The early bursty Universe

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PEOPLE

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Outline

Motivations

Goal: Primordial structure formation and transition from the first metal-free 'PopIII' star formation regime (high-mass or low-mass stars?) to the common, metal-enriched 'PopII-I' one (low-mass 'solar' stars):

→ *What is the formation epoch of first objects?*

→ *What is the role of molecules and metals in the early ISM?*

→ *How relevant is PopIII for star formation and metal spreading?*

→ *What are the effects of different IMFs on SFR?*

→ *What are the implications for early observables (LF, GRB)?*

→ *What are the effects of the underlying matter distribution?*

→ *What are the effects on cosmic re-ionization?...*

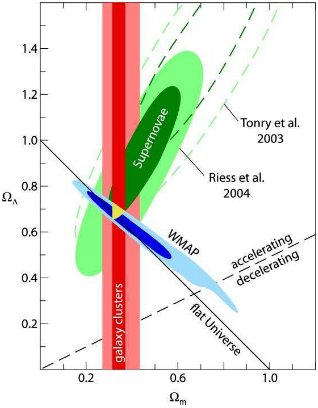
Requirements: Study the chemical properties of cosmic medium during cosmological evolution.

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

Overview of structure formation

The Universe is supposed

- to expand at a rate $\mathrm{H}_0 \simeq 68\ \mathrm{km/s/Mpc}$
- to have flat geometry (zero spatial curvature);
- to consist of dark matter, baryonic matter and cosmological constant/dark energy.



Cosmological parameters (Planck, 2013):

$\Omega_{0,DM} = 0.26$, $\Omega_{0,b} = 0.04$, $\Omega_{0,\Lambda} = 0.7$

$\Rightarrow \Omega_{0,tot} = 1$;

$\sigma_8 = 0.83$, $n = 0.96$

Standard: $\mathrm{H}_0 = 70\ \mathrm{km/s/Mpc}$, $\Omega_{0,\Lambda} = 0.7$, $\Omega_{0,DM} = 0.26$, $\Omega_{0,b} = 0.04$, $\sigma_8 = 0.9$, $n = 1$.

Theoretical scenario:

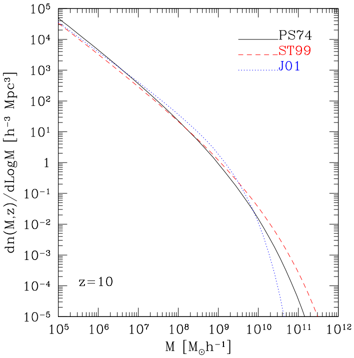
- Cosmic structures originate from the growth of matter perturbations at early times (inflation), in an expanding Universe.
- Baryonic structures form from in-fall and cooling of gas into DM potential well.
- Eventually, a cloud can form if the radiative losses are sufficient to make the gas condense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

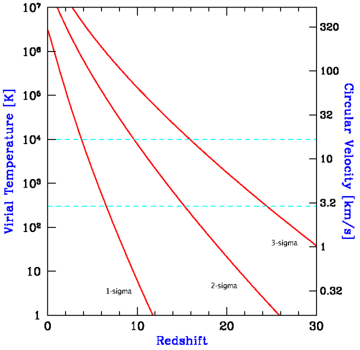
$$t_{cool} = \frac{3}{2}\frac{nkT}{\mathcal{L}(n,T)} \quad \ll \quad t_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

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

primordial environments...

