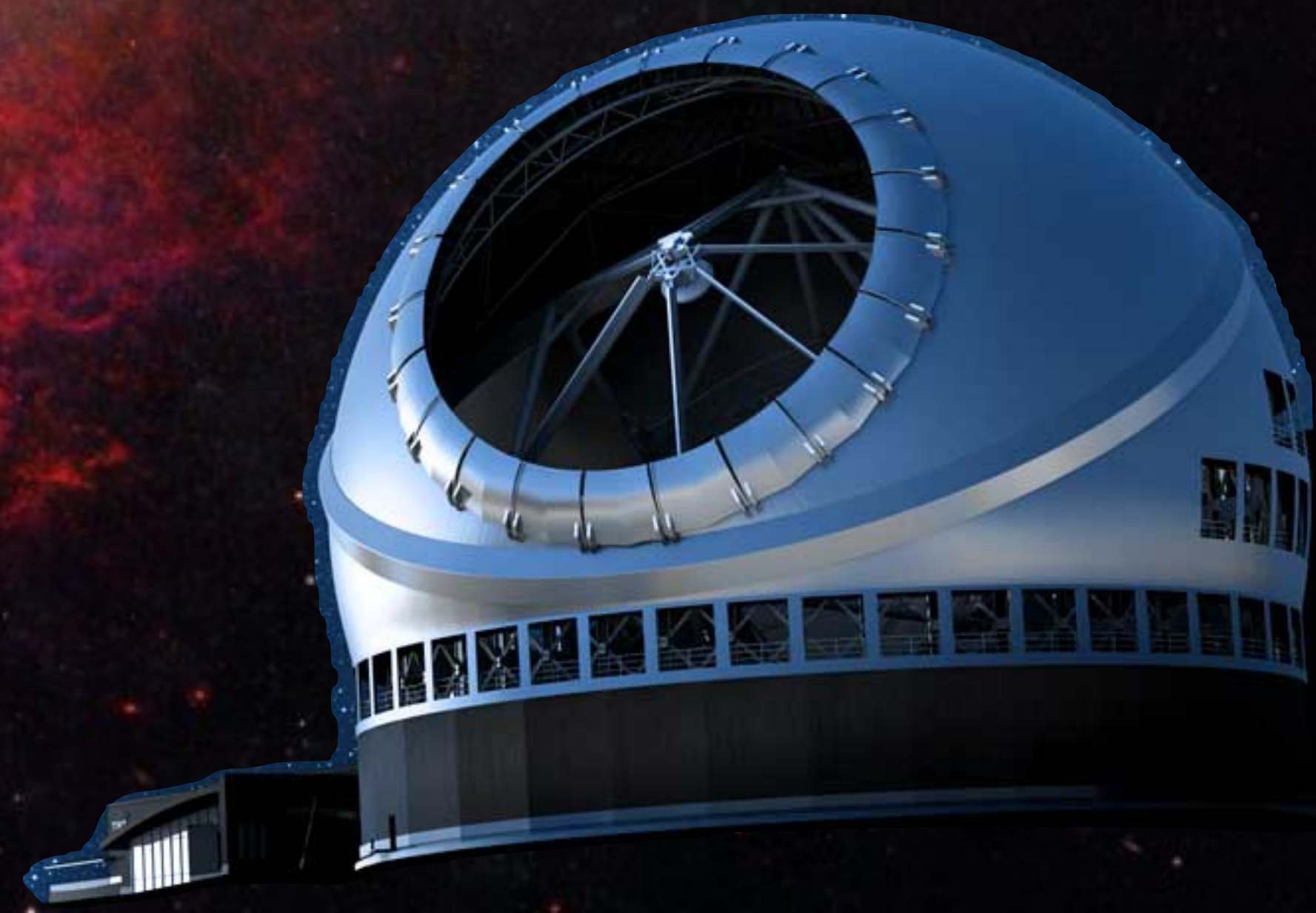


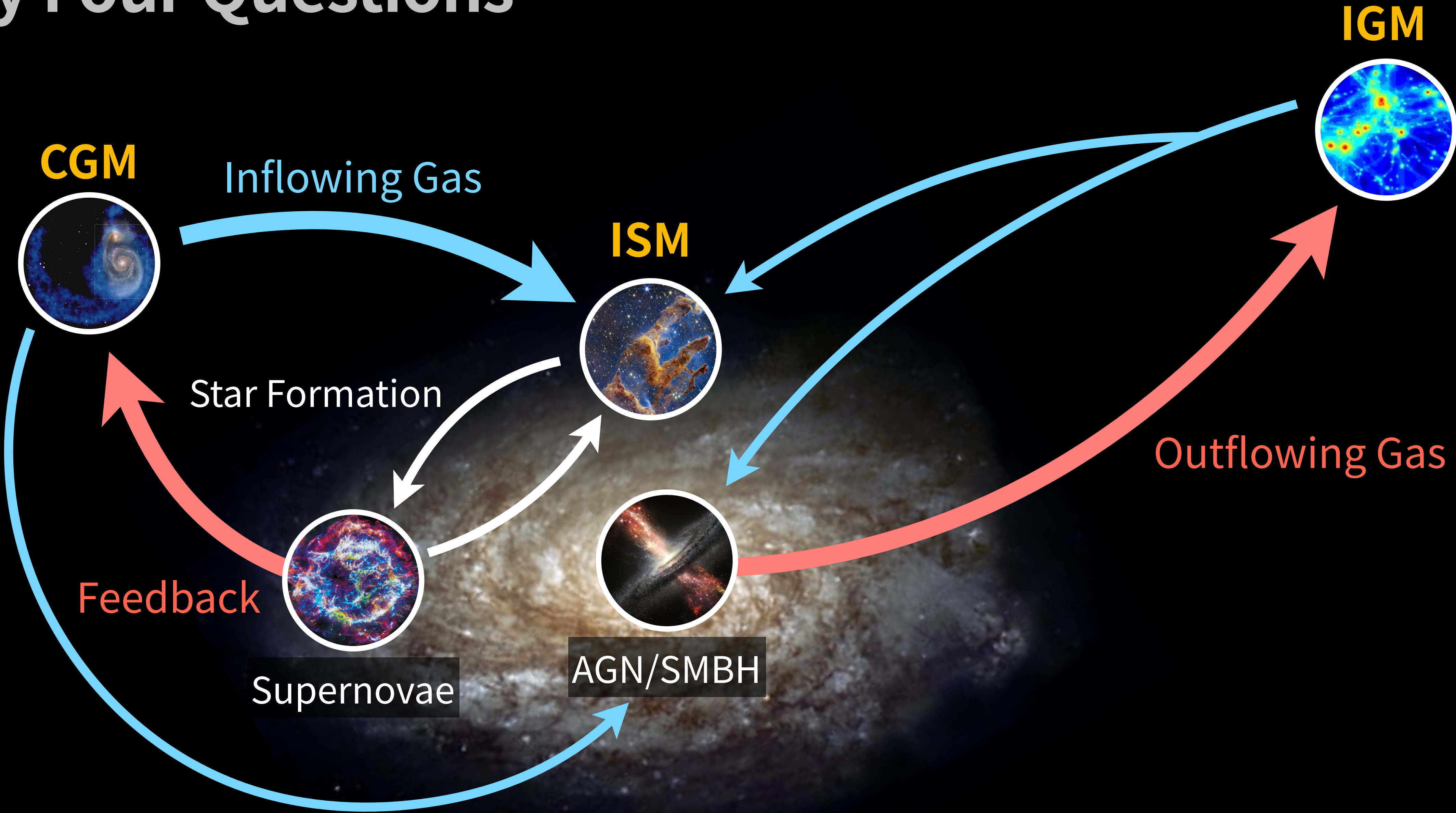
Toward a Unified Picture of the Baryon Cycle in the TMT Era

Rieko Momose (Carnegie Observatories)

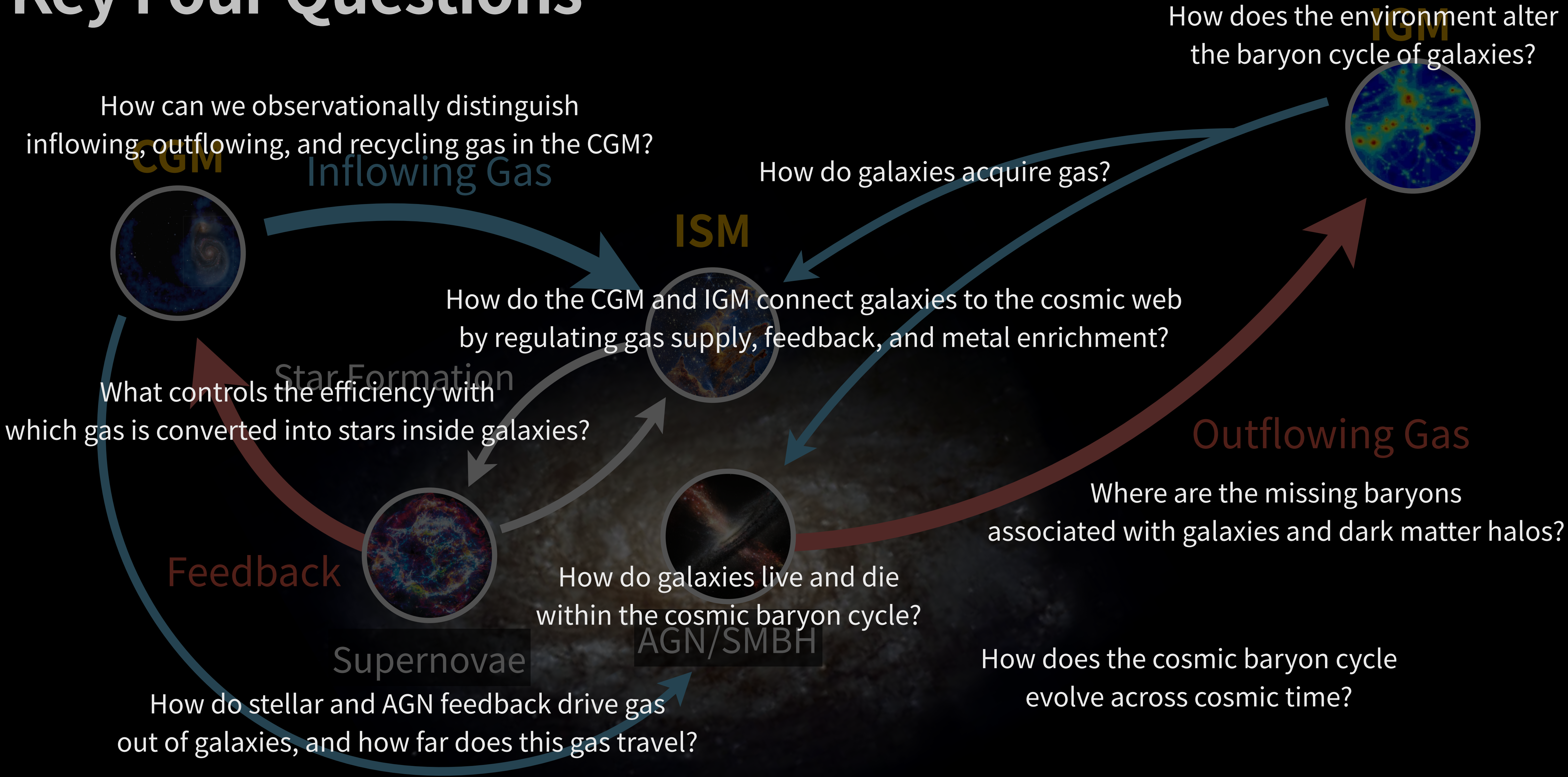
June 18, 2026, Subaru Users Meeting 2026



Key Four Questions



Key Four Questions



Key Four Questions

How can we observationally distinguish inflowing, outflowing, and recycling gas in the CGM?

How does the environment alter the baryon cycle of galaxies?

How do galaxies acquire gas?

Where are the baryons, and in what physical phases do they exist?

How do the CGM and IGM connect galaxies to the cosmic web by regulating gas supply, feedback, and metal enrichment?

How do galaxies exchange gas, metals, and energy with their surroundings?

What controls the efficiency with which gas is converted into stars inside galaxies?

Can we map the baryon cycle from the CGM to the cosmic web?

Where are the missing baryons associated with galaxies and dark matter halos?

How did the cycle emerge during the epoch of reionization?

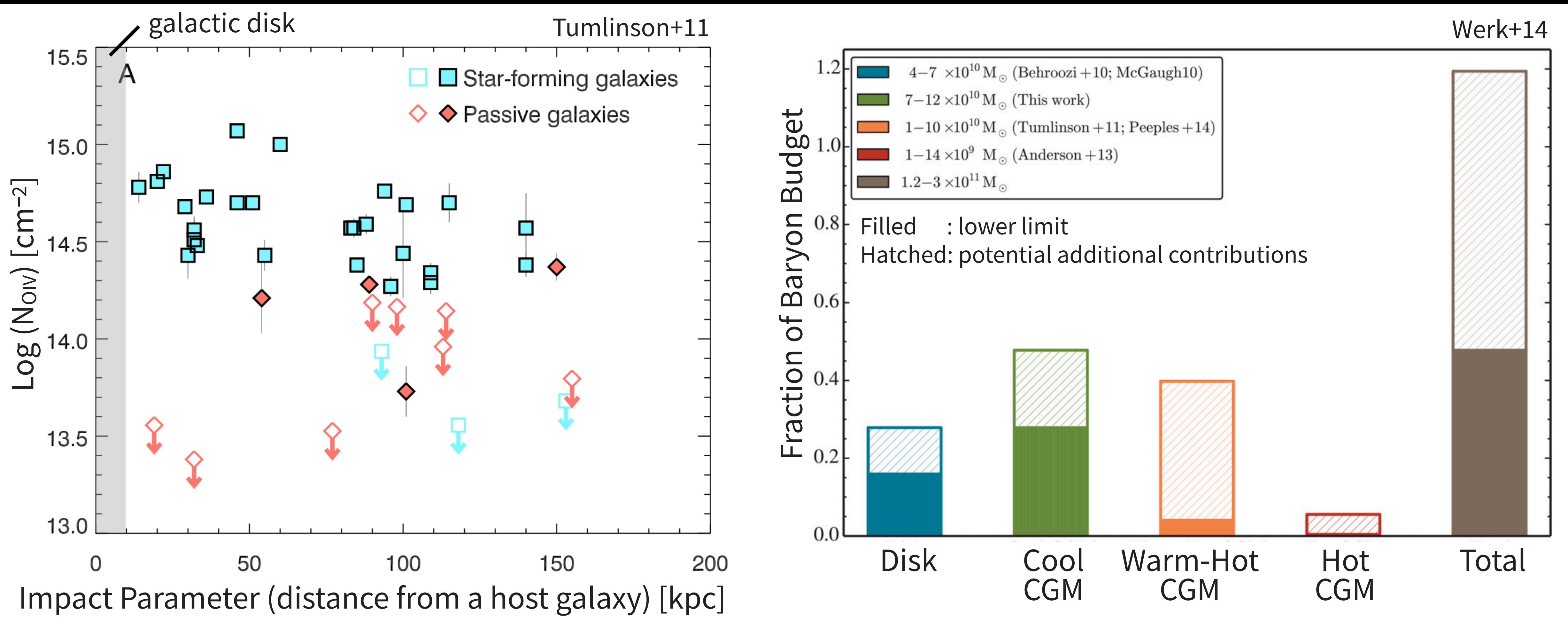
How do galaxies live and die within the cosmic baryon cycle?

How does the cosmic baryon cycle evolve across cosmic time?

How do stellar and AGN feedback drive gas out of galaxies, and how far does this gas travel?

The CGM/IGM as a hidden baryon reservoir

Q1. Where are the baryons, and what phase?

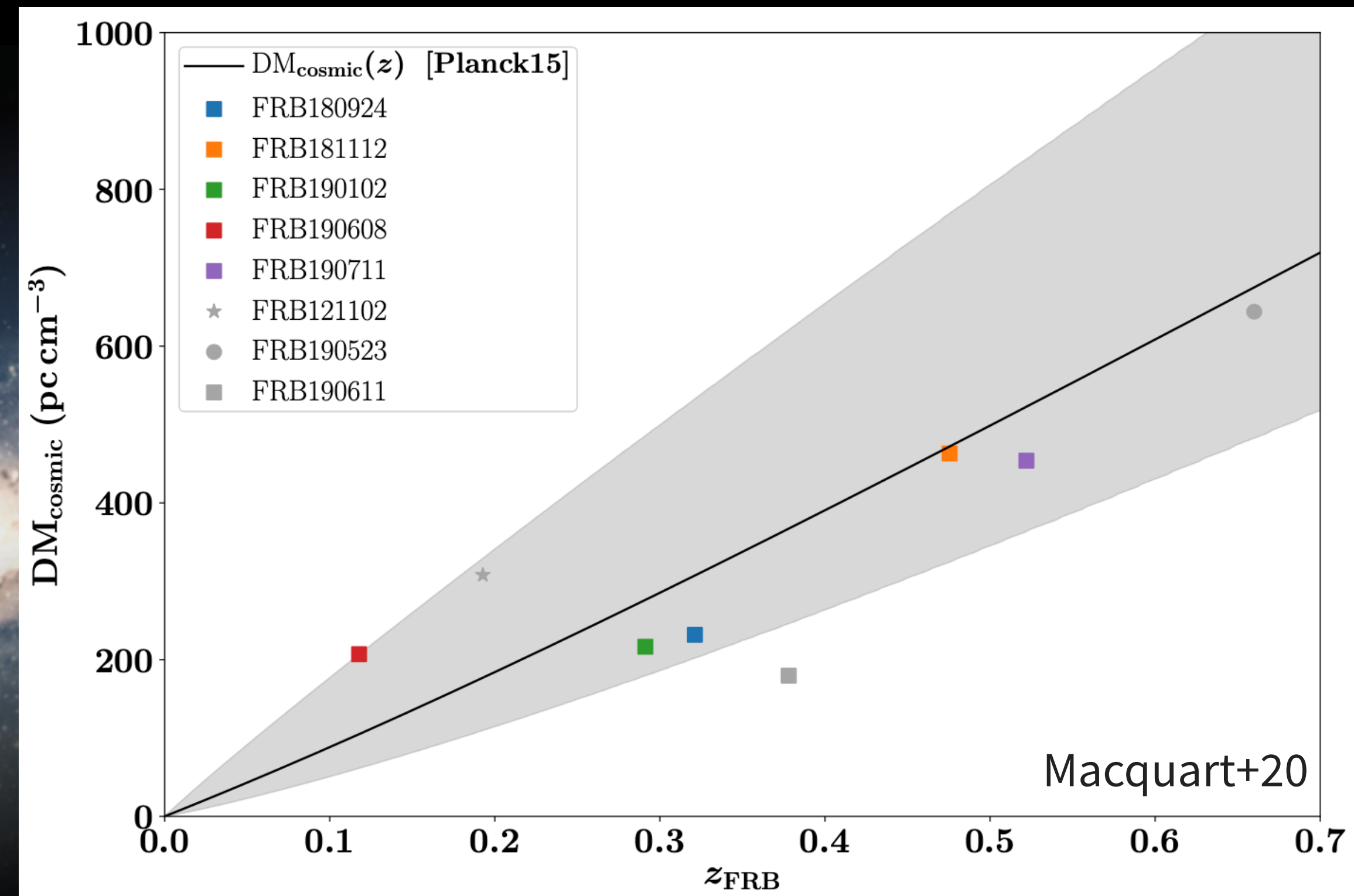
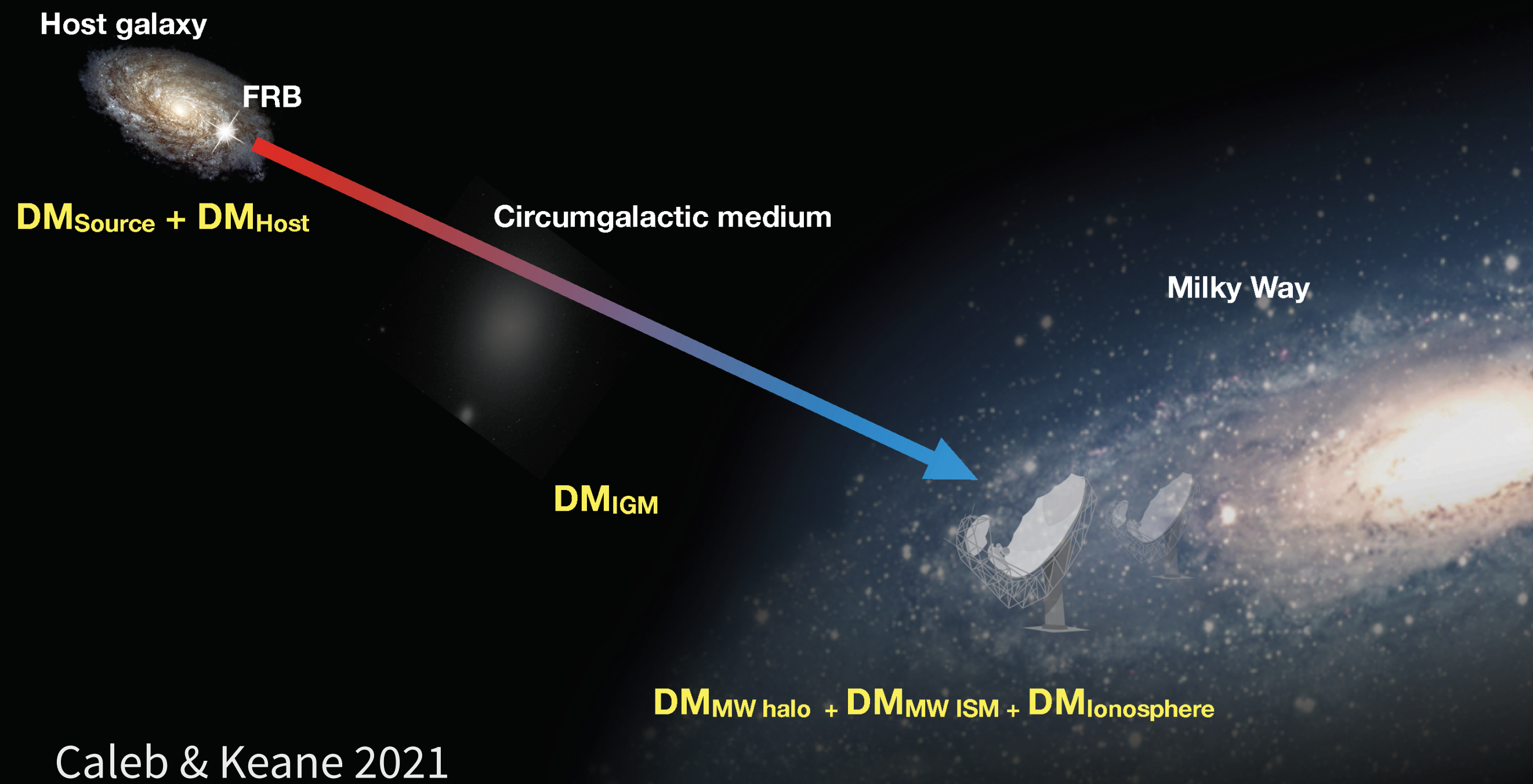


OVI is detected far beyond the stellar disk.

Cool CGM's gas mass can be comparable to the ISM.

