Title: Disappearing stars without a trace: what is their maximum angular momentum?

Speakers: Ariadna Murguia Berthier

Series: Strong Gravity

Date: November 12, 2020 - 1:00 PM

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Abstract: We have tentative evidence of massive stars that disappear without a bright transient. It is commonly argued that this massive stars have low angular momentum and can collapse into a black hole without significant feedback. In this talk I will make use of general-relativistic hydrodynamical simulations to understand the flow around a newly-formed black hole. I will discuss the angular momentum needed in order for the infalling material to be accreted into the black hole without forming a centrifugally supported structure, thus generating no effective feedback. If the feedback from the black hole is significant, the collapse can be halted and, as a result, it is likely followed by a bright transient. With the results from the simulation, I will constrain the maximum rotation rate for the disappearing massive progenitors know, and set a limit on the rate of expected disappearing stars.

Disappearing stars without a trace: what is their maximum angular momentum?

Ariadna Murguia Berthier

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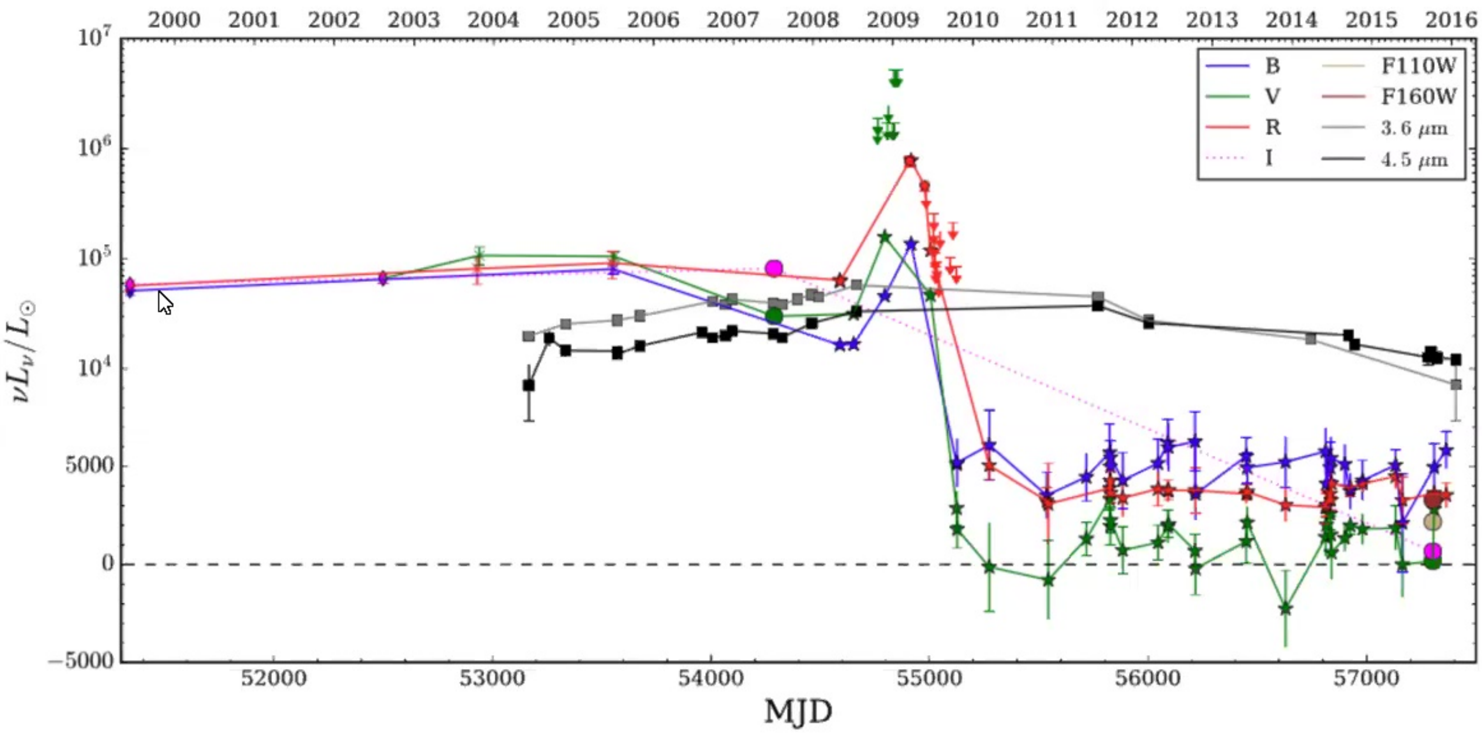
CONACYT

UC Santa Cruz ASTRO

Outline

- Disappearing stars
- Possible explanations
- Direct collapse as an explanation
- Black hole (BH) evolution and accretion disk feedback
- Low angular momentum flows into BH
- Simulations of low angular momentum flows
- Constraining the maximum angular momentum of disappearing stars
- Limits on stellar rotation

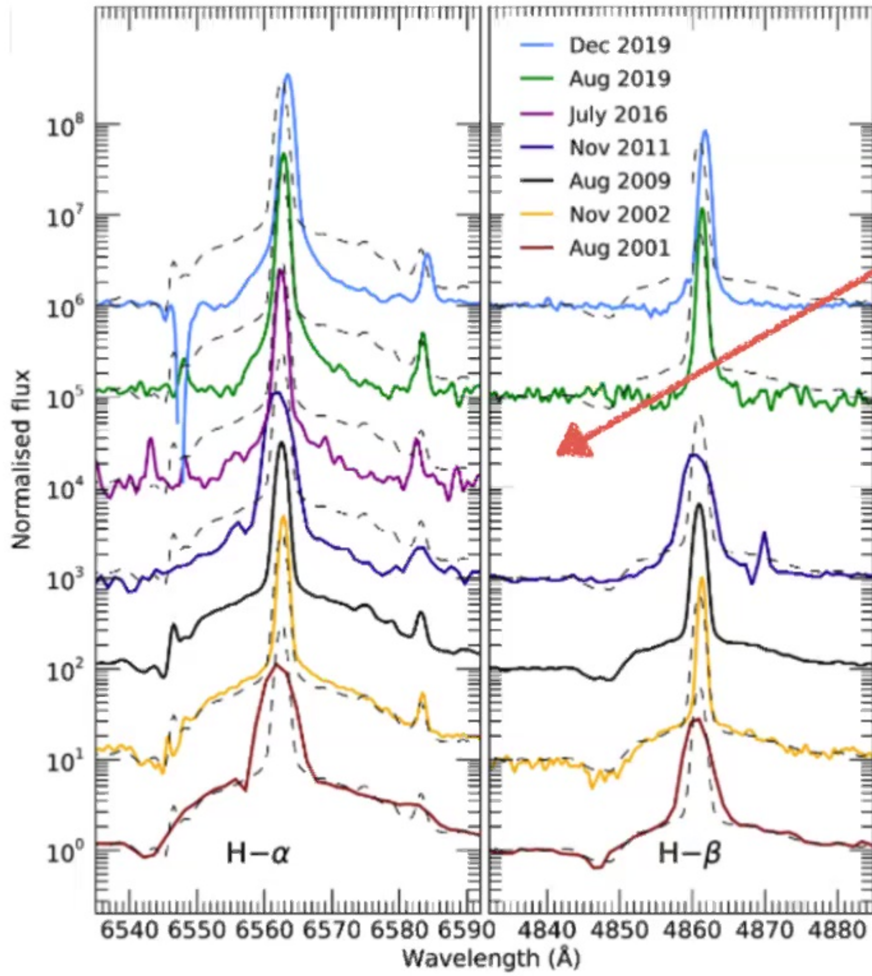
Disappearing stars



Found using the LBT and HST archival images in a dusty galaxy. The mass of the star is around 20-30 solar masses.

N6946-BH1
Gerke et al. 2015
Adams et al. 2017

Disappearing stars

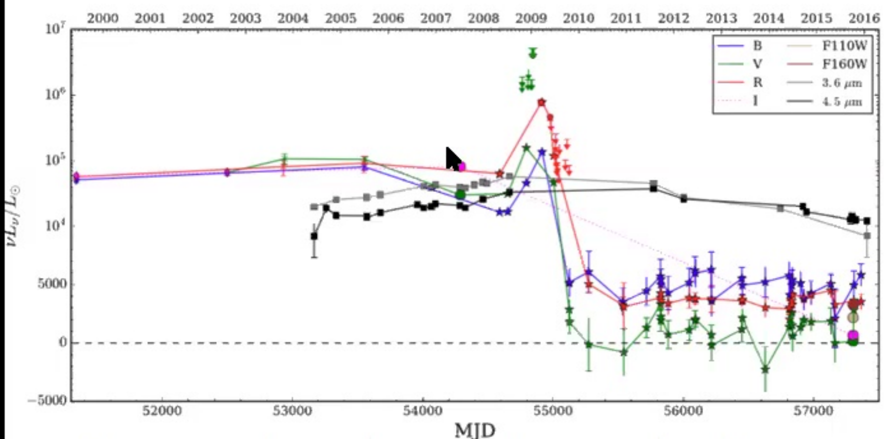


Around 2011 the eruption ends

Luminous Blue Variable of around 80-100 solar masses

PHL293B-LBV
Allan et al. 2020

Disappearing stars



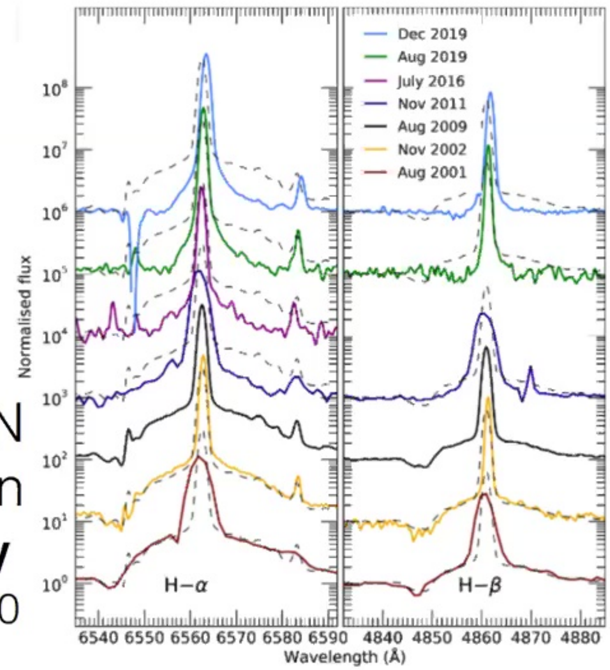
N6946-BH1

Gerke et al. 2015

Adams et al. 2017

Obscuration by a dusty shell

Stellar merger



Pair instability SN

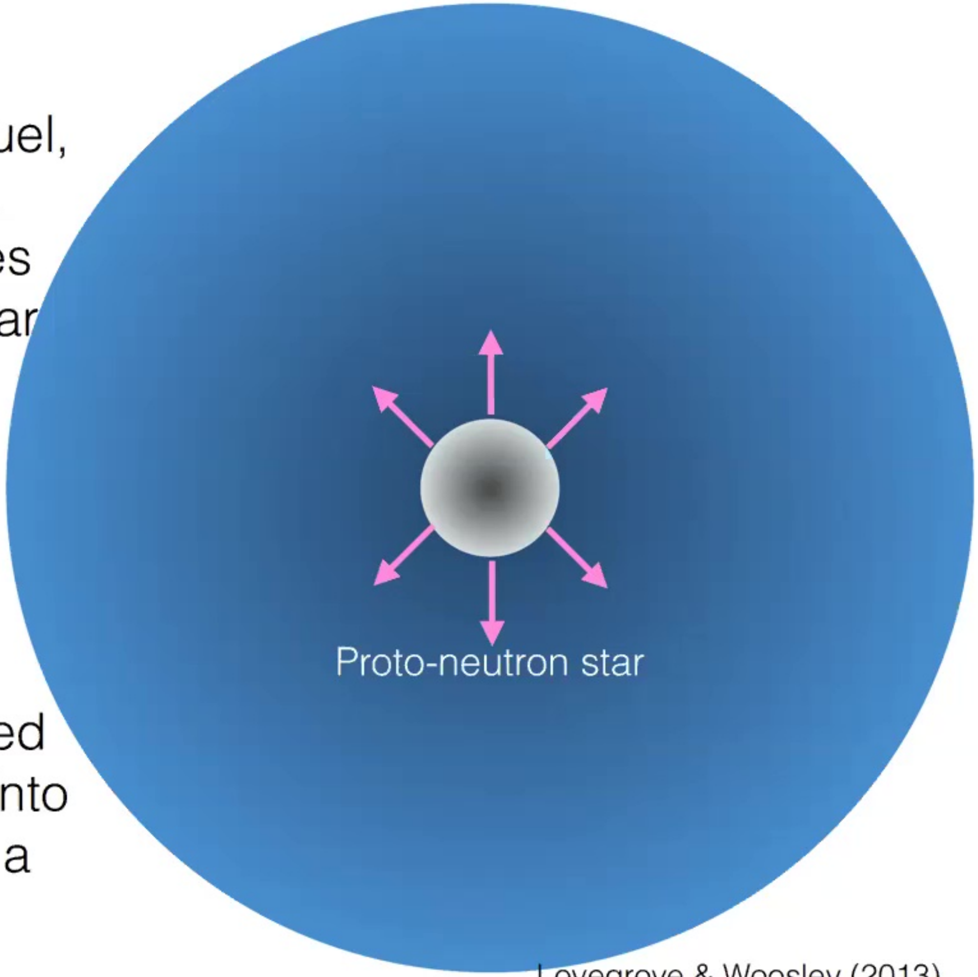
The LBV can erupt again

PHL293B-LBV

Allan et al. 2020

Mild supernova

As the star finishes its fuel, it begins to collapse. The iron core collapses into a proto-neutron star



Neutrinos will be emitted before the core settles into a cold neutron star or a black hole

Lovegrove & Woosley (2013)

Mild supernova

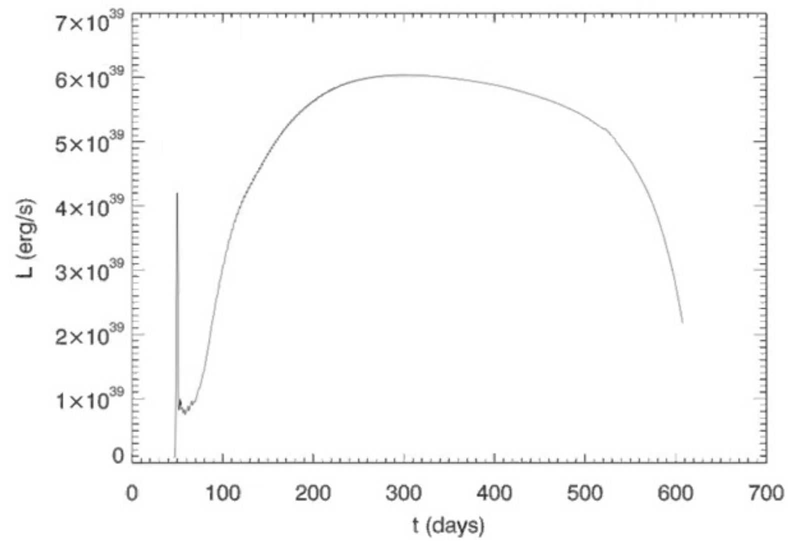
Energy lost in neutrinos

$$\mathrm{BE} \approx 0.084 \left(\frac{M_G}{M_\odot}\right)^2 \; M_\odot$$

Lovegrove & Woosley (2013)
Lattimer & Yahil (1989)

