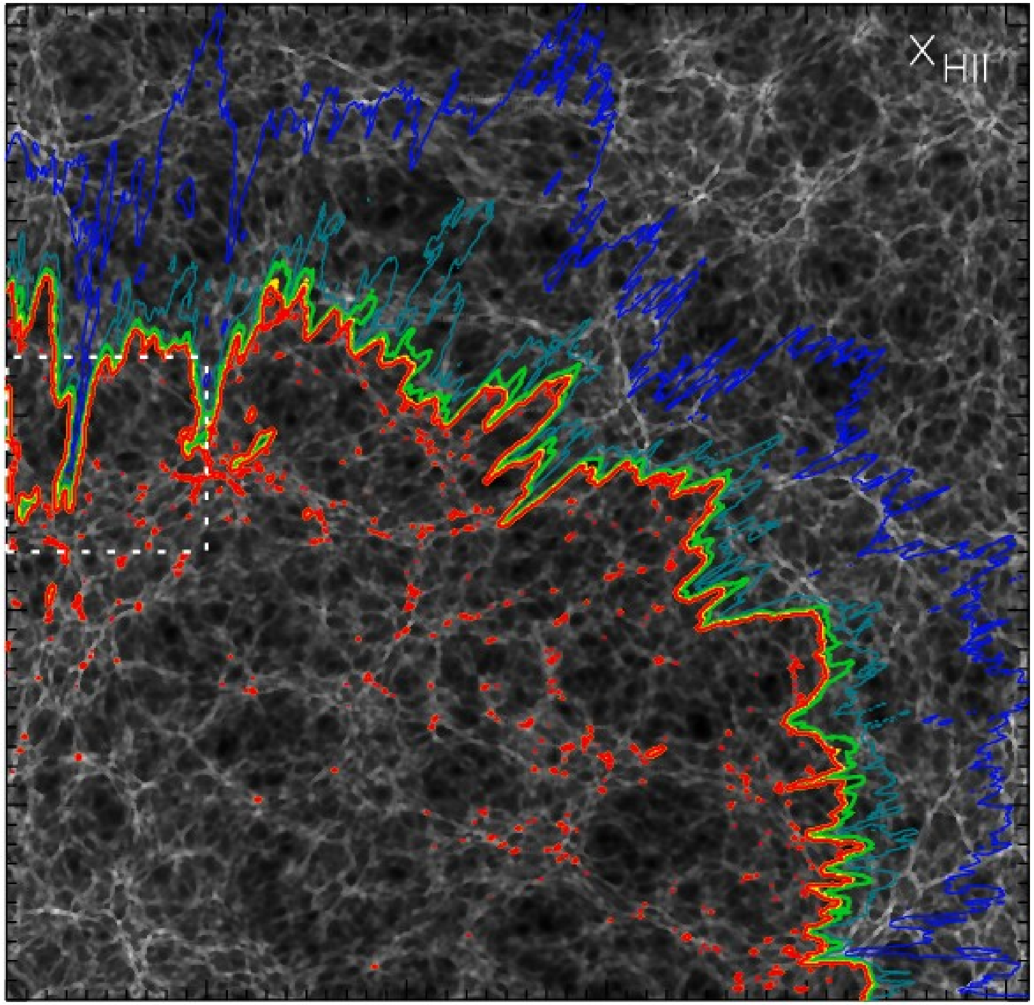


Research Report

Luca Graziani

SCUOLA NORMALE SUPERIORE

- Radiative transfer/Reionization
- Galaxy Formation/Evolution
- Cosmic Dust

Luca Graziani, Scuola Normale Superiore, 09 November 2017, Pisa, Italy

Radiative transfer

- **Solves the radiation transfer through media**
- **Radiation intensity I(ν), frequency (n), spatial coordinates (r,W), time (t)**
- **Absorption κ(ν), emission ε(ν), scattering s(n).**

$$\frac{1}{c}\frac{\partial I}{\partial t} + \vec{\Omega}\cdot\vec{\nabla} I = \epsilon - \kappa I ,$$

Time · Space · Emission · Absorption

Method I: expand the intensity function in a series of momenta

$$I(z,\nu,\mu,t) = \sum_{n=0}^{\infty} \frac{2n+1}{4\pi} I_n(z,\nu,t)\, P_n(\mu)$$

$$I_n(z,\nu,t) = 2\pi \int_{-1}^{+1} I(z,\nu,\mu,t)\, P_n(\mu)\, d\mu$$

Method II: statistically sample the photon field + simulate the radiation-to-matter interaction processes

MONTE CARLO approach

Radiative transfer modelling in protoplanetary disks with the P-N Approximation and Monte Carlo techniques

Mathematical Methods in the Applied Sciences

Published online 18 February 2010 in Wiley InterScience

L. Graziani,[a,b*†] L. Barletti,[c] S. Aiello[b] and C. Cecchi-Pestellini[d]

we solve the stationary RTE for the specific intensity field $I(\vec{r},\nu,\vec{\mu})$:

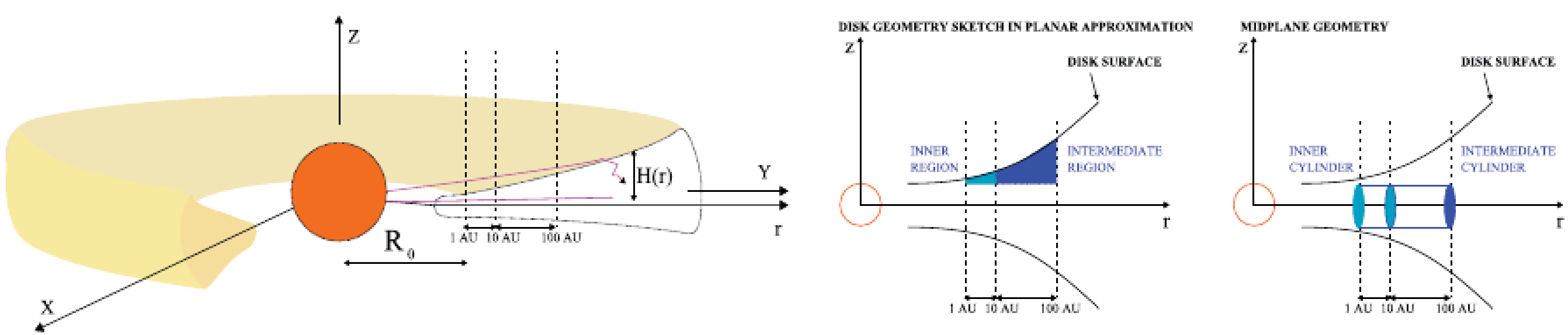
$$\vec{\mu}\cdot\vec{\nabla}I(\vec{r},\nu,\vec{\mu})+\bar{\sigma}I(\vec{r},\nu,\vec{\mu})=\int_0^{\infty}\mathrm{d}\nu'\int_{4\pi}\mathrm{d}\vec{\mu}'\,\frac{\nu}{\nu'}\sigma_S(\nu'\to\nu,\vec{\mu}'\cdot\vec{\mu})I(\vec{r},\nu',\vec{\mu}')$$

$\vec{\mu}\equiv$ photon flying direction, $\nu\equiv$ photon frequency, $\bar{\sigma}\equiv$ total interaction coeff., $\sigma_S\equiv$ in-scattering coeff.

Mid-plane disk region and the cylindrical problem

$$\vec{i}_r=\cos\theta\vec{i}+\sin\theta\vec{j},\quad \vec{i}_z=\vec{k},\quad \vec{i}_\theta=\vec{i}_z\wedge\vec{i}_r=-\sin\theta\vec{i}+\cos\theta\vec{j}$$

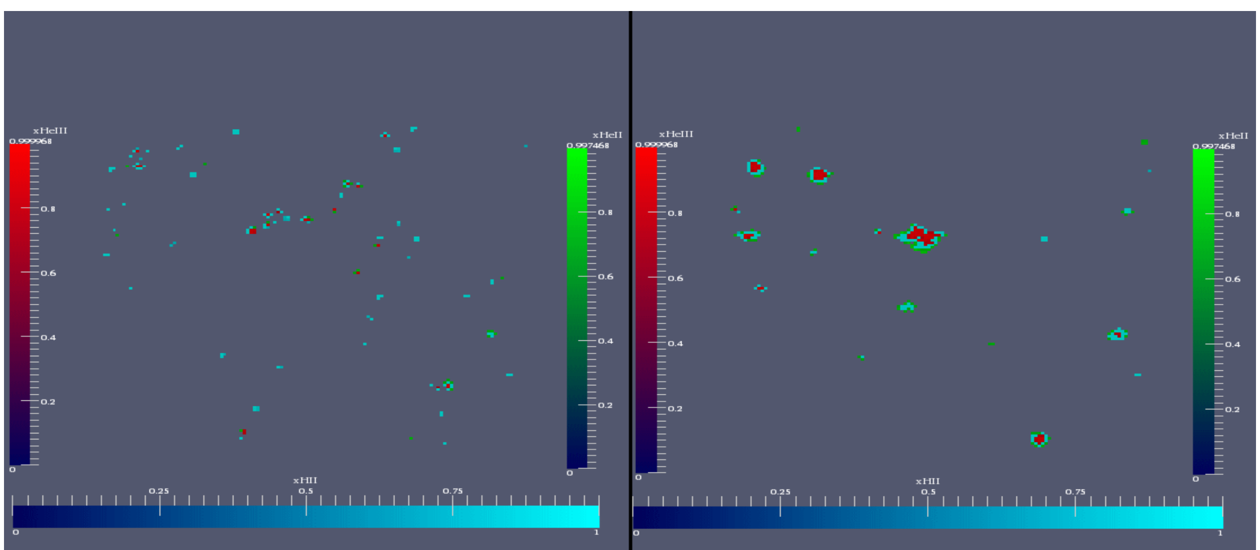
$$\vec{\mu}=\sqrt{1-\mu^2}\cos\varphi_1(\cos\theta\vec{i}+\sin\theta\vec{j})+\sqrt{1-\mu^2}\sin\varphi_1(-\sin\theta\vec{i}+\cos\theta\vec{j})+\mu\vec{k}=\sqrt{1-\mu^2}\cos(\theta+\varphi_1)\vec{i}+\sqrt{1-\mu^2}\sin(\theta+\varphi_1)\vec{j}+\mu\vec{k}$$

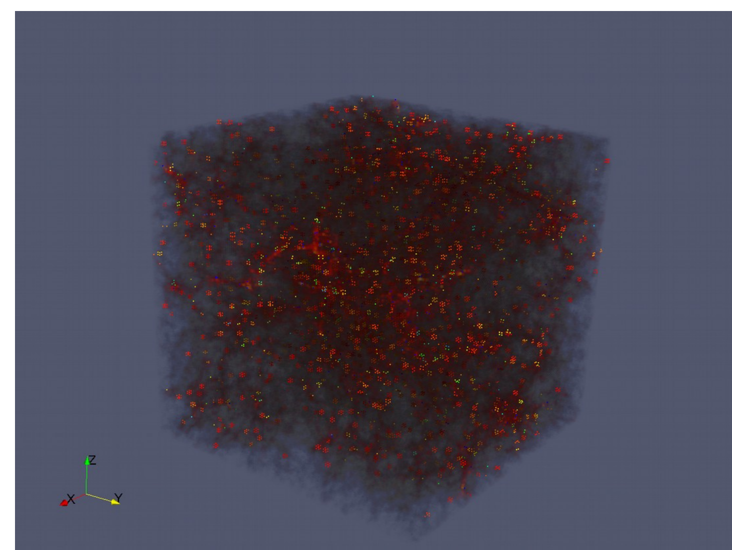


C.R.A.S.H.

Cosmological RAdiative transfer Scheme for Hydrodynamics (Ciardi 2001, Maselli 2003, 2009)

- RT code based on MC + Ray tracing.
- Describes ***3D*** RT cosmological scenarios.
- Solves ***time dependent*** RT on cosmological scales → **Cosmic Reionisation of H and He** (intermediate scale)
- Implements ***detailed H,He physics + metal ions (in pipeline with other codes)*** .

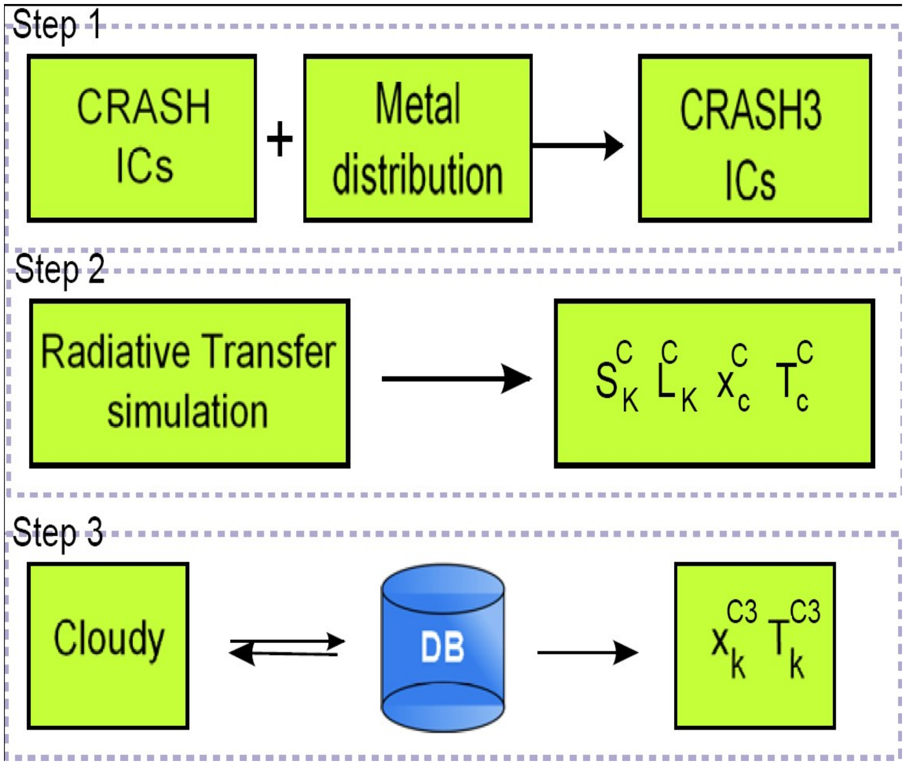




CRASH3: cosmological radiative transfer through metals

L. Graziani,[1]★ A. Maselli[2] and B. Ciardi[1]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS (2013)



STEP1: **Where are the metals?** Extends CRASH ICs by describing the metal distribution in space (k-cells).

STEP2: **RT through H, He**. Extracts spectra in each k-cell during a RT simulation in the entire domain (c-cells)

STEP3: **Compute Metal ions**. Runs Cloudy configs based on (S_k,L_k).

PROBLEMS: → What is the sensitivity of the method?
→ Can we detect fluctuations in ions due to the cosmic web and/or the sources?
→ How important is the contribution in absorption due to the column of metals?

Graziani, Maselli, Ciardi MNRAS, 2013

The effect of intergalactic helium on hydrogen reionisation: implications for the sources of ionising photons at $z > 6$

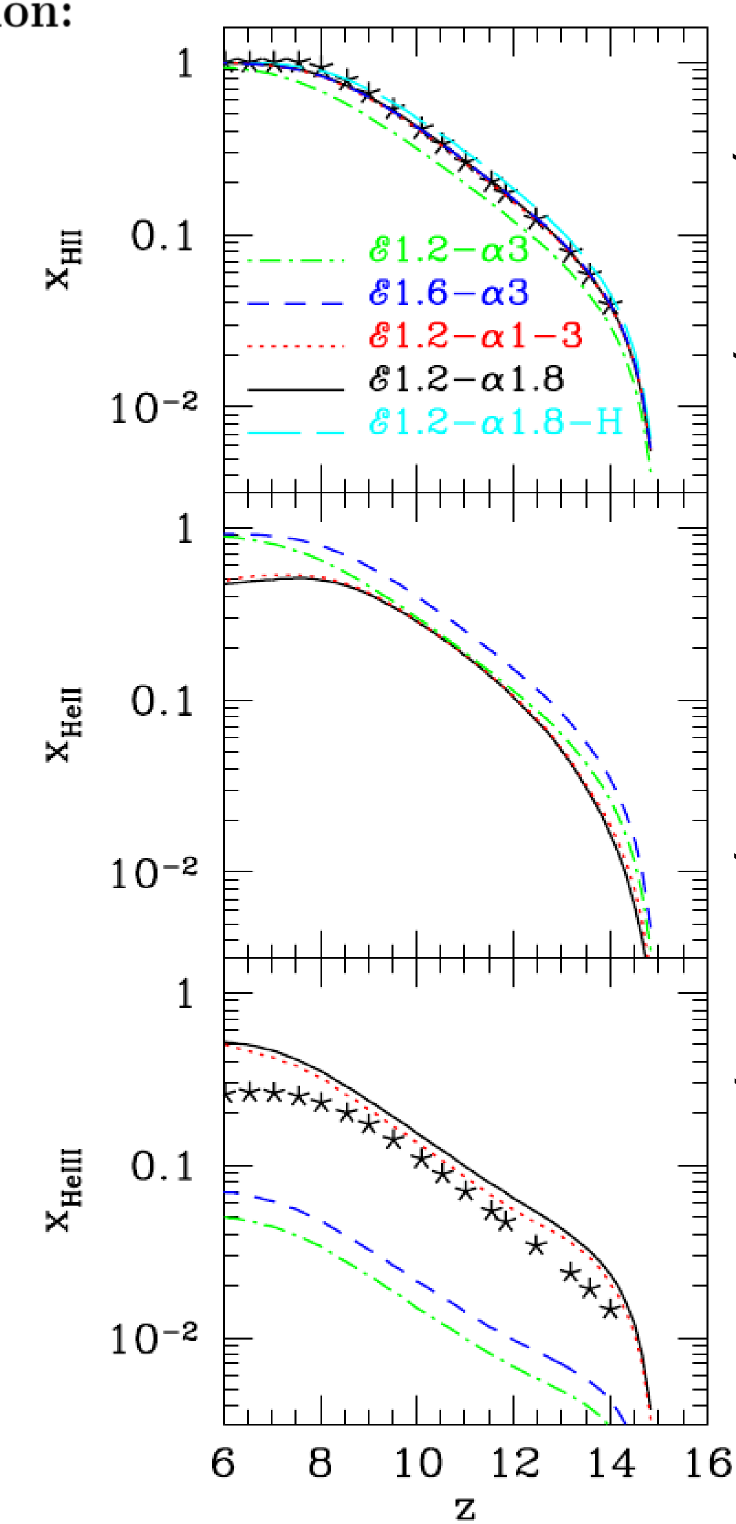
B. Ciardi[1★], J.S. Bolton[2], A. Maselli[3] and L. Graziani[1]

Monte Carlo Radiative Transfer code

(H-ionising UV: 13.6 eV – 200 eV)

Scale: 30 cMpc/h

- Ionisation fractions of H, He
- Gas temperature
- Radiation intensity / SED
- Ionisation and heating rates
- Reionisation history: x(z) ,T(z)



Ciardi, Bolton, Maselli & Grazianil, MNRAS, 2012

The effect of intergalactic helium on hydrogen reionisation: implications for the sources of ionising photons at $z > 6$

