Modulo: New paradigm

Laura Magrini & Daniele Galli
Osservatorio Astrofisico di Arcetri

Initial conditions

1. Homogeneous spherical cold neutral gas cloud with two initial masses: $M=10^9 M_\odot$ and $10^{11} M_\odot$. The gas temperature can assume one of three possible values: 20, 25, 30 K; and the gas density n_{HI} two values: 1 cm^{-3} and 10 cm^{-3}.

2. The volume density of the gas is:

$$\rho_{HI} = m_H \, \mu \, n_{HI} \, ,$$

the radius of the gas sphere is:

$$R_{HI} = [3M_{HI}/(4\pi\rho_{HI})]1/3 \, ,$$

and the surface density of the gas is:

$$\Sigma_{HI} = \rho_{HI} \, R_{HI} \, ,$$

where m_H is the mass of a hydrogen atom, μ is the molecular weight of the gas, in this case μ = 1.2 to take neutral helium into account, and n_{HI} is the HI number density.

Initial molecular cloud conditions

The clouds have three possible values of number density n_{H2}:

Diffuse: n1 = 10^3 cm^{-3}

Compact: n2 = 5 X 10^4 cm^{-3}

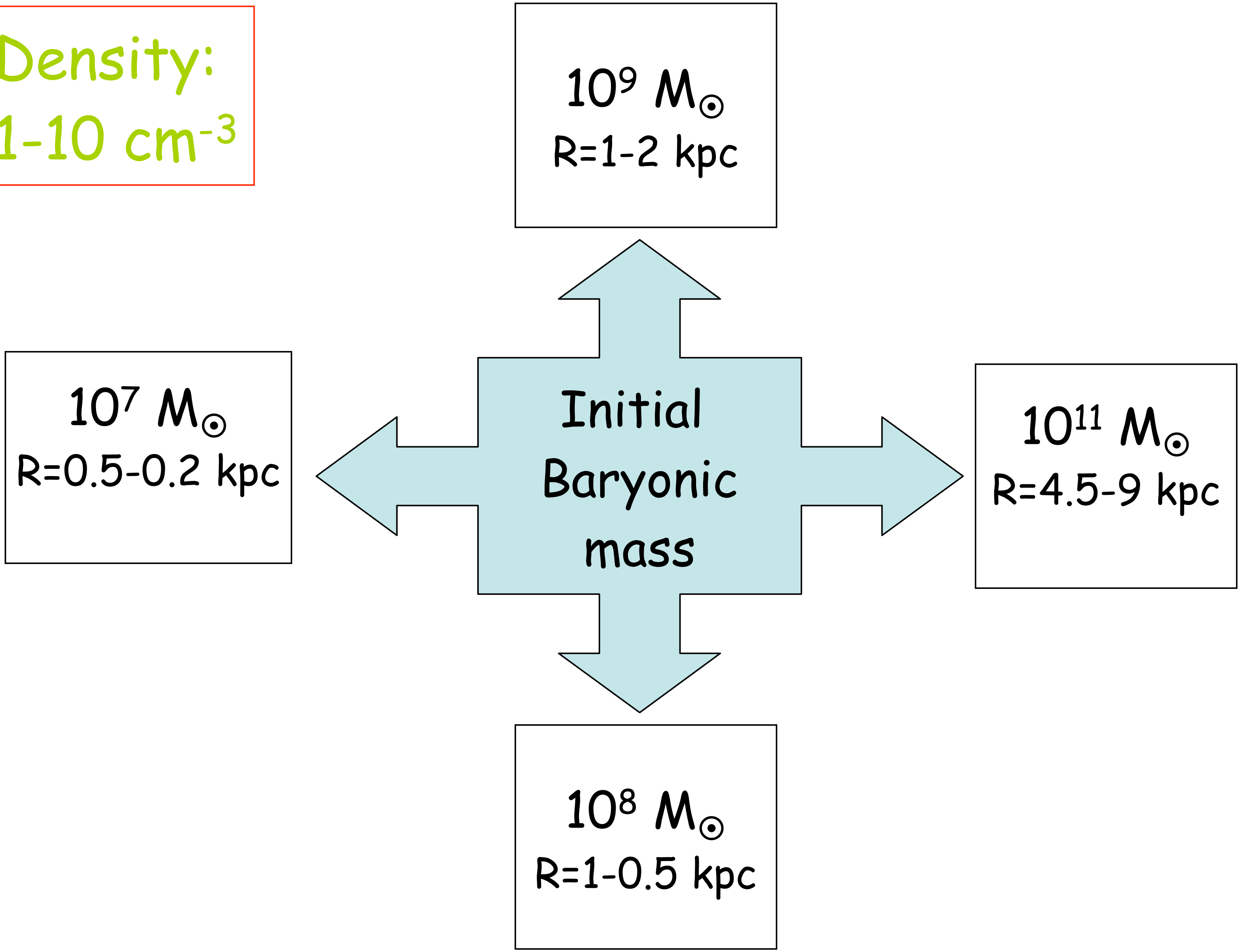
Hyper dense: n3 = 10^6 cm^{-3}

From the cloud densities, we compute their free-fall collapse time:

