Supermassive Black Hole Growth and Merger Rates From N-Body Simulations

Miroslav Micic	Vanderbilt University
Steinn Sigurdsson	Pennsylvania State University
Kelly Holley-Bockelmann	Vanderbilt University
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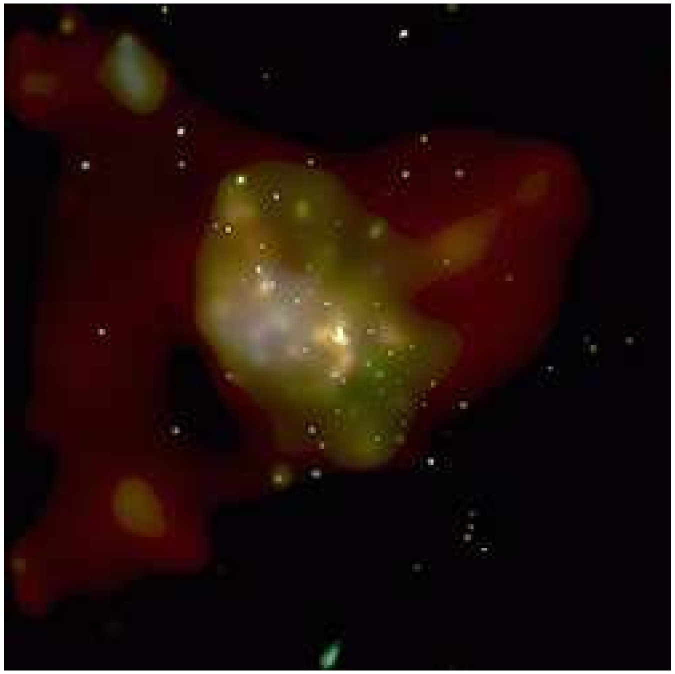
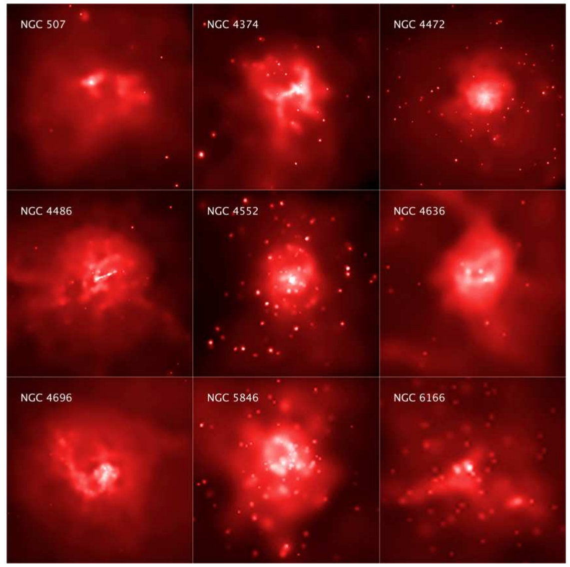
Sagittarius A*

By CHANDRA



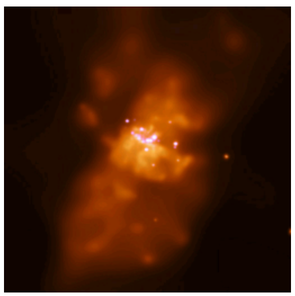
$M_{SMBH} = 3.6 \times 10^6 M_\odot$

- Black Holes have been observed in various environments and broad range of masses.



- Centers of Elliptical Galaxies host SMBH with M ~ billion sollar masses.

Chandra



Starburst M82, $M_{BH} \sim 1000 M_\odot$

HST

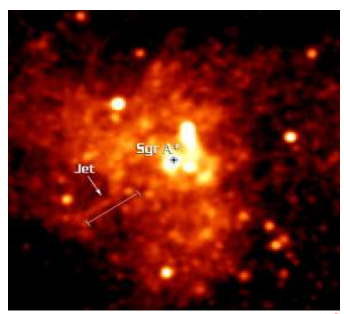
Globular Cluster G1, $M_{BH} \sim 18000 M_\odot$

Chandra

Spiral M74, $100 M_\odot < M_{BH} < 10000 M_\odot$

- Mass range of intermediate mass black holes (IMBH). IMBHs are associated with Ultra Luminous X-Ray sources (ULX).

- Is there a link ?!



Sagittarius A*, $M \sim 3 \times 10^6 M_\odot$

OUTLINE

- How To Grow SMBH ?
  - Population III stars
  - Seed black holes
  - AGN phase
  - Final SMBH
  - Suppression Mechanisms

One of the possible channels.

Primordial Black Holes

Collapse of the Supermassive Star

Direct collapse of a Gas Cloud

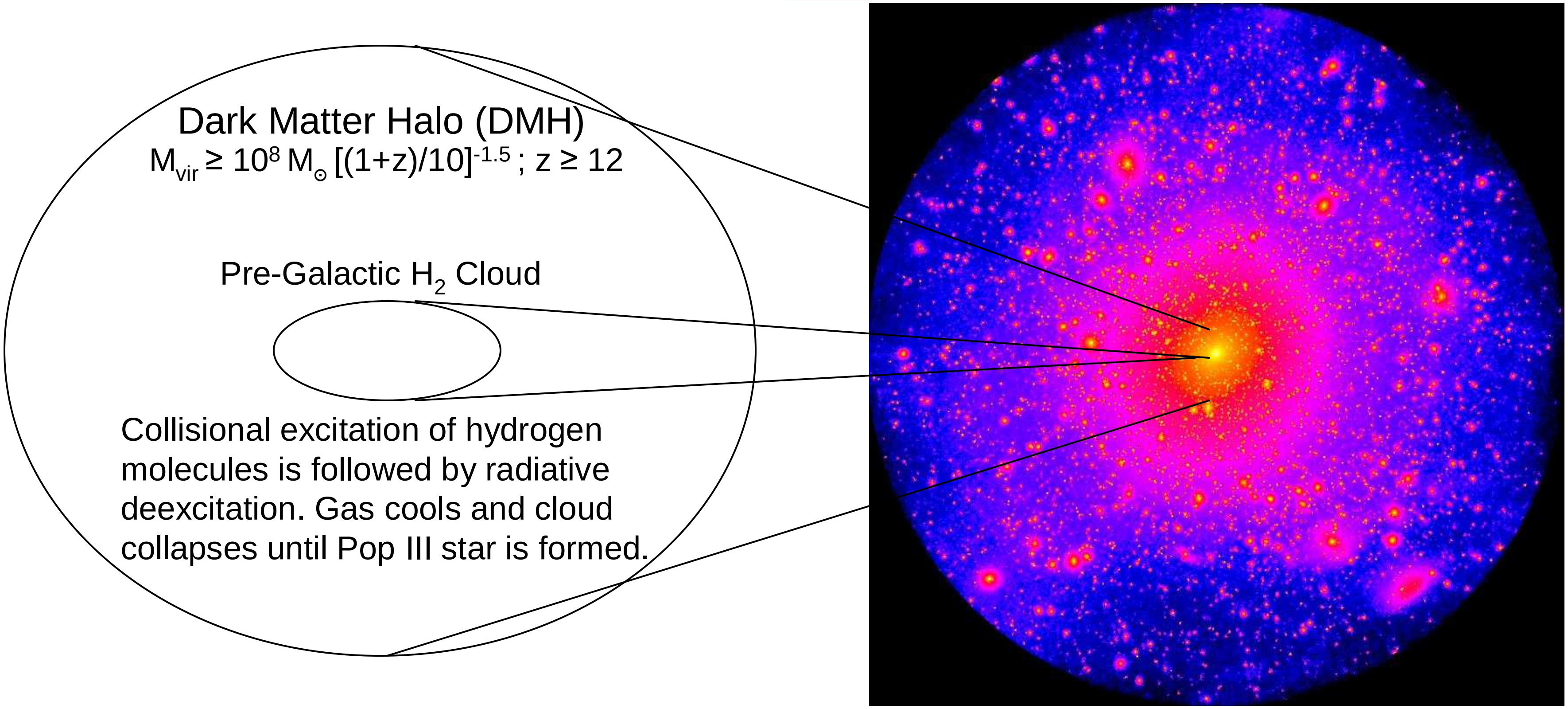
- Numerical Simulations :
  - Black Hole Merger Trees
  - How To Grow SMBH in Numerical Simulations ?
  - Observational Predictions

- Future Work

- How To Grow SMBH -

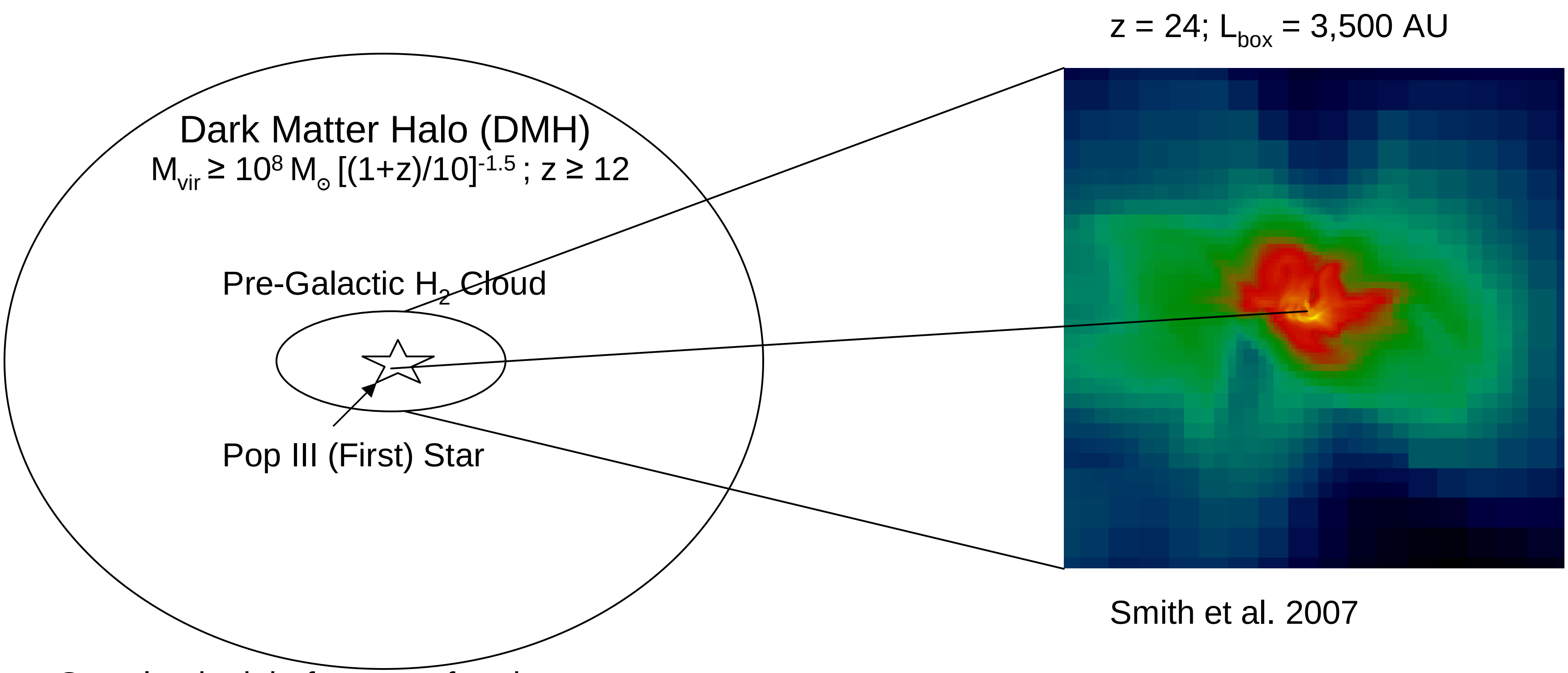
Population III Stars

- DMH is a group of collisionless particles which interact only through gravity and which satisfy one (or more) criteria suggested by your advisor.



