GRMHD simulations meet Galaxy Evolution

Refined models for AGN feedback

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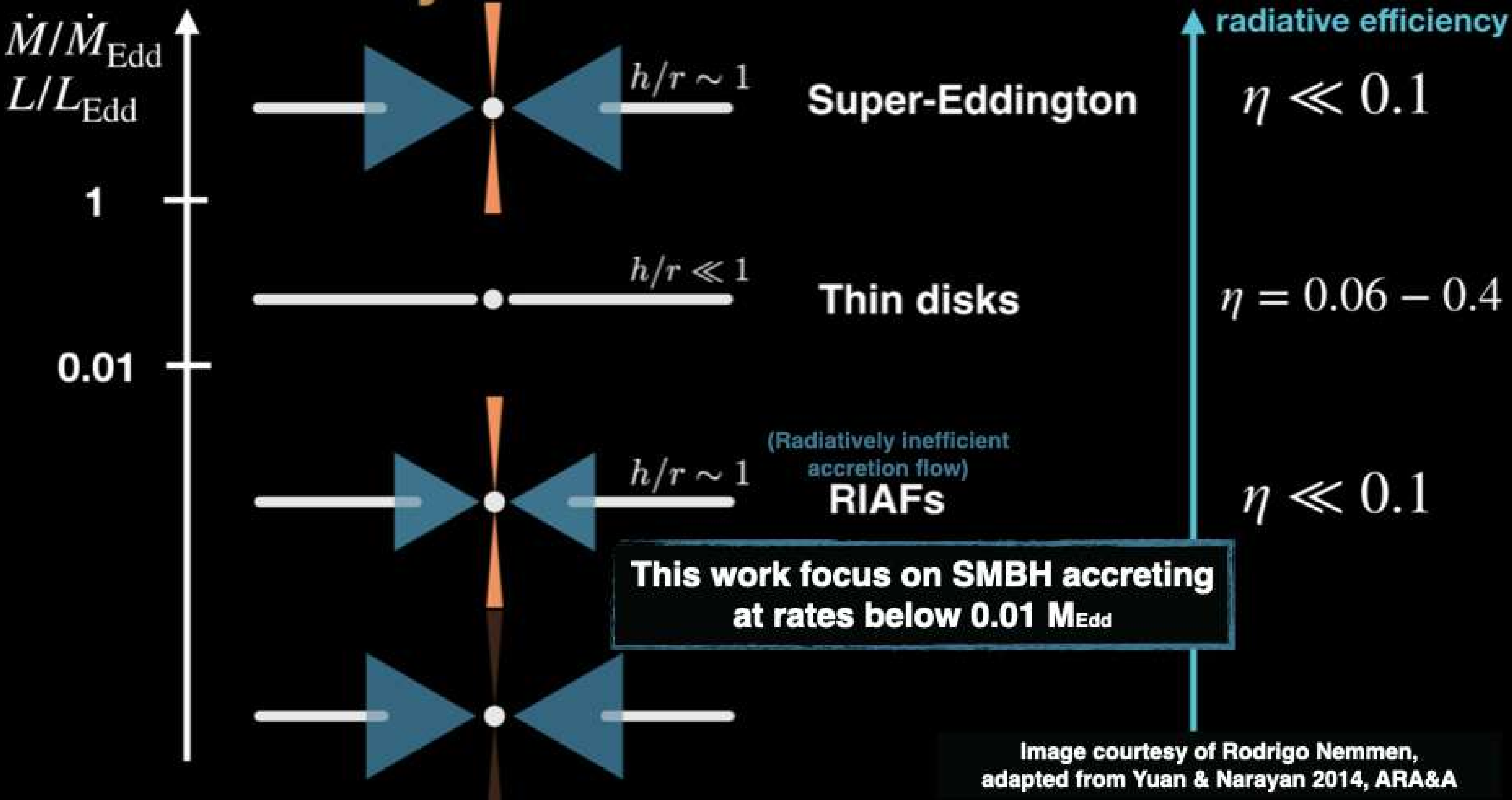
Unified theory of black hole accretion flows



$h/r \sim 1$ **Super-Eddington** $\eta \ll 0.1$

$h/r \ll 1$ **Thin disks** $\eta = 0.06 - 0.4$

$h/r \sim 1$ **RIAFs** (Radiatively inefficient accretion flow) $\eta \ll 0.1$

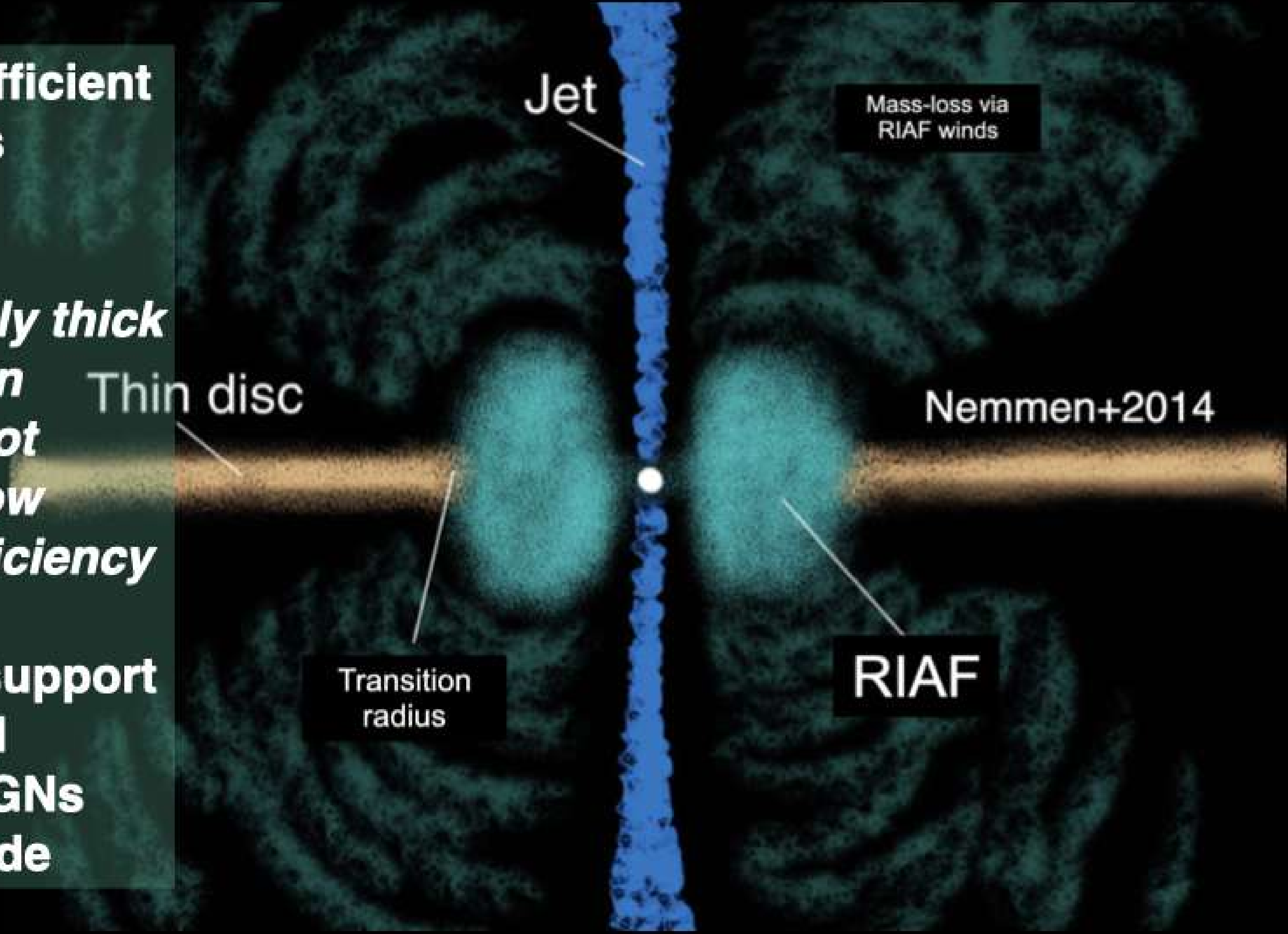
This work focus on SMBH accreting at rates below 0.01 M_{Edd}

