Cosmic metal enrichment by the first galaxies

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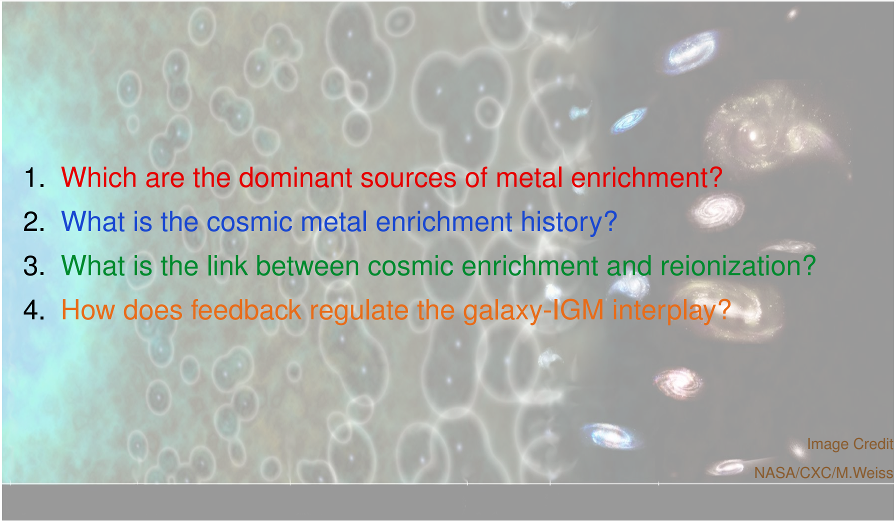
currently looking for a position

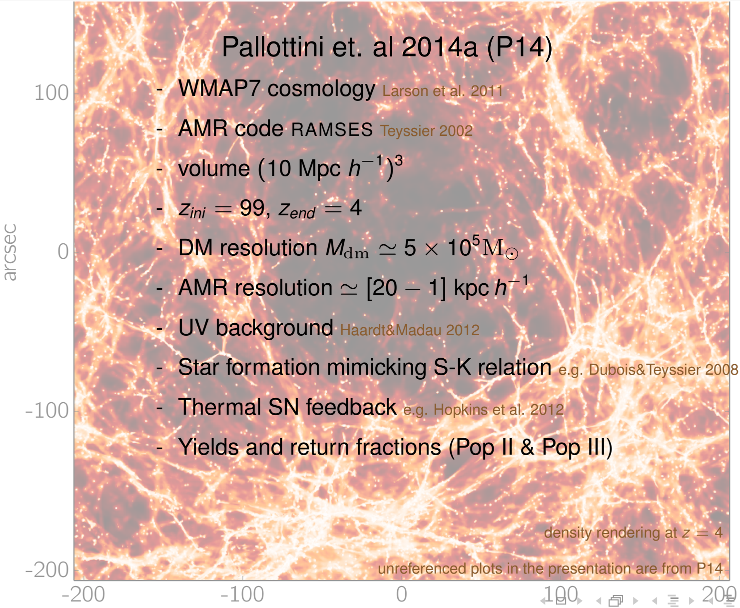
Key questions:



1. Which are the dominant sources of metal enrichment?
2. What is the cosmic metal enrichment history?
3. What is the link between cosmic enrichment and reionization?
4. How does feedback regulate the galaxy-IGM interplay?

Image Credit
NASA/CXC/M.Weiss

Simulating Cosmic Metal Enrichment



Pallottini et. al 2014a (P14)

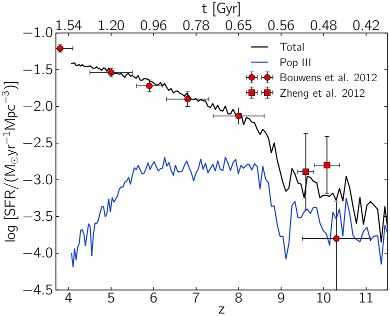
- WMAP7 cosmology Larson et al. 2011
- AMR code RAMSES Teyssier 2002
- volume $(10\ \mathrm{Mpc}\ h^{-1})^3$
- $z_{ini} = 99$, $z_{end} = 4$
- DM resolution $M_{\rm dm} \simeq 5 \times 10^5 \mathrm{M}_\odot$
- AMR resolution $\simeq [20 - 1]\ \mathrm{kpc}\ h^{-1}$
- UV background Haardt&Madau 2012
- Star formation mimicking S-K relation e.g. Dubois&Teyssier 2008
- Thermal SN feedback e.g. Hopkins et al. 2012
- Yields and return fractions (Pop II & Pop III)

