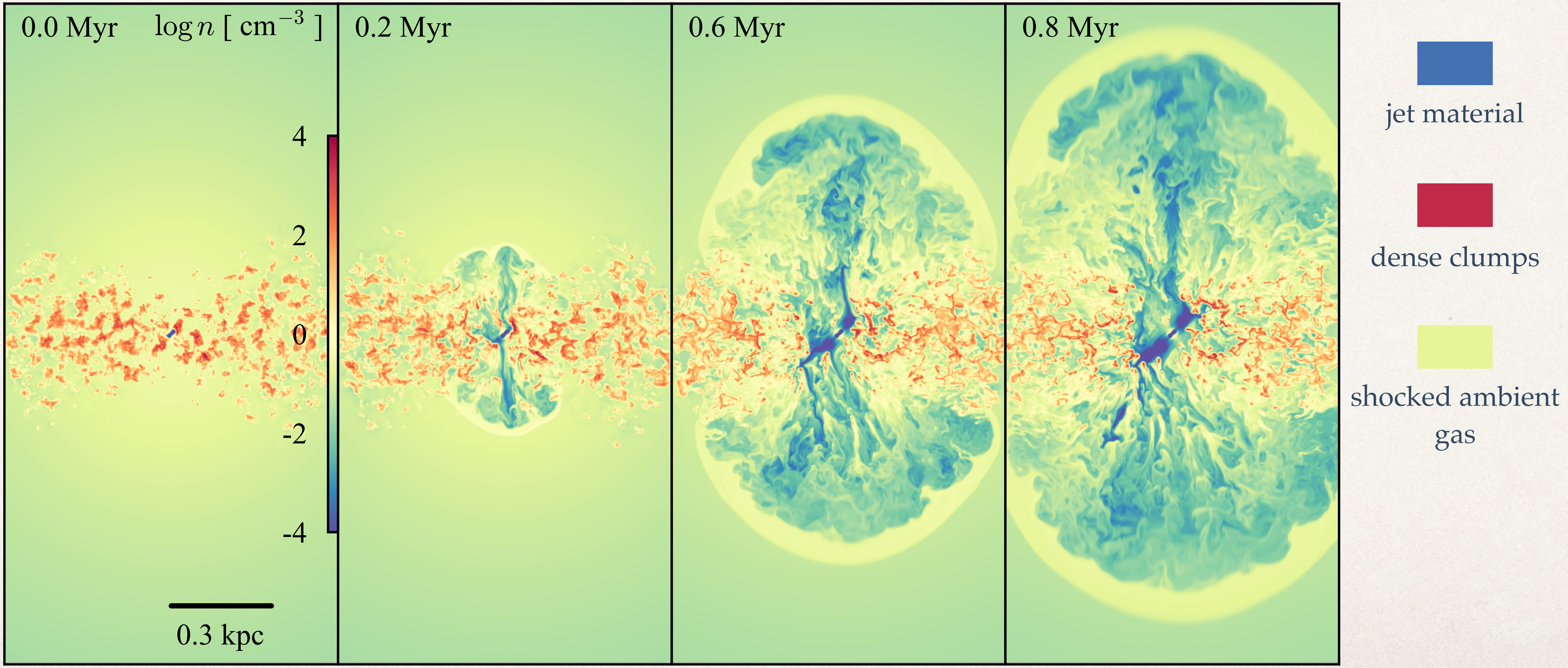
Cygnus A

Simulation of GRB jet drilling through surrounding star

Reference: Zhang, Woosley & Heger 2004

Where do jets deposit their energy?

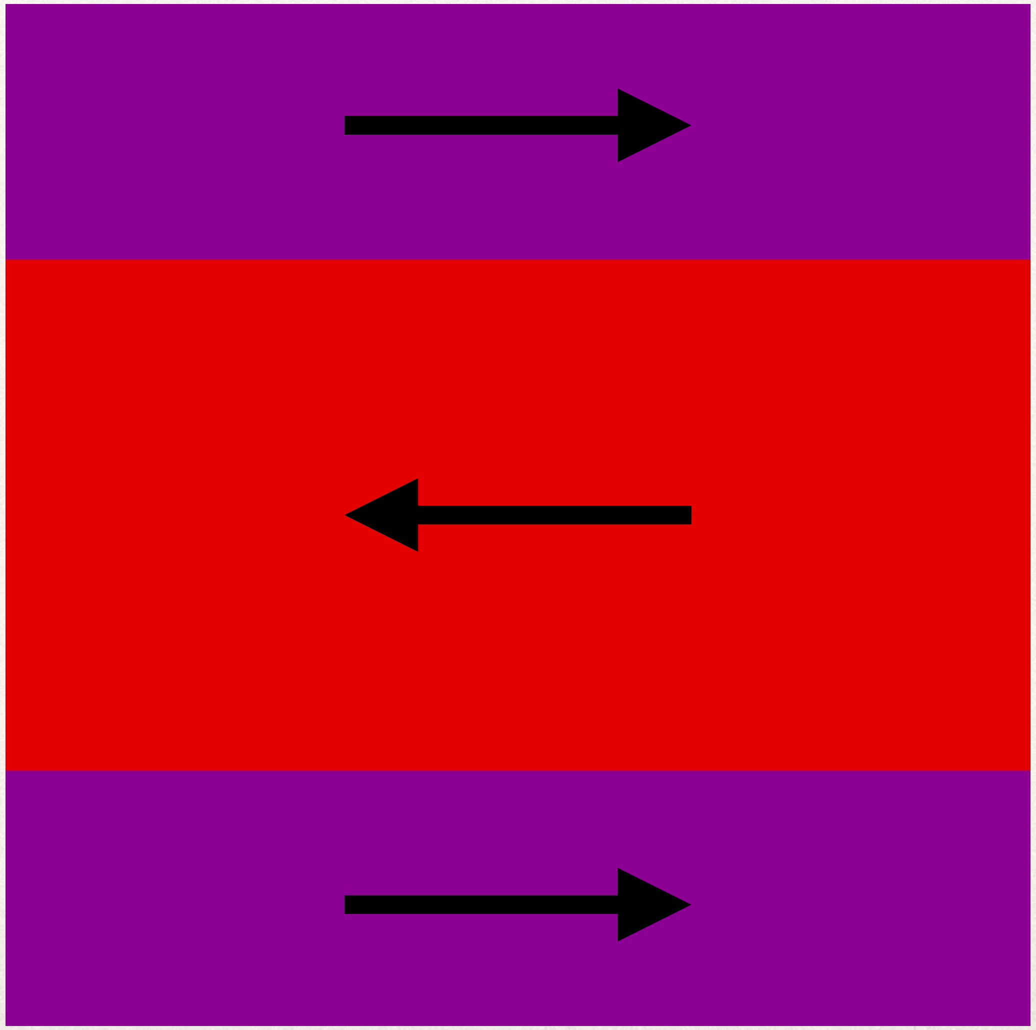
- In some systems, jets deposit their energy very far from the source
- Jets may drive shocks into the CE, thus depositing some fraction of their available energy



Reference: Murthy et al. 2022

Where do jets deposit their energy?

- In some systems, jets deposit their energy very far from the source
- Jets may drive shocks into the CE, thus depositing some fraction of their available energy
- Kelvin-Helmholtz instability may allow for mixing/entrainment



Reference: https://www.astro.princeton.edu/~jstone/Athena/tests/kh/kh.html

Where do jets deposit their energy?

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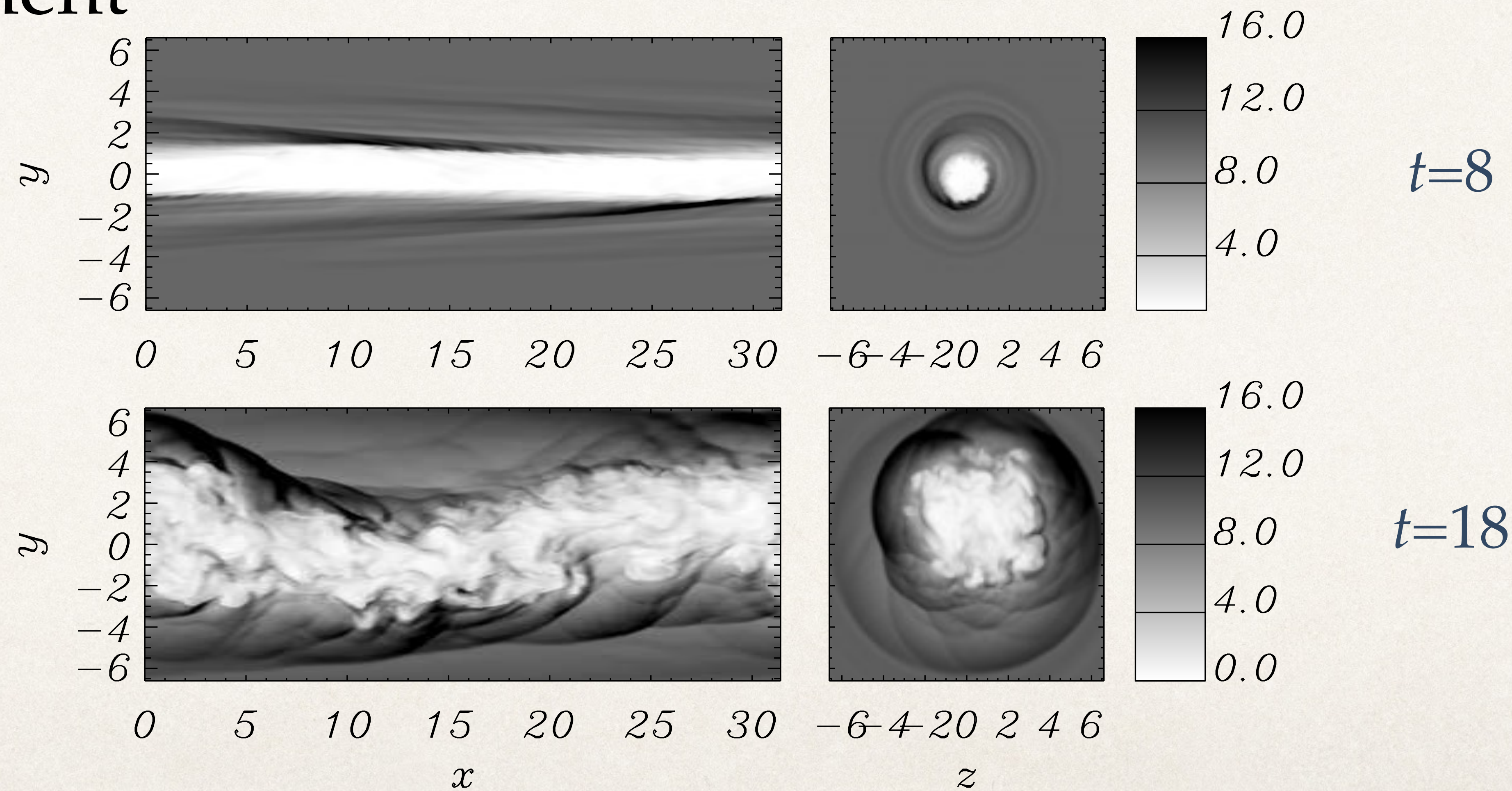
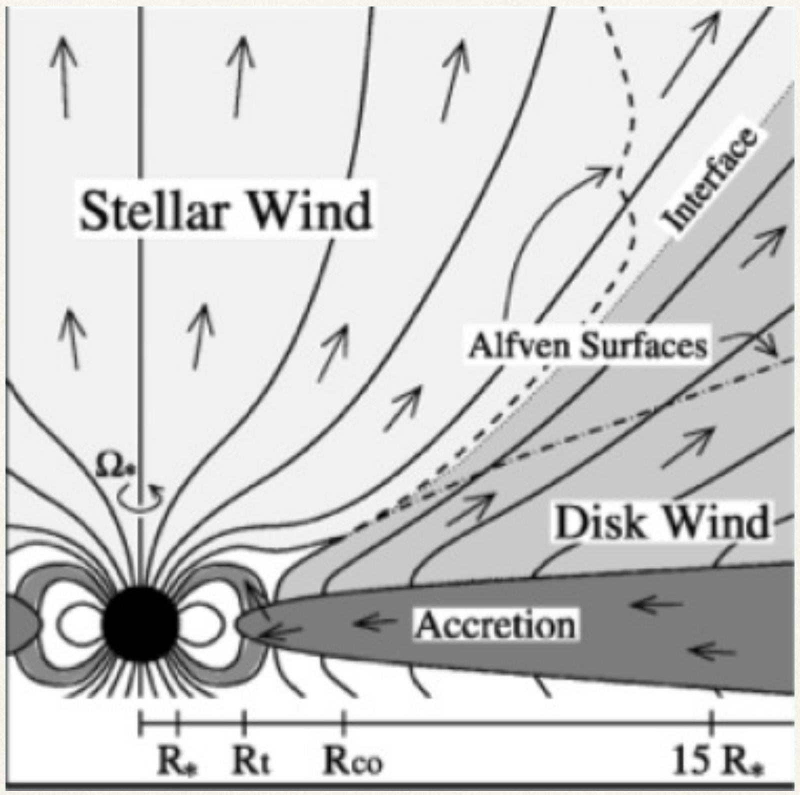
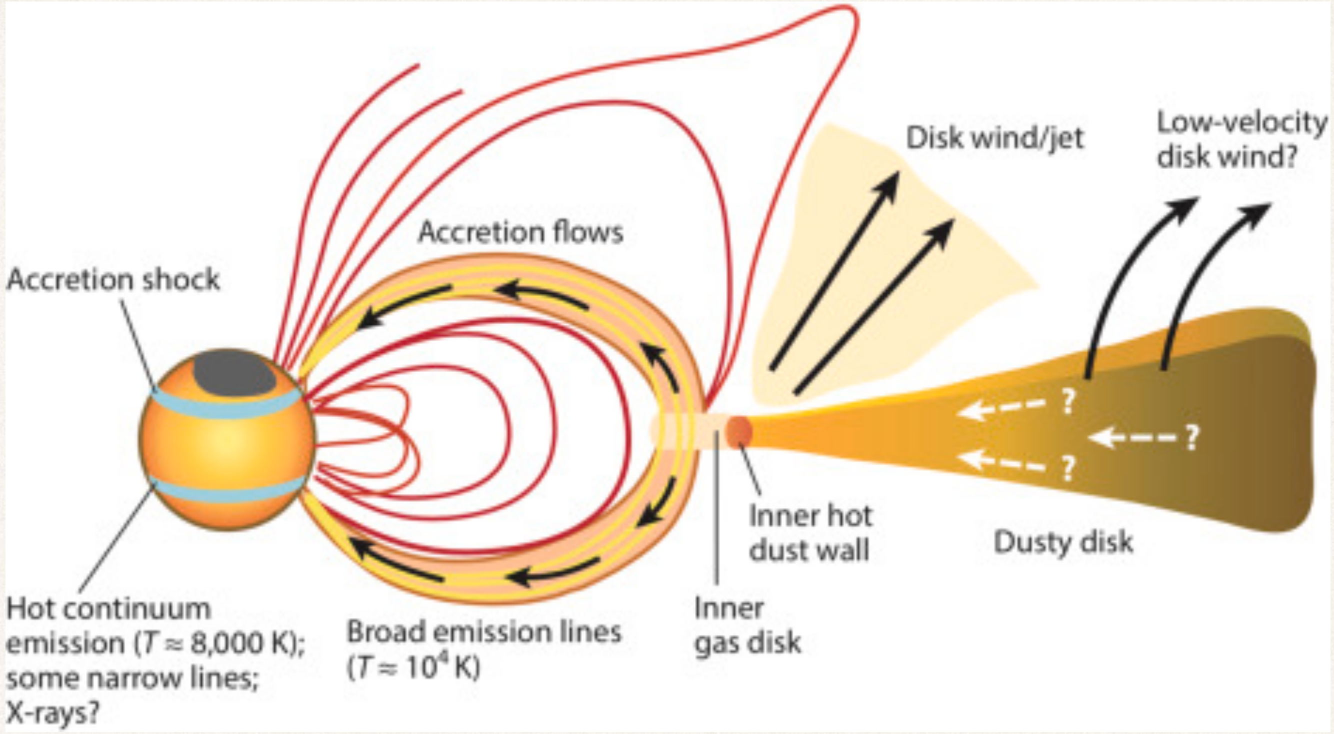


