Escape fraction of ionizing photons in high-z galaxies: implications on DLAs & LAEs

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(June 15 - August 7, IPMU)

Collaborators: Junhwan Choi (UNLV), Hidenobu Yajima (Tsukuba)

Today's T_{high} & humidity

city	T_{high} [°C]	T_{low} [°C]	humidity [%]
Tokyo	32	26	52
Las Vegas	43	32	12

UNLV
Dept. of Physics & Astronomy

- **total 18 faculty**
  - **astrophysics: ~6**
  - atomic, molecular, optical: ~6
  - condensed matter: ~6
  - high pressure: ~5

- 15-20 grad students
- ~5 postdocs
- ~3 research professor
- ~5 supporting staffs









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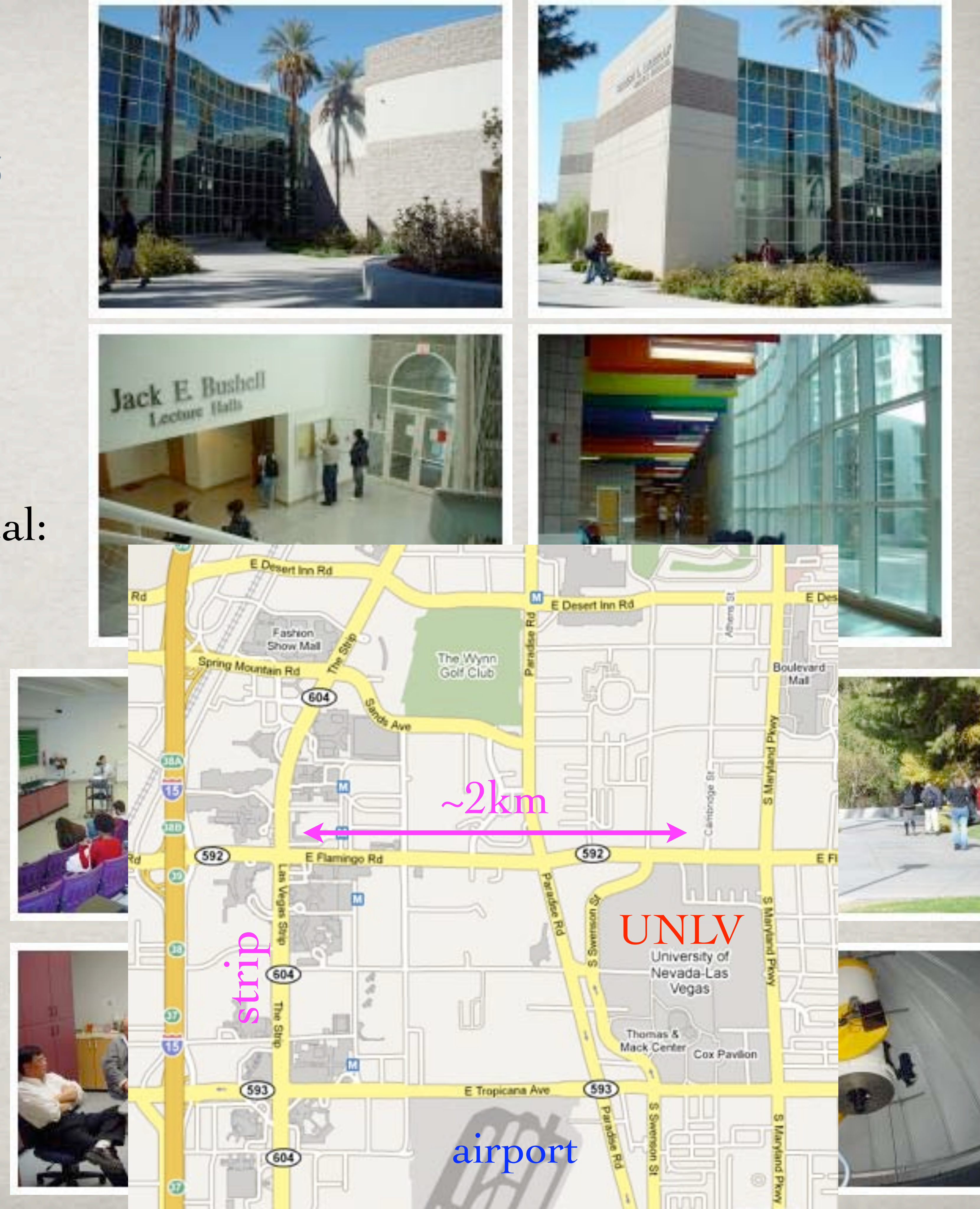


UNLV Astrophysics Faculty

Bing Zhang

GRB theory,
Swift team,
Pulsars

Daniel Proga

Simulations of accretion disk onto compact objects

KN

Cosmology,
Galaxy formation

George Rhee

Galaxy clusters,
lensing,
rotation curve

Diane Smith

Variables stars,
Astronomy lab

Atomic & Molecular

Steve Lepp

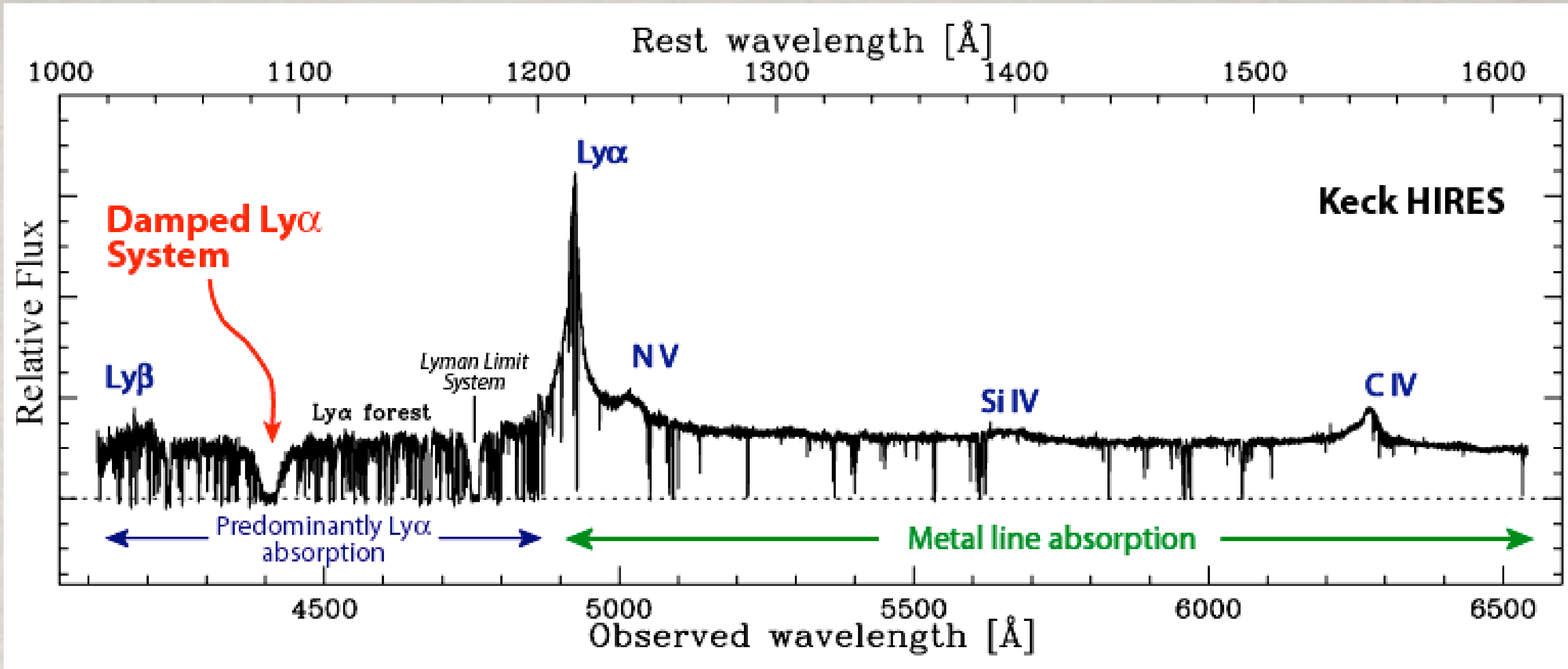
Bernard Zygelman

e.g. Quantum calculations of H_2 molecule

Outline

- **Motivation**: Useful probes of high-z structure formation --- **DLAs** & **LAEs** --- why is **radiation** important for their modeling?
- **Results**: Effects of UV background (UVB) & local stellar radiation --- radiative transfer (RT) calculations
  - **Implications on DLAs & Lyα Emitters**
- **Conclusions**

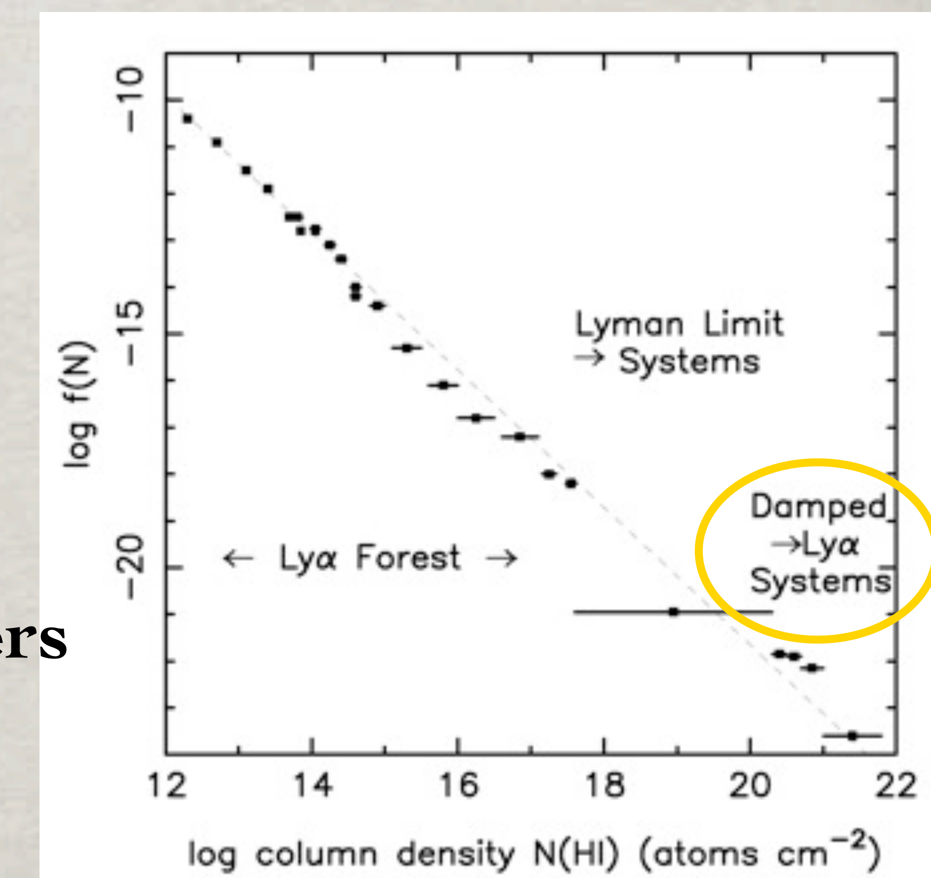
What are DLAs?



quasar

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

(Wolfe+ '86)



Direct probe of HI gas in high-z universe

DLAs are heavy-weight champions of HI absorbers

Would like to understand these systems in the context of CDM model

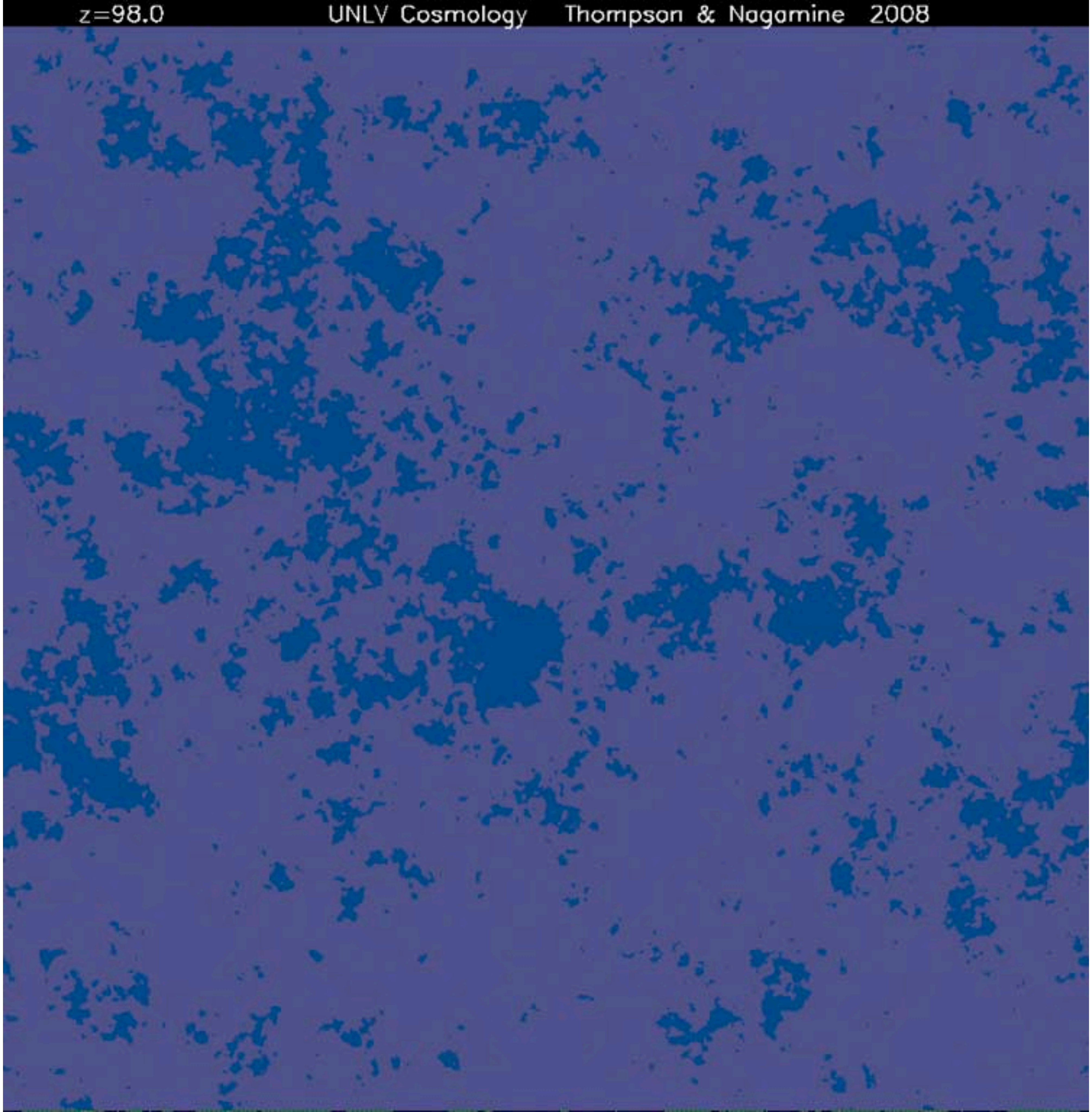
WMAP5 cosmology

Dark matter only sim

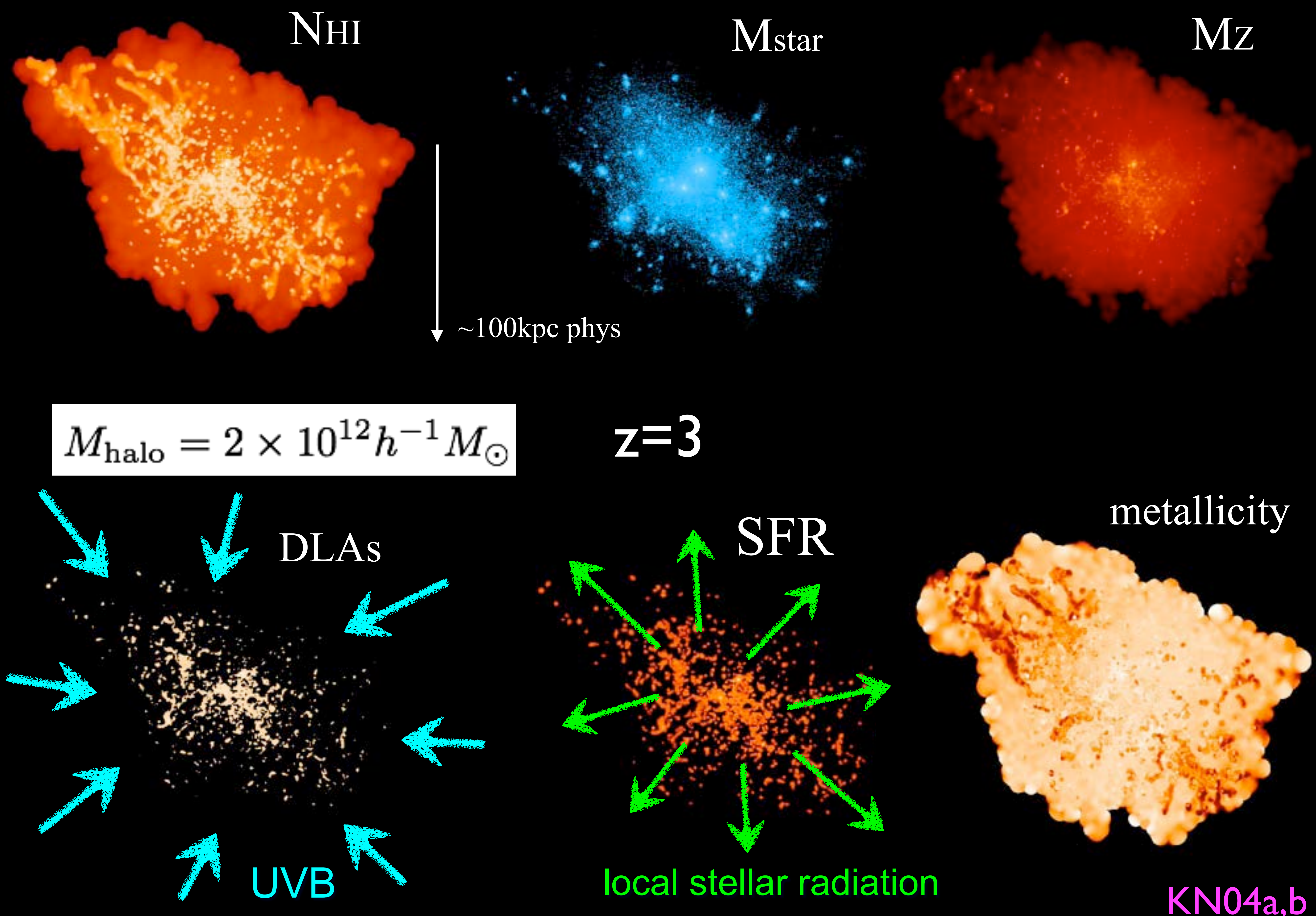
Box size 100 Mpc/h

500^3 ptcls

available on my website



Why is radiation important?



