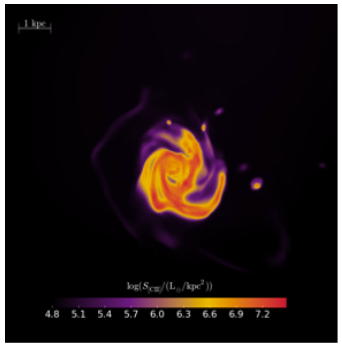
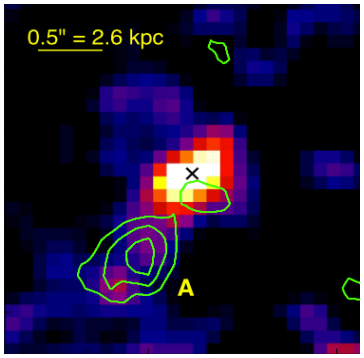
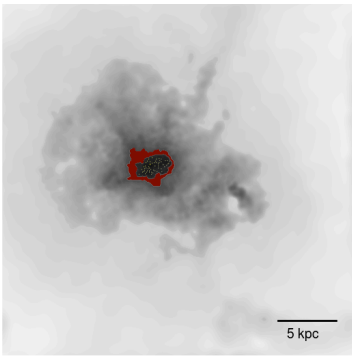
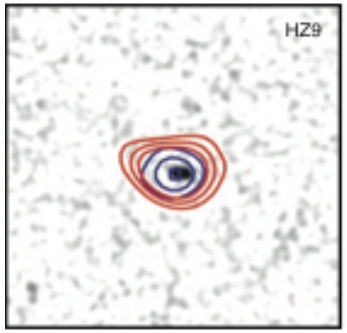






Unveiling the nature of z≈6 galaxies through [CII] emission studies

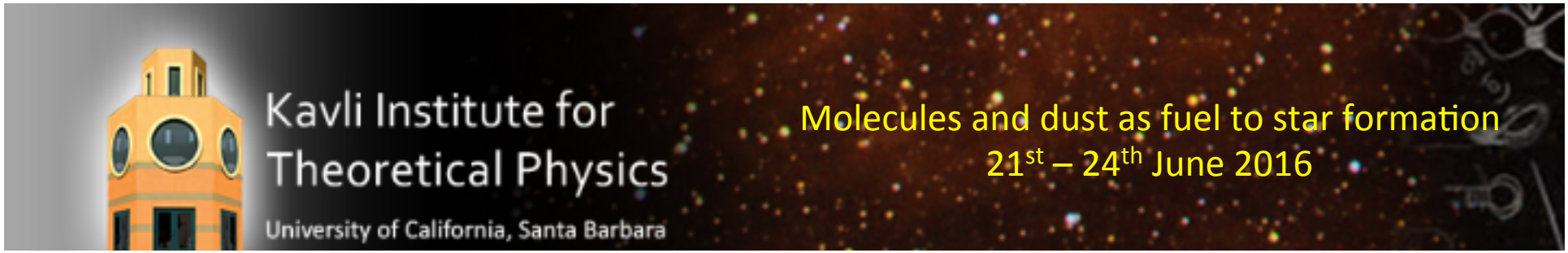


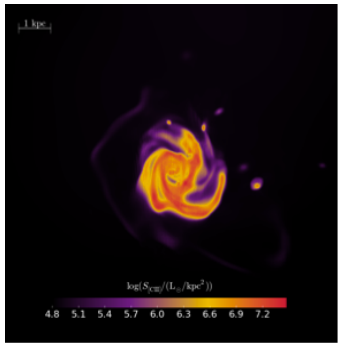
Simona Gallerani

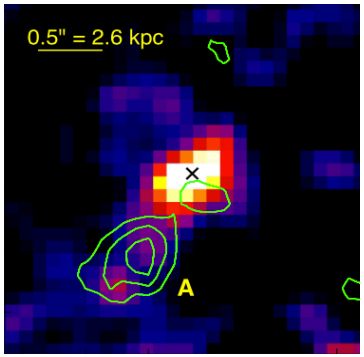
SCUOLA NORMALE SUPERIORE

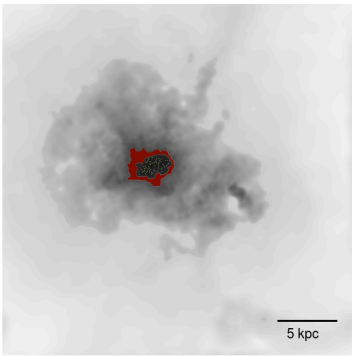
in collaboration with:

Livia Vallini, Andrea Ferrara, Andrea Pallottini,
Roberto Maiolino, Chiara Feruglio, Dominik Riechers, Bin Yue









Unveiling the nature of z≈6 galaxies through [CII] emission studies

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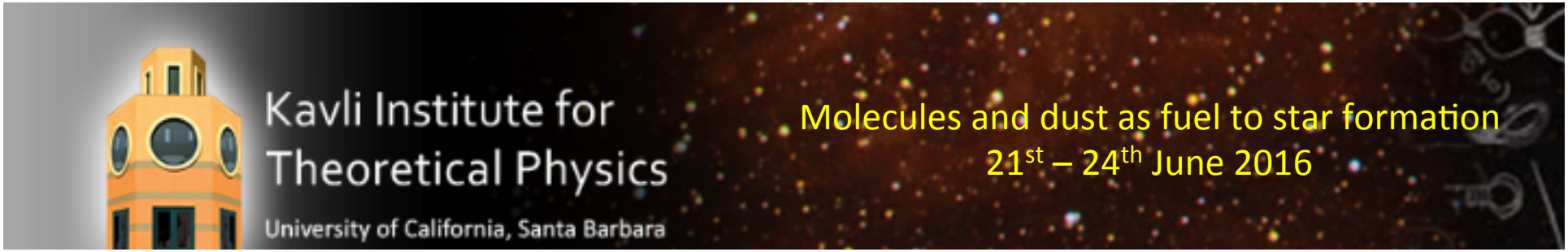
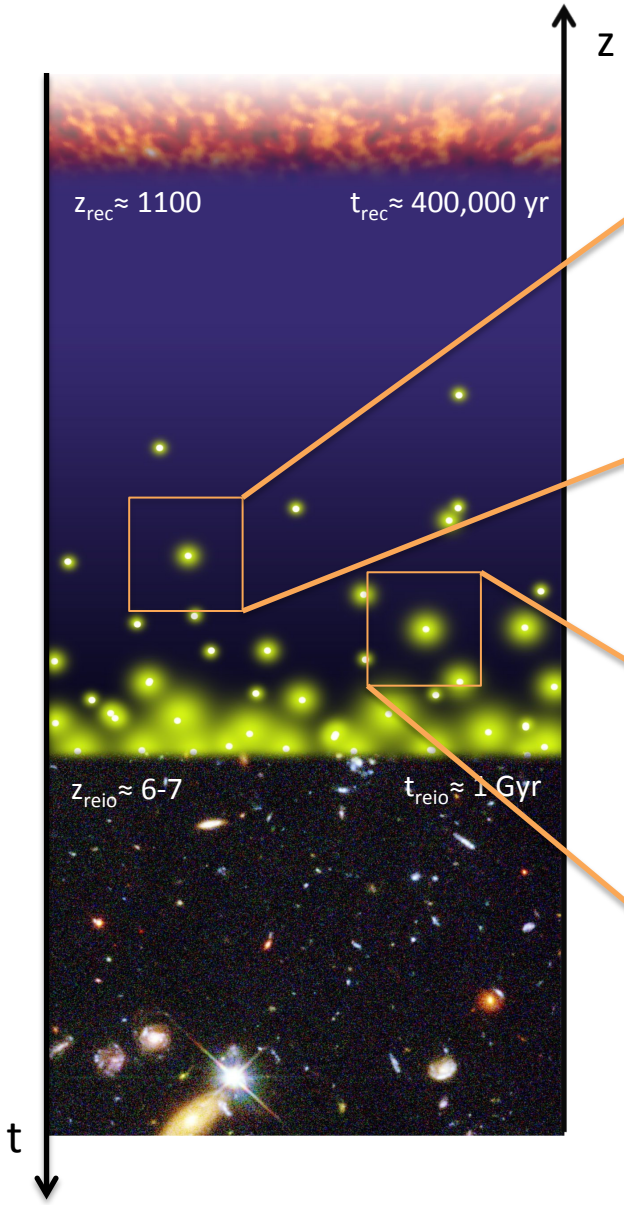
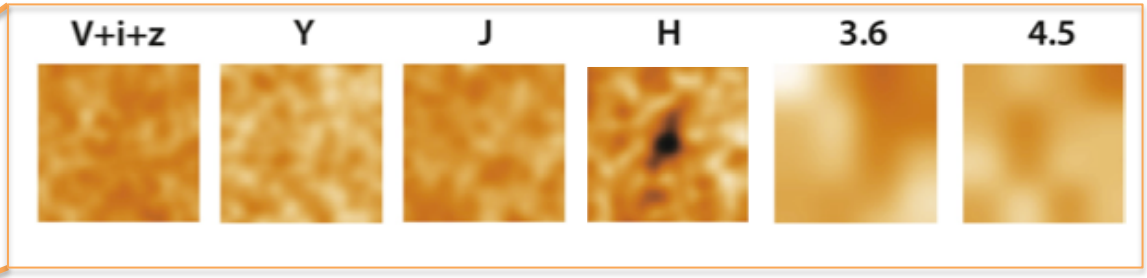


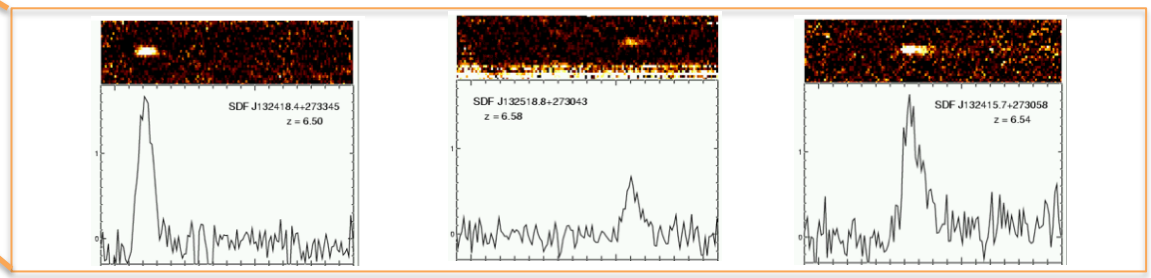
Searching for galaxies in the epoch of reionization



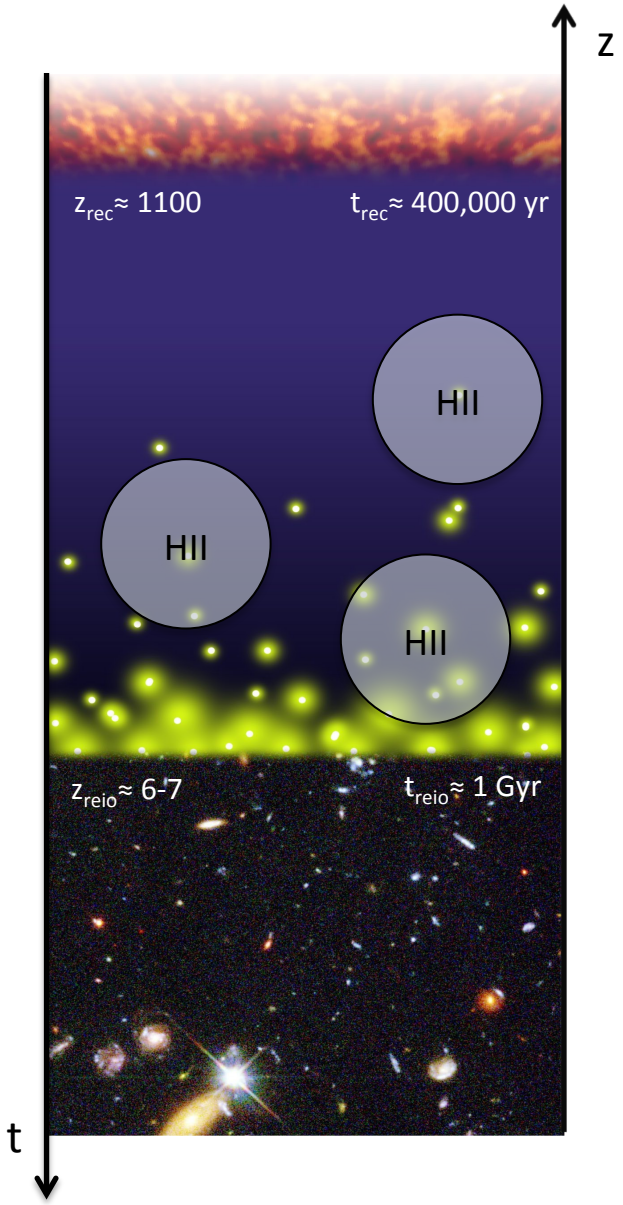
Dropout tecnique: Lyman Break Galaxies



Narrow band technique: Lyman Alpha Emitters



Searching for galaxies in the epoch of reionization



INTRINSIC DIFFICULTIES

Dropout technique: Lyman Break Galaxies

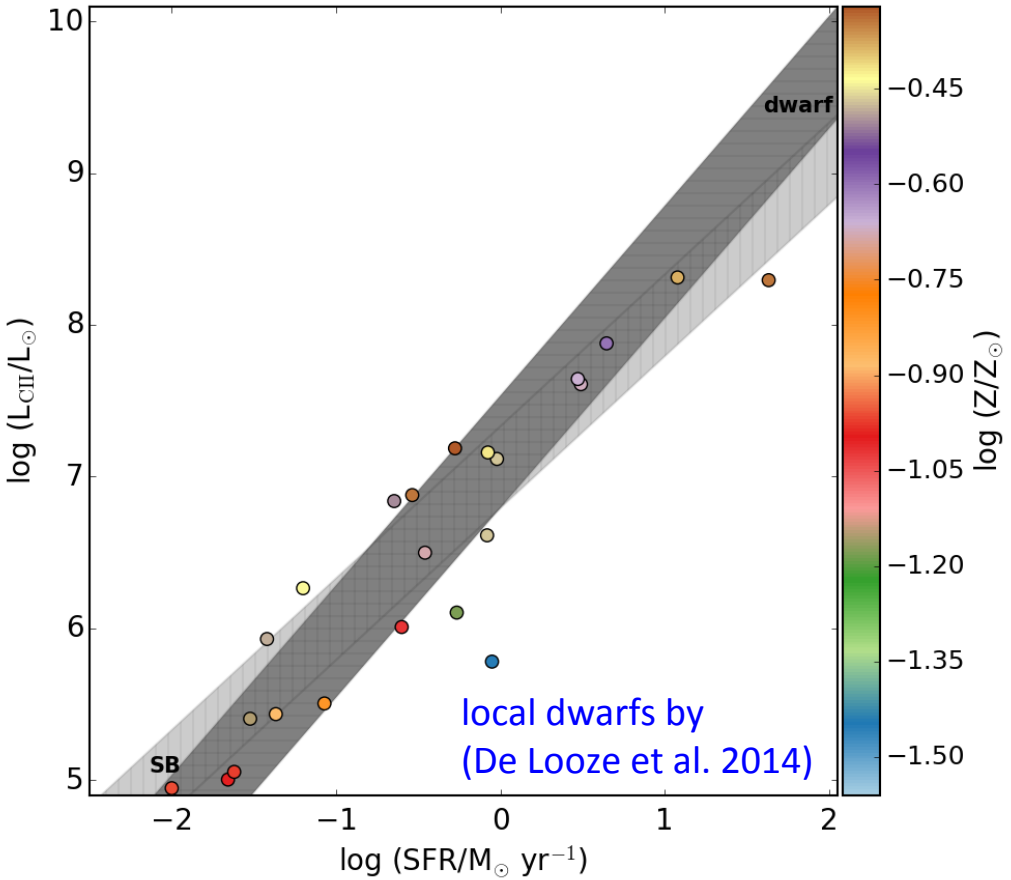
Uncertainties on the galaxy redshifts (Δz/z≈10%)
Contamination from foreground red galaxies
and Galactic cool stars

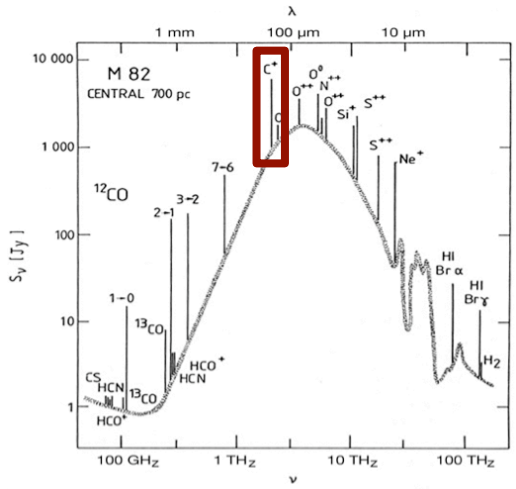
Narrow band technique: Lyman Alpha Emitters

Ionized bubbles allow Lyα photons to escape.
The neutral hydrogen fraction increases at redshifts
approaching the EOR.
The HII region sizes decrease.

