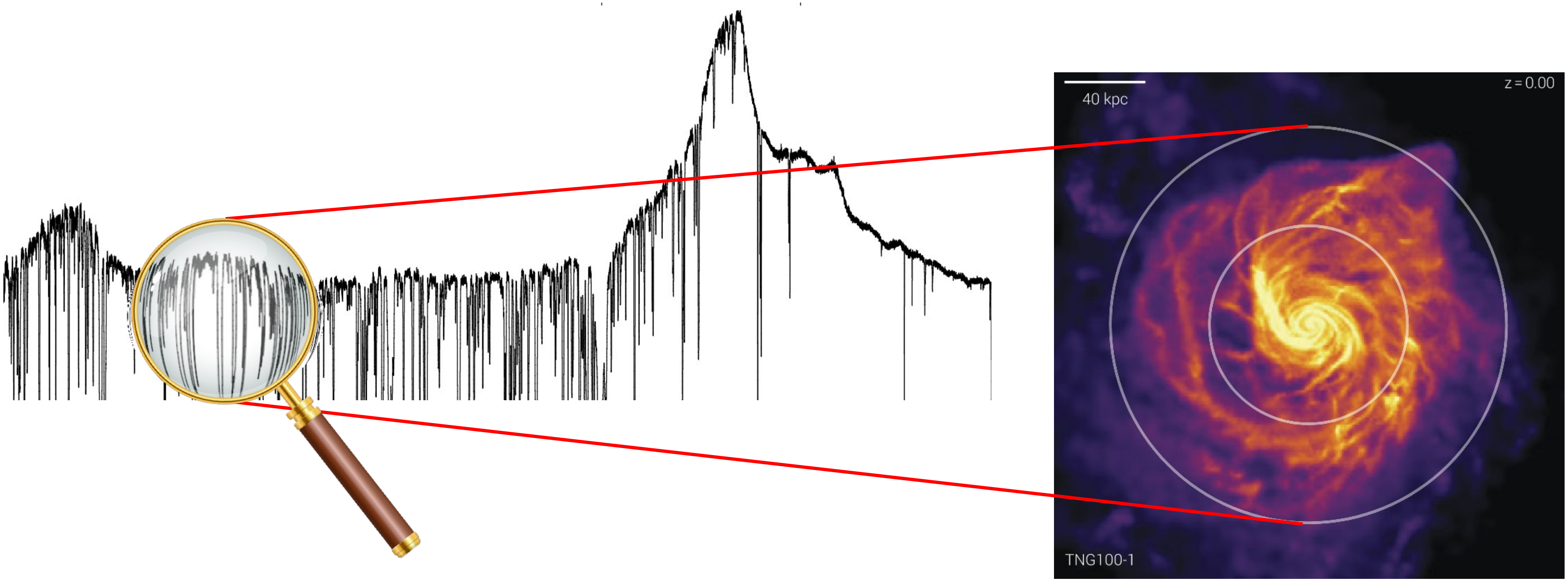
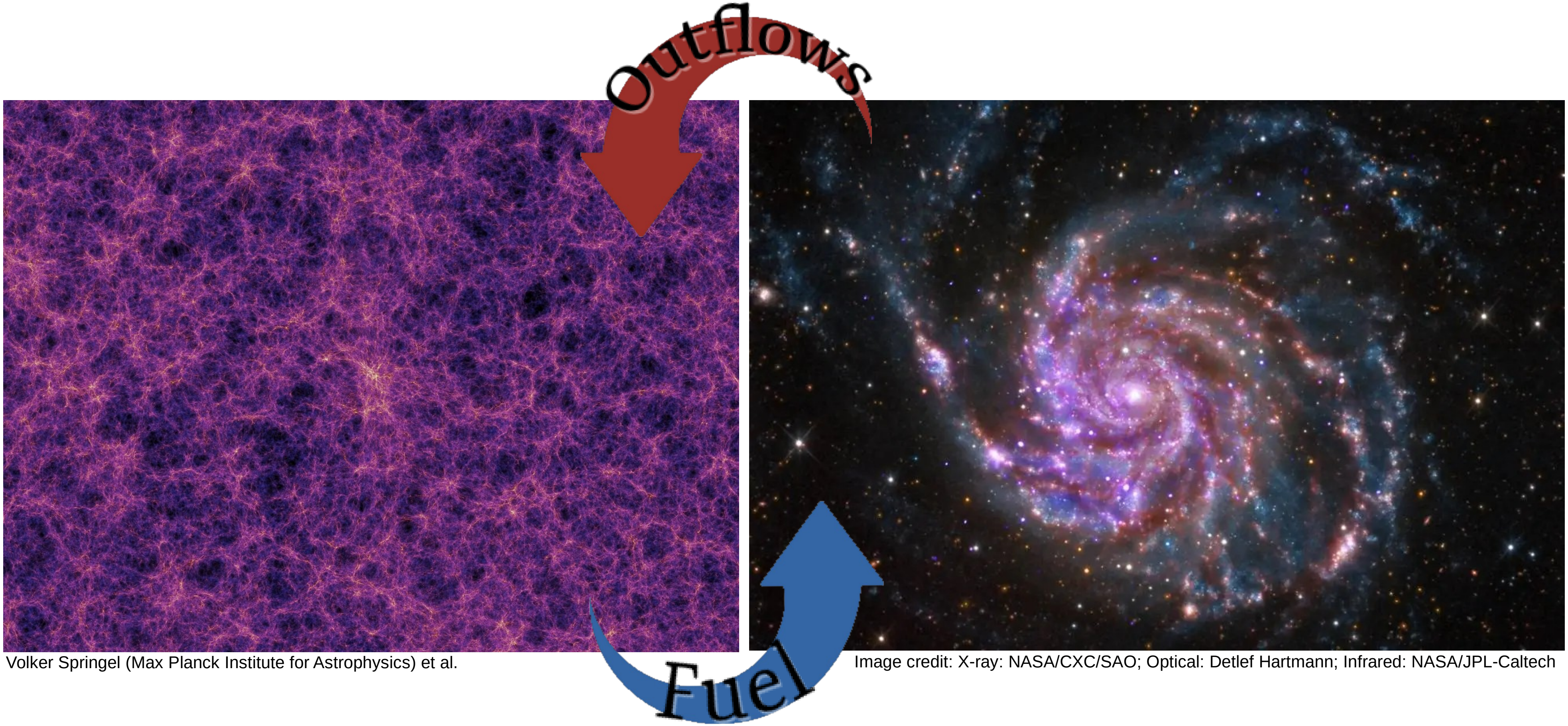
Finding Halos in the Lyman-α forest

Duarte Muñoz Santos

Matthew M. Pieri, Dylan Nelson, Teng Hu, Simon Weng, Manuel Ruiz-Herrera Bernal

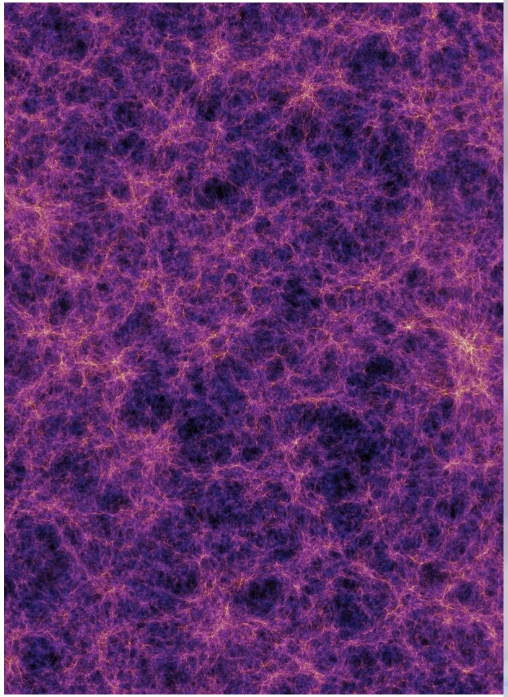


18th Potsdam Thinkshop
July 16th, 2025

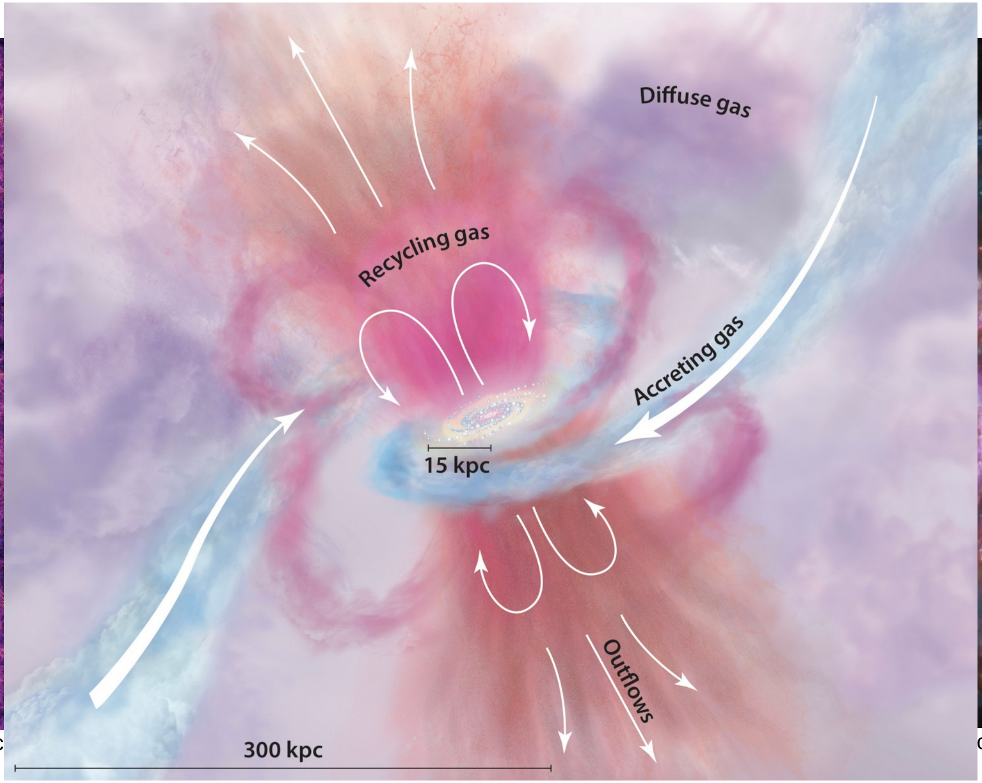


Volker Springel (Max Planck Institute for Astrophysics) et al.