B. Ciardi[1⋆], J.S. Bolton[2], A. Maselli[3] and L. Graziani[1]

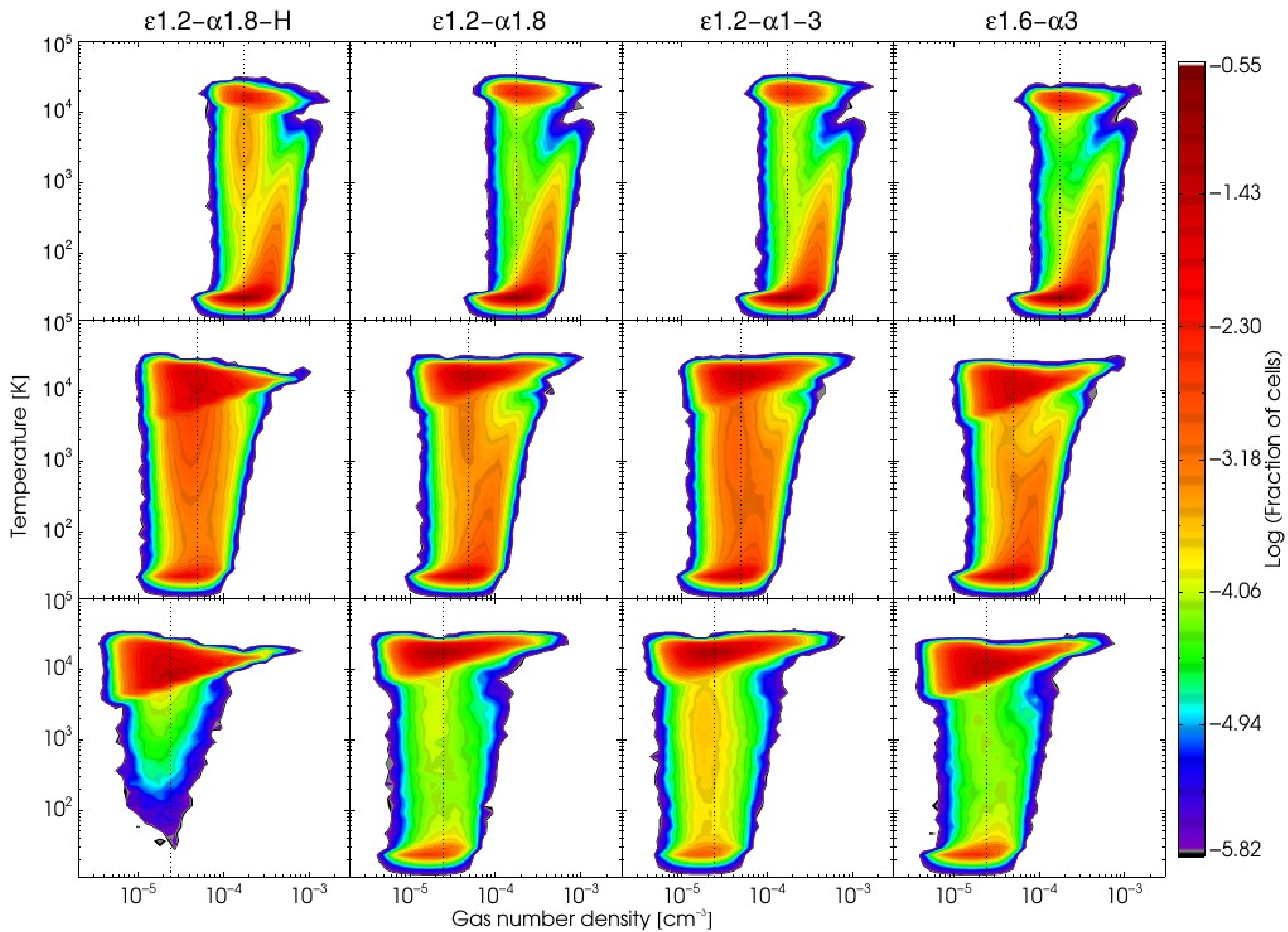
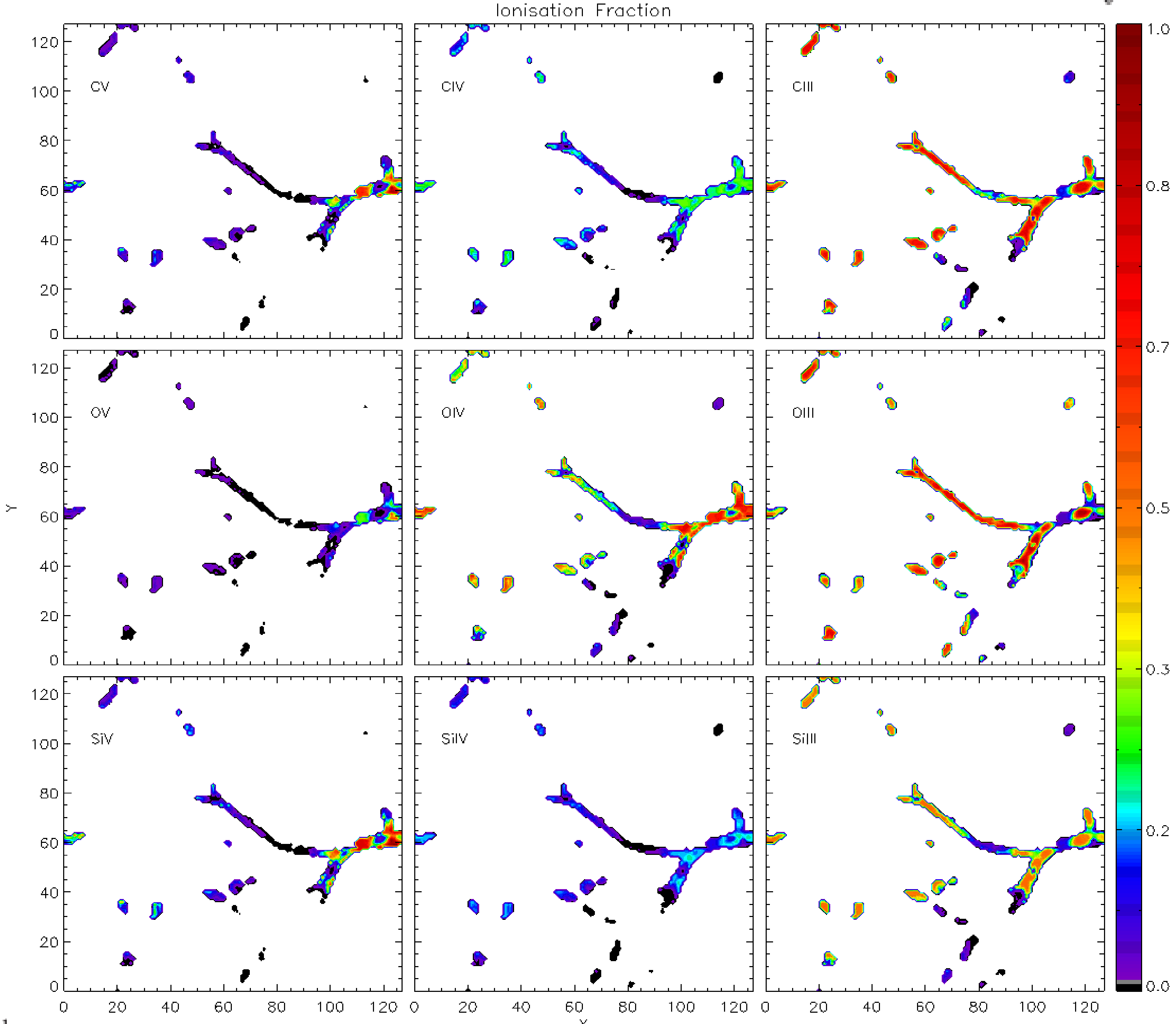


Figure 7. Contour plots of the distribution of gas temperature against proper number density for models $\mathcal{E}$1.2-α1.8-H, $\mathcal{E}$1.2-α1.8, $\mathcal{E}$1.2 α1-3 and $\mathcal{E}$1.6-α3 (from left to right). The colour scale corresponds to the percentage of cells within each contour. The rows refer t redshift z=14, 9 and 7 (from top to bottom). The dashed vertical lines correspond to the average density in the box.

Metal ions in cosmic web filaments

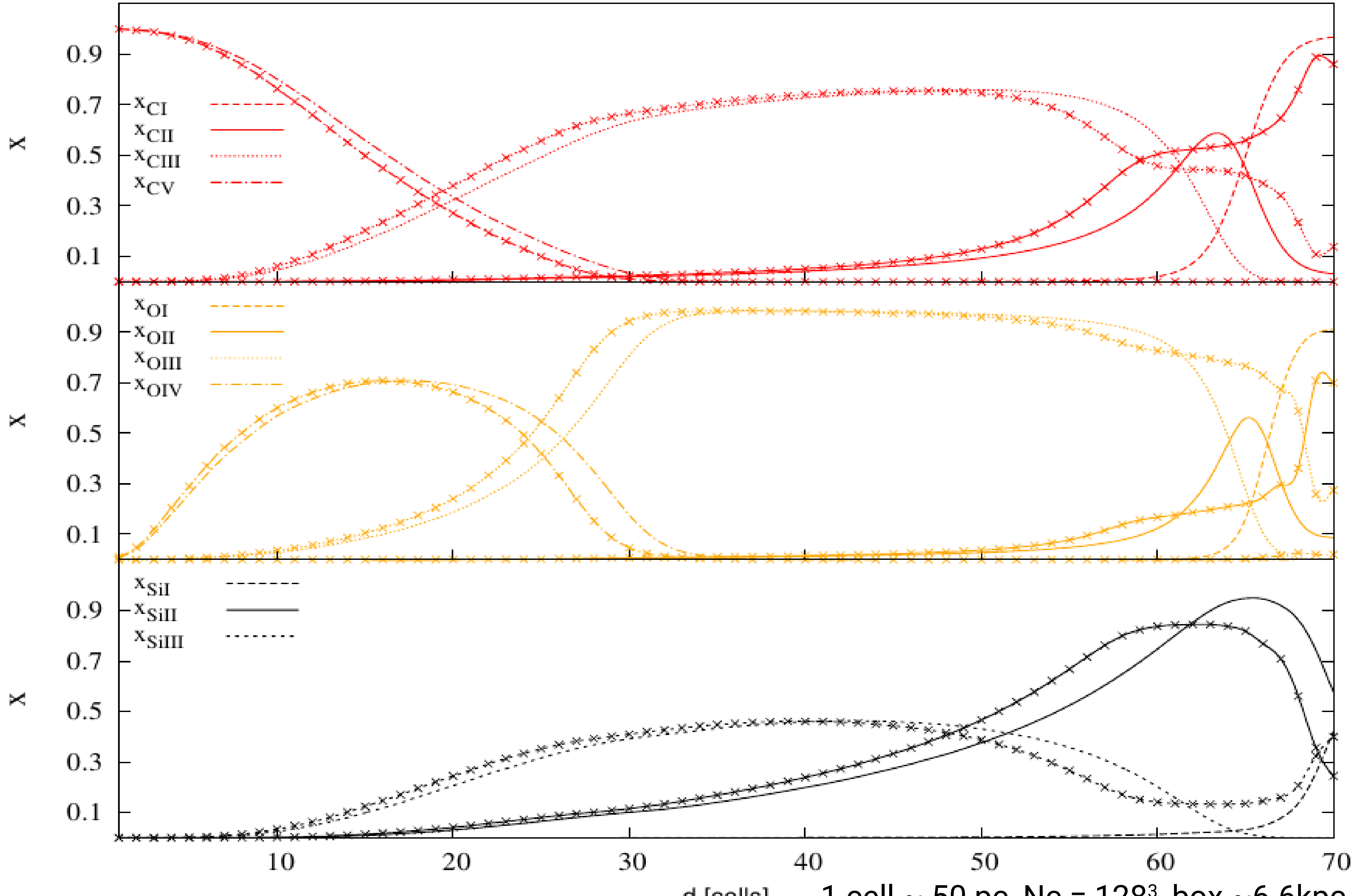
$Z_g = \Delta \times 0.0064 Z_\odot$



$L_b = 0.5\, h^{-1}$ Mpc

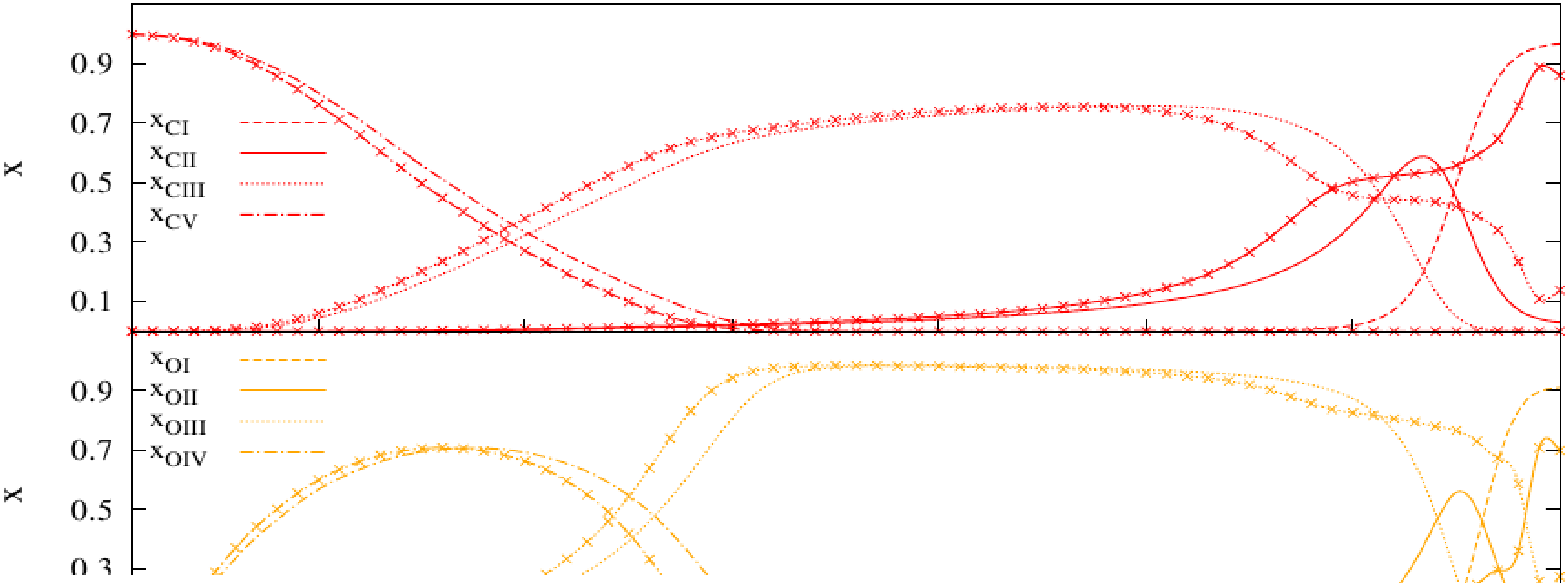
Graziani, Maselli, Ciardi MNRAS, 2013

Metal ions are sensitive to other bands



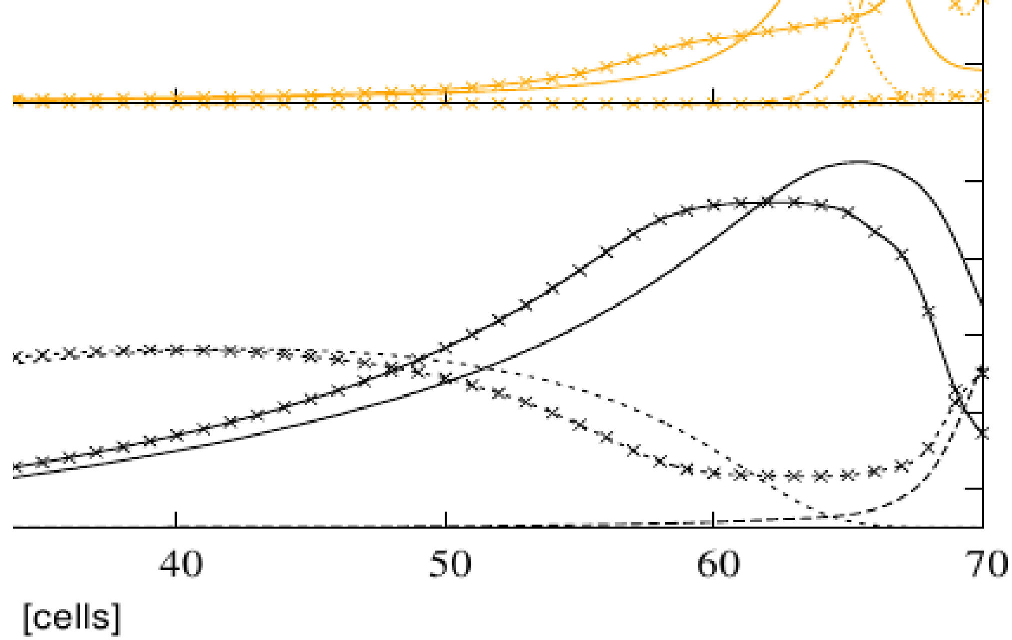
1 cell ~ 50 pc, Nc = 128^3, box ~6.6kpc

Metal ions are sensitive to other bands



E_{ion} [eV]	H	He	C	O	Si
E_{xI}	13.598	24.587	11.260	13.618	8.152
E_{xII}		54.400	24.383	35.118	16.346
E_{xIII}			47.888	54.936	33.493
E_{xIV}			64.494	77.414	45.142
E_{xV}			392.090	113.900	166.770
E_{xVI}			489.997	138.121	205.060

Table 1. Ionisation potentials for H, He, C, O and Si up to the ionisation level VI as used in `Cloudy`.



UV background modelling at z~3

- **UVB uncertain at z~3:** **F. Haardt and P. Madau assume spatially uniform UVB** and model it with 1D code (**CUBA**).
- For photons E>1Ryd (13.6 eV) the **HM assumption can fail** at z~3:

1) POINT SOURCE VARIABILITY:

- **QSOs are rare in space + clustering**
- **Finite lifetime**
- **Spectral variability**

→ HeII reionization is completed by QSOs at z~3 ?

2) RADIATIVE TRANSFER EFFECTS: could affect small and large scales

- Small scale (~10h^{-1} Mpc) RT effects (Maselli&Ferrara 05)
- Large scale: filtering but.. collisionally ionised gas could produce N_{heII}/N_{HI}<10.

SPATIAL FLUCTUATIONS OF THE UVB INTENSITY AND SPECTRAL SHAPE ARE TRACED H, He..

→ **CAN WE USE METAL IONS ??**

Metal ions used to trace the spatial fluctuations of the UVB in the IGM

He reionisation → Fluctuations → metal ions

- **η**: in a photo-ionised IGM is **proportional to the spectral shape** of the ionising background (Miralda-Escude' 93).

$$\eta \propto \frac{\Gamma_{HI}}{\Gamma_{HeII}},$$

Γ_{HI},Γ_{HeII} are photo-ionisation rates of HI and HeII.