The CGM/IGM as a hidden baryon reservoir

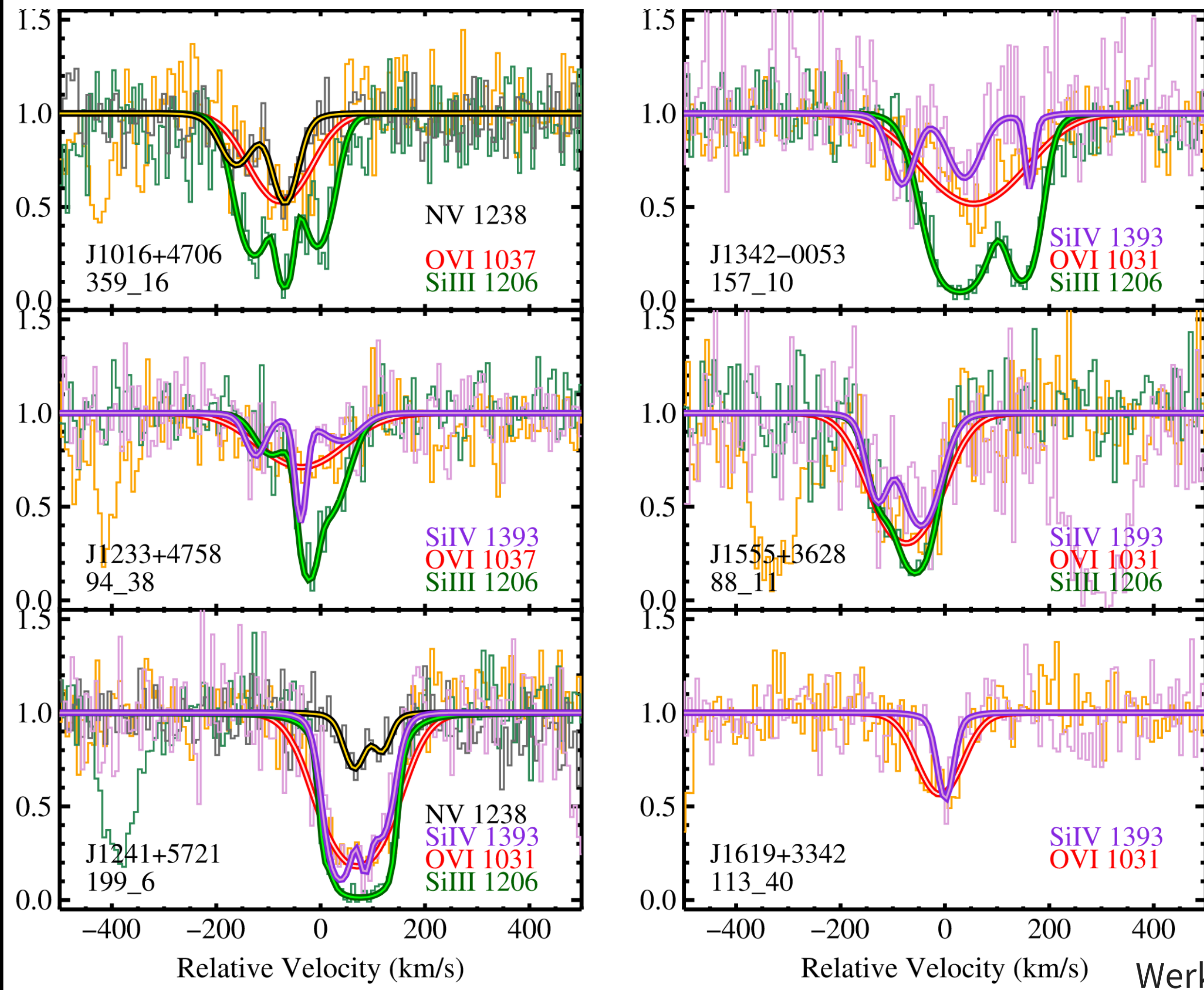
Q1. Where are the baryons, and what phase?



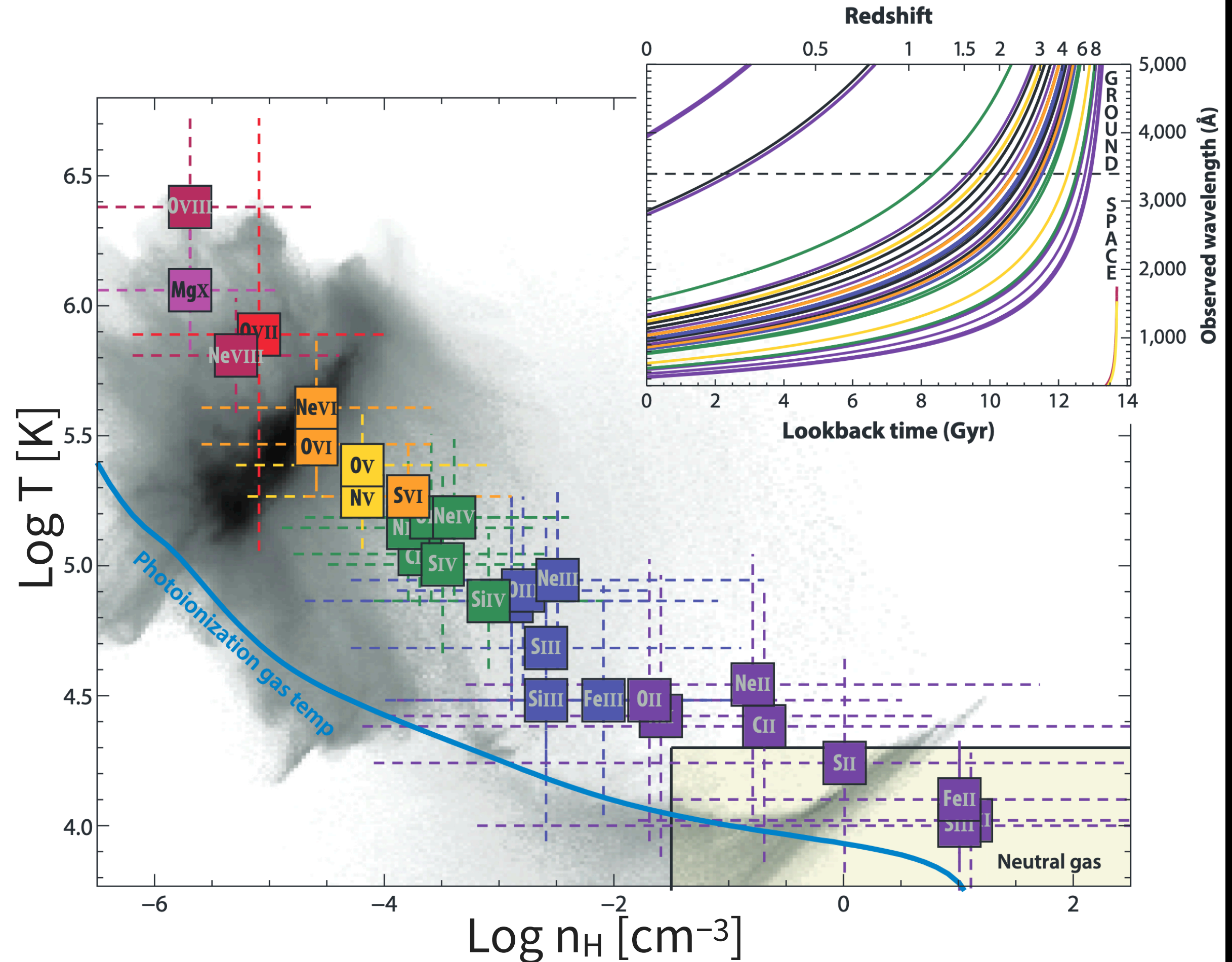
FRB dispersion measures have independently probed the large reservoir of ionized baryons in the diffuse IGM.

The CGM is multiphase: baryons are not in a single reservoir

Q1. Where are the baryons, and what phase?



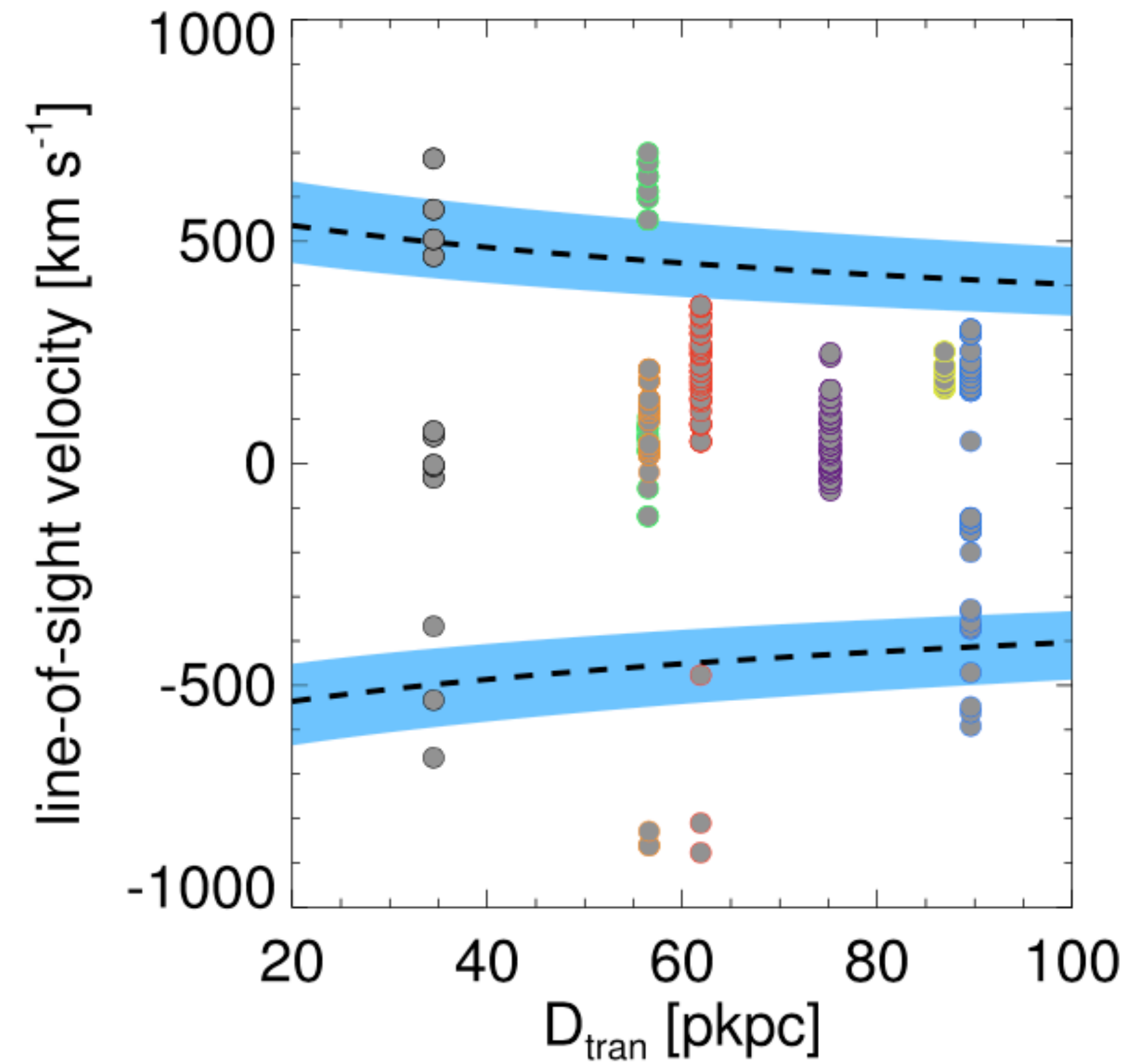
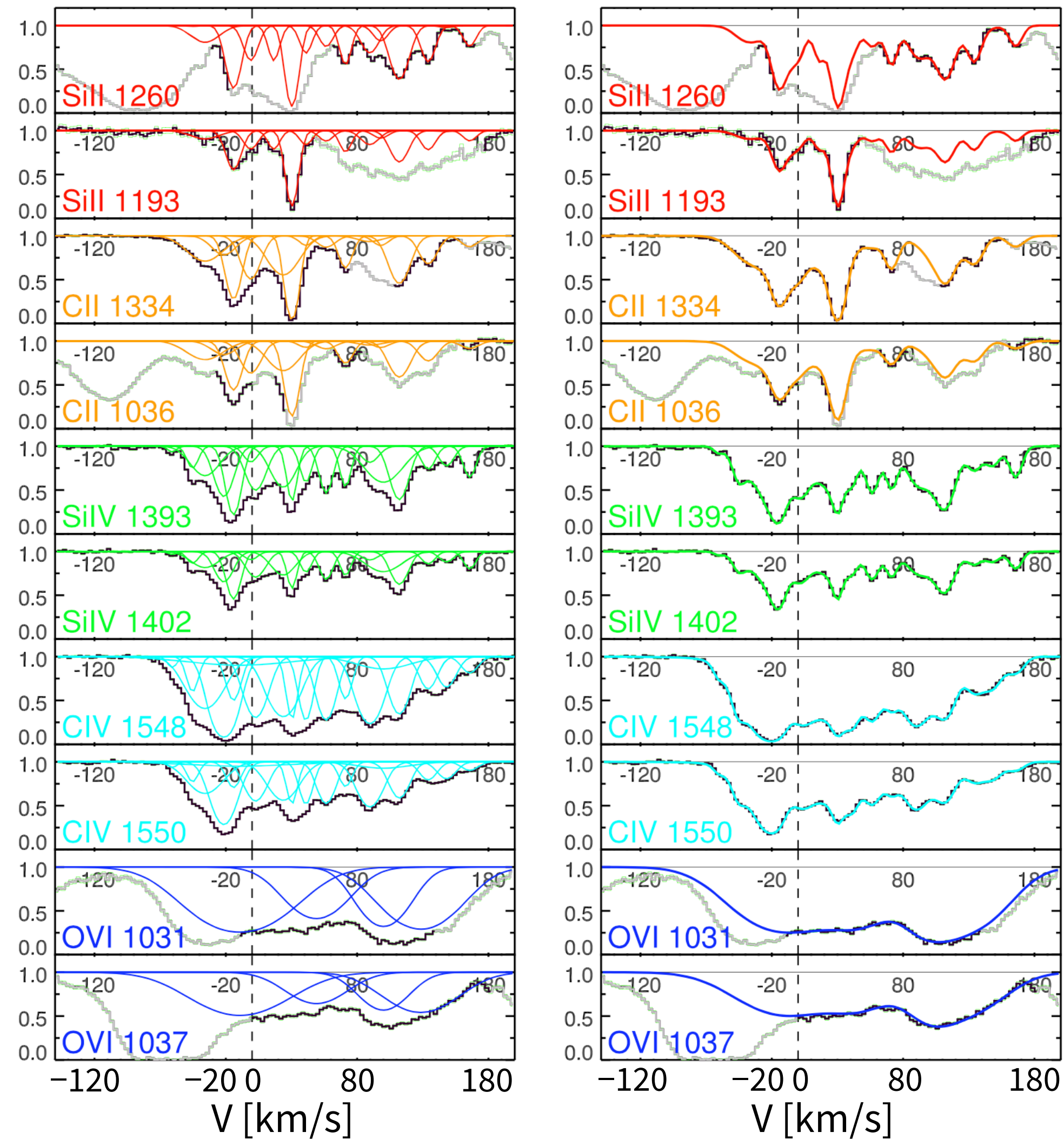
Werk+16



Tumlinson+17

From reservoir to circulation: feedback and metal enrichment

Q2. How do galaxies exchange gas, metals, and energy?



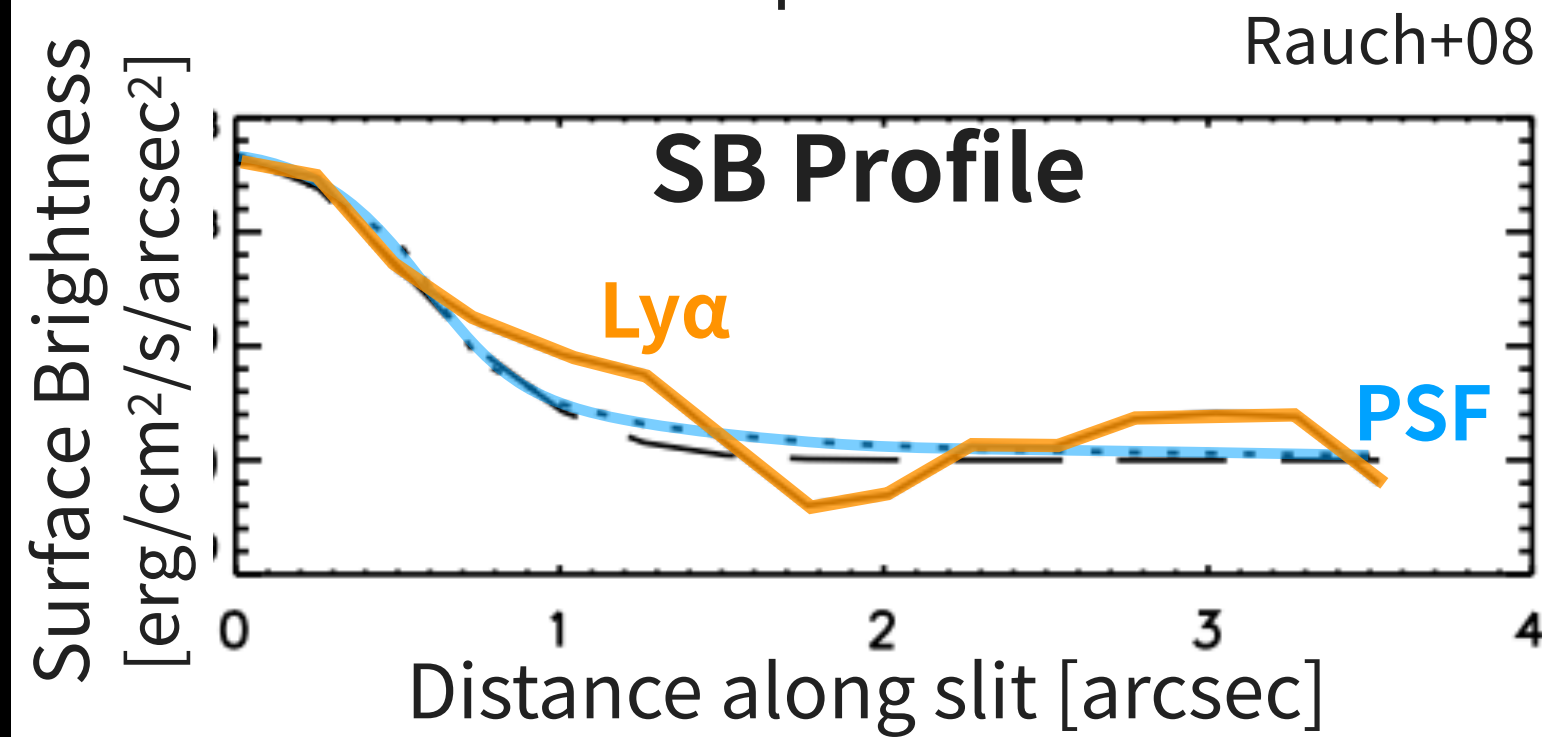
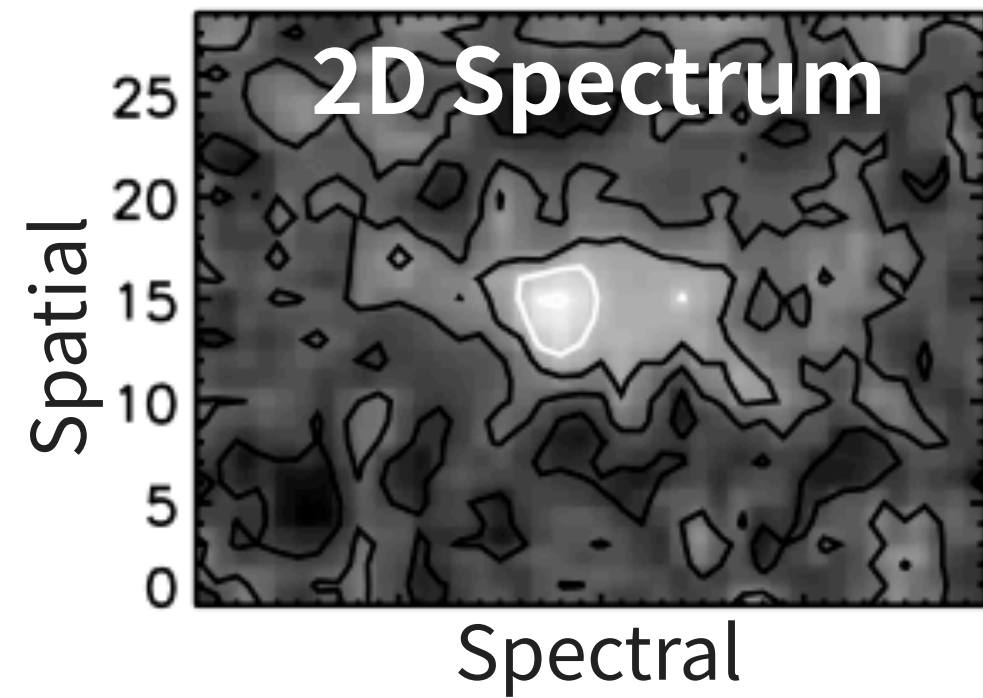
Rudie+19 (e.g., Rudie+12)

From absorption to emission I: searching for halos via emission

Q2. How do galaxies exchange gas, metals, and energy?

