

High-Redshift Galaxy Science with ALMA, the WSU, and Beyond

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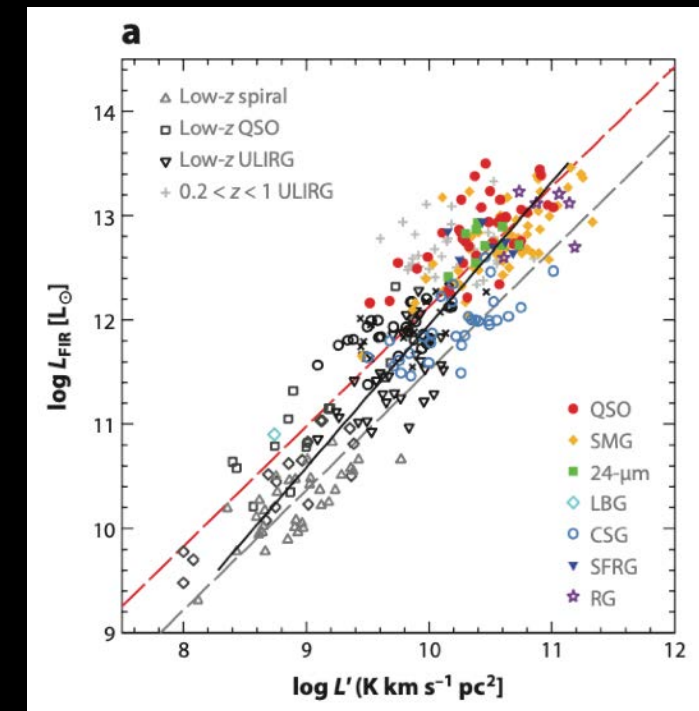
East Asian ALMA Community Workshop: ALMA2040 Science and Technology Perspectives

2026/07/17

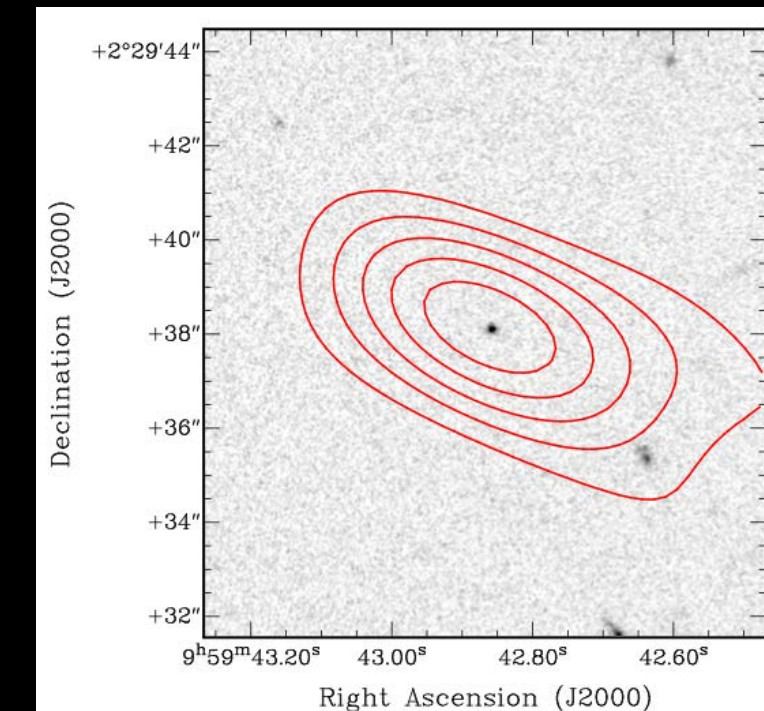
Pre-ALMA

What did we *not* know?

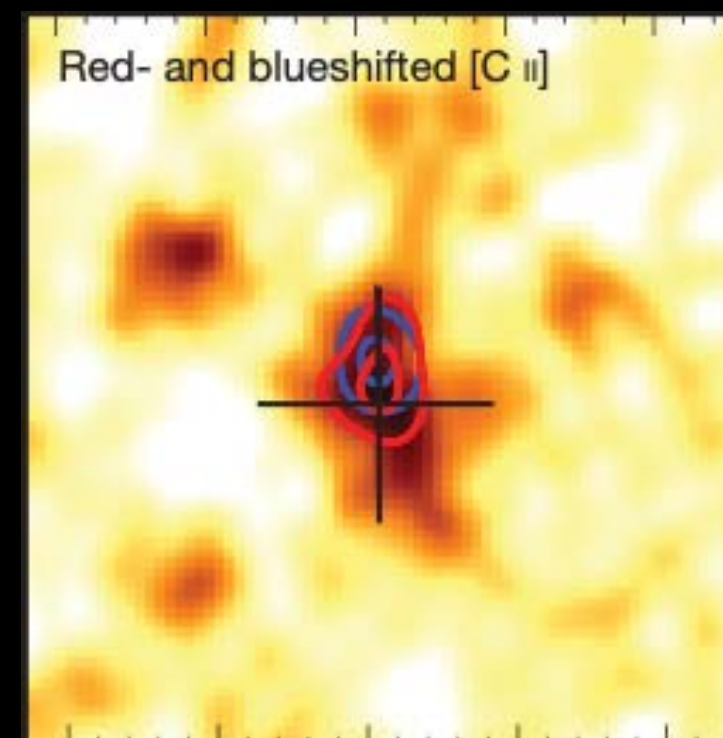
Gas



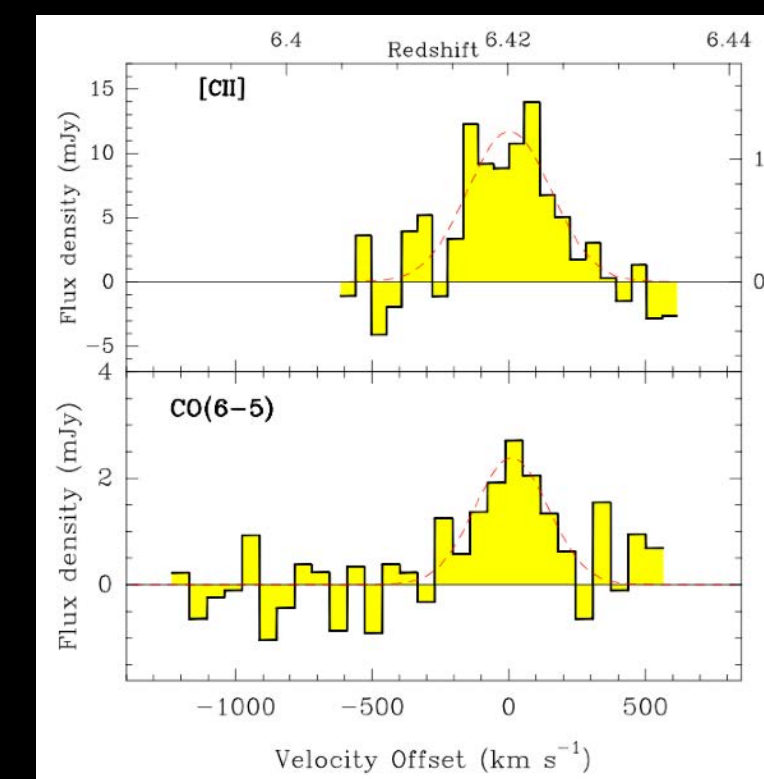
Dust



ISM Physics
Dynamics



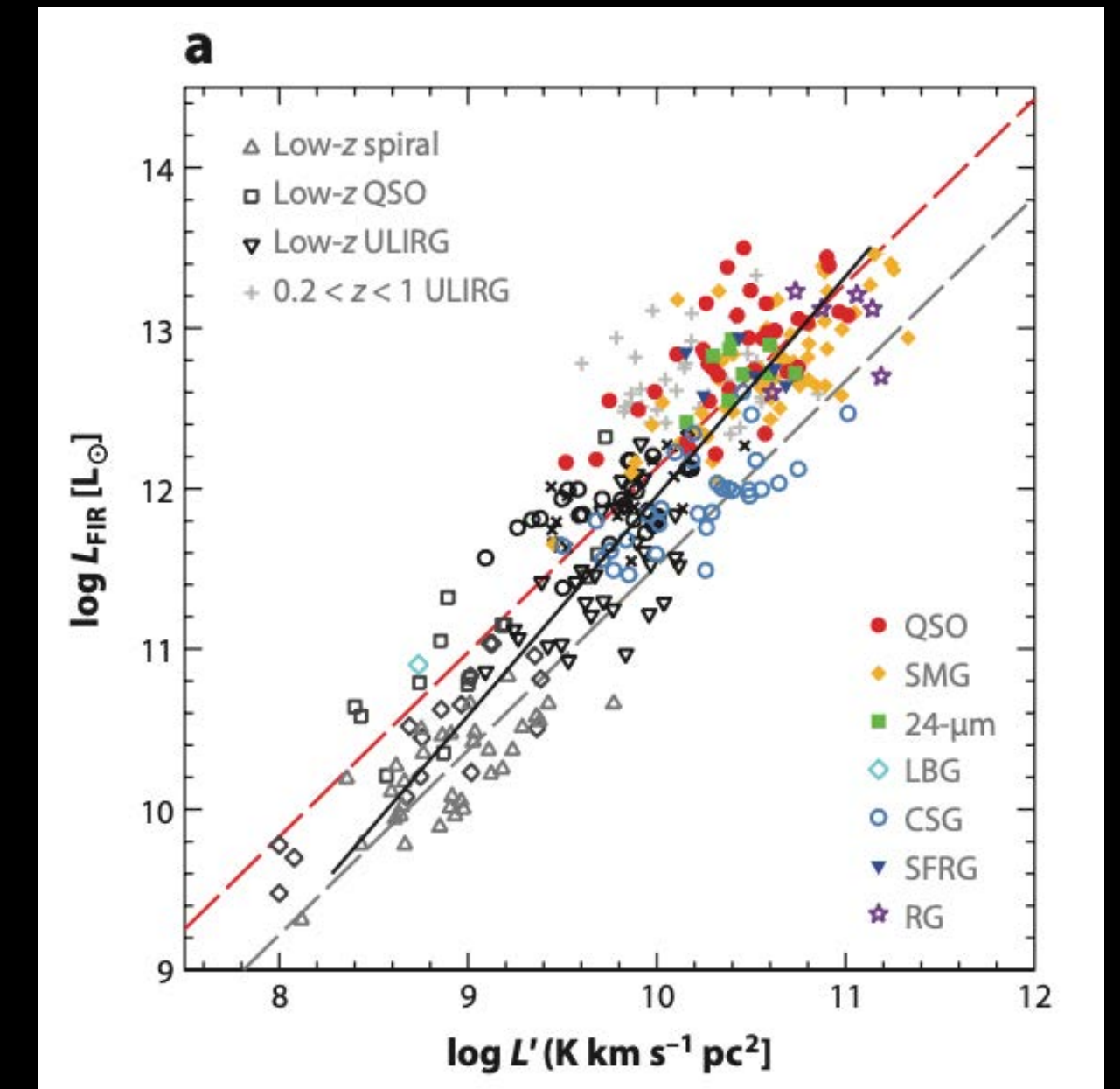
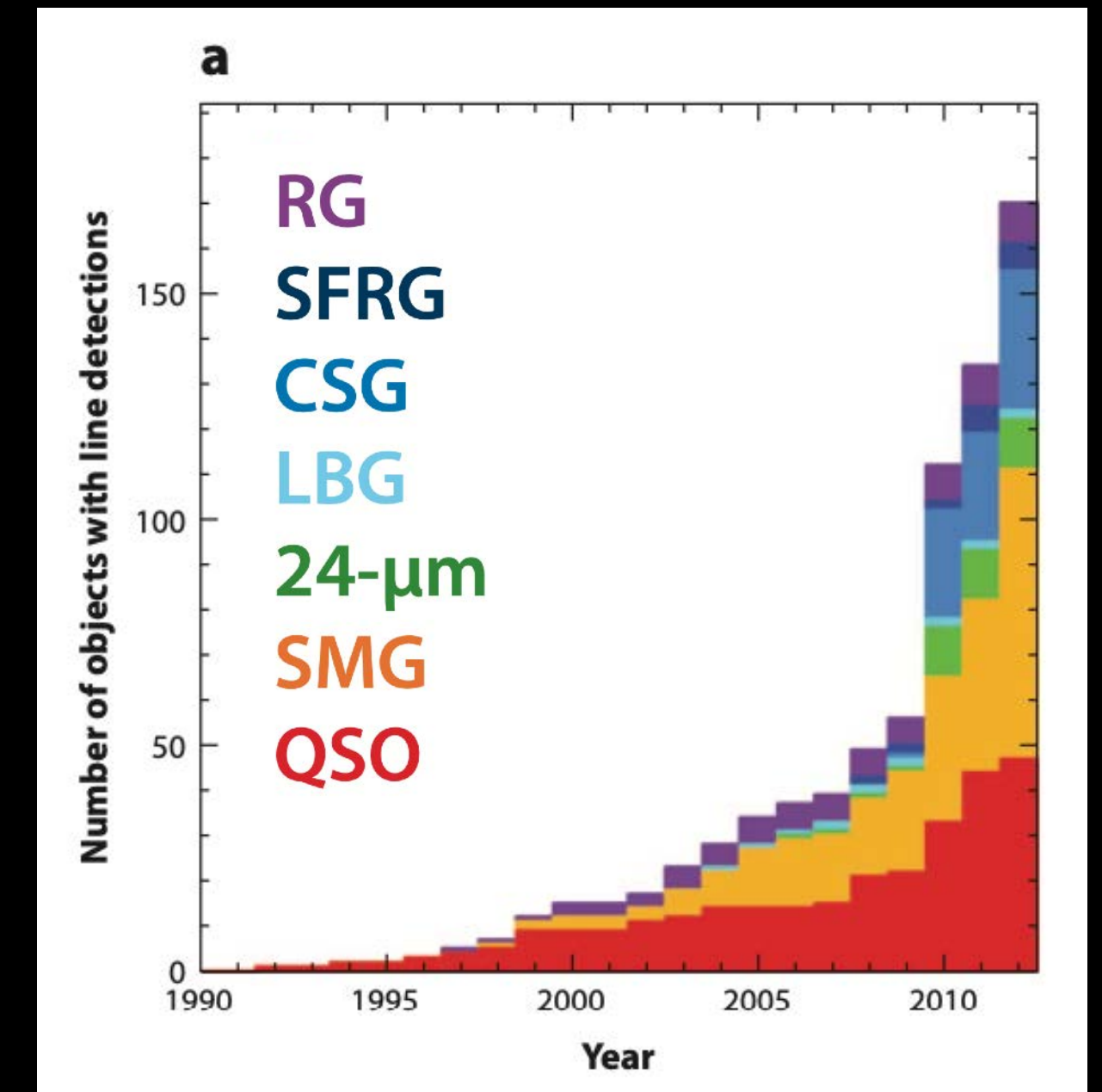
Cosmic Dawn