Small dark-matter haloes





Barkana& Loeb, 2001

H-cooling haloes: $T_{\mathrm{vir}} \geq 10^4$ K

H_2-cooling haloes: $T_{\mathrm{vir}} < 10^4$ K

...hosting molecular and metal evolution in their ISM

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

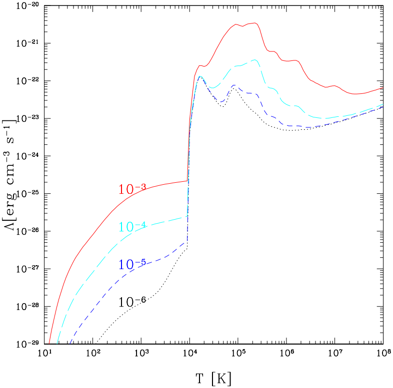
- molecules determine *first* structure formation
- metals determine *subsequent* structure formation
- stellar evolution determines *timescales* and *yields*

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., 2007, 2010)

Gas cooling function and the role of metals ⟶

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

Primordial environments

1 Mpc -

A look into the first structures ($z \simeq 10$)

credit simulation: U. Maio credit animation: P. Creasey

Temperature evolution

100 Mpc ——————————————————————————————-

Structure evolution (down to $z \simeq 0$)

credit simulation: U. Maio credit animation: U. Maio

Metal enrichment in the Universe

Z (absolute)

Total enrichment

O (absolute)

O enrichment

Fe (absolute)

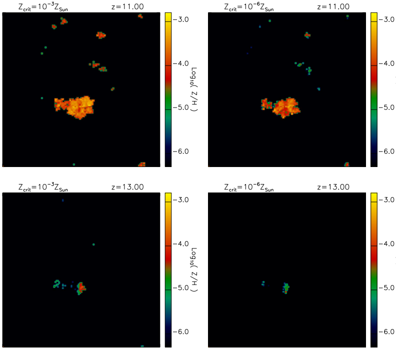
Fe enrichment

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

Results (1/15): effects for different $Z_{\rm crit}$

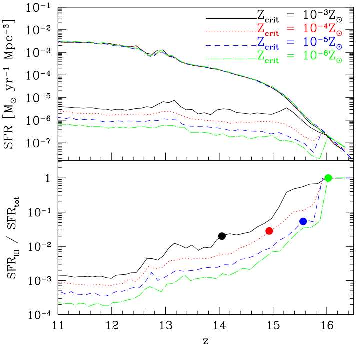
Z_{crit} :

$10^{-3}\,Z_\odot$ $10^{-6}\,Z_\odot$



z=11

z=13



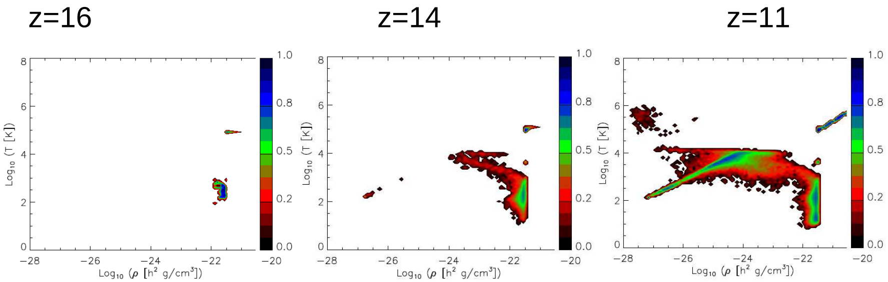
box: 1Mpc^3; popIII IMF: top-heavy with slope=-1.35, range=[100M$_\odot$,500M$_\odot$]

(Maio et al., 2010)

Results (2/15): polluting the surrounding medium

Phase diagrams with color contours for enriched gas

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



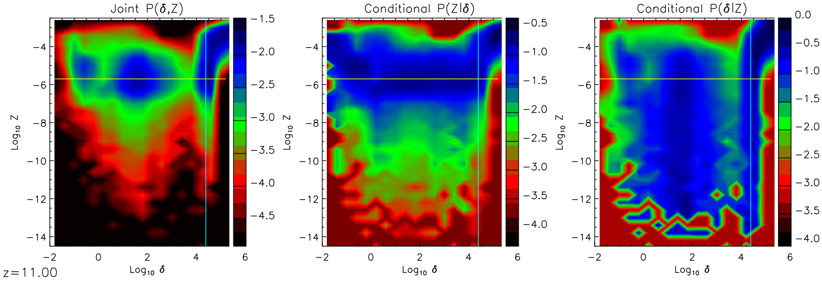
Metals produced by stellar evolution pollute the surrounding, pristine gas with an *“inside-out”* mode.