Neutrinos carry around 0.2-0.5 solar masses in gravitational energy

Can even unbind the already loosely bound H-envelope



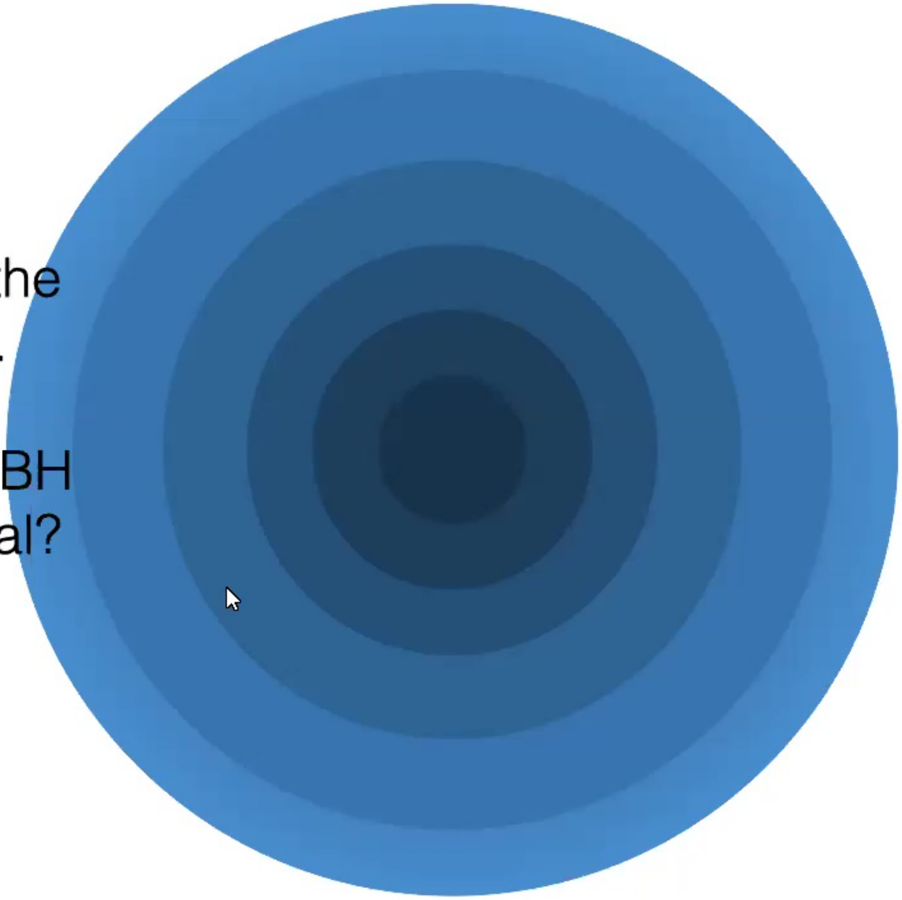
Low luminosity supernova

Lovegrove & Woosley (2013)

Collapse to a BH

A BH is formed after the iron core collapses.

What happens as the BH accretes more material?



Collapse to a BH

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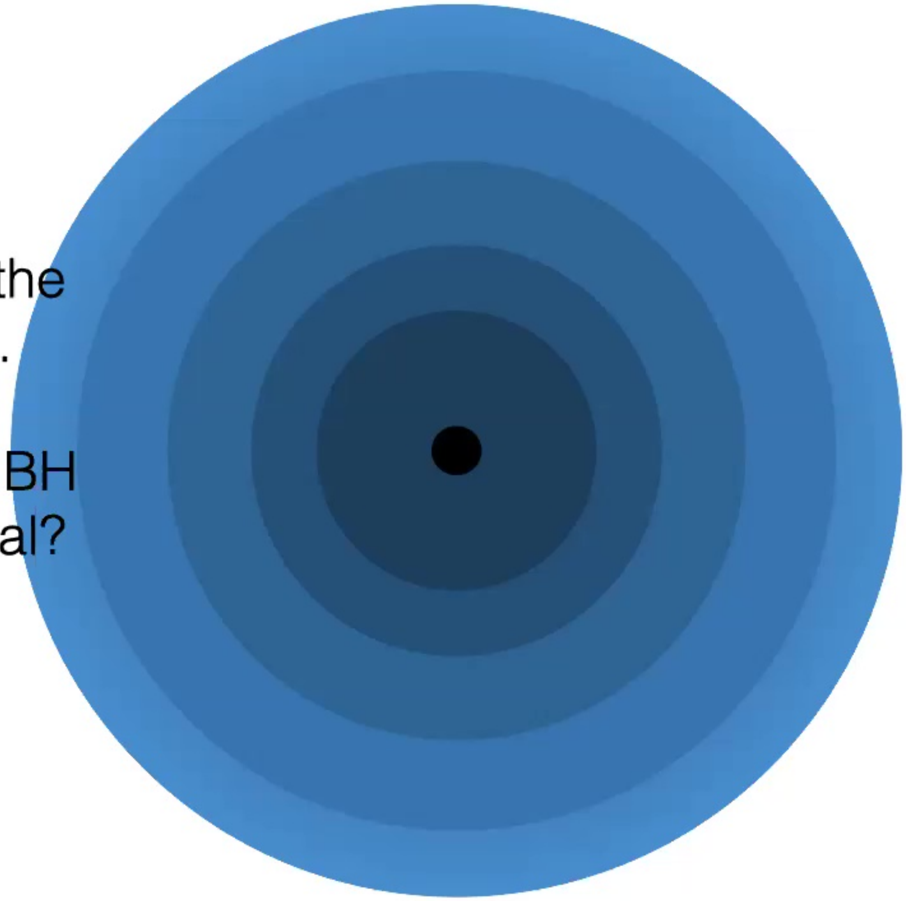
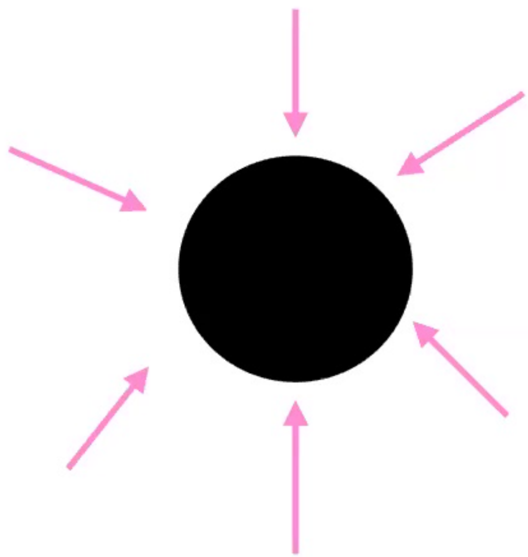


Disk formation

If there is no angular momentum: the material would be directly accreted onto the BH. (Bondi accretion)

No feedback is produced.

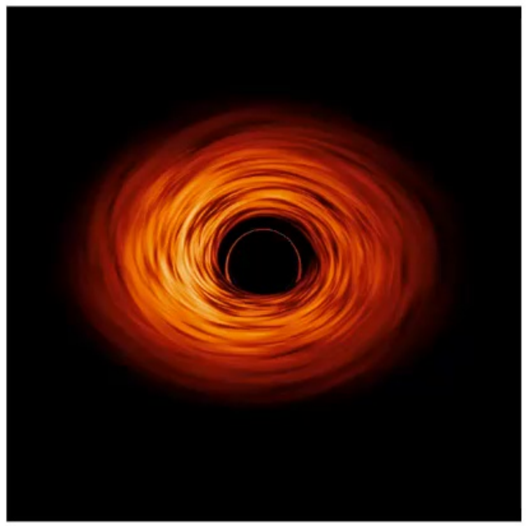


Disk formation

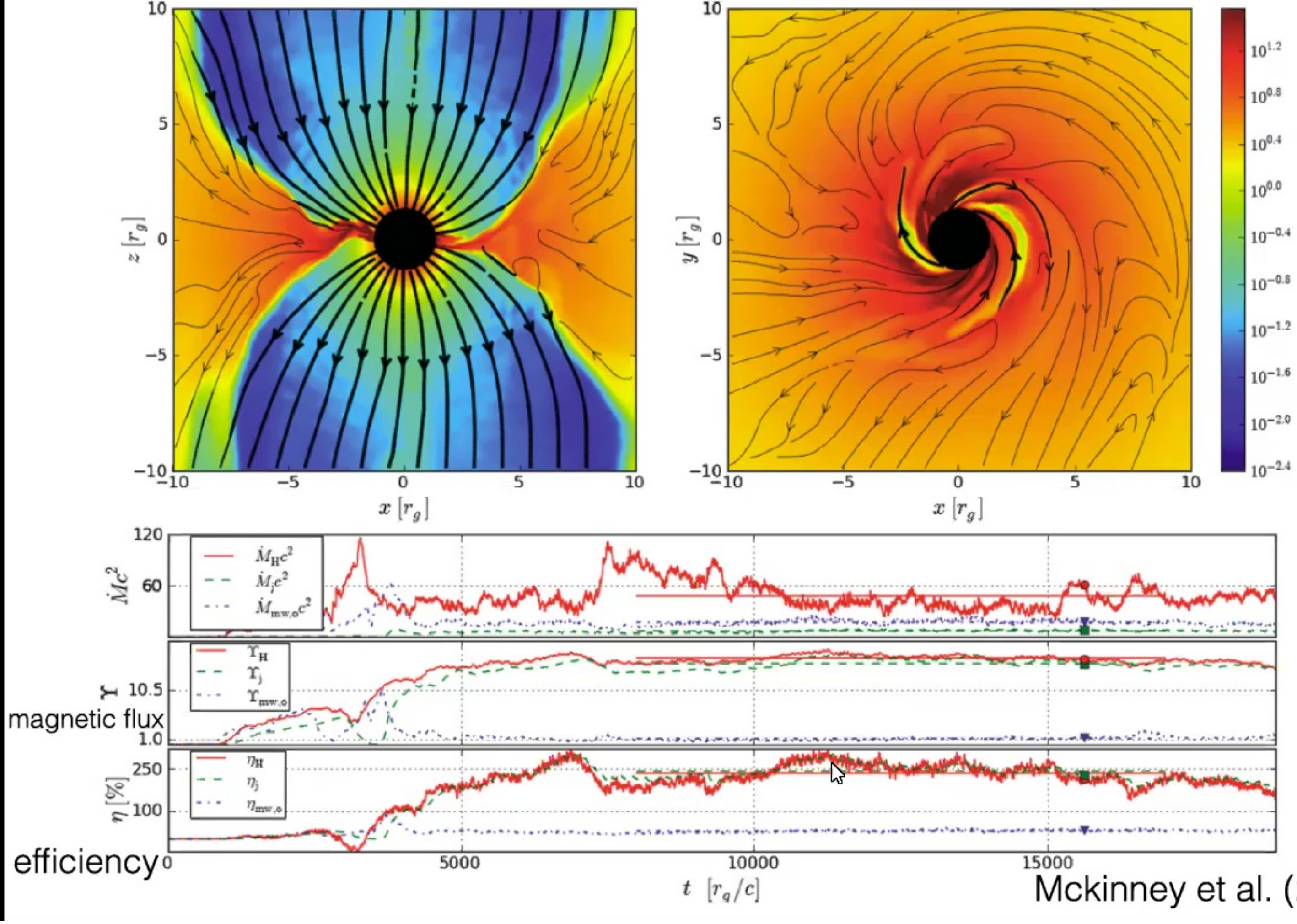
If there is high angular momentum, a disk will be formed.

Magnetic torques will draw material from the disk to the BH, and the material will radiate.

Feedback!



Disk efficiency

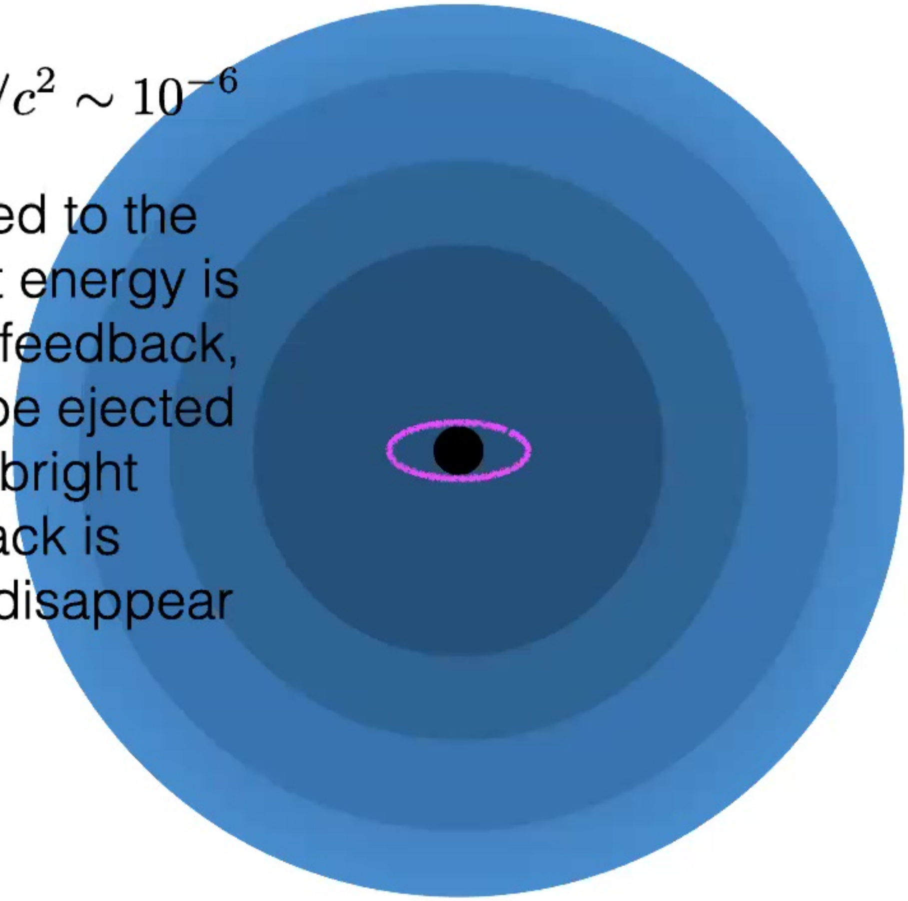


Mckinney et al. (2012)

Collapse to a BH

$$BE_*/BH_{\rm BH} \sim v_{\rm esc}^2/c^2 \sim 10^{-6}$$

If little mass is accreted to the accretion disk, and that energy is efficiently converted to feedback, then the envelope will be ejected and there will be a bright transient. If feedback is inefficient, the star will disappear



BH evolution

As the newly created BH accretes from the infalling material, its angular momentum and mass will change

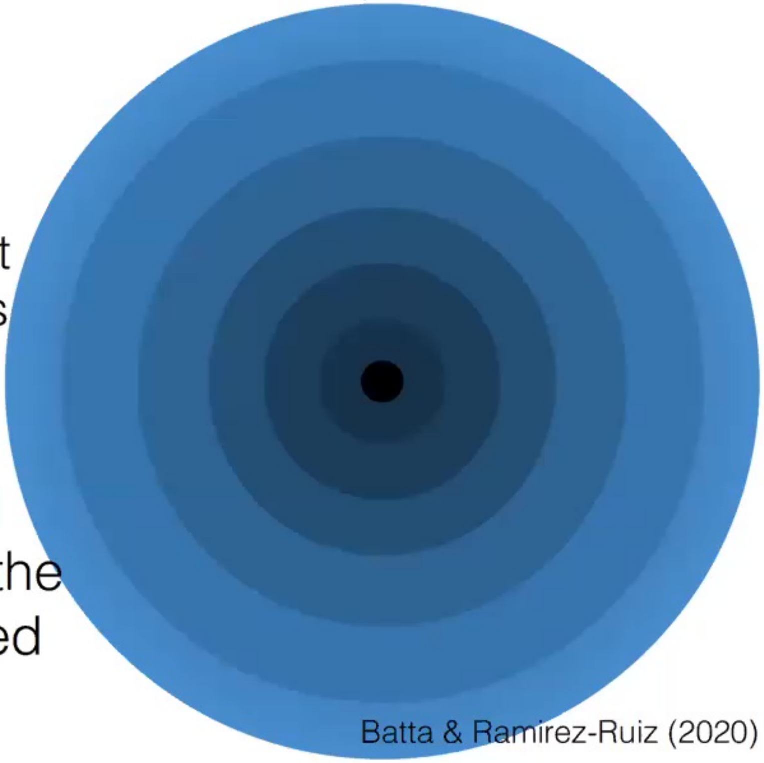
Initially

$$j_{\rm isco}(a, M) = \frac{GM}{c}\left(\frac{2}{3^{3/2}}[1 + 2(3\tilde{r}(a) - 2)^{1/3}]\right)$$

$$\tilde{r}(a) = \frac{r_{\rm isco}(a, M)}{GM/c^2}$$

The innermost stable circular orbit (isco) in a BH is determined by its mass and spin

To understand how the BH evolves, it is easier to divide the star in shells that are accreted onto the BH.



