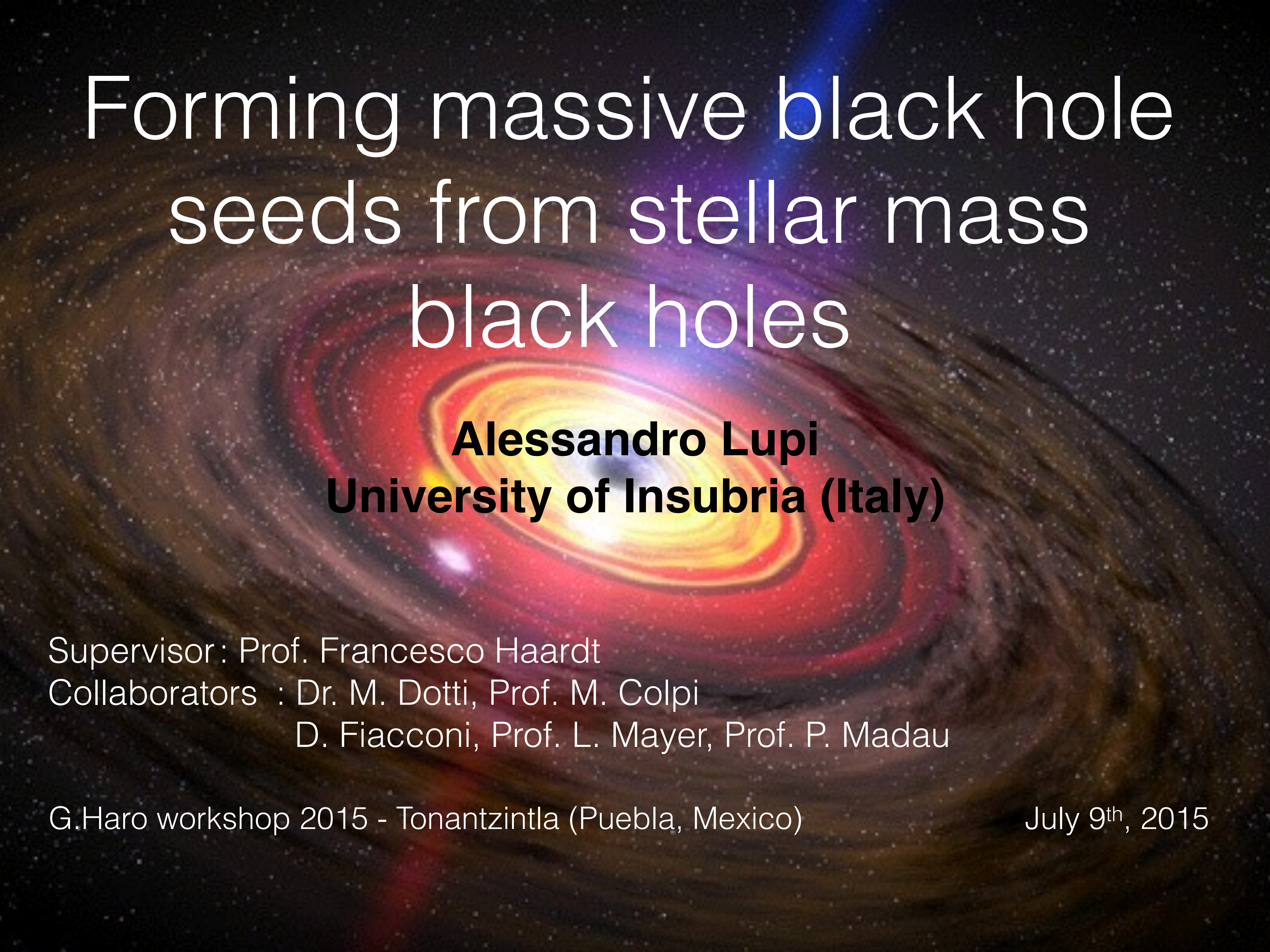

Forming massive black hole seeds from stellar mass black holes

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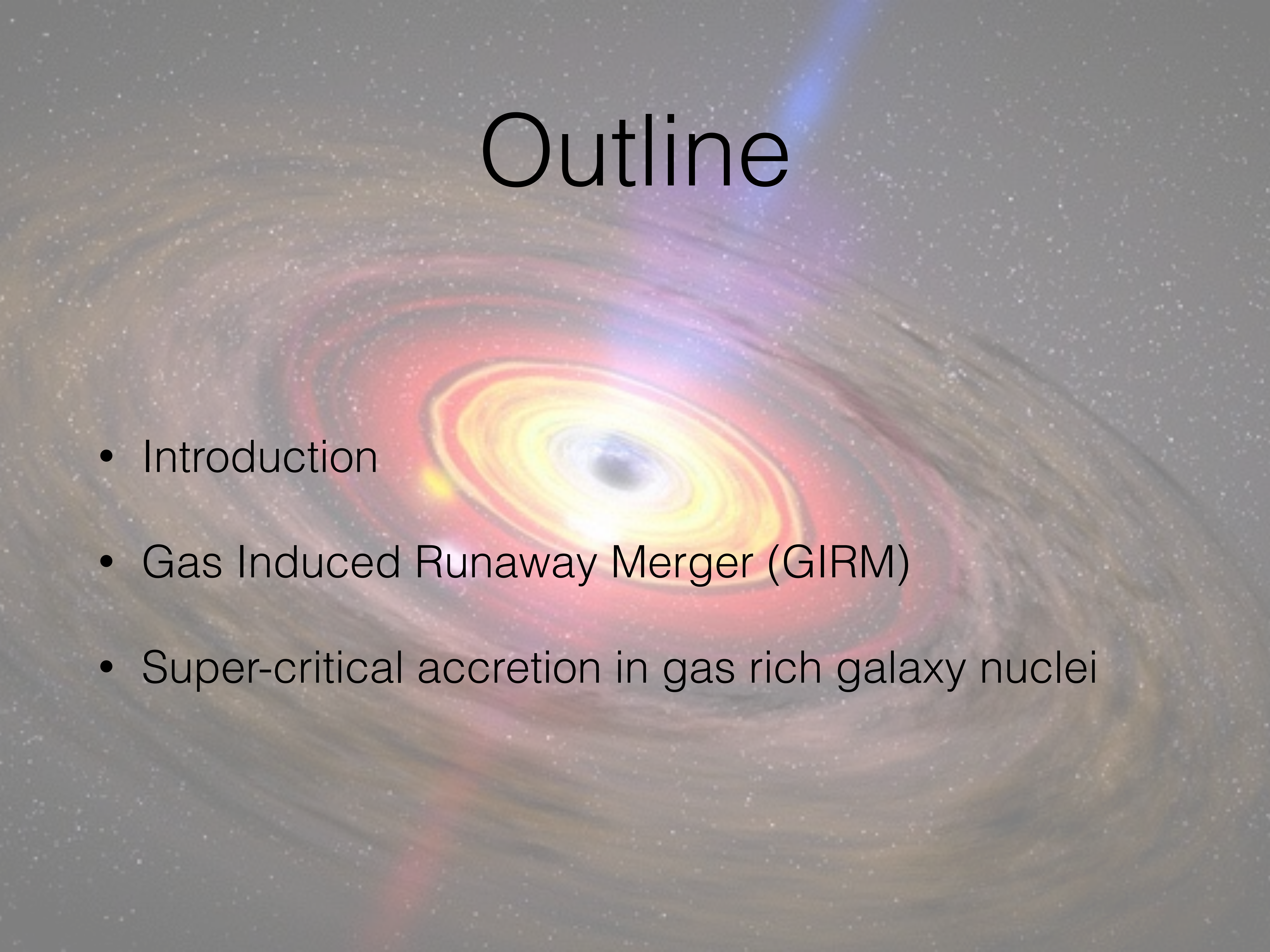
G.Haro workshop 2015 - Tonantzintla (Puebla, Mexico)

July 9th, 2015



Outline

- Introduction
- Gas Induced Runaway Merger (GIRM)
- Super-critical accretion in gas rich galaxy nuclei

Introduction

Two main scenarios for massive black hole formation:

LIGHT seeds

- PopIII remnants ($M \lesssim 10^2\ M_\odot$)

HEAVY seeds

($M \gtrsim 10^4\ M_\odot$)

- Direct collapse of a massive gas cloud
- Quasistars/SMS

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- Super-critical accretion of stellar mass BHs in gas-rich galaxy nuclei

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Gas Induced Runaway Merger of stellar mass BHs in NSCs

