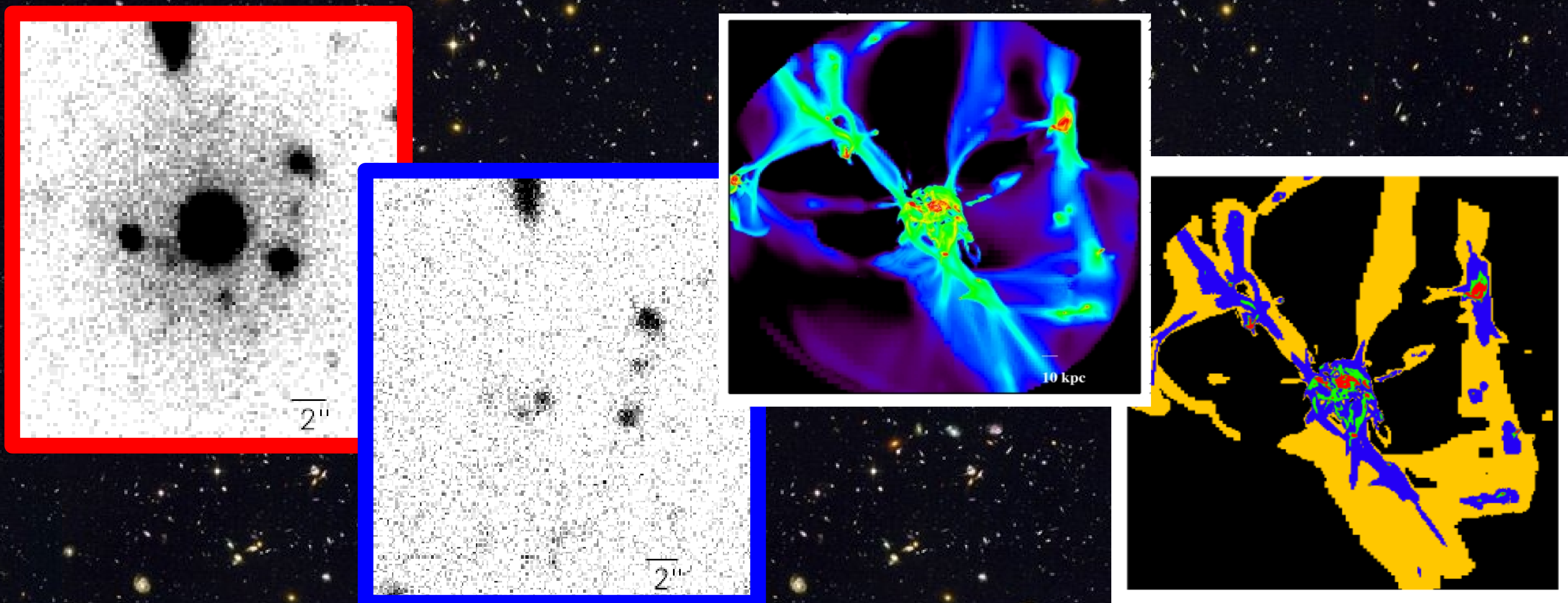
Gas in and around z > 2 galaxies



In collaboration with:

Xavier Prochaska
Daniel Ceverino
Daniel Kasen
Joel Primack
Avishai Dekel

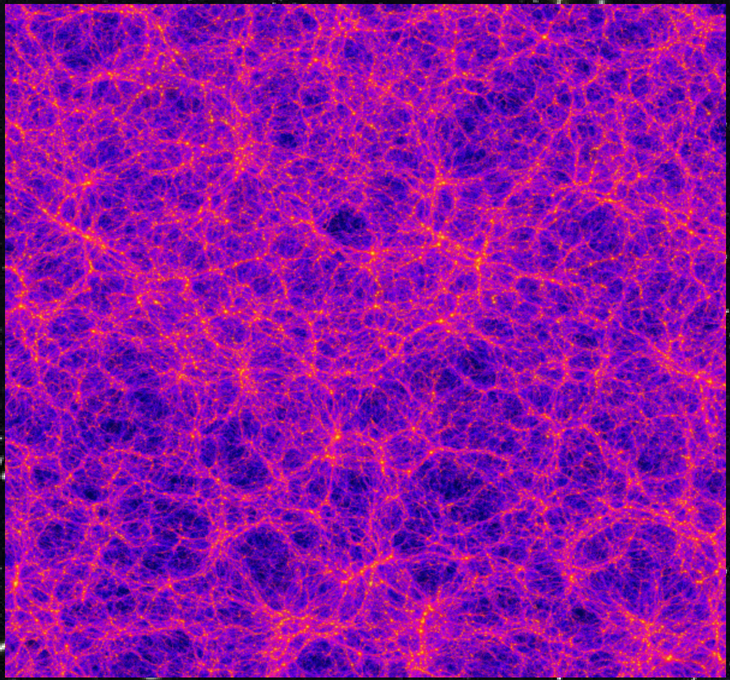
Michele Fumagalli

August 2010 – Santa Cruz

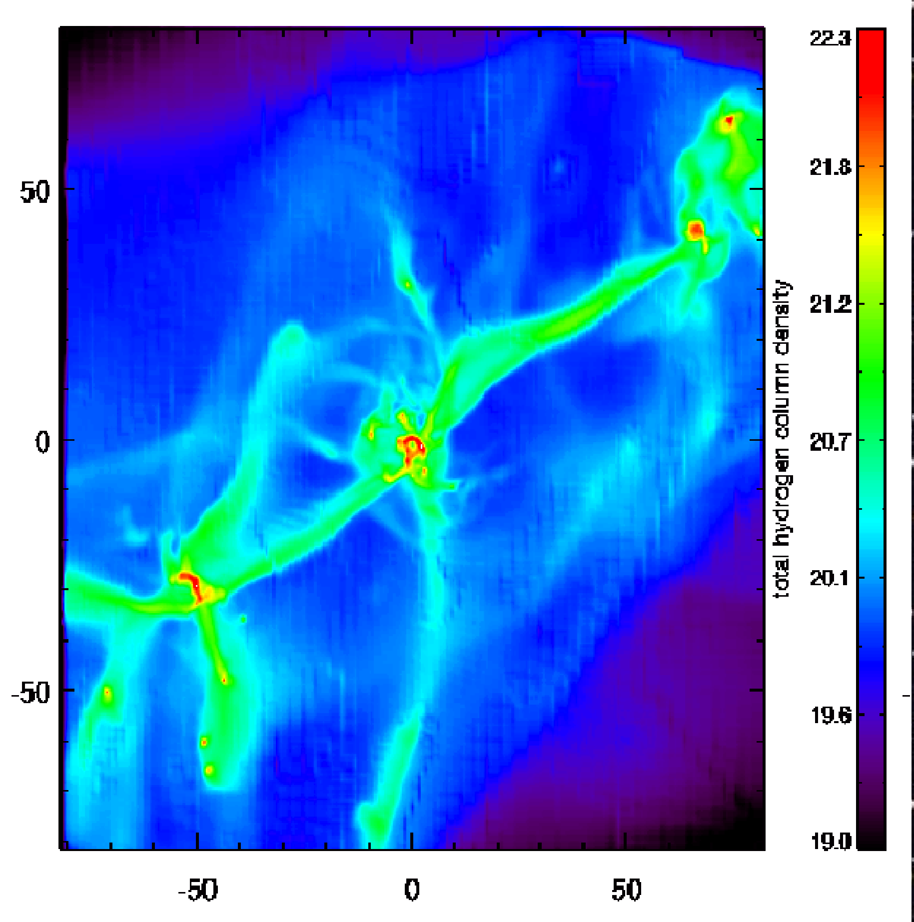
Gas in galaxies from theory

Gas is a fundamental component in galaxies, since ultimately feeds star formation and regulates galaxy evolution.

Simulations make specific predictions on how gas is accreted and distributed in galaxies



