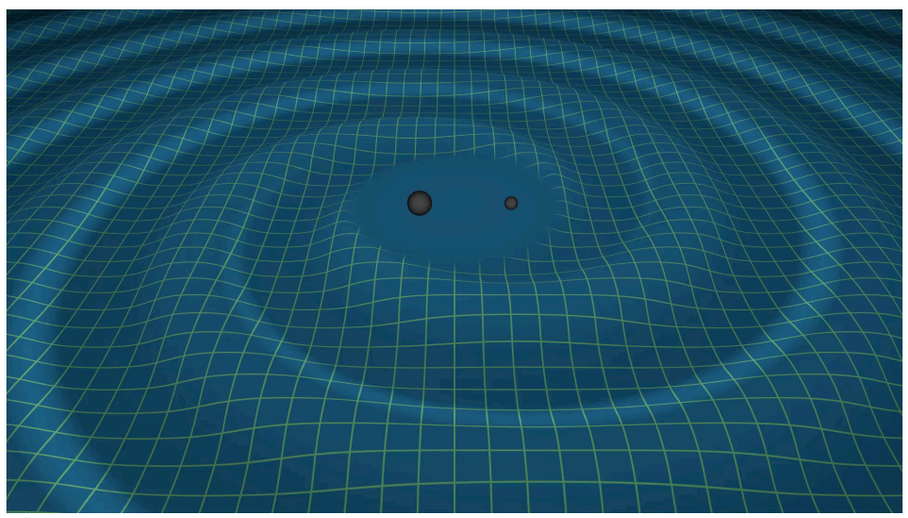
LISA Workshop
13 December 2018

The lonely life of high redshift black holes

Hugo Pfister - pfister@iap.fr

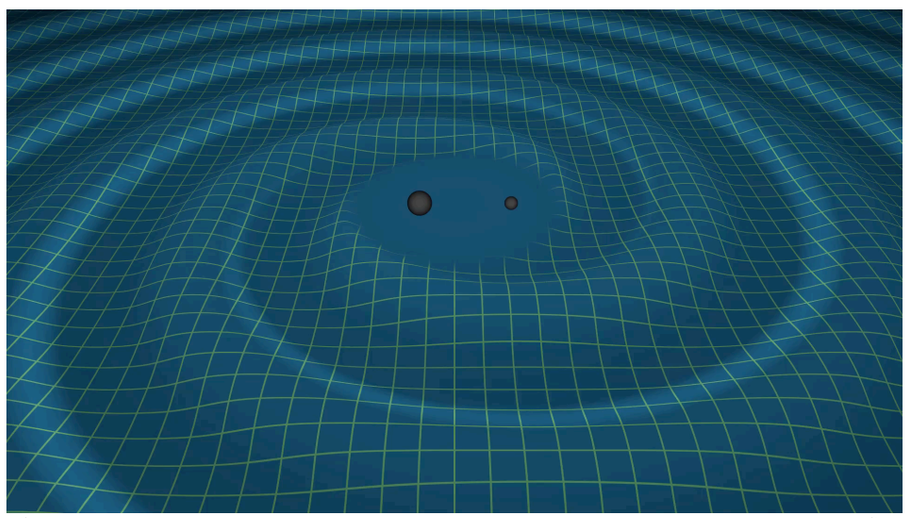
Marta Volonteri, Yohan Dubois, Massimo Dotti & Monica Colpi

Black holes journey over a Hubble time



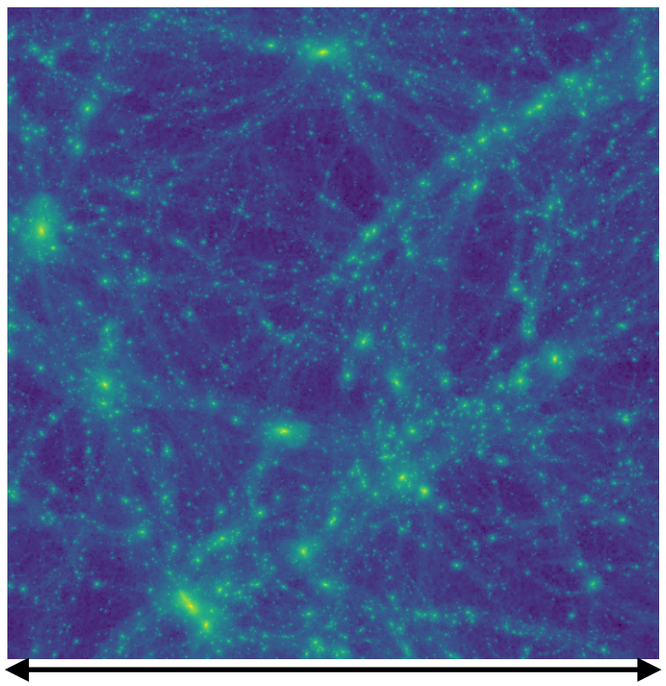
~1 au (BH merger)

Black holes journey over a Hubble time

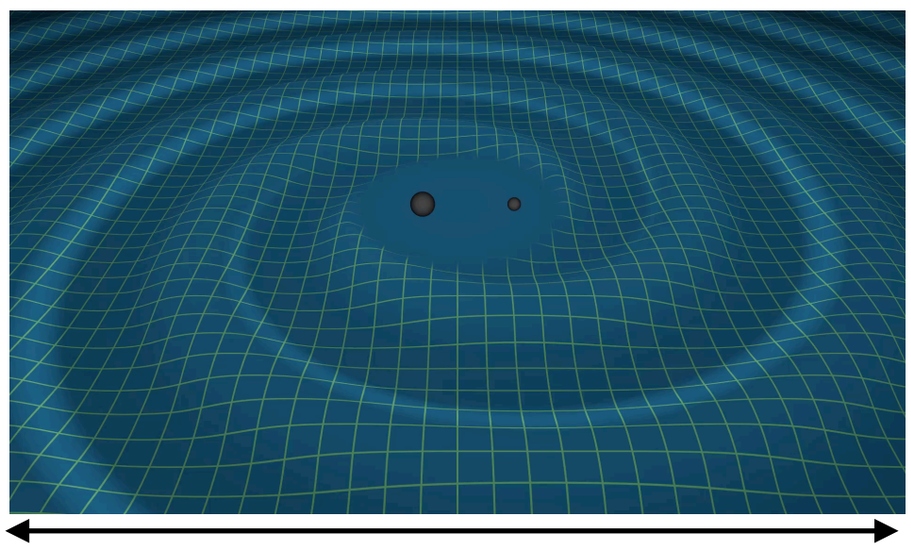


~1 au (BH merger)

Black holes journey over a Hubble time

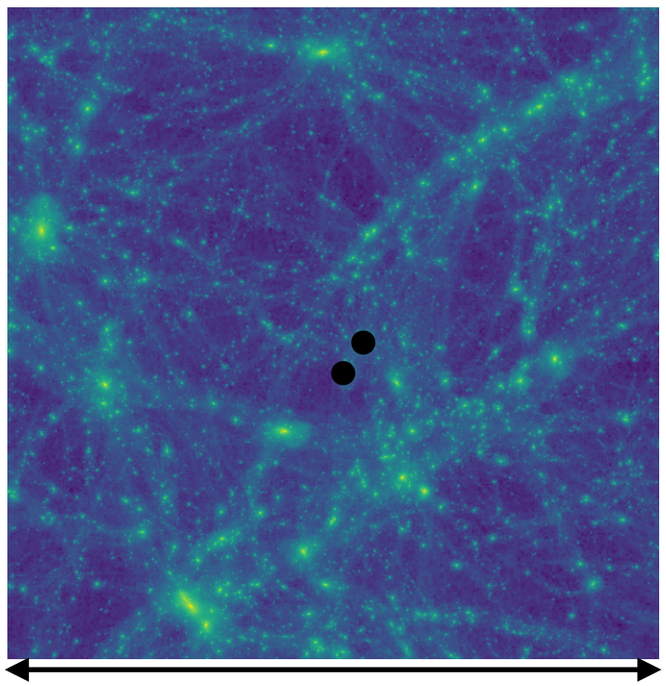


~100 Mpc (cosmology)

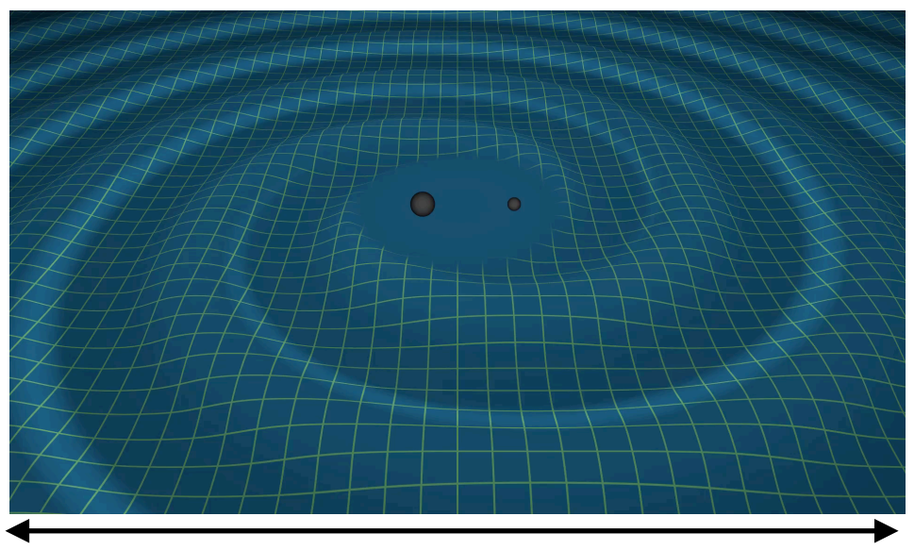


~1 au (BH merger)

Black holes journey over a Hubble time

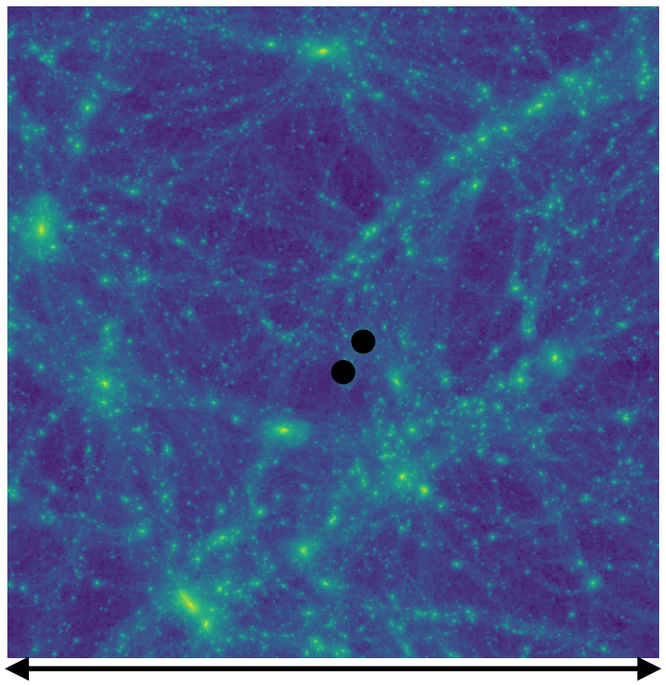


~100 Mpc (cosmology)



~1 au (BH merger)

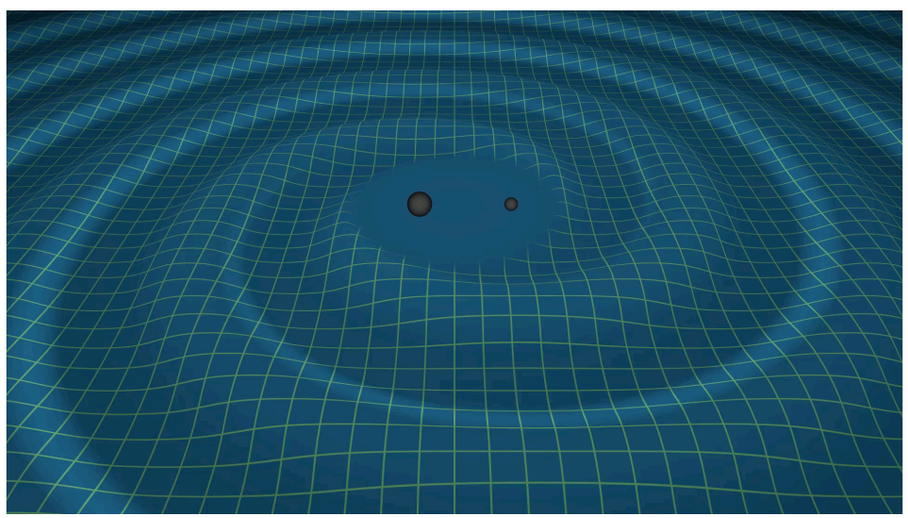
Black holes journey over a Hubble time



~100 Mpc (cosmology)

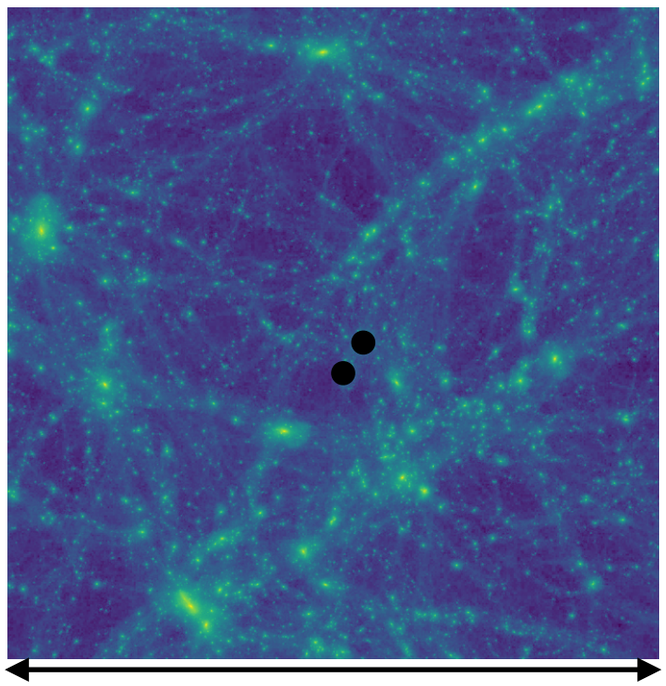
Gravity

~100 kpc (galaxy mergers)



~1 au (BH merger)

Black holes journey over a Hubble time

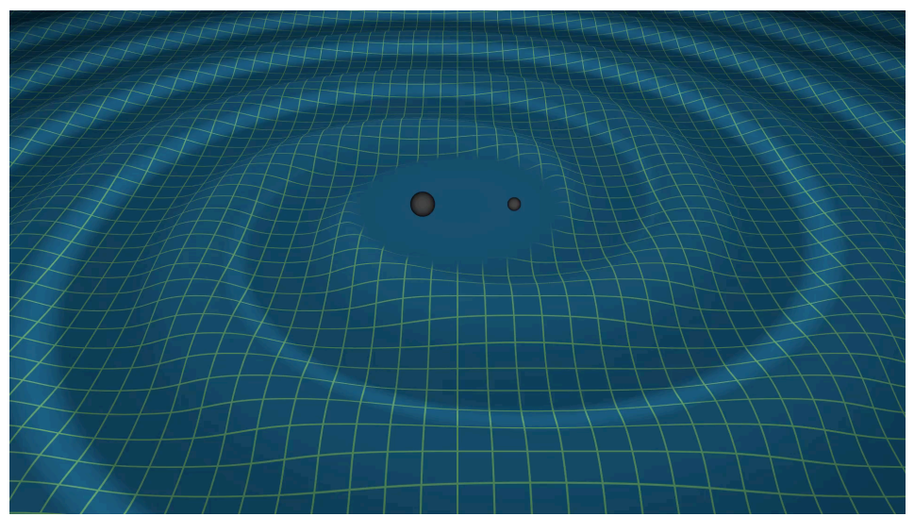


~100 Mpc (cosmology)

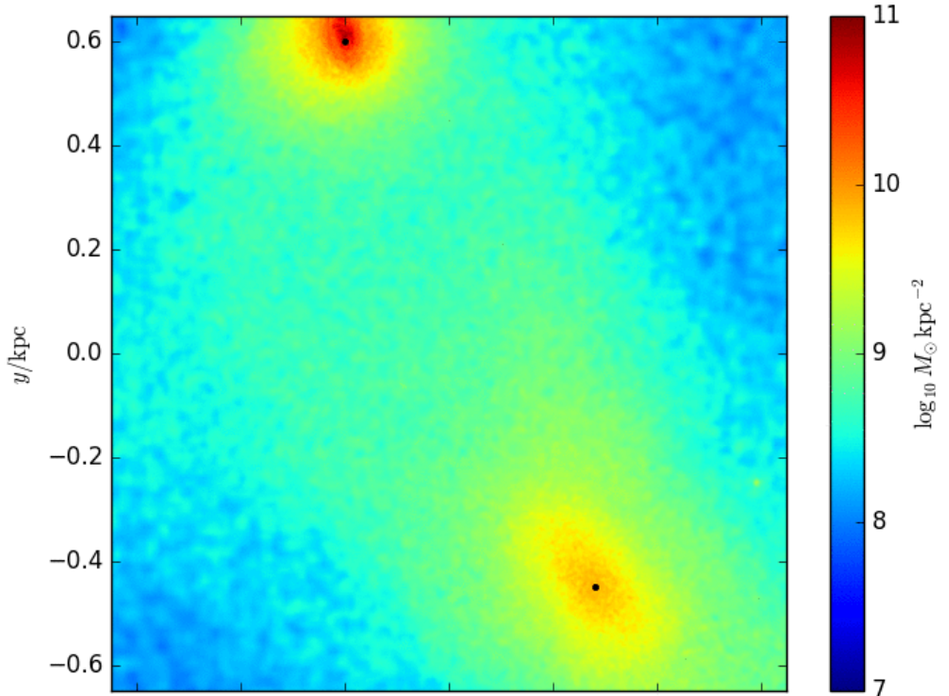
Gravity

~100 kpc (galaxy mergers)

Dynamical Friction



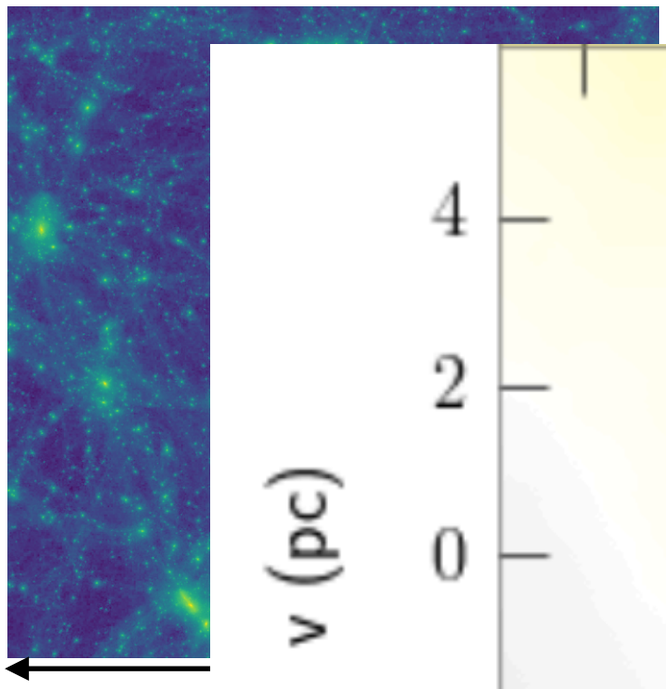
~1 au (BH merger)



