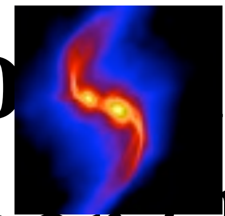
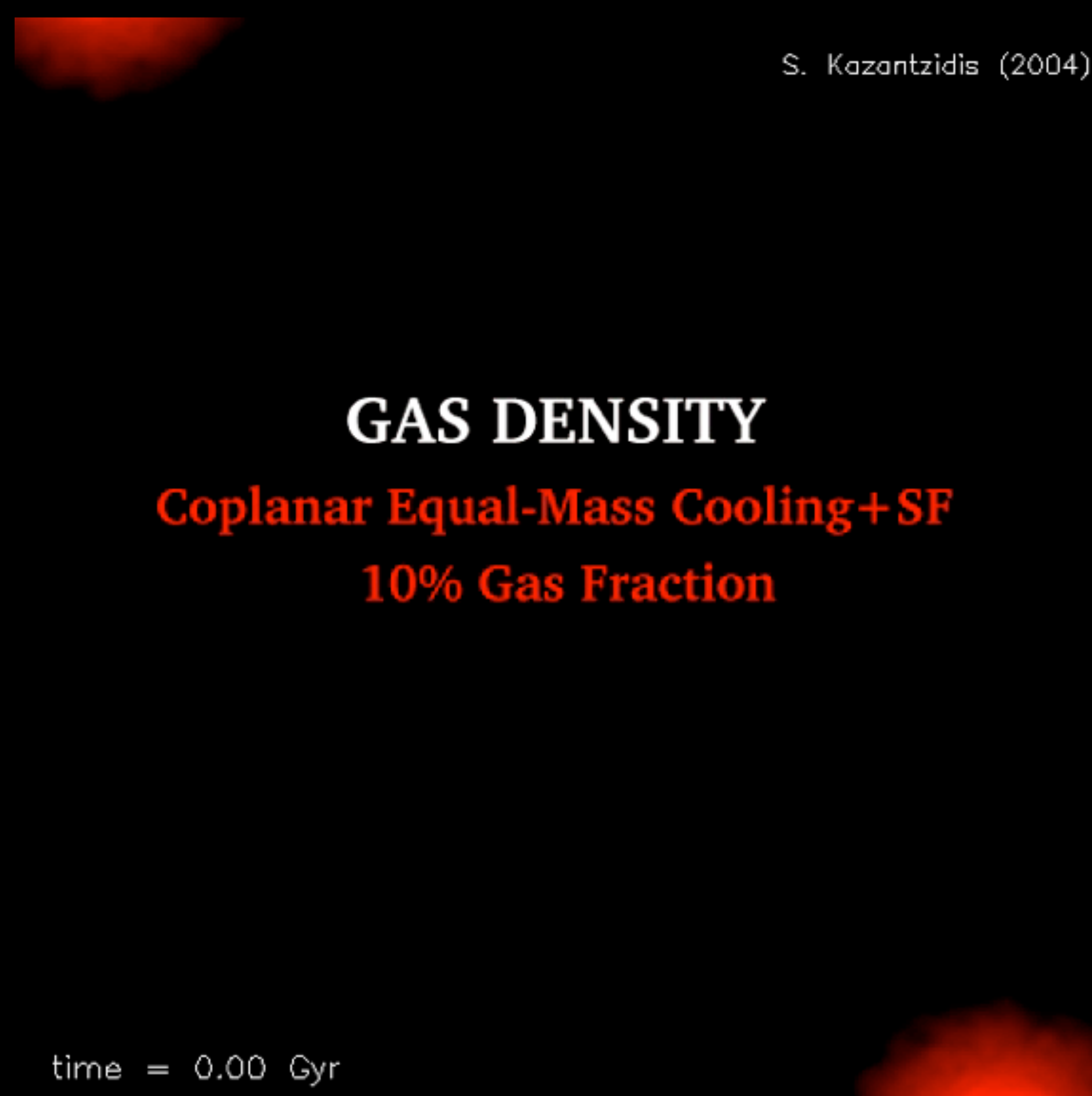
Methodology

Conditions fo e formation of massive seed black holes



1. Major merger (1:3) of gas-rich late-type galaxies (B/T < 0.2)
2. Host halo $M_h > 10^{11} M_{Sun}$
3. No a pre-existing black hole of $M_{BH} > 10^6\ M_{Sun}$

Evolution of the gas component in major merger of disk



Multi-scale galaxy merger simulations
from ~100 kpc to 0.1 pc

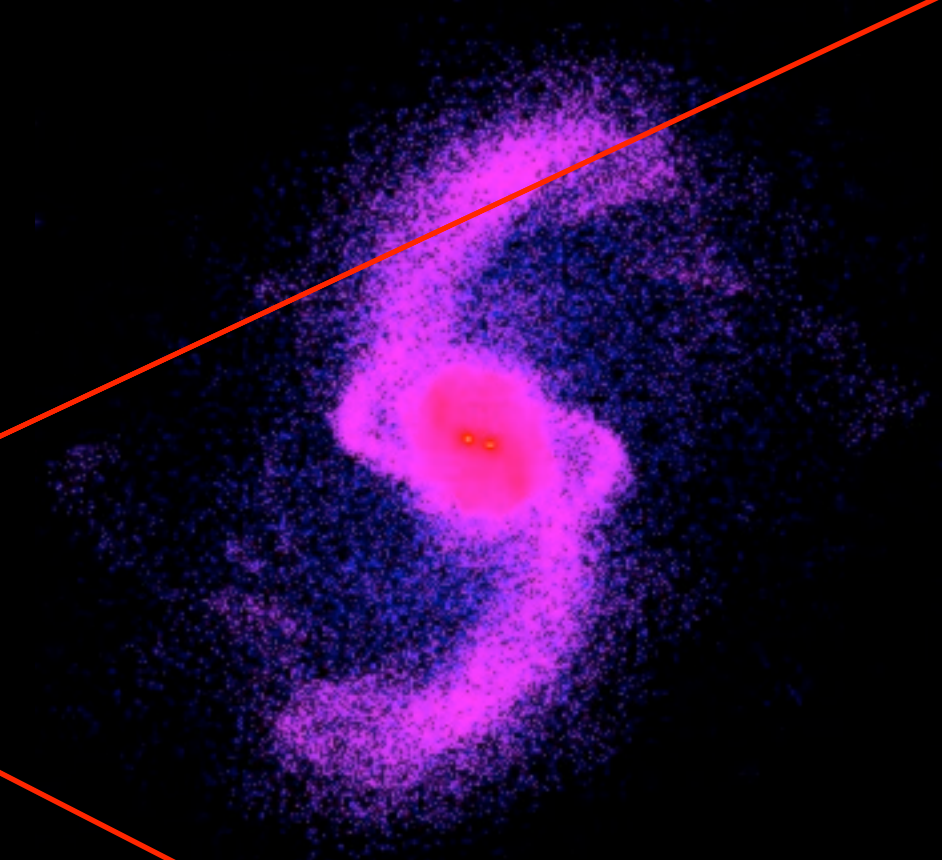
Mayer et al. 2007, 2008, 2010

- Using Smoothed Particle Hydrodynamics (SPH code GASOLINE) + splitting of gas particles (Kitsionas & Withworth 2002, Bromm 2004) to increase mass and spatial resolution as galaxy merger proceeds

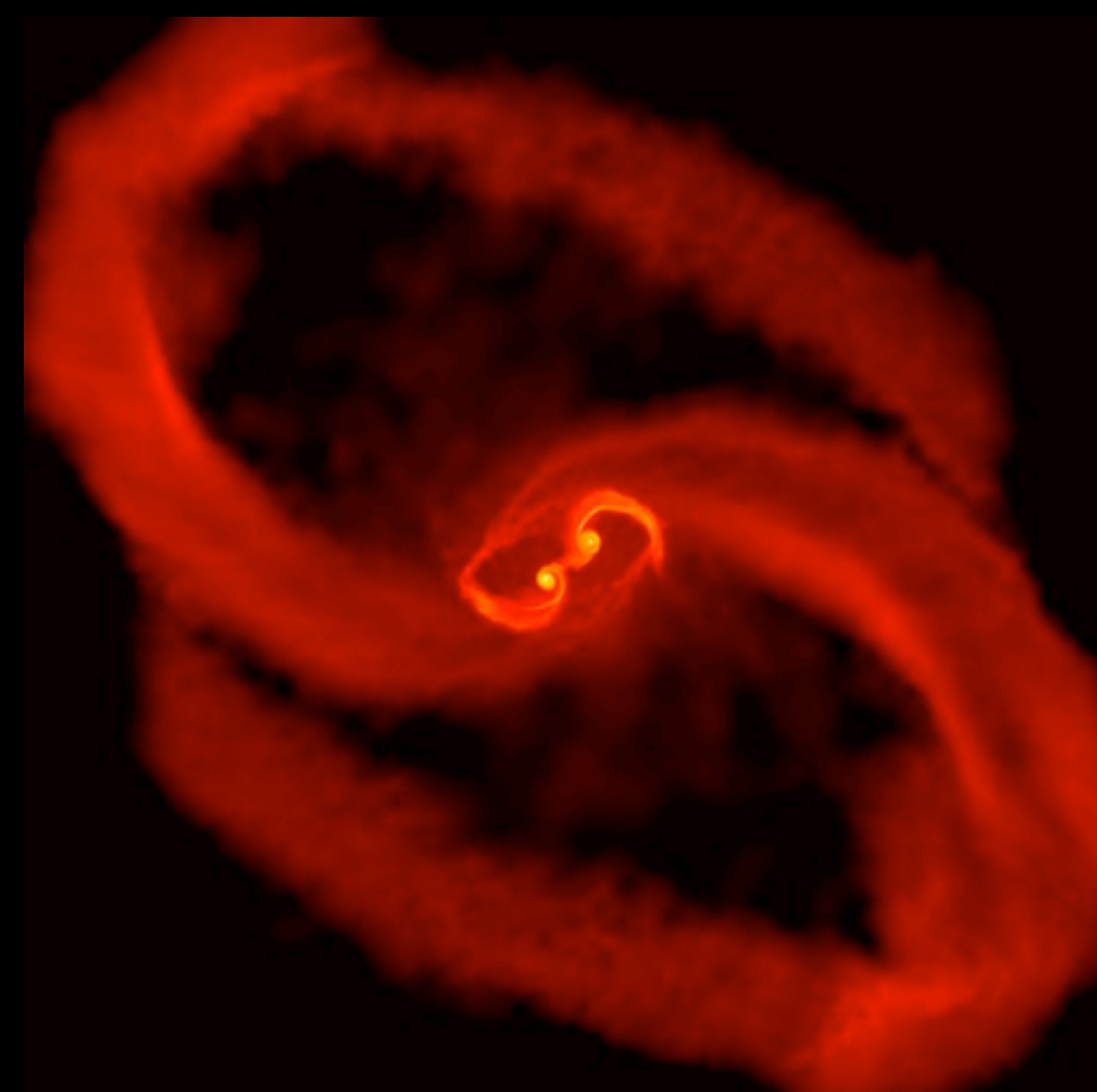
  Max. Resolution 3000 solar masses and 0.1 pc

- Effective equation of state (EOS) - ideal gas, $P = (\gamma-1)\,\rho\,\varepsilon$, varying effective "$\gamma$" - to model local balance between heating and cooling in nuclear region (based on Spaans & Silk 2000;2005 – steady-state interstellar gas model heated by starburst w/ radiative transfer)

200 kpc



60 kpc



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(10^4-10^5cm^{-3}) due primarily to irradiation by dust grains heated by stellar UV (SFR >~ 30 Mo/yr)

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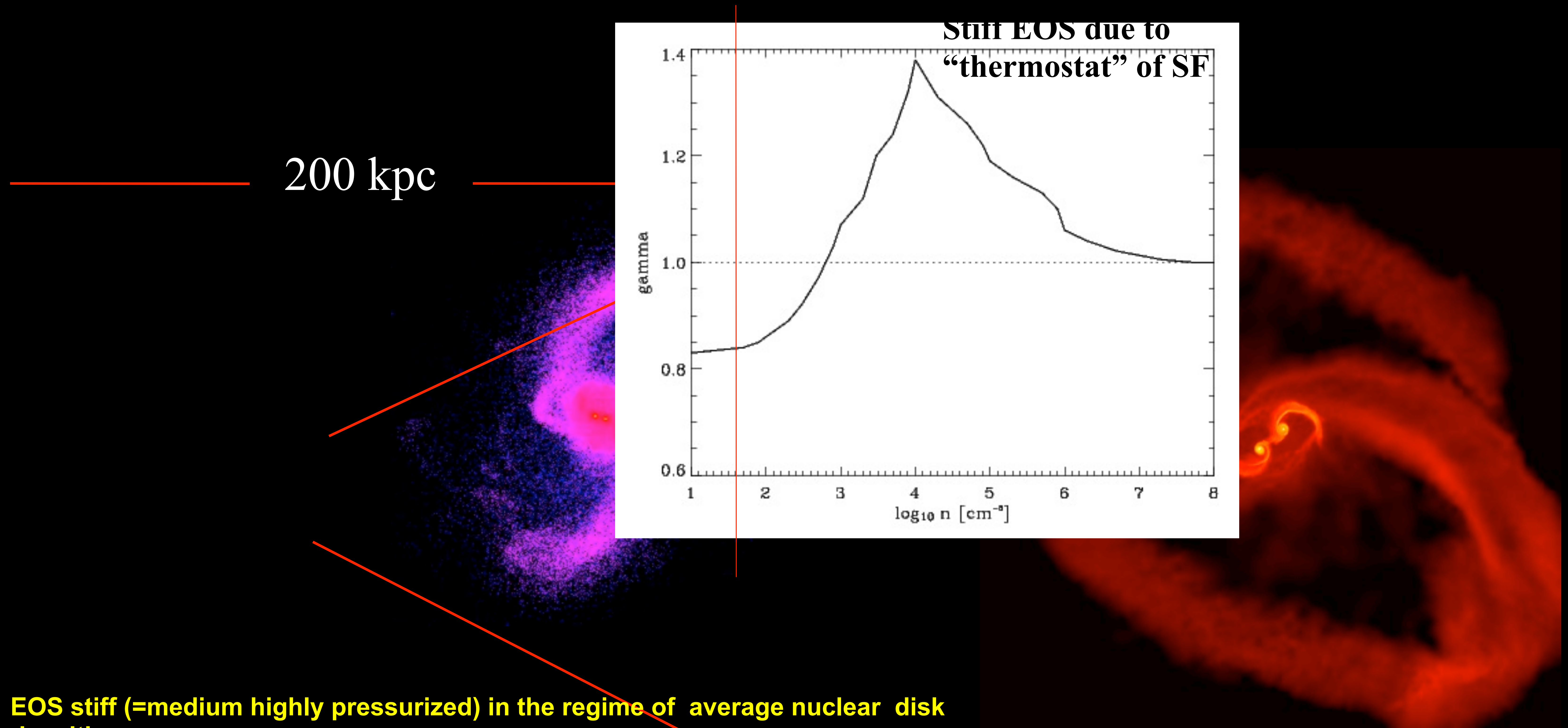

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SELF-GRAVITATING GAS DISKS: STABILITY and INFLOWS

THREE REGIMES:

Toomre parameter $Q = \kappa v_s / \pi G \Sigma$

(from linear local perturbative analysis of self-gravitating rotating fluid in infinitesimally thin disk)

$Q < 1$ locally unstable to collapse --> fragmentation on dynamical timescale (t_{dyn}) --> gas clumps make stars

$1 < Q < 2$ locally stable, globally unstable to non-axisymmetric modes (spiral modes, bar modes)

--> angular momentum transport (on a few t_{dyn}) via spiral density waves (Lynden Bell & Pringle 1979; Lin & Pringle 1987; Laughlin & Adams 2000)
--> gas inflow towards state of minimum energy

$Q > 2$ locally and globally stable --> dynamically uninteresting

-Sweet spot ($1<Q<2$): a non-fragmenting globally unstable disk to sustain central gas inflow
- The dissipation rate in the system is crucial – if cooling efficient amplitude of non-axisymmetric modes increases --> inflow increases but $Q <\sim 1$ approached (Tcool < Tdyn drives Q below 1, while with Tcool > Tdyn self-regulation to $Q >\sim 1$)

