Star Formation & DLAs in Cosmological Simulations

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Outline

- Recipes for star formation (SF) & feedback in cosmological simulations -- past efforts
- Some highlighted results on galaxies and DLAs from Eulerian & SPH simulations
- Alternative SF recipe: Blitz's pressure criteria
- Problems in current simulations
- Future efforts

SF recipes

Two basic models:

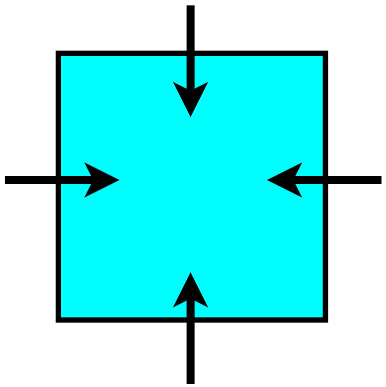
- Cen & Ostriker (1992)
  Eulerian hydro simulation

- Springel & Hernquist (2003):
  SPH (smoothed particle hydrodynamics), subparticle multiphase ISM model -- extention of Yepes et al. (1997)

Cen & Ostriker (1992)

- 4 criteria for a cell to be star-forming:

1. $\delta > \delta_{\rm th}$ (overdense)
2. $\nabla \cdot \vec{v} < 0$ (contracting)
3. $t_{\rm cool} < t_{\rm dyn}$ (cooling fast)
4. $m_{\rm gas} > m_{\rm Jeans}$ (Jeans unstable)



then,

$$\dot{\rho}_\star = c_\star \frac{\rho_g}{t_\star} \qquad (c_\star \sim 0.1)$$

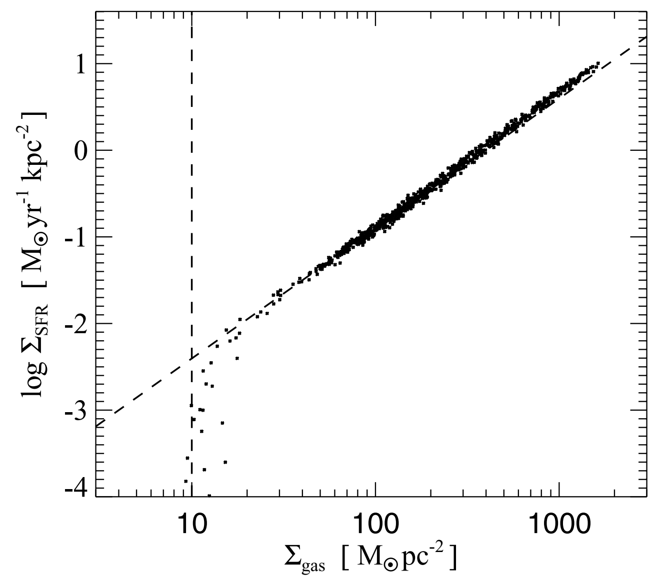
if $t_\star = t_{\rm dyn} \propto \frac{1}{\sqrt{G\rho}}$ $\longrightarrow$ $\dot{\rho}_\star \propto \rho_g^{1.5}$

Springel & Hernquist (2003)

Yepes+ ‘97

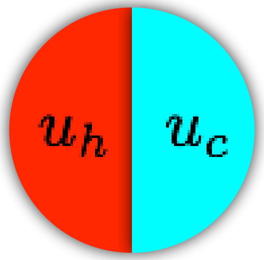
$$\dot{\rho}_\star = (1-\beta)\,\frac{\rho_c}{t_\star}$$

cold gas



$$t_\star = t_\star^0 \left(\frac{\rho_g}{\rho_{\rm th}}\right)^{-0.5} \qquad t_\star^0 = 2.1\,{\rm Gyr}$$

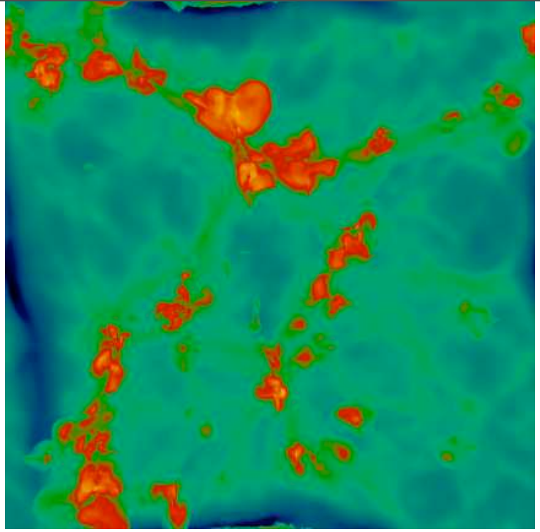
subparticle multiphase ISM model



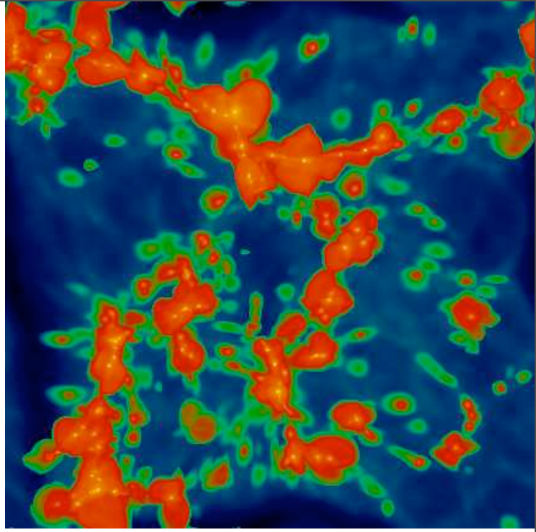
$$\rho_h \frac{du_h}{dt} = \beta \frac{\rho_c}{t_\star}(u_{sn} + u_c - u_h) - A\beta\frac{\rho_c}{t_\star}(u_h - u_c) - f\Lambda_{net}$$

$$u_c = {\rm const.}$$

Feedback



temperature



metallicity

- Cen, KN & Ostriker '05

$$\Delta E_{SN} = \epsilon_{sn} m_\star c^2 \quad (\epsilon_{sn} = 10^{-6} - 10^{-5})$$

$$\Delta E_{UV} = f_{esc,Z}\, \epsilon_{uv,Z}\, m_\star c^2 \quad (\epsilon_{uv,Z} = 10^{-6} - 10^{-4}) \quad (f_{esc} = 2 - 4\%)$$

$$\Delta E_{\rm AGN} = f_\nu\, \epsilon_{\rm AGN}\, m_\star c^2 \quad (\epsilon_{\rm AGN} \sim 10^{-5})$$

- Springel & Hernquist '03

$$\left.\frac{\mathrm{d}\rho_{\rm c}}{\mathrm{d}t}\right|_{\rm EV} = A\beta \frac{\rho_{\rm c}}{t_\star}.$$

(evaporation of cold gas by SN feedback)

$$A(\rho) = A_0 \left(\frac{\rho}{\rho_{\rm th}}\right)^{-4/5},$$

(McKee & Ostriker '77)

Self-regulated star formation

$$\rho_{\rm th} = \frac{x_{\rm th}}{(1 - x_{\rm th})^2} \frac{\beta u_{\rm SN} - (1-\beta) u_{\rm c}}{t_0^\star \Lambda(u_{\rm SN}/A_0)},$$

Galactic wind in SPH simulation

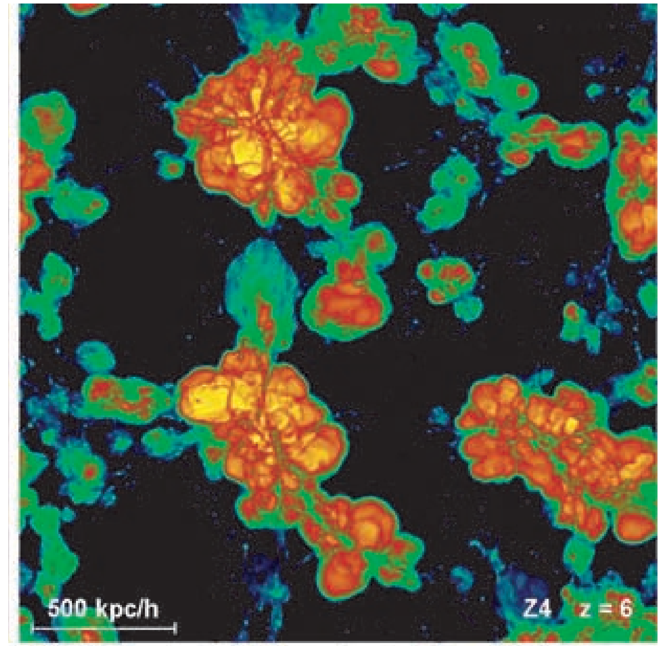
mass loss rate:

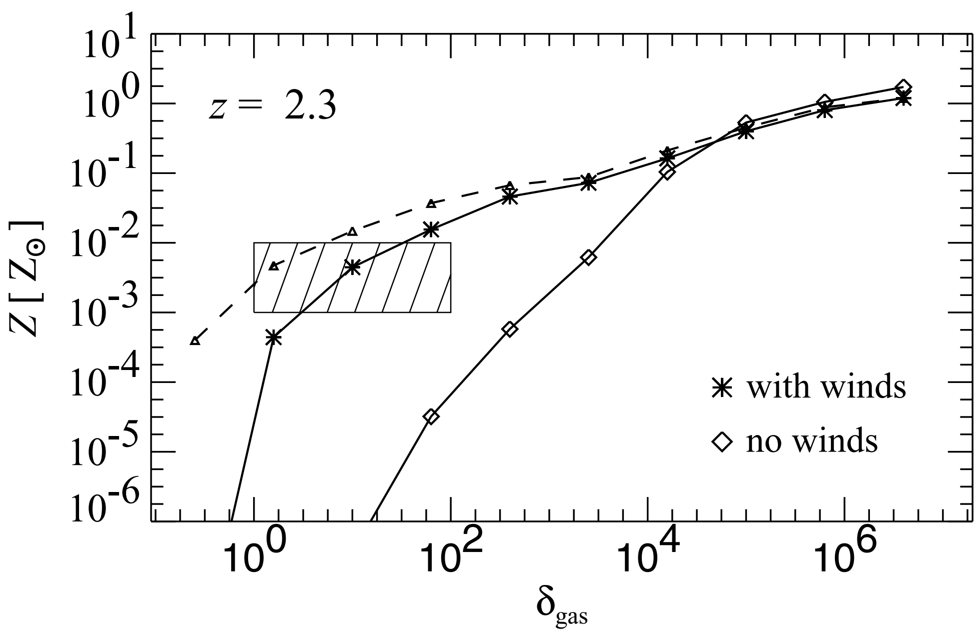
$$\dot{M}_{\rm w} = \eta \dot{M}_\star, \quad (\eta = 2)$$

wind energy:

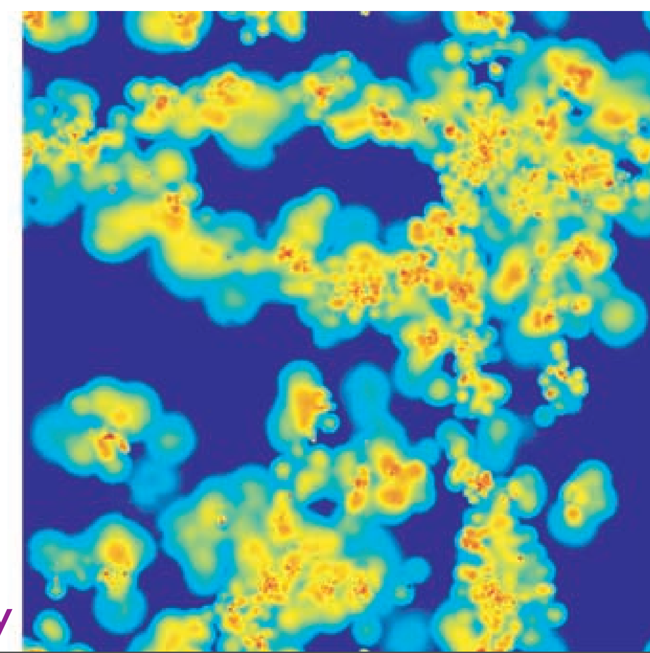
$$\frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 = \chi \epsilon_{\rm SN} \dot{M}_\star, \quad (\chi = 0.25)$$

temperature



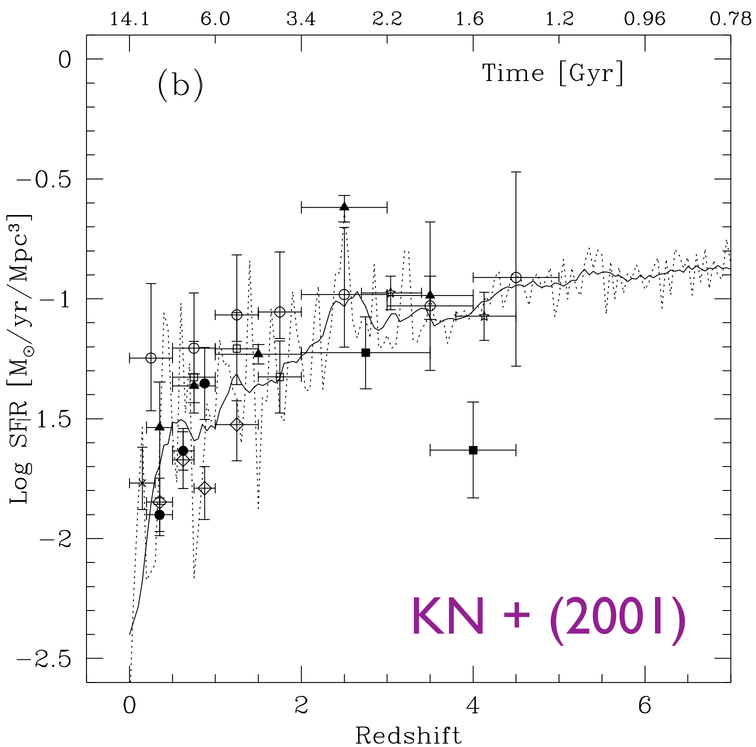


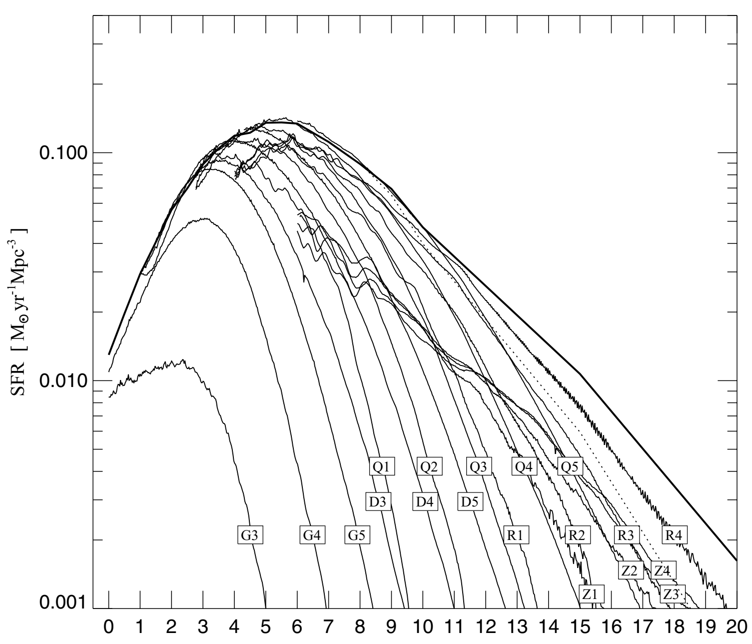
metallicity



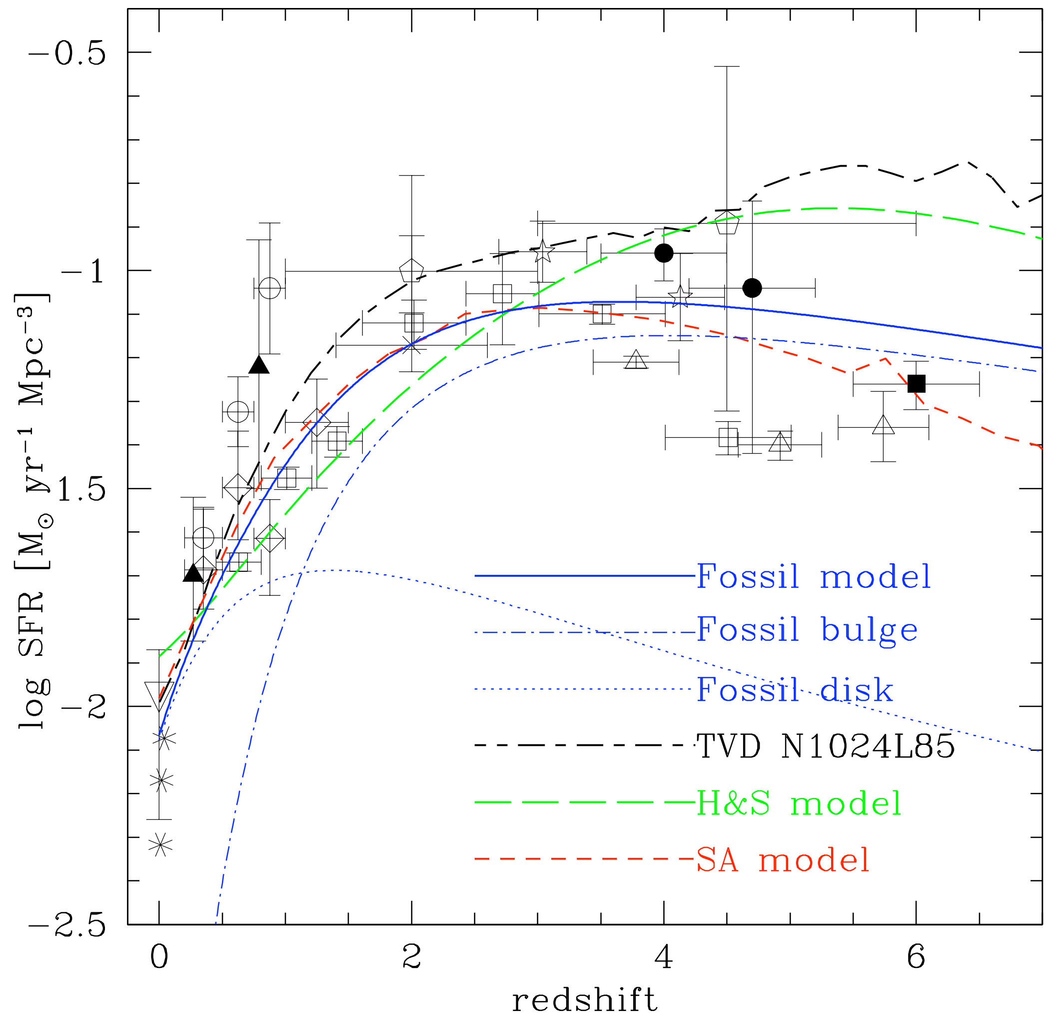
Some highlighted results on galaxies and DLAs

Cosmic Star Formation History



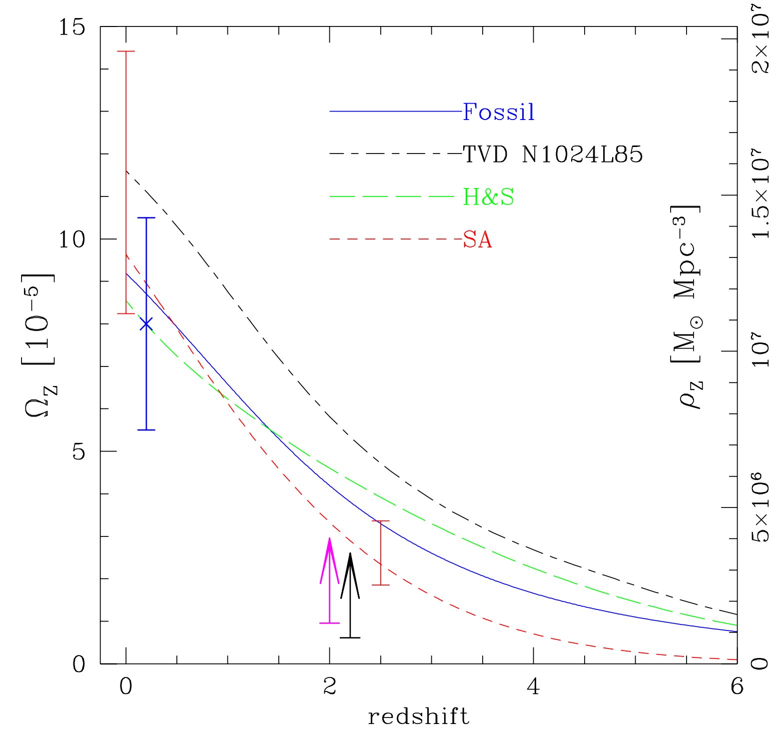


Springel & Hernquist (2003)

