DLAs and Galaxy Formation

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KN+ 04a,b, 05a,b

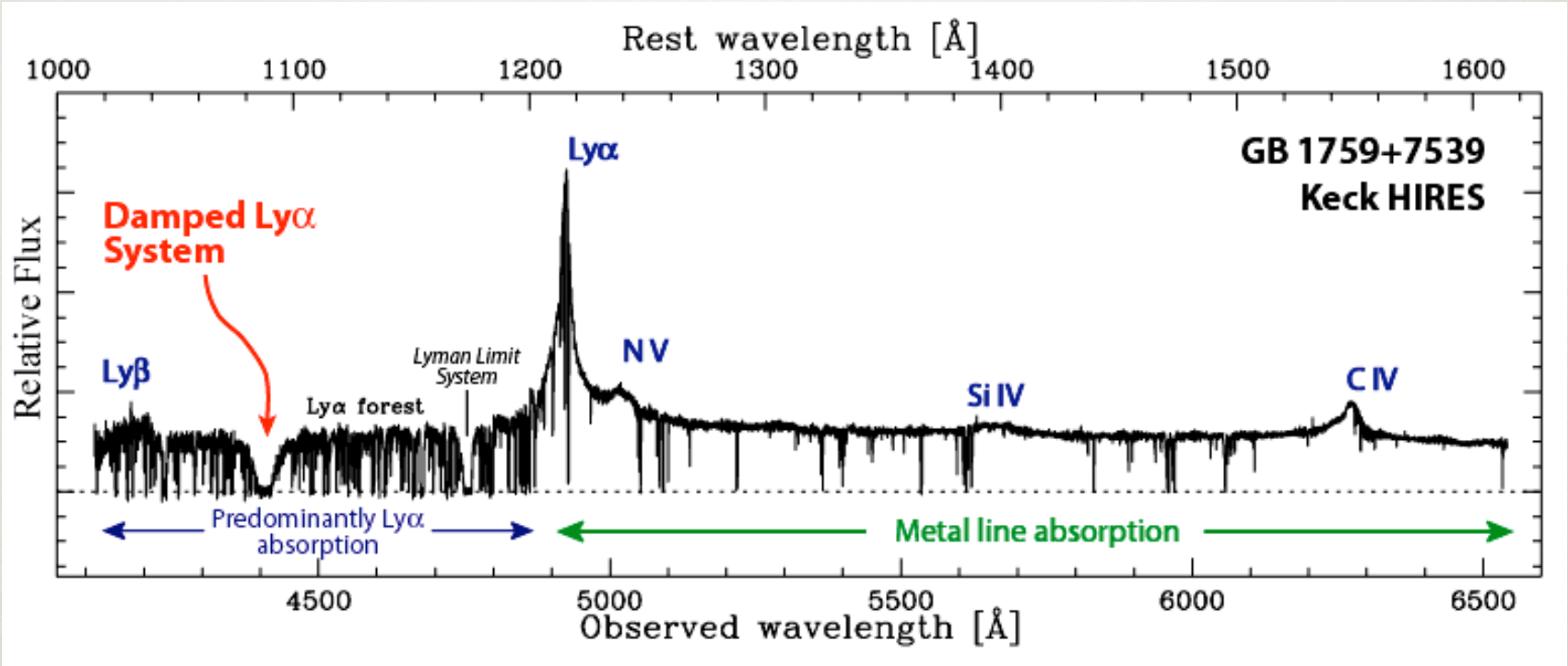
What are the Goals?

- Self-consistent model of galaxy formation (disk & bulge) and BH formation
- How did gas transform into stars?
- A model consistent with low-z & high-z observations? (likewise, small - & large-scale)
- Does the hierarchical cold dark matter model work?

Outline

1. What are DLAs? observations
2. Effects of SN feedback on:
   - ★ Ω_{HI}, f(N_{HI})
   - ★ DLA cross section, rate-of-incidence (dN/dz)
   - ★ physical size & # density
   - ★ mean DLA halo mass, DLA--LBG
   - ★ metallicity
   - ★ how are DLAs distributed in halos?
   - ★ implications on high-z SF
3. [CII] 158 micron emission

What are DLAs?



quasar

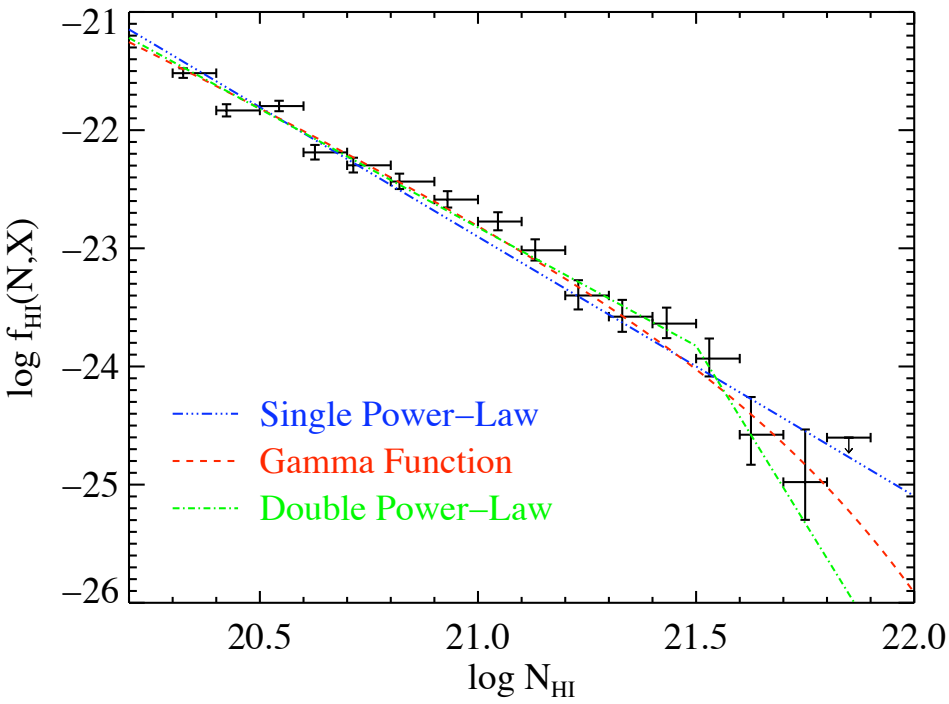
$$N_{\rm HI} > 2 \times 10^{20}\,{\rm cm}^{-2}$$

Wolfe+ '86

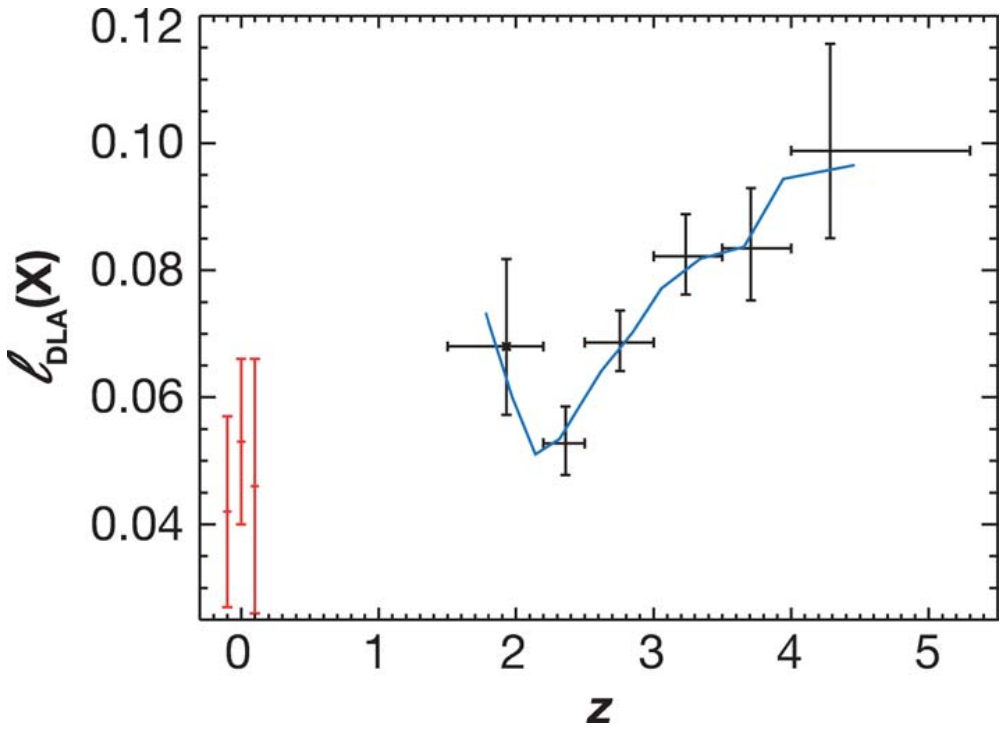
DLA Statistics

Prochaska+ '05 SDSS DR3
>500 DLAs

HI column density distribution



Rate of Incidence



Strong constraints for galaxy formation models

$$\frac{\mathrm{d}N(X)}{\mathrm{d}X} = \int_{N_{\min}}^{N_{\max}} \mathrm{d}N\, f(X, N),$$

Rate-of-Incidence

$$
\begin{aligned}
\mathrm{d}N_{\mathrm{DLA}} &= n_{\mathrm{phys}}(M)\,\mathrm{d}M \cdot \sigma_{\mathrm{DLA}}^{\mathrm{phys}} \cdot c\,\mathrm{d}t \\
&= (1+z)^3\, n_{\mathrm{co}}(M)\, dM \cdot \sigma_{\mathrm{DLA}}^{\mathrm{phys}} \cdot a\,\mathrm{d}r \\
&= n_{\mathrm{co}}(M)\, dM \cdot \sigma_{\mathrm{DLA}}^{\mathrm{co}} \cdot \mathrm{d}r,
\end{aligned}
$$

$$
\frac{dN}{dz} = n_{co}(M) dM \cdot \sigma_{DLA}^{co} \frac{dr}{dz}
$$

'absorption distance' $dX \equiv \frac{H_0}{c}(1+z)^3\, c\,\mathrm{d}t = \frac{H_0}{c}(1+z)^2\,\mathrm{d}r$

$$
\frac{\mathrm{d}N_{\mathrm{DLA}}}{dX} = \frac{c}{H_0}\, n_{\mathrm{co}}(M)\, dM \cdot \sigma_{\mathrm{DLA}}^{\mathrm{phys}}.
$$

Neutral Gas Density

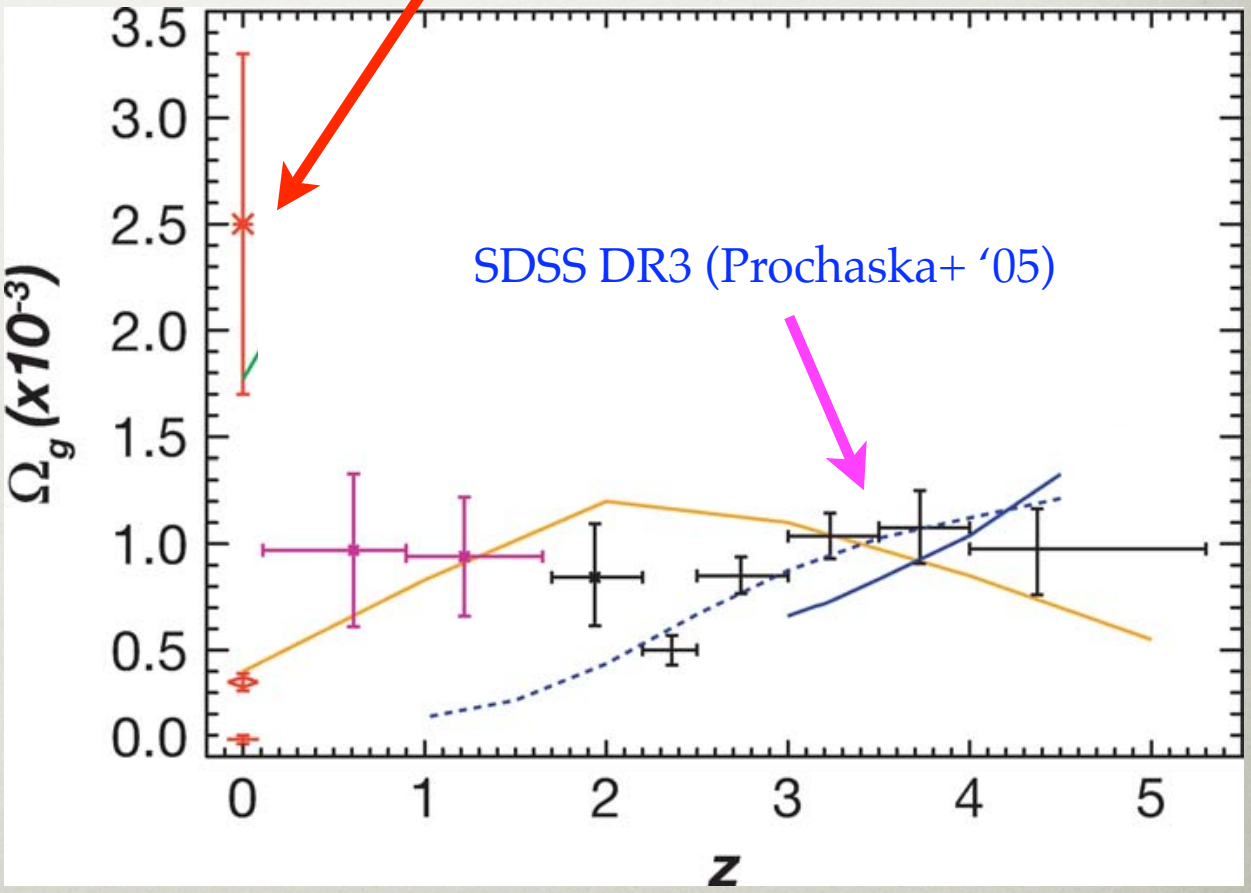
$$\Omega_g = \frac{H_0}{c}\frac{\mu m_H}{\rho_{crit}}\int_{N_{min}}^{N_{max}} dN\, N\, f(N, X),$$

