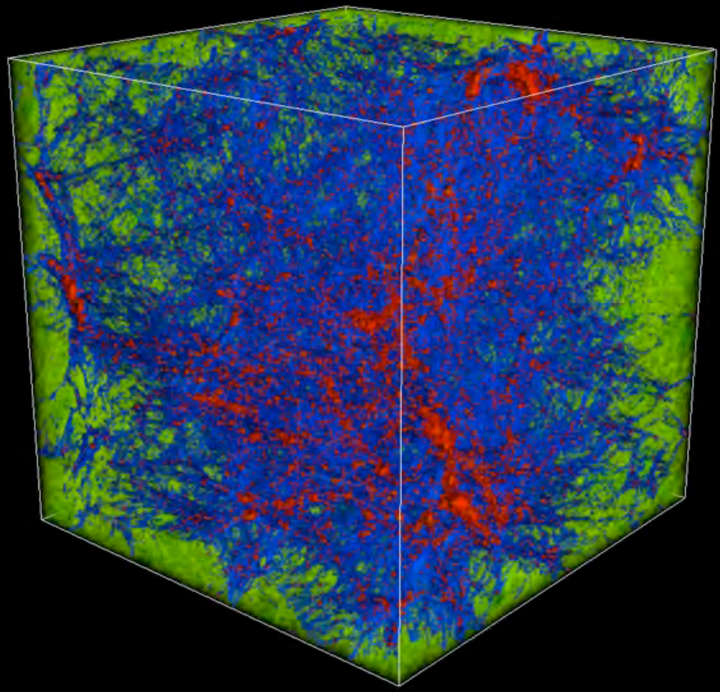
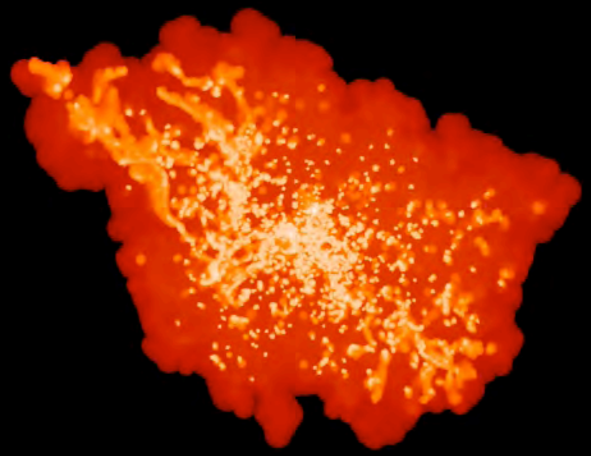
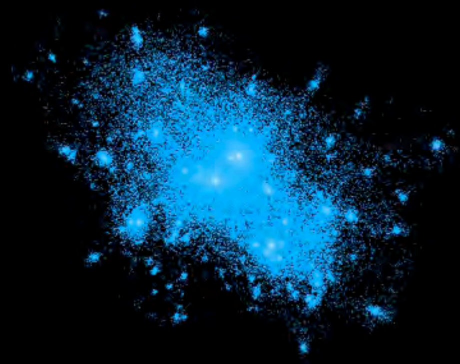
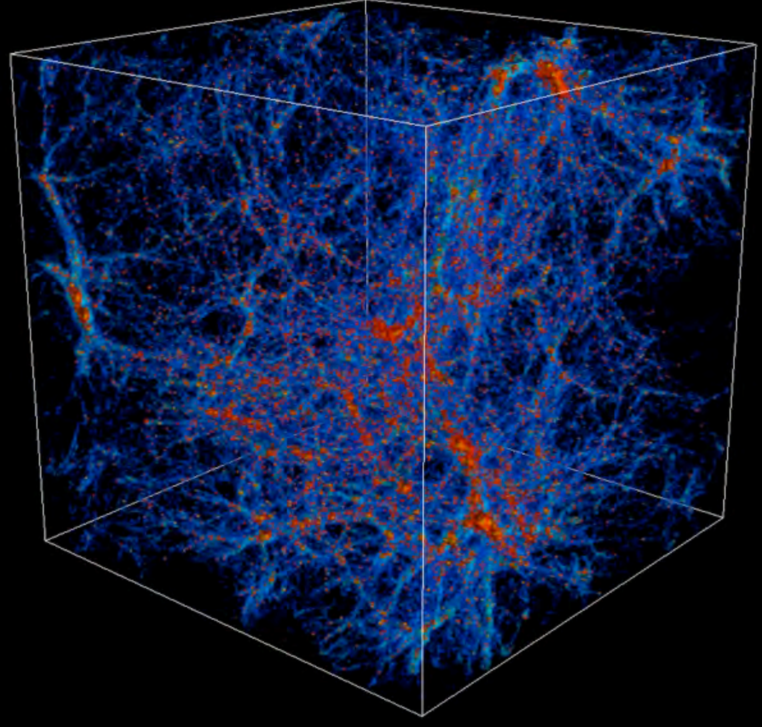
   

DLAs, Escape Fraction, & RT

Ken Nagamine
UNLV

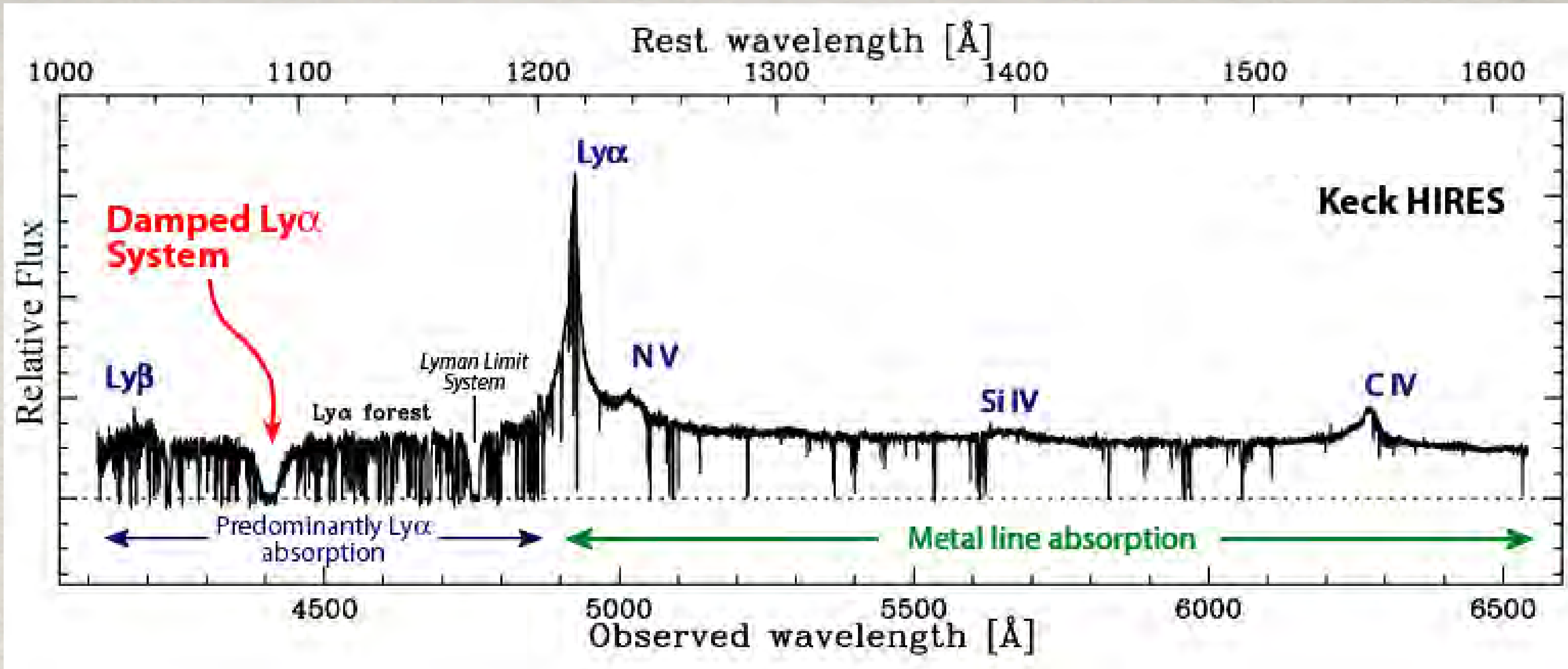
Collaborators: Hidenobu Yajima (Penn State)
Jun-Hwan Choi (Kentucky)
Robert Thompson, Jason Jaacks (UNLV)

KN, Choi, Yajima, 2010, ApJ, 725, L219
Yajima, Choi, KN, 2011, MN, 412, 411
Yajima, Choi, KN, 2012, MN, in press
Thompson, KN+ '12, in prep.

Outline

- Introduction
- DLAs, Column Density Distribution: $f(N_{HI})$
- What physical processes shape $f(N_{HI})$?
  -- effects of radiation (stellar, UVB) & feedback
- How big are DLAs? -- Cross section $\sigma_{DLA}(M_h)$
- Escape Fraction of ionizing photons
- Conclusions

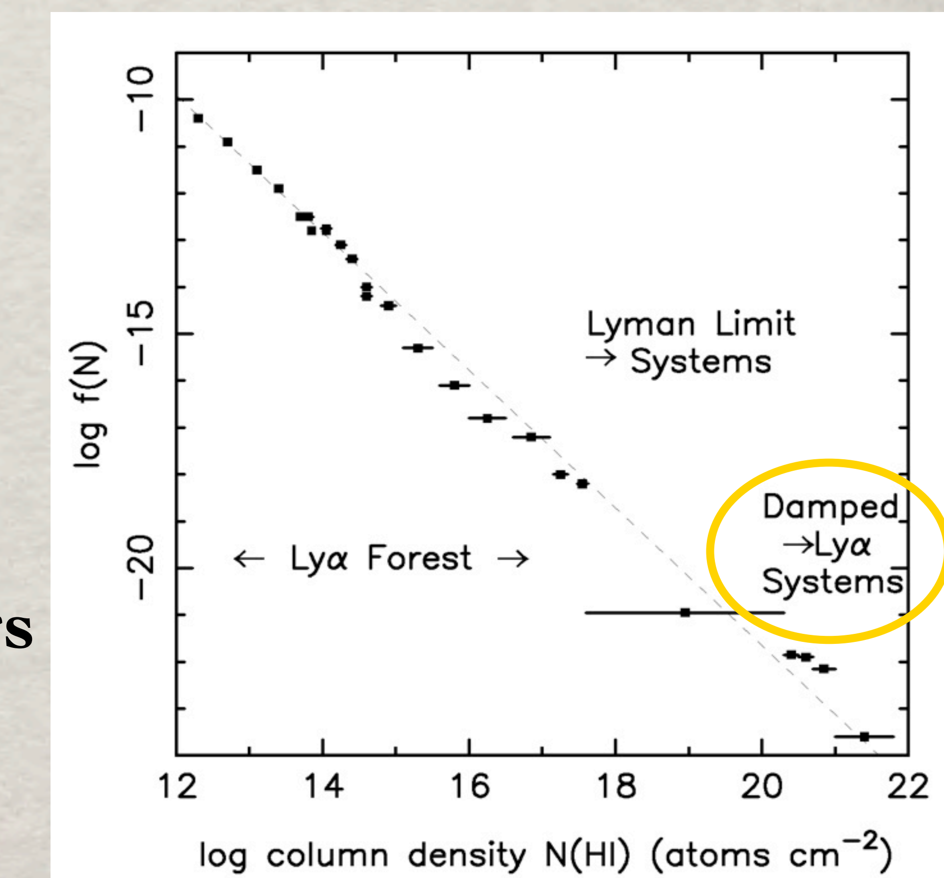
What are DLAs?



quasar

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

(Wolfe+ '86)



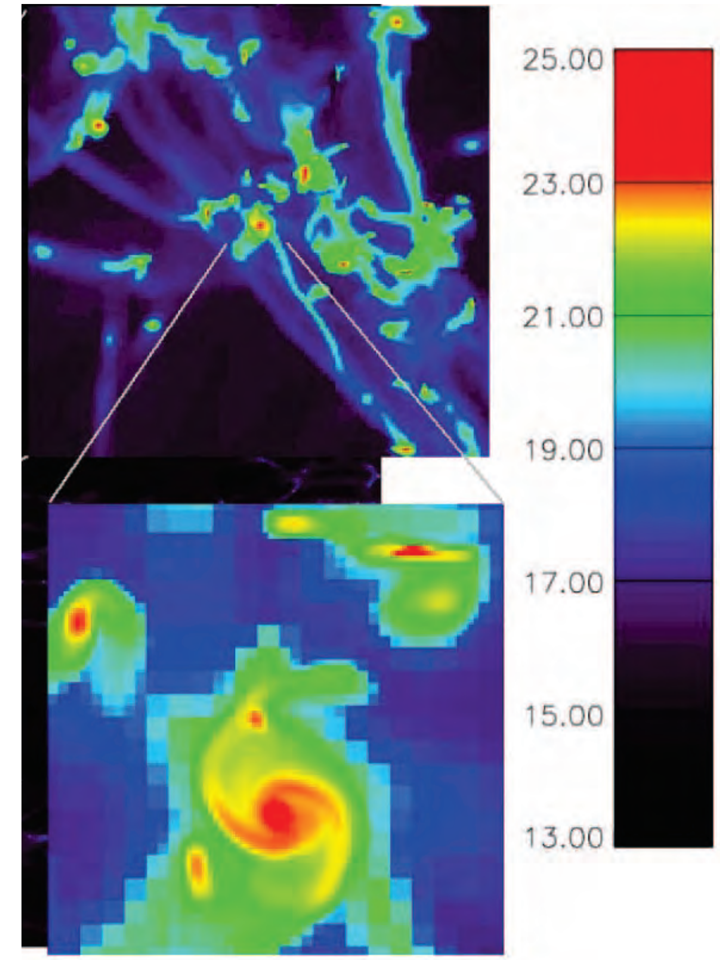
Direct probe of HI gas in high-z universe

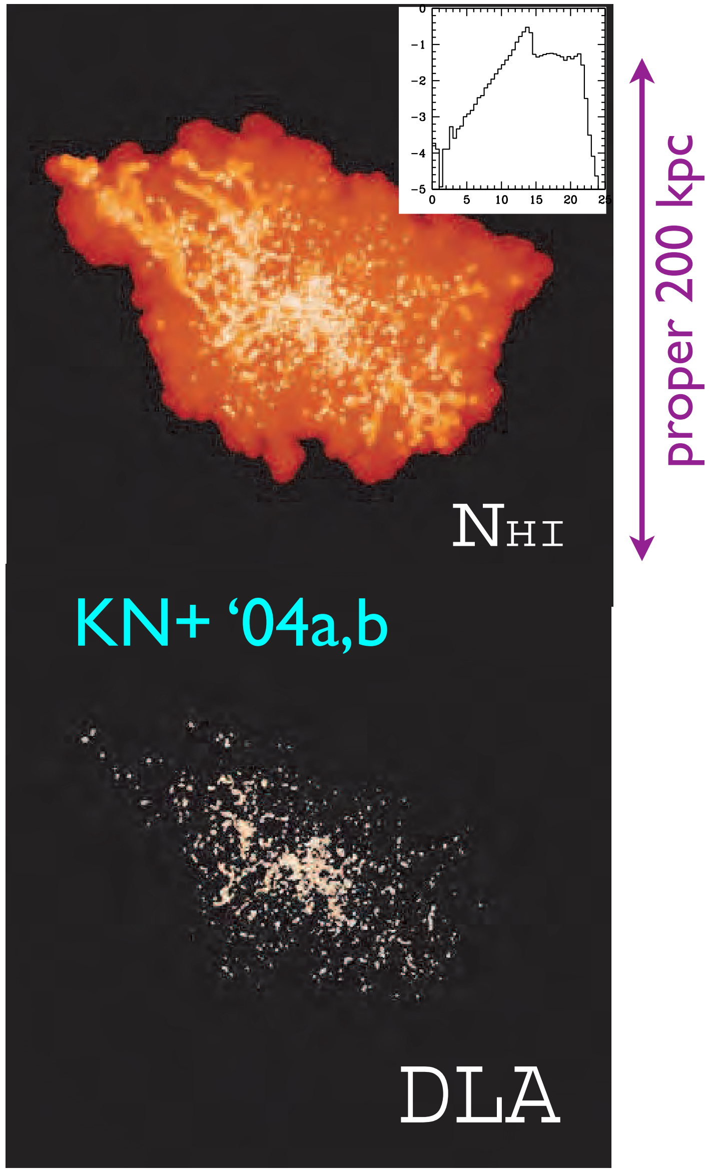
DLAs are heavy-weight champions of HI absorbers