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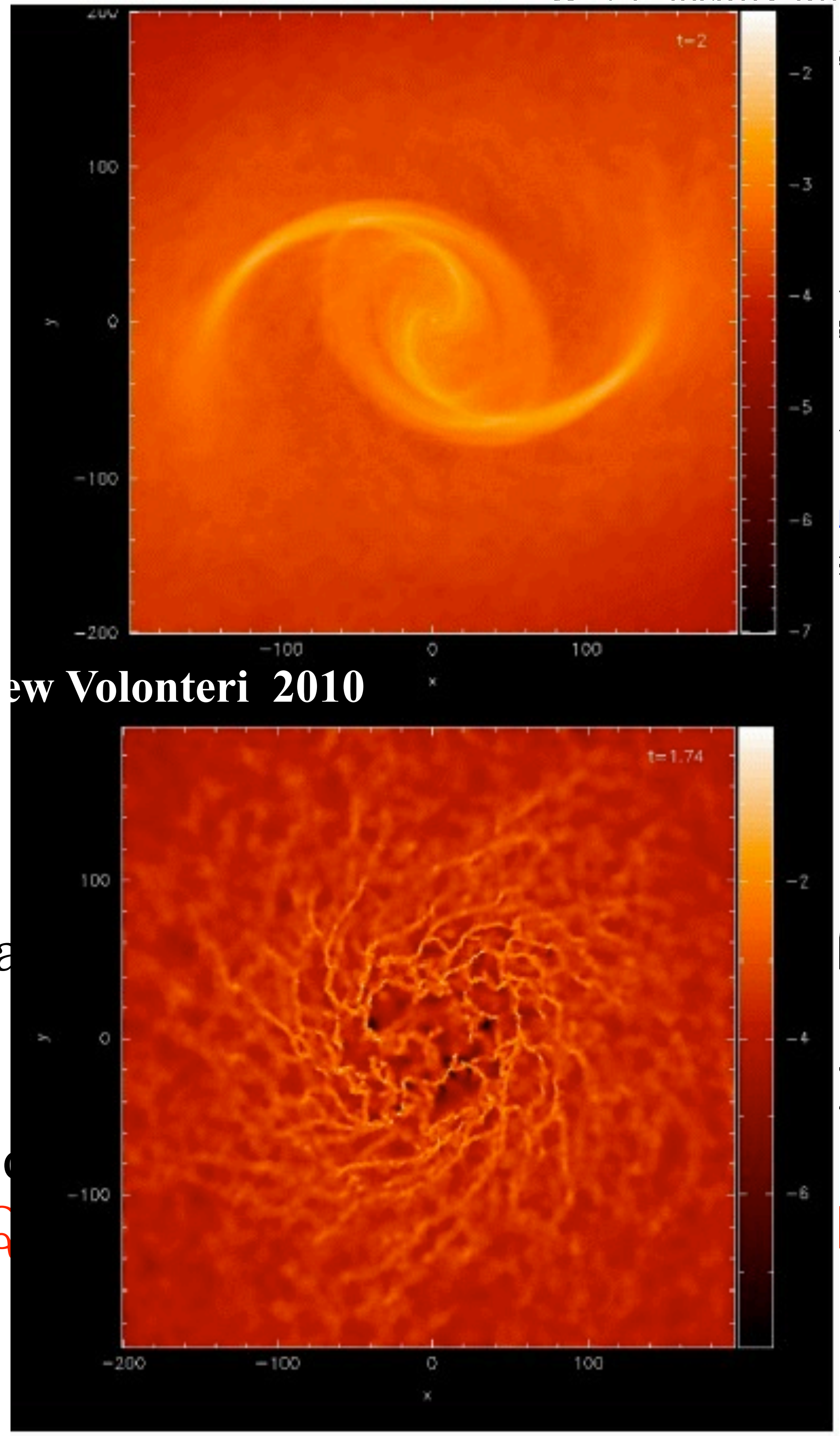

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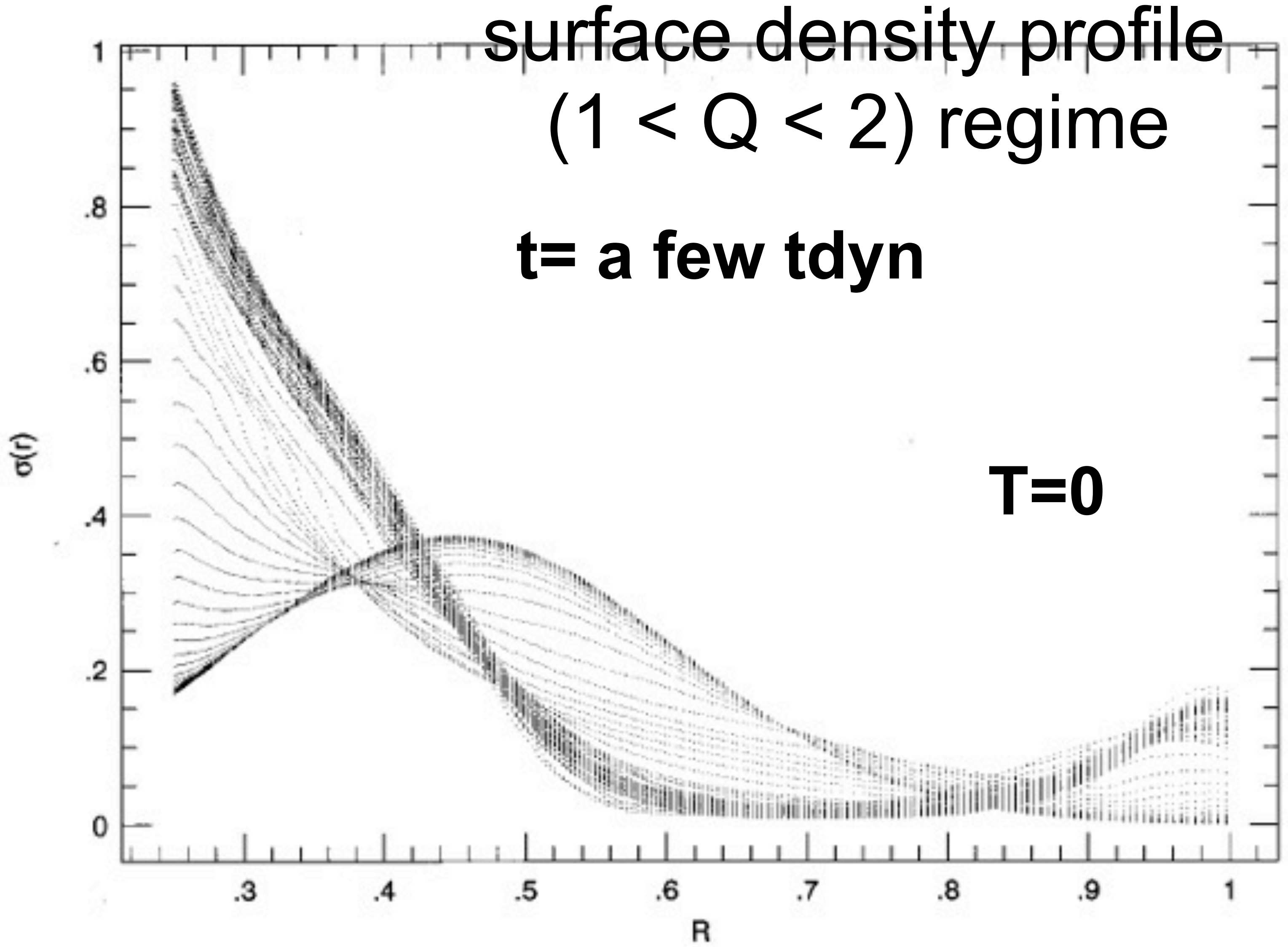

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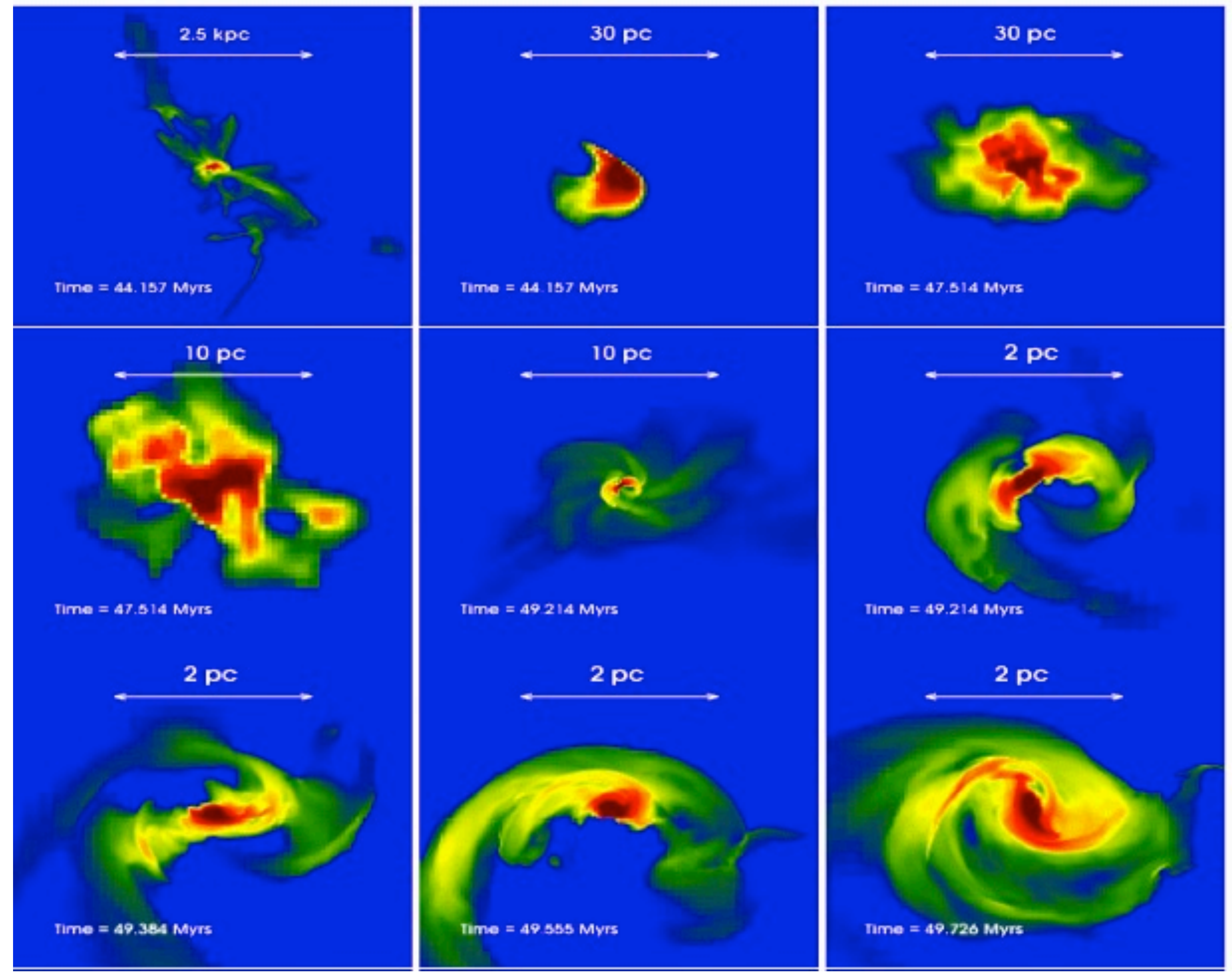
INFLOW BOTTLENECK: COOLING AND FRAGMENTATION

In system that cools rapidly (tcool < tdyn) and accumulates gas via inflow eventually Q drops to < 1 and fragmentation/star formation takes over

CONVENTIONAL WAY-OUT:
SUPPRESS FRAGMENTATION BY SUPPRESSING COOLING (keep $T > 10^4$ K) -→NEED METAL-FREE GAS + H_2 dissociation by Lyman-Werner UV bg above mean cosmic value at z > 2

BUT METAL-FREE GAS UNREALISTIC CONDITION!
(a) Metallicity > 10^{-5} solar reached at z > 10 -→ sufficient to trigger rapid cooling esp. in presence of dust (Omukai et al. 2008).
(b)Weak inflow rates <1 Mo/yr (Wise et al. 2008; Regan & Haenhelt 2009,2010)
Not enough to assemble supermassive clouds/SMS
Indeed no self-gravitating compact object forms

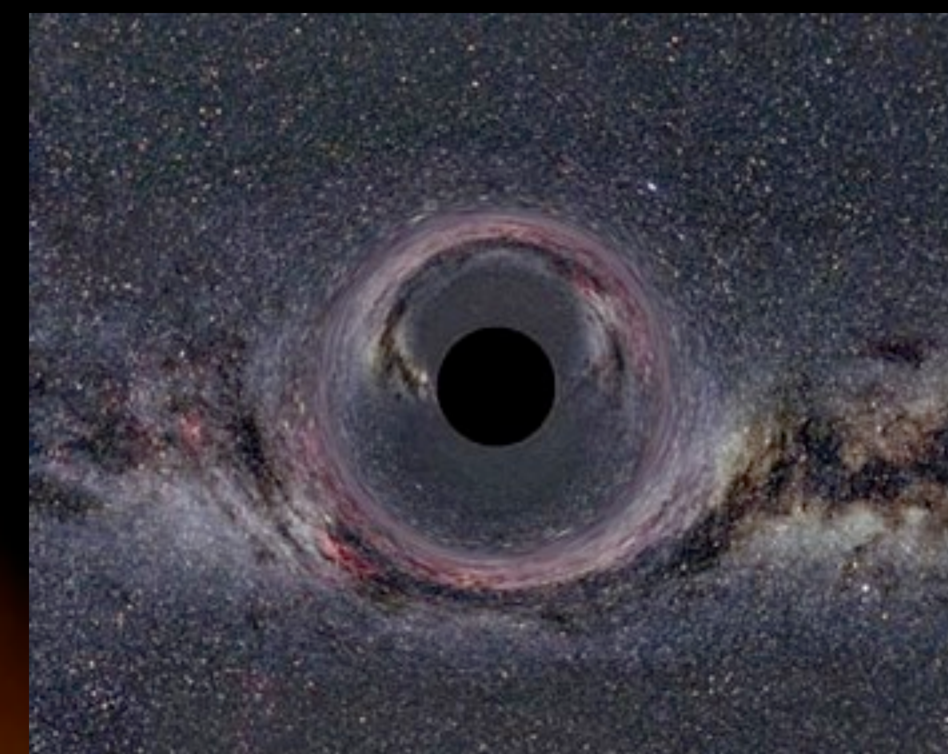


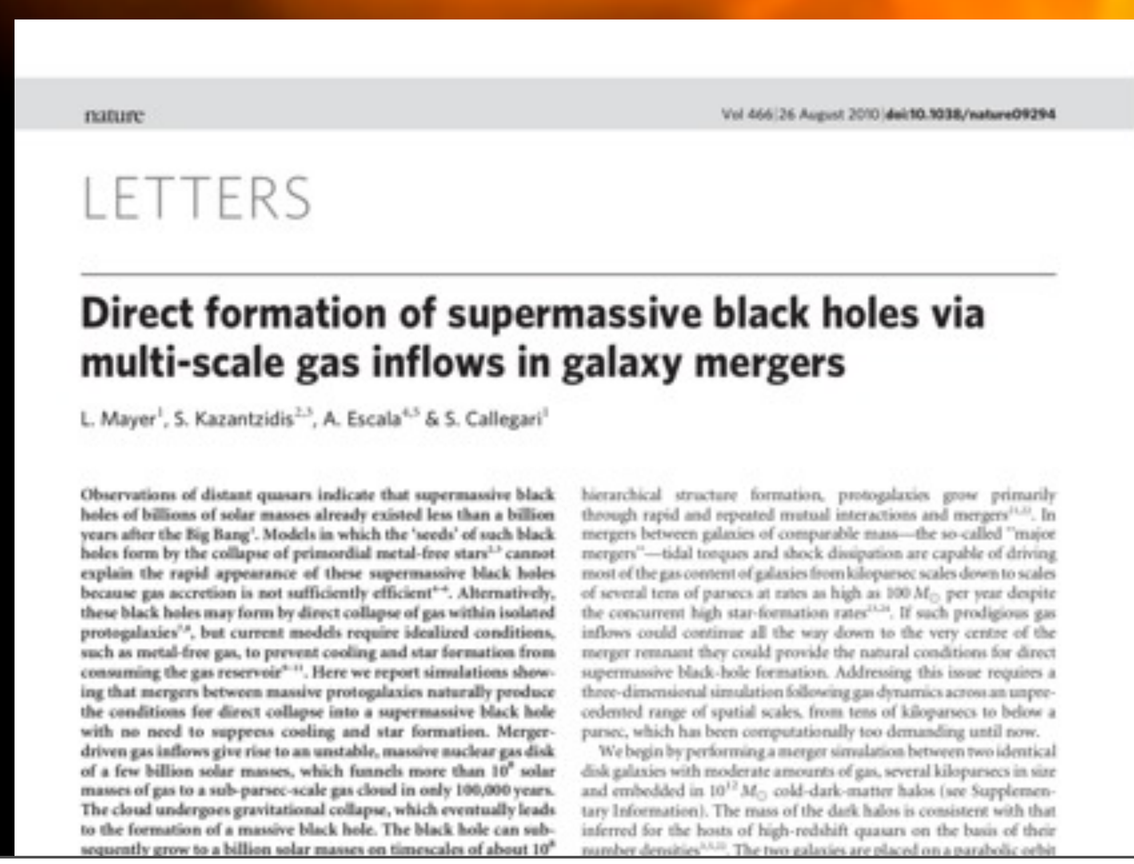
Metal-free protogalaxy simulation
Regan & Haenhelt 2009

Formation of supermassive black holes by direct gas collapse in galaxy mergers

Lucio Mayer

University of Zurich




nature Vol 466 | 26 August 2010 | doi:10.1038/nature09294

LETTERS

Direct formation of supermassive black holes via multi-scale gas inflows in galaxy mergers

L. Mayer[1], S. Kazantzidis[2,3], A. Escala[4,5] & S. Callegari[1]

Observations of distant quasars indicate that supermassive black holes of billions of solar masses already existed less than a billion years after the Big Bang[1]. Models in which the 'seeds' of such black holes form by the collapse of primordial metal-free stars[2,3] cannot explain the rapid appearance of these supermassive black holes because gas accretion is not sufficiently efficient[4-6]. Alternatively, these black holes may form by direct collapse of gas within isolated protogalaxies[7,8], but current models require idealized conditions, such as metal-free gas, to prevent cooling and star formation from consuming the gas reservoir[9-11]. Here we report simulations showing that mergers between massive protogalaxies naturally produce the conditions for direct collapse into a supermassive black hole with no need to suppress cooling and star formation. Merger-driven gas inflows give rise to an unstable, massive nuclear gas disk of a few billion solar masses, which funnels more than 10^8 solar masses of gas to a sub-parsec-scale gas cloud in only 100,000 years. The cloud undergoes gravitational collapse, which eventually leads to the formation of a massive black hole. The black hole can subsequently grow to a billion solar masses on timescales of about 10^8

hierarchical structure formation, protogalaxies grow primarily through rapid and repeated mutual interactions and mergers[11,12]. In mergers between galaxies of comparable mass—the so-called "major mergers"—tidal torques and shock dissipation are capable of driving most of the gas content of galaxies from kiloparsec scales down to scales of several tens of parsecs at rates as high as 100 $M_\odot$ per year despite the concurrent high star-formation rates[13,14]. If such prodigious gas inflows could continue all the way down to the very centre of the merger remnant they could provide the natural conditions for direct supermassive black-hole formation. Addressing this issue requires a three-dimensional simulation following gas dynamics across an unprecedented range of spatial scales, from tens of kiloparsecs to below a parsec, which has been computationally too demanding until now.