$\Omega_\star(z=0)$

DLAs dominate HI mass density at z~3

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

Reservoir of neutral gas for star formation



Wolfe+ '05

Cosmological Hydrodynamic Simulations

- model galaxy formation from first principles in a ΛCDM universe
- GADGET2 Smoothed Particle Hydrodynamics code

radiative cooling/heating, star formation, SN & galactic wind feedback

- LBGs@z=3–6, massive gal@z=1–2, DLAs, ... (KN+ 04ab, 05ab)

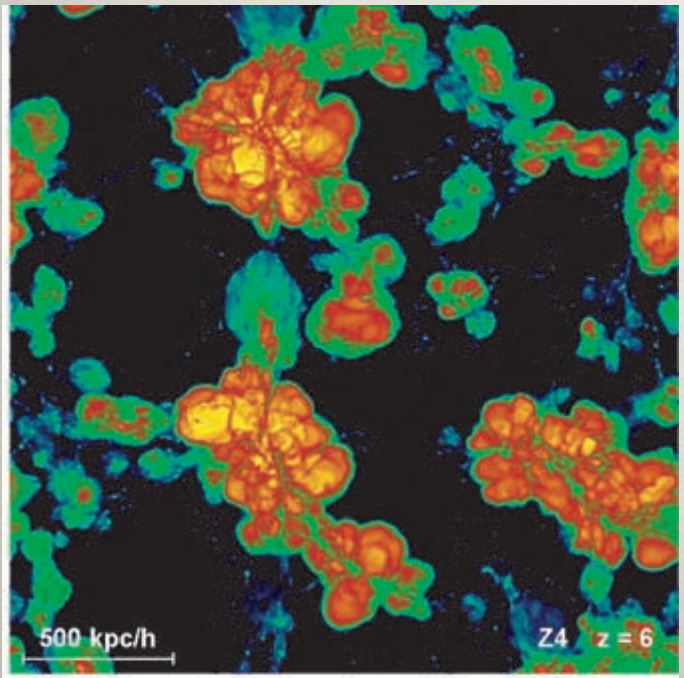
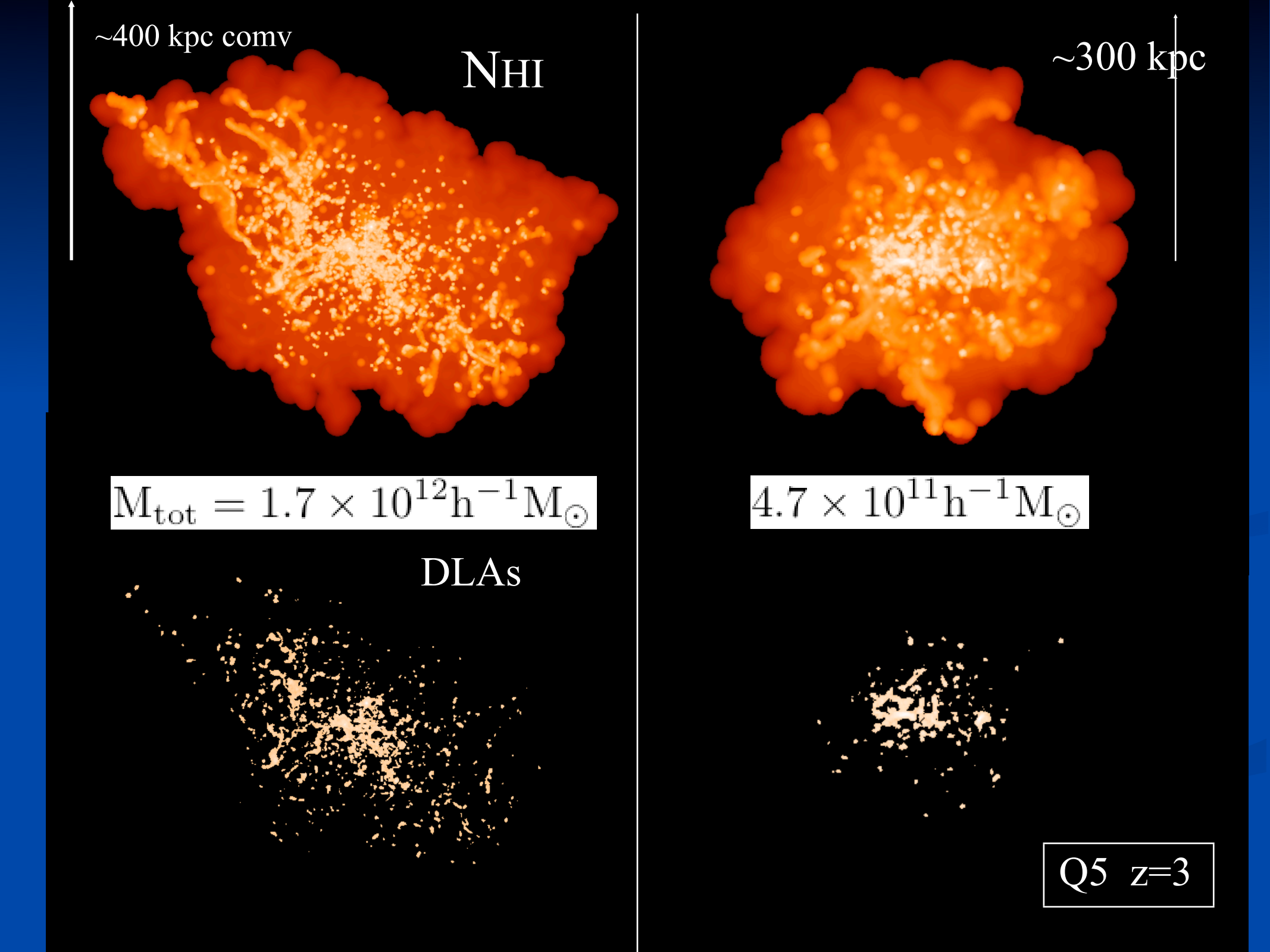
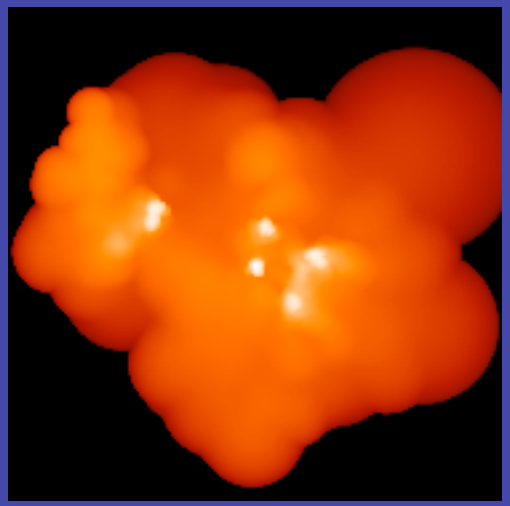


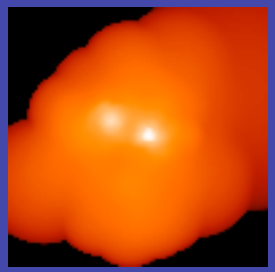
Table 2. Simulation Parameters

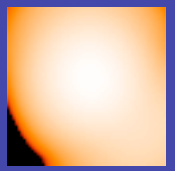
Run	Boxsize	$N_{\rm p}$	$m_{\rm DM}$	$m_{\rm gas}$	ϵ	wind
O3	10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	none
P3	10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	weak
Q3	10.00	2×144^3	2.42×10^7	3.72×10^6	2.78	strong
Q5	10.00	2×324^3	2.12×10^6	3.26×10^5	1.23	strong
	$[h^{-1}{\rm Mpc}]$		$[h^{-1}M_\odot]$		$[h^{-1}{\rm kpc}]$	


~400 kpc comv
NHI
~300 kpc
$M_{tot} = 1.7 \times 10^{12} h^{-1} M_\odot$
$4.7 \times 10^{11} h^{-1} M_\odot$
DLAs
Q5 z=3

NHI





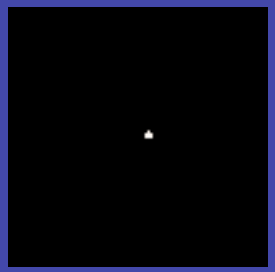


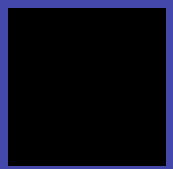
$M_{tot} = 2.6 \times 10^{10} h^{-1} M_\odot$