- DMH hosting Milky Way has R ~ 300 Kpc at z ~ 0 and R ~ 30 Kpc at z ~ 10

Population III Stars



Smith et al. 2007

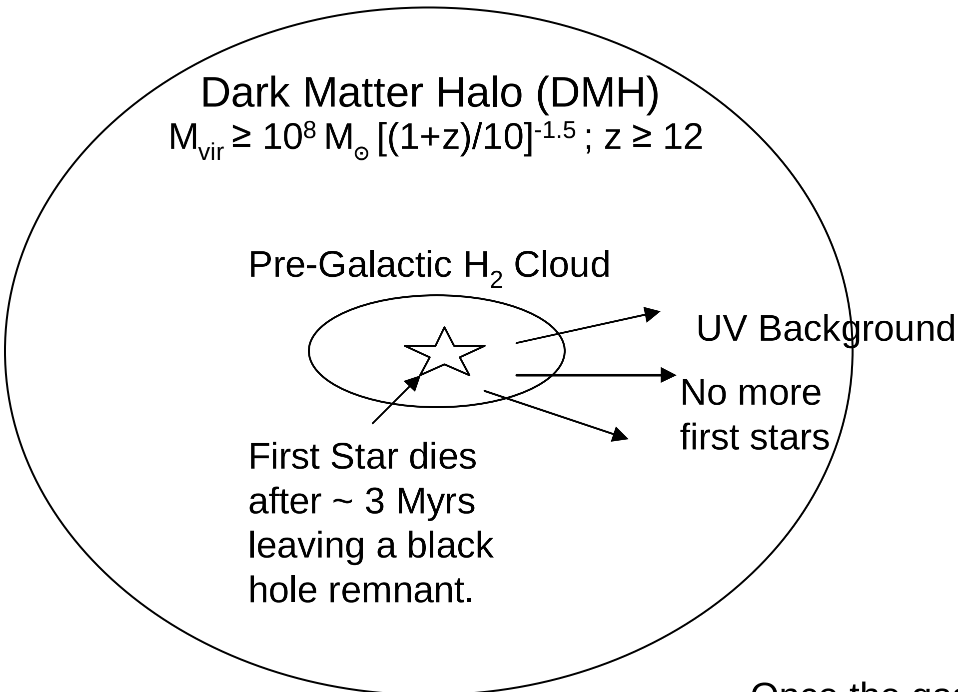
- Gas cloud might fragment forming many first stars. Since fragmentation is not fully understood, the initial mass function (IMF) for the first stars is unknown.

$$30\ M_\odot \lesssim m \lesssim 300\ M_\odot$$

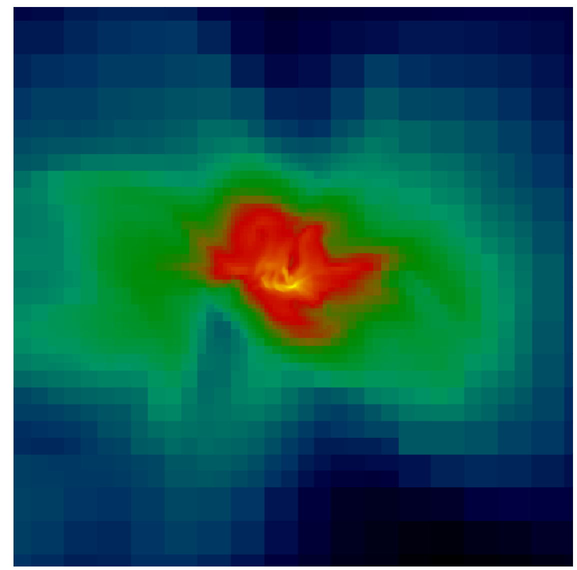
- First stars are metal free so their energy source is restricted to proton – proton burning. Consequently they are hot and live short.

Life time ~ 3 Myrs

Population III Stars



z = 24; L_{box} = 3,500 AU

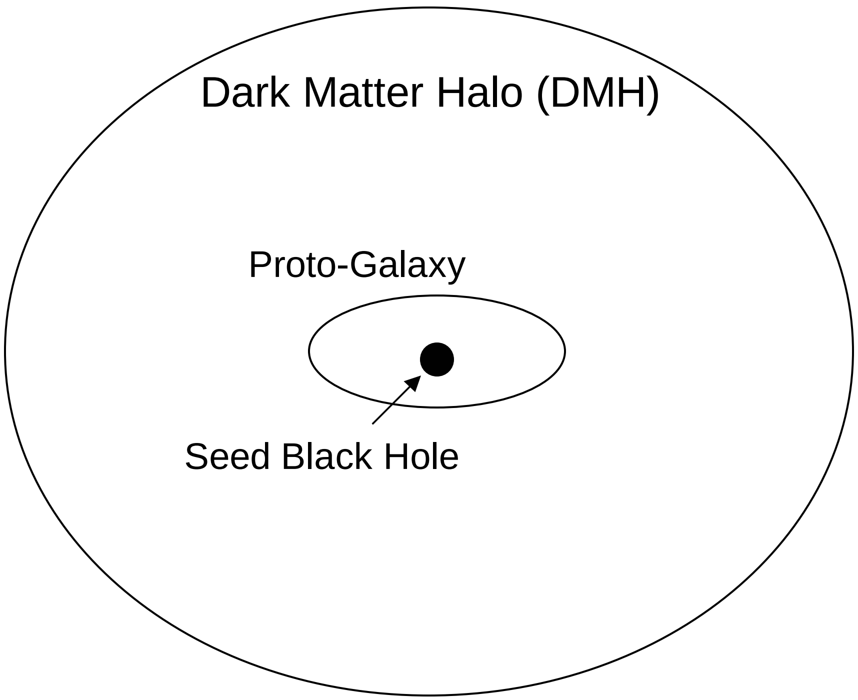


Smith et al. 2007

- Once the gas cloud has created the first generation of Pop III stars, there will be no more Pop III stars forming inside that cloud.

- How To Grow SMBH -

Seed Black Holes



- First stars with mass $m \lesssim 140\ M_\odot$ and $m \geq 260\ M_\odot$ collapse directly into a black hole Heger & Woosley 2002.

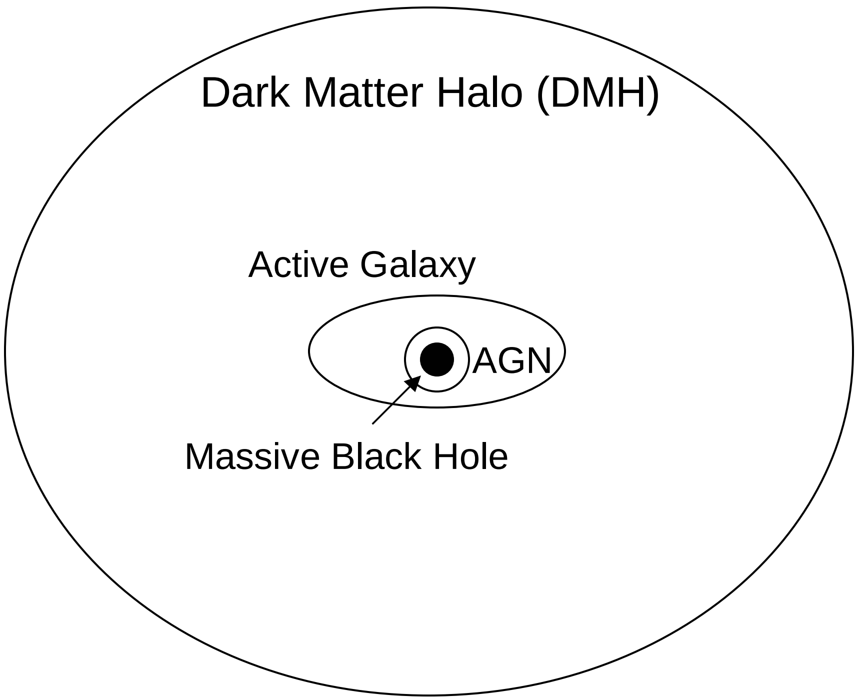
- First stars with mass $140\ M_\odot \lesssim m \lesssim 260\ M_\odot$ go through pair-instability supernova leaving no remnant

- Seed black holes contain at least half of the initial stellar mass, Fryer et al. 2001.

- Because of the uncertainties in Pop III IMF, we do not know what is the typical number of seed black holes in dark matter halos.

- How To Grow SMBH -

Seed black hole grows in mass through gas accretion.
We observe it as AGN during AGN duty-cycle.



AGN duty-cycle = time during which black hole is accreting gas

- AGN duty-cycle is controlled by the DMH merger rate.

- How To Grow SMBH -

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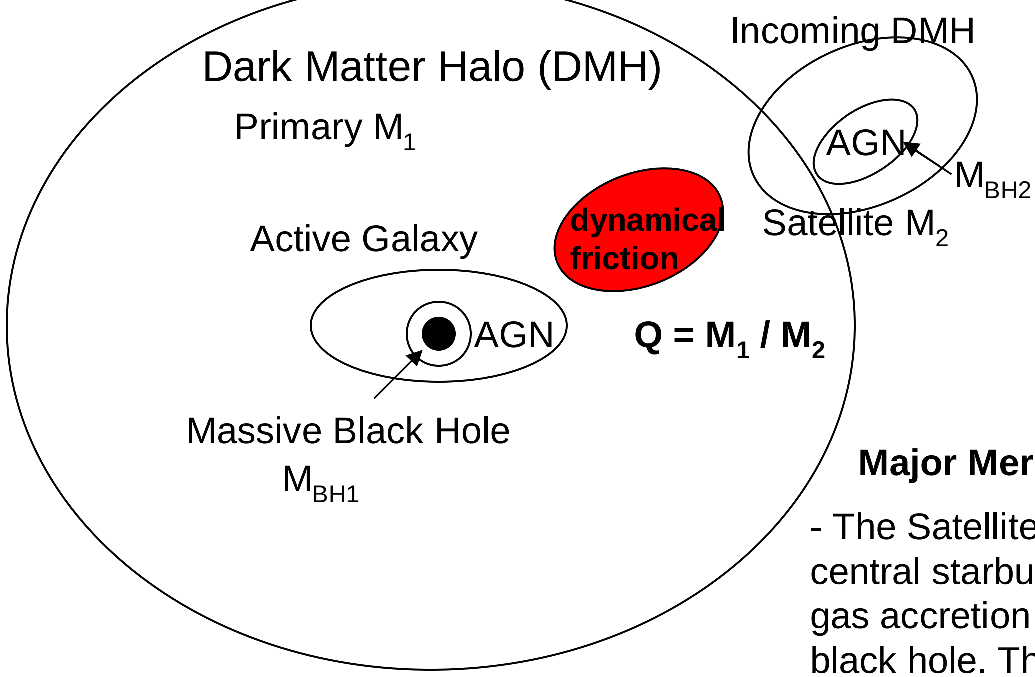


- AGN duty-cycle is controlled by the DMH merger rate.

- Mergers of high redshift DMH maintain AGN duty-cycle and make black hole mergers possible.

- Satellite looses kinetic energy through gravitational interaction with dark matter background density. This process is called dynamical friction.

Major Merger, Q ~ 1

- The Satellite triggers a central starburst, generating gas accretion onto the central black hole. Through gas accretion black hole doubles its mass in:

$t \sim 4 \times 10^7$ yr

$$M_{SMBH} \sim 2 \times (M_{BH1} + M_{BH2})$$

Minor Merger, Q >> 1

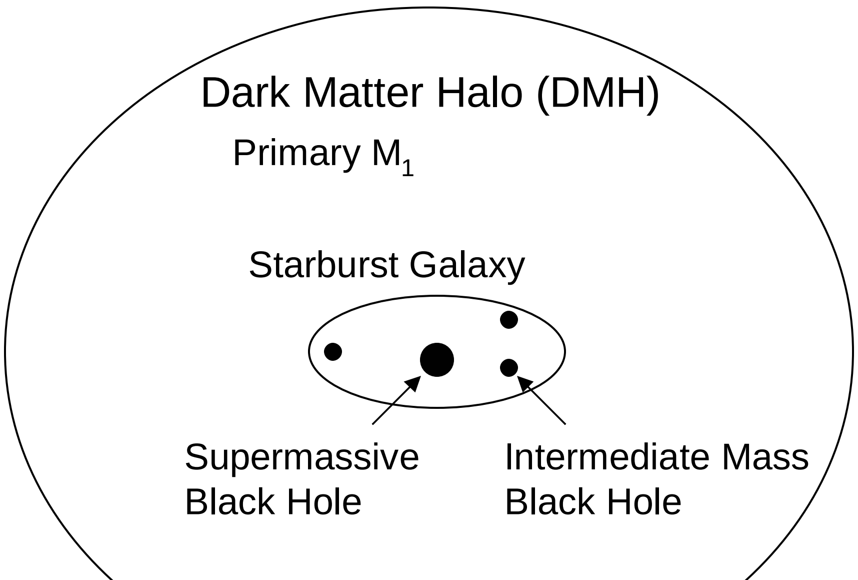
- The Primary shreds the Satellite and gas accretion can not be activated.

$$M_{SMBH} \sim M_{BH1} + M_{BH2}$$

- How To Grow SMBH -

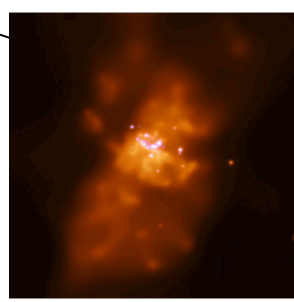
Final SMBH

$$N_{mergers} \times (M_{BH1} + M_{BH2}) \lesssim M_{SMBH} \lesssim 2 \times N_{mergers} \times (M_{BH1} + M_{BH2})$$



Starburst M82, M_{BH}~1000M⊙

Chandra



- Major mergers become rare as the Primary DMH grows large in mass.

- Minor mergers can not maintain the duty-cycle and the AGN shuts down.

- Since the number of minor mergers is still quite large, activity shifts from central regions to off-centered ULX sources.

- If at low redshifts galaxy goes through another major merger, it becomes elliptical galaxy, otherwise it ends up as spiral.

Black Hole Mergers in Numerical Simulations

- **How to make numerical merger tree ?**
  - Difficulties in identifying high redshift structures, tracing their mergers, obtaining numerical merger trees…
- **Evolution of SMBH in numerical simulations.**
  - Growth of SMBH. Black hole merger rates.
  ULX sources?