Is the [CII] emission line a valid alternative?

[CII] emission observations in the local Universe

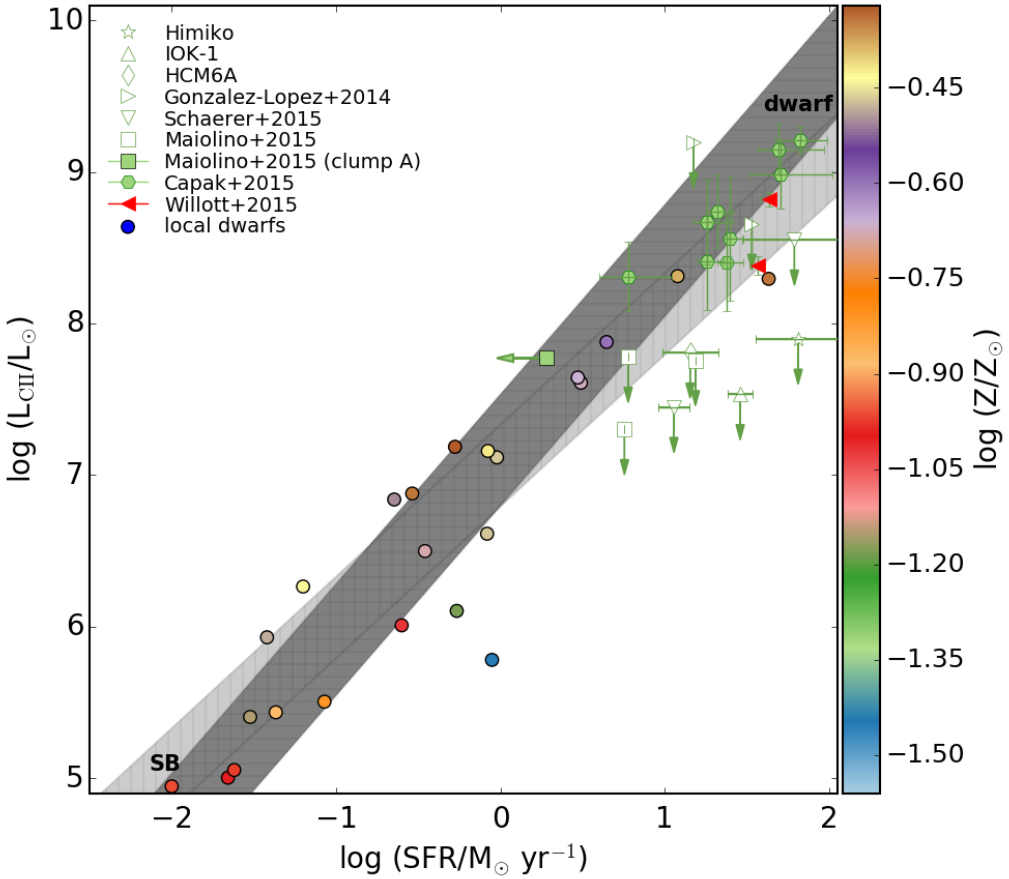




- Major coolant of the ISM in star forming galaxies
- The strongest emission line in most galaxies ($L_{[CII]}$ ~ 0.1-1% L_{FIR})

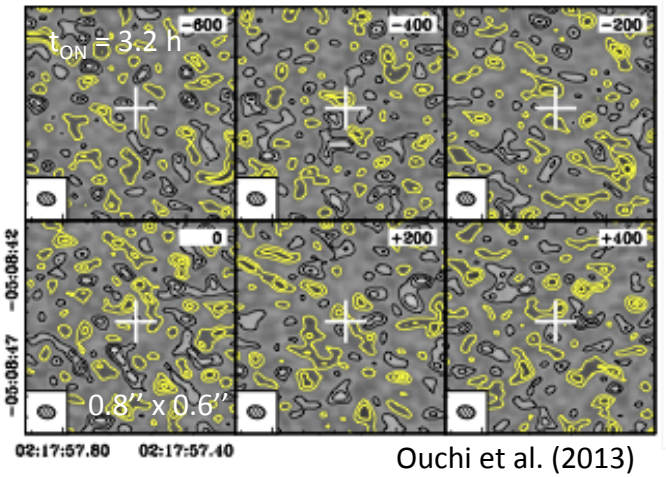
At **z > 4** is redshifted into the mm → **detectable with ALMA**

[CII] emission observations in 5 < z < 7 galaxies



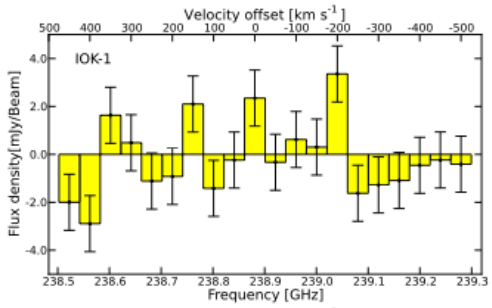
NO DETECTIONS

[CII] in Himiko at z = 6.6 (ALMA)



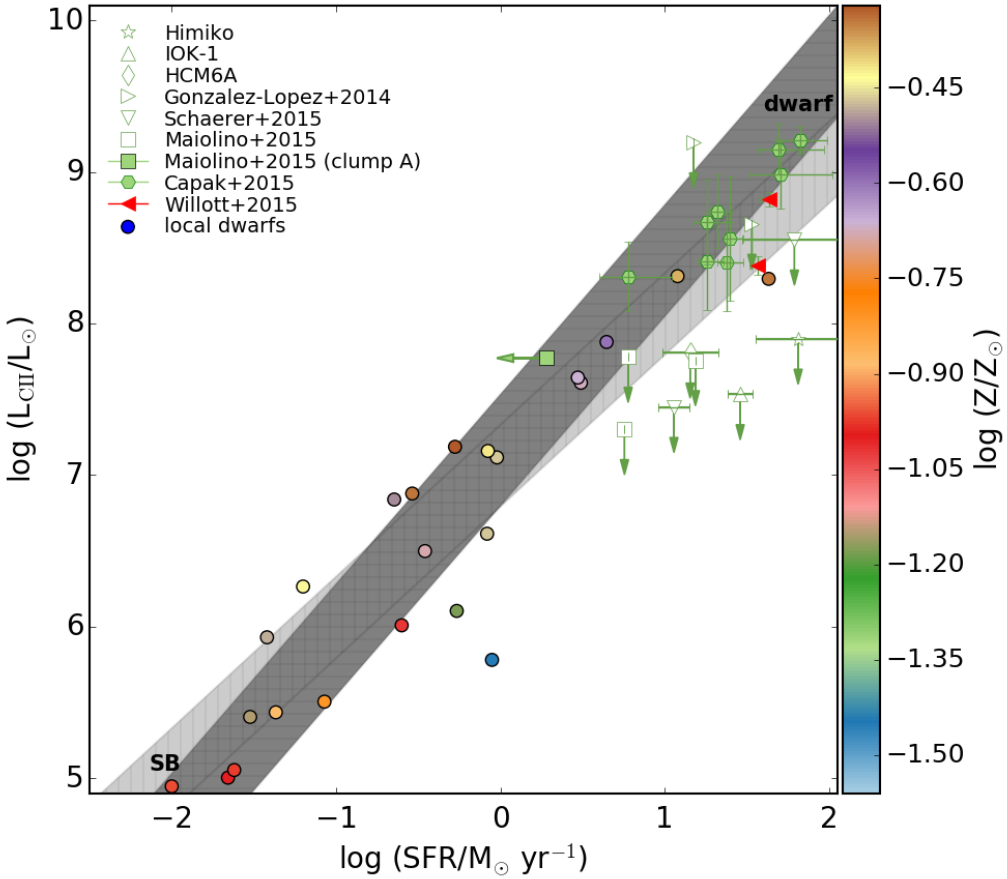
Ouchi et al. (2013)

[CII] in 6.5 < z < 7 LAEs (CARMA+PdBI)



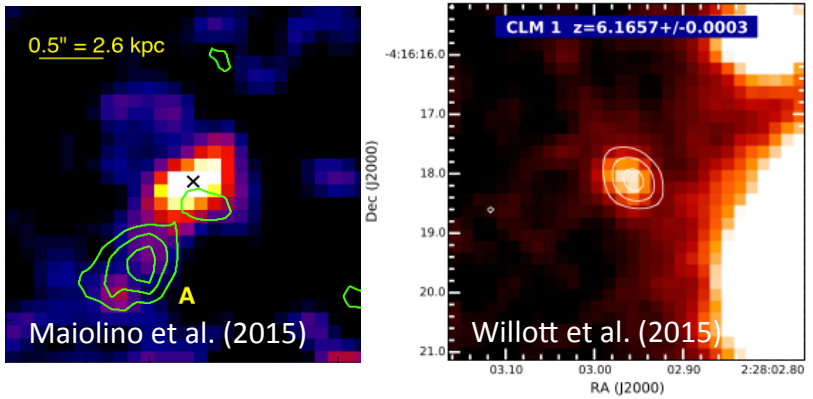
Gonxalez et al. (2014)

[CII] emission observations in 5 < z < 7 galaxies

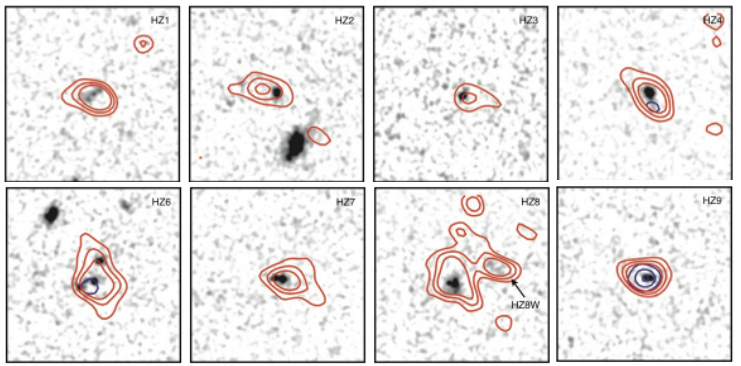


DETECTIONS

[CII] in 6 < z < 7 (ALMA)



[CII] in Himiko at z = 6.6 (ALMA)

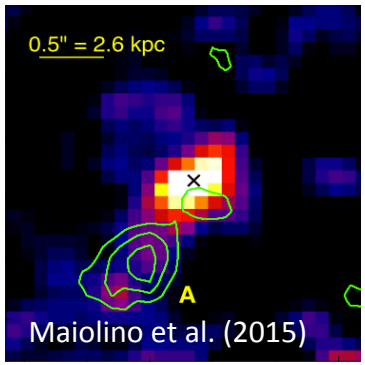


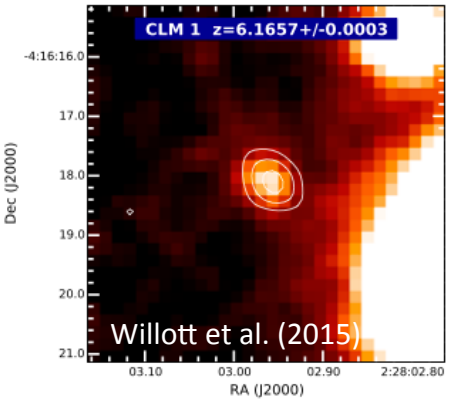
Capak et al. (2015)

What can we learn from high-z [CII] observations on z ≈ 6 galaxy properties?

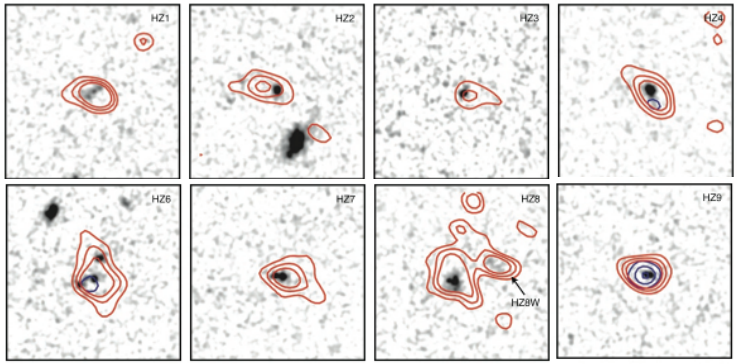
DETECTIONS

[CII] in 6 < z < 7 (ALMA)





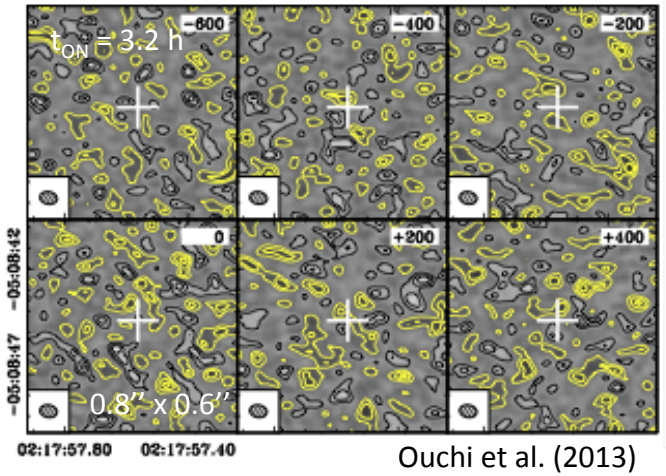
[CII] in Himiko at z = 6.6 (ALMA)



Capak et al. (2015)

NO DETECTIONS

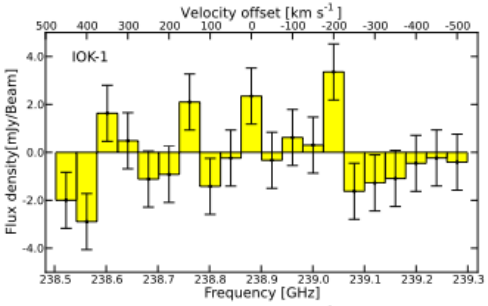
[CII] in Himiko at z = 6.6 (ALMA)



Contours levels in steps of 1σ (0.08 mJy beam^{-1})

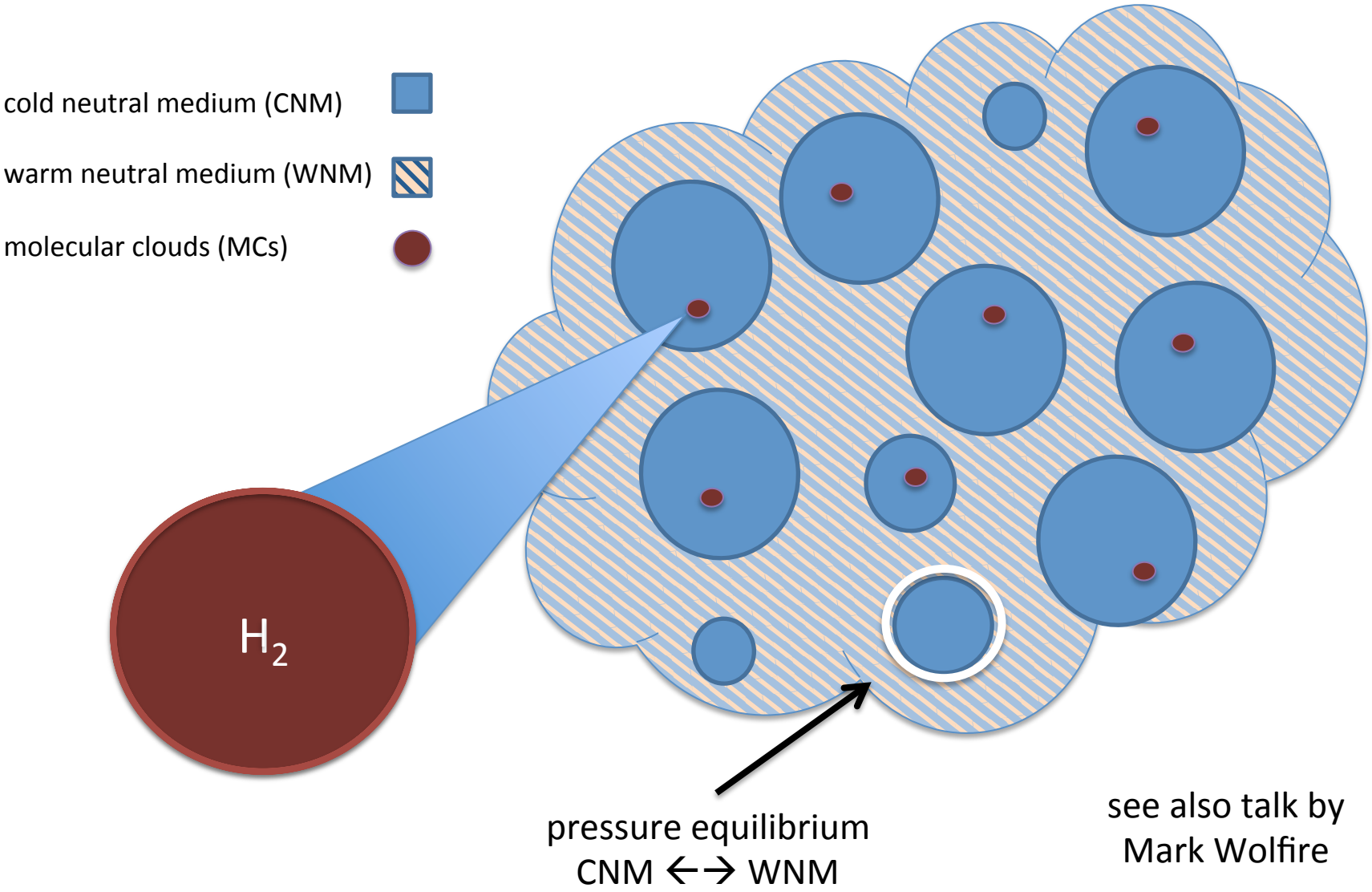
Ouchi et al. (2013)

