GIMIC: Galaxies-Intergalactic Medium Interaction Calculation

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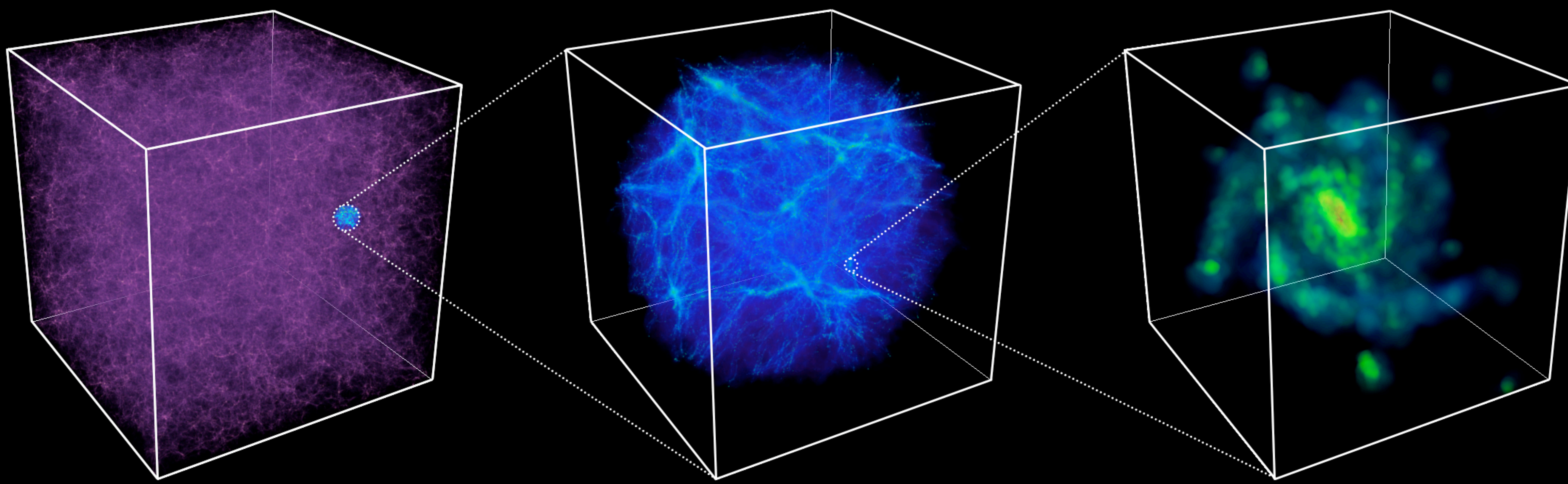

Research Progress Meeting
Lawrence Berkeley National Laboratory
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Why simulate galaxy formation?

Semi-analytic models proven very successful

Reproduce the cosmic star formation history

Reproduce the galaxy population by mass

Reproduce the colour-magnitude relation

....but by design adopt severe simplifications

....phenomenology doesn't play by the rules

Simulating hydrodynamics more teaches us more

Are (semi-)analytic simplifications appropriate?

Can directly probe interaction of galaxies with intergalactic gas.

Interfaces more directly with observables

The simulator's dynamic range double whammy

Galaxies are much bigger than stars and black holes

Individual supernovae and active galactic nuclei impart galaxy-wide effects

Recourse to phenomenology, on some scale, is inevitable.

Galaxies are much smaller than the large-scale structure

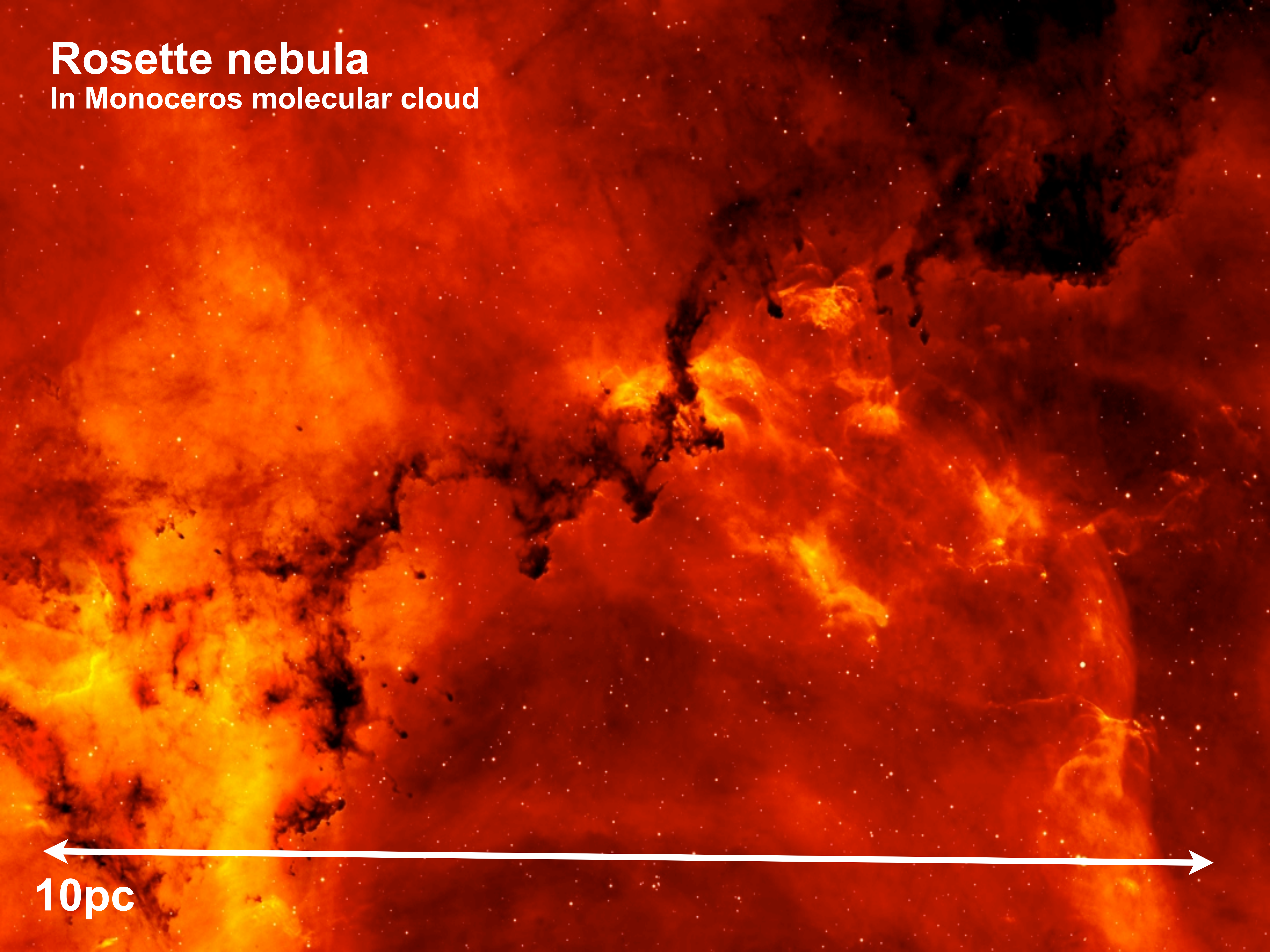
Surveys trace LSS using *millions* of galaxies

Galaxies pollute intergalactic gas with heavy elements on ~Mpc scales

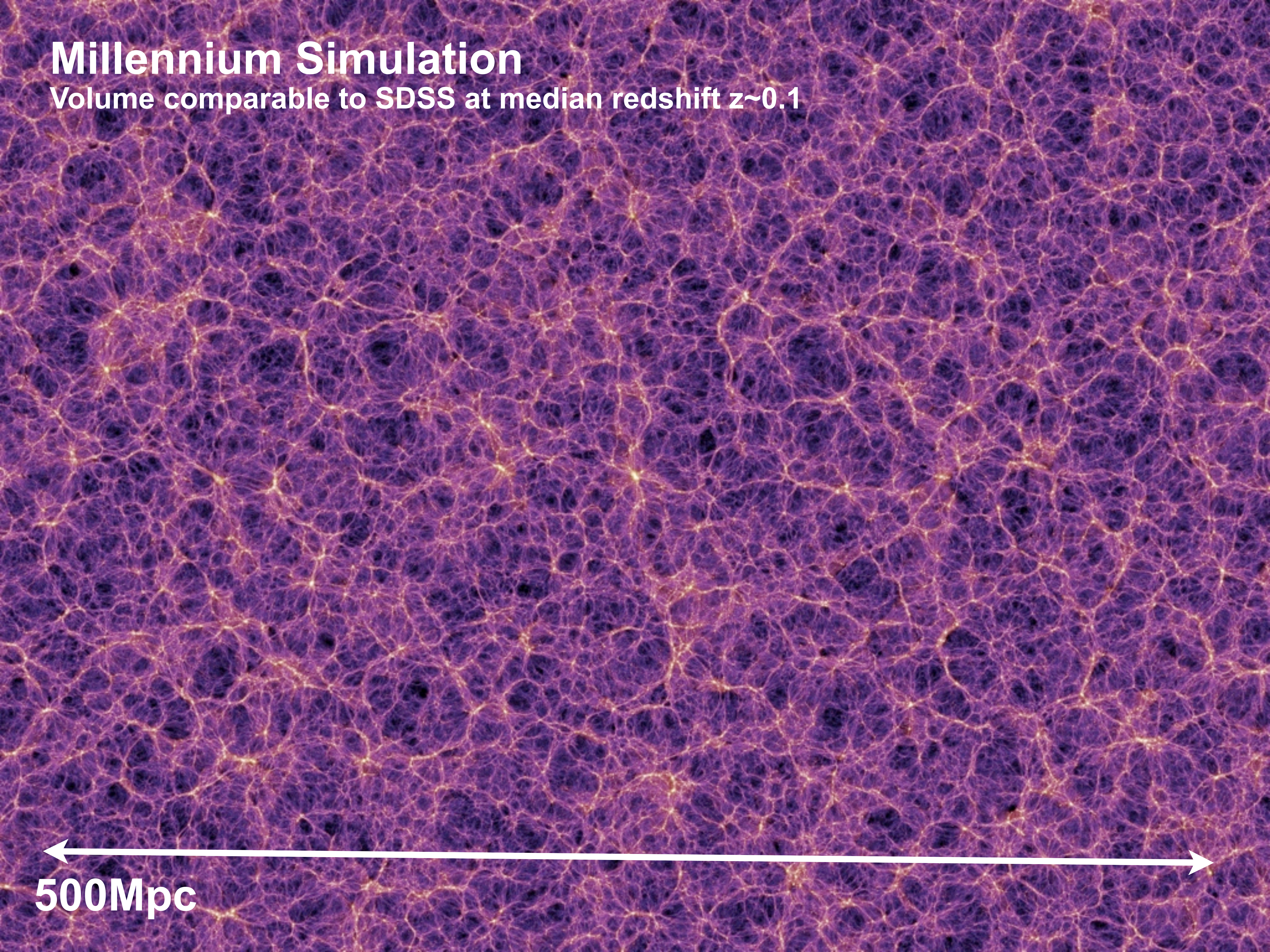
To compete with semi-analytics

Trace volumes of L > 100 Mpc

Use resolution of m_gas < 10^7 Msun


Rosette nebula
In Monoceros molecular cloud
10pc


M31
100kpc


Millennium Simulation
Volume comparable to SDSS at median redshift z~0.1
500Mpc

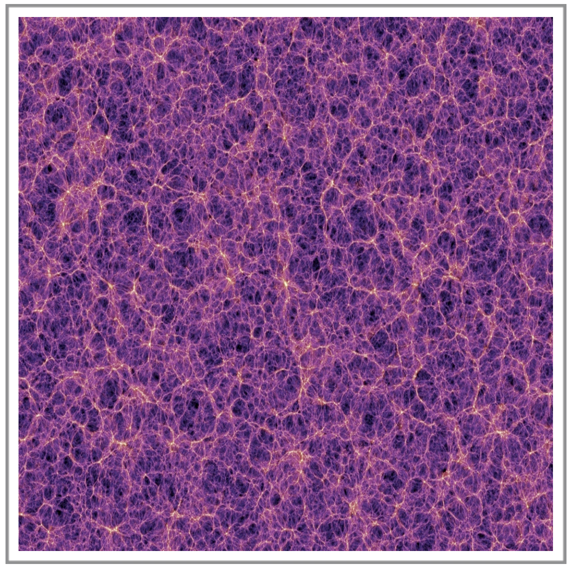
GIMIC: A novel approach

Aim: trace coevolution of galaxies and IGM in a cosmological context

Follow hundreds of galaxies

Large volumes of the IGM

Varied cosmological environments



“Simulation in a simulation”