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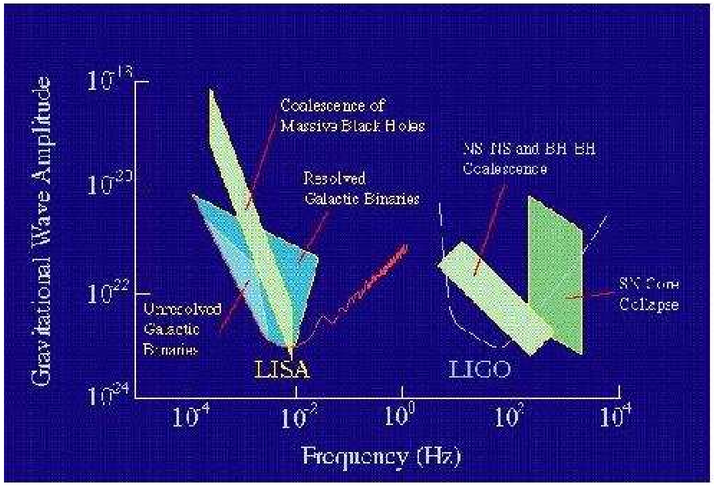
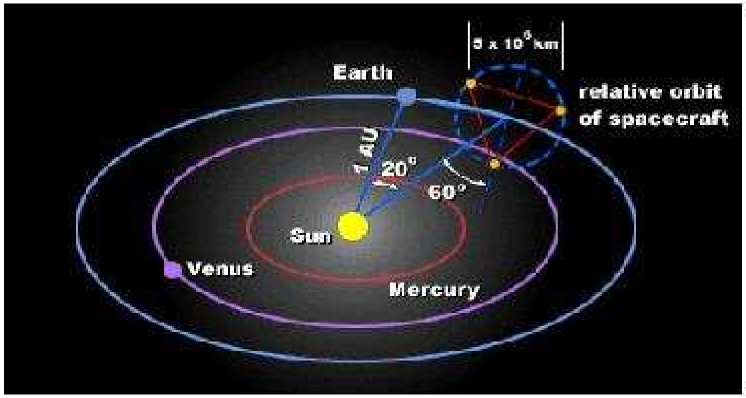
- **What can we observe ?**
  - SMBH/IMBH mergers are the best LISA sources!!!





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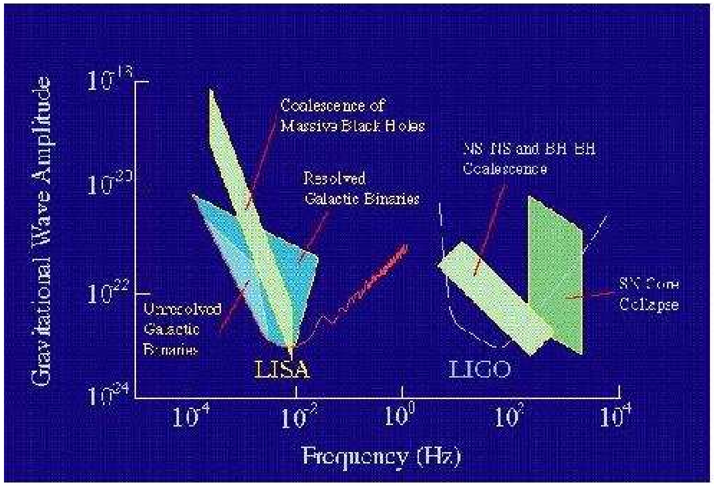
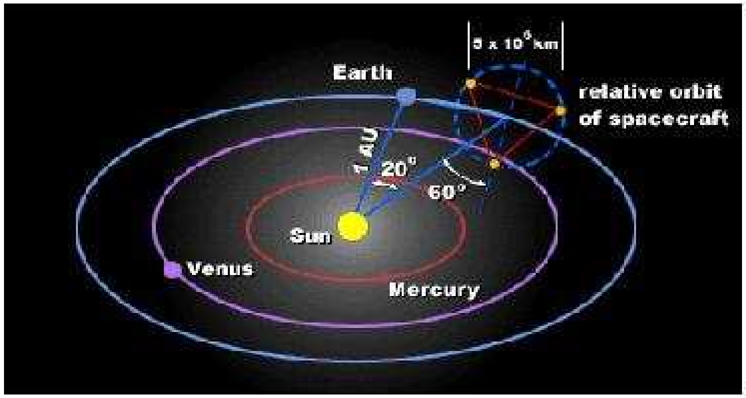




What makes this work unique ?

- Low mass dynamical range in the cosmological context !
  (highly resolved 10^7 $M_\odot$ - 10^{12} $M_\odot$ halos – local group)
- Formation and evolution of Milky Way DMH and its SMBH !
  (during Hubble time !!!)
- Numerical tracing of the mergers in the cosmological context !
- LISA signal from the mergers in the numerical simulations !

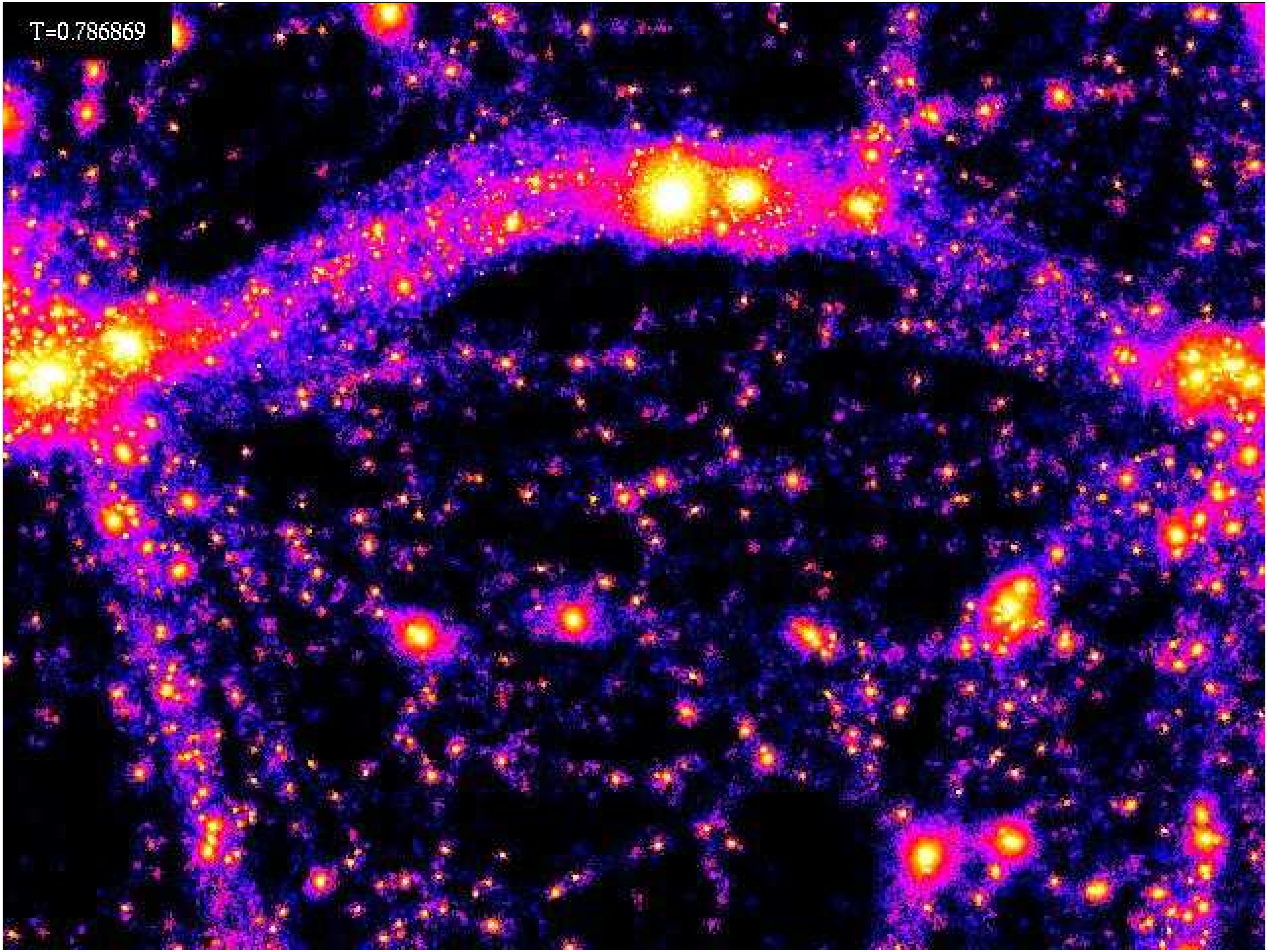
How do we improve previous numerical and Semi-analytical works ?

- ΛCDM , $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $0 < z < 40$, 10 Mpc box
- low-resolution field with ~ 2 million particles, $M_p = 5.6 \times 10^7 M_\odot$
- high-resolution field with ~ 5 million particles, $M_p = 8.5 \times 10^5 M_\odot$

- minimum 32 particles per DMH.
  (10 particles in previous numerical simulations)
- minimum DMH mass $M = 2.8 \times 10^7 M_\odot$
  (100 times better compared to previous numerical simulations)
- DMH identification:
  - FOF + SUBFIND algorithm + $200 \times \rho_{average}$ + $M_{vir} > 10^8 M_\odot (1+z)^{-1.5}$

