Simulating high redshift galaxies

Andrea Pallottini

in collaboration with:

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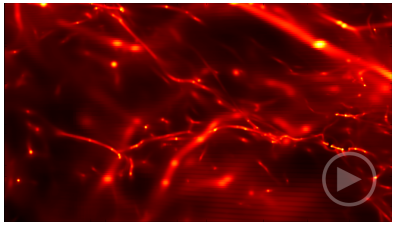

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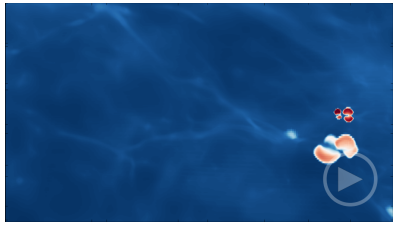
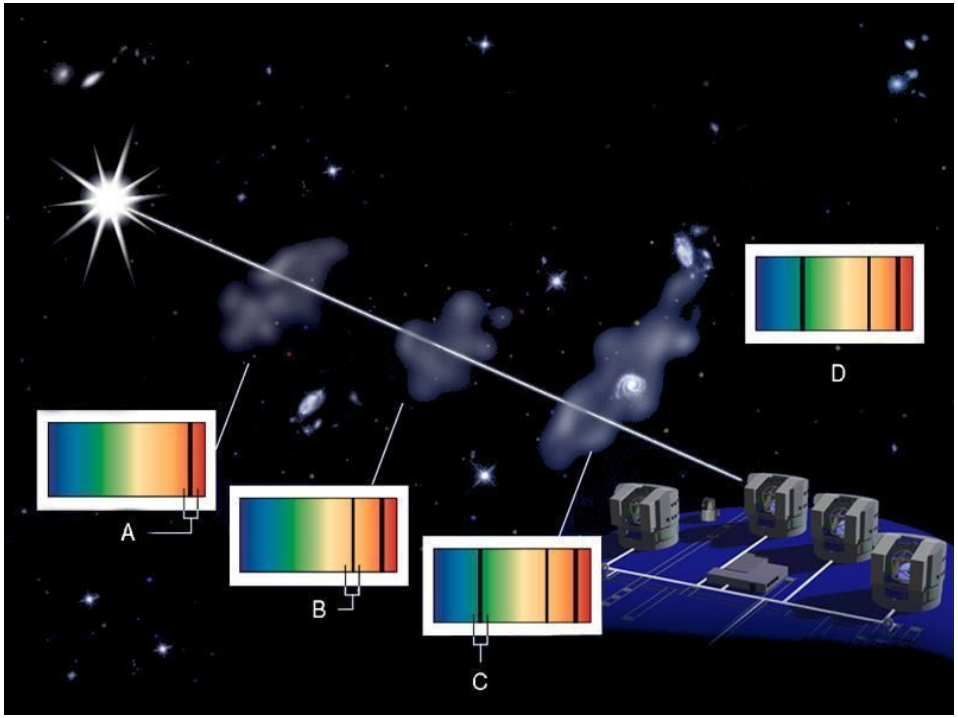
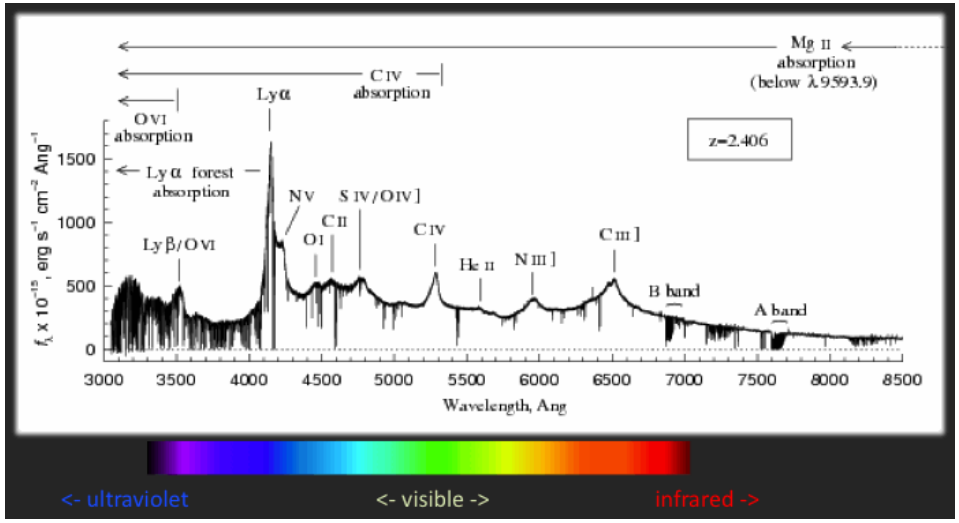
SCUOLA NORMALE SUPERIORE



Observing the intergalactic medium





QSO absorption spectroscopy

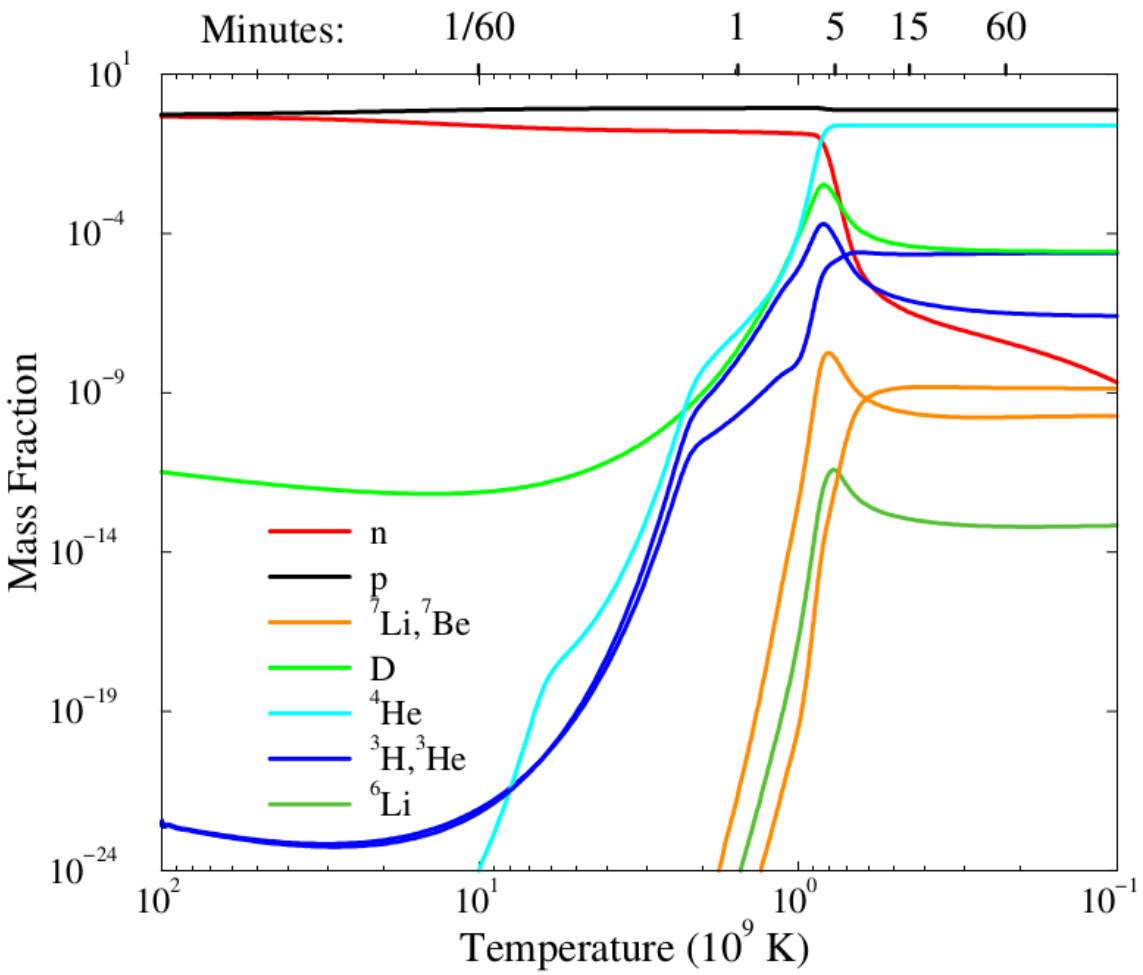
as a tool to characterize the IGM

artistic impression: Ed Janssen, ESO

QSO spectra: Chris Churchill, NMSU

Forging metals: Big Bang Nucleosynthesis

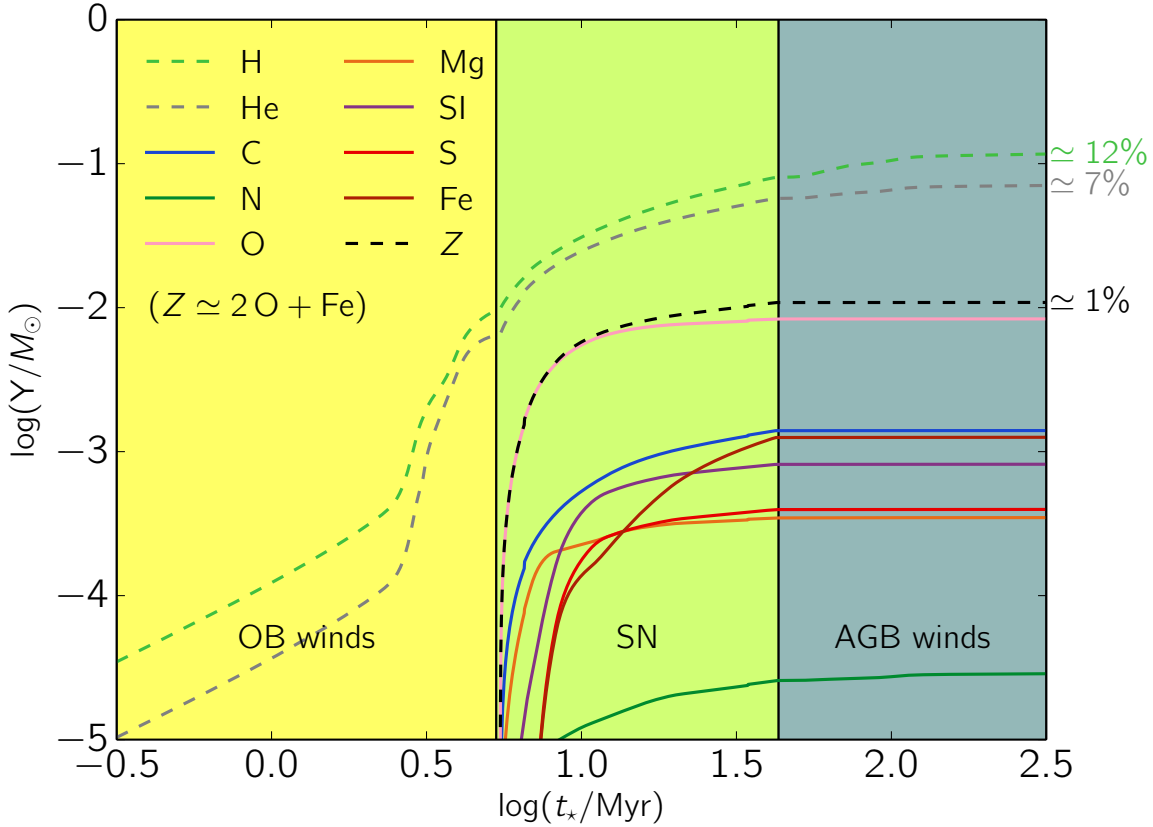
After the BBN the Universe is almost free of heavy elements



Burles et al. 1999

Forging metals: contribution from galaxies

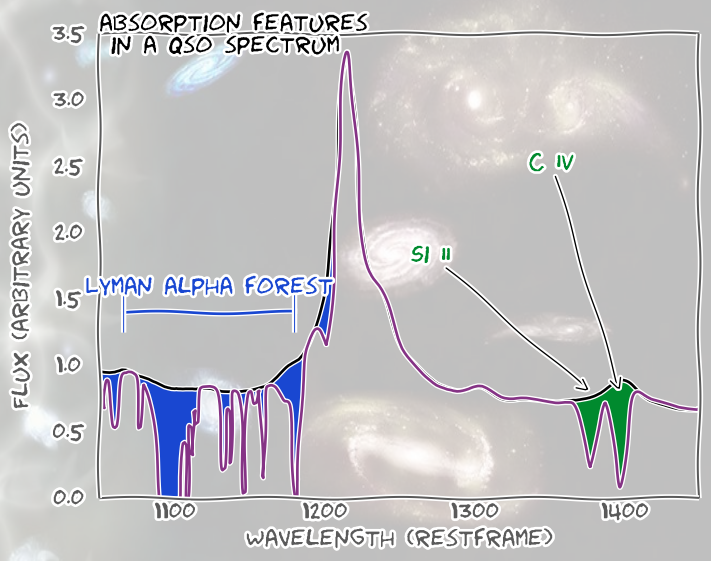
Stars efficiently produce metals by reprocessing H and He



