Simulating the formation and evolution of early-type galaxies:

Star formation history as a function of mass and density

E. Merlin, C. Chiosi, L. Piovan

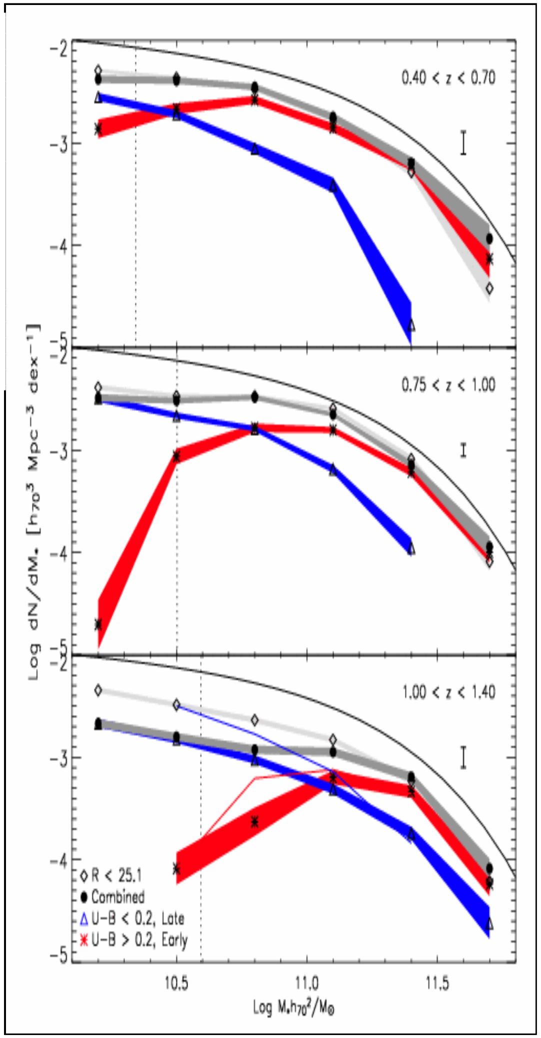
Gee2 - Milano, 7-9/11/2011

How and when did the "red sequence" ETGs (massive ellipticals) form?

Which mechanism(s) can explain the complex SFHs of "blue sequence" low mass galaxies and dwarfs?

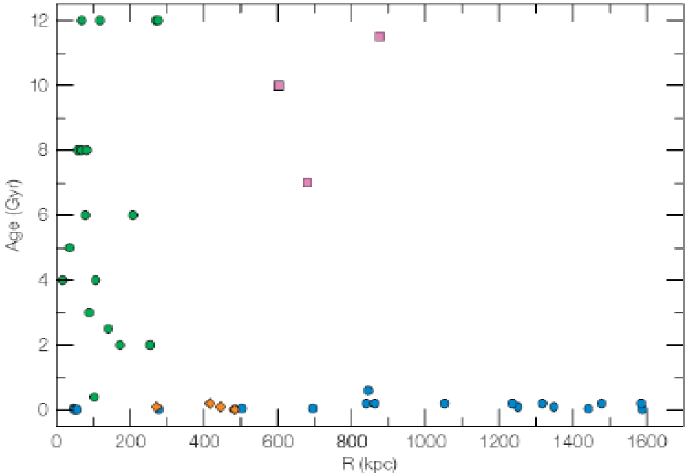
Massive ellipticals

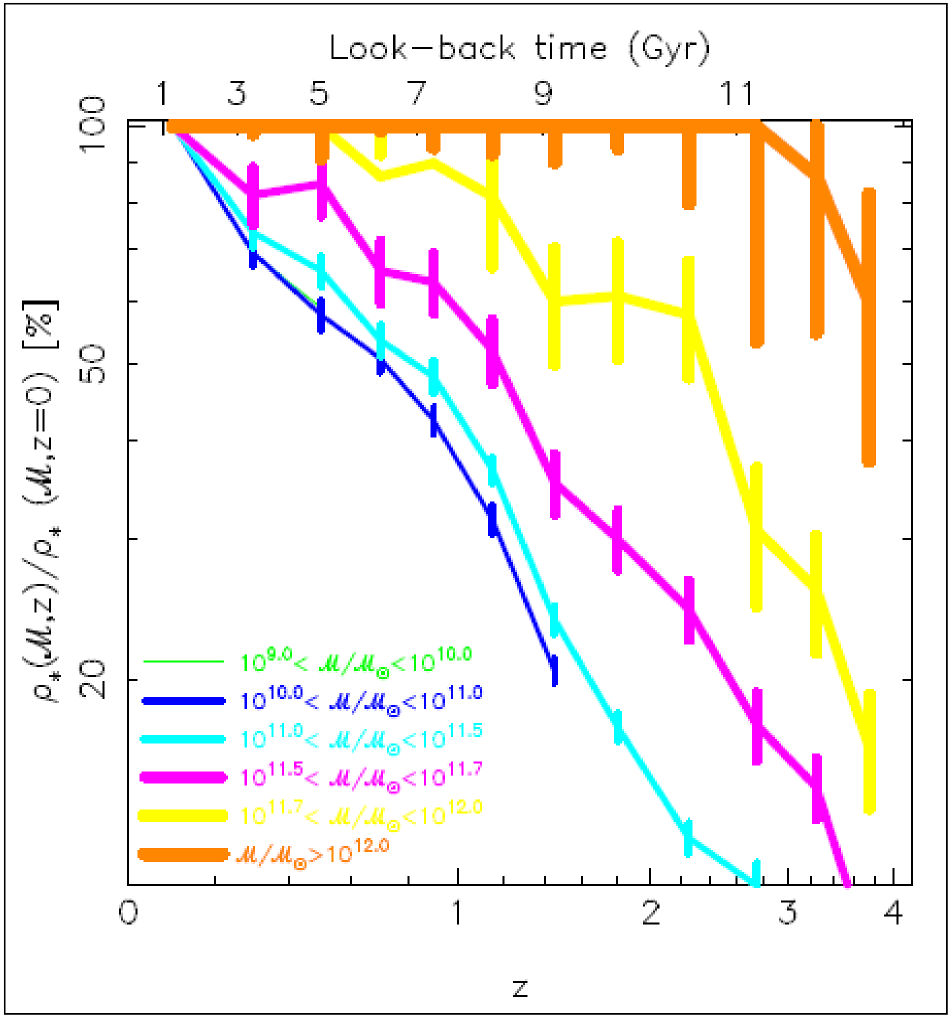
Downsizing scenario: at variance with the hierarchical trend of DM halos, more **massive galaxies tend to form their stars earlier and in a shorter period than smaller galaxies**, which experience more prolonged star formation histories (at odd with 'naive' hierarchical models). See e.g. Bundy et al. 2006, Clemens 2006.
Recent observations of **massive and red spheroids at very high redshift** (e.g. Cimatti 2007, 2008) support this scenario.



Dwarfs

Ages of stars in LG dwarfs (Mateo et al. 1998)





Perez-Gonzalez et al. 2007 - 28'000 Spitzer galaxies from HDFN,CDFS,Lochman Hole

Recently, many numerical studies have focused on the formation of galaxies:
- **Sales et al**. (2010) produced galaxy models with different feedback prescriptions
- **Sommer-Larsen & Toft** (2010) produced a mock cluster and studied its evolution and its galactic population
- **Stinson et al.** (2010) used a multi-resolution technique to study the formation of galaxies within highmass halos
- **Croft et al.** (2009) examined a large set of models extrapolated from a large scale cosmological simulation
- **Naab et al.** (2007b) presented three models produced *without* any source of feedback
- **Cox et al**. (2006) investigated the process of merging between spirals
- **Kobayashi** (2004, 2005) created a very large number of low resolution chemodynamical models of ellipticals.

In the present study, we focus on the **relation between the initial conditions of the host halo and the final properties of the galaxy in terms of stellar populations**

.

With the aid of **N-body T-SPHnumerical simulations**, performed using the parallel code **EvoL** (Merlin et al. 2010), we investigate the cosmological formation process of isolated galaxies with different masses and initial overdensities.

Are the internal properties of a galactic halo sufficient to obtain the zoo of morphologies and physical properties which characterizes the early-type population?

A&A 513, A36 (2010)
DOI: 10.1051/0004-6361/200913514

Astronomy & Astrophysics

EvoL: the new Padova Tree-SPH parallel code for cosmological simulations

I. Basic code: gravity and hydrodynamics

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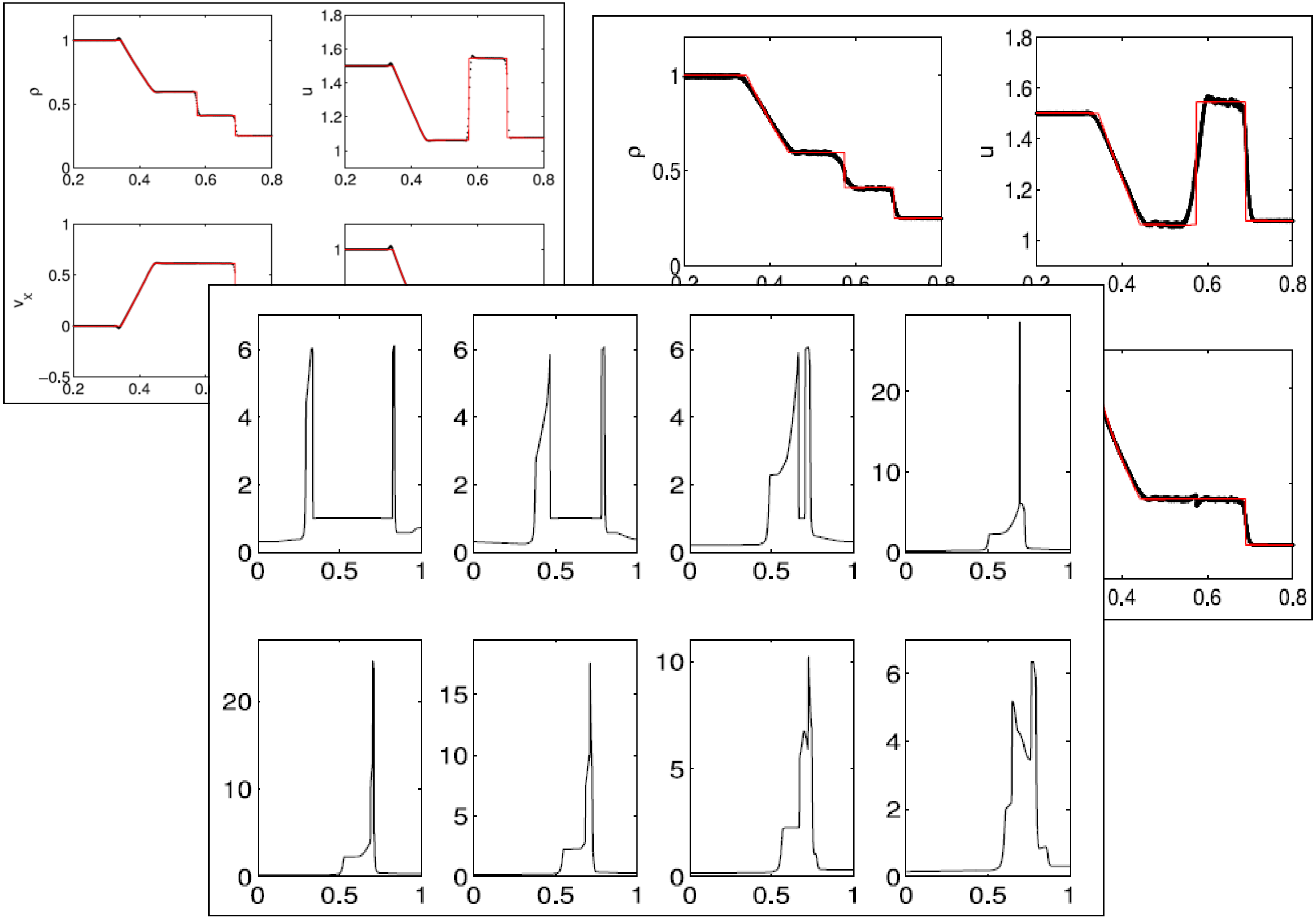
Received 20 October 2009 / Accepted 22 December 2009

