Inflows and outflows regulating AGN feeding and feedback

Andrea Negri

In collaboration with Marta Volonteri
(Negri & Volonteri, to be submitted)

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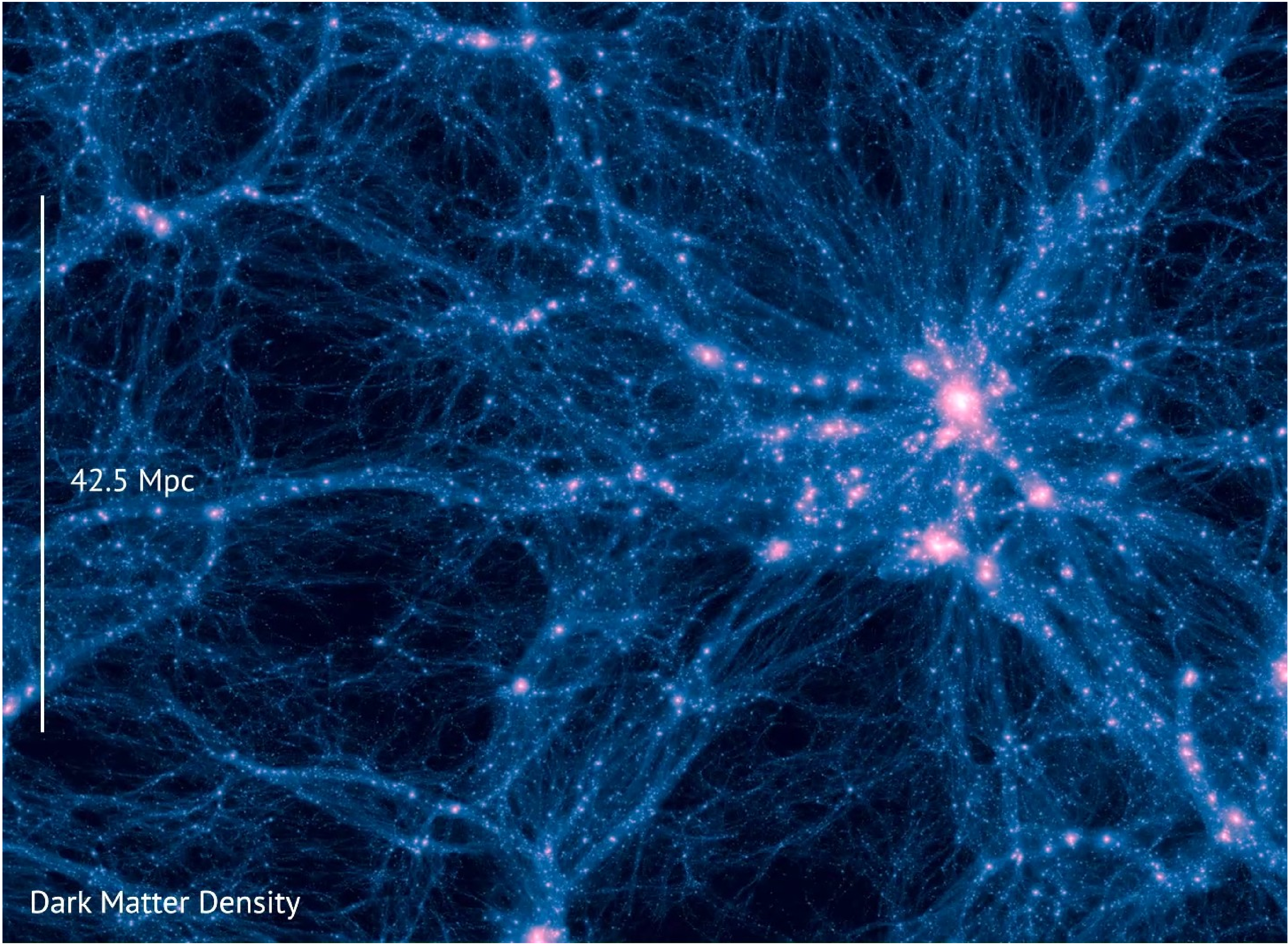
IAP

cnrs advancing the frontiers

Talk outline

- Introduction
- How accretion is implemented in various codes
- Bondi accretion: few details
- The project
- Results


~last decade: hydro cosmological simulations
from Springel+05
Baryons interact with dark matter and stars
in the large scale structure
Projection of the
Illustris simulation
Andrea Negri – AGN feeding and feedback


42.5 Mpc
Dark Matter Density

Scale-lengths

Galaxies

mass: 10^{9}-10^{12} Msun

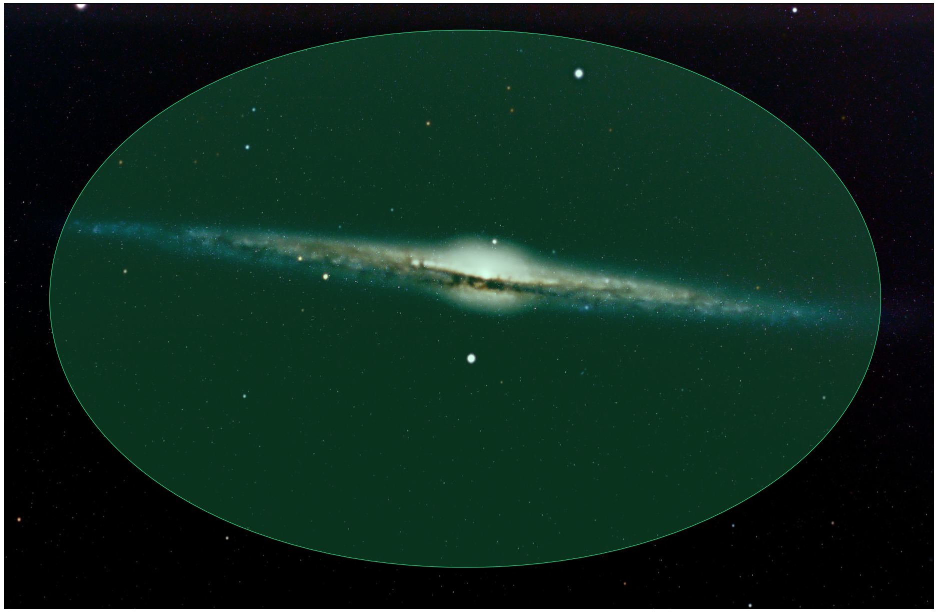
- $R_{halo} \sim G\, M_{halo}/\sigma^2$ Mpc
- $R_{bulge} \sim G\, M_{bulge}/\sigma^2$ kpc

Massive Black holes

mass: 10^{5} - 10^{9} Msun

- $R_{bondi} \sim G\, M_{bh}/c_s^2$ pc
- $R_{sch} \sim G\, M_{bh}/c^2$ μpc

Scale-lengths



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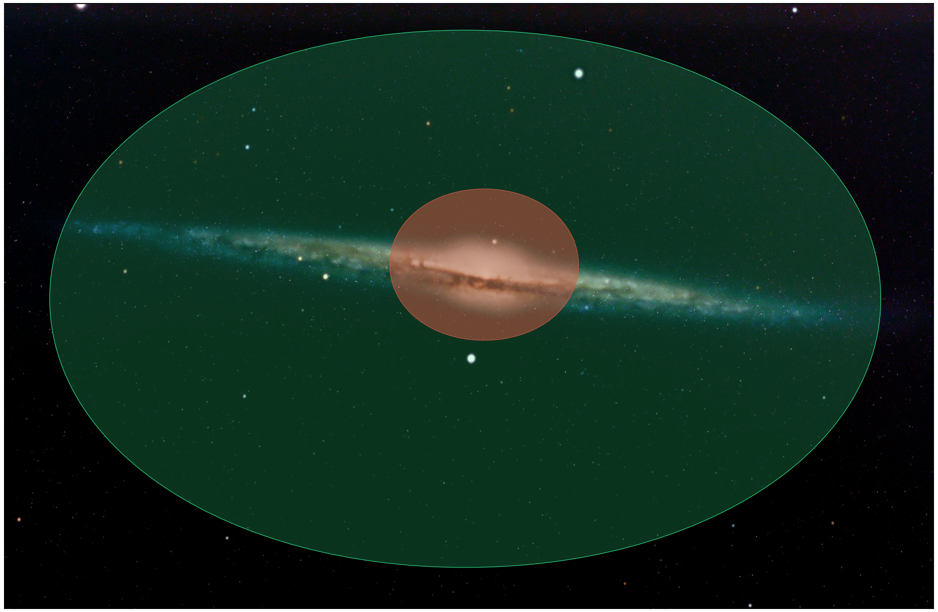

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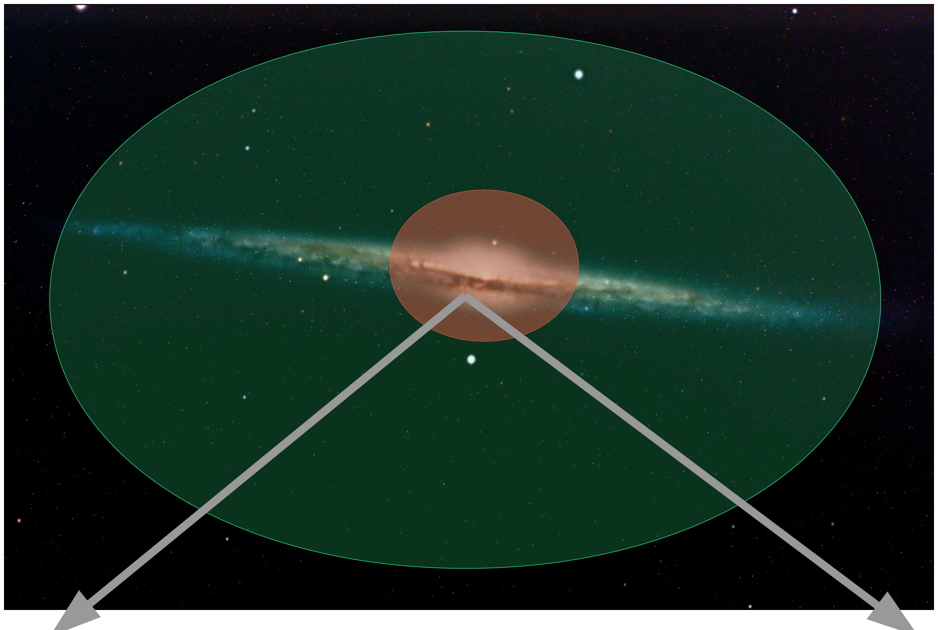