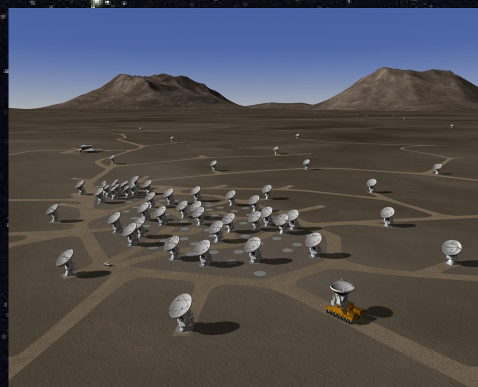
Simulation by Wadsley



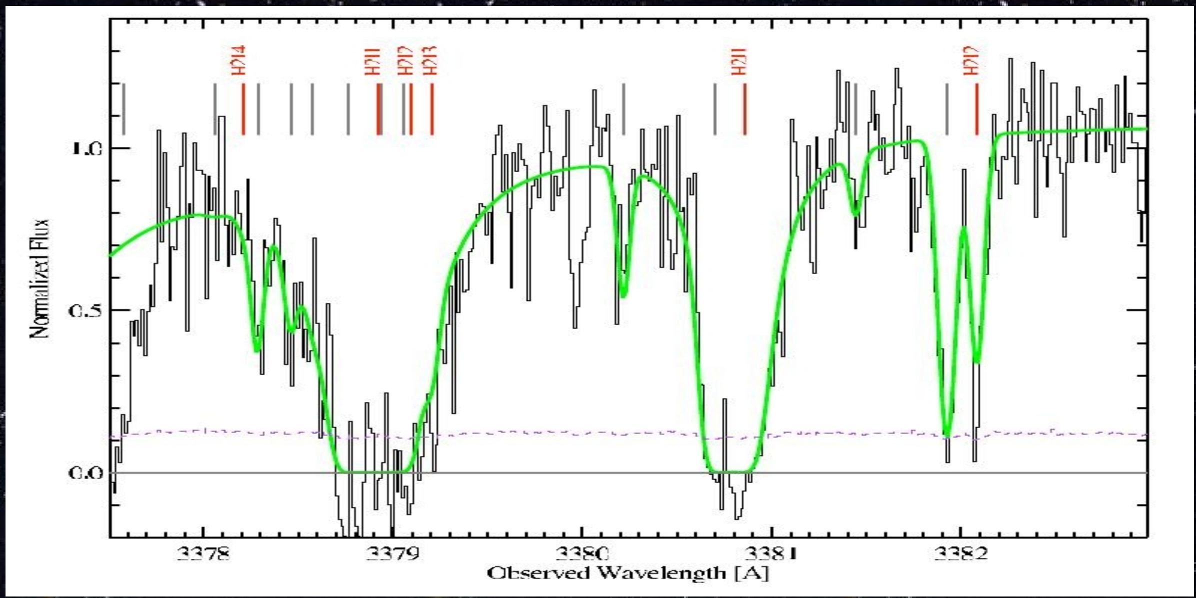
Ceverino+2009-2010

Some observational tests

HI and CO in emission

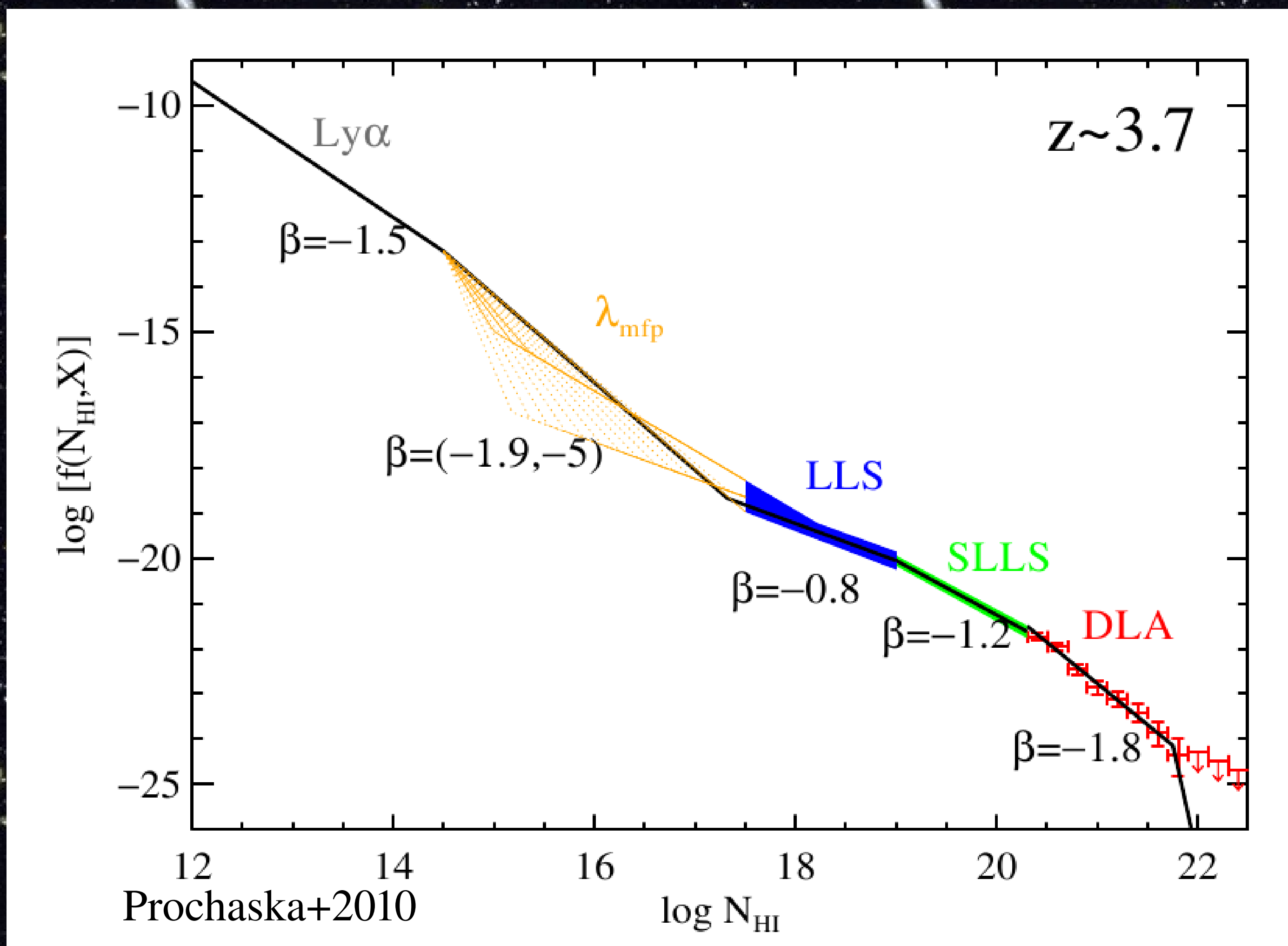


Kinematics, metals and hydrogen (HI and H_2) in absorption



DLA 0812+32B (z=2.6) – Jorgenson+2009

Focus on neutral gas

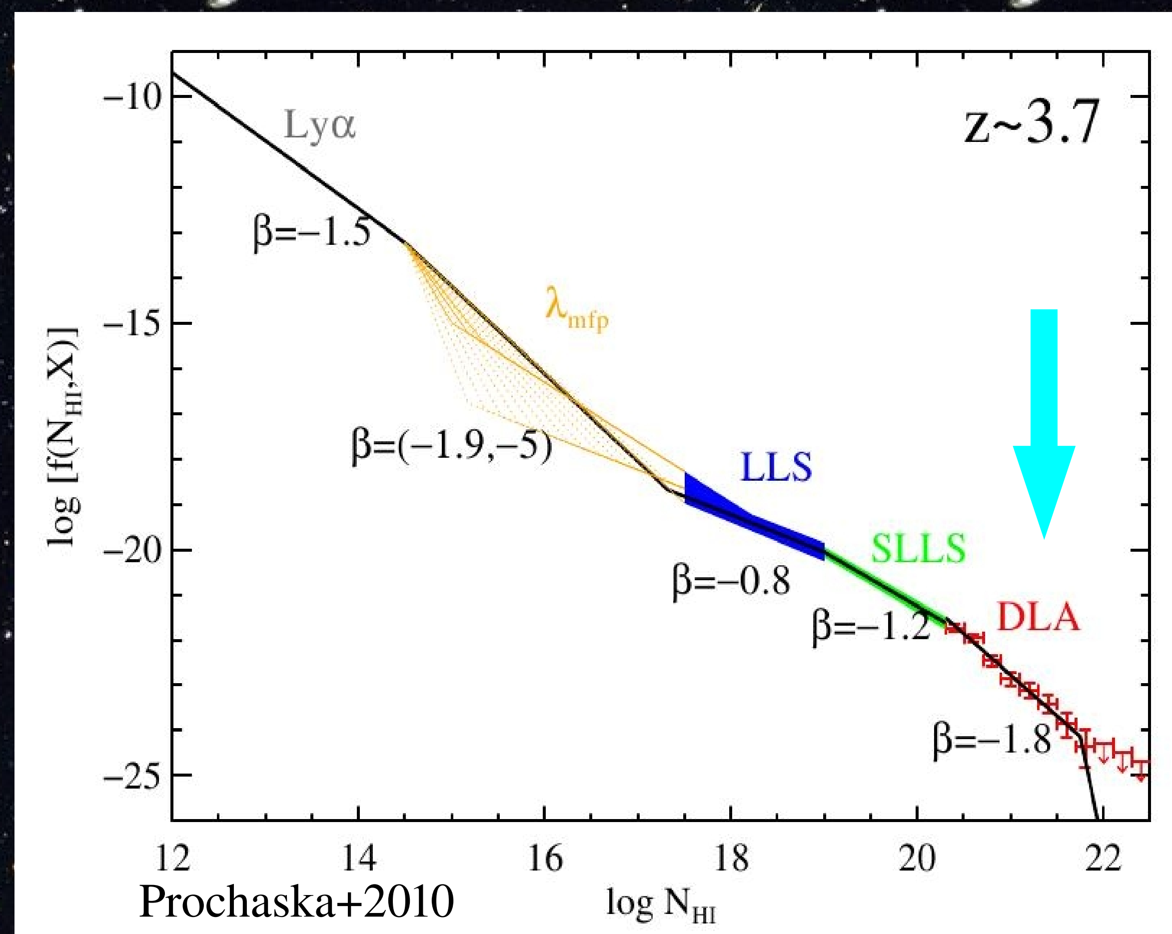


Focus on neutral gas

HI in absorption: different flavors of absorbers

Neutral hydrogen (DLAs):
$N_{HI} > 10^{20}$ cm^{-2}

Gas in overdensities
(galaxies and satellites)

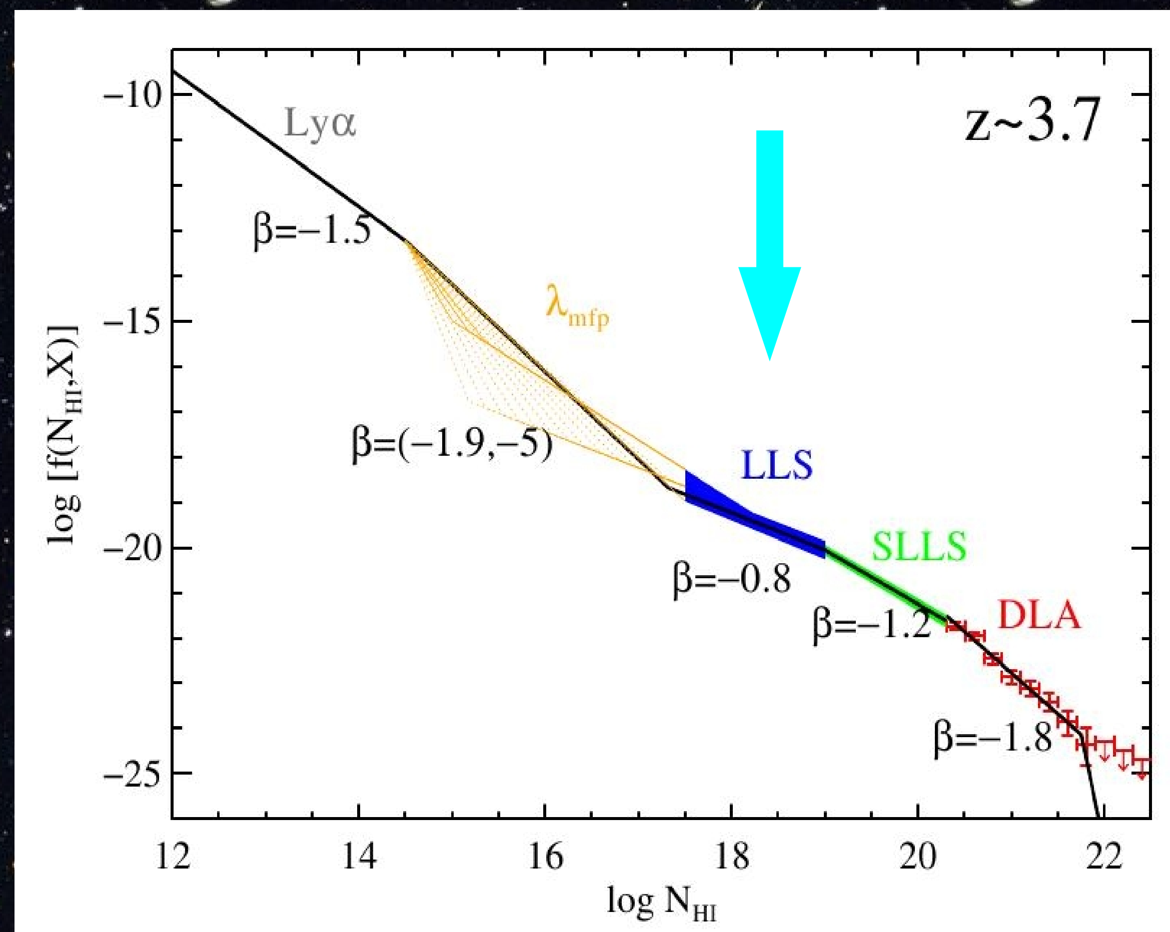


Focus on neutral gas

HI in absorption: different flavors of absorbers

Optically thick gas (LLSs/SLLSs): $N_{HI} > 10^{17}$ cm^{-2}

Ionized gas in and around galaxies(?)



Focus on neutral gas

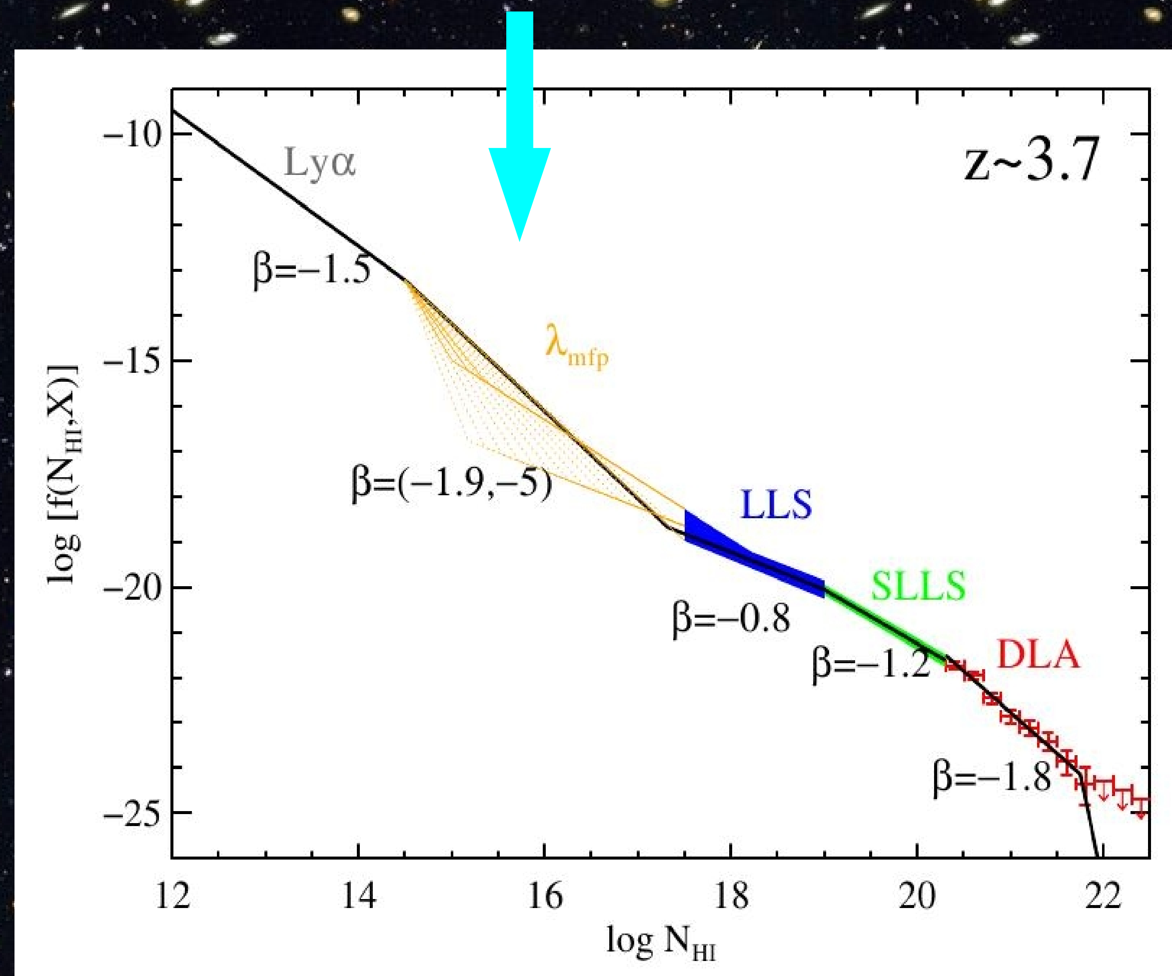
HI in absorption: different flavors of absorbers

Optically thin/thick transition:

$N_{HI} > 10^{15}$ cm^{-2}

An important contributor to the mean opacity

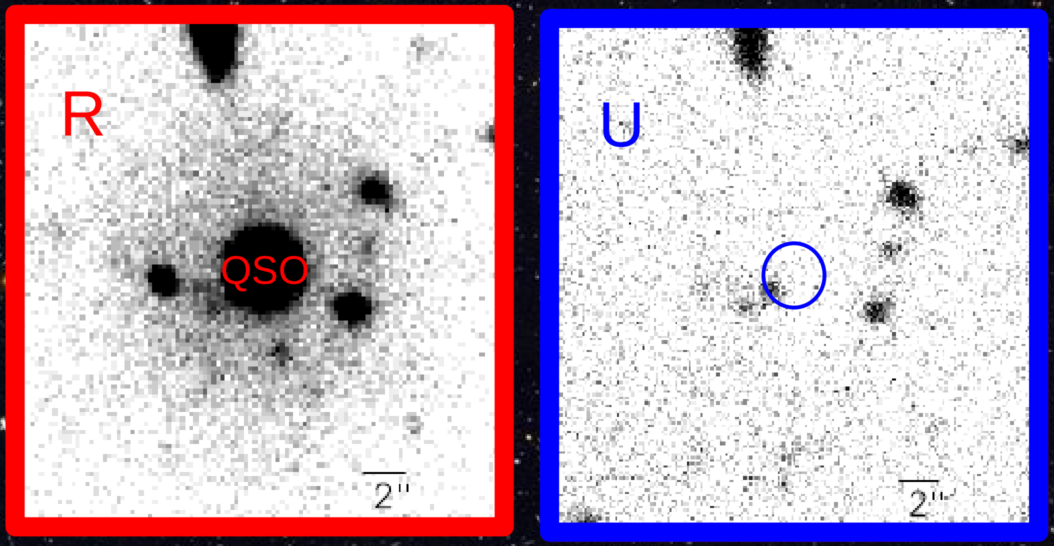
Need to reconnect these observations to the predictions from simulations!



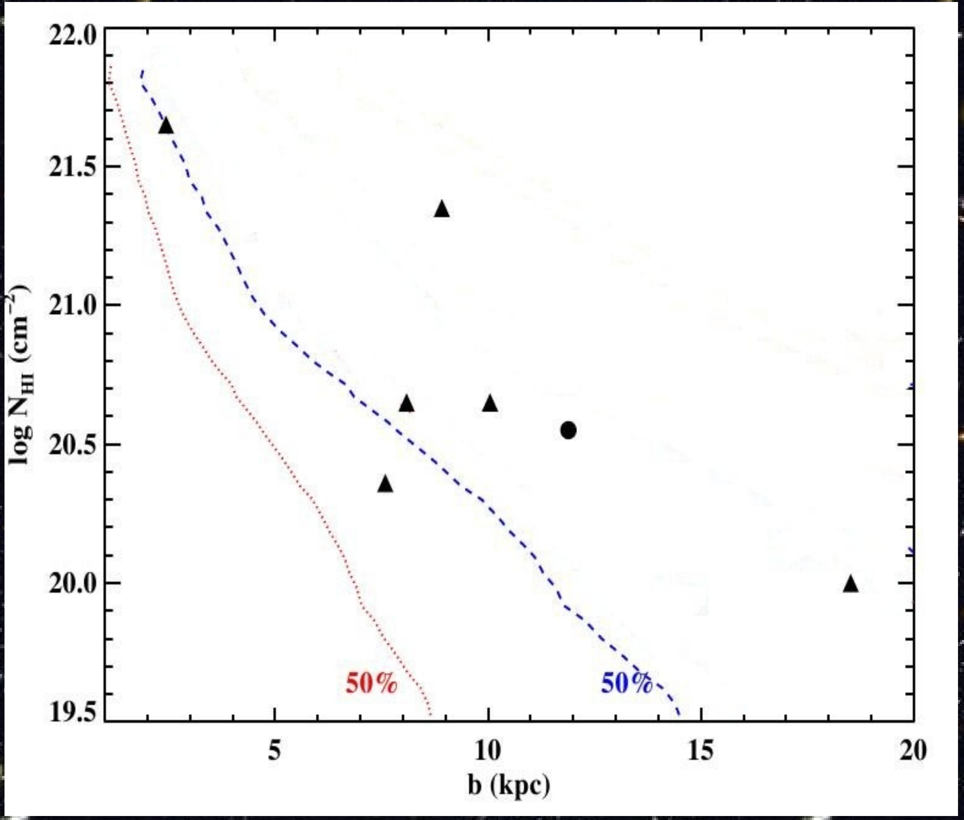
Imaging of HI selected galaxies

(MF, O'Meara, Prochaska, Kanekar, MNRAS, 2010)