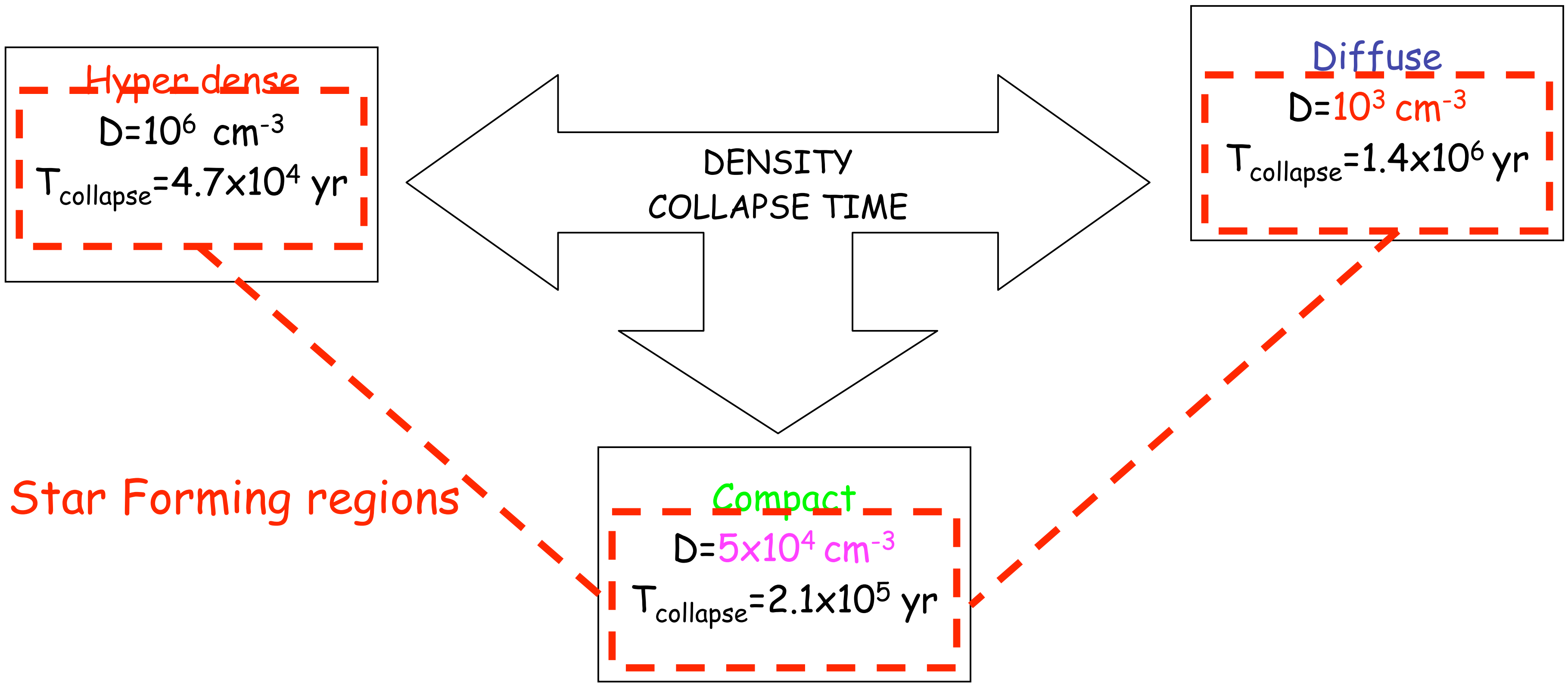
$$t_{ff} = \sqrt{3\pi/32G\rho_{gas}}$$

Characteristics of proto-galaxies

Density:
1-10 cm^{-3}



Clouds characteristics



The phase transformations:

1. <u>From atomic gas to clouds:</u>

Initially the H_2 fraction is zero, for a given metallicity Z and $\Sigma_{gas} = \Sigma_{HI} + \Sigma_{H2}$, the fraction of gas in H_2 can be calculated with the Krumholz, McKee, & Tumlinson (KMT) formulation:

$$f_{H2} = f(Z, \Sigma_{gas}),$$

namely $M_{H2} = f_{H2} M_{gas}$, where $M_{gas} = M_{HI} + M_{H2}$.

2. <u>From molecular clouds to stars:</u>

The star-formation rate SFR surface density is calculated:

$$d\Sigma^*/dt = \Sigma_{gas} f_{H2} \varepsilon / t_{ff(GMC)}$$

The equations of the multiphase model:

Star formation

$$\frac{ds_{1,D}}{dt} = H_{1,D}c_D^2 + a_{1,D}c_D s_{2,D} - D_{1,D}\,,$$

$$\frac{ds_{2,D}}{dt} = H_{2,D}c_D^2 + a_{2,D}c_D s_{2,D} - D_{2,D}\,,$$

Infall

$$\frac{dg_D}{dt} = -\mu_D g_D^n + a'_D c_D s_{2,D} + H'_D c_D^2 + W_D + f g_H\,,$$

Cloud formation

$$\frac{dc_D}{dt} = \mu_D g_D^n - (a_{1,D} + a_{2,D} + a'_D) c_D s_{2,D} - (H_{1,D} + H_{2,D} + H'_D) c_D^2$$