(Maio et al, 2011b)

Results (3/15): metallicity distribution

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

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

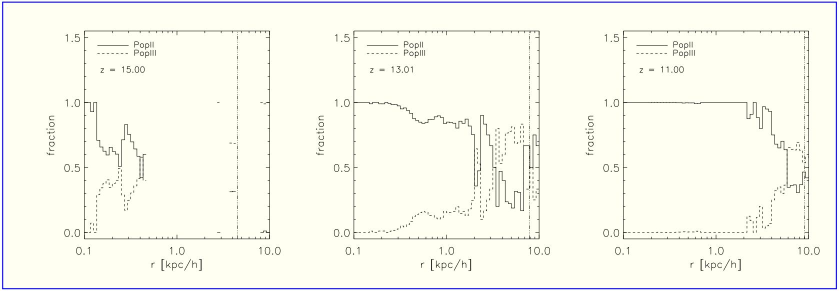


At $z \sim 11$, after $\sim 10^8$ yr from the onset of star formation, most of the enriched mass has $Z > Z_{crit}$.

(Maio et al, 2011b)

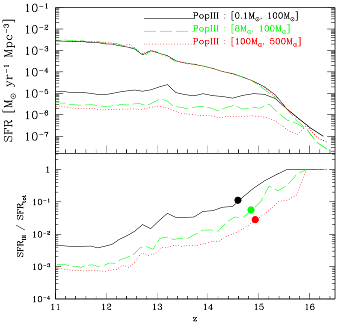
Results (4/15): effects on the surrounding

Radial fractions of PopII and PopIII gas in the most massive halo on scales $\sim 10 - 1000$ pc (physical) (Maio et al., 2011b)

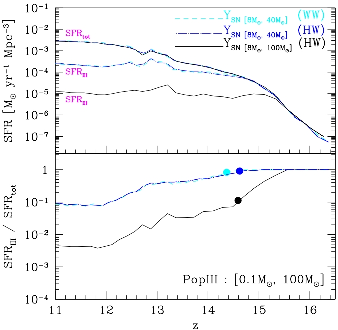


Results (5/15): changing the popIII IMF

PopIII range (Salpeter IMF – top-heavy IMF)



SN range (Salpeter IMF)

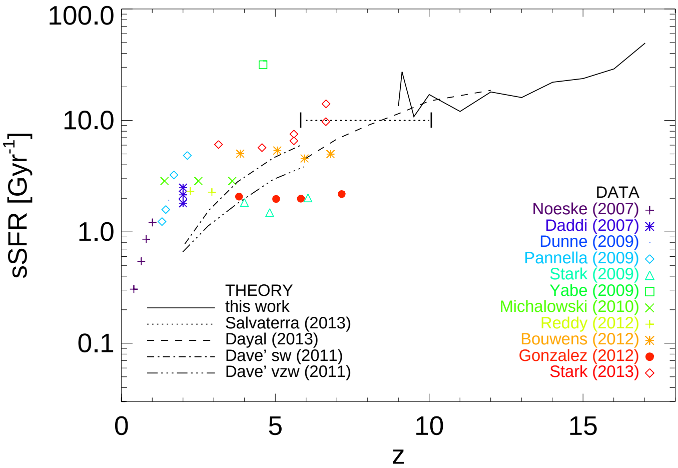


Mass ranges for popIII IMF and/or massive SN have significant impacts:

Larger masses → Shorter stellar lifetimes → Earlier enrichment → Shorter “popIII epoch”

(Maio et al., 2010)

