GIMIC:
Galaxy-Intergalactic Medium Interaction Calculation

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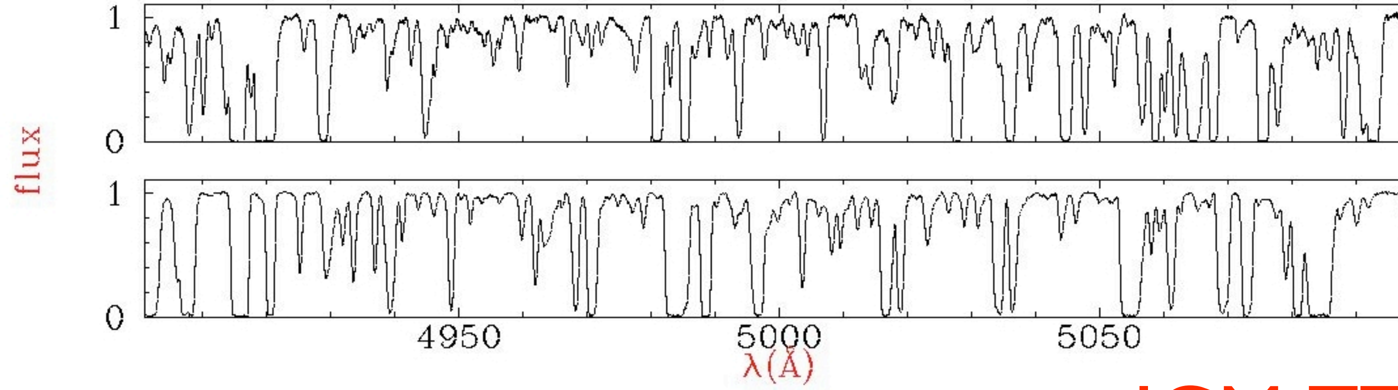
Ian McCarthy, Andreea Font (Cambridge)

Motivation: holistic approach to cluster/IGM/galaxy formation

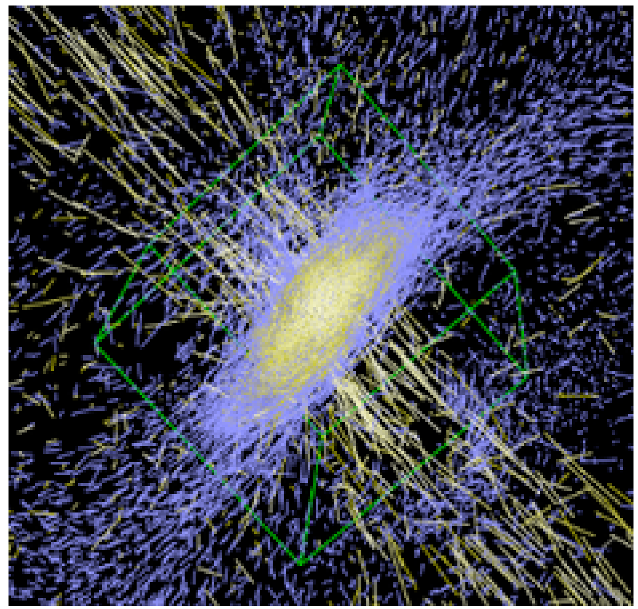
Contents:

- Introduction
- Aim of project
- Results
- Conclusions

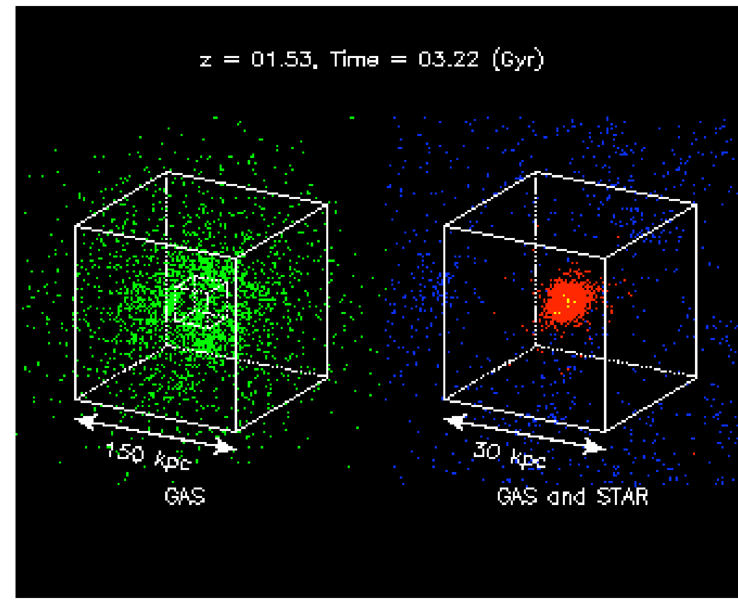
X-ray cluster: Borgani et al



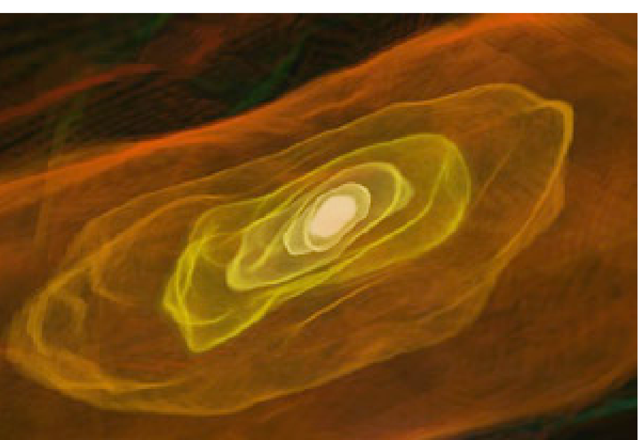
IGM: TT



Galaxy: Springel



Dwarf Galaxy: Kawata



First star: Abel et al

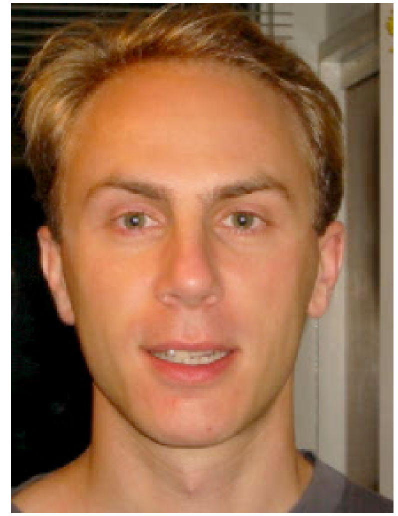
Institute for Computational Cosmology

Galaxies-Intergalactic Medium Interaction Calculation –I. Galaxy formation as a function of large-scale environment.

Robert A. Crain[1,2⋆], Tom Theuns[1,3], Claudio Dalla Vecchia[4], Vincent R. Eke[1], Carlos S. Frenk[1], Adrian Jenkins[1], Scott T. Kay[5], John A. Peacock[6] Frazer R. Pearce[7], Joop Schaye[4], Volker Springel[8], Peter A. Thomas[9], Simon D. M. White[8] & Robert P. C. Wiersma[4] (The Virgo Consortium)

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

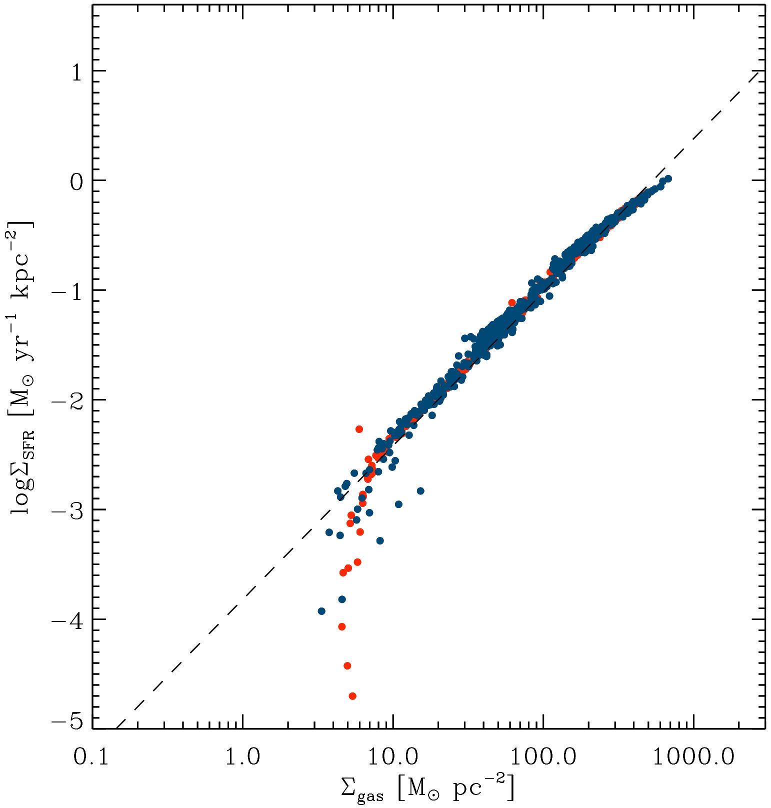
Code in brief

Motivation: holistic approach to formation of galaxies and clusters

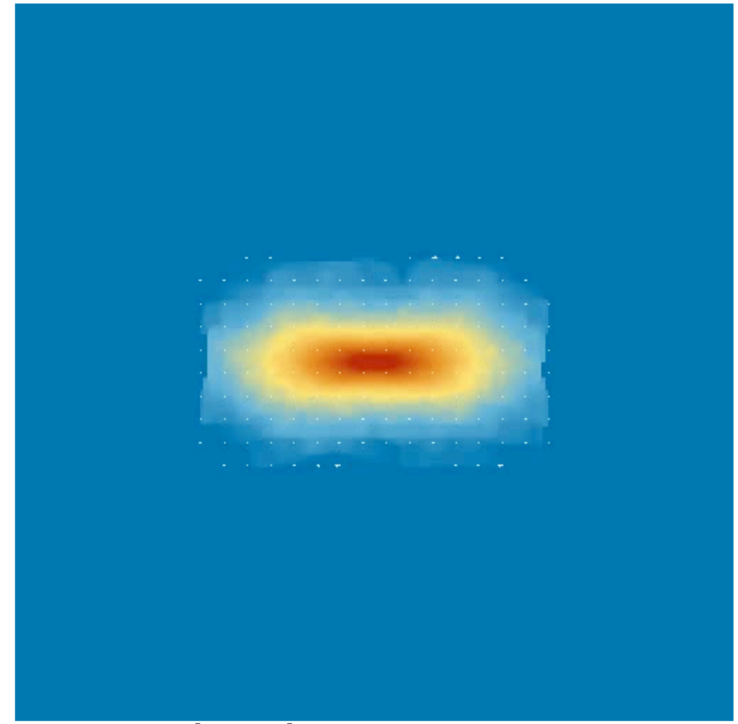
- Simulate cluster/galaxy/dwarf/IGM with same code
- Use zoom technique to overcome dynamic range issues

Code in brief

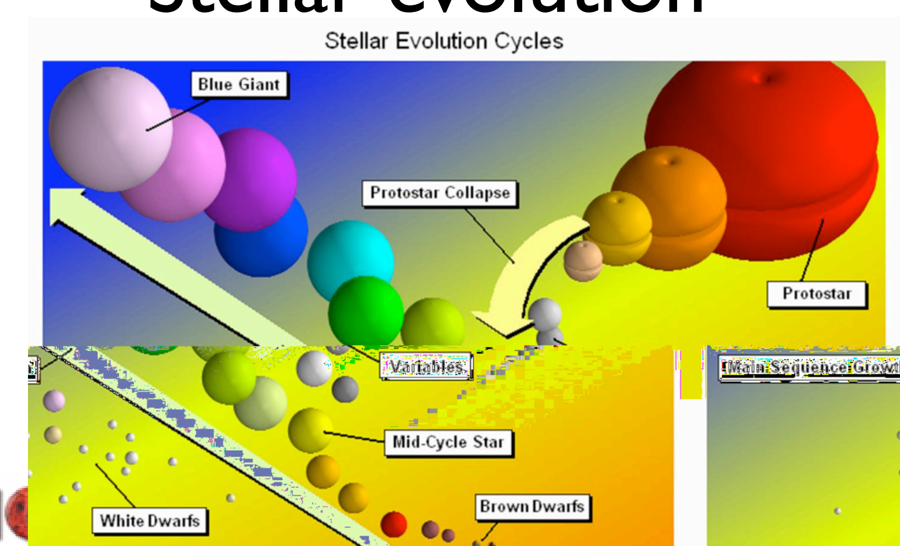
SFR follow Schmidt-law



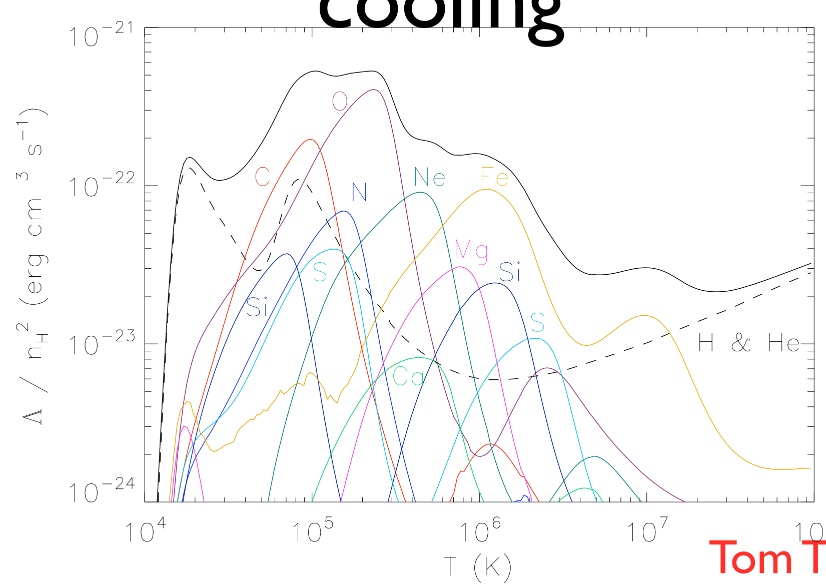
Galactic winds



Stellar evolution



Z+J(nu) dependent cooling



OverWhelmingly Large Simulations: periodic boxes (25,100Mpc) with range of physics (30+models)

Galaxy-Intergalactic Medium Interaction Calculation re-simulations within Millennium box with a single choice of parameters

Name	Box Size (Mpc/h)[a]	Number of Particles[b]	Comment
AGB0_SNIa0_L100N512	100	512	AGB & SNIa mass & energy transfer off
DBLIMFCONTSFV1618_L025N512	25	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind velocity $v_w = 1618kms^{-1}$ and default Schmidt law normalization above the threshold
DBLIMFCONTSFV1618_L100N512	100	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind velocity $v_w = 1618kms^{-1}$ and default Schmidt law normalization above the threshold
DBLIMFV1618_L025N512	25	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind velocity $v_w = 1618kms^{-1}$ and Schmidt law normalization = 2.083e-5 above the threshold
DBLIMFV1618_L100N512	100	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind velocity $v_w = 1618kms^{-1}$ and Schmidt law normalization = 2.083e-5 above the threshold
DBLIMFCONTSFML14_L025N512	25	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind mass-loading = 14.545 and default Schmidt law normalization above the threshold
DBLIMFCONTSFML14_L100N512	100	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind mass-loading = 14.545 and default Schmidt law normalization above the threshold
DBLIMFML14_L025N512	25	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind mass-loading = 14.545 and Schmidt law normalization = 2.083e-5 above the threshold
DBLIMFML14_L100N512	100	512	Top-heavy IMF above $n_H > 30cm^{-3}$ with wind mass-loading = 14.545 and Schmidt law normalization = 2.083e-5 above the threshold
DEFAULT_L025N512	25	512	
DEFAULT_L100N512	100	512	
EOS1p0_L025N512	25	512	Isothermal equation of state, particles with $n_H > 30cm^{-3}$ are instantaneously converted into stars if they are on the equation of state
EOS1p0_L100N512	100	512	Isothermal equation of state, particles with $n_H > 30cm^{-3}$ are instantaneously converted into stars if they are on the equation of state
IMFSALP_L025N512	25	512	Salpeter IMF, SF law rescaled, wind pars as in DEFAULT
IMFSALP_L100N512	100	512	Salpeter IMF, SF law rescaled, wind pars as in DEFAULT
IMFSALPW_L025N512	25	512	Salpeter IMF, SF law and wind mass-loading rescaled (put here the values)
KENNAMPL3x_L025N512	25	512	Schmidt law normalization = 4.545e-4 (rather than 1.515e-4)
KENNAMPL6x_L025N512	25	512	Schmidt law normalization = 9.09e-4 (rather than 1.515e-4)
KENNSLOPE175_L025N512	25	512	Schmidt law slope = 1.75 (rather than 1.4)
MILL_L025N512	25	512	Millenium cosmology: $(\Omega_m, \Omega_\Lambda, \Omega_b h^2, h, \sigma_8, n, Y) = (0.25, 0.75, 0.024, 0.73, 0.9, 1.0, 0.249)$
MILL_L100N512	100	512	Millenium cosmology: $(\Omega_m, \Omega_\Lambda, \Omega_b h^2, h, sigma_8, n, Y) = (0.25, 0.75, 0.024, 0.73, 0.9, 1.0, 0.249)$
NOFB_L025N512	25	512	No SNII winds, no SNIa energy transfer
NOFB_L100NI512	100	512	No SNII winds, no SNIa energy transfer
NOFB_ZCOOL0_L025N512	25	512	No SNII winds, no SNIa energy transfer, cooling uses initial (i.e., primordial) abundances
NOFB_ZCOOL0_L100N512	100	512	No SNII winds, no SNIa energy transfer, cooling uses initial (i.e., primordial) abundances
NOHeHEAT_L025N512	25	512	No He reheating
REION06_L025N512	25	512	Redshift reionization = 6 (rather than 9)
REION12_L025N512	25	512	Redshift reionization = 12 (rather than 9)
SFTHRESZ_L025N512	25	512	Metallicity-dependent SF threshold:
SNIAGAUS_L100N512	100	512	Gaussian SNIa delay distribution (pars:)
WML1V848_L025N512	25	512	Wind mass-loading = 1, v = 848 km/s (rather than 2 and 600)
WML1V848_L100N512	100	512	Wind mass-loading = 1, v = 848 km/s (rather than 2 and 600)
WML4_L025N512	25	512	Wind mass-loading = 4 (rather than 2)
WML4_L100N512	100	512	Wind mass-loading = 4 (rather than 2)
WML8V300_L025N512	25	512	Wind mass-loading = 8, v = 300 km/s (rather than 2 and 600)
WPOT_L025N512	25	512	Momentum driven wind model
WPOT_L100N512	100	512	Momentum driven wind model
WPOTKICK_L025N512	25	512	Momentum driven wind model with extra velocity kick = 2 x local velocity dispersion
WPOTKICK_L100N512	100	512	Momentum driven wind model with extra velocity