Image courtesy of Rodrigo Nemmen, adapted from Yuan & Narayan 2014, ARA&A

Radiatively inefficient accretion flows (RIAFs)

- *Geometrically thick*
- *Optically thin*
- *Extremely hot*
- *Extremely low radiative efficiency*

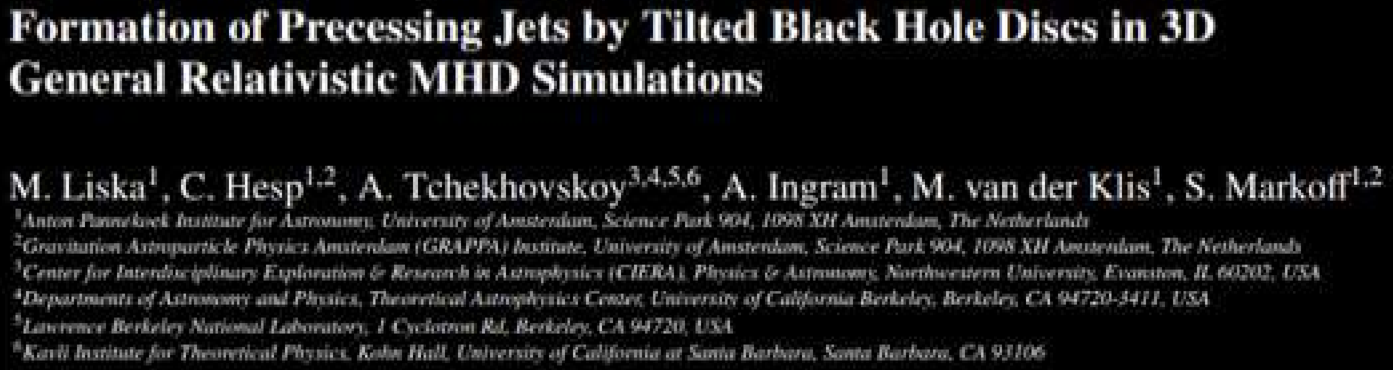
Observations support that in the local universe the AGNs are in RIAF mode



What are the mechanisms behind this AGN feedback?

SMBH outflows are efficient enough to suppress star formation and change the appearance of the galaxy?

H-AMR



Formation of Precessing Jets by Tilted Black Hole Discs in 3D General Relativistic MHD Simulations

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[2] *Gravitation Astroparticle Physics Amsterdam (GRAPPA) Institute, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*
[3] *Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Physics & Astronomy, Northwestern University, Evanston, IL 60202, USA*
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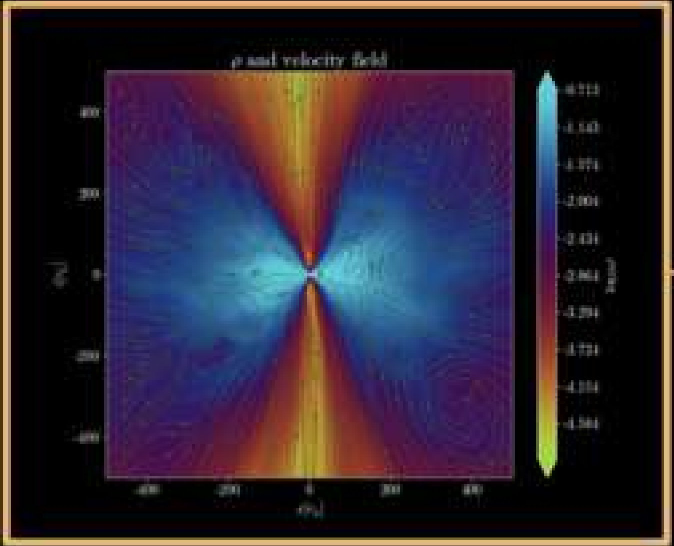
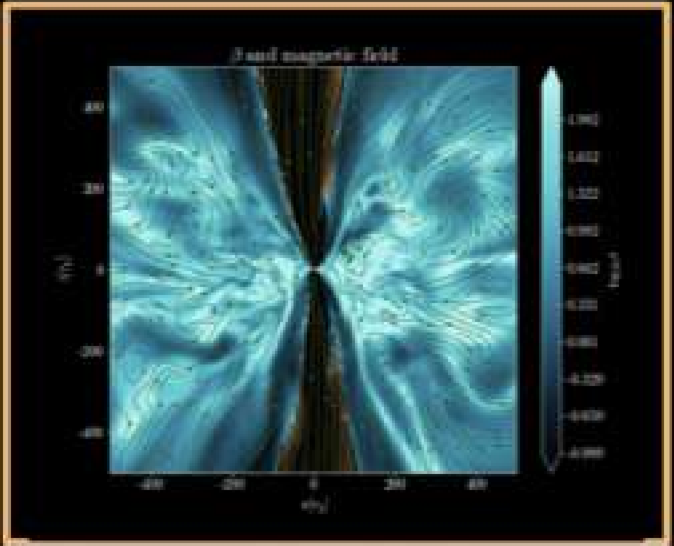
[6] *Kavli Institute for Theoretical Physics, Kohn Hall, University of California at Santa Barbara, Santa Barbara, CA 93106*

Based on HARM Code and optimized to run on GPUs

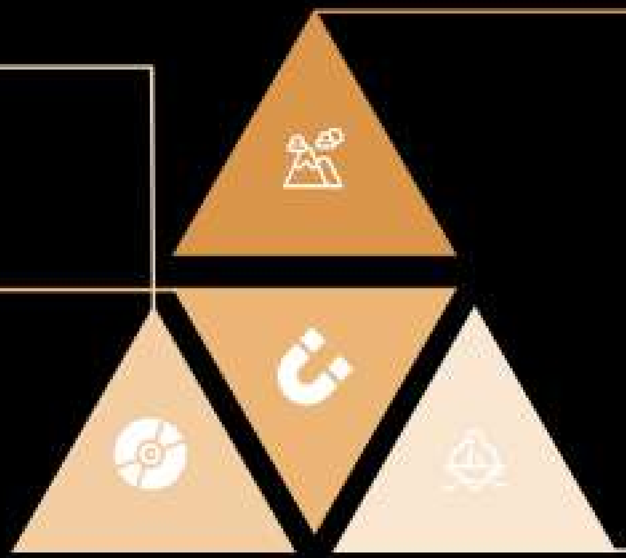
H-AMR is a massively scalable GPU-accelerated general relativistic magnetohydrodynamics (GRMHD) code