Results (6/15): sSFR – early bursty Universe



Results (7/15): UV luminosity functions

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

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

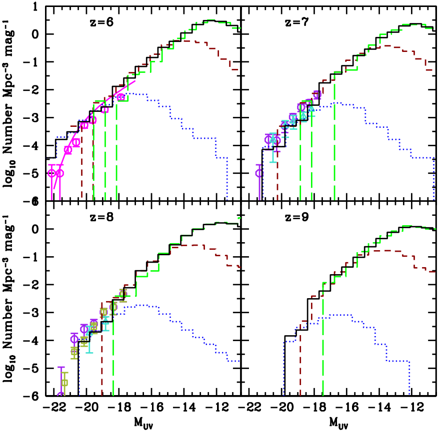
Observational data points from:

Bouwens et al., 2007 (circles); z=6
Bouwens et al., 2011 (circles); z=7-8
McLure et al., 2010 (triangles); z=7-8
Oesch et al., 2012 (squares); z=8

Fit: Su et al., 2012 (solid line); z=6.

Resulting *slope*: ~ -2
consistent with HUDF data

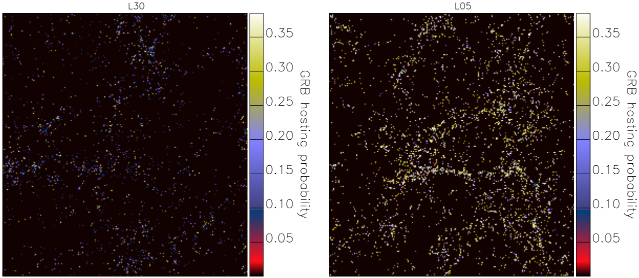
(Dunlop et al., 2013, Dayal, Dunlop, Maio, Ciardi, 2013)



Salvaterra, Maio, Ciardi, Campisi, 2013

Results (8/15): Implications for high-z GRB hosts

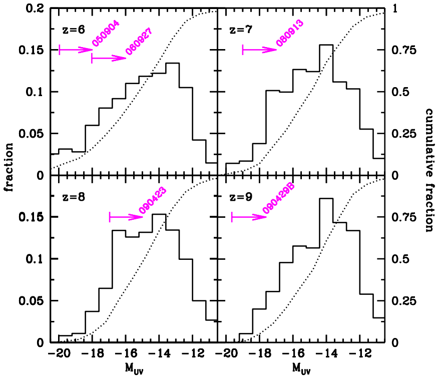
Tracing LGRBs from the SFR of their host galaxies



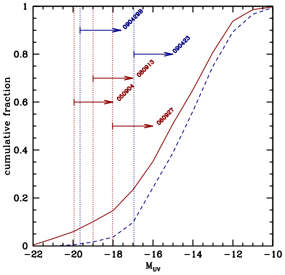
Differential GRB hosting probability → $$dP = \frac{dN_{GRB}(\mathrm{Log}_{10}(SFR[\mathrm{M}_\odot/yr]))}{N_{GRB}\ \mathrm{dLog}_{10}(SFR[\mathrm{M}_\odot/\mathrm{yr}])}$$

Large objects (high SFR) are rarer than small objects (low SFR):
high-z GRBs are more likely found in intermediate-, low-size objects!

Results (9/15): UV luminosities of GRB hosts



Data points from:
Tanvir et al., 2012

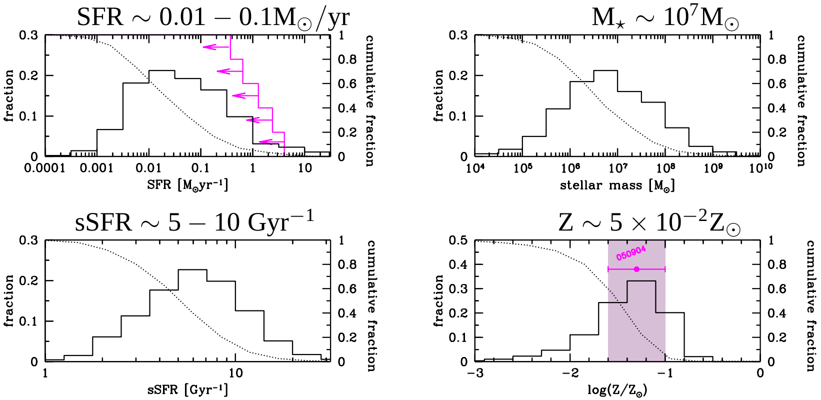


$\nu_{ion} \longrightarrow$

Most high-*z* GRB hosts are primordial faint galaxies
(they lie below current HST, VLT detection limits)