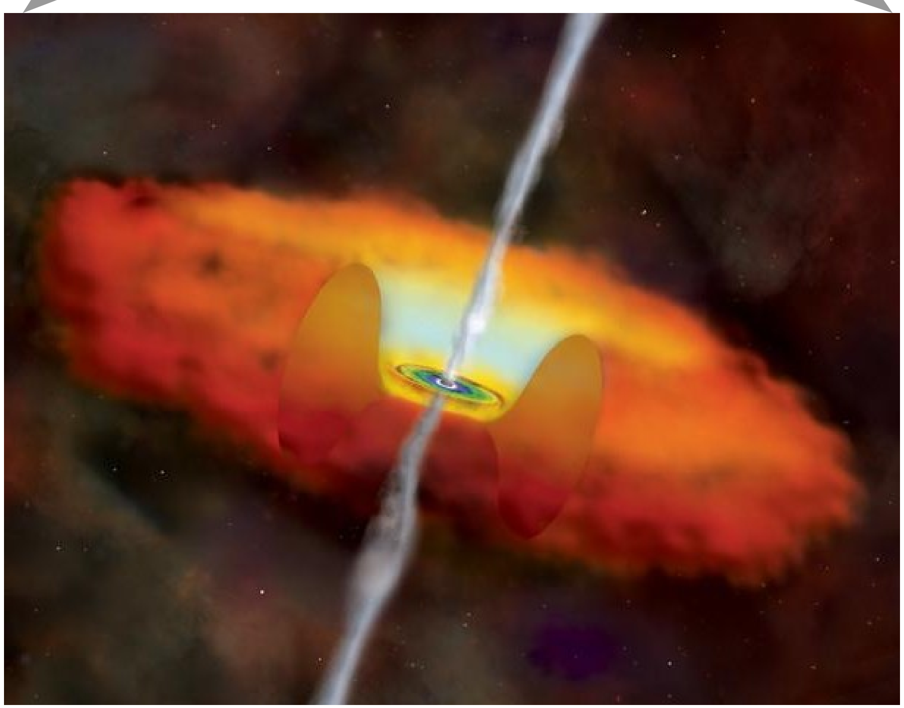

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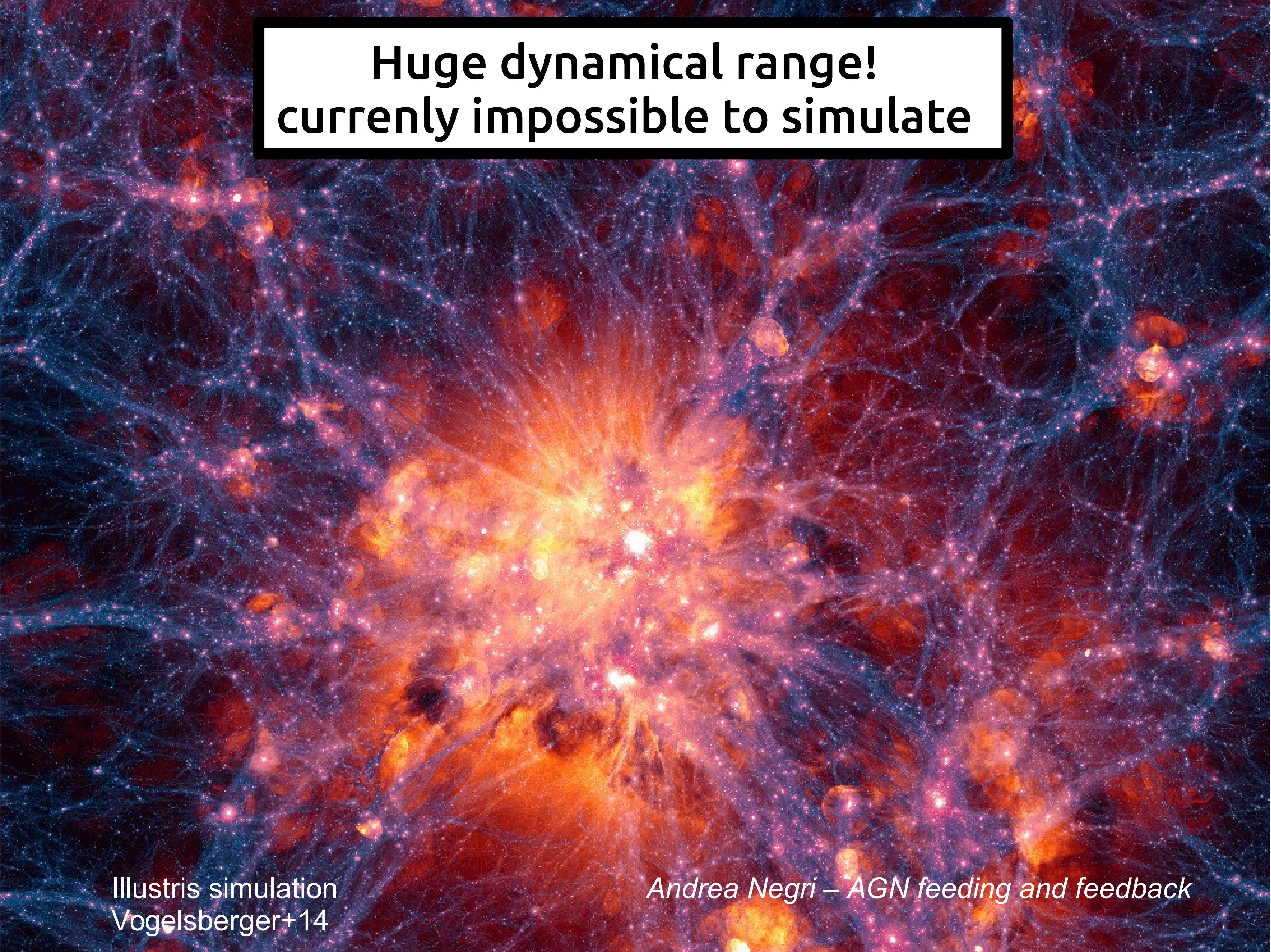
Illustris simulation
Vogelsberger+14

Huge dynamical range! currenly impossible to simulate



Illustris simulation
Vogelsberger+14

Huge dynamical range!
currently impossible to simulate

Simulations are forced to adopt lower resolution

~ 6 kpc for MassiveBlack at z=0 (Di Matteo+2012)
~ 1 kpc for Horizon-AGN (Dubois+2012)
> 750 pc Illustris (10 pc hydro, Vogelsberger+14)
350 pc EAGLE simulation, z=0 (Schaye+14)

need to resort to subgrid models for BH accretion

Illustris simulation
Vogelsberger+14

Subgrid models for BH accretion

Extremely simple, you need only 2 numbers:
density and sound speed at the infinity
in addition to the BH mass

Subgrid models for BH accretion

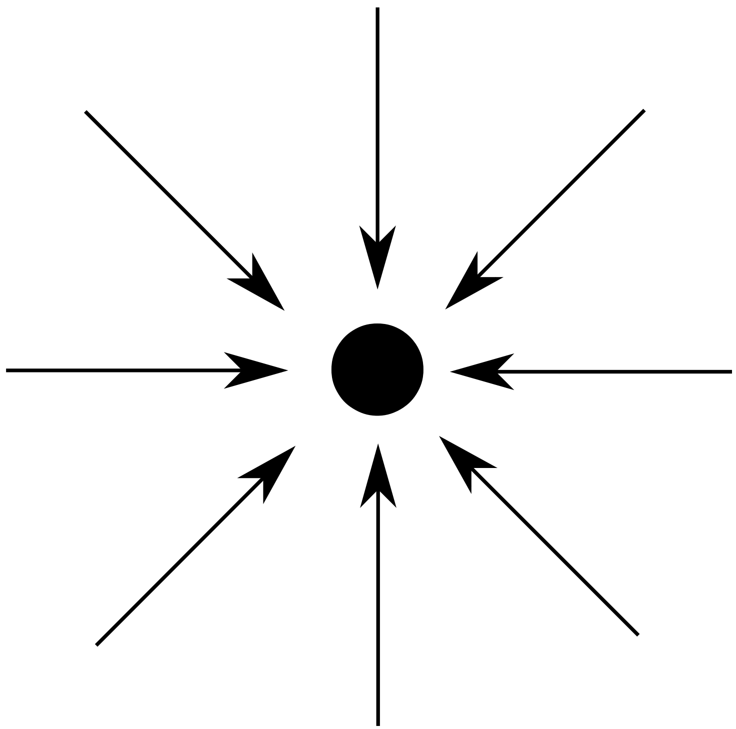
Various models are present in literature, most of them based on Bondi accretion

Introduced in cosmological simulations by Springel+05

$$\dot{M}_{bondi} = \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

Extremely simple, you need only 2 numbers: density and sound speed at the infinity in addition to the BH mass

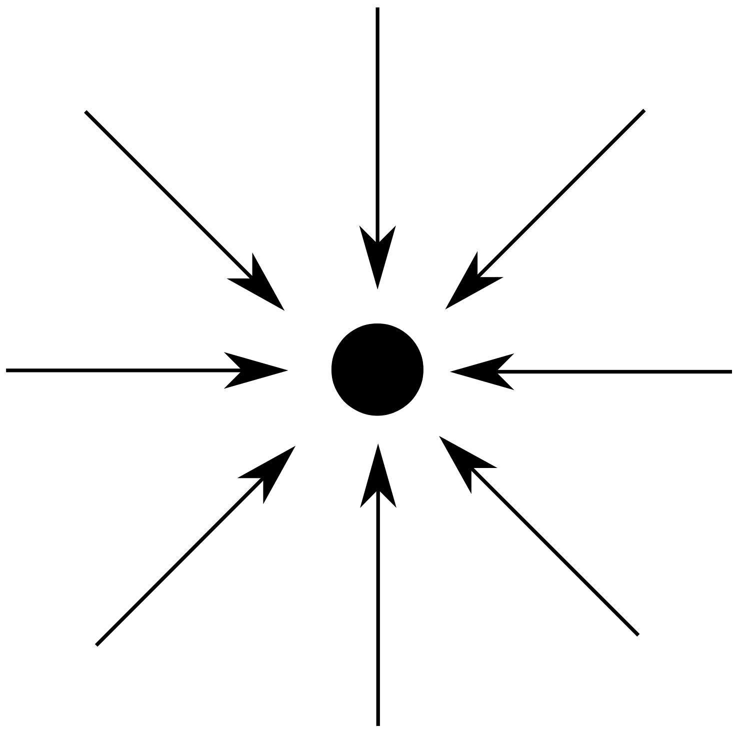
Bondi accretion: assumptions



Bondi accretion: assumptions

Bondi formula describe the BH mass accretion rate under few idealized hypotheses

$$\dot{M}_{bondi} = \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$



- Spherically symmetric (1D)
- No gas angular momentum
- Only BH gravity (no gravity from gas, stars and dark matter)
- Perfect gas (polytrope)
- no radiation feedback from the central object

Bondi accretion: assumptions

Bondi formula describe the BH mass accretion rate under few idealized hypotheses

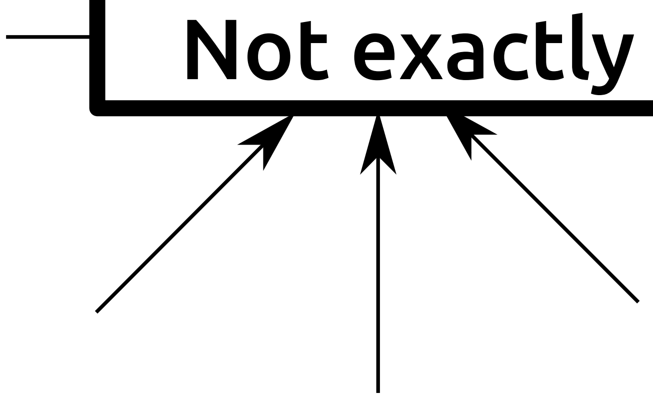
$$\dot{M}_{bondi} = \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

Quite idealized

Even in this case density and speed of sound should be calculated at the infinity

Not exactly what you do in a simulation...

as,



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Bondi accretion: caveats

Bondi accretion: caveats

By allowing 2 or 3 dimensions you can have:

- Non uniform gas flow, with hot atmosphere + cold clumps (Barai+11,12, Park & Ricotti 12, Gaspari+13)
- Rotation produces gas circularization and accretion disk
- Galaxy gravity is not considered
- AGN feedback can substantially modify the picture
  by clearing the gas from the BH surroundings,
  heating the gas on a larger scale
  enhance the formation of a multiphase gas
- Star formation can subtract cold gas, and heating the remaining ISM

Bondi accretion: caveats

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- Non uniform gas flow, with hot atmosphere + cold clumps (Barai+11,12, Park & Ricotti 12, Gaspari+13)

- Rotation … etion disk

But the formula is so simple that is widely adopted

- Galaxy gravity is not considered

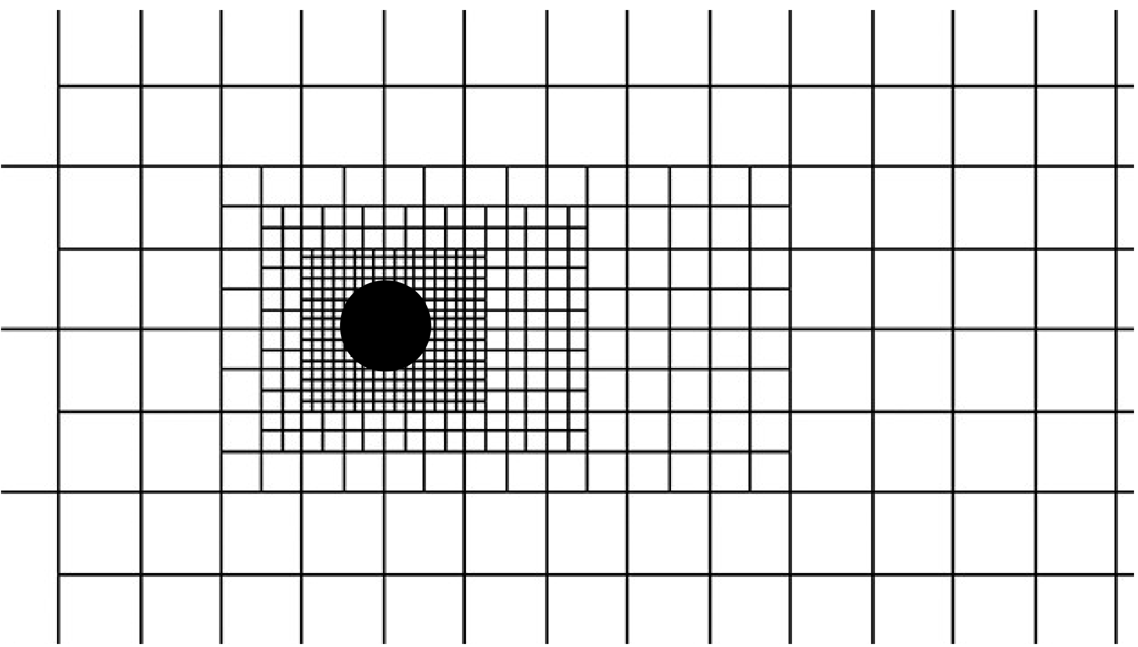
- AGN feedback can substantially modify the picture
  by clearing the gas from the BH surroundings,
  heating the gas on a larger scale
  enhance the formation of a multiphase gas