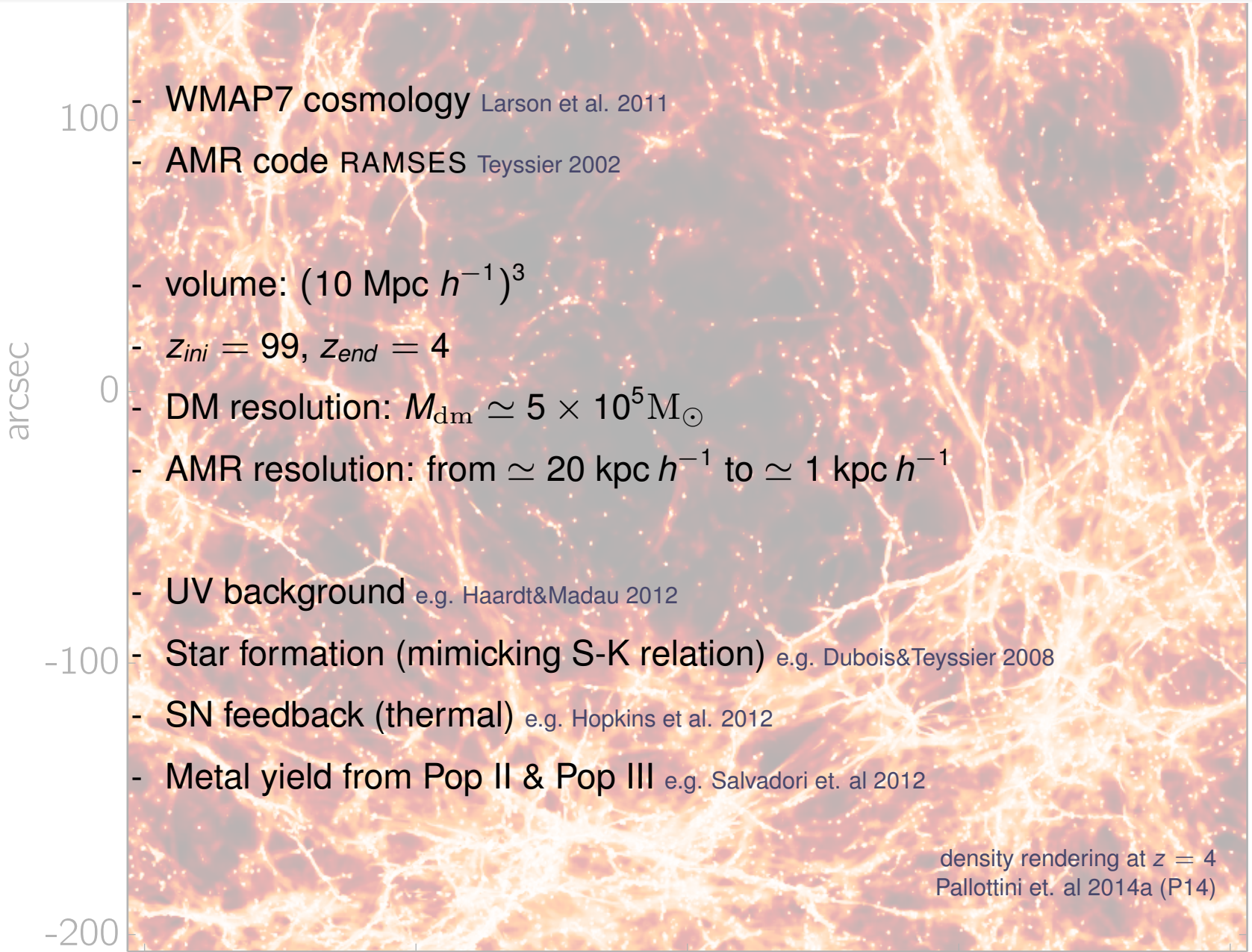
stellar tracks taken from Bertelli et al. 1994

Key questions

1. Which galaxies are the dominant sources of metal enrichment?
2. What is the cosmic metal enrichment history?
3. How does feedback regulate the galaxy-IGM interplay?
4. What is the link between cosmic enrichment and reionization?
5. Can we devise alternative strategy to detect high-z metals?



High-z galaxies in cosmological simulations



- WMAP7 cosmology Larson et al. 2011
- AMR code RAMSES Teyssier 2002

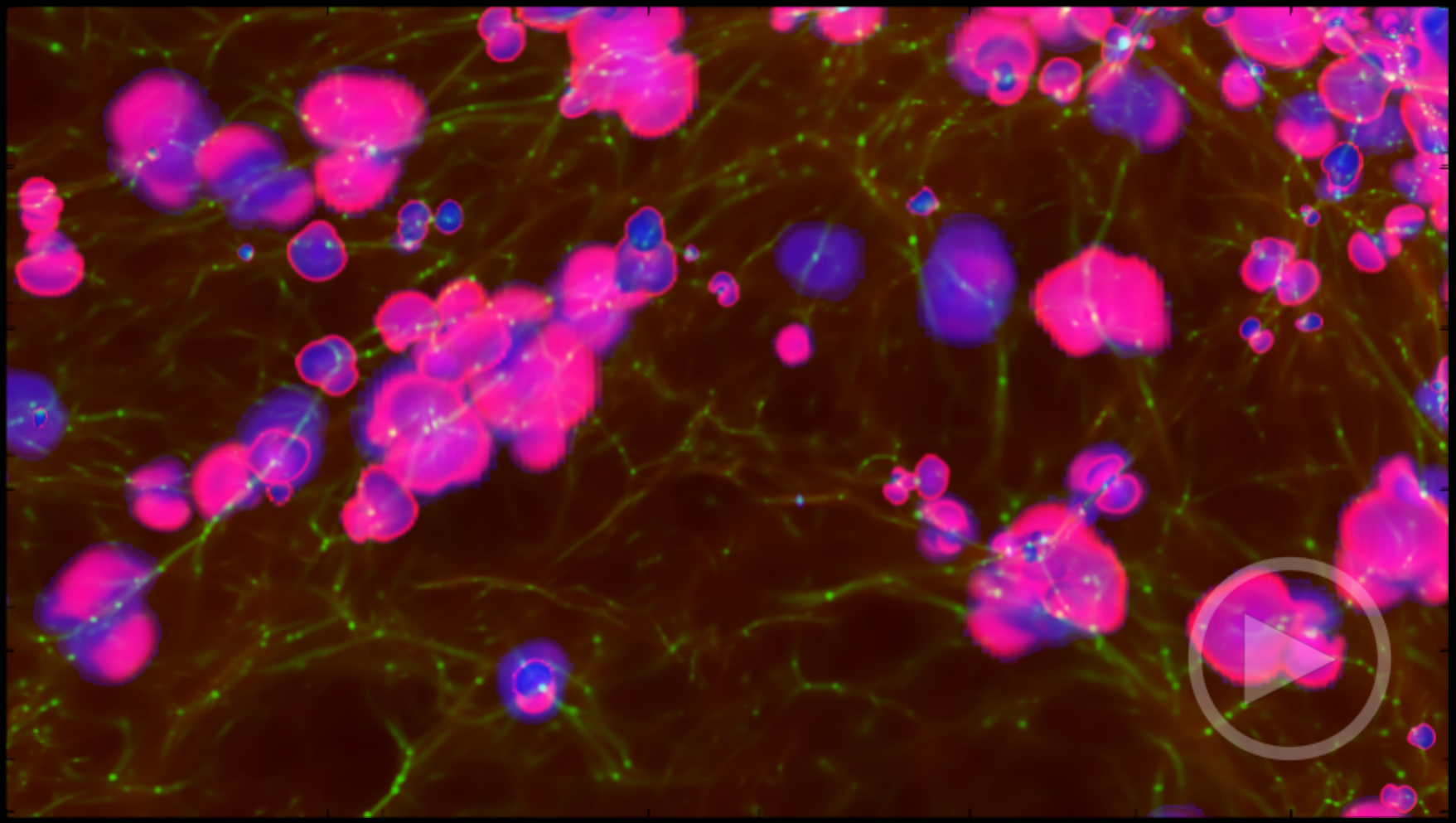
- volume: $(10\ \mathrm{Mpc}\ h^{-1})^3$
- $z_{ini} = 99$, $z_{end} = 4$
- DM resolution: $M_{\mathrm{dm}} \simeq 5 \times 10^5 \mathrm{M}_\odot$
- AMR resolution: from $\simeq 20$ kpc h^{-1} to $\simeq 1$ kpc h^{-1}

- UV background e.g. Haardt&Madau 2012
- Star formation (mimicking S-K relation) e.g. Dubois&Teyssier 2008
- SN feedback (thermal) e.g. Hopkins et al. 2012
- Metal yield from Pop II & Pop III e.g. Salvadori et. al 2012

density rendering at $z = 4$
Pallottini et. al 2014a (P14)

Overview at $z = 6$

Overdensity, Temperature & Metallicity



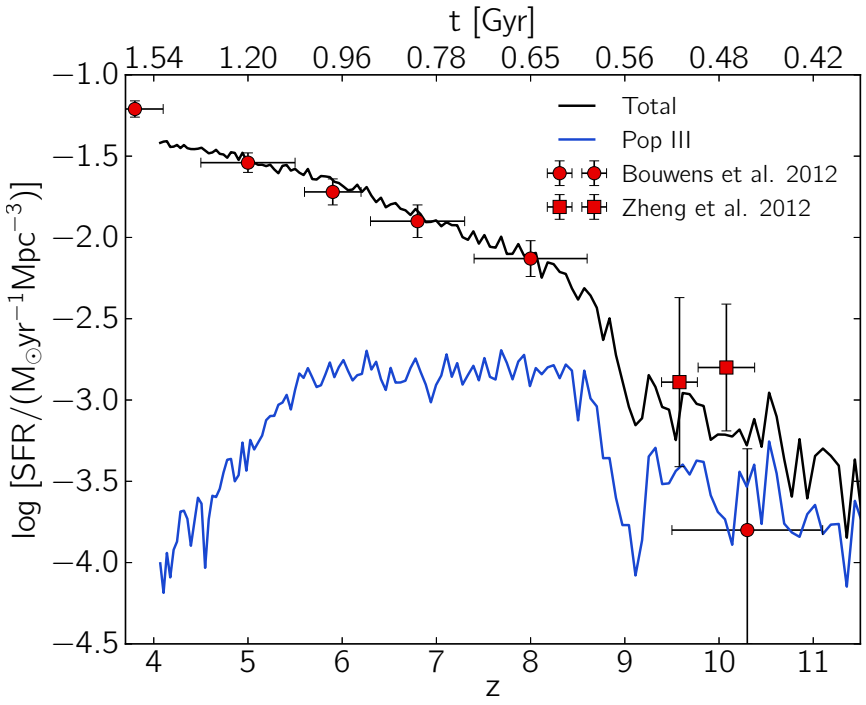
Volume rendering with PyMSES (Labadens et. al 2013)

more movies: `https://www.researchgate.net/profile/Andrea_Pallottini`

Model calibration and test

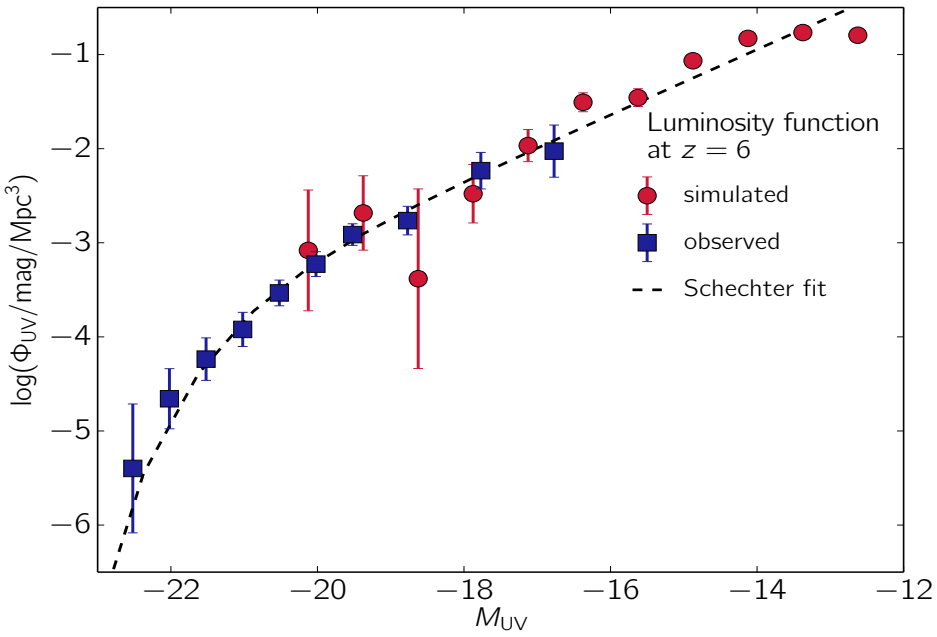
Star formation and feedback sub-grid models

parameters: $t_\star$ (SF time scale) & $\epsilon_{\rm SN}$ (SN coupling efficiency)



