Properties of galaxies in the reionization era: Galaxies at z>6

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and
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Belgium

Milan
Raicevic

Simulation/theory side:

how do we think these galaxies look like, and what are the expected Ly-C emissivities?

Observational side:

to what extent to the observed galaxies contribute to the build-up of the UV-background?

Status of observations at z>6

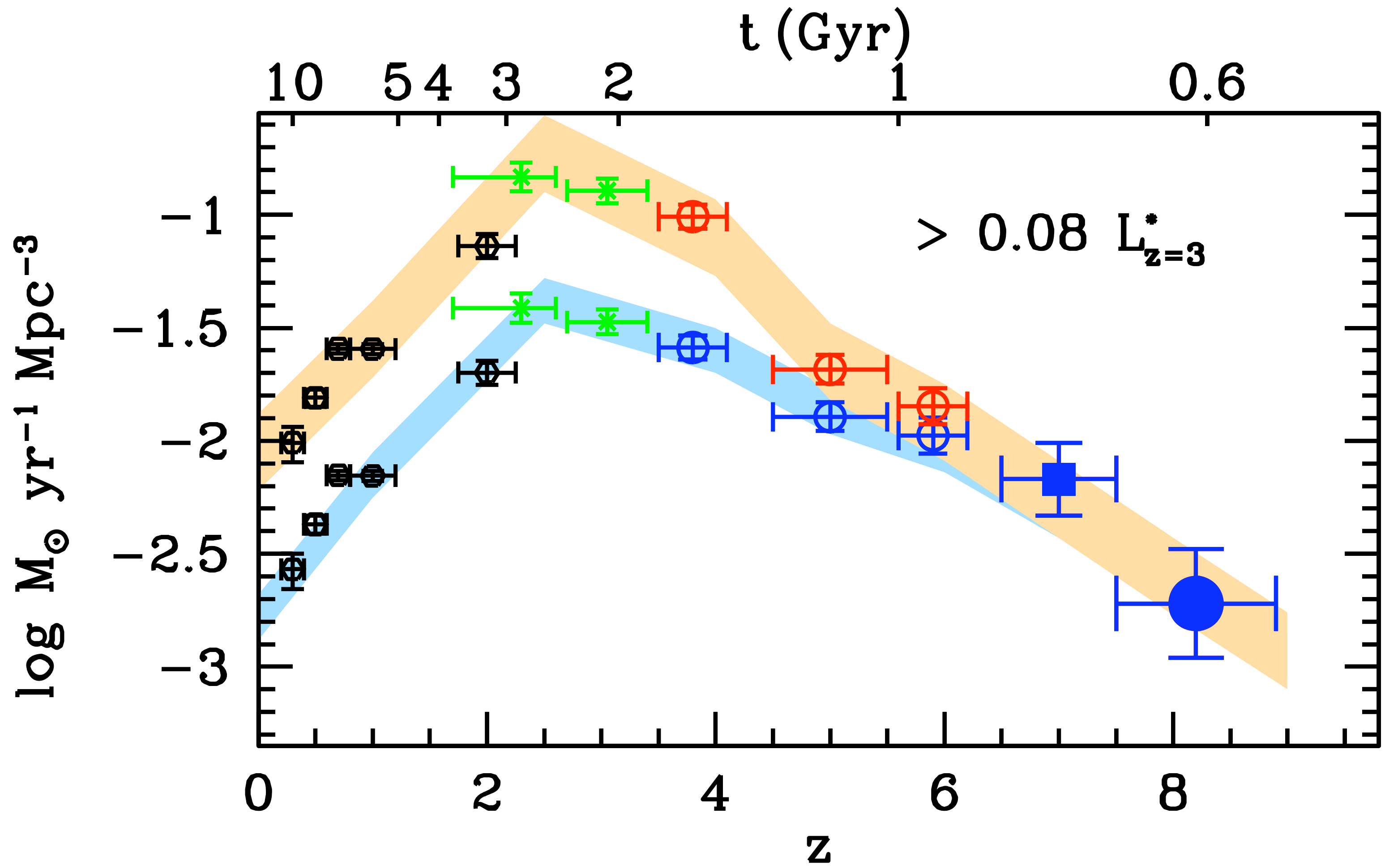
DISCOVERY OF $z \sim 8$ GALAXIES IN THE HUBBLE ULTRA DEEP FIELD FROM ULTRA-DEEP WFC3/IR OBSERVATIONS*

R. J. Bouwens[1,2], G. D. Illingworth[1], P. A. Oesch[3], M. Stiavelli[4], P. van Dokkum[5], M. Trenti[6], D. Magee[1], I. Labbé[7,8], M. Franx[2], C. M. Carollo[3], and V. Gonzalez[1]

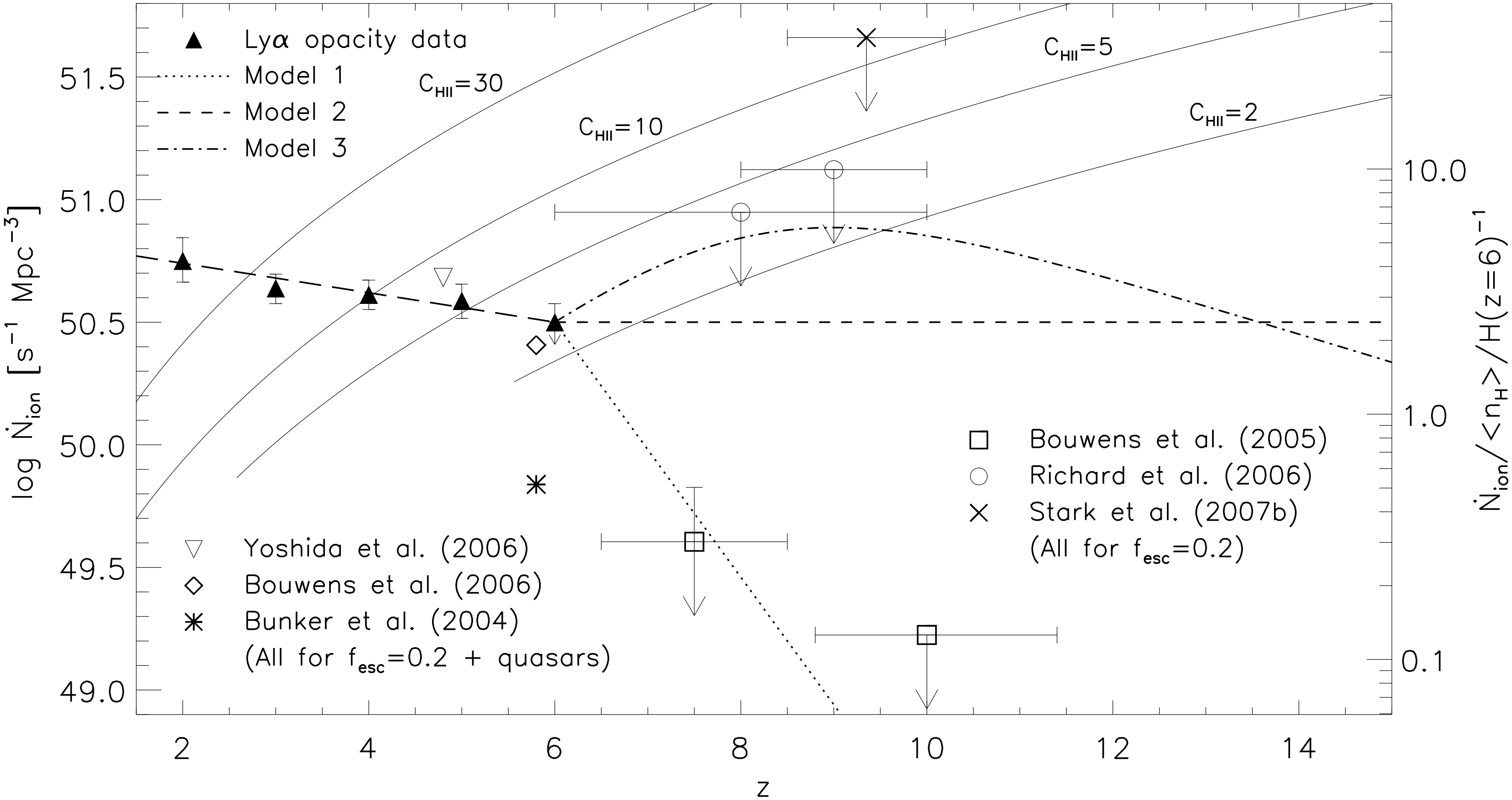
The Contribution of High Redshift Galaxies to Cosmic Reionization: New Results from Deep WFC3 Imaging of the *Hubble* Ultra Deep Field

Andrew J. Bunker[1], Stephen Wilkins[1], Richard S. Ellis[2], Daniel Stark[3], Silvio Lorenzoni[1], Kuenley Chiu[2], Mark Lacy[4]
Matt J. Jarvis[5] & Samantha Hickey[5]

The star formation rate density is a factor of ~10 less than that at z=3-4, and is about half the value at z~6. While based on a single deep field, our results suggest that this star formation rate density would produce insufficient Lyman continuum photons to reionize the Universe unless the escape fraction of these photons is extremely high (f_esc>0.5), and the clumping factor of the Universe is low. Even then, we need to invoke a large contribution from galaxies below our detection limit. The apparent shortfall in ionizing photons might be alleviated if stellar populations at high redshift are low metallicity or have a top-heavy IMF.



Bouwens et al



The observed ionization rate of the intergalactic medium and the ionizing emissivity at $z \geq 5$: Evidence for a photon starved and extended epoch of reionization

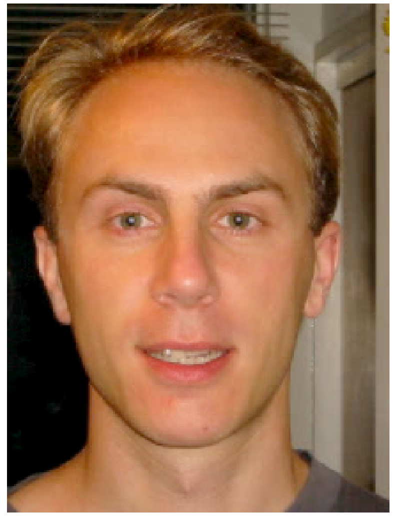
James S. Bolton[1⋆] & Martin G. Haehnelt[2] †

Theoretical expectations:

- From hydro-simulations
- From GalForm

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

Motivation: holistic approach to use simulations to study the formation of galaxies, and their surroundings

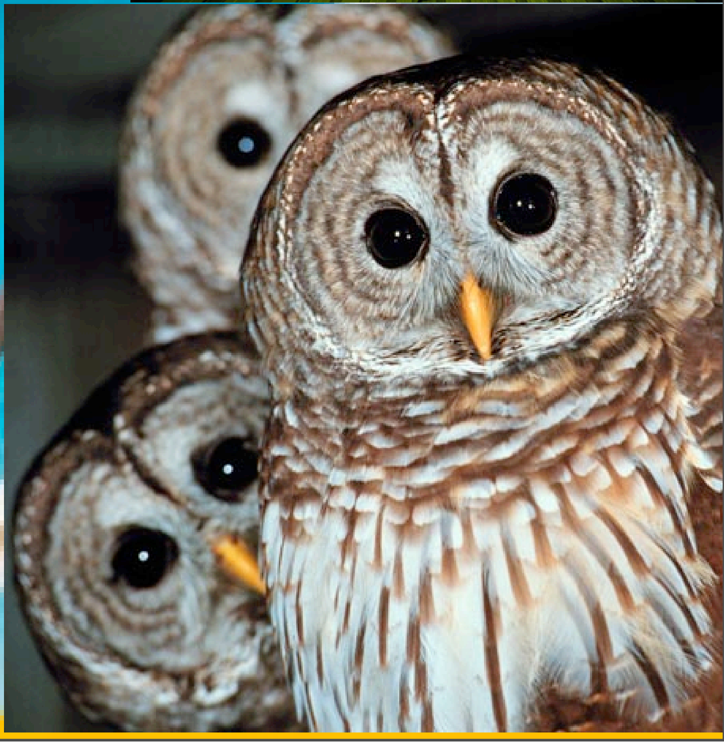
Galaxies-Intergalactic Medium Interaction Calculation –I. Galaxy formation as a function of large-scale environment

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

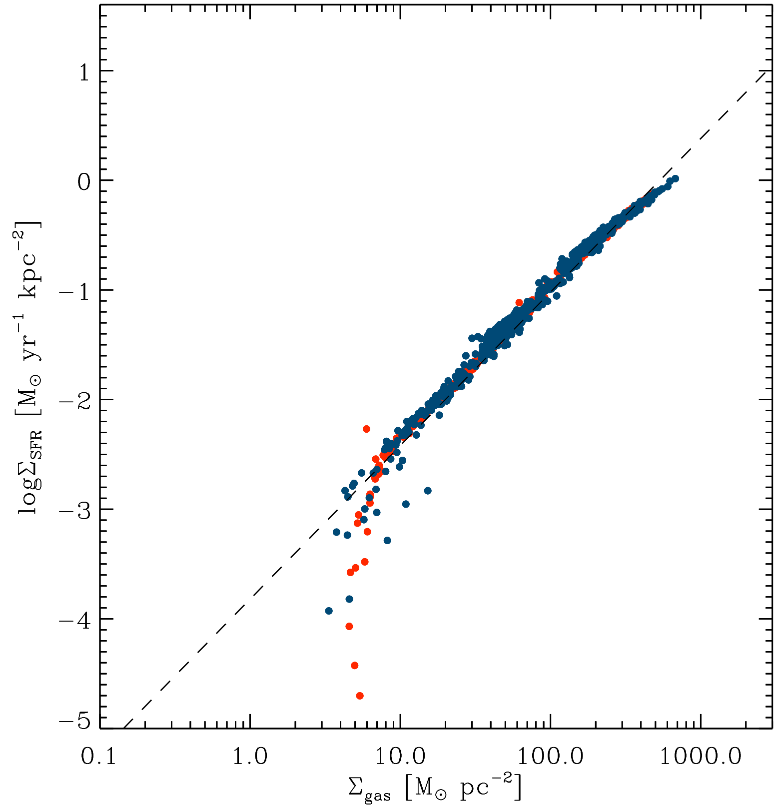
The physics driving the cosmic star formation history

Joop Schaye,[1⋆] Claudio Dalla Vecchia,[1] C. M. Booth,[1] Robert P. C. Wiersma,[1] Tom Theuns,[2,3] Marcel R. Haas,[1] Serena Bertone,[4] Alan R. Duffy,[1,5] I. G. McCarthy,[6] and Freeke van de Voort[1]

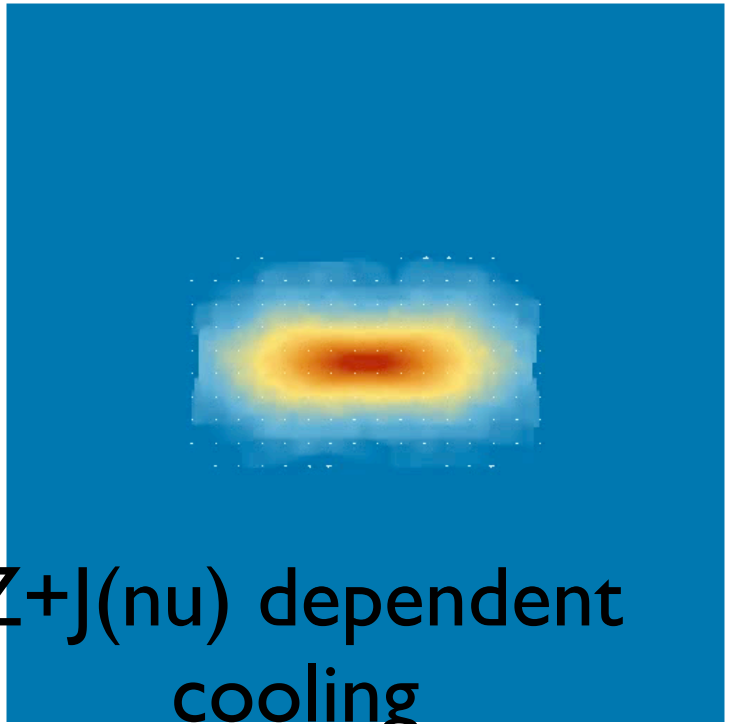


Code in brief

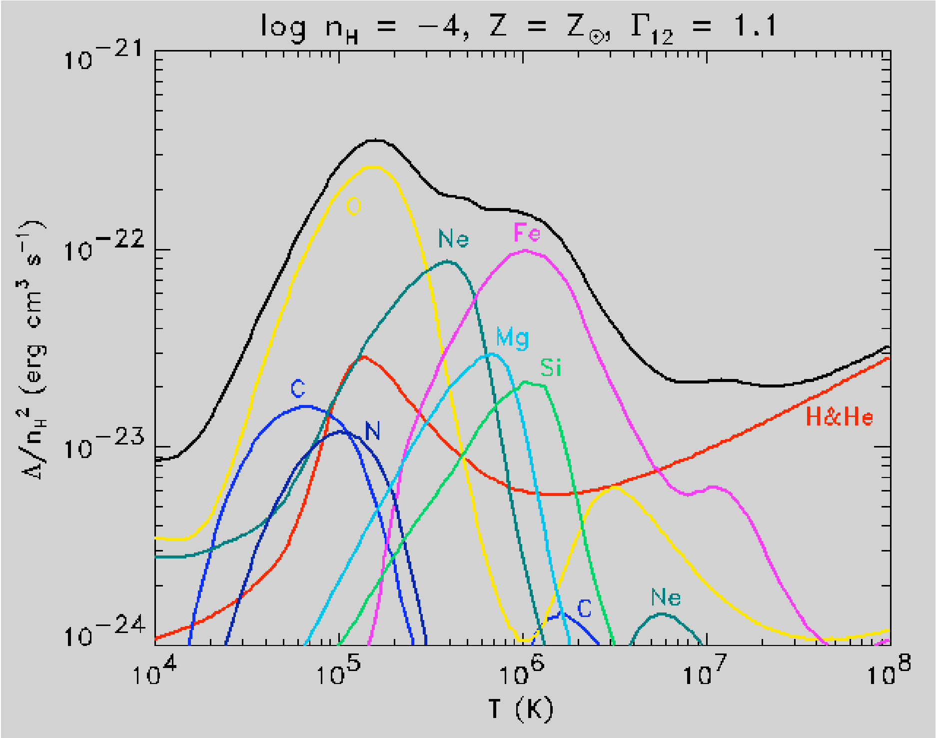
SFR follow Schmidt-law



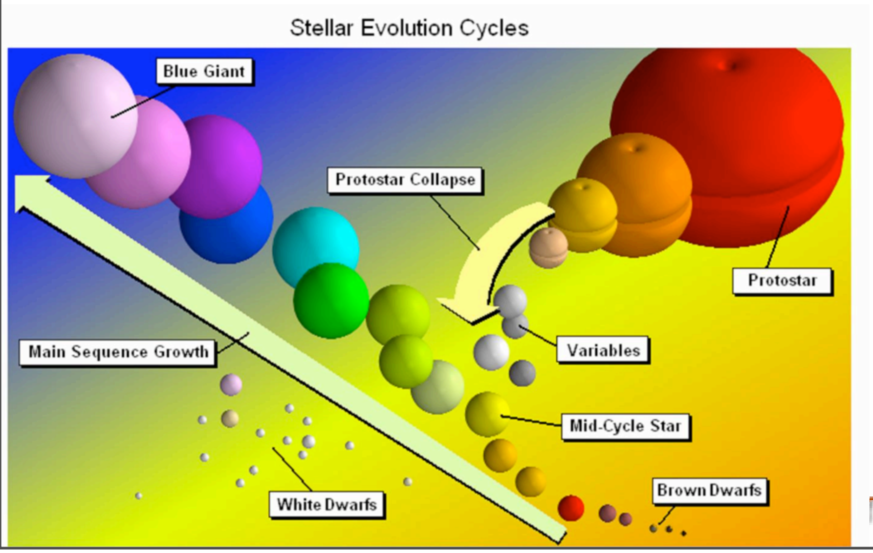
Galactic winds



Z+J(nu) dependent cooling



Stellar evolution



mology 9

What about metal mixing?

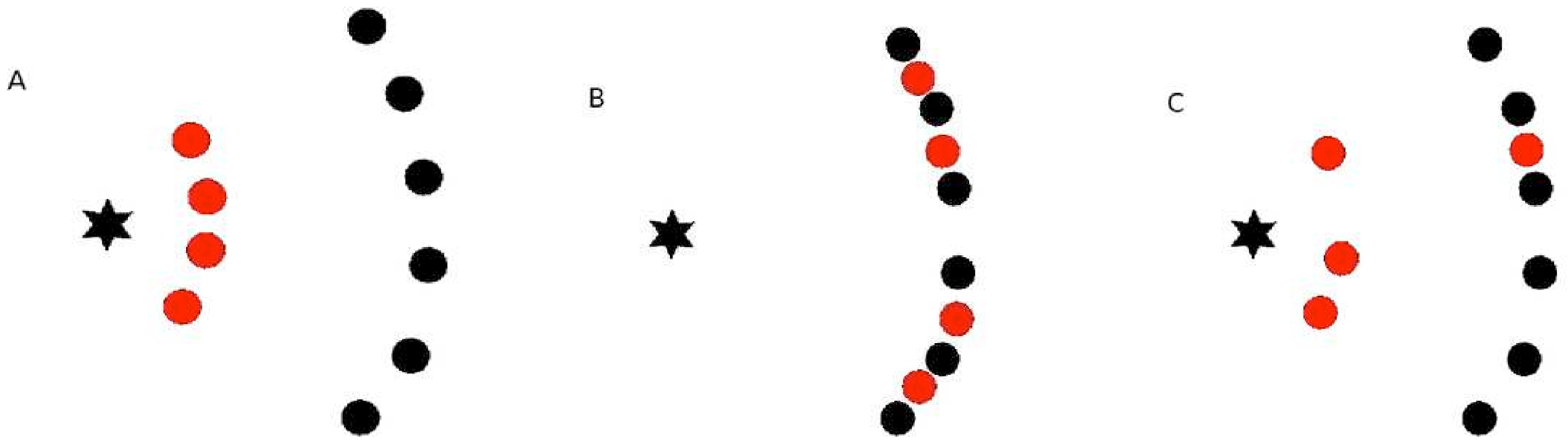
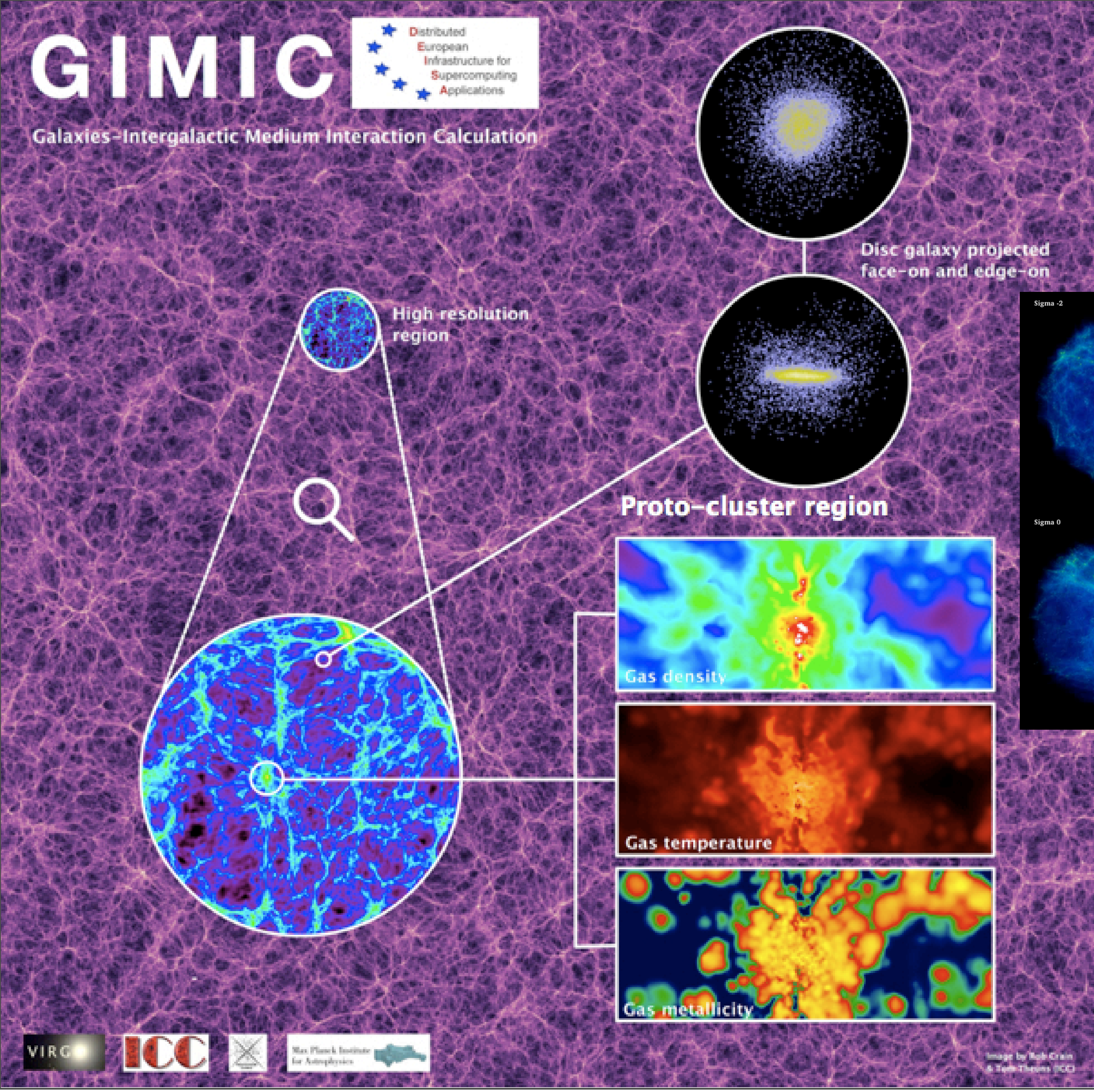
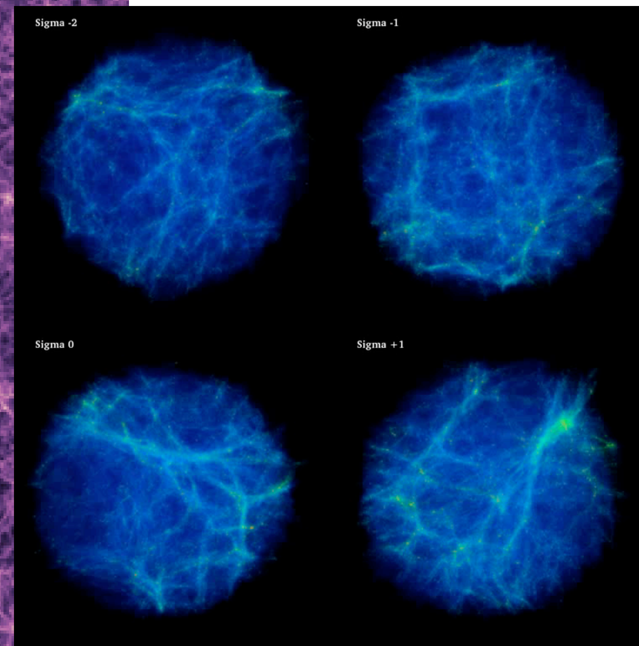


Figure 10. The enrichment sampling problem. *A*: A star particle enriches its neighbouring gas particles (red). *B*: The energy released by massive stars within the star particle drives its neighbours away. Because metals are stuck to particle the local metallicity in the shell fluctuates. *C*: Using kinetic feedback the problem is worse because only a small fraction of the neighbours are kicked.