The Relativistic collapse of a nuclear stellar cluster’s core

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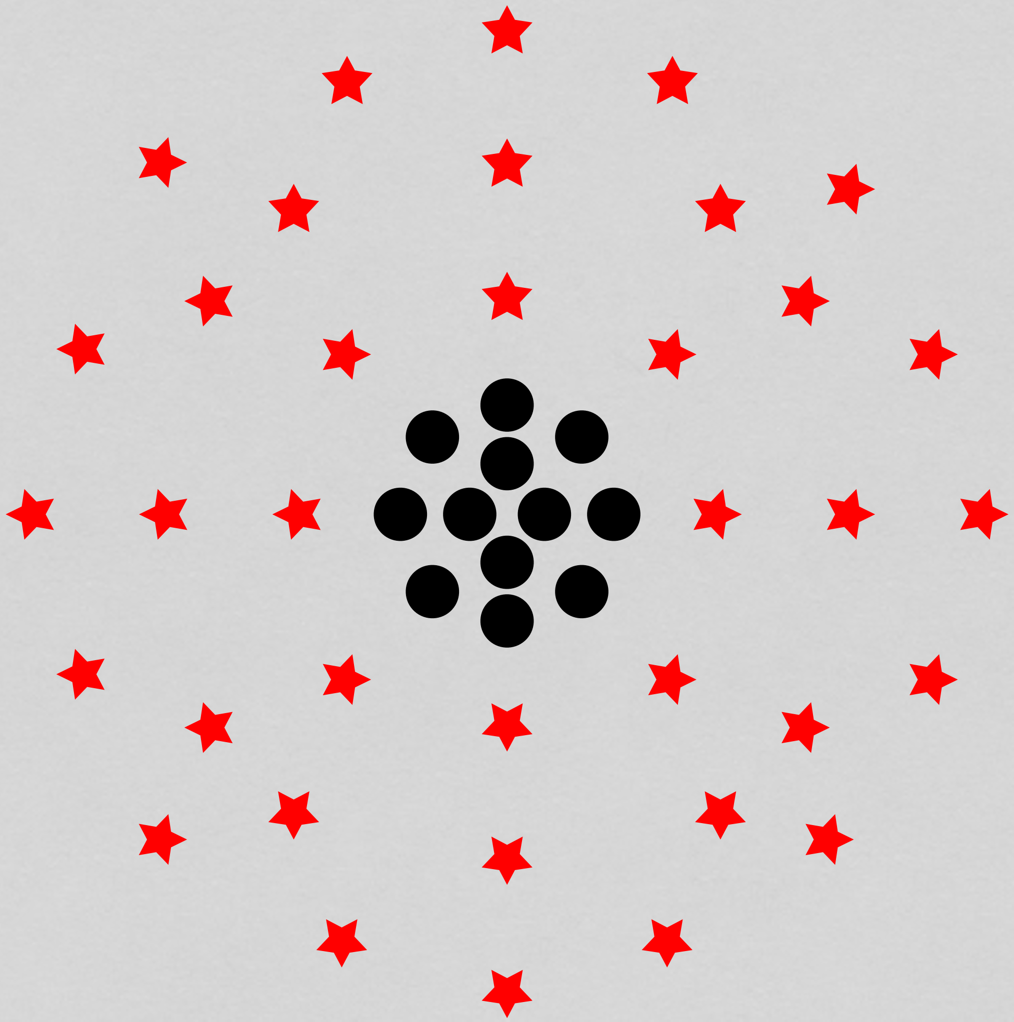

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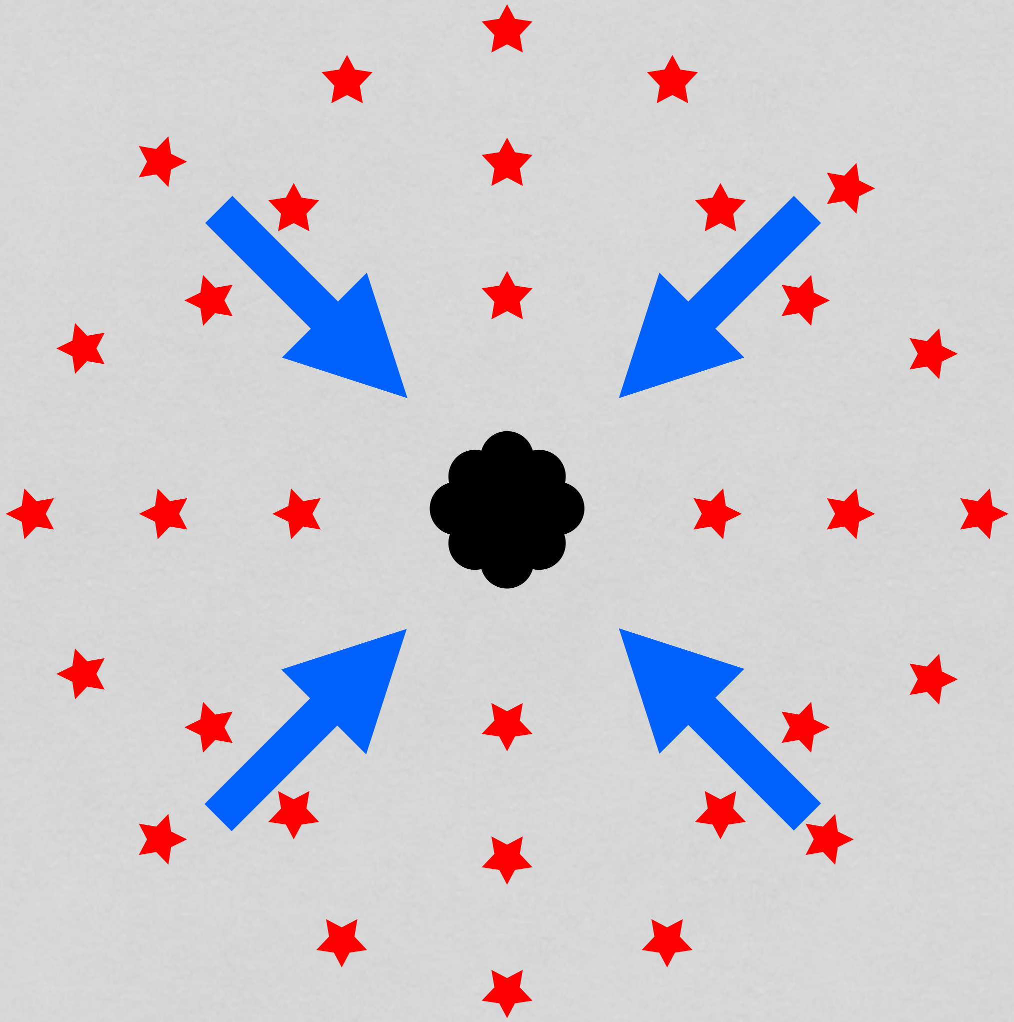

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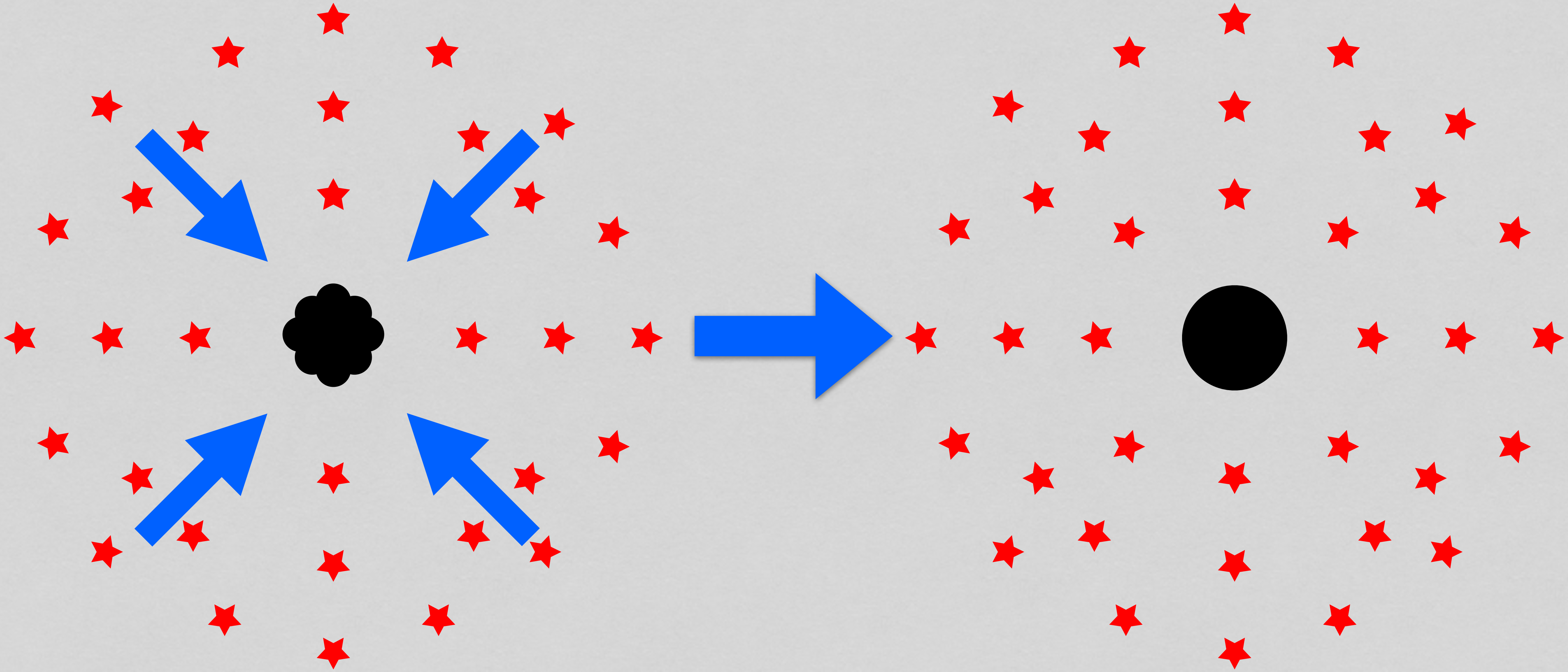

$$\boxed{z_{\rm gr} \approx \frac{|\Phi|}{c^2} \approx \frac{GM_{\rm c}}{r_{\rm c}c^2} = 0.5}$$

The Relativistic collapse of a nuclear stellar cluster's core

But additional effect need to be be considered!