J0731+2854



Probe the size of HI around z > 2 galaxies



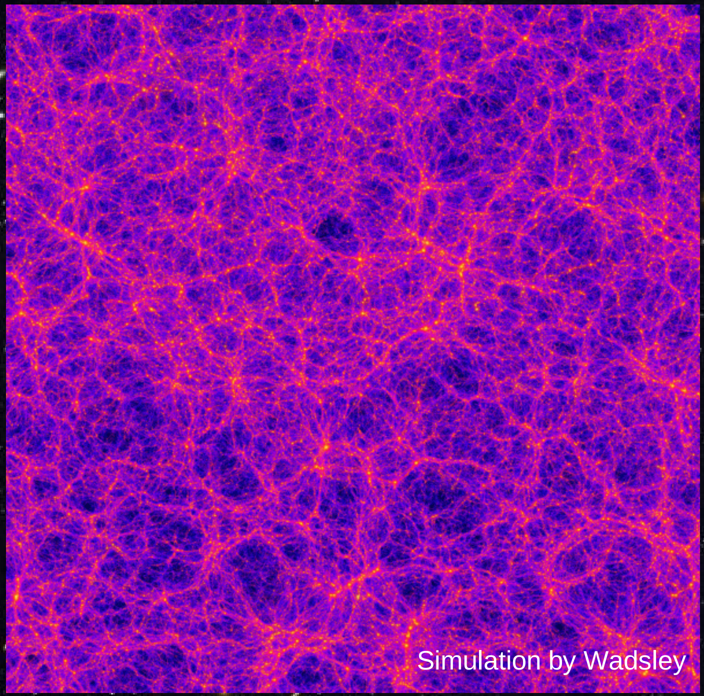
Survey of ~40 QSO fields using Keck and HST

Constrain the luminosity function of DLAs

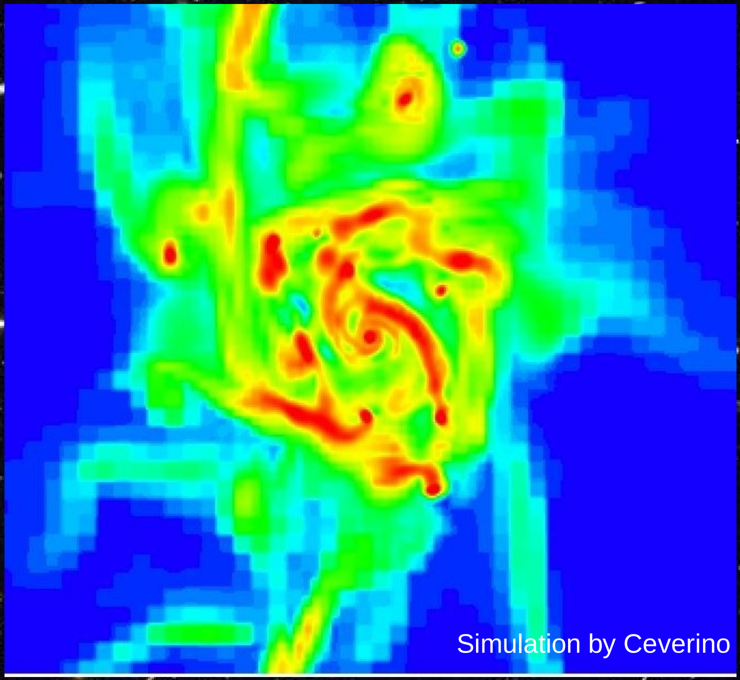
A sample of simulated galaxies

(Ceverino, Dekel, Bournaud, MNRAS, 2010)

Cosmological simulations provide statistics that can be compared with observations from large surveys



Simulations of individual galaxies provide high resolution (~60 pc) where the relevant ISM physics probed in absorption can be explored



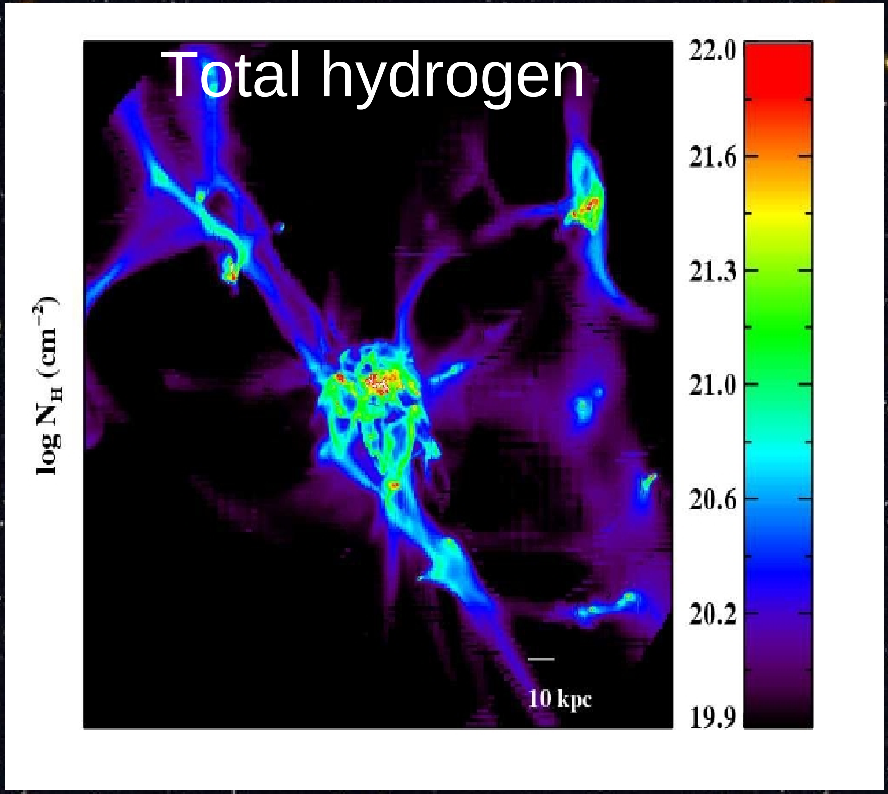
Assemble a sample of individual galaxies (7 galaxies). Reproduce statistical observations from high resolution simulations.

Halos of $M = 10^{11}\ M_{sun} - 10^{12}\ M_{sun}$ at z=2. Redshift range z = 4 to z=1.5

Neutral gas fraction

Accurate predictions of neutral fraction are important to compare against observations

Monte Carlo radiative transfer code (Kasen et al, in prep.) which includes collisions, UVB, dust and ionizing radiation from local sources



Halo 3.7×10^{11} M_{sun} at z=2.3

→ Neutral hydrogen

Neutral gas fraction

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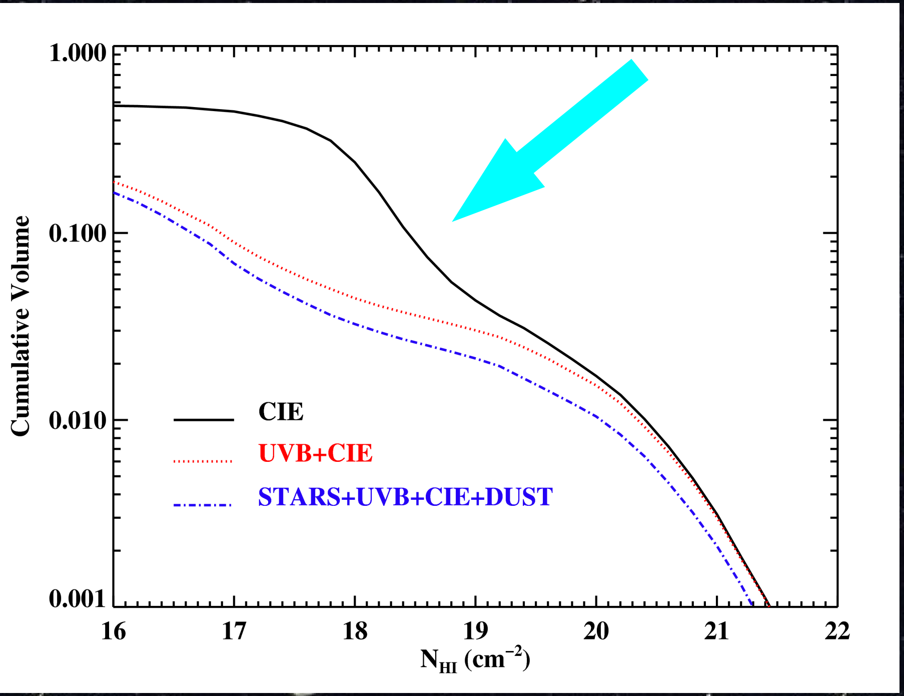
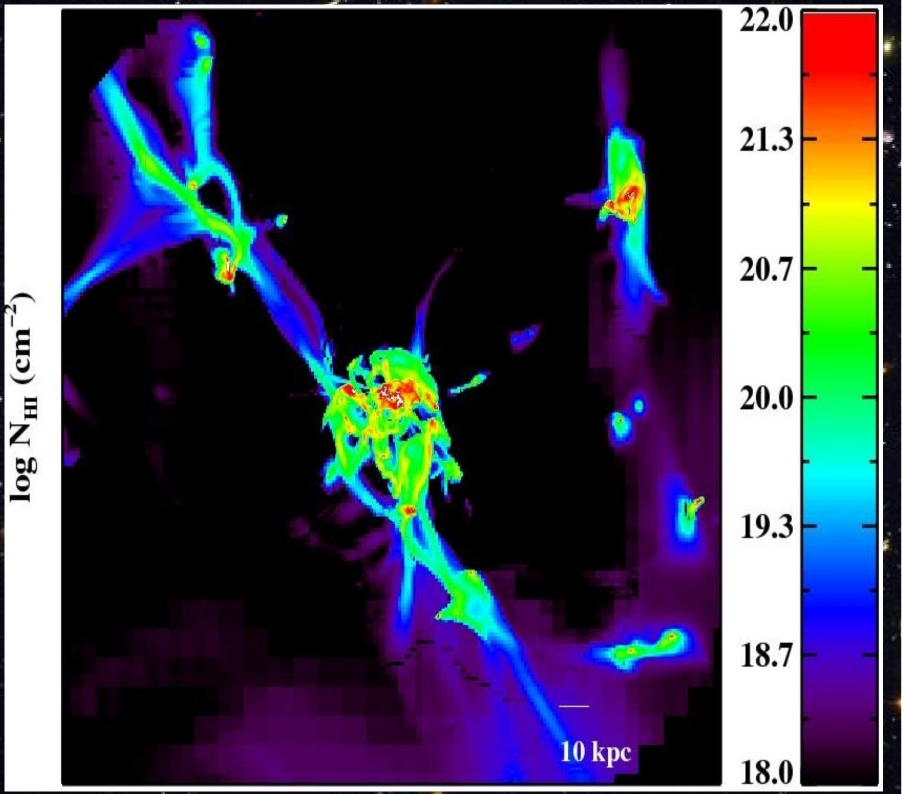


OK above 10^{19} cm^{-2}

CIE



Halo 3.7×10^{11} M_{sun} at z=2.3

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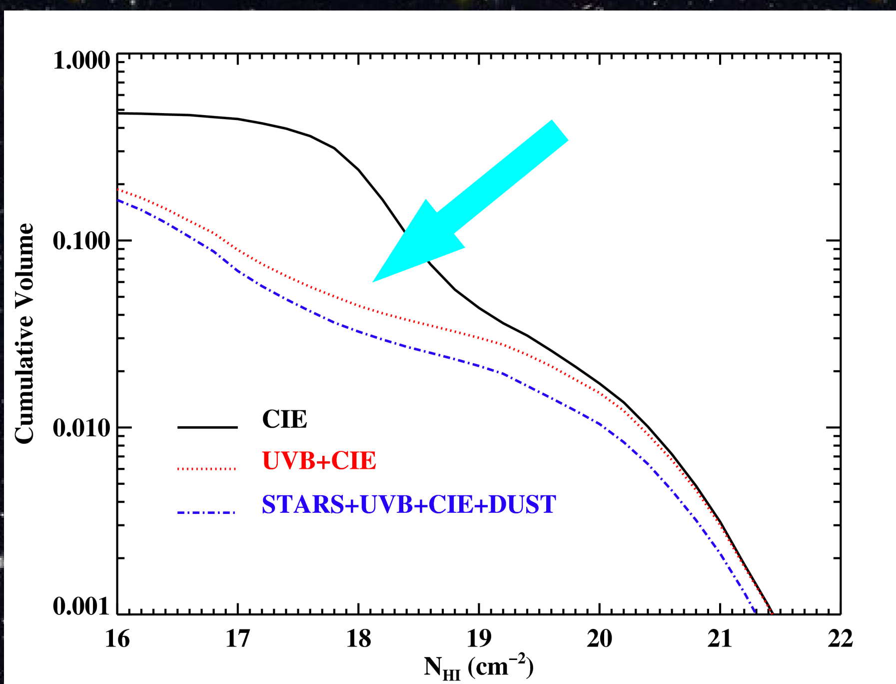
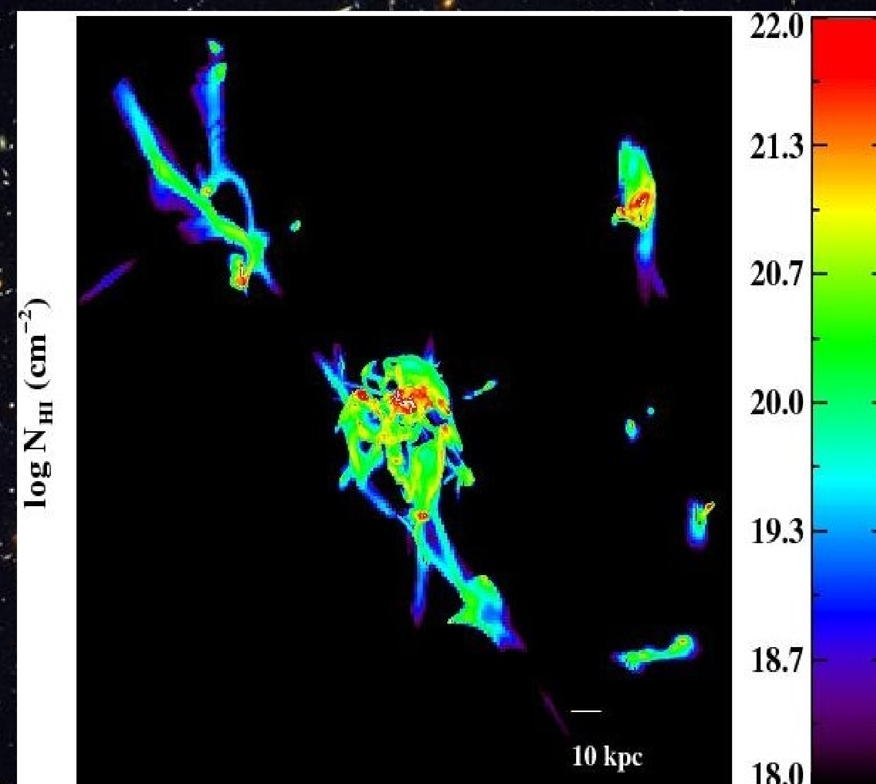