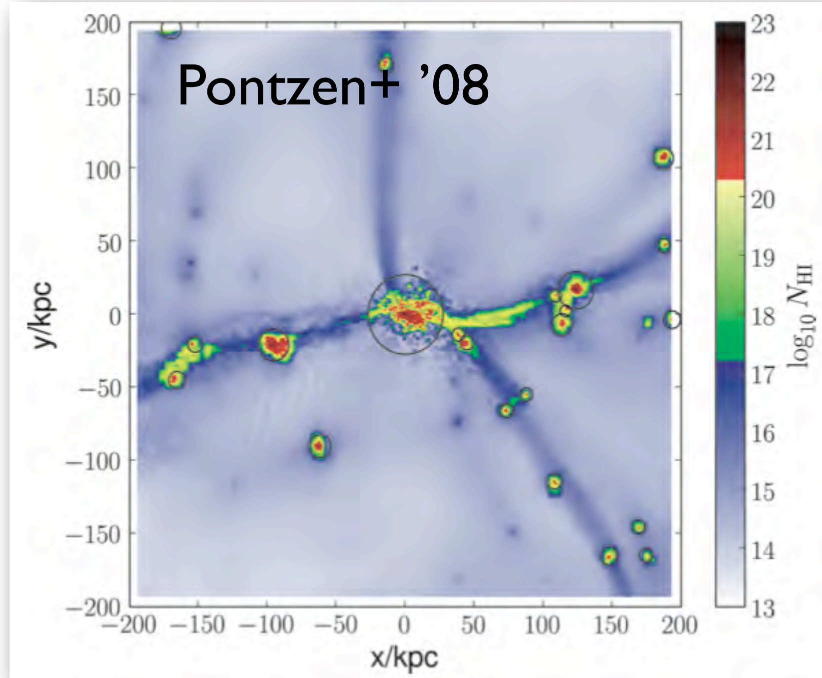
Need to understand these systems in the context of CDM model

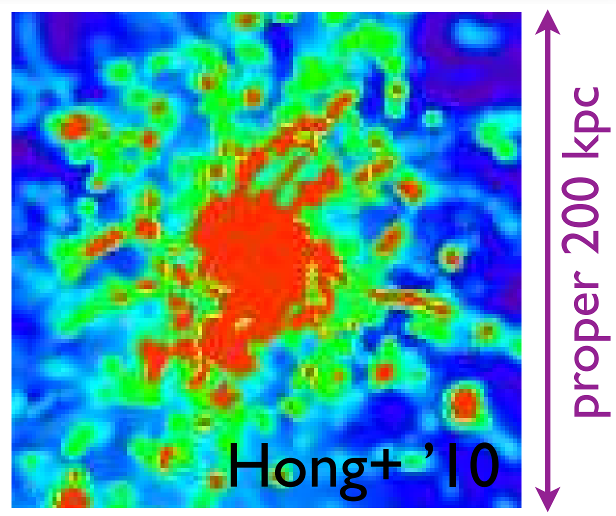
Gallery of DLAs

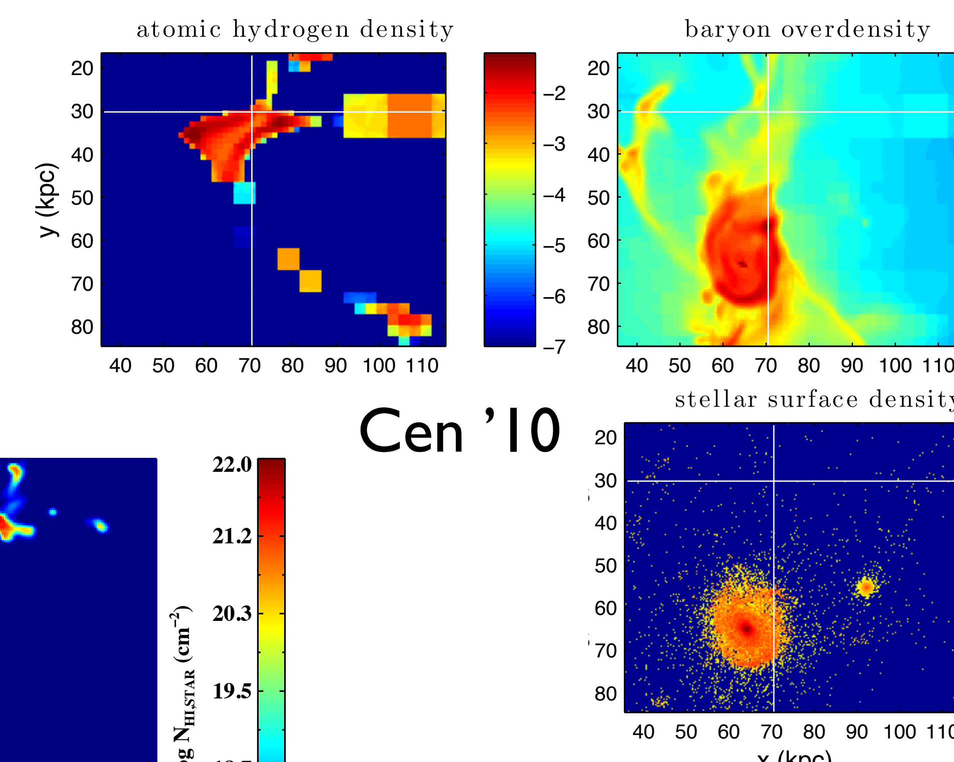
Razoumov+ '06



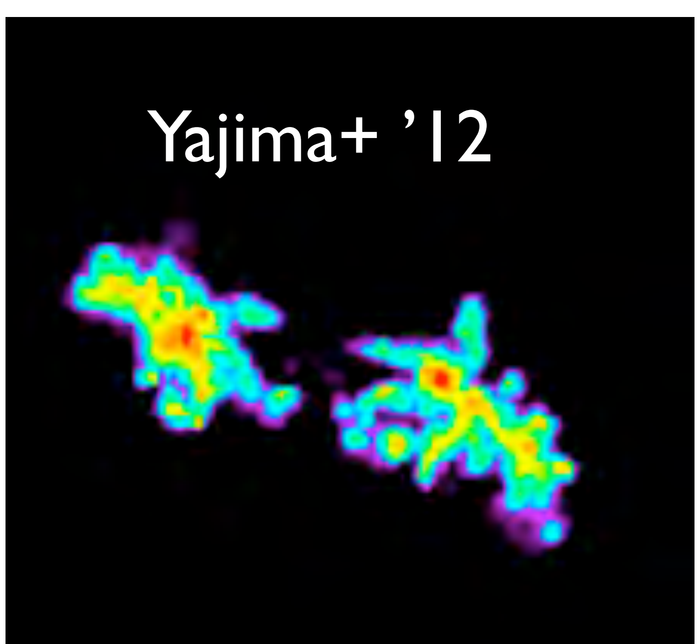


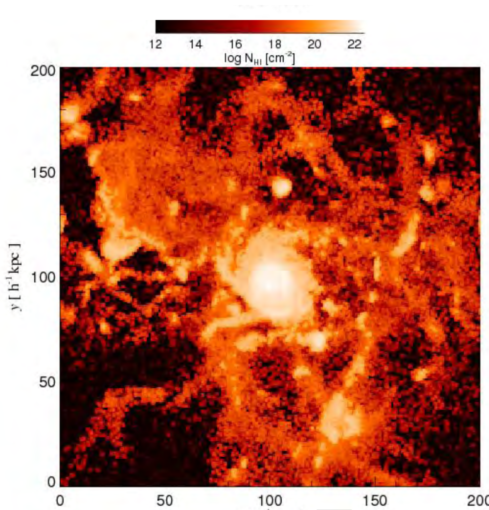




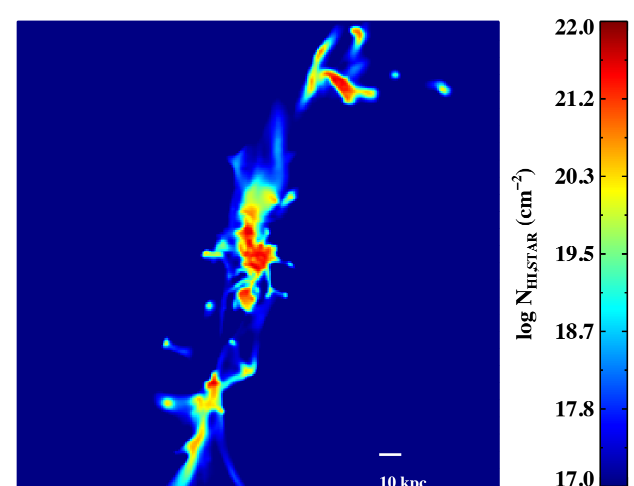


Cen '10

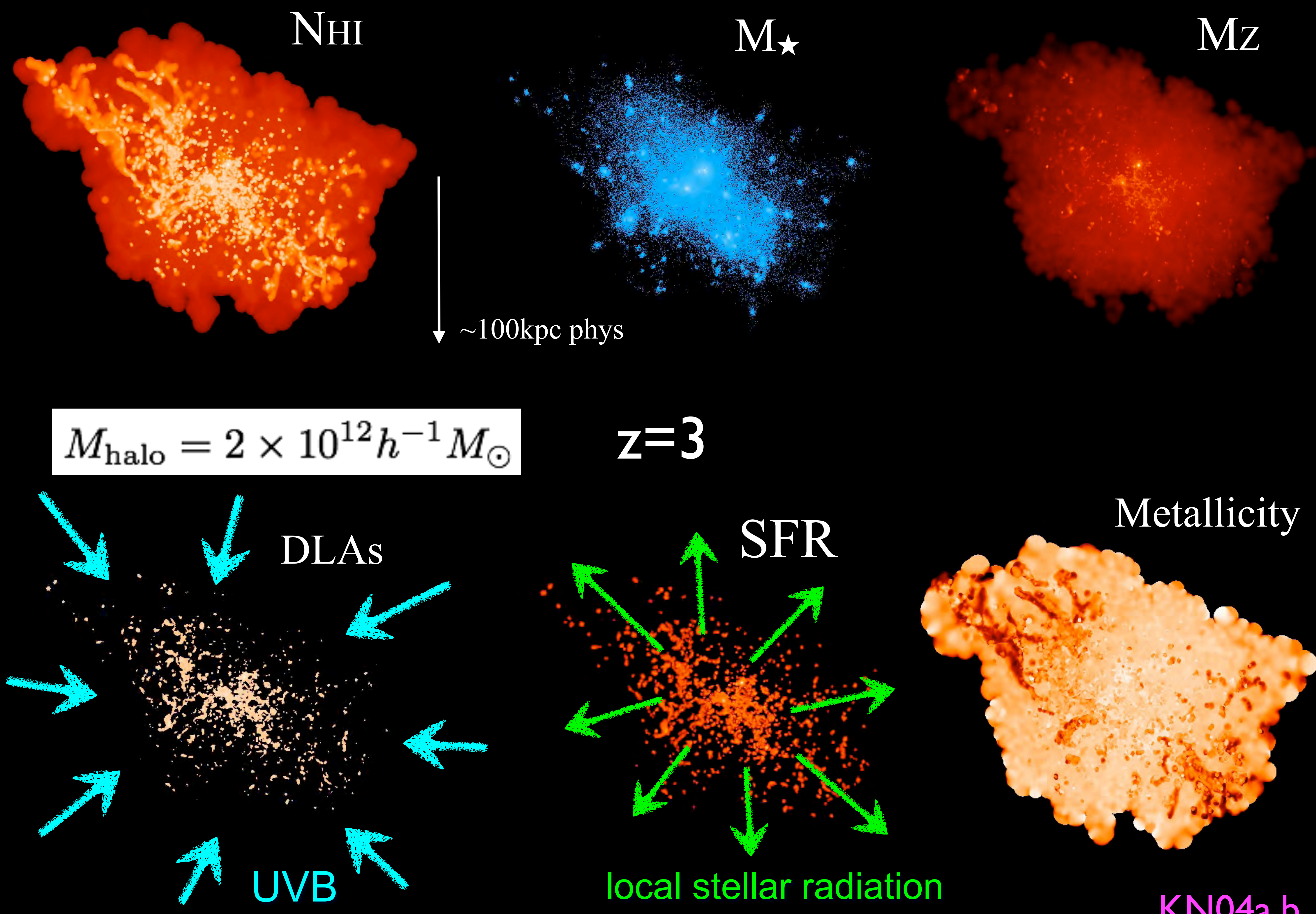




Tescari+'09



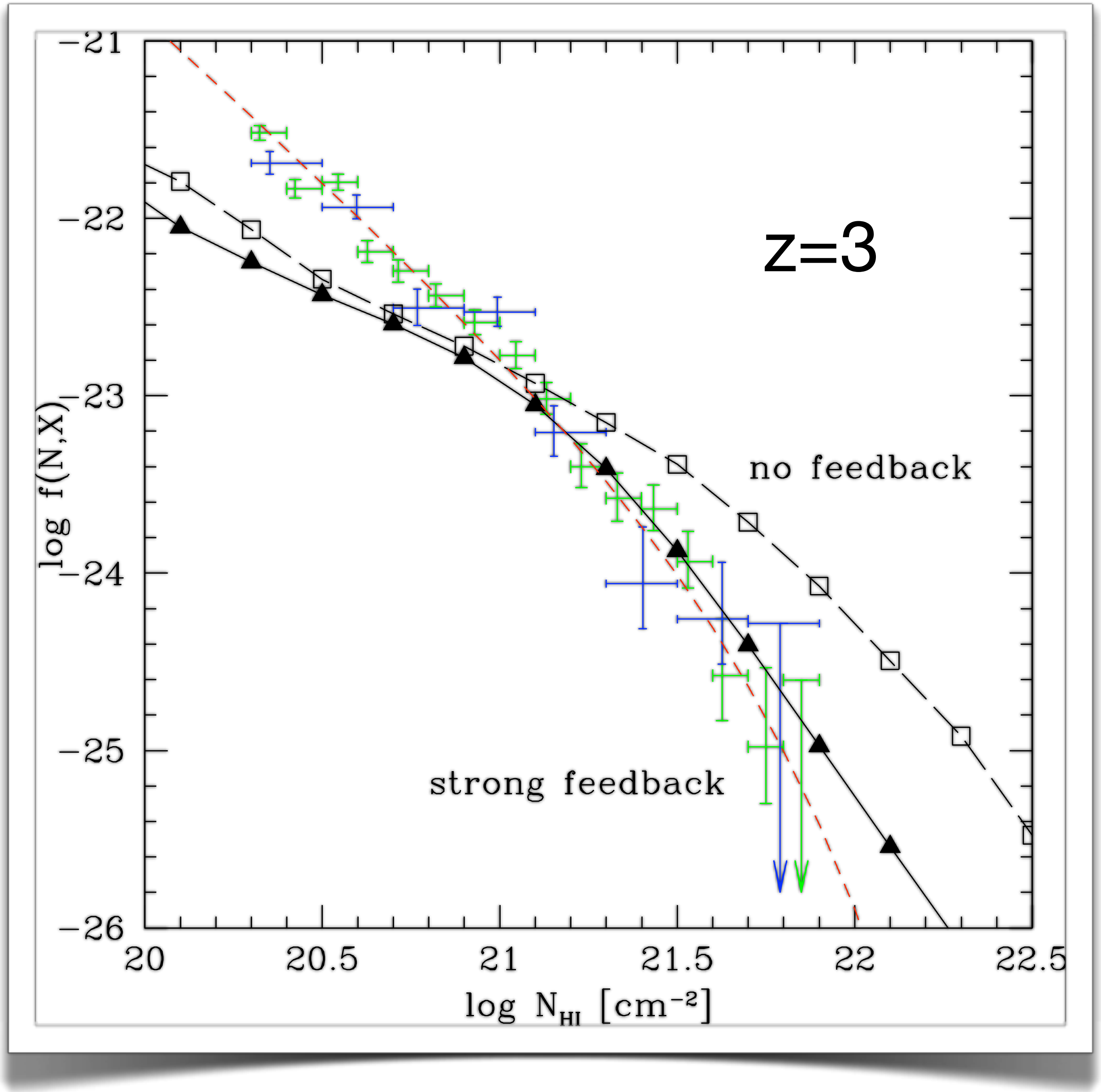
Fumagalli+ '11



N_{HI}
$M_\star$
M_Z
~100kpc phys
$M_{\rm halo} = 2 \times 10^{12} h^{-1} M_\odot$
z=3
DLAs
SFR
Metallicity
UVB
local stellar radiation
KN04a,b

