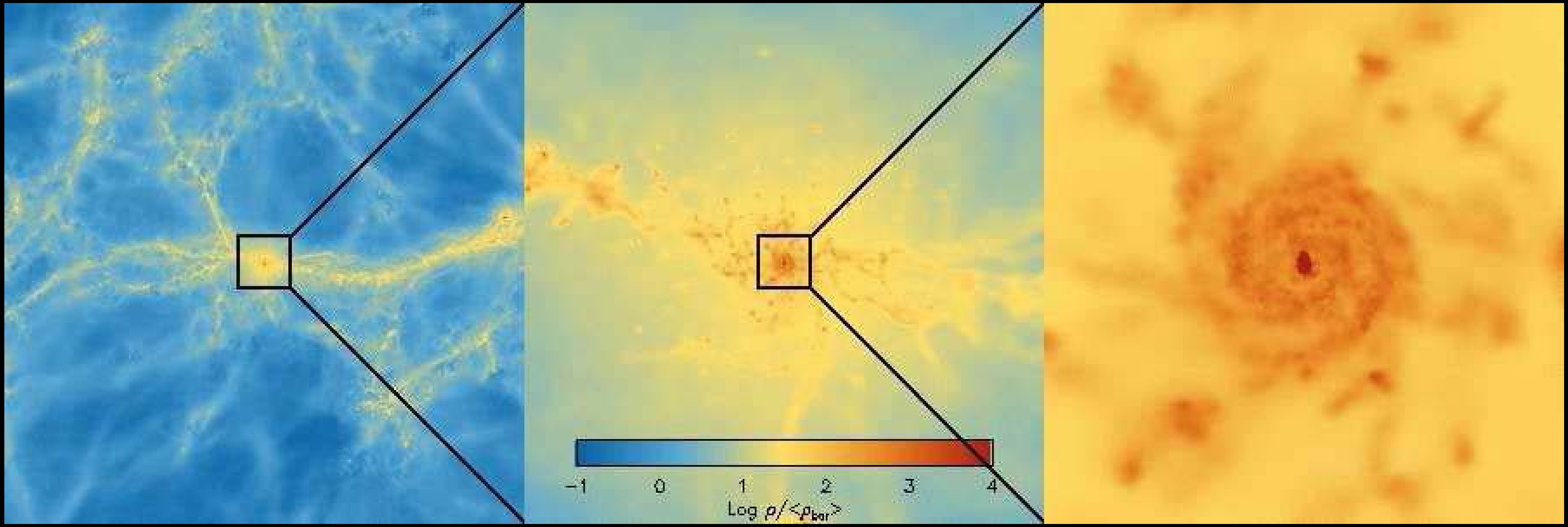
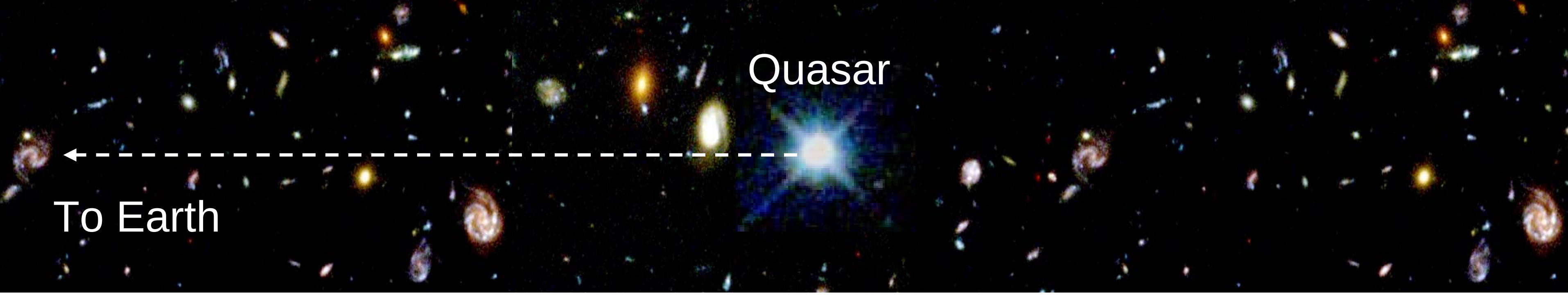
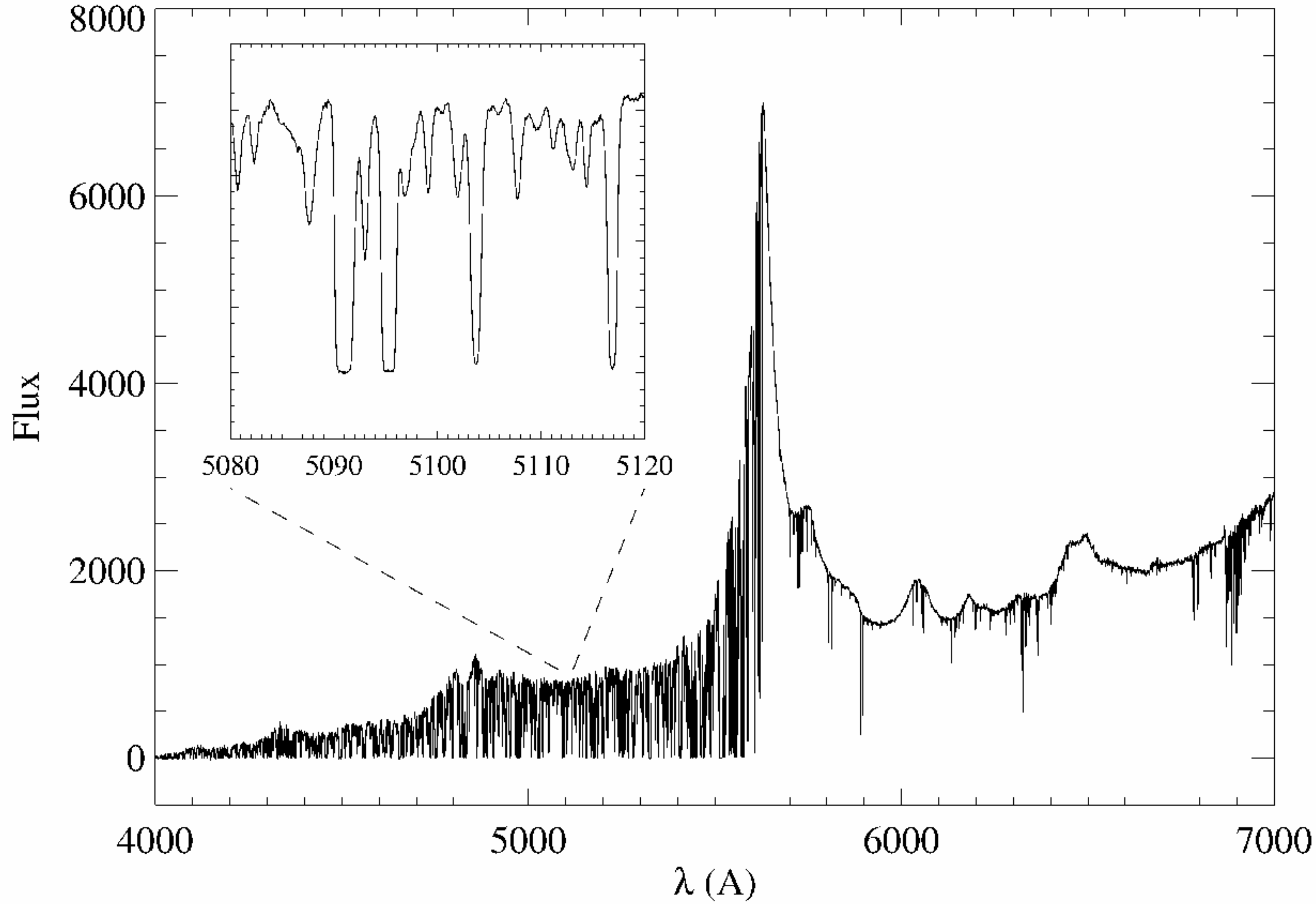
From the cosmic web to molecular clouds with QSO absorbers