Our GRMHD simulations





Following the same idea of Almeida & Nemmen 2020



INITIAL TORUS

Density profile of the geometrically thick RIAF accretion disc

MAGNETIC TOPOLOGY
(Magnetic Potential Vector)

The topology of magnetic field can have an important impact over the accretion flow

GENERAL RELATIVITY

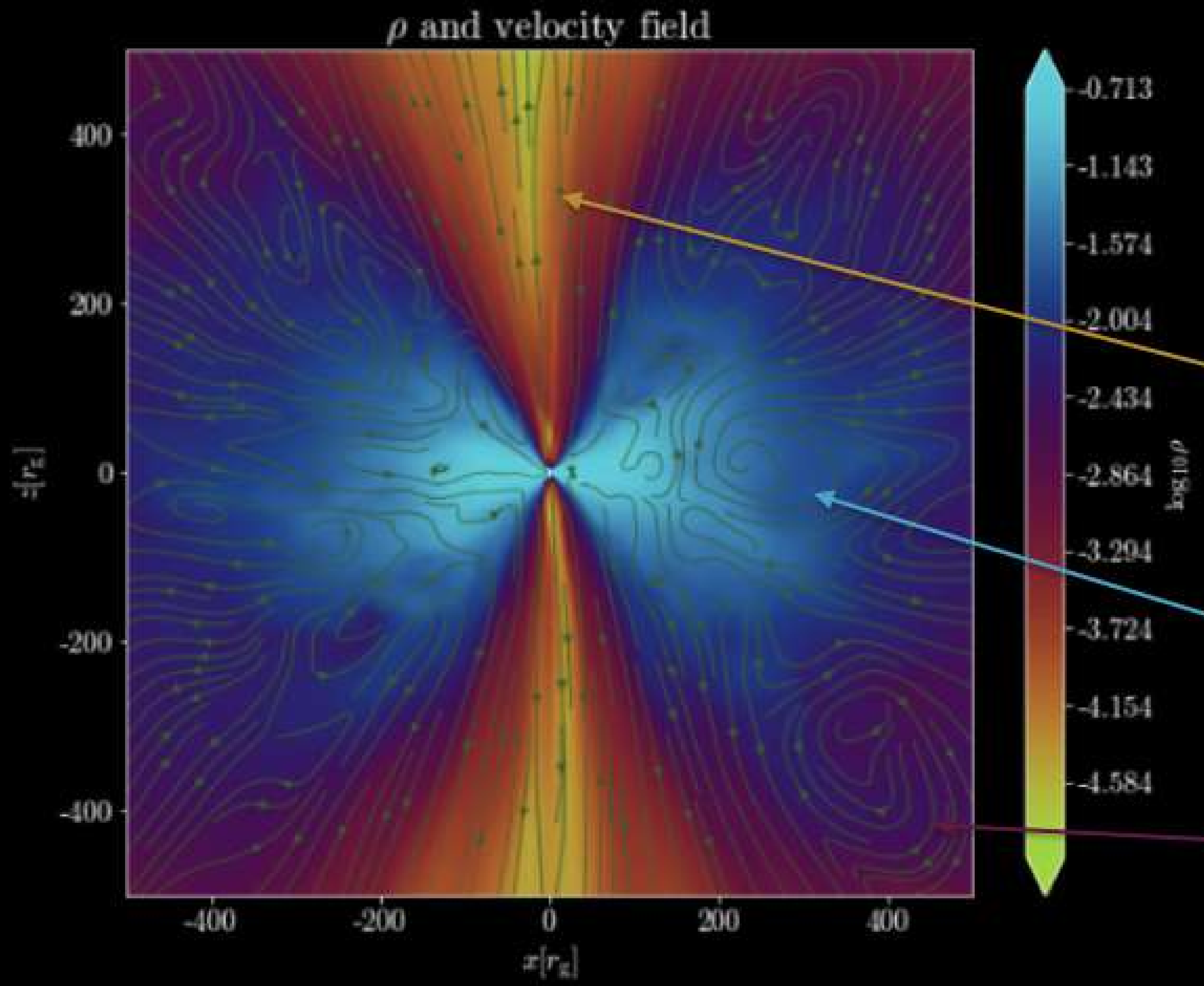
The simulations solve fluid equations under the influence of a rotating black hole (Kerr metric)

Spins **0 and 0.9375**

MAGNETIZED DISC

The disc magnetization is represented as the ratio between the gas pressure and magnetic pressure

$$\beta = \frac{P_{gas}}{P_{mag}}$$



$r_g = 5 \times 10^{-6}$ ($M_{BH}/10^8$ M_{Sun}) pc

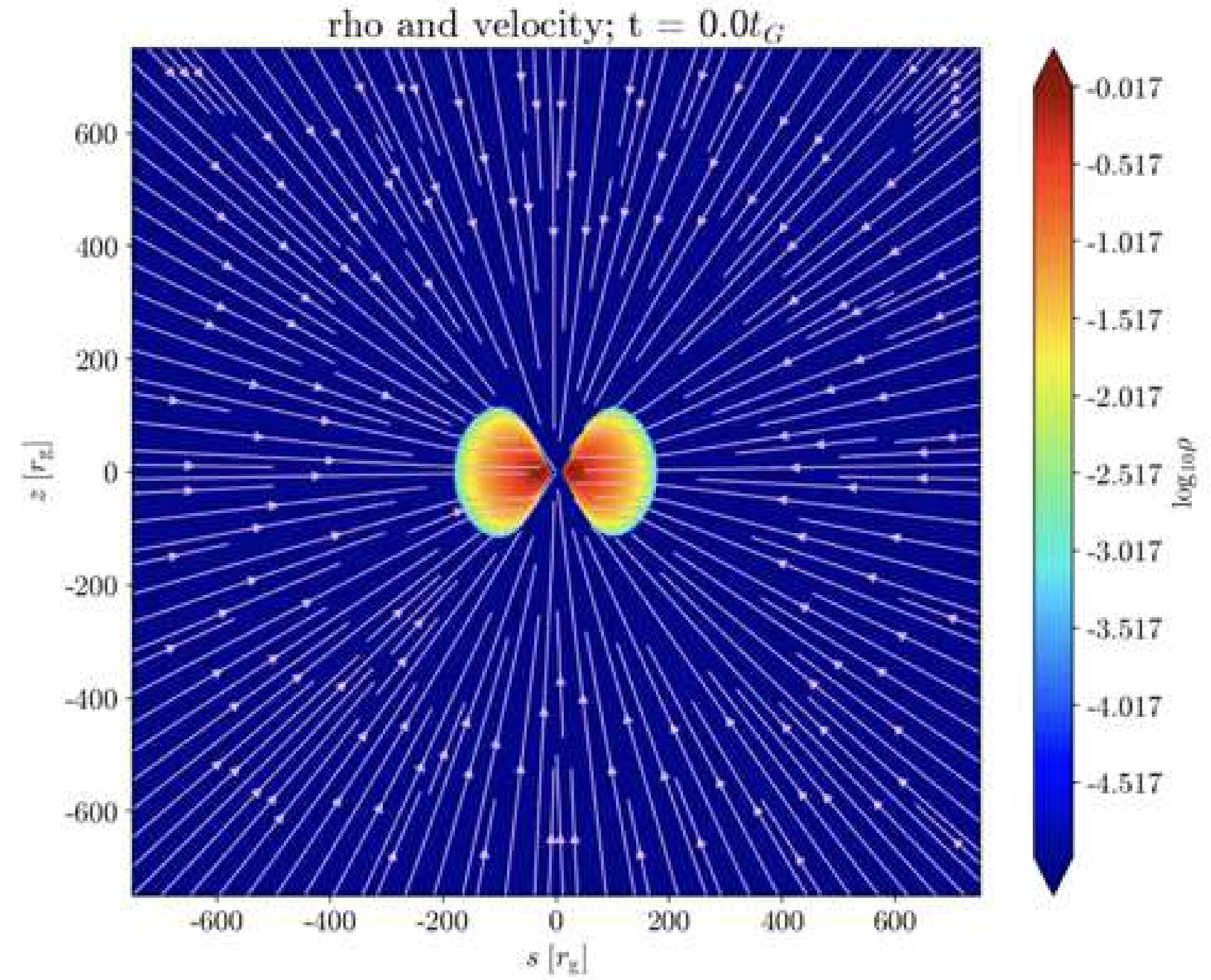
Boxsize: 10000 r_g
Resolution ~ 0.1 r_g (near BH)
Running time ~ 50000 r_g/c
~285 ($M_{BH}/10^8$ Sun) days