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

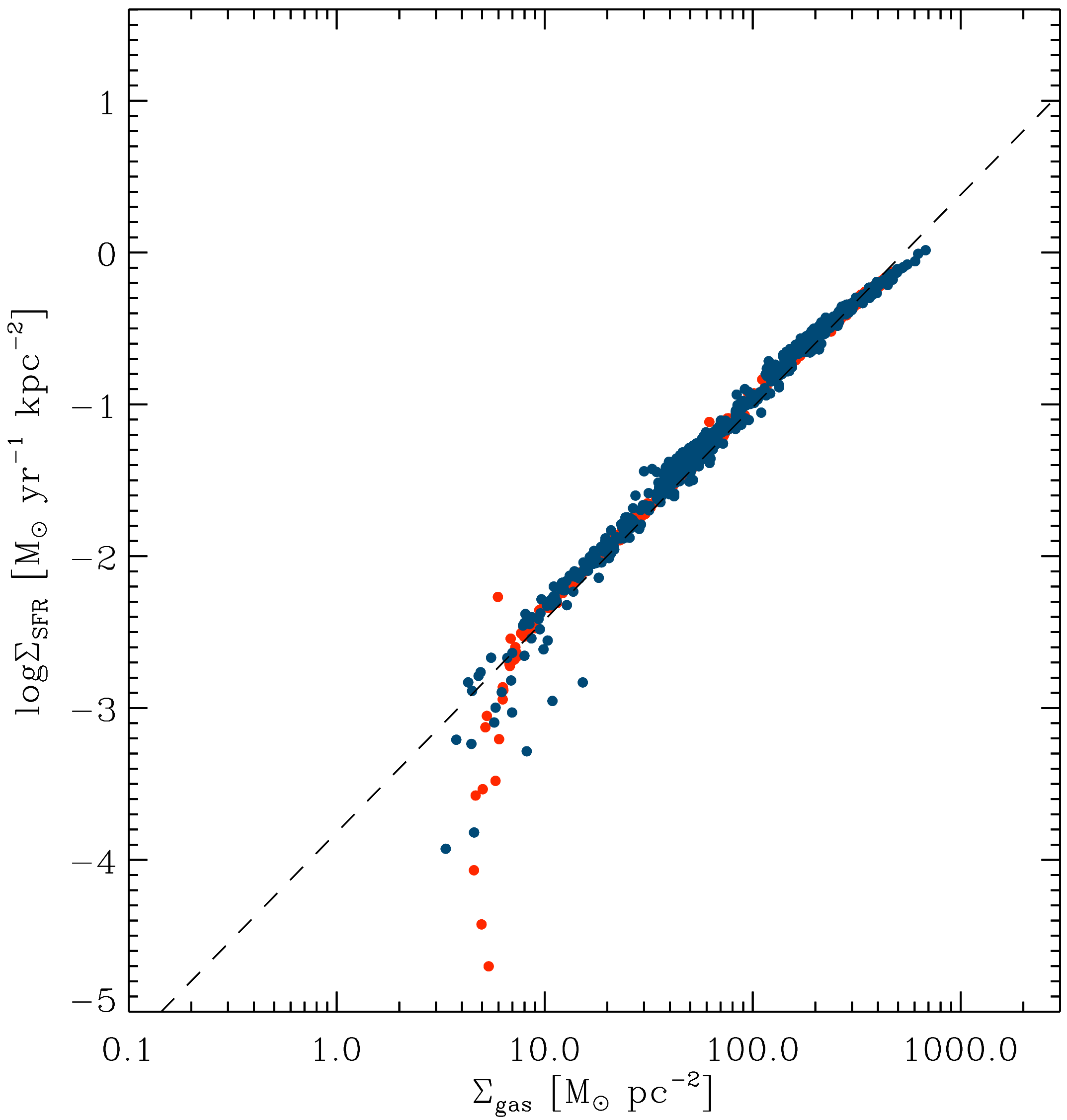
- What comes out

Volume density star formation law

Volume density threshold

J Schaye

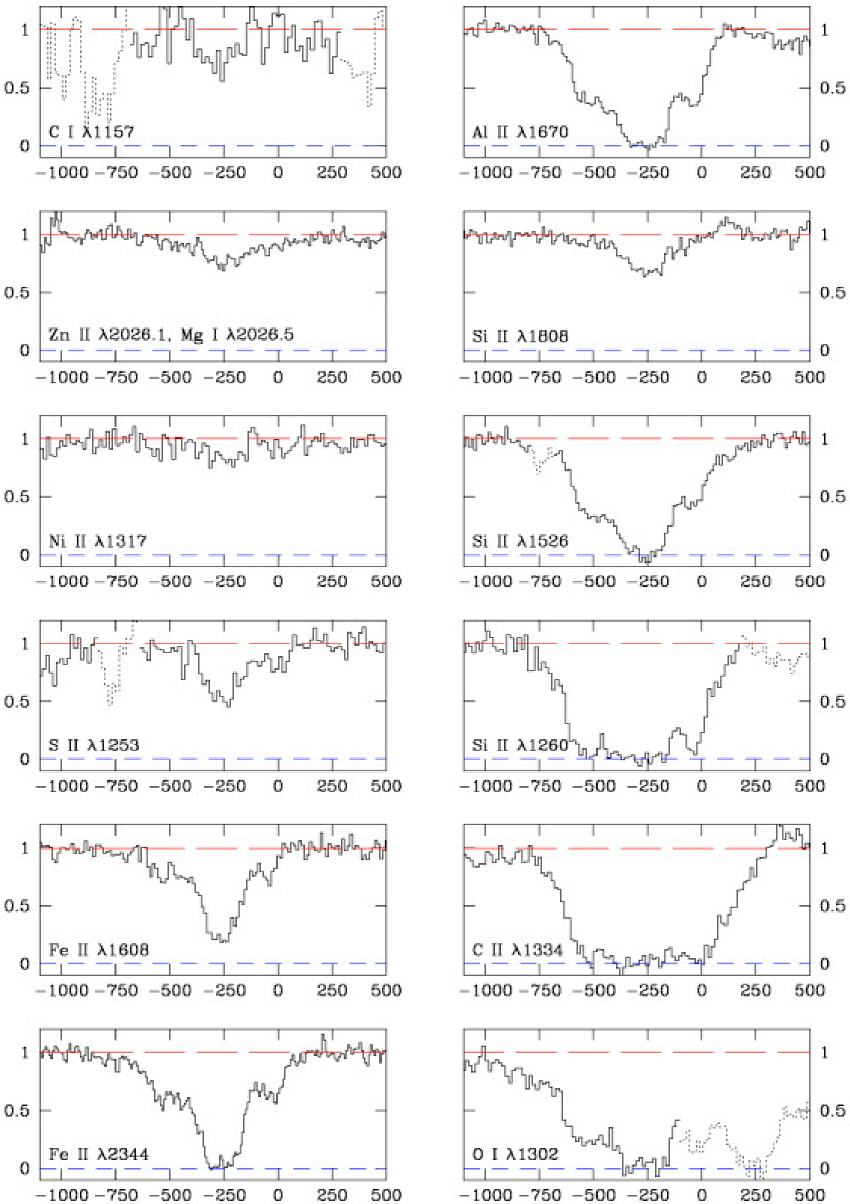
Implementation guarantees a Schmidt law



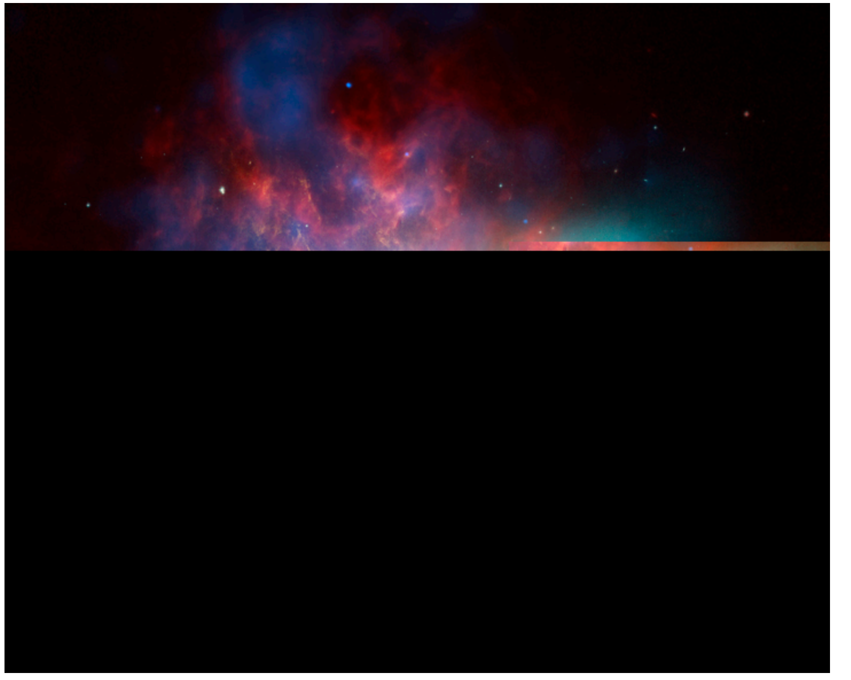
- $N_{\rm part} = 100$
- $N_{\rm part} = 12$

J Schaye

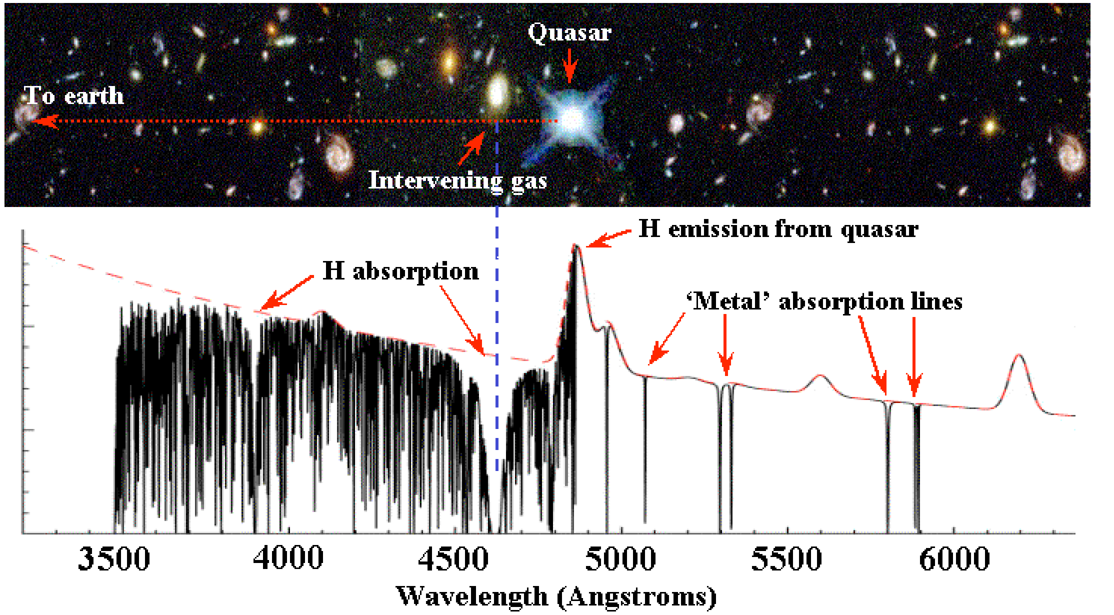
Evidence for galactic winds:



At high z: Pettini et al 02

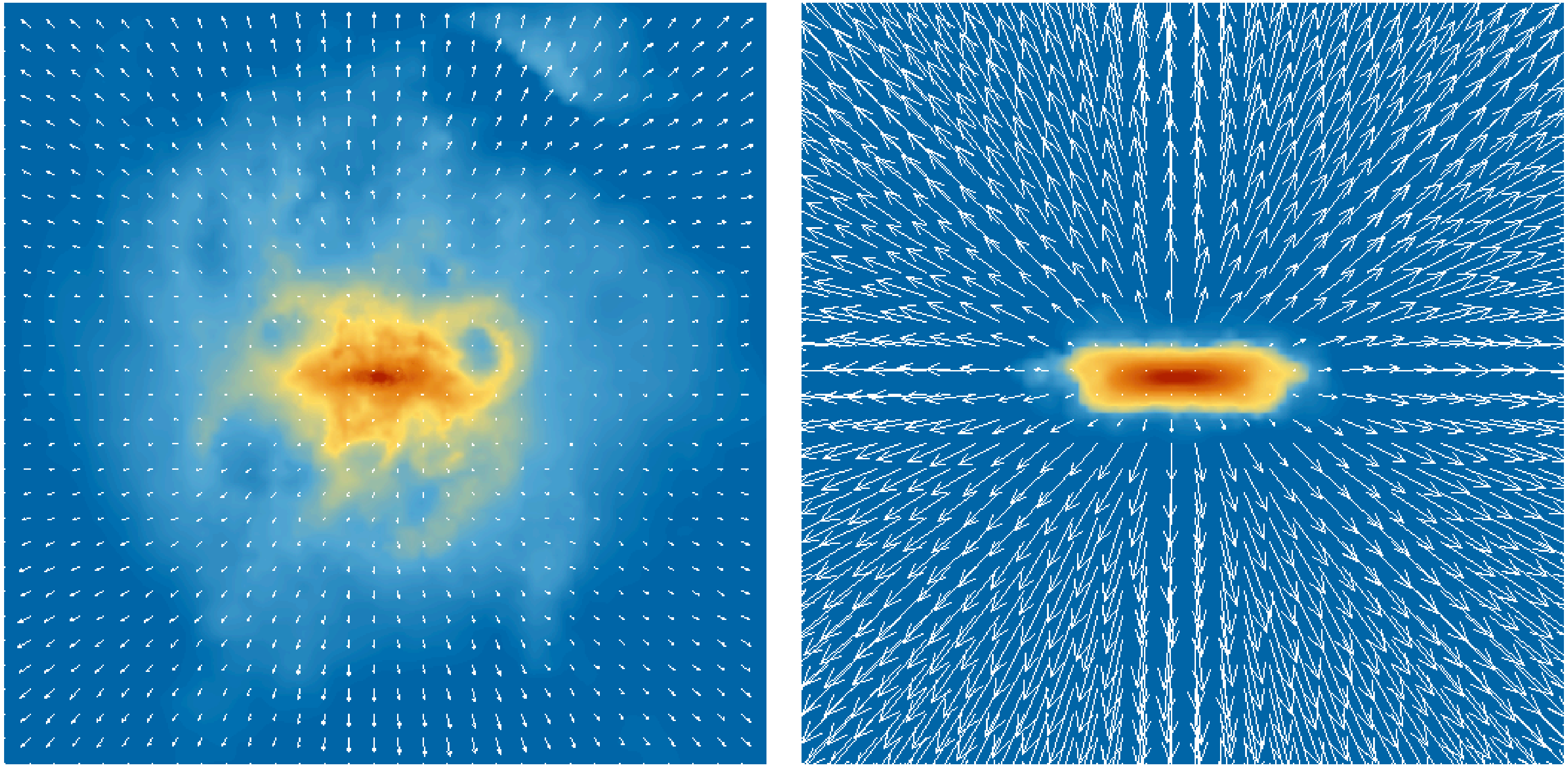


At low z: M82



In absorption

Implementation of winds:



Schaye & Dalla Vecchia 08

CONFRONTING COSMOLOGICAL SIMULATIONS WITH OBSERVATIONS OF INTERGALACTIC METALS

ANTHONY AGUIRRE,[1] JOOP SCHAYE,[2] LARS HERNQUIST,[3] SCOTT KAY,[4,5] VOLKER SPRINGEL,[6] AND TOM THEUNS[7,8]

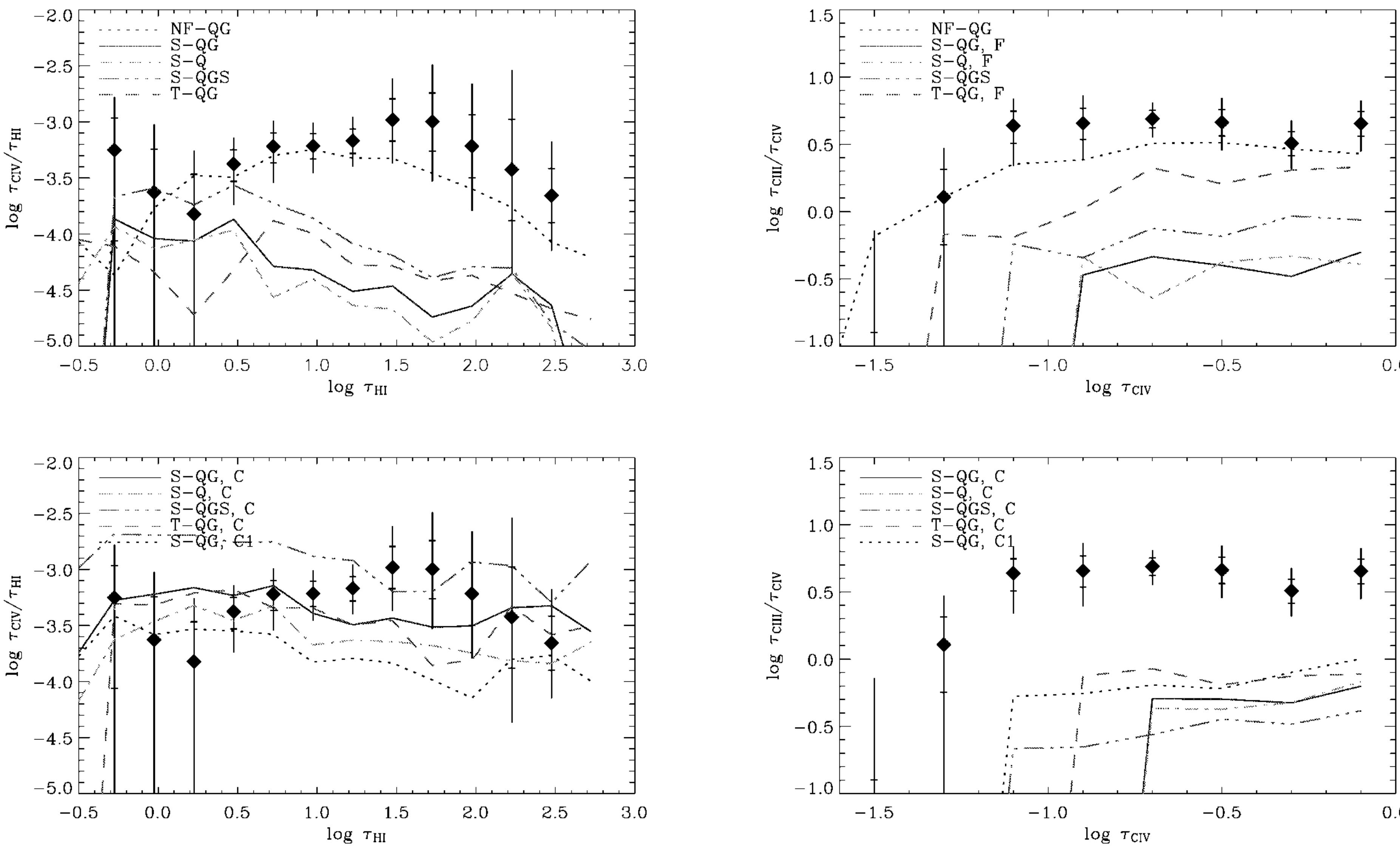
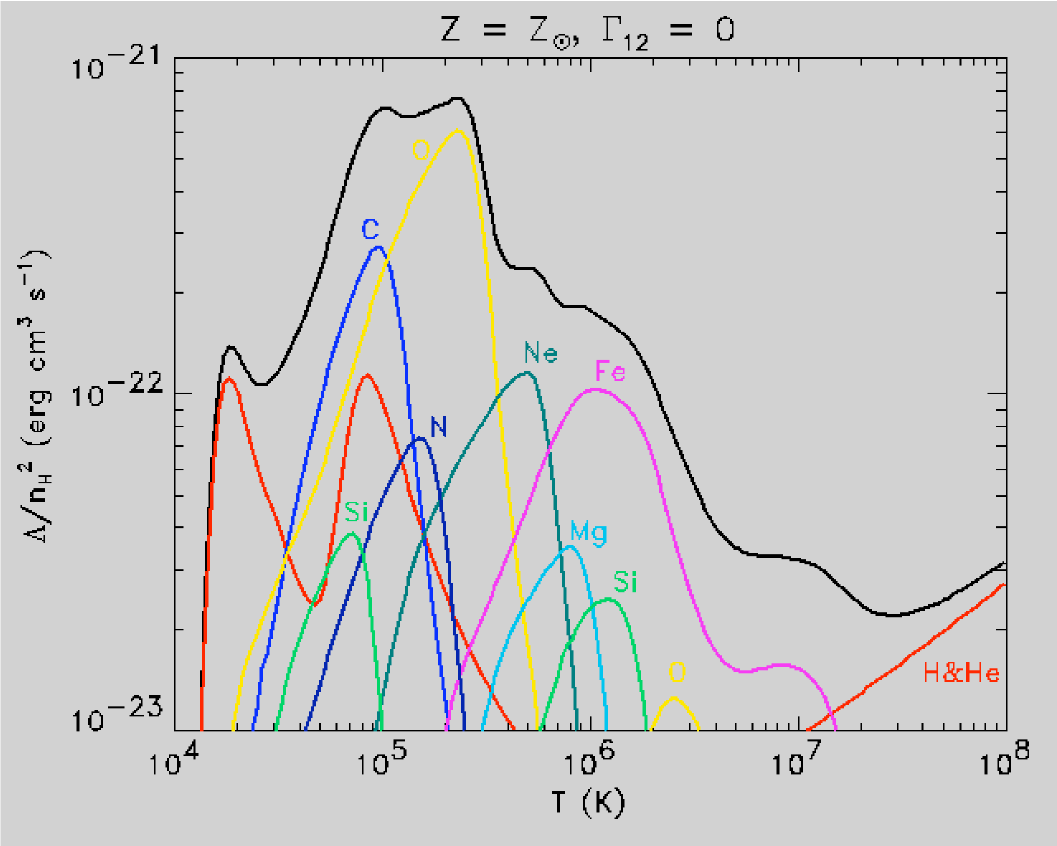


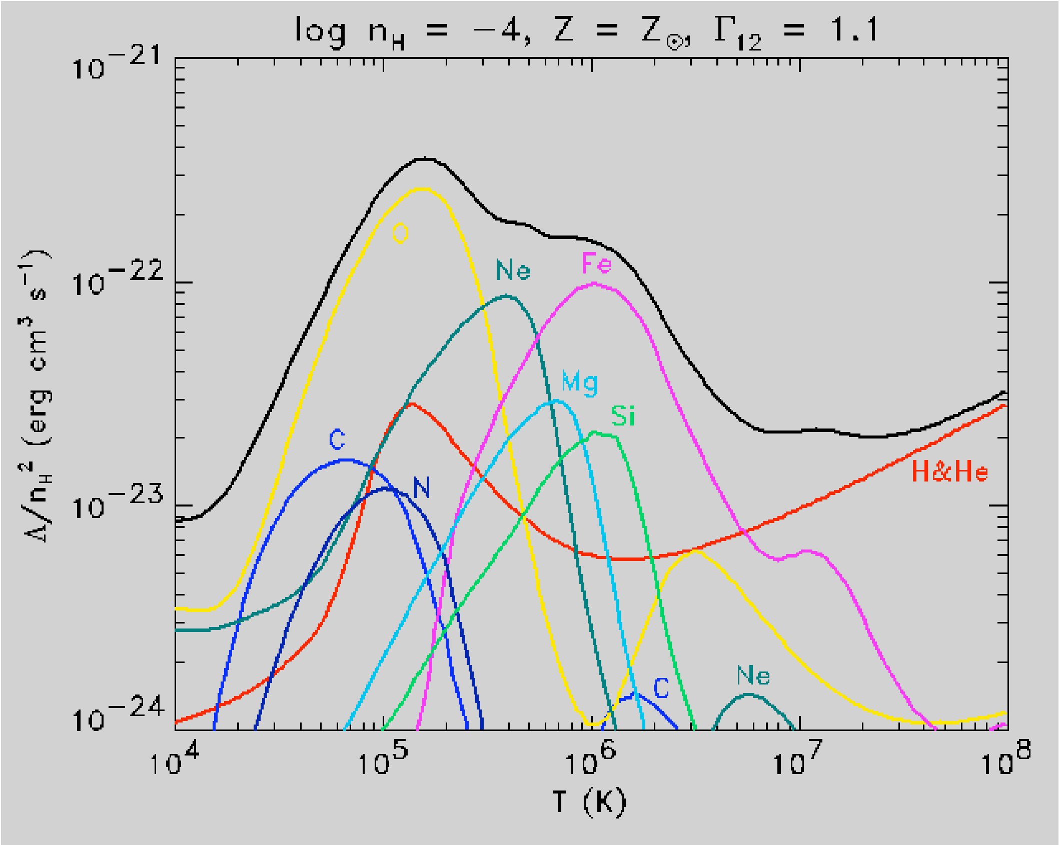
FIG. 1.—Binned optical depth ratios (med $\tau_{\rm C\,IV}$)/$\tau_{\rm H\,I}$ vs. $\tau_{\rm H\,I}$ (*left*) and (med $\tau_{\rm C\,III}$)/$\tau_{\rm C\,IV}$ vs. $\tau_{\rm C\,IV}$ (*right*) for observations (data points with 1 σ and 2 σ errors) and various models. *Top:* Models NF-QG (the Q and QGS backgrounds yield similar results), S-QG S-Q, S-QGS, and T-QG, as per the legend. The effect of changing the UVB in the T simulations is similar. *Bottom:* Same as in the top panels, but the particles with cooling time $t_c < t_{\rm H}$ are set to $T = 2 \times 10^4$ K. The same models are shown, except that the dotted line ("C1") corresponds to S-QG if only particles with $t_c < 0.1 t_{\rm H}$ cool (the effect of this change is similar for the other models). [*See the electronic edition of the Journal for a color version of this figure.*]