Reference: Micono et al. 2000

Systems with known jets

- YSOs
- White dwarfs
- Neutron stars





$$L_{\rm jet} \sim \frac{GM_* \dot{M}_{\rm jet}}{R_*}$$

If $\dot{M}_{\rm jet} \sim 10^{-3} \left(\frac{R_2}{R_\odot}\right) M_\odot \ {\rm yr}^{-1}$

$$L_{\rm jet} \sim 10^{37} \ {\rm erg \ s^{-1}}$$

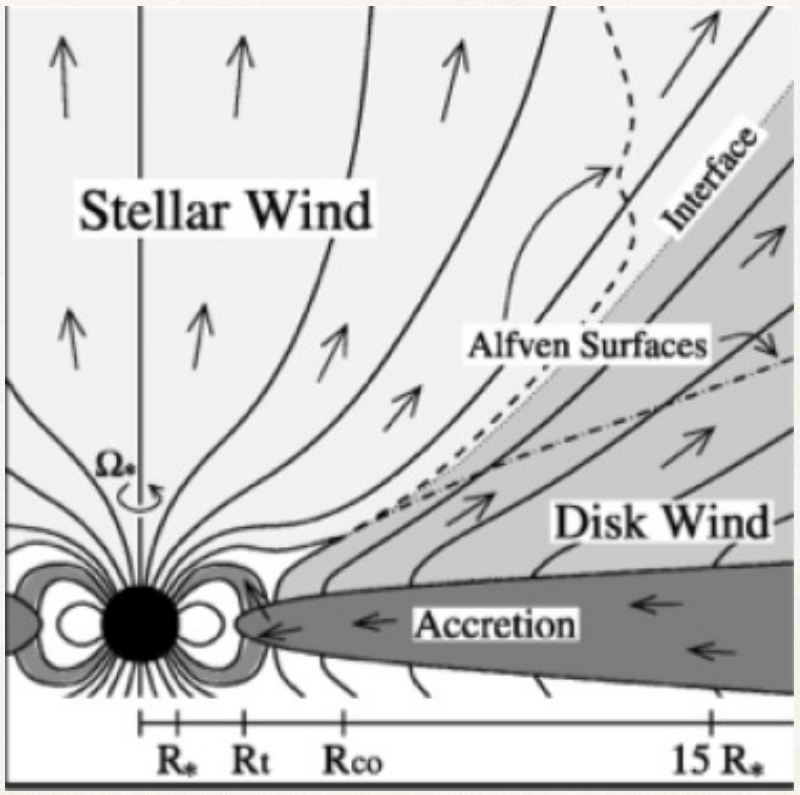
$$v_{\rm jet,MS} \sim 200 \ {\rm km \ s^{-1}}$$
$$v_{\rm jet,WD} \sim 2000 \ {\rm km \ s^{-1}}$$
$$v_{\rm jet,NS} \sim 20000 \ {\rm km \ s^{-1}}$$

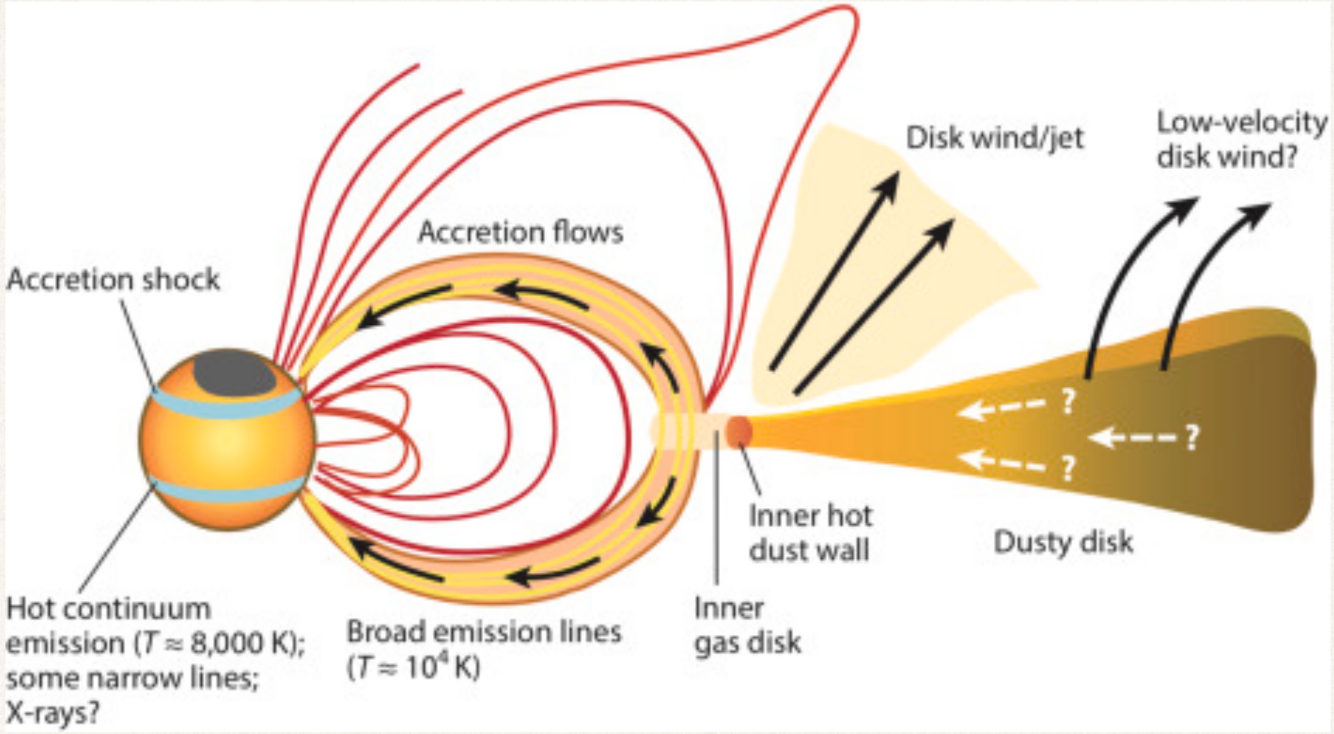
Takeaway point #2: Speed of outflow should depend on the compactness of the accretor.

Reference: Matt and Pudritz 2005; Hartmann et al. 2016

Systems with known jets

- YSOs
- White dwarfs
- Neutron stars





$$L_{\rm jet} \sim \frac{GM_*\dot{M}_{\rm jet}}{R_*}$$

If $\dot{M}_{\rm jet} \sim 10^{-3}\left(\frac{R_2}{R_\odot}\right) M_\odot\ {\rm yr}^{-1}$

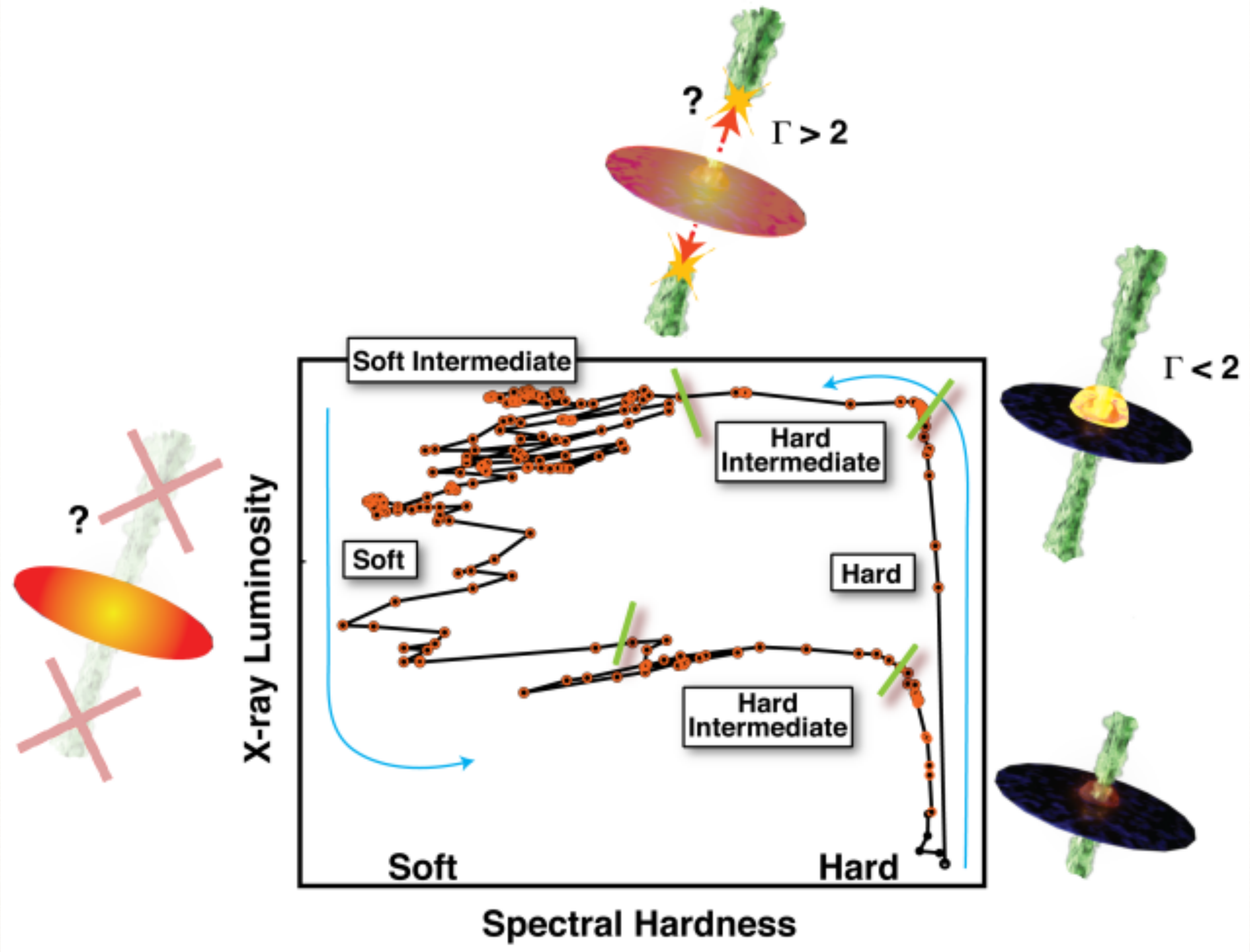
$$L_{\rm jet} \sim 10^{37}\ {\rm erg\ s}^{-1}$$

