What can DLAs and the gas around galaxies tell us about galaxy formation?

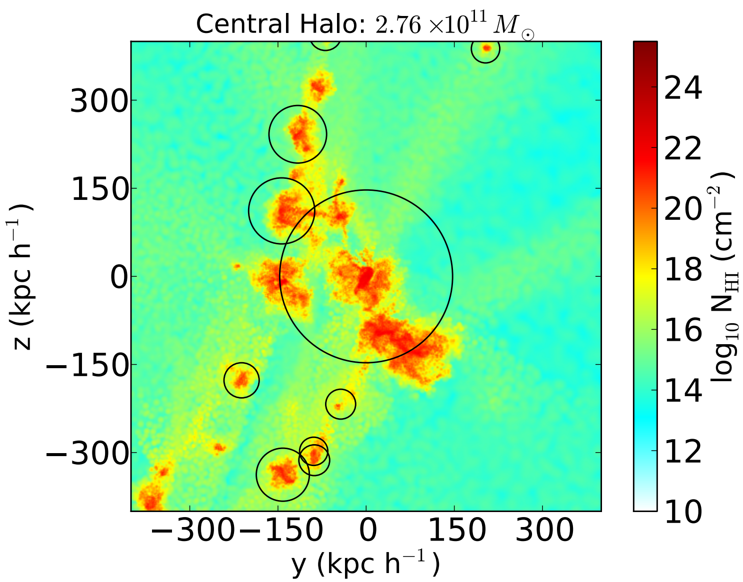
Simeon Bird, CMU

arXiv:1407.7858, 1405.3994

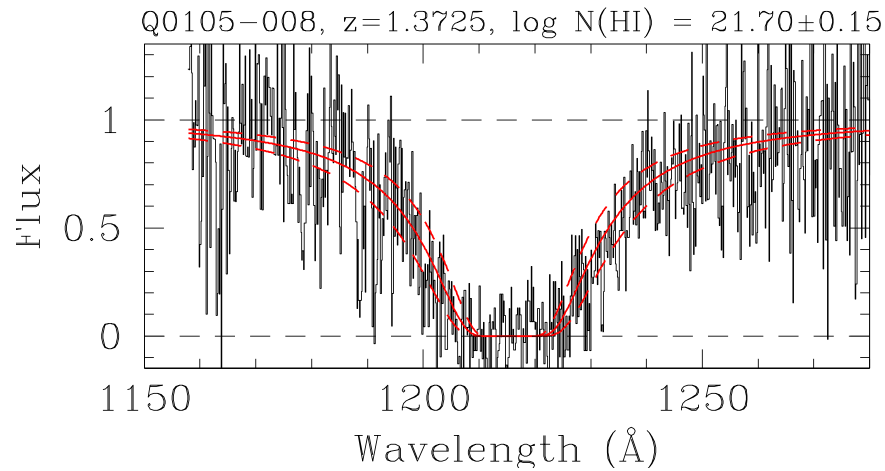
with Martin Haehnelt, Marcel Neeleman, Kate Rubin, Mark Vogelsberger, Shy Genel, Lars Hernquist

What are DLAs?

HI



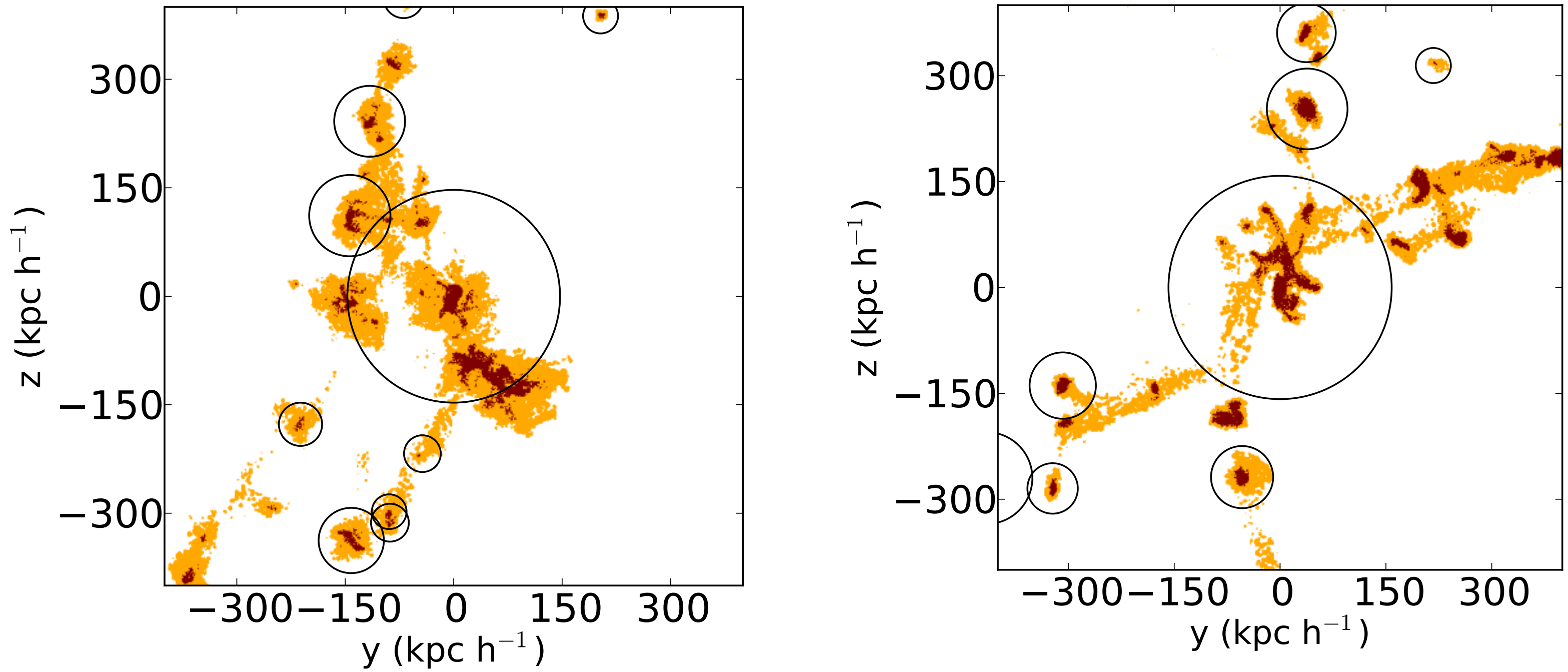
$N_{HI} > 2 \times 10^{20}$ cm^{-2}



Prochaska+ 2008

DLAs: neutral hydrogen reservoirs at z=4-2

What are DLAs?



Dense neutral self-shielded regions

HI Density: 0.01 cm^{-3} or 10% star formation threshold

Why are we interested in DLAs?

1. Several problems making them
   – Velocity width
   – Bias

2. Direct probe of nearly star-forming gas around galaxies

Why are we interested in gas around galaxies?

- We know star formation changes overall galaxy evolution
- People tune sub-grid models to stellar mass function
- Gas provides an independent model check

Why are we interested in gas around galaxies?

1. Gas provides an independent model check

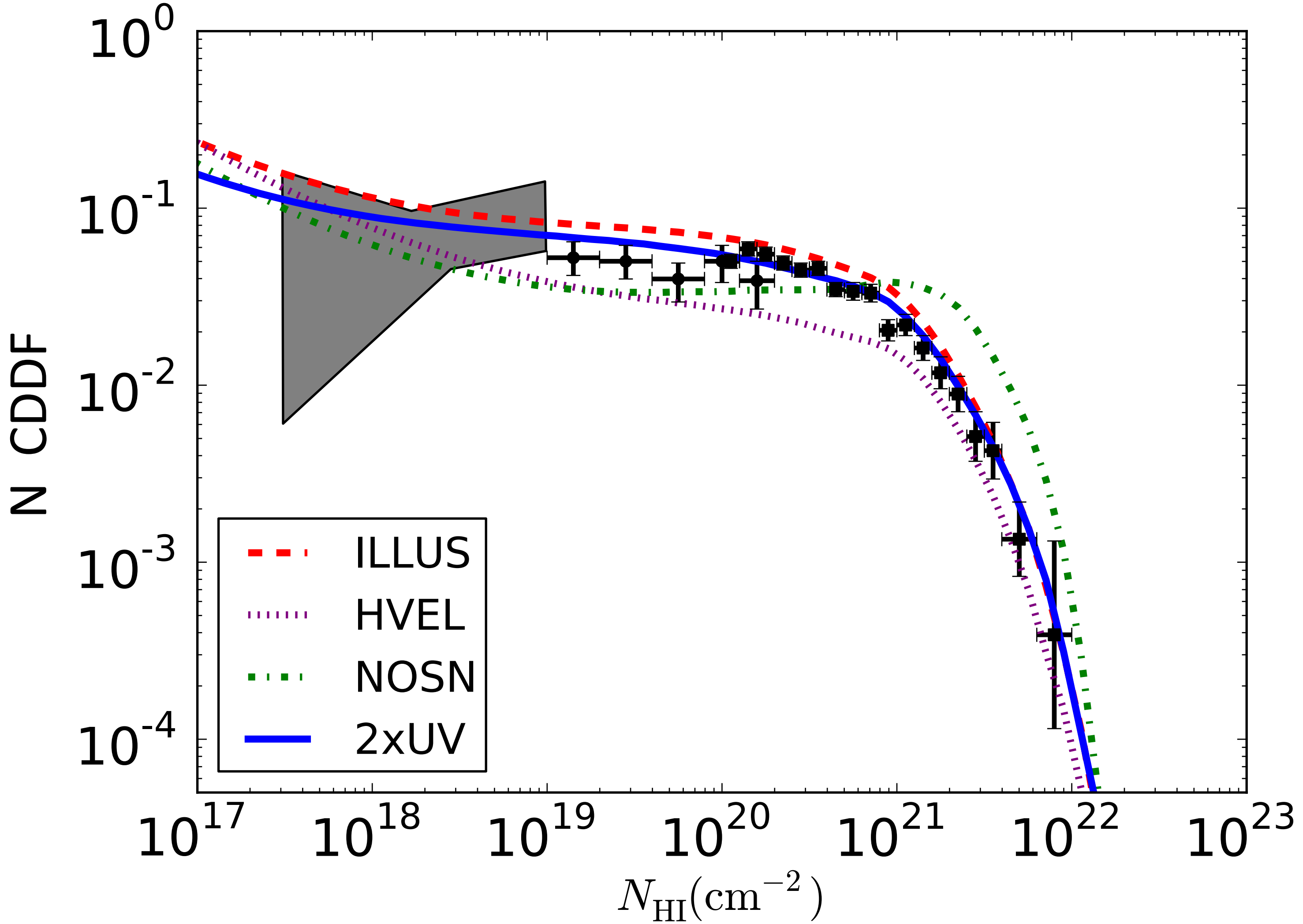
   – Few systematics: sensitive to one ion
   – Hard to get statistics: Quasars are rarer than galaxies