[CII] in 6.5 < z < 7 LAEs (CARMA+PdBI)



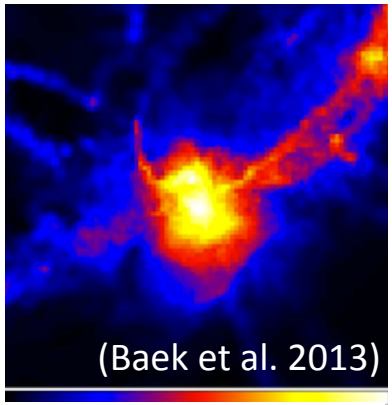
Gonxalez et al. (2014)

The multi-phase structure of the interstellar medium

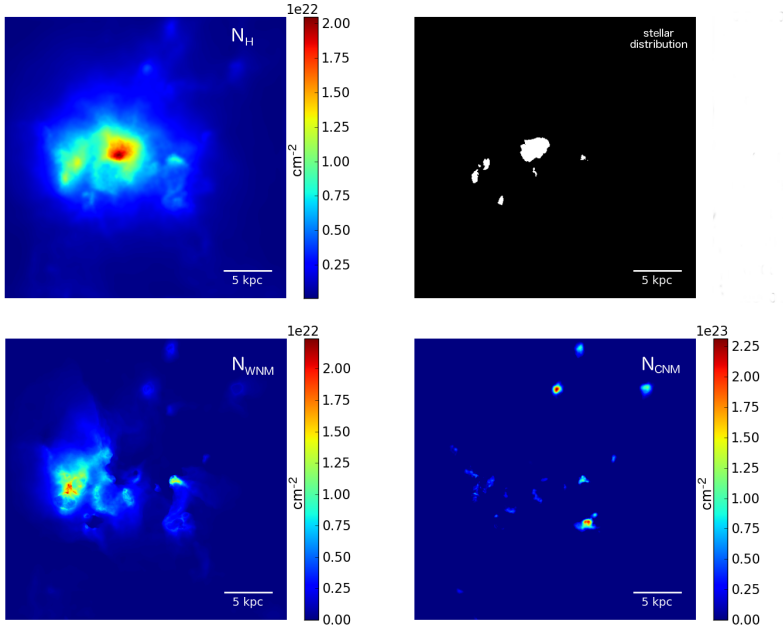


Simulations of [CII] emission in a z ≈ 6 galaxy

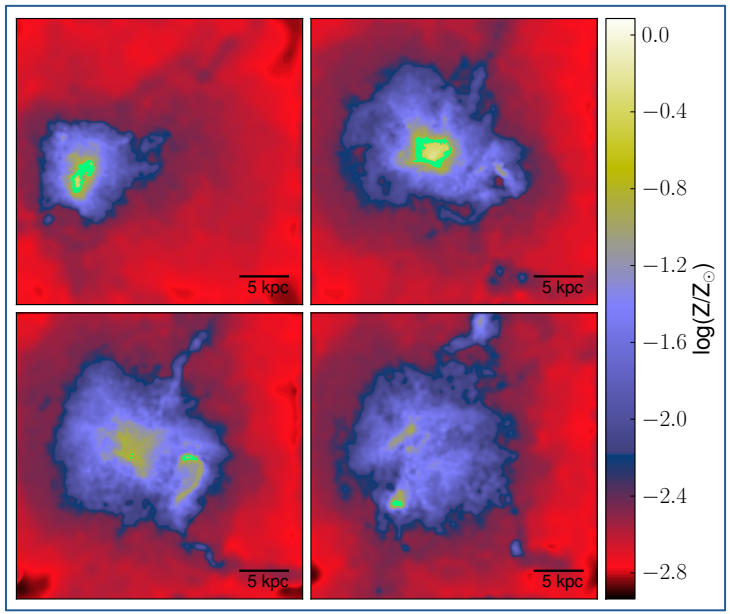
Zoomed **hydro RT** simulation
with a **subgrid model**
for the **WNM/CNM** (Wolfire et al. 2003)
and **molecular clouds**
(Padoan & Nordlund 2011)



$L_{box} = 10\ h^{-1}$ Mpc
$M_{res} = 7 \times 10^5\ M_\odot$
$M_{halo} = 10^{11}\ M_\odot$

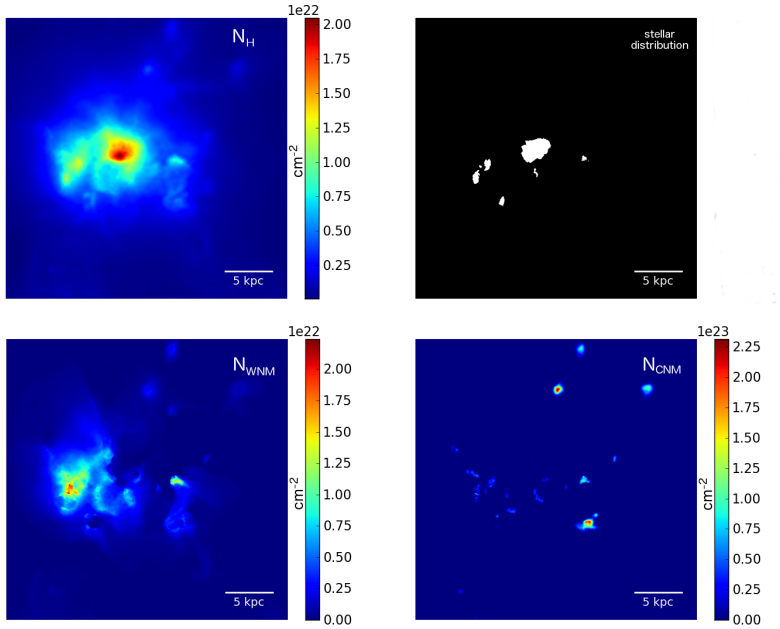


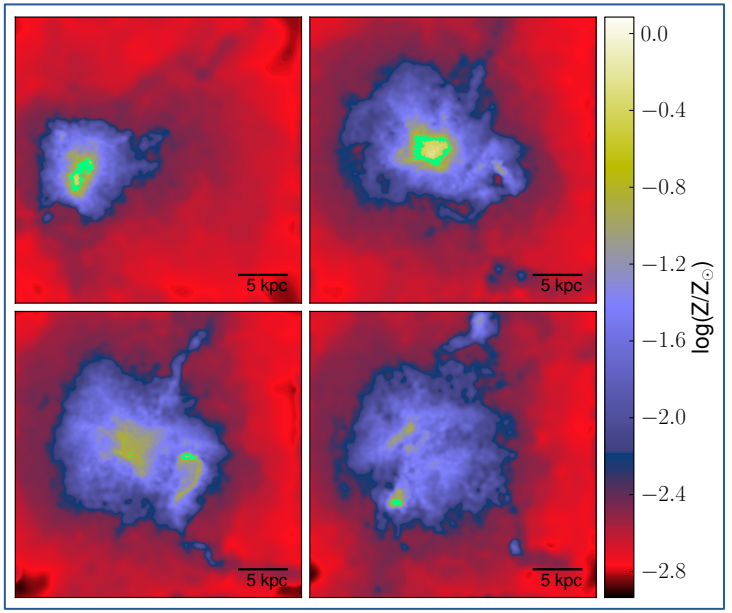
Vallini et al. (2013)



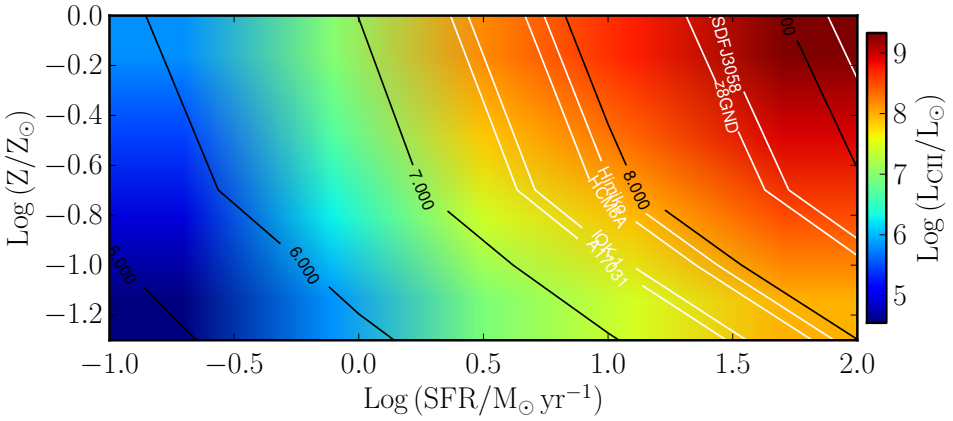
Vallini et al. (2015)

Simulations of [CII] emission in a z ≈ 6 galaxy





Yue et al. (2015)

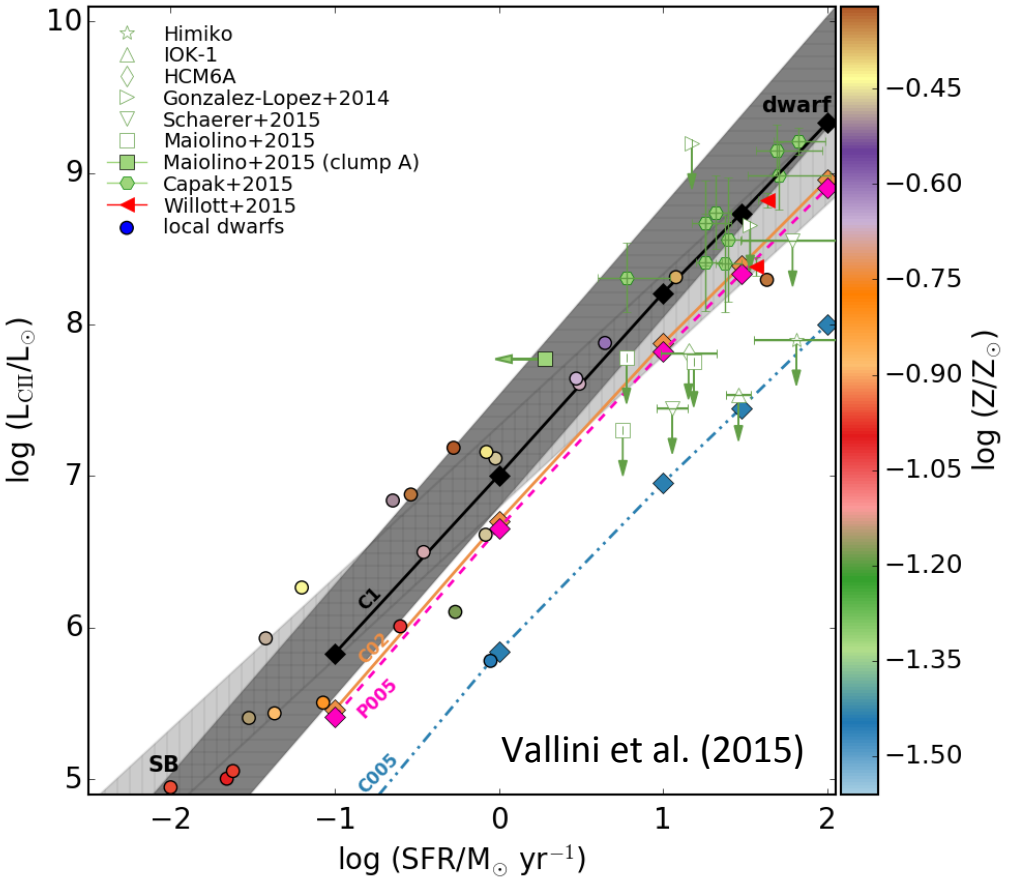


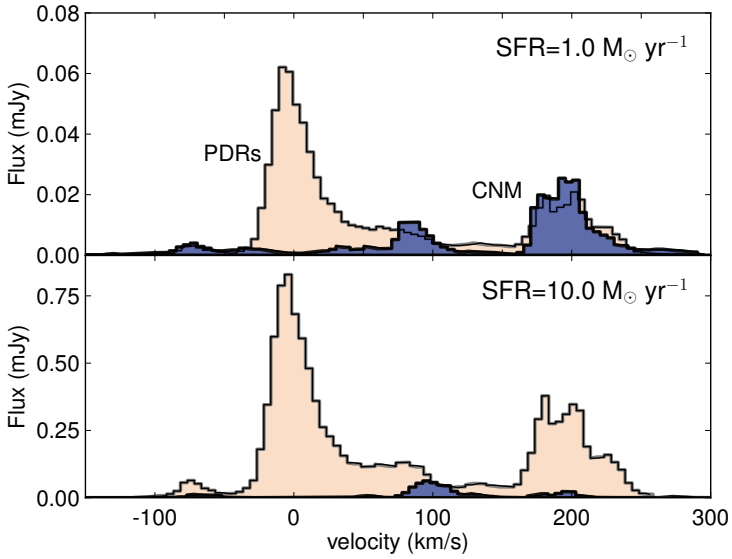
UCL PDR

(Bell et al. 2005, 2007; Bayet et al. 2009)

$$\log(L_{CII}) = 7.0 + 1.2 \times \log(SFR) + 0.021 \times \log(Z) + 0.012 \times \log(SFR)\log(Z) - 0.74 \times \log^2(Z)$$

Simulations of [CII] emission in a z ≈ 6 galaxy

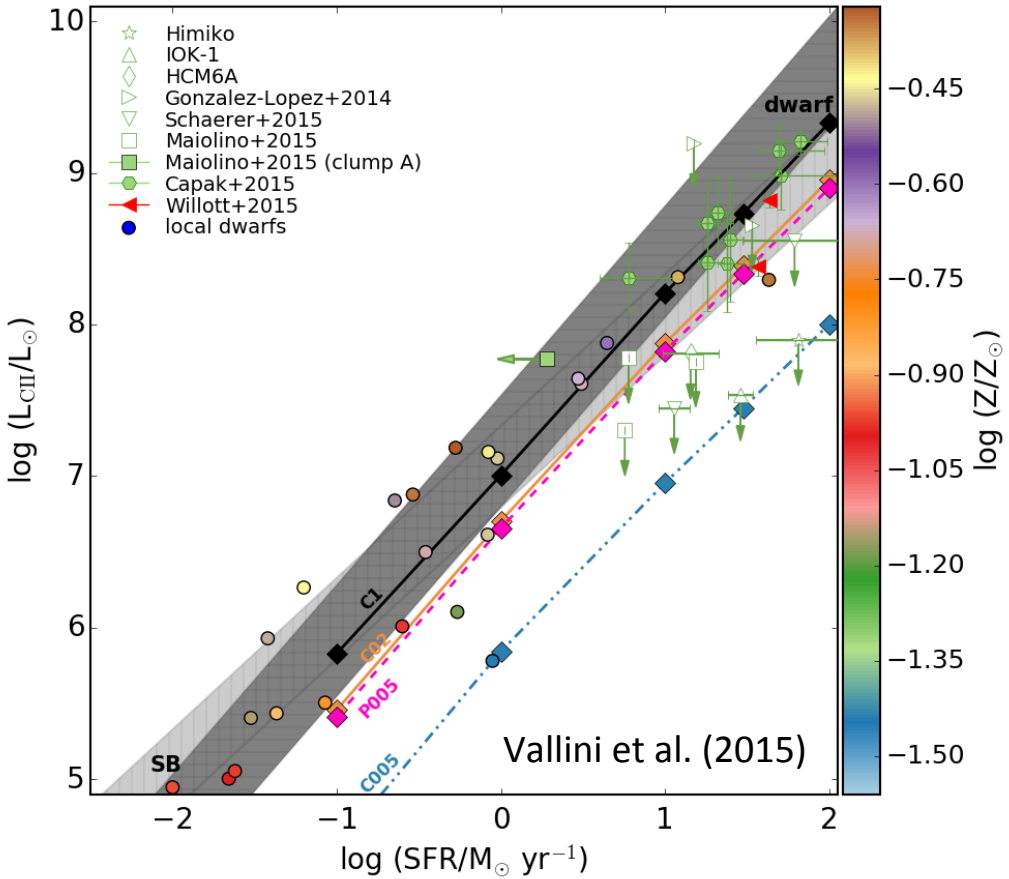




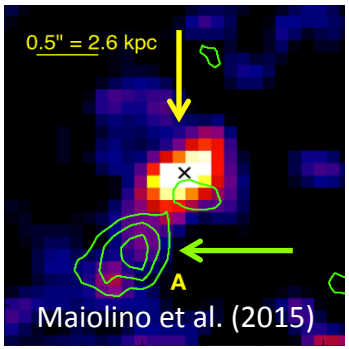
[CII] emission arises predominantly from PDRs (F_{diff}/F_{tot} <40%)

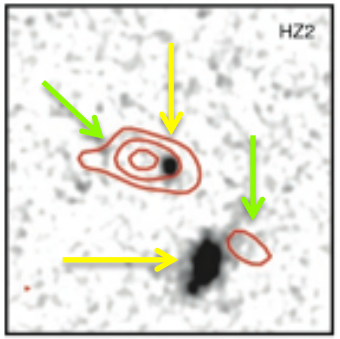
No detection of [CII] emission in z≈6 galaxies can be explained with low gas metallicity values (Z < 0.2 Z_{sun}) or by negative stellar feedback disrupting MC.