Image credit: X-ray: NASA/CXC/SAO; Optical: Detlef Hartmann; Infrared: NASA/JPL-Caltech



Volker Springel (Max Planck Institute for Astrophysic



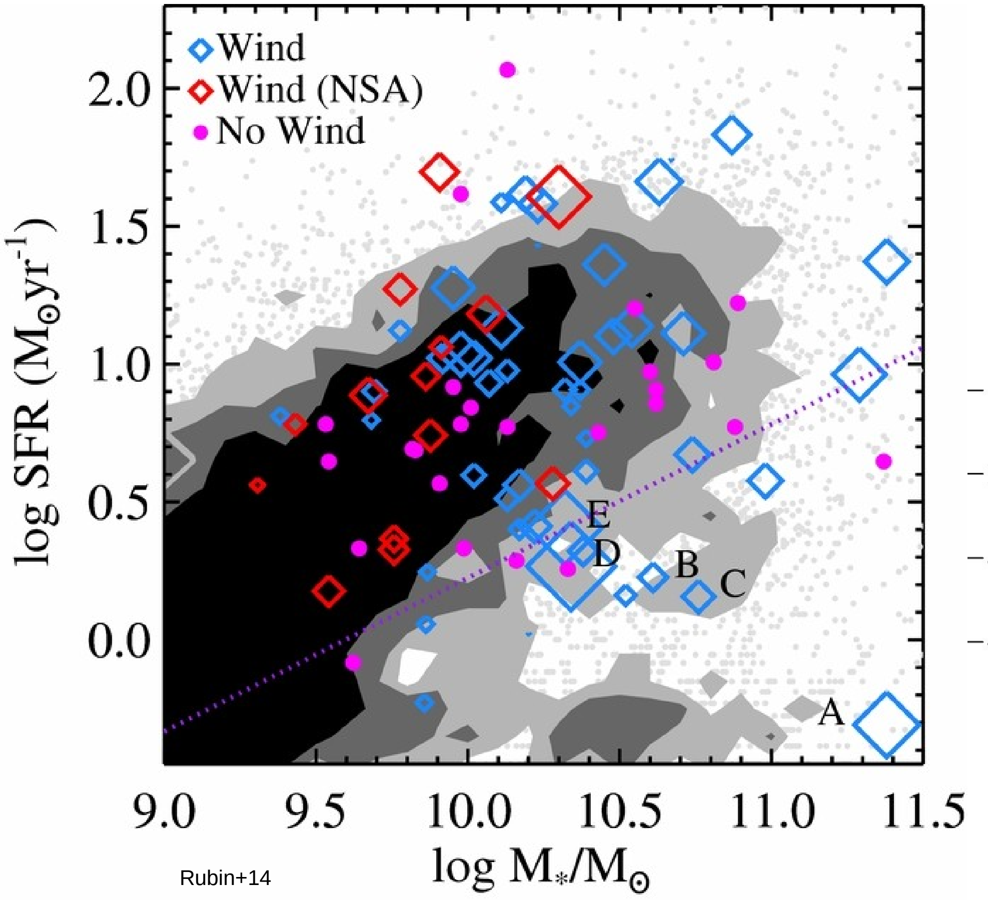
Tumlinson+17

cal: Detlef Hartmann; Infrared: NASA/JPL-Caltech

The Circumgalactic Medium (CGM) is one of the main baryonic reservoirs of the Universe, so studying it is of crucial importance.

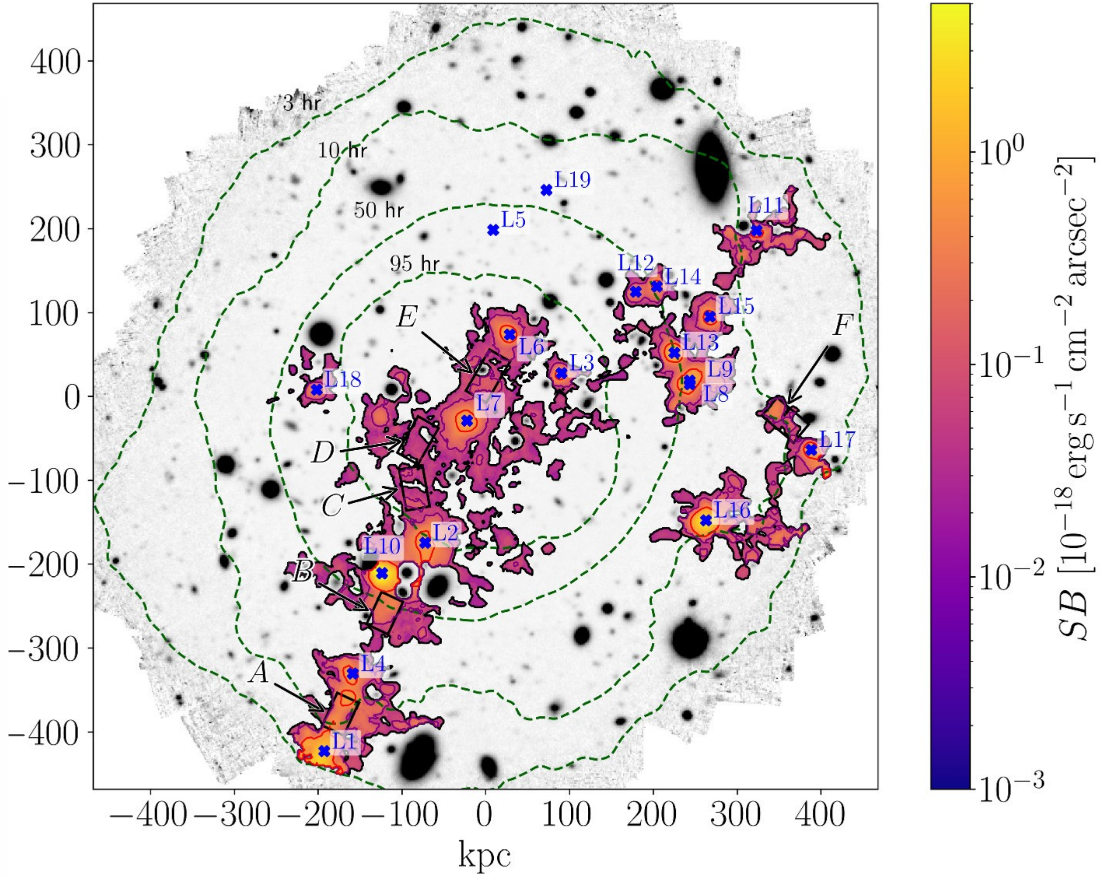
How to study the CGM

"Down the barrel" spectroscopy



Rubin+14

Tornotti+25



Emission line maps

Absorption-line Spectroscopy

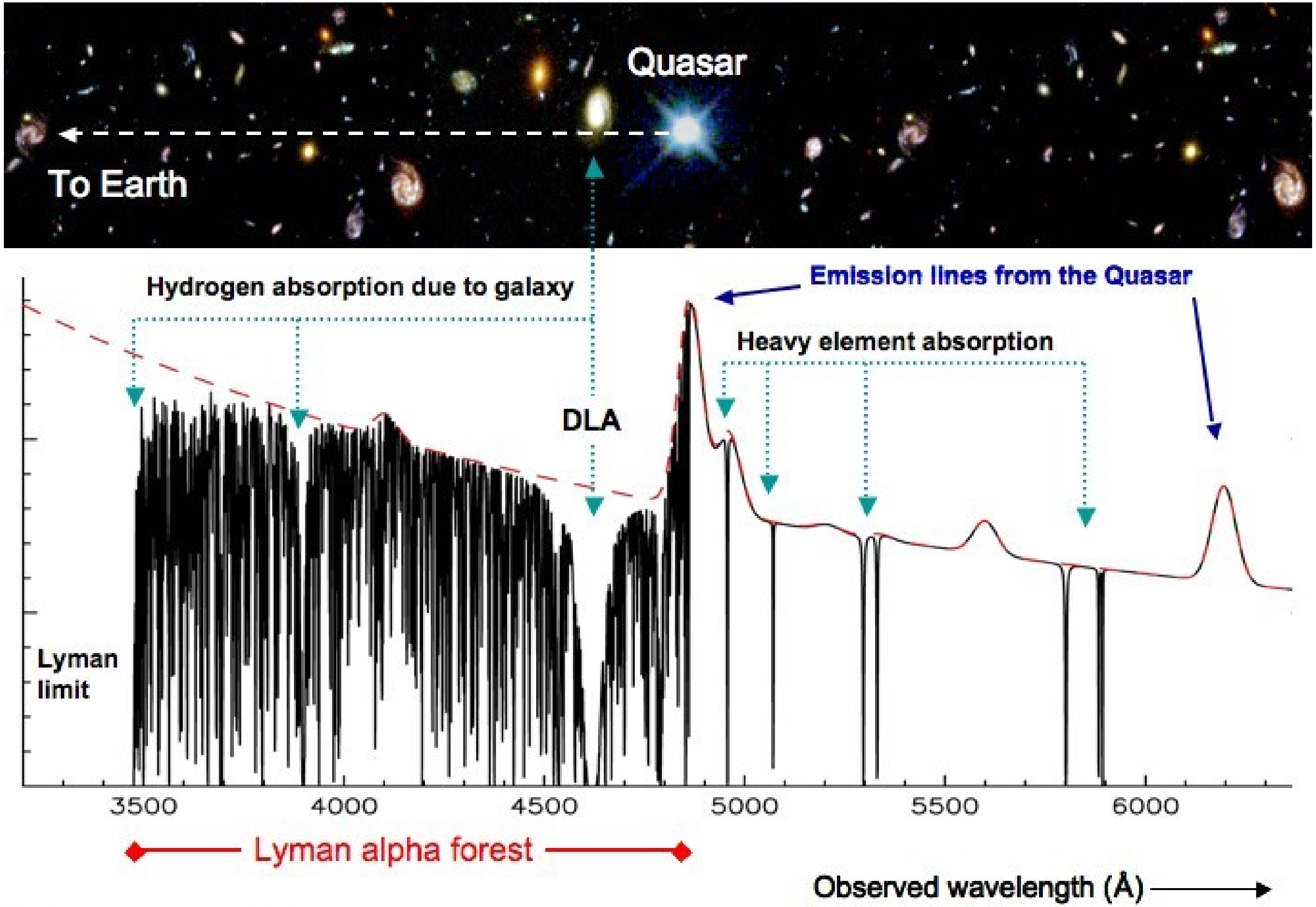
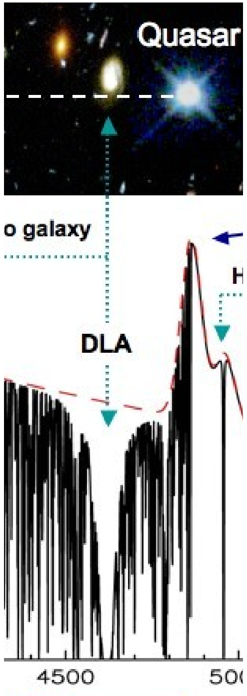


