Title: Bridging Scales in Black Hole Accretion and Feedback: Magnetized Bondi Accretion in 3D GRMHD

Speakers: Hyerin Cho

Series: Strong Gravity

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Abstract: Fueling and feedback couple supermassive black holes (SMBHs) to their host galaxies across many orders of magnitude in spatial and temporal scales, making this problem notoriously challenging to simulate. We use a multi-zone computational method based on the general relativistic magneto-hydrodynamic (GRMHD) code KHARMA that allows us to span 7 orders of magnitude in spatial scale, to simulate accretion onto a non-spinning SMBH from an external medium with Bondi radius ~ 2e5 G*M/c^2, where M is the SMBH mass. For the classic idealized Bondi problem, spherical gas accretion without magnetic fields, our simulation results agree very well with the general relativistic analytic solution. Meanwhile, when the accreting gas is magnetized, the SMBH magnetosphere becomes saturated with a strong magnetic field. The density profile varies as ~ r^(-1) rather than r^(-3/2) and the accretion rate is consequently suppressed by over 2 orders of magnitude below the Bondi rate. We find continuous energy feedback from the accretion flow to the external medium at a level of 1% of the accreted rest mass energy (~ 0.01 Mdot * c^2). Energy transport across these widely disparate scales occurs via turbulent convection triggered by magnetic field reconnection near the SMBH. Thus, strong magnetic fields that accumulate on horizon scales transform the flow dynamics far from the SMBH and naturally explain observed extremely low accretion rates compared to the Bondi rate, as well as at least part of the energy feedback.

Zoom link

Bridging Scales in Black Hole Accretion and Feedback

Magnetized Bondi Accretion in 3D GRMHD

(Published in ApJL, arXiv:2310.19135)

Hyerin Cho (04/25/24)

With Ben Prather, Ramesh Narayan, Priya Natarajan, Kung-Yi Su, Angelo Ricarte, Koushik Chatterjee

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

BLACK HOLE INITIATIVE
HARVARD UNIVERSITY

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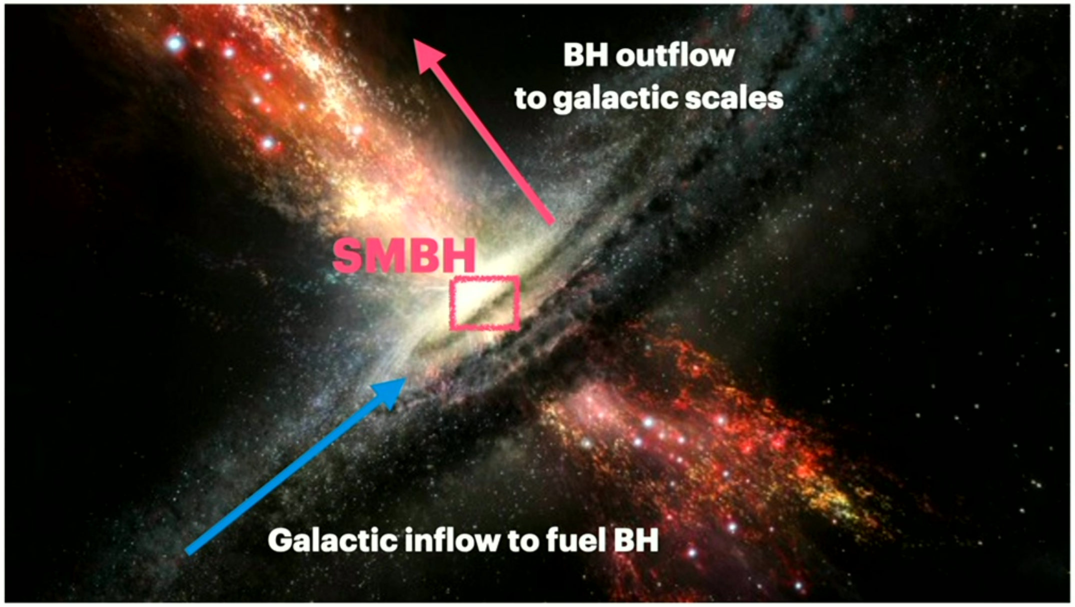
Letter-Background

BH - galaxy coevolution

Two-way communication between different scales required to explain coevolution



Inflow (accretion)

large scale information transferred to black hole

outflow (feedback)

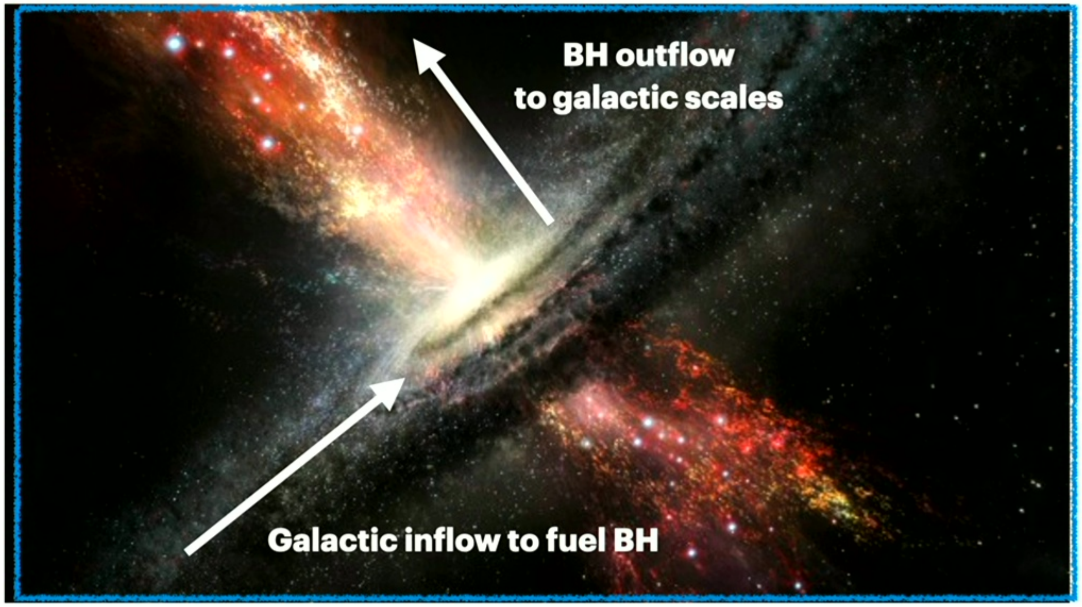
black hole influences the large galactic scales.