Batta & Ramirez-Ruiz (2020)

BH evolution

Angular momentum distribution of shell

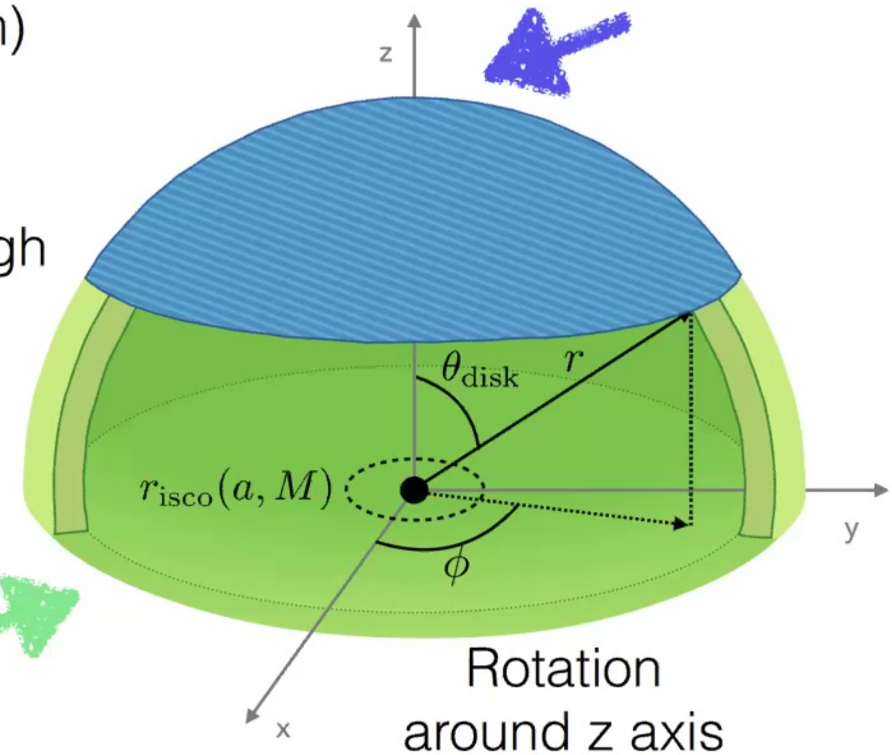
$$j(r,\theta) = \Omega(r) r^2 \sin^2\theta$$

($r \sin\theta$ is the lever arm)

Shell that will be directly accreted

$$j(r,\theta) < j_{\rm isco}$$

The BH can't accrete material directly with high angular momentum.



Rotation around z axis

Shell that will from a disk

$$j(r,\theta) \geq j_{\rm isco}$$

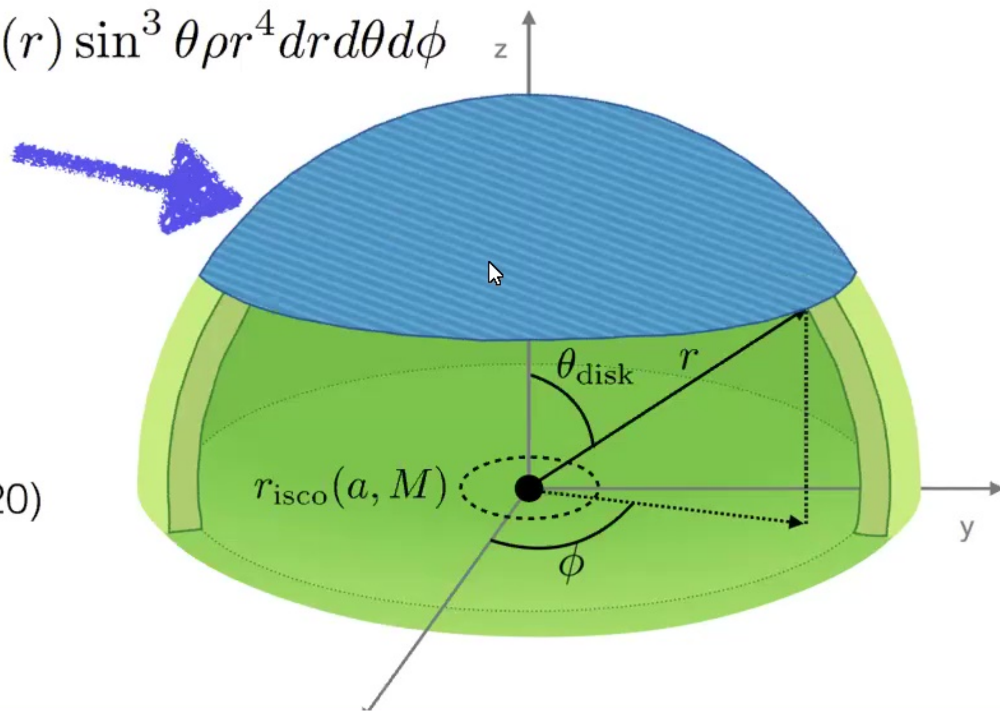
Batta & Ramirez-Ruiz (2020)

BH evolution

As the shells quasi-radially flows into the BH:

$$M_{j<j_{\rm isco}} = 2\int_{\theta<\theta_{\rm disk}} \sin\theta \rho r^2 dr d\theta d\phi$$

$$J_{j<j_{\rm isco}} = 2\int_{\theta<\theta_{\rm disk}} \Omega(r)\sin^3\theta \rho r^4 dr d\theta d\phi$$



Batta & Ramirez-Ruiz (2020)

BH evolution

The shells will have:

$$J_{\rm shell} = J_{j<j_{\rm isco}} + J_{j>j_{\rm isco}}$$

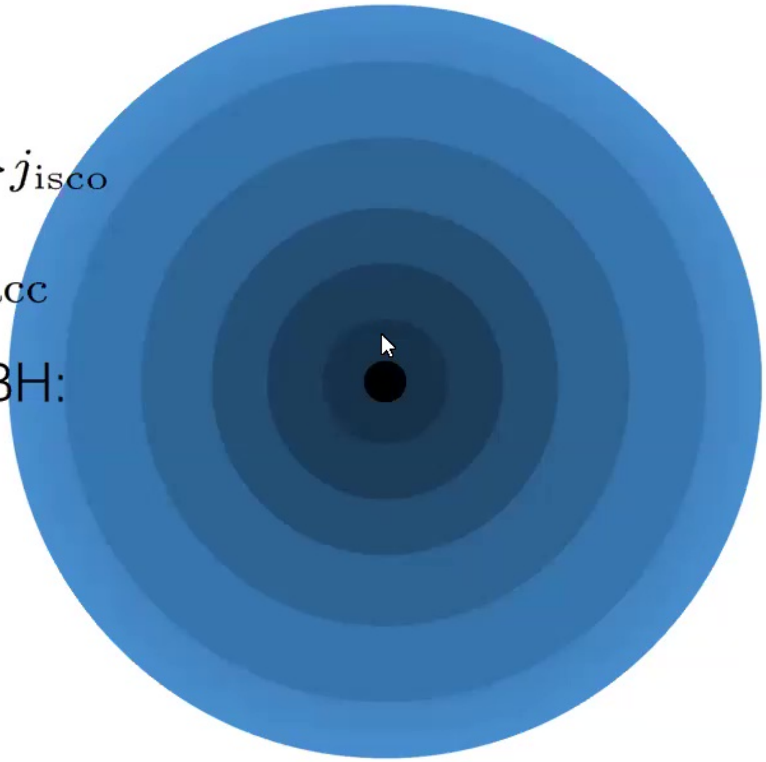
$$M_{\rm shell} = M_{j<j_{\rm isco}} + M_{\rm acc}$$

As they get accreted onto the BH:

$$M_{\rm bh} = M_{\rm bh} + M_{\rm shell}$$
$$J_{\rm bh} = J_{\rm bh} + J_{\rm shell}$$

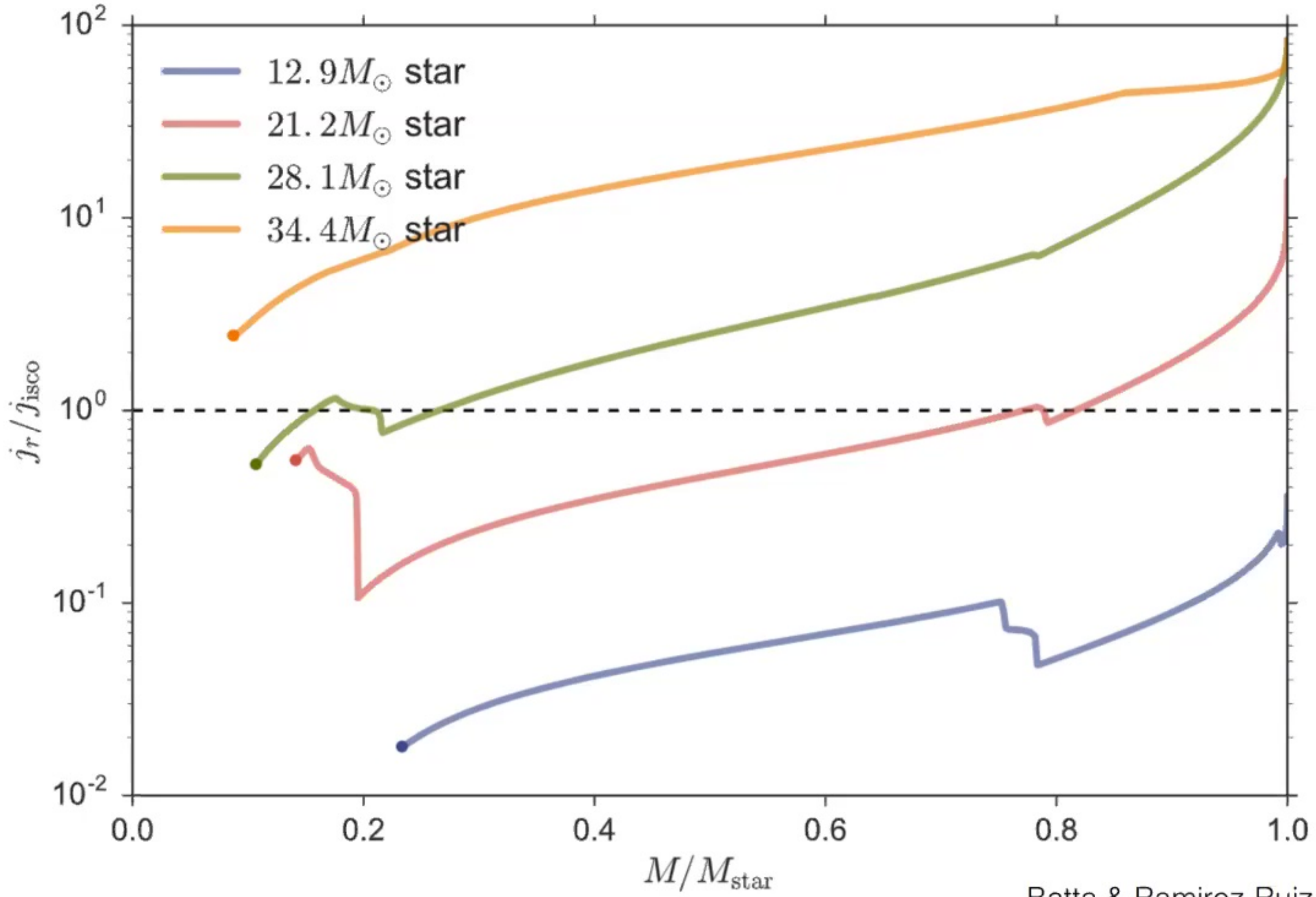
Where:

$$a = \frac{J_{\rm bh} c}{G M_{\rm bh}}$$



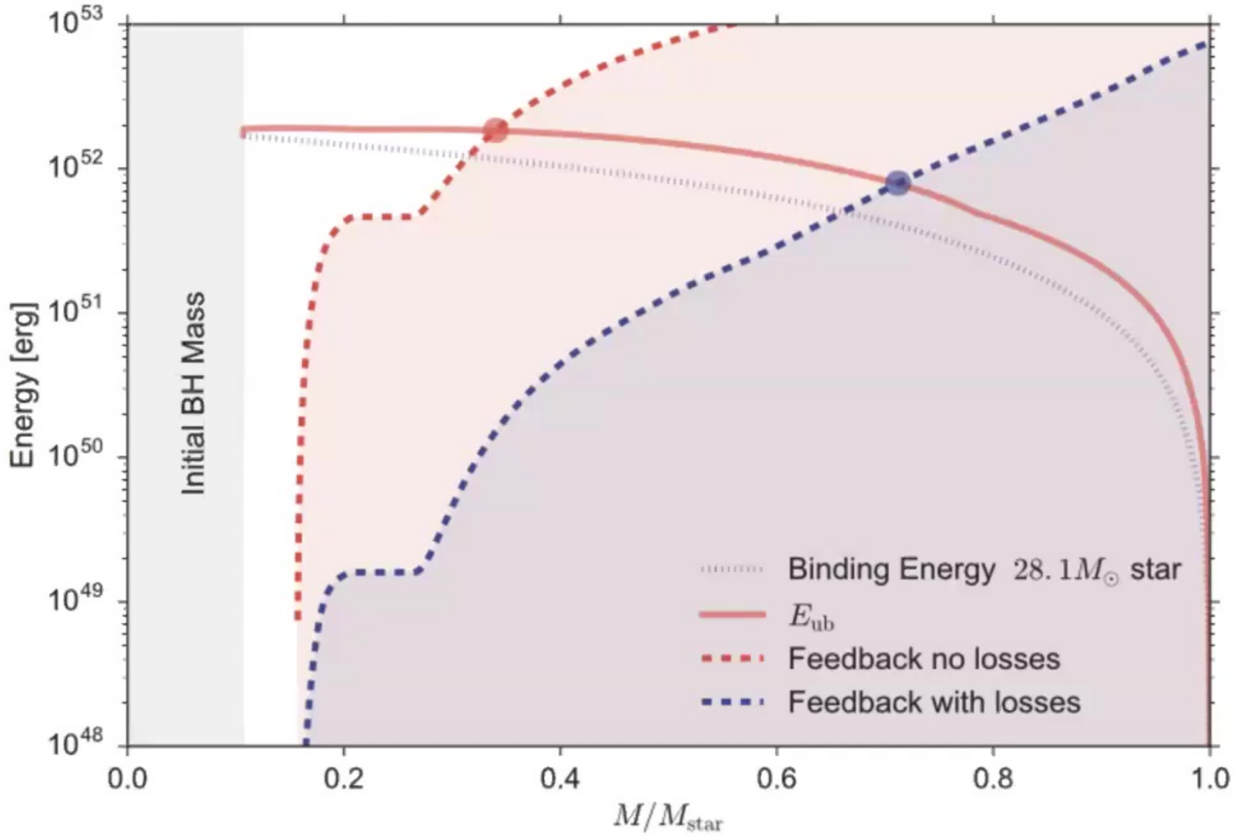
Bardeen (1970)
Thorne (1974)
Batta & Ramirez-Ruiz (2020)