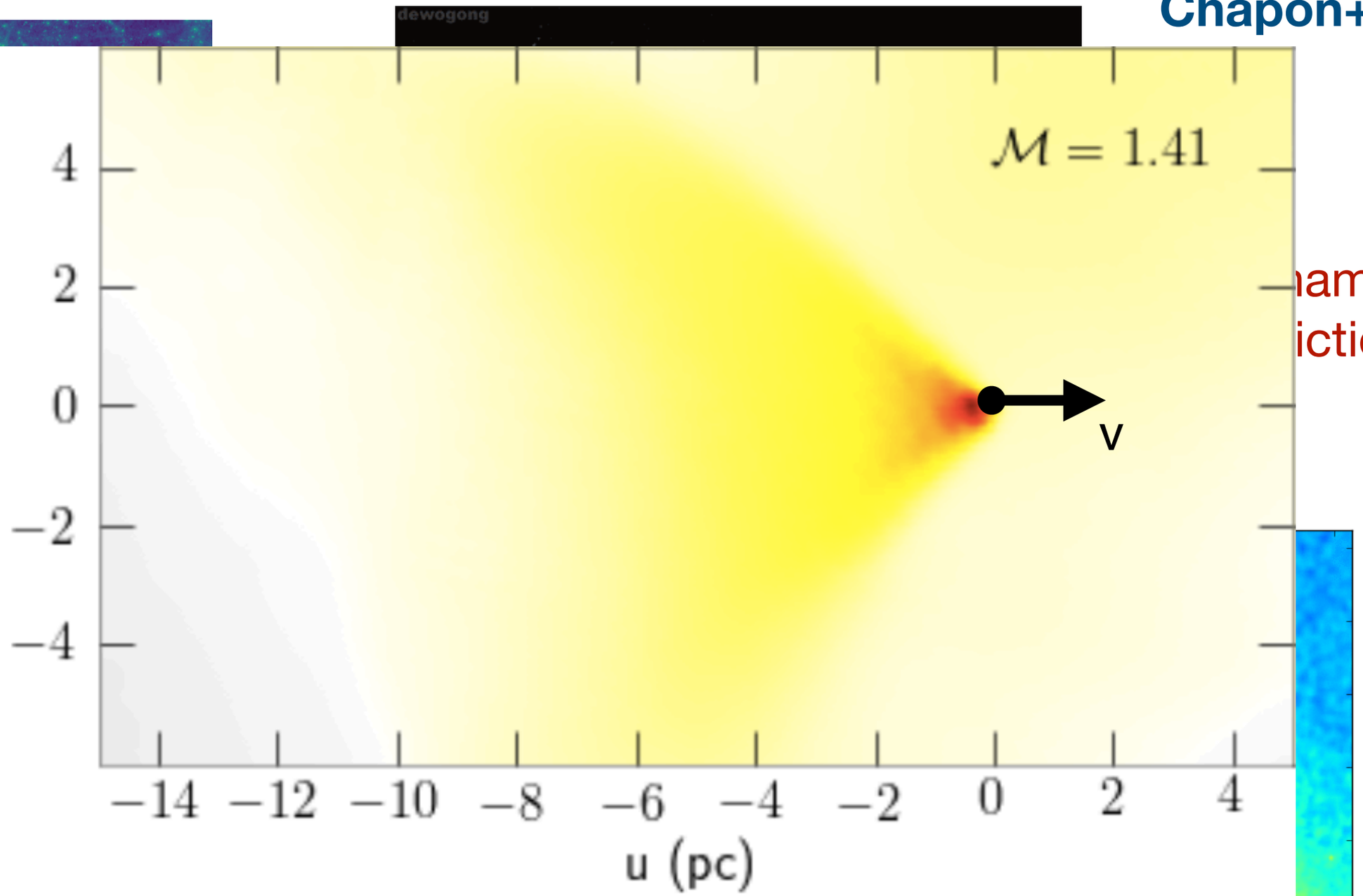
~1 kpc (end of merger)

Black holes journey over a Hubble time

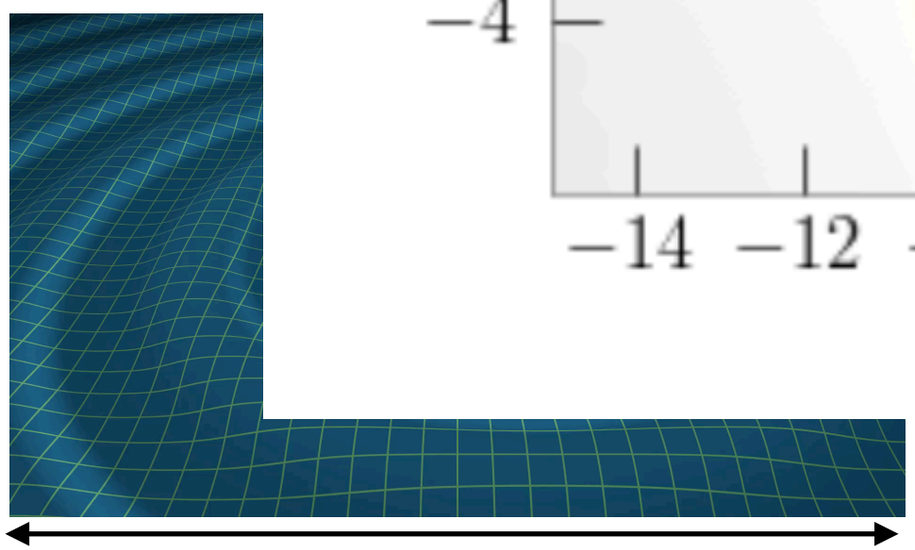
Chapon+12



~100 M



namical
iction

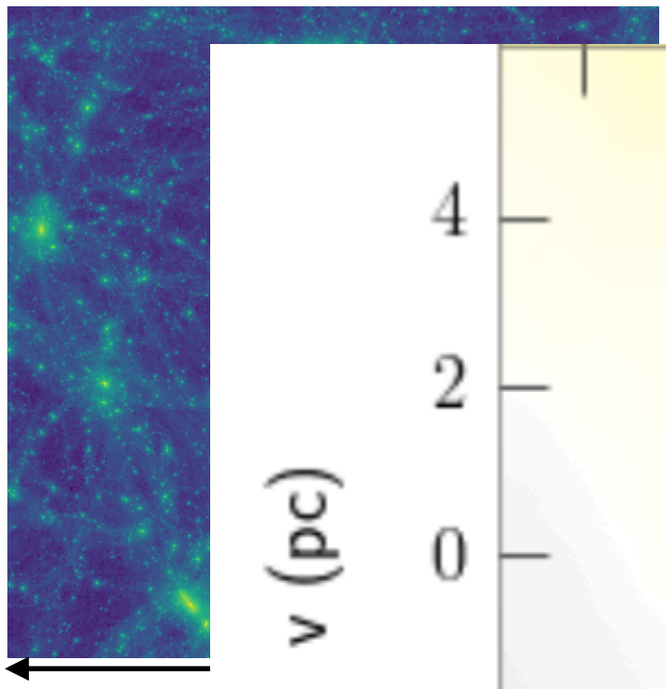


~1 au (BH merger)

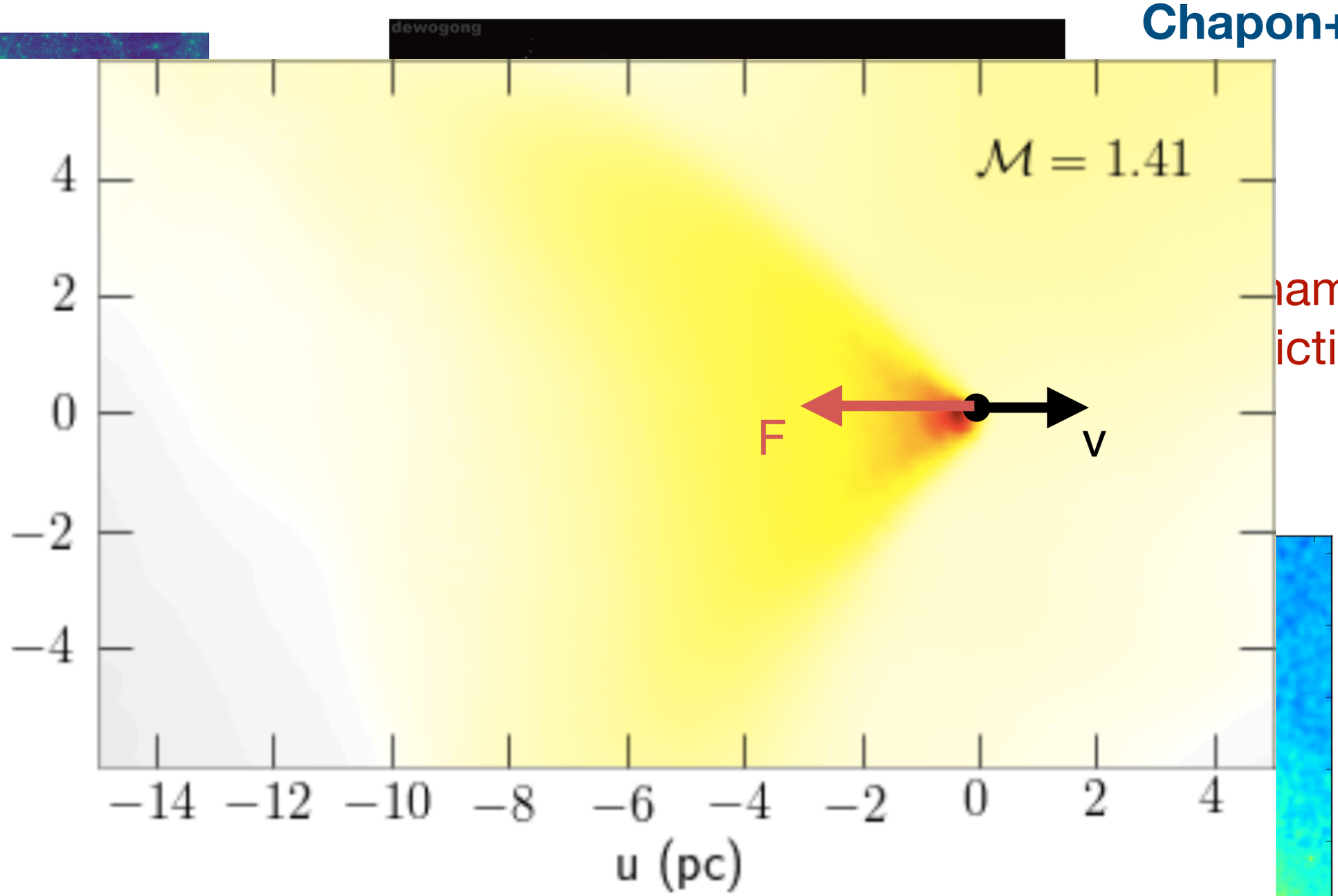
~1 kpc (end of merger)

Black holes journey over a Hubble time

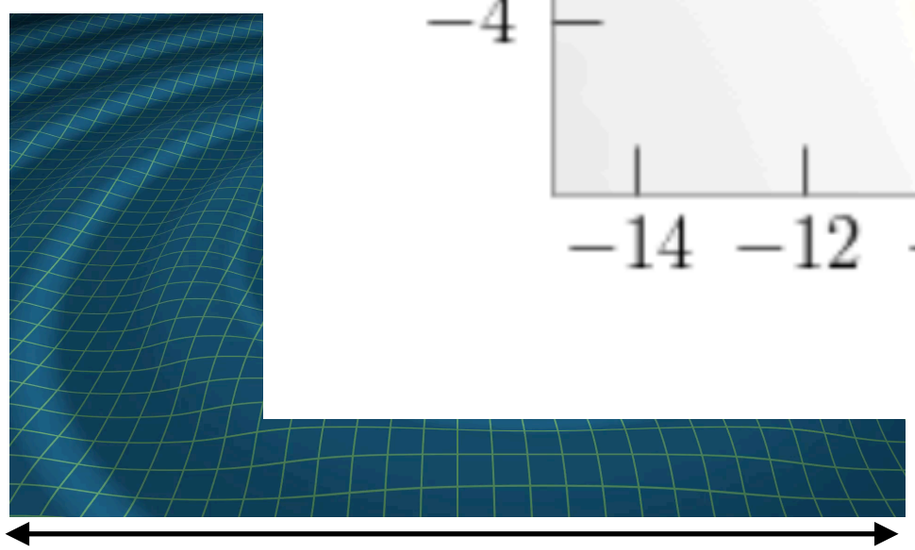
Chapon+12



~100 M



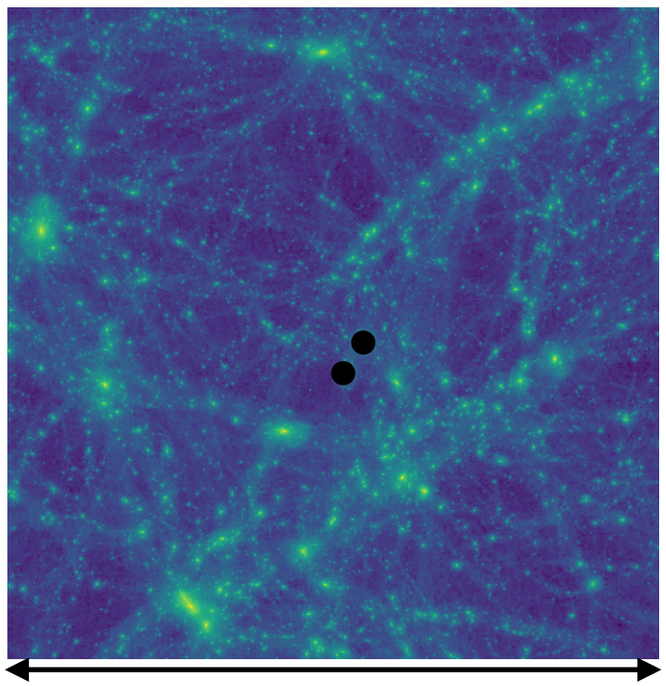
namical
iction



~1 au (BH merger)

~1 kpc (end of merger)

Black holes journey over a Hubble time

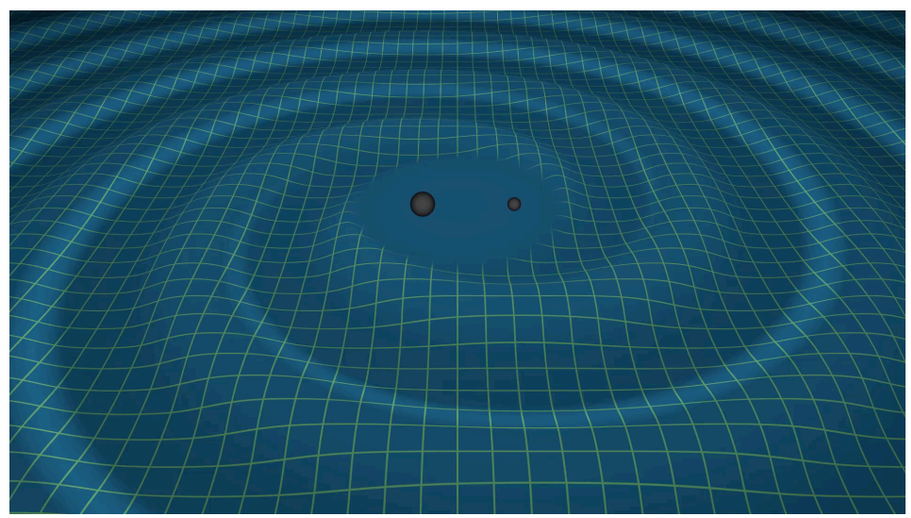


~100 Mpc (cosmology)

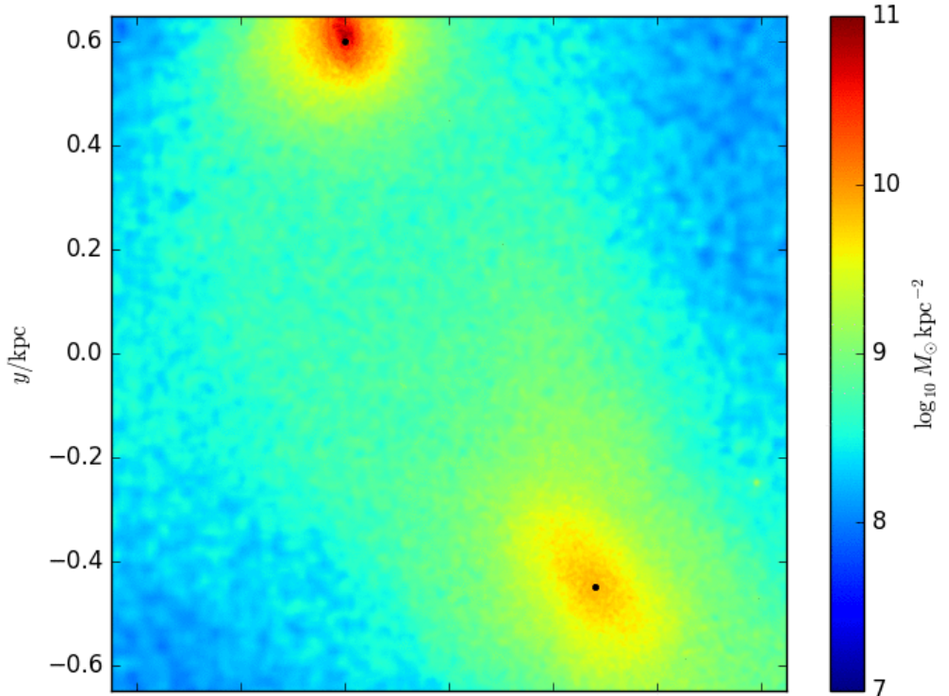
Gravity

~100 kpc (galaxy mergers)

Dynamical Friction

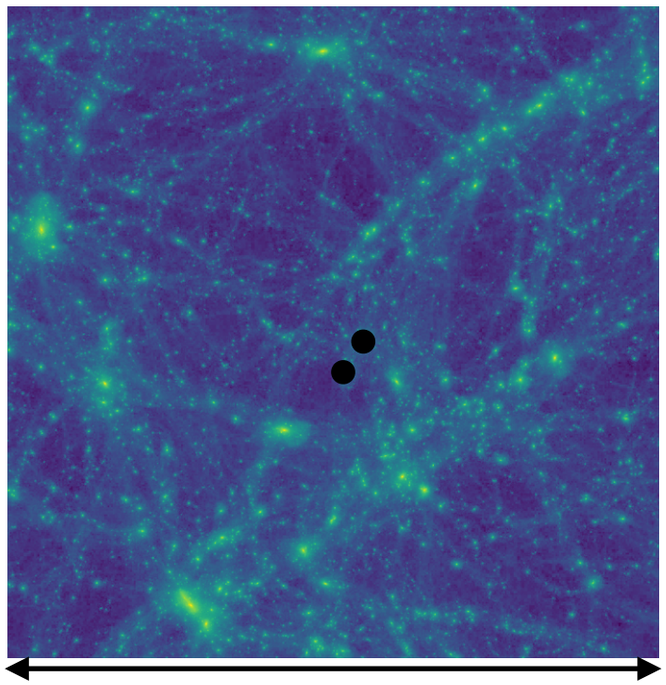


~1 au (BH merger)



~1 kpc (end of merger)