Letter-Background

BH - galaxy simulations

+ Complicated galactic scale physics

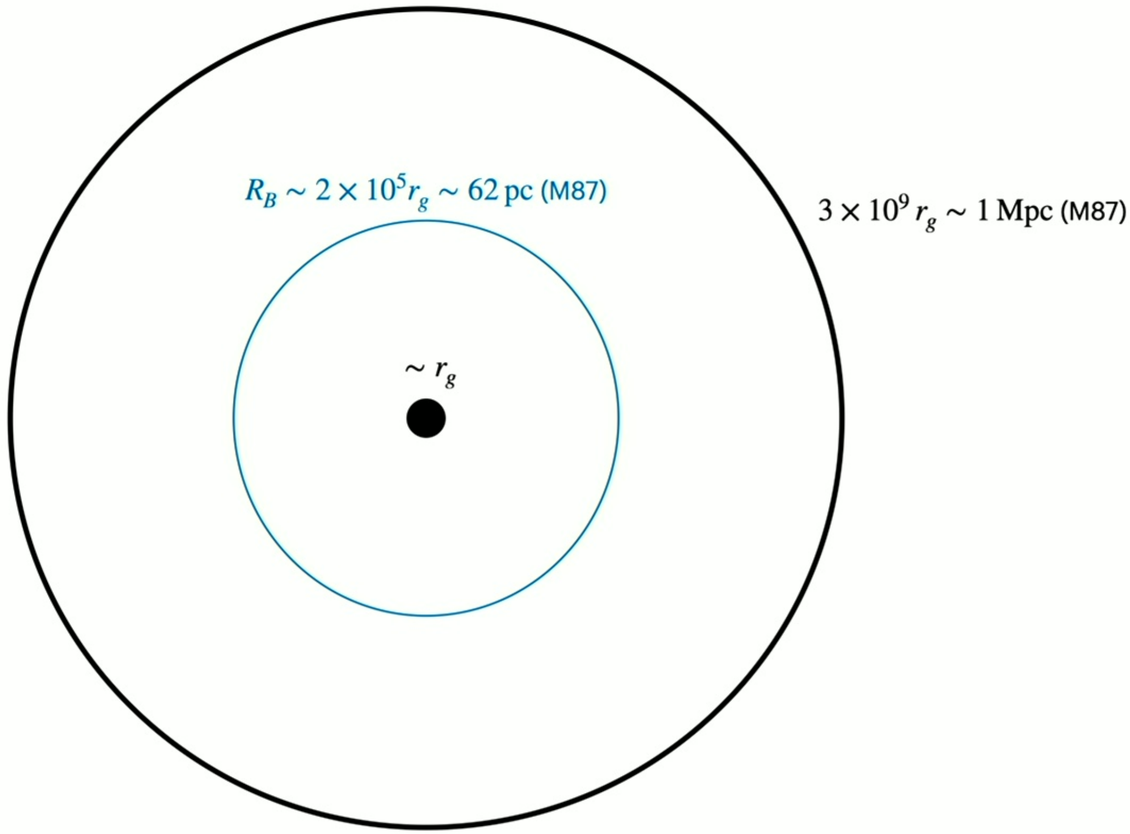
- subgrid prescriptions for BH



Galaxy simulations
With Newtonian (M)HD

Best resolution $\gtrsim 10\,\mathrm{pc}$
($3 \times 10^4\, r_g$ for M87)

Why is it so hard to simulate BH-galaxy self-consistently?



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Letter-Background

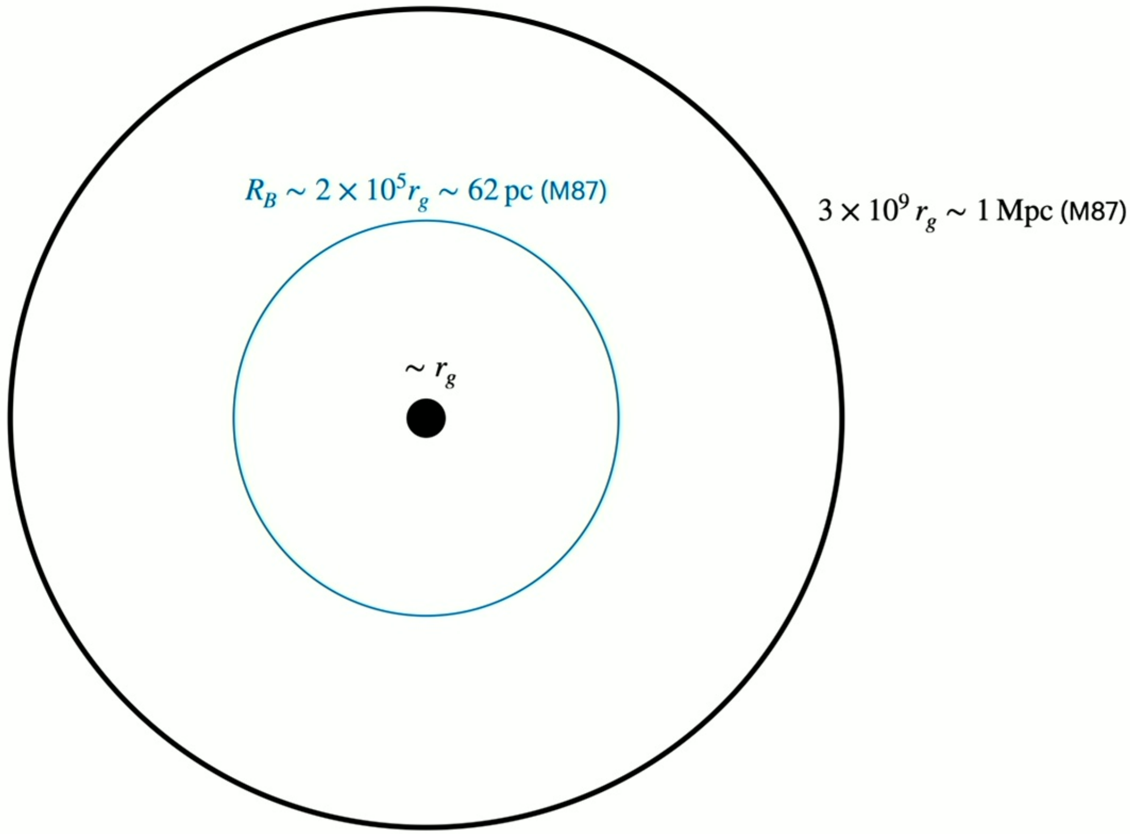
Why is it so hard to simulate BH-galaxy self-consistently?

Δt determined by smallest lengthscale (Courant)

$t_{\rm tot}$ determined by the largest lengthscale

Simulation (128^3, fmks) converging up to $R_{\rm out}$ will

take $\geq 15 \left(\frac{R_{\rm out}}{R_B}\right)$ yrs



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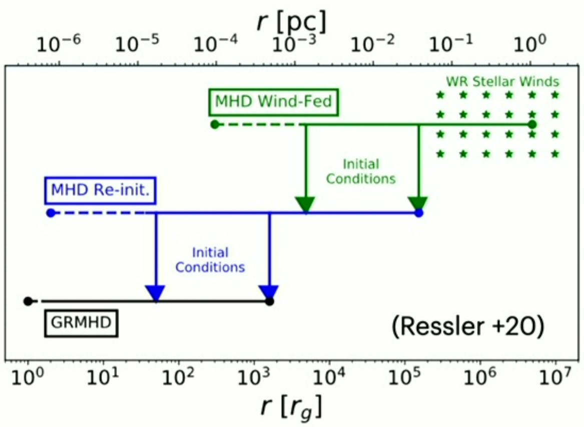
Letter-Background