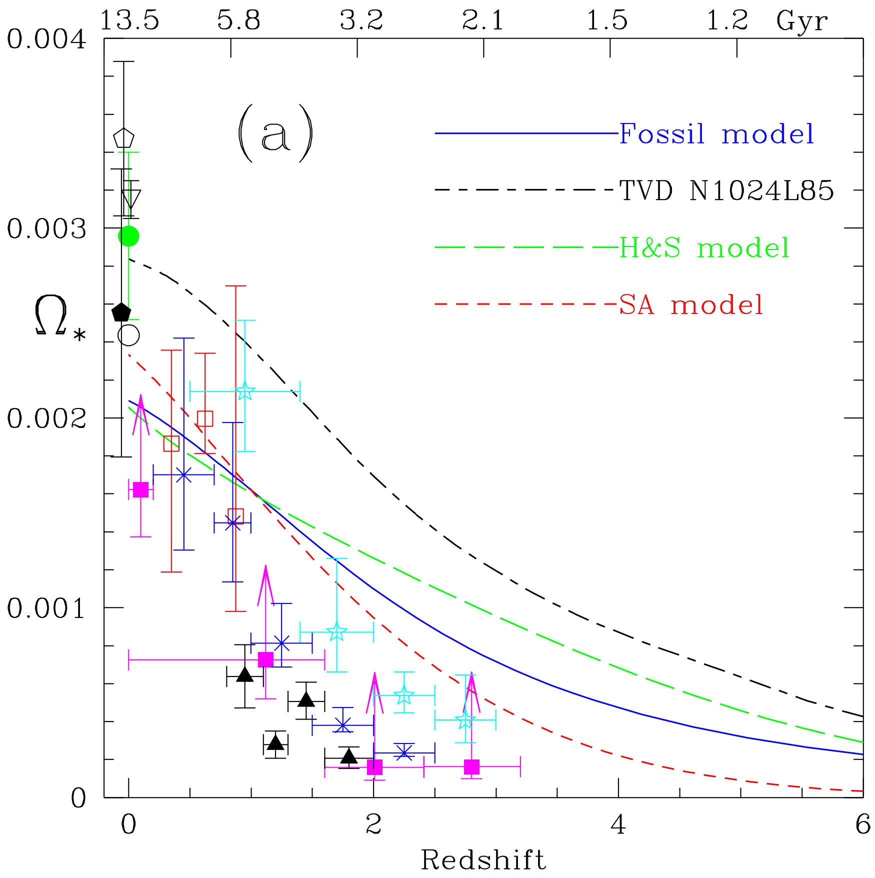


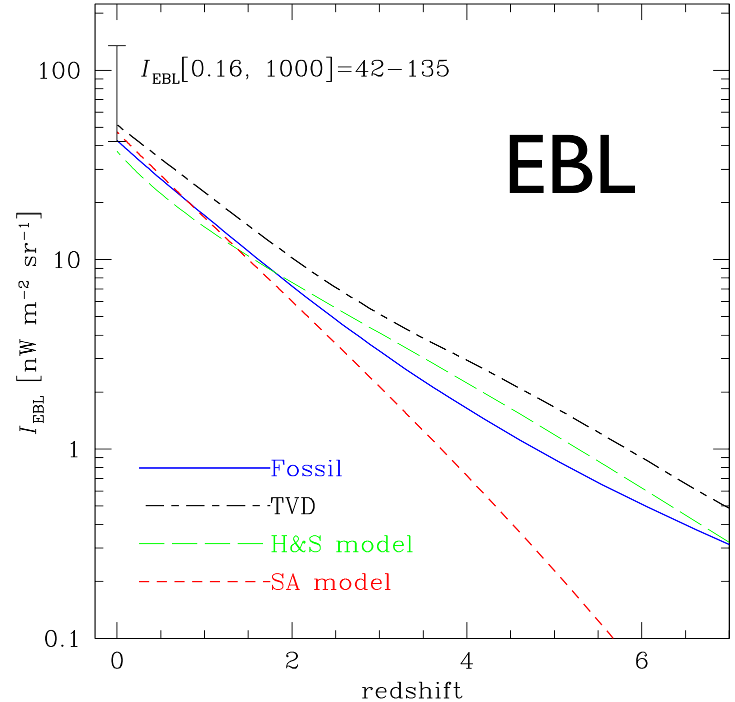
KN + (2006)

