High-z Galaxy Formation and Submm-to-IR emission

Ken NAGAMINE
(Osaka Univ.)

長峯健太郎
（大阪大学）

2014. 12. 3

Outline

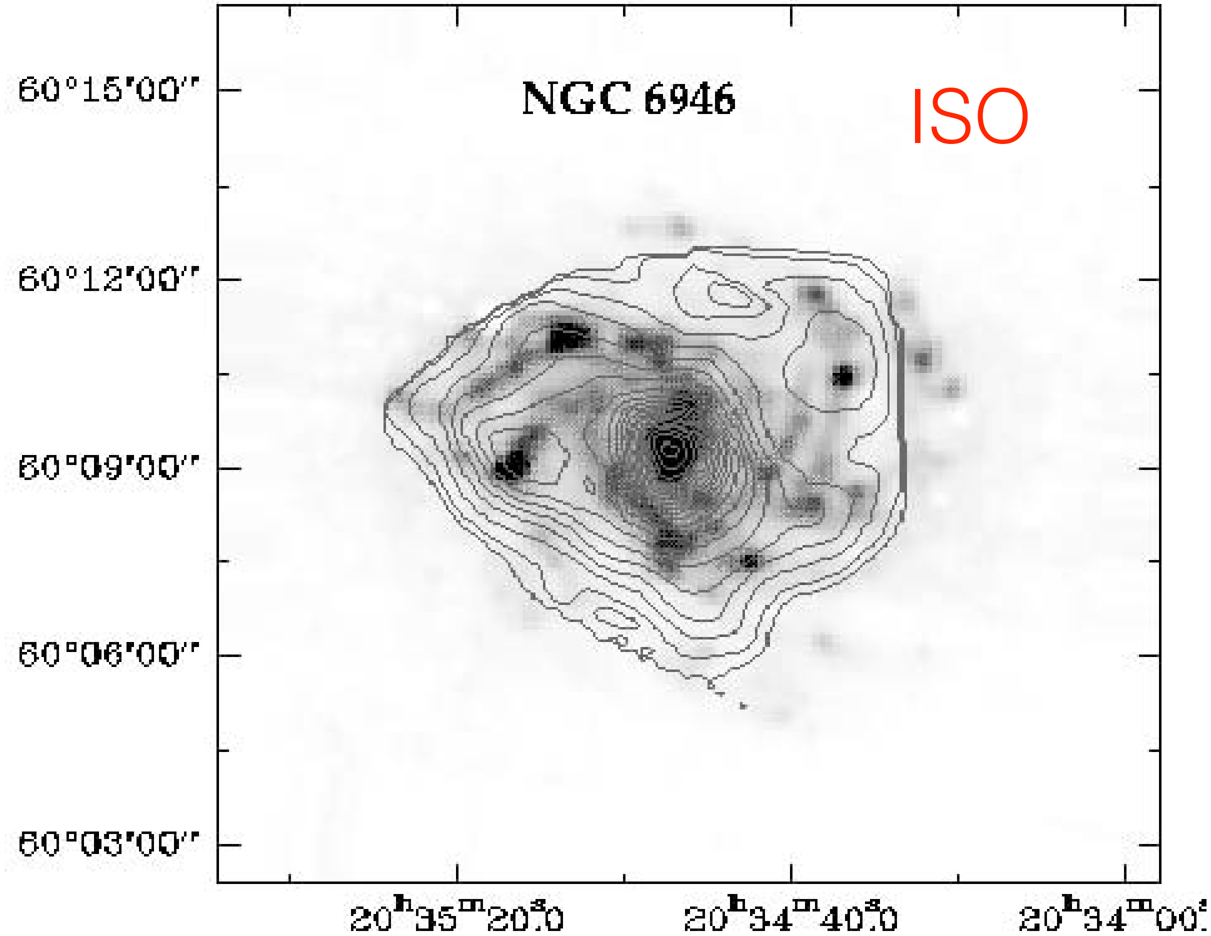
1. What can we study with FIR lines? —> **warm** & **cold** neutral gas (WNM & CNM)

2. How is cold ISM distributed in high-z gal?

3. Damped Lyα Systems (**DLAs**)
   - ★ DLA-LBG connection, feedback effects

4. Can we detect high-z DLA gas directly?
   - ★ **[C_{II}] 158 *μ*m** emission
   - ★ predictions for ALMA & Reaching z≳6

Local Galaxies in [C_{II}]



Contour: **[C_{II}] 158 μm line emission**
Image: 5-8 micron ISOCAM

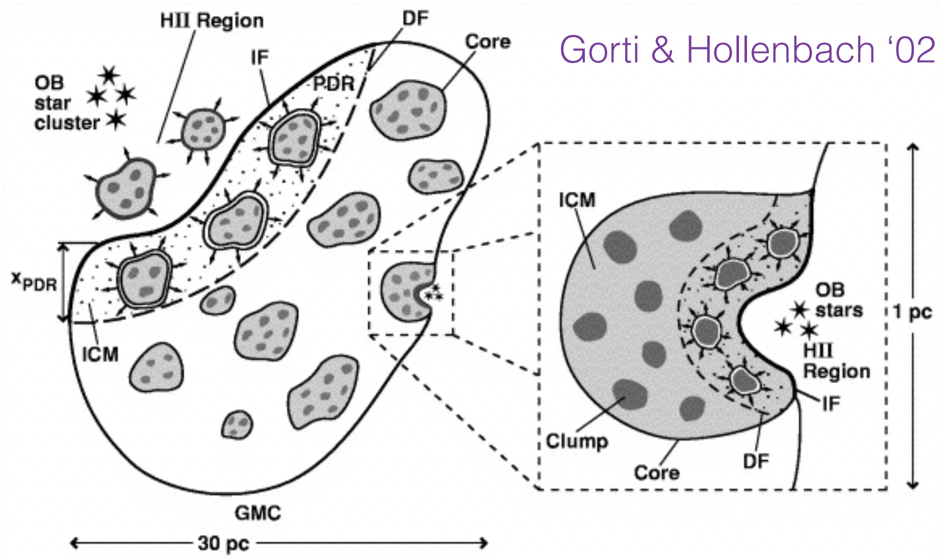
Contursi+ '02

- Dominant coolant of late-type gals.
- Neutral ISM in PDRs
- [Cii]: 1% of total FIR emission
- [Cii]: 40% in diffuse galactic disk

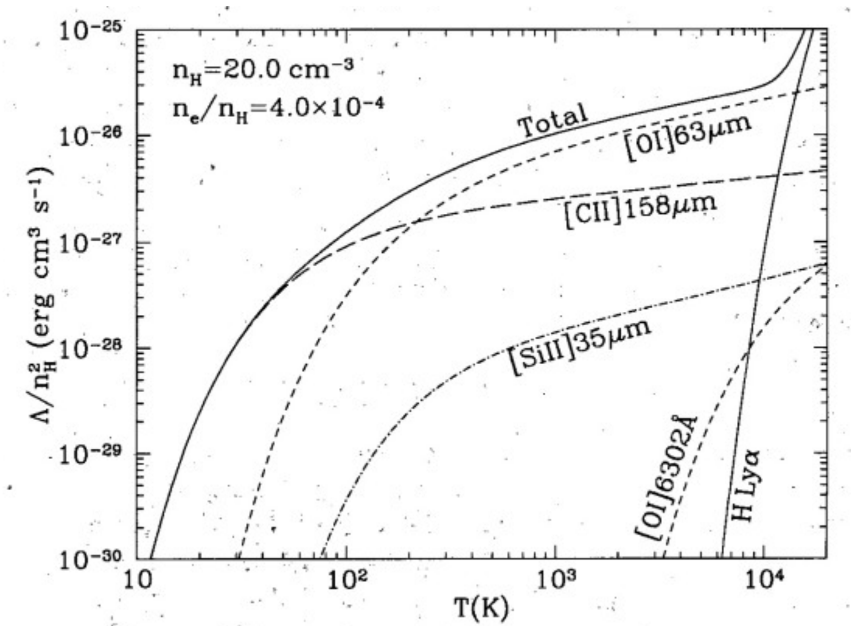
e.g., also
Madden+ '93
Malhotra+ '97, '01
Leech+ '99

PDRs (photo-dissociation regions)

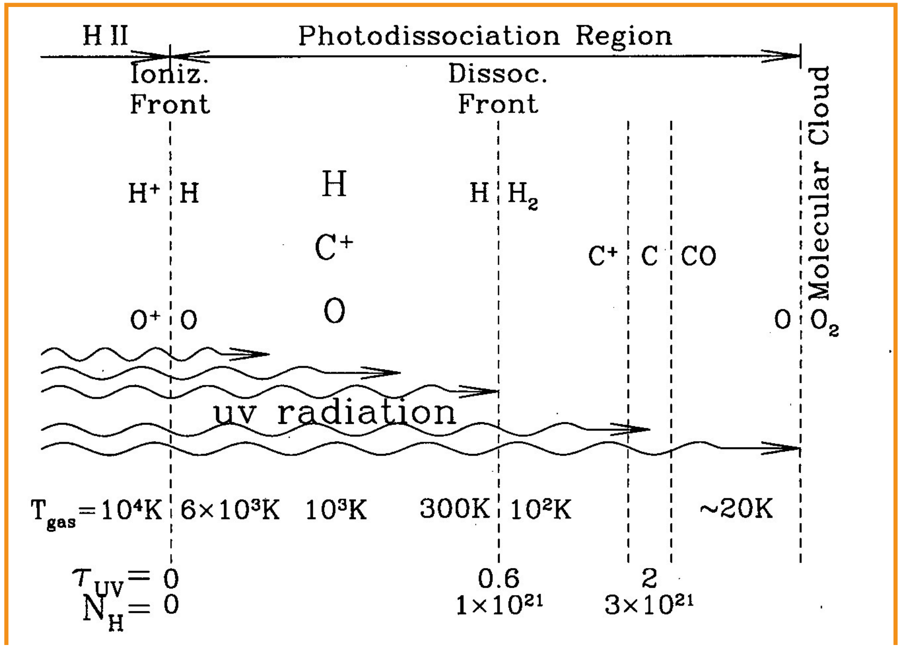
- **R**egions in which the chemical and heating processes are dominated or induced by interaction with FUV photons
- [O i] 63μm and [C ii] 158μm emission from the neutral ISM arises in PDRs