Previous attempts

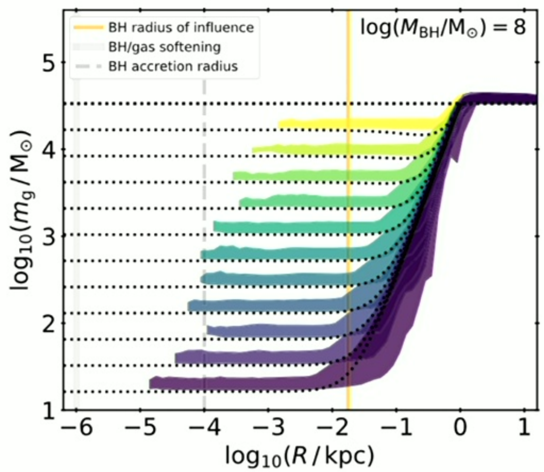
1. Re-simulation of smaller scales



Hopkins +10
Ressler +20
Guo +23

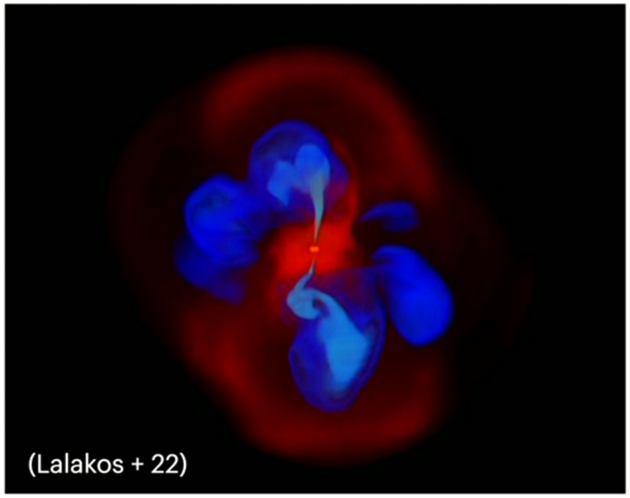
2. Lagrangian hyper-refinement method

(Anglés-Alcázar +21)



Anglés-Alcázar +21
Hopkins +23

3. Extended simulation region



Lalakos +22
Kaaz +23

Letter-Background

Previous attempts

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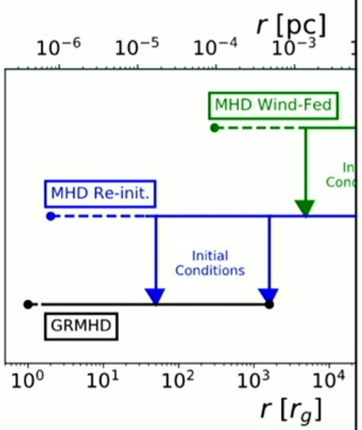
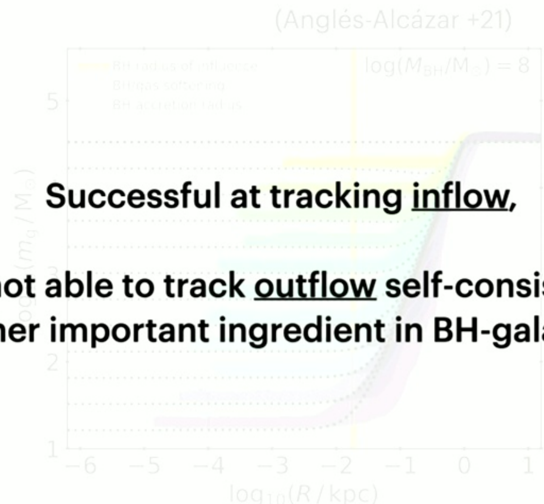
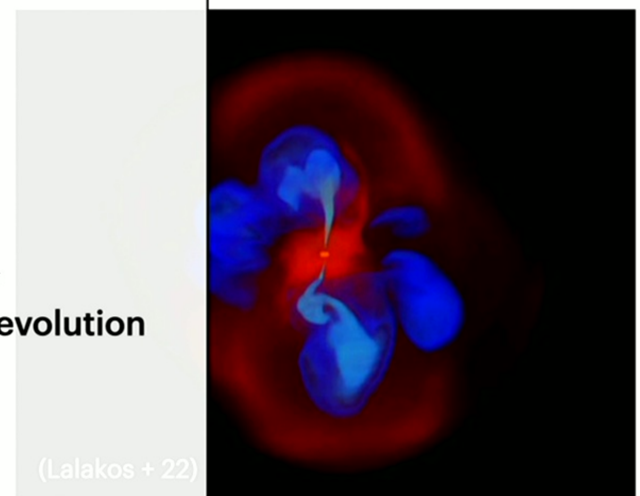






Successful at tracking inflow,

but not able to track outflow self-consistently
which is another important ingredient in BH-galaxy coevolution

Hopkins +10
Ressler +20
Guo +23

Anglés-Alcázar +21
Hopkins +23

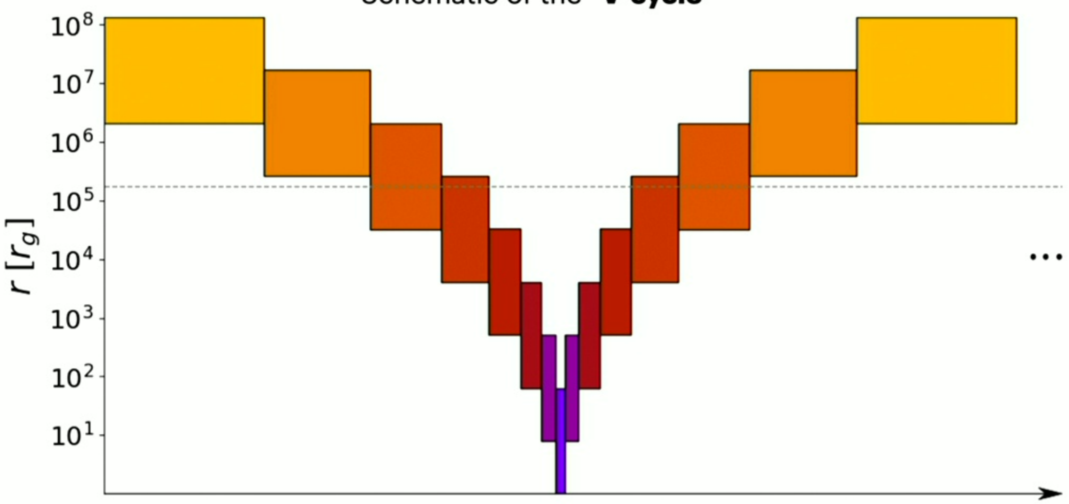
Lalakos +22
Kaaz +23

"Multizone" approach for hot accretion flow

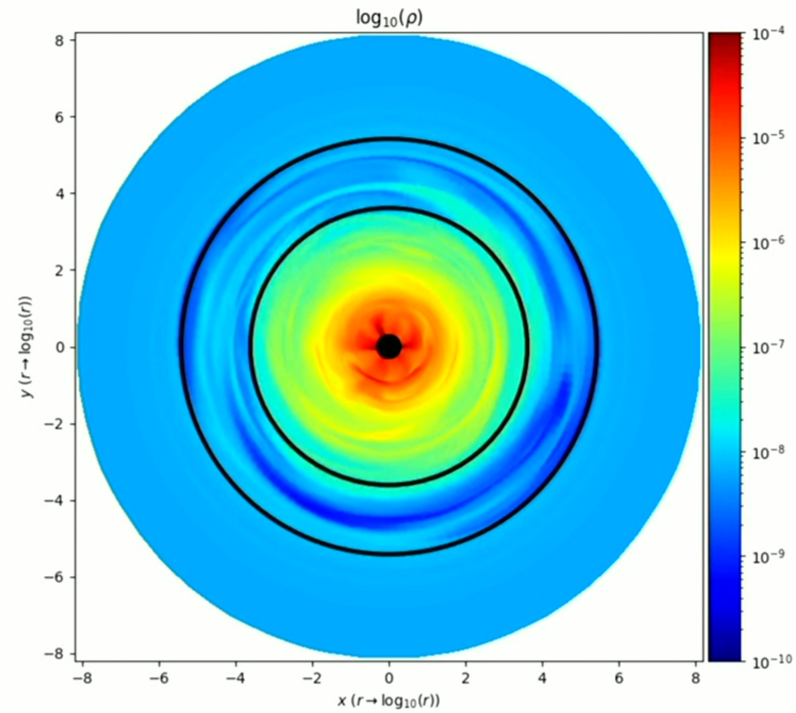
(or Low Eddington, radiative inefficient flow, LLAGN, M87-like ....)