Chemical enrichment in cosmological, smoothed particle hydrodynamics simulations

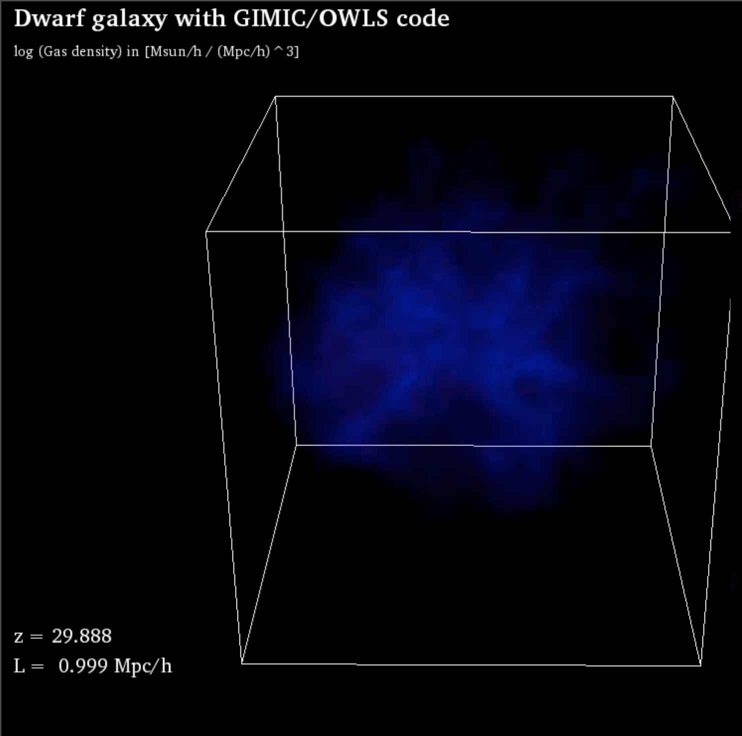
Robert P. C. Wiersma,[1⋆] Joop Schaye,[1] Tom Theuns,[2,3] Claudio Dalla Vecchia,[1] and Luca Tornatore[4,5]

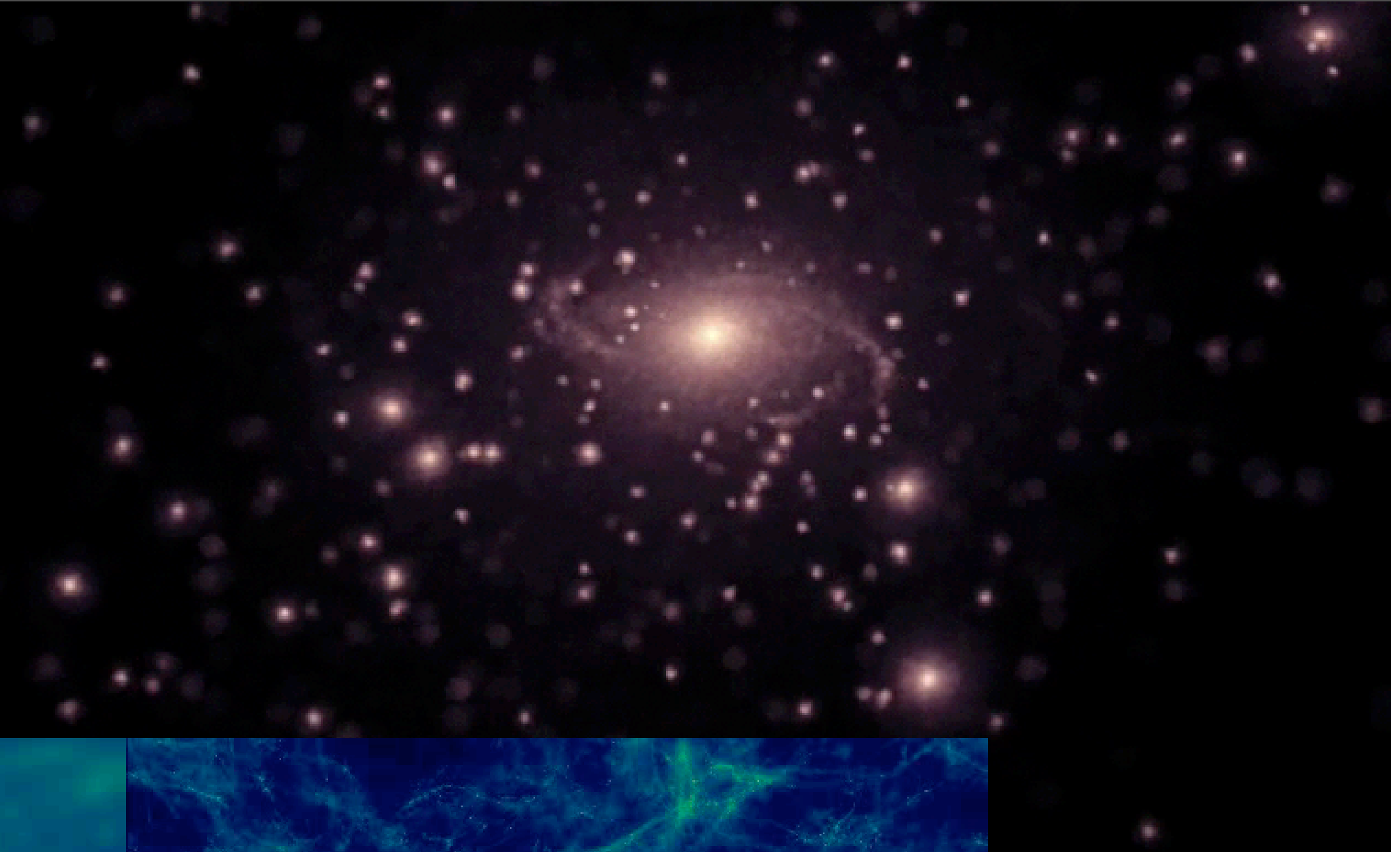

GIMIC
Distributed
European
Infrastructure for
Supercomputing
Applications
Galaxies-Intergalactic Medium Interaction Calculation
Disc galaxy projected
face-on and edge-on
High resolution
region
Proto-cluster region
Gas density
Gas temperature
Gas metallicity
VIRGO
ICC
Max Planck Institute
for Astrophysics

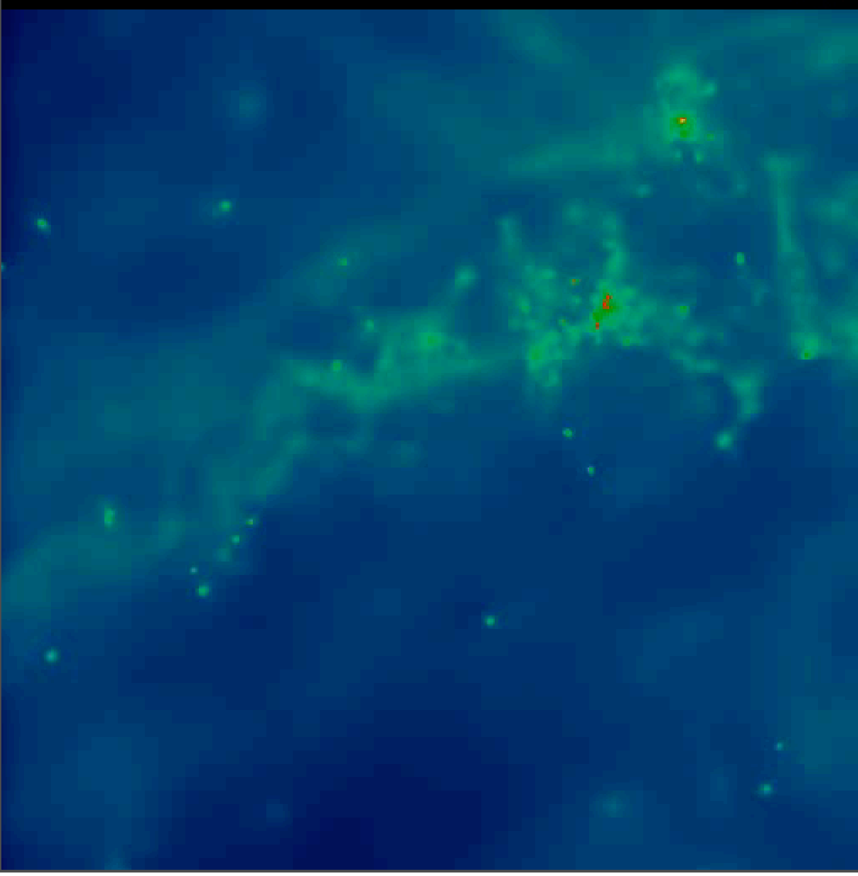

Sigma -2
Sigma -1
Sigma 0
Sigma +1

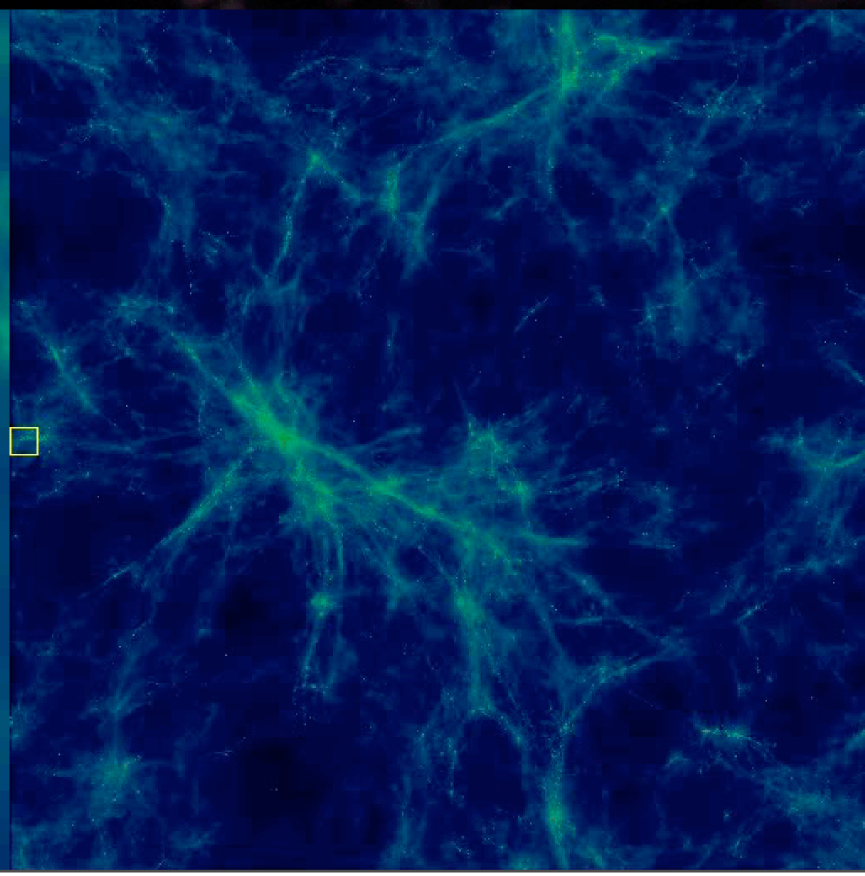
Some of the Physics/Numerics variations in OWLS

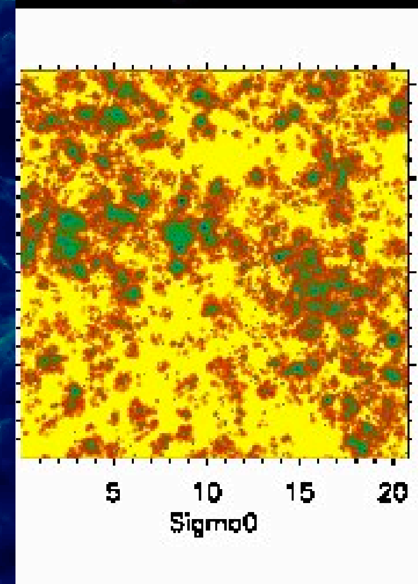
Simulation	L025	L100	Section	Description
AGN	√	√	4.10	Includes AGN
DBLIMFCONTSFV1618	√	√	4.7.2	Top-heavy IMF at high pressure, cont. SF law, extra SN energy in wind velocity
DBLIMFV1618	√	√	4.7.2	Top-heavy IMF at high pressure, extra SN energy in wind velocity
DBLIMFCONTSFML14	√	√	4.7.2	Top-heavy IMF at high pressure, cont. SF law, extra SN energy in mass loading
DBLIMFML14	√	√	4.7.2	Top-heavy IMF at high pressure, extra SN energy in mass loading
EOS1p0	√	√	4.4	Slope of the effective EOS changed to $\gamma_{\rm eff} = 1$
EOS1p67	√	-	4.4	Slope of the effective EOS changed to $\gamma_{\rm eff} = 5/3$
IMFSALP	√	√	4.7.1	Salpeter (1955) IMF
IMFSALPML1	√	-	4.7.1	Salpeter (1955) IMF; wind mass loading $\eta = 2/1.65$
MILL	√	√	4.1	Millennium simulation cosmology, $\eta = 4$ (twice the SN energy of *REF*)
NOAGB_NOSNIa	-	√	4.6	No mass loss from AGB stars and SNIa
NOHeHEAT	√	-	4.3	No extra heat input around helium reionization
NOREION	√	-	4.3	No hydrogen reionization
NOSN	√	√	4.8	No SN energy feedback from SNe
NOSN_NOZCOOL	√	√	4.2	No SN energy feedback from SNe and cooling assumes primordial abundances
NOZCOOL	√	√	4.2	Cooling assumes primordial abundances
REF	√	√	3	Reference model
REIONZ06	√	-	4.3	Hydrogen reionization occurs at $z = 6$
REIONZ12	√	-	4.3	Hydrogen reionization occurs at $z = 12$
SFAMPLx3	√	-	4.5.2	Normalization of Kennicutt-Schmidt SF law increased by a factor of 3
SFAMPLx6	√	-	4.5.2	Normalization of Kennicutt-Schmidt SF law increased by a factor of 6
SFSLOPE1p75	√	-	4.5.2	Slope of Kennicutt-Schmidt SF law increased to 1.75
SFTHRESZ	√	-	4.5.1	Critical density for onset of SF is a function of metallicity (Eq. 4)
SNIaGAUSS	-	√	4.6	Gaussian SNIa delay function
WDENS	√	√	4.8.1	Wind mass loading and velocity depend on gas density (SN energy as *REF*)
WHYDRODEC	√	-	4.8.2	Wind particles are temporarily hydrodynamically decoupled
WML1V848	√	√	4.8.1	Wind mass loading $\eta = 1$, velocity $v_{\rm w} = 848\,{\rm km/s}$ (SN energy as *REF*)
WML4	√	√	4.8	Wind mass loading $\eta = 4$ (twice the SN energy of *REF*)
WML4V424	√	-	4.8.1	Wind mass loading $\eta = 4$; wind velocity $v_{\rm w} = 424\,{\rm km/s}$ (SN energy as *REF*)
WML8V300	√	-	4.8.1	Wind mass loading $\eta = 8$; wind velocity $v_{\rm w} = 300\,{\rm km/s}$ (SN energy as *REF*)
WPOT	√	√	4.9	Wind mass loading and vel. vary with grav. potential ("Momentum-driven")
WPOTNOKICK	√	√	4.9	Same as *WPOT* except that no extra velocity kick is given to winds
WTHERMAL	√	-	4.8.3	SN energy injected thermally
WVCIRC	√	√	4.9	Wind mass loading and vel. vary with halo circ. vel. ("Momentum-driven")


Dwarf galaxy with GIMIC/OWLS code
log (Gas density) in [Msun/h / (Mpc/h) ^3]
z = 29.888
L = 0.999 Mpc/h

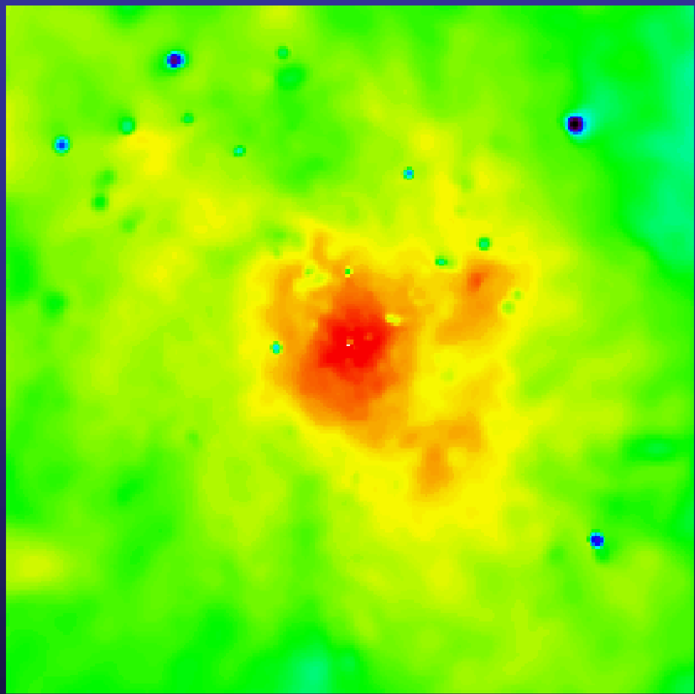






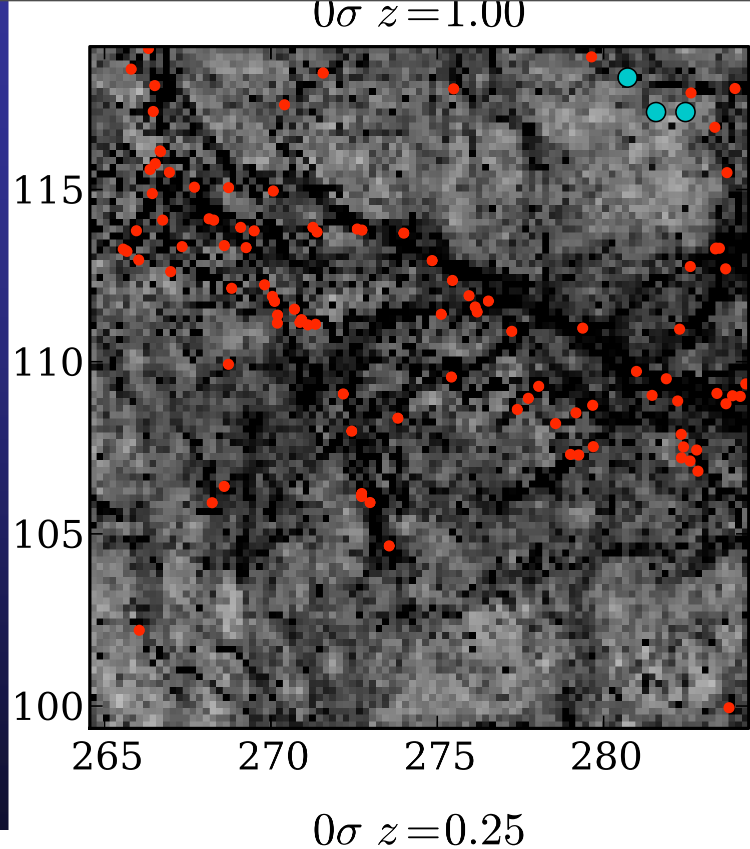

5
10
15
20
Sigma0

Tom Theuns

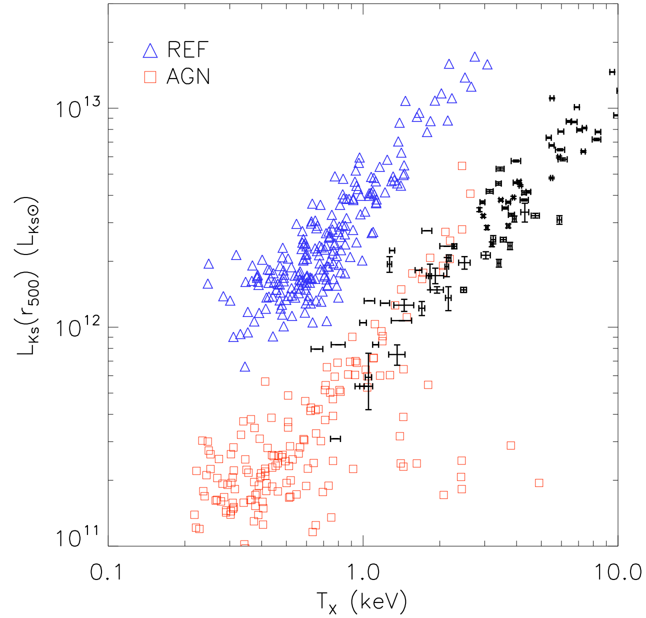


X-ray spectroscopic-like temperature map
[0.5-7.0 keV band]

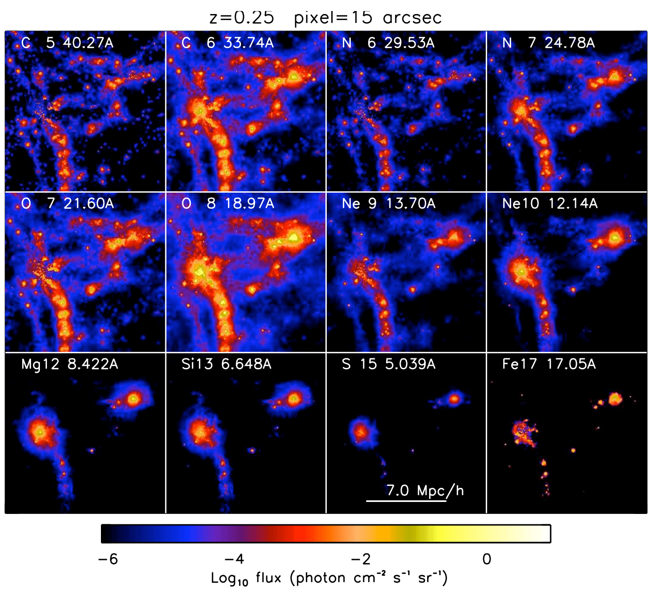
X-rays in MW-like haloes, Crain,+10



Galaxy-Lya absorber pairs: Crighton+,10

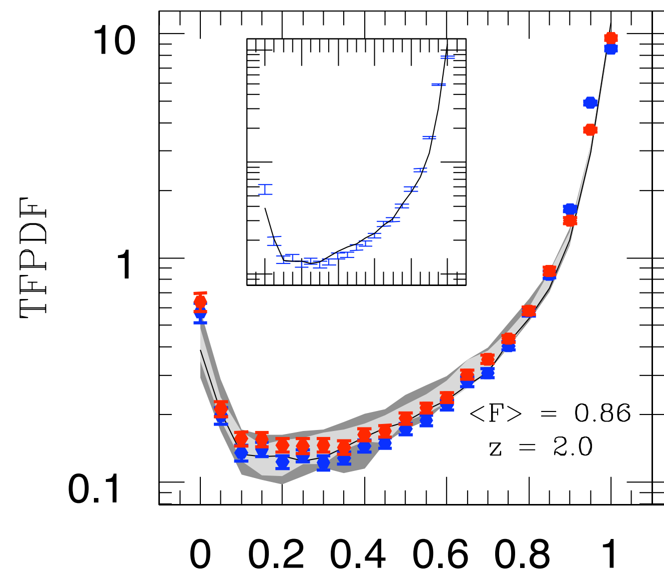


Evidence for AGN in groups, McCarthy+, 10



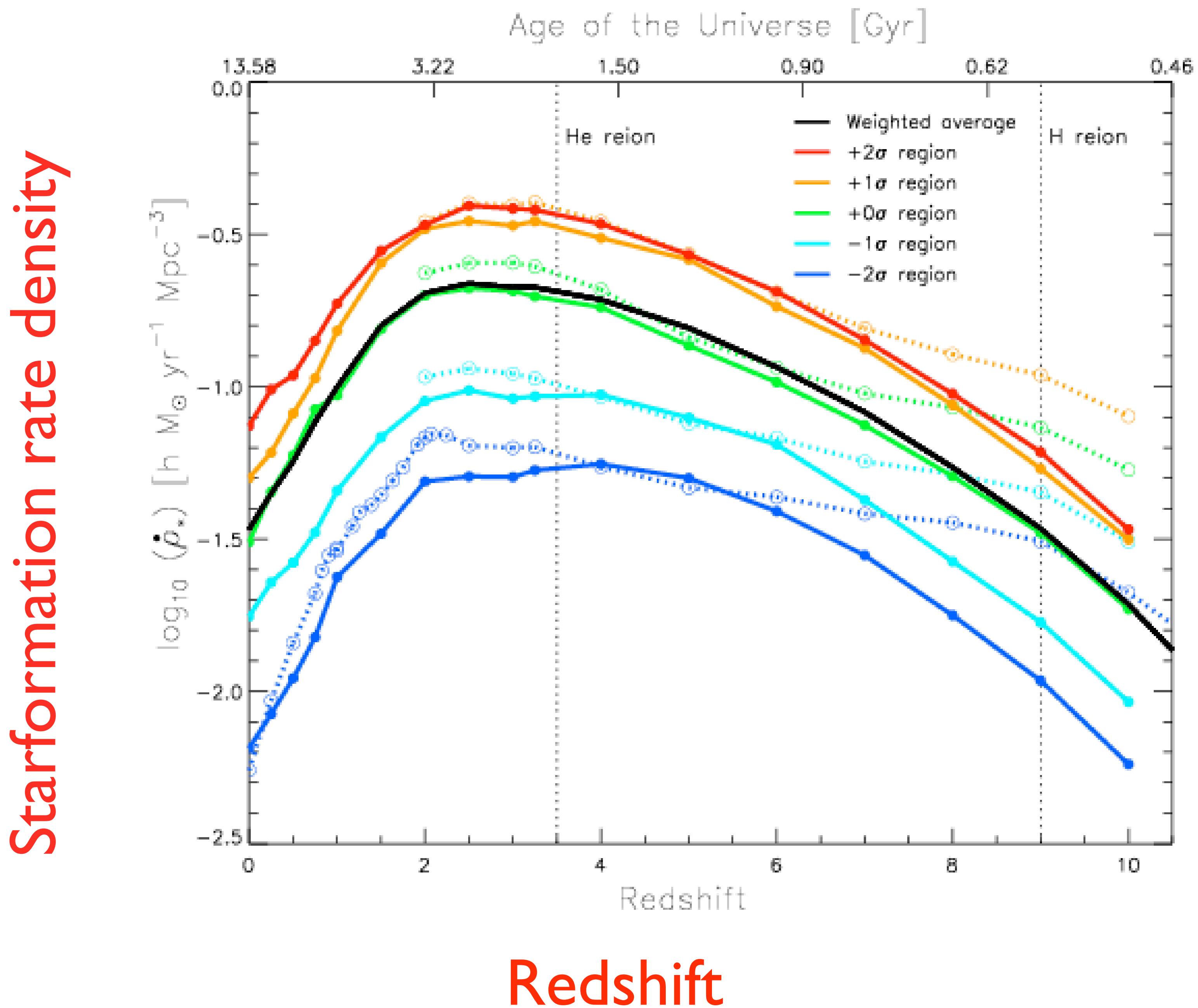
Transmission statistics of Lya forest, Theuns+, 10

X-ray/UV-emission of the WHIM, Bertone+, 10

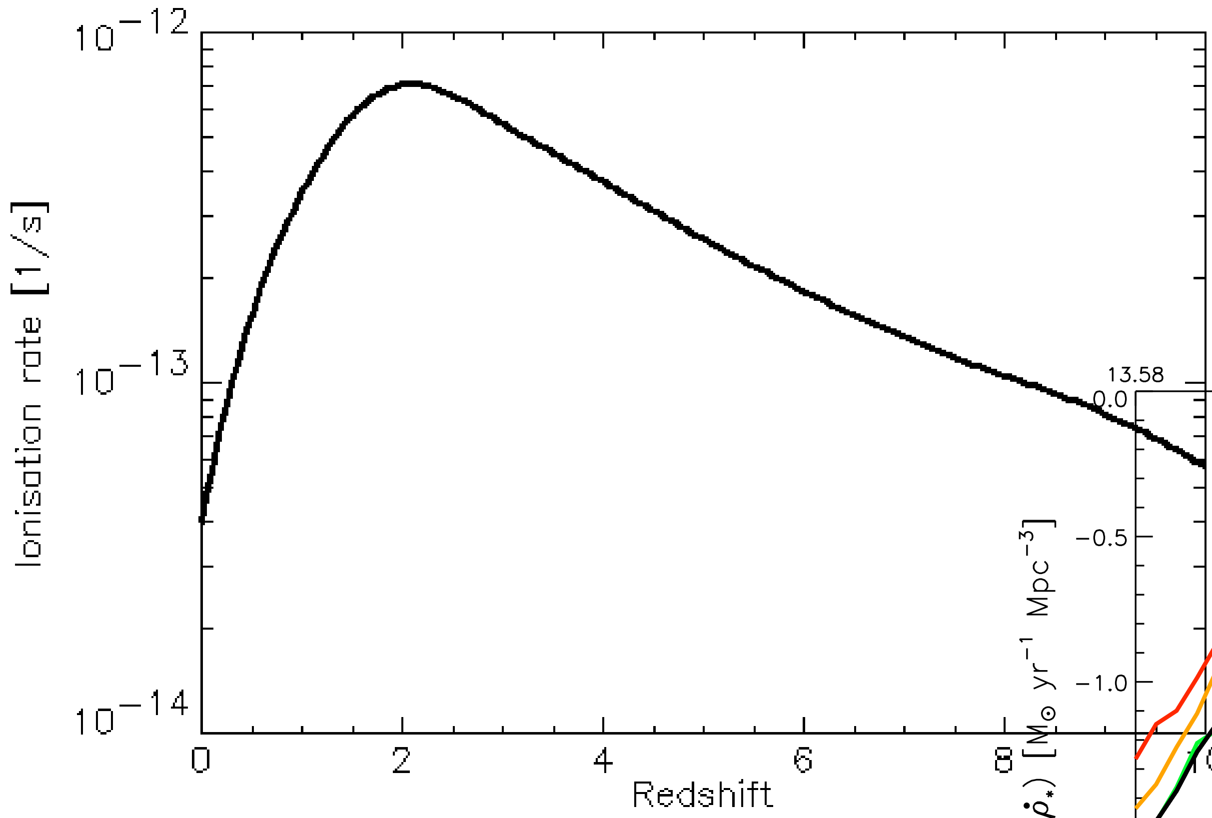


Tom Theuns

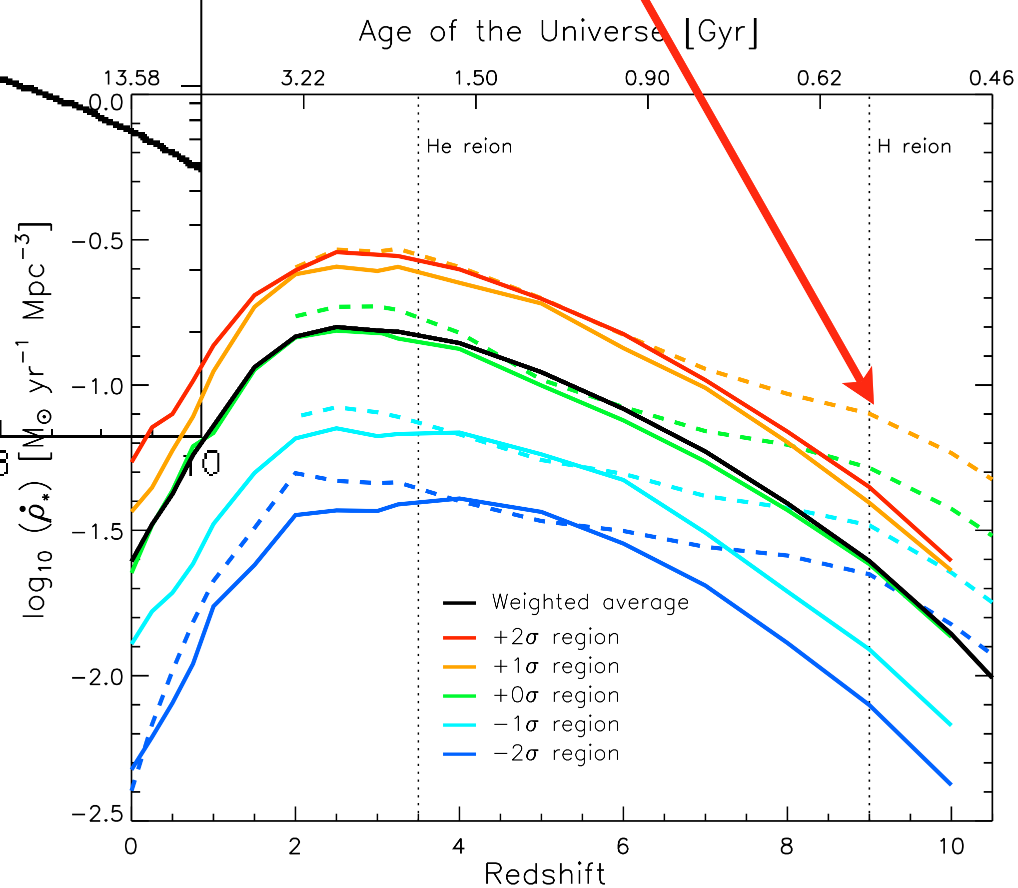
Star formation rate density (Madau/Lilly)