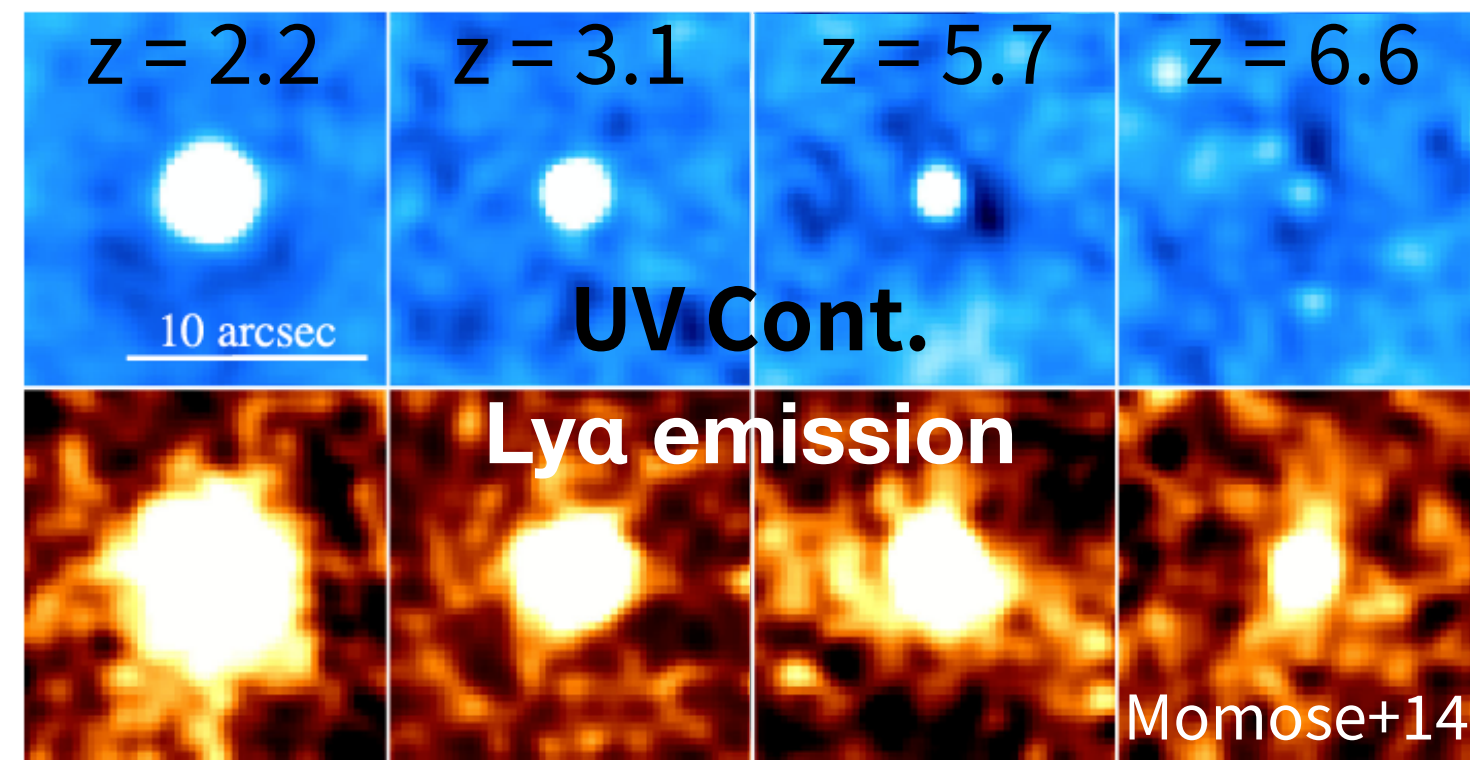
Deep Spectrum

Identifying extended Ly α emission

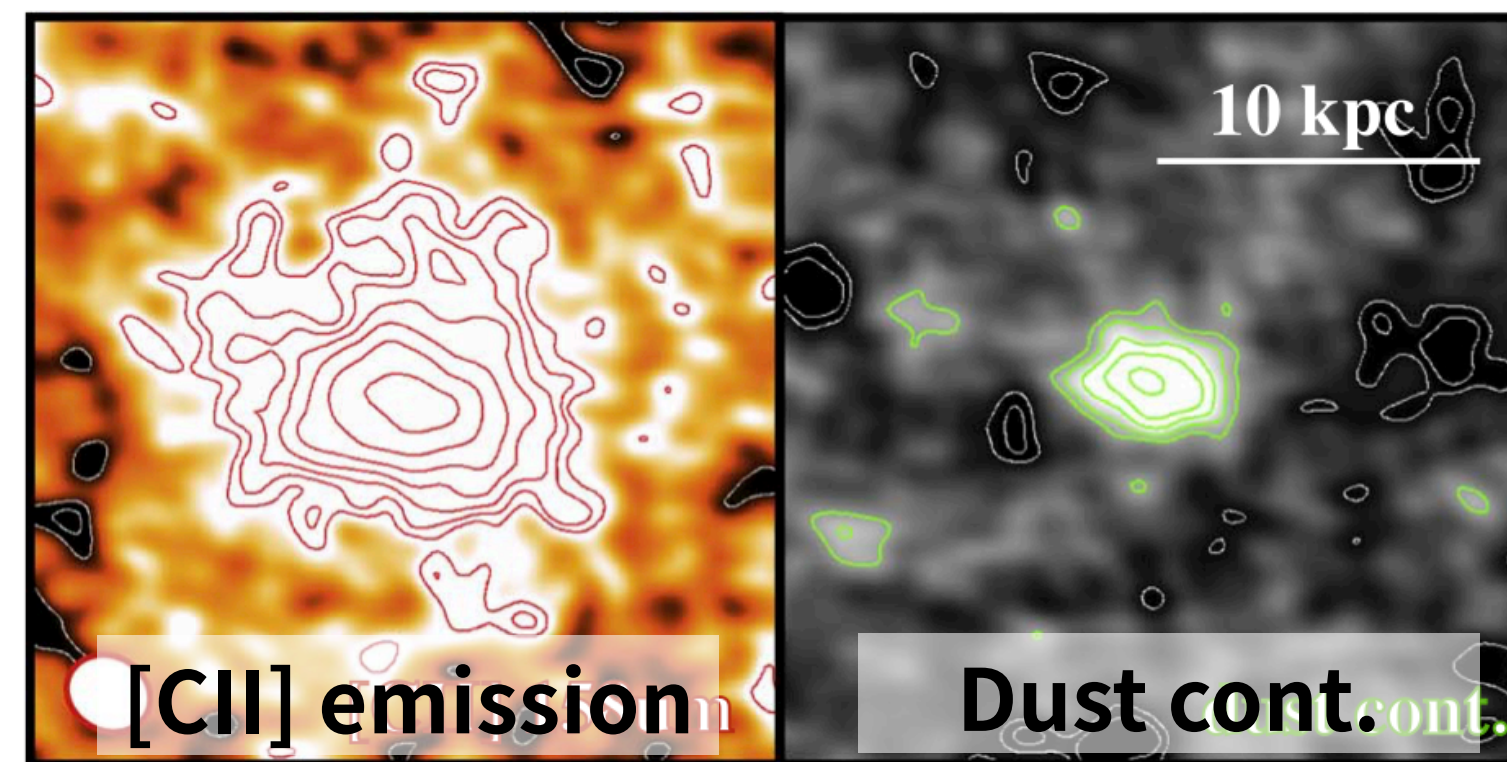


Stacking Analysis

Statistical halo detection



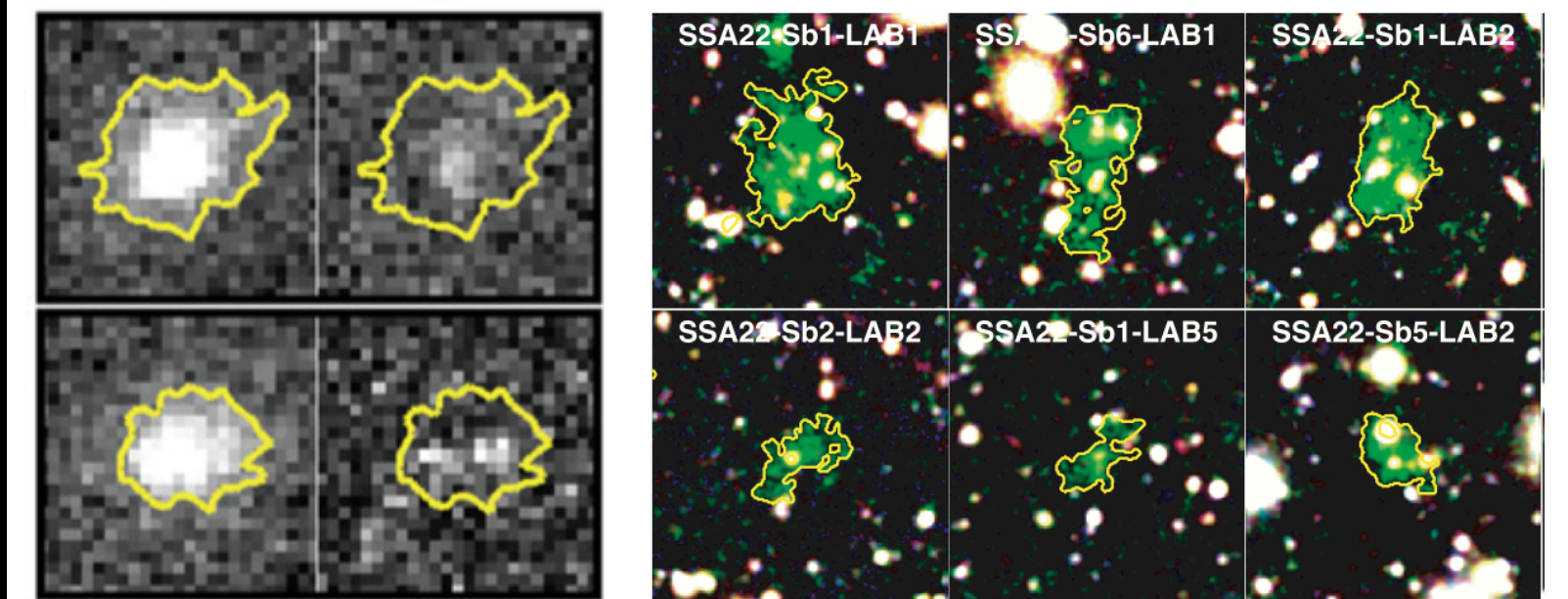
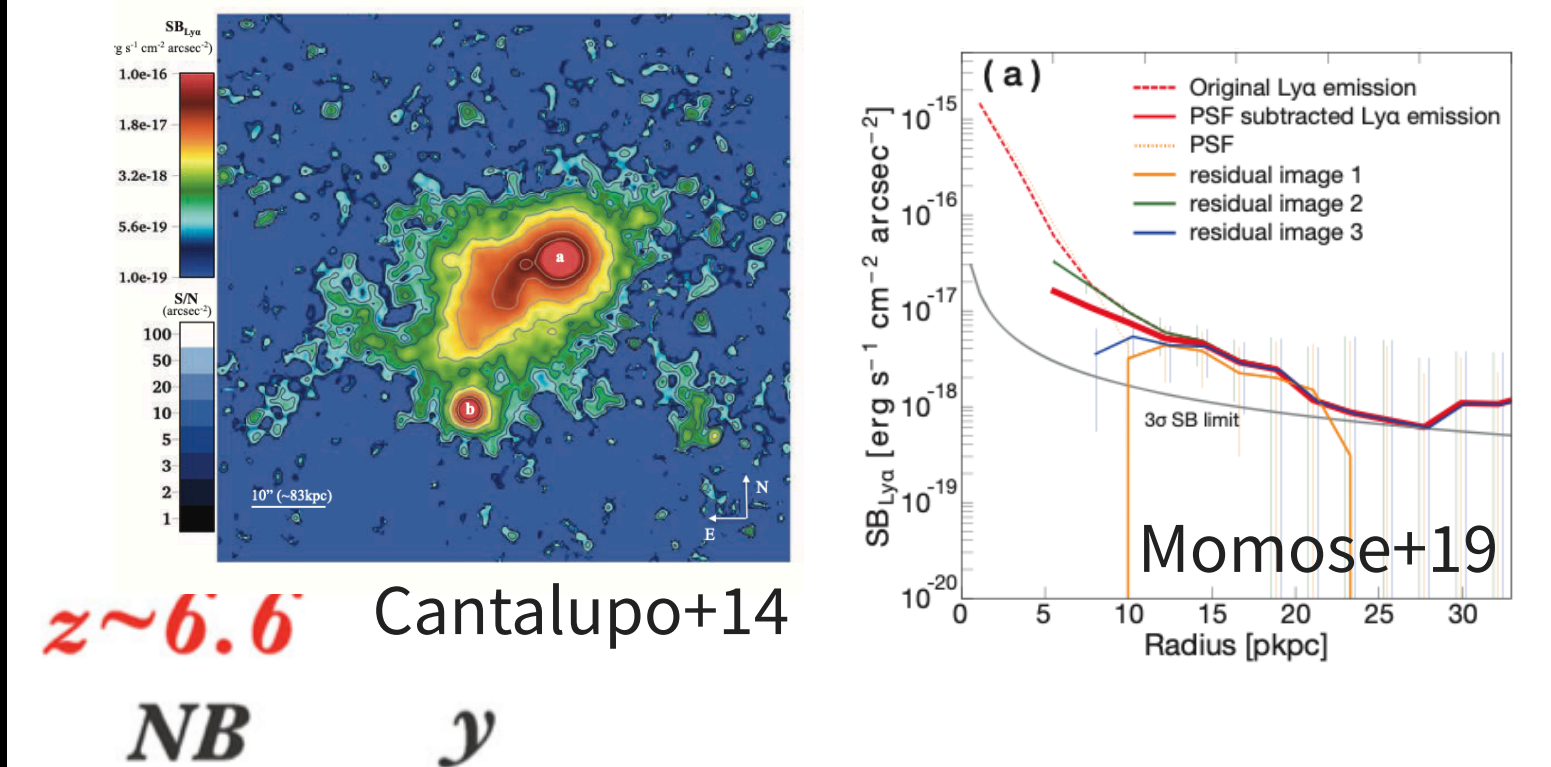
(e.g., Hayashino+04, Steidel+11, Matsuda+12, Zhang+24)



Fujimoto+19 (e.g., Fudamoto+22)

Individual Ly α nebulae

Around quasars and starburst



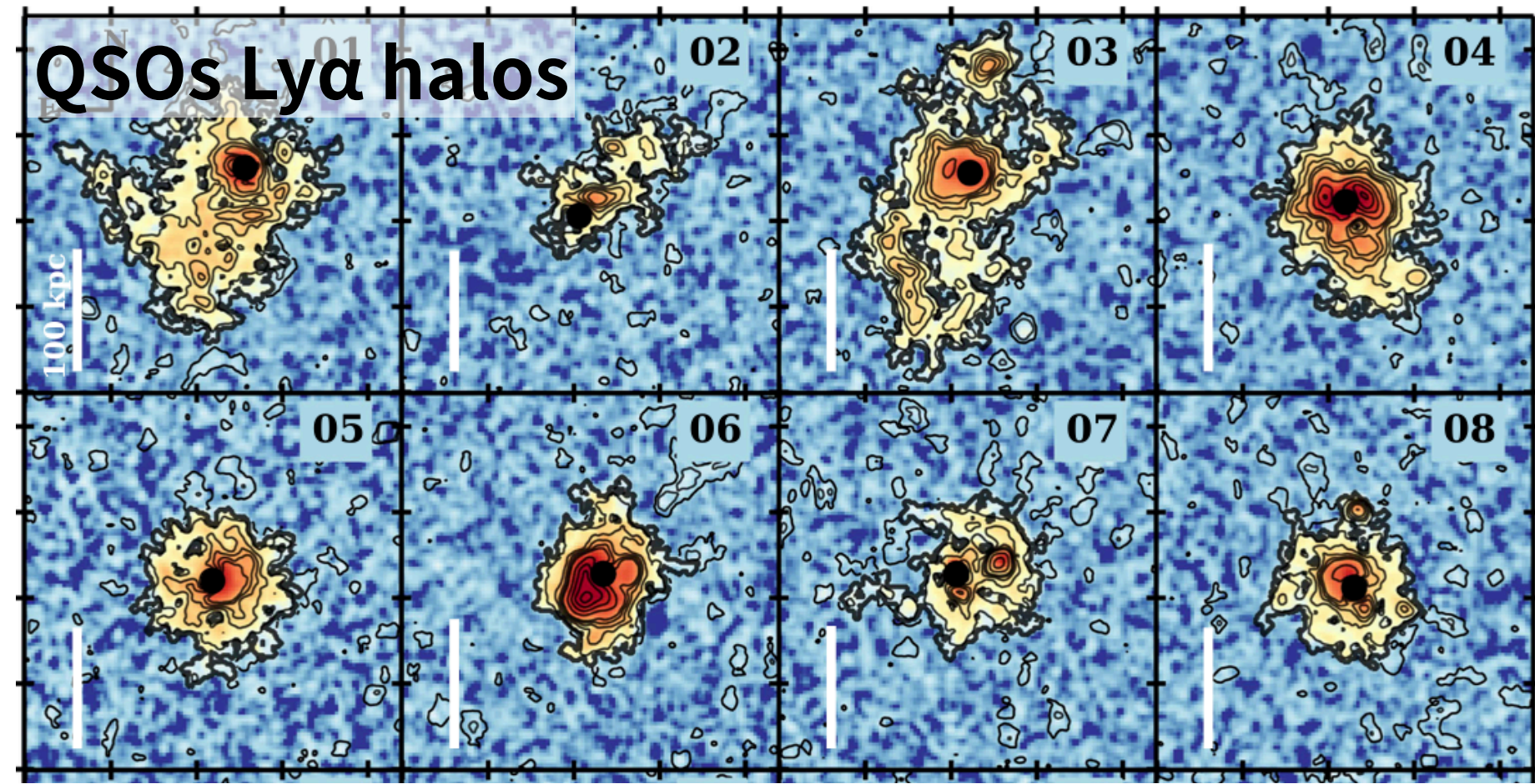
Shibuya+19

Matsuda+11

(see also e.g., Matsuda+04,09, Saito+06, Prescott+08,09, Ouchi+09, Goto+09, Rauch+13, Kashikawa+14, Kikuta+19, Mukae+20, Zhang+20, Vandana+23, Li+24, Shimakawa+25, Byeongha+26)

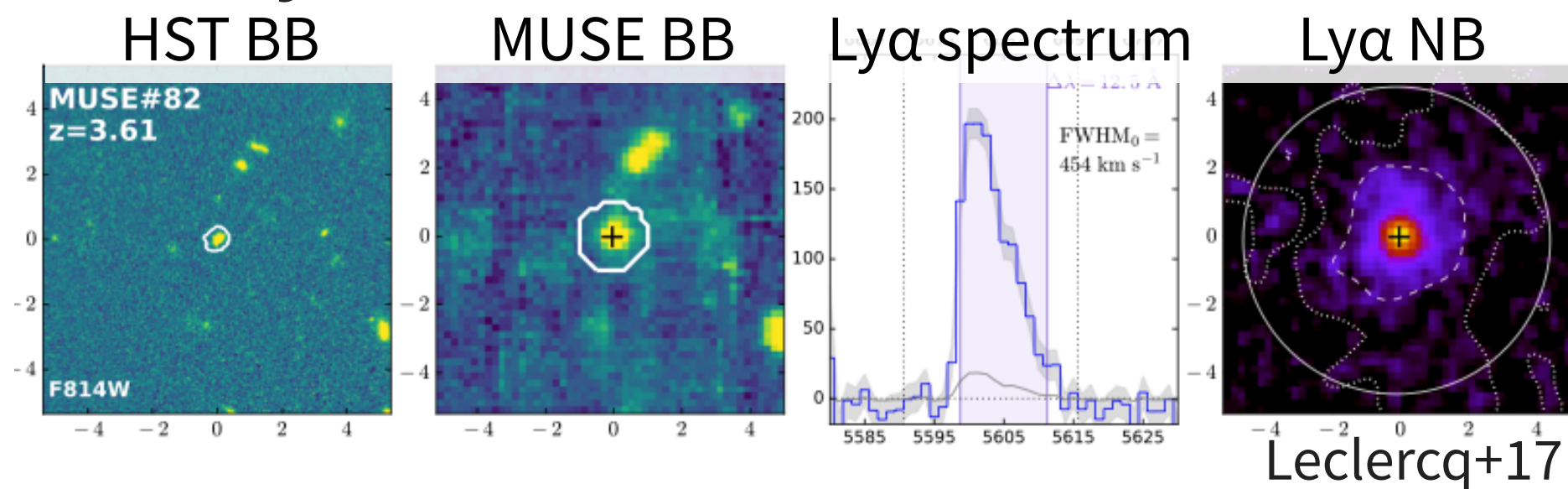
From absorption to emission II: individual CGM structures

Q2. How do galaxies exchange gas, metals, and energy?

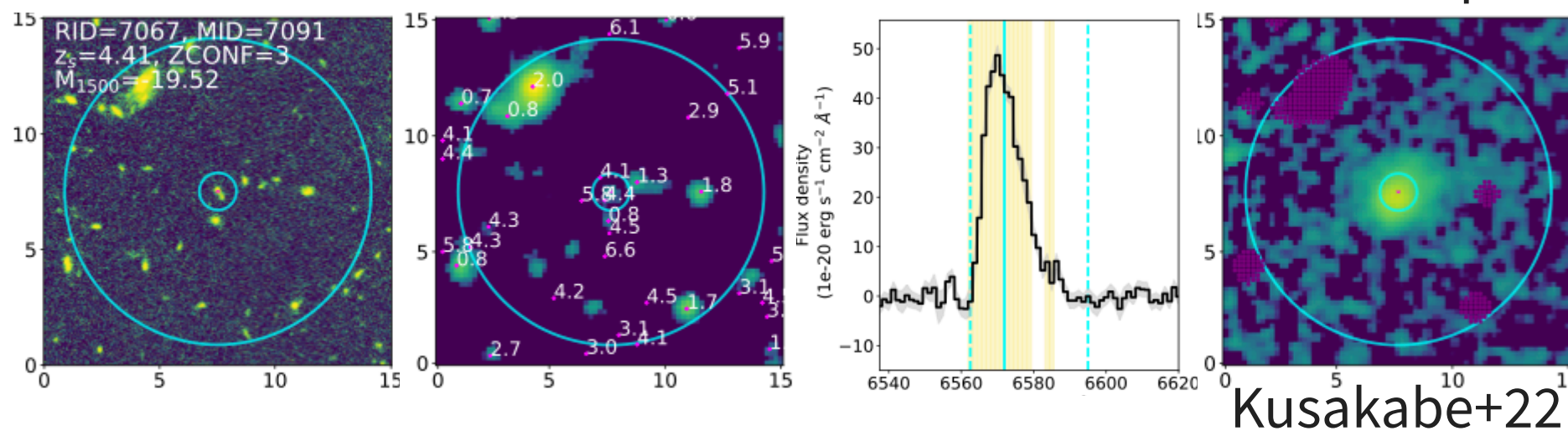


Borisova+16

SFGs Ly-alpha halos

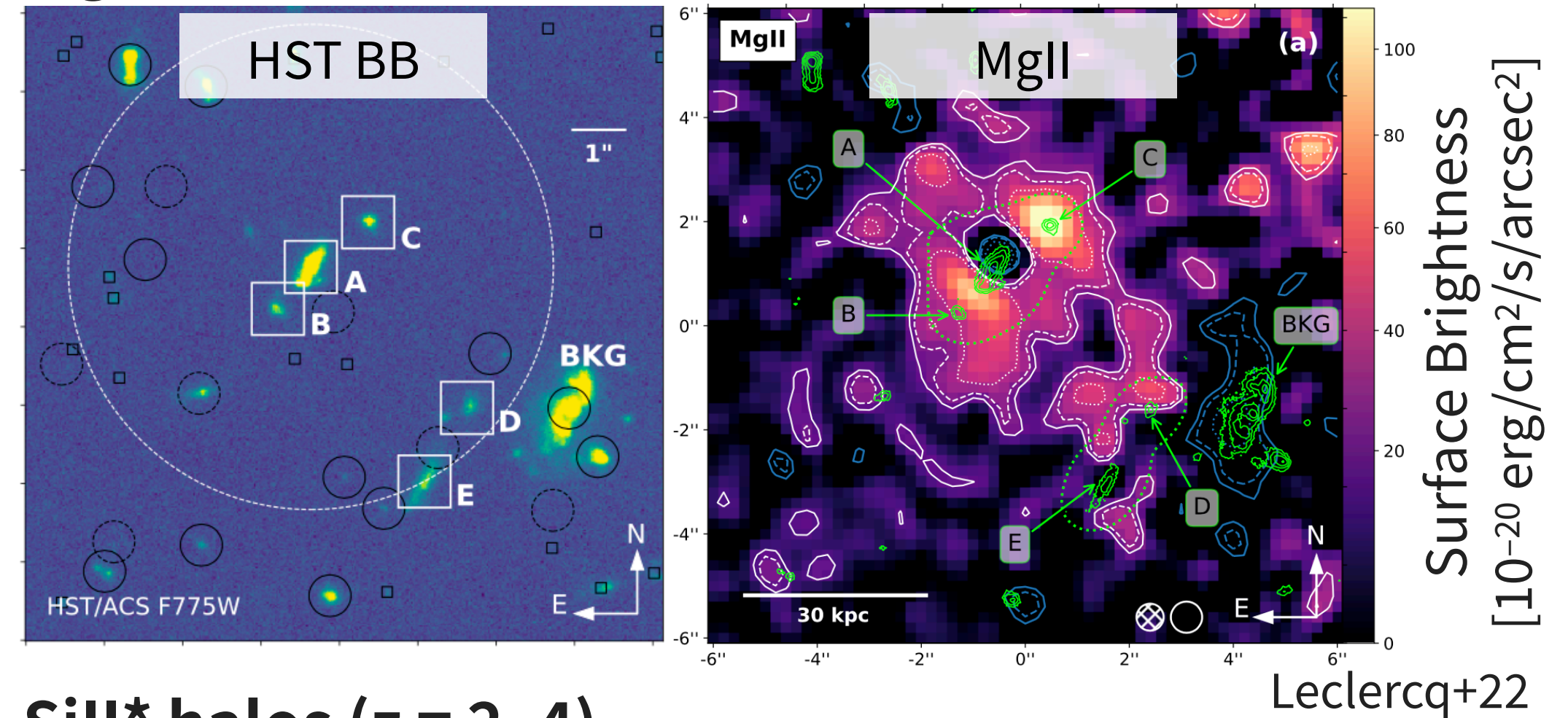


Leclercq+17

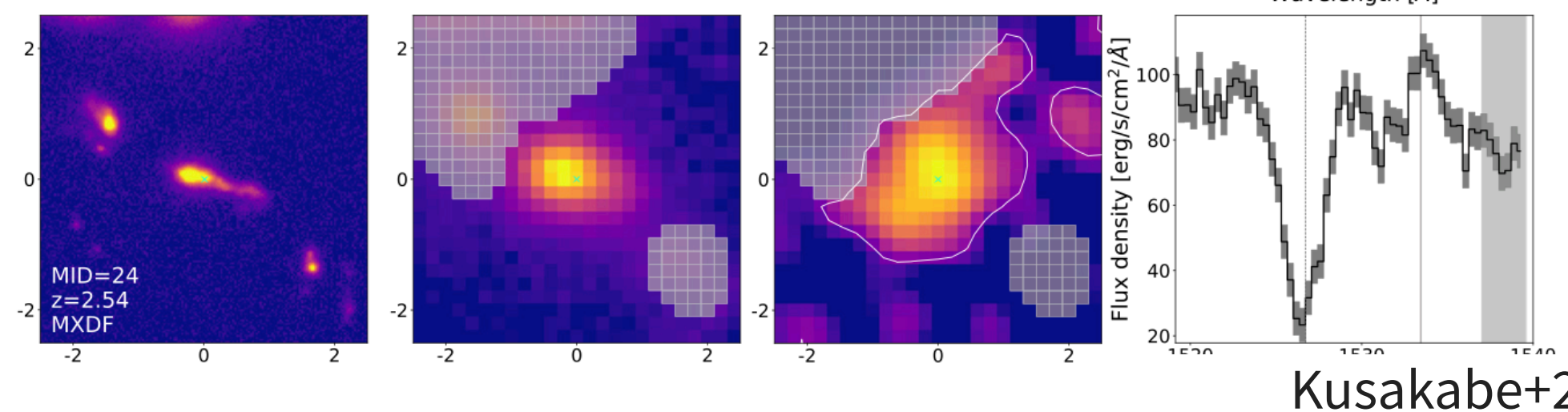
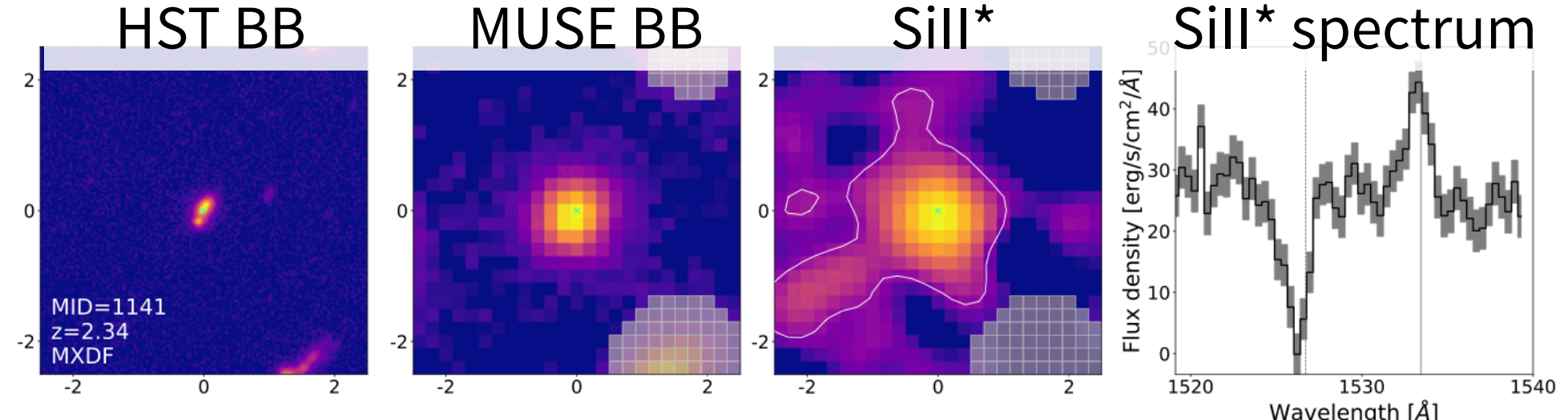