KHARMA: grid based GPU-enabled version of the iharm3d GRMHD code (Prather+ 21)

Schematic of the "**V-cycle**"



(Relative run durations not to scale)



Radii in log(r) scale

Boundary condition:

ρ, u, u^μ, b^μ fixed at the boundaries

$\gtrsim \times 10^5$ speedup in wall time

(128^3 HD run)

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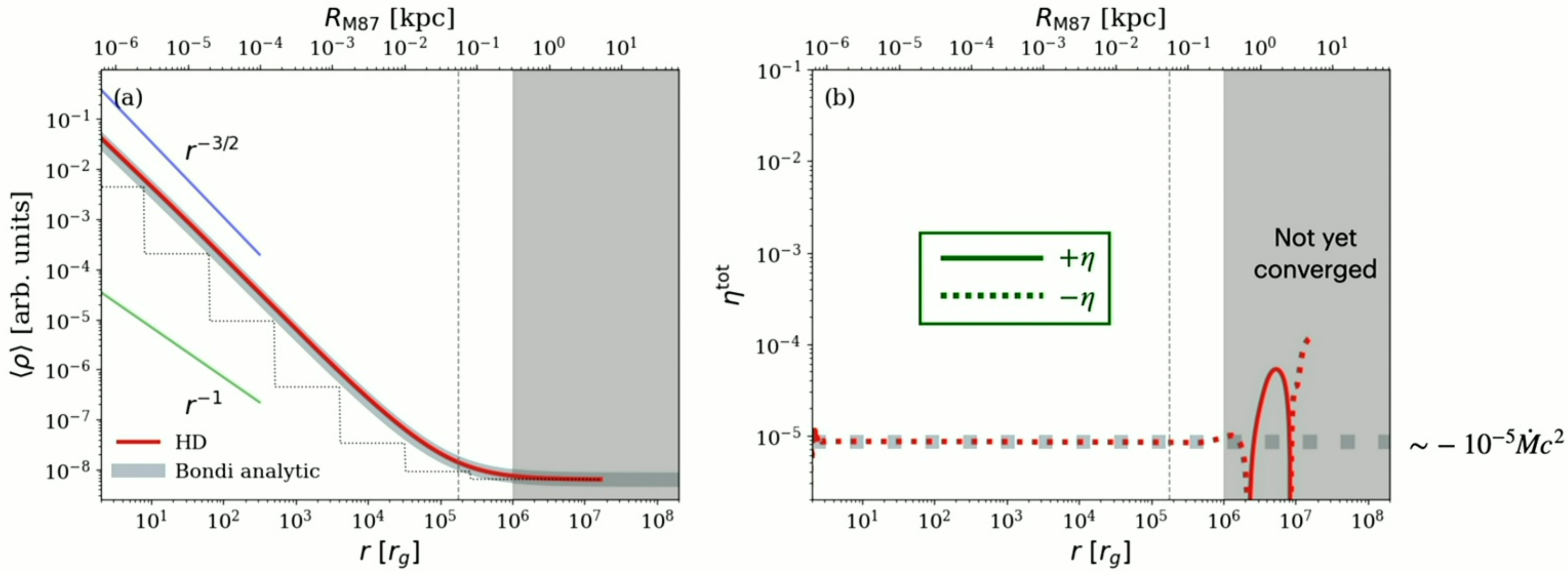
Simple Bondi HD

Schwarzschild BH ($a_* = 0$)
No rotation of gas $\Omega = 0$
Initialized with piecewise constant density

The feedback efficiency
$\eta = \dot{E}_{\rm net}/(\dot{M}c^2)$



$\rho, T, \dot{M}$ all consistent with
Bondi analytic

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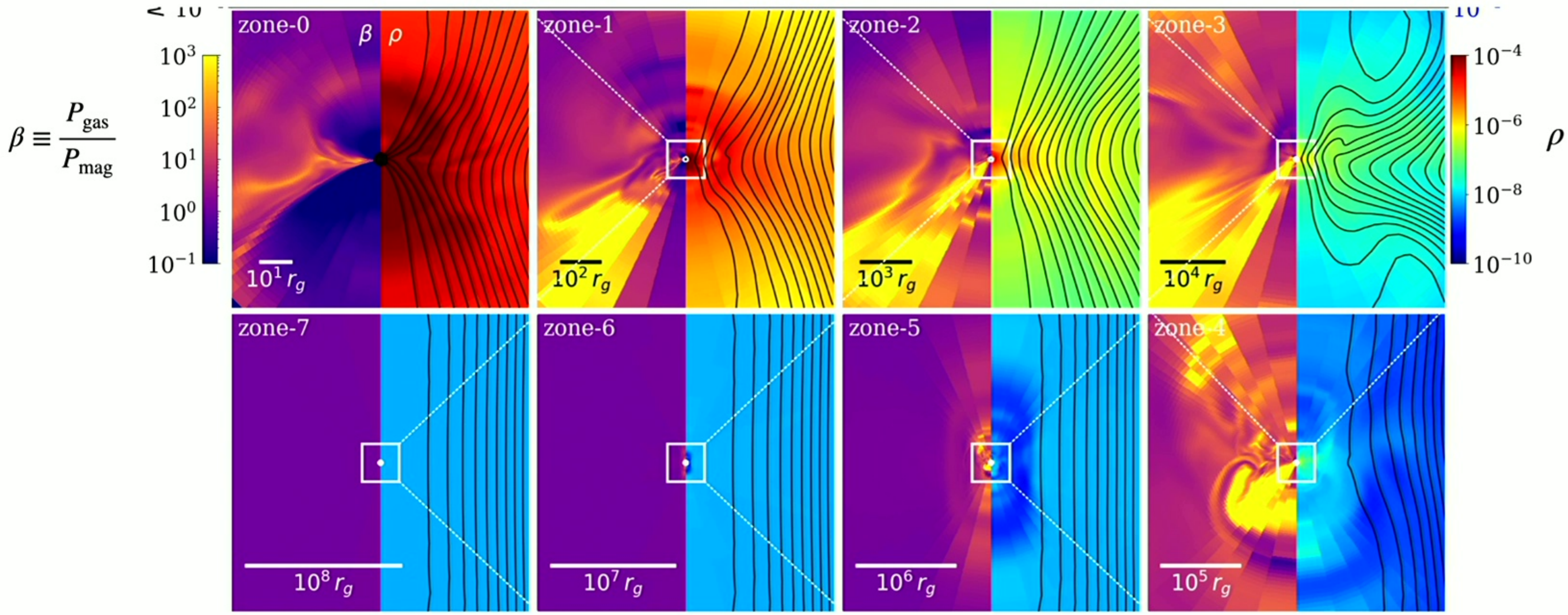
MAD Bondi ($\beta_{\text{init}} \sim 1$): $\dot{M}$ suppressed