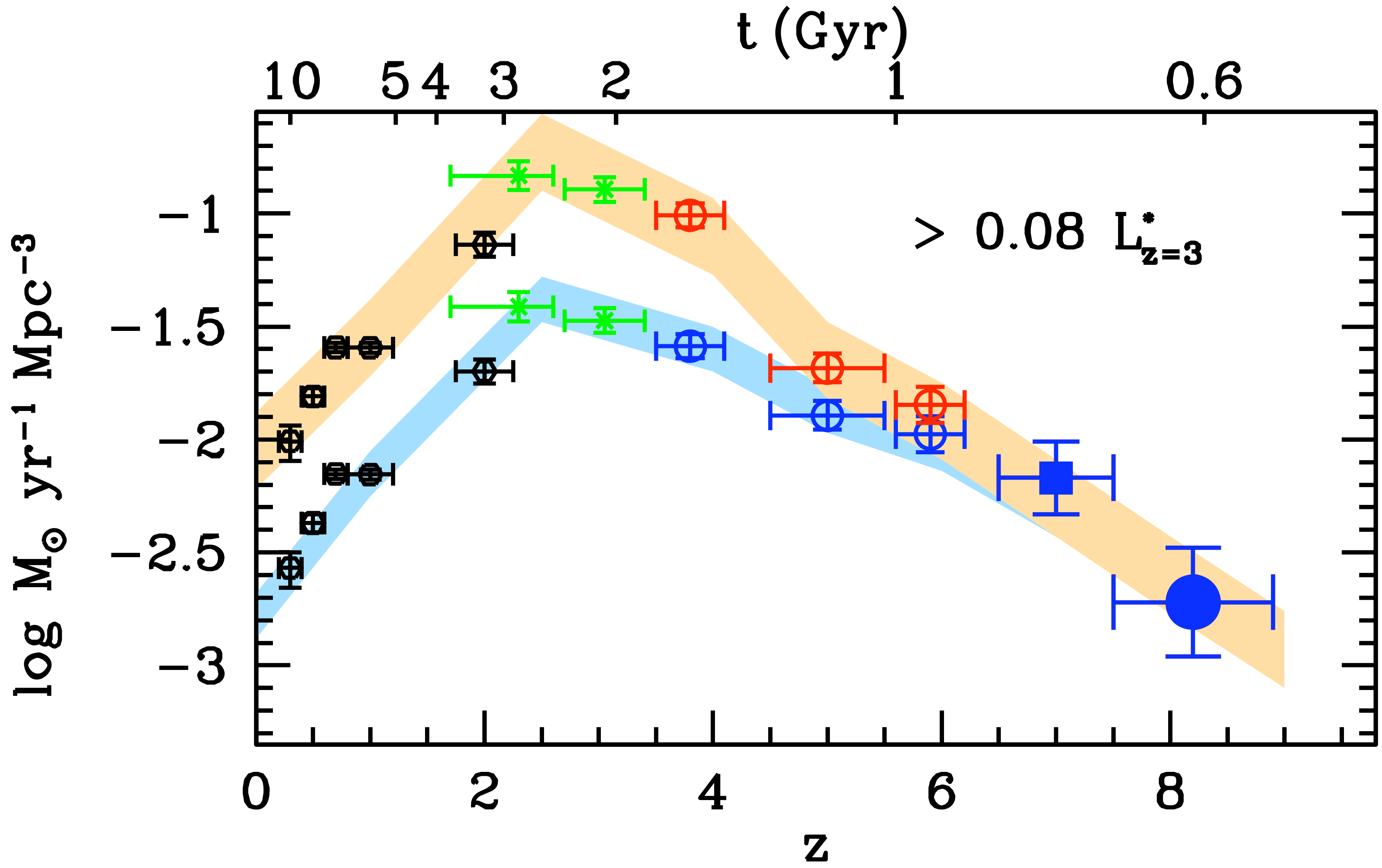
Ionization rate from gals & QSOs as computed by Haardt & Madau



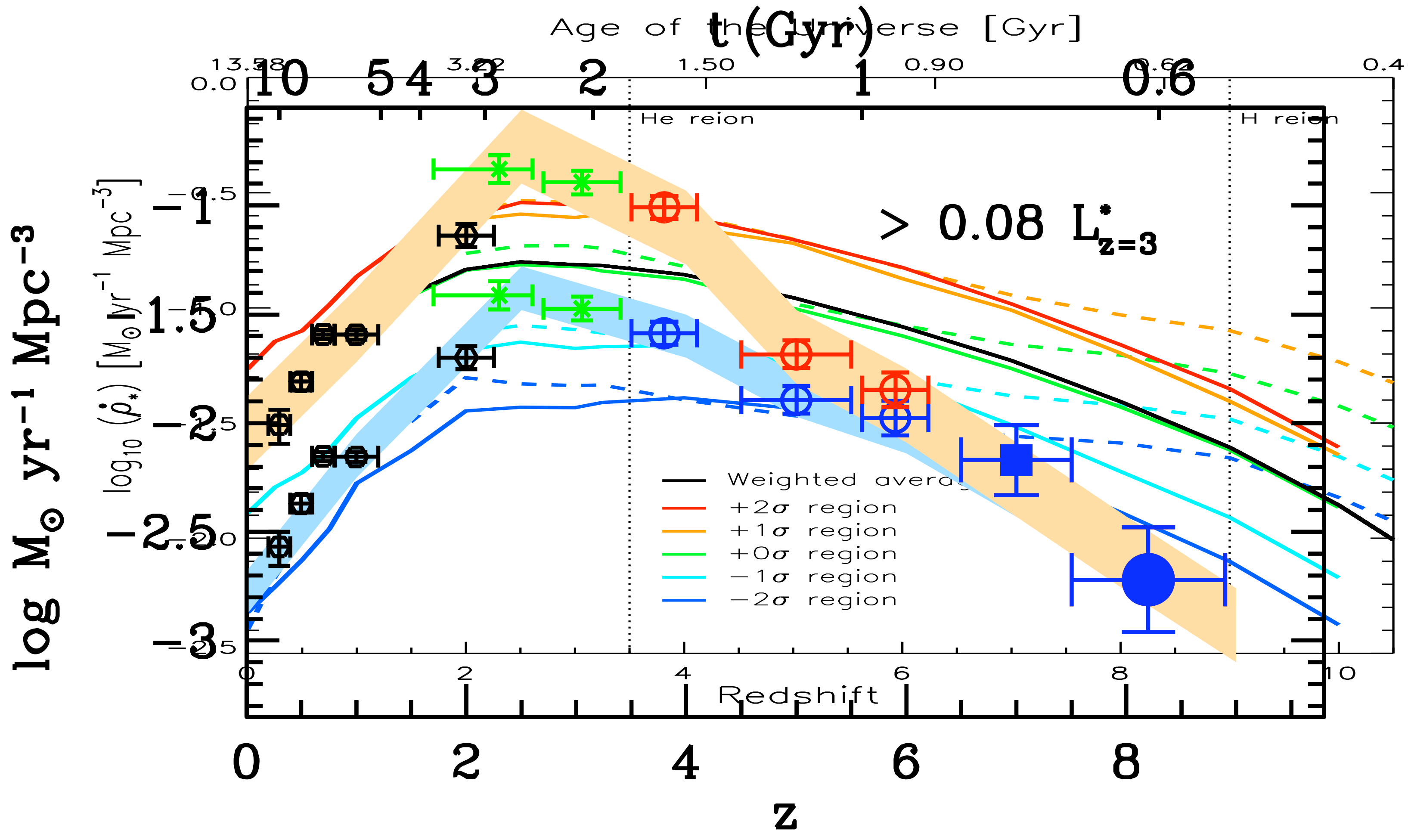
Suppression of star formation during reionisation



Crain, TT, +, 2009

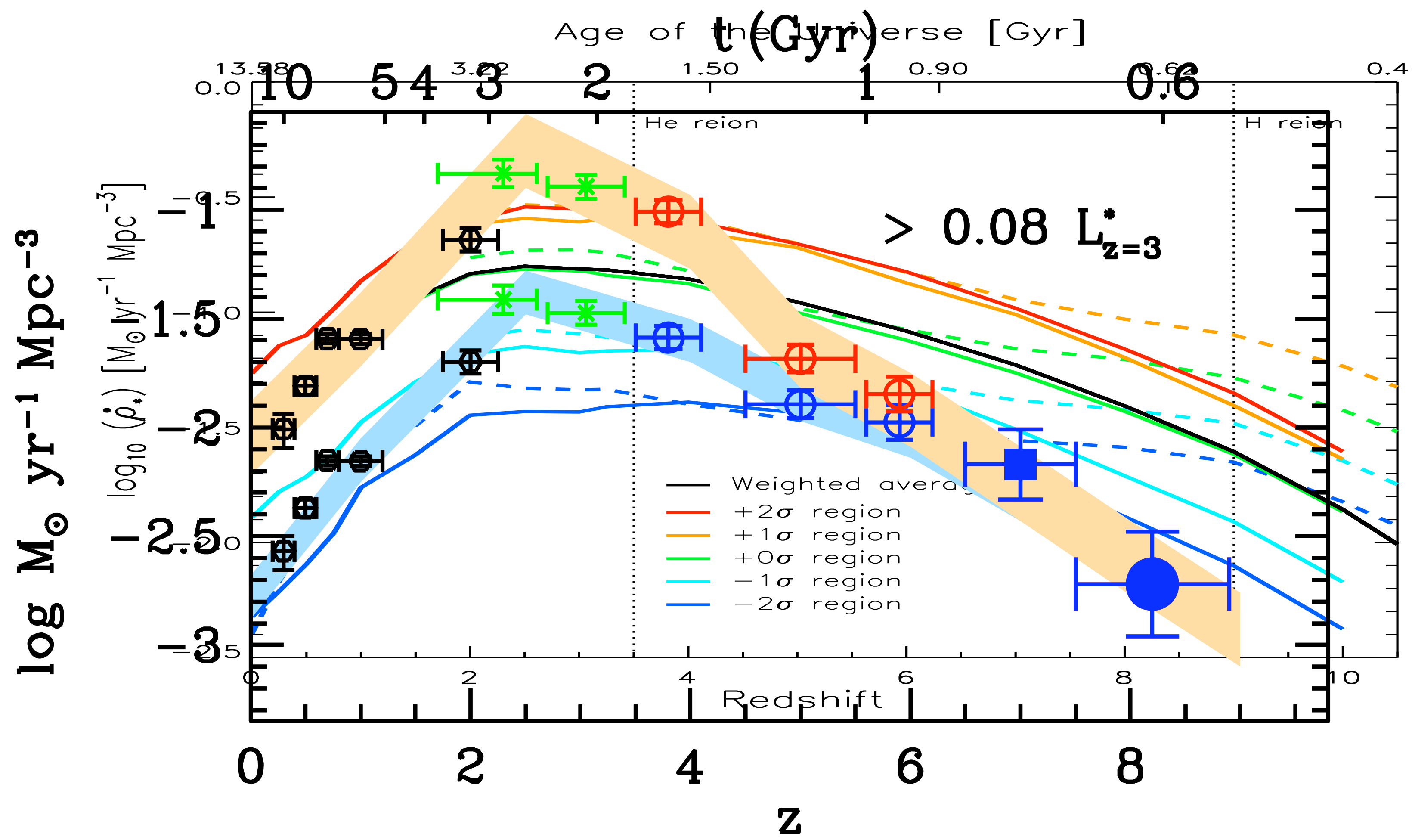


Bouwens et al

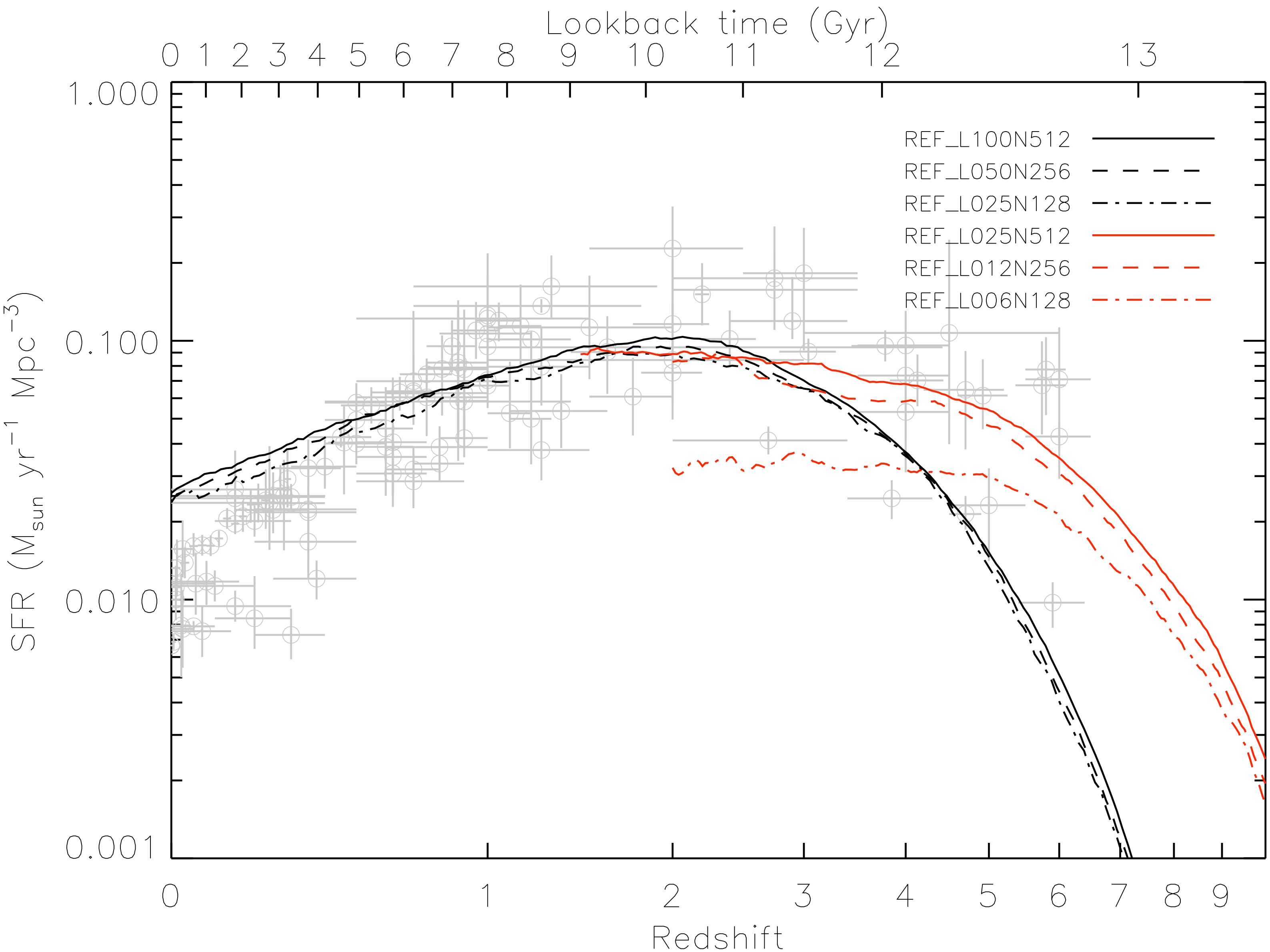


Bouwens et al

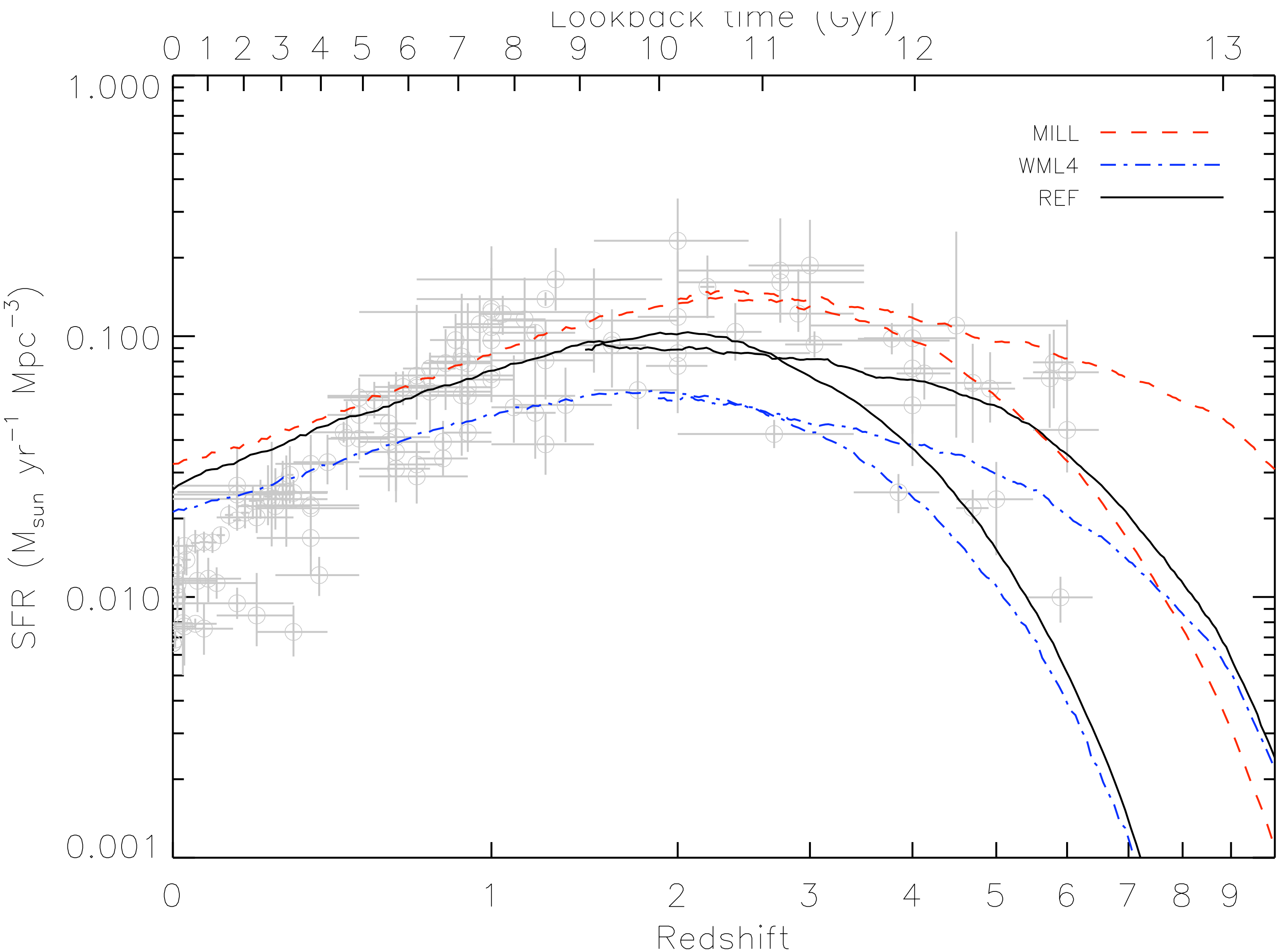
Crain et al



Bouwens et al

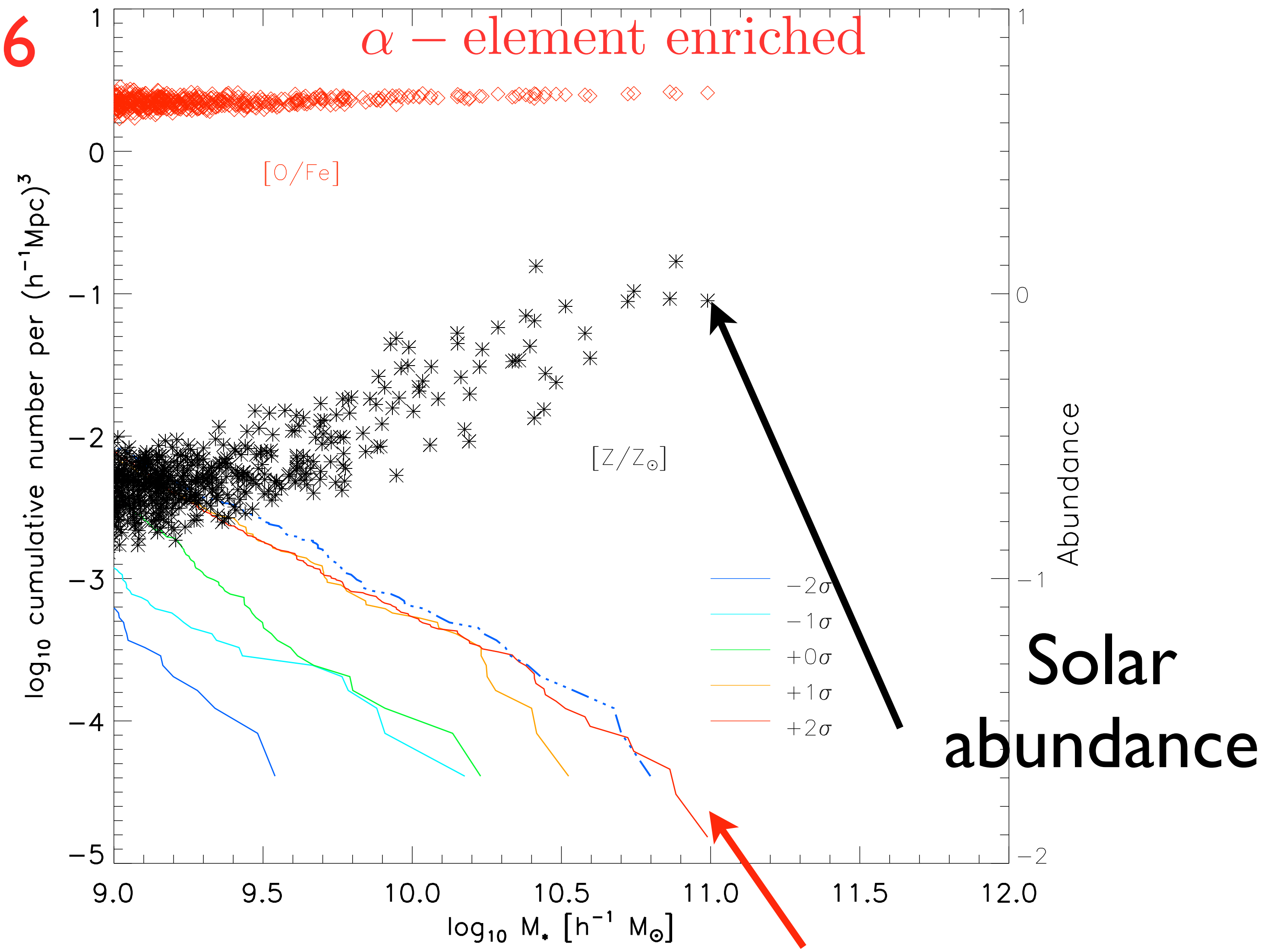


Reference model at different resolutions, (low versus high), compared to Hopkins+ data


Lookback time (Gyr)
0 1 2 3 4 5 6 7 8 9 10 11 12 13
1.000
0.100
0.010
0.001
SFR (M_{sun} yr^{-1} Mpc^{-3})
MILL
WML4
REF
0 1 2 3 4 5 6 7 8 9
Redshift