Metal cooling and the UV-background
Cooling rate



Without ionizing background

With ionizing background from gals & AGN

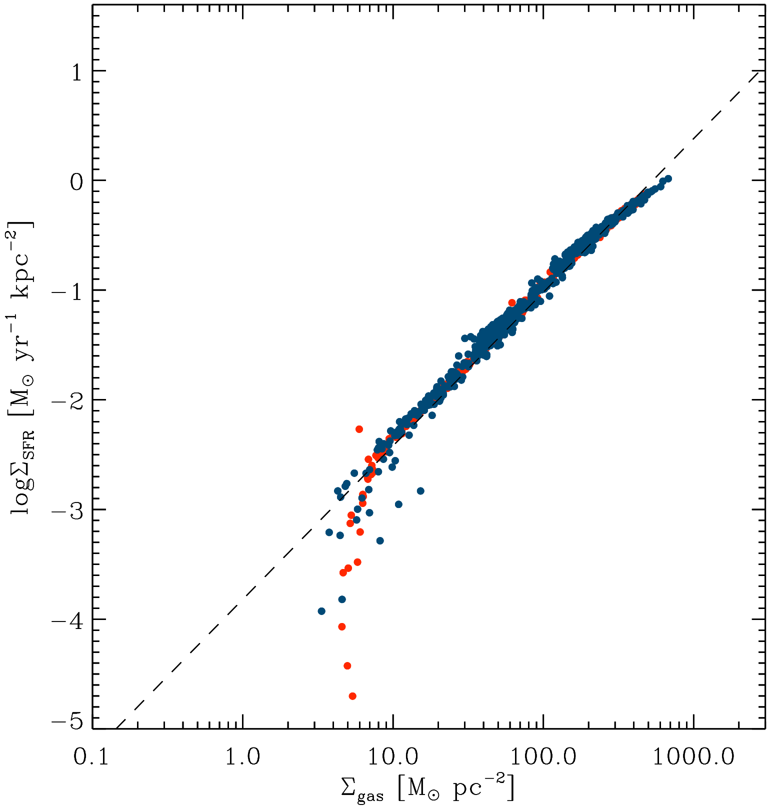


Tom Theuns

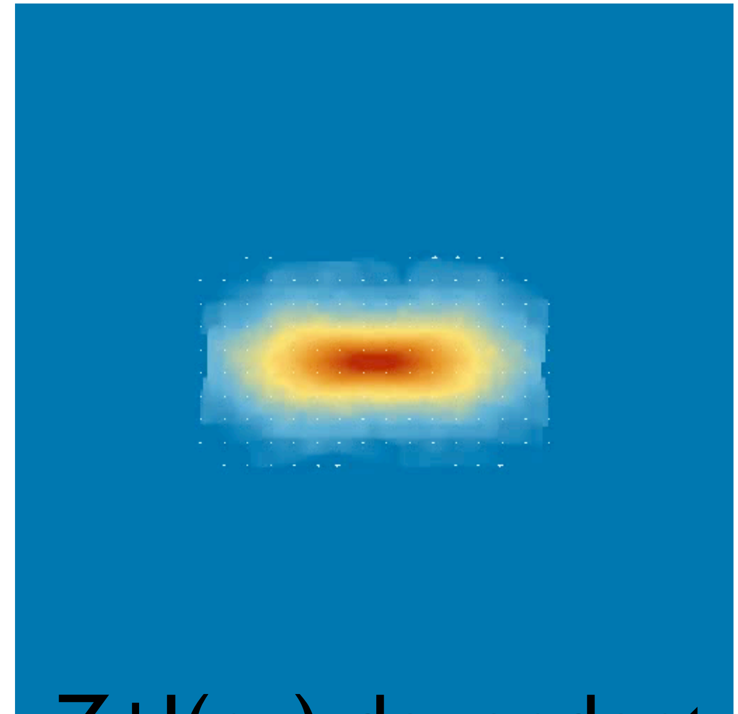
Wiersma et al '08

Code in brief

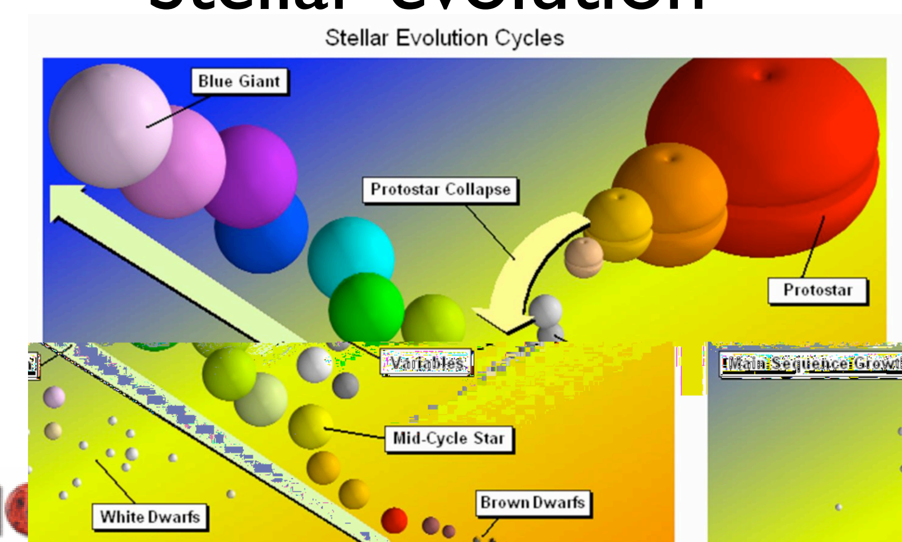
SFR follow Schmidt-law



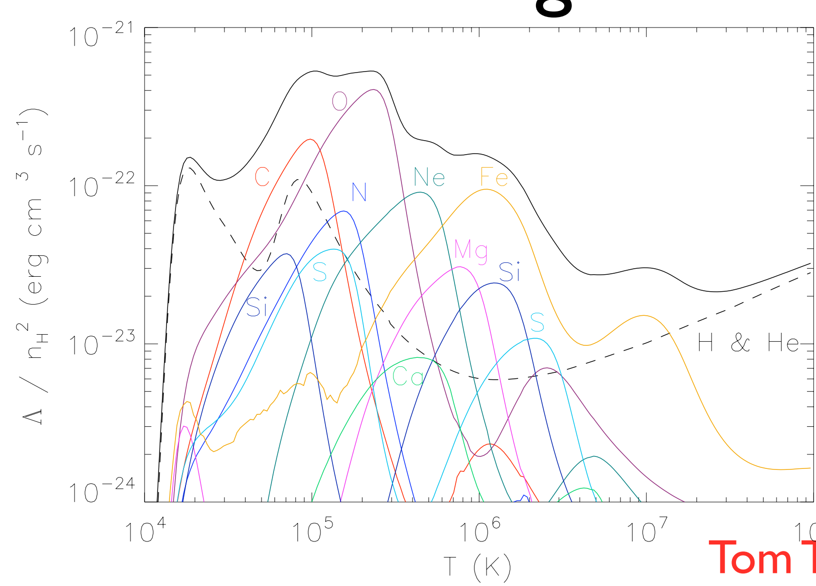
Galactic winds

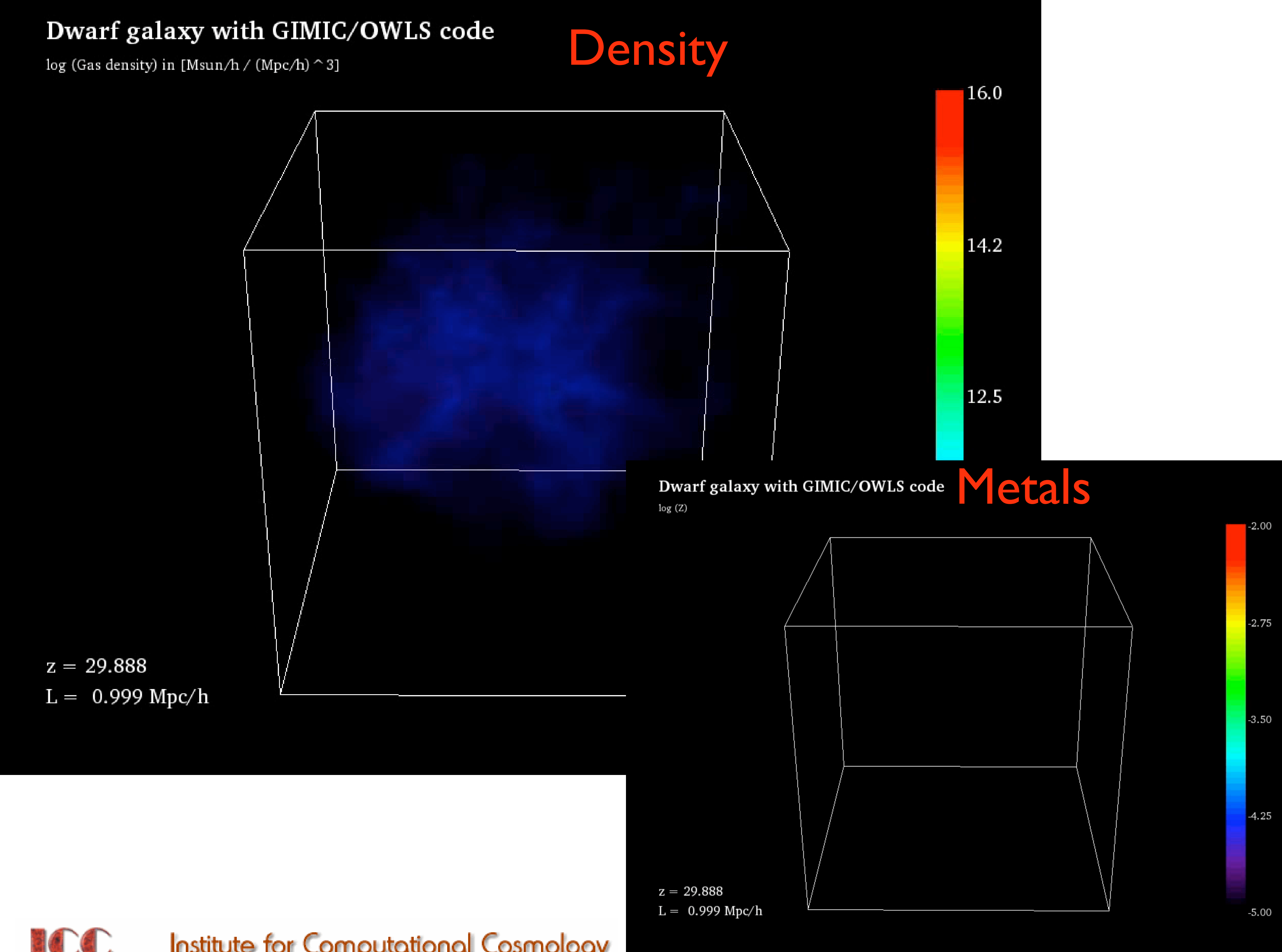


Stellar evolution



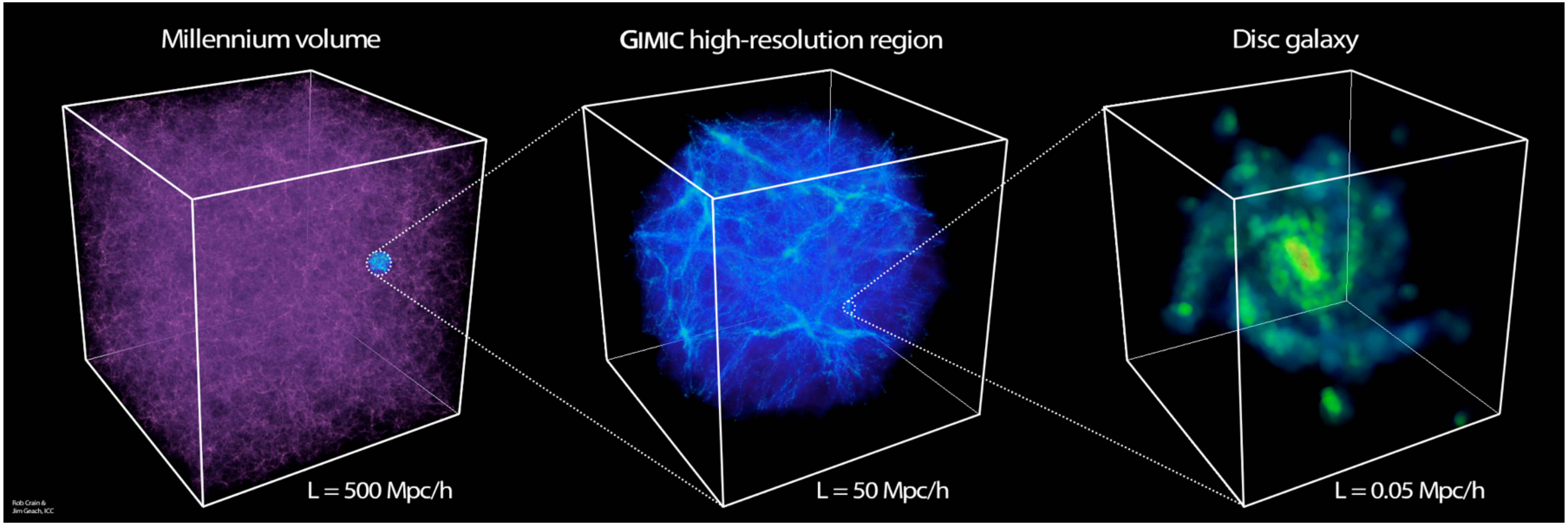
Z+J(nu) dependent cooling




Dwarf galaxy with GIMIC/OWLS code
log (Gas density) in [Msun/h / (Mpc/h) ^ 3]
Density
16.0
14.2
12.5
z = 29.888
L = 0.999 Mpc/h
Dwarf galaxy with GIMIC/OWLS code
log (Z)
Metals
-2.00
-2.75
-3.50
-4.25
-5.00
z = 29.888
L = 0.999 Mpc/h

Suite of simulations: GIMIC/OWLS

Galaxy-Intergalactic Medium Interaction Calculation



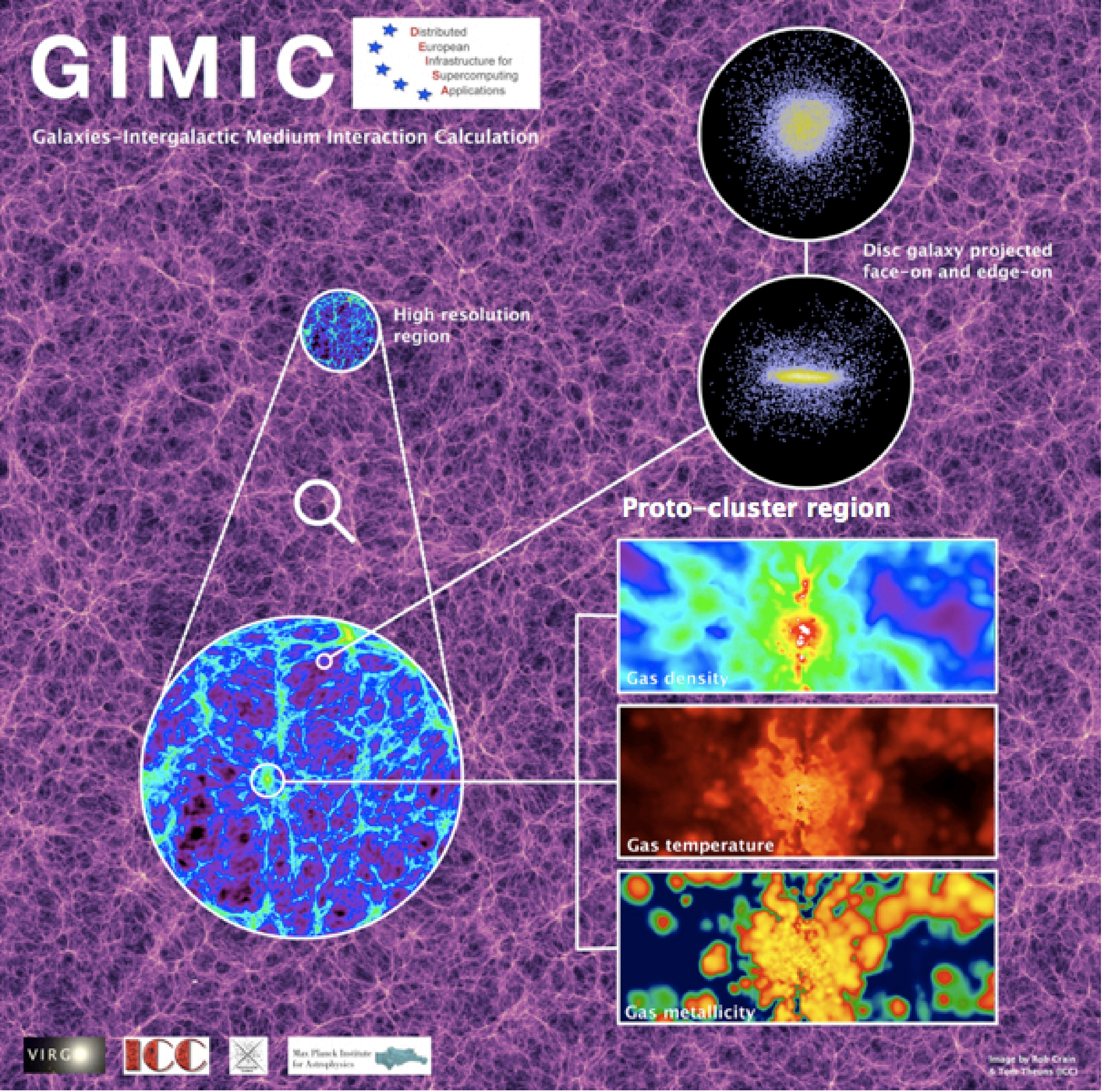
Zoomed simulations of 5 spheres picked from the Millennium Simulation

Combine LSS with high numerical resolution

Tom Theuns

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)


GIMIC
Distributed European Infrastructure for Supercomputing Applications
Galaxies-Intergalactic Medium Interaction Calculation
Disc galaxy projected face-on and edge-on
High resolution region
Proto-cluster region
Gas density
Gas temperature
Gas metallicity
VIRGO
ICC
Max Planck Institute for Astrophysics

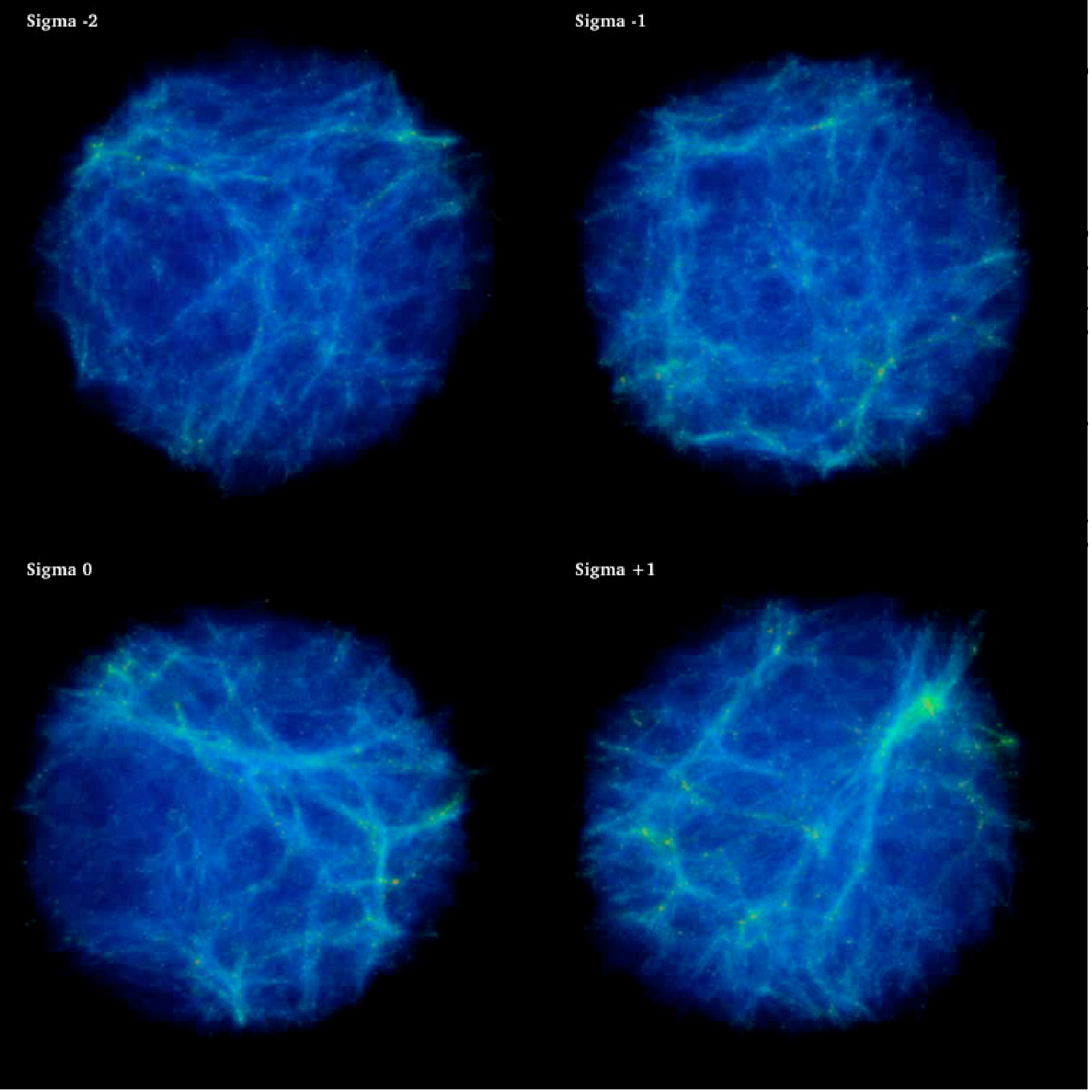
Objectives:

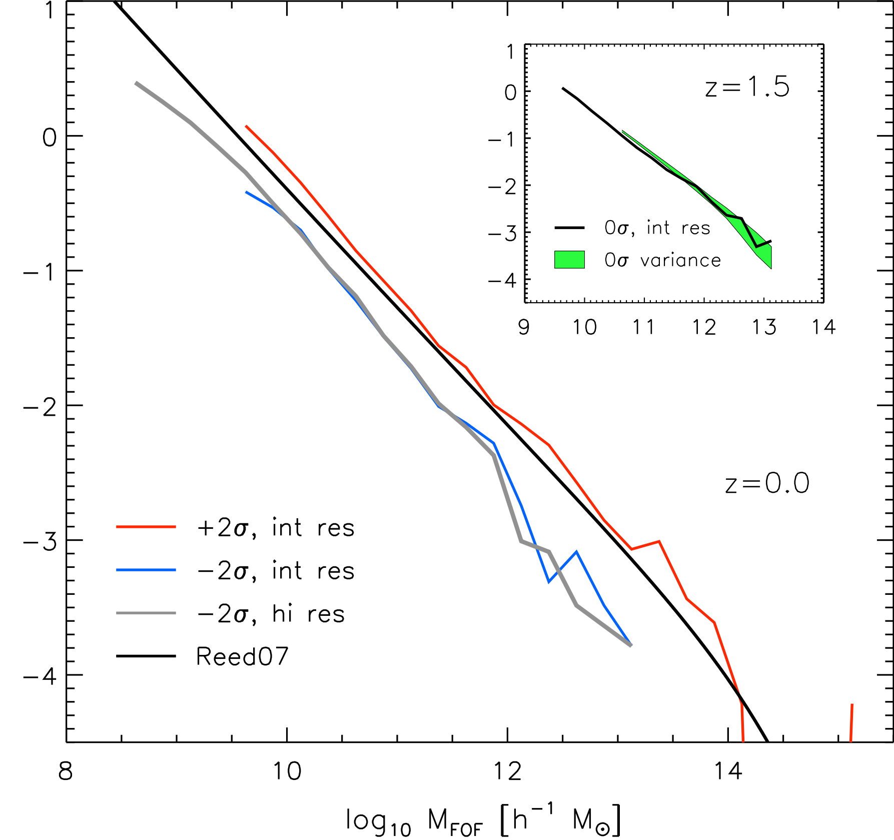
- Galaxy properties and environment
- IGM properties and environment
- Interaction galaxies/IGM
- Complementary to OWLS simulations

all using "same" set of numerical parameters

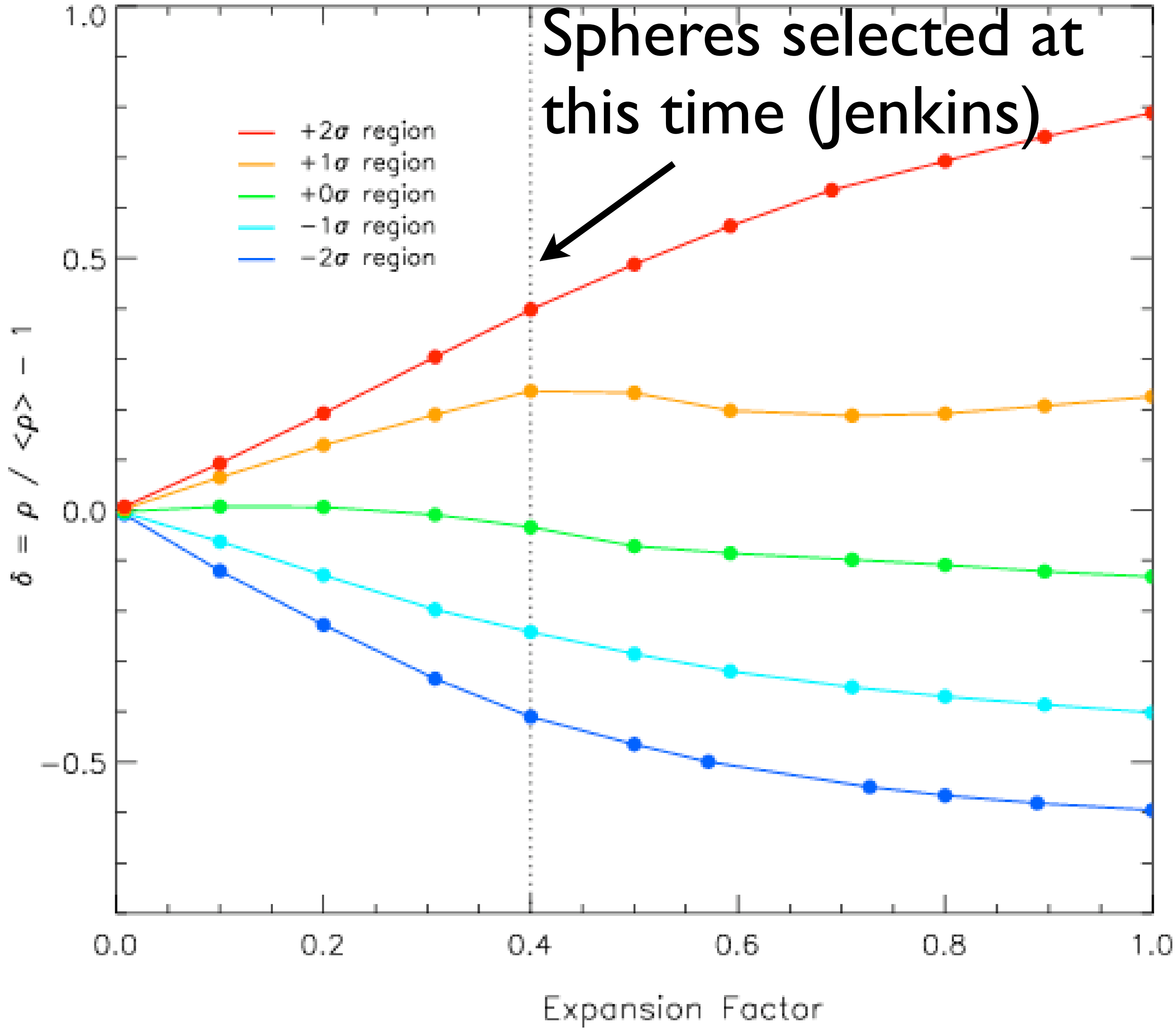
- GIMIC: 5 zoomed simulations in Millennium: "astrophysics"
- OWLS: 30+ simulations of periodic boxes, where "physics" and "resolution" are varied: "physics"

Overview

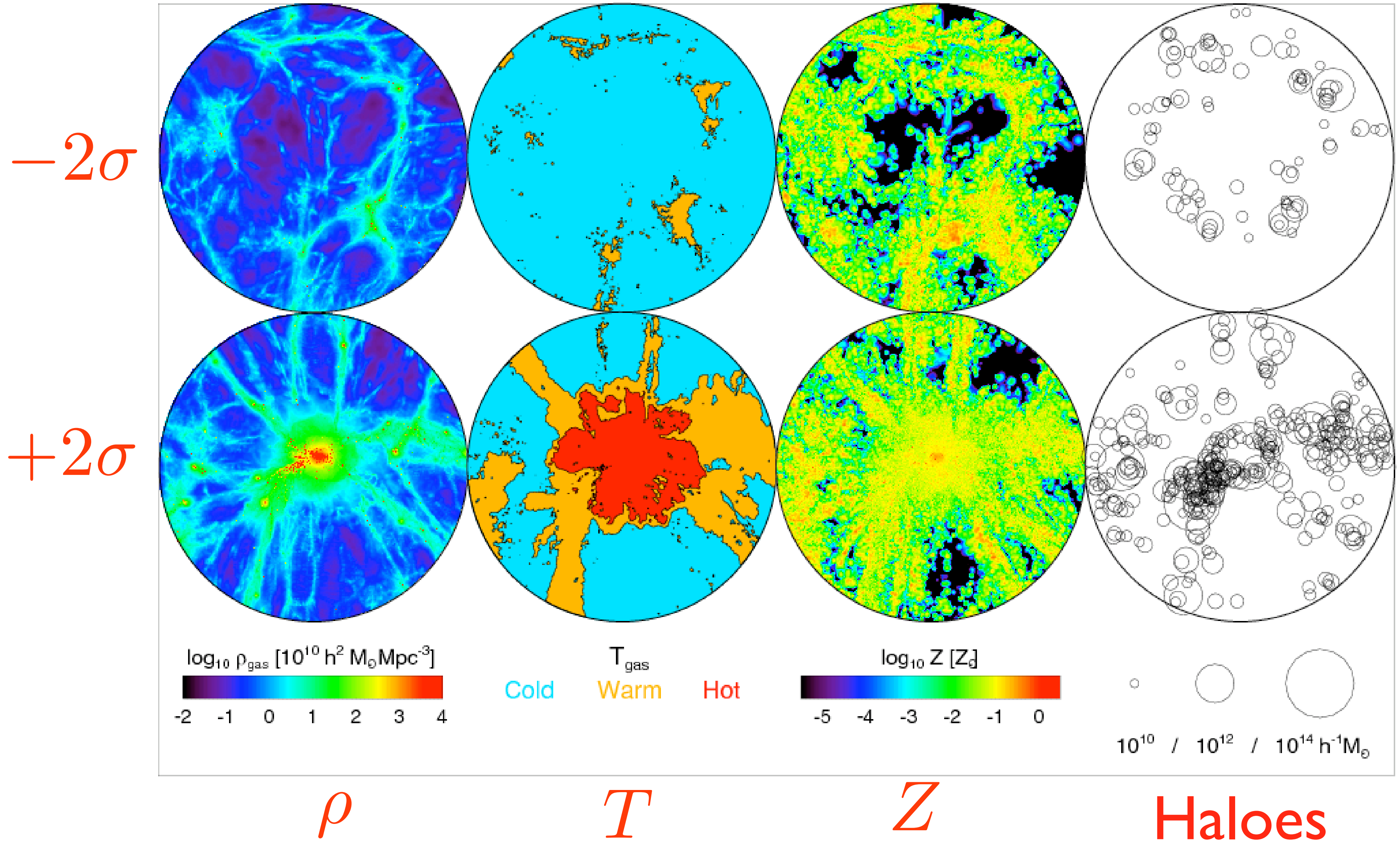

Sigma -2
Sigma -1
Sigma 0
Sigma +1


z=1.5
0σ, int res
0σ variance
z=0.0
+2σ, int res
−2σ, int res
−2σ, hi res
Reed07
log10 MFOF [h−1 M⊙]

Density evolution of 5 GIMIC spheres

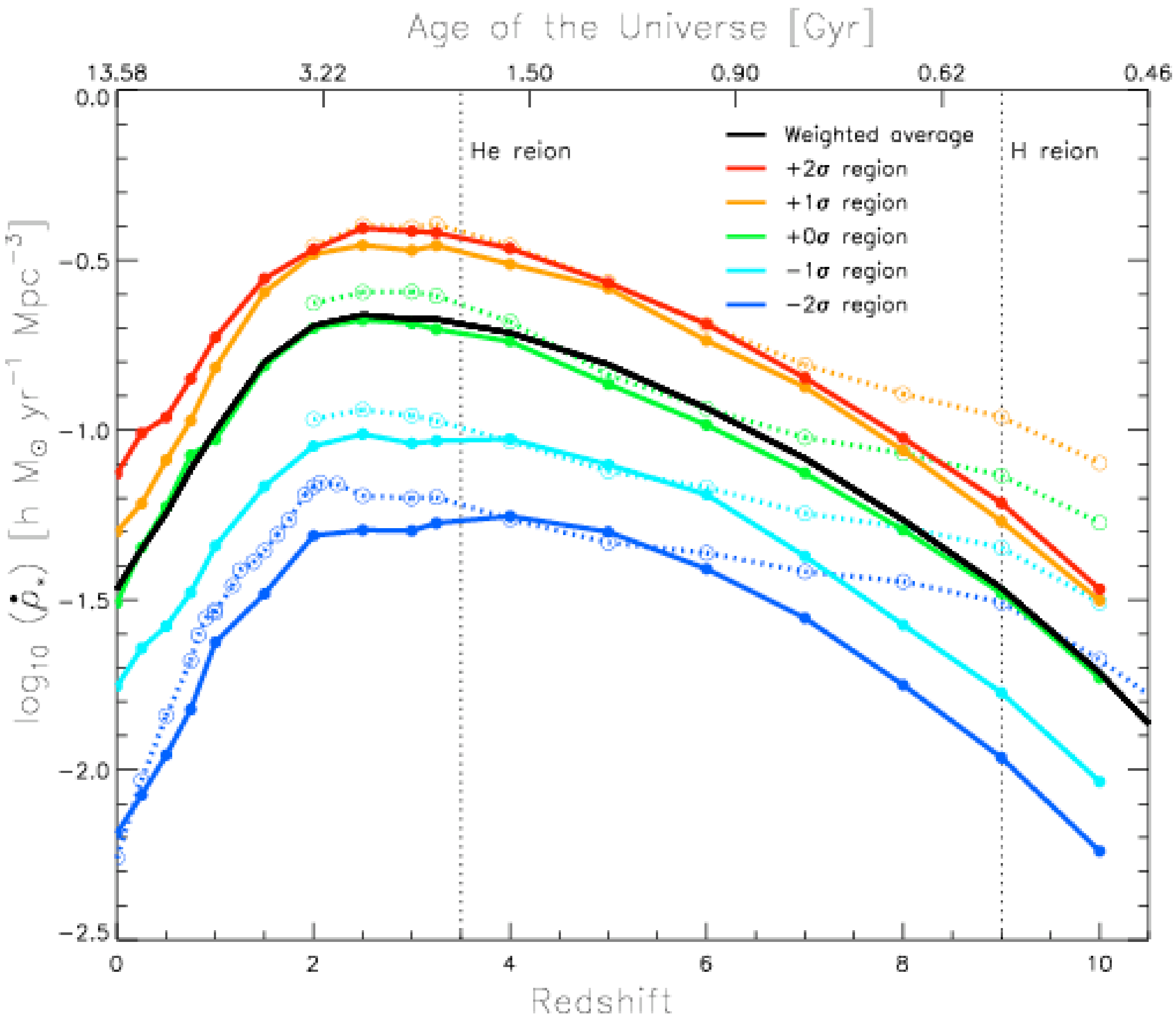


Visual difference between regions (z=0)



Star formation rate density (Madau/Lilly)

Starformation rate density

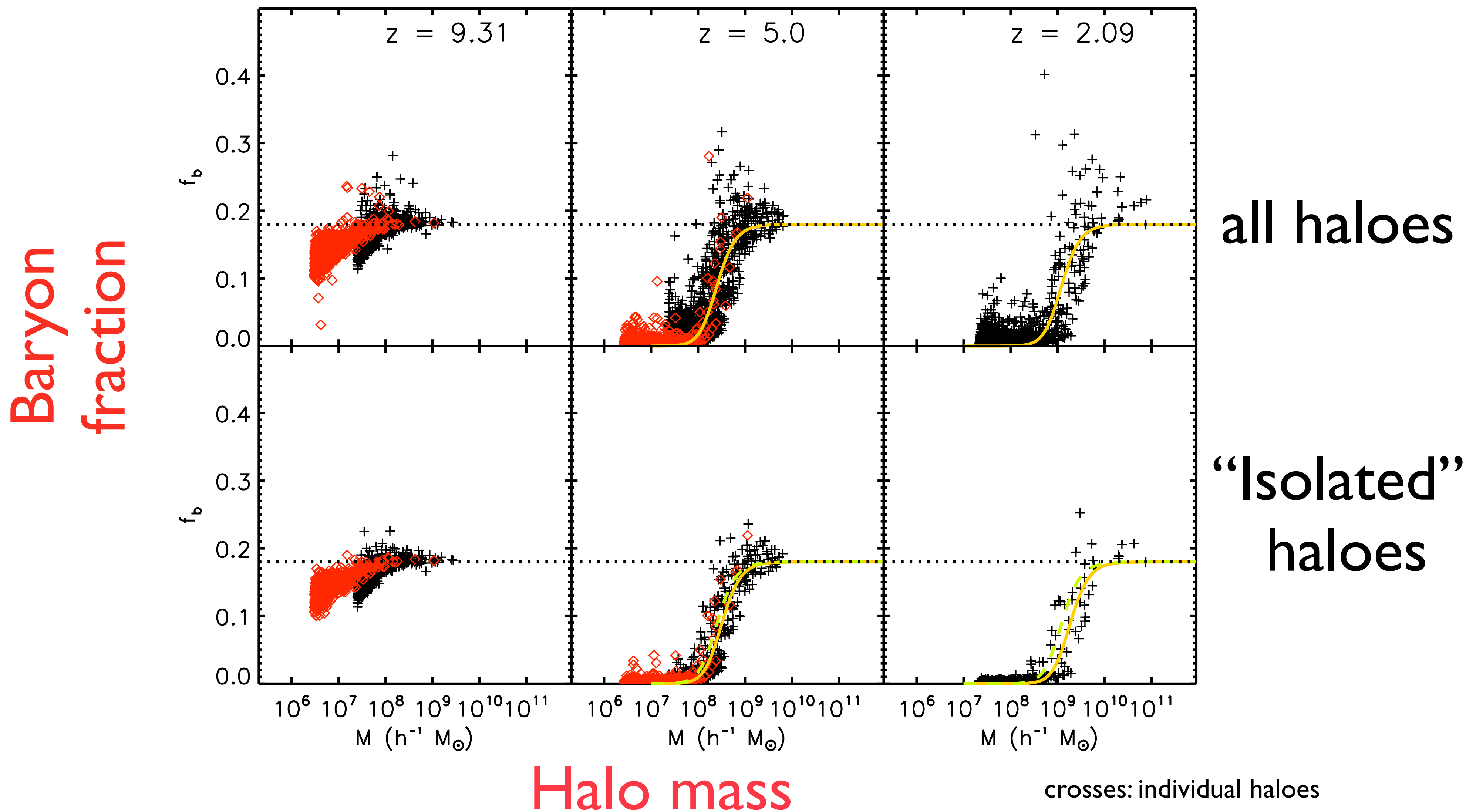


Redshift

Intermezzo

Massloss of galaxies due to a UV-background

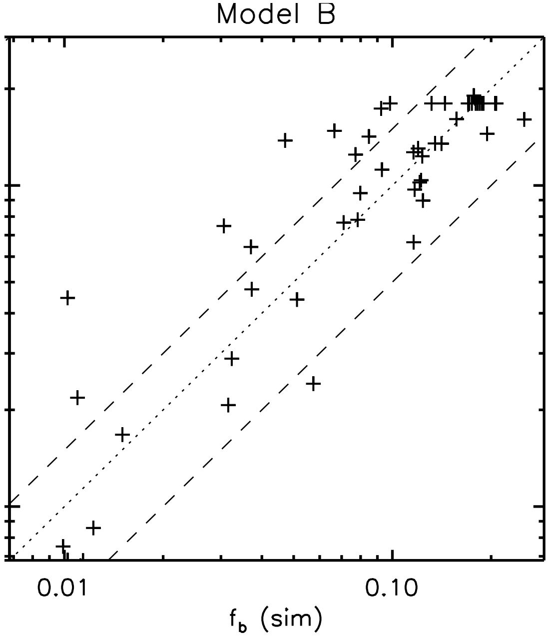
Takashi Okamoto[1⋆], Liang Gao[1,2] and Tom Theuns[1,3]
[1] Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham, DH1 3LE
[2] National Astronomical Observatories, Chinese Academy of Science, Beijing, 100012, China
[3] Department of Physics, University of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



