Pristine Star Formation and Metal Enrichment

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Motivations

Primordial H_2-driven star formation and occurrence of heavy elements in the Universe

outline

Goals

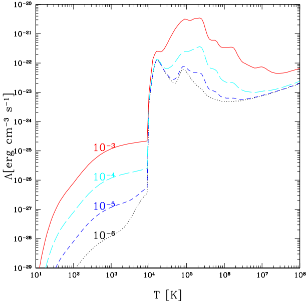
$\rightarrow$ epoch of first objects?

$\rightarrow$ role of molecules and metals in the early ISM and IGM?

$\rightarrow$ implications?

Numerical simulations (G3) with gravity and hydro coupled to

- molecules: determine first collapsing phases (H, H^+, H^-, D, D^+, He, He^+, He^{++}, H_2, H_2^+, HD, HeH^+, e^-)
- metals: determine subsequent cooling (He, C,N, O, Ne, Mg, Si, S, Ca, Fe, etc.)
- stellar evolution: leads yields and timescales of enrichment (SNII, AGB, SNIa)

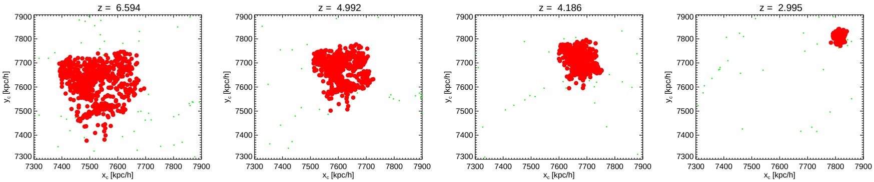


⟵ Cooling function (T,$x_{\rm mol}$, Z)

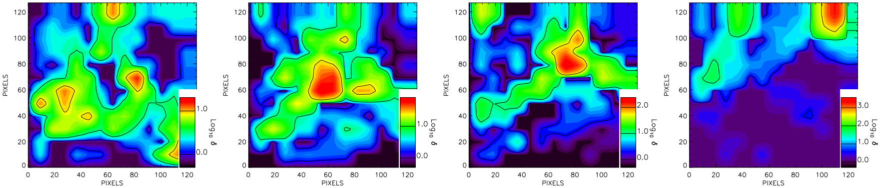
$z = 10$
$L \simeq 1\,\mathrm{Mpc} \rightarrow$ Primordial Universe

$Z_{\rm crit} = 10^{-6} Z_\odot - 10^{-3} Z_\odot$
IMFs: Top-heavy / Salpeter-like
Various M/Z-dep. yield tables
Different box sizes, background cosmologies, bulk flows, ...

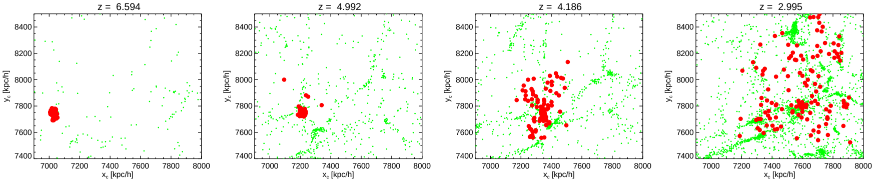
H/H_2-driven gas collapse (inflows)...



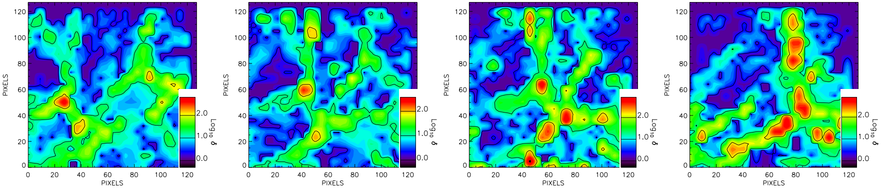
$z \simeq 6.6 \quad \longrightarrow \quad z \simeq 2.9$



... star formation and disruption (outflows) ...