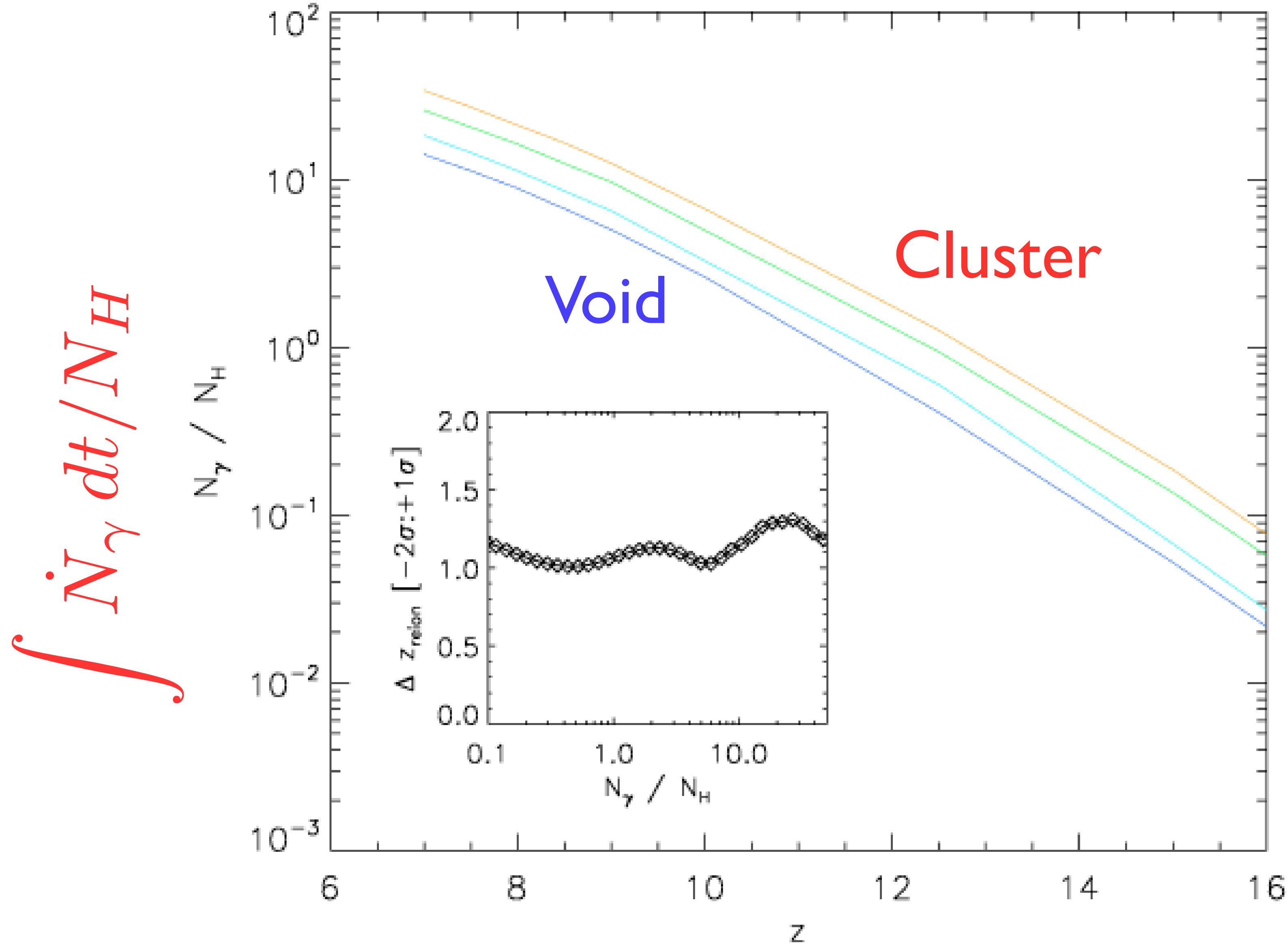
Reionization as function of environment

Stellar mass function z=6



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

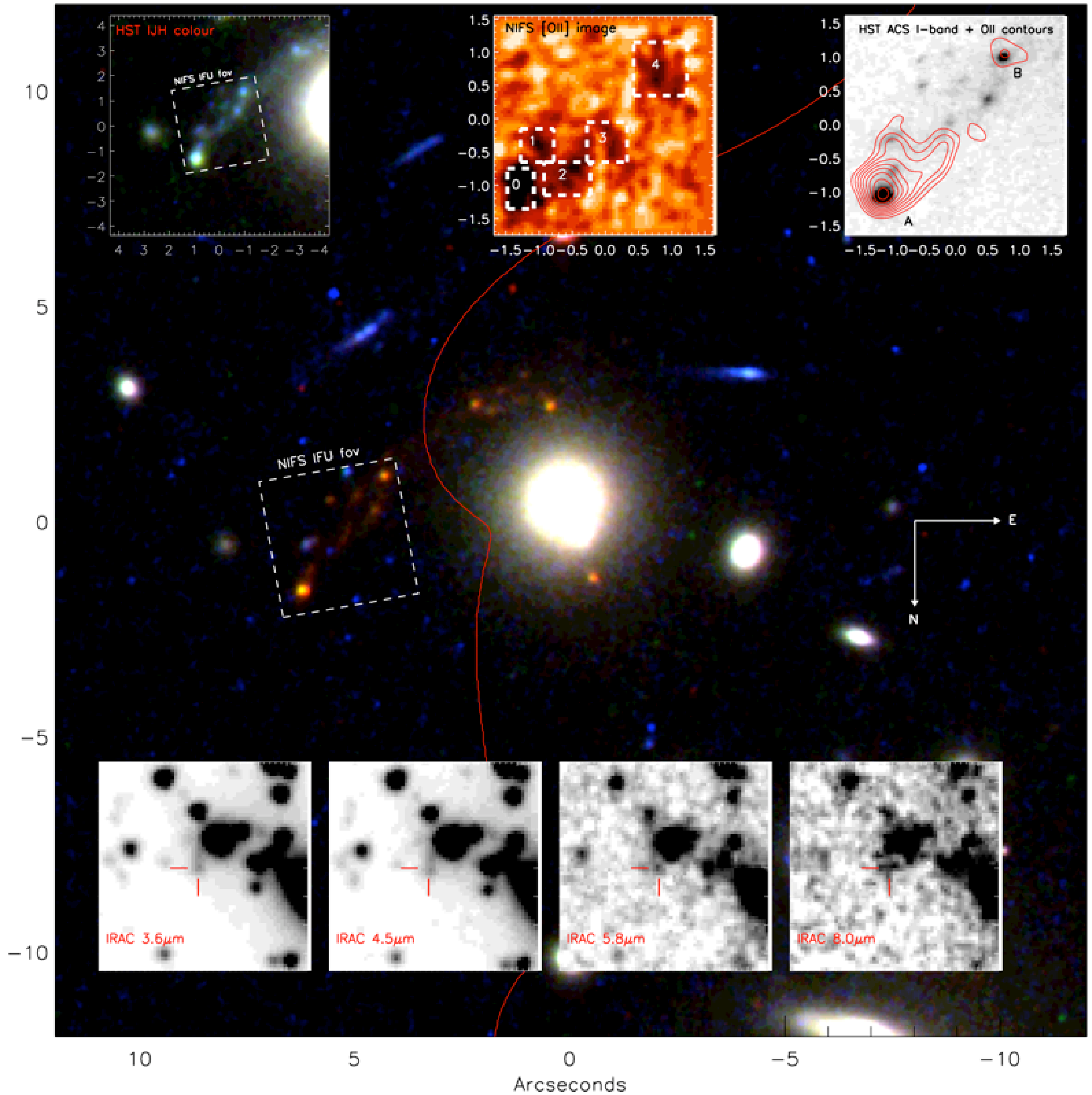
Reionization as function of environment

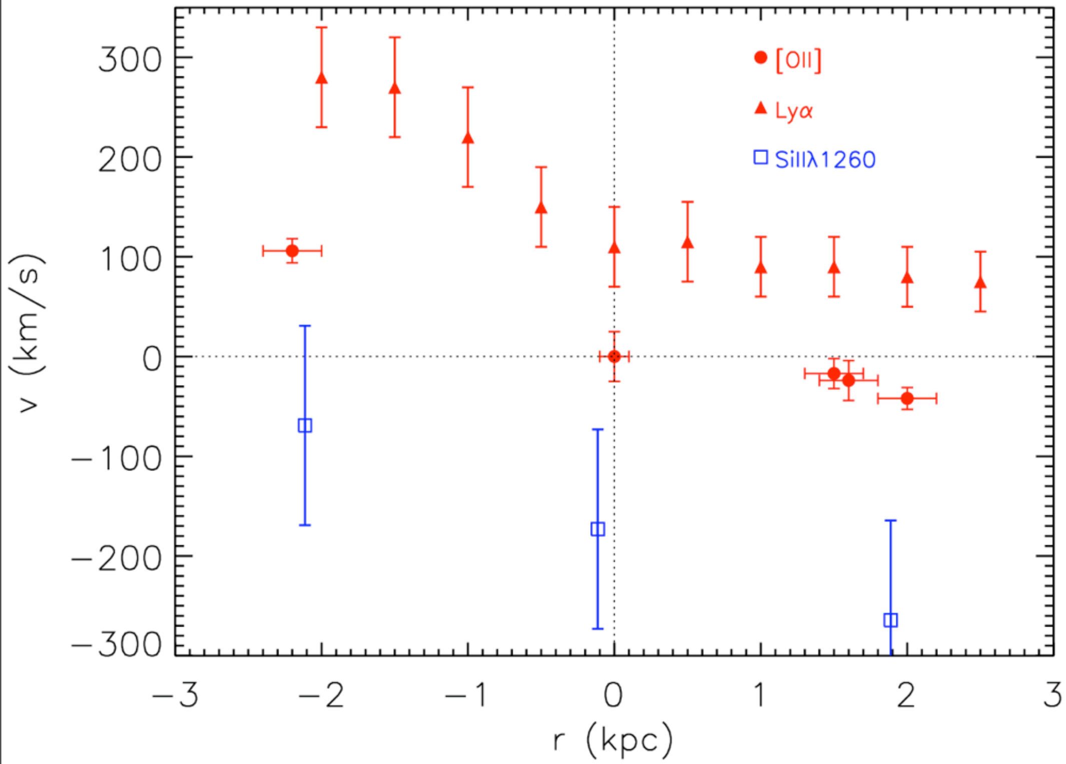


Redshift

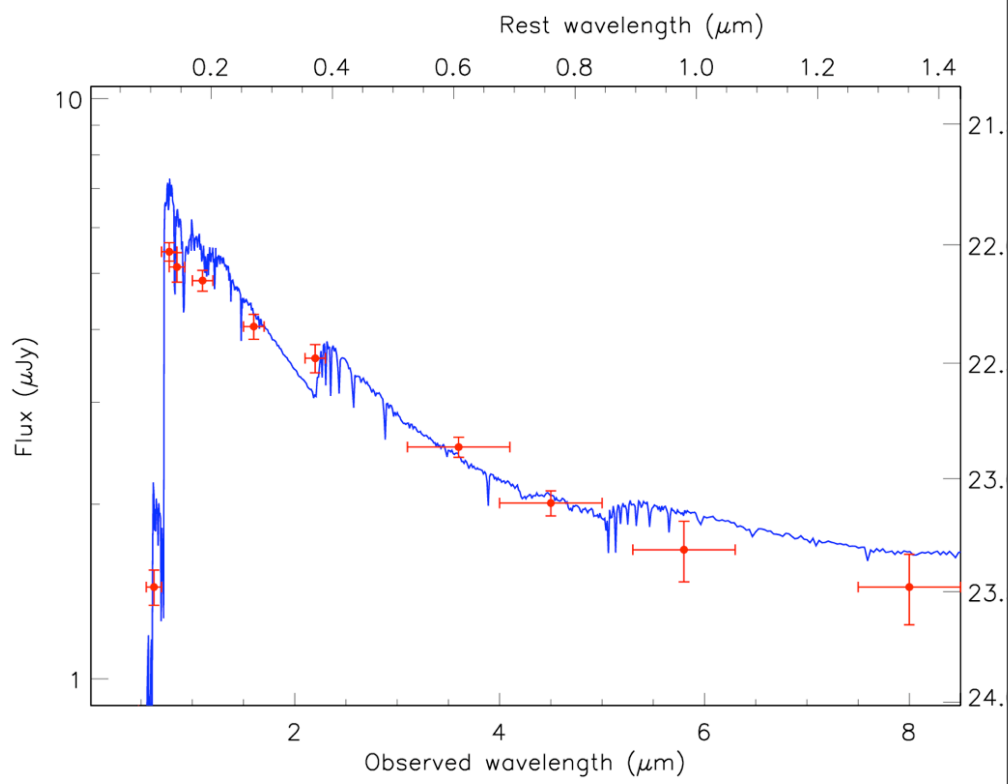
A spatially resolved map of the kinematics, star formation and stellar mass assembly in a star-forming galaxy at $z = 4.9$

A. M. Swinbank,[1★] T. M. Webb,[2] J. Richard,[1] R. G. Bower,[1] R. S. Ellis,[3] G. Illingworth,[4] T. Jones,[3] M. Kriek,[5] I. Smail,[1] D. P. Stark[6] and P. van Dokkum[7]

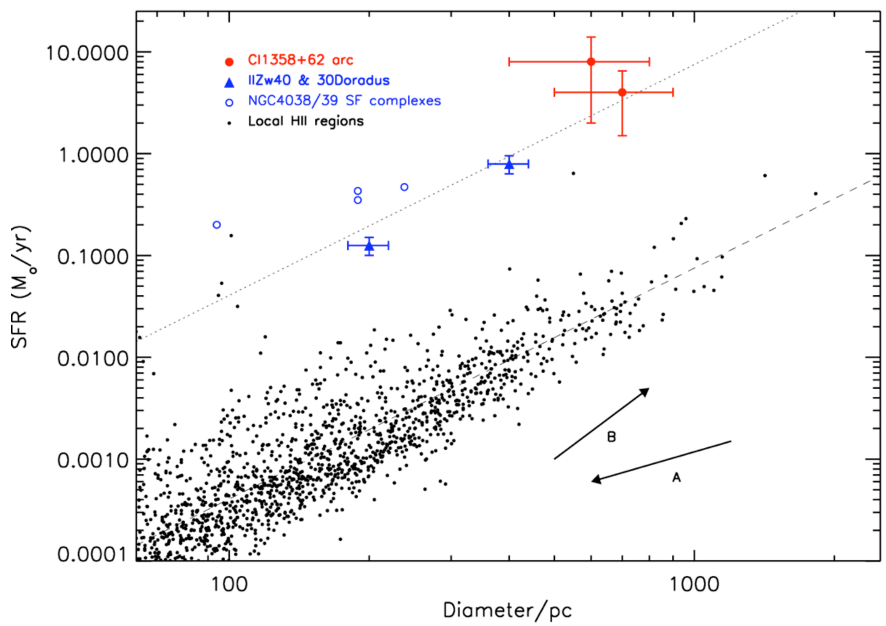




[OII]
Lyα
SiIIλ1260
v (km/s)
r (kpc)
300
200
100
0
−100
−200
−300
−3
−2
−1
0
1
2
3



Rest wavelength (μm)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Flux (μJy)
10
1
21.
22.
22.
23.
23.
24.
2
4
6
8
Observed wavelength (μm)



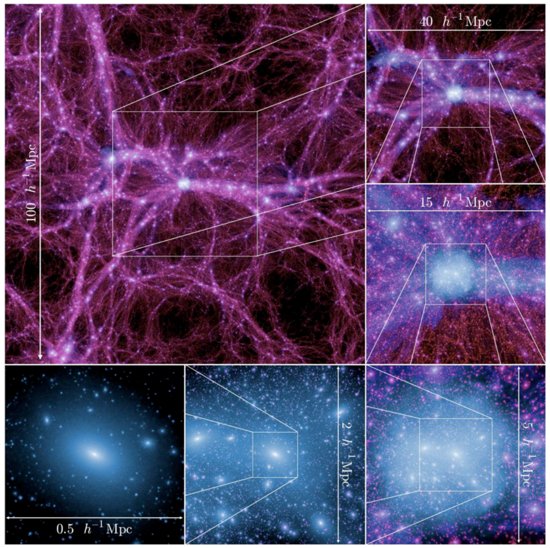
Cl1358+62 arc
IIZw40 & 30Doradus
NGC4038/39 SF complexes
Local HII regions
SFR (M_o/yr)
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
100
1000
Diameter/pc
B
A

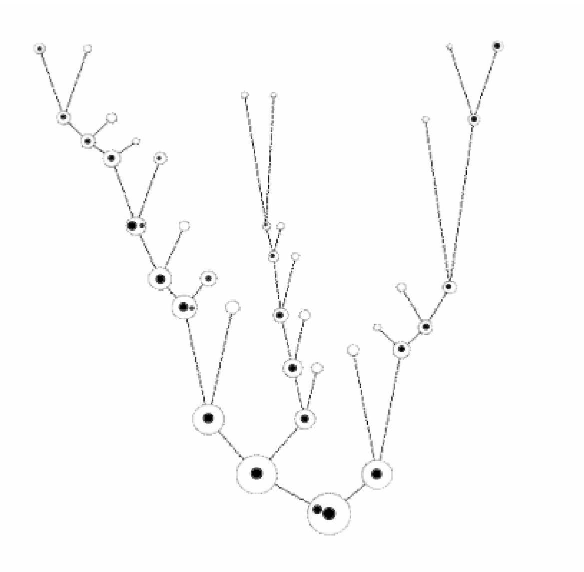
Many “parameters” uncertain: would like to explore parameter space:

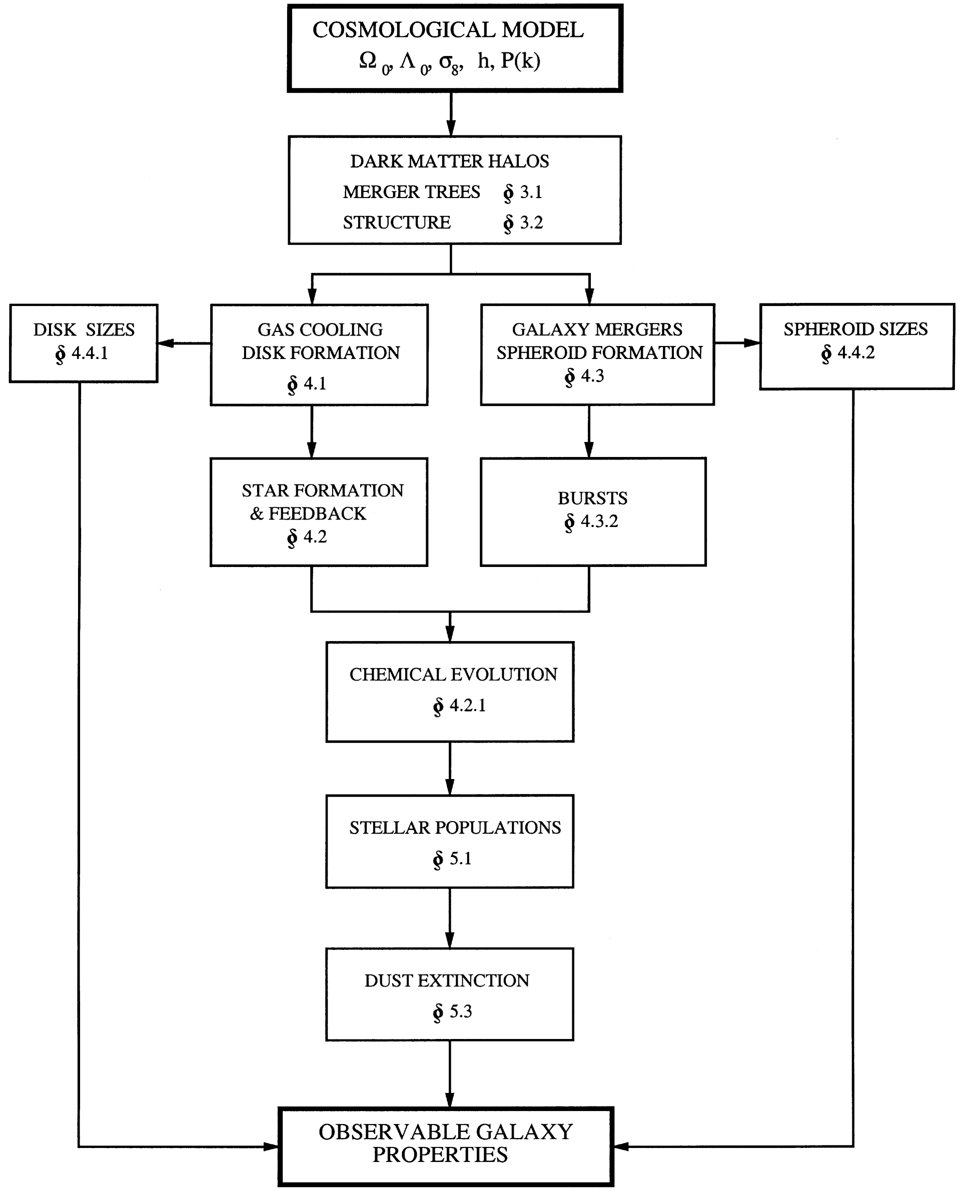
Simulating cosmic reionization: combine GalForm with Simplex

Milan Raicevic

Galaxy formation model Galform

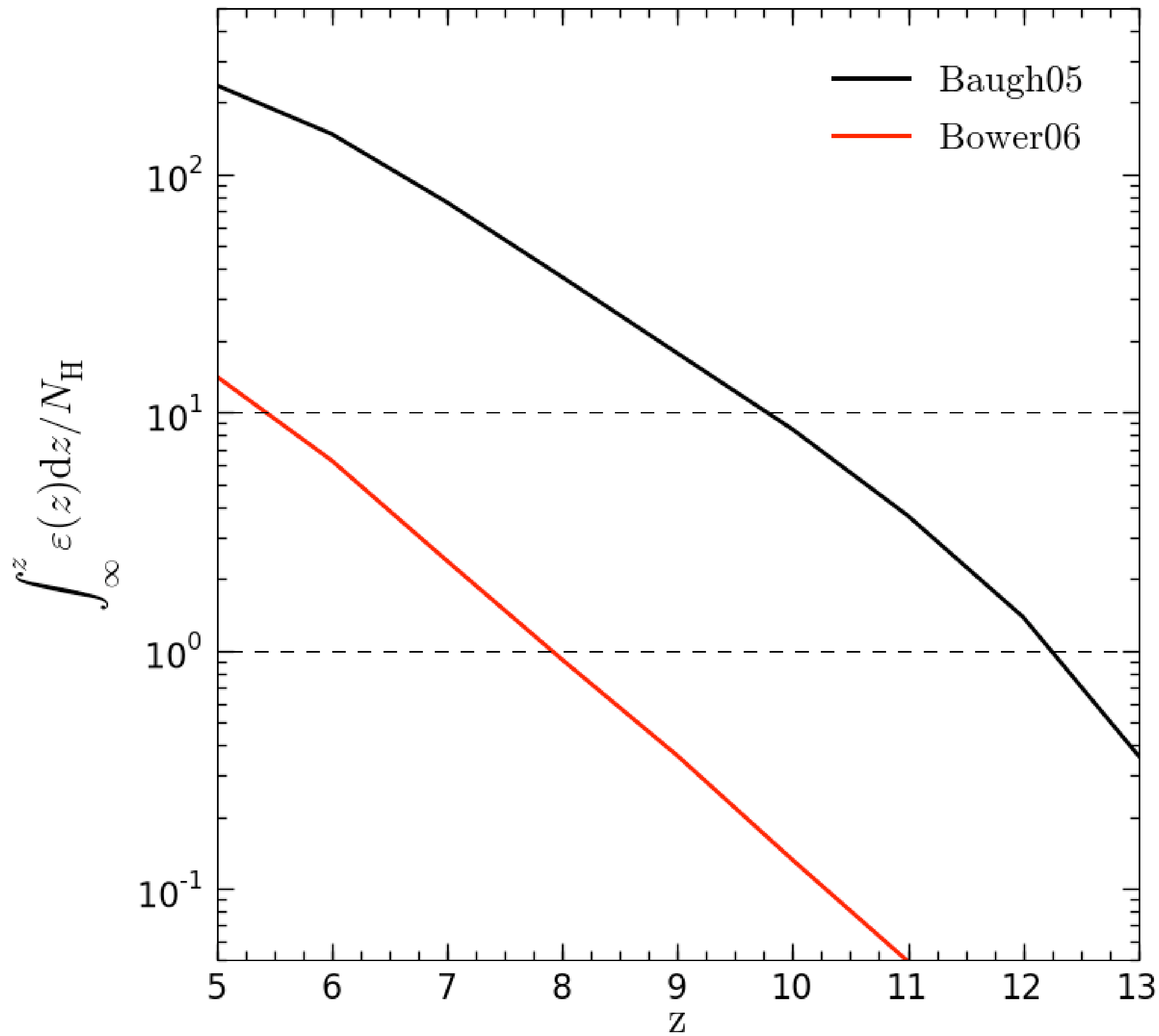




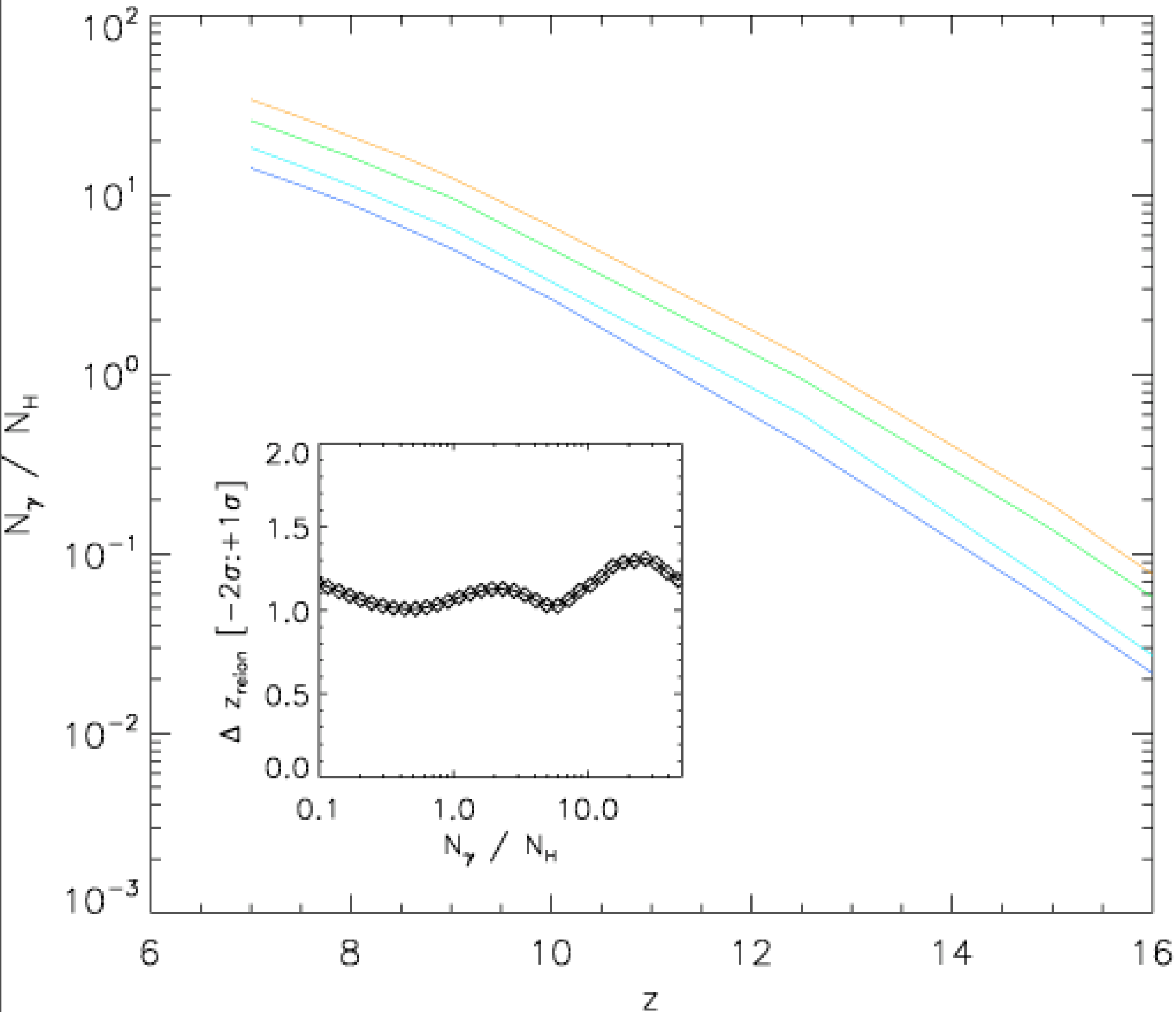


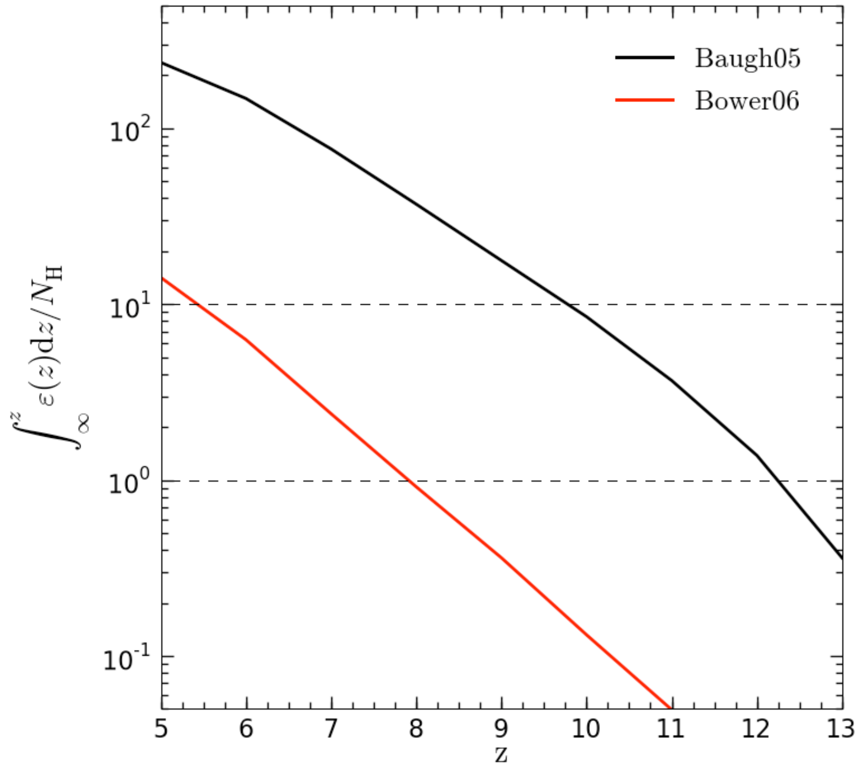
Hierarchical Galaxy Formation

Shaun Cole[1,4], Cedric G. Lacey[1,2,3,5], Carlton M. Baugh[1,6] and Carlos S. Frenk[1,7]

