# Chemical and radiative feedback in the primordial Universe

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## Outline

# Motivations

**Goal:** Early structure formation and transition from the primordial metal-free star formation regime (high-mass or low-mass stars?) to the common, metal-enriched one (low-mass 'solar' stars):

→ *What is the formation epoch of first objects?*
→ *What is the role of early molecules and metals?*
→ *How relevant is popIII star formation?*
→ *How fast is the transition to the standard popII regime?*
→ *What are the effects of different IMFs on SFR?*
→ *What are the effects of the underlying matter distribution?*
→ *What are the effects on cosmic re-ionization?...*

**Requirements:** Study the properties of cosmic gas and metal enrichment from stars, during cosmic evolution.

**Techniques:** N-body/SPH simulations (with Gadget).

- Cosmic structures originate from the growth of matter perturbations at early times (inflation), in an expanding, flat Universe, containing *"dark"* matter and *"baryonic"* matter.
- Baryonic structures form from in-fall and cooling of gas into DM potential well.
- Eventually, a cloud can form if the radiative losses are sufficient to make the gas condense and fragment:

$$t_{cool} = \frac{3}{2}\frac{nkT}{\mathcal{L}(n,T)} \quad \ll \quad t_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

- At early times, the cooling function is dominated by molecules ! After pollution from formed (baryonic) structures ($\longrightarrow$ *chemical feedback*) metals dominate.

# Molecules and metals

For a complete picture: necessity to follow gravity and hydrodynamics joined to molecular evolution and metal production during cosmic time (e.g. Galli& Palla, 1998; Abel et al., 1997)

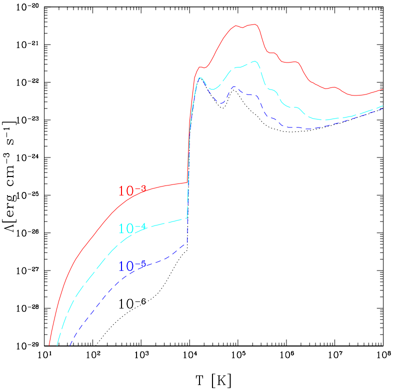
- molecules determine *first* structure formation
- metals determine *subsequent* structure formation
- stellar evolution determines *timescales* and *yields*

Following and implementing metal and molecule evolution in numerical codes (N-body/SPH Gadget) required
(Yoshida et al., 2003; Tornatore et al., 2007; Maio et al., 2006, 2007, 2009, 2010, 2011a,b,c)

Gas cooling function ⟶

In primordial regimes, the main coolants are H, He and molecules ($H_2$ and HD).

In metal enriched ones, metal fine-structure transitions from C, O, Fe, Si (dominant over molecules at low temperatures).




(Maio et. al, 2007)

*Cooling leads the gas in-fall into DM potential wells.*

# $Z_{crit}$: transition from popIII to popII-I star formation

We study the effects connected to the existence of a critical metallicity $Z_{crit}$ (e.g. Bromm & Loeb, 2003; Schneider et al., 2003) and the transition from popIII SF ($Z < Z_{crit}$) to popII-I SF ($Z \geq Z_{crit}$).

In order to address such issues, we perform several numerical simulations of early structure formation adopting different values for $Z_{crit}$ and exploring different scenarios.

## Simulation set-up

(Maio et al., 2010, 2011b, Maio & Iannuzzi, 2011; Maio, 2011; Maio & Khochfar, 2012)

- standard-$\Lambda$CDM cosmology (1,7,14,43,143$\mathrm{Mpc}$ a side);
- molecular and metal chemistry;
- assume $Z_{crit} = (10^{-6}, 10^{-5}, 10^{-4}, 10^{-3})\ Z_{\odot}$
- assume different popIII IMFs ($\rightarrow$ top-heavy/Salpeter)
- assume different matter distributions ($\rightarrow$ G vs non-G)

# Simulations of structure formation (example)

Example of structure formation

# Metal enrichment in the Universe

Z (absolute)

Total enrichment

O (absolute)