$$\frac{dr_D}{dt} = D_{1,D} + D_{2,D} - W_D$$

Modulo in the multiphase model

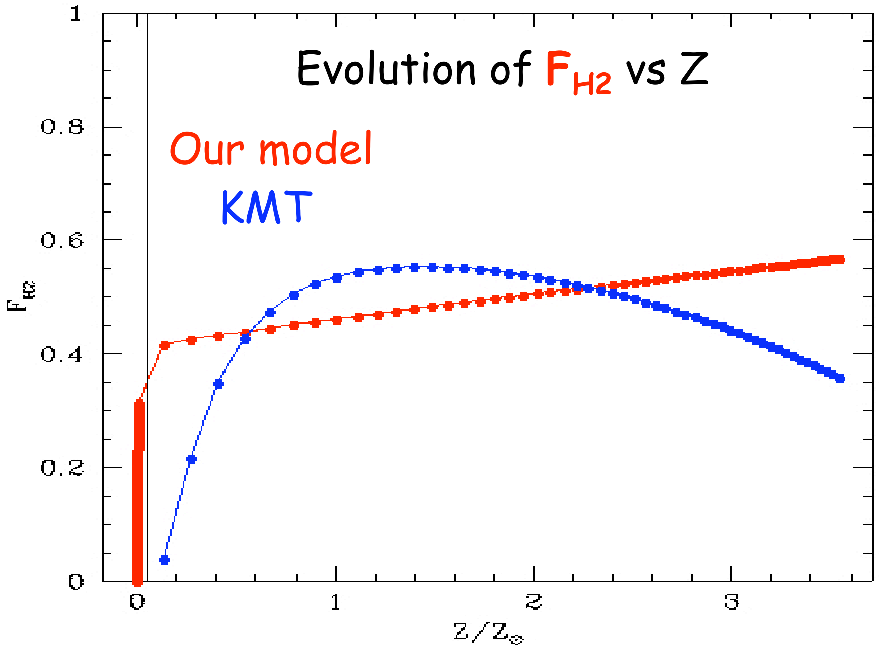
Cloud formation

- The molecular cloud fraction by KMT is not directly introduced, but it is compared with the molecular cloud fraction obtained in our model: molecular clouds are formed from atomic gas collapse, following the relation

$$dF_{H2}/dt= \varepsilon \, F_{HI}^{1.5}$$

The final result for the evolution of the molecular cloud fraction evolution is very similar to the KMT fractions, with several advantages:

1. Easier to compute
2. Applicable also at low metallicity
3. Applicable at any Σ_{gas}



Modulo in the multiphase model

Star formation

- The three different molecular cloud density regimes give us three star formation global efficiency:

$$\Sigma_{gas}\ f_{H2}\ \varepsilon /\ t_{ff(GMC)}$$

- While ε is constant, $t_{ff(GMC)}$ depends inversely on the cloud density, and thus **compact** clouds form stars more efficiently than **diffuse** clouds.

$$\frac{ds_{1,D}}{dt} = \boxed{H_{1,D}}\, c_D^2 + \ldots$$

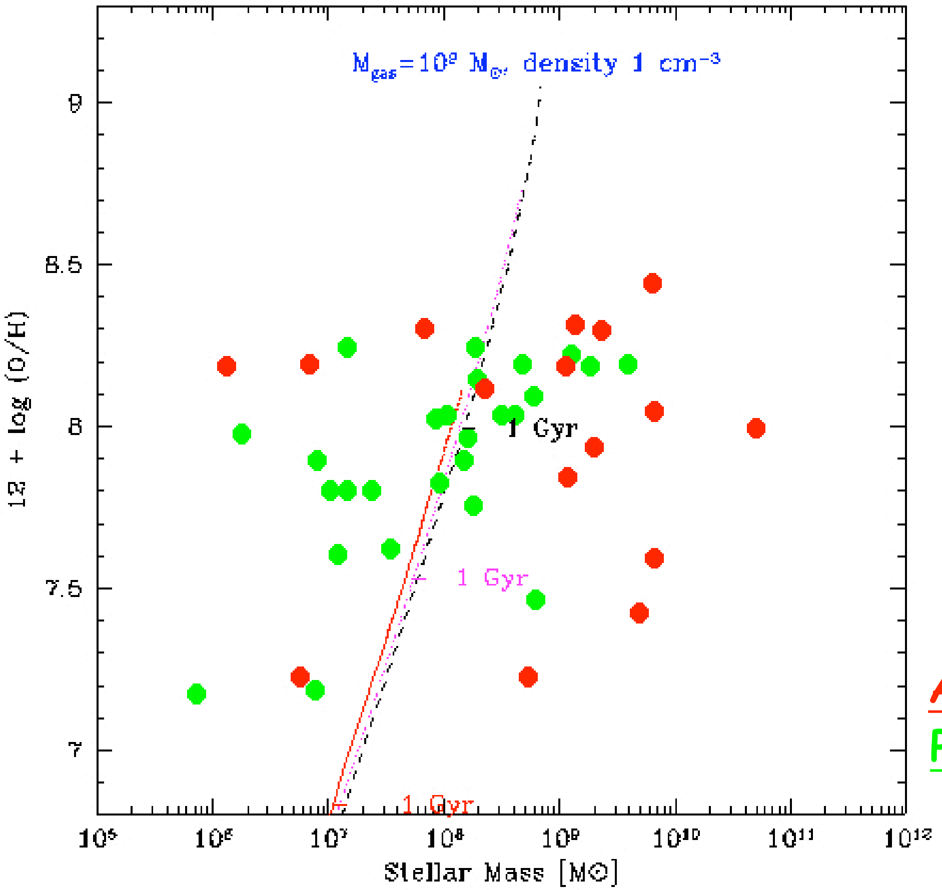
$$\frac{ds_{2,D}}{dt} = \boxed{H_{2,D}}\, c_D^2 + \ldots$$

