GIMIC:
Galaxy-Intergalactic Medium Interaction Calculation

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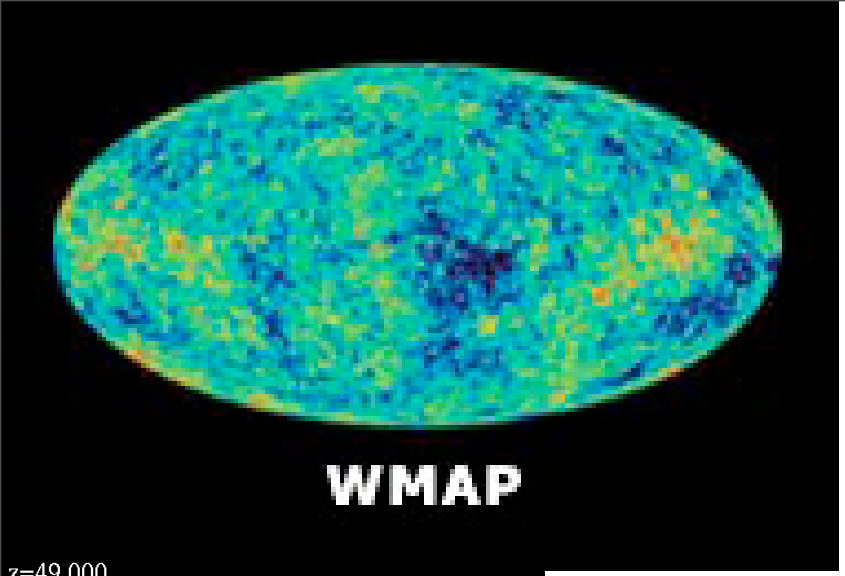
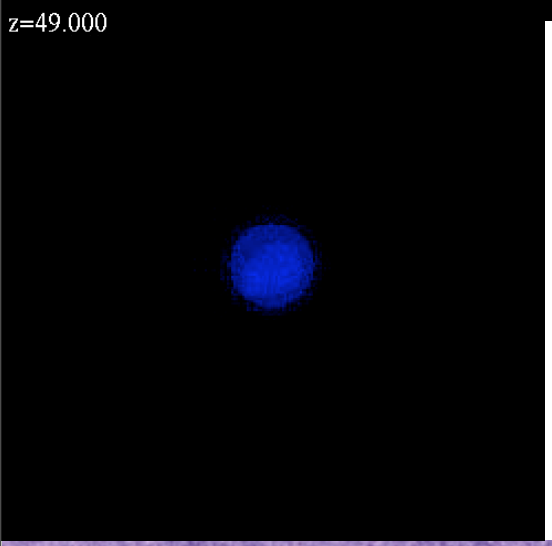
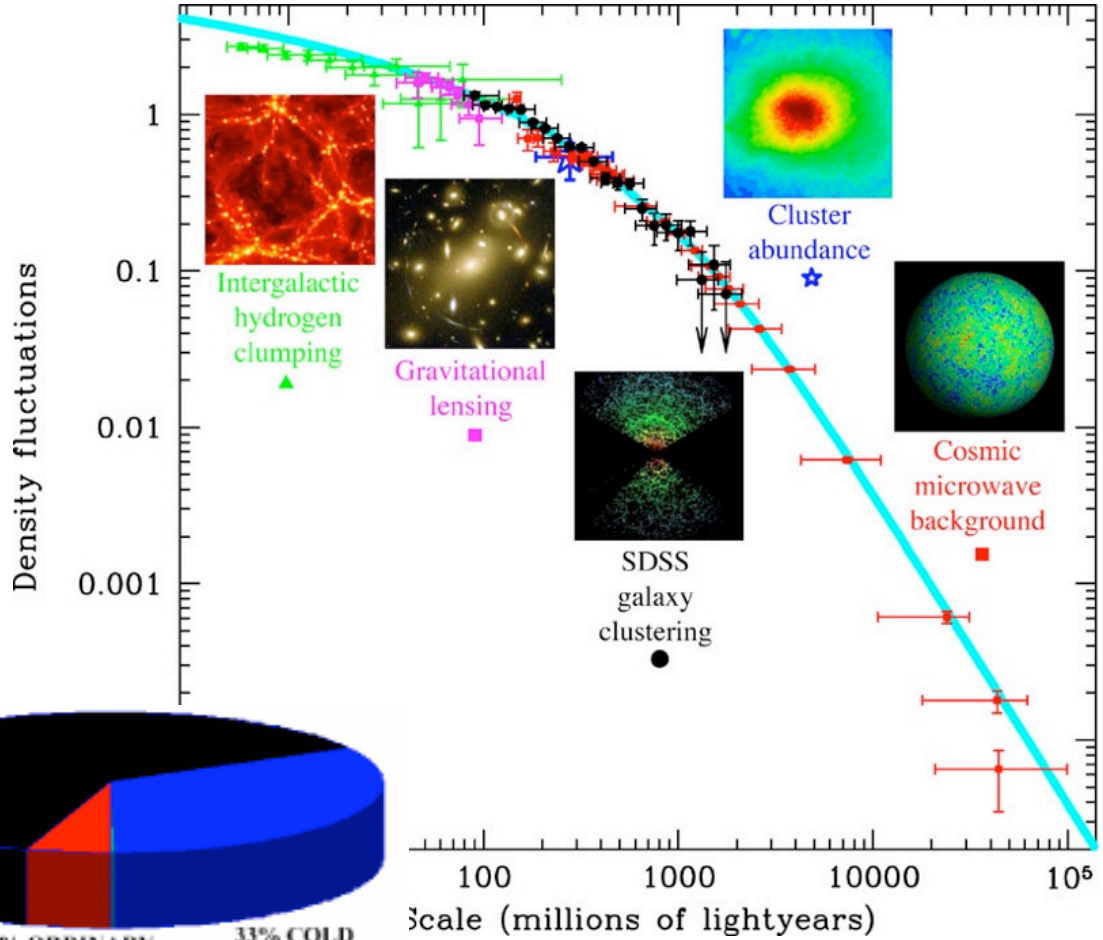
V Springel S White (MPA)
L Tornatore (Trieste)

Contents:

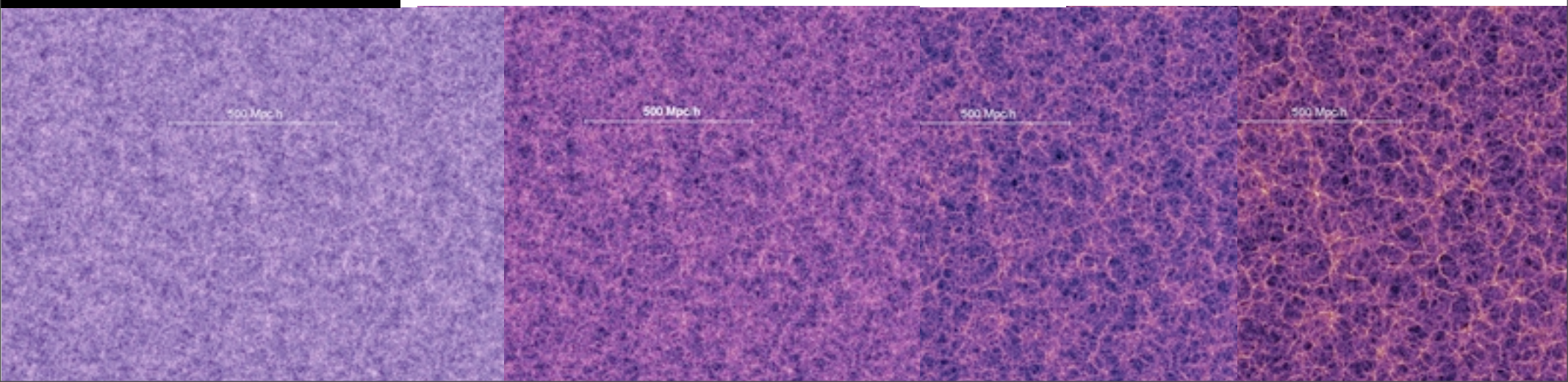
- Introduction
- Aim of project
- Results
- And something completely different
- Conclusions

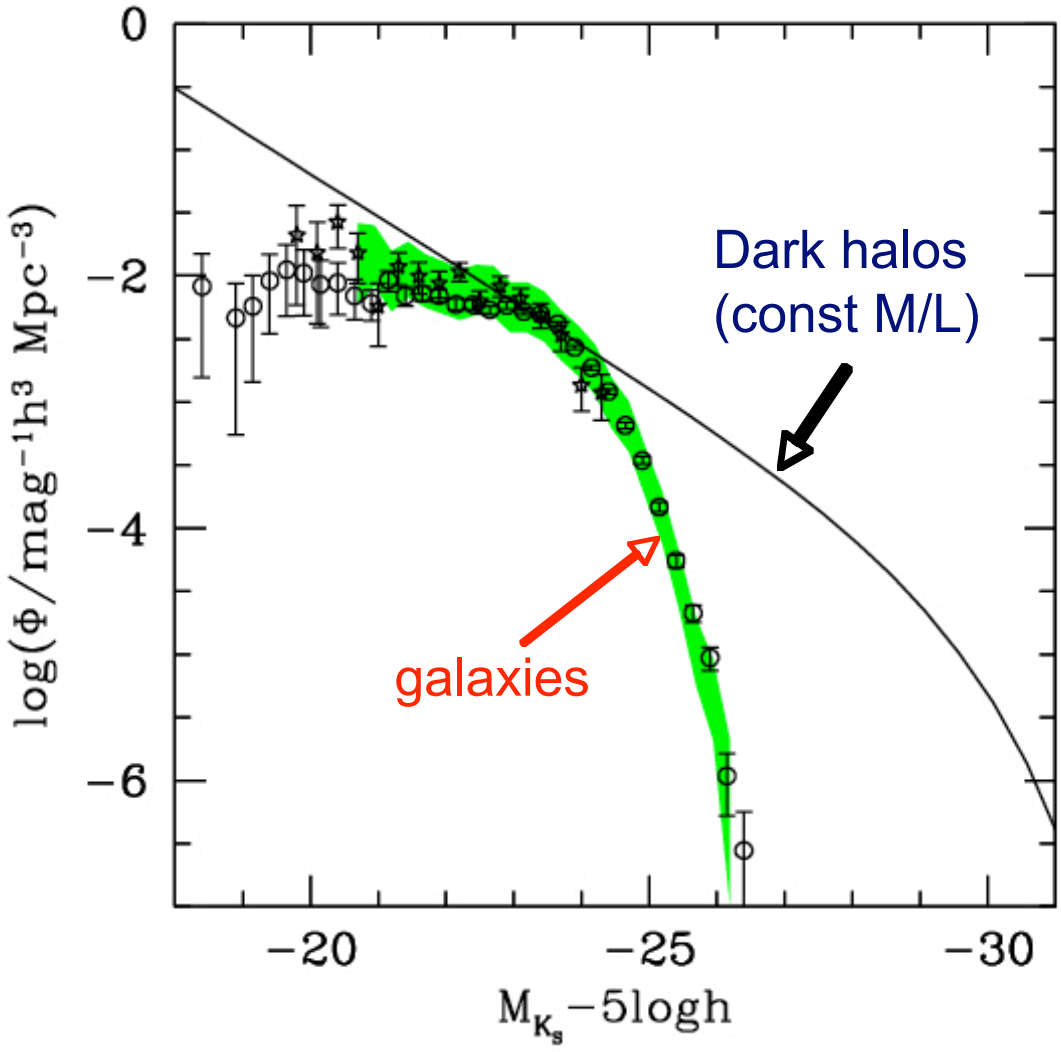

WMAP


z=49.000


Density fluctuations
1
0.1
0.01
0.001
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
SDSS galaxy clustering
Cosmic microwave background
100
1000
10000
10⁵
Scale (millions of lightyears)


62% DARK ENERGY
5% ORDINARY MATTER
33% COLD DARK MATTER


500 Mpc/h
500 Mpc/h
500 Mpc/h
500 Mpc/h


0
−2
−4
−6
log(Φ/mag⁻¹h³ Mpc⁻³)
−20
−25
−30
M_Ks −5logh
Dark halos
(const M/L)
galaxies

GIMIC/OWLS project

Leiden:
Claudio Dalla Vecchia
Joop Schaye

Crain, Robert

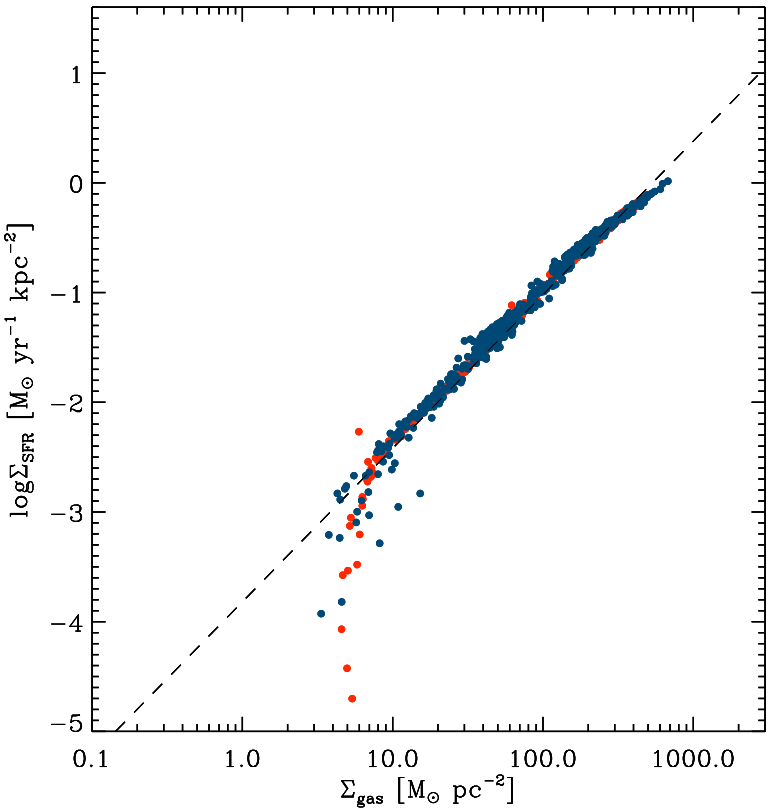
Trieste:
Luca Tornatore

Aims:
- simulate IGM and galaxies together
- investigate numerical/physical uncertainties

MPA:
Volker Springel

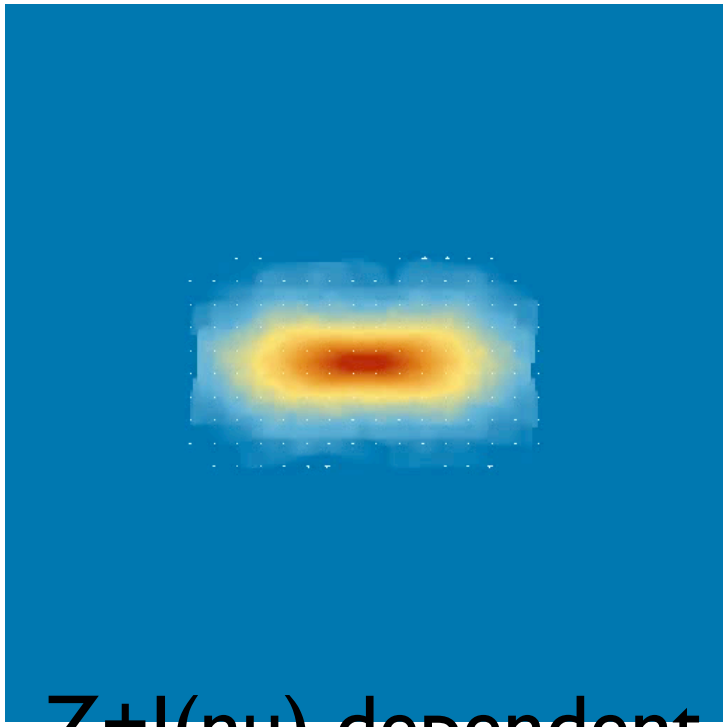
- Gadget 3
- Star formation guarantees Schmidt law
- Stellar evolution
- Galactic winds
- Metal-dependent cooling

SFR follow Schmidt-law

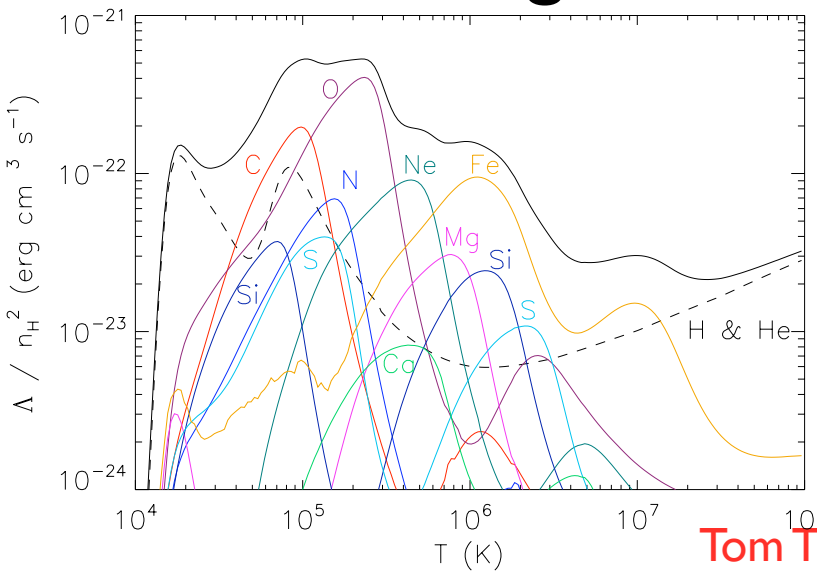


Code in brief

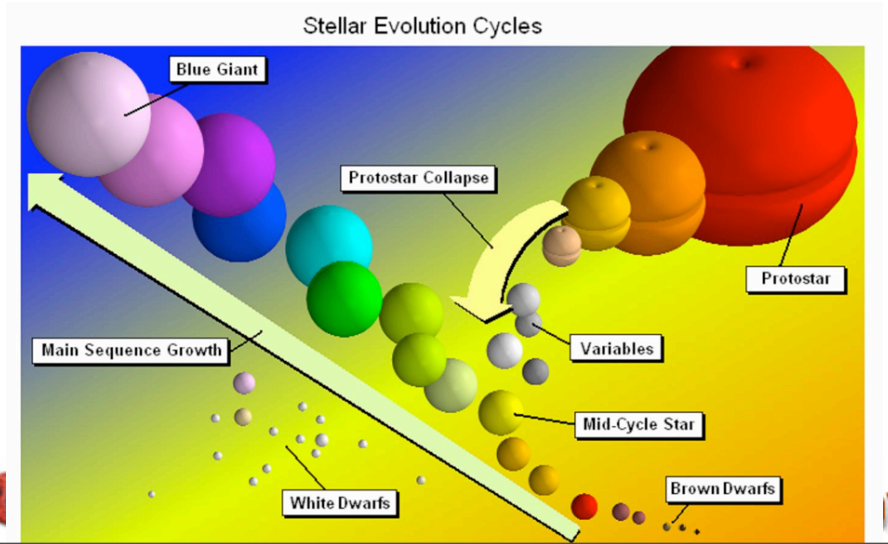
Galactic winds



Z+J(nu) dependent cooling



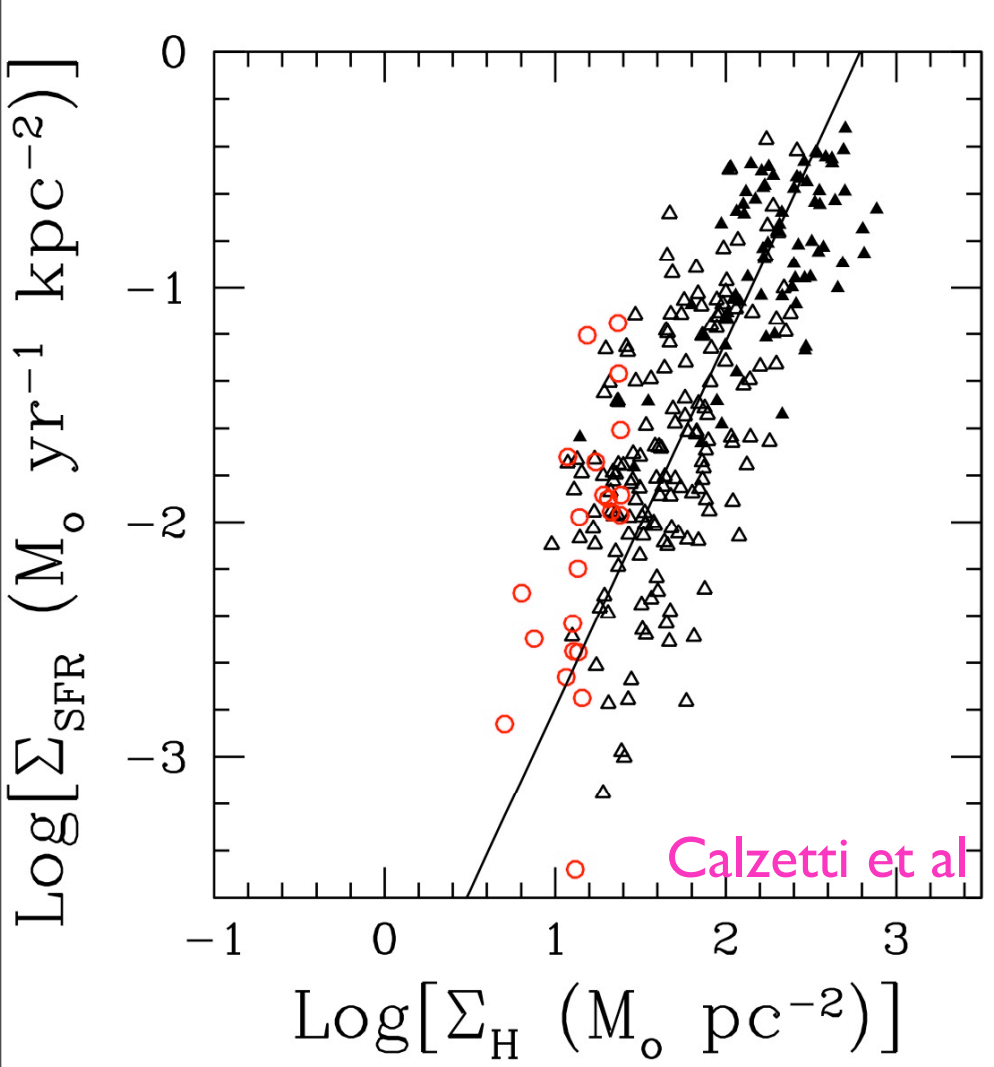
Stellar evolution



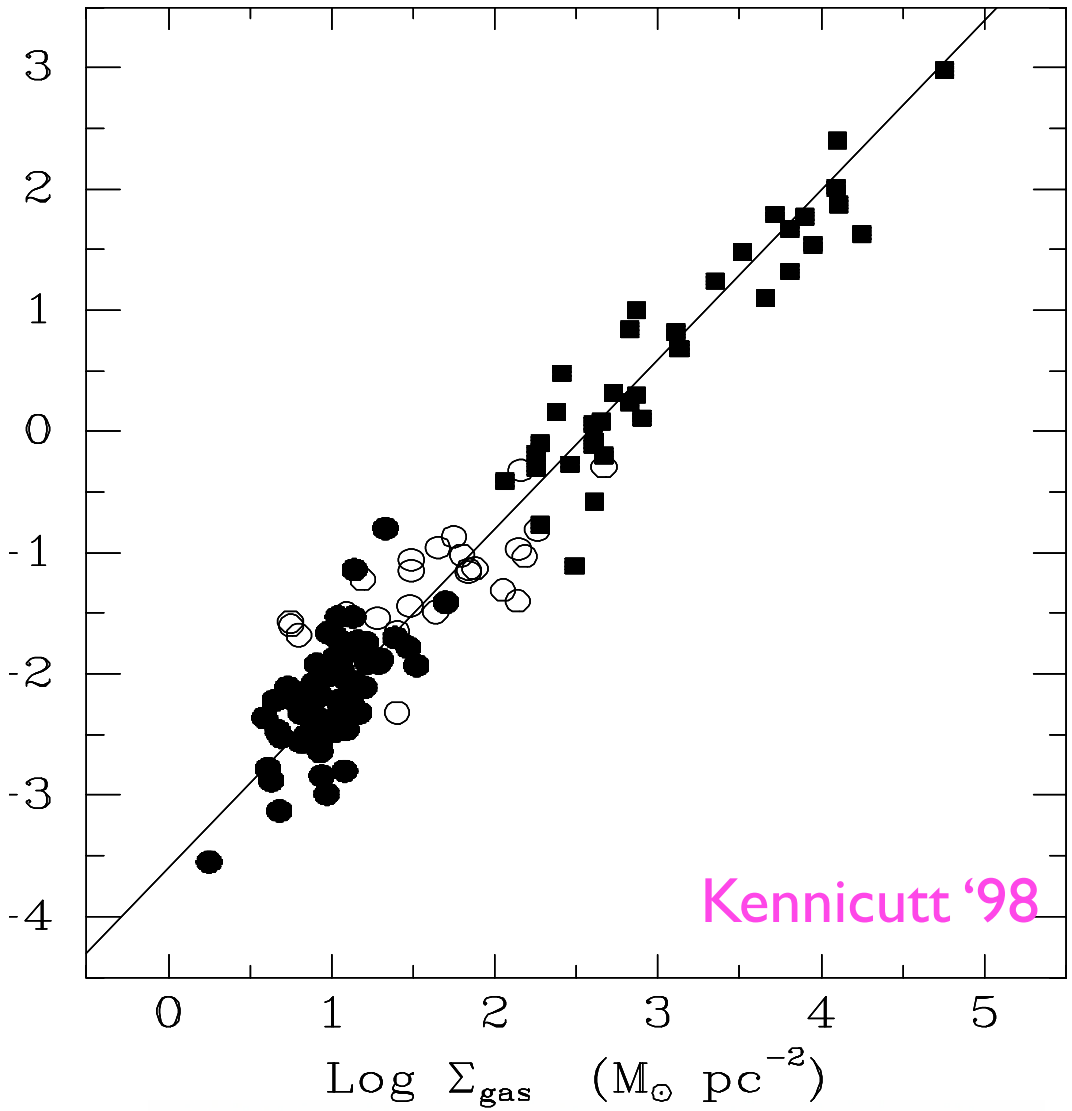
Star formation: what we want: Schmidt law

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{n} \quad (n = 1.4 \pm 0.15)$$

Local: same galaxy



Global: different galaxies



How to obtain Schmidt law? Sub-grid model for SF and ISM

- Insufficient resolution to model multiphase ISM
- Need effective pressure of unresolved, multiphase ISM
- Need star formation law that reproduces observed threshold and Schmidt law with the minimum number of free parameters
- We do not want to simulate more than we can

J Schaye

Sub-grid model for SF and ISM

- What goes in
  - Effective equation of state (gives the pressure of the gas)

$$P \propto \rho_{\rm gas}^{\gamma_{\rm eff}} \quad (\rho_{\rm gas} > \rho_{\rm thr})$$

  - Schmidt law (surface densities)

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{n}$$

  - Surface density threshold

- What comes out
  - Volume density star formation law
  - Volume density threshold

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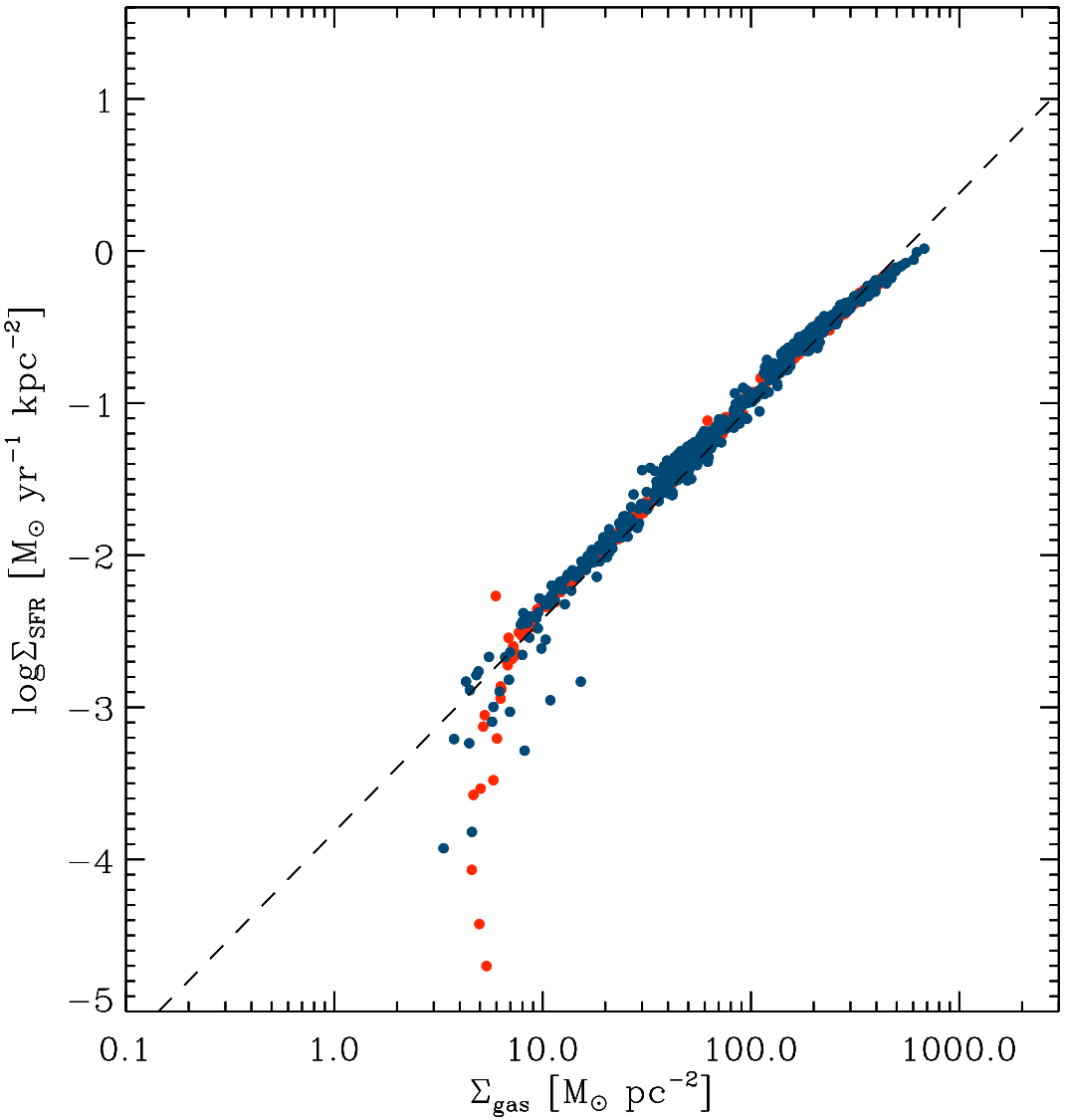
Implementation guarantees a Schmidt law



- $N_{\rm part} = 100$
- $N_{\rm part} = 12$

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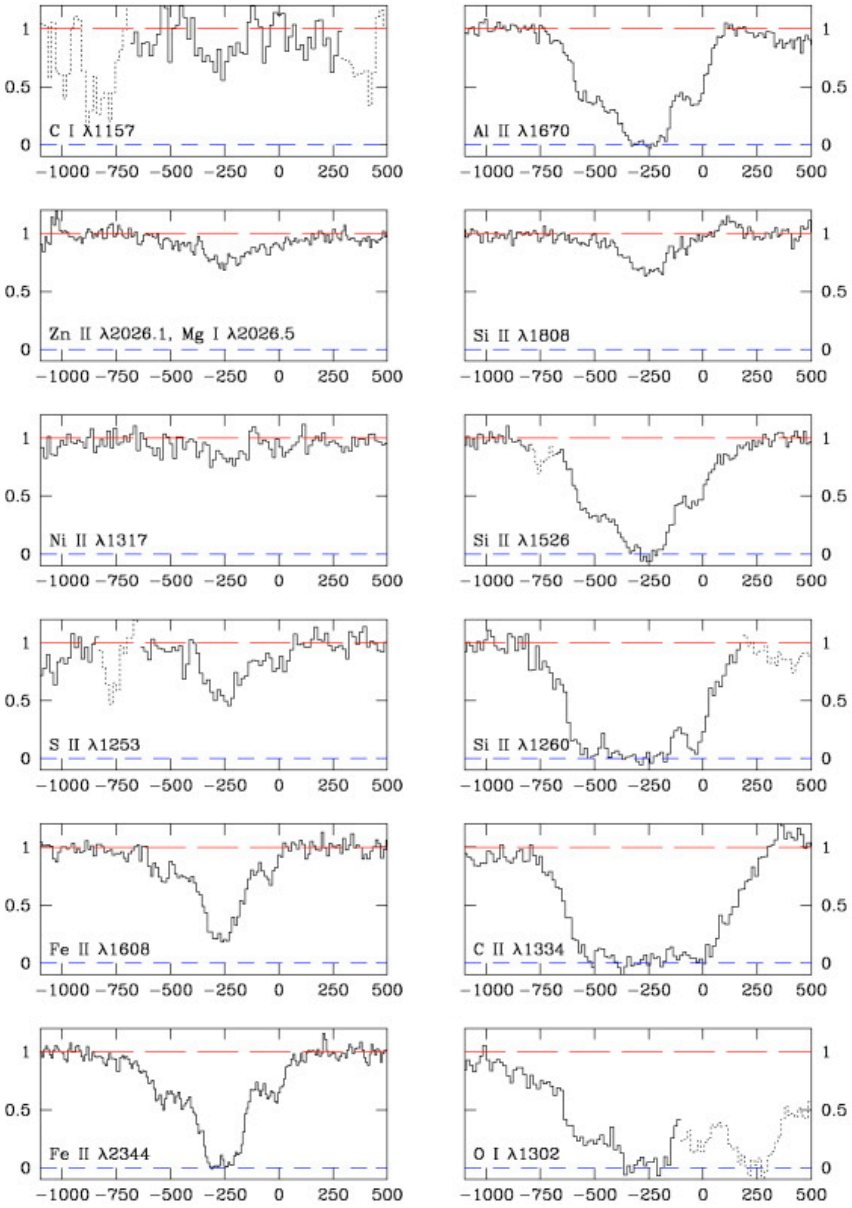
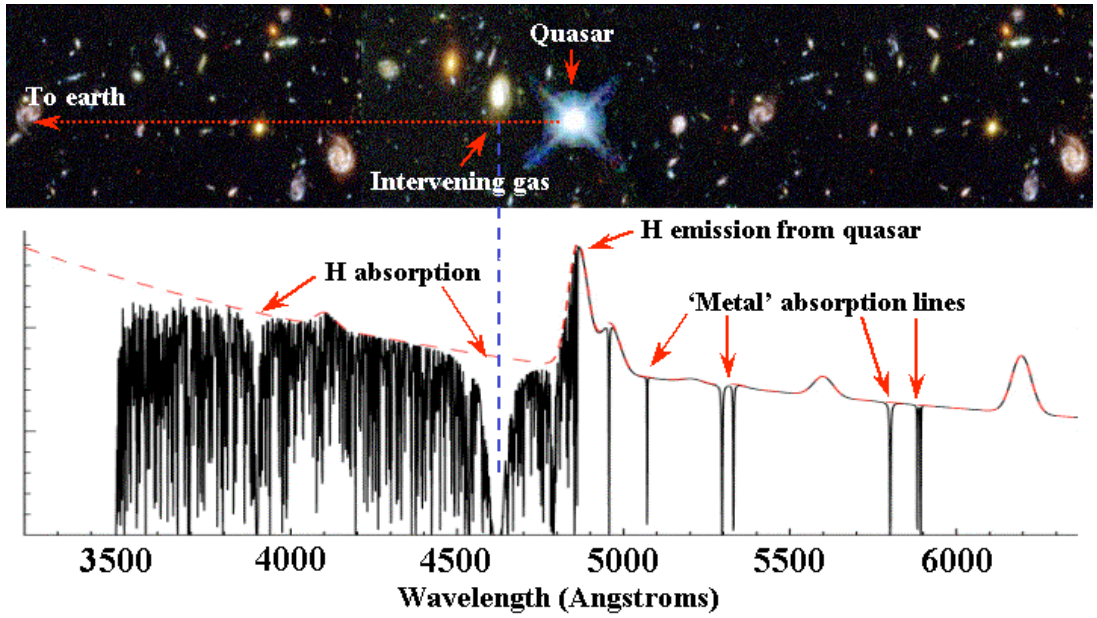
Evidence for galactic winds:



At high z: Pettini et al 02

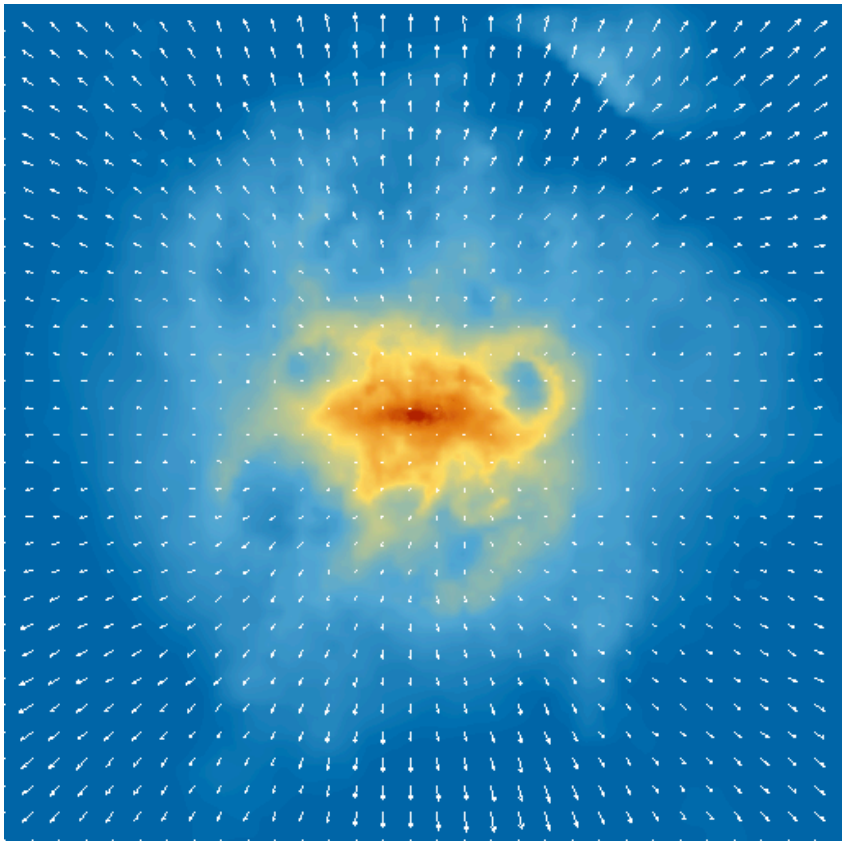
At low z: M82

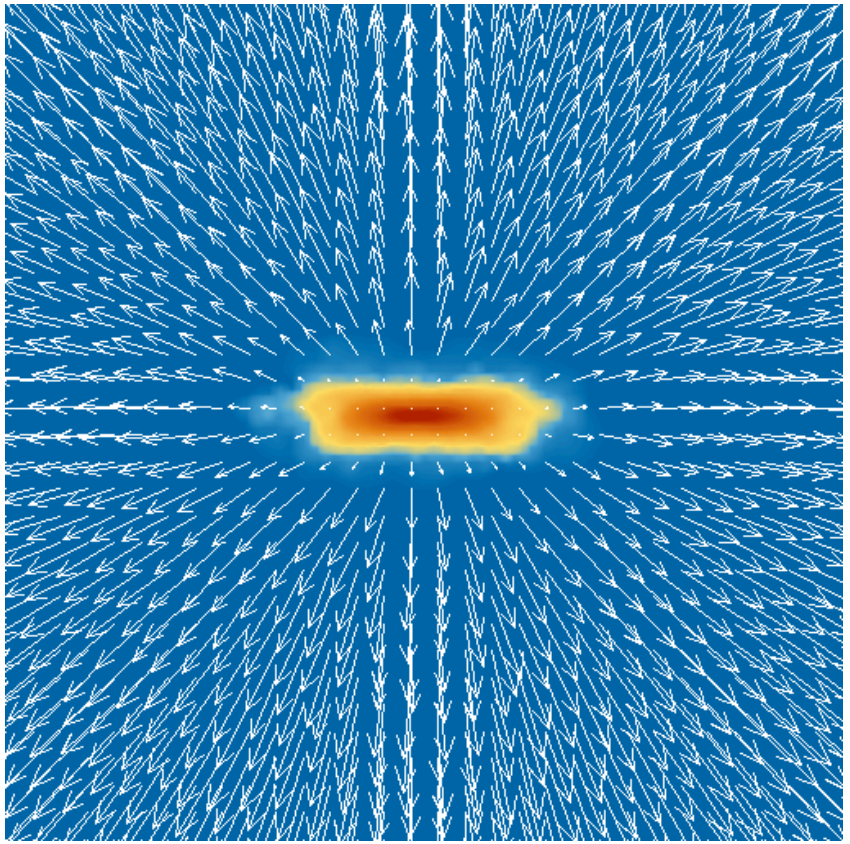


In absorption

Durham University

Implementation of winds:

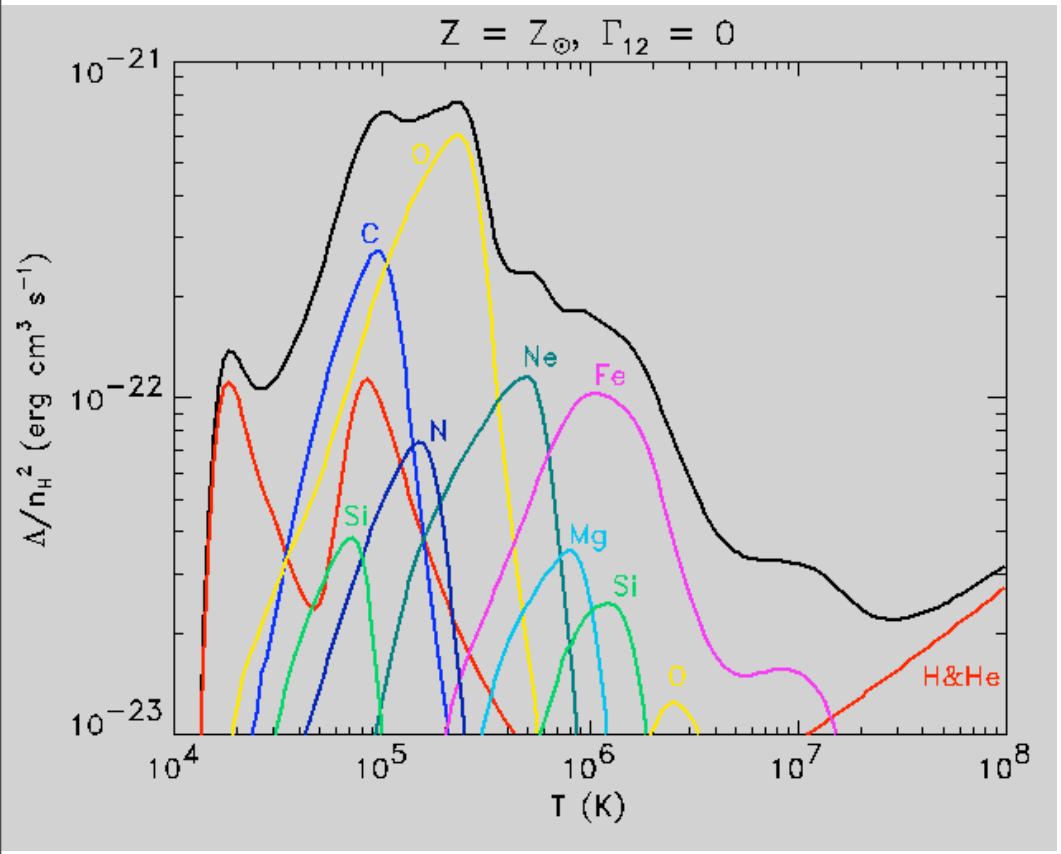




Schaye & Dalla Vecchia 08

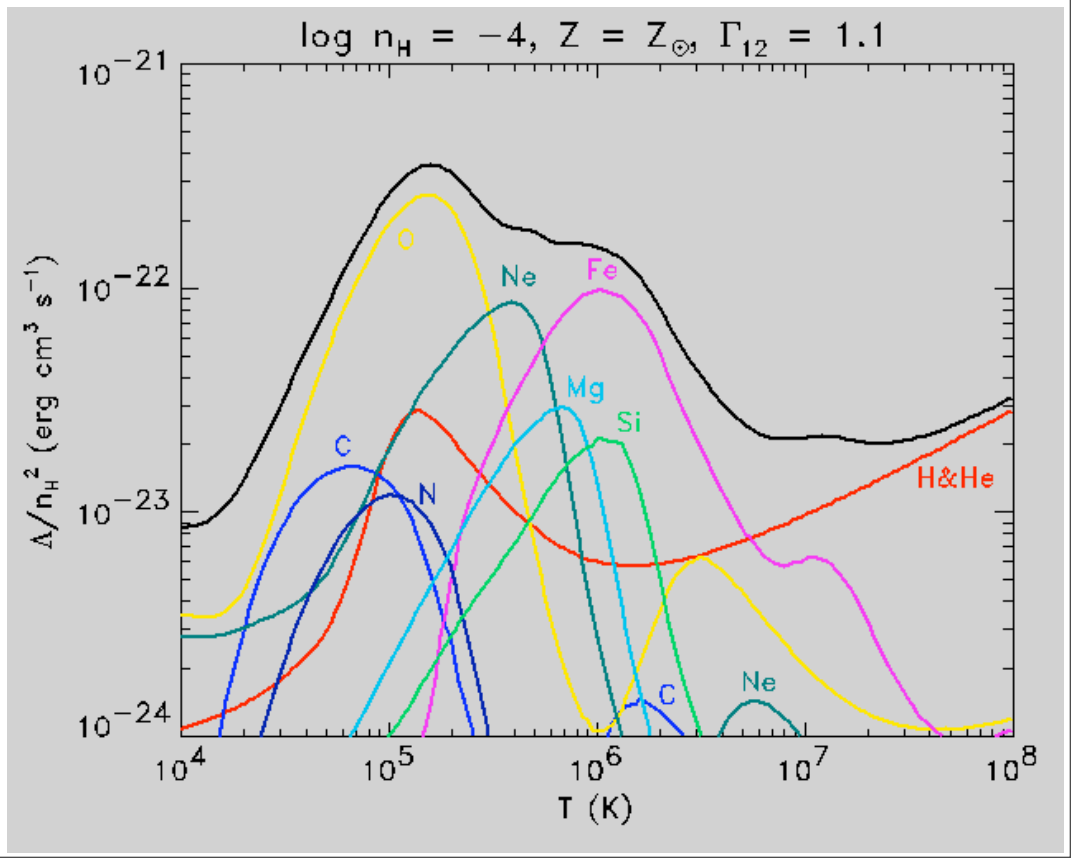
Metal cooling and the UV-background

Cooling rate



Without ionizing background

With ionizing background from gals & AGN



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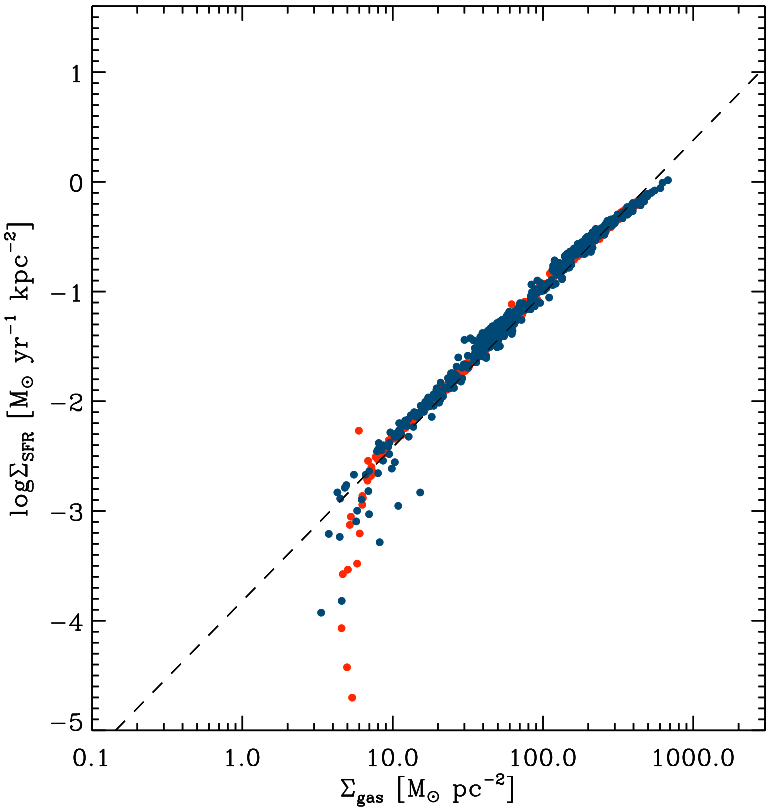
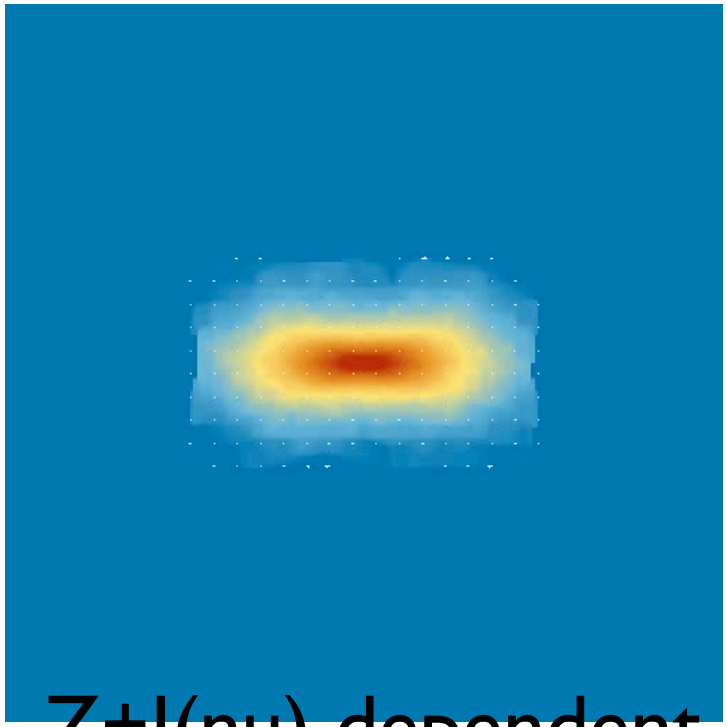
Wiersma et al '08

SFR follow Schmidt-law

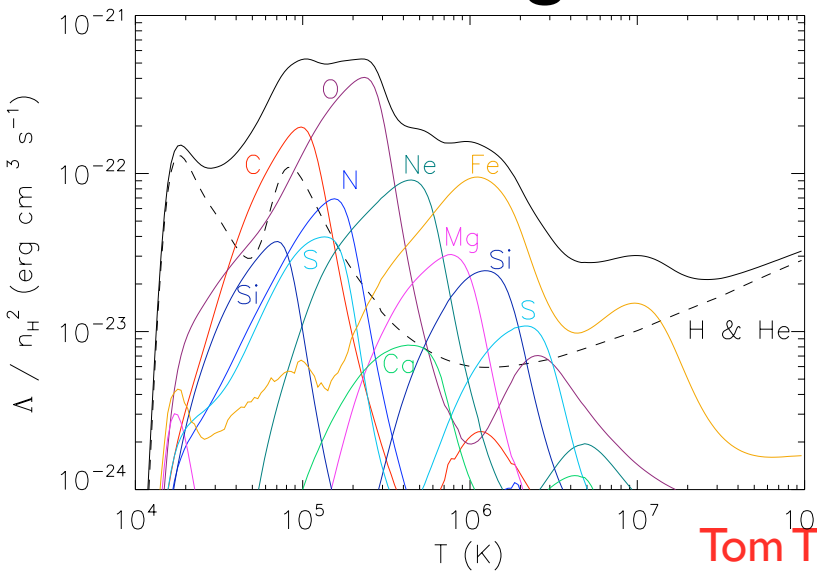


Code in brief

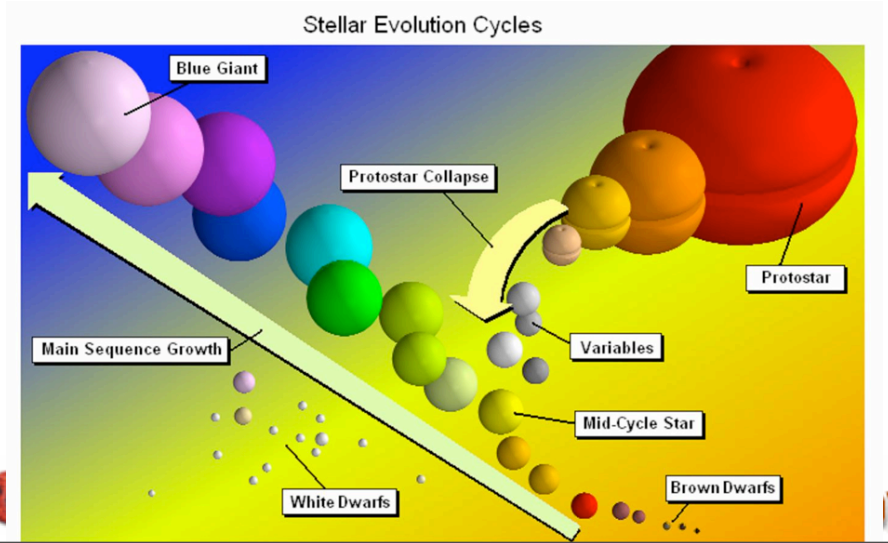
Galactic winds



Z+J(nu) dependent cooling



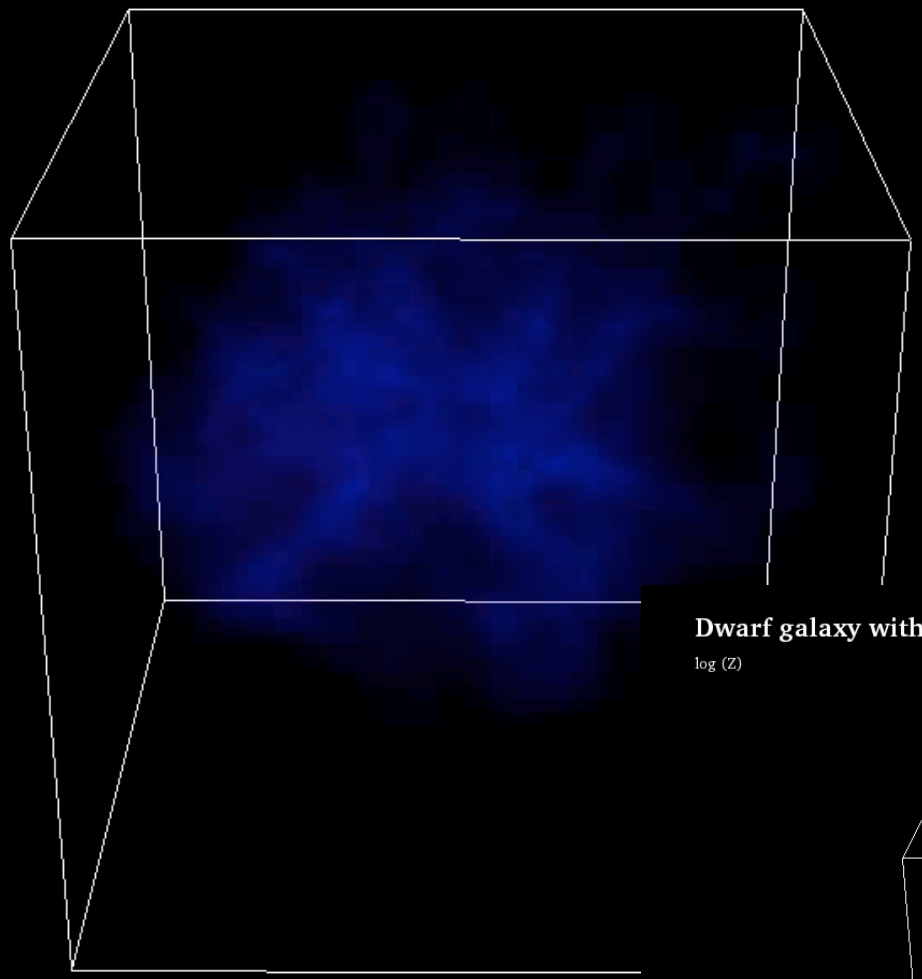
Stellar evolution



Dwarf galaxy with GIMIC/OWLS code

log (Gas density) in [Msun/h / (Mpc/h) ^ 3]

Density



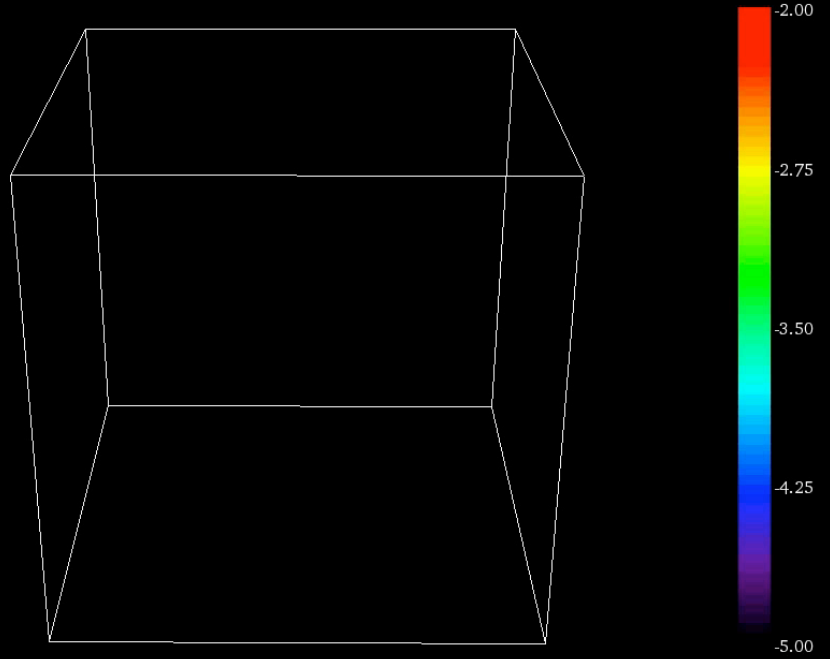
z = 29.888

L = 0.999 Mpc/h

Dwarf galaxy with GIMIC/OWLS code

log (Z)

Metals



z = 29.888

L = 0.999 Mpc/h

Institute for Computational Cosmology

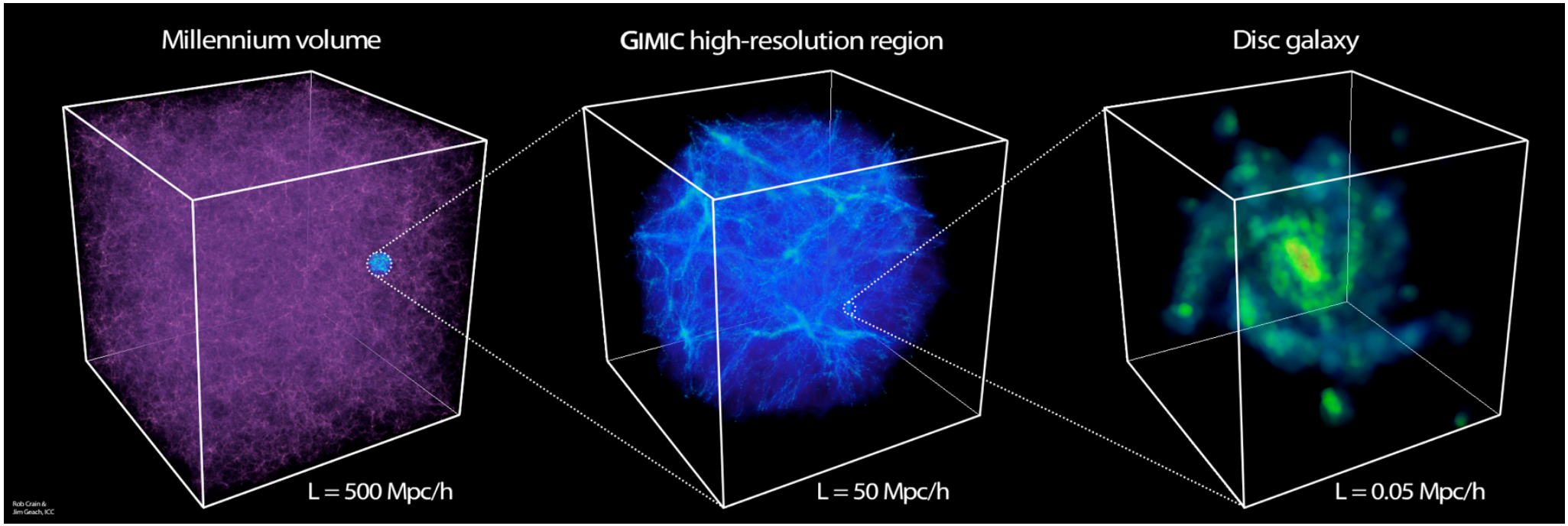
Brief comparison to other implementations

	gimic/owls	Dave et al Borgani et al (several others)	Horizon (Teyssier)
code	Gadget3	Gadget2	Ramses
SF	Schmidt	density+	density+
Winds	hydrodynamic	decoupled	hydrodynamic
ISM	EOS	"multi- phase" (Springel +Hernquist 03)	

Durham University

Suite of simulations: GIMIC/OWLS

Galaxy-Intergalactic Medium Interaction Calculation



Zoomed simulations of 5 spheres picked from the Millennium Simulation

Combine LSS with high numerical resolution

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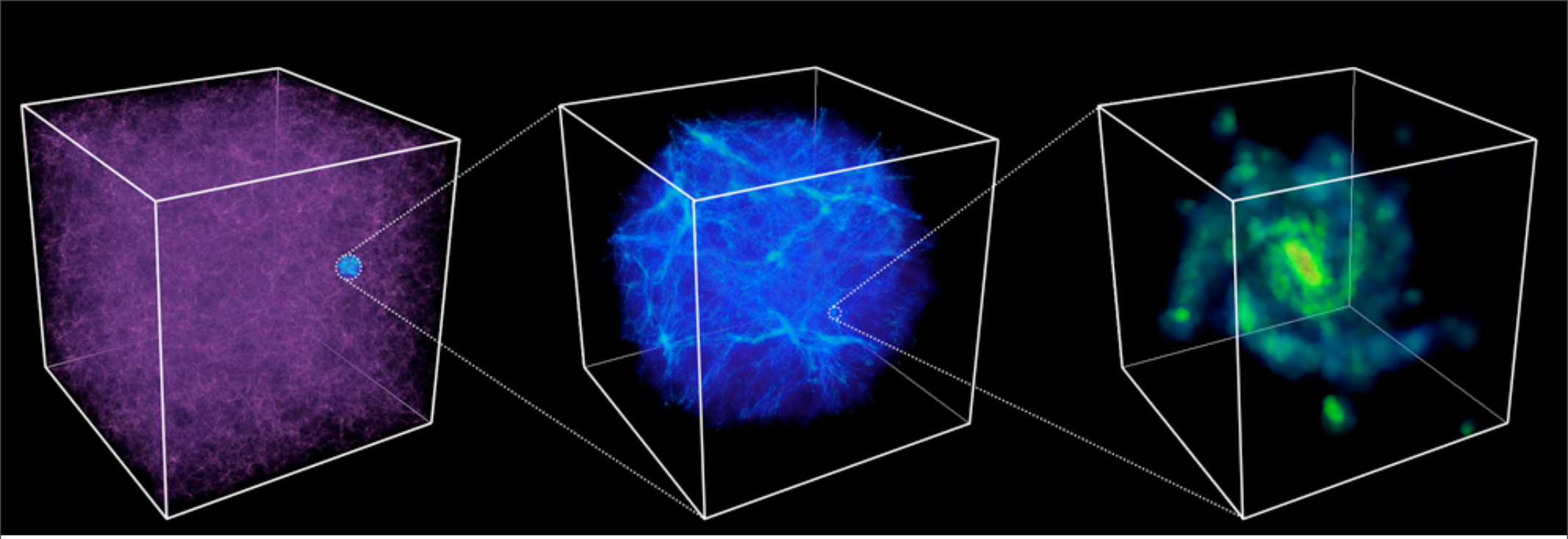
ICC Institute for Computational Cosmology

Motivation for GIMIC:

- include (very) large-scale structure
- good numerical resolution yet able to reach redshift z=0
- formation of unusual objects (massive cluster, deep void)



Millennium volume:

- box is 500 Mpc/h on a side
- cosmology $(\Omega_m, \Omega_\Lambda, \Omega_b, h, \sigma_8, n) = (0.25, 0.75, 0.045, 0.73, 0.9, 1)$
- Springel et al '05

5 regions:

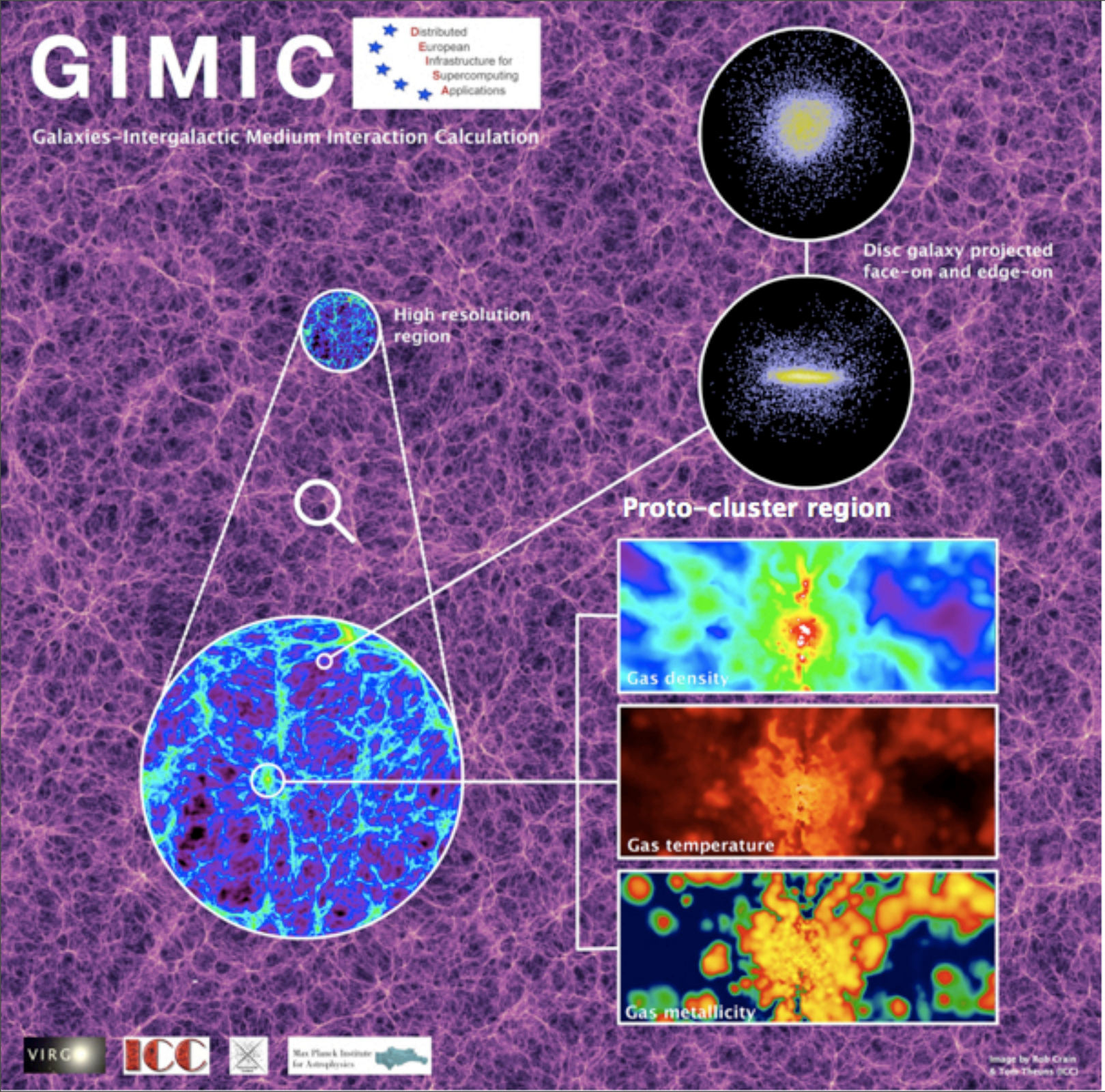
- (-2,-1,0,1,2) sigma
- radius 18 Mpc/h (at z=1.5)
- $m_{\rm gas} = 1.45 \times 10^6\, h^{-1}\, M_\odot$

ICs: A Jenkins

GIMIC

Distributed European Infrastructure for Supercomputing Applications

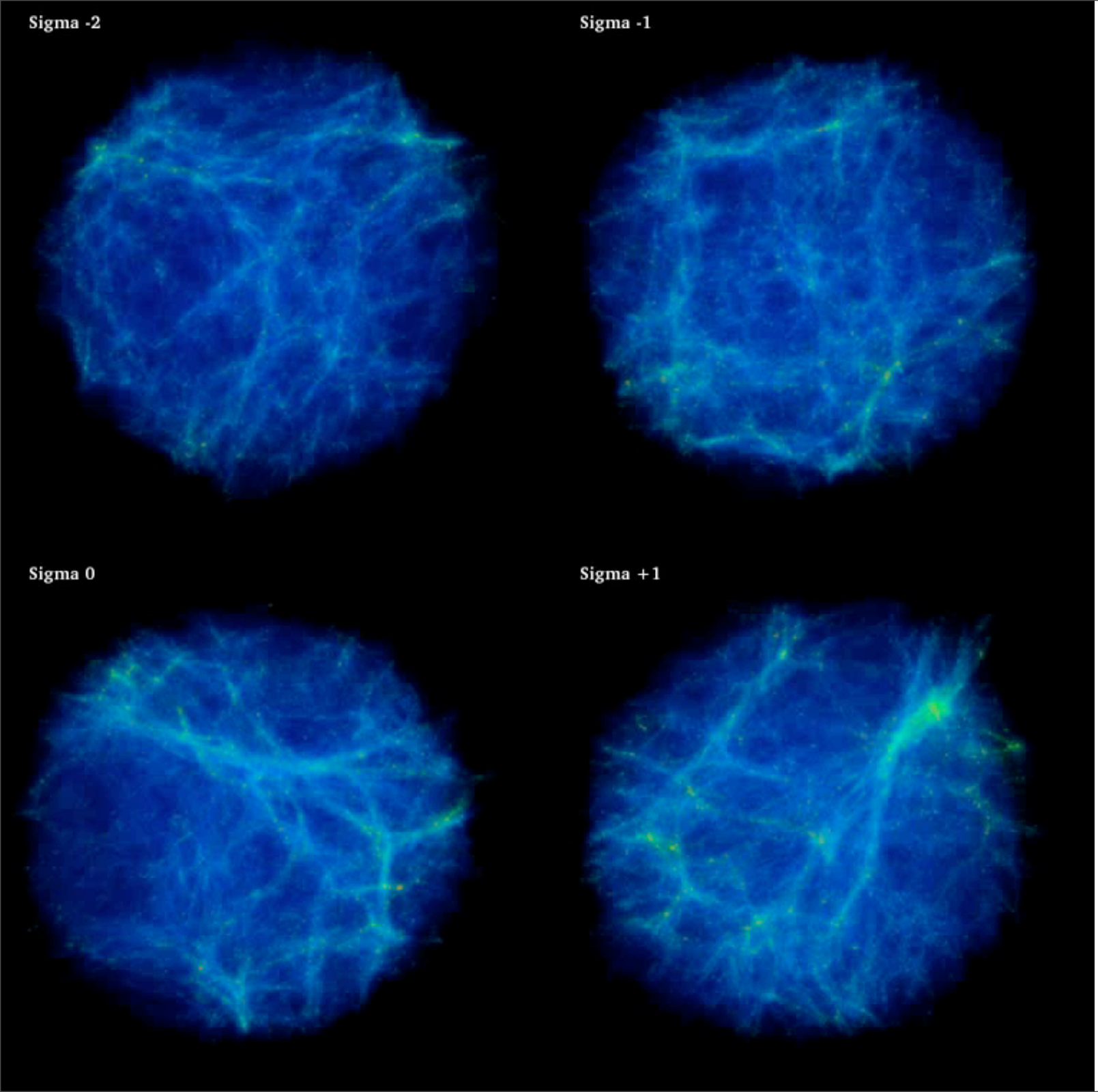
Galaxies-Intergalactic Medium Interaction Calculation