O enrichment

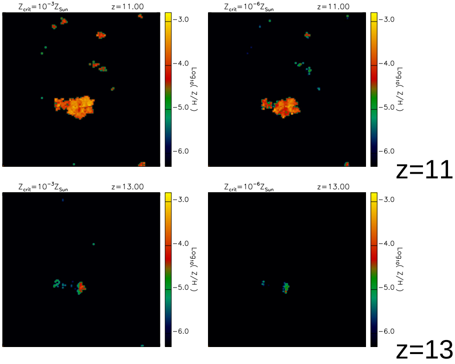
Fe (absolute)

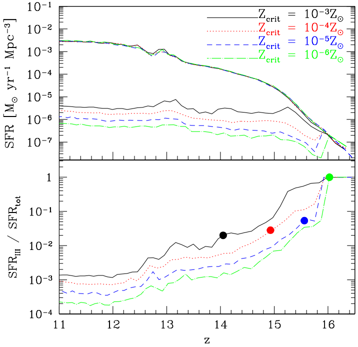
Fe enrichment

Metal enrichment led by stellar evolution: SNII/PISN $\longrightarrow$ O, SNIa $\longrightarrow$ Fe

# Results (1/14): effects for different $Z_{crit}$

$Z_{crit}$ : $10^{-3}\ Z_\odot$ $10^{-6}\ Z_\odot$



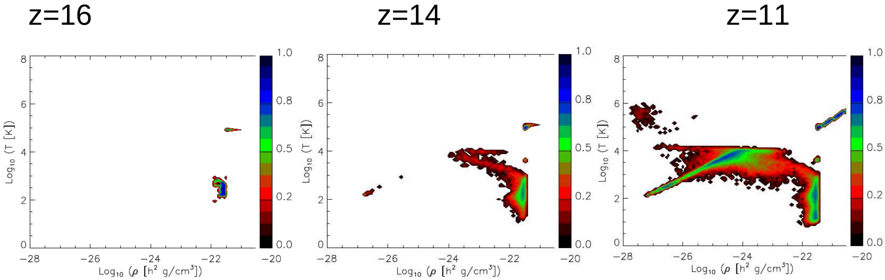

box: 1Mpc$^3$; popIII IMF: top-heavy with slope=-1.35, range=[100$M_\odot$,500$M_\odot$]

(Maio et al., 2010)

# Results (2/14): polluting the surrounding medium

Phase diagrams with color contours for enriched gas

($Z_{crit} = 10^{-4} Z_{\odot}$, box side = 1 Mpc)



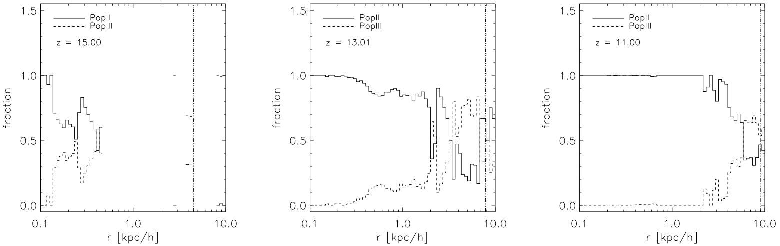

Metals produced by stellar evolution pollute the surrounding, pristine gas with an *"inside-out"* mode.

(Maio et al, 2011b)

# Results (3/14): effects on the surrounding

Radial fractions of popII ($Z \geq Z_{crit}$) and popIII ($0 < Z < Z_{crit}$) enriched gas in the most massive halo at $\sim 10 - 1000$ pc (physical)

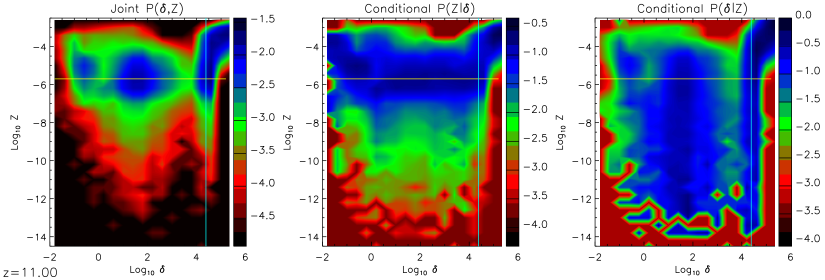
(Maio et al., 2011b)