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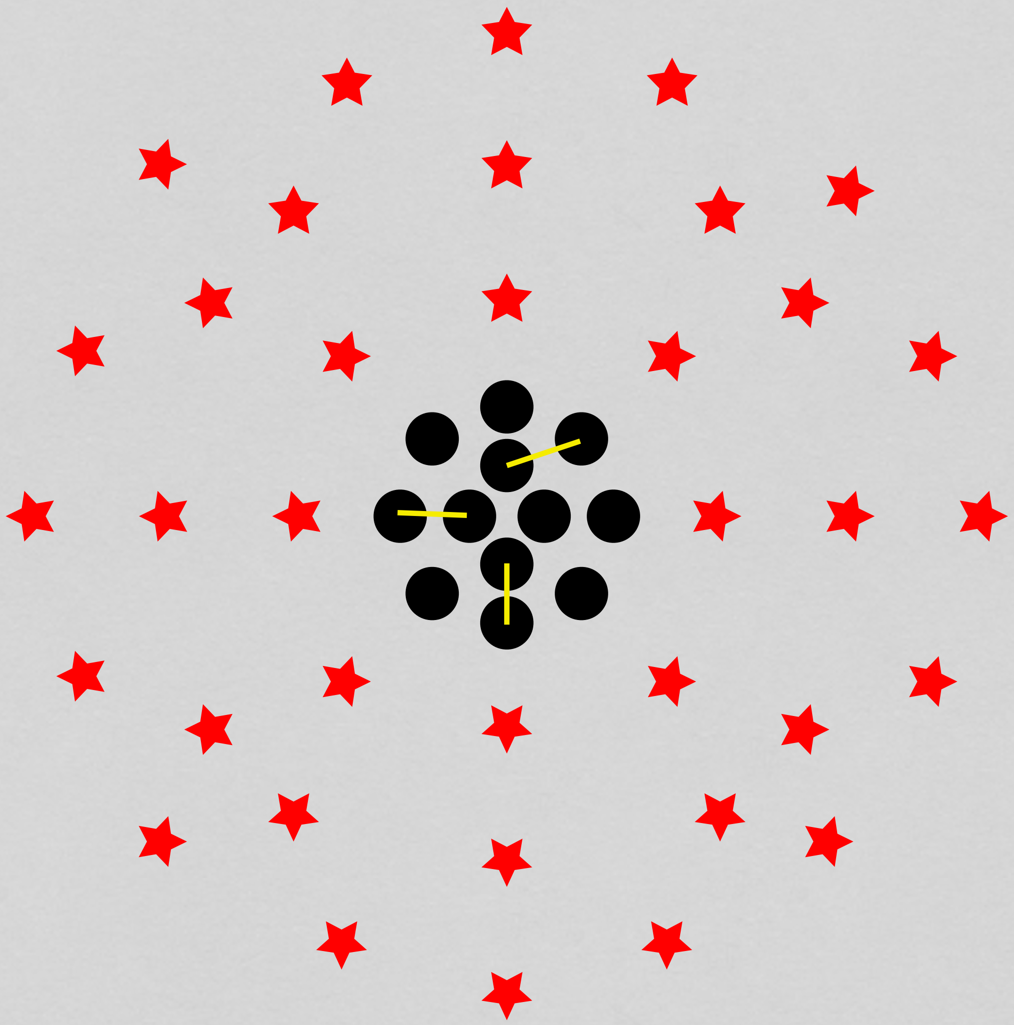

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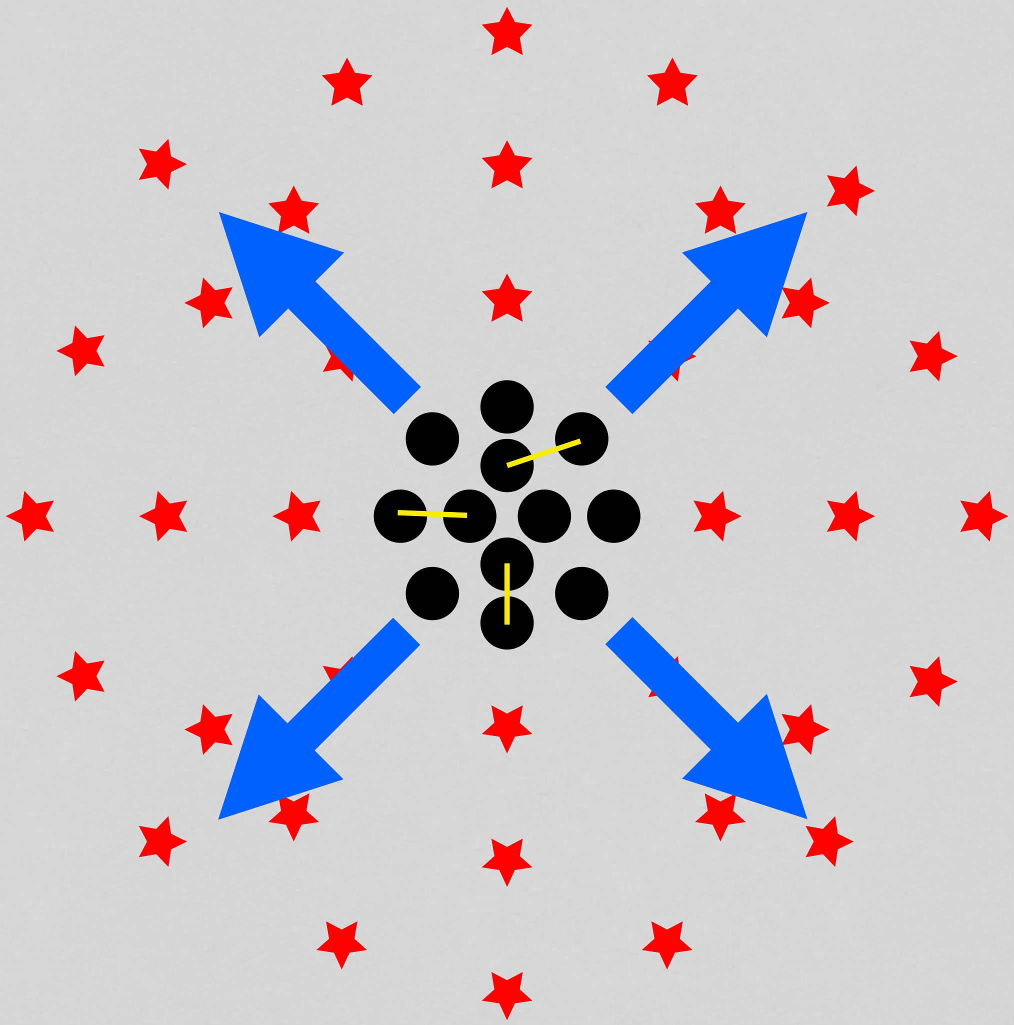

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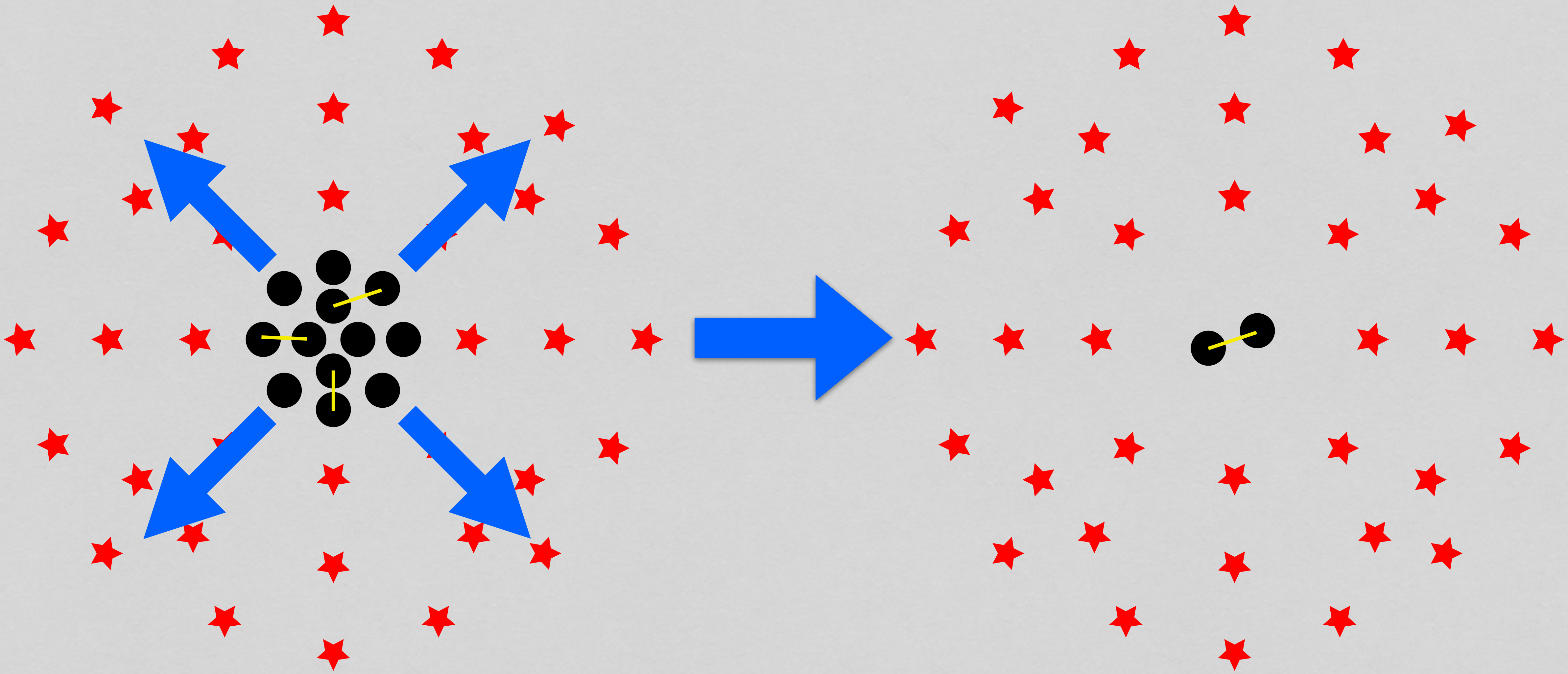

EVAPORATION

GIRM

Davies et al. (2011) reconsidered the fate of a NSC in a cosmological framework.