Molecular Gas

Mostly luminous galaxies

- CO traces H₂ gas, the star-forming gas
- Before ALMA, most CO detections at high- z ($z > 1$):
 - Quasars (QSOs)
 - Submillimeter Galaxies (SMGs)
- High- z galaxies seem to also follow the CO-to-FIR luminosity relation at $z=0$



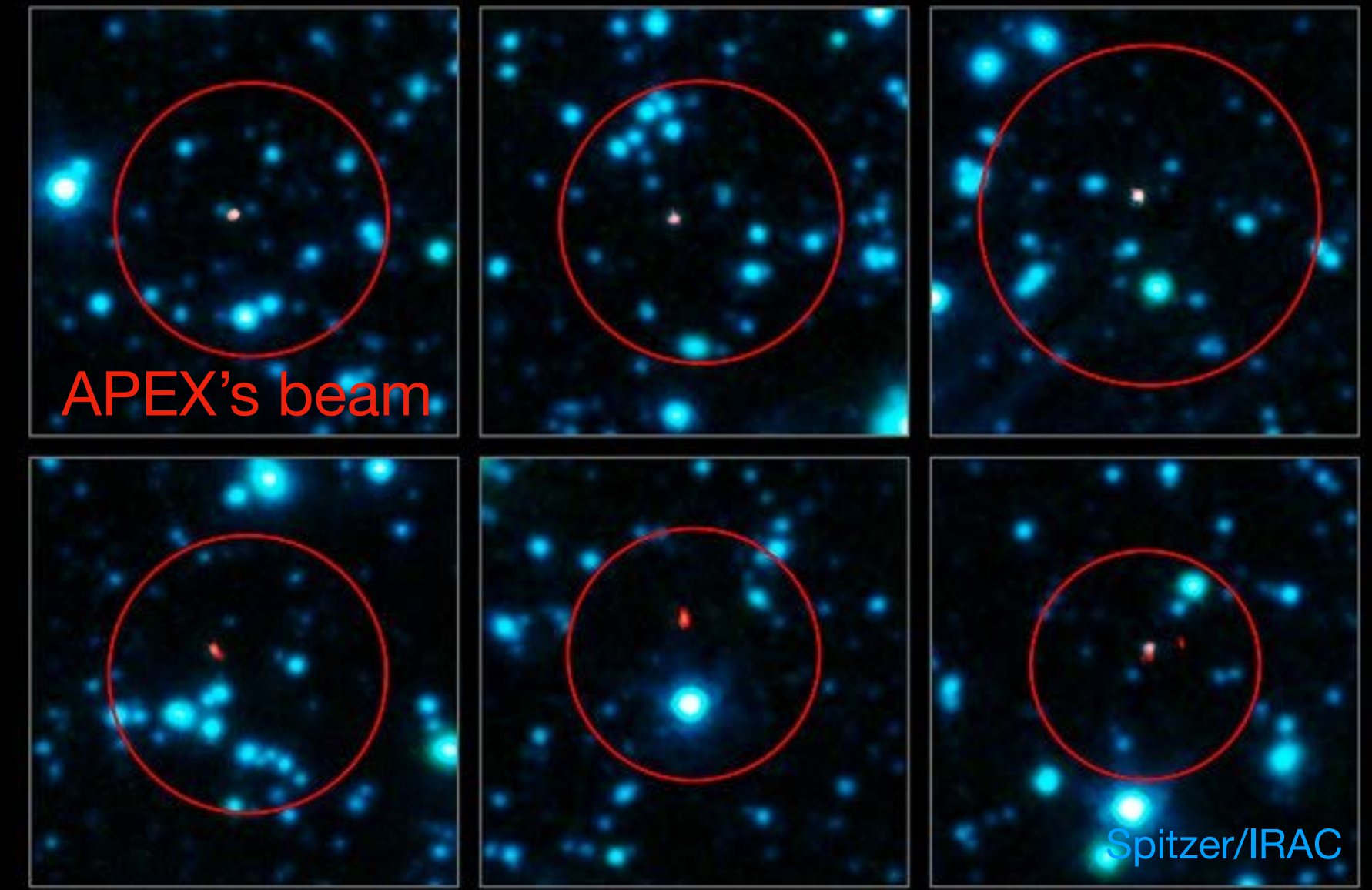
Dust-Obscured Galaxies

limited angular resolution

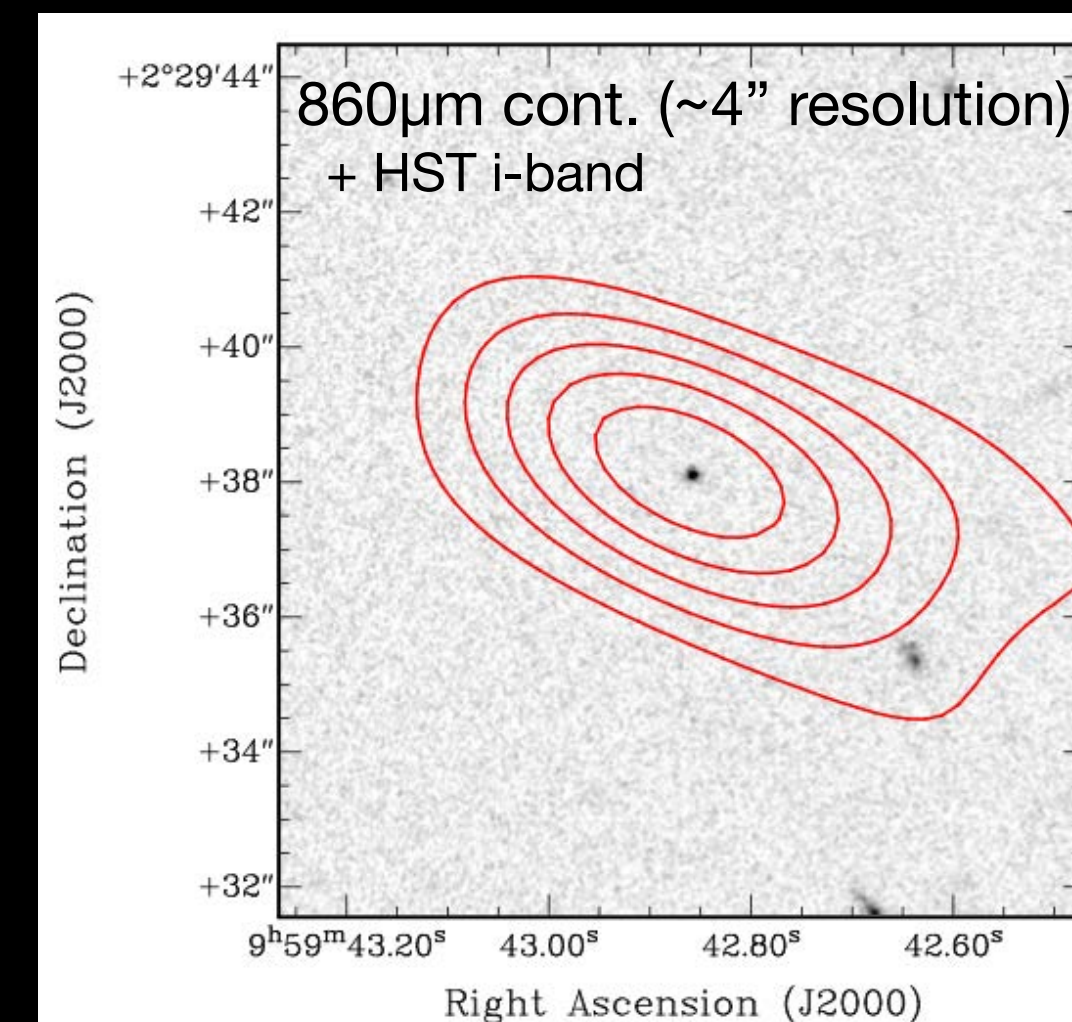
- Dust: obscured galaxies and hidden energy sources
- Detected sources were often confused
 - Due to limited angular resolution
- Redshift determination was not trivial
 - Too faint in optical for spec-z
- High-z Universe appeared to be dusty, but unclear how much