Objectives:

- Galaxy properties and environment
- IGM properties and environment
- Interaction galaxies/IGM
- Complementary to OWLS simulations

all using same set of numerical parameters



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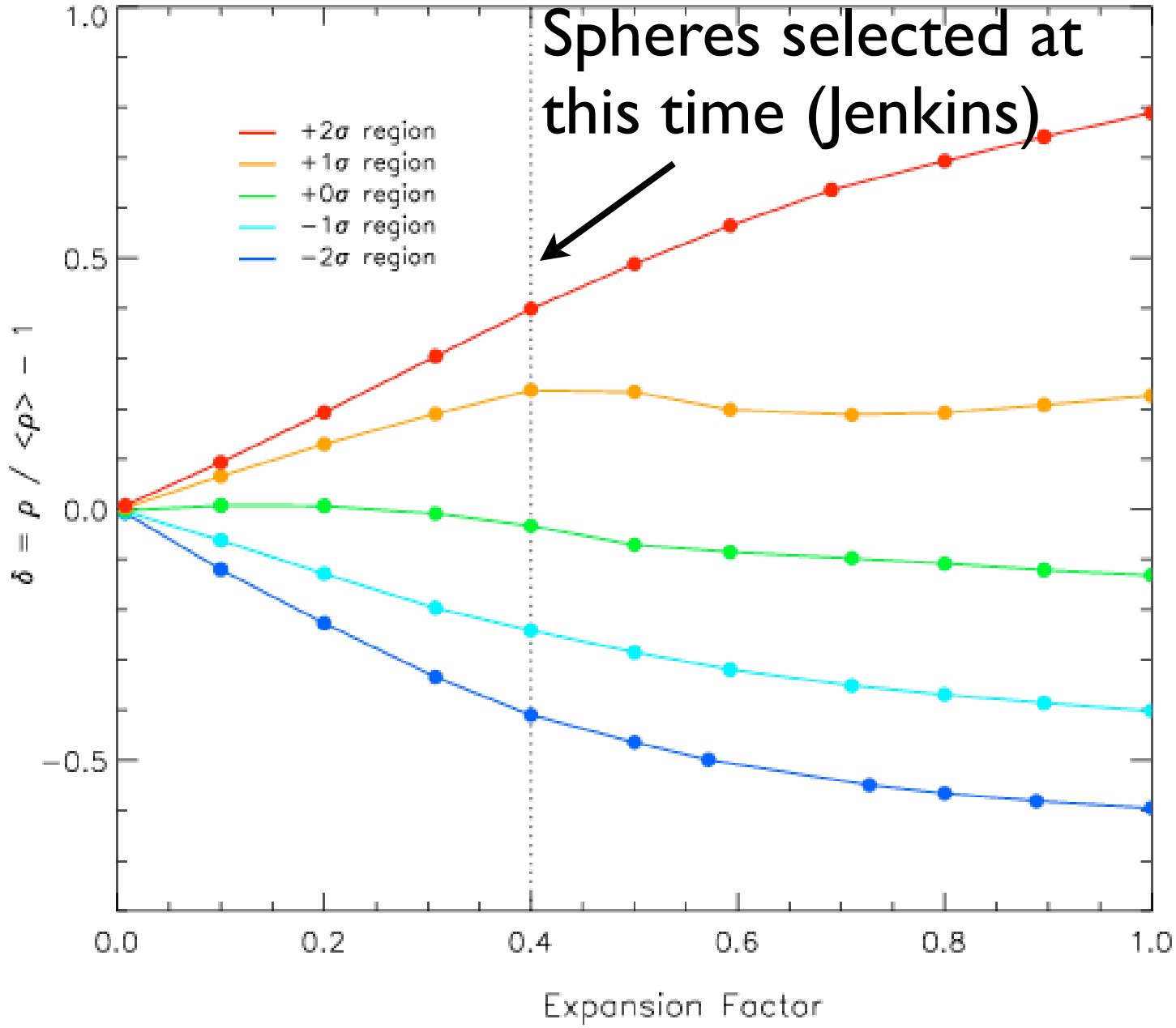
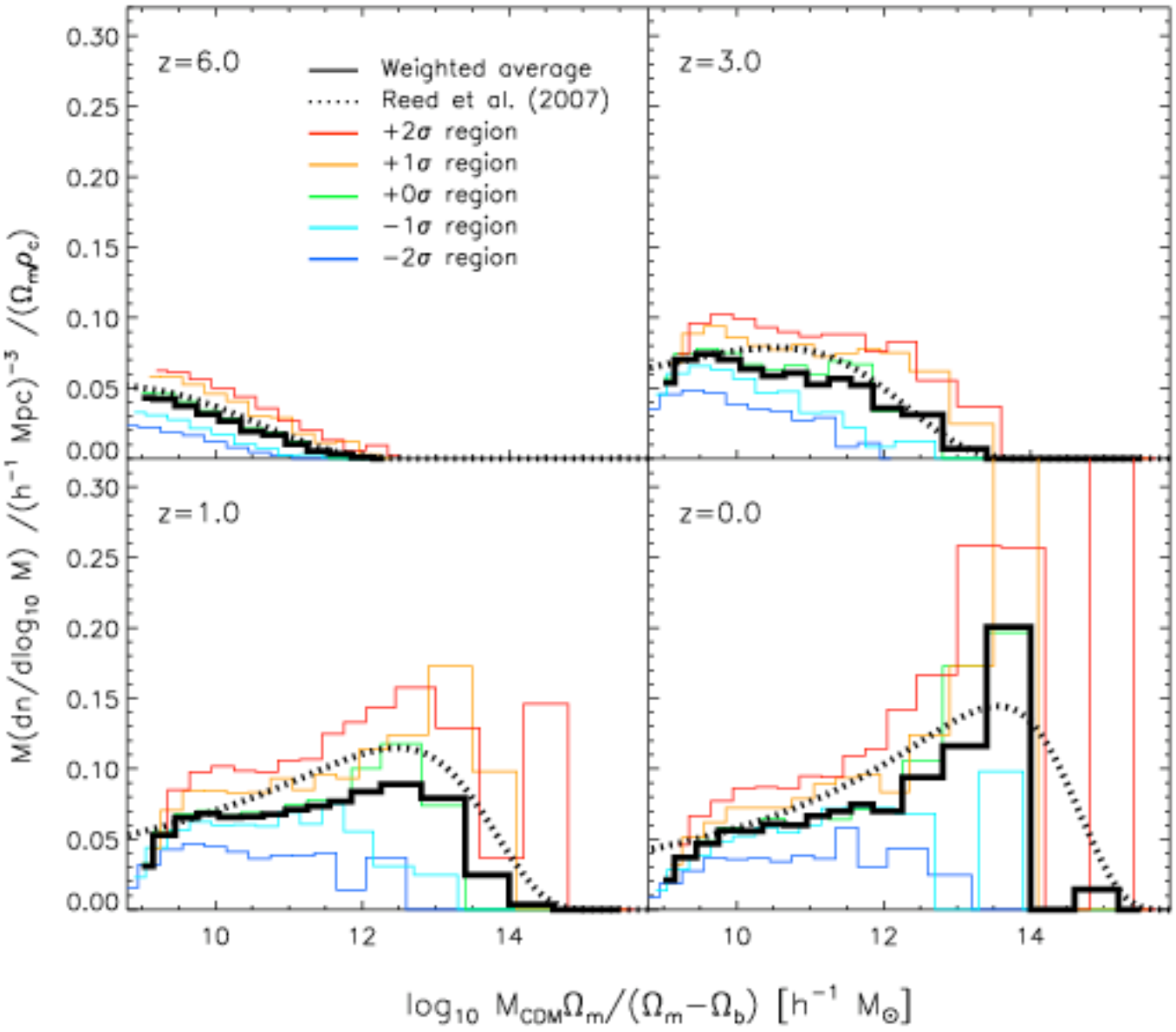
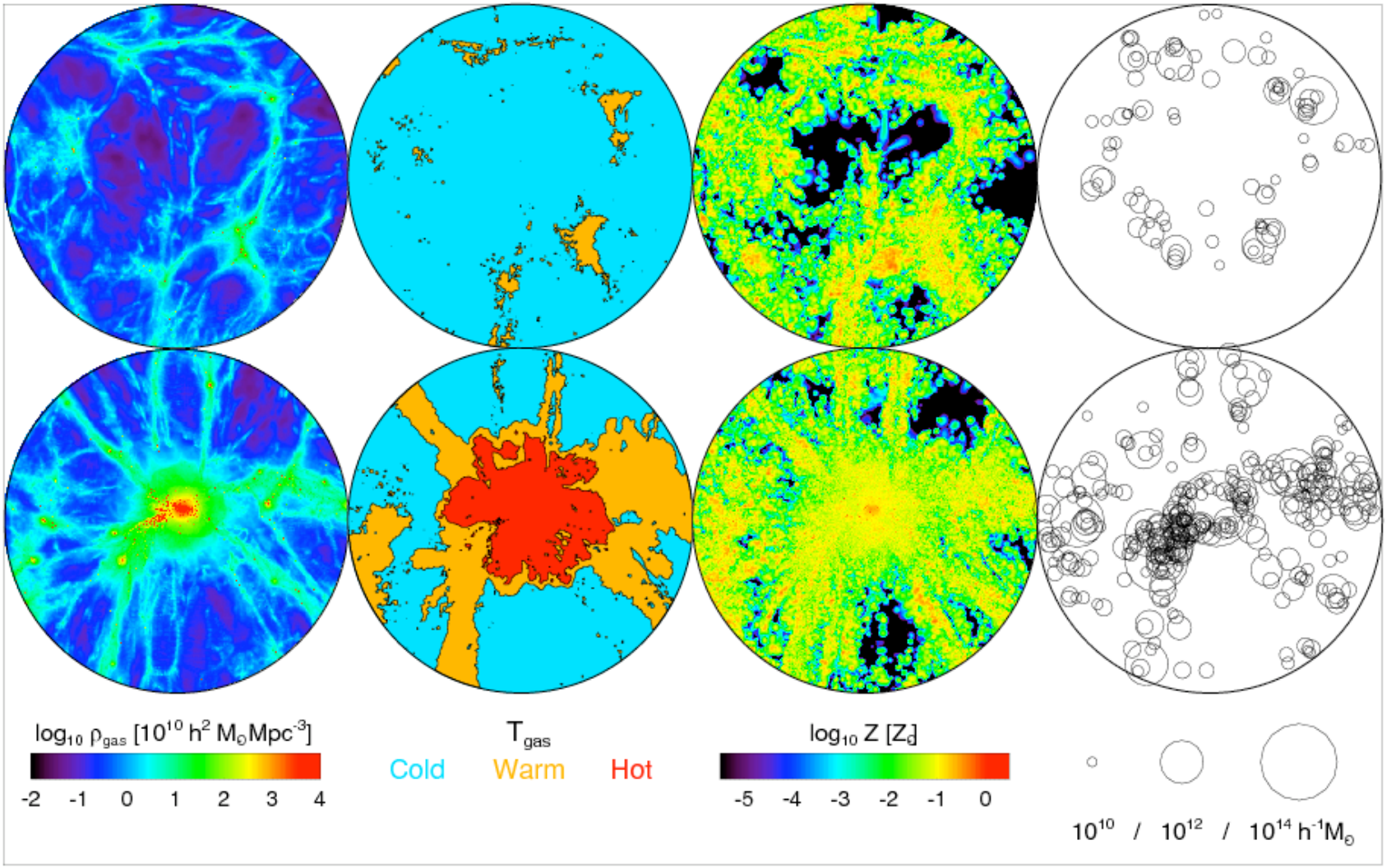
Density evolution of 5 GIMIC spheres



Dark-matter halo (FOF) mass functions

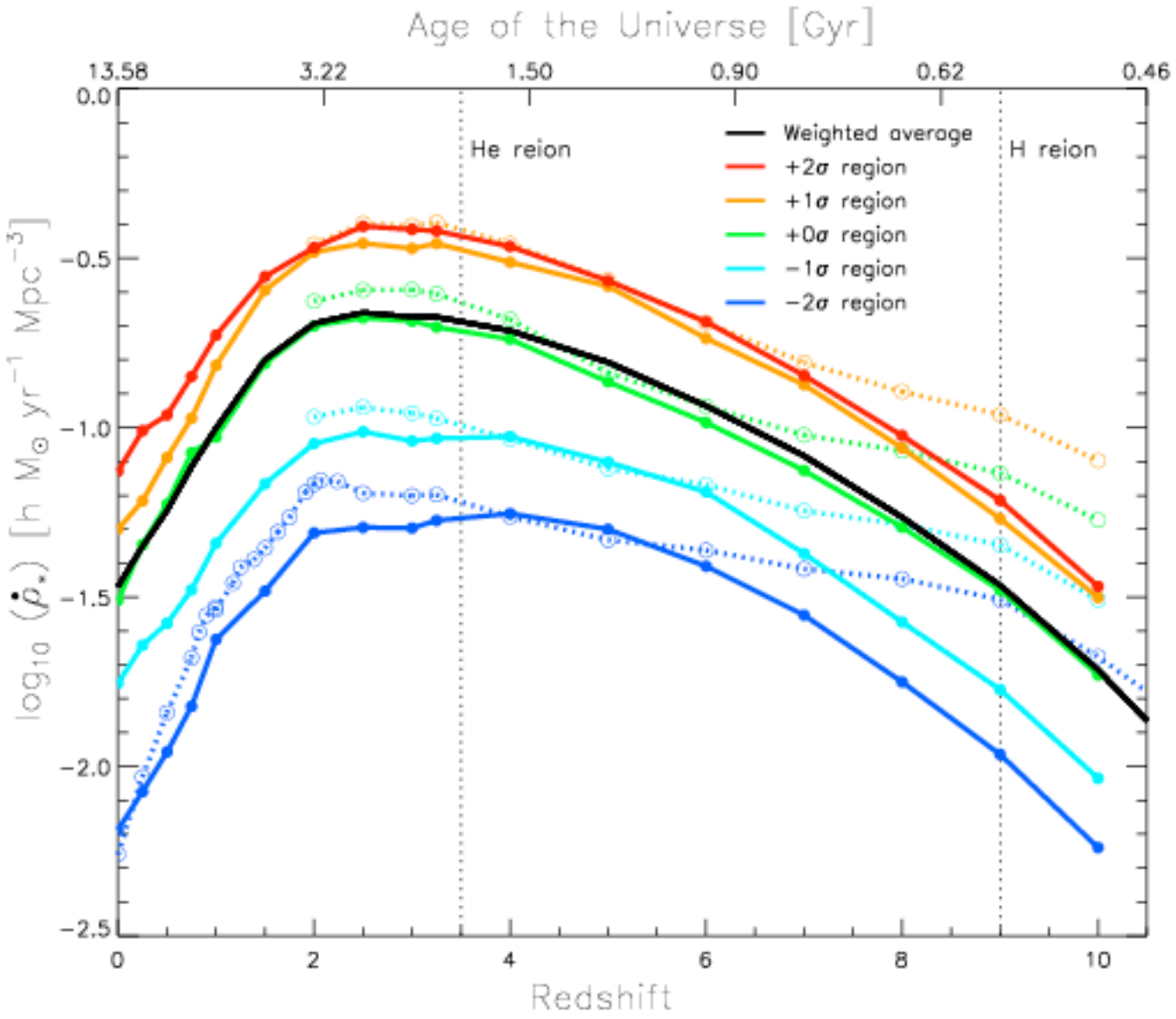


Visual difference between regions (z=0)



Star formation rate density (Madau/Lilly)

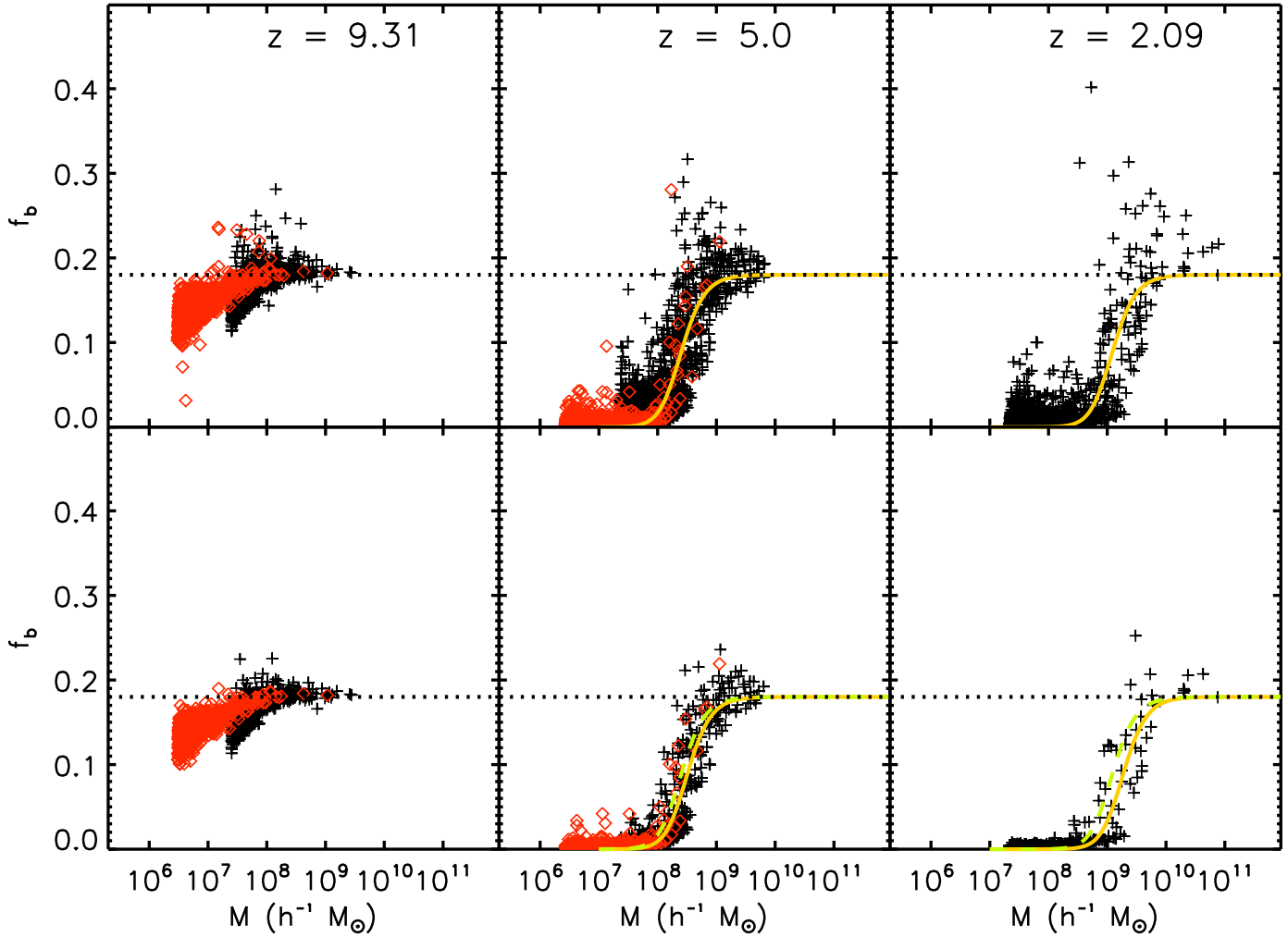
Starformation rate density



Redshift

Massloss of galaxies due to a UV-background

Takashi Okamoto[1⋆], Liang Gao[1,2] and Tom Theuns[1,3]
[1]*Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham, DH1 3LE*
[2]*National Astronomical Observatories, Chinese Academy of Science, Beijing, 100012, China*
[3]*Department of Physics, University of Antwerp, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*



Baryon fraction

all haloes

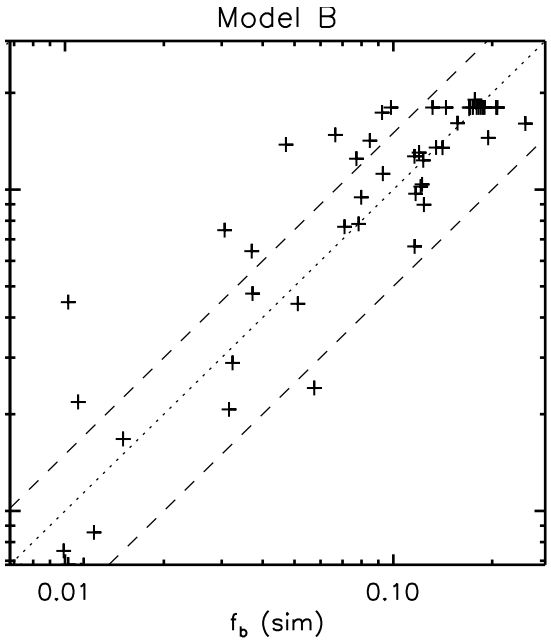
"Isolated" haloes

Halo mass

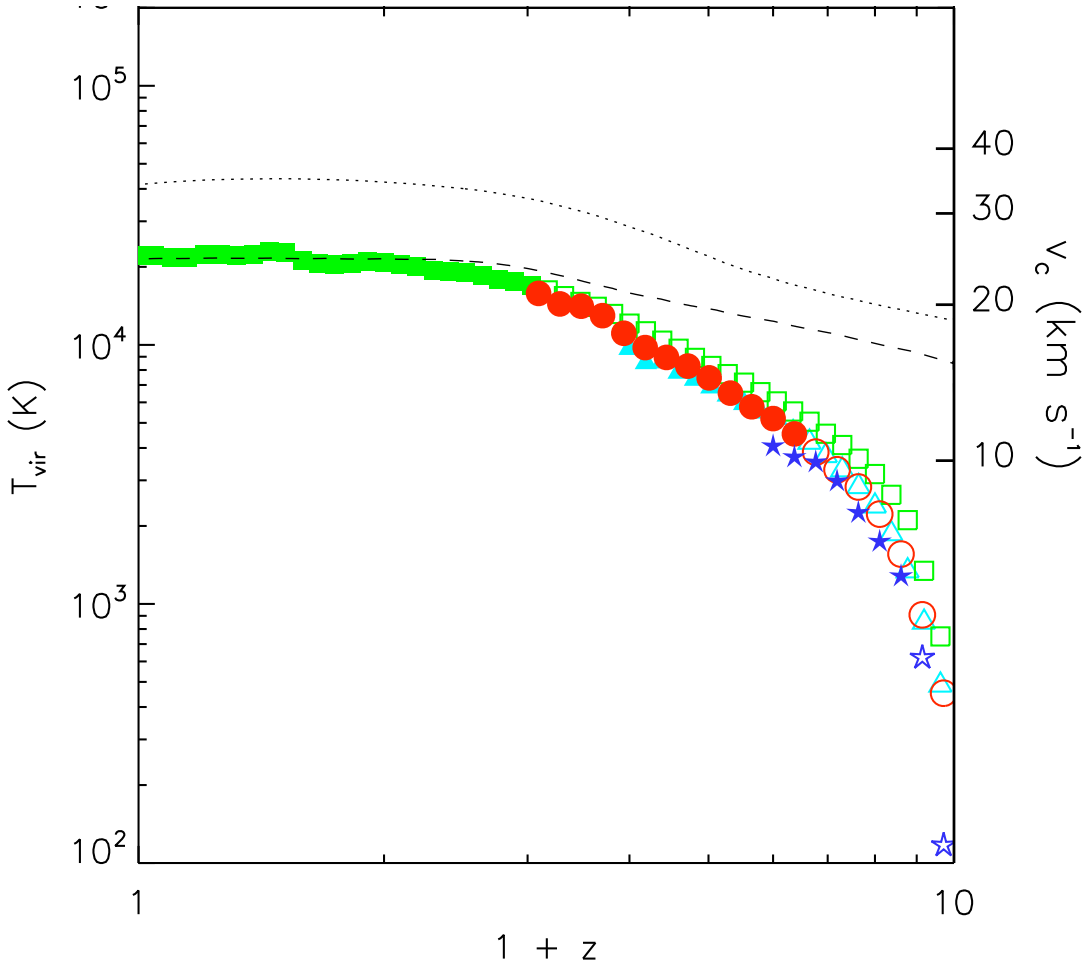
crosses: individual haloes

Characteristic temperature/circular velocity below which haloes lose most of their baryons

Massloss model



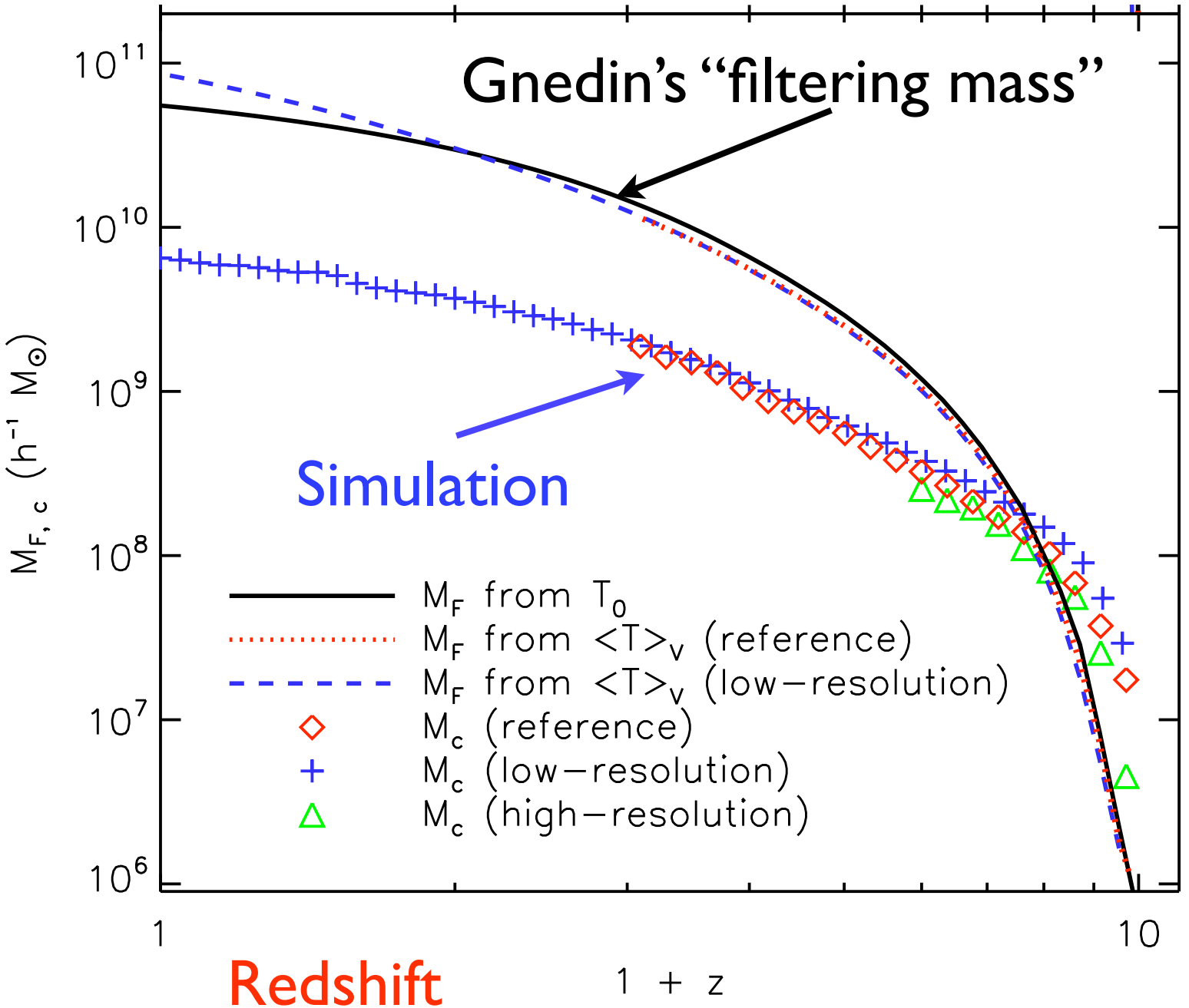
Virial temperature



Virial velocity

Redshift

Characteristic mass is much smaller than Gnedin's filtering mass

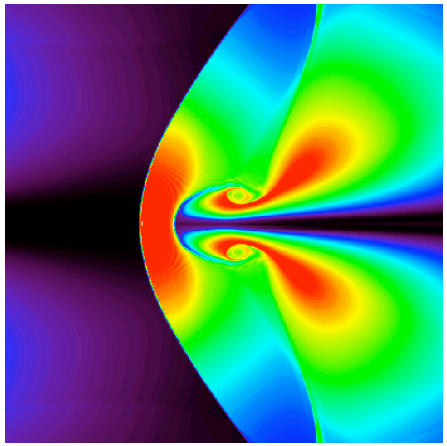


How well does SPH do the hydro?

On the Origin of Cores in Simulated Galaxy Clusters

N. L. Mitchell[1⋆], I. G. McCarthy[1], R. G. Bower[1], T. Theuns[1,2], R. A. Crain[1]

[1] *Department of Physics, Durham University, South Road, Durham, DH1 3LE*
[2] *Department of Physics, University of Antwerp, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*



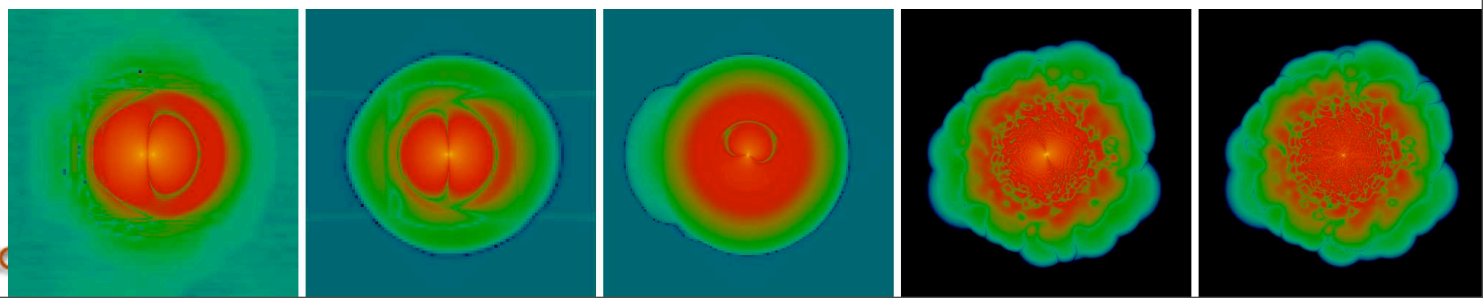
Comparison Gadget (SPH) vs FLASH (AMR) for collisions of isolated clusters (dm +gas, non-radiative)

A test suite for quantitative comparison of hydrodynamics codes in astrophysics

Elizabeth J. Tasker[1⋆], Riccardo Brunino[2], Nigel L. Mitchell[3], Dolf Michielsen[2], Stephen Hopton[2], Frazer R. Pearce[2], Greg L. Bryan[4], Tom Theuns[3]

Translating King profiles

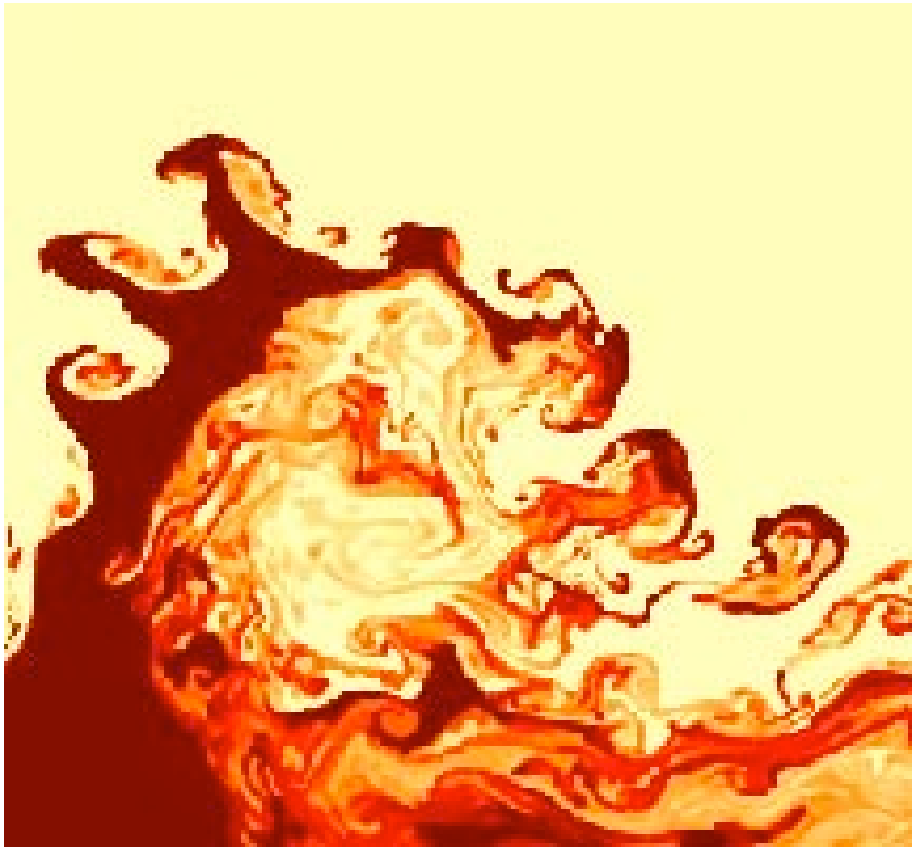
ENZO Flash SPH

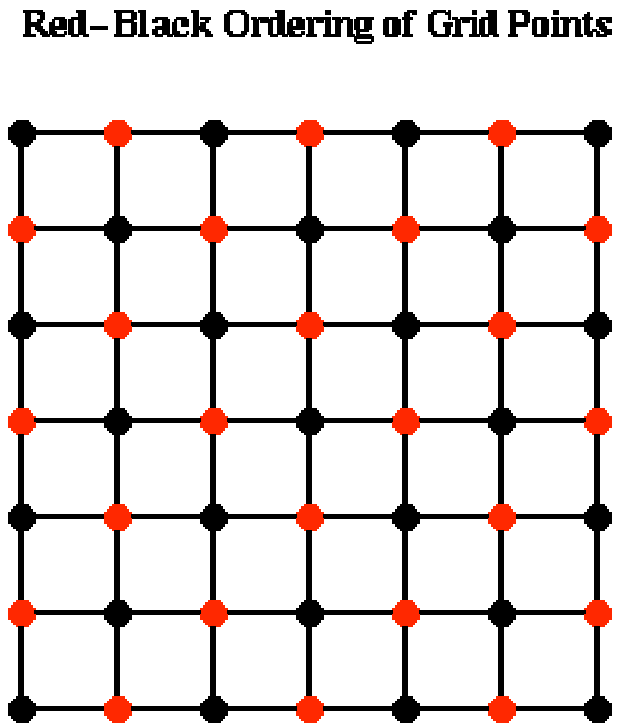


ICC Institute for Compute

A new Poisson-solver for Flash

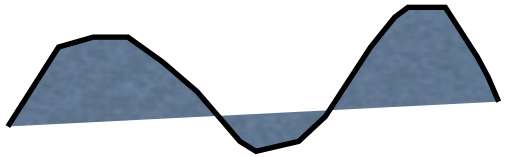
$$\phi^{n+1}(x) = \frac{\phi^n(x+\Delta) + \phi^n(x-\Delta)}{2} - \frac{2\rho(x)}{\Delta^2}$$