Jet
$v_r > 10000$km/s

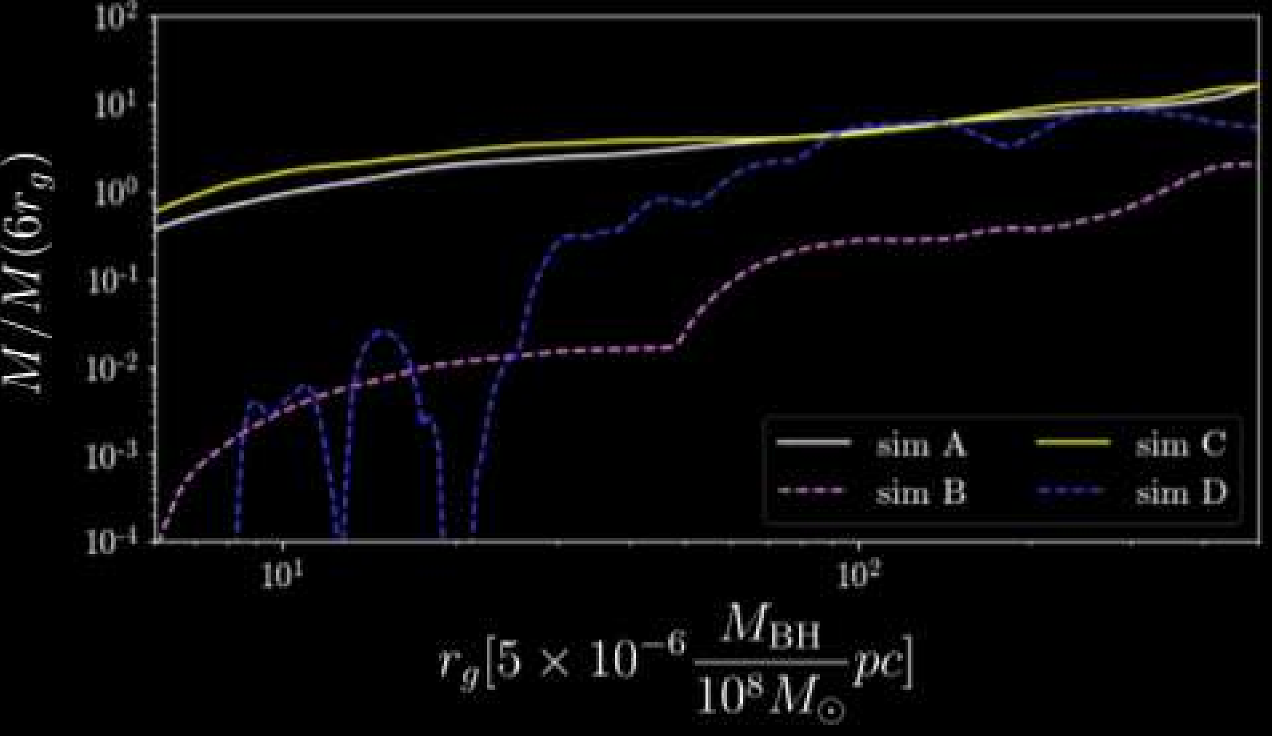
Accretion Disc

Hot Winds
(Magnetically driven)
$v_r \sim 500$km/s

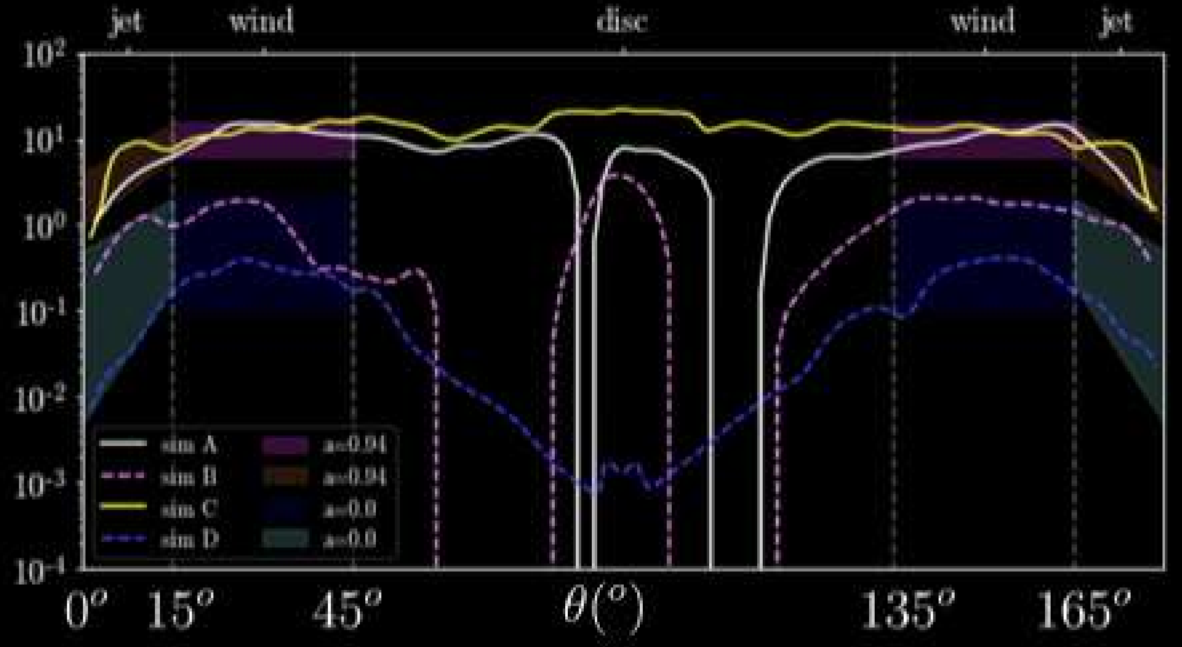
GRMHD simulations – Results



Results: Mass outflow rate



At $r = 500r_g$

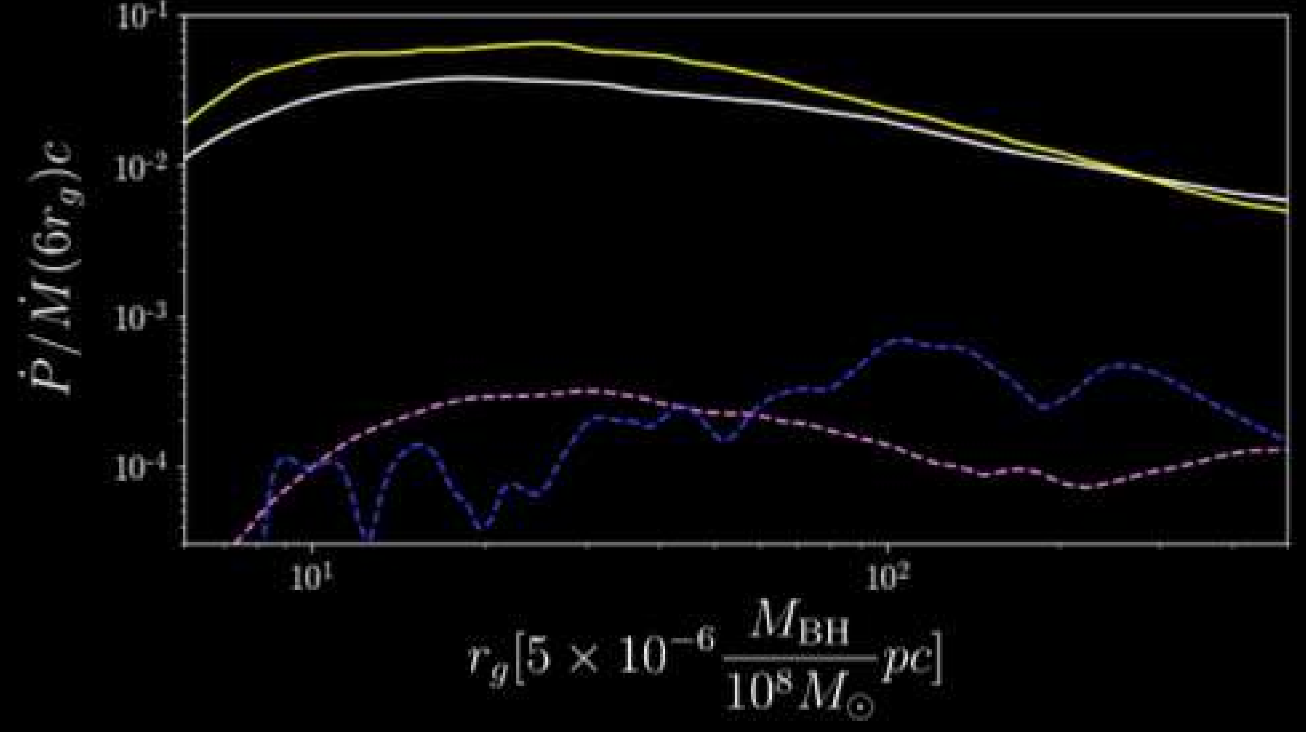