Galaxy properties match observations:

e.g. LF from P14 and Bouwens et al. 2014

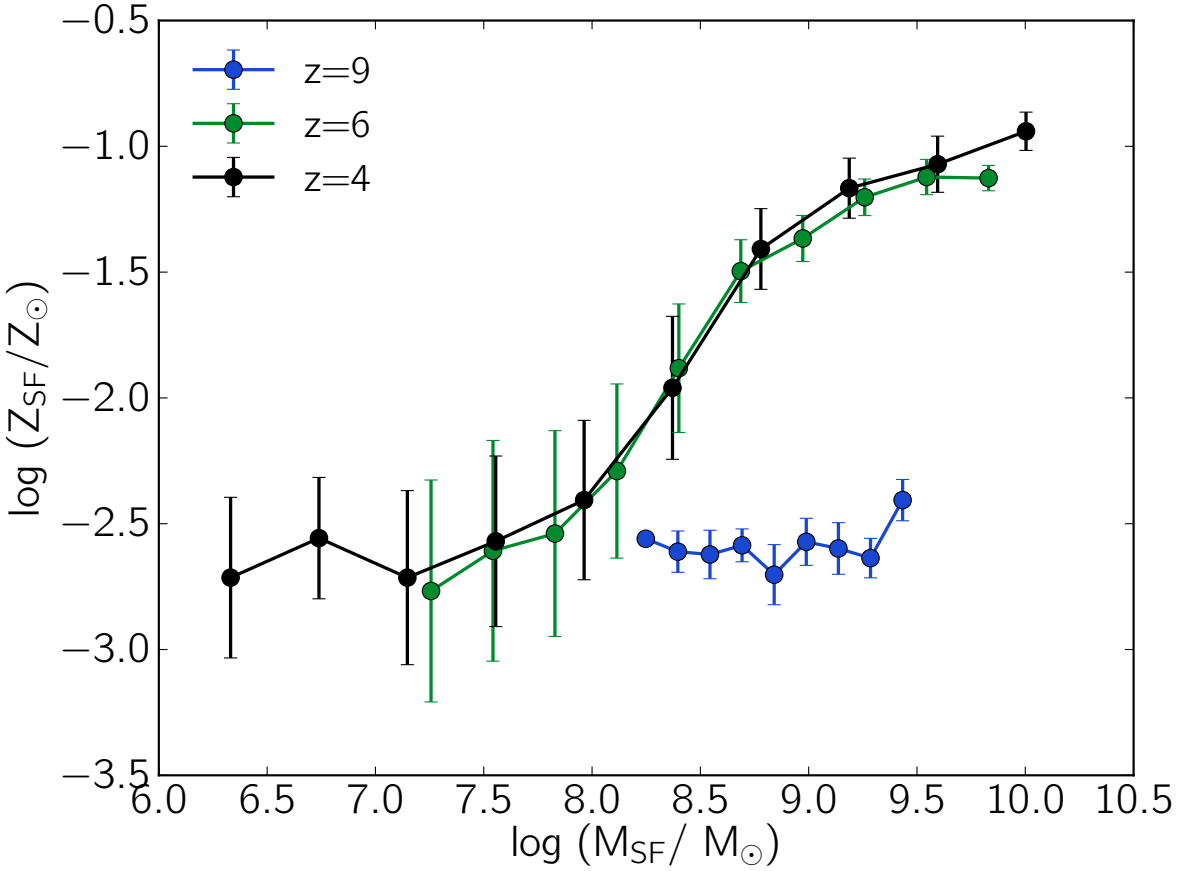


P14, Pallottini et al. 2015a (see also Yue et al 2015)
see Pallottini et al. 2015b for the analysis of
possible Pop III detection in CR7 (Sobral et al. 2015)

High-z galaxies as metal enrichment sources

The mass-metallicity relation is in place at $z = 6$

(Star Forming regions in P14)



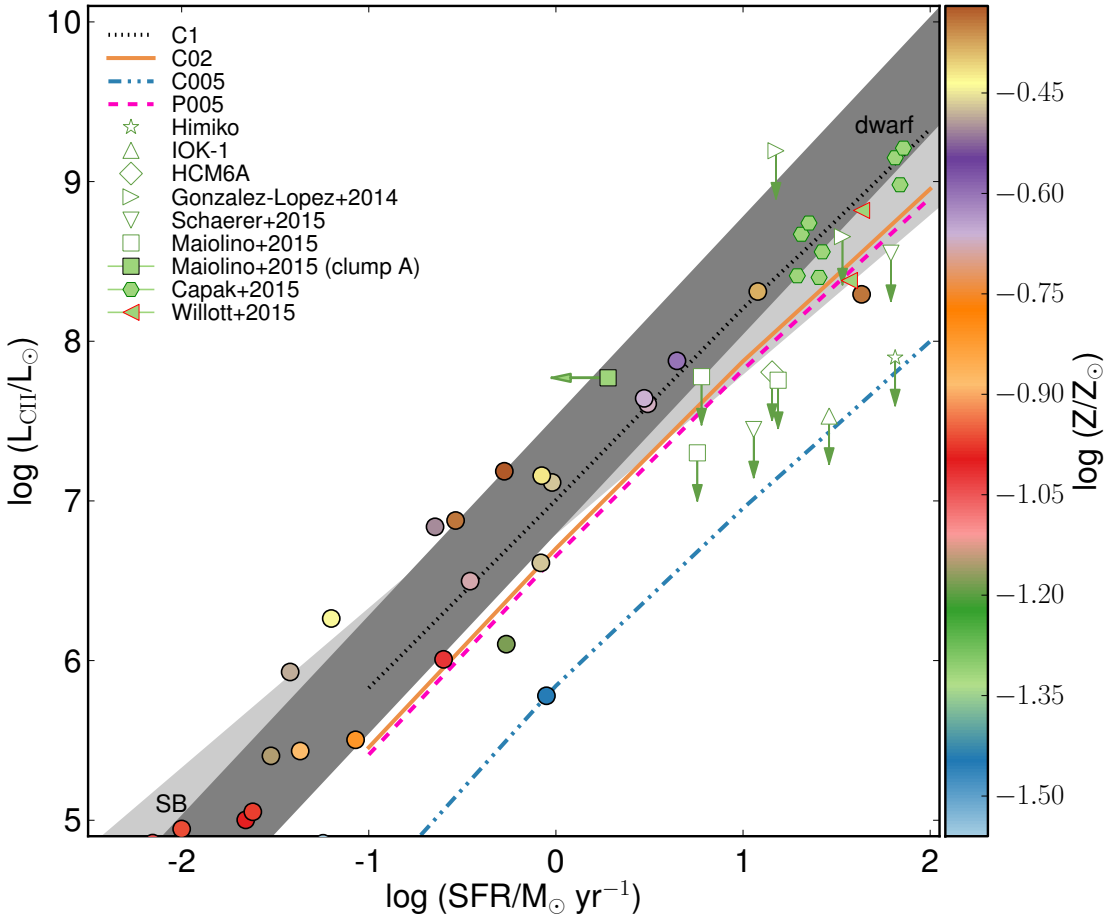
high mass galaxies retain most of the produced metals

low mass galaxies efficiently eject metals

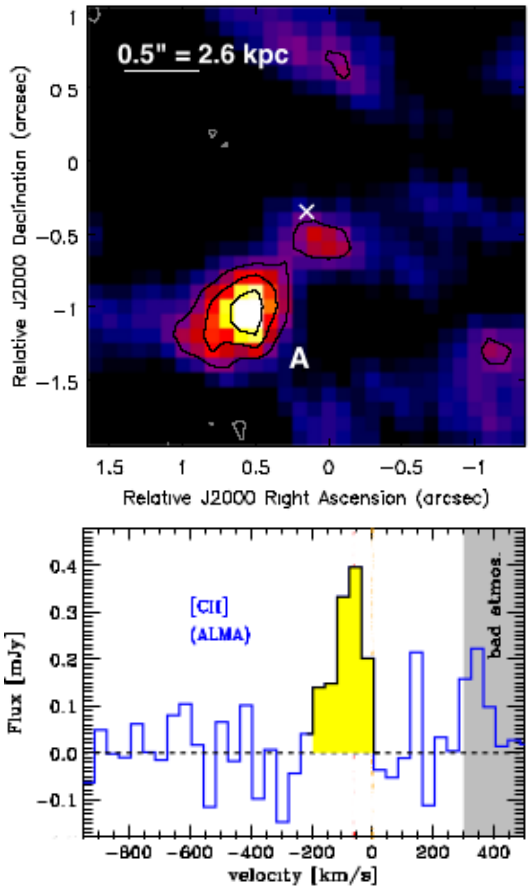
e.g. Mannucci et al. 2010, Troncoso et al. 2013

Using FIR emission to characterize high-z galaxies

Modelling [CII] emission from the multi-phase ISM:
(Radiative transfer simulations)



[CII] detection in BDF3299
with ALMA Maiolino et al. 2015

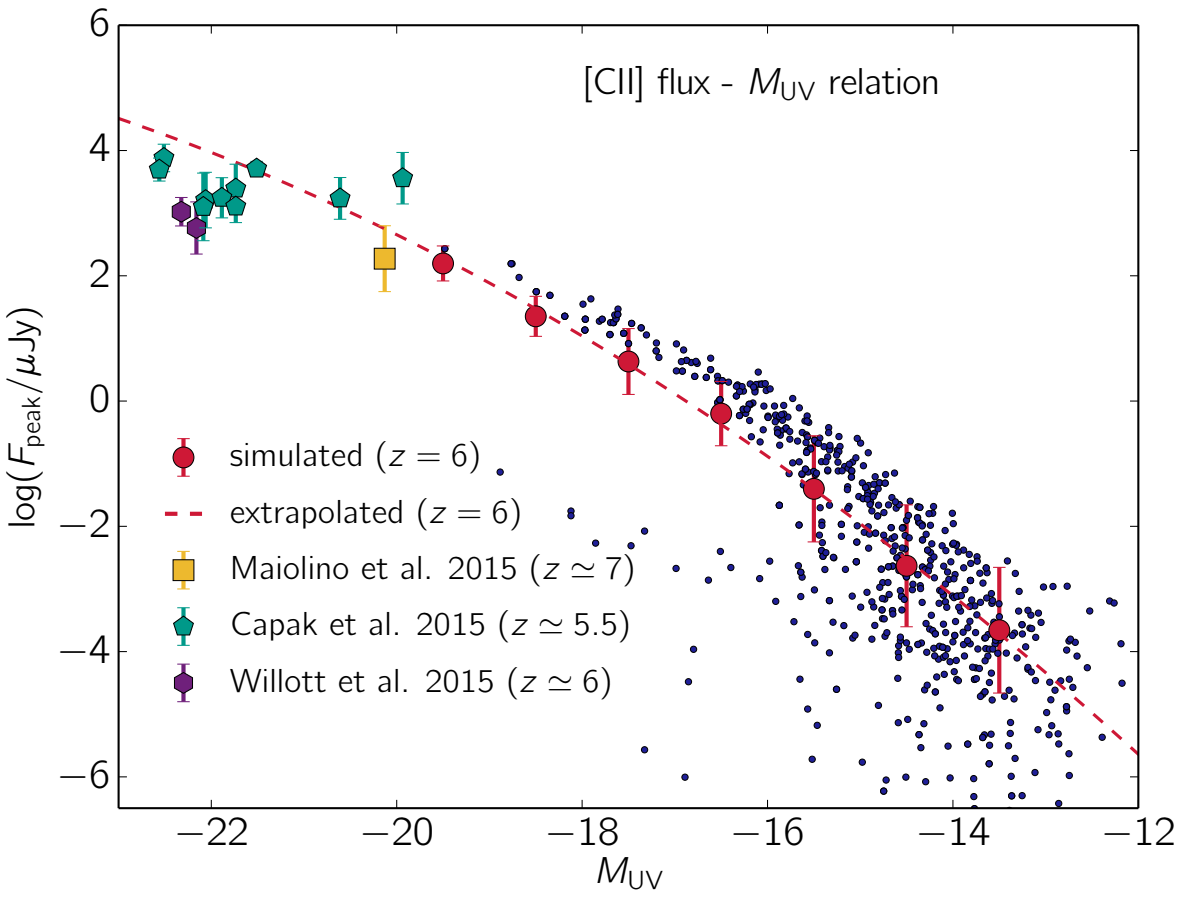


$$\log(L_{\rm CII}) = 7.0 + 1.2\ \log(SFR) + 0.021\ \log(Z) + 0.012\ \log(SFR)\ \log(Z) - 0.74\ \log(Z)$$