We begin by performing a merger simulation between two identical disk galaxies with moderate amounts of gas, several kiloparsecs in size and embedded in 10^{12} $M_\odot$ cold-dark-matter halos (see Supplementary Information). The mass of the dark halos is consistent with that inferred for the hosts of high-redshift quasars on the basis of their number densities[3,5,15]. The two galaxies are placed on a parabolic orbit

Collaborators:

Stelios Kazantzidis (CCAPP Ohio State Univ.)
Simone Callegari (Univ. of Zurich)
Andres Escala (KIPAC Stanford/UChile)
Silvia Bonoli (Univ. Zurich)

Direct gas collapse model: brief intro

Rapid formation of massive BH seed --- mass M_{BH} ~ 10^5 - 10^9 Mo

If happens early (z >~ 8-10) can explain high-z QSOs (M_{BH} > 10^9 Mo) without requiring the continuous Eddington accretion needed for <~100 Mo Pop III (Volonteri & Rees 2006)
Simulations show Pop III seeds accrete well below Eddington, eg Johnson & Bromm 2006; Wise et al 2008; Milosavljevic et al. 2010) due low density gas plus their own radiative feedback

I - Gas inflow in galaxy from kpc to << 1 pc scales to form supermassive gas cloud (M> 10^6 Mo) - need efficient loss of angular momentum in galactic disk gas across many spatial scales (eg Lodato & Natarayan 2006)

II - Depending on mass and internal rotation of supercloud (T/W) two pathways:
(a) supermassive cloud collapses dynamically and globally into massive black hole with M_{BH} ~ M_{cloud} due to radial GR radial instability (Fowler & Hoyle 1966; Zeldovitch & Novikov 1972; Baumgart & Shapiro 1999; Shibata & Shapiro 2002; Saijo & Hawke 2009) ---> direct formation of SMBH

(b) forms a short-lived (>~ Myr) supermassive star collapsing into BH at the center due to catastrophic neutrino cooling (Begelman et al. 2006; Begelman 2008; Begelman & Volonteri 2010). Even if BH initially only 10-100 Mo it accretes super-Eddington from a pressure-supported convective envelope powered by BH accretion energy ("Quasi-star") reaching > 10^{4-5} Mo before cloud dispersal in a few Myr ---> formation of massive BH seed

This talk: how can step (I) be achieved?

TIMESCALE FOR SUPERMASSIVE CLOUD ASSEMBLY: REQUIRED GAS INFLOW RATE

SImple argument: a supermassive star (M_{star} >~ 10^6 Mo) has short lifetime ($t_{life} \sim 10^6$ yr) must be assembled on $t_{form} < t_{life}$

----→ Characteristic gas inflow rate to feed the cloud $dM_g/dt > M_{star}/t_{life} > 1$ Mo/yr for M_{star} >~ 10^6 Mo
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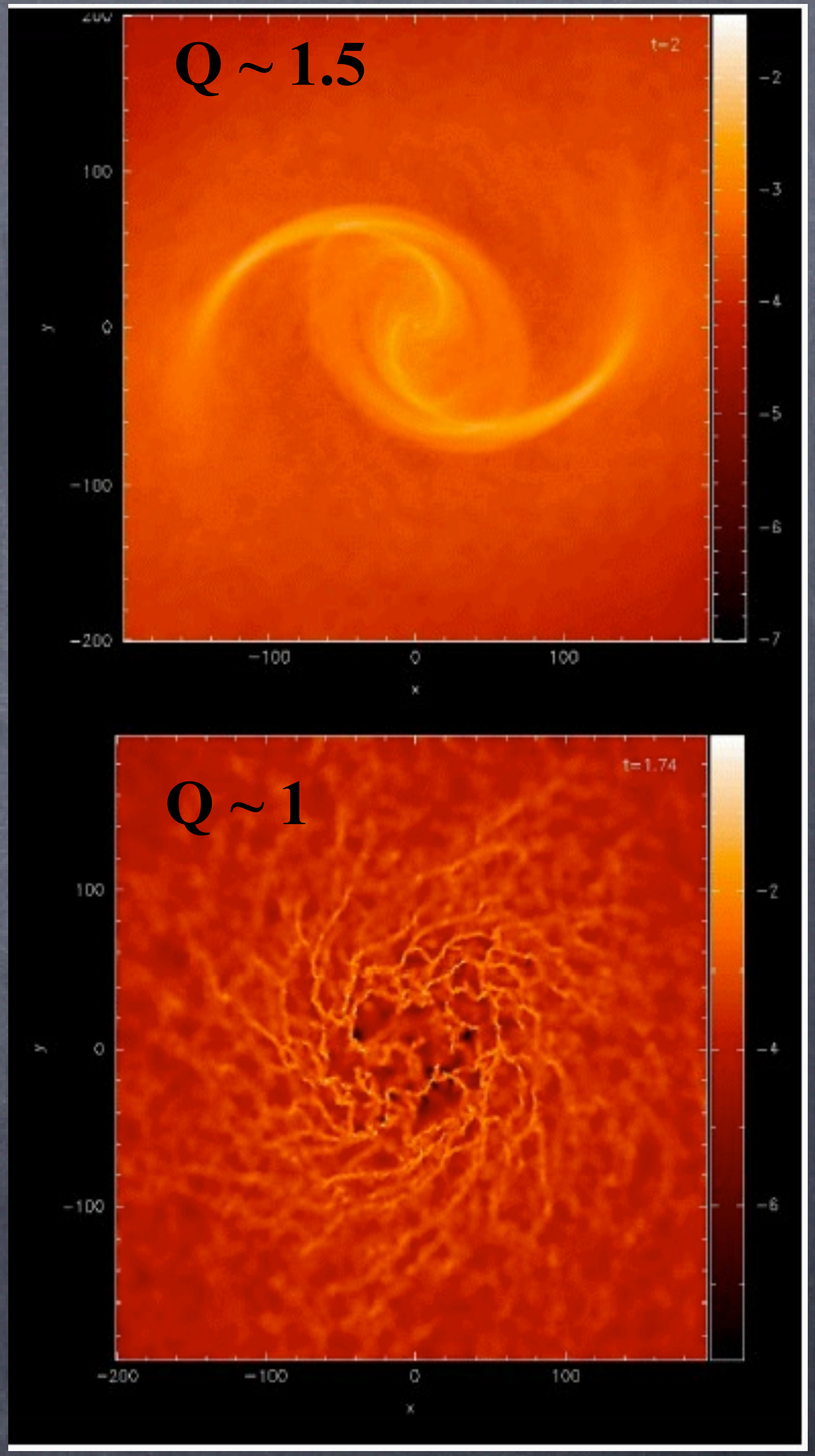
HOW DO WE GET SUCH HIGH GAS INFLOW RATES AT < pc scales?

---->Gravitational torques in self-gravitating, marginally unstable protogalactic disk

(bars-in-bars, spiral modes, see eg Begelman et al. 2006, Lodato & Natarayan 2006; Levine et al. 2009)

Needs massive but "warm" disk (Toomre Q ~ 1.5-2)



How do we keep the disk "warm" and stable?

Standard way: suppress molecular cooling and metal cooling below 10^4 K to keep Q > 1, avoiding fragmentation and star formation (otherwise gas makes stars rather than BH seed --- star formation bottleneck)

-- potentially can work at very high redshift (z > 15) with very low metallcity gas, perhaps requires proximity with massive star forming galaxies shining with high LW flux dissociating H_2 (Dijikstra et al. 2009; Agarwal et al. 2012)

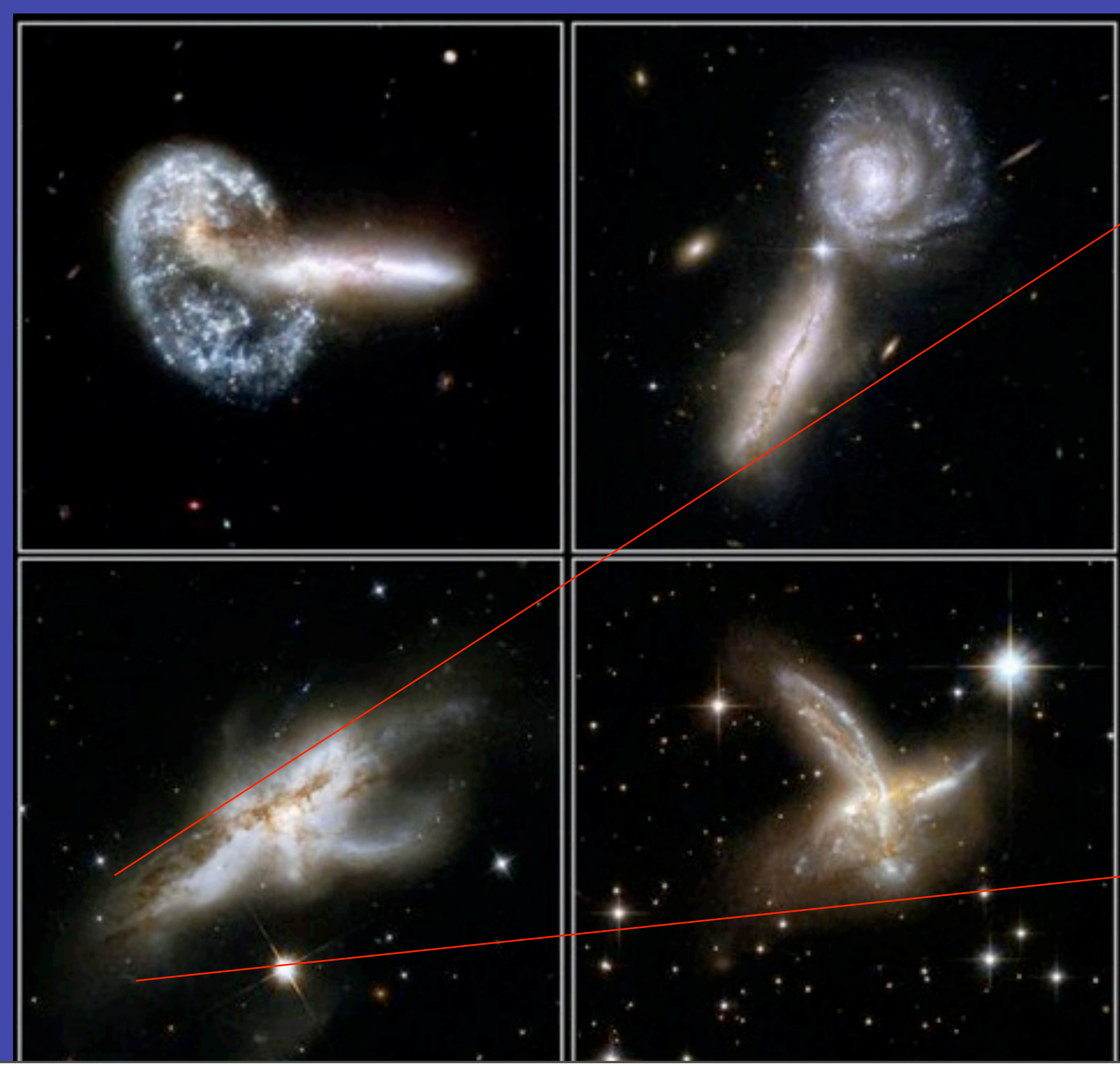
-- characteristic host protogalaxy mass small (~ < 10^8 Mo), a potential problem since inflow rate $dM_{gas}/dt \sim V_{halo}^3/G \sim M_{halo}/G$ <~ 1 Mo/yr neglecting residual angular momentum (roughly consistent with simulations of Wise et al. 2008, Regan & Haenhelt 2009)

TOWARDS NEW BH FORMATION SCENARIO: MASSIVE MULTI-SCALE GAS INFLOWS IN GALAXY MERGERS

–Galaxy mergers are known to trigger the strongest gas inflows in galaxies at 100 pc- 1 kpc scales (due to tidal torques and shocks extracting angular momentum)
----> simulations show dM/dt > 100 Mo/yr (eg Kazantzidis et al. 2005; Li et al. 2006), can sustain high SF rates in ULIRGs and sub-mm galaxies (eg Hopkins et al. 2008)

In mergers gas inflows effective, still most of the gas does not turn into stars!
from observations SF rate ~ $\varepsilon_{sf} M_{gas}/t_{dyn}$,, $\varepsilon_{SF} = 0.01-0.1$, highest efficiencies occurring in high z merging systems (see eg Genzel et al. 2010, Tacconi et al. 2012)

-→ slow gas consumption timescale compared to inflow timescale
$t_{dyn}/\varepsilon_{SF} >> t_{dyn} \sim t_{inflow}$



Bottom line: in mergers there is no "star formation bottleneck", at least down to 100 pc scales, and there is a lot of low angular momentum gas...

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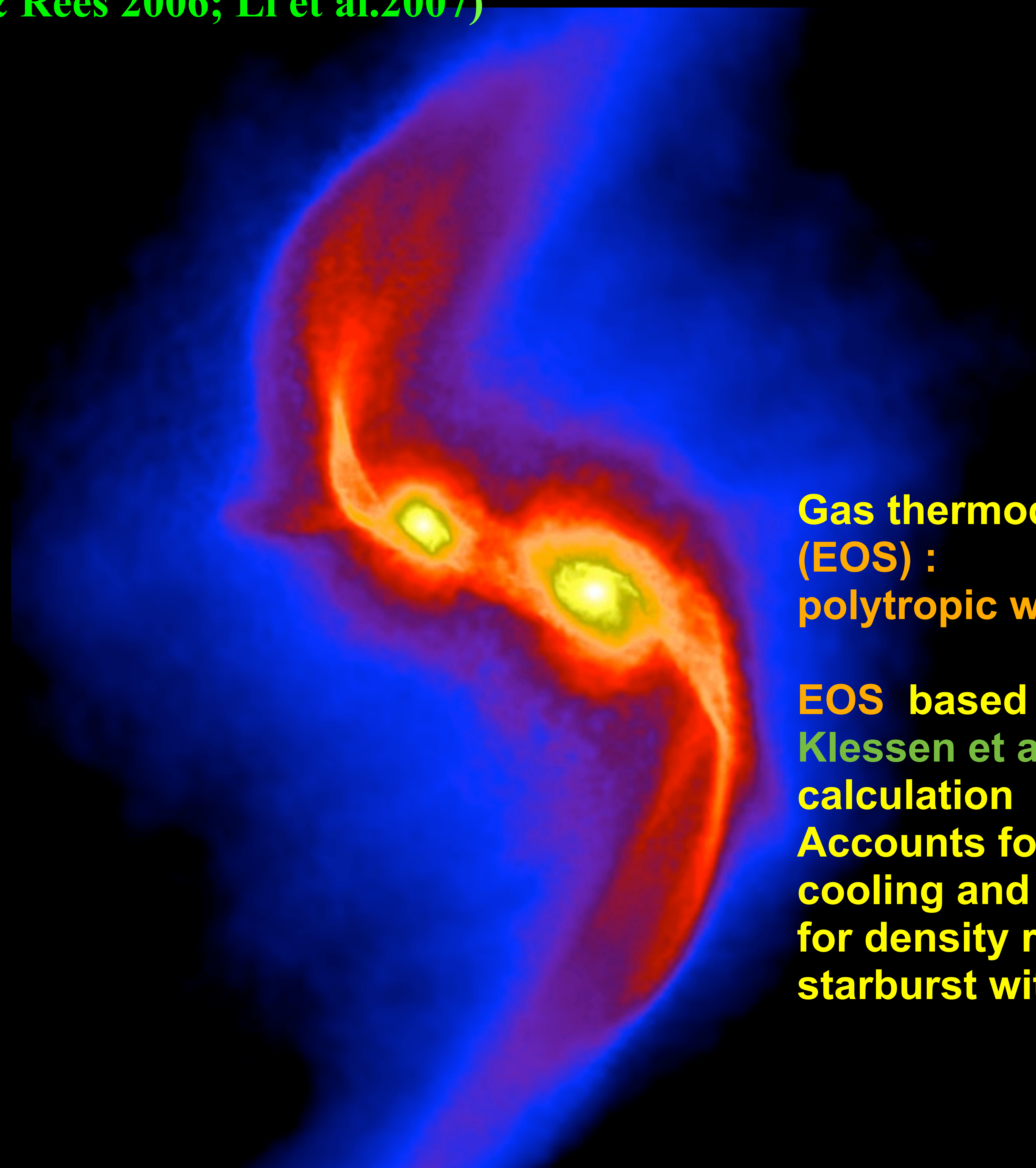
Can the merger-driven inflow continue all the way from 100 pc to << pc scales and form the precursor of a massive BH?