$$L_{\rm jet,SS433} \gtrsim 10^{39}\ {\rm erg\ s}^{-1}$$

Reference: Matt and Pudritz 2005; Hartmann et al. 2016; Watson et al. 1986

There may be more to the story…

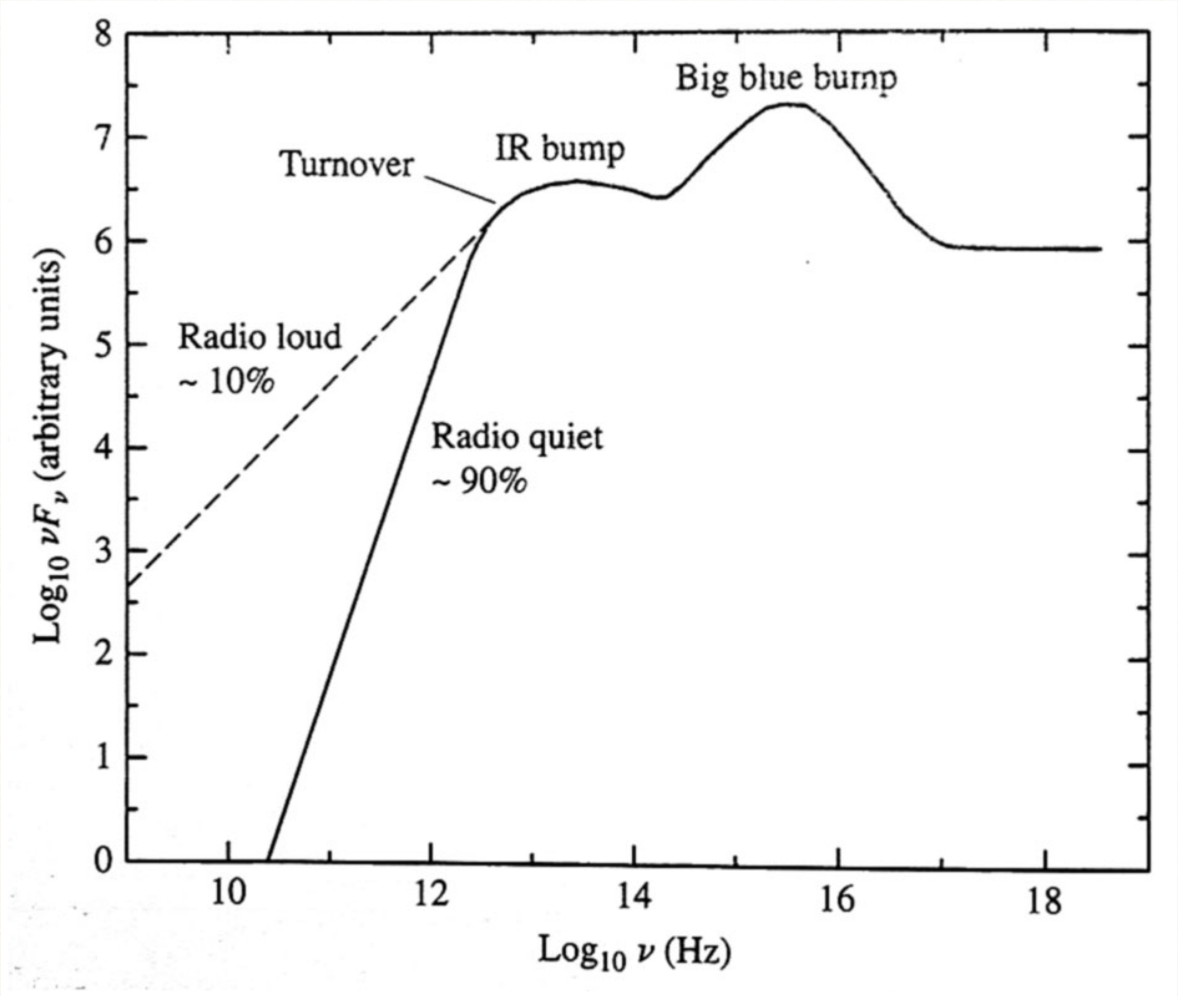
- X-ray binary hardness-intensity (or “q”) diagram
  - single source can sometimes have a jet and sometimes not

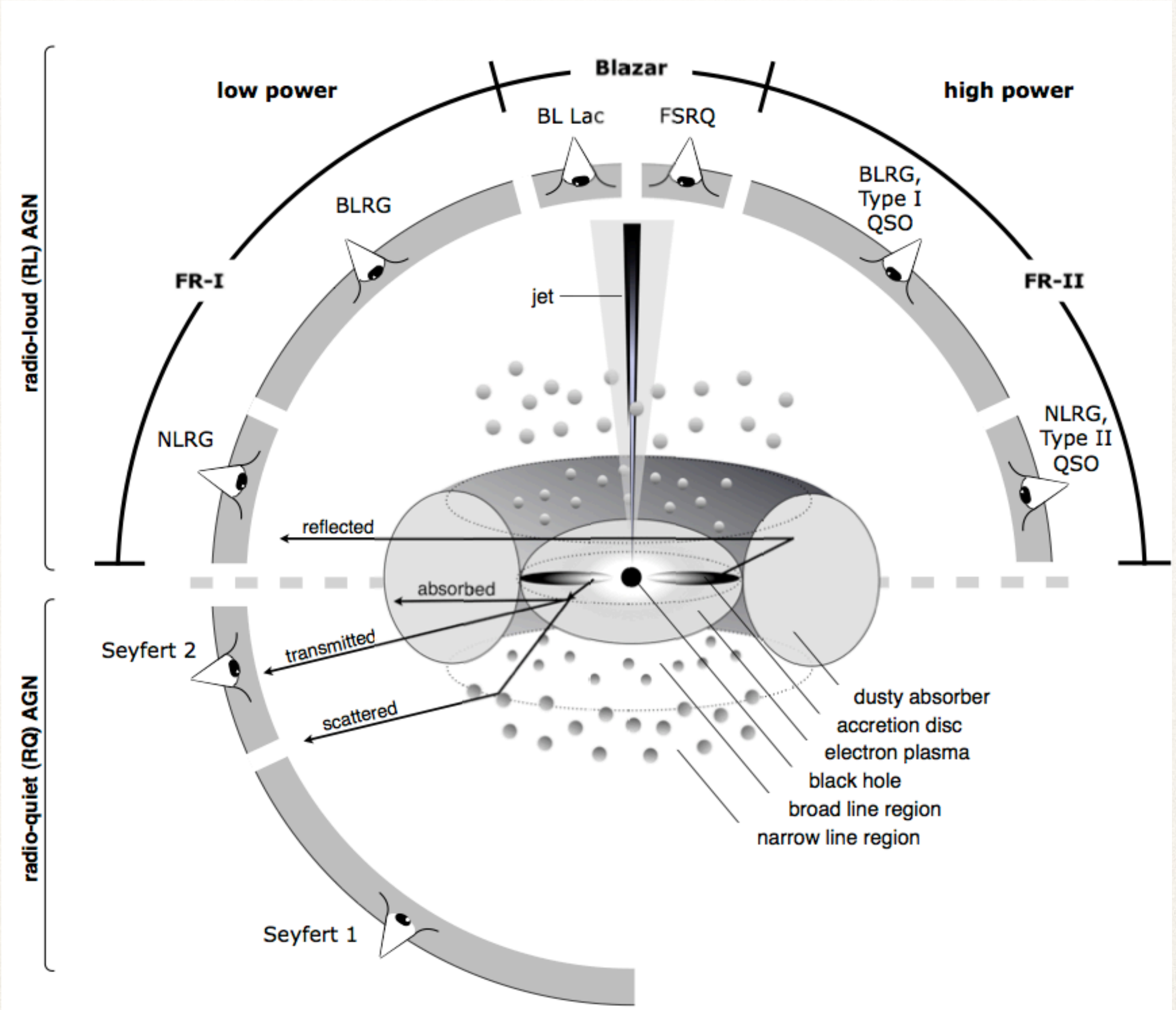


Reference: data for GX 339-4

There may be more to the story…

- X-ray binary hardness-intensity (or "q") diagram
- Radio loud vs. Radio quiet AGN
  - otherwise similar sources can sometimes exhibit jets, sometimes not





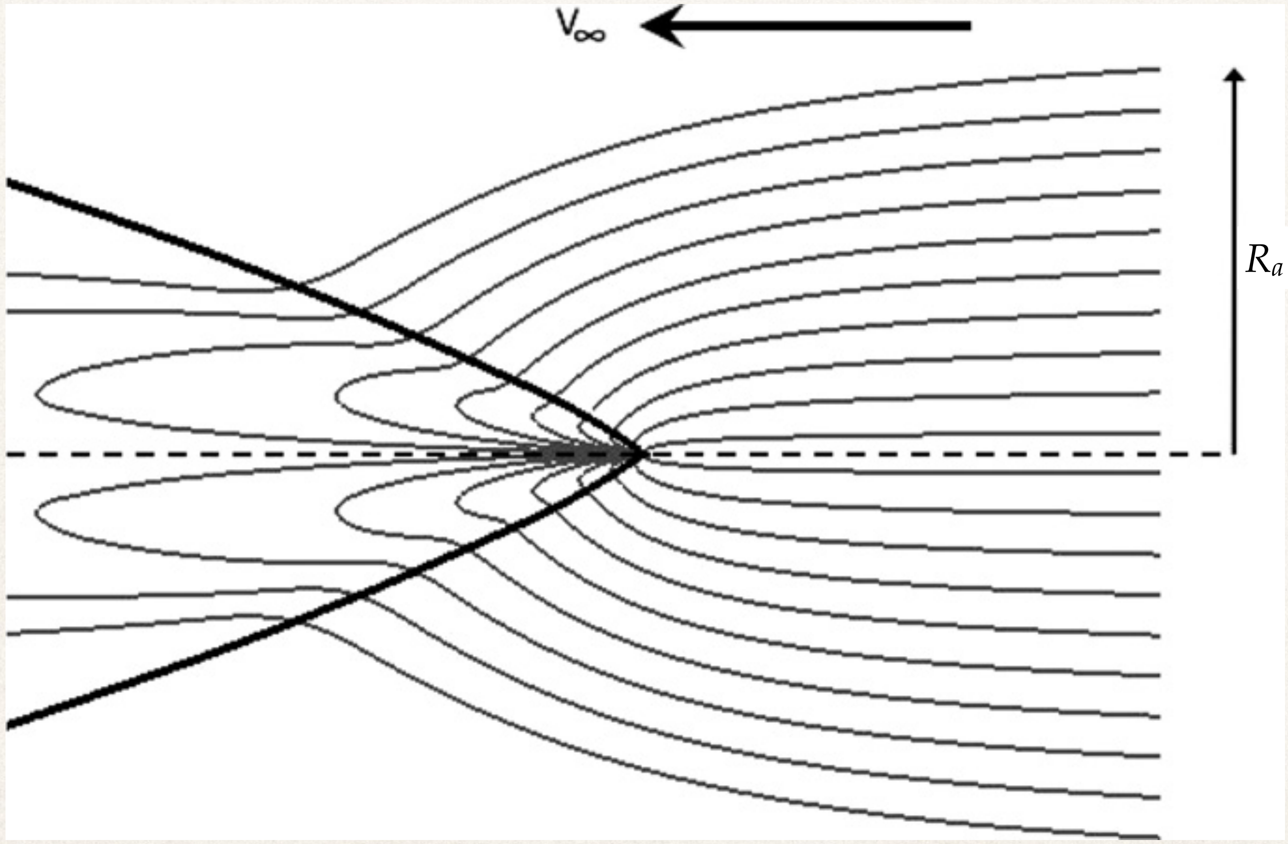
Open question #3: Why do systems sometimes show jets and sometimes not?

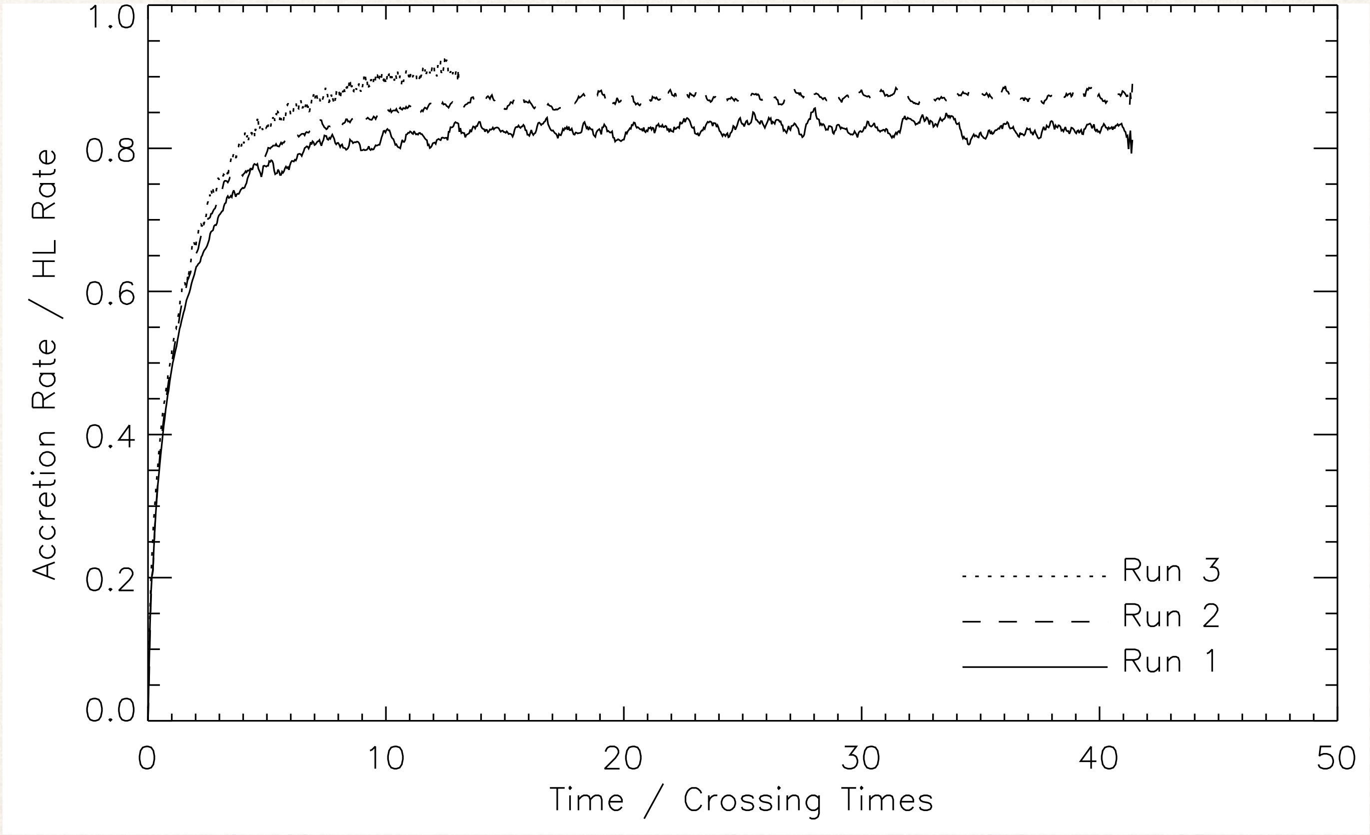
Bondi-Hoyle-Lyttleton accretion

- "Wind tunnel" approximation (whenever $M_2/M_1 < 1/3$)
  - Uniform hydro

$$\dot{M}_{\rm HL} = \pi R_a^2 \rho_\infty v_\infty = \frac{4\pi G^2 M^2 \rho_\infty}{v_\infty^3} \lesssim 1 M_\odot\ {\rm yr}^{-1} \gg \dot{M}_{\rm Edd}$$

