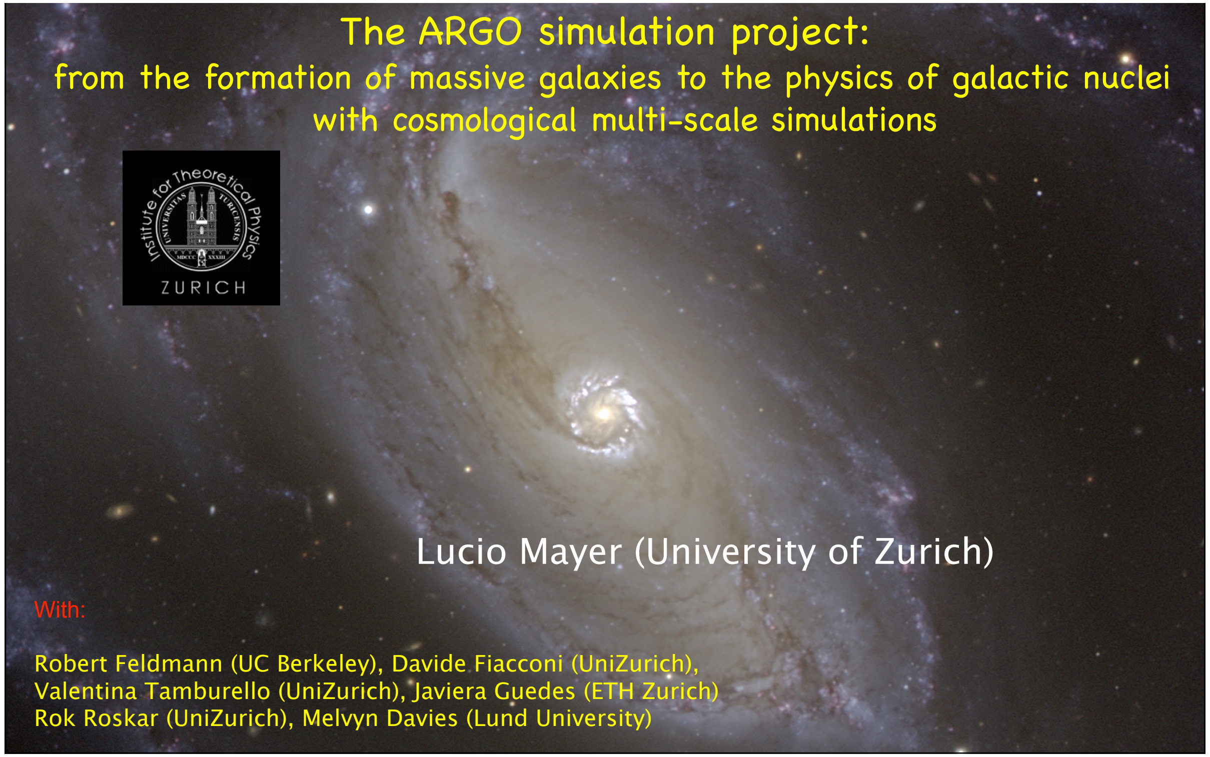
The ARGO simulation project:
from the formation of massive galaxies to the physics of galactic nuclei
with cosmological multi-scale simulations
Institute for Theoretical Physics
ZURICH
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With:
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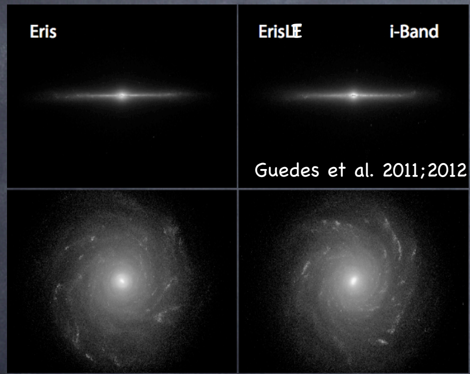
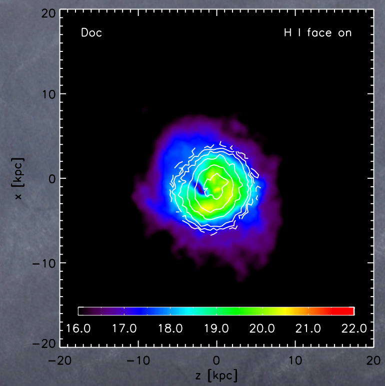
Valentina Tamburello (UniZurich), Javiera Guedes (ETH Zurich)
Rok Roskar (UniZurich), Melvyn Davies (Lund University)