Kusakabe+22

MgII halos (z < 2.3)



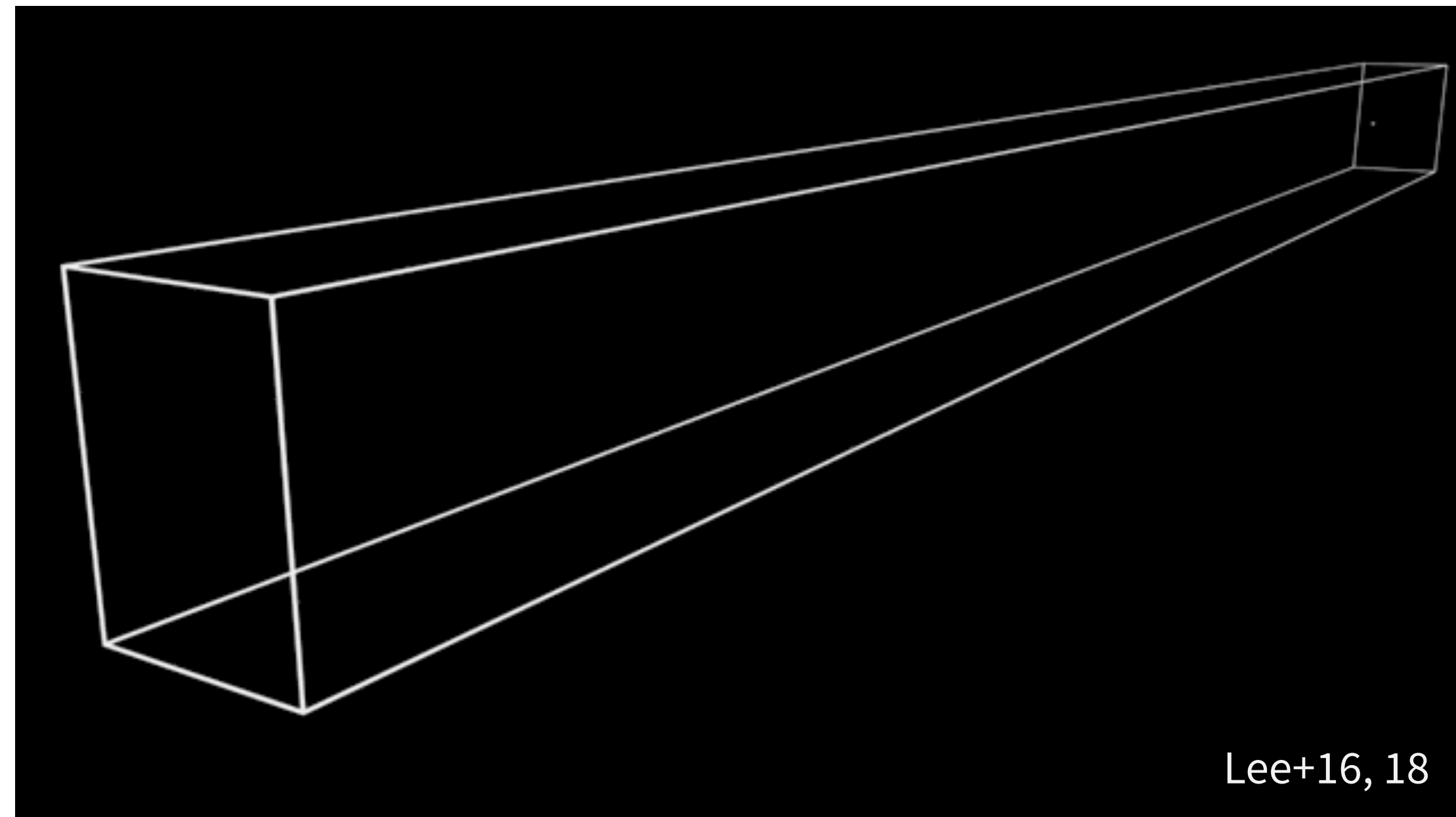
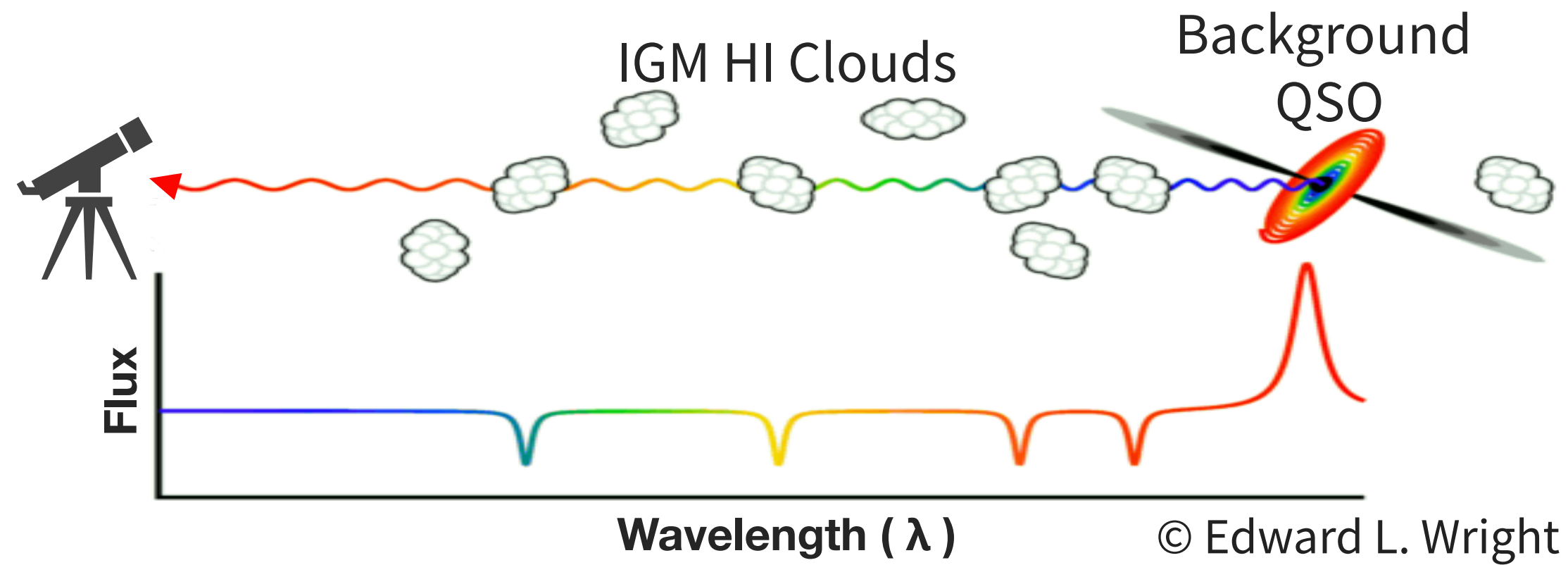
SIII* halos (z = 2-4)



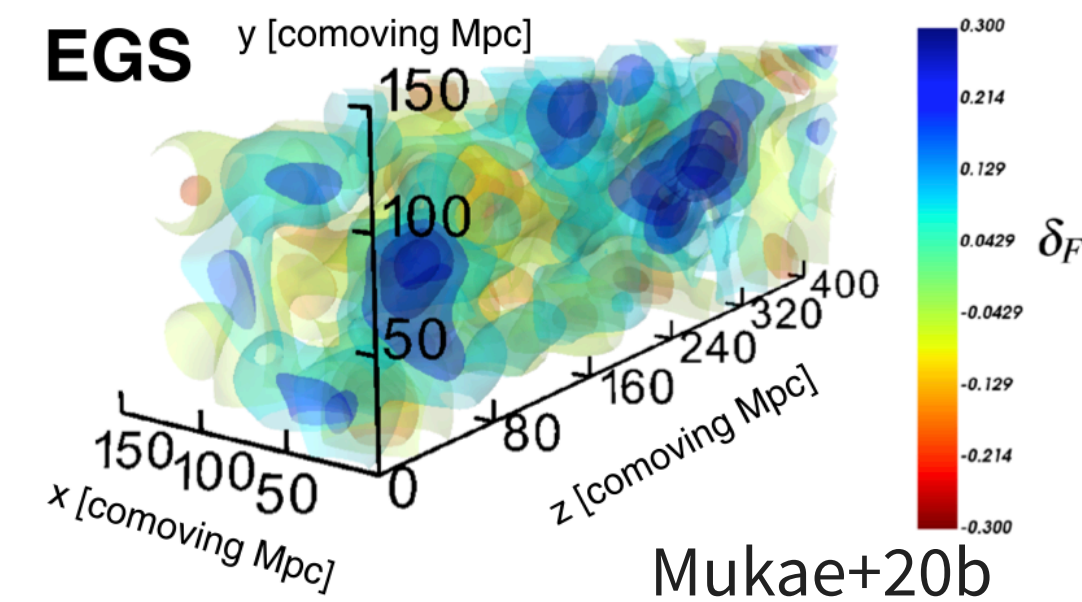
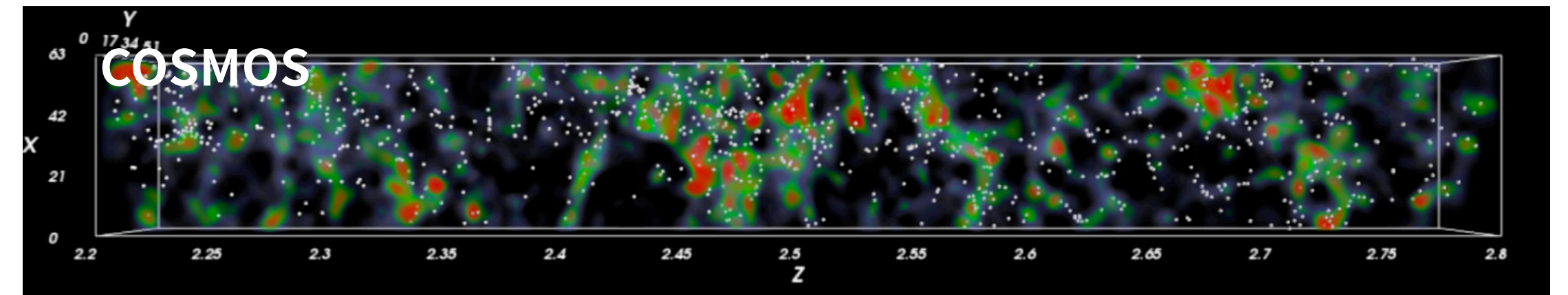
Kusakabe+24

Mapping the baryon cycle in 3D: Ly α forest tomography

Q3. Can we map the baryon cycle?

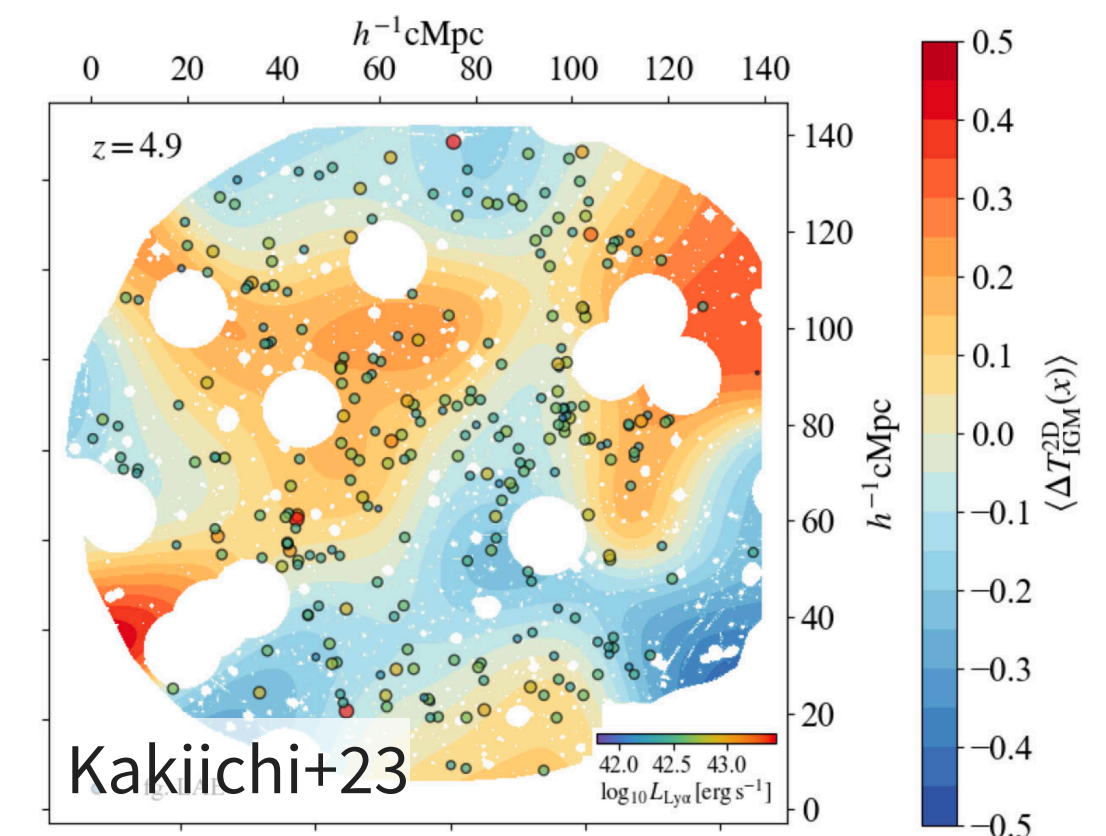
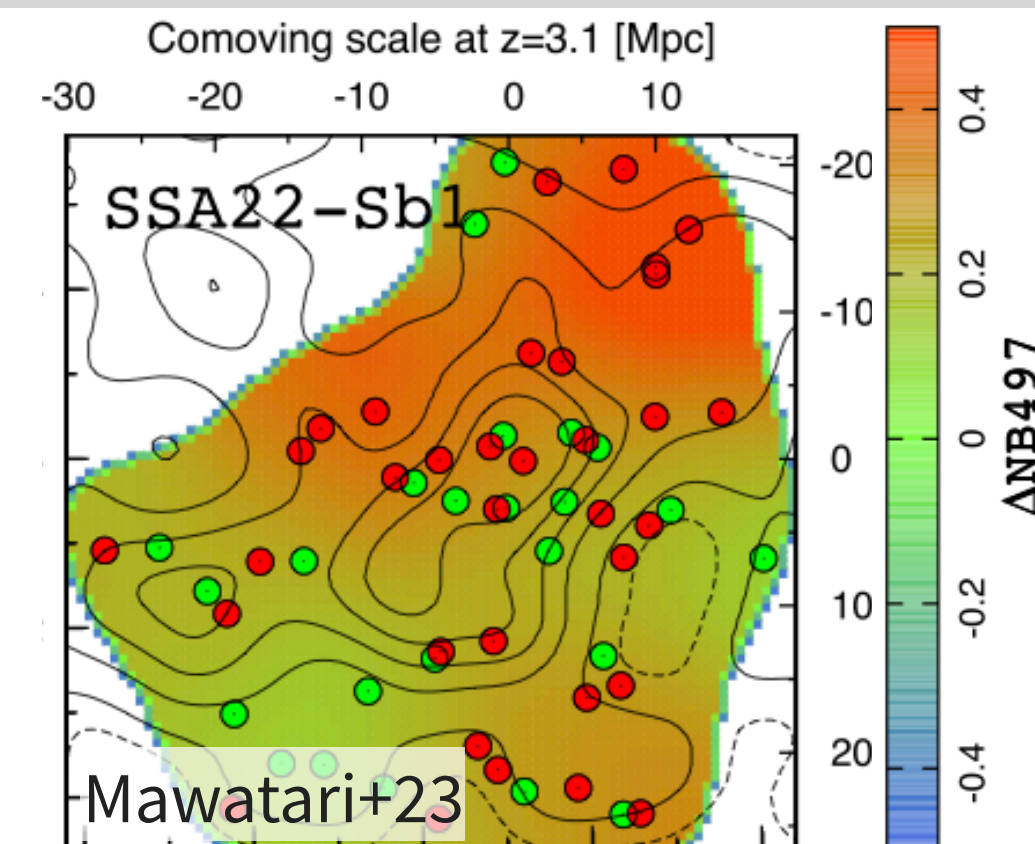


3D IG HI reconstruction



e.g., Lee+16, 18, Mukae+20a,
Ravoux+20; Horowitz +22

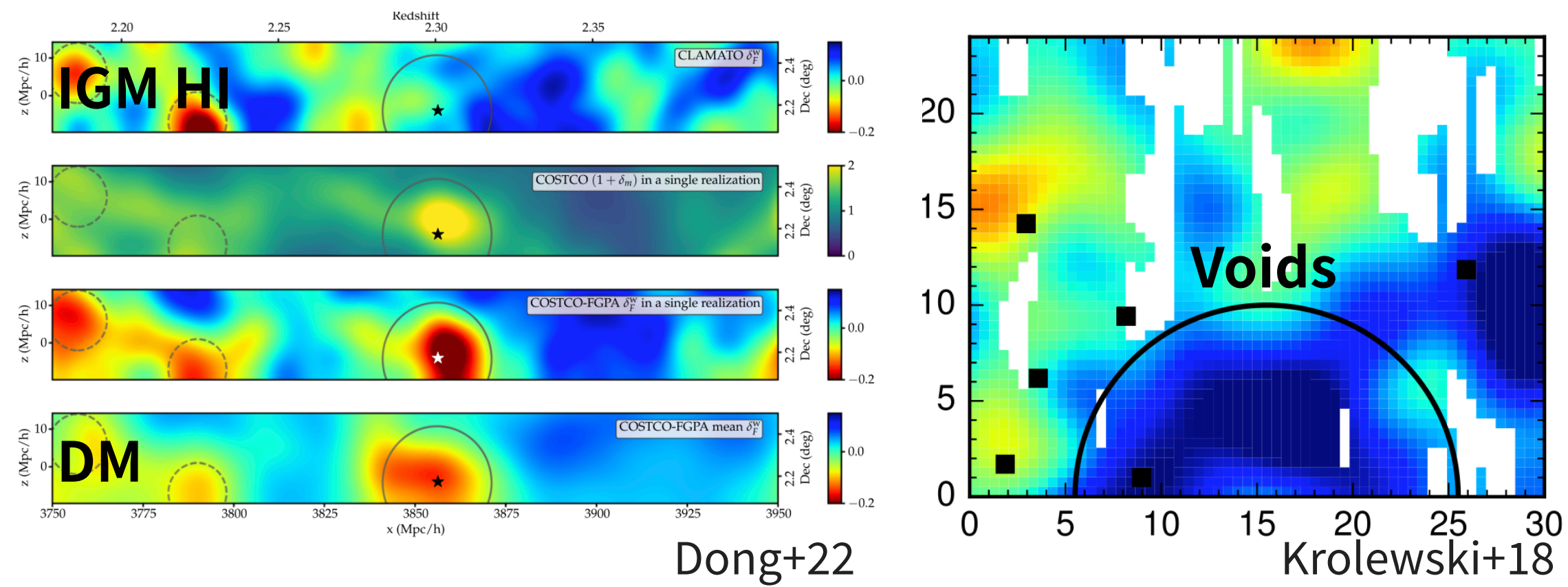
2D IGM HI reconstruction



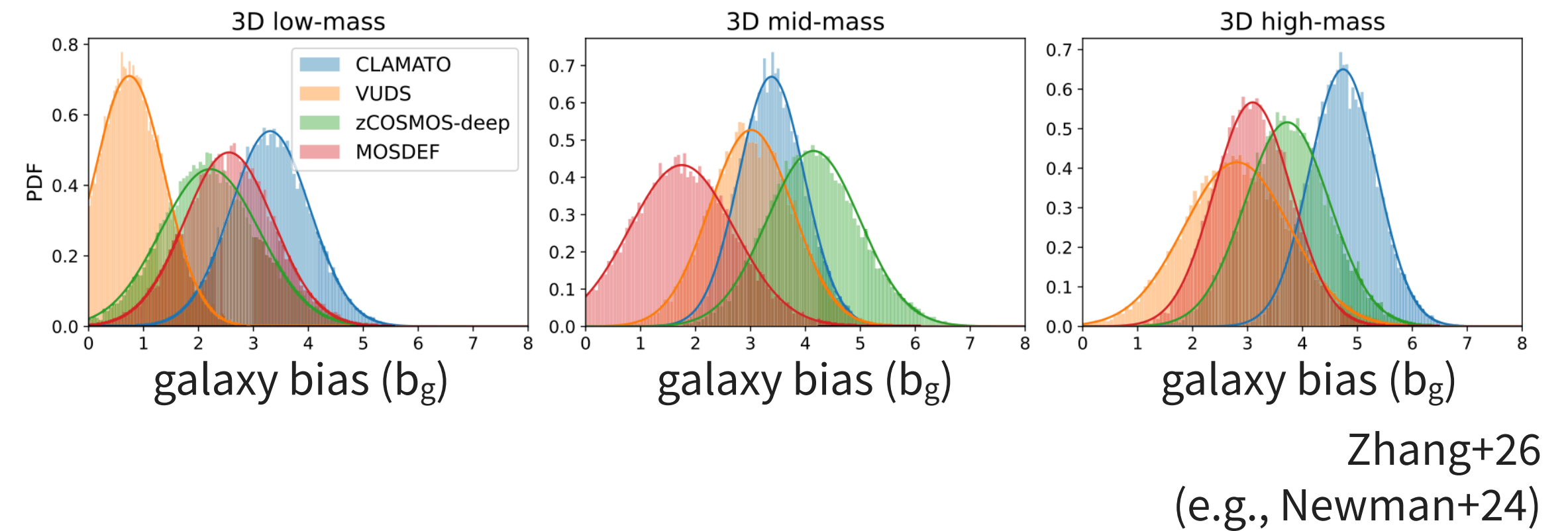
Mapping the baryon cycle in 3D: Ly α forest tomography

Q3. Can we map the baryon cycle?