Joop Schaye (Leiden)




Quasar
To Earth


8000
6000
4000
2000
0
Flux
4000
5000
6000
7000
λ (A)
5080
5090
5100
5110
5120

The Ly-alpha forest

- Observations of QSO pairs point to large sizes (~ 100 kpc) (Bechtold et al. 1994; Dinshaw et al. 1994, 1995; Smette et al. 1995)
- Cosmological simulations reproduce absorber statistics (Bi et al. 1992; Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996; Dave et al. 1999; etc)

  → forest arises in cosmic web of mildly overdense sheets and filaments that contains most of the baryons

The Lya forest explained analytically

- Local hydrostatic equilibrium (LHE):
  $t_{sc} \sim t_{dyn}$ or, equivalently, $L \sim L_{Jeans}$
- LHE restored on minimum of dynamical and sound-crossing time scales
- LHE determines:
  - thickness of the sheets, filaments, and haloes that make up the cosmic web
  - thickness of disks

JS (2001a)

The Lya forest explained analytically

- Two limiting cases:
  - Underdense regions: $t_{dyn} > t_H$
    → Cannot reach LHE
    → Gas traces the dark matter
    → fluctuating Gunn-Peterson approximation
  - Overdense regions: $t_{dyn} < t_H$
    → LHE

$$N_{\rm H,J} \equiv n_{\rm H} L_{\rm J} \sim 1.6 \times 10^{21}\ {\rm cm}^{-2}\ n_{\rm H}^{1/2}\ T_4^{1/2} \left(\frac{f_g}{0.16}\right)^{1/2}$$

- Final ingredient: neutral (and H_2) fraction
  - Optically thin → fully analytic
  - Optically thick → numerical radiative transfer

JS (2001a)

Optically thin case:

$$\frac{n_{\mathrm{H\,I}}}{n_{\mathrm{H}}} = n_e\,\beta_{\mathrm{H\,II}}\,\Gamma^{-1} \sim 0.46\; n_{\mathrm{H}}\,T_4^{-0.76}\,\Gamma_{12}^{-1}$$

↑

HI ionisation rate

Densities

- Proper densities:

$$N_{\rm H\,I} \sim 2.3 \times 10^{13}\ {\rm cm}^{-2}\left(\frac{n_{\rm H}}{10^{-5}\ {\rm cm}^{-3}}\right)^{3/2} \times T_4^{-0.26}\,\Gamma_{12}^{-1}\left(\frac{f_g}{0.16}\right)^{1/2} .$$

- Overdensities: $1+\delta = \rho/\langle\rho\rangle$

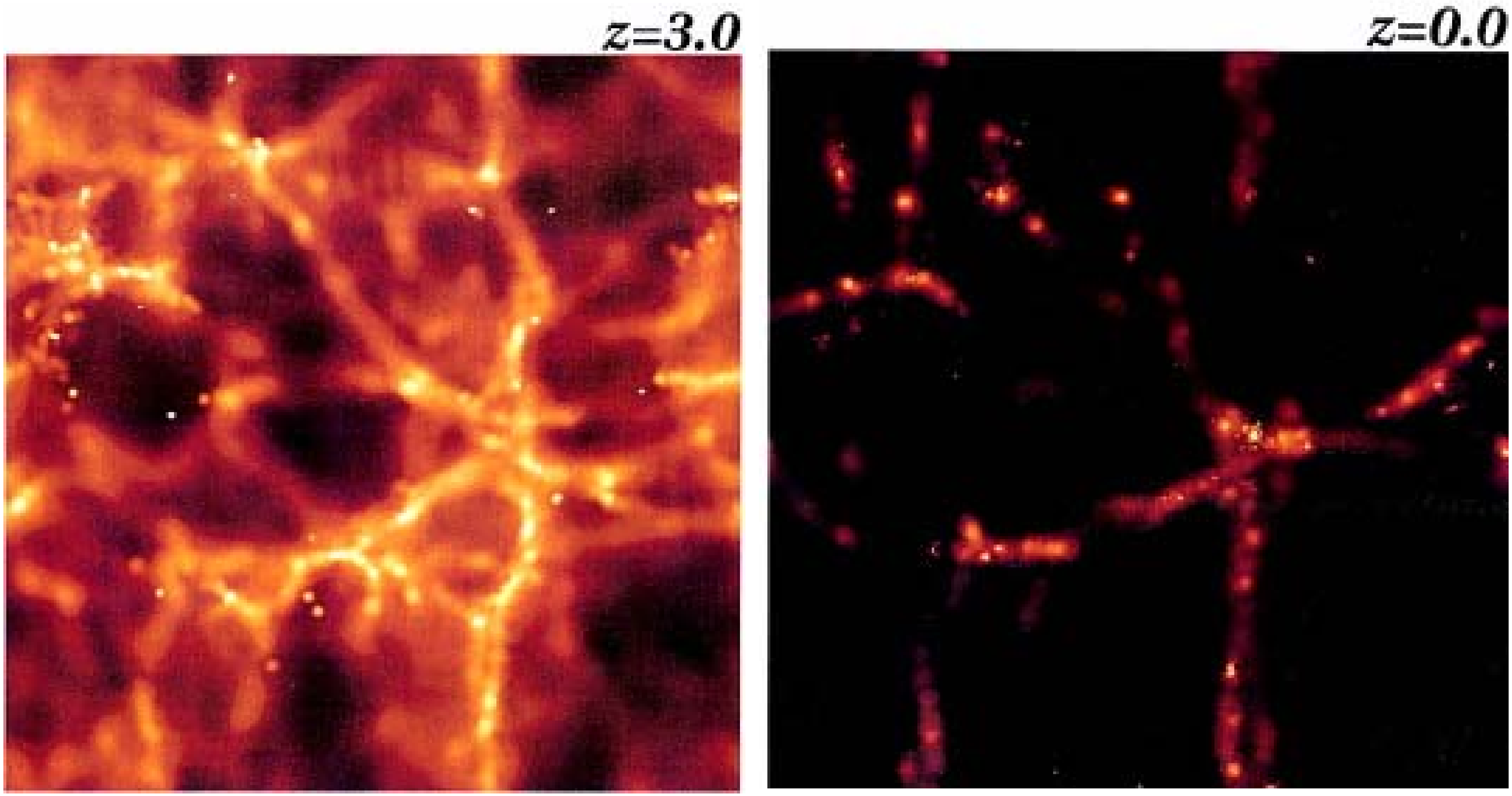
$$N_{\rm H\,I} \sim 2.7 \times 10^{13}\ {\rm cm}^{-2}(1+\delta)^{3/2} T_4^{-0.26}\,\Gamma_{12}^{-1} \times \left(\frac{1+z}{4}\right)^{9/2}\left(\frac{\Omega_b h^2}{0.02}\right)^{3/2}\left(\frac{F_g}{0.16}\right)^{1/2} .$$

- $1+\delta \propto N_{\rm HI}^{2/3}(1+z)^3\Gamma^{2/3}$

→ Fixed HI column corresponds to much lower overdensity at higher z

JS (2001a)

HI column density maps



← 22 Mpc →

Dave et al. (1999)

Sizes and baryon content

- Absorber size (e.g. disk thickness):

$$L_{\rm J} \equiv \frac{c_s}{\sqrt{G\rho}} \sim 0.52 \text{ kpc } n_{\rm H}^{-1/2}\, T_4^{1/2} \left(\frac{f_g}{0.16}\right)^{1/2}$$