Gorti & Hollenbach '02

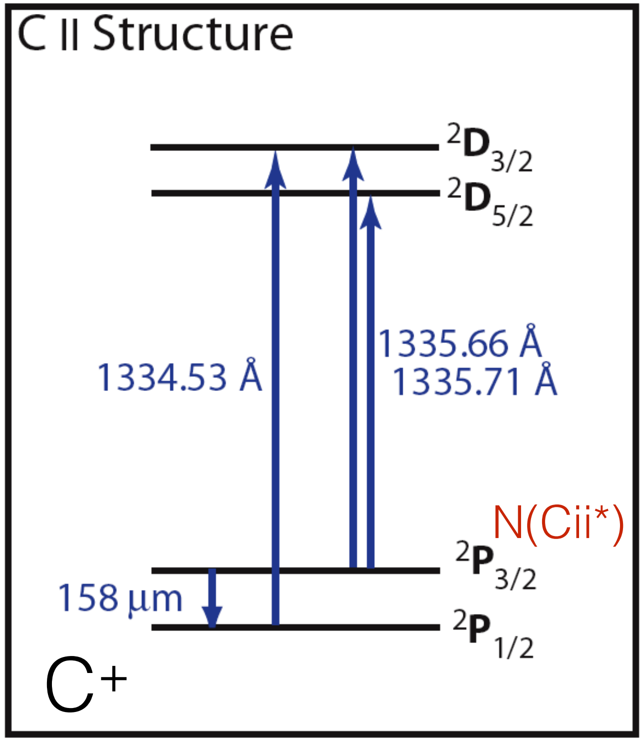


Draine book



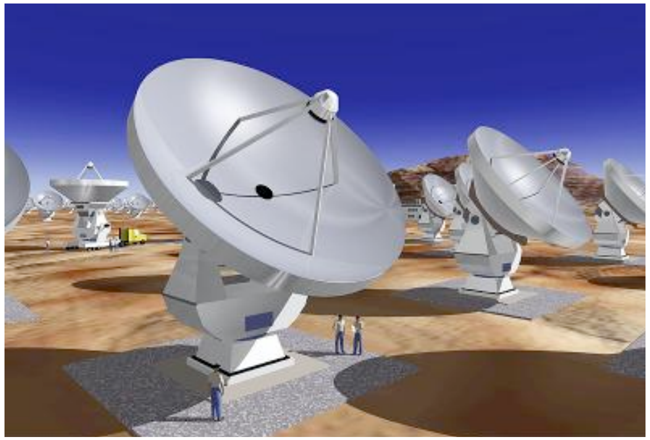
Why [CII]?

- Dominant coolant of MW-like late-type gals.
- Complementary to opt-IR (cf. LBG@z~3)
- A new window for high-z SF using DLAs
  —> use [Cii] to infer SFR
- Cosmological galaxy formation study with ALMA

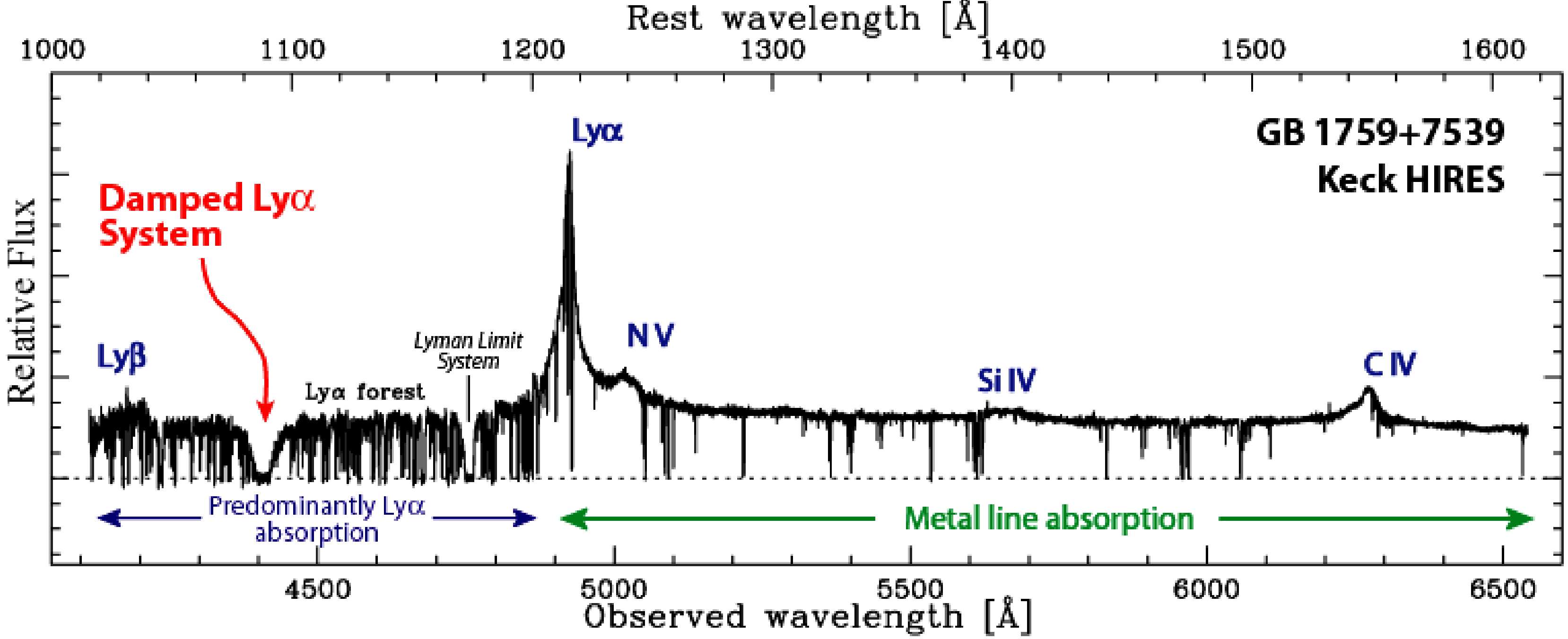


$$n\Lambda_{[CII]} \sim \frac{N(\mathrm{CII}^*)}{N(\mathrm{HI})} h\nu_{21} A_{21}$$

(Pottasch+'79; Wolfe+ '03)



DLAs:

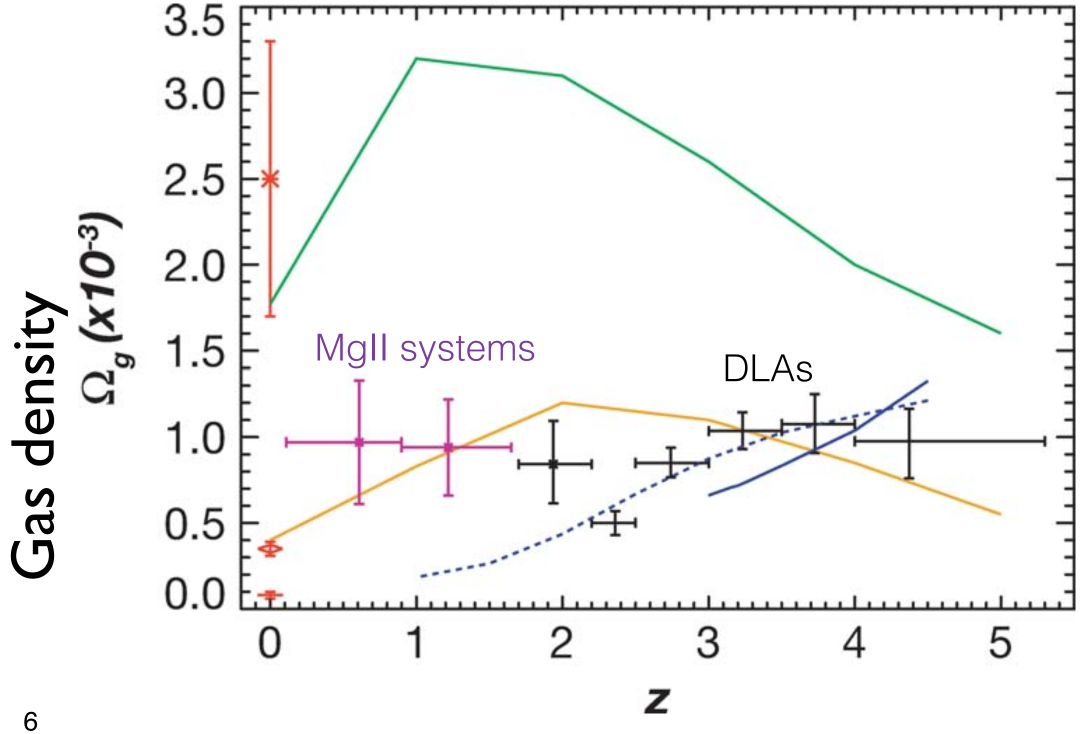


quasar

$$N_{\rm HI} > 2 \times 10^{20}\ {\rm cm}^{-2}$$

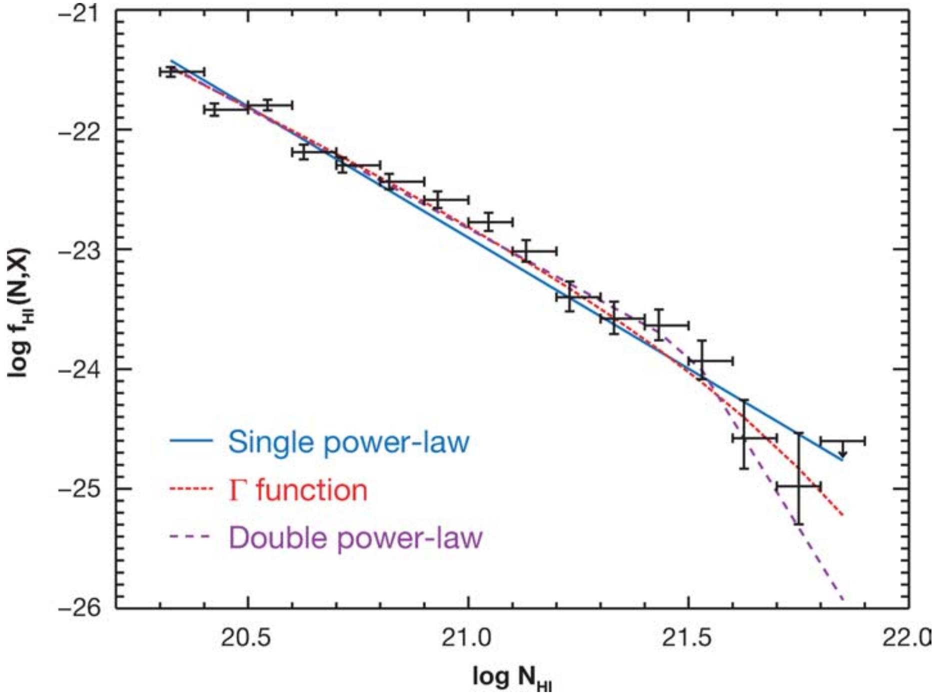
DLAs dominate Hi mass density at z~3

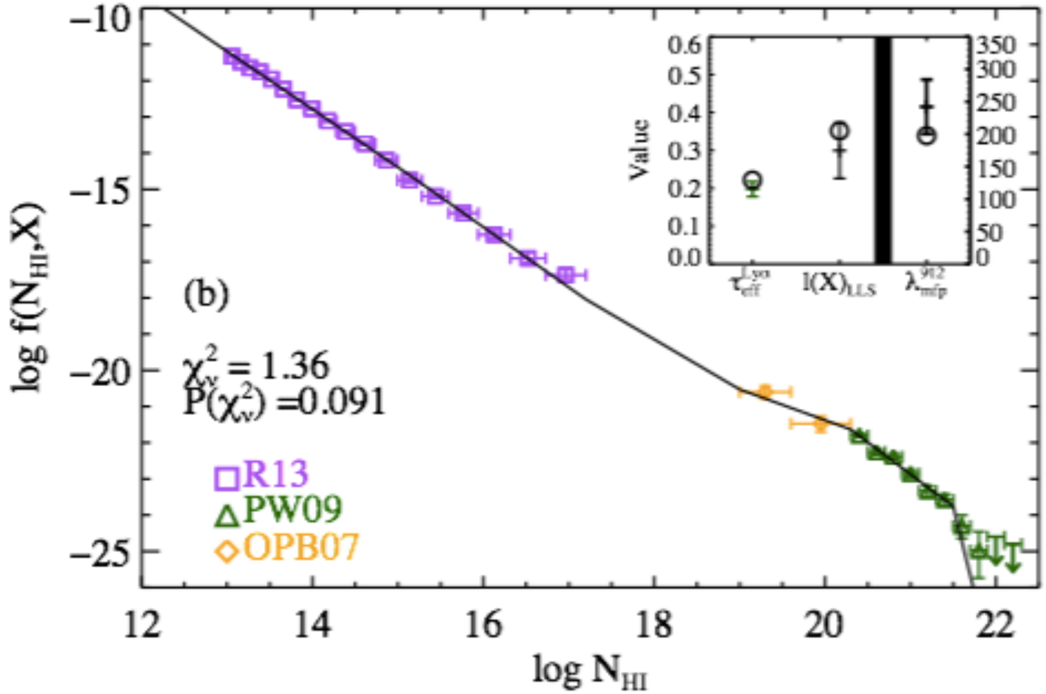
Lanzetta et al. '95
Storrie-Lombardi & Wolfe '00