Vallini et al. 2015

Characterizing metal enrichment sources with FIR lines

We predict that [CII] emission correlates with M_{UV}, in agreement with observations



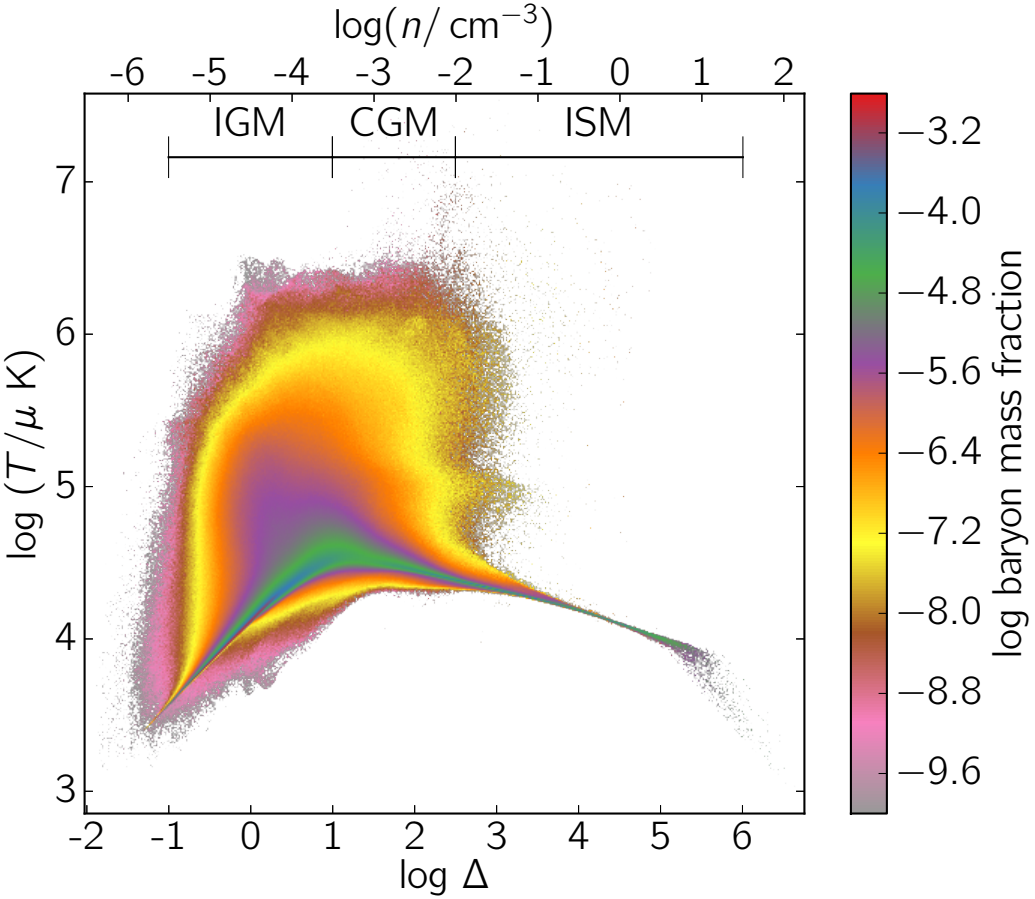
$$\log(F_{peak}/\mu\mathrm{Jy}) = -27.205 - 2.253\, M_{UV} - 0.038\, M_{UV}{}^{2}$$

Pallottini et al. 2015a

Thermodynamical state of the cosmic gas

Equation of State (EoS) at $z = 4$ in P14

(Δ based definitions for IGM/CGM/ISM)

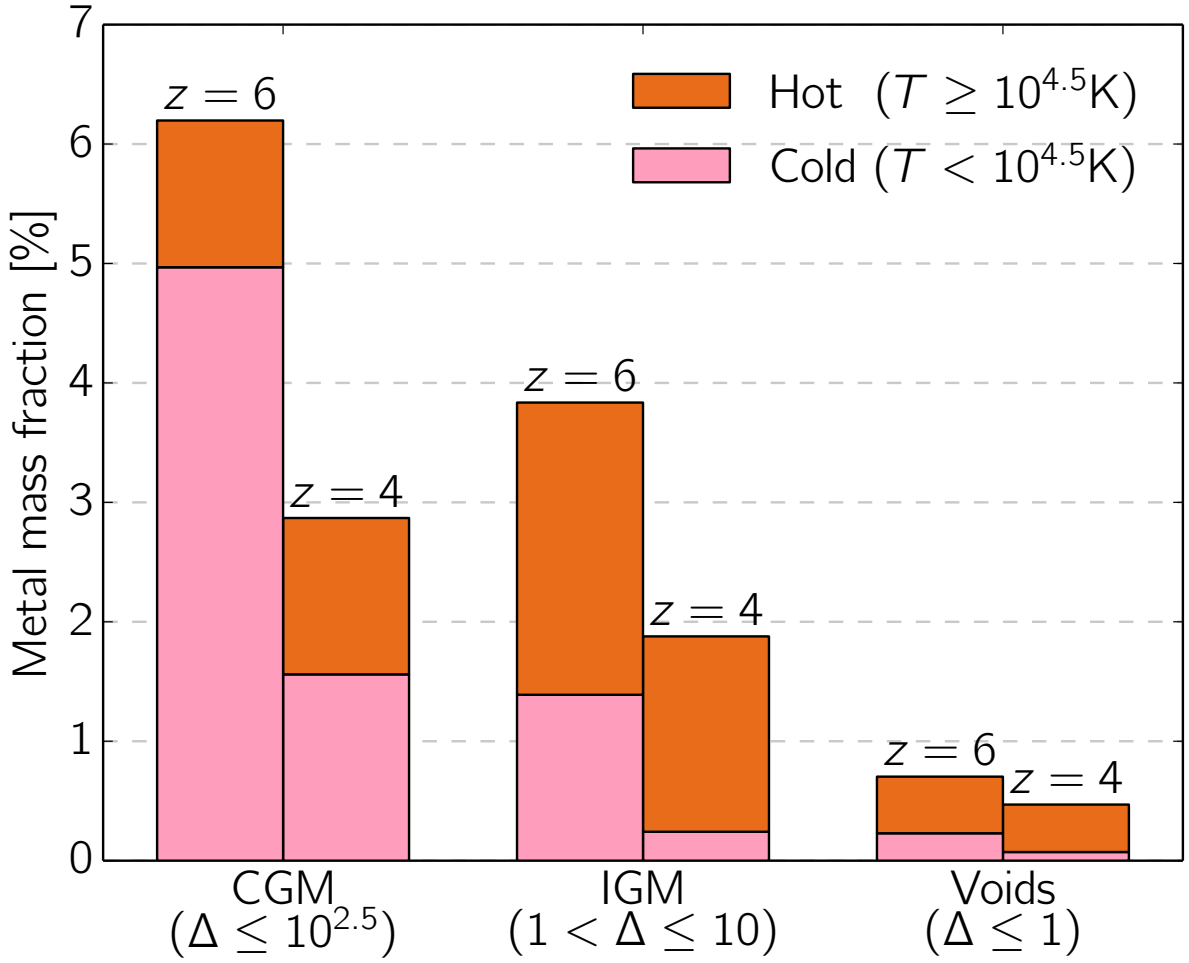


note that the ISM accounts for 10% of the baryon mass and 90% of the total metal mass

see also EOS Rasera&Teyssier 2006, Cen&Chisari 2011, Oppenheimer et al. 2012, Pallottini et. al. 2013

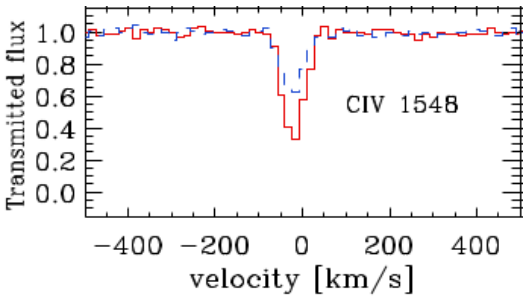
History of the enriched diffuse gas

Phase distributions



see P14 for analysis of synthetic spectra and preliminary comparison with D'Odorico et al. 2014

example of synthetic spectrum:

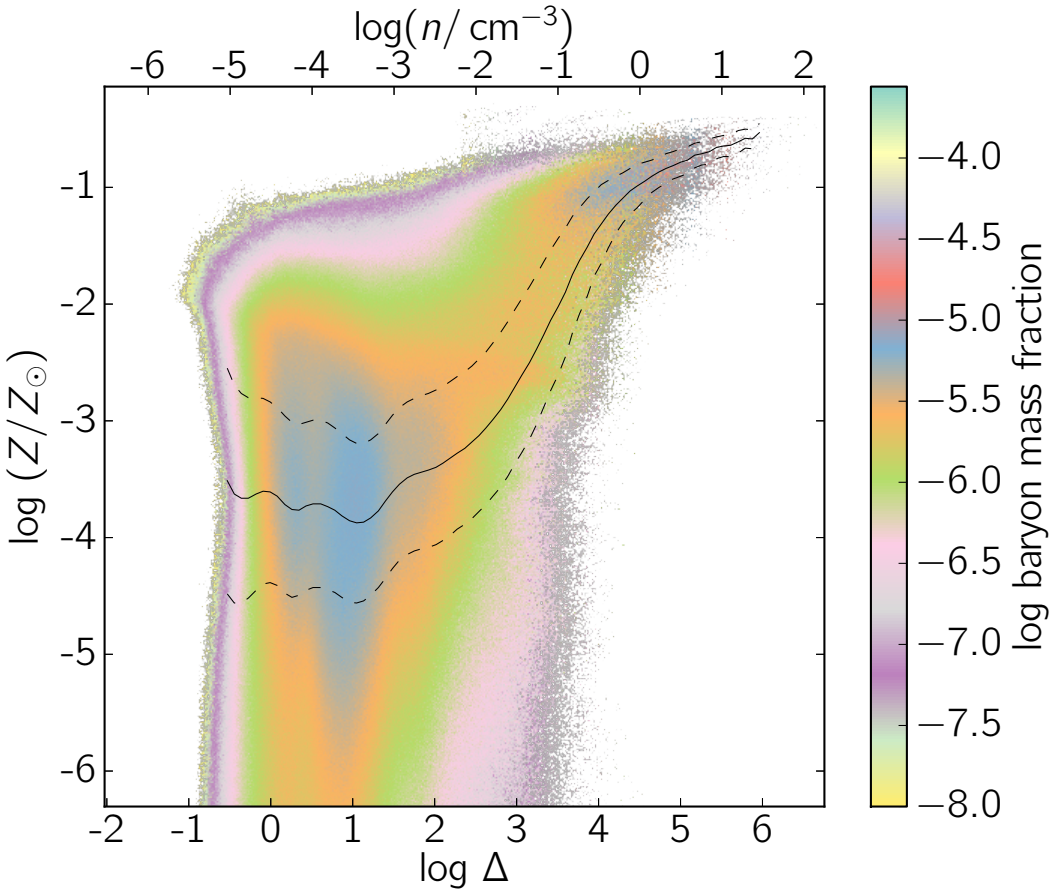


History of the enriched diffuse gas

At $z = 4$, a Δ-Z relation is in place for the ISM/CGM

(Analogously to the $M_\star - Z_\star$ for galaxies)