Gas-rich major mergers of massive proto-disk galaxies (Mdisk ~ 6 x 10^{10} Mo, 6 x 10^9 Mo of gas at merger time) in 10^{12} Mo halos at z ~8

Resolution 0.1 pc in ~ 30 kpc volume using SPH particle splitting with EOS appropriate for nuclear starburst (Spaans & Silk 2000, 2005)

Galaxy halo mass consistent with abundance of high-z SDSS QSOs (Fan et al. 2006, Morlock et al. 2010) i.e. rare 3-4σ peaks at z > 6 (Volonteri & Rees 2006; Li et al.2007)



Shown box size = 200 pc on a side (galaxy cores a few Myr before final collision)

60% of total gas mass accumulated within 200 pc due to tidal torques and shocks

Gas thermodynamics with effective equation of state (EOS) :
polytropic with effective adiabatic index ~ 1.1-1.4

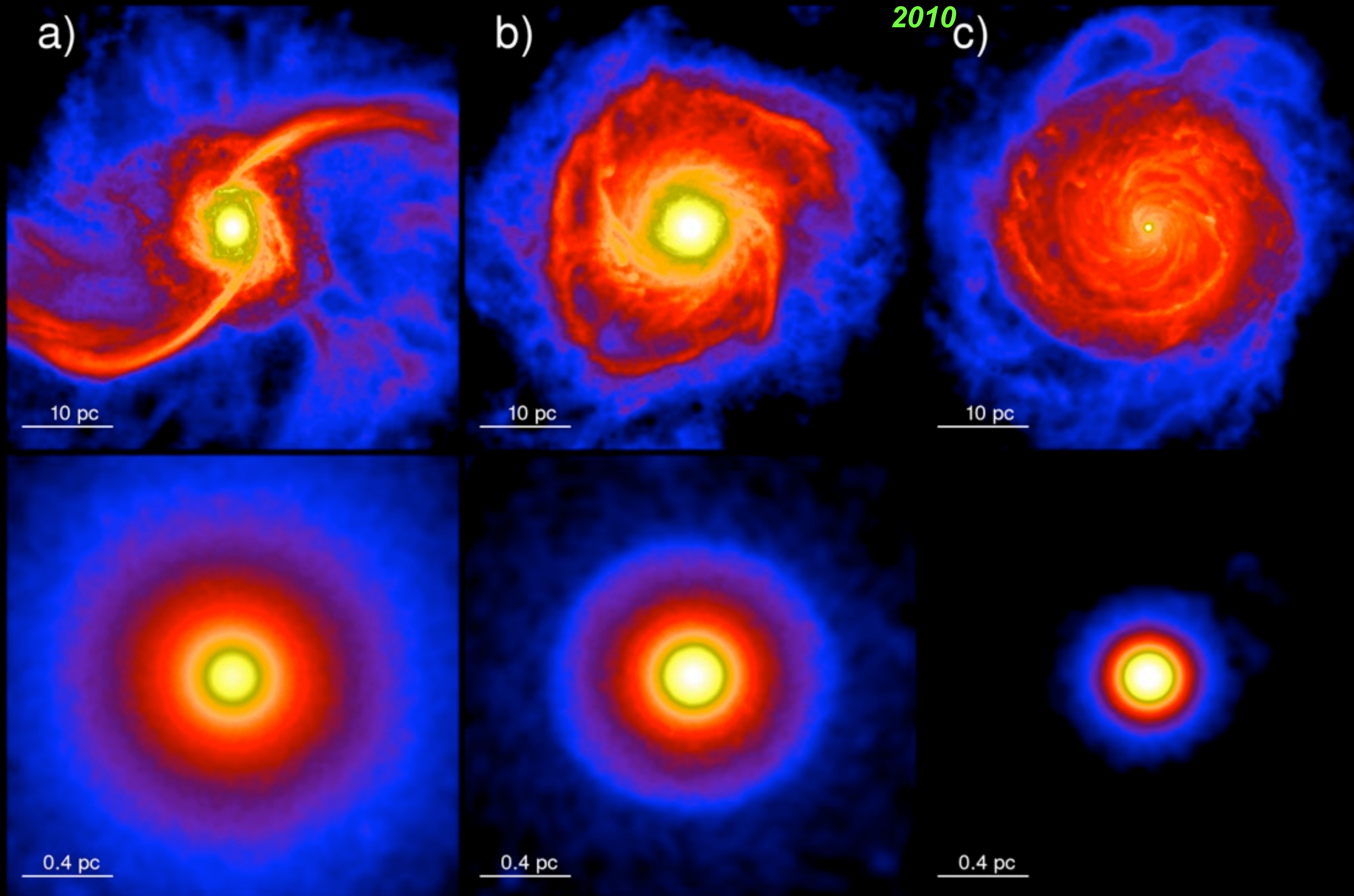
EOS based on model by Spaans & Silk 2005 (also Klessen et al. 2007) calibrated with radiative transfer calculation
Accounts for thermal equilibrium between radiative cooling and heating (UV, IR from dust, cosmic rays) for density range 0.1 to 10^7 atoms/cc in dusty starburst with metal enriched gas (metallicity solar).

Multi-stage gas inflow down to sub-pc in gravitationally unstable circumnuclear gas disk forming in major merger

---> rapid formation of supermassive (> 10^8 Mo) sub-pc scale gas cloud in only ~ 10^5 years after merger (SMBH precursor)

Below logrithmic density map spanning 10^5 yr after merger

Mayer, Kazantzidis, Escala & Callegari, Nature, 2010



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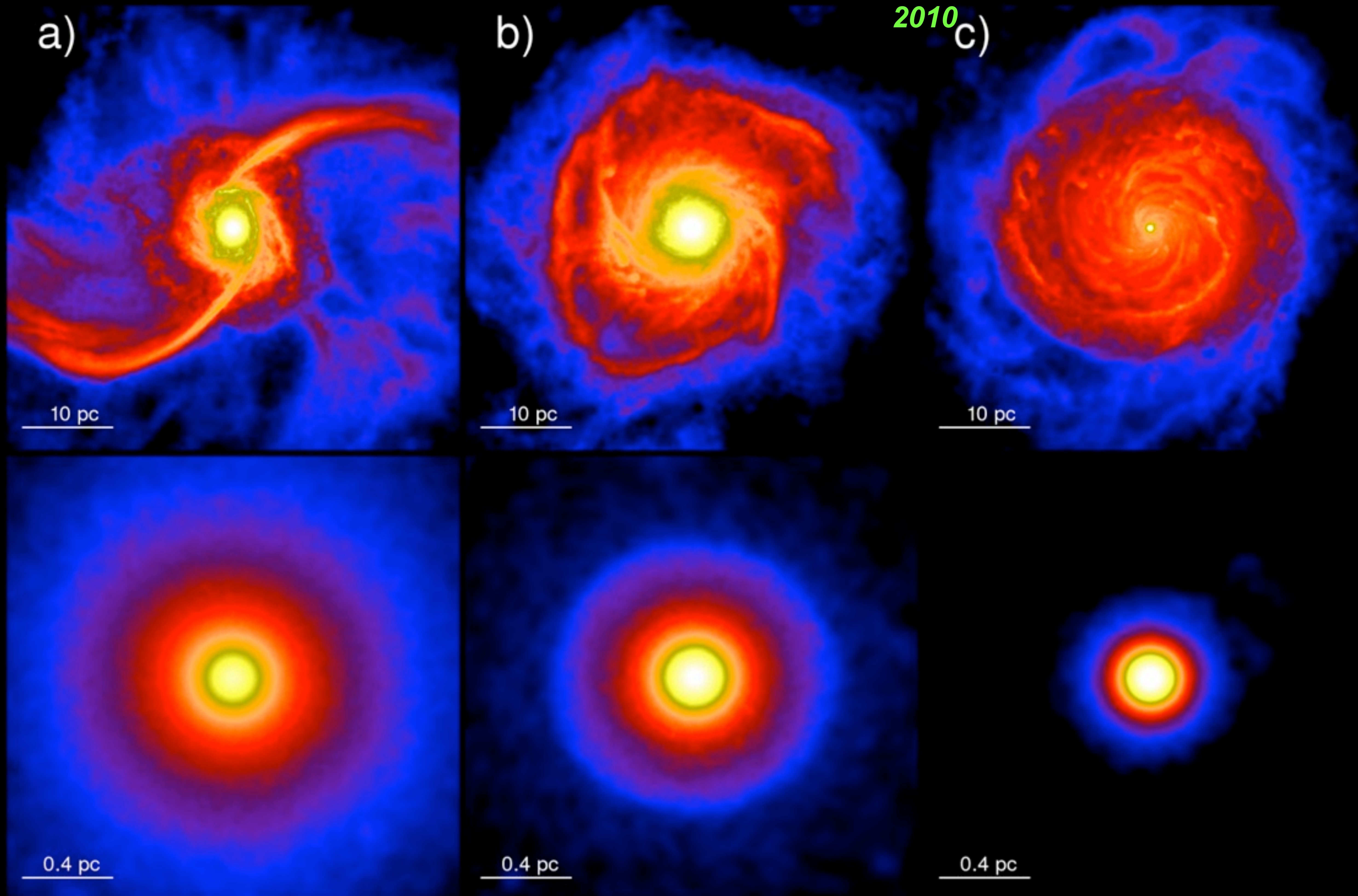
Large scale m=2 mode imprinted by galaxy collision starts inflow in nuclear disk



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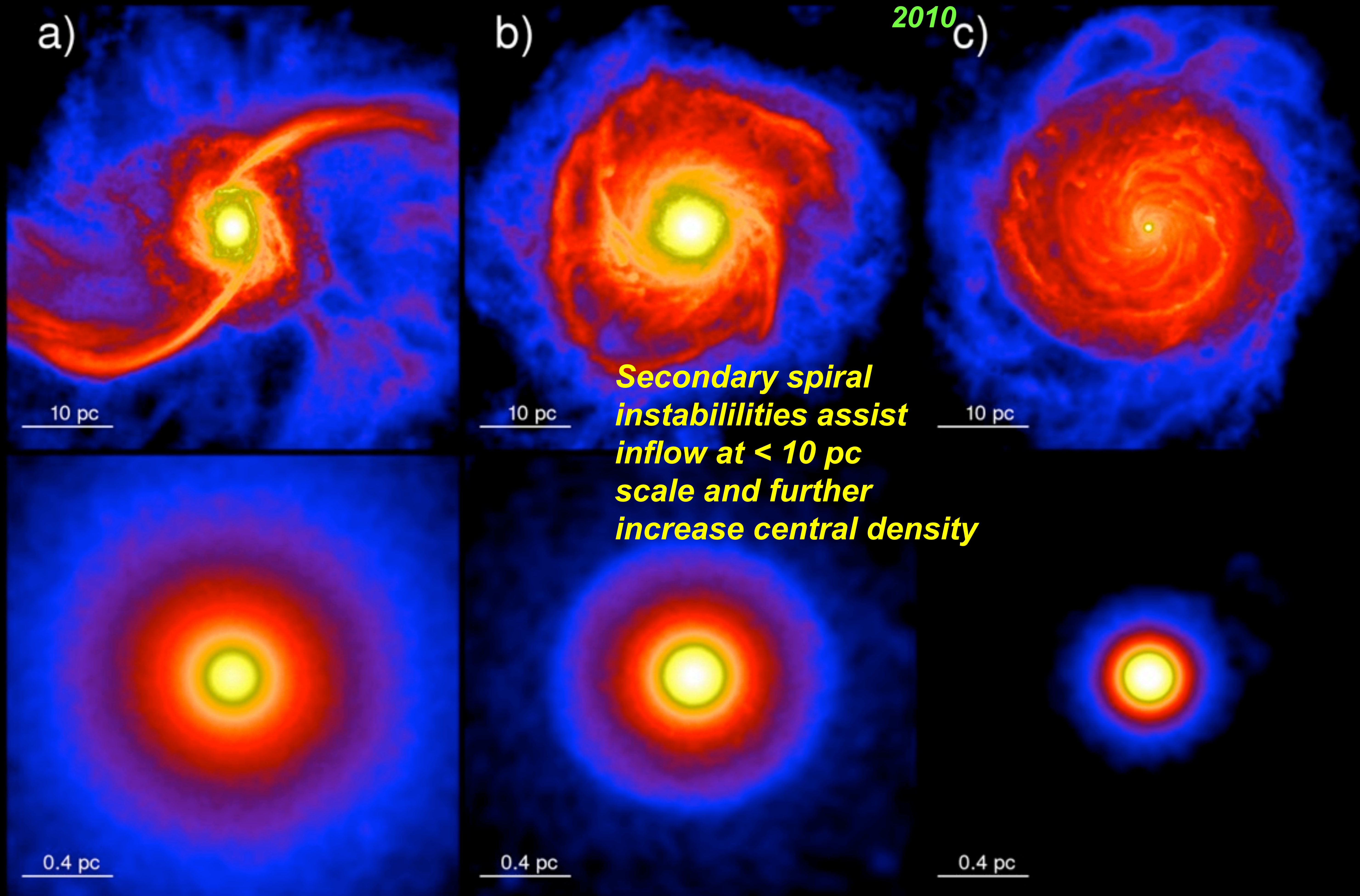