$\mathscr{M}$	4
$r_{\rm in}/R_a$	0.0125





Reference: Blondin & Pope 2009; Edgar 2004

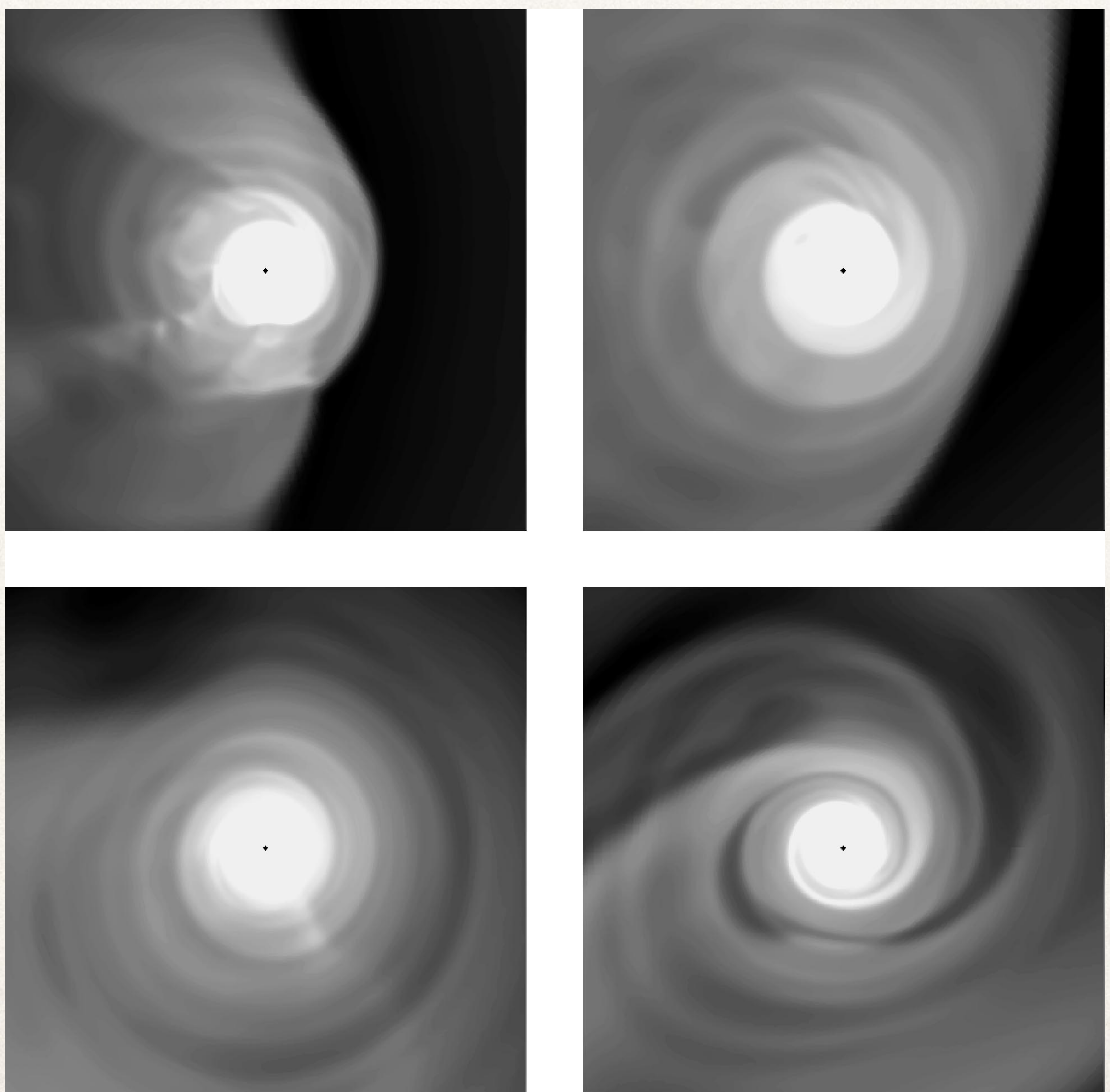
Bondi-Hoyle-Lyttleton accretion

- “Wind tunnel” approximation
  - Structured hydro

$$\rho_\infty \propto e^{\epsilon_\rho \Delta r / R_a}$$

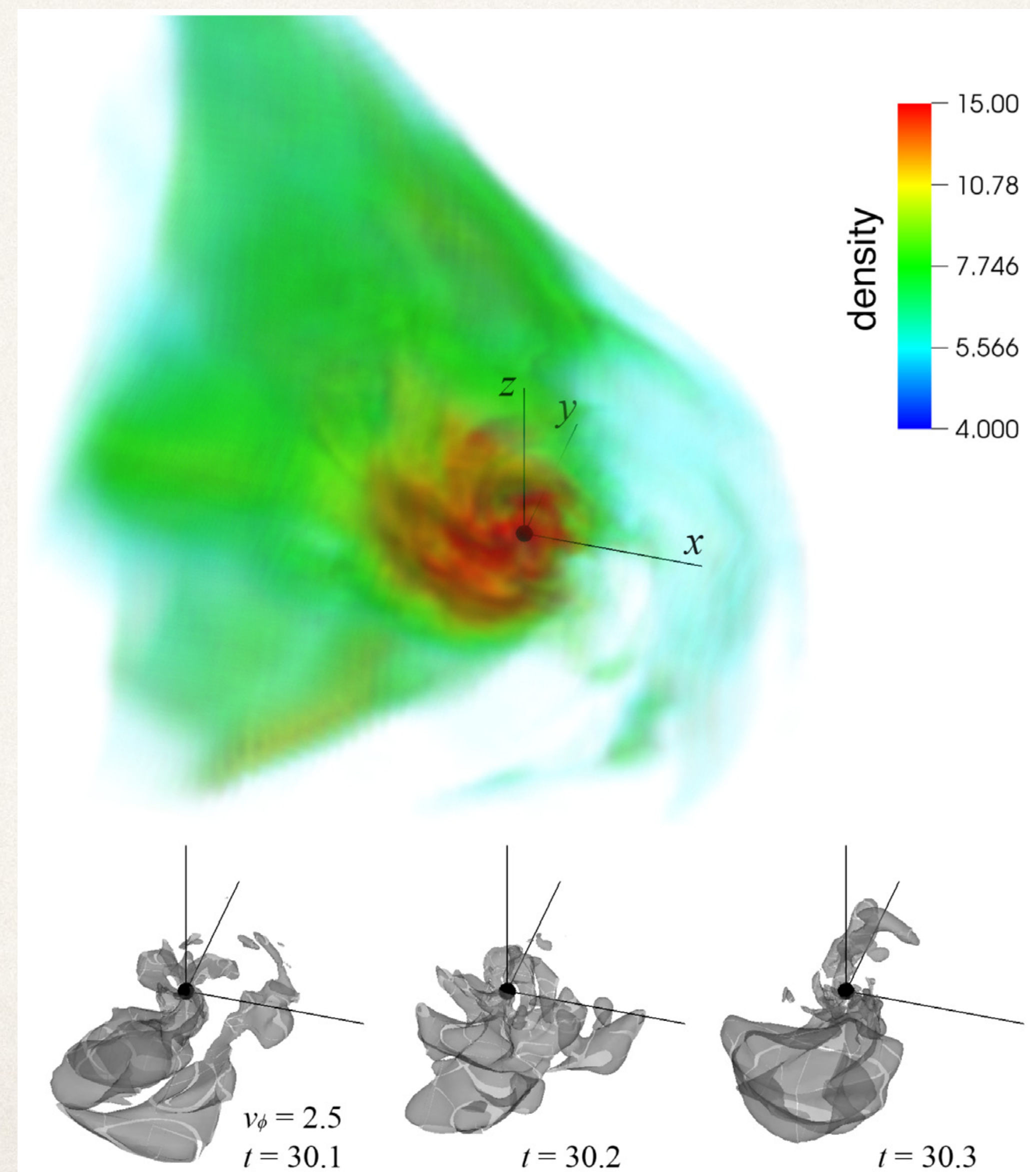
2D simulations

$\epsilon_\rho = 0$ $\epsilon_\rho = 0.1$



$\epsilon_\rho = 0.2$ $\epsilon_\rho = 0.4$

3D simulations

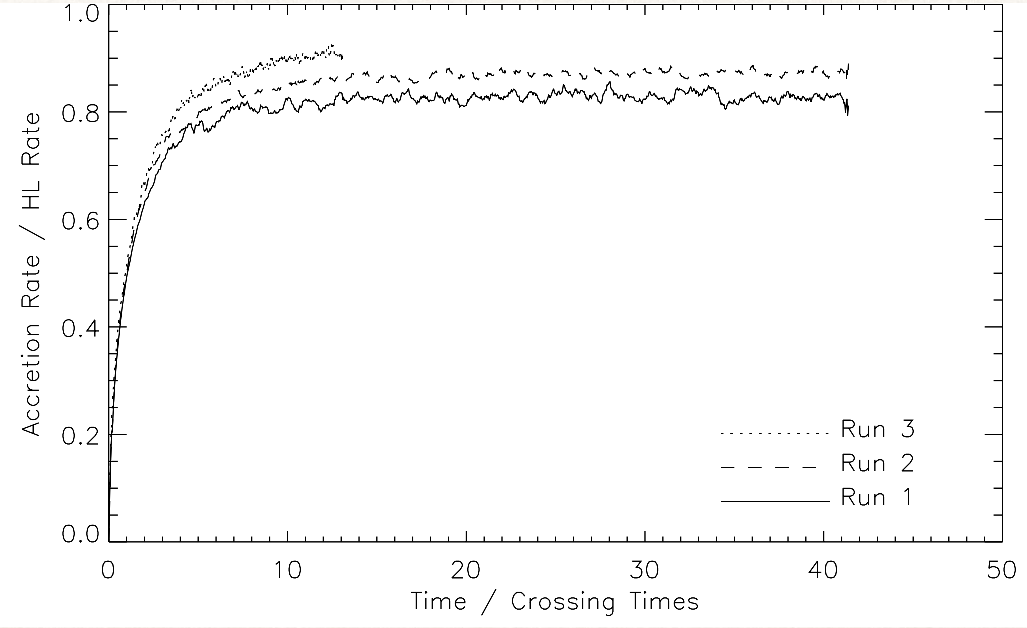


Reference: Armitage & Livio 2000; Xu & Stone 2019

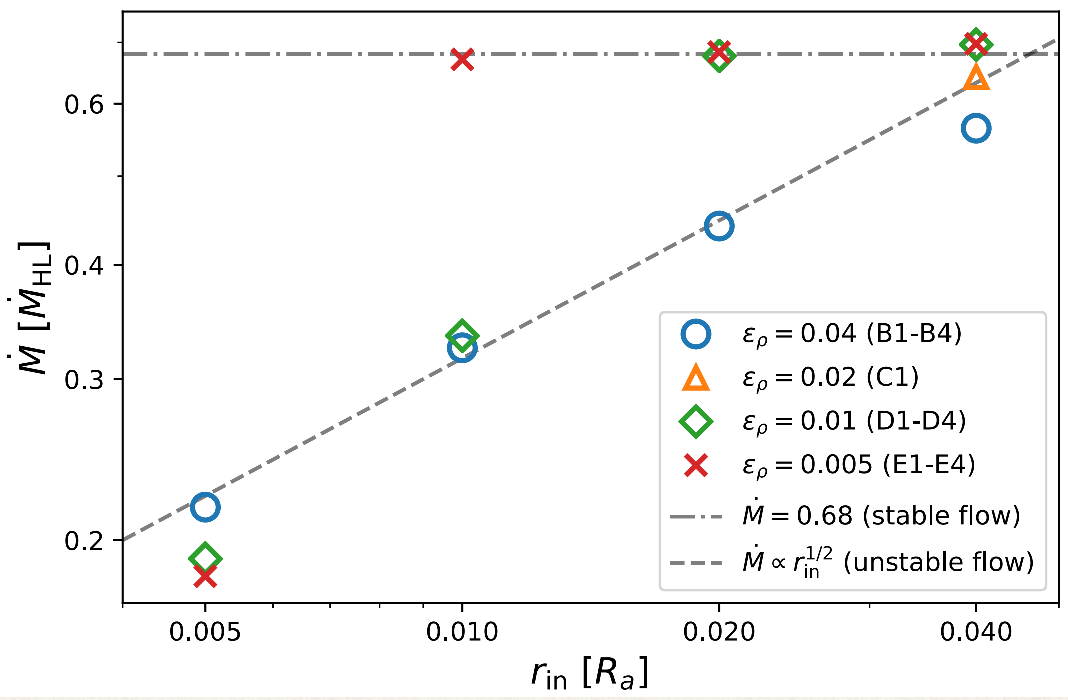
Bondi-Hoyle-Lyttleton accretion

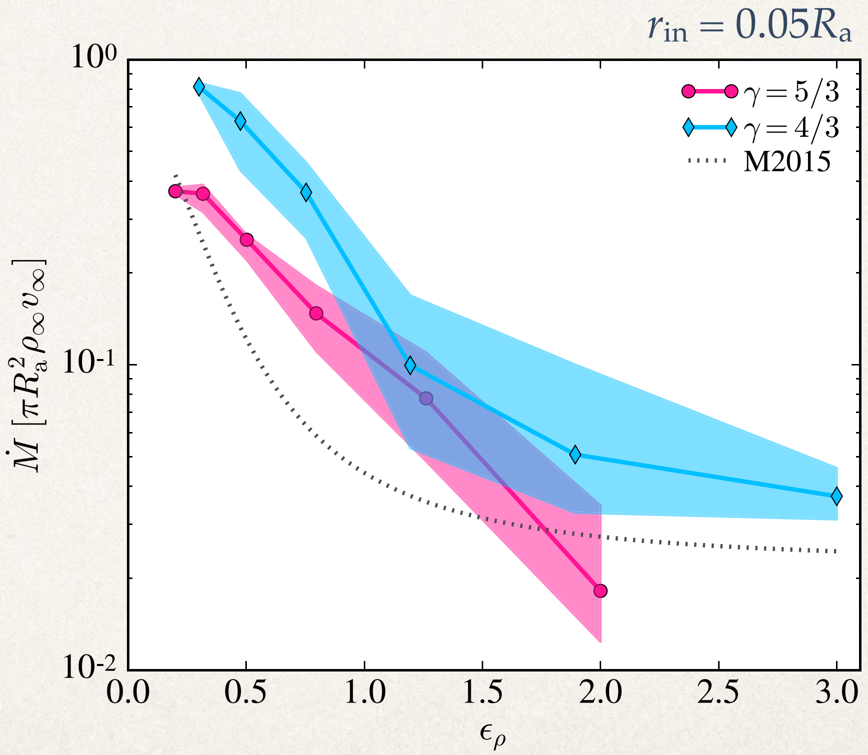
- "Wind tunnel" approximation

Uniform hydro



Structured hydro





Takeaway point #3: Accretion rate onto secondary in CEE will be < $\dot{M}_{HL}$

Reference: Edgar 2004; Xu & Stone 2019; MacLeod et al. 2017

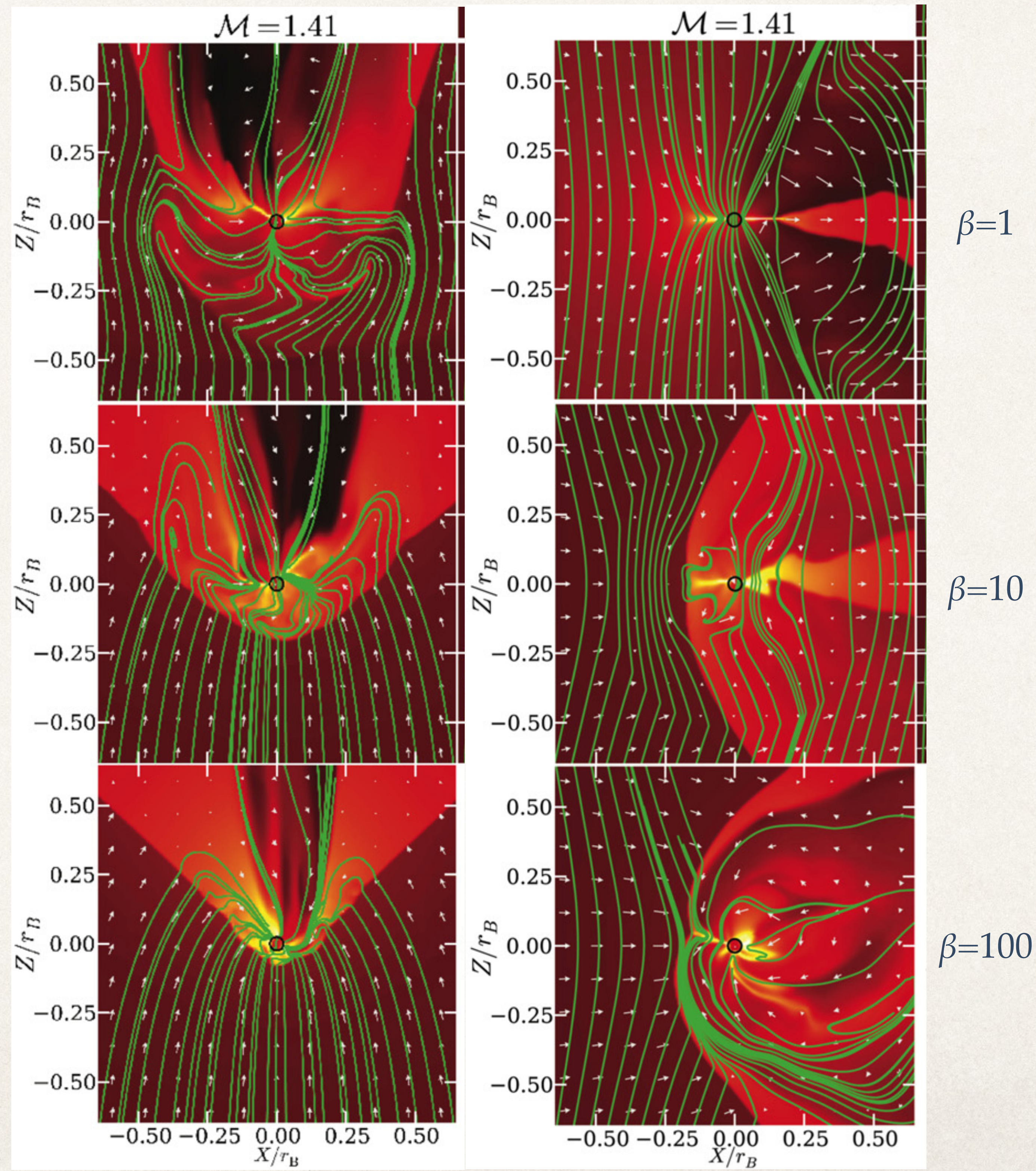
Bondi-Hoyle-Lyttleton accretion

- "Wind tunnel" approximation
  - Magnetized background

$$\dot{M}_{\rm HL} \sim \frac{4\pi G^2 M^2 \rho_\infty}{v_{\rm BH}^2 v_{\rm ABH}}$$