Metal mass density



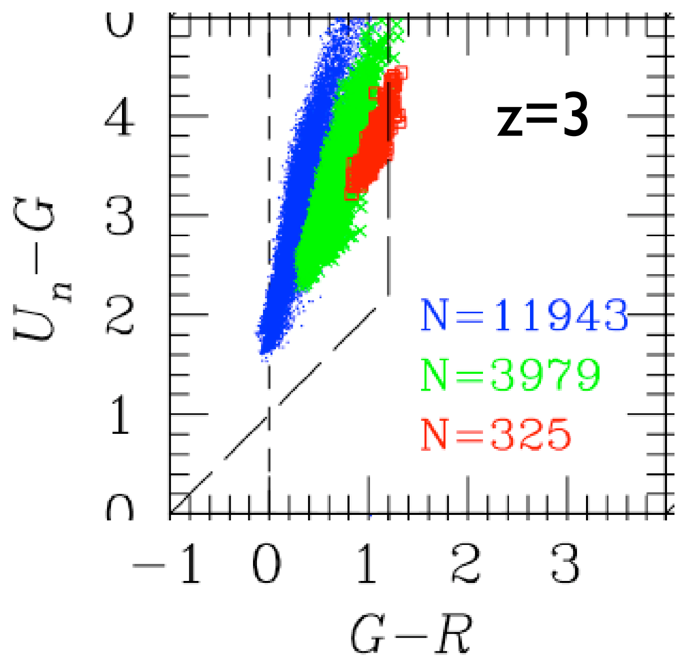
Stellar mass density

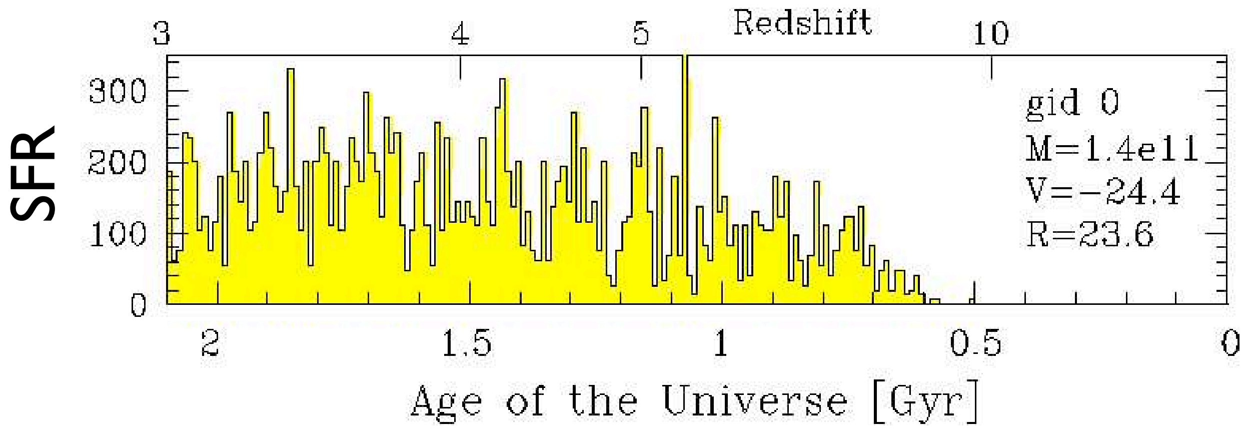




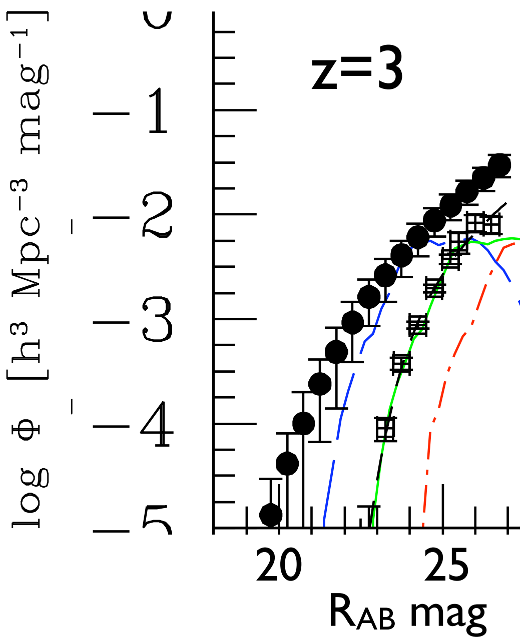
KN+ 2004, 2006

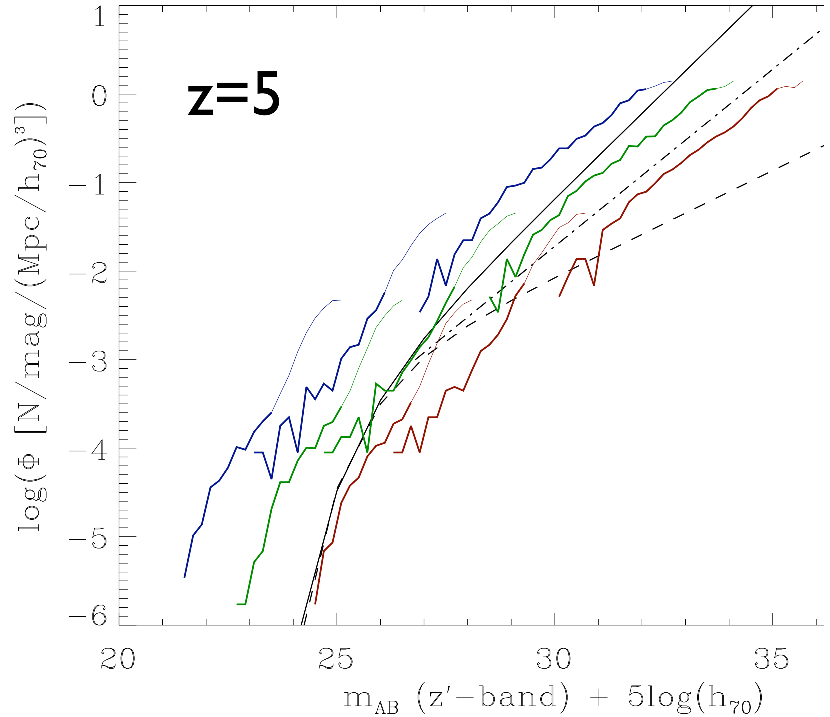
Lyman-break Galaxies at z=3-6





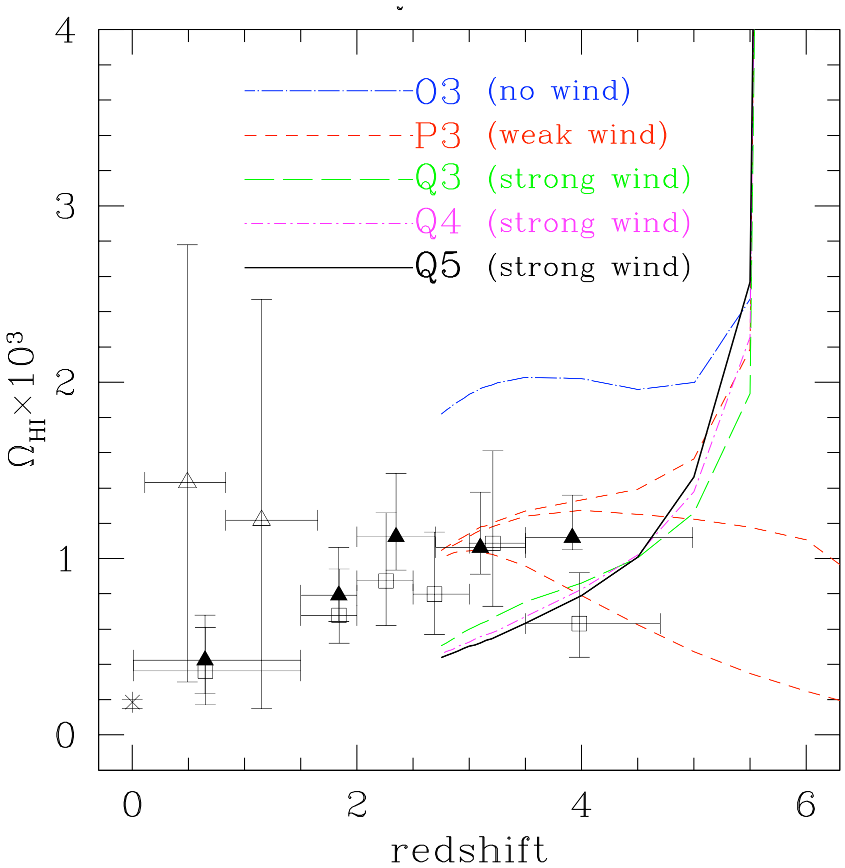
KN+ 2004



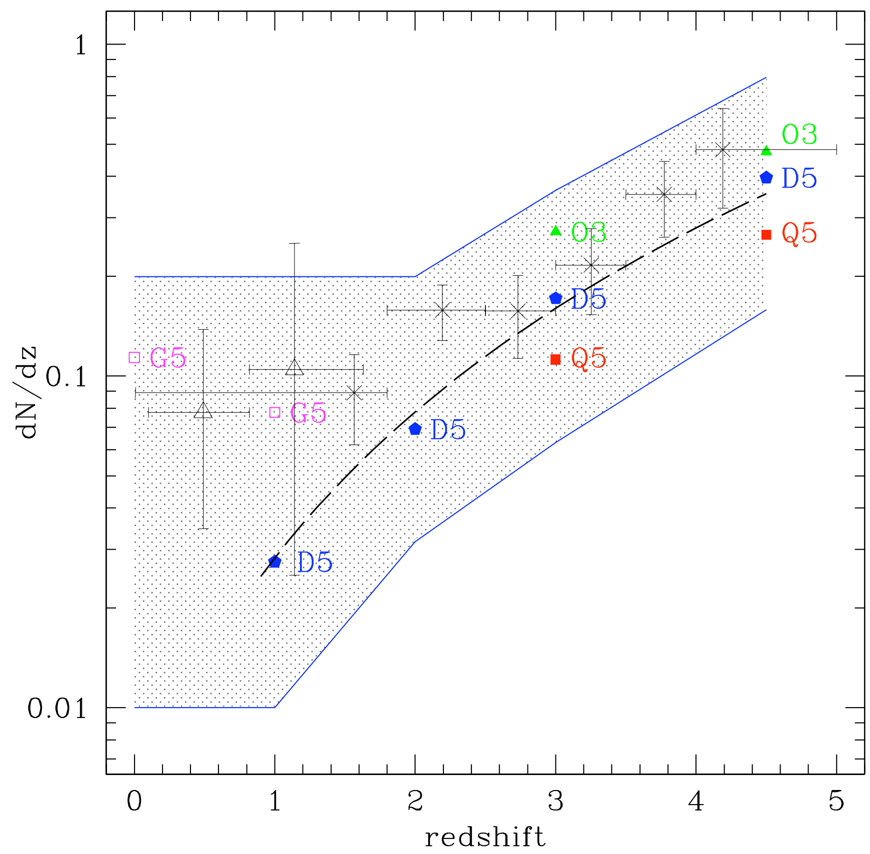


Night, KN+ 2006

HI & DLA statistics

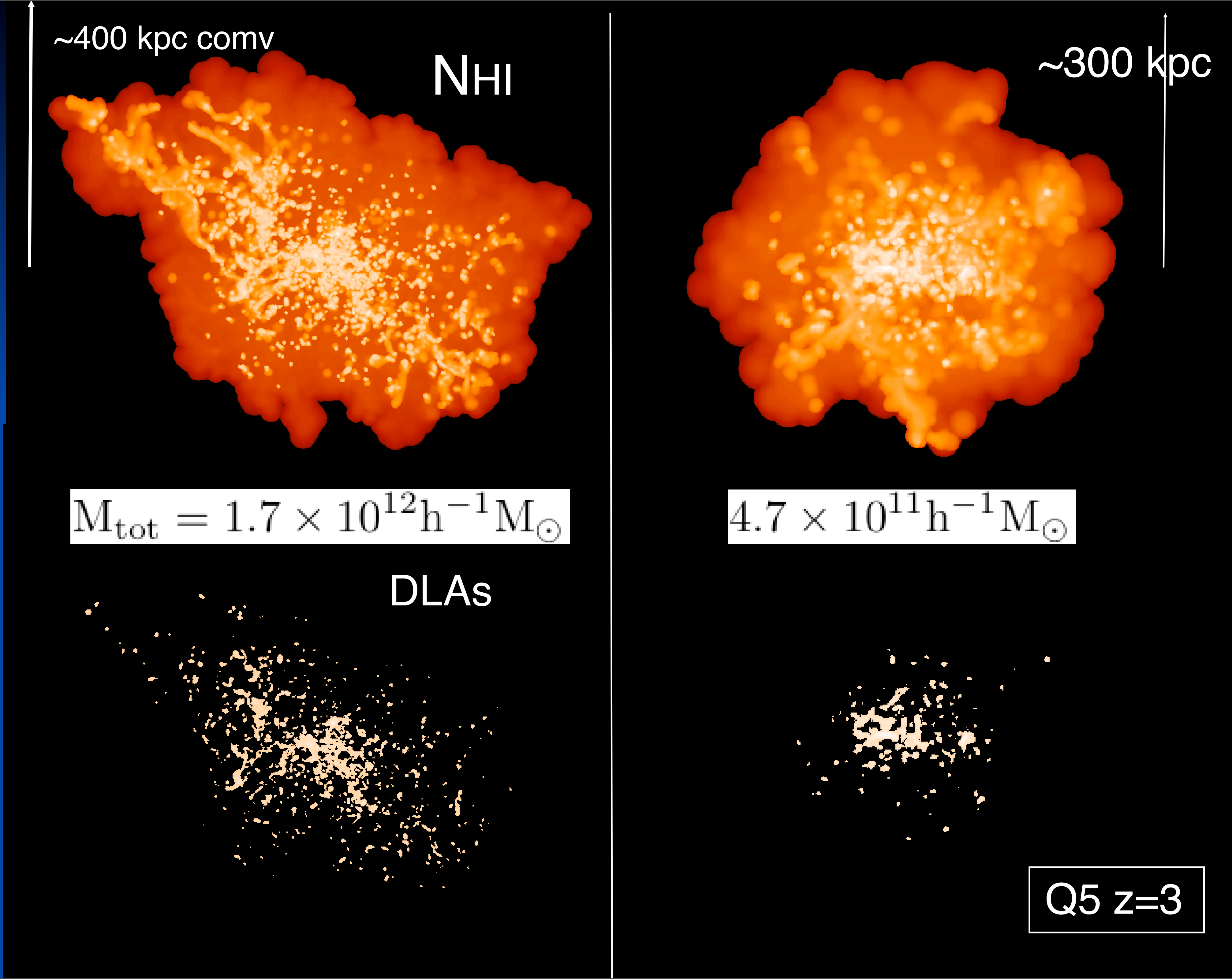


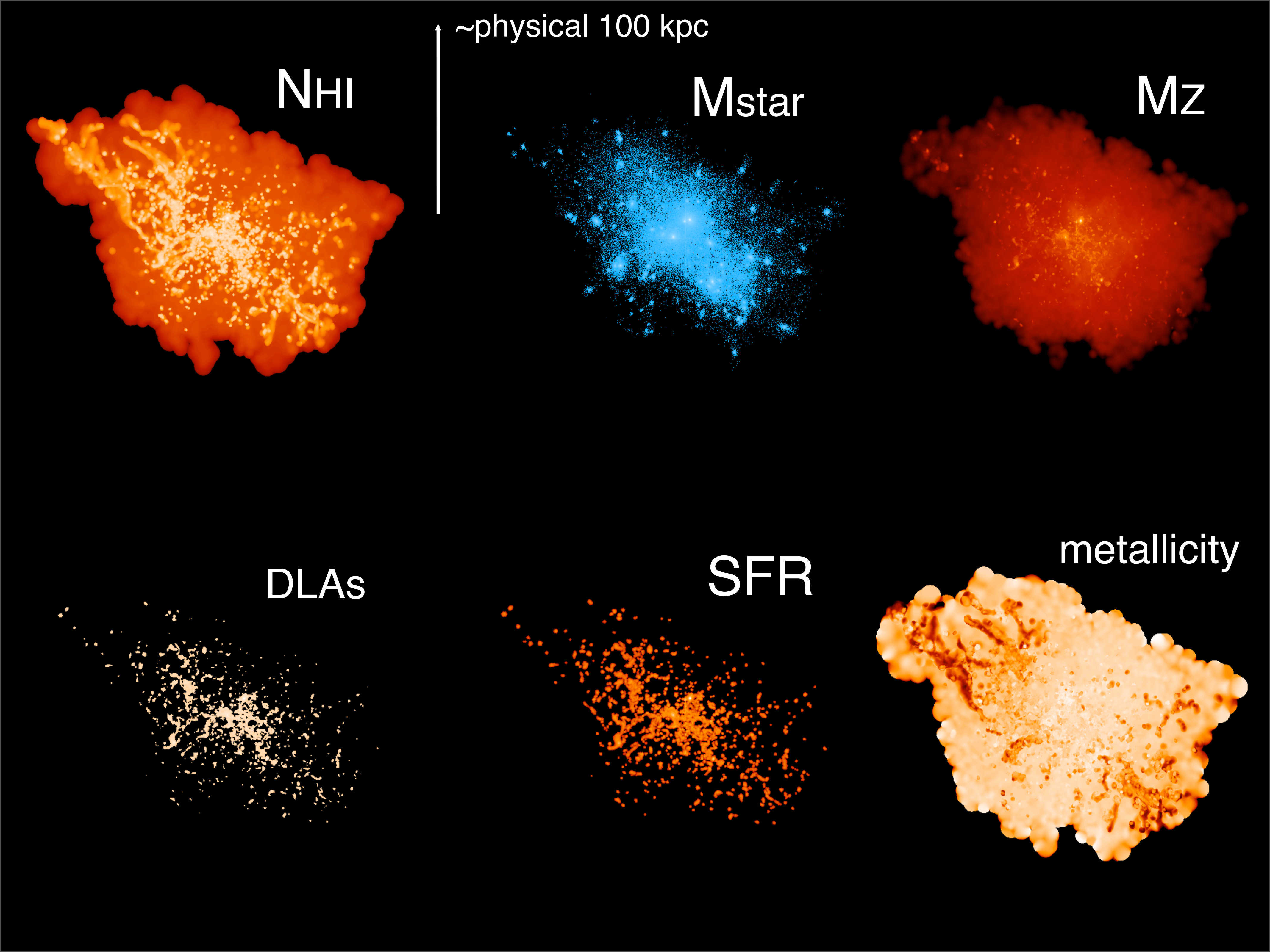