ABSTRACT

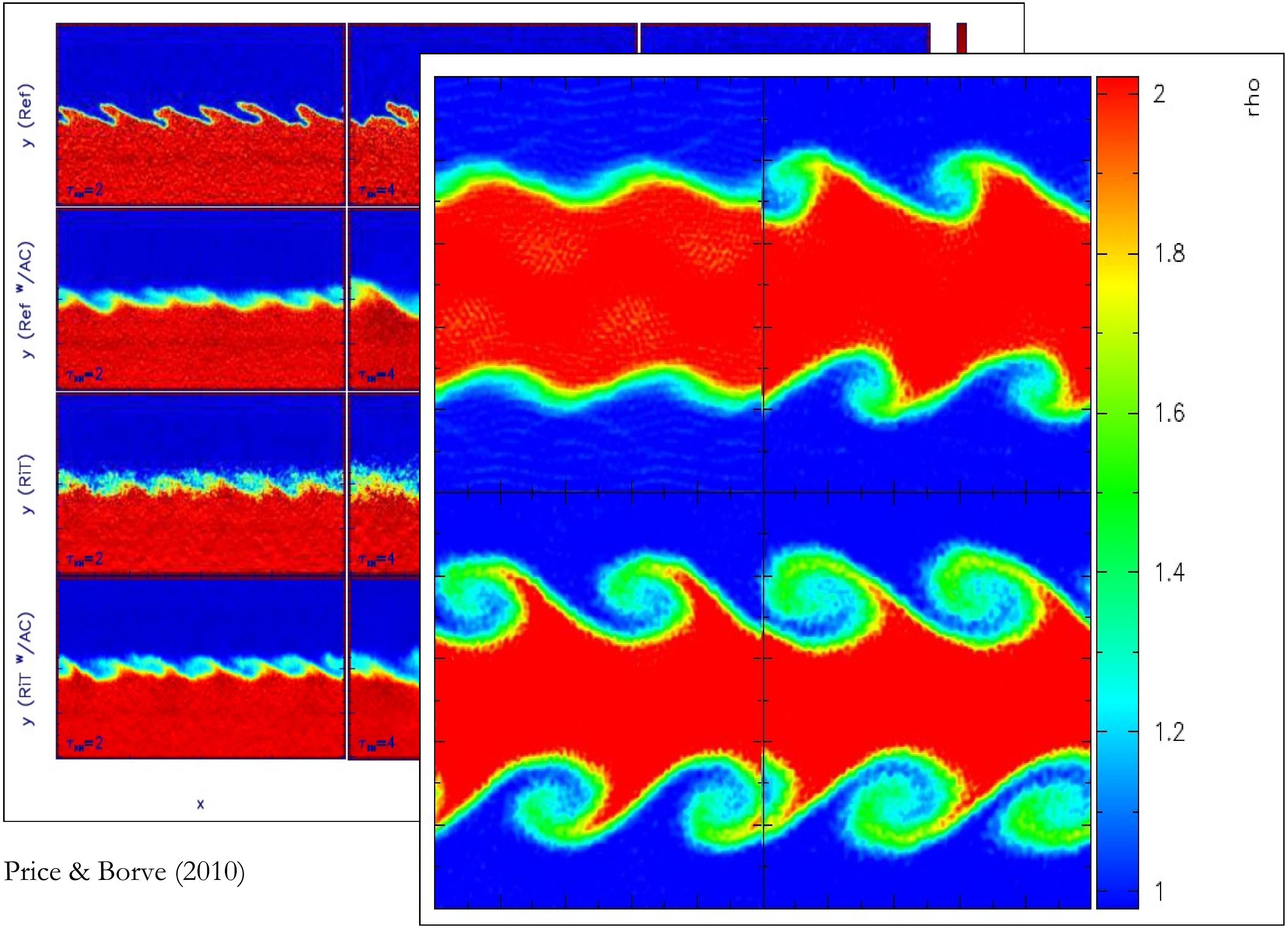
Context. We present the new release of the Padova N-body code for cosmological simulations of galaxy formation and evolution, EvoL. The basic Tree + SPH code is presented and analysed, together with an overview of the software architectures.
Aims. EvoL is a flexible parallel Fortran95 code, specifically designed for simulations of cosmological structure formations on cluster, galactic and sub-galactic scales.
Methods. EvoL is a fully Lagrangian self-adaptive code, based on the classical oct-tree by Barnes & Hut (1986, Nature, 324, 446) and on the smoothed particle hydrodynamics algorithm (SPH, Lucy 1977, AJ, 82, 1013). It includes special features like adaptive softening lengths with correcting extra-terms, and modern formulations of SPH and artificial viscosity. It is designed to be run in parallel on multiple CPUs to optimise the performance and save computational time.
Results. We describe the code in detail, and present the results of a number of standard hydrodynamical tests.

Key words. methods: simulations

EvoL validation tests - Planar shocks

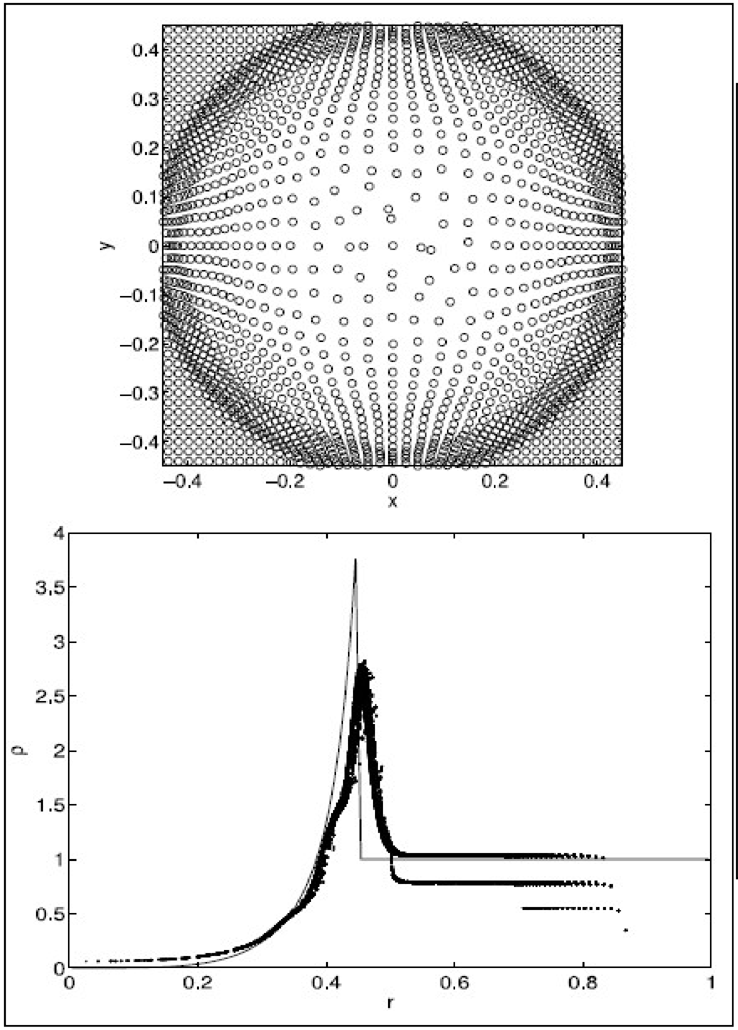


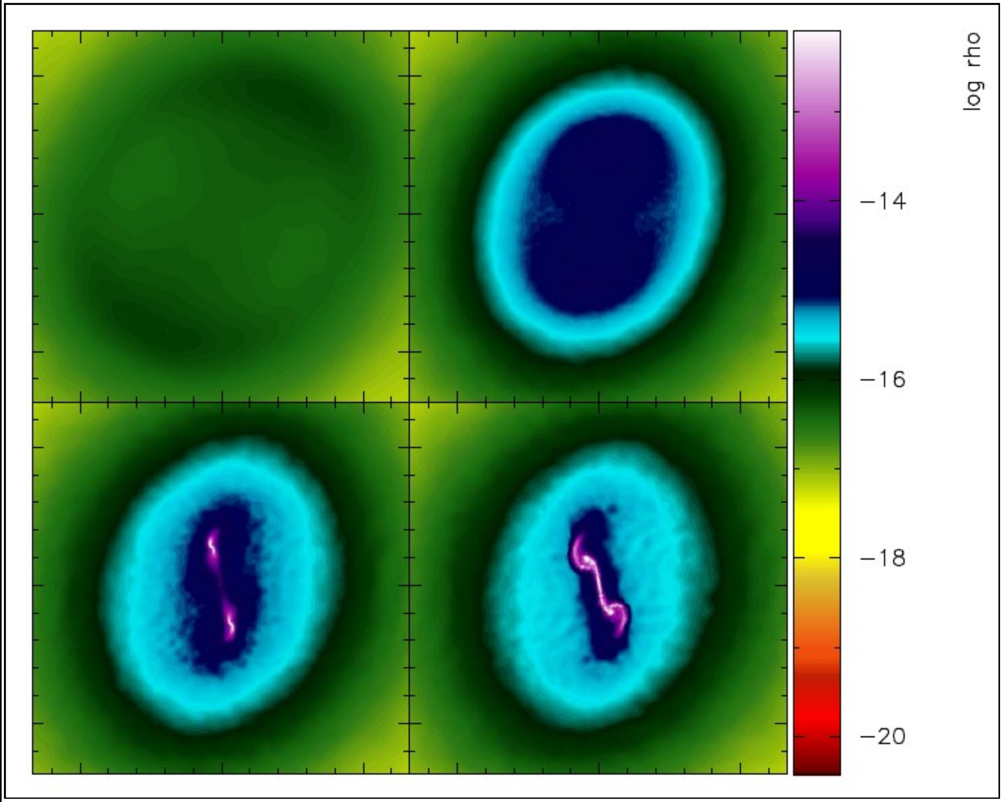
EvoL validation tests - KH instability



Price & Borve (2010)

EvoL validation tests - Explosions and collapses

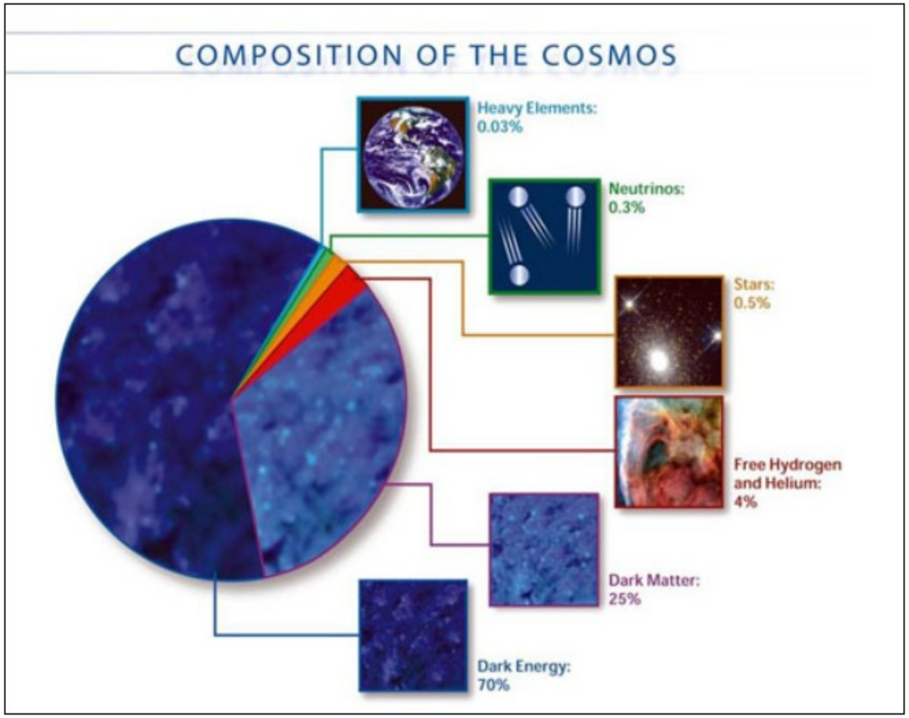




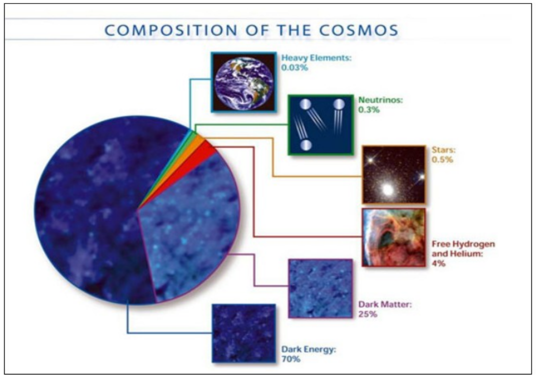
Simulating the formation of cosmic structures