remember that $\simeq$ 10% of the volume is polluted

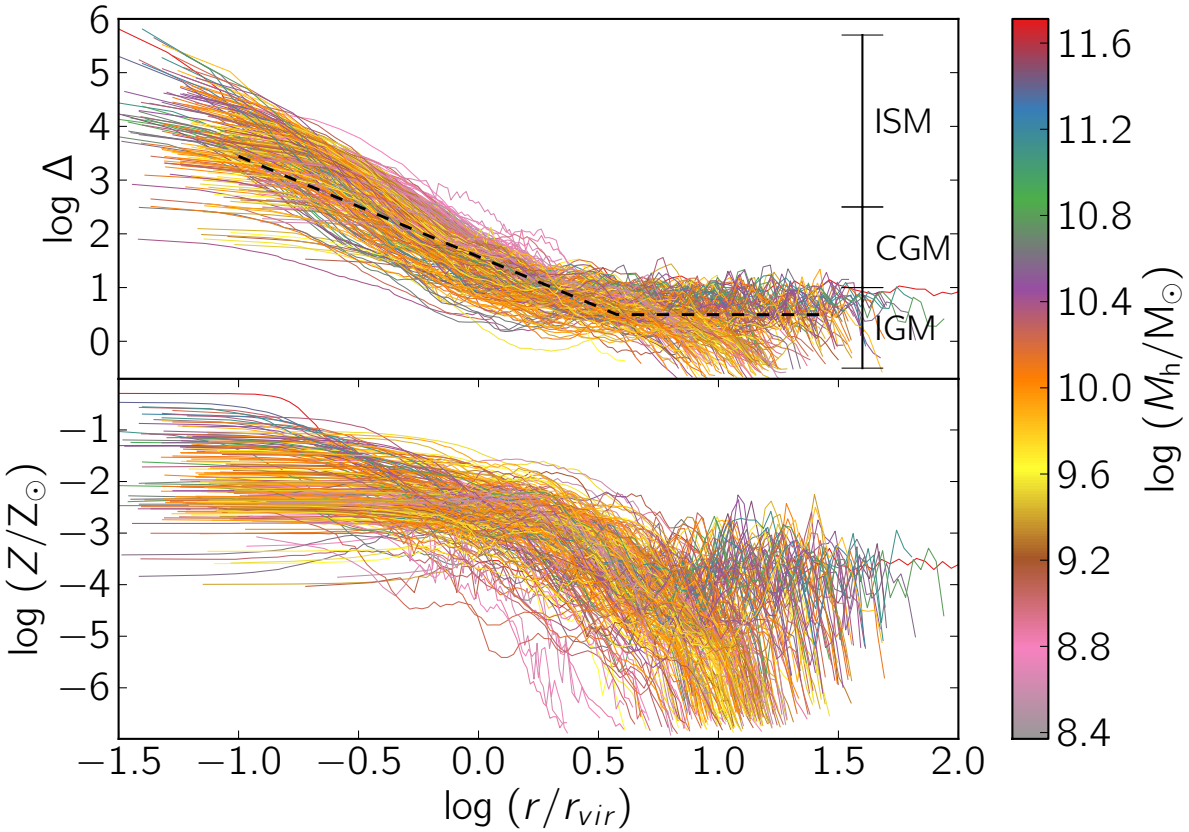


P14, see also Gnedin&Ostriker 1997, Oppenheimer et al. 2012

Feedback regulates galaxy-IGM interplay

Radial profiles for galactic environment: self-similarity of Δ profiles

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



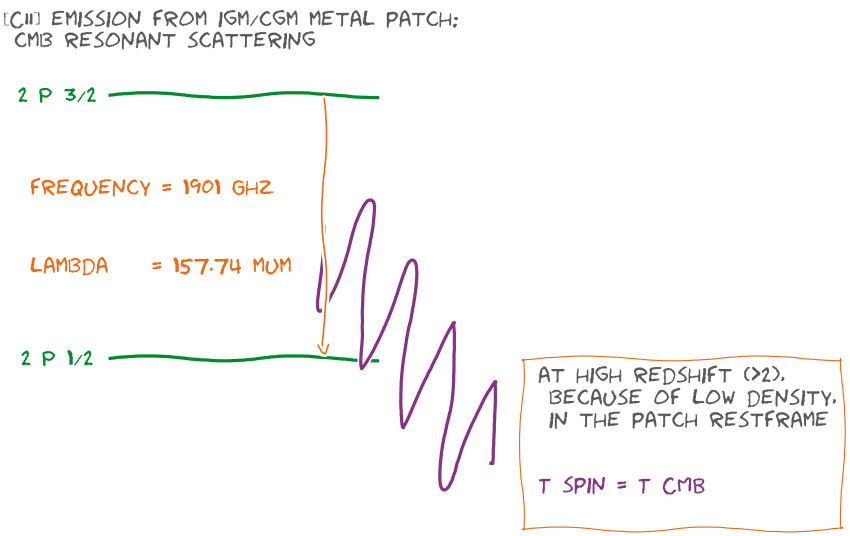
How can we probe these metals? (more on profiles later on) Pallottini et al. 2014b, see also Liang et al 2016

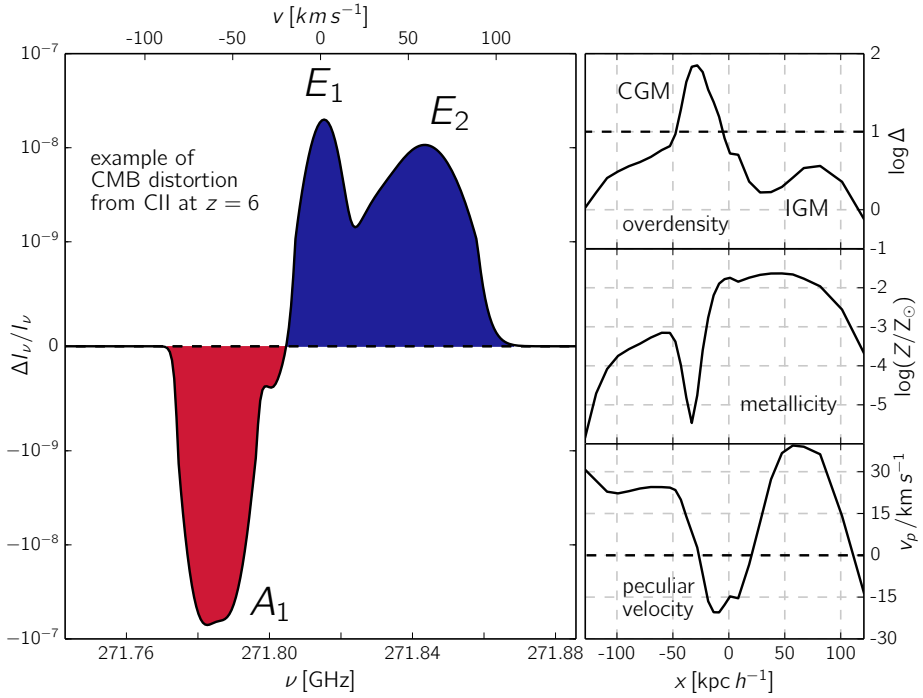
Mapping high-z metals: alternative probes

CMB spectral distortions induced by metals via doppler boosted resonant scattering

e.g. Maoli et al. 1996, Basu 2007, Schleicher et al. 2008

$$\text{CMB spectral distorsions} : \Delta I_\nu \propto v_p \, \Delta Z$$



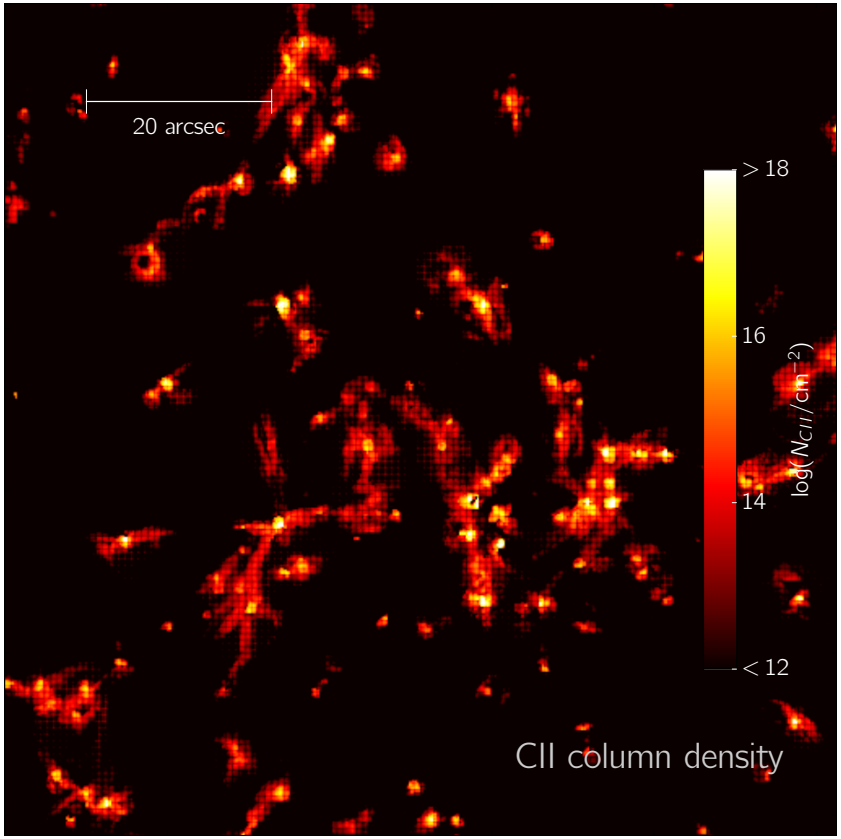


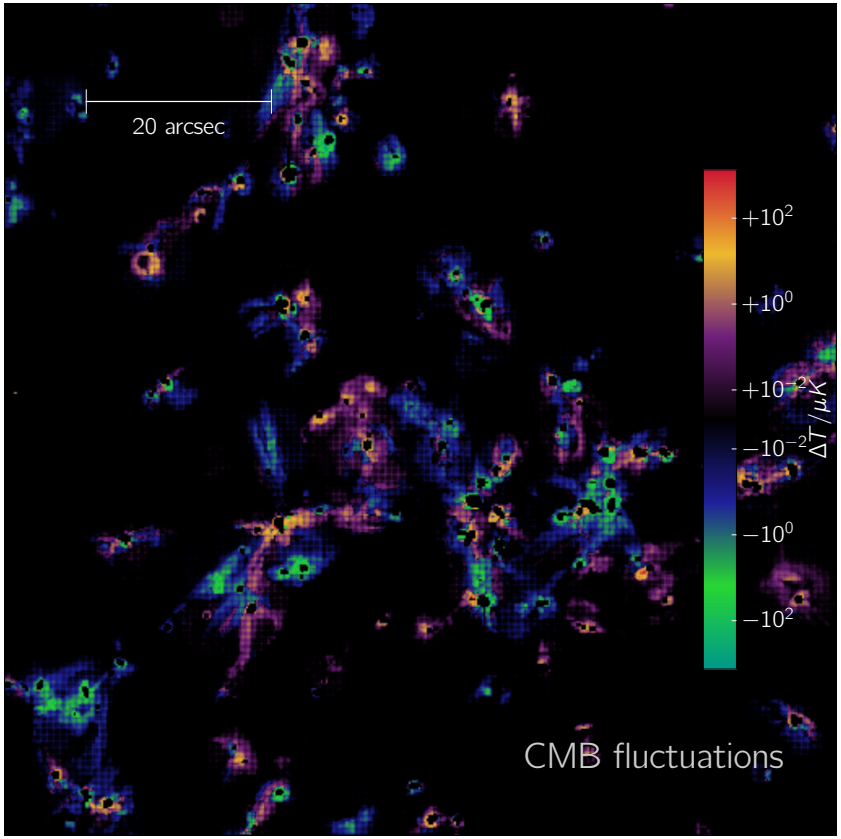
On the shown bandwidth, the cumulative effect is a net absorption, $\Delta I / I \simeq -7 \times 10^{-7}$