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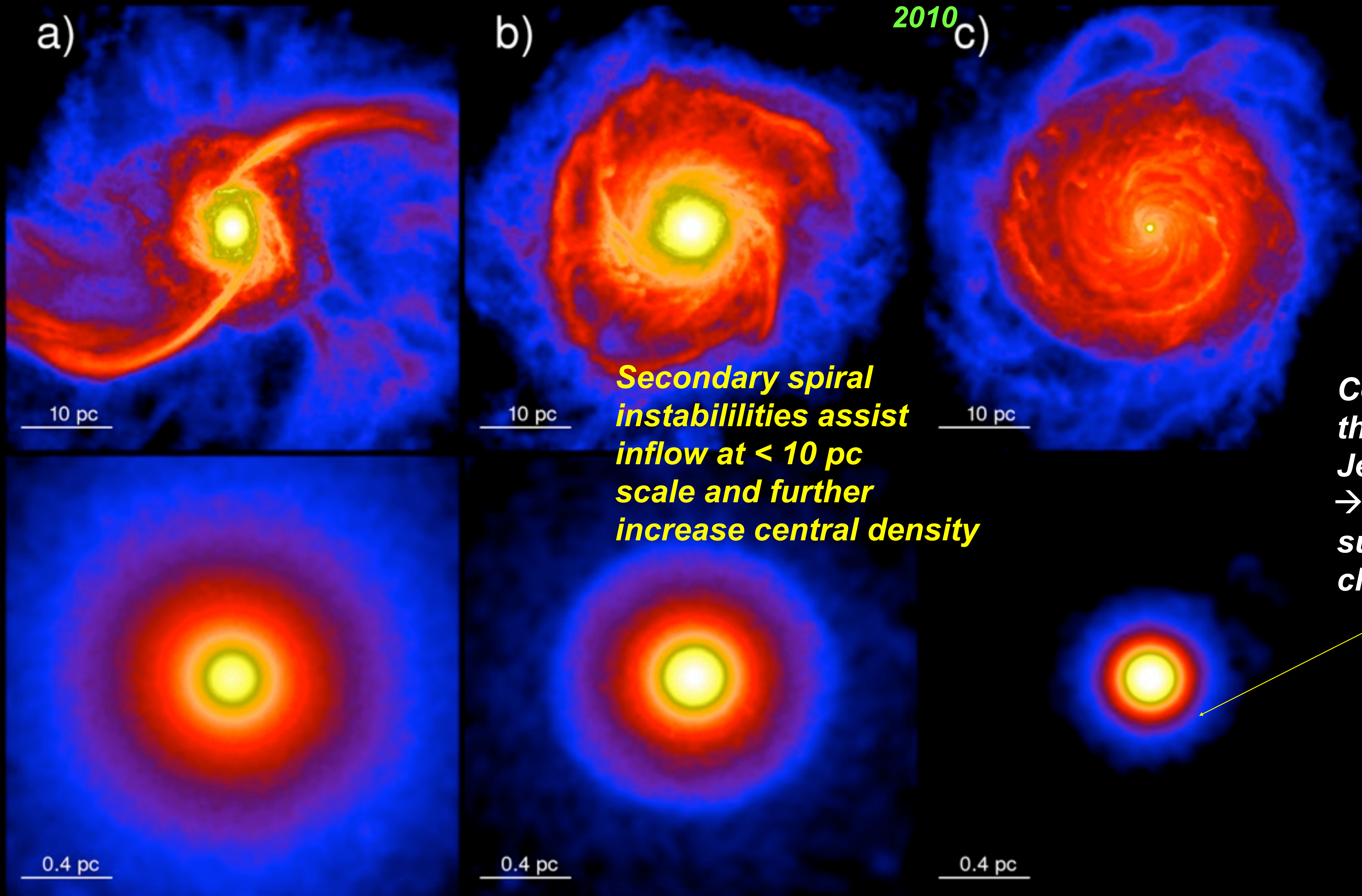
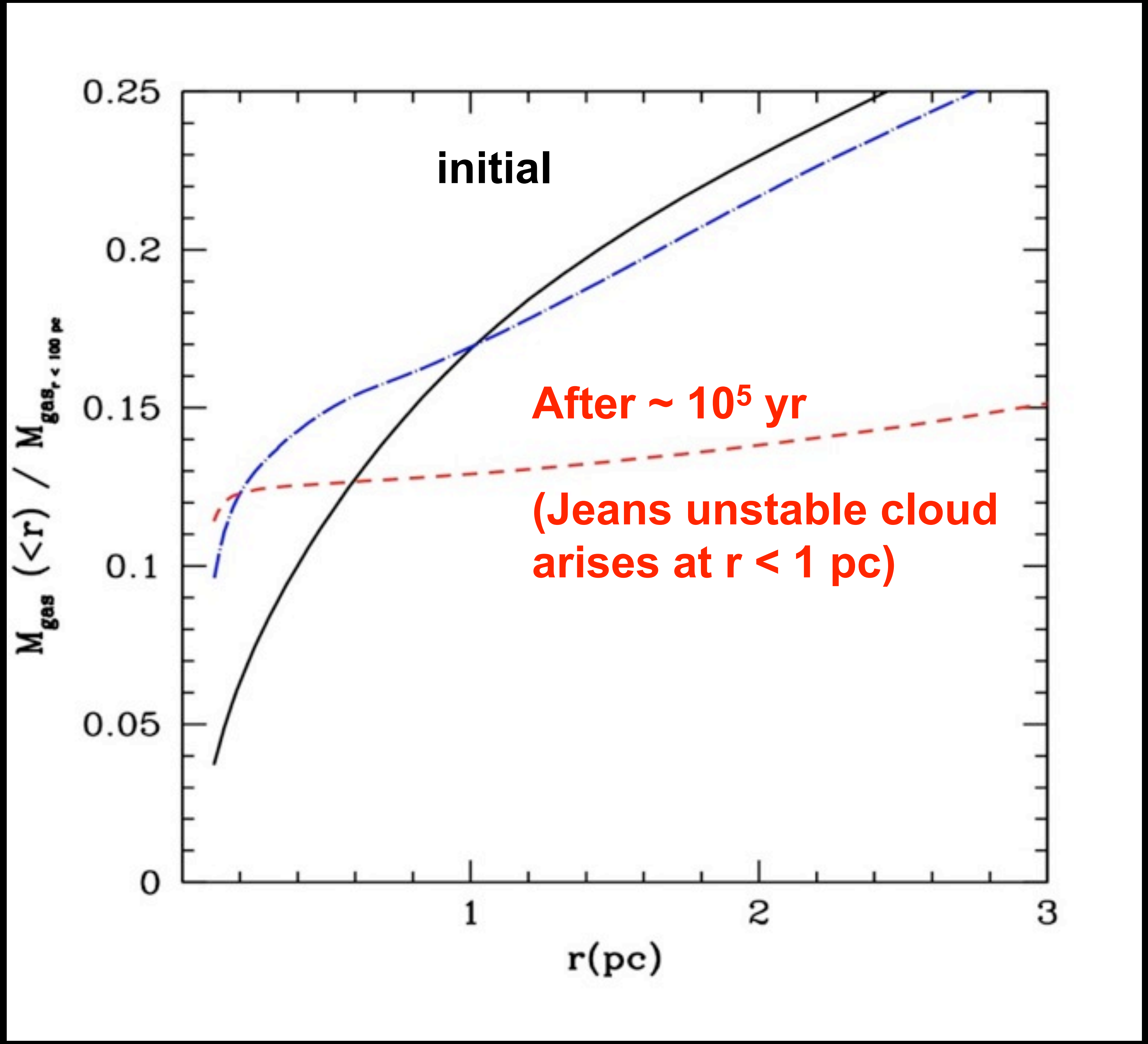


Large scale m=2 mode imprinted by galaxy collision starts inflow in nuclear disk

Secondary spiral instabililities assist inflow at < 10 pc scale and further increase central density

Central region then undergoes Jeans collapse →formation of supermassive cloud (N_{sph} > 10^5)



In first 10^5 yr after merger:

Mass inflow rate
~10^4-10^5 Mo/yr

Star formation rate
(~0.1 x M_g/T_{orb})
~ 10^3 Mo/yr

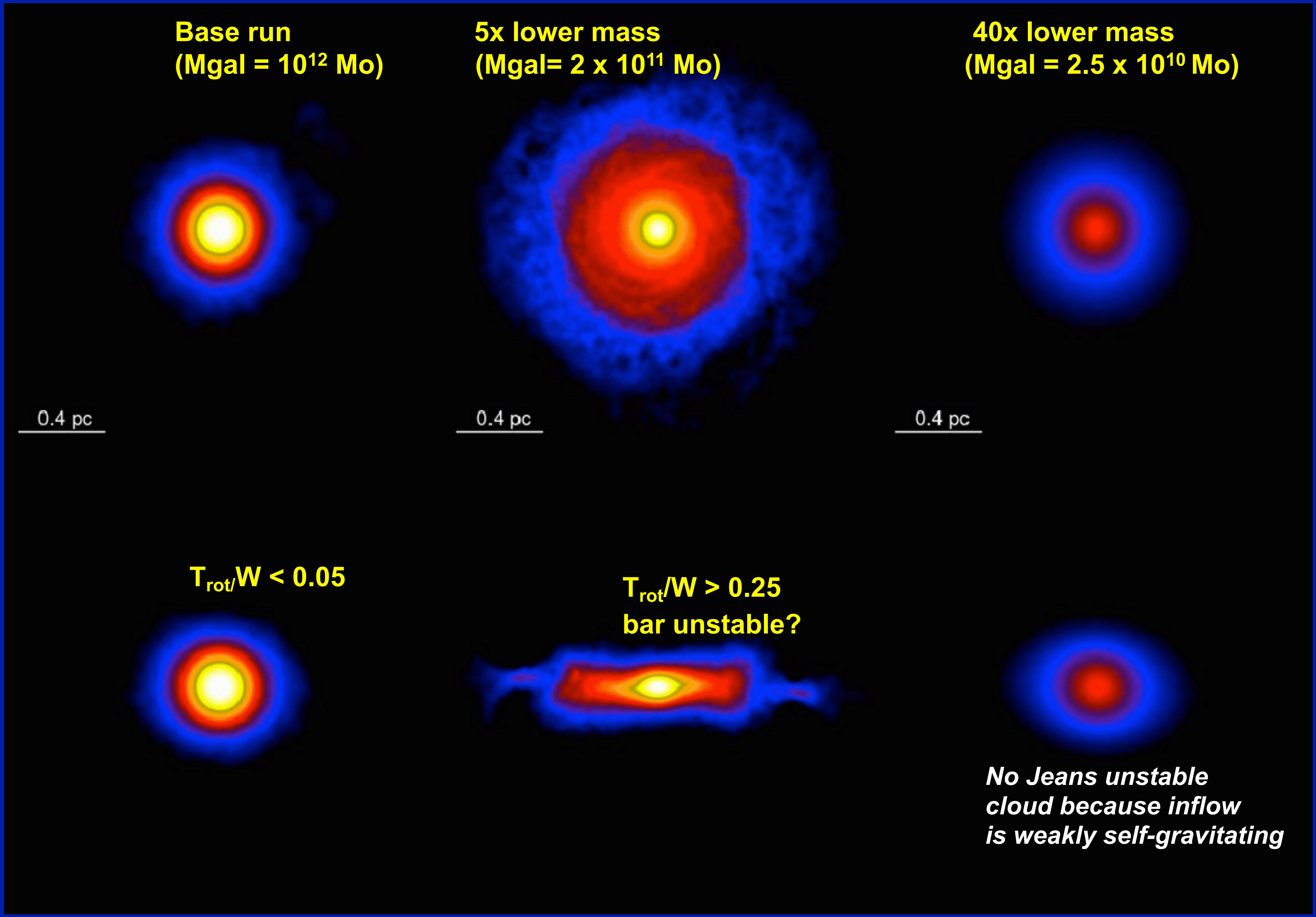
--> ***gas inflow up to 2 orders of magnitude higher than star formation rate***

- **Supercloud Jeans unstable to resolution limit** – *further collapse (a) into supermassive star or (b) directly into > 10^8 Mo SMBH via post-newtonian instability (route (b) requires R ~ $640GM/c^2$ ~ 0.02 pc for M ~ 10^8 Mo from numerical GR simulations results (Shibata et al. 2002; Saijo et al. 2009), for us R_{cloud} ~ 0.5 pc)*

- **Assuming route (a) and, conservatively, that >~ 10^5 Mo BH forms from ultimate collapse of SMS (< 0.1 % super-cloud mass!):**
If initial black hole forms at z ~ 9 then can grow at >~0.7 x Eddington rate to 10^9 Mo in < 3 x 10^8 yr, i.e before z ~ 7

In low mass galaxies (~10^{10} Mo) no SMBH precursor forms

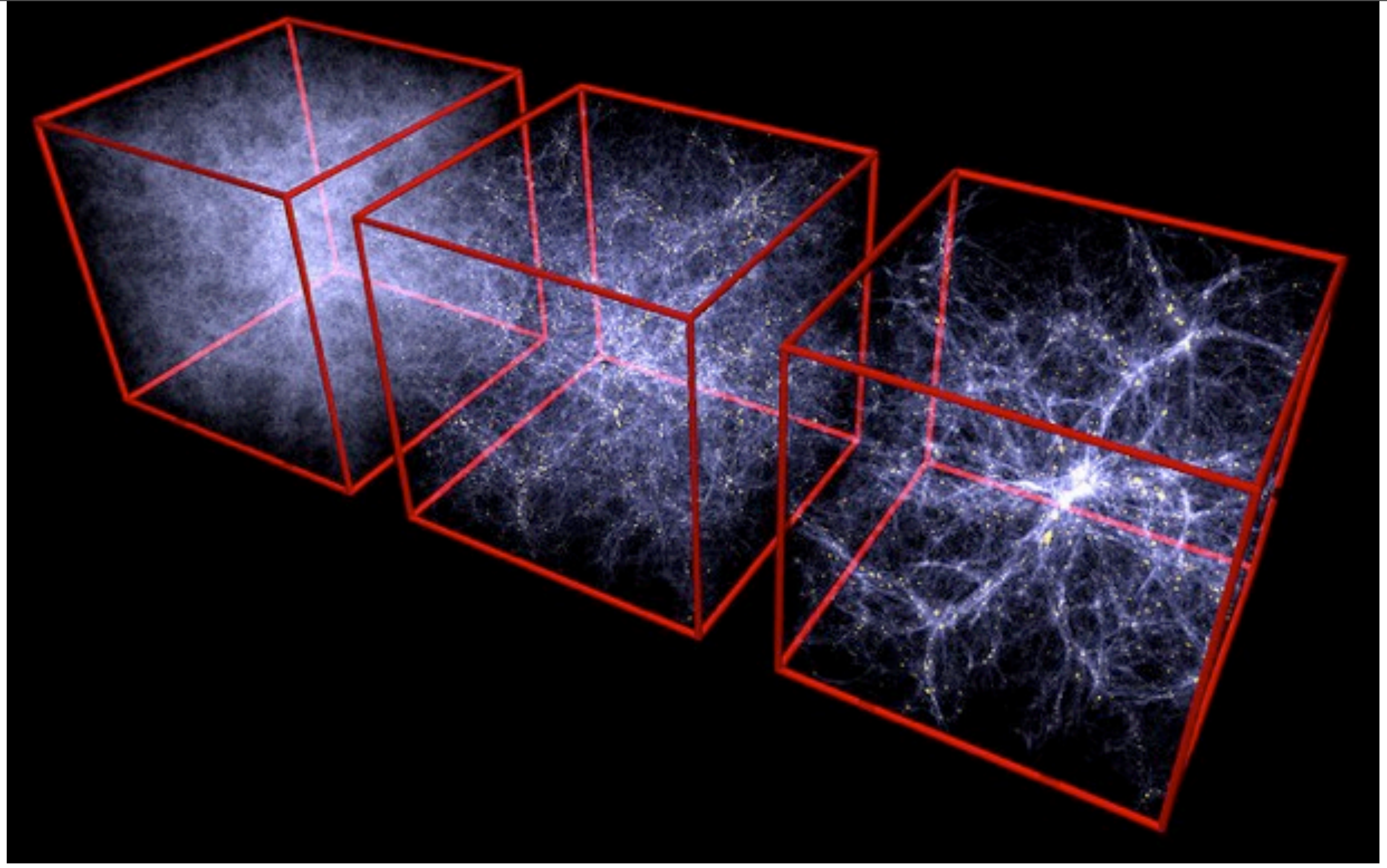
1:1 mergers between galaxies with a range of masses



Shown on left: Logarithmic gas density maps

Embedding our formation scenario in the LCDM galaxy formation paradigm

(Bonoli, Mayer & Callegari 2012)



We use the semi-analytical Munich model of galaxy formation (Croton et al. 2006; Bonoli et al. 2009), applied to the outputs of the Millennium Simulation

→ We have a full population of galaxies evolving in a cosmological framework that allows us to seek the BH seed formation conditions from hydro simulations and statistically test our scenario

We follow the cosmological evolution of galaxies and their black holes:

- **PopIII seeds** (**M = 1000 Mo**) populate ALL newly formed galaxies
- **Direct collapse seeds** (**M= 10^5 Mo**) are formed during major mergers (and replace PopIII black holes), IF certain conditions implied by our simulations are satisfied

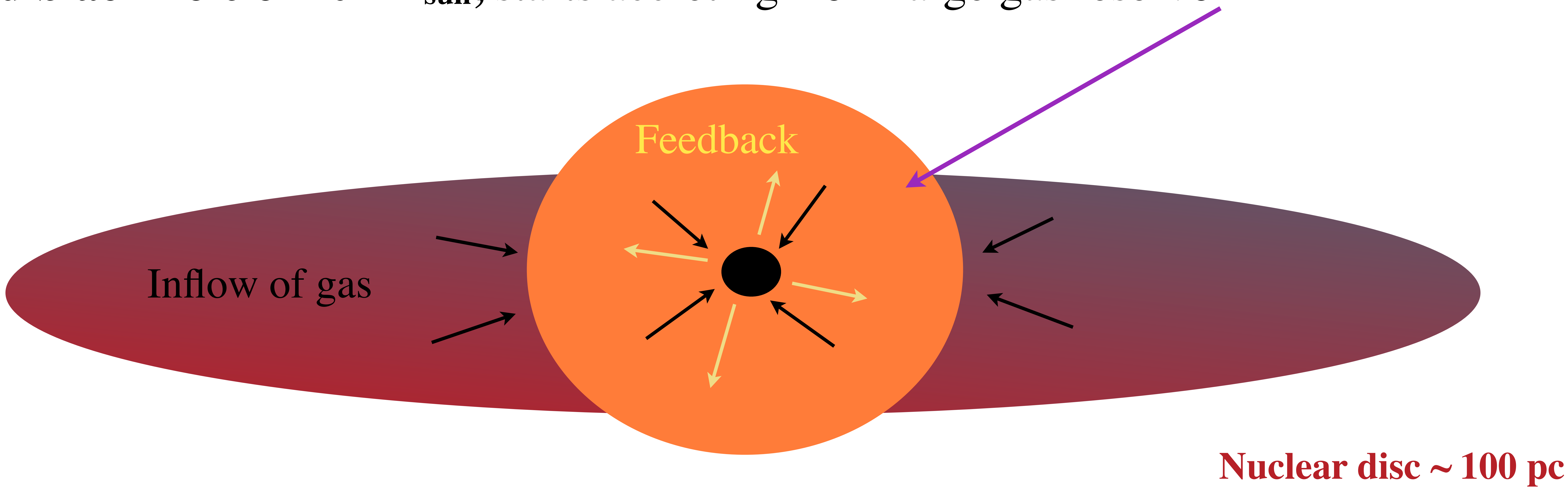
Conditions for the formation of massive seed black holes