$$v_{\rm BH} \equiv (c_s^2 + v_\infty^2)^{1/2}$$

$$v_{\rm ABH} \equiv (c_s^2 + v_\infty^2 + v_A^2)^{1/2}$$

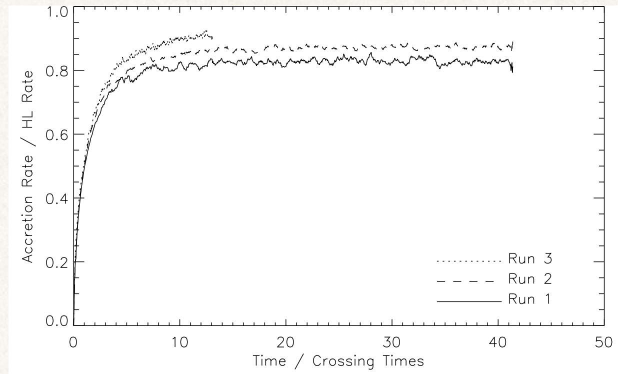


Reference: Lee et al. 2014

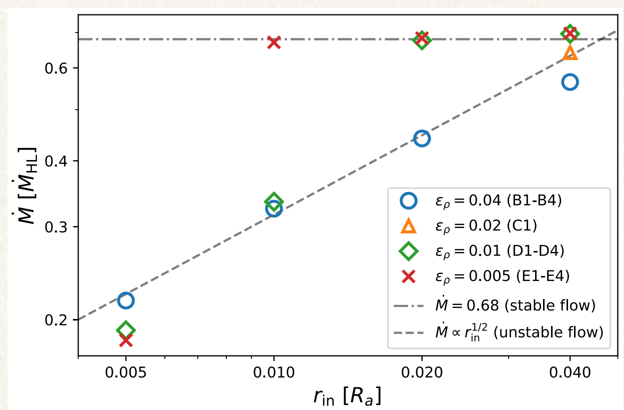
Bondi-Hoyle-Lyttleton accretion

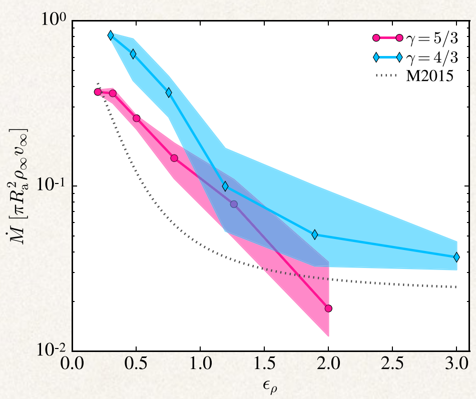
- “Wind tunnel” approximation

Uniform hydro

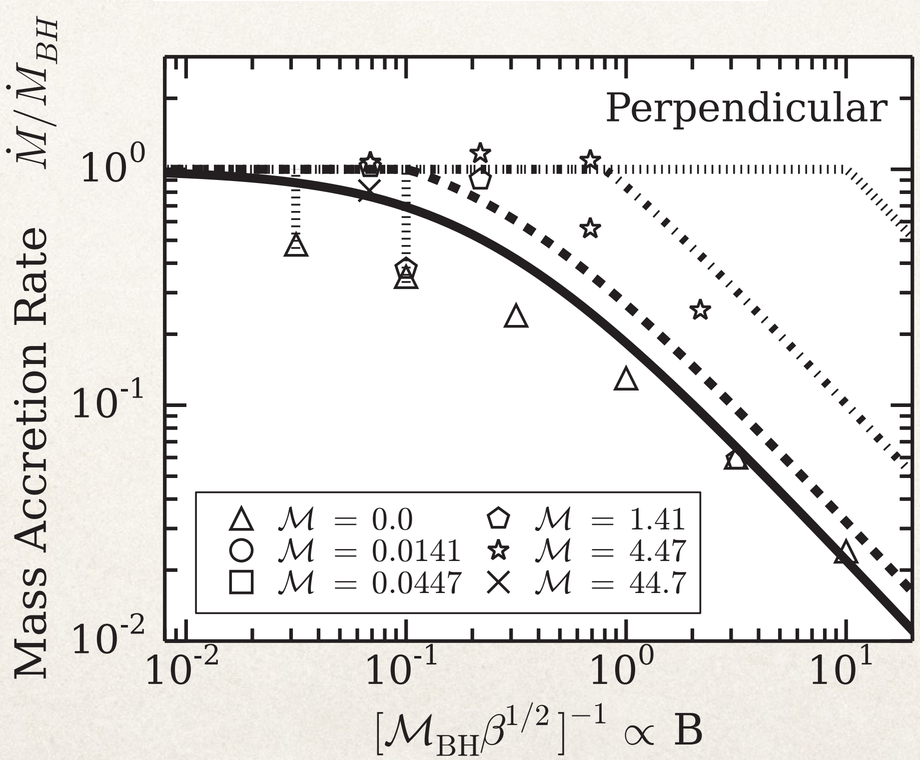


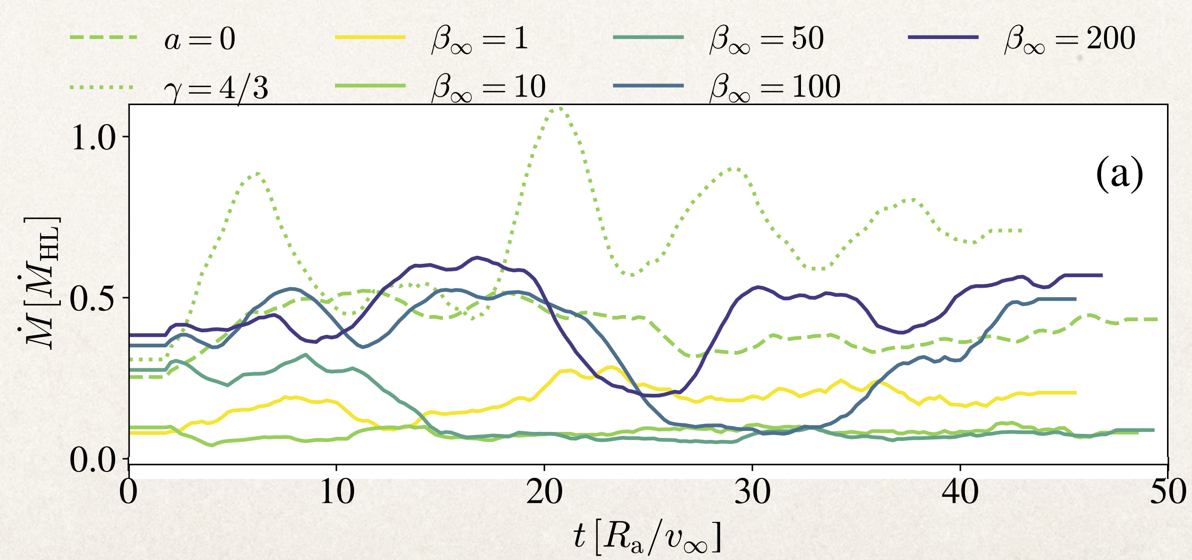
Structured hydro





MHD





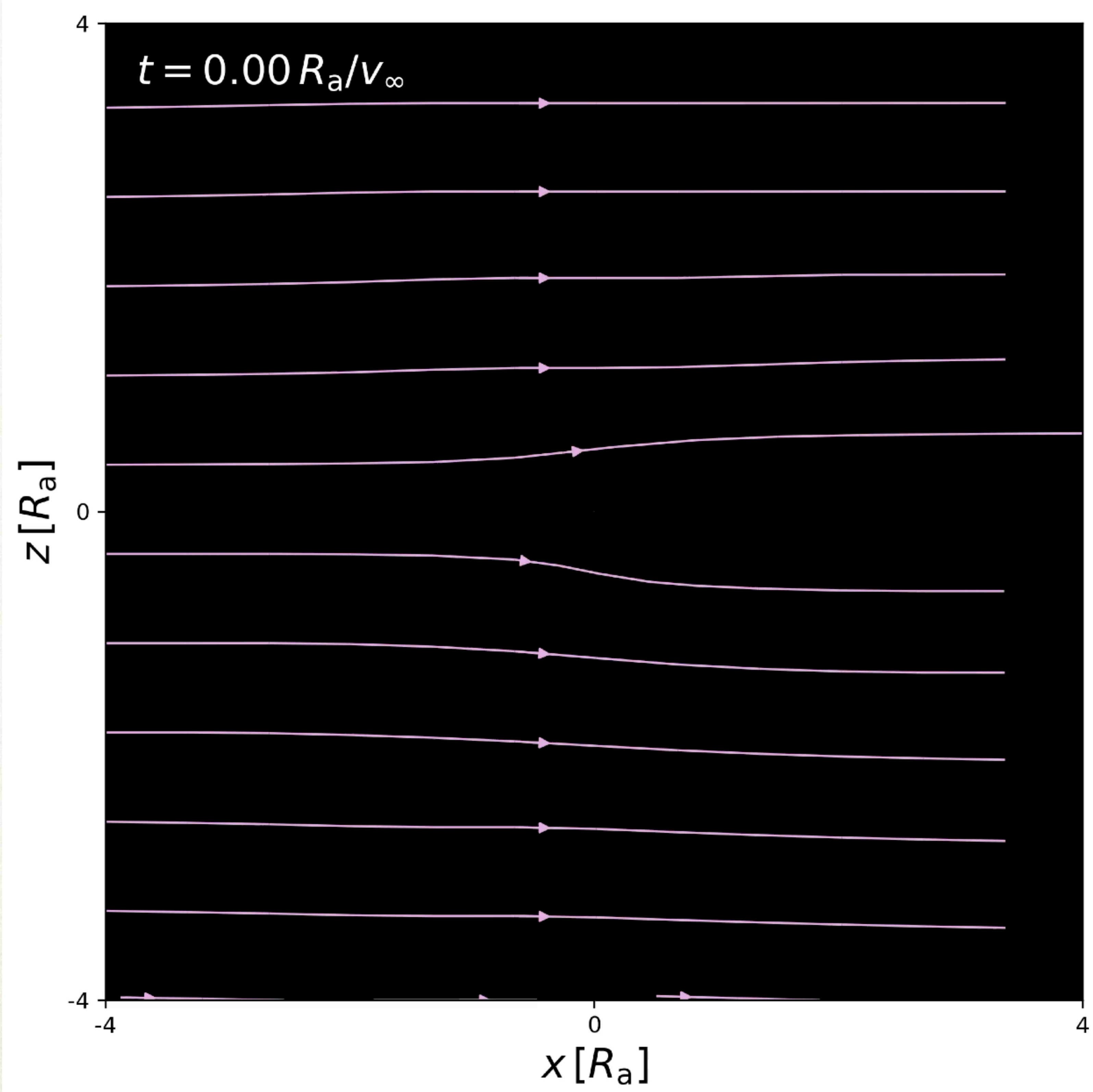
Reference: Edgar 2004; Xu & Stone 2019; MacLeod et al. 2017; Lee et al. 2014; Kaaz et al. 2022 (arXiv)