- Star formation can subtract cold gas, and heating the remaining ISM

How accretion is implemented: AMR

$$\dot{M}_{BH} = \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

ρ and c_s are calculated using information on the surrounding gas, plenty of ways



AMR CODE

- A radius is defined around the BH
- ρ and c_s are calculated in the volume
- Volume weighted (Vogelsberger+13)
- Mass weighted (Horizon-AGN)

How accretion is implemented: AMR

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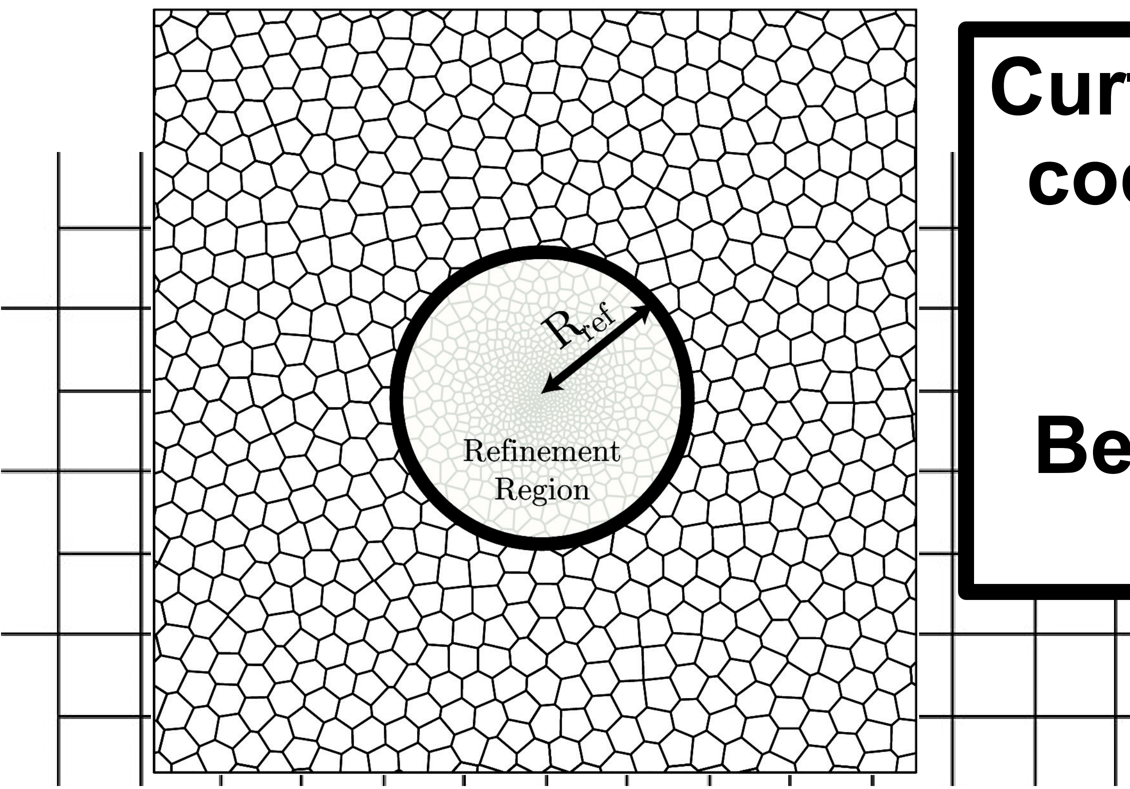


Curtis & Sijacki 15: AREPO code forced to refine the BH surroundings

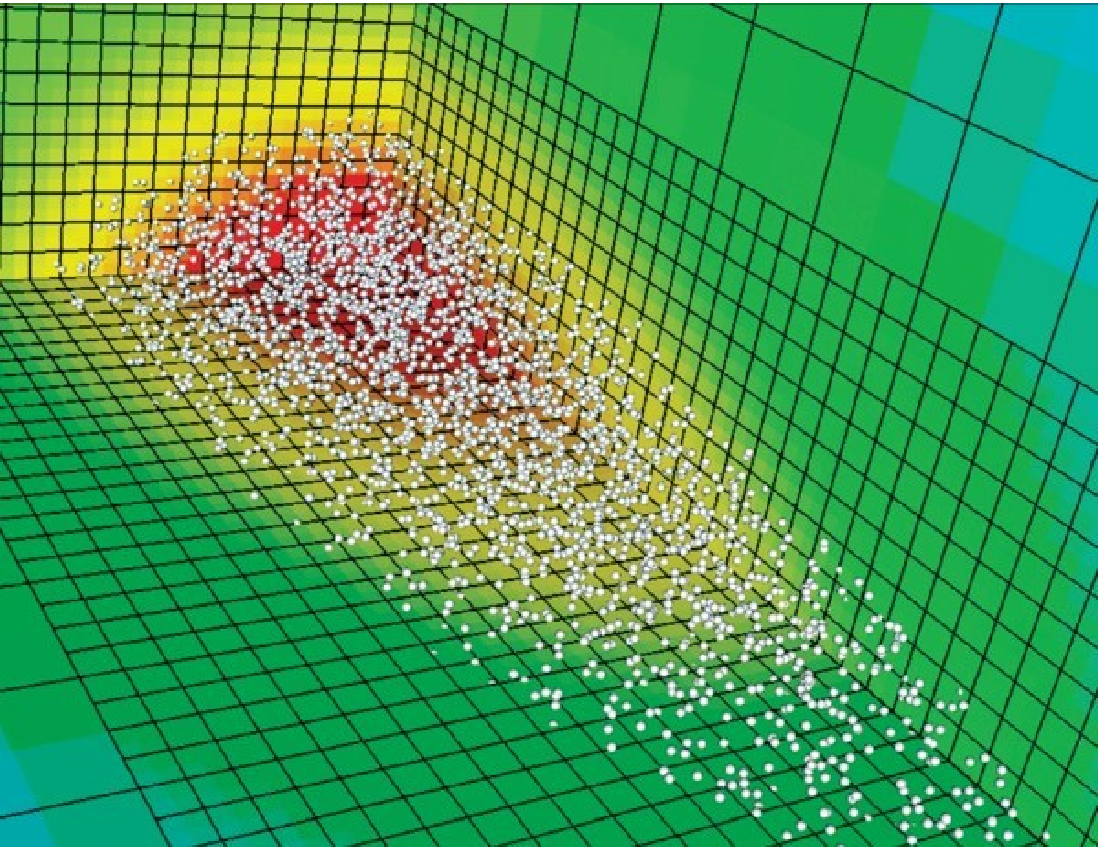
Better refinement almost down to Rbondi

Volume weighted (Vogelsberger+13)

- Mass weighted (Horizon-AGN)

How accretion is implemented: SPH codes

$$\dot{M}_{BH} = \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3} \qquad \rho = \sum_{j=1}^{n} m_j W_{BH}(r_j, h)$$



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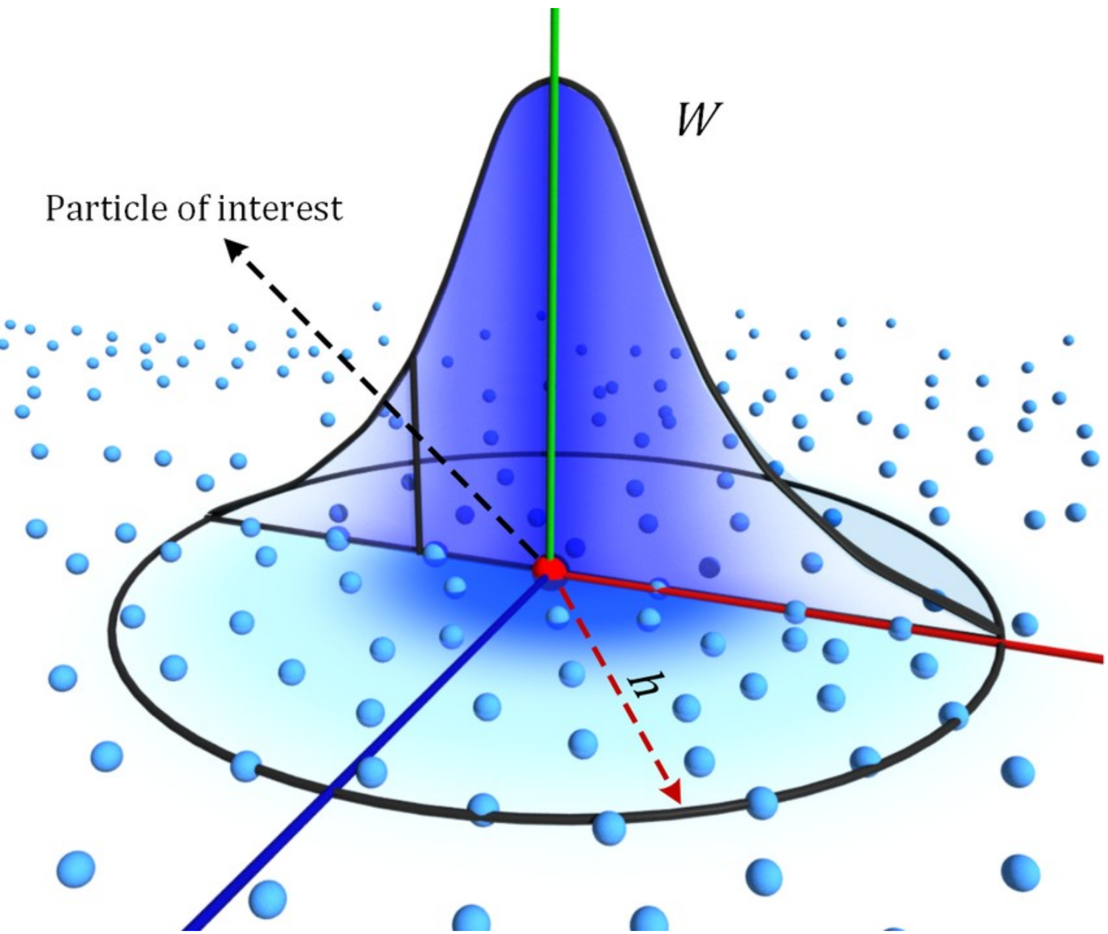

W_{BH} is the kernel centered on the BH

Dimensionally is 1/volume

h is the smoothing length: any particle outside h is not important

How accretion is implemented: SPH codes

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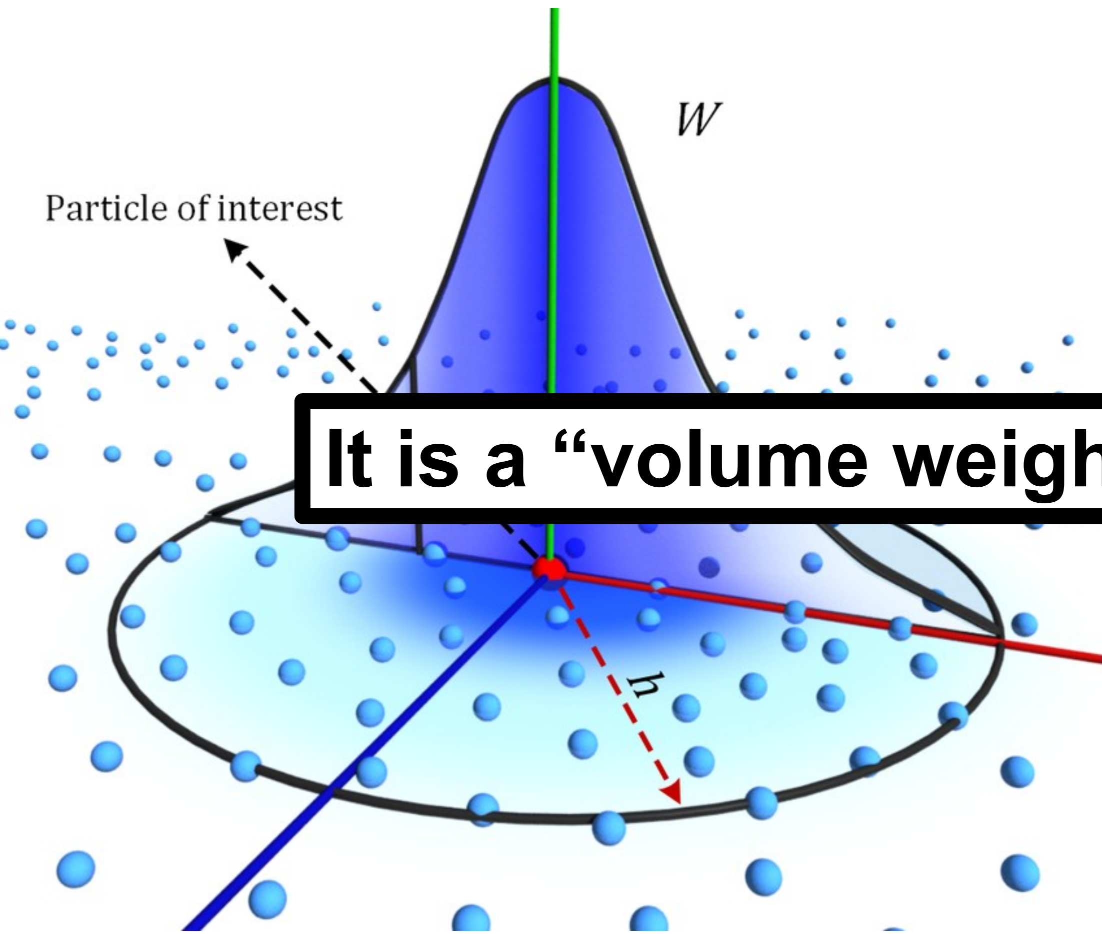