Illustration courtesy of John Webb

Absorption-line Spectroscopy

Galaxies are often associated exclusively with DLAs and sometimes LLS, however…



Absorption-line Spectroscopy

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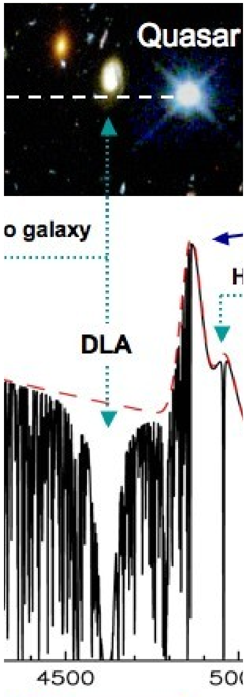
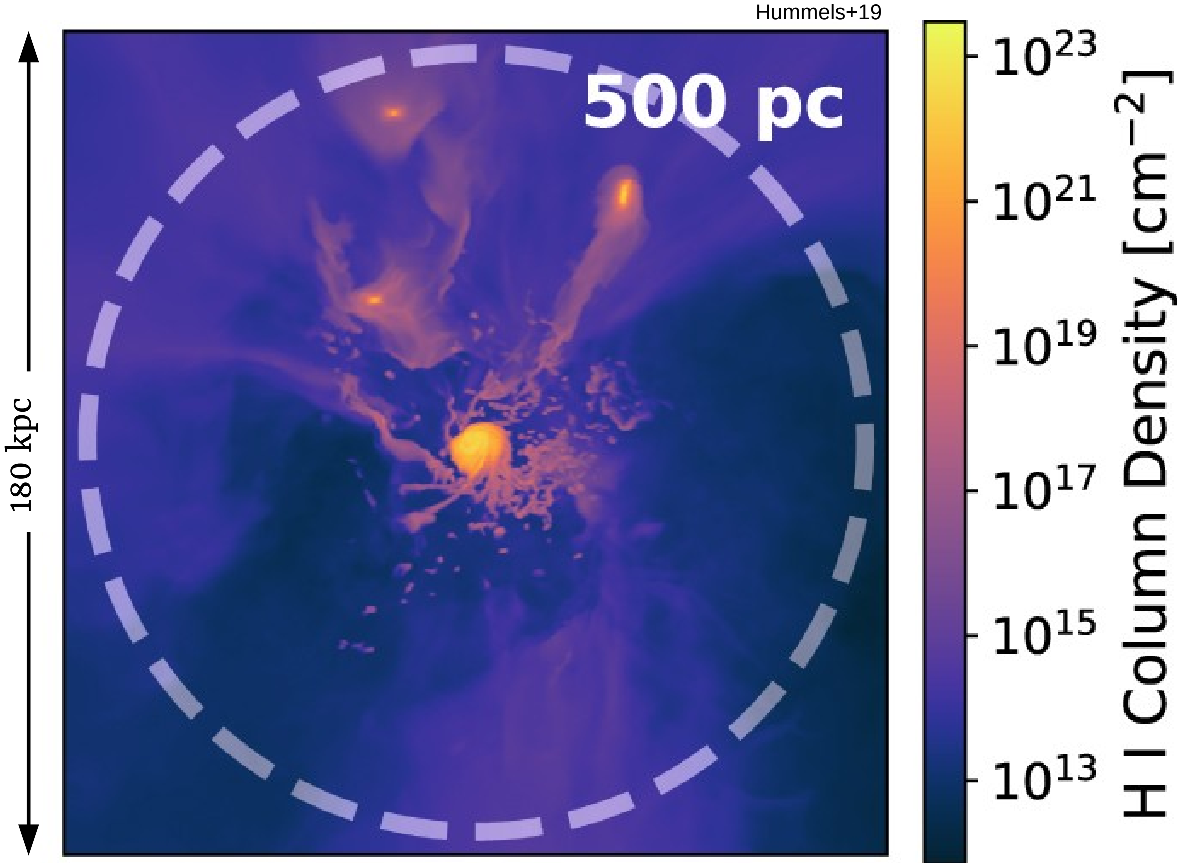
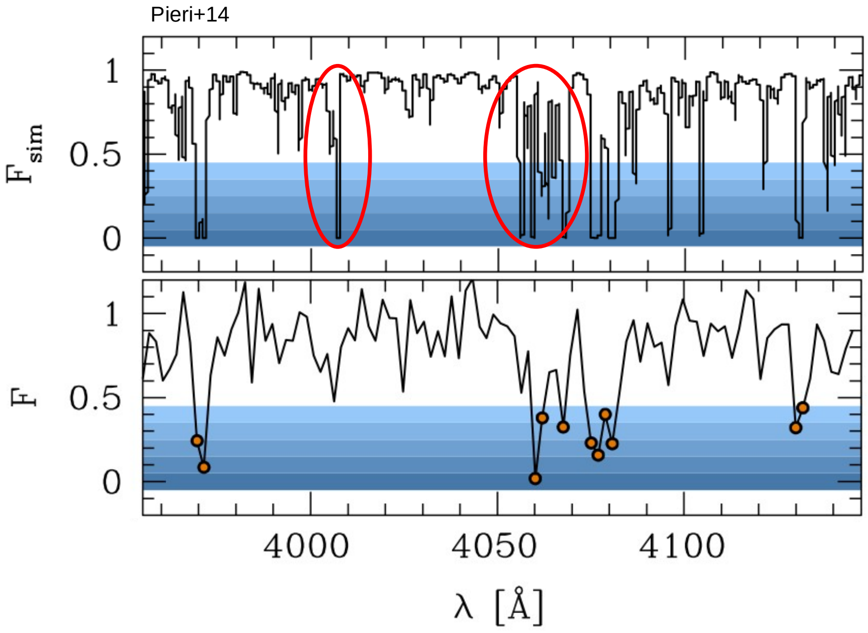




...the real picture is far more complicated.

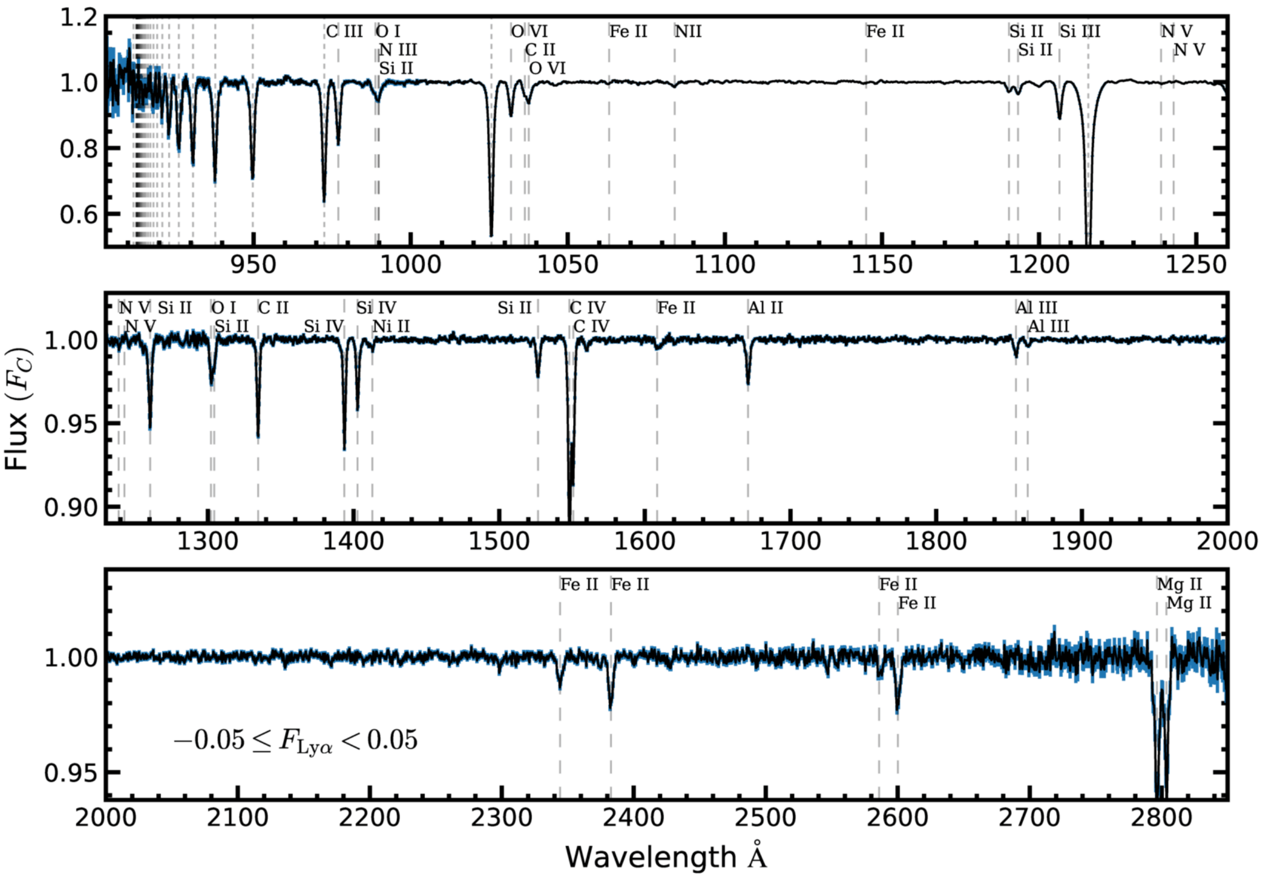
How do we study these systems?