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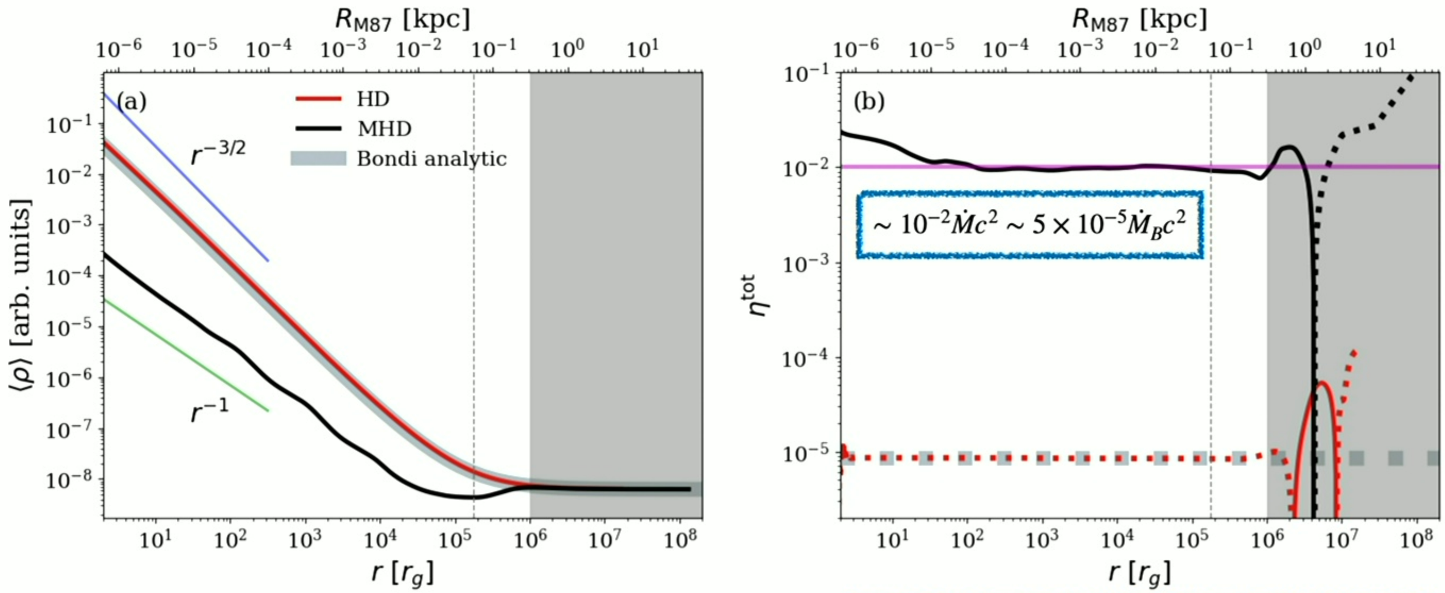
MAD Bondi: feedback

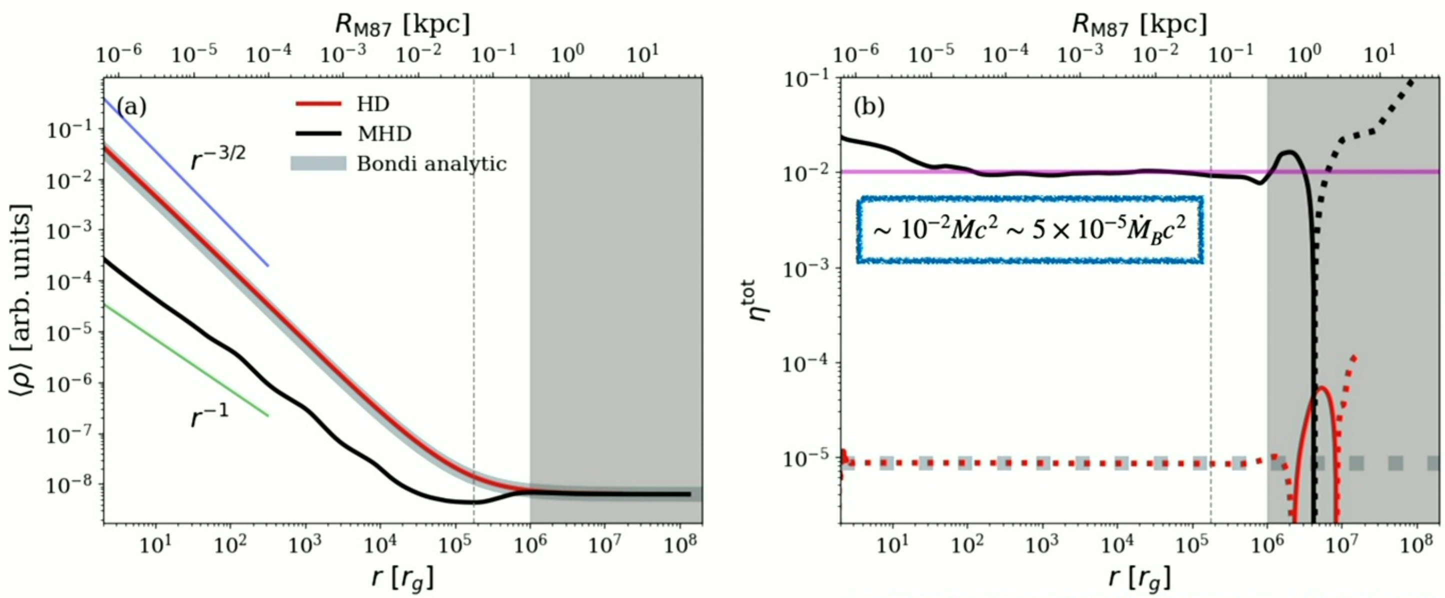


Feedback present even when
$a_* = 0$ and $\Omega = 0$!