✓1. Major merger (1:3) of gas-rich late-type galaxies (B/T < 0.2)

✓2. Host halo $M_h > 10^{11} M_{Sun}$

✓3. No pre-existing black hole of $M_{BH} > 10^6\ M_{Sun}$

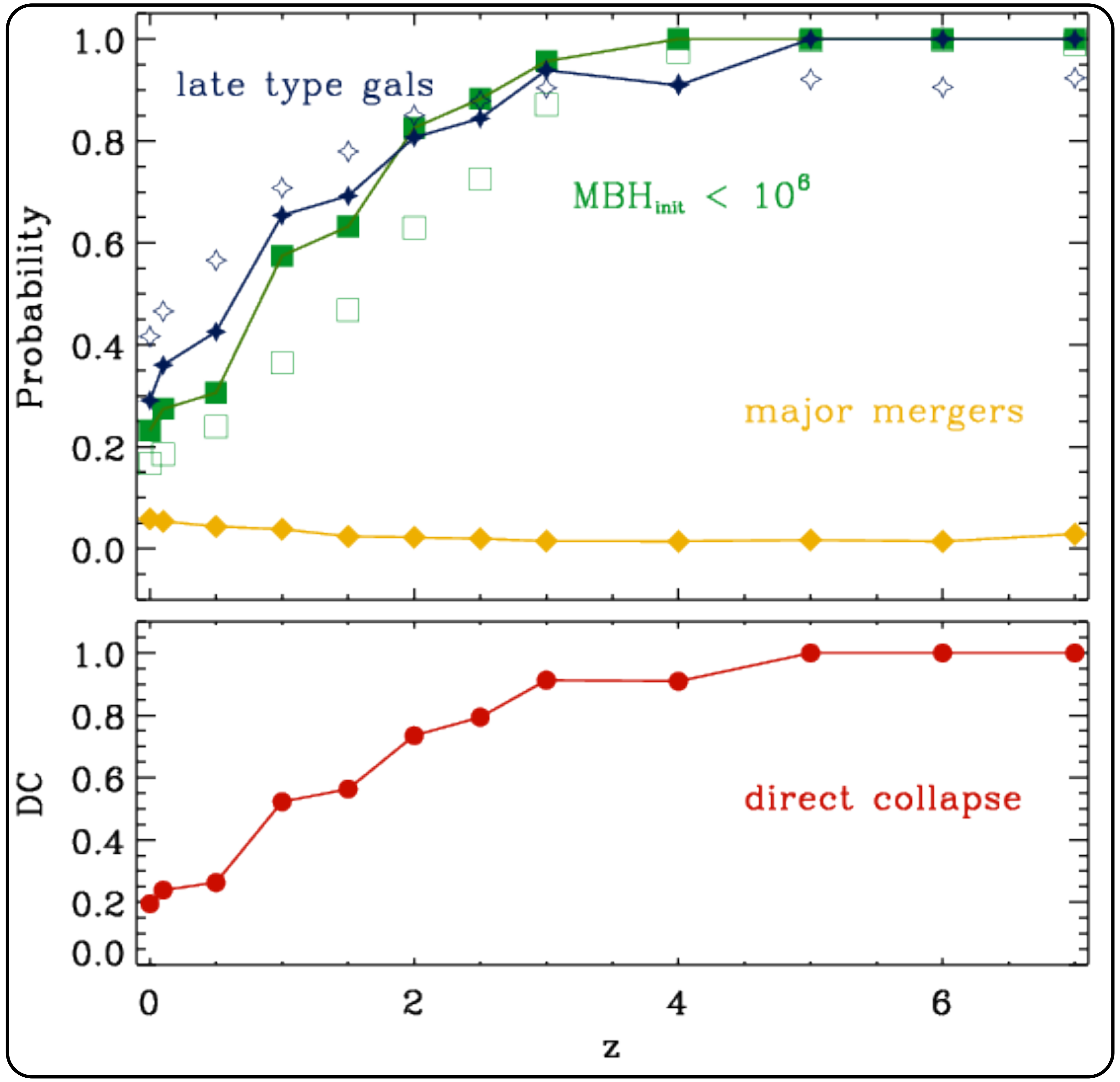
Seed black hole of $10^5\ M_{sun}$, starts accreting from large gas reservoir



Self regulation: accretion stops once the feedback energy released by the black hole unbinds the reservoir (assumed isotropic thermal feedback with 0.05 coupling efficiency). BH will continue grow Eddington limited during subsequent mergers in the same way as Pop III seeds (a la Croton et al. 2006)

Radius of the reservoir is a free parameter (0.1-1pc), determines its binding energy

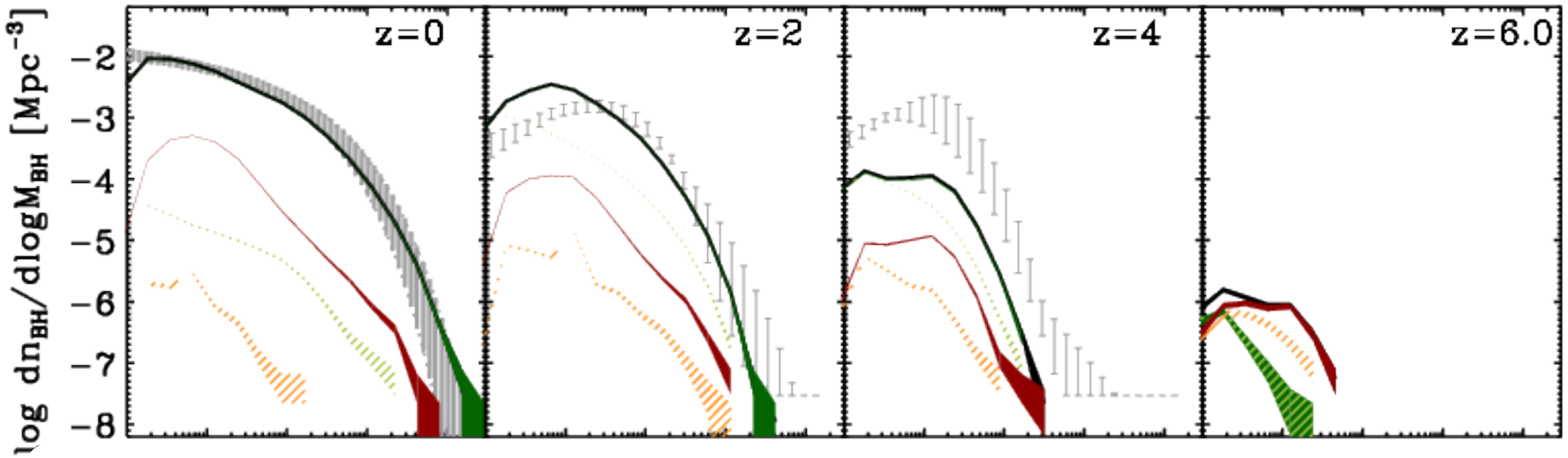
How frequent is our direct collapse route as a function of redshift?



- **Above z~4 all major mergers could lead to direct collapse**
- **Major merger events giving rise to direct collapse MBH seeds can happen even at low z (though large majority at z > 3)**

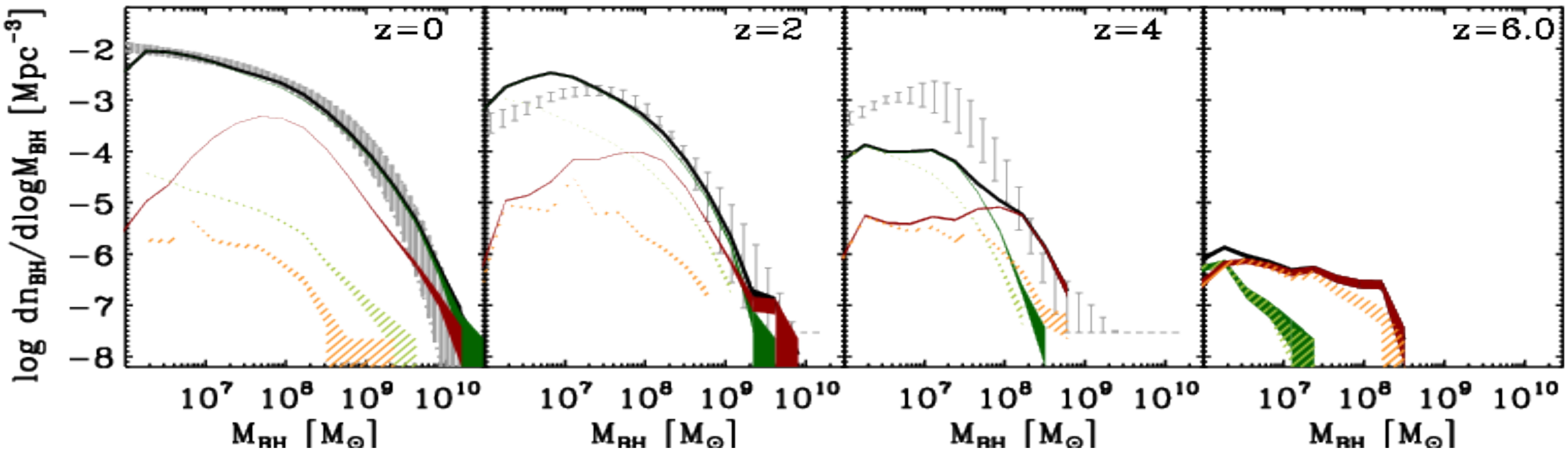
Properties of the mass function (data from Merloni & Heinz 2005)

1 pc reservoir

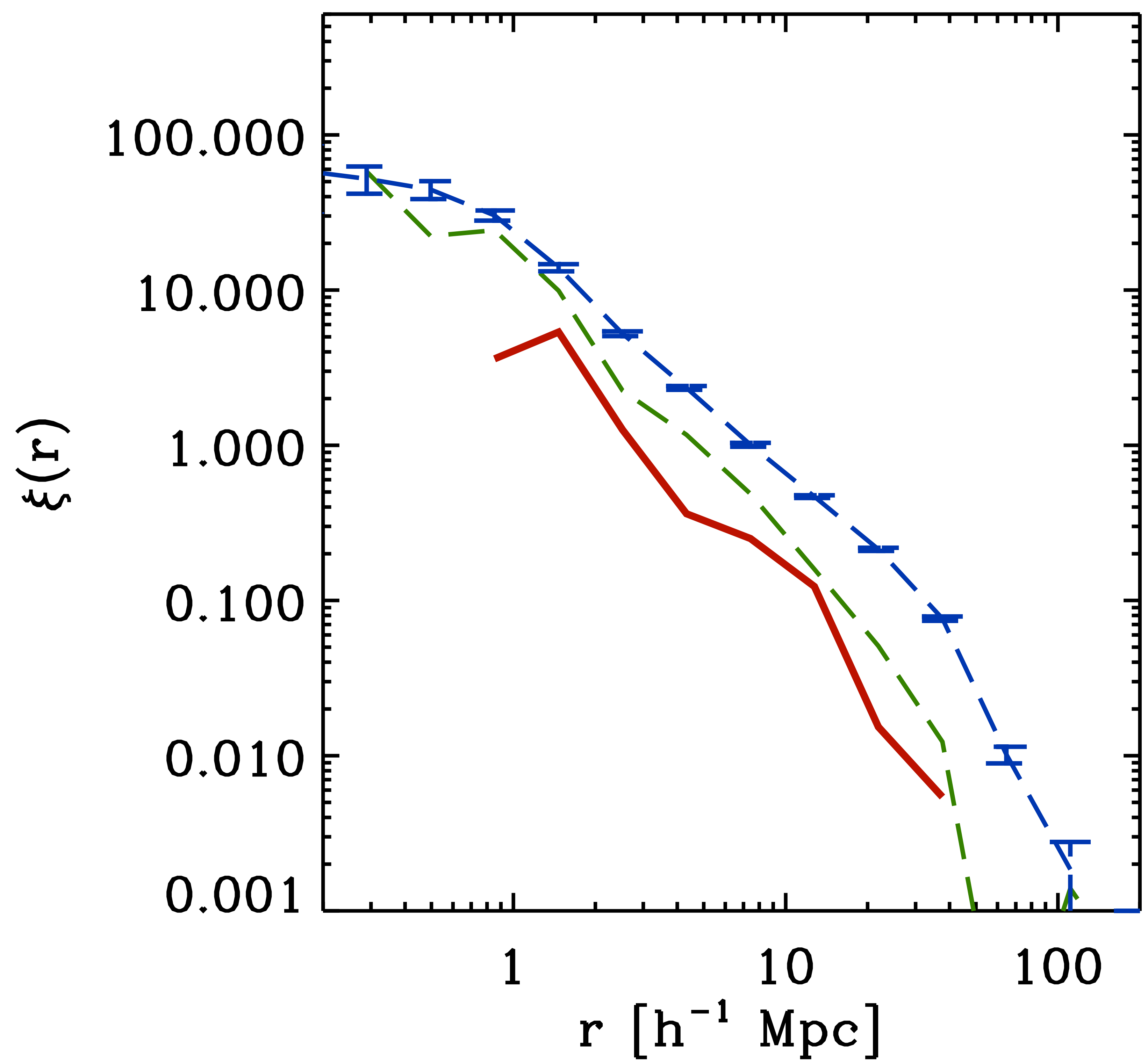


POP III
DC

0.1 pc reservoir



Clustering of galaxies forming direct collapse BHs at z < 0.1: two-point correlation function



Red : Hosts of Direct Collapse BH seeds formed at z < 0.1

Green: Recent major mergers which do not form BH seeds by direct collapse (but have Pop III seeds) and have same galaxy stellar mass distribution

Blue: Random Sample with same stellar mass distribution of host galaxies

Low clustering amplitude relative to global BH population
because host galaxies had few or no mergers for nearly an Hubble time (otherwise Pop III seed grows and prevents direct collapse), i.e. fairly isolated objects

Qualitatively similar to low clustering of blue galaxies vs. global galaxy population (eg Li et al. 2006)

Open issues and implications

- Does direct collapse into a SMBH really occur after formation of supermassive cloud and *Which path does it take? Global post-newtonian instability? Supermassive star + quasi-star?*
  -- Modeling of cloud collapse at even higher resolution w/post-newtonian effects and then interface with full General Relativistic simulations
  -- Better characterization of cloud physical state – beyond EOS w/radiative transfer, neutrino diffusion in collapsing hot core etc..