"Perfect" Resolution

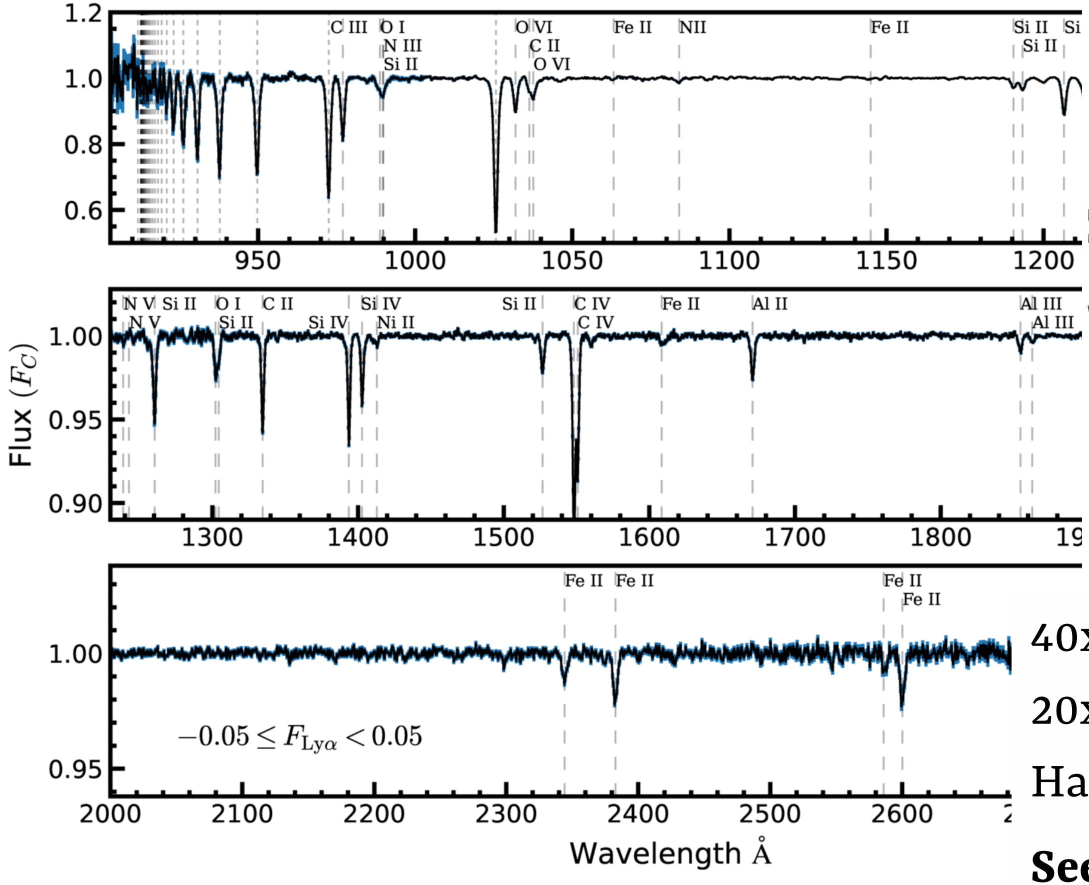
SDSS 2-pixel Resolution

Blends of Strong Absorption

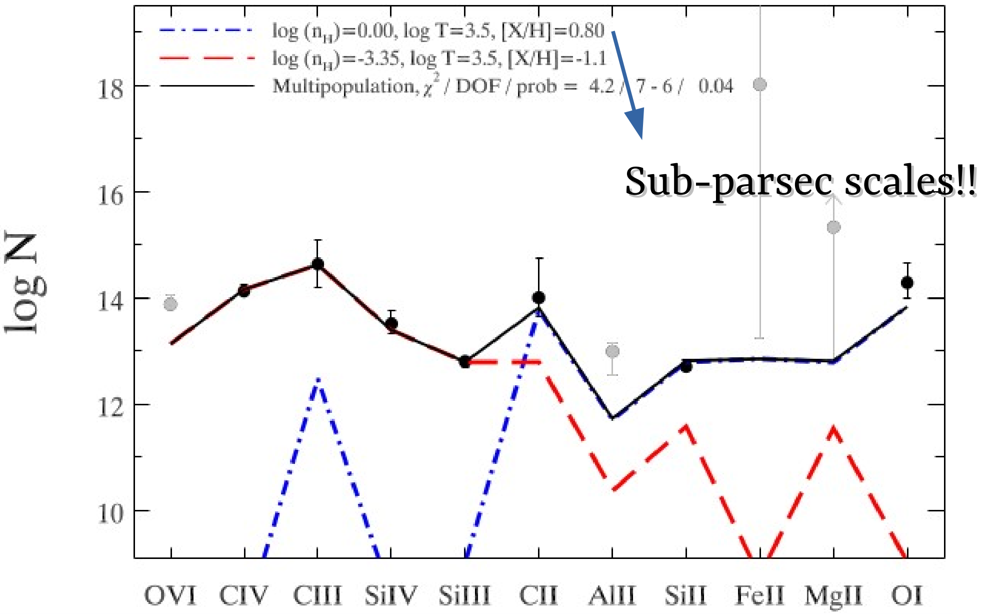


Morrison+24

Blends of Strong Absorption



Morrison+24



40x more SBLAs than DLAs.

20x more SBLAs than LLS.

Halo masses of about 10^{12} $M_\odot$.

See Mat Pieri's poster for more details!

SBLA

Strong, Blended Lyman-alpha (SBLA) absorbers are defined as having:

- Low Lyman-α flux transmission (noiseless $F_{Ly\alpha} < 0.25$);
- Large velocity scales (138 km/s).

SBLA

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- Large velocity scales (138 km/s).

However, there's still many unanswered questions…

How effectively do SBLAs trace halos?

Can we generalise this?

Fresh off the press...

Finding Halos in the Lyman-α Forest

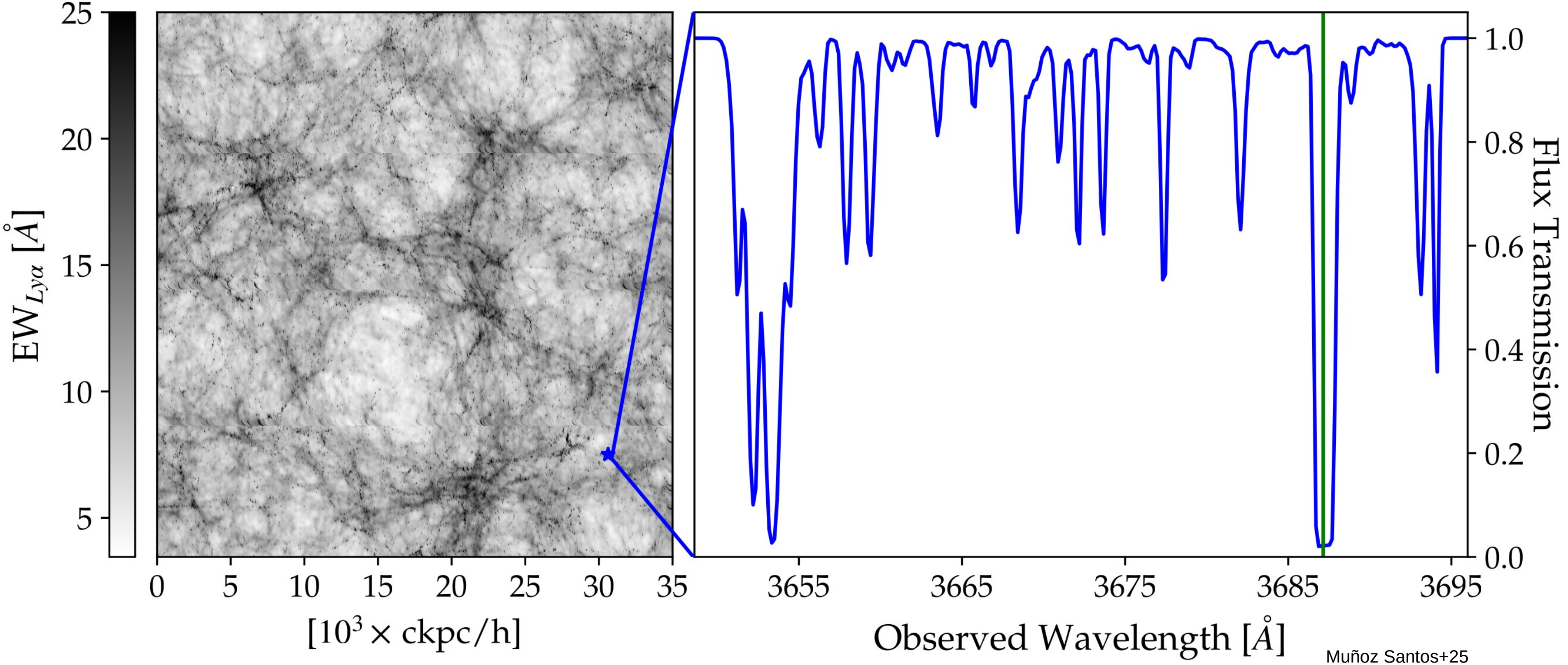
Duarte Muñoz Santos[1], Matthew M. Pieri[1], Dylan Nelson[2], Teng Hu[1], Simon Weng[1], and Manuel F. Ruiz-Herrera Bernal[3,4]