Black holes journey over a Hubble time

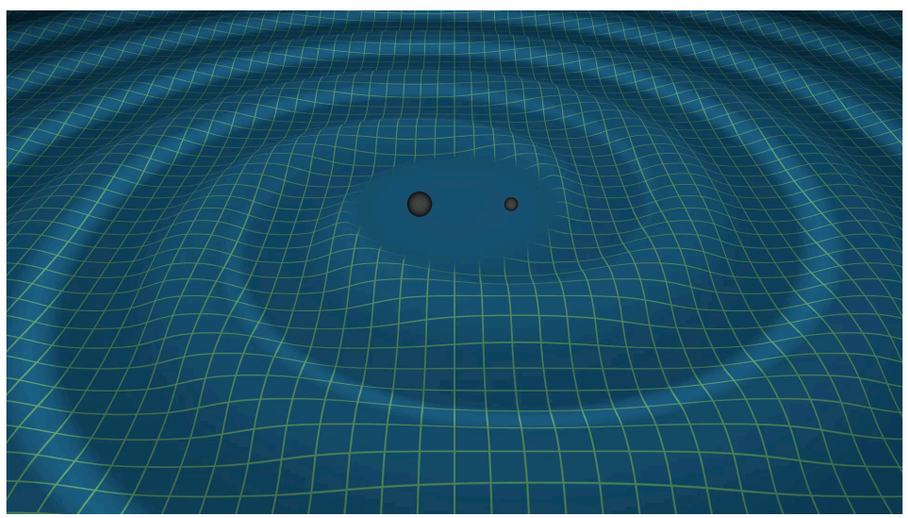


~100 Mpc (cosmology)

Gravity

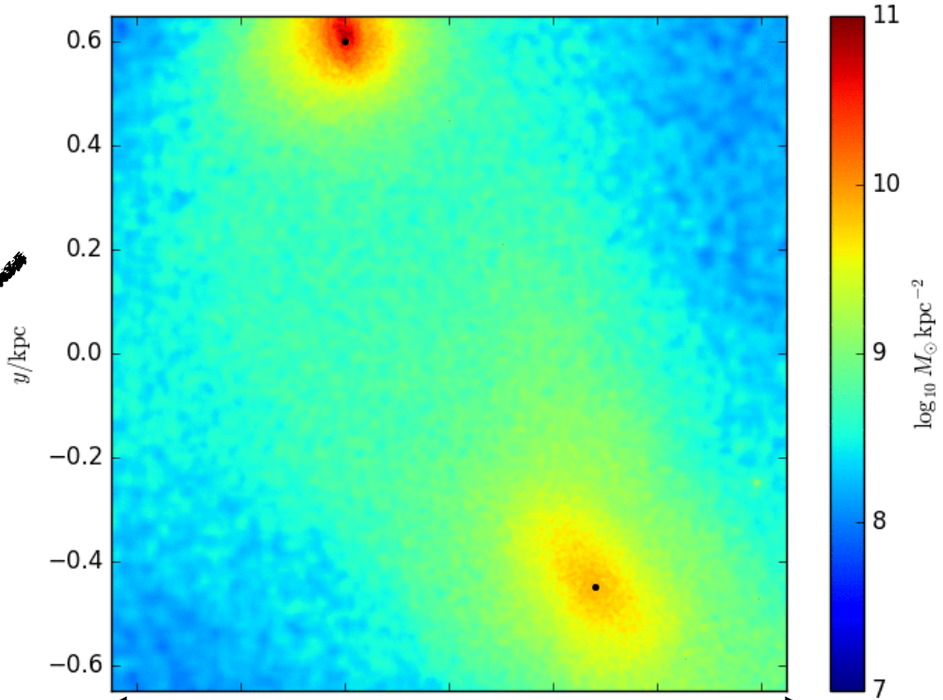
~100 kpc (galaxy mergers)

Dynamical Friction



~1 au (BH merger)

Gas torques?
Stellar scattering?
Last pc problem



~1 kpc (end of merger)

Goal

Estimate the merger rate of seed BHs that we will detect with LISA

Tool

Cosmological simulation to get self consistent physics and large statistics

Issues

Huge range of scales, therefore difficult to balance resolution vs volume, and dynamics of BHs hard to compute

Outline

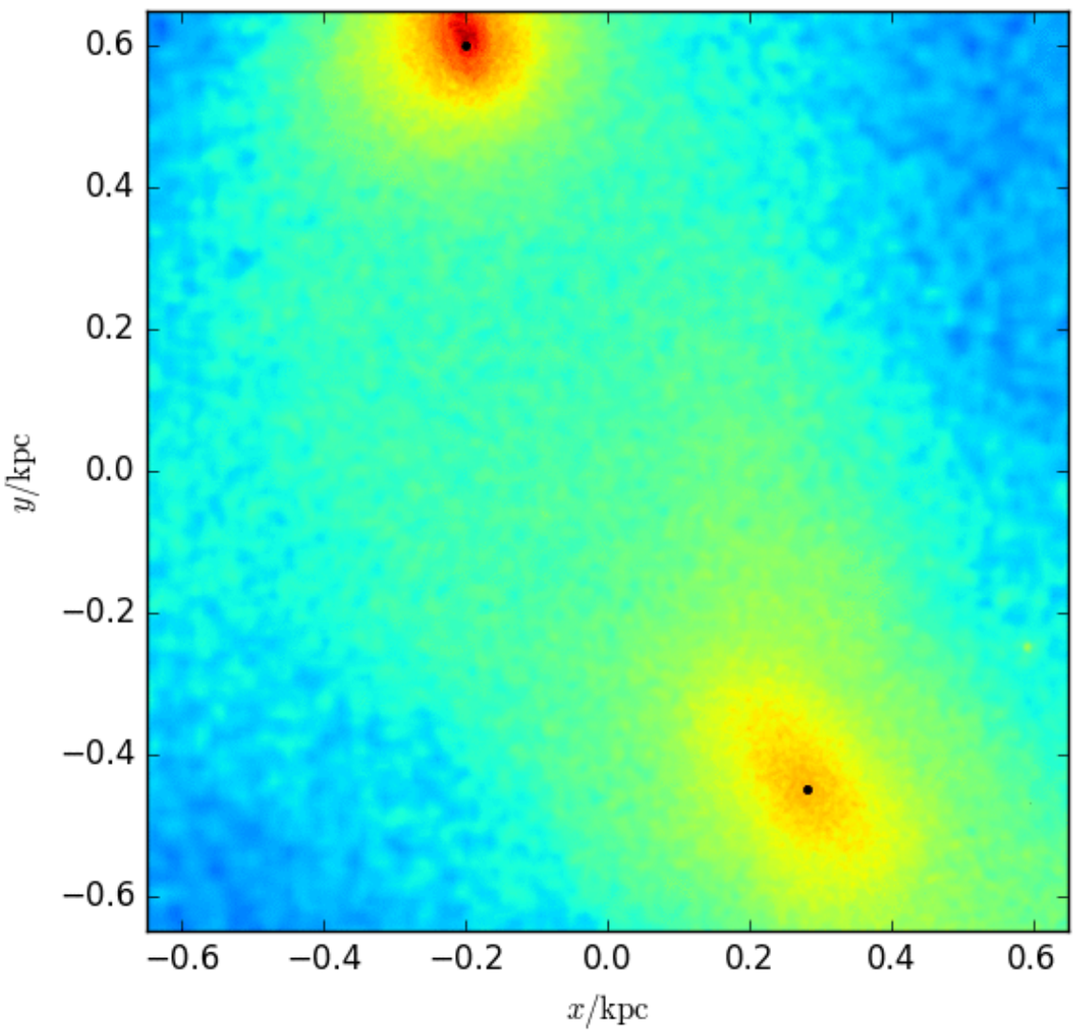
A. A first step to better track the dynamics of BHs

   1. Effects of resolution **(Pfister+17)**

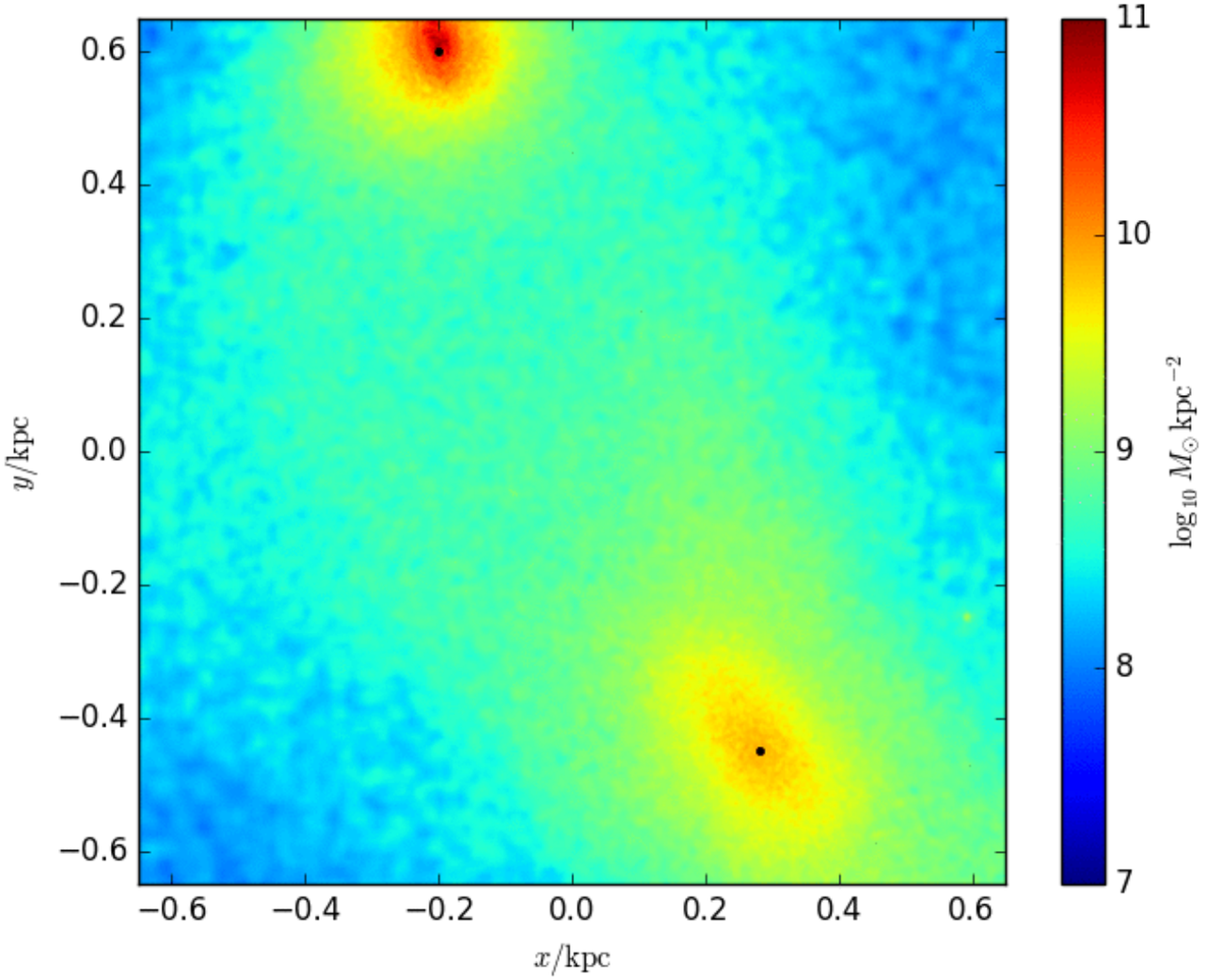
   2. Unresolved dynamics **(Pfister in prep)**