Ingredients and recipes

- *Matter*
  - Dark Matter
  - Gas
  - Stars
- *Interactions*
  - Gravity
  - Hydrodynamics
  - "Specials"
- Cosmological framework
- Temporal evolution



Simulating the formation of cosmic structures



Ingredients and recipes: N-body - T-SPH code

- *Matter*
  - Dark Matter
  - Gas
  - Stars

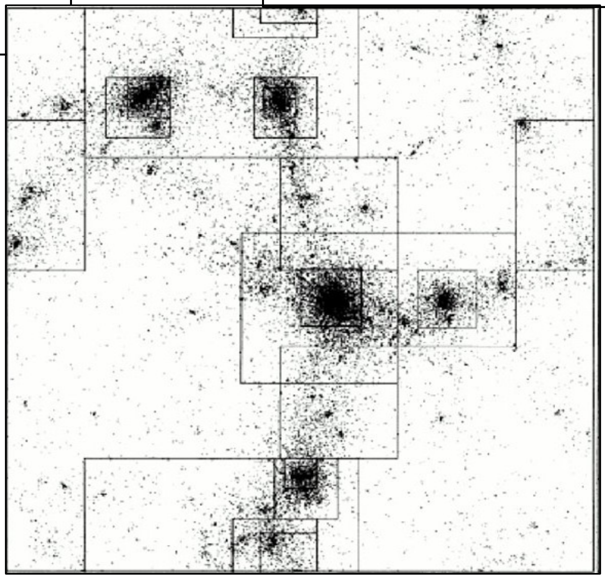
"Particles" ("bodies") with different properties, moving in the phase space

- *Interactions*
  - Gravity → **Newton's law**
  - Hydrodynamics
  - "Specials"

$$\vec{a}_i = \sum_j G \frac{m_j}{\left|\vec{r}_{ij}\right|^3} \vec{r}_{ij}$$

Particle-particle (N^2)

Tree structure (N logN)

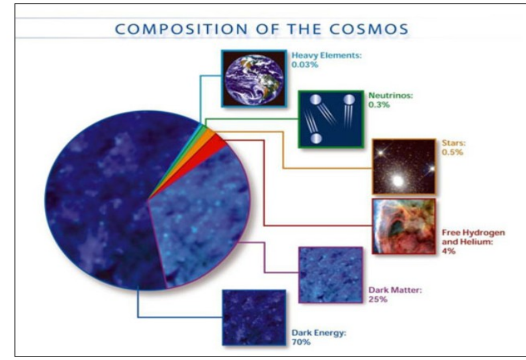


- Cosmological framework

- Temporal evolution

Simulating the formation of cosmic structures

Ingredients and recipes: N-body - T-SPH code



- *Matter*
    - Dark Matter
    - Gas
    - Stars

“Particles” (“bodies”) with different properties, moving in the phase space

- *Interactions*
    - Gravity
    - Hydrodynamics
    - “Specials”

Conservation laws

$$\frac{d\rho}{dt} = -\rho\nabla v$$

$$\frac{dv}{dt} = -\frac{1}{\rho}\nabla P - \nabla\Phi$$

$$\frac{du}{dt} = -\frac{P}{\rho}\nabla u + S$$

(Only for gas particles)

Smoothed Particle Hydrodynamics

$$\rho_a = \sum_{,} m_b W_{ab}$$

$$\frac{d\vec{v}_a}{dt} = -\sum_b m_b \left(\frac{P_a}{\rho_a^2} + \frac{P_b}{\rho_b^2} + \Pi_{ab}\right) \nabla_a W_{ab}$$

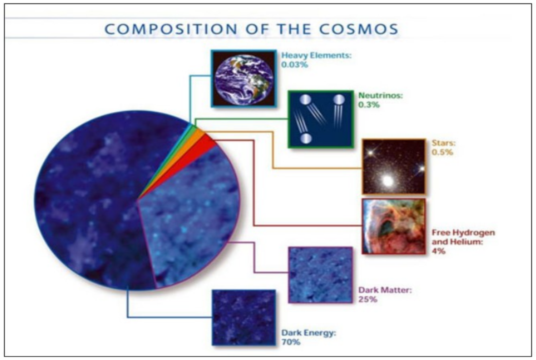
$$\frac{du_a}{dt} = \sum_b m_b \left(\frac{P_a}{\rho_a^2} + \frac{1}{2}\Pi_{ab}\right) \vec{v}_{ab} \cdot \nabla_a W_{ab}$$

- Cosmological framework

- Temporal evolution

Simulating the formation of cosmic structures

Ingredients and recipes: N-body - T-SPH code



- *Matter*
    - Dark Matter
    - Gas
    - Stars

→ "Particles" ("bodies") with different properties, freely moving in the phase space

- *Interactions*
    - Gravity
    - Hydrodynamics
    - "Specials"

→
- Energy sinks and sources:
    - Cooling (radiative cooling, inverse Compton effect)
    - Heating (Stellar feedback, UV cosmic background, "exotic" sources)
- Chemical composition and enrichment
- Star formation
- …

- Cosmological framework
- Temporal evolution

→
- Cosmological expansion of the Universe
- Appropriate boundary conditions

Simulating the formation of cosmic structures

Challenges in simulating the formation and evolution of galaxies

Extremely large ranges in physical values

- mass: 10^6 ---> 10^{14} Msol (8 orders of magnitudes)
- temperature: 10 ---> 10^8 K (7 orders of magnitudes)
- distances: 1 ---> 10^7 pc (7 orders of magnitudes)
- times: 1 ---> 10^{10} years (10 orders of magnitudes)
- density: 10^{-33} ---> 10^{-18} g/cm3 (25 orders of magnitudes)

Very large numbers of particles are (would be…) needed

Barionic mass of a typical galaxy: 10^{11} Msol
Mass of a typical small structure: 10^6 Msol
Particles to resolve small structures: 100
---> 10^7 particles (without considering outskirts...) - currently unfeasible ---> lower resolution

Extremely violent phenomena

Supernova explosions
Supersonic turbulence and shocks
AGN feedbacks

Formation and evolution of early-type galaxies. III - Star formation history as a function of mass and density

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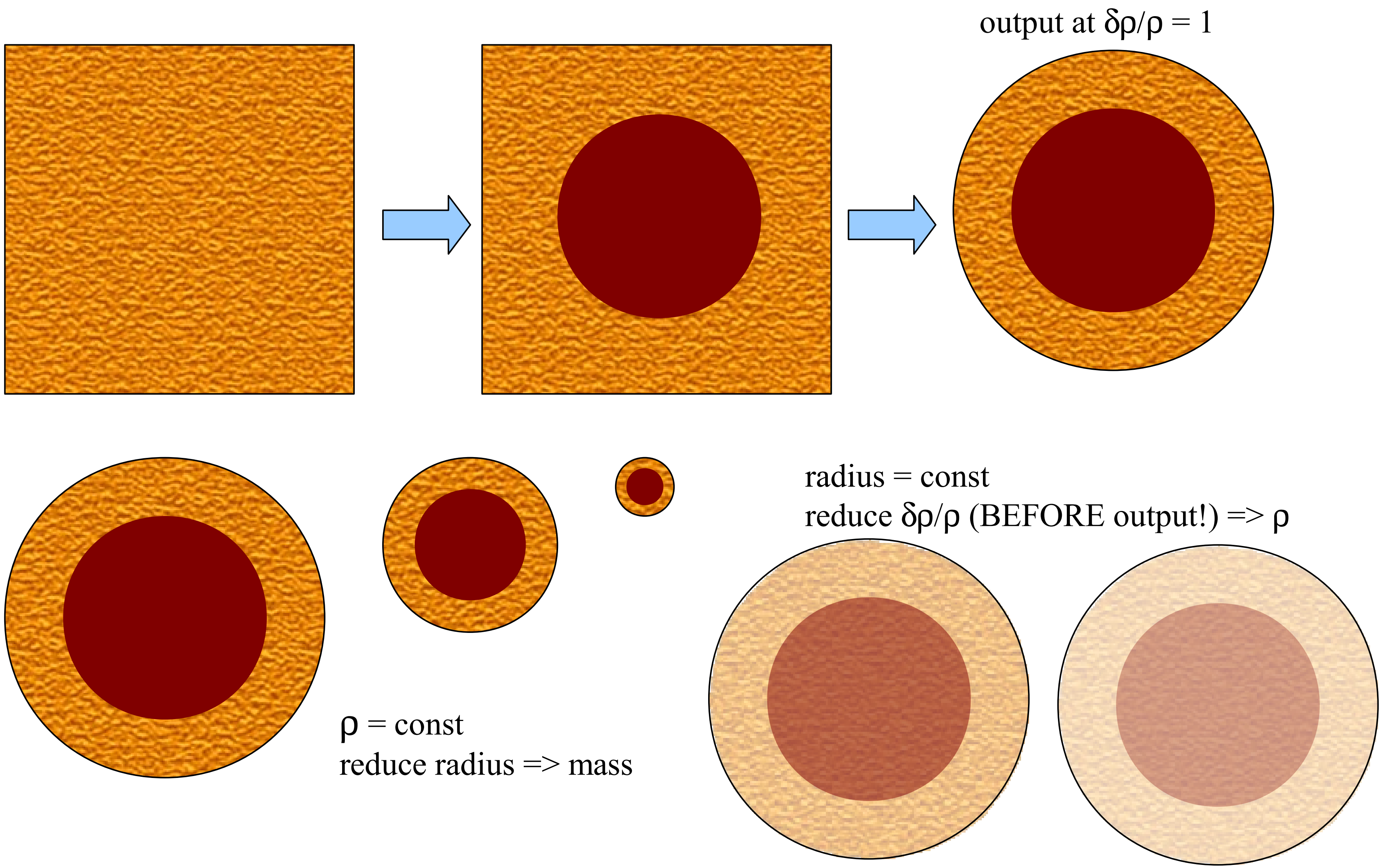
Received: ; Accepted:

ABSTRACT

Context. To date, a consistent and comprehensive theory of galaxy formation is still missing. Growing observational evidencies claim for a population of massive, red galaxies at very high redshifts, appearently at odds with the theoretical concordance cosmology scenario, in which larger systems form later via merger of smaller subunits. How did the big, early red objects form? Did they assemble their stellar content in an early, *monolithic*-like burst of star formation activity? Is this scenario consistent with the theoretical cosmological background?
Aims. We investigate the influence of the initial proto-galaxies over-densities and masses on their evolution, to understand whether the internal properties of the proto-galactic halos are sufficient to account for the varied properties of the galactic populations.
Methods. By means of fully hydrodynamical N-body simulations performed with the code EvoL we explore the parameters space producing twelve self-similar models of early-type galaxies following their evolution from the epoch of their detachment from the linear regime, i.e. $z \geq 20$, to $z \leq 1$ (we also produce some more ancillar models for further analysis). The simulations include radiative cooling, star formation, stellar energy feedback, a reionizing photoheating background, and chemical enrichment of the ISM. We do not consider the possible presence of Active Nuclei.
Results. We find a stunning correlation between the initial properties of the proto-halos and their star formation histories. Massive ($M_{tot} \simeq 10^{13} M_{\odot}$) halos experience a single, intense burst of star formation (with rates $\geq 10^3 M_{\odot}$/yr) at early epochs, consistently with observations, with a less pronounced dependence on the initial overdensity; intermediate mass ($M_{tot} \simeq 10^{11} M_{\odot}$) halos histories strongly depend on their initial overdensity, whereas small ($M_{tot} \simeq 10^9 M_{\odot}$) halos always have fragmented histories, resulting in multiple stellar populations, due to a "galactic breathing" phenomenon. The galaxy models have morphological,