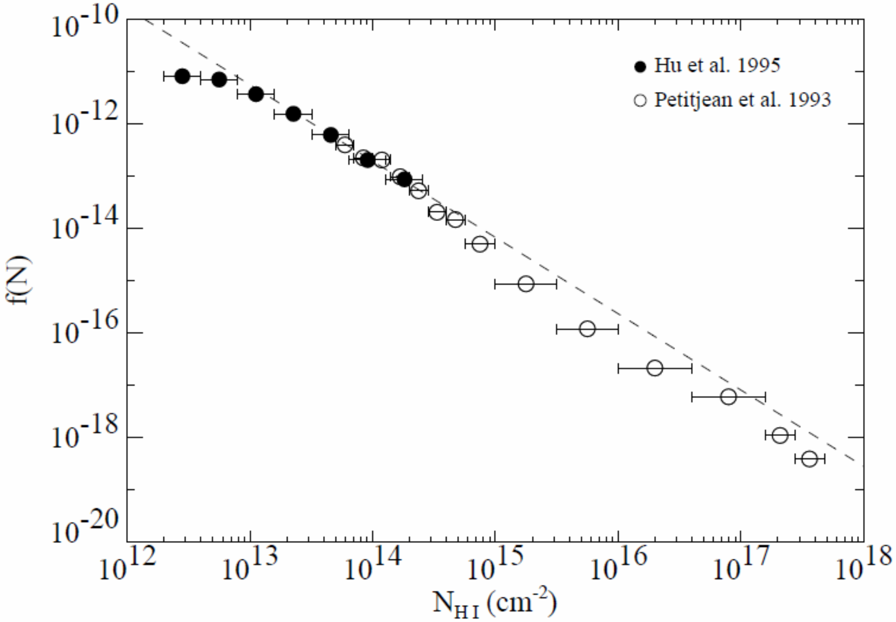
$$L \sim 1.0 \times 10^2 \text{ kpc} \left(\frac{N_{\rm H\,I}}{10^{14}\ {\rm cm}^{-2}}\right)^{-1/3} T_4^{0.41}\, \Gamma_{12}^{-1/3} \left(\frac{f_g}{0.16}\right)^{2/3}$$

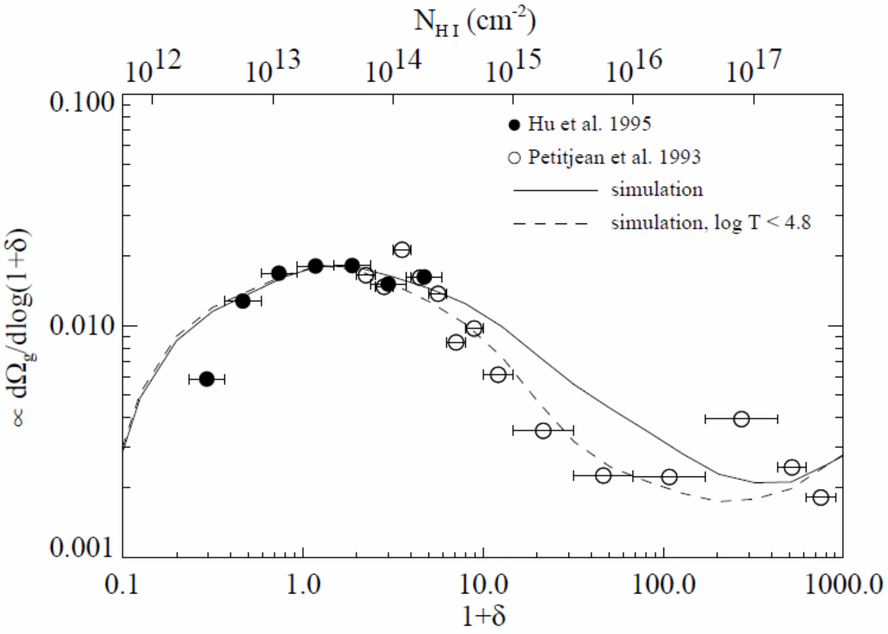
- Density parameter:

$$\Omega_g = \frac{8\pi G m_{\rm H}}{3H_0\, c(1-Y)} \int N_{\rm H\,I} \frac{n_{\rm H}}{n_{\rm H\,I}} f(N_{\rm H\,I}, z)\, dN_{\rm H\,I}$$

JS (2001a)

The mass distribution of the universe at z=3





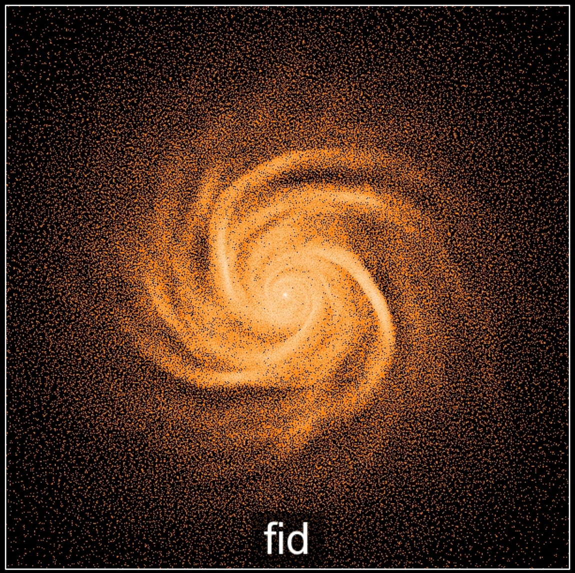
JS (2001a)

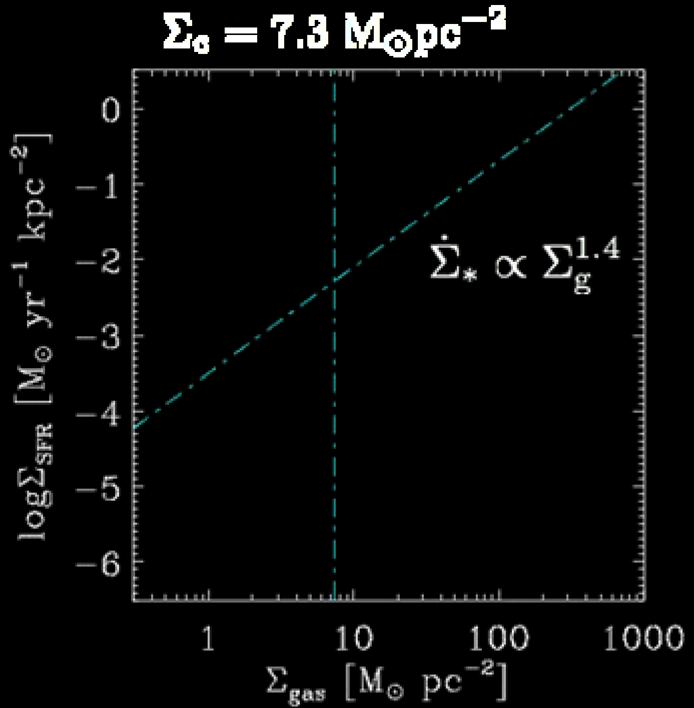
Local hydrostatic equil. relates:

- Surface density to volume density
  → relate Schmidt and Kennicutt-Schmidt SF laws
- Surface density to pressure
  → easy implementation of Kennicutt-Schmidt and Blitz relations into 3-D simulations

JS & Dalla Vecchia (2008)