Galactic Wind Feedback

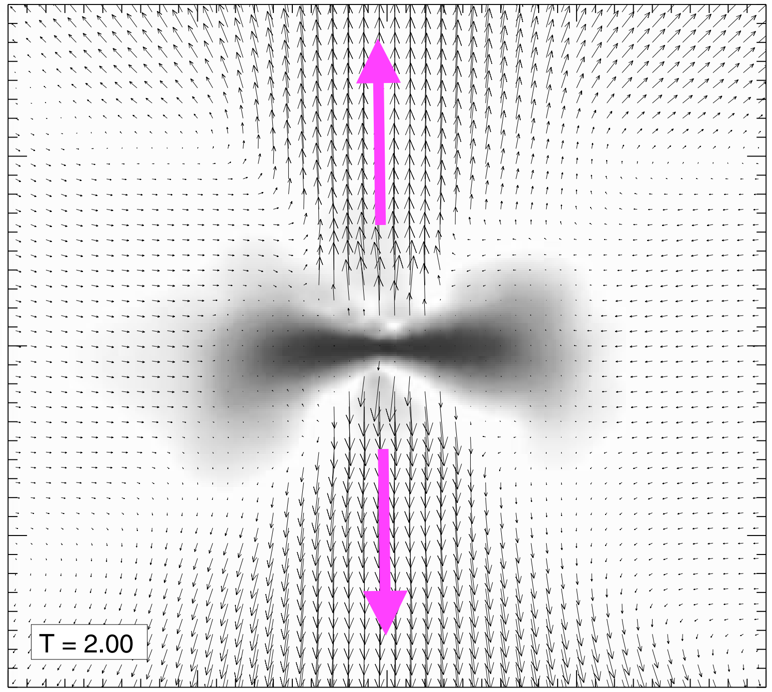
mass-loss rate
$$\dot{M}_W = \eta \dot{M}_\star$$

wind energy
$$\frac{1}{2}\dot{M}_W v_W^2 = \chi \epsilon_{\rm SN} \dot{M}_\star$$

$$v_{\rm w} = \sqrt{\frac{2\beta\chi u_{\rm SN}}{\eta(1-\beta)}}.$$

We now know that this formulation is not satisfactory, so we are in the process of updating the wind model based on the momentum-driven wind model (Murray+ '05) and the observed wind velocities as a func. of galaxy mass.

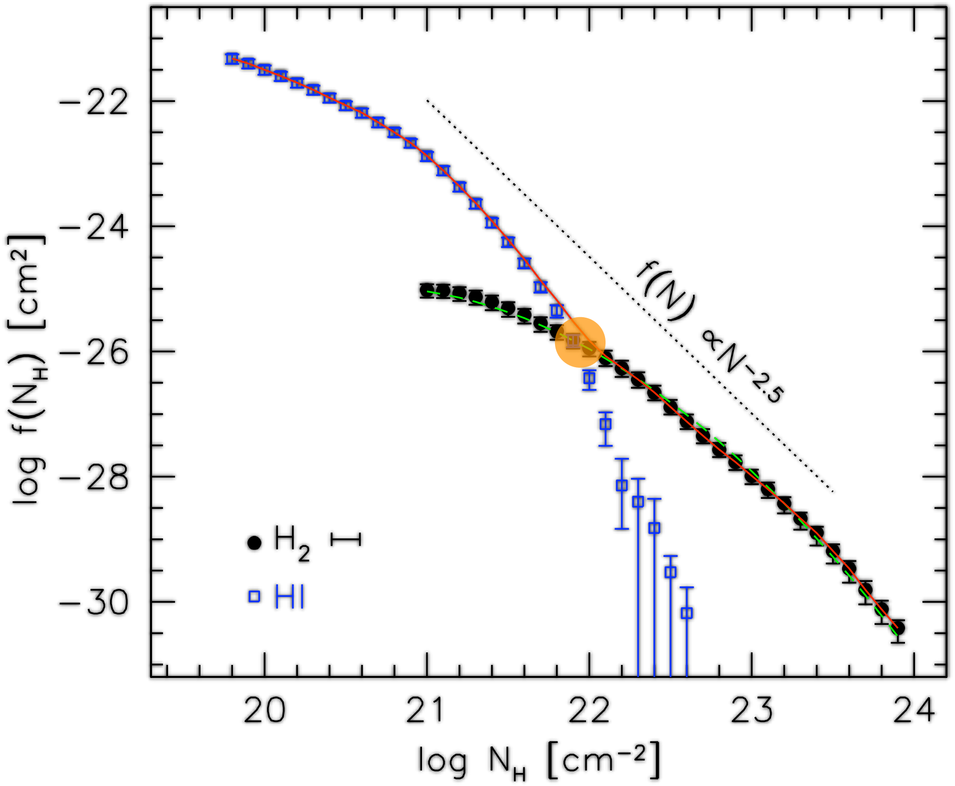
X-ray + Opt + IR



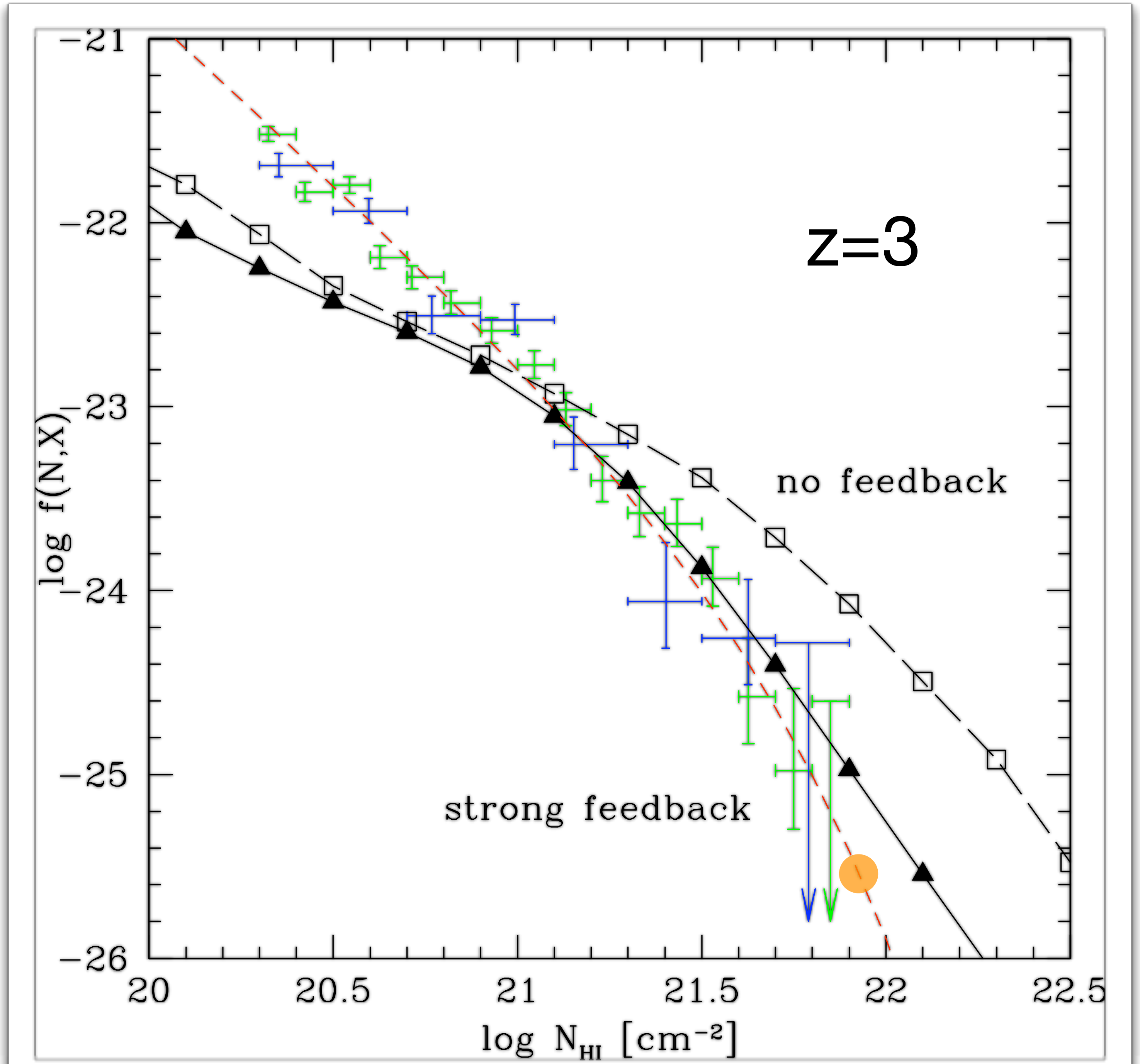
Springel & Hernquist (2003)

Column density distribution f(N_{HI})

- High N_{HI}-end OK for strong feedback run.
- No feedback run overpredicts at high N_{HI}.
- Shortage of f(N_{HI}) at logN_{HI}<~21 in sim.

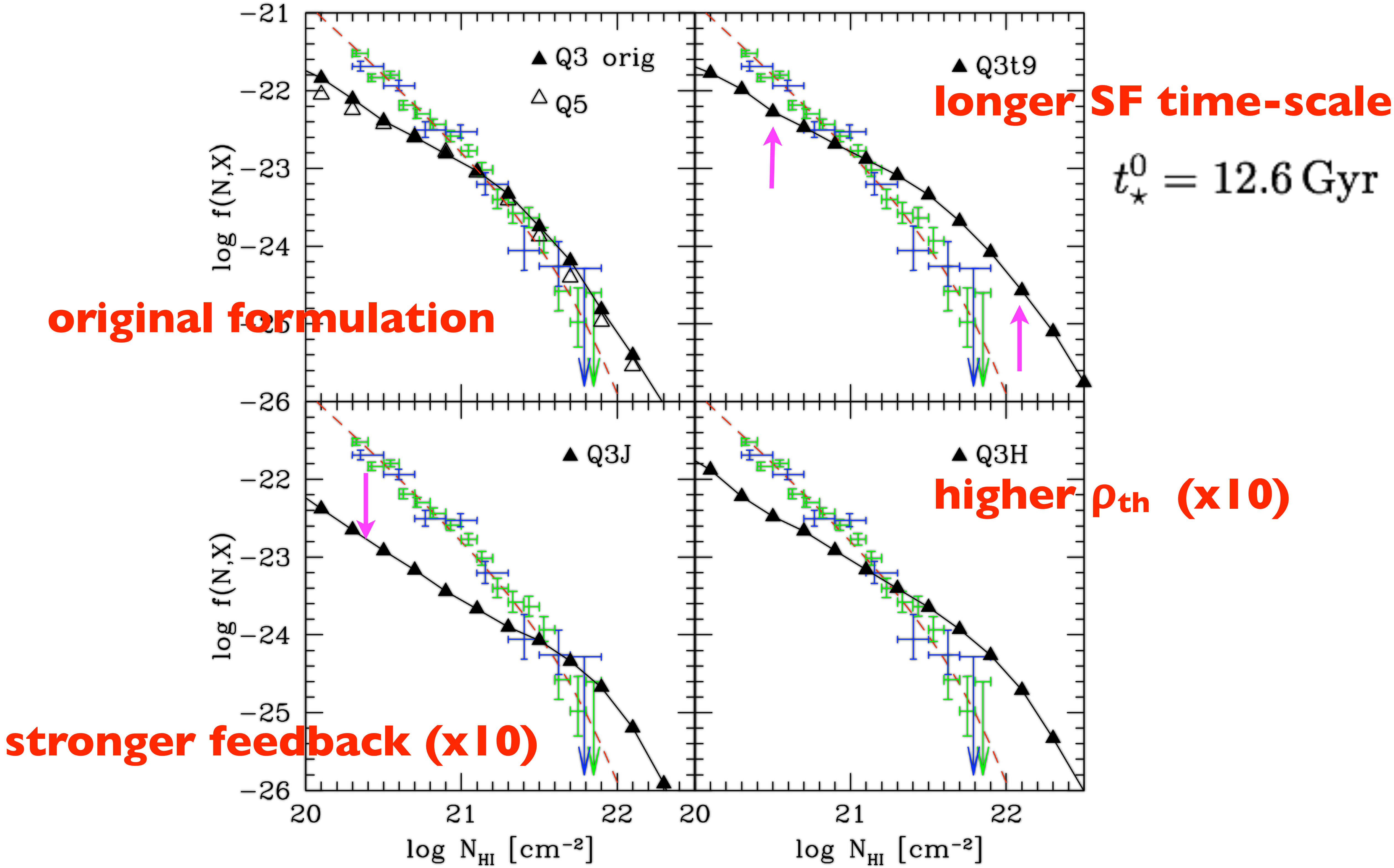


Zwaan+ '06



KN+ '04a,b

Column density distribution



DLA Cross Section

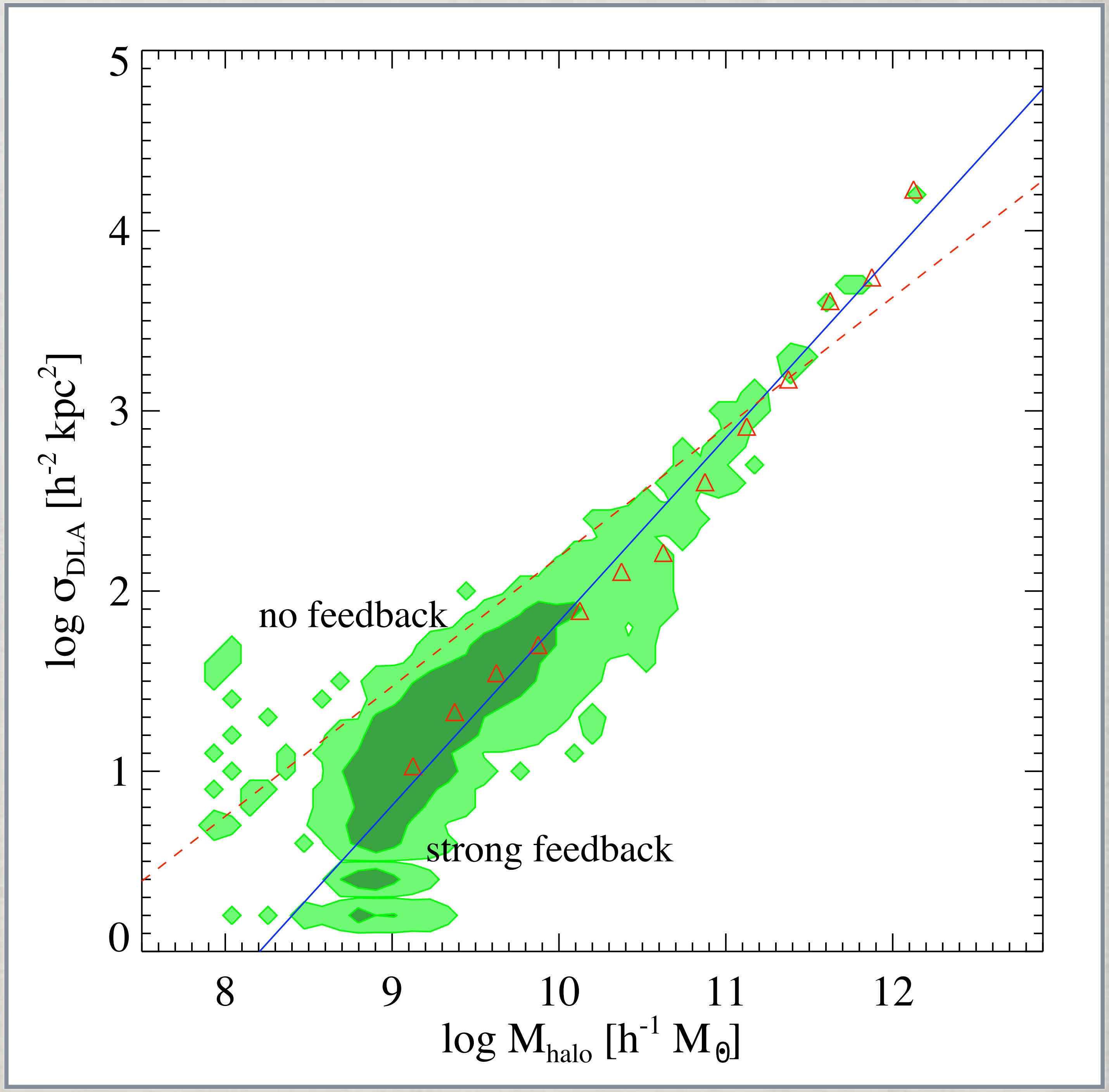
$$\sigma_{\rm DLA} \propto M_{\rm halo}^{\alpha}$$