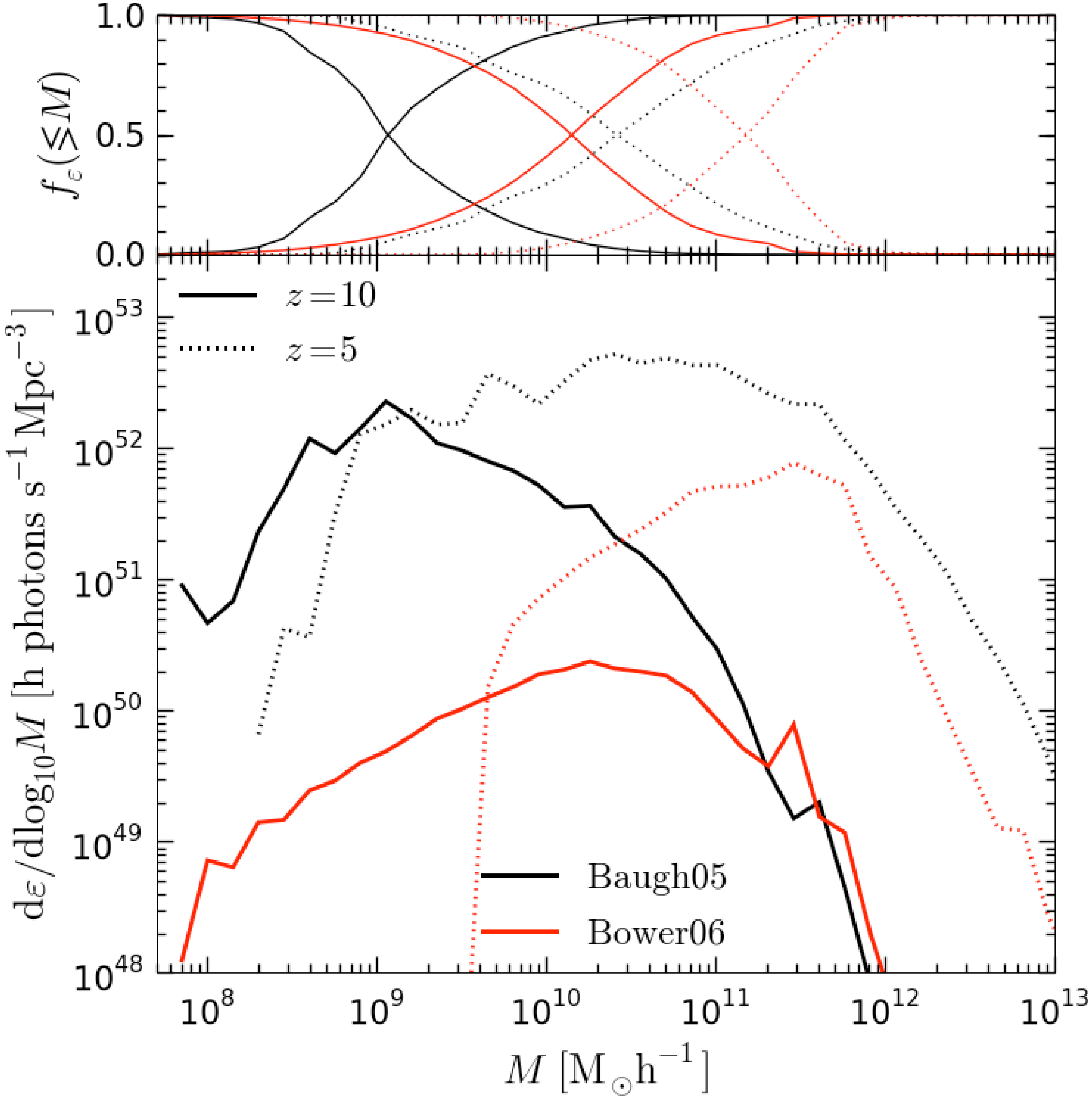


Emissivity in two popular GalForm flavours

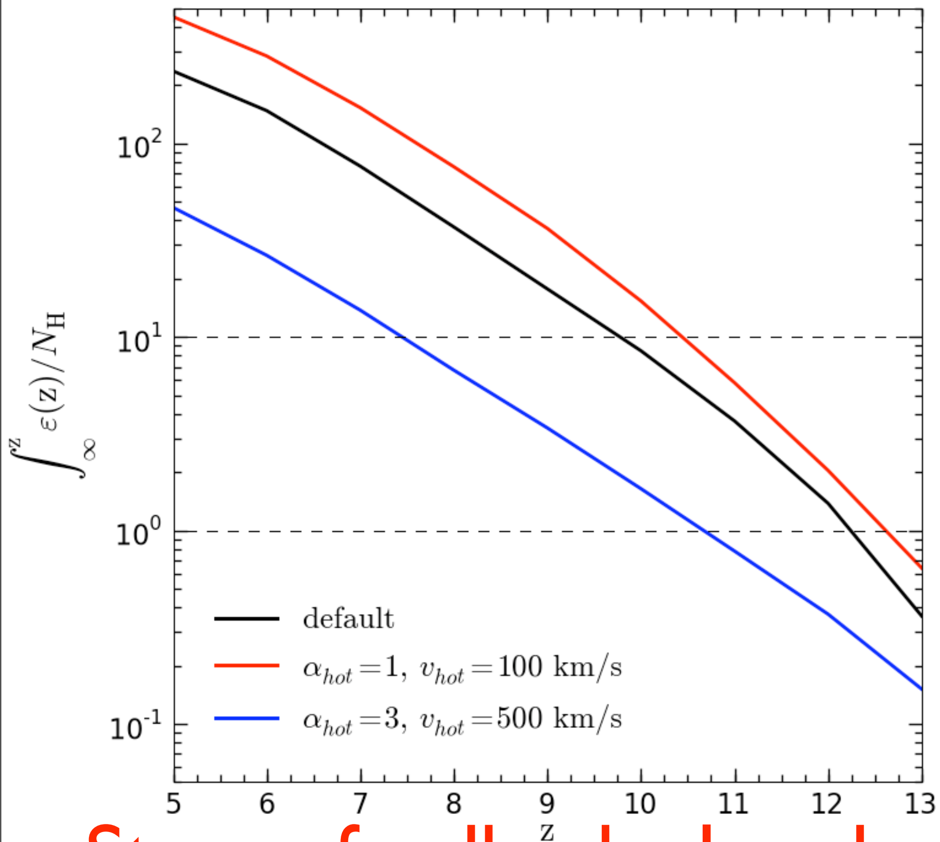




As compared to hydro-sims



Emissivity as function of halo mass

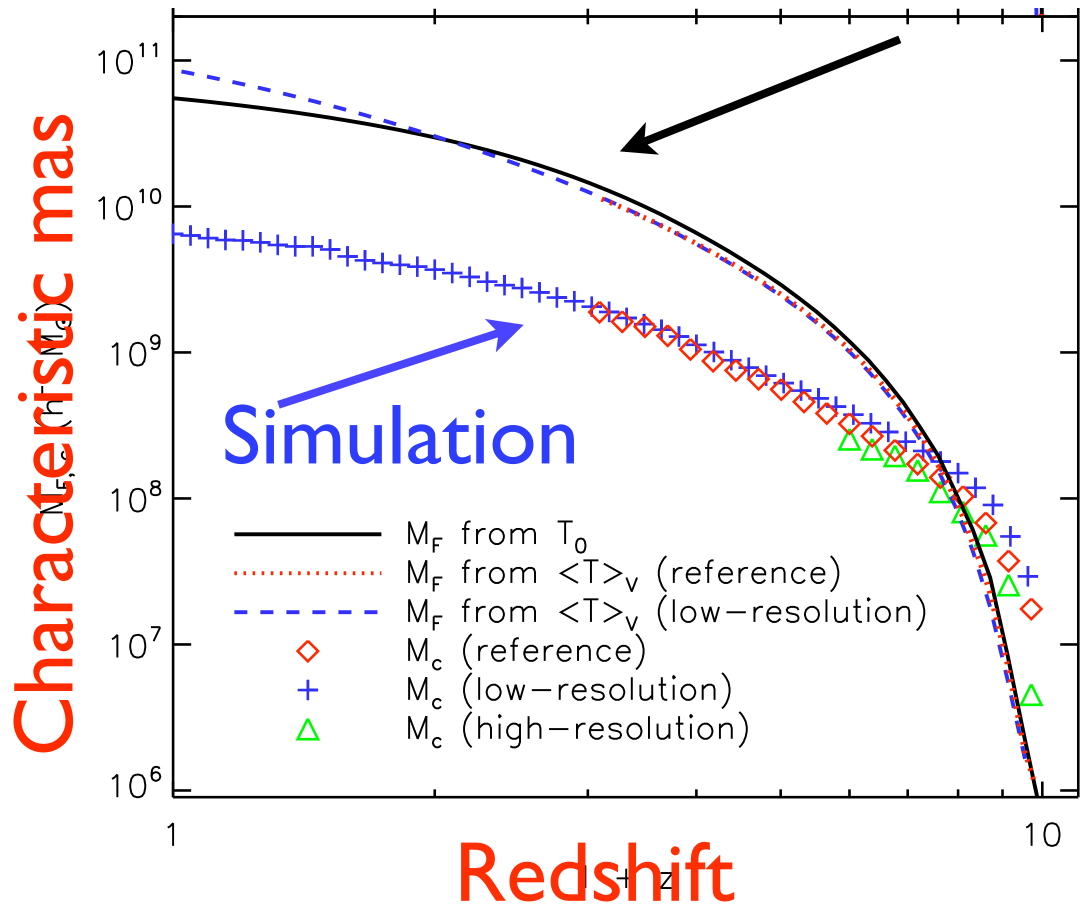


Massloss of galaxies due to a UV-background

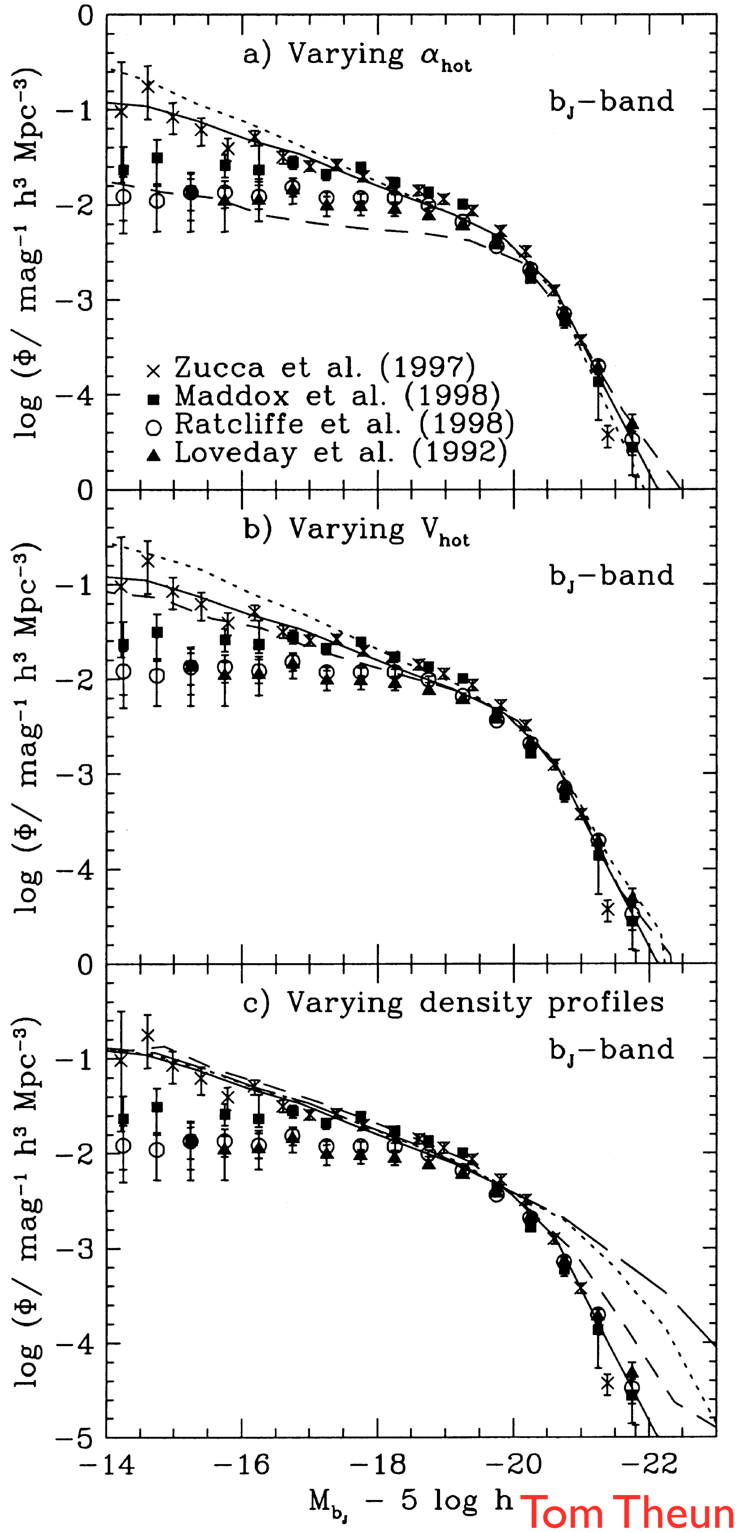
Takashi Okamoto[1⋆], Liang Gao[1,2] and Tom Theuns[1,3]
[1] Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham, DH
[2] National Astronomical Observatories, Chinese Academy of Science, Beijing, 100012, China
[3] Department of Physics, University of Antwerp,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

Gnedin's "filtering mass"

Strong feedback already suppresses small galaxies

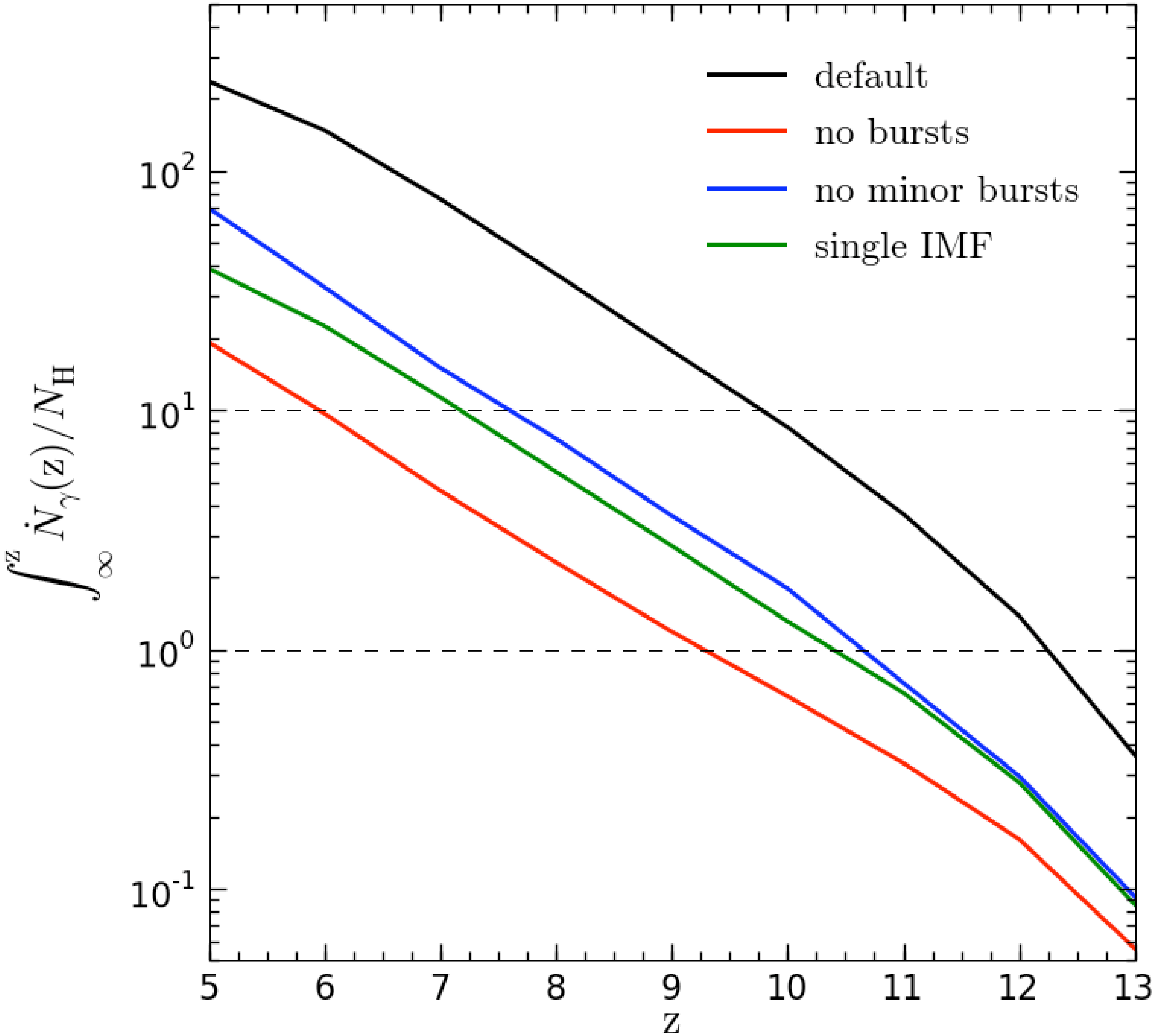


The SNe feedback shapes the faint-end slope alpha of the luminosity function



Hierarchical galaxy formation

Shaun Cole,[1★] Cedric G. Lacey,[1,2,3★] Carlton M. Baugh[1★] and Carlos S. Frenk[1★]

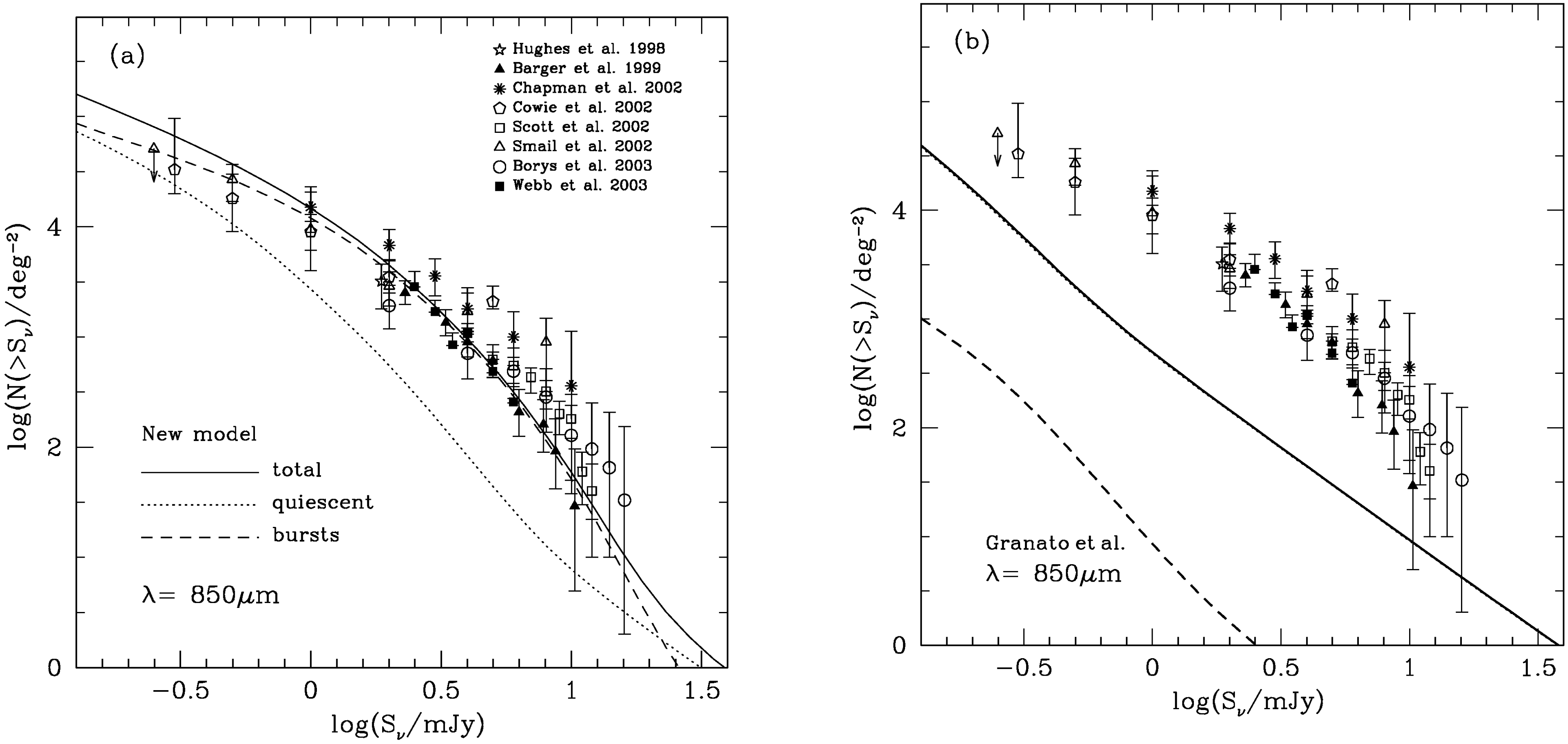


Dependence on star formation model

Sub-mm counts require top-heavy bursty mergers

bursts

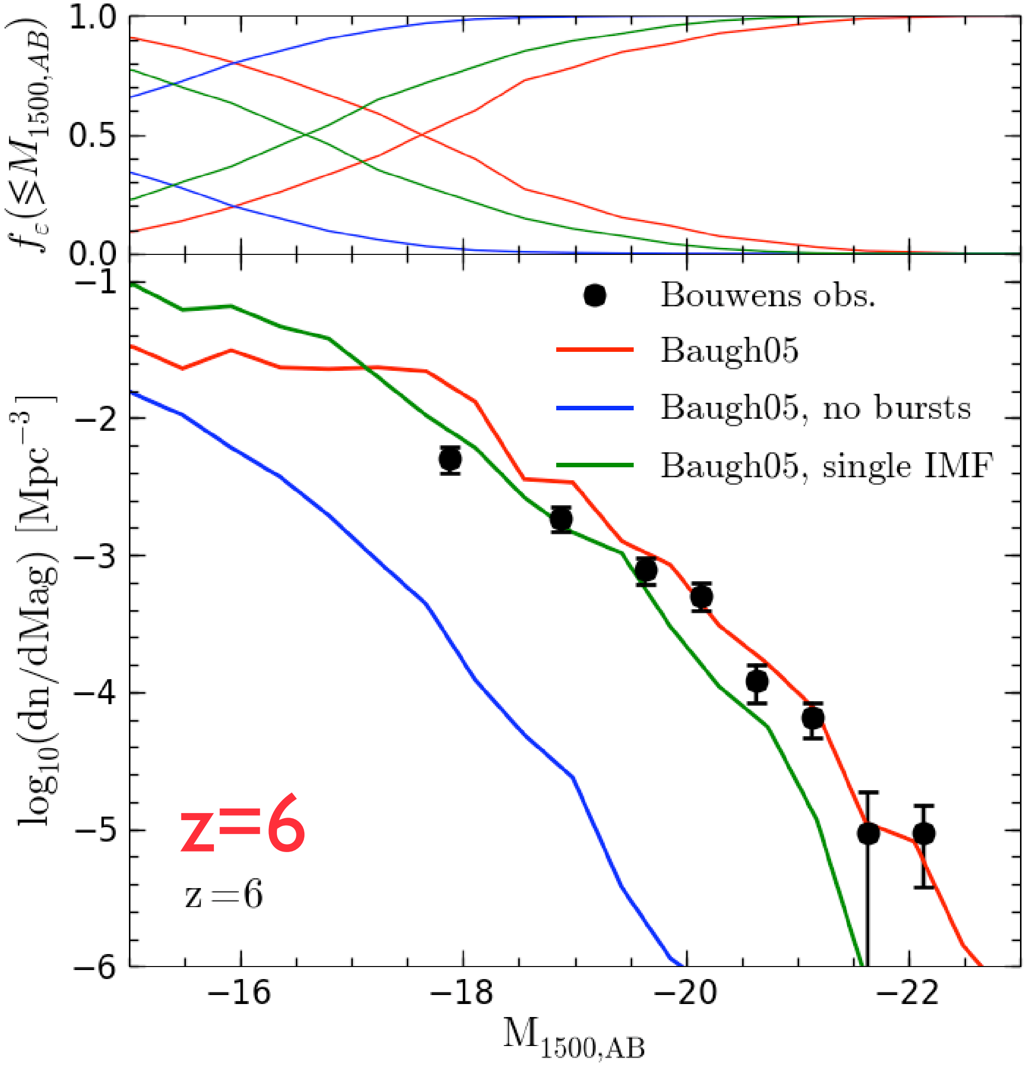
no bursts

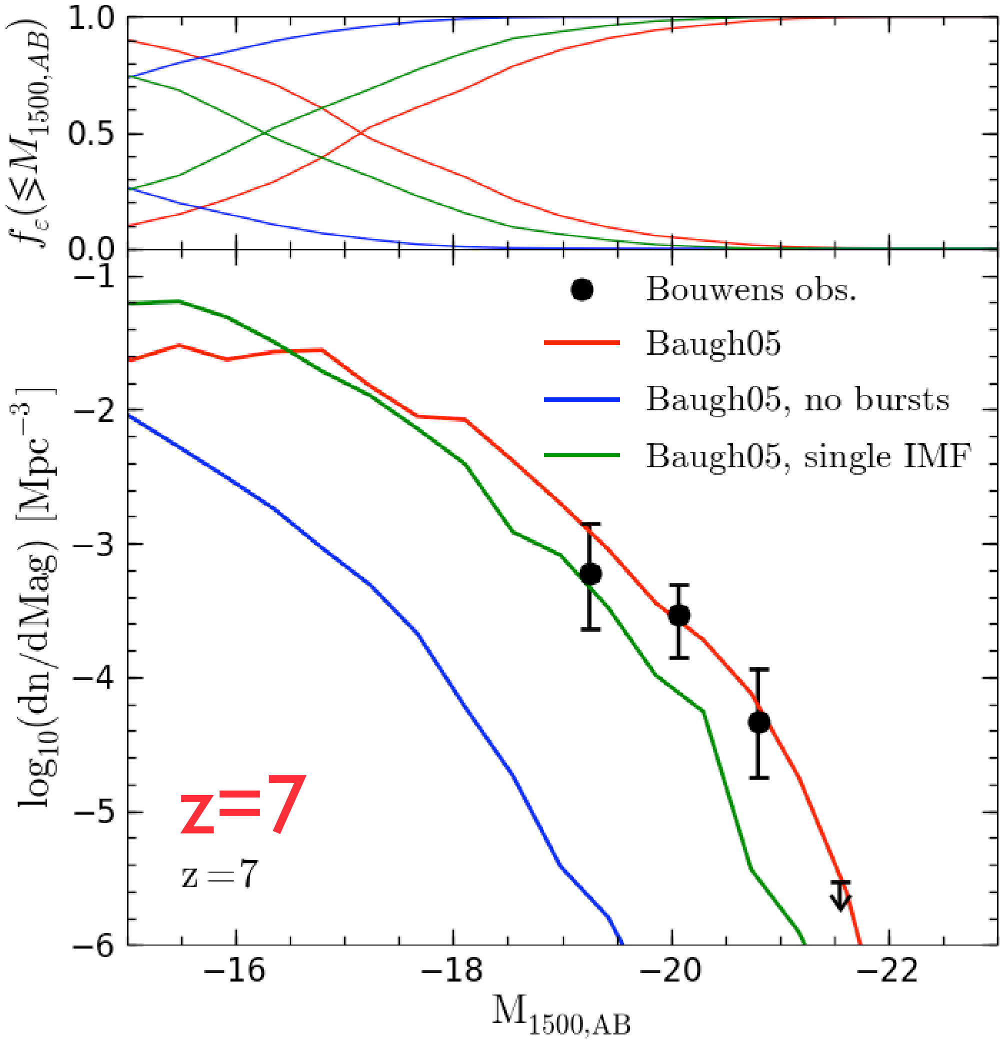


Can the faint submillimetre galaxies be explained in the Λ cold dark matter model?

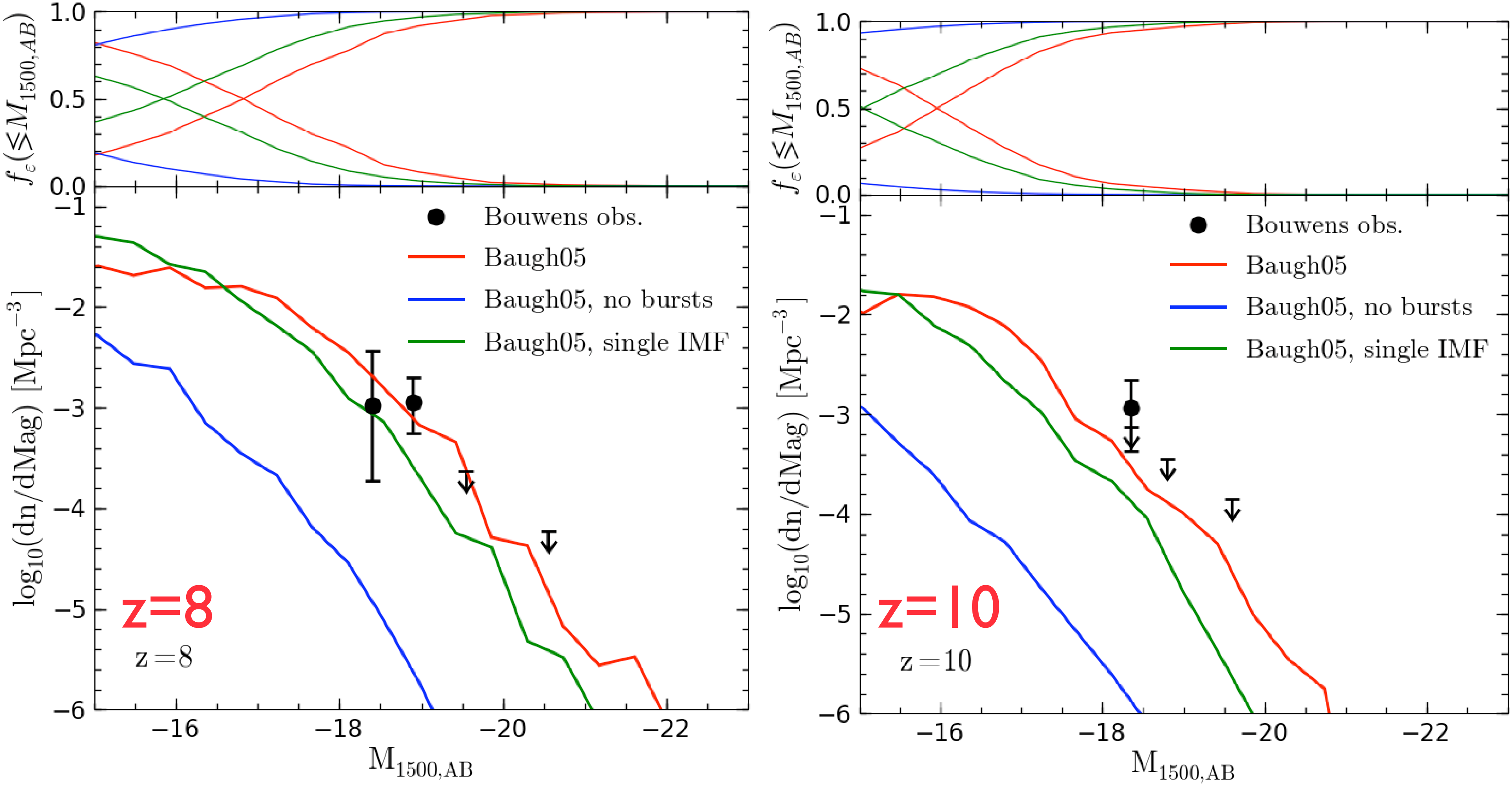
C. M. Baugh,[1★] C. G. Lacey,[1] C. S. Frenk,[1] G. L. Granato,[2] L. Silva,[3] A. Bressan,[2] A. J. Benson[4] and S. Cole[1]