1. Deepening of the potential well
2. Tighter stellar/compact object orbits and smaller core radius
3. Binaries cannot prevent further contraction

↓

RUNAWAY MERGER

GIRM

In Lupi et al. (2014) we implemented this model in a semi-analytic code by B. Devecchi (Devecchi et al. 2009).

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- Merger trees provided by Pinocchio (Monaco, 2002), a semi-analytic code aimed at following the cosmic evolution of dark matter haloes.
- The code by Devecchi builds and follows the baryonic components within the dark matter haloes.
  - Gas inflows are self-consistently computed.
  - Different models for BH seed formation can be included.

GIRM

NSC’s core contraction

Toy model:

- stars on nearly circular orbits
- single star angular momentum conservation during the inflow event

$$l_\star = \sqrt{GM(< r_0)r_0} = \sqrt{G\left[M(< r_0) + M_{\rm gas}\right] r}$$

↓

$$\frac{r}{r_0} = \frac{M(< r_0)}{M(< r_0) + M_{\rm gas}} \qquad \xi \in (0,3)$$

GIRM

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$$l_\star = \sqrt{GM(<r_0)r_0} = \sqrt{G\left[M(<r_0) + M_{\rm gas}\right]r}$$

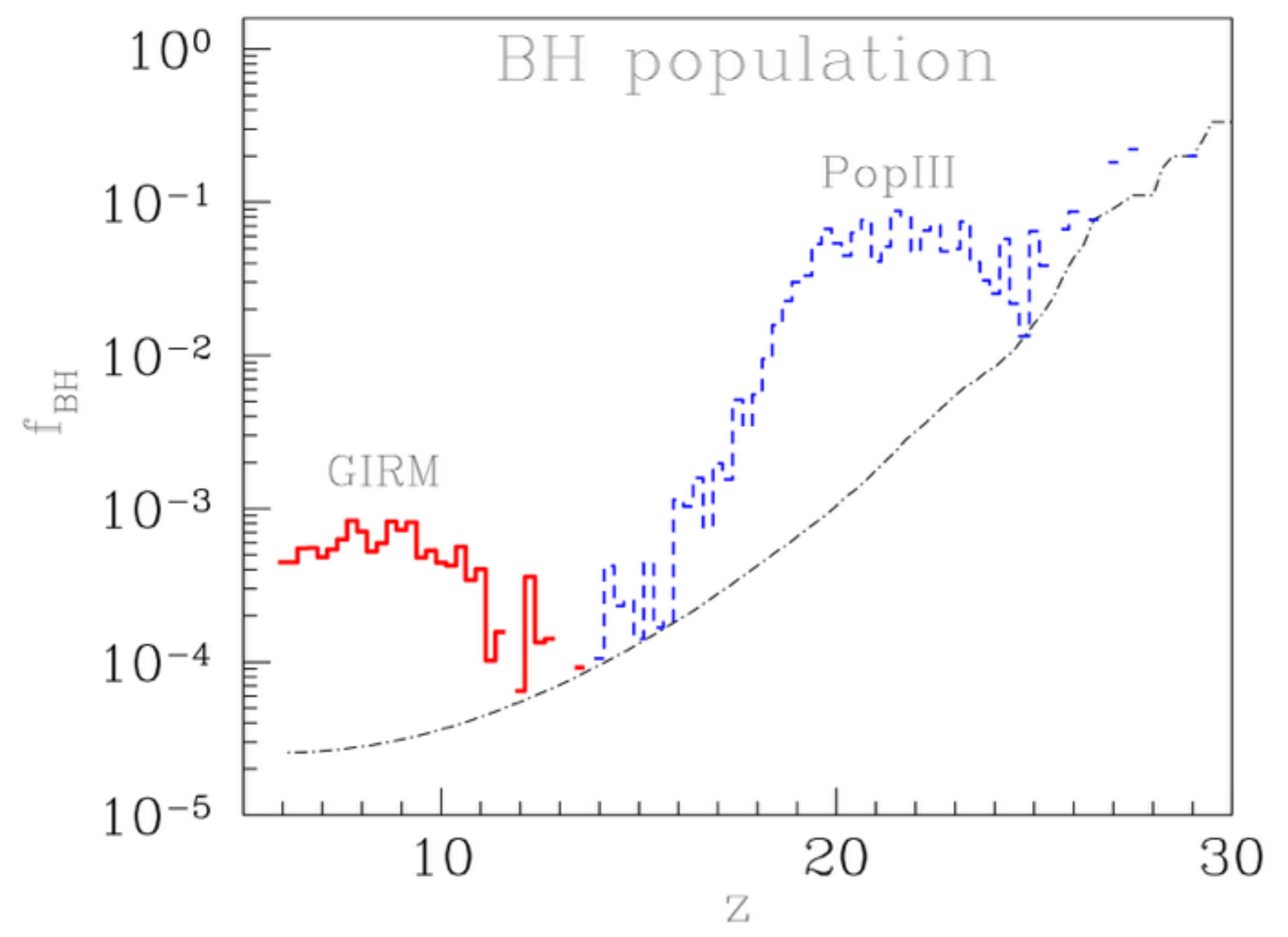
↓

$$\frac{R}{R_0} = \left[\frac{M_0}{M_0 + M_{\rm gas}}\right]^{\xi} \qquad \xi \in (0,3)$$