DLA Statistics

HI column density distribution



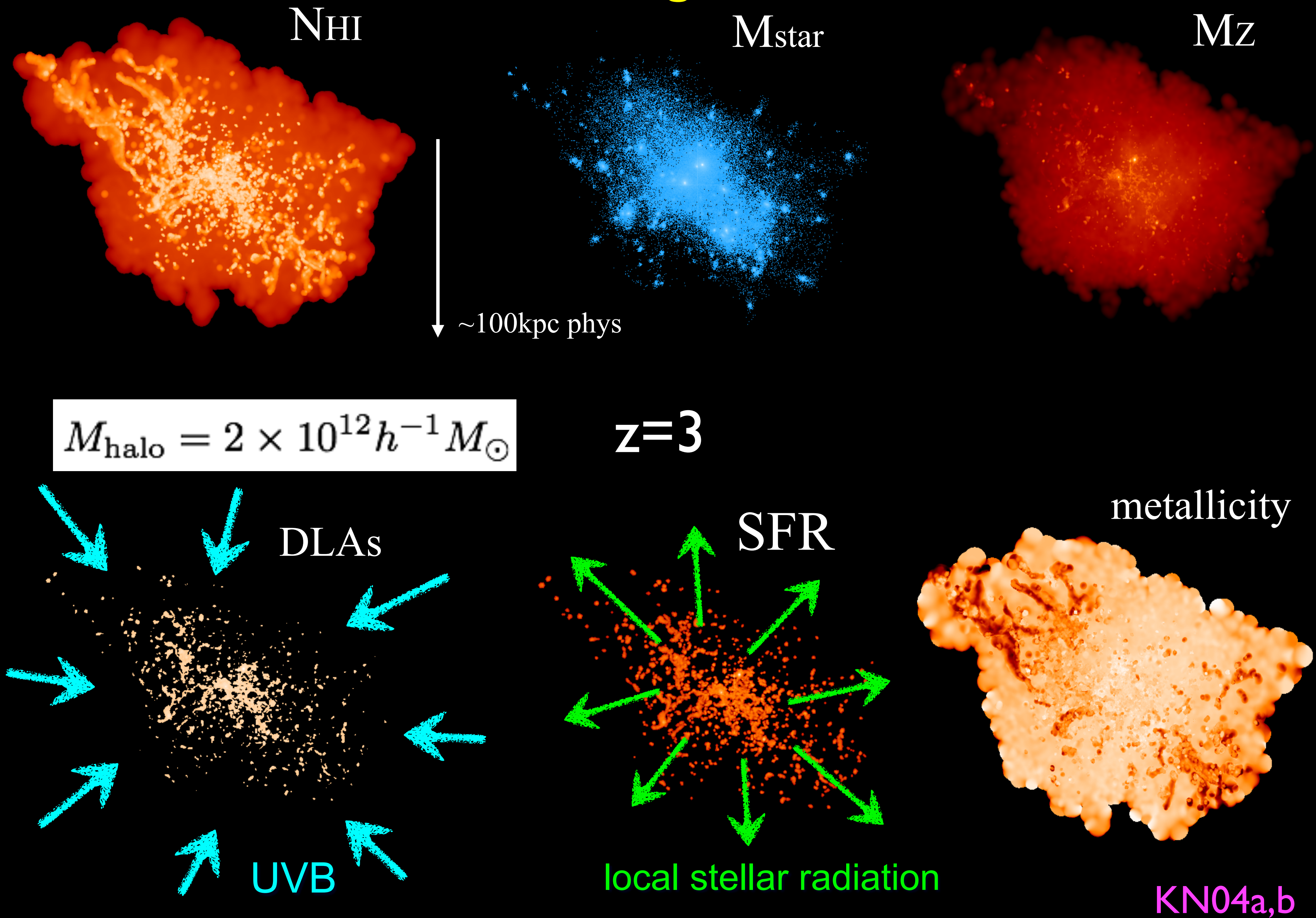


Prochaska+ '05 SDSS DR3
>500 DLAs
Wolfe+ '05 ARA&A

Prochaska+'14

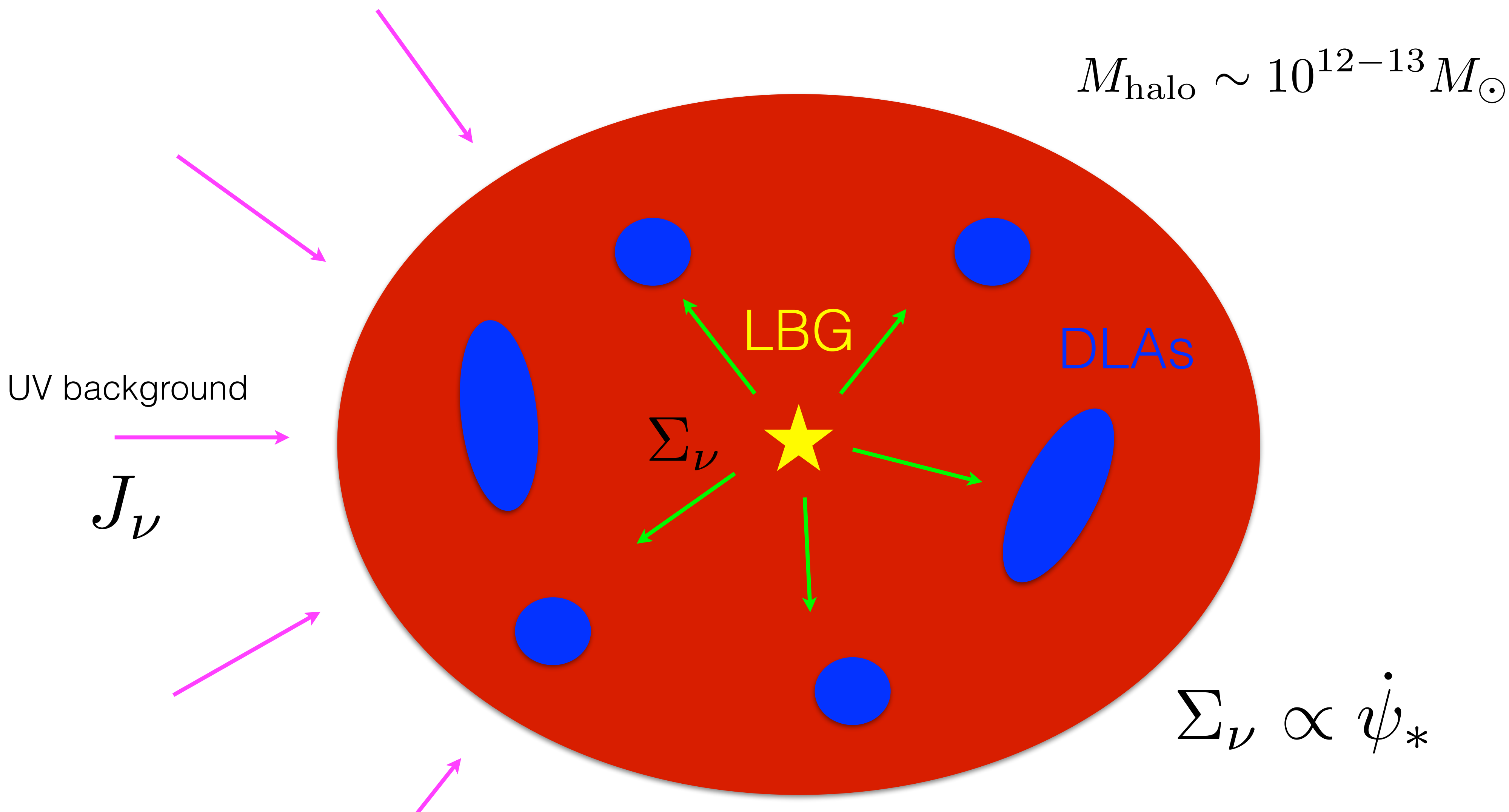
Strong constraint for structure formation sims

DLAs in Cosmological Simulations



The `New' Picture of DLAs @ high-z

(vs. the `old' picture of simple massive galactic disk)

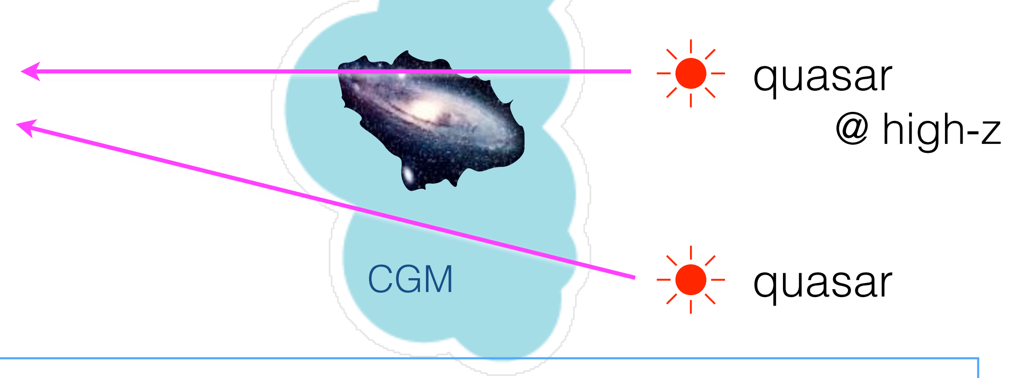


(cf. Brisbin+'14)

(cf. solves Z-problem too.)

Rubin+ ‘14

(Hennawi+)

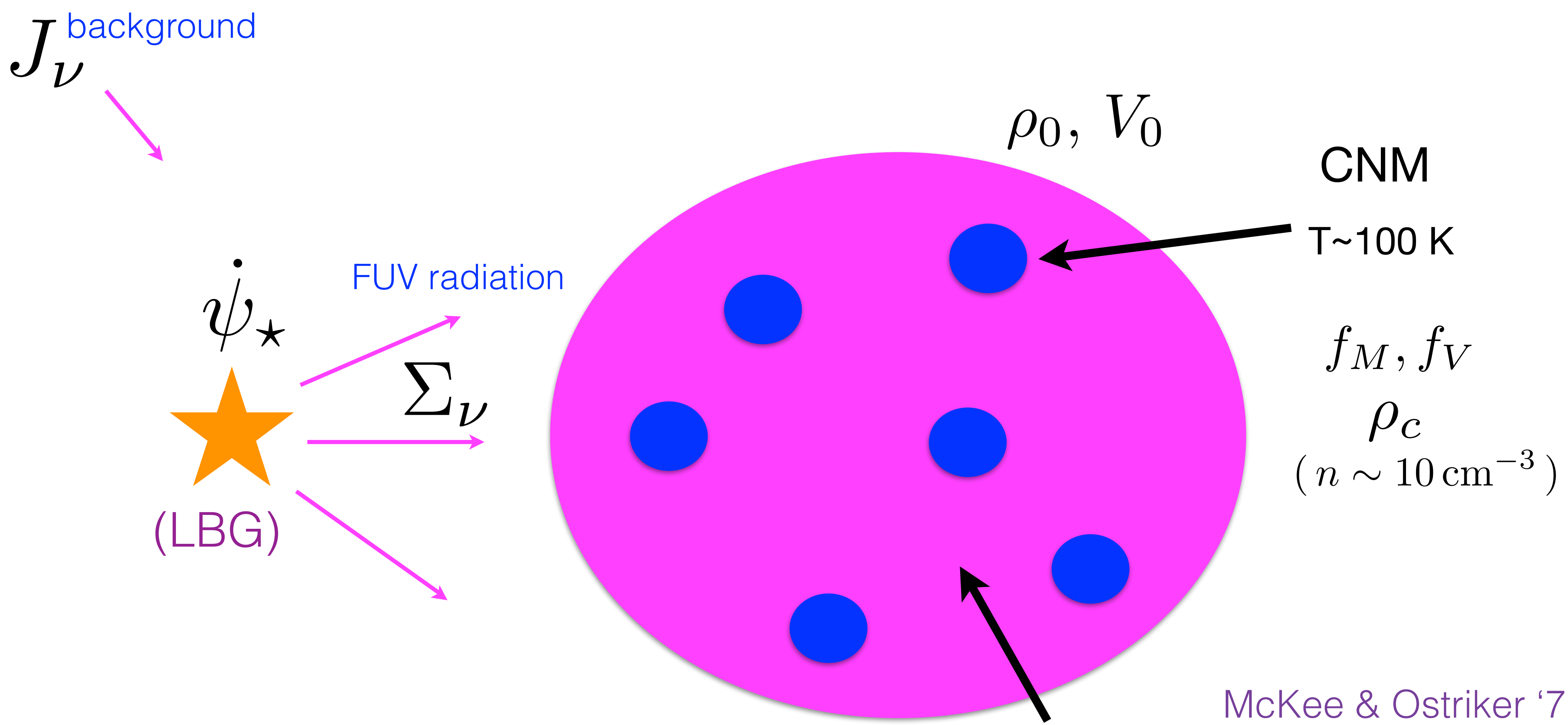


- Probing CGM (circum-galactic medium) around DLAs using QSO pair sight-lines
- 40 DLAs at $1.6<z<3.6$
- the second quasar sightline probes Lyα, Cii, Si II, and Civ absorption in the **CGM transverse to the DLA to projected distances $R_{\perp} < 300$ kpc.**
- Covering fraction of optically thick Hi ($N_{HI} > 10^{17.2}$ cm^{-2}) ≈ 30% within $R_{\perp} < 200$ kpc of DLAs.
- DLAs arise close to the centers of their host halos rather than on their outskirts.
- So maybe our clumpy CNM picture for DLA is not so bad after all…

(cf. Brisbin+’14)

How can we compute [Cii] emission in cosmological hydrodynamic simulations?