-> minimum amount of BH feedback

Letter-Result 2 MHD

MAD Bondi: feedback

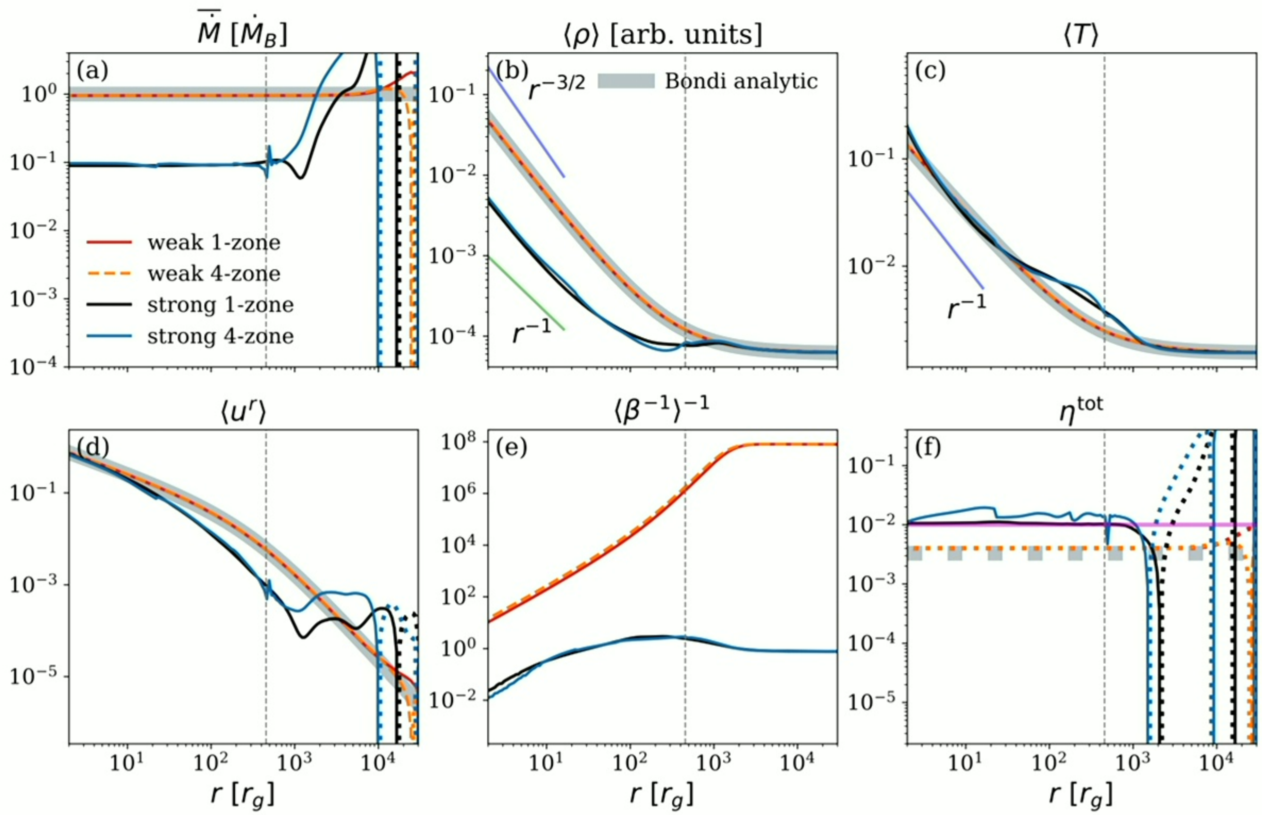


Feedback present even when
$a_* = 0$ and $\Omega = 0$!

-> minimum amount of BH feedback

n=4 small scale test

Multizone's steady state $\dot{M}$, η, and ρ radial scaling are all consistent with 1-zone



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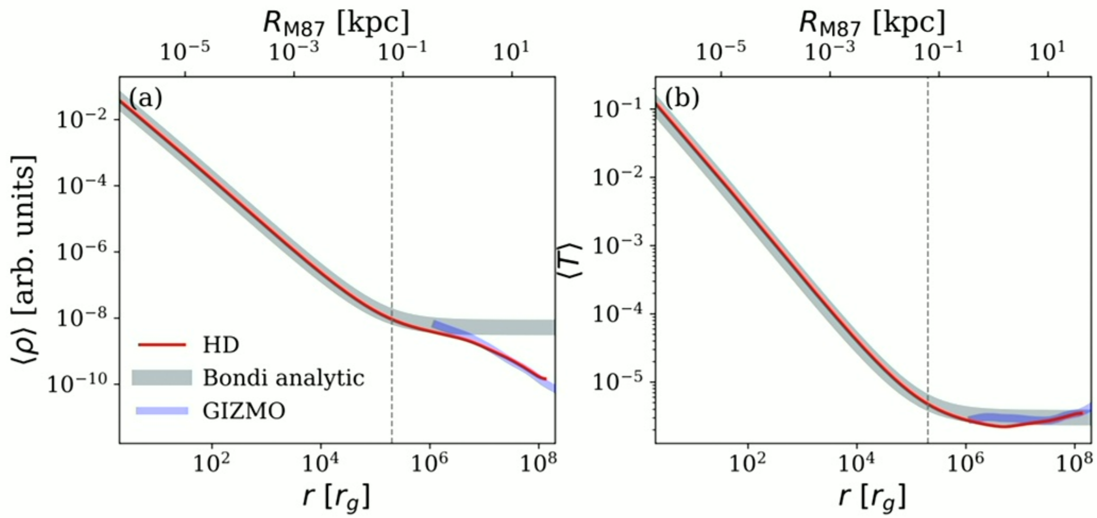
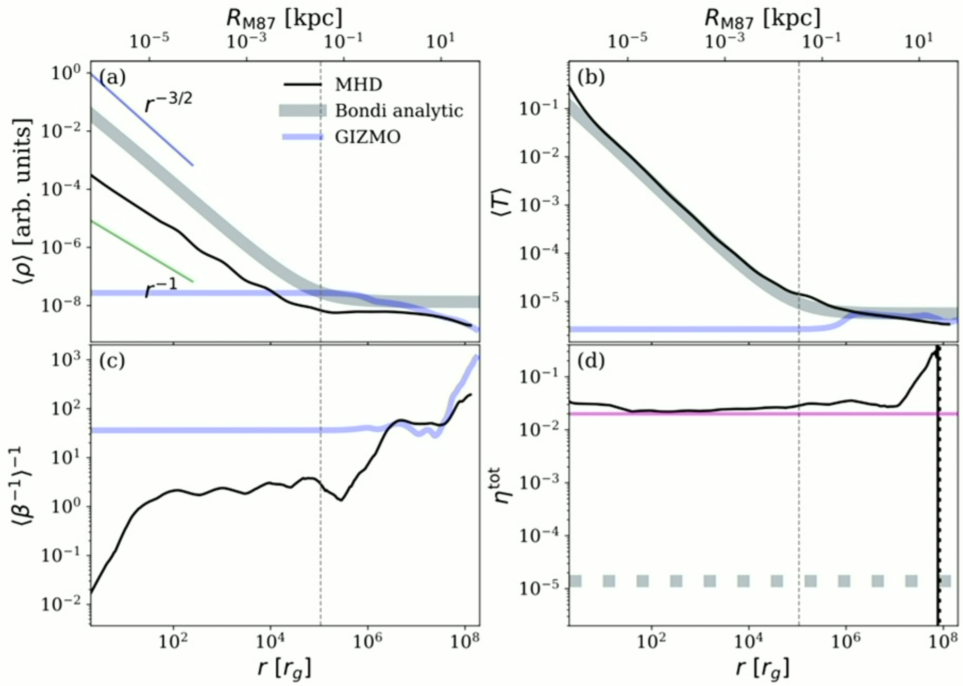
GIZMO with external gravity

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

The external gravitational potential Φ_g -> information on galactic gravitational sources such as DM, stars, and gas