The BCD sample:
constraints from observations

X conversion factor = 3.000e+20 cm^-2 (K km/s)^-1

Name	Distance (Mpc)	12+ logOH	<B-K>	<LK> (Msun)	Diameter NED (kpc)	LogMstar min (Msun)	LogMstar avg (Msun)	HI Sigma(HI) (cm^-2)	HI Sigma(HI) (Msun/pc^2)	Flag	CO Sigma(H2) (cm^-2)	CO Sigma(H2) (Msun/pc^2)	Flag	SFR (Msun/yr)	SFR (Msun/yr/kpc^2)	
Haro3	16.8	8.30	2.89	9.72	4.79	9.09	9.35	1.282e+21	10.3	m21	5.940e+20	9.5	OK	1.90	0.106	13.
IIZw40	10.3	8.12	1.24	9.13	1.04	8.09	8.34	1.145e+22	91.7	m21	1.500e+20	2.4	OK	3.90	4.610	13.
IZw18	13.0	7.19	1.10	7.71	0.93	6.51	6.88	4.919e+21	39.4	m21	3.000e+20	4.8	UL	0.09	0.134	13.
Mrk209	5.4	7.81	2.49	7.83	1.09	7.29	7.36	1.773e+21	14.2	m21	1.350e+20	2.2	OK	0.05	0.051	13.
Mrk33	24.9	8.45	3.17	10.09	6.86	9.59	9.79	5.416e+20	4.3	m21	1.863e+21	29.8	OK	3.80	0.103	13.
Mrk71=NGC2363A	3.4	7.90	0.12	7.96	0.81	6.54	6.89	1.545e+21	12.4	cm2	1.020e+20	1.6	UL	0.11	0.214	13.
Mrk900	13.3	8.04	2.49	9.07	2.90	8.54	8.60	4.465e+20	3.6	m21	2.040e+20	3.3	OK	0.09	0.014	13.
NGC1140	18.2	8.20	3.30	9.84	6.55	9.30	9.58	1.965e+21	15.7	m21	2.910e+20	4.7	OK	0.82	0.024	13.
NGC1156	7.1	8.23	2.53	9.56	5.93	8.62	9.10	6.274e+20	5.0	m21	2.280e+20	3.7	OK	0.19	0.007	13.
NGC1741	55.1	8.05	1.96	10.41	22.44	9.29	9.81	1.218e+21	9.8	m21	4.590e+20	7.4	OK	16.00	0.040	13.
NGC2537	8.0	8.19	3.07	9.58	3.72	9.14	9.26	6.910e+20	5.5	m21	1.680e+20	2.7	OK	0.15	0.013	13.
NGC4214	3.3	8.20	2.23	9.20	7.19	8.66	8.67	2.918e+20	2.3	m21	2.700e+20	4.3	OK	0.13	0.003	13.
NGC5253	3.5	8.19	2.95	9.40	3.14	8.63	9.05	3.406e+20	2.7	m21	2.175e+20	3.5	OK	1.40	0.181	13.
SBS0335-052	53.7	7.23	2.38	9.21	3.35	7.79	8.72	3.071e+21	24.6	m21	1.625e+21	26.0	UL	1.35	0.154	13.
UM448	81.2	8.00	3.62	10.87	8.18	10.30	10.69	4.274e+21	34.2	m21	2.460e+20	3.9	OK	35.20	0.669	13.
UM462	15.3	7.97	2.01	8.79	2.44	7.95	8.20	2.018e+21	16.2	m21	1.650e+20	2.6	OK	0.28	0.060	13.

Results of the model:



The model curves correspond to different cloud density :

10^3 cm^{-3}

$5x10^4$ cm^{-3}

10^6 cm^{-3}

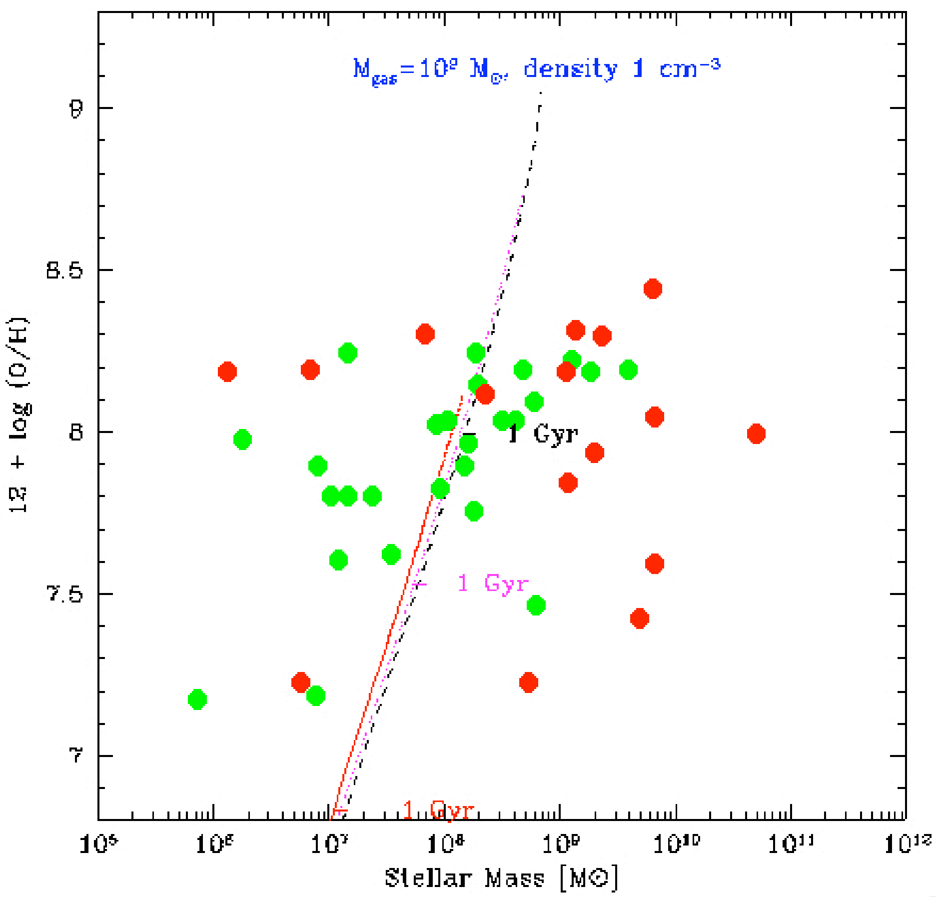
producing different time evolution

Active galaxies: SFR > 1 Msun/yr

Passive galaxies: SFR < 1 Msun/yr

Galaxies with diffuse clouds have a slower evolution than galaxies with compact clouds: at a given time in their evolution they have lower metallicity and stellar mass