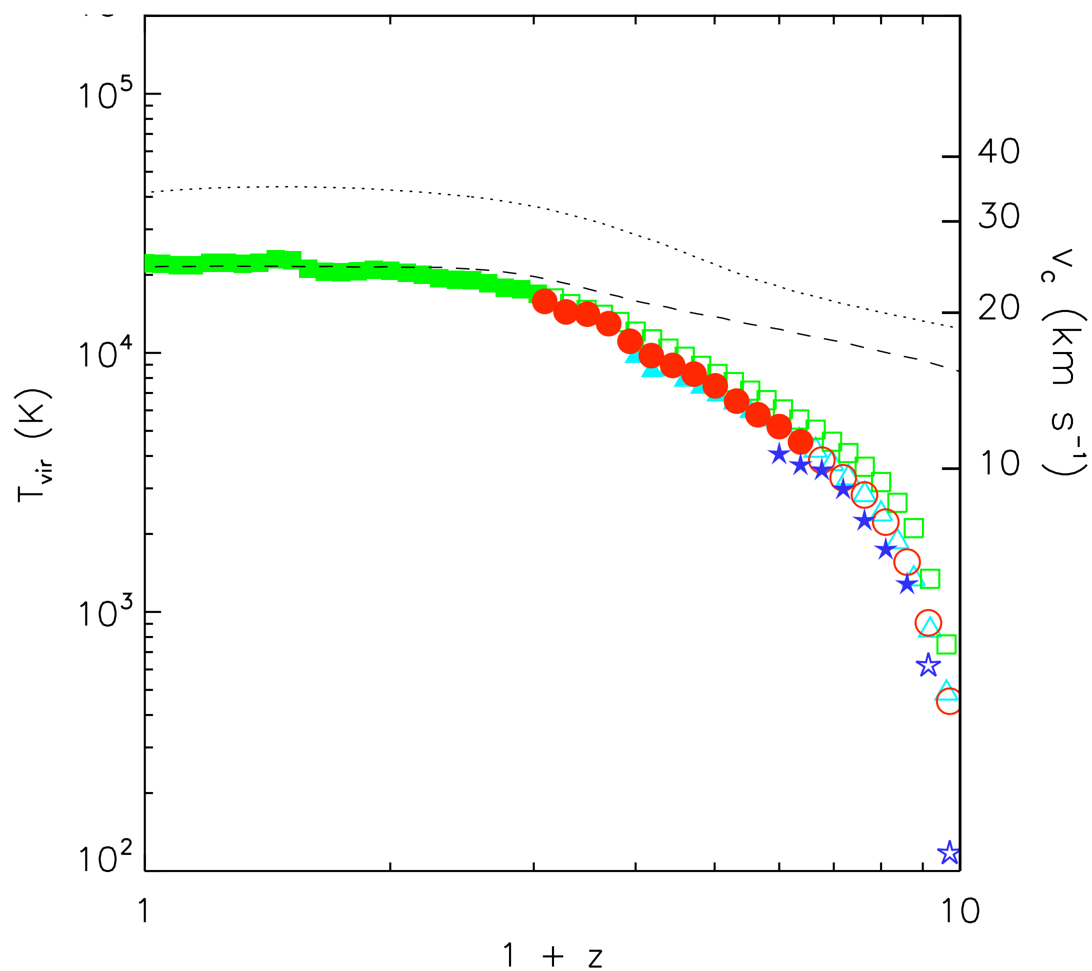
crosses: individual haloes

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

Massloss model



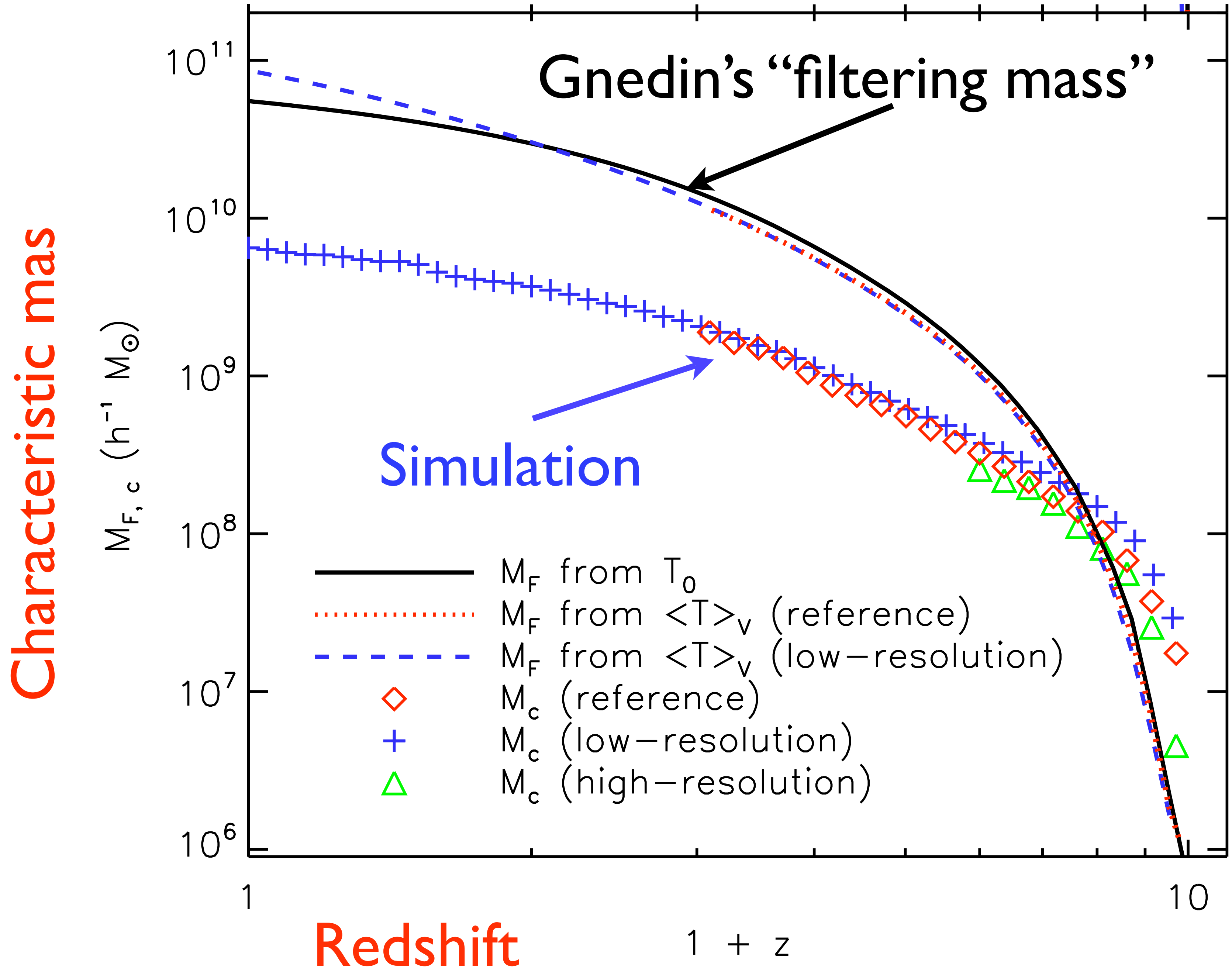
Virial temperature



Virial velocity

Redshift

Characteristic mass is much smaller than Gnedin's filtering mass

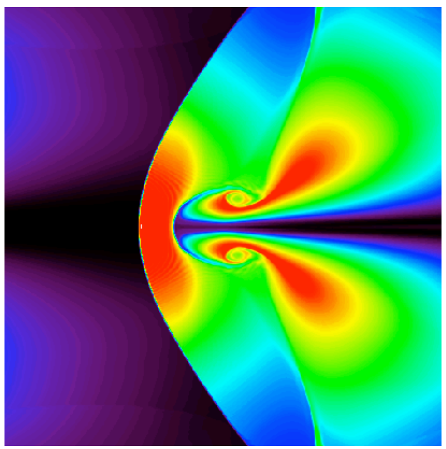


How well does SPH do the hydro?

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*



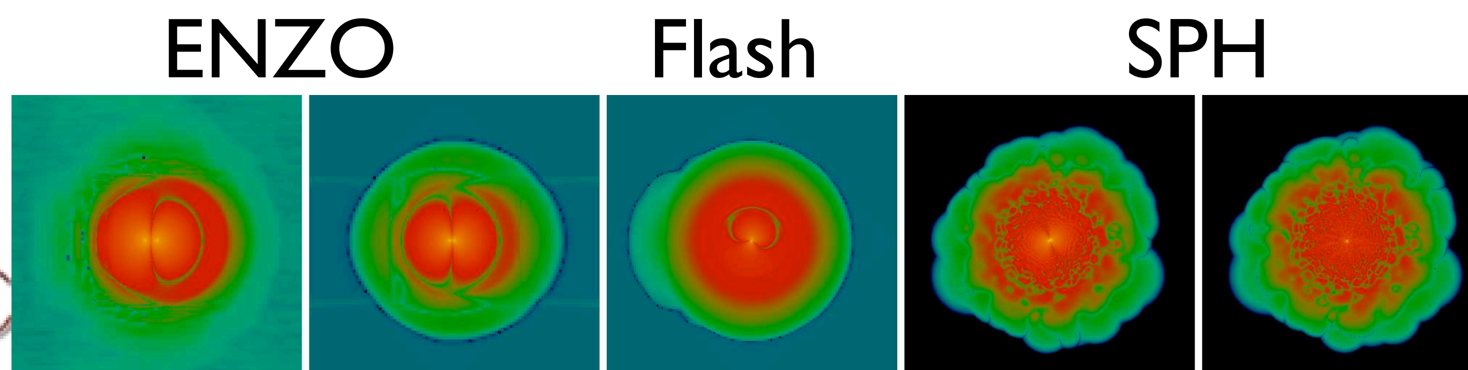
Comparison Gadget (SPH) vs FLASH (AMR) for collisions of isolated clusters (dm +gas, non-radiative)

A test suite for quantitative comparison of hydrodynamics codes in astrophysics

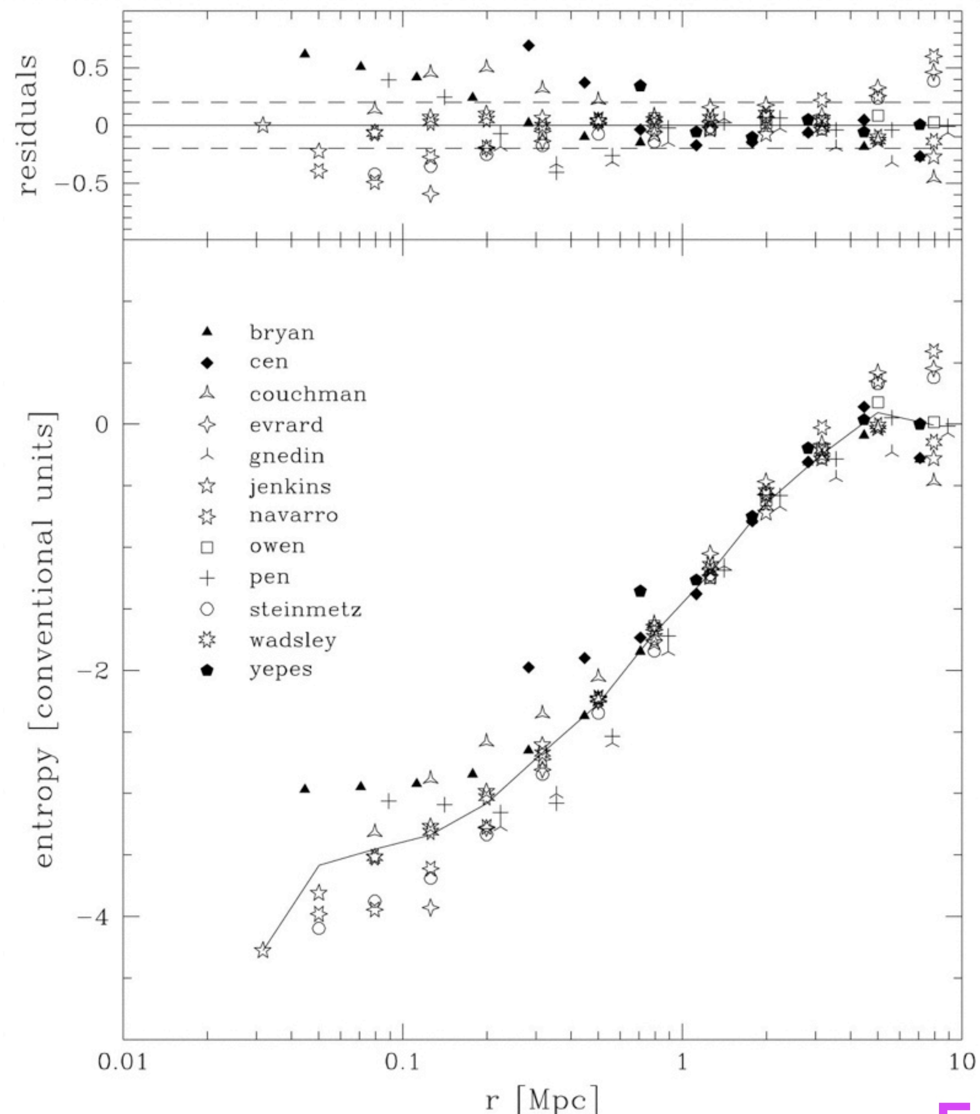
Elizabeth J. Tasker[1⋆], Riccardo Brunino[2], Nigel L. Mitchell[3], Dolf Michielsen[2], Stephen Hopton[2], Frazer R. Pearce[2], Greg L. Bryan[4], Tom Theuns[3]

Translating King profiles

Tom Theuns



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



Frenk et al '99

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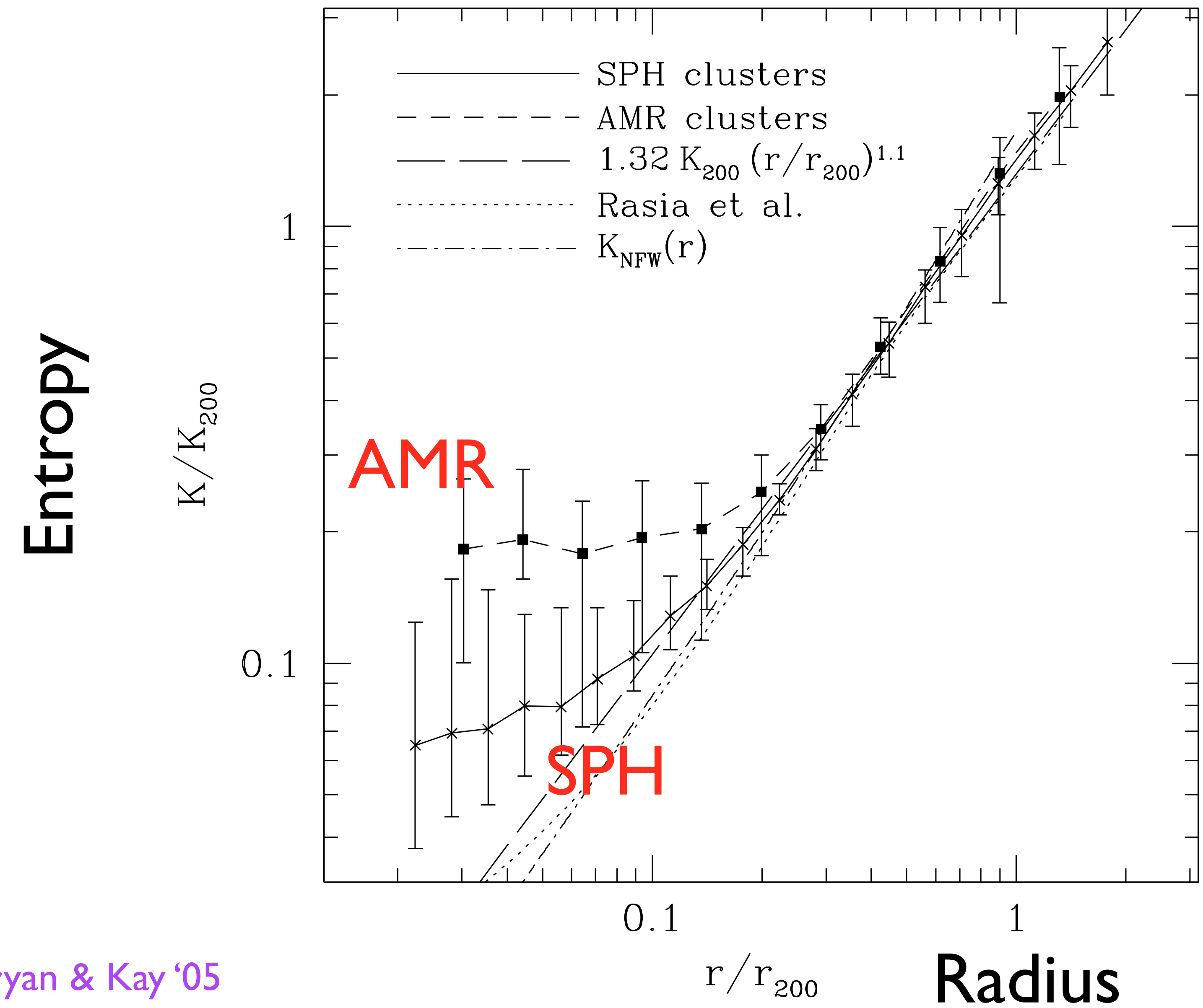
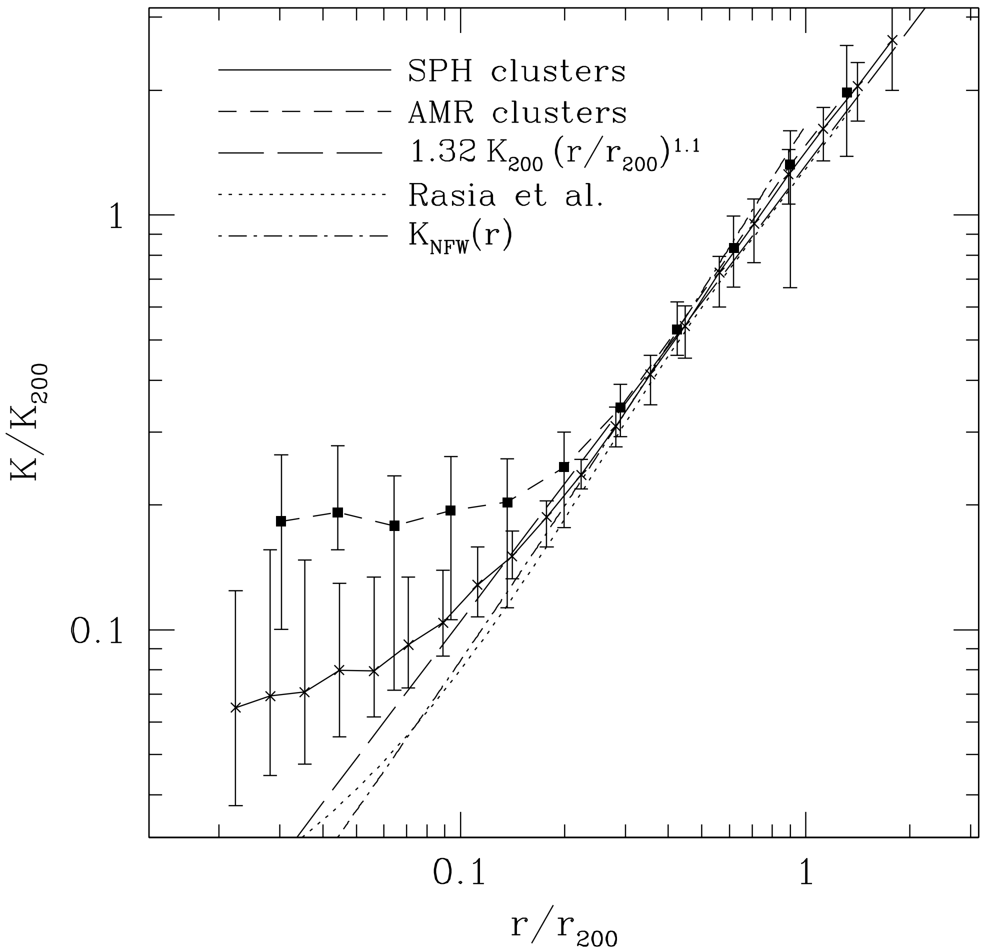
Cluster entropy profiles: SPH vs AMR



Voit, Bryan & Kay '05

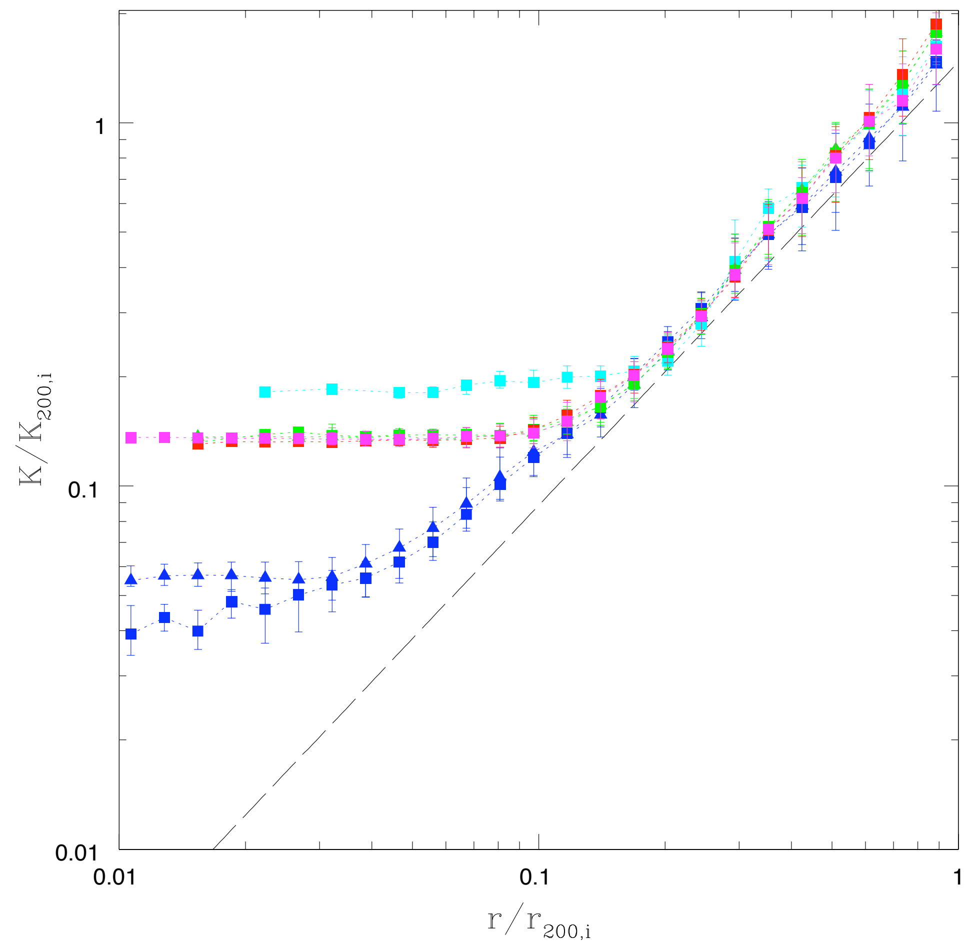
Cluster entropy profiles: *NOT* due to cosmology