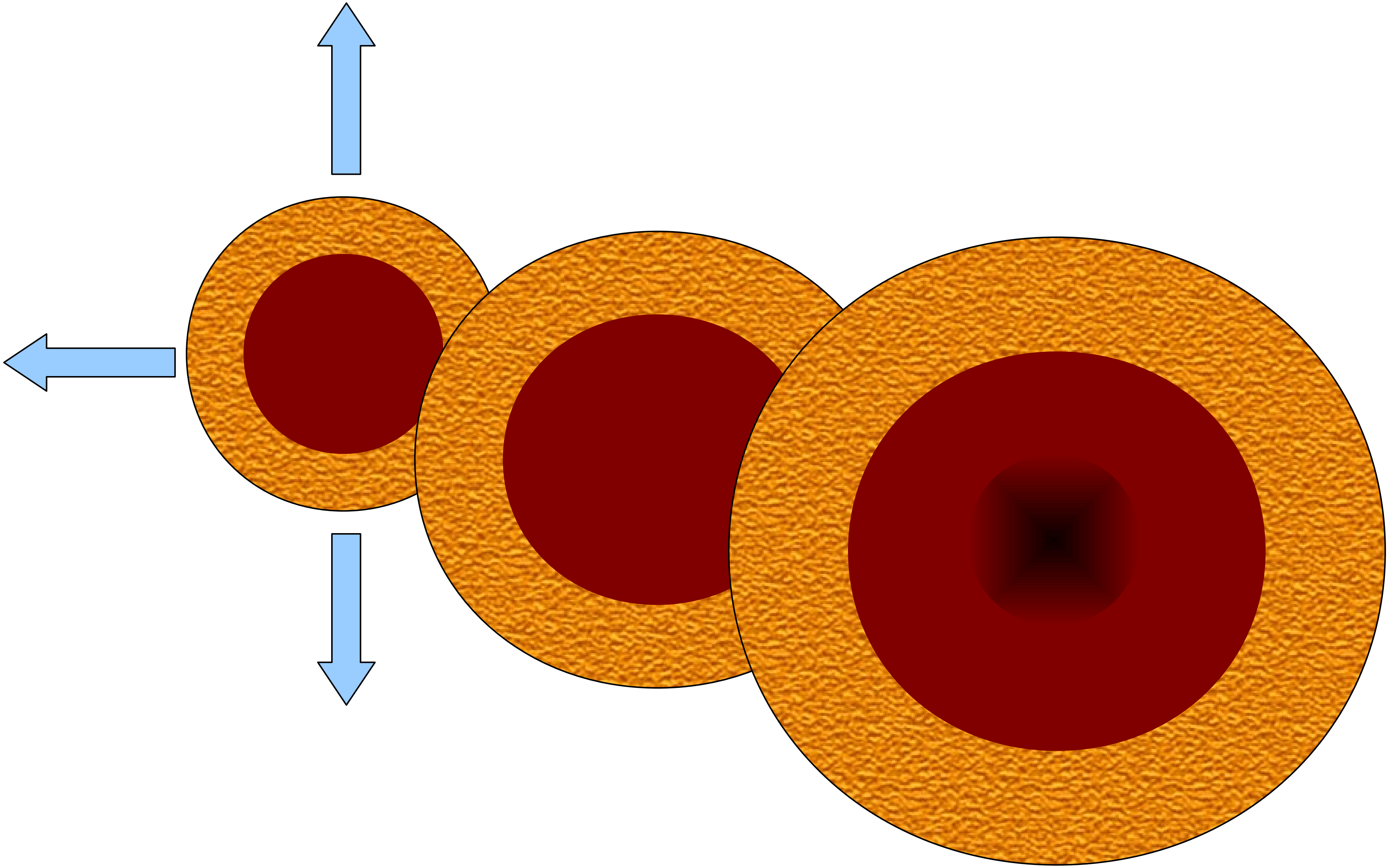
Setting of the initial conditions; methods

Code: COSMICS (E. Bertschinger) + Refining stuff

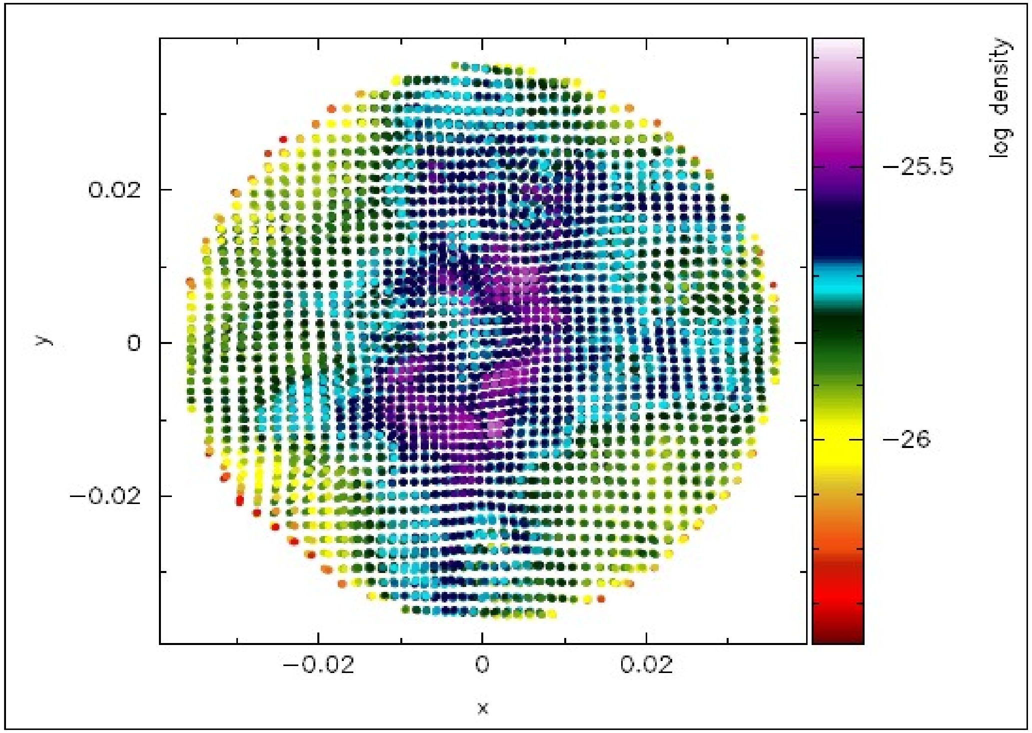


Setting of the initial conditions; methods

Add Hubble expansion, gas, and let go



Setting of the initial conditions; methods



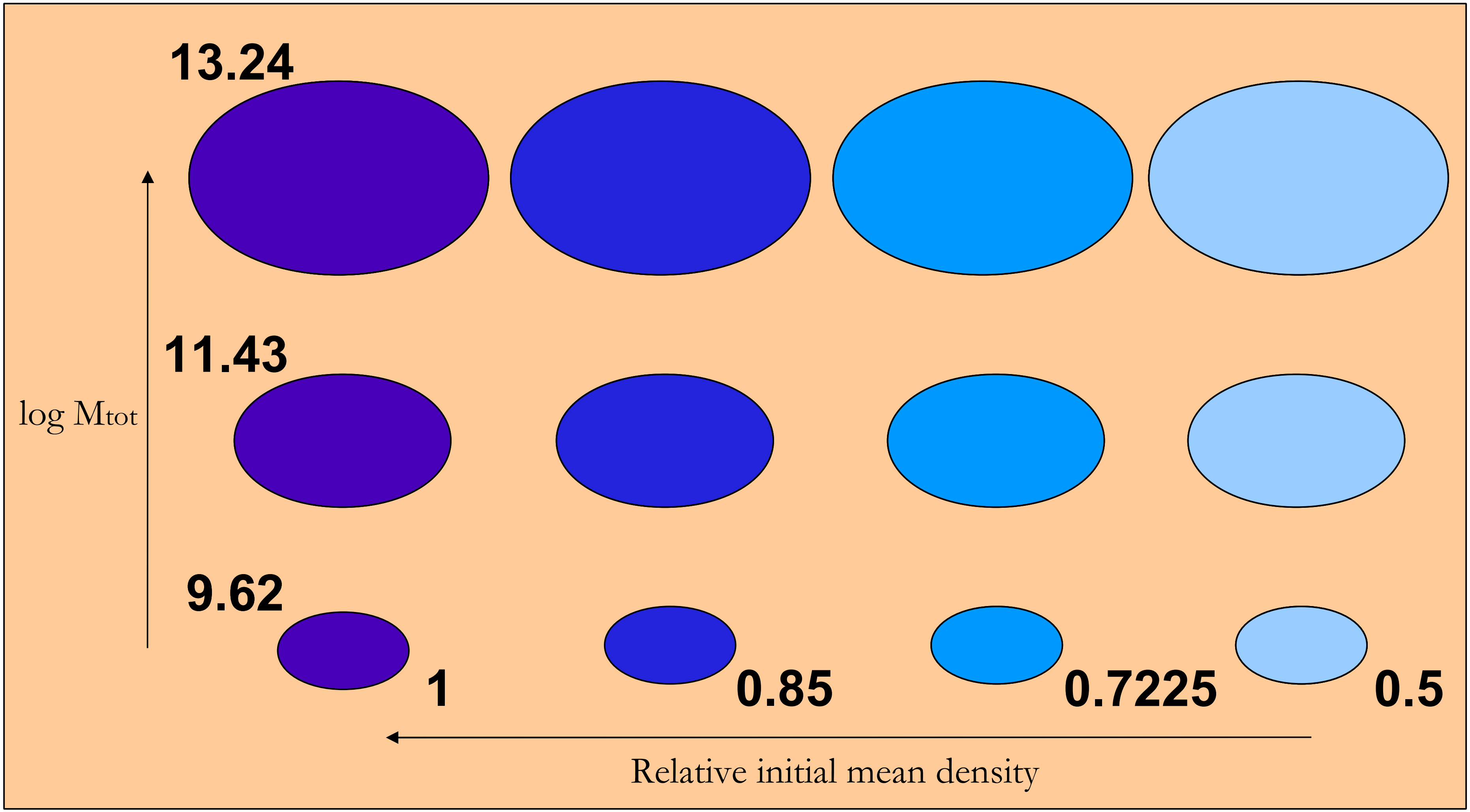
- 12 self-similar models with identical scale-free random perturbations
- artificially modified total masses (factors of 64) and densities (factors of 0.75)
- spherical proto-galaxies with 60000 gas + 60000 DM particles (==> different resolution)
- Hubble flow added to peculiar velocities to simulate expansion
- Λ-CDM W-Map5 cosmology adopted (H_0 = 70.1 km/s/Mpc, Ω_Λ=0.721, Ω_m=0.279, n=0.96, f_{bar}=0.1656)