$$\alpha \sim 1$$

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

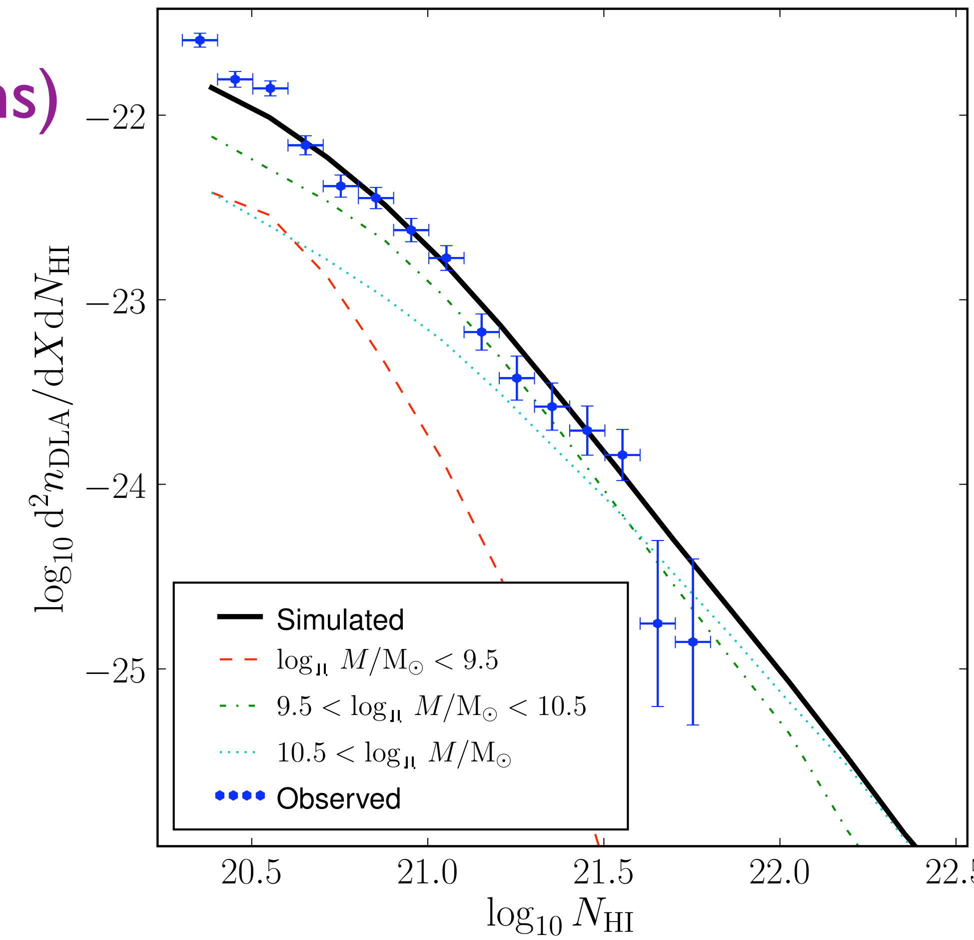
$$\alpha > 1$$

Earlier studies underestimated the value of α

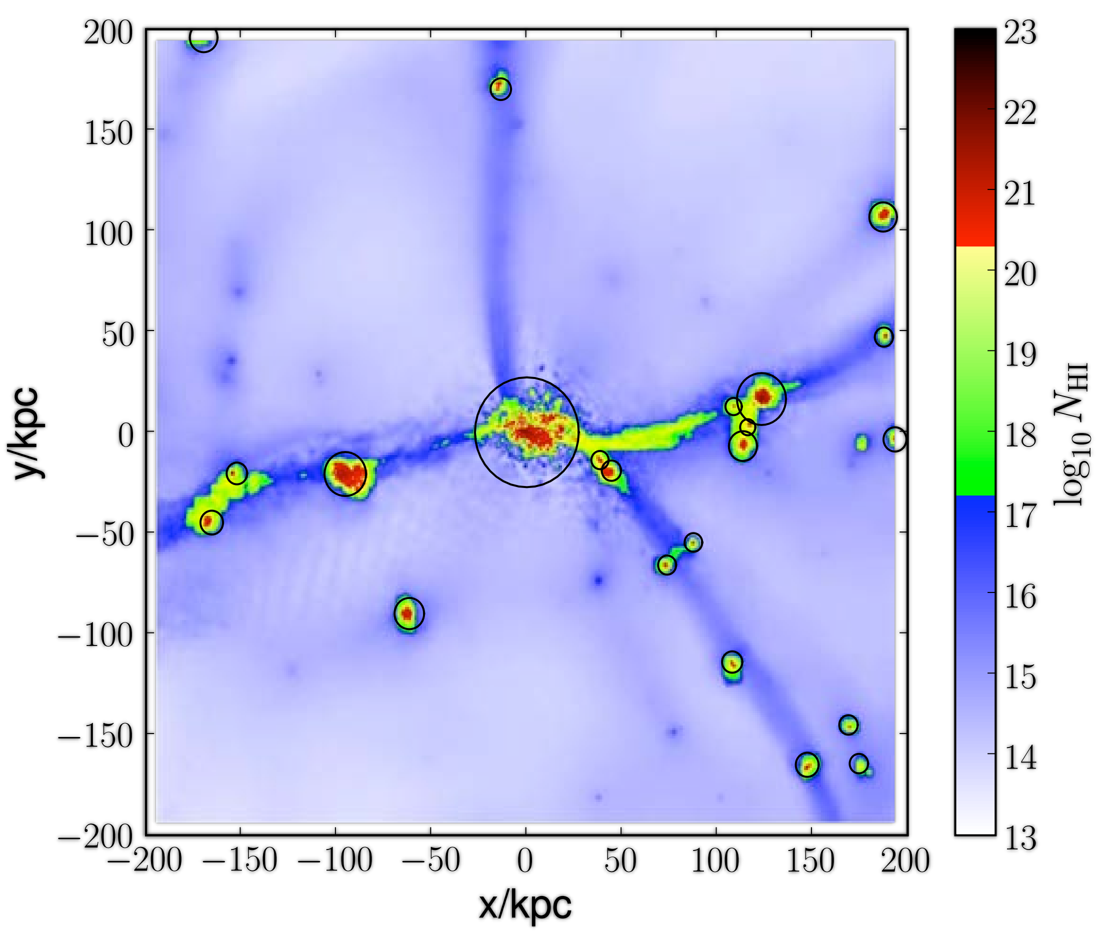


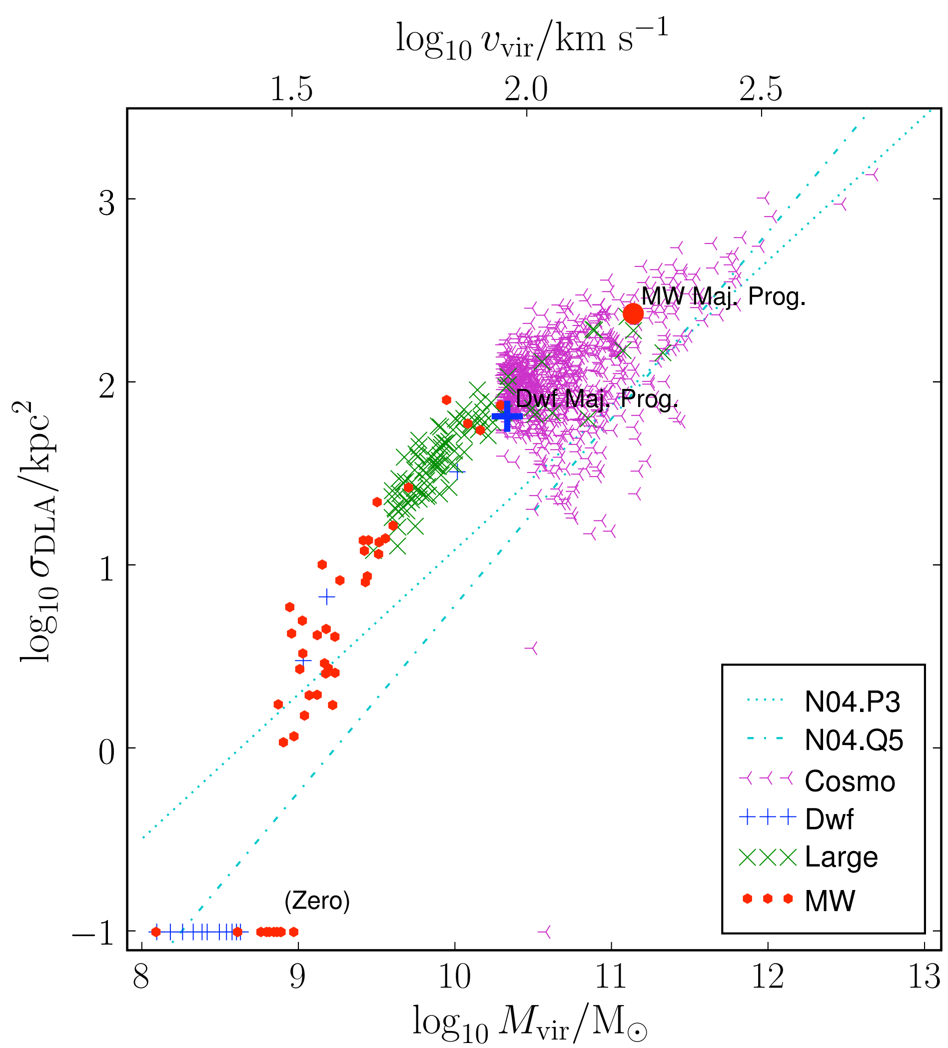
KN+ '04a

Pontzen+ '08 (Governato+ '08 zoom-in sims)



- larger DLA cross section
- more effective feedback puffs up the ISM?
- $f(N_{HI})$: composite from diff. runs.
- No IGM DLAs (cf. Razoumov+ '06)

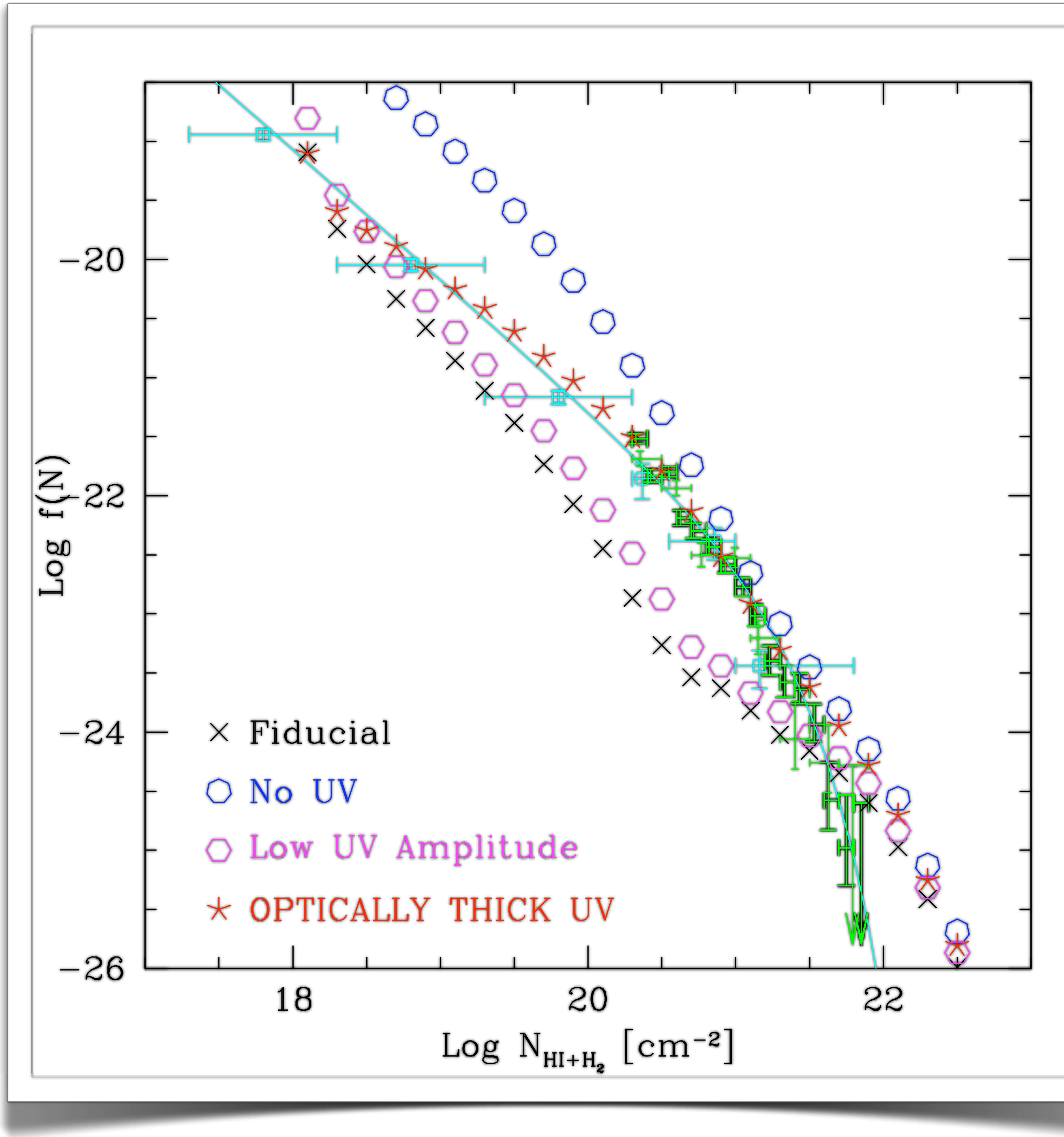




Effect of UVB

- Previous runs assumed optically thin approx.
- No-UVB run completely overpredicts.
- Weakening the UVB doesn't change the result compared to the orig run.
- Perhaps the UVB was sinking in too much into the halo.
- The run that limits UVB to $\rho<0.01\rho_{th}$ agrees well w/ data.

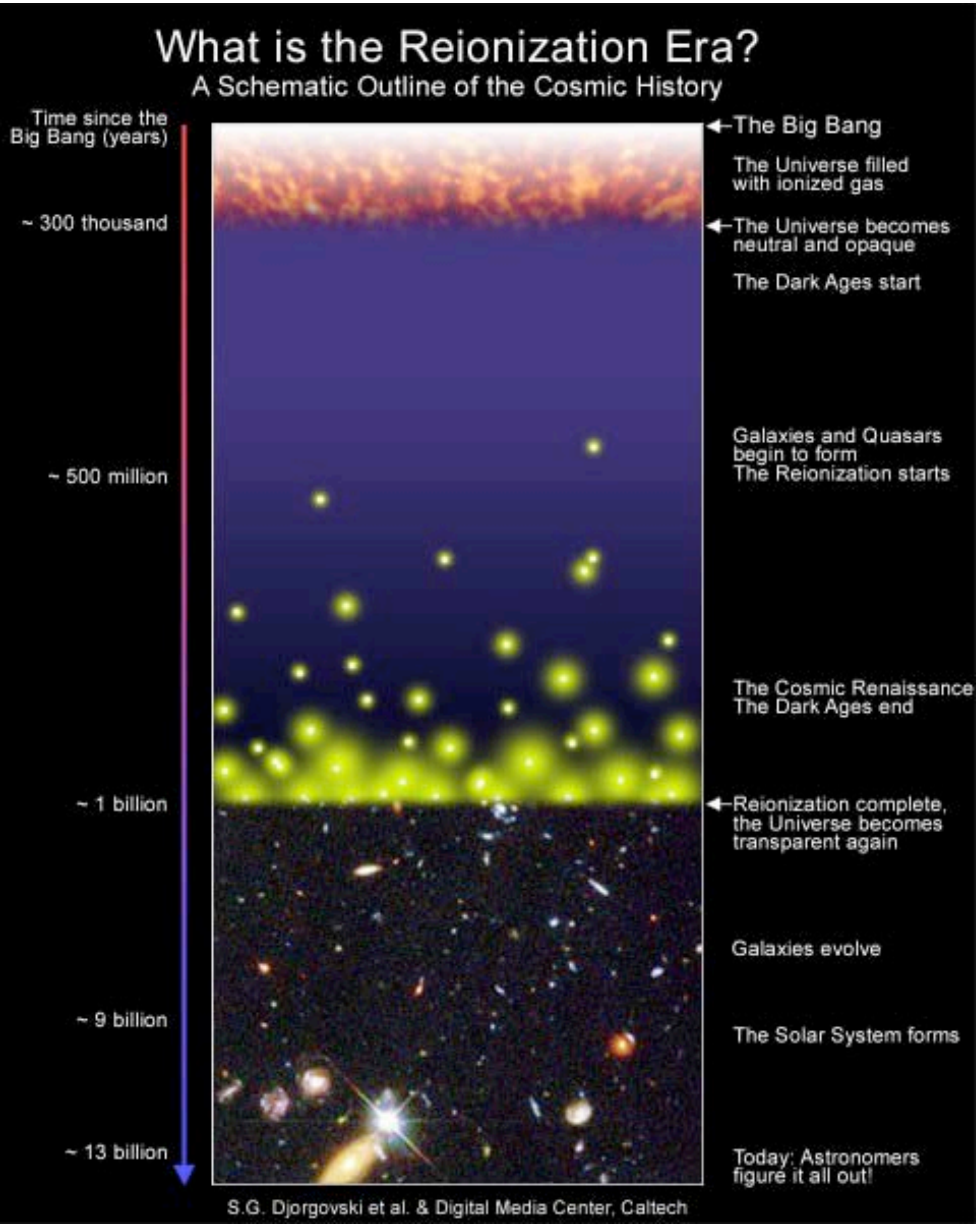
$\rho_{th}\sim 0.1$ cm^{-3}

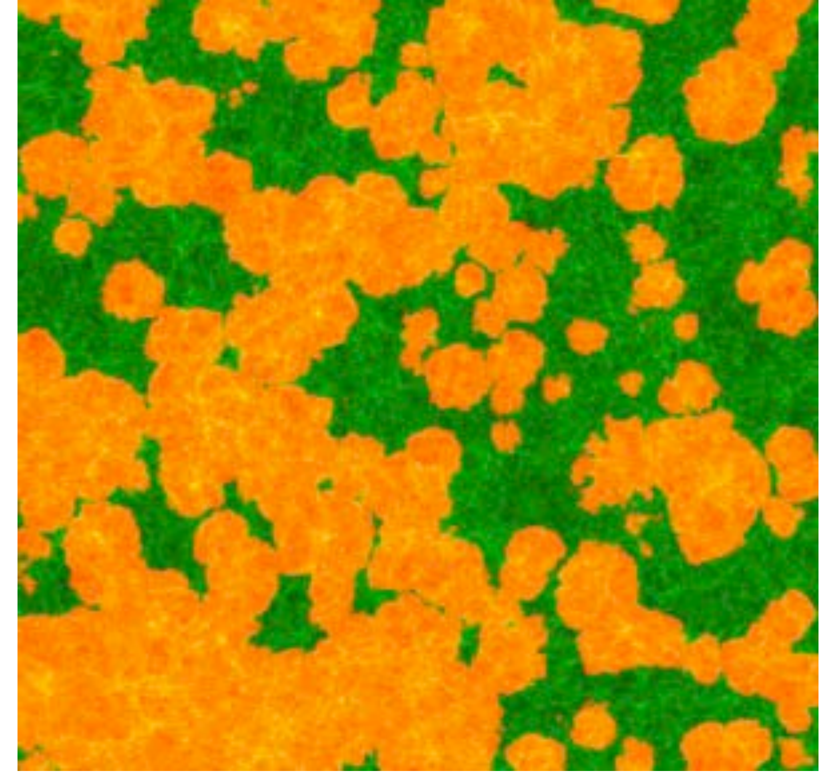


(cf. Kollmeier+ '09)