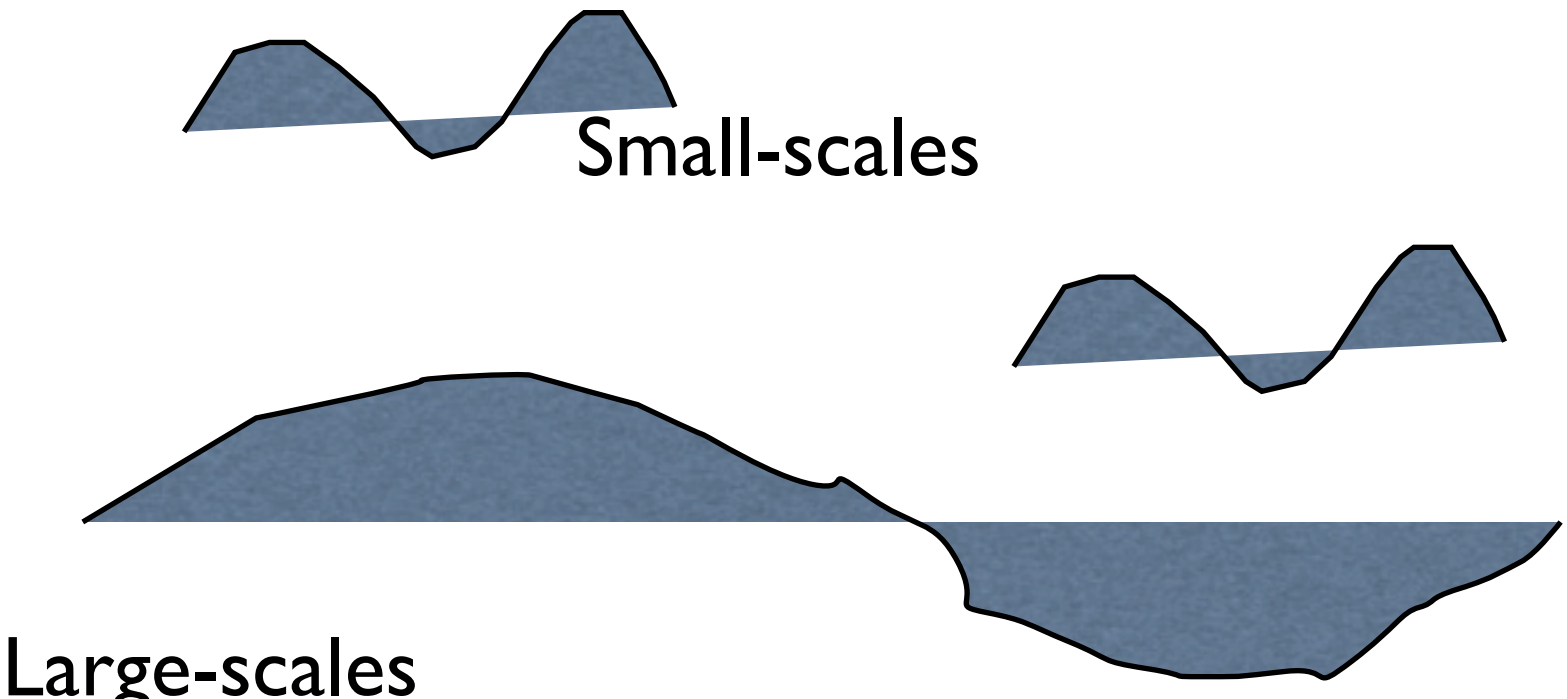


Updating of boundary points requires communication every sweep

$$\phi^{n+1}(x) = \frac{\phi^n(x+\Delta) + \phi^n(x-\Delta)}{2} - \frac{2\rho(x)}{\Delta^2}$$

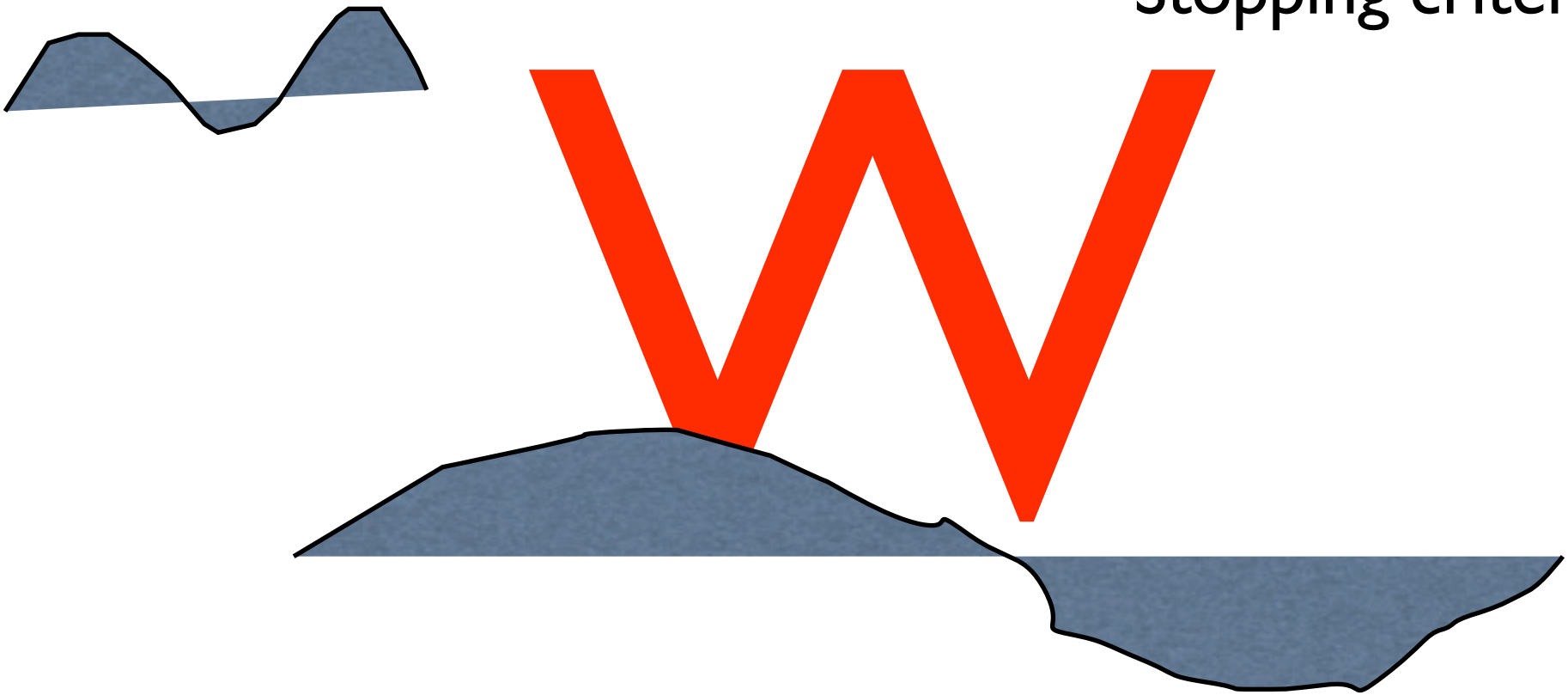


$$\phi^{n+1}(x) = \frac{\phi^n(x+\Delta) + \phi^n(x-\Delta)}{2} - \frac{2\rho(x)}{\Delta^2}$$

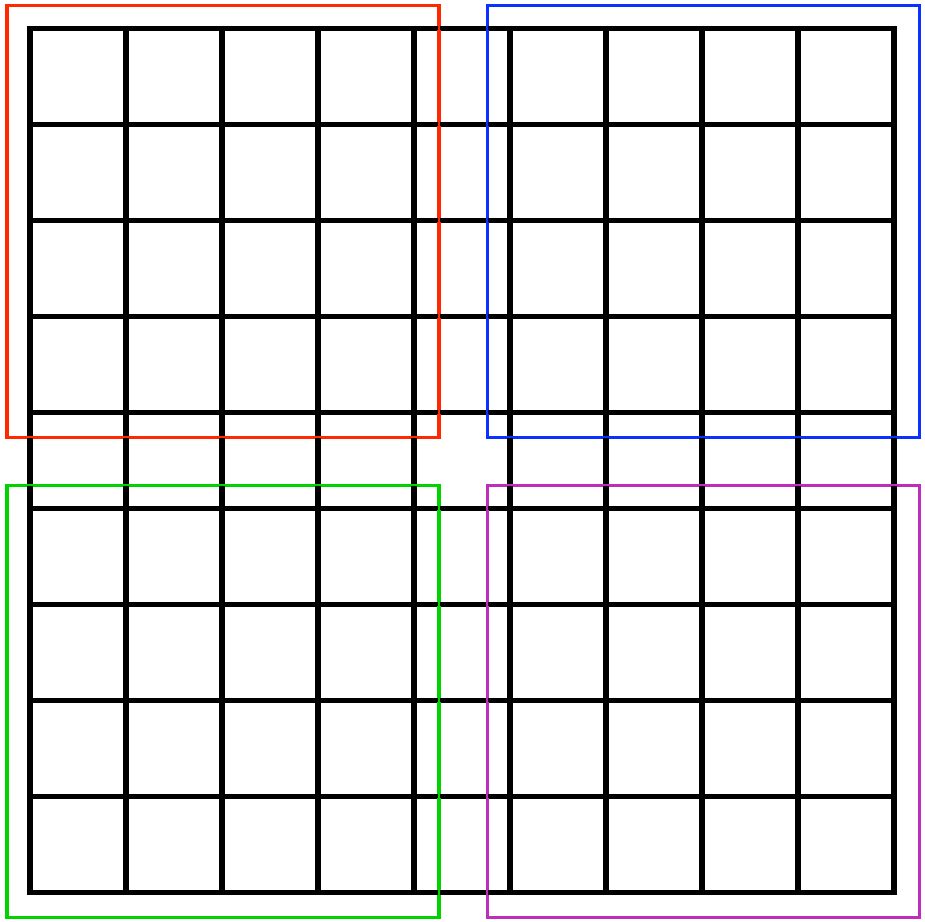


$$\phi^{n+1}(x) = \frac{\phi^n(x+\Delta) + \phi^n(x-\Delta)}{2} - \frac{2\rho(x)}{\Delta^2}$$

Stopping criterion?



Partitioning of the 2D Poisson Equation



Boundary conditions need to be exchanged between processors every step

Issues:

- Updating of BCs expensive — Dominates time
- Parallelization — Few blocks at coarse level

FFTs?

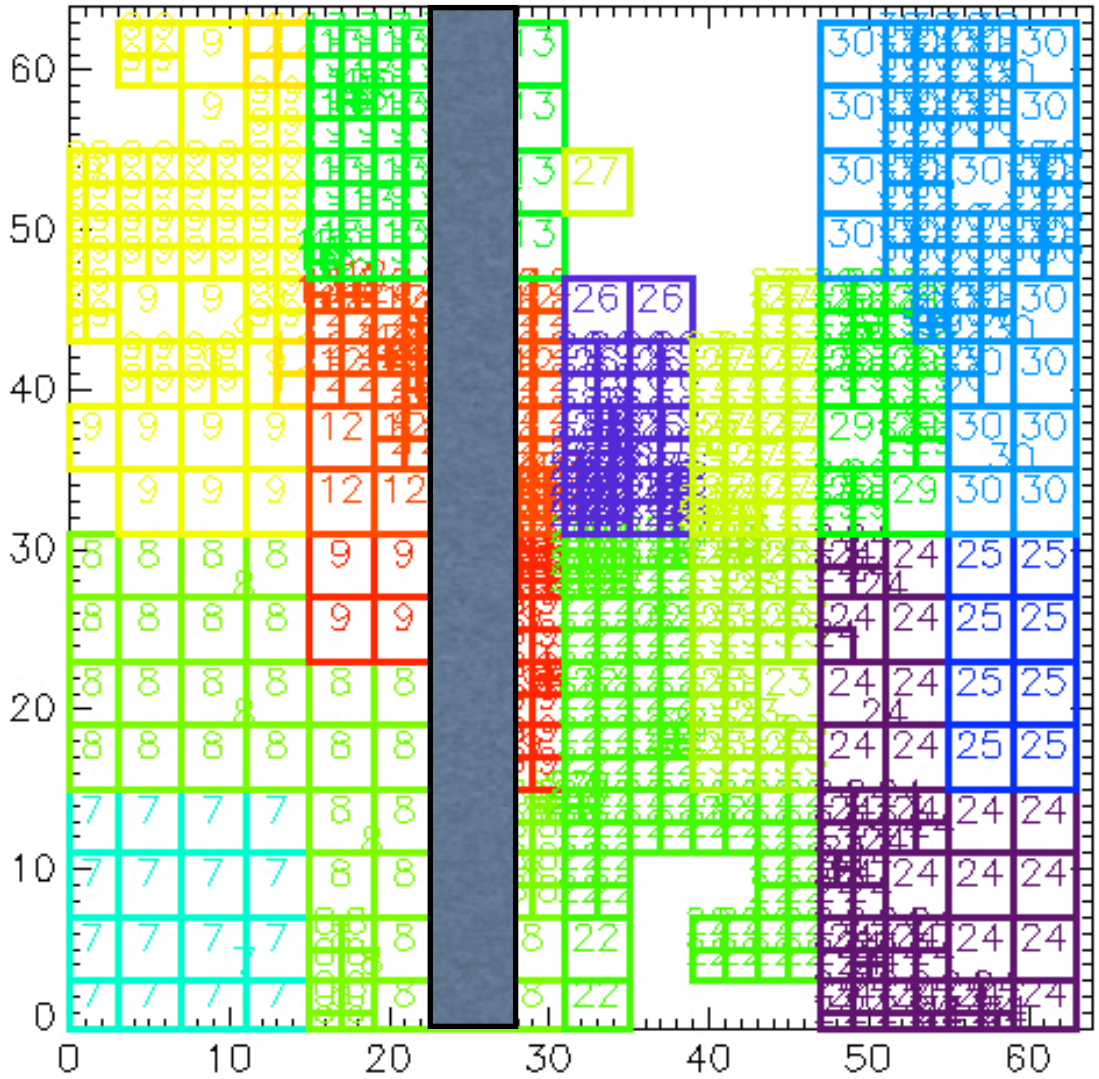
New Implementation:

- use FFTs on mesh
- use GS on further refinements

✓*Works well*

✓*Mapping of particles to mesh takes >80 % of CPU time*

FFT-plane



AMR-blocks

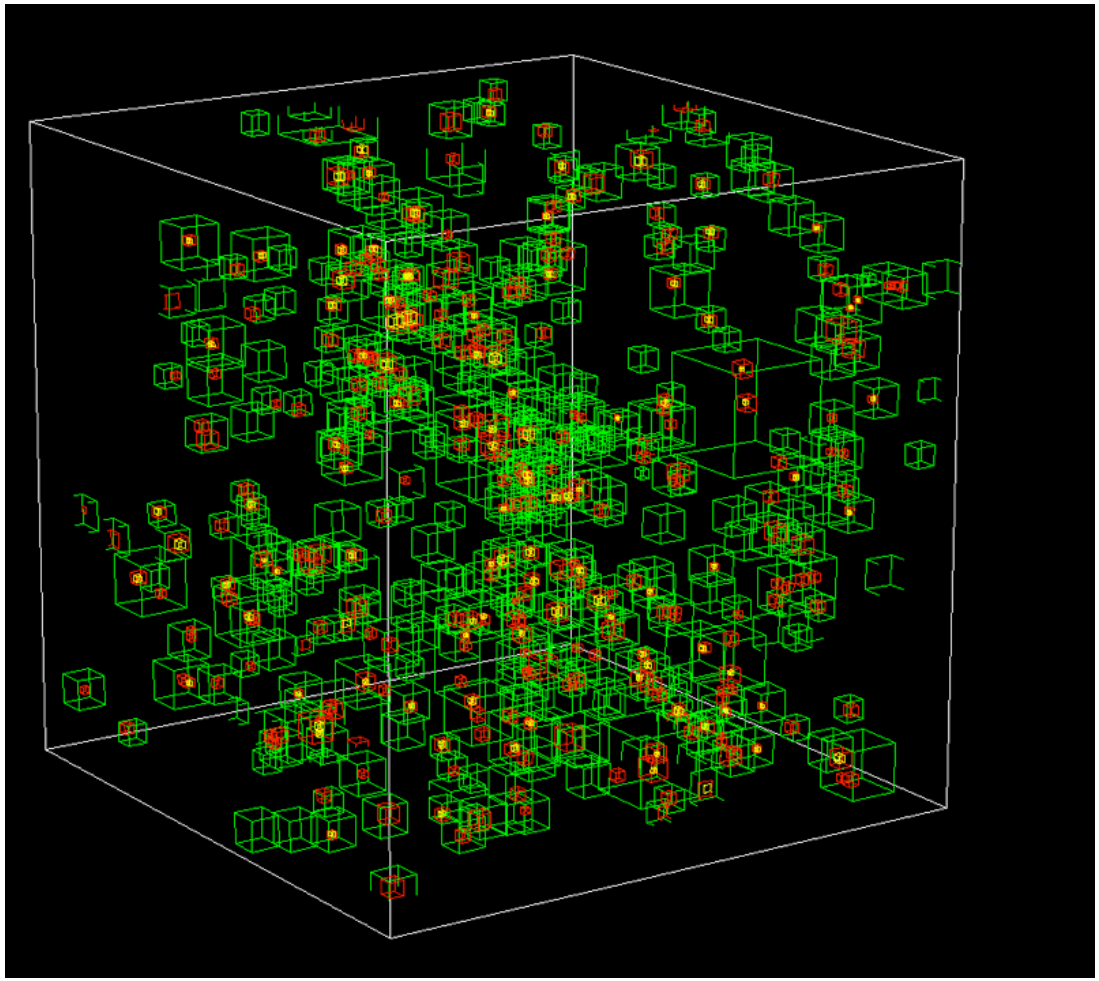
- Compute density on AMR block
- Set-up FFT planes (FFTW, pFFT) Pick FFT level
- Copy AMR density to FFT density
- Perform FFT
- Multiply with Green's function
- Perform inverse FFT
- Copy potential to AMR potential May need to restrict.
- Prolong potential to finer AMR blocks
- Iterate fine potential

Stopping criterion?

Wish list / issues

- Massive particles in small cells?
- PP-step for particles
- Isolated BCs
- Isolated FFTs (Refinements)

Multiple timesteps?

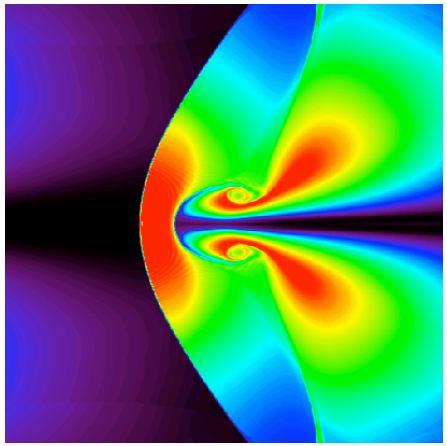


How well does SPH do the hydro?

On the Origin of Cores in Simulated Galaxy Clusters

N. L. Mitchell[1⋆], I. G. McCarthy[1], R. G. Bower[1], T. Theuns[1,2], R. A. Crain[1]

[1] *Department of Physics, Durham University, South Road, Durham, DH1 3LE*
[2] *Department of Physics, University of Antwerp, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*



Comparison Gadget (SPH) vs FLASH (AMR) for collisions of isolated clusters (dm +gas, non-radiative)

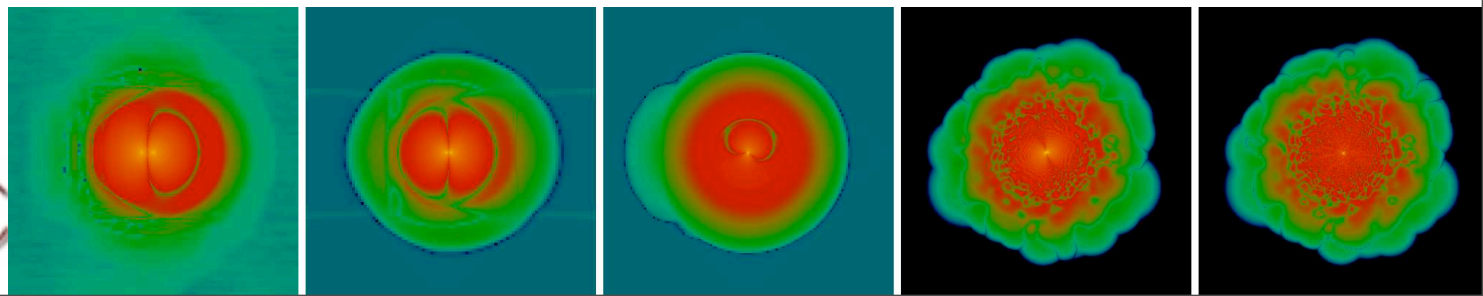
A test suite for quantitative comparison of hydrodynamics codes in astrophysics

Elizabeth J. Tasker[1⋆], Riccardo Brunino[2], Nigel L. Mitchell[3], Dolf Michielsen[2], Stephen Hopton[2], Frazer R. Pearce[2], Greg L. Bryan[4], Tom Theuns[3]

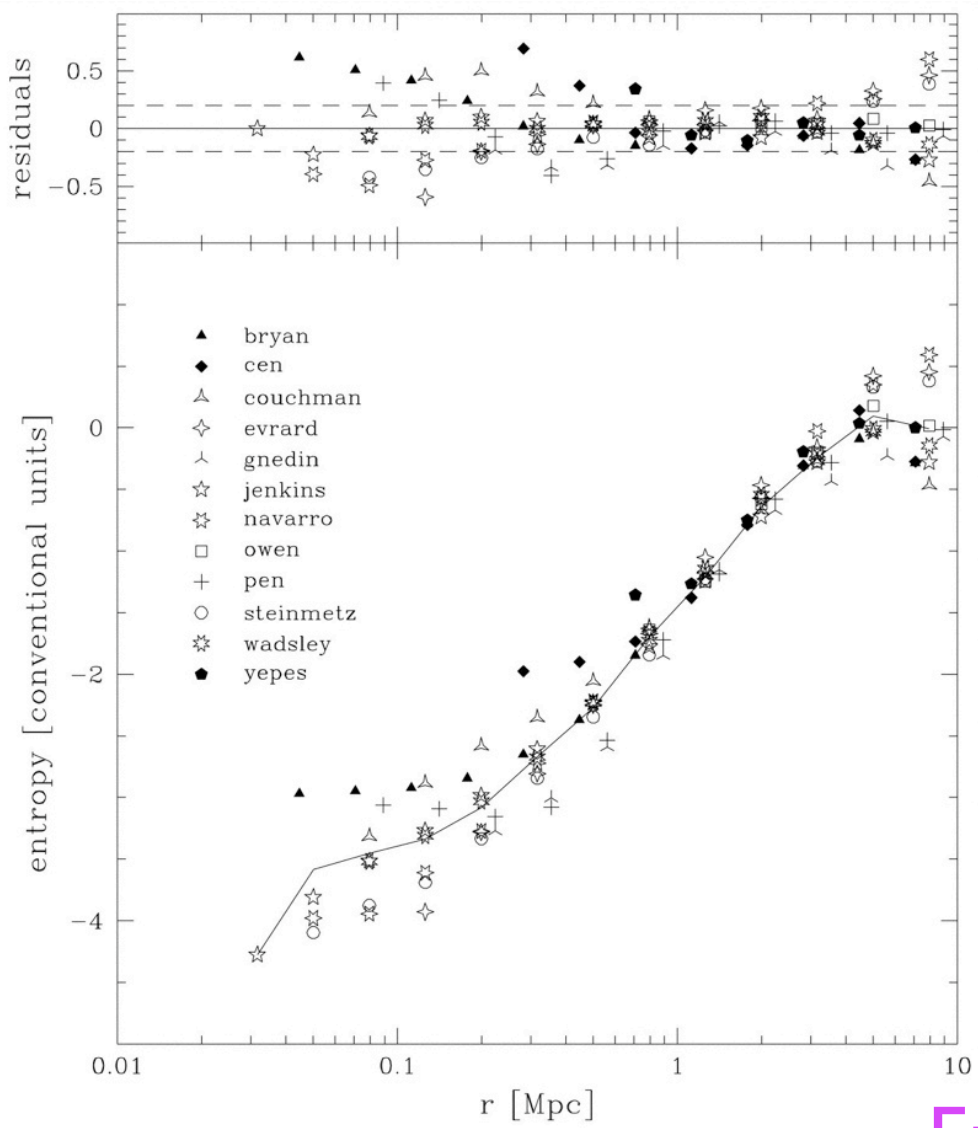
Translating King profiles

Tom Theuns

ENZO Flash SPH

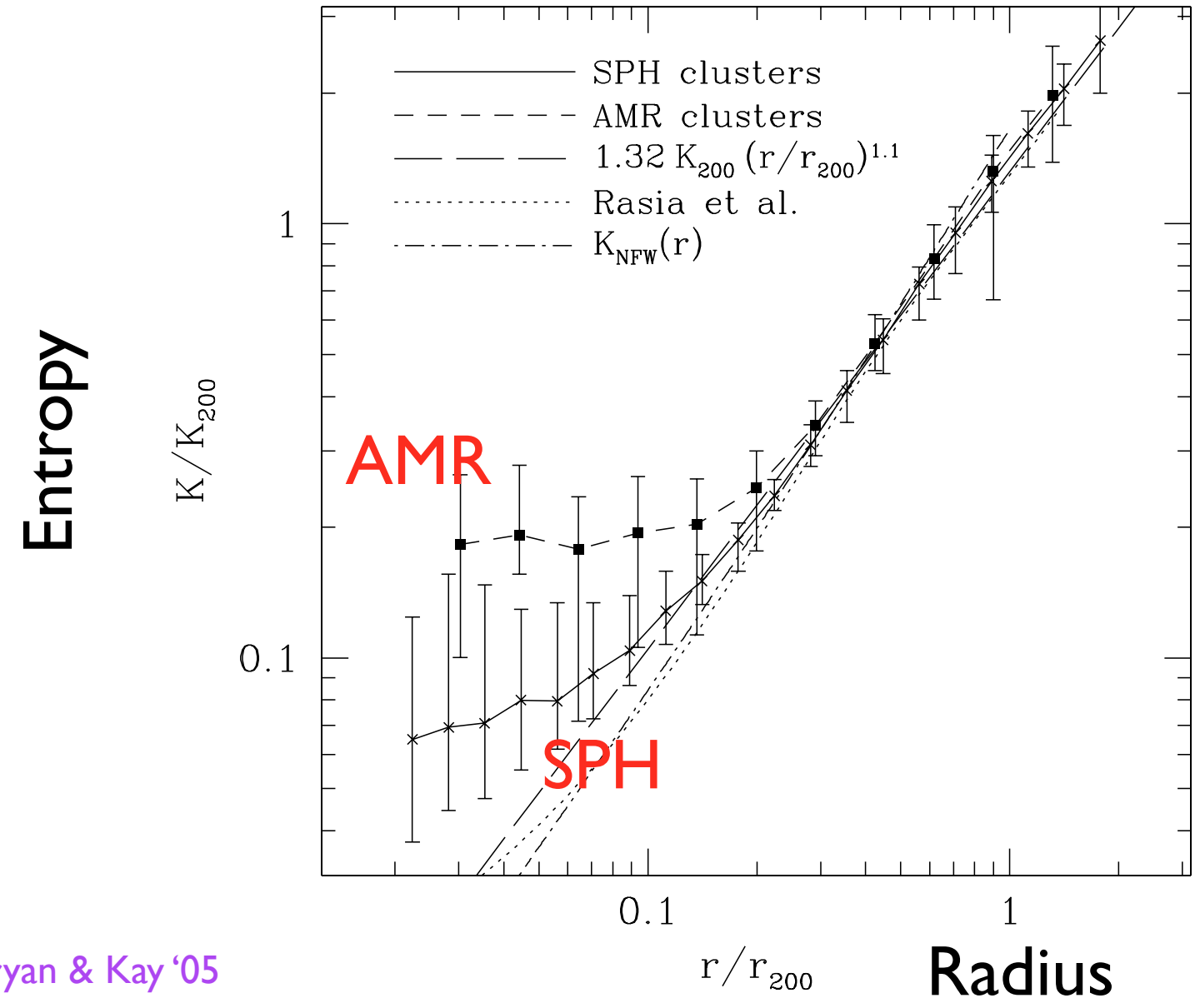


The Santa Barbara Cluster Comparison Project: A Comparison of Cosmological Hydrodynamics Solutions



Frenk et al '99

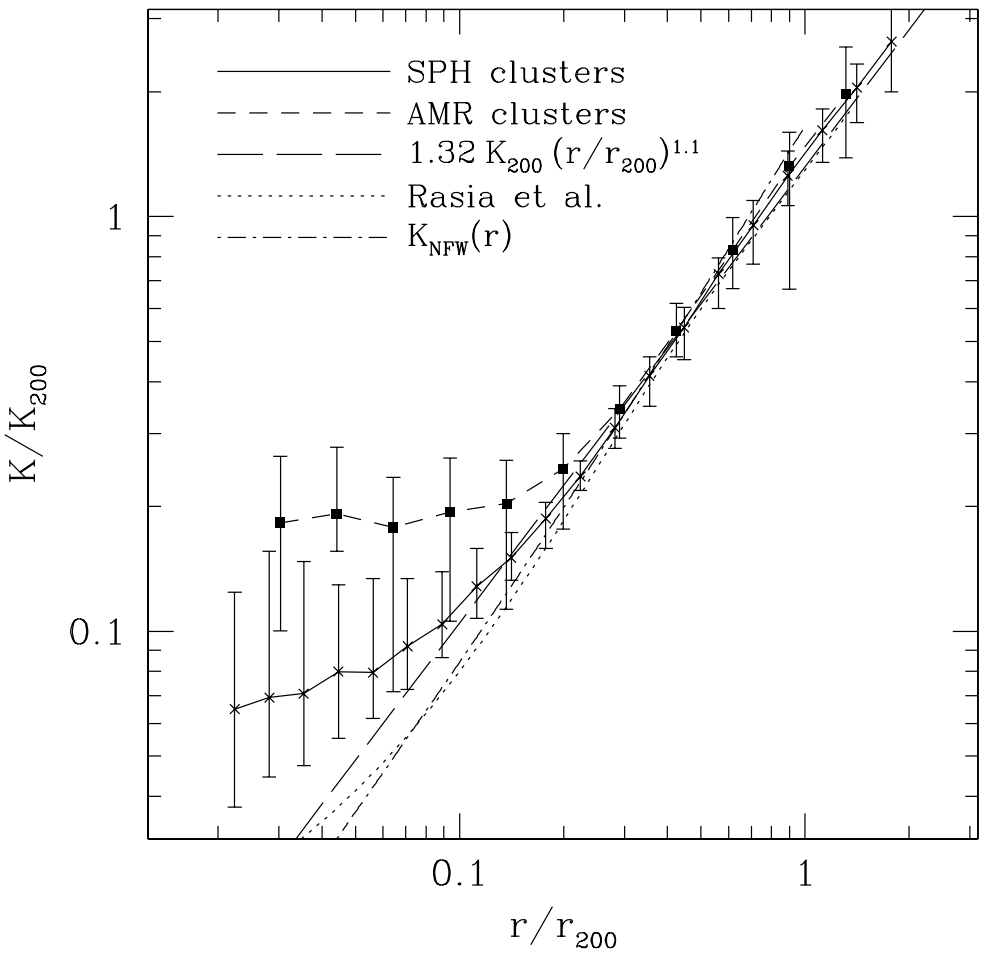
Cluster entropy profiles: SPH vs AMR



Voit, Bryan & Kay '05

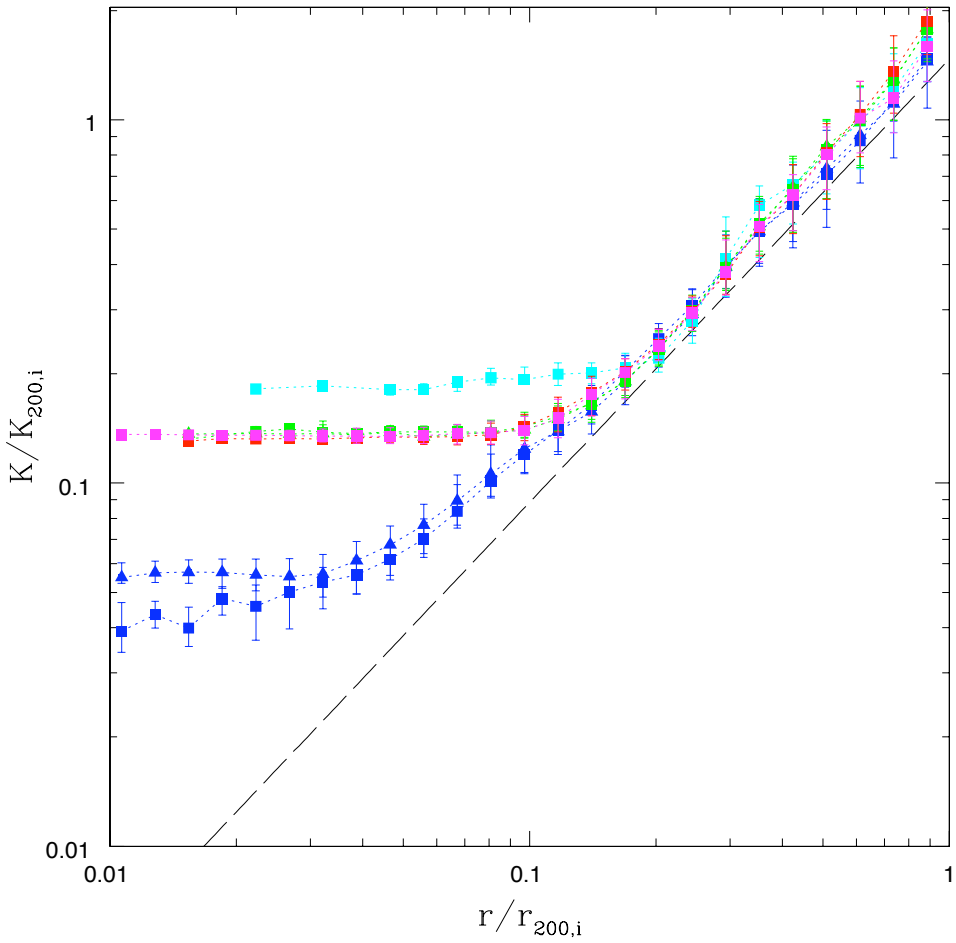
Cluster entropy profiles: *NOT* due to cosmology