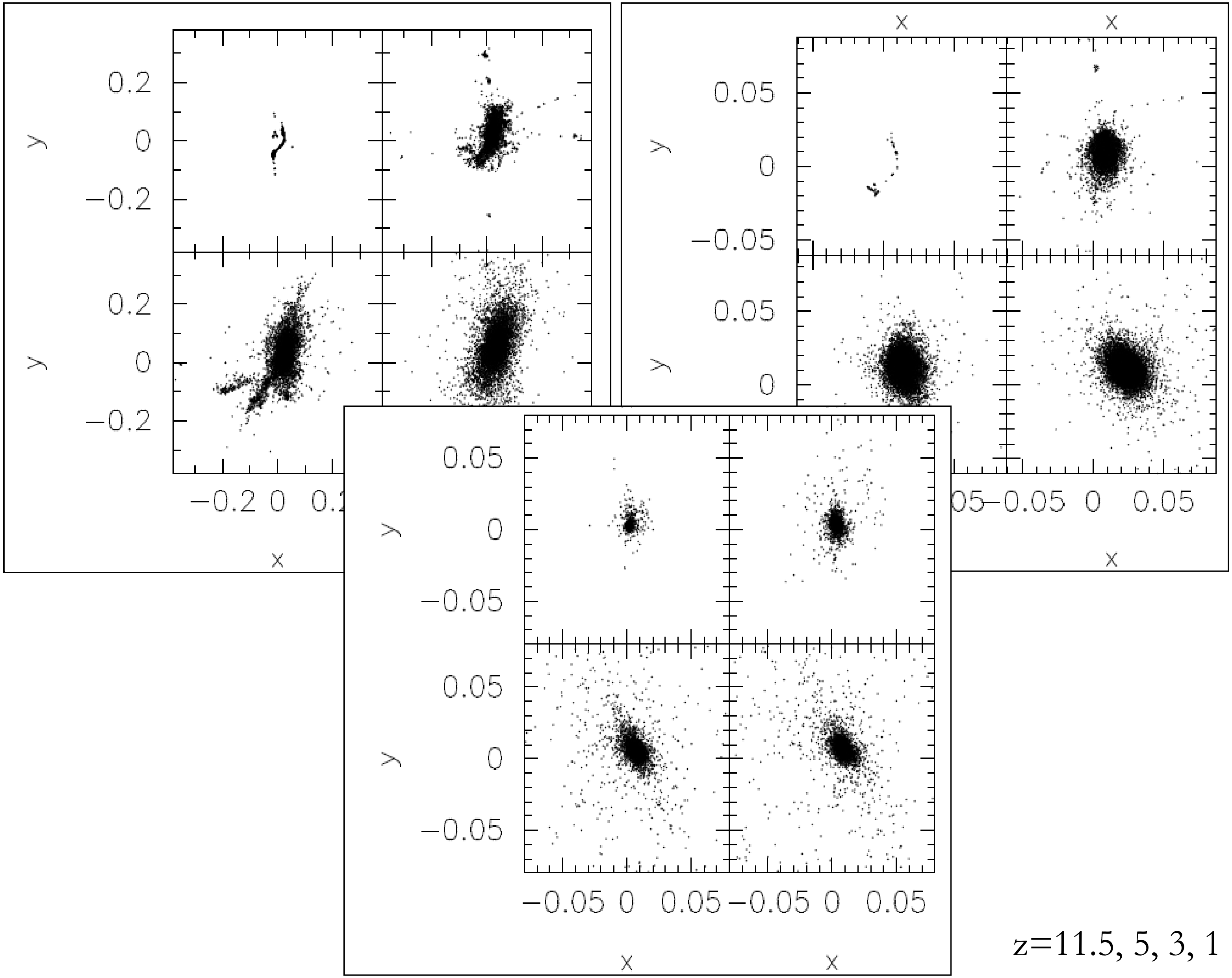
- Simulations include: adaptive softening lengths, radiative + Compton cooling, Jeans pressurization, reionizing background, star formation, stellar feedback (SN + winds)
- Simulations do NOT include: magnetic fields, AGN and other sources of feedback

dm

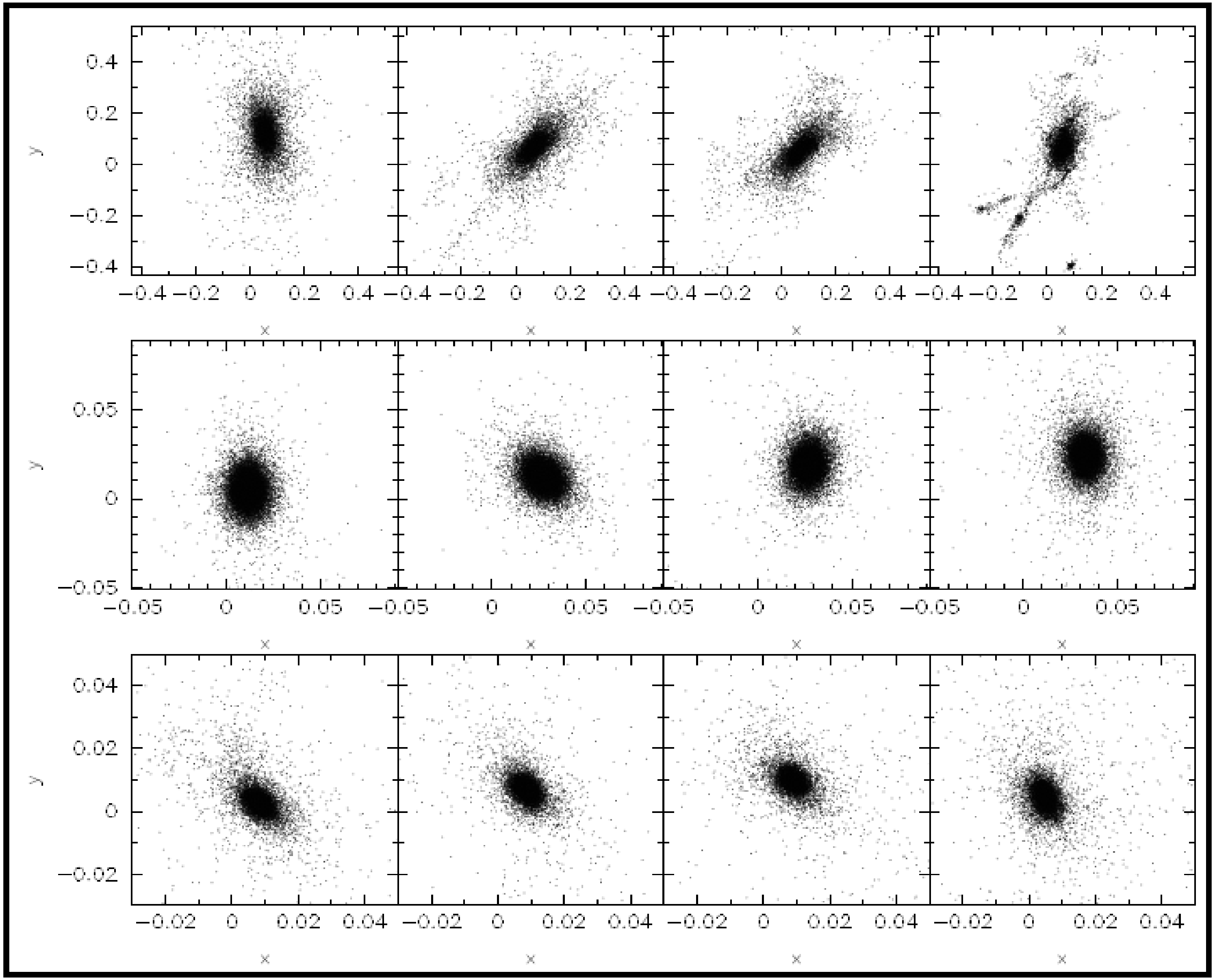
Model	$M_{tot}\ [M_\odot]$	$M_{gas,ini}\ [M_\odot]$	$< \delta\rho - 1 >_{z=30}$	z_{ini}	r_{ini} [kpc]	$m_{gas}\ [M_\odot]$
HDHM	1.75×10^{13}	2.90×10^{12}	0.39	46.34	97.17	4.97×10^{7}
IDHM	1.75×10^{13}	2.90×10^{12}	0.30	39.24	114.31	4.97×10^{7}
LDHM	1.75×10^{13}	2.90×10^{12}	0.23	33.20	134.49	4.97×10^{7}
VLDHM	1.75×10^{13}	2.90×10^{12}	/	22.67	194.34	4.97×10^{7}
HDMM	2.69×10^{11}	4.45×10^{10}	0.46	53.79	20.99	7.79×10^{5}
IDIM	2.69×10^{11}	4.45×10^{10}	0.33	45.57	24.69	7.79×10^{5}
LDIM	2.69×10^{11}	4.45×10^{10}	0.25	38.59	29.05	7.79×10^{5}
VLDIM	2.69×10^{11}	4.45×10^{10}	/	26.37	41.98	7.79×10^{5}
HDLM	4.17×10^{9}	6.91×10^{8}	0.54	63.23	4.48	1.22×10^{4}
IDLM	4.17×10^{9}	6.91×10^{8}	0.39	53.60	5.27	1.22×10^{4}
LDLM	4.17×10^{9}	6.91×10^{8}	0.29	45.40	6.20	1.22×10^{4}
VLDLM	4.17×10^{9}	6.91×10^{8}	0.16	31.11	8.96	1.22×10^{4}