B. Lonely black holes at high redshift

Effects of resolution

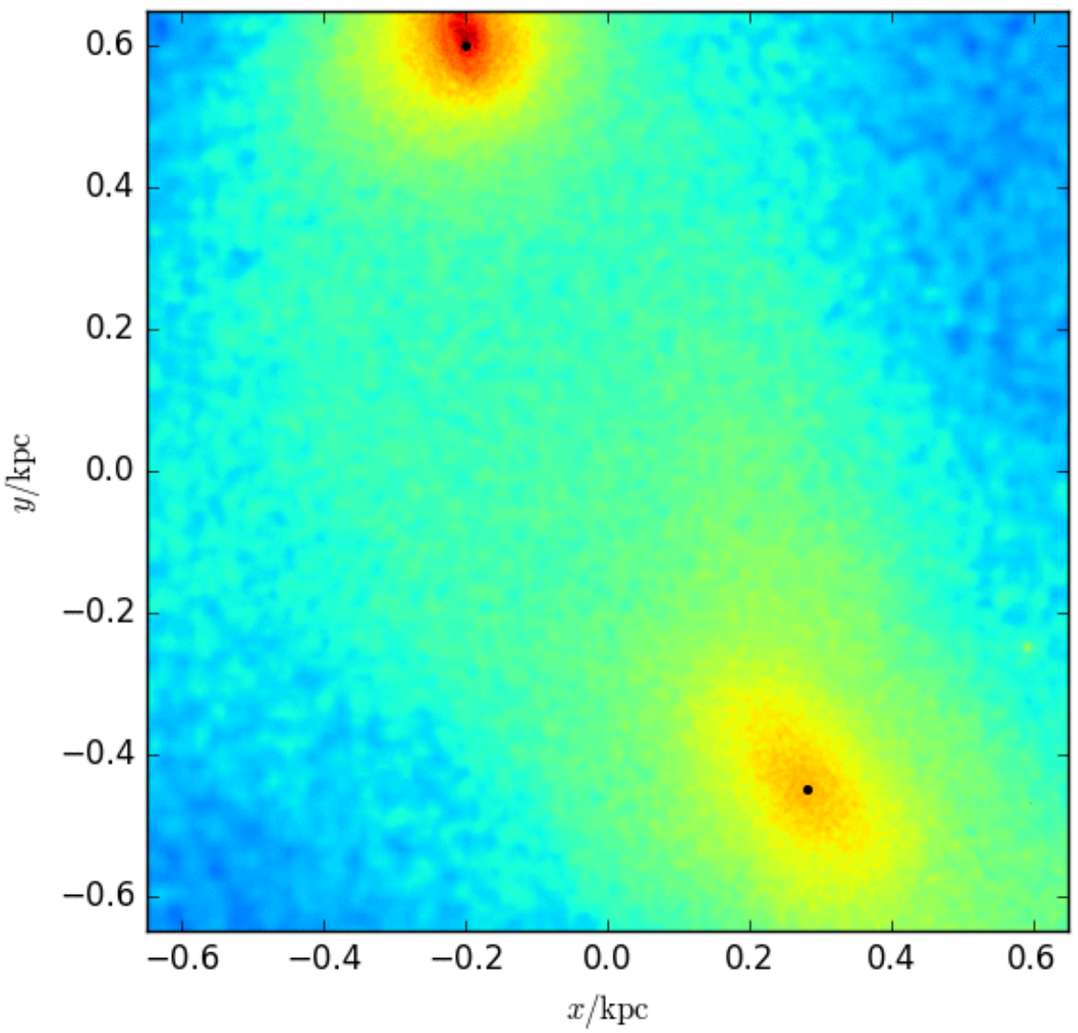


20 pc resolution

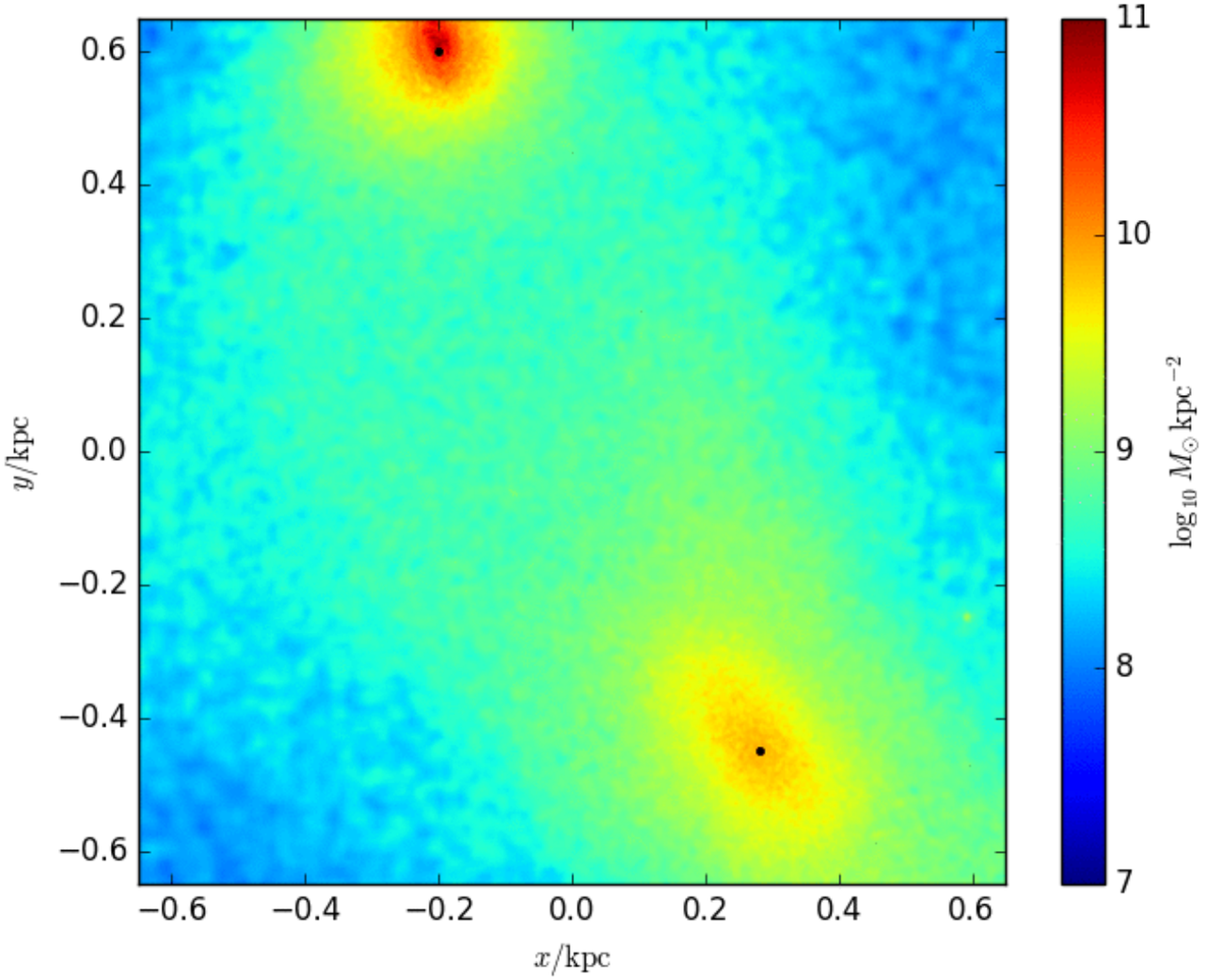


1 pc resolution

Effects of resolution

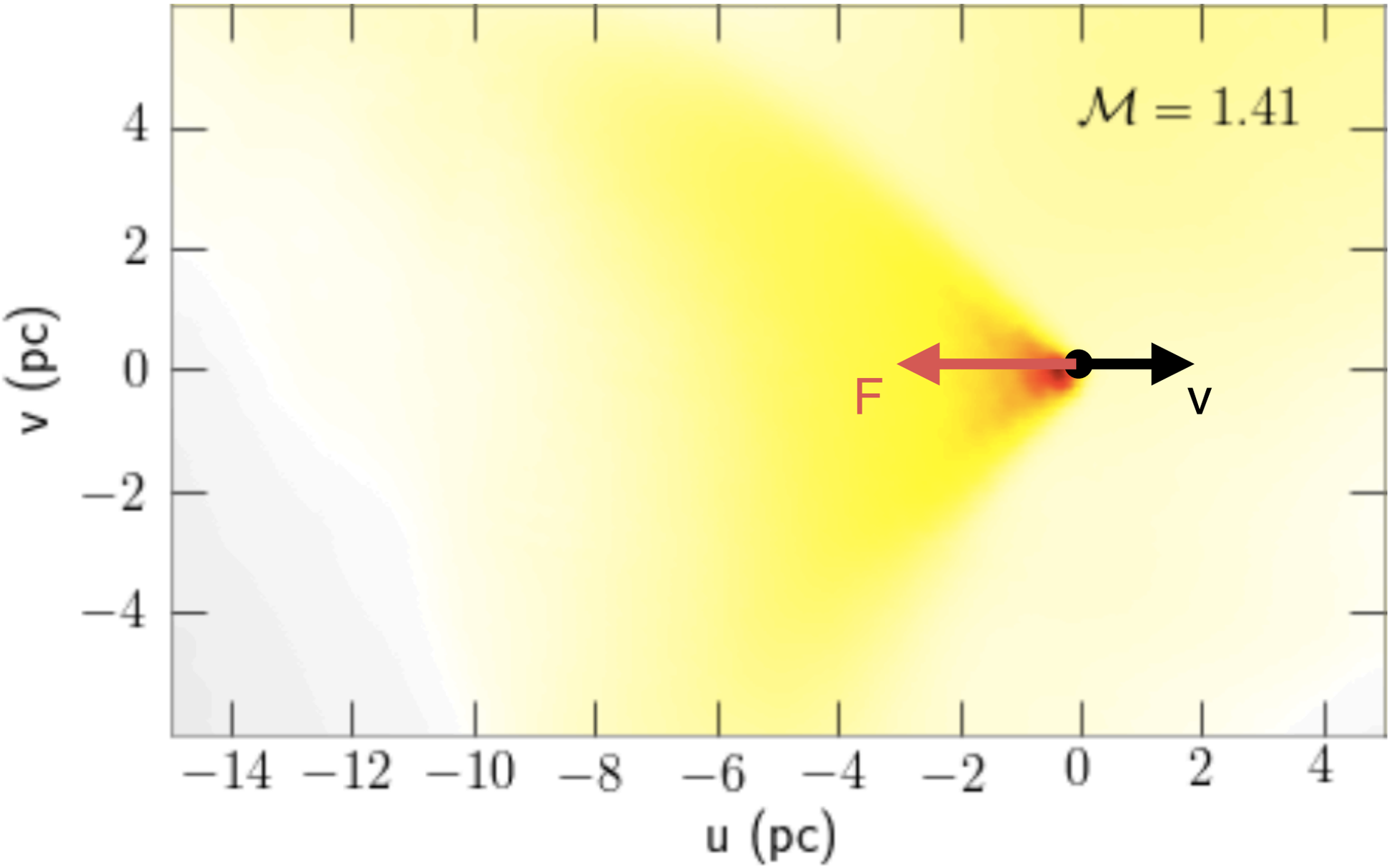


20 pc resolution



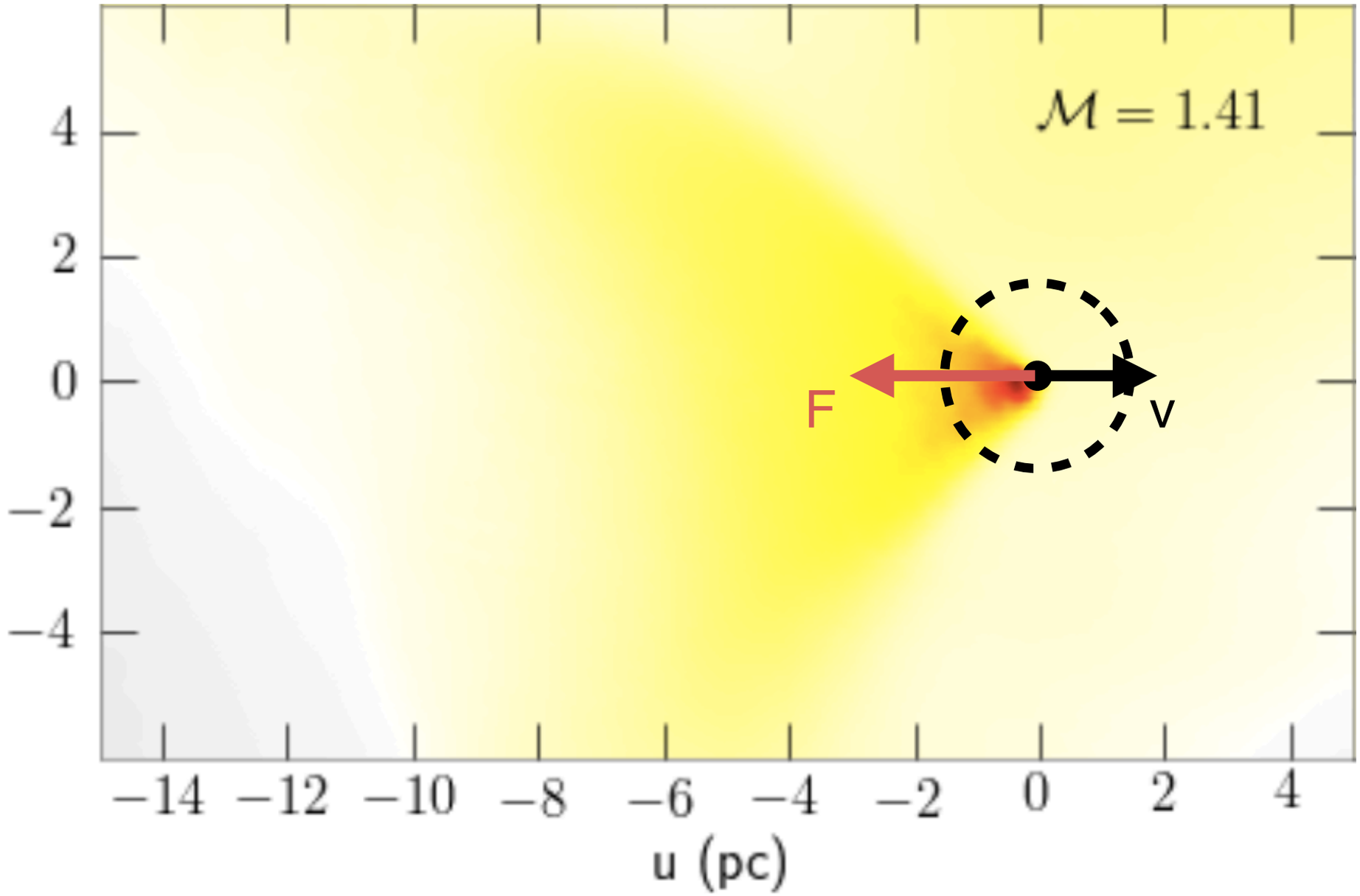
1 pc resolution

Effects of resolution



Chapon+12

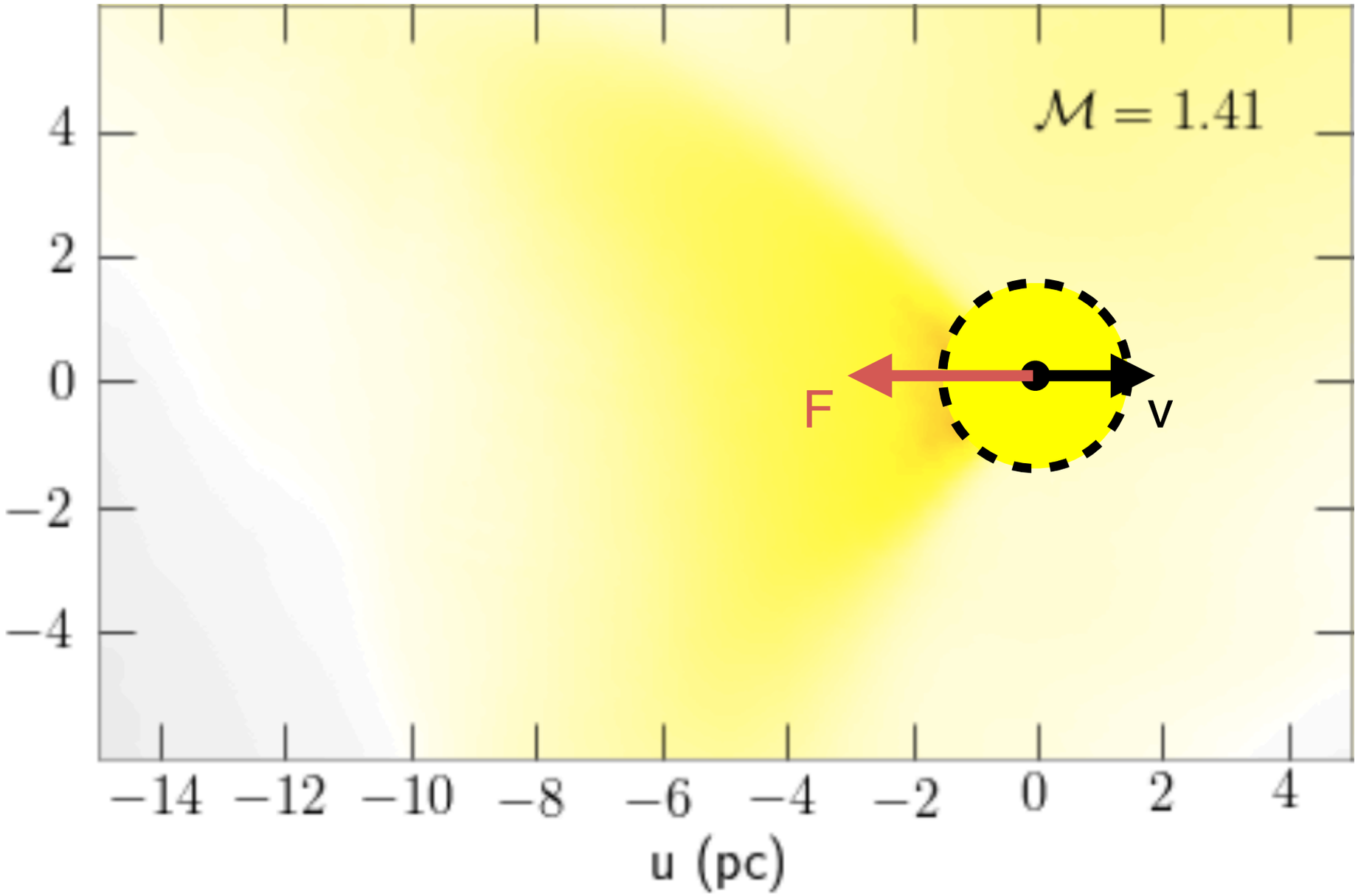
Effects of resolution



Chapon+12

$$r_{\rm def} = 1\ {\rm pc} \left(\frac{M_\bullet}{10^7 M_\odot} \right) \left(\frac{v}{200 {\rm km\ s^{-1}}} \right)^{-2}$$

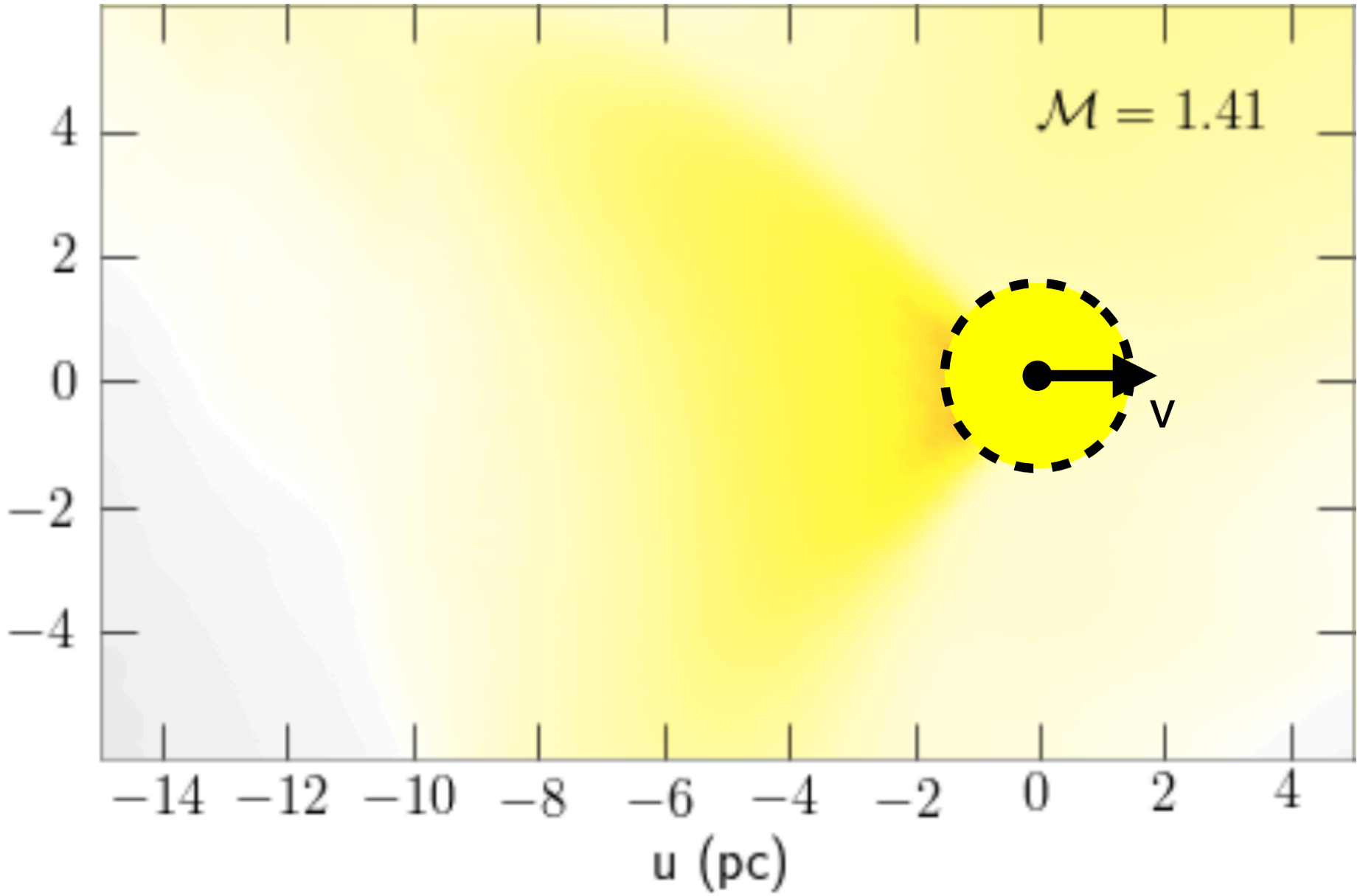
Effects of resolution



Chapon+12

$$r_{\rm def} = 1\ {\rm pc} \left(\frac{M_\bullet}{10^7 M_\odot} \right) \left(\frac{v}{200 {\rm km\ s}^{-1}} \right)^{-2}$$

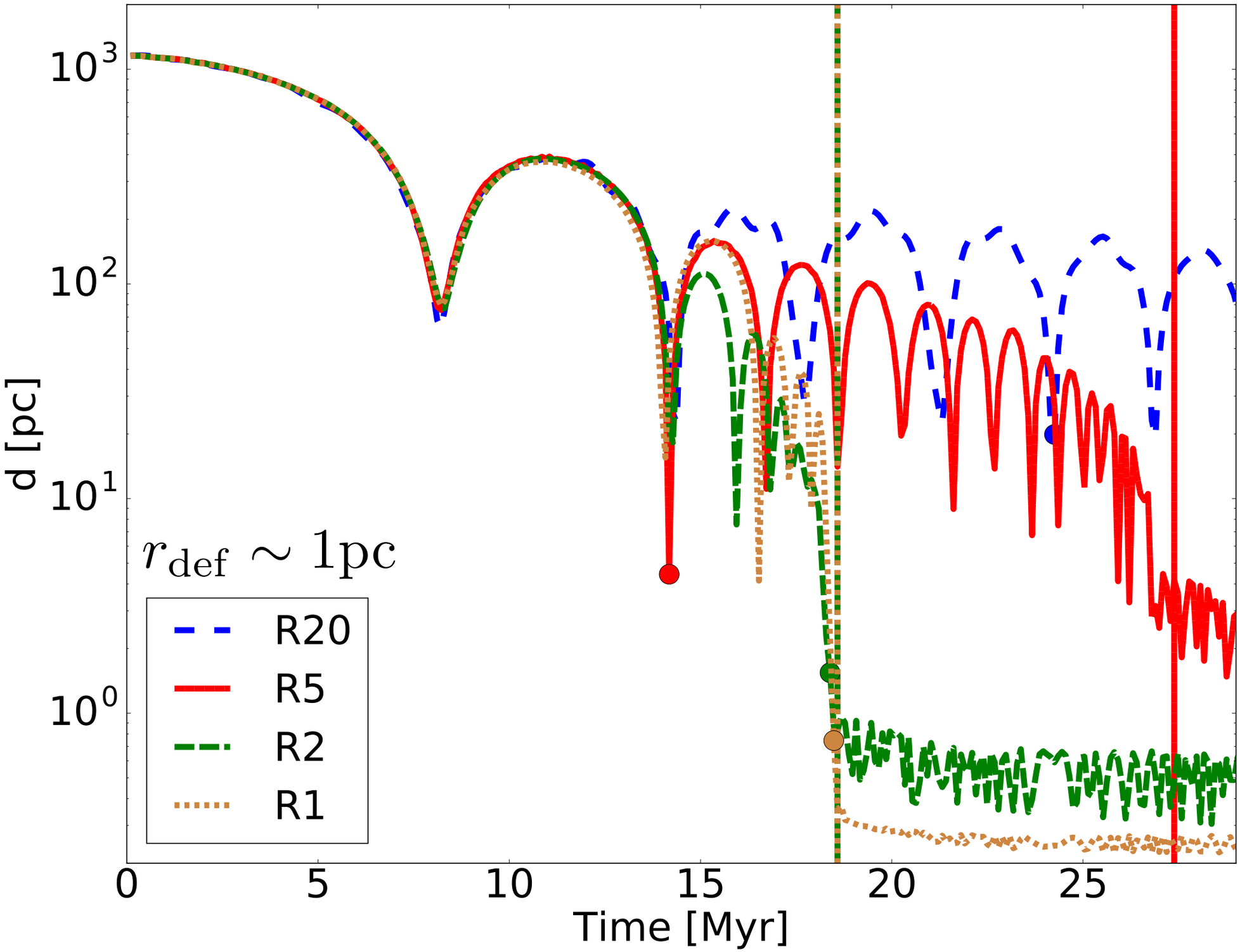
Effects of resolution



Chapon+12

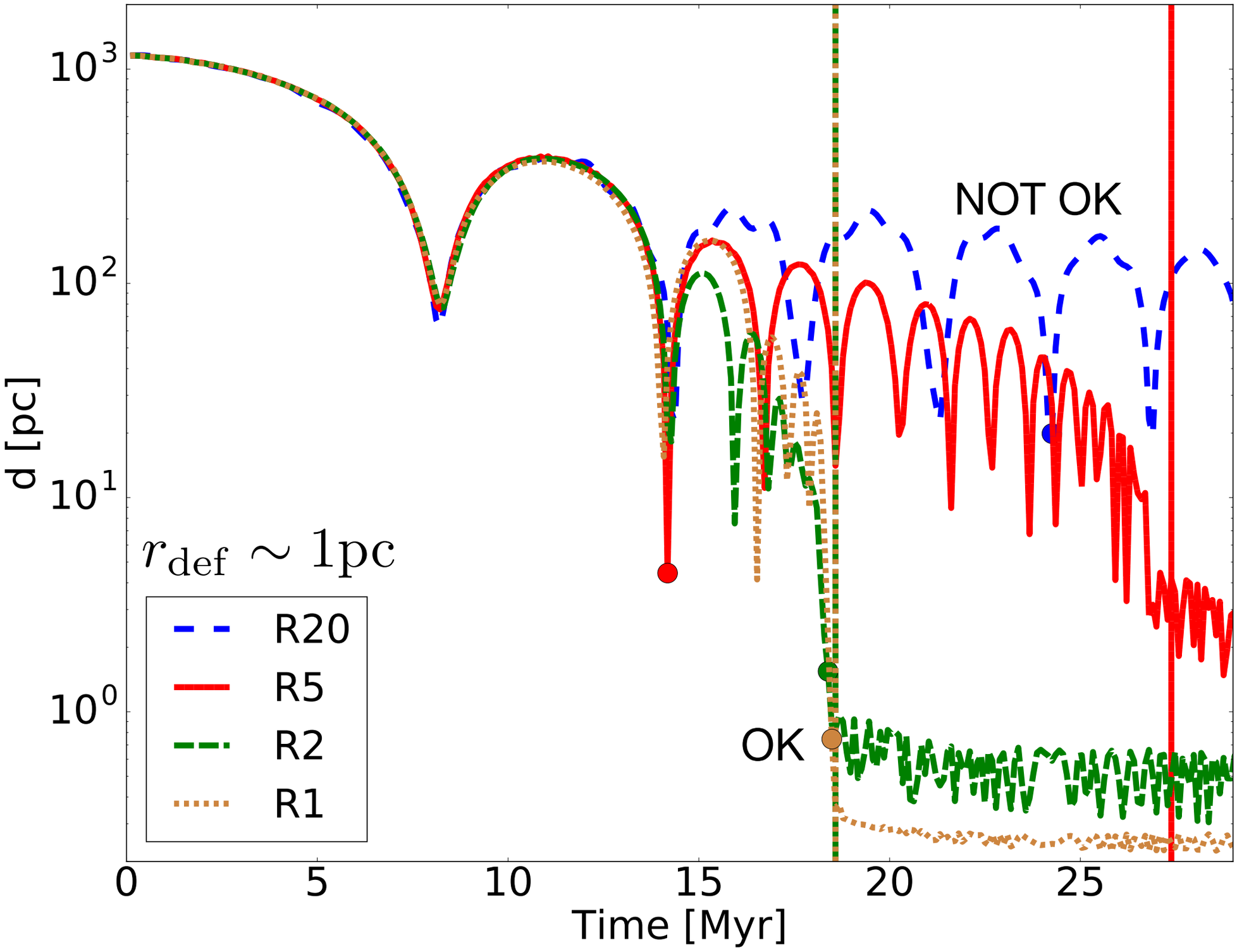
$$r_{\rm def} = 1\ {\rm pc} \left(\frac{M_\bullet}{10^7 M_\odot} \right) \left(\frac{v}{200 {\rm km\ s}^{-1}} \right)^{-2}$$

Effects of resolution



Hugo Pfister - pfister@iap.fr

Effects of resolution



Hugo Pfister - pfister@iap.fr

Unresolved dynamics

Unresolved dynamics

- For a 10^7 Msun BH moving in a 200 km s^{-1} velocity dispersion galaxy, resolution must be ~1 pc.

