Observables of the primordial Universe

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Outline

Motivations

Goal: Primordial galaxy formation and evolution and the occurrence of chemical (heavy) elements in the Universe:

→ *What is the formation epoch of first objects?*
→ *What is the role of molecules and metals in the early ISM?*
→ *How relevant is 'PopIII' star formation and metal spreading?*
→ *What are the effects of different IMFs on SFR?*
→ *What are the implications for early observables (LF, GRB, Z)?*
→ *What are the effects of the underlying matter distribution?...*

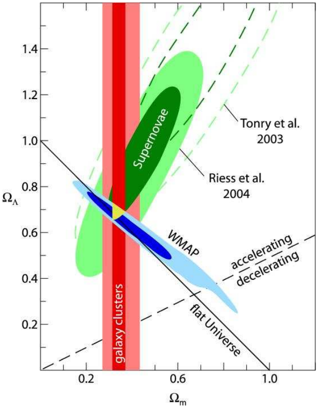
Requirements: Study of the properties of cosmic environments via cosmological hydro chemistry sims.

Relevance: Upcoming international technological missions – SKA, JWST, ALMA, HST Frontier Field, E-ELT ...

Overview of structure formation

The Universe is supposed

- to expand at a rate $H_0 \simeq 68$ 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: $H_0 = 70$ 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:

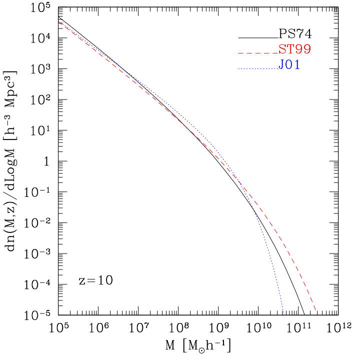
- Cosmic structures originate from the growth of matter perturbations at early times (inflation), in an expanding Universe.
- Baryonic structures form from in-fall and cooling of gas into DM potential well.
- Eventually, a cloud can form if the radiative losses are sufficient to make the gas condense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

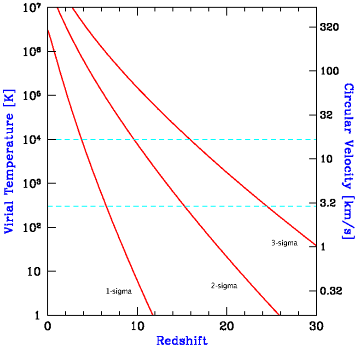
$$t_{cool} = \frac{3}{2}\frac{nkT}{\mathcal{L}(n,T)} \quad \ll \quad t_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

- 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: $T_{vir} \geq 10^4$ K

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

...hosting molecular and metal evolution in their ISM

For a complete picture $\longrightarrow$ follow gravity and hydrodynamics *coupled* to molecule formation (e.g. Galli& Palla, 1998; Abel et al., 1997) and metal production from stellar evolution (e.g. Tinsley, 1980; Matteucci, 2001) through cosmic time

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

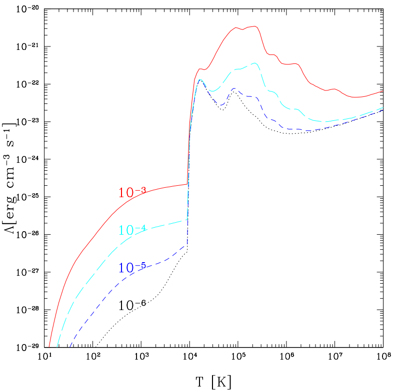
Following and implementing metal and molecule evolution in numerical codes (N-body/SPH Gadget) required
(Springel, 2001, 2005; Yoshida et al., 2003; Tornatore et al., 2007; Maio et al., 2007, 2010; Biffi & Maio, 2013)

Cooling and star formation

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).

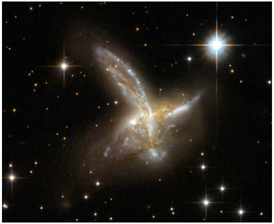


(Maio et. al, 2007)

Cooling leads gas in-fall and star formation

Feedback mechanisms

Mechanical feedback



Interactions, SN explosions, shocks, stripping, winds, etc.