Cosmological clusters



Voit, Bryan & Kay ‘05

Binary collisions



Mitchell, McCarthy, Bower & TT

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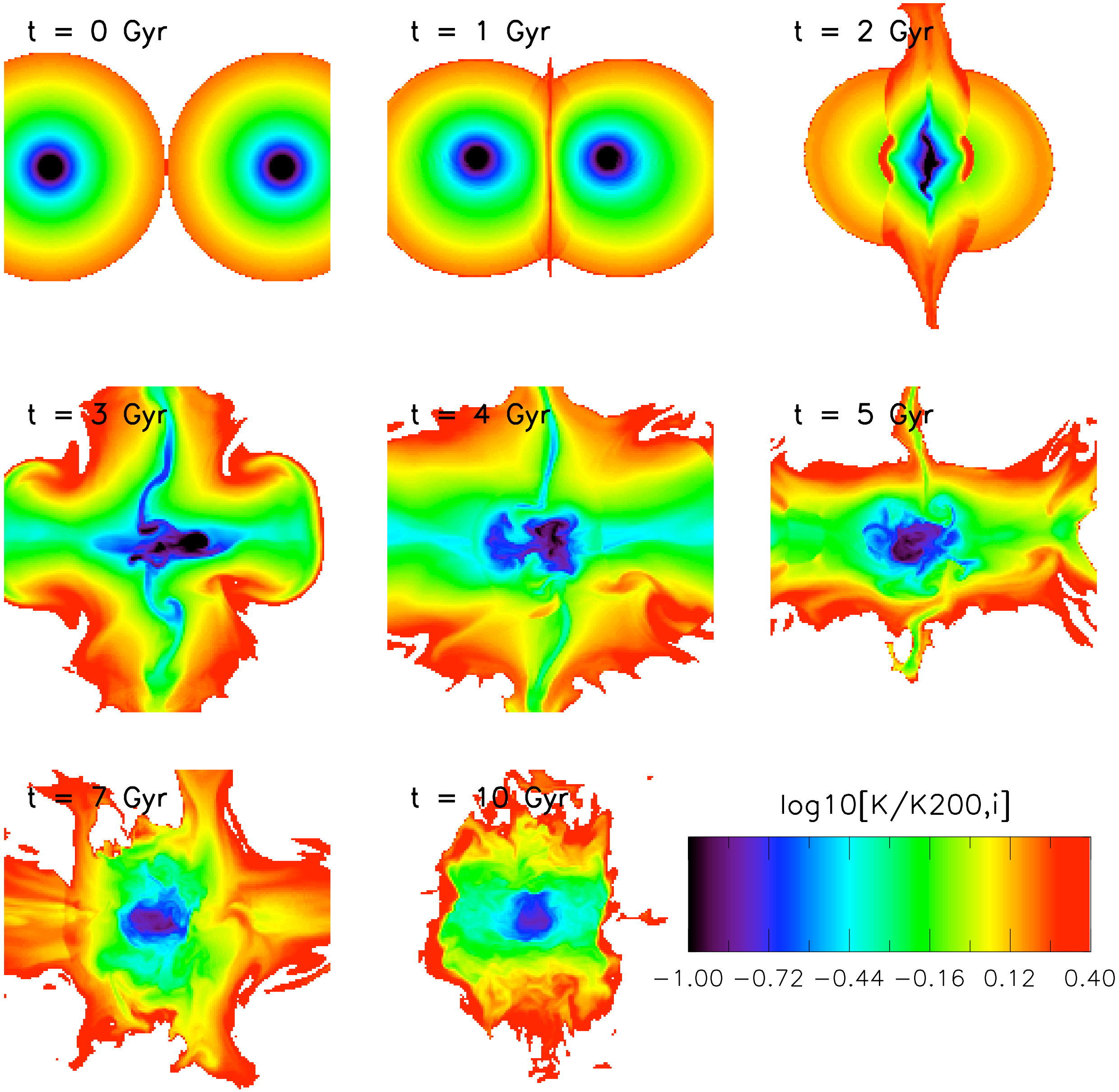
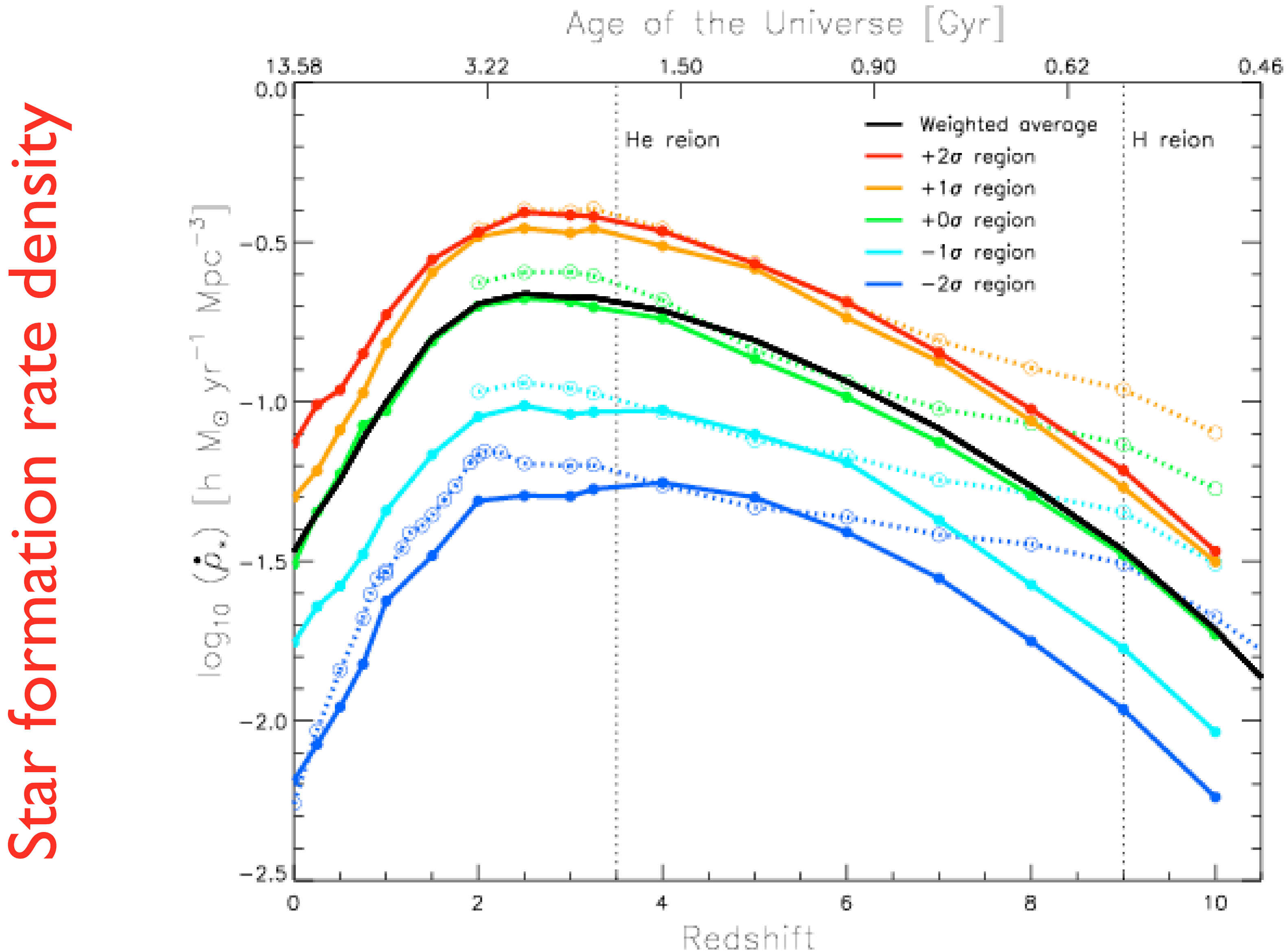
Generation of entropy (FLASH)



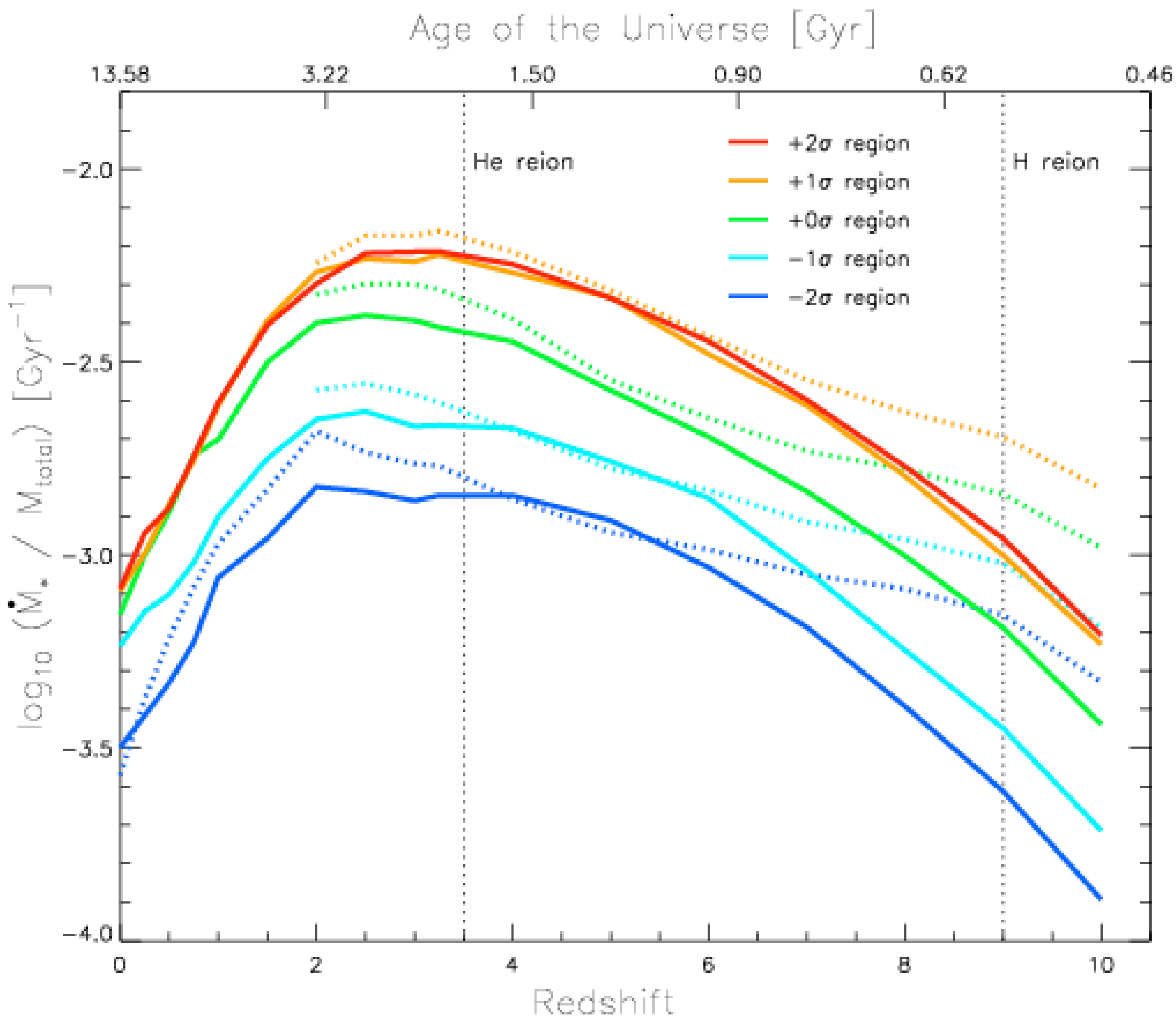
Overview (continued)

Star formation rate density (Madau/Lilly)



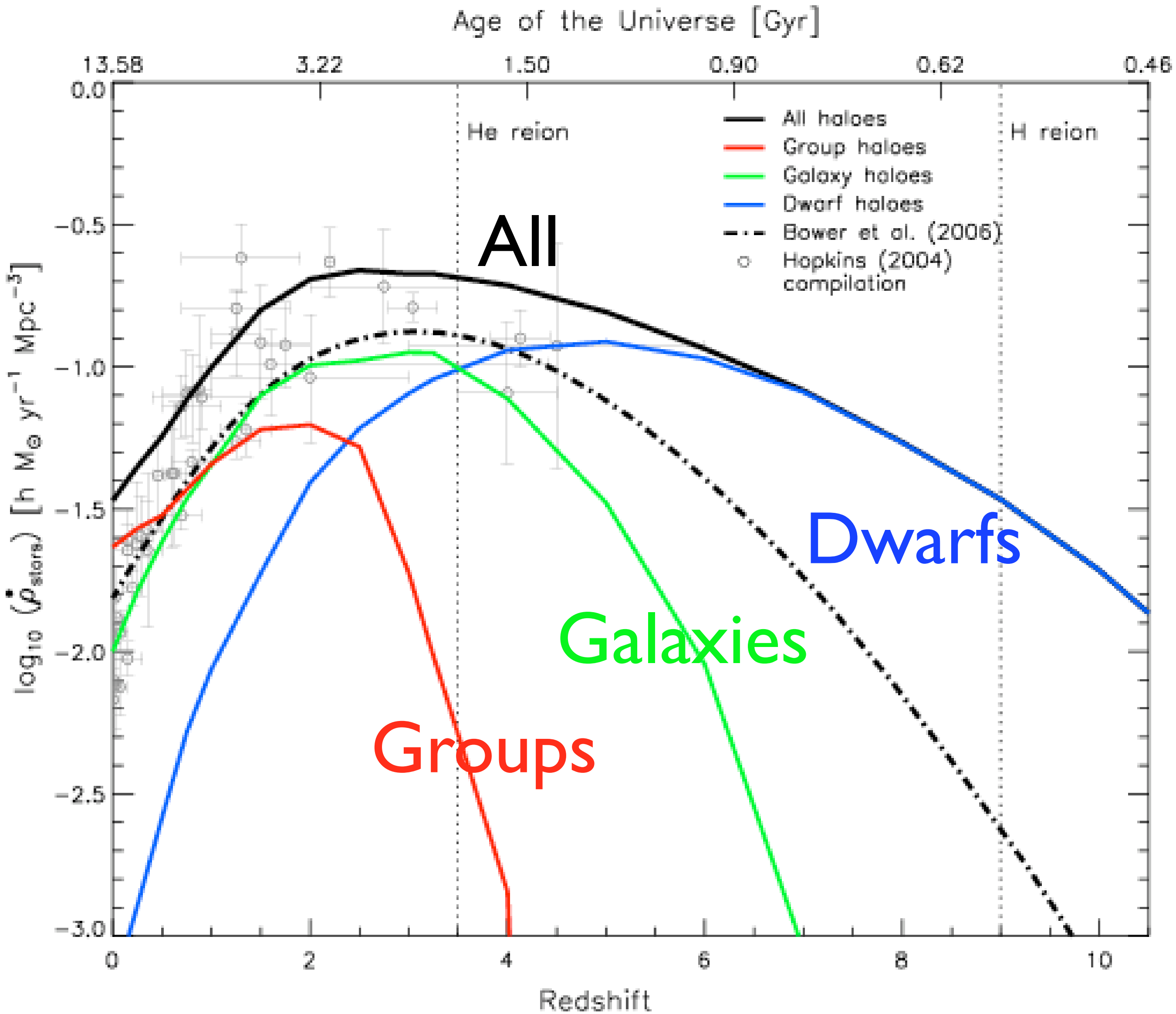
Specific star formation rate

Star formation rate per unit mass



Redshift

Star formation as function of halo mass then

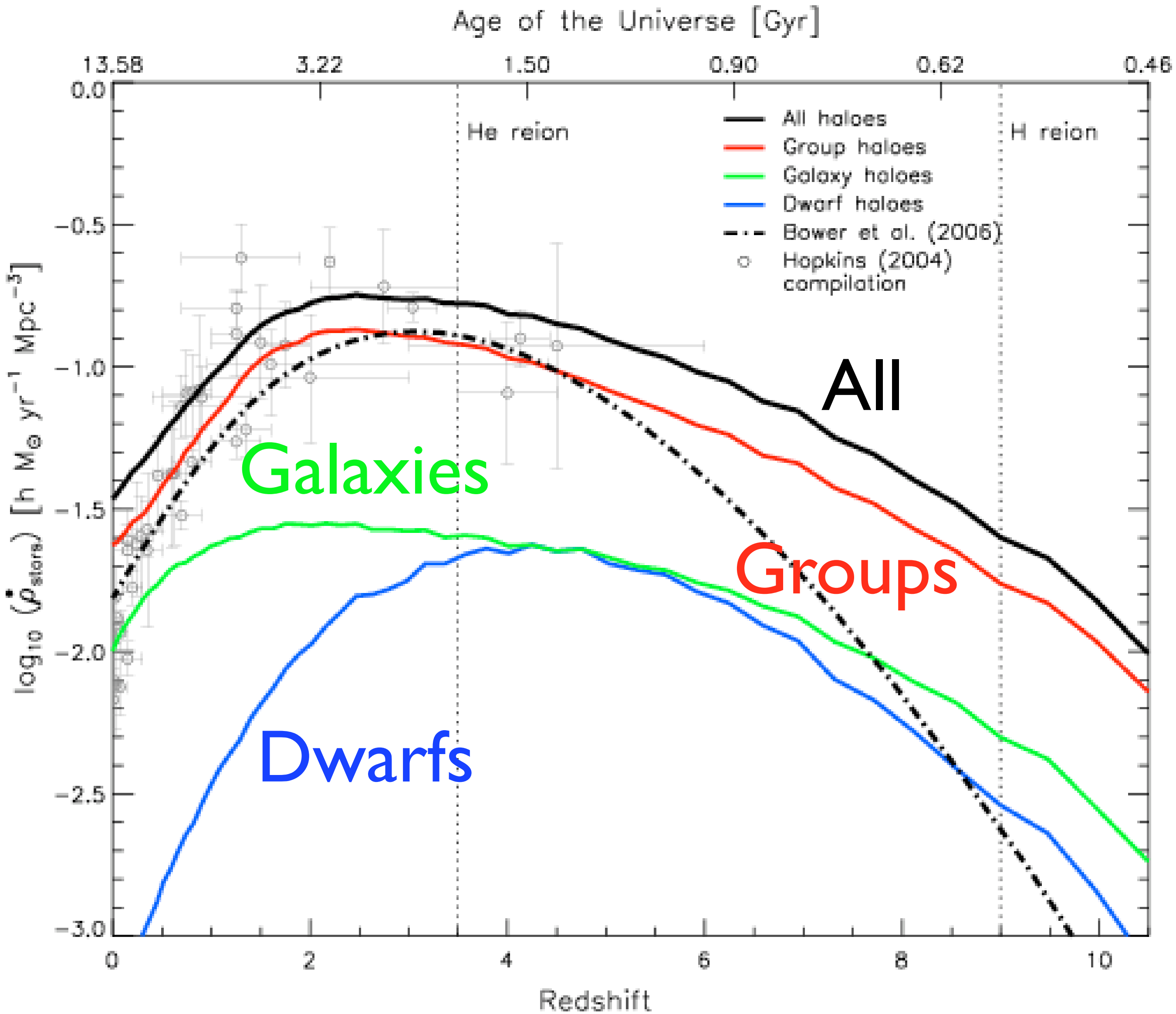


Star formation rate density

Redshift

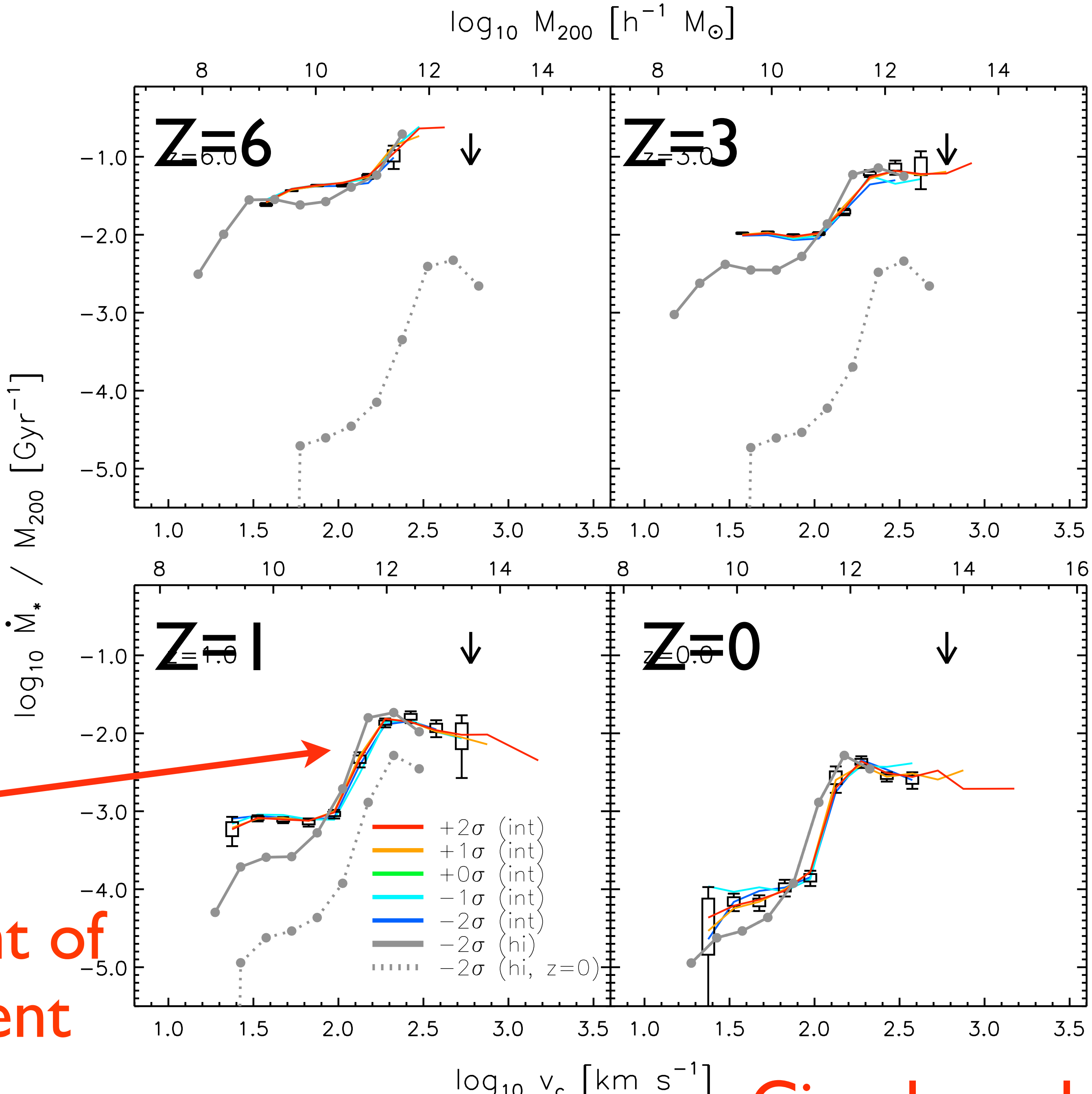
Star formation as function of halo-mass now