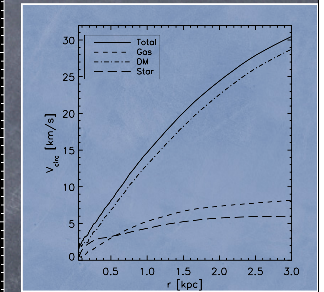
I - Simulating galaxy formation across mass scales and environments

In zoom-in simulations many properties of “field” disk-dominated galaxies and dwarfs can now be explained within LCDM



Guedes et al. 2011;2012

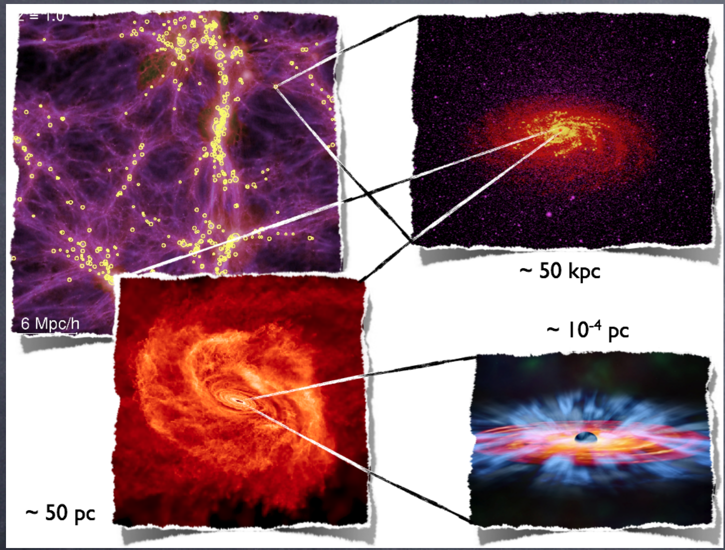




From Shen et al. (in prep. - see talk by Piero Madau)

Does the same recipe (high res + high SF density threshold + blastwave feedback + no AGN feedback) work to explain also massive early type galaxies and galaxies that evolve in denser environments with a variety of assembly histories?

II -Multi-scale gas inflows in galaxies to form and grow massive BHs



Picture From Alex Hobbs (2012)

At all scales gas needs to lose angular momentum, eg through repeated non-axisymmetric instabilities (Levine et al. 2008; Hopkins & Quataert 2010)

Scale of circumnuclear disk (1 pc - 100 pc - stay tuned for Medling et al. 2013)

- crucial, it feeds the accretion disk, hence the actual accretion flow directed to the black hole

- interplay with large scale dynamics and thermodynamics of galactic scale gas (and stars) because feeding from large scales (eg cold flows, galaxy wide inflows triggered by mergers and dynamical/secular instabilities)

The ARGO project: large-volume zoom-in(s) + particle splitting to reach sub-pc scale resolution (Fiacconi, Feldmann & Mayer in preparation)

Formation of a galaxy group

- virial mass at z=0: $10^{13}\,M_\odot$
- $m_{DM}=8\times10^{5}\,M_\odot$, $h_{DM}=250$ pc
- $m_{SPH}=2\times10^{4}\,M_\odot$, $h_{SPH}=120$ pc
- $n_{SF}=5$ cm^{-3}

R. Feldmann, 2012
Fermi National Accelerator Laboratory

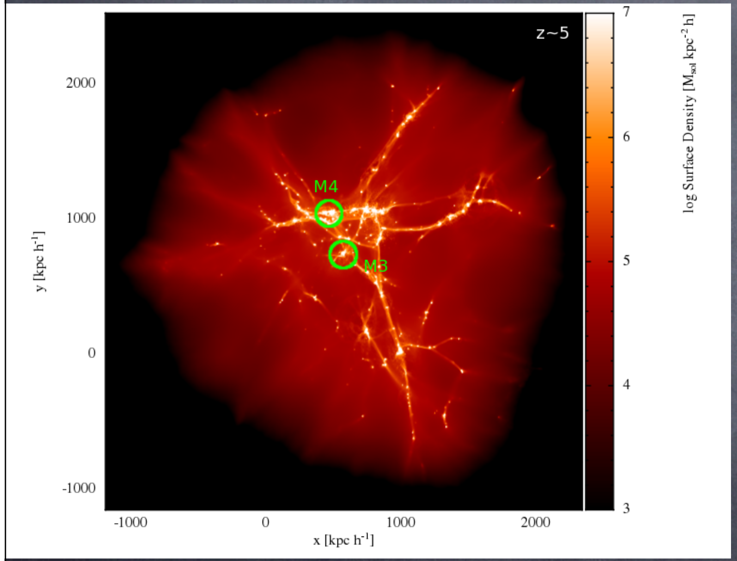
Simulations with modern SPH (GASOLINE)
Hi-res region ~ 1 Mpc at z ~ 3.