However, to reproduce the mass-metallicity relationship we need to compare with a grid of model for different initial masses



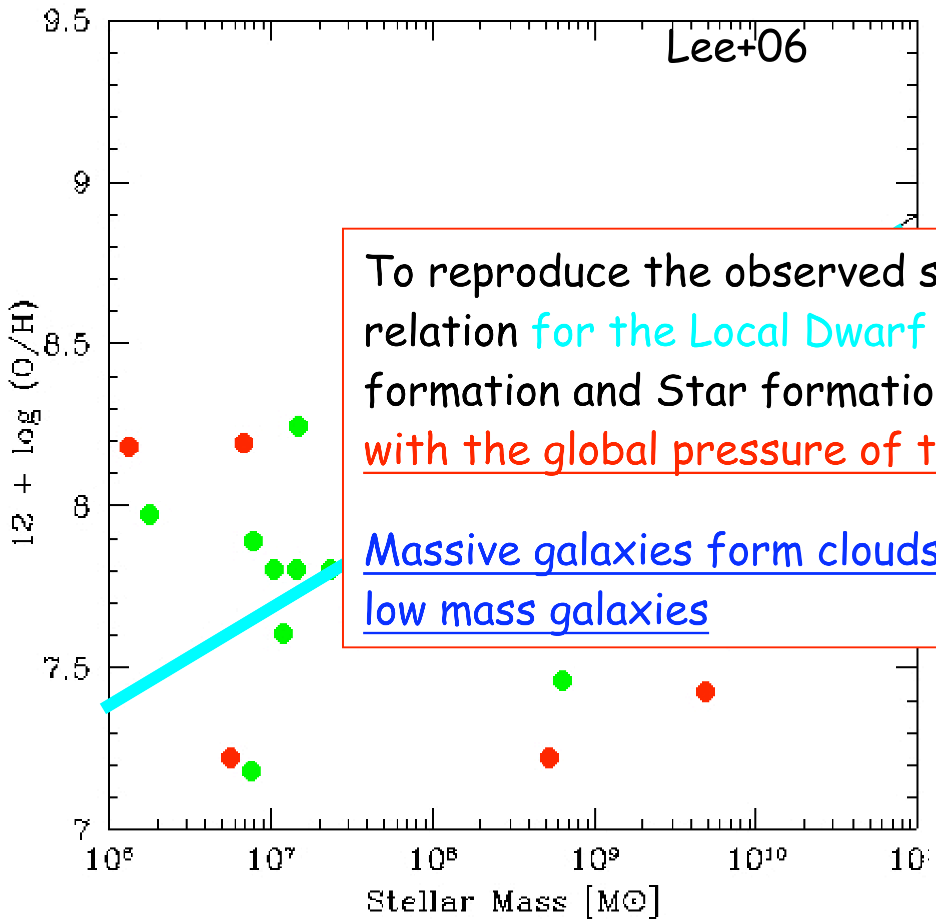
Active galaxies: SFR > 1 Msun/yr

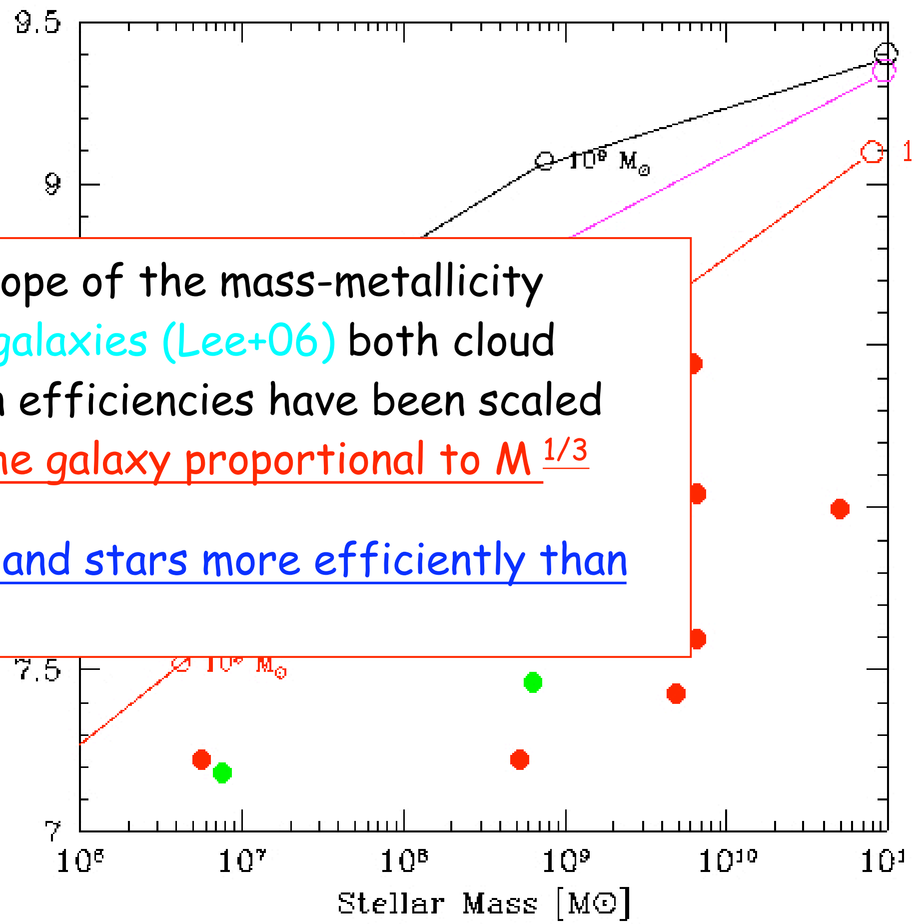
Passive galaxies: SFR < 1 Msun/yr

Mass-metallicity relationship

Observations: **active** and **passive** galaxies and the mass-metallicity rel. from Lee+06

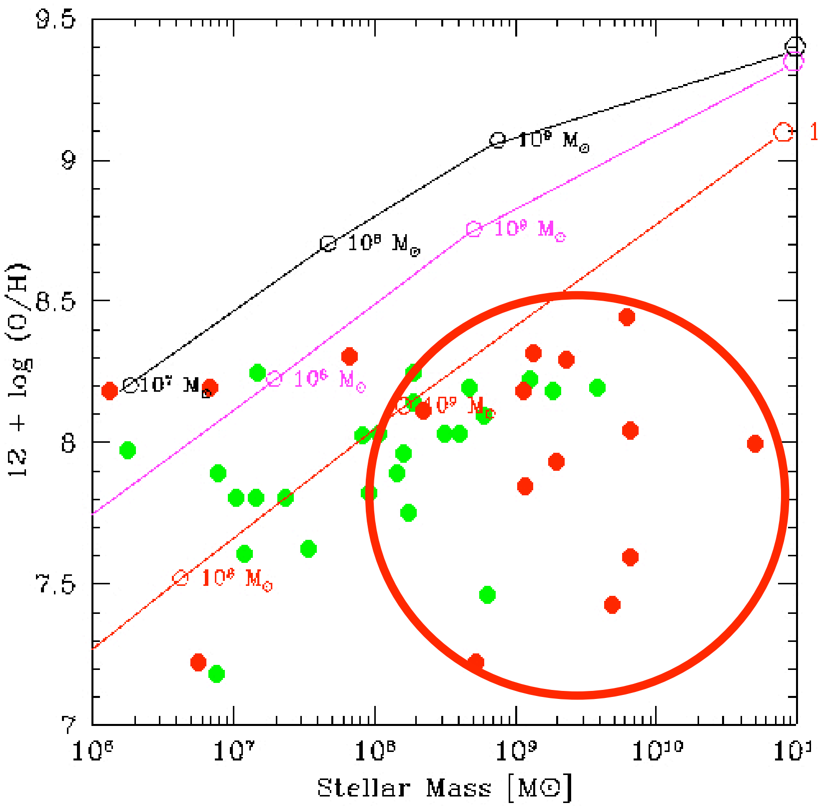
Models: curves at present time with three densities: **hyper-dense**, **compact**, **diffuse**