To model different responses we assumed a power-law relation

GIRM

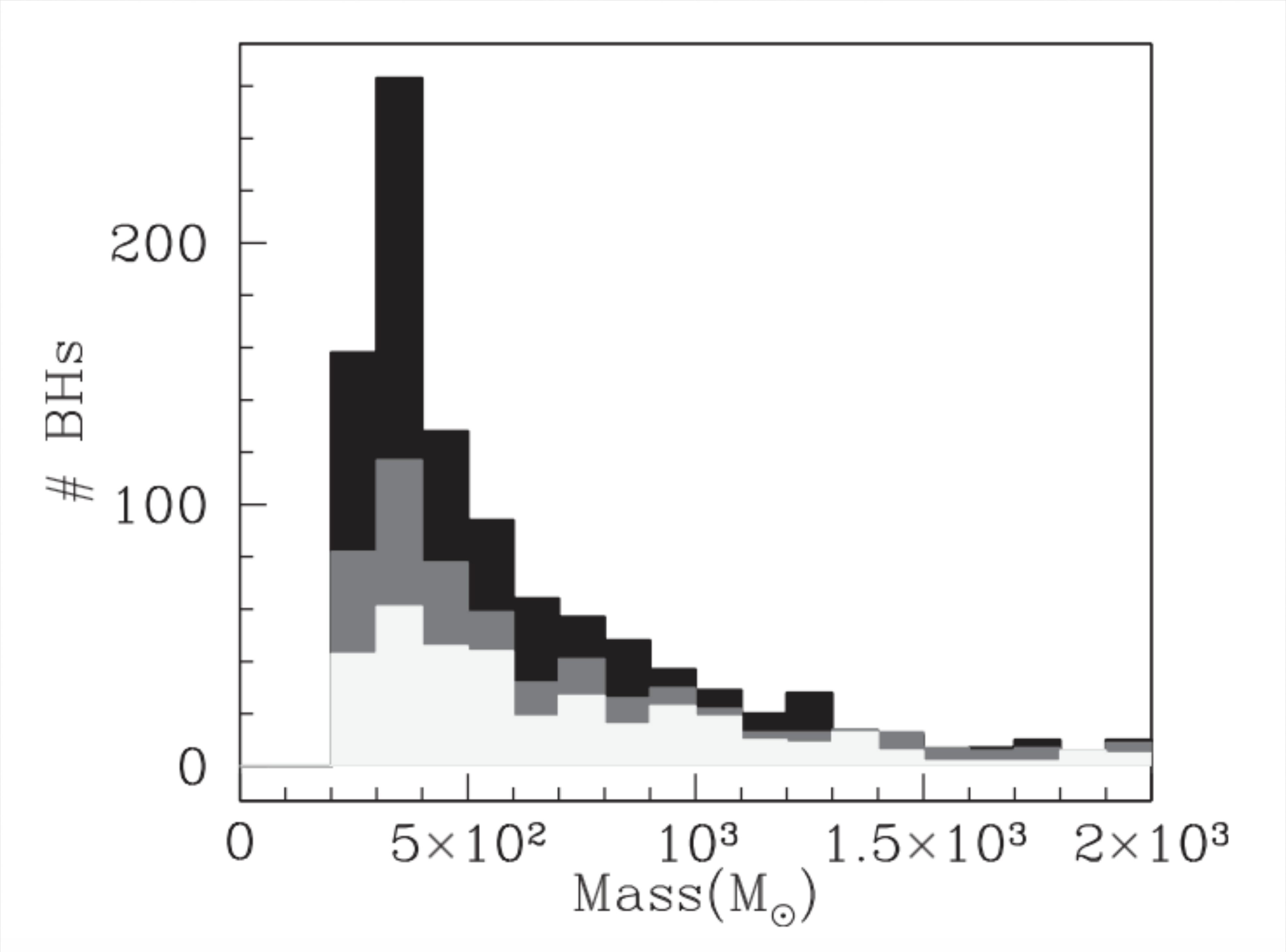
Fraction of haloes hosting a BH seed



$\xi = 0.5$

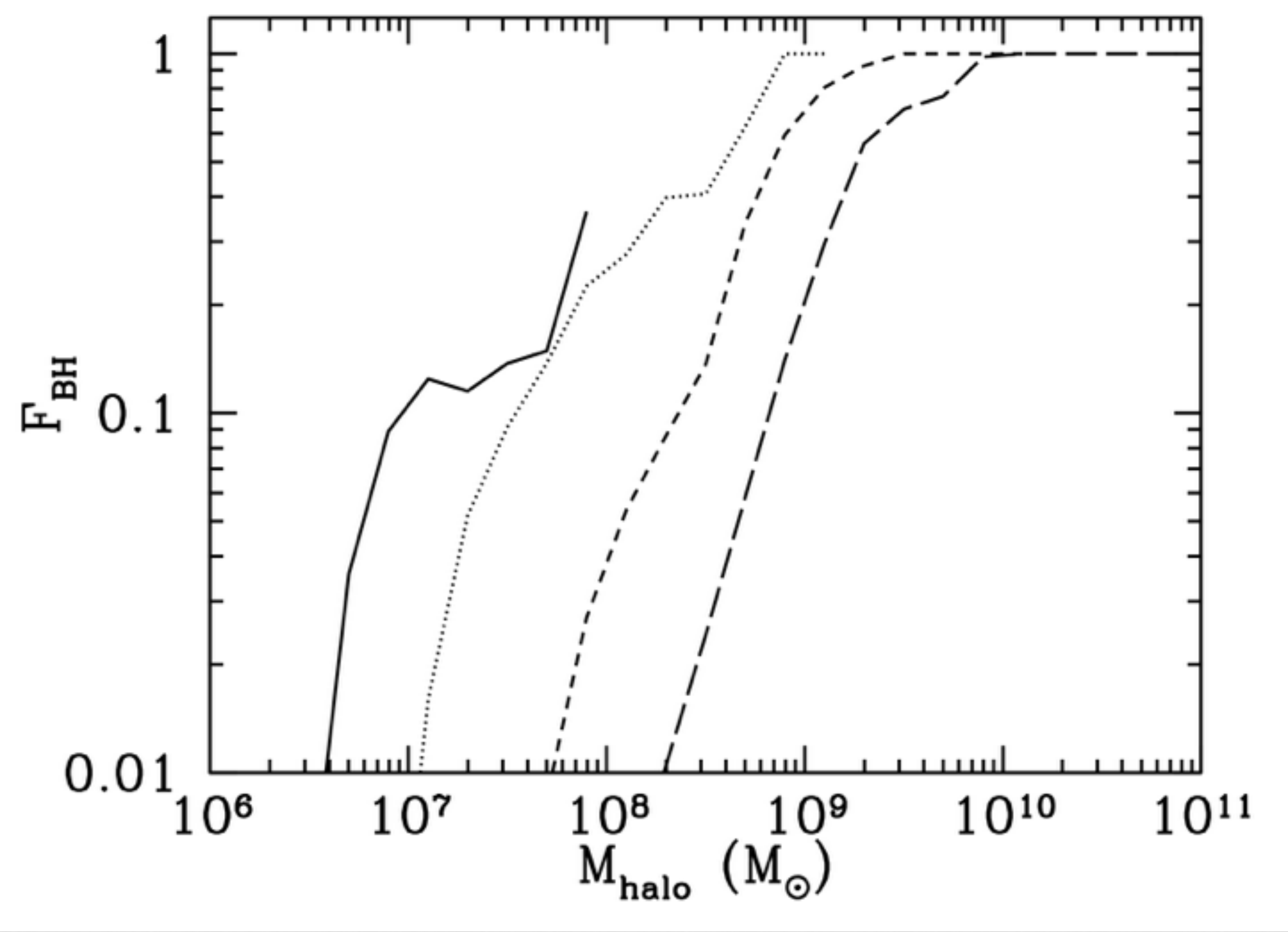
GIRM

BH seed mass distribution



GIRM

BH occupation fraction



From left to right:
z=20,15,10,6

Summary

Results:

- GIRM channel would be active at lower redshift than the PopIII channel (z ~ 10)
- GIRM is competitive to other channels like PopIII, resulting in a comparable population
- GIRM would produce intermediate mass BHs as coalescence of stellar mass BHs, ($M_{BH} \sim 10^{2\text{-}3}\,M_\odot$) in situ

Open issues:

- The NSC must be prone to a very large gas inflow
- The gas inflow should be confined in the centre without fragmenting and forming stars
- The inflow events should occur on timescales shorter than the typical BH ejection timescale

Super-critical accretion of stellar mass BHs in gas-rich galaxy nuclei

The heavy seed scenario

What we need:

The heavy seed scenario

What we need:

- To avoid gas fragmentation

The heavy seed scenario

What we need:

- To avoid gas fragmentation
- To effectively dissipate angular momentum

The heavy seed scenario

What we need:

- To avoid gas fragmentation
- To effectively dissipate angular momentum
- To drive gas toward the centre of galaxies at rates of at least 1 $M_\odot$/yr

The heavy seed scenario

What we need:

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- To effe
- To driv
  1 M$_\odot$/yr

Further and more detailed investigations would be necessary

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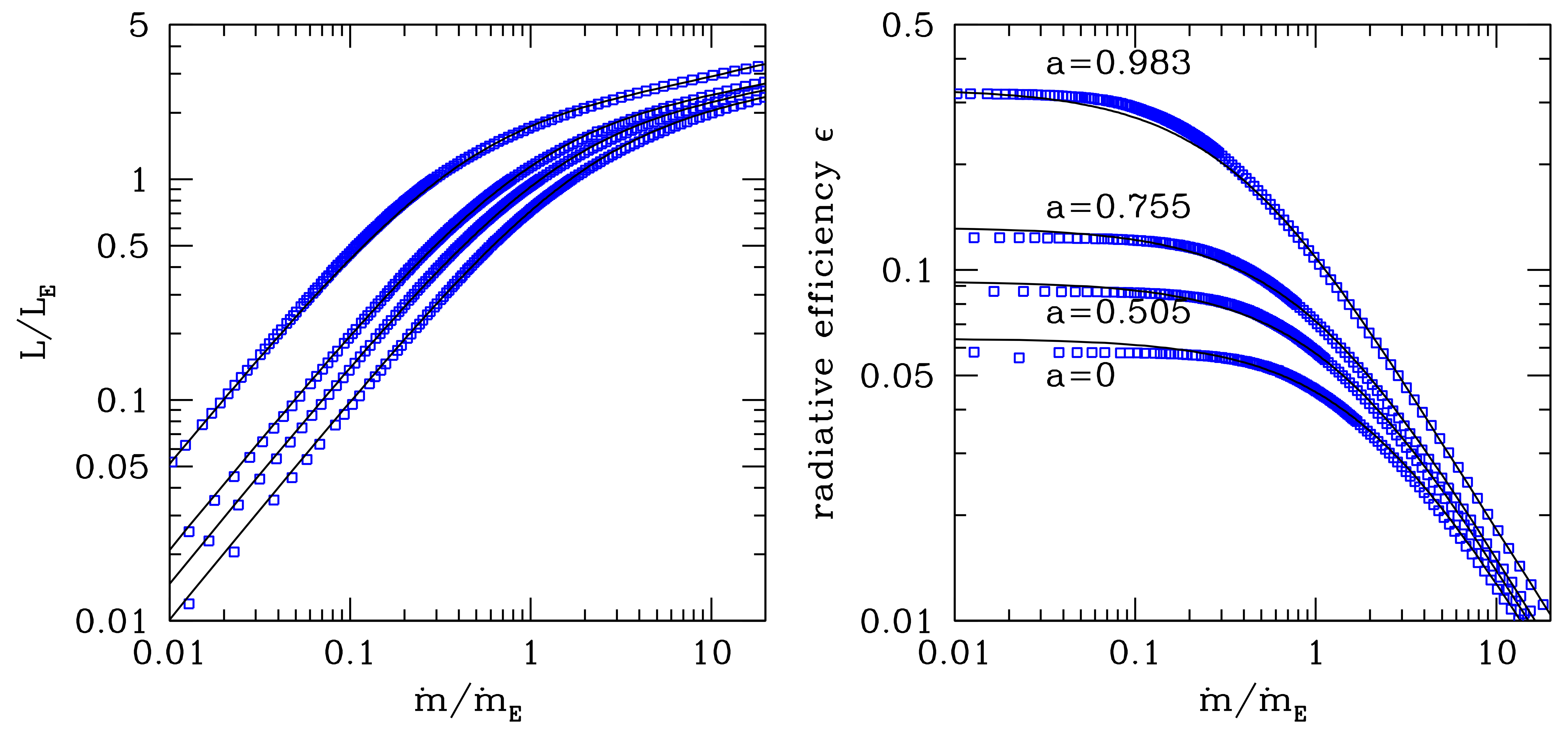
Further and more detailed investigations would be necessary

Madau, Haardt & Dotti (MHD, 2014) discussed super-critical (super-Eddington) accretion onto stellar mass BHs as a viable mechanism to bypass the difficulties associated to both light and heavy seed scenarios

The Slim Disc Model

Abramowicz et al. (1988), Sadowski et al. (2009,2014)



Credits: Madau et al. (2014)

Super-critical accretion on stellar mass BHs in gas-rich galaxy nuclei

(Lupi et al. in preparation)

MHD (and Volonteri, Silk & Dubus, 2014) discussed how the conditions for super-critical accretion are plausible in the dense environments of high redshift massive proto-galaxies.