$2.4 \times 10^{9} h^{-1} M_\odot$

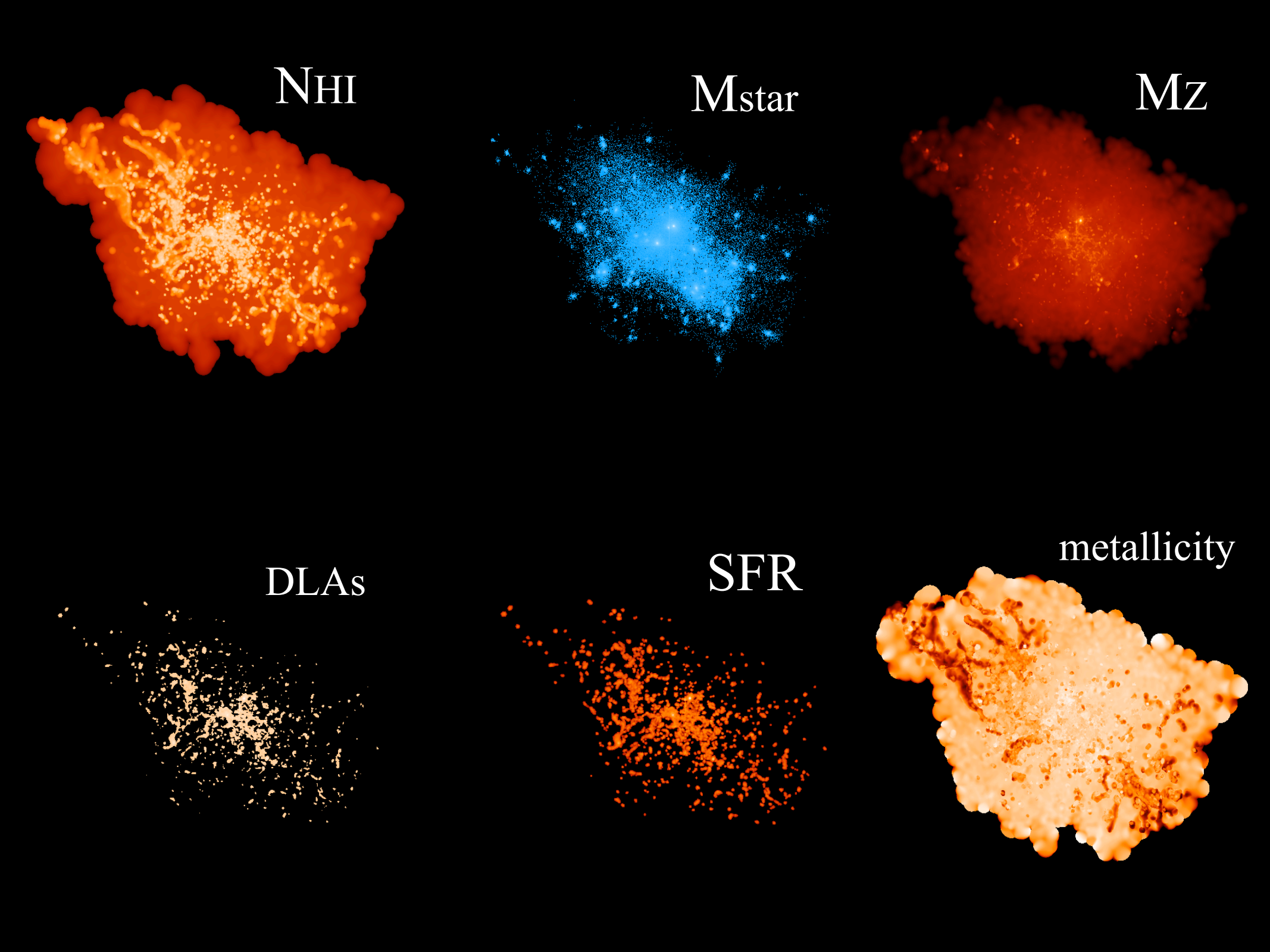
$2.4 \times 10^{8} h^{-1} M_\odot$

DLAs

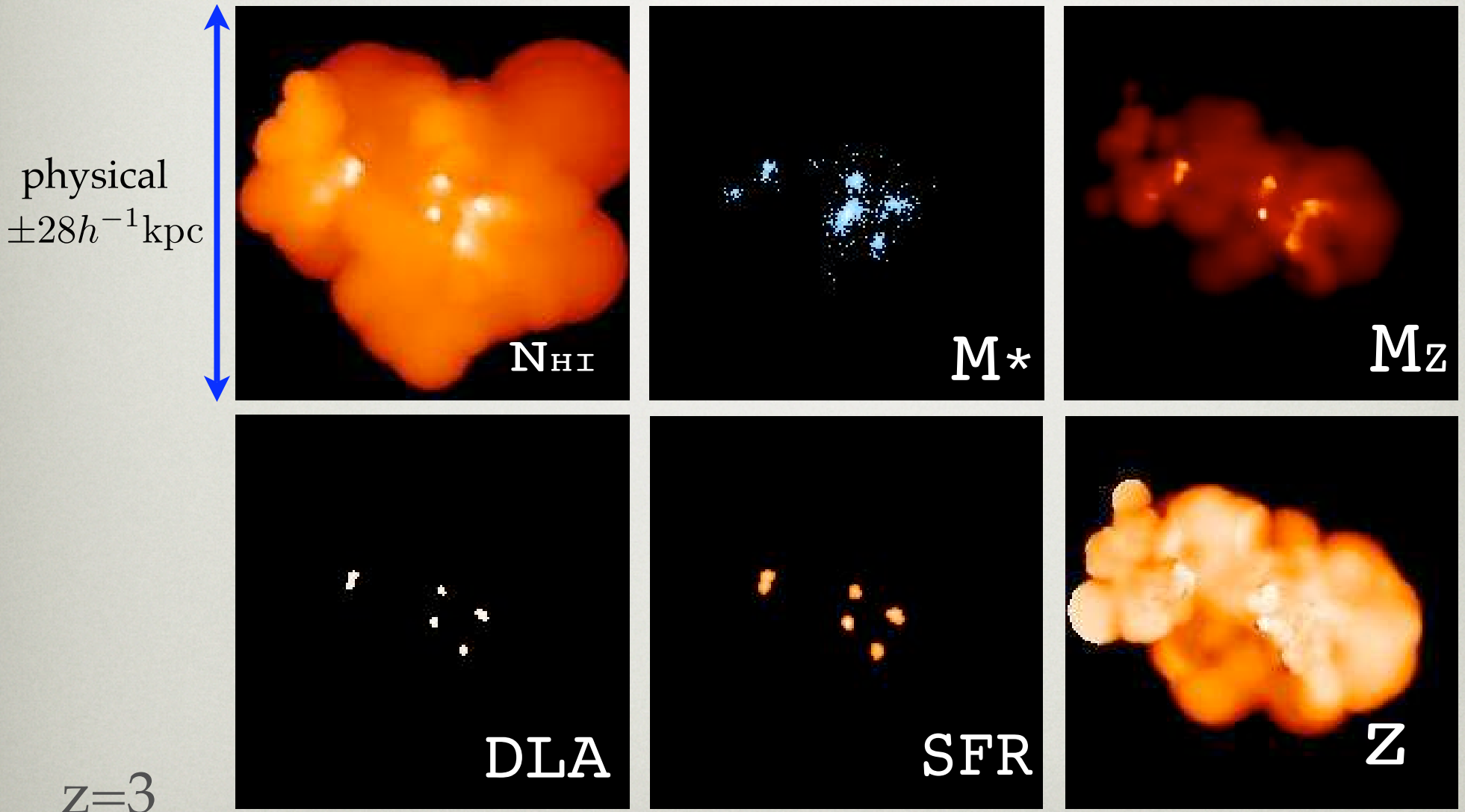




Q5 z=3


NHI
Mstar
MZ
DLAs
SFR
metallicity

DLAs in Cosmological Simulations



$M_{\rm halo} = 2.6 \times 10^{10}\, h^{-1} M_\odot$

KN+ 2004a,b

Star Formation Model

Four criteria for SF in a cell

$$\delta > \delta_c \quad \text{(overdense)}$$

$$\nabla \cdot \vec{v} < 0 \quad \text{(converging flow)}$$

$$m_{\rm gas} > m_{\rm Jeans} \quad \text{(Jeans unstable)}$$

$$t_{\rm cool} < t_{\rm dyn} \quad \text{(cooling fast)}$$

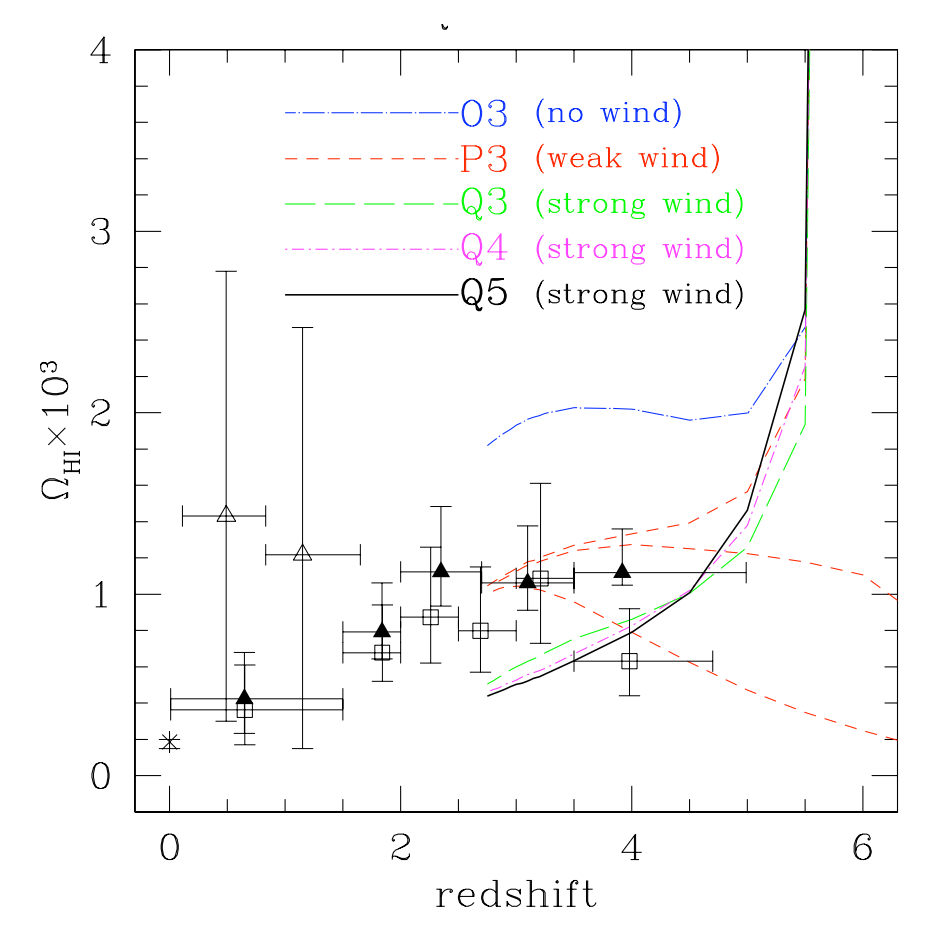
$$\Delta m_\star = c_\star \frac{m_{\rm gas}}{t_\star} \Delta t$$

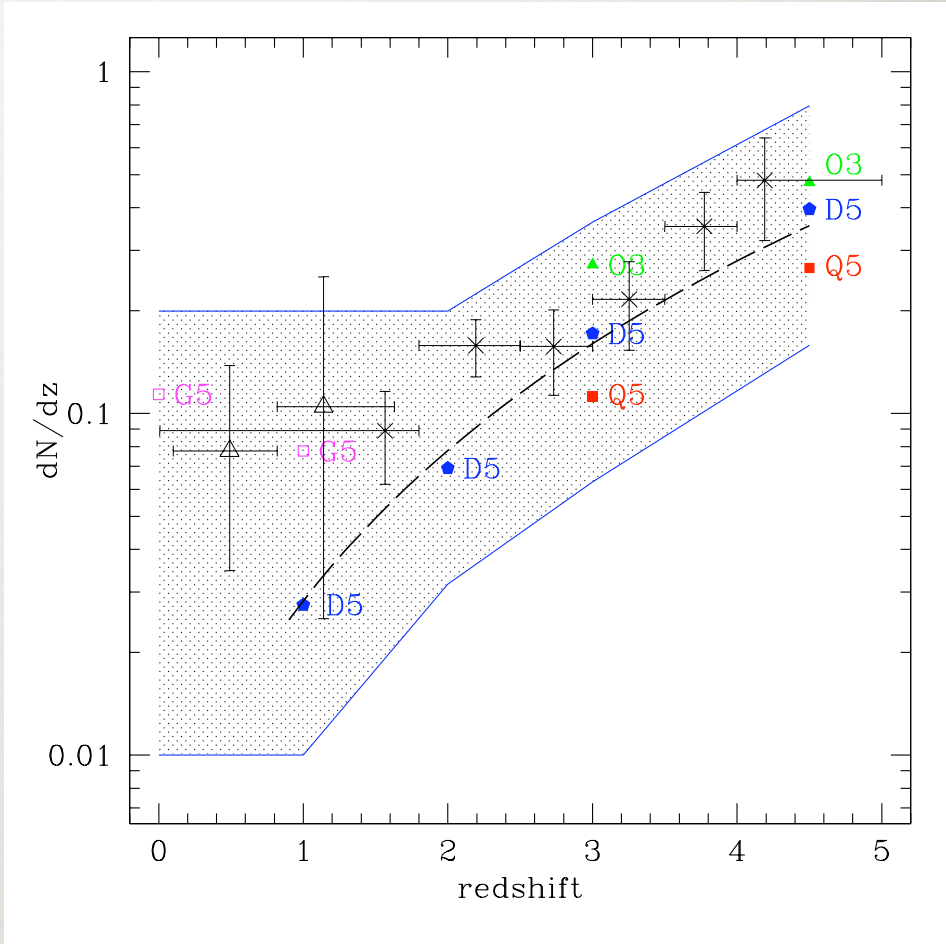
$$t_\star = \max(t_{\rm cool},\ t_{\rm dyn})$$