Column density distribution $f(N_{HI})$

- No-feedback run **overpredicts** at high N_{HI}.
- Strong feedback suppresses the high N_{HI}-end. (SH03 SF model)
- But **under**-estimate at $N_{HI} <\sim 21$ dex
- Assumed optically-thin UVB



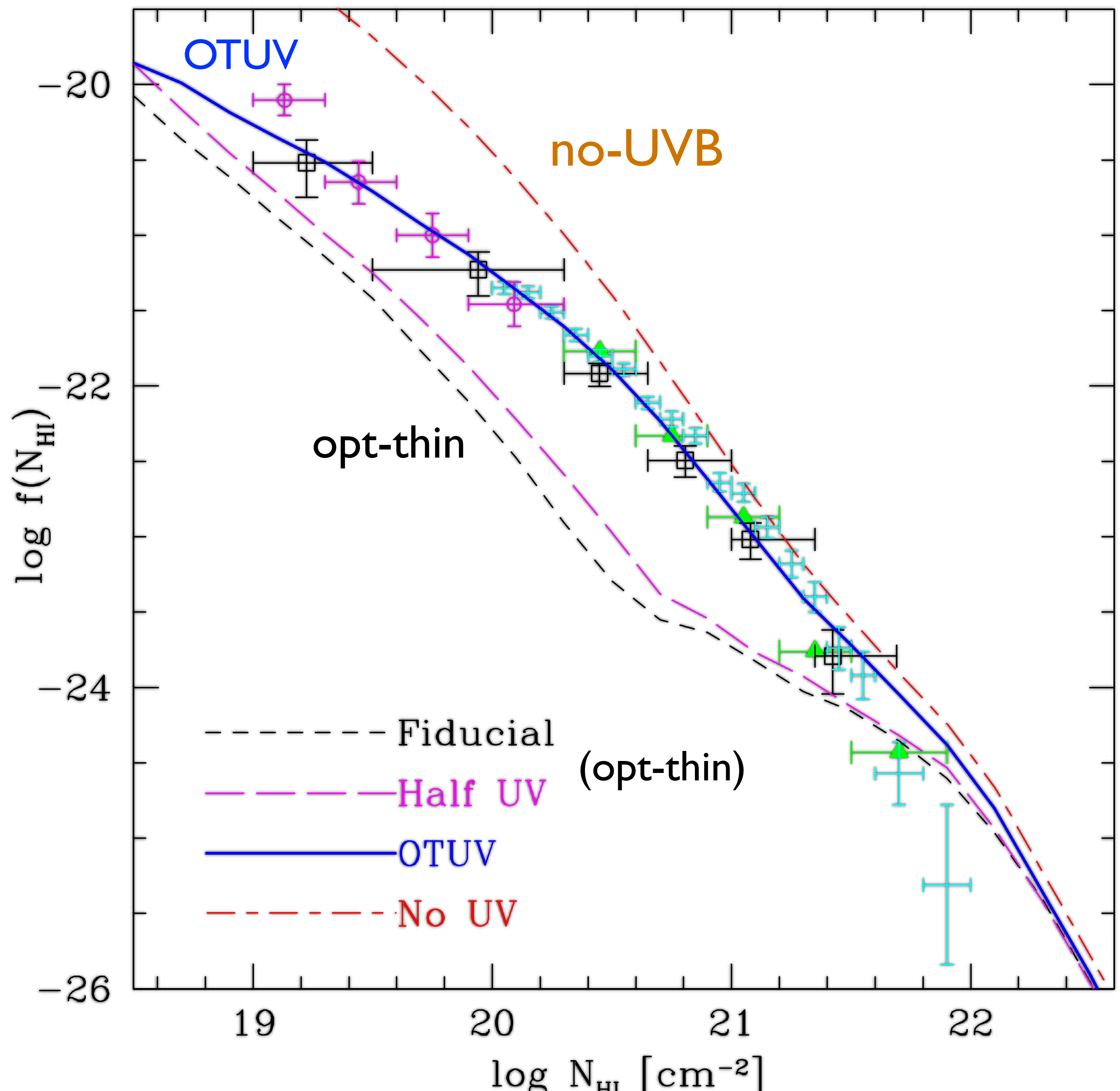
KN+ '04a,b

Effect of UVB on f(N_{HI})

- No-UVB run overpredicts.
- UVB sinks in too much w/ opt-thin approx.
- Shutting off UVB at $\rho > 0.01\,\rho_{th,SF}$ yields good result.

$\rho_{th}^{UV} \sim 10^{-3}$-$10^{-2}$ cm^{-3}

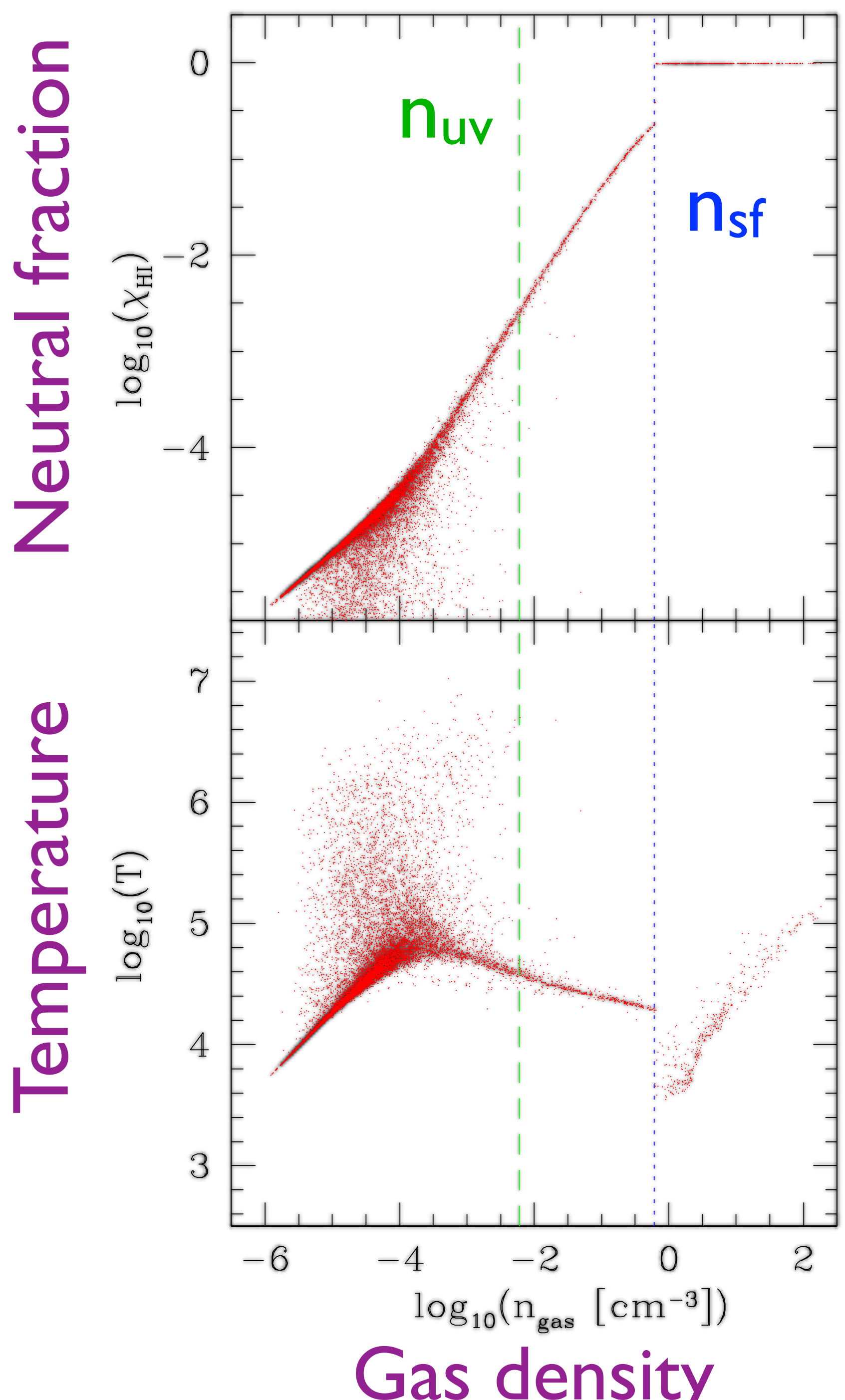
(cf. Tajiri & Umemura '98; Kollmeier+ '09)



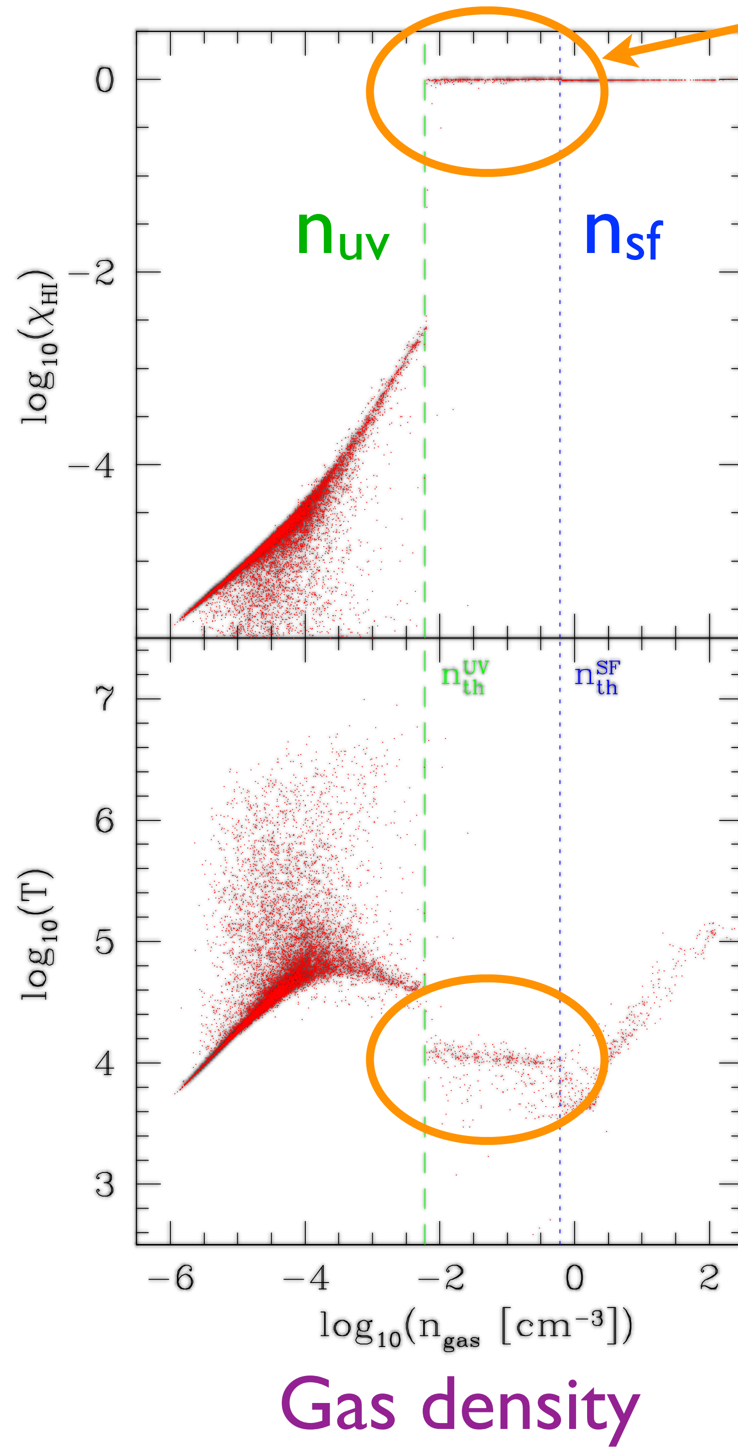
KN+ '10

Effects of UVB and Self-Shielding

Opt-thin approx.



OTUV model



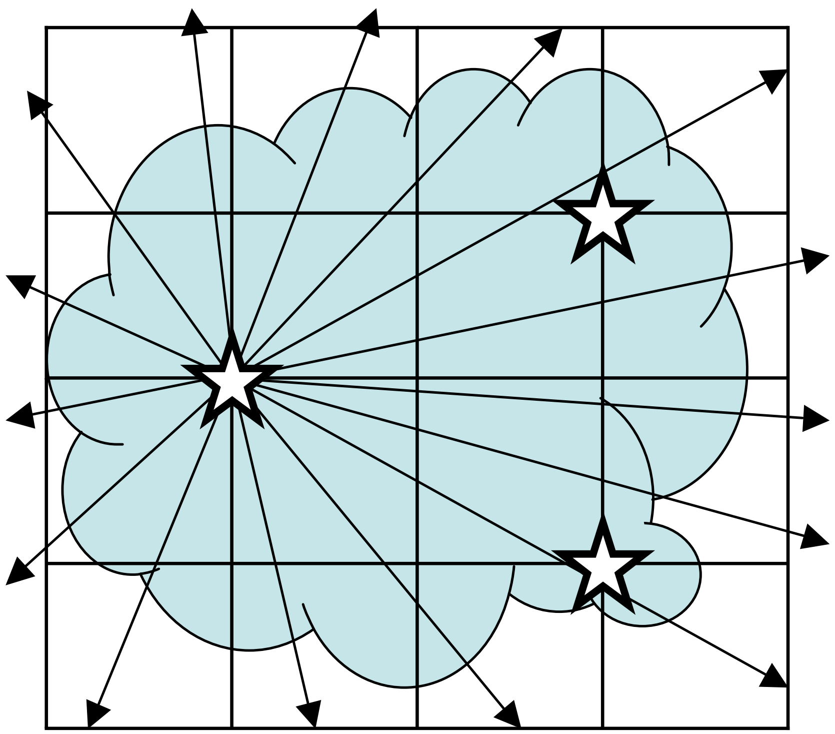
Important for DLA gas!