# Results (4/14): metallicity distribution

Metallicity distributions with color contours for enriched gas at $z = 11$

($Z_{crit} = 10^{-4} Z_{\odot}$, box side = 1 Mpc)

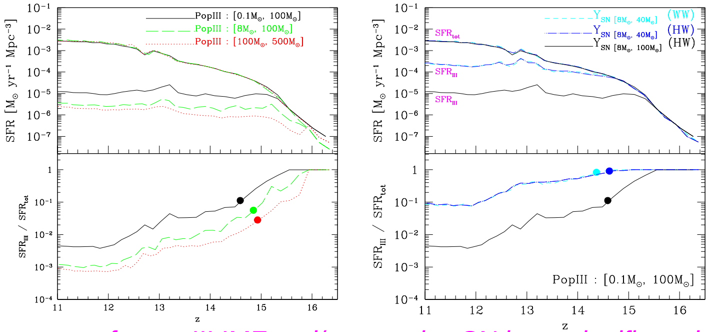



At $z \sim 11$, after $\sim 10^8$ yr from the onset of star formation, most of the enriched mass has $Z > Z_{crit}$.

(Maio et al, 2011b)

# Results (5/14): changing the popIII IMF

**PopIII range** (Salpeter IMF – top-heavy IMF) **SN range** (Salpeter IMF)




*Mass ranges for popIII IMF and/or massive SN have significant impacts:*

Larger masses → Shorter stellar lifetimes → Earlier enrichment → Shorter "popIII epoch"

(Maio et al., 2010)

# Results (6/14): Luminosity functions

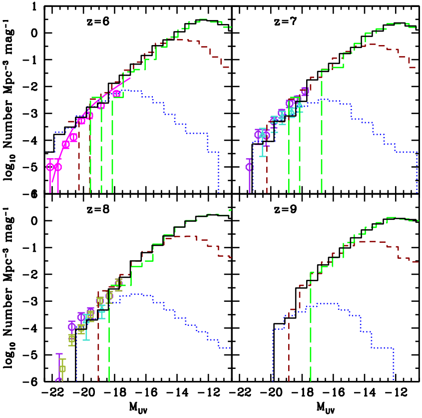
For each galaxy: $L_\lambda = L_\lambda^{\mathrm{II}} + L_\lambda^{\mathrm{III}}$
in L5, L10, L30

*PopII-I SEDs* from Starbust99 (Leitherer, 1999; Vazquez & Leitherer, 2005) *PopIII SEDs* from Schaerer (2002) *No dust assumed*

Observational data points from:

Bouwens et al., 2007 (circles)
Bouwens et al., 2011 (circles)
McLure et al., 2010 (triangles)
Oesch et al., 2012 (squares)

Fit at $z = 6$ from Su et al., 2012.



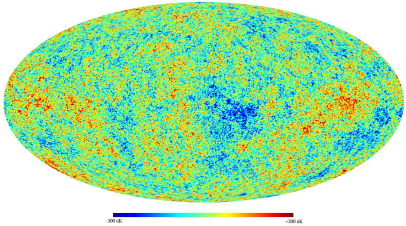

(see also Salvaterra et al., 2012)

# Results (7/14): primordial matter distributions and Non-Gaussianities

Basic assumption: Gaussian perturbations → evidences for non-Gaussianities (CMB). Primordial non-Gaussianities are introduced via (Salopek & Bond, 1990; Desjacques & Seljak, 2010)

$$\Phi = \Phi_L + f_{\rm NL} \left(\Phi_L^2 - < \Phi_L^2 >\right)$$

$\Phi$ is the Bardeen potential (Newton potential at sub-Hubble scales), $\Phi_L$ is the *linear* (Gaussian) part, and $f_{\rm NL}$ the non-Gaussian parameter.