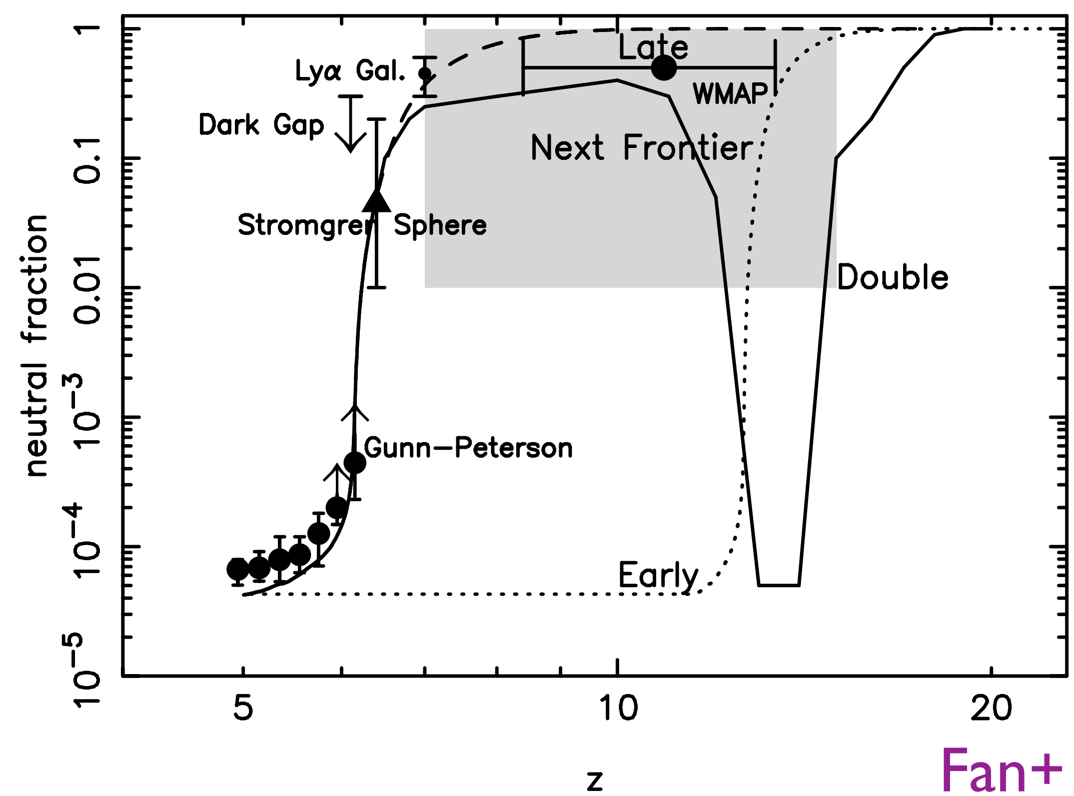
Escape fraction of ionizing photons -- effects of local stellar radiation

Why care about $f_{esc,ion}$?





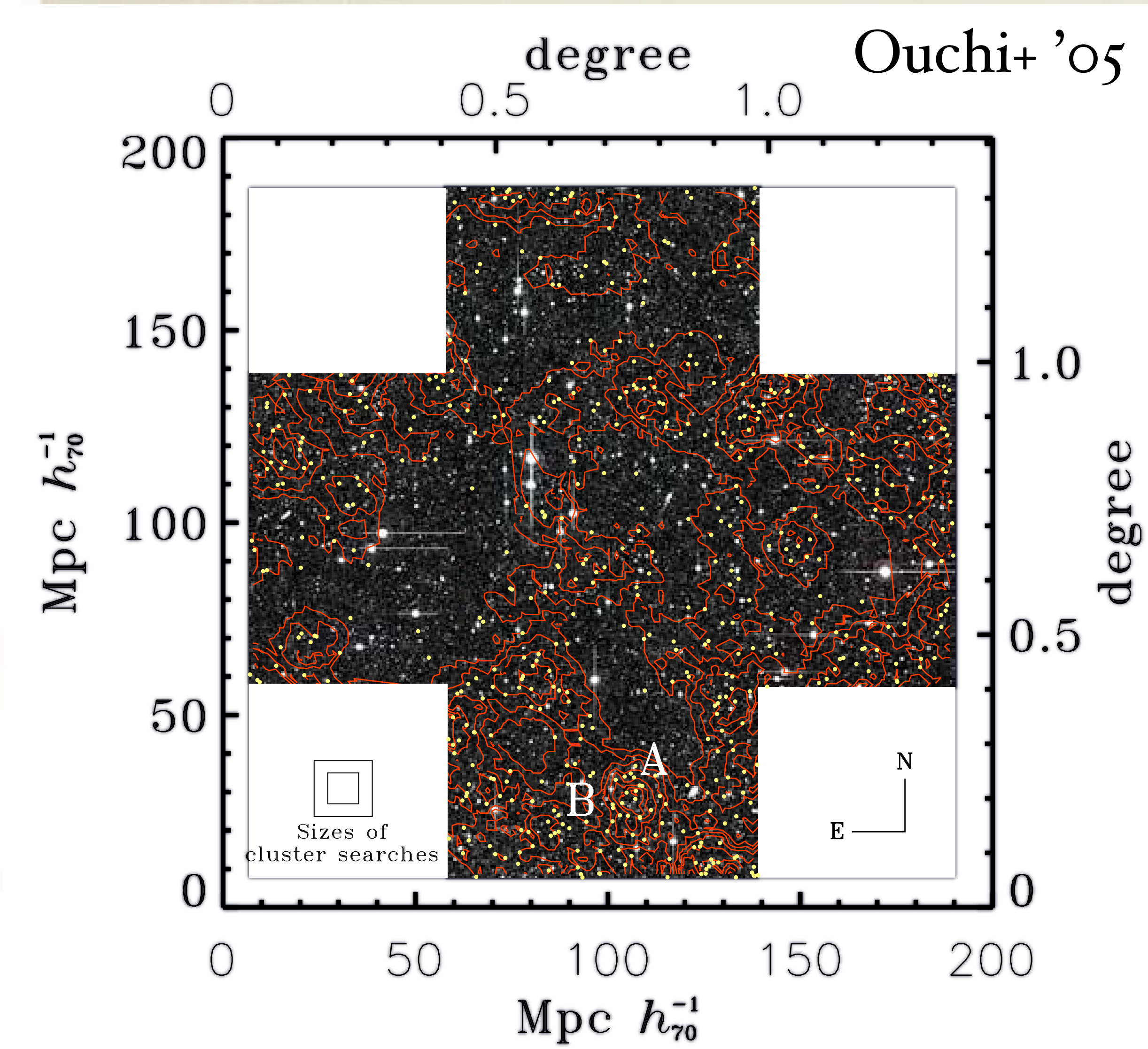
Illiev+ '06



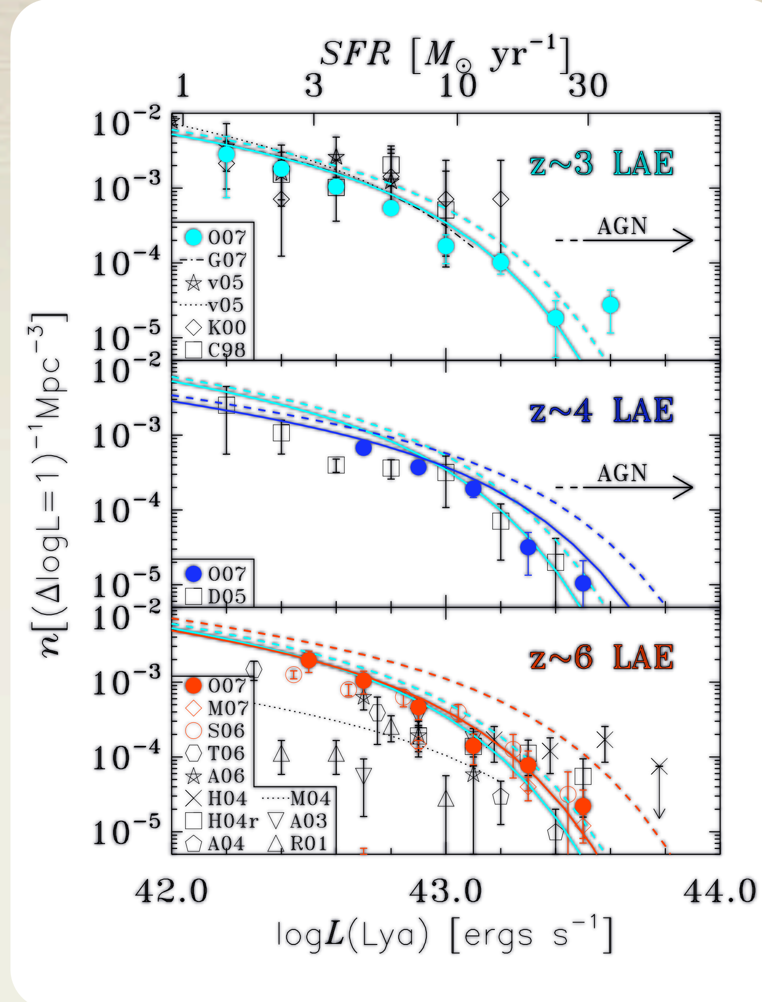
Fan+ '08

What are the sources responsible for reionization?

Large-scale structure traced by LAEs at z>3

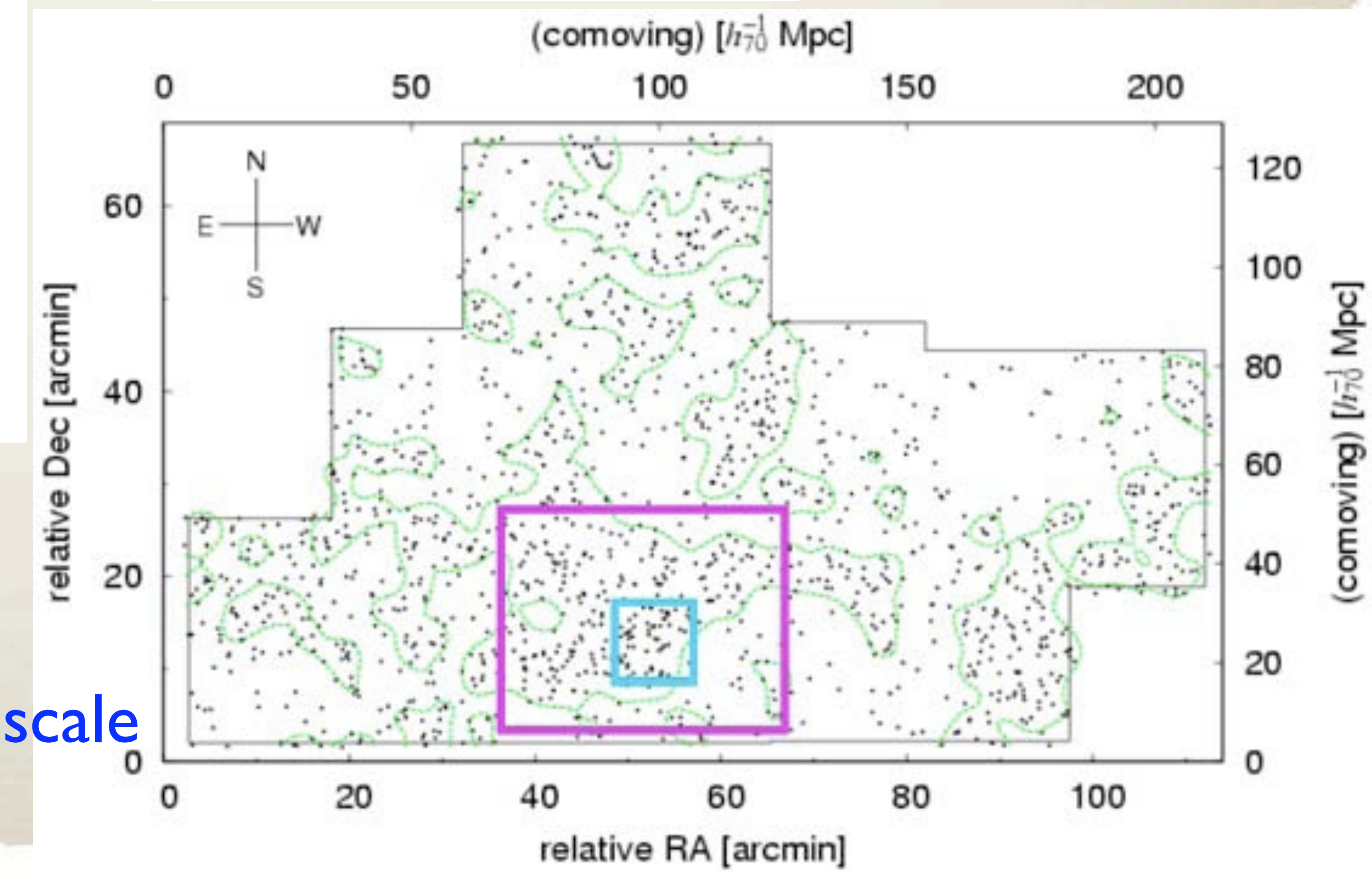


SXDS, 515 LAEs



Ouchi+ '08

Partridge & Peebles '67
Rhoads & Malhotra '01
Shapley+ '03
Malhotra & Rhoads '04
Ouchi+ '05
Hu & Cowie '06
Shimasaku+ '06
Kashikawa+ '06
Gronwall+ '07
Gawiser+ '07.....



~1400 LAEs @ z=3.1 over 200 Mpc scale

Nakamura, Yamada+ '08

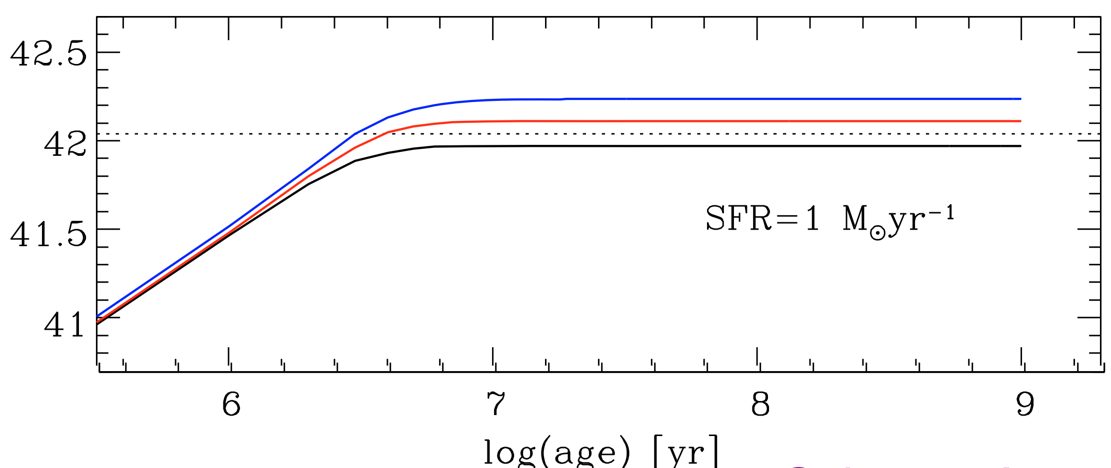
Lyα Luminosity Function

Assuming

$$\frac{L_{\mathrm{Ly}\alpha}}{10^{42}\mathrm{erg\,s^{-1}}} = \frac{\mathrm{SFR}}{1M_\odot\,\mathrm{yr}^{-1}}$$