Cosmological clusters



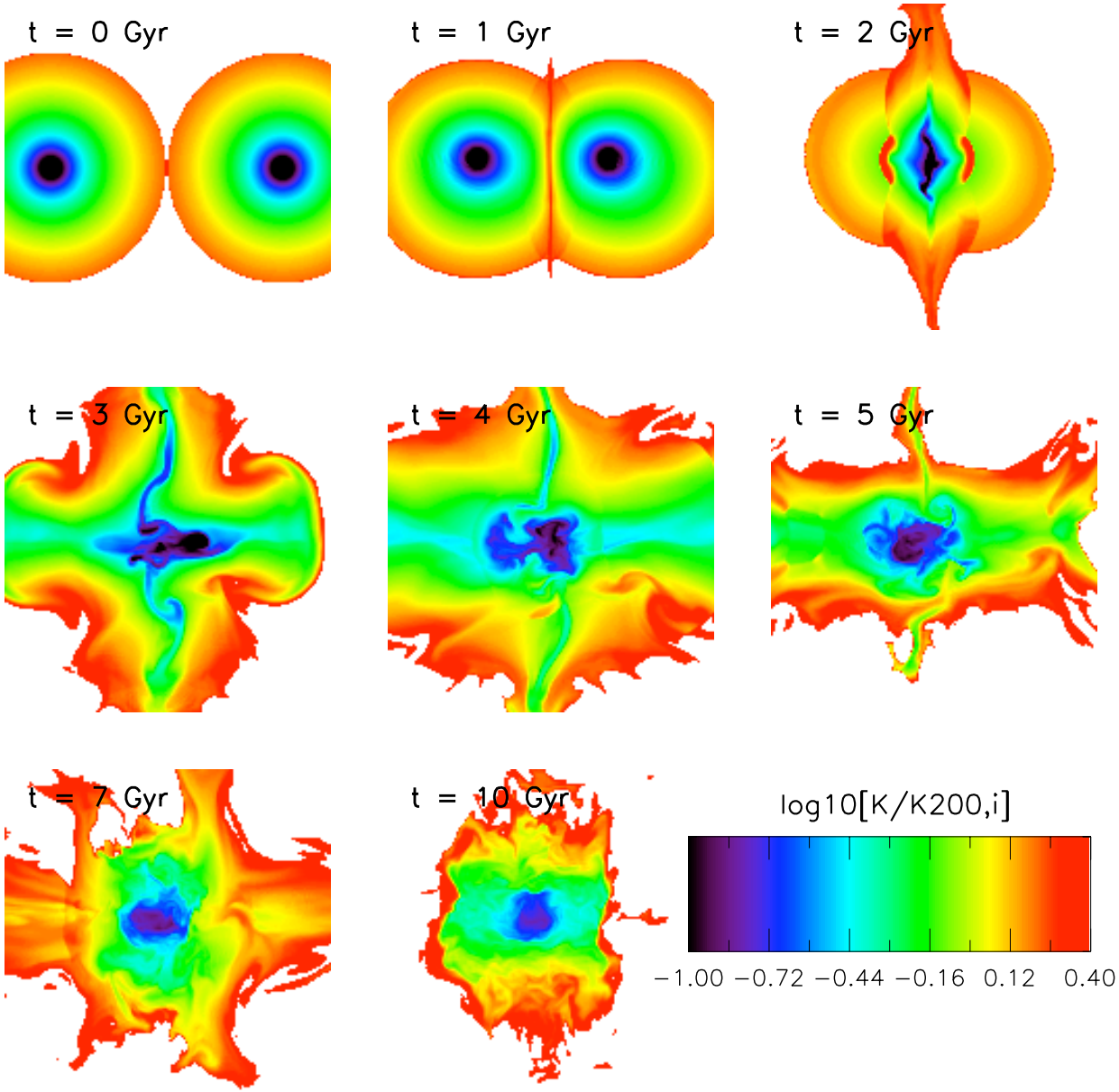
Voit, Bryan & Kay '05

Binary collisions

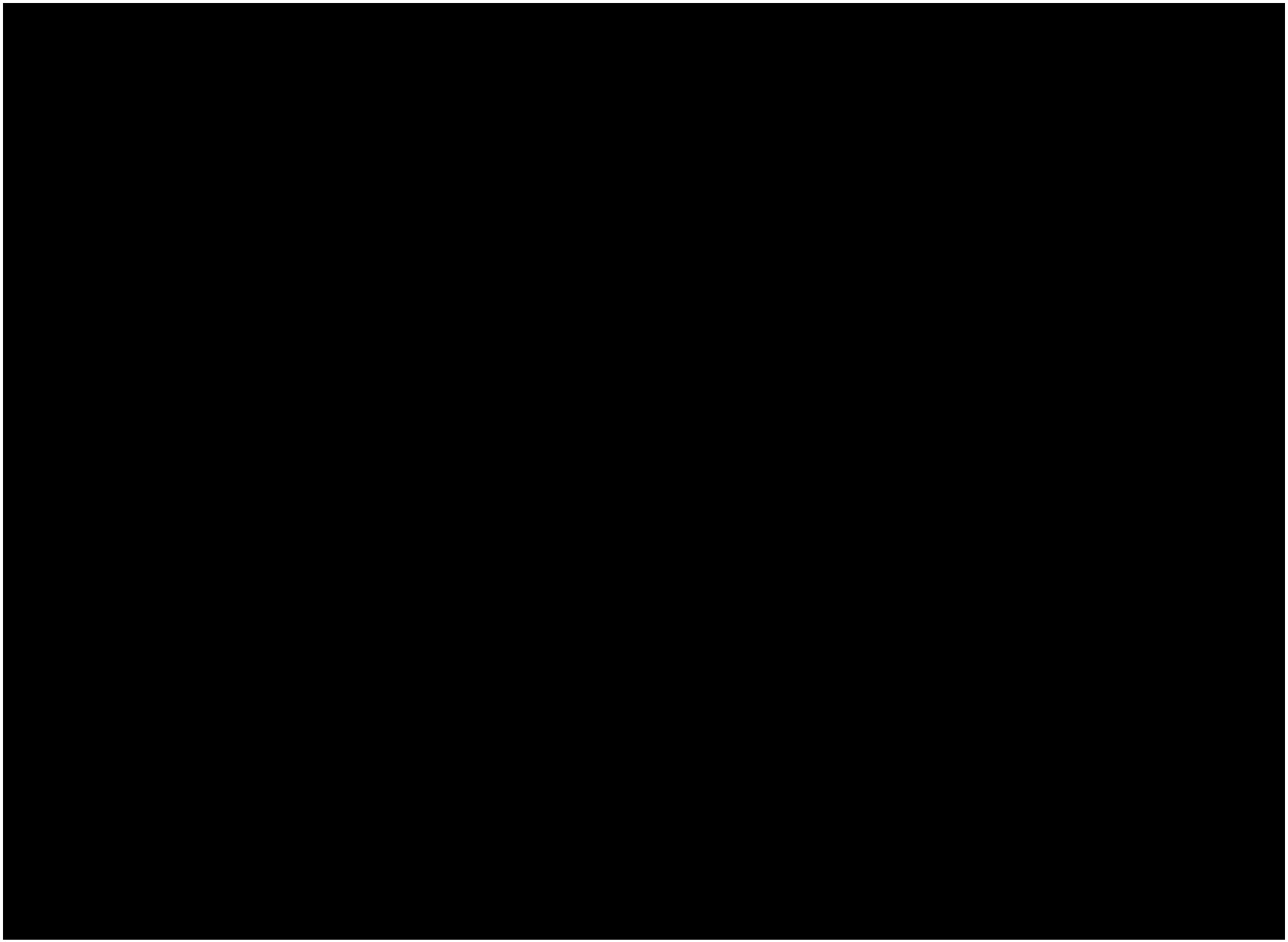


Mitchell, McCarthy, Bower & TT

Generation of entropy (FLASH)

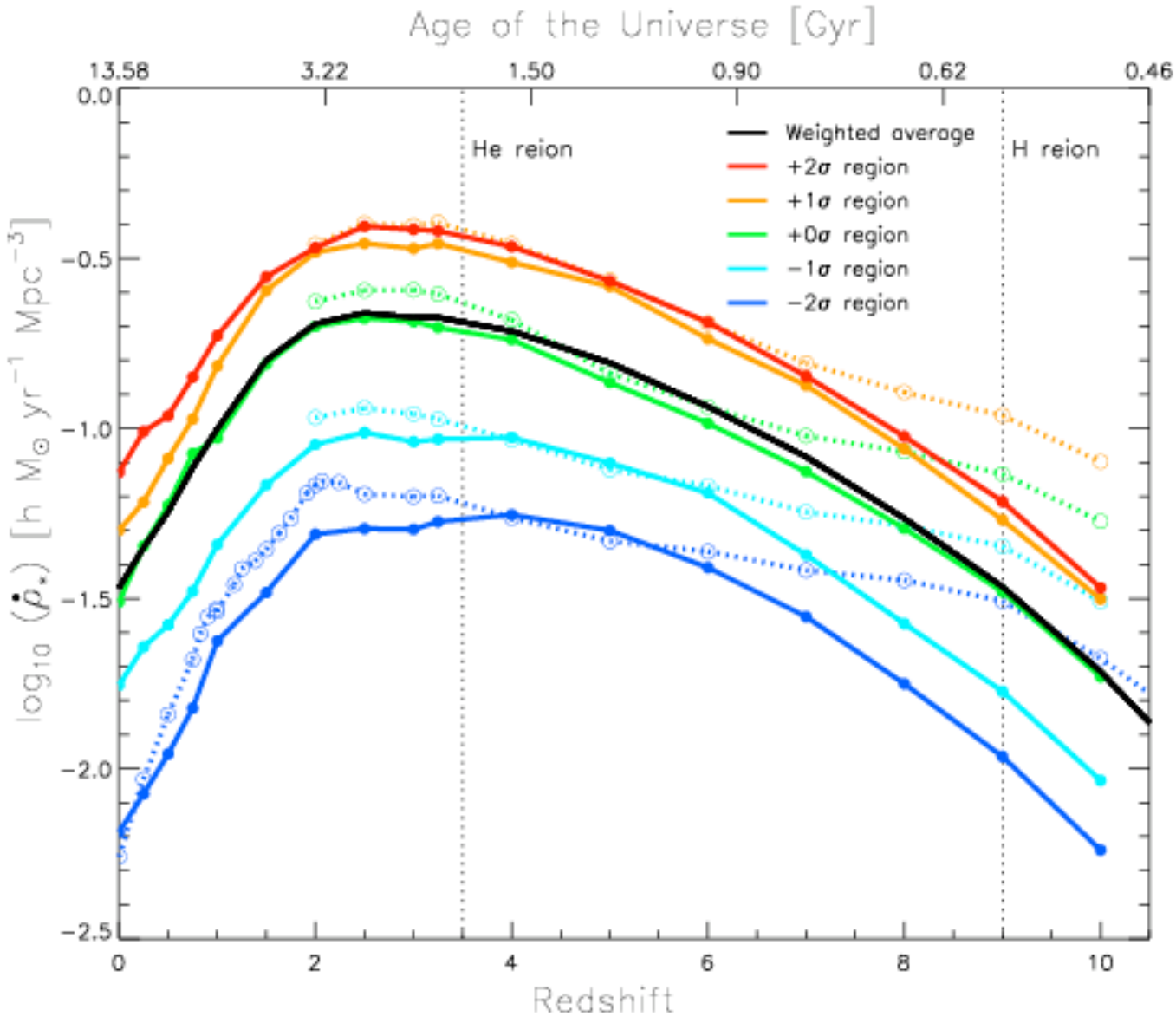


SPH AMR



Star formation rate density (Madau/Lilly)

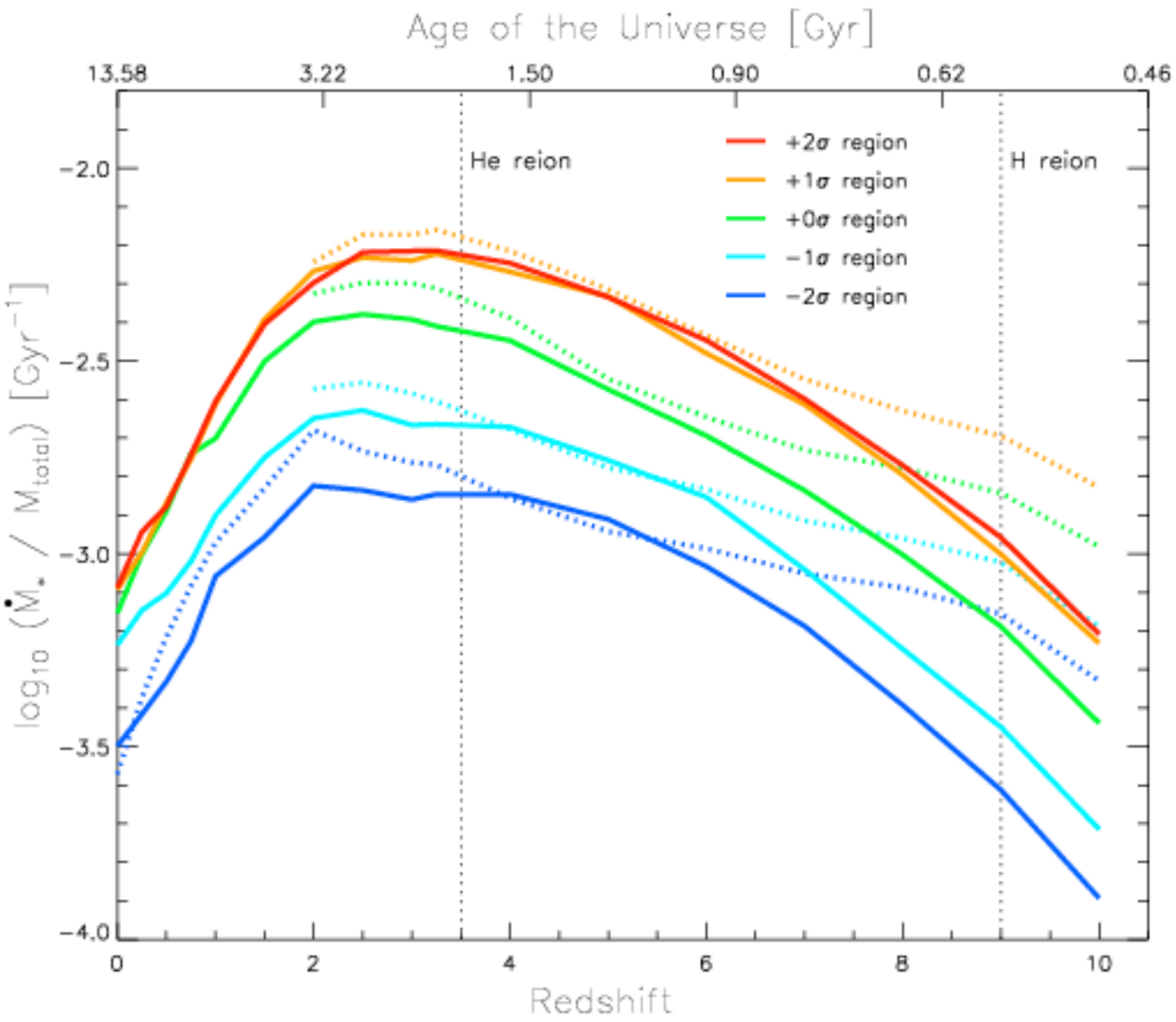
Star formation rate density



Redshift

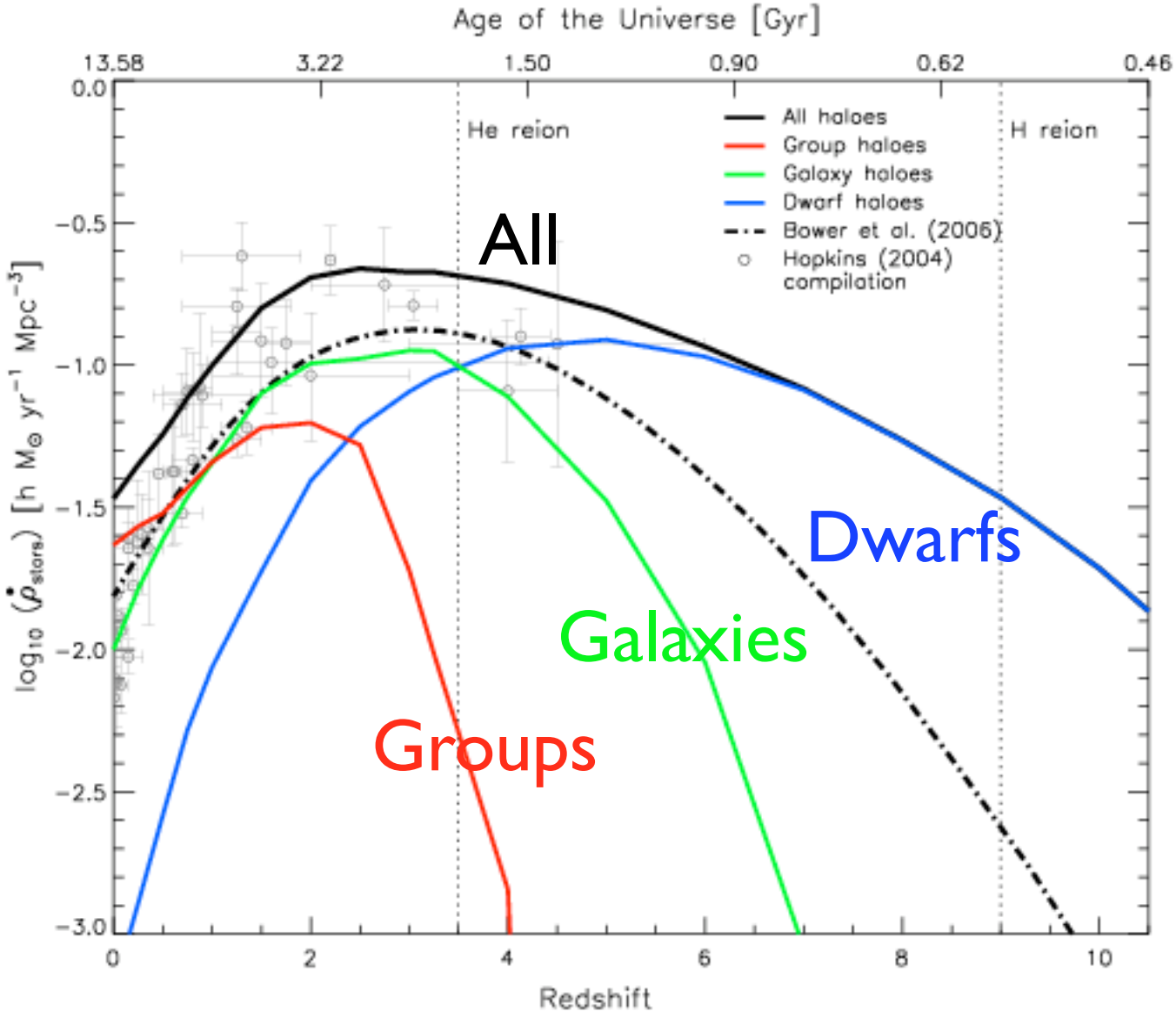
Specific star formation rate

Star formation rate per unit mass



Redshift

Star formation as function of halo mass then

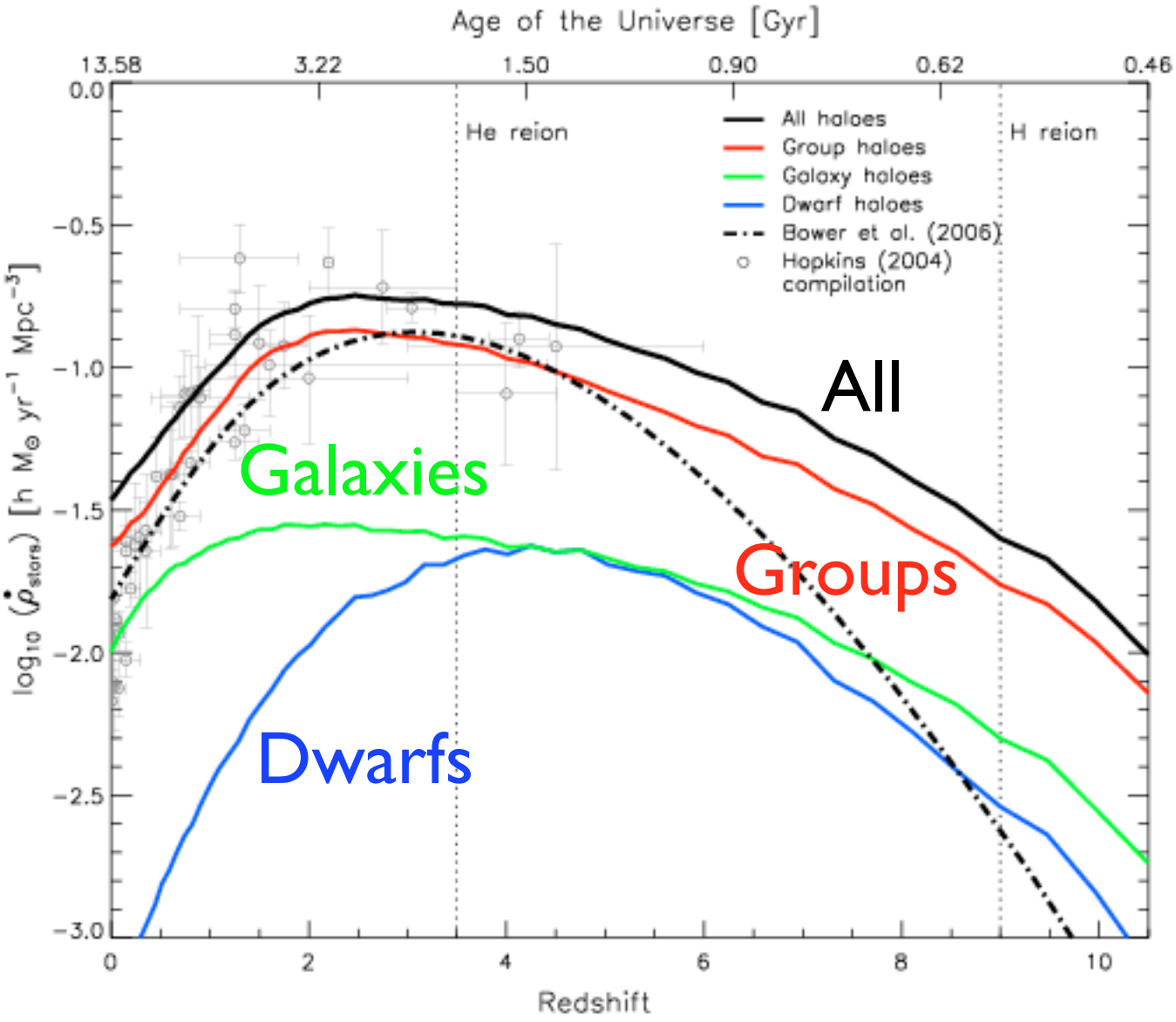


Star formation rate density

Redshift

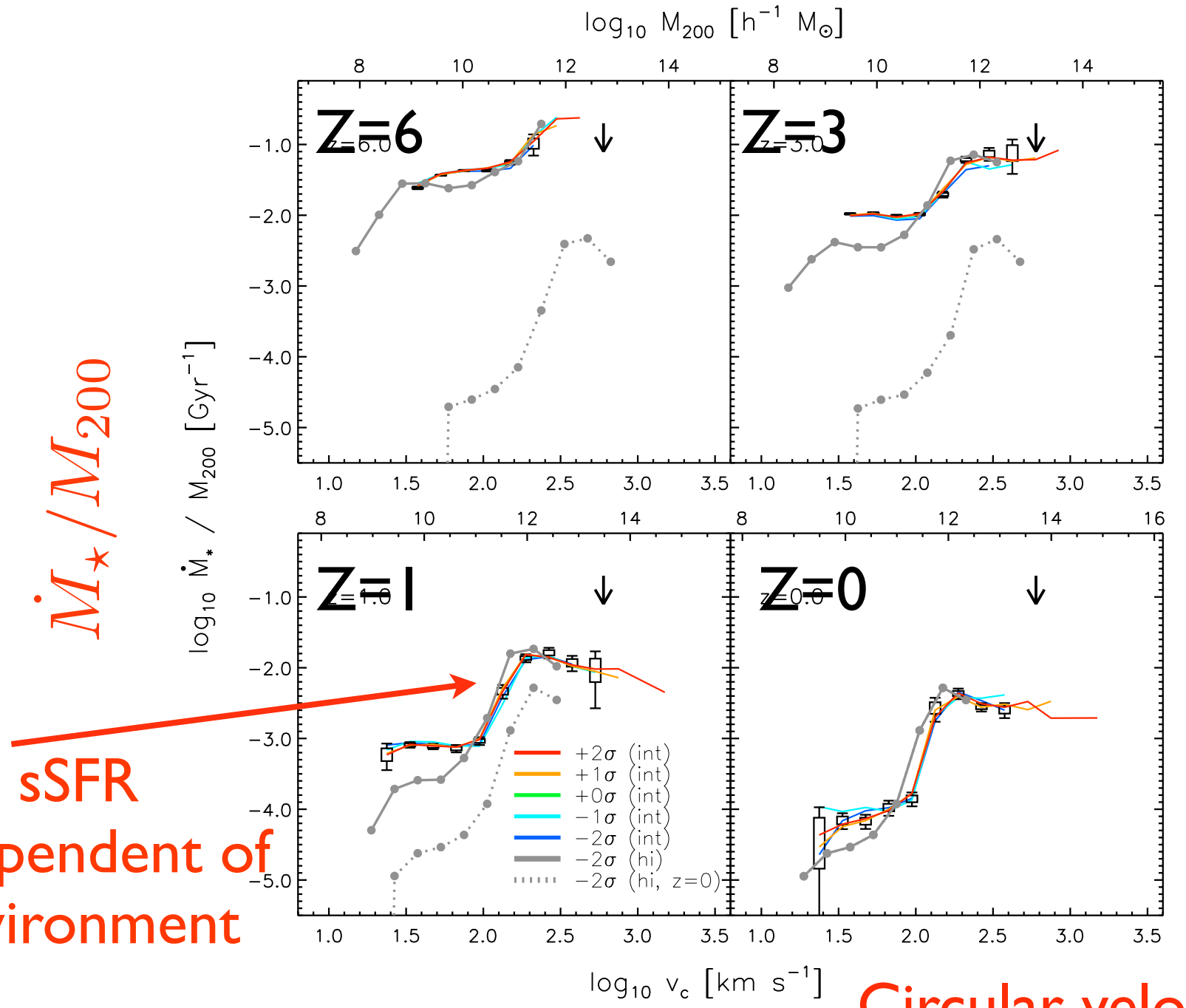
Star formation as function of halo-mass now