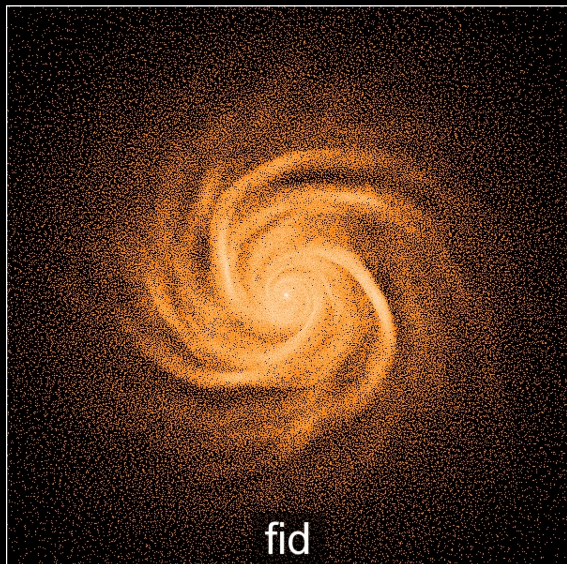
Kennicutt-Schmidt law

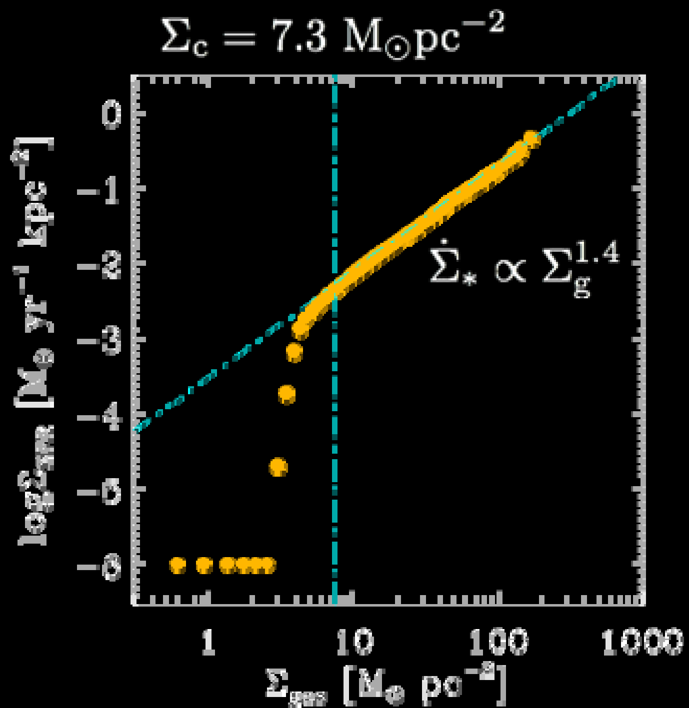




JS & Dalla Vecchia (2008)

Kennicutt-Schmidt law





$$\dot{\Sigma}_* = \begin{cases} 0 & \text{if } \Sigma_g < \Sigma_c \\ A\left(\Sigma_g/1\ M_\odot\ pc^{-2}\right)^n & \text{if } \Sigma_g \geq \Sigma_c \end{cases}$$

$$\dot{m}_* = m_g A\left(1\ M_\odot\ pc^{-2}\right)^{-n}\left(\frac{\gamma}{G} f_g P\right)^{(n-1)/2}$$

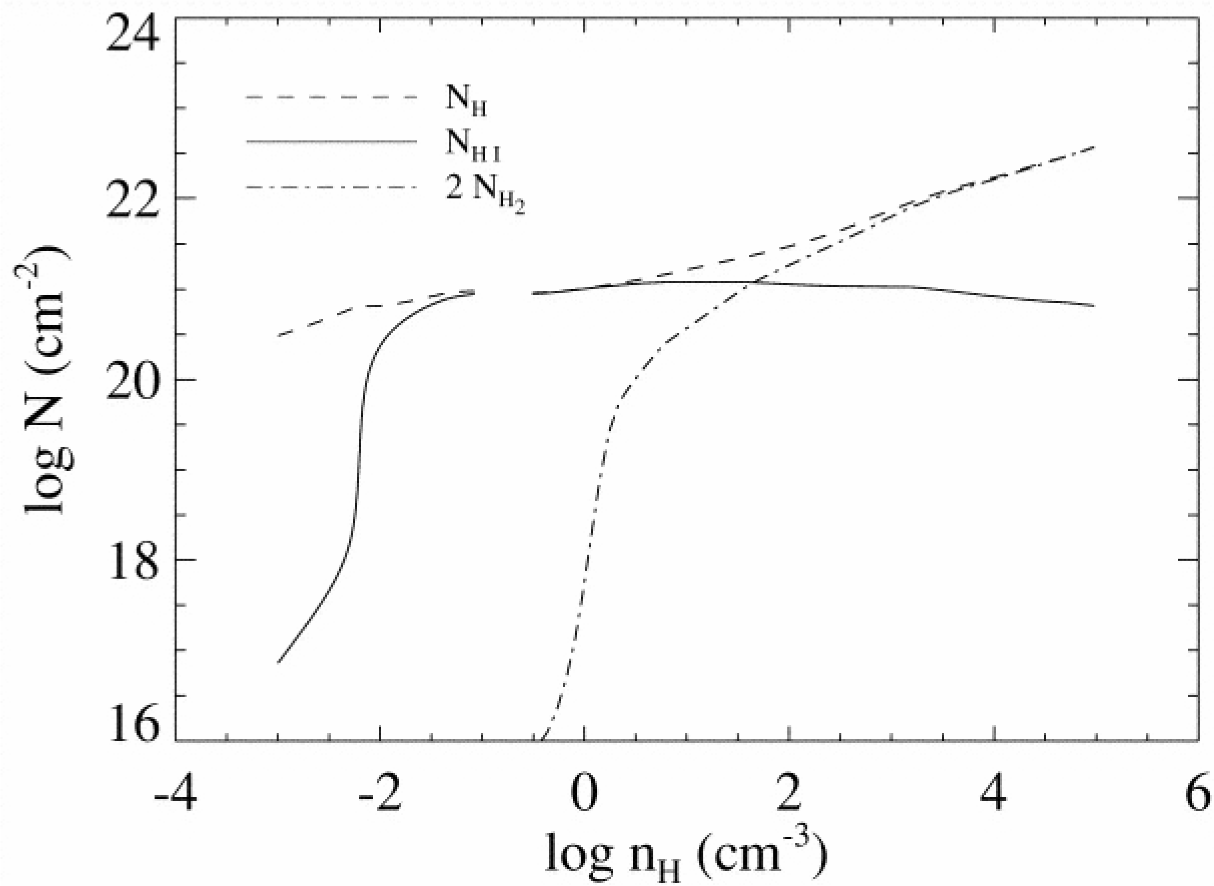
JS & Dalla Vecchia (2008)

Optically thick limit:
Combining LHE (i.e. self-gravity) with numerical radiative transfer

A poor man's radiative transfer

- Self-shielded for $\tau > 1$
  - → $N_{HI,ss} \sim 10^{18}$ cm^{-2}
  - → $n_{H,ss} \sim 10^{-2}$ cm^{-3} $\Gamma_{12}^{2/3}$ (JS 2001a)
  - → $1+\delta_{ss} \sim 10^{3}$ at $z = 3$
- Optically thin for lower densities
- Fully neutral for higher densities

A physical upper limit on N(HI)



Cloudy models of
self-gravitating disks (LHE)