Unresolved dynamics

- For a 10^7 Msun BH moving in a 200 km s^{-1} velocity dispersion galaxy, resolution must be ~1 pc.
- Most cosmological simulations have a resolution of ~1 kpc, even zooms can only reach ~10 pc.

Unresolved dynamics

- For a 10^7 Msun BH moving in a 200 km s^{-1} velocity dispersion galaxy, resolution must be ~1 pc.
- Most cosmological simulations have a resolution of ~1 kpc, even zooms can only reach ~10 pc.

‘Fix’ BHs in the center of halos/galaxies.

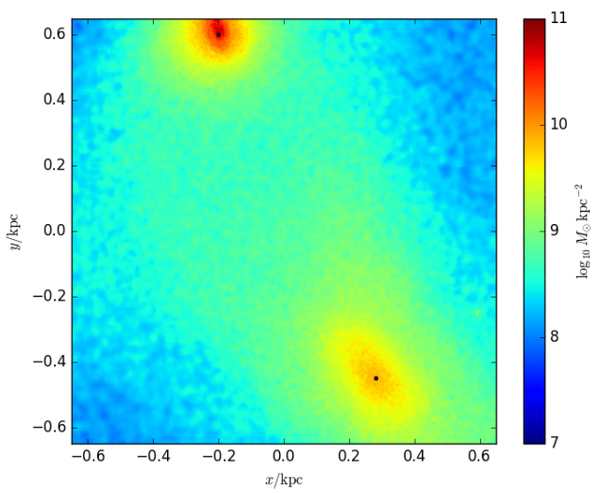
This results in very fast BH mergers following galaxy mergers.

Unresolved dynamics

- For a 10^7 Msun BH moving in a 200 km s^{-1} velocity dispersion galaxy, resolution must be ~1 pc.
- Most cosmological simulations have a resolution of ~1 kpc, even zooms can only reach ~10 pc.

‘Fix’ BHs in the center of halos/galaxies.

This results in very fast BH mergers following galaxy mergers.

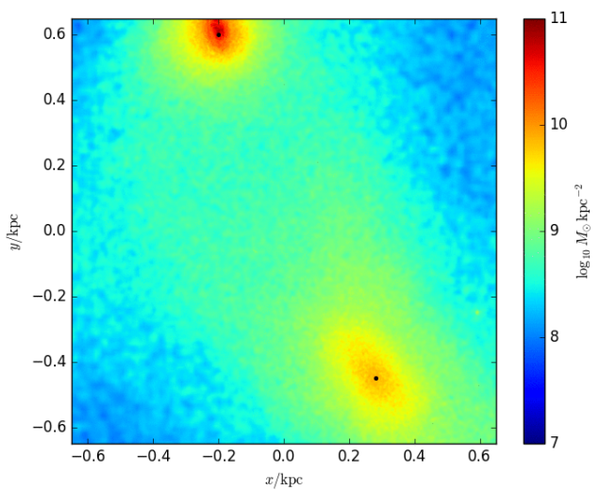


Unresolved dynamics

- For a 10^7 Msun BH moving in a 200 km s^{-1} velocity dispersion galaxy, resolution must be ~1 pc.
- Most cosmological simulations have a resolution of ~1 kpc, even zooms can only reach ~10 pc.

‘Fix’ BHs in the center of halos/galaxies.

This results in very fast BH mergers following galaxy mergers.



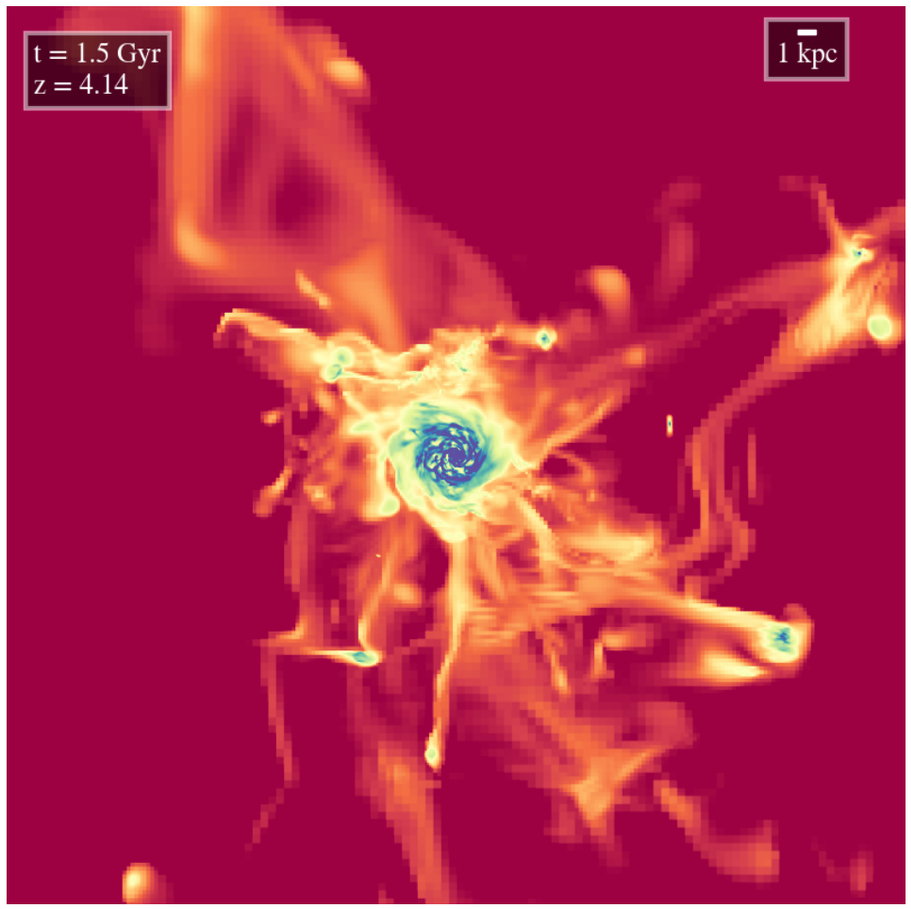
We adopt a more physical option.

We remove ‘by hand’ the momentum which should be removed due to unresolved dynamical friction by **gas, stars and dark matter**.

BH orbits naturally evolve: sink or wander.

Unresolved dynamics

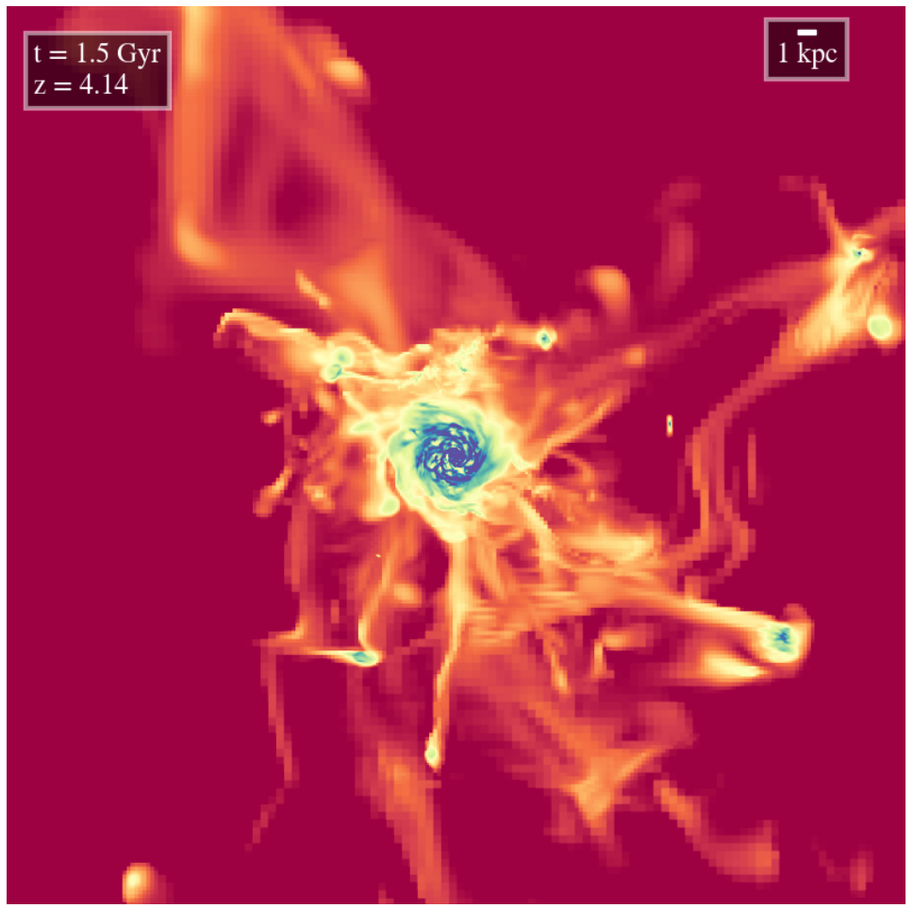
Gas (non collisionless)



Ostriker+99
Dubois+11 (Ramses)

Unresolved dynamics

Gas (non collisionless)



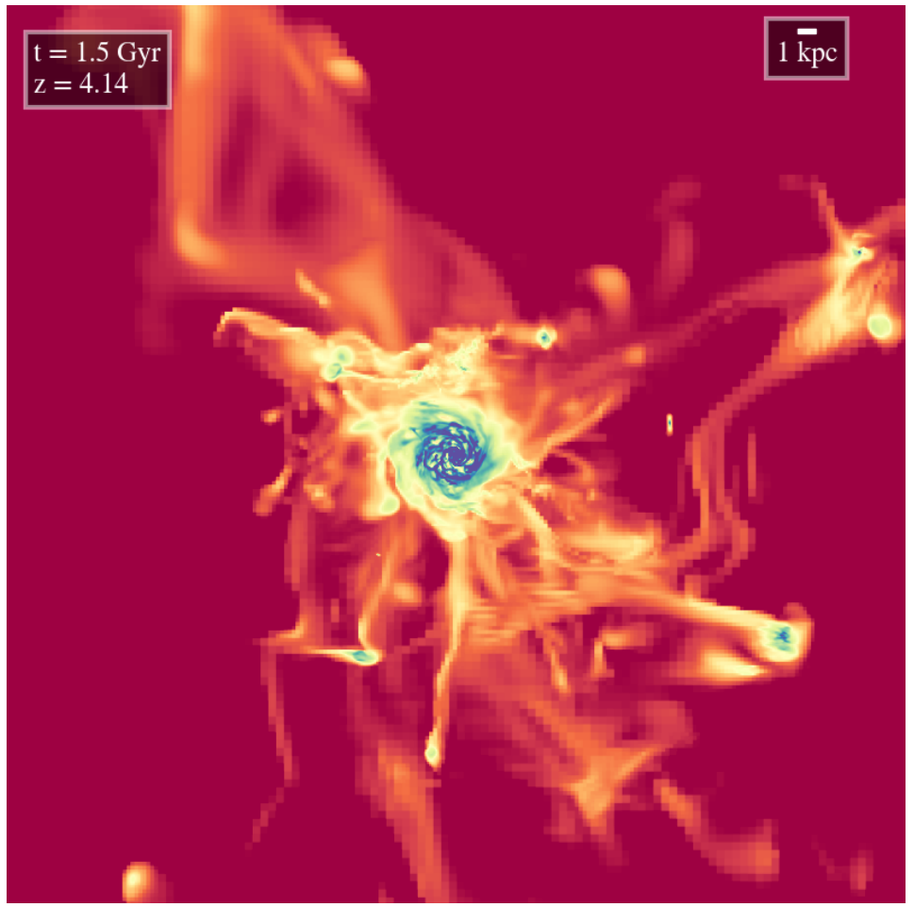
Ostriker+99

Dubois+11 (Ramses)

✅

Unresolved dynamics

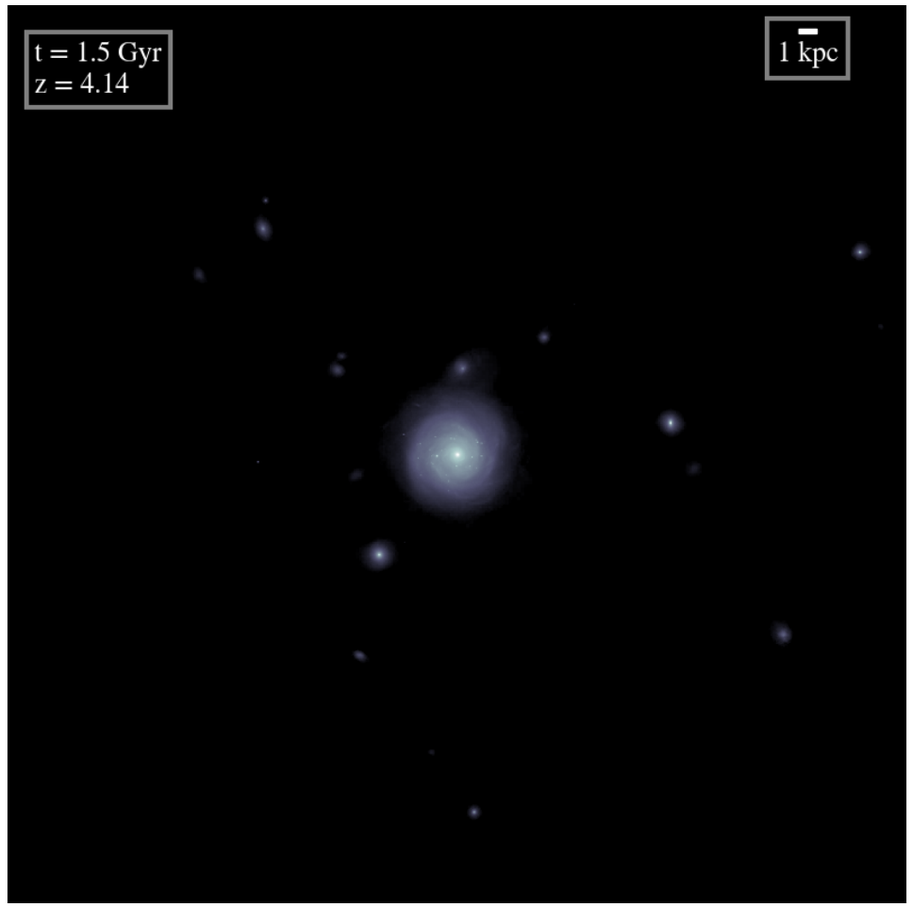
Gas (non collisionless)



Ostriker+99
Dubois+11 (Ramses)

✅

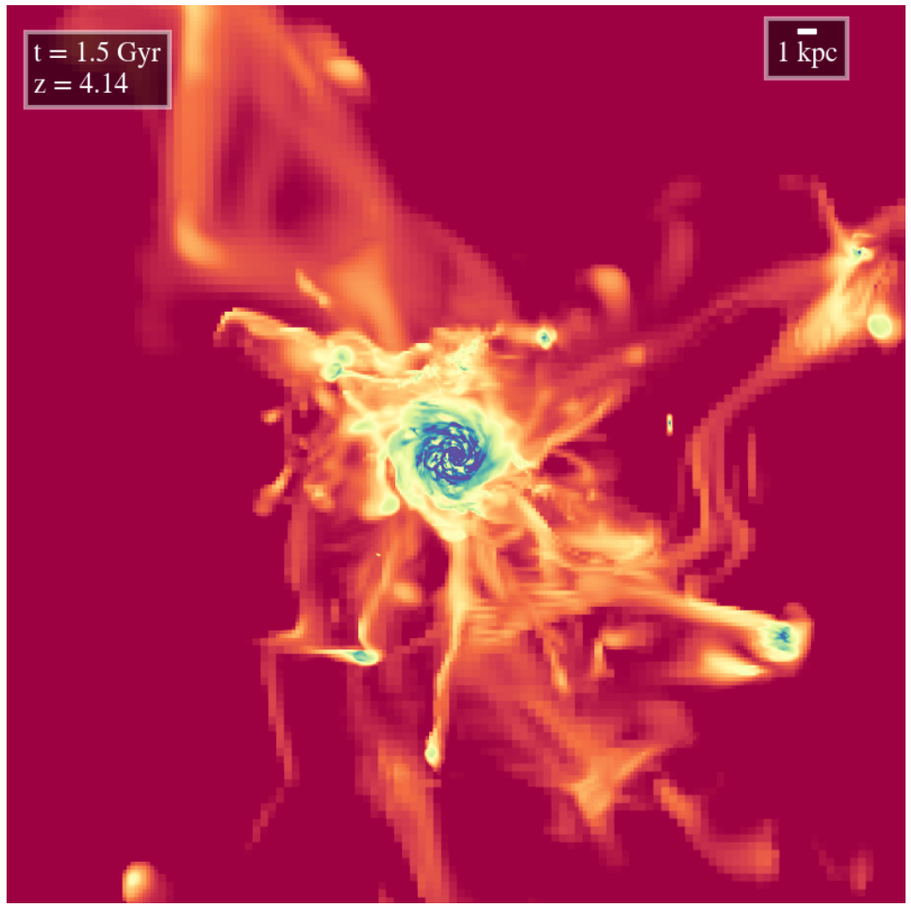
Stars/DM (collisionless)