Radiative feedback

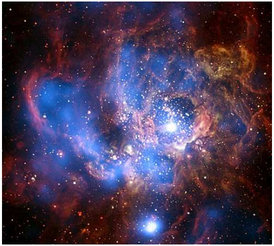
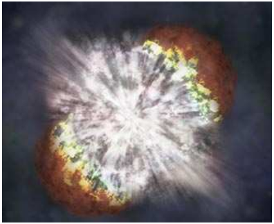


photo-ionization/dissociation, gas heating, etc.

Chemical feedback



Changes of chemical composition

Primordial star formation and popIII regime

Mass of first stars connected to the existence of a critical metallicity Z_{crit} (e.g. Bromm & Loeb, 2003; Schneider et al., 2003) below which cooling is not efficient: popIII ($Z < Z_{crit}$) $\longrightarrow$ popII-I ($Z \geq Z_{crit}$)

Numerical simulations exploring different scenarios needed!

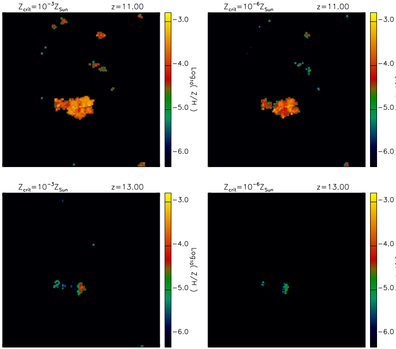
Simulation set-up

(Maio et al., 2010, 2011, Maio & Iannuzzi, 2011; Biffi & Maio, 2013; Maio & Viel, 2014)

- ΛCDM cosmology (1,7,14,43,143 Mpc a side);
- molecules, metals, $Z_{crit} = (10^{-6}, 10^{-5}, 10^{-4}, 10^{-3})\ Z_{\odot}$
- assume different popIII IMFs ($\rightarrow$ top-heavy/Salpeter)
- assume different matter distributions ($\rightarrow$ G vs non-G)
- assume different dark-matter flavors ($\rightarrow$ CDM vs WDM)

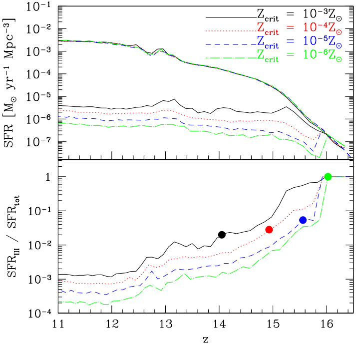
Results (1/18): effects for different Z_{crit}

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



z=11

z=13

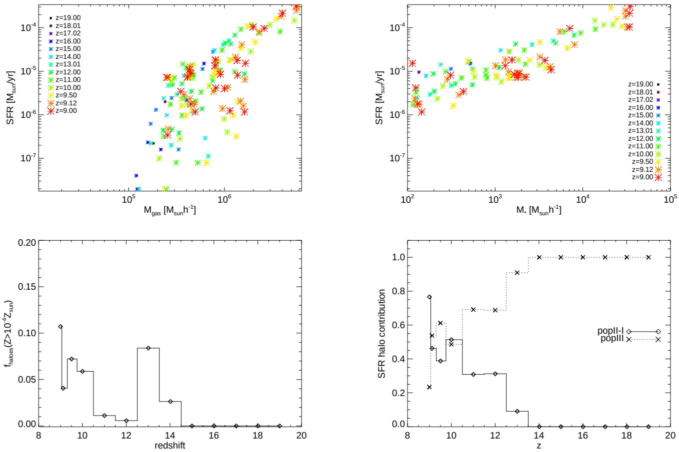


box: $1 Mpc^3$; popIII IMF: top-heavy with slope=-1.35, range=[$100 M_{\odot}$,$500 M_{\odot}$]