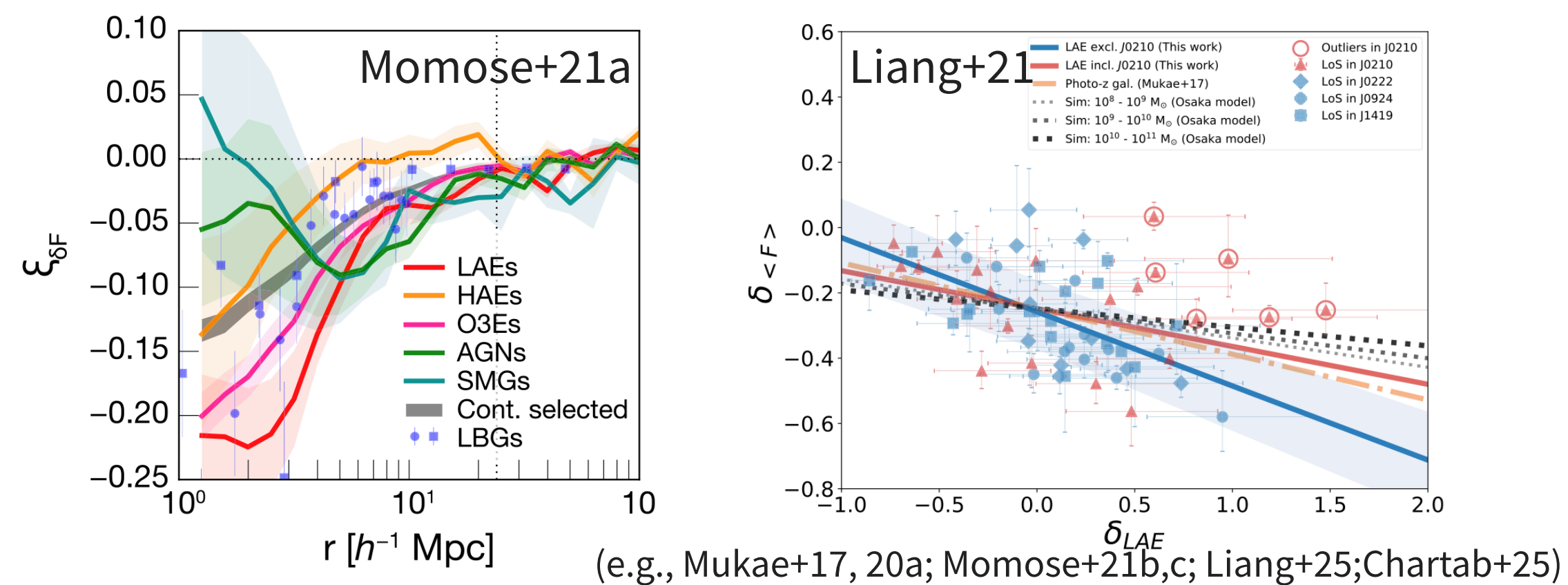
Searching for unique environments



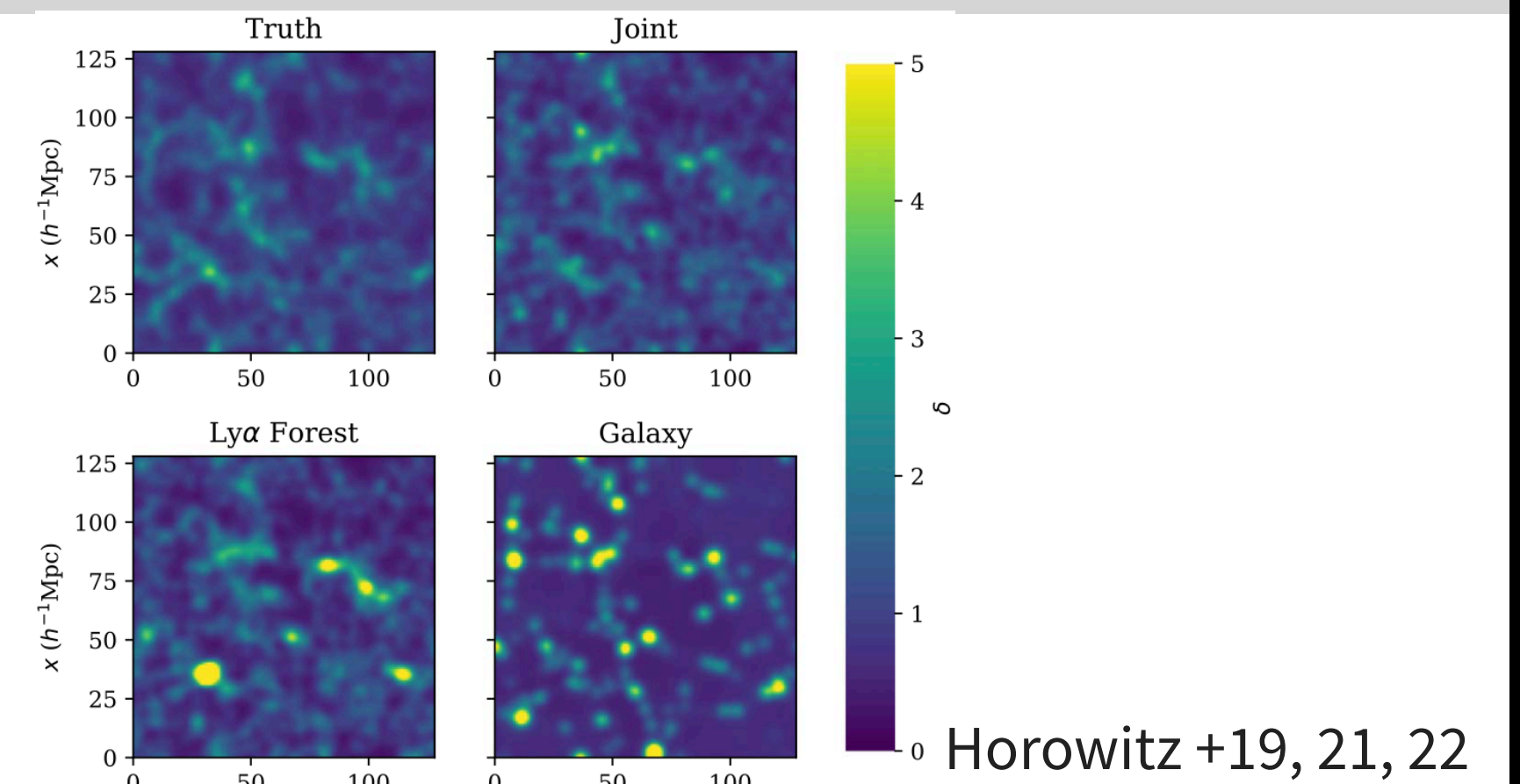
Estimating halo masses of galaxies



Investigating the large-scale gas environments



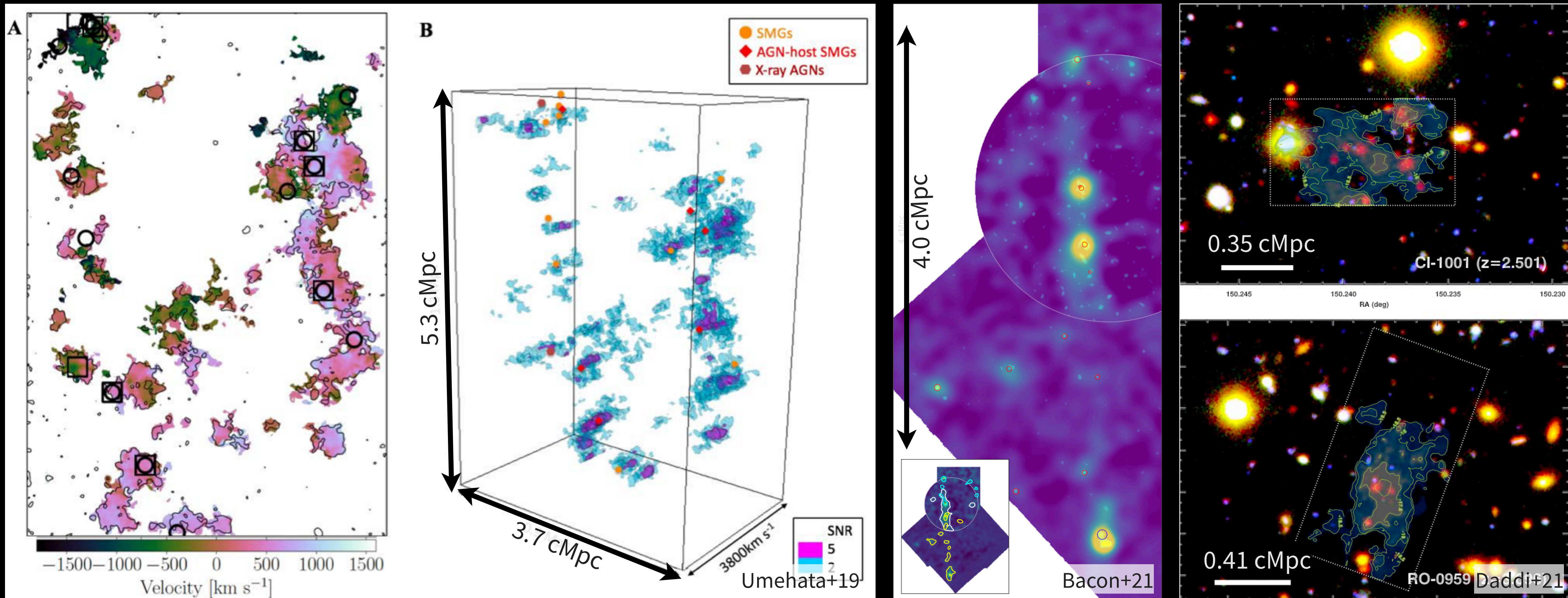
Estimating the underlying matter density fields



Seeing the cosmic web in emission

Q3. Can we map the baryon cycle?

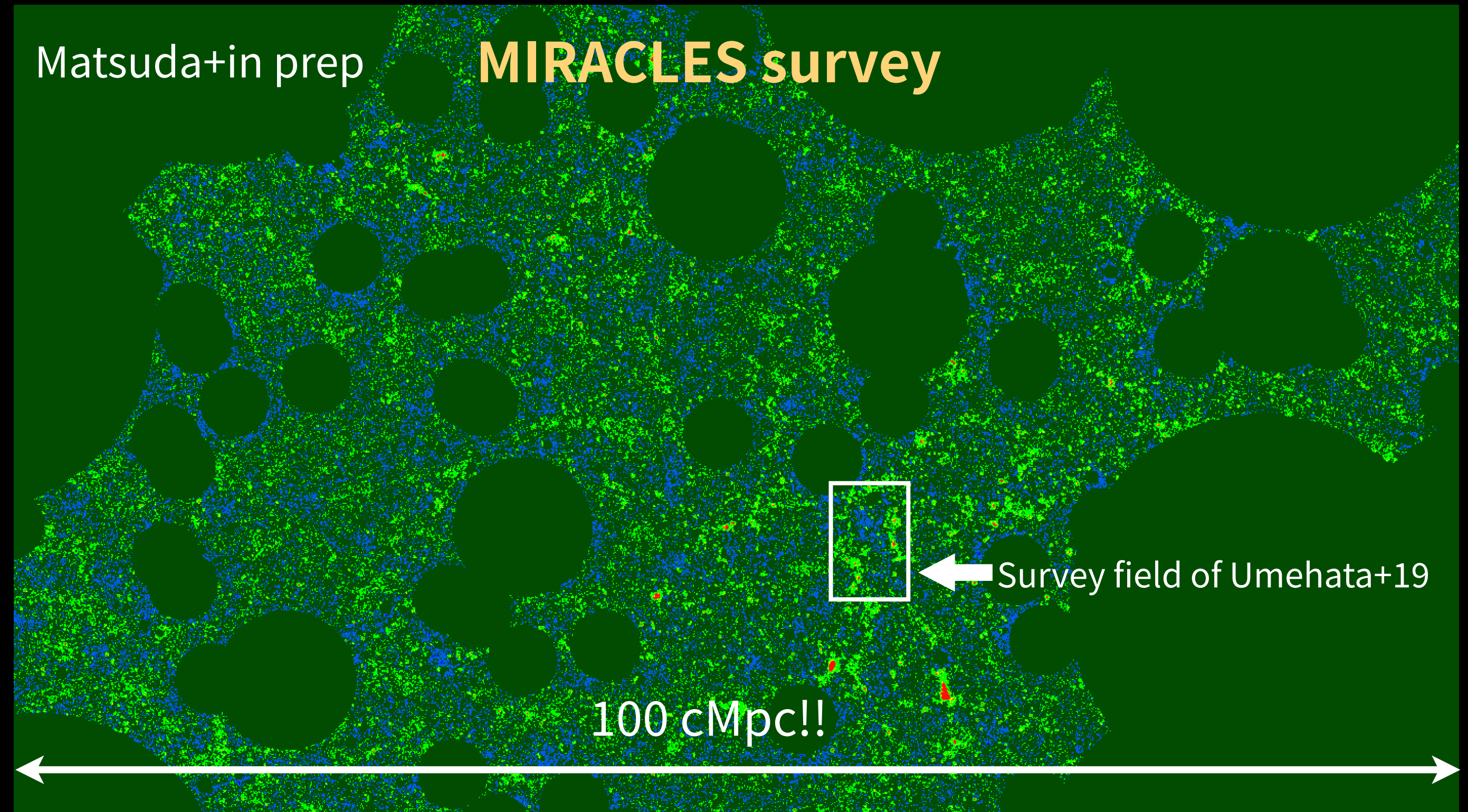
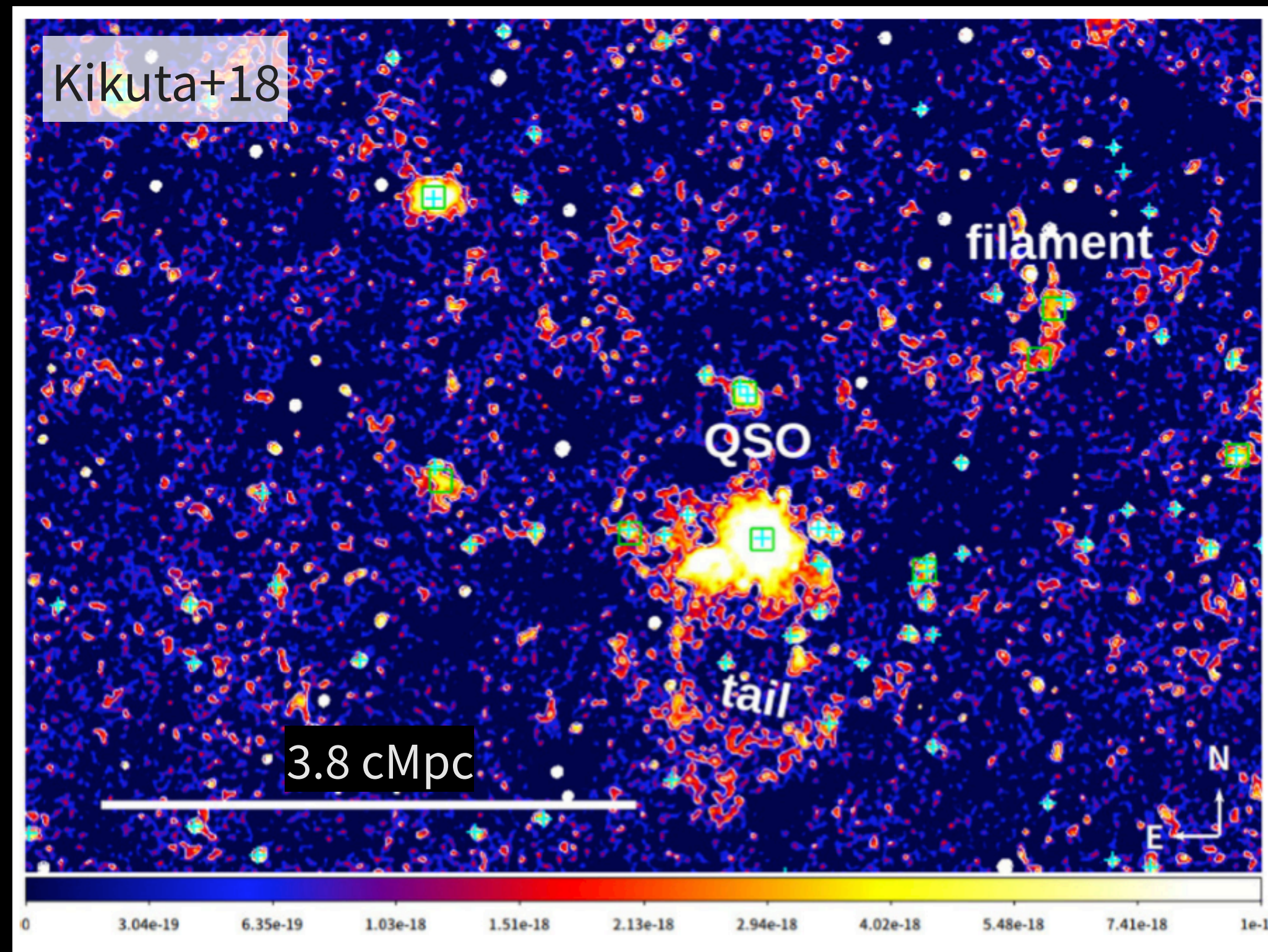
Mpc-scale Ly α emission has been revealed around overdense regions by wide-field IFUs



Seeing the cosmic web in emission

Q3. Can we map the baryon cycle?

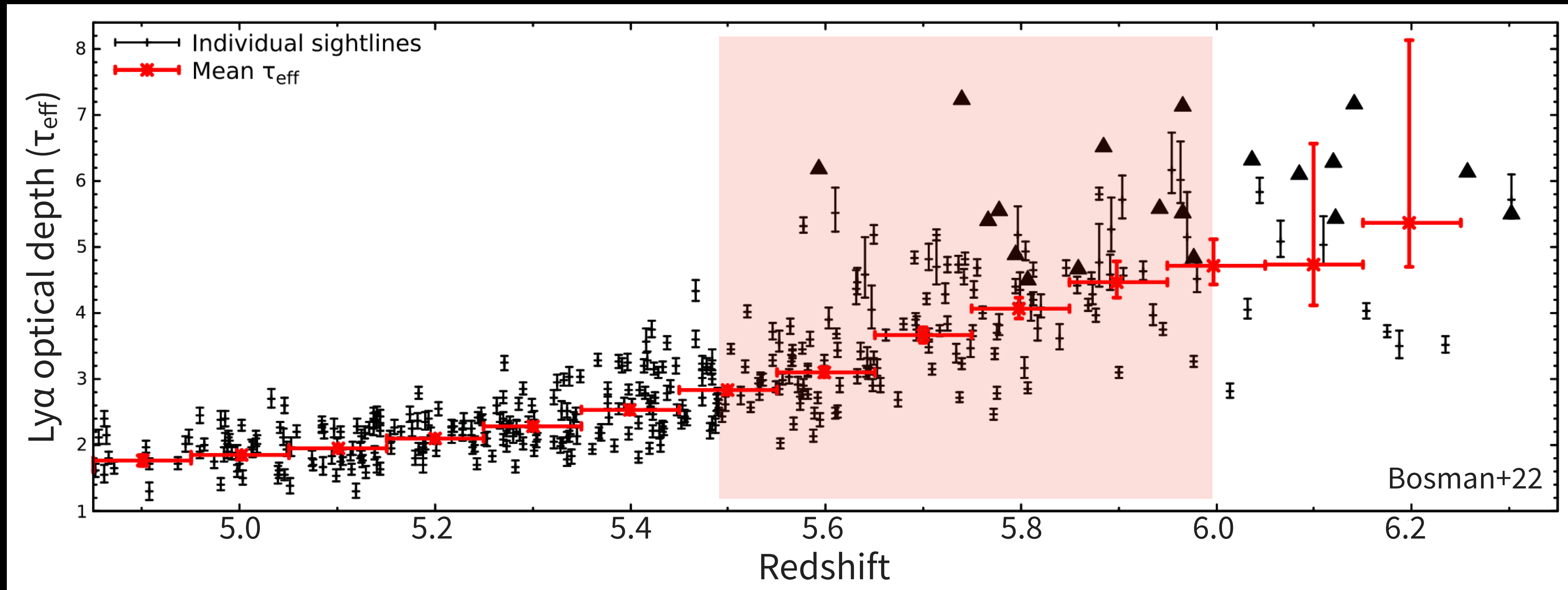
Deep imagings by the **Subaru/HSC** has also contributed to mapping out the cosmic web



The early baryon cycle: patchy and late reionization

Q4. How did the cycle emerge during the epoch of reionization?

How the topology of the IGM is connected to the large-scale galaxy distributions?