- seeding redshift: $12 < z < 20$ (Wise & Abel 2005); $M_{seed} = 200 M_\odot$

- gas accretion: BH doubles its mass 40Myrs after galaxies merge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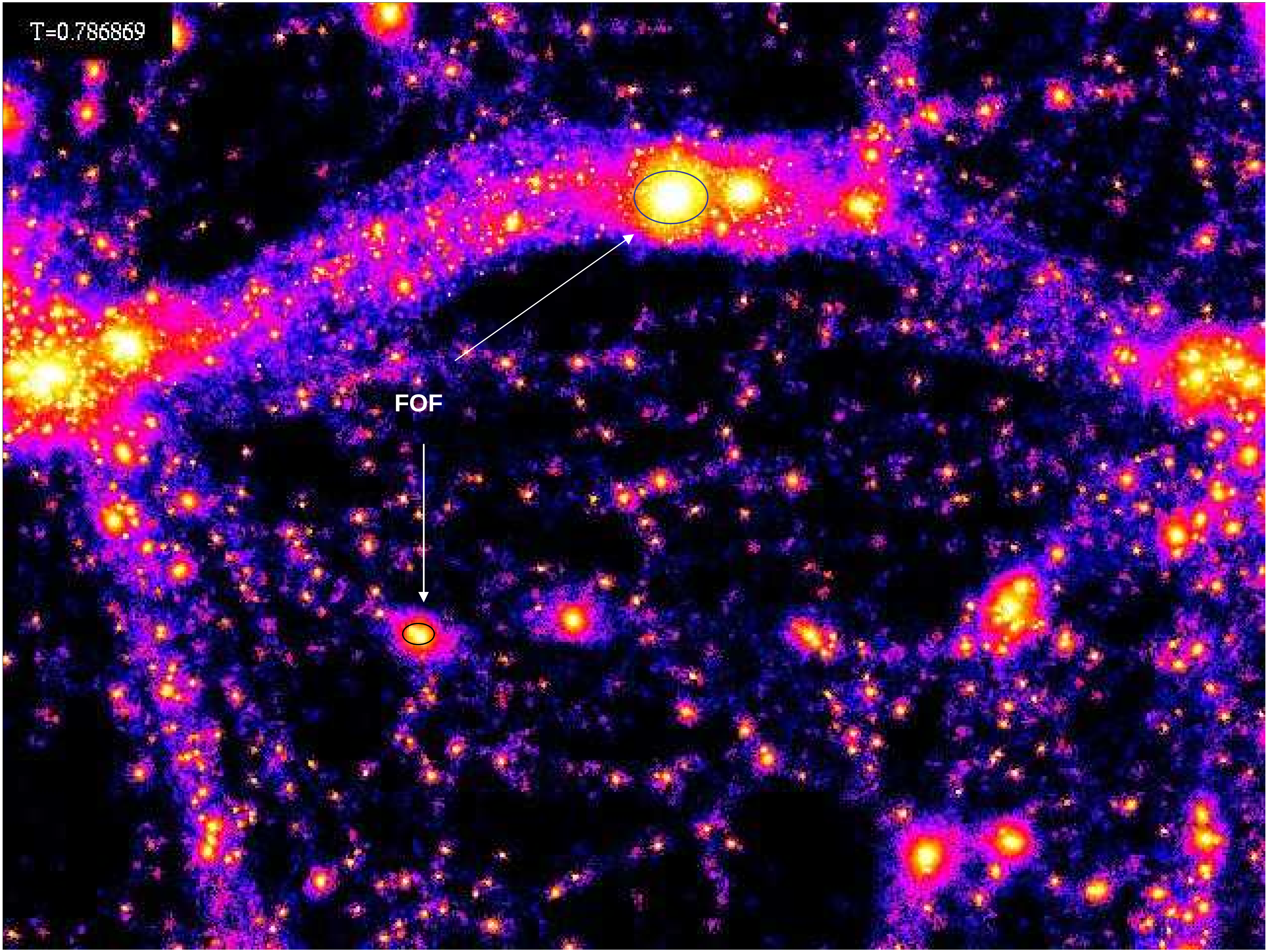
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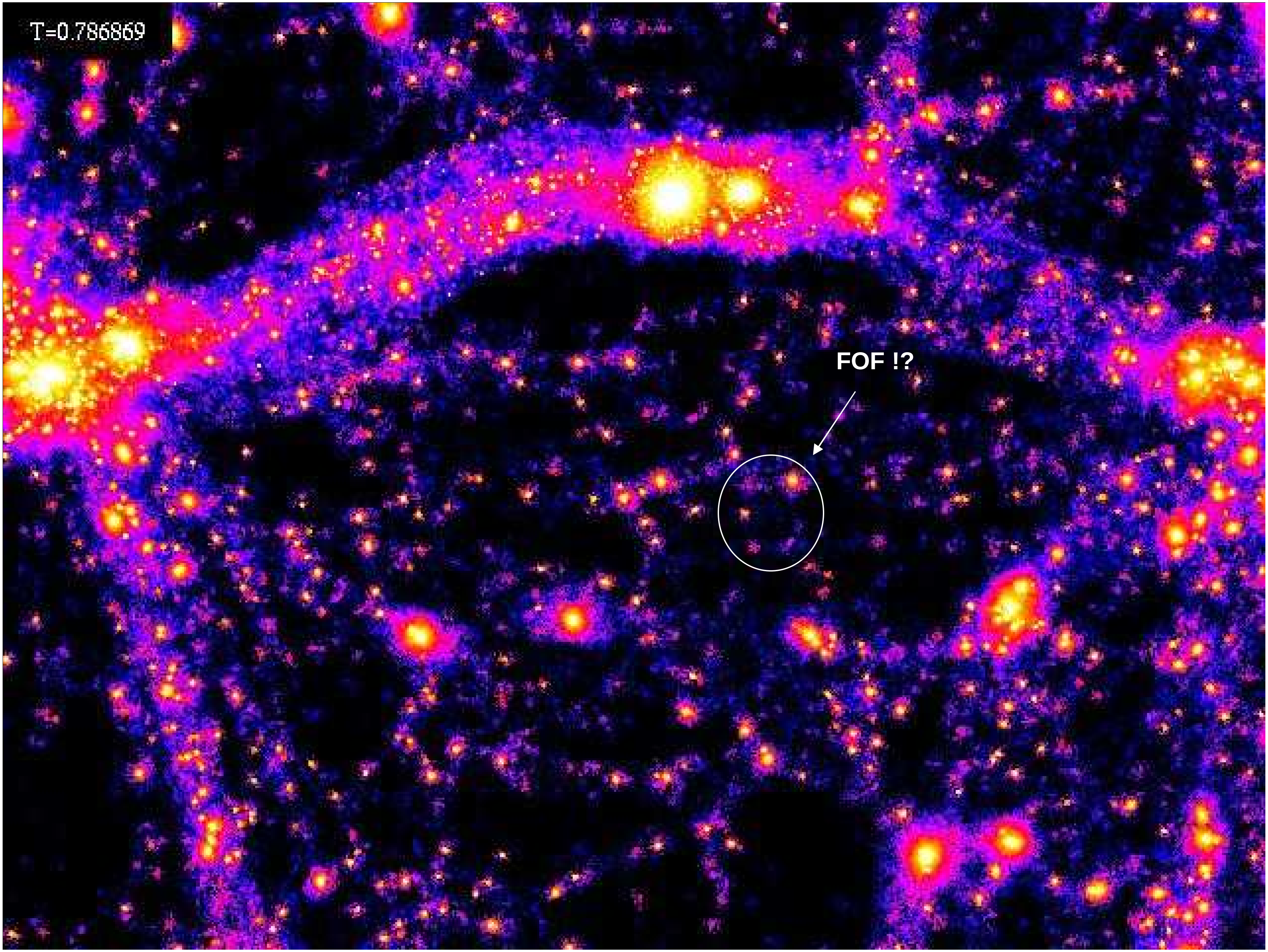
FOF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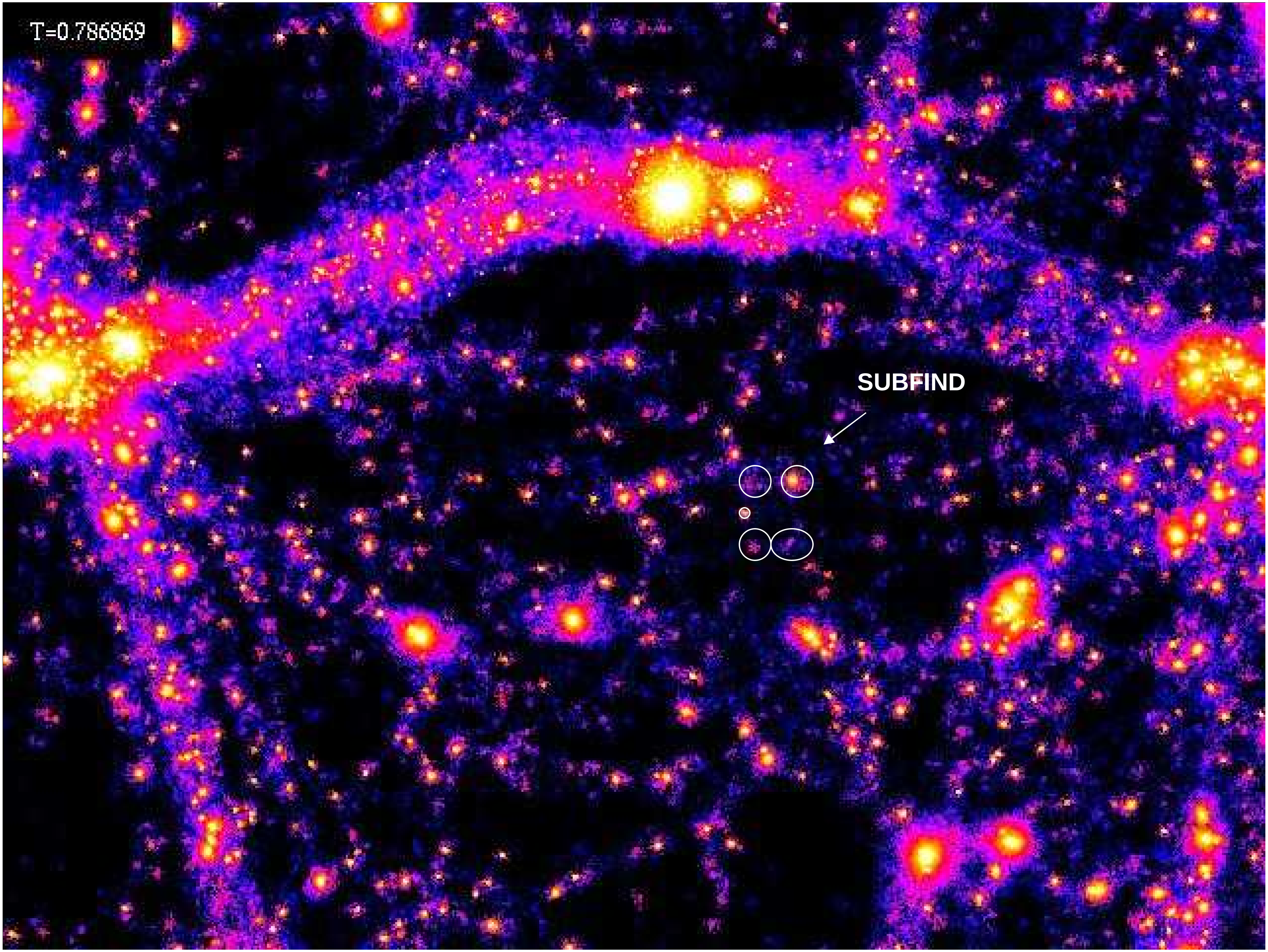