Basic Results

1. **Column Density**

2. Metallicity

Column Density at z=3



Stellar Feedback

Outflows with velocity proportional to halo circular velocity (high mass loading to suppress star formation in dwarfs)

Mass loading:

$$\eta \propto v_{\rm w}^{-2}$$

Wind velocity:

$$v_{\rm w} = 3.7\sigma_{\rm 1D}$$

Outflows in small halos SLOWER but push out more mass

Stellar Feedback

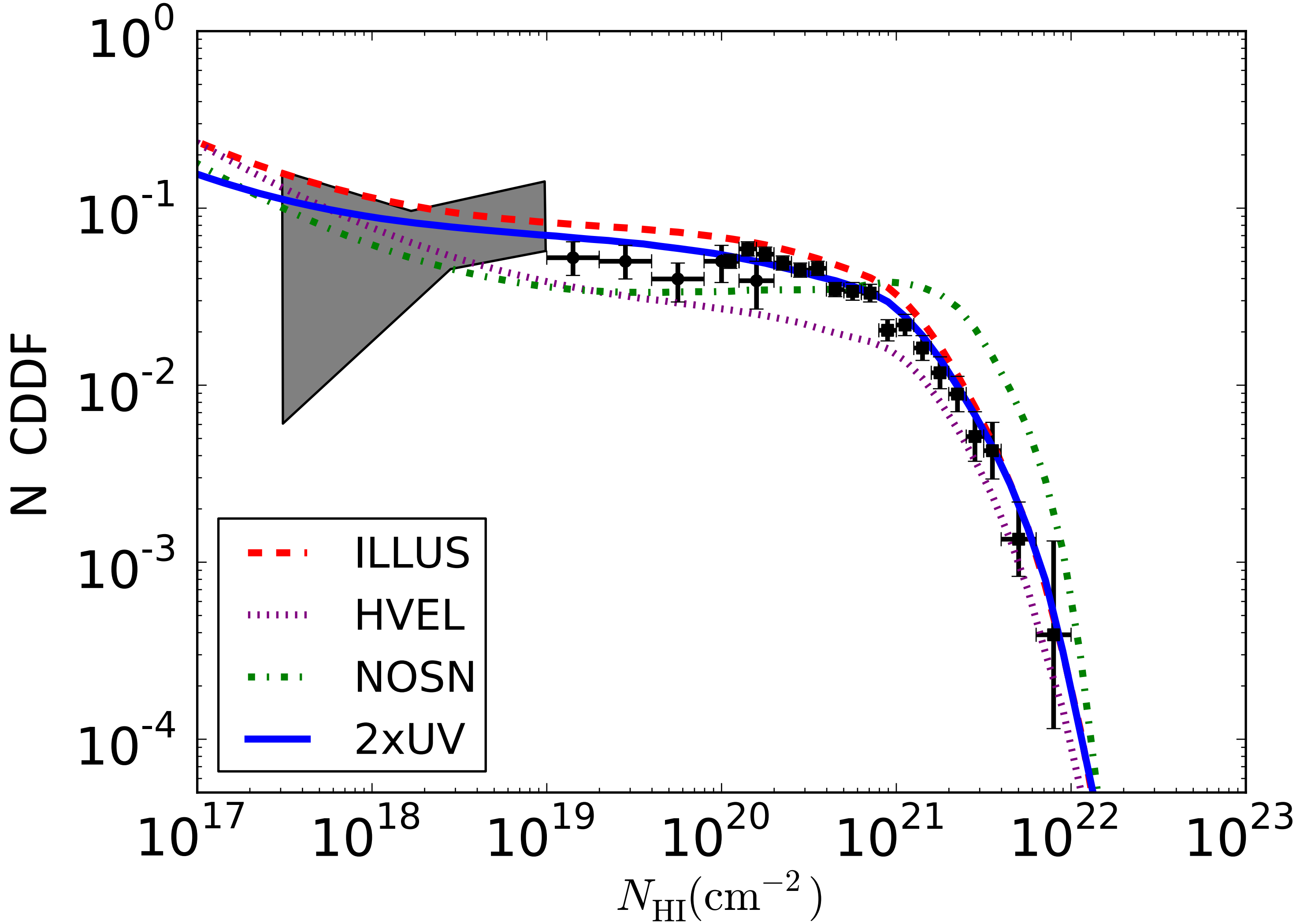
Four different models:

1. NOSN: No (effective) feedback
2. ILLUS: Illustris model
3. 2xUV: Illustris model with 2xUVB amplitude
4. HVEL: Constant velocity winds: 600 km/s