$n_{sf} \sim 0.6\ cm^{-3}$

$n_{uv} \sim 6e\text{-}3\ cm^{-3}$

KN+ '10

ART method



Authentic Ray Tracing Method

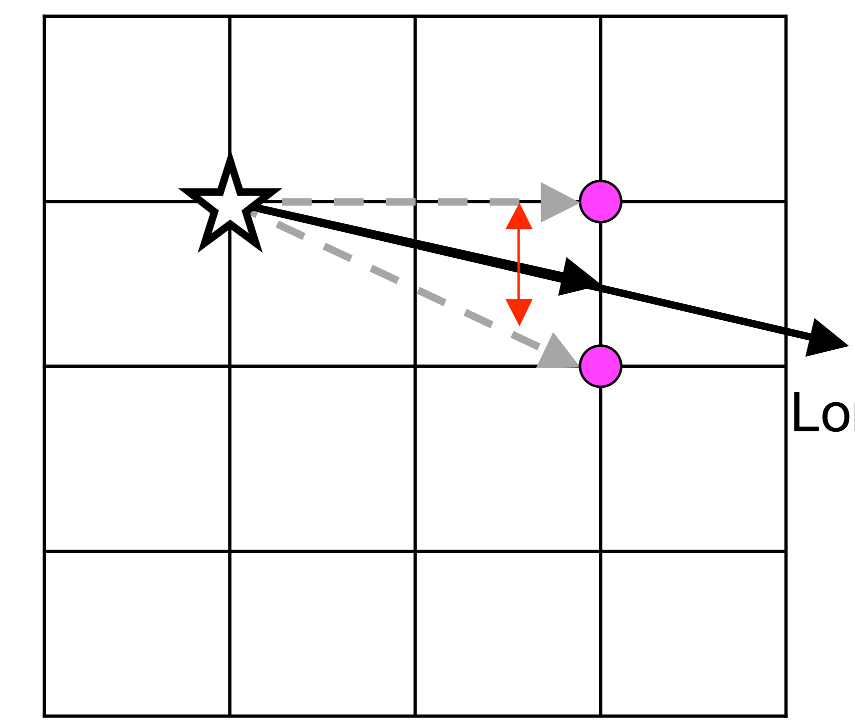
(Nakamoto et al. 2001, Iliev et al. 2006)

- Radiation meshes are arranged radially from each sources independently of fluid meshes.

- The radiation field on fluid meshes are estimated by interpolating from near radiation meshes.

- The order of calculation amount

$$N_{source} \times N_\theta \times N_\phi \times N_{path}$$



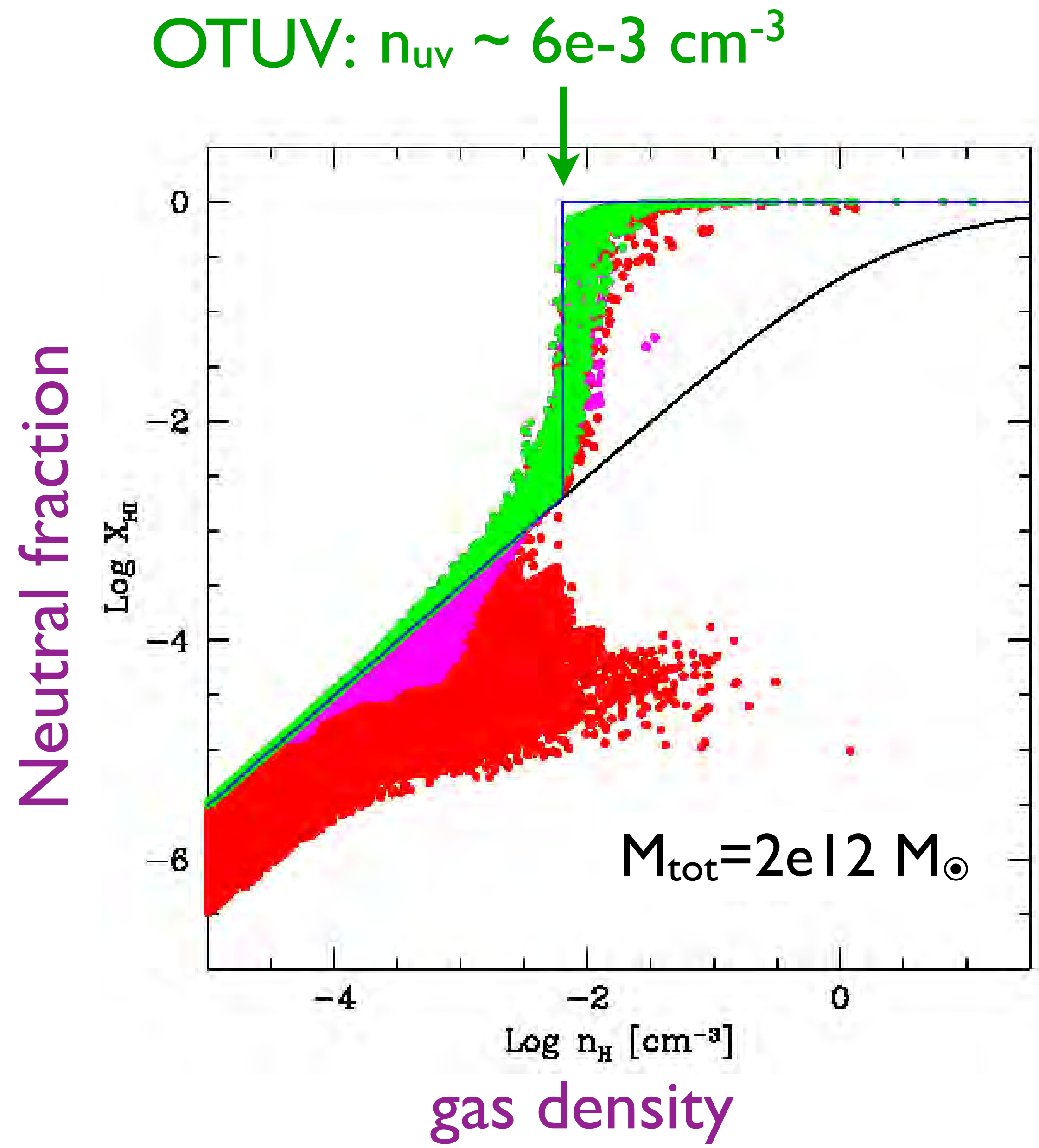
Long characteristic method: $N_{source} \times N_x \times N_y \times N_z \times N_{path}$

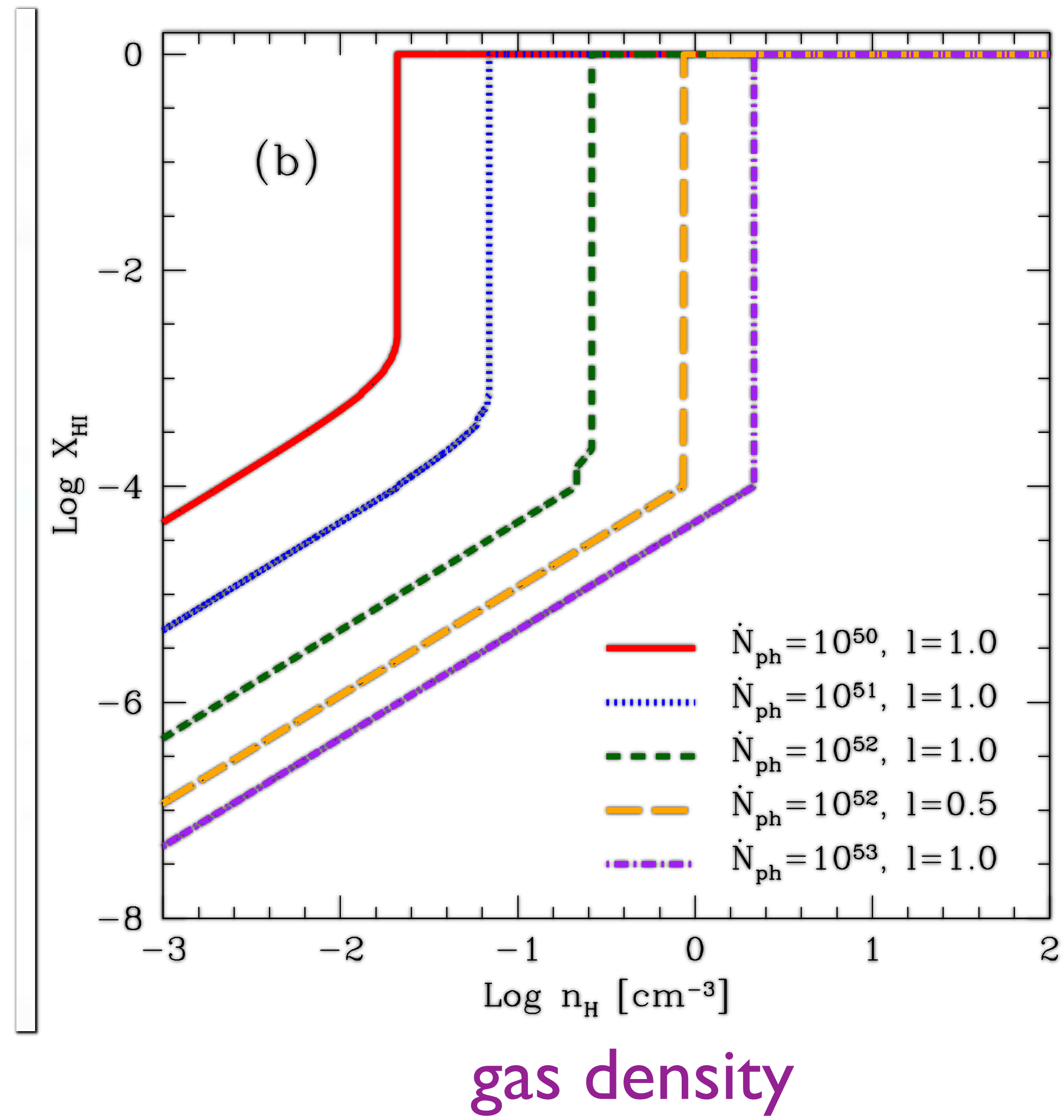
Basic equation: $\dfrac{dI_\nu}{ds} = -\alpha_{abs} I_\nu + \varepsilon_\nu$

(from Yajima, '09)

Validating OTUV model w/ RT calculation

Yajima, Choi, KN '12





$$\Gamma^{\gamma}_{\rm star} = \dot{N}_{\rm ph}\sigma_0 \exp(-\tau)/4\pi\ell^2$$

$$\tau = \sigma_0 n_{\rm HI}\ell$$

green: UVB RT

magenta: UVB RT + collis. ioniz.

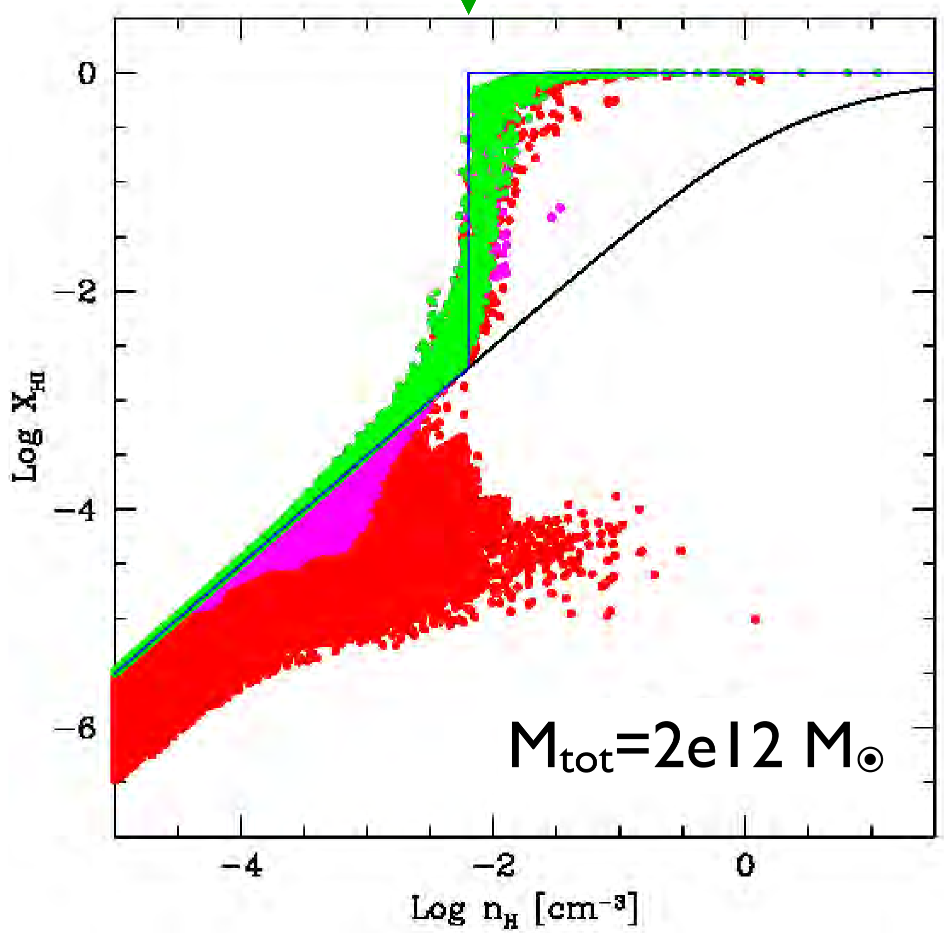
red: UVB RT + collis. ioniz. + stellar RT

Validating OTUV model w/ RT calculation

Yajima, Choi, KN '12

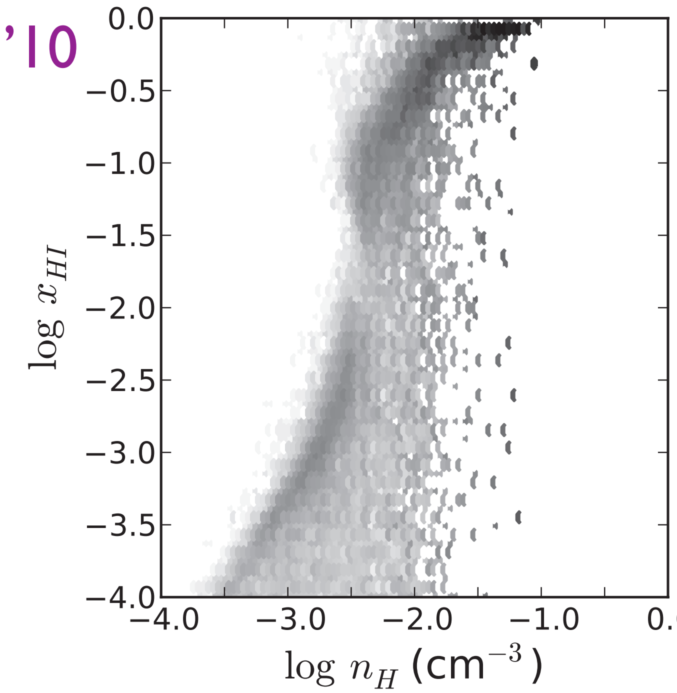
OTUV: $n_{uv} \sim 6e\text{-}3\ cm^{-3}$