Chandrasekhar+43
Tremmel+15 (ChaNGa)

Unresolved dynamics

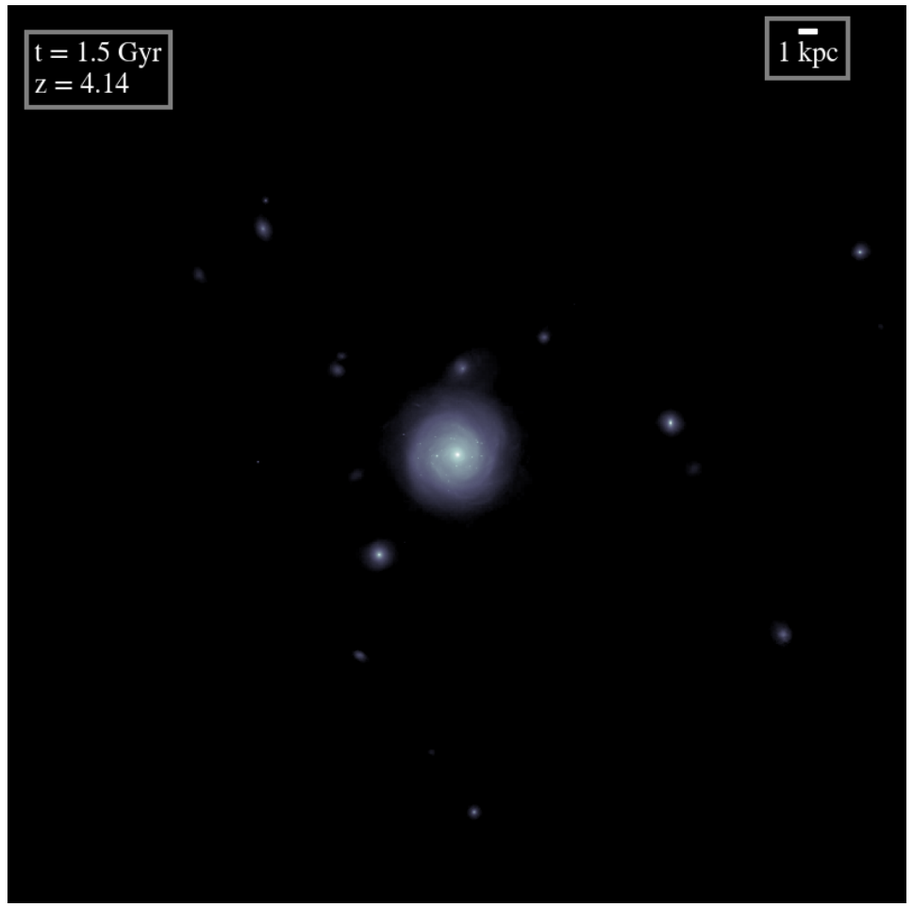
Gas (non collisionless)



Ostriker+99
Dubois+11 (Ramses)

✅

Stars/DM (collisionless)

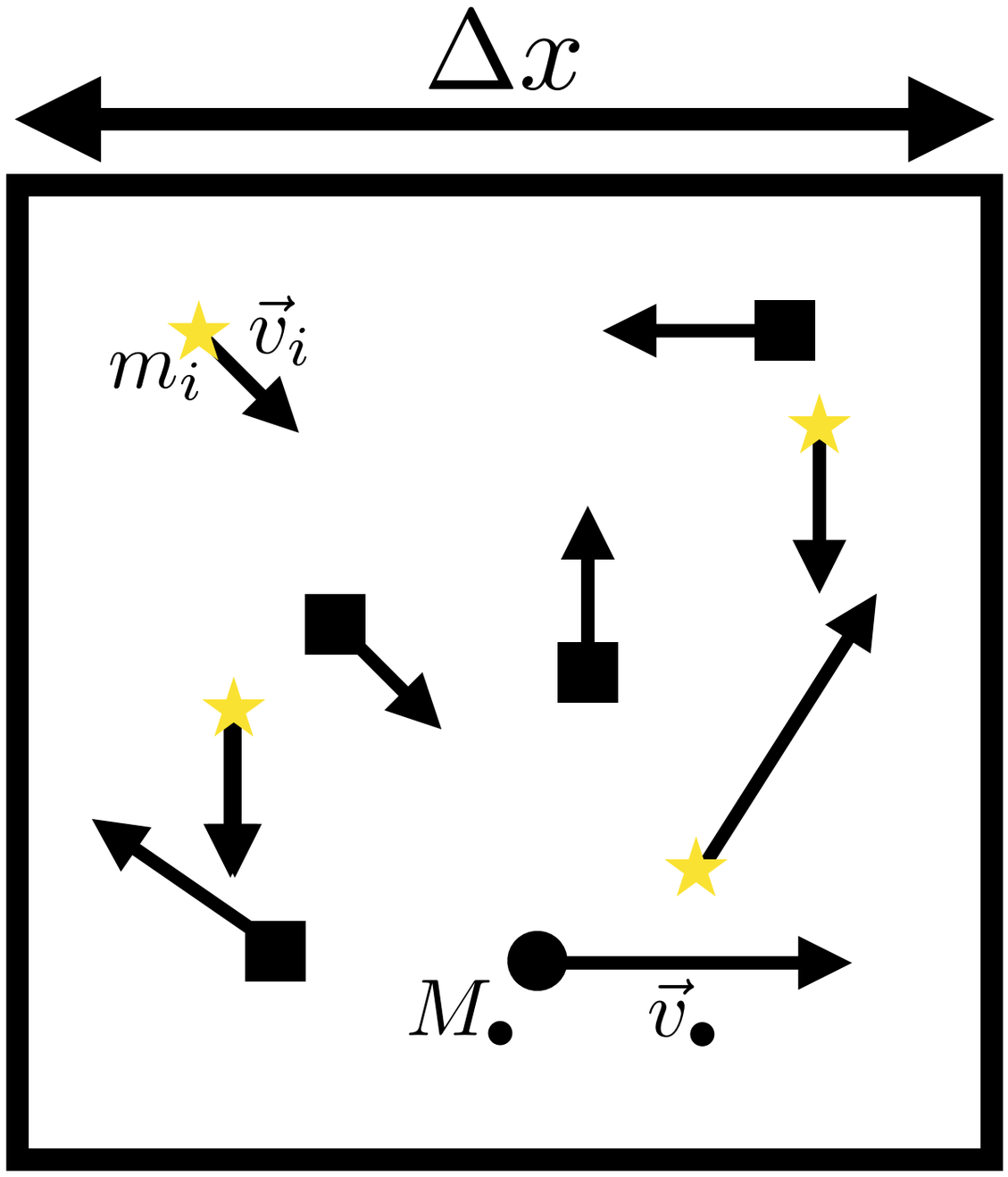


Chandrasekhar+43
Tremmel+15 (ChaNGa)

🛠️

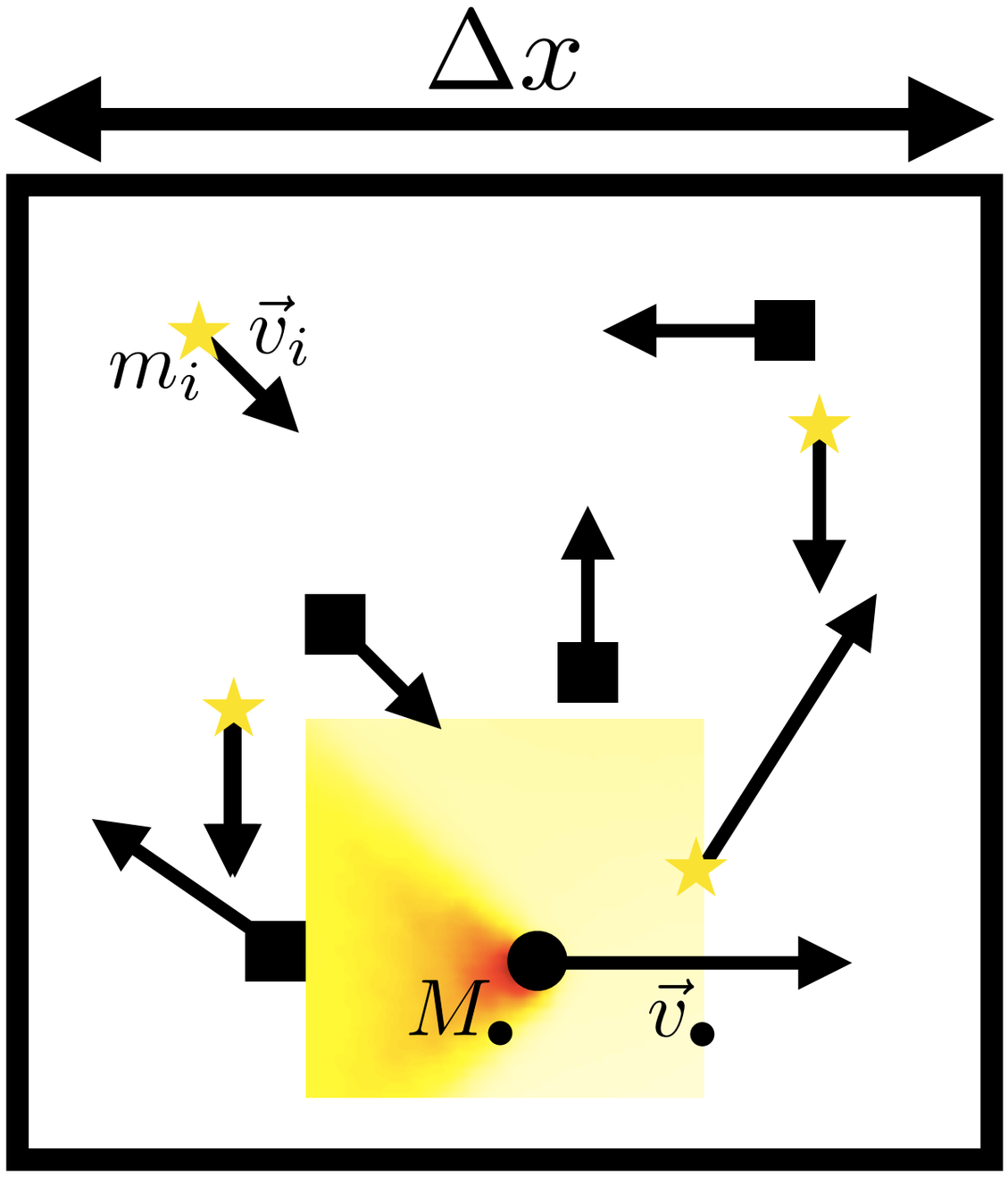
Unresolved dynamics

We use the cosmological code Ramses **(Teyssier+02)** and implement a subgrid model to take into account dynamical friction from stars and dark matter.



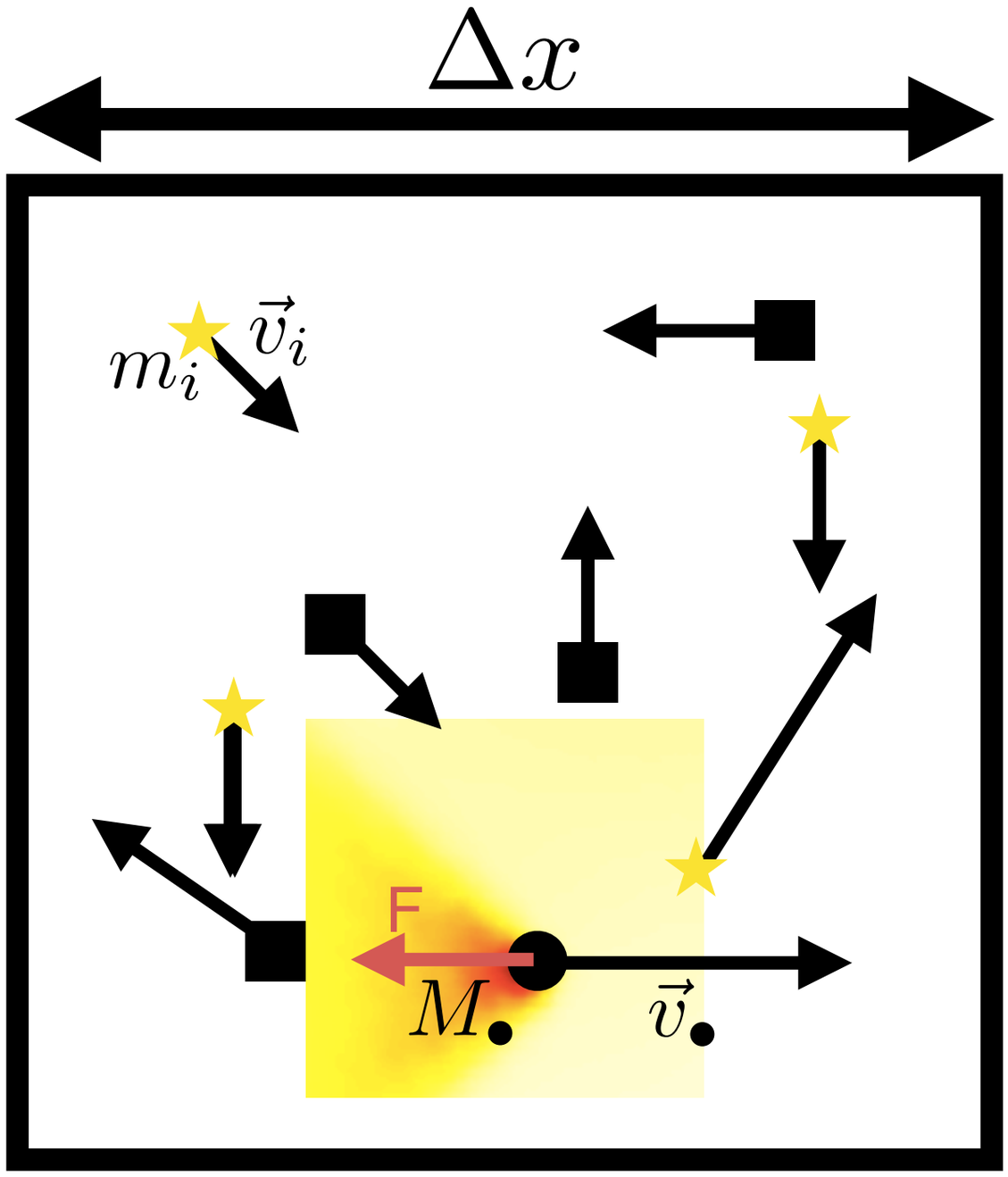
Unresolved dynamics

We use the cosmological code Ramses **(Teyssier+02)** and implement a subgrid model to take into account dynamical friction from stars and dark matter.



Unresolved dynamics

We use the cosmological code Ramses **(Teyssier+02)** and implement a subgrid model to take into account dynamical friction from stars and dark matter.



Unresolved dynamics

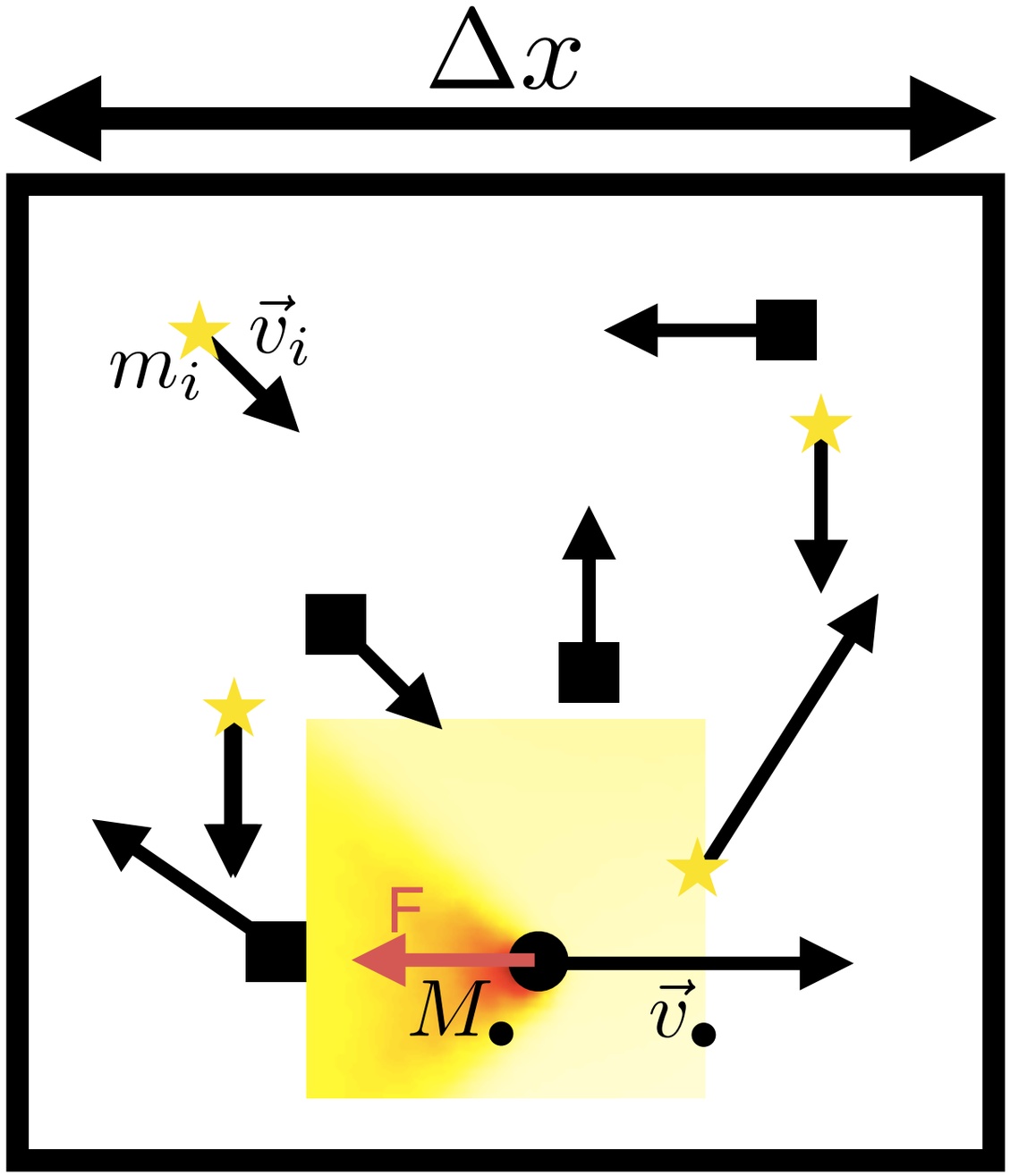
We use the cosmological code Ramses **(Teyssier+02)** and implement a subgrid model to take into account dynamical friction from stars and dark matter.

$$\vec{F}_\star = -4\pi \mathrm{G}^2 M_\bullet^2 \frac{\vec{v_\bullet}}{v_\bullet^3} \left\{ \ln\Lambda \int_0^{v_\bullet} 4\pi v^2 f(v) dv + ... \right.$$
$$\left. ... \int_{v_\bullet}^{\infty} 4\pi v^2 f(v) \left[\ln\left(\frac{v+v_\bullet}{v-v_\bullet} \right) - 2\frac{v_\bullet}{v} \right] dv \right\}$$

with:

$$\ln\Lambda = \ln(4\Delta x / r_{\mathrm{def}})$$

$$4\pi v^2 f(v) = \frac{3}{256\pi\Delta x^3} \sum_{i\in\mathcal{S}} m_i \delta(v_i - v)$$