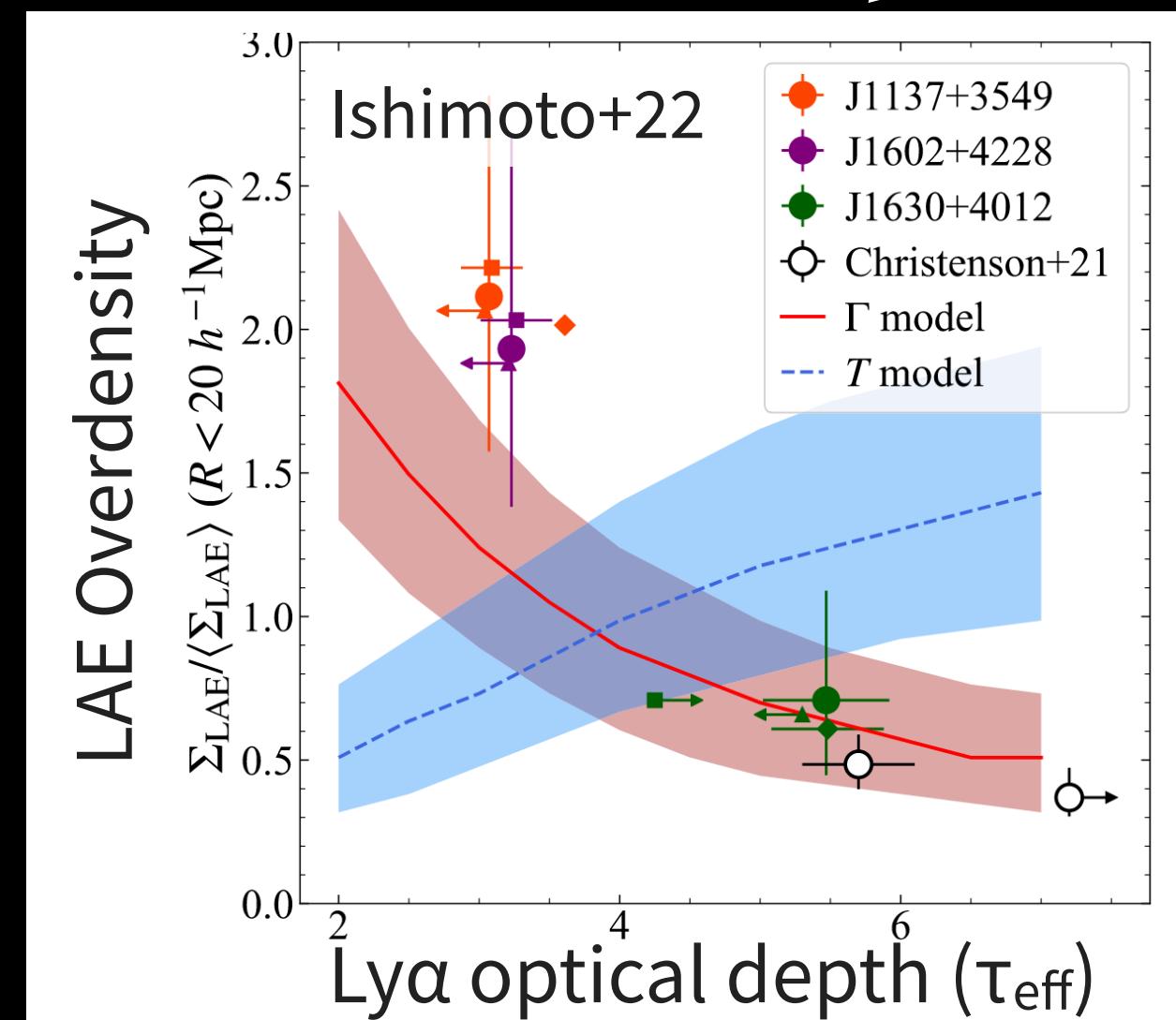
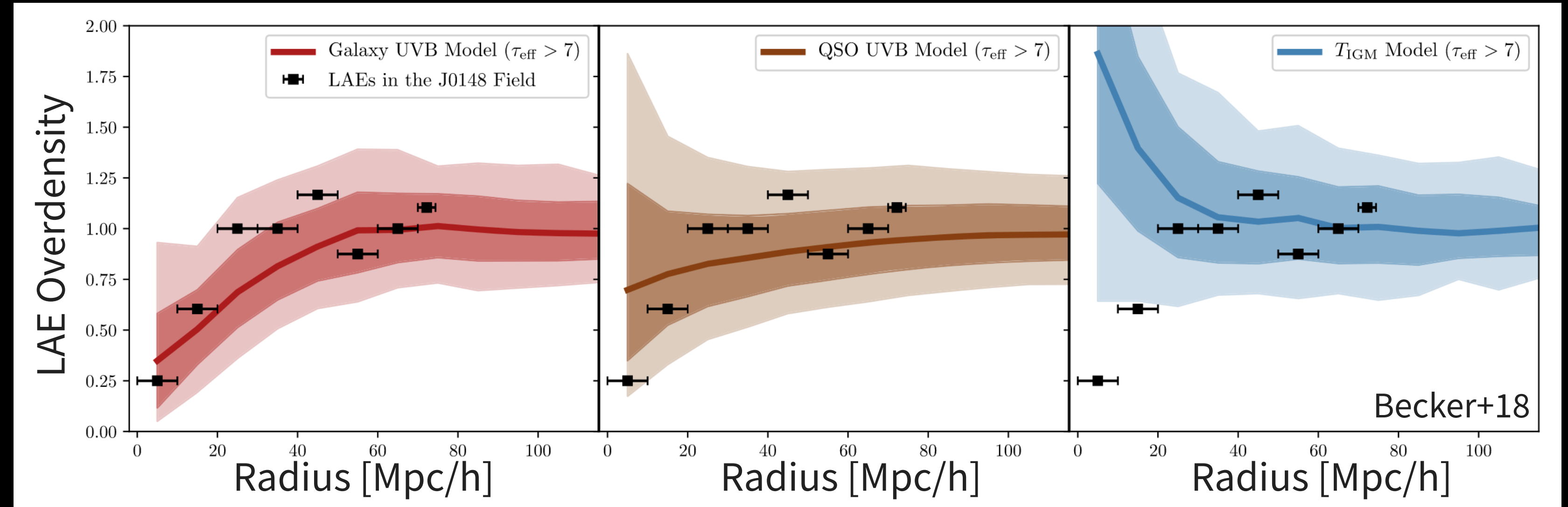
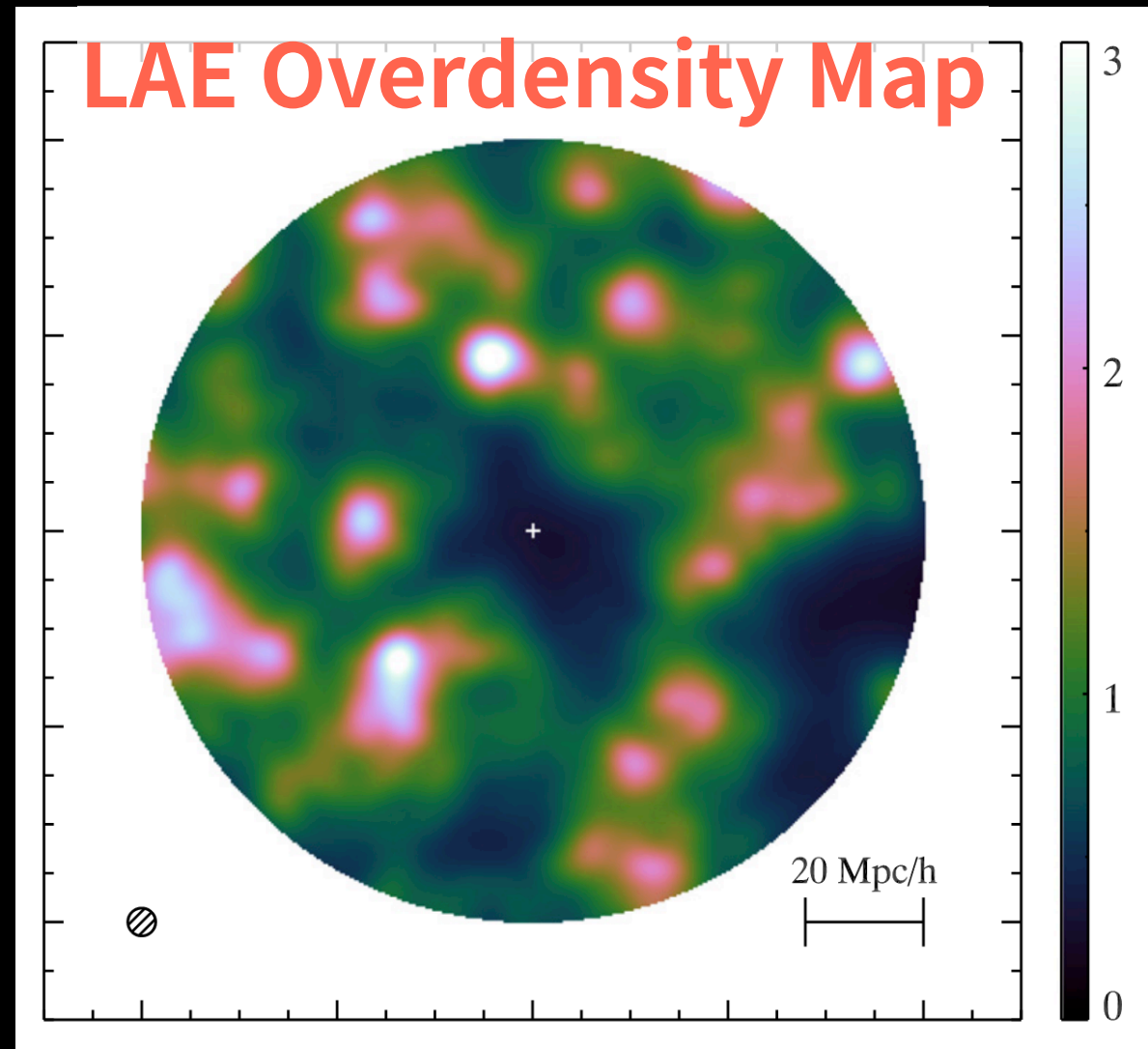


Reionization can be patchy and inhomogeneous,
and possibly extended to later time

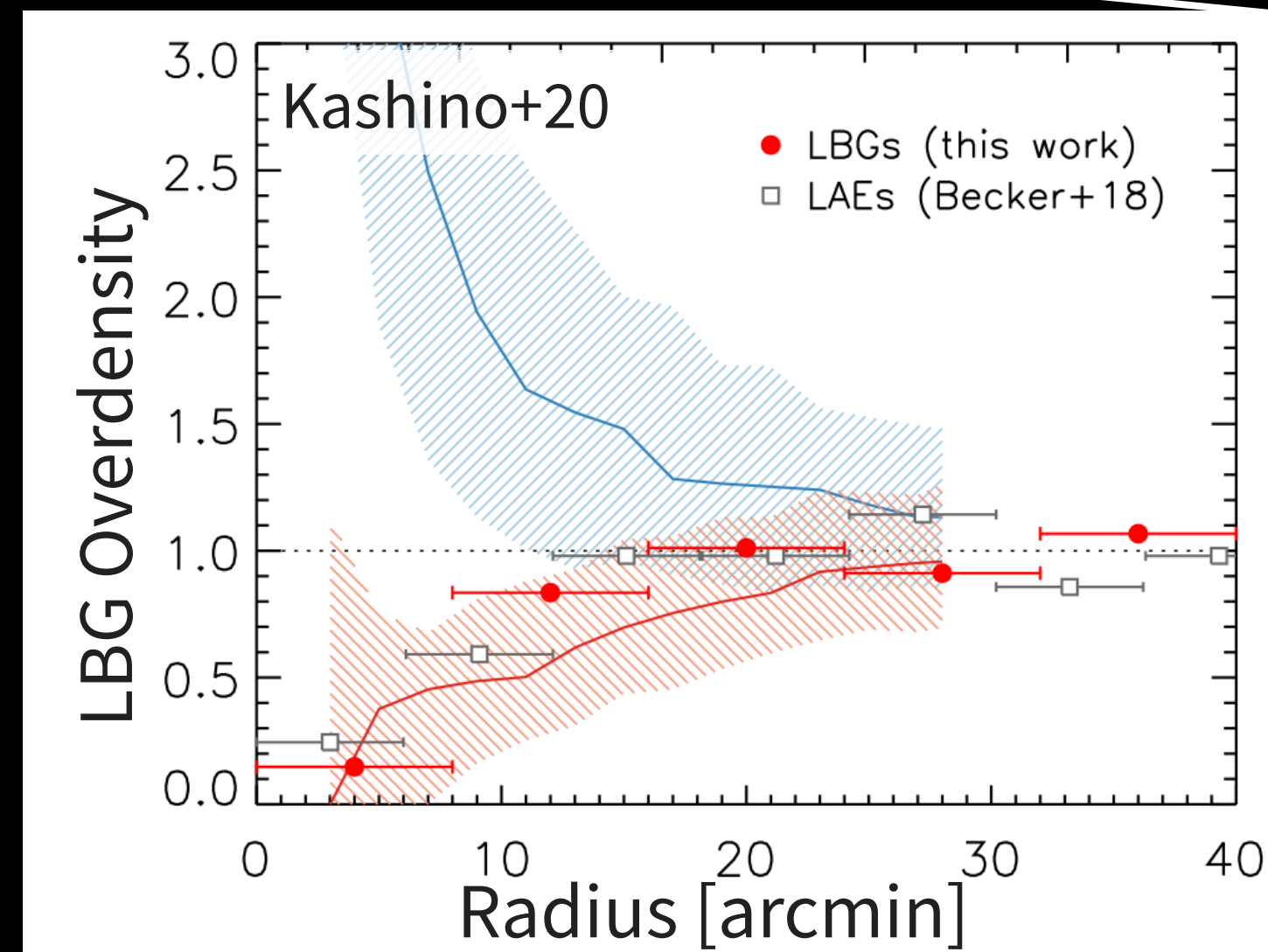
e.g., Fan+06, Becker+15

The early baryon cycle: patchy and late reionization

Q4. How did the cycle emerge during the epoch of reionization?



e.g., Christenson+21, 23



Unveiling the Reionization Process through Subaru Intensive Program (S25A-047QI)

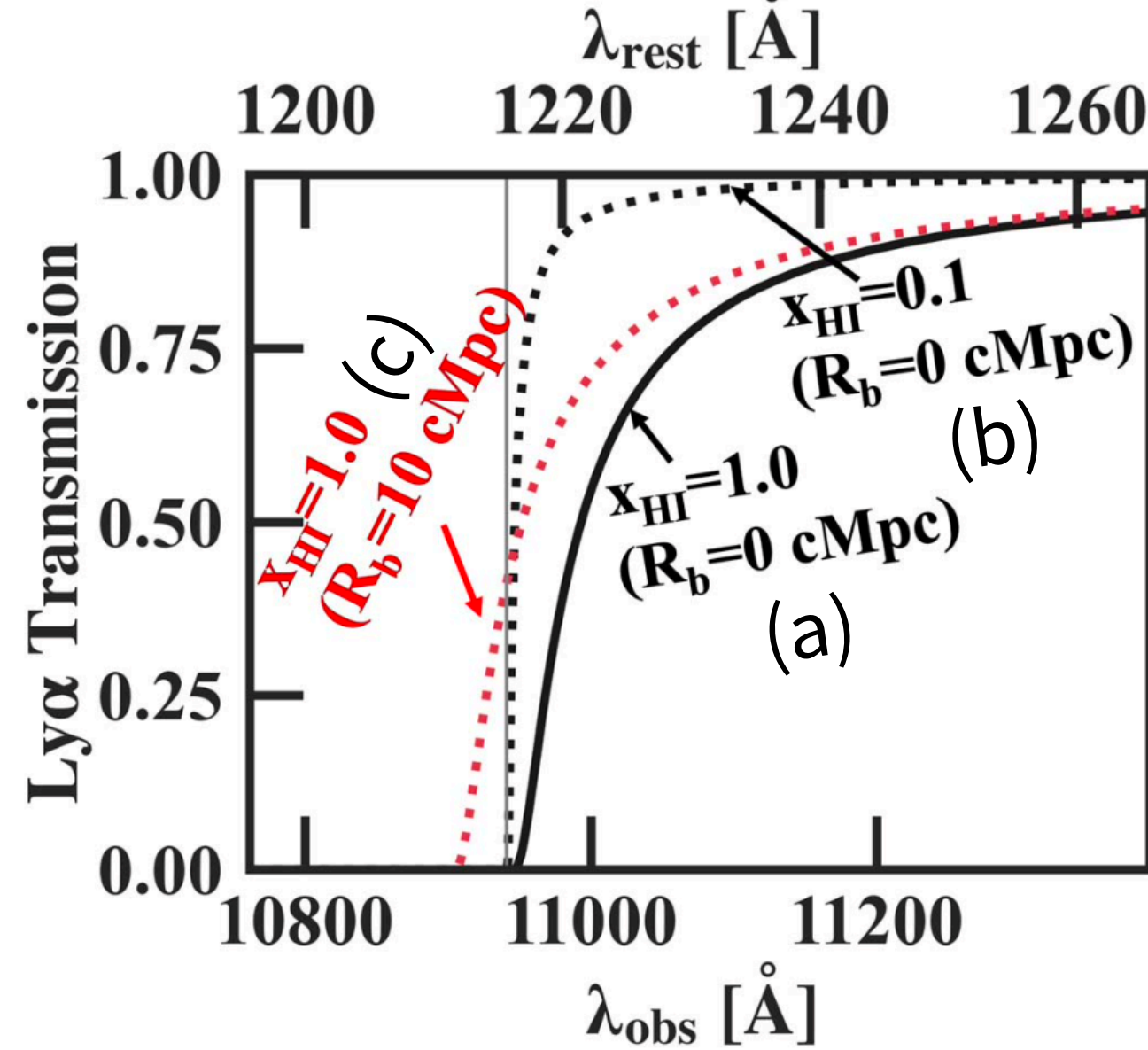
Rieko Momose (Carnegie Observatories/Univ. Tokyo)

Michael Rauch (Carnegie Observatories), Katsuya Okoshi (Tokyo Univ. of Science), Nobunari Kashikawa (Univ. Tokyo), Kazuhiro Shimasaku (Univ. Tokyo), Akio Inoue (Waseda Univ.), Toru Misawa (Shinshu Univ.), Fakhri Zahedy (Univ. North Texas), Kentaro Nagamine (Univ. Osaka), Ikko Shimizu (Kagawa College), Yoshiaki Ono (Univ. Tokyo)

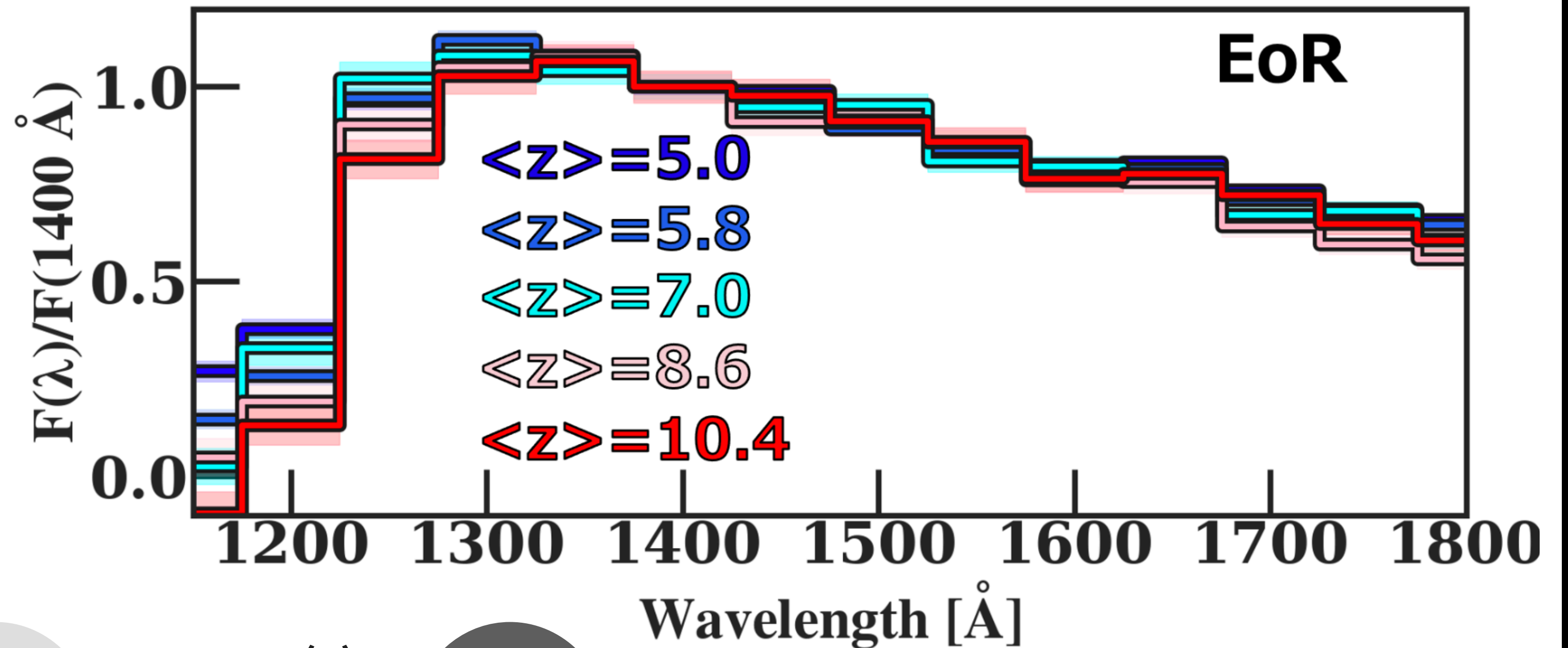
JWST connects early galaxies to the CGM/IGM

Q4. How did the cycle emerge during the epoch of reionization?

Example of Ly α damping wing profile ($z = 8$)



Observed Ly α damping wing profile ($z = 8$)