Gas resolution: 116 $M_{\odot}/h$ (Maio et al., 2010)

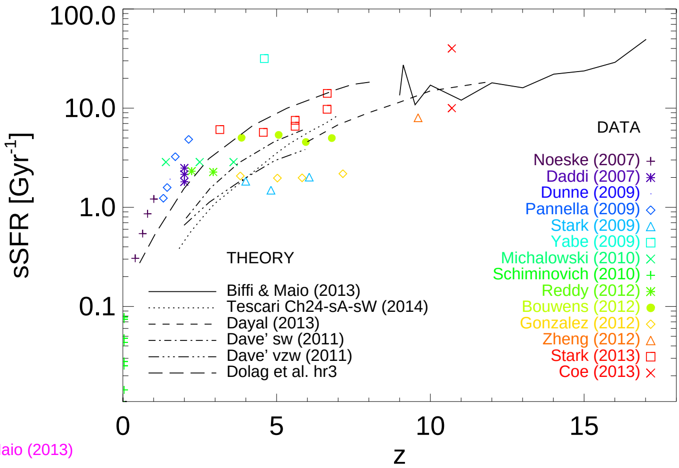
Results (2/18): primordial galaxies in the 1st Gyr

$M_{gas}\,[M_\odot/h]$ $\quad$ $M_\star\,[M_\odot/h]$



For further baryonic relations and dynamical features see Biffi & Maio (2013)

Results (3/18): sSFR – early bursty Universe



Biffi & Maio (2013)

Results (4/18): UV luminosity functions at $z \sim 6 - 9$

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

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

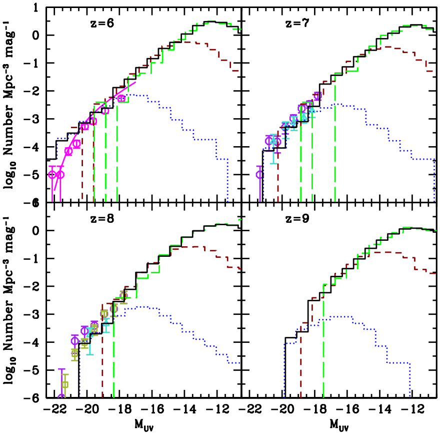
Observational data points from:

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

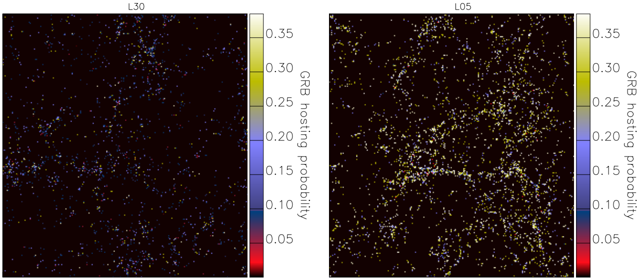
(Dunlop et al., 2013; Dayal, Dunlop, Maio, Ciardi, 2013)



Salvaterra, Maio, Ciardi, Campisi (2013)

Implications for high-z GRB hosts

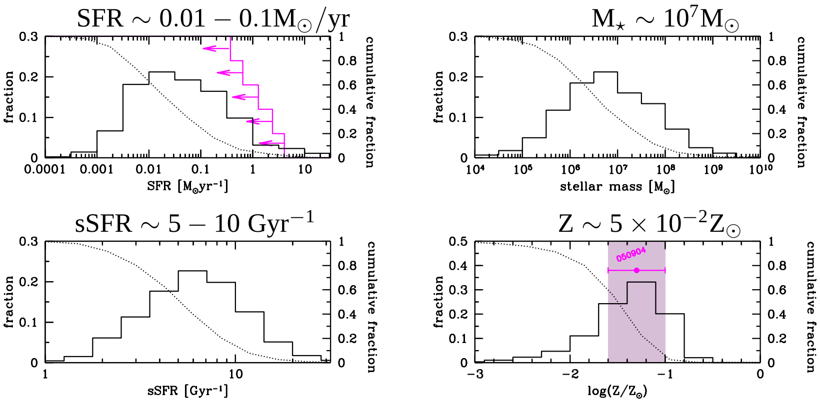
Tracing LGRBs from the SFR of their host galaxies