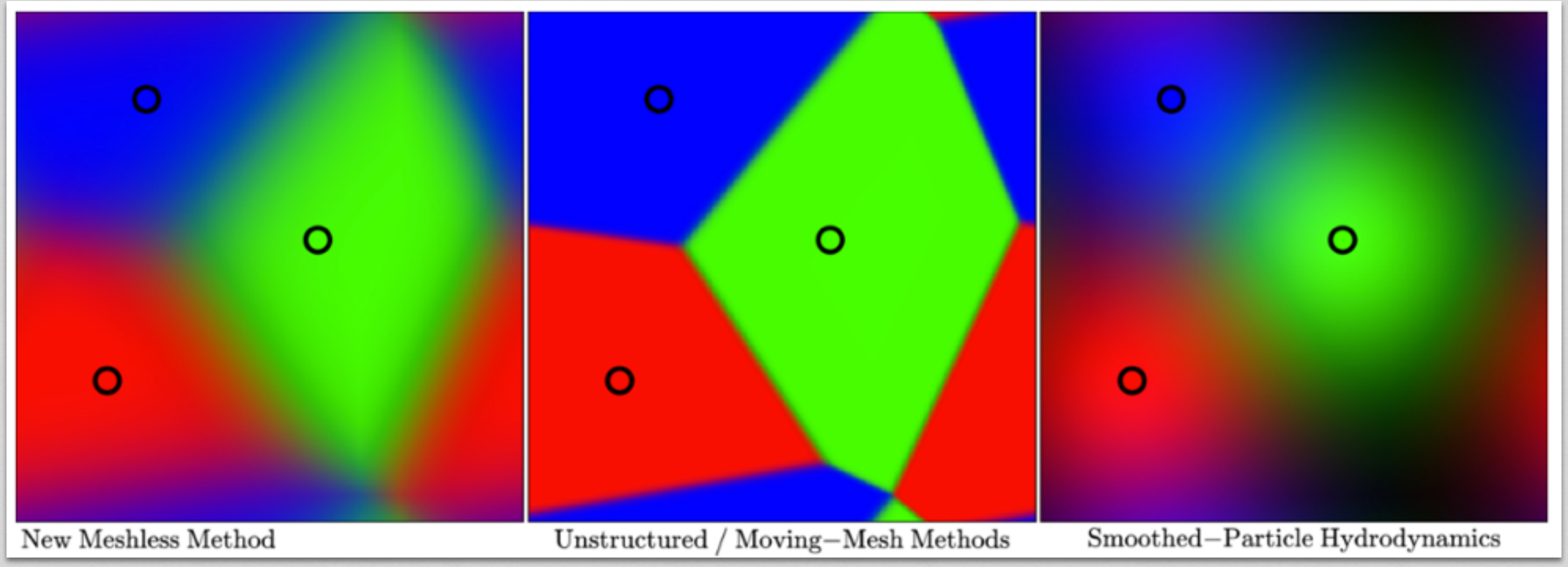
Initial conditions

- Gaseous disc
  - M = $10^8\ M_\odot$
  - R_0 = 50 pc
  - T_0 = 10^4 K
- Stellar background
  - M = $2\times10^8\ M_\odot$
  - R_0 = 100 pc
- 20 stellar mass BHs

The code: GIZMO (Hopkins, 2015)

New mesh-free Lagrangian methods to solve the hydrodynamics equations.

1. Volume partition scheme to model the gas distribution starting from a discrete set of tracer points ("particles")



2. "Godunov-type" method to solve the Riemann problem between two particle "effective faces"

BH accretion/feedback

We considered our BHs as sink particles and we implemented the following recipes:

- Flux accretion prescription (Bleuler et al., 2014)

$$\dot{M}_{\mathrm{flux}} = -\int_{\Omega_{\mathrm{acc}}} \mathrm{div}\big(\rho(\boldsymbol{v} - \boldsymbol{v}_{\mathrm{sink}})\big)\mathrm{d}V.$$

- BH feedback, following Booth & Schaye (2009), assuming the radiative efficiency - accretion rate relation derived in MHD:

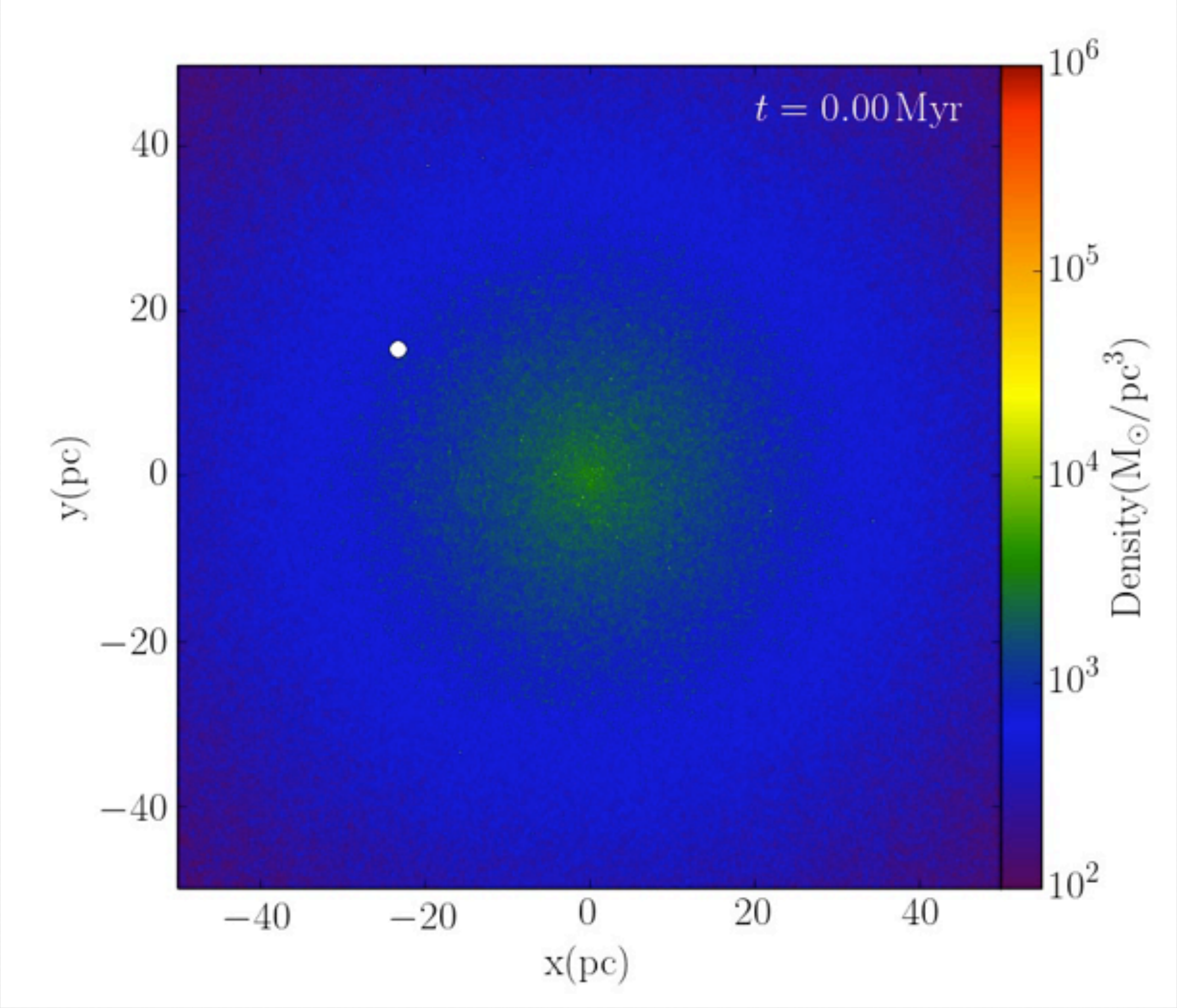
$$\eta = \frac{r}{16} A(a) \left[\frac{0.985}{r + B(a)} + \frac{0.015}{r + C(a)} \right]$$

$$\begin{aligned} A(a) &= (0.9663 - 0.9292a)^{-0.5639}, \\ B(a) &= (4.627 - 4.445a)^{-0.5524}, \\ C(a) &= (827.3 - 718.1a)^{-0.7060}. \end{aligned}$$

$$r = \dot{M}_{\mathrm{E}}/\dot{M}$$

[1] *http://grackle.readthedocs.org* (The Enzo Collaboration et al. 2014; Kim et al. 2014)