Star formation rate density



Redshift

Specific star formation rate per halo



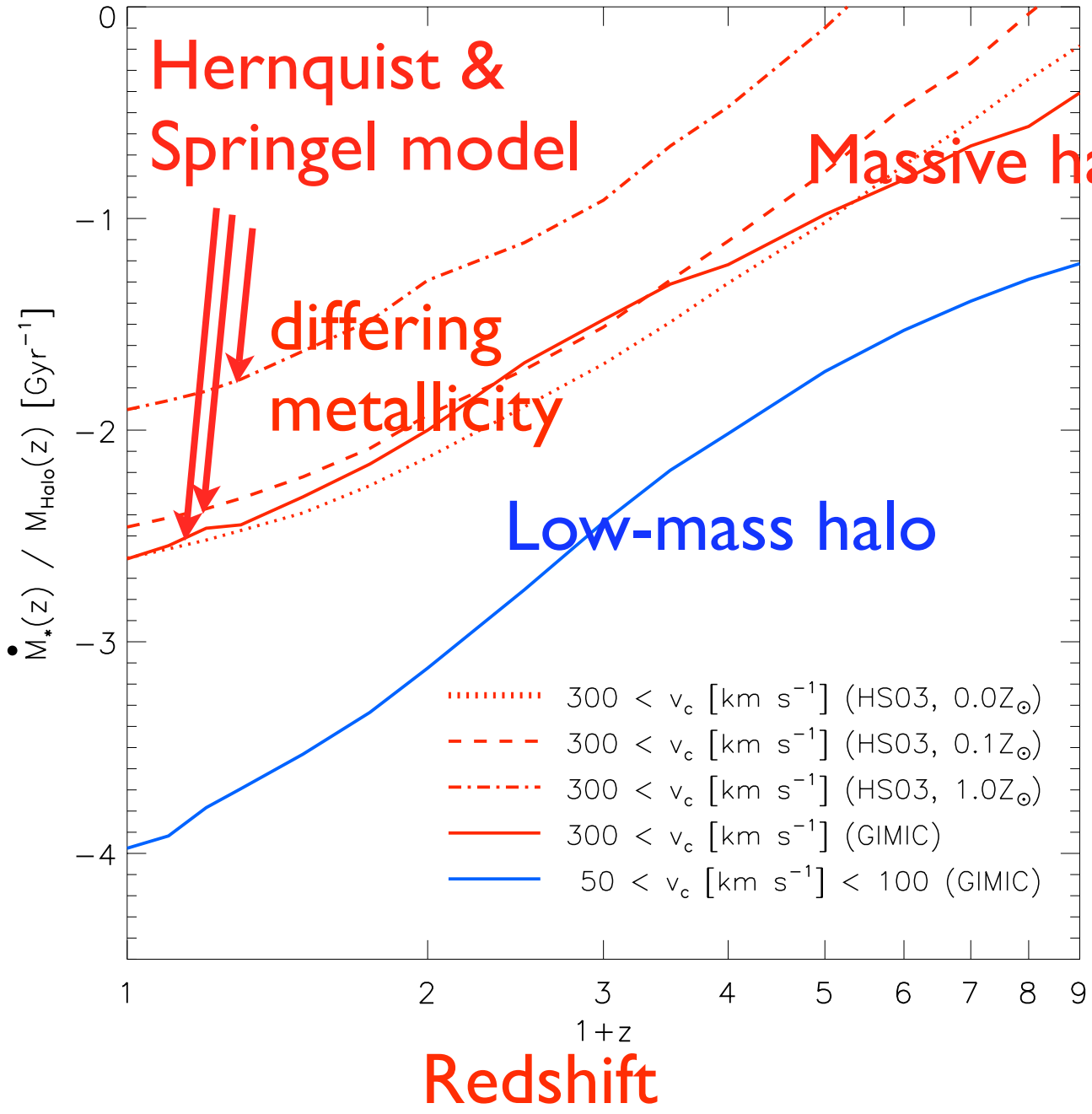
$\dot{M}_\star / M_{200}$

sSFR independent of environment

Circular velocity

sSFR as function of redshift

$\dot{M}_\star / M_{200}$



Redshift

Stellar multiplicity function

z=6 z=1 z=0

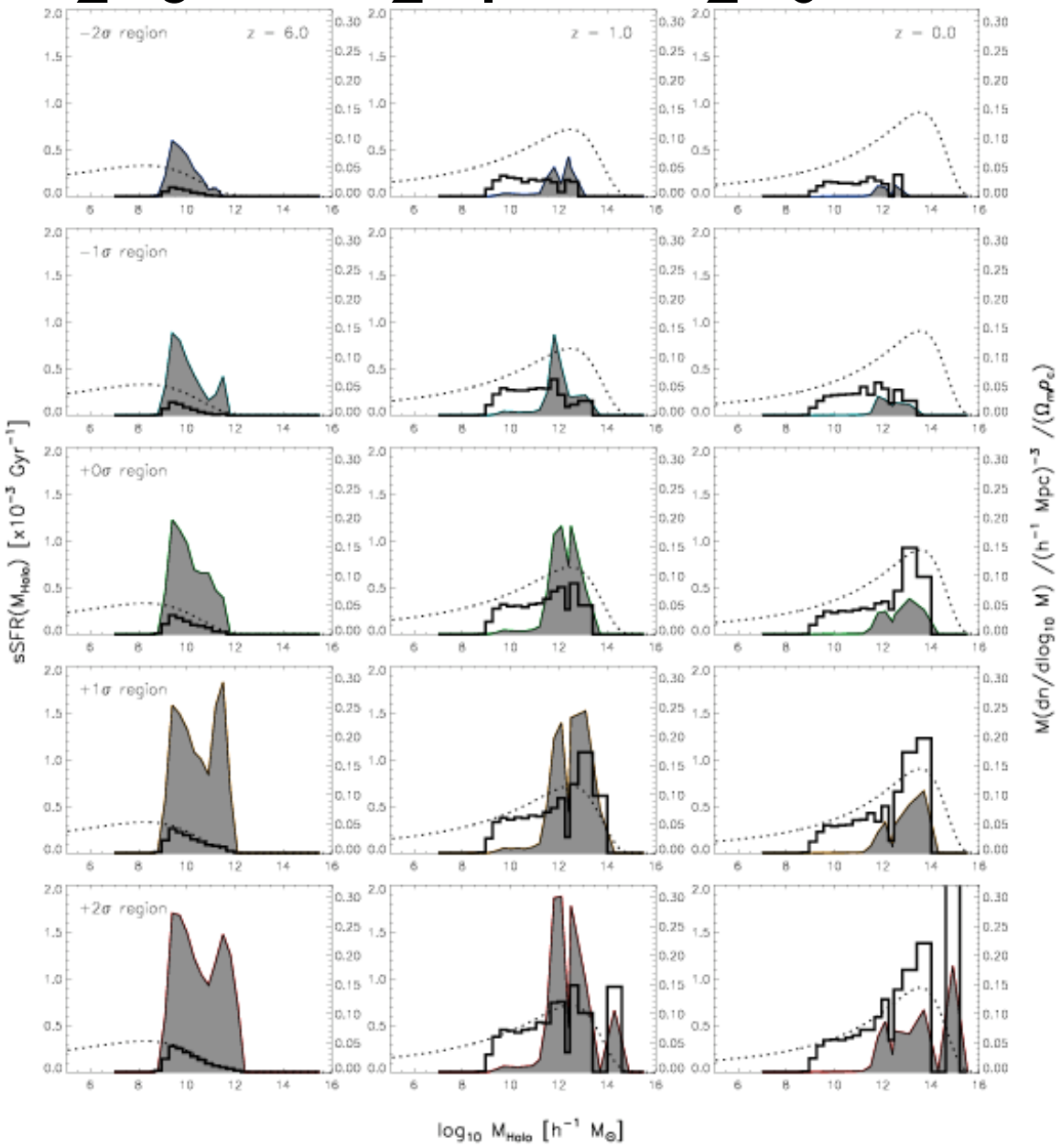
-2σ

-1σ

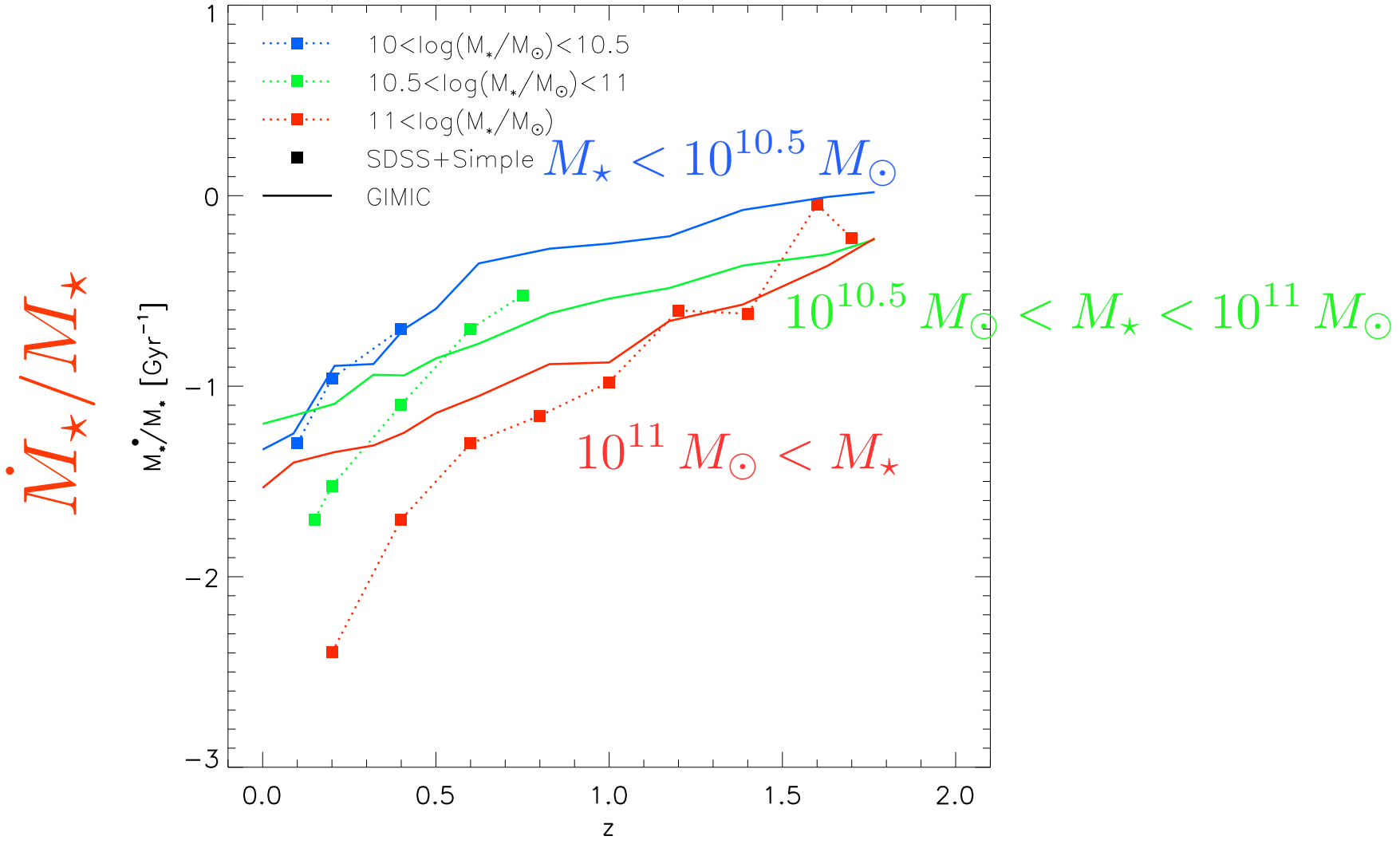
0σ

$+1\sigma$

$+2\sigma$

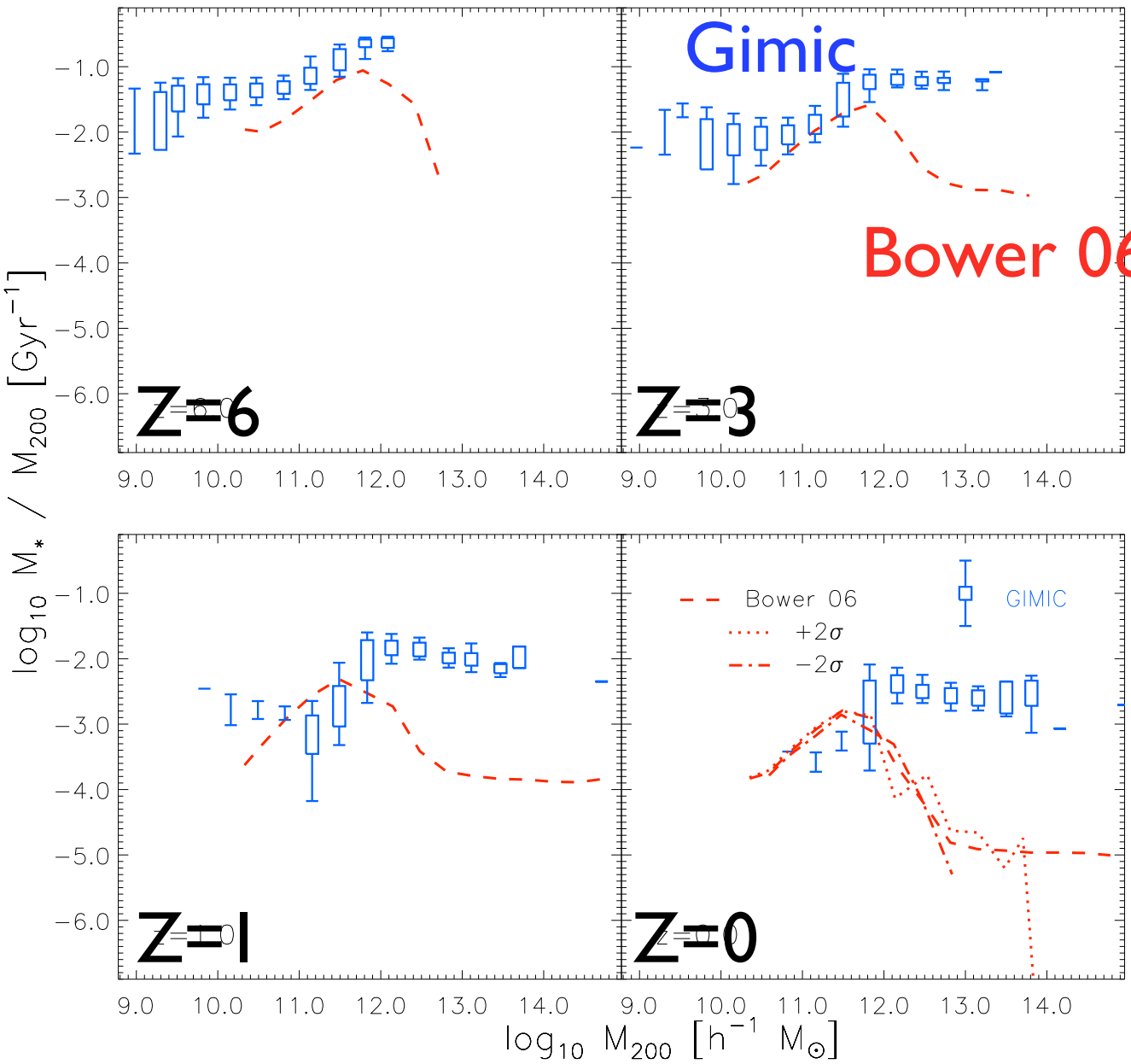


sSFR as function of redshift compared to SDSS



Redshift

sSFR GIMIC vs Galform



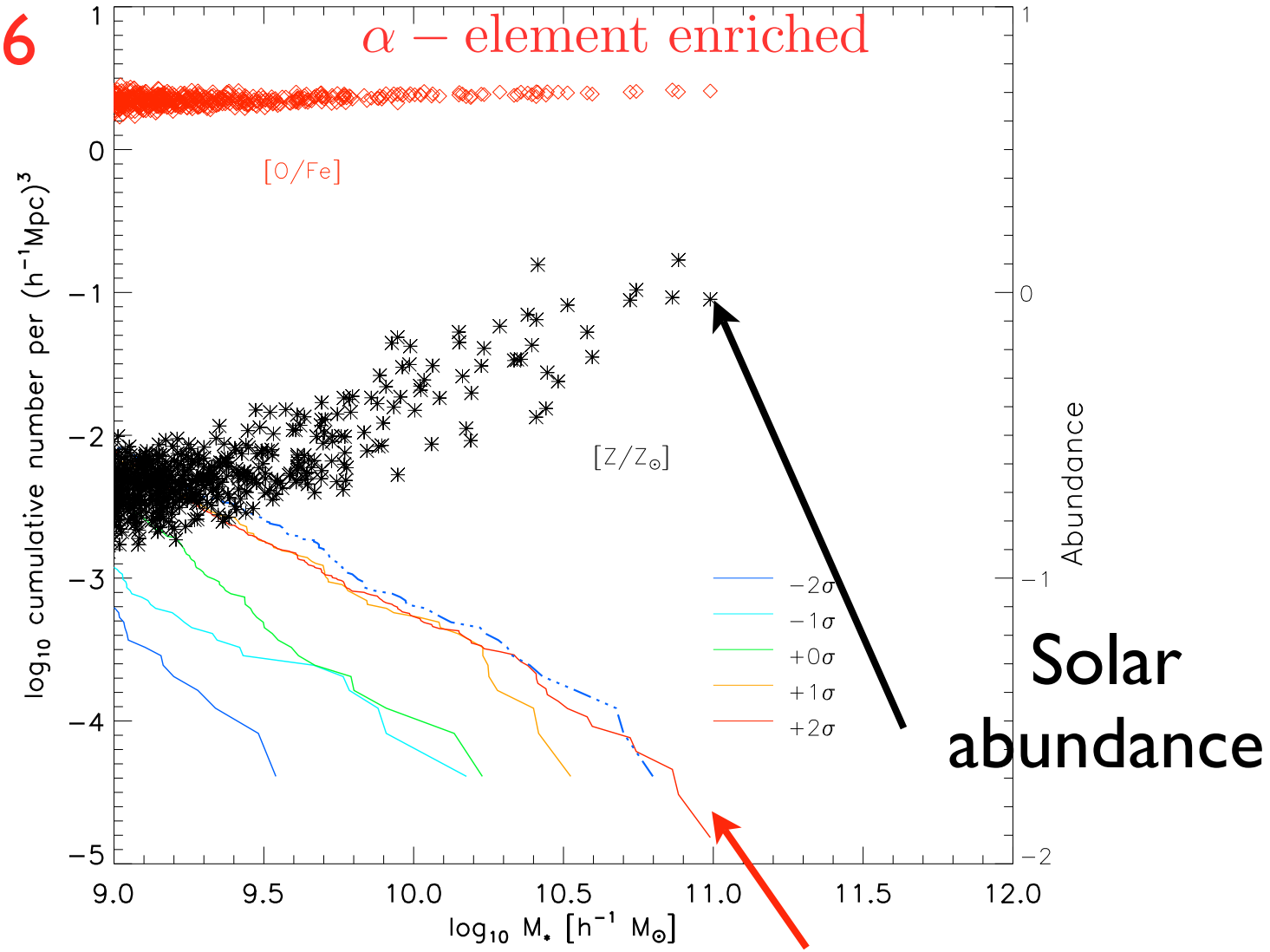
$\dot{M}_\star / M_{200}$

DM halo mass

Star formation at high z

Reionization as function of environment

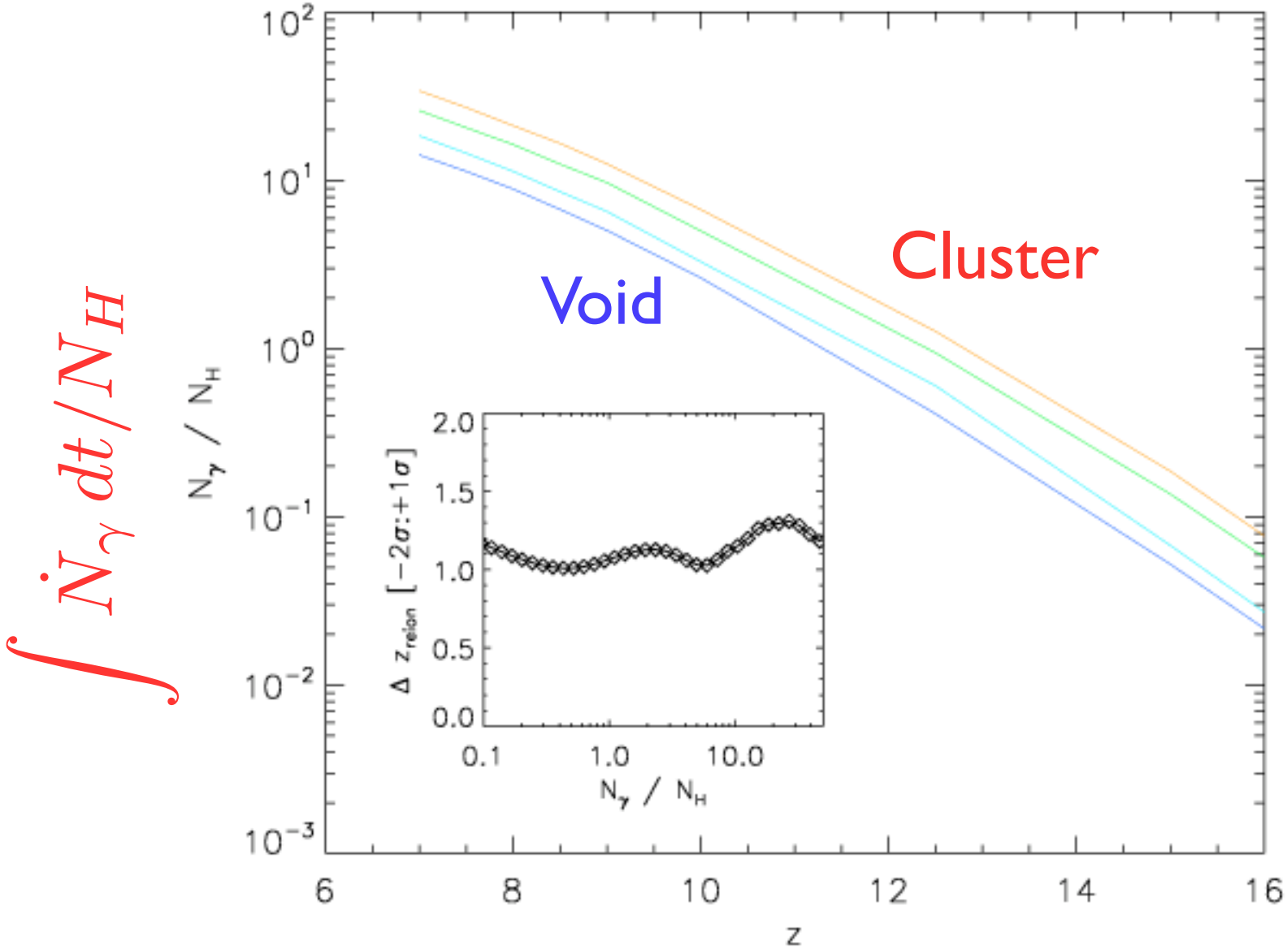
Stellar mass function z=6



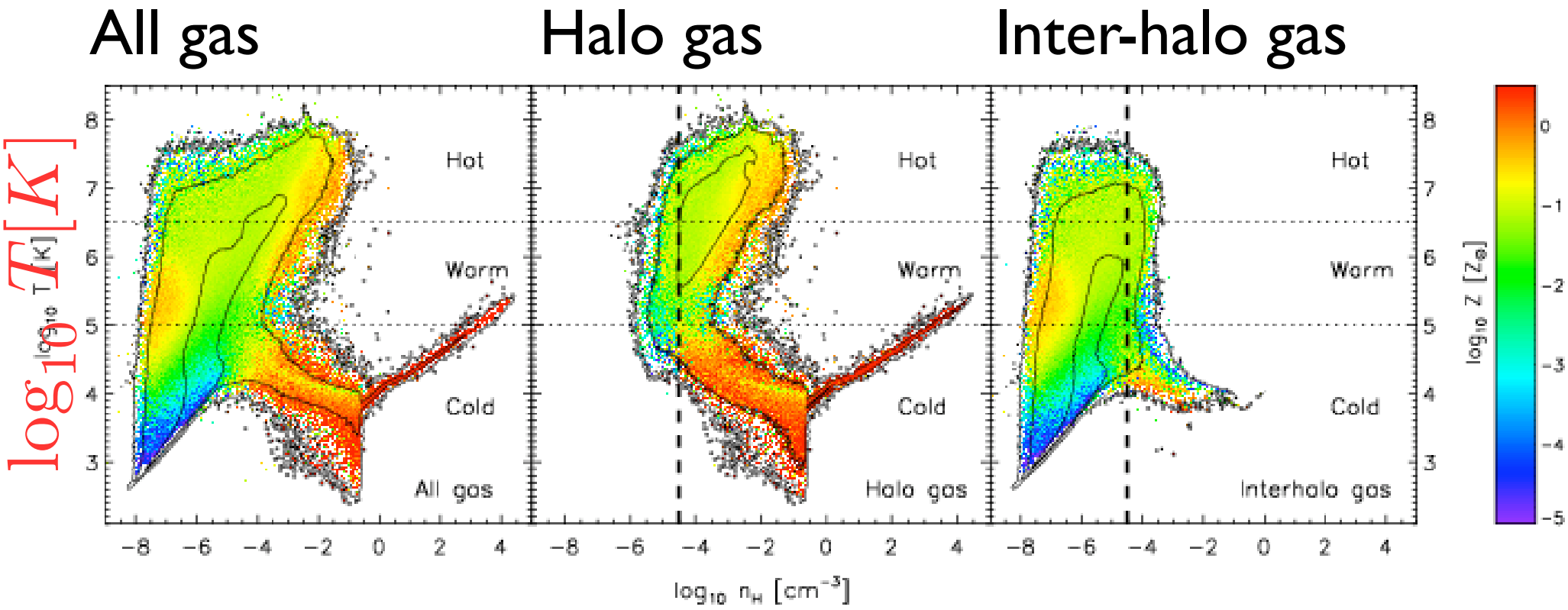
Solar abundance

$M_\star = 10^{11}\, M_\odot$ solar-abundance galaxy

Reionization as function of environment

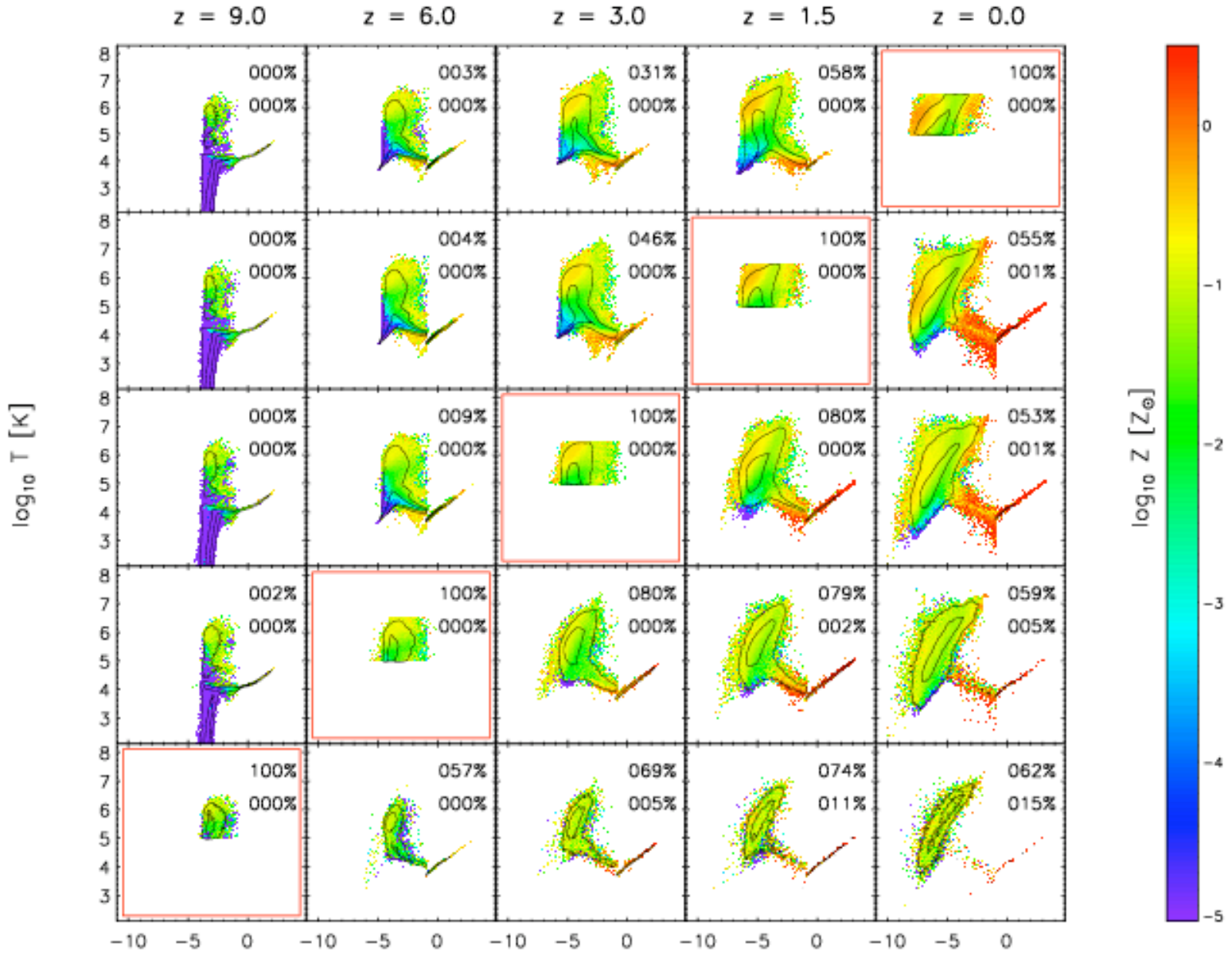


Temperature/Density/Metallicity at z=0



$$\log_{10} n_H [cm^{-3}]$$

Cycling of gas through whim phase

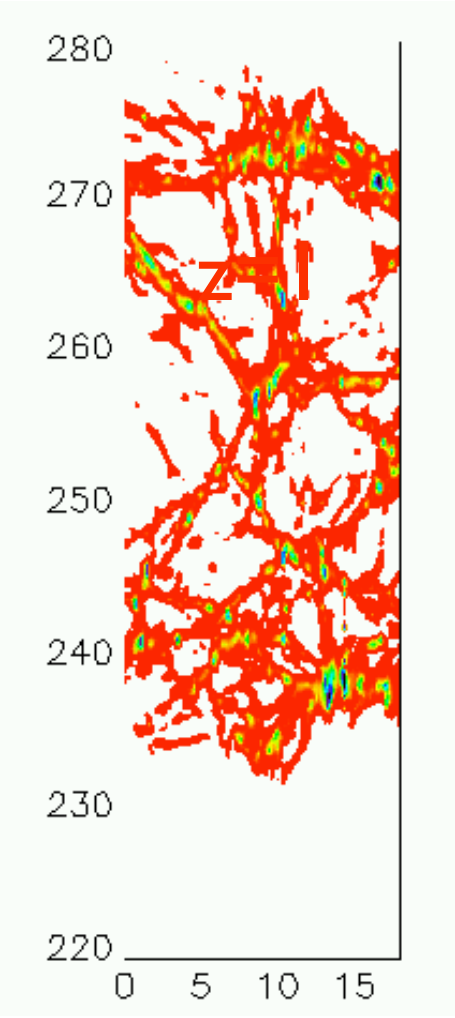


$\log_{10} T[K]$

$\log_{10} n_H[cm^{-3}]$

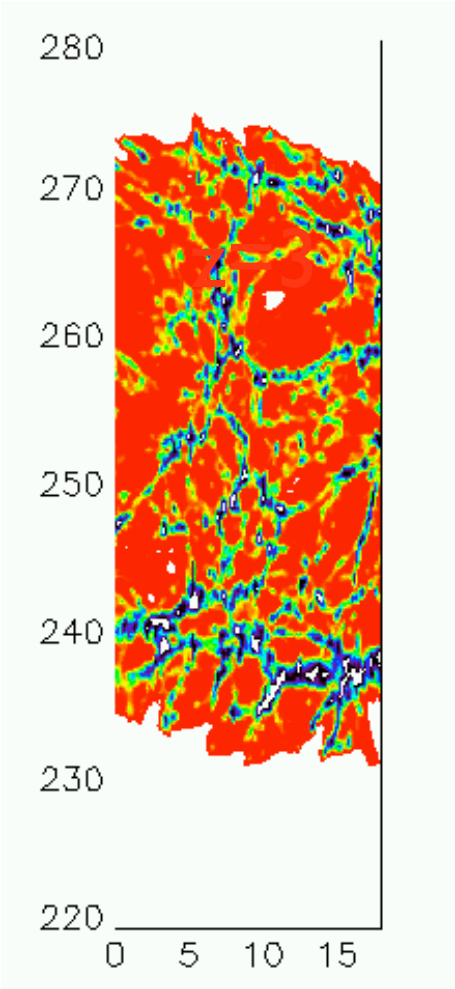
LSS in the IGM

z=0



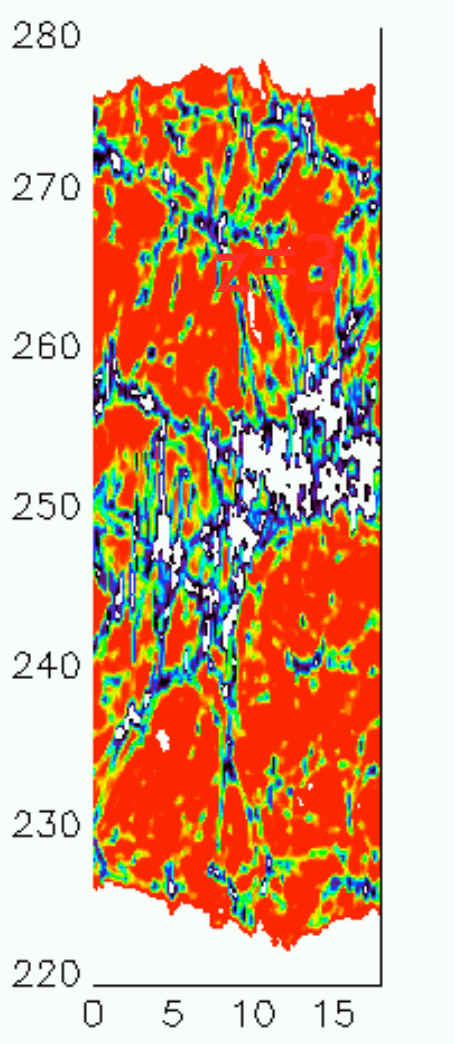
0σ

z=3

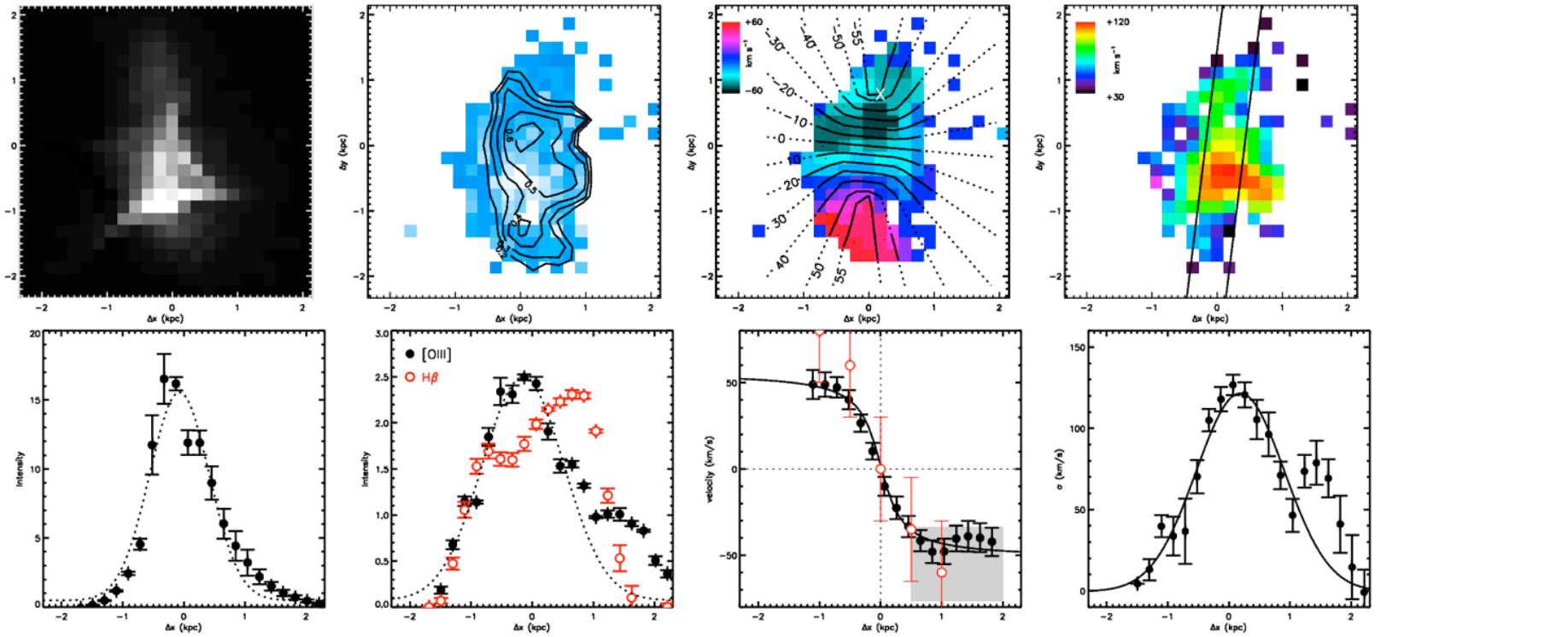


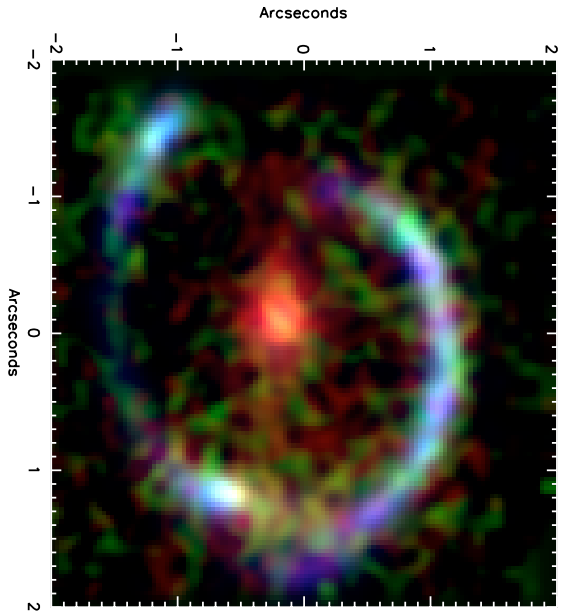
0σ

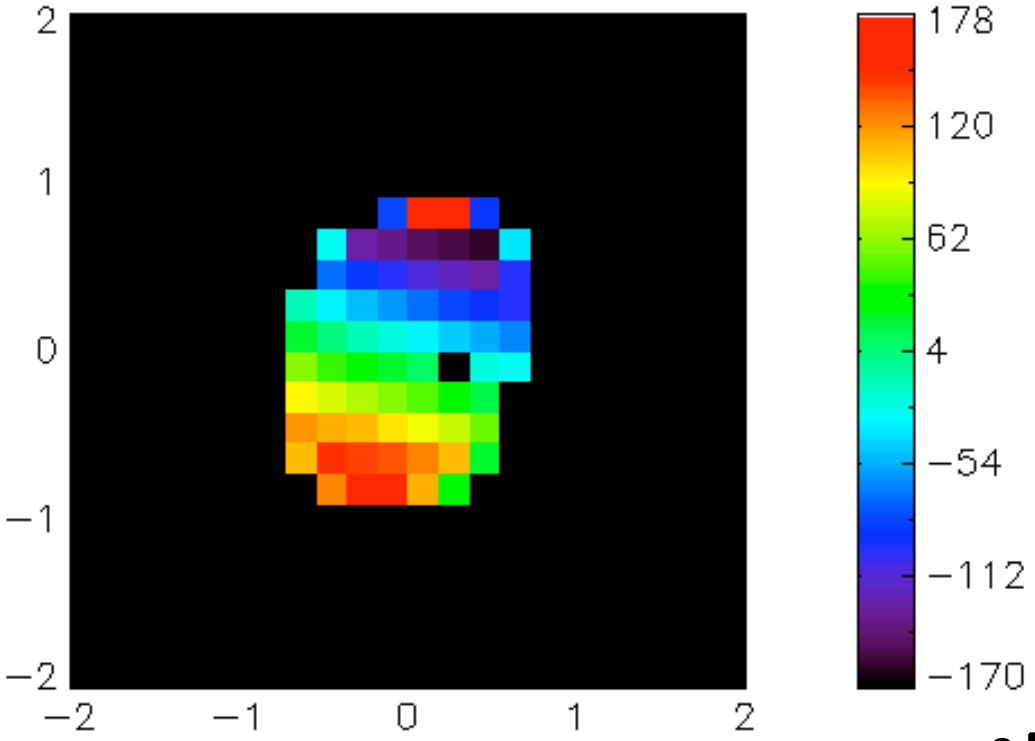
z=3

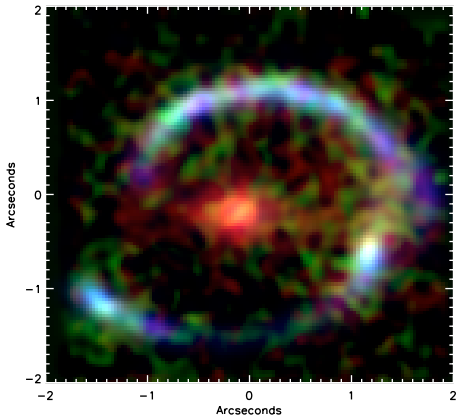


$+2\sigma$


Δx (kpc)
Δy (kpc)
+60
−60
km s⁻¹
+120
+30
Intensity
[OIII]
Hβ
velocity (km/s)
σ (km/s)