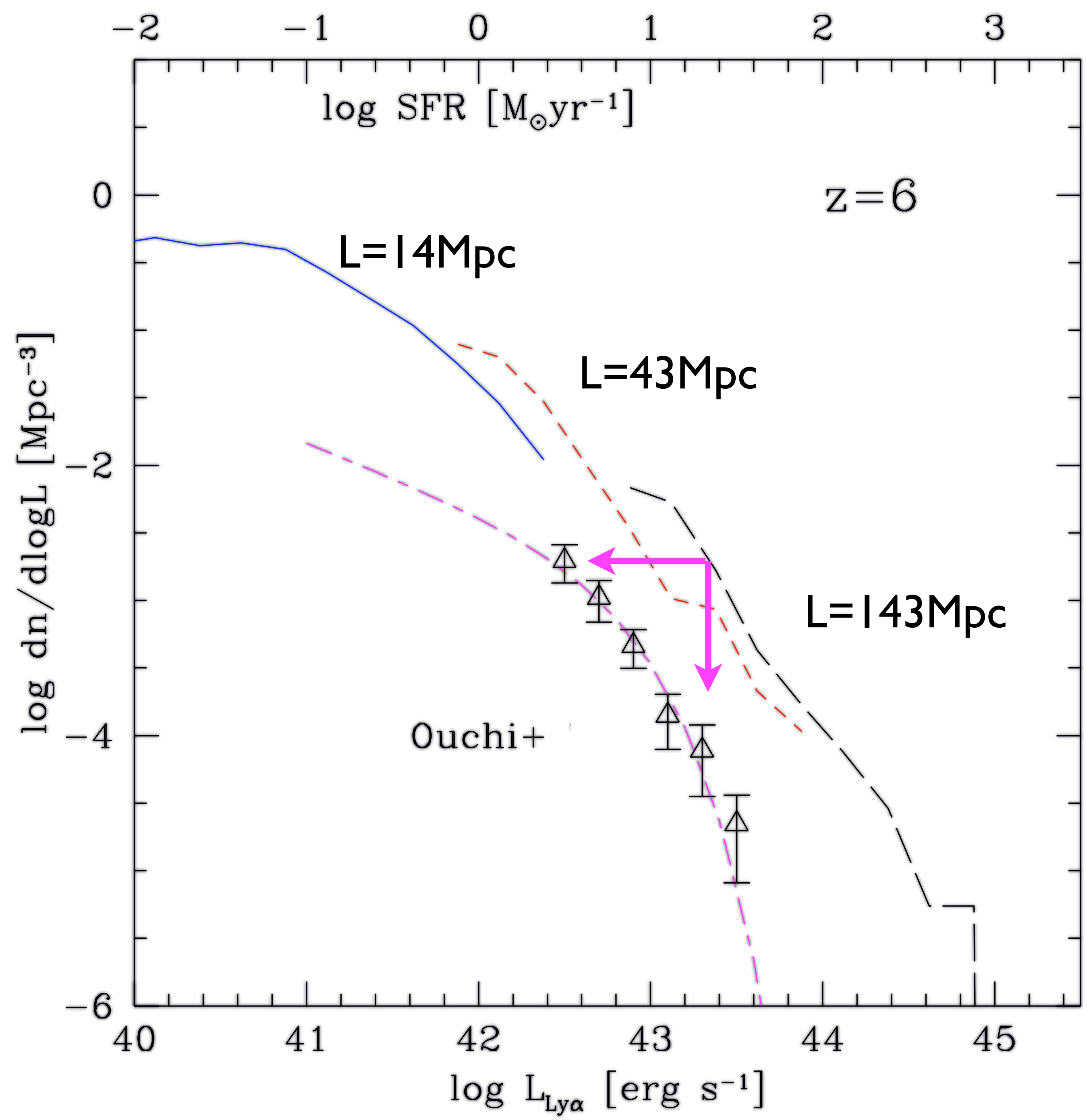
(Kennicutt '98; Leitherer+ '99)

Salpeter IMF, [0, 100]M⊙, 0.05<Z/Z⊙<2



Schaerer '03

- Without any corrections, models based on CDM overpredict the Lyα LF by a factor of 5-10

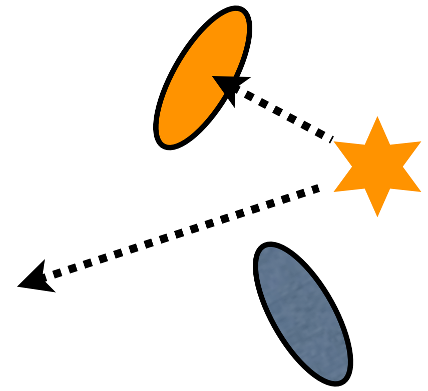


Two simple scenarios

- **"Escape fraction" scenario:**
  - all LBGs emit Lyα emission, but uniformly attenuated by a factor of **$f_{\mathrm{Ly}\alpha}$**: $L_{\mathrm{Ly}\alpha}^{\mathrm{observed}} = f_{\mathrm{Ly}\alpha} L_{\mathrm{Ly}\alpha}^{\mathrm{intrinsic}}$

Effective escape fraction

$$\boxed{f_{\mathrm{Ly}\alpha} = f_{\mathrm{dust}} \left(1 - f_{\mathrm{esc}}^{\mathrm{ion}}\right) f_{\mathrm{IGM}},}$$



- **"Stochastic" scenario:** (or duty cycle)
  - only a fraction **C_{stoc}** of star-forming gals are active (or *can be observed*) as LAE

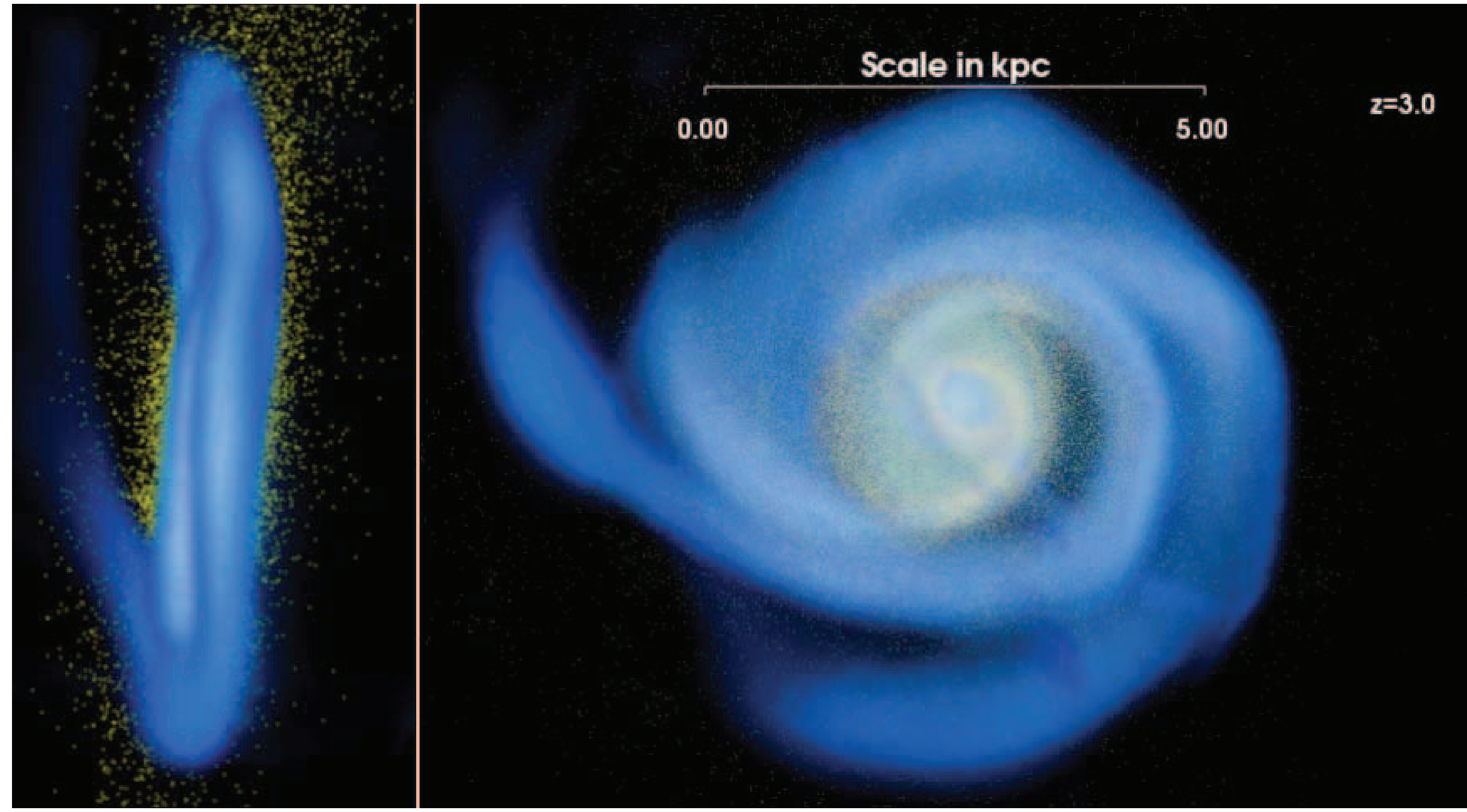
(due to "interstellar weather")

KN+ '08

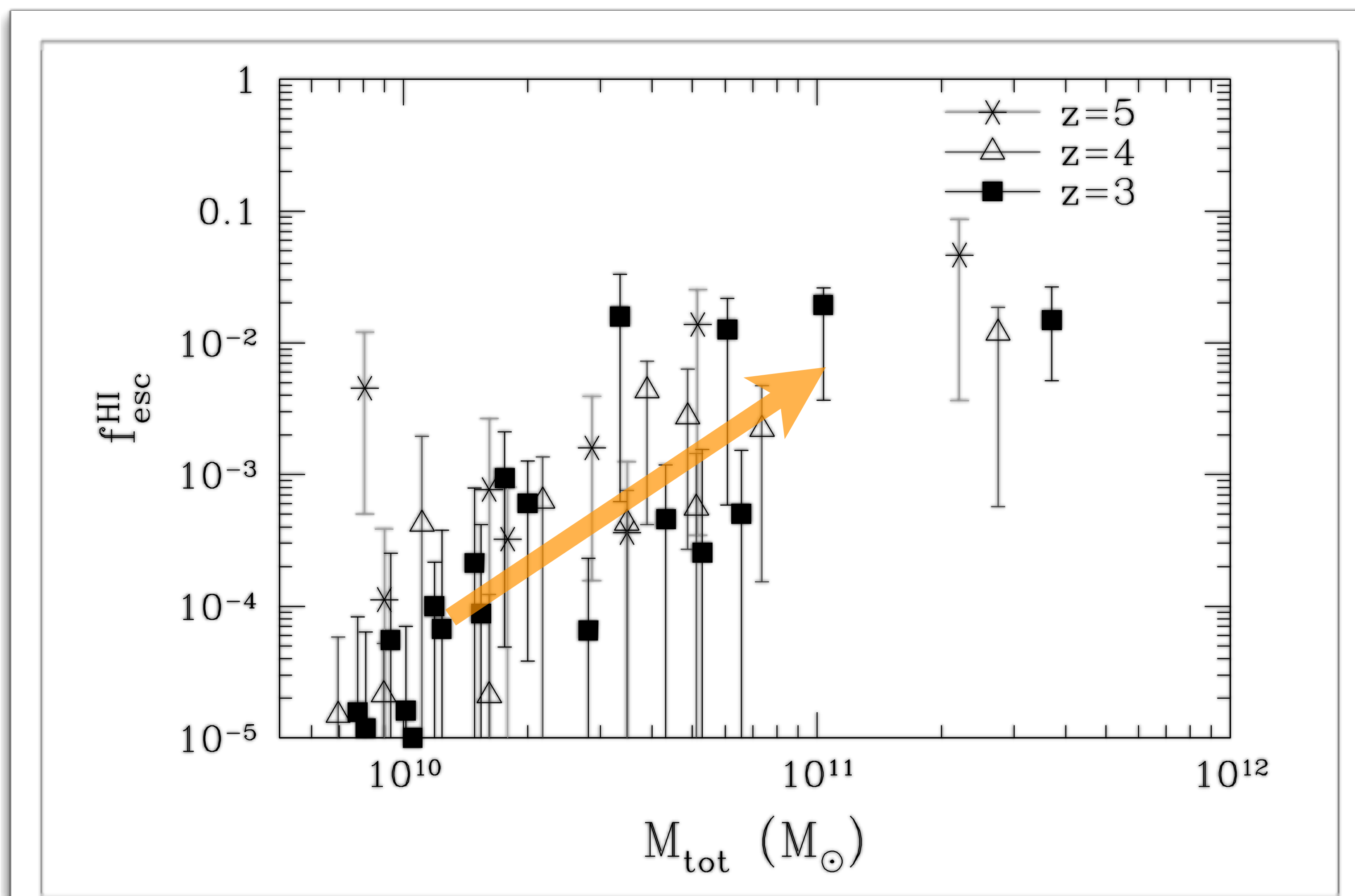
Radiative Transfer Calculations

- **Gnedin+ '09**
- ART AMR code (Kravtsov+'02)
- 6 Mpc/h cosmo box
- phys. resol. 65pc @ z=3
- OTVET algorithm (Gnedin & Abel '01)
- **Very low f_{esc}**
- **Increasing func of M_{halo}**
- **No redshift dependence**

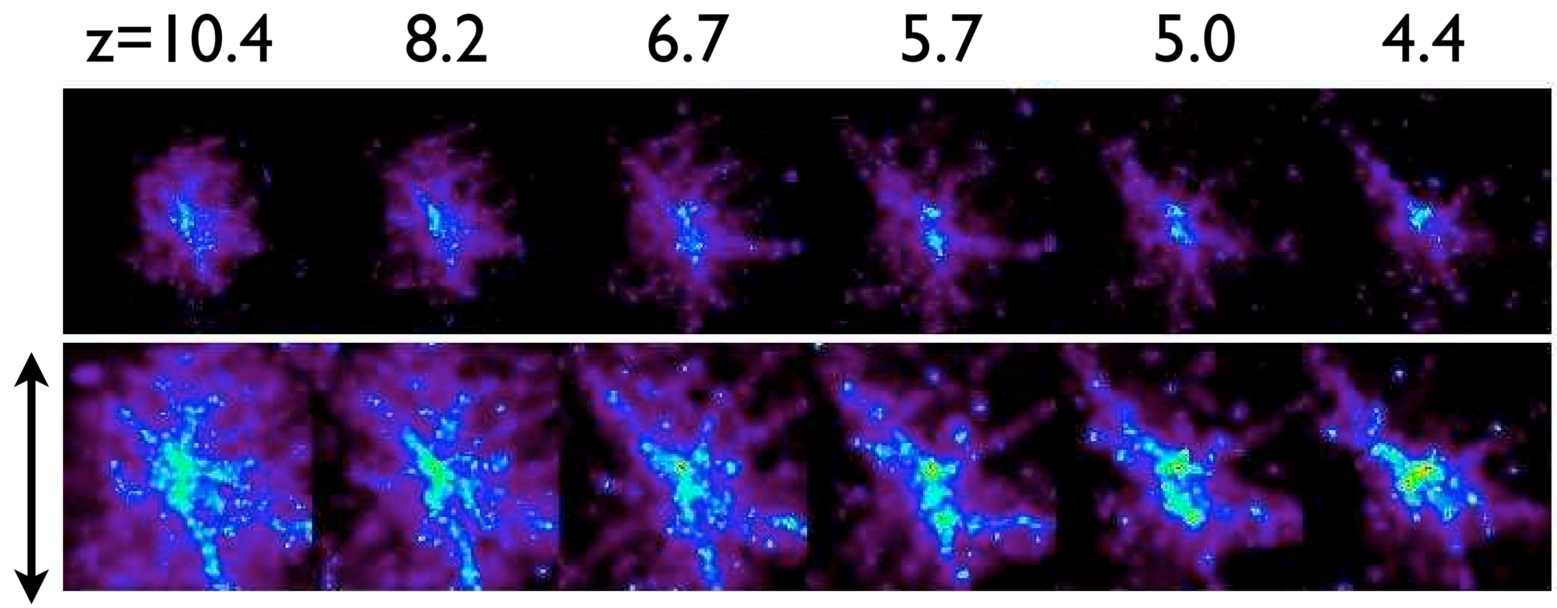
These results are puzzling in many ways...