UVB

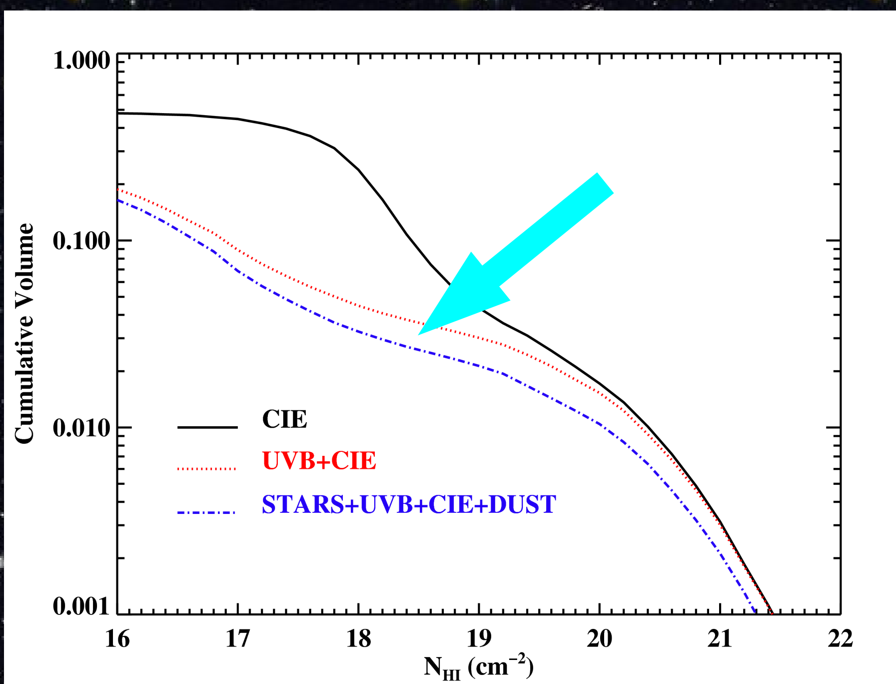


Halo 3.7×10^{11} M_{sun} at $z=2.3$

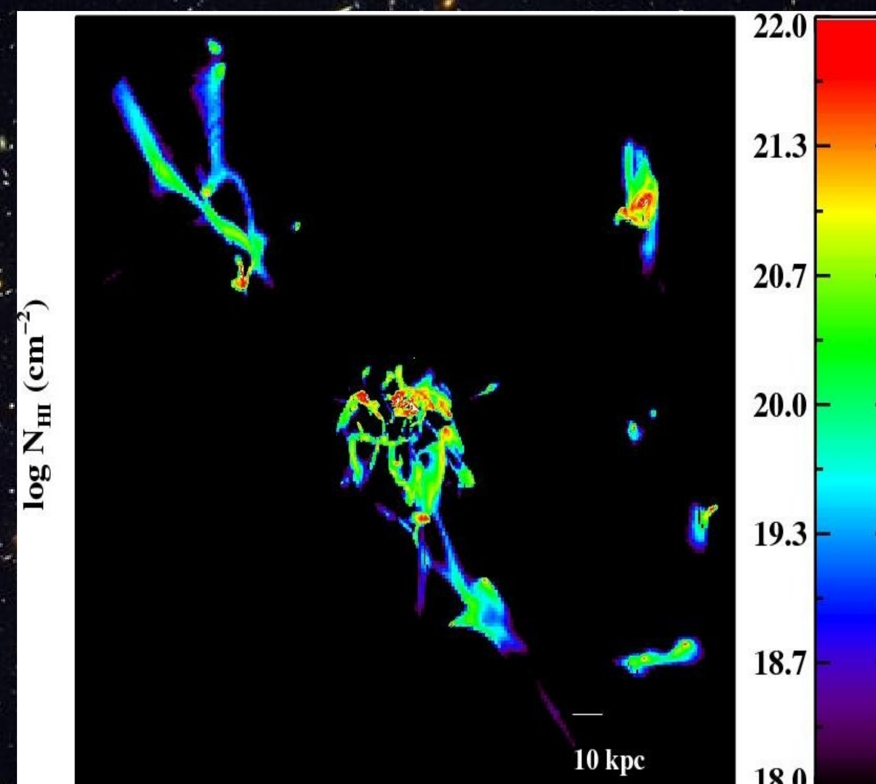
Neutral gas fraction

Accurate predictions of neutral fraction are important to compare against observations

Monte Carlo radiative transfer code (Kasen et al, in prep.) which includes collisions, UVB, dust and ionizing radiation from local sources



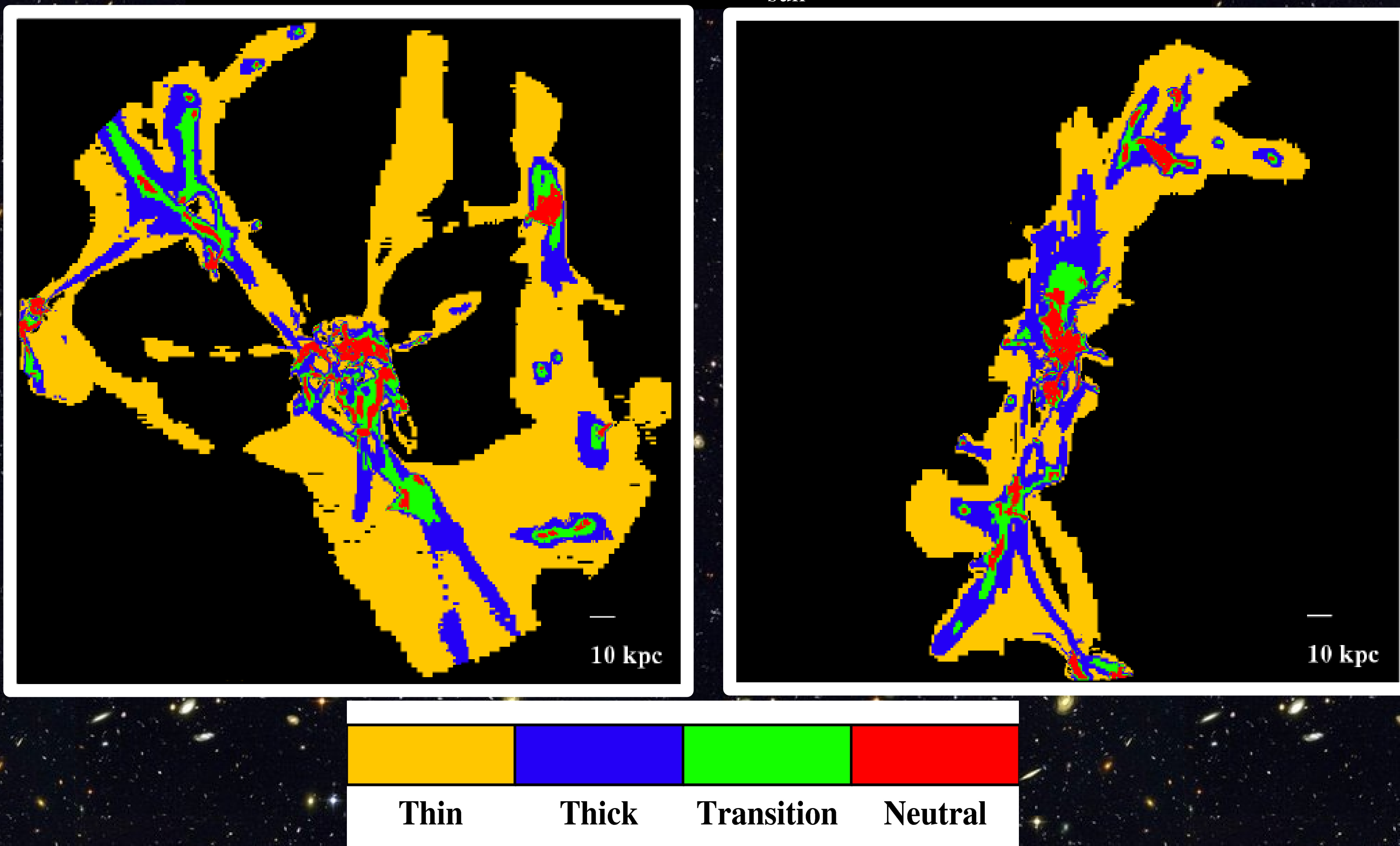
FULL



Halo 3.7×10^{11} M_{sun} at z=2.3

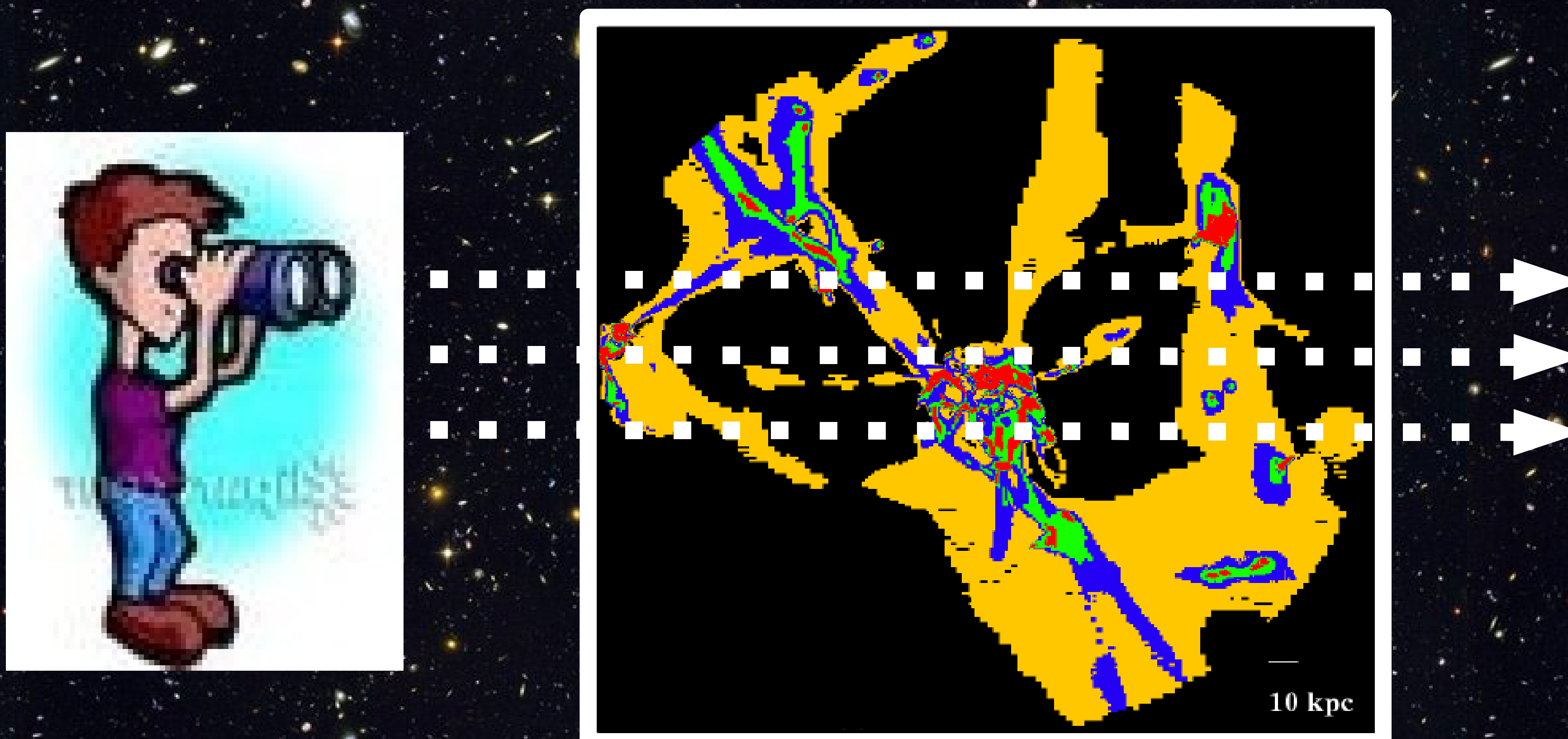
Where is the optically thick gas?

A test with a 3.7×10^{11} M_{sun} galaxy at z=2.3

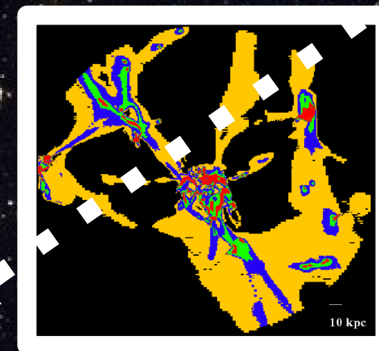


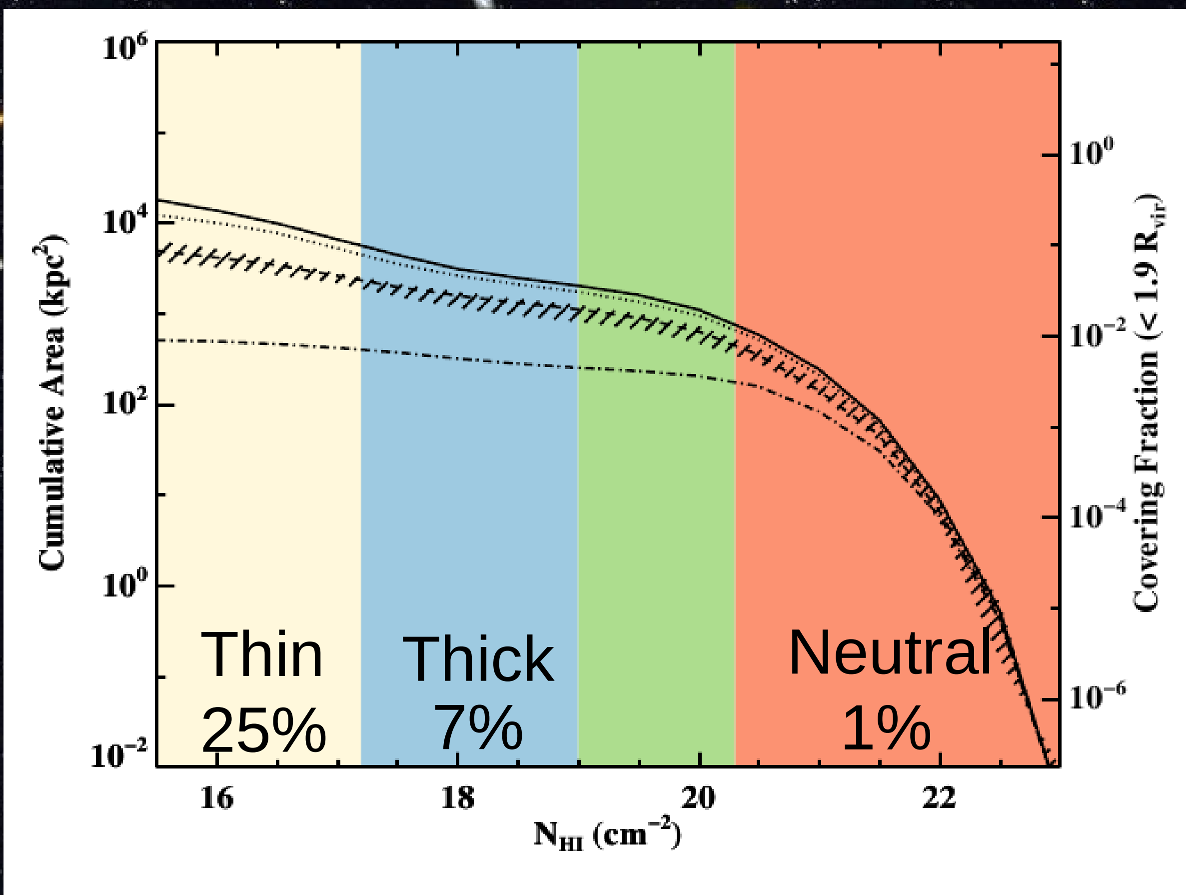
Where is the optically thick gas?