Unresolved dynamics

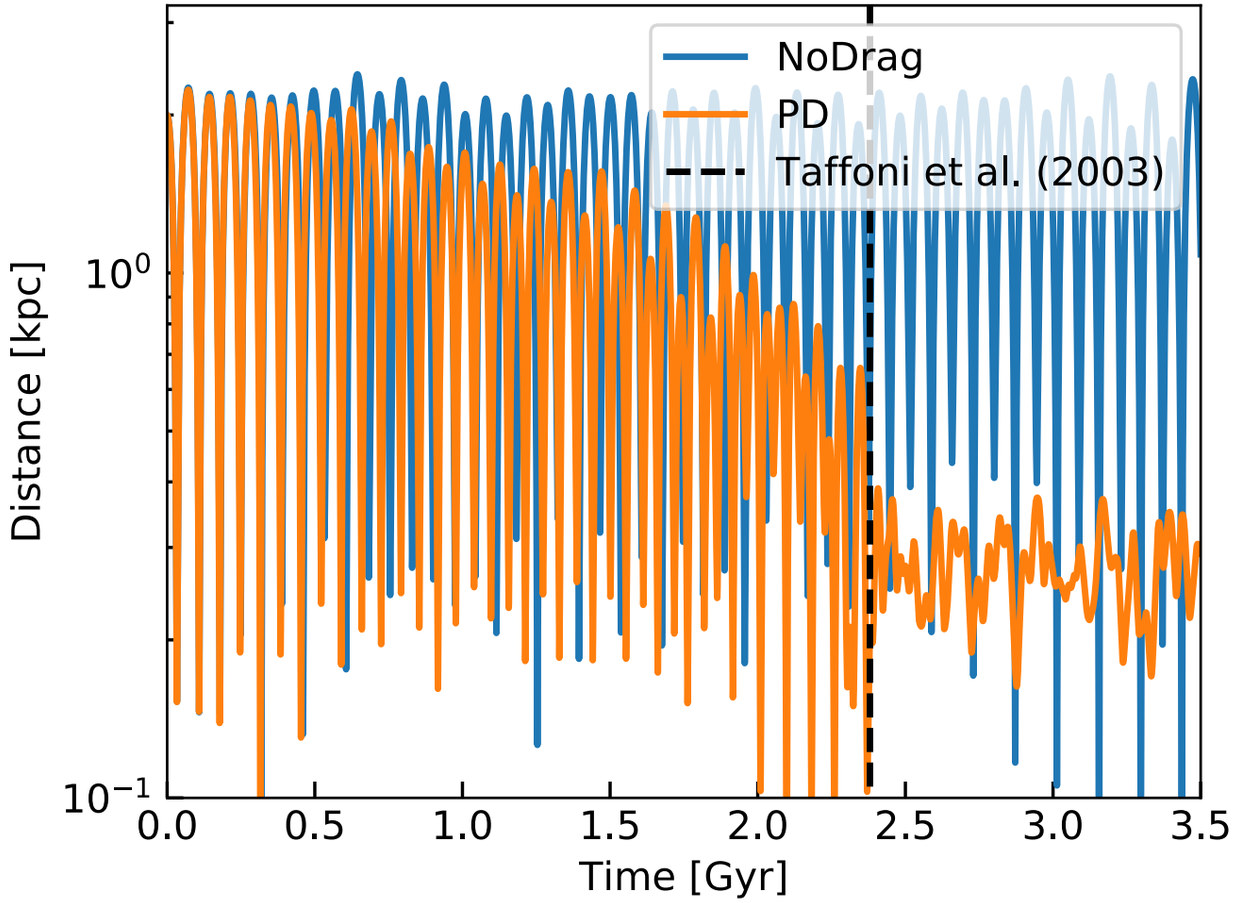
- BH infalling in an NFW halo.

- Comparison with theoretical estimates of **Taffoni+03.**

- Resolution 50 pc > r_{def} ~ 10 pc

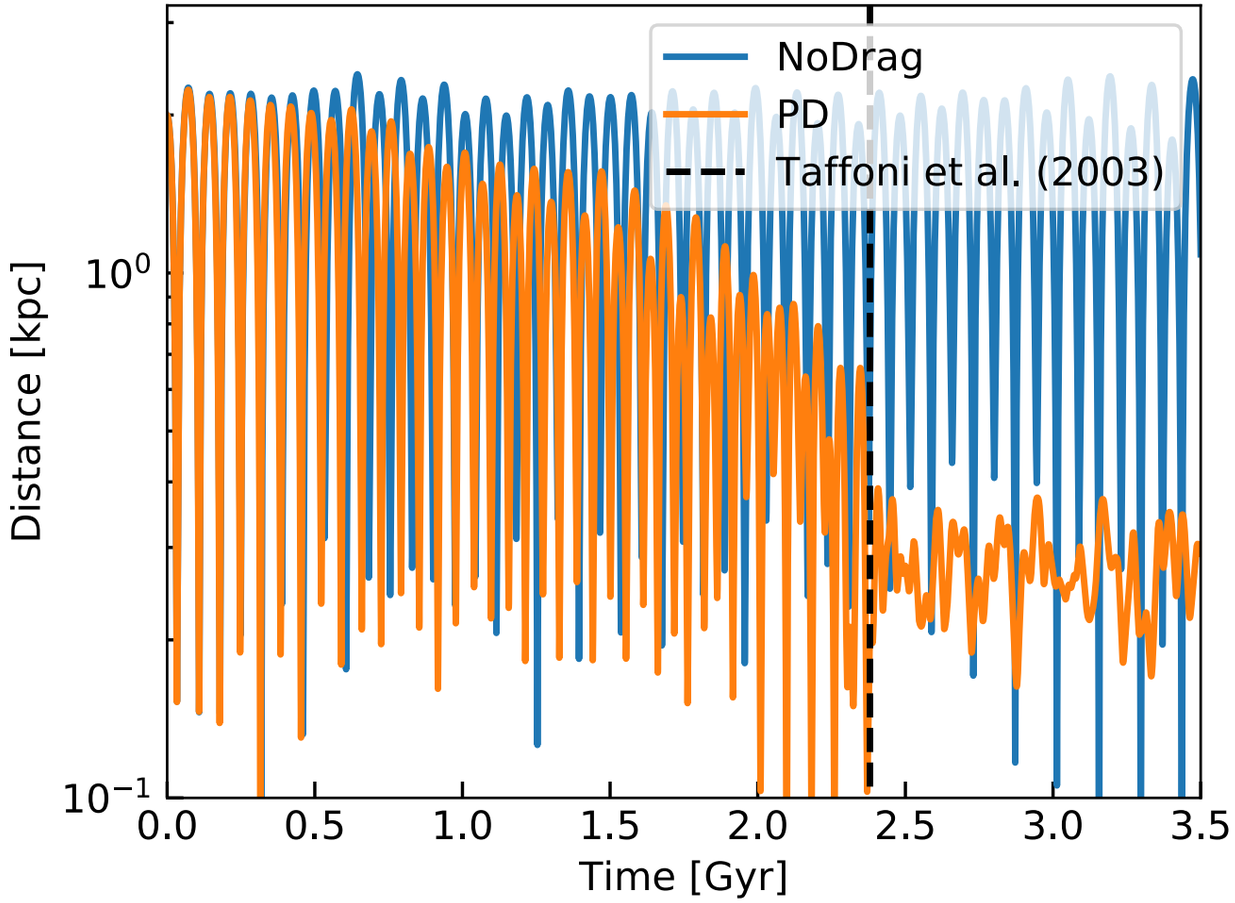
Unresolved dynamics

- BH infalling in an NFW halo.
- Comparison with theoretical estimates of **Taffoni+03.**
- Resolution 50 pc > r_{def} ~ 10 pc



Unresolved dynamics

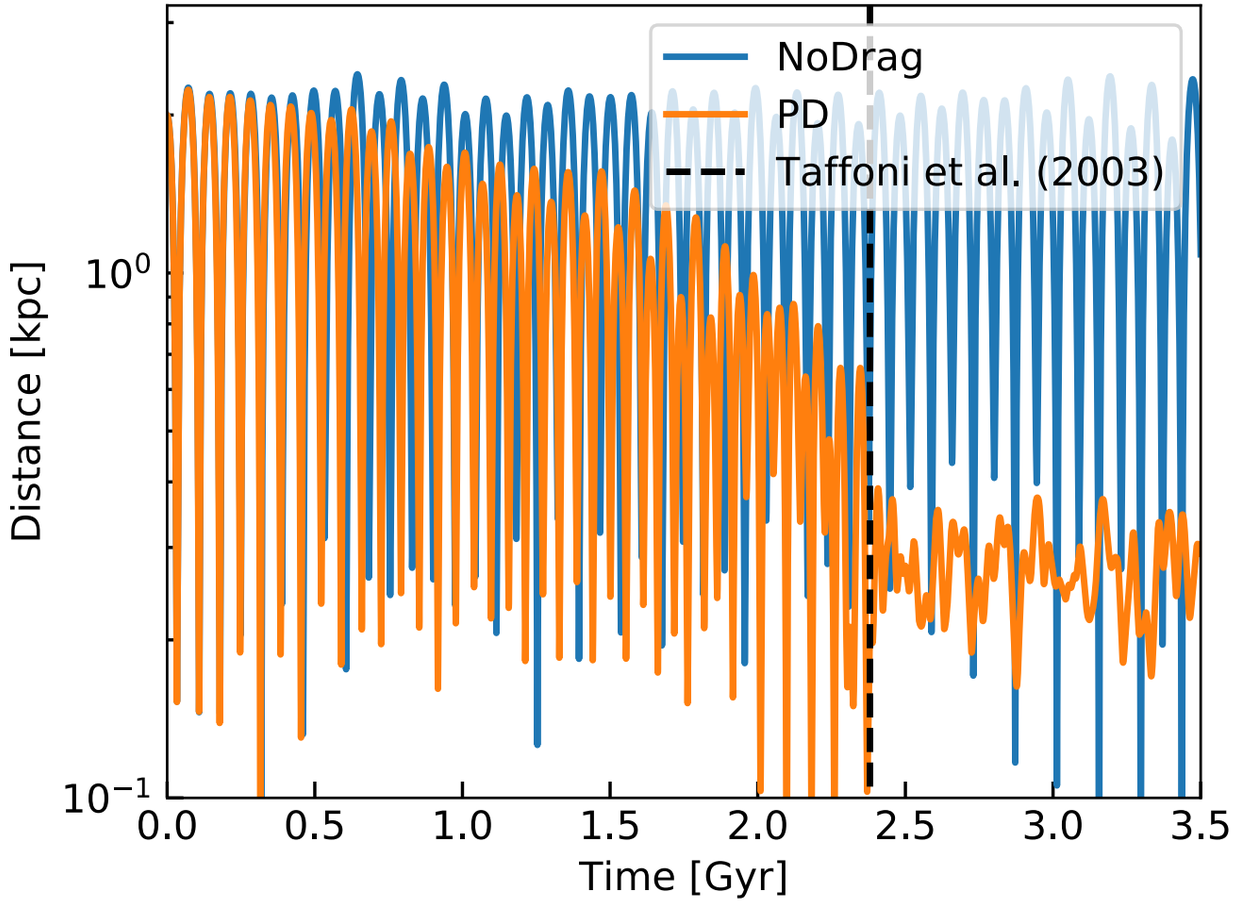
- BH infalling in an NFW halo.
- Comparison with theoretical estimates of **Taffoni+03.**
- Resolution 50 pc > r_{def} ~ 10 pc



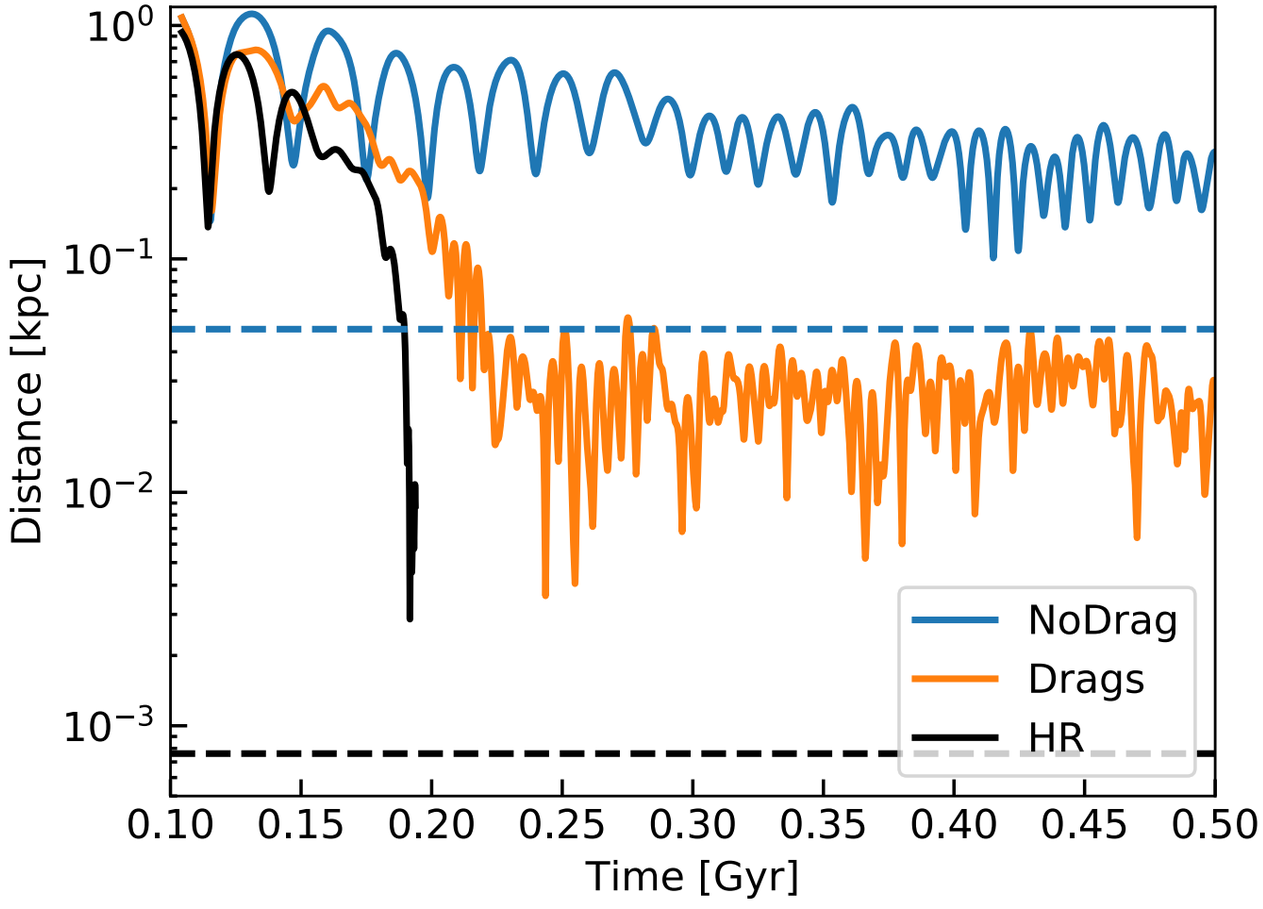
- BH infalling in a ‘complete’ galaxy with DM, stars, gas and many physical processes such as star formation, cooling, feedback etc…
- Comparison with a very high resolution simulation

Unresolved dynamics

- BH infalling in an NFW halo.
- Comparison with theoretical estimates of **Taffoni+03.**
- Resolution 50 pc > r_{def} ~ 10 pc



- BH infalling in a ‘complete’ galaxy with DM, stars, gas and many physical processes such as star formation, cooling, feedback etc…
- Comparison with a very high resolution simulation



Outline

A. A first step to better track the dynamics of BHs

B. Lonely black holes at high redshift **(Pfister in prep)**

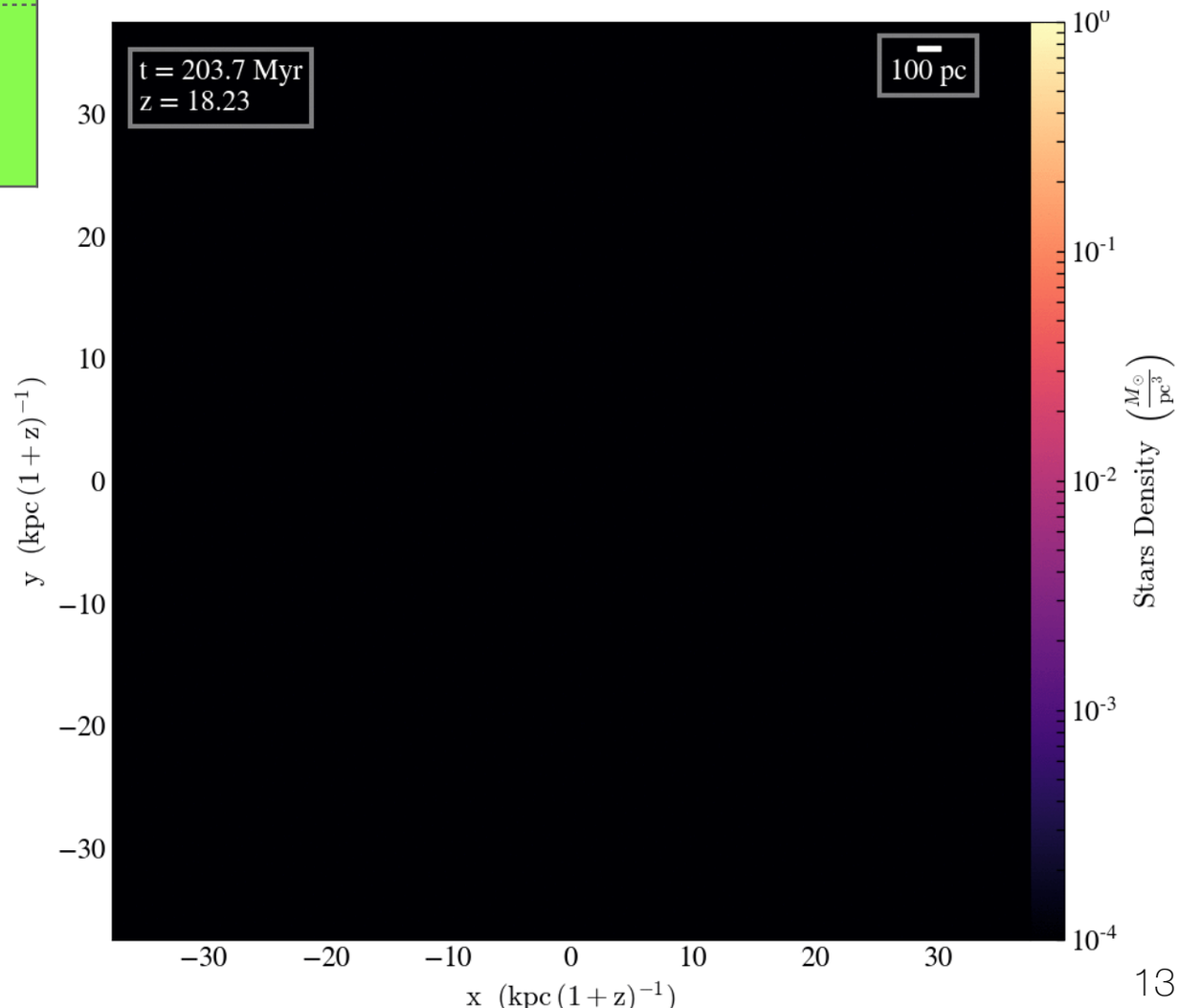
    1. Set up

    2. Results

Set up

Name	Δx	Drag	Seed BH
72pc_PD_BH1e4	72	All	$10^4\ M_\odot$
36pc_PD_BH1e4	36	All	$10^4\ M_\odot$
9pc_PD_BH1e4	9	All	$10^4\ M_\odot$

