The bursty cosmic dawn

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Outline

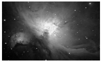
Motivations

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?*
→ *How fast is the transition to the standard popII regime?*
→ *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?...*

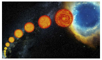
Astrochemistry

For a complete picture ⟶ 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* gas collapsing events

metals determine *subsequent* structure formation



stellar evolution determines *yields* and *timescales*

Following and implementing metal and molecule evolution in numerical codes (e.g Gadget, etc.) required
(Springel, 2001, 2005; Yoshida et al., 2003; Tornatore et al., 2007; Maio et al., 2007, 2010, 2011; Biffi & Maio, 2013)

Primordial regimes

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!

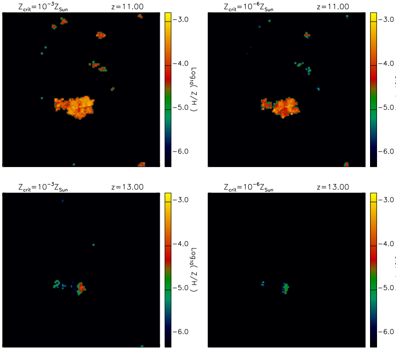
Simulation set-up

(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)

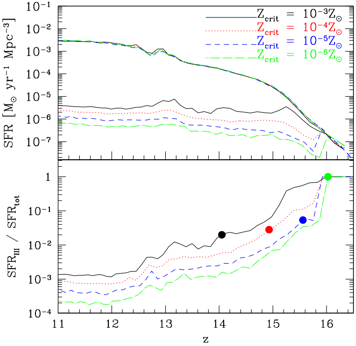
Results (1/10): effects for different Z_{crit}

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



z=11

z=13

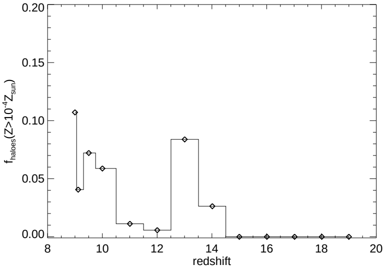


box: $1 Mpc^3$; popIII IMF: top-heavy with slope=-1.35, range=[$100 M_{\odot}$,$500 M_{\odot}$]

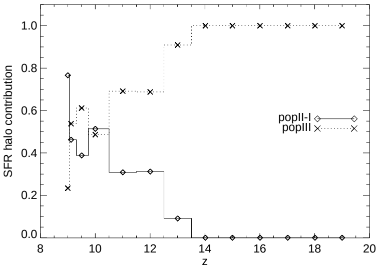
Gas resolution: 116 $M_{\odot}/h$ (Maio et al., 2010)

Results (2/10): primordial populations in the 1st Gyr

fraction of popII haloes (i.e. with mean $Z_{\rm halo} > Z_{\rm crit}$) vs z

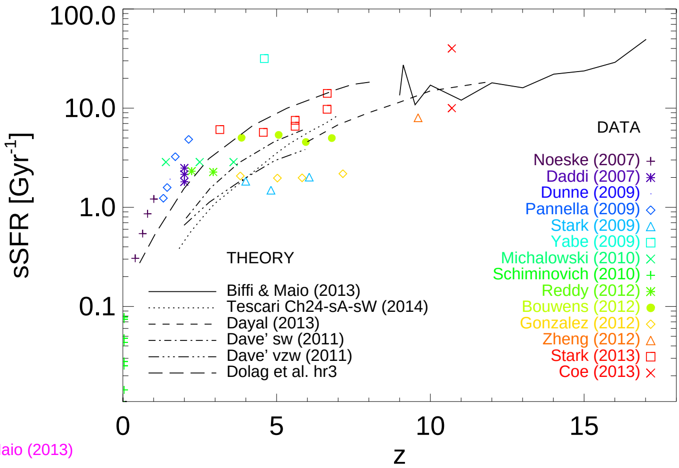


SFR contribution from popII and popIII haloes vs z



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

Results (3/10): sSFR – early bursty Universe



Biffi & Maio (2013)

Results (4/10): UV luminosity functions at $z \sim 6 - 9$

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

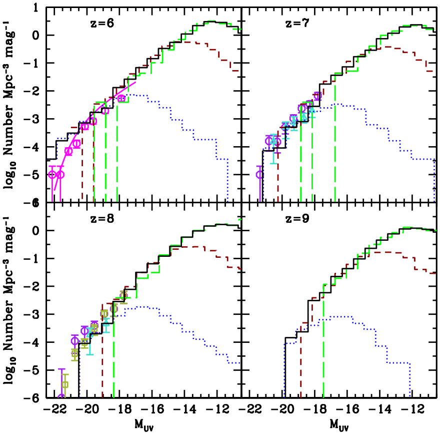
Observational data points from:

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

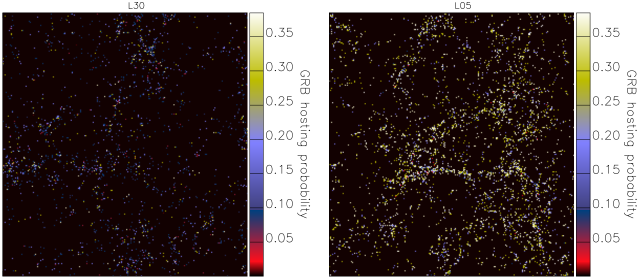
(Dunlop et al., 2013; Dayal, Dunlop, Maio, Ciardi, 2013)



Salvaterra, Maio, Ciardi, Campisi (2013)

Implications for high-z GRB hosts

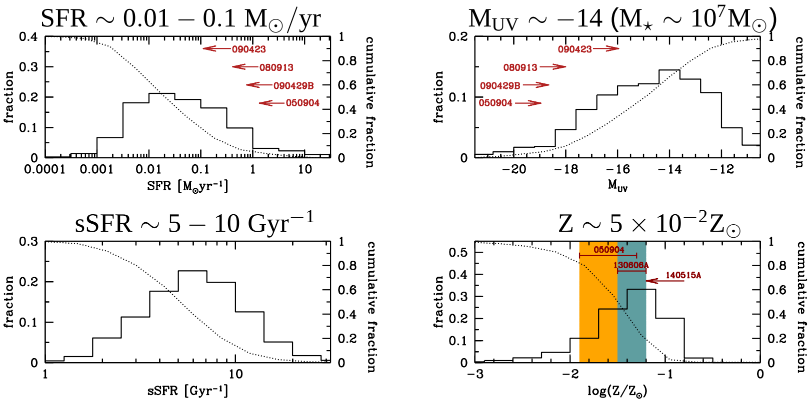
Tracing LGRBs from the SFR of their host galaxies



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

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

Results (5/10): Statistical properties of GRB hosts



Data from: Tanvir et al., 2012; Thöne et al., 2013; Hartoog et al., 2014; Chornock et al. 2014

See: Salvaterra et al. (2013, 2015); Ma et al. (2015)

Results (6/10): PopIII-GRB rates and hosts

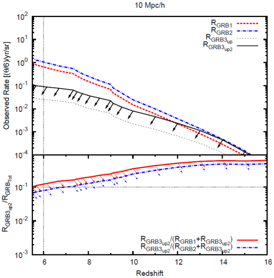
LGRB rate:

different progenitors
i.e. stars with

1: $Z > Z_{crit}$
→any popII-I

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

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



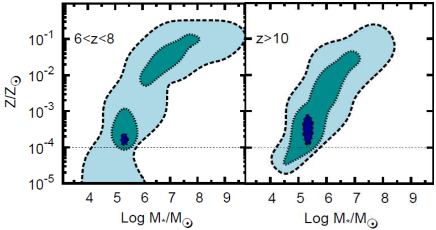
$$R_{GRB} = \frac{\gamma_b \zeta_{BH} f_{GRB}}{4\pi} \int_z \dot{\rho}_\star \frac{dz'}{(1+z')} \frac{dV}{dz'} \int_{L_{th}(z')} \Psi(L')dL'$$

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 (7/10): PopIII stellar populations at $z \gtrsim 5$?

Indirect signatures: abundance ratios

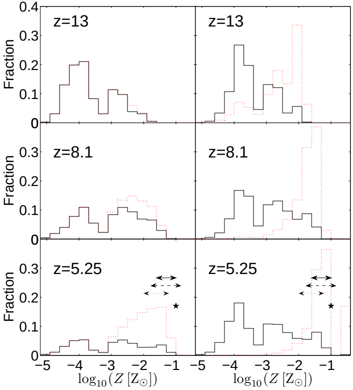
GRB 050904 ($z = 6.3$): no PopIII
$[C/O] = -0.1$, $[S/O] = 1.3$
$[Si/O] = -0.3$, $Z \simeq 0.03\,Z_\odot$
(Kawai et al., 2006; Thöne et al., 2013)

GRB 130606A ($z = 5.9$): unlikely PopIII
$[S/O] < 1.24$, $[Si/O] < 0.55$
$[Fe/O] < -0.34$,
$Z \simeq 0.1\,Z_\odot - 0.01\,Z_\odot$
(Castro-Tirado et al., 2013)

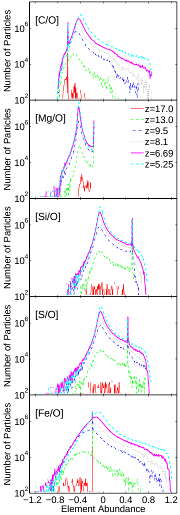
GRB 111008A ($z = 5.0$): unlikely PopIII
$[S/H] = -1.7$, $Z \gtrsim 0.01\,Z_\odot$
(Sparre et al., 2014)