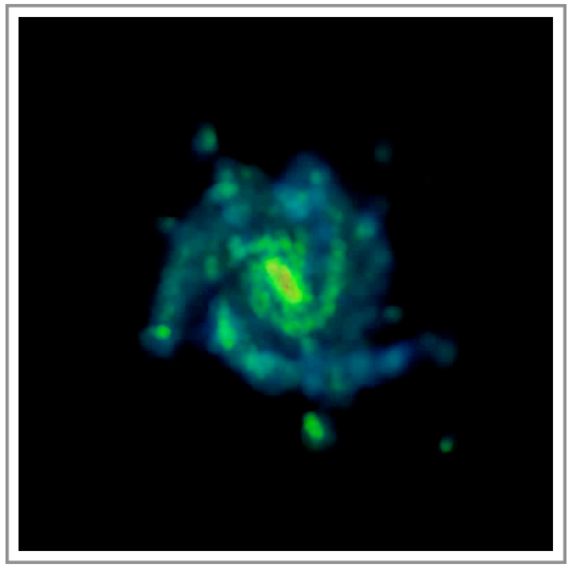
Method: adopt ‘zoomed’ initial conditions

Take large parent dark matter volume at z=0

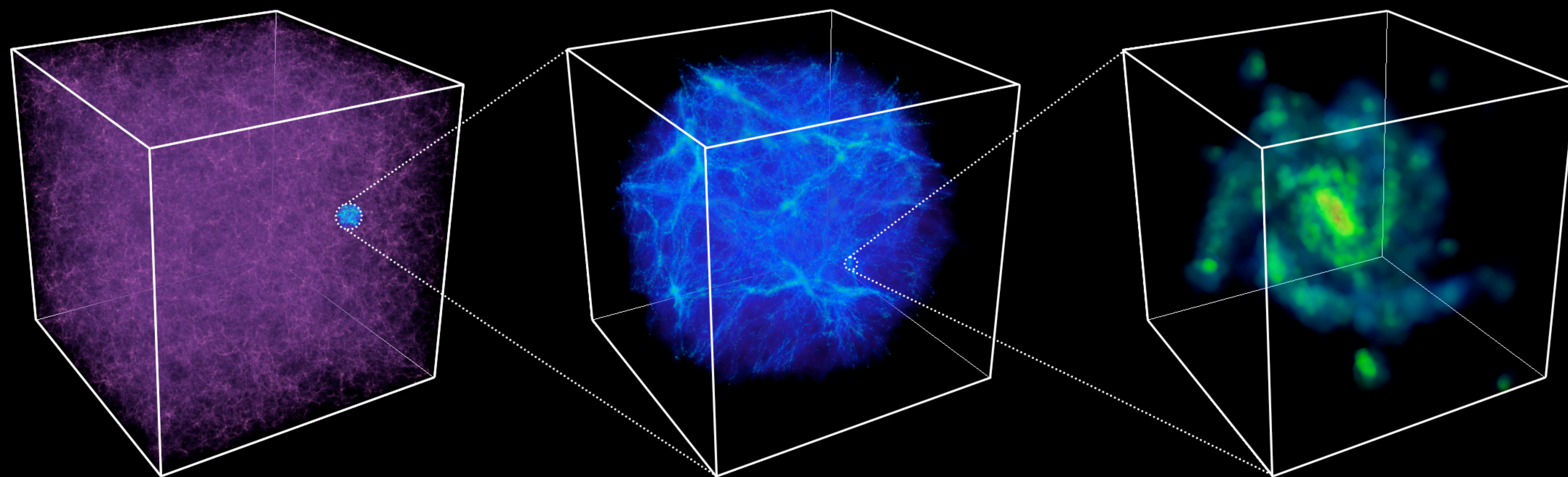
Trace back regions of interest to early times

Resample density field with multi-resolution scheme, adding small scale power.

Add gas to high-resolution region and re-run



Six orders of magnitude in length scale

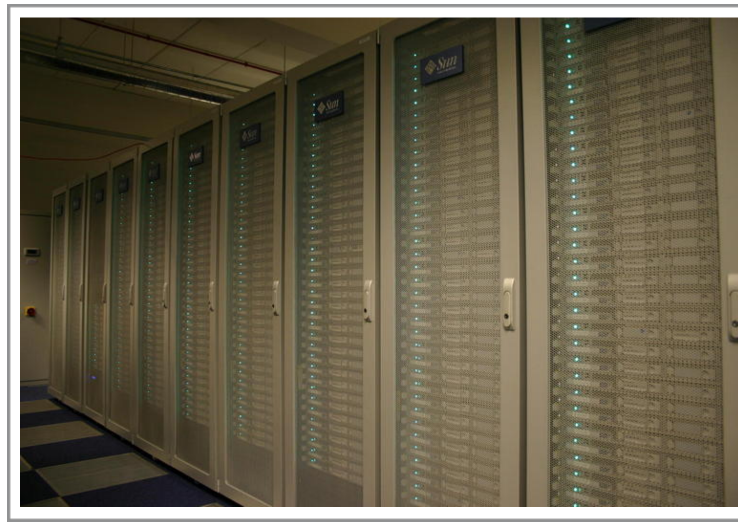


Millennium Volume
L = 500 Mpc/h

GIMIC hi-res region (1 of 5)
L ~ 50 Mpc/h

GIMIC galaxy (1 of ~1000)
force resolution ~500pc

GIMIC: the simulation code



Gadget-3

Domain decomposition optimised for high-dynamic range problems (also: Aquarius)

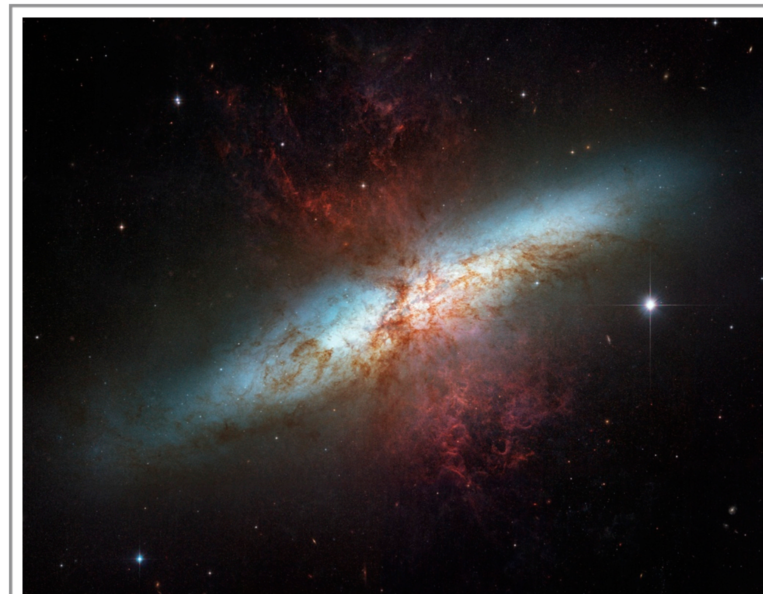
New physics modules: cooling, SF, kinetic feedback (also: Overwhelmingly Large Simulations, OWLS)

Key features

High-density gas (interstellar medium) is single phase

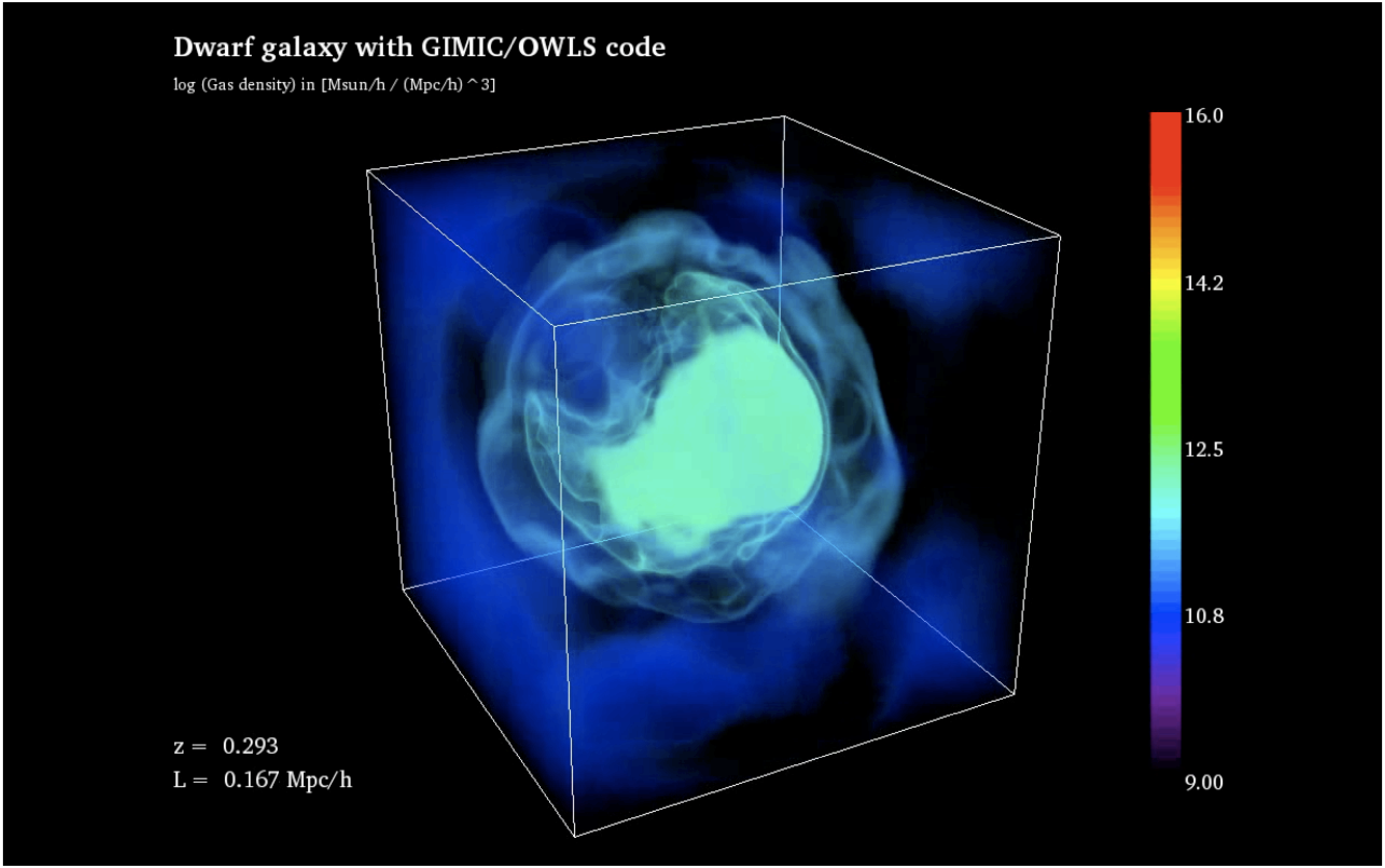
Apply equation of state, *P* = *k.rho^gamma* to yield ISM **effective pressure**