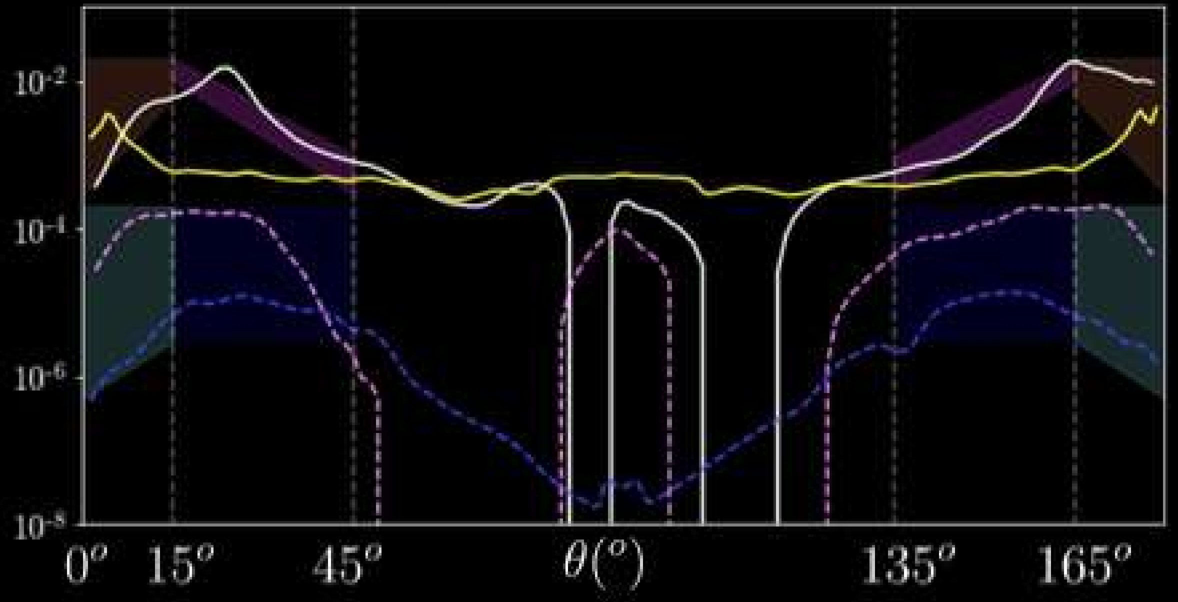
- The hot wind carries away more mass than the jet
- Mass outflow rate increases with radius

Sim ID	a	β	A_ϕ
A	0.9375	20	$A_\phi \propto \rho R^3 \sin^3\theta$
B	0.0	20	$A_\phi \propto \rho R^3 \sin^3\theta$
C	0.9375	20	$A_\phi \propto \rho^2 R^5$
D	0.0	20	$A_\phi \propto \rho$