Simulations of [CII] emission in a z ≈ 6 galaxy



Deficit of CII
at the location of the UV emission





The CII *is detected*
in the displaced clump

No detection of [CII] emission in z≈6 galaxies can be explained with low gas metallicity values ($Z < 0.2\ Z_{sun}$) or by negative stellar feedback disrupting MC.

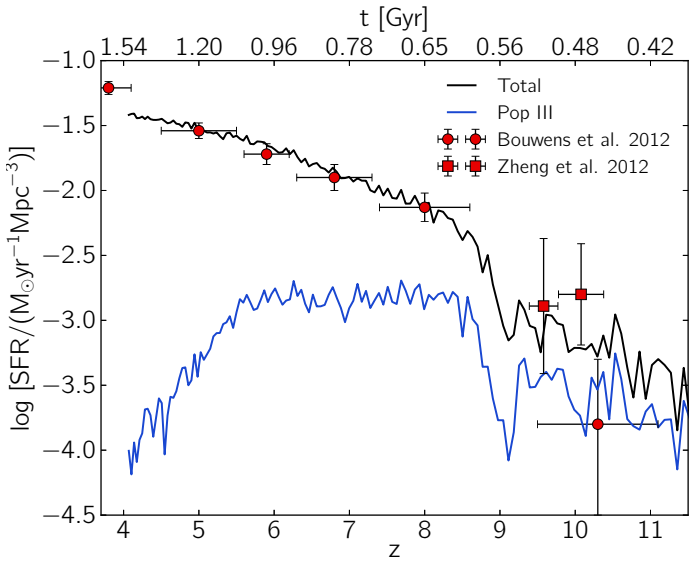
Simulating cosmic metal enrichment by the first galaxies

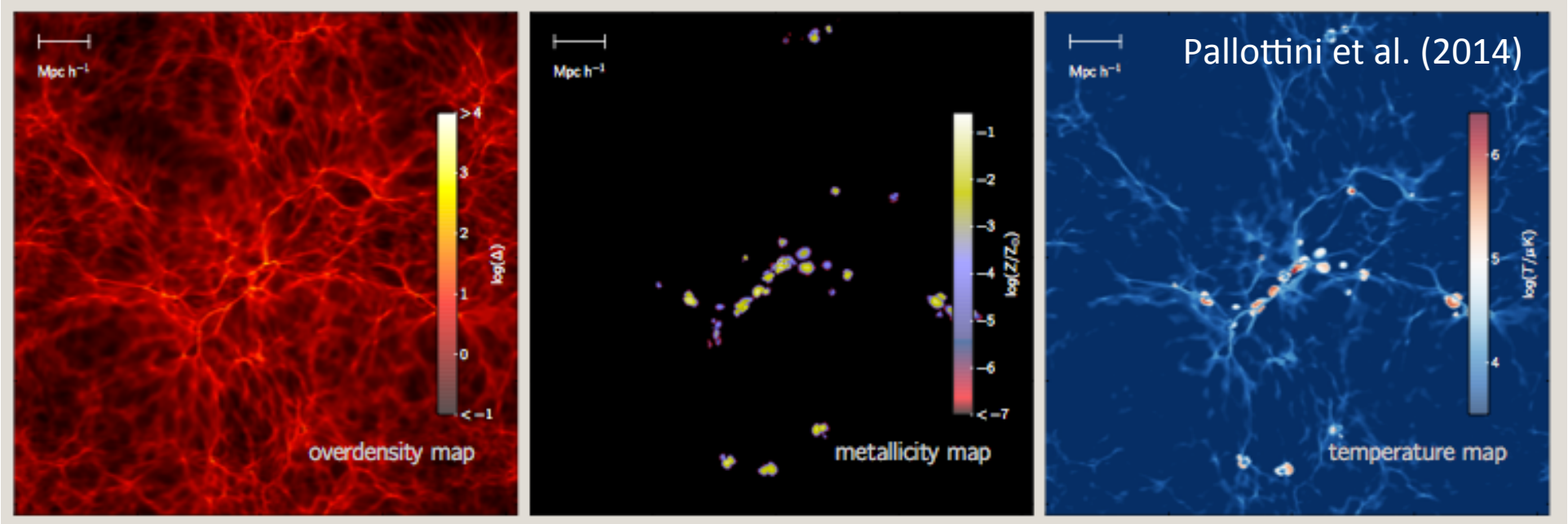
AMR code (RAMSES)

10 Mpc h^{-1}

$M_{dm} \approx 5 \times 10^5 M_{sun}$

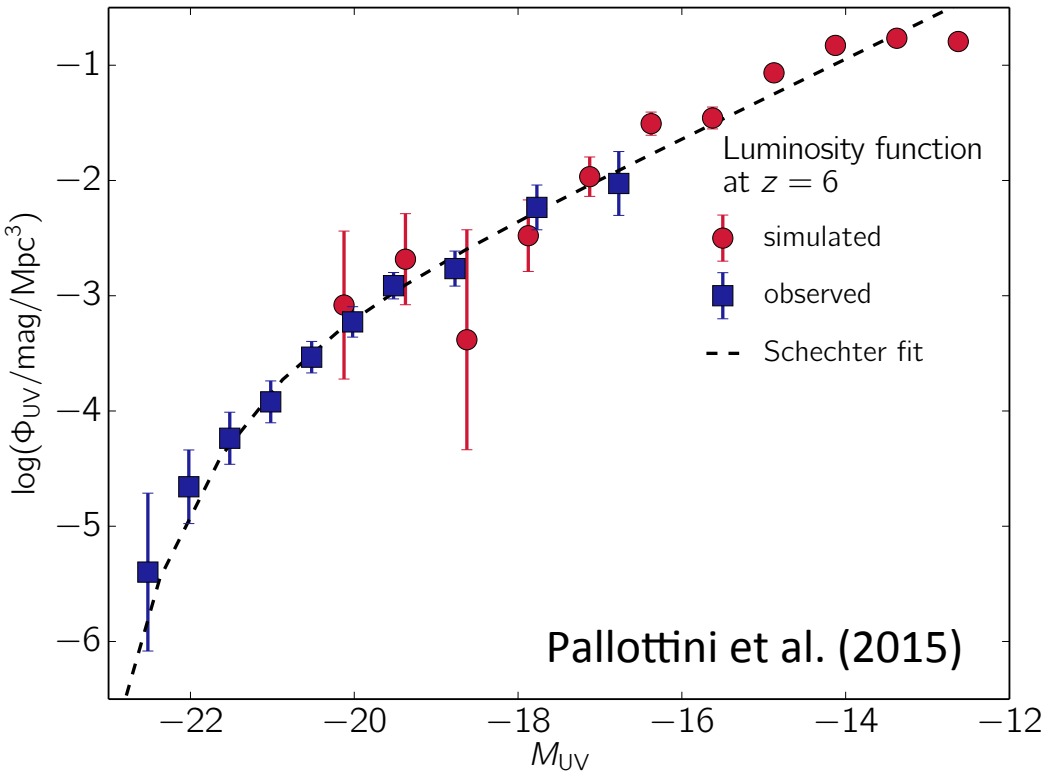
$\Delta x \approx$ (20-1) kpc h^{-1}





The UV luminosity function of z ≈ 6 galaxies

Good greement between simulations
and UV LF observations (Bouwens et al. 2015)



[CII] emission in z ≈ 6 galaxies

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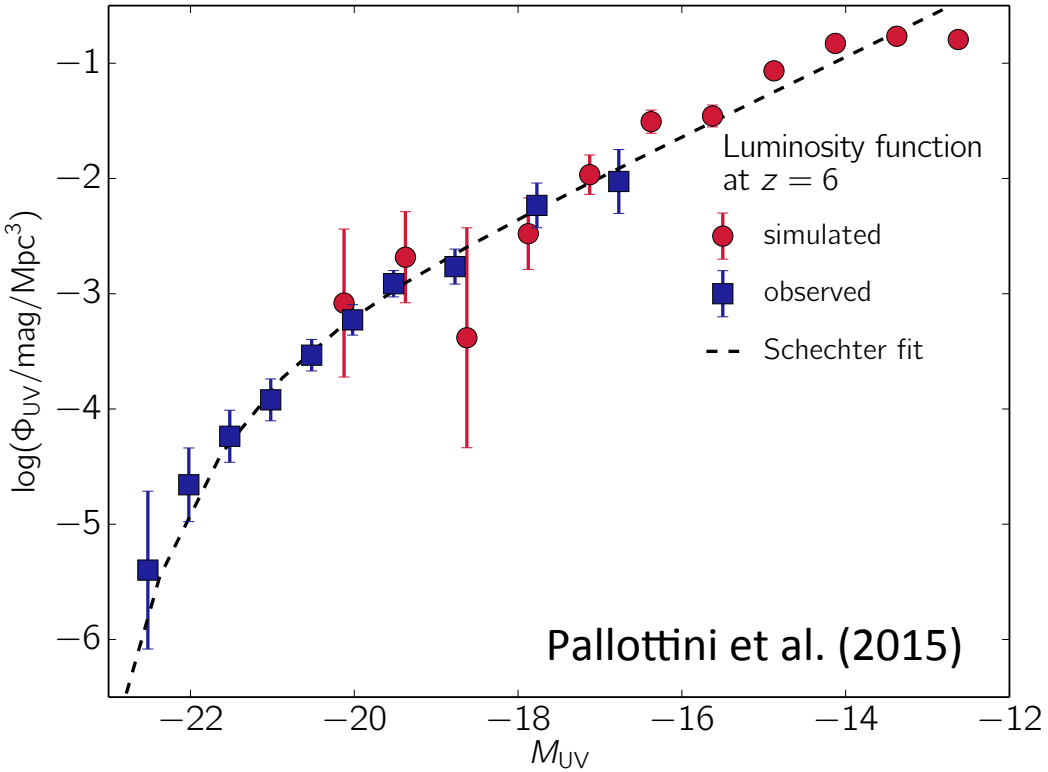
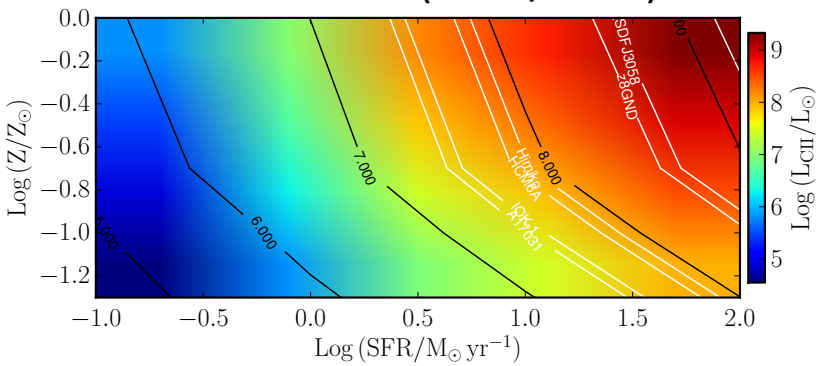


Vallini et al. (2013/2015)



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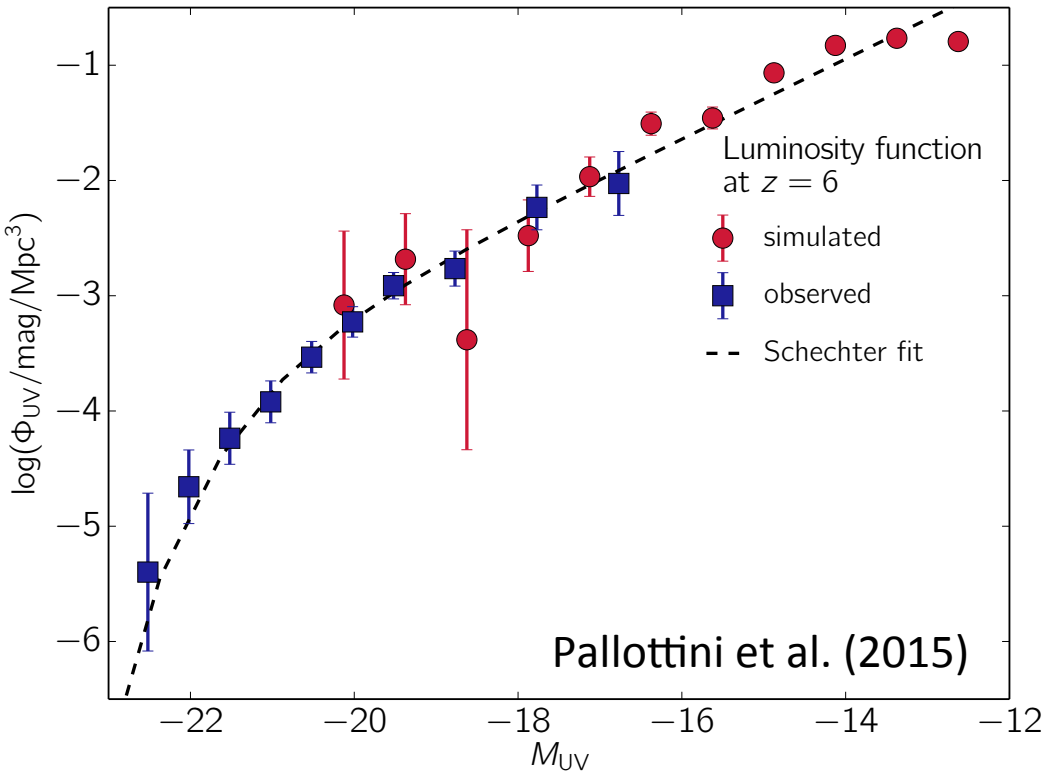
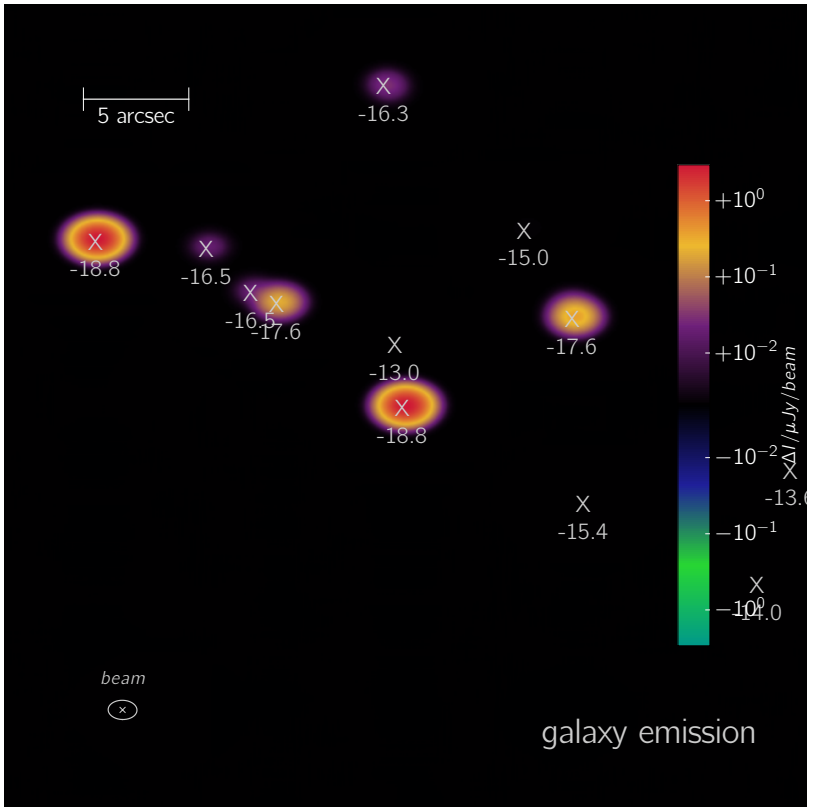
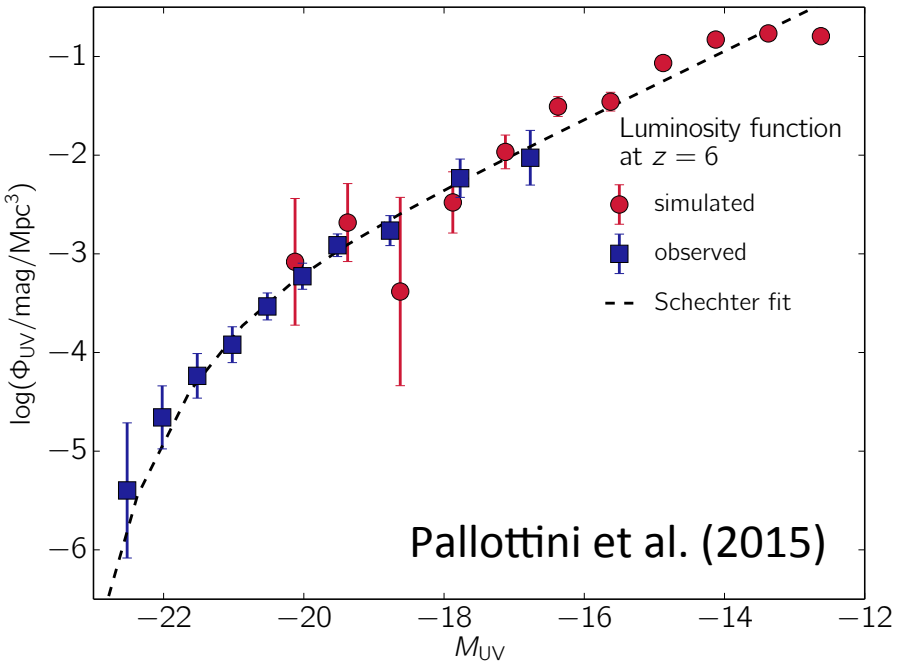