Star formation based on density, parametrised by **observables**

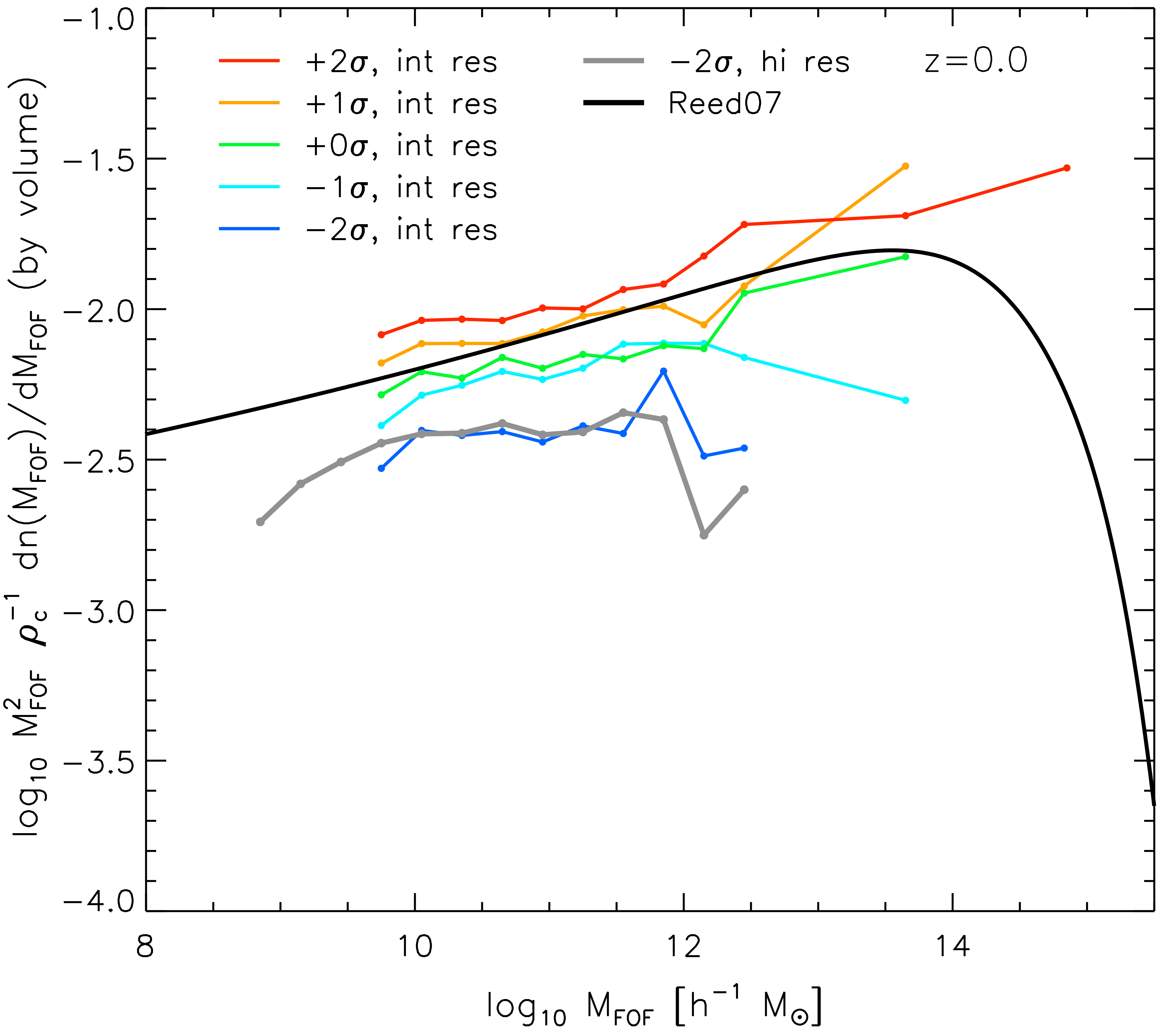


Supernova-driven winds triggered locally and not decoupled from hydrodynamical forces

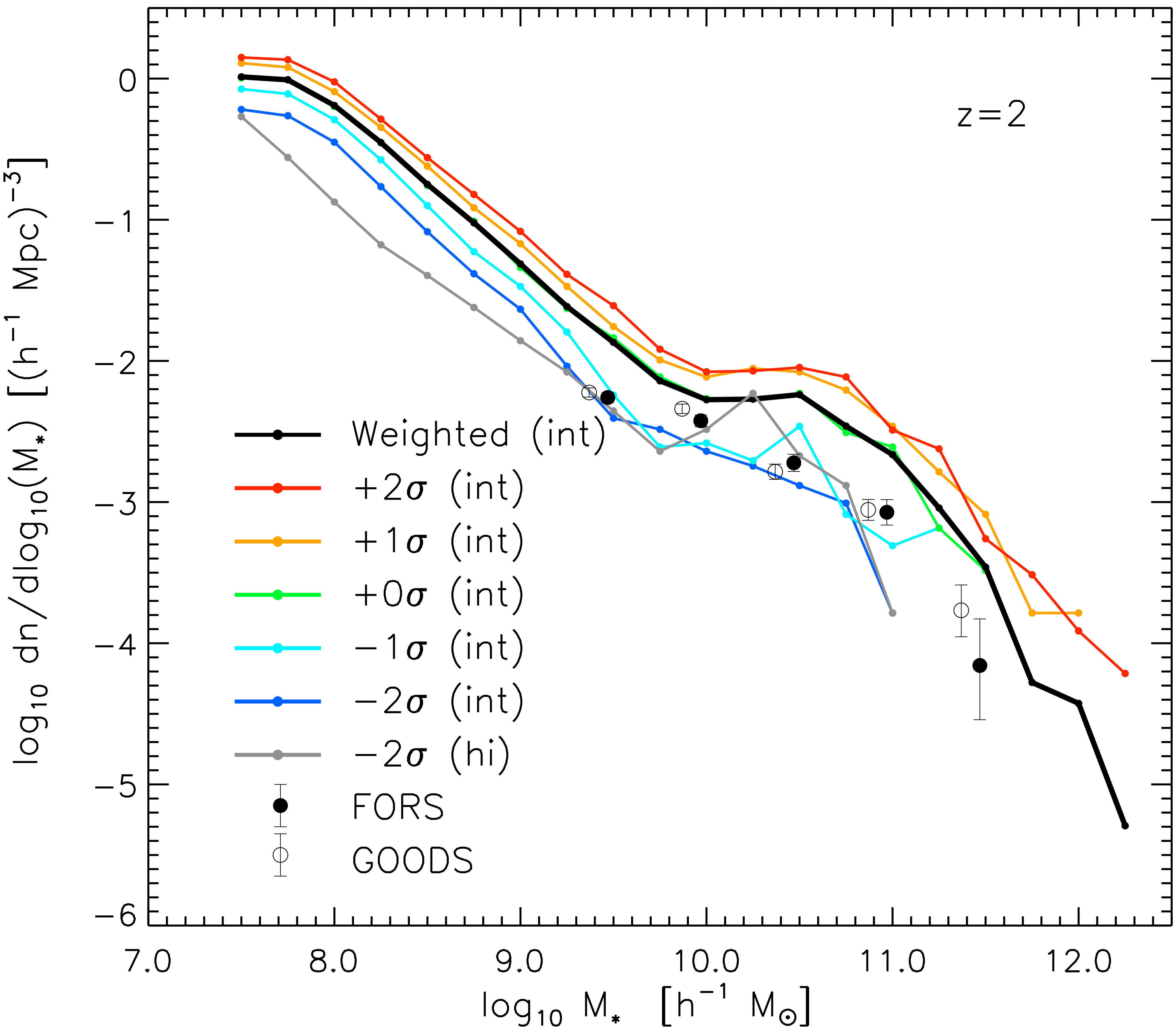
Gas cooling rate considers 11 heavy elements and UV background


Dwarf galaxy with GIMIC/OWLS code
log (Gas density) in [Msun/h / (Mpc/h) ^3]
16.0
14.2
12.5
10.8
9.00
z = 0.293
L = 0.167 Mpc/h