Blue is my favourite

Green is my least favourite

Column Density at z=3

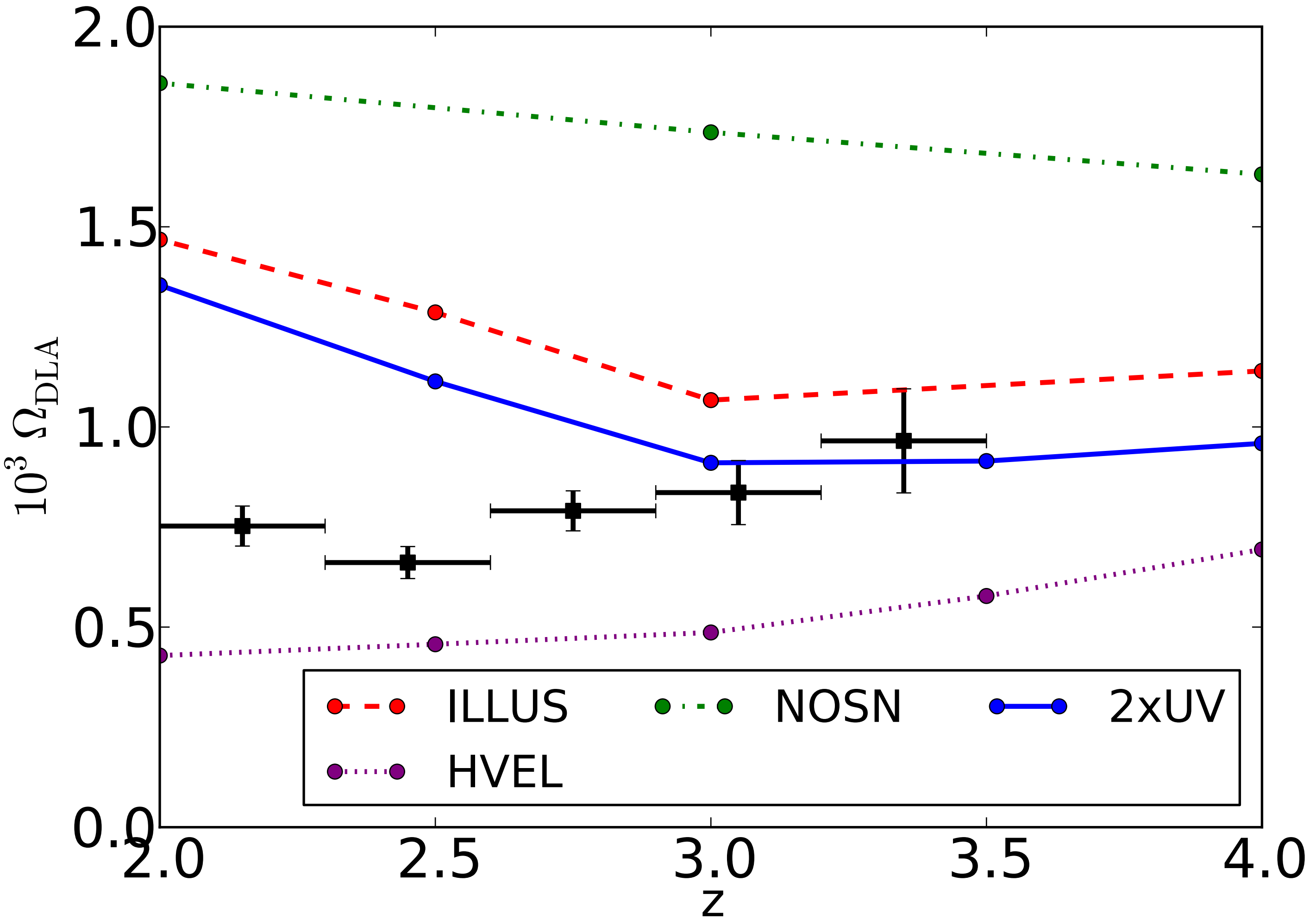


Basic Results

1. **Column Density**
   - **2xUV is ok at z=3!**

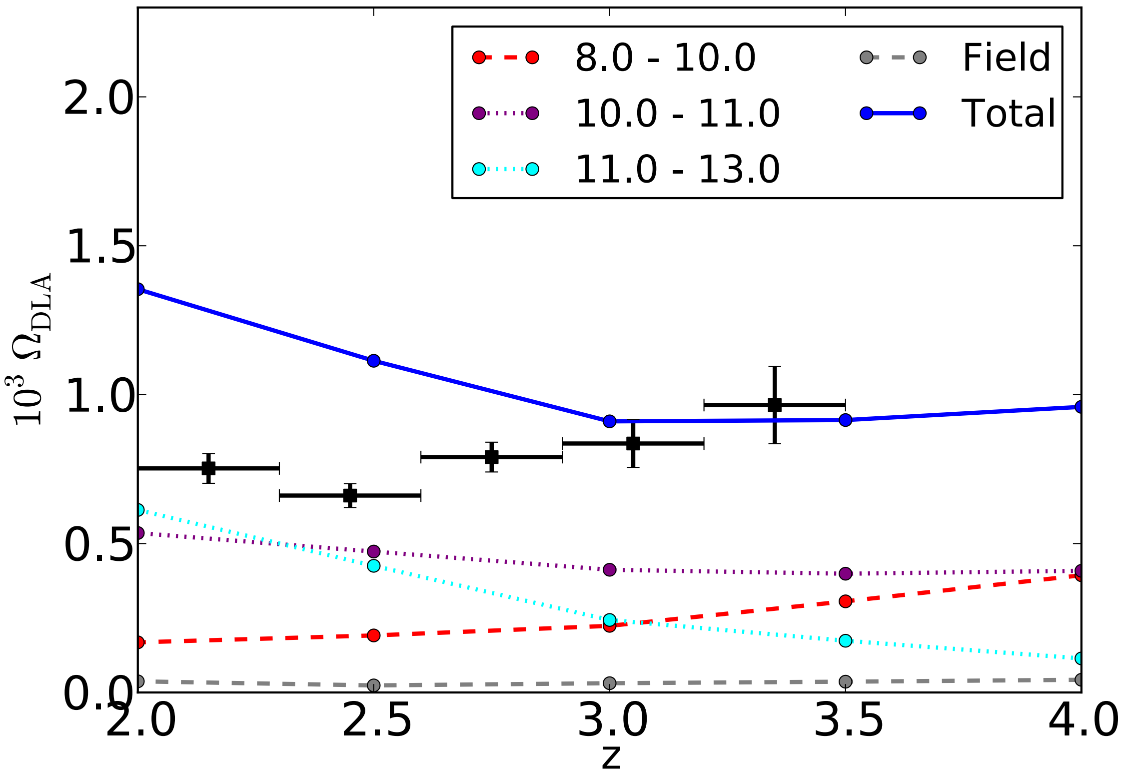
2. Metallicity

Neutral Hydrogen Abundance



Data: Noterdaeme+ 2012

Neutral Hydrogen Abundance



- At z=2 larger halos are forming
- Here supernova winds are not as effective
- Too much cold gas

Basic Results

1. **Column Density**
    - **Ok at z>3!**
    - **Too much at z=2**

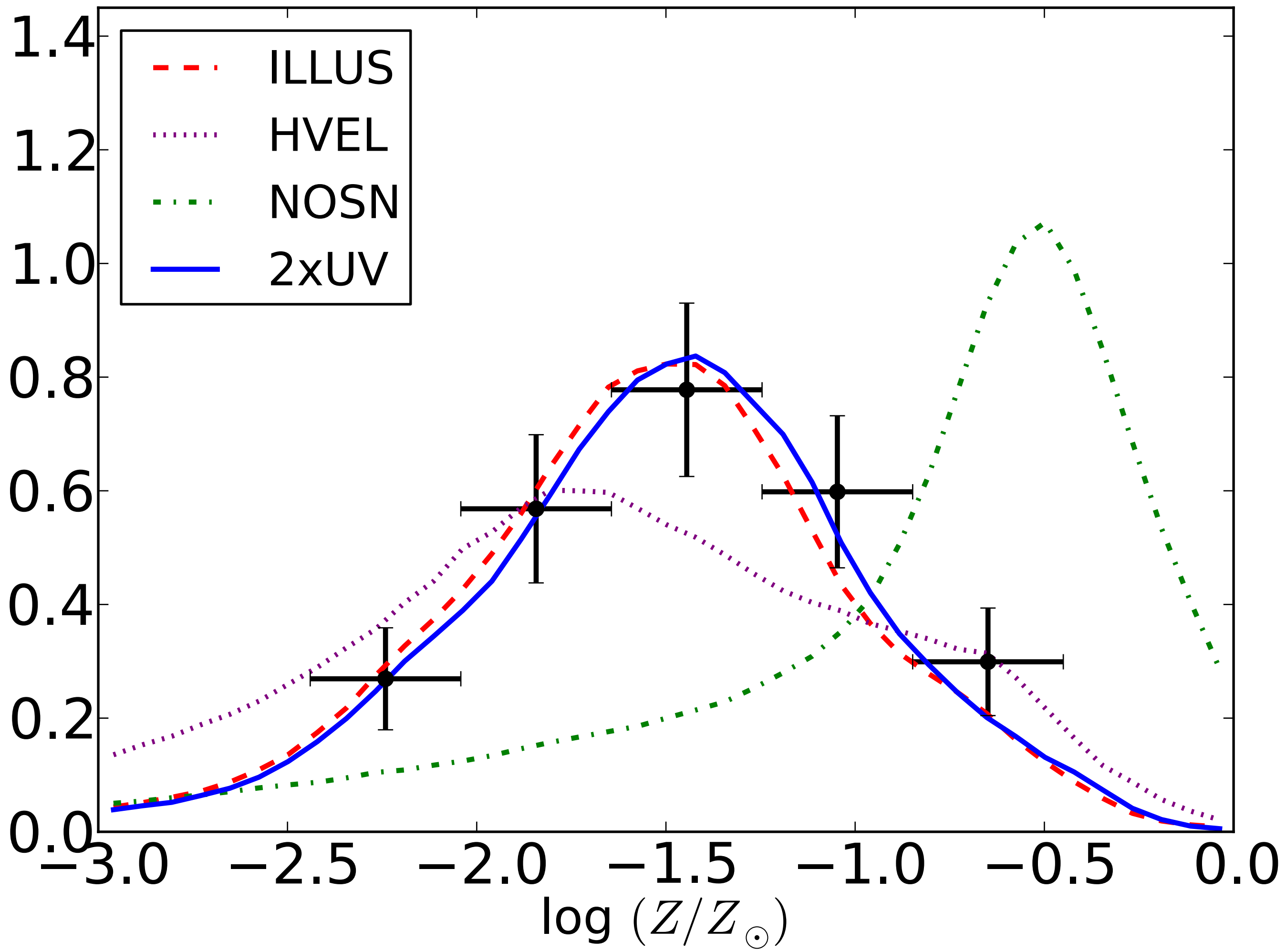
2. Metallicity

Basic Results

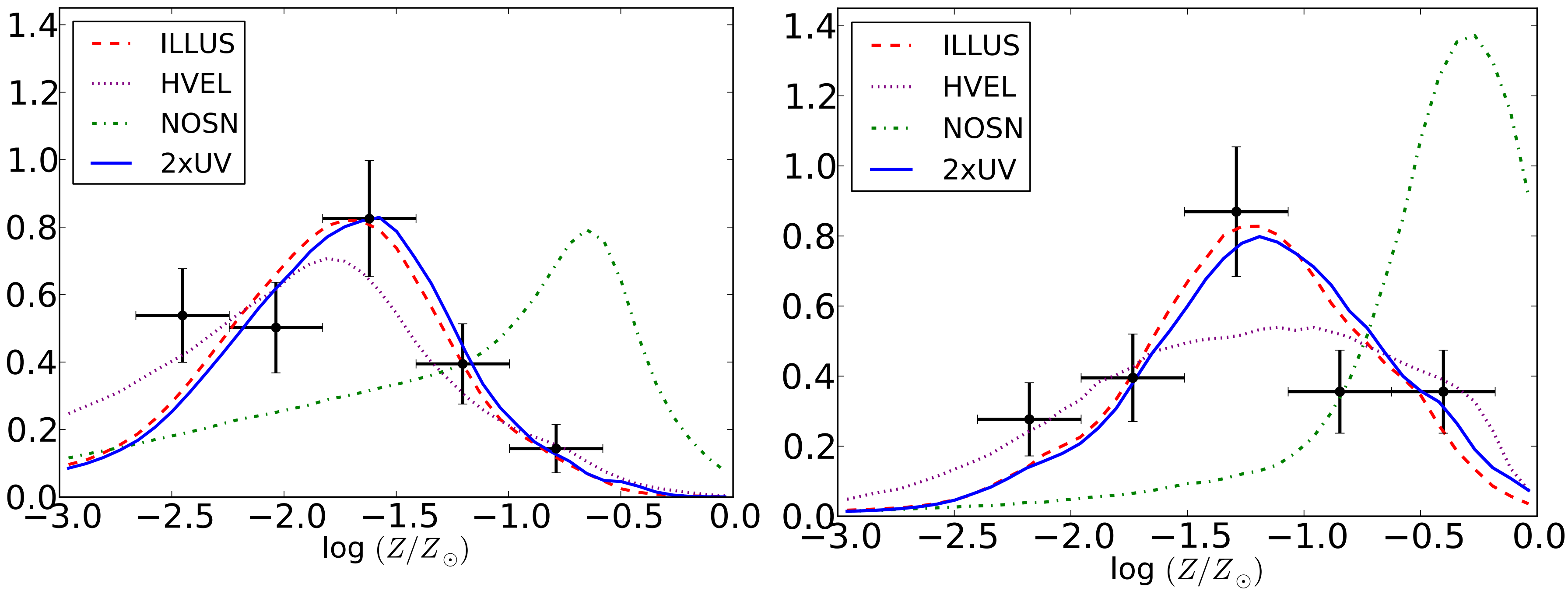
1. Column Density
   - Ok at z>3!
   - Too much at z=2