BH evolution



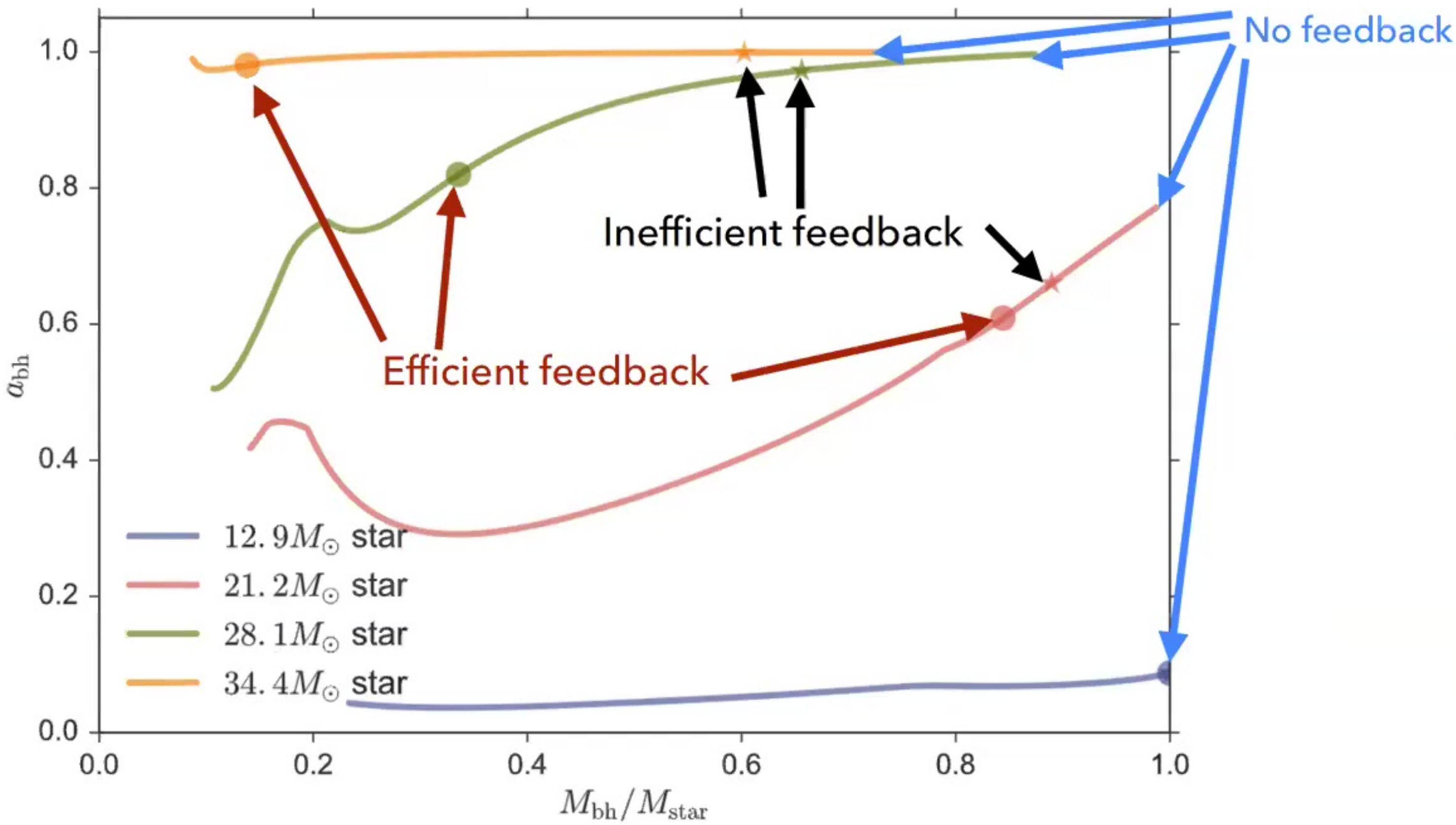
Batta & Ramirez-Ruiz (2020)

BH feedback



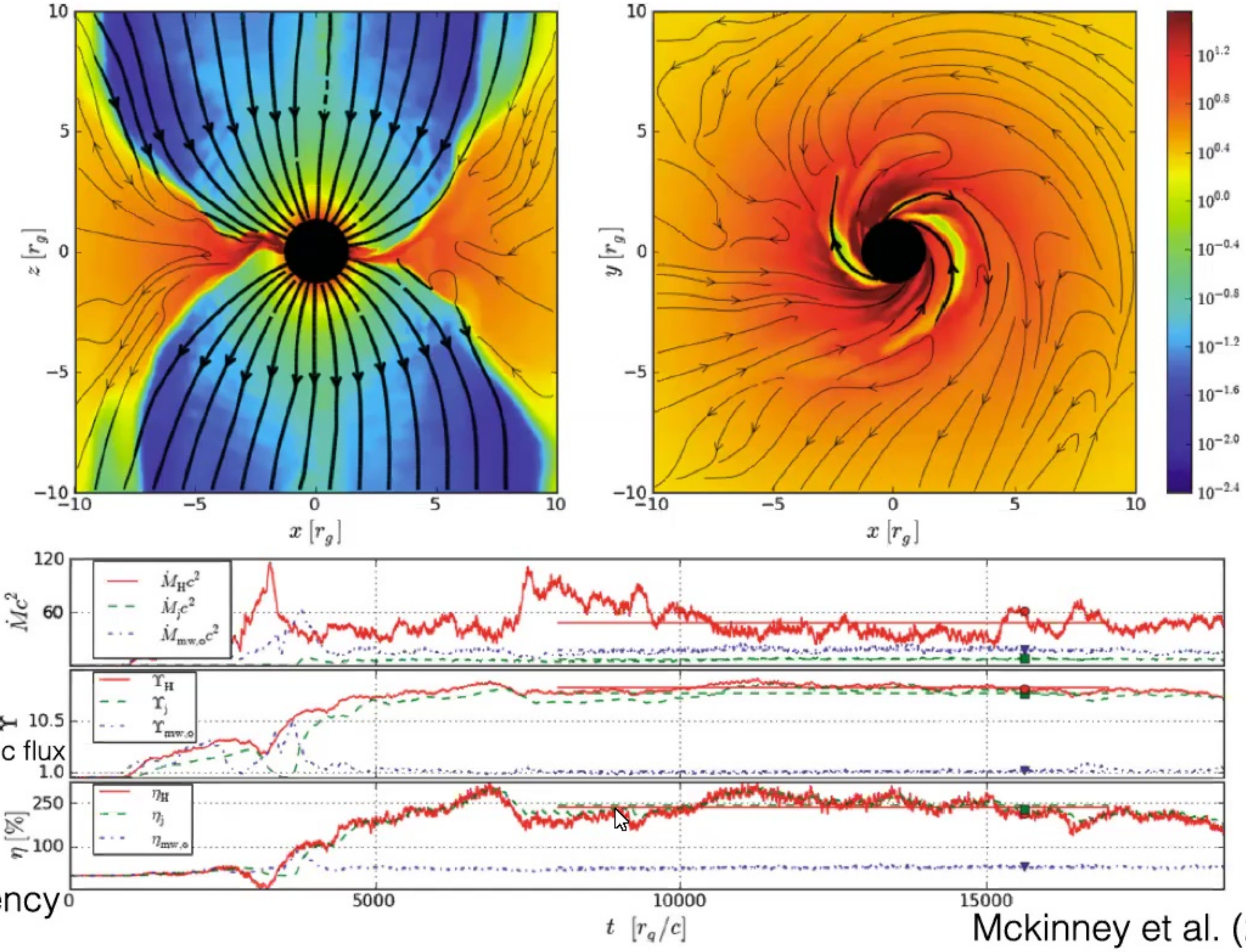
Batta & Ramirez-Ruiz (2020)

BH feedback



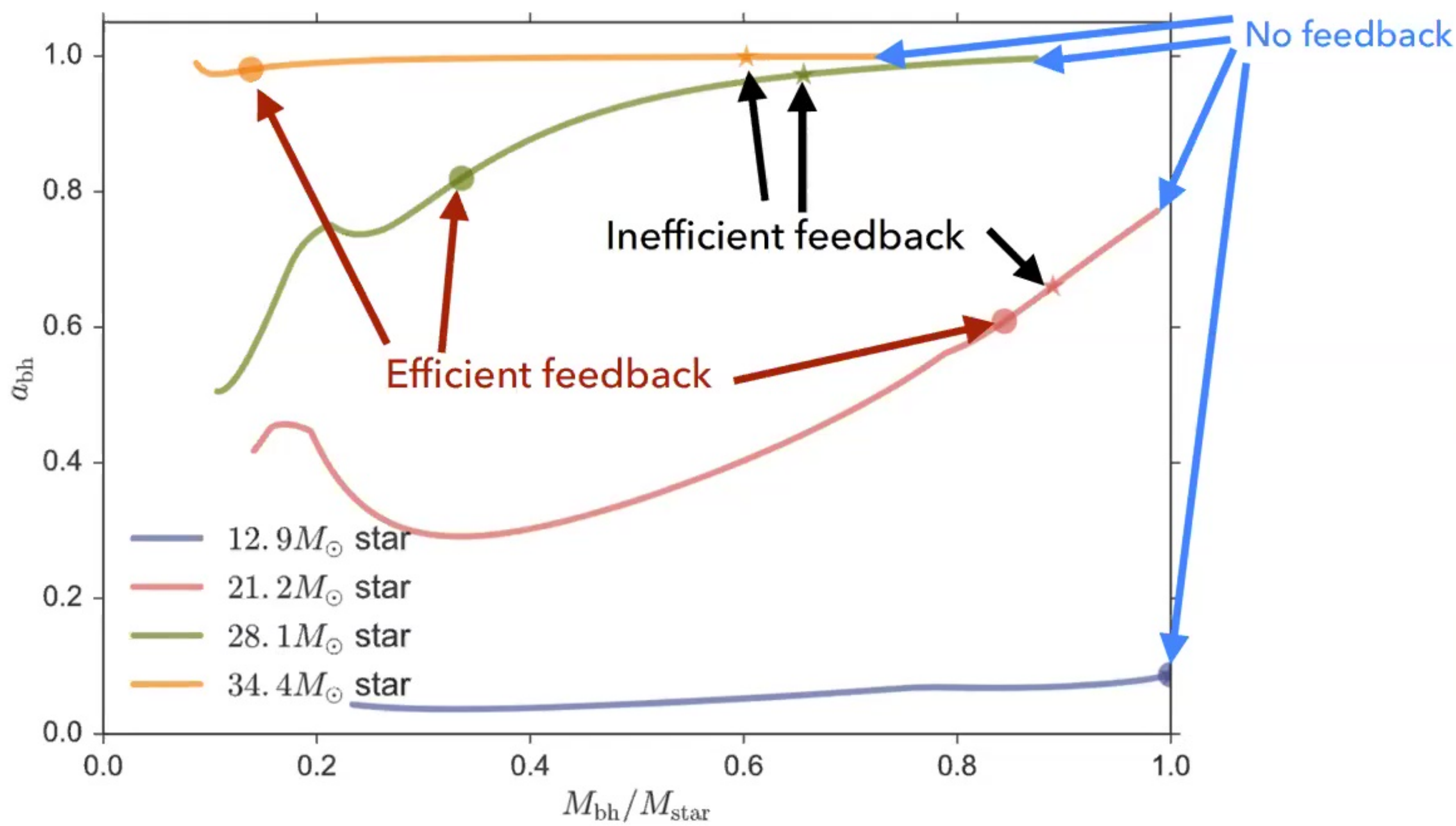
Batta & Ramirez-Ruiz (2020)

Disk efficiency



Mckinney et al. (2012)

BH feedback



Batta & Ramirez-Ruiz (2020)

BH feedback

What is the largest rotation rate a star can have before forming an accretion disk?

$$\beta = \frac{\Omega}{\Omega_{\rm break}}$$

Is it possible to have "disk" formation when $j < j_{\rm isco}$?

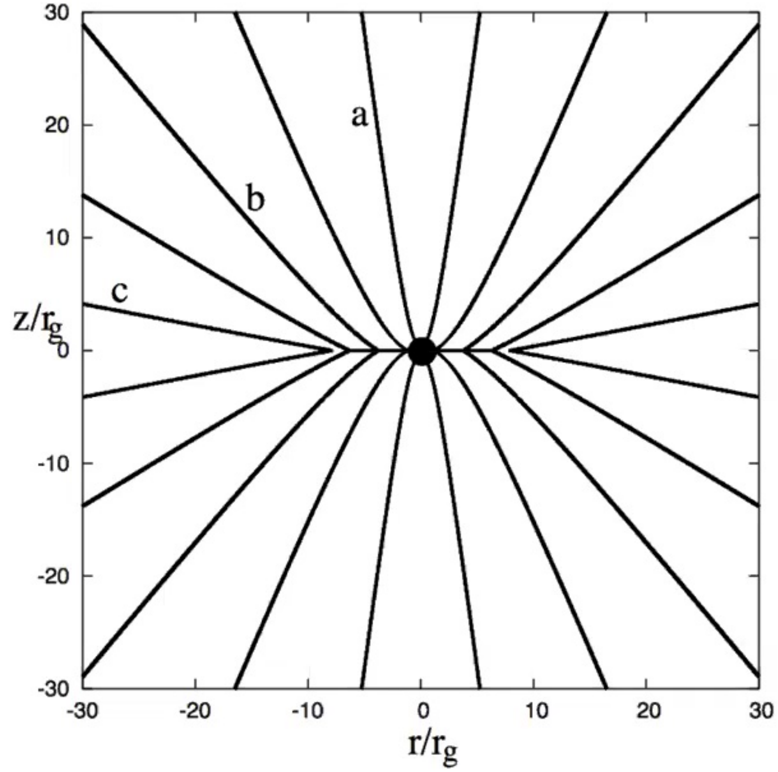
Is disk formation enough to guarantee an efficient feedback?

BH feedback

Trajectories for particles entering a BH

a) No angular momentum: Directly accreted

c) Have enough angular momentum to stay in orbit

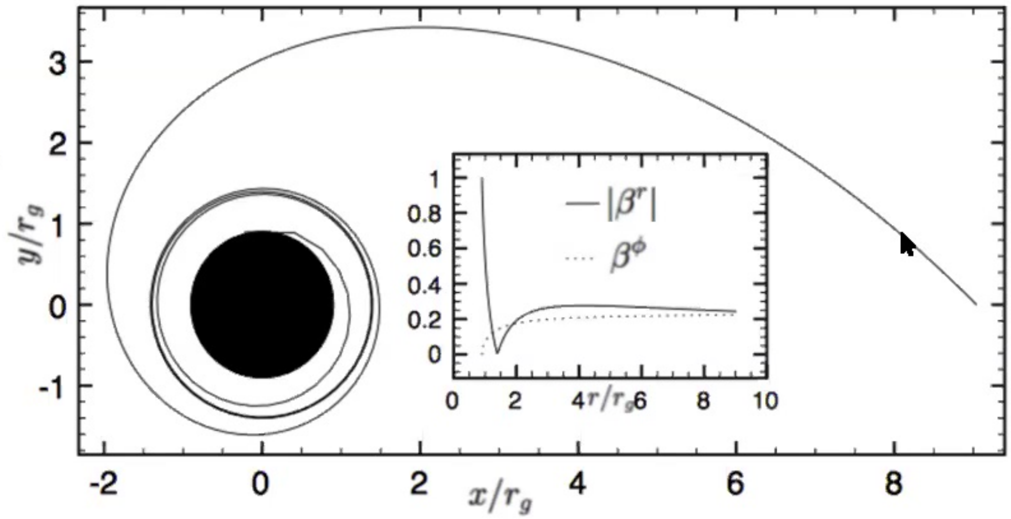


Lee & Ramirez-Ruiz (2006)