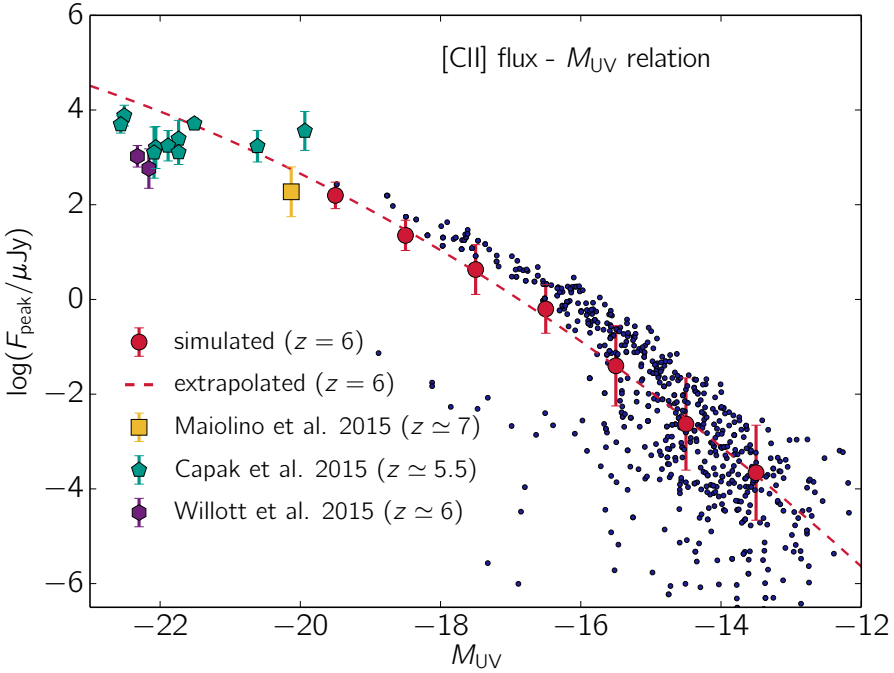


[CII] emission in z ≈ 6 galaxies

Good greement between simulations and UV LF observations (Bouwens et al. 2015)



Good greement between simulations and [CII] observations



[CII] emission in z ≈ 6 galaxies

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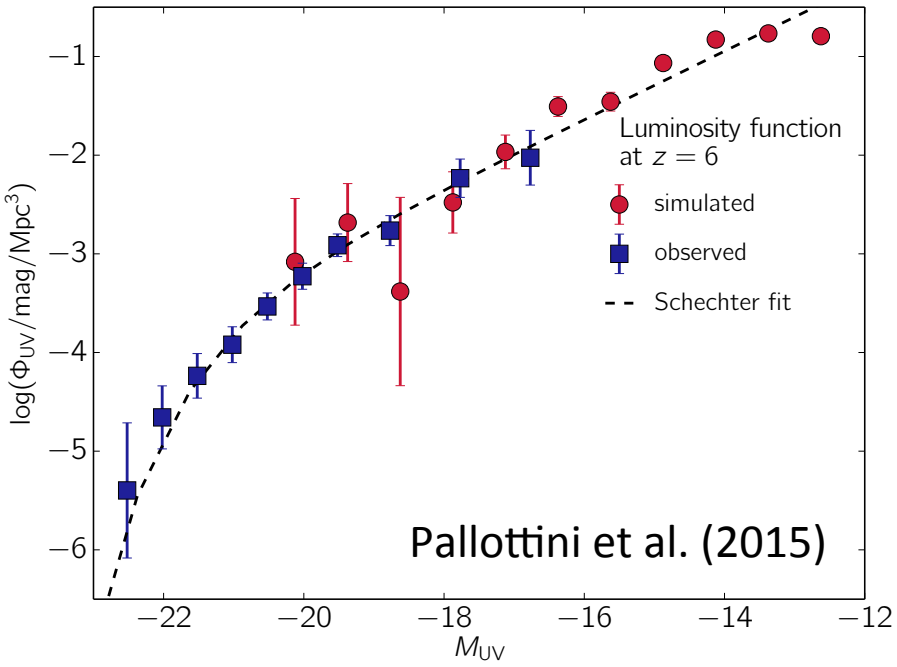
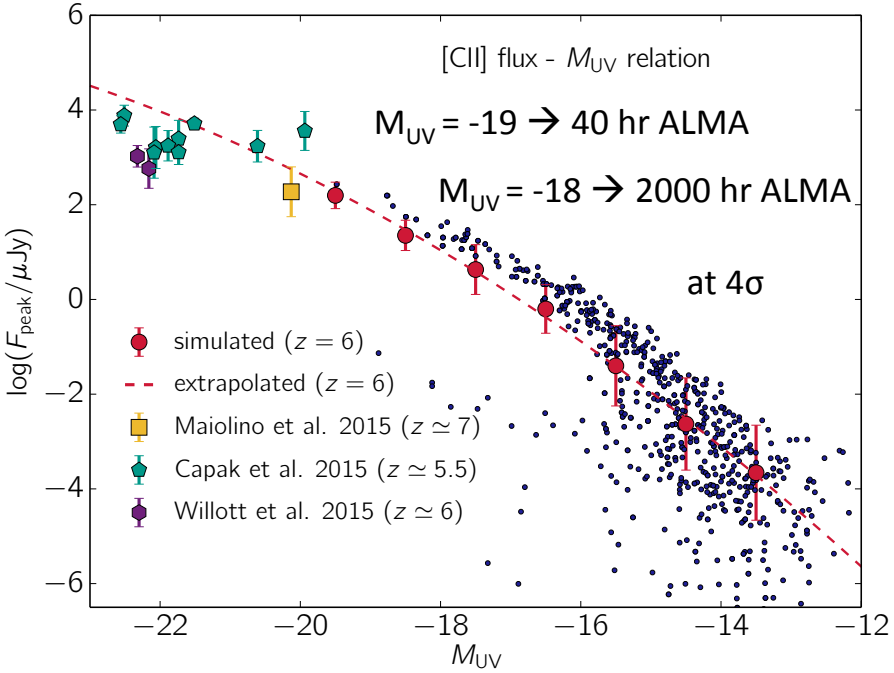


Good greement between simulations and [CII] observations

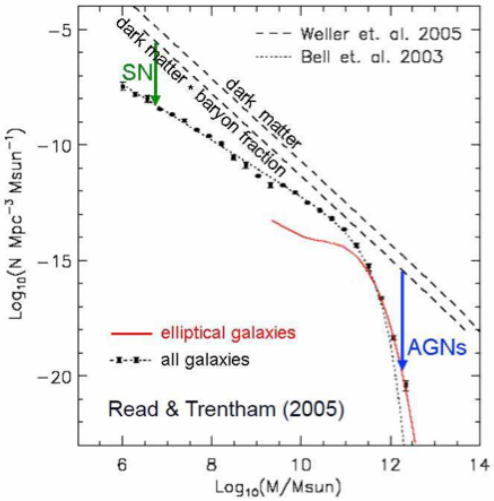


Challenging to detect reionization sources even with ALMA

… unless lensed galaxies

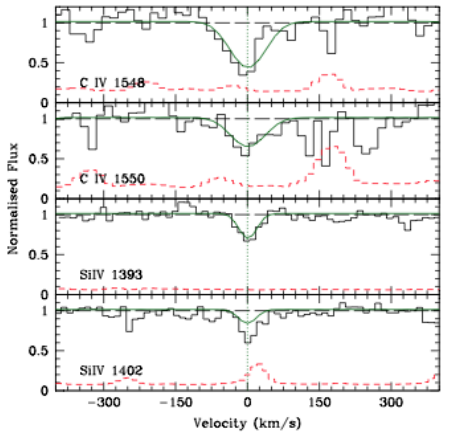
The importance of outflows in z ≈ 6 galaxies

Invoked by theoretical model to explain the discrepancy in the low-mass tail of the stellar mass function with the dark matter halo mass function



Outflows shape the galaxy star formation histories and can produce cavities in their interstellar medium that may allow ionizing photons to escape

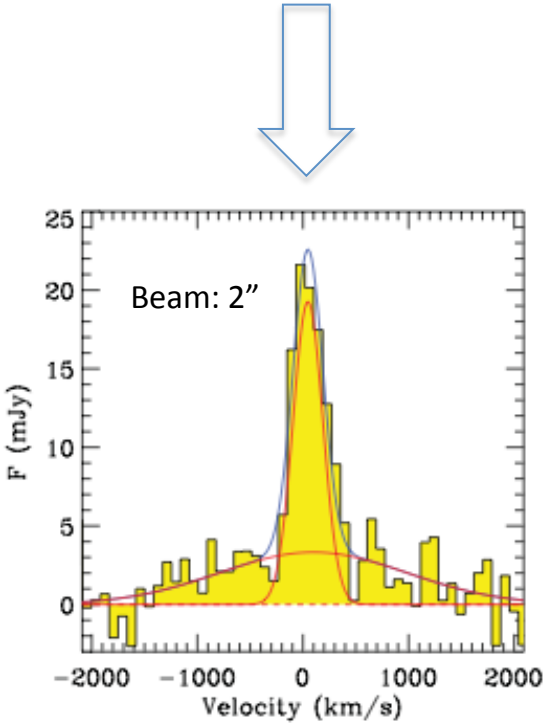
D'Odorico et al. (2013)



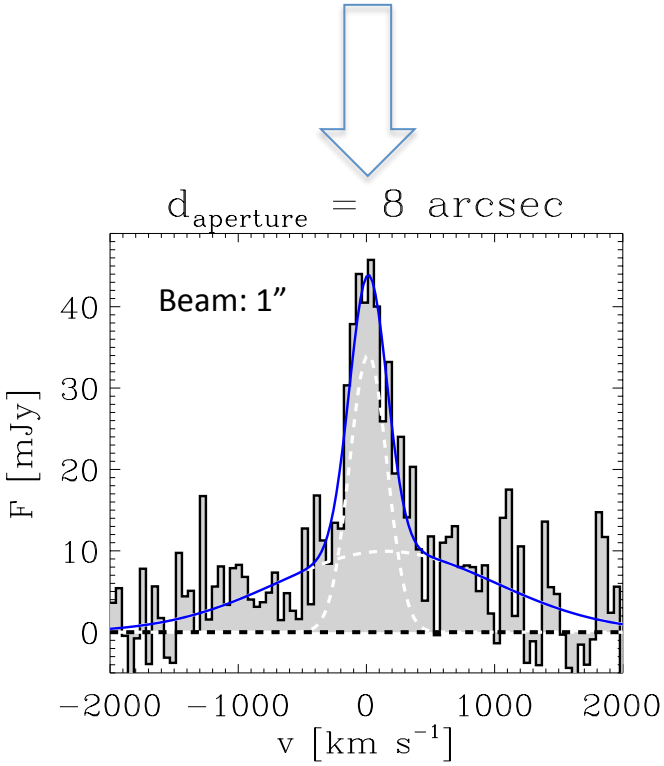
Quasar absorption studies show that the inter-galactic medium is enriched with metals up to z ≥ 6

Signatures of outflowing gas in z ≈ 6 quasars

Detection of broad wings in the [CII] line of a z=6.4 quasar



Maiolino et al. (2012)

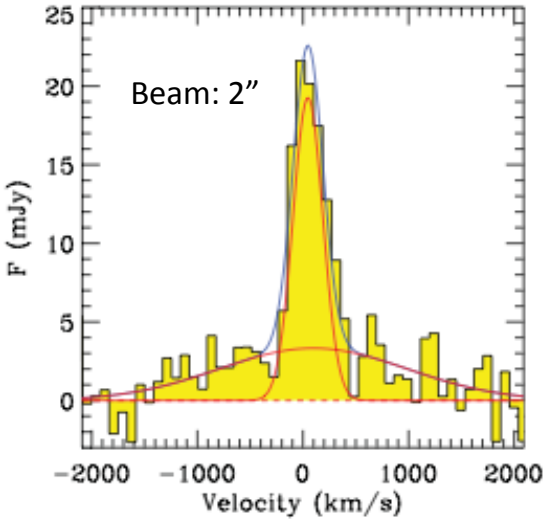


Cicone et al. (2015)

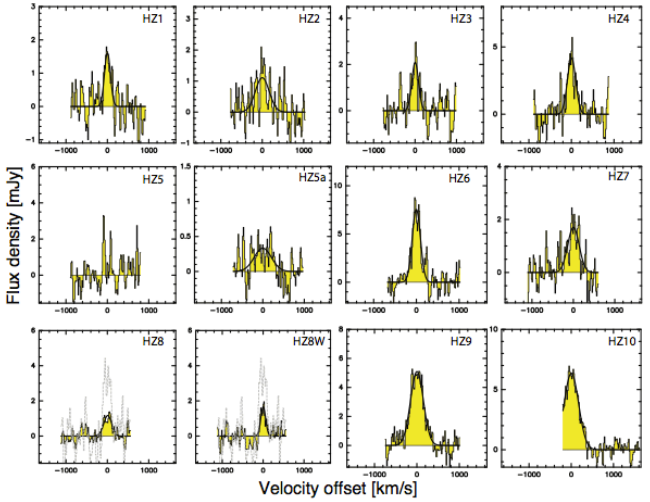
see also talk by Alberto Bolatto

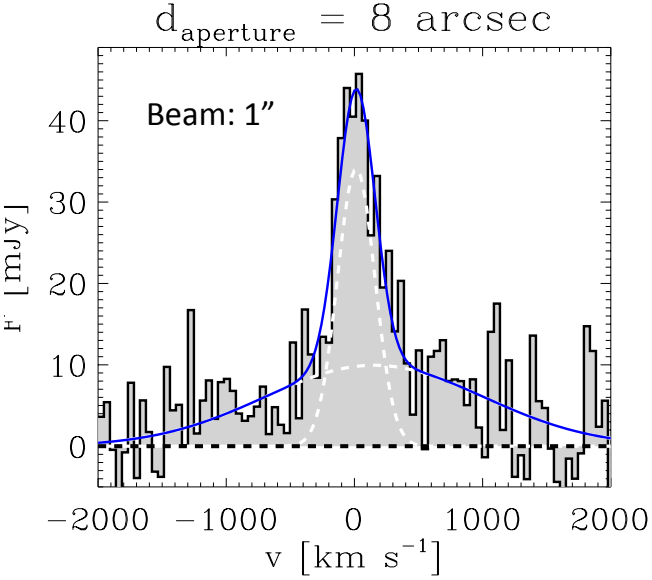
Signatures of outflowing gas in z ≈ 6 quasars

Are broad wings also present in [CII] lines of z≈6 galaxies?