2. **Metallicity**

DLA Metallicity: z=3



DLA Metallicity: z=4,2



Change in mean metallicity due to change in mean halo size

Basic Results

1. Column Density
    - Ok at z>3!
    - Too much at z=2

2. **Metallicity**
    - **Ok!**

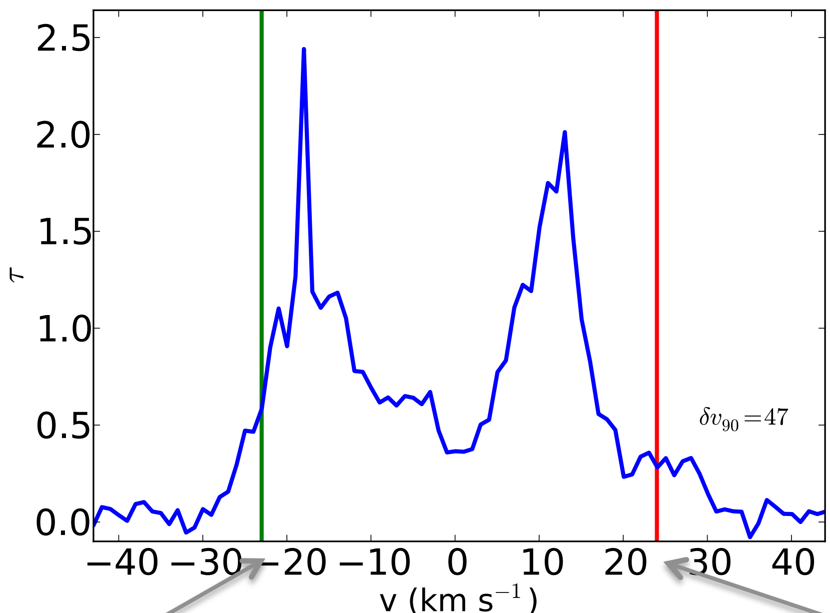
Less Basic Results

1. **Velocity Width**

2. Edge-leading Spectra

3. Bias

Measuring DLA Velocity Structure



Use metal lines:
Lyman-α saturated

Velocity width: 90% of total optical depth

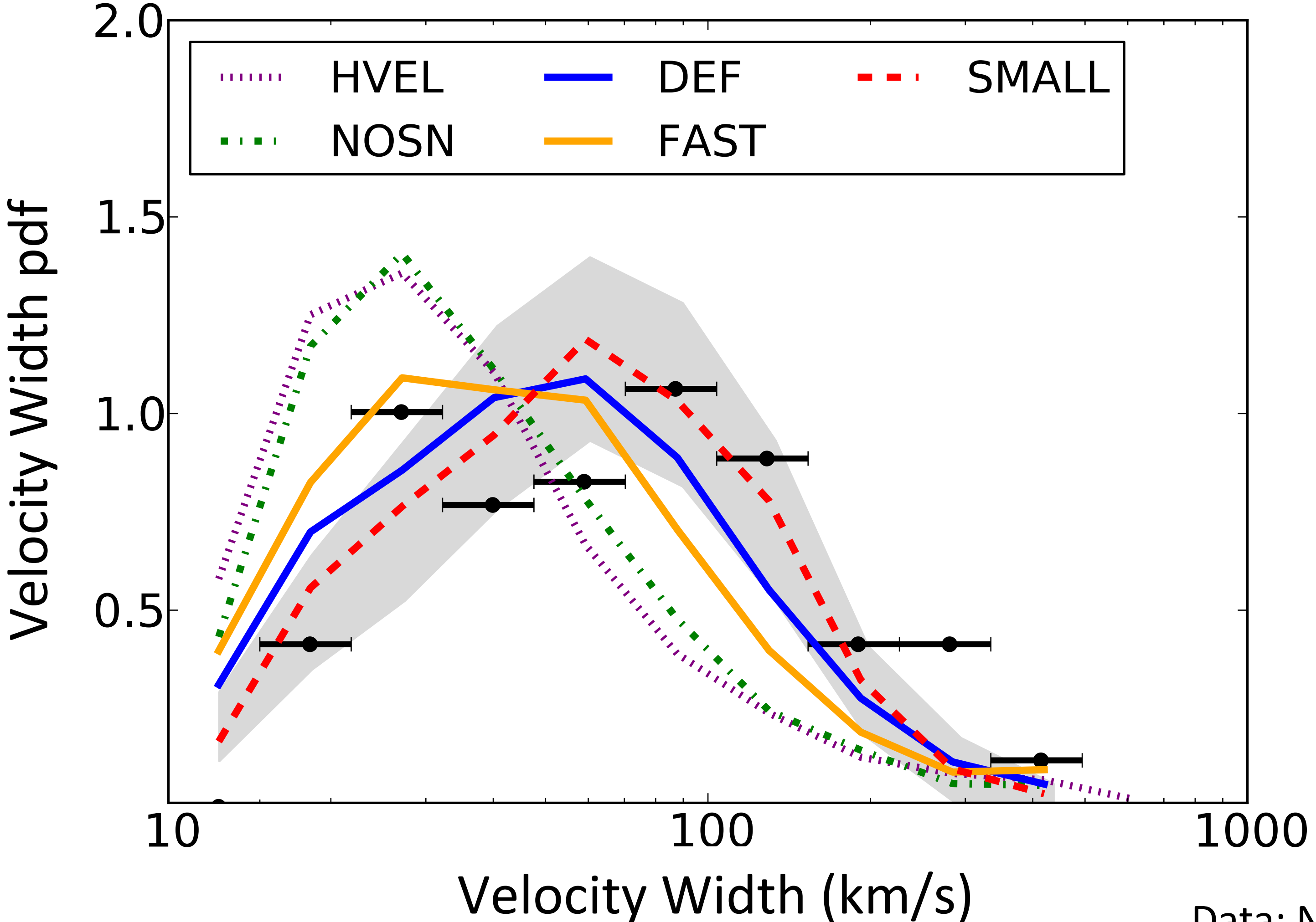
Correlates with halo virial velocity

Stellar Feedback

New models:

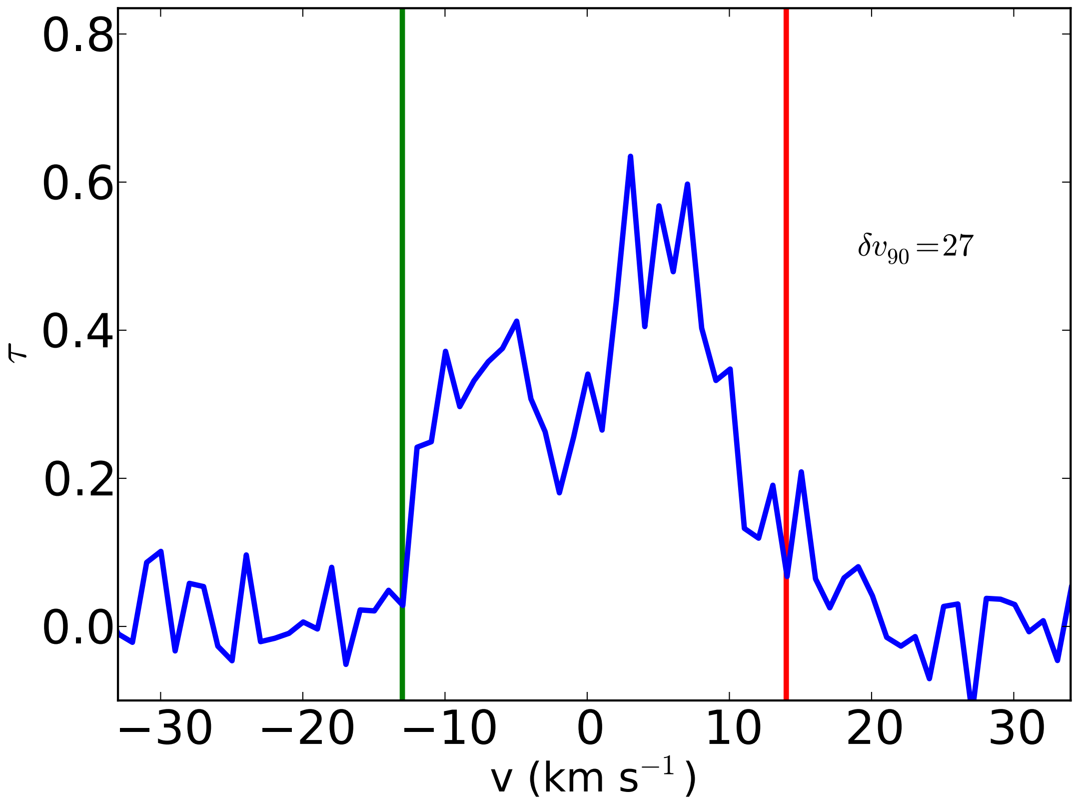
1. NOSN: No (effective) feedback
2. DEF: Illustris model and 2xUV
3. FAST: Same as DEF with 50% faster winds
4. HVEL: Constant velocity winds: 600 km/s
5. (SMALL: As DEF but 10 Mpc box)

Velocity Widths



Data: Neeleman+ 2013

How did we do this?