Differential GRB hosting probability $\longrightarrow \mathrm{d}P = \dfrac{\mathrm{d}N_{GRB}(\mathrm{Log}_{10}(SFR[\mathrm{M}_\odot/yr]))}{N_{GRB}\ \mathrm{dLog}_{10}(SFR[\mathrm{M}_\odot/\mathrm{yr}])}$

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

Results (5/18): Statistical properties of GRB hosts



Data from: Tanvir et al., 2012 (SFRs); Kawai et al., 2006, Castro-Tirado et al. 2013 (Z)

See Salvaterra, Maio, Ciardi, Campisi (2013)

Results (6/18): PopIII-GRB rates and hosts

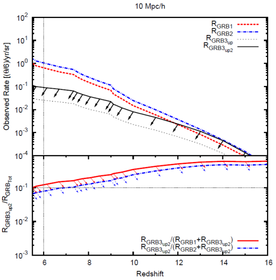
LGRB rate:

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)



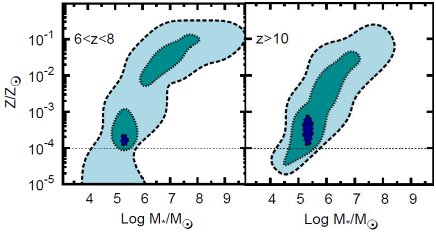
$$R_{GRB} = \frac{\gamma_b \zeta_{BH} f_{GRB}}{4\pi} \int_z \dot{\rho}_\star \frac{dz'}{(1+z')} \frac{dV}{dz'} \int_{L_{th}(z')} \Psi(L') dL'$$

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), $Z_{crit} = 10^{-4} Z_{\odot}$
PopIII IMF: top-heavy over [100, 500] $M_{\odot}$
PopII IMF: Salpeter over [0.1, 100] $M_{\odot}$

Detectable *fraction* (by BAT/Swift) of PopIII GRBs:
$\sim$ 10% at $z > 6$
$\gtrsim$ 40% at $z > 10$
(Campisi, Maio, Salvaterra, Ciardi, 2011)

NB: SC sub-sample accounts for only
$\sim$ 1% at $z > 6$ (Maio & Barkov, 2014)

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



Results (7/18): stellar populations from GRBs at $z \sim 6$

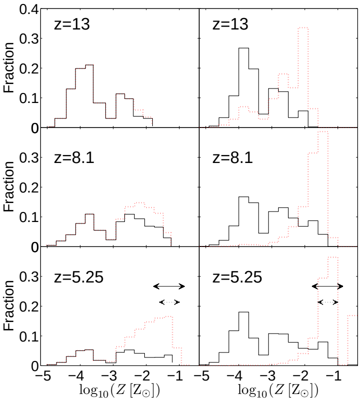
Look for indirect signatures of popIII/popII-I regime: abundance ratios

GRB050904

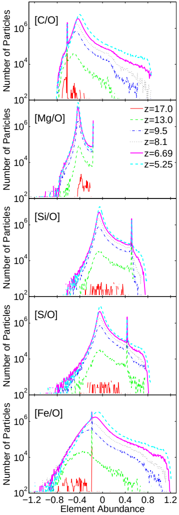
($z \simeq 6.3$) no PopIII
$[C/O] = -0.1$
$[Si/O] = -0.3$
$[S/O] = 1.3$
(Kawai et al., 2006)