HI mass density

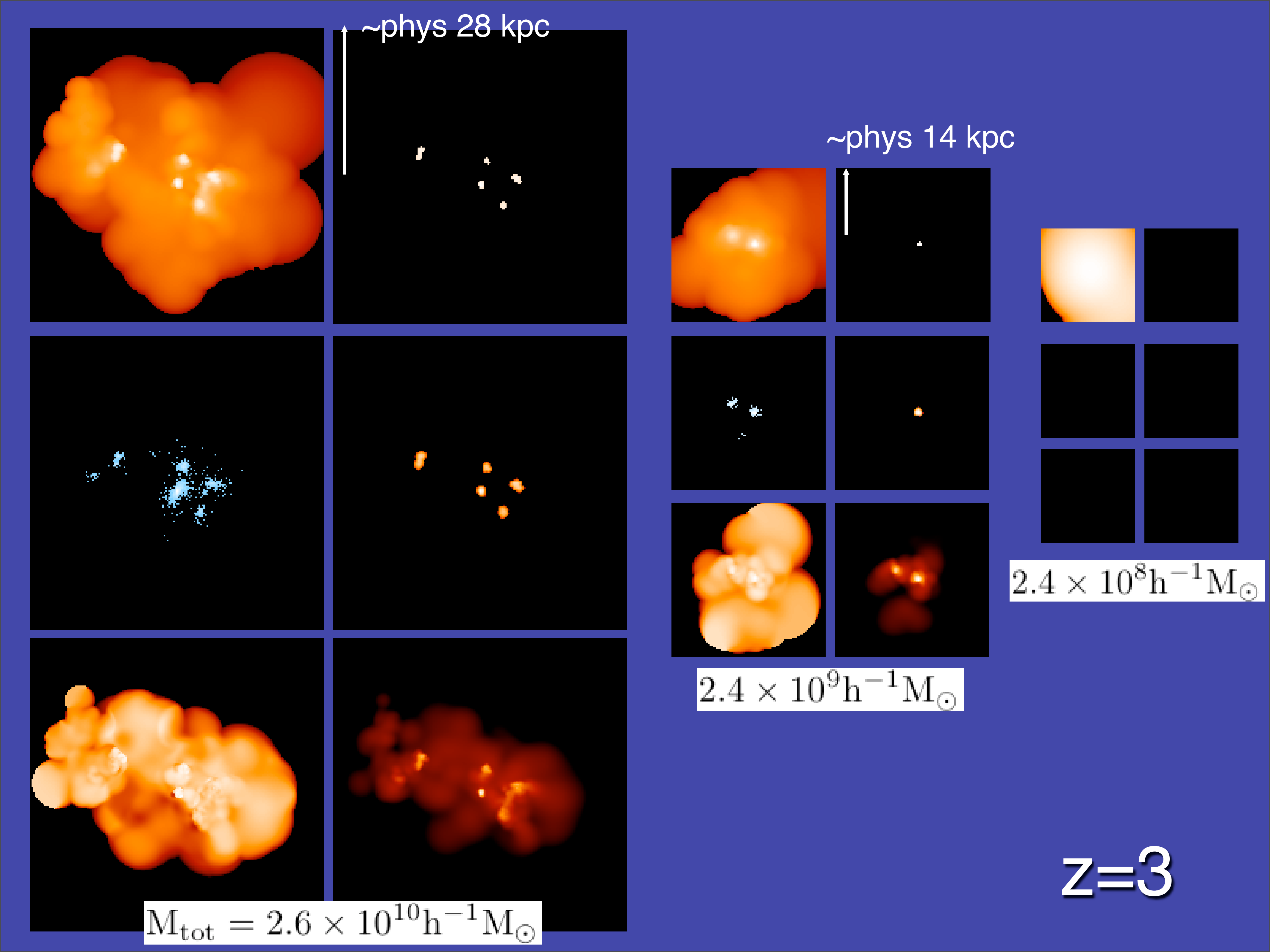


DLA rate-of-incidence

KN+ (2004a,b; 2006)


~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

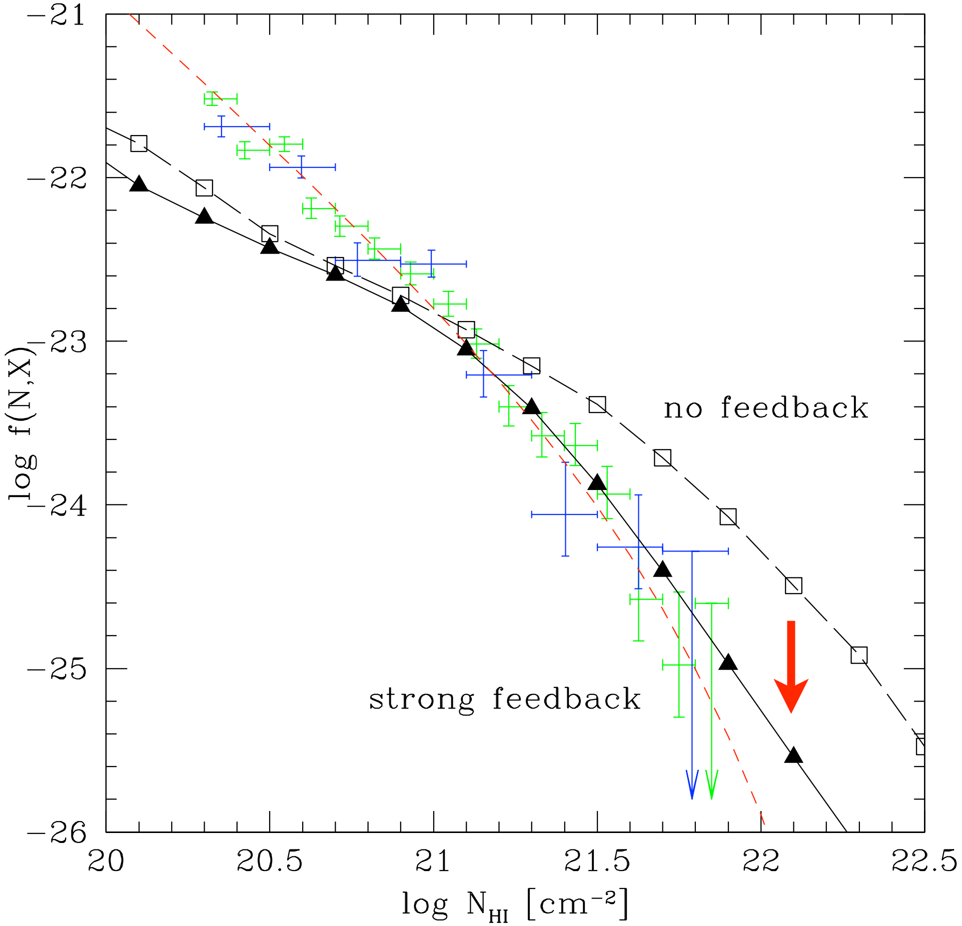

~physical 100 kpc
NHI
Mstar
Mz
DLAs
SFR
metallicity

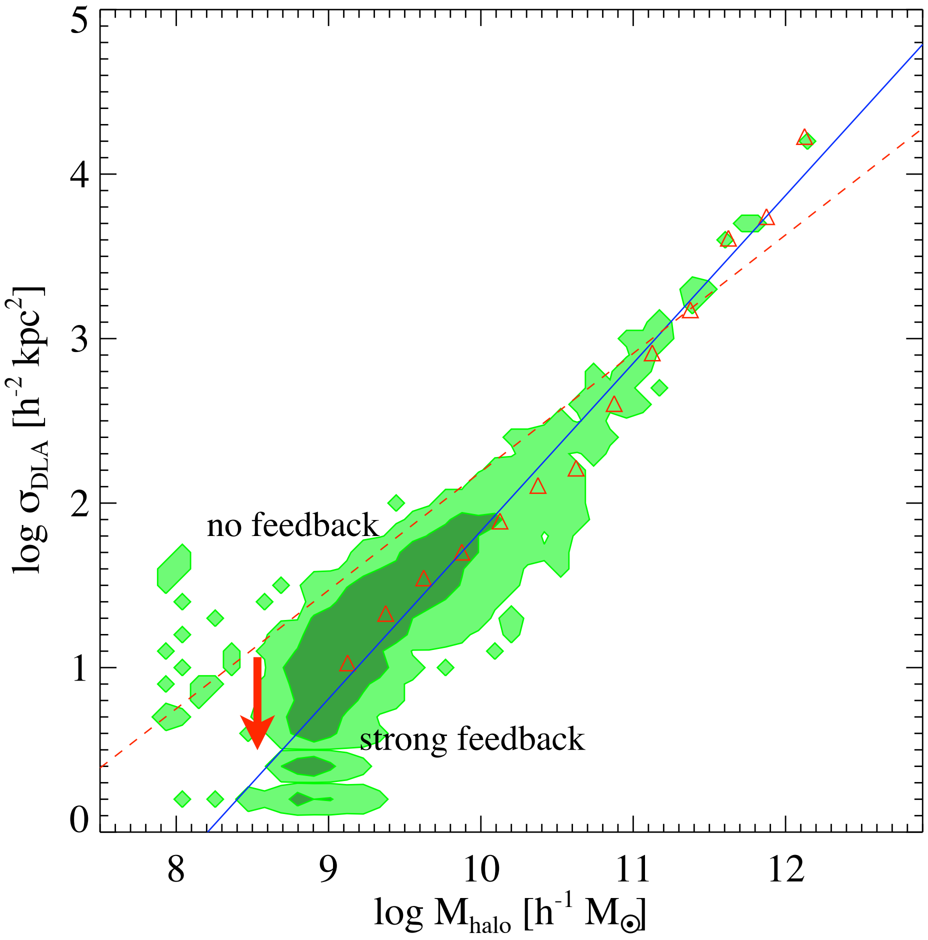


~phys 28 kpc
~phys 14 kpc
$2.4 \times 10^8 h^{-1} M_\odot$
$2.4 \times 10^9 h^{-1} M_\odot$
$M_{tot} = 2.6 \times 10^{10} h^{-1} M_\odot$
z=3

DLA statistics

KN+ (2004a,b; 2006)