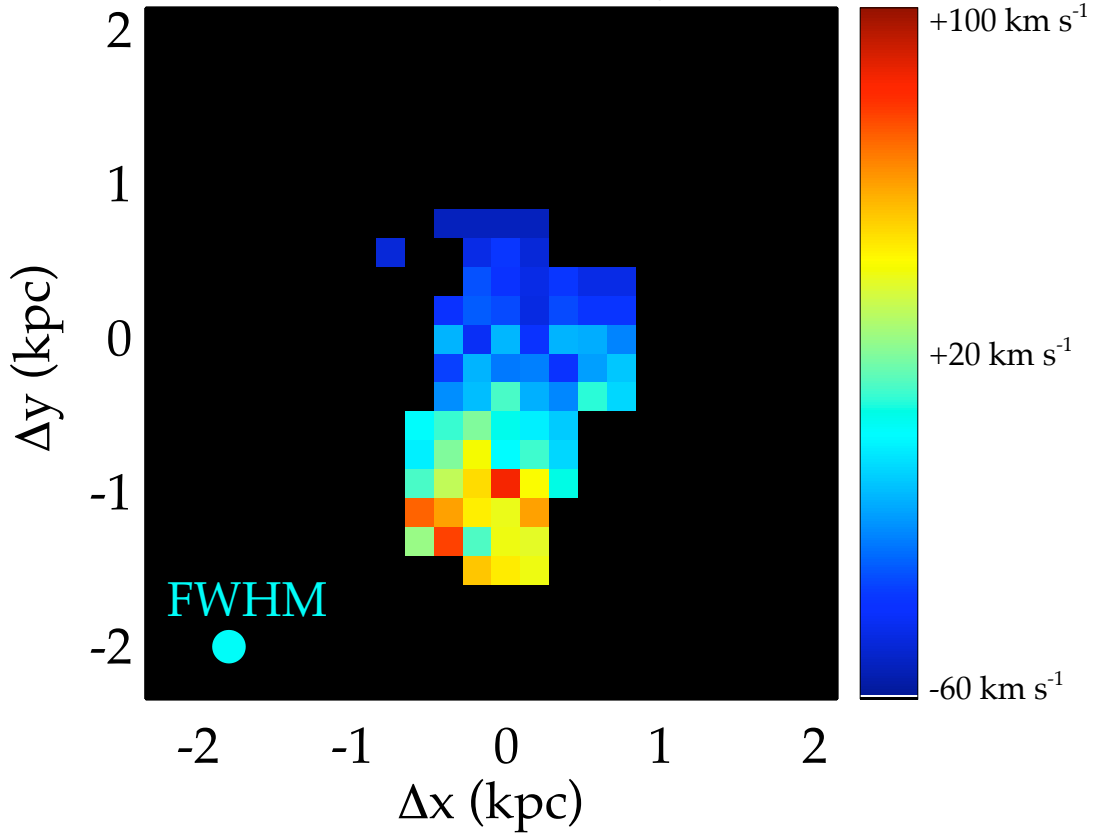

Arcseconds
Arcseconds



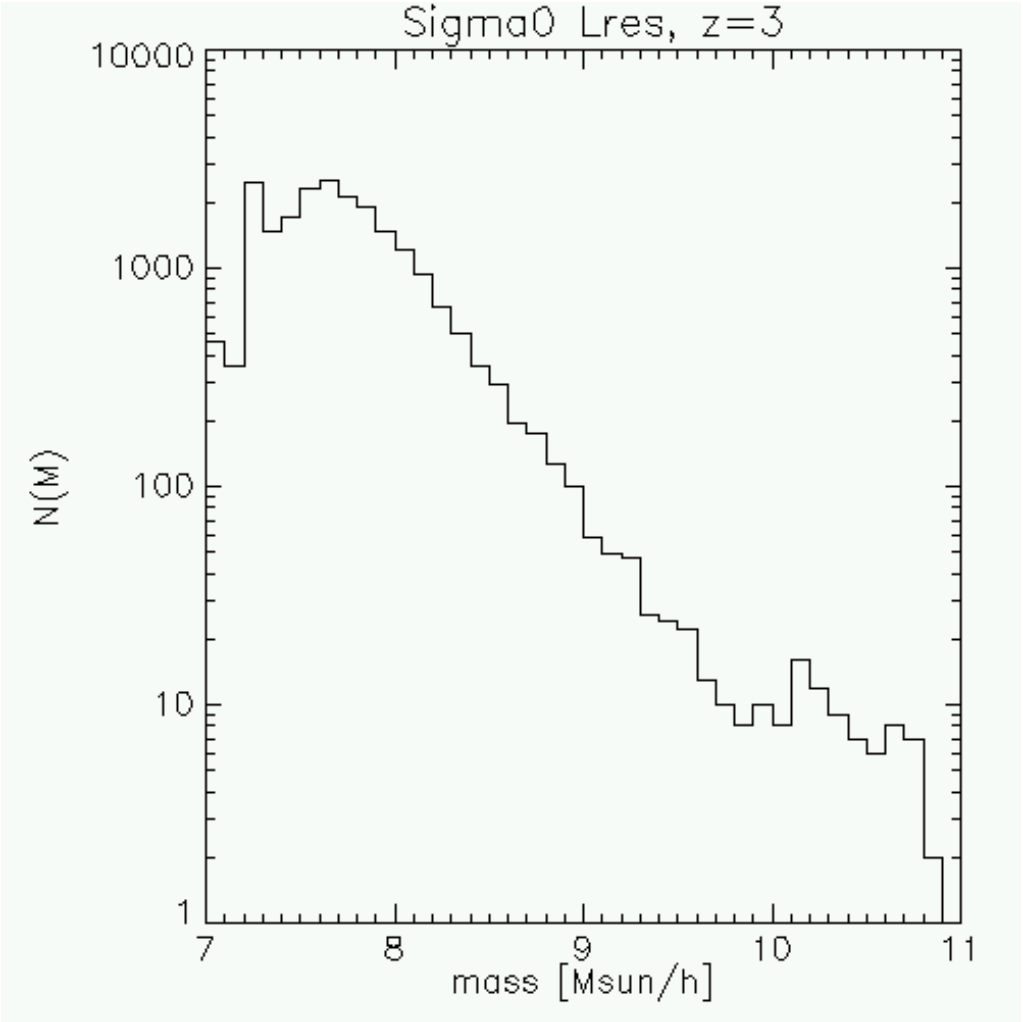


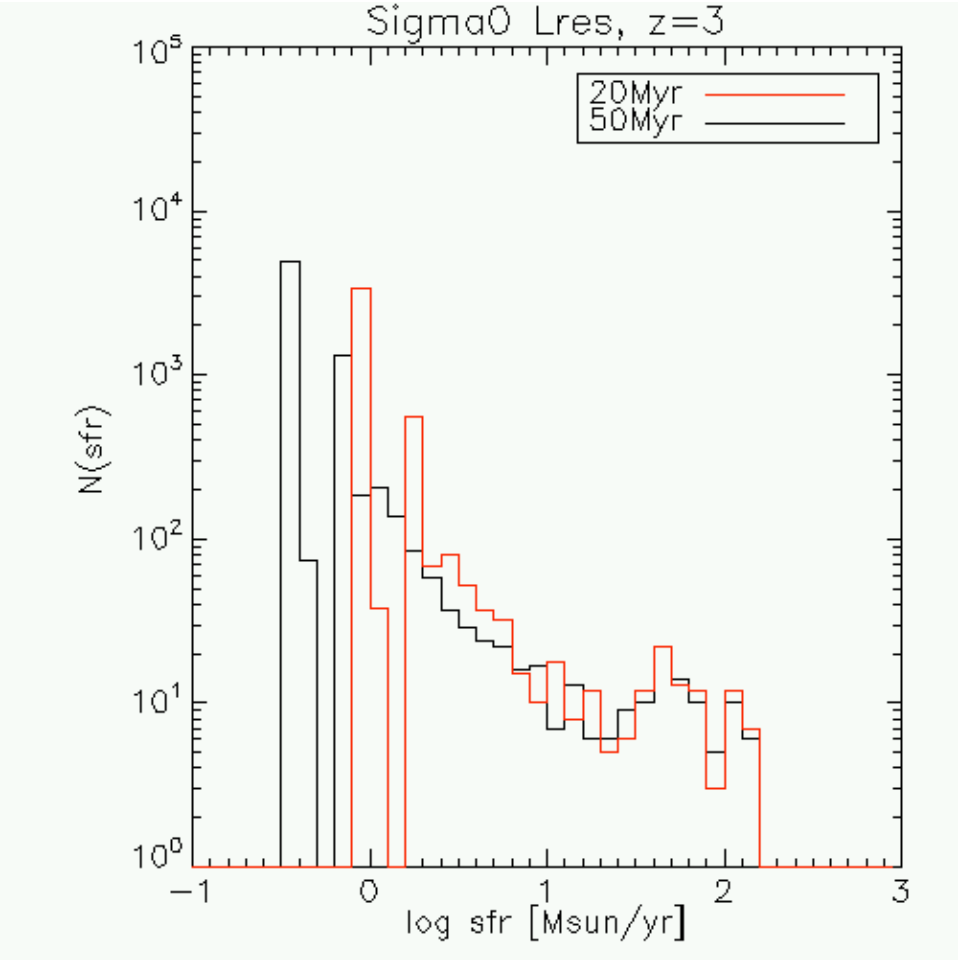
AMS 1

[OIII] velocity



$M_*=10^8\ M_0$, SFR=5 M_0/yr, z=2.75

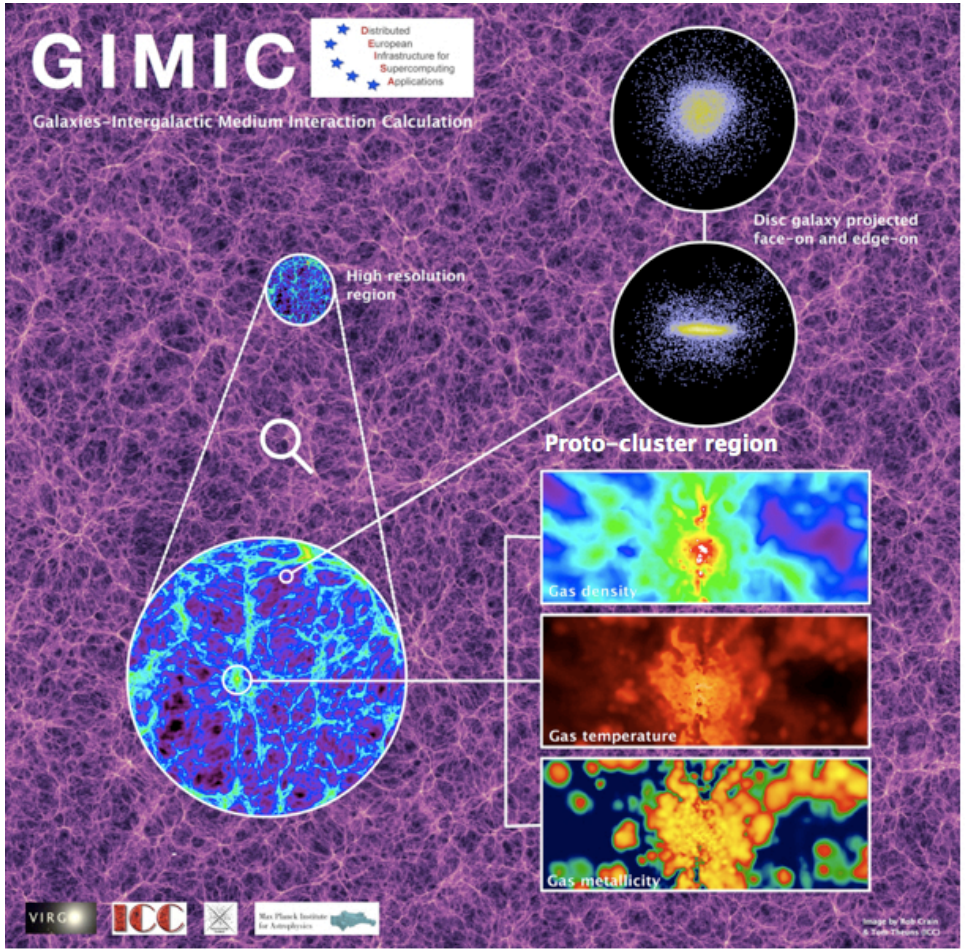




Main conclusion:

- SFR depends strongly on environment
- sSFR as function of halo mass, does not
- dependence driven by DM-mass function

Interested in using these simulations? Let me know!



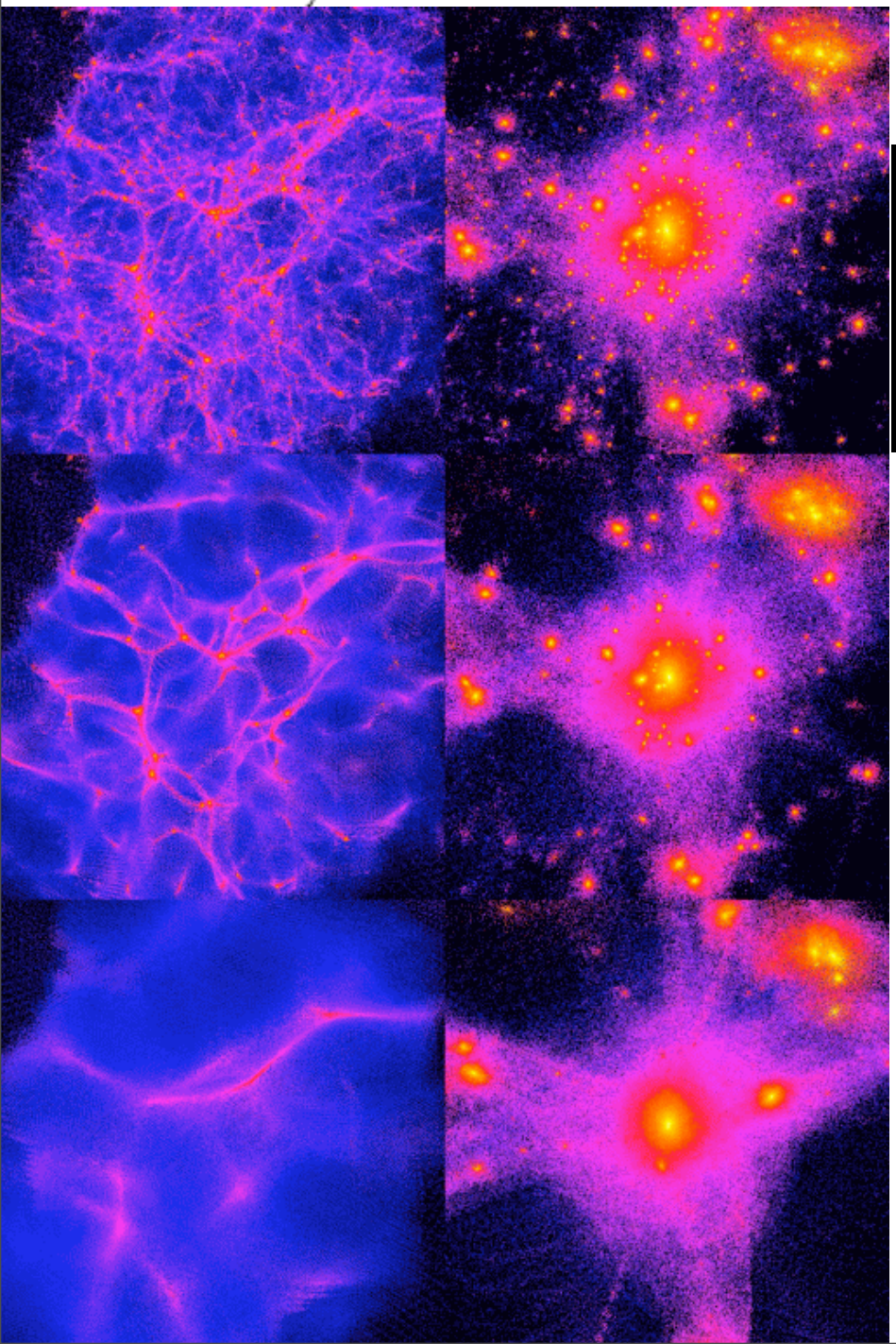
Durham University

... and finally ....

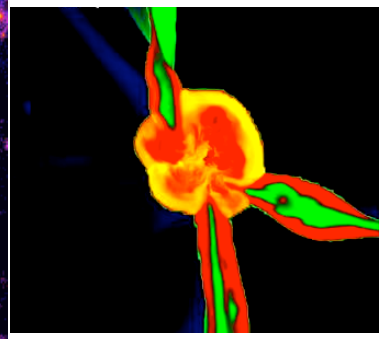
And now for something completely different!

Durham University

First stars and the nature of the dark matter

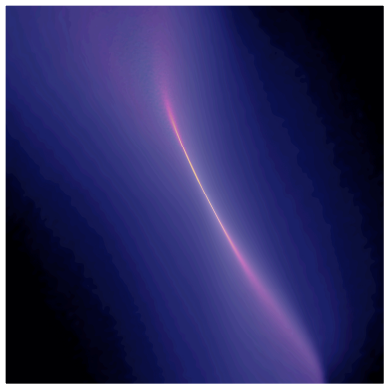


Cold Dark Matter



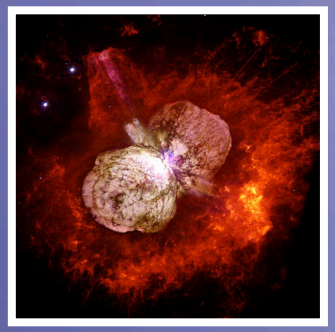
- Single star per halo
- Massive: 30-300 M_sun
- Short-lived: 2-4 Myr
- Very luminous
- No strong mass loss
- die as SN or BH

Warm Dark Matter

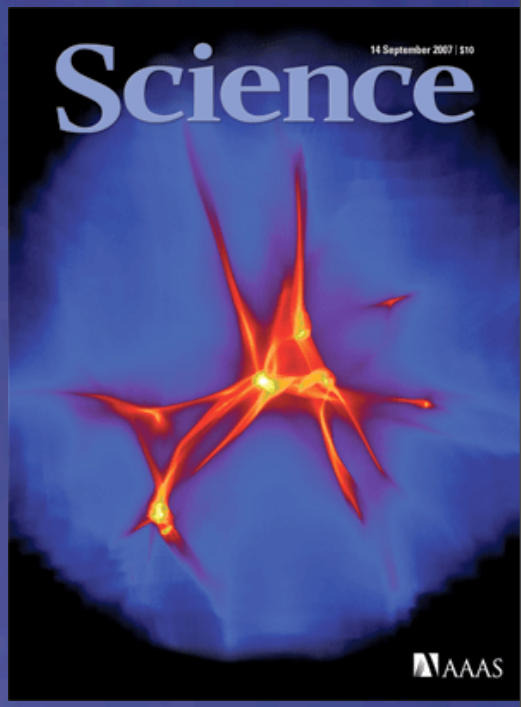


- Many stars per filament
- Low and high mass
- Milky Way remnants?

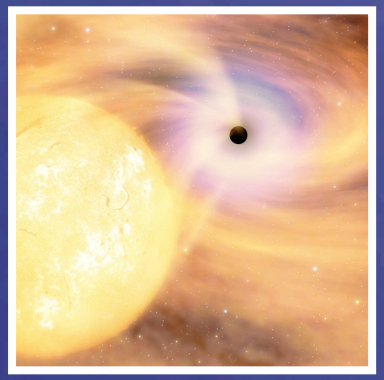
Institute for Computational Cosmology



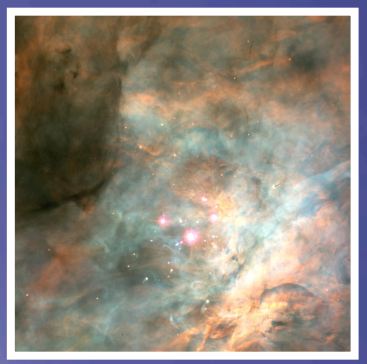
Massive stars



Gao & Theuns 07



Seed for super-massive BH

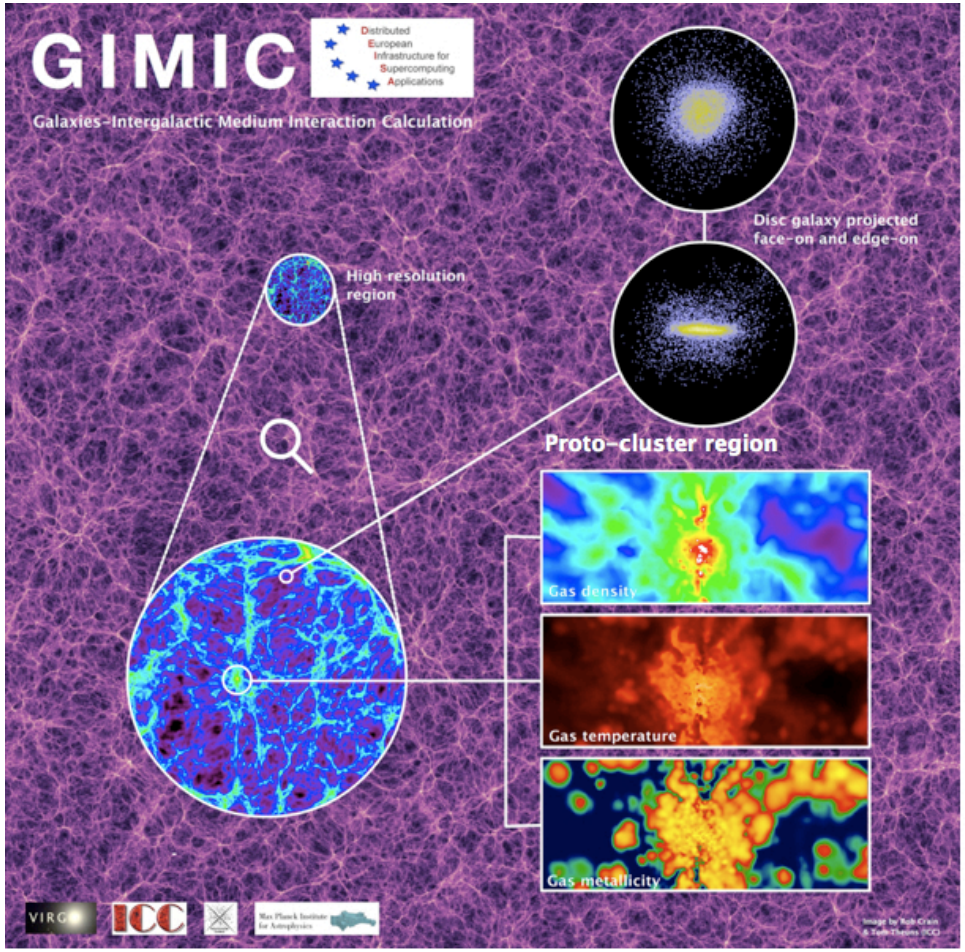


Low-mass stars

Main conclusion:

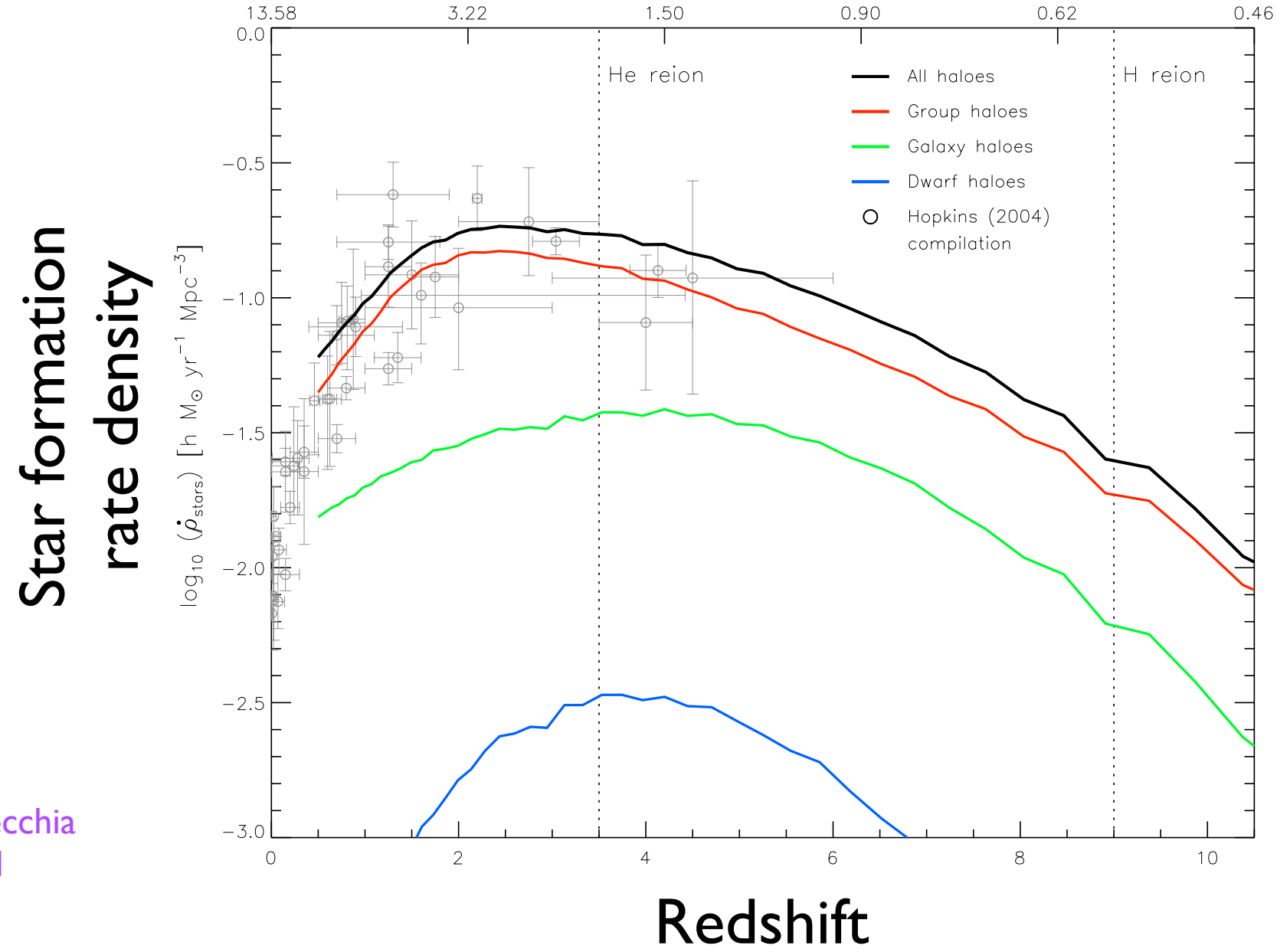
- SFR depends strongly on environment
- sSFR as function of halo mass, does not
- dependence driven by DM-mass function

Interested in using these simulations? Let me know!



Simulating galaxies and the intergalactic medium

Cosmic star formation history

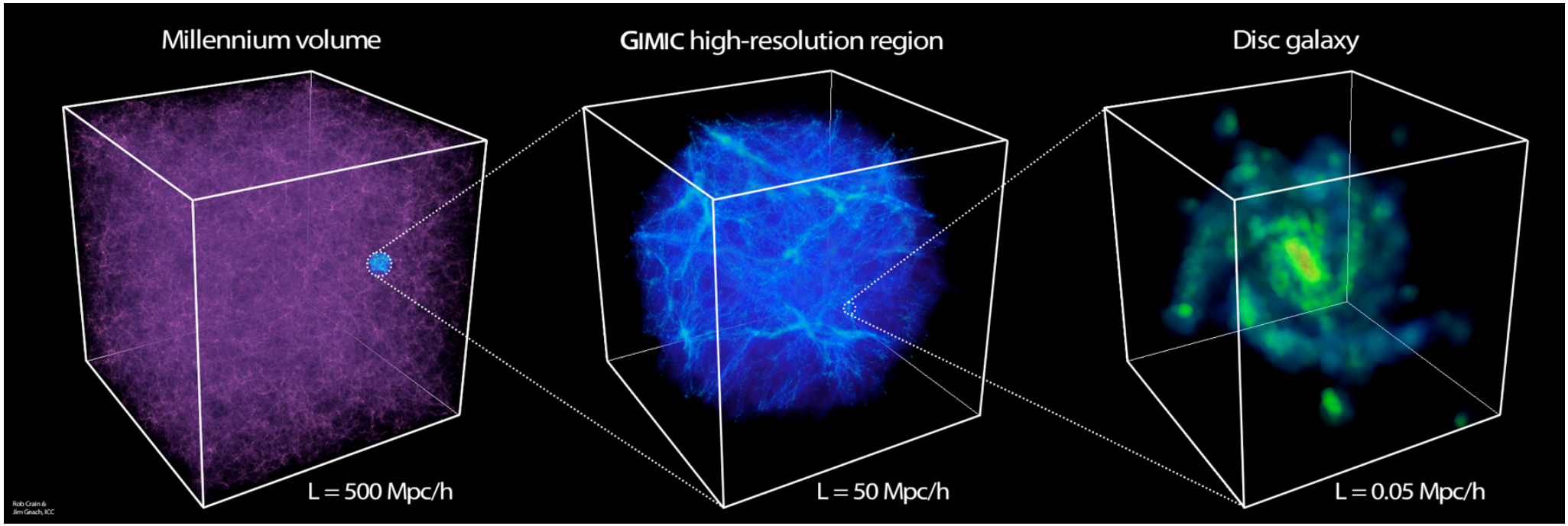


Schaye
Dalla Vecchia
Springel
TT

Durham University

Suite of simulations: GIMIC/OWLS

Galaxy-Intergalactic Medium Interaction Calculation



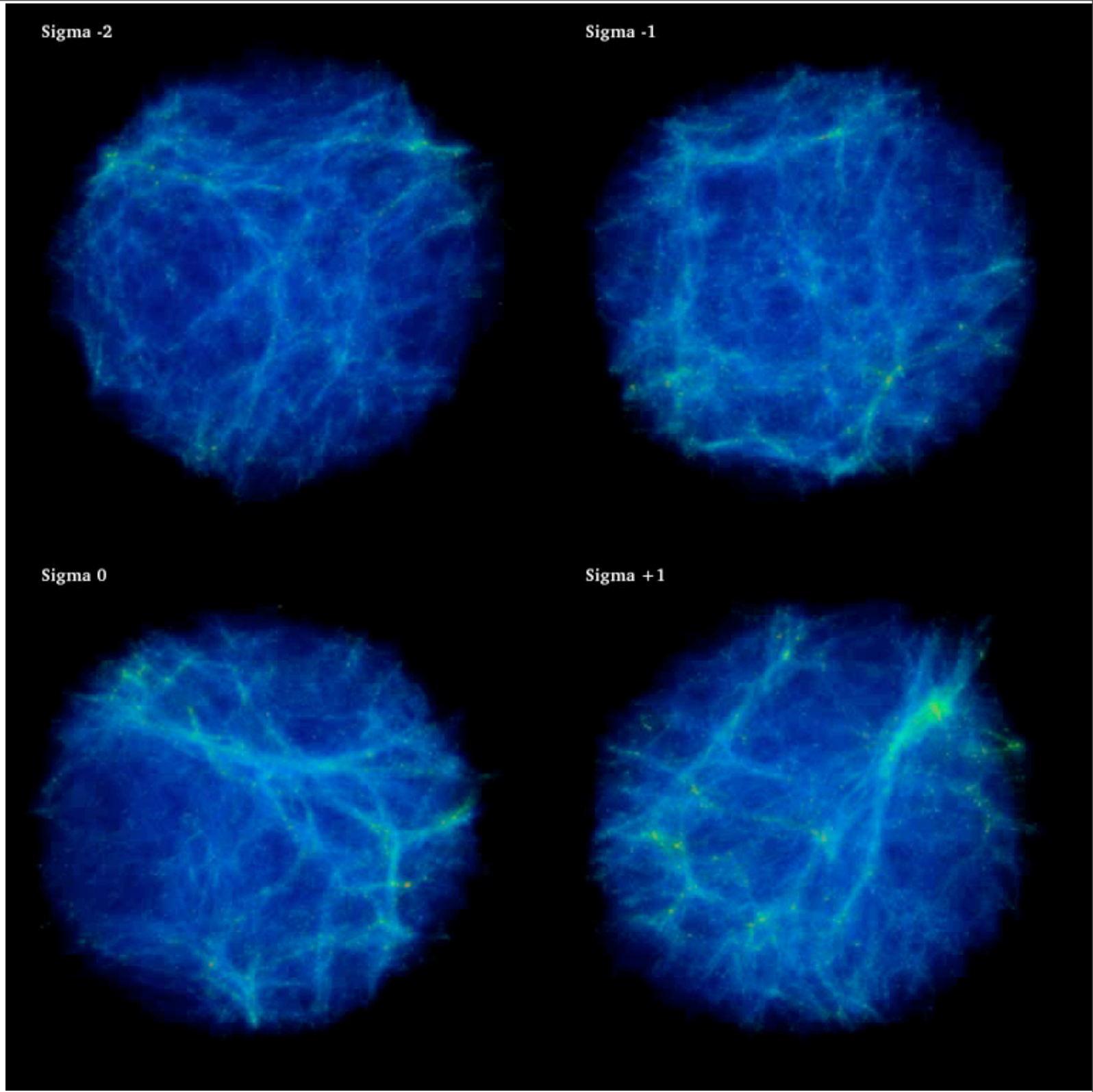
Zoomed simulations of 5 spheres picked from the Millennium Simulation

Combine LSS with high numerical resolution

Tom Theuns

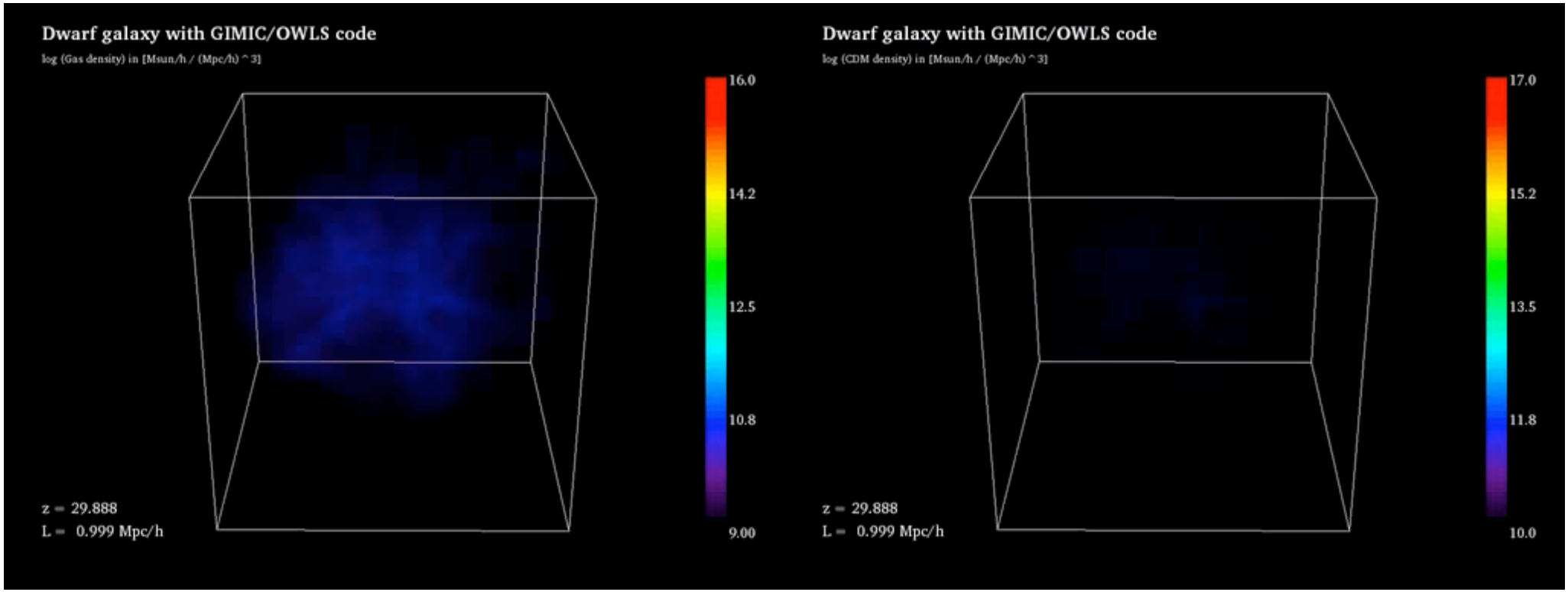
ICC Institute for Computational Cosmology