Maiolino et al. (2012)

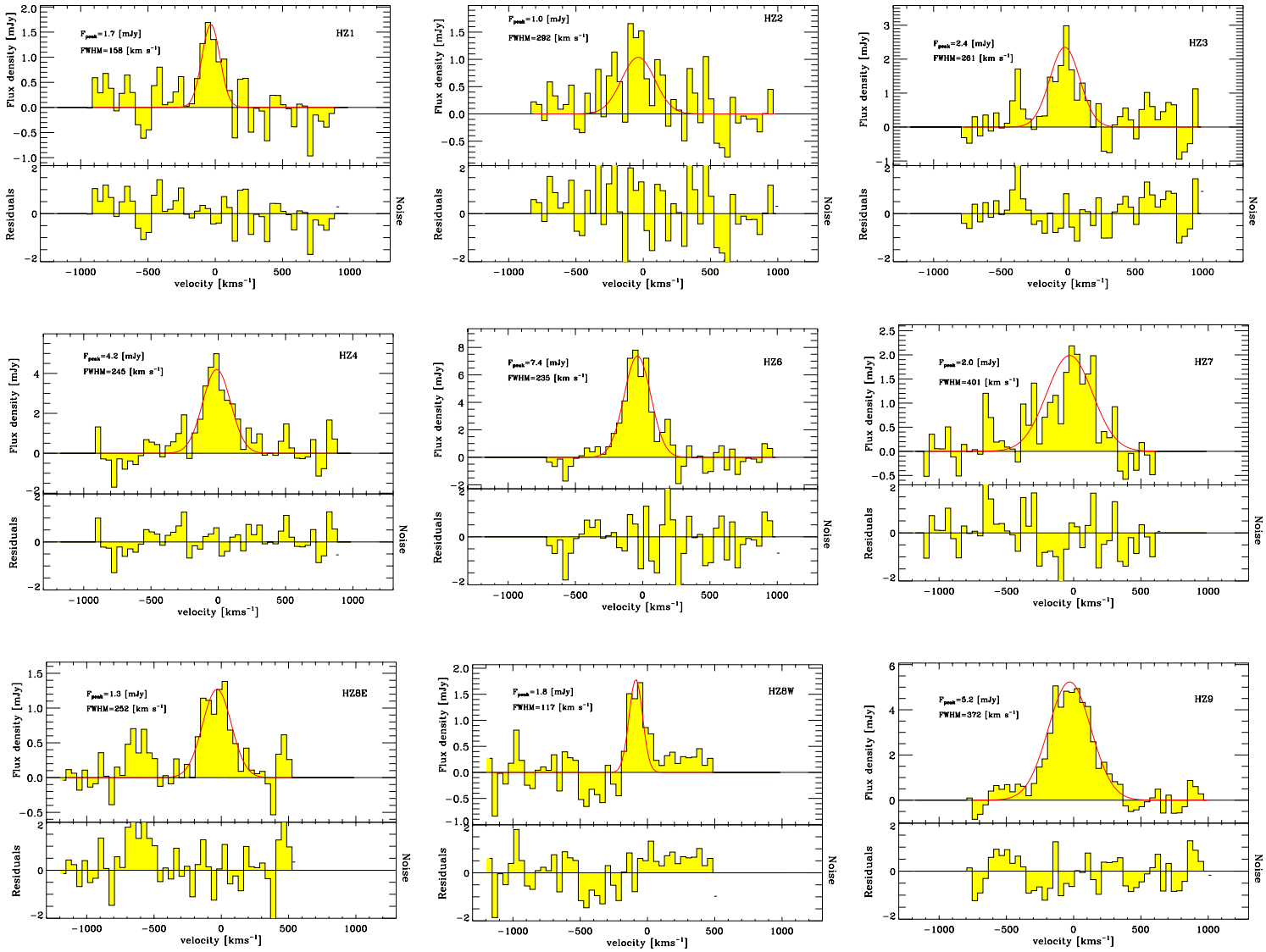




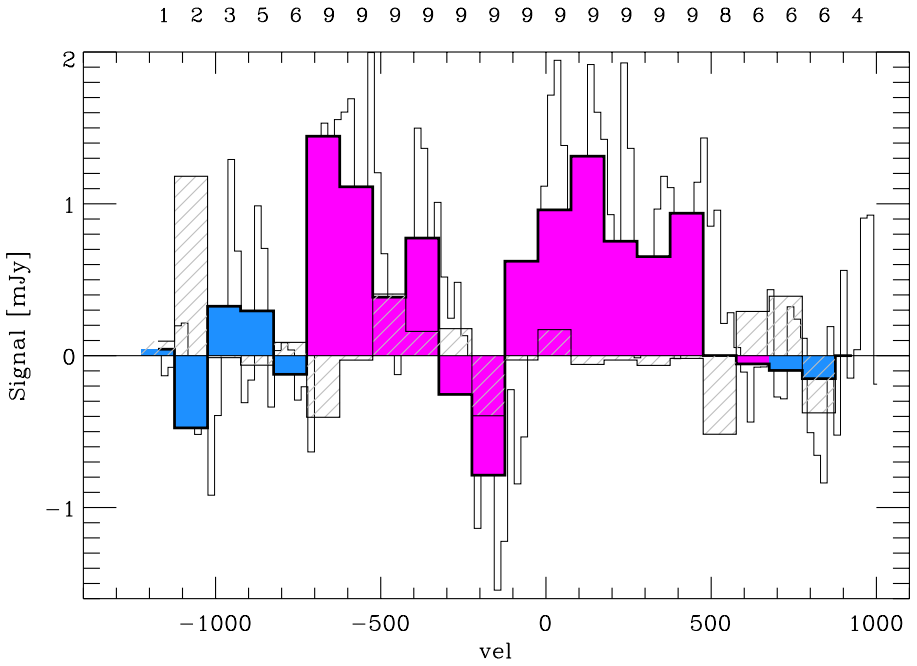
Cicone et al. (2015)

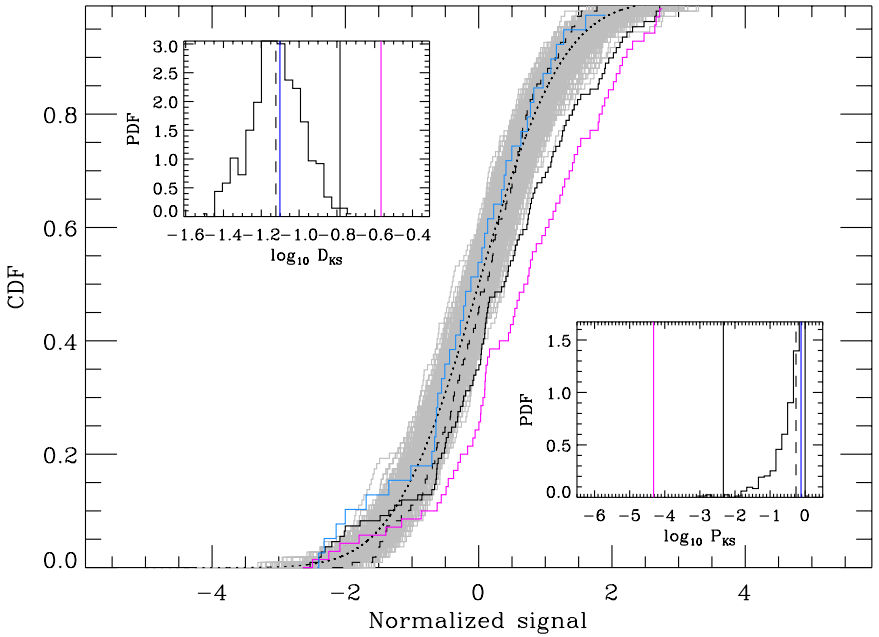
No evidence in single sources ⇒ **Stacking** of 9 galaxy spectra

Stacking the residuals of Capak et al (2015) galaxy spectra



Stacking the residuals of Capak et al (2015) galaxy spectra



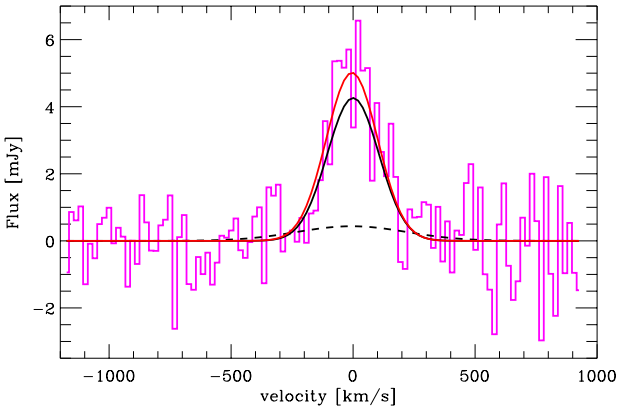


We *tentatively* detect (at ≈ 3σ) a **flux excess** in the stacked signal that **strongly deviates** from a **standard normal distribution**

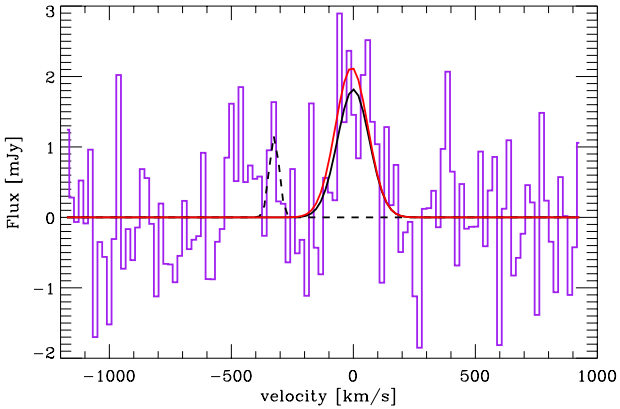
Is this the signature of outflowing gas we were looking for?

Galaxy emission line profiles

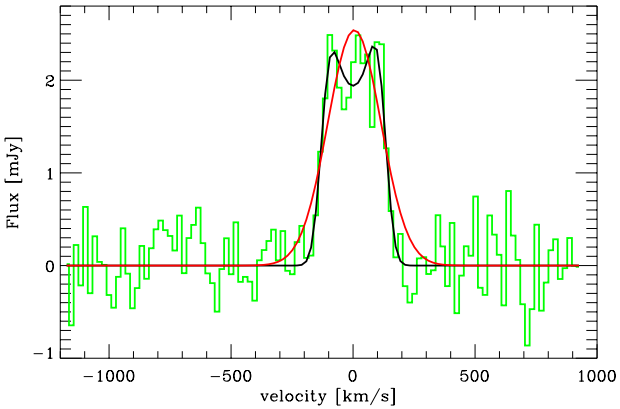
Double Gaussian profile

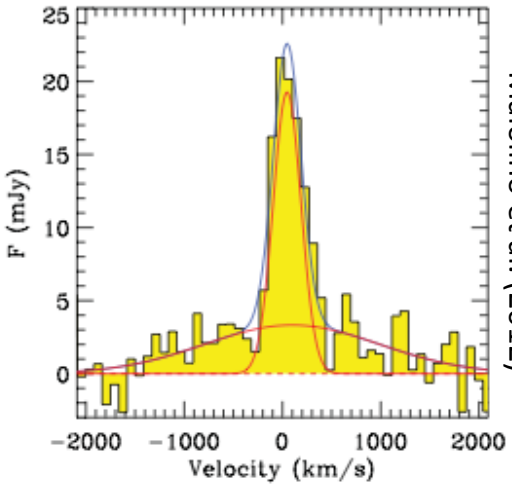


Gaussian profile + satellites

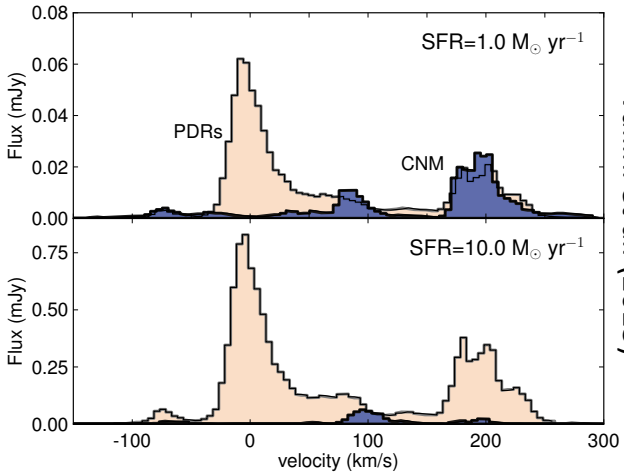


Double horn profile

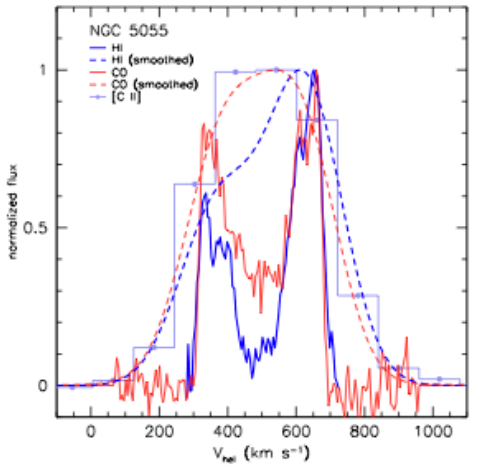




Maiolino et al. (2012)

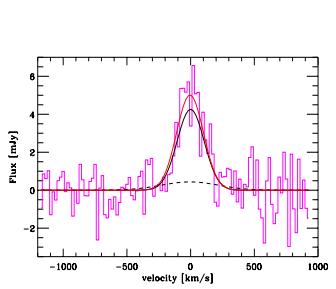


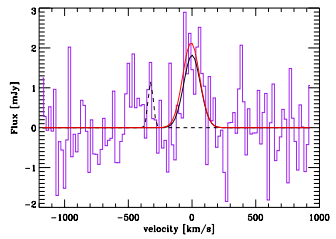
Vallini et al. (2015)

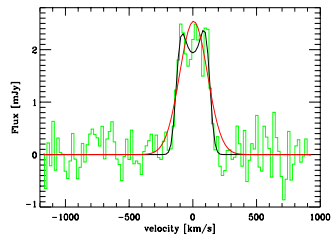


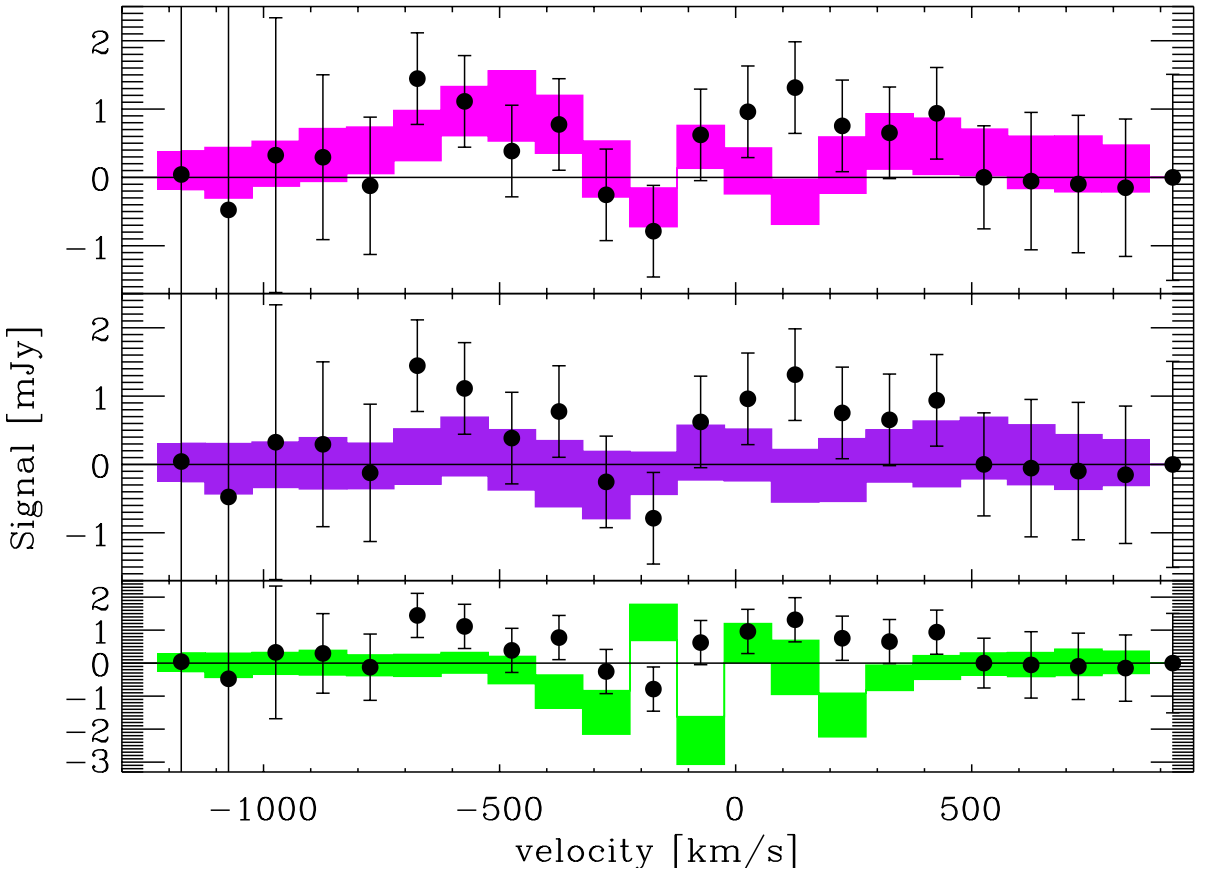
Deblok et al. (2016)