→ **Spatially fluctuating spectral shape?**

- **T**: equation of state of photo-ionised medium follows (Hui&Gnedin 97; Valageas et al. 02):

$$T = T_0 \Delta^{\gamma - 1},$$

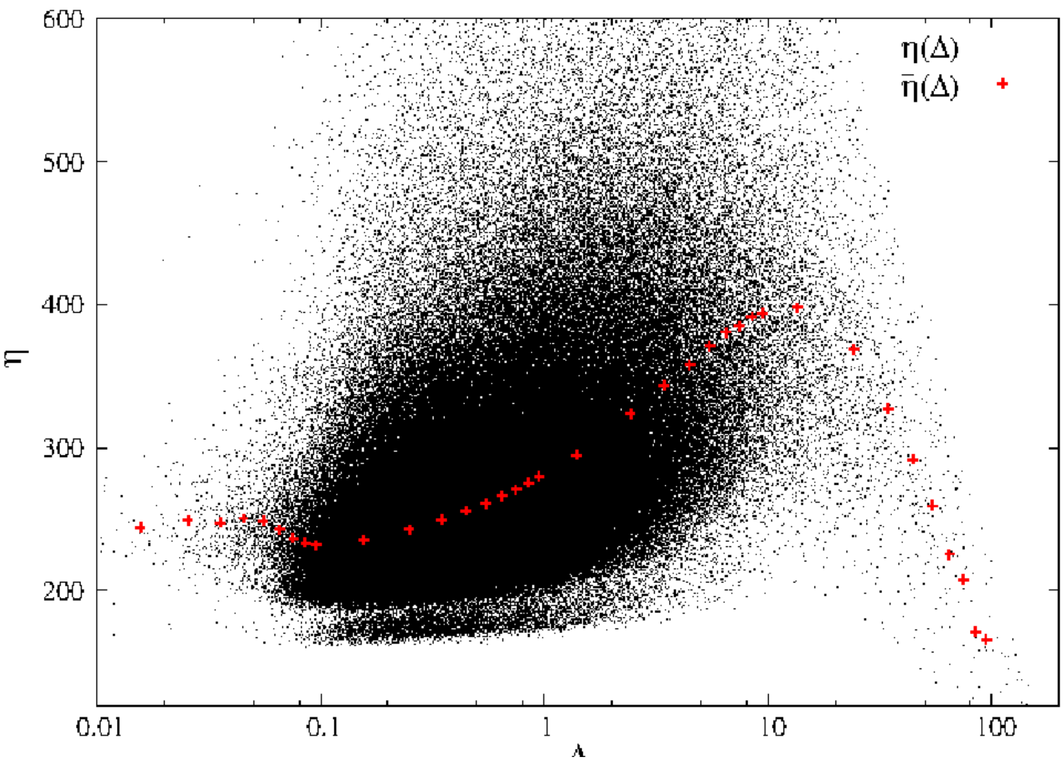
where T_0 is temperature at mean density and Δ is the gas overdensity. → **Fluctuations in γ ?**

Fluctuations in η

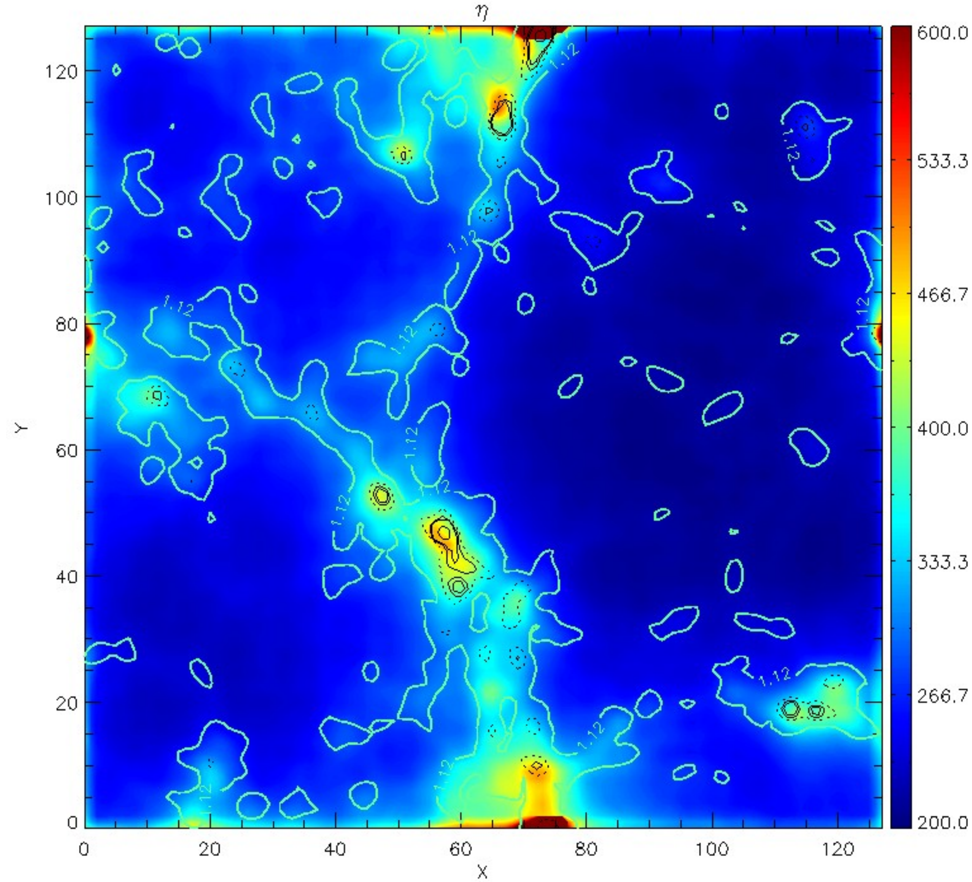
We use the approximation in Fardall 98..

$$\eta \sim \frac{\alpha_{\rm HeII}(T)}{\alpha_{\rm HI}(T)} \frac{n_{\rm HeIII}}{n_{\rm HII}} \frac{\Gamma_{\rm HI}}{\Gamma_{\rm HeII}},$$

Evident **spatial correlation $\eta(\Delta)$**



Scatter plot of $\eta(\Delta)$ at t~5.5 10[6] yrs. The average value of $\eta(\Delta)$ in red crosses.



Slice cut at t~5.5 10[6] yrs. Δ ~1 white solid line, Δ ~5 black dashed, Δ~10 black solid

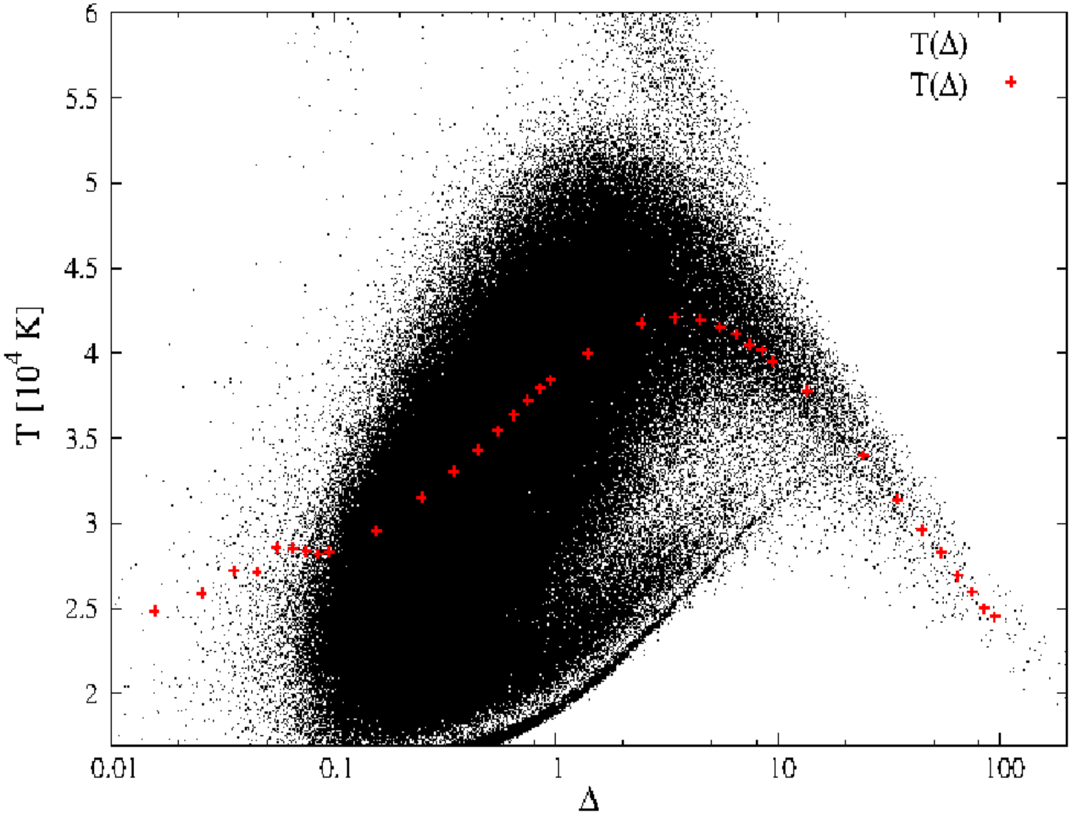
- $<\eta>$ ~ 277 at z~3
- **210 < η < 285 in 80% cells volume, $\delta\rho/<\rho>$ ~ 10-20% fluctuations.**
- **$\delta\rho/<\rho>$ up to 60% in 20% volume.**

Fluctuations in T

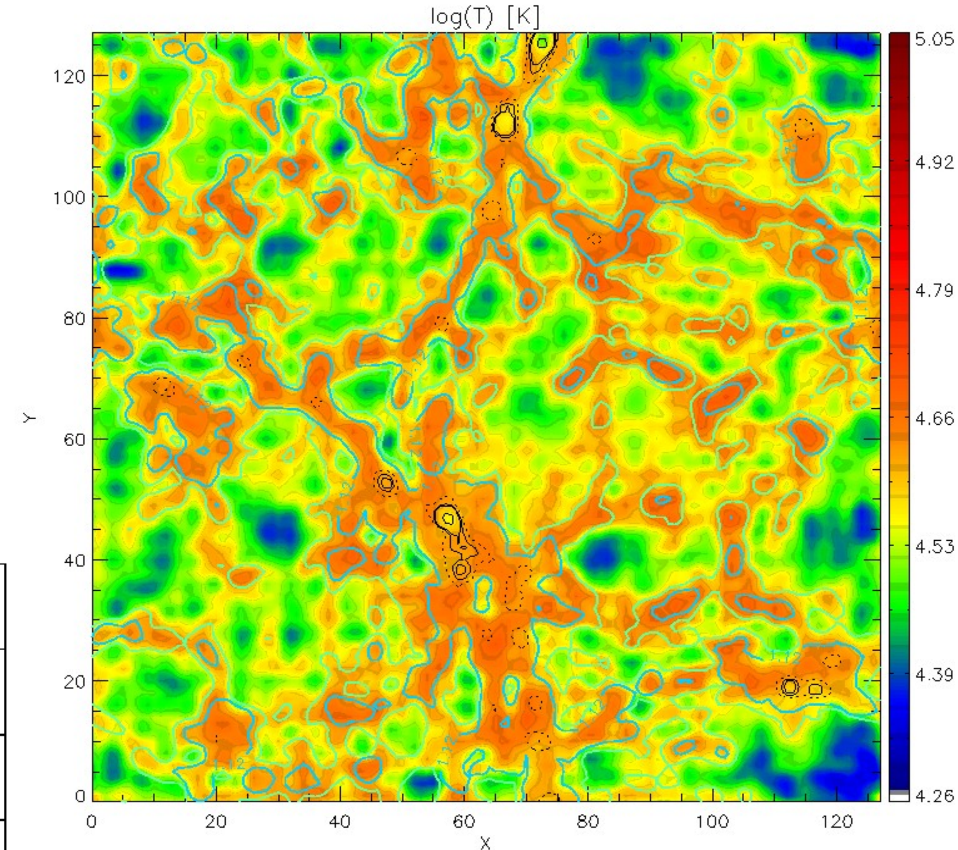
Calculated self-consistently with H,He, metal cooling.

Evident **spatial correlation T(Δ)**

Metal cooling efficient in **few percent of volume** (Z >0.5ZSol) introduces scatter**.**



Scatter plot of T(Δ) at t~5.5 10^6 yrs. The average value of T(Δ) in red crosses.



Slice cut at t~5.5 10^6 yrs. Δ ~0.5 cyan solid line, Δ ~1 white solid line, Δ ~5 black dashed, Δ~10 black solid

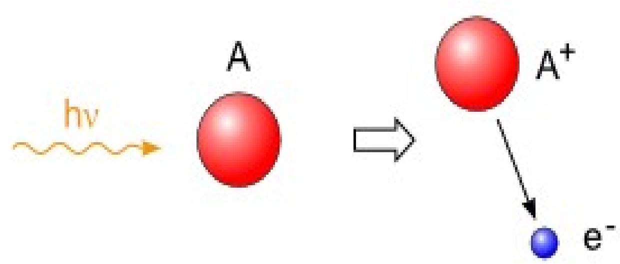
- **<T>** 3.2 10^4 [K] at z~3
- **δT/<T> ~ 10% in Δ < 1.**
- **δT/<T> up to 40% in Δ > 1.**

CRASH4 → Large scale Reionization

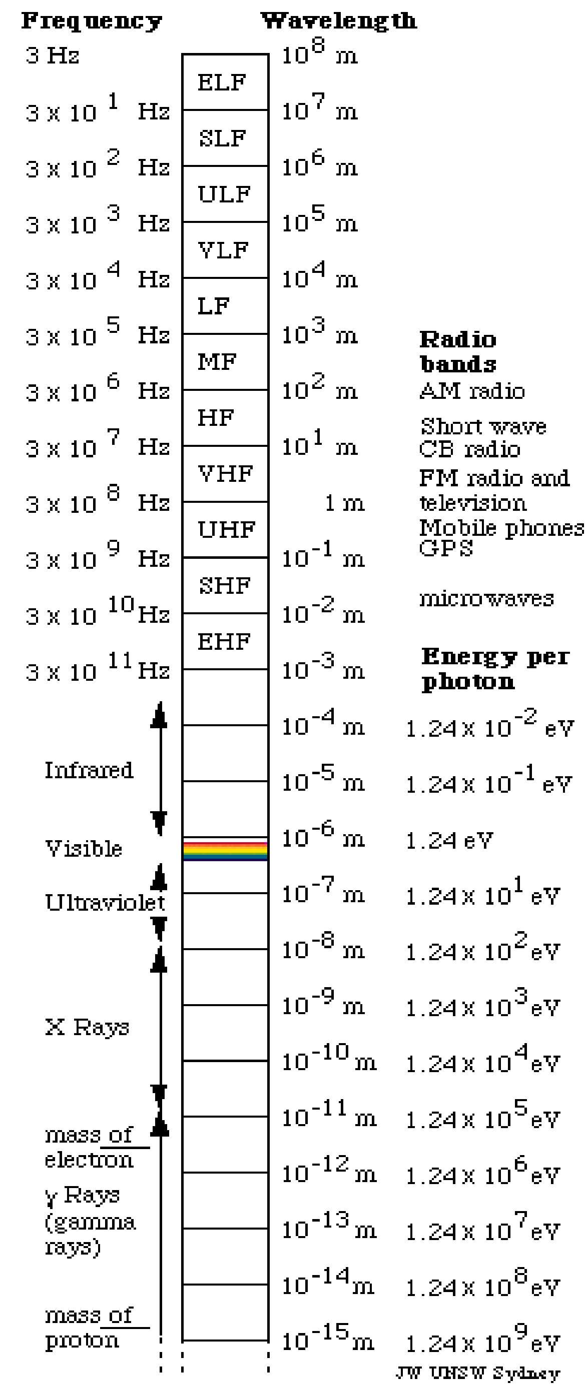
- **Multi-frequency band RT**:
  - → Extend up to soft x-rays: 10 KeV.
  - → Include Lyα RT coupled with continuum.
  - → LW band and molecules: H_2, CO.
  - → Dust → photon scattering **IS** relevant.

- Secondary ionisation

$$E_\gamma - I_A = E_e$$



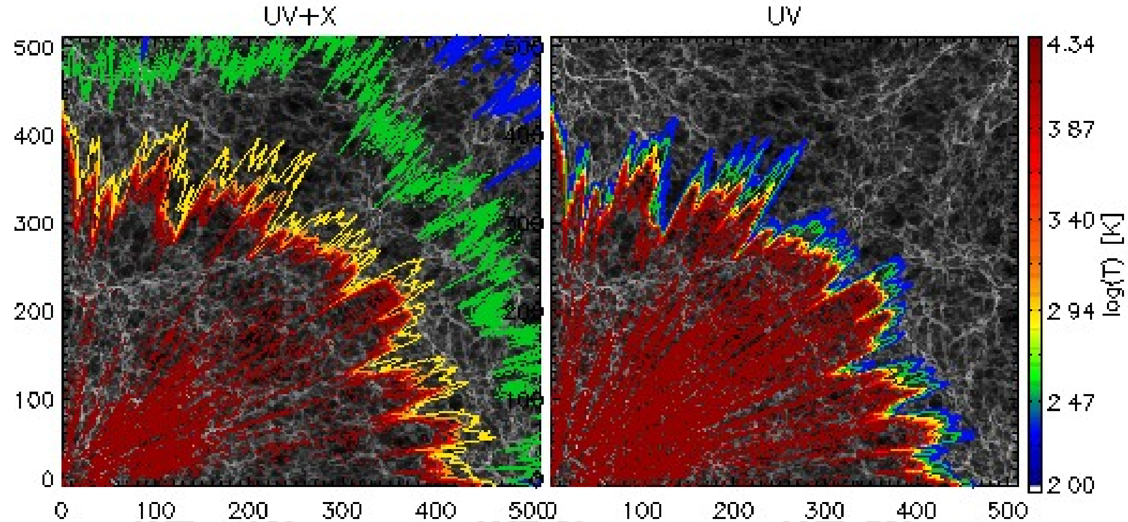
$E_e > 30eV$ could collisionally **ionise/excite** the remaning neutral part.

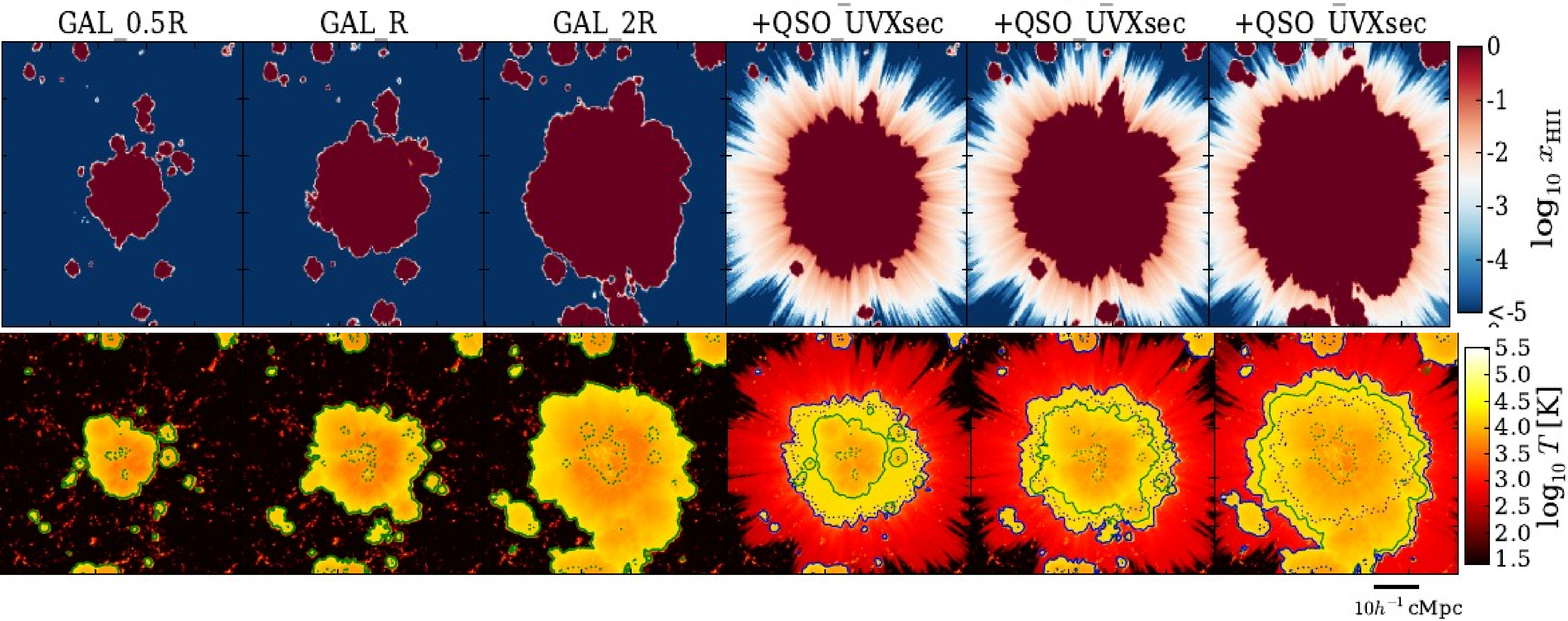


RT Feedback by ULAS J1120+0641 (LG et al. in prep.)