Most ionizing photons are produced in faint galaxies
(at $z = 6$ and $z = 8$)

Results (10/15): Statistical properties of GRB hosts



$\mathrm{SFR} \sim 0.01 - 0.1 \mathrm{M}_\odot/\mathrm{yr}$

$\mathrm{M}_\star \sim 10^7 \mathrm{M}_\odot$

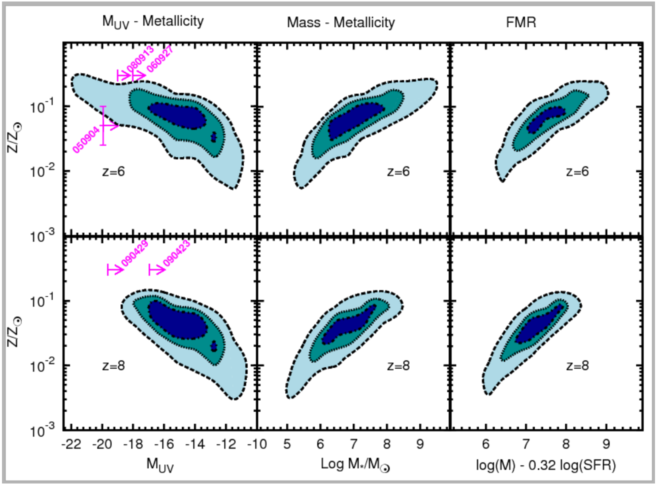
$\mathrm{sSFR} \sim 5 - 10\ \mathrm{Gyr}^{-1}$

$\mathrm{Z} \sim 5 \times 10^{-2} \mathrm{Z}_\odot$

Data from: Tanvir et al., 2012 (SFRs), Kawai et al., 2006 (Z)

See Salvaterra, Maio, Ciardi, Campisi, 2013

Results (11/15): Physical relations for GRB hosts



Results (12/15): PopIII-GRB rates and hosts

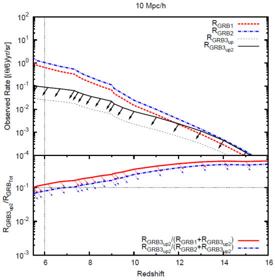
LGRB rate:

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)



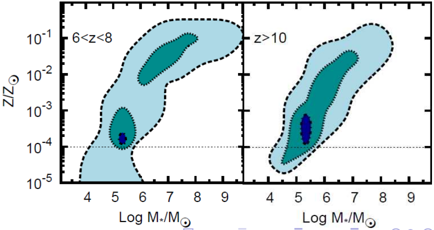
$$R_{GRB} = \frac{\gamma_b \zeta_{BH} f_{GRB}}{4\pi} \int_z \dot{\rho}_\star \frac{dz'}{(1+z')} \frac{dV}{dz'} \int_{L_{th}(z')} \Psi(L') dL'$$

R_{GRB}: gamma-ray burst rate, γ_b: beaming factor, ζ_{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 $[100, 500]\mathrm{M}_\odot$
PopII IMF: Salpeter over $[0.1, 100]\mathrm{M}_\odot$