$z \simeq 6.6$ $\longrightarrow$ $z \simeq 2.9$

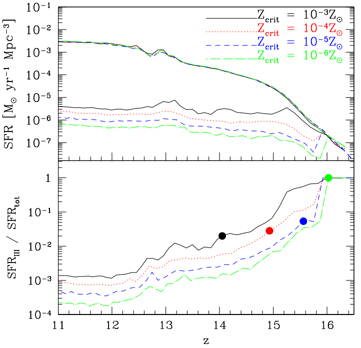


... with metal spreading of individual heavy elements

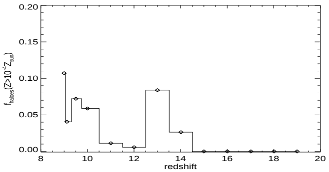
Z (absolute)	O (absolute)	Fe (absolute)
Total enrichment	O enrichment	Fe enrichment

Metal enrichment and stellar evolution: massive SN $\longrightarrow \alpha$, SNIa $\longrightarrow$ Fe

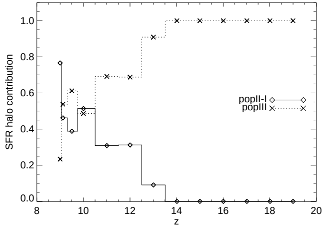
Star formation in the pristine Universe



enriched ('popII') haloes



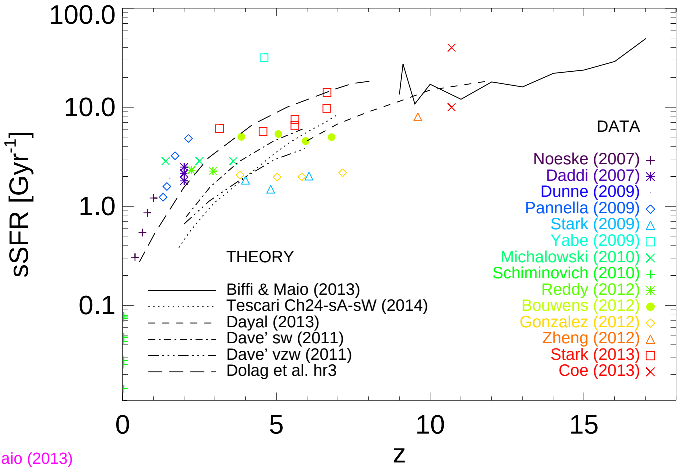
SFR halo contribution



Salpeter PopII IMF over [0.1, 100] $M_\odot$
top-heavy PopIII IMF over [100, 500] $M_\odot$
(low-mass PopIII IMFs ⟶ similar qualitative trends)

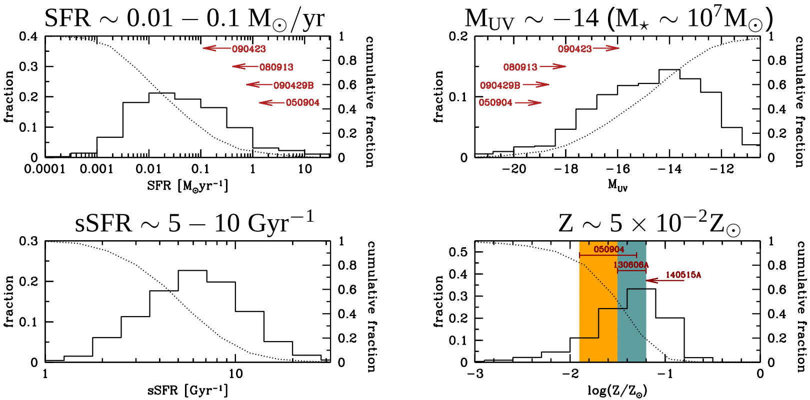
See Maio et al. (2010, 2011); Biffi & Maio (2013)

sSFR – early bursty Universe



Biffi & Maio (2013)

Expected properties of primordial galaxies



GRB Data: Tanvir et al. (2012); Thöne et al. (2013); Hartoog et al. (2014); Chornock et al. (2014)

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

Disentangling popIII and popII stellar populations

Abundance ratios as
indirect signatures:

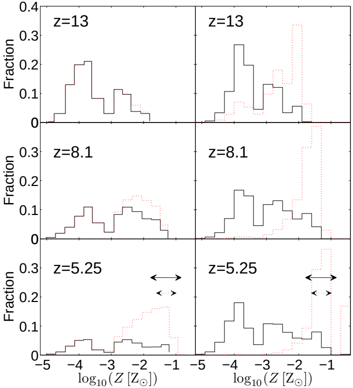
GRB 050904 ($z = 6.3$): no PopIII
$[C/O] = -0.1$, $[S/O] = 1.3$
$[Si/O] = -0.3$, $Z \simeq 0.03\,Z_\odot$
(Kawai et al., 2006; Thöne et al., 2013)

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)

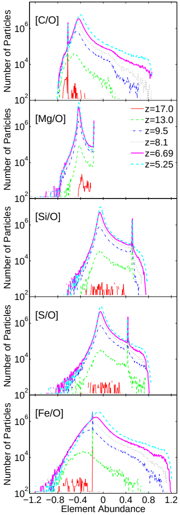
GRB 111008A ($z = 5.0$): unlikely PopIII
$[S/H] = -1.7, Z \gtrsim 0.01\,Z_\odot$
(Sparre et al., 2014)

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)

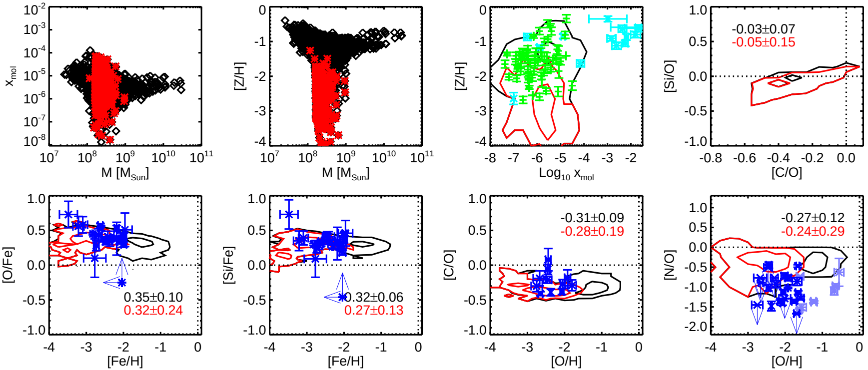


PopII-I star forming haloes
PopII-I star forming haloes pre-enriched by popIII



Molecular content and abundance ratios at later times

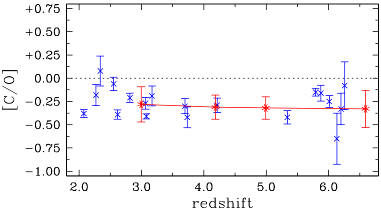
$z \simeq 3$ (preliminary...)



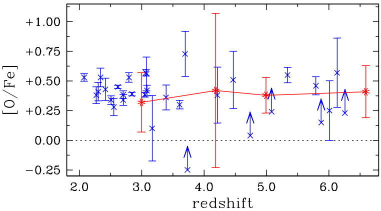
DLA data: Dessauges-Zavadsky et al. (2001), Becker et al. (2012); Cooke et al. (2015); Noerdaeme et al. (2008, 2012), Srianand et al. (2010), Albornoz Vásquez et al. (2013), Zafar et al. (2014)
Simulations (N-body/hydro + molecules + metals + feedback): Maio et al. (2010, 2011); Tescari et al. (2014)

Abundance redshift evolution

mean [C/O] vs *z*



mean [O/Fe] vs *z*



SNII/AGB $\longrightarrow$ left; SNIa $\longrightarrow$ right (more line broadening at $z < 5$?)
Spread naturally explained by metal mixing within 3D models

No PopIII needed to explain data at $z \sim 2 - 7$

Summary...

- Hydro/chemistry simulations (including *non-equilibrium molecule* formation and metal *pollution from stellar evolution*).
- Study the formation of galaxies, their expected properties and observational signatures in various contexts.

Conclusions...

- Early ($z \sim 5 - 20$) star formation is very bursty and metal enrichment from the first stars leads to a rapid popIII/popII-I transition.
- Observationally, metal abundance ratios can help disentangle early populations, but current data do not show popIII signatures.
- NB: among the possible alternative scenarios, WDM implications can be dramatic. See Maio & Viel (2015).

The End

Thank you!

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