Results: Momentum outflow rate

At $r = 500r_g$

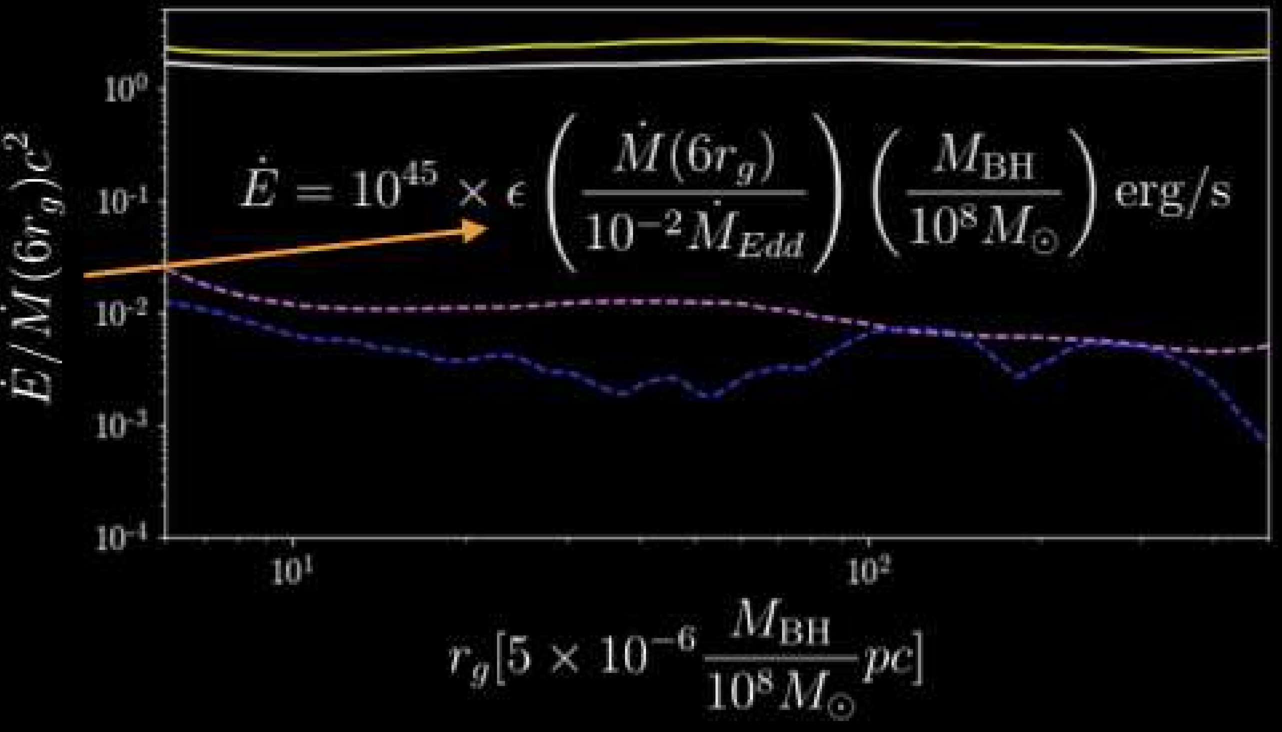




- **Strong influence of spin**
- **Momentum outflow rate decreases with radius**

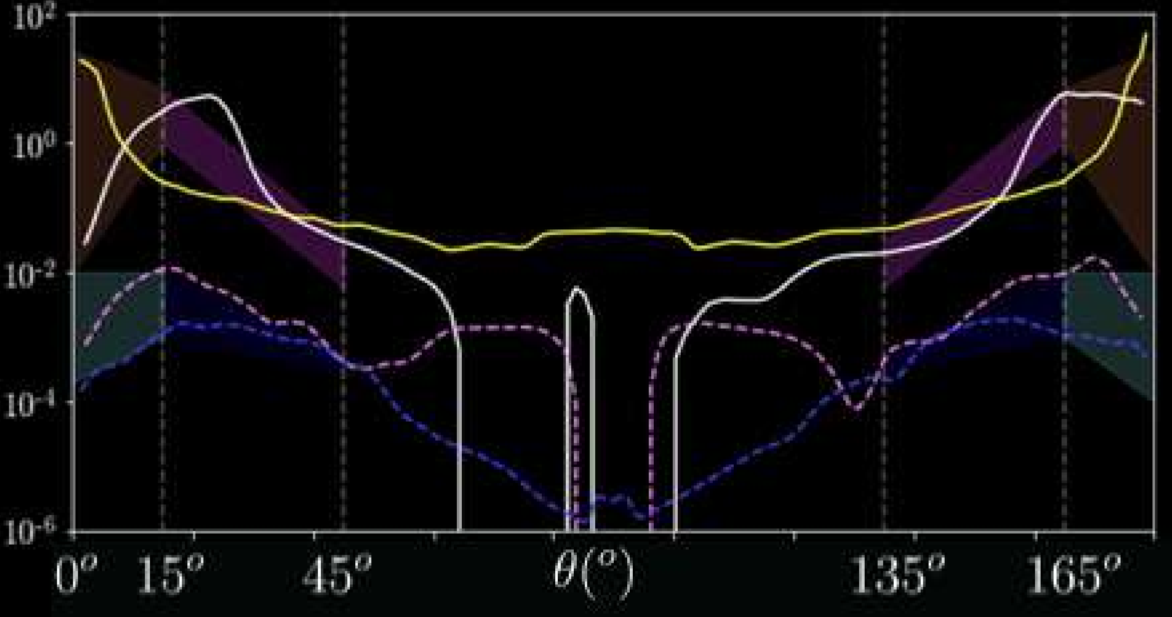
Sim ID	a	β	A_ϕ
A	0.9375	20	$A_\phi \propto \rho R^3 \sin^3\theta$
B	0.0	20	$A_\phi \propto \rho R^3 \sin^3\theta$
C	0.9375	20	$A_\phi \propto \rho^2 R^5$
D	0.0	20	$A_\phi \propto \rho$

Results: Energy outflow rate



$$\dot{E} = 10^{45} \times \epsilon \left(\frac{\dot{M}(6r_g)}{10^{-2}\dot{M}_{Edd}}\right)\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right) \text{erg/s}$$

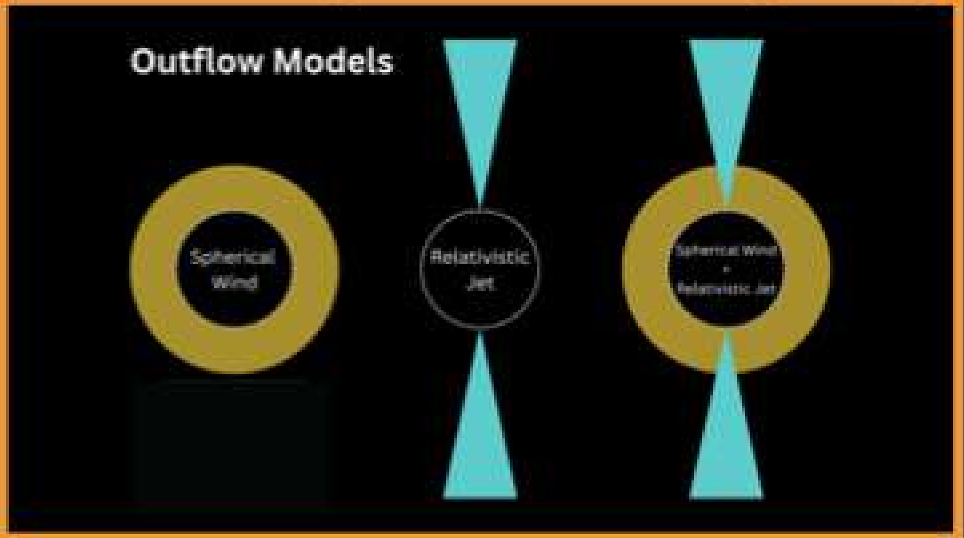
At r = 500r_g



- Jet efficiency ~200%
- Wind efficiency 0.1-2% (a=0) and 2-8% (a=0.9375)
- Energy outflow rate is almost constant with radius