Super-critical accretion on stellar mass BHs in gas-rich galaxy nuclei



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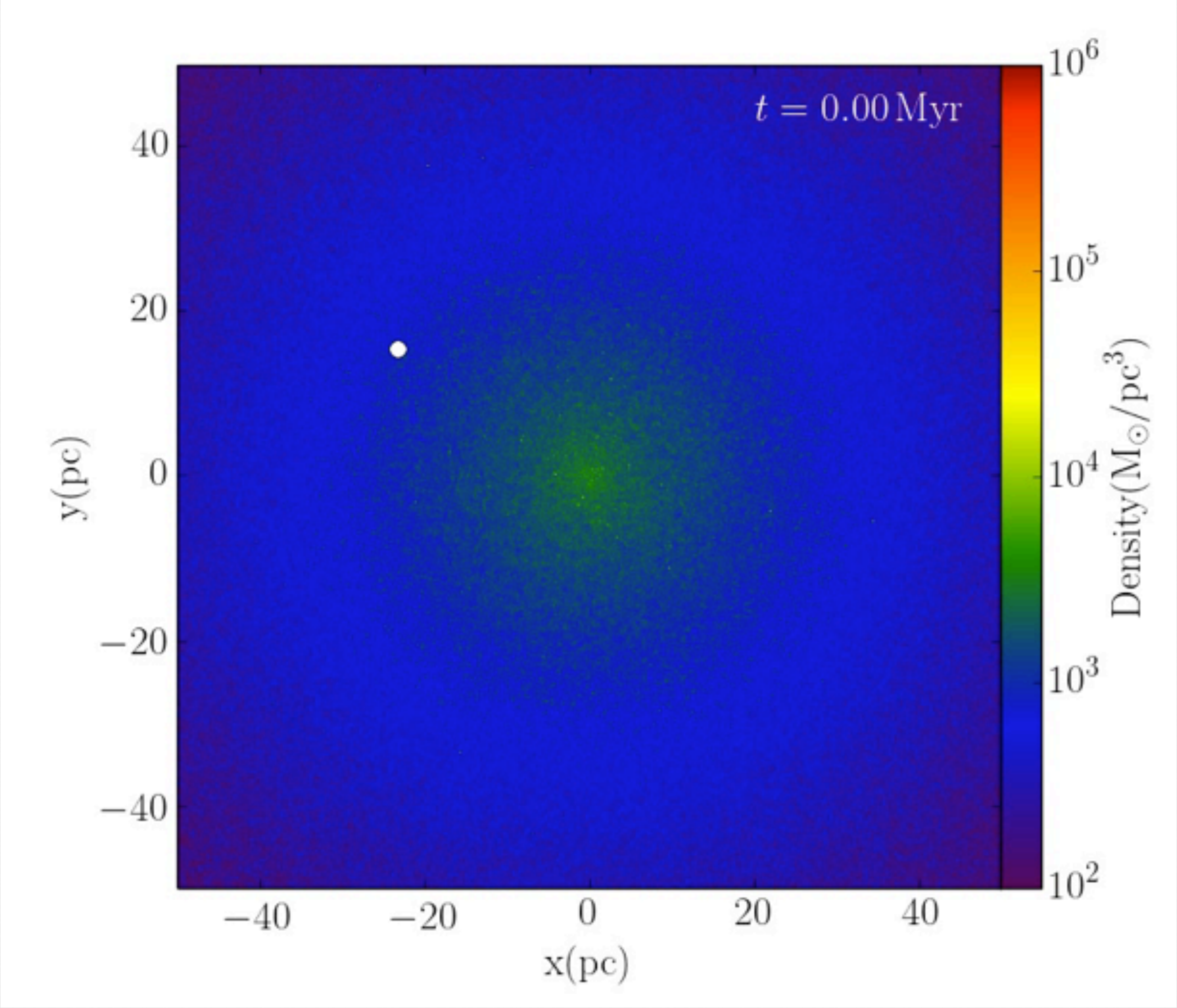
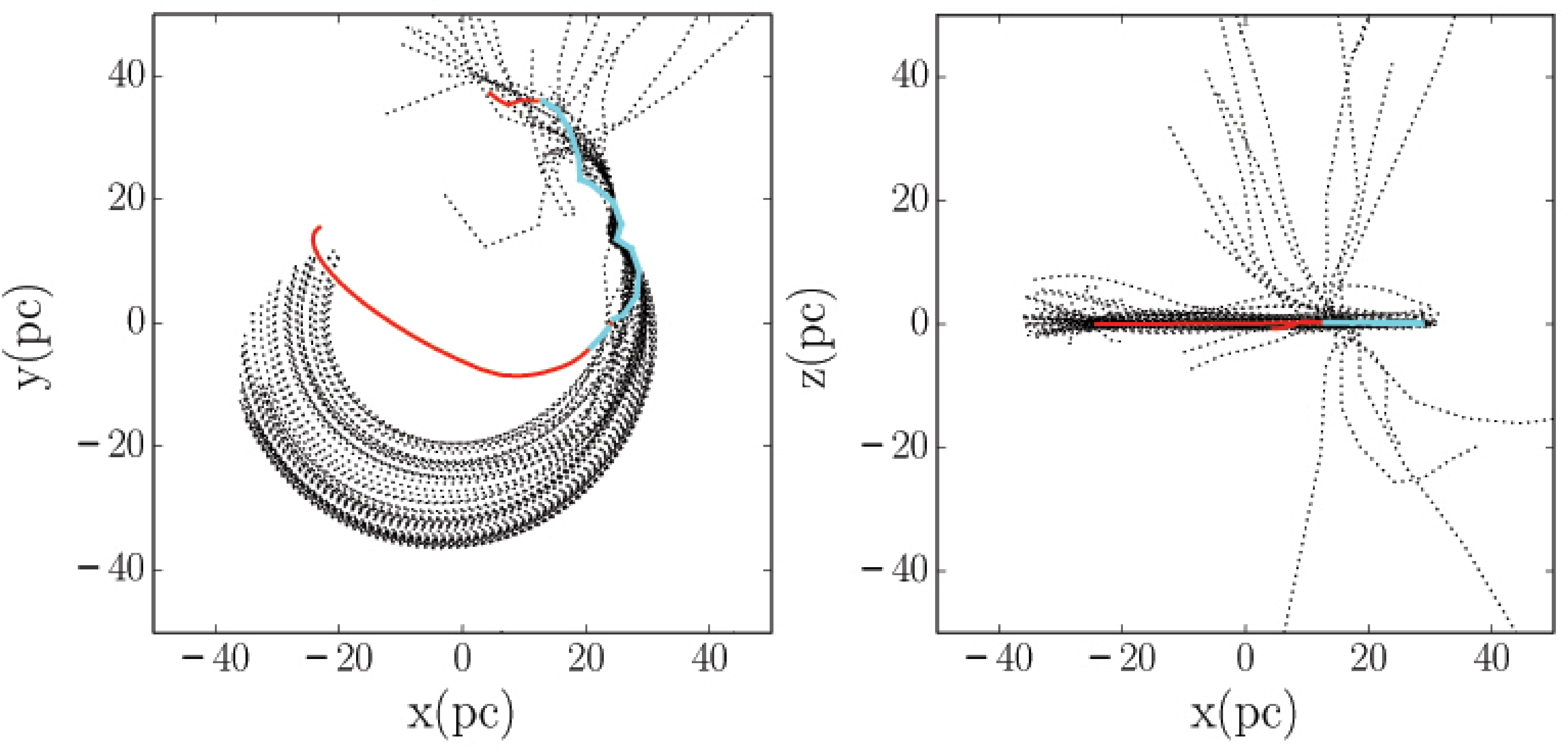
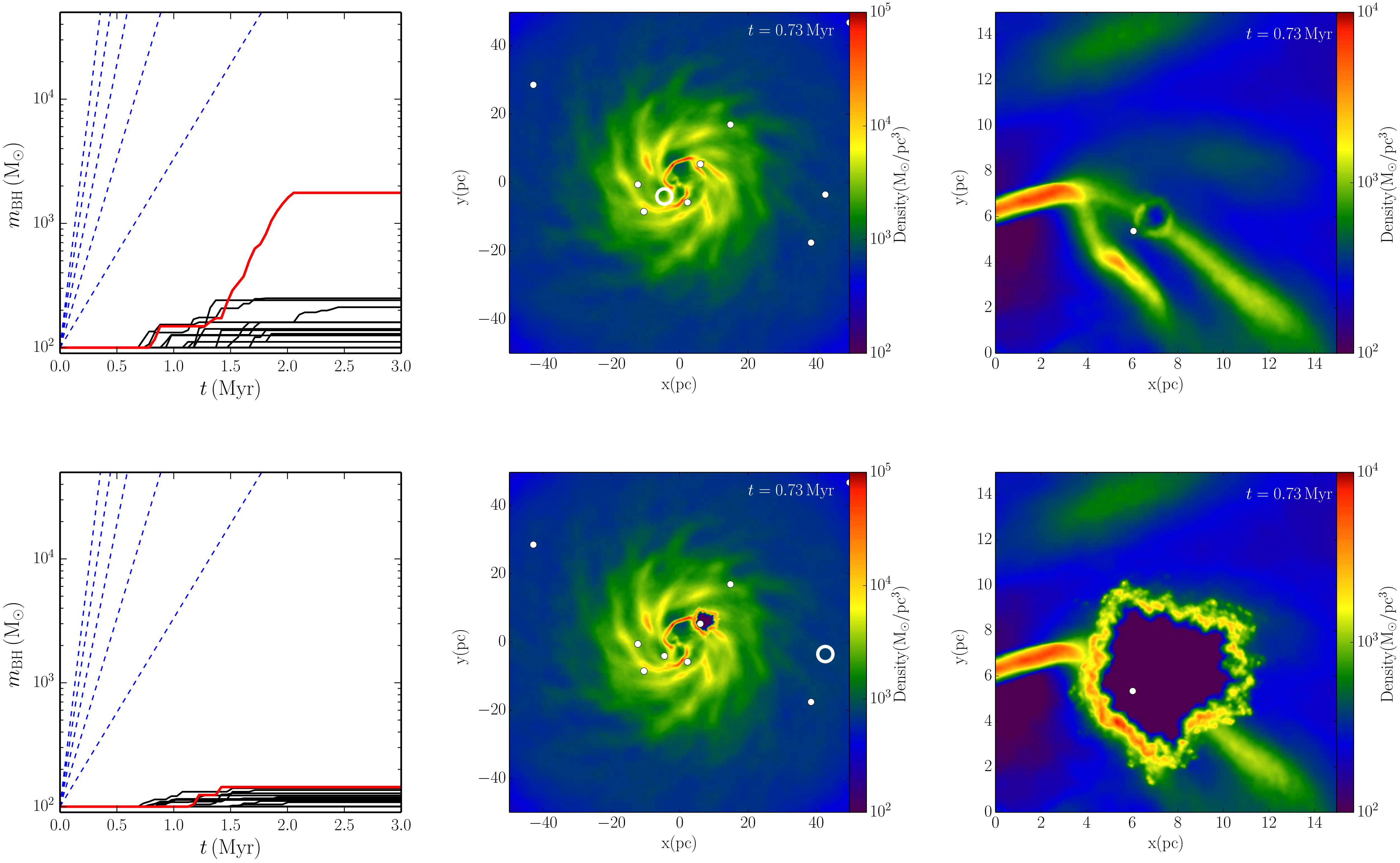