Effects of x-rays on HII regions of high-z QSOs

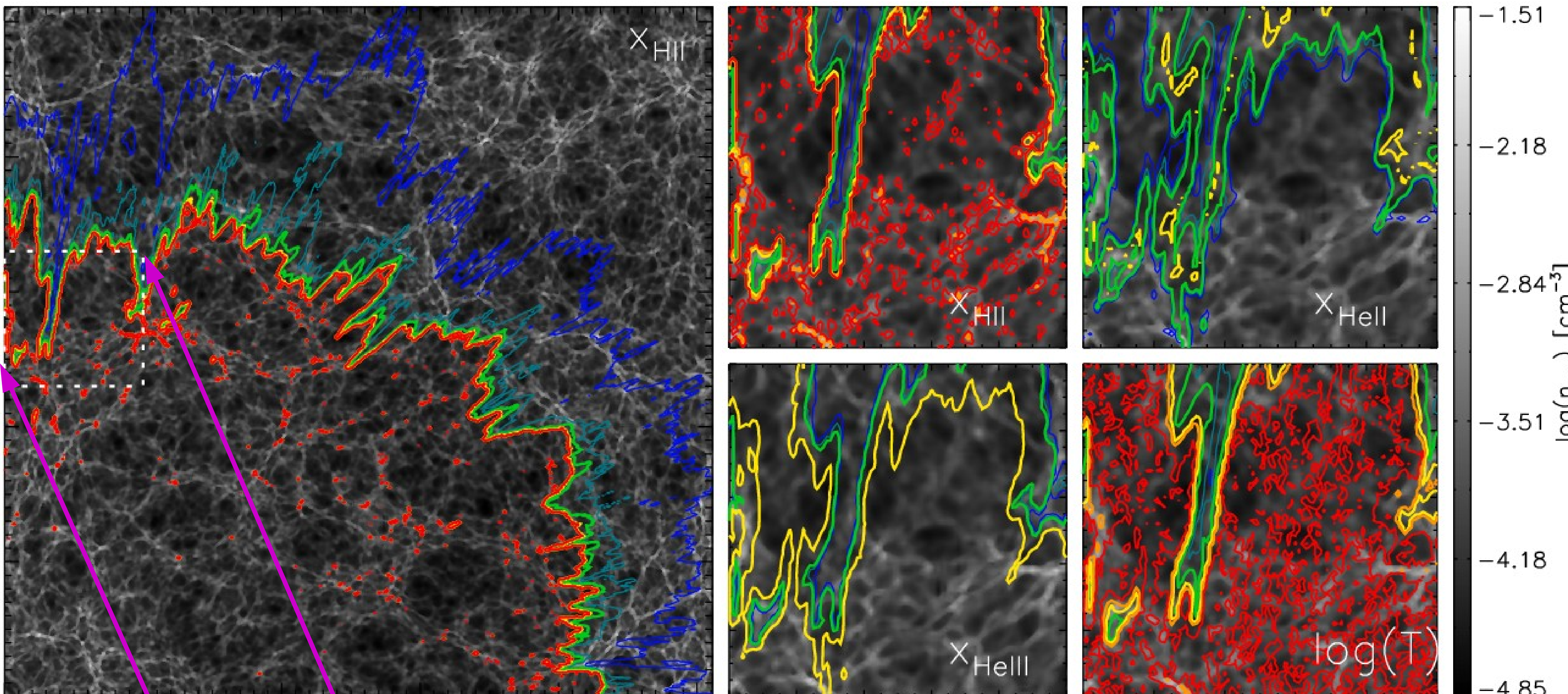
→ How big is the HII region?
→ Role on x-rays in heating ?

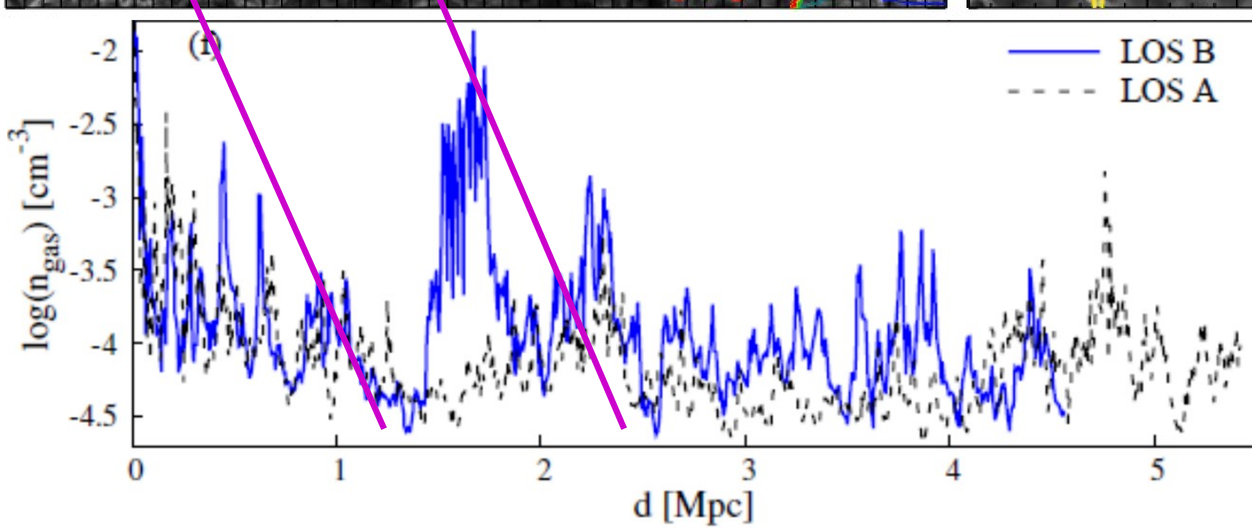




Kakiichi, Graziani, Ciardi et al. MNRAS, 2016

HII size on a peculiar LOS !





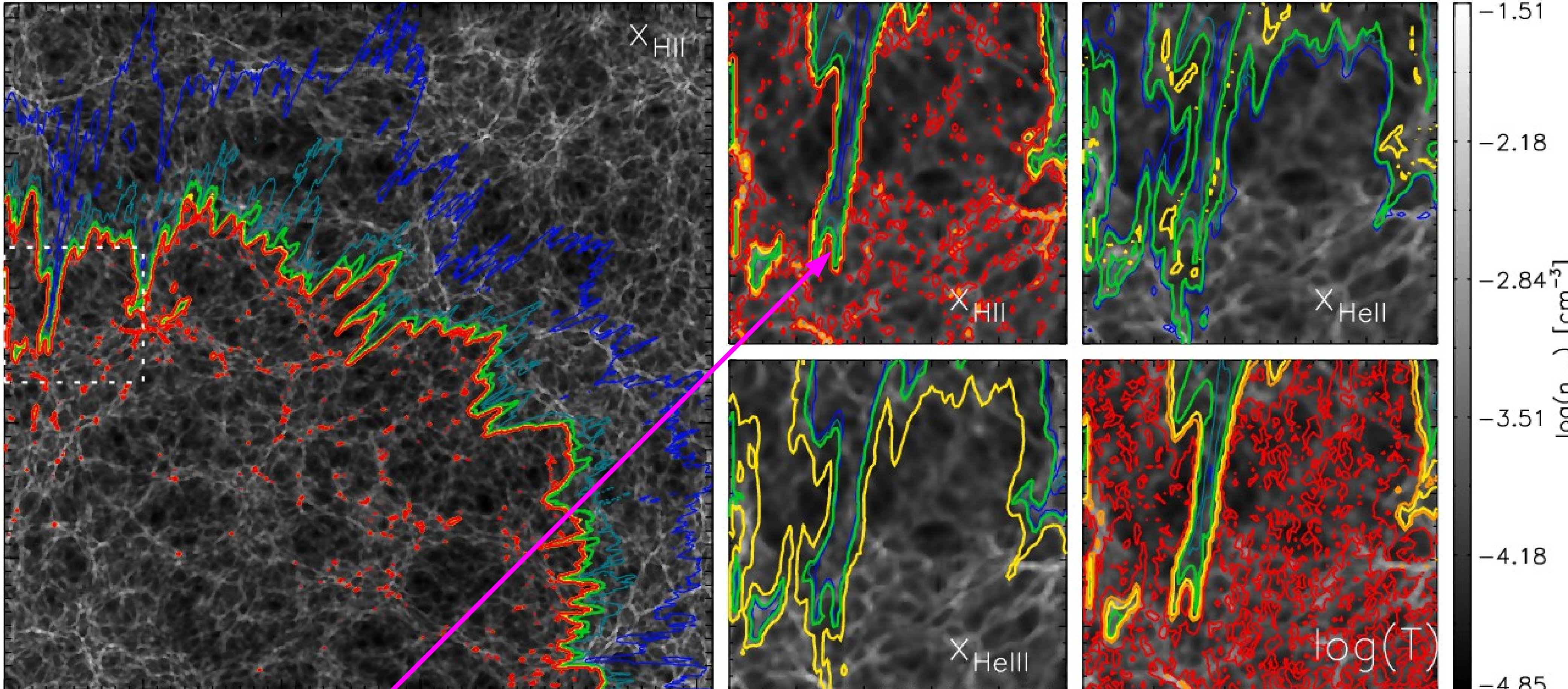
But on a peculiar LOS

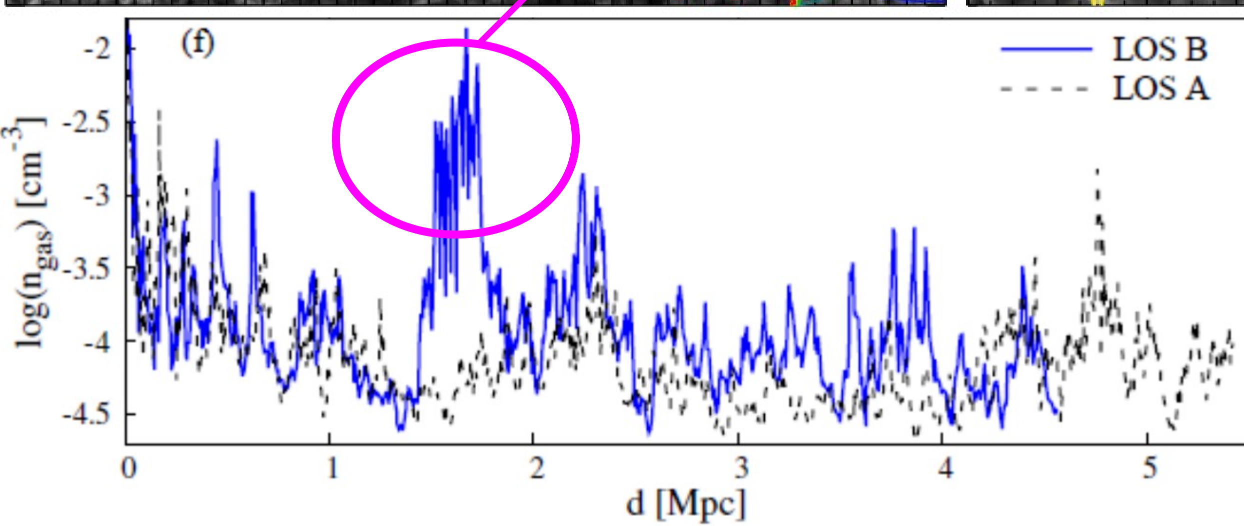
.. R_s < 2 pMpc!

RT effects matter!

$\square=\square(n,\sigma(\nu),d)$

HII size on a peculiar LOS !





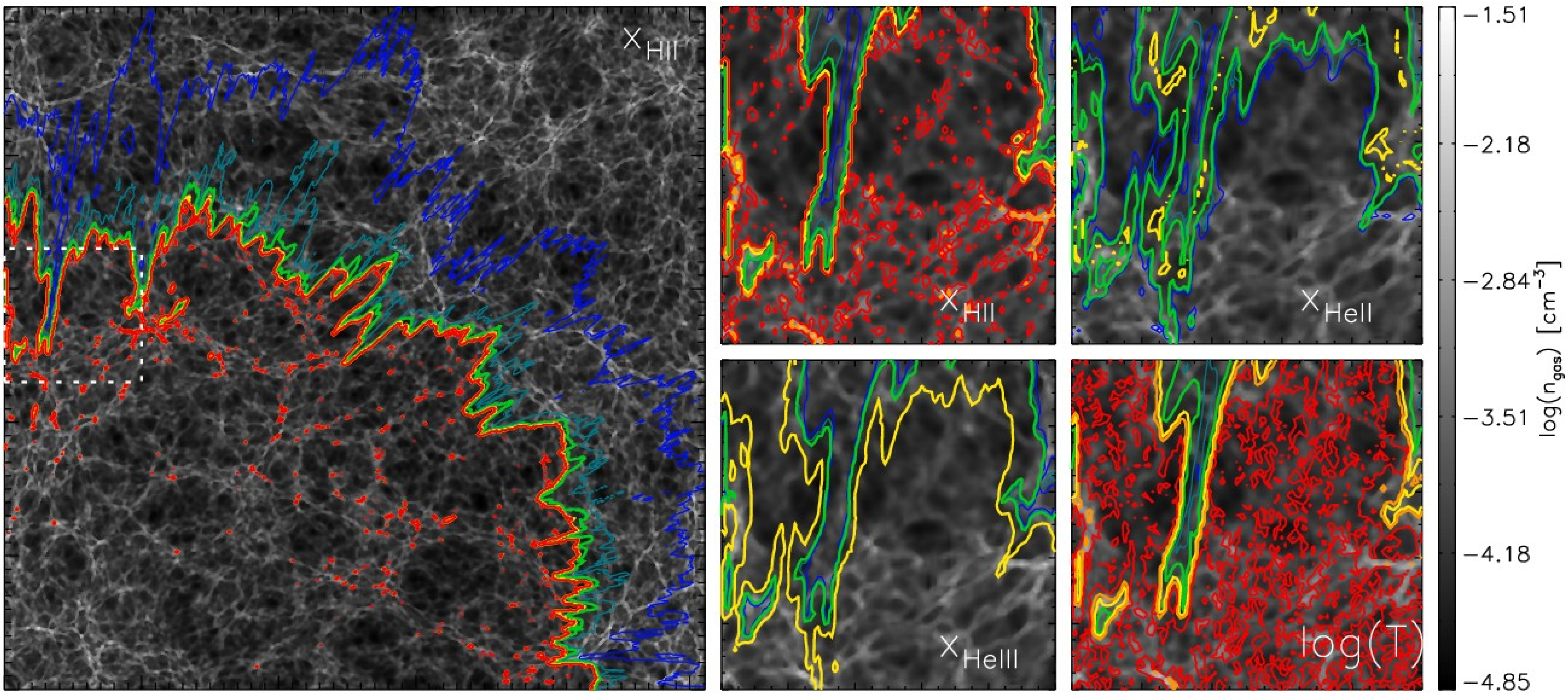
But on a peculiar LOS

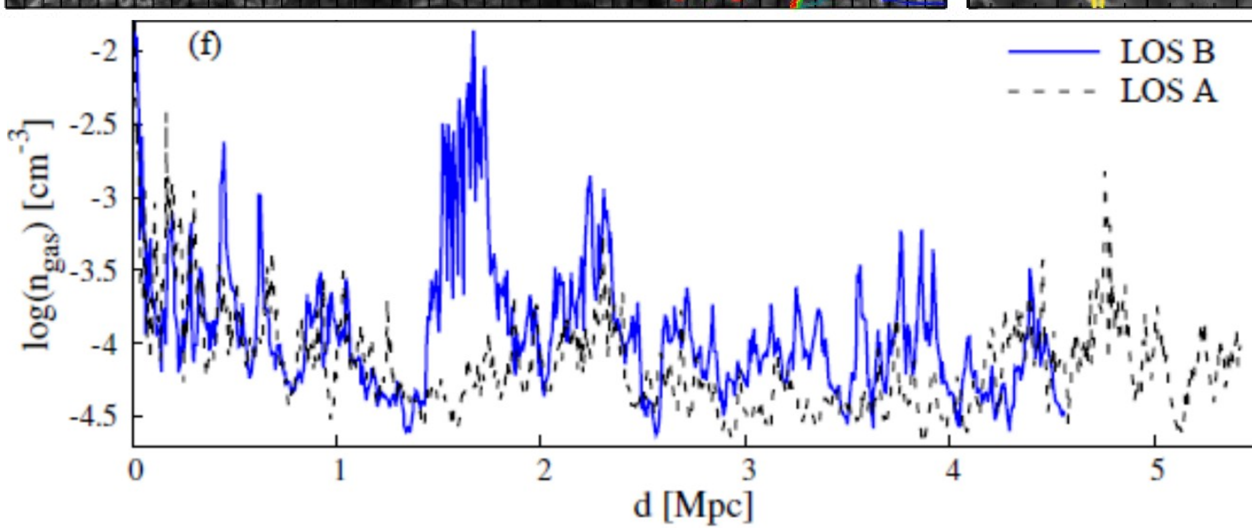
.. R_s < 2 pMpc!

RT effects matter!

$\square = \square(n, \sigma(\nu), d)$

HII size on a peculiar LOS → Scatter induced by RT !!





But on a peculiar LOS

.. $R_s < 2$ pMpc!

RT effects matter!

$\tau = \tau(n, \sigma(\nu), d)$

2) High-z QSOs IGM heating

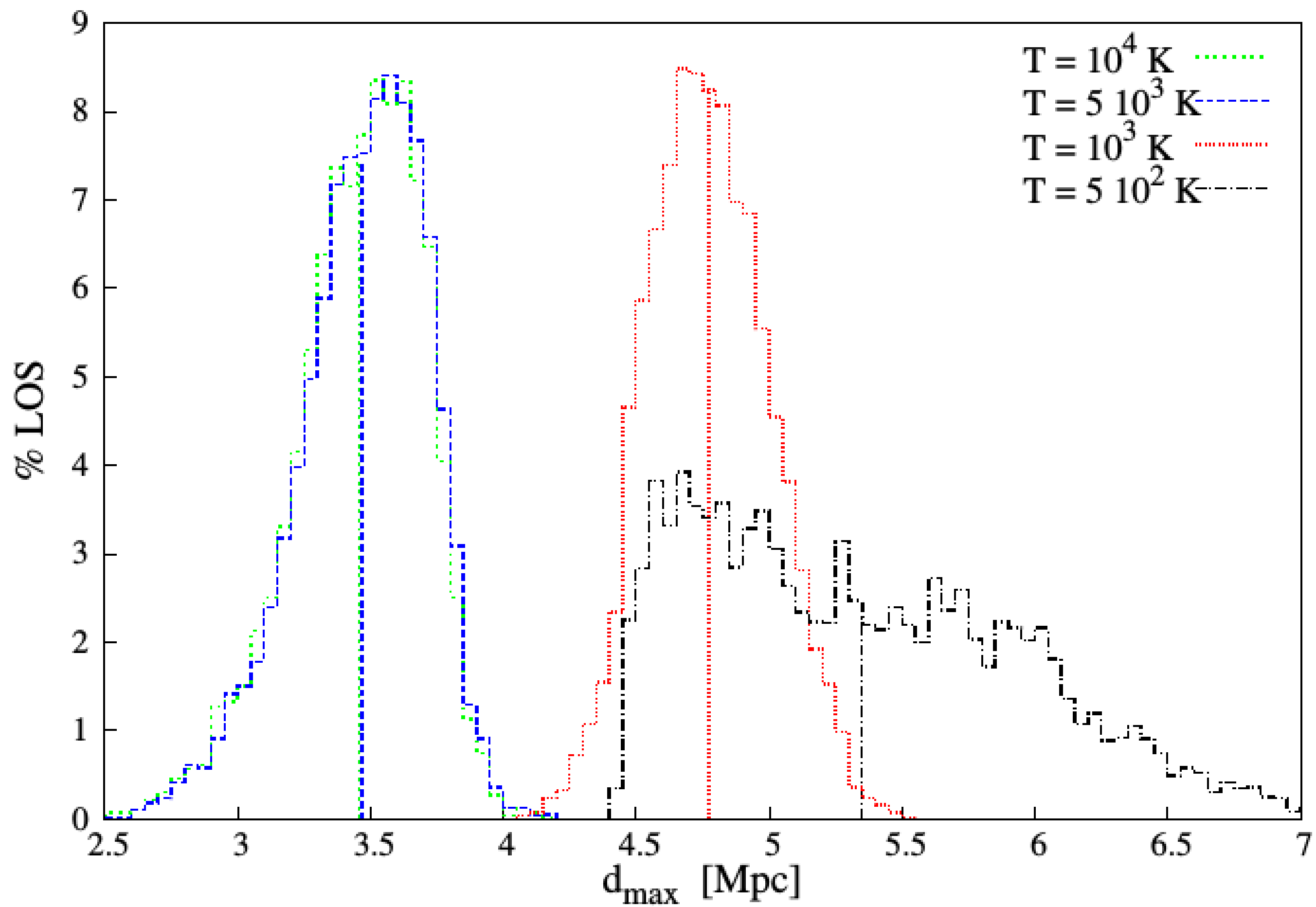
Sensitive impact on T (large scales): the entire box is affected.