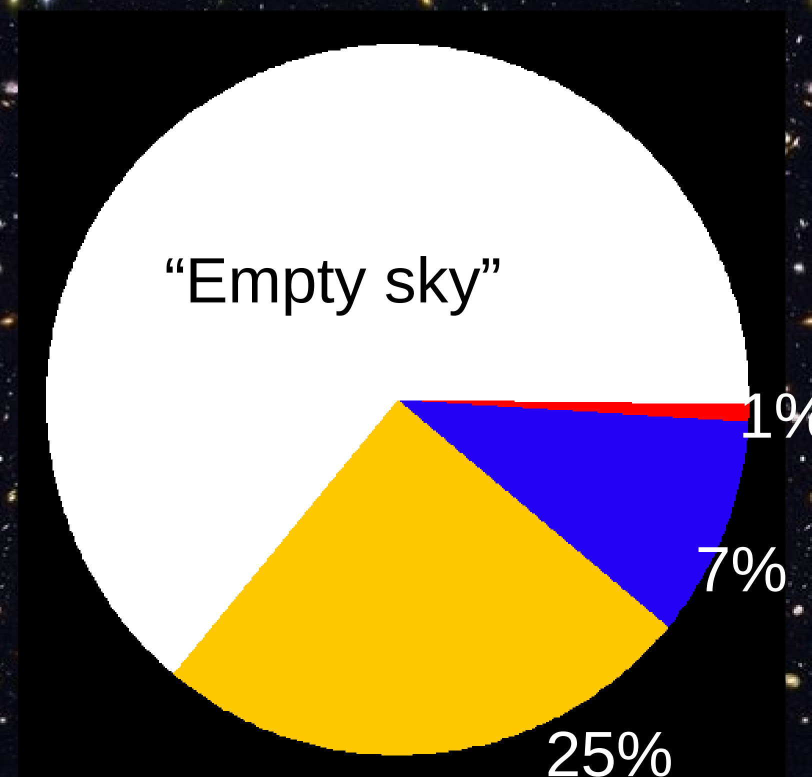
Looking through the galaxy: what is the probability to intersect optically thick gas?



Looking through the galaxy: what is the probability to intersect optically thick gas?







The incidence of absorbers

How does this covering fraction compare with observations?

A back of the envelope calculation

Some extrapolations!

$$P(X) \propto n A s$$

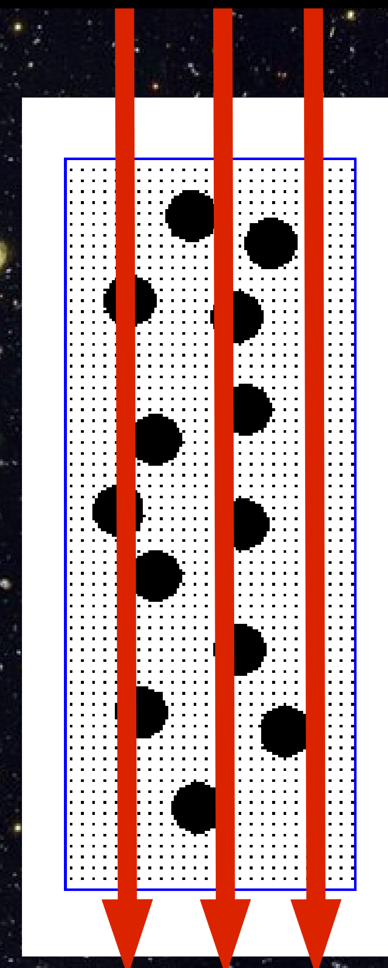
$$l(z) \propto n_{co} A_{co} f_{als} \frac{ds}{dz}$$

$$n_{co}(4 \times 10^{11} M_{sun}) \sim 8 \times 10^{-4} Mpc^{-3}$$

$$\frac{ds}{dz} \sim 1300\, Mpc \wedge A_{co} \sim 0.6\, Mpc^{2}$$

$$l_{dla}(z) \sim 0.007 \sim 0.04\, observed$$

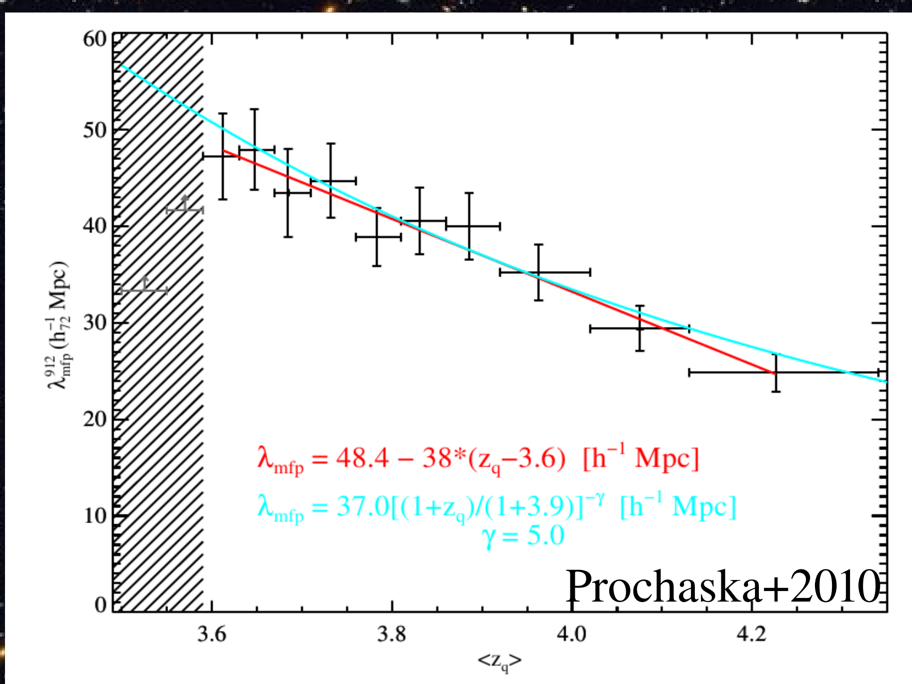
$$l_{lls}(z) \sim 0.05 \sim 0.15\, observed$$



The optical depth in the universe

An important source of opacity to Lyman limit continuum radiation is gas at the transition optically thin/thick

This is a fundamental quantity in the EUVB calculation



$$\lambda_{mfp} \sim 250\, h_{72}^{-1}\, Mpc\ @\ z \sim 2.3$$

$$\lambda_{mfp}^{-1} \propto n_{co}\, A_{eff}$$

$$n_{co}(4\times10^{11}\, M_{sun}) \sim 8\times10^{-4}\, Mpc^{-3}$$

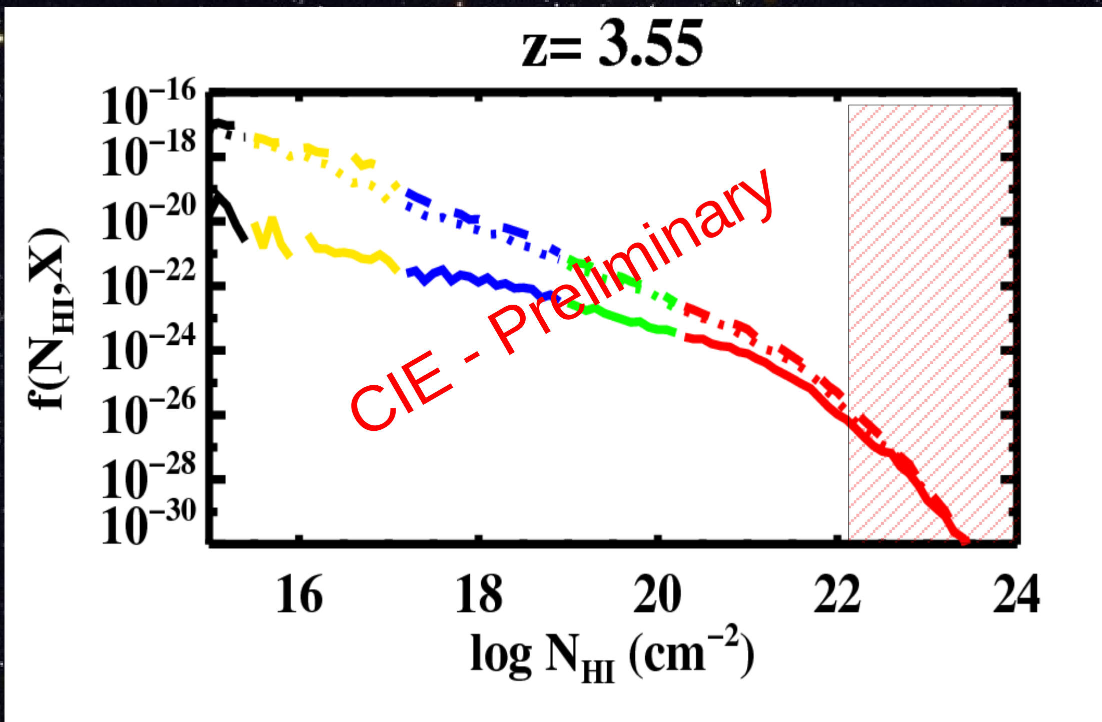
$$f_{als} \sim 0.25 - A_{eff} \sim 0.06\, Mpc^{2}$$

$$\lambda_{mfp}^{sim} \sim 6000\, h_{72}^{-1}\, Mpc$$

$$\frac{\kappa_{sim}}{\kappa_{obs}} \sim 0.04$$

Some extrapolations!

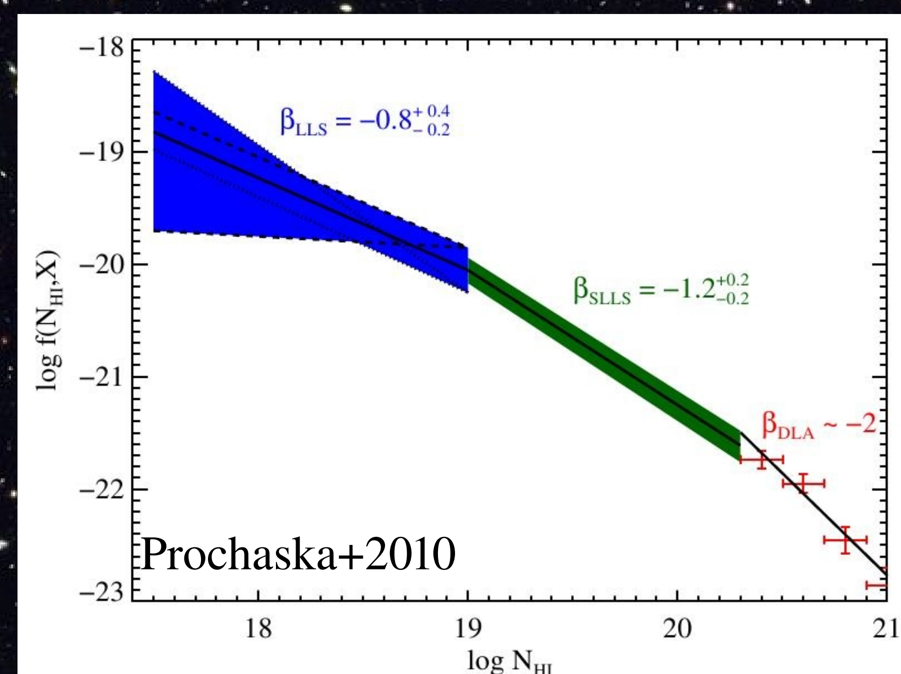
What's next?



Can we find galaxy/cold flows signatures in the f(N,X)?

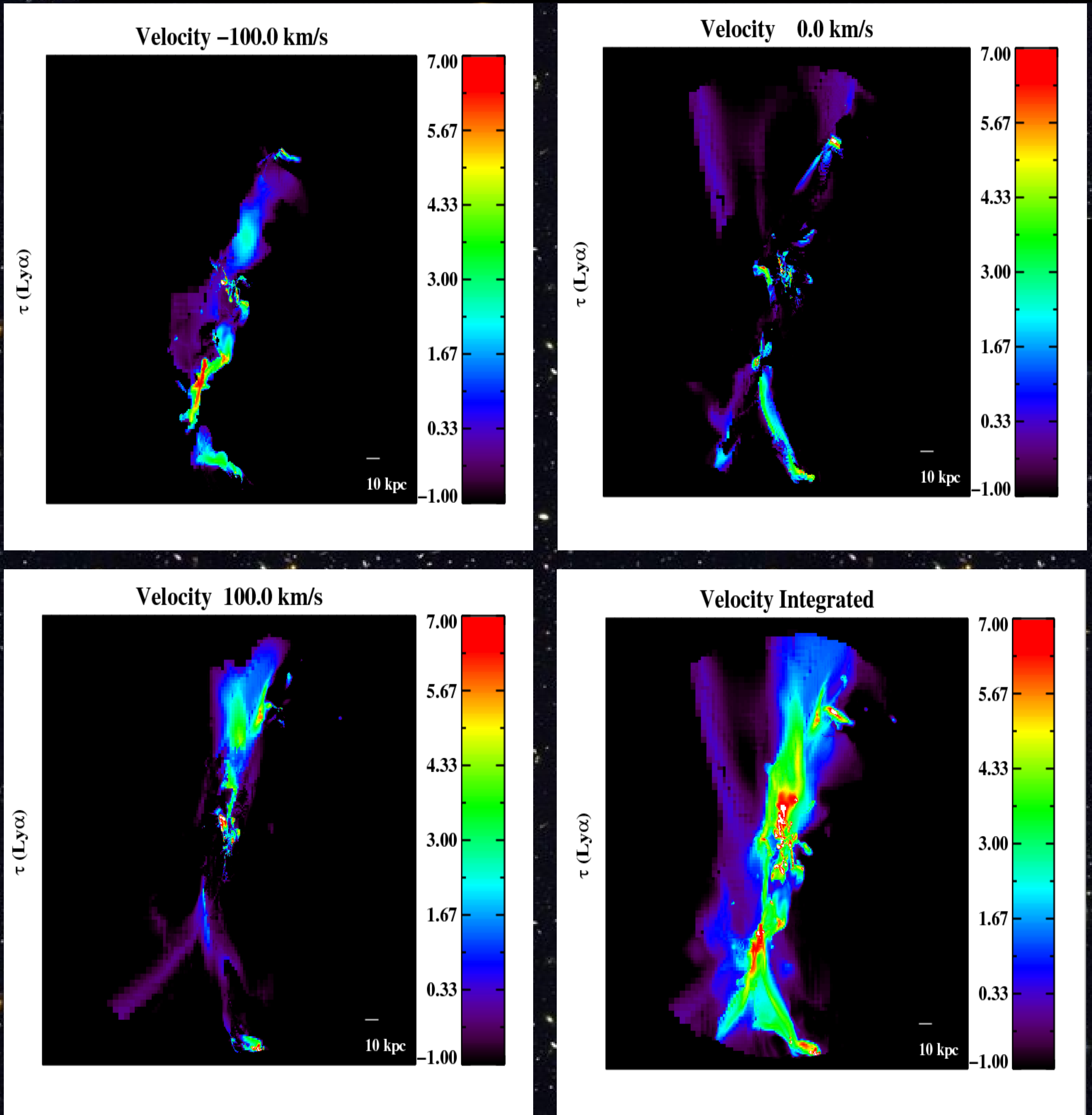
Simulated

Observed



Learn about HI rich galaxies (DLAs) and also some ionized gas in cold flows (LLSs)

What's next?



A look at kinematics: are inflows visible?