UV-luminosity functions:
Default Baugh compared to Bouwens

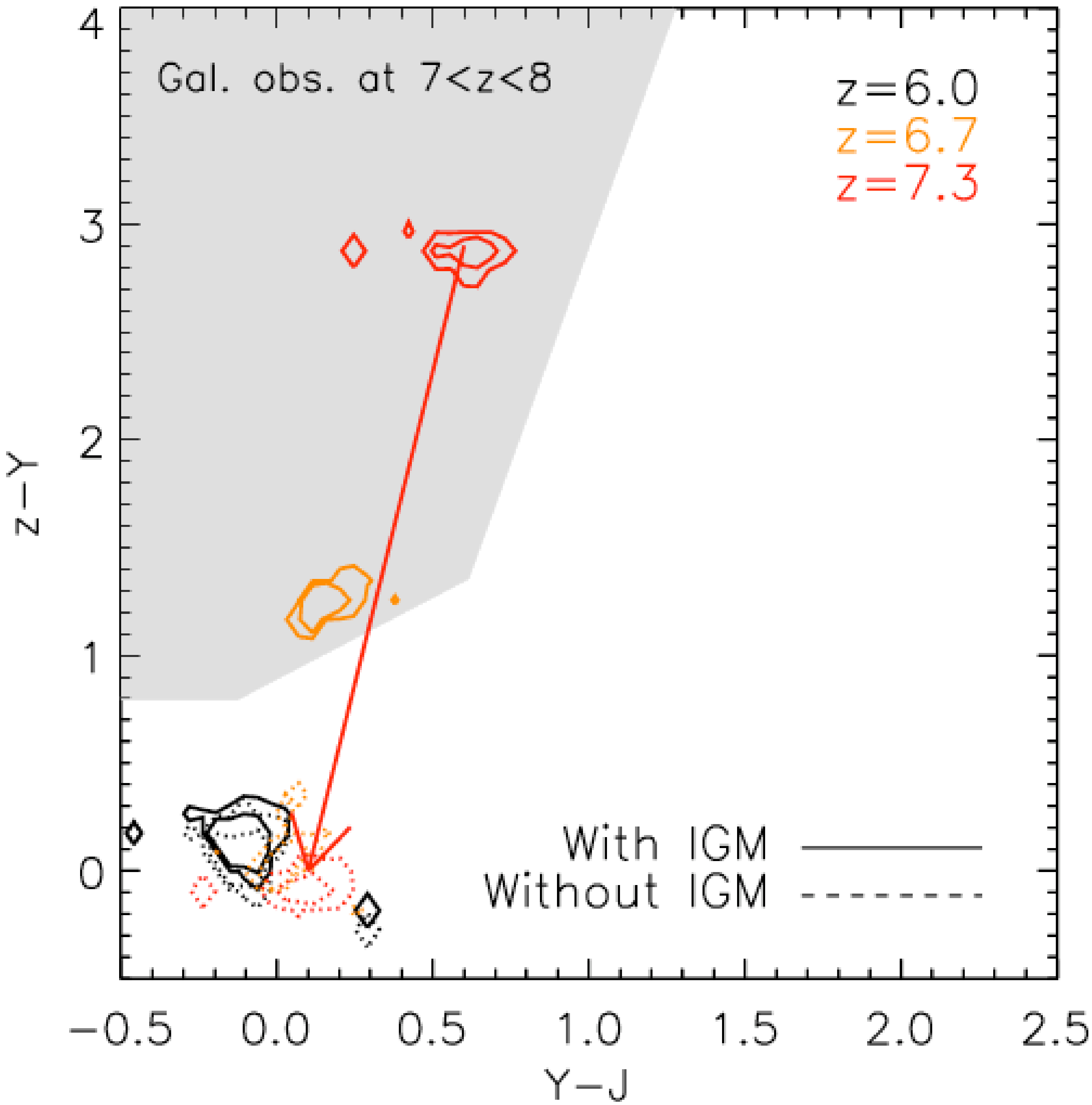




UV-luminosity functions:
Default Baugh compared to Bouwens



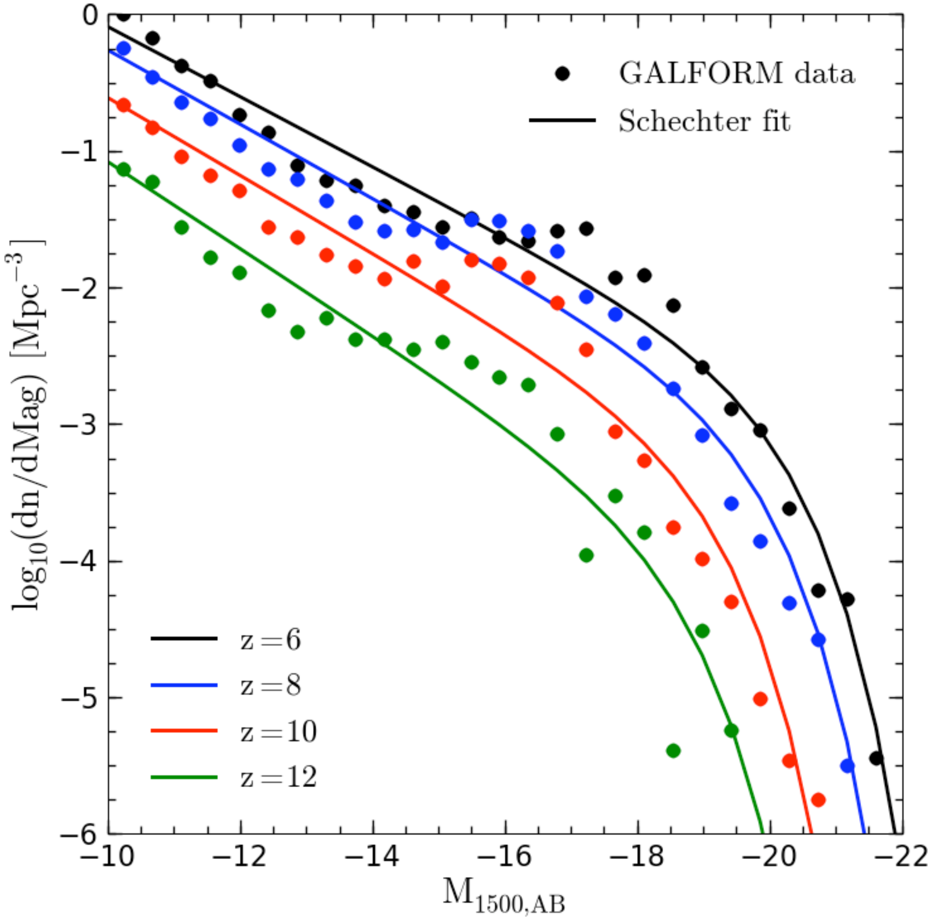
Galaxy colours compared to Bouwens

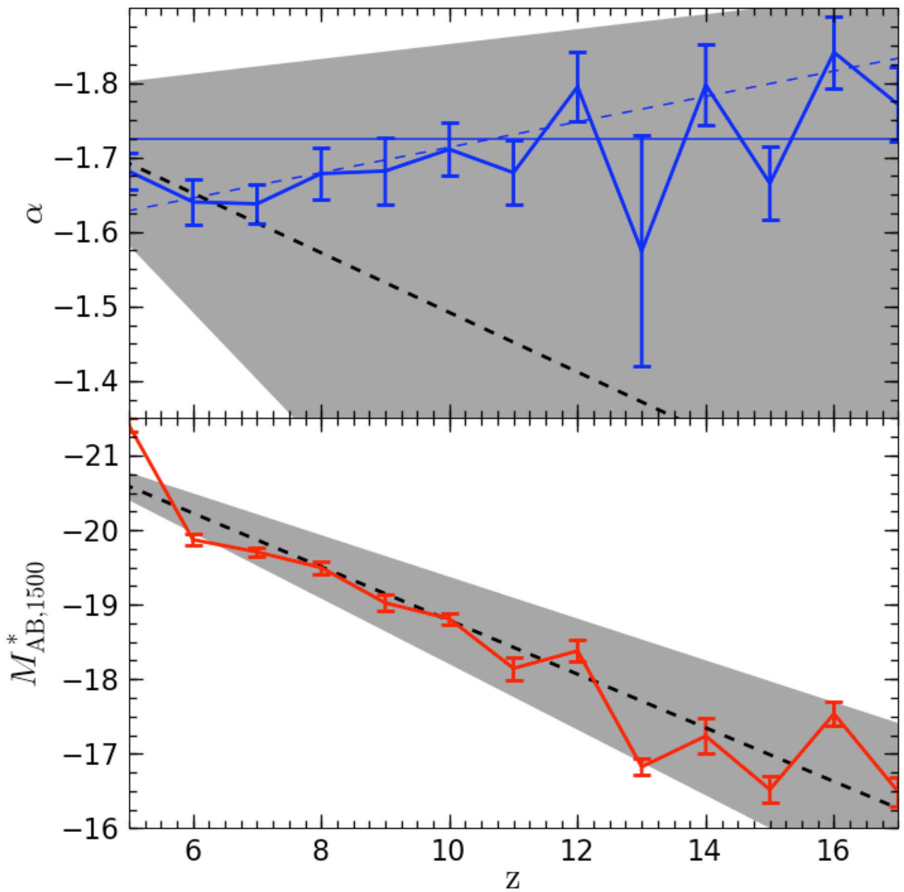


ICC

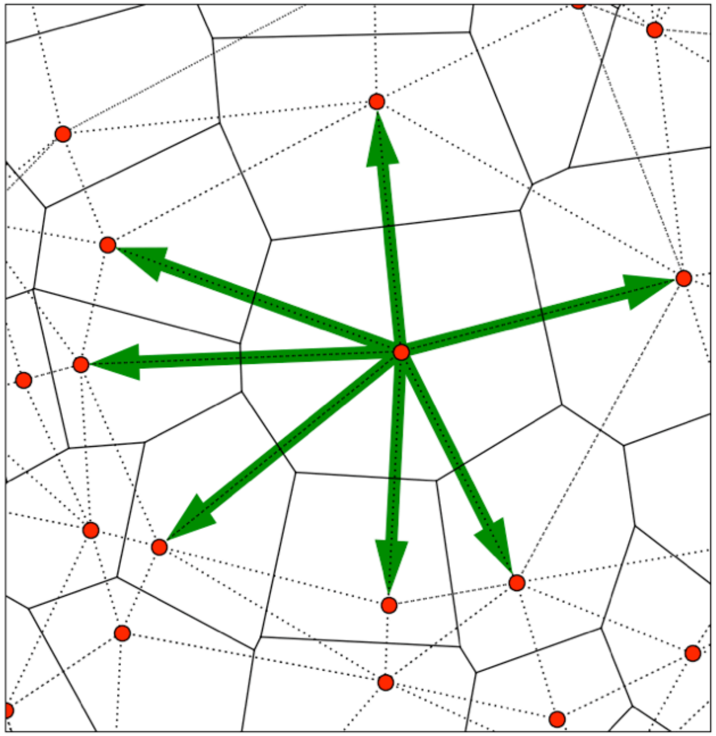
Tom Theuns

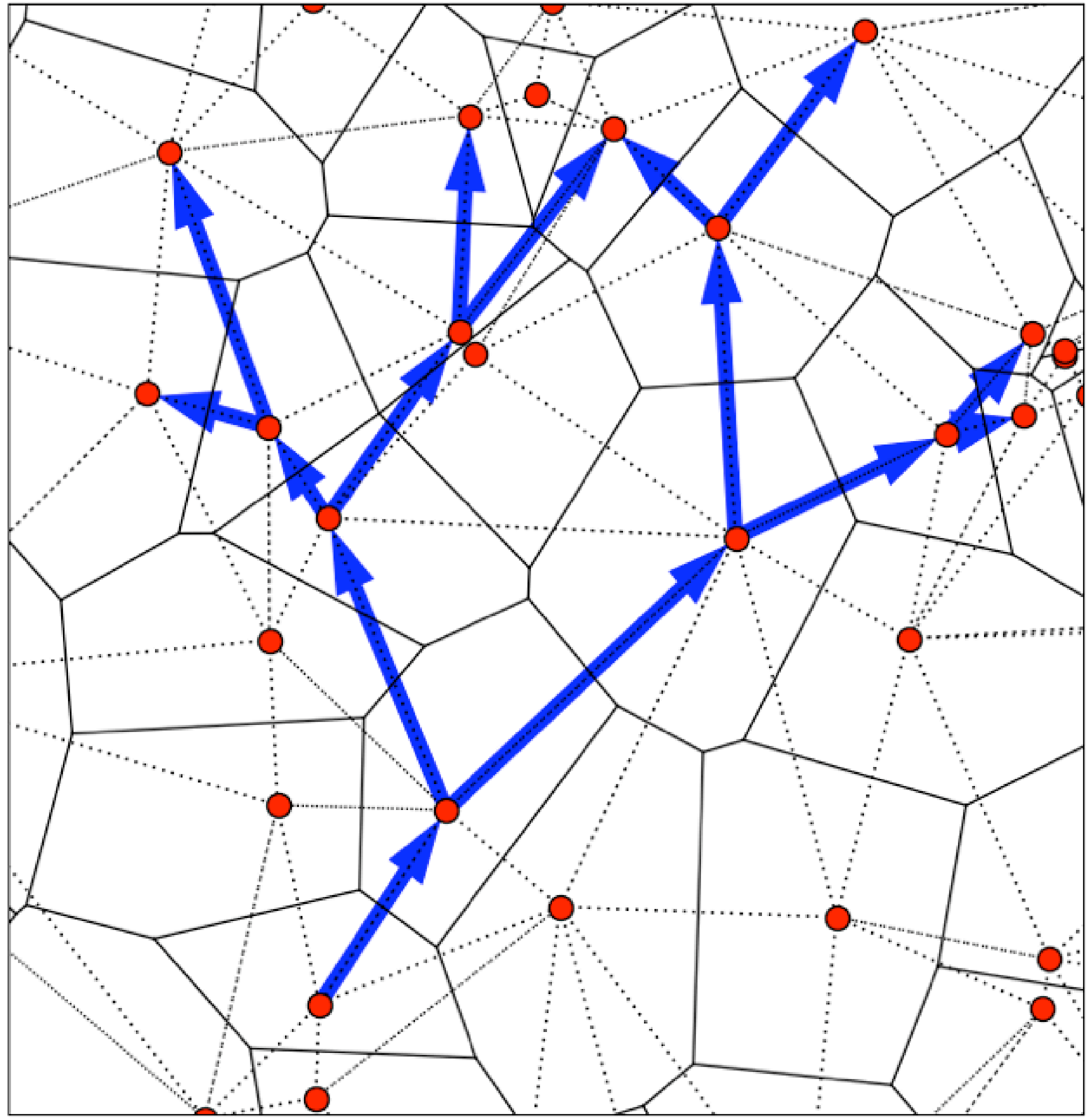
Luminosity function shapes





SimpleX

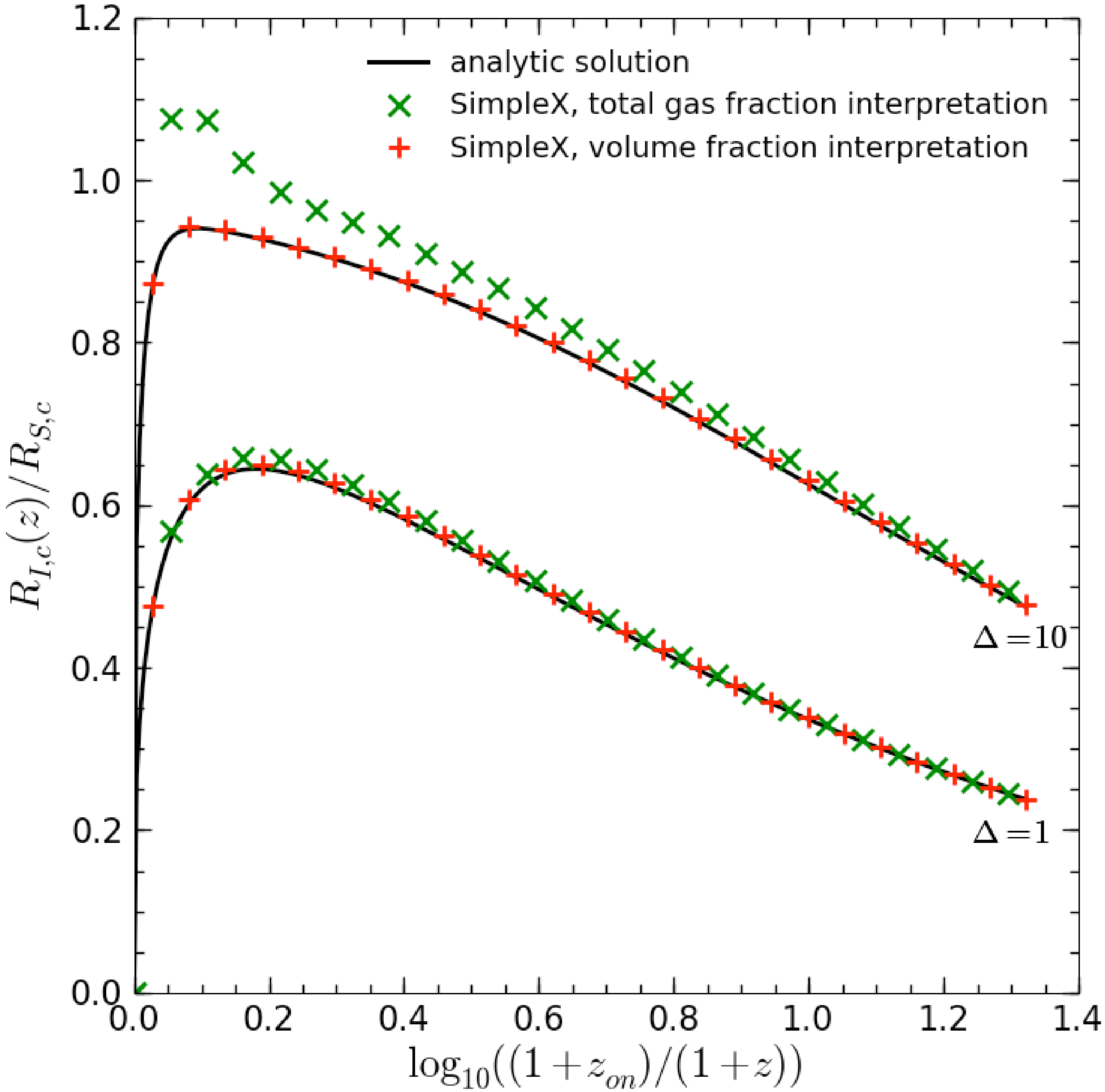




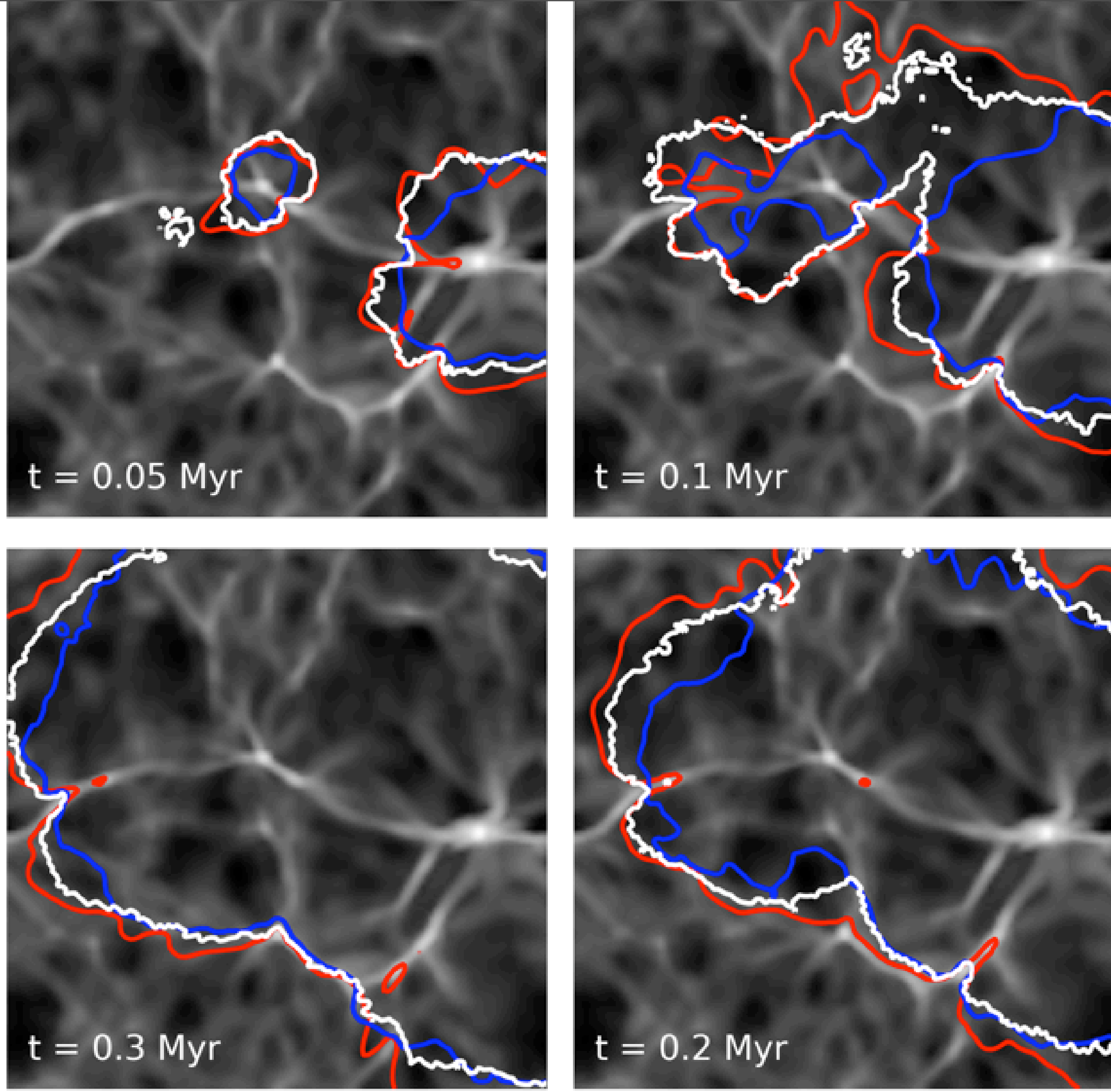
Triangulating Radiation:
Radiative Transfer on Unstructured Grids

J. Ritzerveld[1⋆], V. Icke[1] and E.-J. Rijkhorst[1]

Radius of cosmological HII region



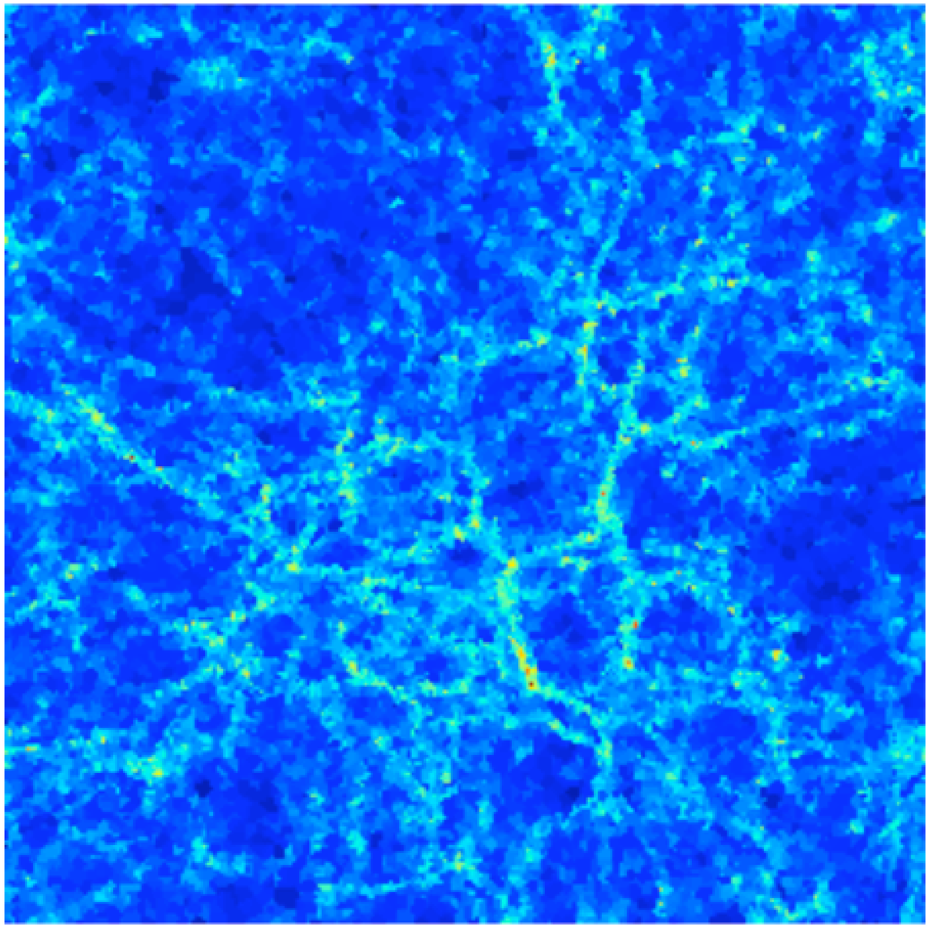
“Photon conservation”

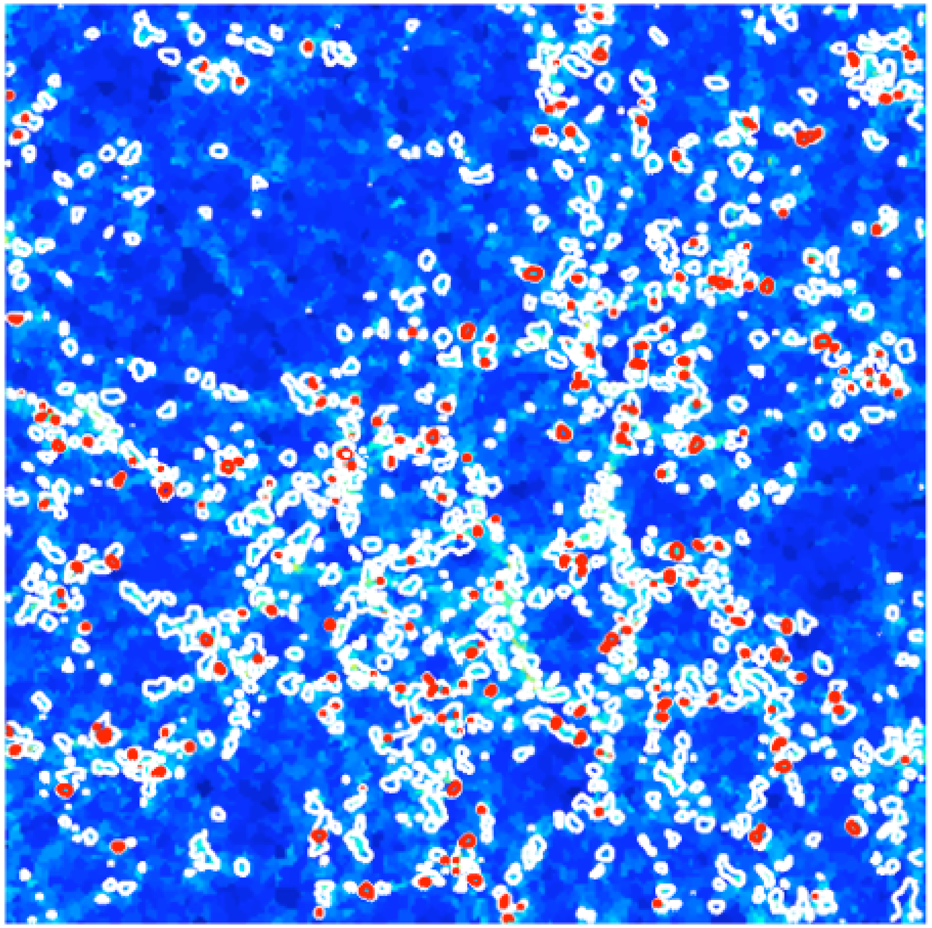


Cosmological Radiative Transfer Codes Comparison Project I: The Static Density Field Tests

Ilian T. Iliev[1⋆], Benedetta Ciardi[2], Marcelo A. Alvarez[3], Antonella Maselli[2], Andrea Ferrara[4], Nickolay Y. Gnedin[5,6], Garrelt Mellema[7,8], Taishi Nakamoto[9], Michael L. Norman[10], Alexei O. Razoumov[11], Erik-Jan Rijkhorst[8], Jelle Ritzerveld[8], Paul R. Shapiro[3], Hajime Susa[12], Masayuki Umemura[9], Daniel J. Whalen[10,13]

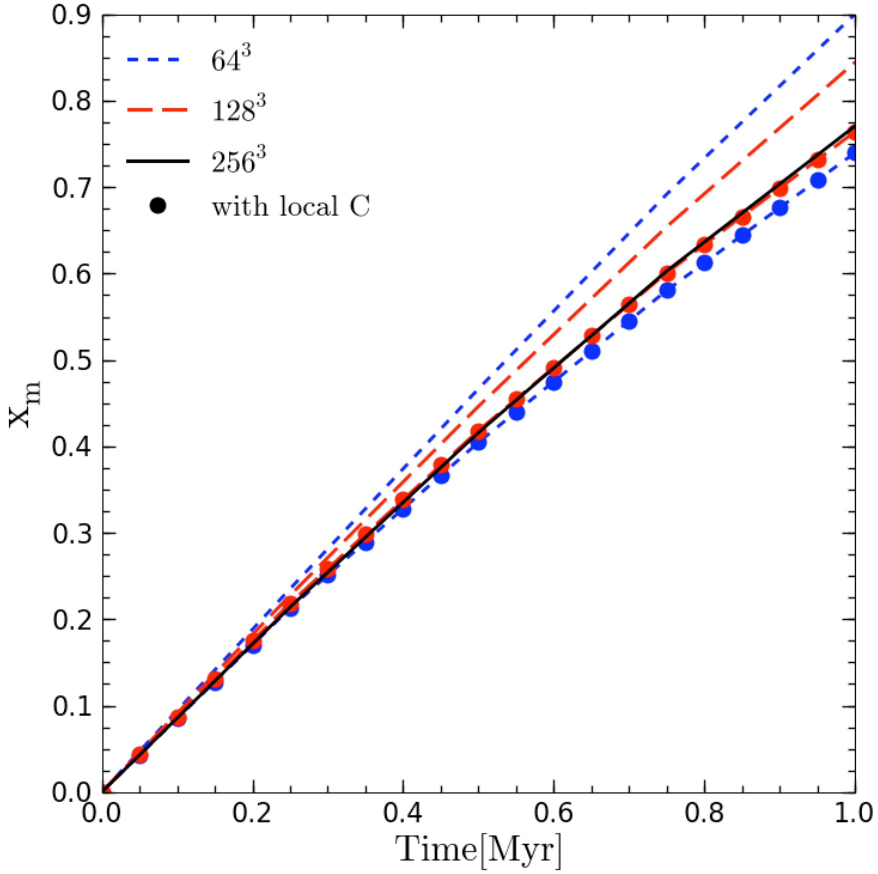
RT with millions of sources

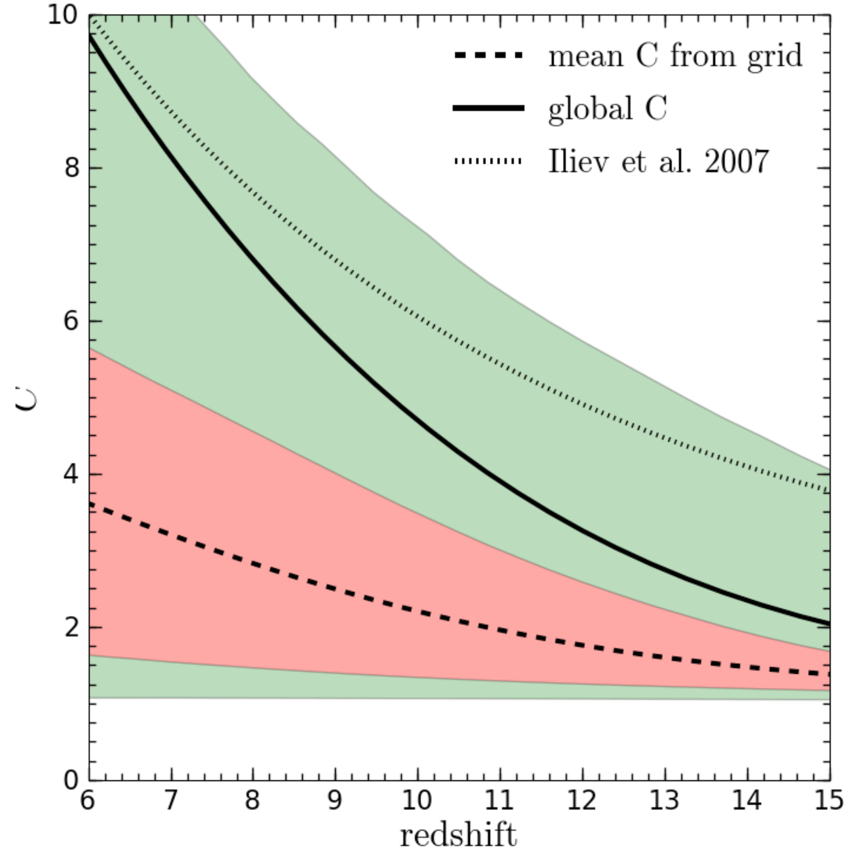




Simulation	L_{box}	N_{DM}	m_{DM}
	[Mpc/h]		[10^5 $M_\odot$/h]
L12.5N128	12.5	128^3	646.2
L20N512	20	512^3	41.35
L10N512	10	512^3	5.17
L10N1024	10	1024^3	0.65
L20N1024	20	1024^3	5.17