Each massive galaxy (M_{vir} <~ 10^{11} Mo) is as well resolved as the single galaxy in the Eris simulation, i.e by a few million SPH particles (Guedes et al. 2011).
Simulation currently at z ~ 3 (40 million SPH + star particles, m_{gas} = 2 x 10^4 Mo) -- will be pushed to as low as as possible z (1.5 million CPU hrs already)

-- at z ~ 4.5 and z ~3 splitting of SPH particles in selected sub-volumes of most massive galaxies to increase resolution to ~ 2000 Mo in the gas phase (0.1 pc spatial) and follow dynamics of gas inflows in mergers.

-- sub-grid star formation and feedback model (blastwave feedback) as in the Eris simulations (SF density threshold = 5 atoms/cc)
+ internal energy (and metal) diffusion + GD force to capture mixing and instabilities at fluid interfaces (Wadsley et al. 2008; Shen et al. 2010 - see James Wadsley's talk)

The ARGO project: large-volume zoom-in(s) + particle splitting to reach sub-pc scale resolution (Fiacconi, Feldmann & Mayer in preparation)



Simulations with modern SPH (GASOLINE)
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-- at z ~ 4.5 and z ~3 splitting of SPH particles (Galvagni et al. 2012) in selected sub-volumes of most massive galaxies to increase resolution to 2000 Mo in the gas phase (0.1 pc softening) and follow dynamics of gas inflows in mergers.

-- sub-grid star formation and feedback model (blastwave feedback) as in the Eris simulations (SF density threshold = 5 atoms/cc)
+ internal energy (and metal) diffusion + GD force to capture mixing and instabilities at fluid interfaces (Wadsley et al. 2008; Shen et al. 2010 - see James Wadsley's talk)

64x resolution versions of zoom-in simulation of galaxy group formation of Feldmann et al. (2010;2011) which produced massive central early-type central galaxies (M_{star} >~ 3 x 10^{11} Mo) and companion galaxies with a variety of morphologies at z=0

Key features:

(a) **Yields a population of galaxies in hi-res volume of virialized group halo** (~ 1.5 Mpc at z = 0)
The 13 most massive galaxies are at least as massive as ERIS (M_{star} ~ 10^{10} Mo at z~2) and equally well resolved ---> highest resolution zoom-in with multiple galaxies (eg ~ 10x higher resolution than AREPO simulations in Marinacci et al. 2013)

(b) **One simulation that spawns many**
Several galaxies resampled with particle splitting at selected epochs in order to achieve resolution of 2000 Mo and 0.1 pc during interesting phases (eg mergers)

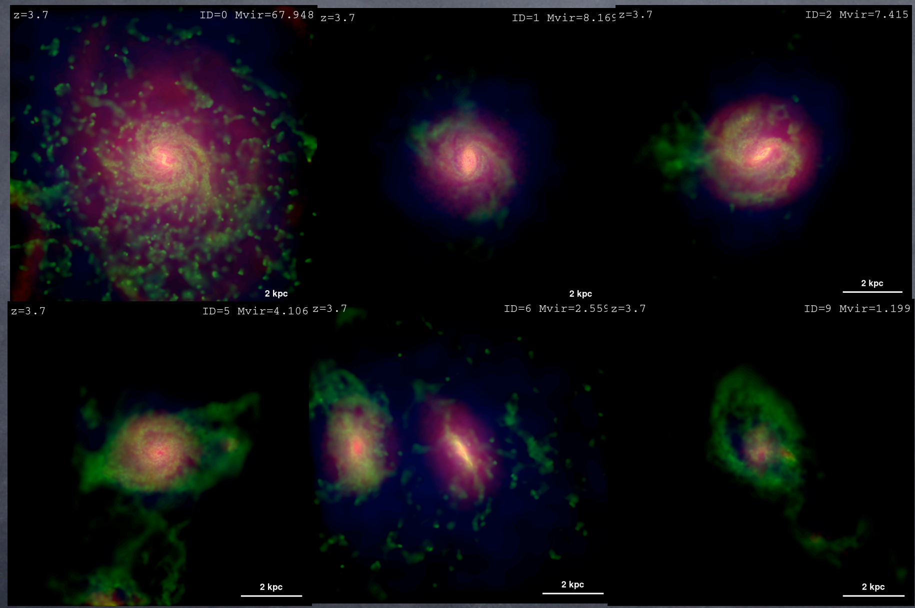
Main Goals:

I - Study the formation of galaxies in a dense environment, including massive early-types, with the same "recipe" (sub-grid physics + resolution) that produced a realistic late-type spiral in the Eris simulations ---> can we produce a "template Hubble sequence"?
In particular assess how much success can be achievded WITHOUT including AGN feedback from a central black hole (note case for central role of AGN feedback in galaxy evolution weaker and weaker - see eg highlights of KITP Black Hole Conference on latest multi-wavelength surveys comparing AGN hosts and non-AGN hosts, eg COSMOS+XMM in Bongiorno et al. 2012)

II - Study multi-scale central gas inflows from kpc to sub-pc scales to make progress on:
(a) formation of massive BH seeds in the merger-driven for supermassive+quasi-stars proposed by Mayer et al. (2010) and Bonoli, Mayer & Callegari (2013) and (b) more in general on the fueling of massive BHs (following up on earlier studies by eg Hopkins & Quataert without cosmological ICs)

III - Study star cluster formation and evolution in the dense galactic environment at high redshift ----> connection with origin of nuclear star clusters and possible link between hyper-dense star clusters undergoing fast core collapse and massive BH formation (see Davies et al. 2011;2012).

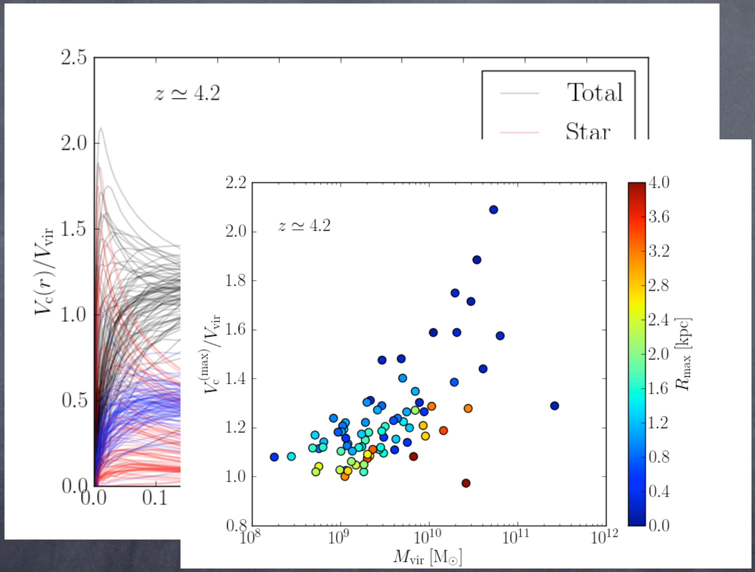
The galaxy population in ARGO at high-z (Fiacconi et al., in prep.)



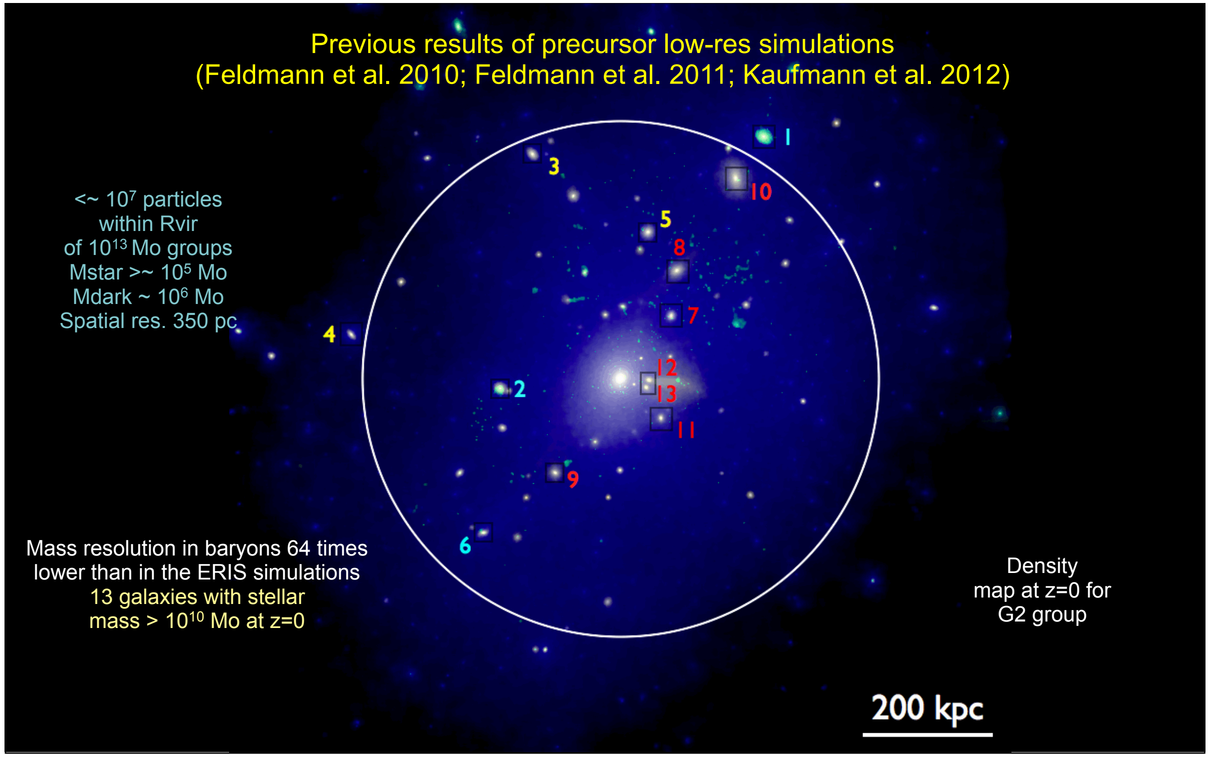
logarithmic surface density maps
red = stars
green = gas
blue = DM