To reproduce the observed slope of the mass-metallicity relation for the Local Dwarf galaxies (Lee+06) both cloud formation and Star formation efficiencies have been scaled with the global pressure of the galaxy proportional to $M^{1/3}$

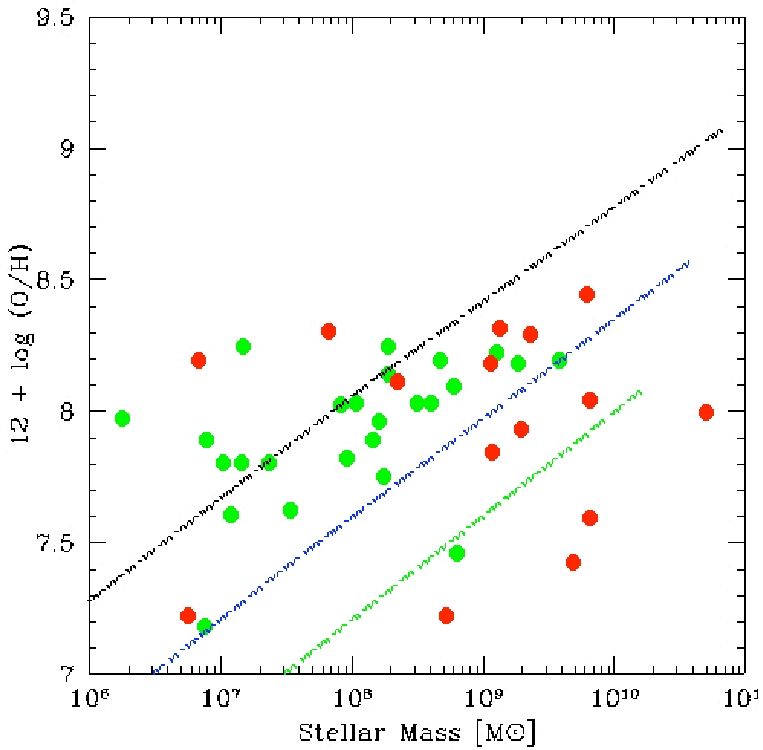
Massive galaxies form clouds and stars more efficiently than low mass galaxies



Most of the active galaxies do not follow the mass-metallicity relationship: they have higher stellar mass than expected for their metal content.