Bondi-Hoyle-Lyttleton accretion

- Jets from magnetized medium accreting onto rotating BH

β	50
a_*	0.9
Γ	5/3
$\mathscr{M}$	2.45
R_a/r_g	200

$\vec{B} \parallel \vec{J}_{BH} \perp \vec{v}$



Reference: Kaaz et al. 2022 (arXiv)

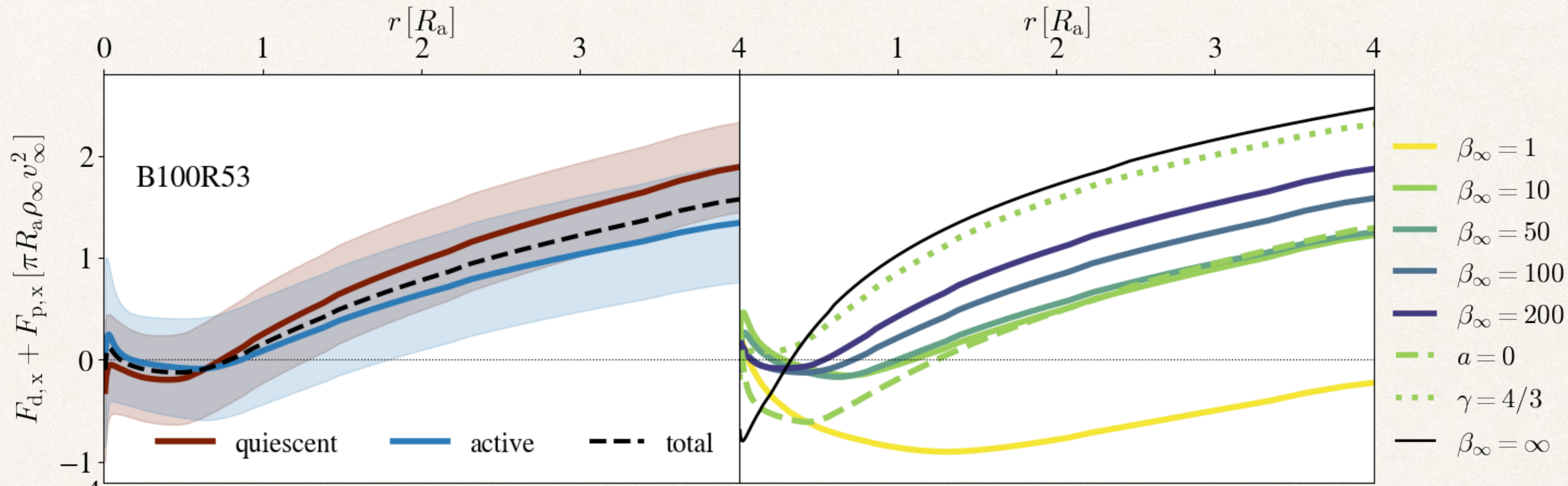
Bondi-Hoyle-Lyttleton accretion

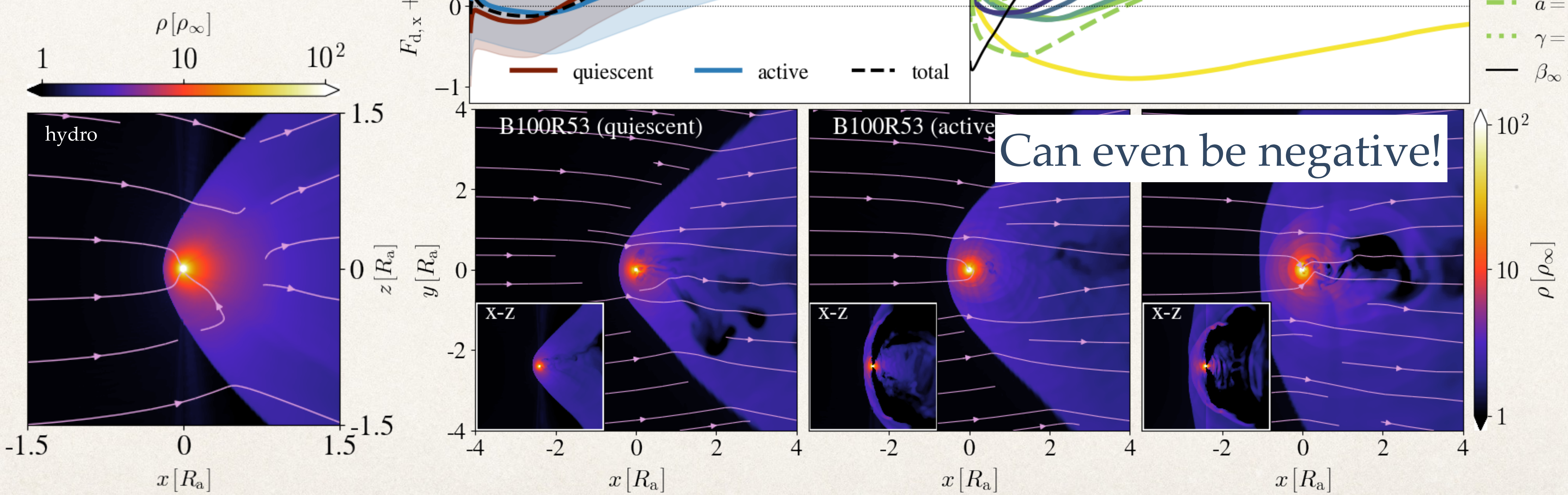
- Drag force acting on accretor

$$F_{\rm HL} = \dot{M}_{\rm HL} v_\infty = \frac{4G^2M^2\rho_\infty}{v_\infty^2}$$

$$F_{\rm d,x} = \int \rho \frac{x}{r^3} dV$$

$$F_{\rm p,x} = \int T^r_x \sqrt{-g}\, d\theta d\phi$$





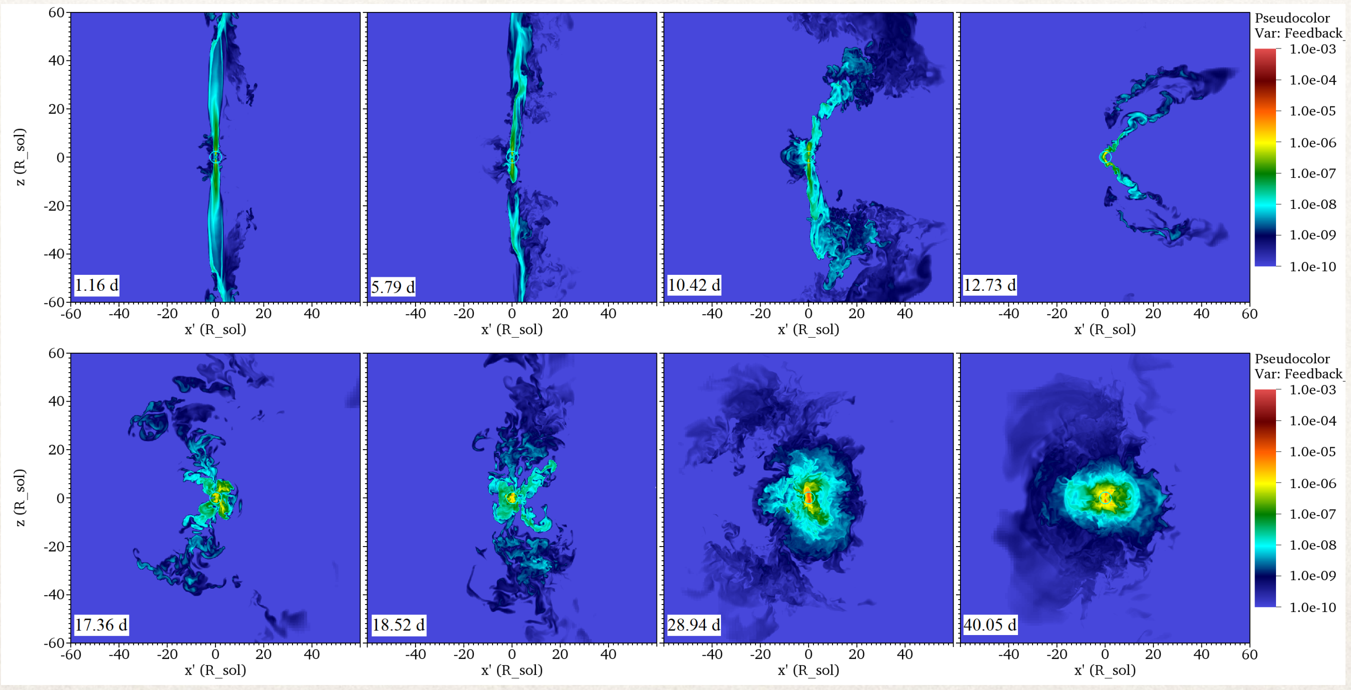
Can even be negative!