BH feedback

Trajectories for particles entering a BH

b) Particles that would be accreted, but cross the equator



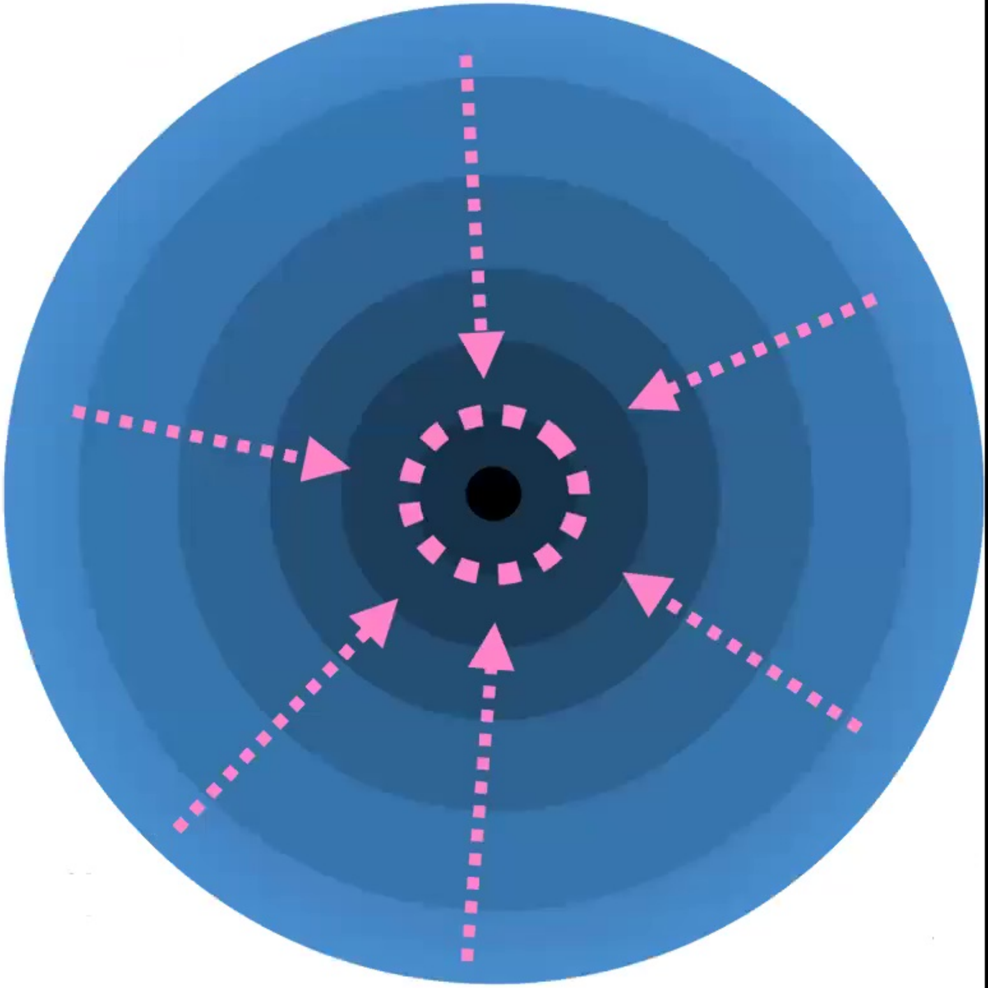
The particles will encounter material from the opposite hemisphere, dissipate energy away and form a thin disk.

Lee & Ramirez-Ruiz (2006)
Zalamea & Beloborodov (2009)
Illarionov & Beloborodov (2001)

Simulation setup

$$G = c = 1$$

$$r_g = \frac{GM_{\rm BH}}{c}$$



Simulation setup: HARM

HARM: High Accuracy Relativistic Magentohydrodynamics

Solves the conservation equations in GRMHD

$$\nabla_\mu(\rho u^\mu) = 0 \quad \nabla_\mu(T^{\mu\nu}) = 0$$

$$G = c = 1$$

With $T^{\mu\nu} = T^{\mu\nu}_{\rm gas} + T^{\mu\nu}_{\rm EM}$

Polytropic EOS: $P = (\gamma - 1)u \quad P = K\rho^\gamma$

No Magnetic fields

$$\gamma = 4/3$$

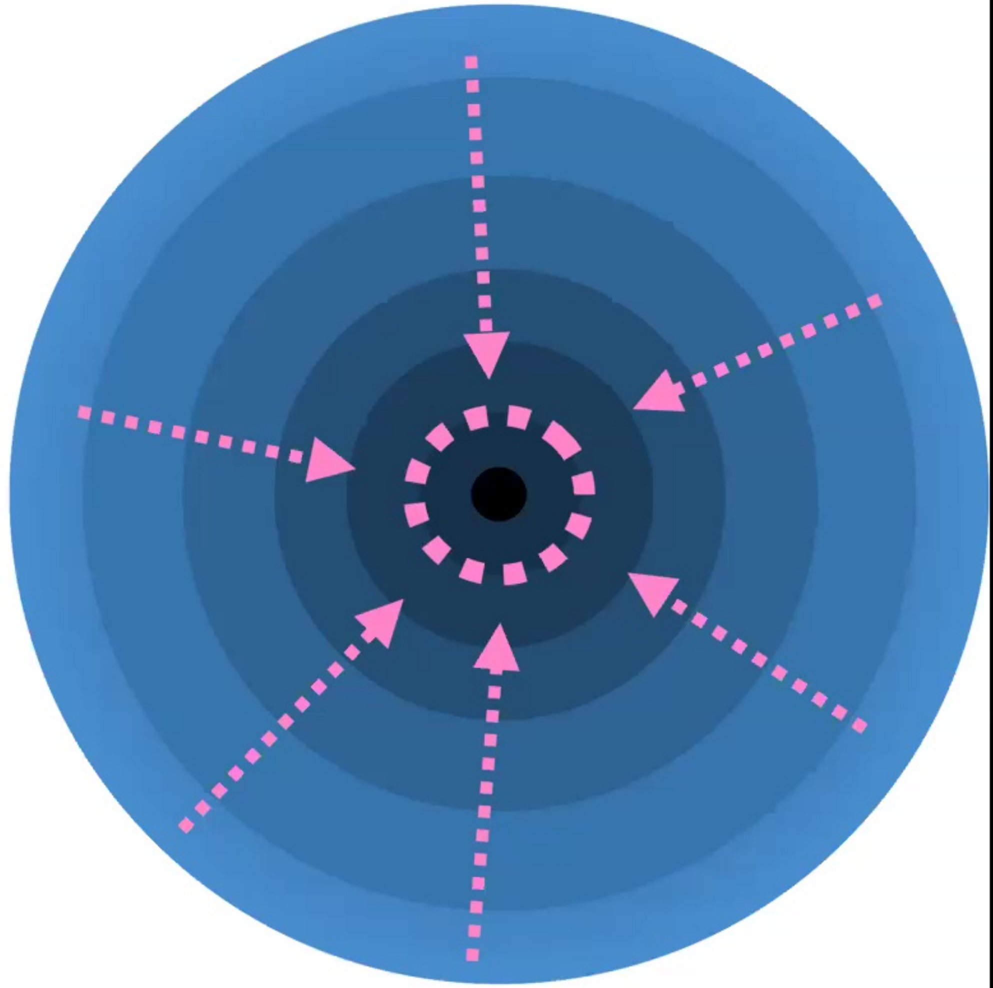
Shameless self-promotion: Neutrinos+tabulated EOS in HARM added in Murguia-Berthier et al. in prep

Gammie et al. (2003)
Noble et al. (2006)

Simulation setup

$$G = c = 1$$

$$r_g = \frac{GM_{\rm BH}}{c}$$



Simulation setup

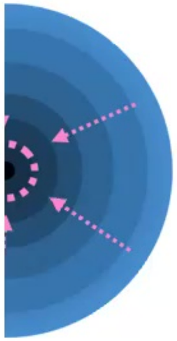
Angular momentum

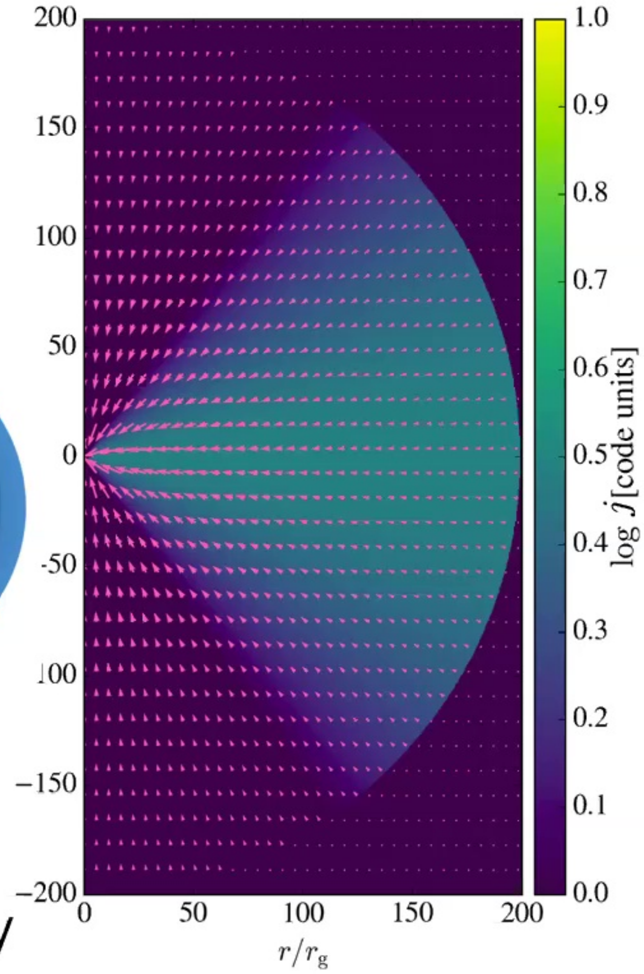
Assumptions: constant angular momentum as a function of radius

$$j = C j_{\mathrm{isco}} \sin^2 \theta$$

Slowdown parameter

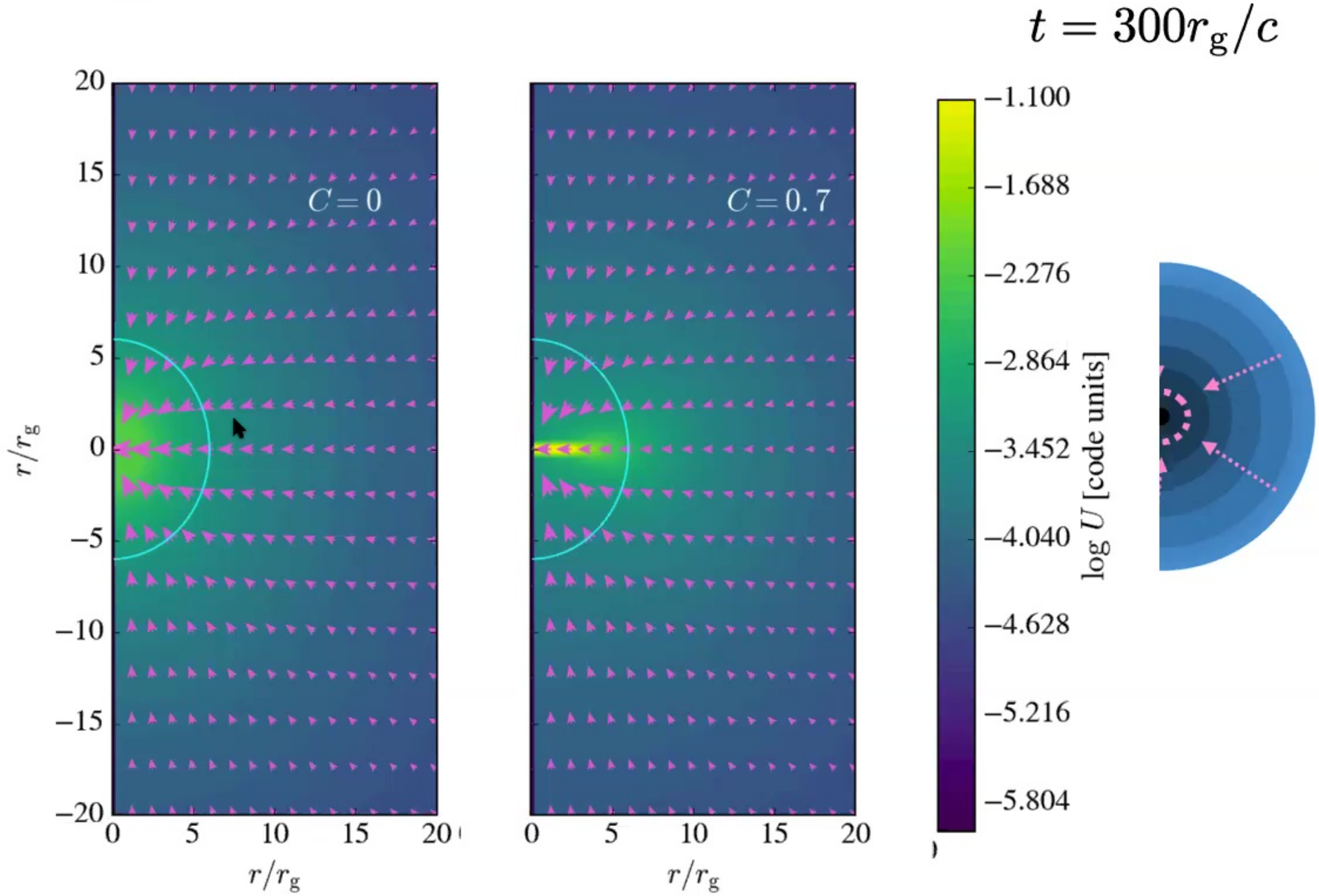
So that the angular momentum smoothly disappears at the boundary





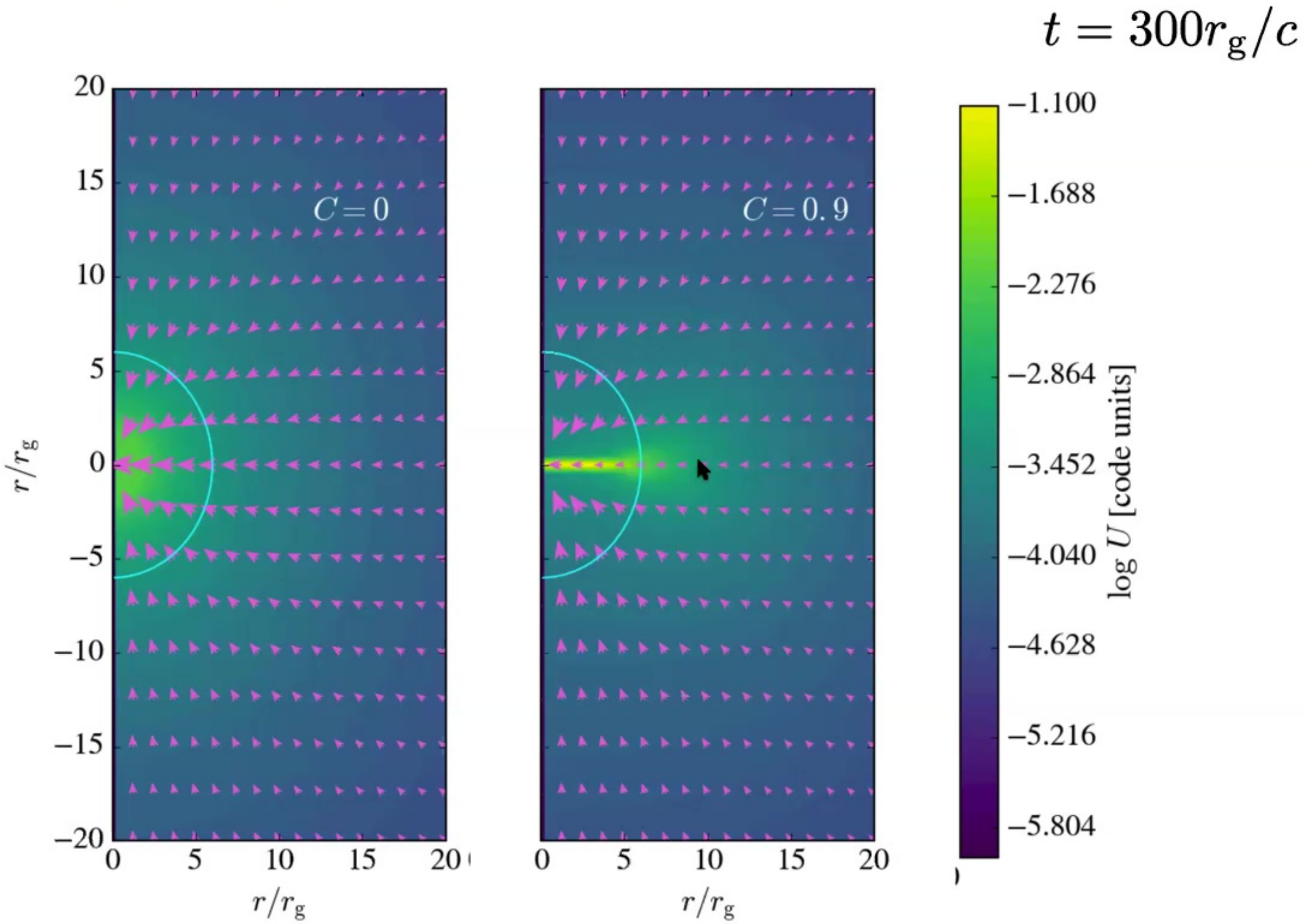
$C = 0.9$

Accumulation of matter near the BH



Murguia-Berthier et al. (2020)