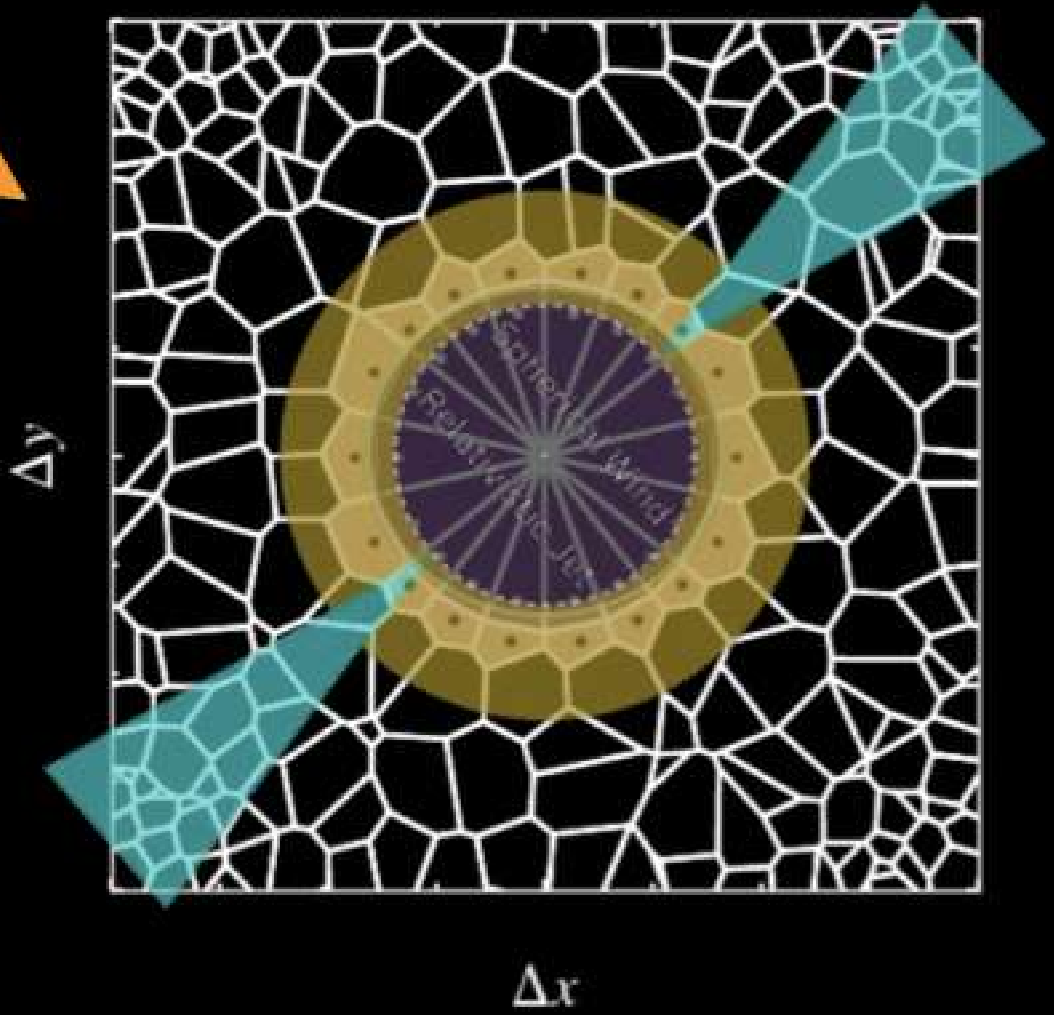
Sim ID	a	β	A_ϕ
A	0.9375	20	$A_\phi \propto \rho R^3 \sin^3\theta$
B	0.0	20	$A_\phi \propto \rho R^3 \sin^3\theta$
C	0.9375	20	$A_\phi \propto \rho^2 R^5$
D	0.0	20	$A_\phi \propto \rho$

Link these profiles into a galaxy



AREPO + BOLA

(Springel 10) (Costa+ 20)



BOLA is a spheric boundary surface where we can inject the fluxes (outflow profiles) into a simulation

Details: *https://www.mas.ncl.ac.uk/tiago.costa/BOLA_documentation.pdf*

Link these profiles into a galaxy

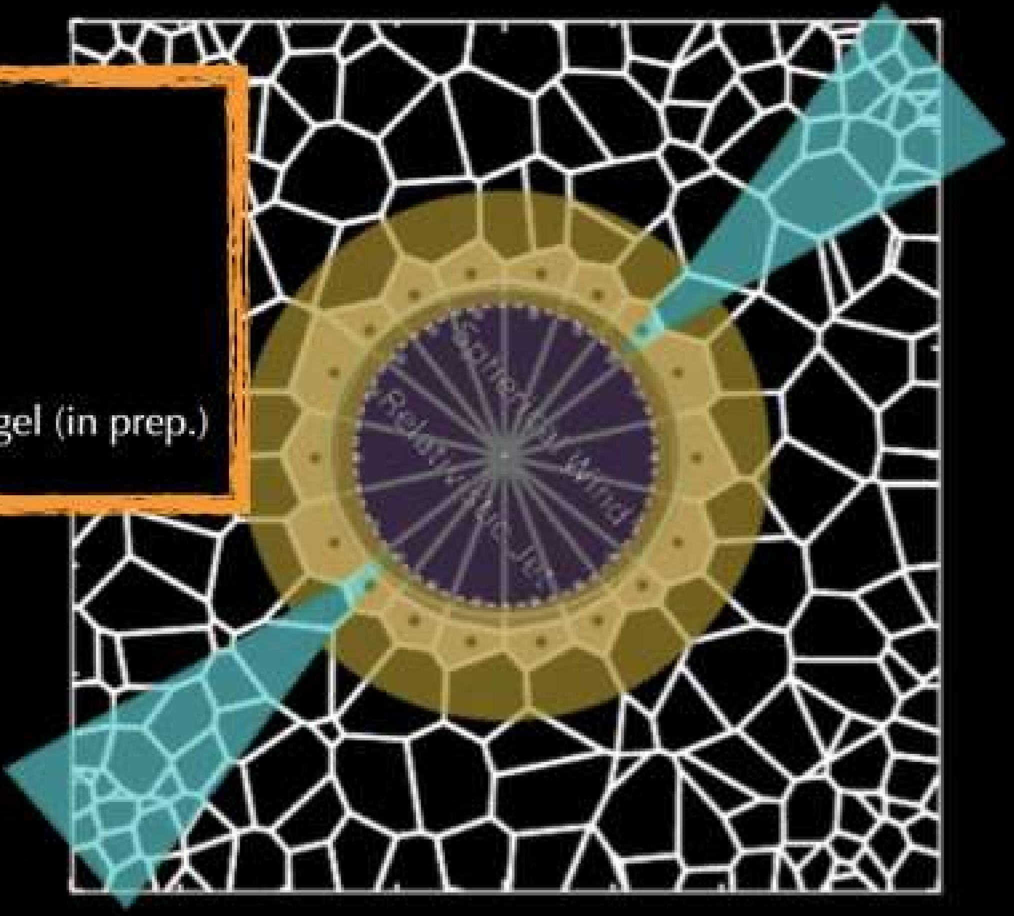
BOLA

Add a boundary surface & model a wind/jet through appropriate boundary conditions.