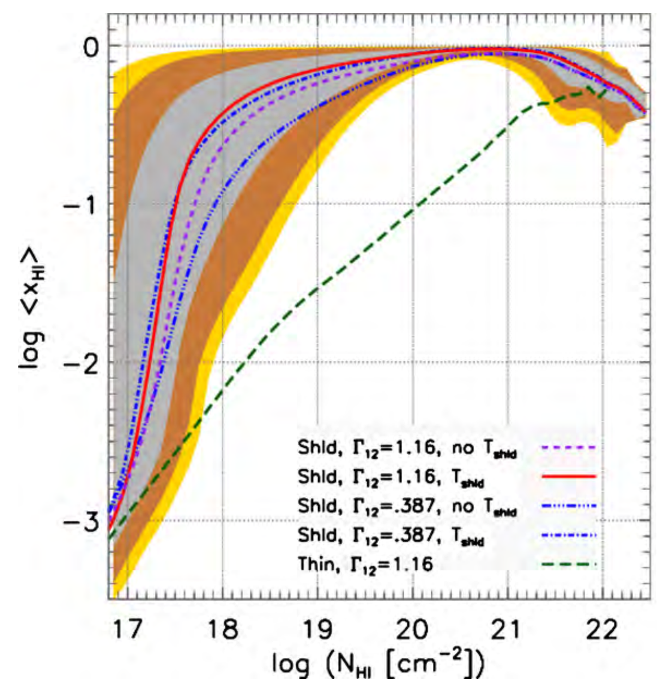
Neutral fraction



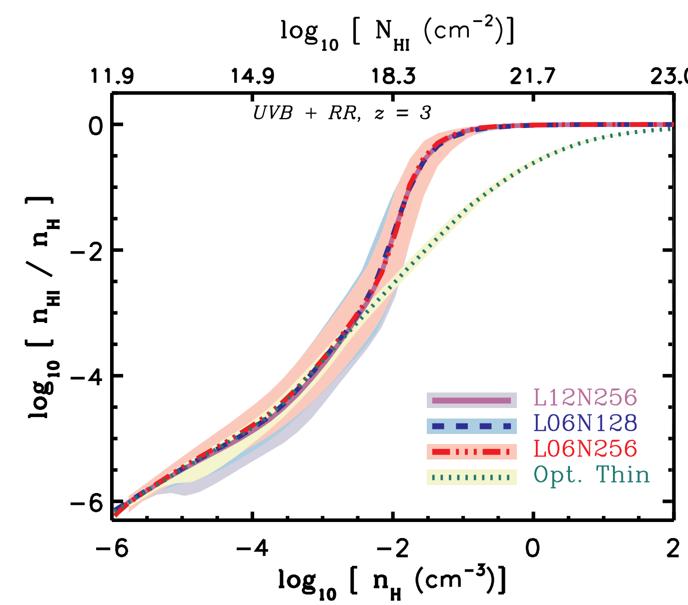
gas density

Faucher-Giguere+ '10





Altay+ '11



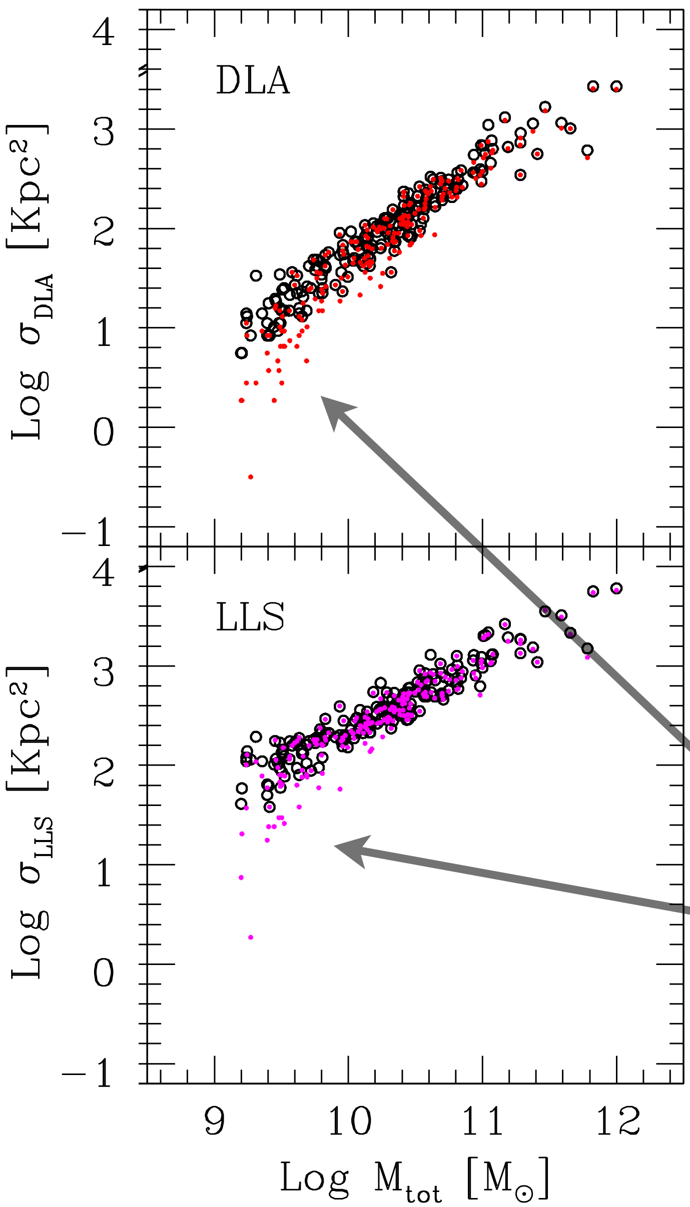
Rahmati+ '12

green: UVB RT

magenta: UVB RT + collis. ioniz.

red: UVB RT + collis. ioniz. + stellar RT

Effects of Local Stellar Radiation on DLAs

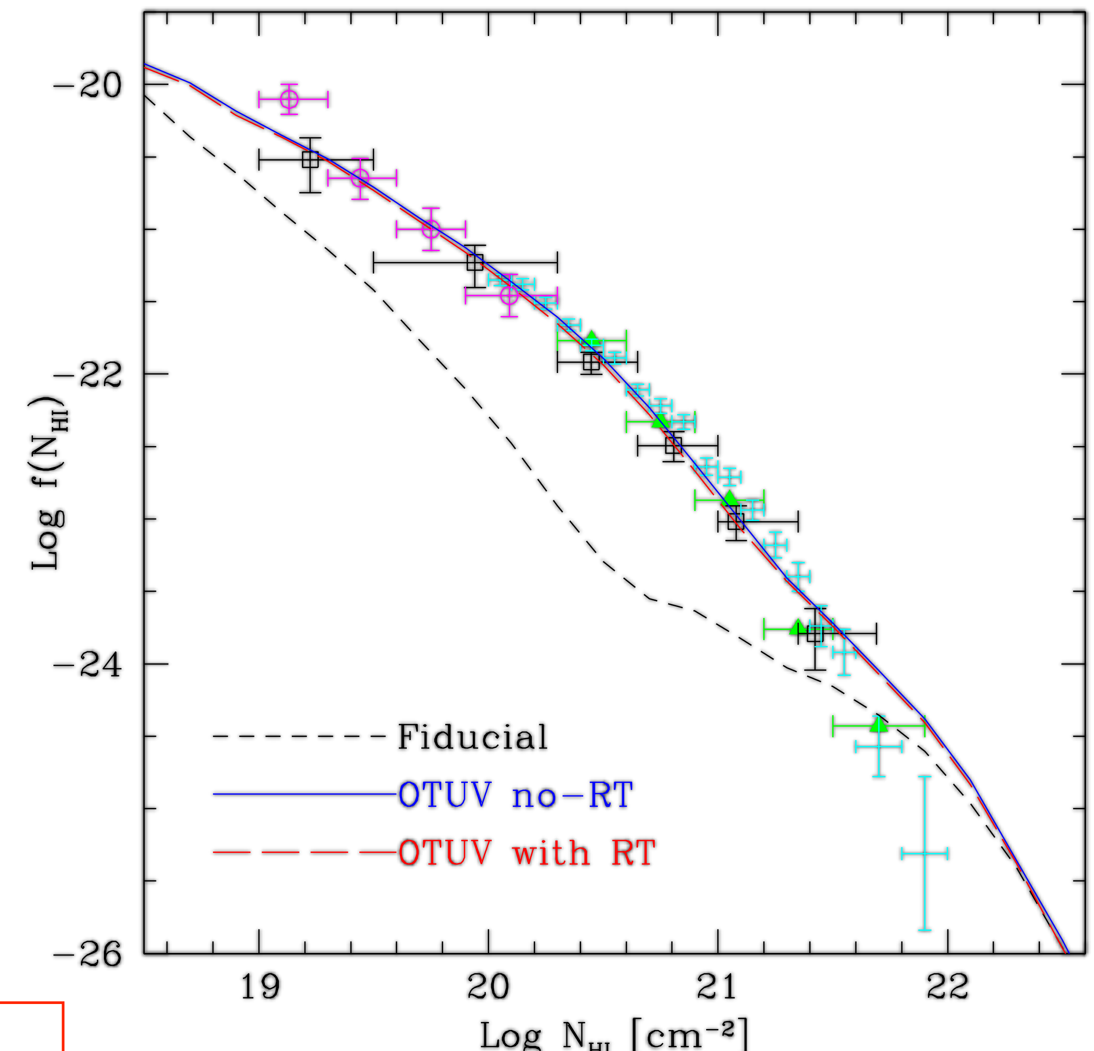


open circle -- before RT (OTUV)

red & magenta points -- after stellar RT

slight reduction in σ by stellar RT

Yajima+ '12



KN+ '10

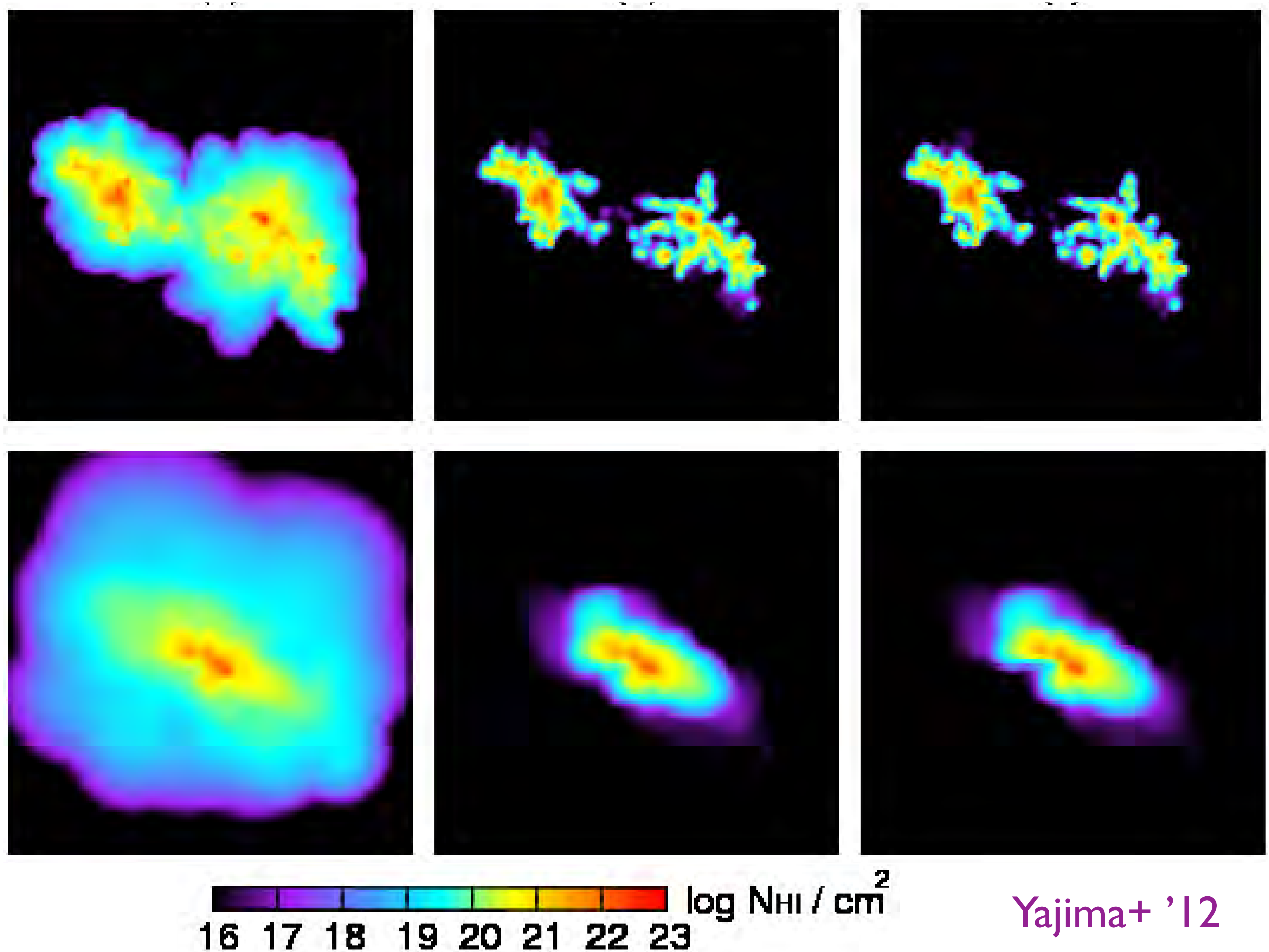
f(N_{HI}) is not so much affected by stellar rad RT

Effects of Radiation on N_{HI}

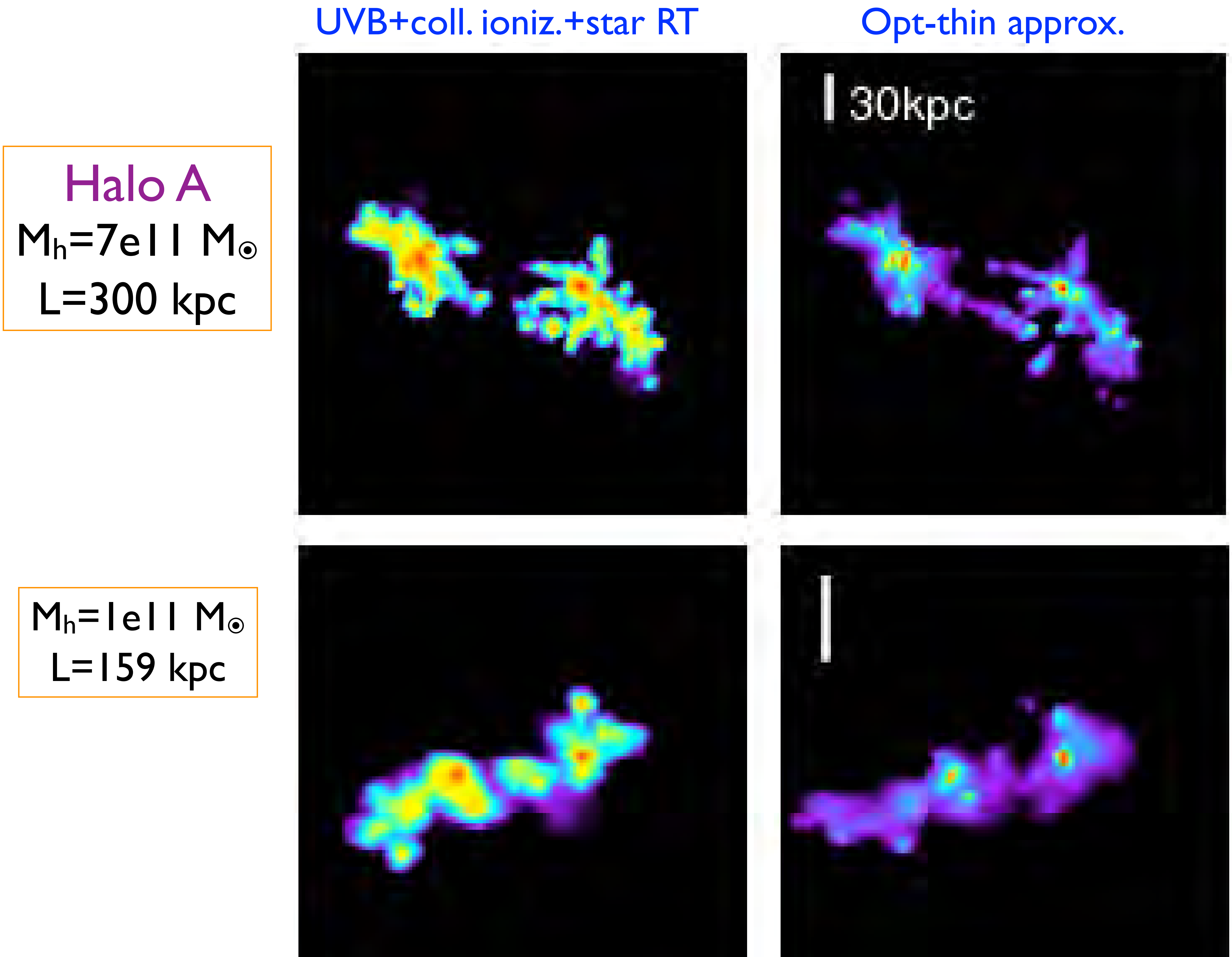
no RT | UVB RT + coll. ioniz. | UVB+coll. ioniz.+star RT