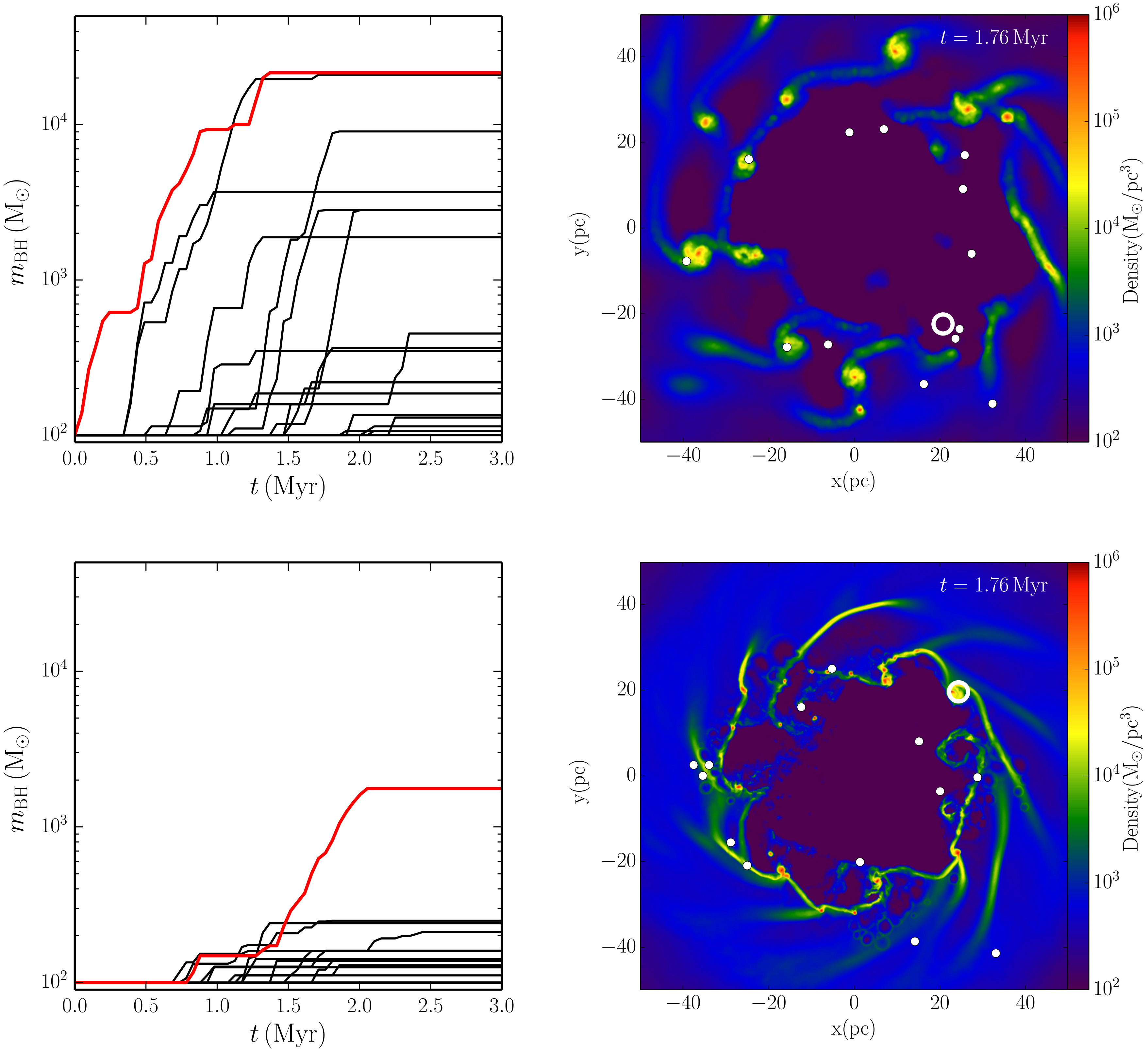
BH-clump capture process



Effect of the radiative efficiency



Effect of the resolution



Summary

Results:

- A radiatively inefficient accretion is a necessary condition to grow supermassive BHs in less than 1 Gyr, able to explain the most massive quasars

- A stellar mass BH embedded in a fragmenting CND can experience a gravitational capture by a massive gaseous clump, which provides a large enough inflow to trigger a phase of super-critical accretion

- The radiatively inefficient accretion on to the BH prevents the clump from being disrupted, allowing for an unimpeded fast growth able to increase the BH mass ~10-100 times more than with a standard Shakura & Sunyaev accretion model.

Summary

Open issues:

- The accretion history strongly depends on the spatial resolution achieved in our runs.
- Despite the high resolution reached we cannot properly resolve the accretion disc scales, so our accretion rates are overestimated.
  —> A quantitative convergence is far from being reached.
- Our simulations are highly idealised. We totally neglected the galaxy scales, which could provide large inflows to replenish the nucleus previously depleted from the gas as consequence of SNa explosions.
- The BH-clump capture process can occur only until the BH mass exceeds the clump mass.

Next steps

Fiacconi et al. in preparation

L ~ 85 Mpc comoving up to z=6.5

$M_{gas} \sim 880\ M_\odot$

ε = 47 physical pc (hi-res region ~ 2.5 R_{vir} at z=6)

~1.5×10^8 particles a z=6.5 (~ 3.5×10^7 within the virial radius)

$M_{halo} \sim 1.2 \times 10^{13}\ M_\odot$ at z=0 (~$10^{11}\ M_\odot$ at z=6.5)

R_{vir} ~ 25 kpc at z=6.5

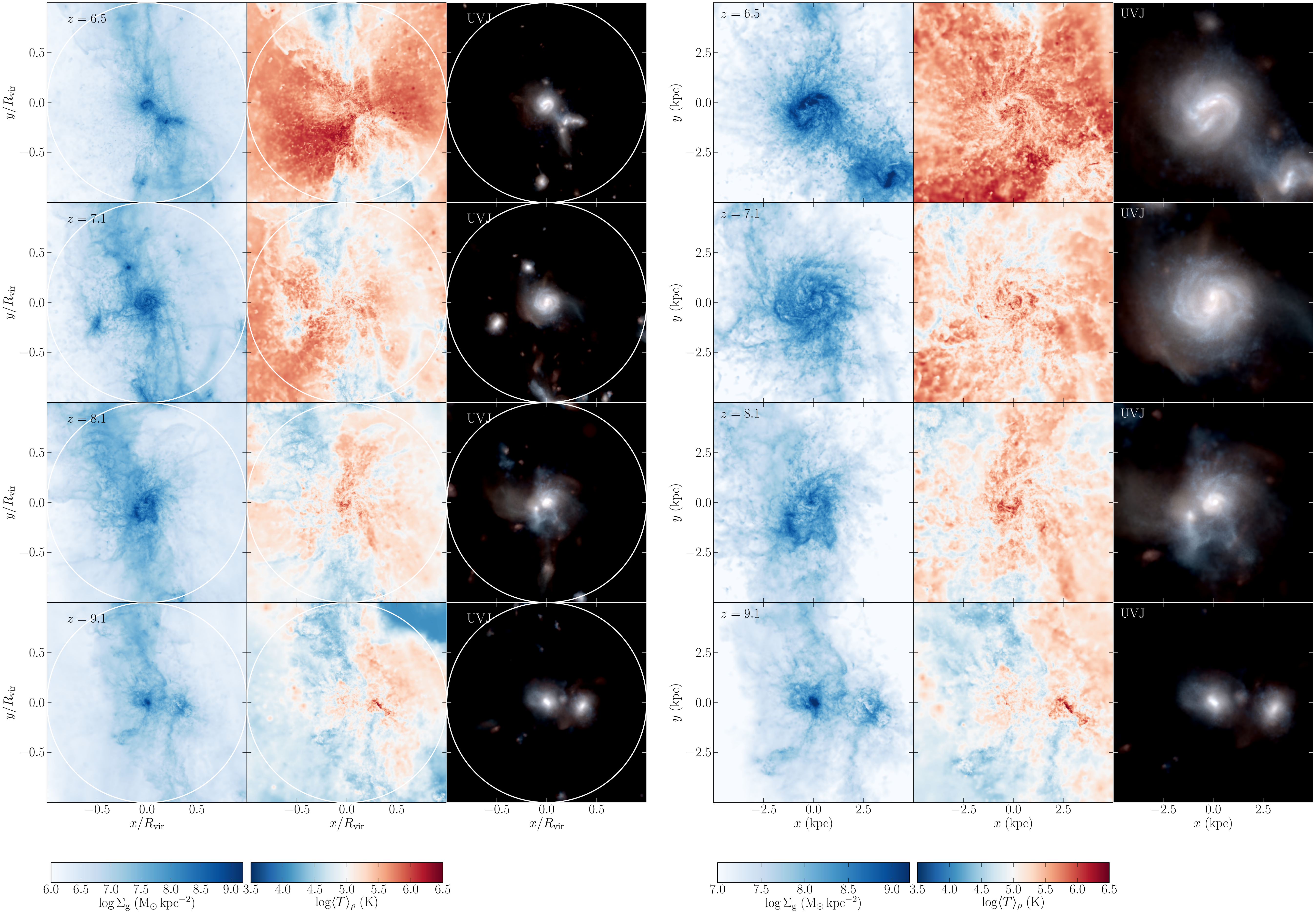
Metal cooling

Haardt & Madau (2012) UV background

Blast wave SN feedback

Kroupa (2001) IMF

Pressure floor (to resolve at least 3 elements)


z = 6.5
z = 7.1
z = 8.1
z = 9.1
UVJ
y/R_vir
x/R_vir
y (kpc)
x (kpc)
−0.5
0.0
0.5
−2.5
2.5
log Σ_g (M_⊙ kpc^−2)
6.0 6.5 7.0 7.5 8.0 8.5 9.0
7.0 7.5 8.0 8.5 9.0
log⟨T⟩_ρ (K)
3.5 4.0 4.5 5.0 5.5 6.0 6.5

Thanks for your attention