M_{tot}~$4 \times 10^{11} M_{sun}$ f_{esc}=1.5%

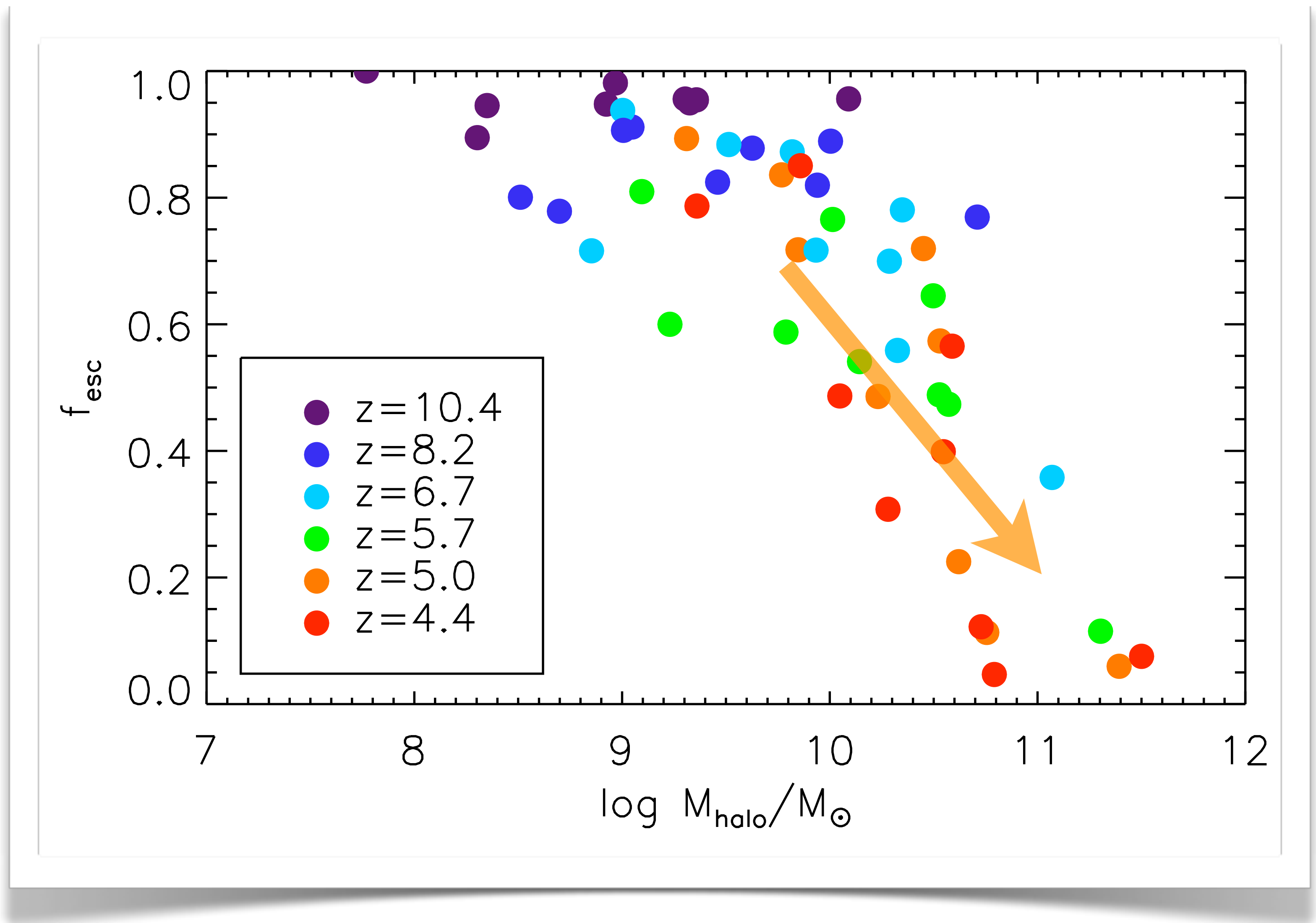


Razoumov+ '09



phys 250kpc

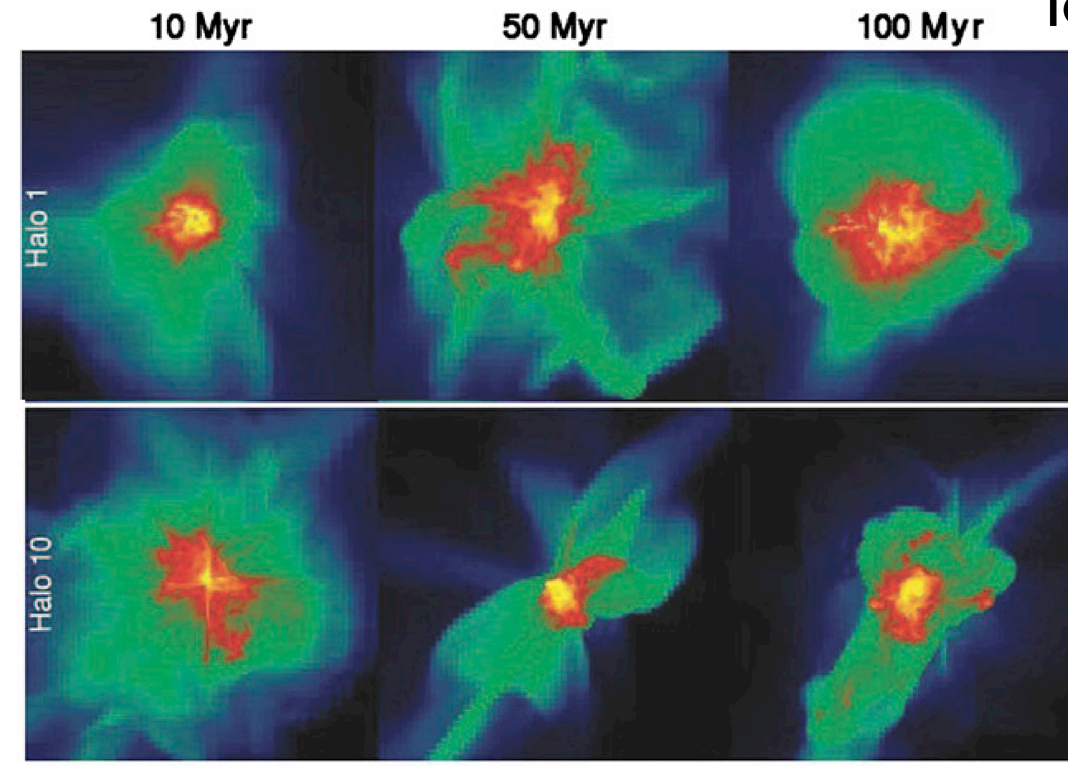
- SPH code (Sommer-Larsen +'03)
- resim. 9 gals in 6 Mpc/h cosmo box; M_{halo}=6e7 - 3e11 M_{sun}
- phys. resol. ~0.5 kpc
- **Decresing f_{esc} as a func of M_{halo} & redshift**



Wise & Cen '09

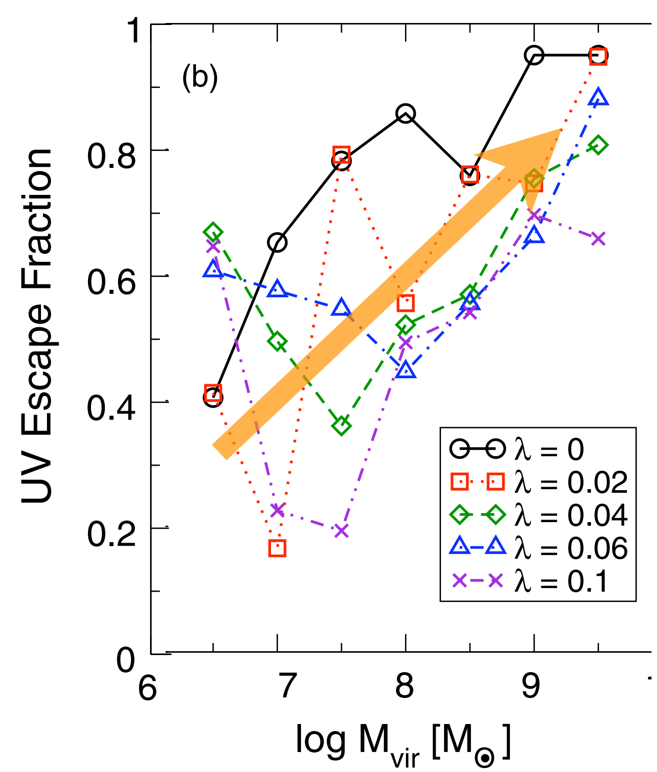
- Enzo AMR code (Bryan & Norman '97)
- resim. 10 selected halos in 2 & 8Mpc box down to **z=8**; **claimed resol. of 0.1 pc**
- focus on lower mass halos: M_{halo}~ 3e6 - 3e9 M_{sun}
- **large f_{esc} variation -- perhaps increasing f_{esc} as a func of M_{halo}**
- f_{esc} can reach up to 0.8 for top-heavy IMF (but varied only N_Y)

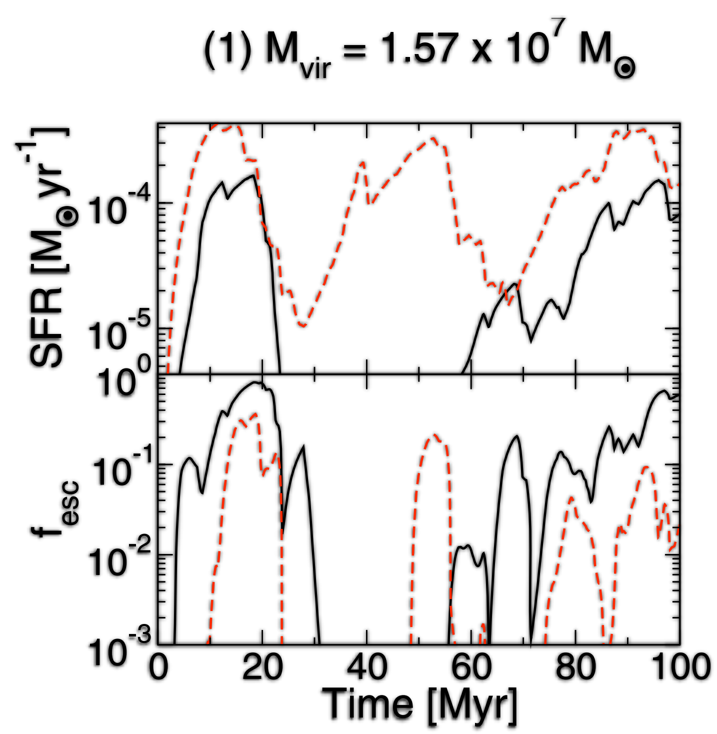
logMvir



7.2

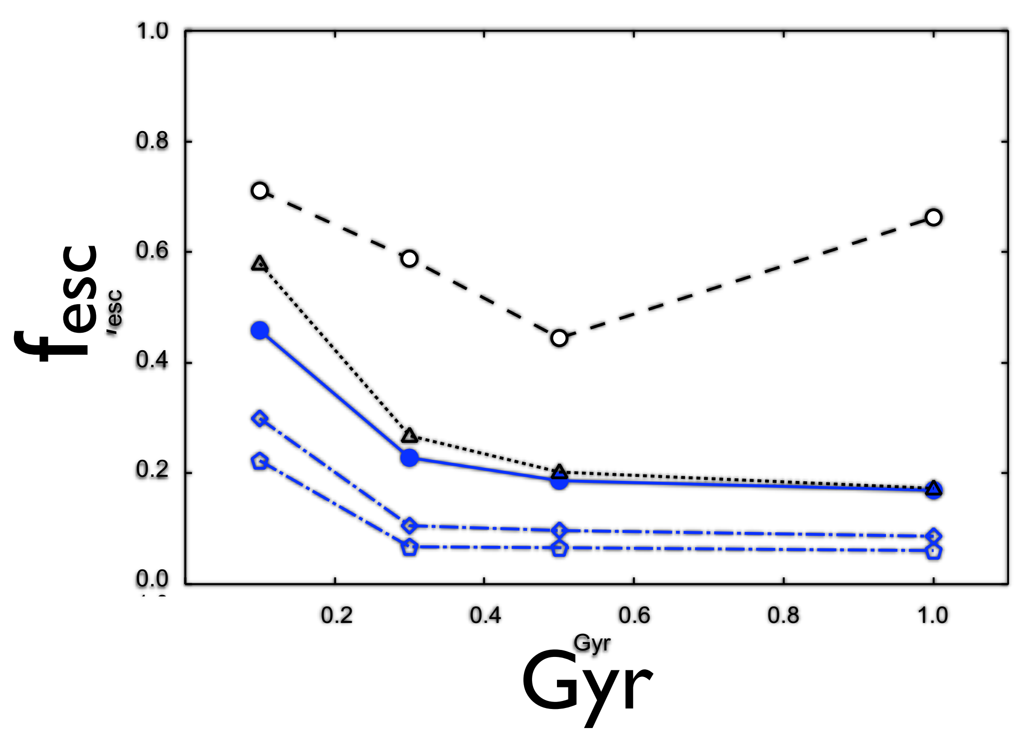
9.6





Yajima, Umemura, Mori, Nakamoto '09

- Mori & Umemura '06 Eulerian simulation --- but not cosmo sim.
- **Decreasing f_{esc} with time** -- but no gas infall into the environment
- f_{esc}=0.07-0.47 (LAE phase); 0.06-0.17 (LBG phase)



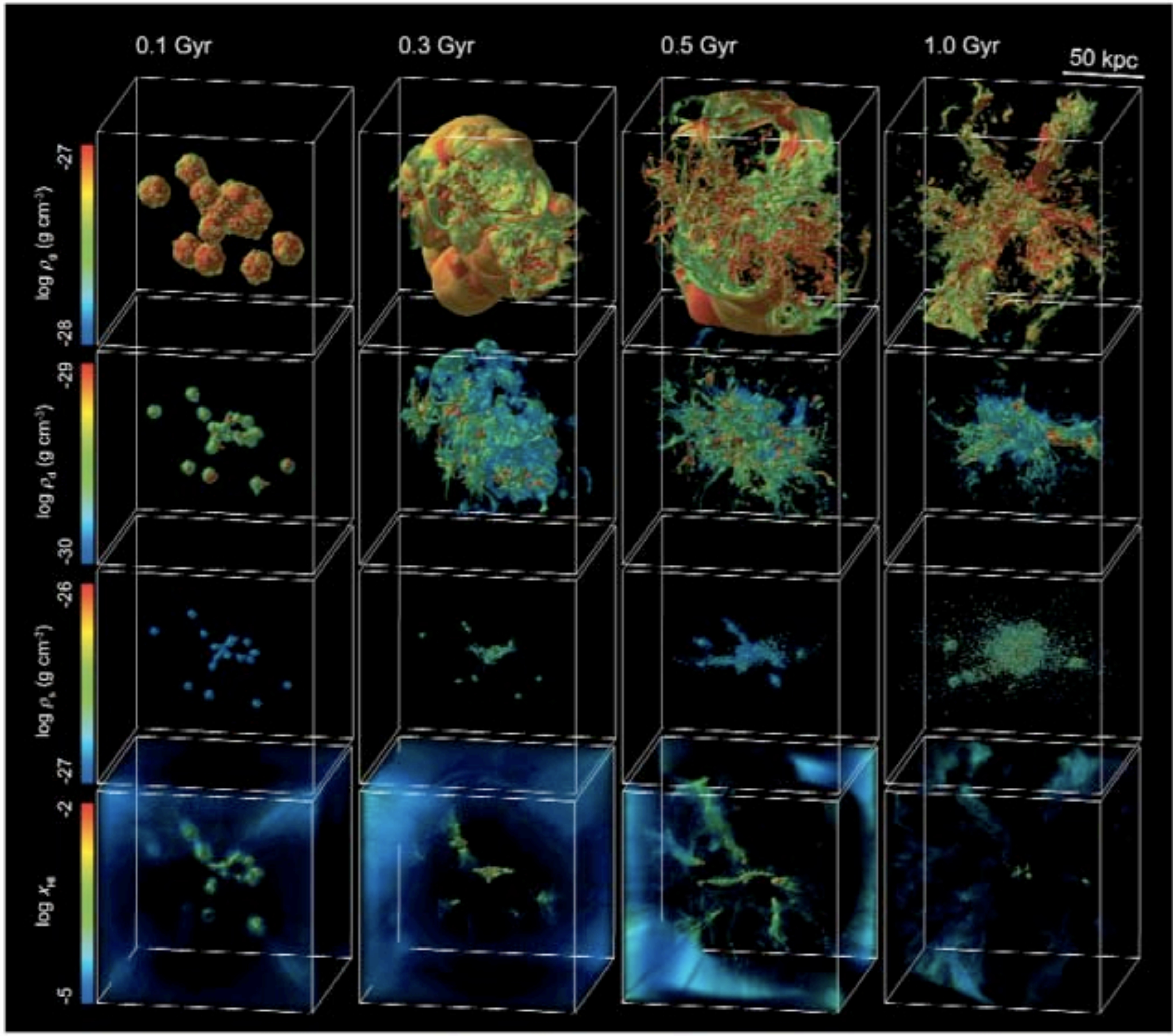
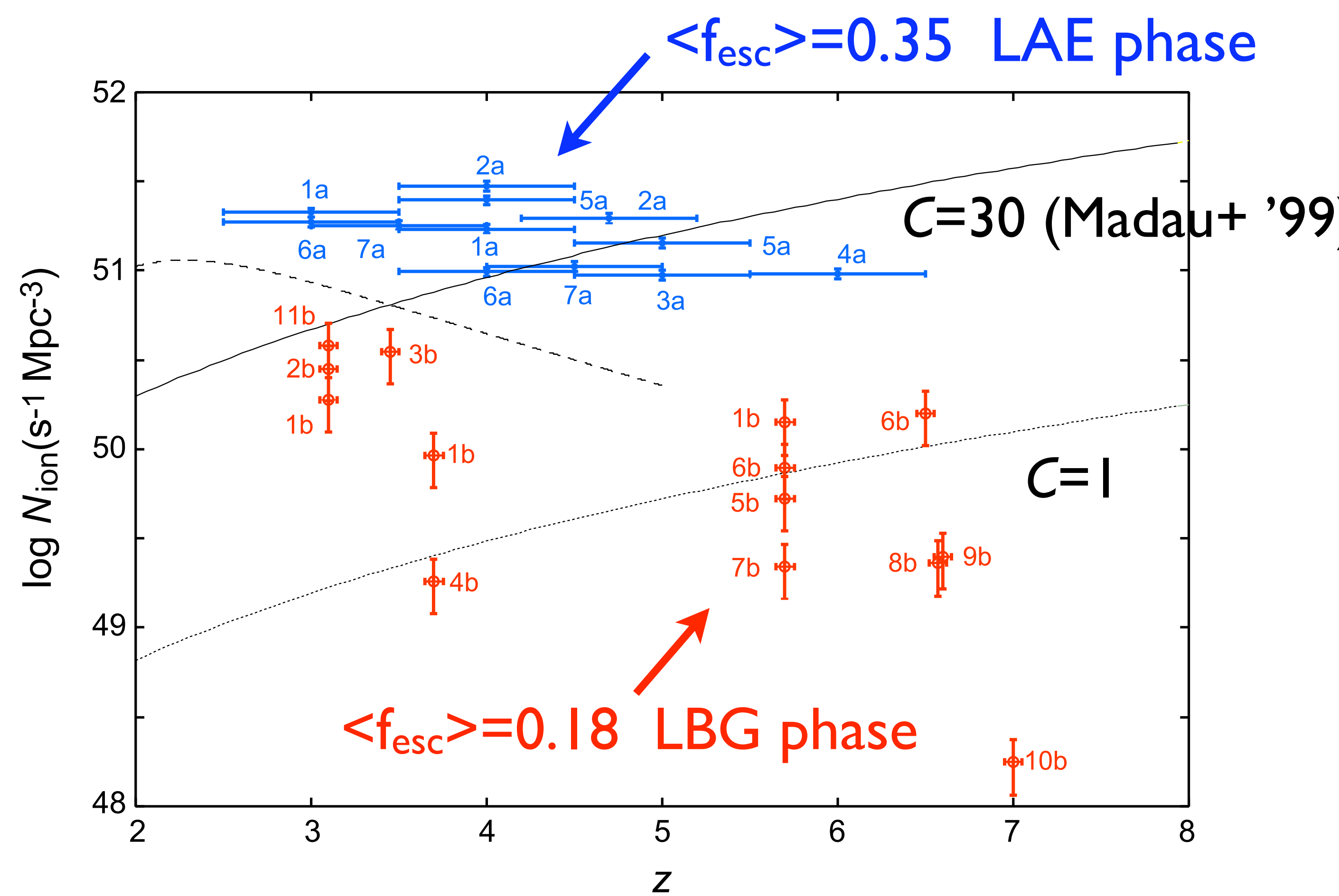


Figure 1. Snapshots of the evolution of the model galaxy with total mass of $10^{11} M_{\odot}$, at t_{age} = 0.1, 0.3, 0.5 and 1.0 Gyr. Each panel in row corresponds the spatial distributions of gas density ρ_g (g cm^{-3}), dust density ρ_d (g cm^{-3}), stellar density ρ_s (g cm^{-3}), and fractions of neutral hydrogen in logarithmic scale χ_{HI}, respectively. The simulation box is 134 kpc in physical scale.

phys. 134 kpc/h box

Implications on Reionization

- Yajima, Umemura+'09: LBG+LAE can reionize the Universe up to z~6
- Dwarf gals (M_{halo}~10^8 - 10^{10} M_{sun}) w/ high f_{esc} may play an important role for reionization