Pallottini et al. 2015a

Mapping high-z metals

Theoretical analysis of the [CII] fluctuations



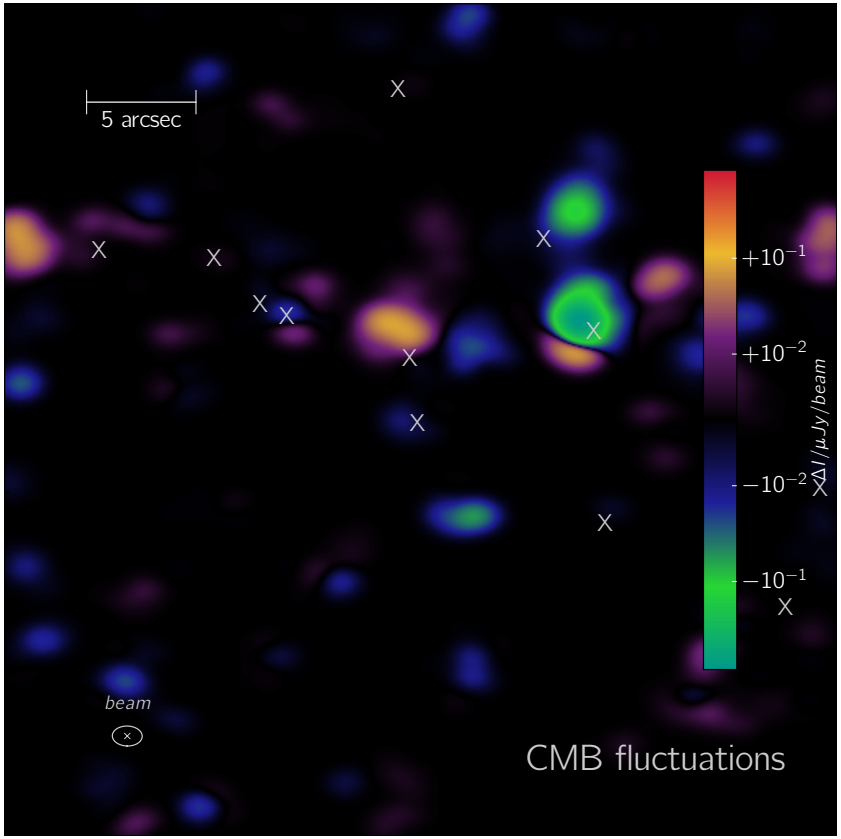


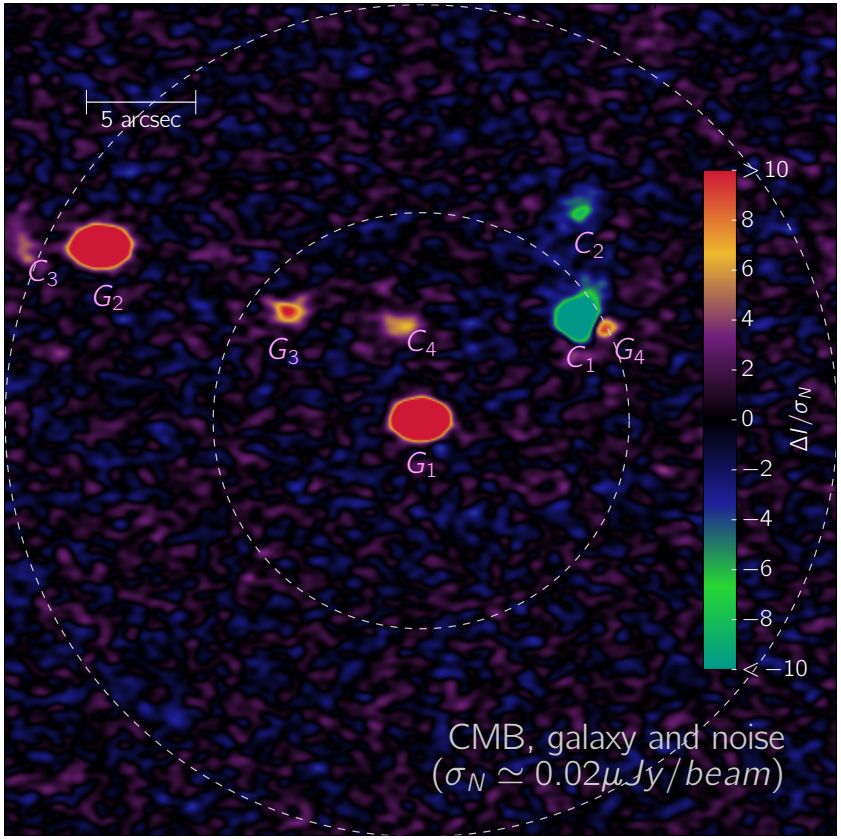
Signal peaks at $\theta \simeq 1''$, in correspondence of CGM with $\log(N_{\rm CII}/{\rm cm}^{-2}) \simeq 16$

Pallottini et al. 2015a

Mapping high-z metals

Probing metals in the ISM/CGM/IGM: ALMA synthetic maps





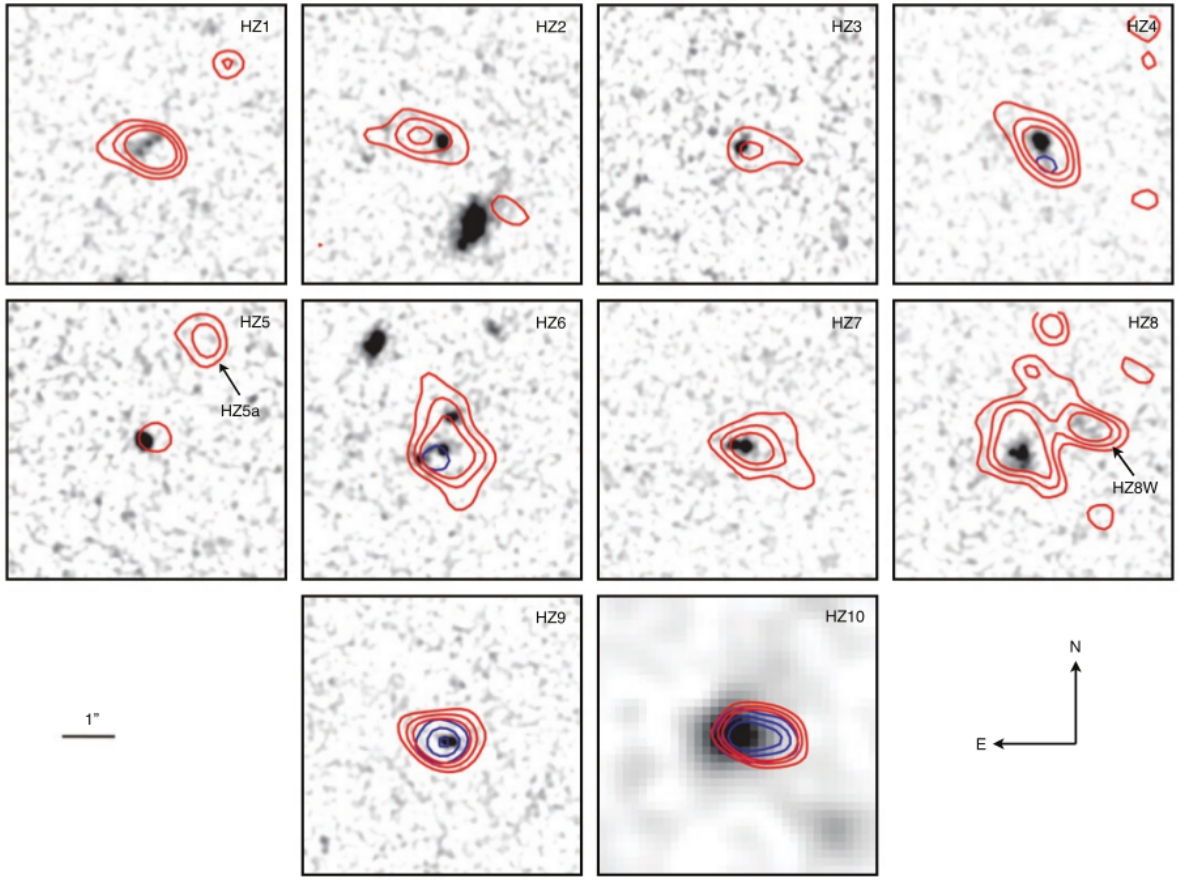
With this set-up, detection is challenging with current facilities (lensing?)

Pallottini et al. 2015a

Feedback regulates galaxy-IGM interplay

Detection of [CII] in $z \sim 6$ galaxies from Capak et al 2015

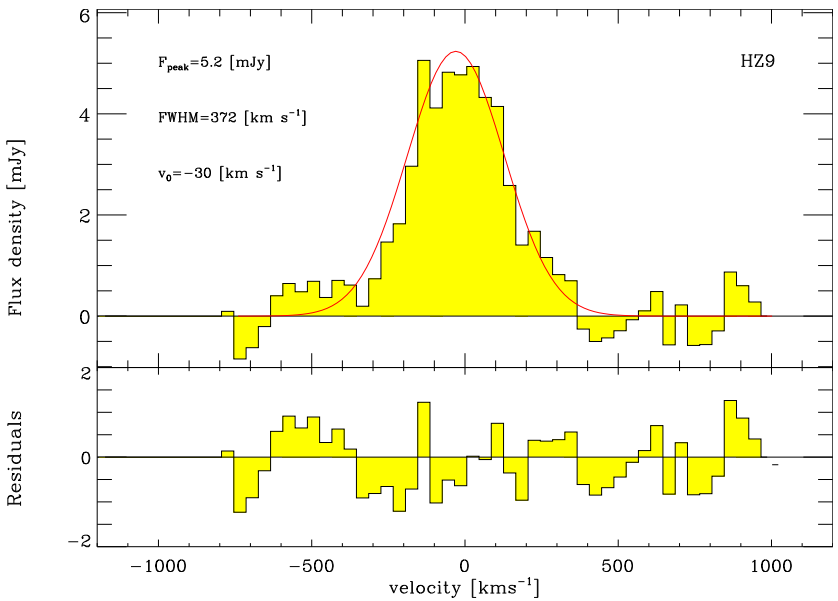
[CII] emission, dust continuum, UV restframe



We can use these detections to get information on the outflows

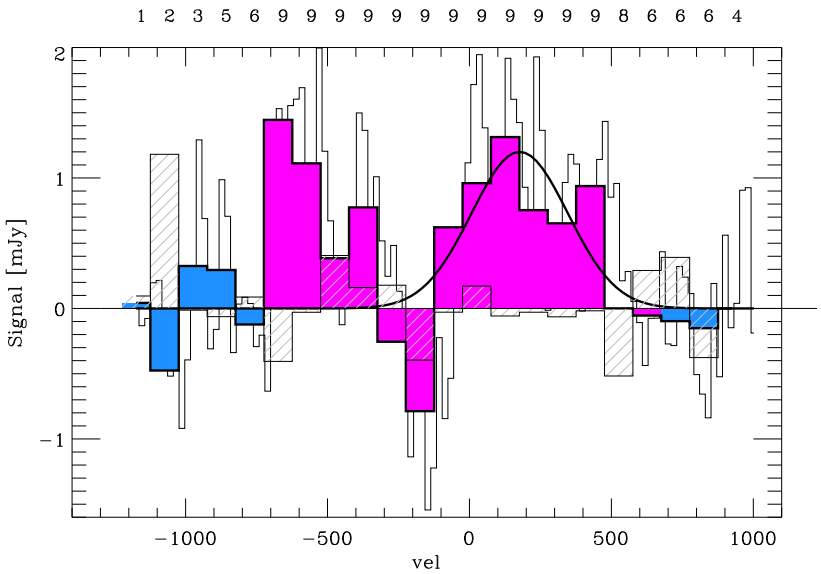
First statistical detection of outflows from $z \sim 6$ galaxies

Residual flux: example



$$\text{residual} = (\text{data} - \text{fit})/\sigma$$

Stacking residuals



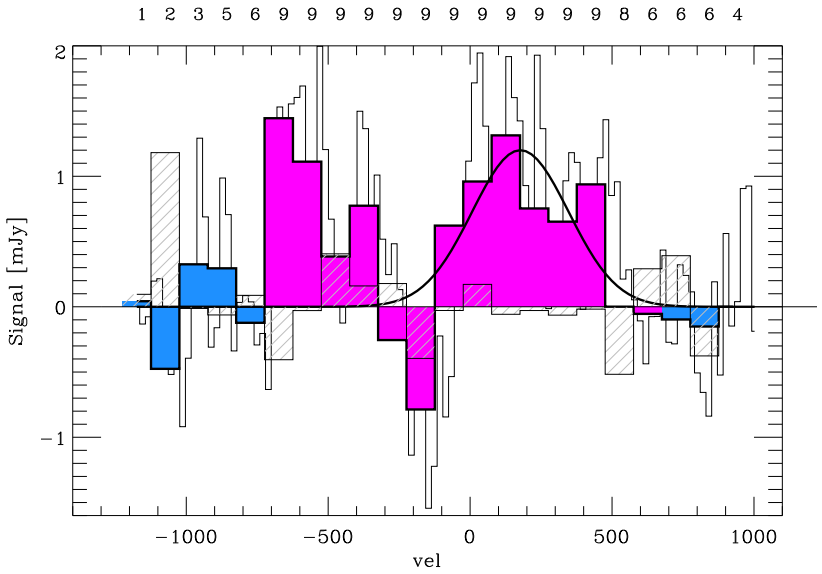
$$\text{signal} = \text{residuals} \times < \sigma >$$

	p-value KS
Residuals	0.5%
Residuals ($\lvert v \rvert < v_{\rm cont}$)	0.005%
Residuals ($\lvert v \rvert > v_{\rm cont}$)	76%
$\mathcal{G}$ random sampling	55%