The dark matter halo population



The galaxy population, by stellar mass



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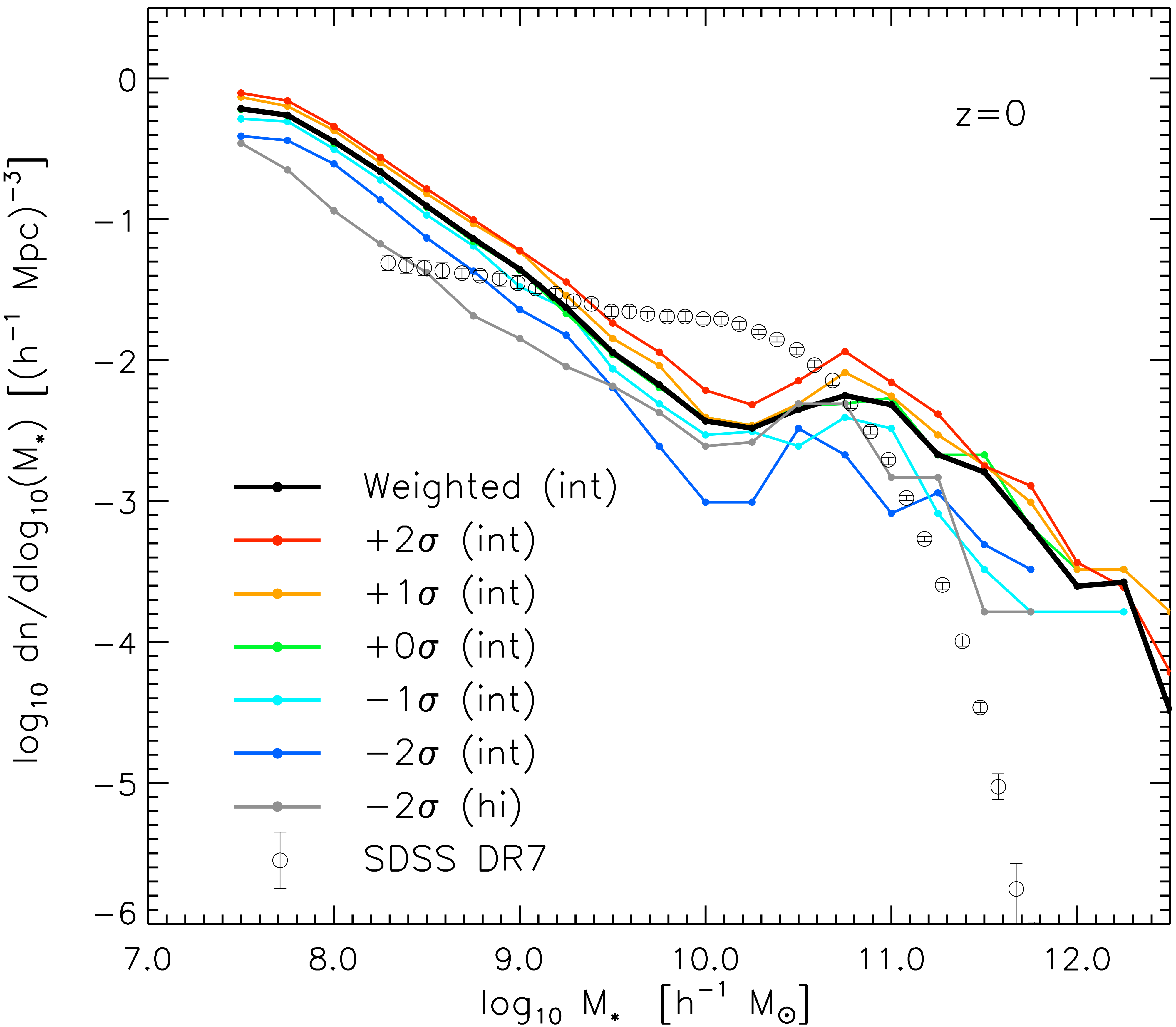
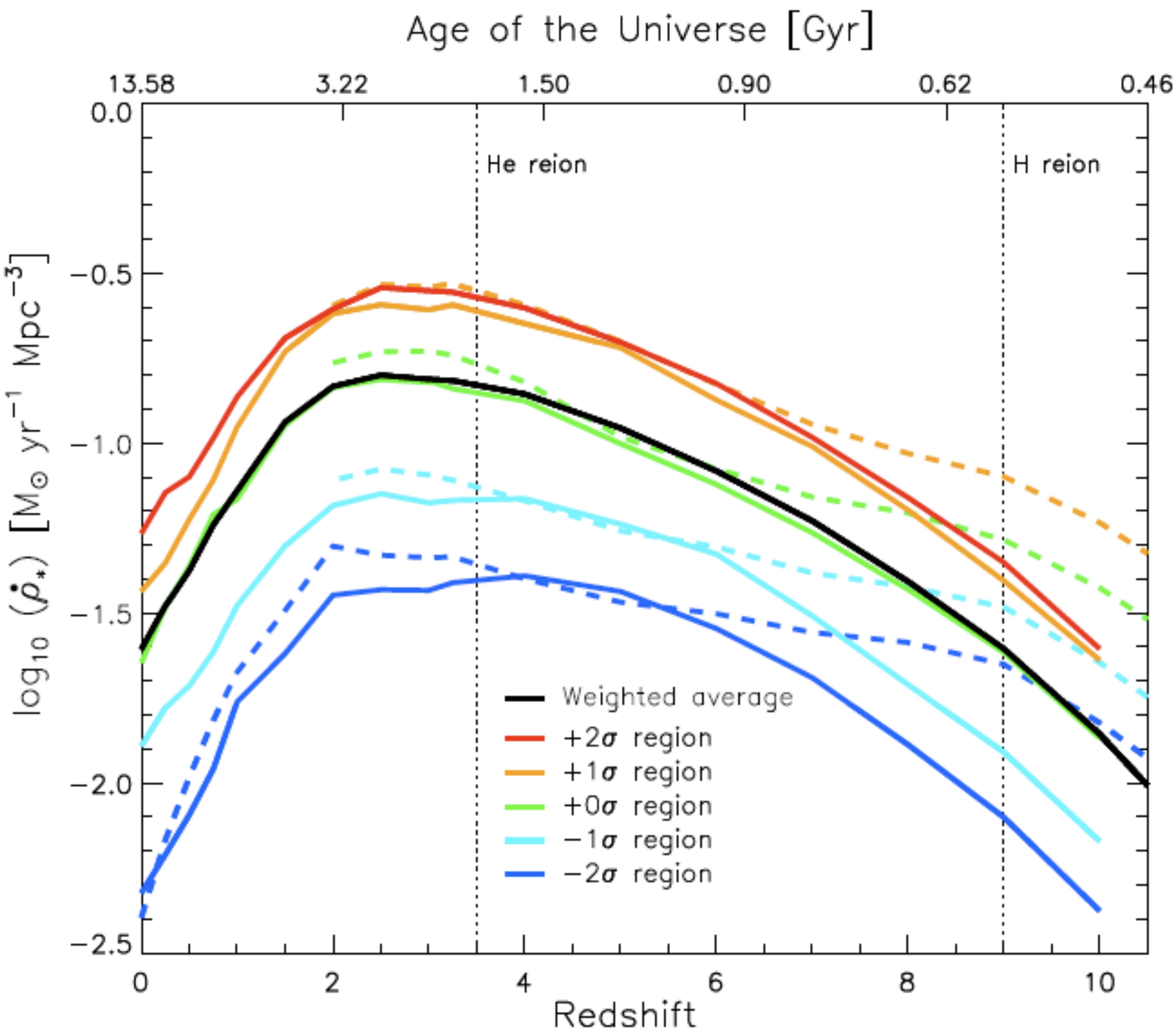
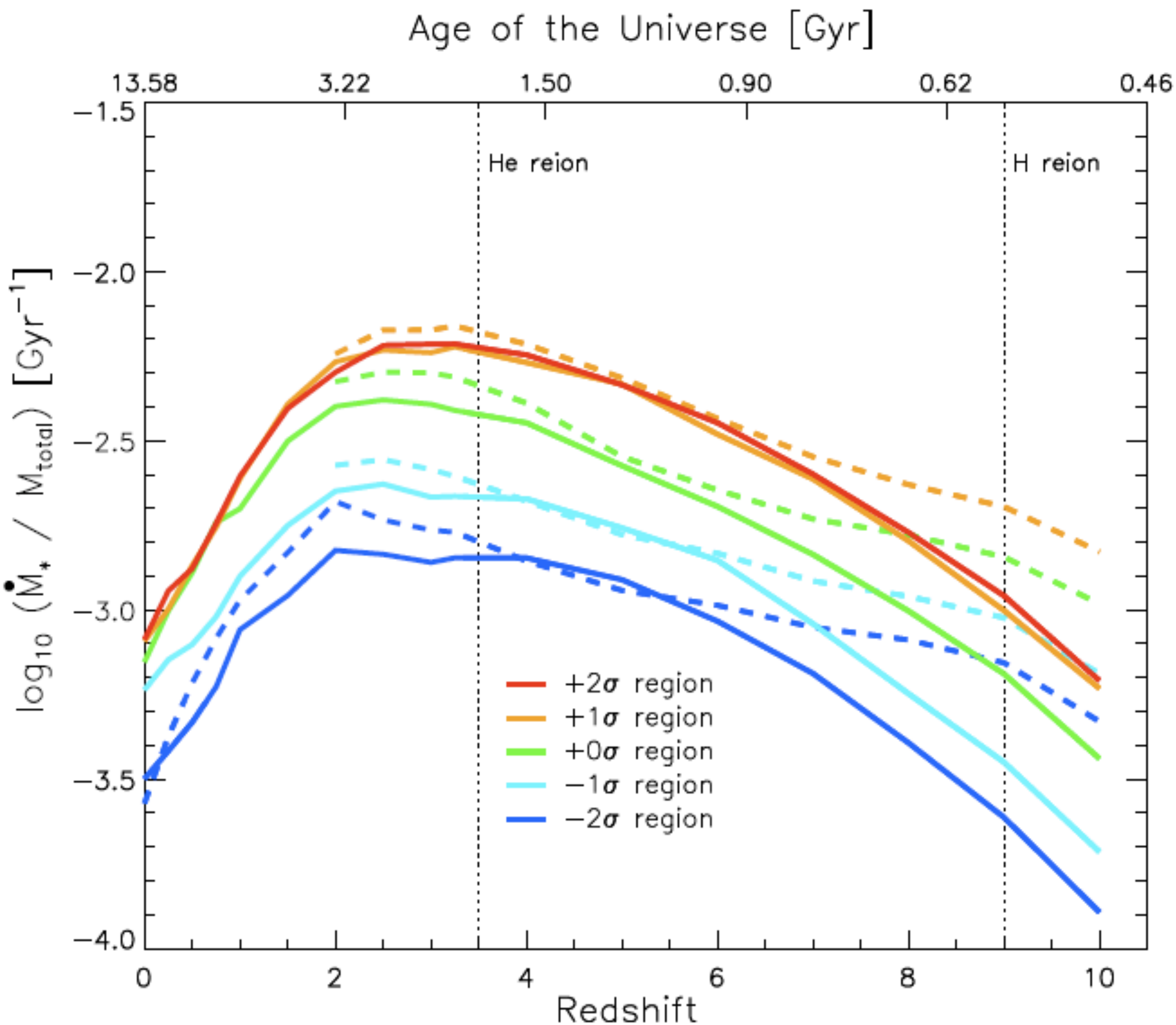