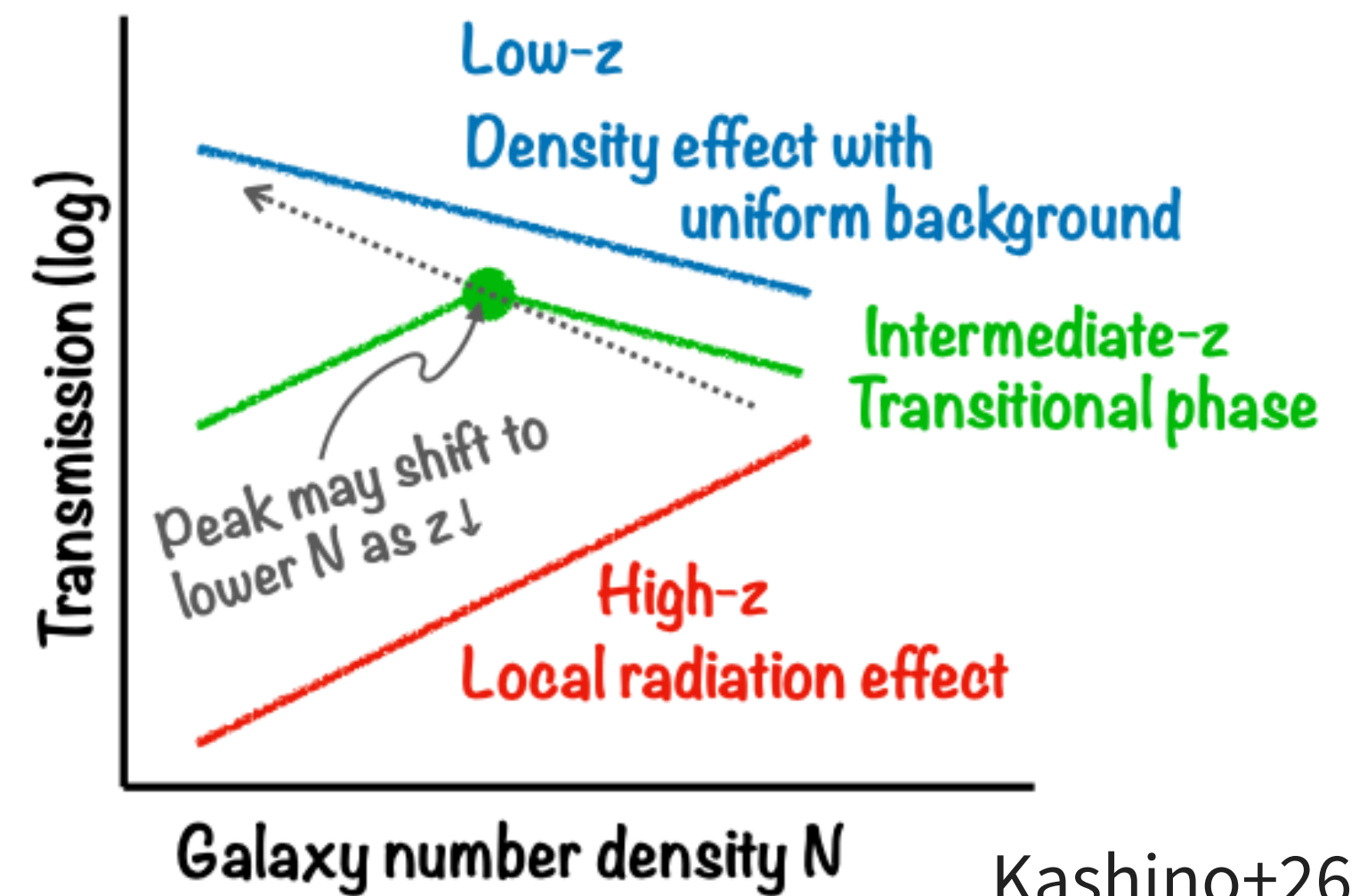
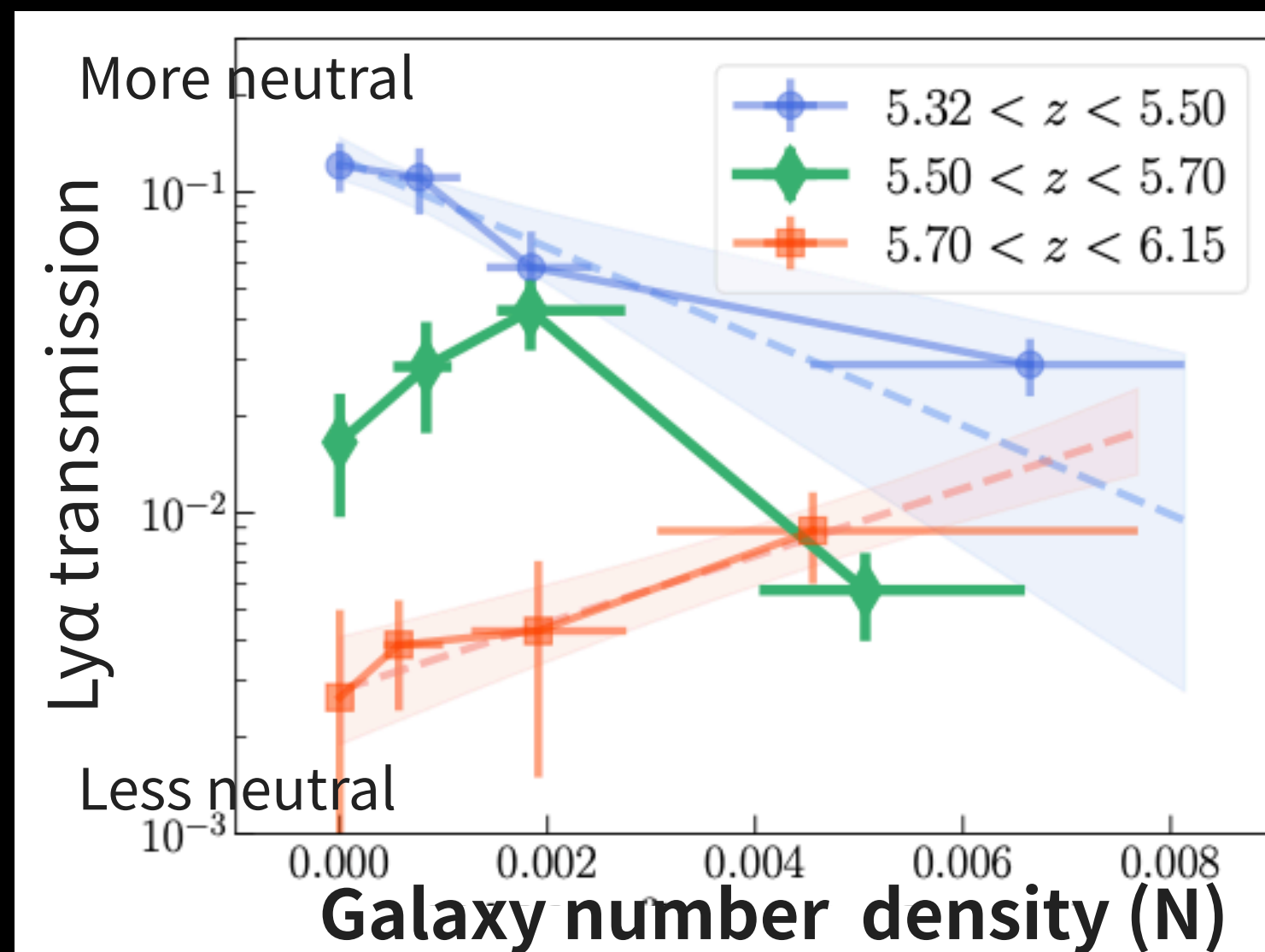
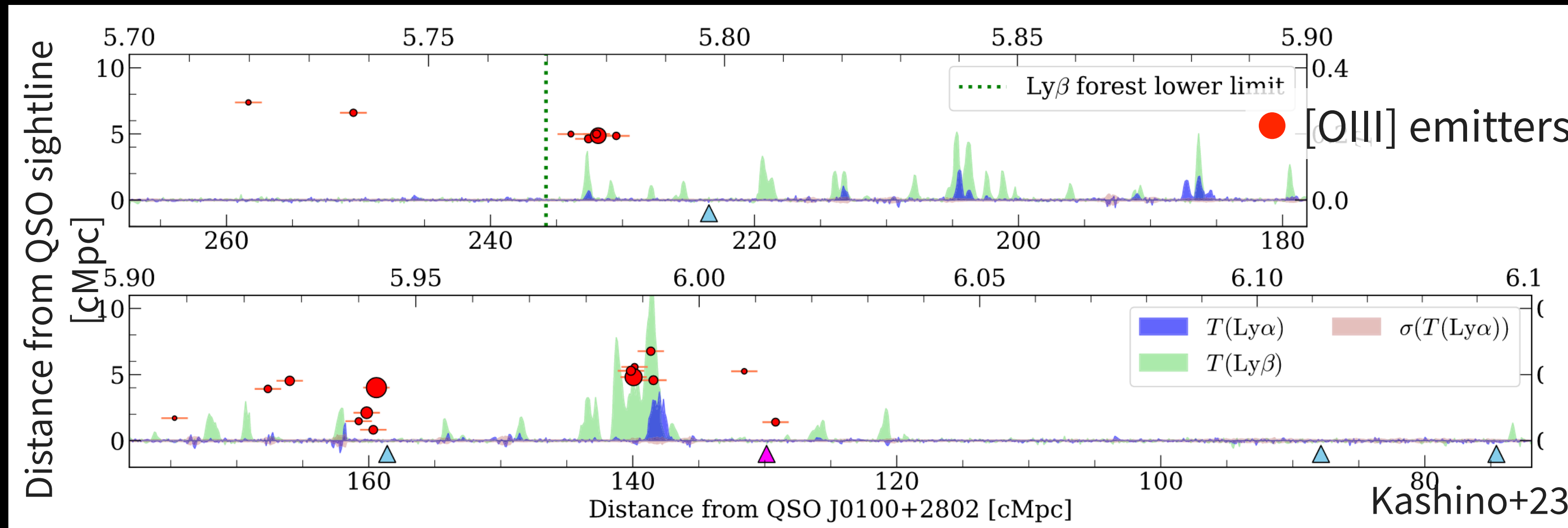
⊗ x_{HI} : HI fraction of the universe
 ⊗ R_b : ionized bubble size

Ionized bubble

Umeda+24, 26

JWST connects early galaxies to the CGM/IGM

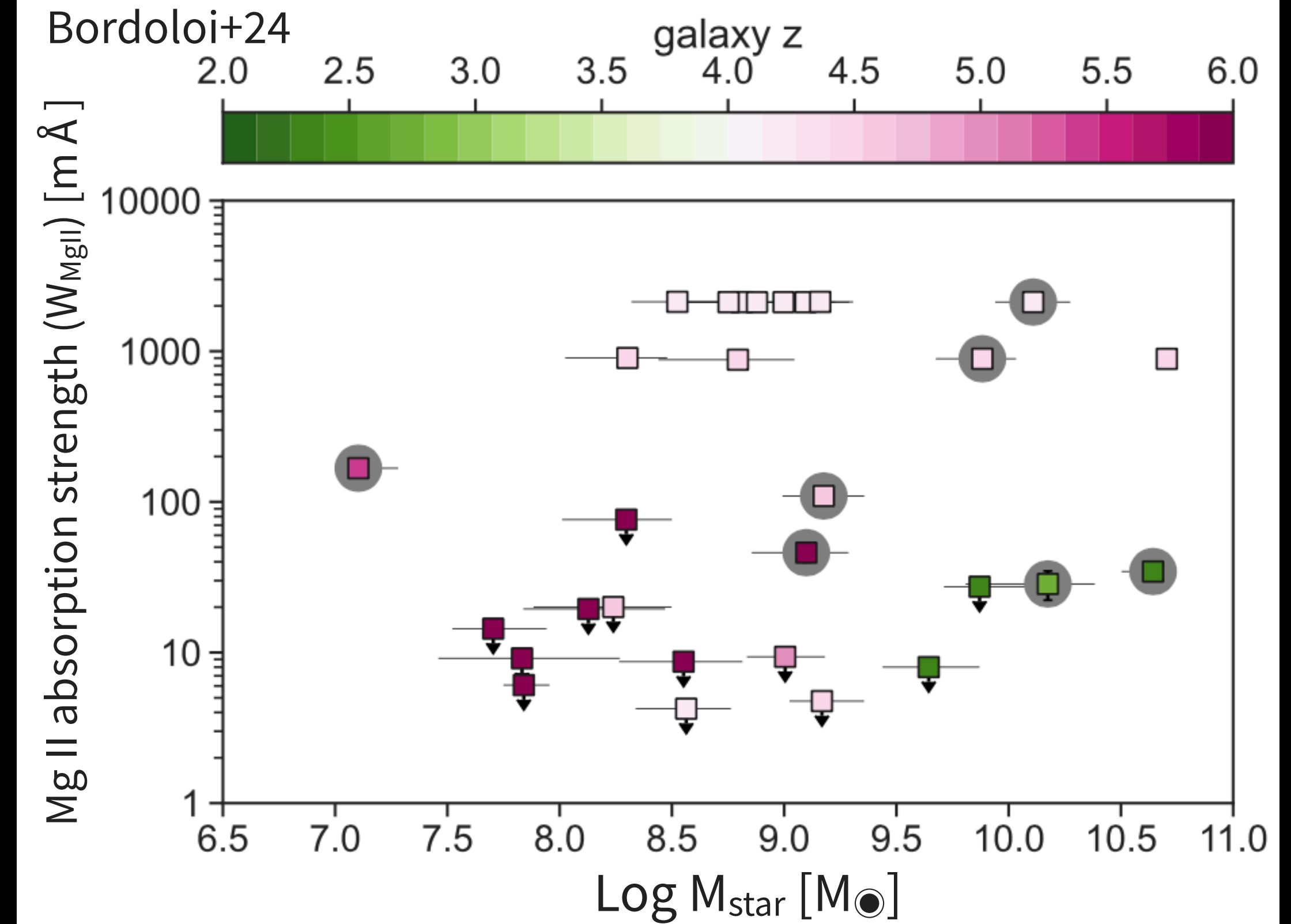
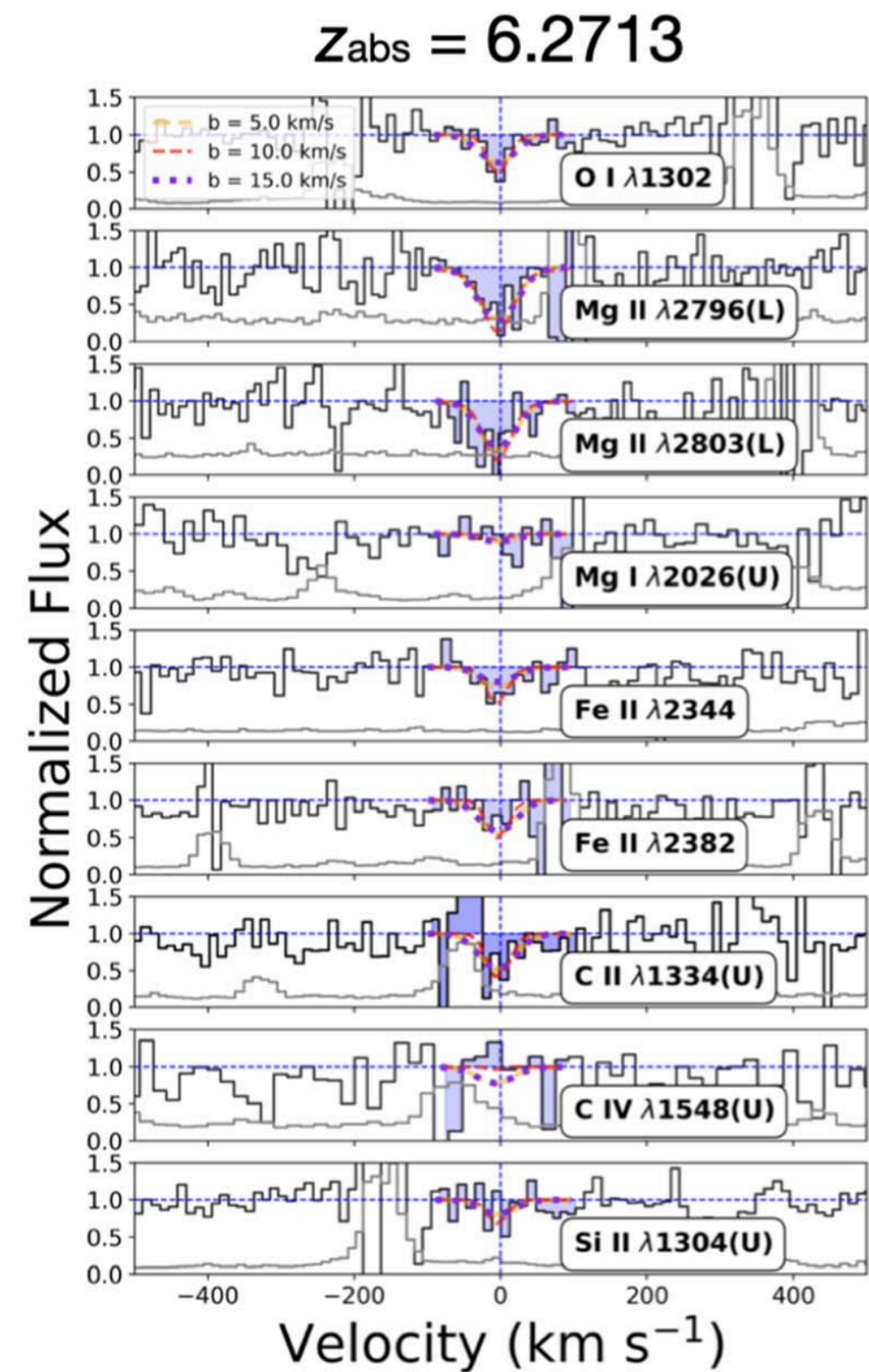
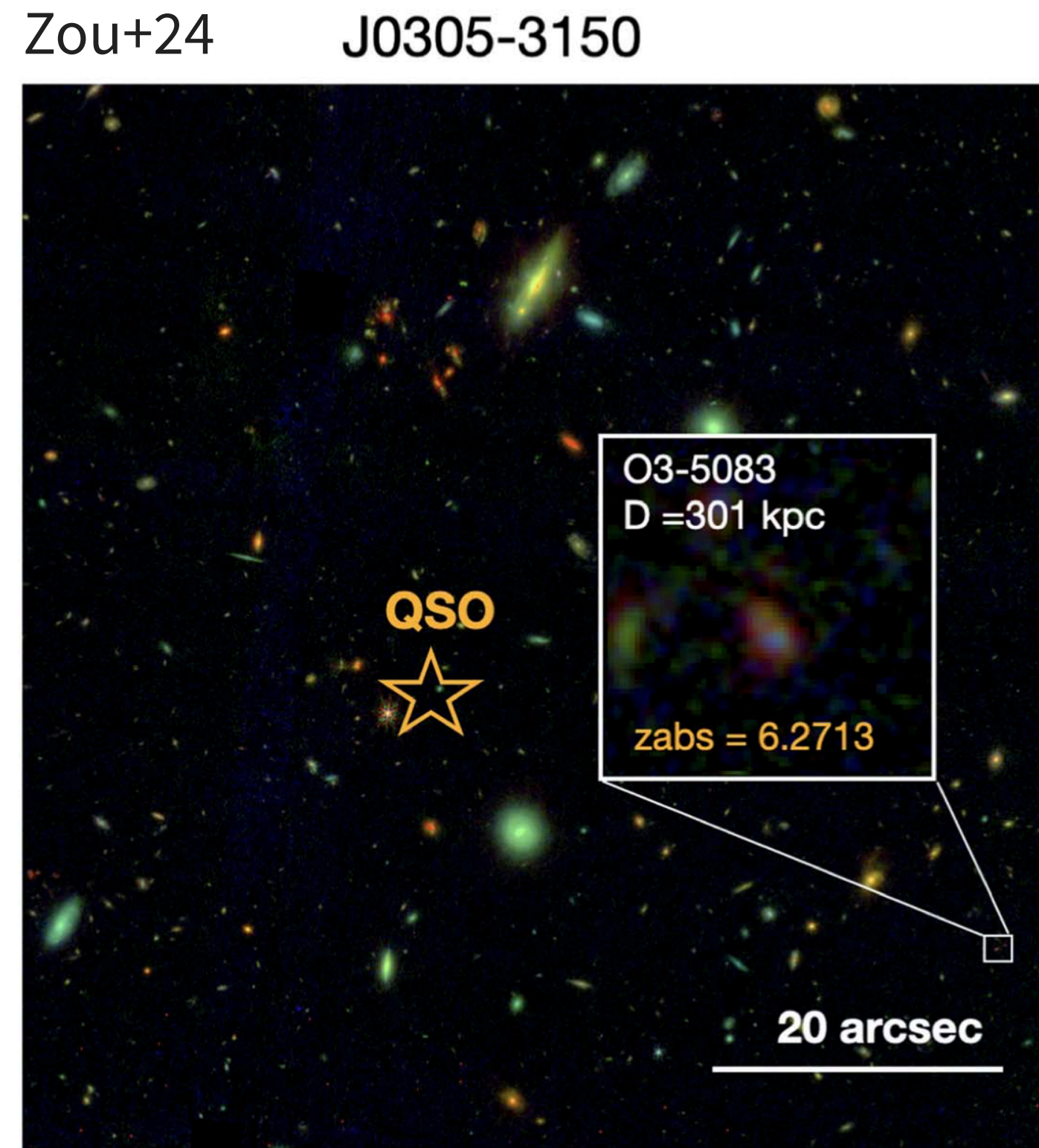
Q4. How did the cycle emerge during the epoch of reionization?



Kashino+26

JWST connects early galaxies to the CGM/IGM

Q4. How did the cycle emerge during the epoch of reionization?



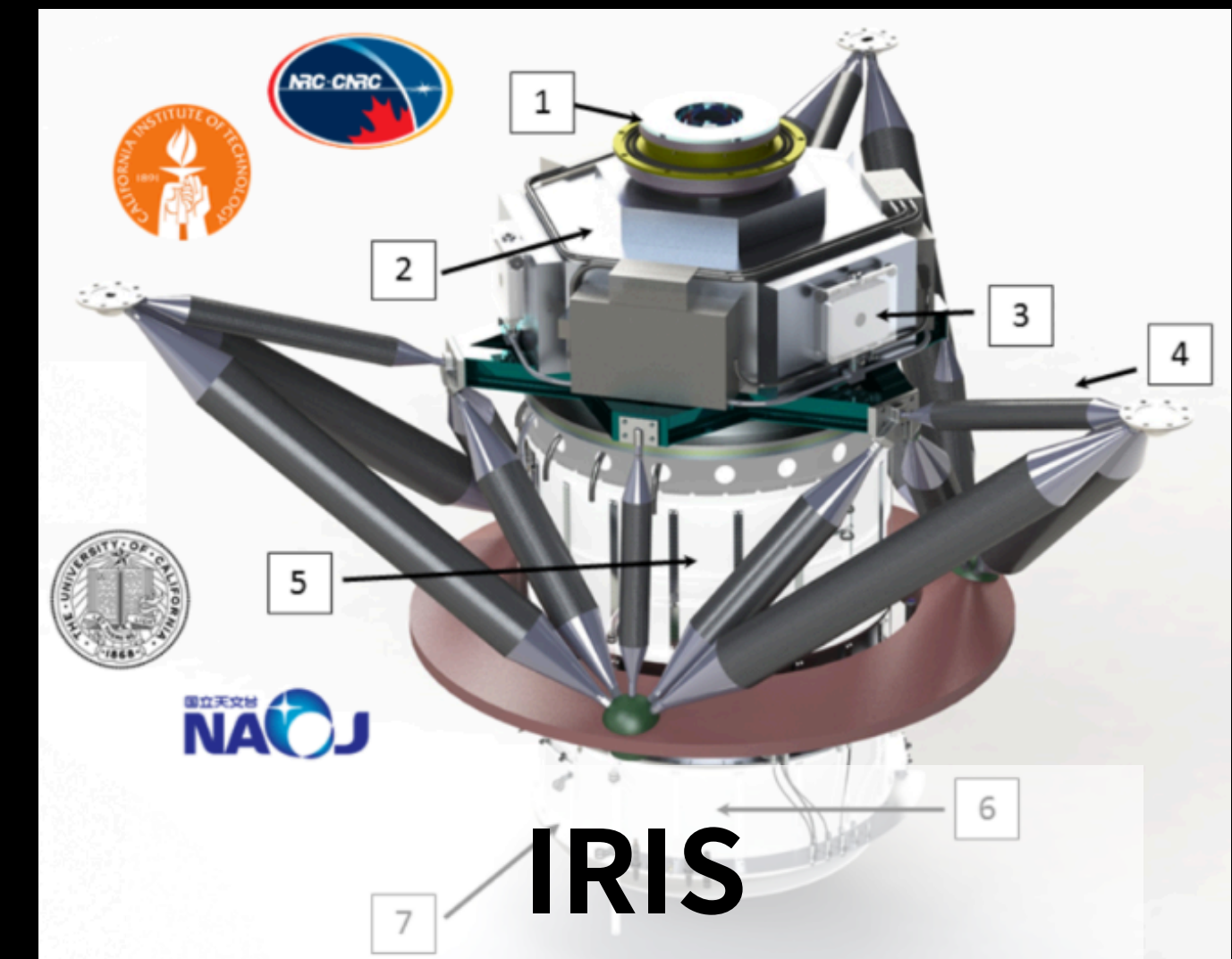
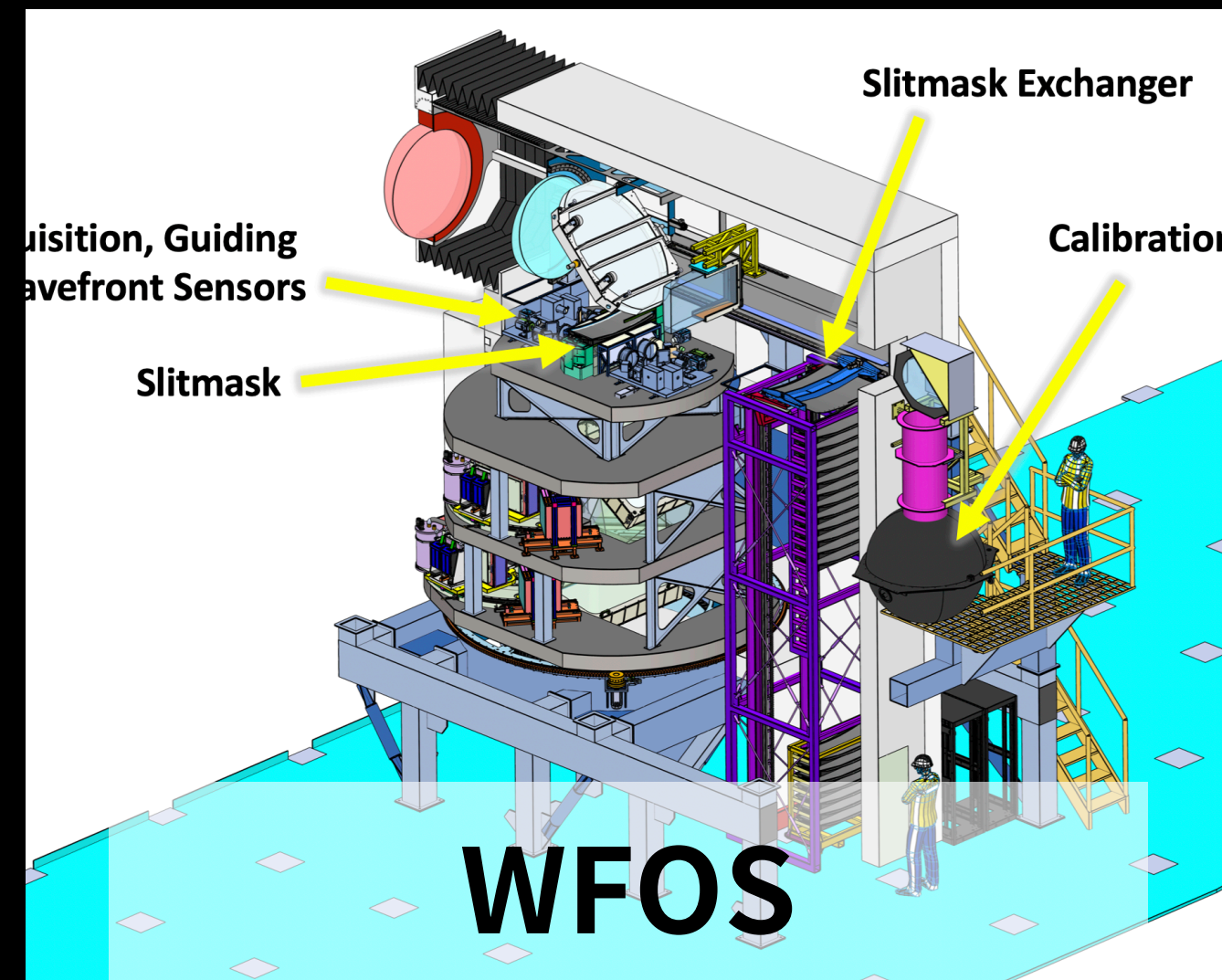
What is still missing from a unified picture?