Each star ptcl is tagged w/

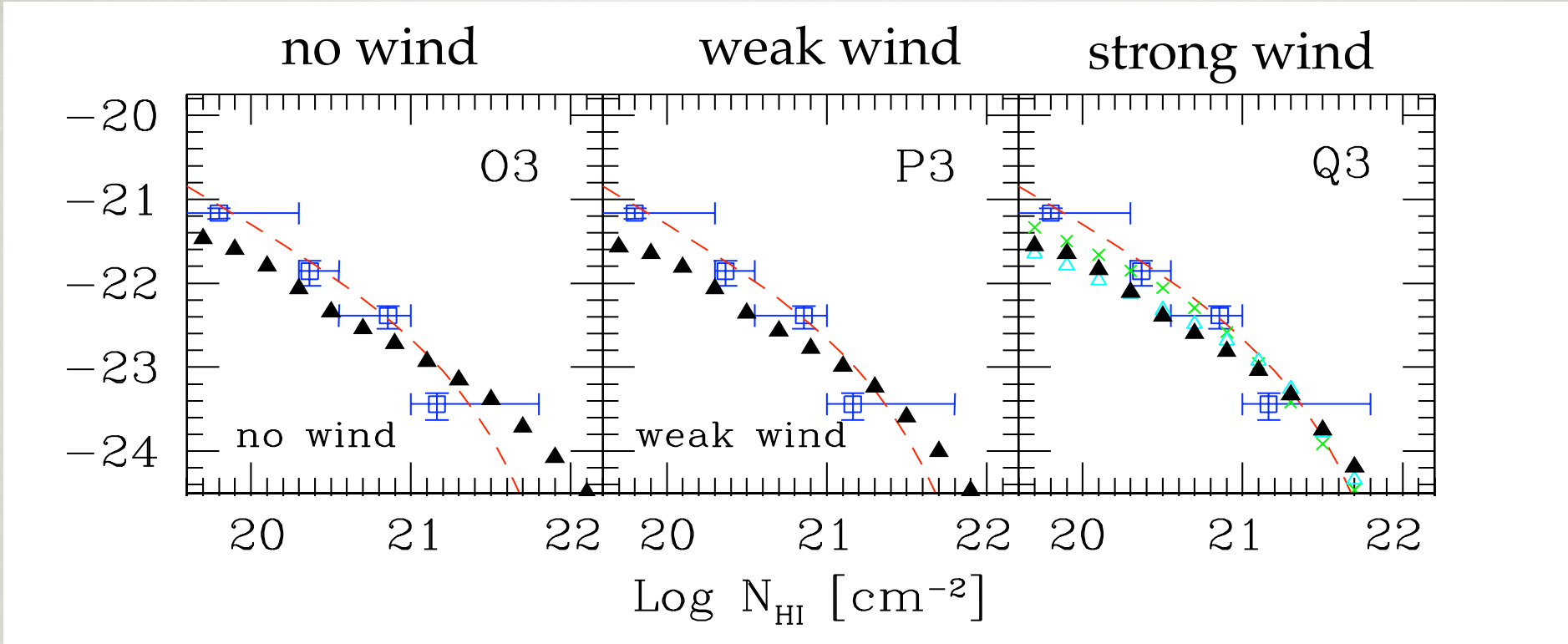
$(m_\star, t_{\rm form}, Z/Z_\odot)$

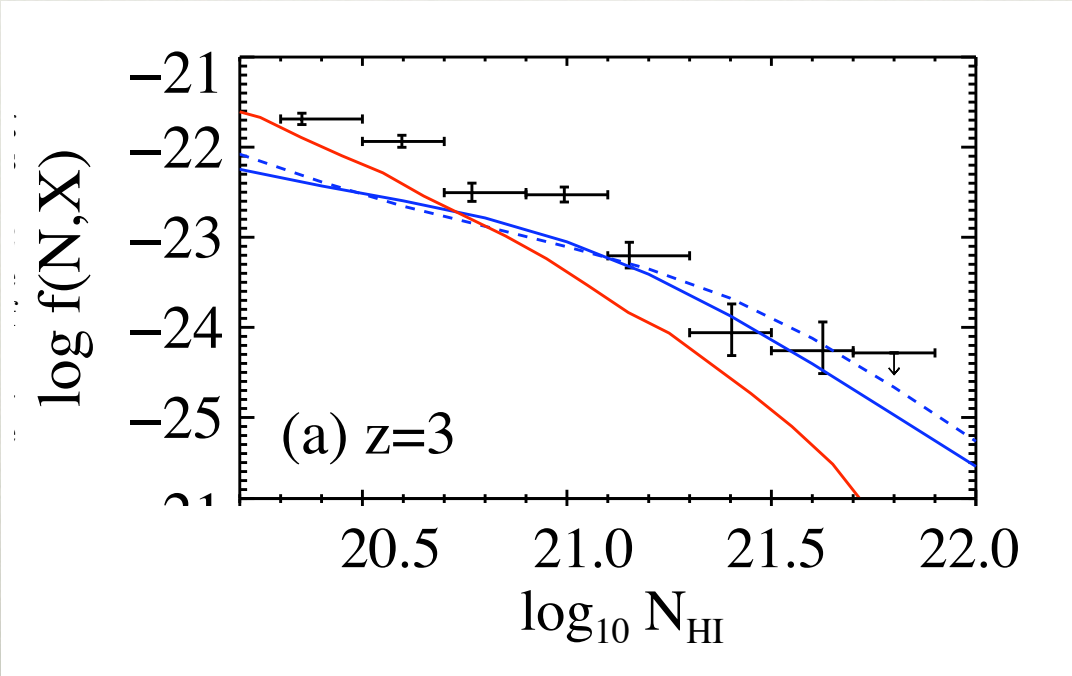
$$\Delta E_{\rm SN} = \epsilon_{\rm SN} \Delta m_* c^2$$


Q3 (no wind)
P3 (weak wind)
Q3 (strong wind)
Q4 (strong wind)
Q5 (strong wind)
$\Omega_{HI}\times10^3$
redshift
0
1
2
3
4
0
2
4
6


dN/dz
redshift
0.01
0.1
1
0
1
2
3
4
5
G5
G5
D5
D5
D5
Q3
Q3
Q5
Q5
D5

KN+ '04a


no wind
weak wind
strong wind
−20
−21
−22
−23
−24
O3
P3
Q3
no wind
weak wind
20
21
22
Log N_HI [cm^-2]


−21
−22
−23
−24
−25
log f(N,X)
(a) z=3
20.5
21.0
21.5
22.0
log10 N_HI

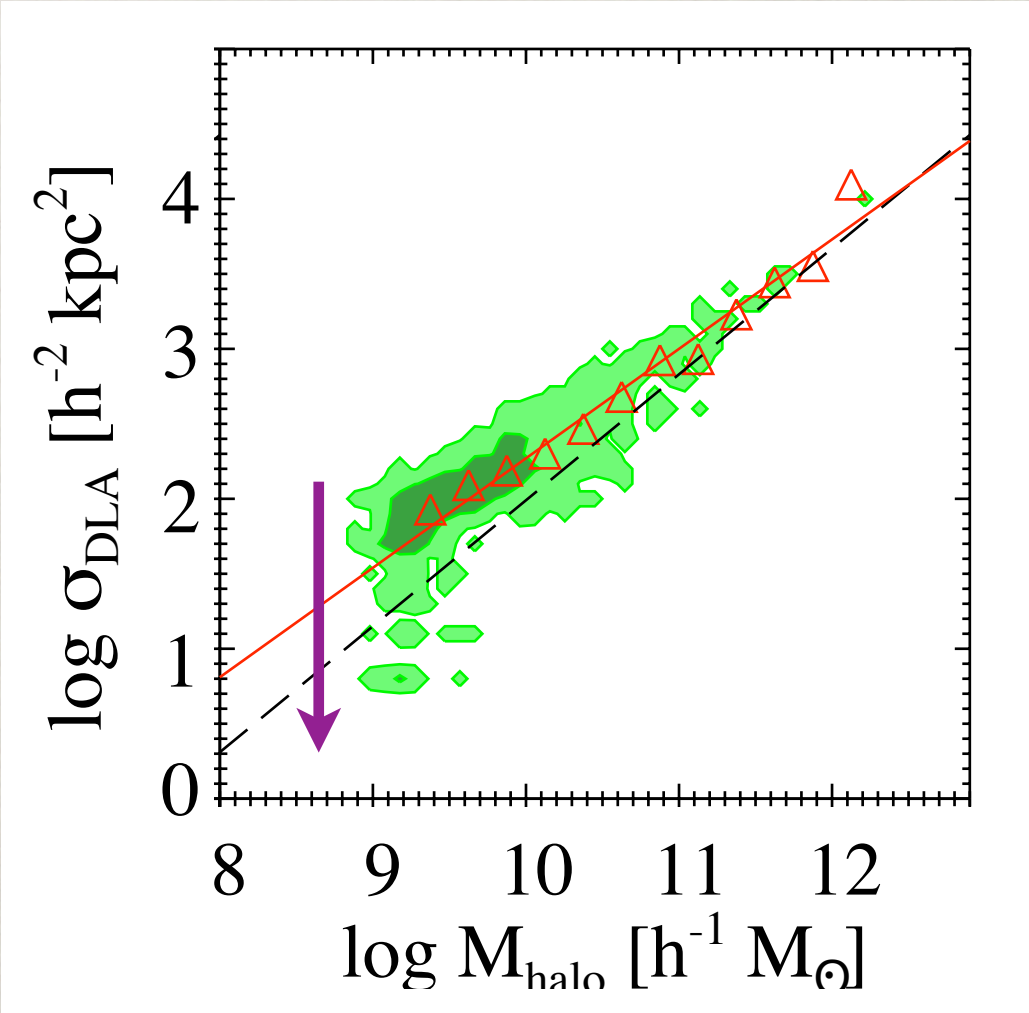
DLA Cross Section

$$\sigma_{\rm DLA} \propto M_{\rm halo}^{\alpha}$$

$$\alpha \sim 1$$

Stronger feedback suppresses $\sigma_{\rm DLA}$ for low mass halos

$$\alpha > 1$$



KN+ '04a

DLA distribution

$$\frac{\mathrm{d}N_{\mathrm{DLA}}}{\mathrm{d}z\,\mathrm{d}\log M} = \frac{\mathrm{d}r}{\mathrm{d}z}[\,M\,n(M,z)\,\ln(10)\,]\,\sigma^{\mathrm{co}}_{\mathrm{DLA}}(M,z),$$

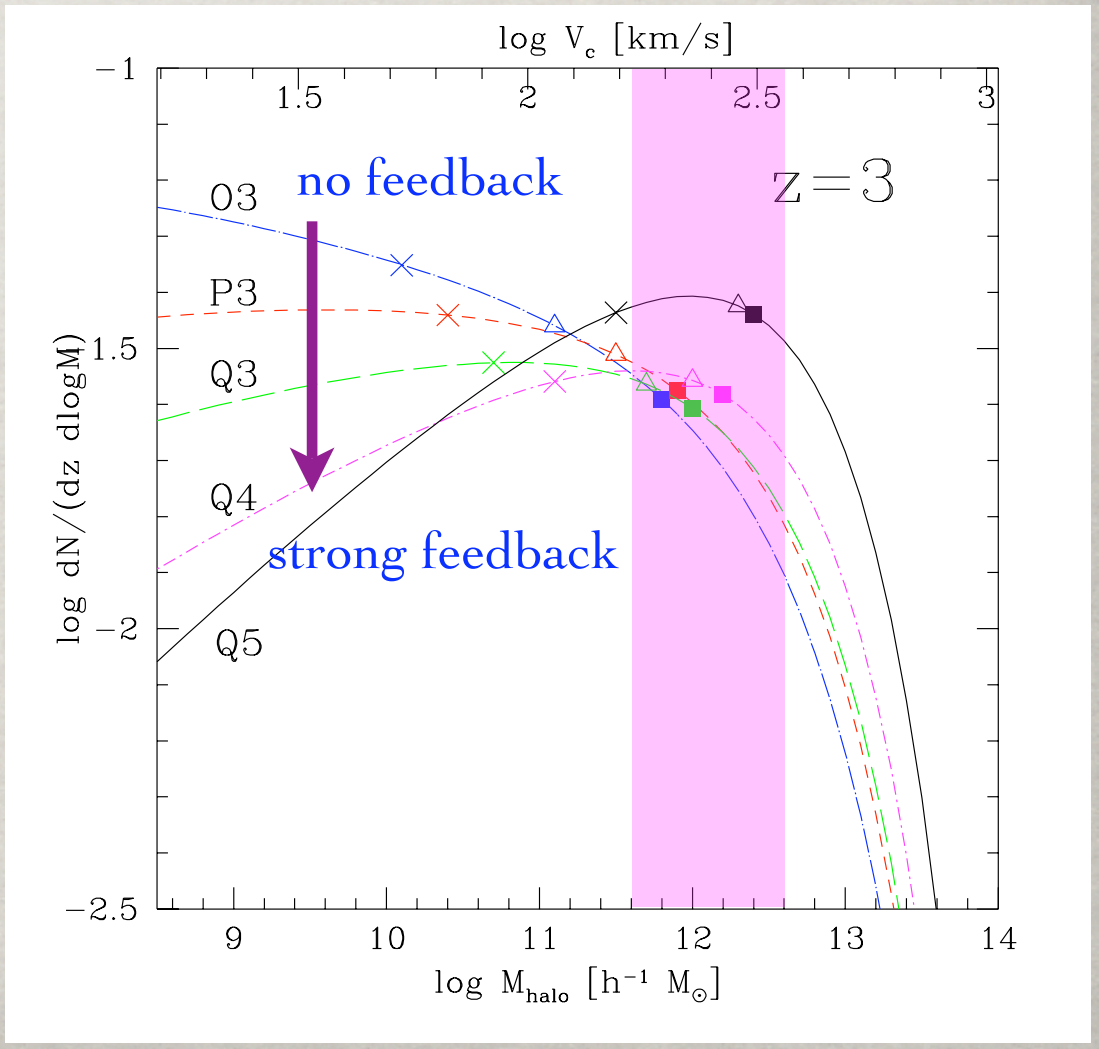
$$\sigma_{\mathrm{DLA}} \propto M^{\alpha}_{\mathrm{halo}}$$

Mean DLA halo mass

$$\langle M_{\mathrm{DLA}}\rangle = \frac{\int_0^\infty M\,\frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}\log M}\mathrm{d}\log M}{\int_0^\infty \frac{\mathrm{d}N}{\mathrm{d}z\mathrm{d}\log M}\mathrm{d}\log M}$$

$$\langle M_{\mathrm{DLA}}\rangle \simeq 10^{11.5-12.5}\,M_\odot$$

~ LBG halo mass



DLA--LBG connection

$$\xi_{\rm DLA\text{-}LBG}(r) = \frac{D_{\rm DLA}D_{\rm LBG} - D_{\rm DLA}R_{\rm LBG} - R_{\rm DLA}D_{\rm LBG} + R_{\rm DLA}R_{\rm LBG}}{R_{\rm DLA}R_{\rm LBG}},$$