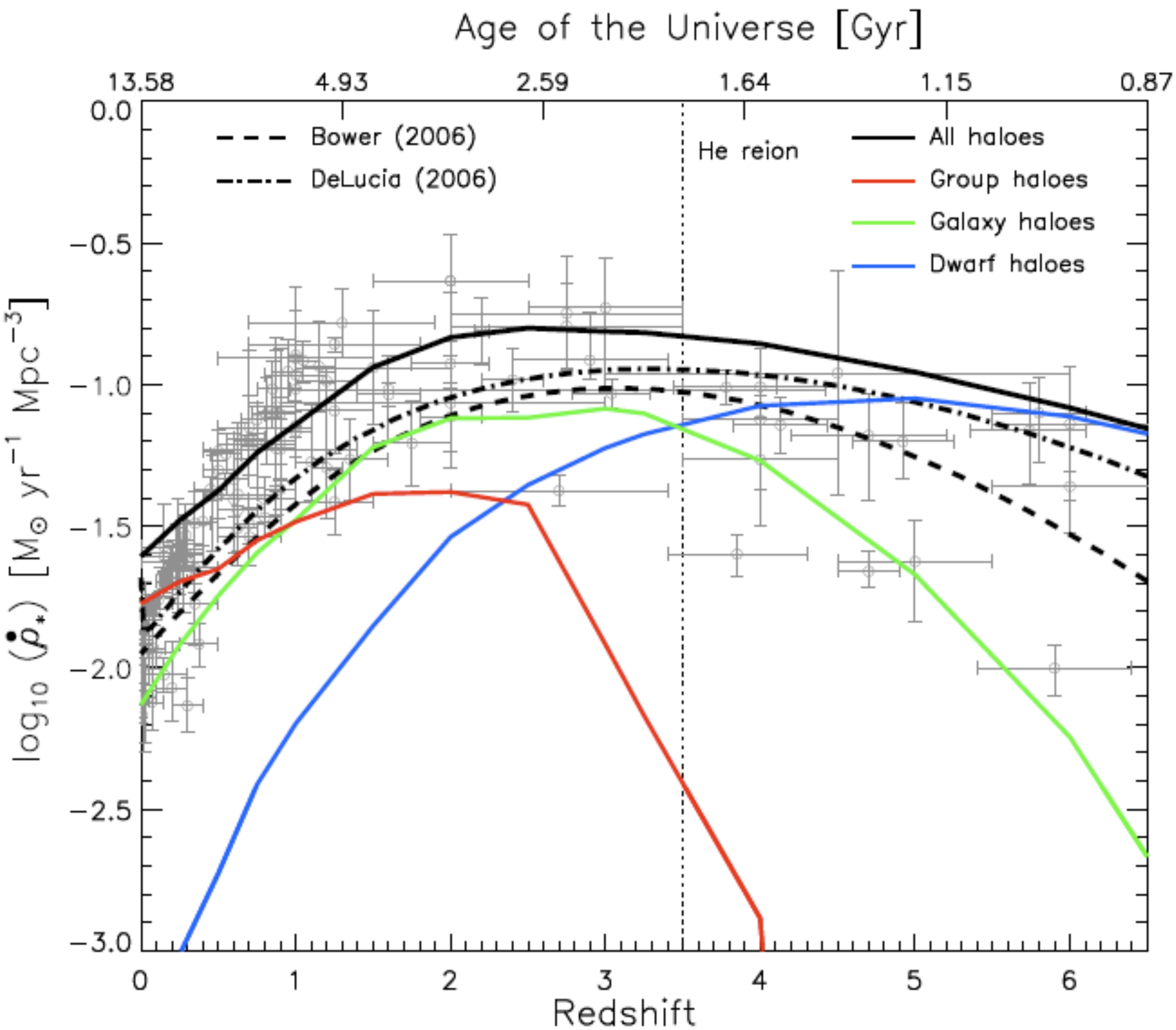
The star formation rate density



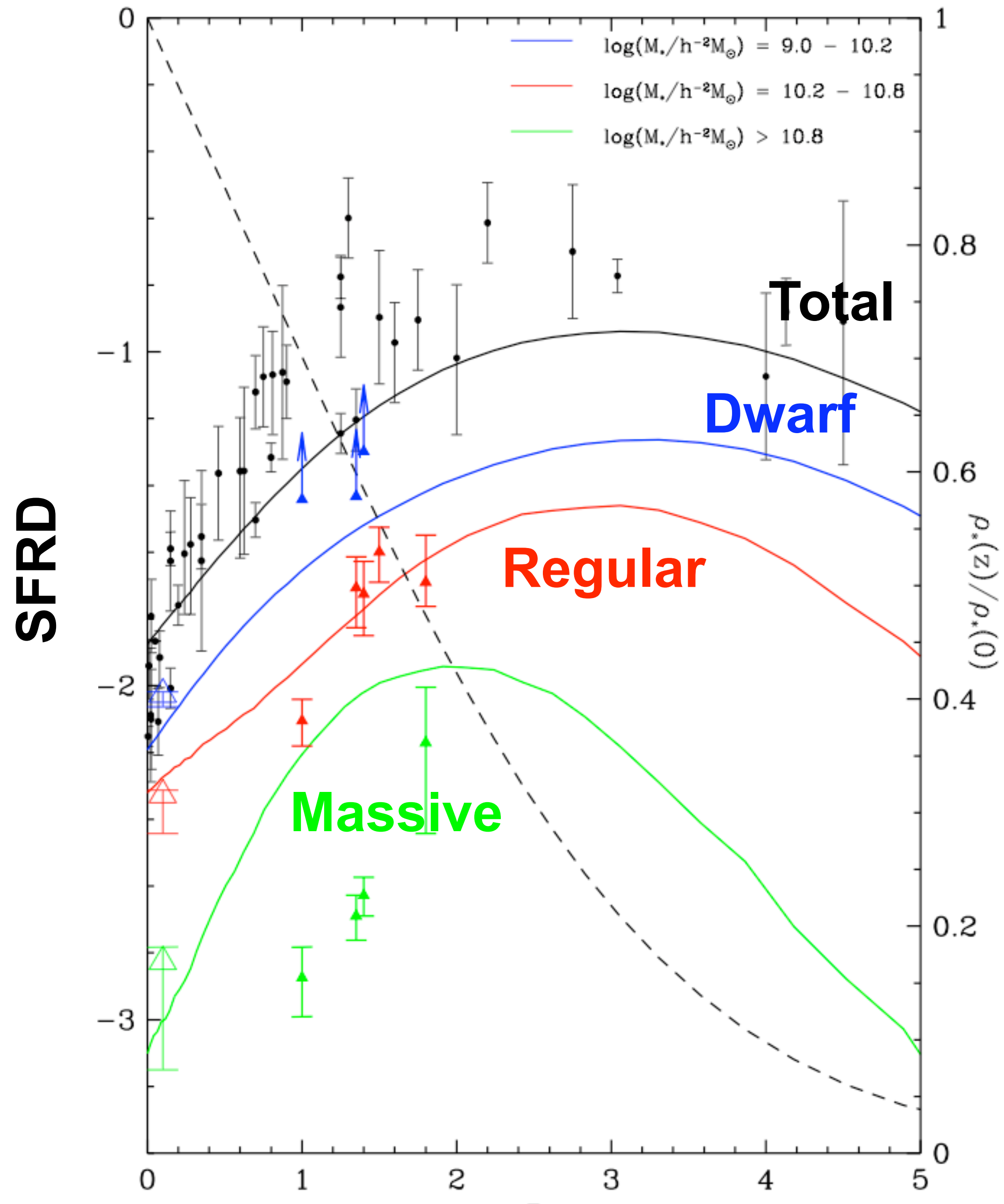
The star formation rate density (mass normalised)

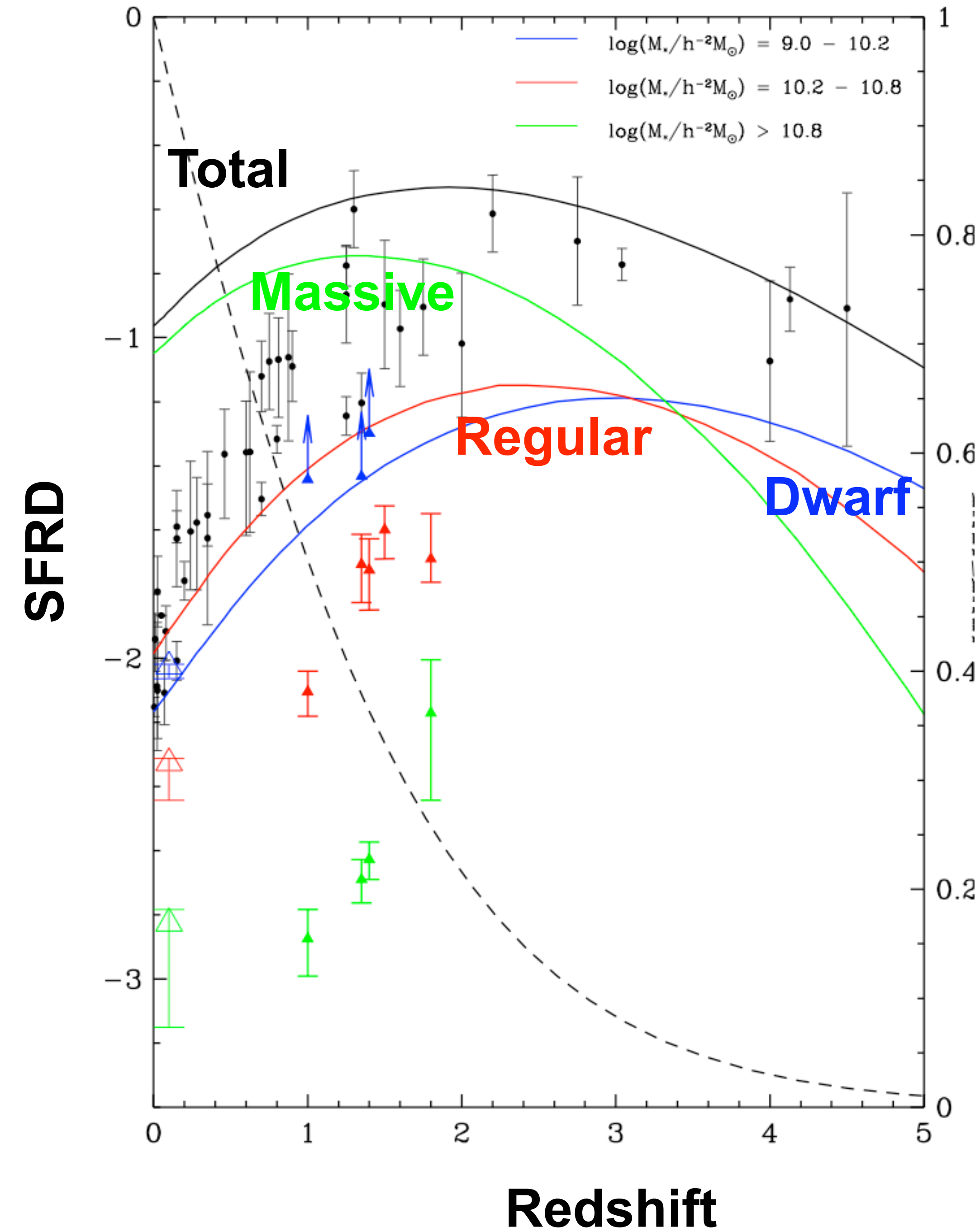


The star formation rate density is hierarchical



Durham semi-analytic model - broken hierarchy





Bowers+ ’06, with AGN

Dwarf galaxies always dominate

Massive galaxies become passive quickly

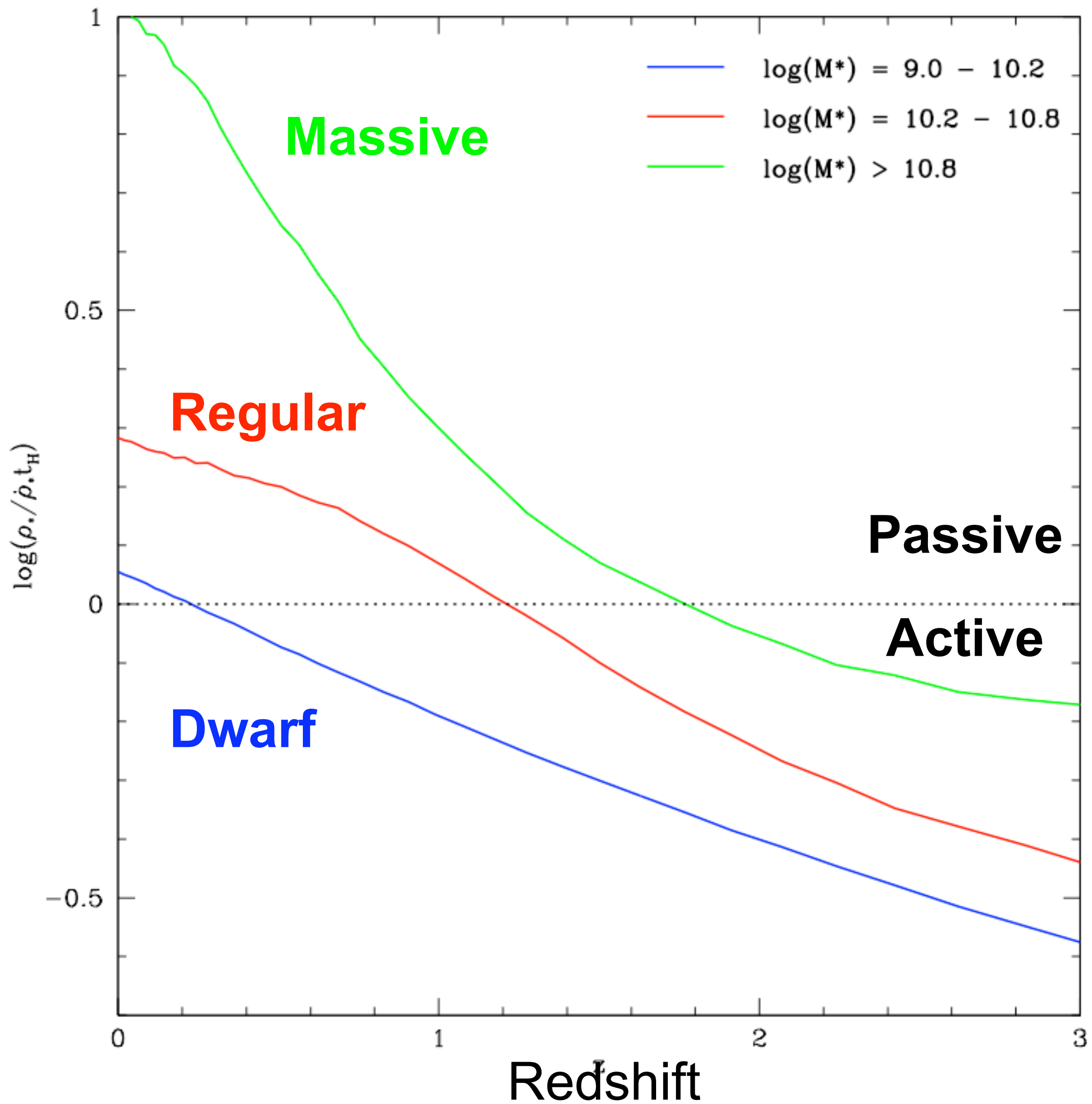
Bower+ ’06, AGN ‘off’