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

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

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

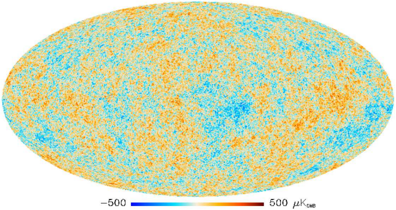


Results (13/15): primordial matter distributions and Non-Gaussianities

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

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

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



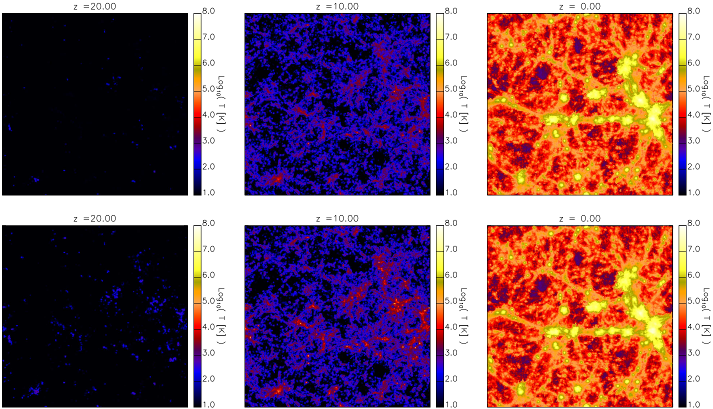
credit: Planck

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

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

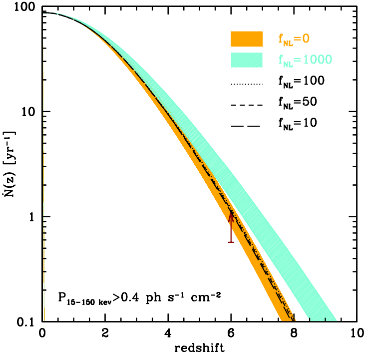
Results (14/15): Non-G and the cosmic web

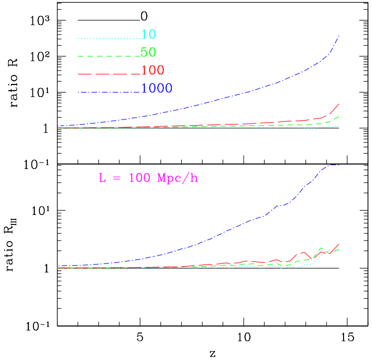
f_{NL}=0



f_{NL}=1000

Results (15/15): Non-G and the GRB rate





From Swift data

Maio, Salvaterra, Moscardini, Ciardi (2012)

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 $\underline{\sim 10^{-3}}$ for top-heavy popIII IMF and $\underline{\sim 10^{-2} - 10^{-1}}$ 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), heat surrounding gas inhibiting further SF and possibly affect the IGM thermal state
- 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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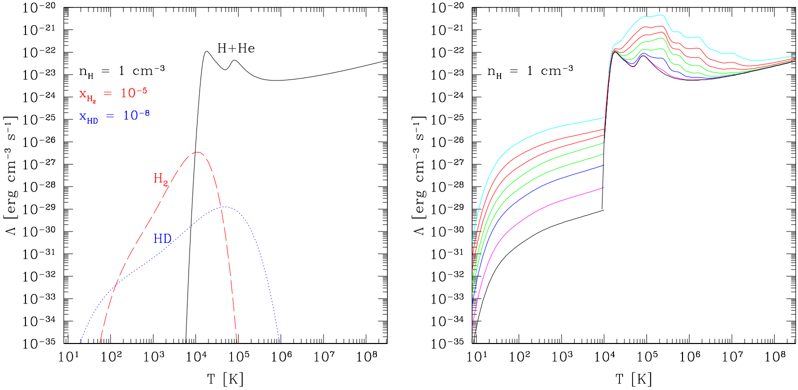
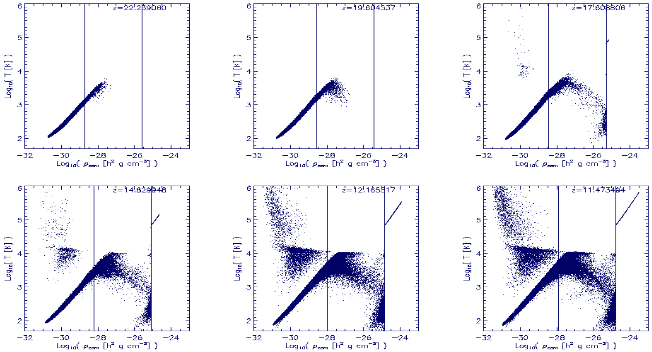
Extra: cooling functions...