Evidence for outflows in z ≈ 6 galaxies with ALMA









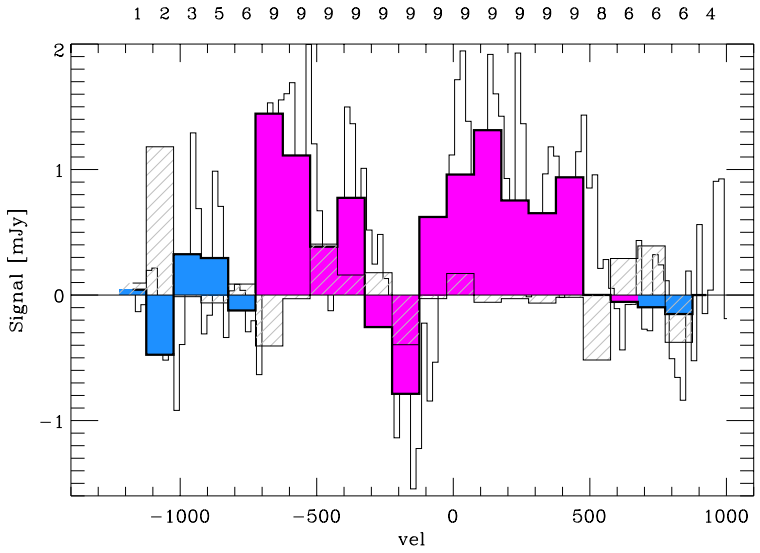
$\chi^2_{obs} = 12.6$
$n_{dof} = 17$
$P(\chi^2 > \chi^2_{obs}) = 0.8$

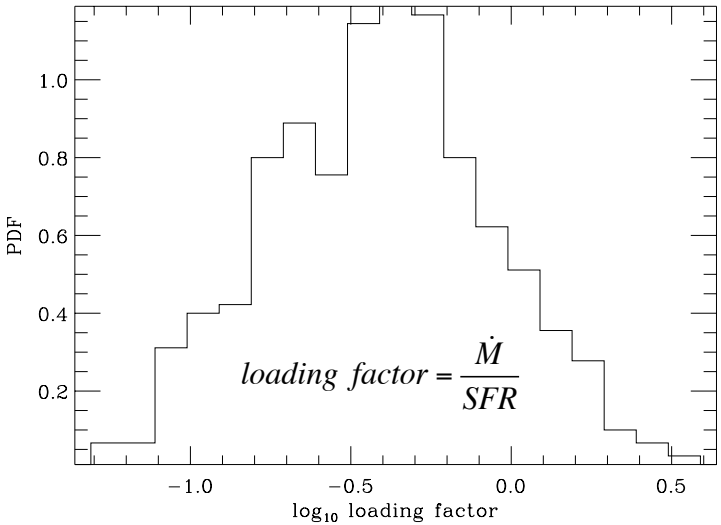
$\chi^2_{obs} = 16.5$
$n_{dof} = 16$
$P(\chi^2 > \chi^2_{obs}) = 0.4$

$\chi^2_{obs} = 69$
$n_{dof} = 18$
$P(\chi^2 > \chi^2_{obs}) < 10^{-4}$

The **double Gaussian** is the **favored profile** for the **observed [CII] emission lines**

Evidence for outflows in z ≈ 6 galaxies with ALMA





The flux excess we detect
is consistent with a loading factor ≈ 0.4

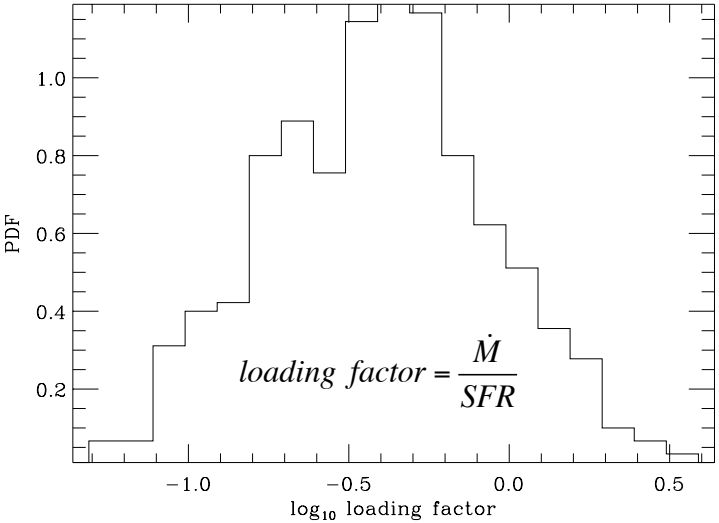
Comparison with z<0.2 starburst galaxies:

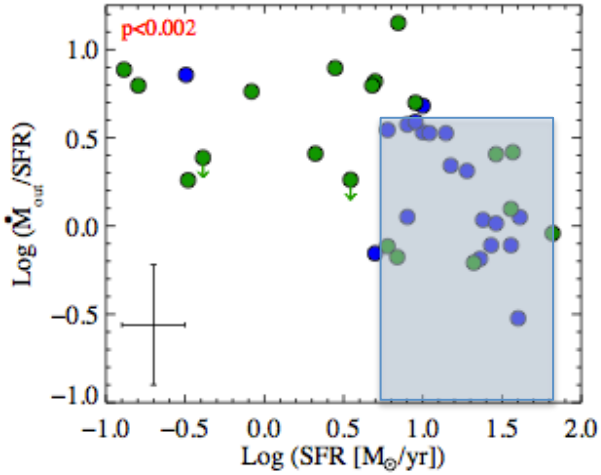
Properties of the Capak et al. (2015) sample

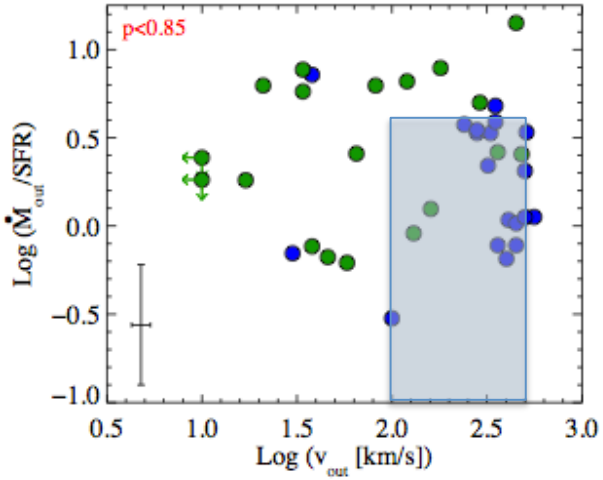
$$5 \le \frac{SFR}{[\dot{M}\ yr^{-1}]} \le 70$$

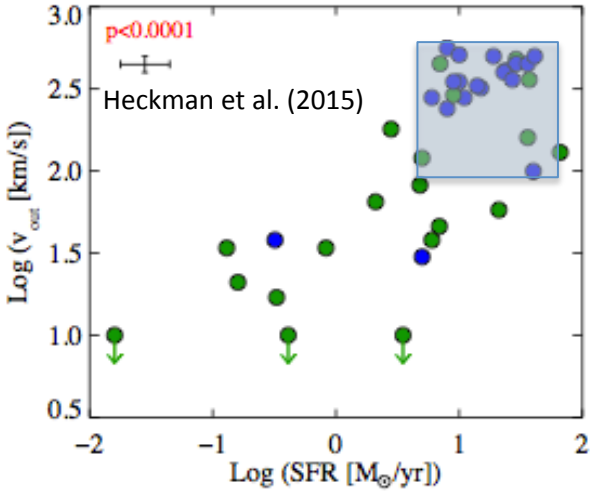
$$-1.3 \le \log_{10} \frac{\dot{M}}{SFR} \le 0.6$$

$$100 \le \frac{v_{outflow}}{[km\ s^{-1}]} \le 500$$





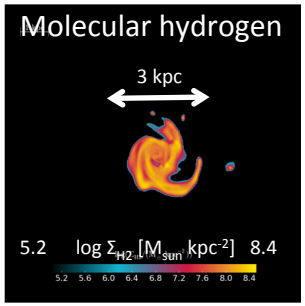




Dahlia (Pallottini et al. 2016)

AMR code (RAMSES)

$M_{DM} = 1.8 \times 10^{11}\ M_{sun}$
$M_{star} = 1.6 \times 10^{10}\ M_{sun}$
$M_{H2} = 3.6 \times 10^{8}\ M_{sun}$
$SFR = 100\ M_{sun}\ yr^{-1}$

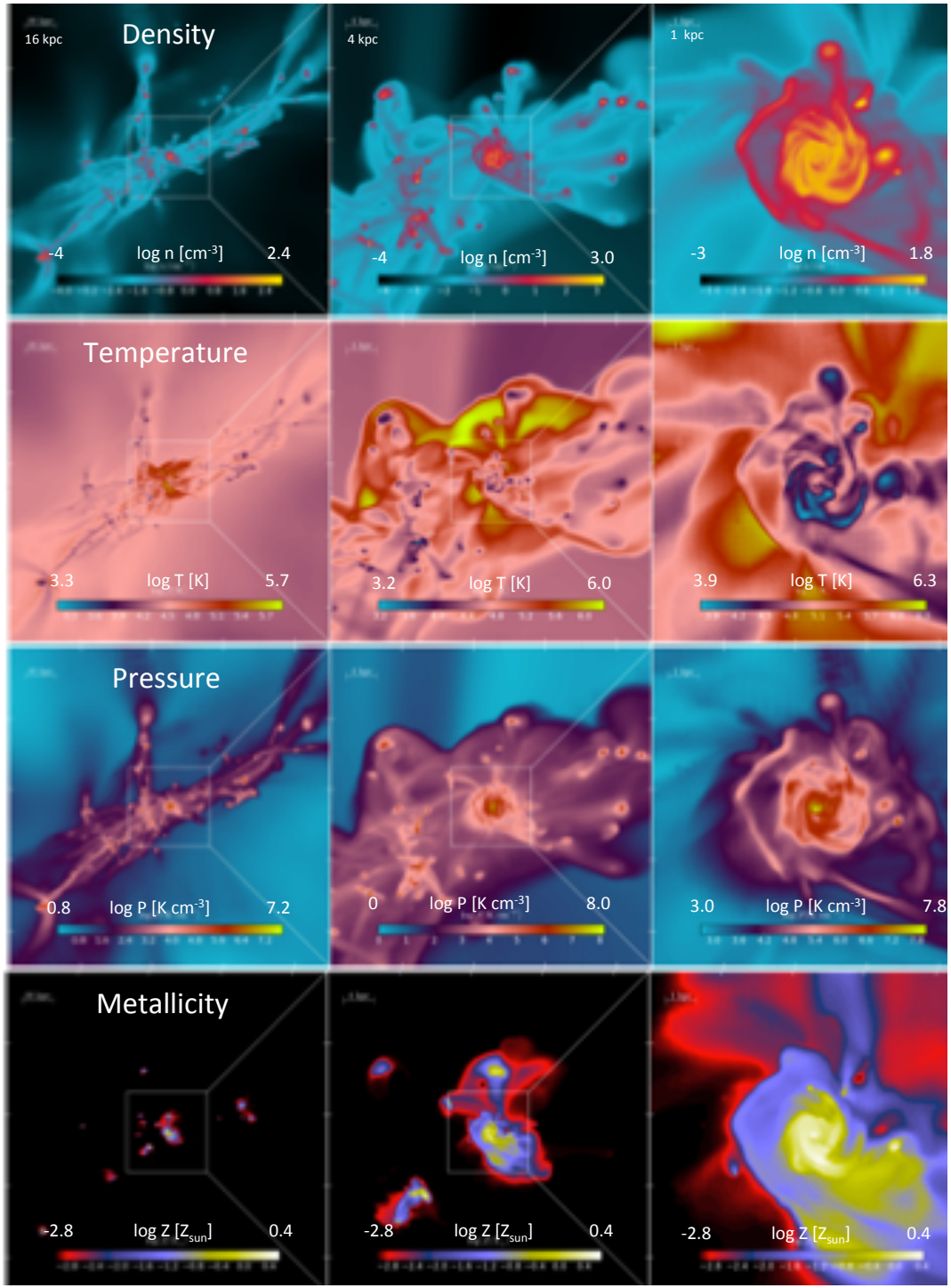


STAR FORMATION
H_2 dependent SK relation
(Krumholz et al. 2009)

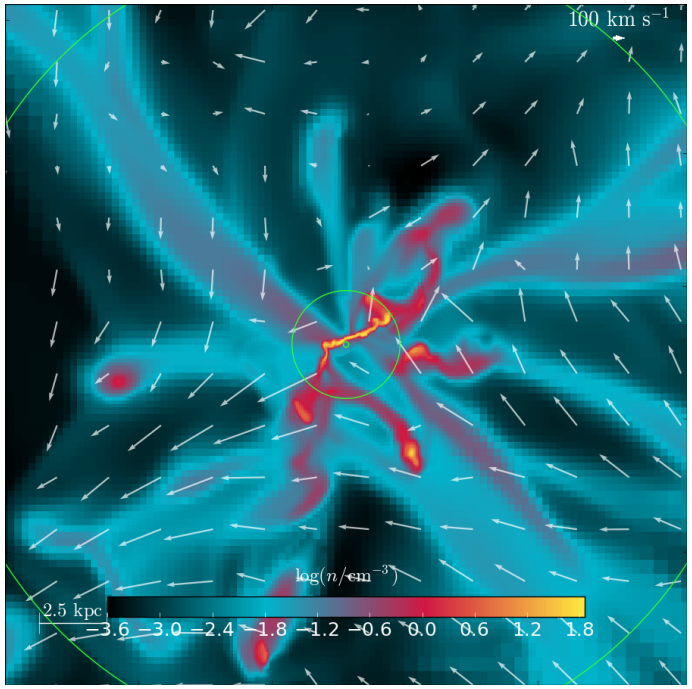
STELLAR FEEDBACK
- SN explosion: thermal and kinetic

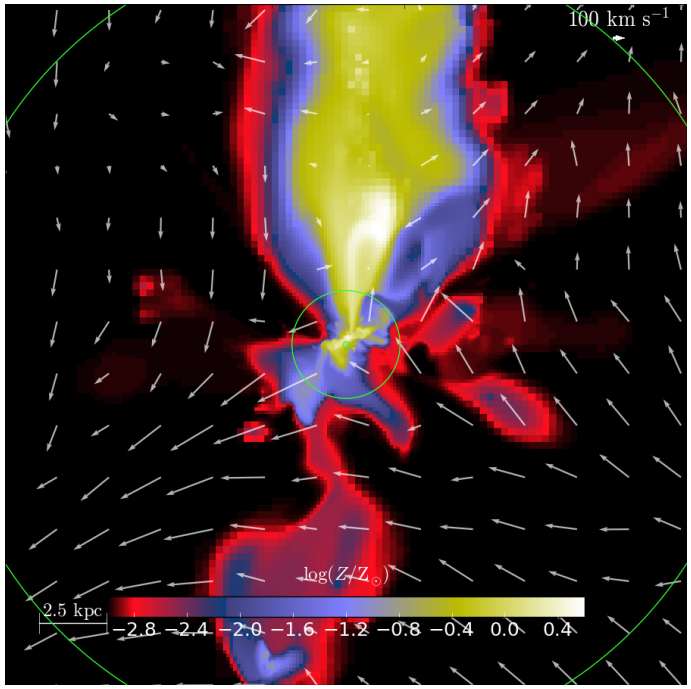
(blast-wave model by Ostriker & McKee)
- stellar wind
- radiation pressure

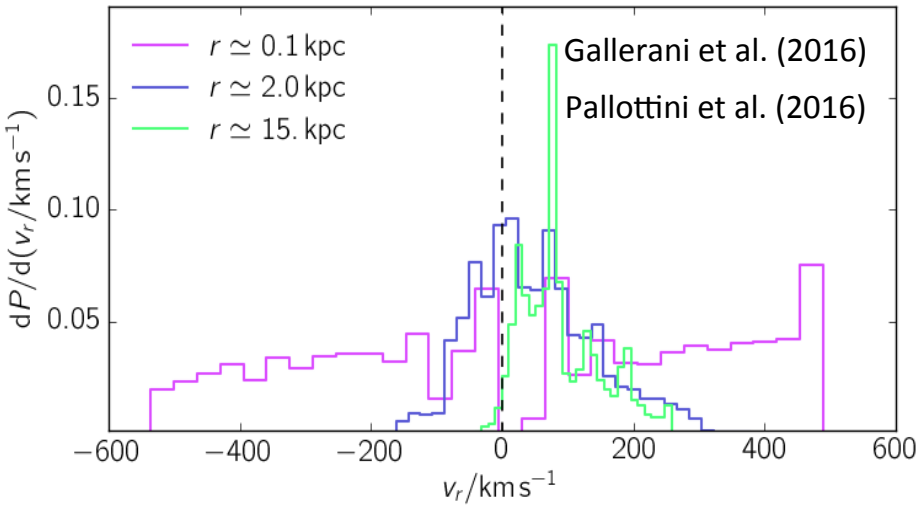
	L_{box} [Mpc h^{-1}]	M_{DM} [Msun h^{-1}]	Δx_{max} [kpc h^{-1}]	Δx_{min} [pc]
cosmo	20	3×10^7	78	-
zoom	2.1	7×10^4	10	32