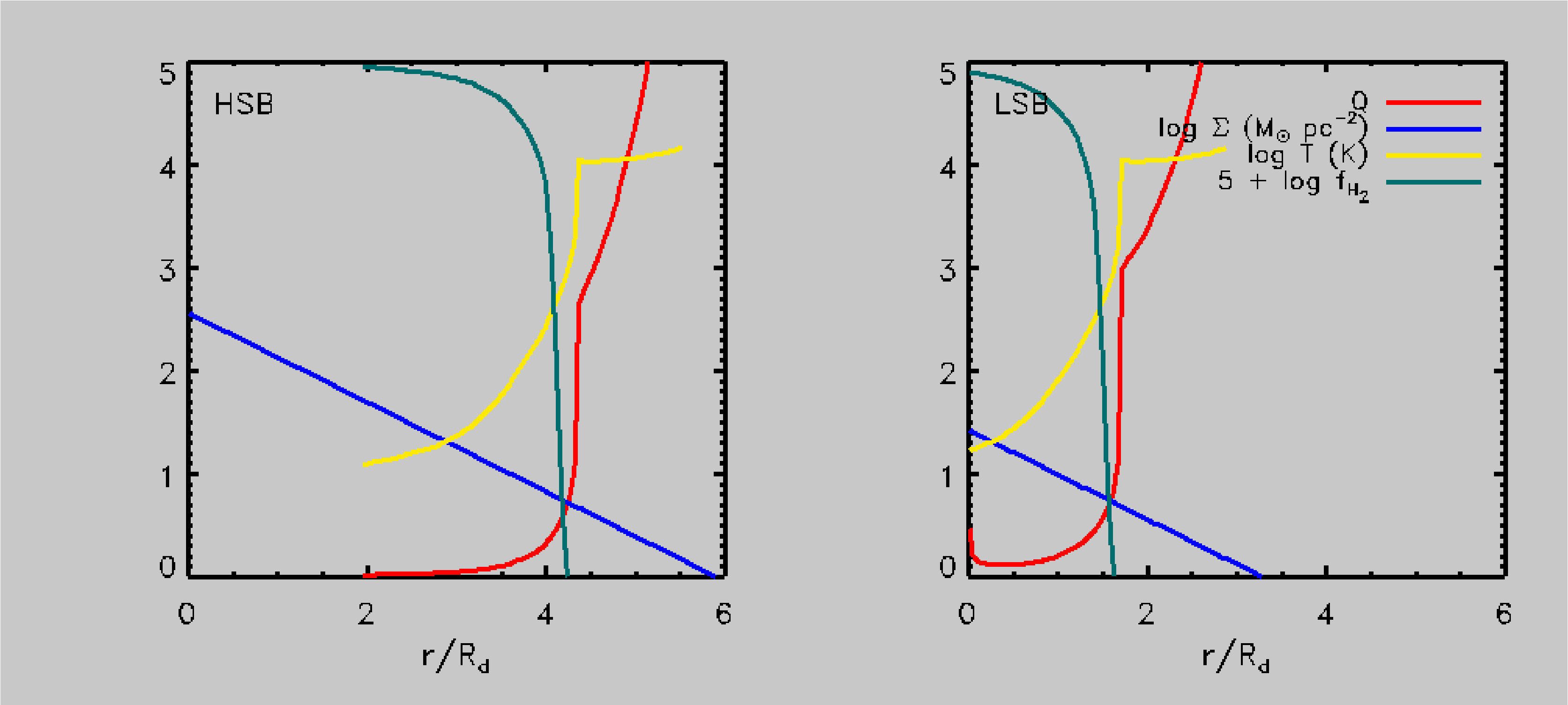
JS (2001b)

HI saturation

- HI surface density saturates due to conversion to H_2
- Maximum HI surface density depends on metallicity (and UV), but is of order 10 $M_{\odot}$ pc^{-2} or, equivalently, 10^{21} HI cm^{-2}
- Explains saturation observed in 21 cm and observed metallicity-dependent cut-off of DLA column density distribution

JS (2001b), Krumholz et al. (2009)

What Sets the SF Threshold?



$M_{200} = 10^{12} M_{\odot}, \quad \lambda = 0.05$ $\qquad$ $M_{200} = 5 \times 10^{10} M_{\odot}, \quad \lambda = 0.1$

$c = 10, \quad j_d = m_d = 0.05$

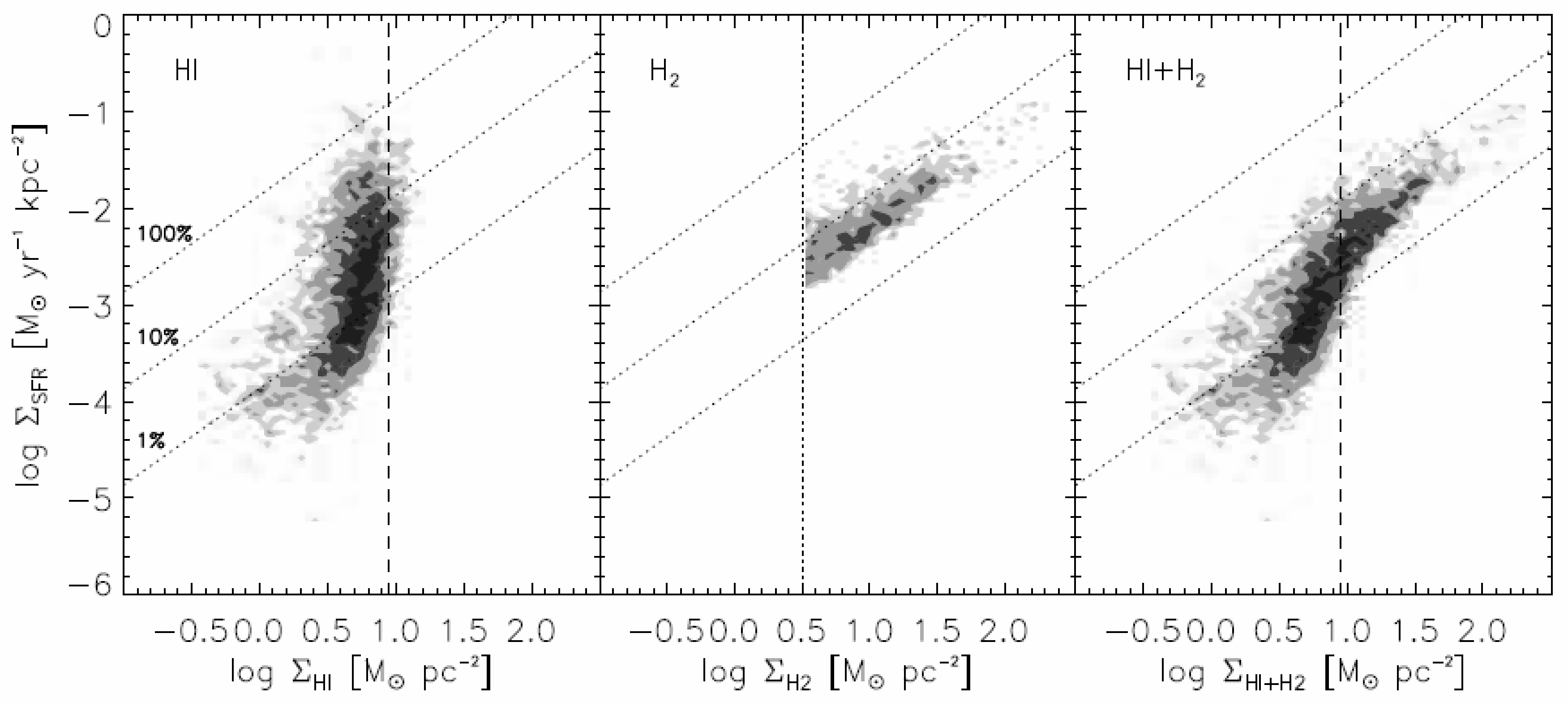
JS (2004)

SF thresholds

- The HI - H_2 transition corresponds to a phase transition from warm (10^4 K) to cold (‹‹ 10^4 K) gas
- The corresponding reduction in the Jeans mass is necessary for, and triggers, SF
  - → SF correlates locally with H_2 rather than with HI
  - → Predicts *metallicity-dependent* SF threshold surface density (on the 10^2 - 10^3 pc scale, i.e. Jeans scale of warm phase) that agrees with observations

JS (2004)

Spatially resolved observations



Bigiel et al. (2010)

SF thresholds

- Molecular cloud formation requires small Jeans scale (→ low temperature)
- Phase transition requires minimum dust column (shielding from UV & cooling rates ~ρ^2 ~ P^2 ~ N^4)
- H_2 requires minimum dust column (shielding)