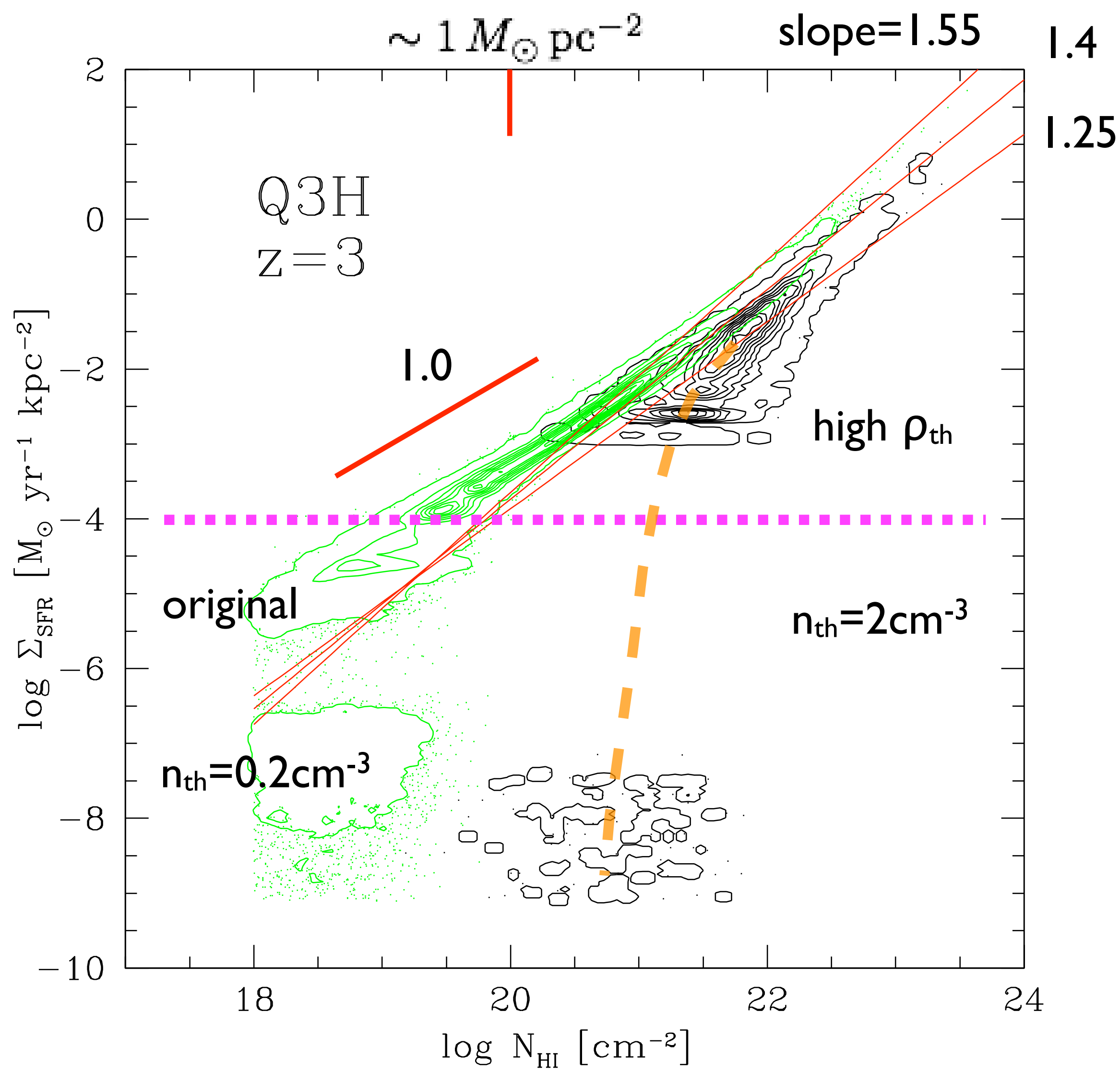
Column density distribution function

DLA cross section vs. Halo mass

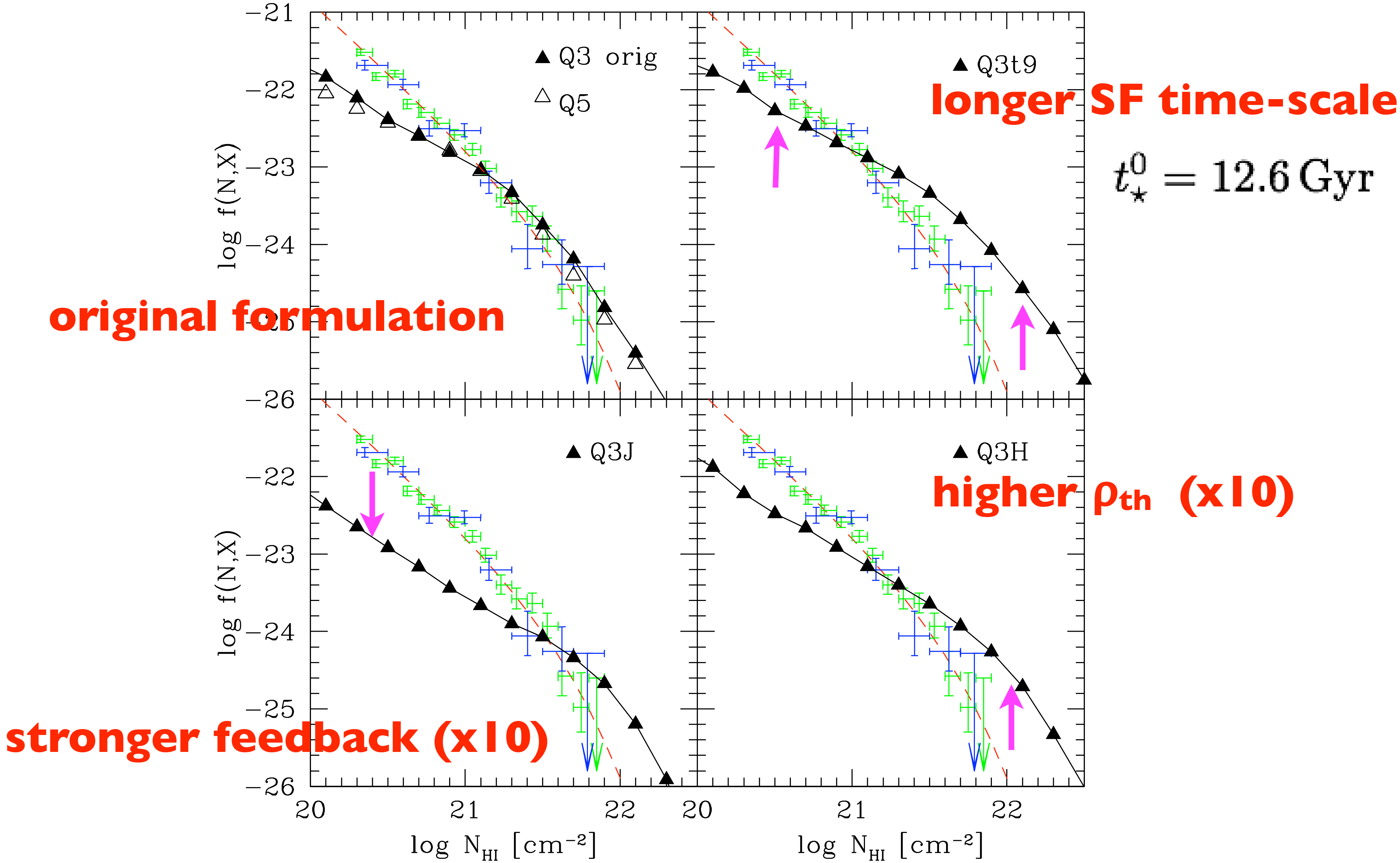
Kennicutt Law

Kennicutt Law in Cosmological SPH Simulations

- Too much SF at low N_{HI} in the original sim?
- Raising ρ_{th} seems to work better
  (cf. Kravtsov '03: n=50 cm^{-3})
- Making SF time-scale longer just lowers normalization



Column density distribution



Alternative SF recipe: Blitz’s Pressure Criteria

Blitz's Pressure SF Criteria

$$\Sigma_{\mathrm{SFR}} = \epsilon \Sigma_g f_{mol} \left[\frac{\Sigma_{\mathrm{H2}}(\mathrm{HCN})}{\Sigma_{\mathrm{H2}}(\mathrm{CO})} \right]$$

$$f_{mol} = \frac{\Sigma_{\mathrm{H2}}}{\Sigma_g} = \frac{R_{mol}}{(1 + R_{mol})} = \left[1 + \left(\frac{P_{ext}}{P_0} \right)^{-\alpha} \right]^{-1}$$

$$R_{mol} \equiv \frac{\Sigma_{\mathrm{H2}}}{\Sigma_{\mathrm{HI}}}$$

$\epsilon \sim 10\ \mathrm{Gyr}^{-1}$ $\left[\frac{\Sigma_{\mathrm{H2}}(\mathrm{HCN})}{\Sigma_{\mathrm{H2}}(\mathrm{CO})} \right] \sim 0.1$

$\alpha \sim 0.92$ $P_0 = (4.3 \pm 0.6) \times 10^4\ \mathrm{K\ cm^{-3}}$

Blitz & Rosolowsky (2006)

Blitz's Pressure SF Criteria

$$\Sigma_{\rm SFR} = \frac{\Sigma_g}{\left[1 + \left(\frac{P_{ext}}{P_0}\right)^{-\alpha}\right]} \ {\rm Gyr}^{-1}$$

$$\dot{\rho}_\star = \frac{\rho_g}{\left[1 + \left(\frac{P_{ext}}{P_0}\right)^{-\alpha}\right]} \ {\rm Gyr}^{-1}$$

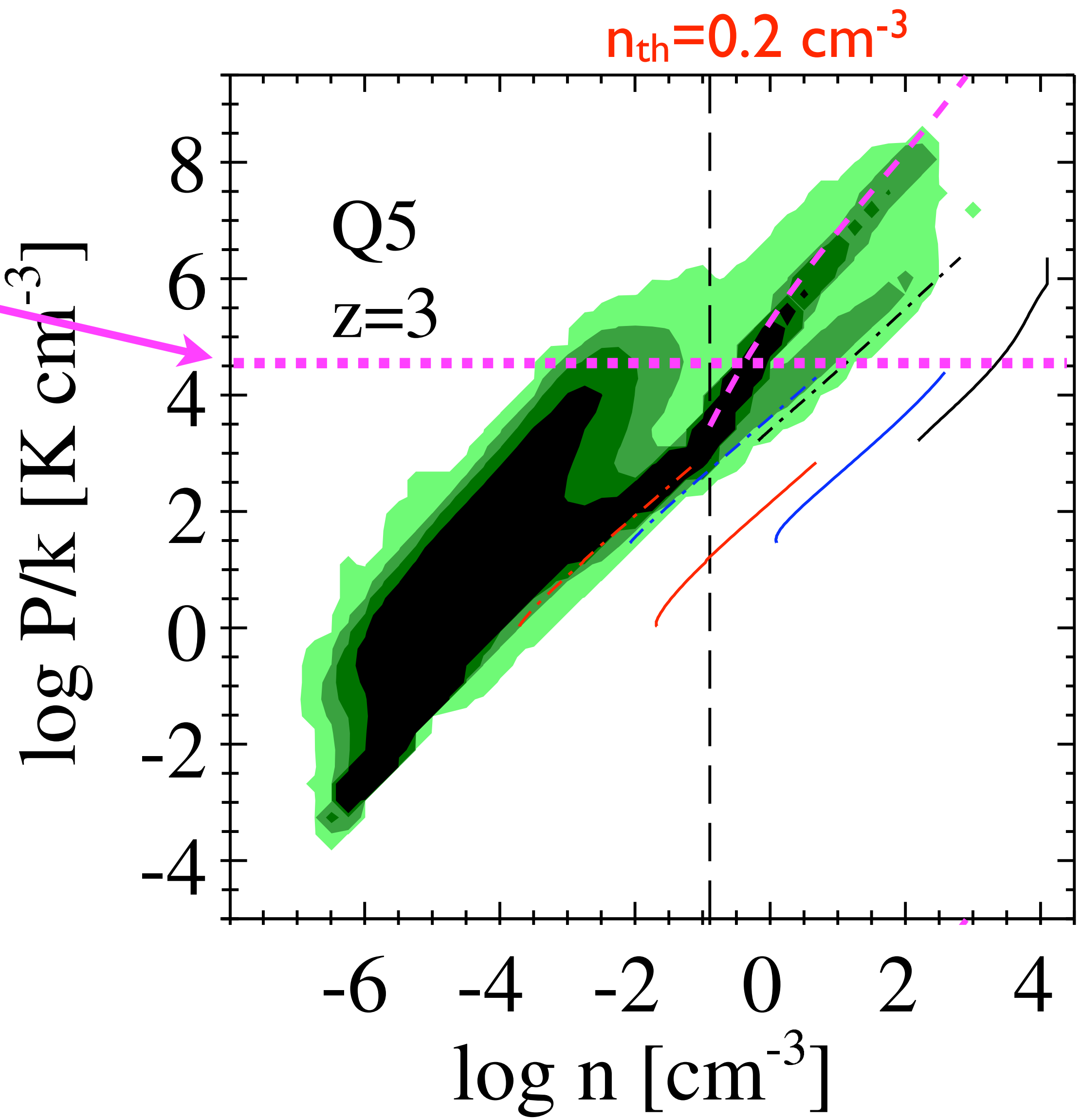
(cf. Kravtsov '03: $\dot{\rho}_\star \propto \rho_g$)