Run cosmological hydro simulation (box: 25 & 10 Mpc)

Sample snapshot randomly for 5000 DLA spectra

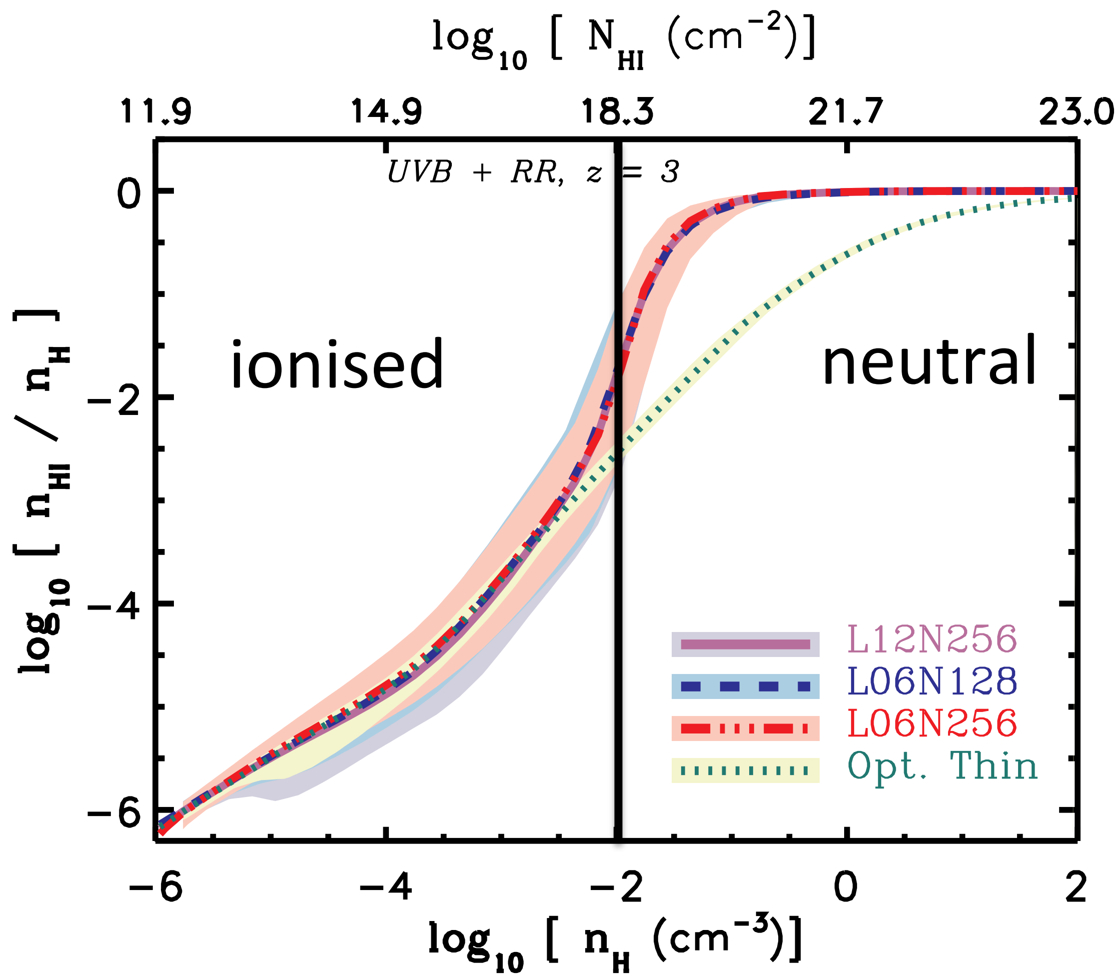
How did we do this?

Two Important Ingredients

1. **Make metal (SiII) cover larger region of halo**
2. Make halos (a bit) larger

Shielding

Photo-ionization rate reduced by self-shielding

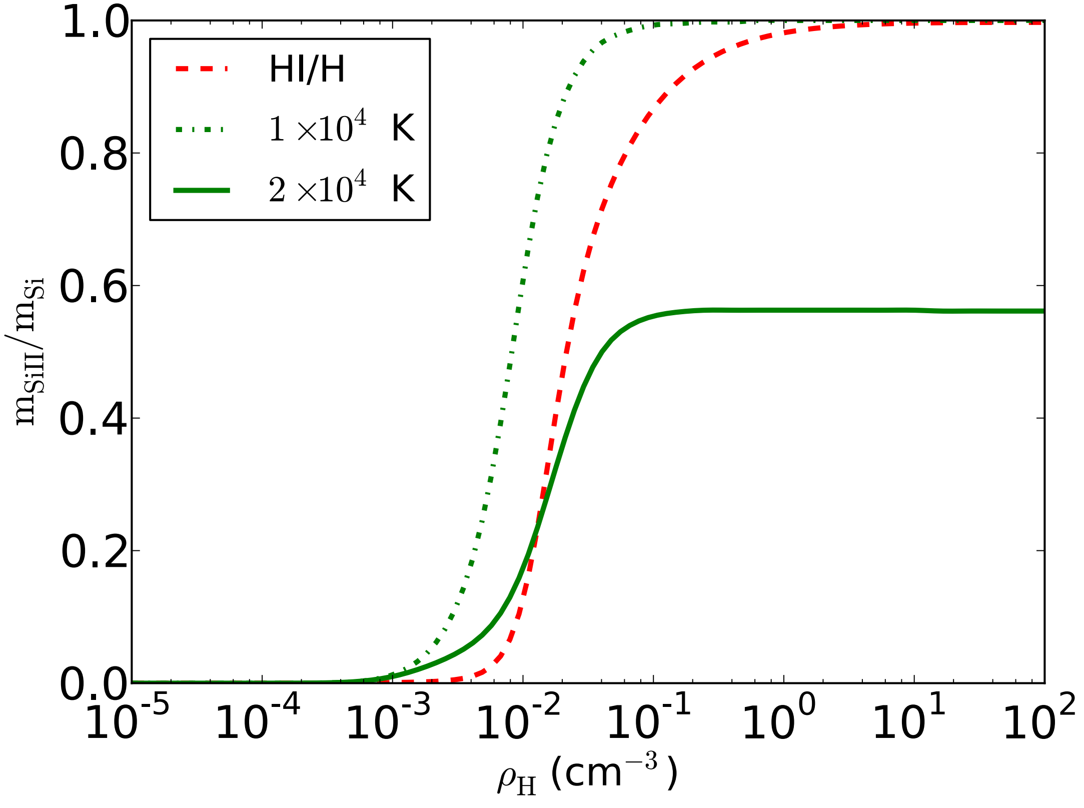


Rahmati+ 2013

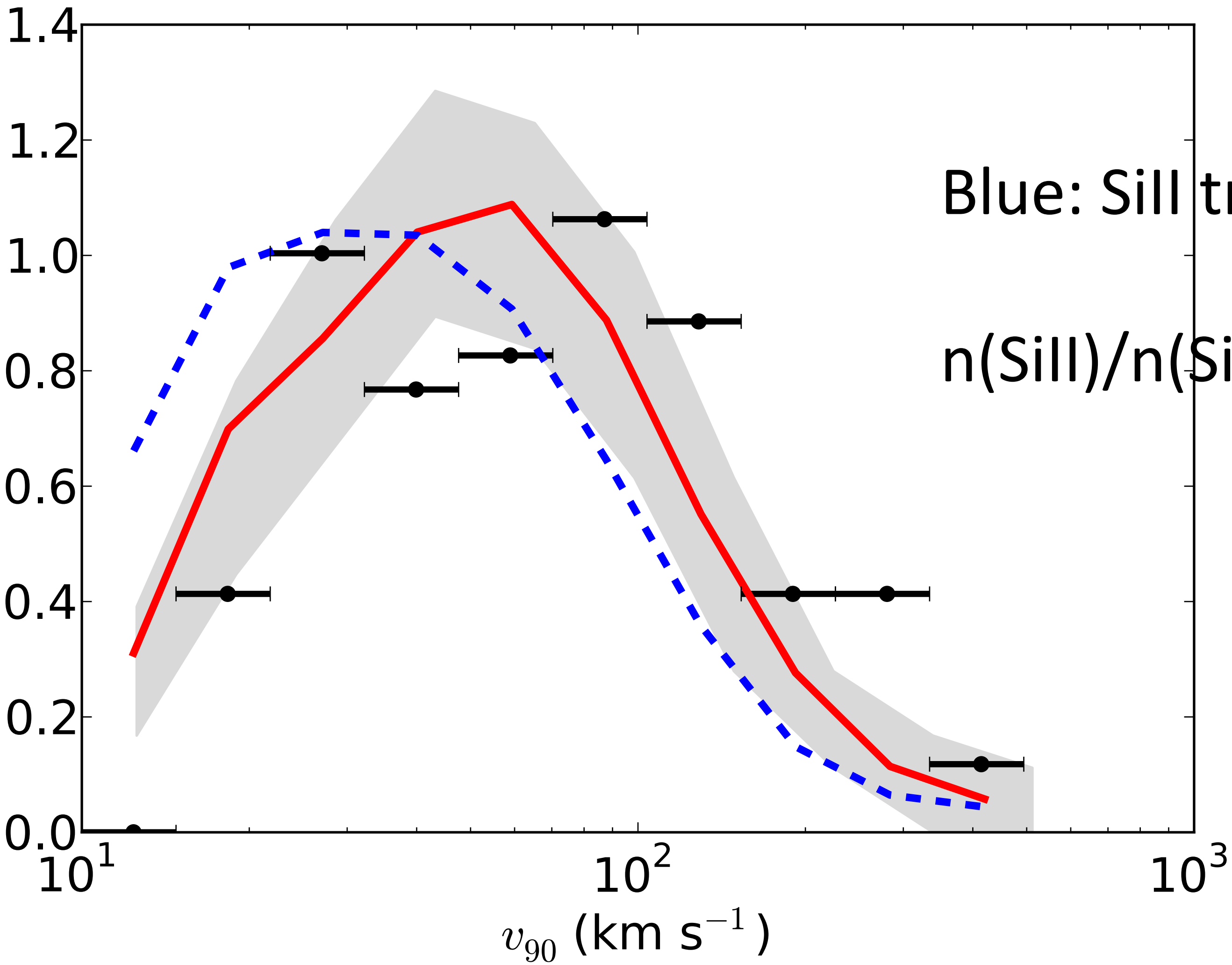
Shielding for Metals

Same self-shielding for E > 1 Rydberg

SiII at lower density than HI (16.3 eV > 13.6 eV)