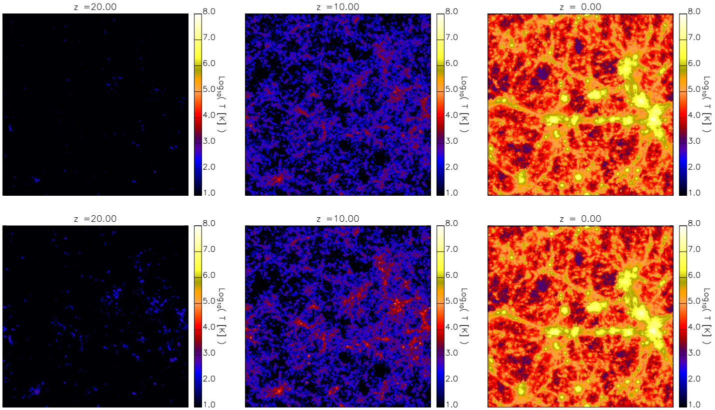

credit: WMAP

$f_{\rm NL}$ = 0, 10, 50, 100, 1000
box sides: 0.5 and 100 Mpc/h
number of particles: $2 \times 320^3$
gas mass resolution: $42\ {\rm M}_{\odot}/h$ and $3 \times 10^8\ {\rm M}_{\odot}/h$

See: Maio & Iannuzzi (2011); Maio (2011)

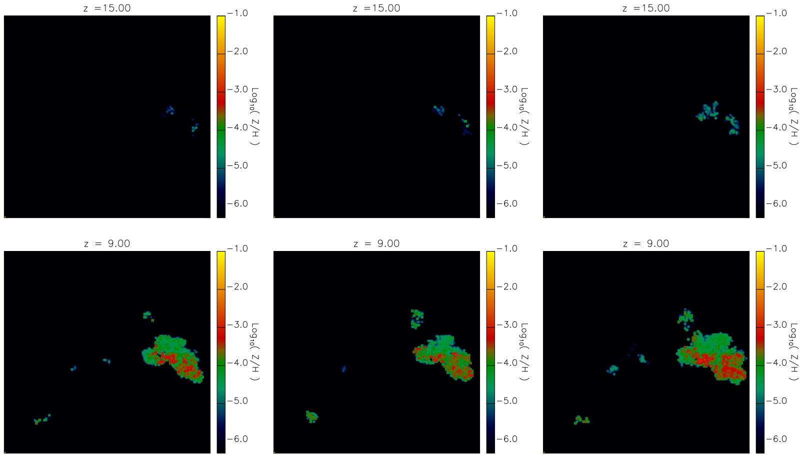
# Results (8/14): Non-G and the cosmic web

$f_{NL}$=0




$f_{NL}$=1000

# Results (9/14): Non-G and chemical feedback

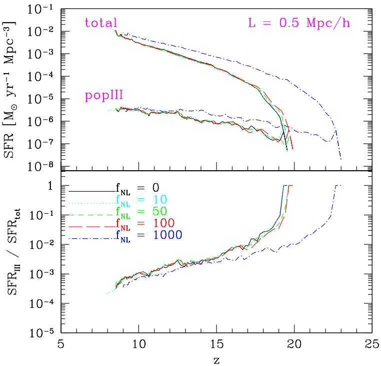



$f_{NL}$=0

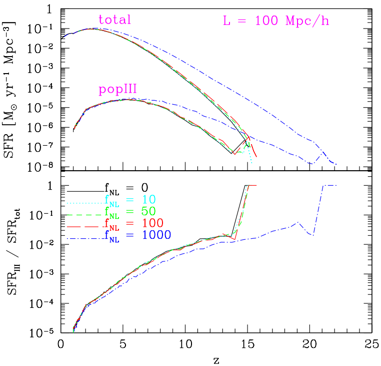
$f_{NL}$=100

$f_{NL}$=1000

# Results (10/14): Non-G effects on star formation




L=0.5 Mpc/h




L=100 Mpc/h

# Results (11/14): Implications for LGRBs

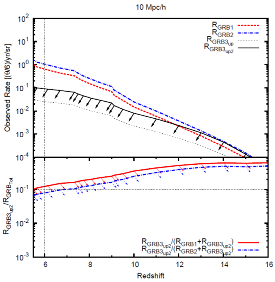
LGRB rate:

different progenitors
i.e. stars with

1: $Z > Z_{crit}$
$\rightarrow$*any popII-I*

2: $Z_{crit} < Z \leq 0.5 Z_\odot$
$\rightarrow$*low-Z popII*

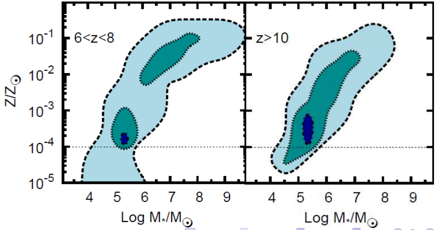
3: $Z \leq Z_{crit}$
$\rightarrow f_{GRBup} = 0.006$
$\rightarrow f_{GRBup2} = 0.022$
(upper limits from
Swift sample, 2011)




Detectable *fraction* (by BAT/Swift) of popIII GRBs:
$\sim$ 10% at $z > 6$
$\gtrsim$ 40% at $z > 10$
of the whole population

*GRB-hosts*:
the highest probability of finding popIII GRBs is in hosts with $M_\star < 10^7 M_\odot$ and $Z \gtrsim Z_{crit}$ (efficient pollution)

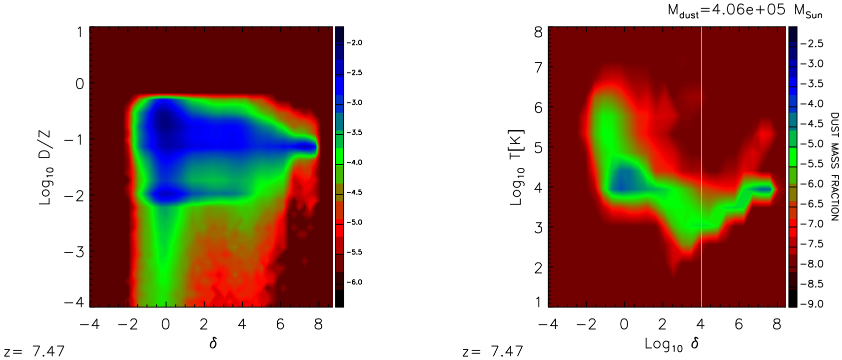
(from Campisi, Maio, Salvaterra, Ciardi, 2011)




$$R_{GRB} = \frac{\gamma_b \zeta_{BH} f_{GRB}}{4\pi} \int_z \dot{\rho}_\star \frac{dz'}{(1+z')} \frac{dV}{dz'} \int_{L_{th}(z')} \Psi(L') dL'$$

$R_{GRB}$: gamma-ray burst rate, $\gamma_b$: beaming factor, $\zeta_{BH}$: fraction of expected BH (IMF), $f_{GRB}$: fraction of expected GRB from collapse onto a BH (Swift), $\dot{\rho}_\star$: star formation rate density (simulation), $\Psi(L)$: Schechter luminosity fct. (assumption), $L_{th}$: instrumental sensitivity (Swift)
PopIII IMF: top-heavy over [100, 500]$M_\odot$
PopII IMF: Salpeter over [0.1, 100]$M_\odot$

# Results (12/14): dust from PISN/SN




D/Z is NOT constant! *(Fiby preliminary results)*

# Results (13/14): radiative feedback on gas cooling

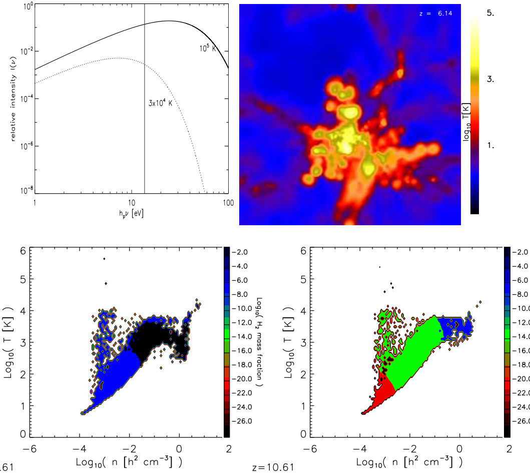
## RT from ionizing sources:

(Petkova & Springel, 2009, 2011; Petkova & Maio, 2012)

- stars are sources of photons
- Planck spectrum $s_\gamma(\nu)$
- multi-frequency method sampling the spectrum with $\sim$ 150 frequency bins
- molecules are self- shielded

  (e.g., Draine & Bertoldi, 1996)

- NB: RT is coupled with hydro and chemistry self-consistently, and NOT run on post-processing
- see also: Abel & Gnedin (2001); Ricotti et al. (2001); Ahn & Shapiro (2007); Whalen & Norman (2009)



# Results (14/14): effects on re-ionization

No RT

With RT

(Preliminary results!!!)

## Summary...

- We have presented results from cosmological N-Body, hydrodynamical, chemistry and radiative simulations
- We studied the early stellar populations, the transition from popIII to popII-I one, and its interplay with the surroundings.

## Conclusions...

- Early ($z \sim 15 - 20$) metal enrichment from the first stars is very strong: the popIII/popII transition is very rapid ($\sim 10^7 - 10^8\,\mathrm{yr}$), and the early contribution to the total SFR is $\sim 10^{-3}$ for top-heavy popIII IMF and $\sim 10^{-2} - 10^{-1}$ for Salpeter-like popIII IMF (after only $\Delta t \sim 10^8\mathrm{yr}$ from SF)
- Radiation from massive popIII stars can easily dissociate molecules (where not shielded), and heat surrounding gas inhibiting further SF (work in progress)
- Results are not very sensitive to the *assumed* $Z_{crit}$, popIII metal *yields*, IMF *slope*, *primordial non-Gaussianities*, etc.

# The End

Thank you...

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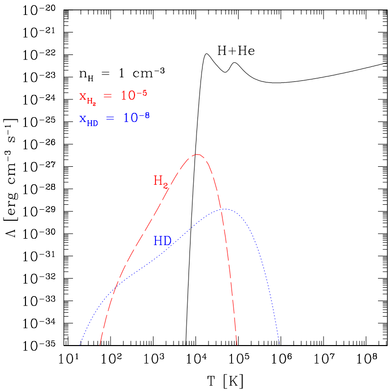
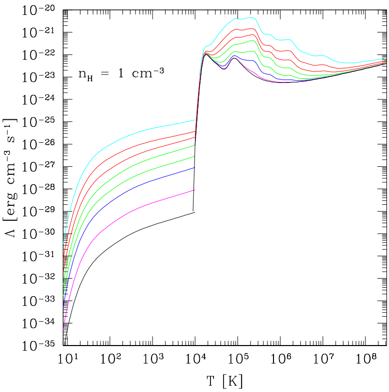
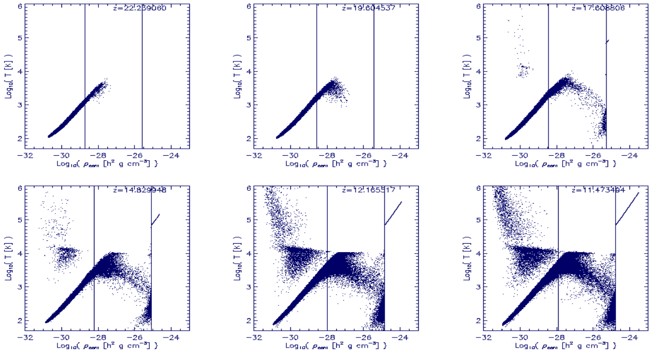
# Extra: cooling functions...