→ SF correlates with H_2 because both trace cold, shielded gas

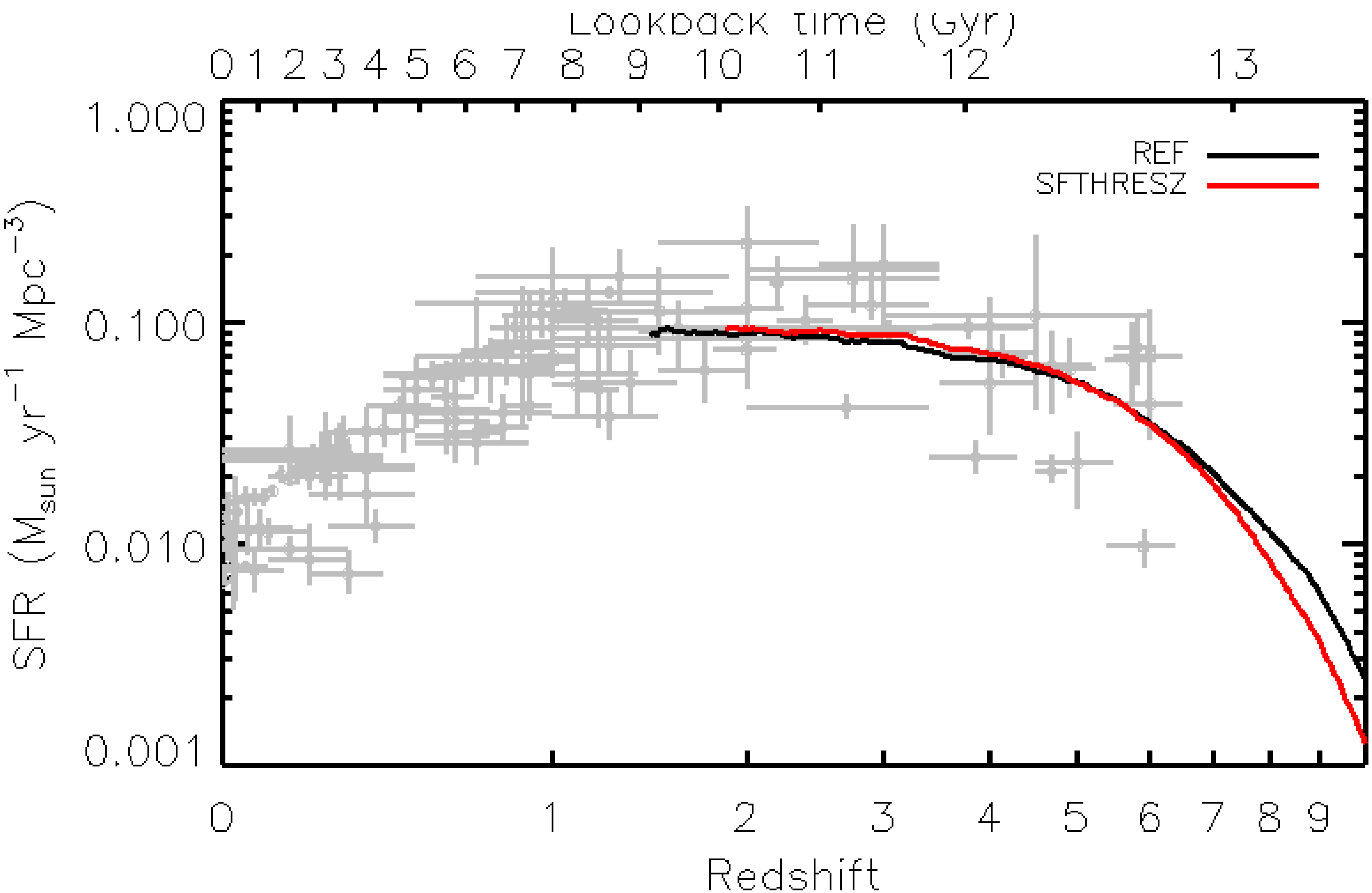
→ SF - H_2 relation NOT fundamental (H_2 neither important for cooling, nor for shielding)

JS (2004), Krumholz et al. (2011)

Metallicity-dependent SF

- SF law dependent on metallicity could reduce SF efficiency in low-mass galaxies, particularly at high redshift (e.g. Gnedin & Kravtsov 2011; Feldmann et al. 2011; Kuhlen et al. 2011; Krumholz & Dekel 2011)

A metallicity-dependent SF law in OWLS



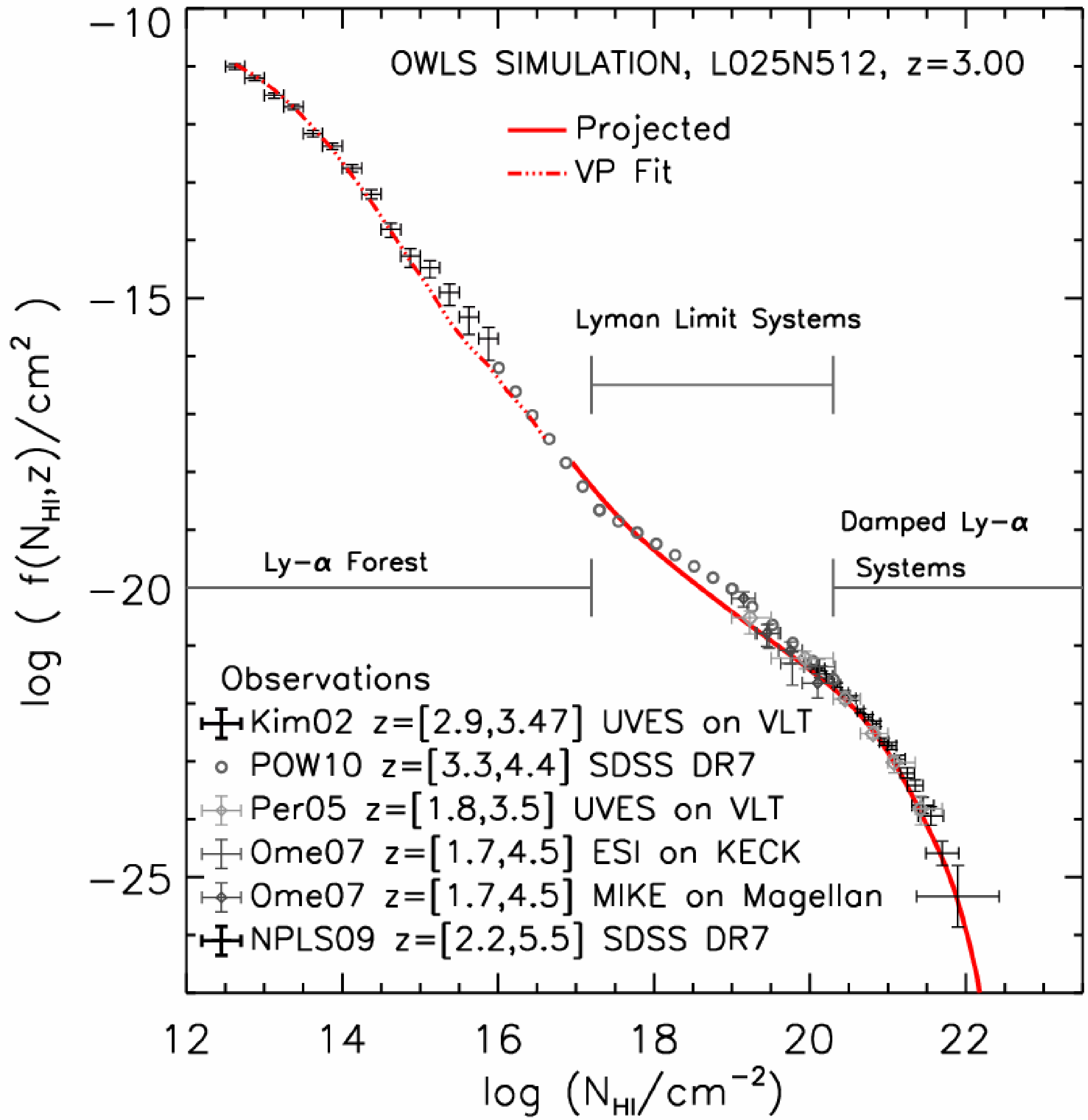
JS et al. (2010)

Metallicity-dependent SF

- SF law dependent on metallicity could reduce SF rates in low-mass galaxies, particularly at high redshift (e.g. Gnedin & Kravtsov 2011; Feldmann et al. 2011; Kuhlen et al. 2011; Krumholz & Dekel 2011)
- OWLS predicts only a minor metallicity effect.
- As a result of self-regulation, the SF law controls amount of high-density gas rather than the amount of star formation! (JS et al. 2010; Hopkins et al. 2011)