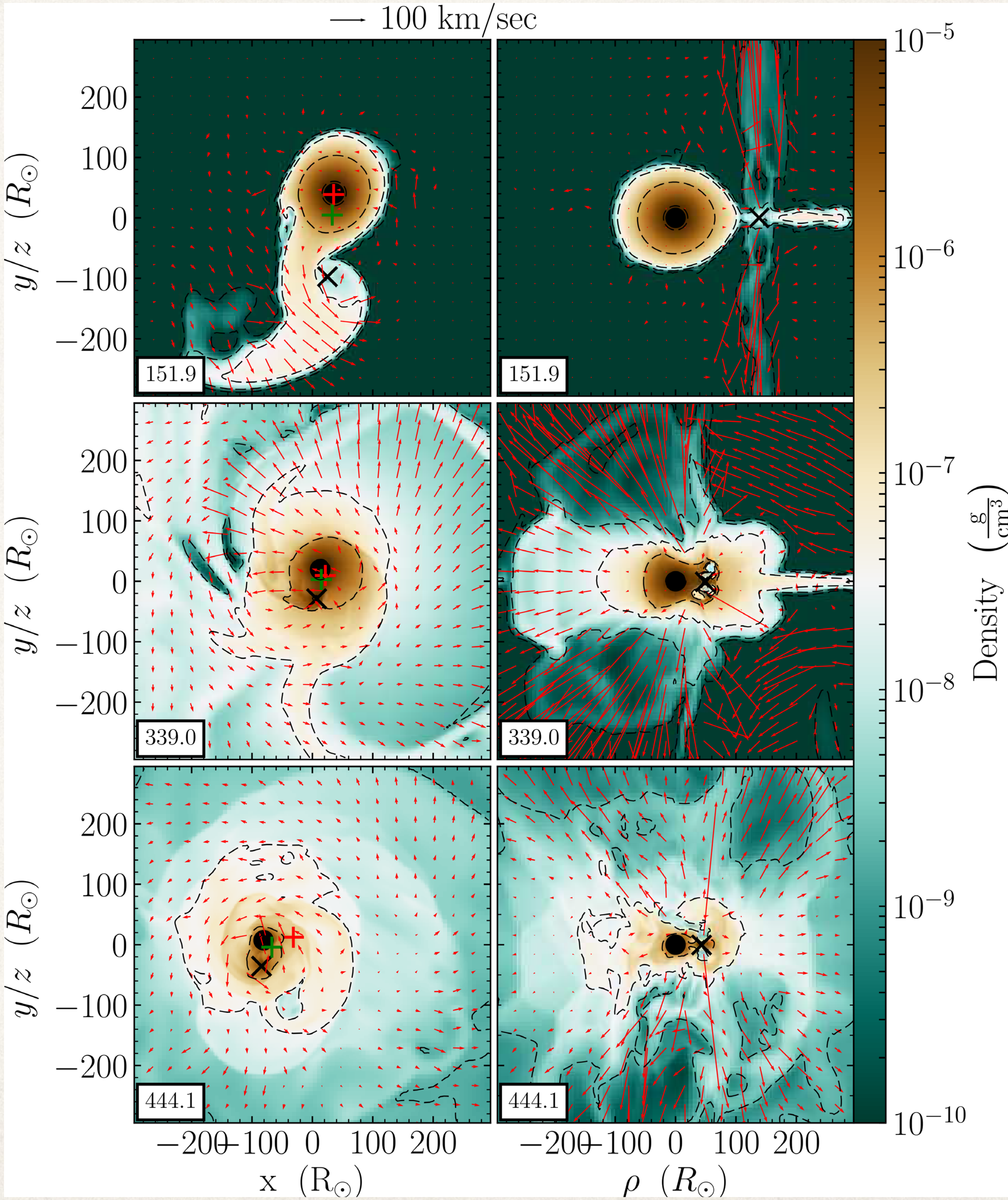
Takeaway point #5: Drag force is less efficient with stronger B-fields

Reference: Kaaz et al. 2022 (arXiv)

Jets in simulations of CE evolution

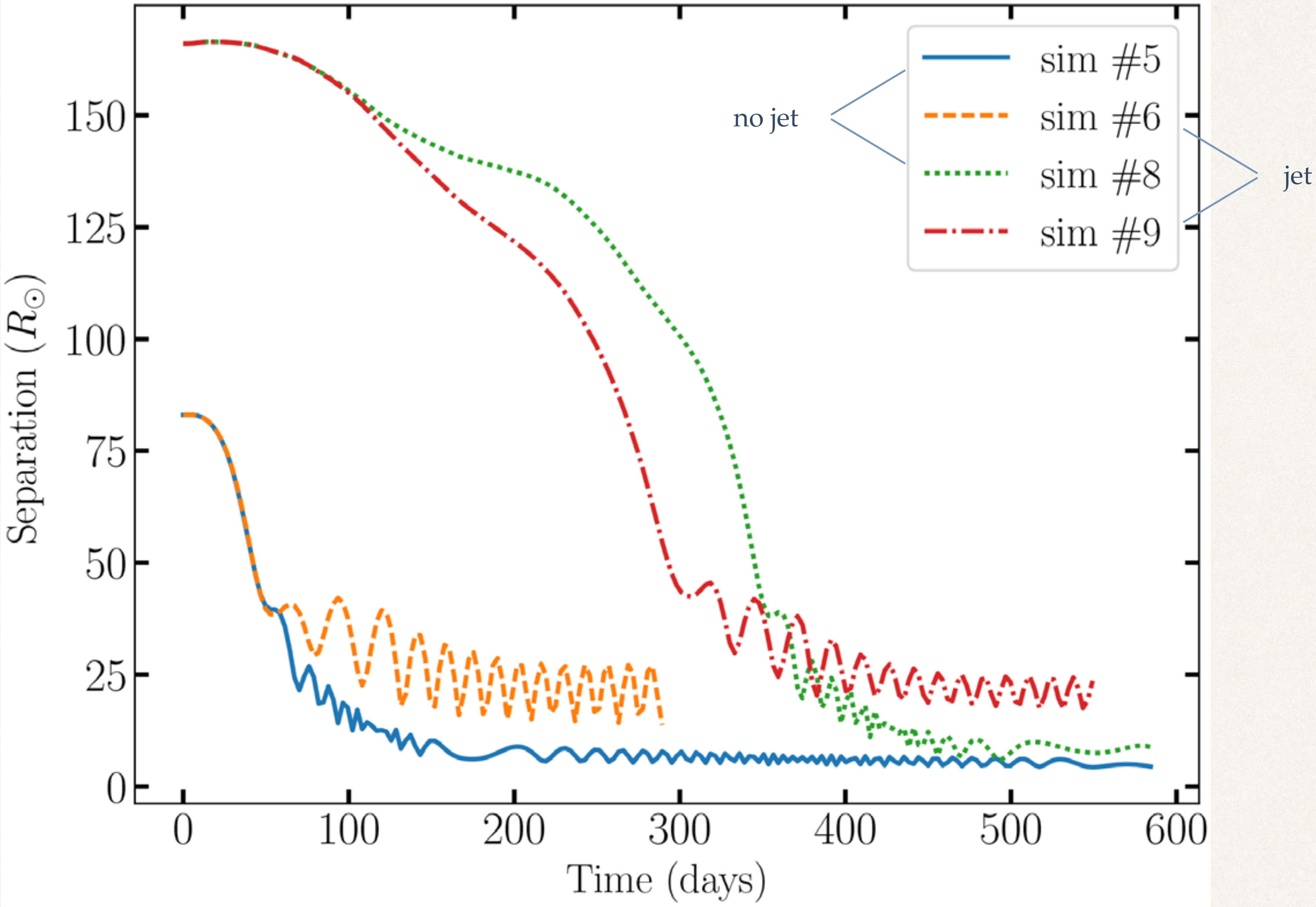
t_f (d)	584
M_{out} ($M_\odot$)	0.3
$M_{out}^{unbound}$ ($M_\odot$)	0.24
$M_{gas,in}$ ($M_\odot$)	0.1
a_f ($R_\odot$)	26.1
e_f	0.56





Reference: Shiber et al. 2019; Zou et al. 2022 (arXiv)