Massive galaxies dominate z<3

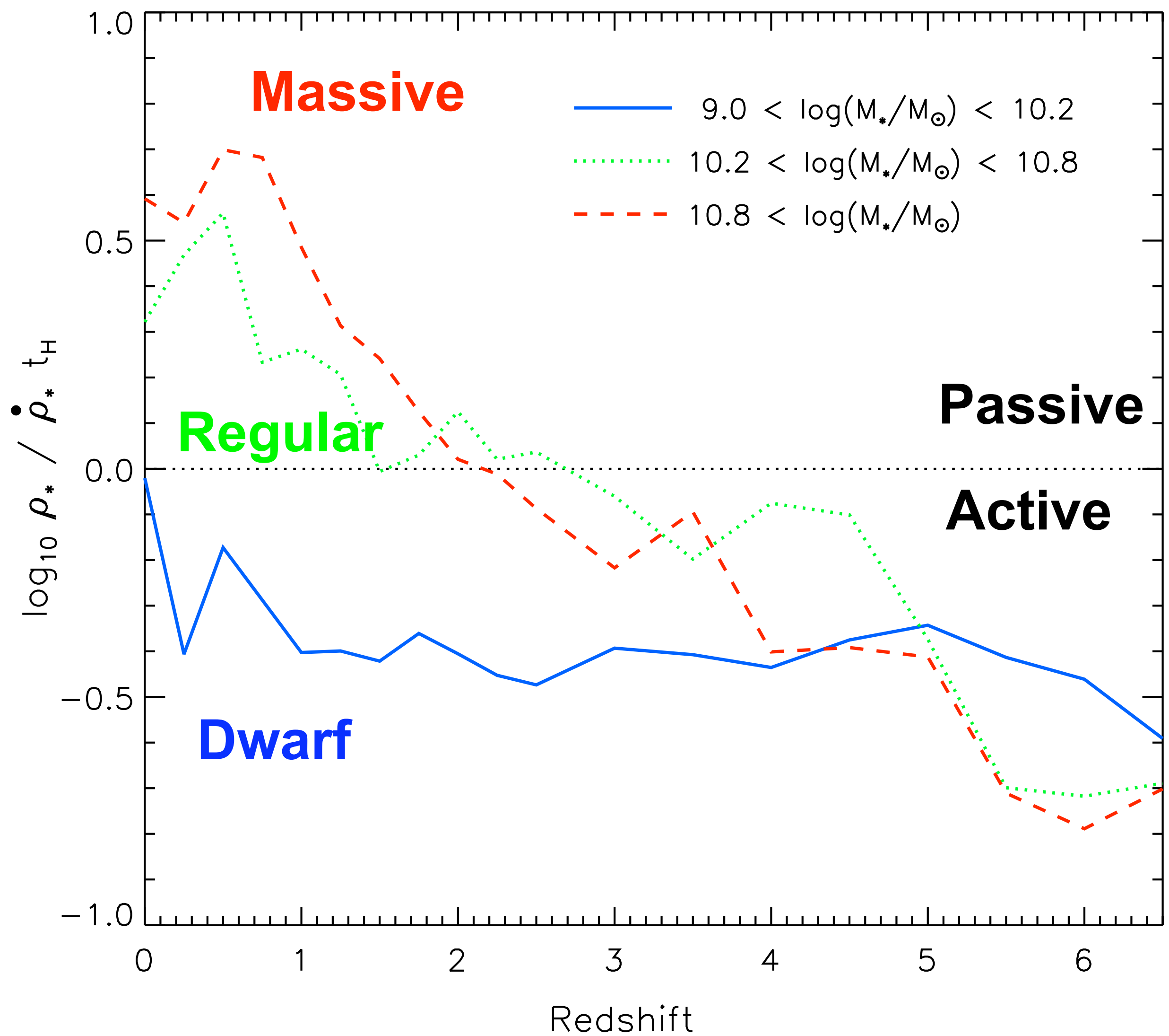
Qualitatively agrees with GIMIC

An aside on downsizing

Bower+ ‘06



GIMIC, Crain+ ’09



Ratio past average : present star formation rate

value > 1, past SFR dominates: passive

value < 1, present SFR dominates: active

Massive galaxies become passive earliest

Similar behaviour in GIMIC, w/out AGN

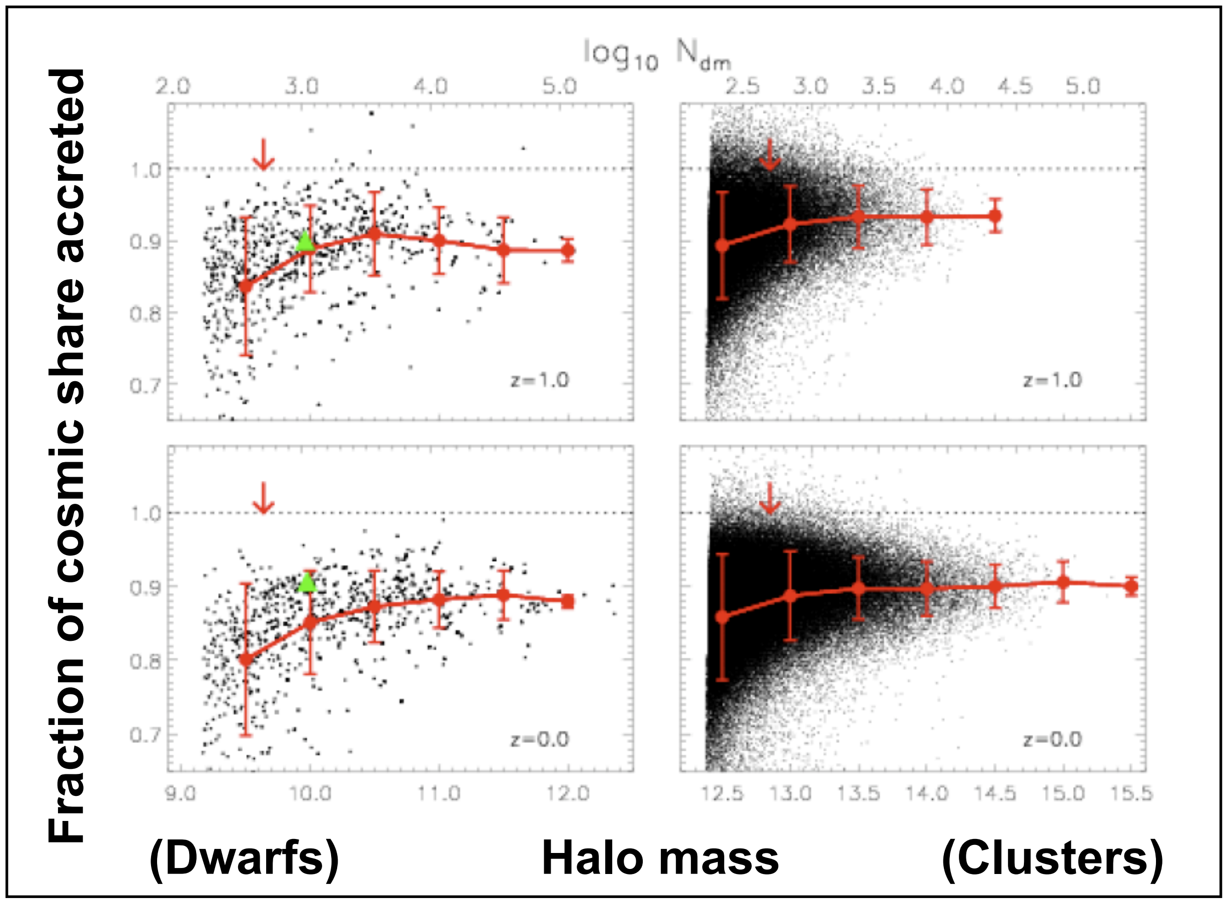
Massive galaxies passive before dwarfs

Just not as passive as with AGN

AGN exacerbate (not cause of) shutdown

Baryons (gas, stars) in haloes

Crain+ ’07, no cooling, SF or feedback

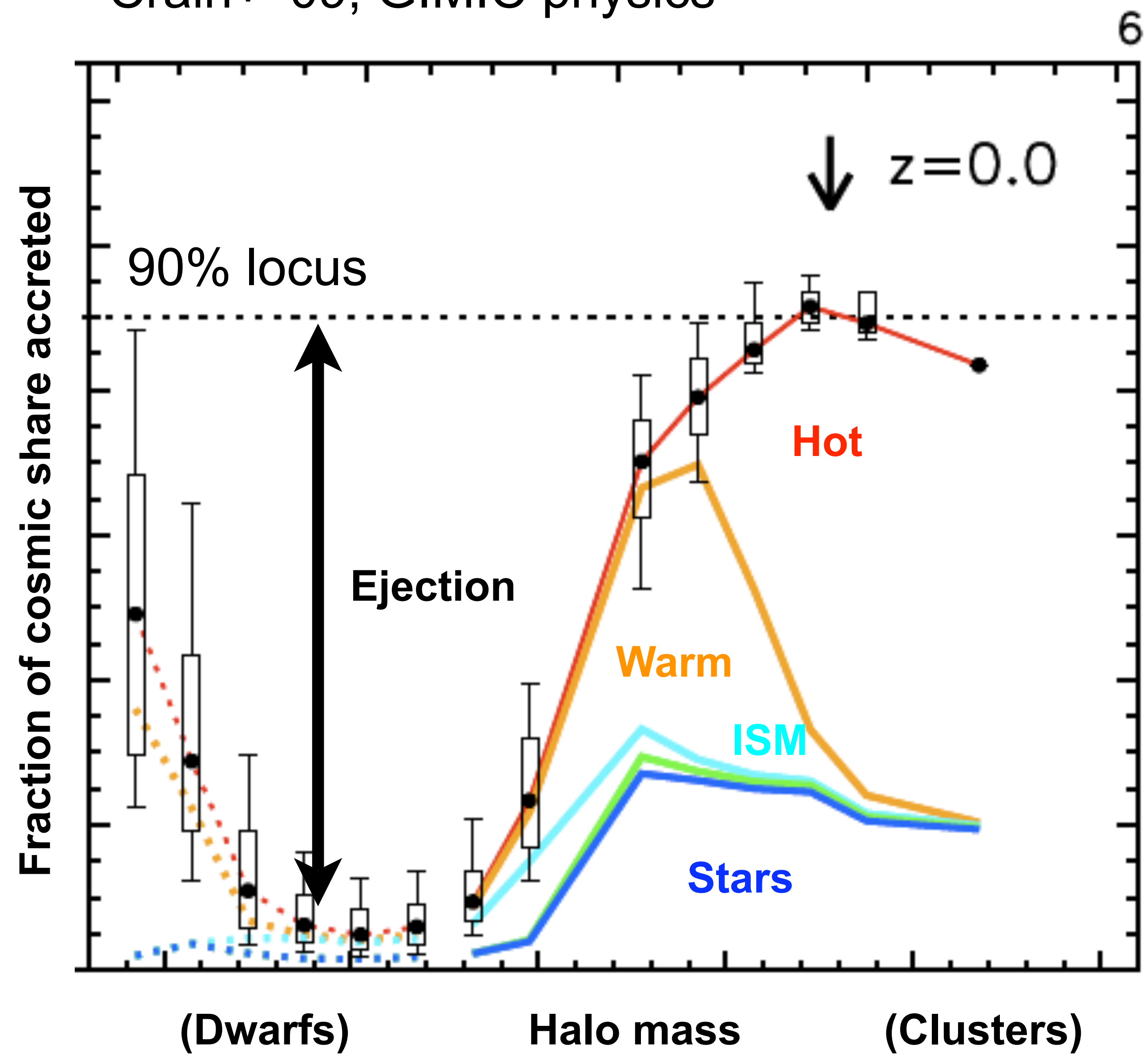


In non-radiative regime, the haloes accrete ~90% of their cosmic share of baryons