GIZMO with external gravity + B field

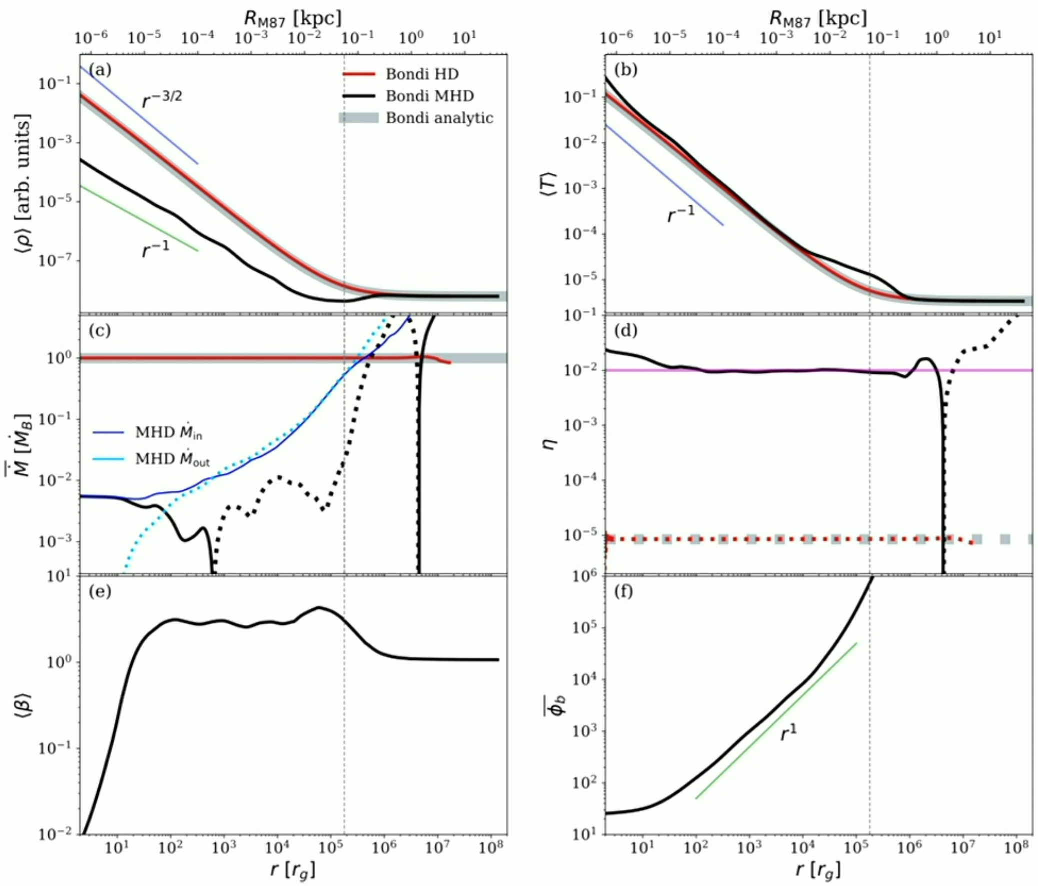


- Rotation (3D velocity from GIZMO)

$$\Omega \sim 0.1\Omega_K$$

- magnetic field from GIZMO

Bondi MHD



$\dot{M} \approx 5 \times 10^{-3} \dot{M}_B$

$\sim 10^{-2}\dot{M}c^2 \sim 5 \times 10^{-5}\dot{M}_B c^2$

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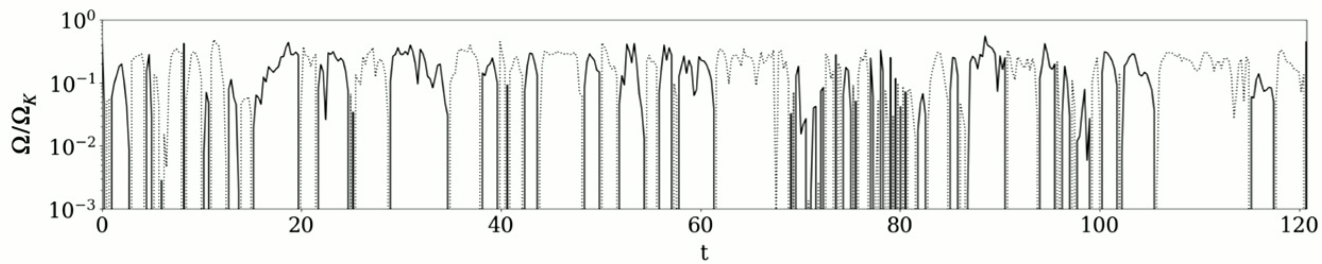
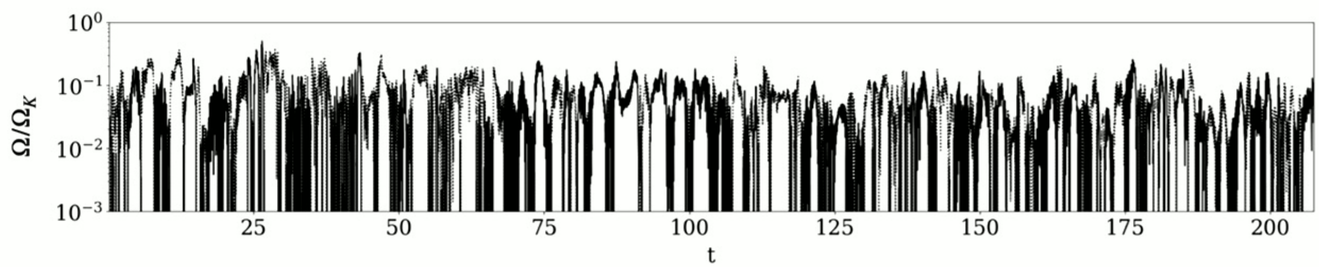
Can multi-zone handle rotation?

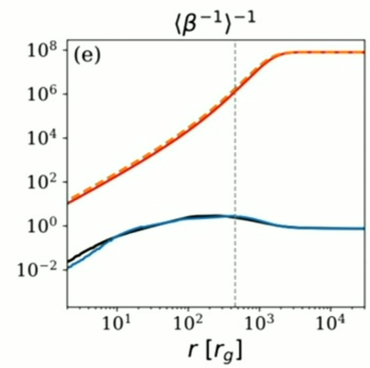
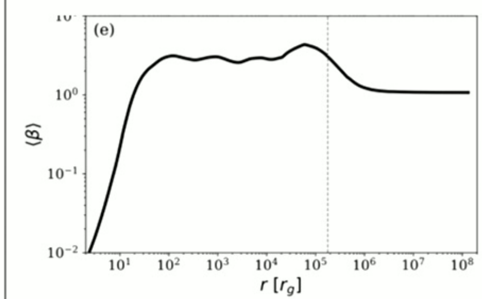
1-zone



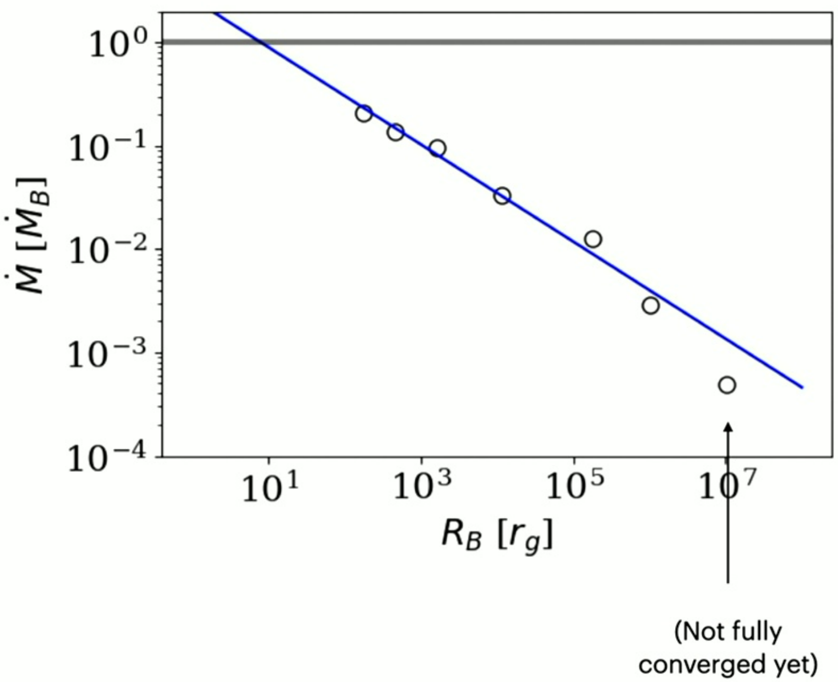
4-zone



Different R_B

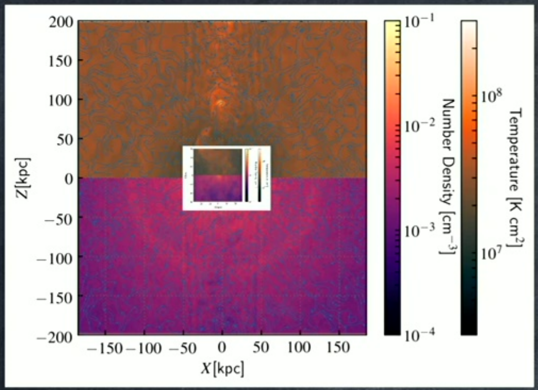
	$R_B \approx 500$	$R_B \approx 2 \times 10^5$
density	$\propto r^{-1}$	$\propto r^{-1}$
Plasma-beta		
Feedback efficiency	$\sim 1\,\%$	$\sim 1\,\%$
Accretion rate		