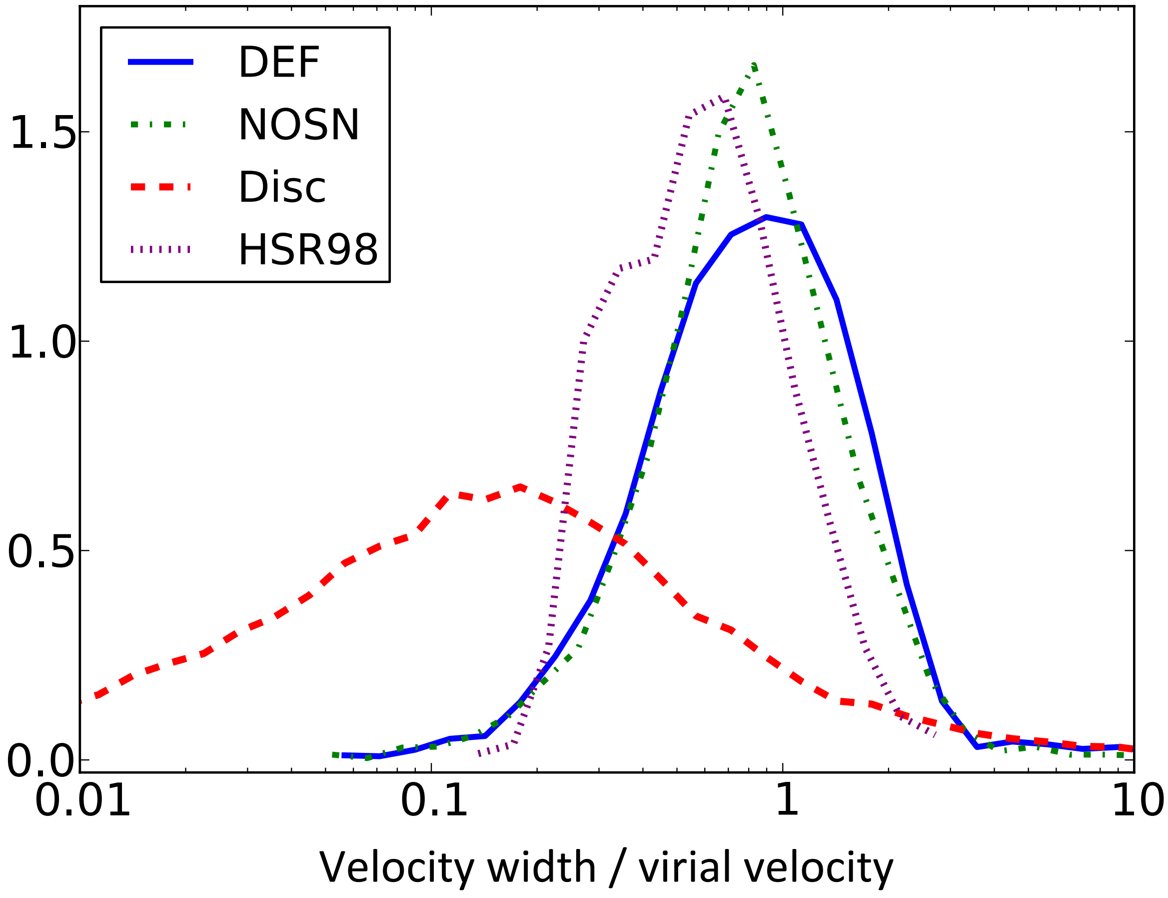
Ionisation state



Blue: SiII traces HI

n(SiII)/n(Si) = n(HI)/n(H)

Velocity width approx virial velocity



DEF: Illustris model

NOSN: No feedback

Disc: A semi-analytic model of DLAs as discs

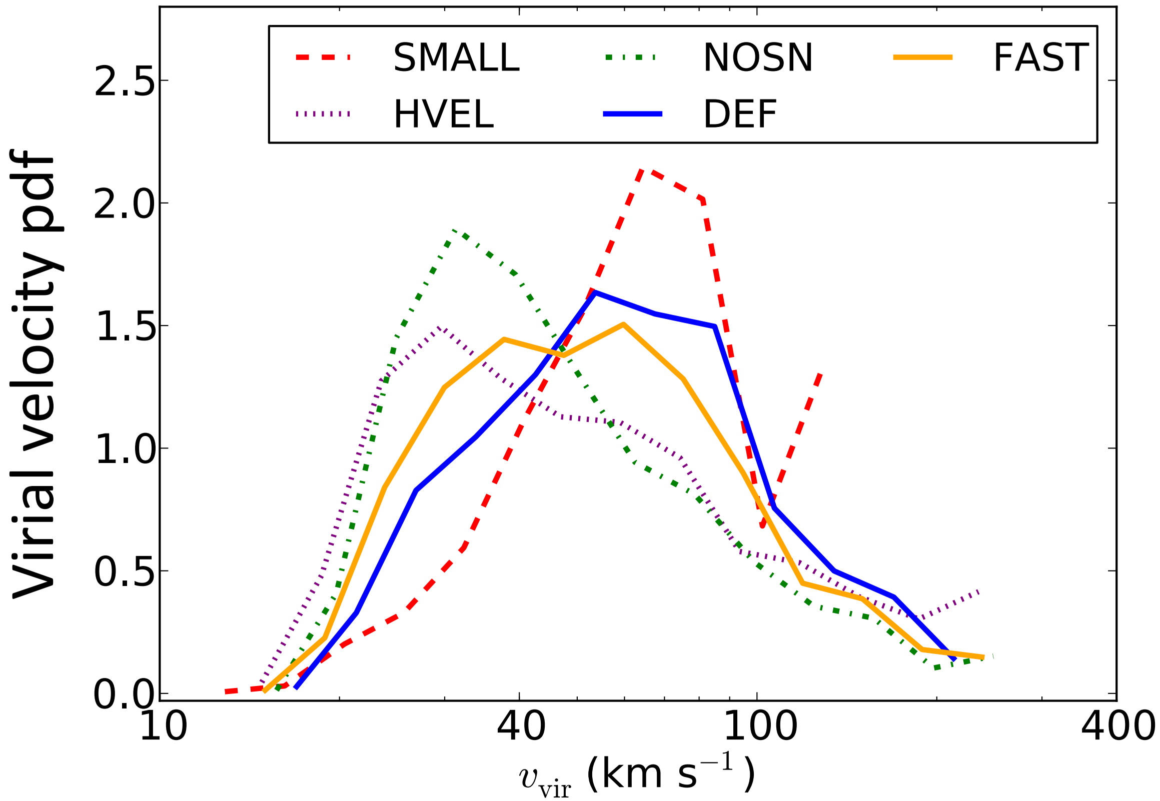
HSR98: Haehnelt+98 simulations

How did we do this?

Two Important Ingredients

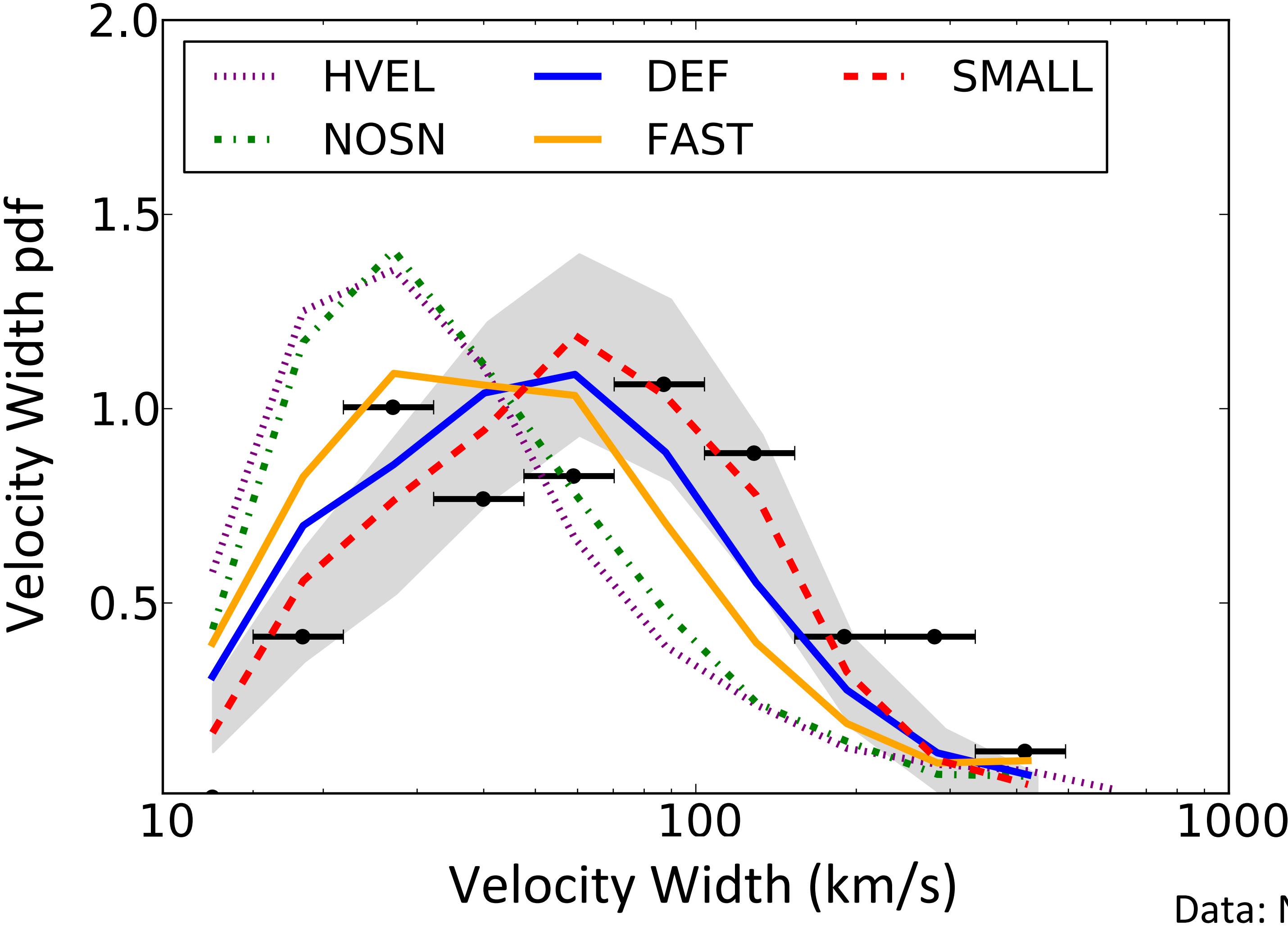
1. Make metal (SiII) cover larger region of halo
2. **Make halos (a bit) larger**