small losses due to assembly shocks
self-similar process, no preferred scale

Scales come from non-gravitational physics

Crain+ ’09, GIMIC physics

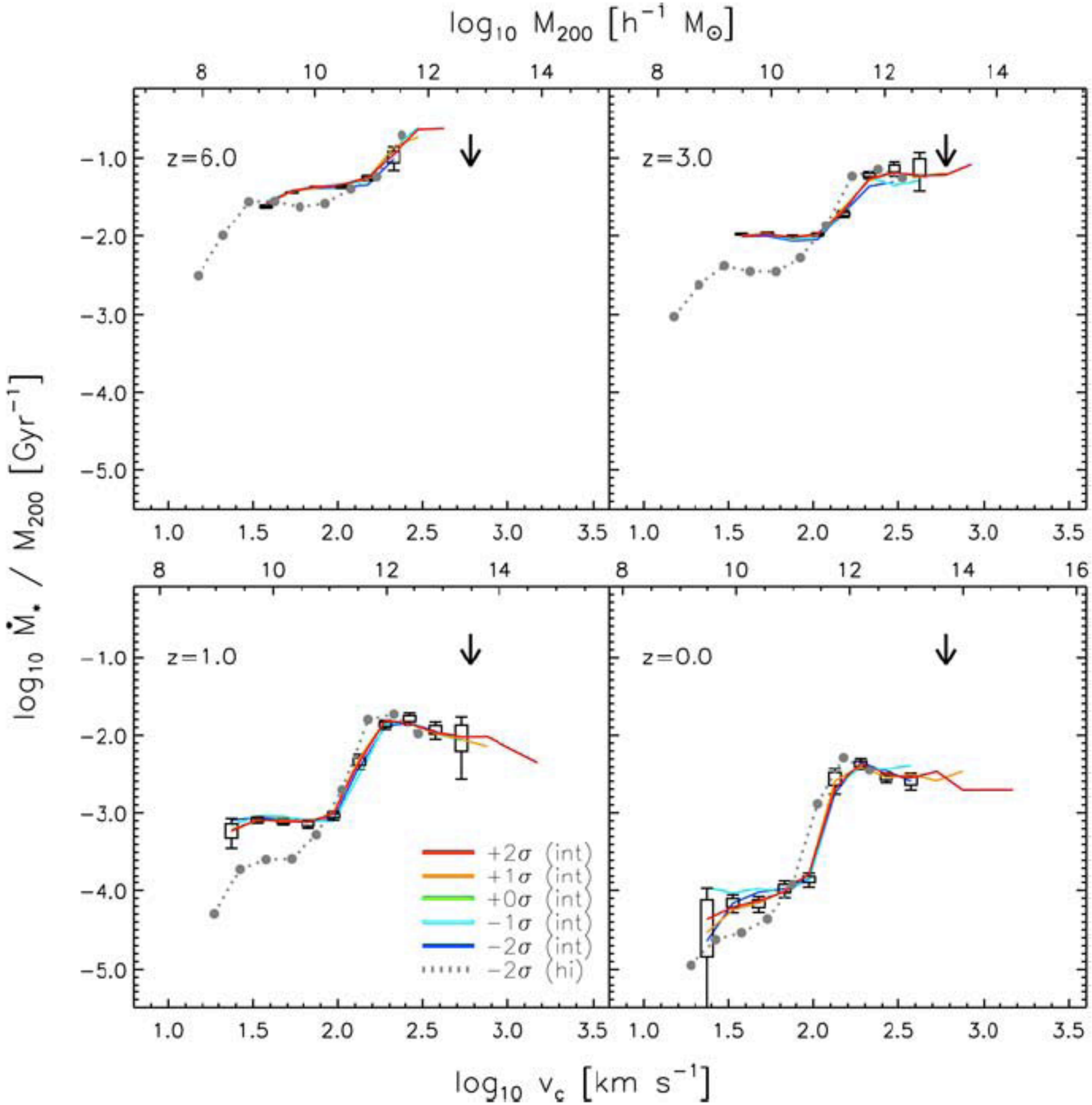


Arrow shows halo ‘velocity’ of 600km/s

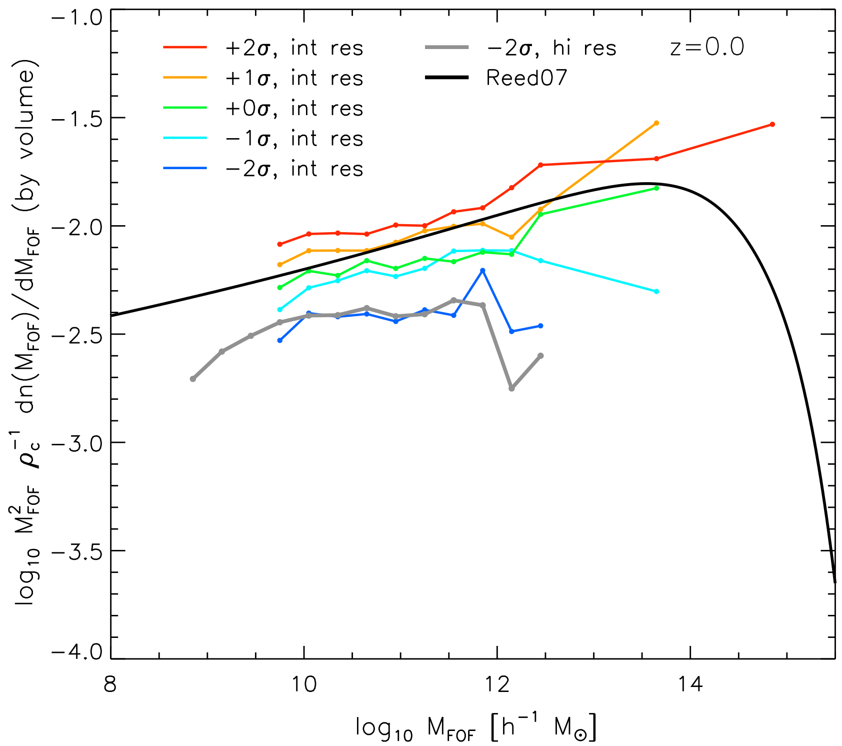
Below this scale baryons are ejected

Balance of heating & cooling establishes complex thermal structure: tough to observe!

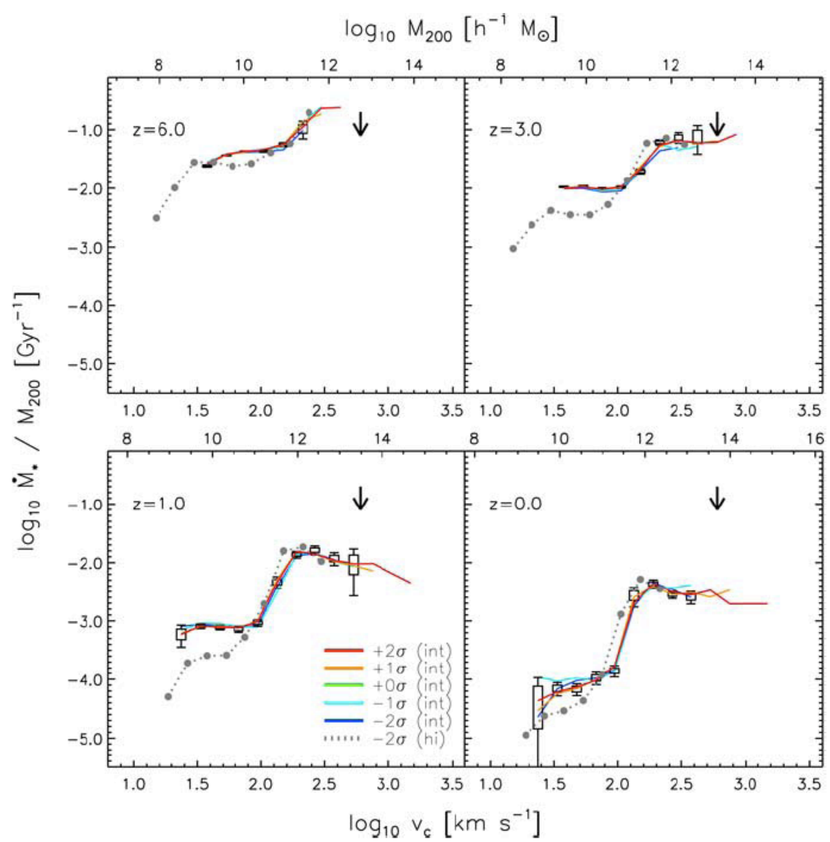
Halo star formation efficiency - SFR per unit total mass



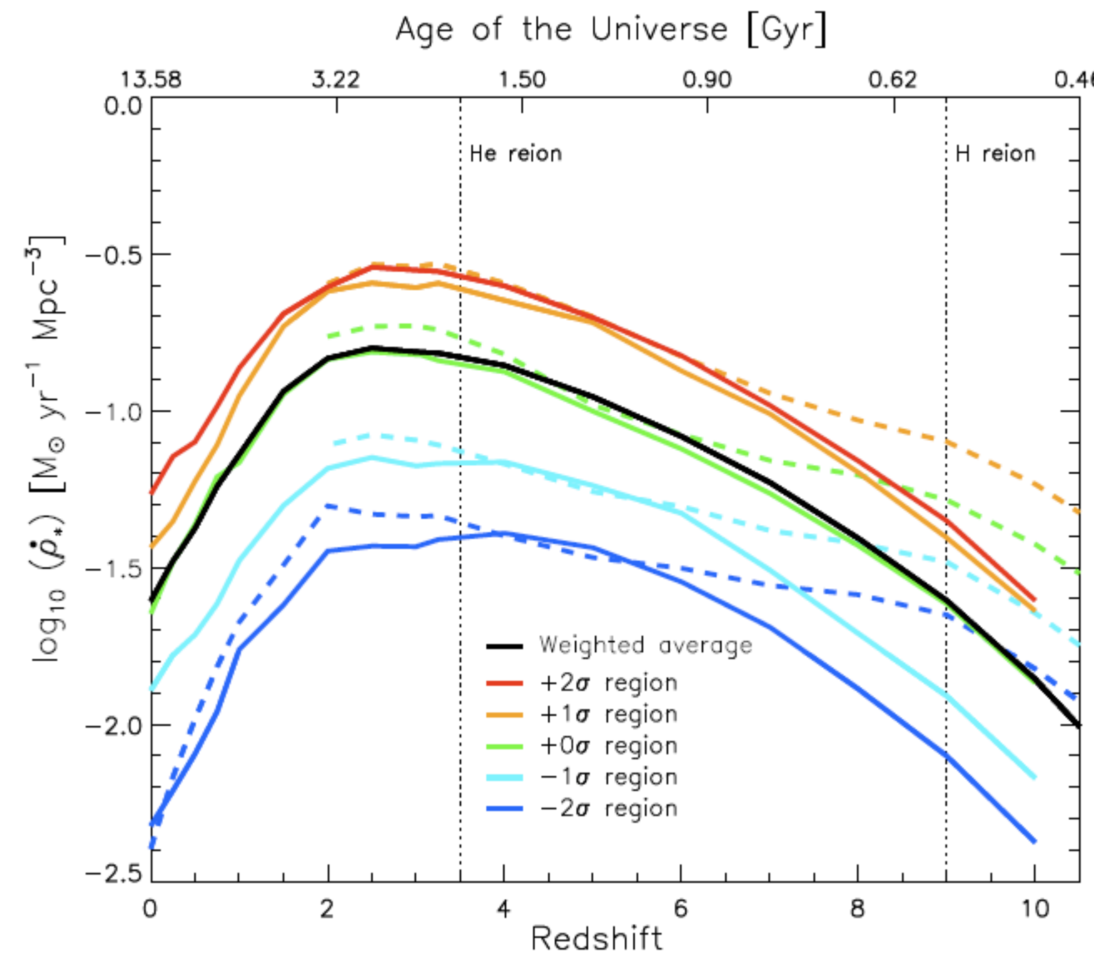
Halo mass is king - yet environment still matters



Environmentally varying halo mass function



Environmentally invariant halo SF efficiency



Star formation rate density

Case study of hydro benefits: the X-ray halo problem

Analytic galaxy formation models in CDM:

- Disc galaxies are common, but fragile
- ‘Easy come, easy go’ - must still be forming today
- Fuelling by cooling flow from hydrostatic halo gas at virial temperature of 10^6K