Disjoined HII (fully ionised by UV front) and large, excited/heated regions by x-rays

What feedback on other systems??

Impact on large scale reionisation simulations??

21 cm?? but also RRL detectability??



Statistics of LOS showing d_{max} at certain T = 10^4K, 5 10^3 K, 10^3 K..

Large scale Reionization with H+He (M. Berge Eide, LG, et al., sub.)

Effects of x-rays on HII regions of high-z QSOs on Global reionisation.

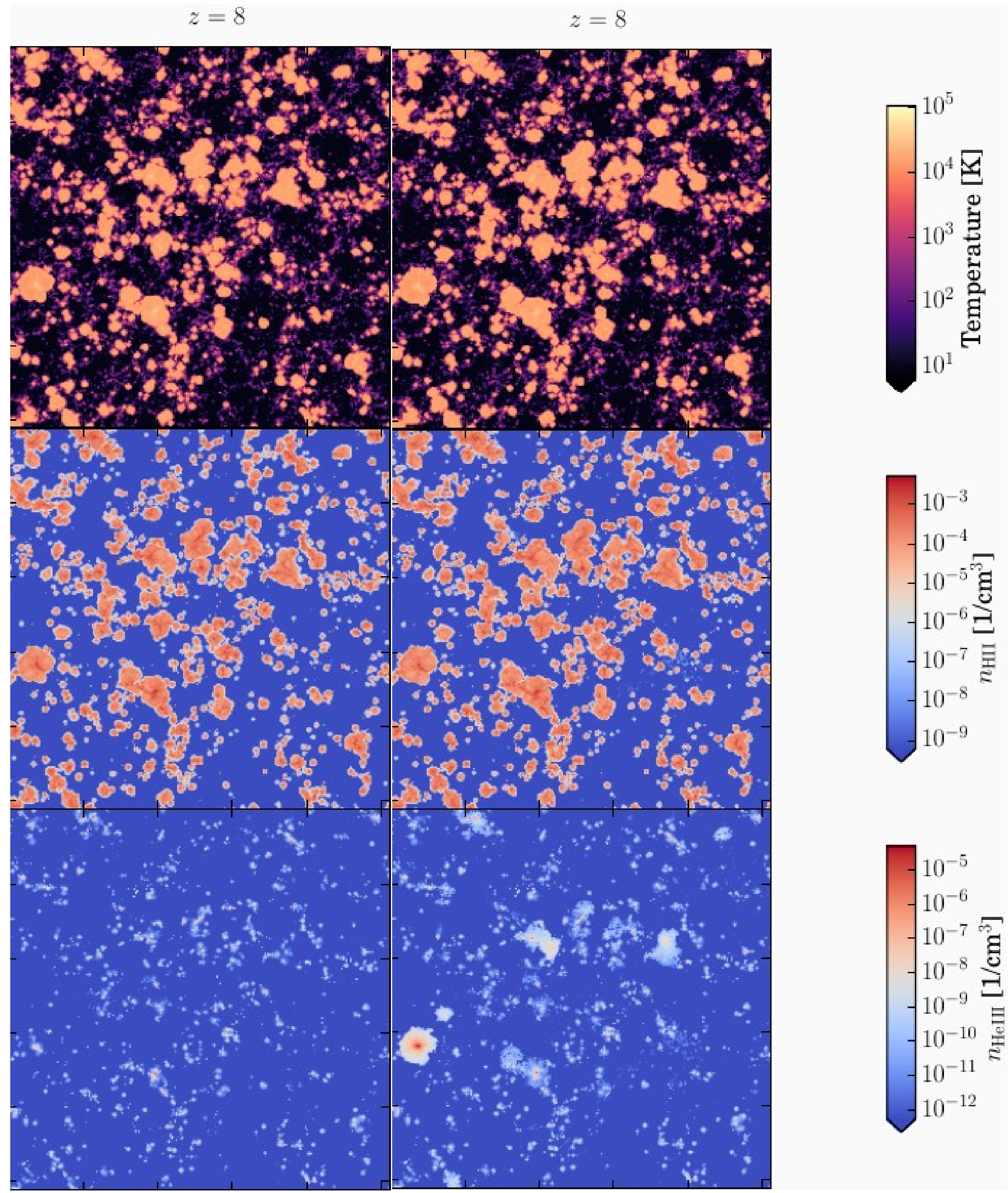
→ How does the topology of ionised bubbles change?

→ Relative roles of stars/QSOs
→ IGM heating
→ x-rays from binaries??

Feedback from radiation → SF missing!

Nature of galactic sources still not clear: galaxies modeled with uncertain escape Fraction.

Galaxies only / Galaxies + QSOs



Epoch of Heating: before the first QSO (M. Berge Eide, LG, et al., sub.)

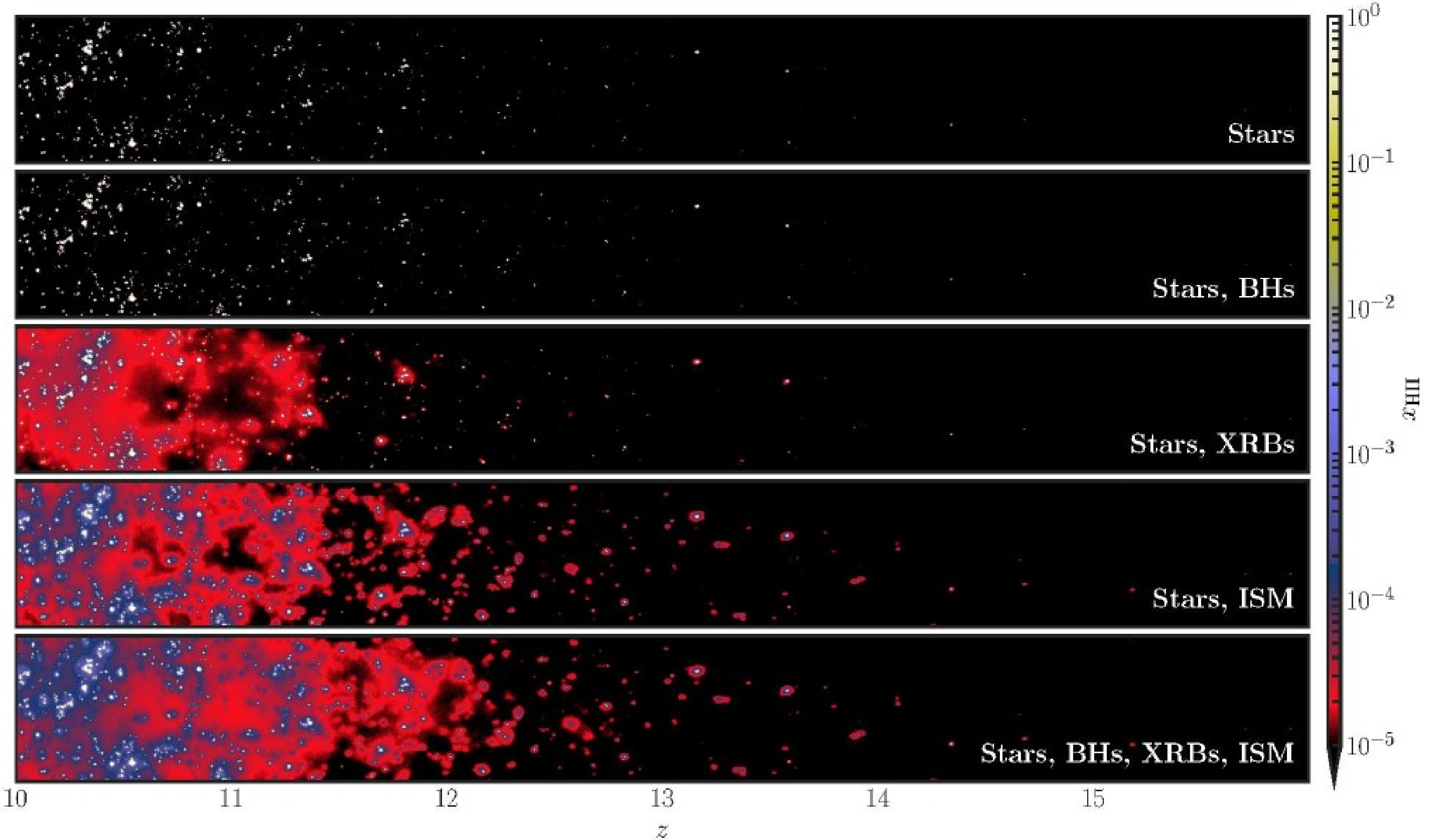


Figure 3. Lightcones showing the evolution of the ionized hydrogen fraction $x_{\rm HII}$ in the simulations with different combinations of source types, as indicated in the labels. The vertical size is $100h^{-1}$ cMpc and the aspect ratio between the axes is given at $z = 10$, hence the evolution in the angular diameter distance is not taken into account. The combined effect of all source types leaves the IGM without fully neutral regions at $z \lesssim 11.5$.

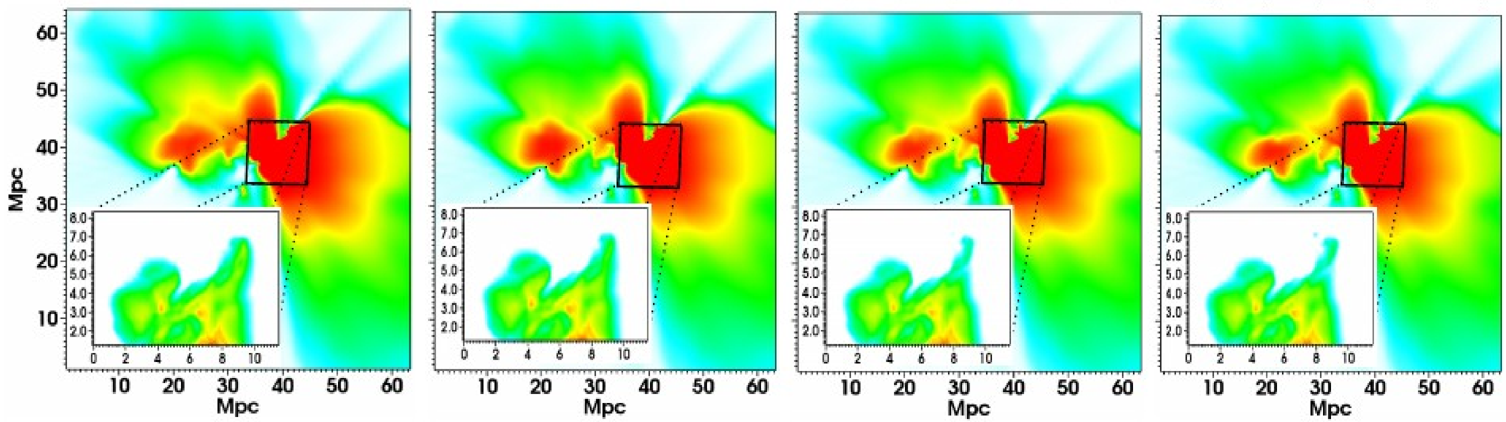
Handling spatial resolution → CF / AMR

Clumping factors of HII, HeII and HeIII

Akila Jeeson-Daniel,[1,2,3★] Benedetta Ciardi[2] and Luca Graziani[2]

Enabling Radiative Transfer on AMR grids in CRASH

N. Hariharan[1,4★], L. Graziani[1,5], B. Ciardi[1], F. Miniati[2], H.-J. Bungartz[3]



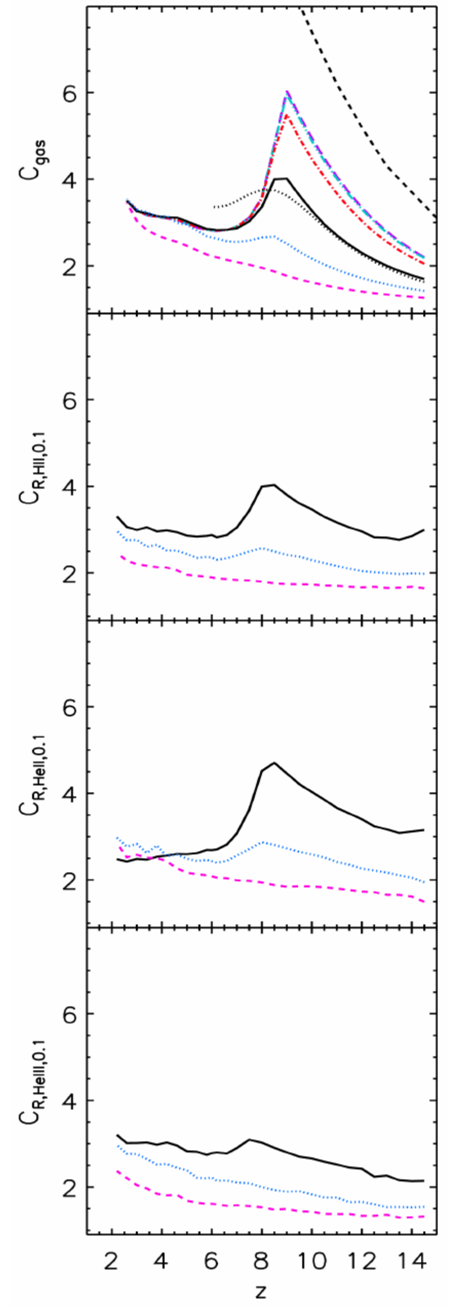
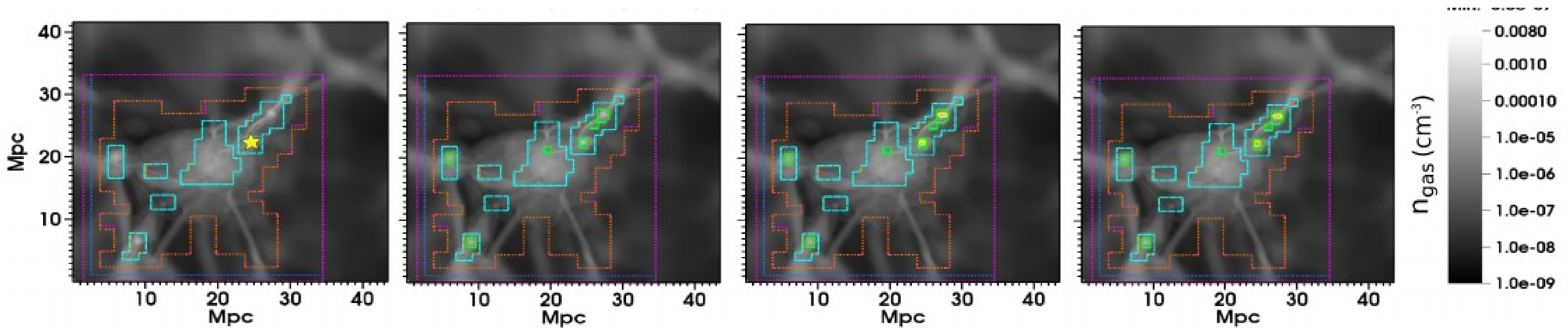


Figure 5. Redshift evolution of the clumping factor C_{gas} and $C_{R,i,0.1}$ for i = HII, HeII and HeIII for the simulations 2.2G448 (purple long dashed line), 2.2G384 (cyan triple dot dashed line), 2.2G256 (red dot dashed line), 2.2G128 (black solid line; reference), 2.2G64 (blue dotted line) and 2.2G32 (magenta dashed line). Also, plotted for comparison are the C_{100} curve of $r9L6N256$ simulation of Pawlik, Schaye, & van Scherpenzeel (2009) (black dotted line) and the C_{100} for the $B2$ simulation of Emberson, Thomas, & Alvarez (2013) (black dashed line).