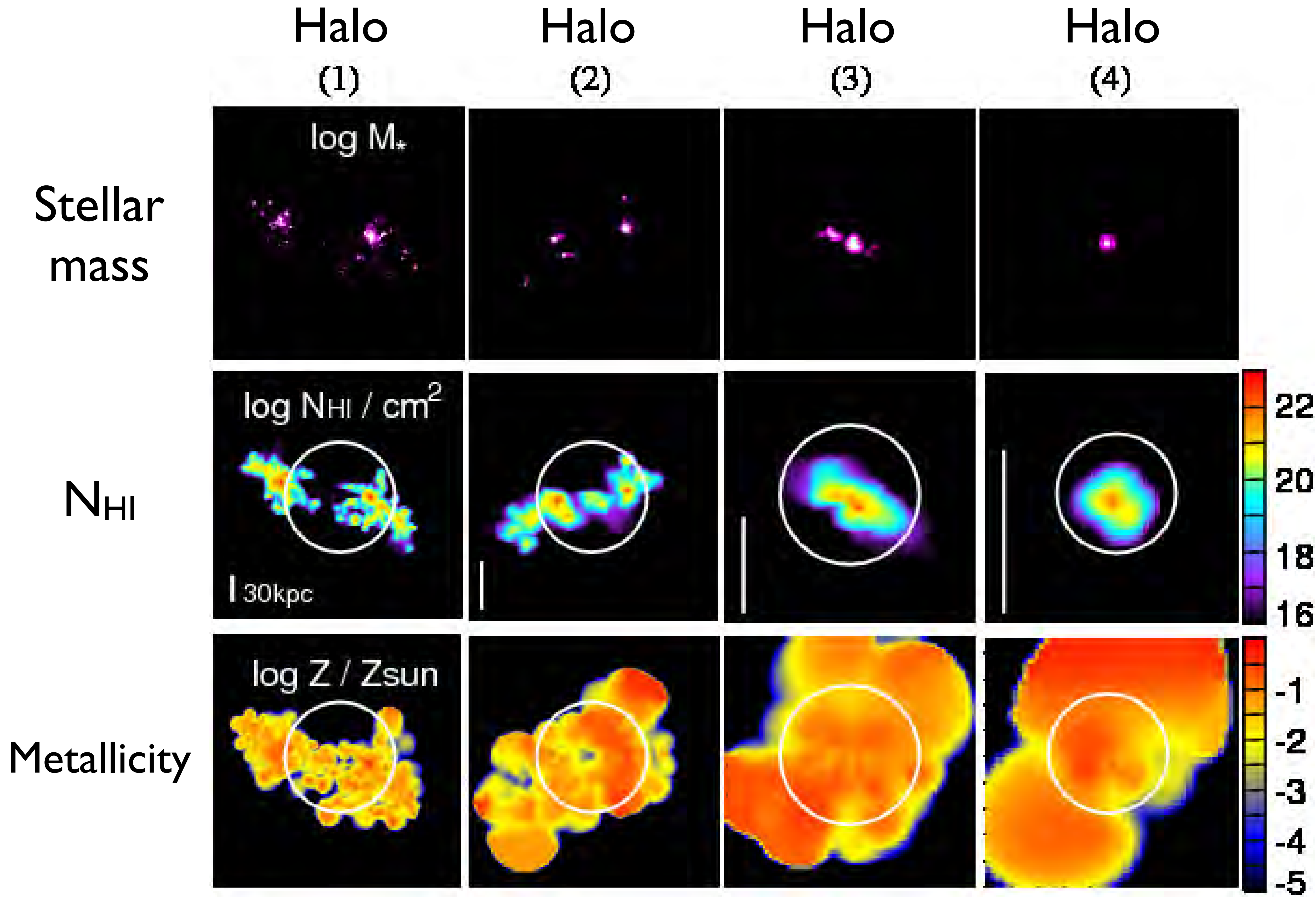
Halo A
M_h=7e11 $M_\odot$
L=300 kpc

Halo B
M_h=3e10 $M_\odot$
L=80 kpc



Yajima+ '12

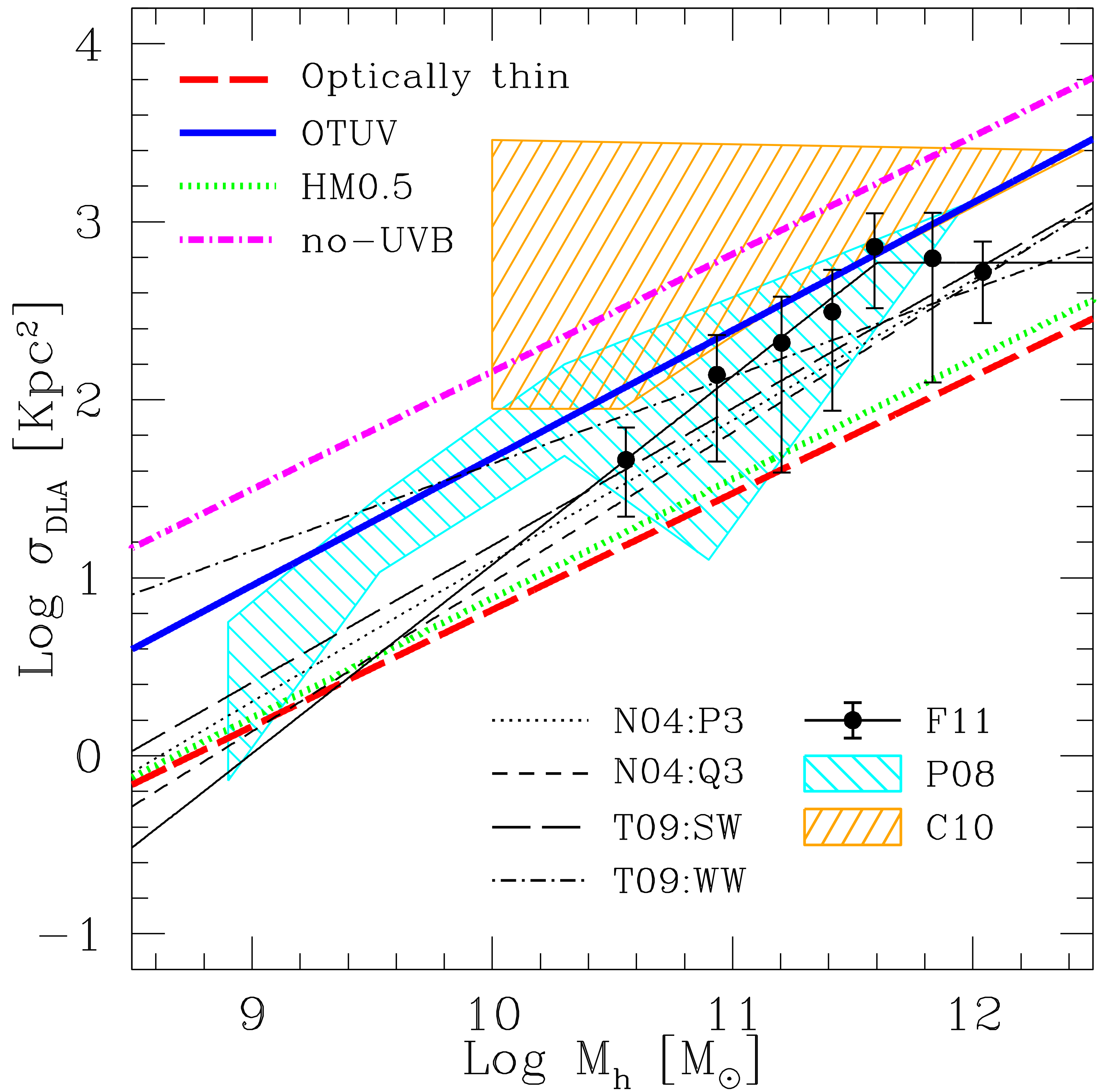

UVB+coll. ioniz.+star RT
Opt-thin approx.
30kpc
Halo A
Mh=7e11 M⊙
L=300 kpc
Mh=1e11 M⊙
L=159 kpc



(Circles: physical R_{vir} = 68, 37, 23, 11 kpc)

Yajima, Choi, KN '12

DLA Cross Section vs. Halo Mass

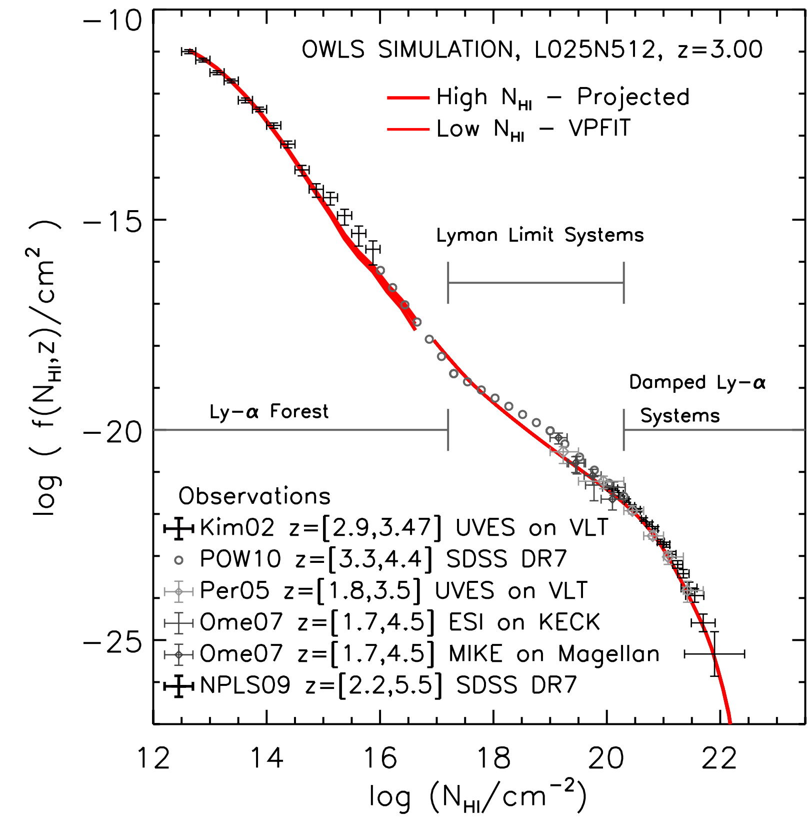


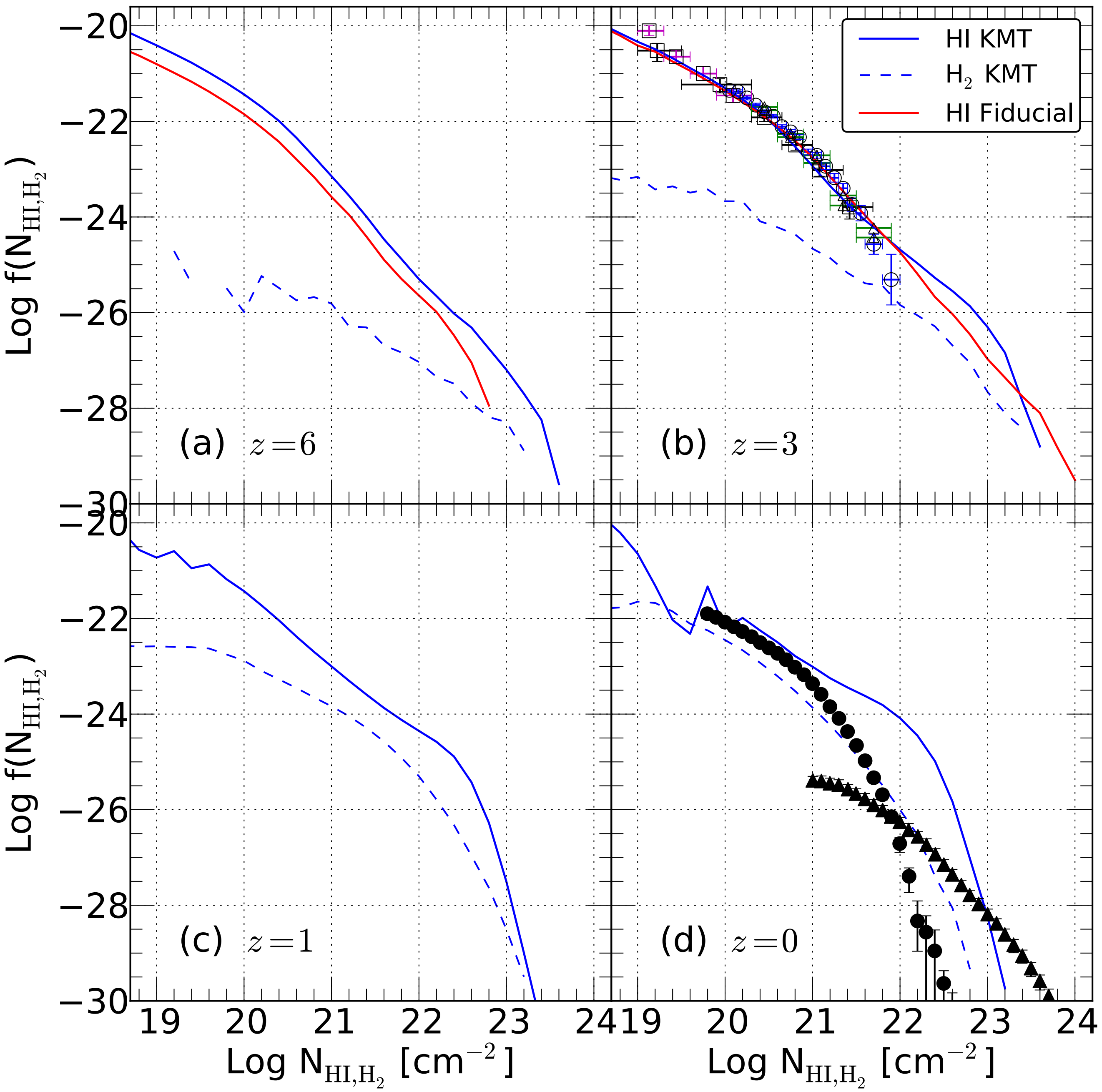
Tescari+ '09; GADGET SPH
Fumagali+ '11; ART AMR
Pontzen+ '08; GASOLINE SPH
Cen '10; Enzo AMR