It is a "volume weighted" algorithm

W_{BH} is the kernel centered on the BH

Dimensionally is

h is the smoothing length: any particle outside h is not important

A step further towards simulations

$$\dot{M}_{BH} = \alpha \, \dot{M}_{Bondi} = \alpha \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

- **Usually the accretion rate is boosted** (Springel+05, Booth+09):

α (~100-300) is a **boost factor**, depends on resolution and sub-grid models of ISM (Korol, Ciotti Pellegrini16)

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Philosophy behind α:

Low resolution: ISM cold phase not resolved

Bondi radius not resolved

- ρ underestimated
- c_s overestimated

BH accretion rate underestimated

A step further towards simulations

$$\dot{M}_{BH} = \alpha \dot{M}_{Bondi} = \alpha \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

- In Springel+05 (SPH) they adopted 100

- Booth & Schaye 09 proposed $\alpha=1$ when n_gas < n_SF=0.1
  α=(n_gas/n_sf)$^{\beta}$ with $\beta=2$ otherwise
  due to the fact that low density gas is ~ spherical
  Adopted for OWL, COSMO-OWL, BAHAMAS, EAGLE simulations
  Horizon-AGN (RAMSES code, AMR) gas particles are disseminated
  near the BH, a mass weighted kernel is then used

- Pelypessy+07: ISM subgrid model, the accretion rate is the sum of both cold and hot phase, α is prop. to the gas fractions
  Adopted in MassiveBlack (DeGraf +12), Massiveblack II (Khandai +15) and BLUETIDES simulations (Feng+2016; Di Matteo +16)

A step further towards simulations

$$\dot{M}_{BH} = \alpha \dot{M}_{Bondi} = \alpha \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

- Changa and GASOLINE directly calculate BH accretion for 32 gas particles

- AREPO: volume weighted mean is performed, alpha is lowered when no star forming gas is present near the BH (ILLUSTRIS, Vogelsberger+14)

- RAMSES: new sinks methods in Bleuler & Teyssier (2014)

- Enzo: density is extrapolated at the Bondi radius, no boosting

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A step further towards simulations

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Past attempts to calibrate the BH accretion
by simulating the Bondi solution
has been performed
without feedback

see Wurster+13, Elahi+16 for a comparative
study of AGN feedback algorithms
But they still employ sub-grid recipes

A simple idea

Fiducial simulations comparison with

Sims with same setup but with Bondi accretion:

- Different schemes of weighting
- Different resolutions

A simple idea

Simulations of an isolated galaxy:

• High resolution ~ **0.1 pc** (cold and hot phase)
• **Well resolved** Bondi radius for all the T
• **No** parametrized accretion

Fiducial simulations comparison with

Sims with same setup but with Bondi accretion:
• Different schemes of weighting
•Different resolutions

Simulations in a nutshell

Code: ZEUSMP (modified in Novak et al. 2011)

- 2.5D axisymmetric
- $M_{BH} = 3 \times 10^7 M_\odot$
- R_{bondi} = 0.1 pc at T=10^8 K
- r from 0.1 pc to 250 kpc
- Star formation

- Mechanical Feedback from broad absorption line (BAL) winds
- Radiative feedback
- Compton heating/cooling
- Radiative cooling
- SN Ia & SNII

Simulations in a nutshell

Code: ZEUSMP (modified in Novak et al. 2011)

fiducial simulations:

BH accretion is the mass flux on the innermost radial grid

The code takes care of the boundaries

•2.5D ... rom ... BAL)

•M_{BH}

• R_{bo} ... ng

T=1

•r fro...

•Star formation

•SN Ia & SNII

Initial conditions

- Spherical stellar population (Jaffe model)
  Reff = 5,3 kpc $M_{star} = 3 \times 10^{10}\ M_\odot$

- BH potential well M_{BH}=3 × $10^7\ M_\odot$
  + Singular Isothermal Sphere (v_c=150 km/s)

- Initial ISM density profile: flat at low r, at large radii r^{-2}

- Two different central ISM density: 1 and 0.01 cm^{-3}

- (Almost) no rotation

Initial conditions

- Spherical stellar population (Jaffe model)
  Reff = 5,3 kpc $\qquad M_{star} = 3 \times 10^{10}\, M_\odot$

- BH

  \+ S

$M_{BH} = 3 \times 10^{7}\, M_\odot$ with 0.1 pc resolution
we are able to resolve the Bondi radius
up to $T = 10^{8}$ K

- Initial ISM density profile: flat at low r, at large radii r^{-2}

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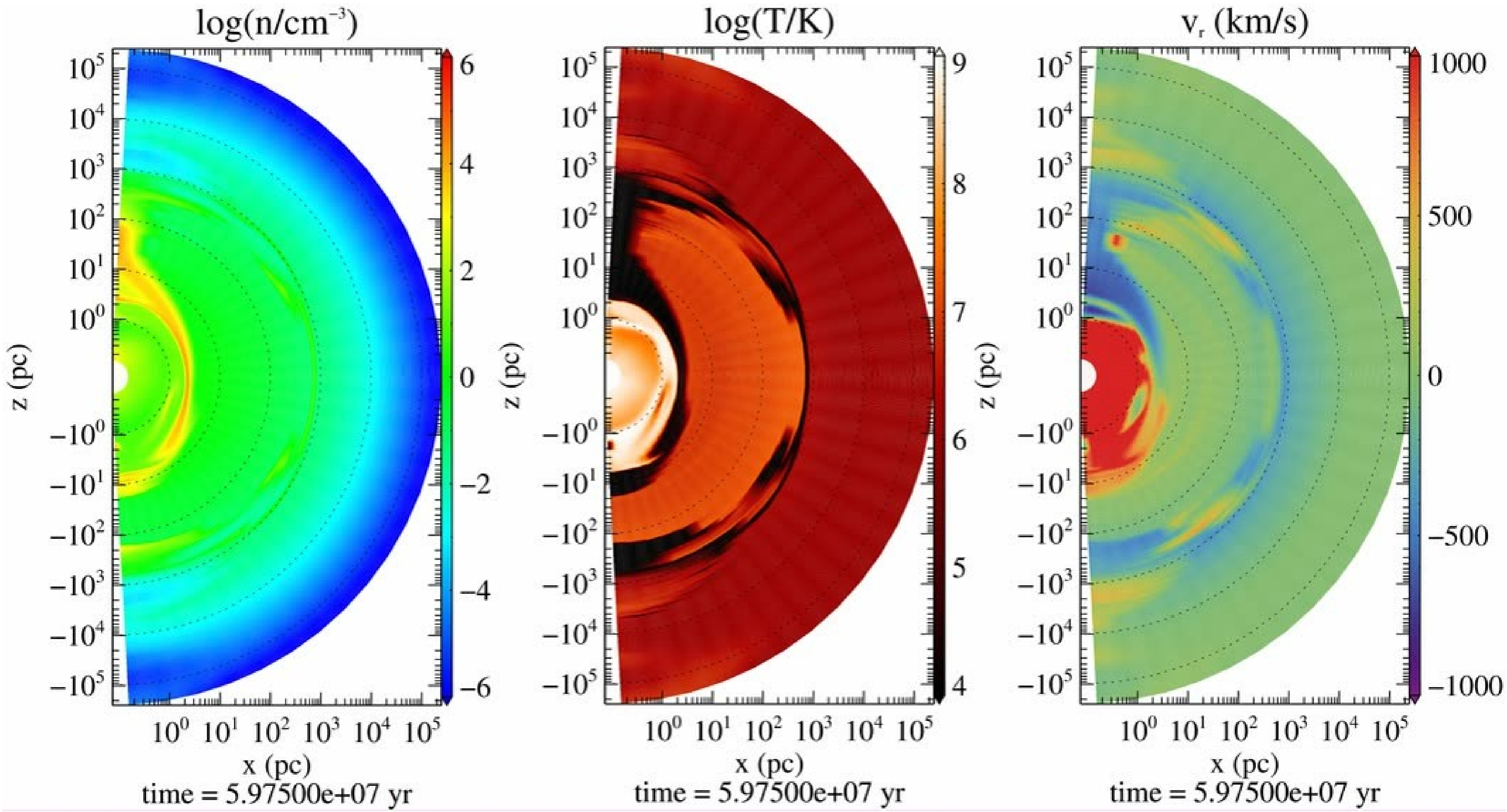
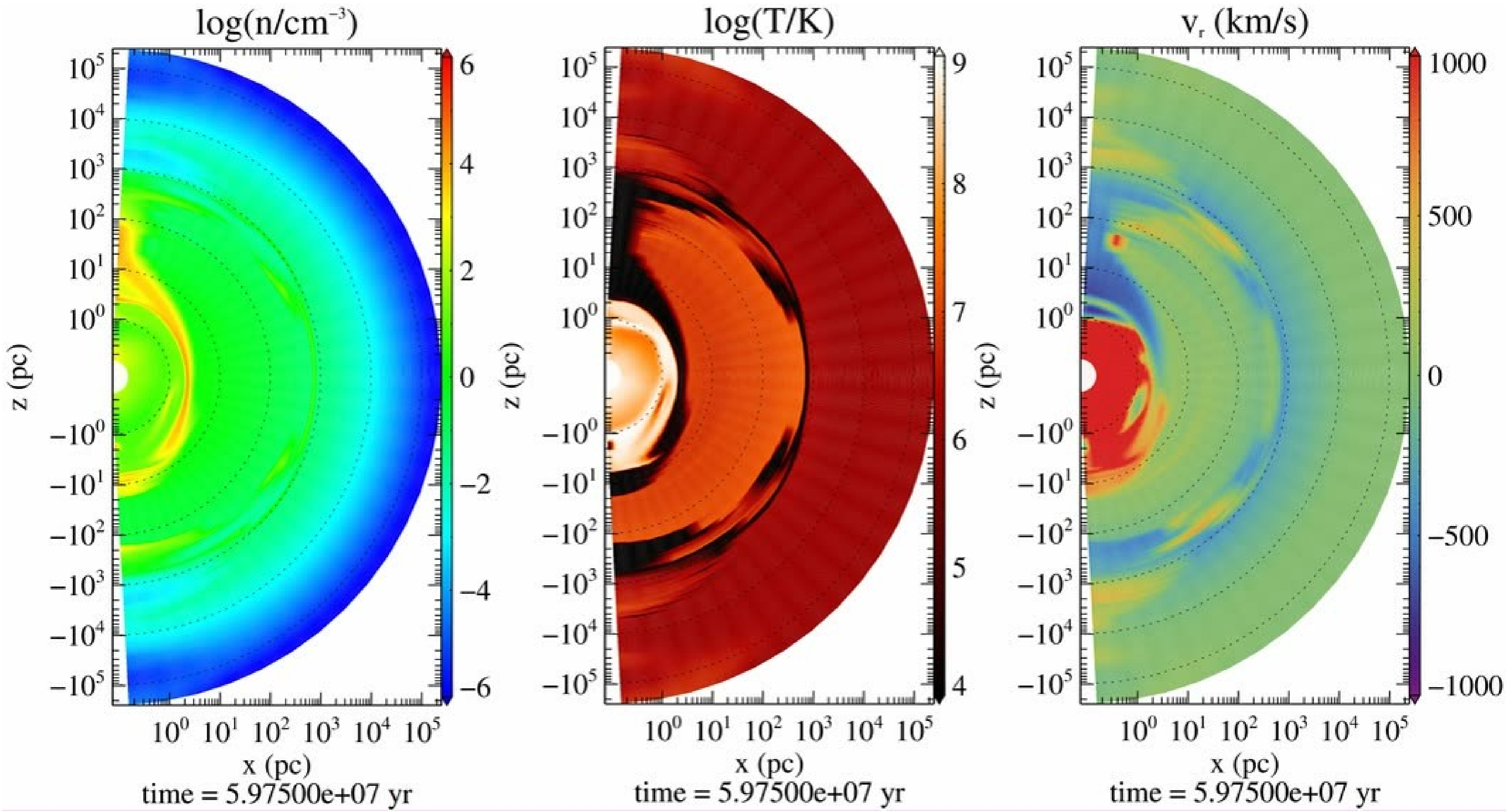