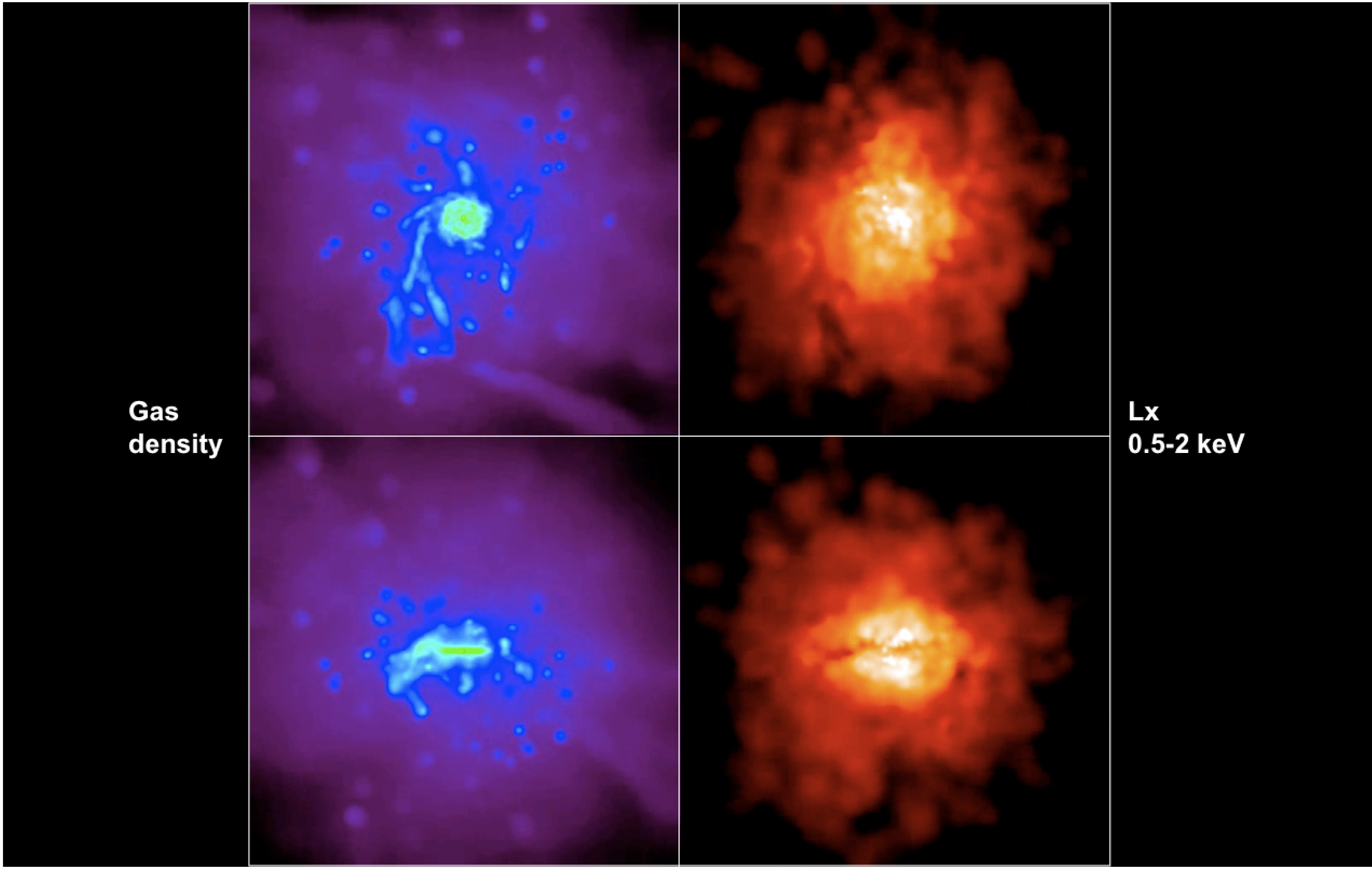
Cooling should be in soft X-ray band, at fluxes readily detected by ROSAT

No detections with ROSAT (e.g. Benson+ ’00)

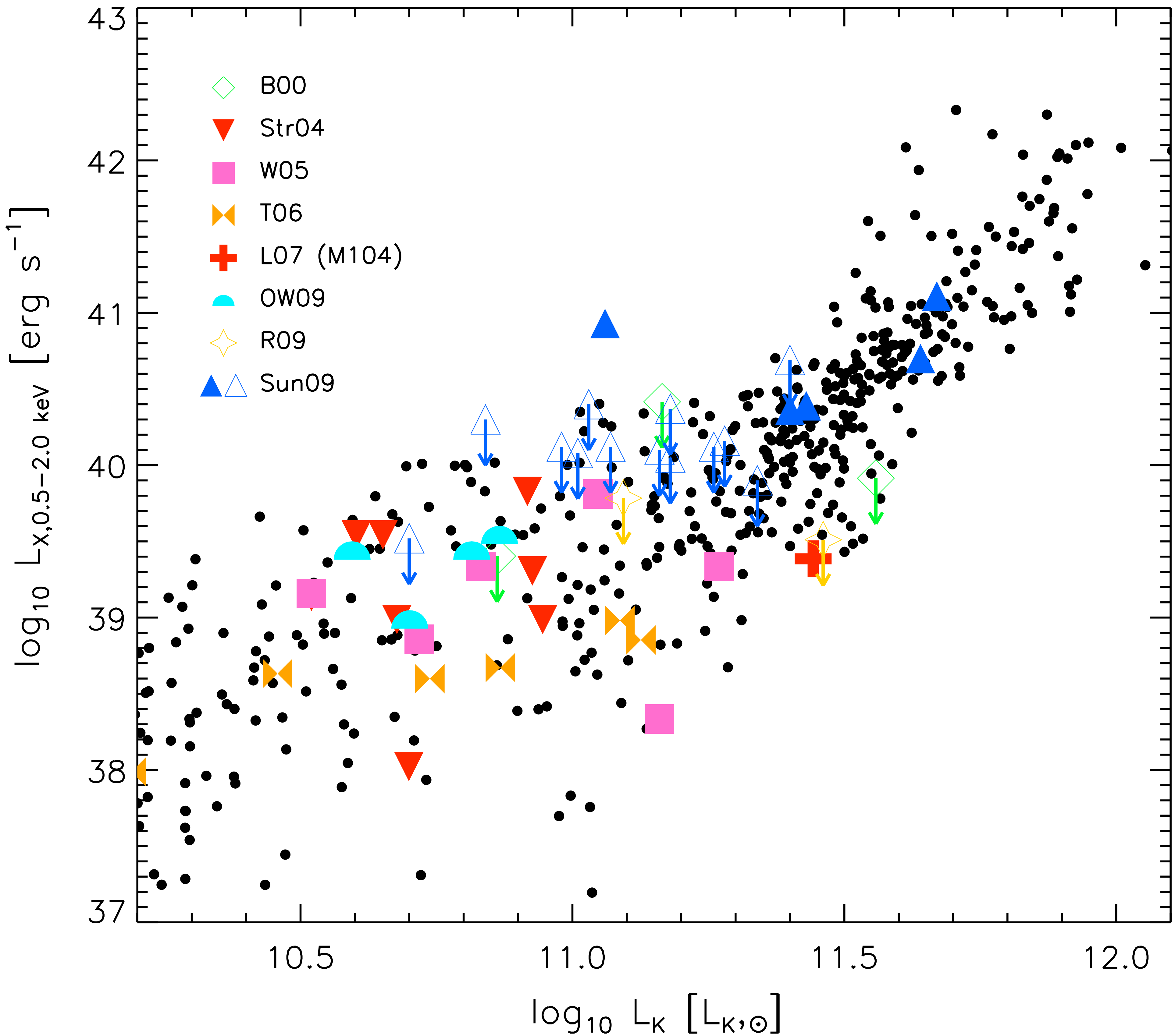
Handful of XMM, Chandra detections, inferred luminosities 1-2dex below predictions

Cited as a problem for CDM

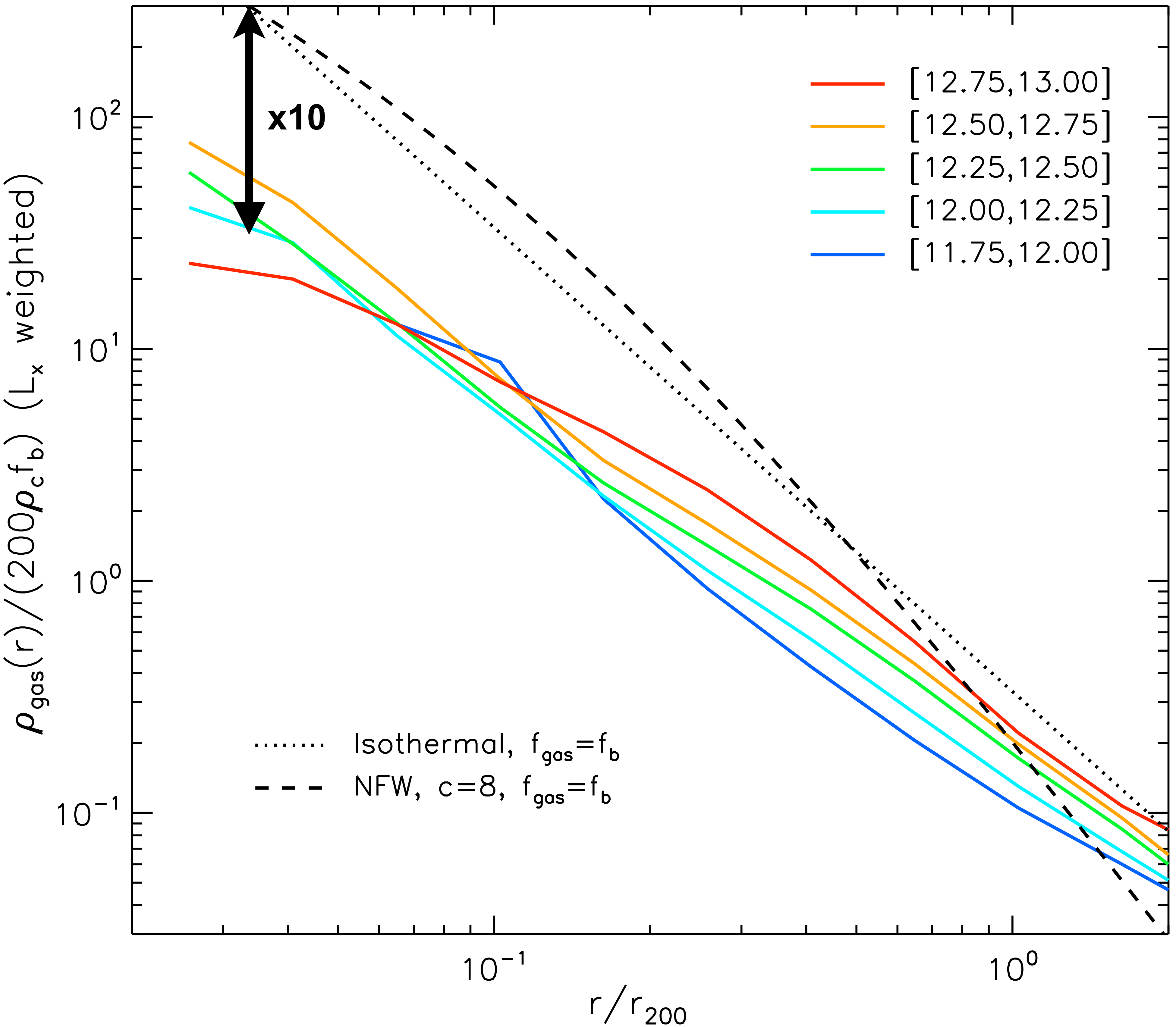
Might it be that model assumptions merely inaccurate? Can test with hydro.


Gas
density
Lx
0.5-2 keV

Acid test: Lx - Lk relation



Bottom line: SF and ejection alter hot gas radial profile



Summary

Novel techniques required to keep pace with observations

Use of ‘zoomed initial conditions’, or ‘simulations within simulations’ enables well-resolved galaxies to be studied within a cosmological context

Halo mass is key driver of star formation history

The volume-normalised star formation rate differs on multi-Mpc scales by up to ~x10. Driven by halo mass function rather than an environmental effect on galaxies.

The importance of black holes to the cosmic star formation history remains an open, and critical, issue.

Hydro highlights weaknesses in analytic prescriptions

Gas treatments in (semi-)analytic models can be over-simplified, leading to a mis-interpretation of observational findings, e.g. X-ray halo problem.