Yajima, Choi, KN '12

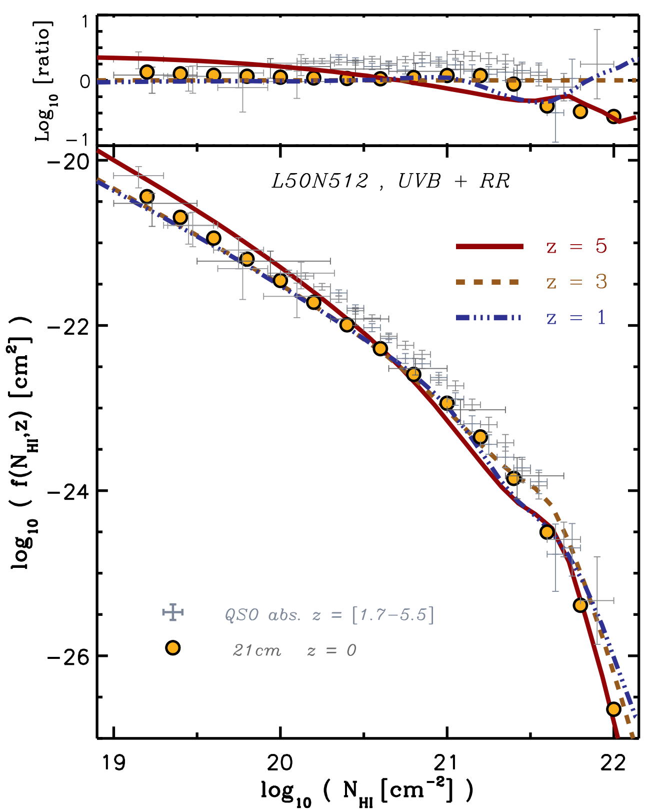
Effect of H_2 on $f(N_H)$

Altay+ '11

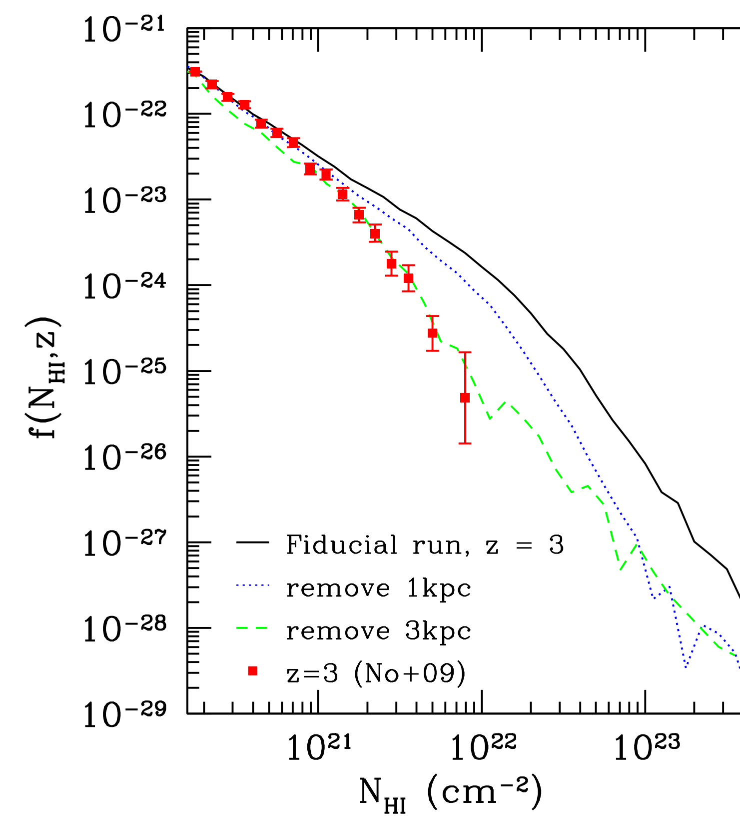




Thompson, KN+ '12



Rahmati+ '12



Erkal+ '12

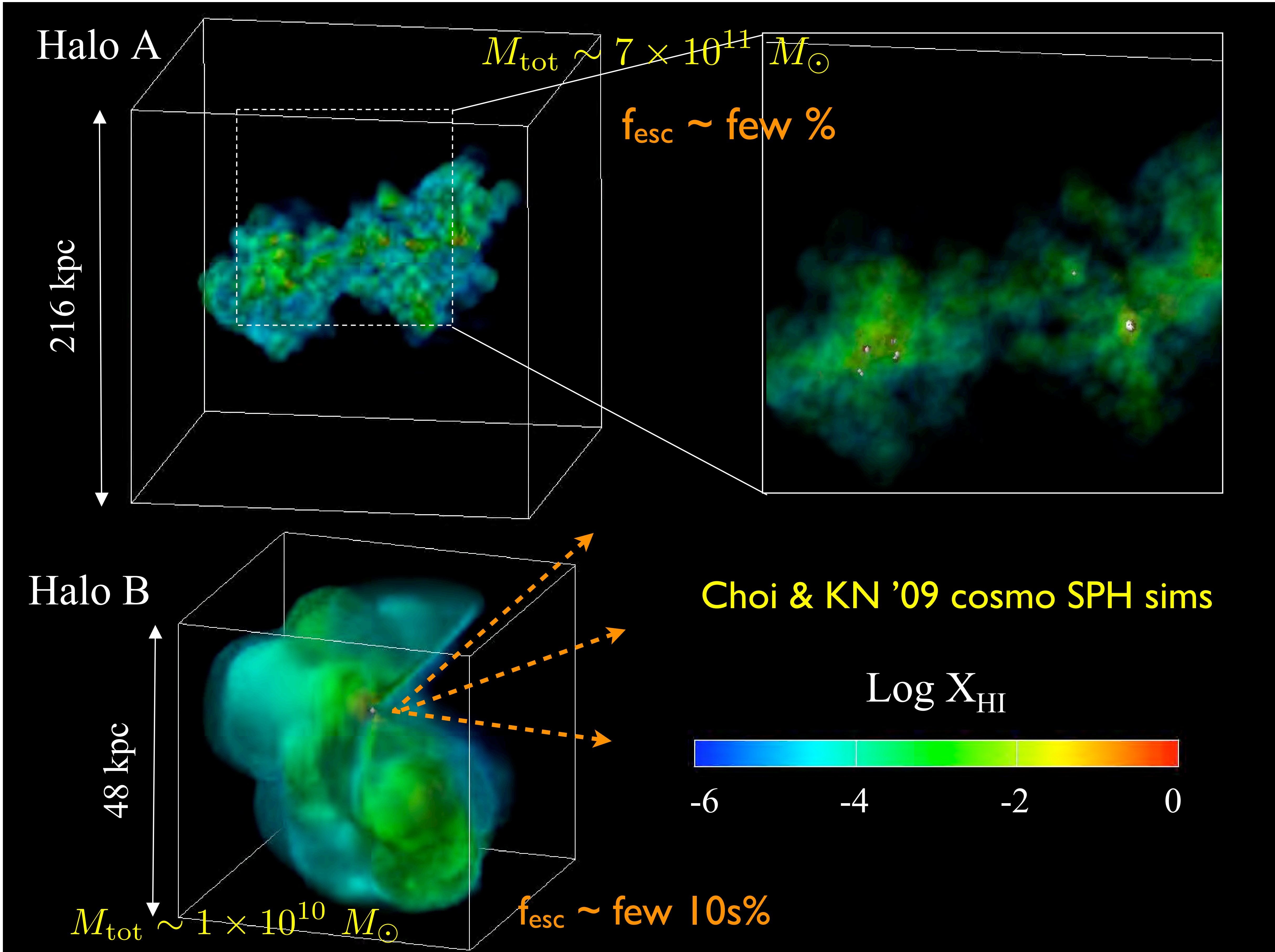
Cosmology (Ω_b, σ_8), SF, FB, UVB, H2, ...

Escape Fraction

Yajima, Choi, KN '11

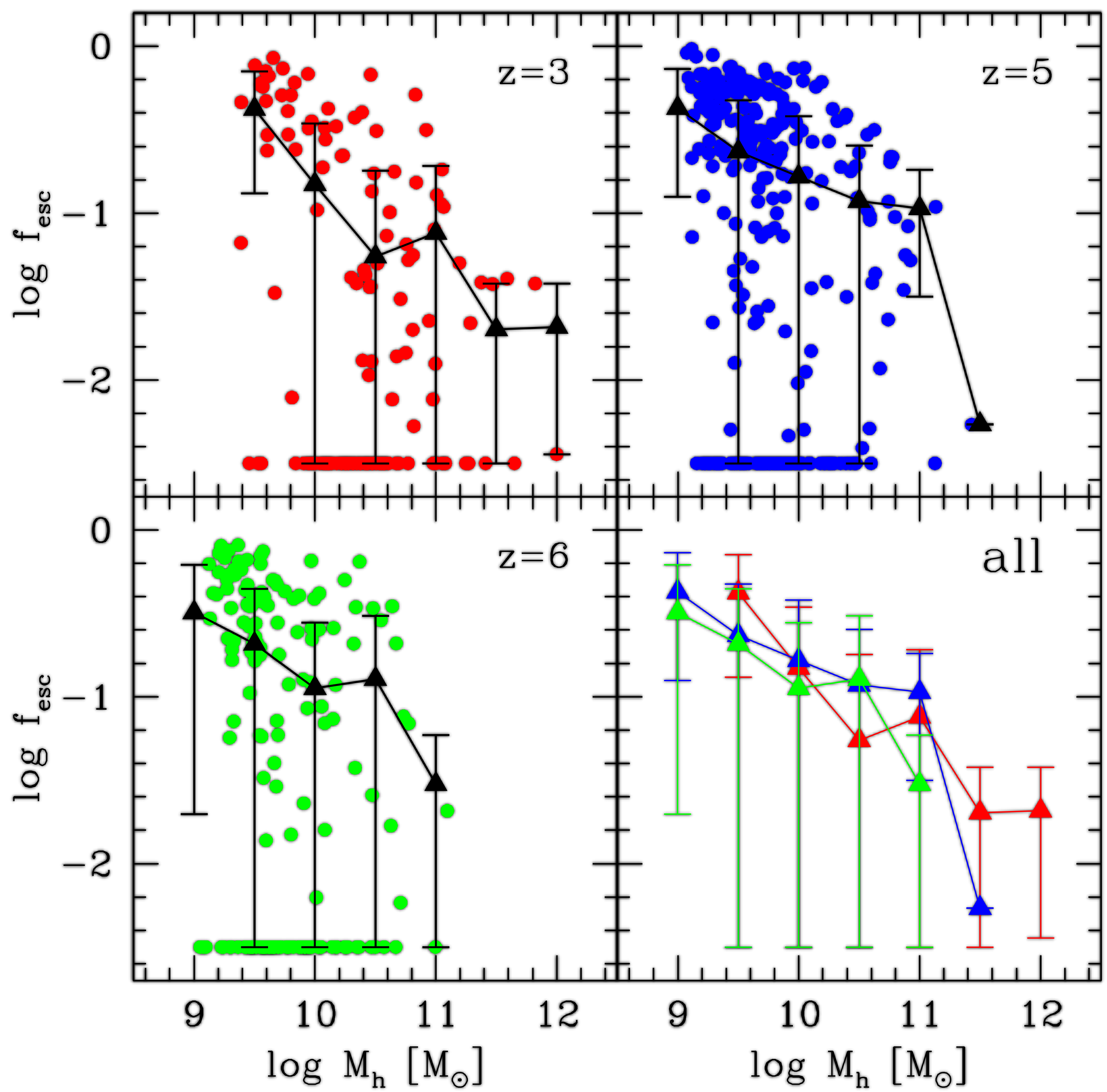
Authentic Ray Tracing method

(Nakamoto+ '01, Illiev+ '06, Yajima+ '09)



f_{esc} as a function of M_{halo} & redshift

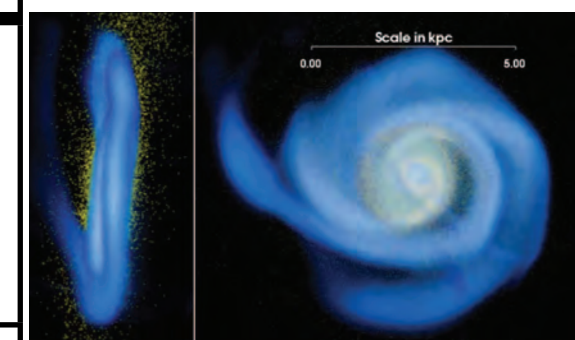
- Choi & KN '09 cosmo SPH sims w/ MVV wind feedback models
- **Decreasing f_{esc} as a func of M_{halo}** --- roughly consistent with Razoumov+'09; but different from Gnedin +'09, Wise & Cen '09

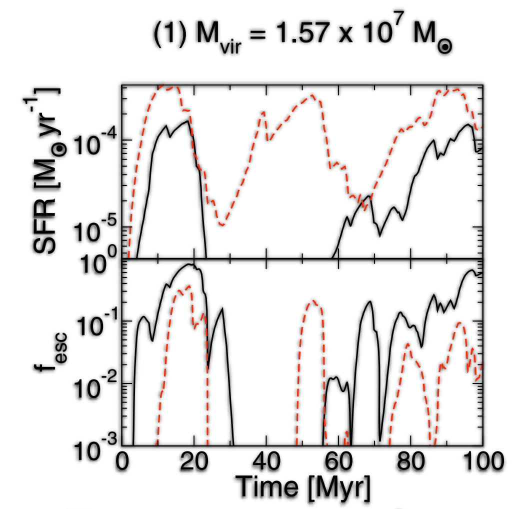


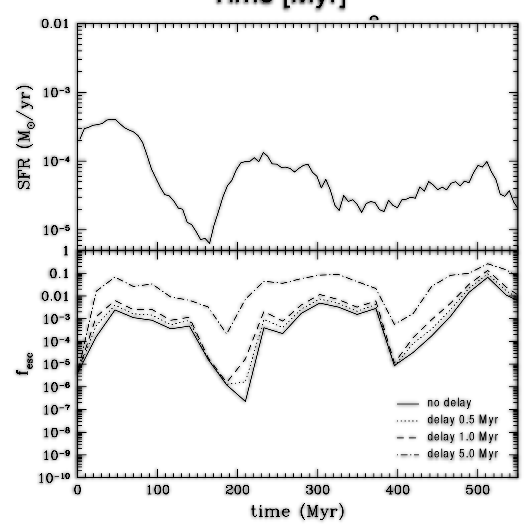
Yajima, Choi, KN '11

Escape Fraction of Ionizing Photons

Authors	$f_{esc,ion}$ (M_{halo})	Method
Gnedin+ '09	Very low 10^{-5}-10^{-1}, 10^{11}-10^{12} $M_{\odot}$	AMR, 6Mpc box, 65pc res, OTVET, z=3
Razoumov+'09	1.0-0.0, 10^{8}-10^{11} $M_{\odot}$	SPH, 6Mpc box, ~0.5kpc res, resim 9 gals, z=4-10
Wise & Cen +'09	Large scatter & time evol. 0-0.4, 10^{6}-10^{9} $M_{\odot}$	AMR, 2 & 8Mpc box, 0.1pc res, z=8
Yajima+ '09	0-0.5, with time	Eulerian (Mori & Umemura '06 sim, single system, t=0-1Gyr)
Yajima, Choi, KN '11	1.0-0.0 10^{9}-10^{12} $M_{\odot}$	SPH, 10Mpc box, ~0.5kpc res, z=3-6 100s of gals.