Winds: Costa, Pakmor & Springel (2020), **Accretion:** Costa, Pakmor & Springel (in prep.)
https://www.mas.ncl.ac.uk/tiago.costa/BOLA_documentation.pdf

AREPO + BOLA

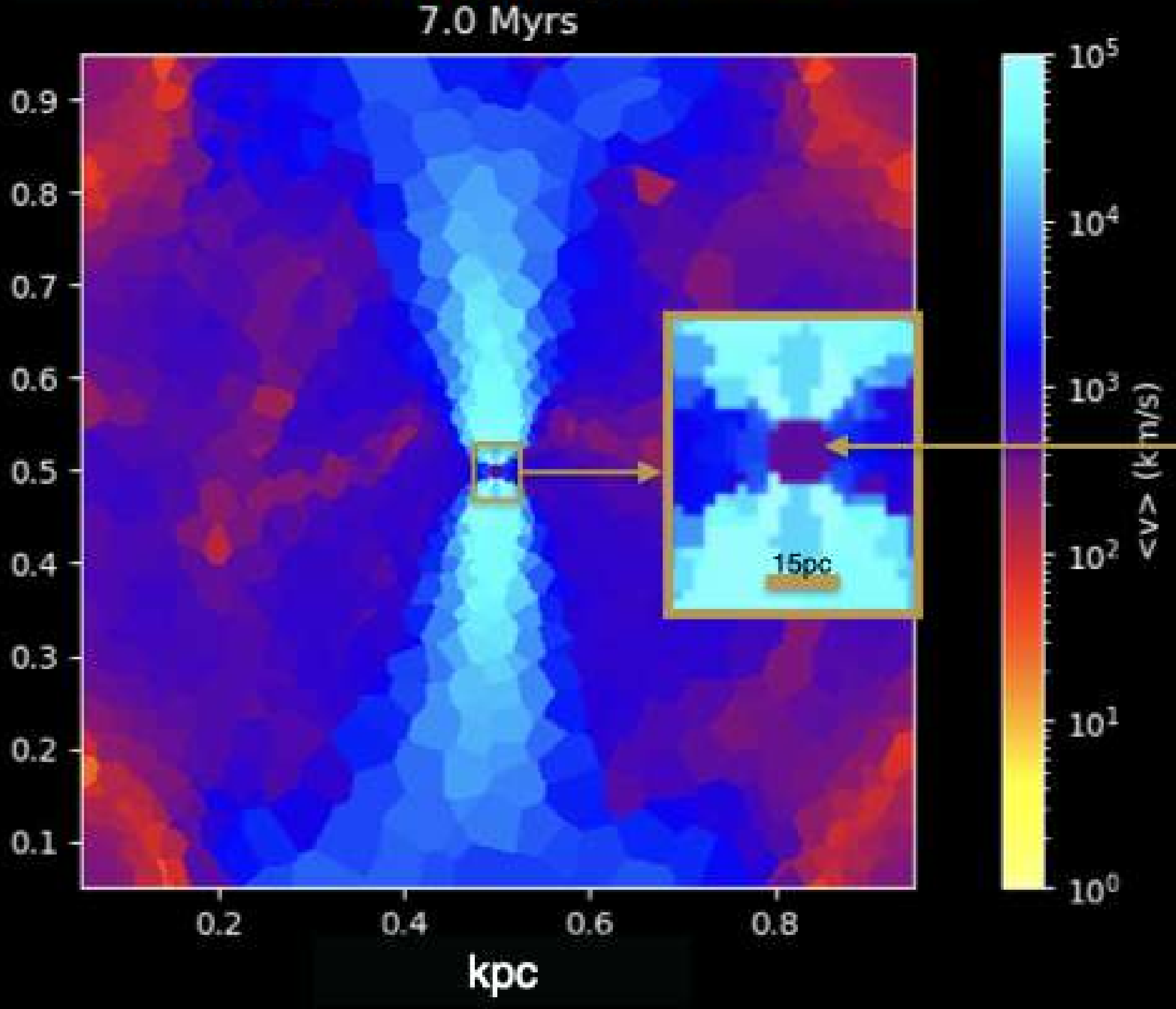
(Springel 10) (Costa+ 20)



BOLA is a spheric boundary surface where we can inject the fluxes (outflow profiles) into a simulation

Details: https://www.mas.ncl.ac.uk/tiago.costa/BOLA_documentation.pdf

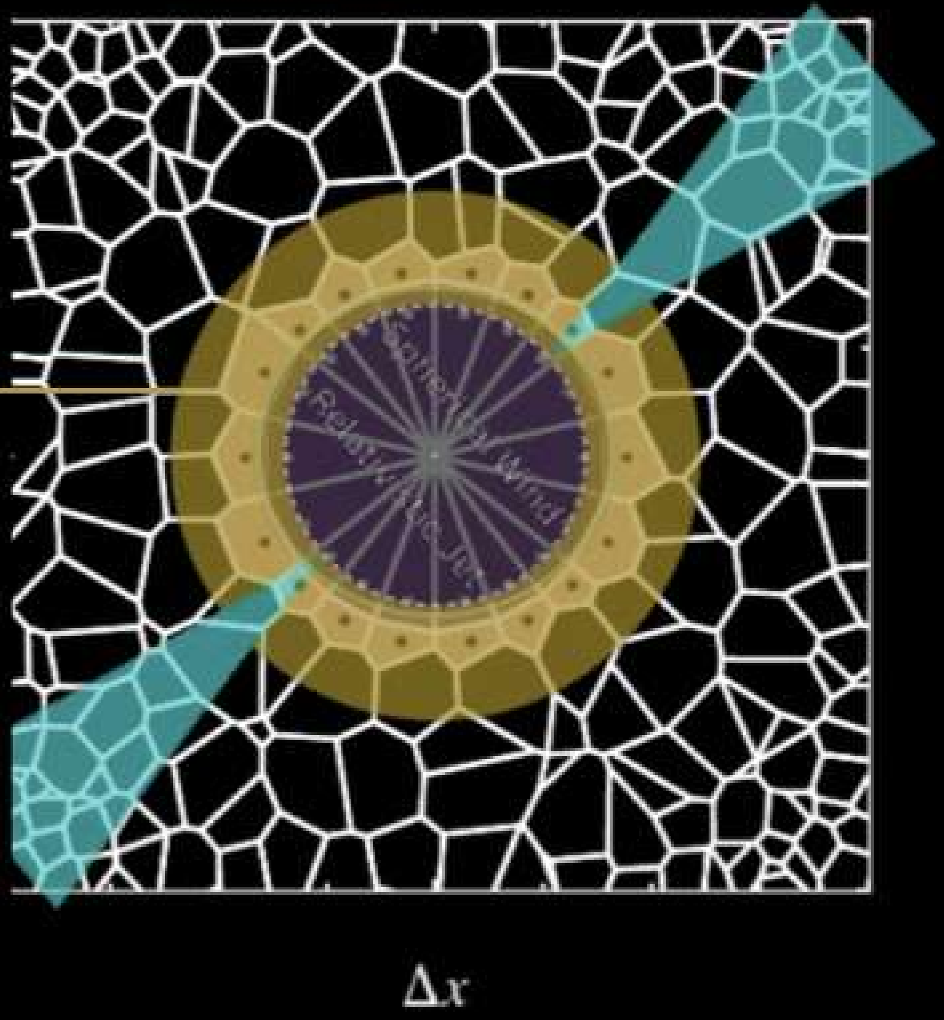
Very preliminary results



AREPO + BOLA

(Springel 10, Weinberger+ 19)

(Costa+ 20)



Take-Home Message

- AGN feedback spans over 10 orders of magnitude, making it impossible to capture all the scales simultaneously.
- Our GRMHD simulations predicted jets (hot winds) with energetic efficiencies >200% (2-8% for a = 0.9375; 0.1-2% for a = 0).
- From the energetics of GRMHD simulations, we expect that even spinless AGN hot winds could impact the inner kiloparsec of the host galaxy; however, a more detailed study is necessary.
- Our goal is to create a more physically motivated model for AGN feedback from GRMHD simulations, following the measured profiles.

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