Multi-phase ISM model



McKee & Ostriker ‘77
Wolfire+ ‘95
Wolfe+ ‘03

CNM preferred for DLAs
(Wolfe+ ‘03b; Howk+ ‘05)

CNM mass fraction

$$\rho_C V_C + \rho_W V_W = \rho_0 V_0$$ (mass conservation)

(CNM) **(WNM)**

$$V_C + V_W = V_0$$ (volume conservation)

$$f_M \equiv \frac{\rho_C V_C}{\rho_0 V_0}$$ **(CNM mass fraction)**

$$= \frac{1 - (\rho_W/\rho_0)}{1 - (\rho_W/\rho_C)}$$

Given $\rho_0,\ \rho_C,\ \rho_W,$ → f_M

KN+ '06

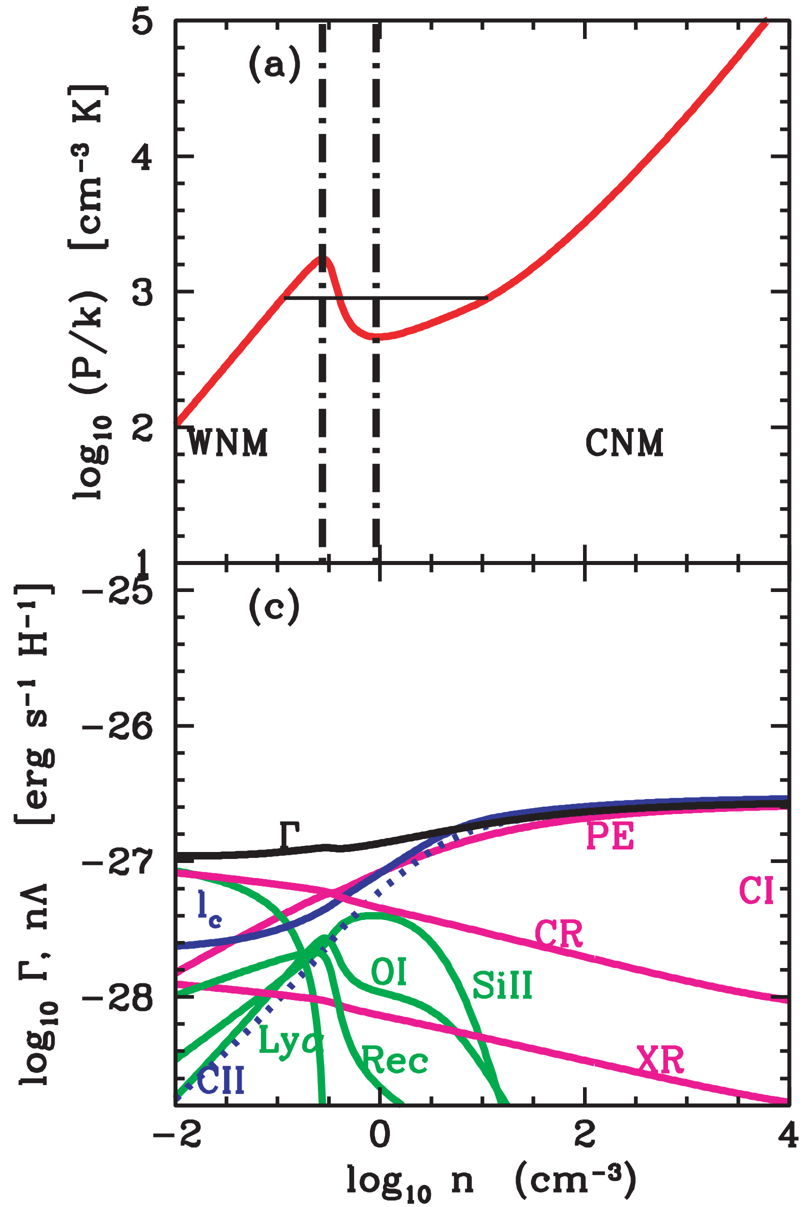
Phase Diagram

Equilibrium:

$$\Gamma = n\Lambda$$

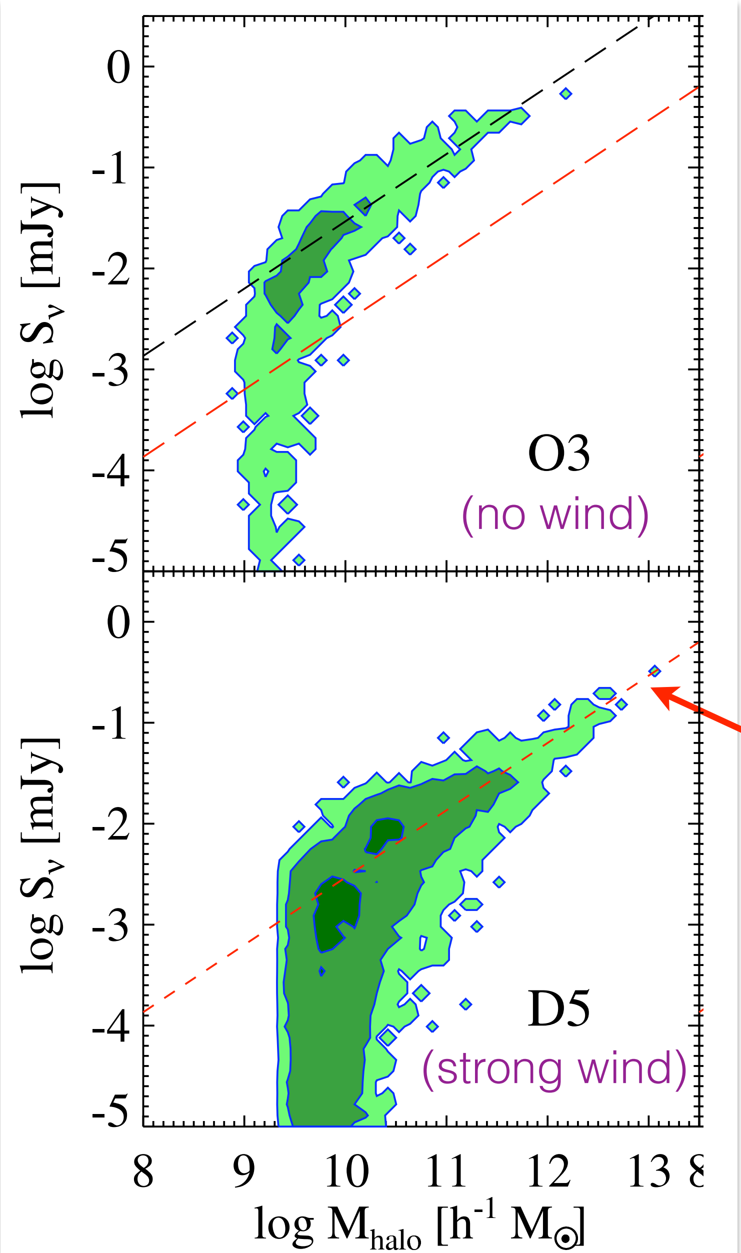
[C$_{II}$] cooling rate per H atom (dotted line)

$\ell_{C_{II}}$ **: spontaneous [Cii] energy emission rate**



Wolfe+ '03

[CII] Flux Density vs. Halo mass



$$S_\nu = \frac{(1+z)L_\nu}{4\pi d_L^2},$$

$$L_\nu = \frac{L_{\rm CII}}{\nu_{158}\left(\frac{v_c}{c}\right)0.6} \propto M_{\rm halo}^{2/3}$$

$$v_c = \left(\frac{GM}{r_{200}}\right)^{1/2}$$ circular velocity

$$S_\nu \approx C_2 \left(\frac{M_{\rm halo}}{10^{12}h^{-1}M_\odot}\right)^{2/3} \;{\rm mJy},$$