Numerical simulations of a z ≈ 6 galaxy



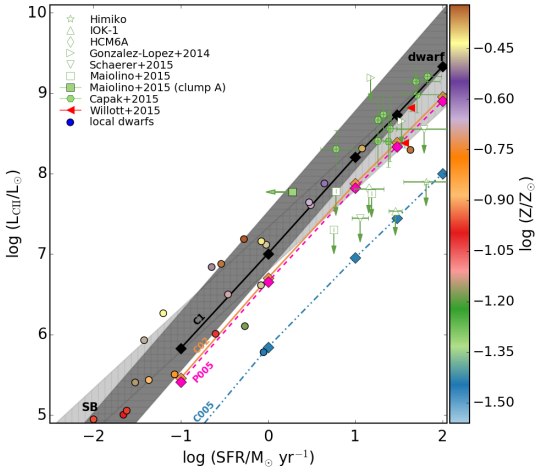




SUMMARY

The [CII] emission line is a promising tool for characterizing the ISM of high-z galaxies

No detection for Z < 0.2 Z_{sun} galaxies



Vallini et al. (2013-2015)

SUMMARY

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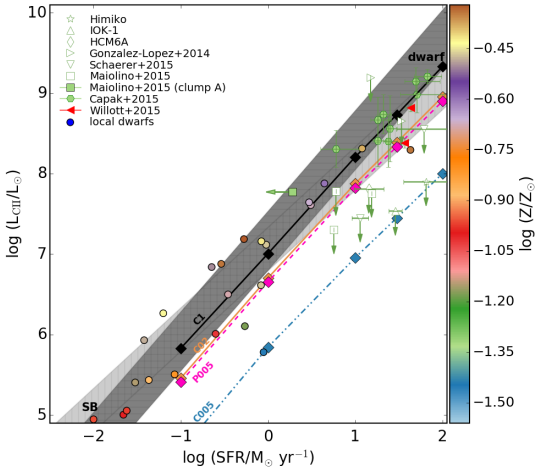
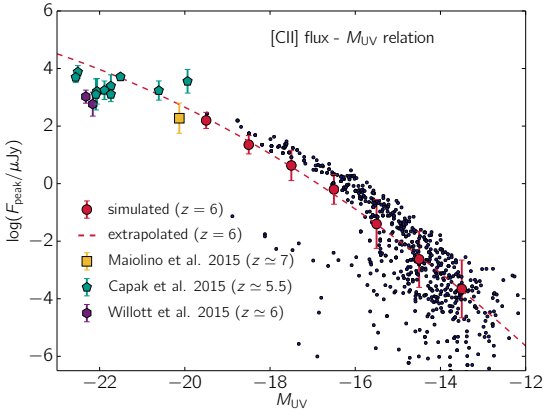


Vallini et al. (2013-2015)



Pallottini et al. (2014-2015)

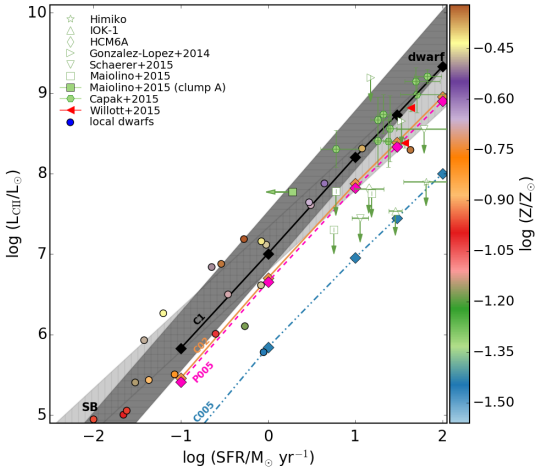
Detections of the [CII] line emitted by the sources of cosmic reionization are challenging even for ALMA (unless lensed)

M_{UV} = -19 → 40 hr ALMA **M_{UV} = -18 → 2000 hr ALMA**

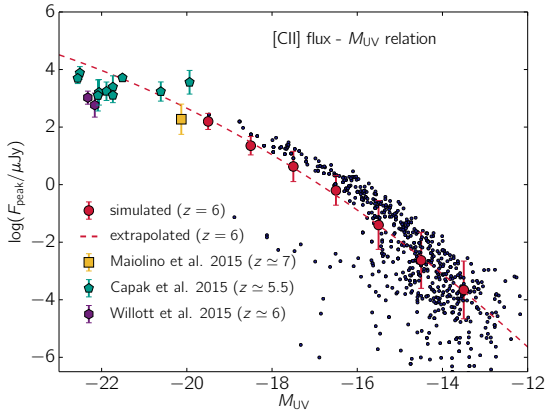
SUMMARY

The [CII] emission line is a promising tool for characterizing the ISM of high-z galaxies

No detection for Z < 0.2 Z_{sun} or MC photoevaporation



Vallini et al. (2013-2015)



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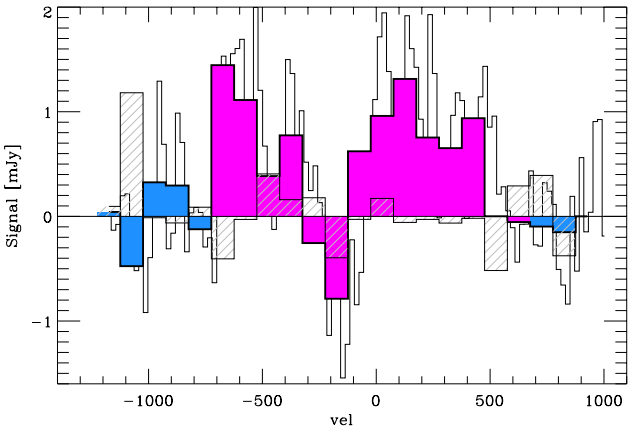
Detections of the [CII] line emitted by the sources of cosmic reionization are challenging even for ALMA (unless lensed)

M_{UV} = -19 → 40 hr ALMA

M_{UV} = -18 → 2000 hr ALMA

Tentative detection of outflowing gas from the [CII] emission line profile in a sample of z ≈ 6 galaxies

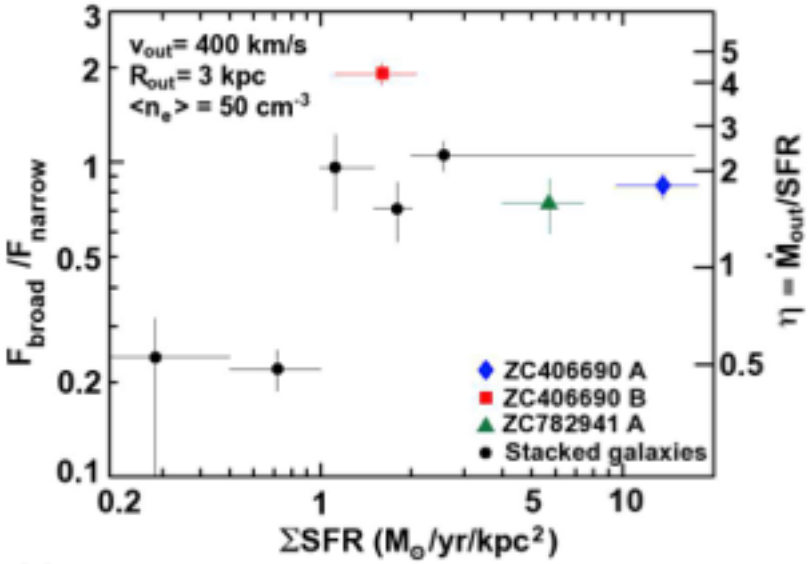
100 <$v_{outflow}$ < 500 [km/s]

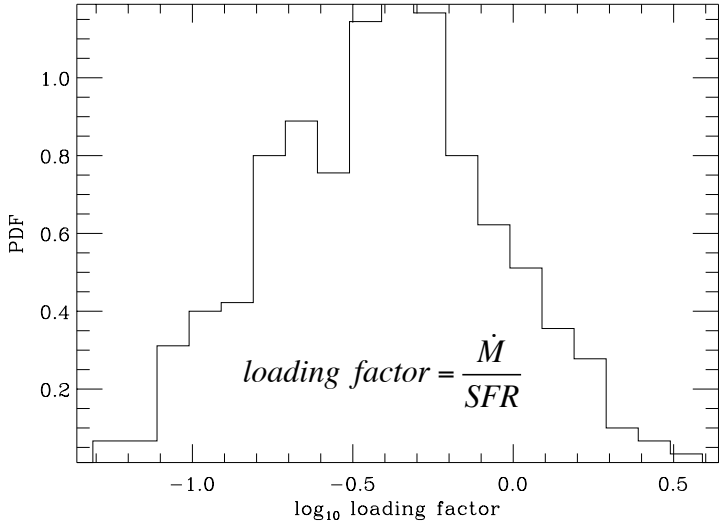


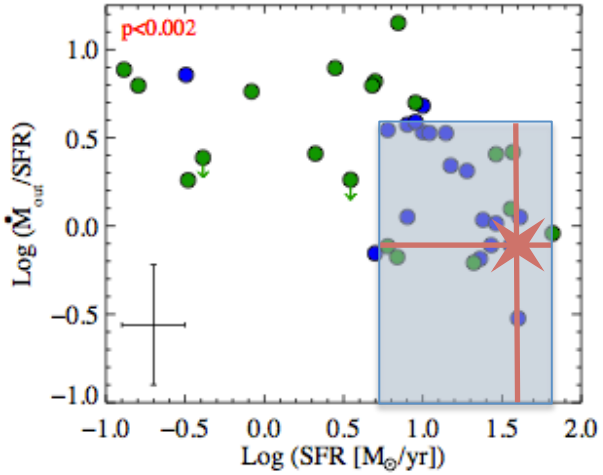
Gallerani et al. (2016)
Pallottini et al. ()2016

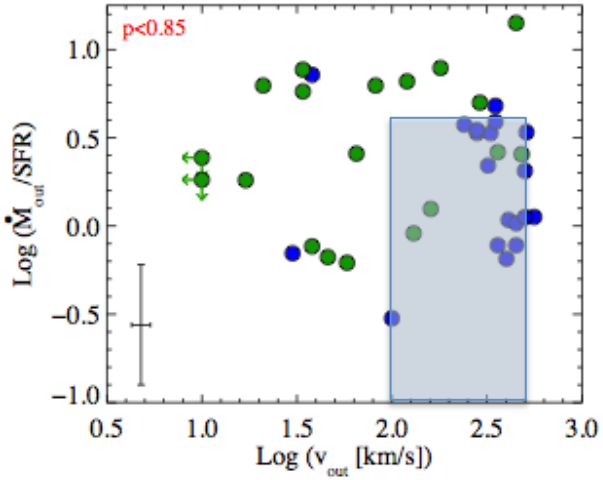
Comparison with z<0.2 starburst galaxies:

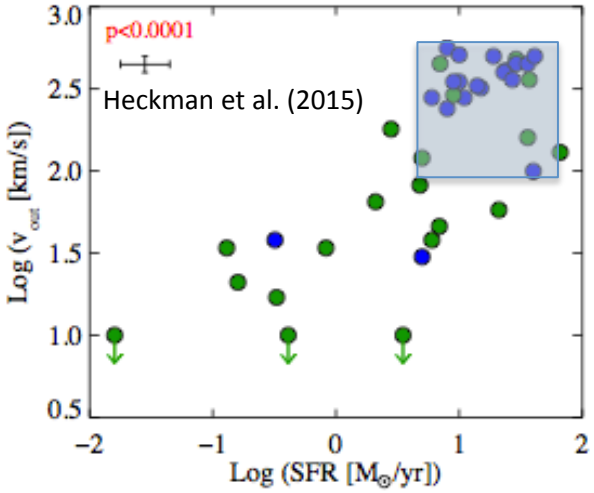
Newman, Genzel et al. 2012



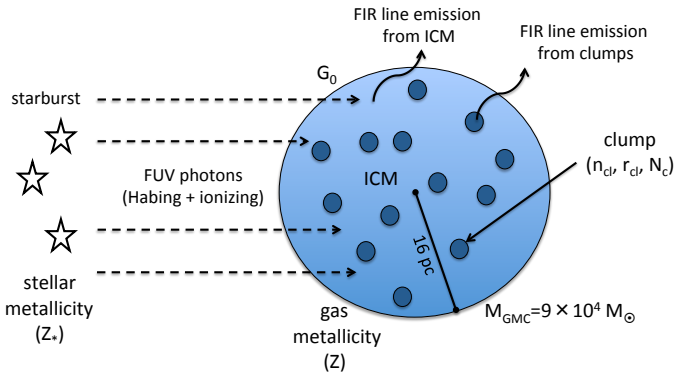




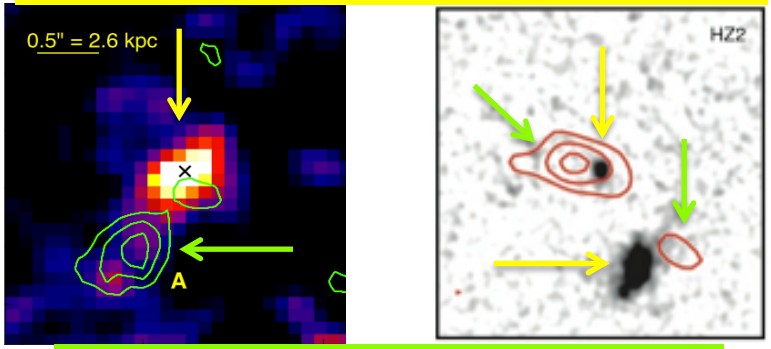




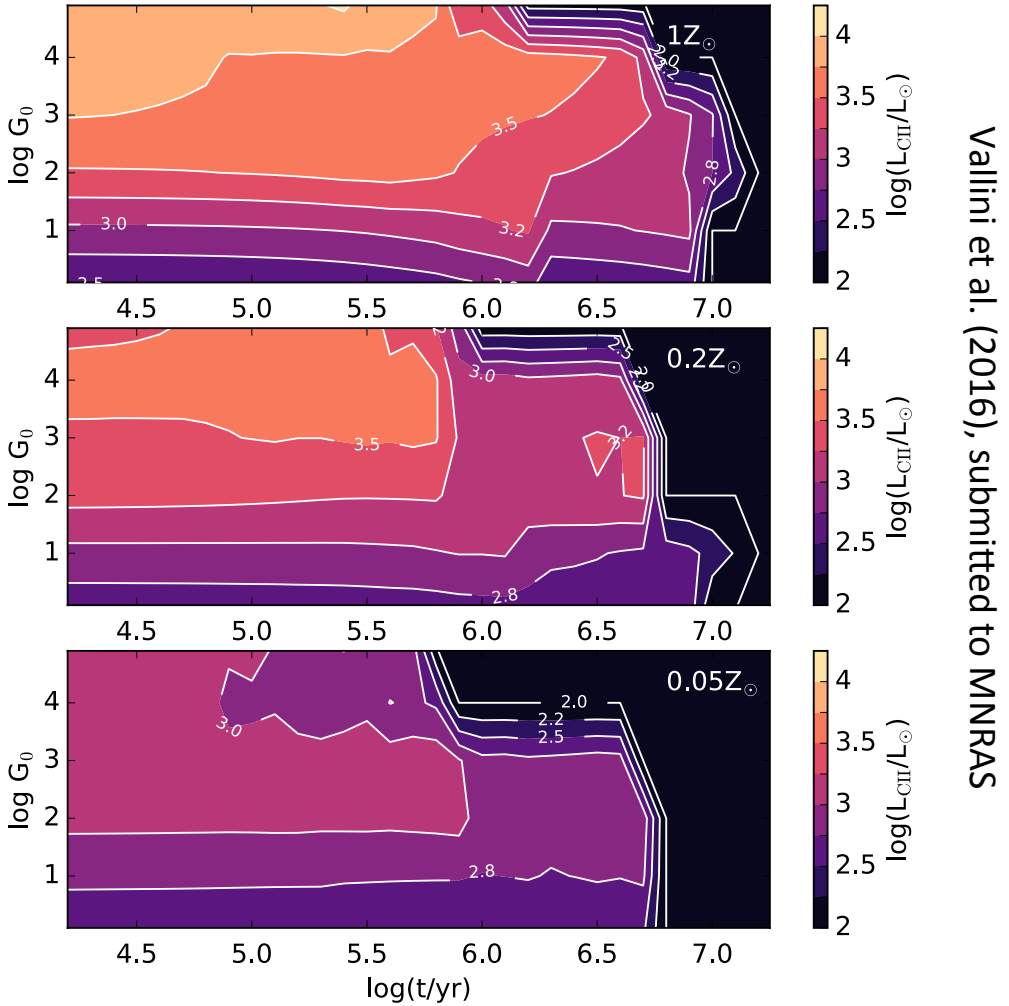
MC photo evaporation effects on the [CII] emission



Deficit of CII at the location of the UV emission



The CII *is detected* in the displaced clump



Vallini et al. (2016), submitted to MNRAS

The inclusion of MC photo evaporation strongly reduces [CII] emission possibly explaining no detections in some of the targeted z≈6 galaxies

Galaxy emission line profiles