The twelve main models



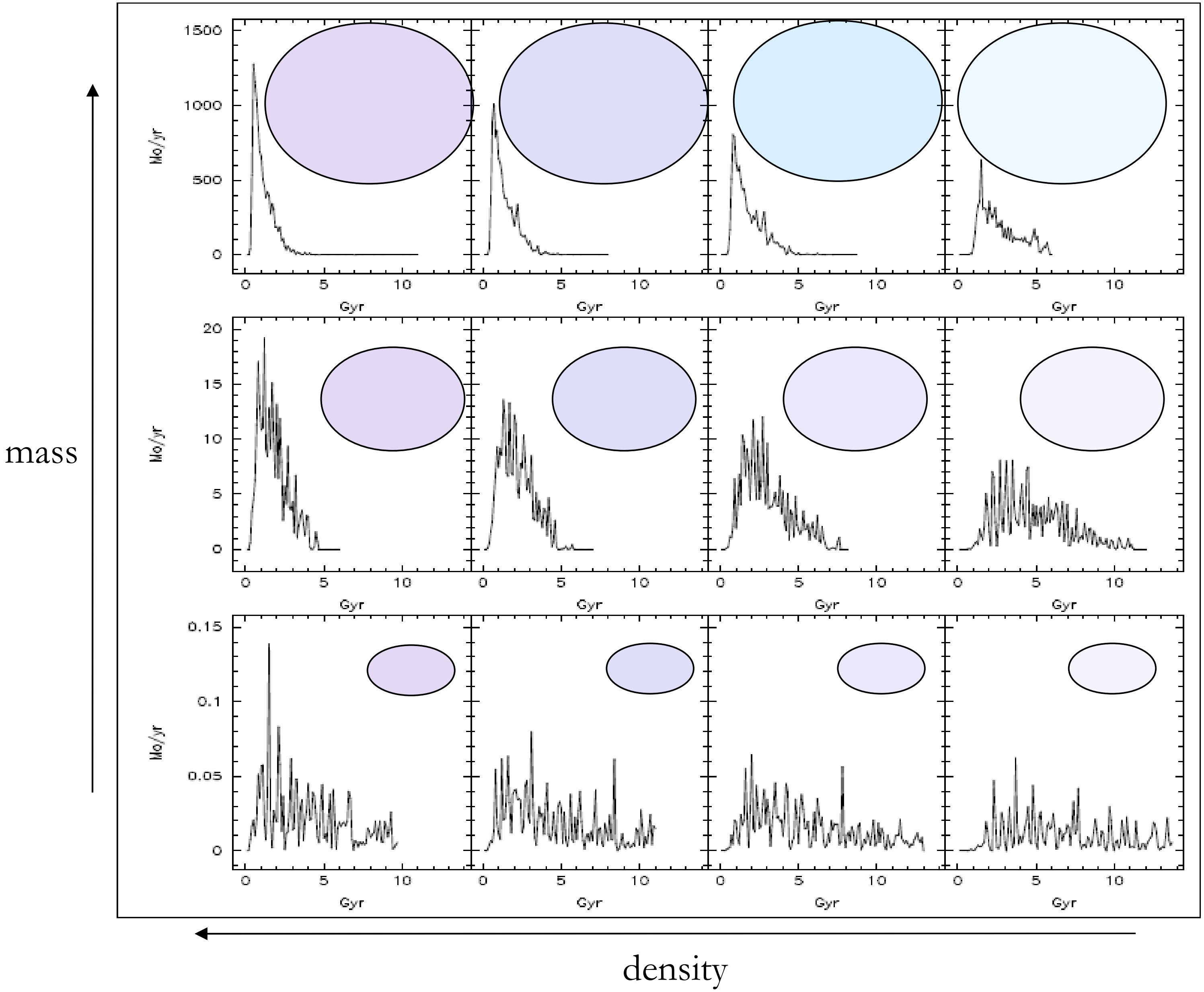


z=11.5, 5, 3, 1


y
x
0.4
0.2
0
−0.2
−0.4
0.05
−0.05
0.04
0.02
−0.02

Model	z_{end}	t_{end} [Gyr]	M_* [$M_\odot$]	M_{vir} [$M_\odot$]	M_*/M_{vir}	$M_*/M_{gas,ini}$	$r_{vir,tot}$ [kpc]	$r_{eff,*}$ [kpc]	b/a_{XY}
HDHM	0.22	11.0	7.5×10^{11}	1.5×10^{13}	0.050	0.26	153.0	15.6	0.56
IDHM	0.77	8.0	7.4×10^{11}	1.5×10^{13}	0.050	0.26	141.8	16.5	0.48
LDHM	0.50	8.7	7.3×10^{11}	1.5×10^{13}	0.049	0.25	133.8	15.8	0.57
VLDHM	0.83	6.6	6.3×10^{11}	1.3×10^{13}	0.048	0.22	112.5	11.2	0.52
HDIM	1.0	5.8	2.0×10^{10}	2.1×10^{11}	0.10	0.45	37.6	5.7	0.62
IDIM	0.75	7.0	1.9×10^{10}	2.1×10^{11}	0.08	0.43	35.7	5.8	0.63
LDIM	0.58	8.1	1.9×10^{10}	2.0×10^{11}	0.10	0.42	33.3	5.2	0.75
VLDIM	0.15	11.8	1.7×10^{10}	1.4×10^{11}	0.12	0.38	28.3	4.9	0.83
HDLM	0.36	9.7	1.5×10^{8}	3.3×10^{9}	0.045	0.19	9.2	2.3	0.74
IDLM	0.22	11.0	1.4×10^{8}	3.3×10^{9}	0.04	0.16	10.0	2.4	0.67
LDLM	0.05	13.0	1.4×10^{8}	3.2×10^{9}	0.04	0.19	11.8	2.1	0.79
VLDLM	0.0	13.7	1.0×10^{8}	3.0×10^{9}	0.03	0.10	10.5	2.7	0.65