GRB130606A

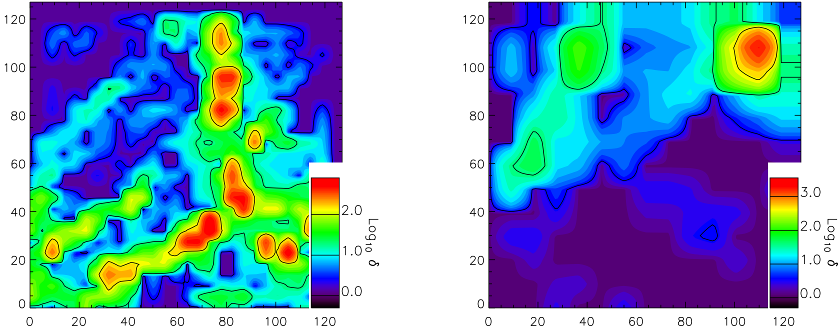
($z \simeq 5.9$) uncertain
$[S/O] < 1.24$
$[Si/O] < 0.55$
$[Fe/O] < -0.34$
(Castro-Tirado et al., 2013)



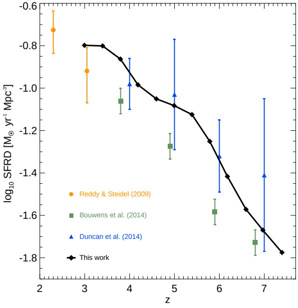
PopII-I star forming haloes
PopII-I star forming haloes pre-enriched by popIII

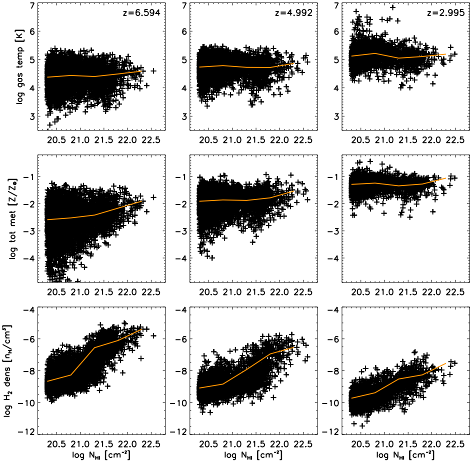


Implications for high-z (metal-poor) DLAs

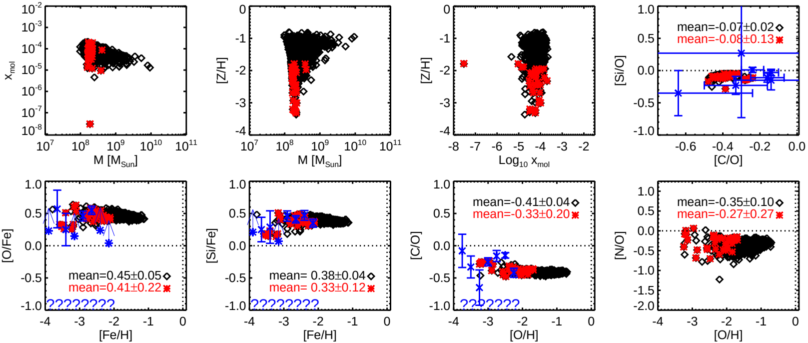


Results (8/18): DLA systems at $z \sim 2 - 7$



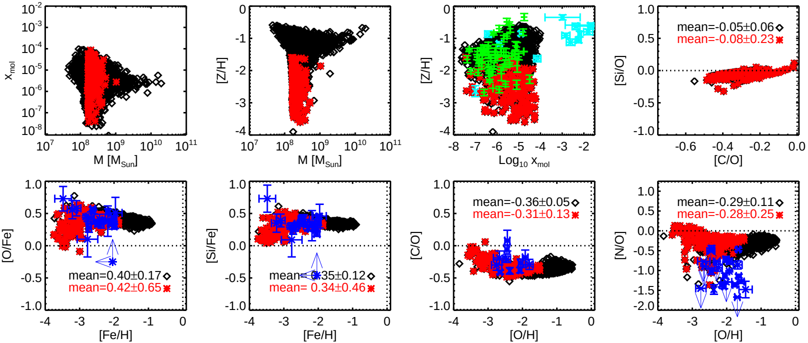


Results (9/18): abundance ratios from DLAs at $z \sim 7$



data: Becker et al. (2012), Cooke et al. (2011, 2014)

Results (10/18): abundance ratios from DLAs at $z \sim 4$



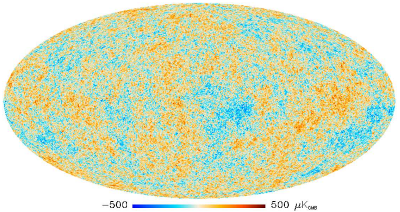
data: Noterdaeme et al. (2008), Srianand et al. (2010), Albornoz Vásquez et al. (2013), Cooke et al. (2011, 2014)

Effects of 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.