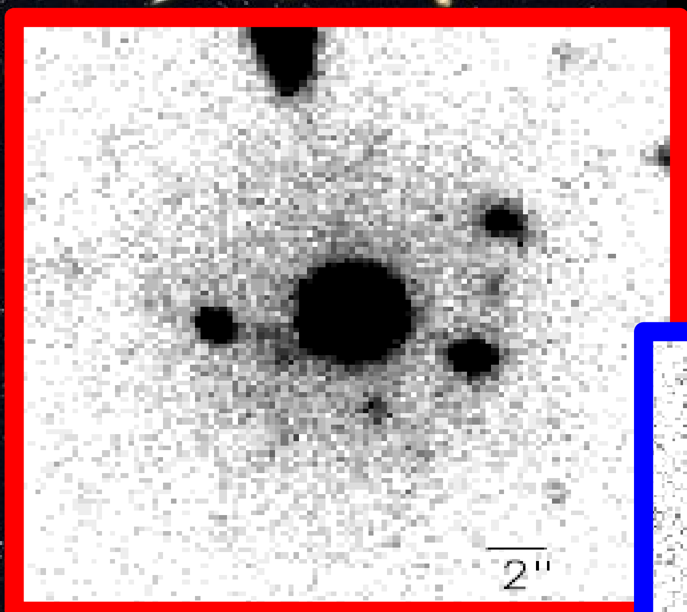
Study Ly α optical depth in velocity space

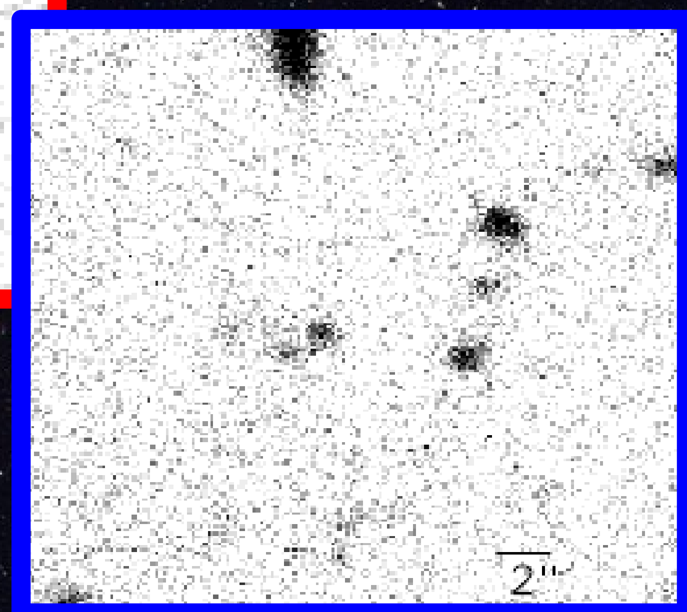
Conclusions

Imaging of HI rich galaxies at z > 2

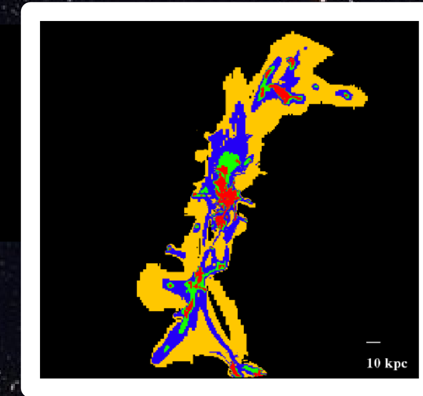
An ongoing program to characterize emission properties and gas extension of galaxies detected in absorption

(MF, O'Meara, Prochaska, Kanekar, 2010, MNRAS)





Conclusions

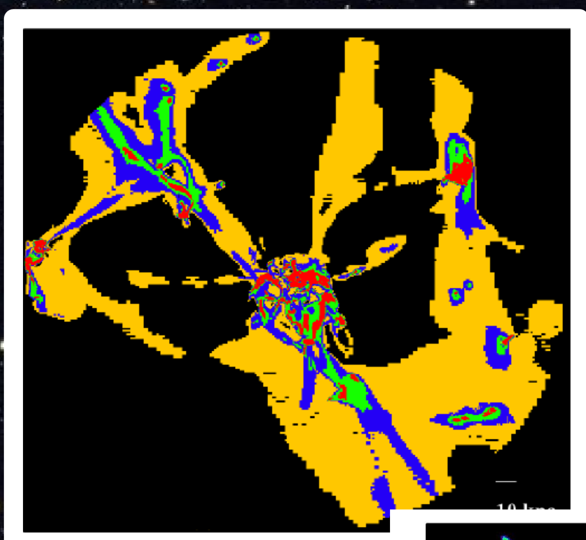


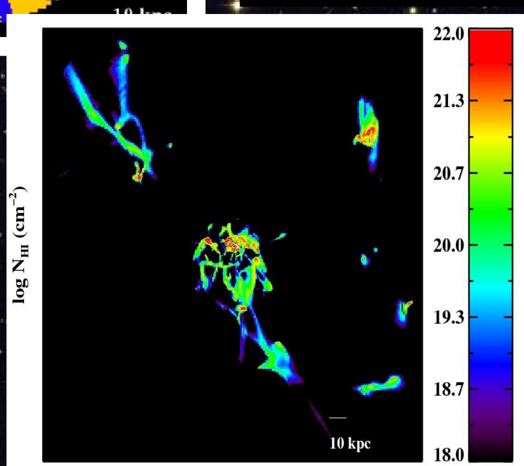
Neutral gas in galaxies from $> 10^{11}\ M_{sun}$ halos at $z \sim 2$ with proper radiative transfer

A small fraction of the sky is covered by optically thick gas (~7%)

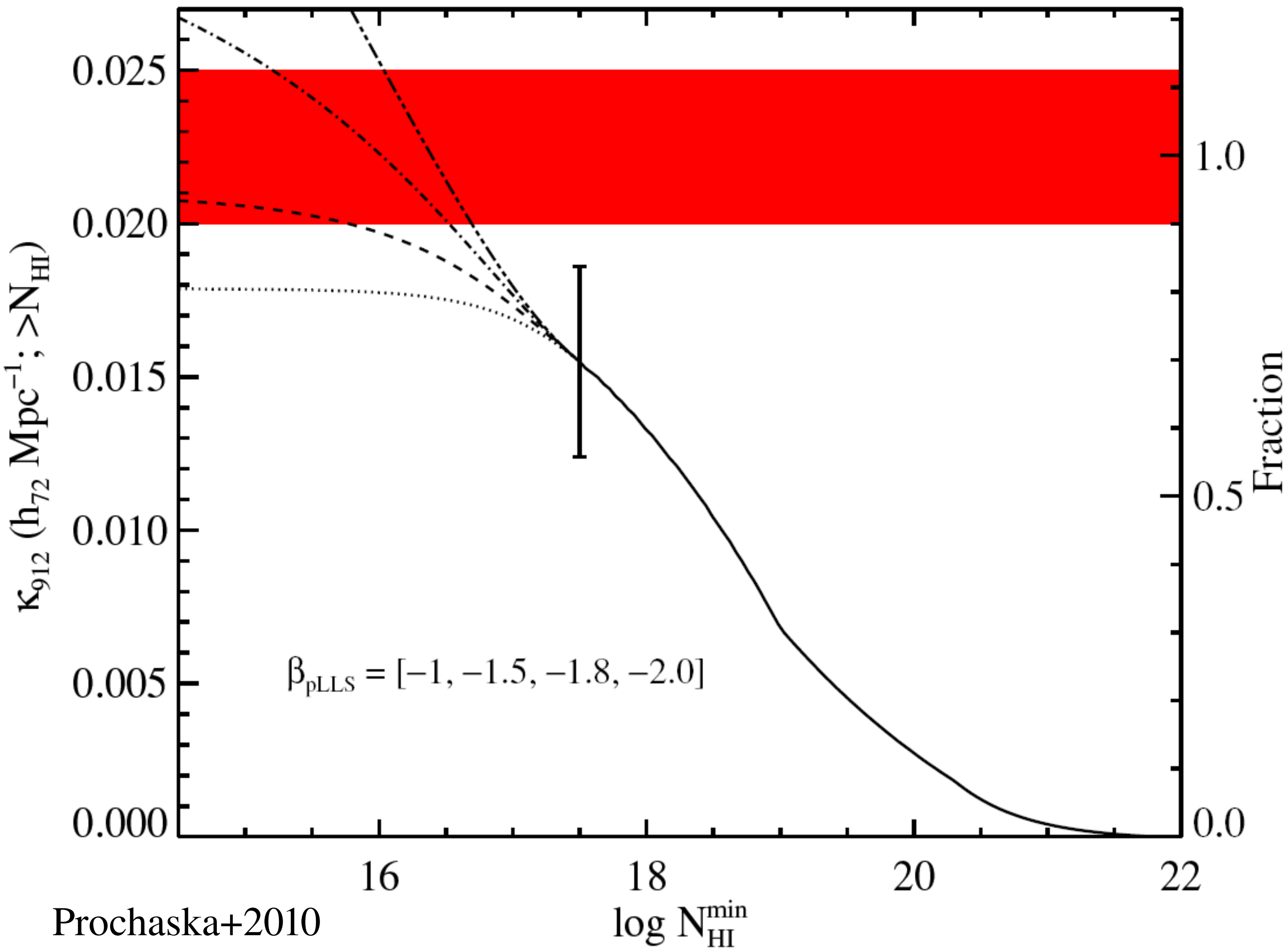
¼ of the sky is covered by gas that contributes little to the mean opacity of the Universe.

Most of neutral gas is in smaller halos and 15% of LLSs can be in "stream-fed" galaxies.

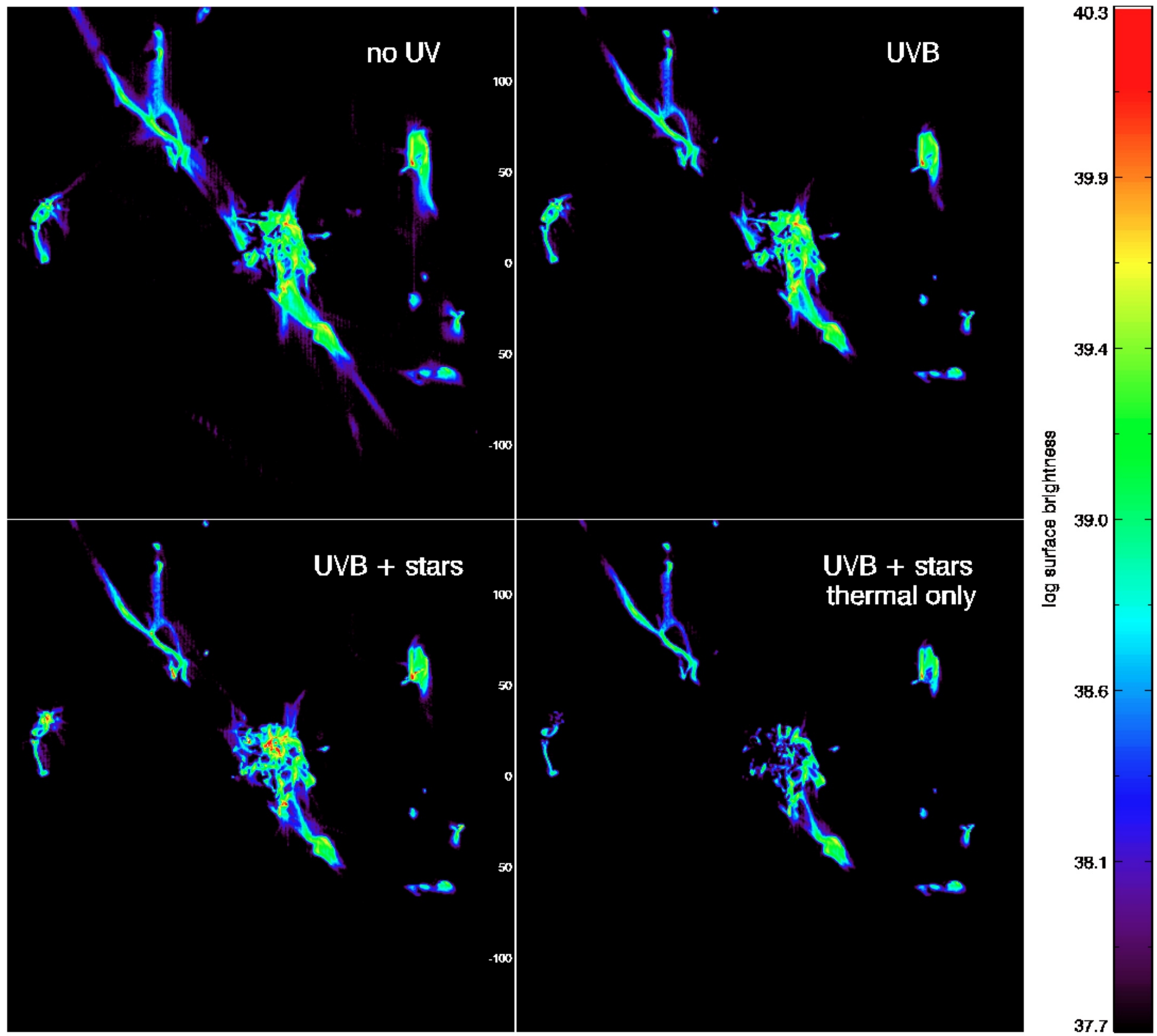




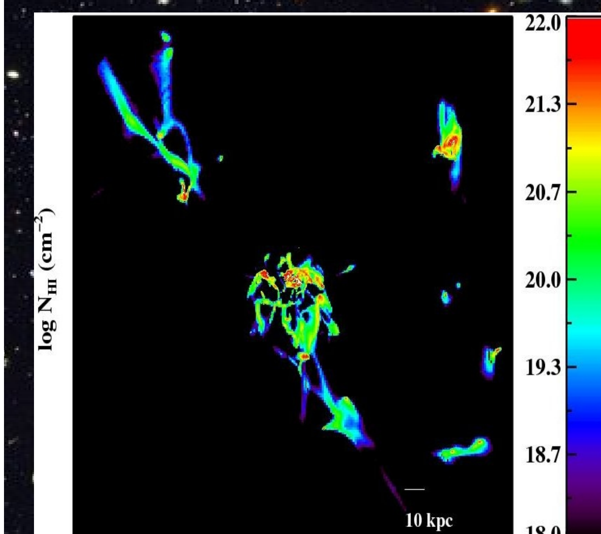
More on kinematics and redshift evolution coming soon!