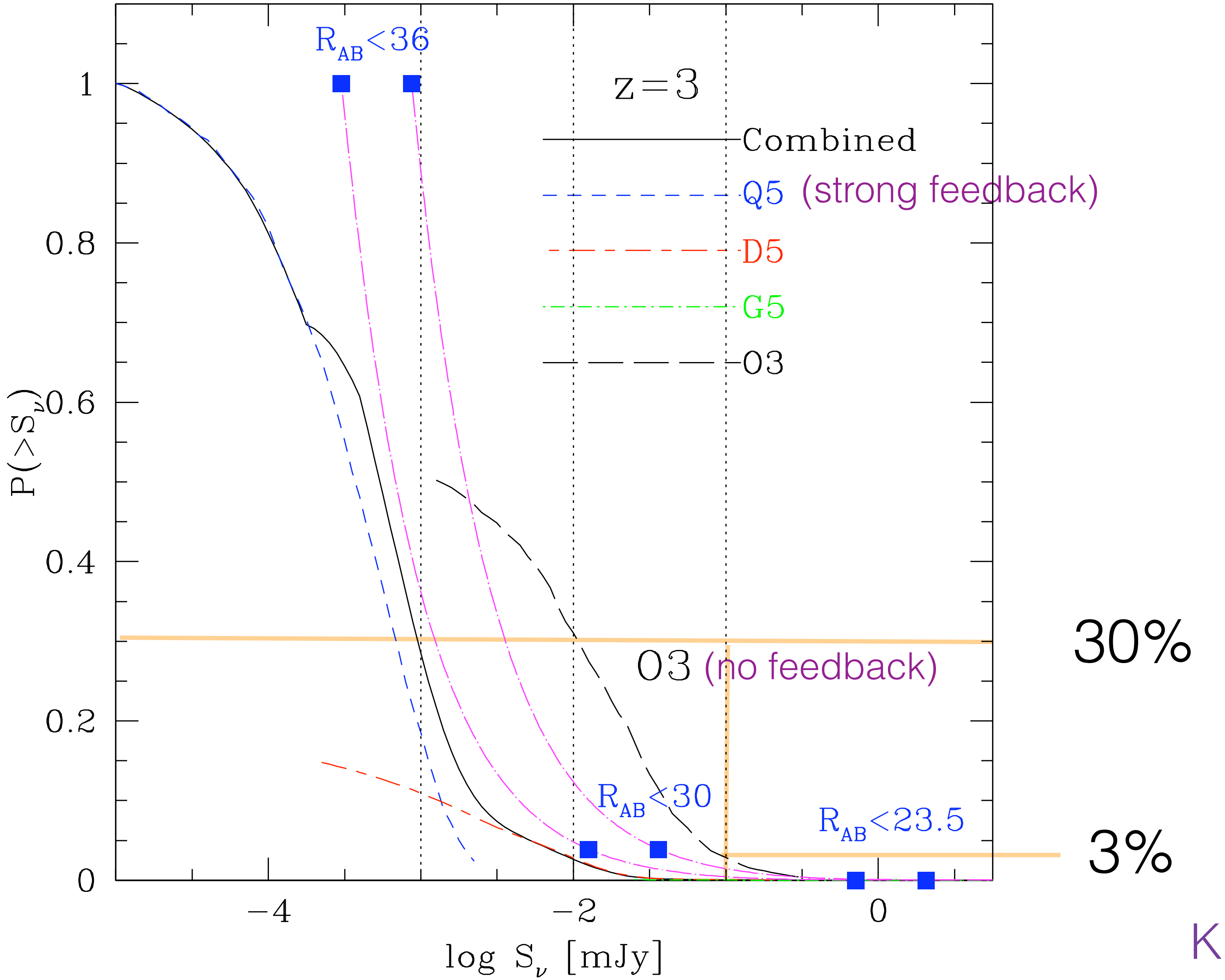
$C_2 = 0.6\,{\rm mJy}$ (no feedback)

$C_2 = 0.06\,{\rm mJy}$ (strong feedback)

KN+ '06

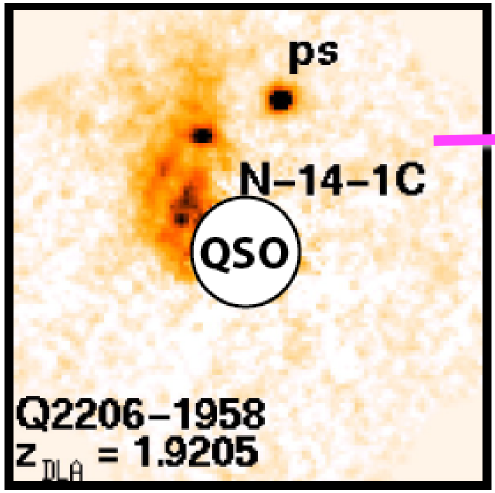
Cumulative [Cii] Flux Density PDF

(Gadget-3 cosmological SPH simulations)

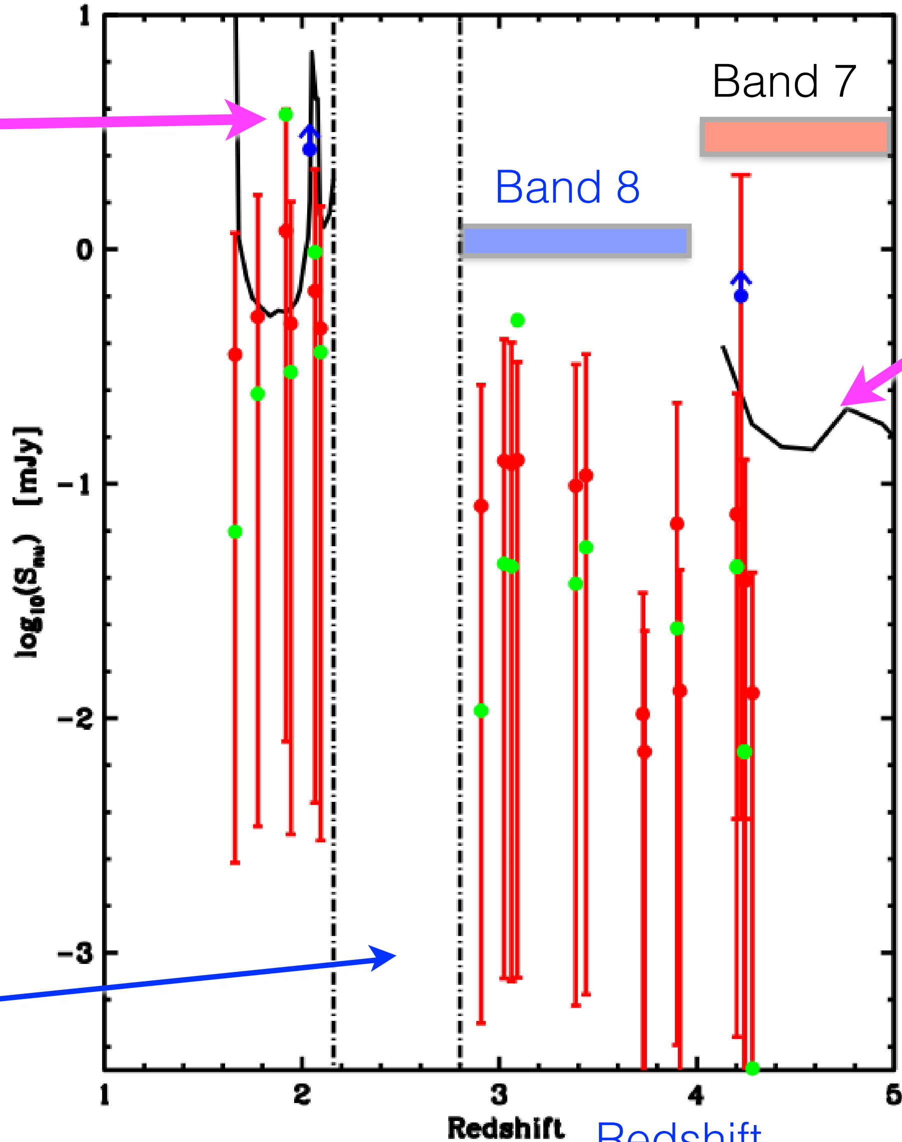


KN+ '06

Estimates for Actual DLA galaxies



(Moller+ ‘02)



ALMA 20 hr integration
1-sigma sensitivity

redshift desert

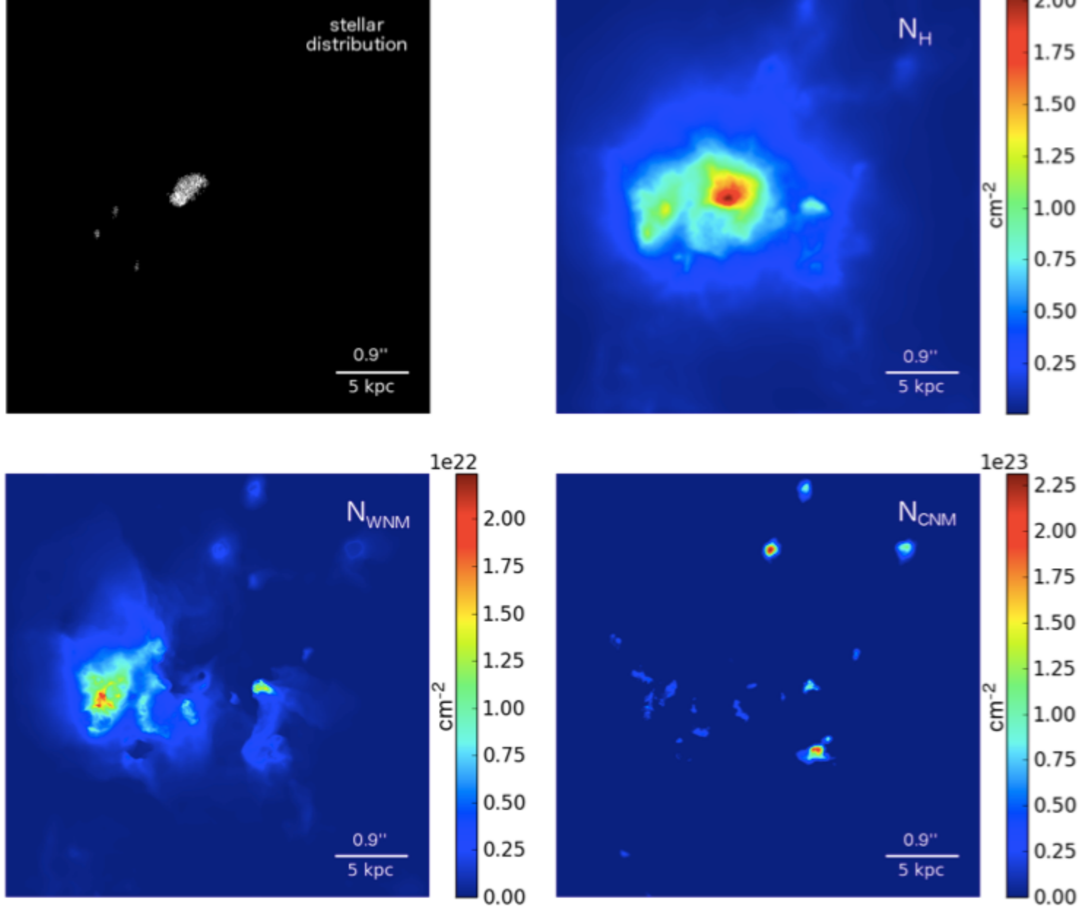
(atmospheric window)