unreferenced plots in the presentation are from P14

Model calibration and test

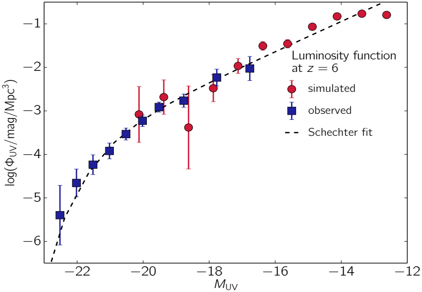
Calibrated sub-grid models

parameters: $t_\star$ & $\epsilon_{\rm SN}$



Resulting galaxy properties match observations

LF from P14 and Bouwens et al. 2014



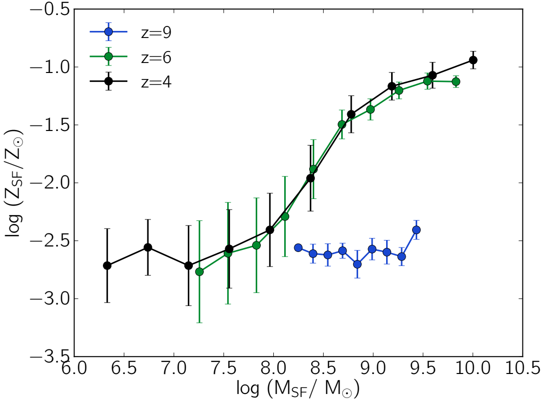
(Disclamer: presentation not focused on Pop III,

happy to discuss after the talk)

Pallottini et al. 2015a submitted

Metal enrichment sources

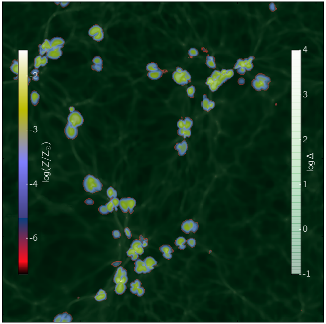
Evolution of the mass-metallicity ($M_\star - Z_\star$) relation



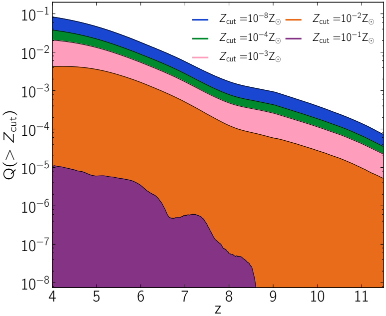
$M_\star \simeq 10^{8.5} \mathrm{M}_\odot \mapsto \log(O/H) + 12 \simeq 8.2$, as observed by Troncoso et al 2013

Metal enrichment history

Metals in the cosmic web at $z = 4$



Evolution of the metal filling factor



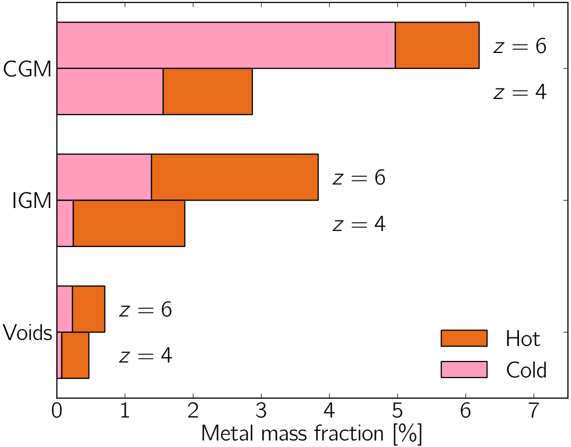
α-blending of P14 maps

e.g. Cen et al. 2005, Oppenheimer&Dave 2006, Oppenheimer et al. 2009

Metal enrichment history

Phase distribution of the enriched diffuse gas

($\sim$ 90% metal mass in galaxies)



CGM $10 < \Delta \leq 10^{2.5}$

IGM $1 < \Delta \leq 10$

voids $\Delta \leq 1$

hot $T \geq 10^{4.5}\mathrm{K}$

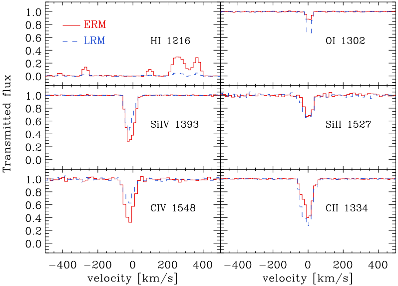
cold $T < 10^{4.5}\mathrm{K}$

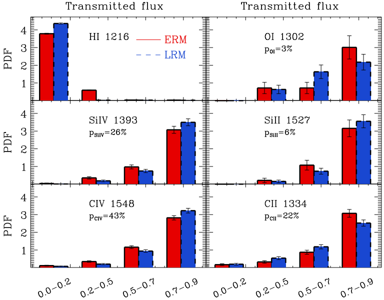
The link between cosmic enrichment and reionization