GRB 100219A ($z = 4.7$): unlikely PopIII
$[C/H] = -2.0$, $[Fe/H] = -1.9$
$[O/H] = -0.9$, $[S/H] = -1.1$
$Z \simeq 0.1\,Z_\odot$
(Thöne et al., 2013)

Ma, Maio et al. (2015)



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



Effects of CDM and WDM

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

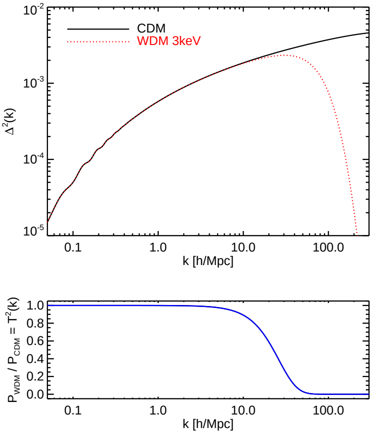
– WDM described by a sharp decrease of P(k) at large k

– Implications for IGM, lensing, clustering, satellite problem

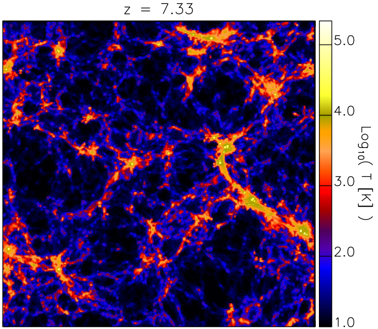
– What about primordial epochs?

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

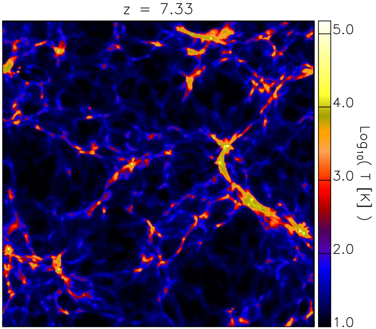
See Maio & Viel (2015)



CDM and WDM structures

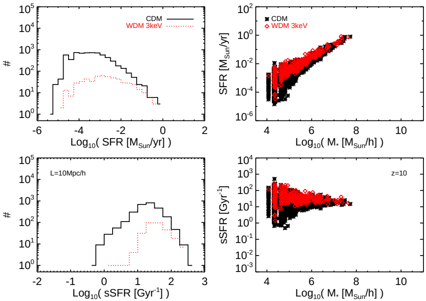


CDM

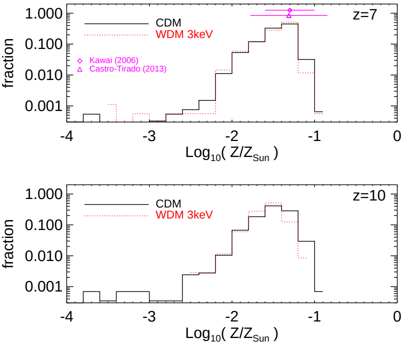


WDM

Results (8/10): CDM and WDM star formation and Z



z=10

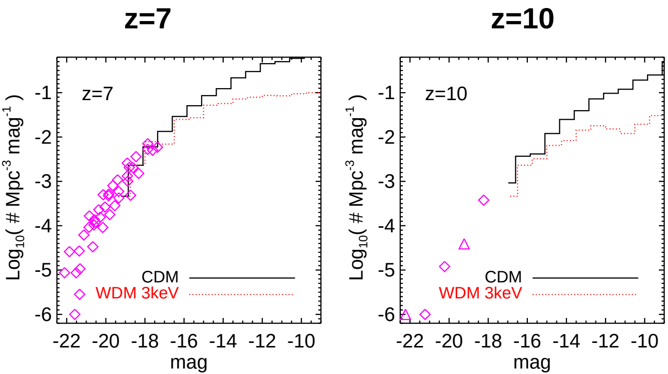


z=7

z=10

WDM galaxies 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 $z = 7, 10, 15$

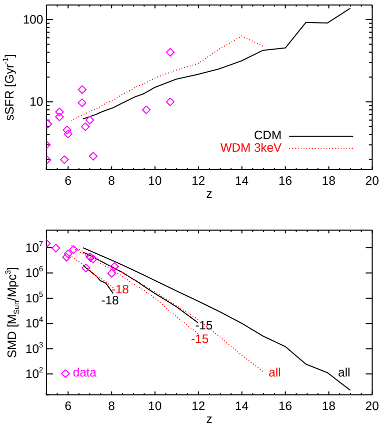
Results (9/10): CDM and WDM luminosities



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

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

Results (10/10): 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 simulated properties and observational expectations (SFR, LF, sSFR, SMD, Z, abundance ratios) in various cosmological contexts.

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 and metal ratios can constrain early structure properties (such as GRB hosts and DLA systems) – current data are compatible with popII regimes.
- Among the possible alternative scenarios, WDM implications are the most dramatic at early times (IMFs, matter non-G or supersonic gas *bulk flows* have lower impacts).

The End

Thank you!

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