Star formation rate density



Redshift

Specific star formation rate per halo



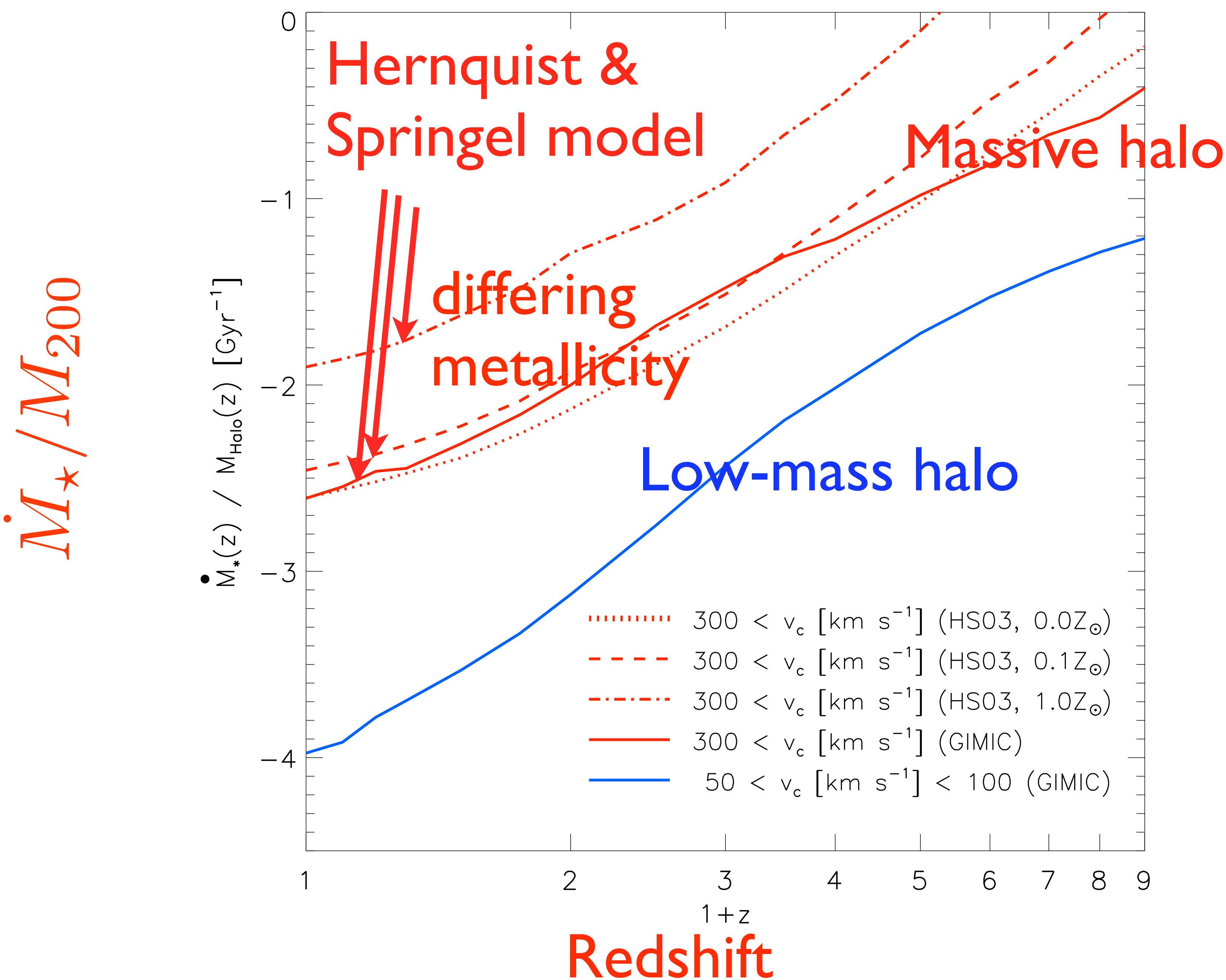
$\dot{M}_\star / M_{200}$

sSFR independent of environment

Circular velocity

Tom Theuns

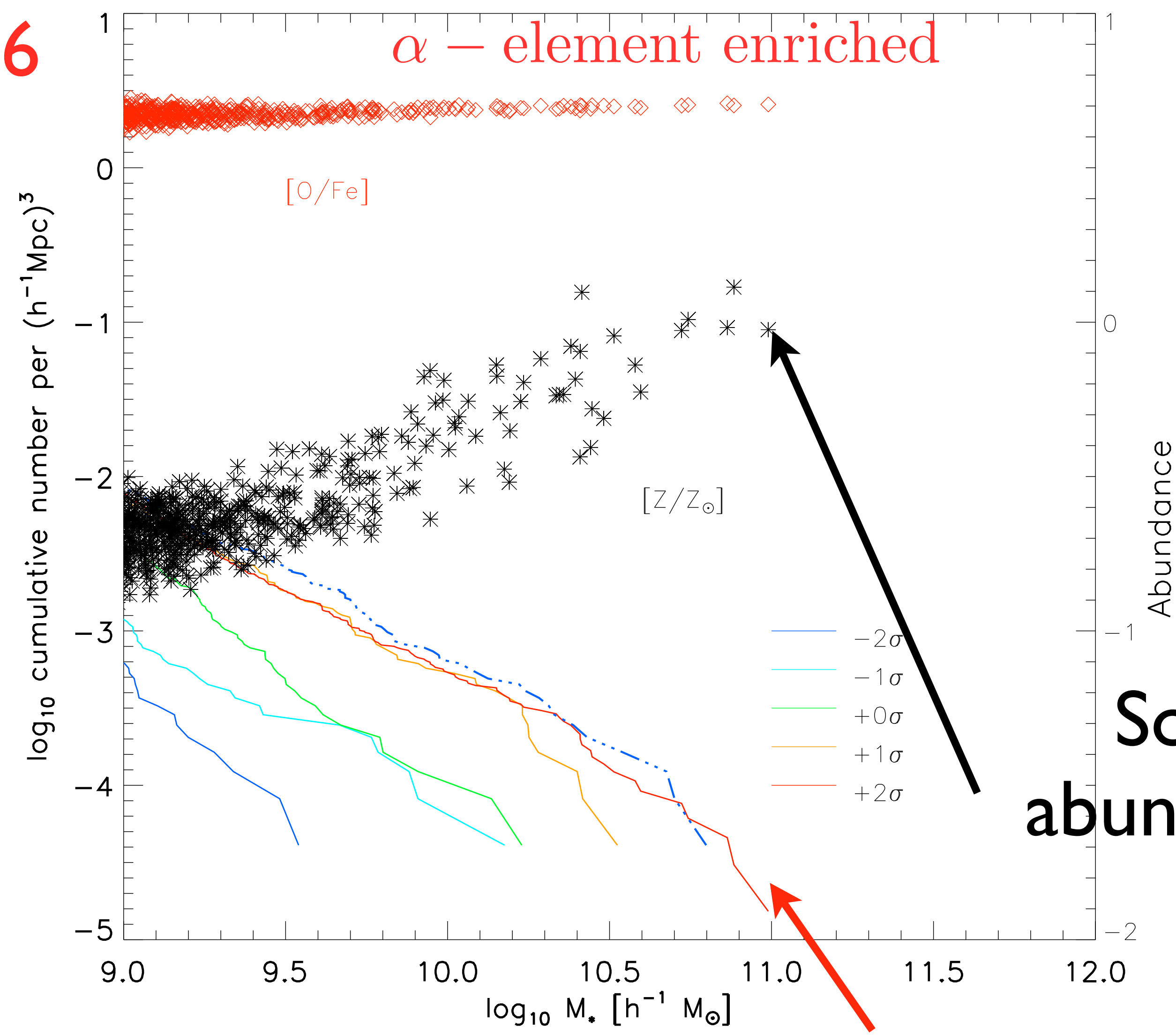
sSFR as function of redshift



Star formation at high z

Reionization as function of environment

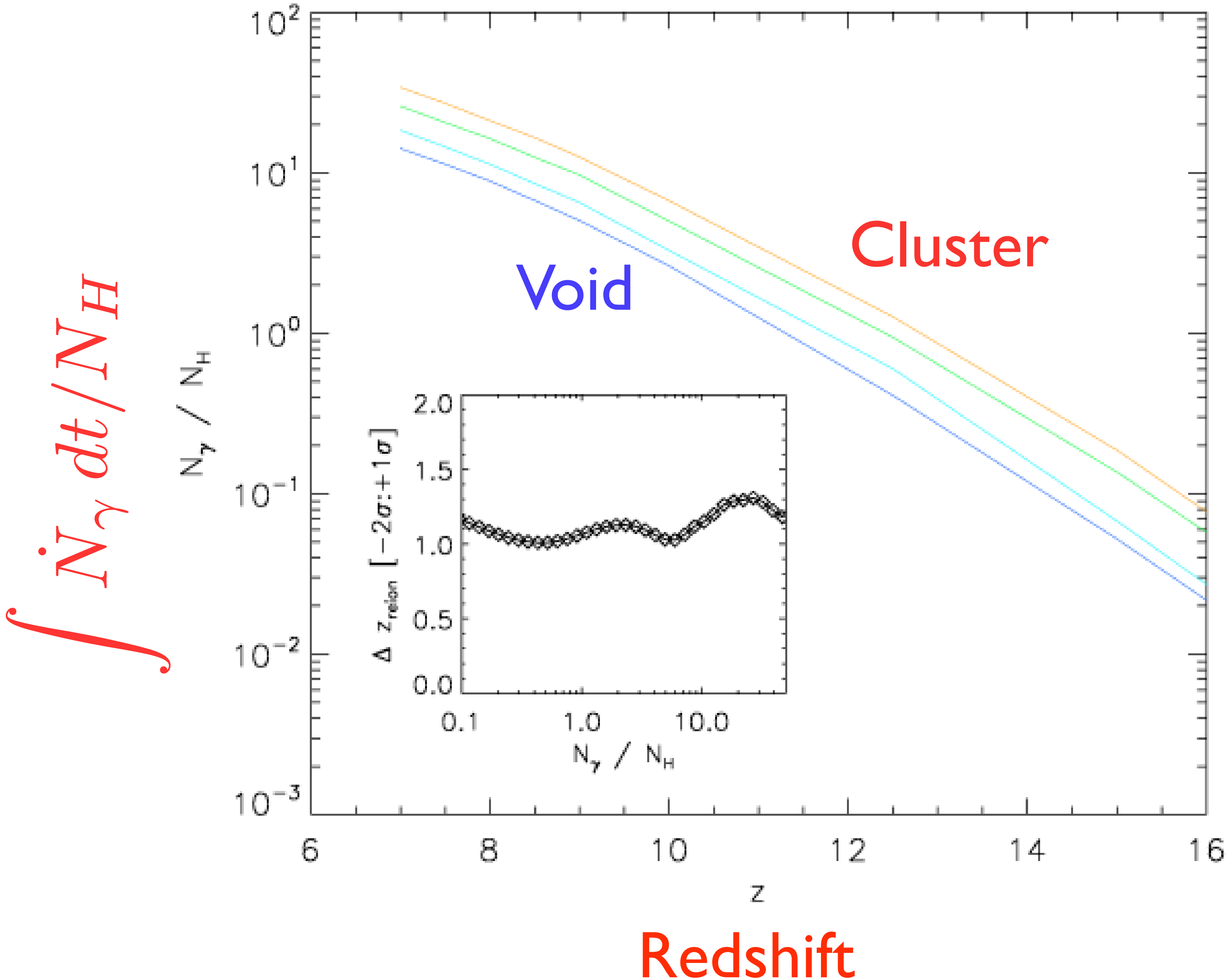
Stellar mass function z=6



Solar abundance

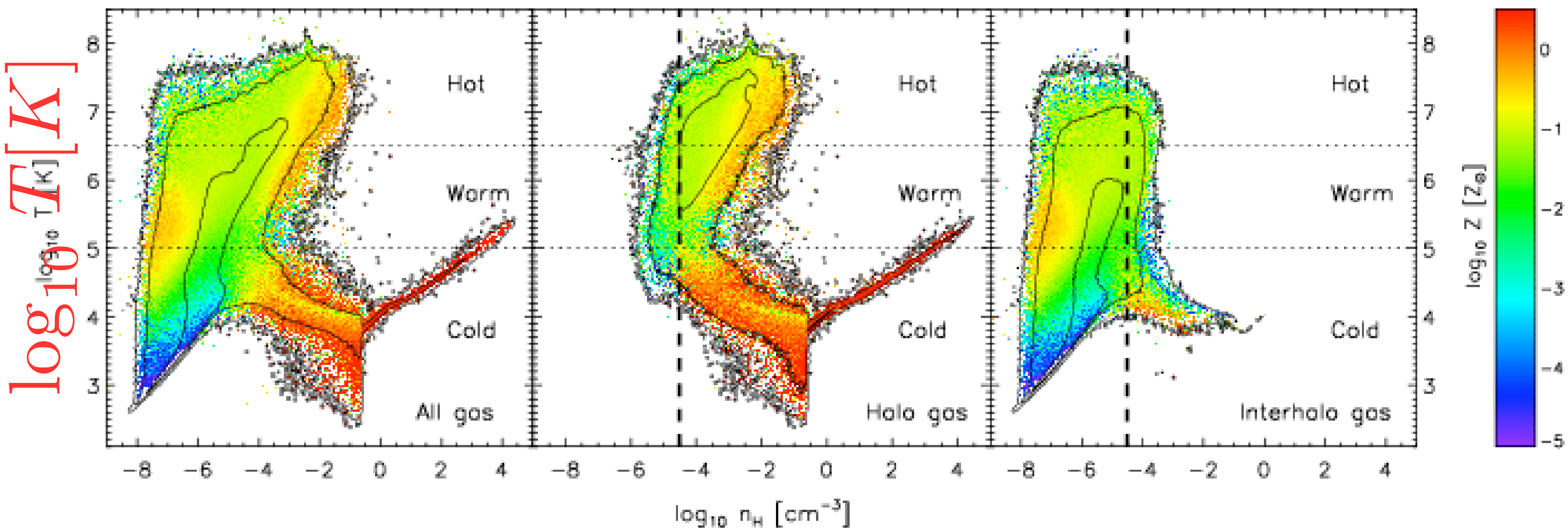
$M_\star = 10^{11}\, M_\odot$ solar-abundance galaxy