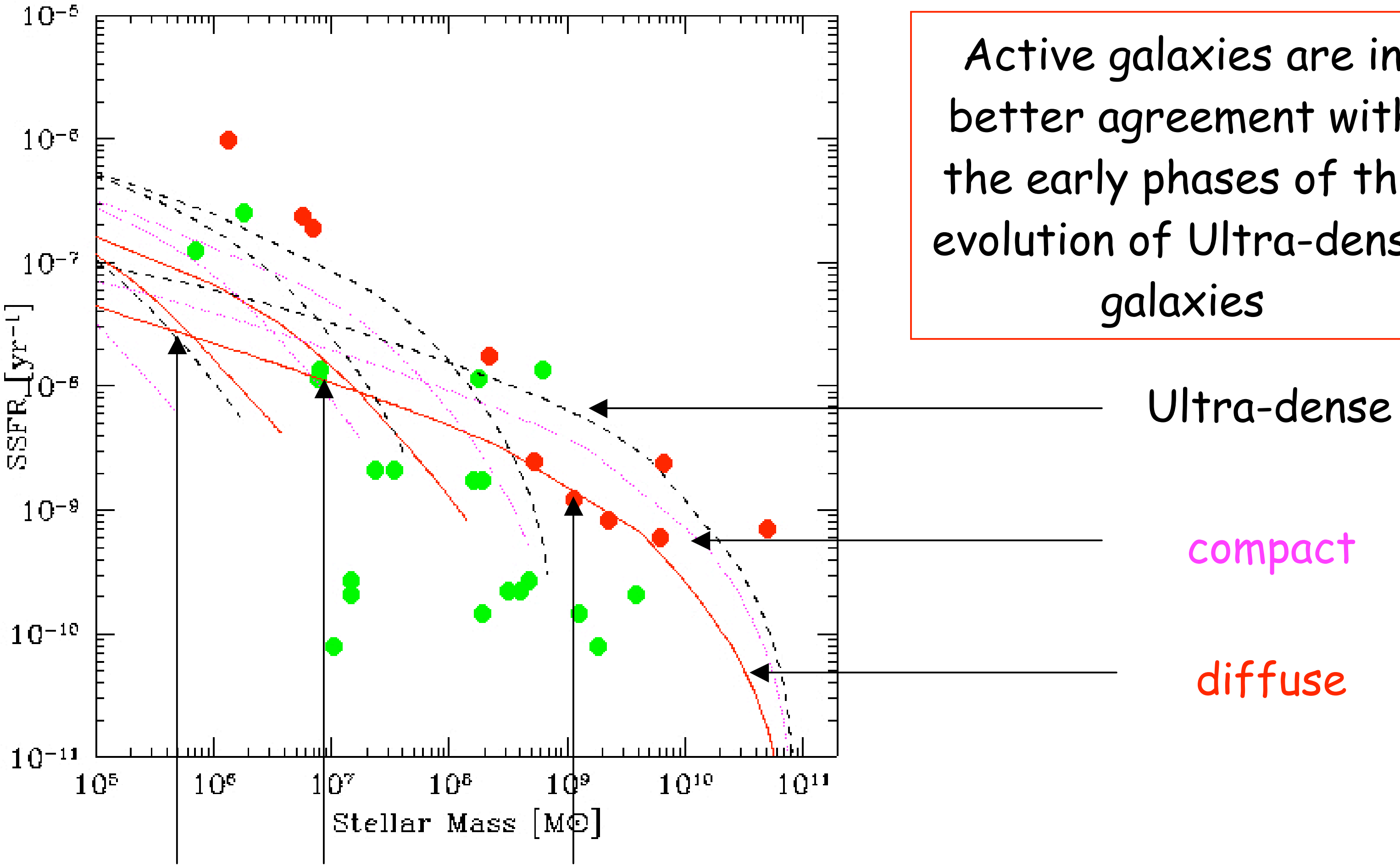
Let's fix the cloud density, i.e. the SF efficiency, and study the time evolution of the mass-metallicity relationship-->
Active galaxies are consistent with galaxies in the early phases of their evolution

Present-time
Redshift z~2
z~3



The specific star formation rate:

in the three density cases
and with different initial masses

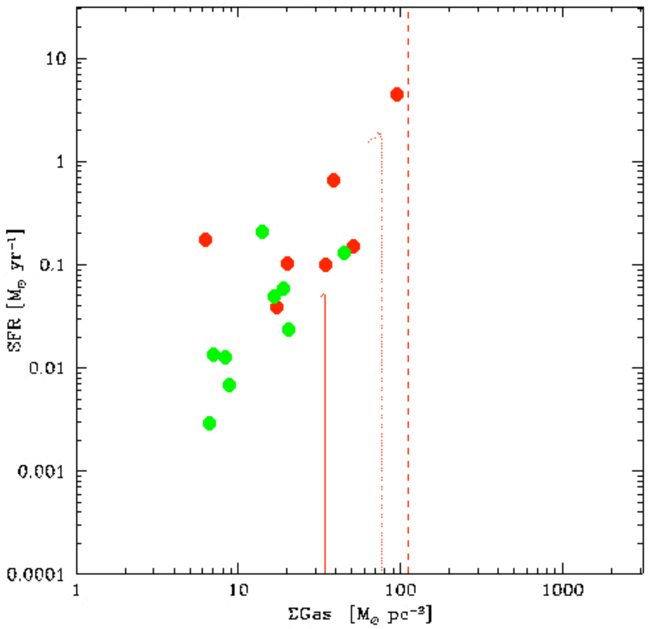


Active galaxies are in better agreement with the early phases of the evolution of Ultra-dense galaxies