Accumulation of matter near the BH



Murguia-Berthier et al. (2020)

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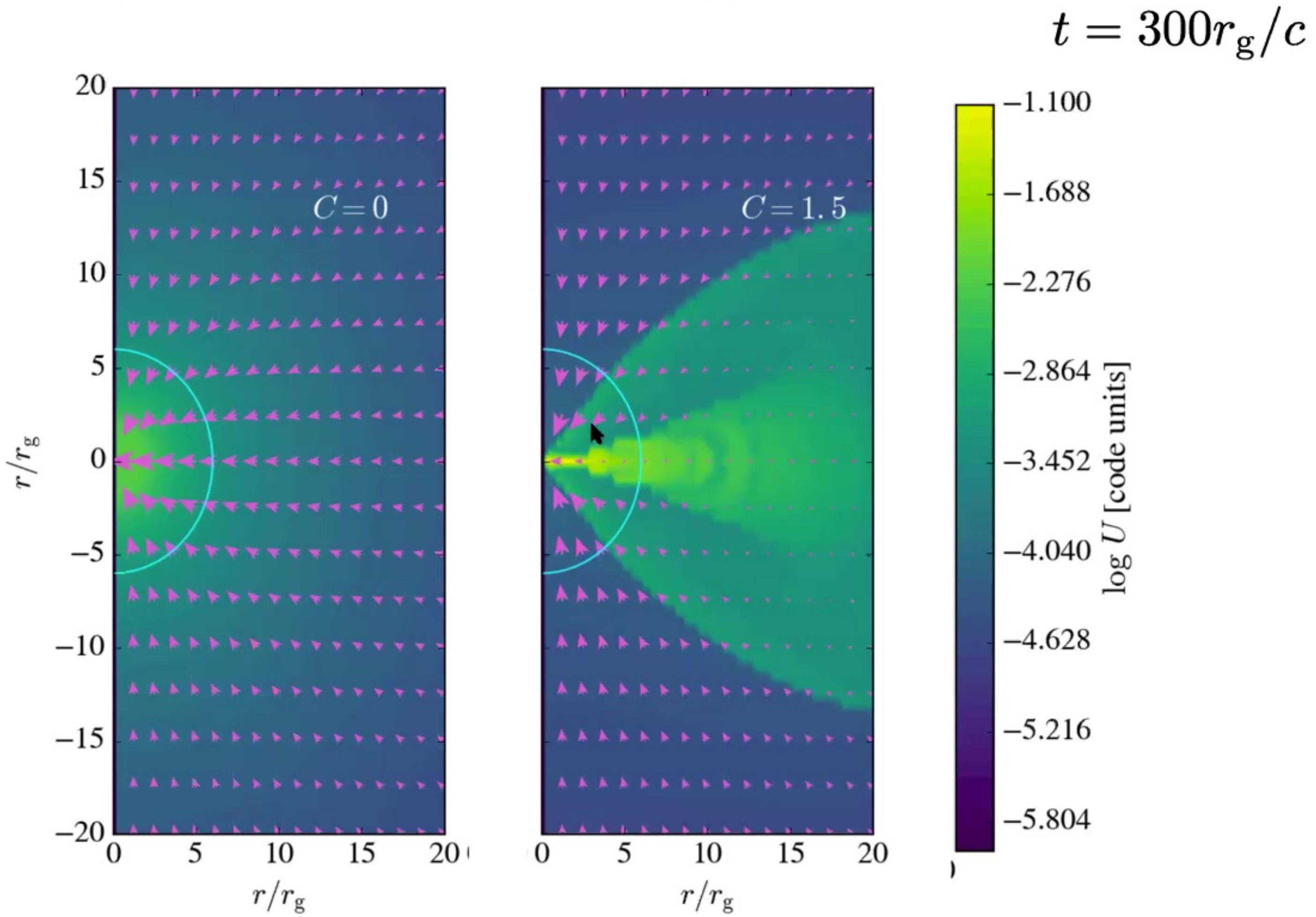
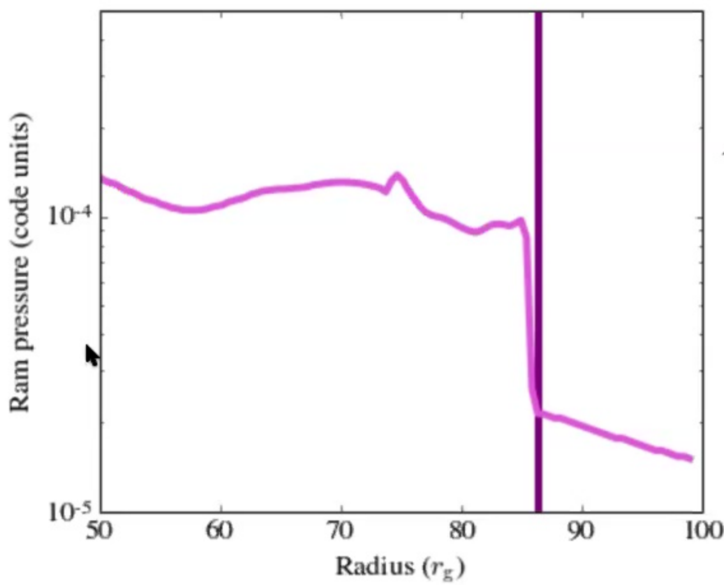
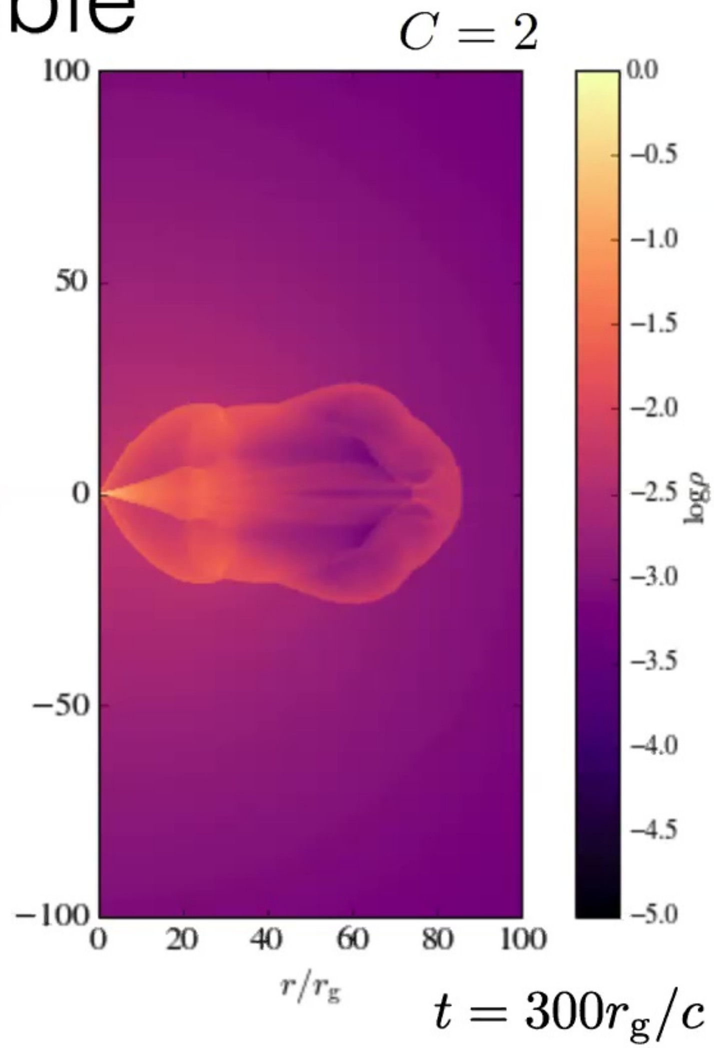


Murguia-Berthier et al. (2020)

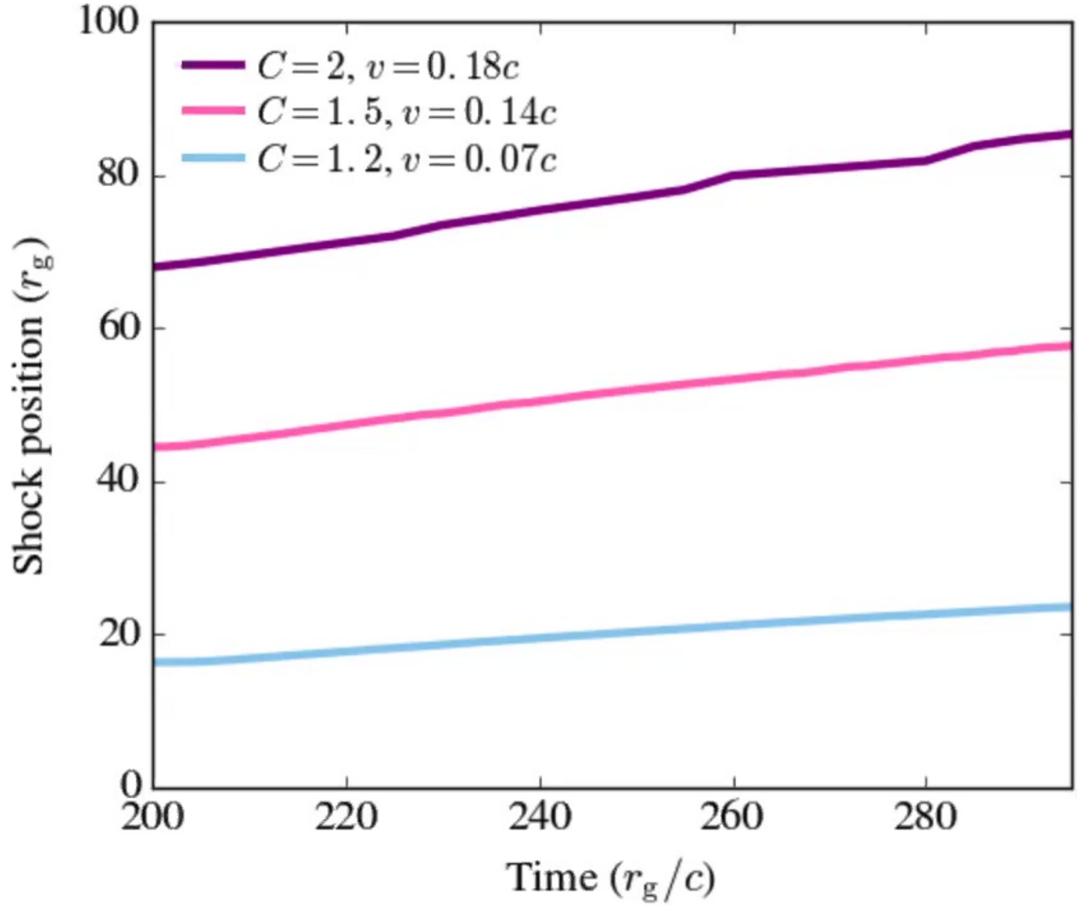
Shock in the bubble



In the equator



Shock in the bubble

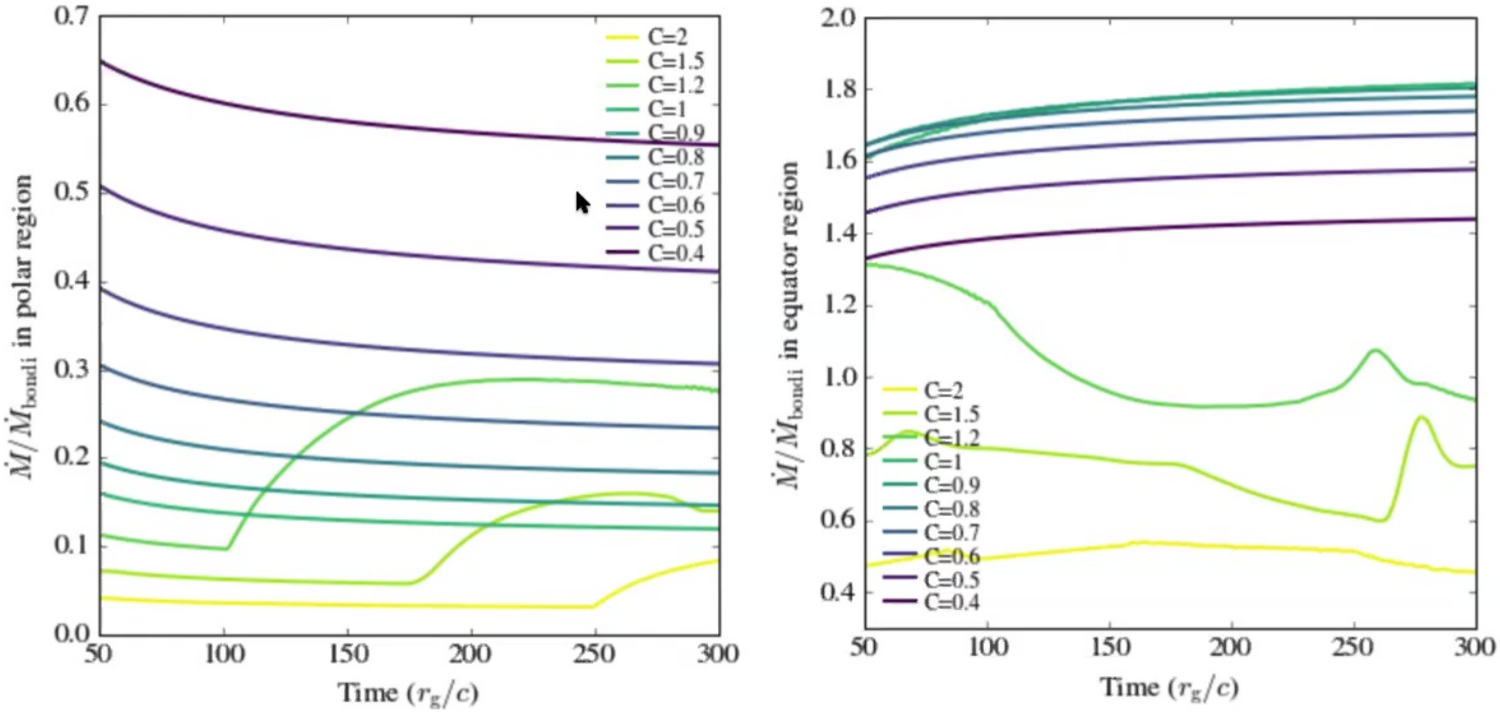


At the edge of the domain:

$$v = 0.07c$$

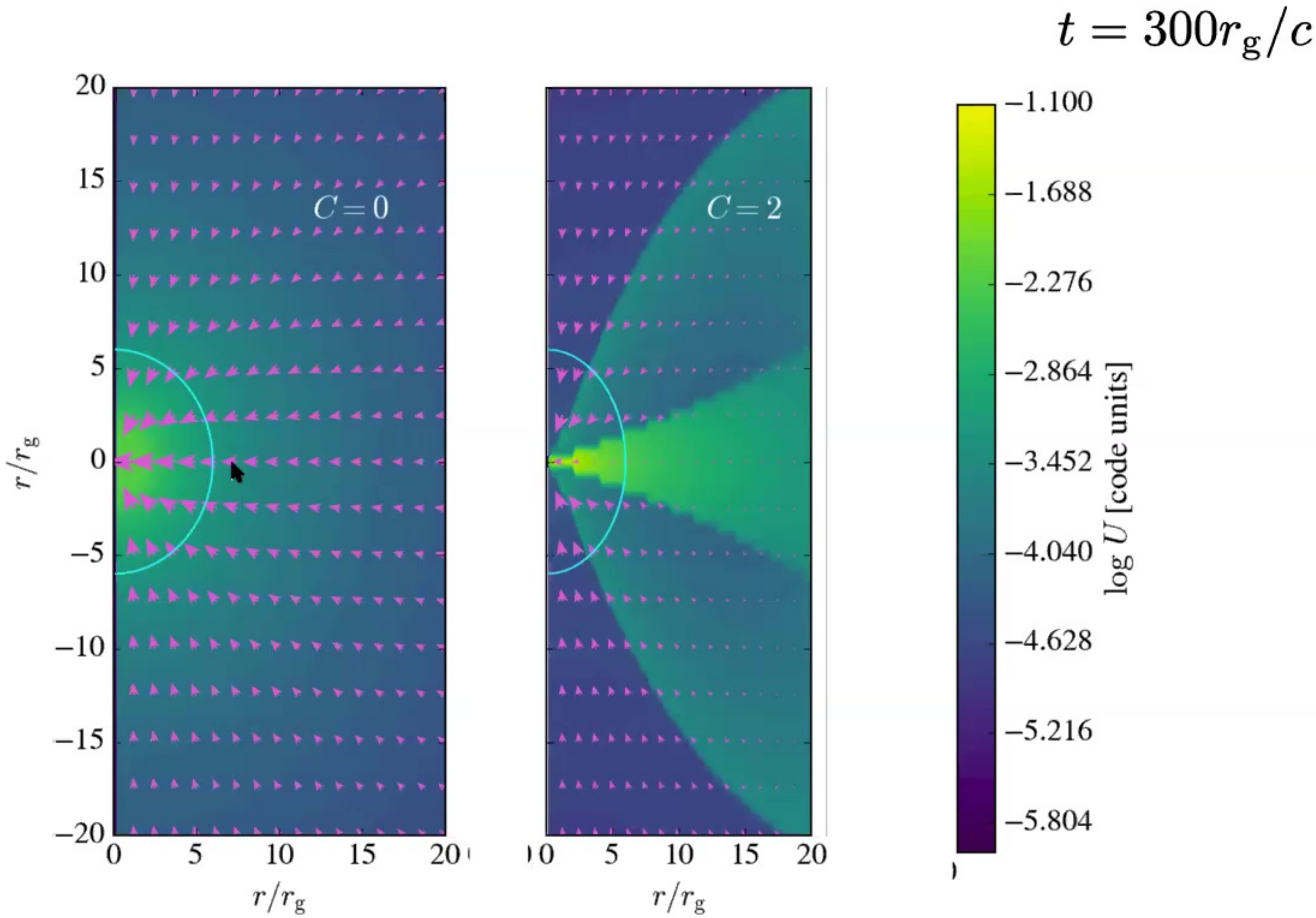
Murguia-Berthier et al. (2020)

Mass accretion rate



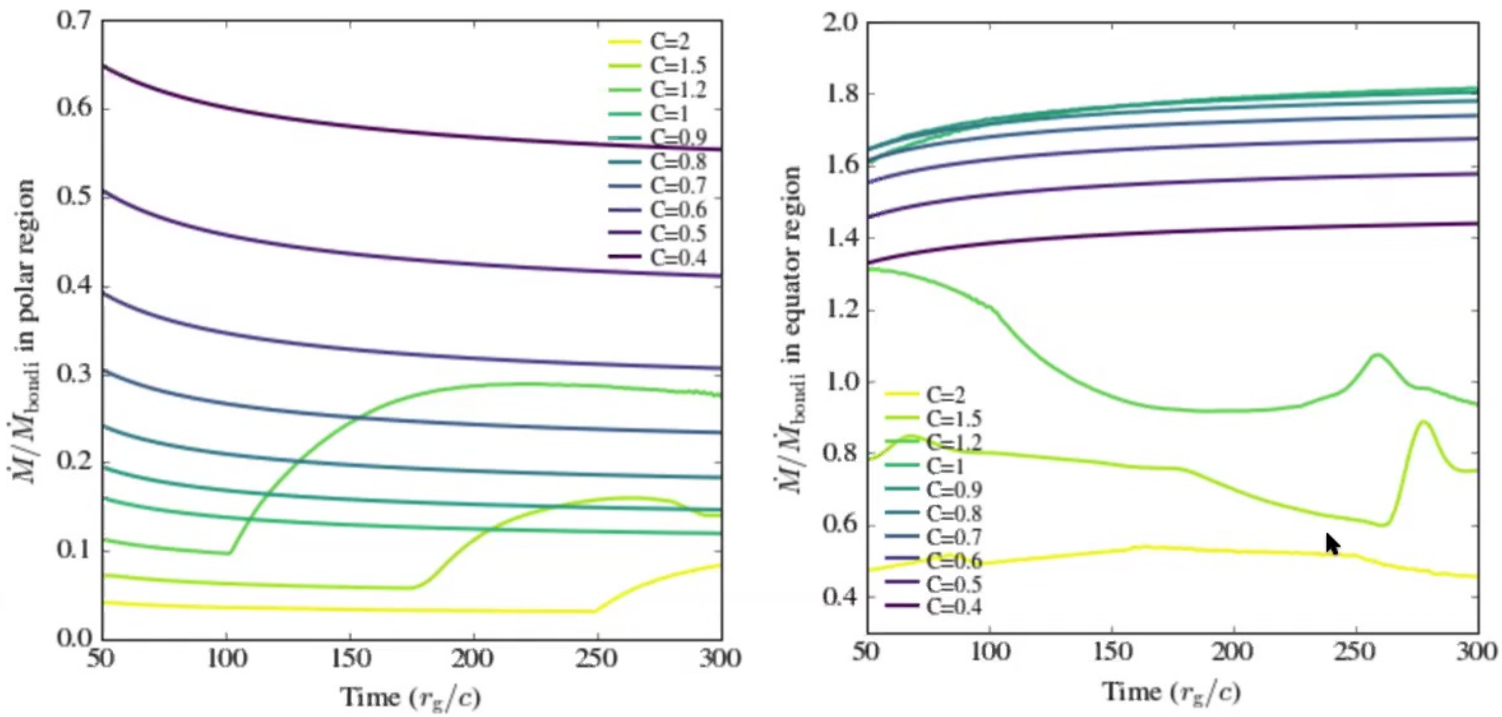
Murguia-Berthier et al. (2020)

Accumulation of matter near the BH



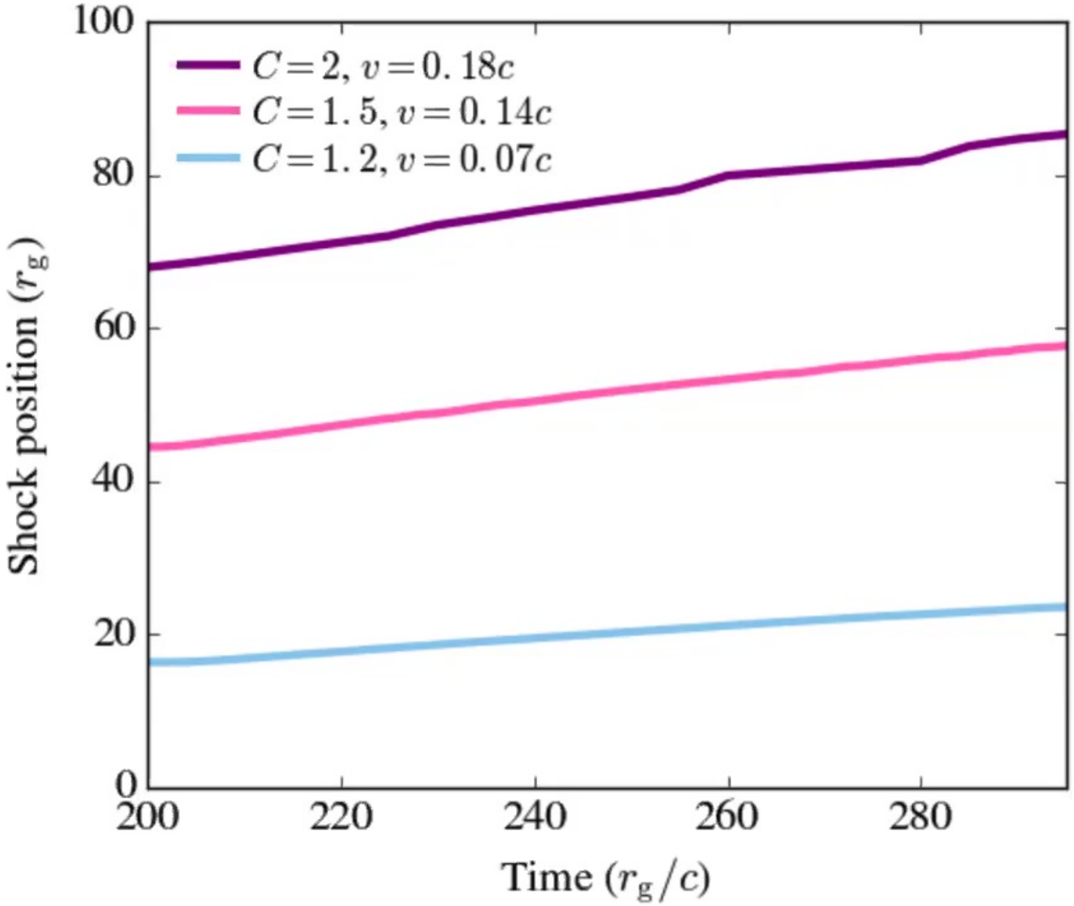
Murguia-Berthier et al. (2020)

Mass accretion rate



Murguia-Berthier et al. (2020)

Shock in the bubble

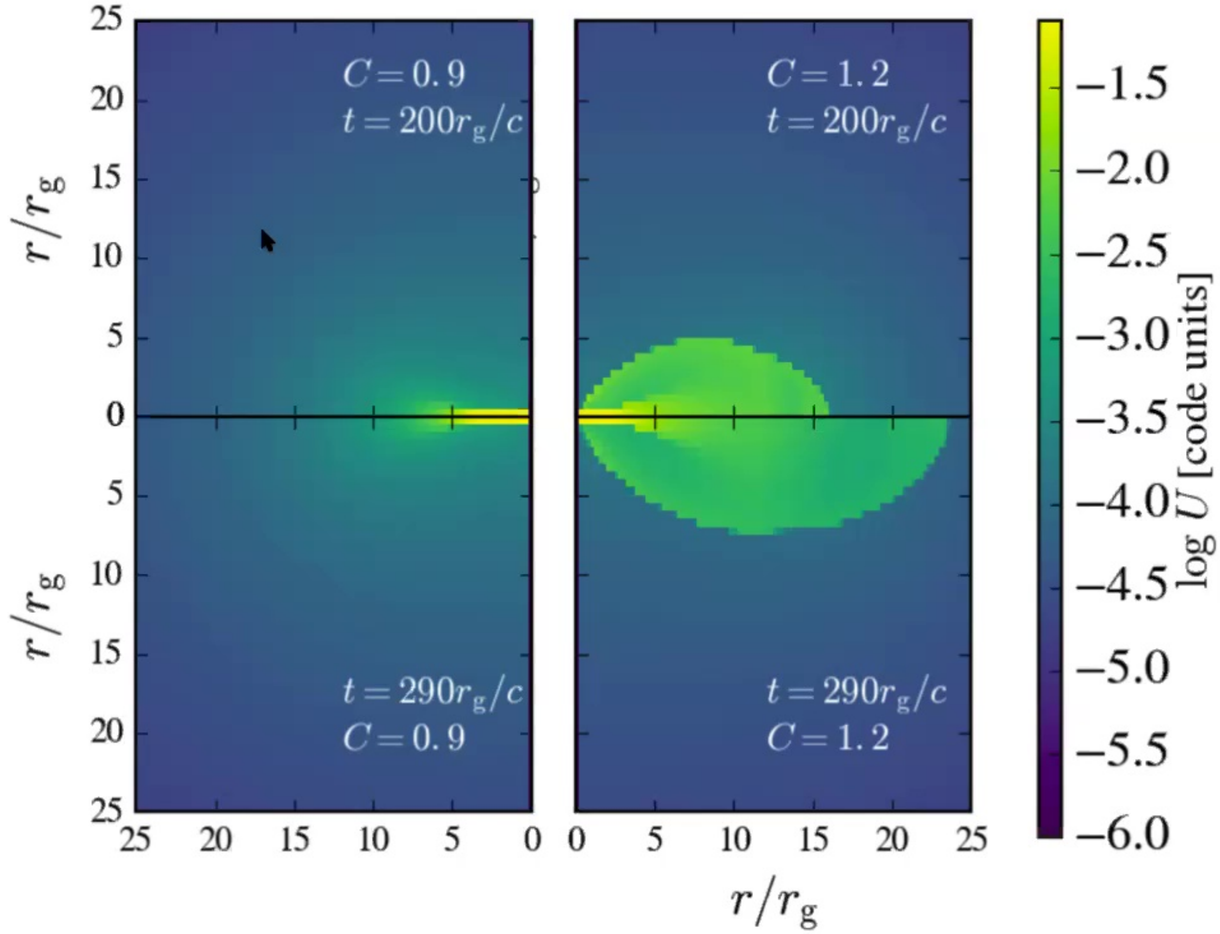


At the edge of the domain:

$$v = 0.07c$$

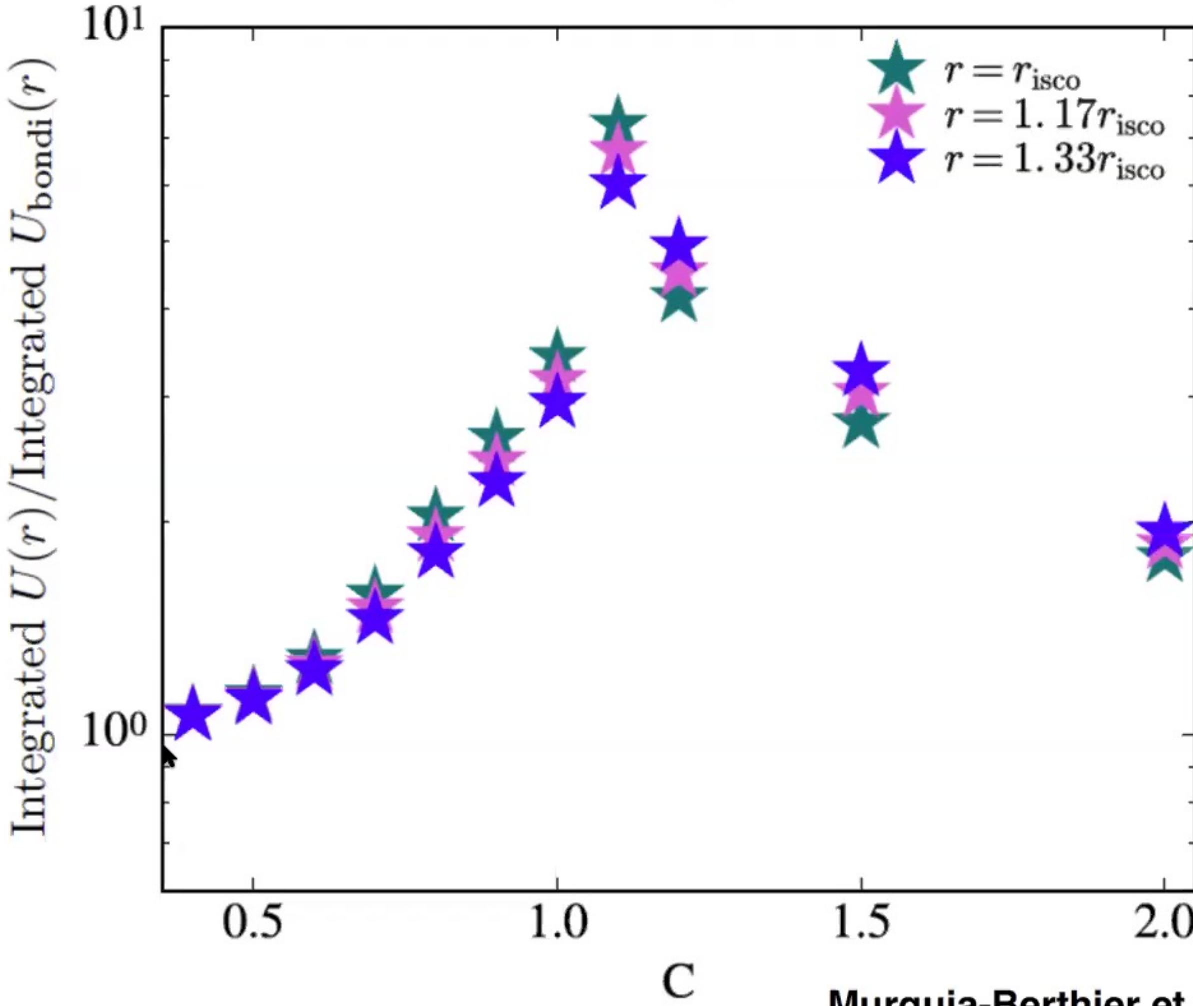
Murguia-Berthier et al. (2020)