Red sources: ALMA

Hodge et al. 2013

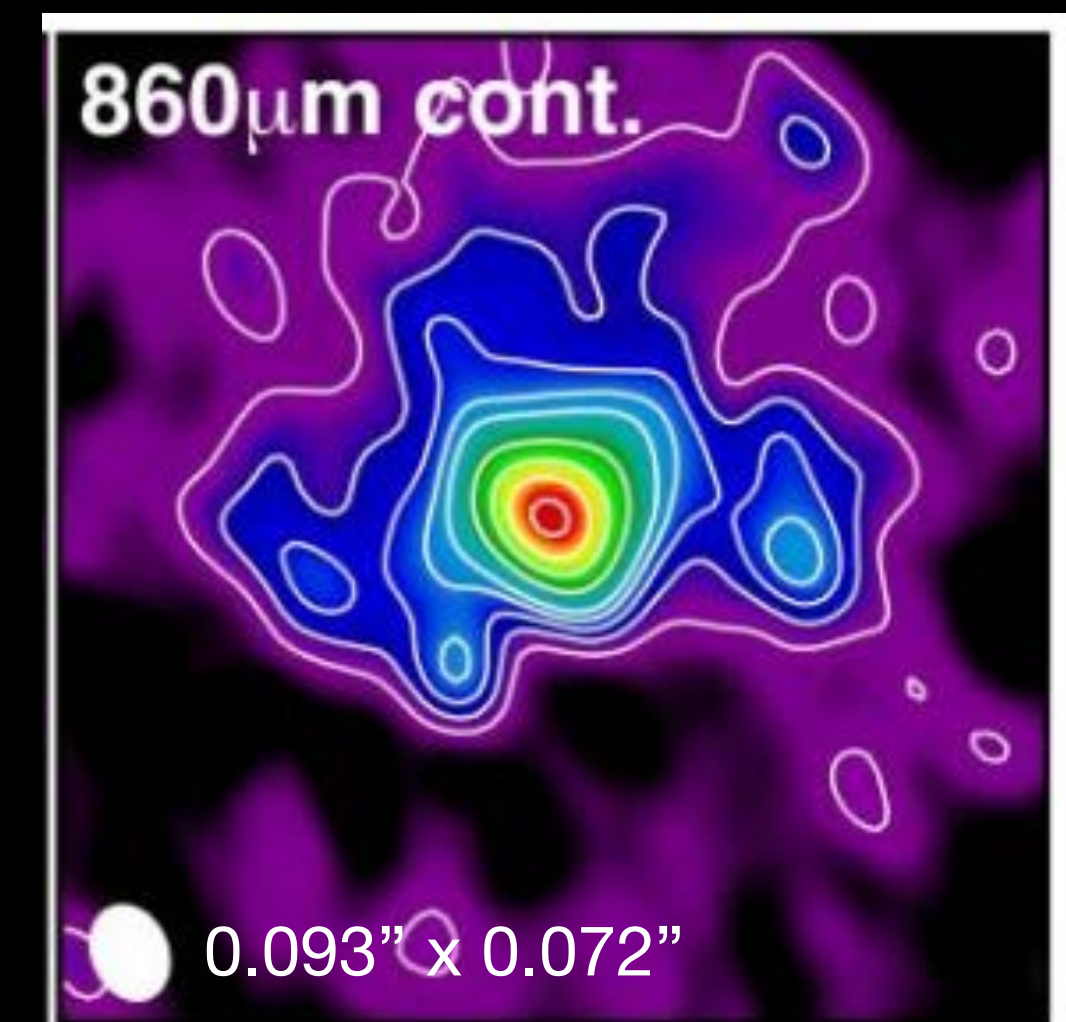


SMA



Yun et al. 2015

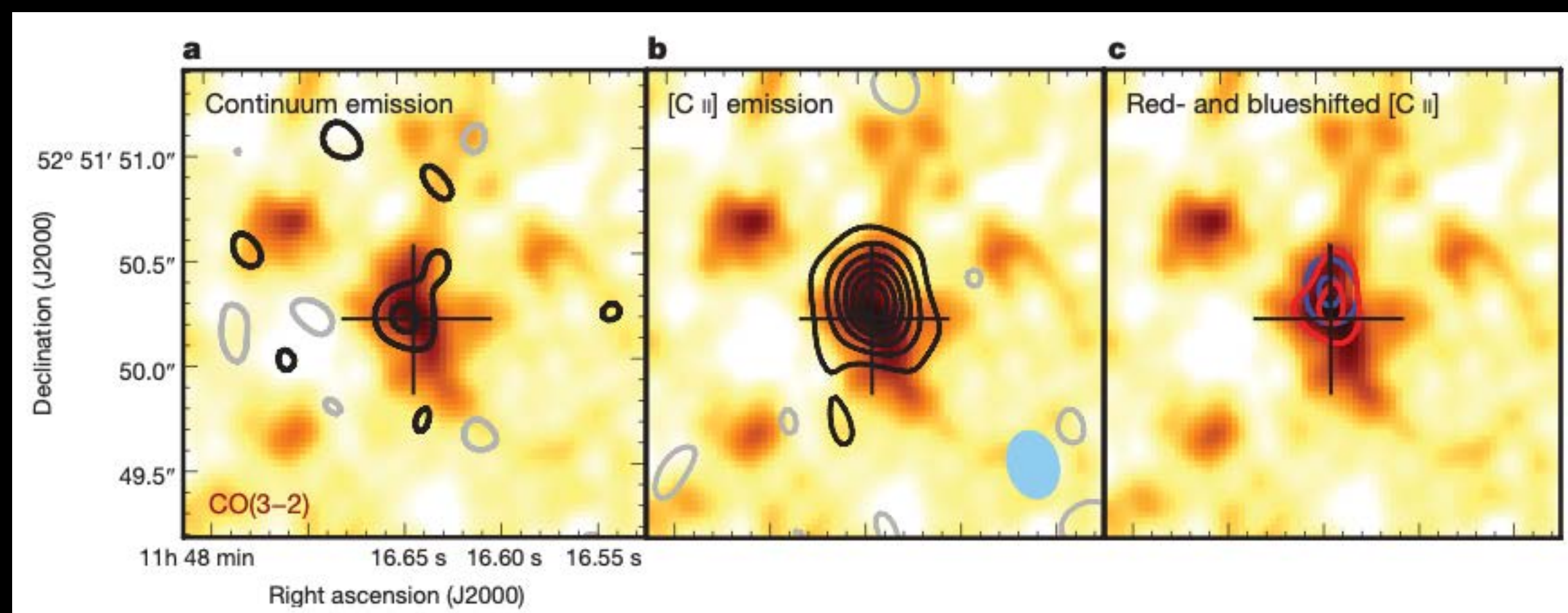
ALMA



Tadaki et al. 2018

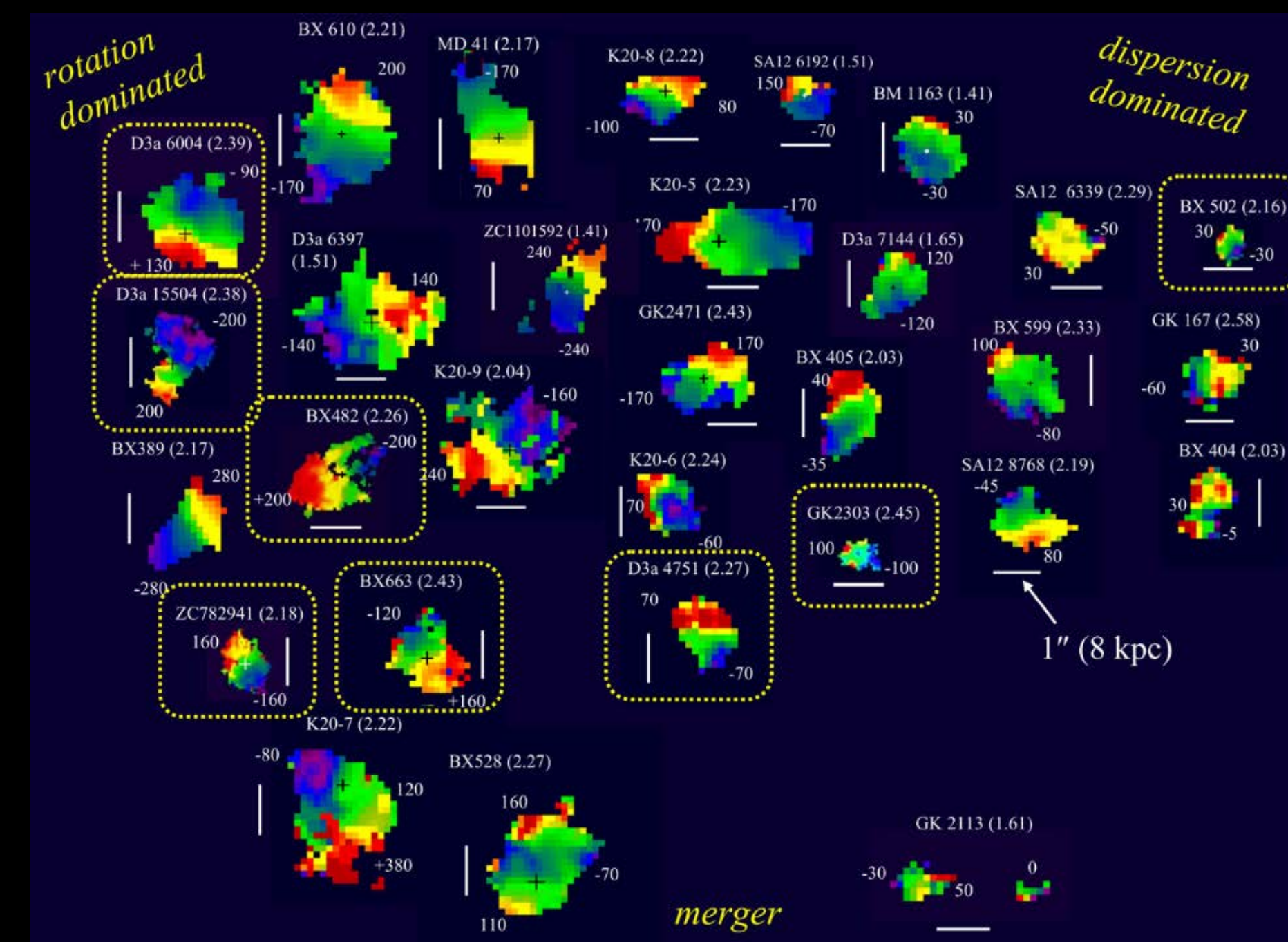
Cool ISM Dynamics at $z > 4$ almost impossible

- Rest optical IFU for $z \sim 2$ galaxies
- Resolved observations of the cool ISM were limited to a few extremely luminous galaxies.
- An example for a QSO at $z=6.42$