Gallerani et al. 2016

Estimated outflow properties

Stacking



$$\text{signal} = \text{residuals} \times < \sigma >$$

Line fit:

$F_{\rm peak}$	=	$(1.2 \pm 0.4)\,\mathrm{mJy}$
$FWHM$	=	$(400 \pm 160)\,\mathrm{km\,s^{-1}}$
v_0	=	$(177 \pm 68)\,\mathrm{km\,s^{-1}}$

Outflow rate: $\dot{M}_{\rm out} \sim 65\,\mathrm{M_\odot/yr}$

Compatible with $\dot{M}_{\rm out}$ expected from simulations

Gallerani et al. 2016

Introducing Dahlia

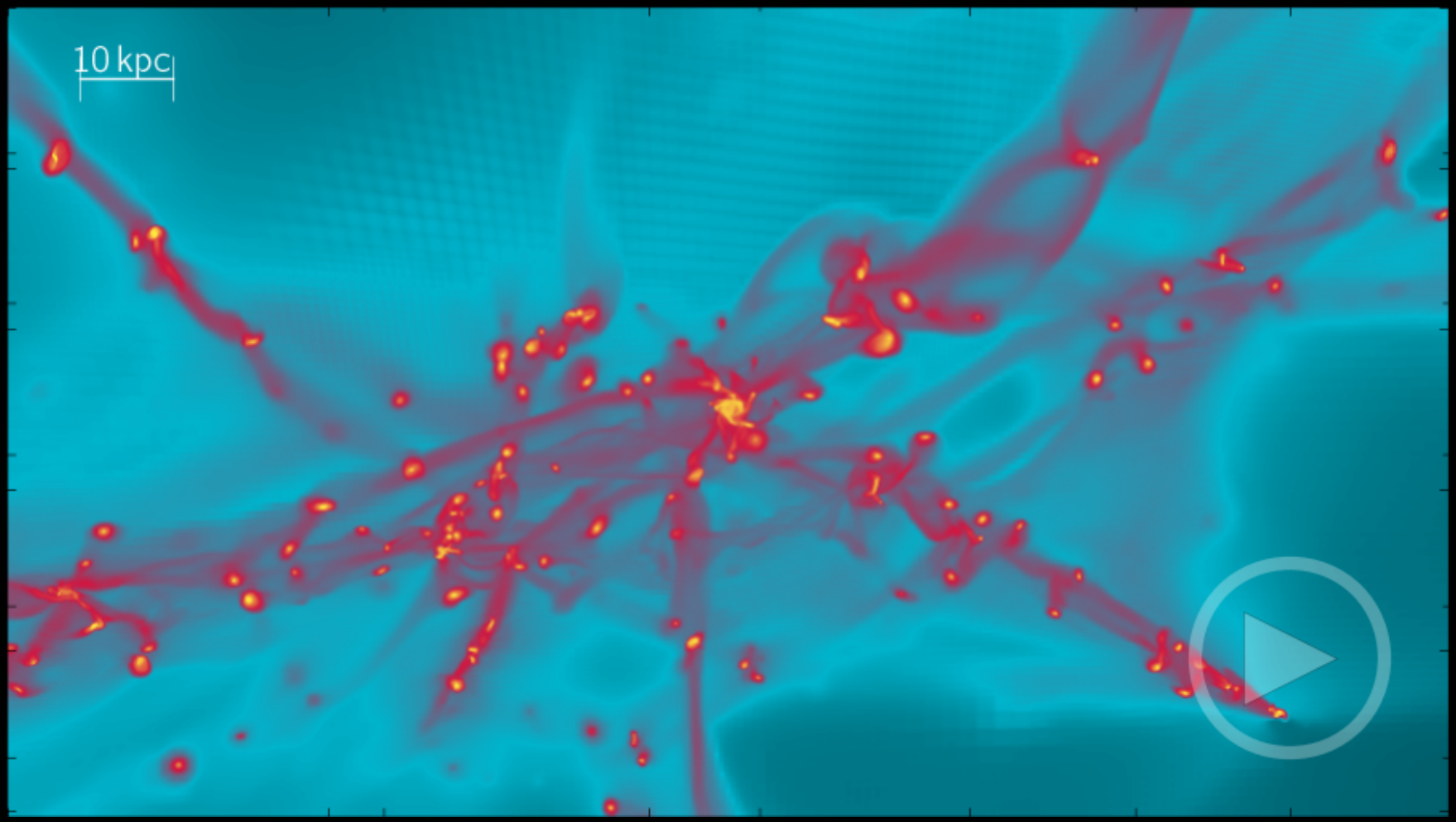
a prototipical LBG galaxy at $z \sim 6$		
dark matter	$M_{\rm dm} \sim 10^{11} {\rm M}_\odot$	
size	$r_{\rm vir} \simeq 15\,{\rm kpc}$	$r_{\rm eff} \simeq 0.5\,{\rm kpc}$
stars	$SFR \sim 100\,{\rm M}_\odot/{\rm yr}$	$M_\star \sim 10^{10} {\rm M}_\odot$
gas	$M_H \sim 10^{10} {\rm M}_\odot$	$M_{\rm H2} \sim 10^{8} {\rm M}_\odot$
enrichment	$Z \simeq 0.5\,{\rm Z}_\odot$	$M_{\mathcal{D}} \sim 10^{7} {\rm M}_\odot$

- AMR code RAMSES Teyssier 2002
- IC MUSIC Hahn 2011
- H2 star formation (SK relation) Krumholz et al. 2009
- Stellar track from STARBURST99 Leitherer et al 2010
- SN explosions/AGB winds/Radiation Pressure see Agertz et al 2015
- gas mass resolution $m_g \simeq 10^4 {\rm M}_\odot$
- AMR resolution $\Delta x \simeq 30\,{\rm pc}$

nomination for best image set for Wikimedia Eesti

European Science Photo Competition 2015

A zoomed view of Dahlia from cosmological simulation

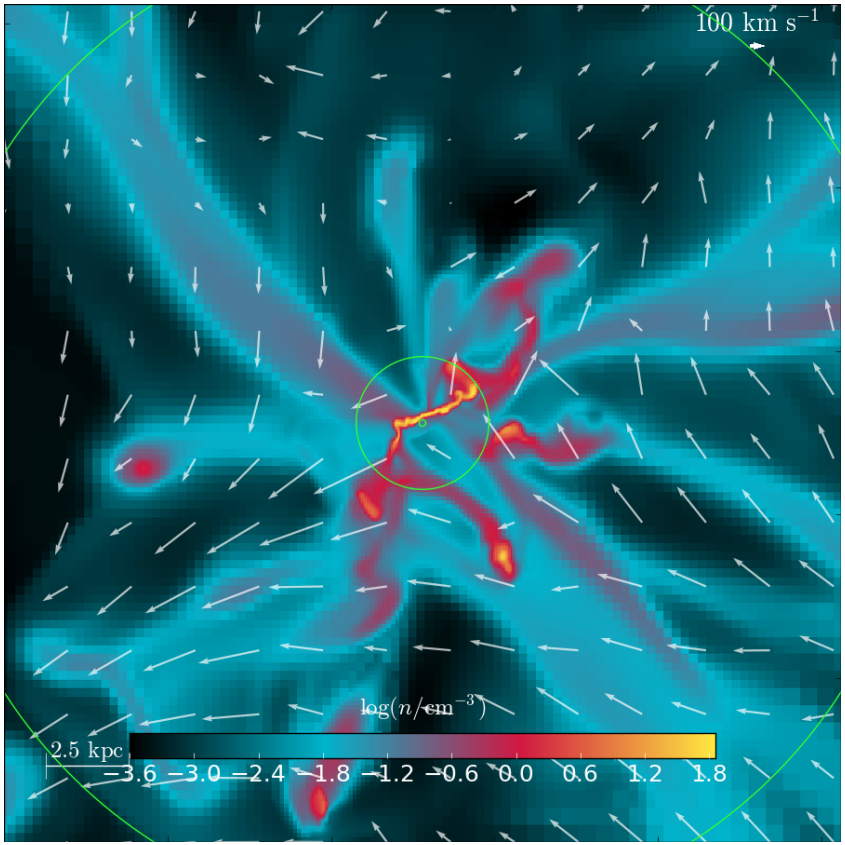


density field view

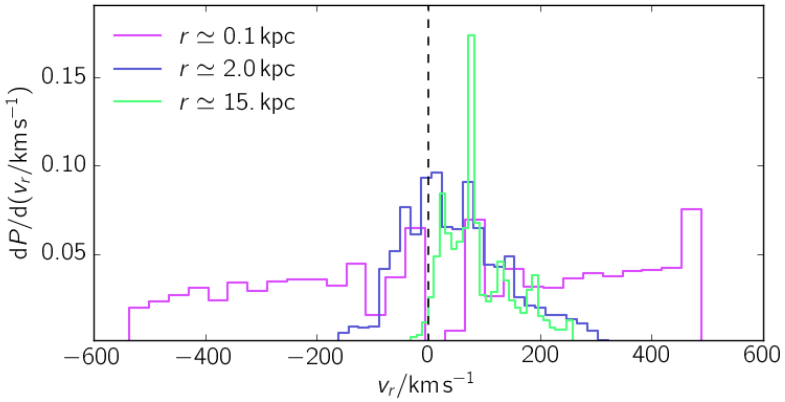
soon will be uploaded on https://www.researchgate.net/profile/Andrea_Pallottini

Outflow characteristics in Dahlia

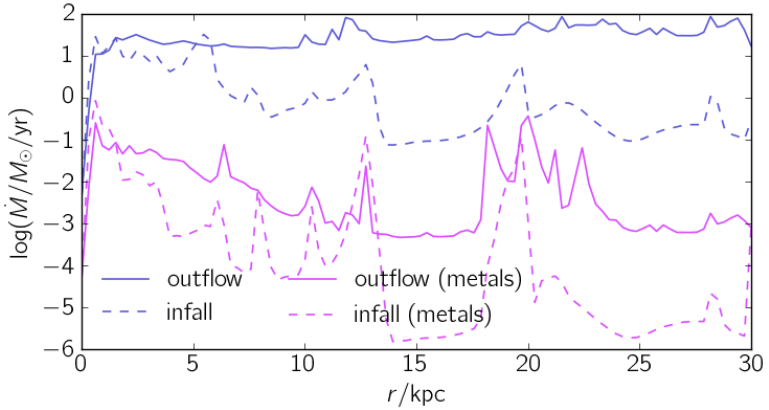
Density and velocity maps



Velocity PDF at different radii



Outflow/infall rates

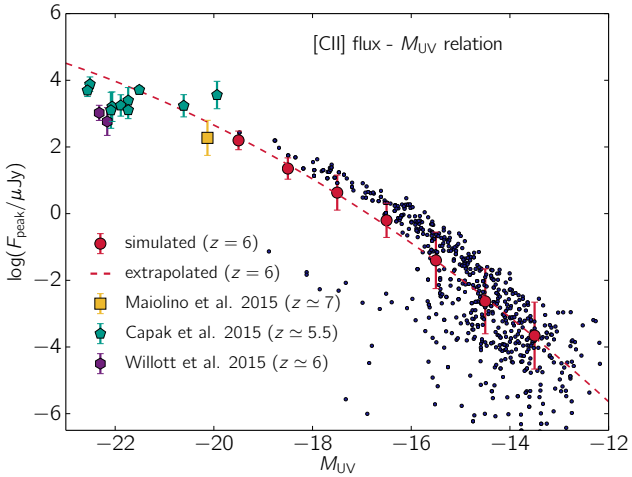


Outflow rate in Dahlia: $\dot{M}_{\mathrm{out}} \sim 30\,\mathrm{M}_\odot/\mathrm{yr}$

Gallerani et al. 2016, Pallottini et al. 2016 in preparation

Conclusions

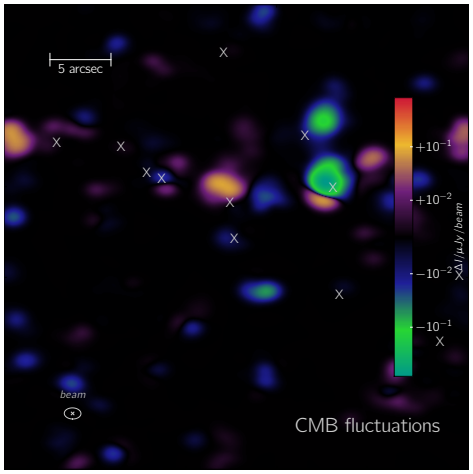
[CII] emission from high-z galaxies



A **[CII] – M_{UV}** relation is found, and [CII] is detected from $M_{UV} \simeq -20$ galaxies in 1 hr.