# Resolving the gas in-fall: evolution in the $\rho$ – T space

Hydrodynamic cosmological simulation with molecular chemistry and metal cooling/pollution; $2 \times 128^3$ particles in $(276\ \mathrm{kpc}/h)^3$ box: $M_{gas} \sim 10^2\ M_\odot/h$; $\Omega_{0,\Lambda} = 0.7$, $\Omega_{0,M} = 0.3$, $\Omega_{0,b} = 0.04$, $\sigma_8 = 1.2$, $n = 1$

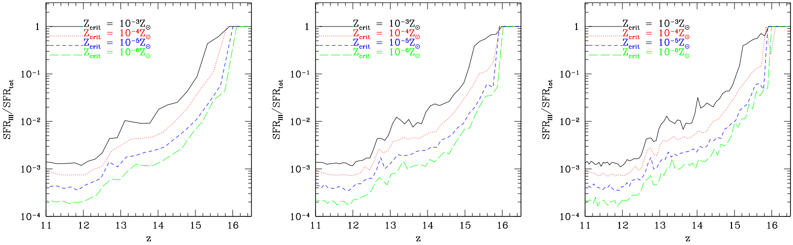



temperature: T [K] $\longrightarrow$

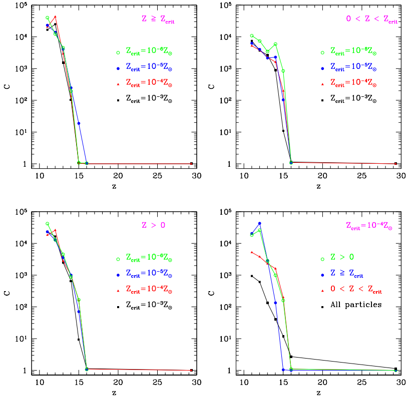
comoving density: $\rho_{com}$ $[h^2\ \mathrm{g\ cm}^{-3}]$ $\longrightarrow$

redshift interval: $z \simeq 22 - 11$

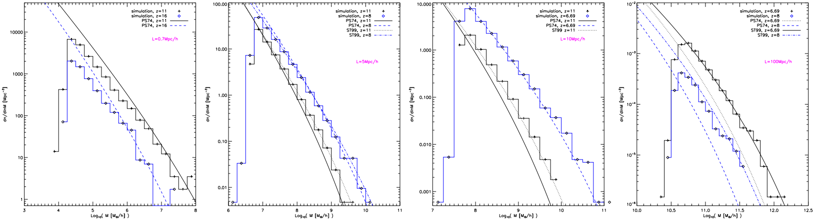
# Extra: star formation ratio (box side = 1 Mpc)...



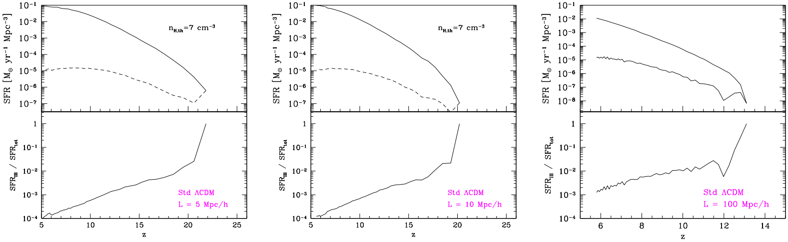
# Extra: clumping factors (box side = 1 Mpc)



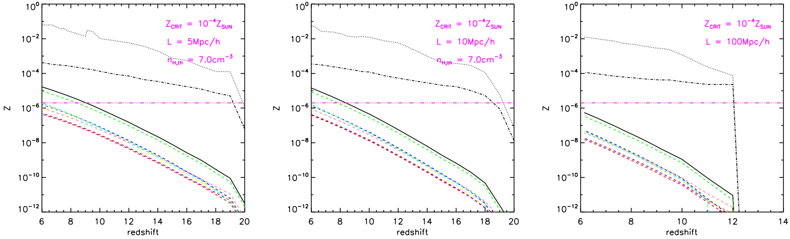
# Extra: Mass functions (larger simulations)