It has been demonstrated that one can track down galaxies in absorption 'hidden' in the Lyman-α forest through the use of 'strong, blended Lyman-α' (or SBLA) absorption. Specifically a series of publications studied SBLA absorption systems with Lyman-α flux transmission, $F_{Ly\alpha} < 0.25$ on scales of 138 km s^{-1} in the Sloan Digital Sky Survey (SDSS). In order to better understand the connection between halos and these SBLAs, we make use of several million synthetic absorption spectra from the TNG50 cosmological simulation, at z=2 and z=3. We explore spectra with SDSS-like resolution in order to understand the nature of SBLAs as defined thus far, as well as with high resolution (or 'resolved') spectra to generalise and optimise SBLAs as halo finders. For the SDSS SBLAs, we find that up to 78% of these absorption systems reside in hlaos, where the stronger the absorption and the lower the redshift, the higher the probability. We also manage to recover a mean halo mass of $10^{12.25} M_\odot$, in line with what is measured in observations. For the resolved SBLAs, we expand on the previous definition and allow the SBLA spectra size to vary between 54 km s^{-1} and 483 km s^{-1}. We find that the largest absorbers have the highest probability of finding halos. When applying a hierarchical framework, where we allow the largest SBLAs to consume the smaller ones, we find that the halo mass distributions for each SBLA spectral size becomes narrower with respect to the non-hierarchical case. We are also able to probe halo masses from $M_h \approx 10^{9.5} M_\odot$ (for 100 km s^{-1} SBLAs) to $M_h \approx 10^{11.5} M_\odot$ (for 450 km s^{-1} SBLAs). With these results, we show that we are able to transform the Lyman-α forest into a powerful halo finding machine for not only identifying CGM regions, but also estimating their host halo masses.

https://arxiv.org/abs/2507.08940

TNG50 Simulation

We used the TNG50 simulation (Nelson+19) at **z = 2 and z = 3**, with access to mock SDSS-like and nearly resolved spectra in each pixel of the box. We have **4 million parallel spectra in random** sightlines.



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Selection

We selected SBLAs with the following conditions:

1) $\begin{cases} F_{Ly\alpha} < 0.25 \\ F_{Ly\alpha} < 0.15 \\ F_{Ly\alpha} < 0.05 \end{cases}$

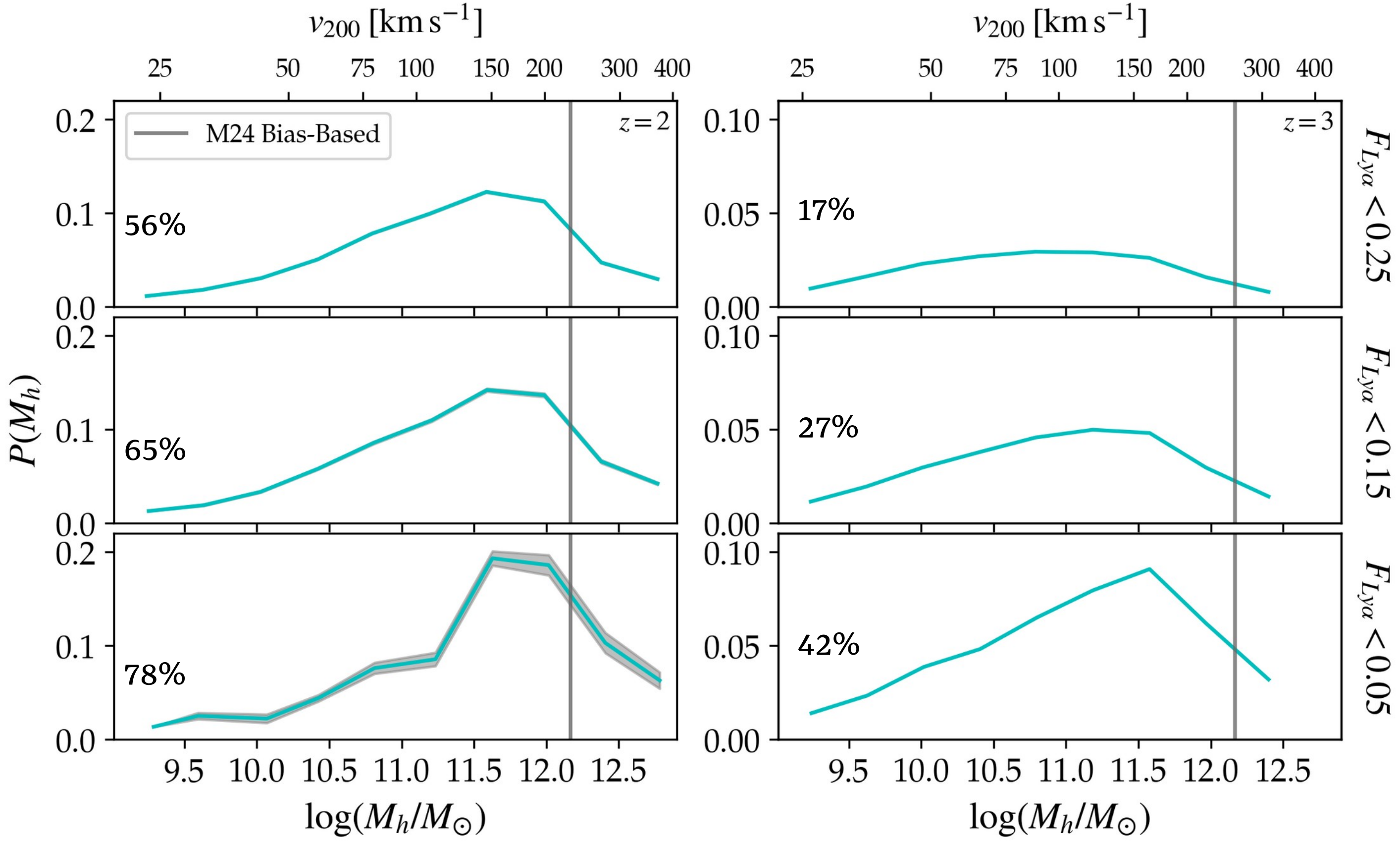
2) Excluding DLAs

Next, we find the SBLAs inside halos:

$$\begin{cases} (x_{SBLA} - x_{Halo})^2 + (y_{SBLA} - y_{Halo}) \leqslant R^2_{\mathrm{Virial}} \\ c\,\dfrac{|z_{SBLA} - z_{Halo}|}{1 + z_{Halo}} \leqslant v_{Halo} \end{cases}$$

Where: $v_{Halo} = \sqrt{\frac{GM_{200}}{R_{200}}}$

SDSS SBLAs



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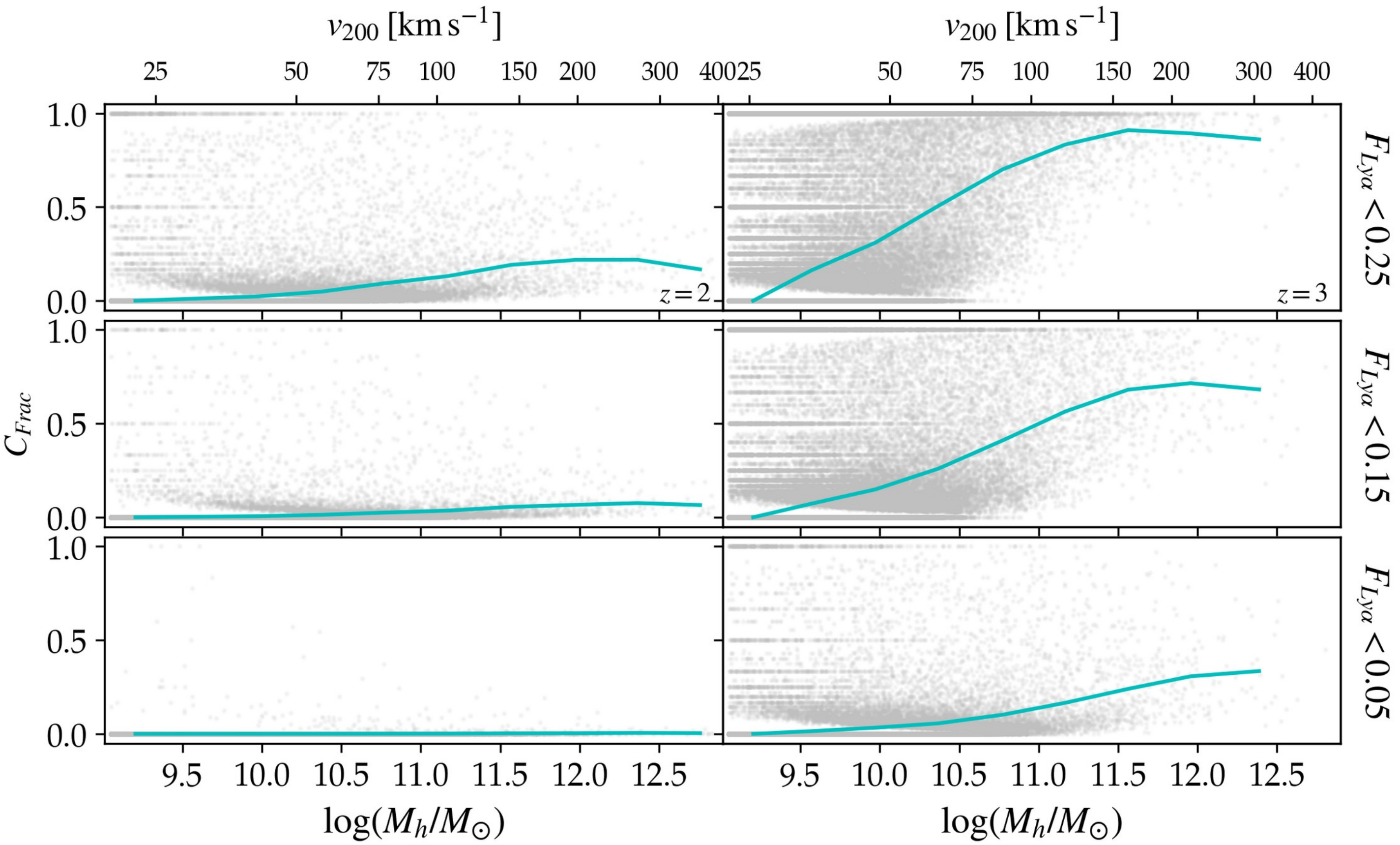
Up to **78% of SDSS SBLAs find halos.**

We are **consistent** with **the mean halo mass from Morrison+24** ($10^{12.25}$ $M_\odot$).