Reionization as function of environment



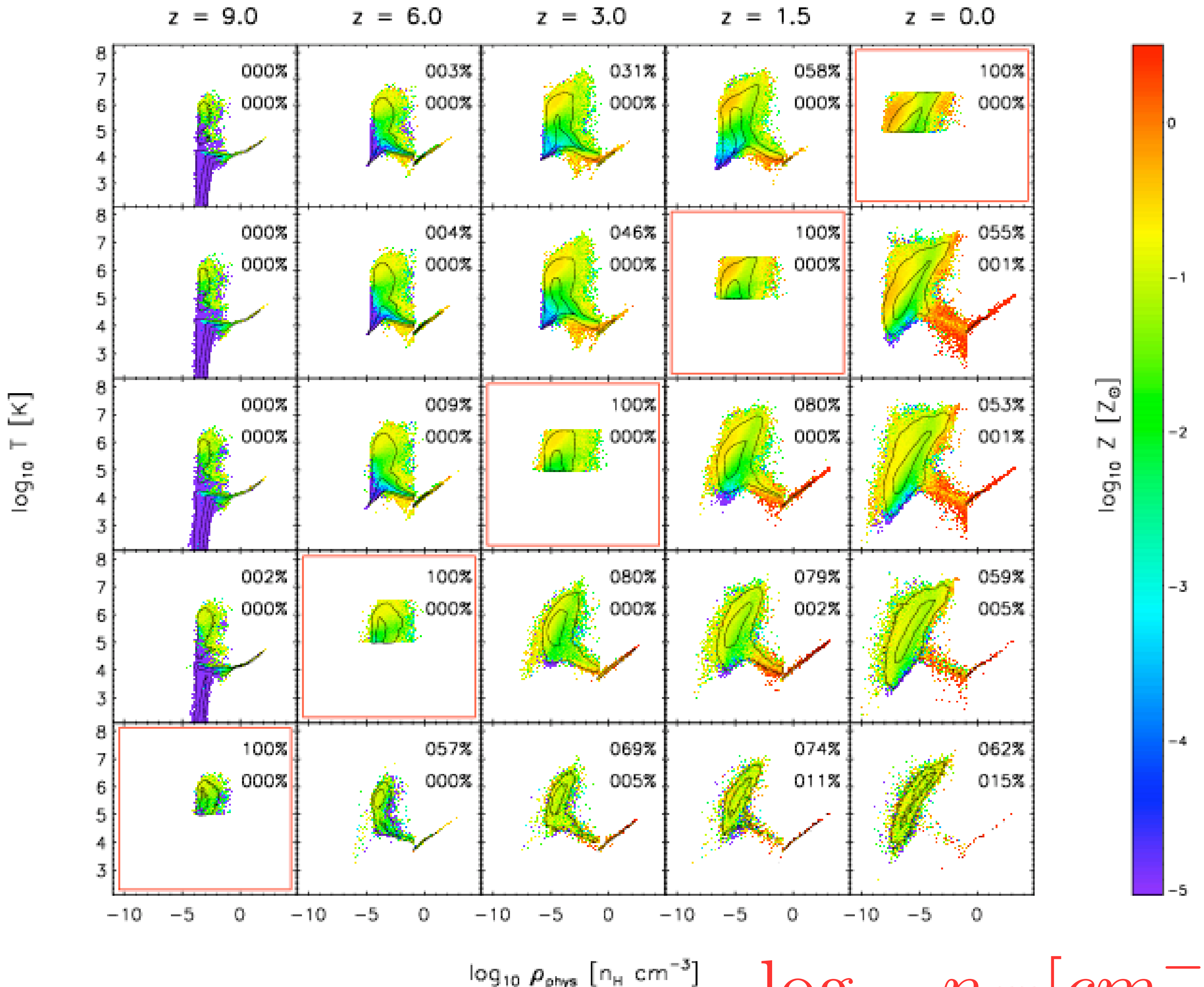
Temperature/Density/Metallicity at z=0

All gas Halo gas Inter-halo gas



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

Cycling of gas through whim phase



$\log_{10}\, T[K]$

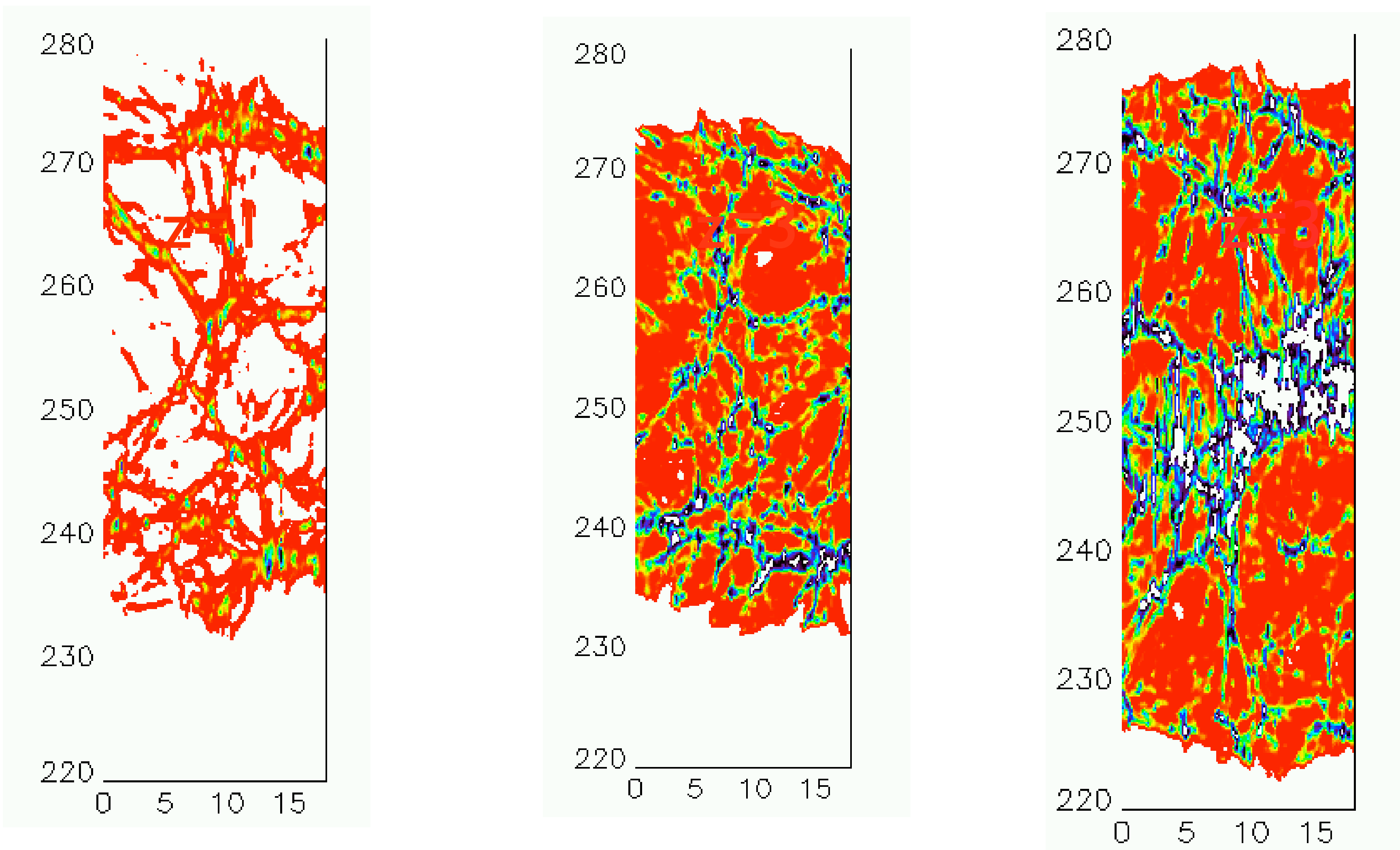
$\log_{10}\, n_H[cm^{-3}]$

The intergalactic medium

Lyman-alpha forest

LSS in the IGM

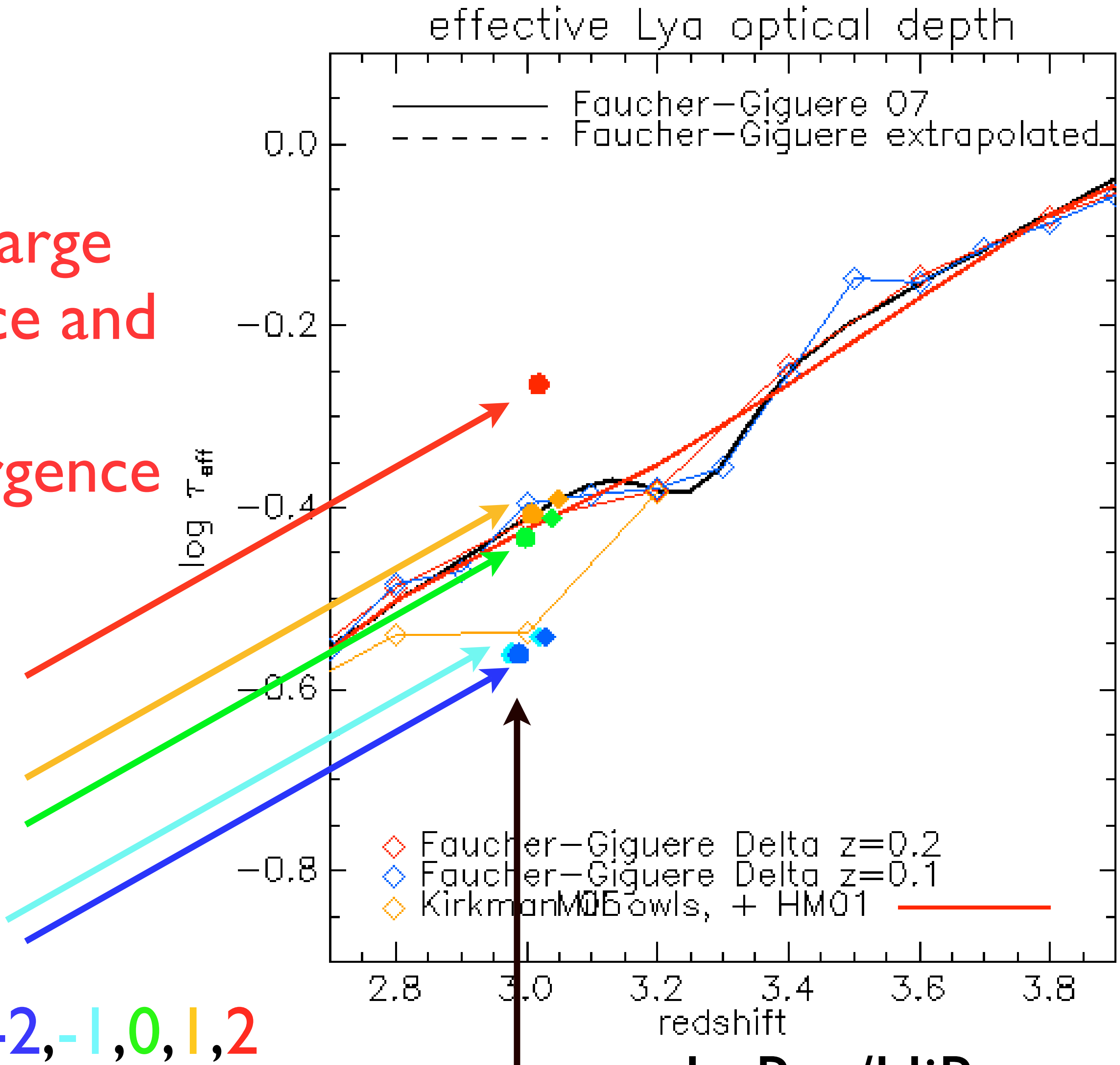
z=0 z=3 z=3



0σ 0σ $+2\sigma$

Optical depth evolution: data + GIMIC

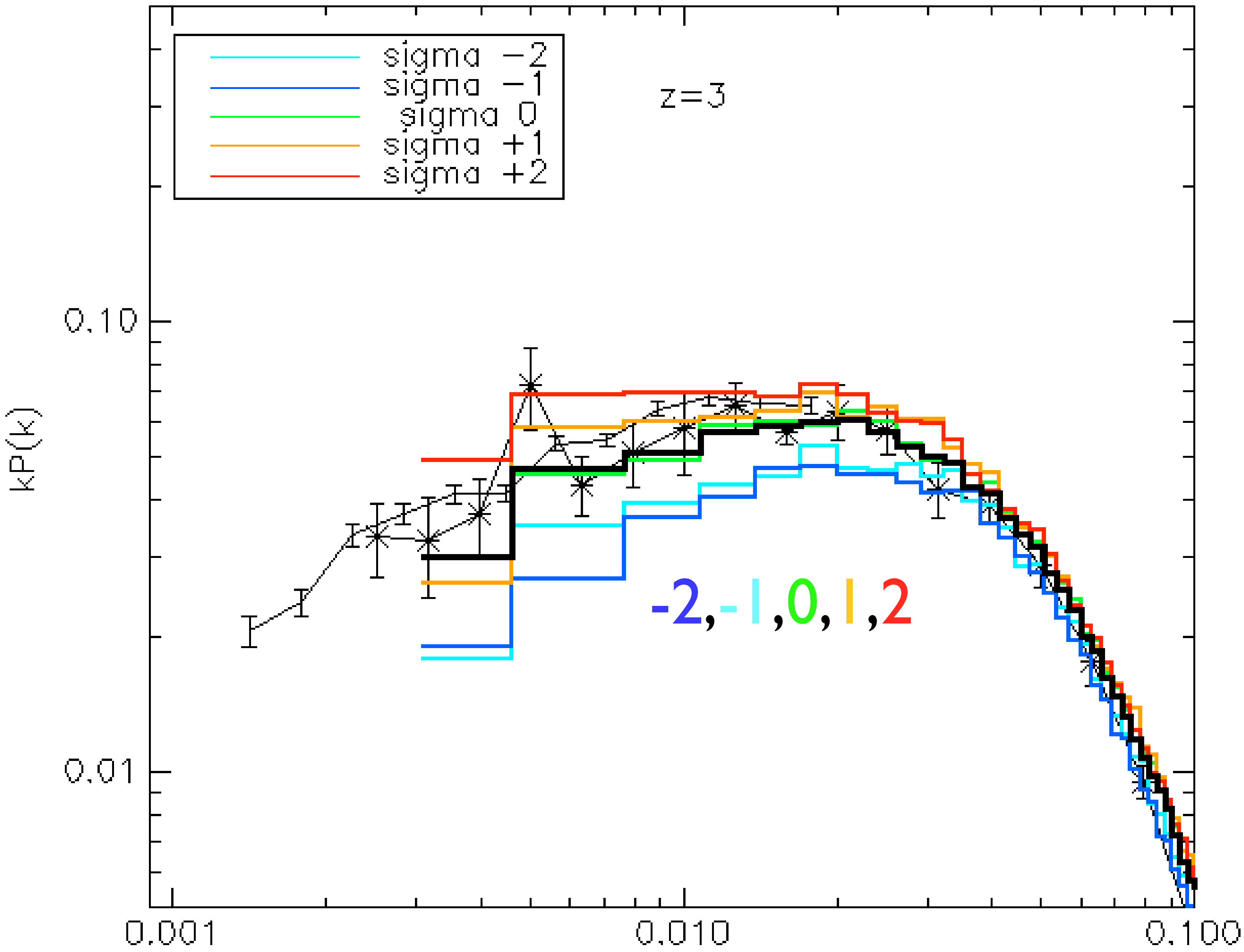
Note large variance and good convergence



-2,-1,0,1,2

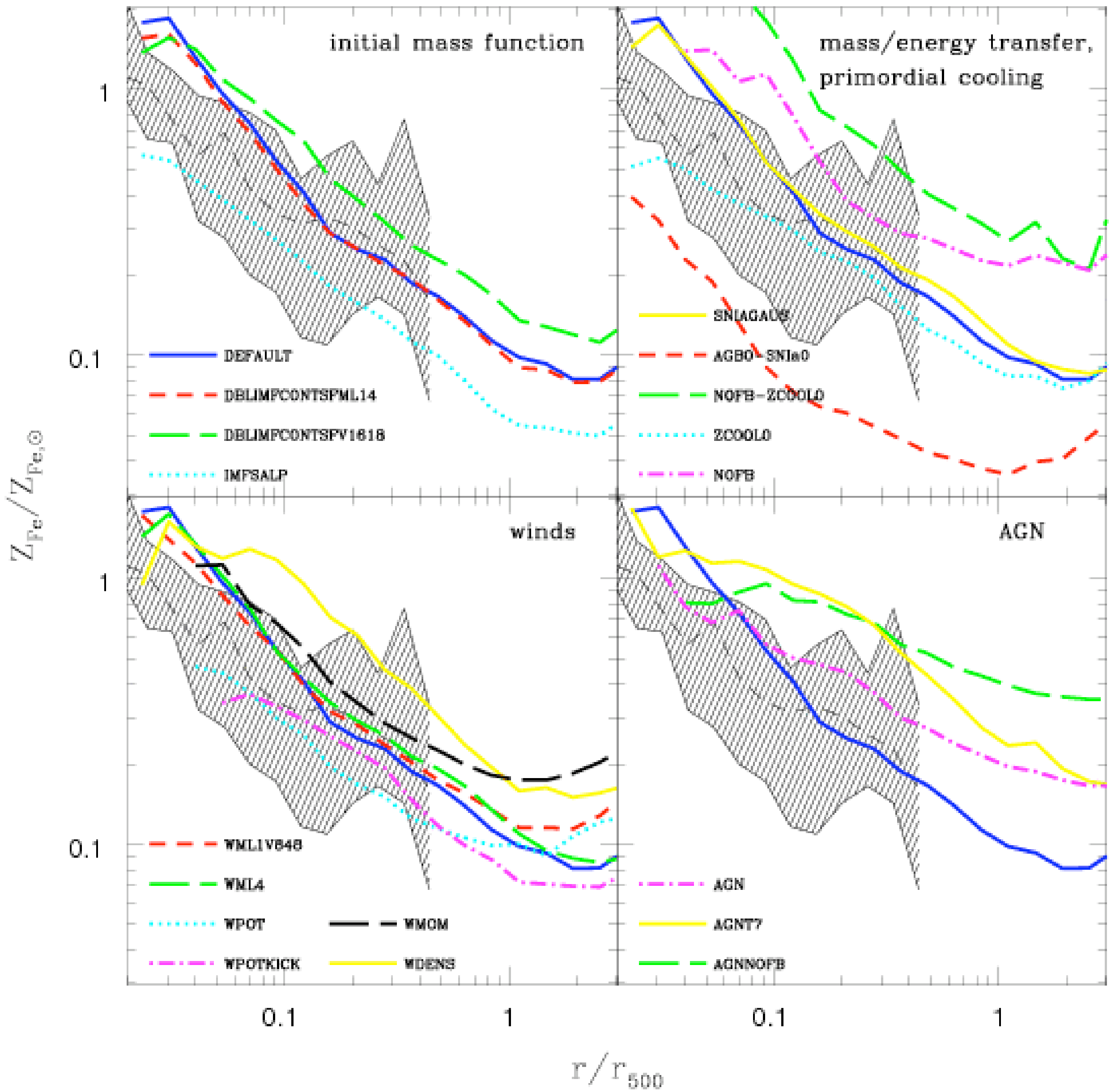
LoRes/HiRes

Flux power-spectrum of different spheres

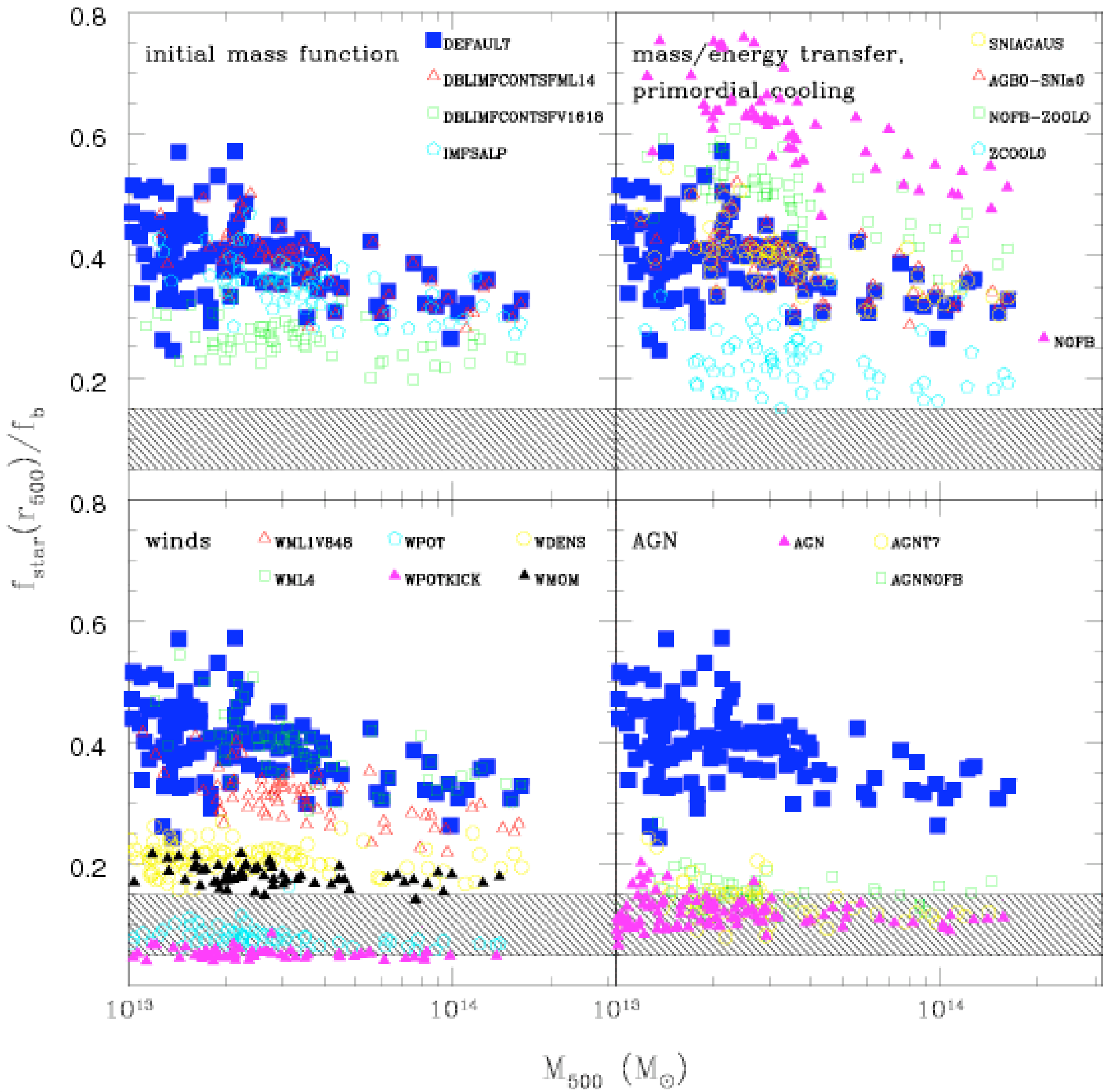


Galaxy clusters

Metallicity in galaxy clusters for different numerical parameters

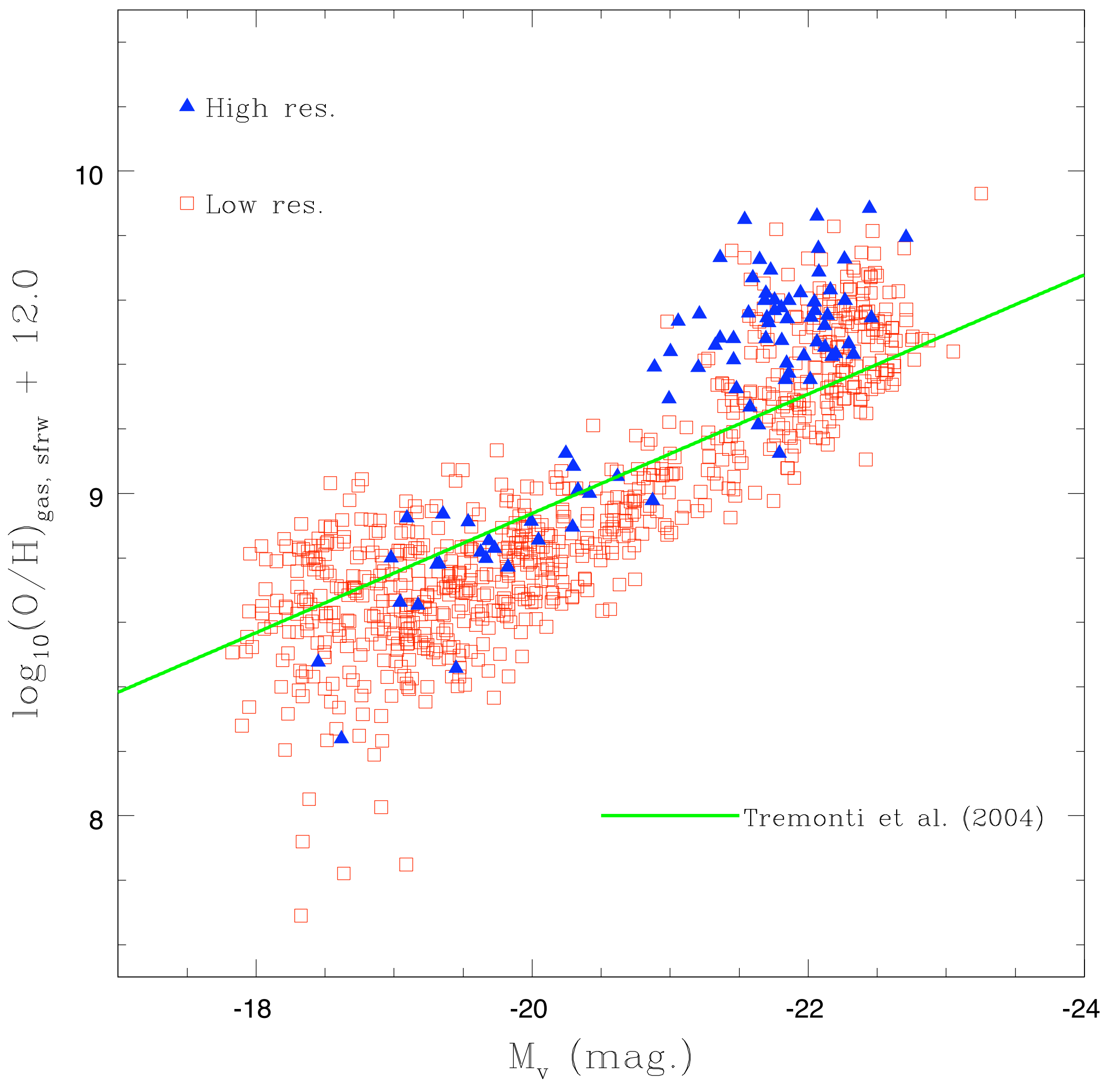


Stellar mass fraction in galaxy clusters for different numerical parameters

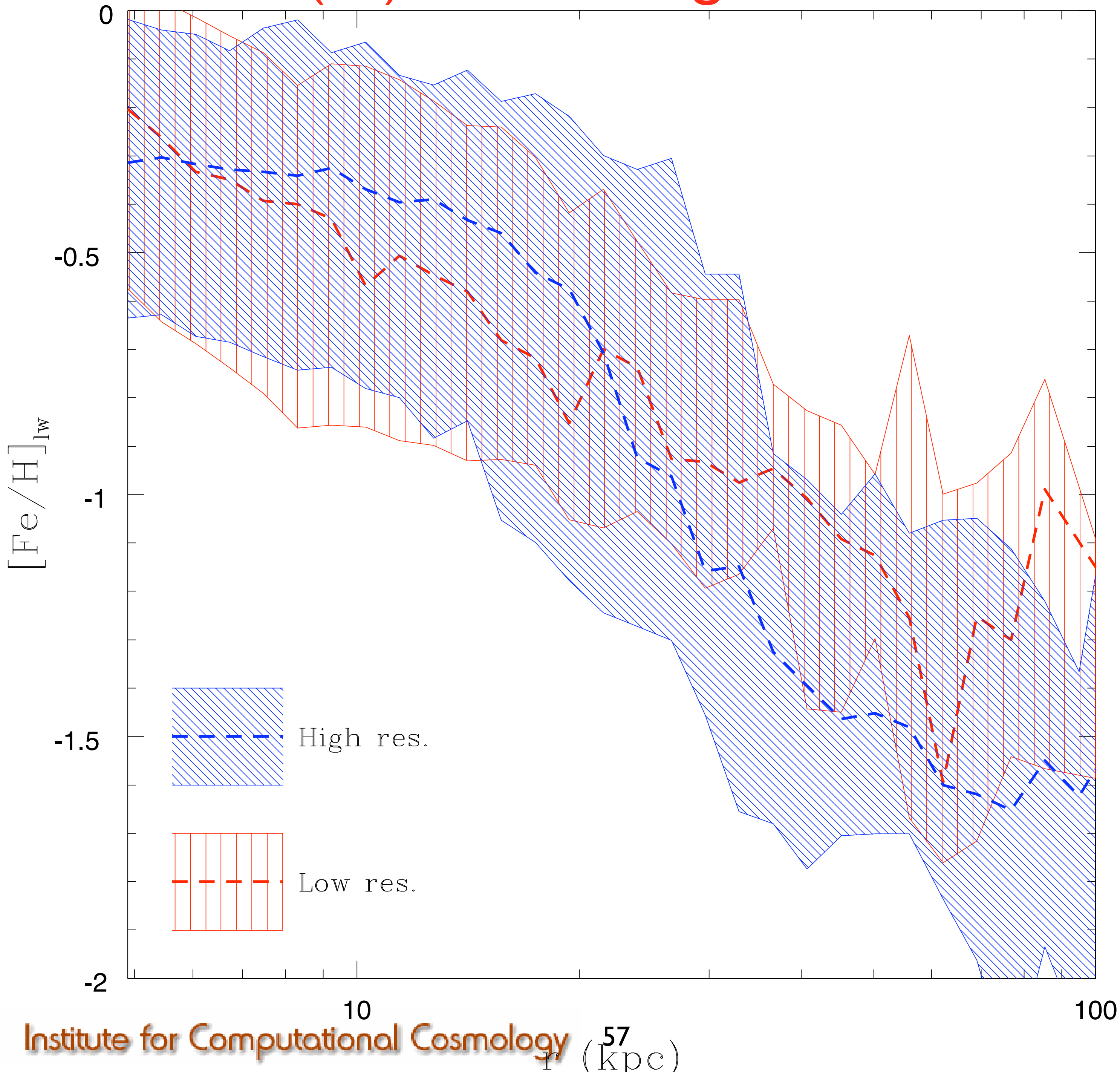


Milky Way-like haloes, and their satellite galaxies

Luminosity-metallicity relation



(Fe) Abudance gradients



Summary:

- Holistic approach to galaxies/clusters and IGM
- Set of zoomed simulations (GIMIC: astrophysics)
- Set of isolated boxes (OWLS: physics)

Interested in using these simulations? Let me know!