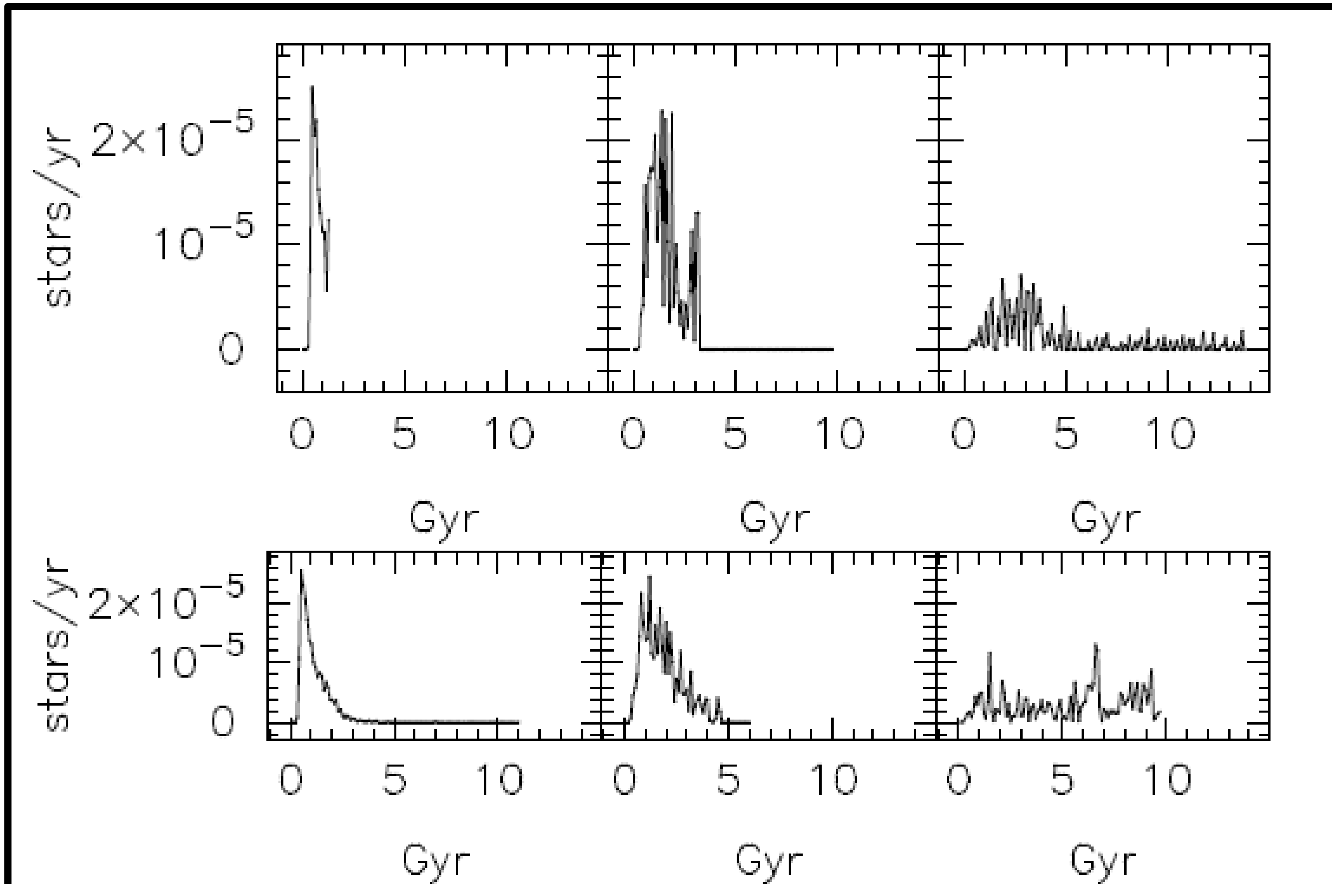
SFHs


mass
1500
1000
500
0
Mo/yr
0
5
10
Gyr
20
15
10
5
0
0.15
0.1
0.05
density

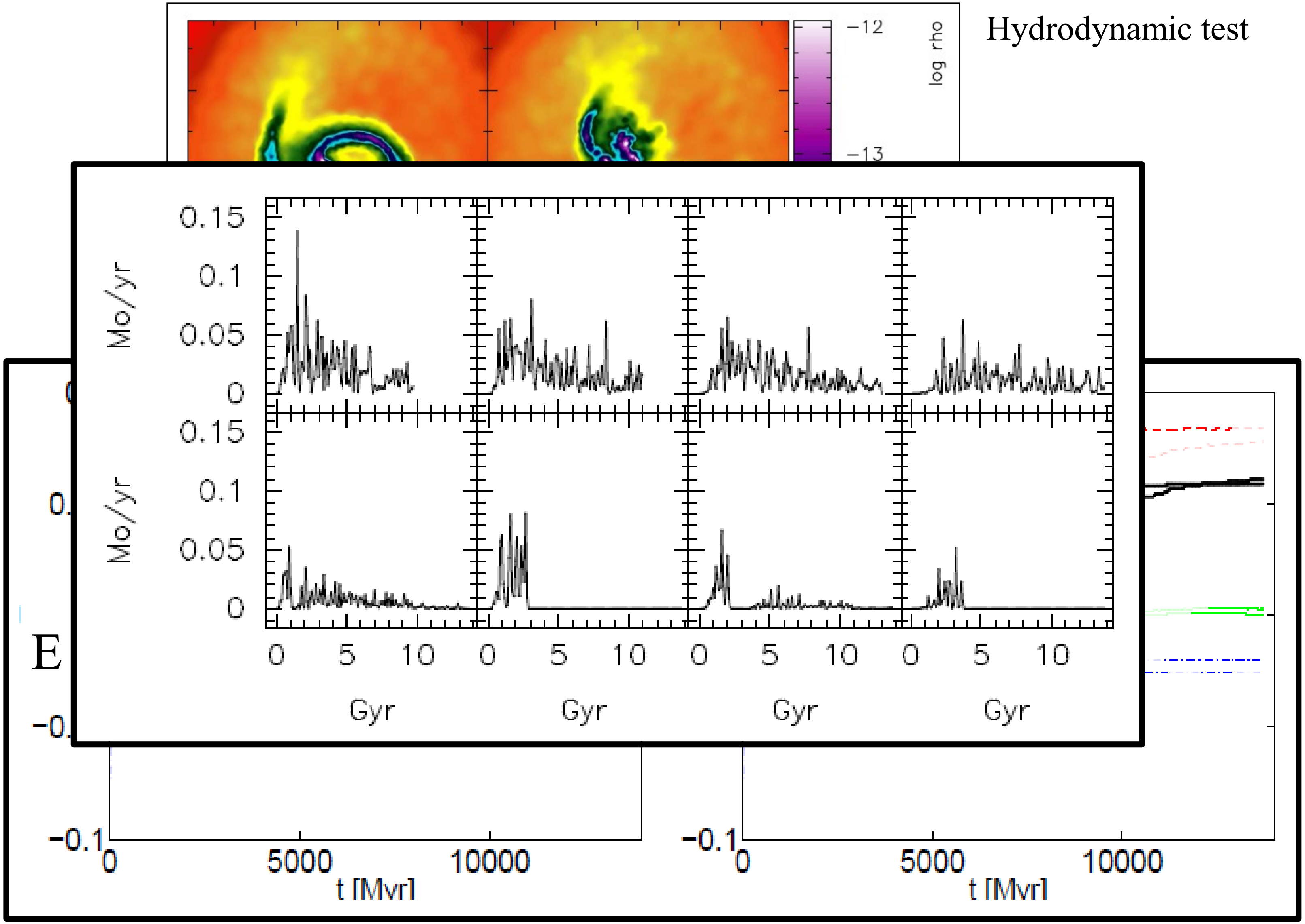
On resolution issues

LowRes

HiRes



On adaptive softening lengths

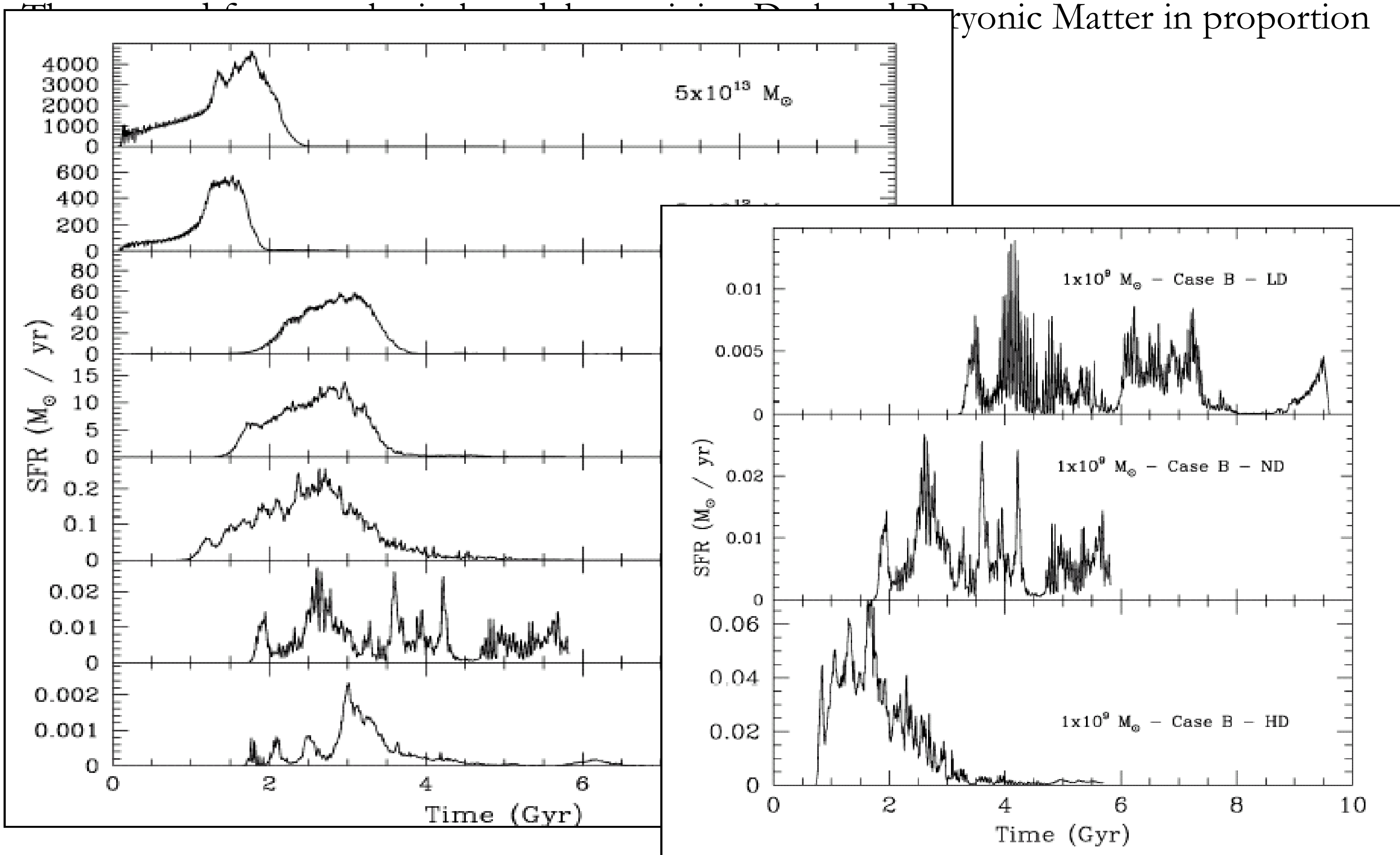


Hydrodynamic test

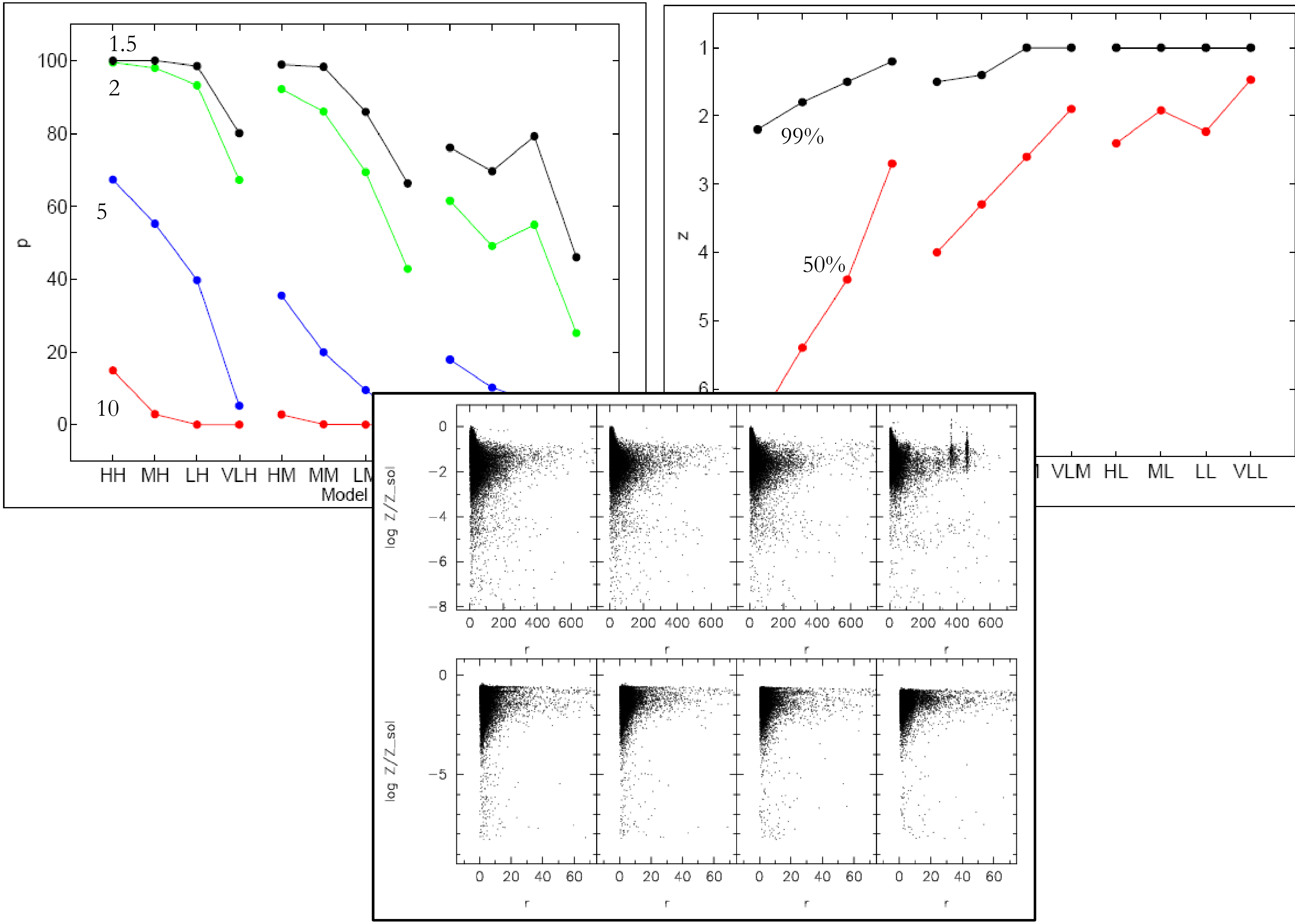
First experiment: Chiosi & Carraro (2002)

Using an early version of the Padova Tree-SPH code, they produced models of ellipticals.