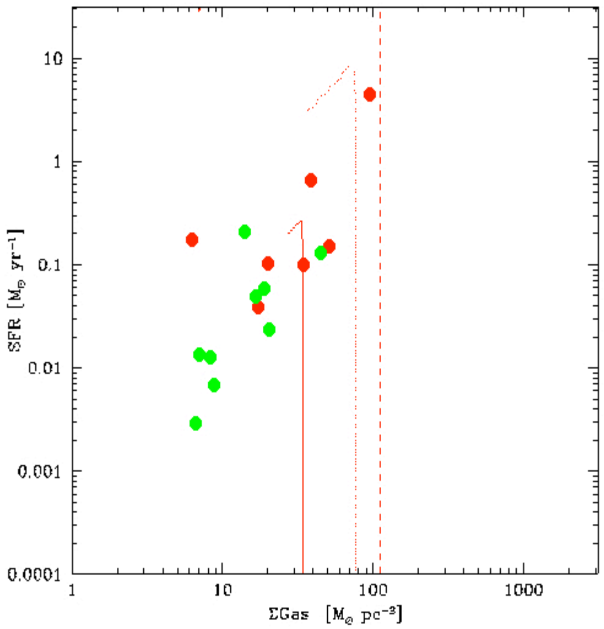
Initial mass : 10^8 10^9 10^{11} Msun

Kennicut-Schmidt law

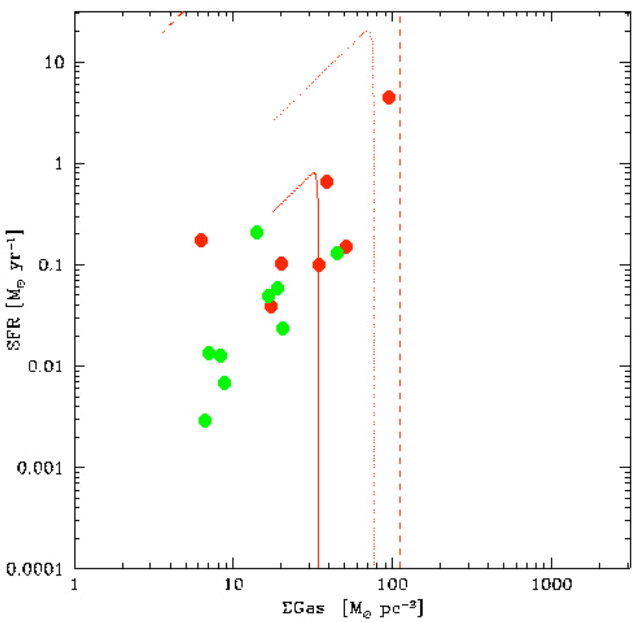
Low density



Medium density



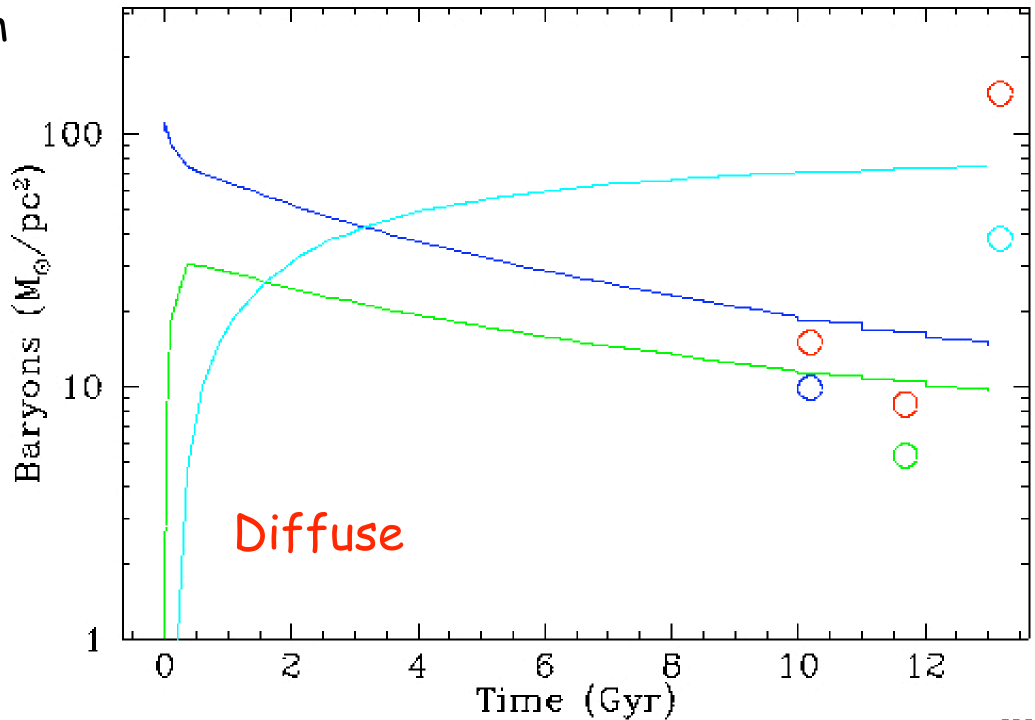
High density



Baryonic component evolution

Curves:
Surface density from Model

Gas
Clouds
Stars



Circles:
Observed surface Densities

Molecular clouds
Atomic gas
Stars

In red active galaxies

$M \sim 10^{11}$ Msun

Conclusions

- The multiphase model is able to reproduce the main observational constraints of the BCD sample: SFR, SSFR, mass-metallicity and Kennicut-Schmidt relations, evolution of the baryonic Surface densities

- Different cloud densities gives different rate of evolution, and seems to associate active galaxies with a younger population evolving rapidly than passive galaxies