SDSS SBLAs seem to **favour specific halo masses**.

SDSS SBLAs

SDSS SBLAs are more **numerous** and cover **more halo lines-of-sight** at **higher redshifts** and **higher flux transmissions.**



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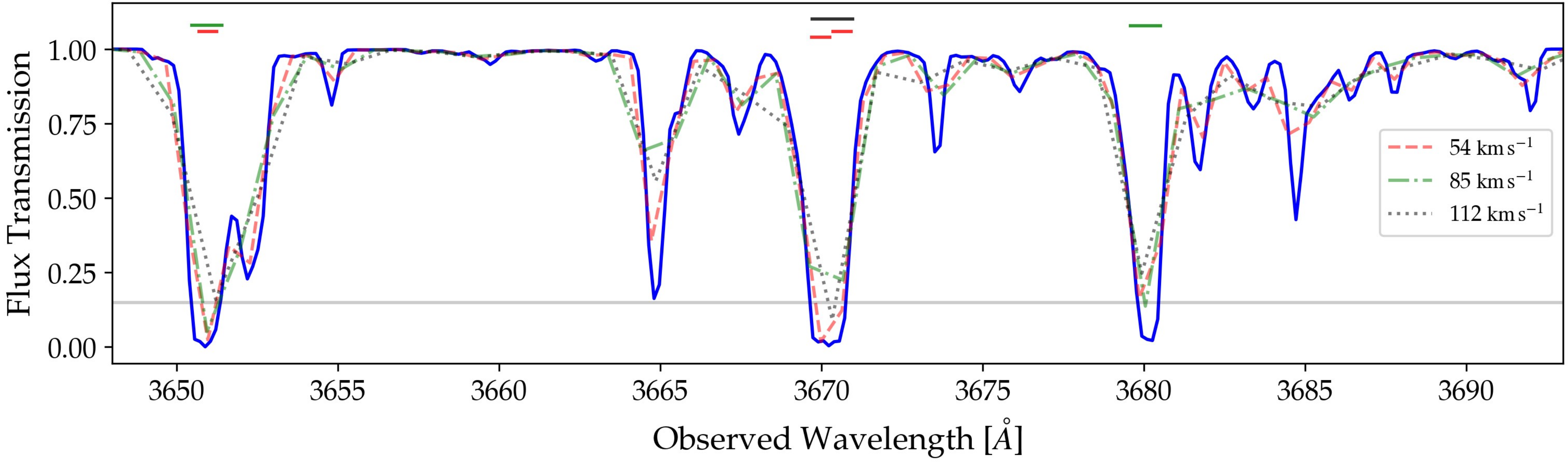
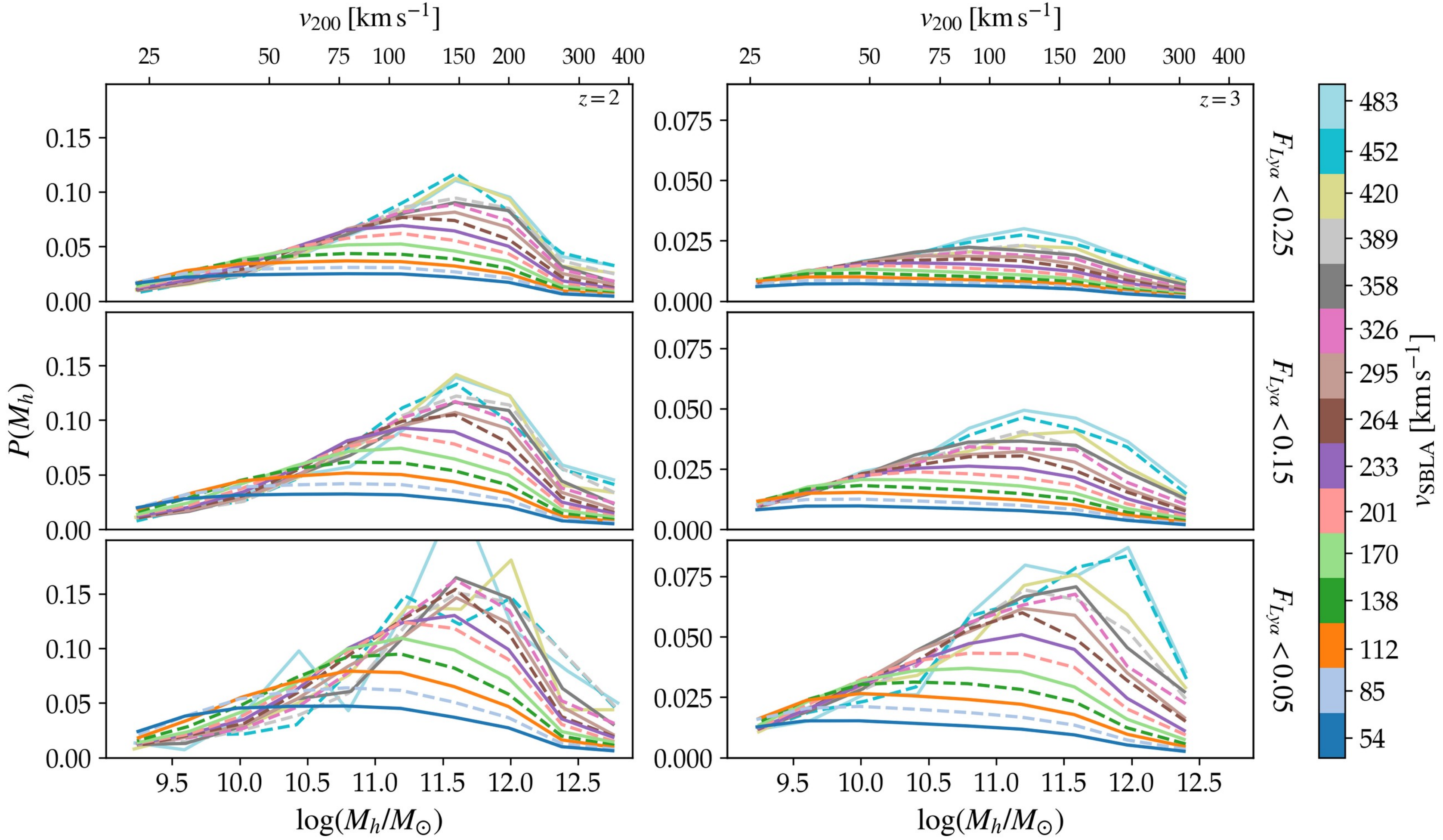
Generalising SBLAs

We rebinned each spectrum between 54 km/s and 488 km/s, in 30 km/s bins.



Clear relation between SBLA spectral size and halo mass...

But **halo mass distributions are wide**.



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Hierarchy

Resolved SBLAs can **trace the same system more than once** – we need to understand which SBLAs are **independent** from one another!