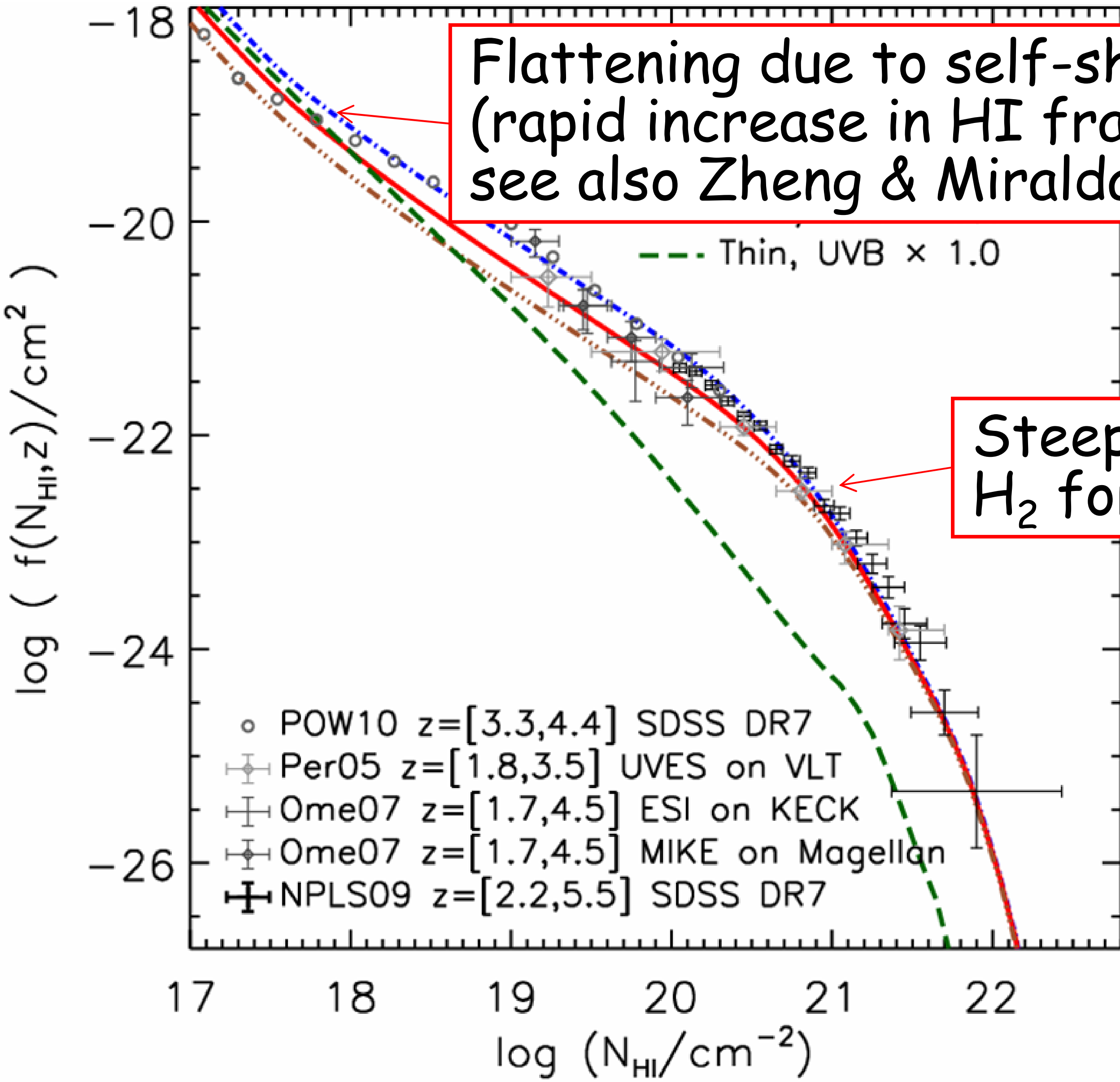
Post-processing hydro simulations (OWLS) with numerical radiative transfer (UV background only) and the Blitz pressure-dependent H_2 fraction

HI column density distribution at z=3



Altay et al. (2011)

Effect of self-shielding

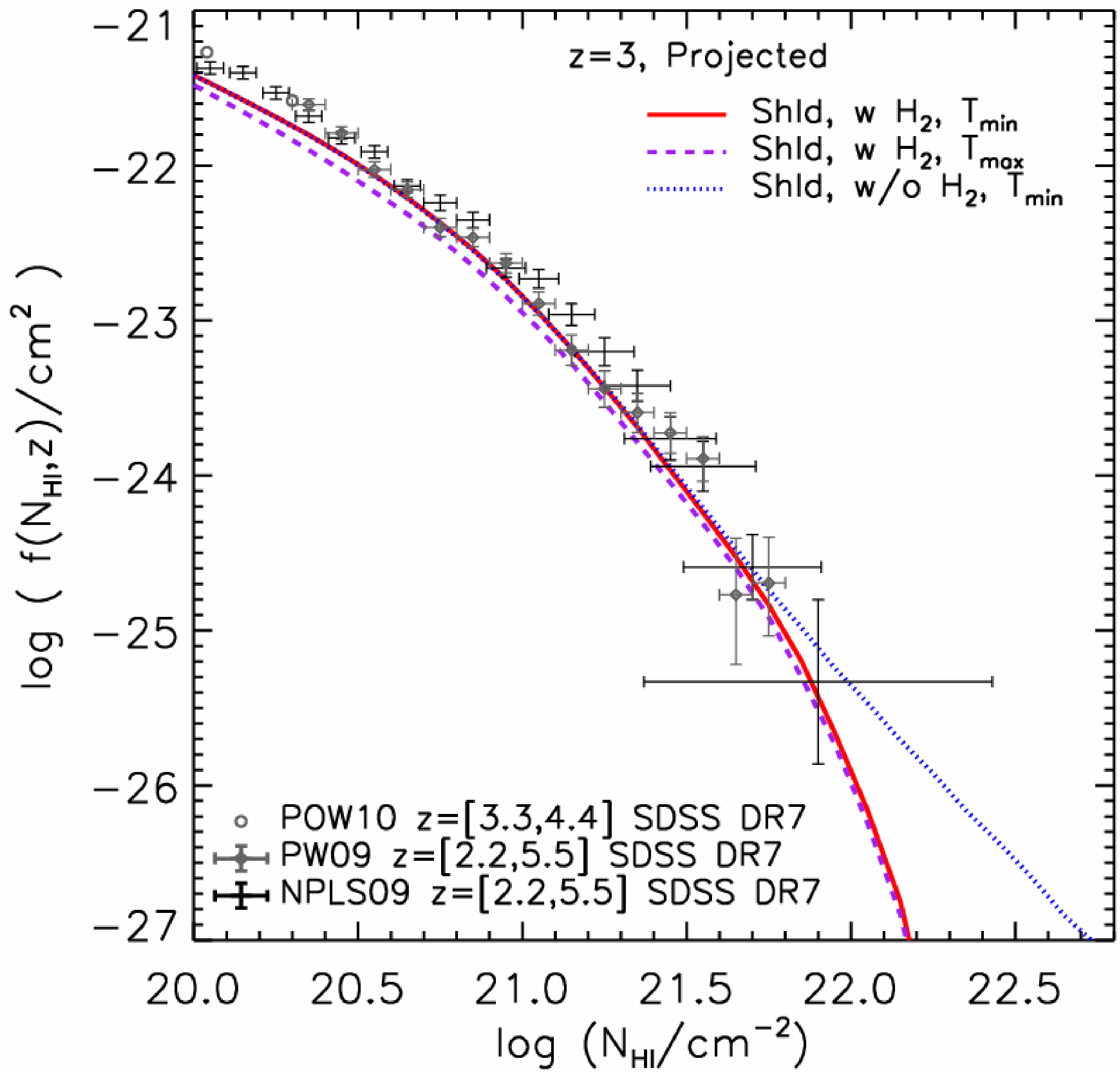


Flattening due to self-shielding (rapid increase in HI fraction; see also Zheng & Miralda-Escude 2002)

Steepening due to H_2 formation (JS 2001b)