Walter et al. 2009

H-alpha velocity maps

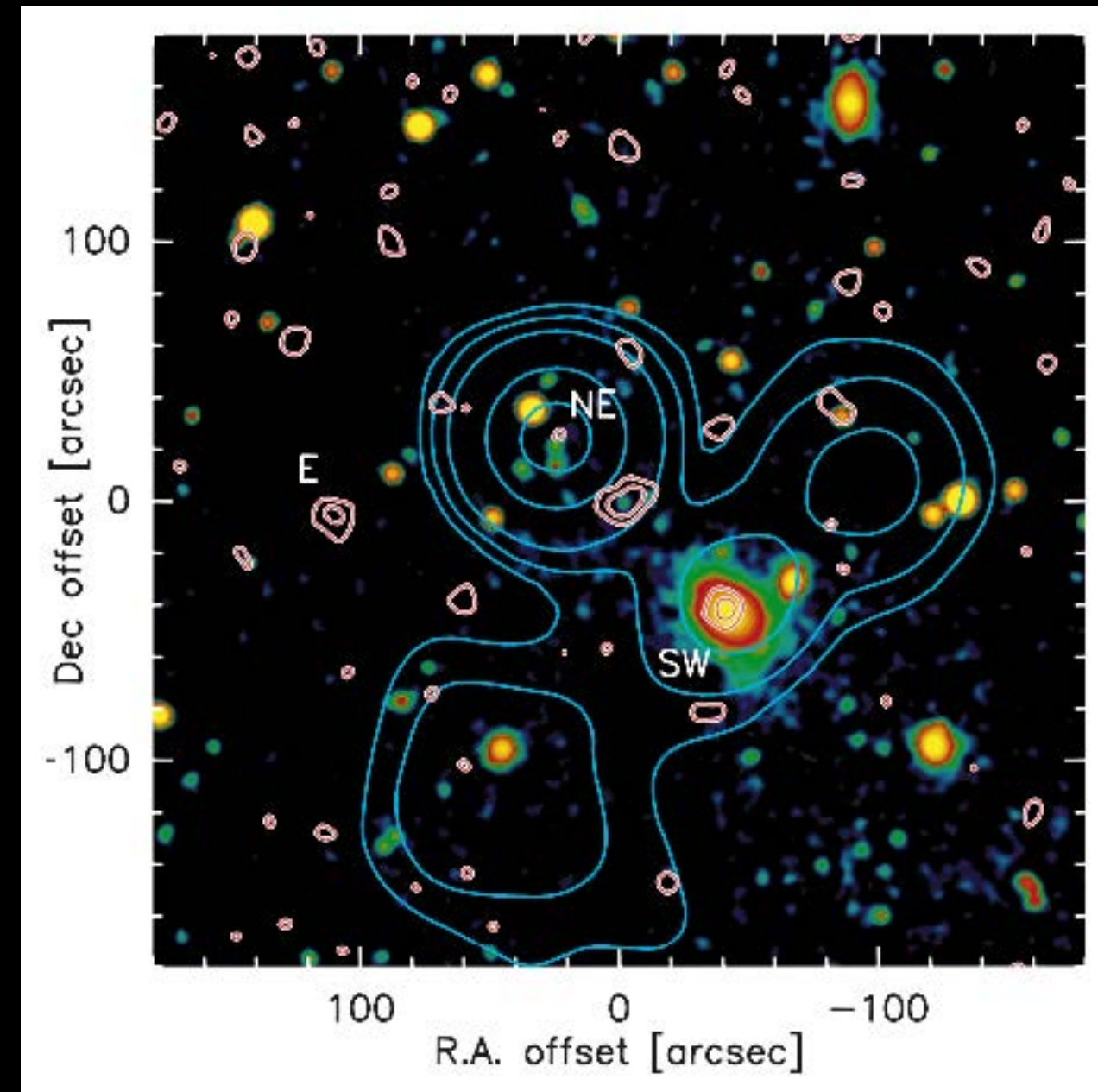


Förster Schreiber et al. 2009

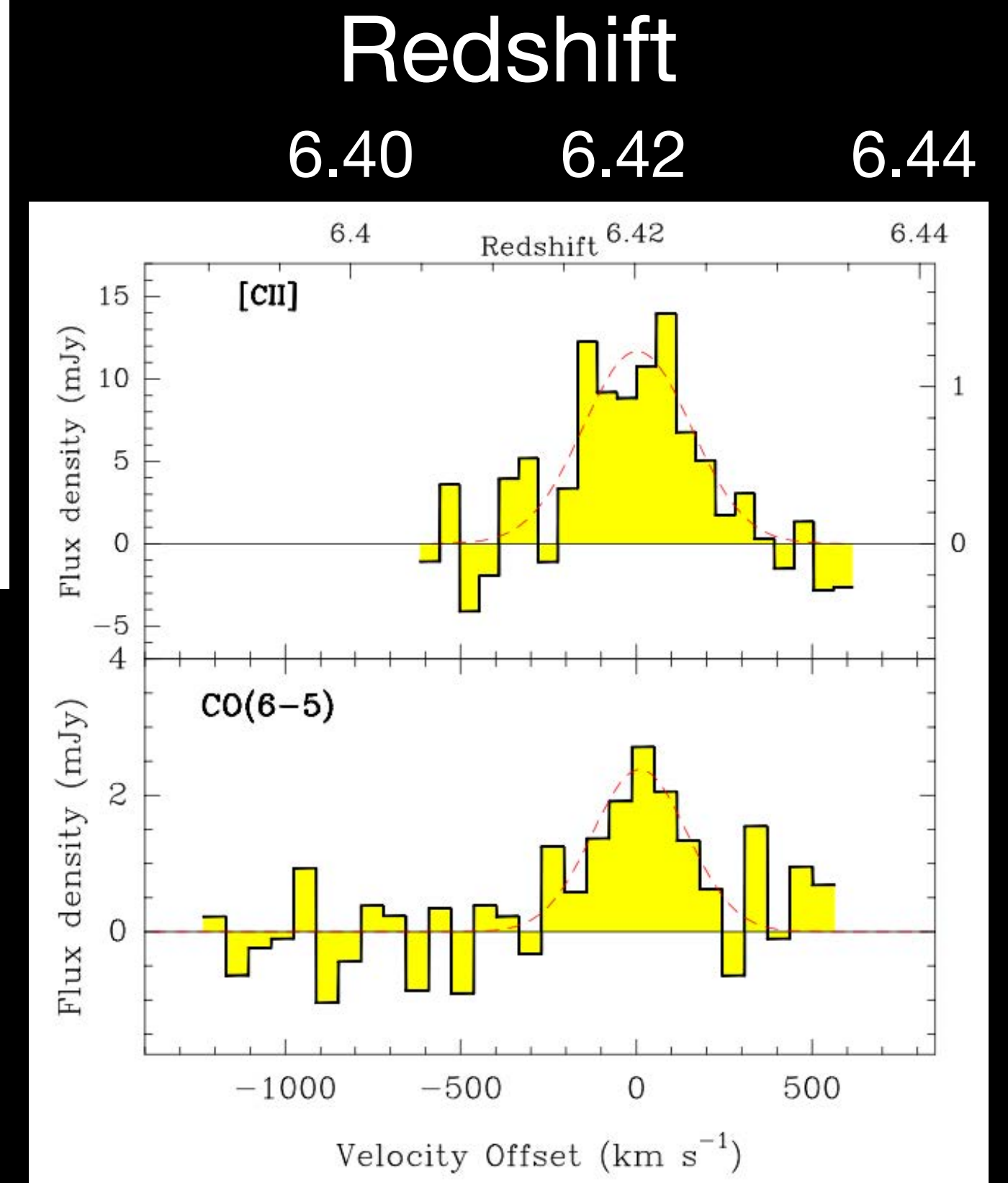
ISM of the Epoch of Reionization

virtually unexplored

- Was there dust?
 - Was there molecular gas?
 - Could [C II] even be detected?
-
- $z=6.42$ QSO observed with IRAM-30m
 - CO and CII detections
 - Dust detections



Red: MAMBO rest- $165\mu\text{m}$



15 years of ALMA

What has ALMA *revolutionized*?

ALMA has *changed the questions* we can ask:

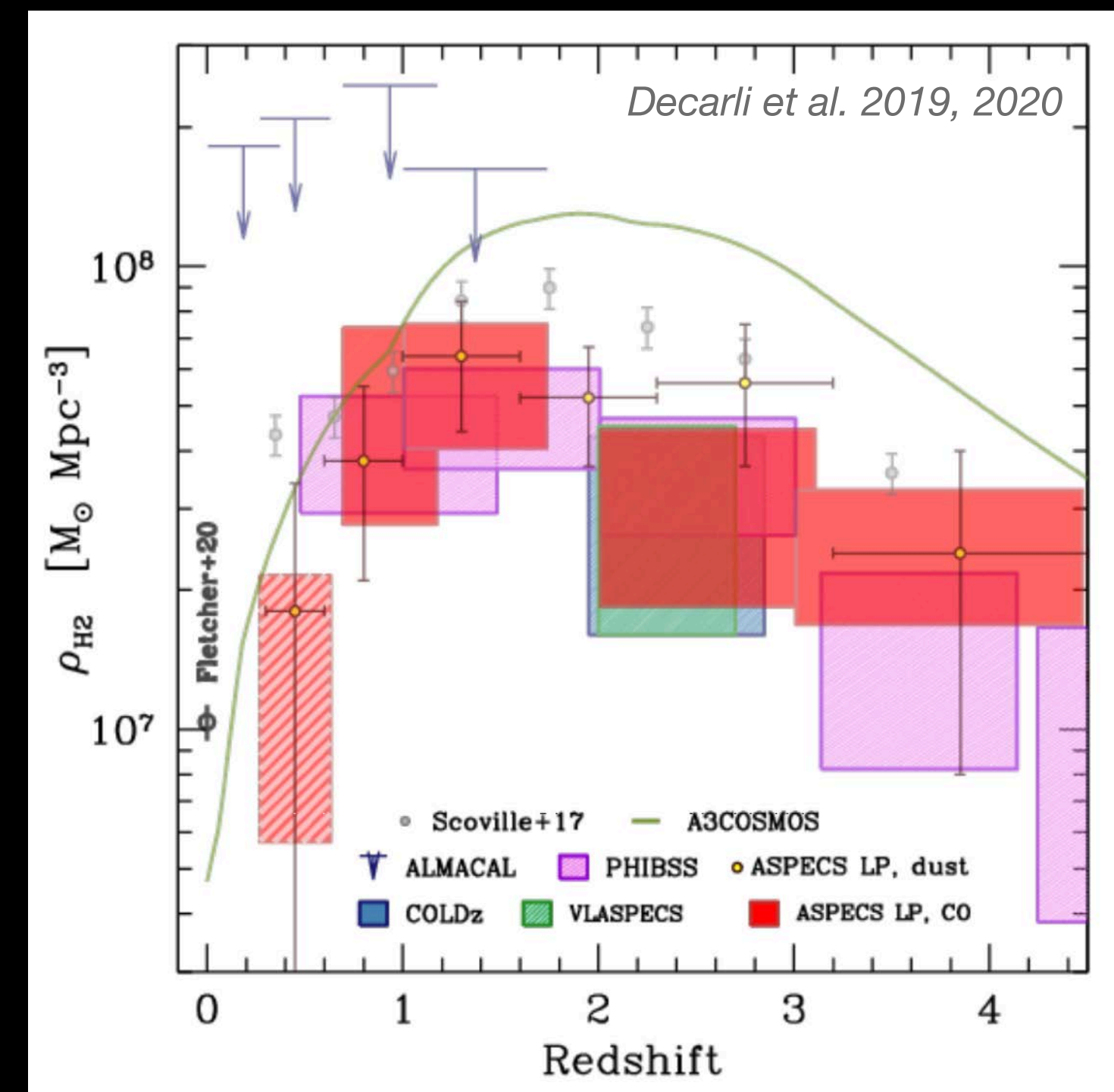
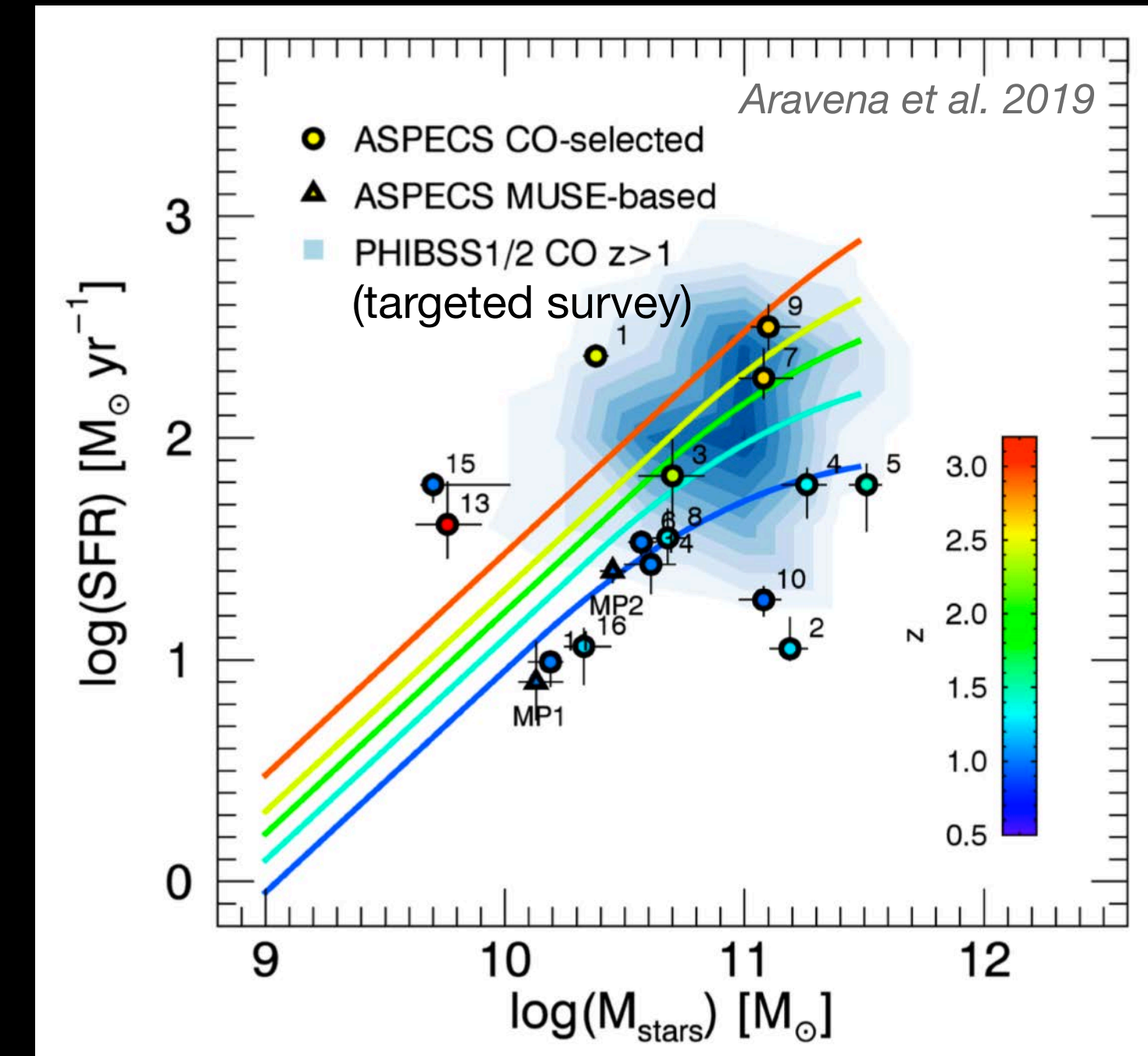
	Pre-ALMA	ALMA
<i>Gas</i>	Can we detect molecular gas?	What are the gas properties of galaxies?
<i>Dust</i>	Are galaxies dusty?	What are the dust properties?
<i>ISM Physics, Dynamics</i>	Can we detect the cool ISM?	What are its structures and dynamics?
<i>Cosmic Dawn</i>	What happened during reionization?	How are early galaxies assembled?