Host Virial Velocity



- Feedback suppresses halos < 40 km/s
- Characteristic velocity now 70 km/s

Velocity Widths



Data: Neeleman+ 2013

Less Basic Results

1. Velocity Width

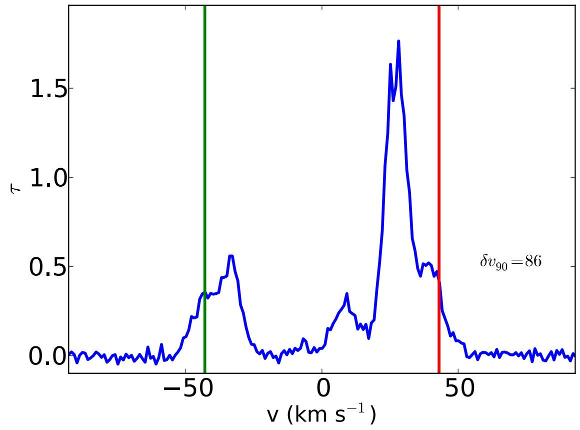
2. **Edge-leading Spectra**

3. Bias

Edge-Leading Spectra

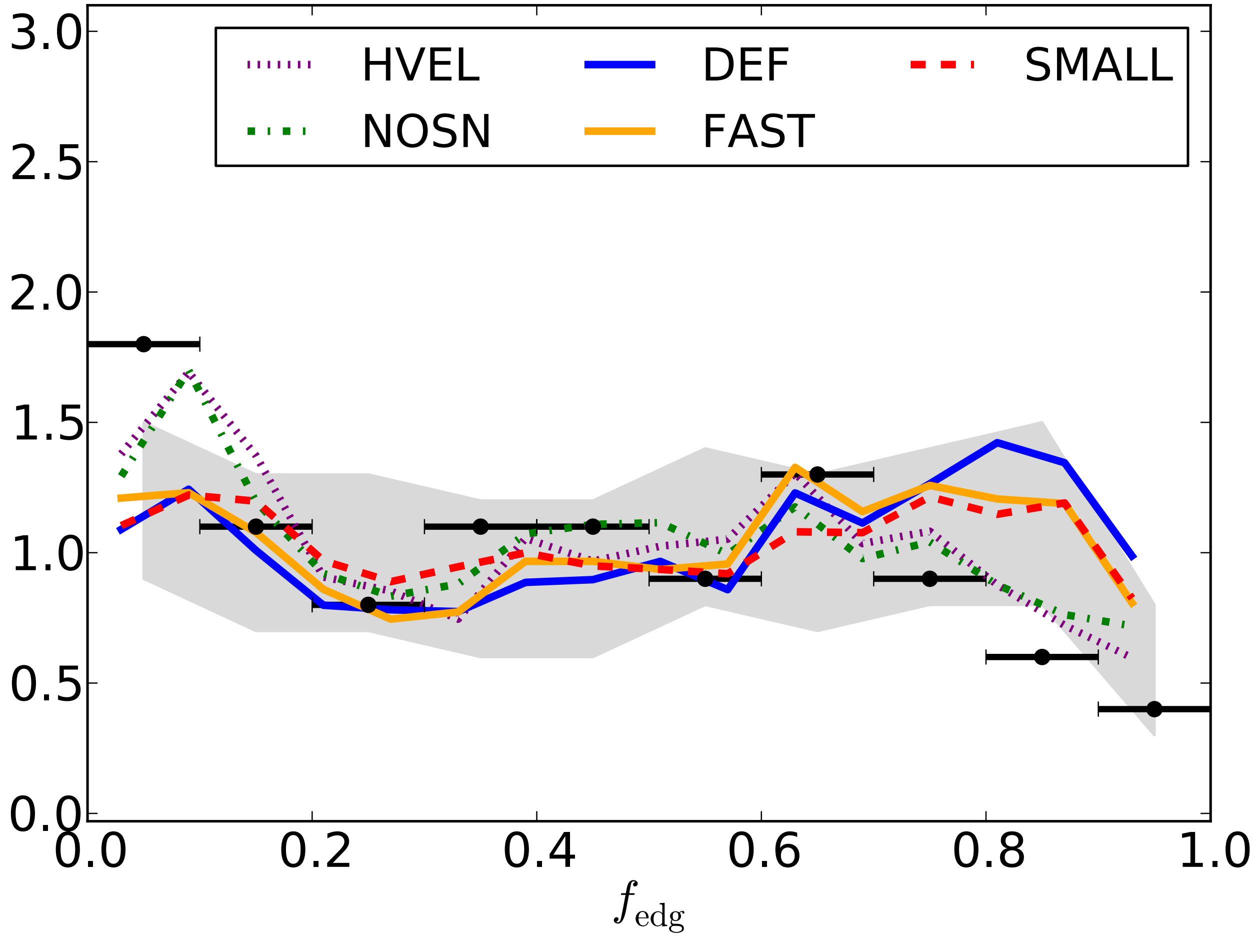
- Edge-leading statistic

$$\frac{v_{\mathrm{pk}} - v_{\mathrm{mean}}}{\Delta v/2}$$



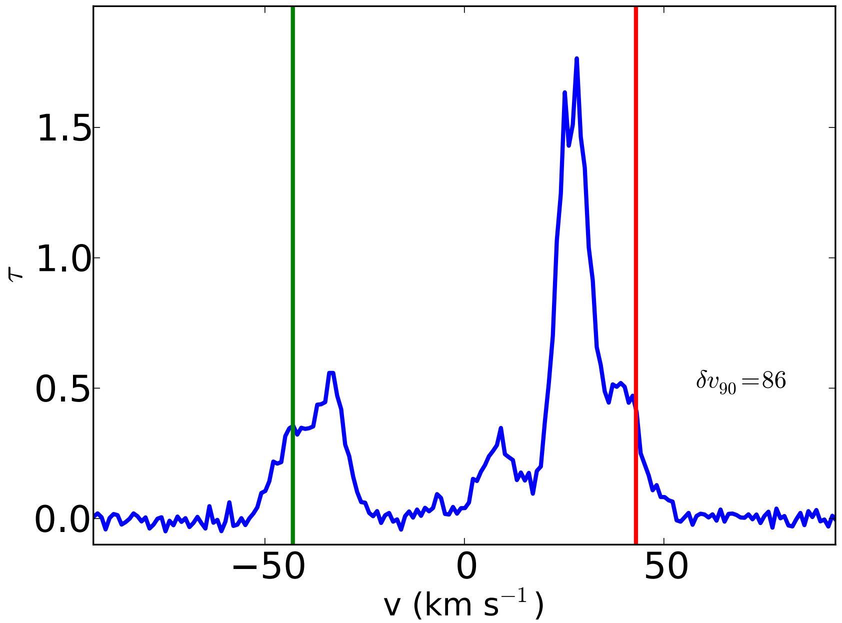
- Difference between position of peak and midpoint of total absorption in units of velocity width

Edge-Leading Spectra



Absorption concentrated at edges: marginally significant

Edge-Leading Spectra



A guess: outflows have a special velocity.