Enabling Radiative Transfer on AMR grids in CRASH

N. Hariharan[1,4*], L. Graziani[1,5], B. Ciardi[1], F. Miniati[2], H.-J. Bungartz[3]



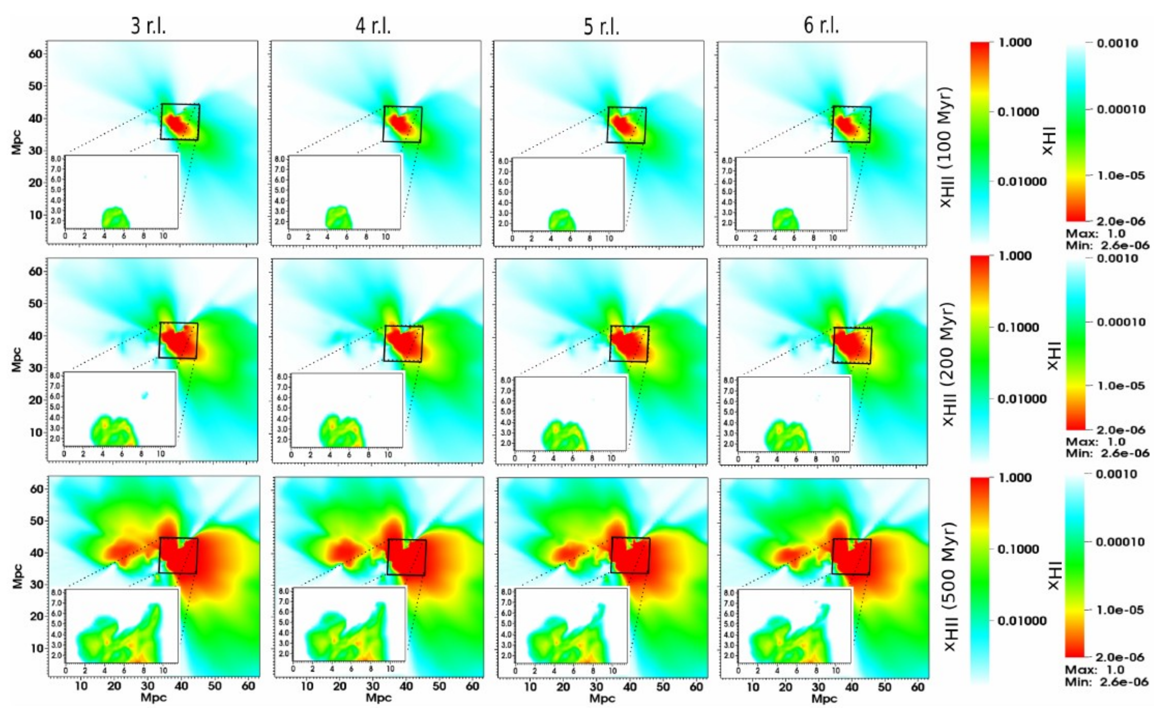
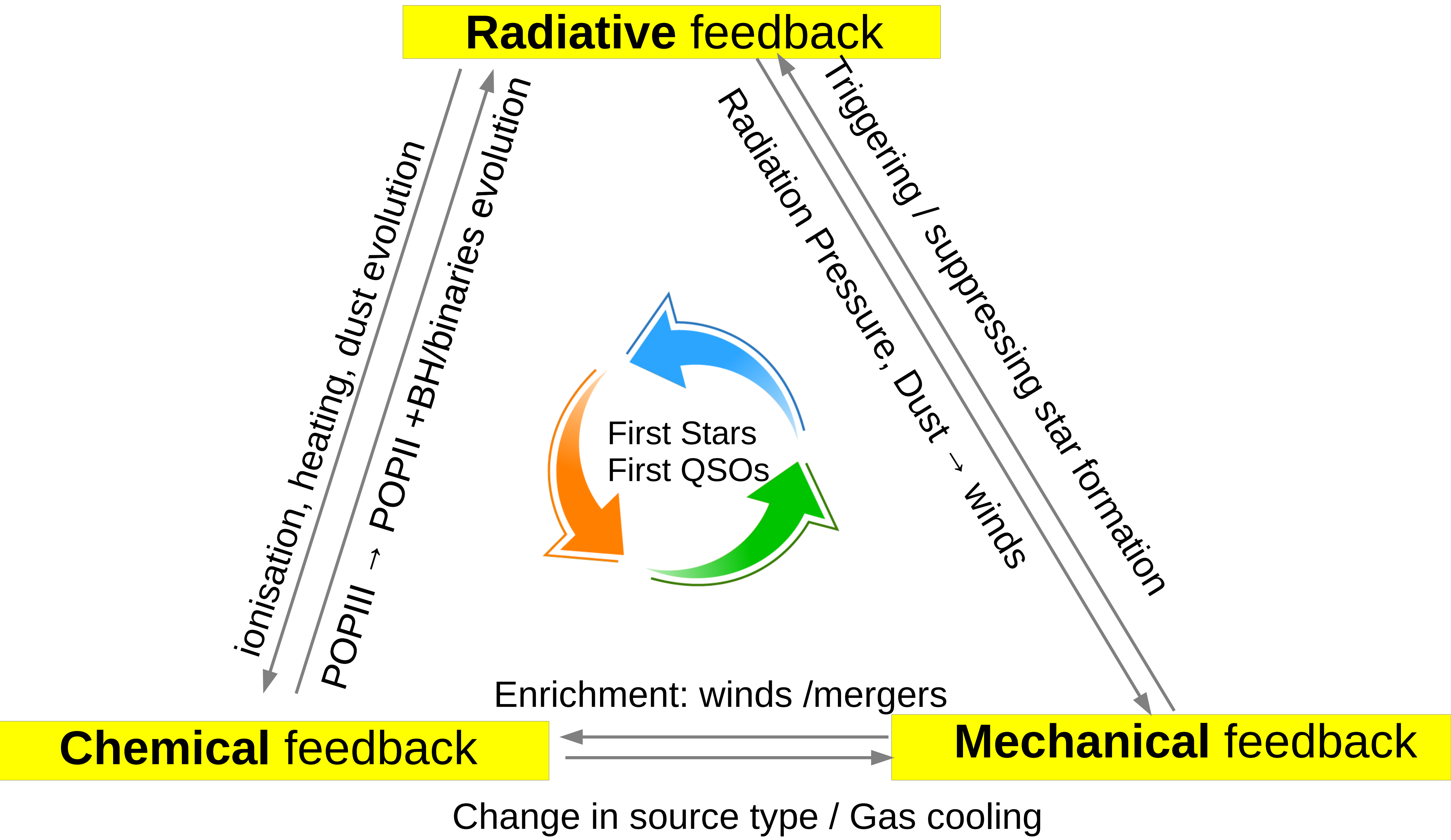


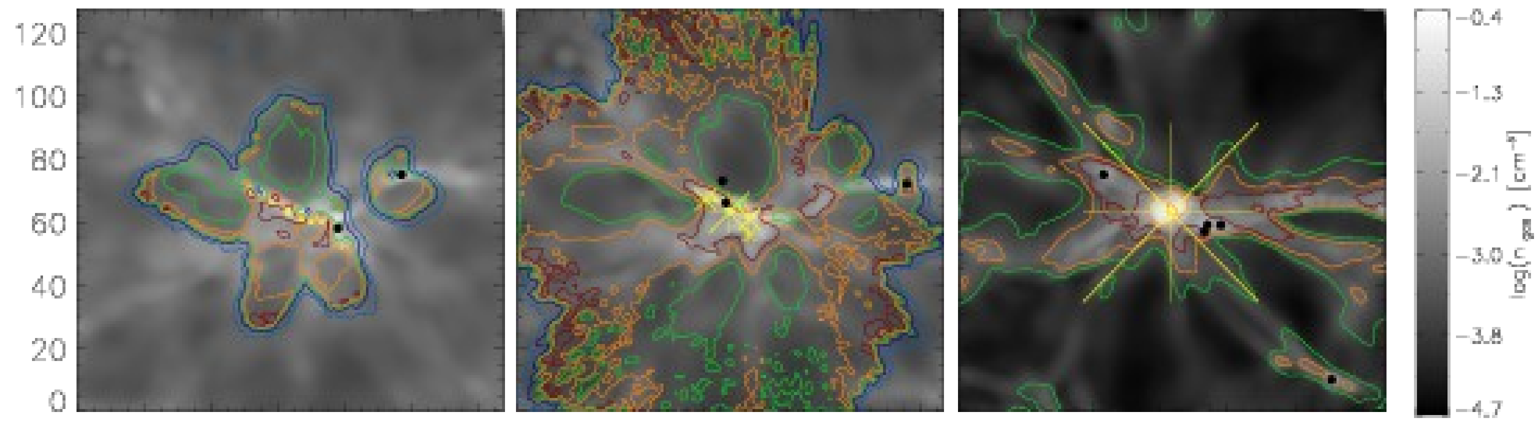
Figure 10. Maps cut through the simulation volume for Test 2c. **Top:** Maps of $x_{\rm HII}$ at time $t = 100$ Myr. **Middle:** Maps of $x_{\rm HII}$ at time $t = 200$ Myr. **Bottom:** Maps of $x_{\rm HII}$ at time $t = 500$ Myr. From left to right, the columns refer to simulations run with three, four, five and six refinement levels (see text for more details). Panel insets show the neutral fraction of the gas in the zoom-in areas; their colour codings refer to the second palette on the right. Min and max values, when not represented by the palette, are written as reference.

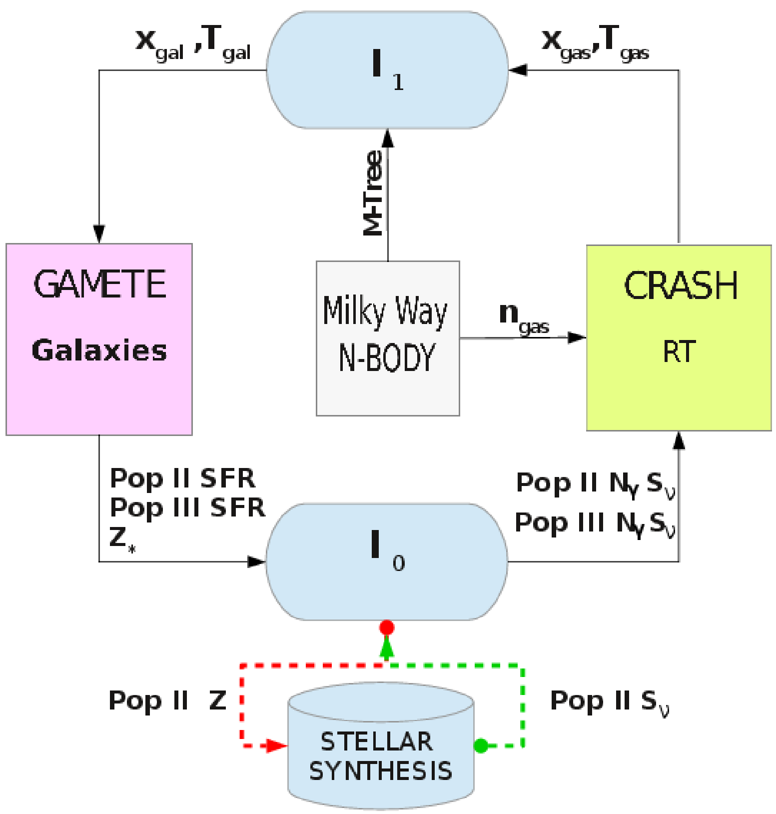
Feedback shapes Galaxy formation



Galaxy formation with radiative and chemical feedback

L. Graziani,[1★] S. Salvadori,[2] R. Schneider,[1] D. Kawata,[3] M. de Bennassuti[1]
and A. Maselli[4]



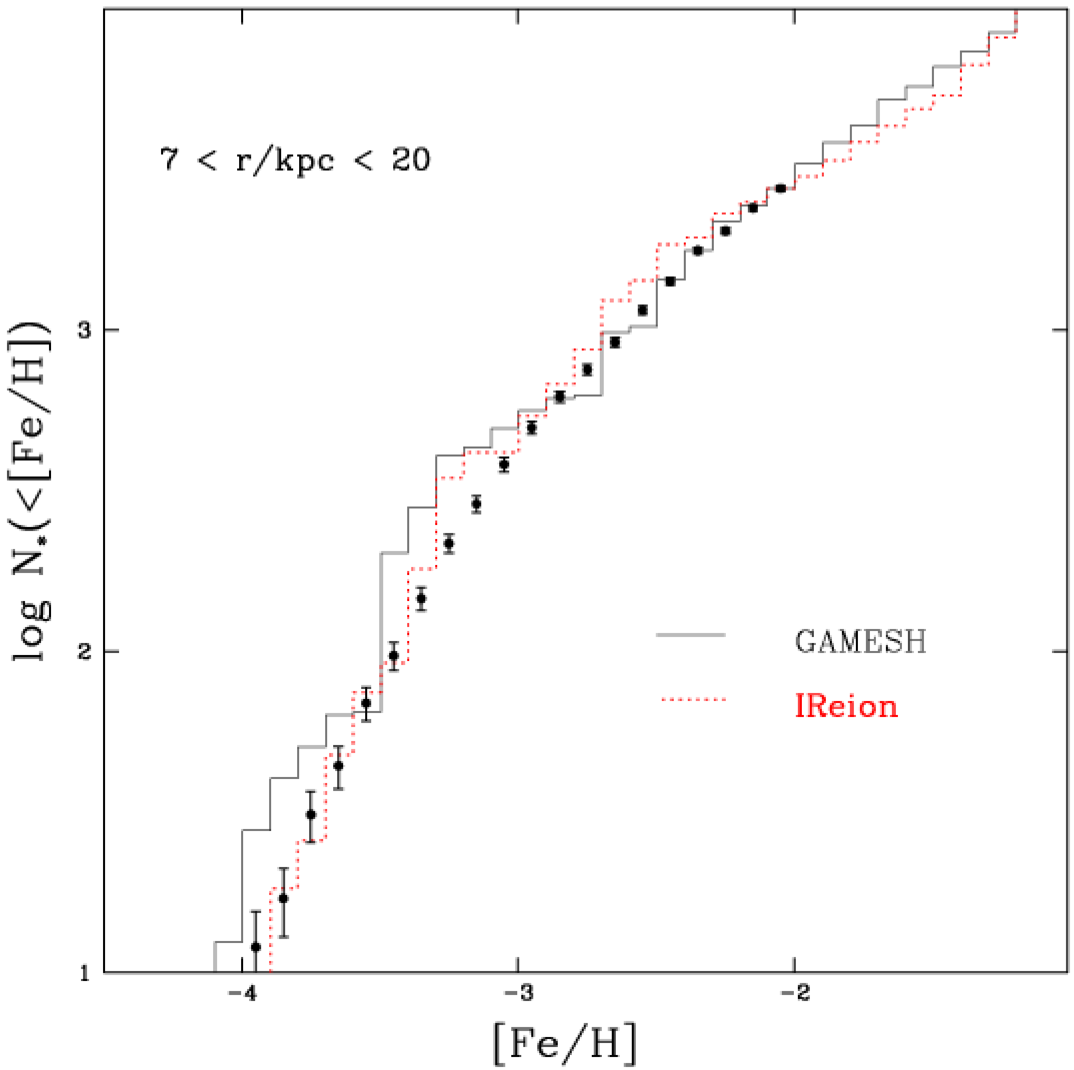


N-Body simulation: dynamical evolution of DM halos

GAMETE simulation: Star formation, metal production

CRASH simulation: RT, gas ionisation heating

Testable consequences: the MDF of the Milky Way at z=0



Low metallicity tail of the Milky Way MDF

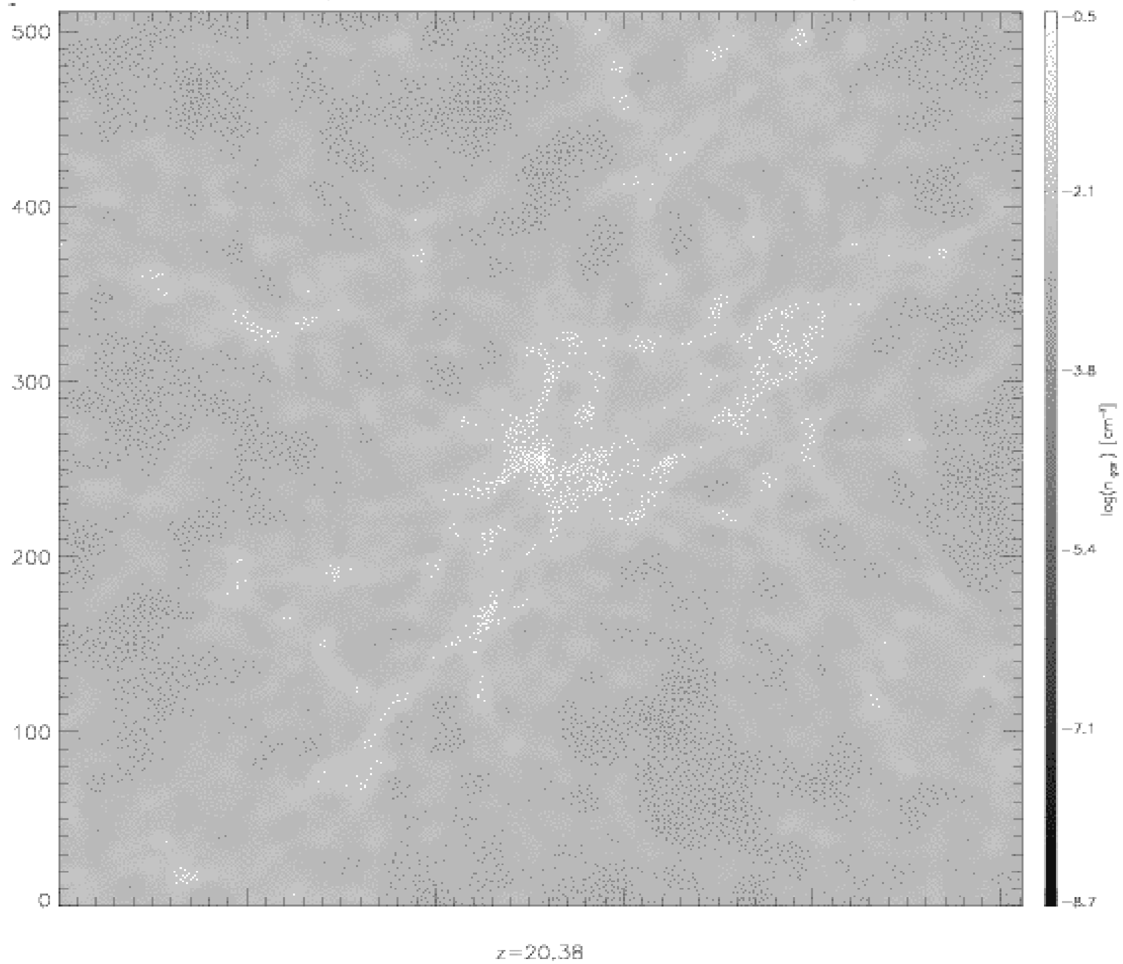
Sensitive to reionisation.

Sensitive to metal enrichment.

IRA assumption should be removed → Stellar evolution plays a relevant role

The history of the dark and luminous side of Milky Way-like progenitors

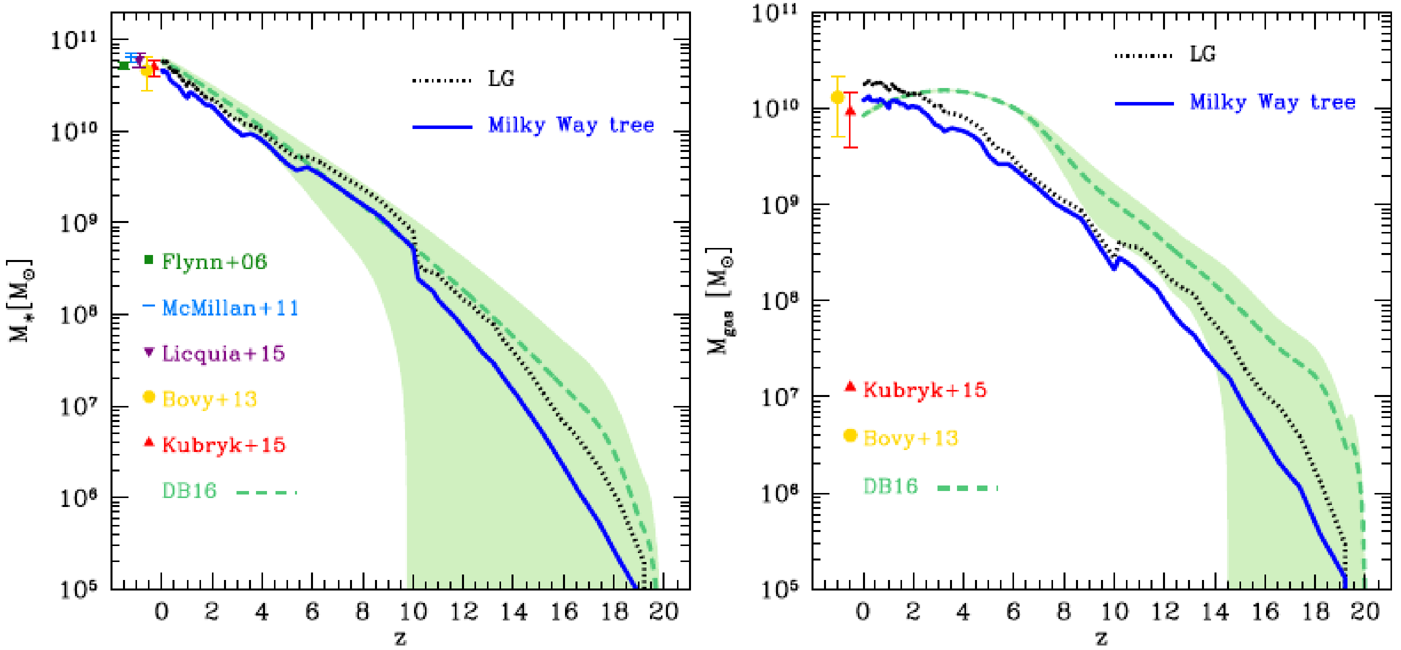
L. Graziani[1⋆], M. de Bennassuti[2,1], R. Schneider[2,1], D. Kawata[3], S. Salvadori[4]