cooling – accretion – feedback – hot bubble cycle



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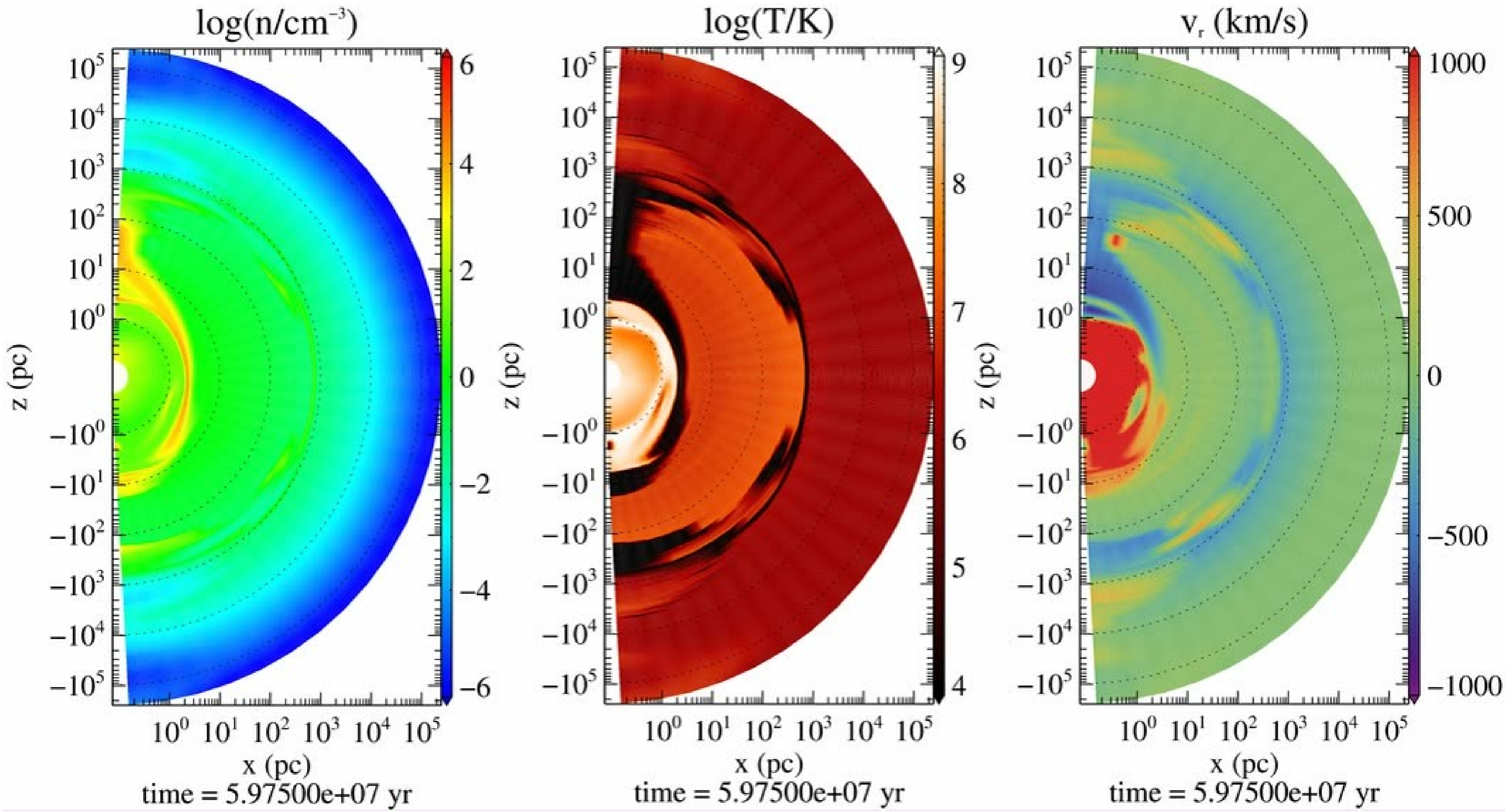
CHAOTIC ACCRETION



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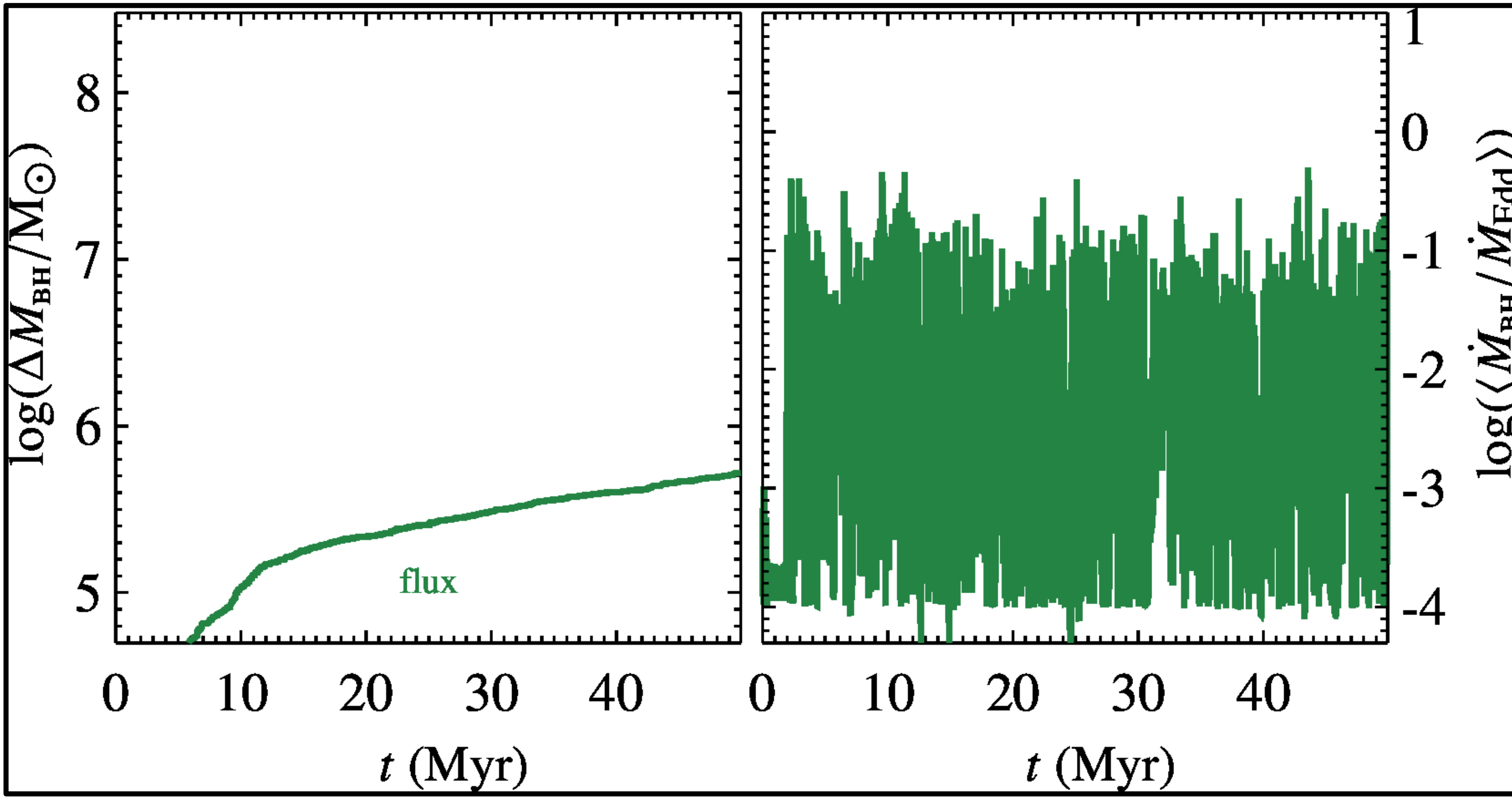
CHAOTIC ACCRETION

Feedback self-limits accretion to sub-Eddington values



cooling – accretion – feedback – hot bubble cycle

CHAOTIC ACCRETION

Feedback self-limits accretion to sub-Eddington values

What happens with Bondi?

$$\dot{M}_{BH} = \alpha \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3}$$

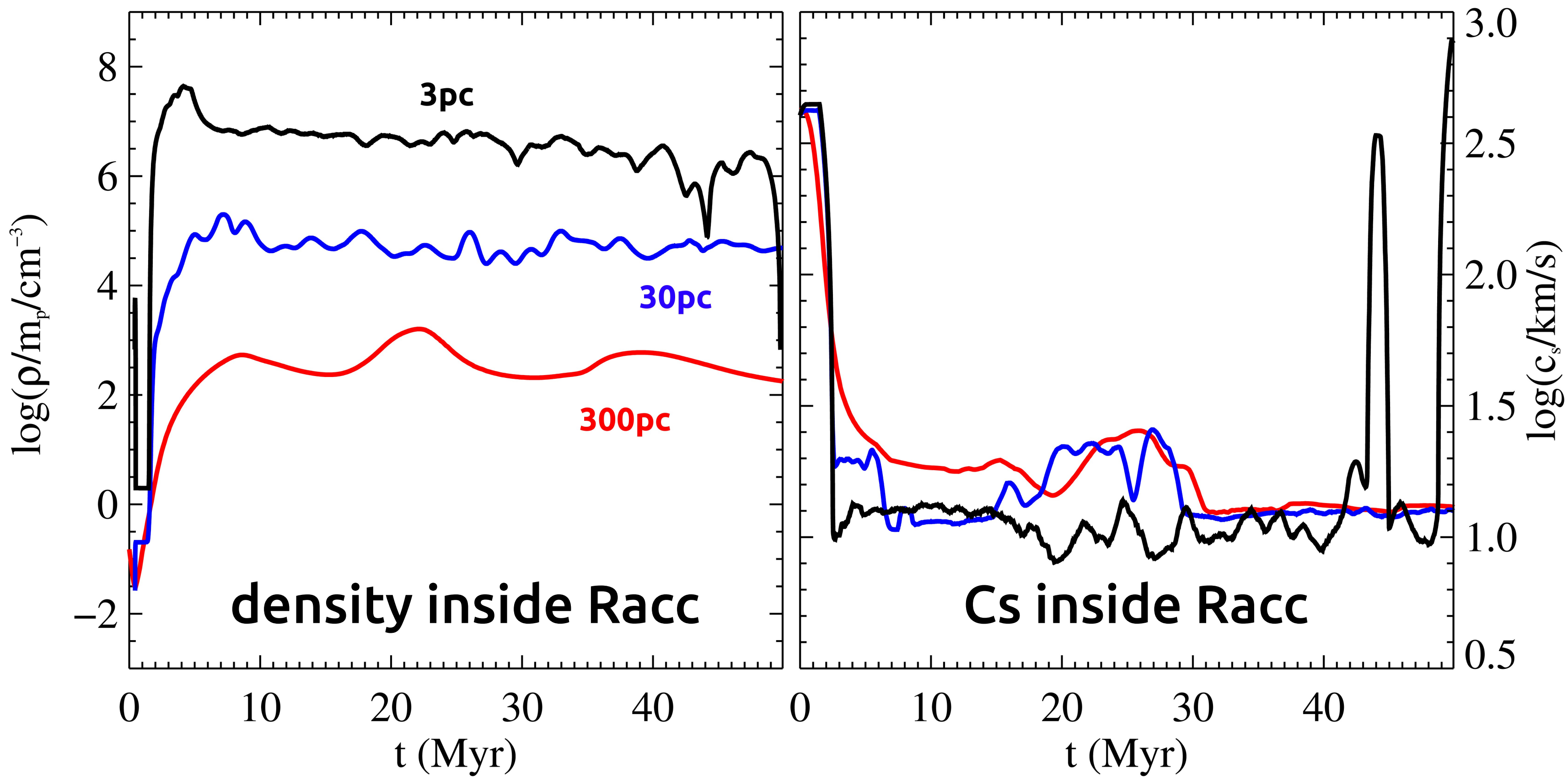
1) Define accretion radius r_{acc} (3, 30, 300 pc)
2) Calculate ρ and c_s inside r_{acc}
3) value of alpha (=1 in my case)

Explored different setups:

- High vs low resolution runs
- Mass vs Volume weighted

Bondi low resolution mass weighted NO AGN

The central resolution is 3, 30 and 300 pc



The expected trend is recovered in absence of AGN feedback

Bondi low resolution mass weighted

Explored r_{acc} = 3, 30, 300 pc

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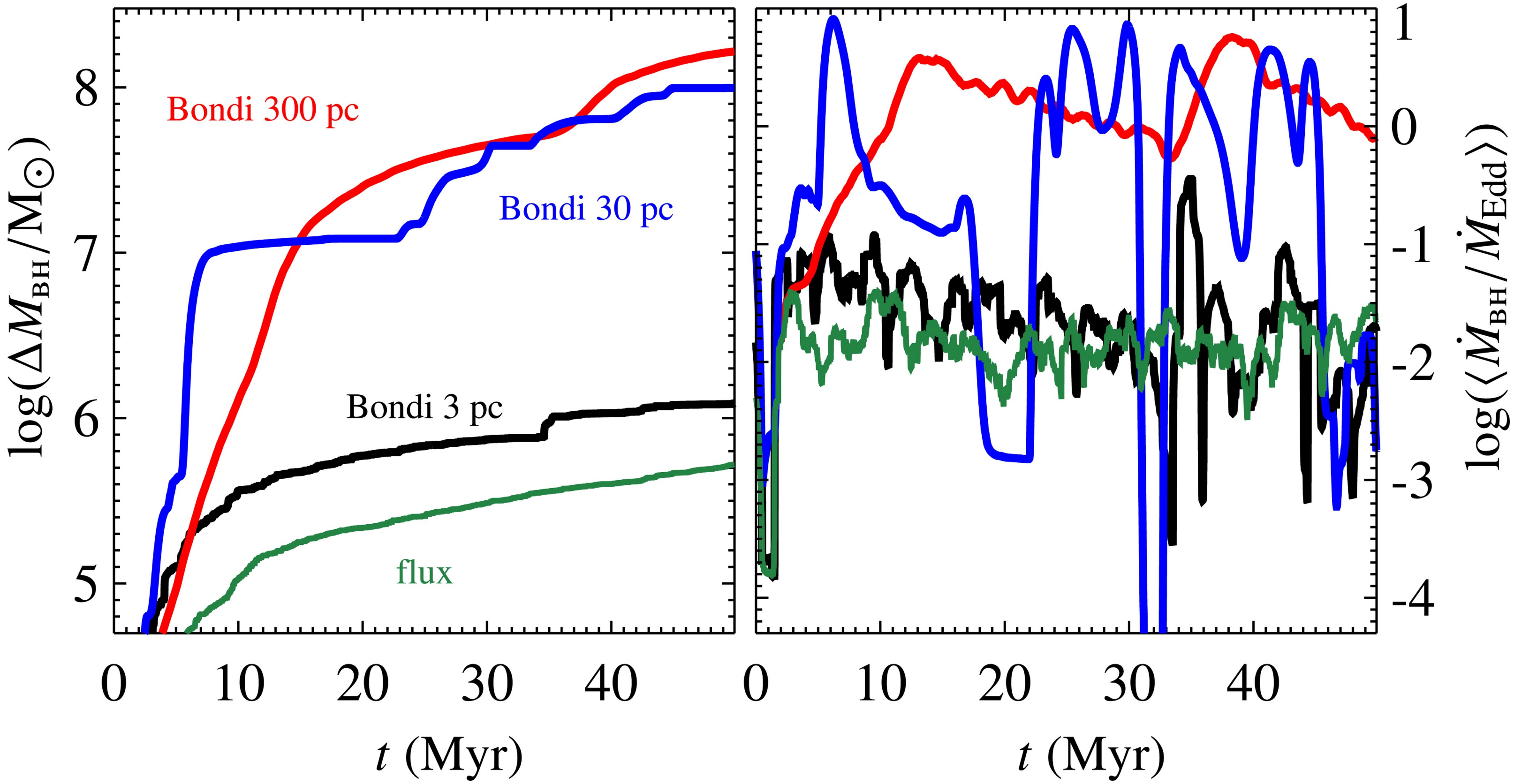
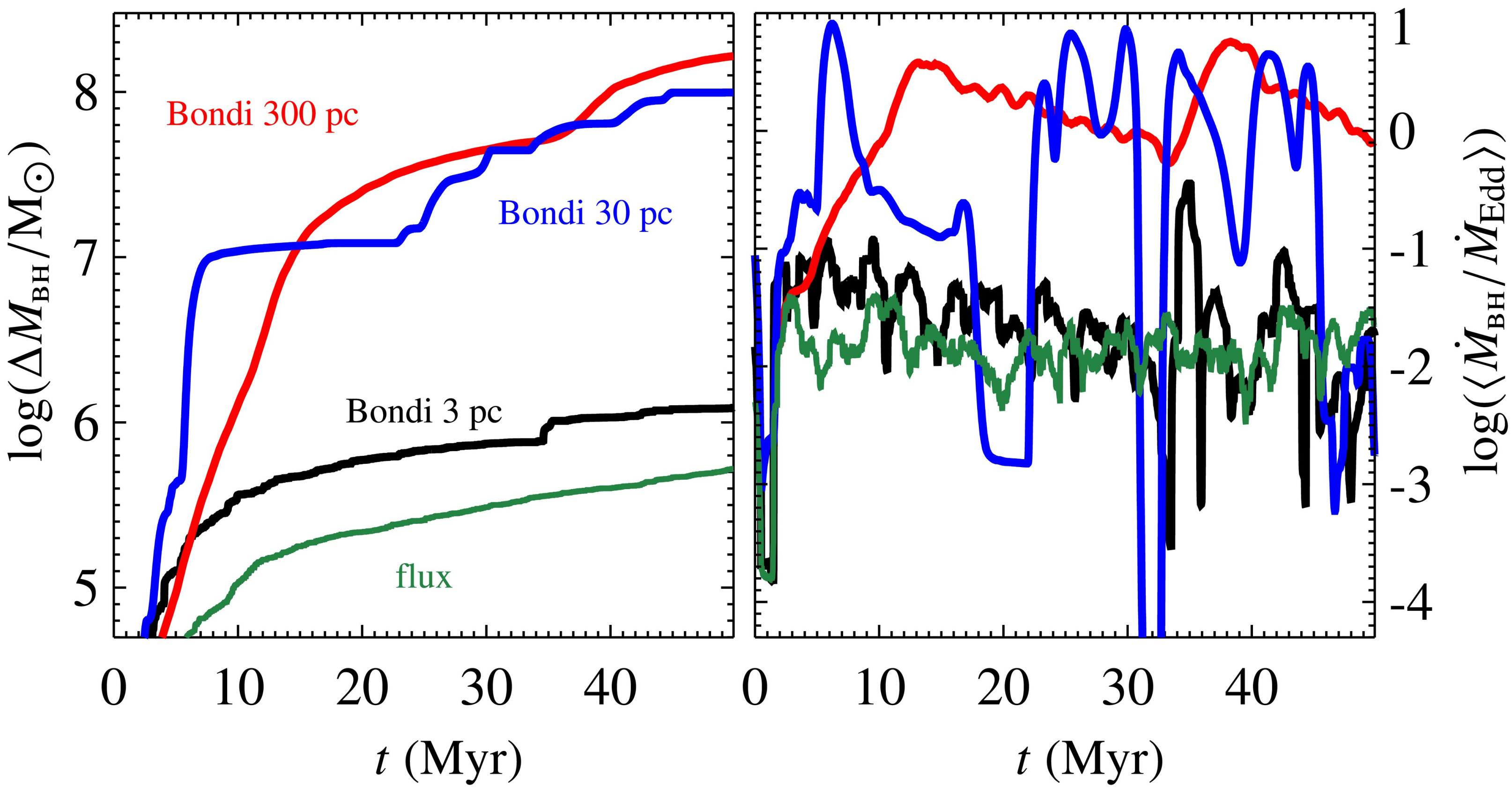


Bondi low resolution
mass weighted

Explored r_{acc} = 3, 30, 300 pc



Trend: the larger r_{acc} the larger ΔM_{BH}!

Bondi low resolution
mass weighted

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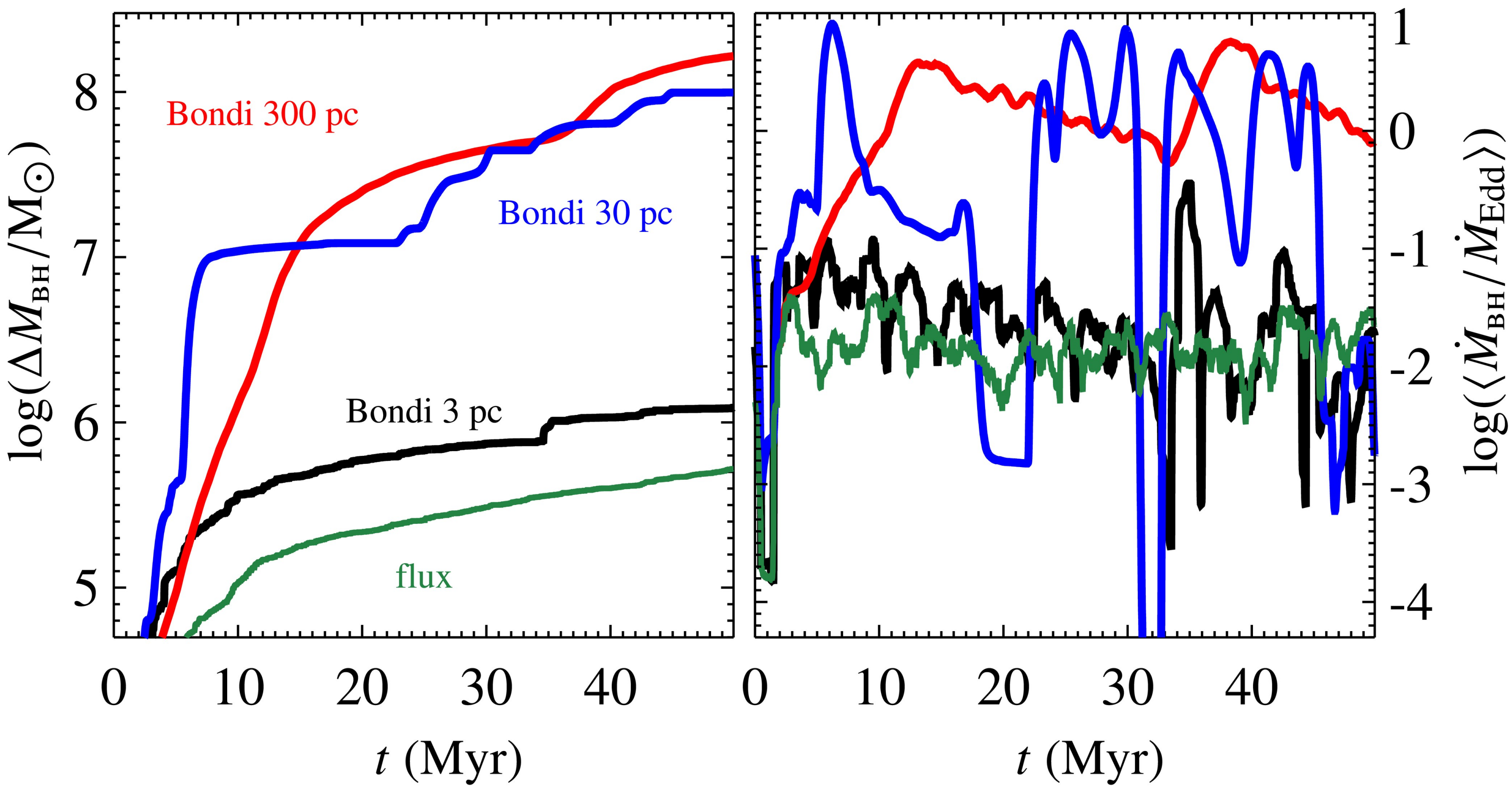


Trend: the larger r_{acc} the larger ΔM_{BH}!