Cooke+ '05

Best-fit

$r_0 = 3.3 \pm 1.3\,h^{-1}{\rm Mpc}$

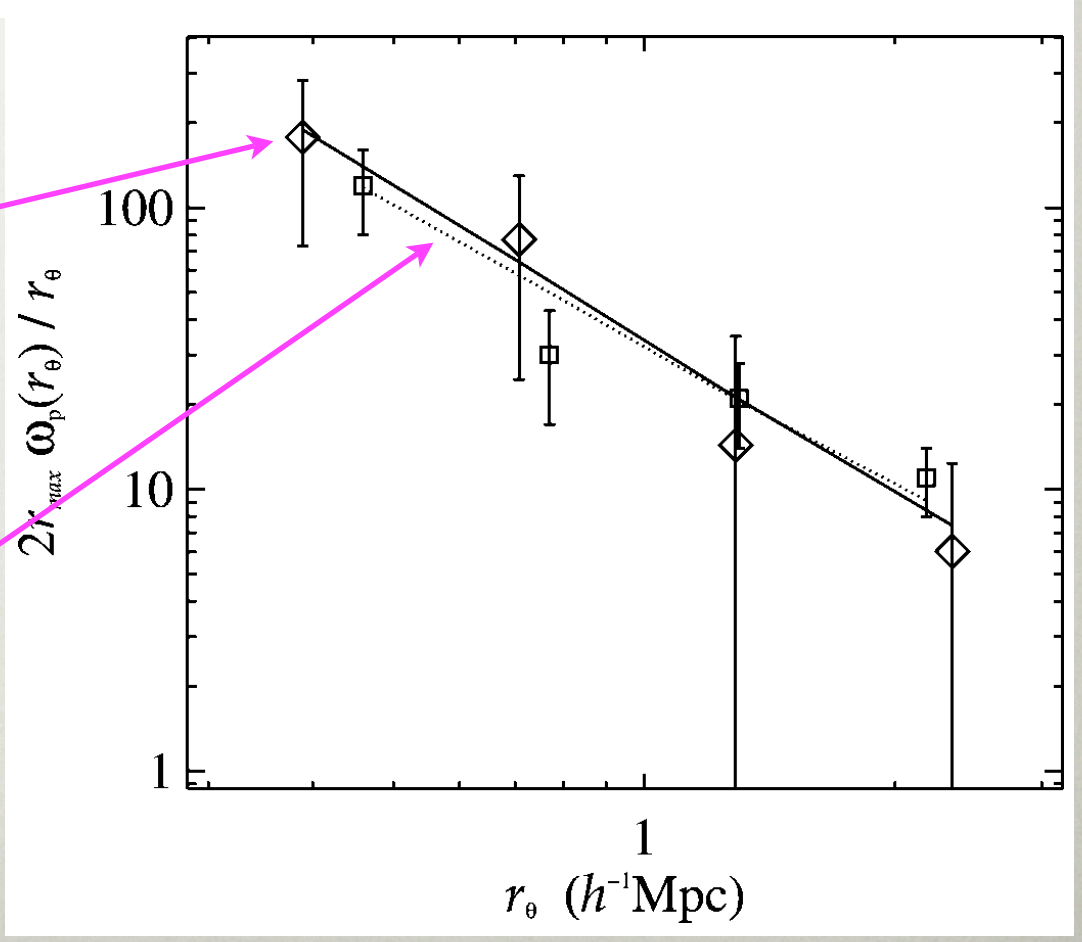
$\gamma = 1.7 \pm 0.4$

LBG-auto

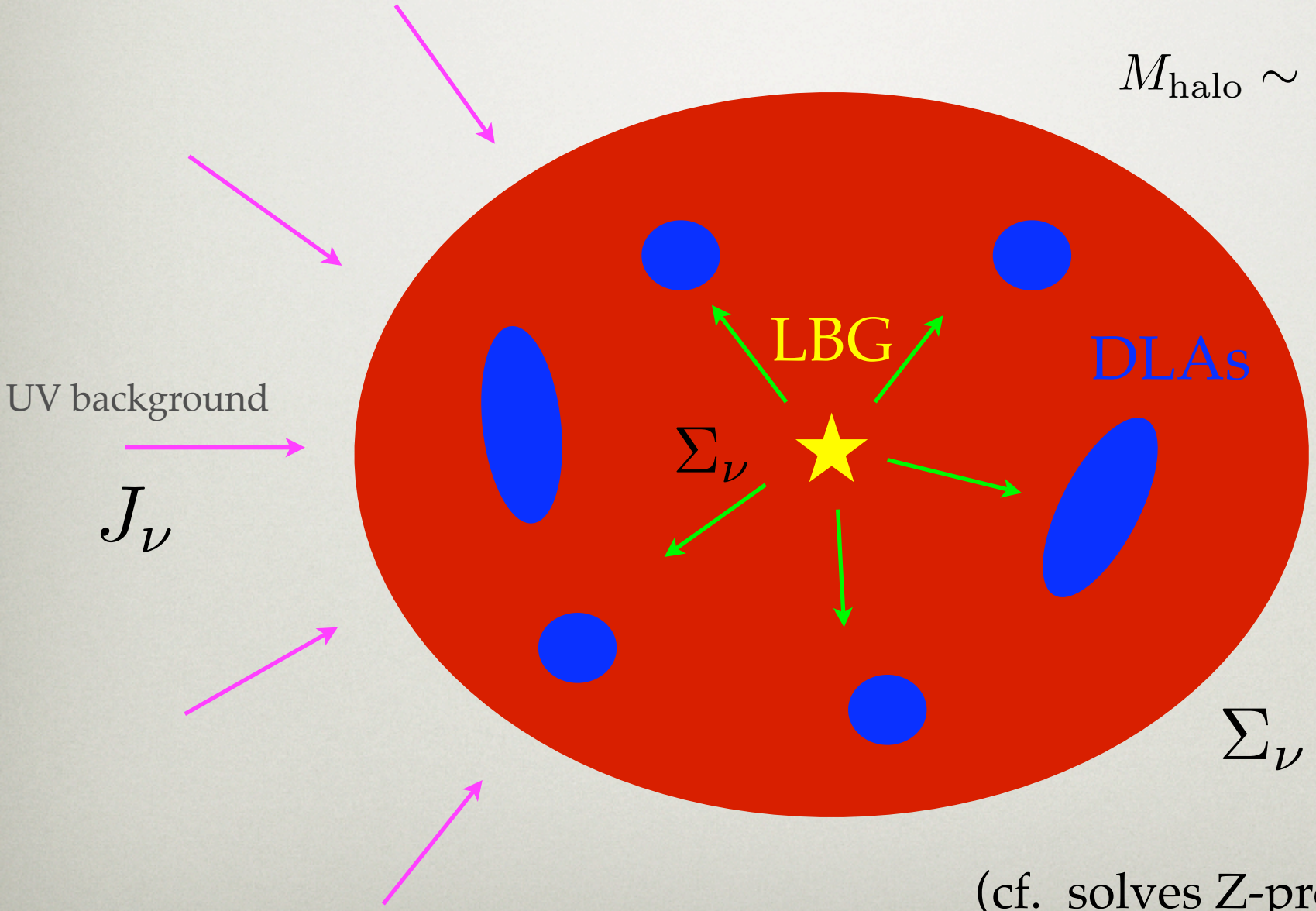
$r_0 = 3.96 \pm 0.29\,h^{-1}{\rm Mpc}$

$\gamma = 1.55 \pm 0.15$

$\langle M_{\rm DLA}\rangle \simeq 10^{11.2} M_\odot$

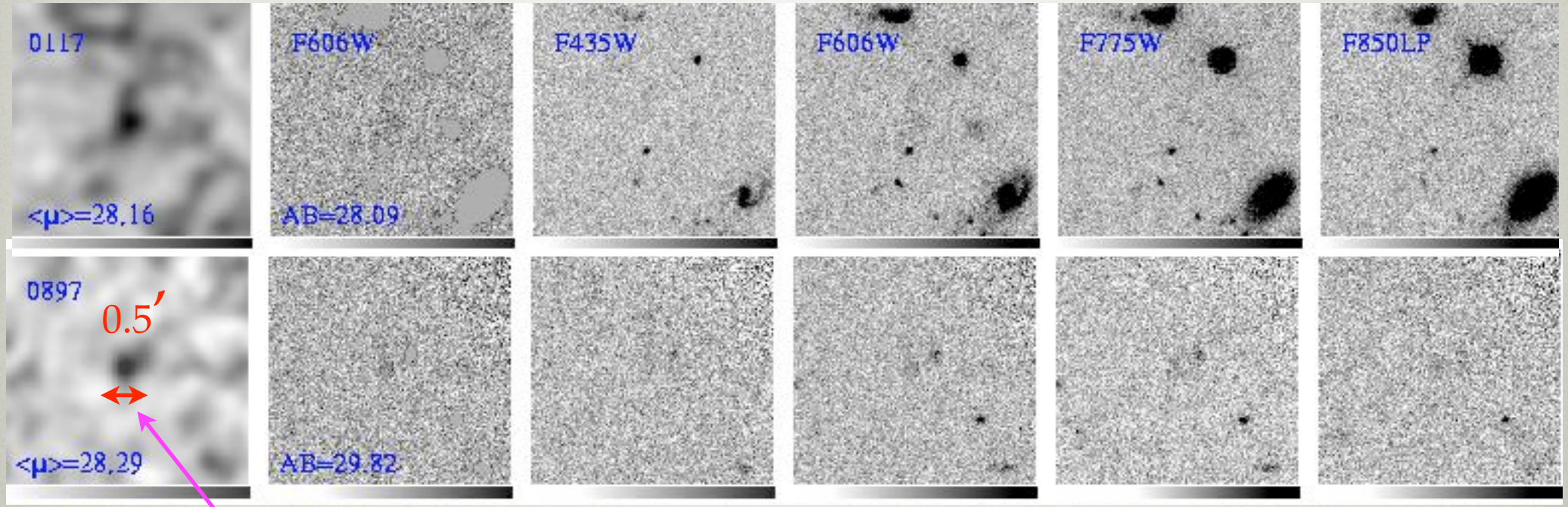


The New Picture



(cf. solves Z-problem too.)

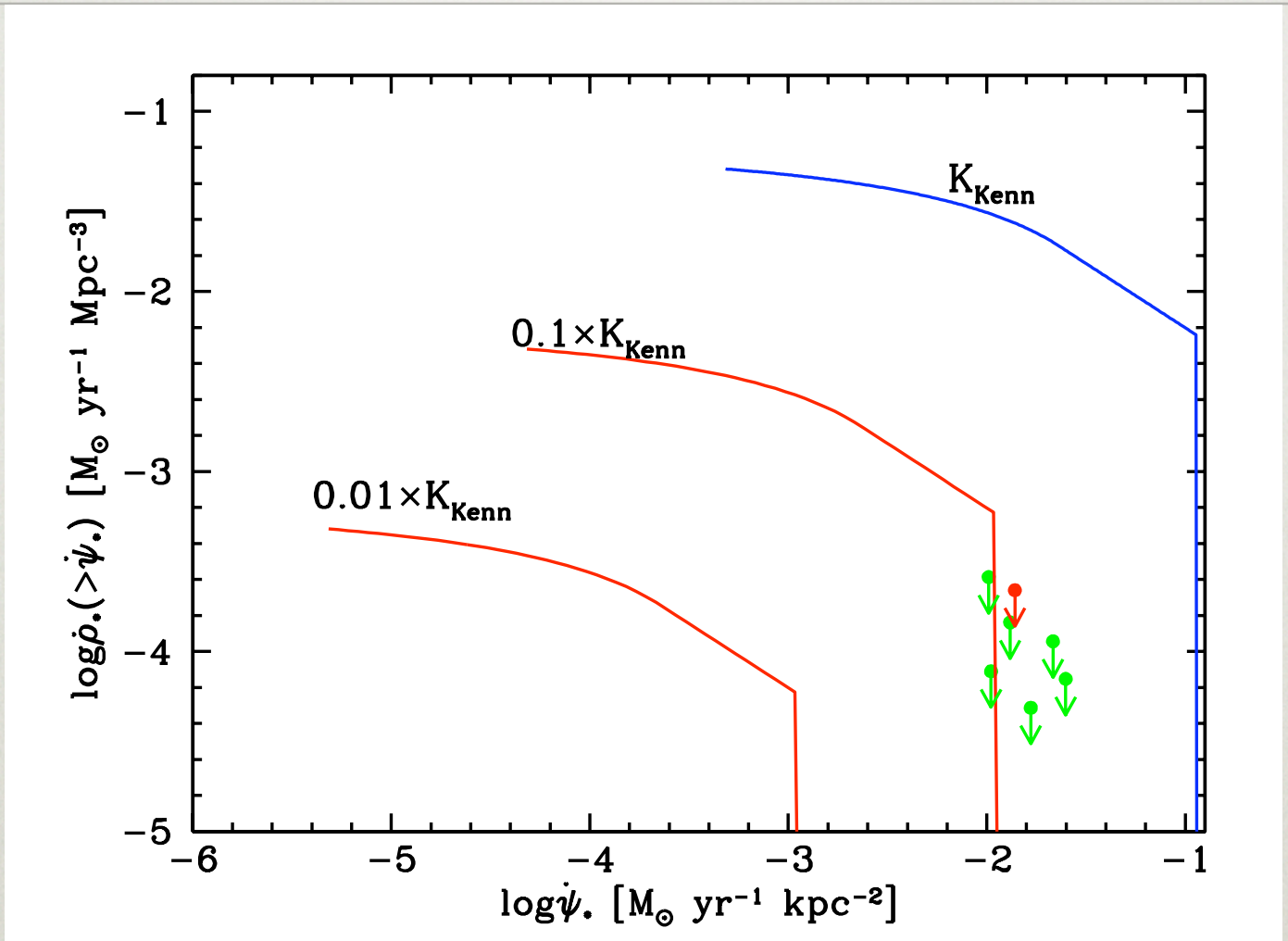
Faint Galaxies in UDF



No extended SF region detected at high-z.