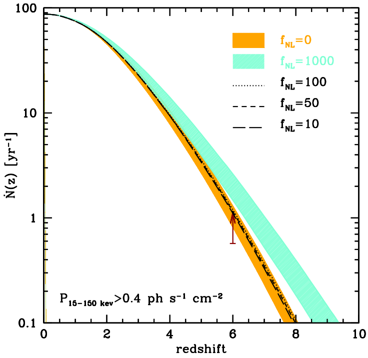


credit: Planck

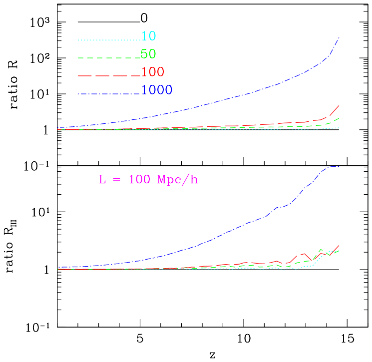
$f_{\rm NL}$ = 0, 10, 50, 100, 1000
box sides: 0.5 and 100 Mpc/h
number of particles: 2×320^3
gas mass resolution: $42\ \mathrm{M_\odot}/h$ and $3 \times 10^8\ \mathrm{M_\odot}/h$

See: Maio & Iannuzzi (2011), Maio (2011), Pace & Maio (2013)

Results (11/18): Non-G and the GRB rate



From Swift data



Maio, Salvaterra, Moscardini, Ciardi (2012)

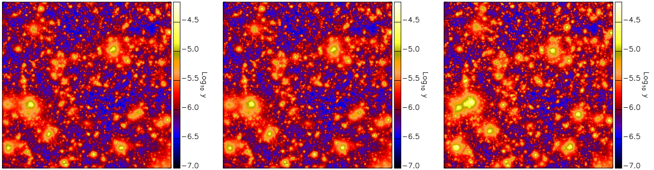
Results (12/18): Non-G and the SZ effect

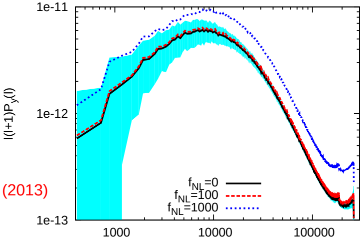
Power spectrum and bi-spectrum for the y parameter:

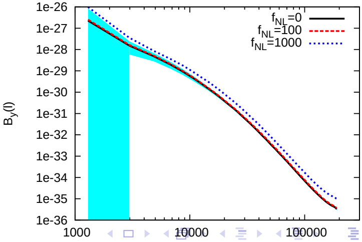
$$y = \frac{k_B \sigma_T}{m_e c^2} \int n_e T_e \, dl$$

over sets of 100 random light-cones

f_{NL}=0 f_{NL}=100 f_{NL}=1000







Pace & Maio (2013)

Effects of CDM and WDM

– WDM mass compatible with currently known cosmological observables: 3keV

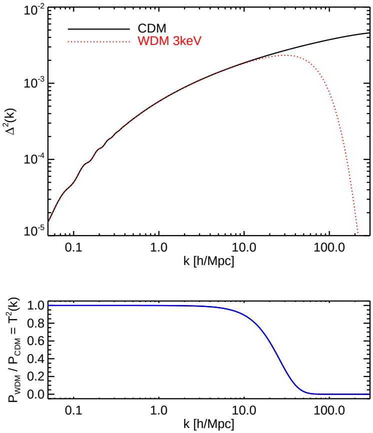
– WDM described by a sharp decrease of P(k) at large k