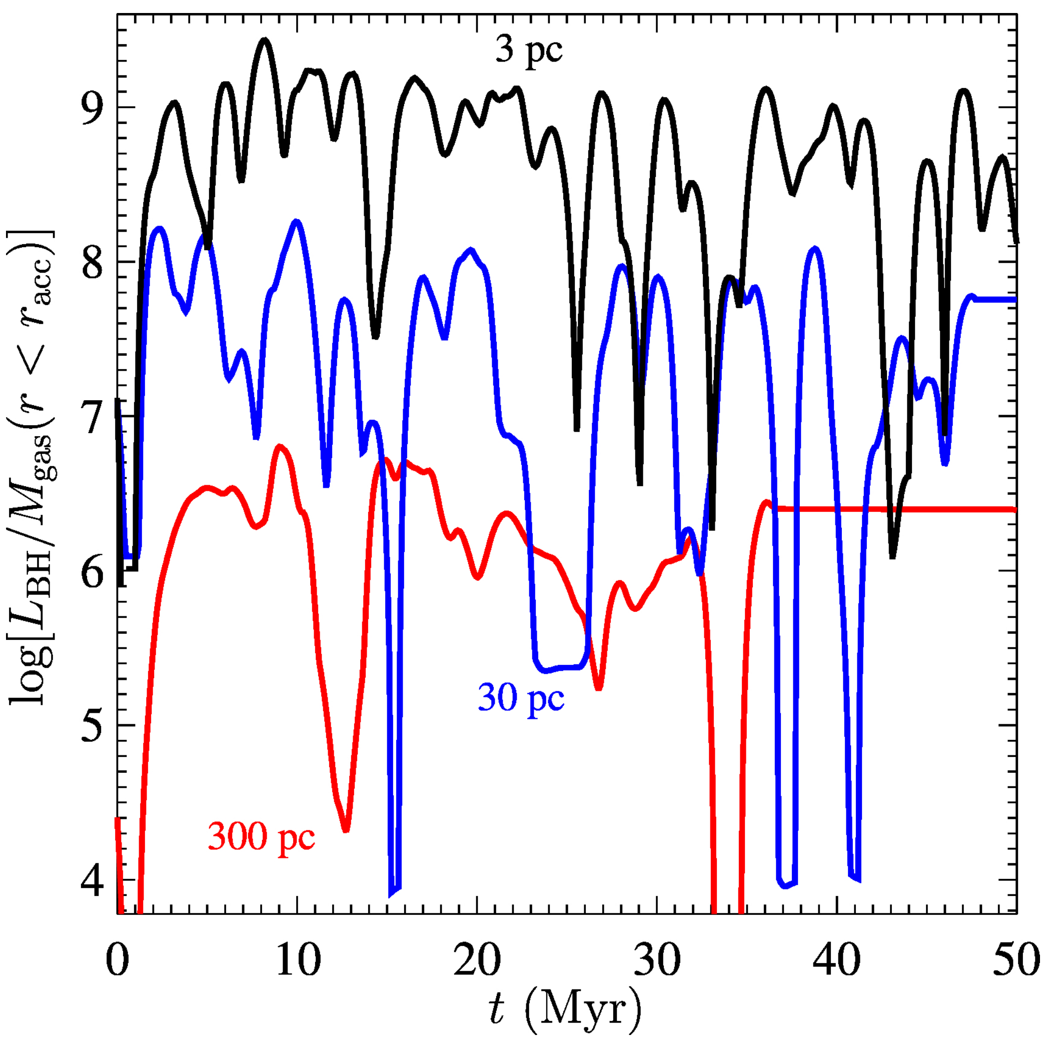
I was expecting the opposite!

Bondi low resolution

Sims with large r_{acc} there is a stronger feedback but a larger gas mass to heat/sweep away to stop the accretion

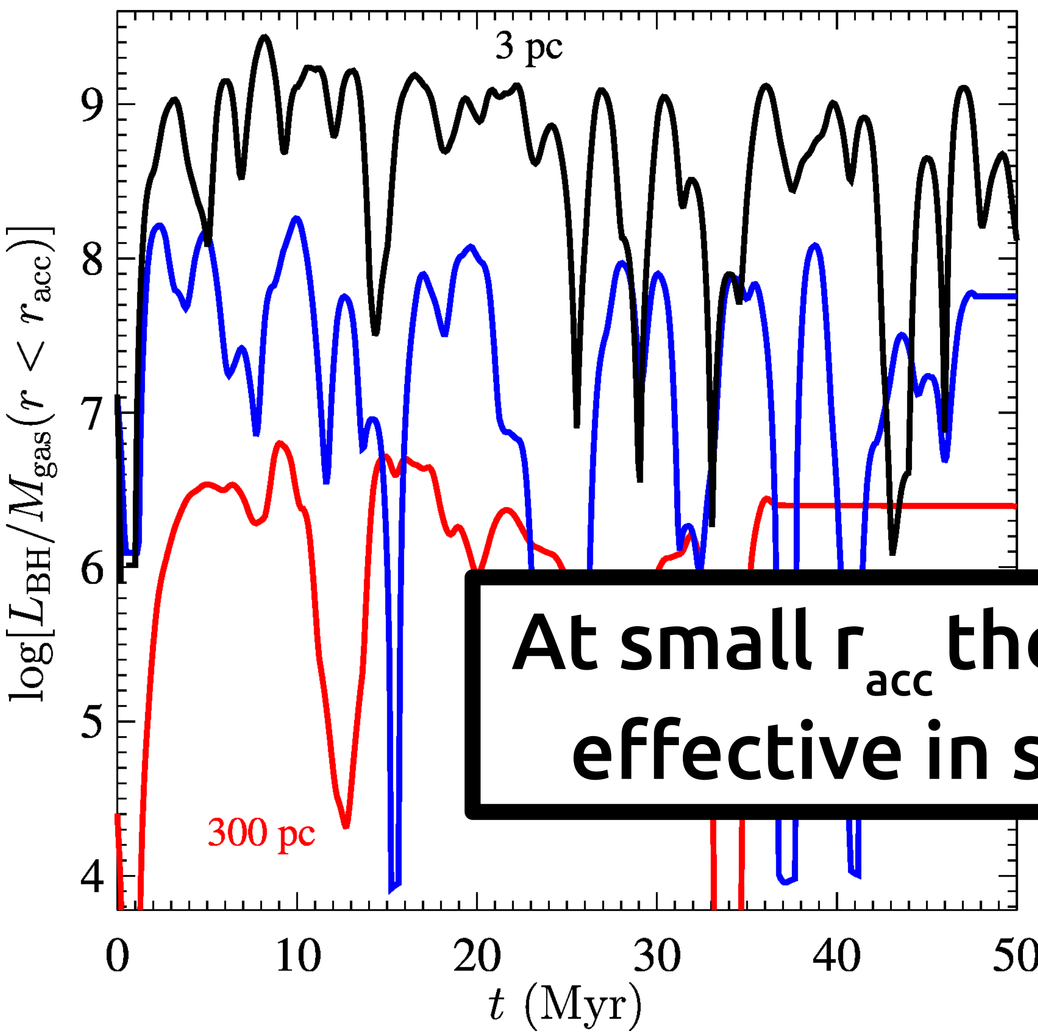
Bondi low resolution

Sims with large r_{acc} there is a **stronger feedback** but a **larger gas** mass to heat/sweep away to stop the accretion



Bondi low resolution

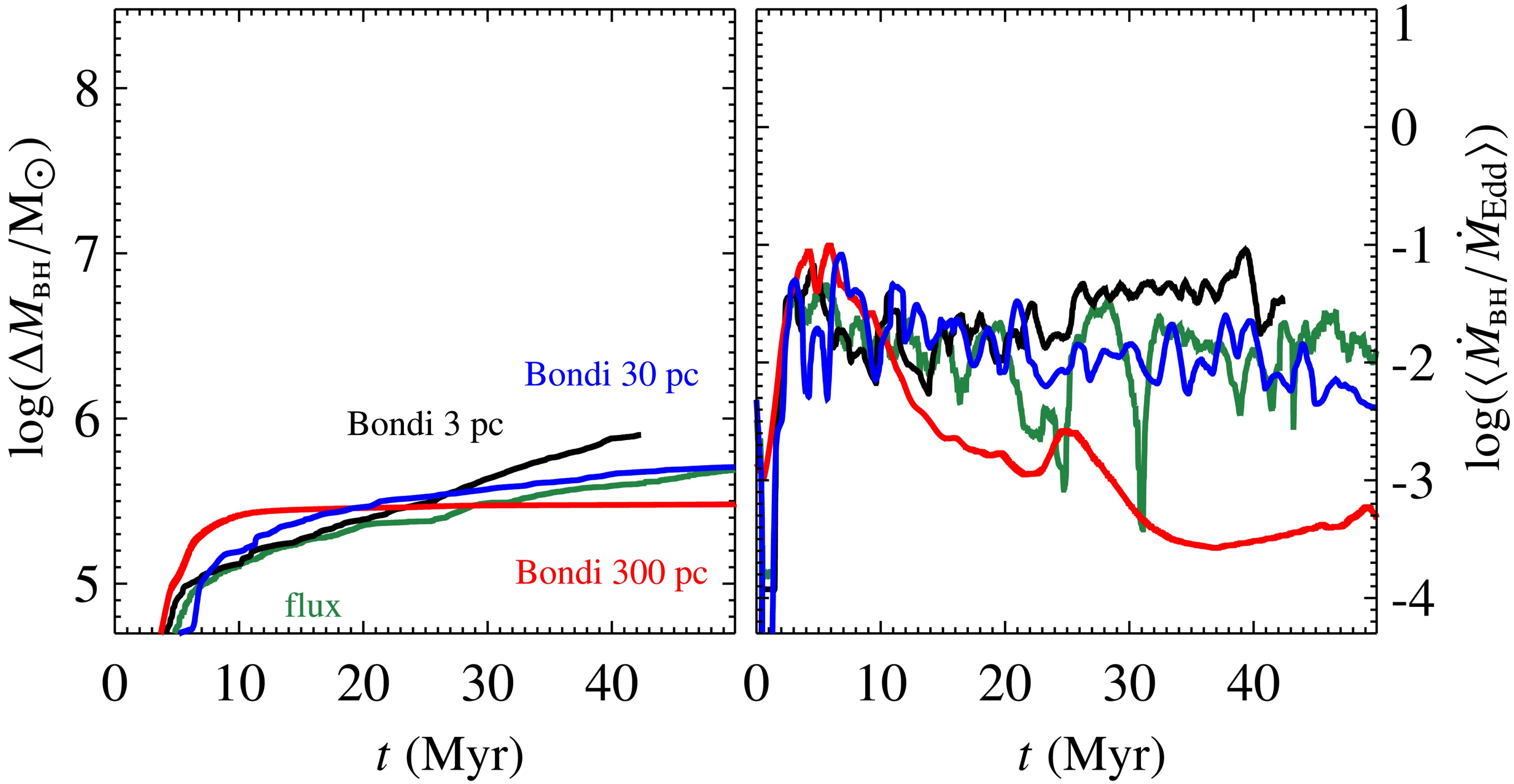
Sims with large r_{acc} there is a stronger feedback but a larger gas mass to heat/sweep away to stop the accretion



At small r_{acc} the AGN feedback is more effective in stopping the accretion

Bondi low resolution volume weighted

Again, at low resolution the AGN feedback is less efficient
Compensates the fact that the accretion is dominated by hot mode



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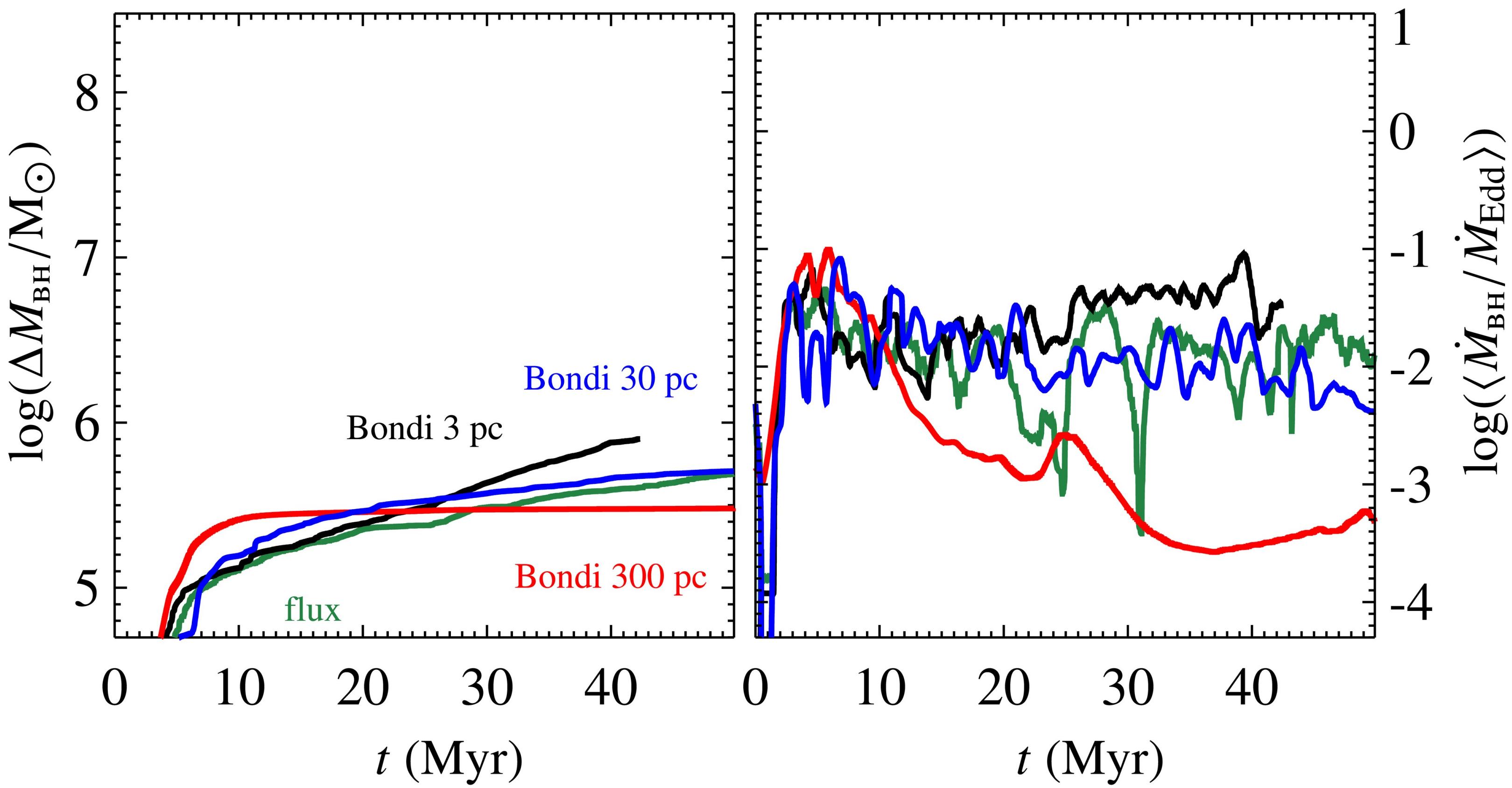