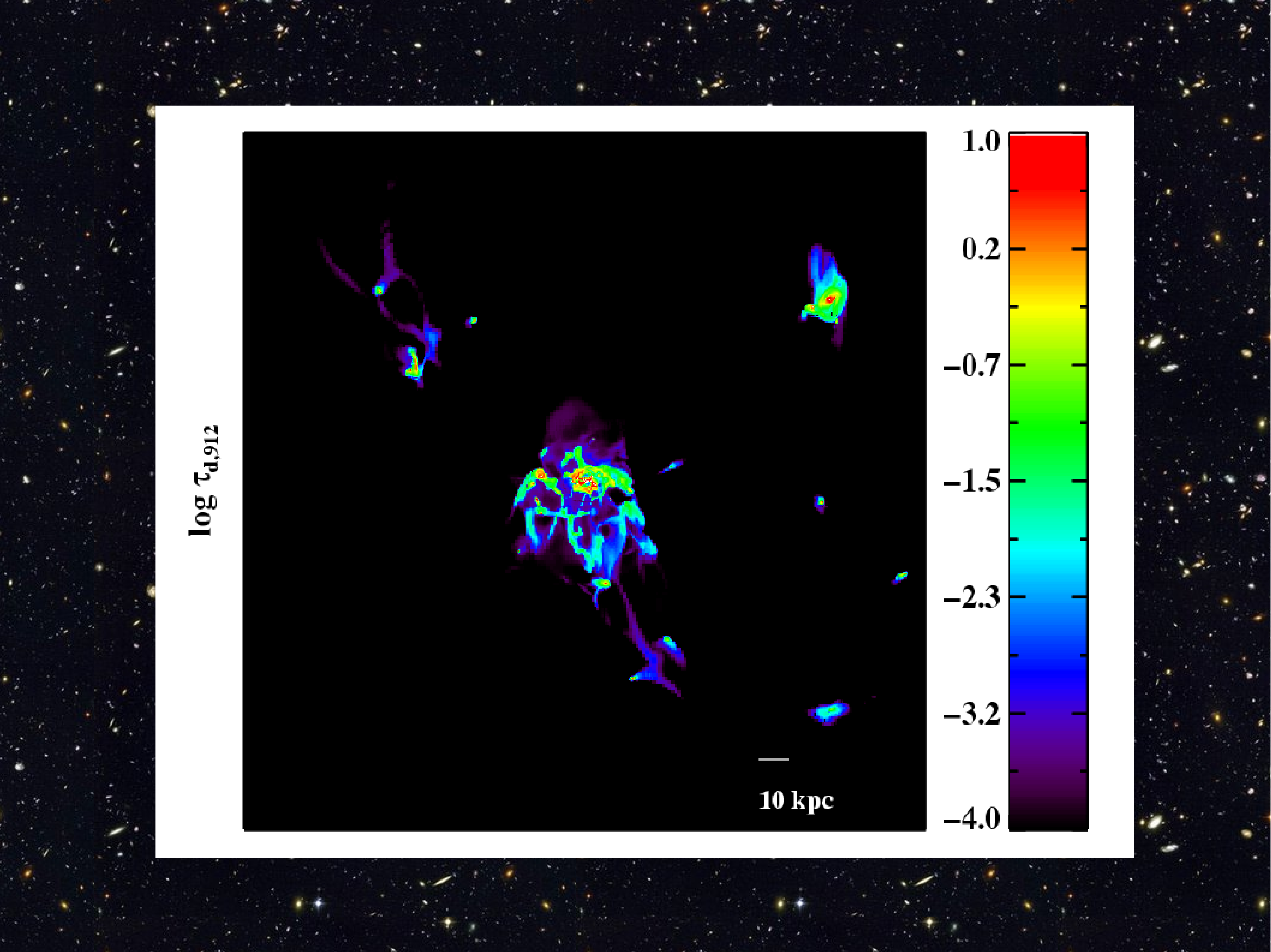
Prochaska+2010



no UV
UVB
UVB + stars
UVB + stars
thermal only
100
50
0
50
-100
log surface brightness
40.3
39.9
39.4
39.0
38.6
38.1
37.7



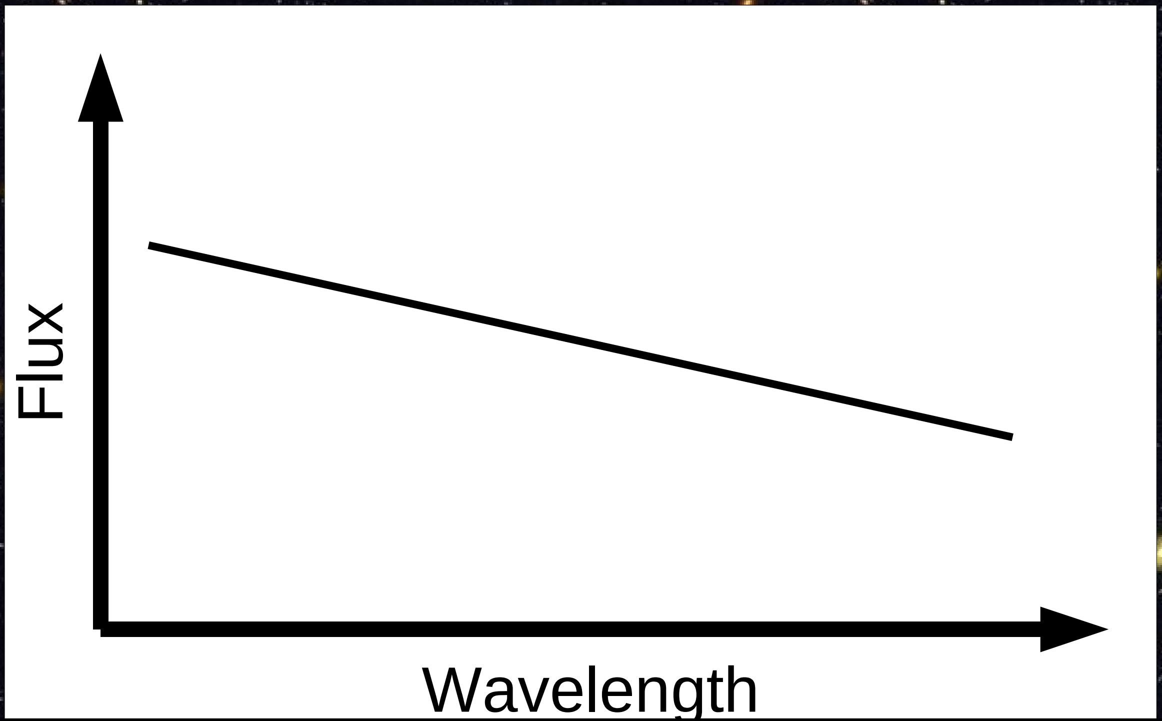
log N_{HI} (cm^{-2})
10 kpc
22.0
21.3
20.7
20.0
19.3
18.7
18.0



log $\tau_{d,912}$
1.0
0.2
−0.7
−1.5
−2.3
−3.2
−4.0
10 kpc

Our strategy...

We use a Lyman limit drop out technique, similar to the one adopted for LBGs, but to avoid the QSO light (O'Meara+2006)



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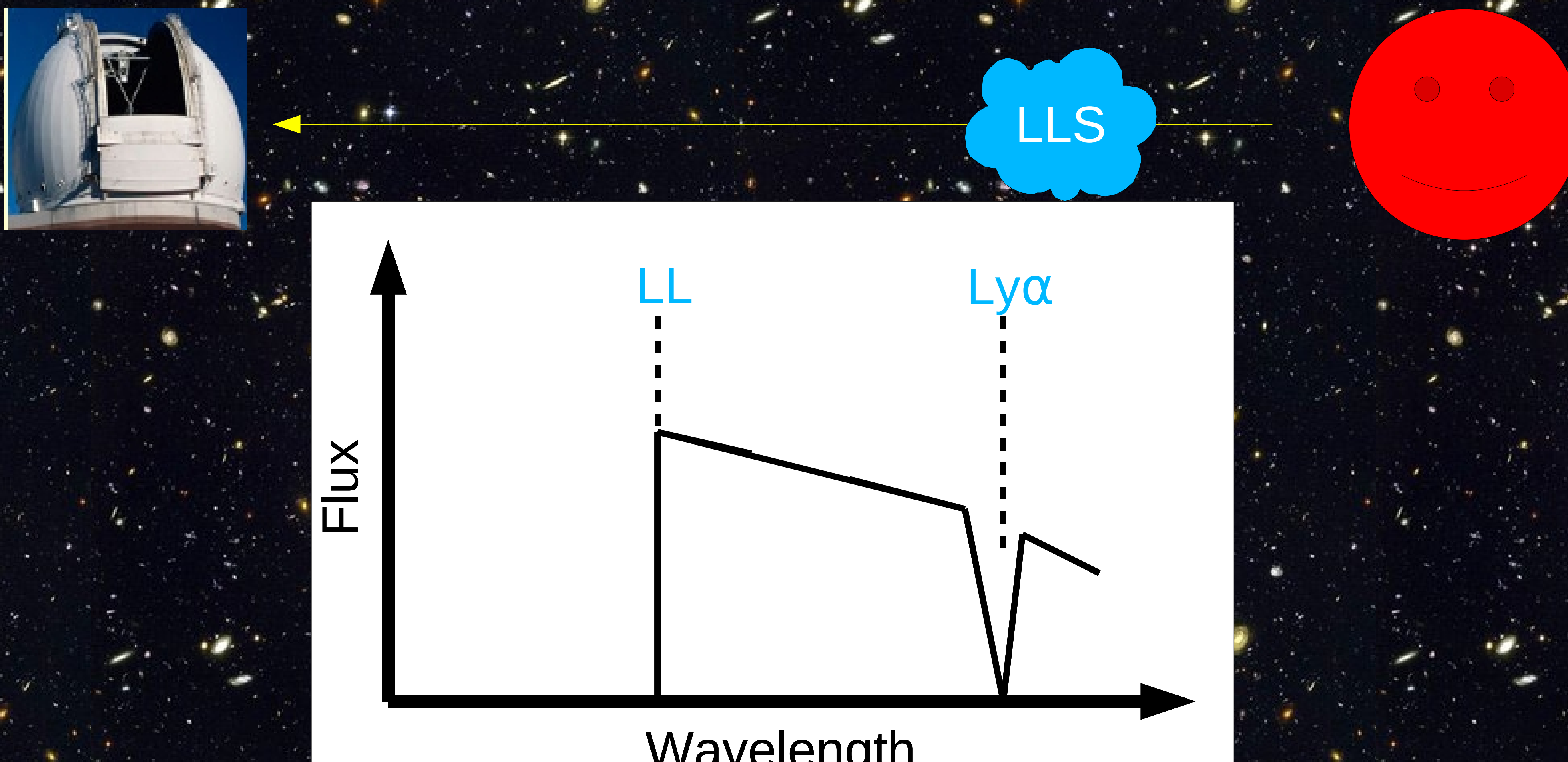

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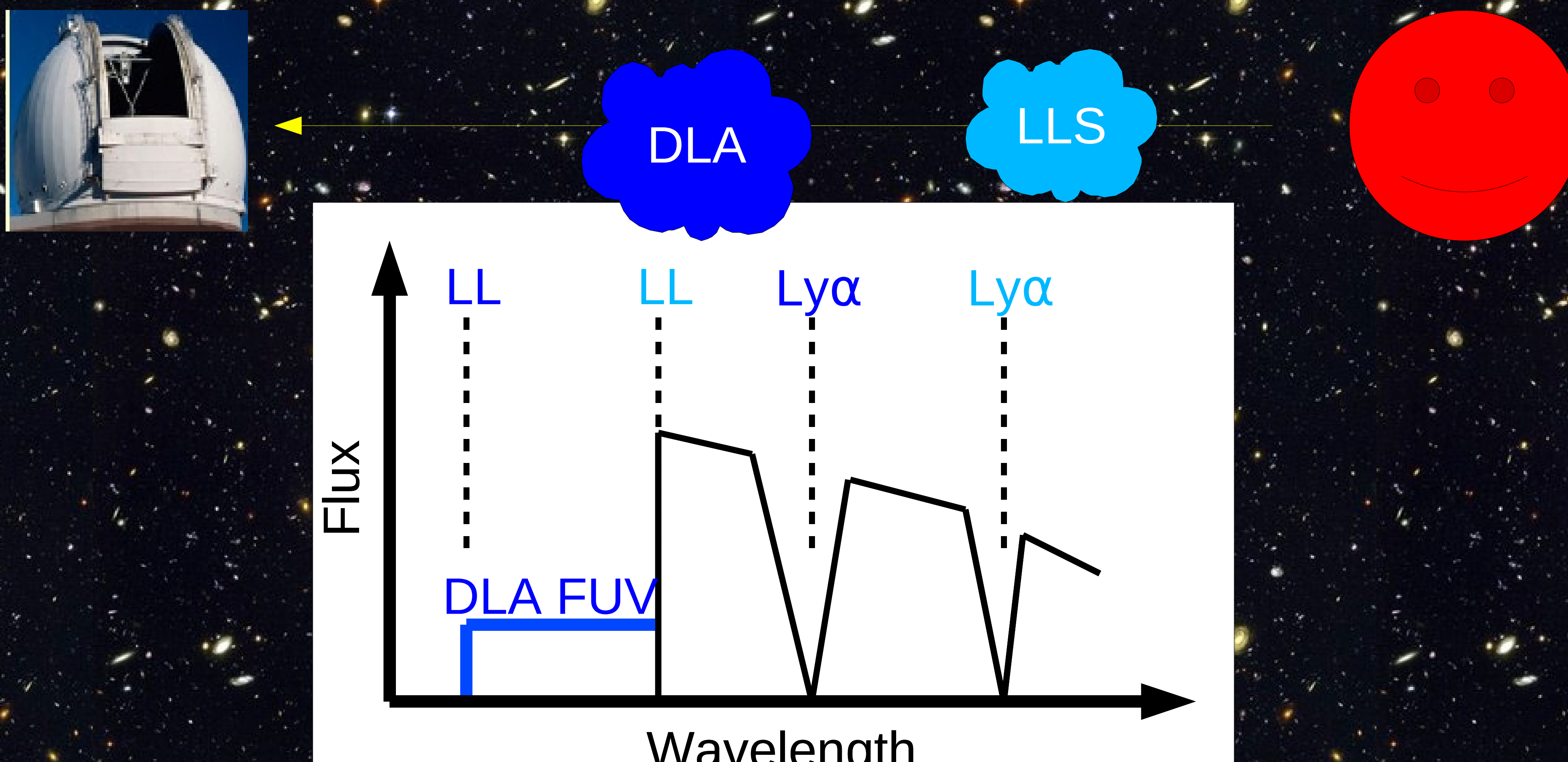