FOF !?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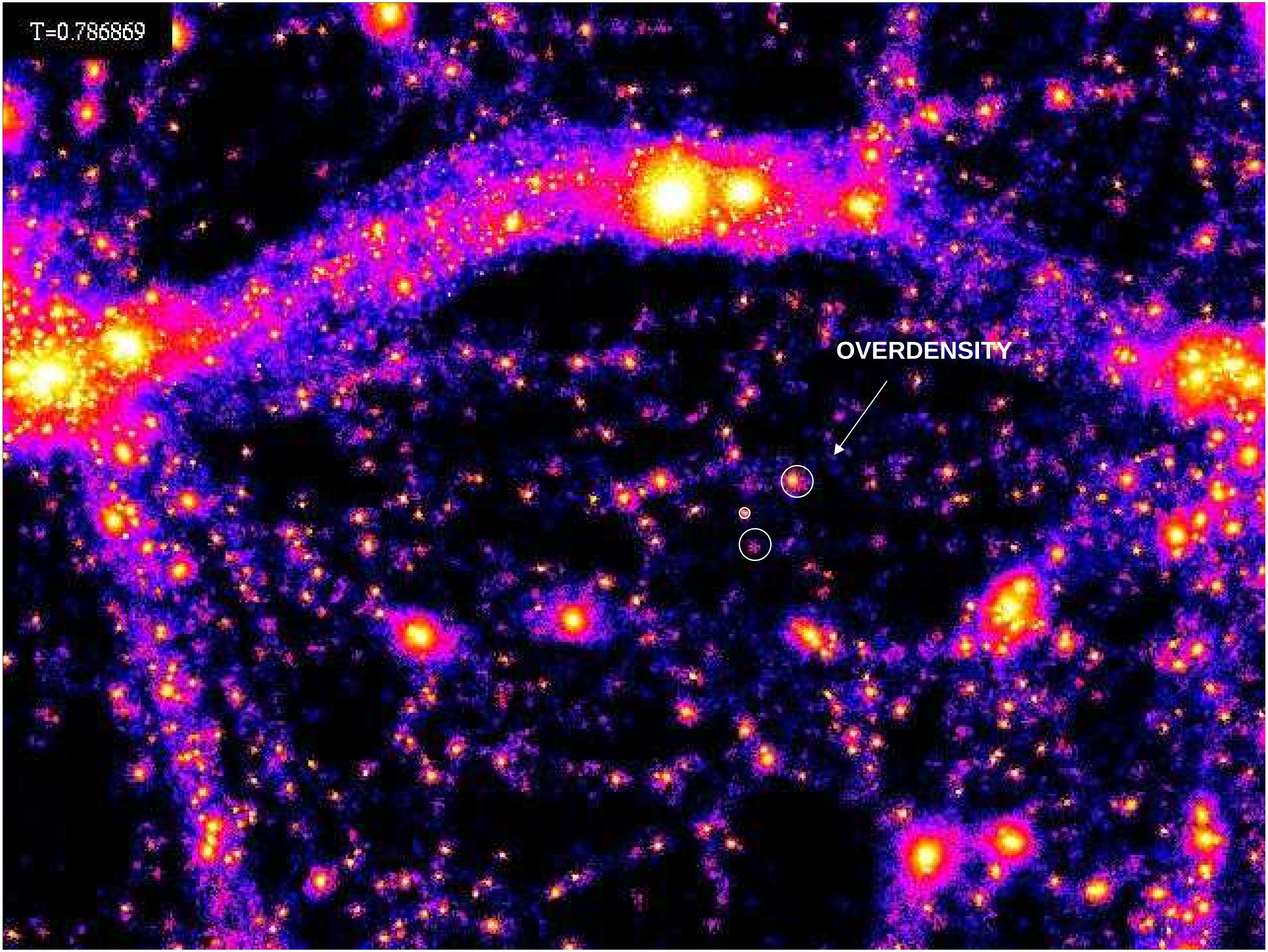
SUBFIND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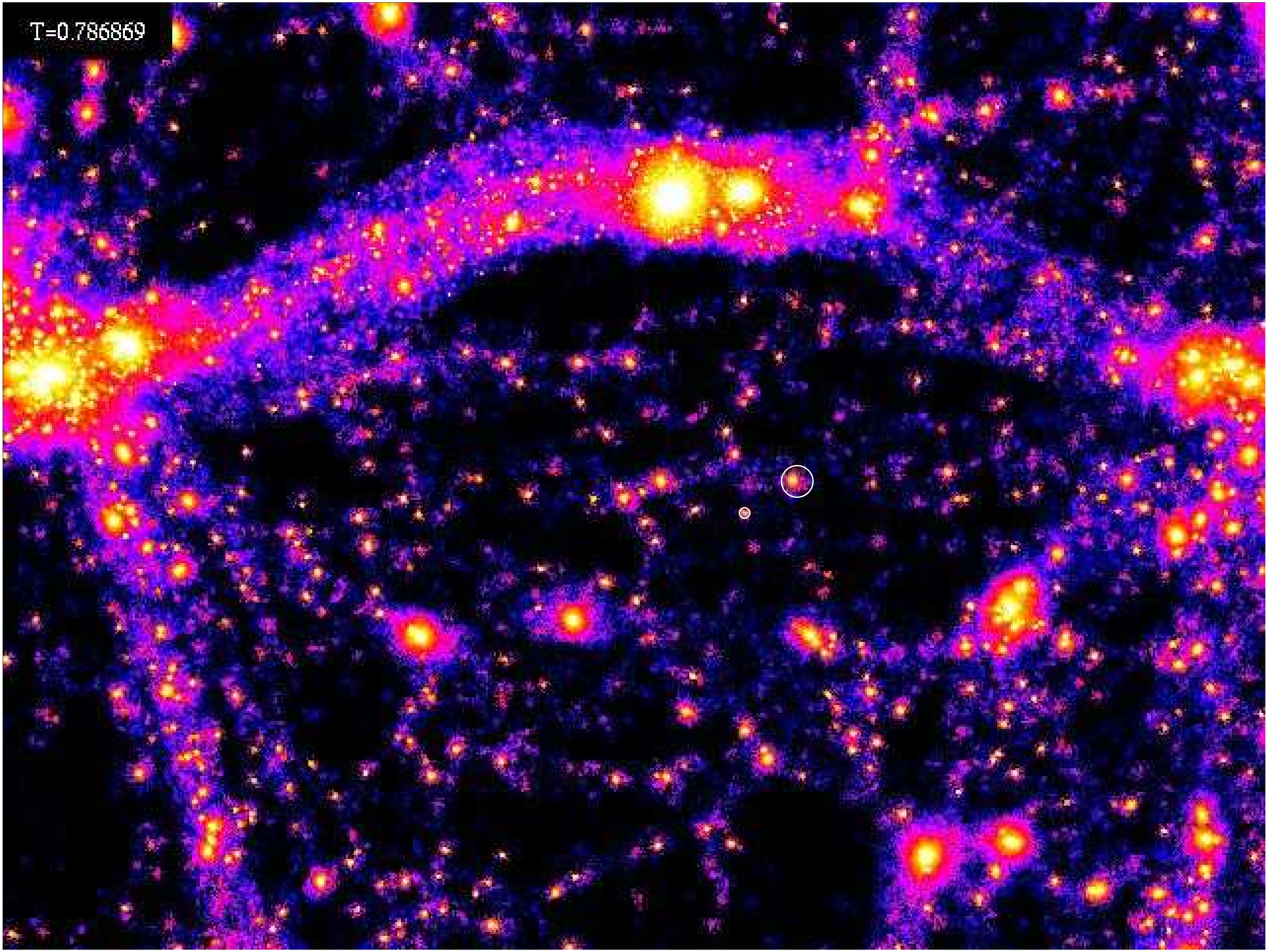
OVERDENSITY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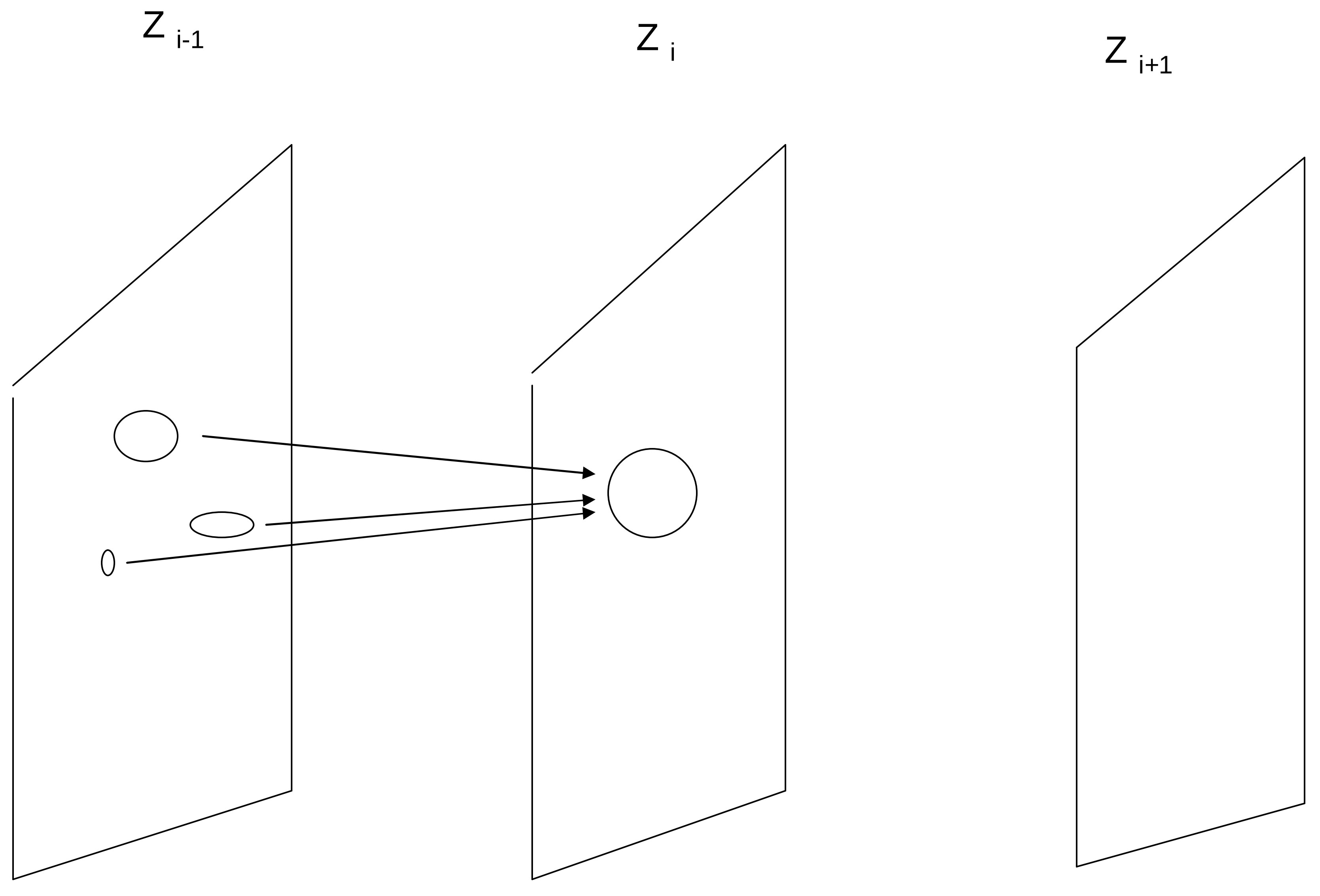
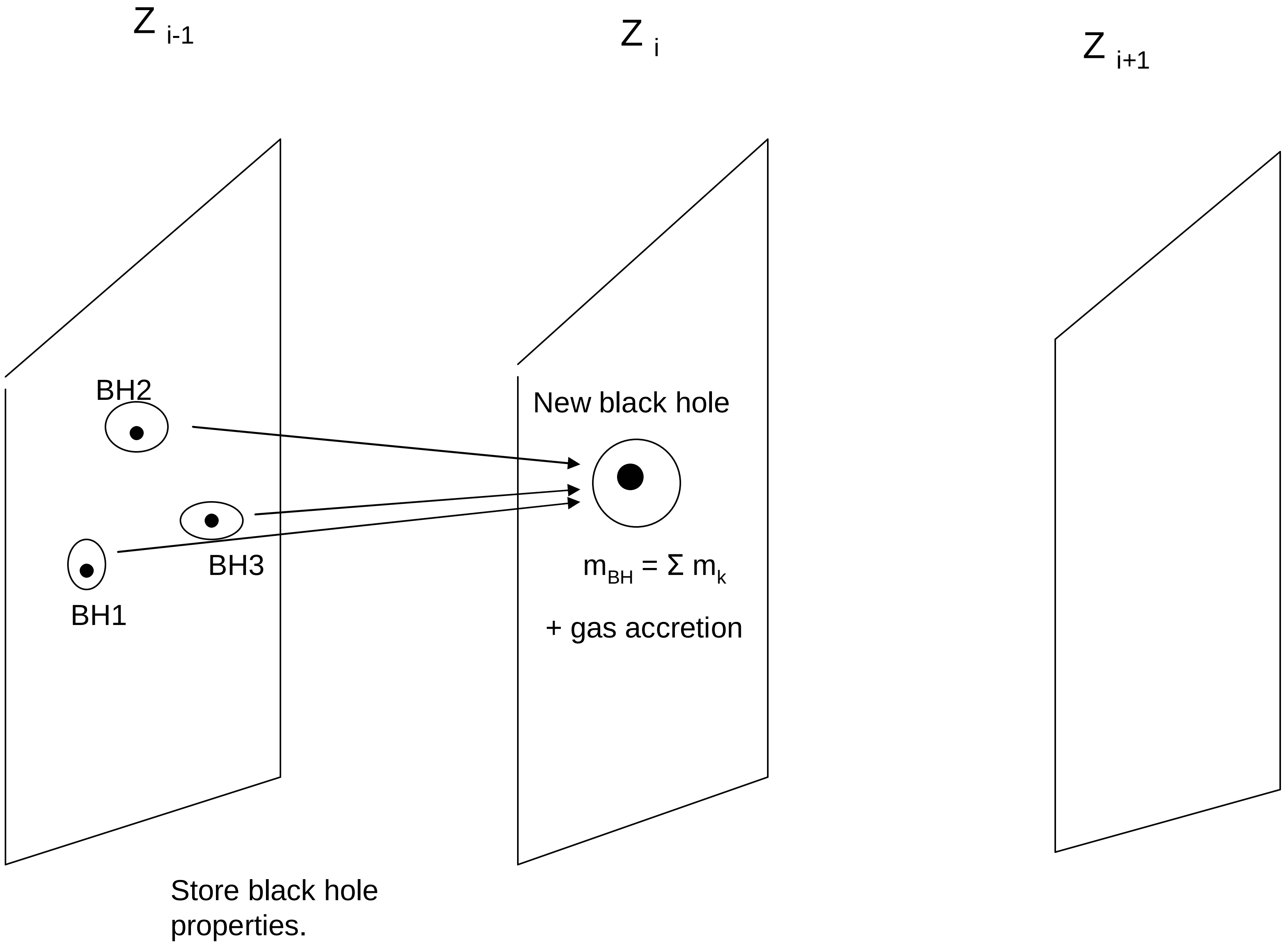
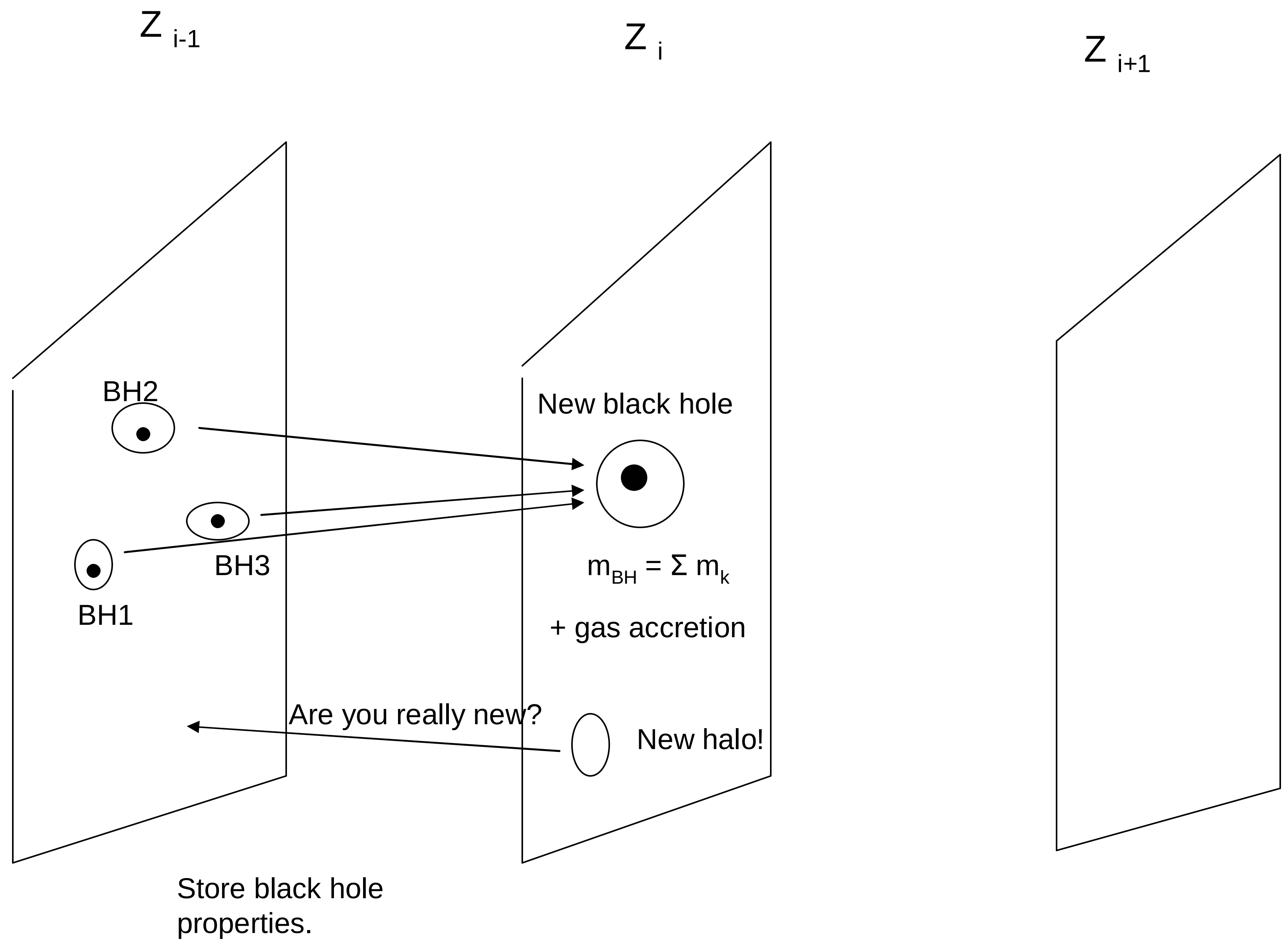