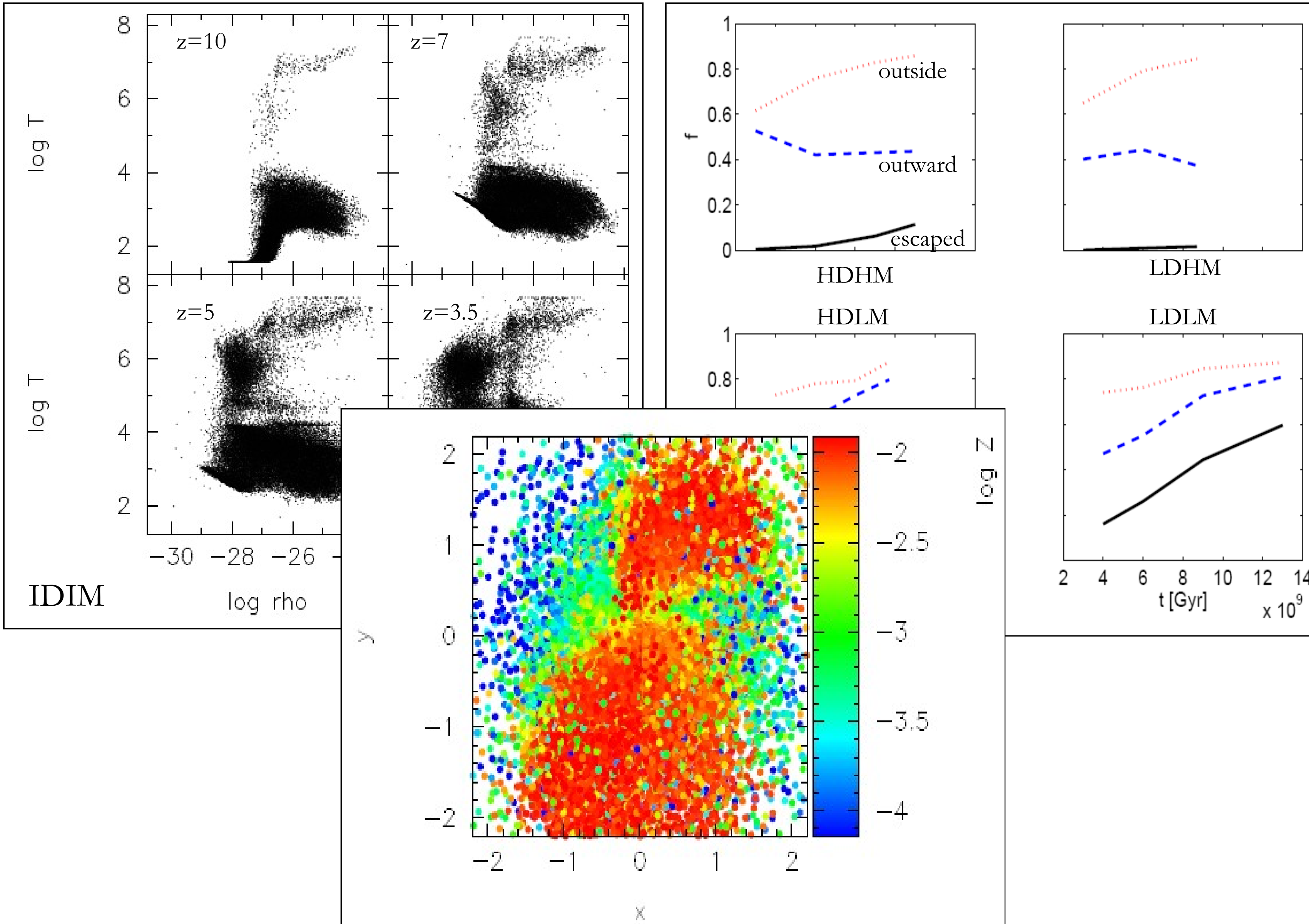
ryonic Matter in proportion



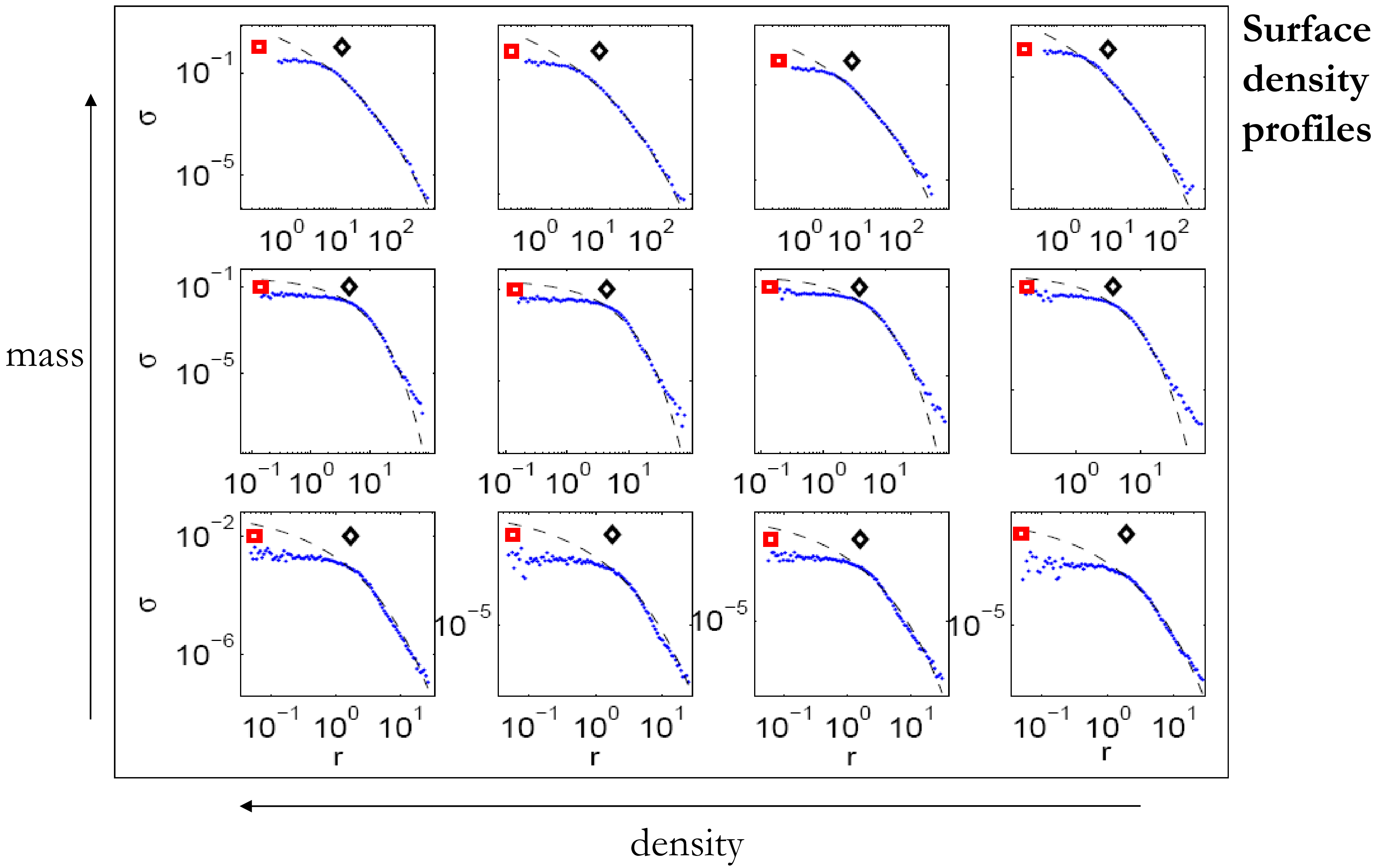
Stellar mass assembly; metallicity



Winds

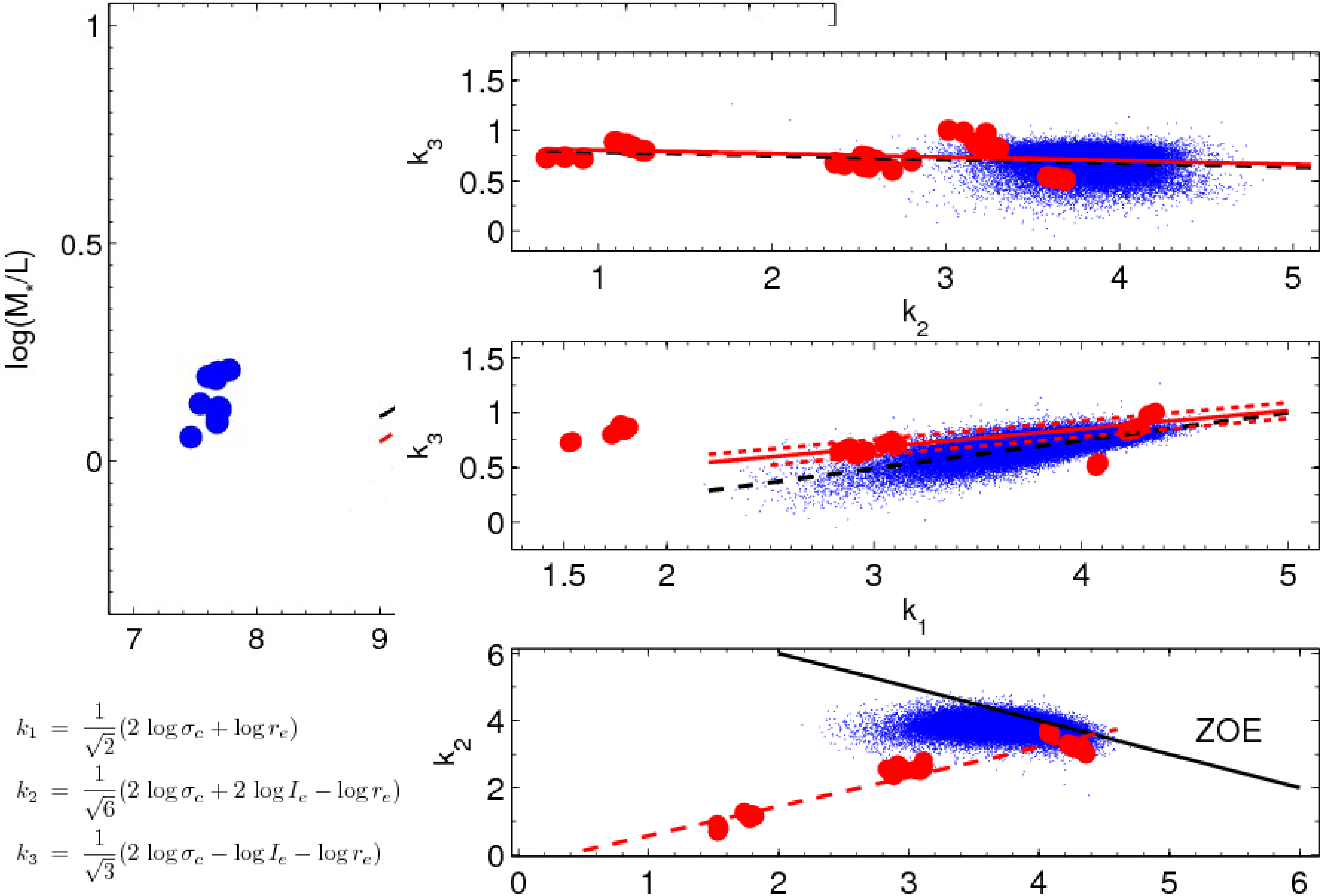


z=10
z=7
z=5
z=3.5
log T
log rho
IDIM
outside
outward
escaped
f
HDHM
LDHM
HDLM
LDLM
t [Gyr]
x 10^9
log Z
y
x



Surface density profiles
mass
density
σ
r

Diagnostic planes #1

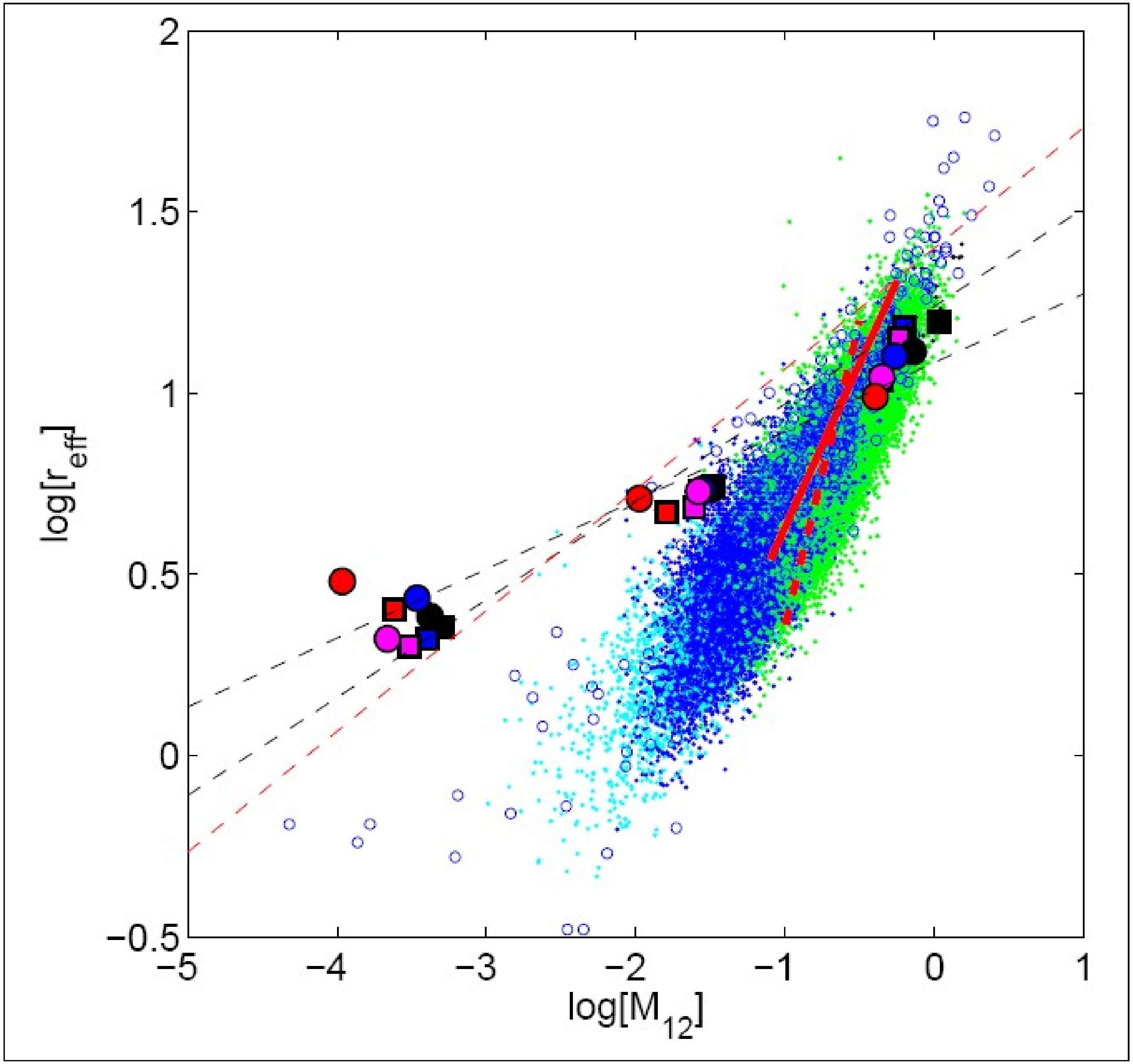


$$k_1 = \frac{1}{\sqrt{2}}(2\,\log\sigma_c + \log r_e)$$

$$k_2 = \frac{1}{\sqrt{6}}(2\,\log\sigma_c + 2\,\log I_e - \log r_e)$$

$$k_3 = \frac{1}{\sqrt{3}}(2\,\log\sigma_c - \log I_e - \log r_e)$$

Diagnostic planes #2



Conclusions

- **The SFH of a model is strongly dependent on its initial total mass**. Massive models (Mtot = 10^13 Msol) build their stellar content via an initial burst of activity at early times. Low mass systems (Mtot = 10^9 Msol) continue to form stars throughout their lifetime (galactic breathing).
- Models with the same initial mass have different star formation histories depending on their initial overdensity: **the strongest the perturbation, the more peaked, early and intense the activity**.
- The structural and chemical properties of our models are in good agreement with those of the observed real galaxies, with some significative exceptions (e.g. the density profiles in the central regions; the mass-to-metallicity relation) which we reckon to be due to our unusual choice for the star formation dimensionless efficiency parameter.
- We suggest a possible interpretation of the **origin of the mass-radius relation for early type galaxies** (next talk by C. Chiosi).
- **An early hierarchical (*z*>2), monolithic-like burst of early star formation is sufficient to explain the bulk of the observed features of massive ellipticals**. Events of late major merging are possible, but they are not required, and it is easy to understand that they would alter the delicate equilibrium which leads to the remarkable tightness of the early-type properties.
- Noticeably, the **stellar feedback** seems to be sufficient to quench the star formation process in massive objects without the action of more exotic sources of energy.
- On the other hand, we are able to recover **the complex, episodic star formation histories typical of many dwarf galaxies**. Without any external intervention, the galactic breathing phenomenon is fairly reproduced by our models, simply relying on an accurate treatment of the stellar feedback process.
- **We conclude that the fate of a proto-galaxy is essentially determined by its initial conditions in terms of mass and overdensity**, while external factors such as encounters, mergers and disruptions, while substantially altering the evolution of the involved systems, are not a fundamental ingredient in the global evolution of early type galaxies population.