Wolfe & Chen '06, in prep

Different SF Threshold at high-z?

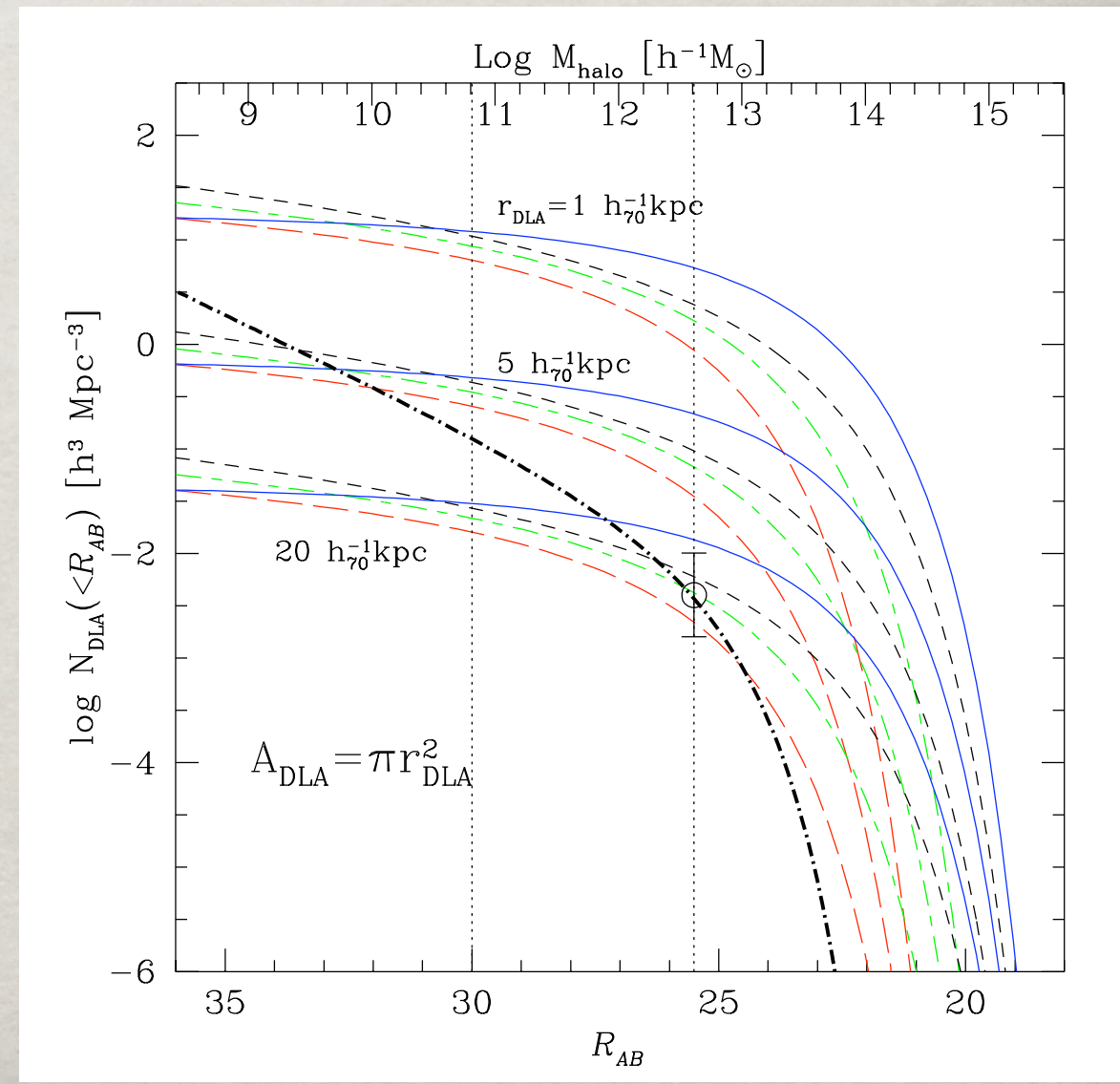


$$\dot{\rho}_\star(>\dot{\psi}_\star) \propto \int_{N_{\rm HI}}^{\infty} f(N_{\rm HI}) K_{\rm enn}(N_{\rm HI}) dN_{\rm HI}$$

Wolfe & Chen '06, in prep

Number Density of DLAs

More DLAs than LBGs down to R_{AB}=30 mag if A_{DLA}<5 kpc



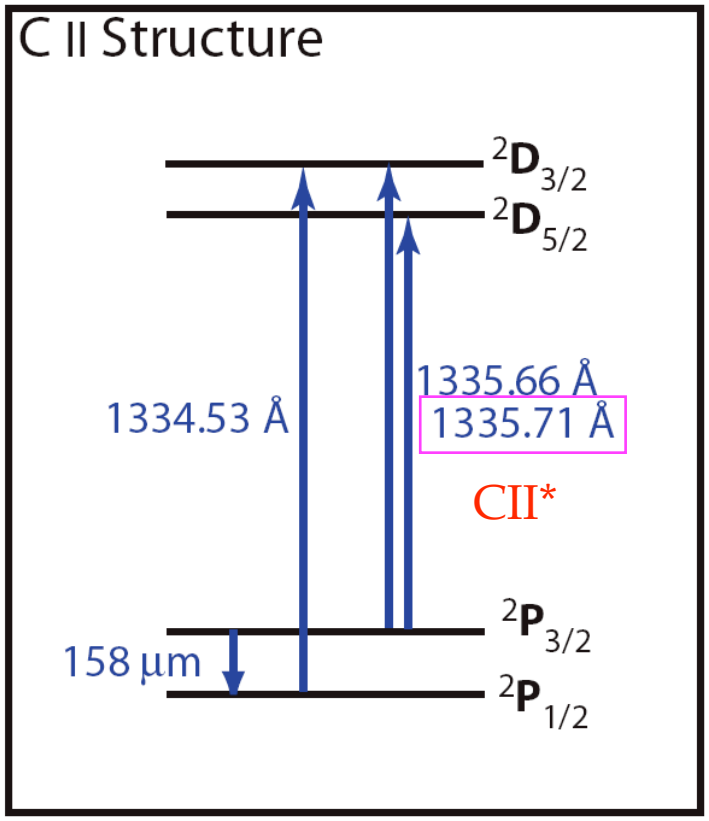
Can we detect DLA gas directly?

Why CII?

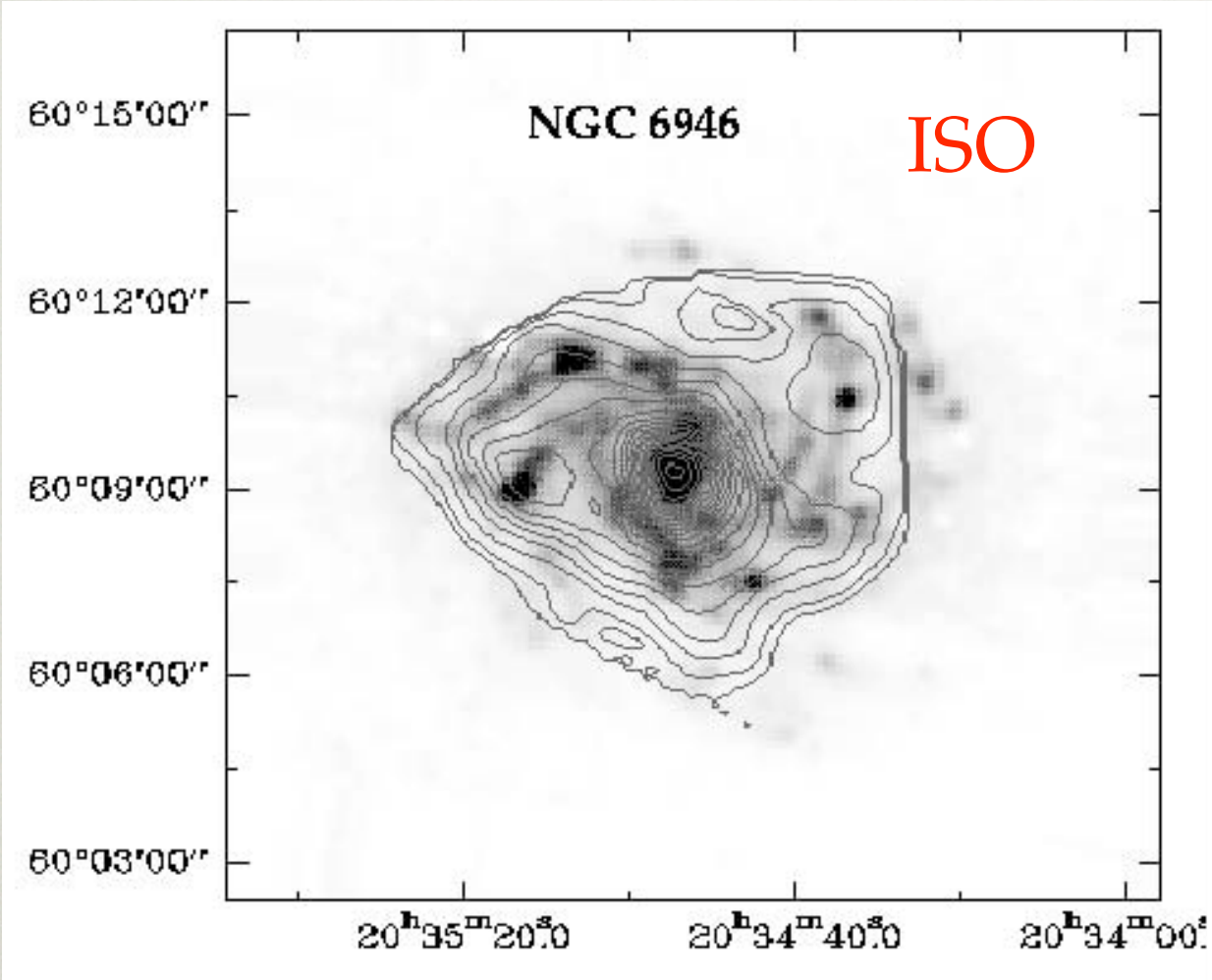
- Dominant coolant of MW
- Complementary to opt-IR
  (cf. Lyman break galaxies @ z~3)
- A new window for high-z SF using DLAs
  (Wolfe+ '03)

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

- Cosmological galaxy formation study with ALMA



Local Obs of [CII]