Key Four Questions	Current Understanding	Remaining Questions
Where are the baryons, and in what physical phases do they exist?	<ul style="list-style-type: none">✓ CGM/IGM are large baryon reservoir.✓ CGM/IGM are multiphase and complex.	<ul style="list-style-type: none">✓ Determine the baryon fraction of phase-resolved mass and redshift✓ Evaluate lifetime and coupling between phases
How do galaxies exchange gas, metals, and energy with their surroundings?	<ul style="list-style-type: none">✓ Outflow/galactic feedback transport metals widely spreading to the CGM/IGM.	<ul style="list-style-type: none">✓ Observationally unveil inflow✓ Evaluate the contributions of inflow vs outflow vs recycling on galaxy evolution
Can we map the baryon cycle from the CGM to the cosmic web?	<ul style="list-style-type: none">✓ Mapping CGM via emission is now available with wide-field IFUs.✓ Tomography is another option to reconstruct CGM/IGM in 3D.	<ul style="list-style-type: none">✓ Map the CGM/IGM via multiple emission to individual basis✓ Map the gas flow from the Mpc cosmic web to a galactic scale (kpc-pc)
How did the cycle emerge during the epoch of reionization?	<ul style="list-style-type: none">✓ CGM/IGM has shown the patchy, inhomogenous reionization.✓ The connection of CGM/IGM with its host galaxies is now accessible with JWST.	<ul style="list-style-type: none">✓ Map the large-scale topology of both galaxies and the IGM✓ Unveil the first metal enrichment by first galaxies (pop III stars)

Why TMT is the next step

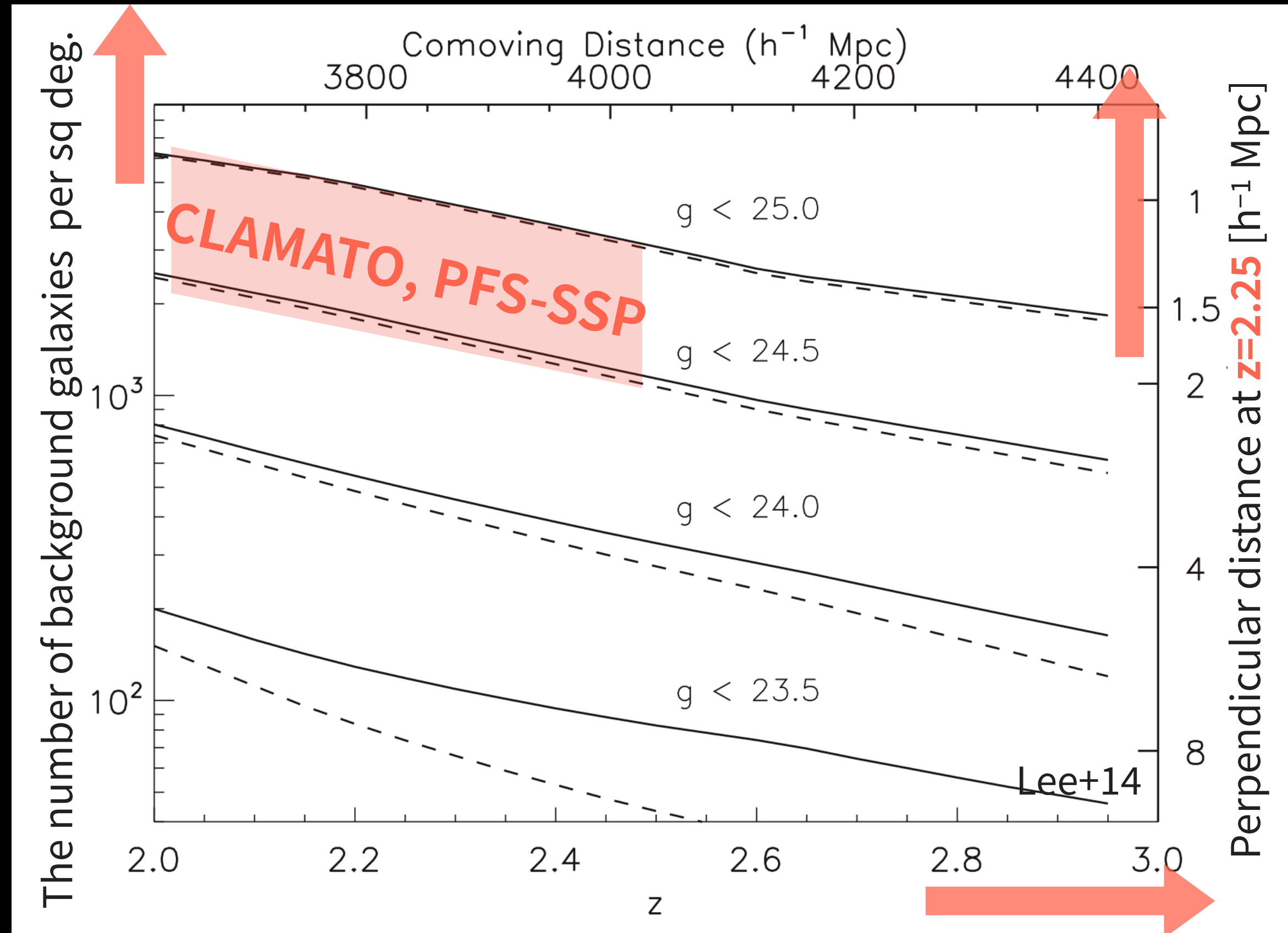


1st light Instruments

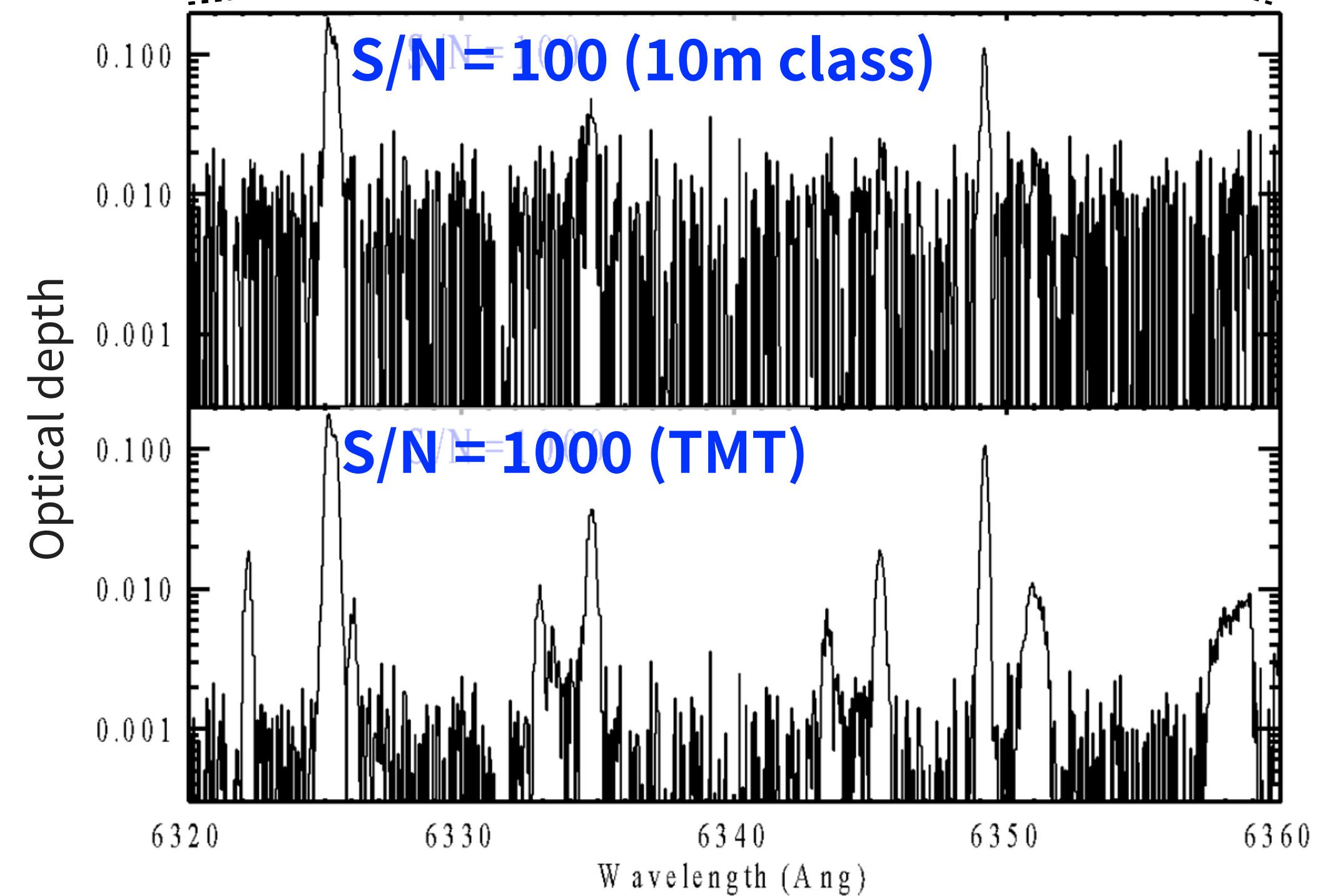
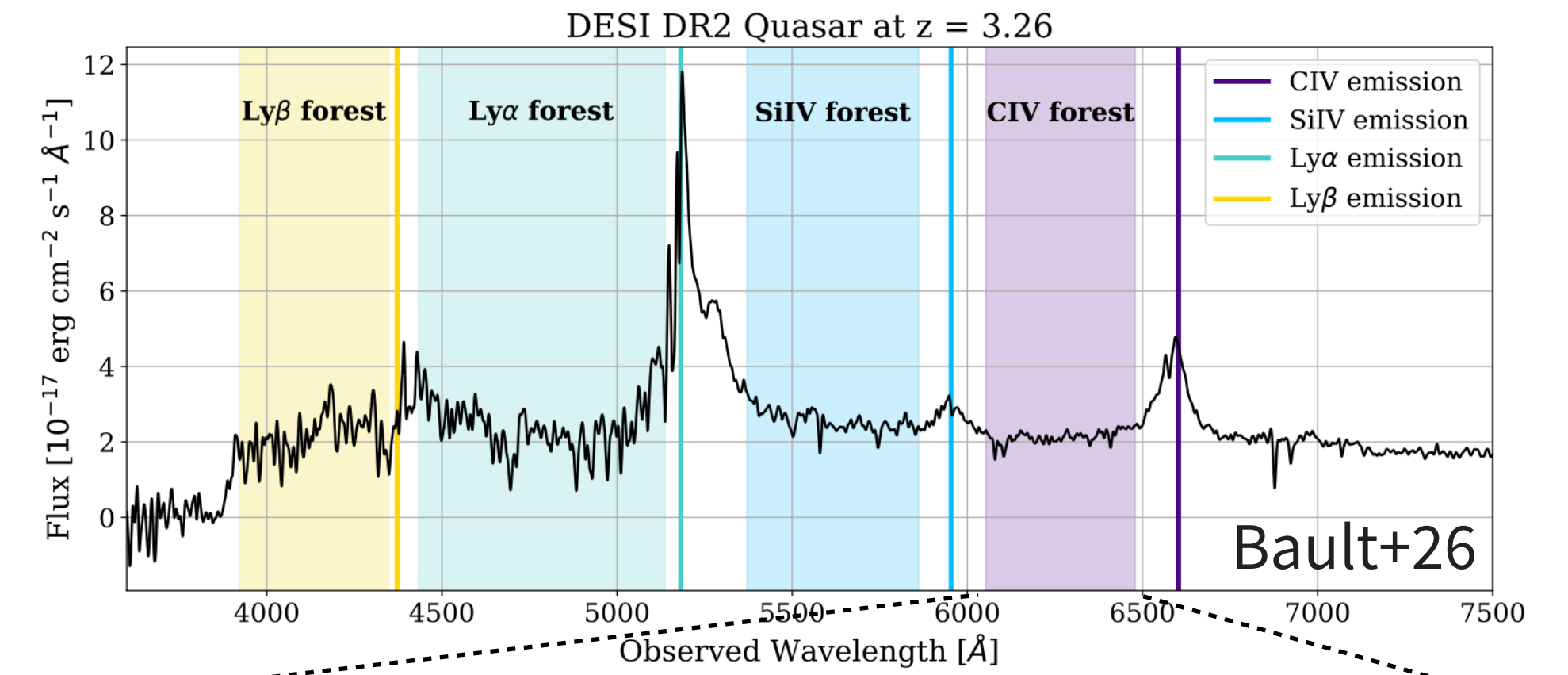


IFUs	Possibly	✓
Wavelength [μm]	0.31 — 1.0	0.84 — 2.4
FoVs	8.3' x 3'	0.512" x 0.512" — 2.250" x 4.400"
Sampling	0.05"	0.004" — 0.05"
R	1500, 3500, 5000 (on the slits size)	4000, 8000, 10000

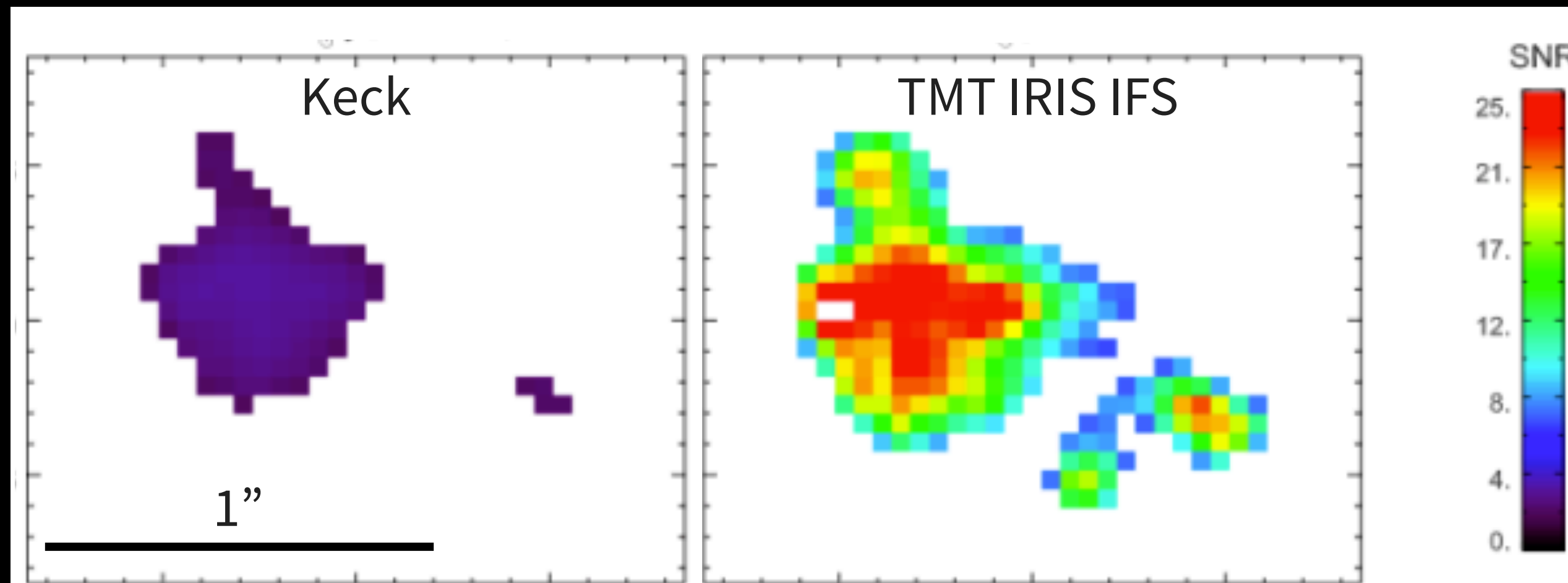
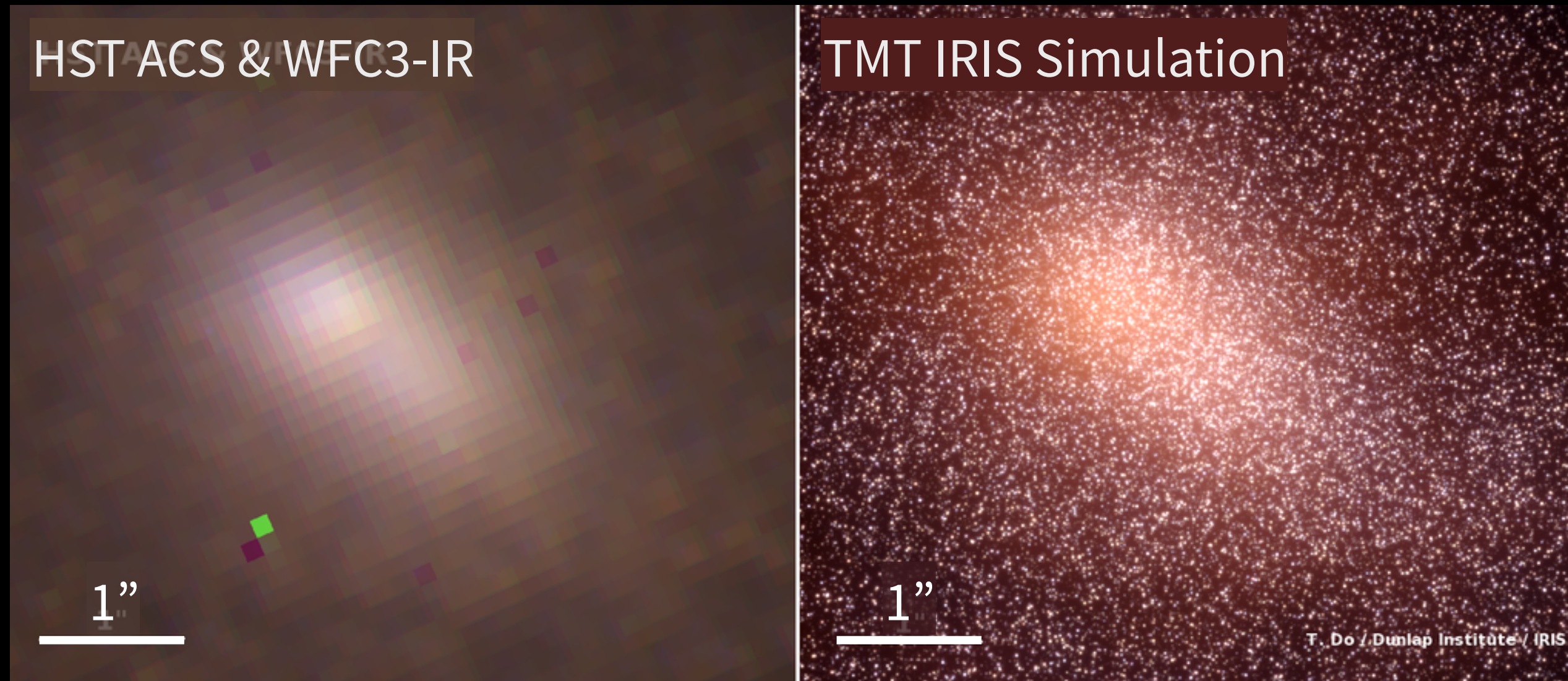
TMT Science Case 1: dense CGM/IGM tomography



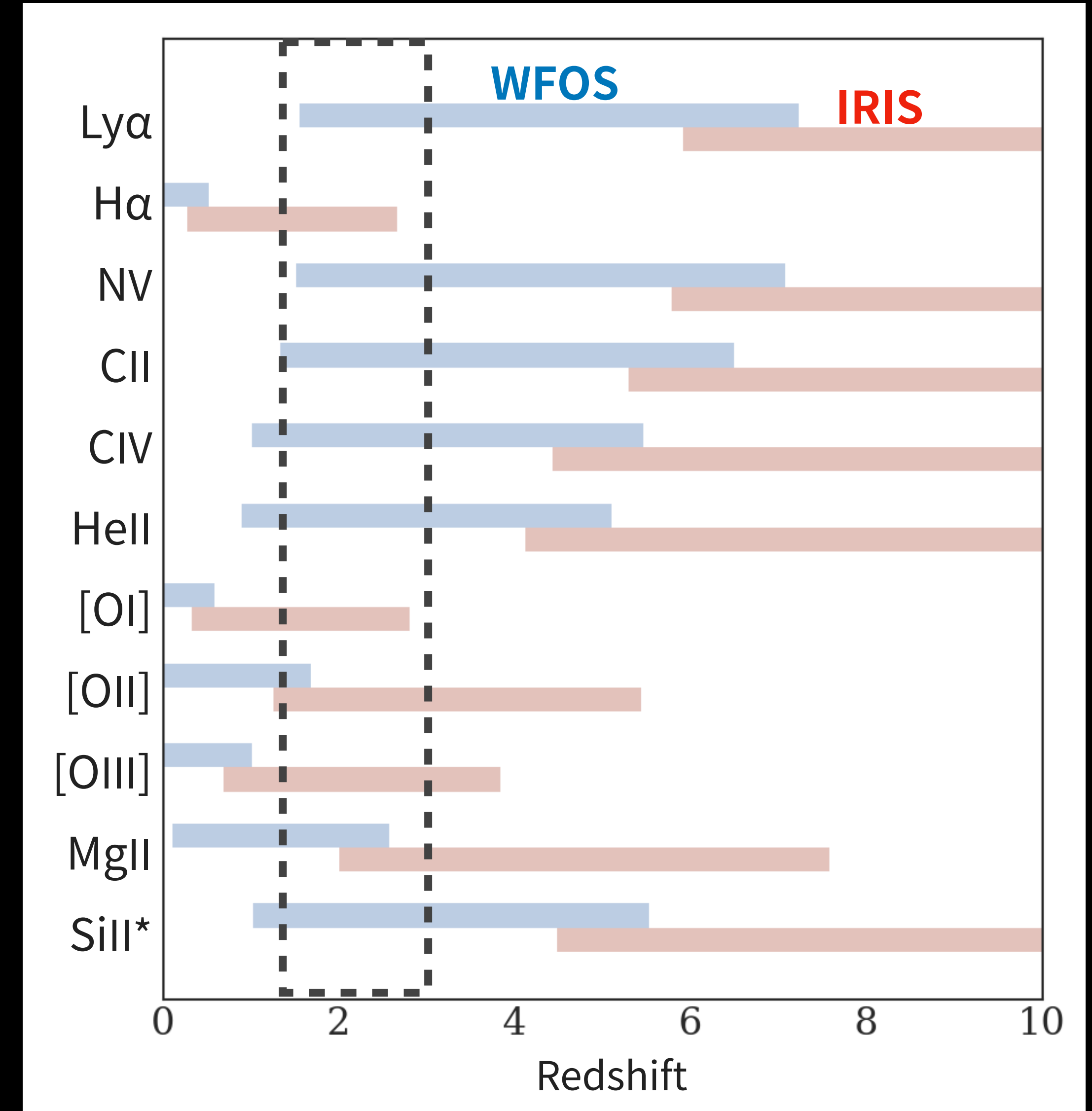
TMT Science Case 2024



TMT Science Case 2: resolved feedback and metal transport



A galaxy with SFR = $10M_{\odot}/\text{yr}$ at $z = 2.30$



Copyright: OIR LAB, UC San Diego; Wright+14

Summary: toward a unified baryon-cycle picture