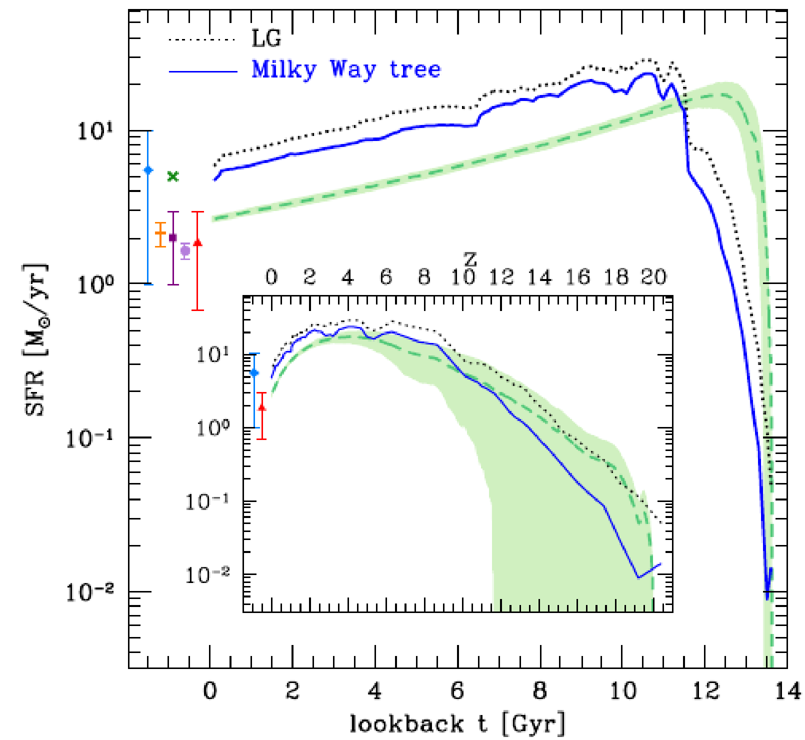
- Box side L: 8/4/1 cMpc
- M_p = 3.38d5 M_{sun}
- 0 < z < 20 → 155 snaps
- Grids: 513^3 cells
- 3 levels: 8 → coarse
  4 → fine (halo LG)
  1 → zoom-in
- Planck Cosmology
- FoF → max 13000 halos / 100 particles/halo
- Full particle based MergerTree ancestors/descendant
- Lya /mini-halos classified: T_{vir} = 2d4 K
- Central MW-like halo M=1.7d12M_{sun}
- Accretion history ← accretion from IGM

- MW-like halo fine in DM properties: M, T, V_c, c
- 4 cMpc, well resolved volume → LG
- Satellite statistics good!
- M31 position → wrong! Outside the LG!, M32, M33, LMC like halos present but in arbitrary positions

GAMESH2 → BARYONS in MW and MW progenitors

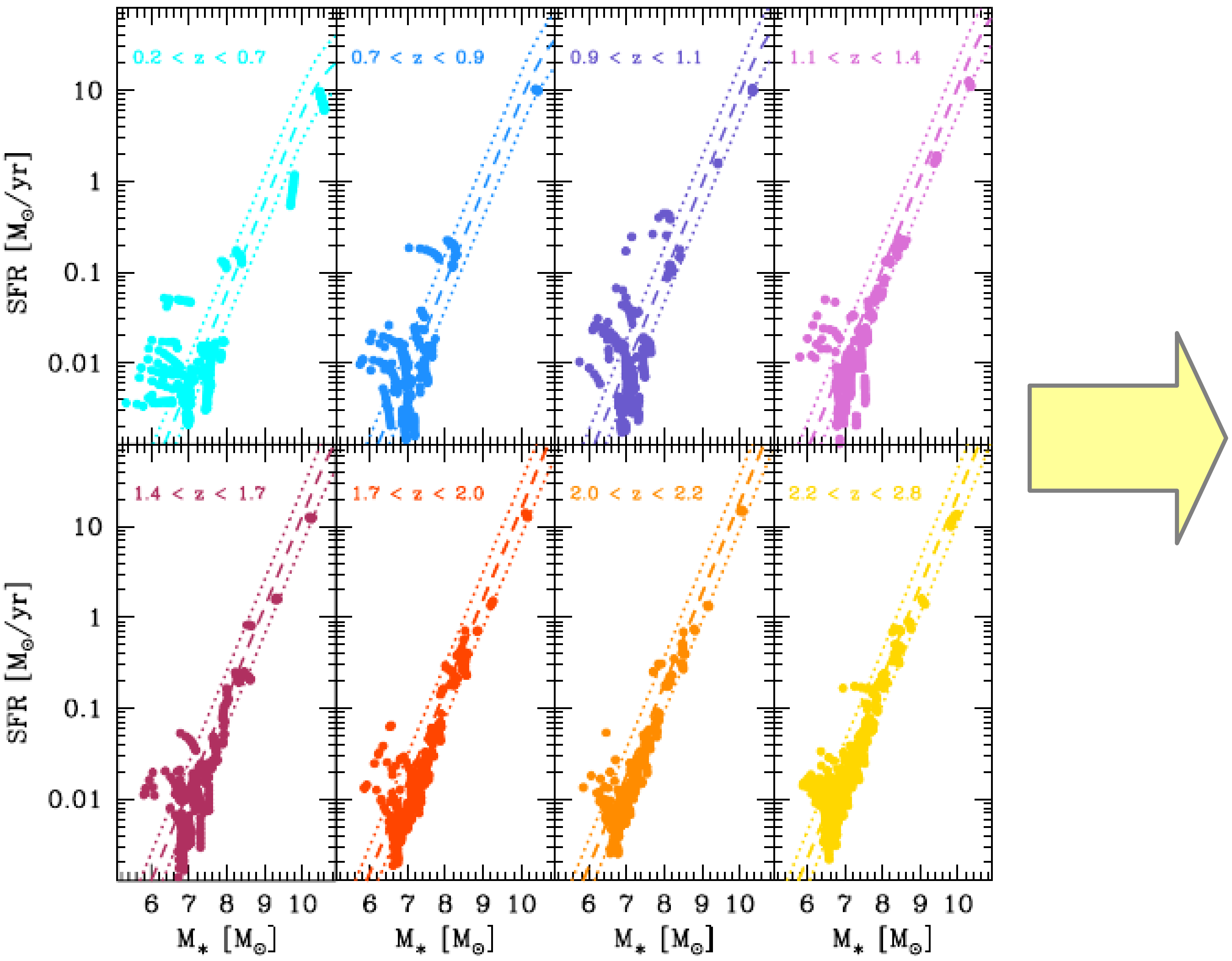


- MW-like halo fine in Baryonic props :
  M_{gas}, M_*, M_Z, SFR → OK
- SF efficiency 9%



Graziani, de Bennassuti, Schneider et al., MNRAS, 2017

GAMESH2 → BARYONS in MW and MW progenitors



Main Sequence → OK

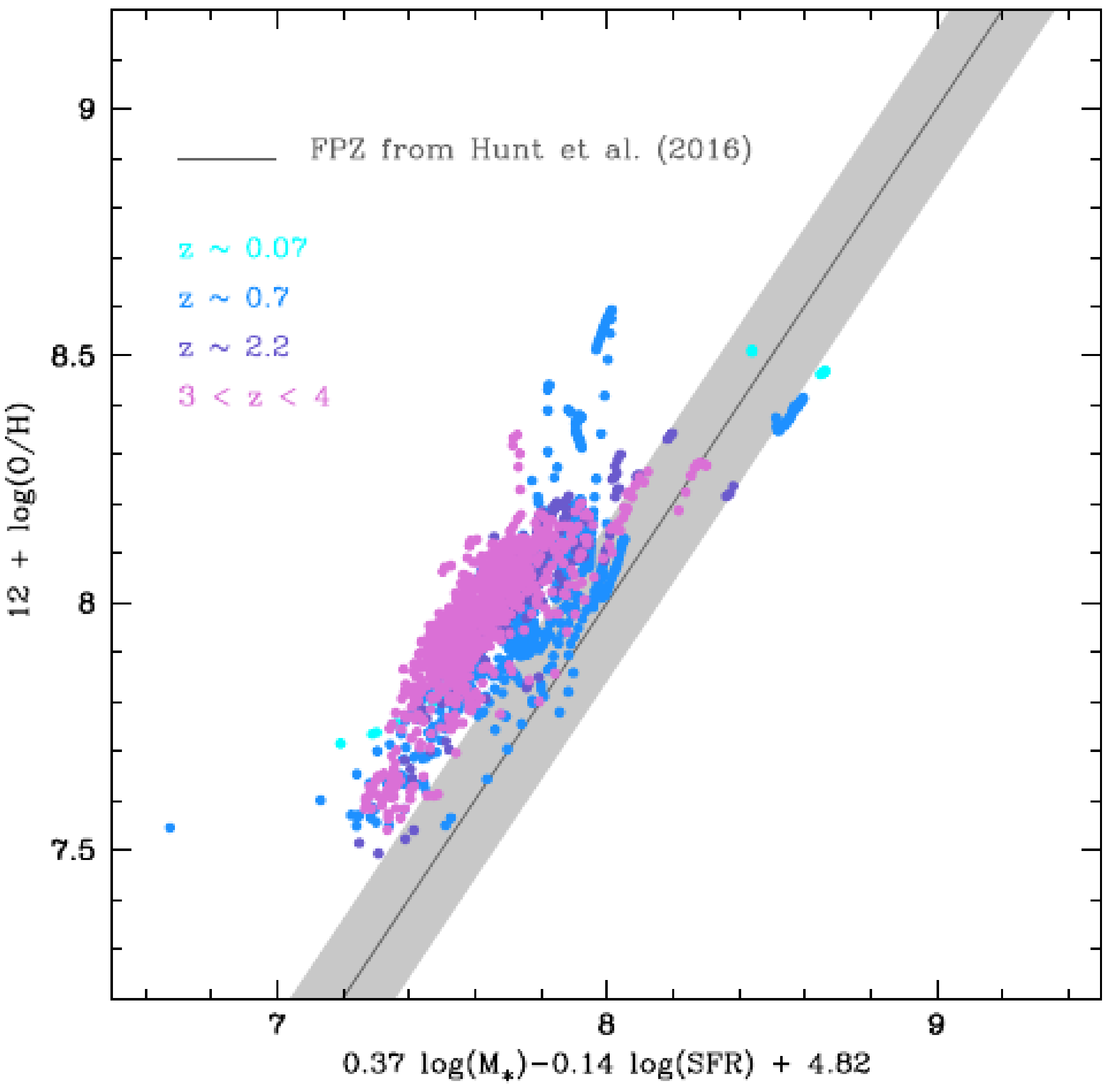
Along z !

Small objects → dispersion

→ FEEDBACK!

Graziani, de Bennassuti, Schneider et al., MNRAS, 2017

GAMESH2 → BARYONS in MW and MW progenitors



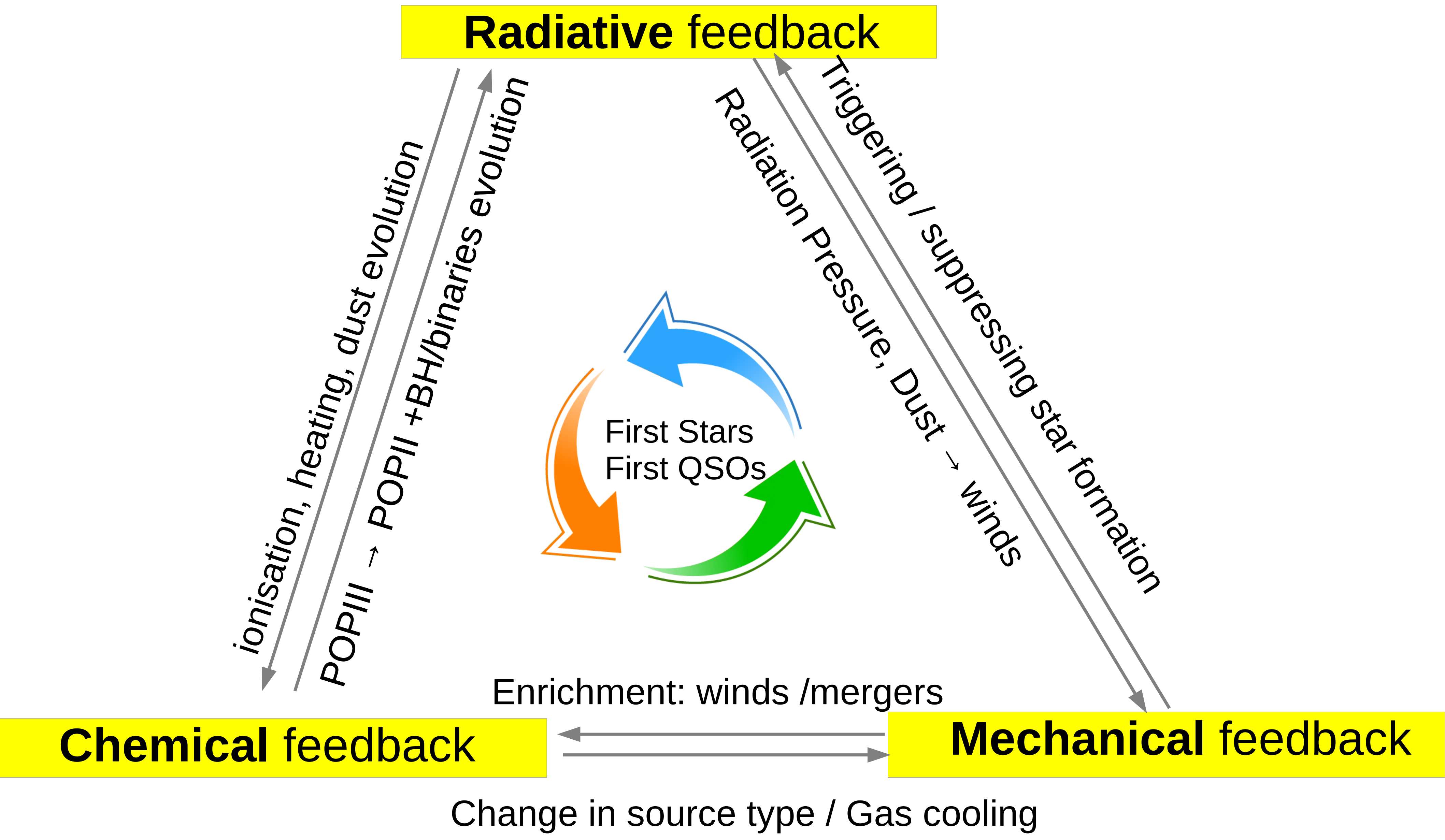
Distribution of the MW progenitors relative to the fundamental plane of metallicity (Hunt et al. 2016a)

This scaling relation is believed to originate from the interplay between gas accretion, star formation and SN-driven outflows

The description of these physical processes obtained by GAMESH leads to results consistent with observations.

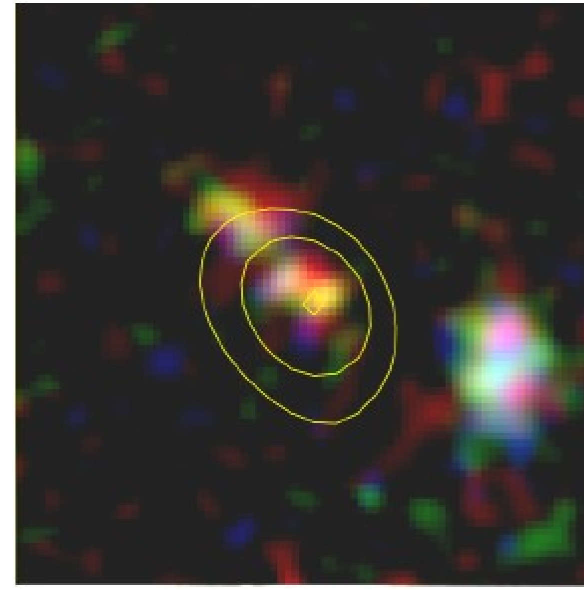
Graziani, de Bennassuti, Schneider et al., MNRAS, 2017

Feedback shapes Galaxy formation



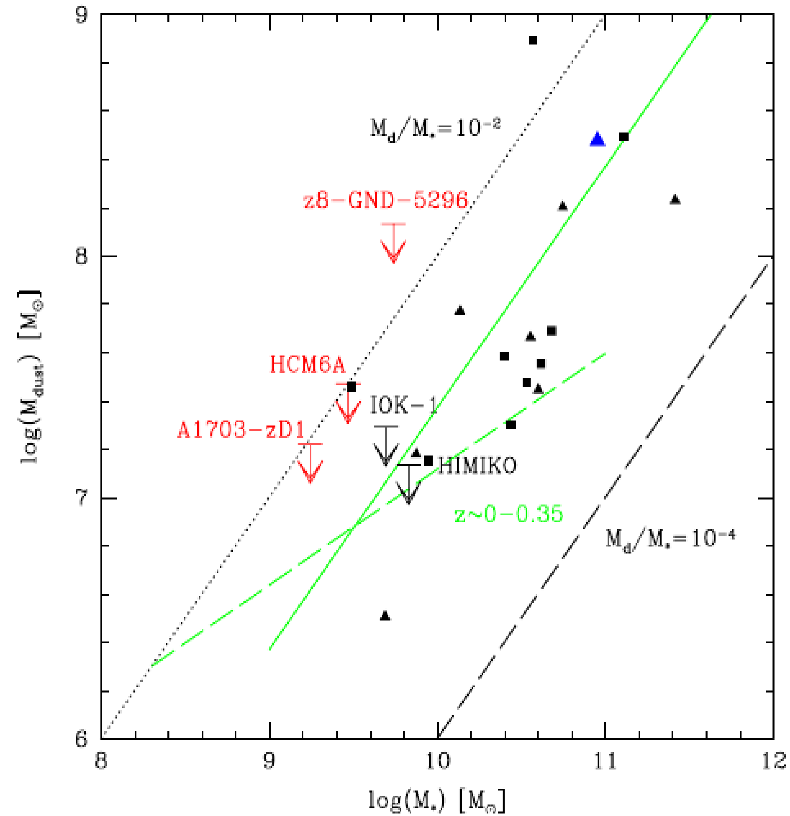
High redshift (6.5 < z < 7.5) dusty galaxies

- **Watson et al., 2015: Direct detection of dust emission!**
- **Schaerer et al., 2015: Sample of five high-z, star-forming galaxies: estimates for dust properties, stellar emission, star formation rates, dust masses, [C II] luminosity, UV attenuation, stellar masses.**
- **Maiolino et al., 2015: three spectroscopically confirmed Lyman Break Galaxies at 6.8<z<67.1. CII line detection (also see Gallerani et al. 2012, Williams et al., 2014)**



Watson et al. Nature 2015

- **Access the properties of the ISM of high-z Galaxies.**
- **Disentangle the role of various feedback Processes in place**
- **Estimate of the evolutionary status of the galaxy by both SFR, atomic metals and dust.**
- **Interplay between ISM and IGM ->Escape fraction in many spectral bands → Reionisation**



Schaerer et al. A&A 2015

The dust mass in $z > 6$ normal star forming galaxies

Mattia Mancini[1,2★], Raffaella Schneider[1], Luca Graziani[1], Rosa Valiante[1], Pratika Dayal[3], Umberto Maio[4,5], Benedetta Ciardi[6] and Leslie K. Hunt[7]

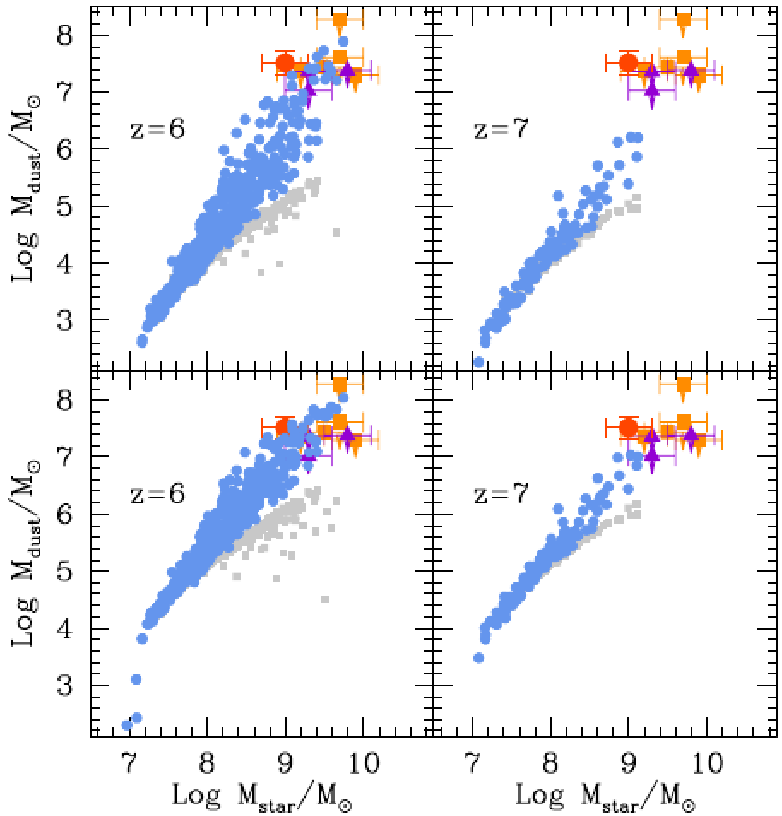


Figure 1. Predicted dust masses of the simulated galaxies as a function of the stellar mass. For each galaxy, the dust mass without (with) grain growth is shown by a square grey (circle blue) point (see text). The adopted grain growth timescale is $\tau_{acc,0} = 2\,\mathrm{Myr}$. In the lower panels, the reverse shock destruction of SN dust is neglected. For the sake of comparison, we have reported the same data points shown in Table 1 in the two panels: Schaerer et al. (2015, squares), Maiolino et al. (2015, triangles) and Watson et al. (2015, circle point).