Blind CO survey

ASPECS: the ALMA Spectroscopic Survey in the HUDF

- A flux-limited view of molecular gas content in a fixed cosmic volume
 - Main-sequence, lower SF, less massive compared to previous targeted surveys
- Molecular gas density evolution largely follows the SFR density evolution
- Glimpse of molecular gas masses, gas fractions, gas depletion times, scaling relations

E.g., Walter et al. 2016,2020, Klitsch et al. 2019 (ALMACAL)

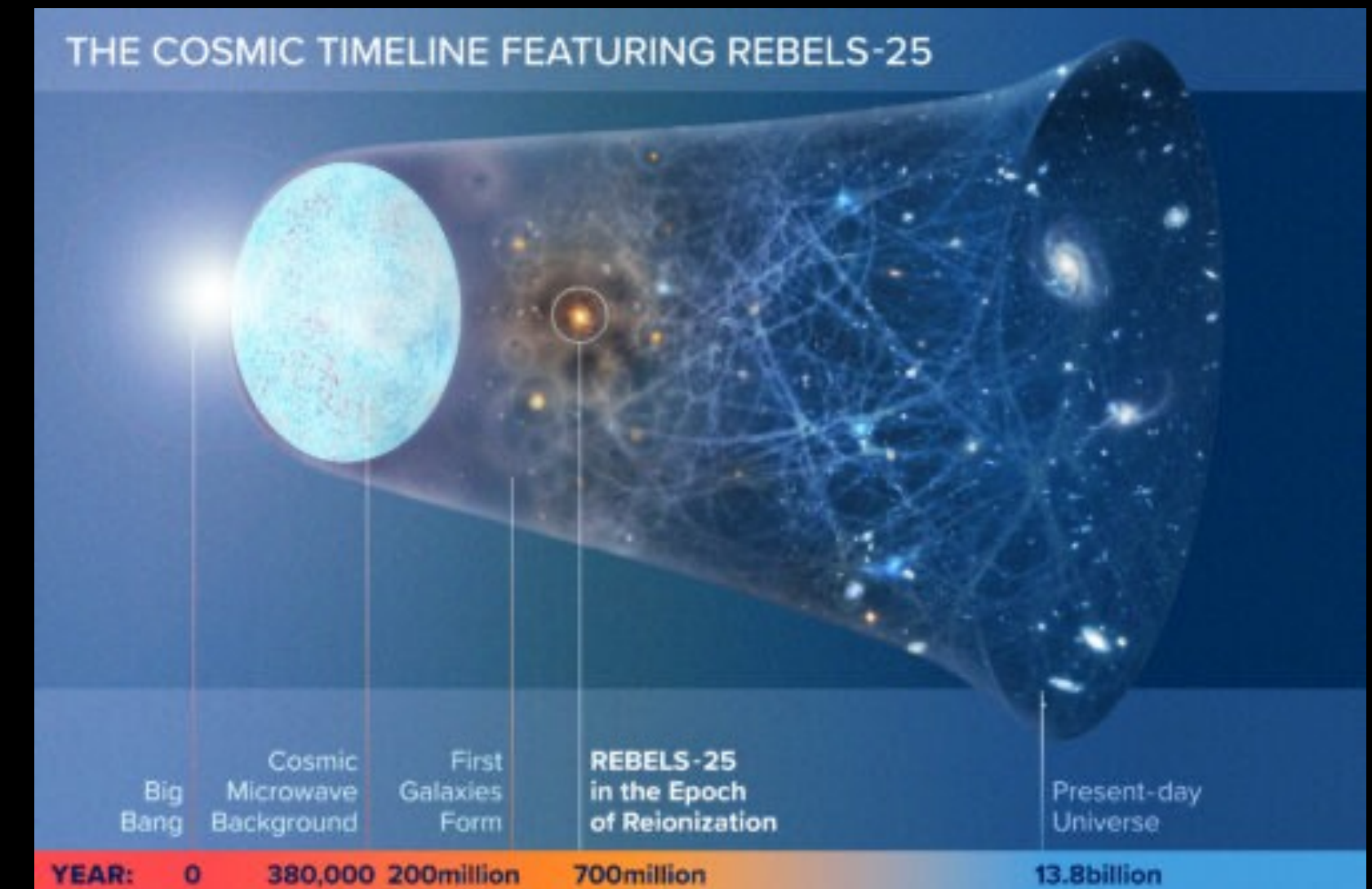
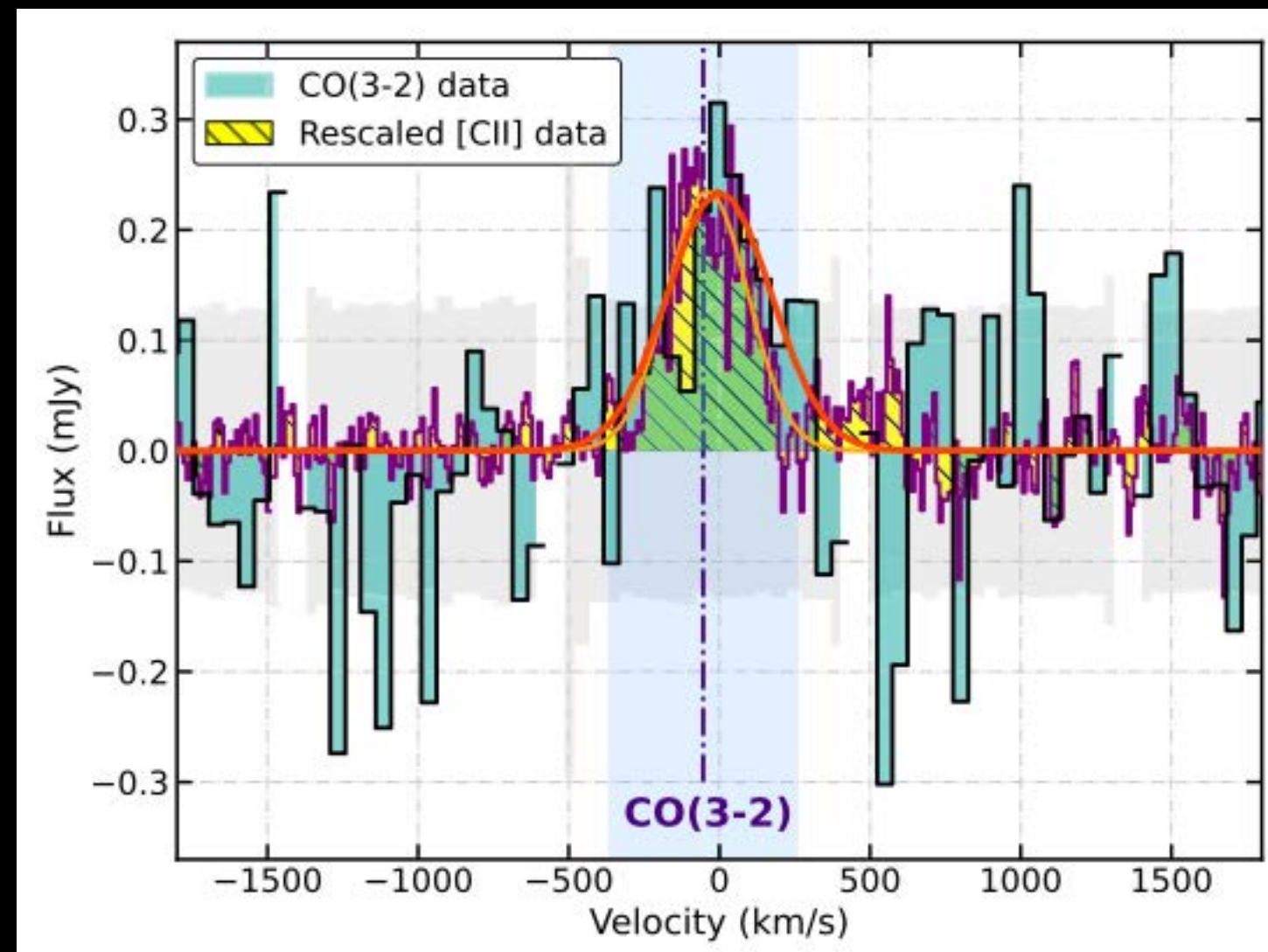
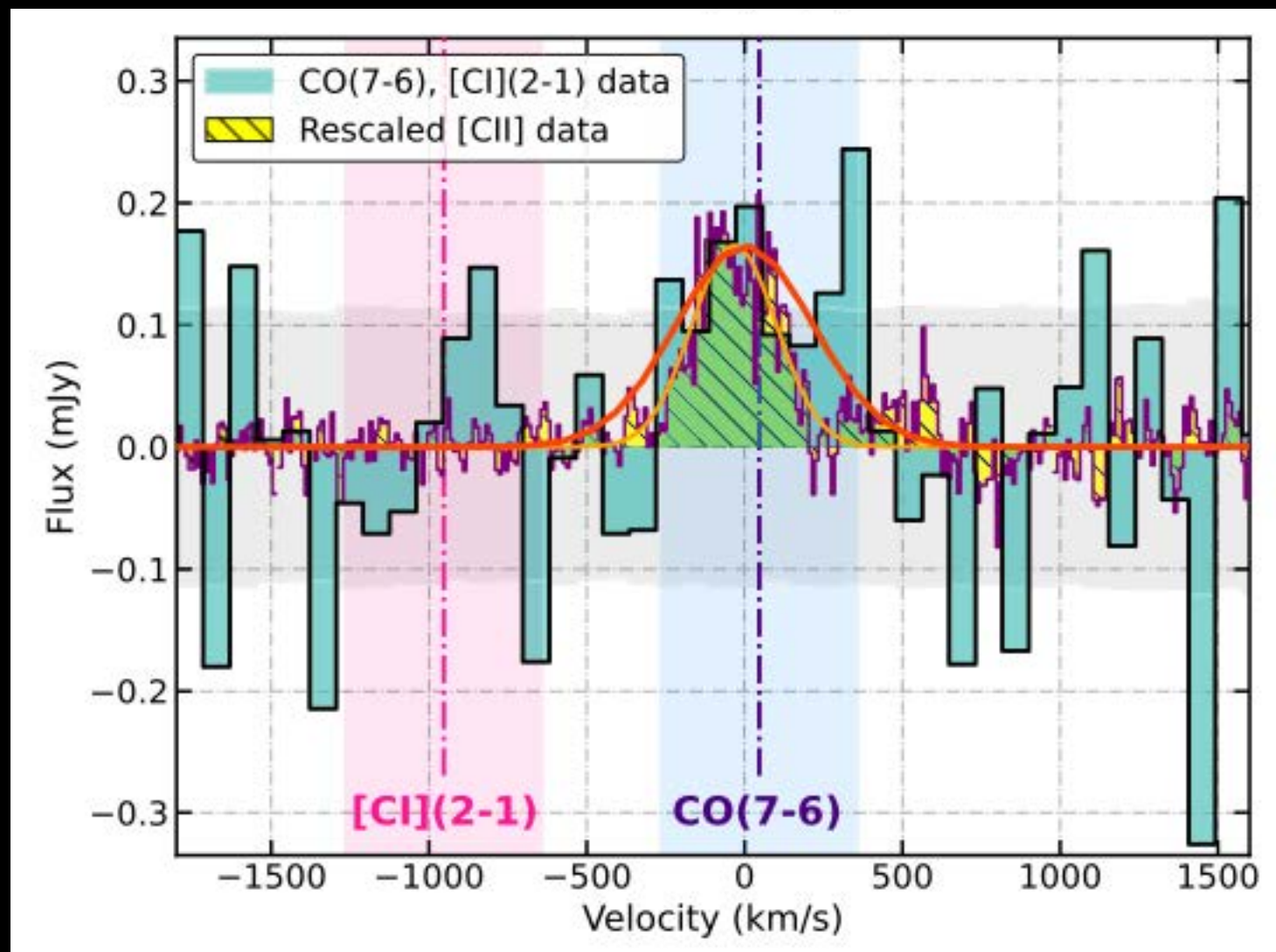


Molecular Gas Mass Density

Direct CO detection at $z=7.31$!