- How does direct SMBH formation scenario depend on the structure/initial angular momentum content of merging galaxies? What is the role of gas turbulence?
  Disks at high z clumpier and more turbulent than our ICs! Gravitoturbulence should aid collapse by extracing angular momentum further

- Does it stop working at low galaxy mass as our models with effective EOS suggest?
  Likely yes --- in galaxies with M <~ 10^{10} Mo *supernovae driven outflows should prevail over inflows, remove 2/3 of baryons (Governato, Brook, Mayer et al. 2010; Brook et al. 2011)*

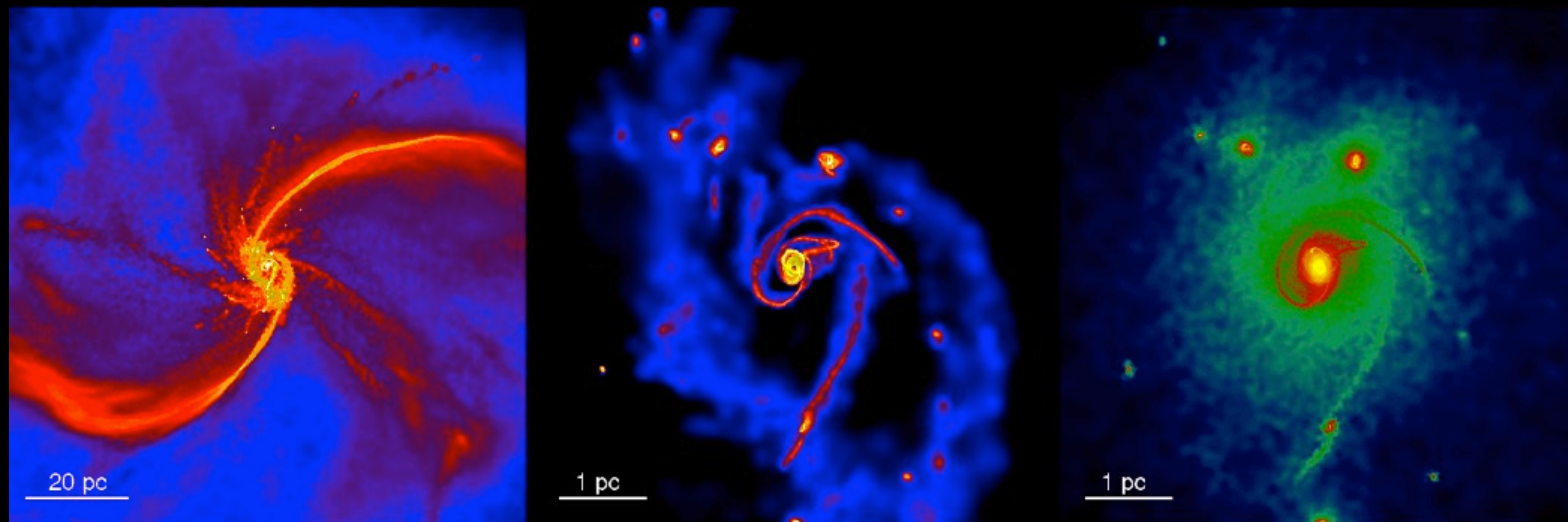
Predictions (simulation combined with SAM):

- BH formed by merger-driven collapse also at low z, and should have low clustering amplitude(those that form at high z are instead highly clustered as expected for high-sigma peaks)

- At z > 2 large deviations from the local M_{bulge}-M_{BH} : SMBH already in place while galaxy/ bulge has nearly an Hubble time let to grow

- If quasi-star phase precedes BH seed formation could be observable with JWST (blackbody emission at a few microns), although only very few per JWST field expected (see also Volonteri & Begelman 2010). At low z such events about an order of magnitude less frequent but gamma ray and radio emission could be detected if jets develop in quasi-stars, perhaps explaining unidentified sources in gamma-ray catalogs (Czerny et al. 2012)

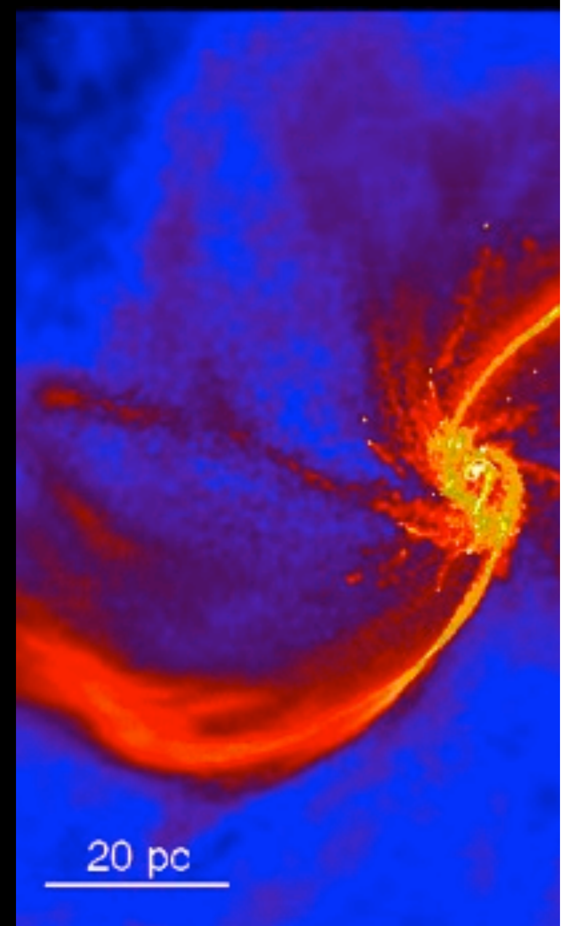
From EOS model to model with explicit radiative cooling and star formation

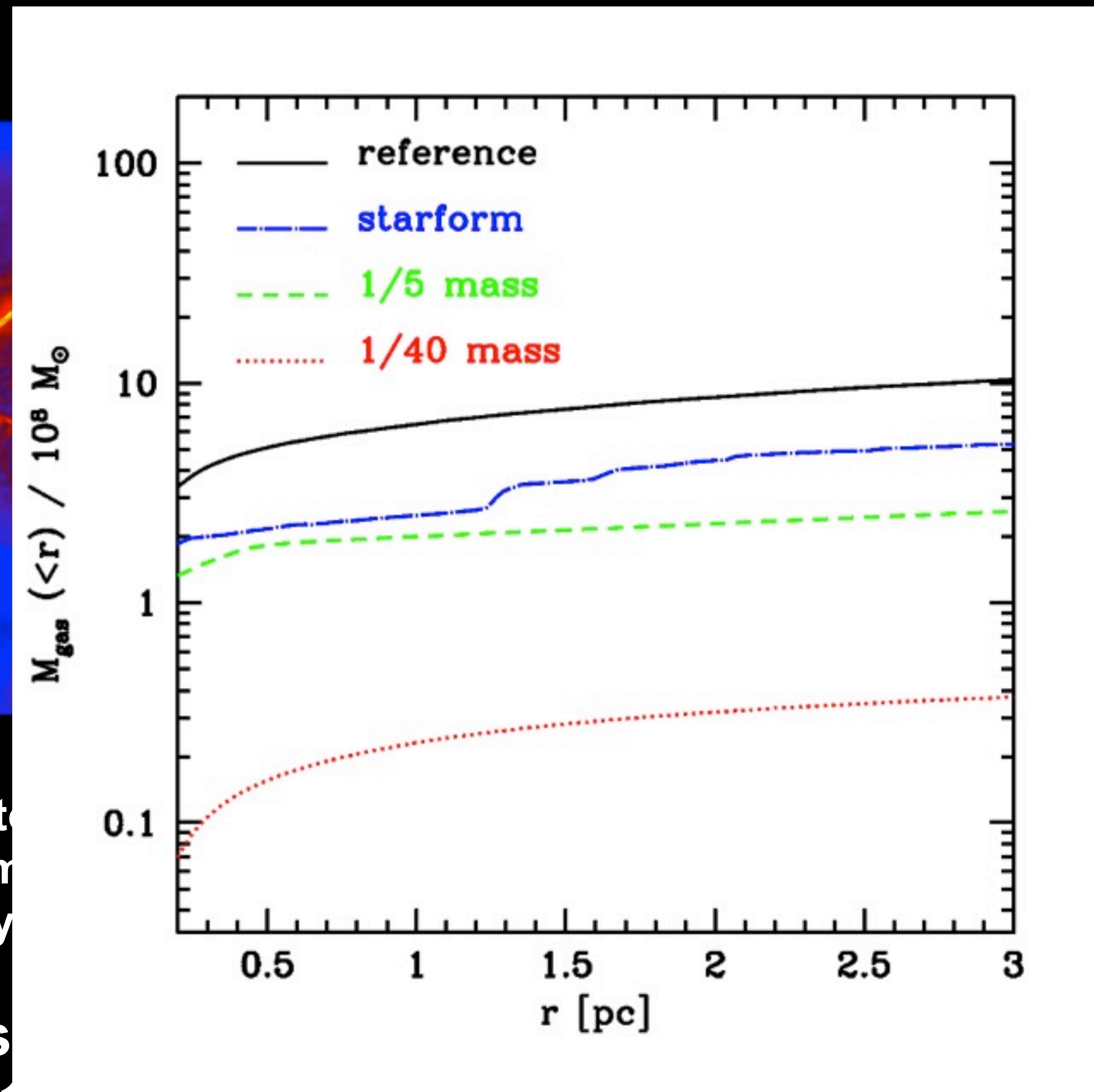


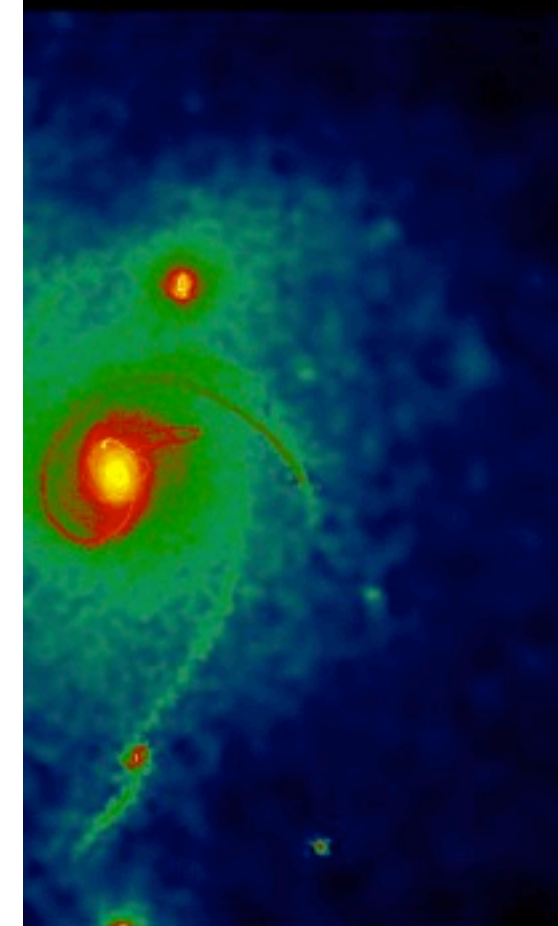
Gas cools radiatively and turns into stars above a density of 10^4 cm^{-3} + pressurization of medium to avoid spurious fragmentation below local Jeans length (no radiative transfer or heating by stellar/supernovae feedback, so max. fragmentation)

< 10^5 yr after the merger star formation has turned 30% of the nuclear gas disk into stars but > 10^8 Mo of gas still concentrates at < 0.5 pc in supermassive flattened cloud
-→ *even stronger inflow than with EOS model* *(gravitoturbulent regime, see also Begelman & Shlosman 2010)*

From EOS model to model with explicit radiative cooling and star formation







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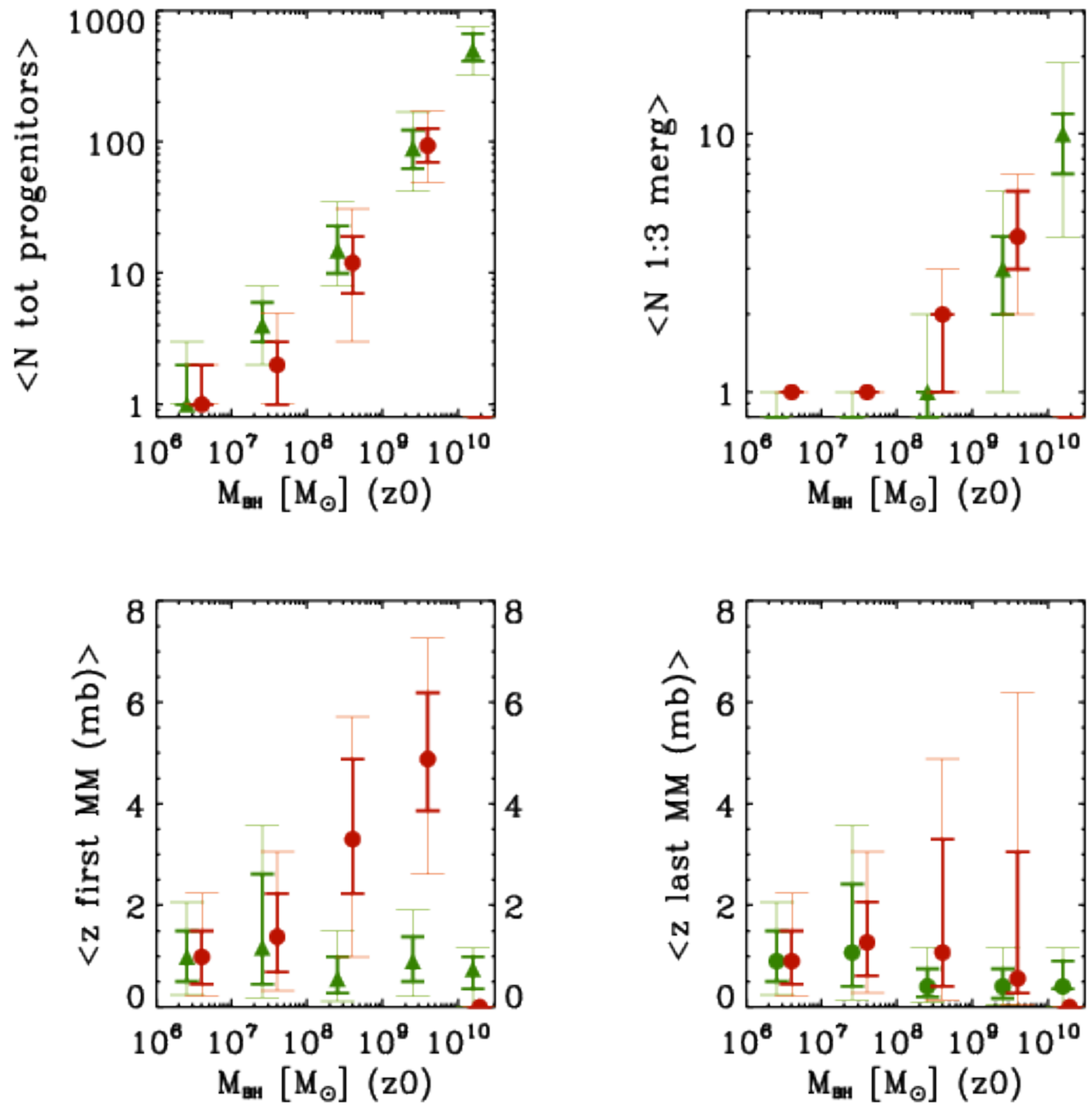
-→ *even stronger inflow than with EOS model* *(gravitoturbulent regime, see also Begelman & Shlosman 2010)*