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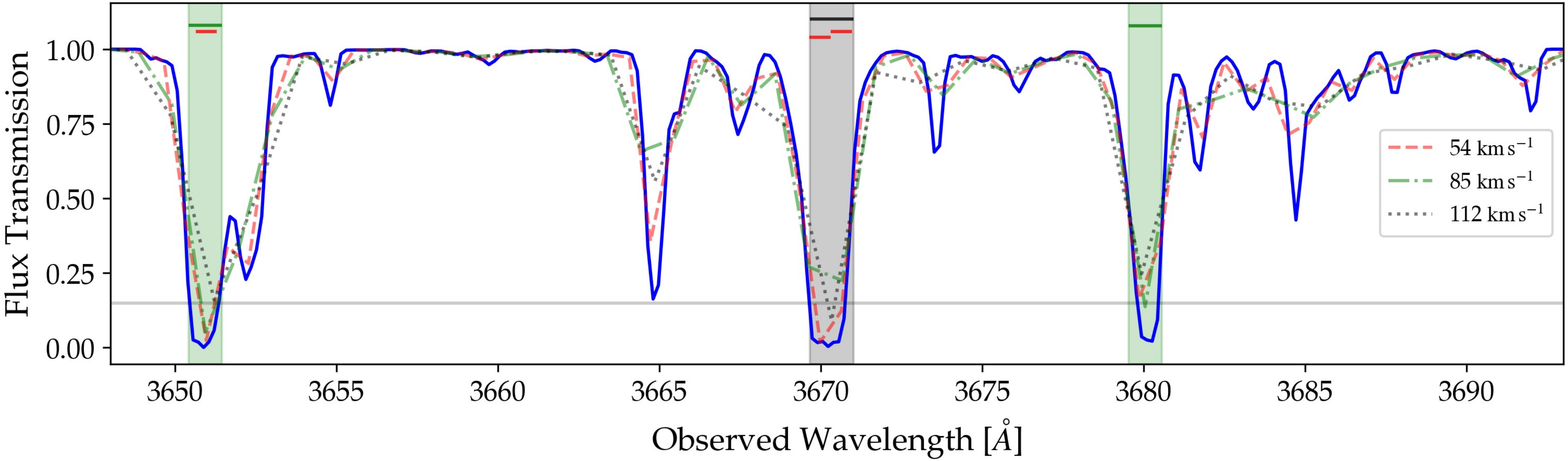
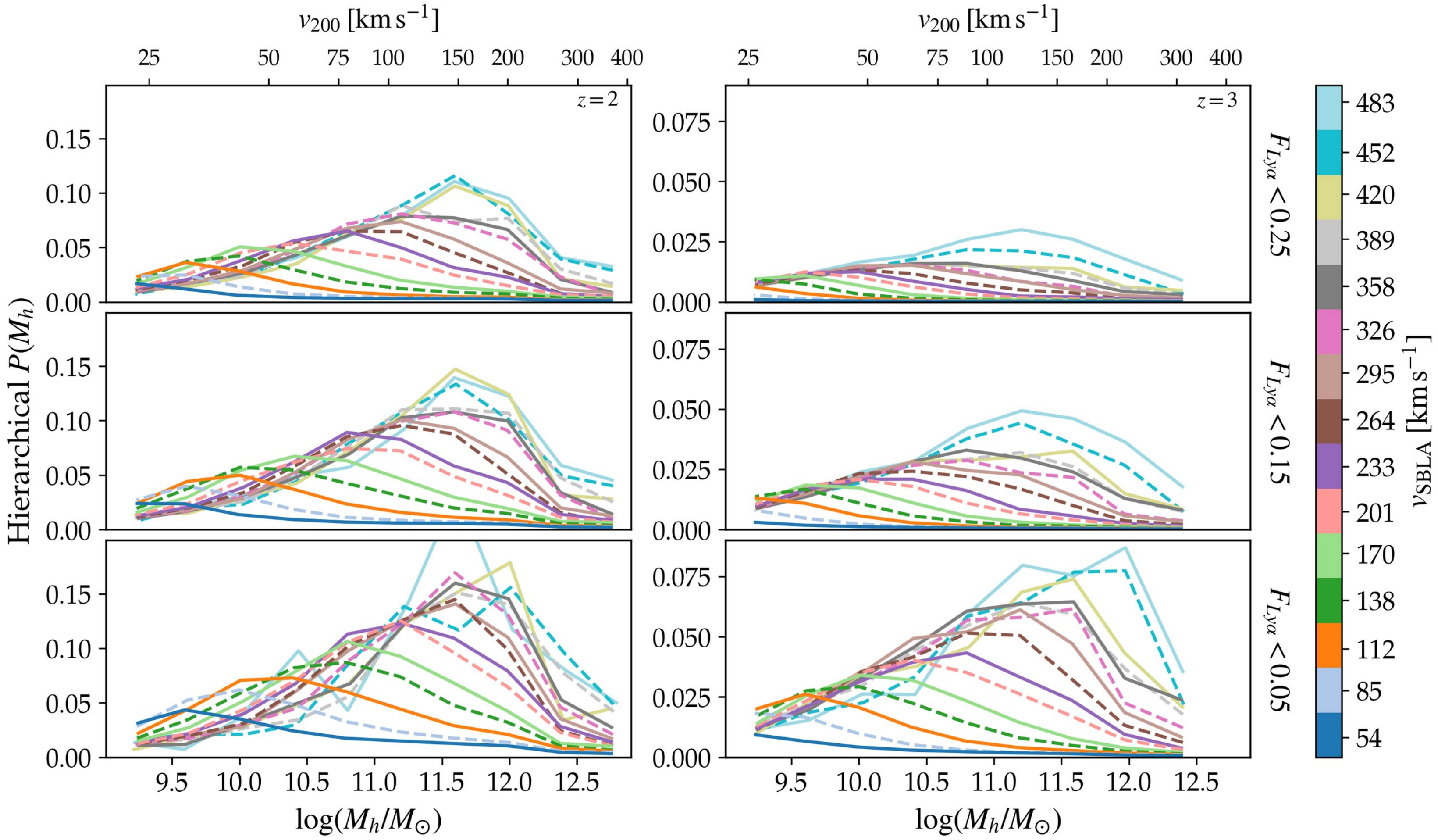