Less Basic Results

1. Velocity Width

2. Edge-leading Spectra

3. **DLA Bias**

DLA Bias

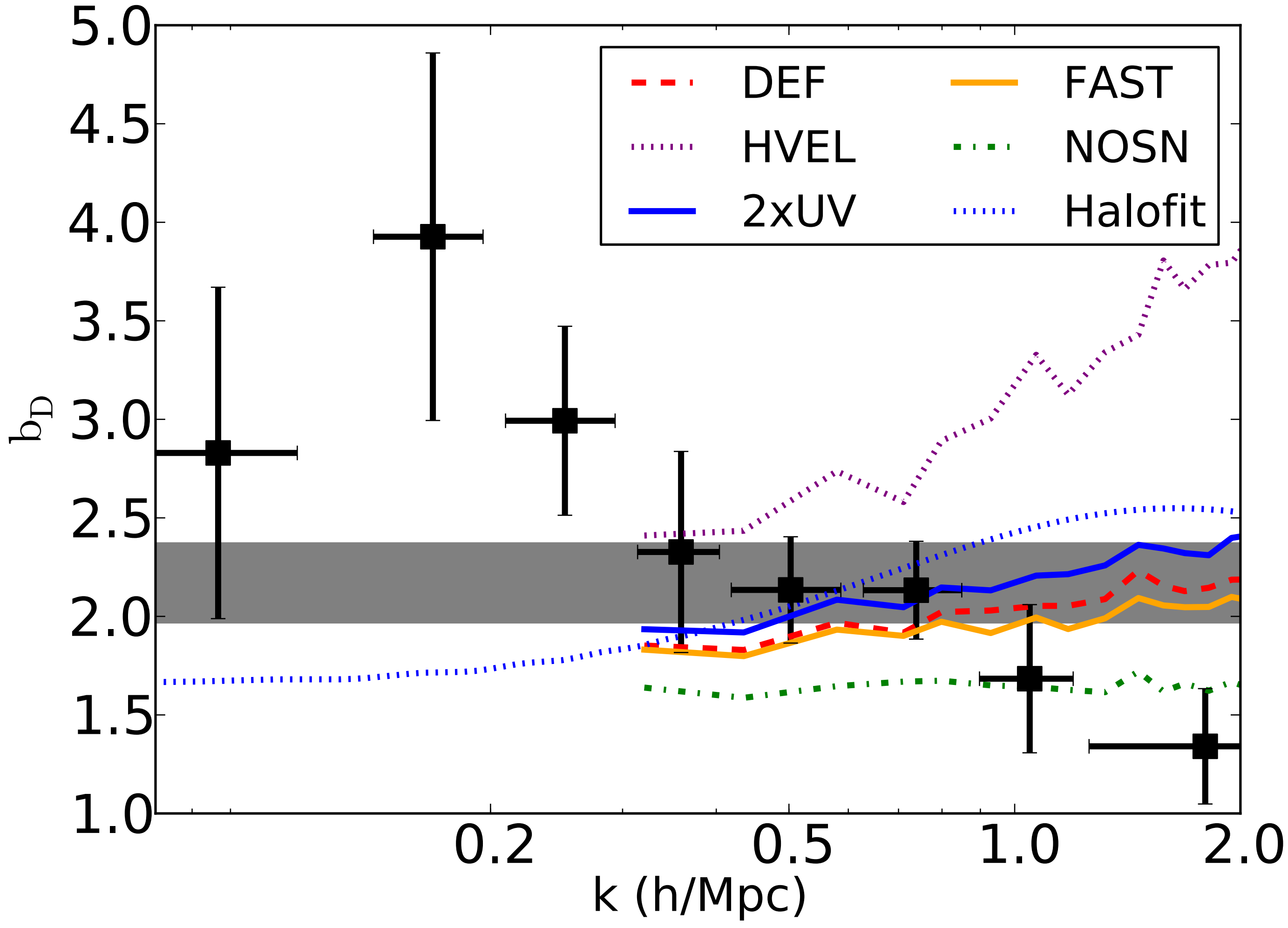
- Bias b = DLA power / matter power
- Gives host halo mass

- Observed (Font-Ribera 2012):
  bias (b) = 2.4 => M = $10^{11} – 10^{12}$

- We have halos M = $10^{10} – 10^{10.5}$

- Evidence for larger halos?

DLA Bias



Data: Font-Ribera+2012

DLA Bias

- Two reasons we get higher bias than expected:
  - b = 2.2 => M = 10^{11} – 10^{12} assumes:

$$\sigma_{\rm DLA} = \sigma^0 \left(\frac{M}{10^{10}} \right)^{\alpha} \qquad \alpha = 1 \text{ vs } 1/2$$

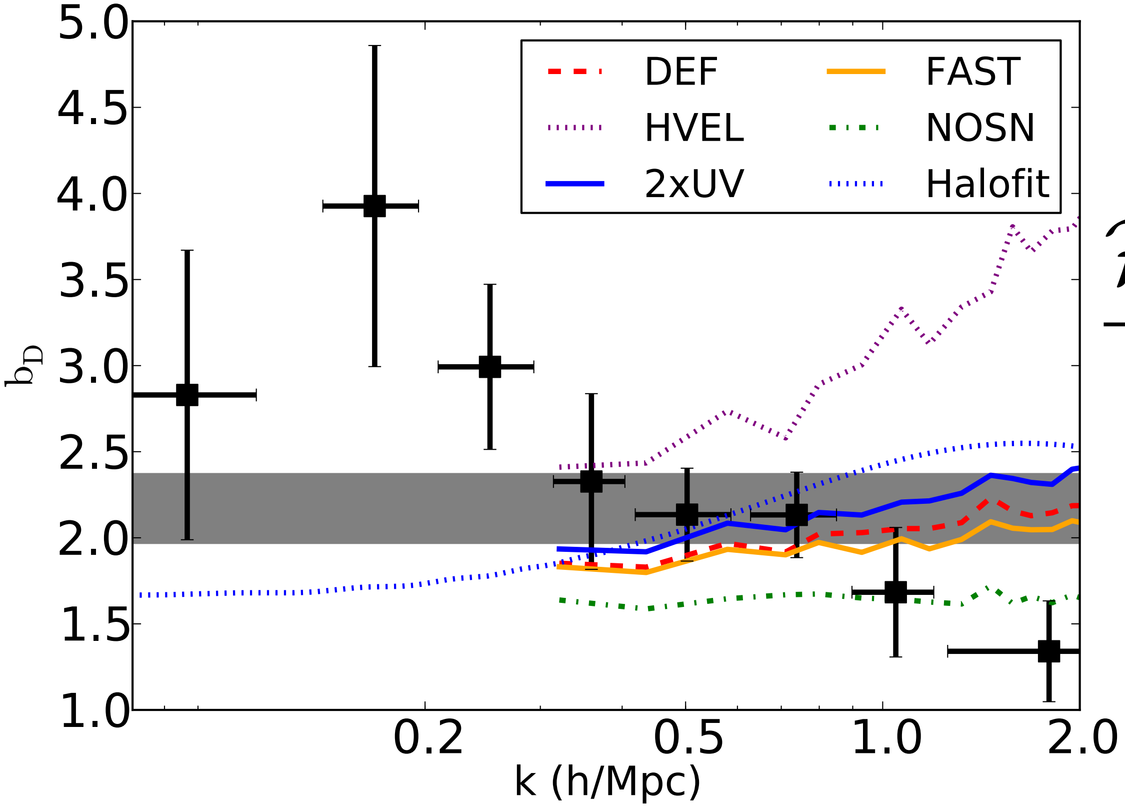
  - More DLAs in large galaxies

DLA Bias

- DLAs are an integral over a wide range of halo masses
- Non-linear effects occur at the non-linear scale for the most biased objects, not objects at the mean bias
- Non-linear growth is faster, so larger objects contribute more

DLA Bias

Non-linear effects boost DLA power spectrum



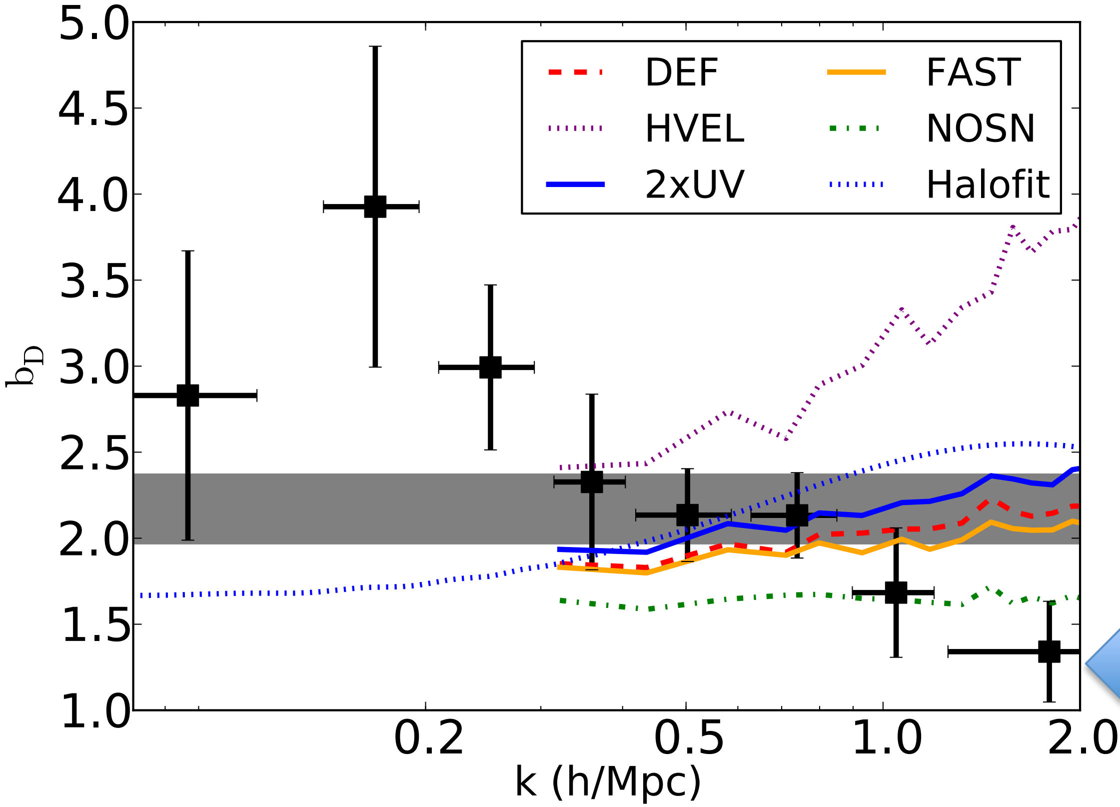
$$\frac{\mathcal{H}[b^2 P(k)]}{\mathcal{H}[P(k)]} > b^2$$

Data: Font-Ribera+2012

DLA Bias

Odd scale dependence

Non-linear growth faster, more power on small scales



Cross-correlation?

Power decrease

Data: Font-Ribera+2012

Conclusions

- People have asked whether DLAs are large milky-way discs (10^{12}) or small dwarfs (10^{10})
- They are both, but mostly in between (10^{11}).
- Can reproduce velocity width and DLA bias

Conclusions

- Reducing star forming gas works
- A model tuned to the stellar mass function makes a decent showing on DLAs.
- DLAs sensitive to mass of gas removed and return time – not details of outflows