40 hr are needed for $M_{UV} = -19$, galaxies closer to the true **reionization sources**.

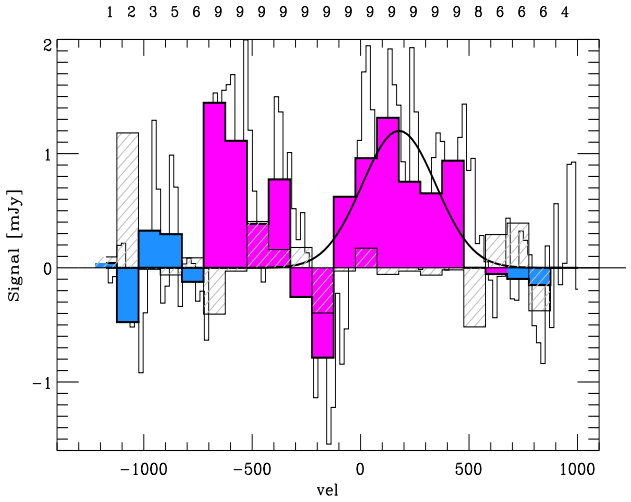
Mapping metals with CMB fluctuations



CMB fluctuations represent a **powerful**, **unique** tool to map metals through cosmic times.

This experiment is **challenging**, and galaxy **lensing** may help the detection.

Outflows from $z \sim 6$ galaxies

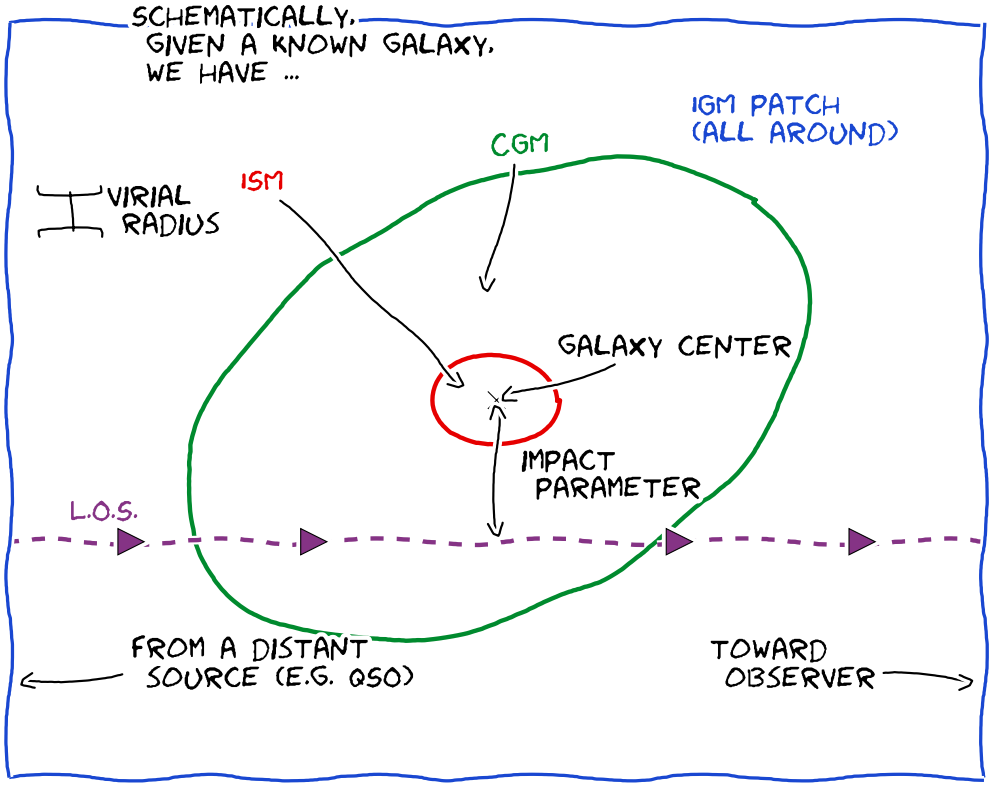


First attempt to detect outflow confirmed with statistical inference.

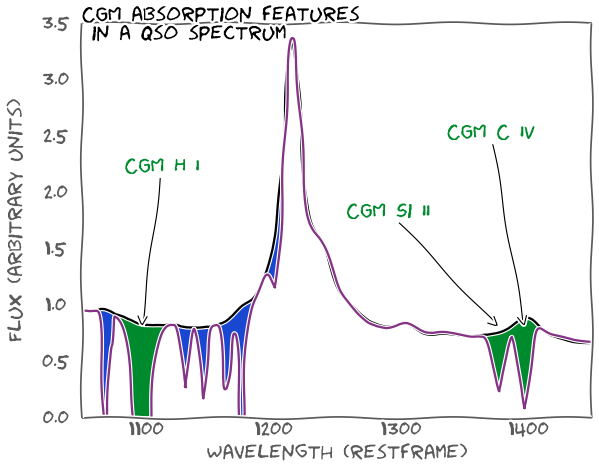
Numerical simulation supports the interpretation, waiting for ALMA direct detection.

About this morning CGM discussion

Sketch of source-absorber pair observation



disclaimer: this is not a simulation snapshot

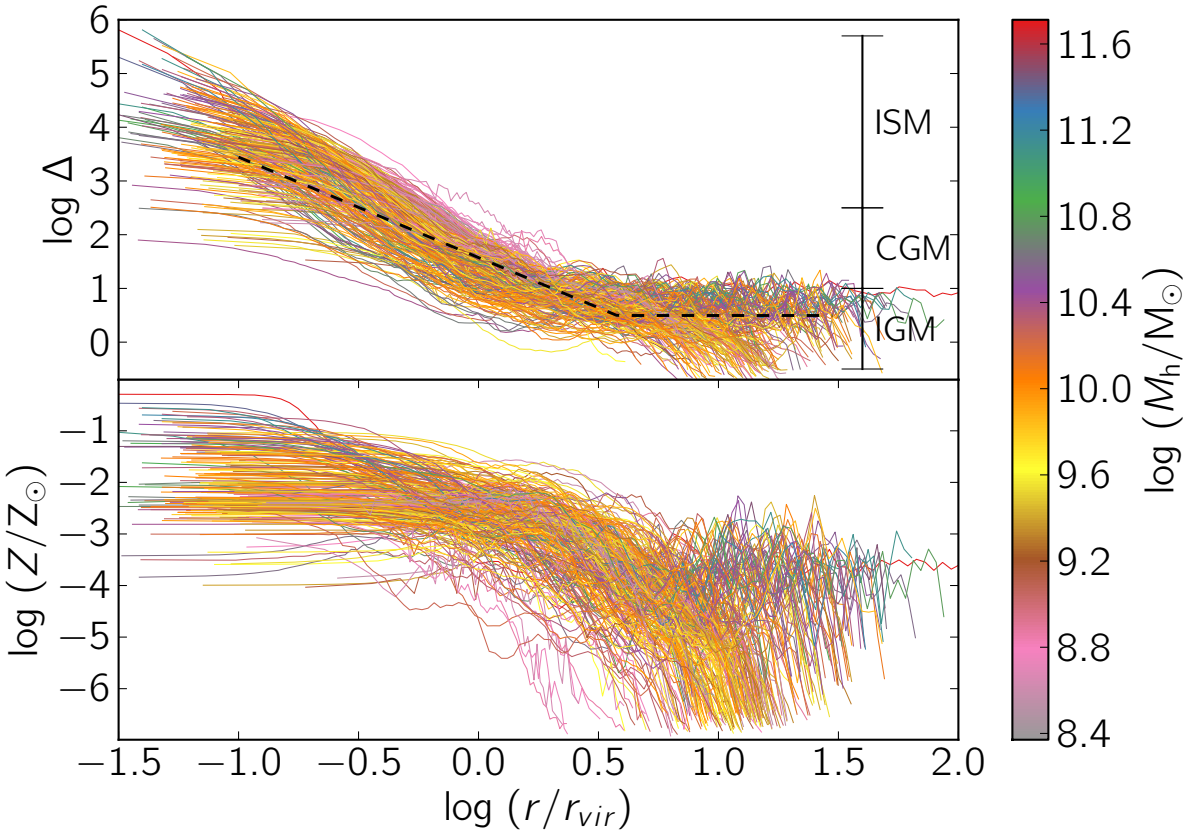


It is possible to statistically probe the CGM profile by using QSO/absorber pairs

Feedback regulates galaxy-IGM interplay

Radial profiles for galaxy groups: self-similarity of Δ profiles

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

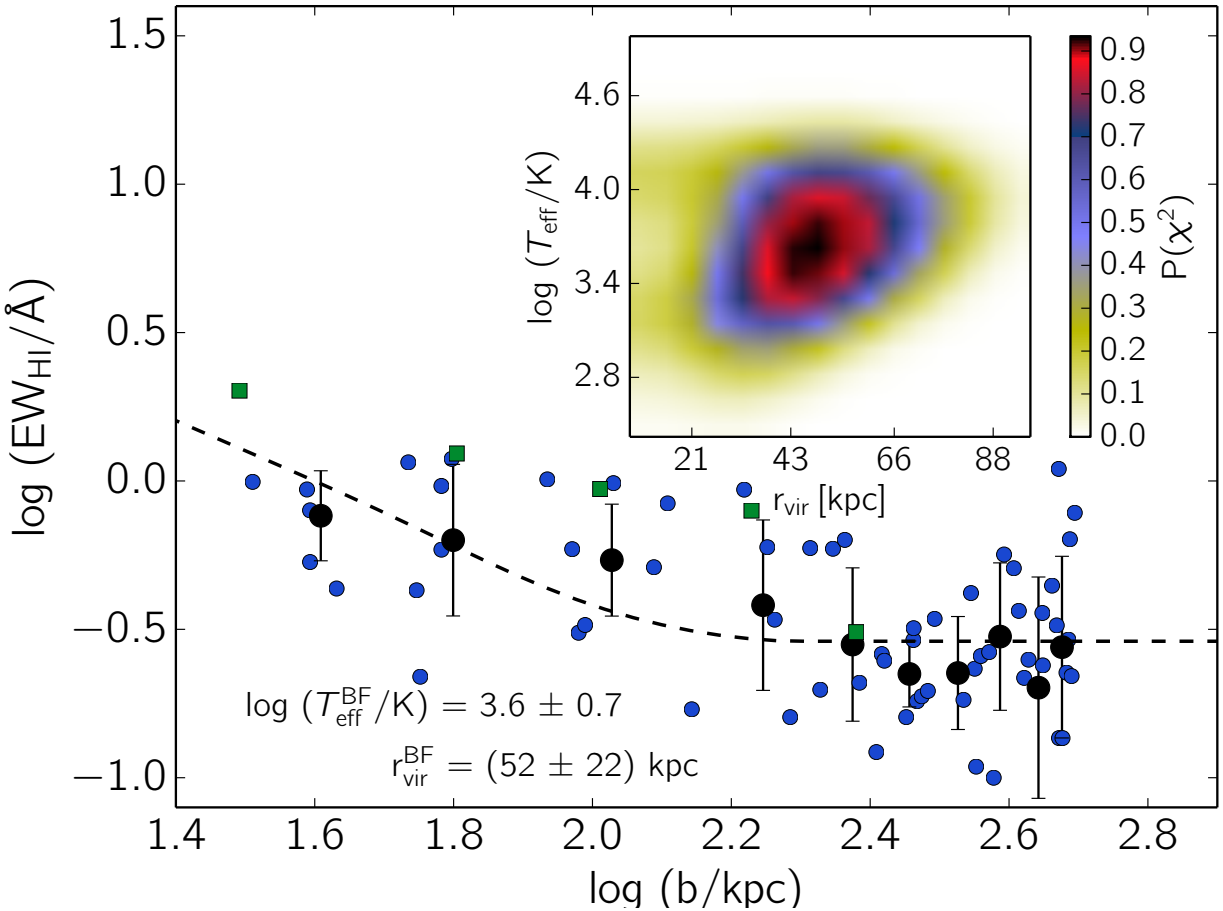


we can build an analytical model for HI absorption

Pallottini et al. 2014b

Feedback regulates galaxy-IGM interplay

Comparison with HI observations suggests that CGM profile does not evolve with z



Observations:
- Liang&Chen 2014 ($z \simeq 0$)
- Steidel et al. 2010 ($z \simeq 2$)

Model predictions:
- dashed line ($z \simeq 0$)

Pallottini et al. 2014b (see also Chen 2012, Liang et al. 2015)