$\dot{M}$ vs R_B

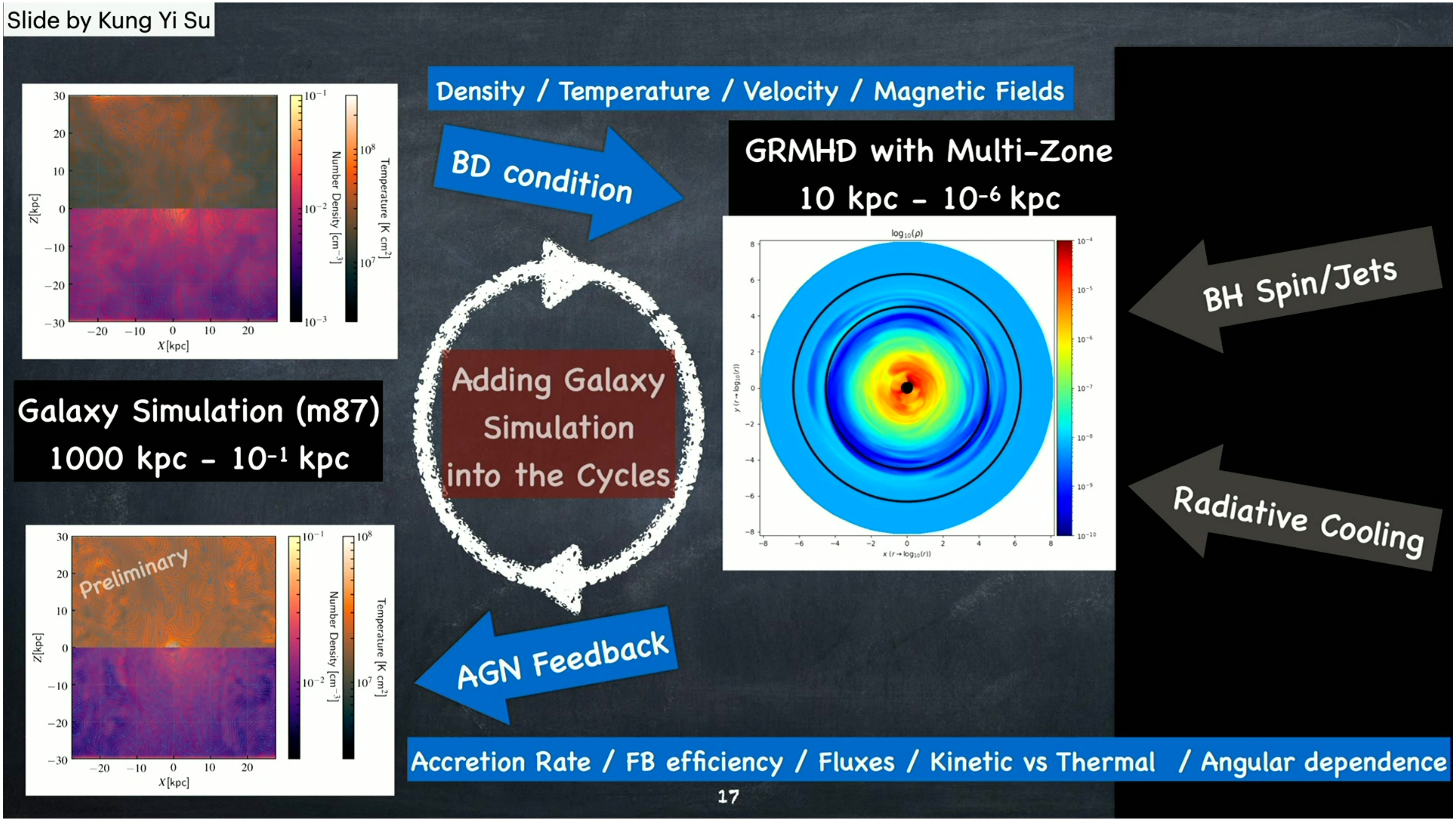


$\dot{M}/\dot{M}_B \approx 2.7\, R_B^{-0.47}$

Slide by Kung Yi Su



Galaxy Simulation (m87)
1000 kpc – 10^{-1} kpc



Slide by Kung Yi Su
Density / Temperature / Velocity / Magnetic Fields
BD condition
GRMHD with Multi-Zone
10 kpc – 10-6 kpc
BH Spin/Jets
Radiative Cooling
Adding Galaxy Simulation into the Cycles
Galaxy Simulation (m87)
1000 kpc – 10-1 kpc
Preliminary
AGN Feedback
Accretion Rate / FB efficiency / Fluxes / Kinetic vs Thermal / Angular dependence
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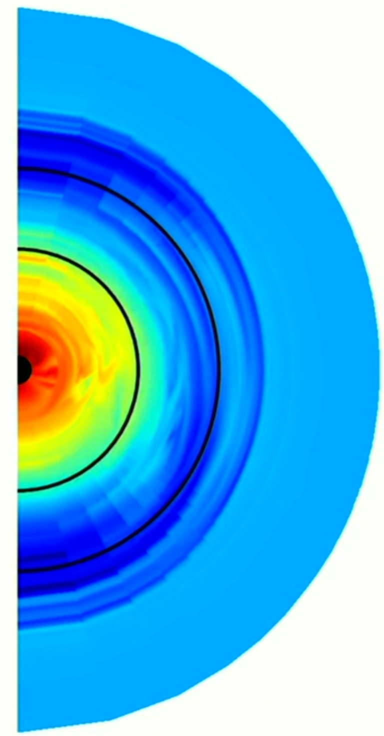
Summary and Future Work

Paper link



Summary and Future Work

Paper link

- Two-way communication of BH - galaxy possible using “multizone” approach
- simple HD Bondi case ($a_* = 0$, $v_\theta = v_\phi = 0$, $R_B = 2 \times 10^5 r_g$)
    - Perfect agreement with the Bondi analytic solutions for $\rho, T, \dot{M}$
    - No feedback, $\sim 10^{-5}\dot{M}c^2$ advected
- Strongly magnetized Bondi case
    - Density $\rho \propto r^{-1}$ and accretion rate suppressed $\dot{M} \approx 5 \times 10^{-3}\dot{M}_B$
    - Feedback $\sim 10^{-2}\dot{M}c^2 \sim 5 \times 10^{-5}\dot{M}_B c^2$ even in the absense of BH spin or gas rotation
- Future work
    - Kerr BH -> stronger feedback (prescription to cosmology simulations)
    - Ultimately, a library of self-consistent BH-galaxy simulations over a wide dynamic range