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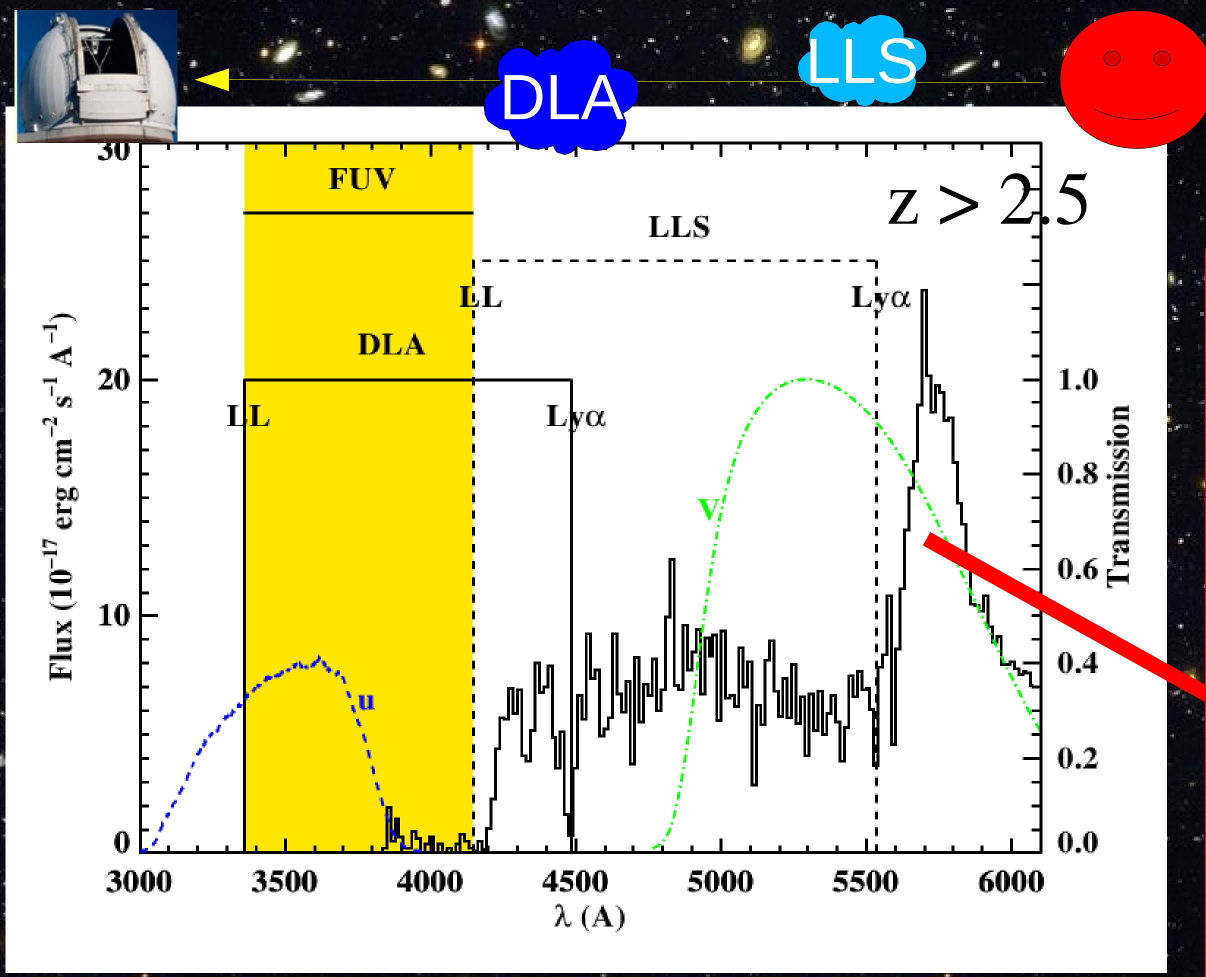
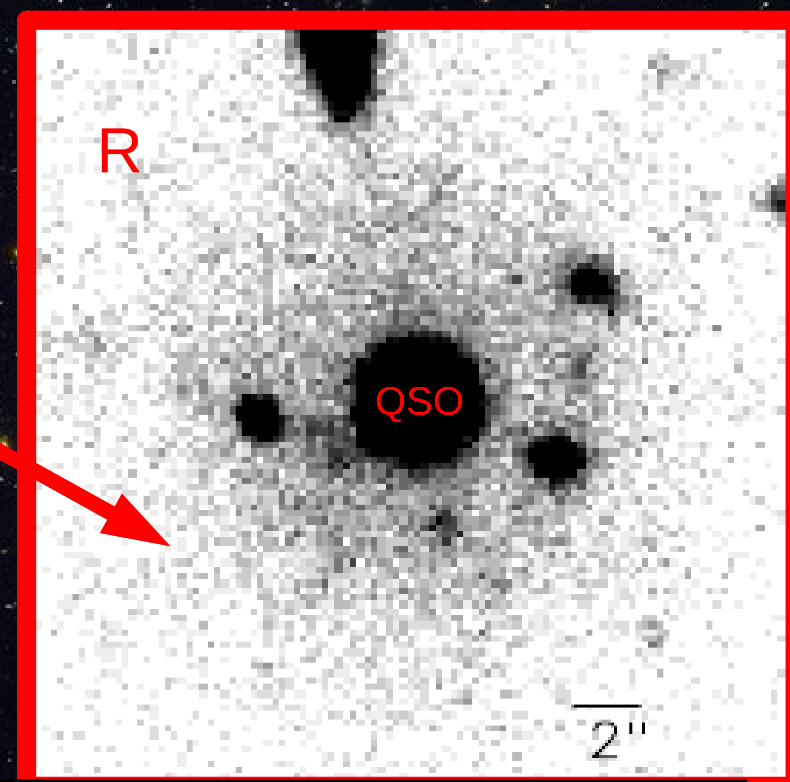


J0731+2854



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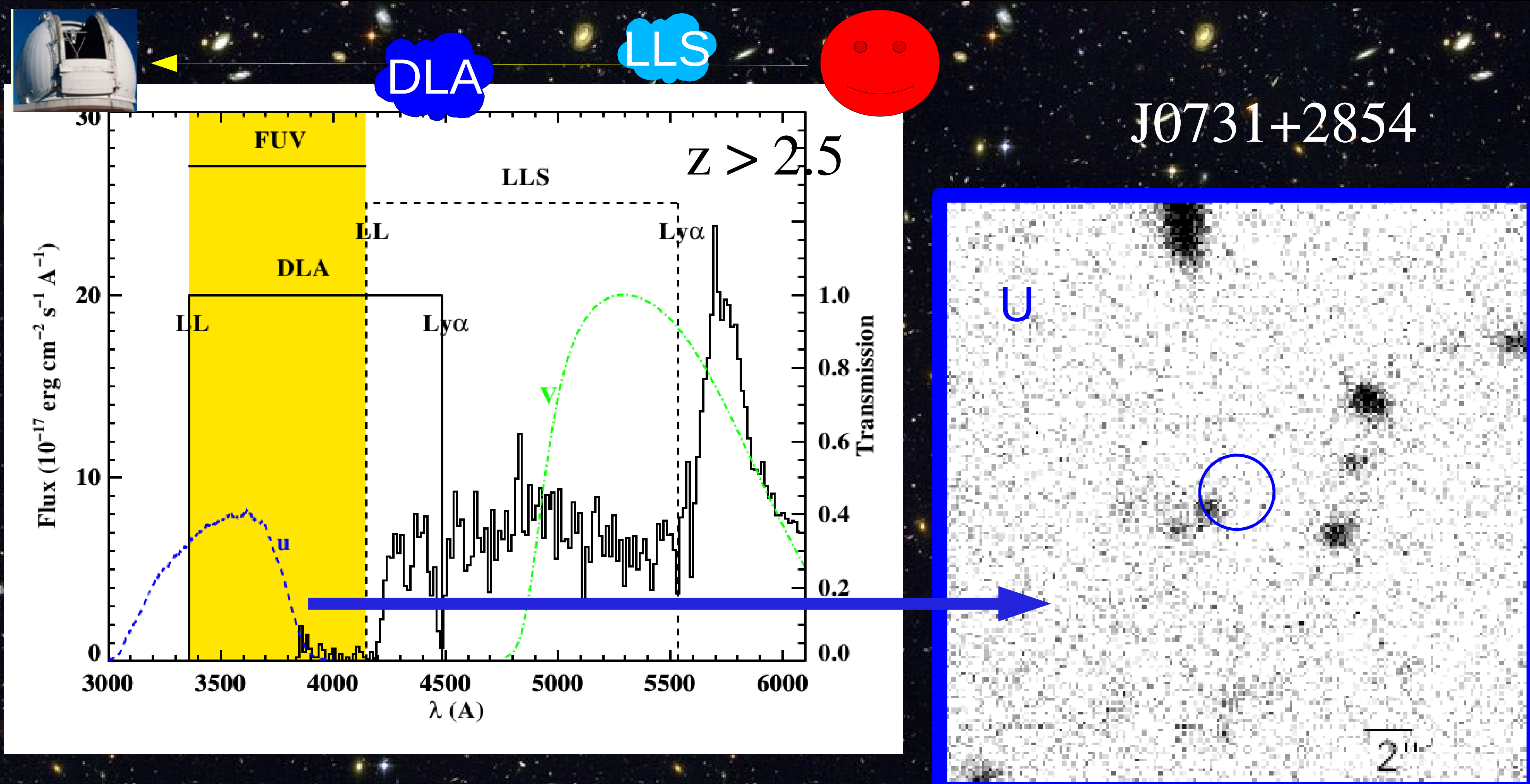
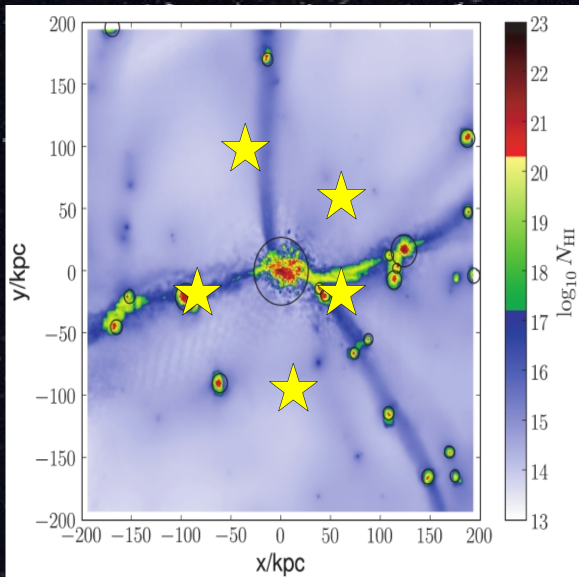
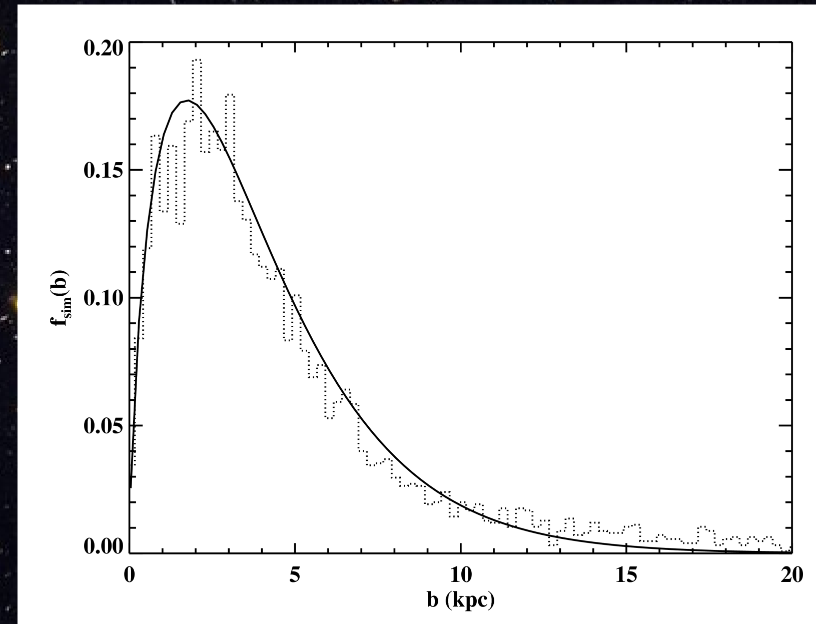
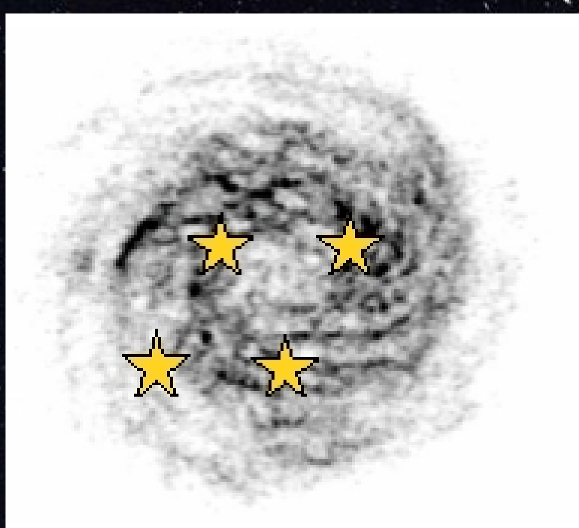




Pontzen+,08

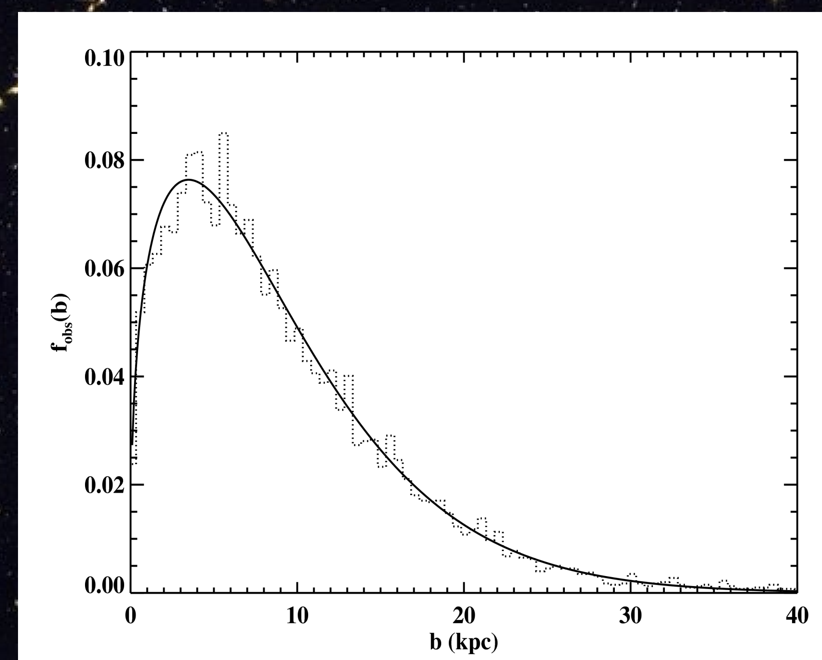
Cosmic-weighted distribution of DLAs





Walter+,08

Weighted on HIMF and HI cross section. Toy model: radius evolution $(1+z)^{-1}$ at constant Σ_{HI}.



OBSERVATIONS – Imaging of DLAs

$$f(N_{HI}, X) \propto \frac{n}{\Delta N_{HI} \Delta X}$$

→ The column density distribution in an ensemble of objects

What are we looking at?

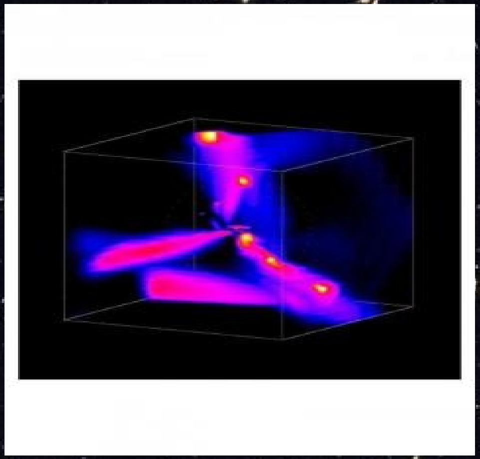
IGM/outflows/inflows?

How many and how big?

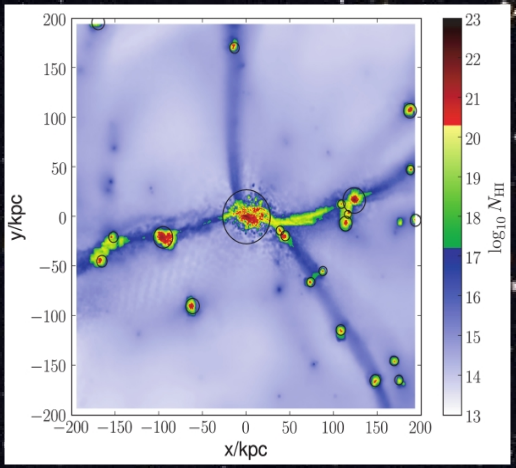
Merging clumps?

What shape?

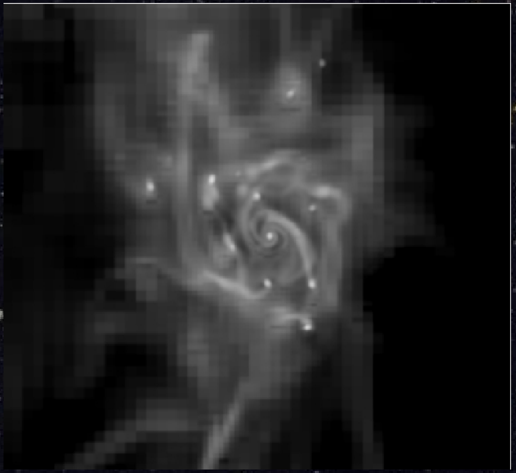
Massive disks?



(Dekel +, 2009)



(Pontzen +, 2008)



(Ceverino +, 2010)

Modeling with simulations can help...
and observations of the host galaxies