– Implications for IGM, lensing, clustering, satellite problem

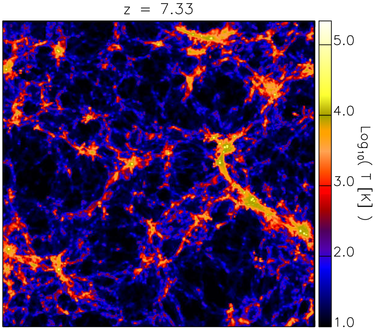
– What about primordial epochs?

$\longrightarrow$ Sims. $\mathrm{L} = 10\,\mathrm{Mpc}/h$, 2×512^3

Maio & Viel (2014)



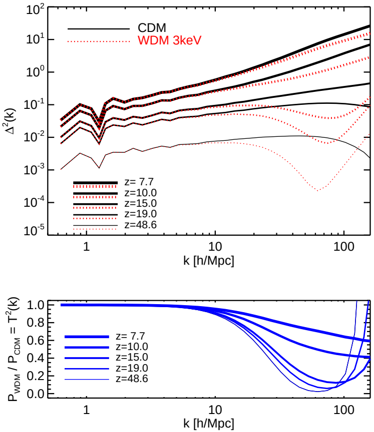
Results (13/18): CDM and WDM structures



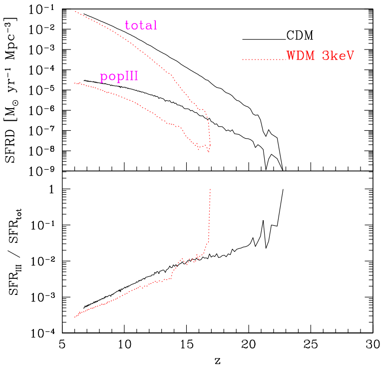
CDM **WDM**

Results (14/18): CDM and WDM growth

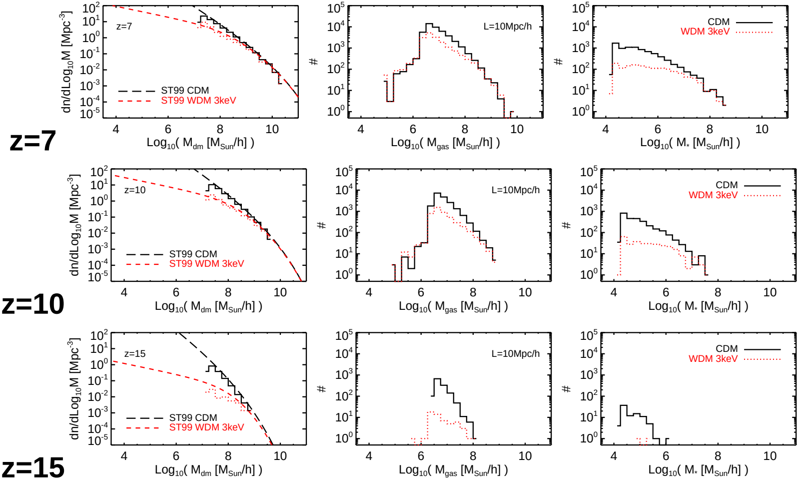
Power



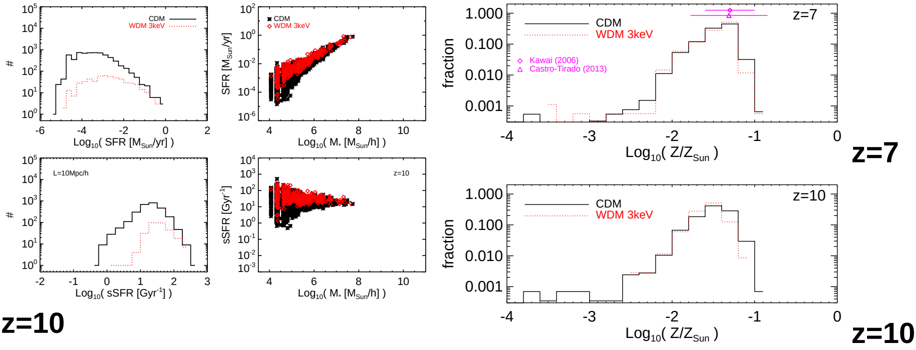
SFRD



Results (15/18): CDM and WDM mass functions



Results (16/18): CDM and WDM star formation and Z

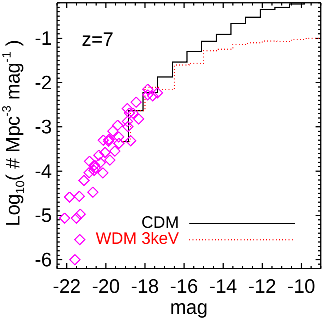


WDM objects are more bursty than CDM:

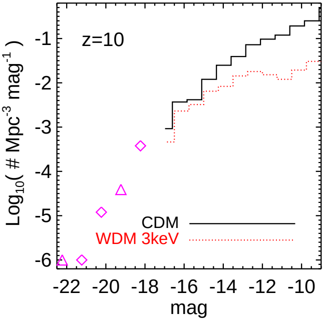
fraction of WDM star hosting haloes = 70%, 55%, 40% at $z = 7, 10, 15$

fraction of CDM star hosting haloes = 67%, 43%, 17% at $z = 7, 10, 15$

Results (17/18): CDM and WDM luminosities



z=7



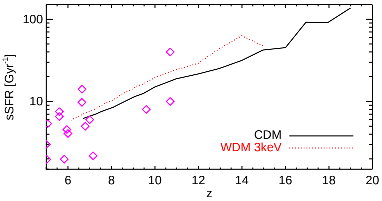
z=10

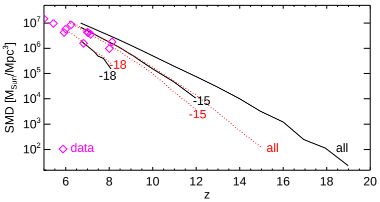
$$T_{\rm mag}(z) \equiv \frac{\phi_{\rm WDM}(z)}{\phi_{\rm CDM}(z)}$$

$$T^{Fit}_{\rm mag}(z) = 1 - \beta \exp\left\{ - \left[\frac{mag}{mag_\star(z)} \right]^\gamma \right\}$$

$$mag_\star(z) = -16 \left(\frac{1+z}{10} \right)^{0.2}, \quad \beta = 0.91, \quad \gamma = 6$$

Results (18/18): CDM and WDM sSFR & SMD