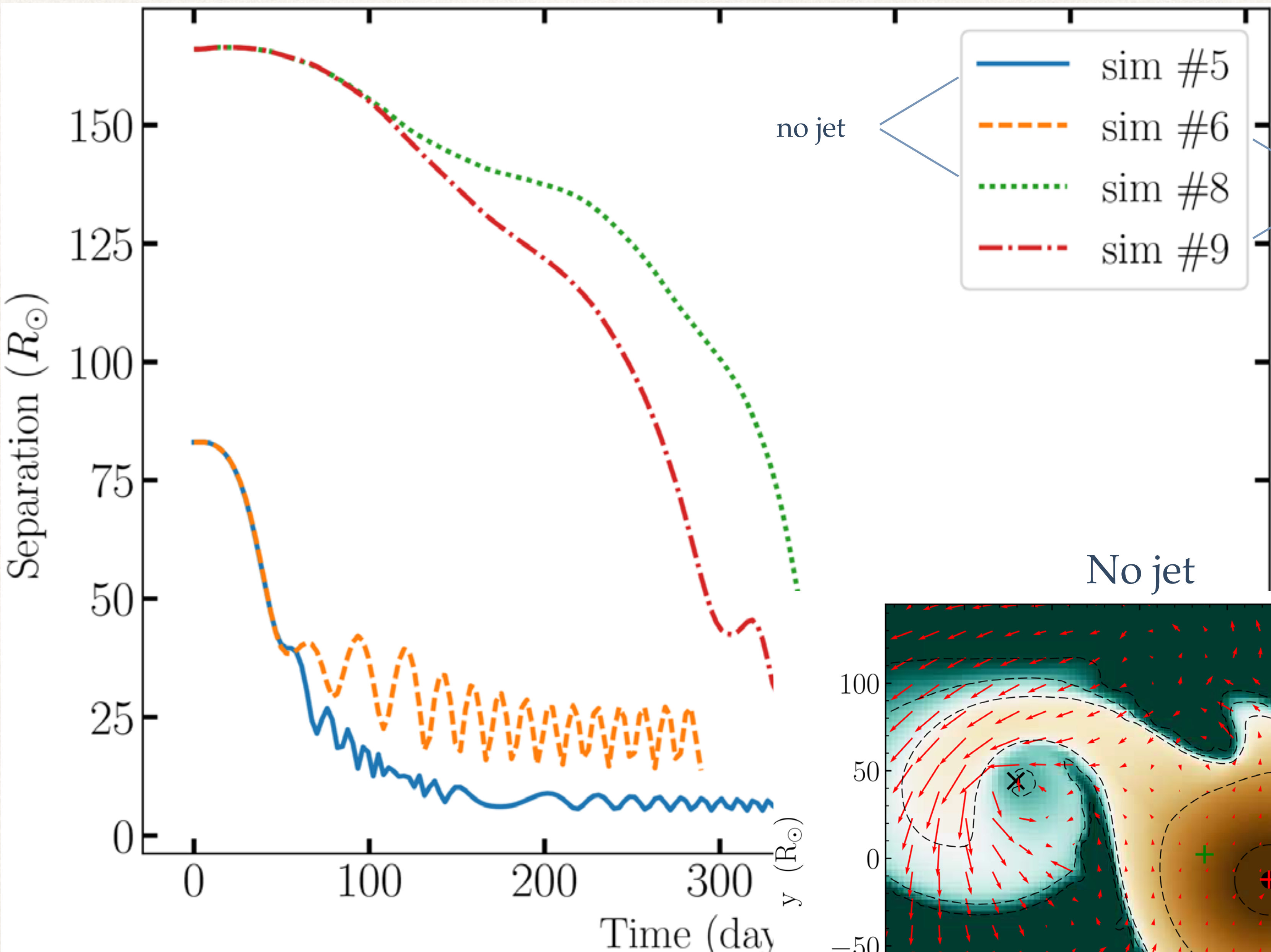
Jets in simulations of CE evolution



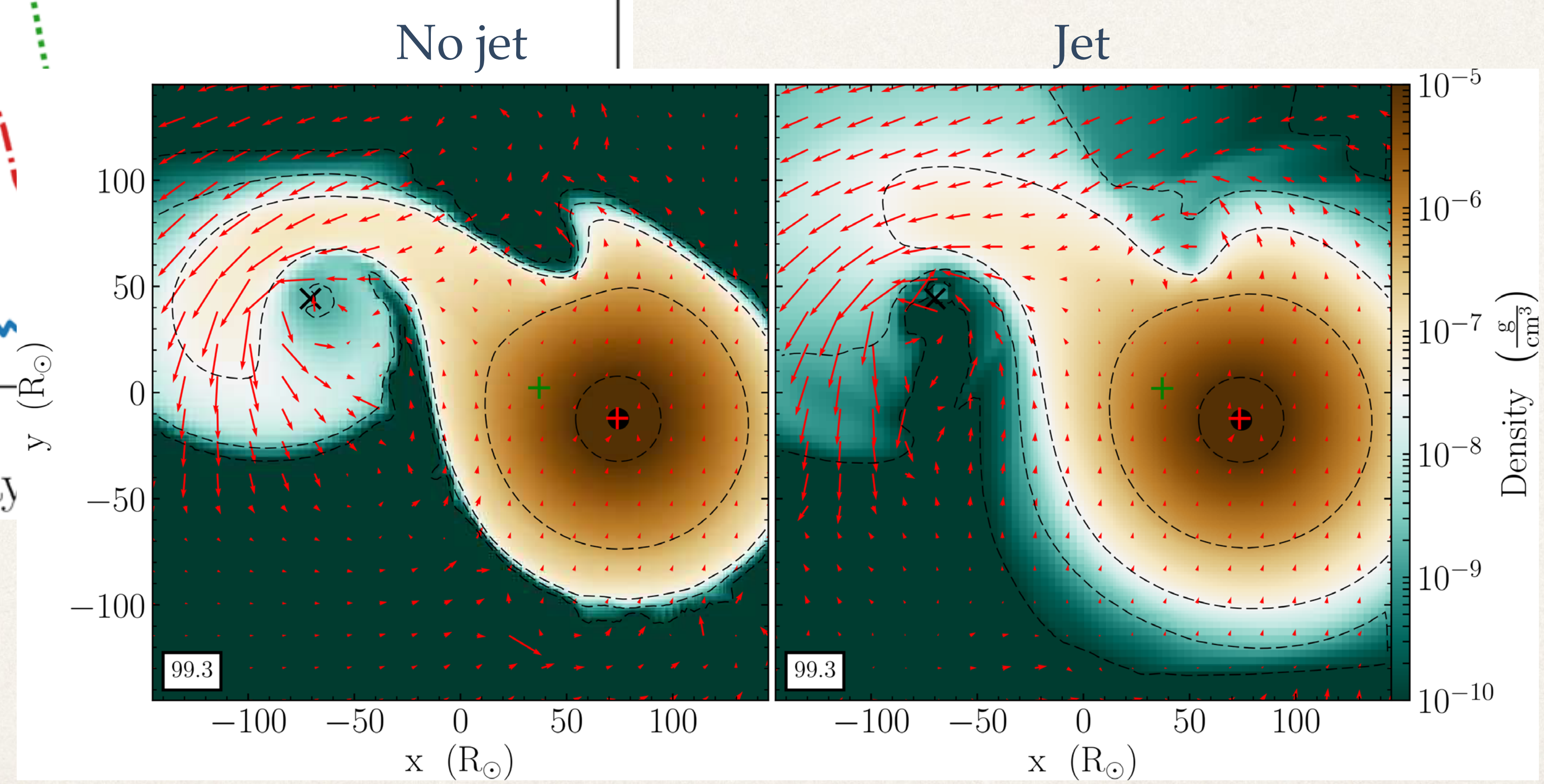
Takeaway point #6: Presence of outflows may stop inspiral sooner and at larger radii

Reference: Shiber et al. 2019

Jets in simulations of CE evolution



Reason has to do with distribution of gas around companion with and w/o jets

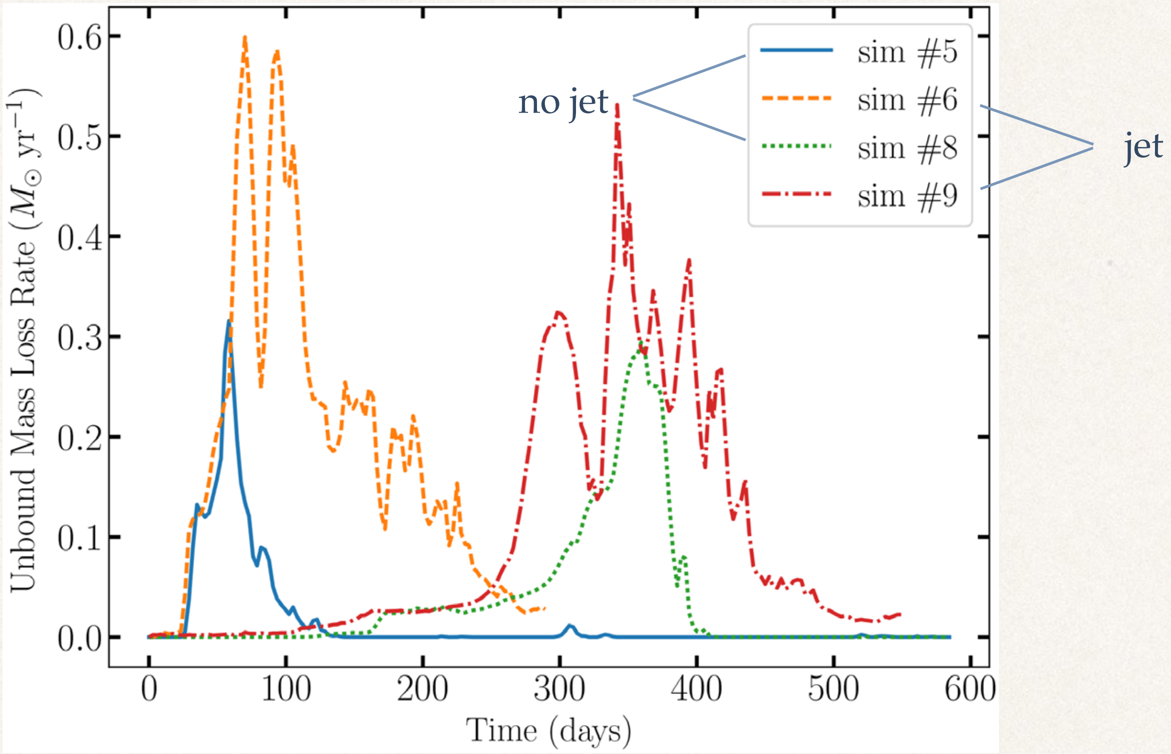


Takeaway point #6: Presence of outflows may stop inspiral sooner and at larger radii

Reference: Shiber et al. 2019

Jets in simulations of CE evolution

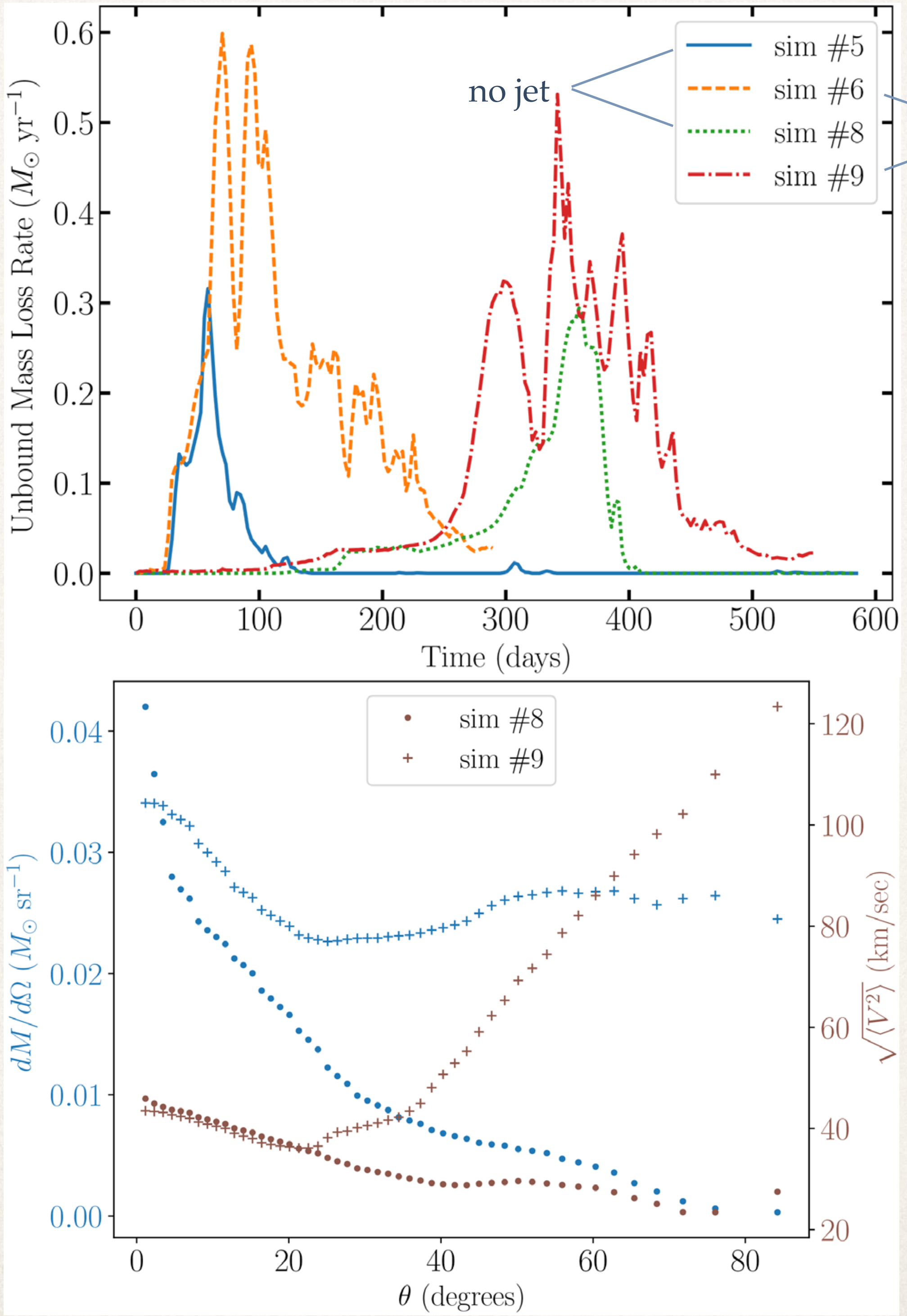
- Presence of jets leads to (3x) greater mass loss

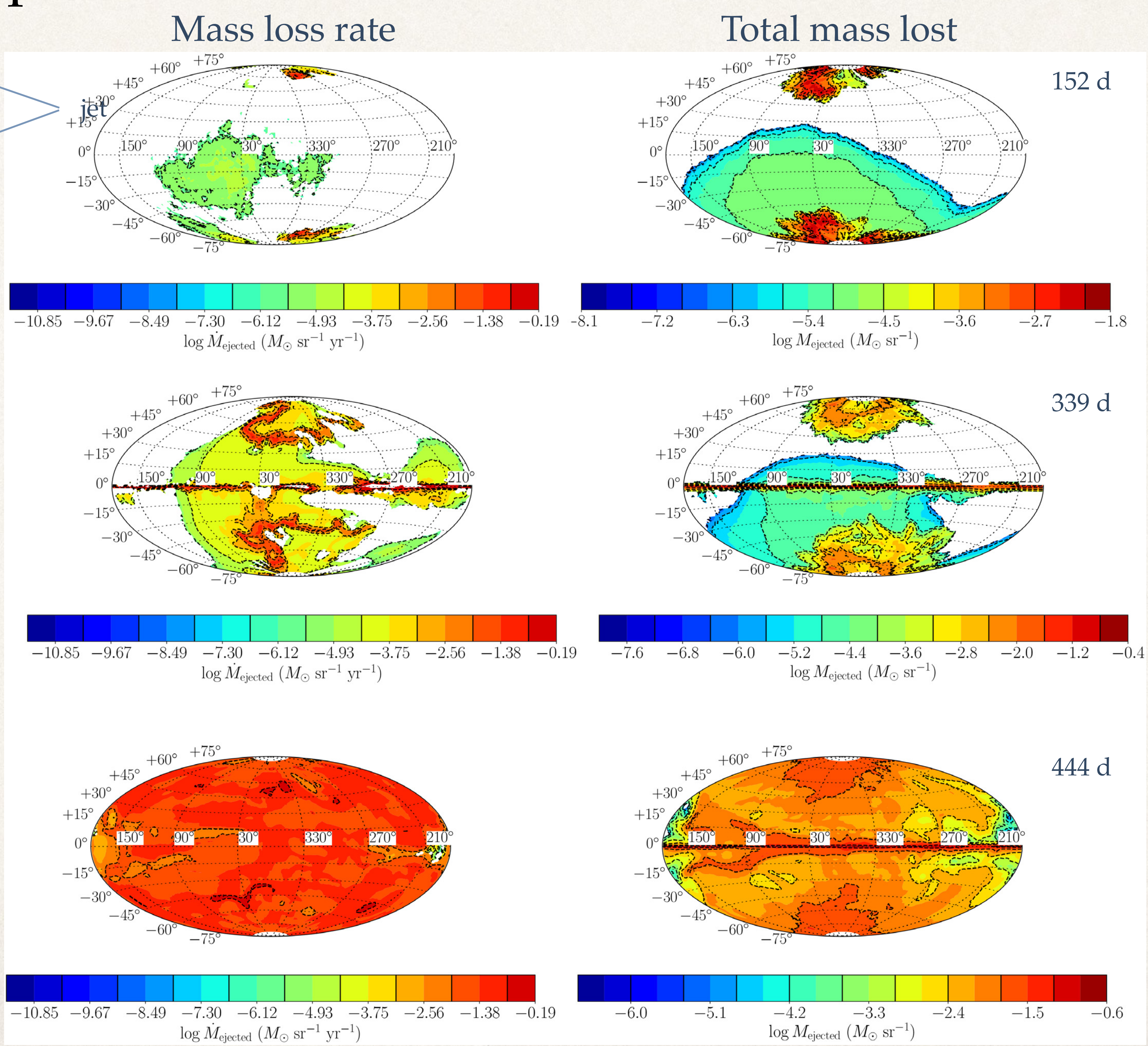


Reference: Shiber et al. 2019

Jets in simulations of CE evolution

- Presence of jets leads to (3x) greater mass loss
  - Particularly in the polar direction





Reference: Shiber et al. 2019

Takeaway points

- Make sure what you inject is consistent with your energy budget.
- Speed of outflow should depend on the compactness of the accretor
- Accretion rate onto secondary in CEE will be $< \dot{M}_{\mathrm{HL}}$
- Persistence & strength of magnetized jet depends on β_∞
- Drag force is less efficient with stronger B-fields
- Presence of outflows may stop inspiral sooner and at larger radii

Open questions

- Are the jet ingredients provided by the central object or a surrounding accretion disk?
- How much of a disk's angular momentum is carried away by the jet?
- Why do systems sometimes show jets and sometimes not?
- We know jets can drill out of stars (GRBs), so what would be different in CEE?