Durham University



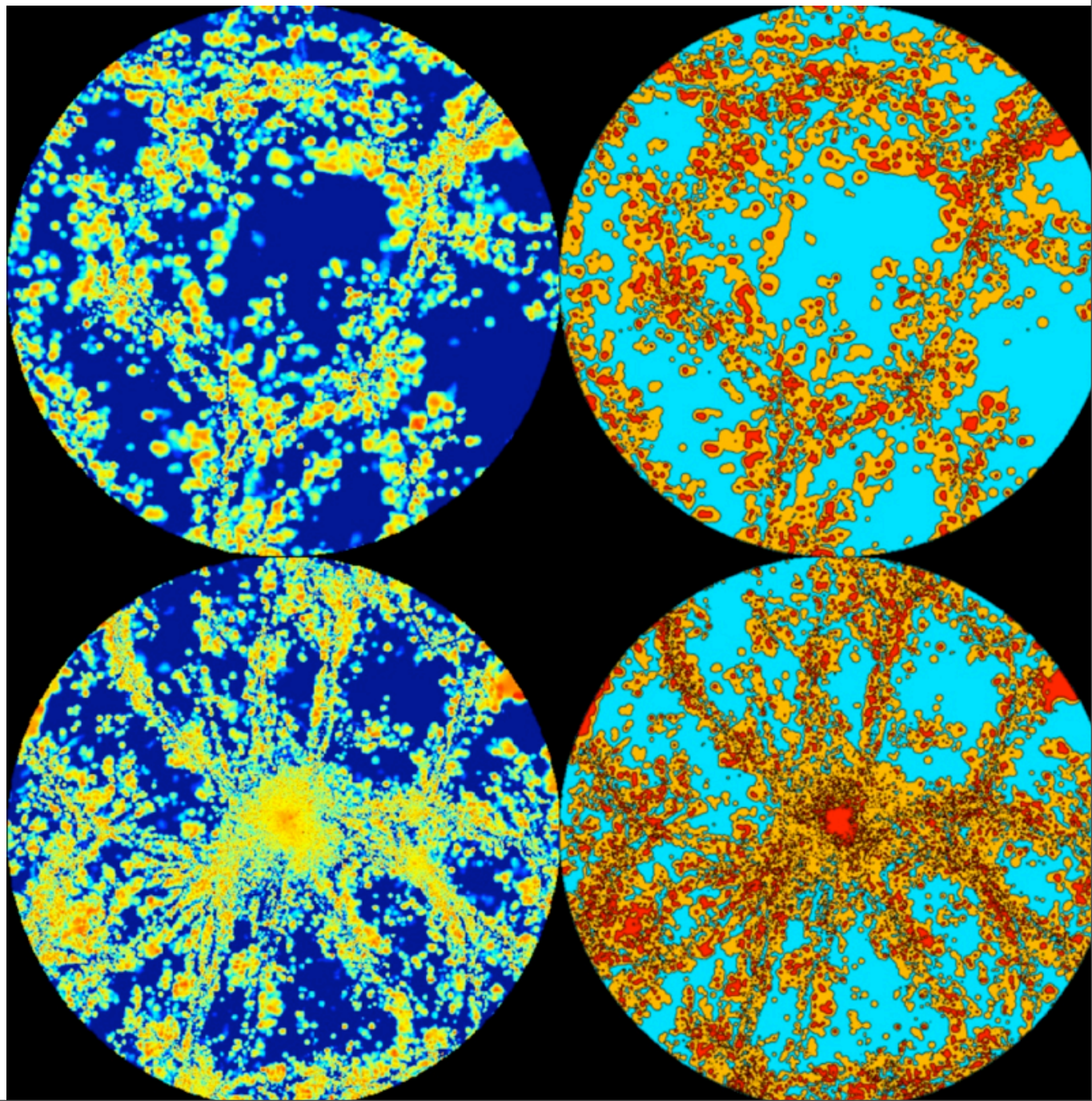
Tom Theuns

Galactic winds enrich surroundings with metals



Durham University

Metal enrichement

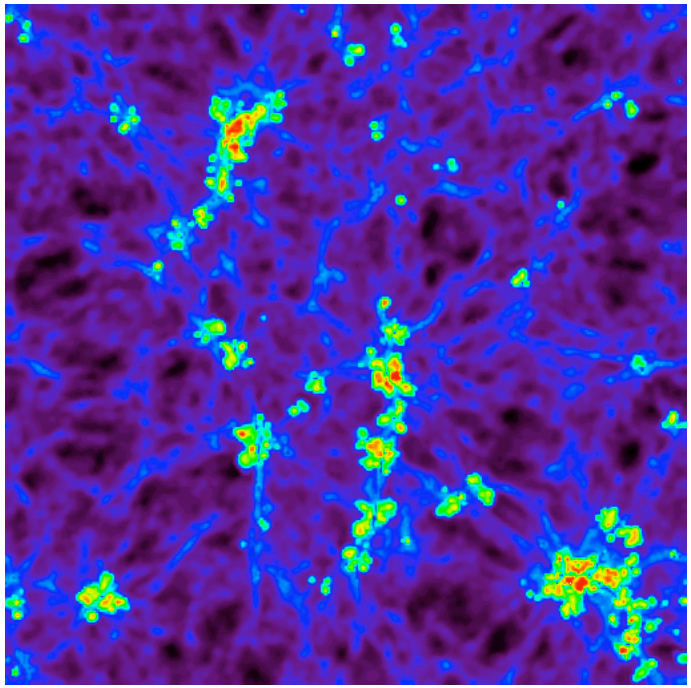


Tom Theuns

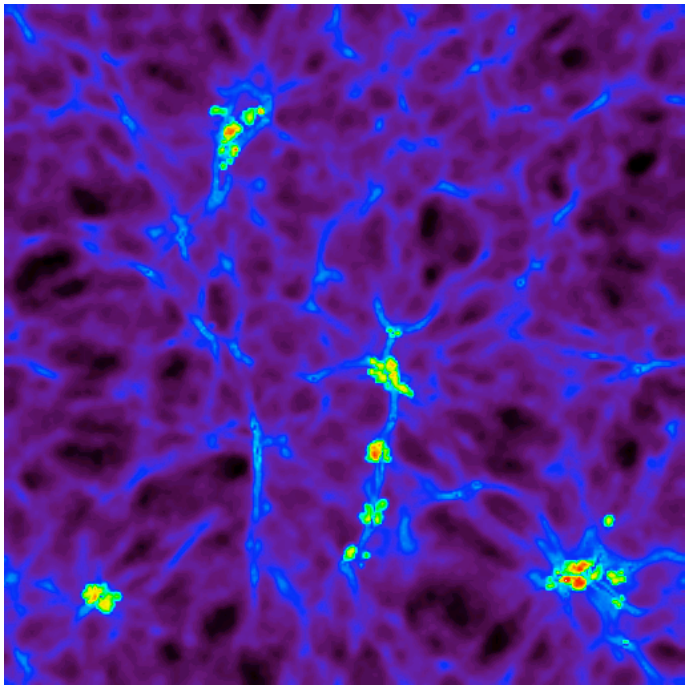
Effect of dark matter type

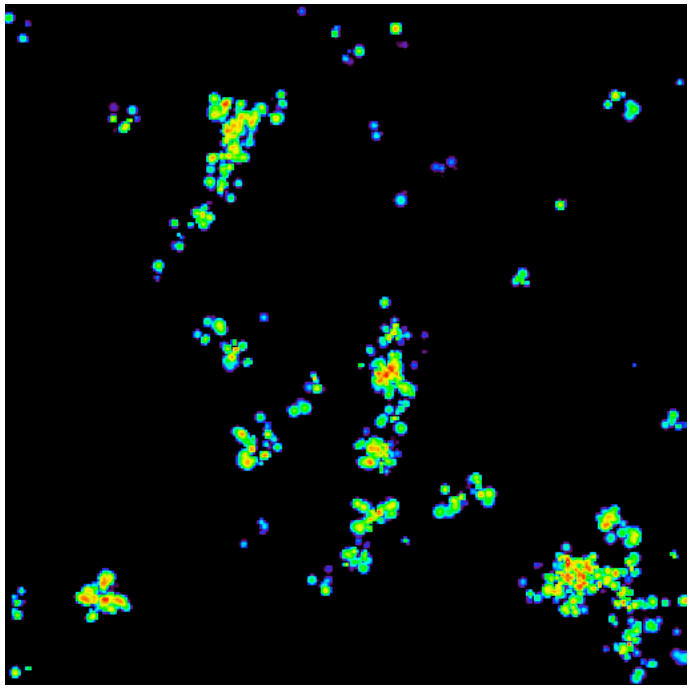
7 keV

1 keV

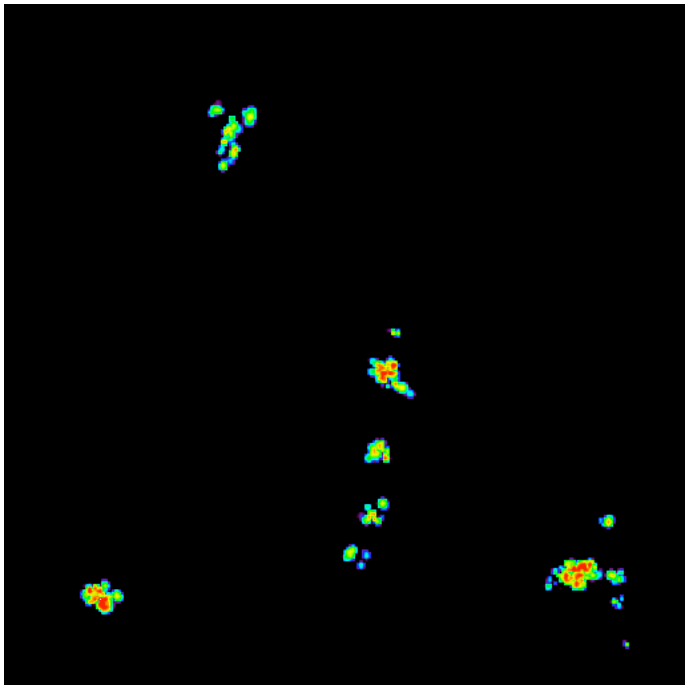


temperature





metallicity

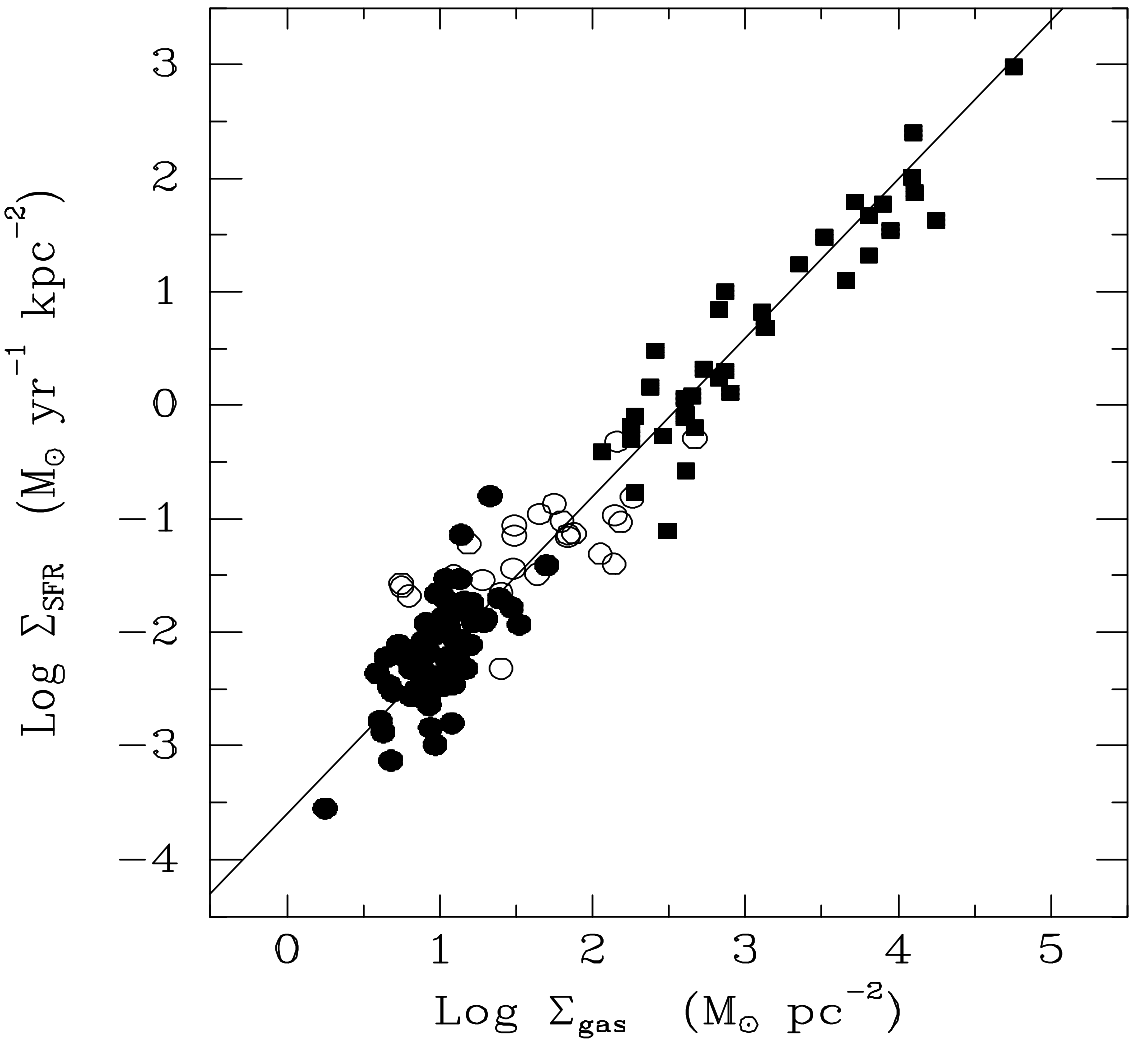


Redshift = 4

Observed star formation:

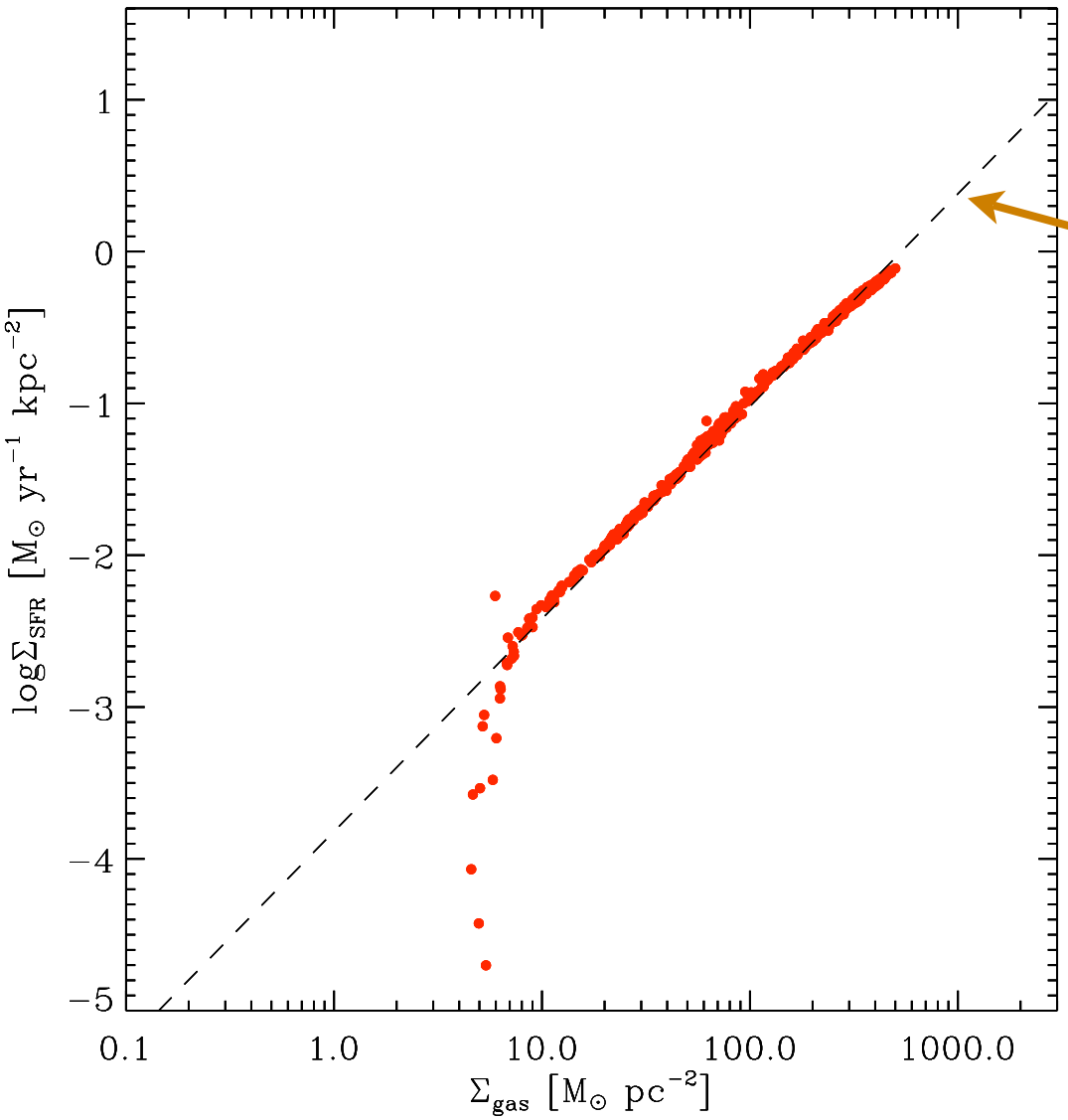
Schmidt law

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{n} \quad (n = 1.4 \pm 0.15)$$



(Kennicutt 1989)

Simulated star formation:

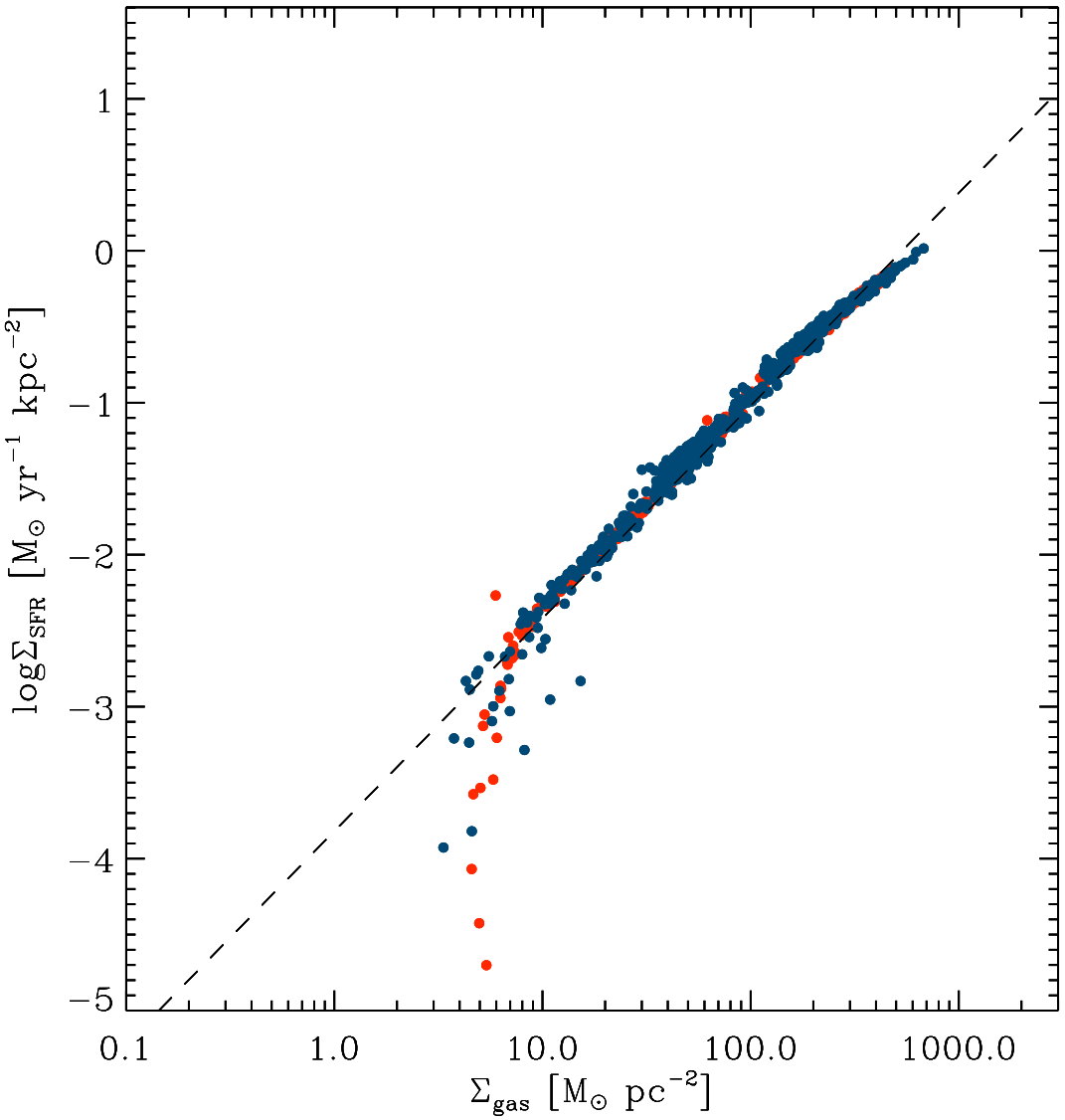


this is not a fit

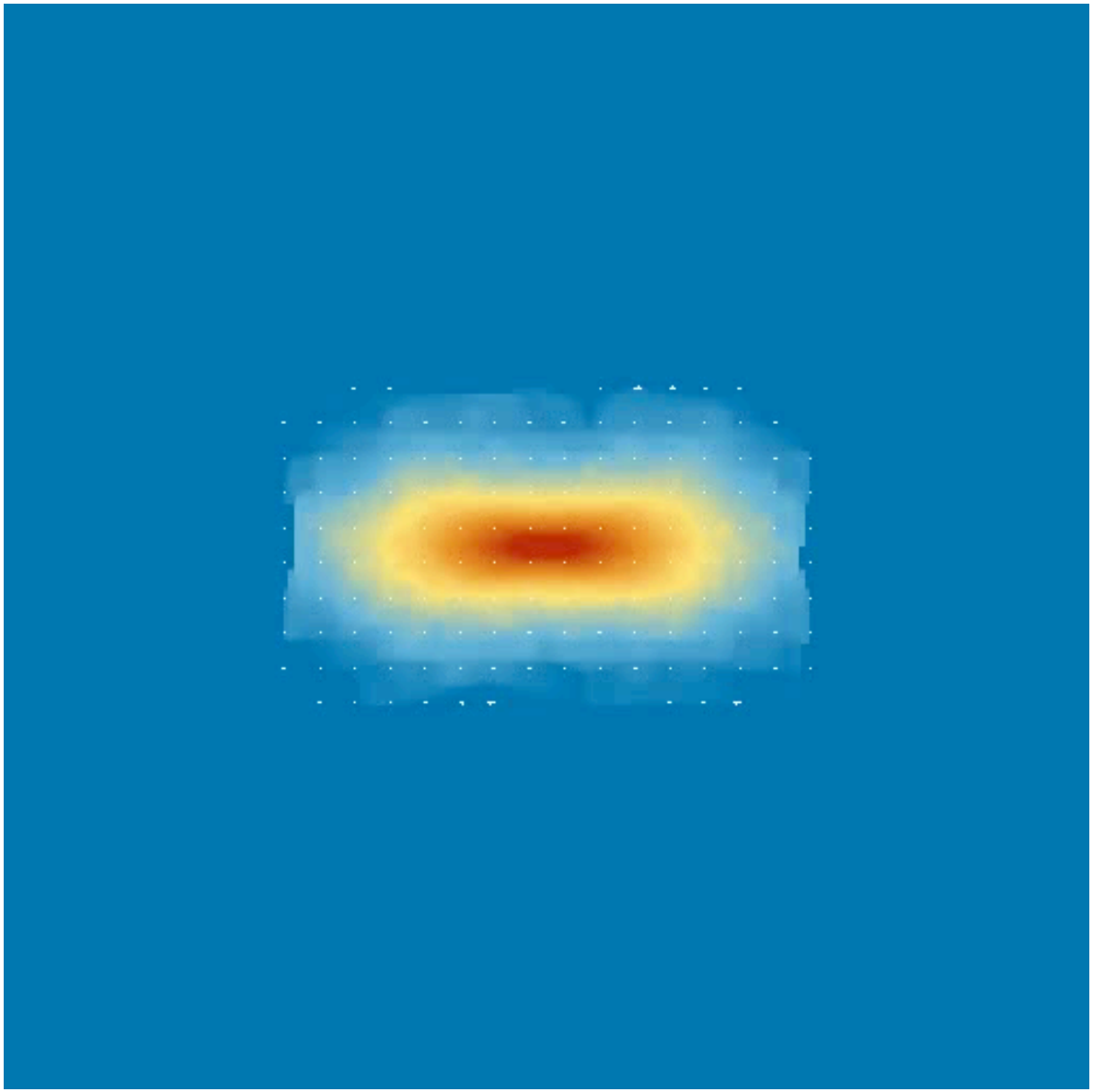
- $N_{\rm part} = 100$

Simulated star formation:

"resolution independent"

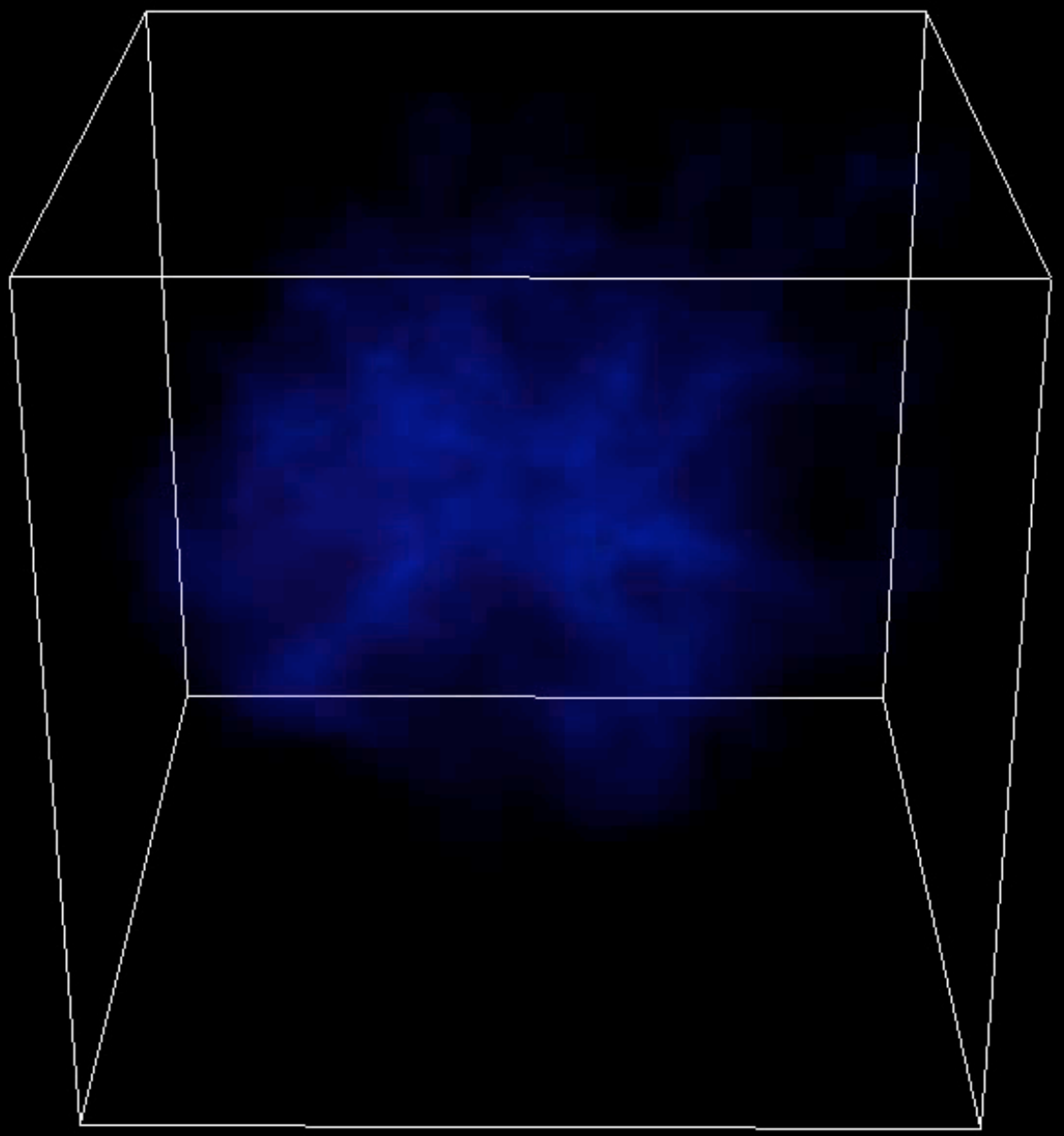


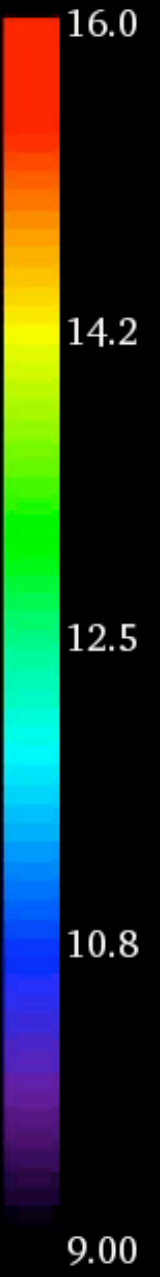
- $N_{\rm part} = 100$
- $N_{\rm part} = 12$



Dwarf galaxy with GIMIC/OWLS code

log (Gas density) in [Msun/h / (Mpc/h) ^ 3]



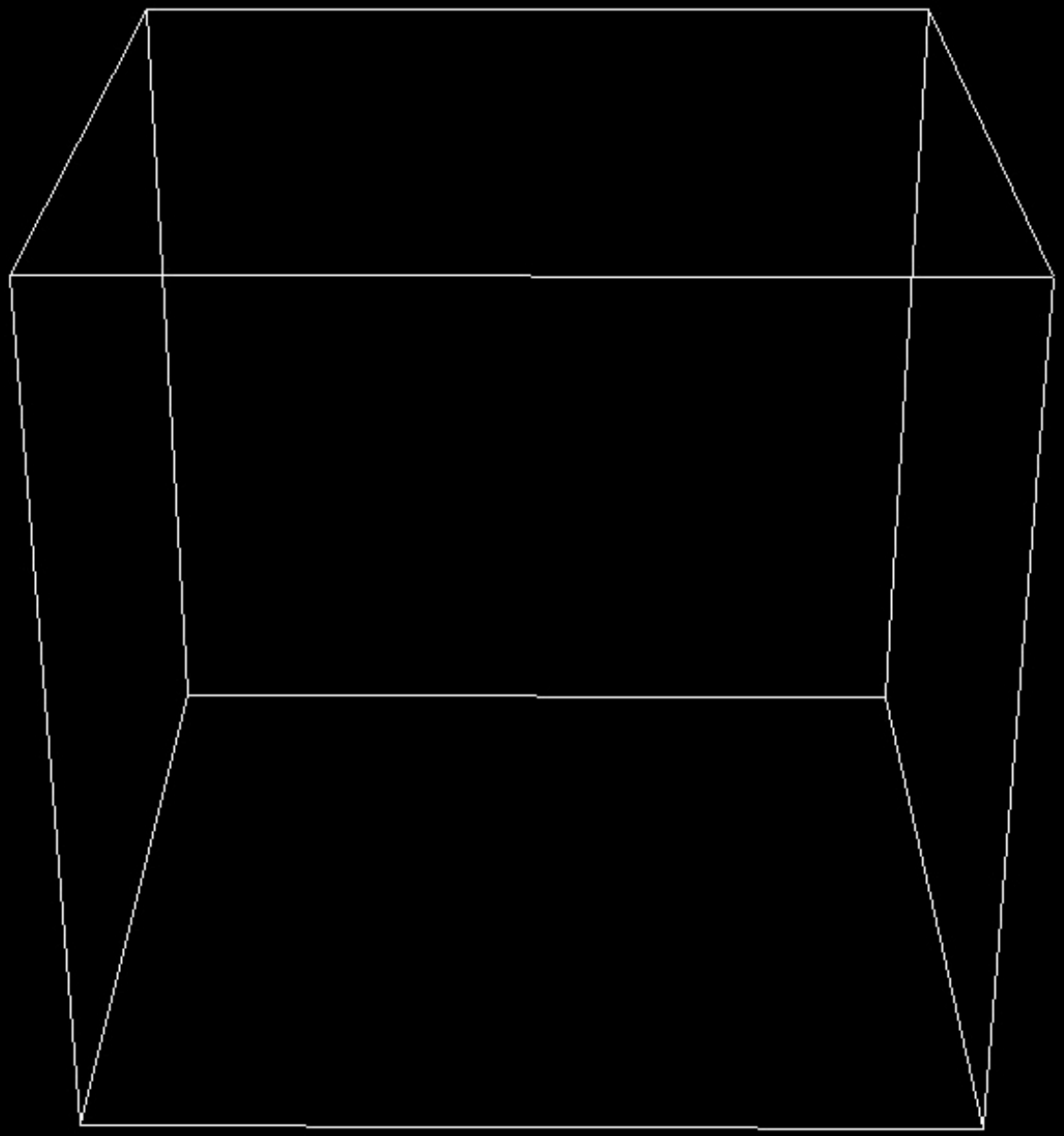


z = 29.888

L = 0.999 Mpc/h

Dwarf galaxy with GIMIC/OWLS code

log (Z)



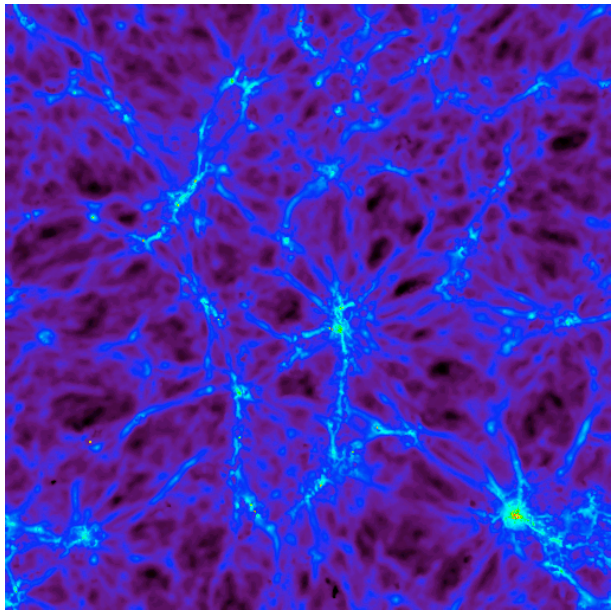
z = 29.888

L = 0.999 Mpc/h

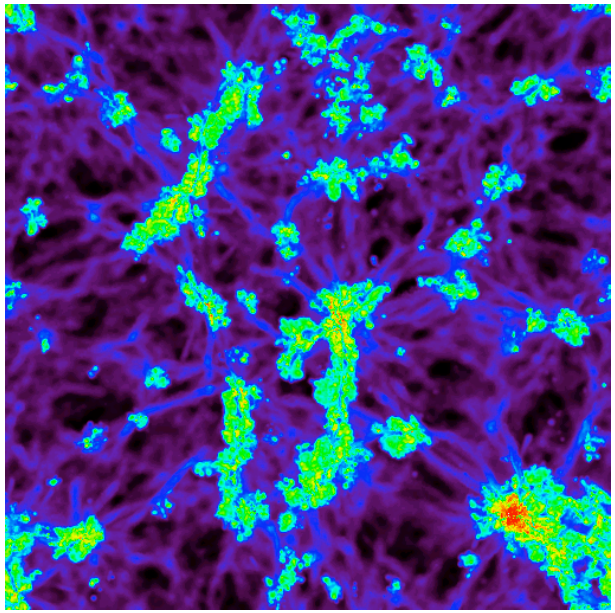
Suite of simulations varying:

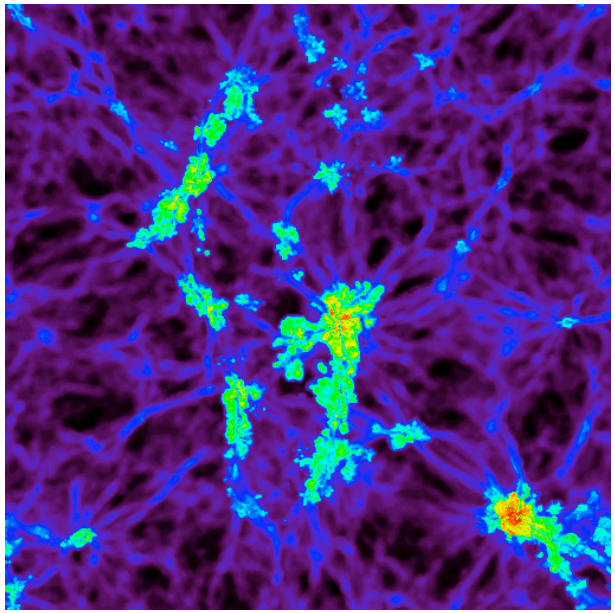
- Star formation parameters
- Wind implementation
- Resolution
- Box size
- Cosmology
- Reionization history

Density



Temperature





Metallicity