SBLAs + Hierarchy



Distributions are **narrower** and **peak** halo mass is **better defined!**

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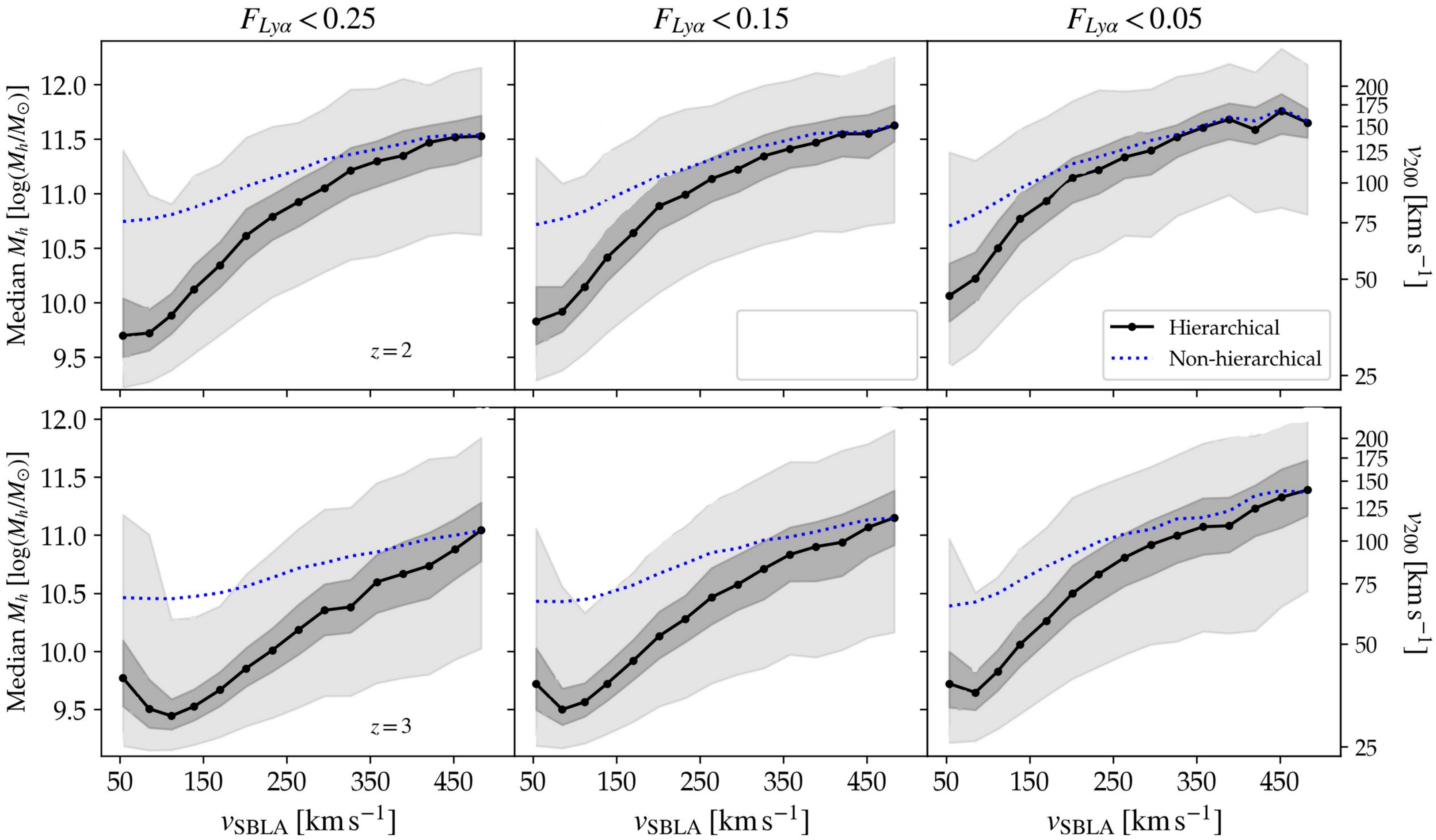
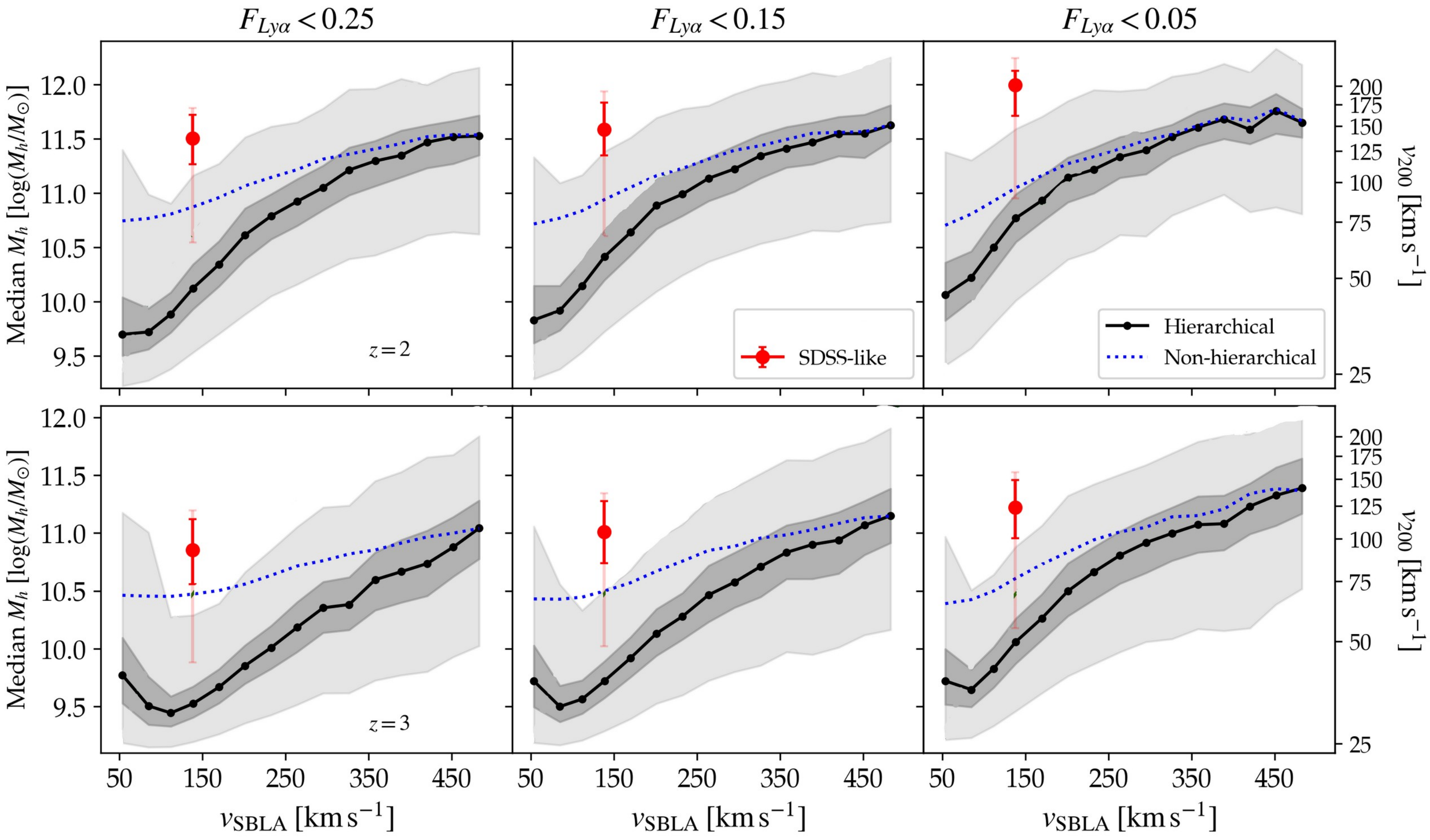
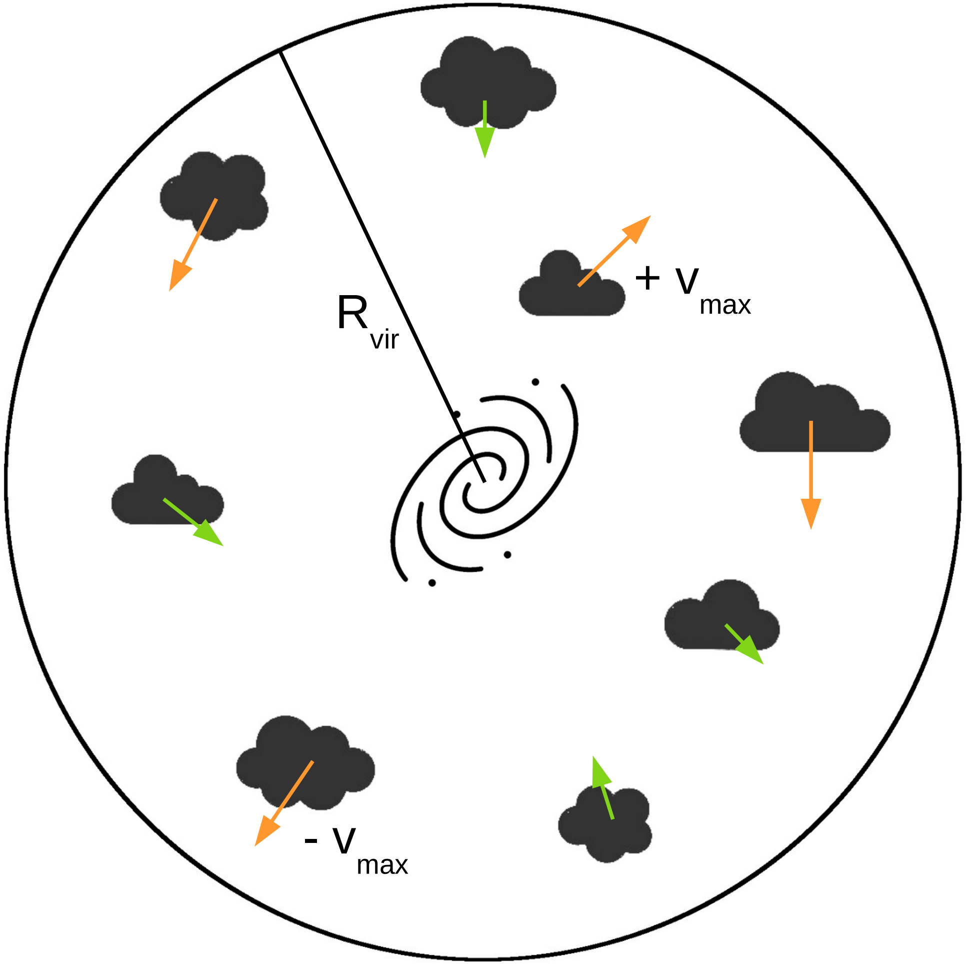
Halo Mass and SBLA Size



Halo Mass and SBLA Size



Circular Velocity



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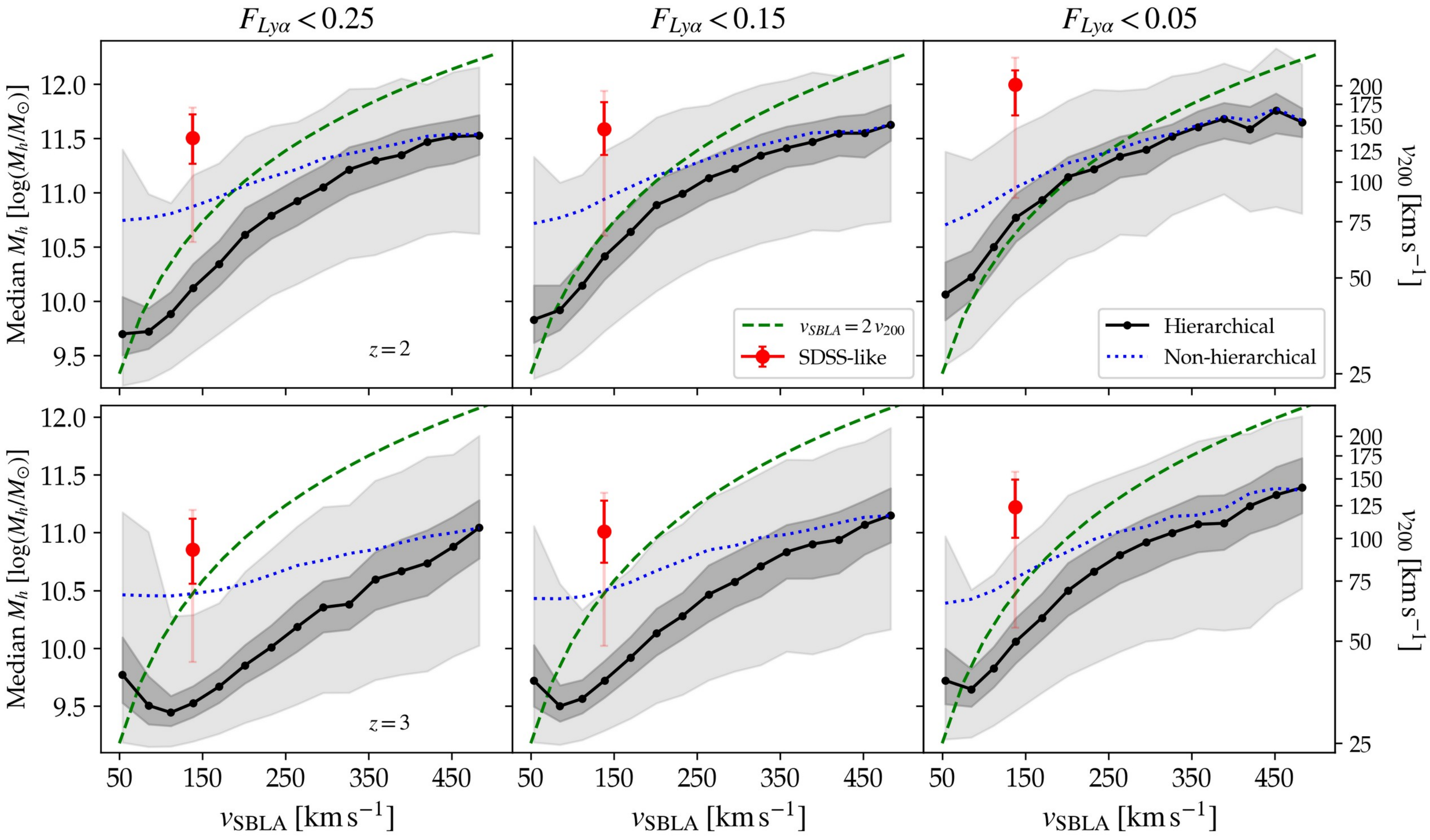

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Conclusions

- SBLAs are powerful halo finding machines – **nearly 80%** of them **find halos!**

- We **recover** similar halo masses from **observations;**

- Increasing **SBLA spectral sizes** trace increasing **halo masses**;

- **Hierarchical framework** is crucial so that SBLAs can better distinguish halo masses, **allowing for a wide selection** ($10^{9.5} < M_h\ [M_\odot] < 10^{11.5}$);

- Further **refinements are needed**, but **we are ready** to apply this method to **observations!**
  - WEAVE-QSO, KODIAQ, SQUAD, 4MOST, DESI, etc...

THANK YOU!