Synthetic QSO spectra at $z = 6$

-ERM: $\Gamma/(10^{-12}\mathrm{s}^{-1}) \simeq 0.35$

-LRM: $\Gamma/(10^{-12}\mathrm{s}^{-1}) \simeq 0.16$



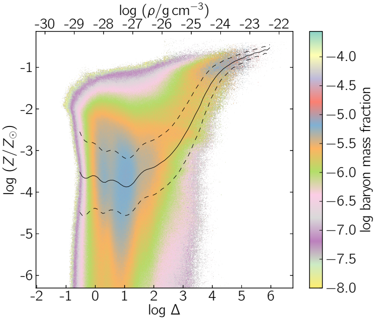


Preliminary analysis in agreement with observations (D'Odorico et al. 2013)
Additional analysis in preparation (column density distribution, ...)

Feedback regulates galaxy-IGM interplay

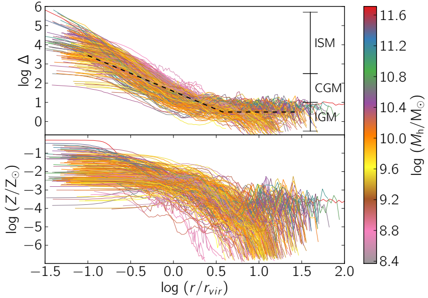
Metallicity-overdensity plane

The Δ-Z relation at $z = 4$



Self-similarity of Δ profiles

$\Delta \propto (r/r_{\rm vir})^{-1.9}$ for $r/r_{\rm vir} \lesssim 4$



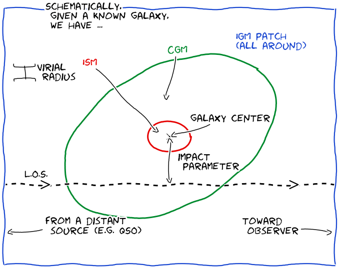
e.g. Gnedin & Ostriker 1997, Oppenheimer et al. 2012

for an application of the Δ-Z, see Vallini et al. 2015 submitted

Pallottini et al. 2014b

Feedback regulates galaxy-IGM interplay

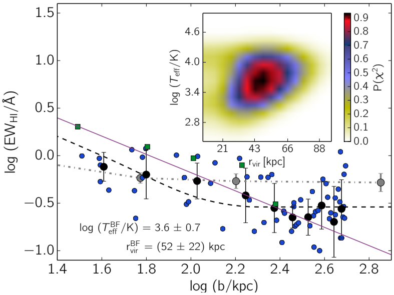
Sketch of CGM observations



disclamer: this is not a simulation snapshot

Comparison with observations

Lack of evolution of the HI absorption profile?



analytical model at $z = 0$ (calibrated at $z = 4$)
$z \simeq 0$ Liang&Chen 2014 (and errorbars), $z \simeq 2$ Steidel et al. 2010, model by Chen et al. (1998,2001), synthetic spectra at $z = 4$

Conclusions

1. By $z = 6$ a galactic mass-metallicity relation is established. For galaxy with stellar mass $M_\star \gtrsim 10^{7.5}\mathrm{M}_\odot$, such relation shows little evolution from $z = 6$ to $z = 4$. At $z = 4$, the extension of the relation at $M_\star \lesssim 10^{6.5}\mathrm{M}_\odot$ mark the presence of satellites forming in pre-enriched environments.
2. At $z = 6$ ($z = 4$) metals not locked in galaxies are distributed in the CGM/IGM/voids with the following mass fractions: 6%/4%/1% (3%/2%/1%).
3. Given the prevailing thermodynamical/ionization conditions of the enriched gas, C IV QSO spectroscopy can only probe up to $\simeq$ 5% of the total produced carbon. However, metal absorption lines are very effective tools to study reionization.
4. Analogously to the mass-metallicity relation for star forming regions, at $z = 4$ a $\Delta - Z$ relation is in place for the IGM/CGM. This is relation is due to the self-similarity of the radial density profiles.
5. Our EW_{HI} analytical model (calibrated at z = 4) successfully reproduces CGM/IGM observations both at $z = 0$ (Liang&Chen 2014) and at $z = 2$ (Steidel et al. 2010), suggesting that the density profiles evolve very weakly with redshift.