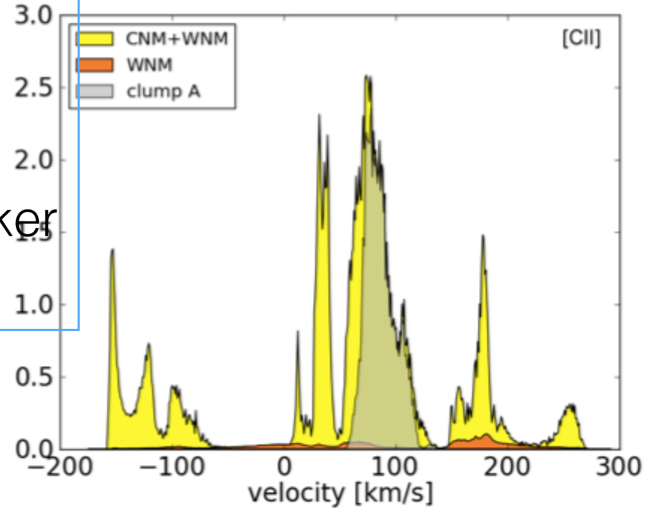
Redshift

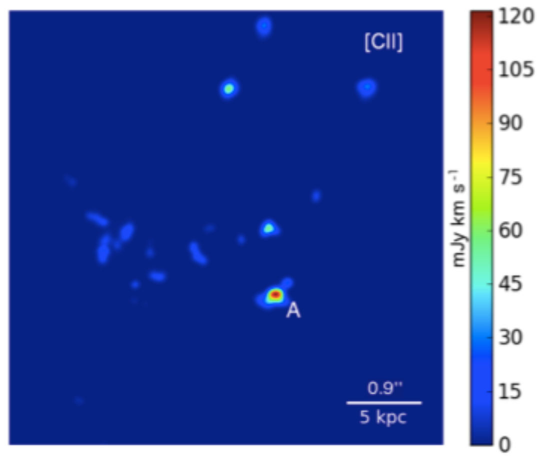
(Waiting for Cycle 2 obs)

Vallini+ ‘13

- Cosmo sim (Gadget-2) + postprocess RT (LICORICE) + subgrid multi-phase ISM model
- But no metal-cooling, SF & feedback in the original sim —> gas dist unreliable.
- z=6 gal (≈Himiko-like LAE)
- [Cii] peak offset from galaxy by ~100 km/s; f~185 mJy km/s (for $Z=Z_\odot$); 95% from CNM, 5% from WNM
- [Oi] 63μm, [Nii] 122μm much weaker than [Cii]







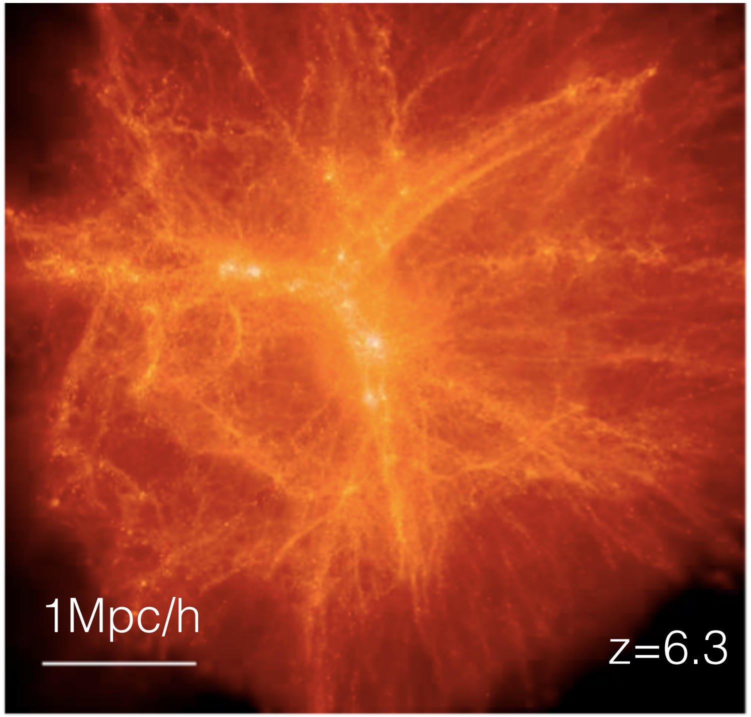
Towards $z>6$

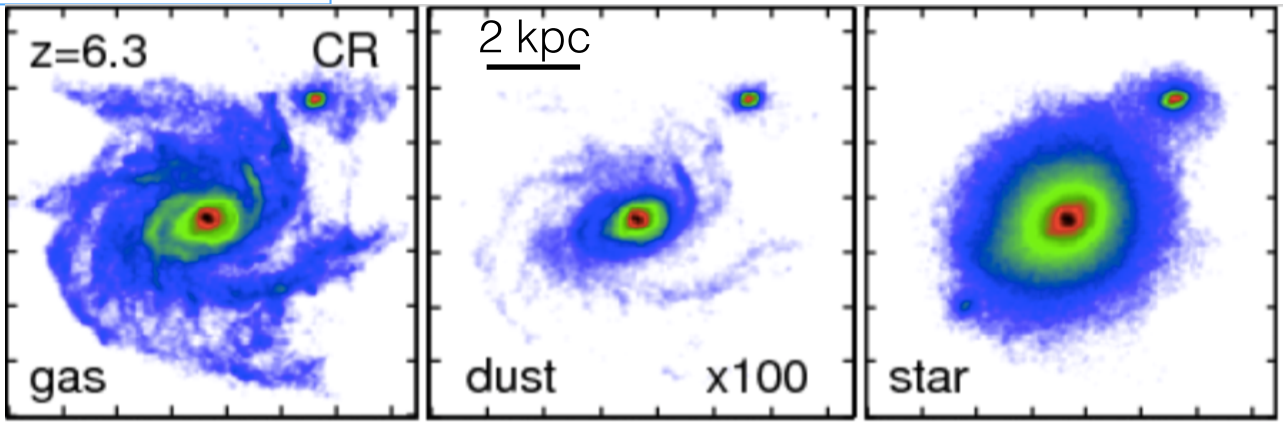
Yajima+ '14

(Romano-diaz+'13 sim.)

	$N_{\rm SPH}$	$R_{\rm box}$ (h^{-1}Mpc)	$R_{\rm box}^{\rm zoom}$ (h^{-1}Mpc)	$m_{\rm DM}$ (h^{-1}M$_\odot$)	$m_{\rm SPH}$ (h^{-1}M$_\odot$)	$m_{\rm star}$ (h^{-1}M$_\odot$)	ϵ (pc, comoving)
CR	1024^3	20	3.5	4.66×10^5	1.11×10^5	5.55×10^4	300
UCR	512^3	20	7.0	3.73×10^6	8.90×10^5	4.40×10^5	300

- Gadget-3 cosmo sim w/ full physics + dust model + postprocess RT
- Constrained realization of 5-σ density peak ≈ quasar environment at z>6
- 30 pc (phys) resol. @ z=9





Yajima+ '14

Very high SFR

The most massive galaxy:

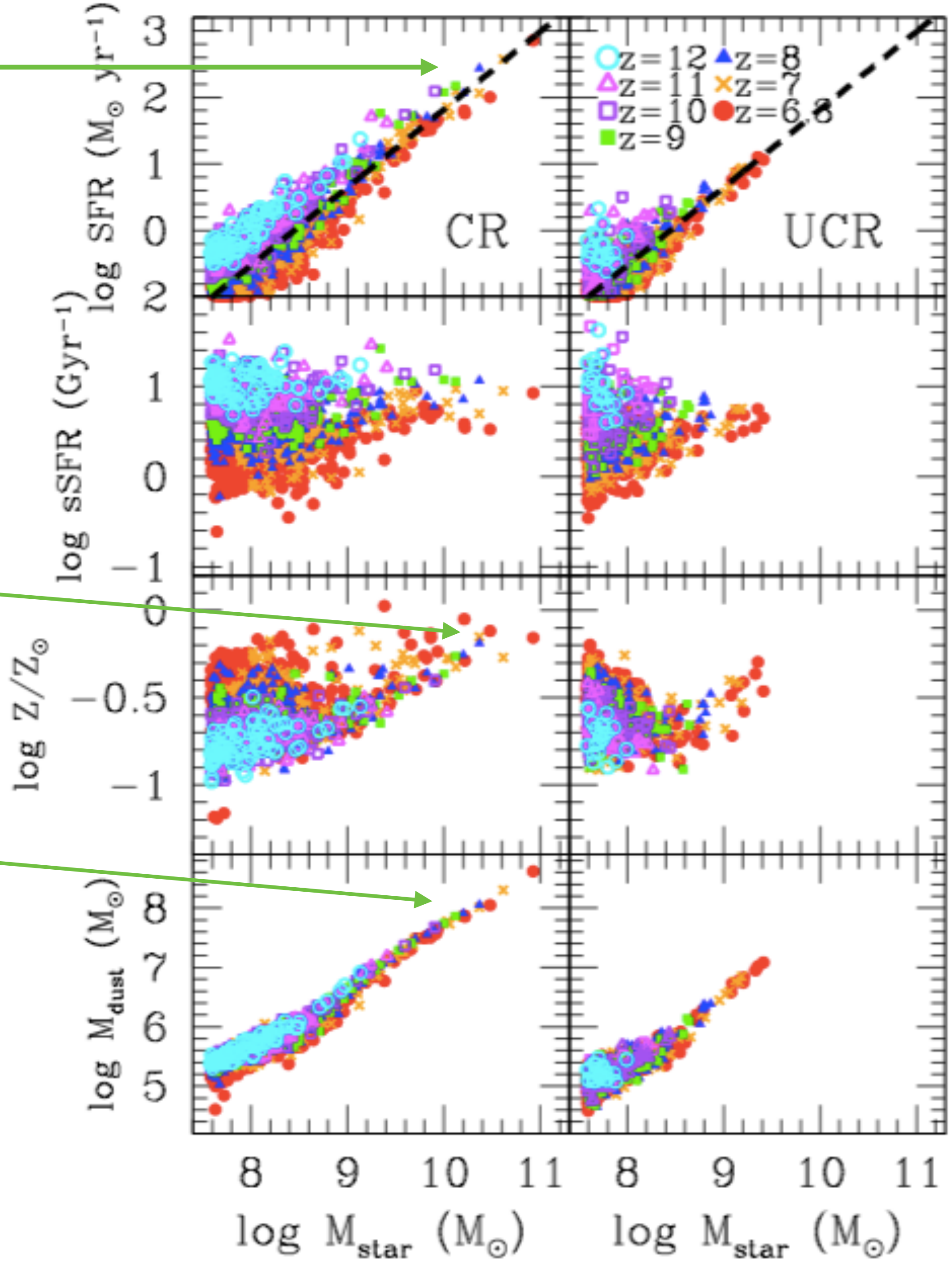
$M_{star} \sim 8.4 \times 10^{10}\ M_\odot$,

$M_{dust} \sim 4.1 \times 10^{8}\ M_\odot$,

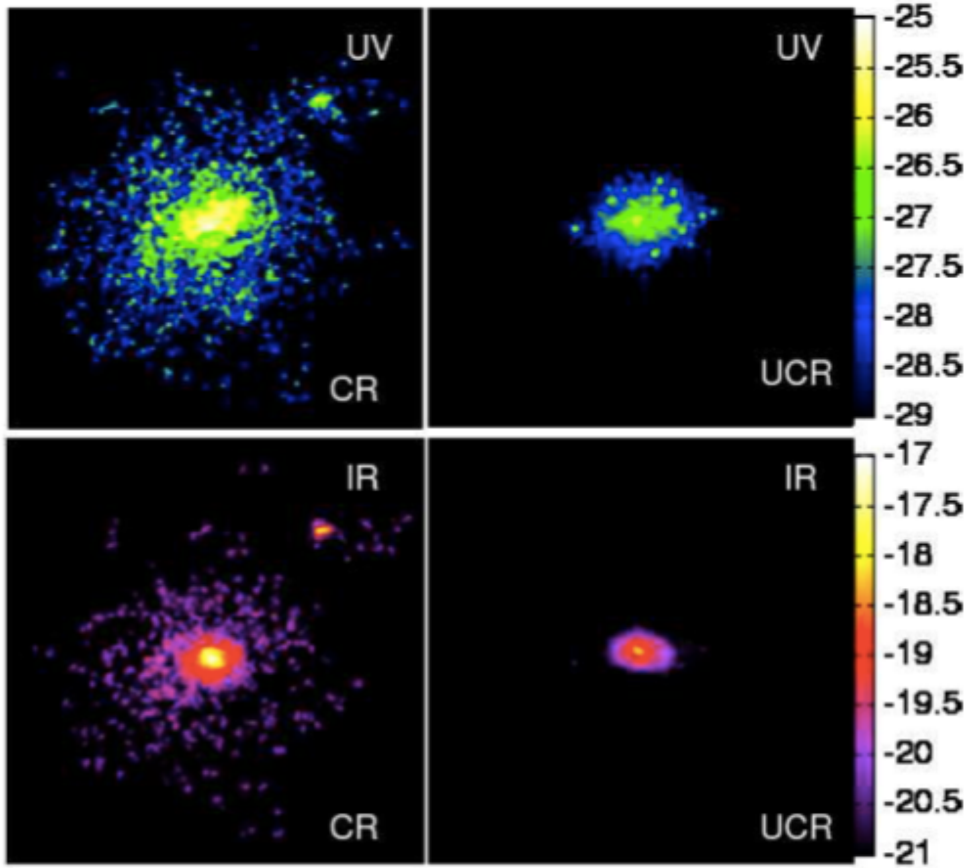
$SFR \sim 745\ M_\odot\ yr^{-1}$ $(z = 6.3)$

Sub-solar metallicity

Large amount of dust in massive gals

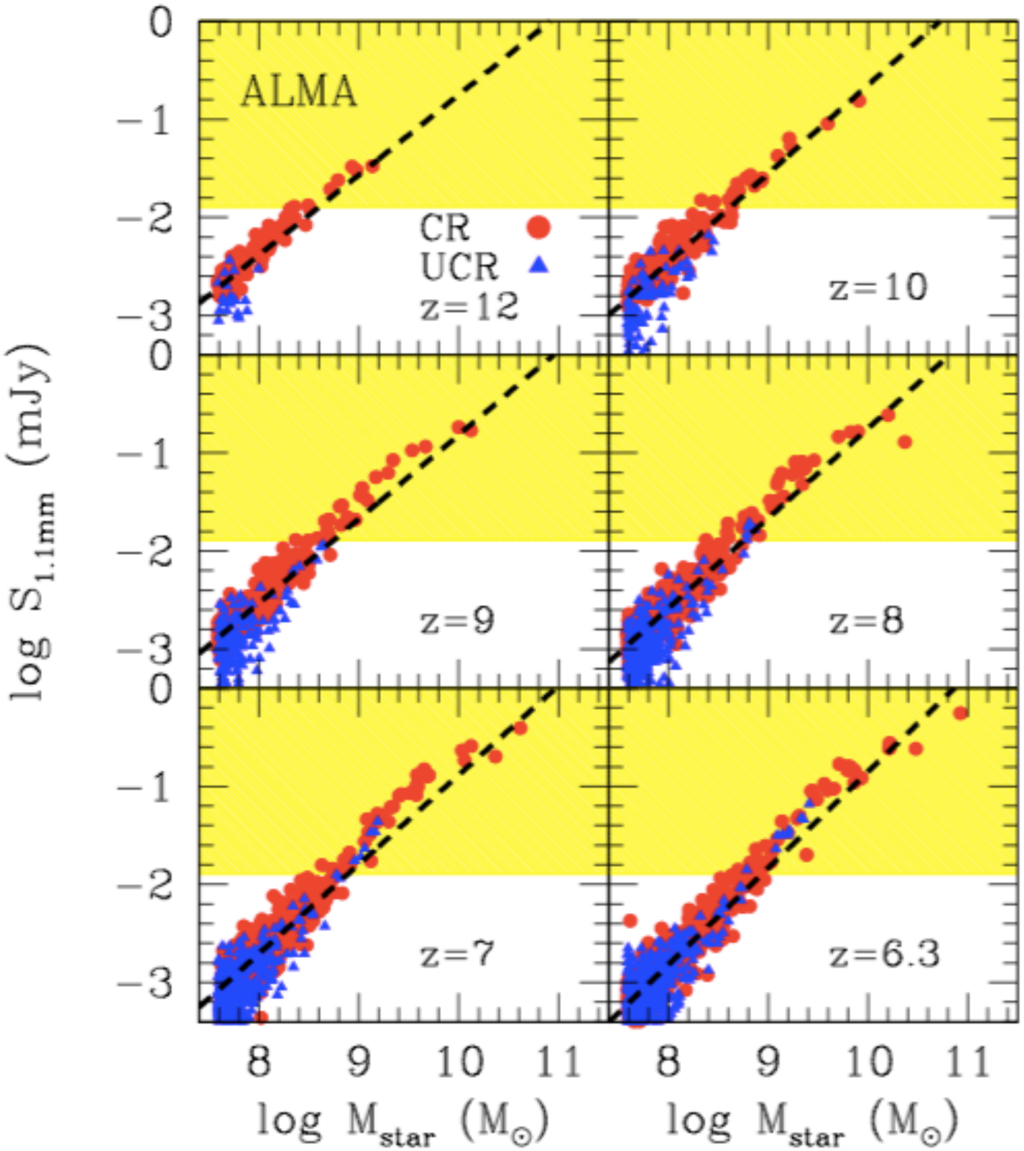


UV: 1600 A rest-frame



IR: 106 μm rest (850 μm obs)

surface brightness in the log scale in units of erg s^{-1} cm^{-2} Hz^{-1} $arcsec^{-2}$.



Yajima+ '14

Conclusions

- **[Cii] emission** & DLAs give us useful insights on ISM in high-z gals.
- DLAs could be clumpy CNM gas.
- Dominance of faint galaxies for DLAs: a generic prediction of a CDM model
- Most massive gals at $z \gtrsim 6$ can be observed with ALMA if we know where to look.