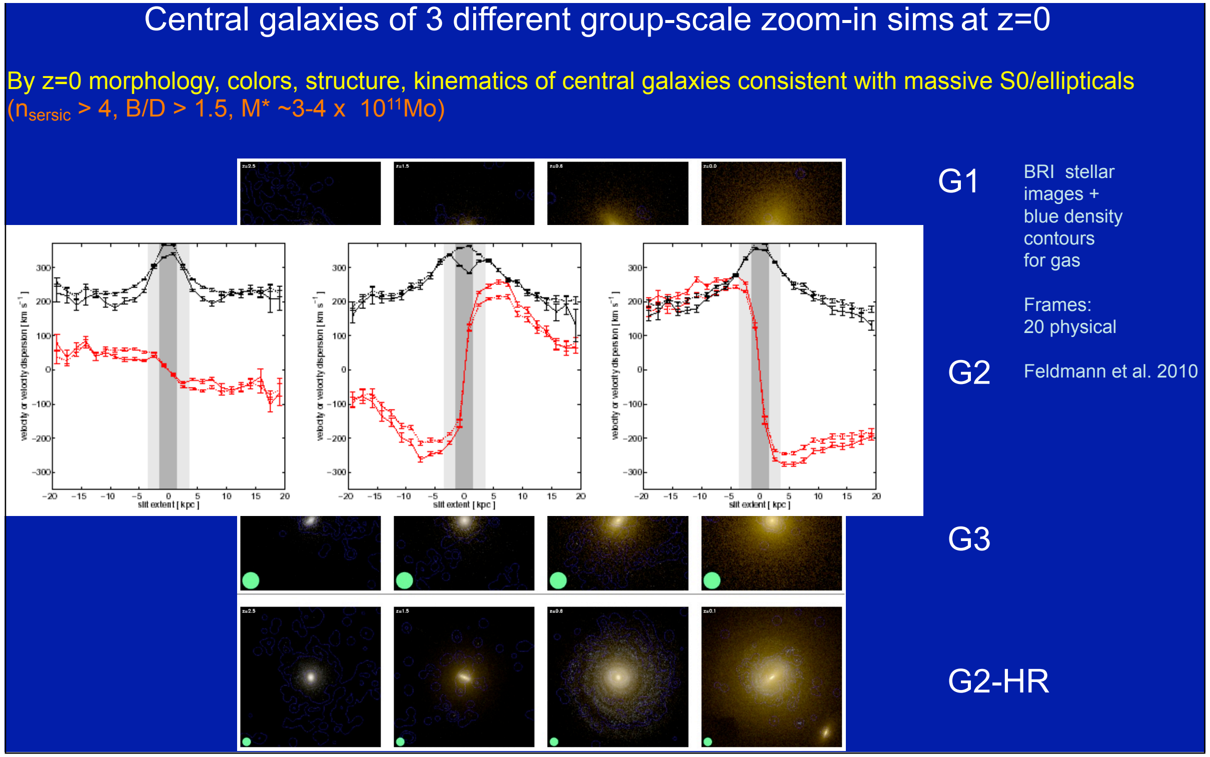
A variety of galaxies, all with a prominent disk at z ~ 5-3

A zoo of structural properties: rotation curves at z ~ 4



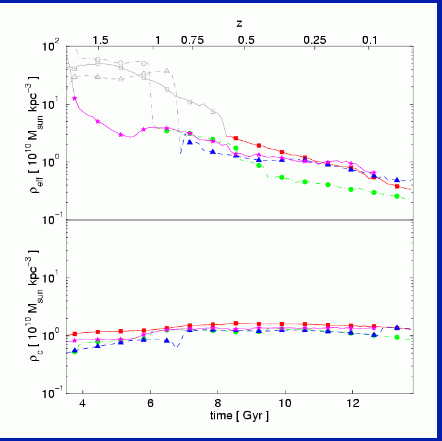
Is there a key parameter or several that determine such variety of galactic structural properties already at high z?