700M years after the Big Bang

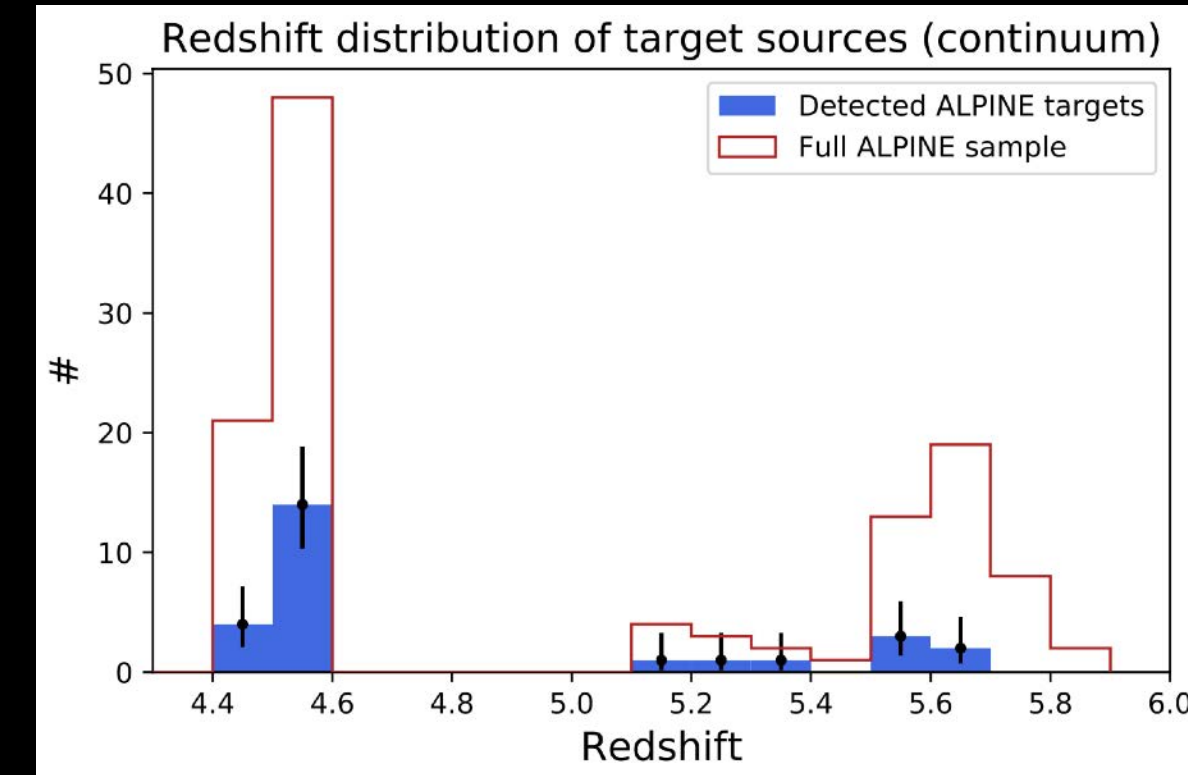
- The most distant detection of CO emission
 - CO(7-6) with ALMA and CO(3-2) with VLA
- Cold molecular gas reservoir in a massive star-forming galaxy at $z=7.4$



Dust observations

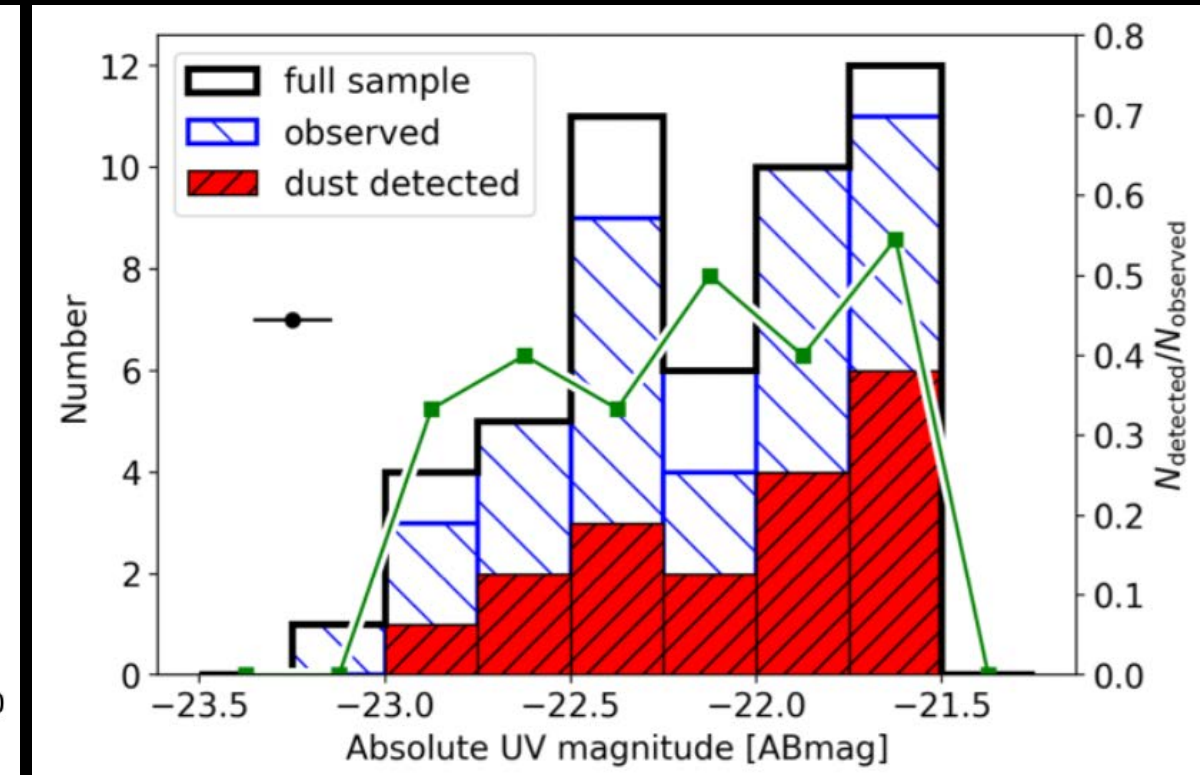
- Identifying individual dust emission
- Significant amount of obscured star formation from $z \sim 3$ to $z \sim 7$
 - The Universe appears to be dusty when < 1 Gyr old
- Very rapid buildup of dust
 - Supernovae likely play the major role
- These targets are *UV-selected* targets

ALPINE: 23/118 (19%) detections

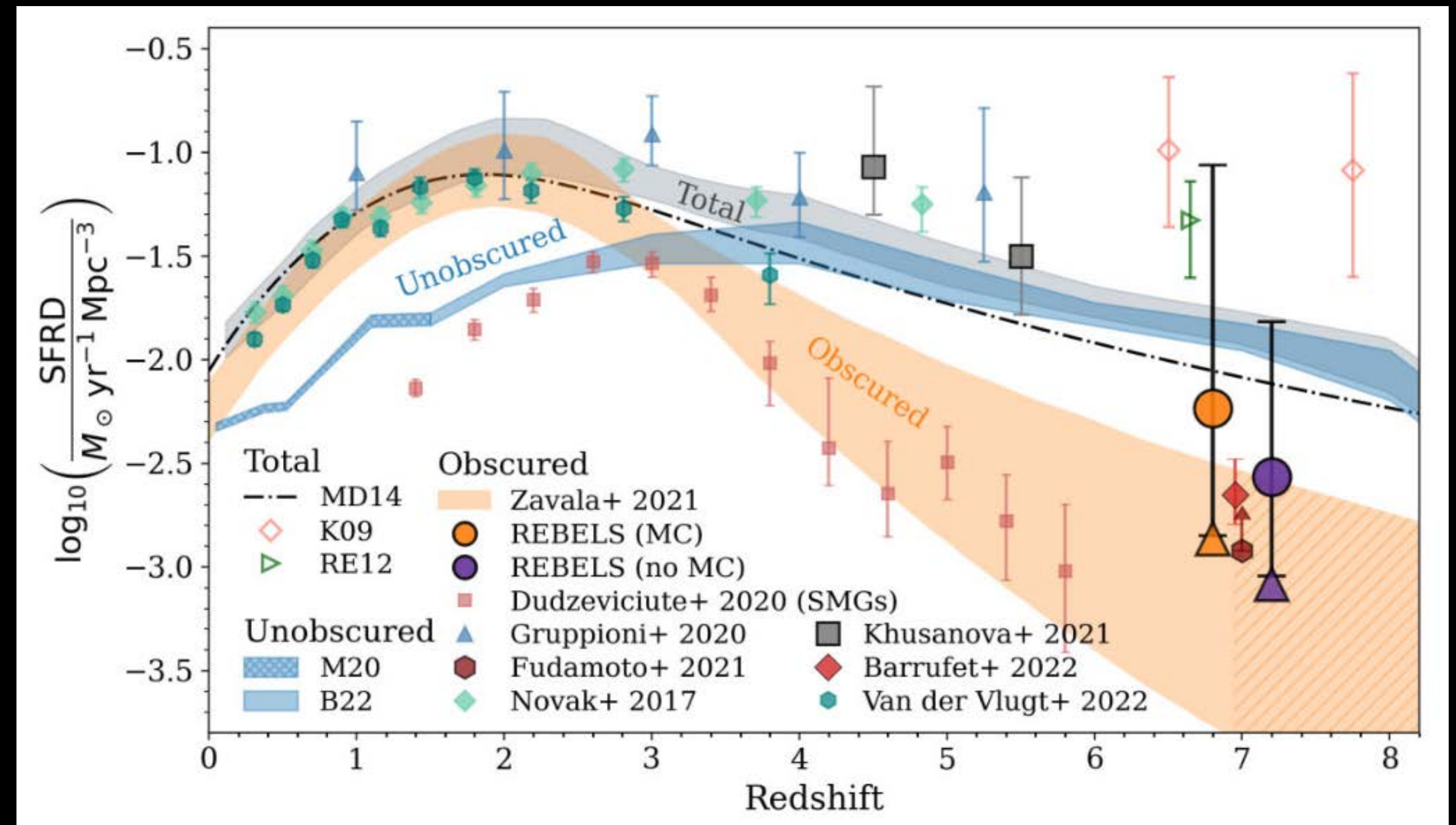


Bethermin et al. 2020

REBELS: 16/40 (40%) detections



Inami et al. 2022



Algera et al. 2023

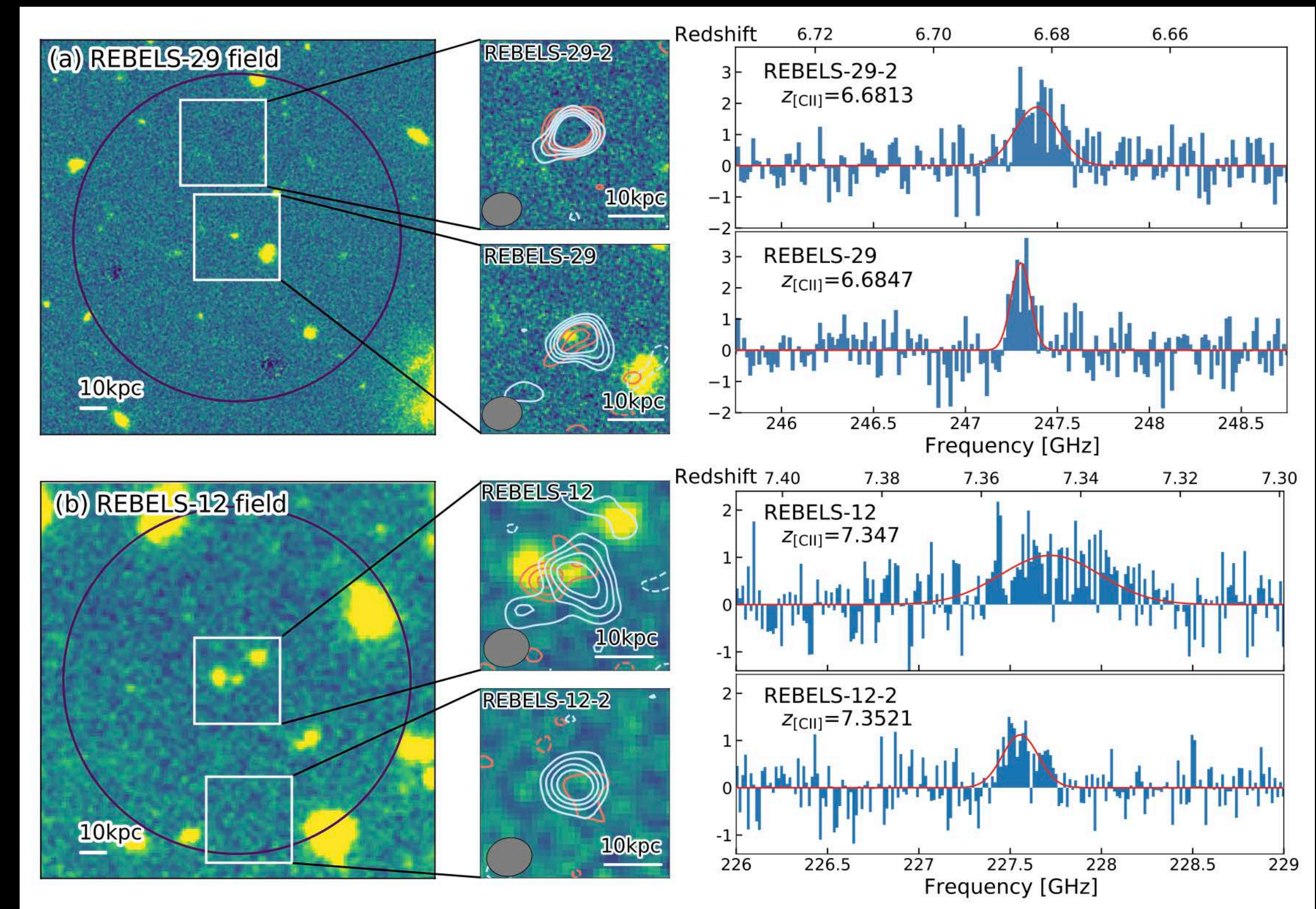
Cf. ALPINE, REBELS, MORA, SERENADE

Khusanova et al. 2021, Gruppioni et al. 2020, Yan et al. 2020, Loiacono et al. 2021, Zavala et al. 2018,2021, Inami et al. 2022a, Schouws et al. 2022a, Bowler et al. 2021