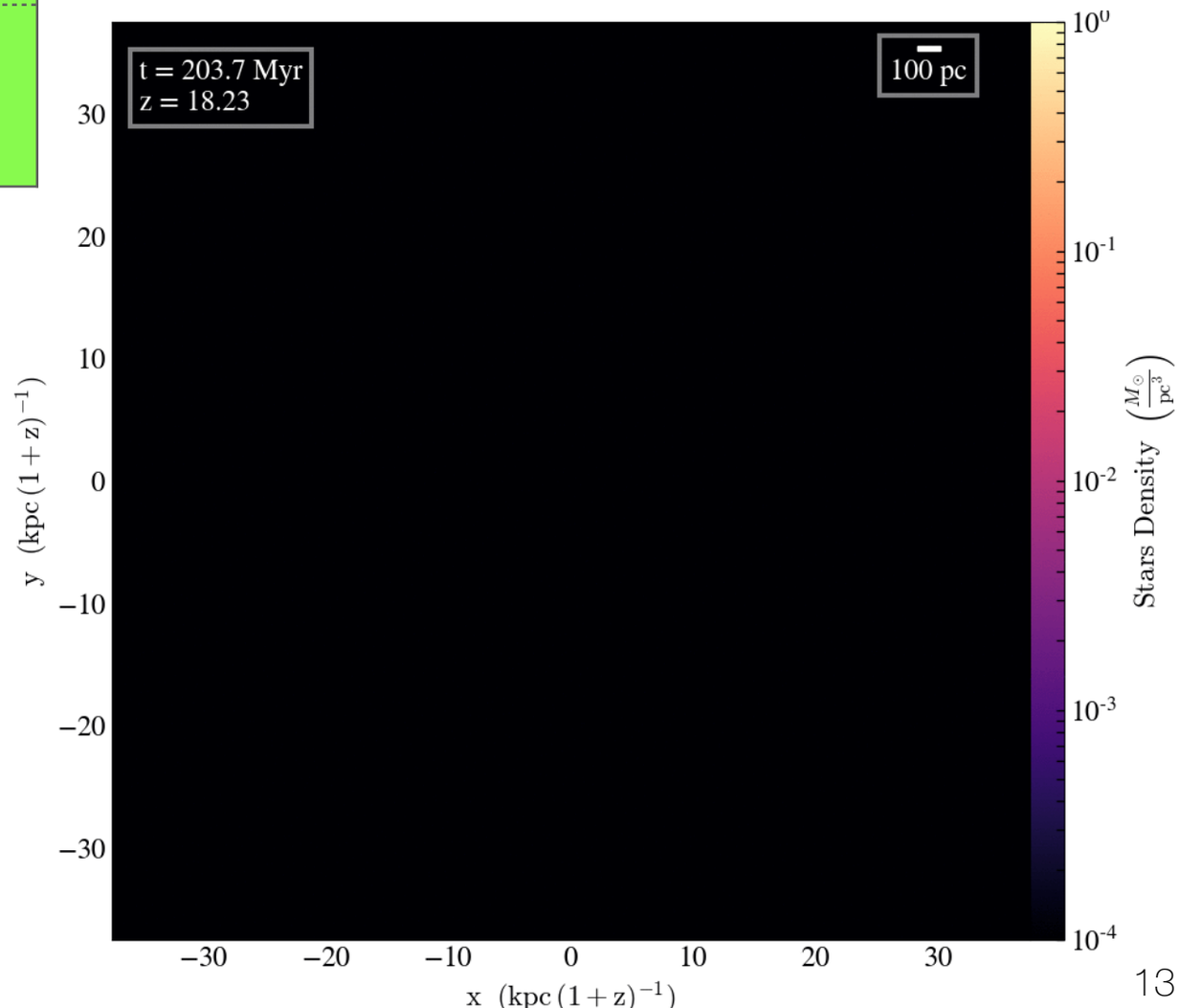
- Zooms on a $10^{12}\ M_\odot$ halo at z=2
- State of the art subgrid physics: metals, cooling, star formation, supernovae, AGNs



Set up

Name	Δx	Drag	Seed BH
72pc_PD_BH1e4	72	All	$10^4\ M_\odot$
36pc_PD_BH1e4	36	All	$10^4\ M_\odot$
9pc_PD_BH1e4	9	All	$10^4\ M_\odot$

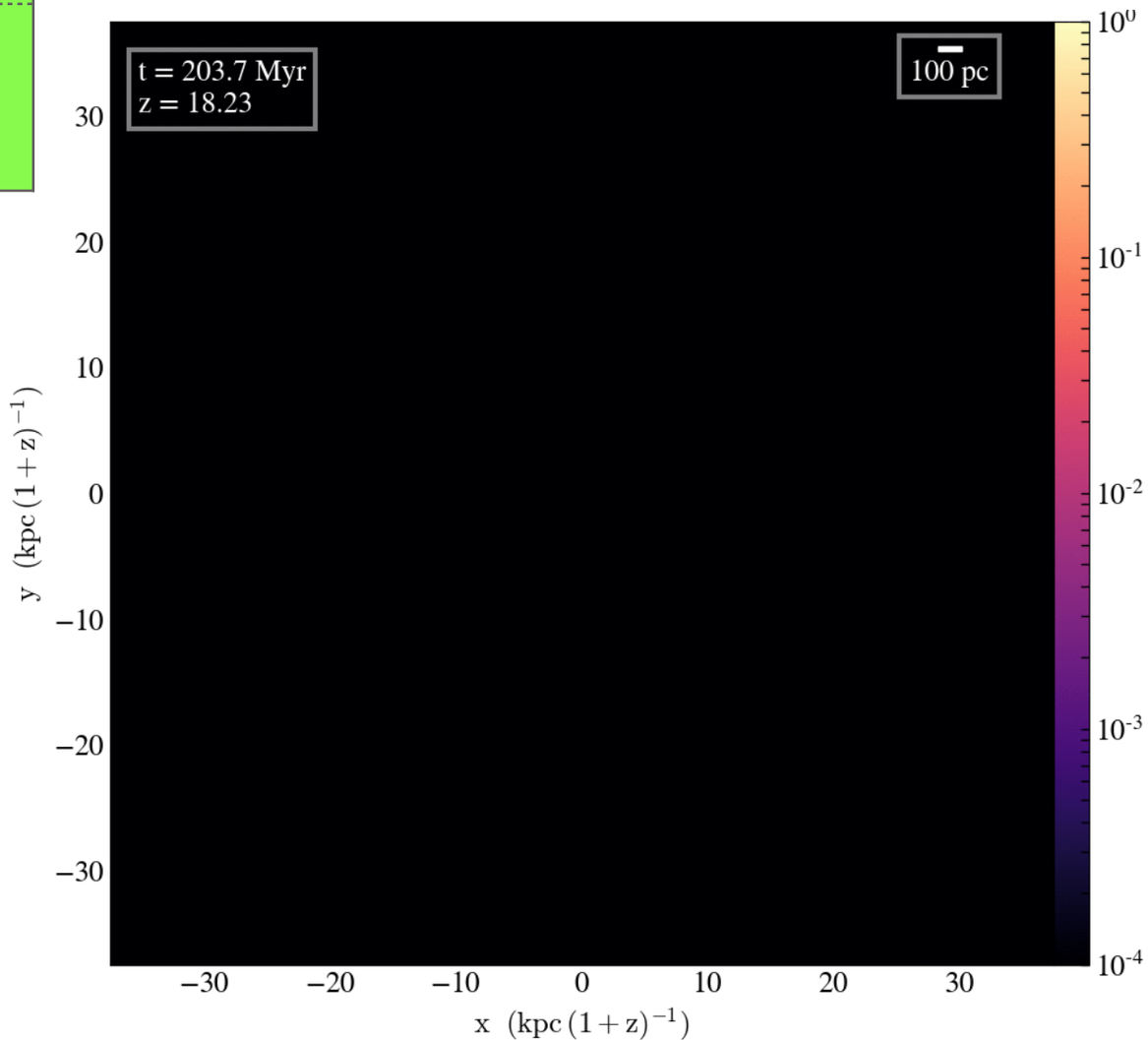
- Zooms on a $10^{12}\ M_\odot$ halo at z=2
- State of the art subgrid physics: metals, cooling, star formation, supernovae, AGNs

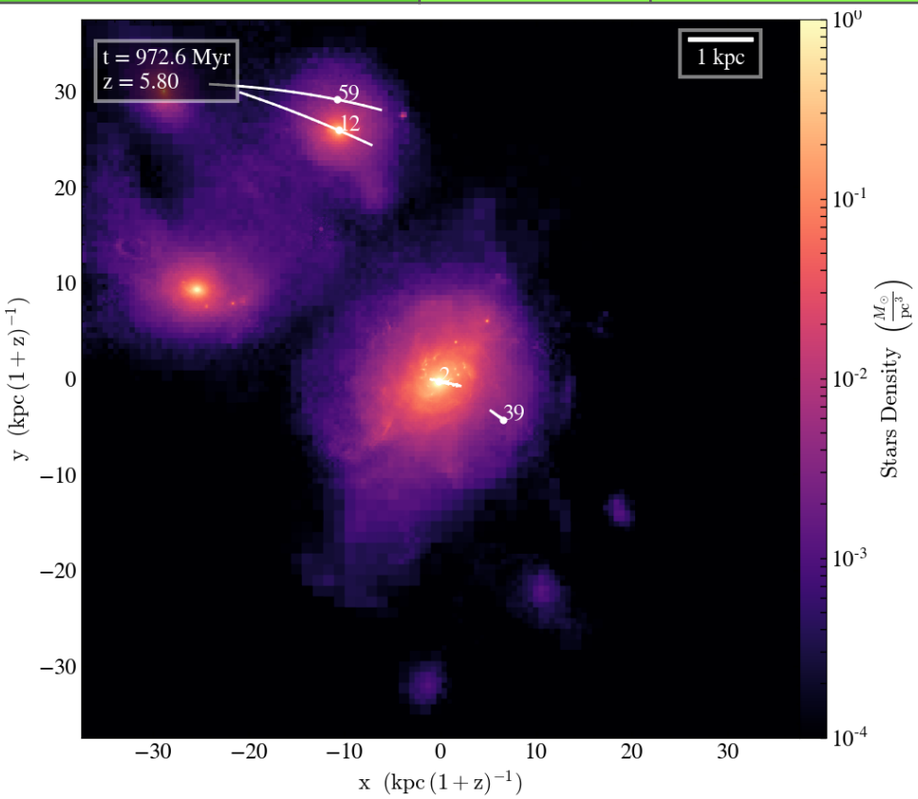


Set up

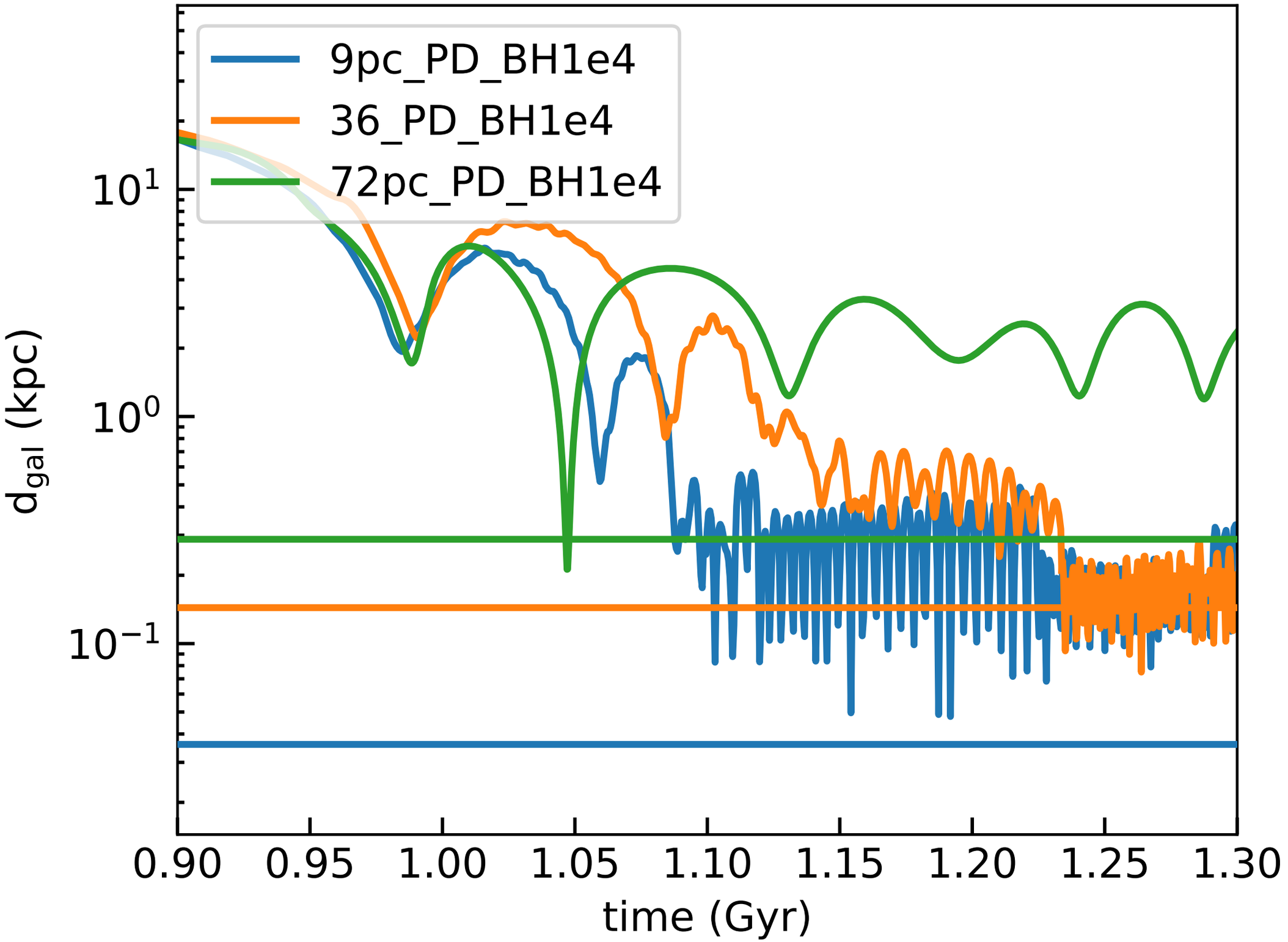
Name	Δx	Drag	Seed BH
72pc_PD_BH1e4	72	All	$10^4\ M_\odot$
36pc_PD_BH1e4	36	All	$10^4\ M_\odot$
9pc_PD_BH1e4	9	All	$10^4\ M_\odot$

- Zooms on a $10^{12}\ M_\odot$ halo at z=2
- State of the art subgrid physics: metals, cooling, star formation, supernovae, AGNs

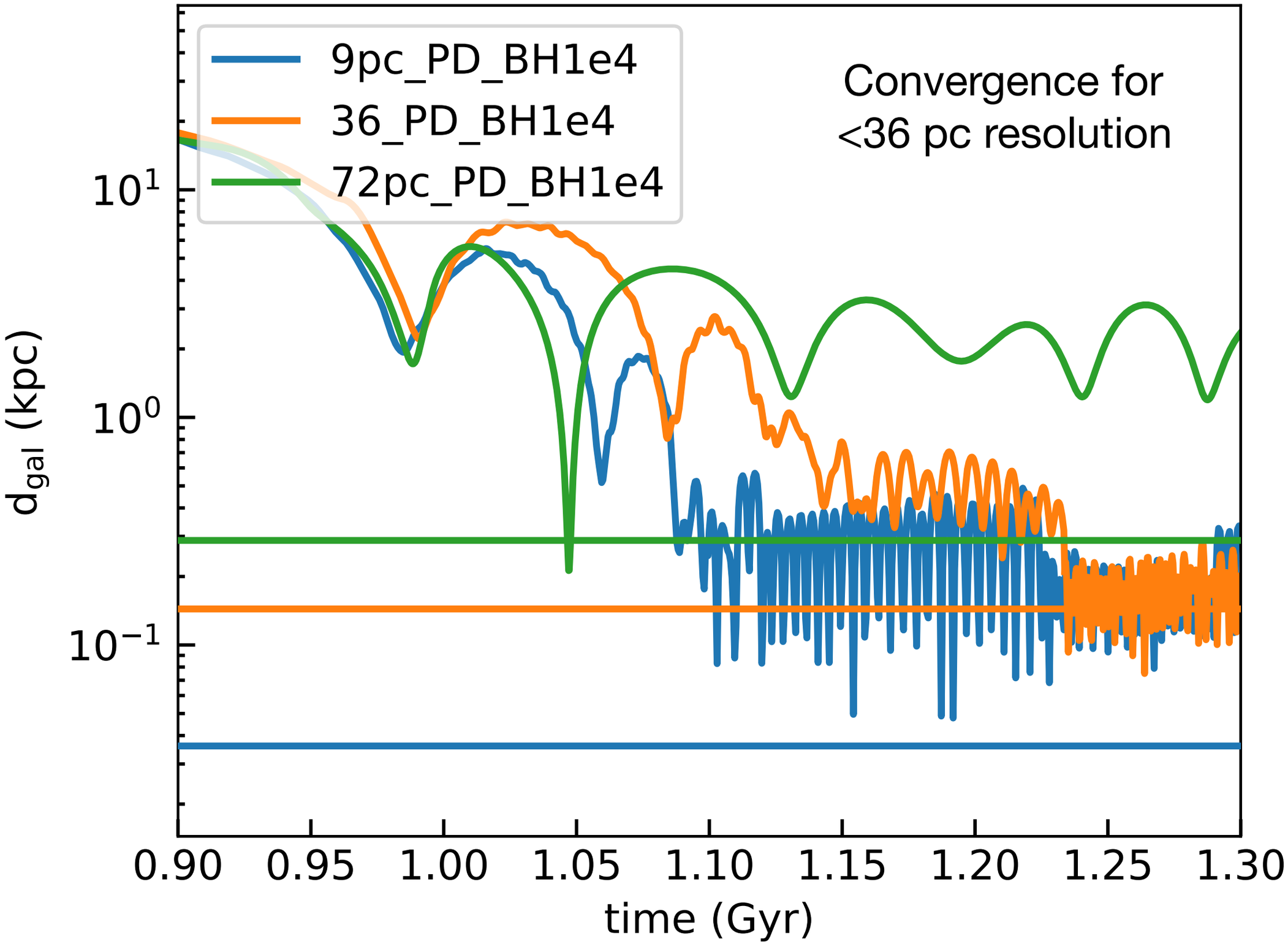




Results


9pc_PD_BH1e4
36_PD_BH1e4
72pc_PD_BH1e4
10^1
10^0
10^{-1}
d_{gal} (kpc)
0.90
0.95
1.00
1.05
1.10
1.15
1.20
1.25
1.30
time (Gyr)

Results


9pc_PD_BH1e4
36_PD_BH1e4
72pc_PD_BH1e4
Convergence for
<36 pc resolution
10^1
10^0
10^{-1}
d_{gal} (kpc)
0.90
0.95
1.00
1.05
1.10
1.15
1.20
1.25
1.30
time (Gyr)

Conclusions

- **Resolve the influence radius of the BH is necessary** to self-consistently compute the dynamics of BHs in the dynamical friction phase.

- We developed a physically motivated model to take into account dynamical friction from stars/DM in Ramses. **It is the only code with a physically motivated subgrid model for dynamical friction from gas, stars and DM.**

- This model still requires high resolution (~10 pc): it is not optimal for cosmological studies down to z=0 or with large volumes.

- but affordable at high redshift to investigate seeds BHs. A key project for LISA.

- Future work: extension to “correct” also low resolution simulations to reach z=0 or simulate large volumes.