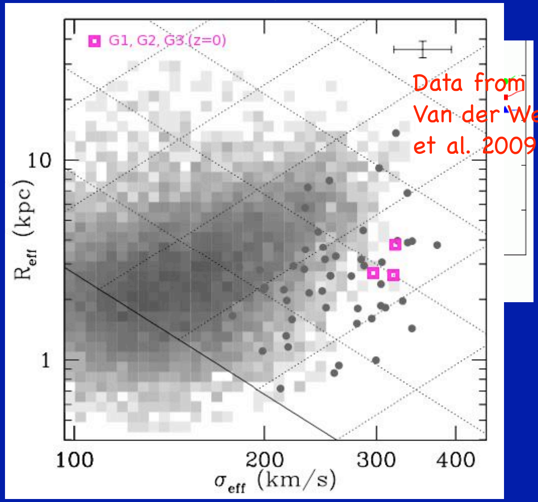

Previous results of precursor low-res simulations
(Feldmann et al. 2010; Feldmann et al. 2011; Kaufmann et al. 2012)
<~ 10⁷ particles within Rvir of 10¹³ Mo groups Mstar >~ 10⁵ Mo Mdark ~ 10⁶ Mo Spatial res. 350 pc
Mass resolution in baryons 64 times lower than in the ERIS simulations
13 galaxies with stellar mass > 10¹⁰ Mo at z=0
Density map at z=0 for G2 group
200 kpc
1
2
3
4
5
6
7
8
9
10
11
12
13


Central galaxies of 3 different group-scale zoom-in sims at z=0
By z=0 morphology, colors, structure, kinematics of central galaxies consistent with massive S0/ellipticals
(n_{sersic} > 4, B/D > 1.5, M* ~3-4 x 10^{11}Mo)
G1
BRI stellar images + blue density contours for gas
Frames: 20 physical
G2
Feldmann et al. 2010
G3
G2-HR
velocity or velocity dispersion [km s^{-1}]
slit extent [kpc]

Structural evolution and final structure of central galaxies; weak evolution of central stellar densities

Feldmann et al. 2010; Feldmann, Mayer & Carollo 2011, Kauffman, Mayer, Carollo & Feldmann 2012



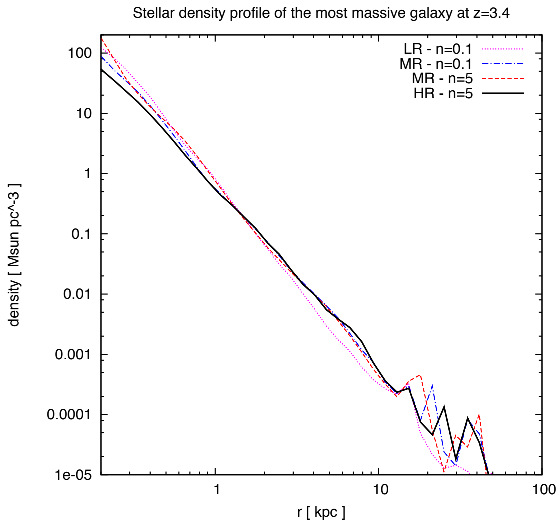


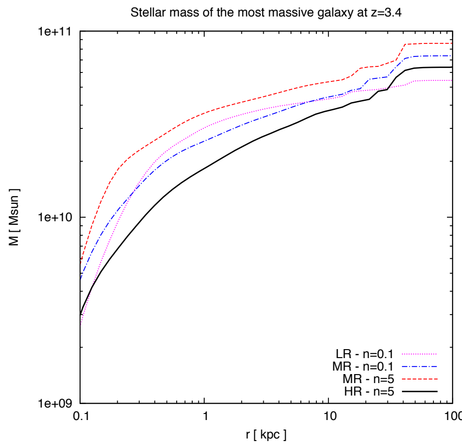
- Central density (< 2 Kpc) does not evolve – is set at formation
- Density within effective radius evolves because effective radius evolves

(galaxies grow inside-out, 70% by accreting stars via mergers, the rest evenly between in-situ SF and secular evolution via e.g. bar instabilities in disk phase)

However galaxies too compact at z=0 relative to typical present-day early-types -→ reminiscent of concentration problem for disk galaxies

Central densities decrease significantly (effective radii double and stellar mass halves) as we increase resolution AND sf density threshold
----> hints that clustered SF + supernovae feedback is enough to produce realistic early-type galaxies?