Dust observations

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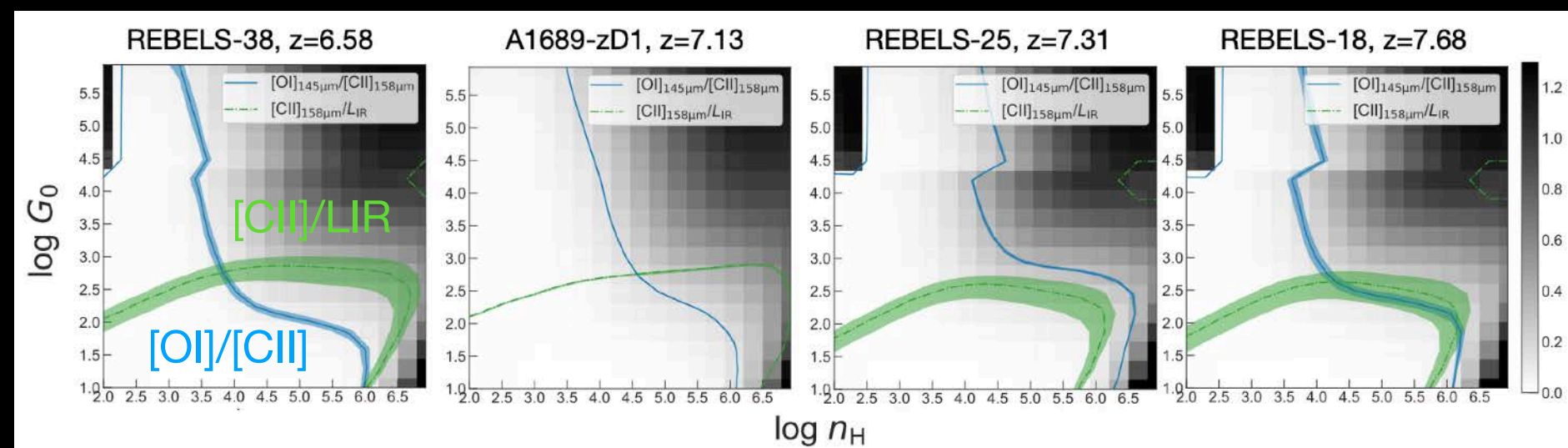
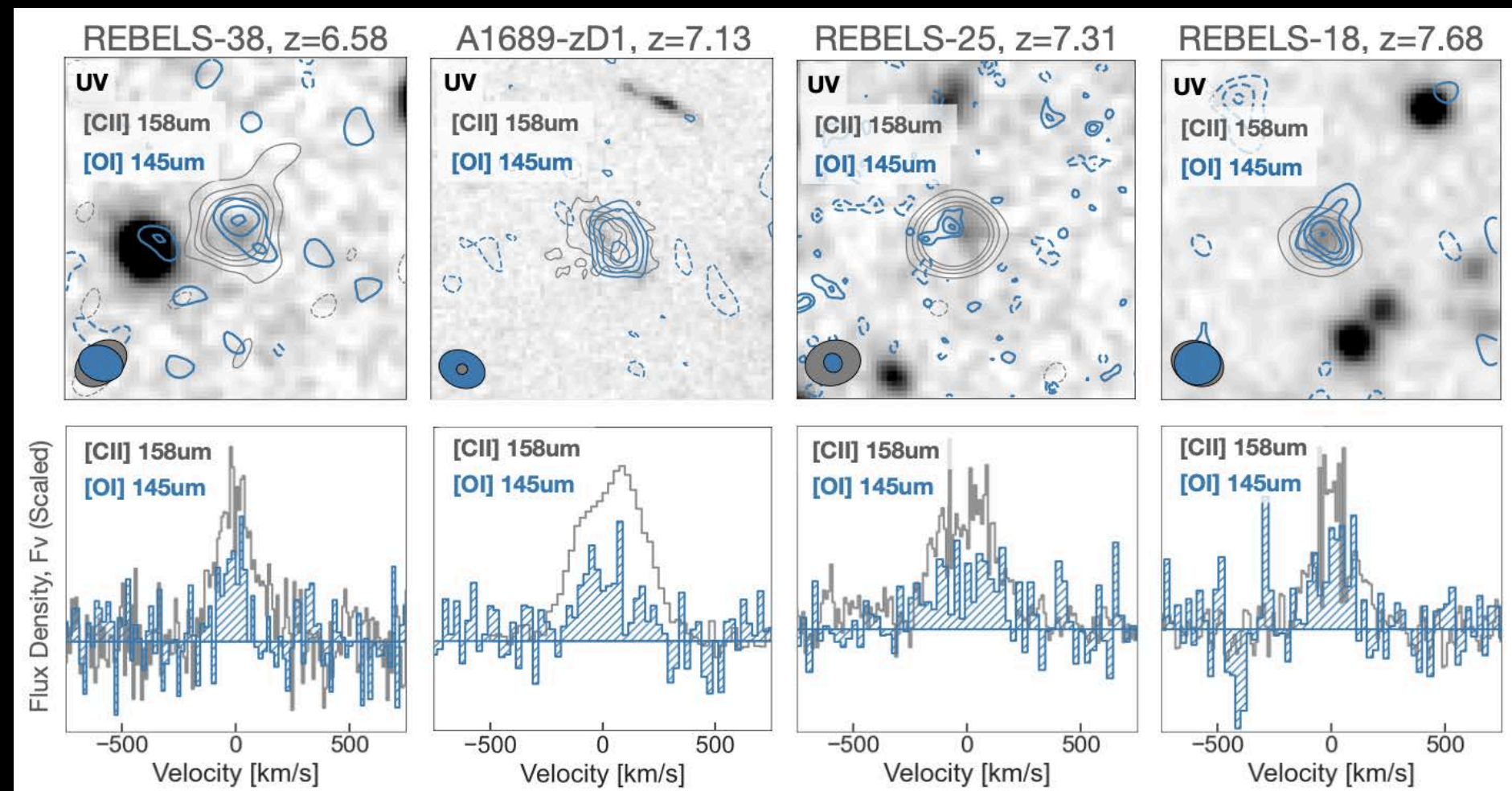
Completely dust embedded galaxies at $z \sim 7$!