Resolving the gas in-fall: evolution in the ρ – T space

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

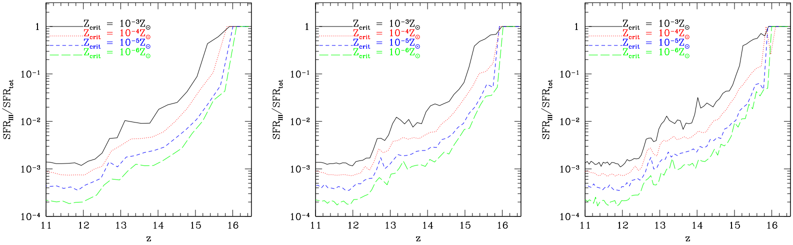


temperature: T [K] $\longrightarrow$

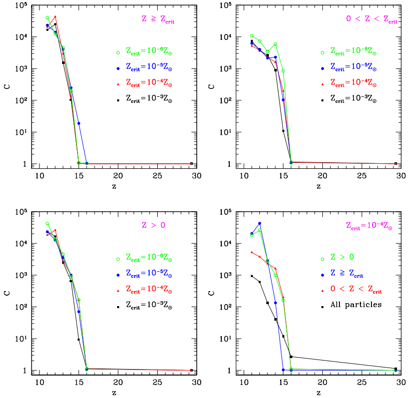
comoving density: ρ_{com} $[h^2\,\mathrm{g\,cm}^{-3}]$ $\longrightarrow$

redshift interval: $z \simeq 22 - 11$

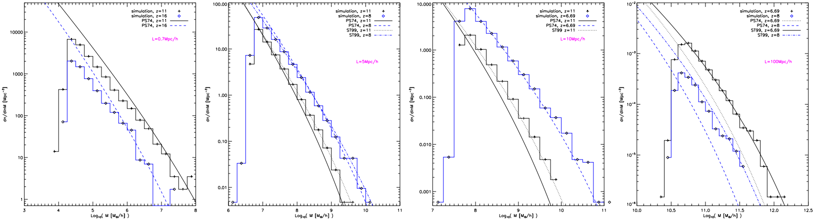
Extra: star formation ratio (box side = 1 Mpc)...



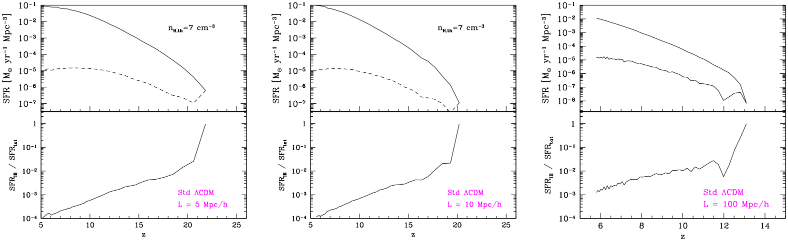
Extra: clumping factors (box side = 1 Mpc)



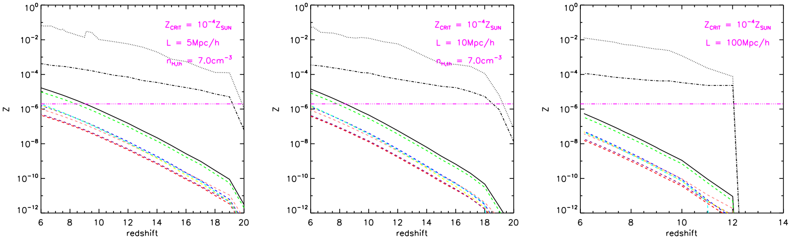
Extra: Mass functions (larger simulations)



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)