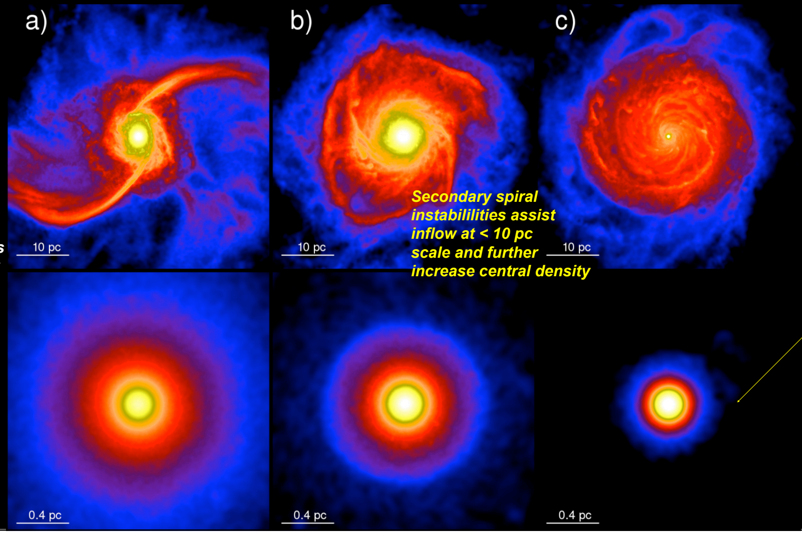
Multi-stage gas inflow from kpc to sub-pc scales: formation of massive BH seeds via direct gas collapse in major merger

---> rapid formation of supermassive (> 10^8 Mo) sub-pc scale Jeans unstable gas cloud in only ~ 10^5 years after merger of two "high sigma peaks" ~10^{12} Mo galaxies at z ~ 7 (possible SMBH precursor)

Mayer, Kazantzidis, Escala & Callegari, Nature, 2010

Below logrithmic density map spanning 10^5 yr after merger

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

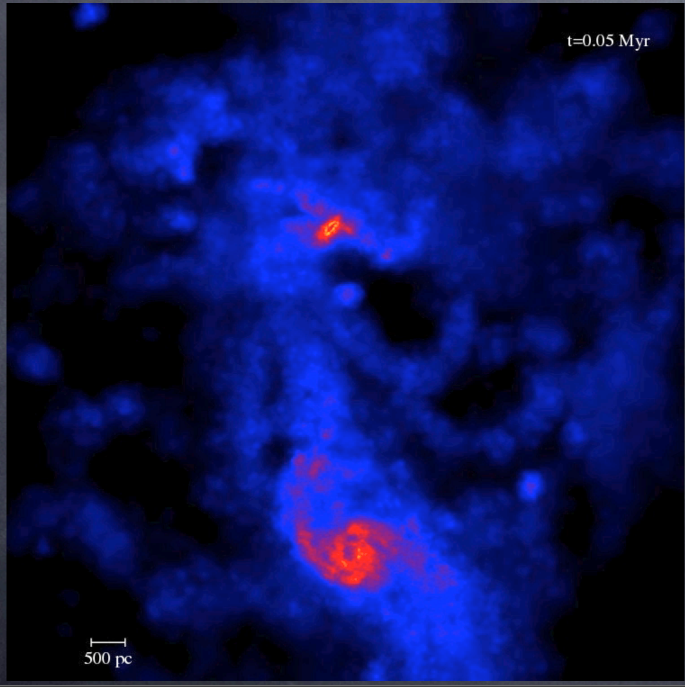
Key factor: sustained dM/dt ~10^3-10^4 Mo/yr for about 10^5 yr

Central region then undergoes Jeans collapse →formation of supermassive cloud (M > 10^8 Mo, N_{sph} > 10^5) --> SMBH precursor?

Is this scenario confirmed within a fully cosmological framework?

Circumnuclear disk formation in cosmological simulations

(Fiacconi et al., in prep.)