Z_{i-1}
Z_i
Z_{i+1}


Z i-1
Z i
Z i+1
BH2
BH3
BH1
New black hole
$m_{BH} = \Sigma m_k$
+ gas accretion
Store black hole
properties.


Z i-1
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m_BH = Σ m_k
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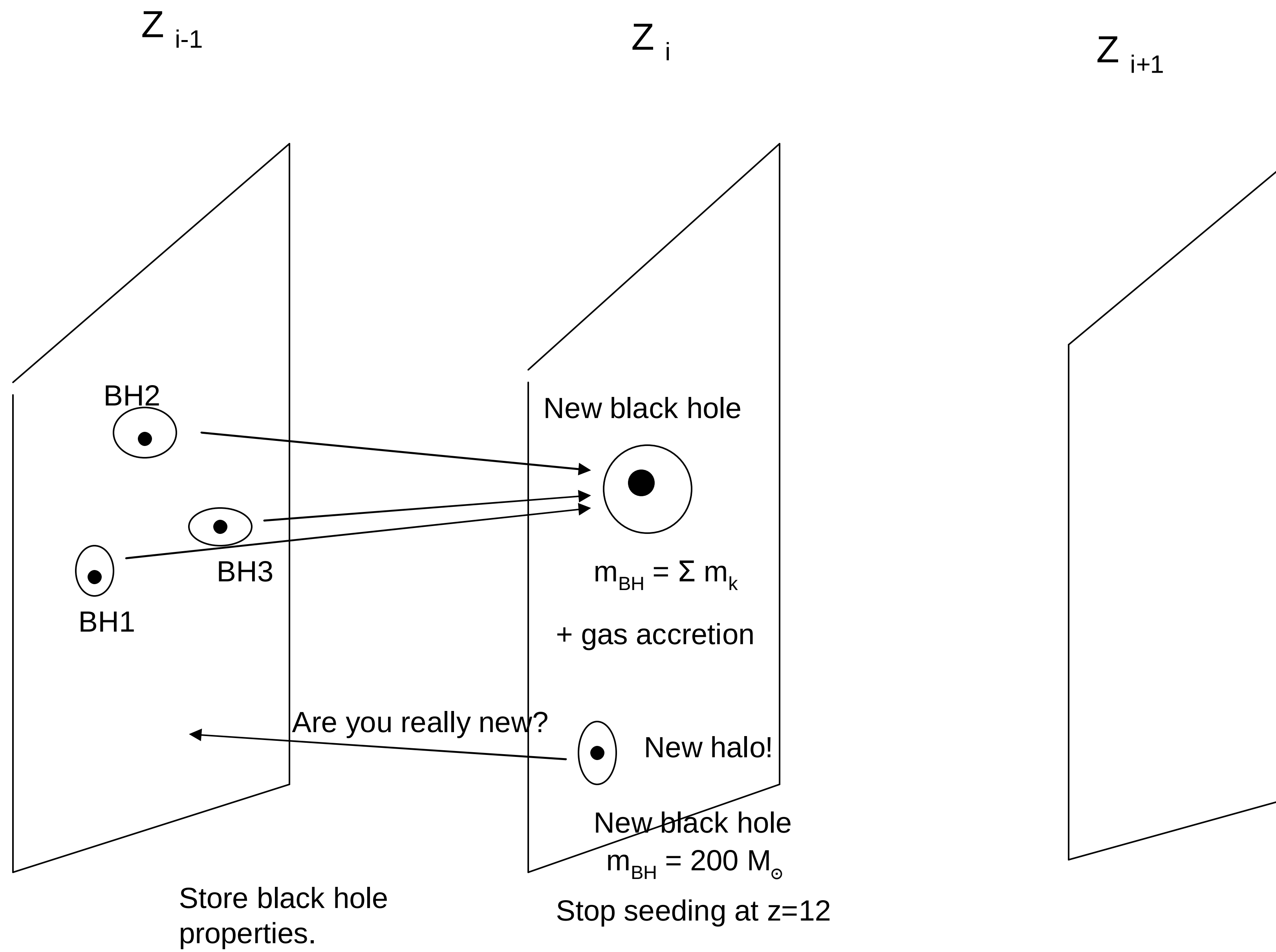
Are you really new?
New halo!
Store black hole properties.



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New black hole
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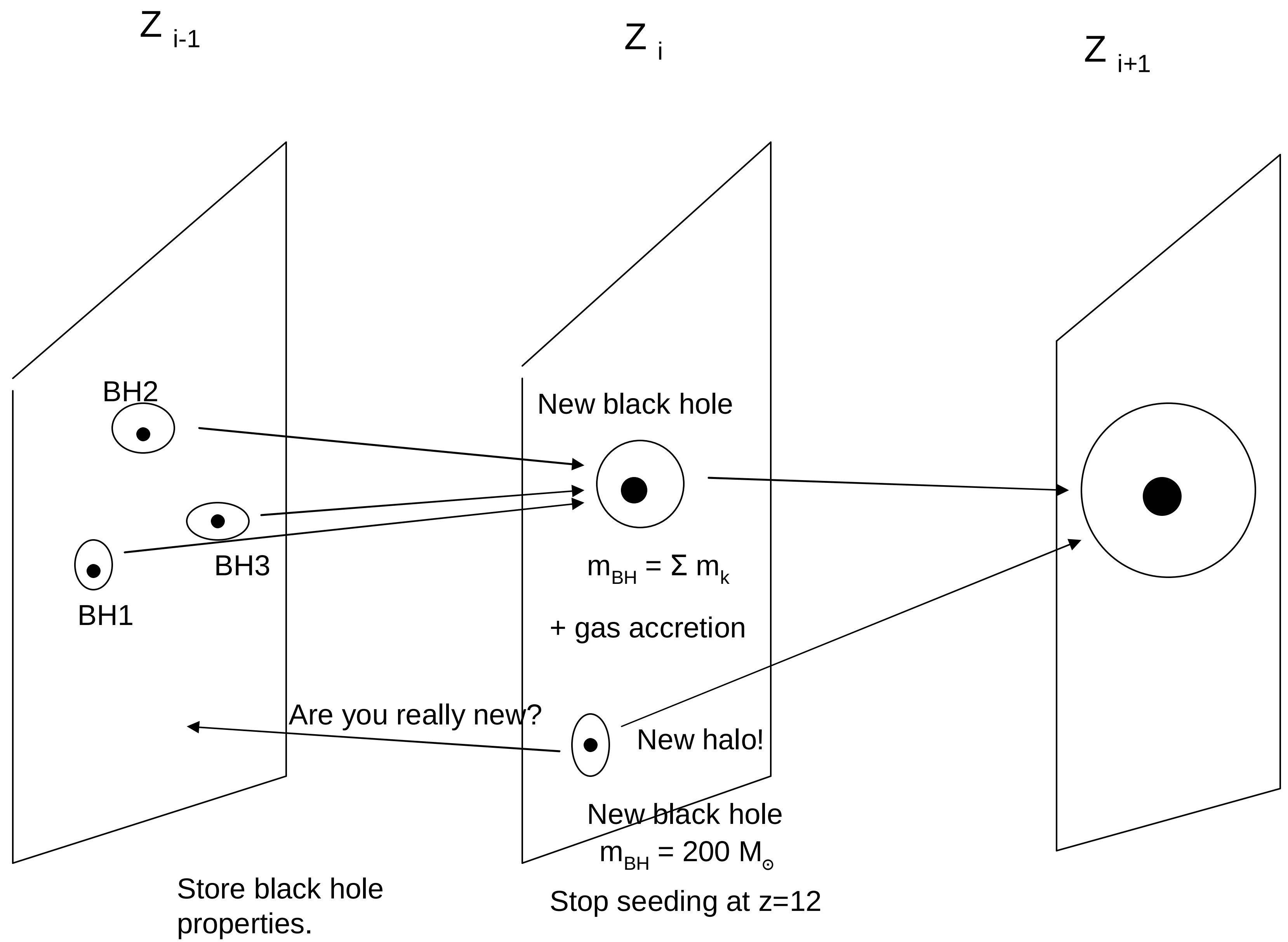
$m_{BH} = \Sigma\, m_k$
+ gas accretion
Are you really new?
New halo!
New black hole
$m_{BH} = 200\ M_{\odot}$
Store black hole properties.
Stop seeding at z=12



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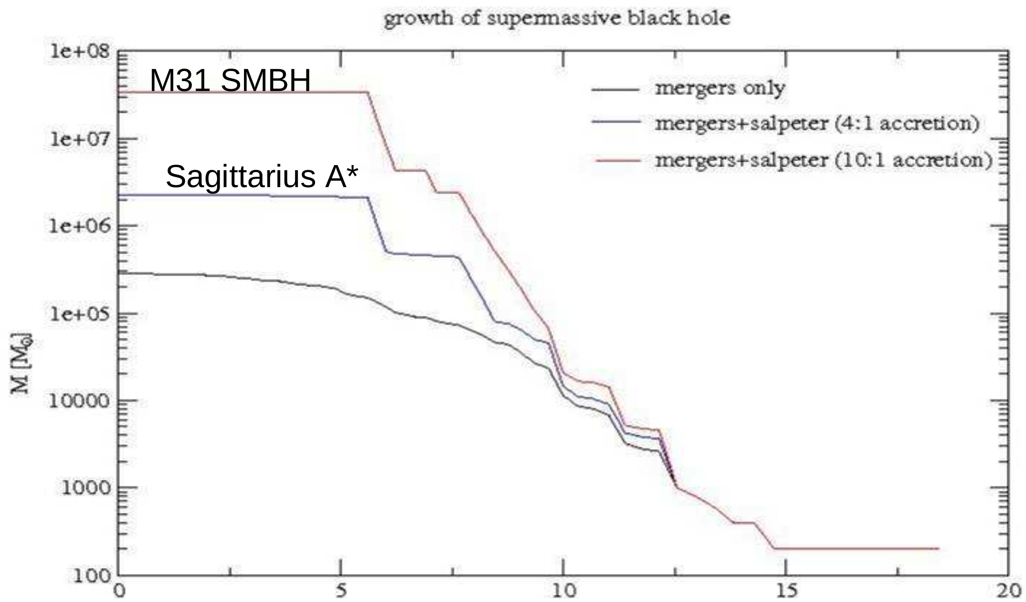
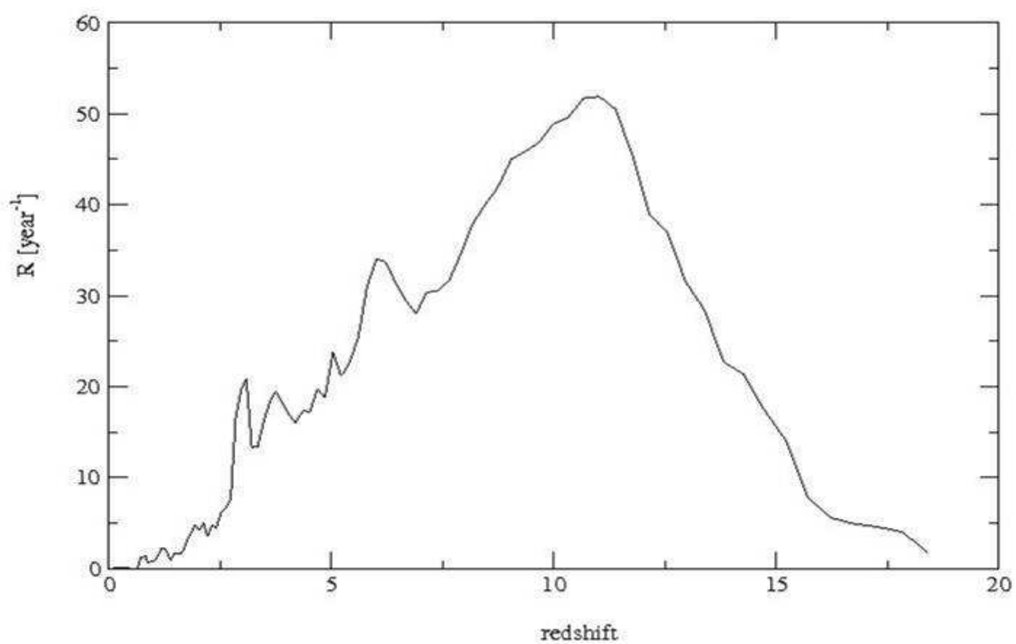