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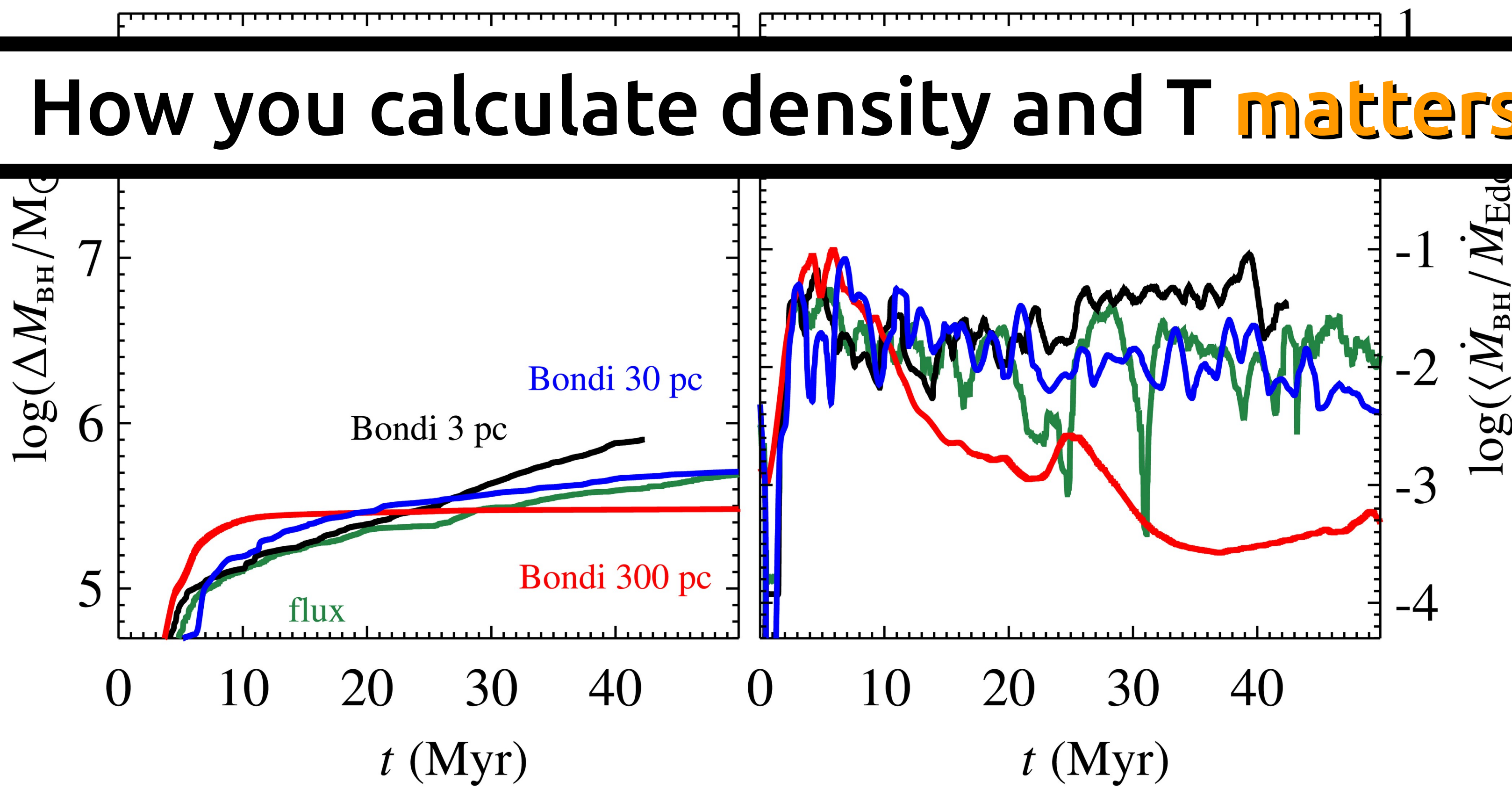
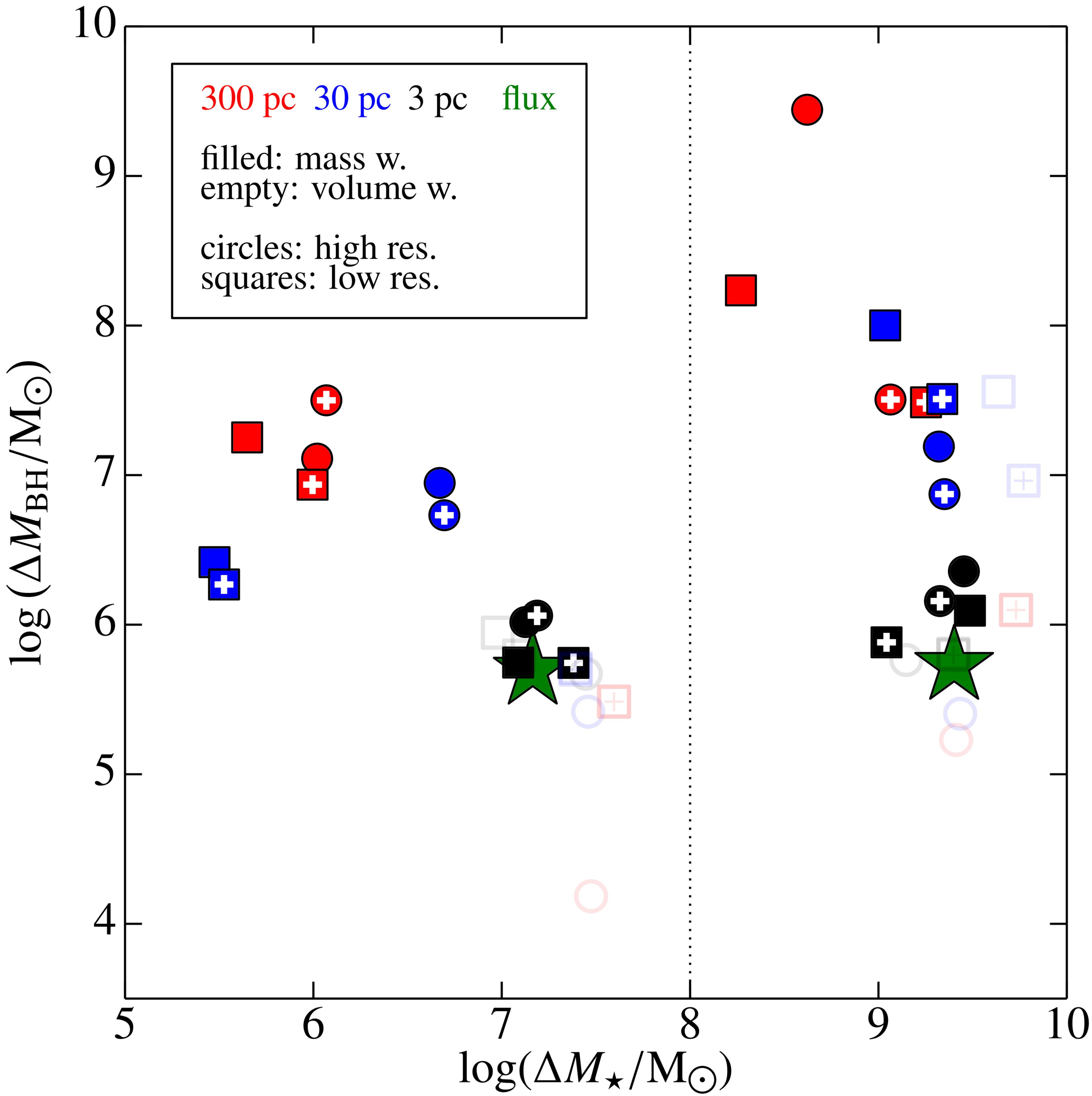


Mass weighted sims



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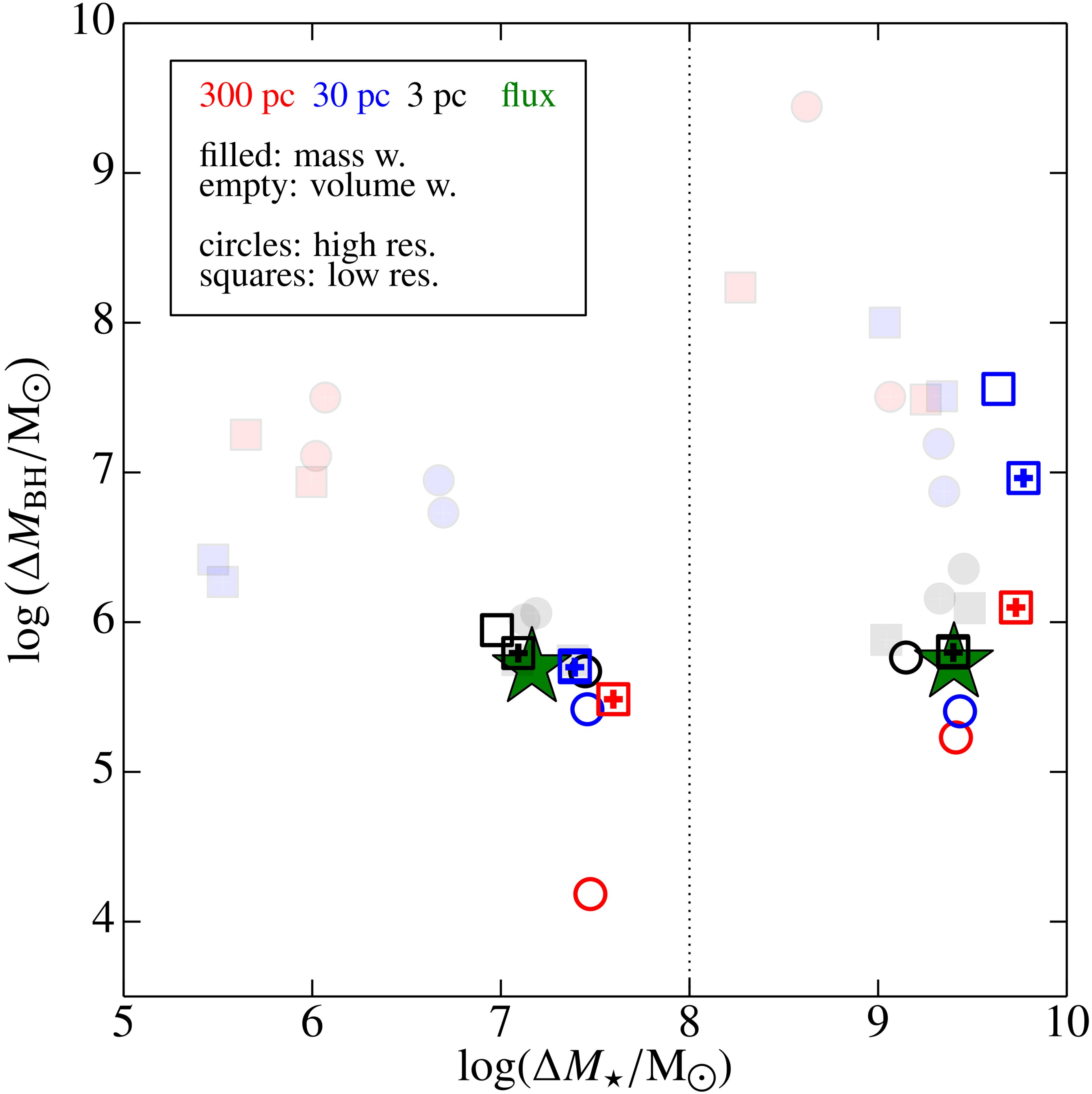
Volume weighted sims



Take home points

- At high resolution high oscillating BH accretion: self-limited evolution, kept sub-Eddington without artificial limiters

- The common assumption of low resolution = low accretion is not verified in presence of feedback

- Efficency of feedback in stopping accretion is low at low resolution

- Accretion boosting is justified only with volume weighted algorithms (SPH and Illustris simulations) but you need to be very careful!

- alpha is resolution and problem dependant