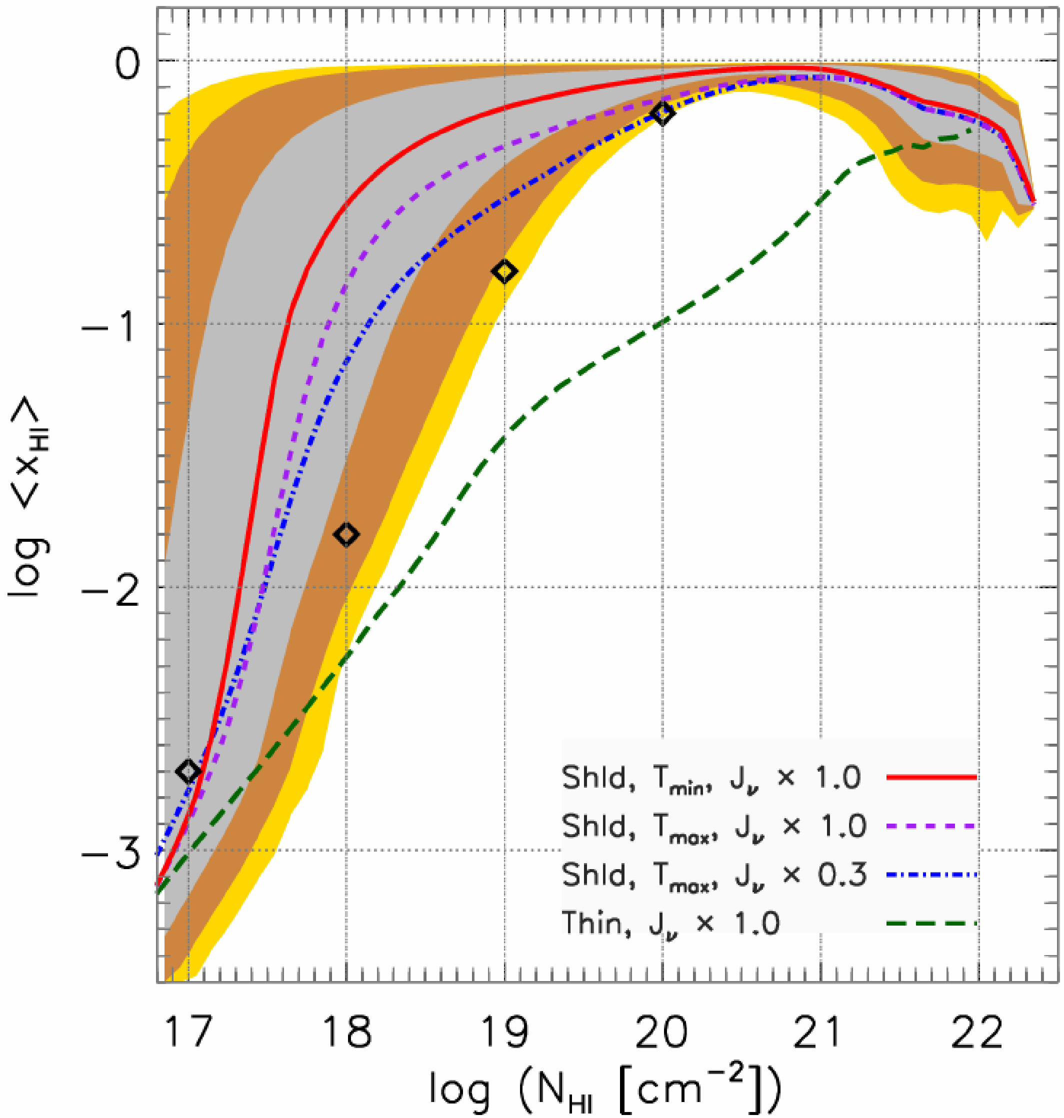
Altay et al. (2011)

Effect of molecules



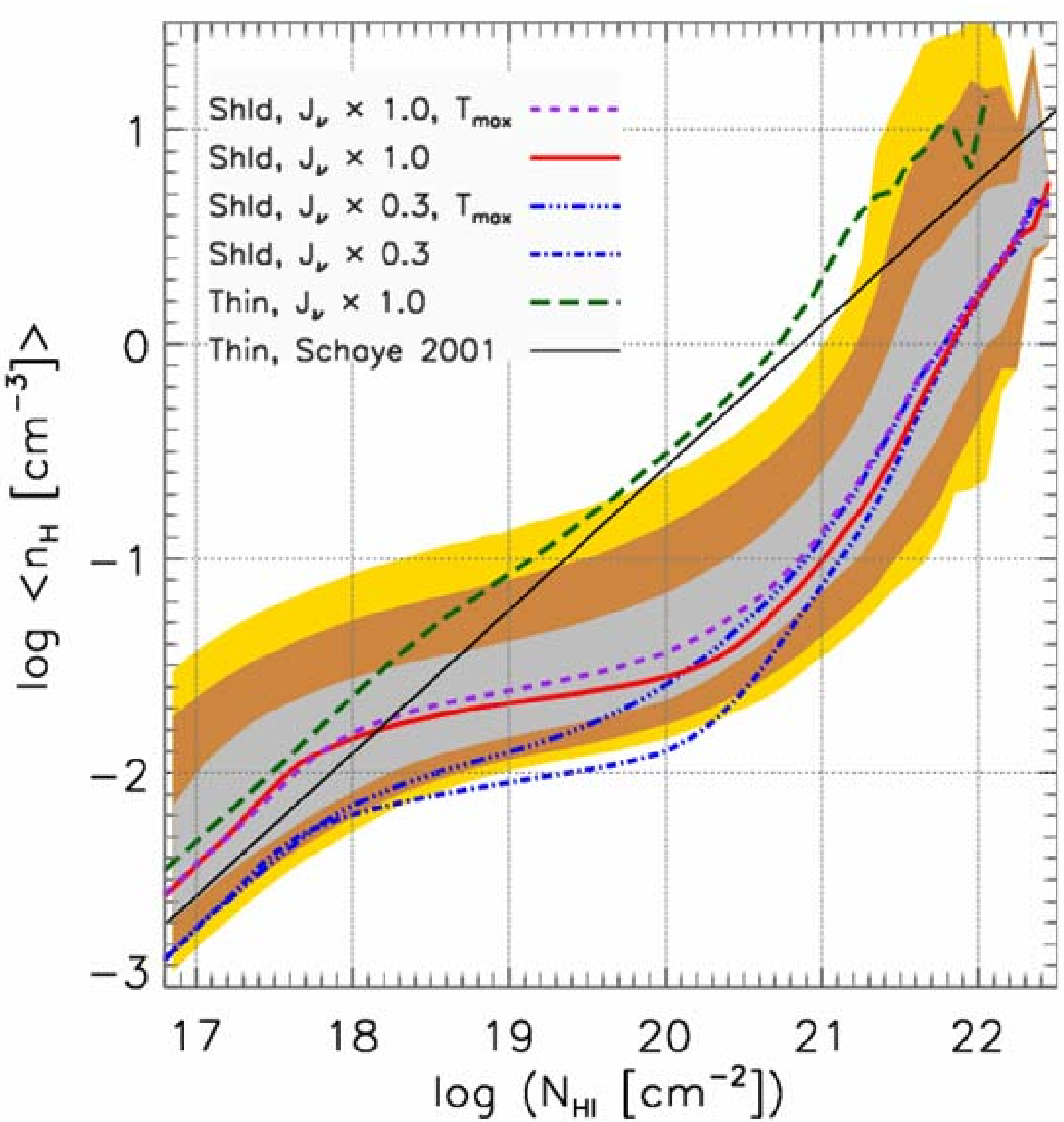
Altay et al. (2011)

Neutral fraction vs N_{HI}



Altay et al. (2011)

Volume density - N_{HI} relation



Altay et al. (2011)

The HI column density distribution

- Reproduced by hydro simulations over 10 orders of magnitude
- Reflects the mass distribution as a function of volume density, modulated by self-shielding and molecule formation (better: phase transition)