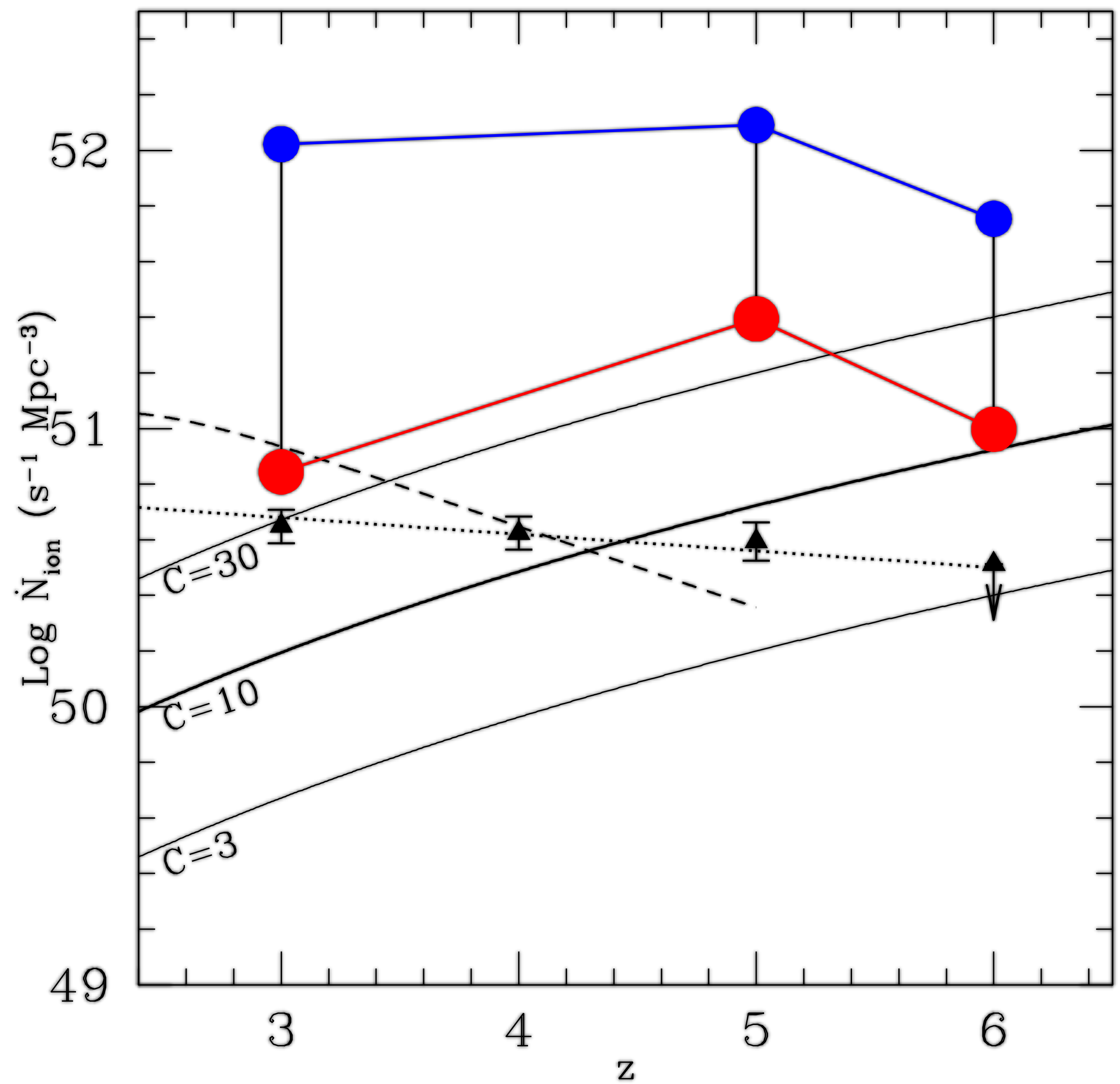




Paardekooper+ '11

Reionization of the Universe

- Simulations suggest that the Universe can be reionized by the star-forming galaxies at z=6 if C≤10.
- High f_{esc} for low-mass gals helps.
- Dashed line: possible quasar contribution
- Dotted line: Bolton & Haehnelt '07



Blue points: intrinsic emission rate density

Red points: escaped photons

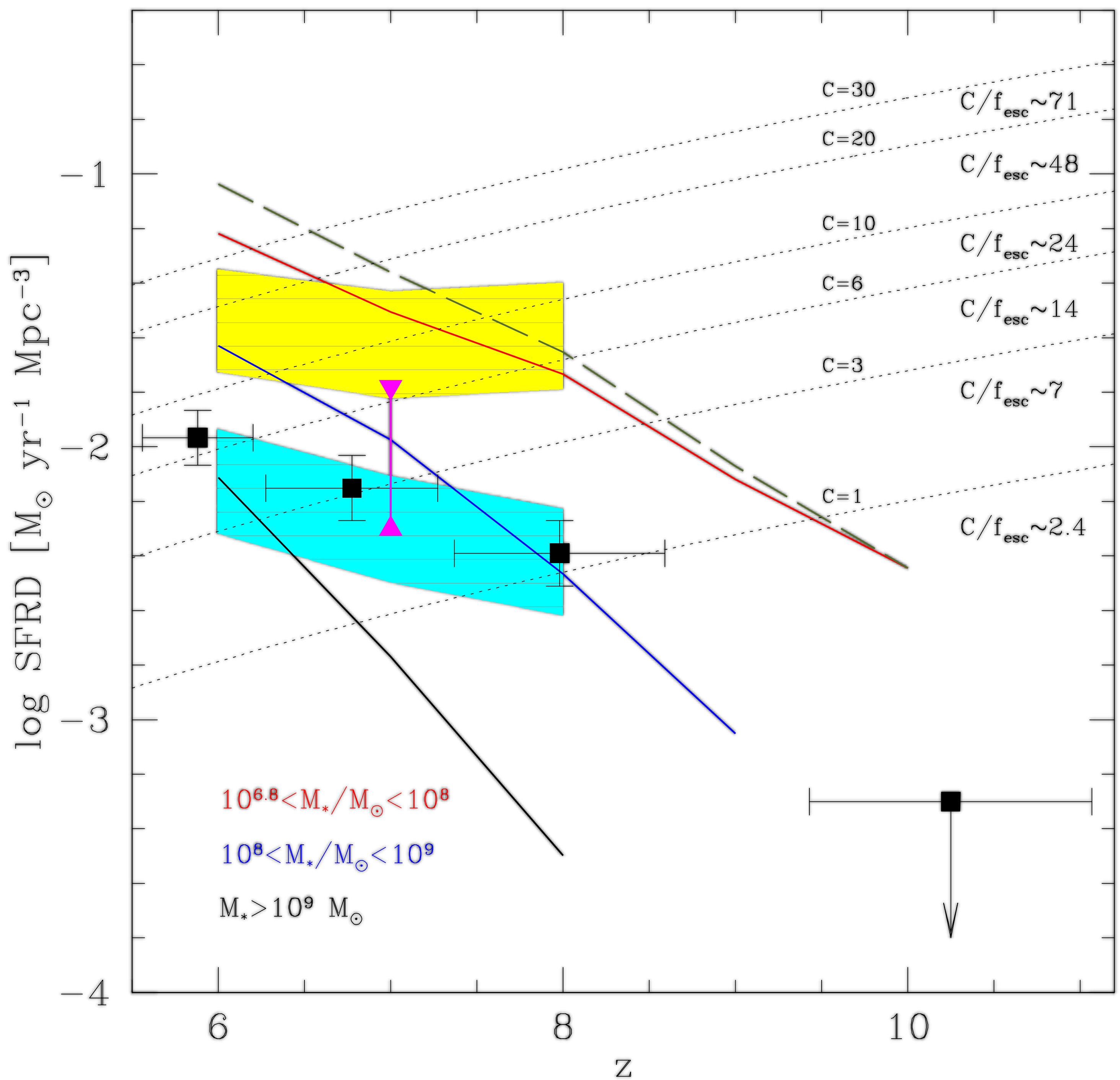
Yajima, Choi, KN '11

Reionization of the Universe

- Starforming gals can reionize the Universe by z=6.
- Showing contribution from diff. gal. mass ranges
- yellow & cyan shade: results from Munoz & Loeb '11
- dotted line: required SFRD based on Madau '99:

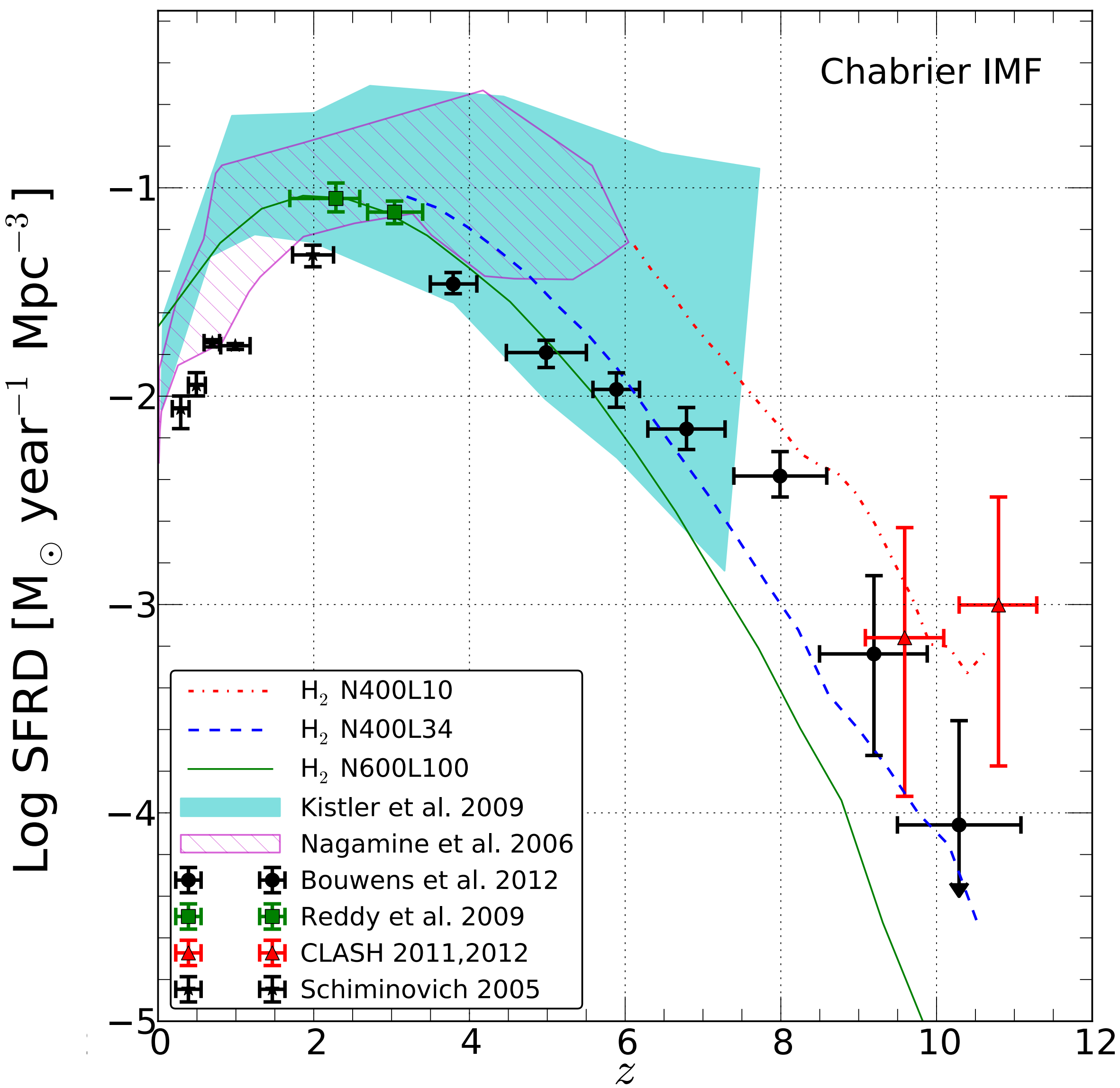
$$\dot{\rho}_\star \approx 2 \times 10^{-3} \left(\frac{C}{f_{esc}}\right) \left(\frac{1+z}{10}\right)^3$$

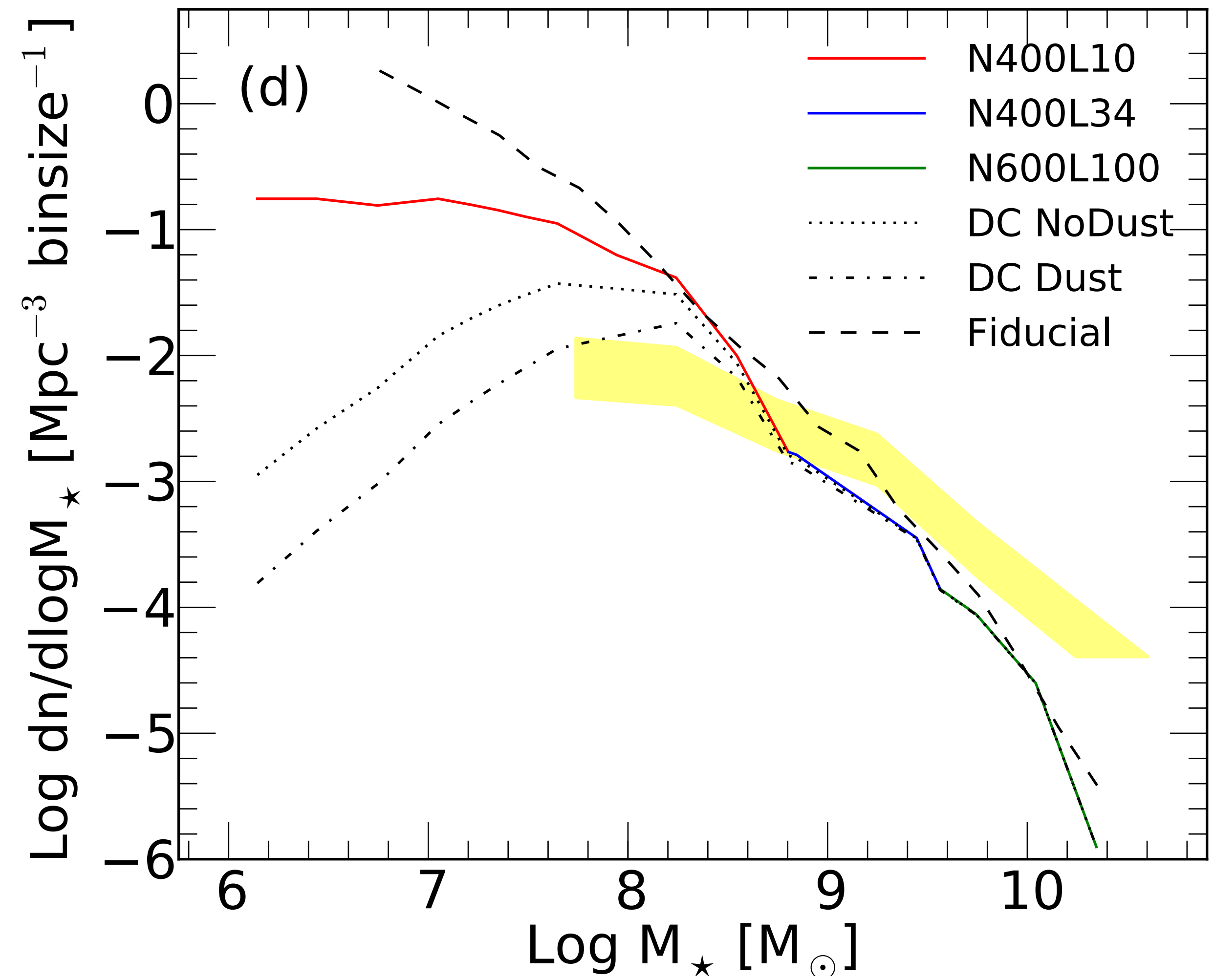
<fesc>=0.42 from RT result of Yajima+ '11



Jaacks, Choi, KN '12

Impact of H_2-based SF model





Implementation of Krumholz+ '08, '09 H_2 models into cosmo sims

Thompson, KN+ '12

Conclusions

- **Shape of $f(N_{HI})$**: not fully understood yet -- Very rich subject
- **DLA cross section:** $\sigma_{DLA} \approx 10^3$ kpc^2 for $M_h = 10^{12}\ M_\odot$ --- but slope and shape of $\sigma(M_h)$; more study needed.
- Opt-thin approx is no good; the OTUV model is a good approx. to the RT result. (KN+ '10; Yajima+ '12)
- **f_{esc}:** wide variety; not understood. Scatter and time variation
- **Future work:** Improve SF and feedback (SN/AGN); H_2 effect; Metallicity & radiation dependence (metal diffusion; turbulence…)

End