Yajima, Umemura+ '09

① Necessary photon number to ionize the IGM

$$N_{\rm ion}(z) = (10^{51.2}\,{\rm s}^{-1}{\rm Mpc}^{-3})\,C_{30}\left(\frac{1+z}{6}\right)^3\left(\frac{\Omega_{\rm b}h_{50}^2}{0.08}\right)^2$$

(Madau et al. 1999)

(C_{30}:clumpiness factor)

VS

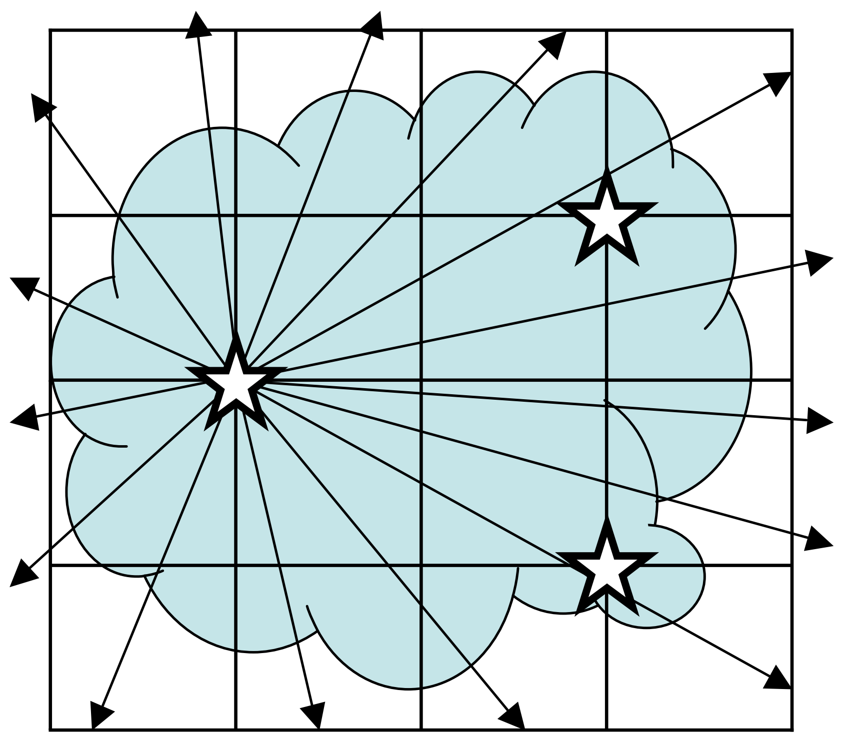
② Photon number radiated by LAEs and LBGs

$$N_{\rm ion}(z) = \left(10^{53.1}\,{\rm s}^{-1}{\rm Mpc}^{-3}\right)\times \underbrace{SFRD(z)}_{\text{Observation data}} \times \underbrace{f_{\rm esc}}_{\text{Our results !}}$$

(Madau et al. 1999)

SFRD : star formation rate density
f_{esc} : escape fraction

ART method



Authentic Ray Tracing Method

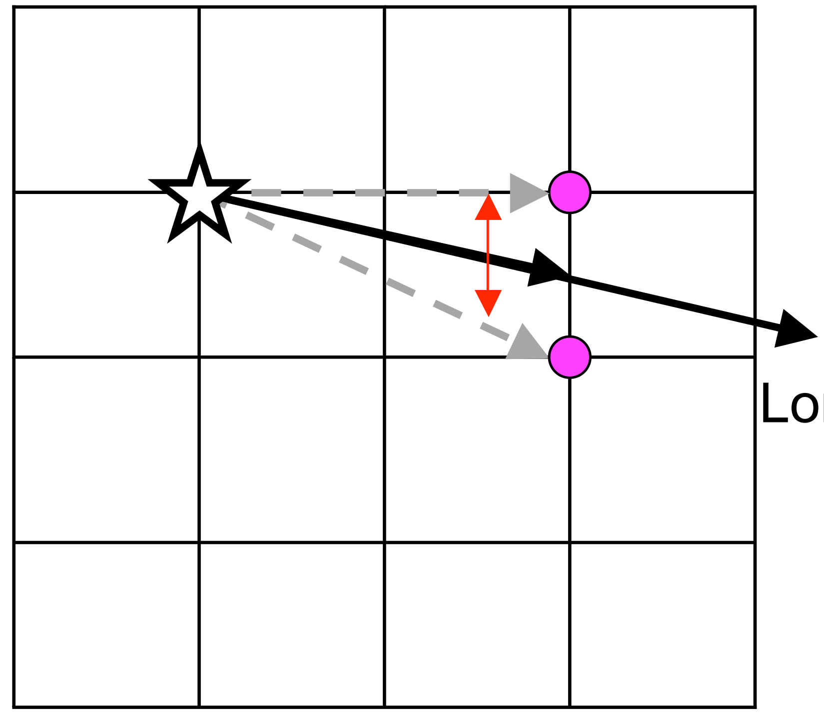
(Nakamoto et al. 2001, Iliev et al. 2006)

● 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

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

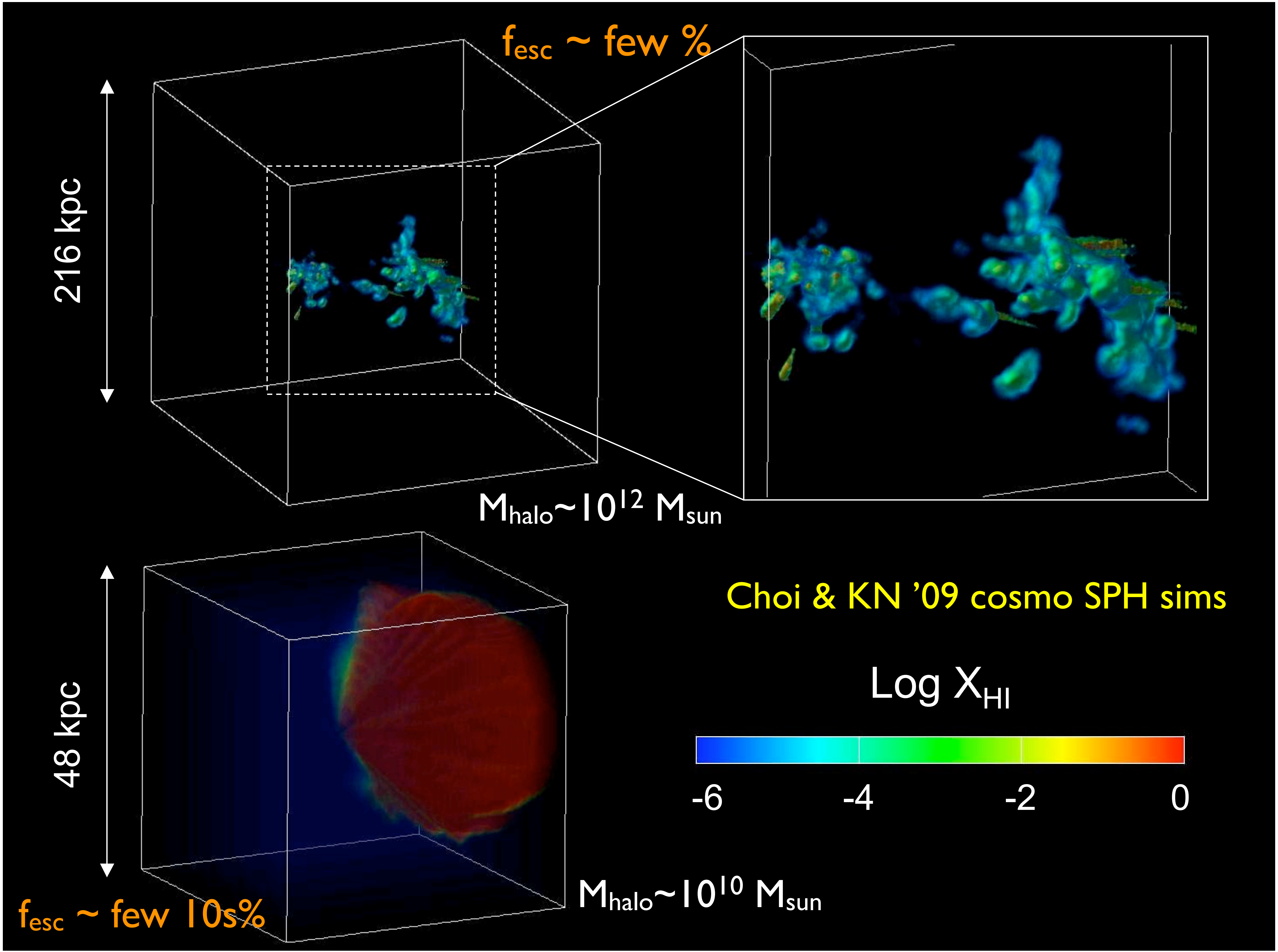


Long characteristic method: $N_{source} \times \underbrace{N_x \times N_y \times N_z}_{} \times N_{path}$

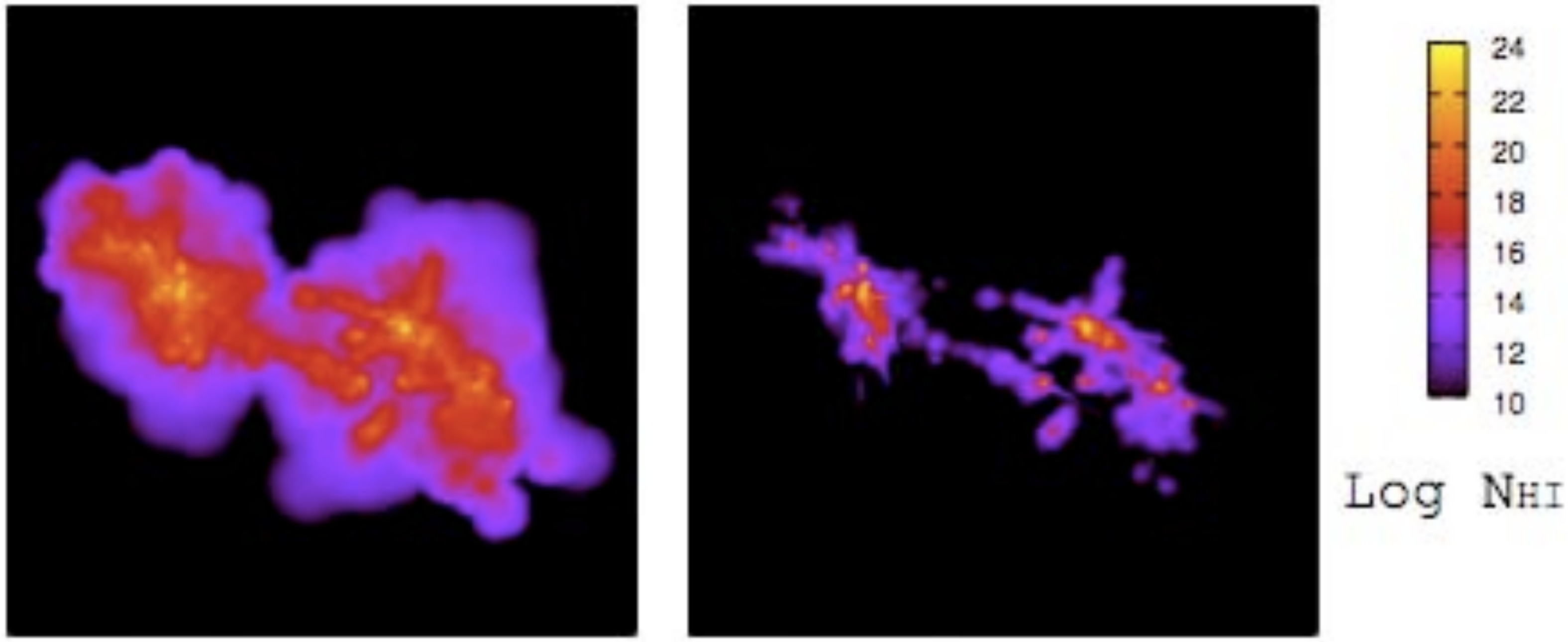
Basic equation: $\dfrac{dI_\nu}{ds} = -\alpha_{\rm abs} I_\nu + \varepsilon_\nu$

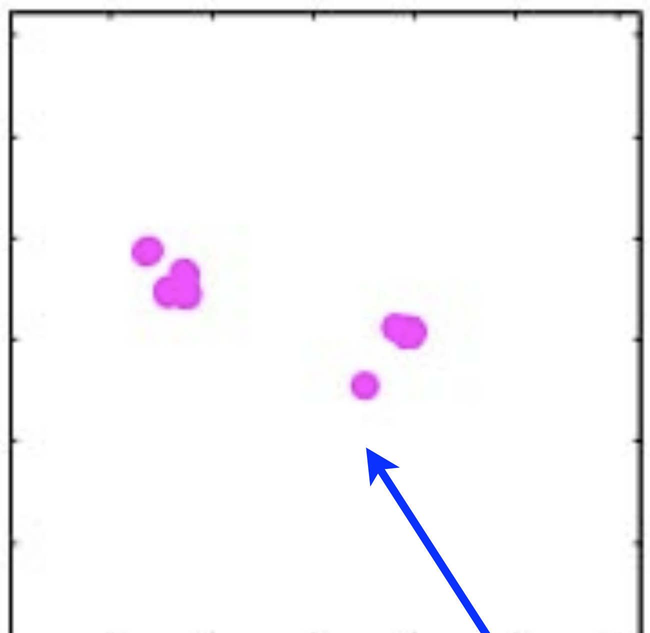
(from Yajima, '09)

Yajima, Choi, KN '09 (in prep.)