# Extra: SFR (larger simulations)



# Extra: Metallicity evolution (larger simulations)



# Results: metallicity evolution

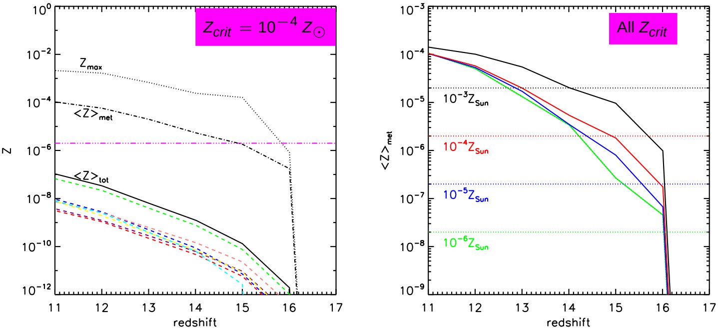
Dotted lines: maximum metallicity.

Dot-dashed lines: average metallicity over the enriched particles.

Solid lines: average metallicity over the whole box.

Dashed lines: average individual metallicities over the whole box.

(e.g., Maio et al, 2010)



$H + e^- \rightarrow H^+ + 2e^-$
$H^+ + e^- \rightarrow H + \gamma$
$H + \gamma \rightarrow H^+ + e^-$
$H^- + e^- \rightarrow H + 2e^-$
$H^- + \gamma \rightarrow H + e^-$
$He + e^- \rightarrow He^+ + 2e^-$
$He^+ + e^- \rightarrow He + \gamma$
$He^+ + e^- \rightarrow He^{++} + 2e^-$
$He^{++} + e^- \rightarrow He^+ + \gamma$
$He^+ + \gamma \rightarrow He^{++} + e^-$
$He + \gamma \rightarrow He^+ + e^-$
$H + e^- \rightarrow H^- + \gamma$
$H^- + H \rightarrow H_2 + e^-$
$H + H^+ \rightarrow {H_2}^+ + \gamma$
${H_2}^+ + H \rightarrow H_2 + H^+$
$H_2 + H \rightarrow 3H$
$H_2 + H^+ \rightarrow {H_2}^+ + H$
$H_2 + e^- \rightarrow 2H + e^-$
$H^- + H \rightarrow 2H + e^-$

$H_2 + \gamma \rightarrow H_2^+ + e^-$
$H_2^+ + \gamma \rightarrow 2H^+ + e^-$
$H_2 + \gamma \rightarrow 2H$
$H_2^+ + \gamma \rightarrow H + H^+$
$H^- + H^+ \rightarrow 2H$
$H^- + H^+ \rightarrow {H_2}^+ + e^-$
${H_2}^+ + e^- \rightarrow 2H$
${H_2}^+ + H^- \rightarrow H + H_2$
$D + \gamma \rightarrow D^+ + e^-$
$D^+ + e^- \rightarrow D + \gamma$
$D + H_2 \rightarrow HD + H$
$D^+ + H_2 \rightarrow HD + H^+$
$HD + H \rightarrow D + H_2$
$HD + H^+ \rightarrow D^+ + H_2$
$H^+ + D \rightarrow H + D^+$
$H + D^+ \rightarrow H^+ + D$
$He + H^+ \rightarrow HeH^+ + \gamma$
$HeH^+ + H \rightarrow He + H_2^+$
$HeH^+ + \gamma \rightarrow He + H^+$

# Numerical RT – A Multi-Frequency Moment Method

Petkova & Springel (2009,2011), Petkova & Maio (2012)

- The RT equation for the photon number density per frequency

$$\frac{\partial n_\gamma(\nu)}{\partial t} = c\,\frac{\partial}{\partial x_j}\left(\frac{1}{\kappa(\nu)}\frac{\partial n_\gamma(\nu) h^{ij}}{\partial x_i}\right) - c\,\kappa(\nu)\,n_\gamma(\nu) + s_\gamma(\nu),$$

where

$$n_\gamma(\nu) = \frac{1}{c}\frac{4\pi I(\nu)}{h_p \nu}.$$

- Closure relation – Eddington tensor $h^{ij}$ that gives effective radiation direction
- Stars are the sources of ionizing photons
- Source function $s_\gamma(\nu)$ – stellar luminosity has a black-body spectrum