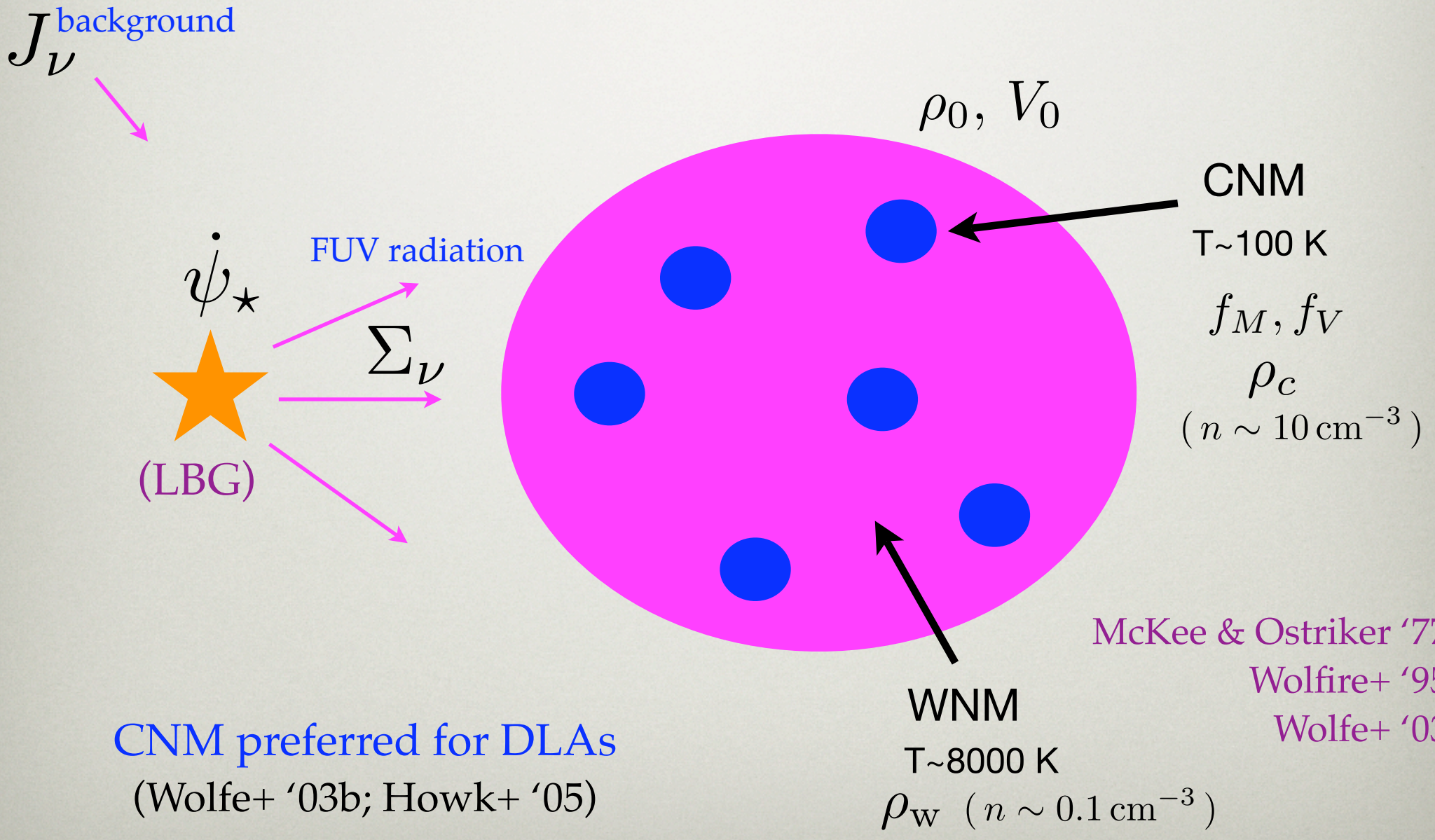


Contoursi+ '02

Contours: CII line emission
Image: 5-8 micron ISOCAM

e.g.
Madden+ '93
Malhotra+ '97, '01
Leech+ '99
Contoursi+ '02

Multi-phase ISM model



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

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

CNM mass fraction

$$\underset{\text{(CNM)}}{\rho_C V_C} + \underset{\text{(WNM)}}{\rho_W V_W} = \rho_0 V_0 \quad \text{(mass conservation)}$$

$$V_C + V_W = V_0 \quad \text{(volume conservation)}$$

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

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

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

KN+ ‘06

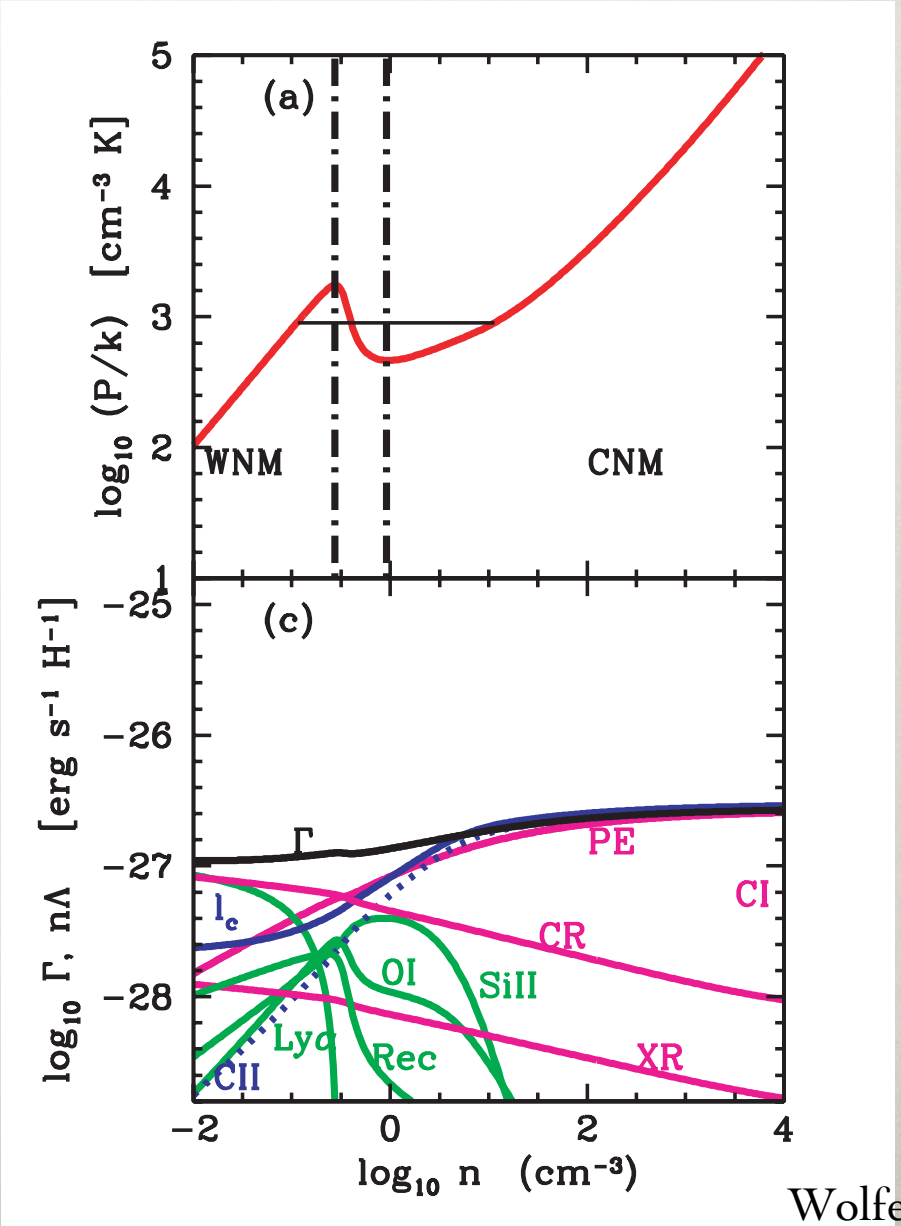
Phase Diagram

Equilibrium:

$$\Gamma = n\Lambda$$

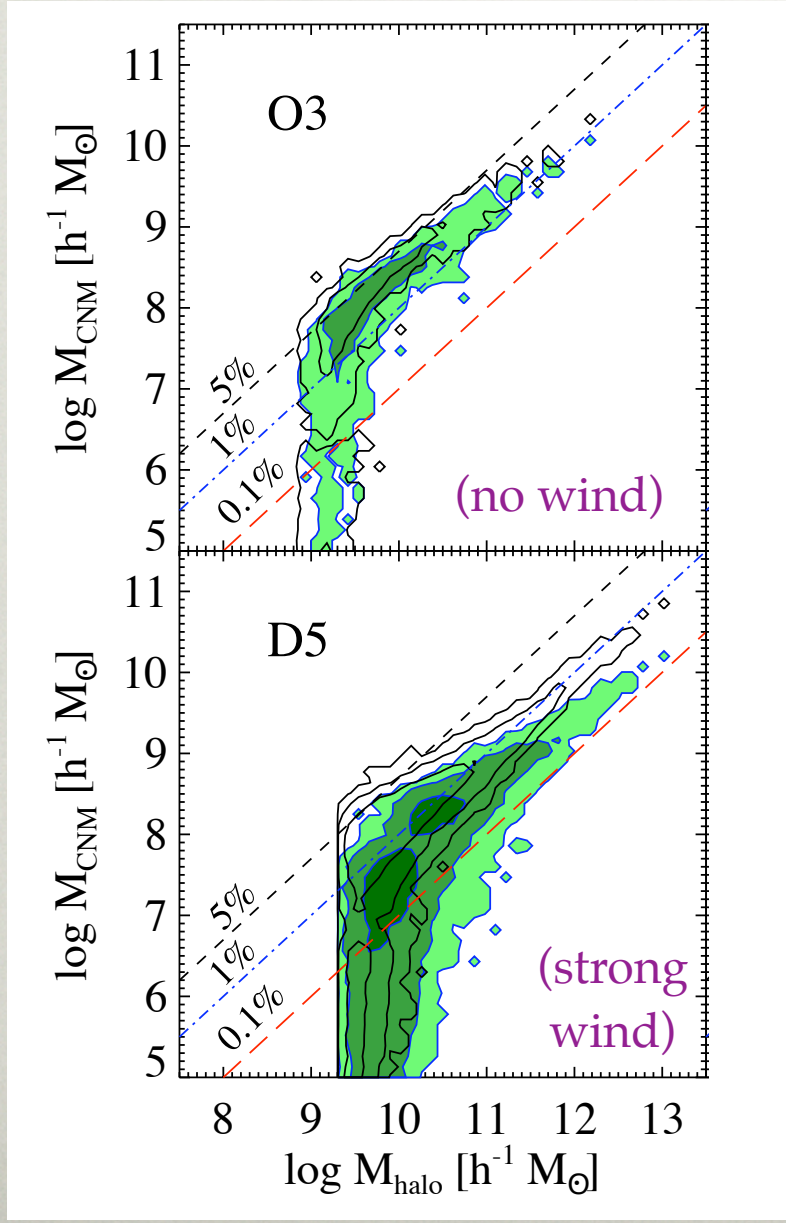
CII luminosity per H atom (dotted line)

$$\ell_{CII}$$



Wolfe+ '03

CNM mass vs. Halo mass



Given ρ_0, $\dot{\psi}_\star$, Z from simuluation,

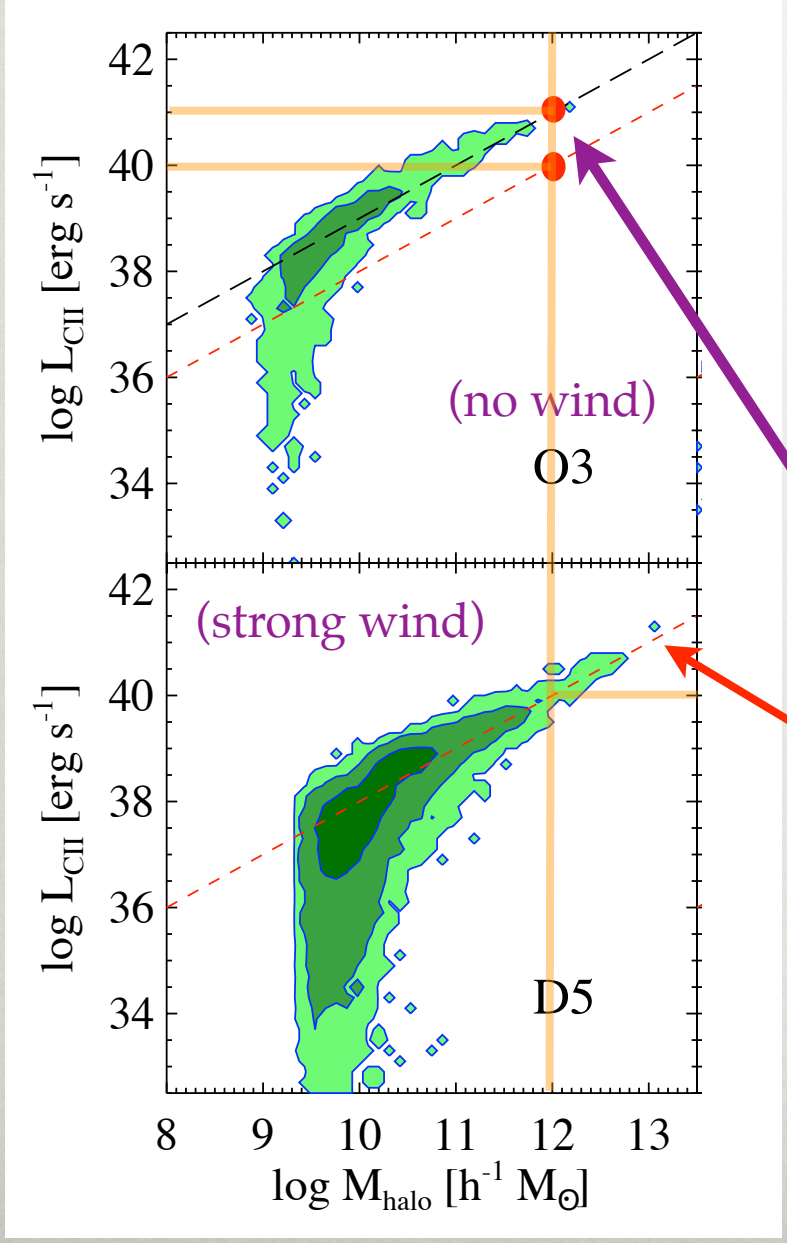
and ρ_C, ρ_W from the model,

$$M_{\rm CNM} = \Sigma_i \; f_M \rho_0 V_0$$

Semi-analytic model of Mo, Mao, White (1998): disk mass fraction = 0.05

Simulation suggests lower neutral mass fraction in halos.