Micic, Holley-Bockelmann, Sigurdsson, Abel, 2007, MNRAS, 380, 1533

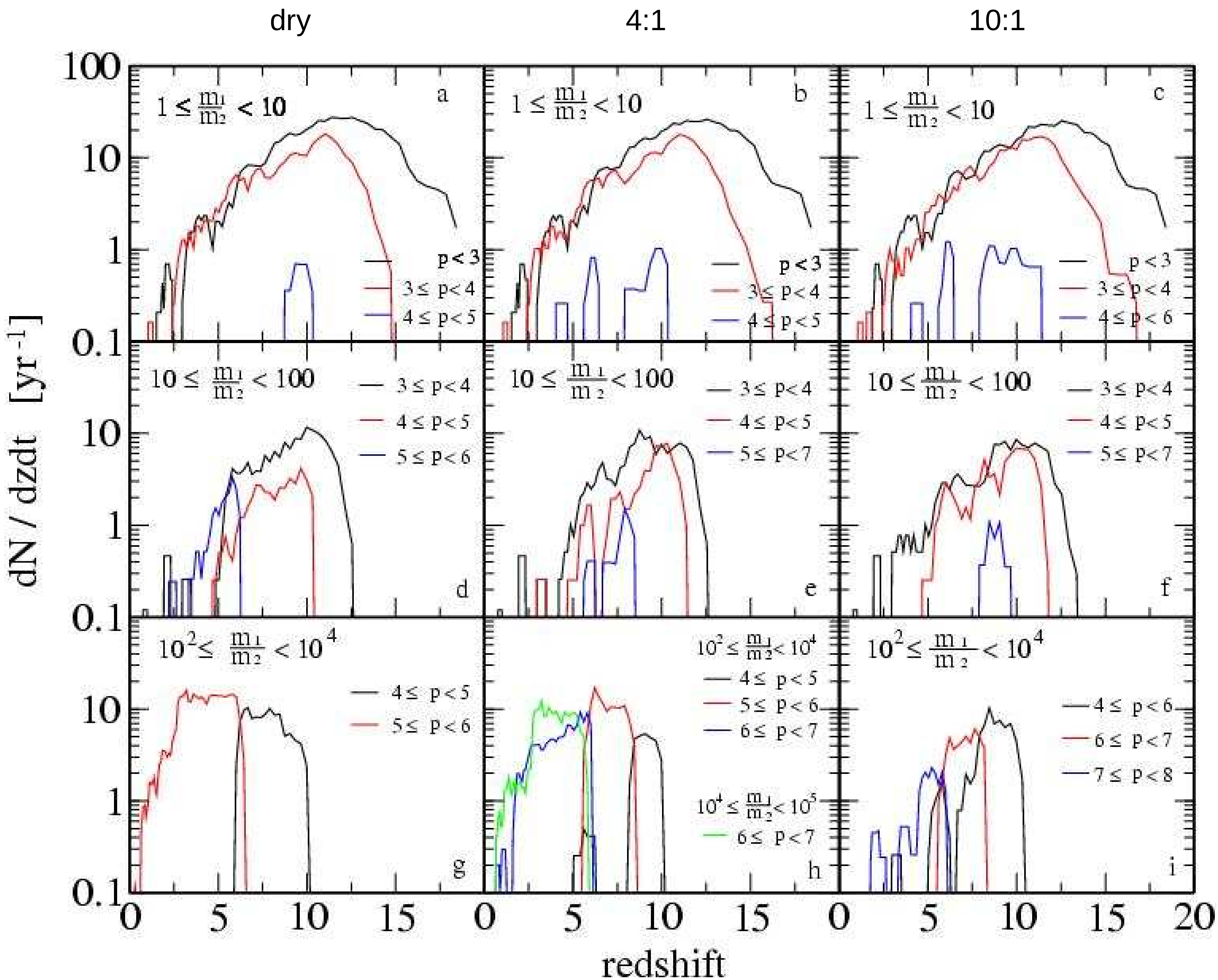


- If merging DMH with mass ratios 4:1 and smaller are allowed to have gas accreting SMBH, it is easy to grow Sagittarius A* size black hole.

- If mass ratio is 10:1, M31 SMBH can form. 4:1 mergers would give the same result if allowed larger simulation box

- DMH gain mass through cycle of steady accretion and rapid mergers (z=11, 6, 3)

- Maximum merger rate of 55 at z ~ 11



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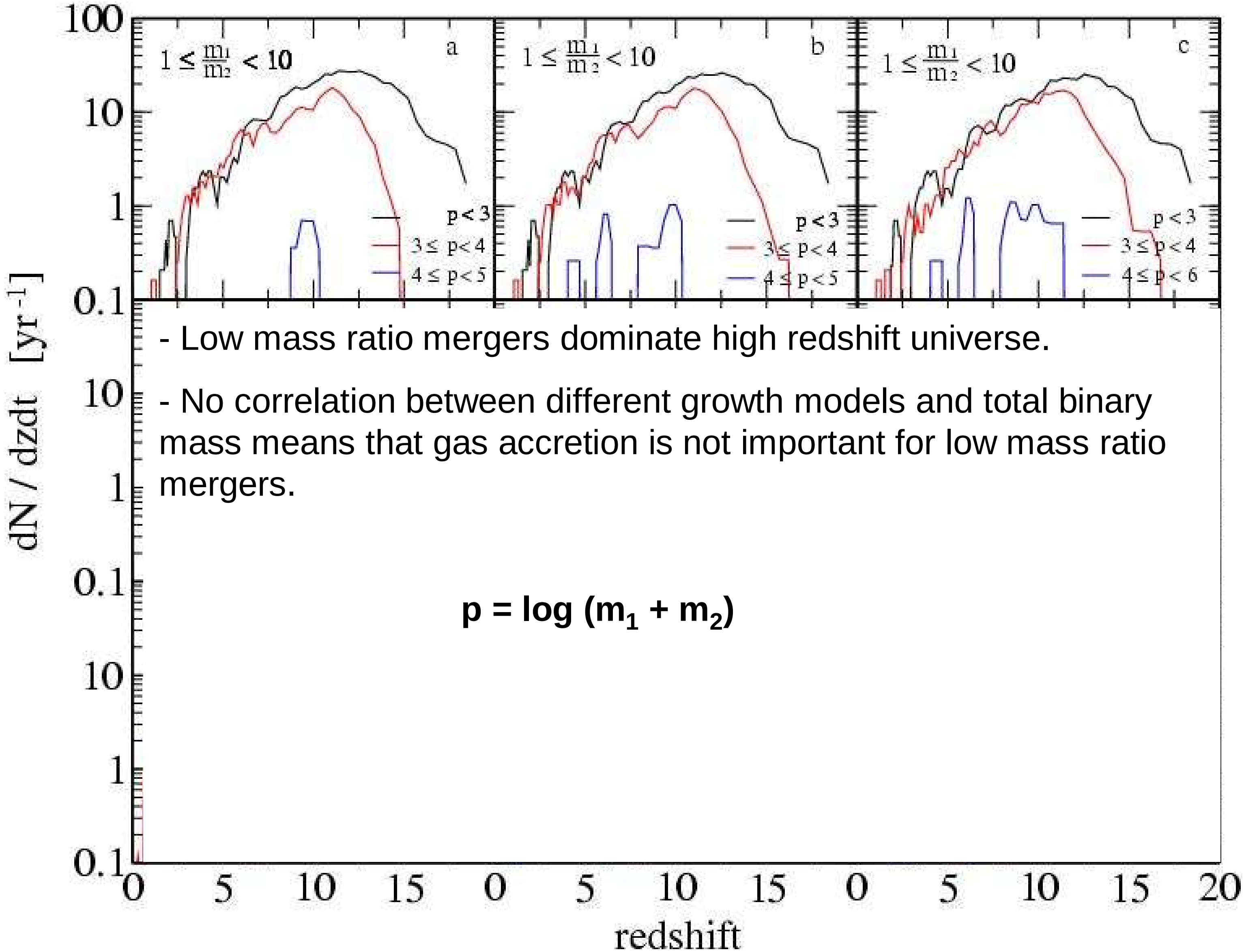
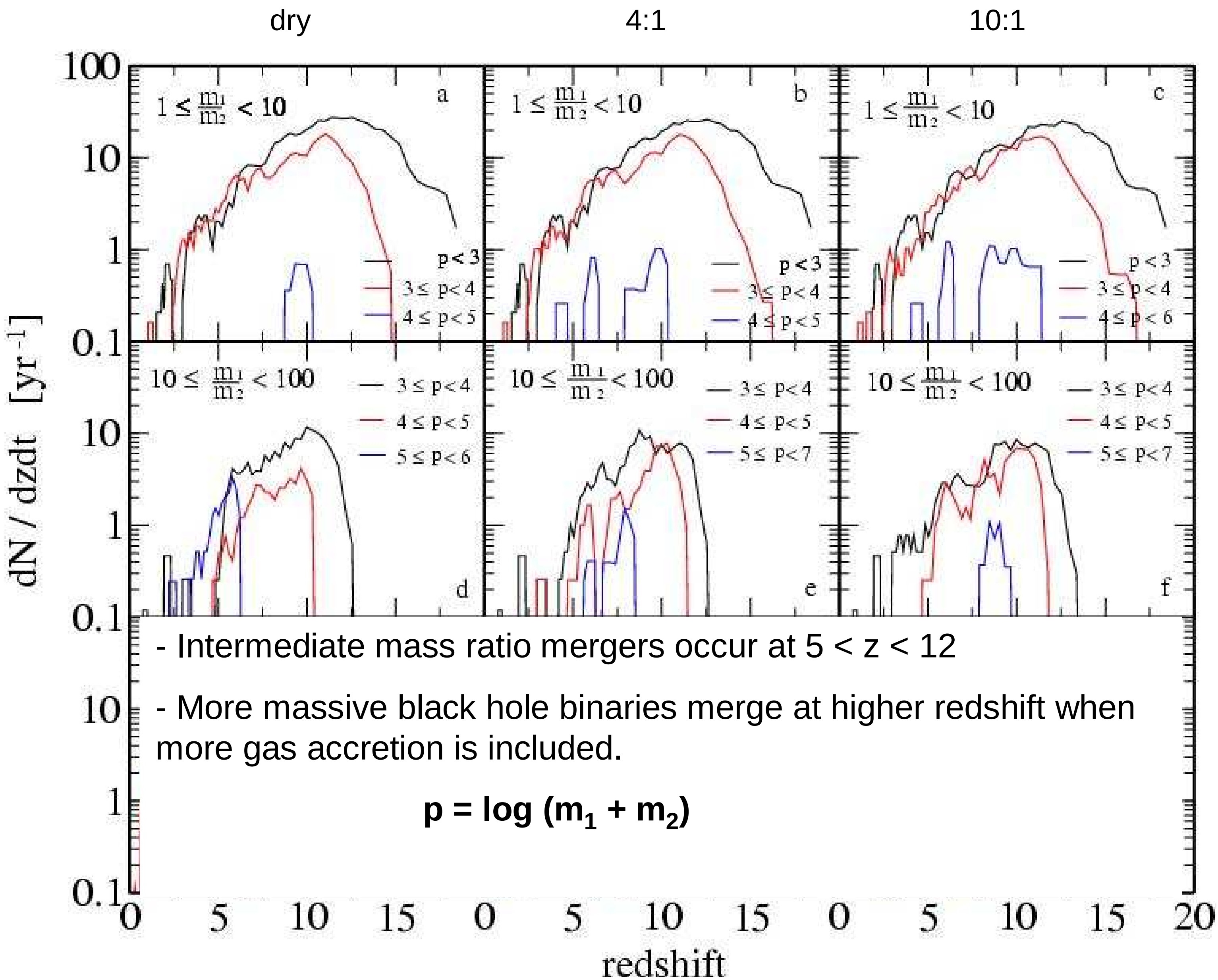
dry 4:1 10:1



- Low mass ratio mergers dominate high redshift universe.
- No correlation between different growth models and total binary mass means that gas accretion is not important for low mass ratio mergers.

$p = \log (m_1 + m_2)$

Micic, Holley-Bockelmann, Sigurdsson, Abel, 2007, MNRAS, 380, 1533



- Intermediate mass ratio mergers occur at 5 < z < 12
- More massive black hole binaries merge at higher redshift when more gas accretion is included.