Set of N-body runs varying box size and numerical resolution to investigate numerical convergence

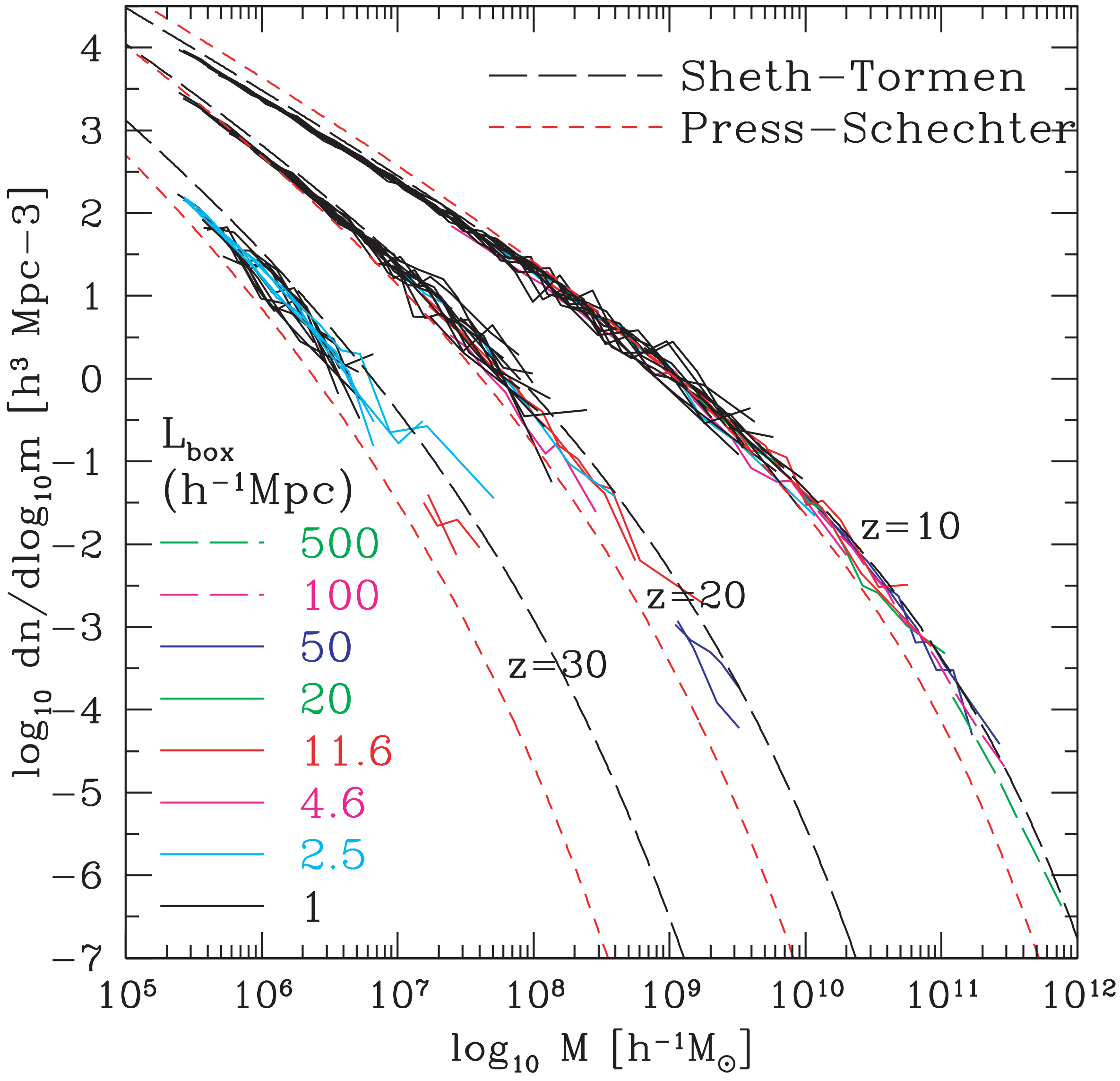




“local” clumping factor

The halo mass function from the dark ages through the present day

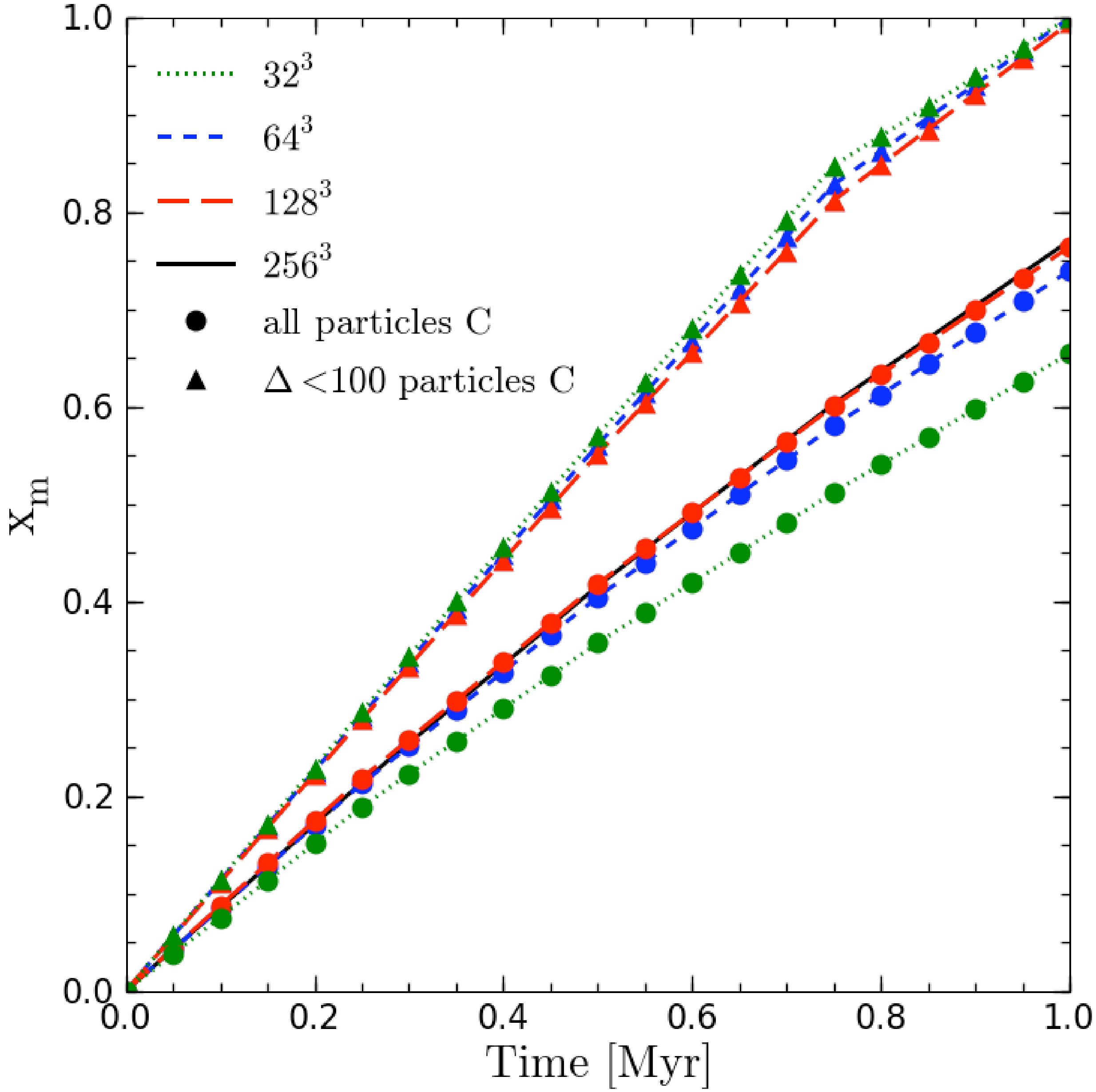
Darren S. Reed,[1★] Richard Bower,[1] Carlos S. Frenk,[1] Adrian Jenkins[1]
and Tom Theuns[1,2]



(b) Global mass function

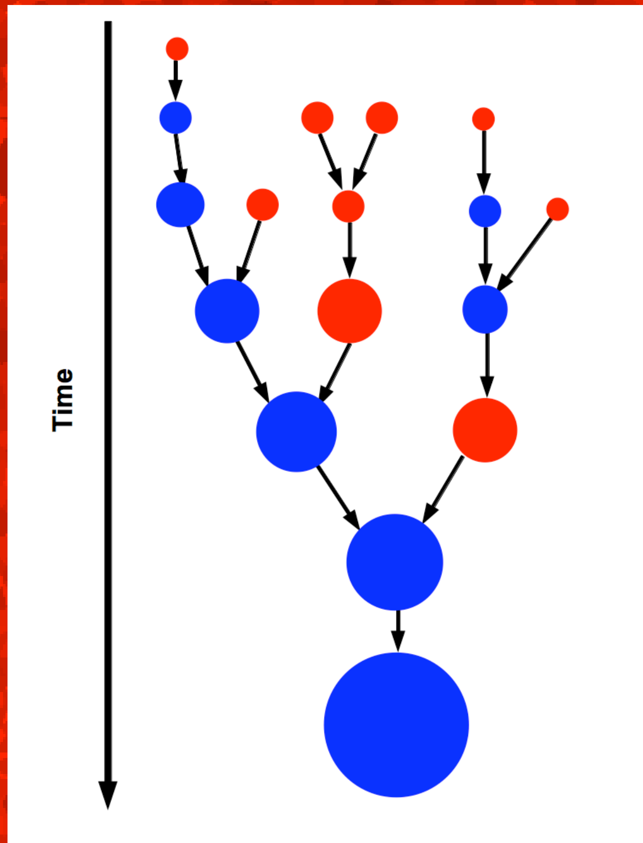
Reed +, 2007

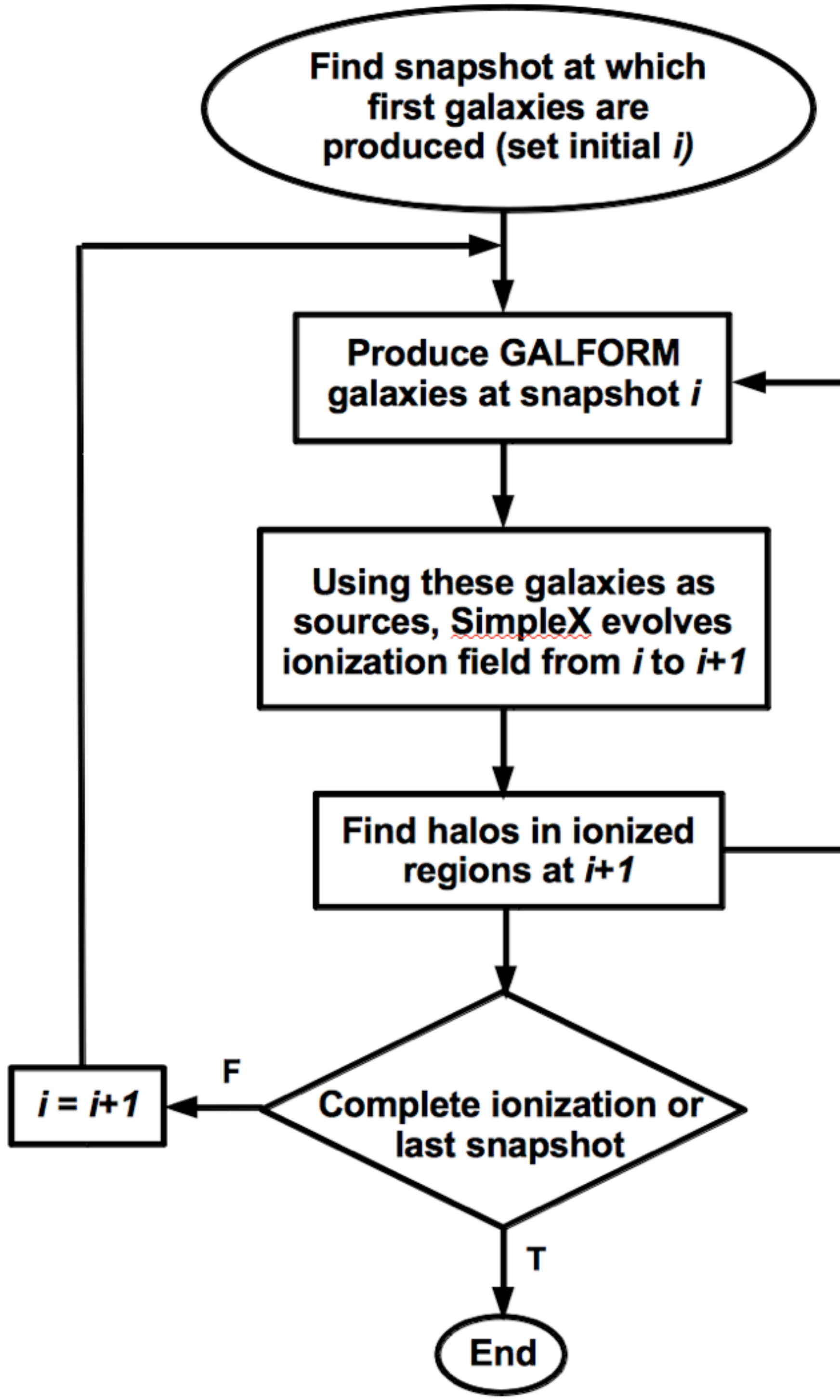
The effect of resolution on ionisation fraction with/without a "local" clumping factor



z = 21.7

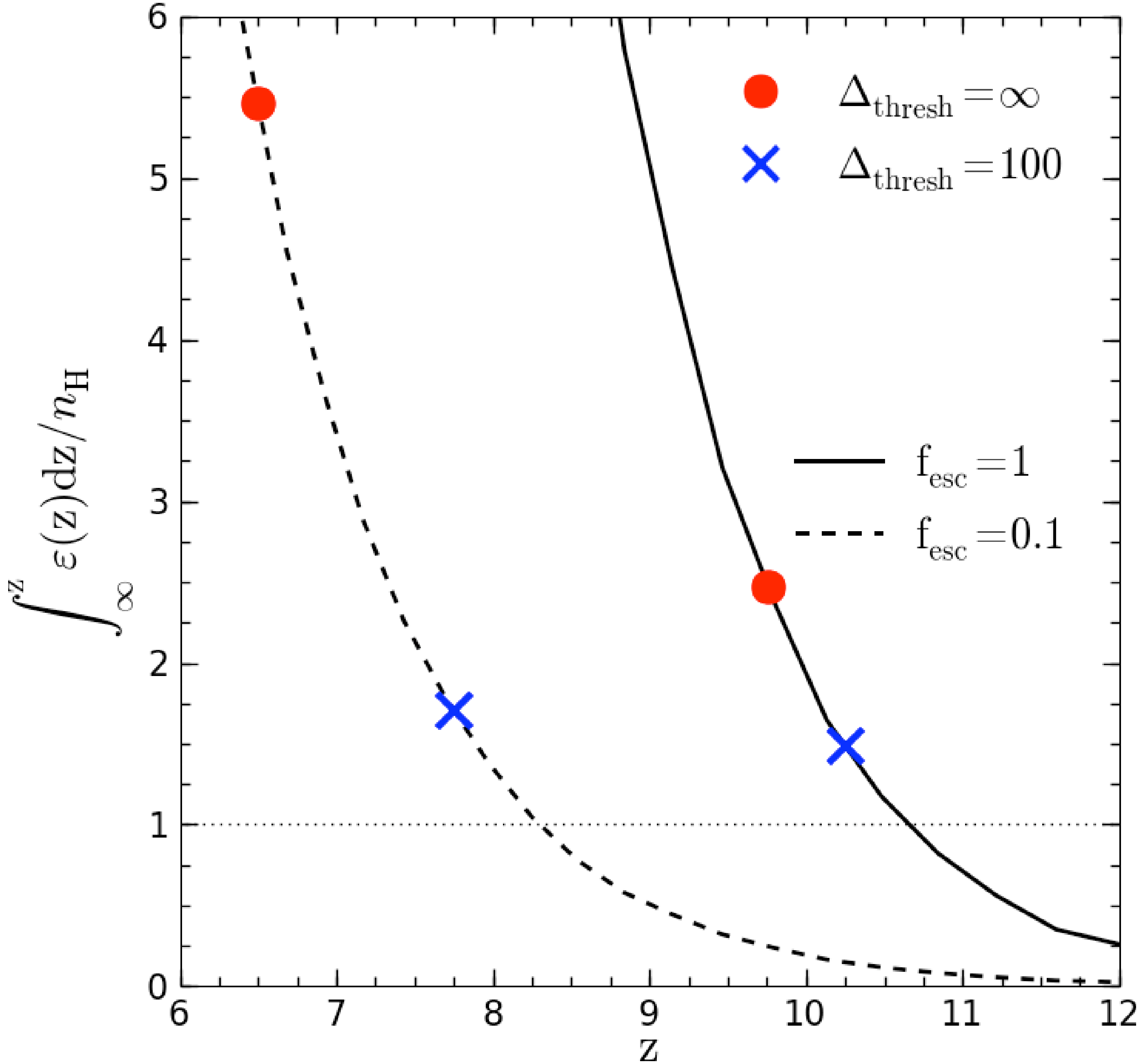
Coupling GalForm with SimpleX



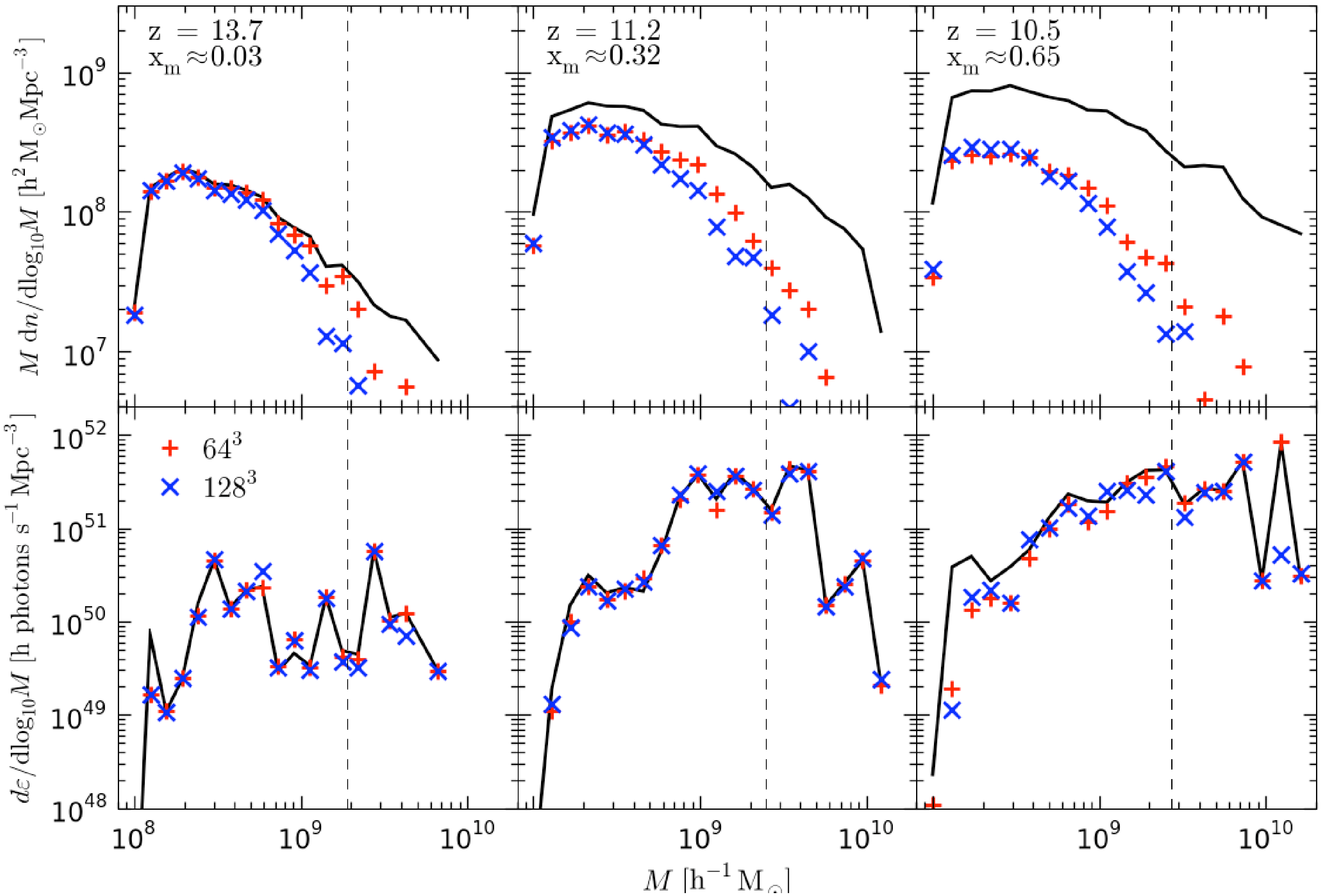


Full run takes less than 24 hours at 128^3 resolution, few days at 256^3 resolution, on workstation

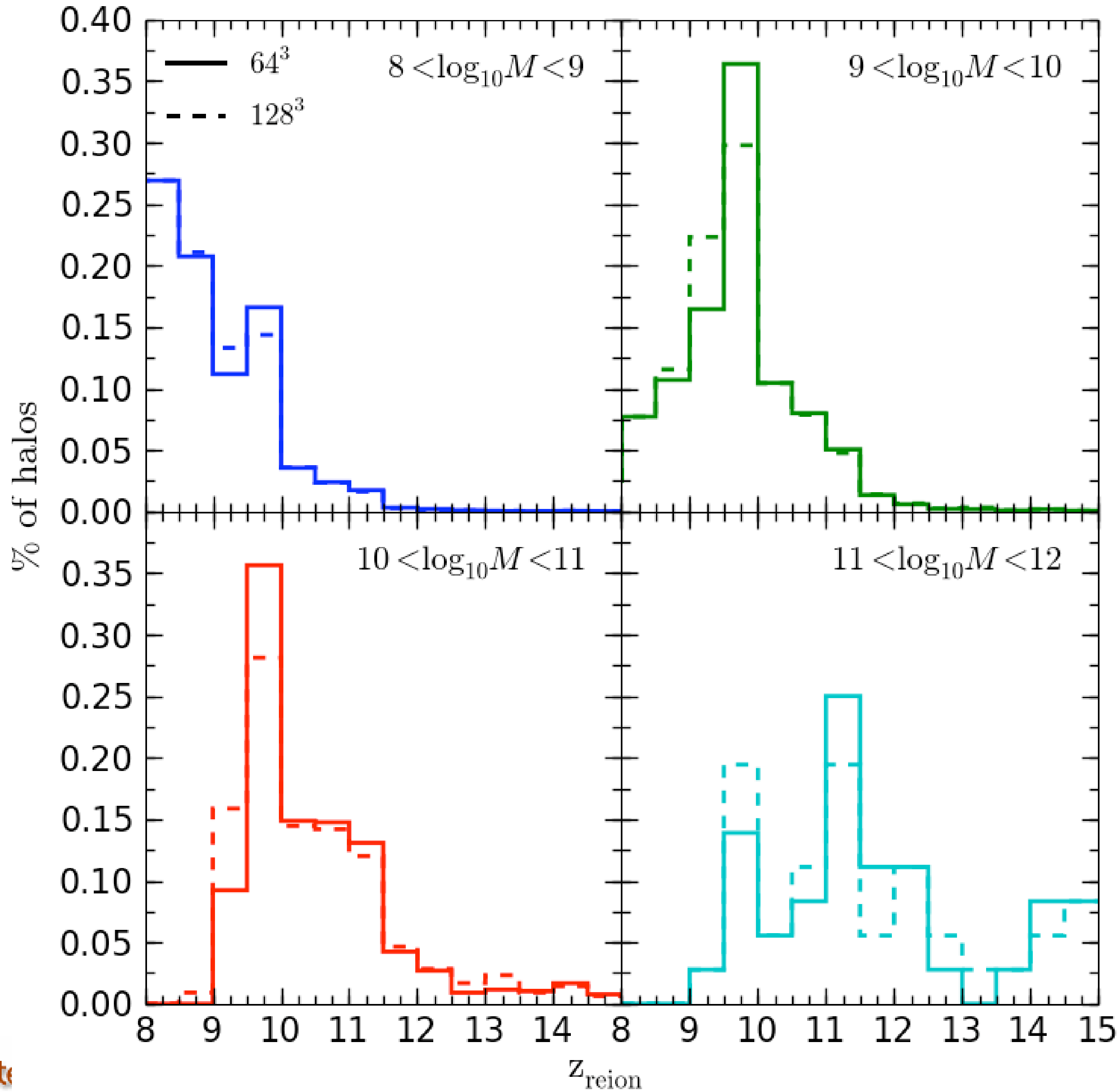
Effect of recombinations in haloes on reionisation



MF of "neutral" haloes



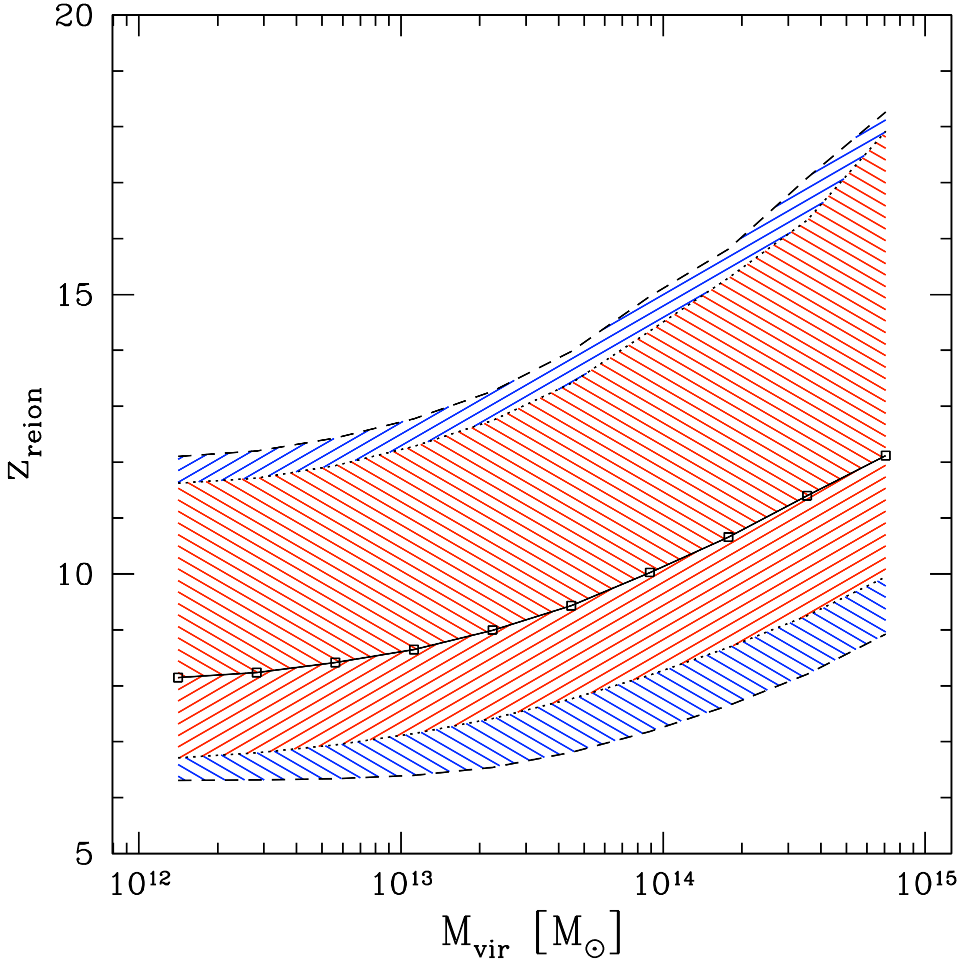
When is halo first "ionized?