CII LUMINOSITY VS. HALO MASS



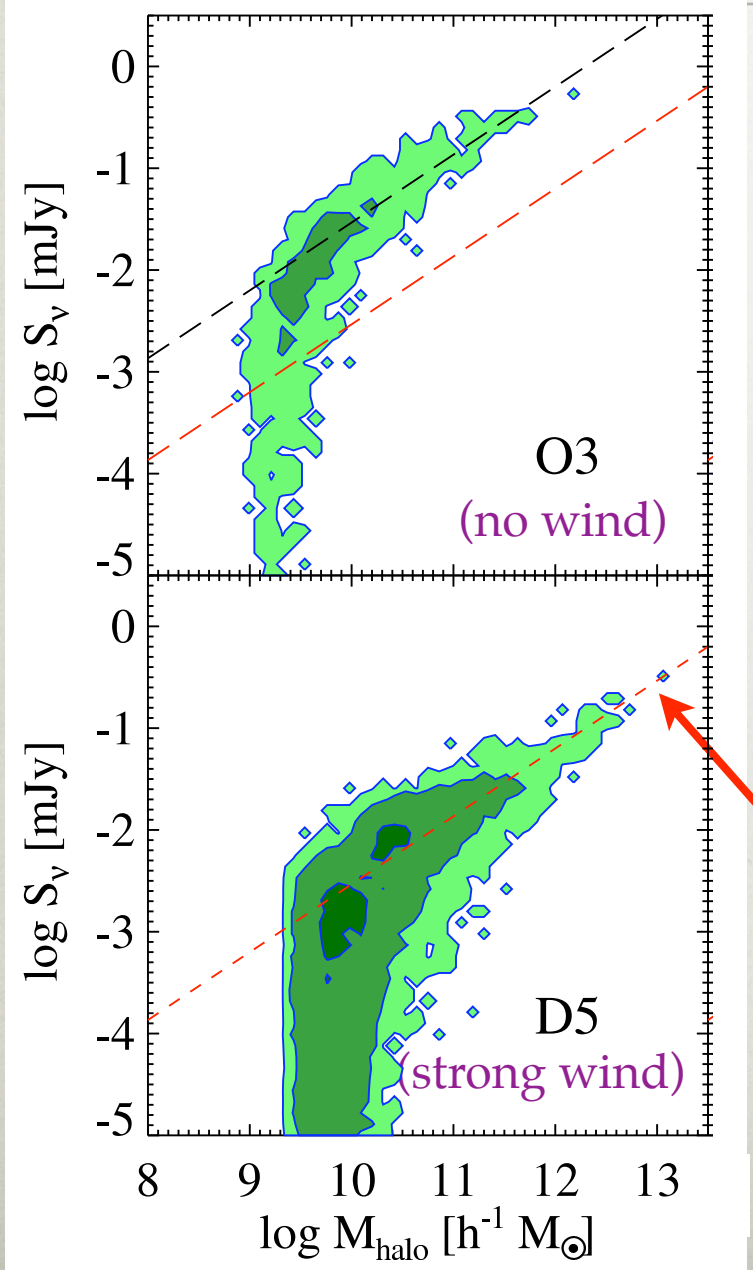
$$L_{\rm CII} = \ell_C \cdot \frac{M_{\rm CNM}}{\mu m_{\rm H}} \propto M_{\rm halo}$$

$$L_{\rm CII} \approx C_1 \left(\frac{M_{\rm halo}}{10^{12} h^{-1} M_\odot} \right),$$

$C_1 = 10^{41}$ erg/s (no feedback)

$C_1 = 10^{40}$ erg/s (strong feedback)

CII Flux Density vs. Halo mass



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

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

median

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

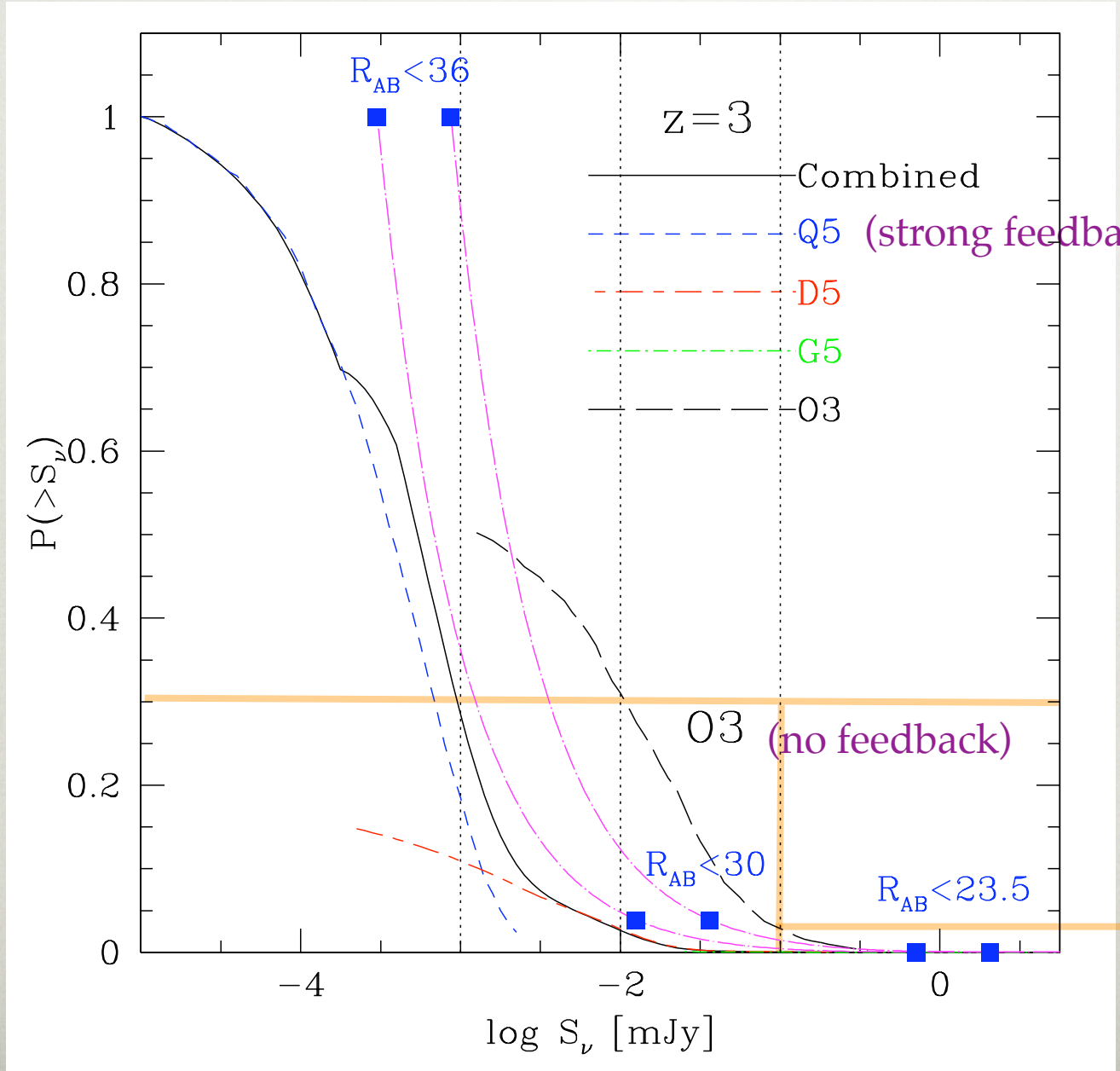
circular velocity

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

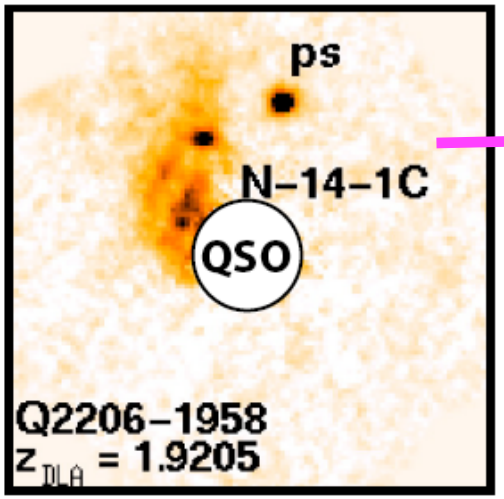
$C_2 = 0.6\,{\rm mJy}$ (no feedback)

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

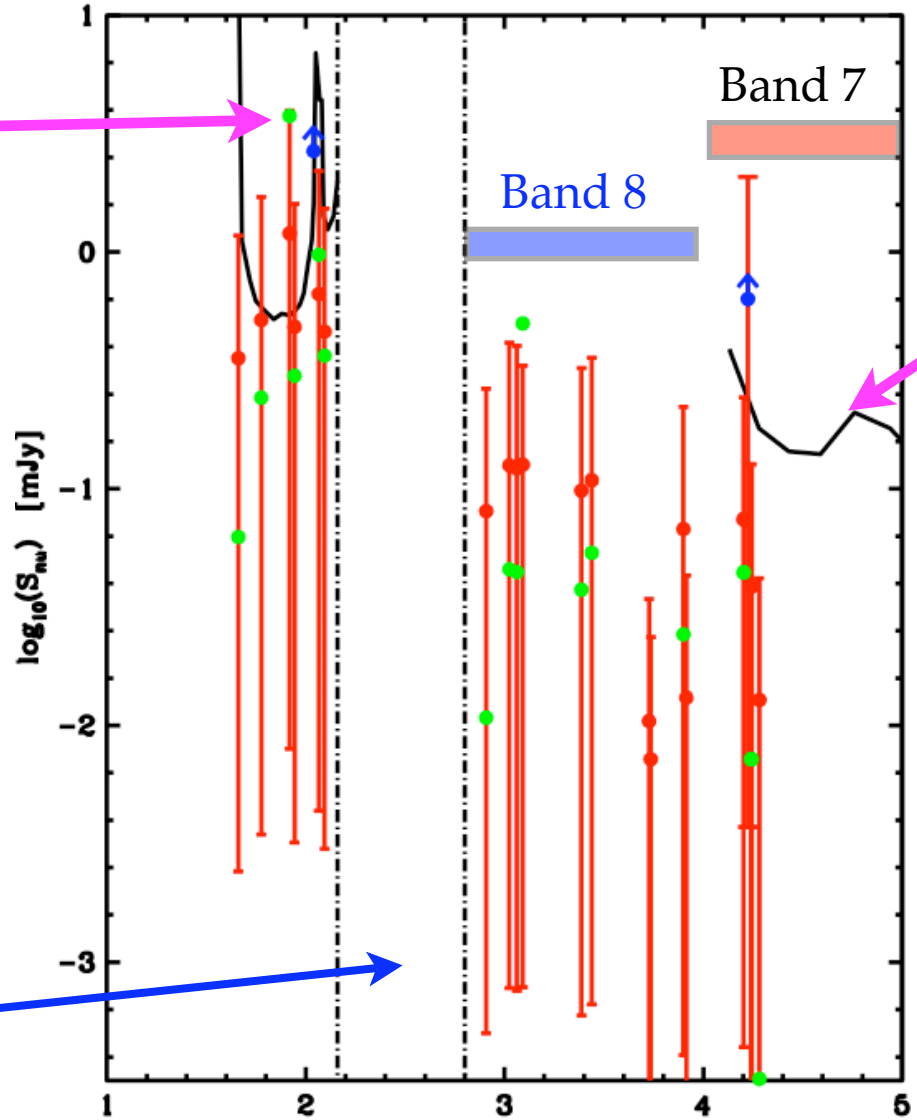
Flux Density PDF



Estimates for Actual DLA galaxies



(Moller+ '02)



ALMA 20 hr integration
1-sigma sensitivity

redshift desert
(atmospheric window)

Conclusions

- DLAs are useful for high-z galaxy formation study
- Numerical modeling challenging
- Mean DLA halo mass: $\log \langle M_{\rm DLA} \rangle \simeq 11.5 - 12.5$
- possible DLA -- LBG connection
- SF threshold different at high-z?
- [CII] 158 micron emission: ~1 mJy for bright gals

--> Future project for ALMA & SPICA