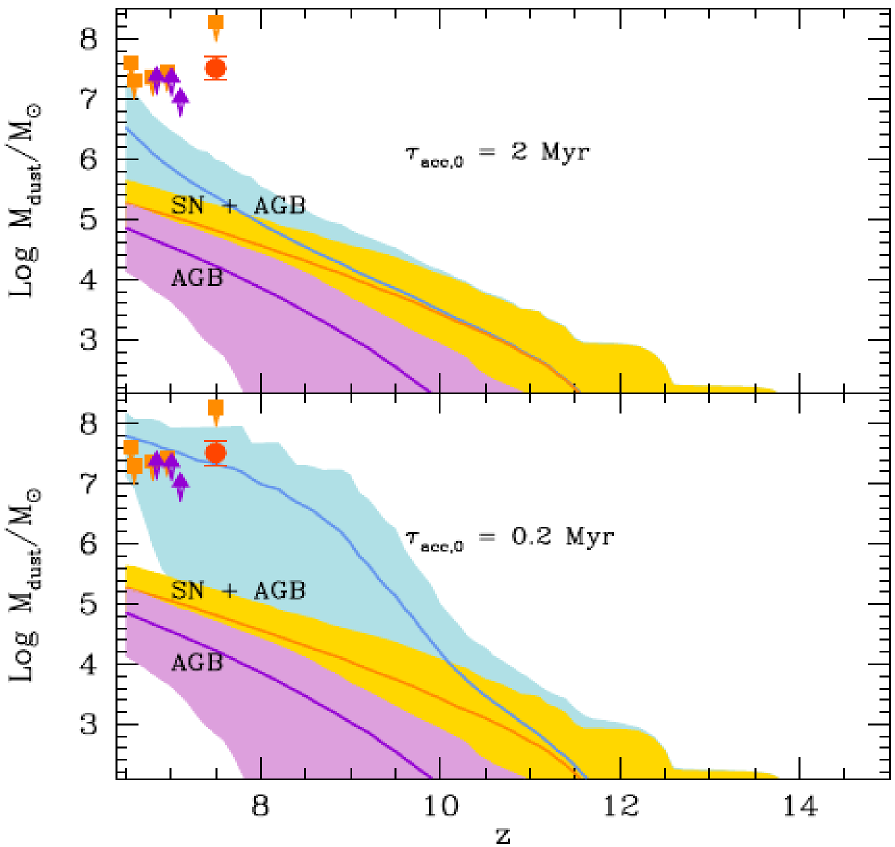


Figure 2. Redshift evolution of the dust mass for the simulated galaxies with stellar masses in the range $\mathrm{Log}\,M_{star}/M_{\odot} \geq 9$. Each line represents the average contribution of all the galaxies with the shaded area indicating the dispersion among different evolutionary histories. The lower, intermediate and upper lines show the contribution to the total mass of dust of AGB stars, stellar sources and grain growth with an accretion timescale of $\tau_{acc,0} = 2\,\mathrm{Myr}$ (upper panel) and 0.2 Myr (lower panel).

Where does galactic dust come from?

M. Ginolfi[1⋆], L. Graziani[1], R. Schneider[1,2], S. Marassi[1], R. Valiante[1], F. Dell'Agli[3,4], P. Ventura[1], L. K. Hunt[5]

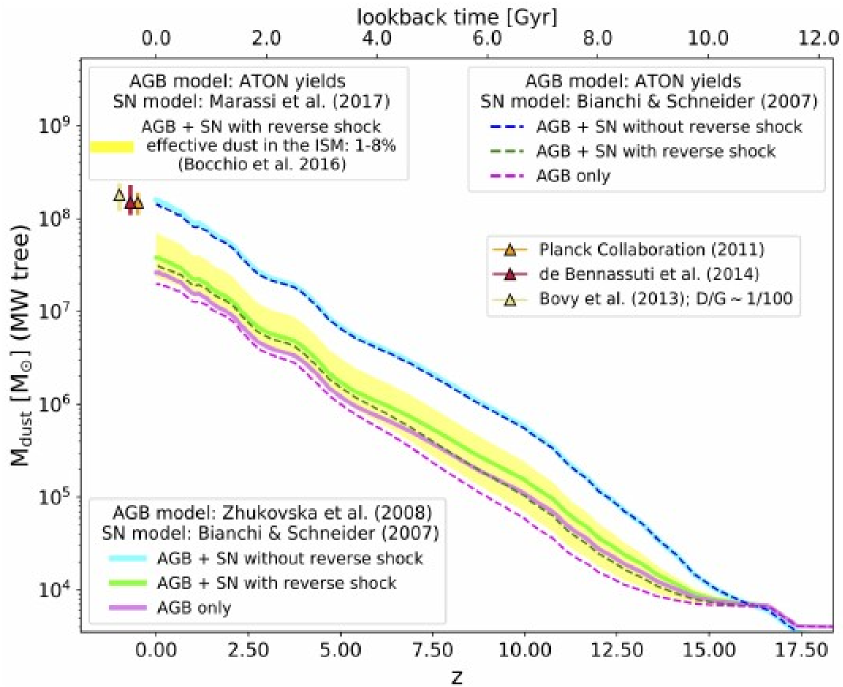


Figure 1. The dust mass evolution of the MW-sized halo as a function of redshift and lookback time. Different line styles correspond to different models of dust production by stellar sources: solid lines (dashed lines) refer to SN dust yields by BS07 and AGB dust yields by Z08 (ATON). Different line colours discriminate RS and nRS models (see the legenda). An AGB-only model is also explored (pink lines). The shaded yellow region correspond to the new M17 (SN) + ATON (AGB) model. The triangular points represent the MW dust mass at $z = 0$, as inferred by observations from Planck Collaboration et al. (2011) (orange) and Bovy & Rix (2013) (yellow, in this case the measured gas mass has been converted in dust mass assuming a standard $D/G_{\rm MW} \sim 1/100$) and simulations (de Bennassuti et al. 2014).

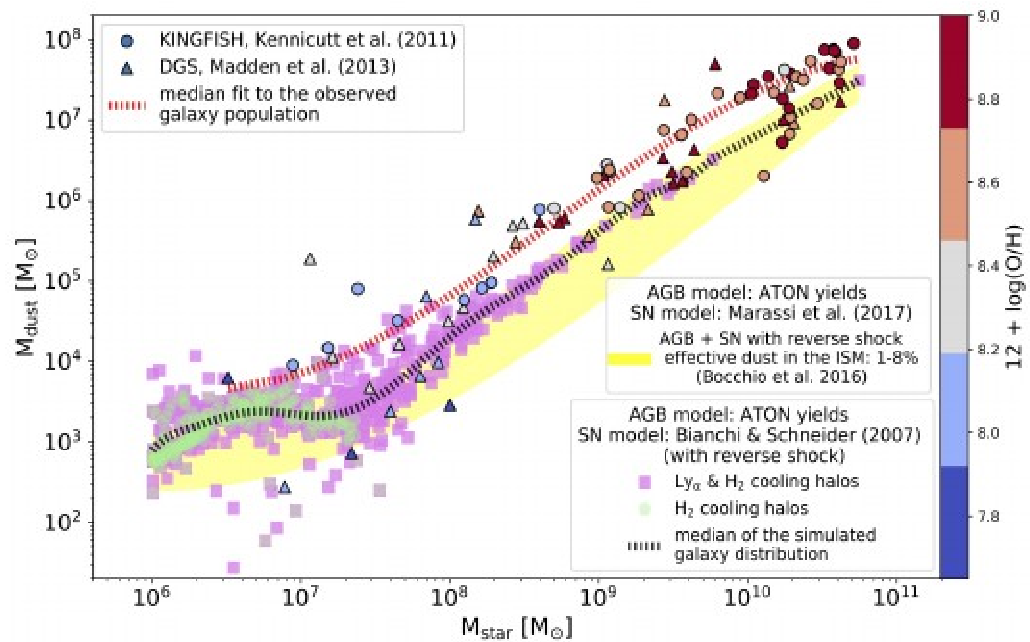


Figure 2. The dust mass of simulated galaxies (pink squares) at $z = 0$ as a function of their stellar mass. Green dots represent the sub-sample of galaxies with virial temperature $T_{\rm vir} < 2 \times 10^4$K. The black dashed line indicates the median trend of the simulated galaxy distribution. Here, ATON + BS07 (with RS) and ATON + M17 (with RS) models for dust production by stellar sources are adopted. Observational points of galaxies from the DGS (triangles) and KINGFISH (circles) surveys are shown, colour coded for different values of their metallicity. The red dashed line indicates the median trend of the observed galaxy distribution.

Interpreting the evolution of galaxy colours from $z = 8$ to $z = 5$

Mattia Mancini[1,2,3]★, Raffaella Schneider[1,3], Luca Graziani[1,3], Rosa Valiante[1], Pratika Dayal[4], Umberto Maio[5,6], Benedetta Ciardi[7]

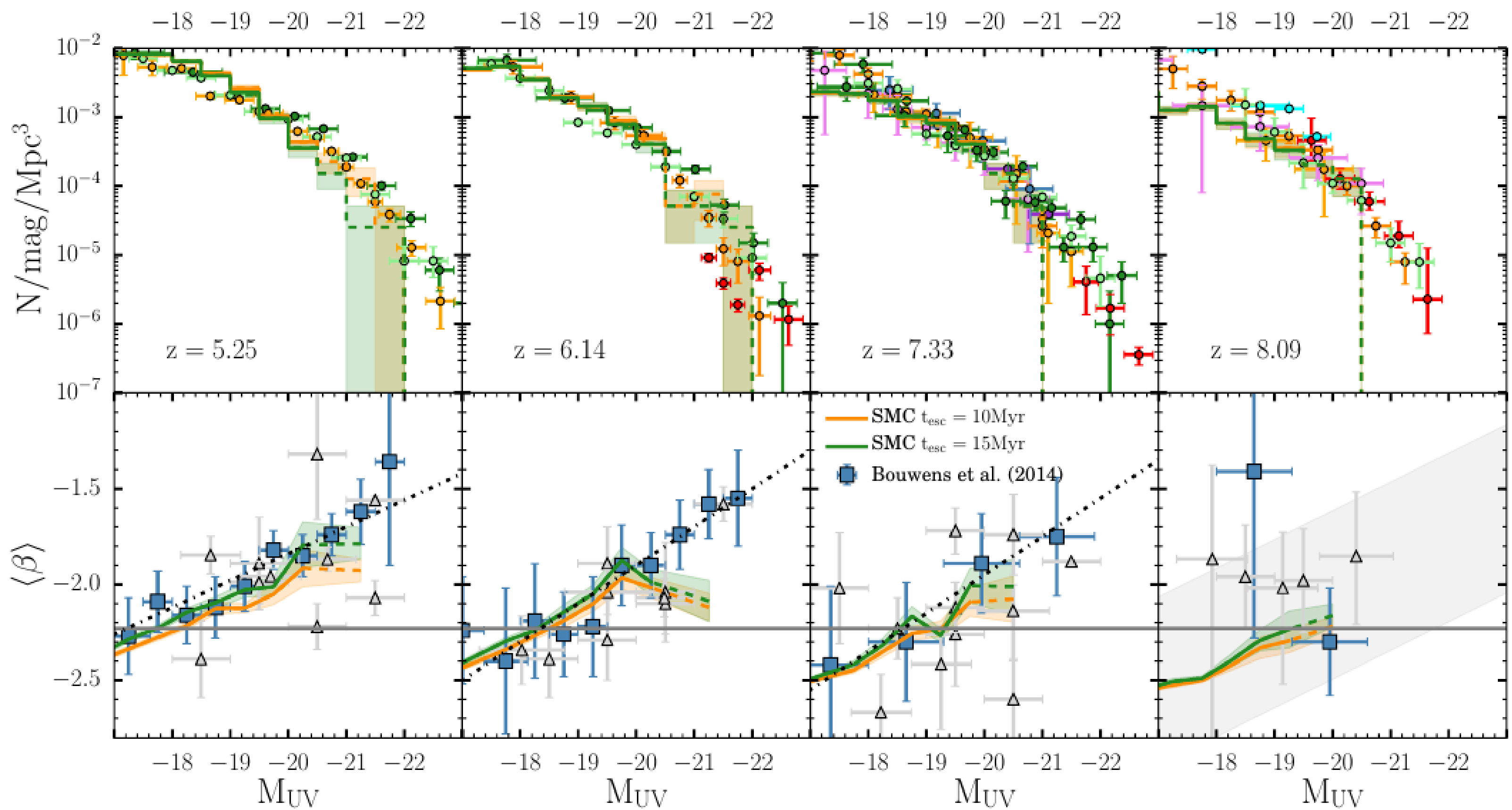


Figure 7. Comparison between the predicted UV luminosity functions (*top panels*) and ⟨β⟩ slopes (*bottom panels*) with observations. Data are the same a in Fig. 2. In the bottom panels we have added observations from Wilkins et al. (2011), Finkelstein et al. (2012), Bouwens et al. (2012), Dunlop et al. (2012 2013), and Duncan et al. (2014, all shown with grey data points). The black dot-dashed lines represent the best-fit to the observations of Bouwens et al. (2014 blue data points) at $z \sim 5, 6$, and 7 and the shaded grey region is obtained extrapolating the lower-z slope and the best-fit intercept at $z \sim 8$. The theoretica models adopt a SMC extinction curve and $t_{\rm esc} = 10$ (solid orange) and 15 Myr (solid green) with shaded regions representing the Poissonian errors in eacl magnitude bin (*top panels*) and the standard errors on the mean values (*bottom panels*). Dashed lines indicate the luminosity range where less than 10 mode galaxies are found in each magnitude bin (see text). The horizontal grey lines show the value $\beta = -2.23$ adopted in the Meurer et al. (1999) relation. A colourec version of this Figure is available online.

dustyGadget : simulates the production and evolution of dust and atomic metals in Gadget

Production:

- **DETAILED STELLAR EVOLUTION**: NON-IRA for **SNIa**, **SNII**, **AGB**
- **METAL/DUST ENRICHMENT:** Metals (Tornatore 2007) + DUST

  → Dust yields for **POP III**, **SNII** and **AGB** stars. See Raffaella´s Talk

  → *Radiation feedback on dust is not included at this stage.*

Evolution:

- **DUST ASTRATION**: Star formation incorporates dust.
- **GRAIN GROWTH:** Dust can grow in cold, metal enriched molecular clouds by accreating atomic metals.
- **GRAIN SUBLIMATION:** In the hot ISM the solid component could return into the gas phase

dustyGadget : simulates the production and evolution of dust and atomic metals in Gadget

Evolution:

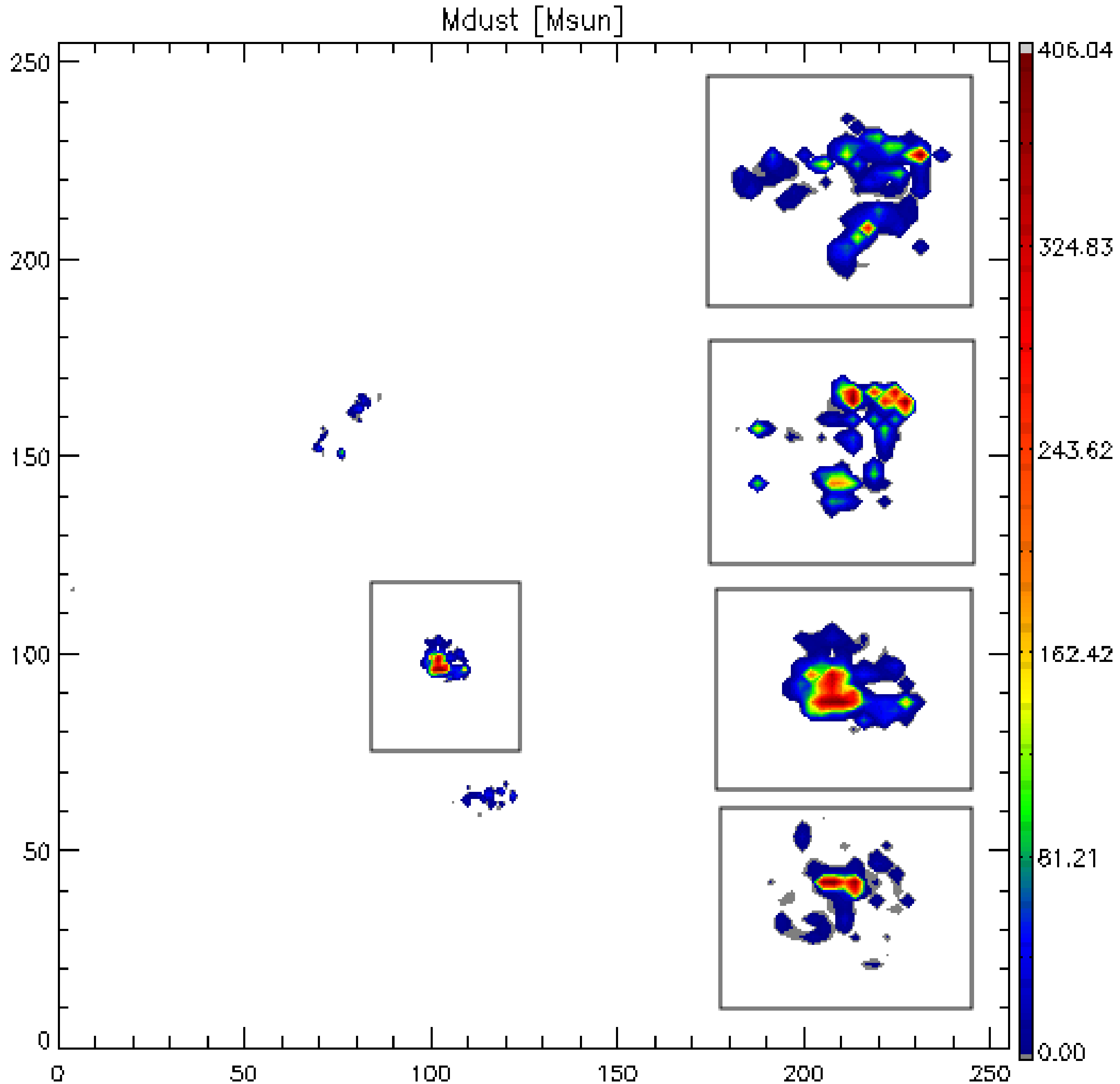
- **DUST ASTRATION**: Star formation incorporates dust.
- **GRAIN GROWTH:** Dust can grow in cold, metal enriched molecular clouds by accreating atomic metals.
- **GRAIN SUBLIMATION:** In the hot ISM the solid component could return into the gas phase

All these are environment dependent processes!

DustyGadget : Dust Formation/Evolution/Spreading

Simulation with dust.

- Z =5.67
- Box size: 10 cMpc/h
- Spreading: dust distribution highly In-homogeneous
- Huge gradients in the enriched regions of the box



Projects @ SNS

RT throught a QSO outflow

RT on AMR galaxy