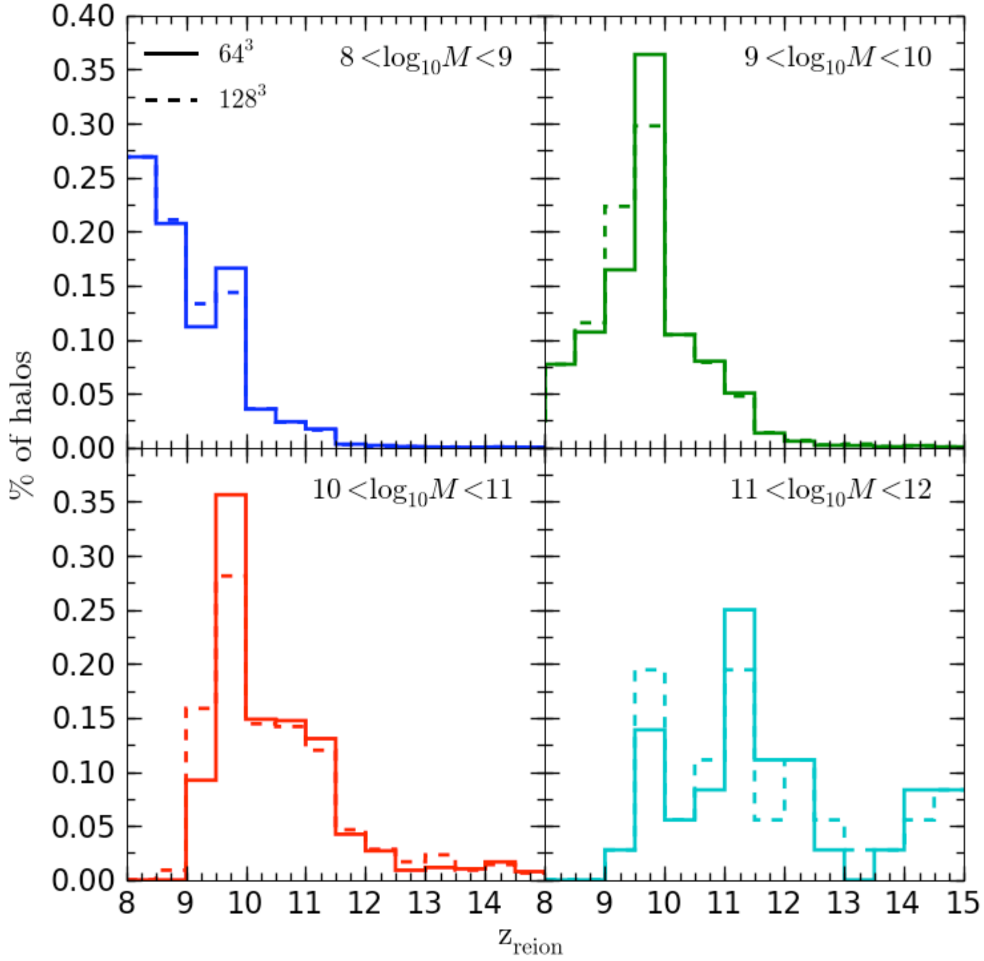


Institute

om Theuns

When is halo first "ionized?



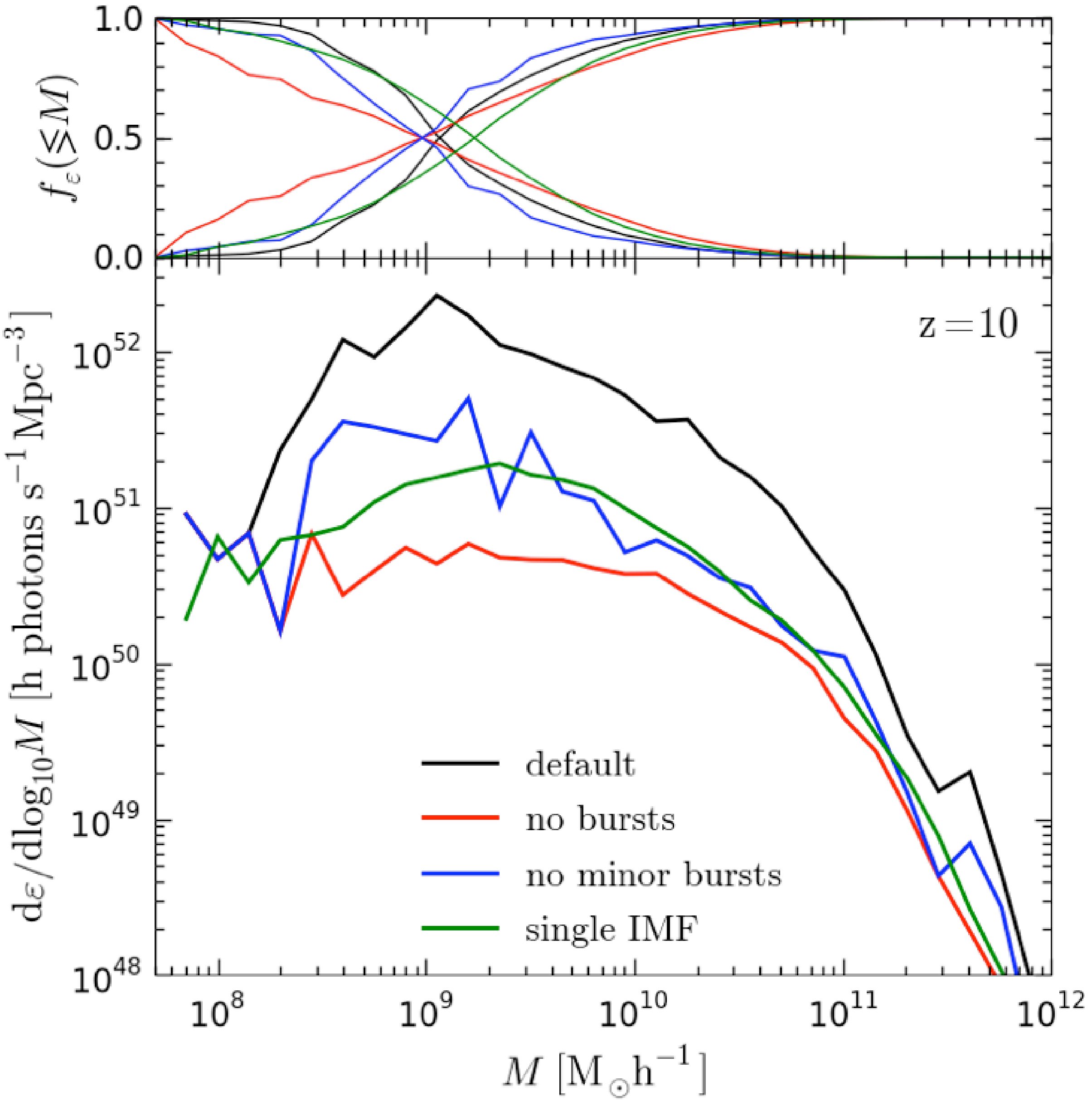


CONNECTING REIONIZATION TO THE LOCAL UNIVERSE

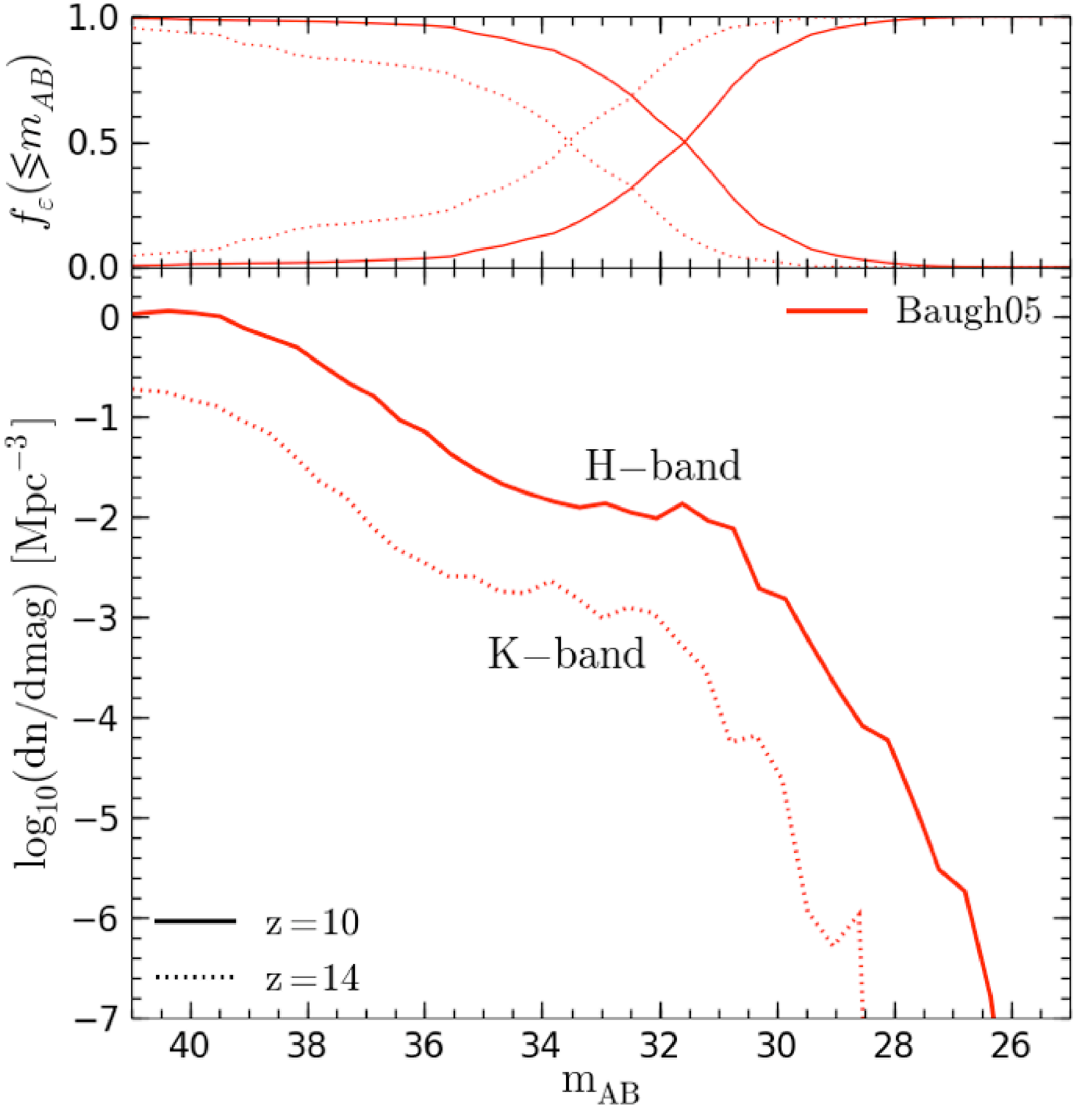
MARCELO A. ALVAREZ, MICHAEL BUSHA, TOM ABEL, AND RISA H. WECHSLER
Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Menlo Park, CA 94025

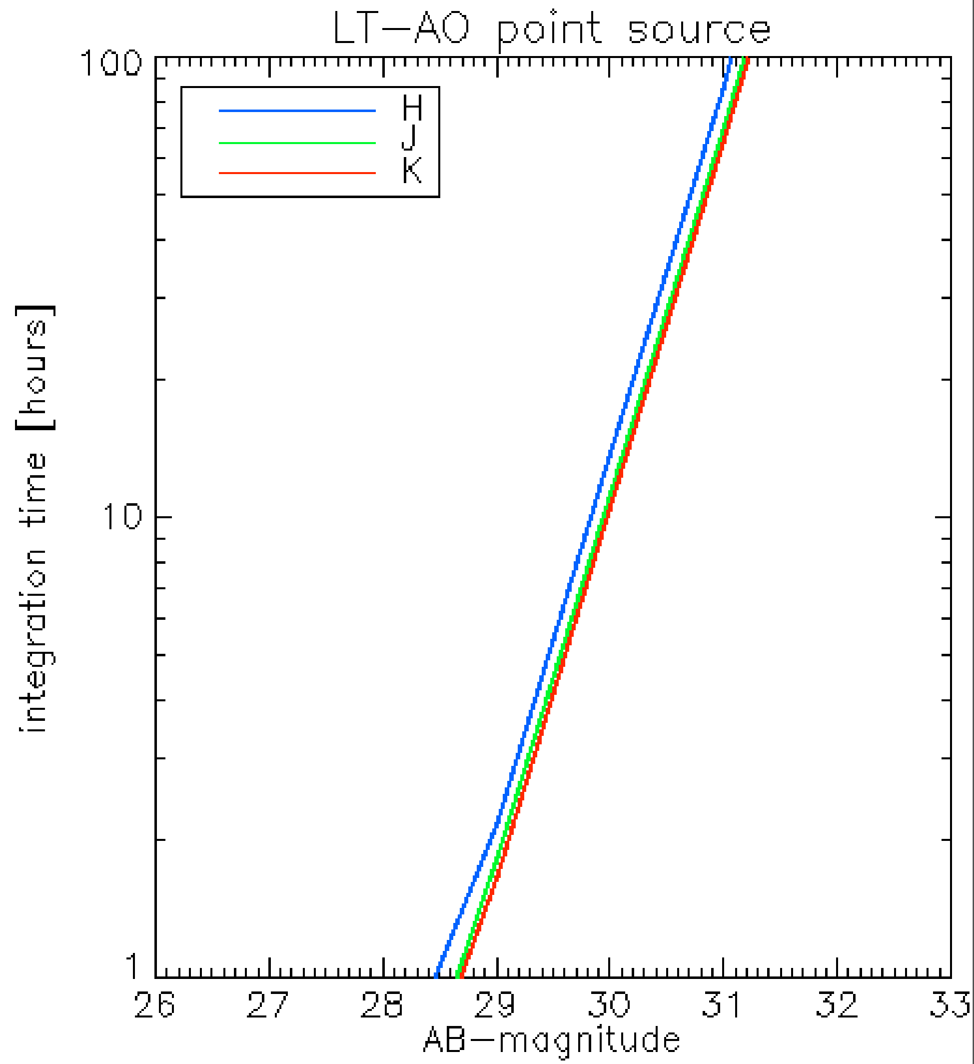
Draft version December 19, 2008

Which galaxies produce the ionizing photons? Halo masses.



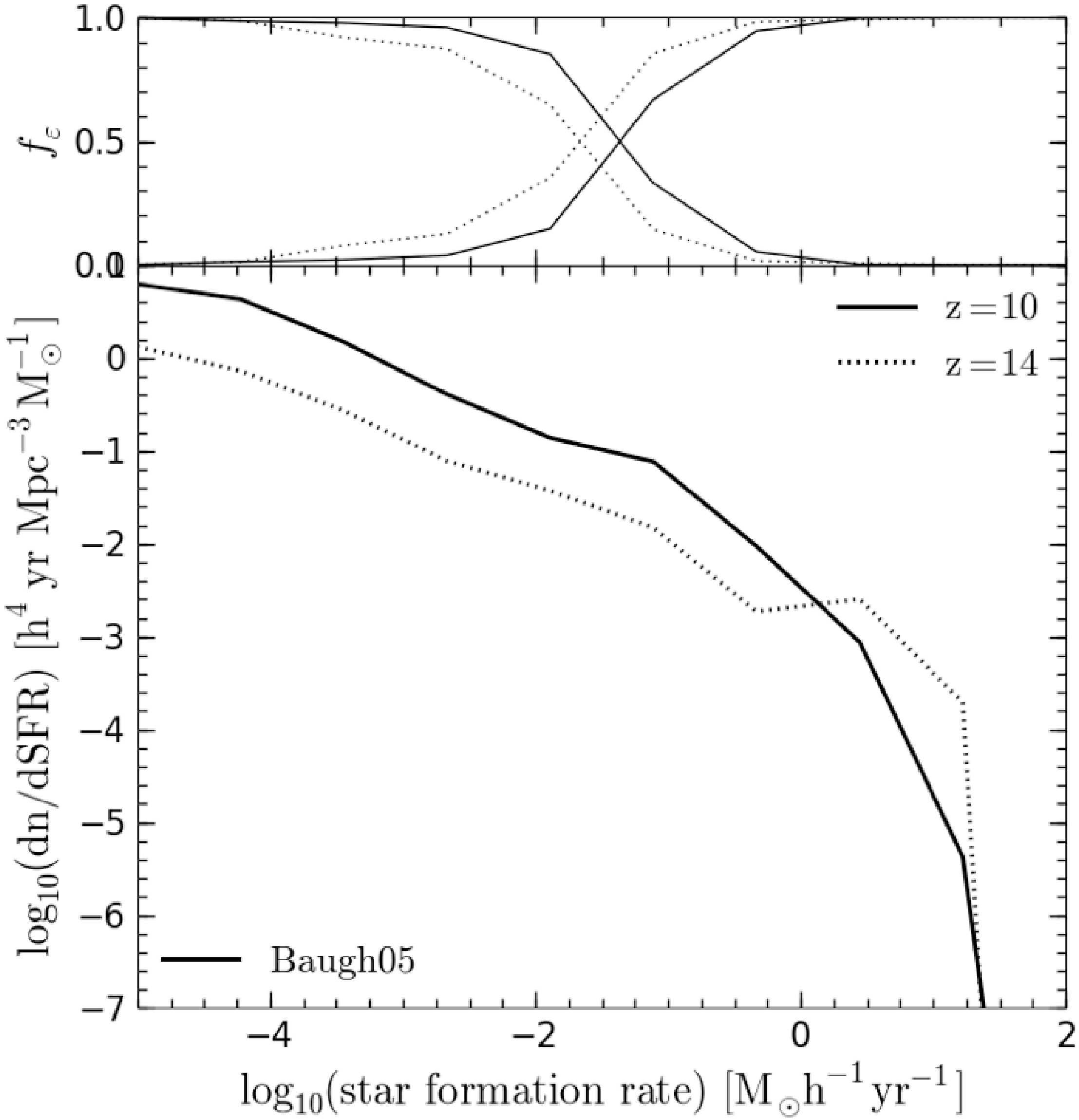
Which galaxies produce the ionizing photons? Continuum luminosities.



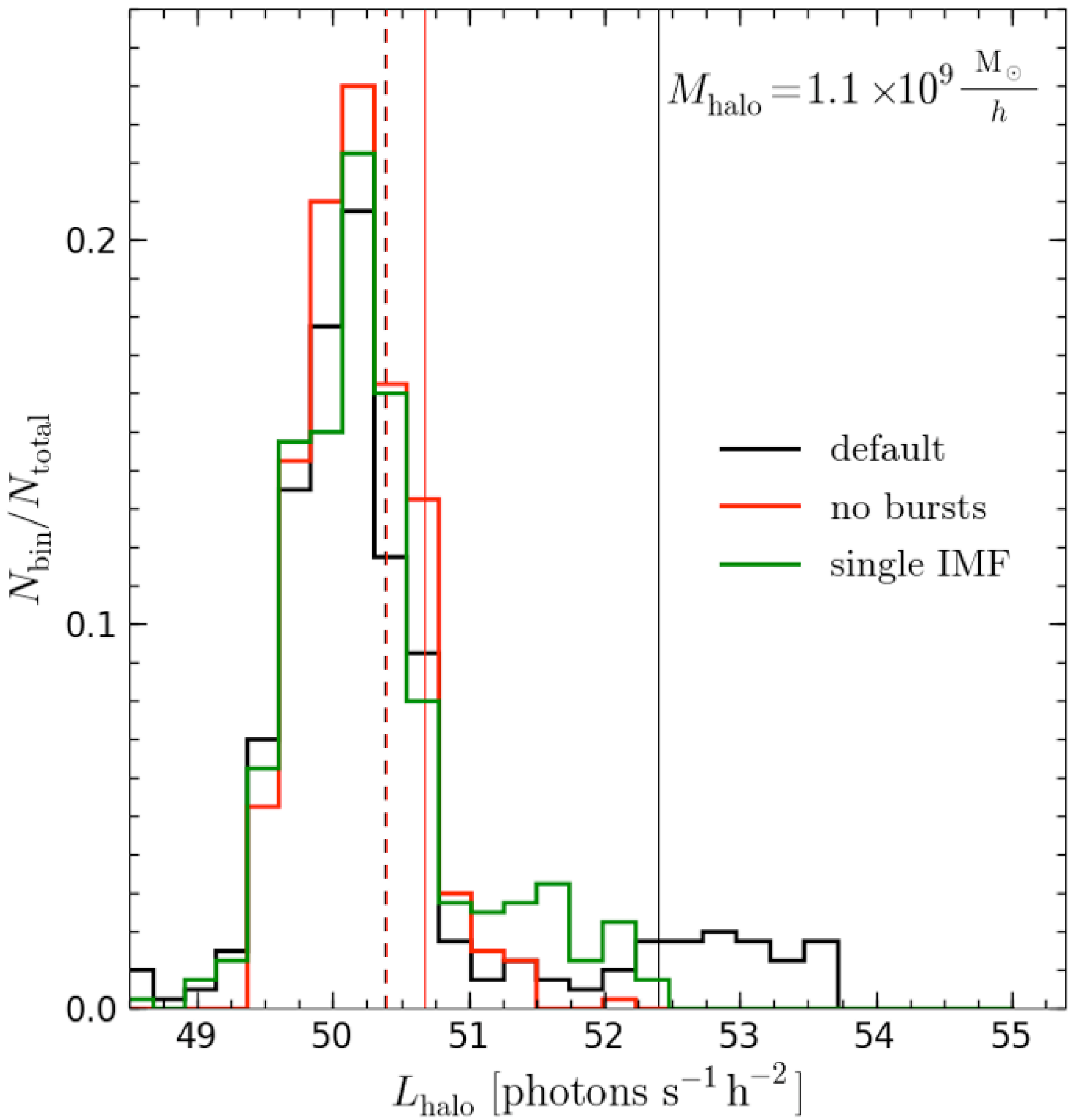


E-ELT integration time with Laser-Tomography Adaptive Optics Tom Theuns

Which galaxies produce the ionizing photons? SFRs.

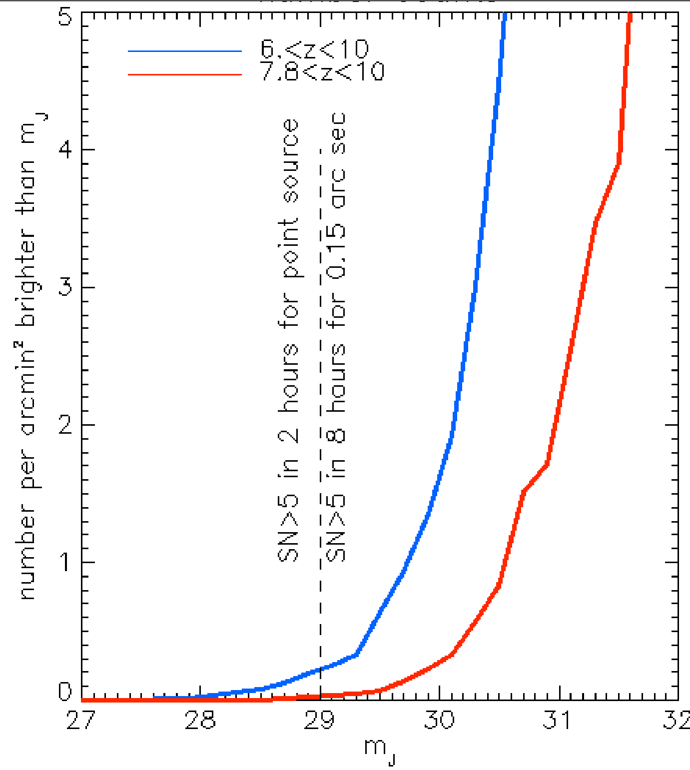


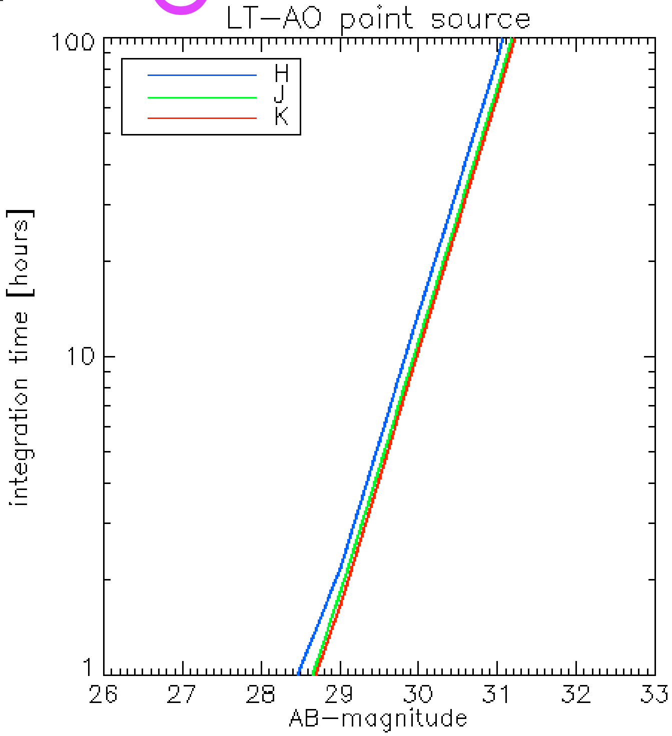
Bursts cause large dispersion in luminosity as function of halo mass

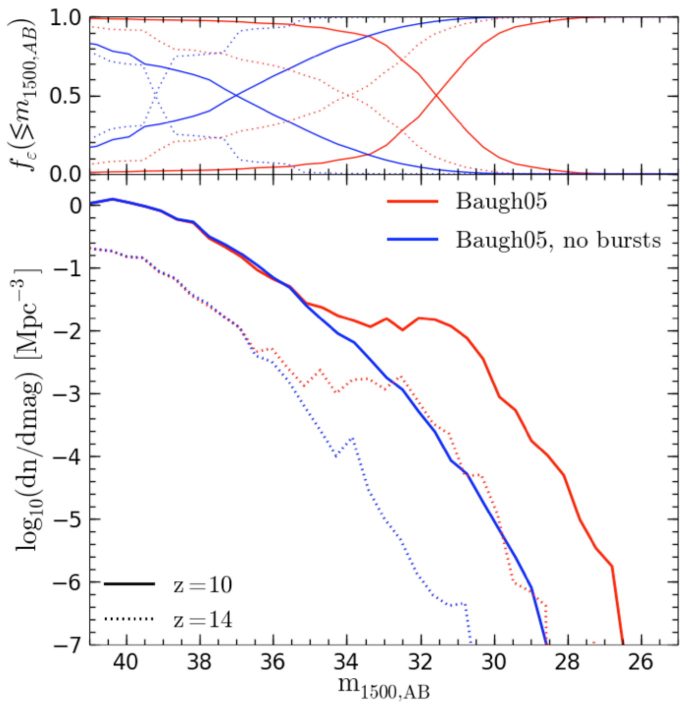


Observability of reionization galaxies with JWST/E-ELT

Violeta Gonzalez



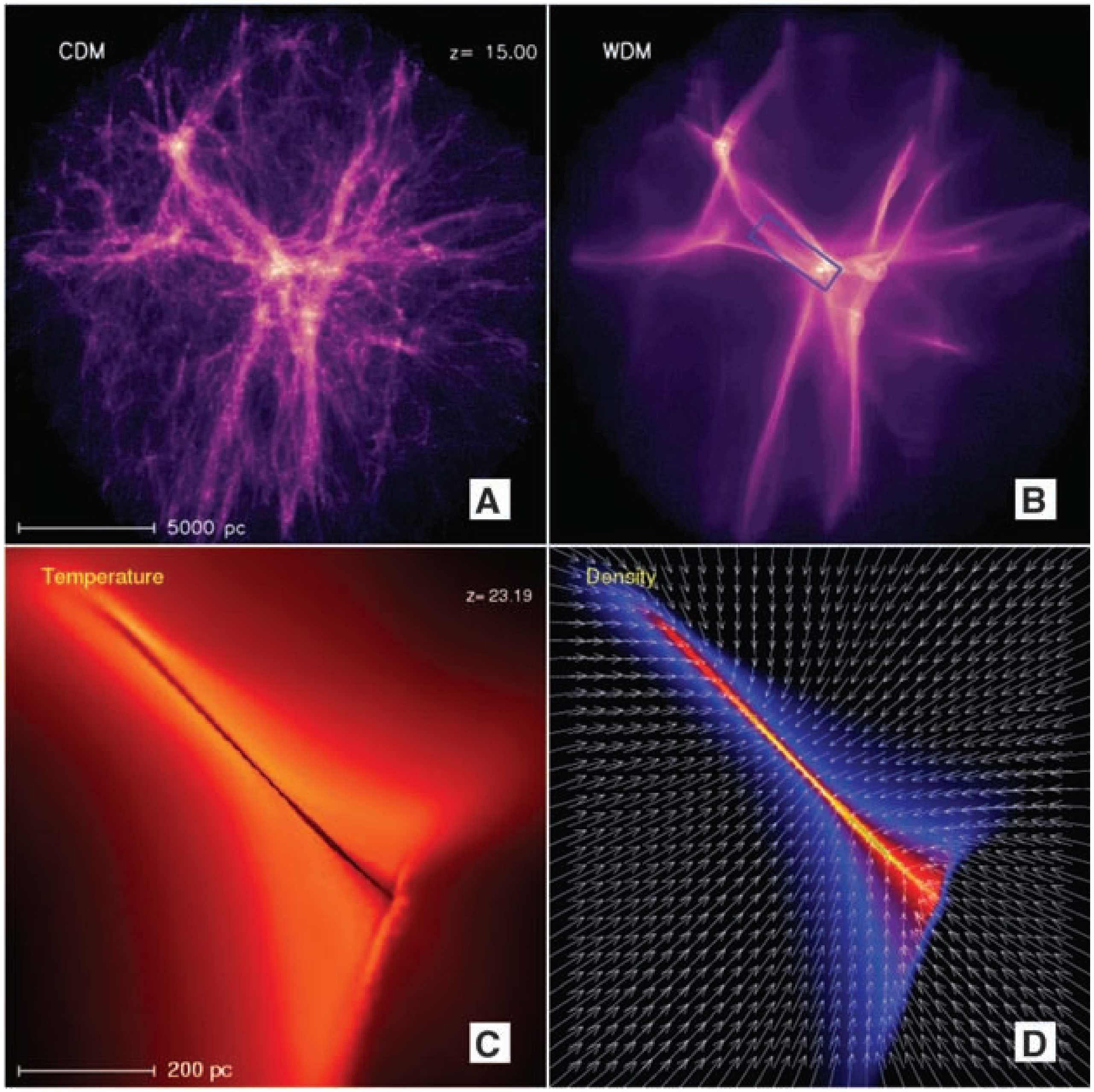




Lighting the Universe with Filaments

Sci 317, 2007

Liang Gao[1*] and Tom Theuns[1,2]



Conclusions

- Full hydro-sims provide reasonable number of ionising photons
    - caveat: faint-end slope too steep at low-z
- GalForm gives galaxies z>6 with observed colours and luminosities; currently detected galaxies contribute little to ionisation rate
- most ionising photons produced in small galaxies, with top-heavy IMF during a burst
- escape fractions of 0.1-1 give reasonable reionisation redshift
- source suppression in GalForm has only small effect on reionisation redshift
- combined Simplex + GalForm can generate model in a few days on a desk-top computer, with full statistics on galaxy population at all z.

Thank you!