$p = \log (m_1 + m_2)$

Micic, Holley-Bockelmann, Sigurdsson, Abel, 2007, MNRAS, 380, 1533

dry 4:1 10:1

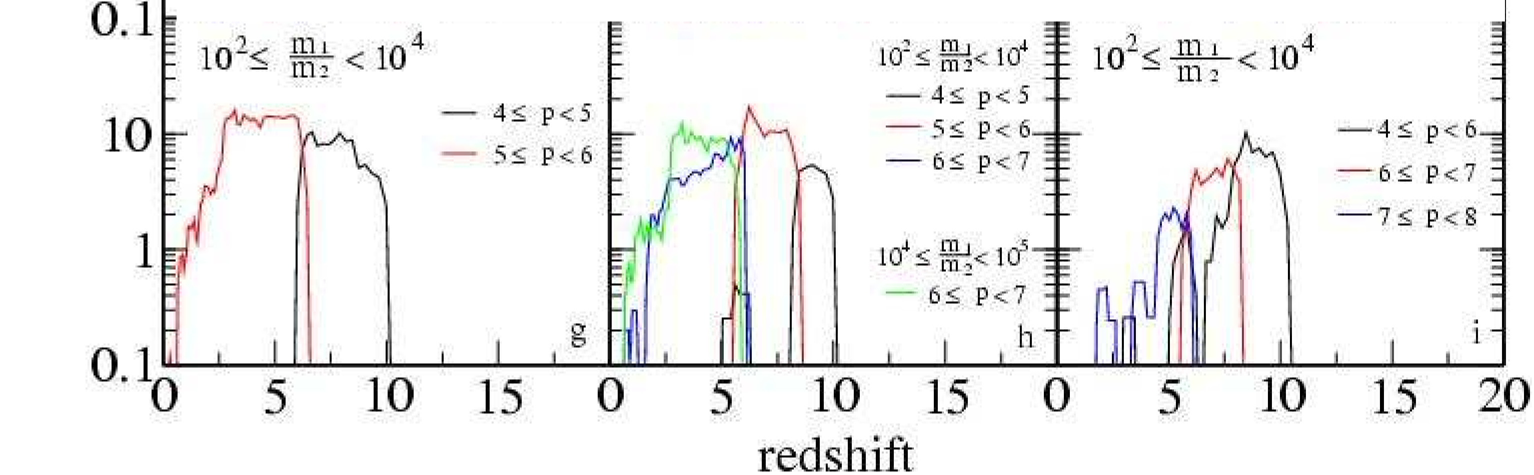
- Surprisingly high merger rate for SMBH/IMBH mergers !

  ~ 15 per year for 2 < z < 6 (LISA range !)

- Before SMBH/IMBH merger occurs, IMBH will behave as ULX source.

- Corresponding number density of ULX ~ 5 – 10 for 2 < z < 6 per Milky Way type galaxy.

p = log (m_1 + m_2)

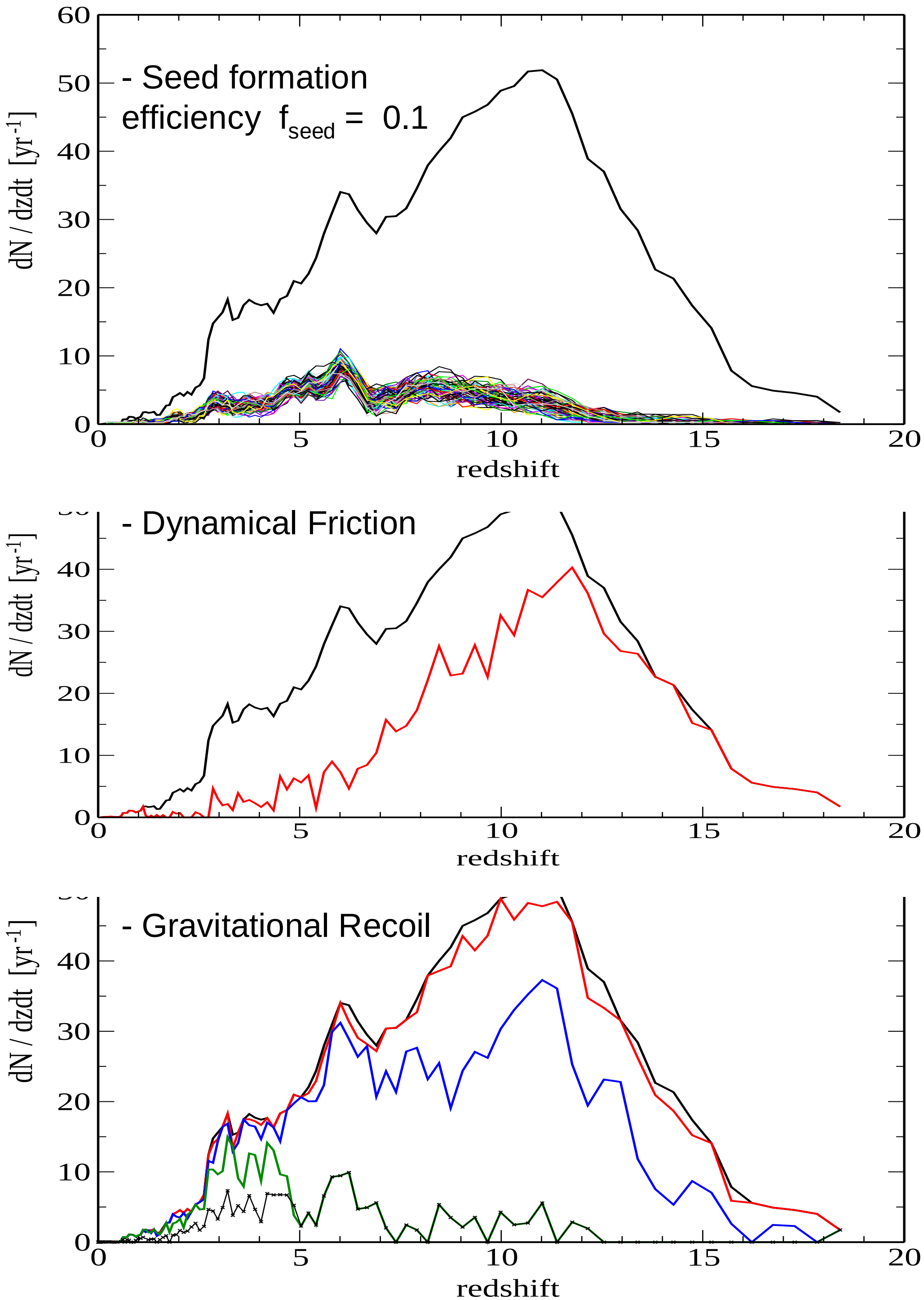


Micic, Holley-Bockelmann, Sigurdsson, Abel, 2007, MNRAS, 380, 1533

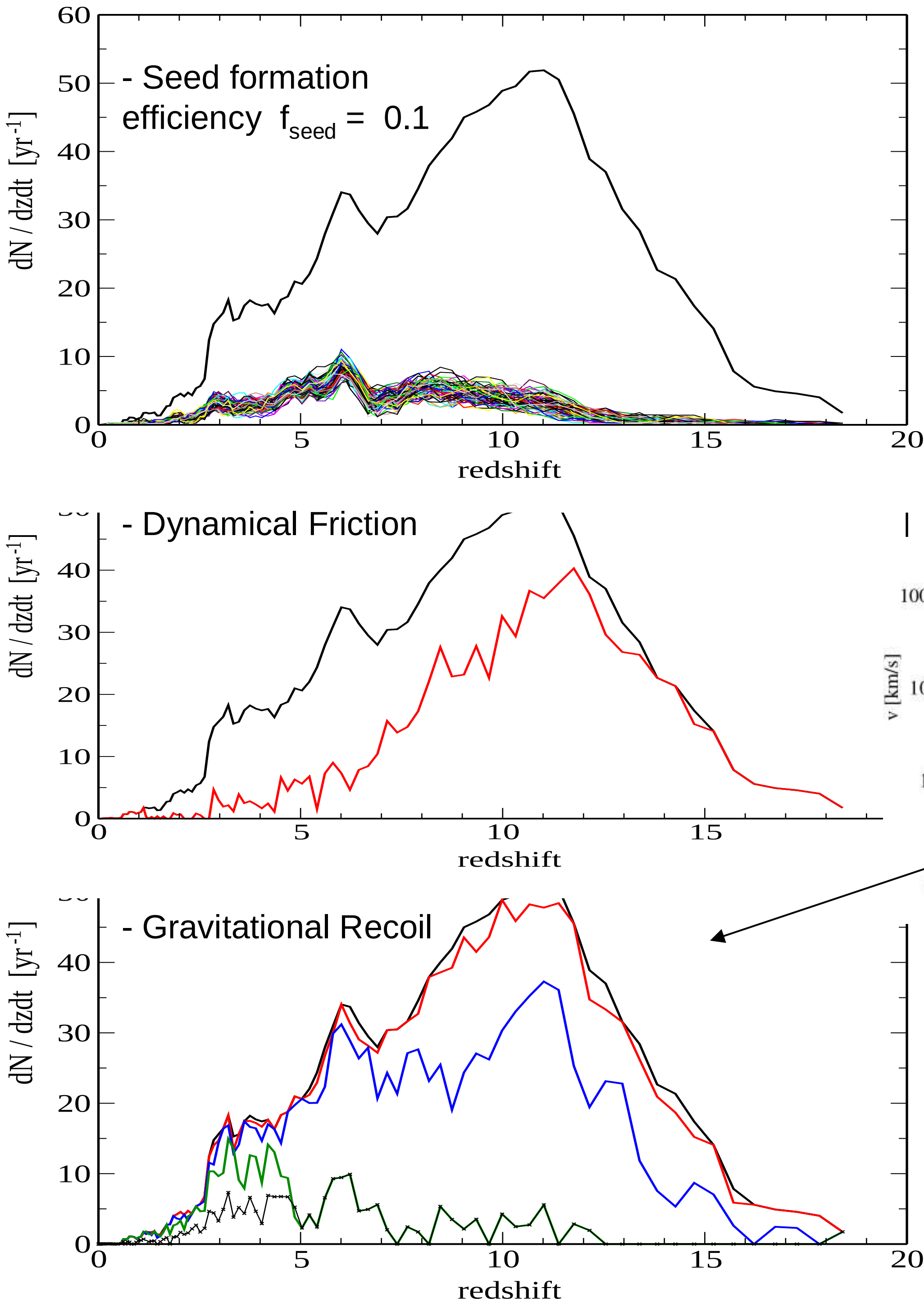
Currently working on . . .

Suppression Mechanisms

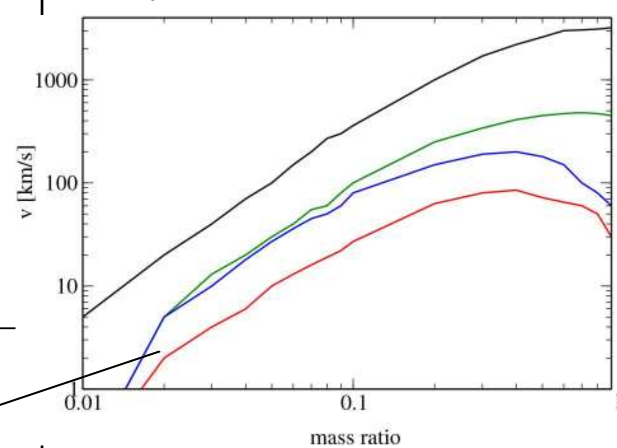
- Black Hole Seeds Formation Rate
  - $M_{POPIII} \lesssim 140\ M_{\odot}$ and $M_{POPIII} \geq 260\ M_{\odot}$ produce seed black holes.
  - IMF unknown! Expected to be top-heavy, nothing like Salpeter IMF.
  - The fraction of the first stars which produces seed black holes could be as low as 10%, Schneider et al. 2002.
- Dynamical Friction
  - The effect of Satellite sinking toward the center of Primary due to dynamical friction is suppressed by the tidal interaction.
  - This effect does not play a role in major mergers but in the case of minor mergers it increases the dynamical friction time scale.
  - If the Satellite is fully stripped, the SMBH will be left wandering in the galactic halo, Volonteri et al. 2003.
- Gravitational Recoil From Black Hole Mergers
  - The anisotropic emission of gravitational waves which carries away linear momentum from the black hole binary can cause the recoil in the final black hole.
  - The magnitude of kick depends on the orbital configuration and the mass ratio of merging black holes and can be as large as 4000 km/s. Typical kick is expected to be below 500 km/s.



- Seed formation efficiency f_{seed} = 0.1
- Dynamical Friction
- Gravitational Recoil
dN / dzdt [yr^{-1}]
redshift



Plot is from Volonteri 2007, kick ranges from Baker et al. 2007 and Campanelli et al. 2007



- Low spin aligned
- Optimal orbital configuration
- Low spin anti-aligned
- Spin axis in orbital plane, anti-aligned

SUMMARY

- First N-body merger rates.

- Maximum merger rate ~ 55 $year^{-1}$ at z=11. (but without suppression!!!)

- z=6 may be a critical redshift for the transition from the AGN duty cycle dominated by high mass ratio DMH mergers to a starburst galaxy phase where low mass ratio DMH mergers supply a galaxy with a population of ULXs.

- SMBH/IMBH merger rate ~ 15 per year (2 < z < 6). Very high!!!
Good news for LISA!!!

- N_{ULX} ~ 5 – 10 per year per Milky Way type galaxy.

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FUTURE

- As we work on suppression mechanisms, we also run simulations at Columbia High-End Computing program where we have 200,000CPU hours.

- We are testing cosmic variance and trying to incorporate dynamical friction and kicks “on the fly”.