for all haloes and for haloes brigther than -15 and -18 mag

sSFR data from: Bouwens et al. (2012), Gonzalez et al. (2012), Reddy et al. (2012), Zheng et al. (2012), Coe et al. (2013), Stark et al. (2013), Duncan et al. (2014).

SMD data from: Labbe et al. (2010), Gonzalez et al. (2011), Stark et al. (2013), Duncan et al. (2014).

– Detection of faint primordial galaxies could help disentangle CDM and WDM (e.g. ALMA, JWST, SKA)

– WDM effects are more dramatic than the ones from non-G, dark-energy models, high-order corrections etc.

Summary...

- We have presented results from cosmological N-Body hydrodynamical chemistry simulations
- We study the formation of first galaxies, their expected properties and observational expectations (SFR, LF, sSFR, SMD, Z, abundance ratios) in various contexts (CDM, WDM, nonG).

Conclusions...

- Early ($z \sim 10 - 20$) metal enrichment from the first stars is very strong with a rapid popIII/popII-I transition ($z \sim 10$).
- Observationally, LF, sSFR, SMD, Z can constrain early structure properties (such as GRB hosts and DLA systems).
- Among the possible alternative scenarios, WDM implications are the most dramatic, while changes in the IMF parameters and in the matter distributions (non-G) have minor effects.

The End

Thank you!

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