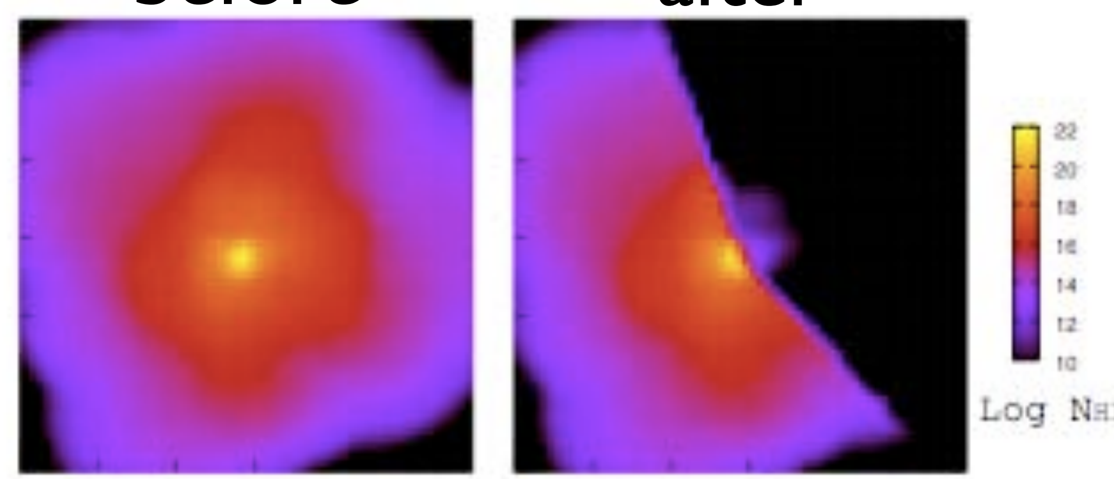


before RT after $M_{halo} \sim 10^{12}\ M_{sun}$

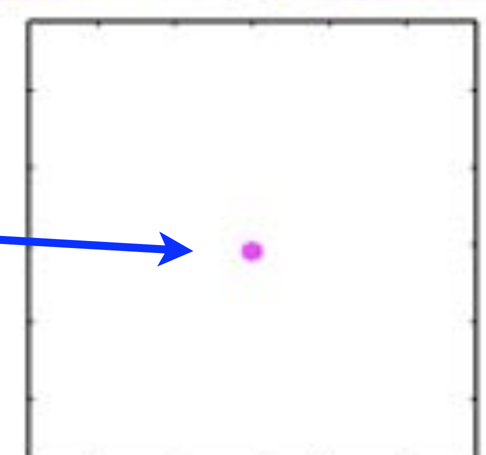




before after



locations of
young star clusters



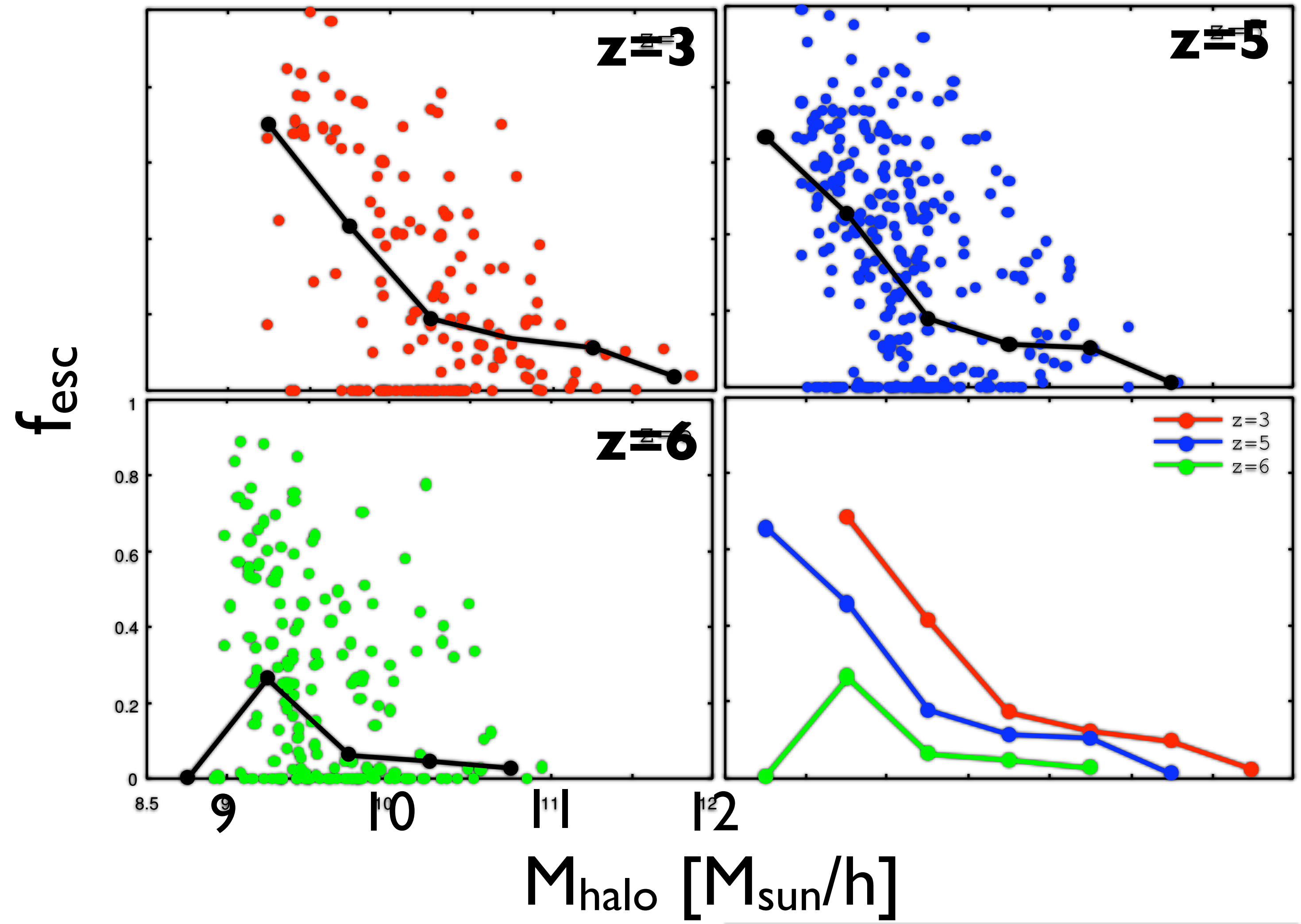
$M_{halo} \sim 10^{10}\ M_{sun}$

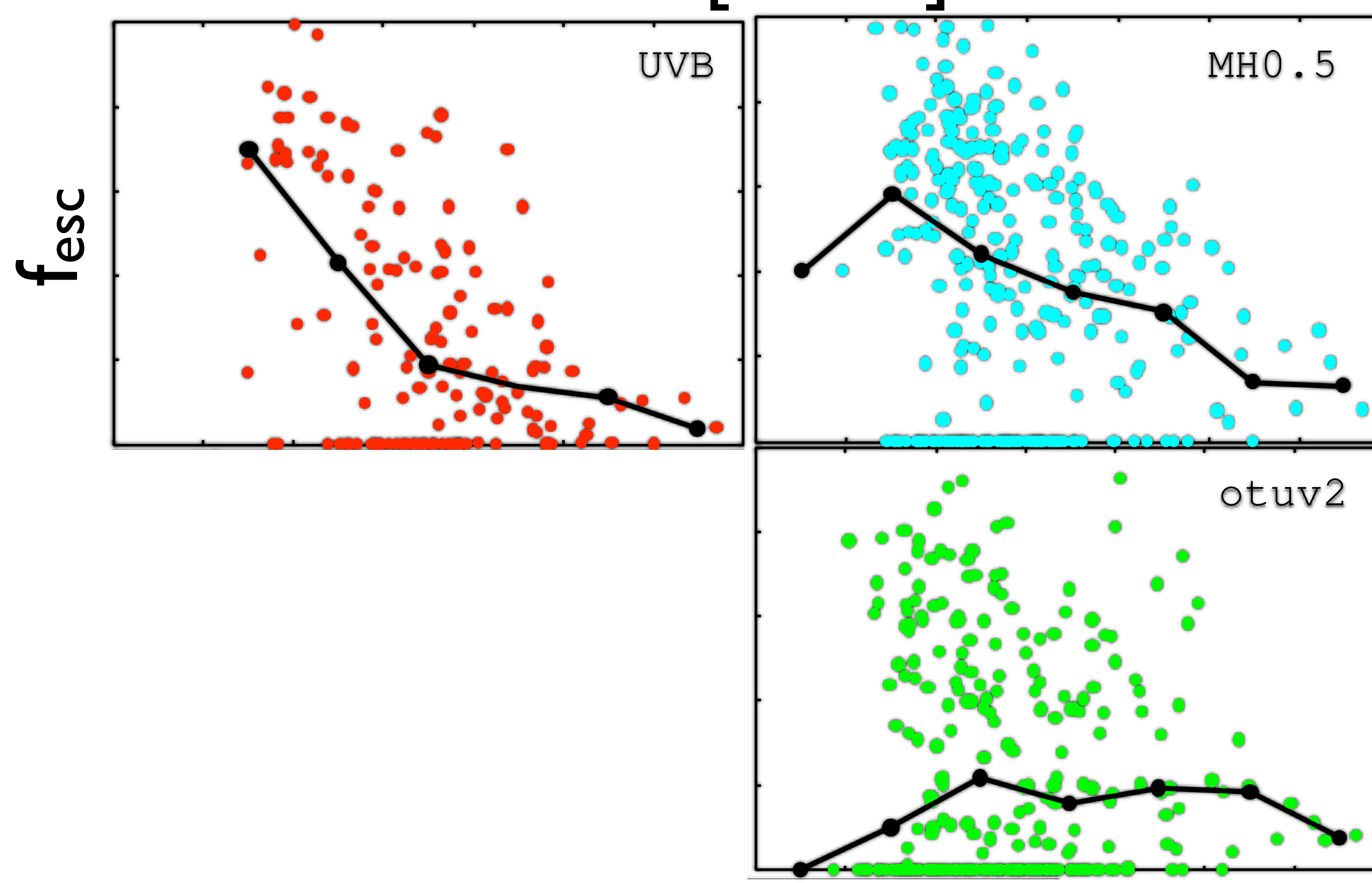
Yajima, Choi, KN ’09 (in prep)

Yajima, Choi, KN '09

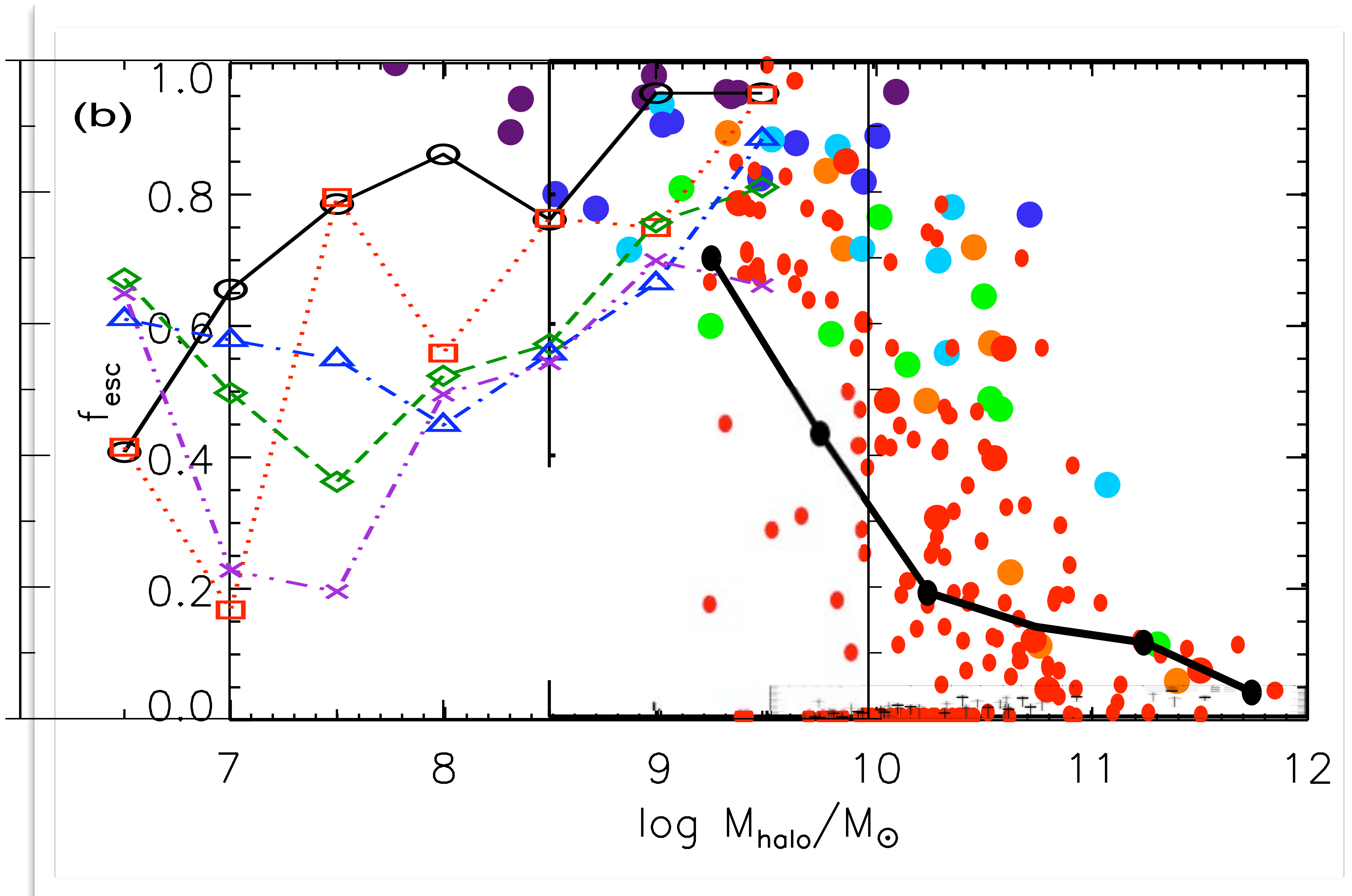
(in prep.)

- Choi & KN '09 cosmo SPH sims -- w/ realistic feedback models, calibrated against galaxy obs.
- **Decreasing f_{esc} as a func of M_{halo}** --- roughly consistent with Razoumov +'09; inconsistent with Gnedin+'09 & Wise & Cen '09
- f_{esc} decreases with decreasing redshift (??)
- **f_{esc}** decreases as the effect of UVB decreases



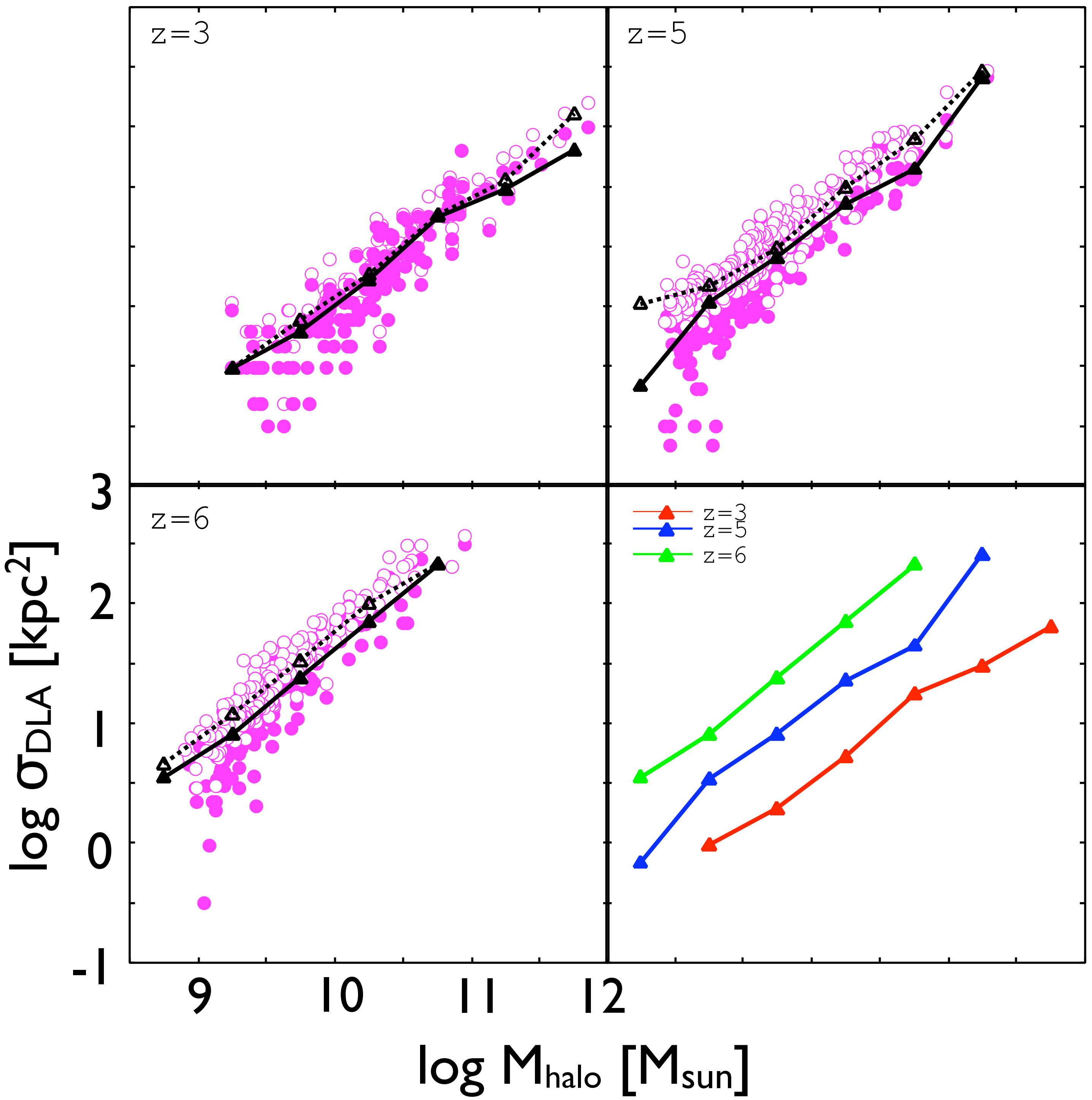


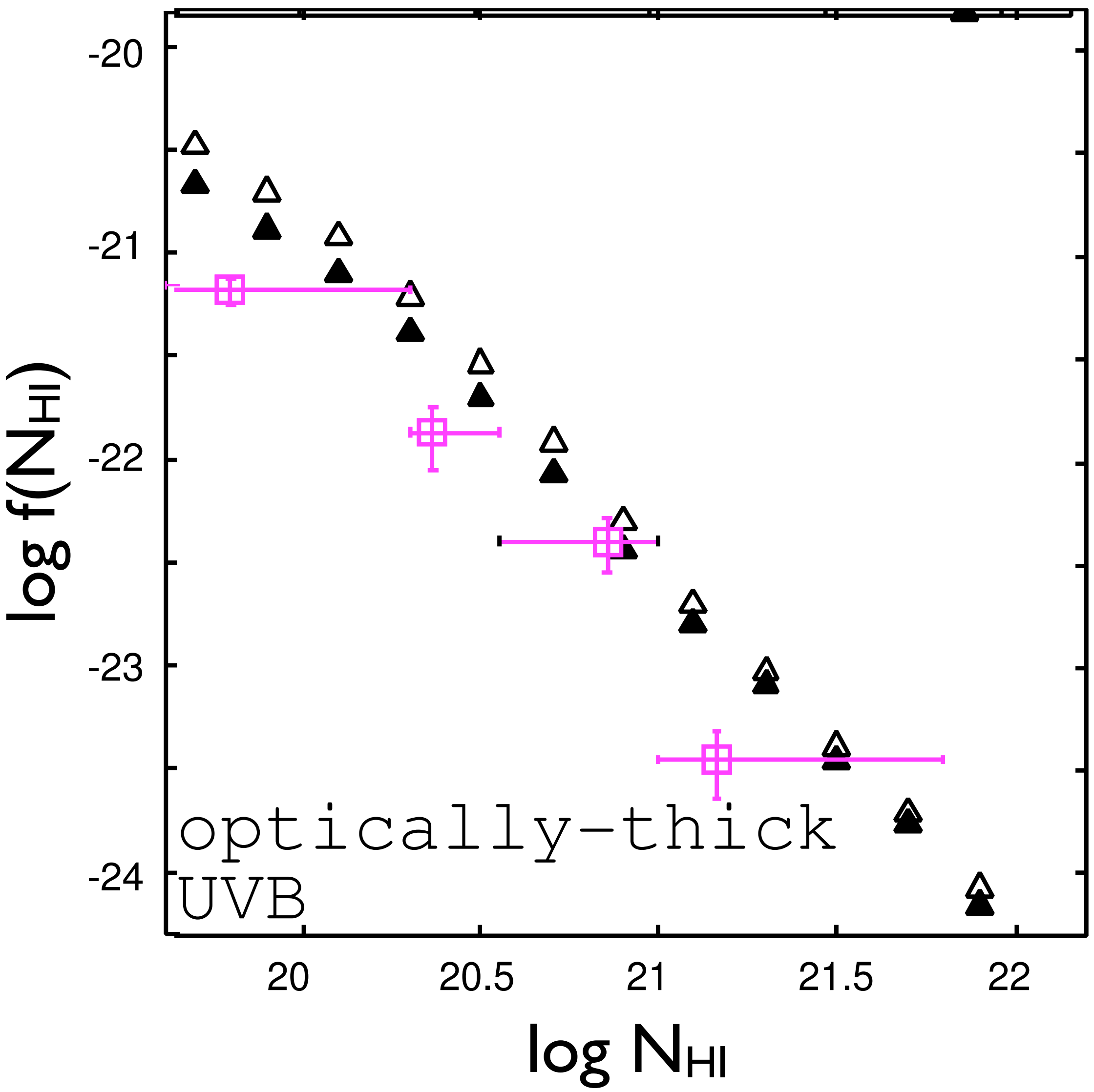
Unified Picture of $f_{esc,ion}$?



- **$f_{esc,ion}$ may have a peak at around 10^9 M_{sun}**

Effect of local stellar radiation on DLA cross section





Not so much effect on f(N_{HI})

Yajima, Choi, KN '09 (in prep)

Conclusions

- UVB was probably sinking in too much into the gas due to opt. thin approx --> effect of UBV quite strong.
- Local stellar radiation decreases the DLA cross section and $f(N_{HI})$, but the effect is not so strong.
- Current results on f_{esc} from diff sims varies a lot.
- Proposal of the **unified picture of $f_{esc,ion}$**
- Future work: LAE & reionization modeling need to take all of the above (scatter & mass dependence of f_{esc}, dust) into account.