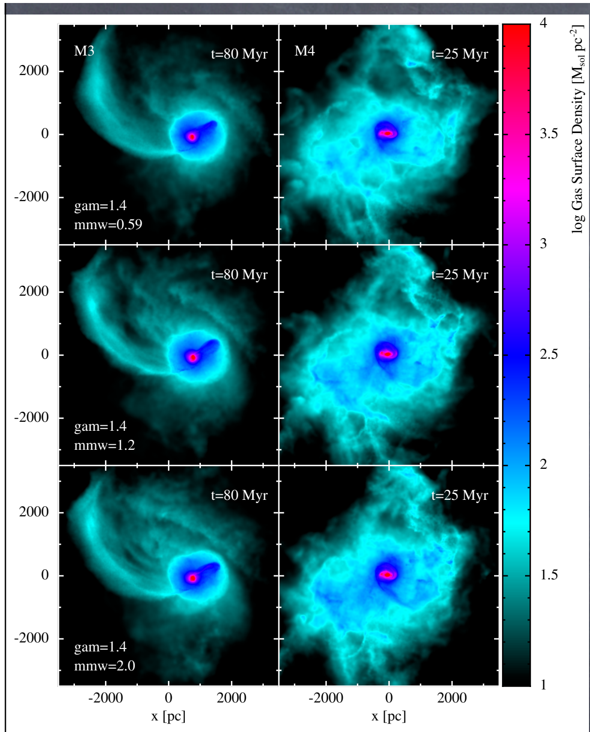


Last stage of major merger (~1:3) between two galaxies at z ~4.5 (Mvir <~ 10^{11} Mo)

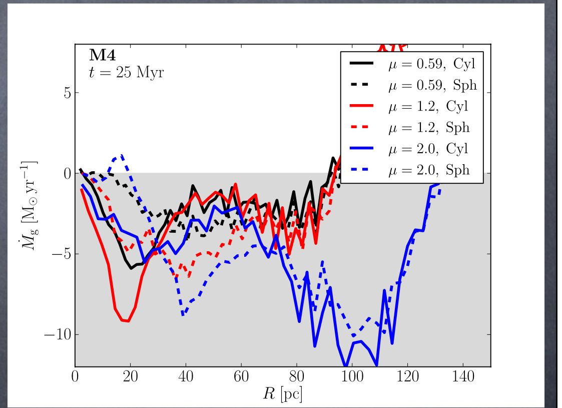
Gas mass resolution 2000 Mo, spatial resolution 0.1 pc

Simulations with (a) polytropic EOS (adiabatic index in range 1.1-1.4) and (b) cooling/heating, star formation, supernovae feedback, thermal energy and metal diffusion, a new model for radiative trasfer effects in the optically thick regime (Roskar et al. in preparation)

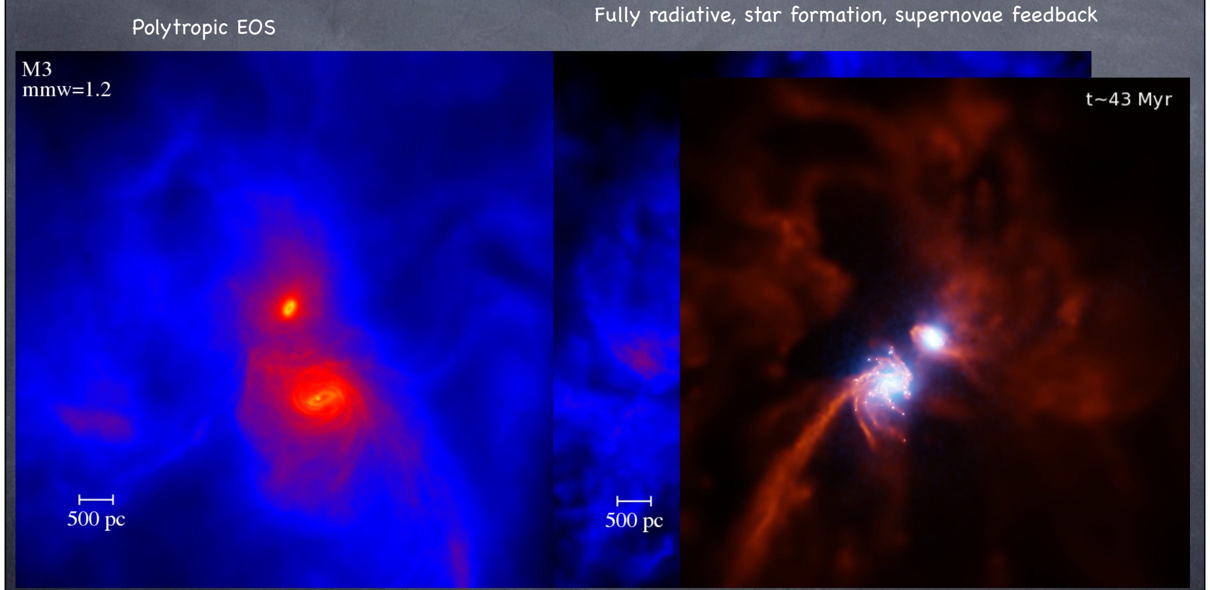
Shown is color-coded density map, starting when the larger scale portion of the galatic disks have been already disrupted by the interaction



Example (runs with stiff EOS, fixed gamma=7/5): gas inflow at 1-10 Mo/yr, good for rapid growth of existing SMBHs, too small to trigger formation of supermassive cloud precursor of massive BH seed



The importance of radiation, star formation and feedback....



Thanks,
and stay tuned for ARGO results...