Formation of a bubble



Murguia-Berthier et al. (2020)

Energy comparisons



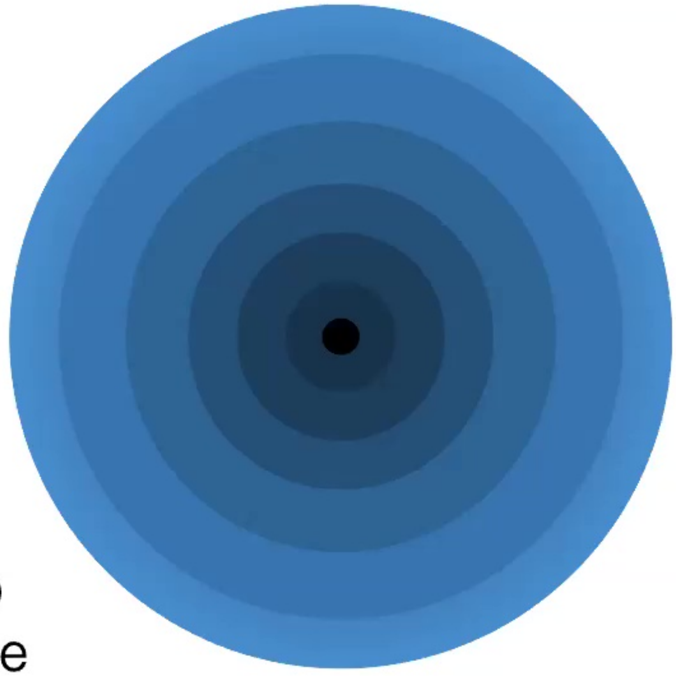
Murguia-Berthier et al. (2020)

Maximum angular momentum of disappearing stars

For inefficient feedback we need this to hold at all radii

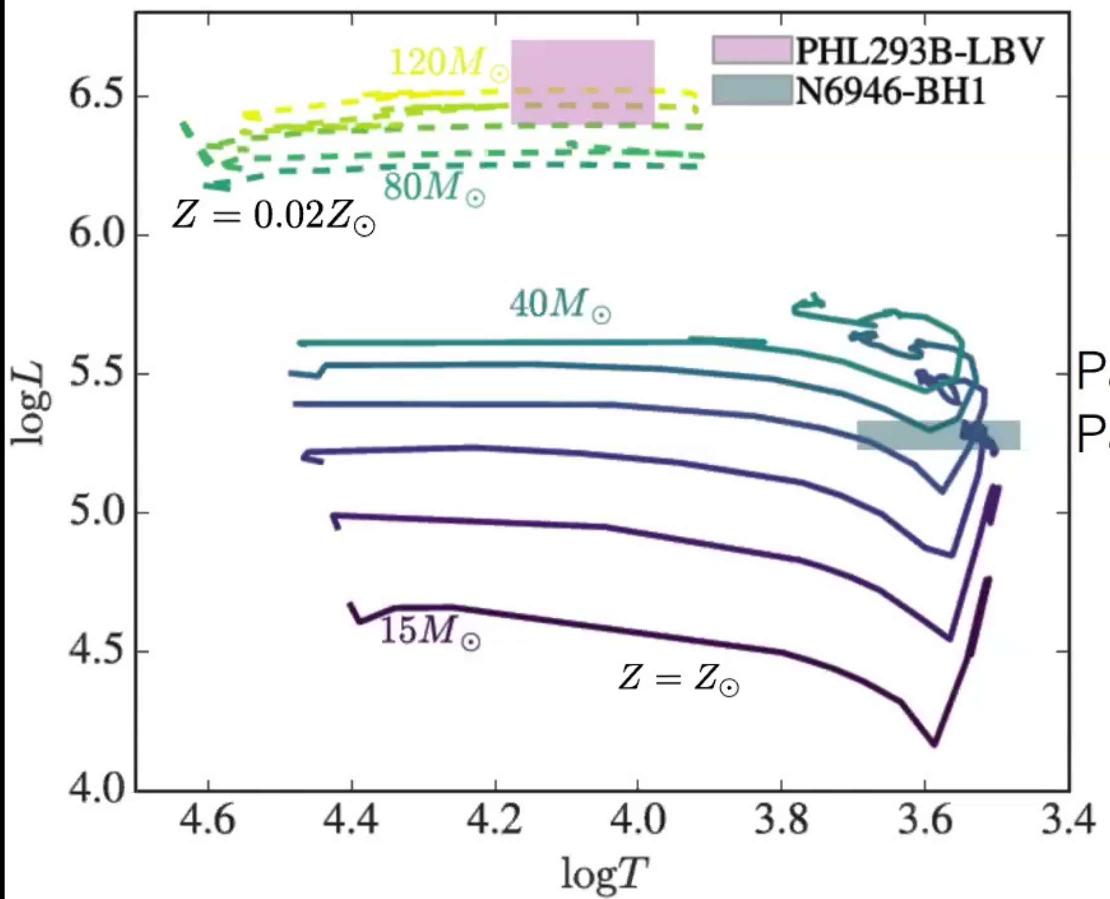
$$j(r) \leq C_{\rm fb} j_{\rm isco}(r)$$

$$C_{\rm fb} = 1.2$$



Note that the angular momentum at the isco has to self-consistently change as the black hole accretes more shells of material.

Disappearing stars



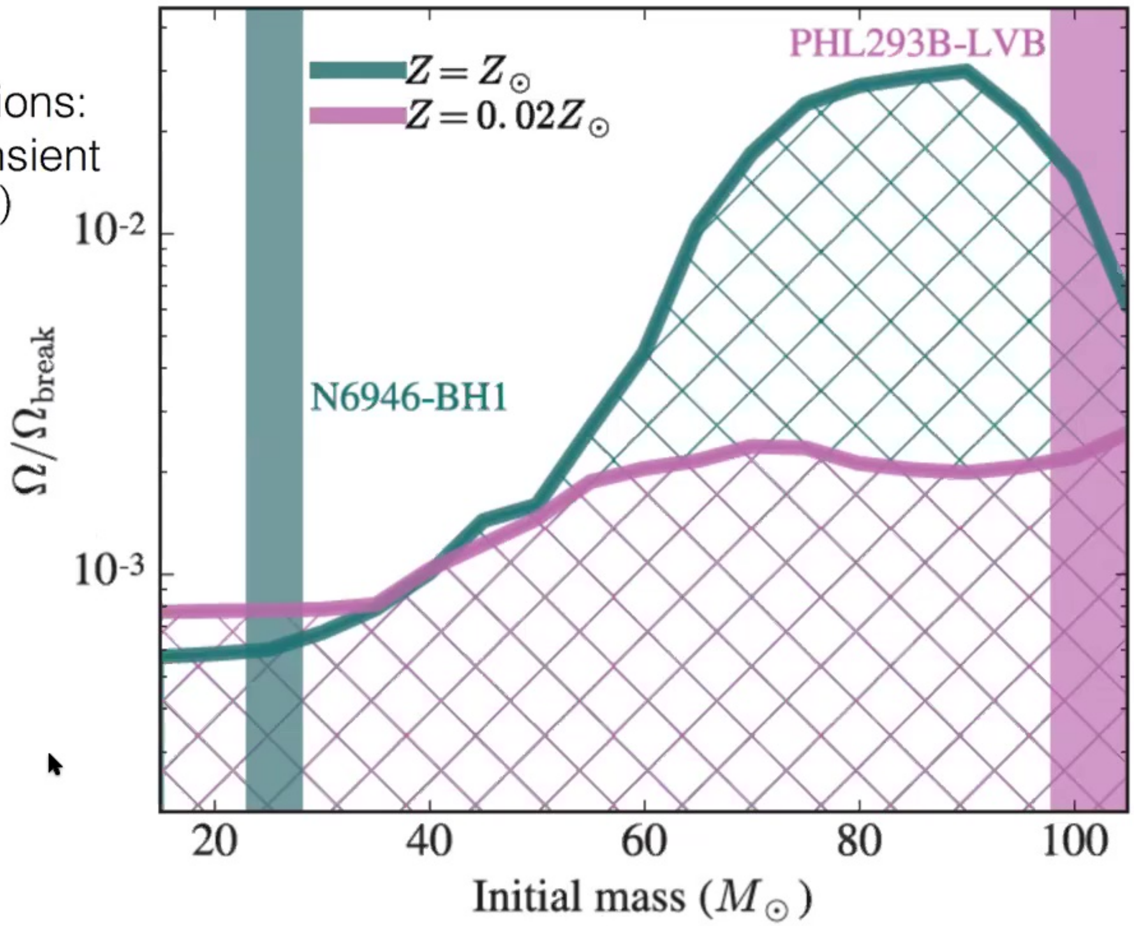
MESA models:
Paxton et al. (2011)
Paxton et al. (2013)

Murguia-Berthier et al. (2020)

Disappearing stars

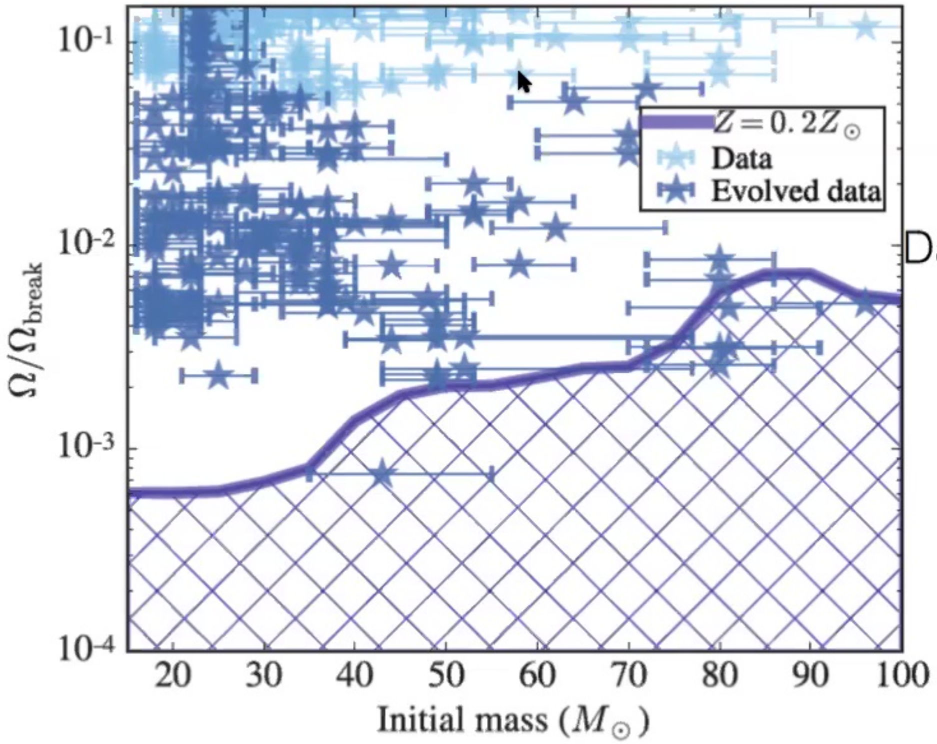
Hatched regions:
No bright transient
$j(r) \leq C_{\rm fb} j_{\rm isco}(r)$
$C_{\rm fb} = 1.2$

Note: this is the angular velocity



Murguia-Berthier et al. (2020)

Stellar rotation limits

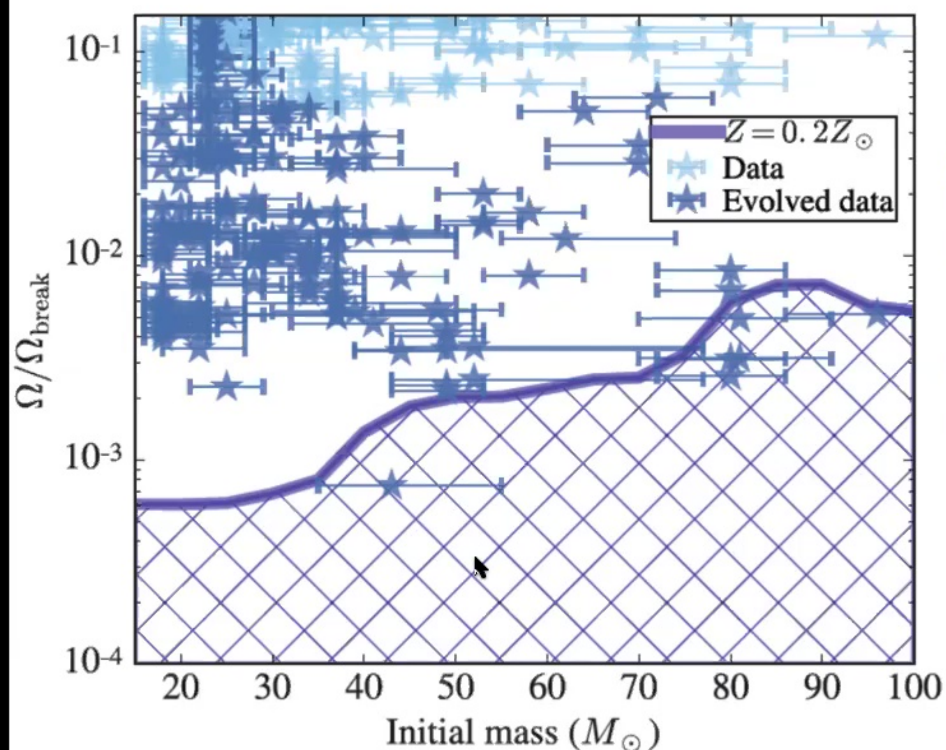


Data from Ramírez-Agudelo et al. (2013), Weidner & Vink (2010)

$$\frac{1}{\Omega}\frac{d\Omega}{dt} = -\frac{1}{I_*}\frac{dI_*}{dt} + \frac{2}{3}\frac{R_*^2}{I_*}\frac{dM_*}{dt}$$

Murguia-Berthier et al. (2020)

Stellar rotation limits



Around 5% of the stars end up disappearing without a bright transient.

Observational limit (Gerke et al. 2015) is around 7%

Murguia-Berthier et al. (2020)

Also ask me about:

- **GW170817**: Murguia-Berthier et al. (2017a)
- **sGRB: Interaction of relativistic jets with winds**: Murguia-Berthier et al. (2014), Murguia-Berthier et al. (2017b), Murguia-Berthier et al. (2020)
- **Common envelope evolution: flows around the secondary:** Murguia-Berthier et al. (2017c)
- **Adding neutrino+tabulated EOS in HARM3D: post-merger simulations and TCAN collaboration:** Murguia-Berthier et al. in prep (2020)