Features of merger histories for galaxy hosts of different BH seeds

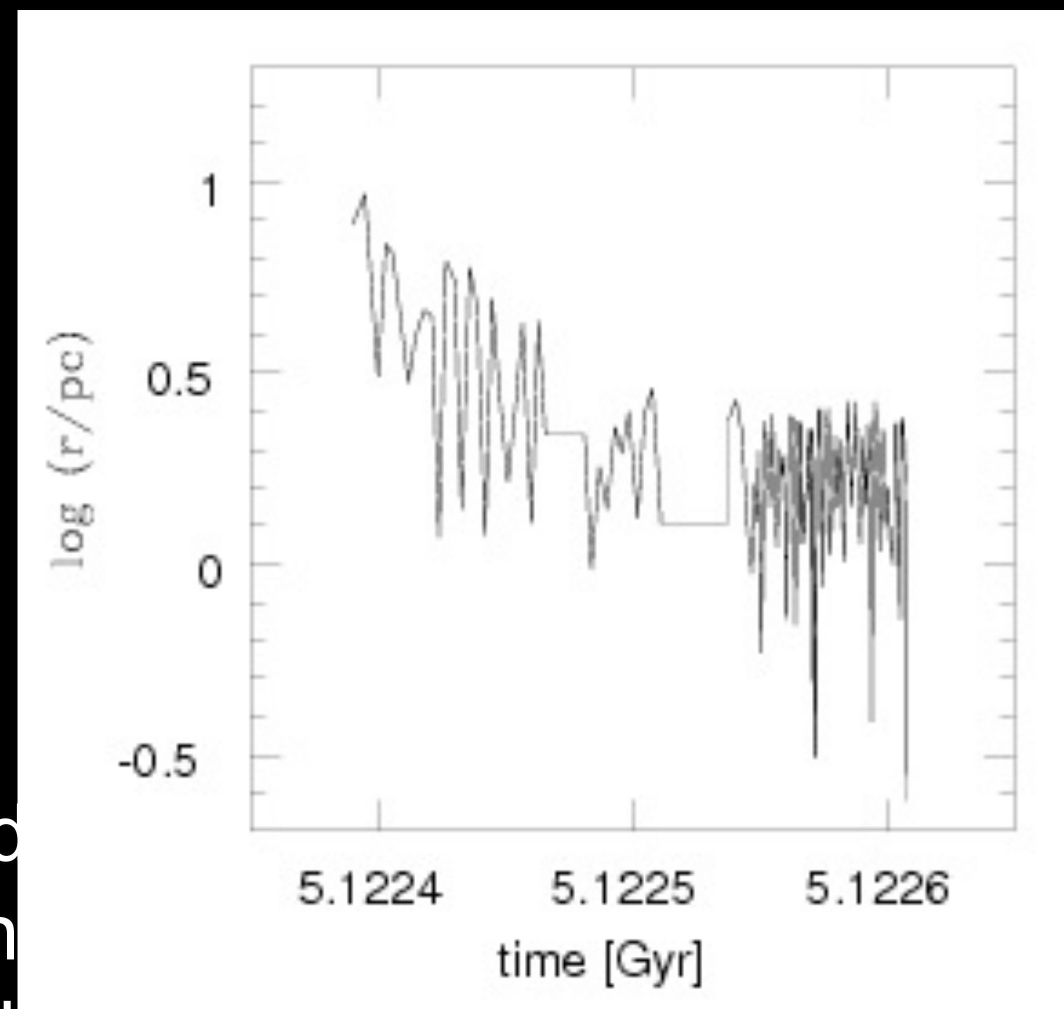
POP III (small seeds)
DC

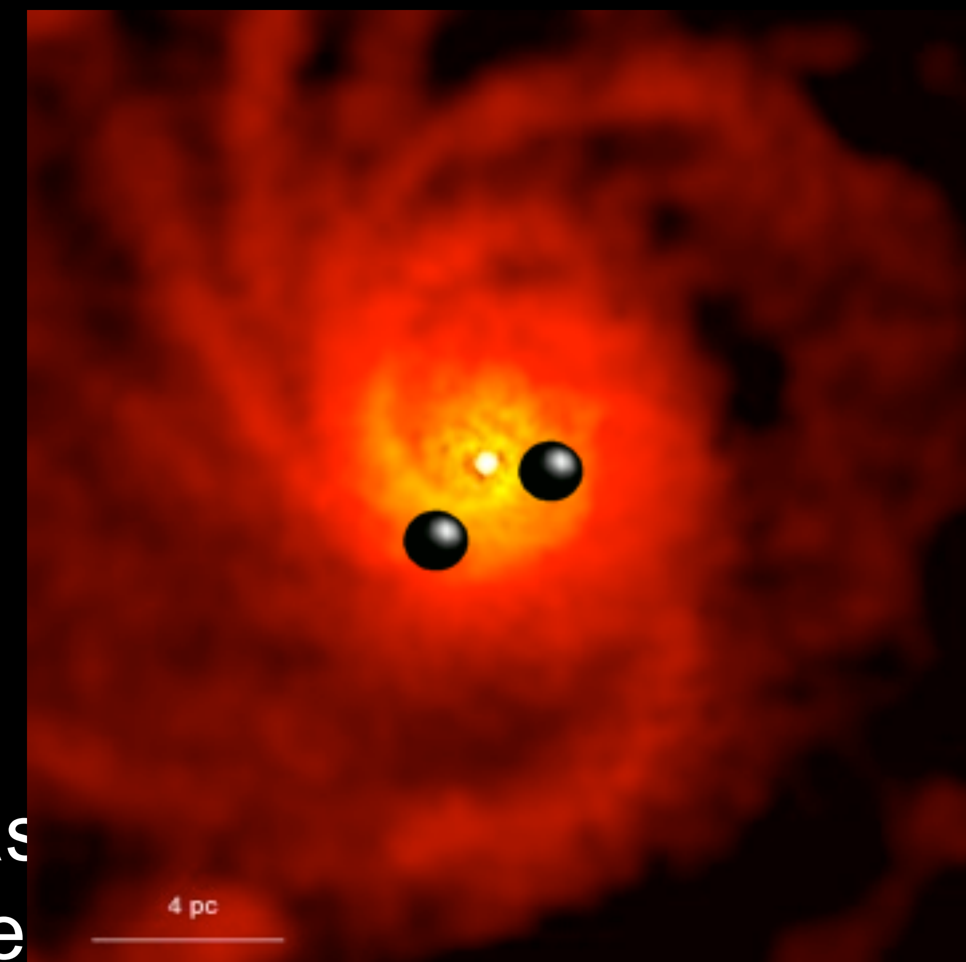
other colors for other percentiles



Only clear distinction between seeding scenarios: hosts of direct collapse seeds have first major merger earliest

A binary SMBH stalls at ~ 0.5 pc in a nuclear disk capable of forming a central massive supercloud



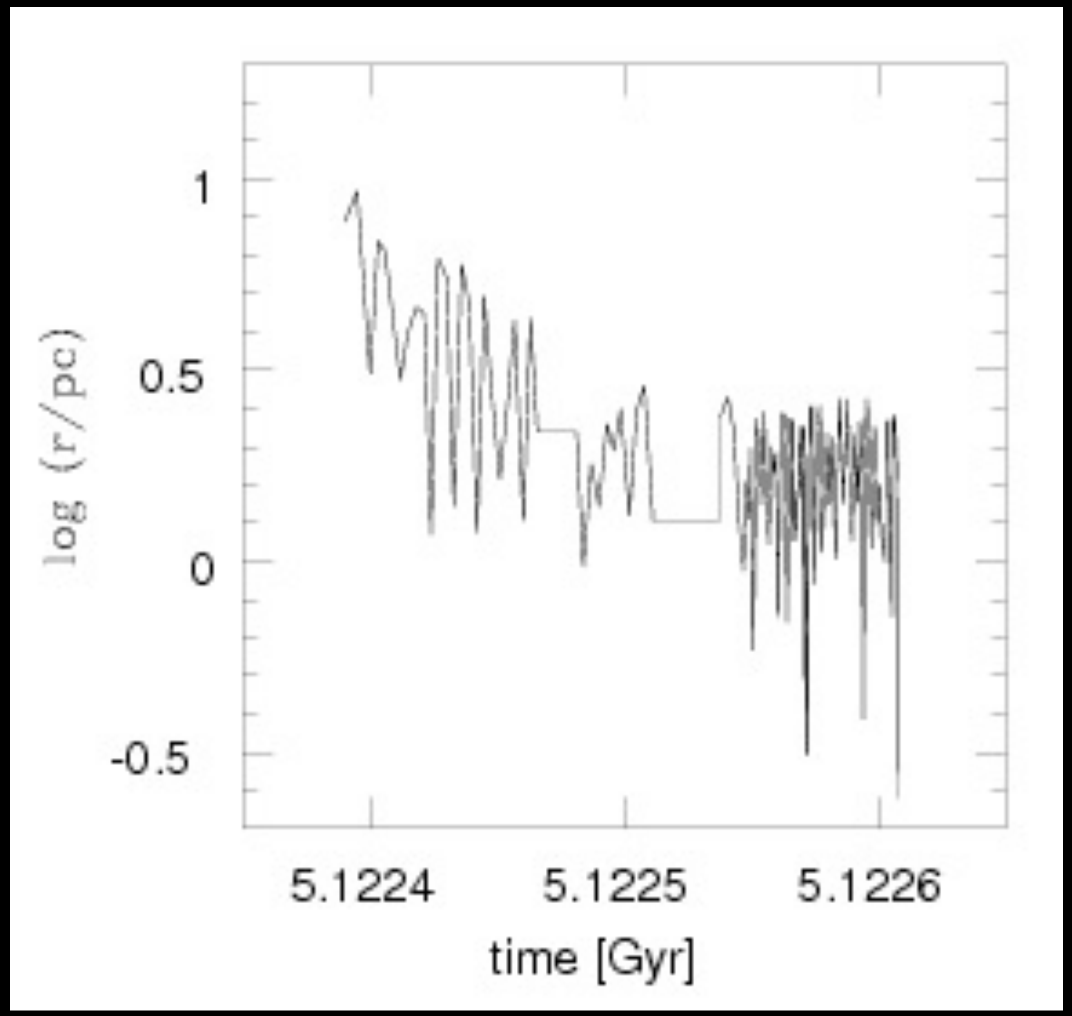


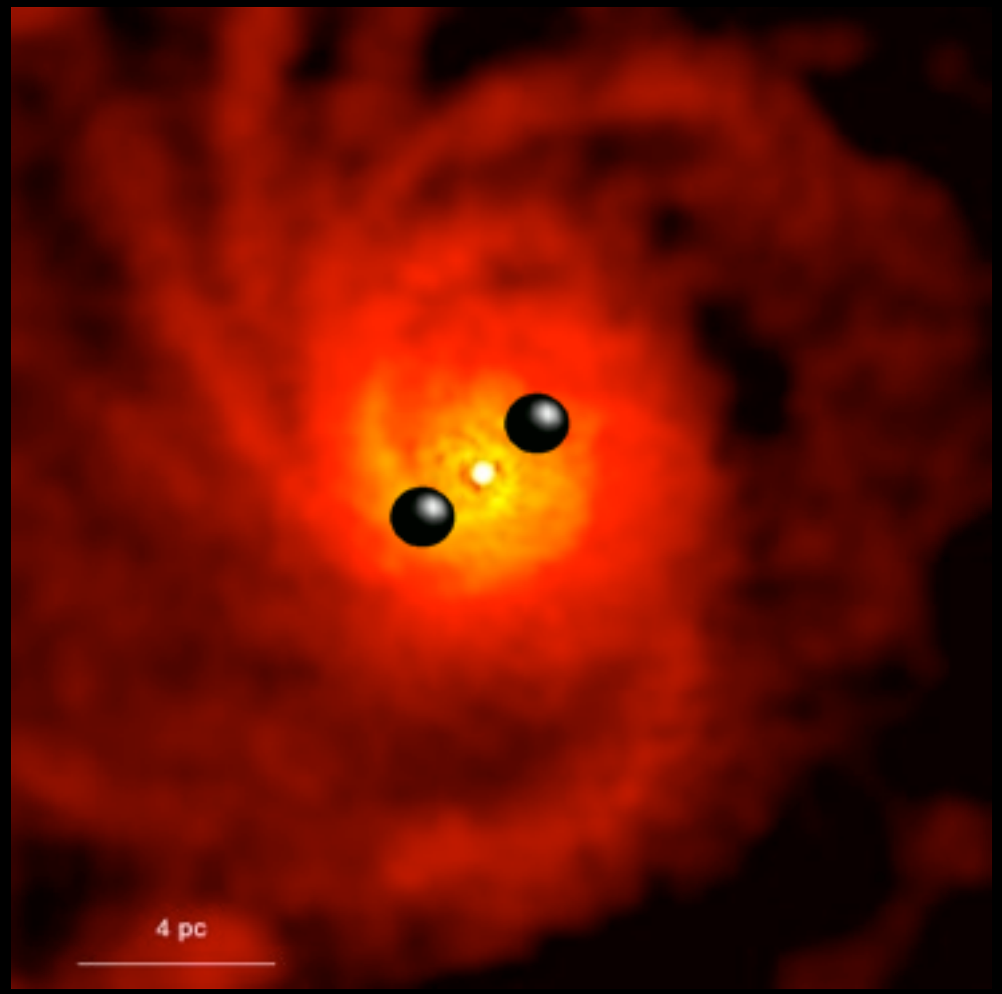
Dynamical friction from bacground ... ales as
is the local gas density and v_{bh} th ... elative
Both SPH (Mayer et al. 2007) and AMR simulations (Chapon, Mayer & Teyssier 2011)
show that binary of SMBH hardens down to about ~ 1 pc separation in ~ 10^6 yr.

But in less than 10^5 yr (1) density increases by x10 (the supercloud) at scales < 1 pc over ~10^5 years but decreases x10 just outside 0.5 pc +(2) v_{bh} increases because larger mass in the center (=supercloud)

---→ ***df slows inefficient because*** **$t_{inflow} < t_{df}$**

A binary SMBH stalls at ~ 0.5 pc in a nuclear disk capable of forming a central supercloud





But is a nuclear gas disk with a central supercloud a realistic configuration when two SMBHs are already present?

The answer is: probably not

Attractive scenario (to be investgated);

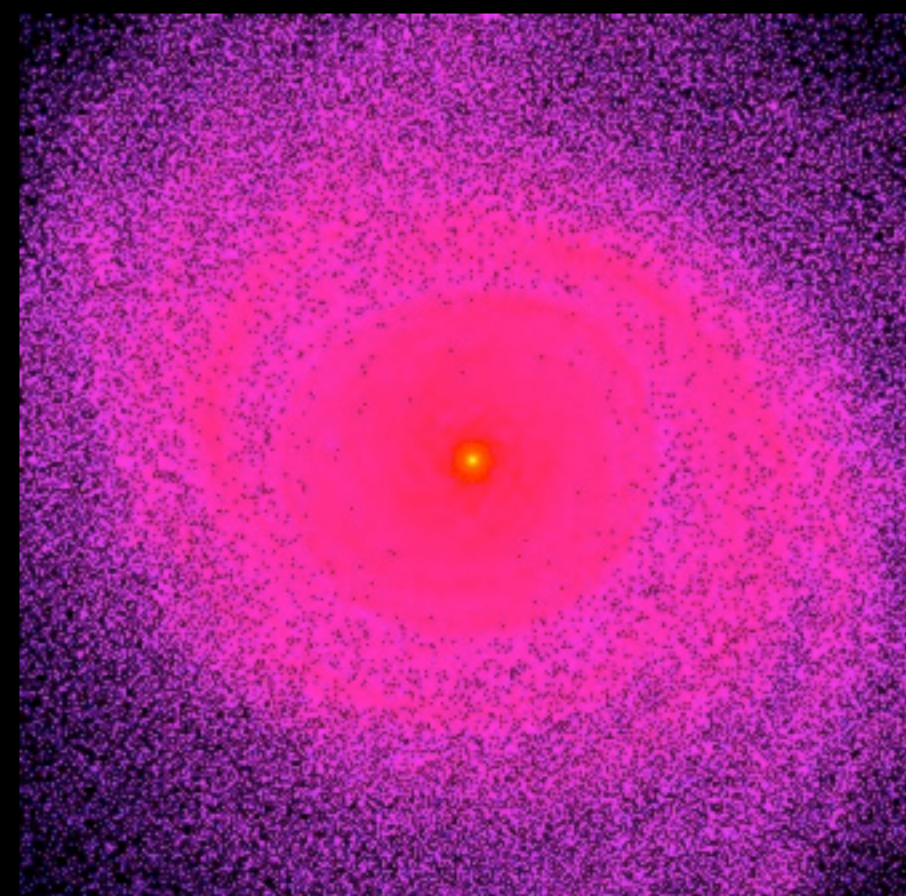
- ***when no pre-existing black hole is present disk is violently unstable, drives a strong inflow and central supercloud collapse --→ massive SMBH seed formation in massive merging protogalaxies at z > 5***

(ii) when one or two massive black holes are already in place in the nuclear disk (M_{BH} >= 10^6 Mo) they accrete gas and heat the disk via radiative feedback, stabilizing it against spiral instabilities and thus suppressing the central collapse
(Q > 2 from Eddington limit accretion and 10% of accretion energy released as thermal/turbulent kinetic energy over about 10^8 yr)→
the disk profile does not become so steep and the binary can sink down to separations < 0.1 pc.
→Binary SMBH coalescence successful + no formation of new SMBH seed

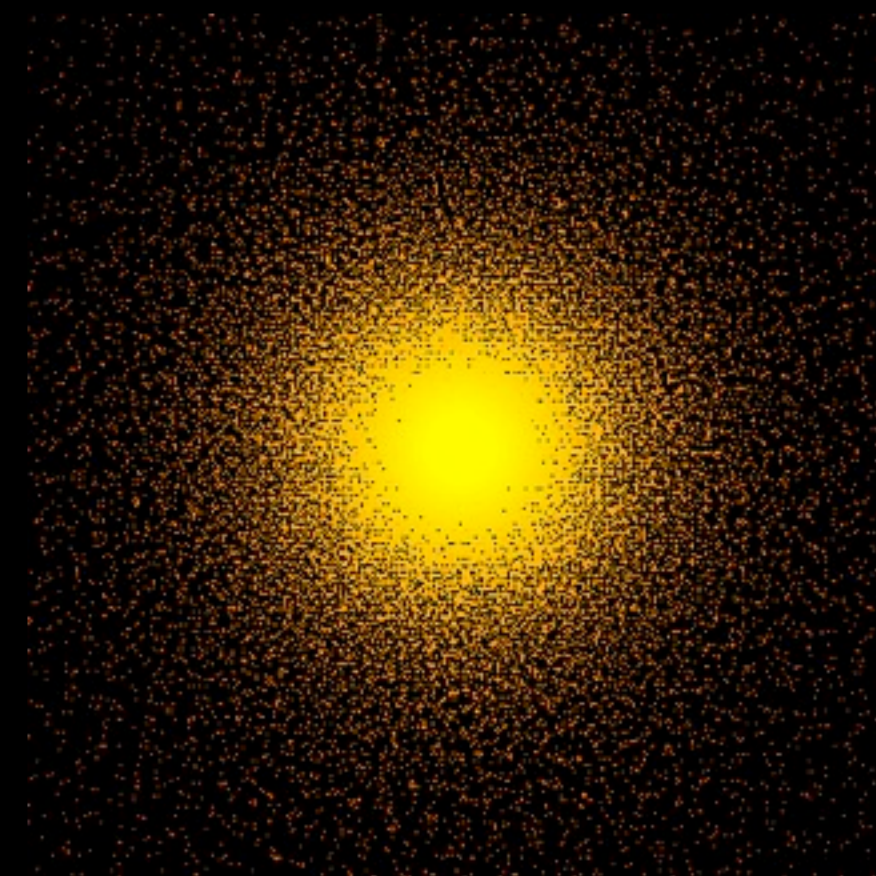
Which fate of the “supercloud”?

New ongoing simulation campaign to study supercloud collapse to post-netwonian regime (Mayer, in prep.)
First step; verification that cloud collapses continues below 0.1 pc in the newtonian case, including superclouds with highest angular momentum, by repeating simulations with 0.02 pc resolution (at even higher res PN corrections necessary)

3 pc box



0.05 pc box



Cloud evolved with $\gamma = 1.1$ and $\gamma = 4/3$ (likely more realistic, should be optically thick to its own radiation →radiation pressure supported cloud)

After 2 free-fall times $\gamma=4/3$ cloud in sim with highest Trot/W (> ~0.25) has turned into a core-disk envelope structure (no bar instability occurs)
Core contains ~ 7 x 10^7 Mo, is ~ 0.04 pc in size and is still Jeans unstable at $t=2t_{ff}$ (end of sim)