Pressure-density diagram in cosmological SPH simulation

Blitz' external ISM pressure `P_0'
when the molecular fraction is
unity

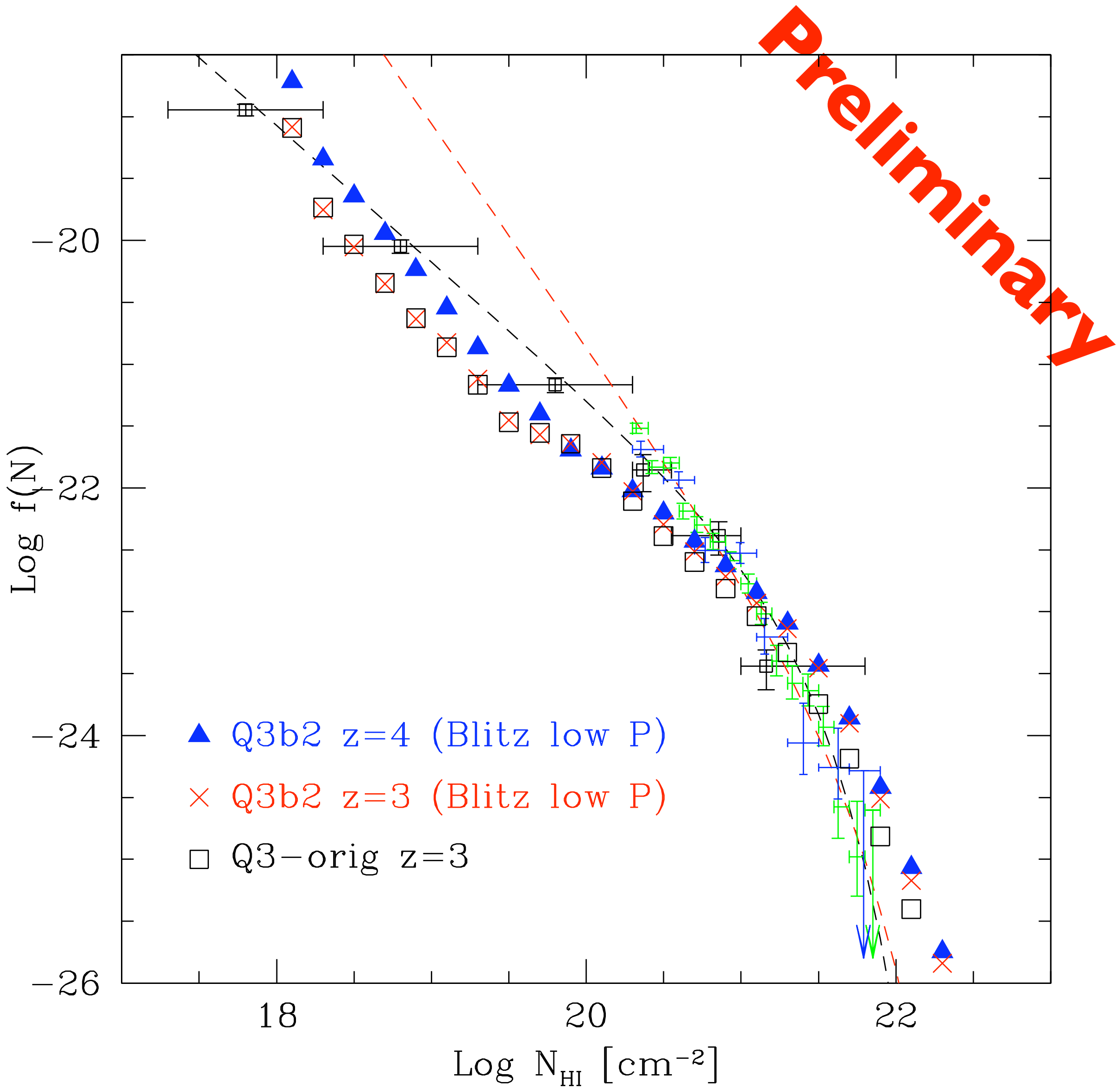
Test run:

Q3b:
Blitz's low pressure + S&H (at $P>P_0$)



$f(N_{HI})$ with Blitz SF criteria

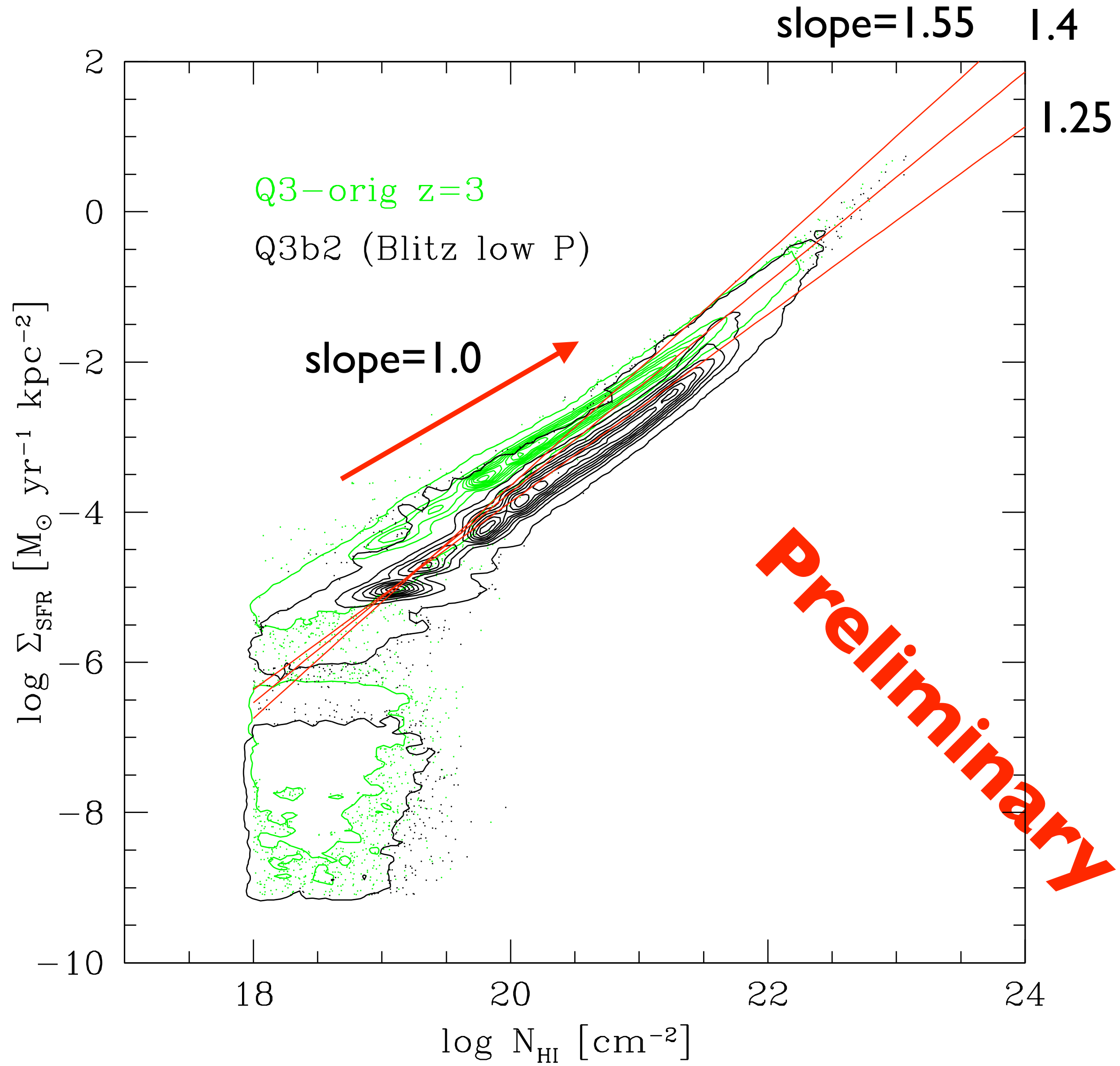
- Some overprediction at log $N_{HI}>21$.



Blitz SF criteria

- slope became closer to 1.4.

  (encouraging)



green contour: original Q3 run

(10 Mpc/h, 2x144^3, S&H SF model)

Problems in Current Cosmological Simulations

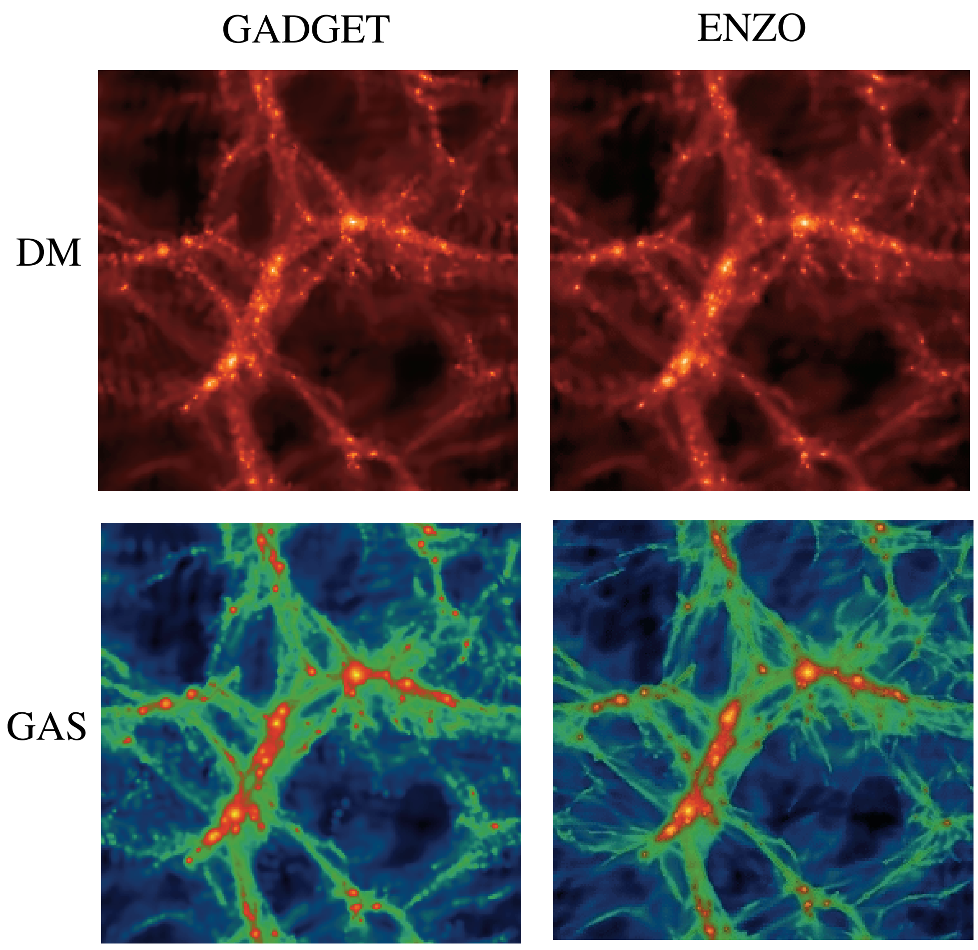
- Inadequate resolution
- Angular momentum transfer problem
- Feedback by SNe and BHs
- Radiative Transfer

Future efforts

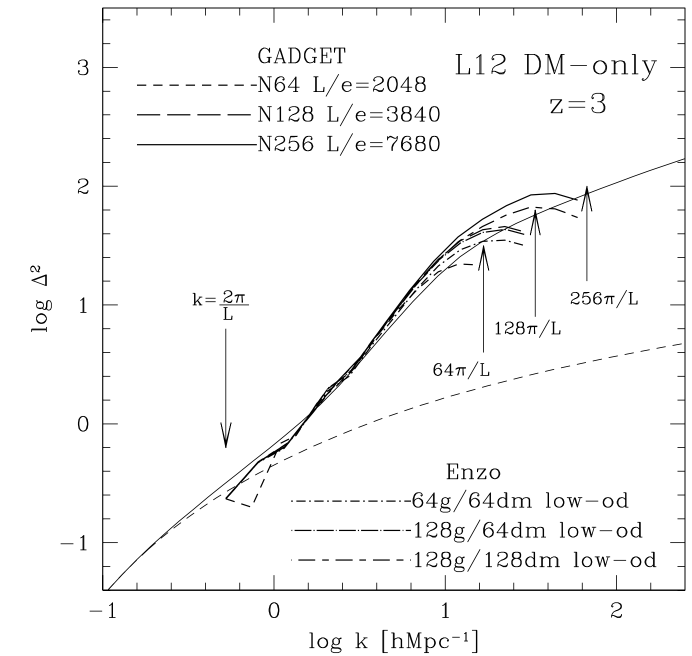
- Higher resolution: 1000^3 - 2000^3
- More realistic models of SF and feedback -- multiphase ISM
- Radiative transfer
- Code comparisons: e.g. AMR vs. SPH

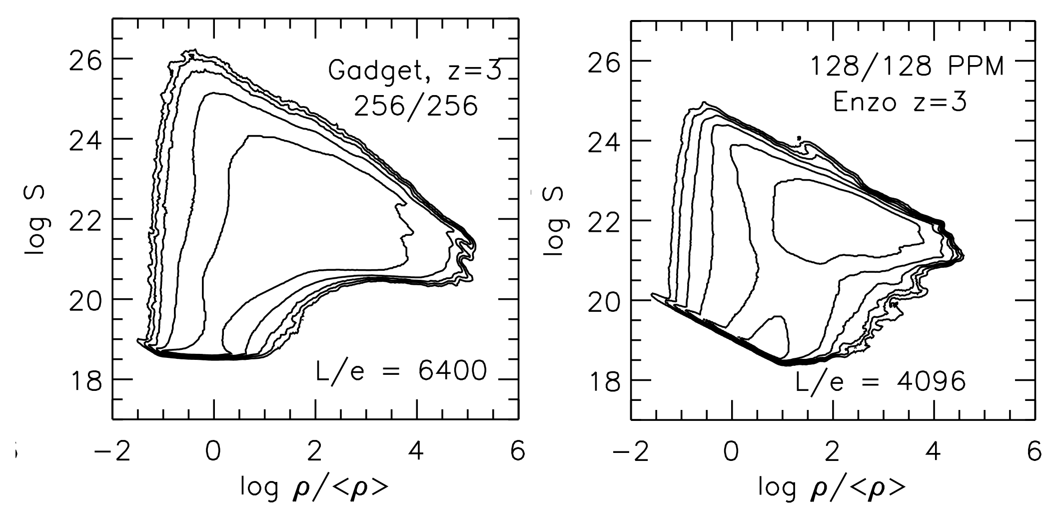
  (Adaptive Mesh Refinement vs. Smoothed Particle Hydrodynamics)

Code comparison: SPH vs. AMR



dark matter power spectrum

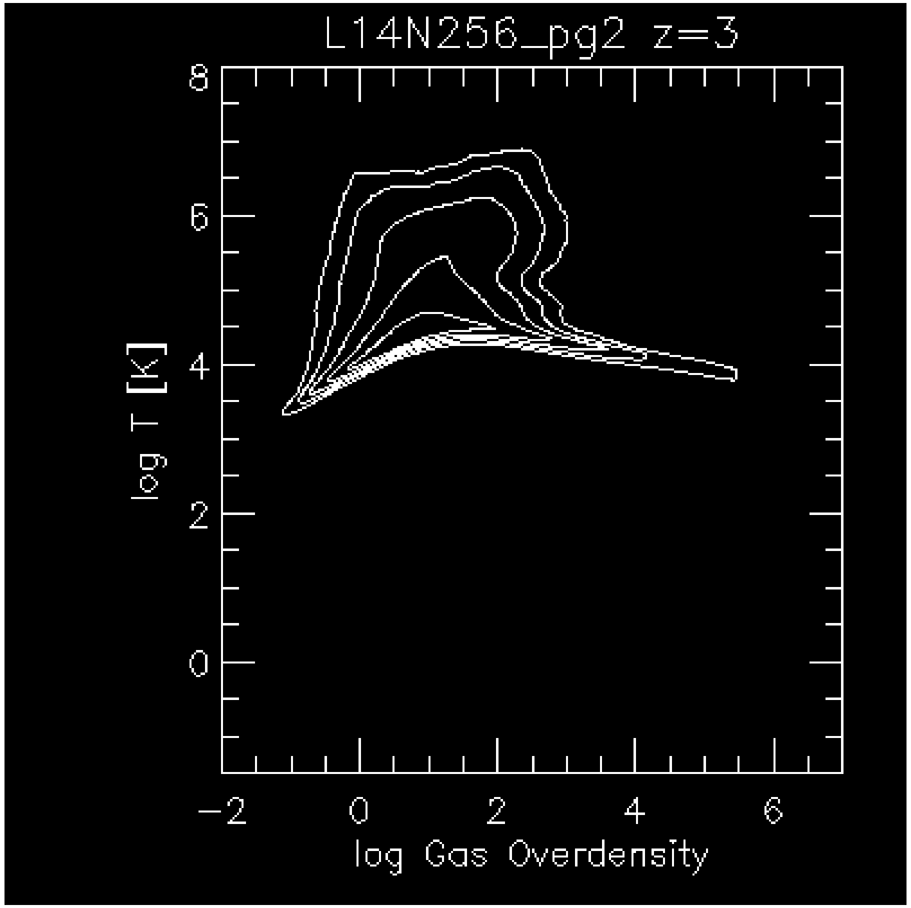




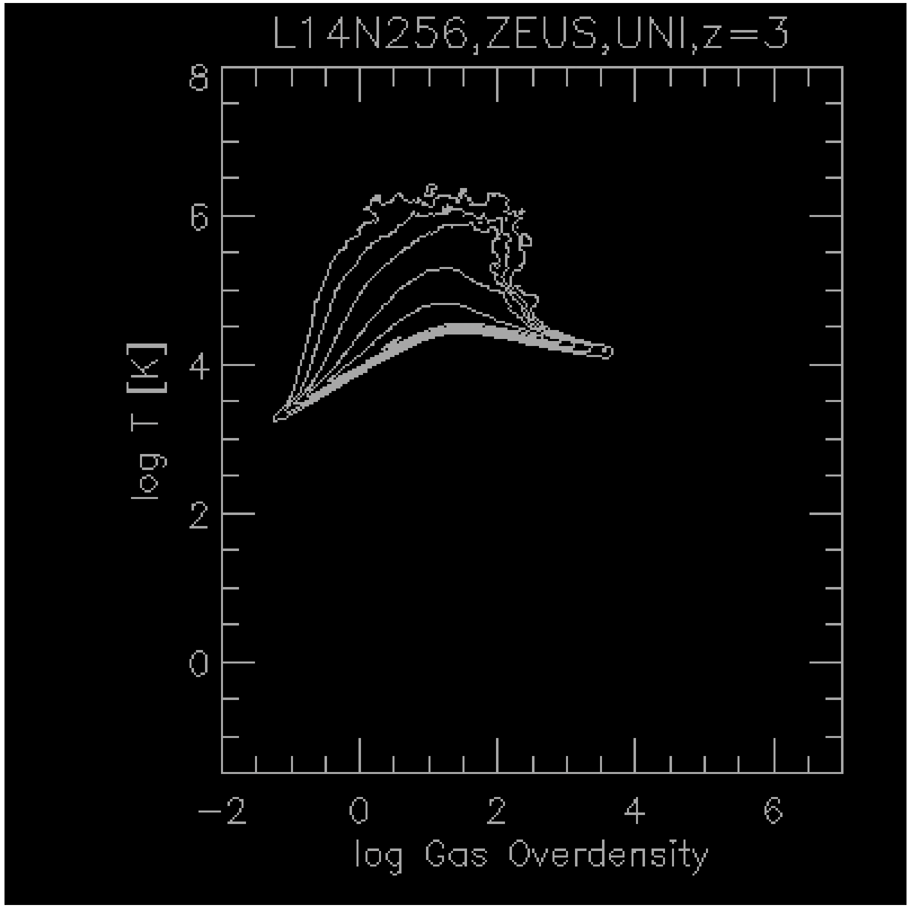
O'Shea, KN + 2005

entropy vs. gas density

Extending the comparison to the runs with cooling & SF



Gadget SPH



Enzo AMR

The End