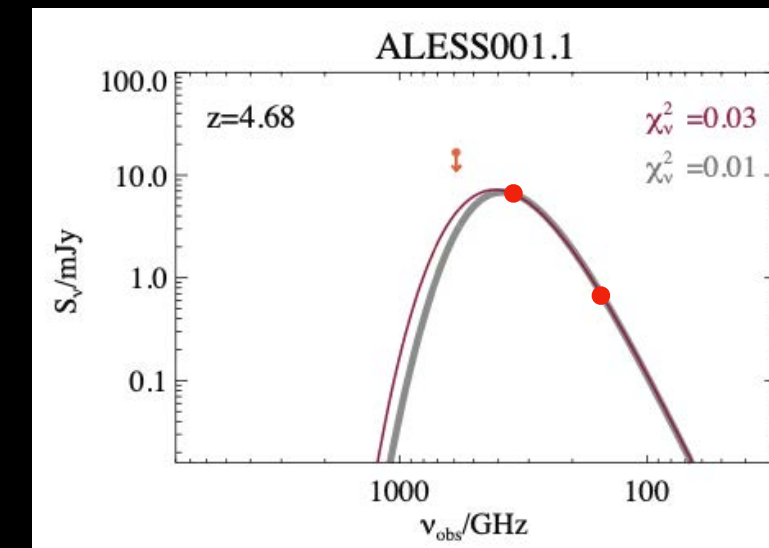
Fudamoto et al. 2021

Multi-Band Observations

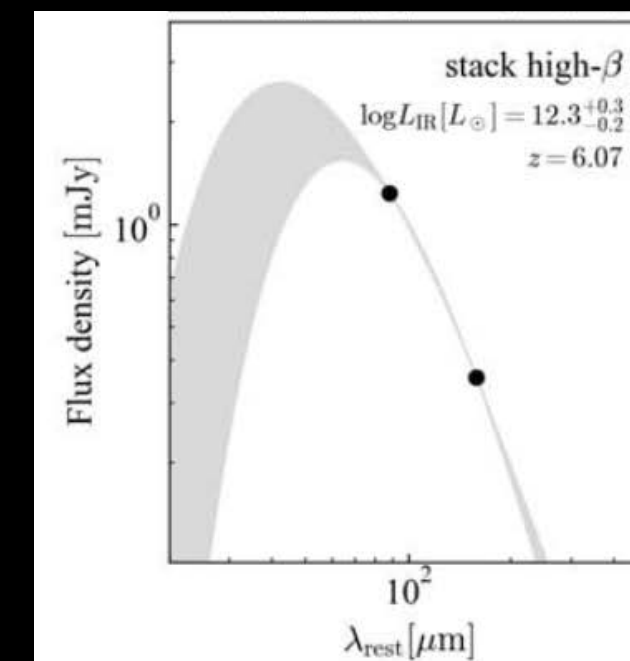
Enabling studies of galaxy properties



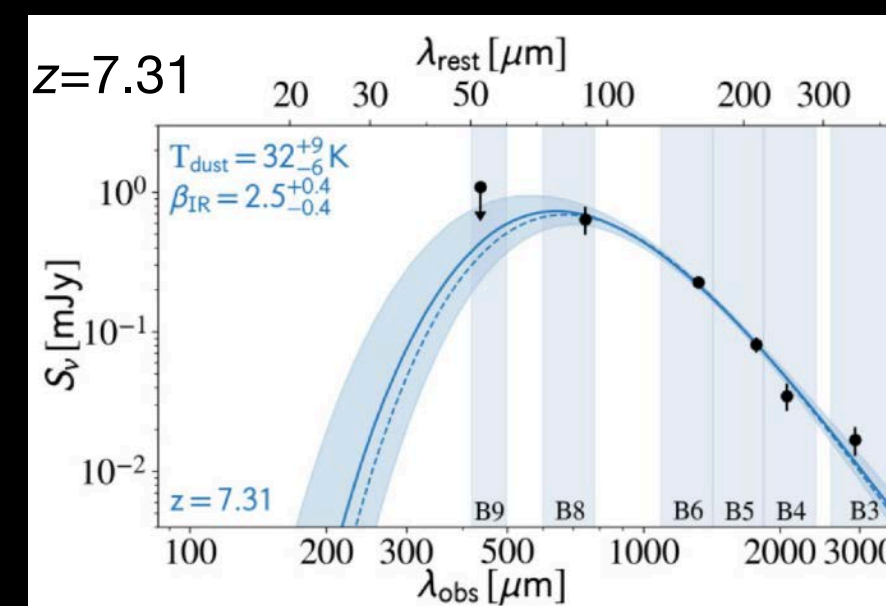
Fudamoto et al. 2026



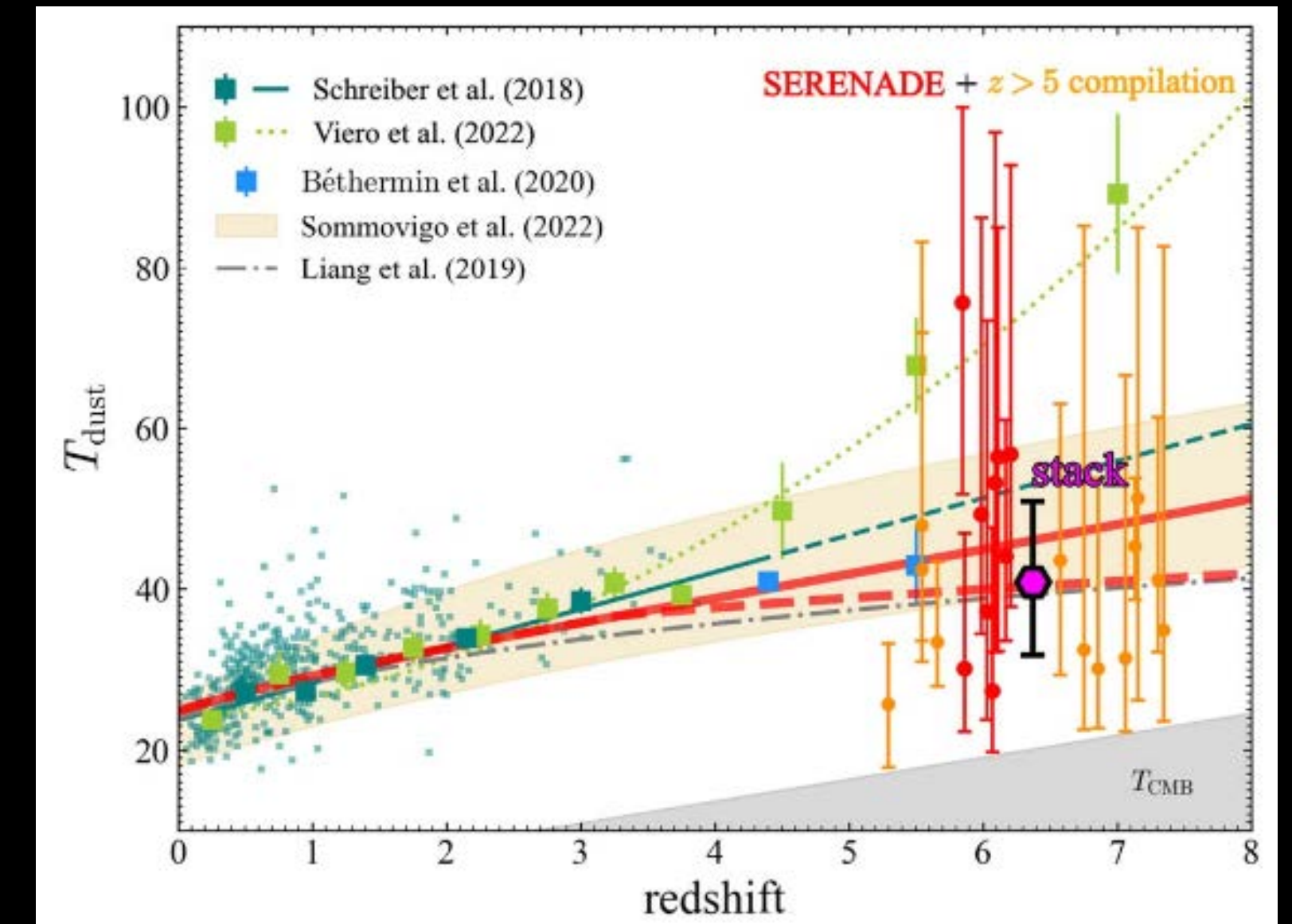
daCunha et al. 2021



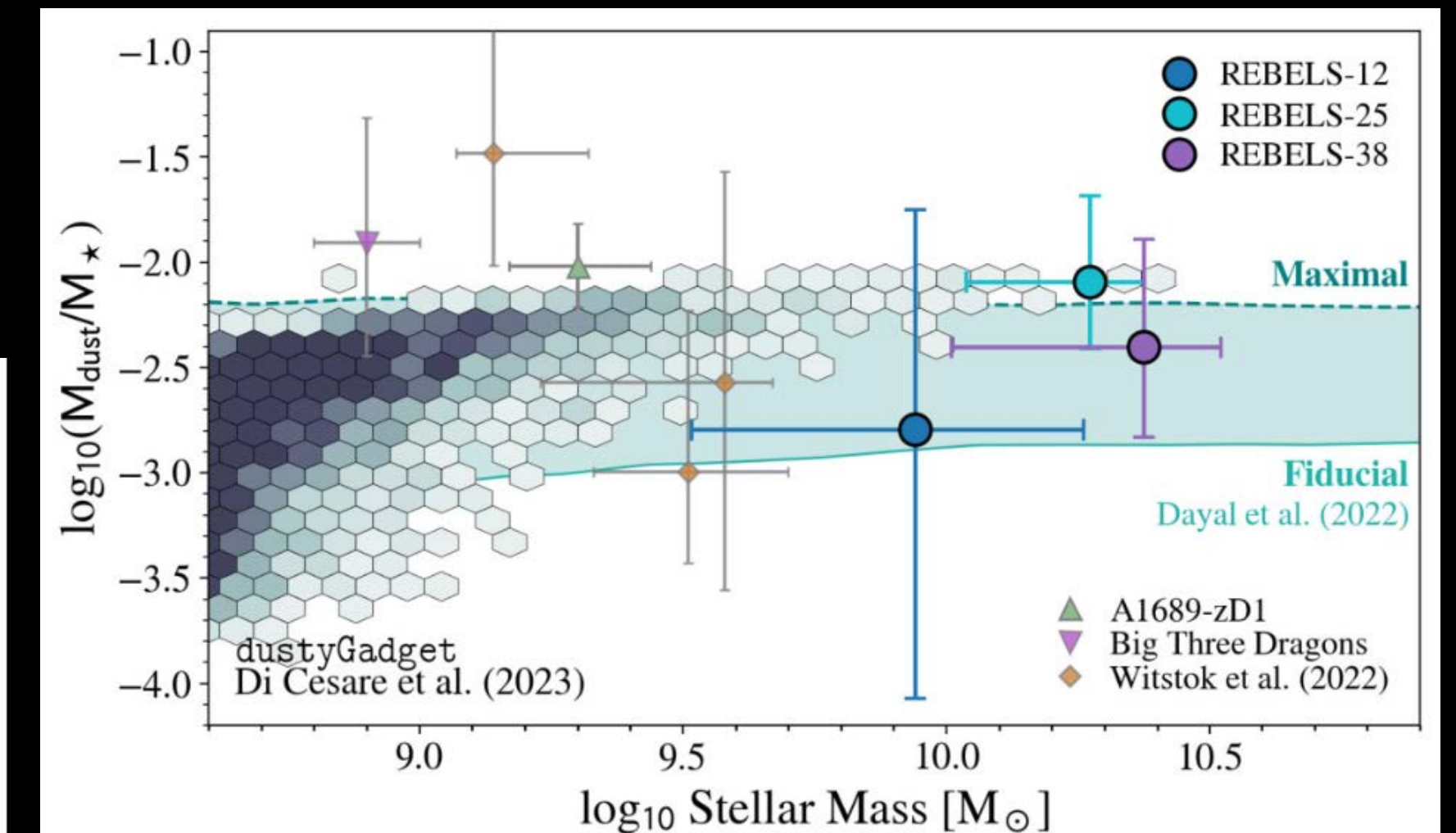
Witstok et al. 2022



Algera et al. 2024b

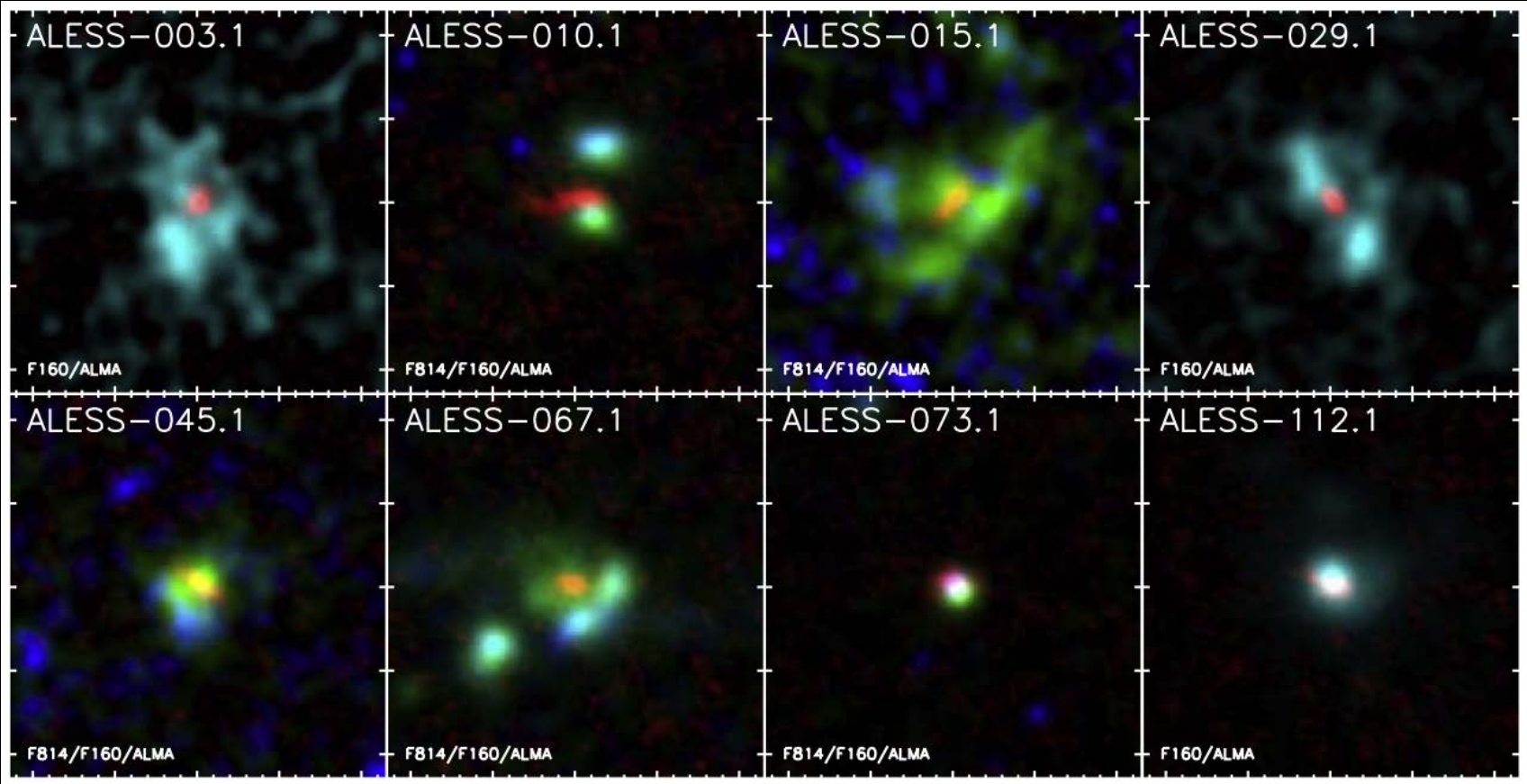


Mitsuhashi et al. 2024



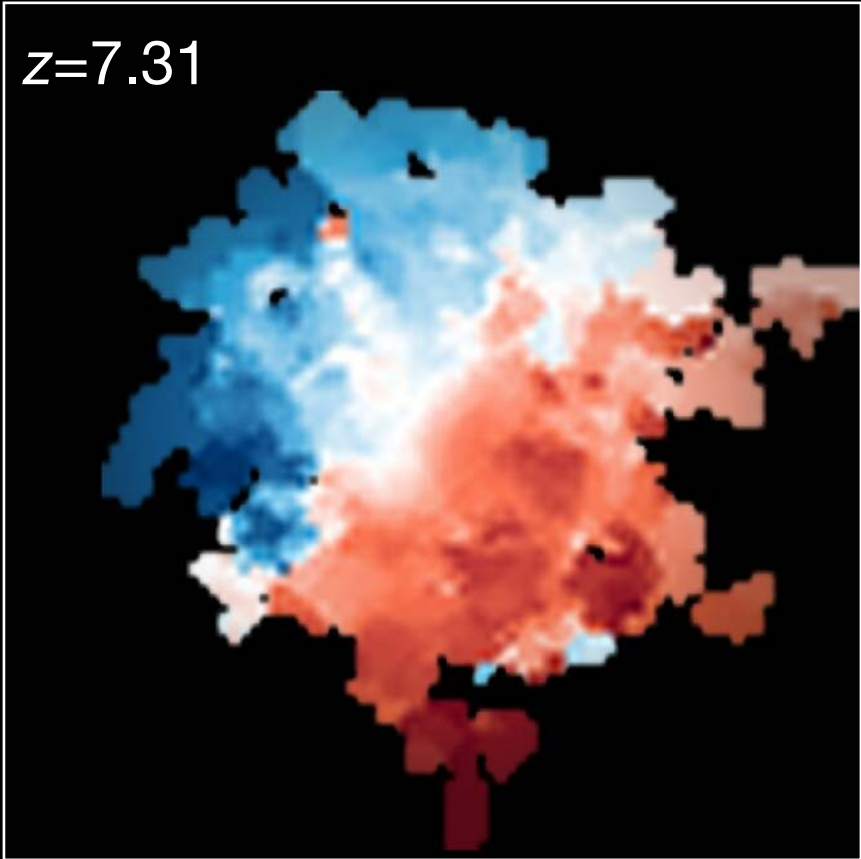
Algera et al. 2024a

Detecting and Resolving the Cool ISM

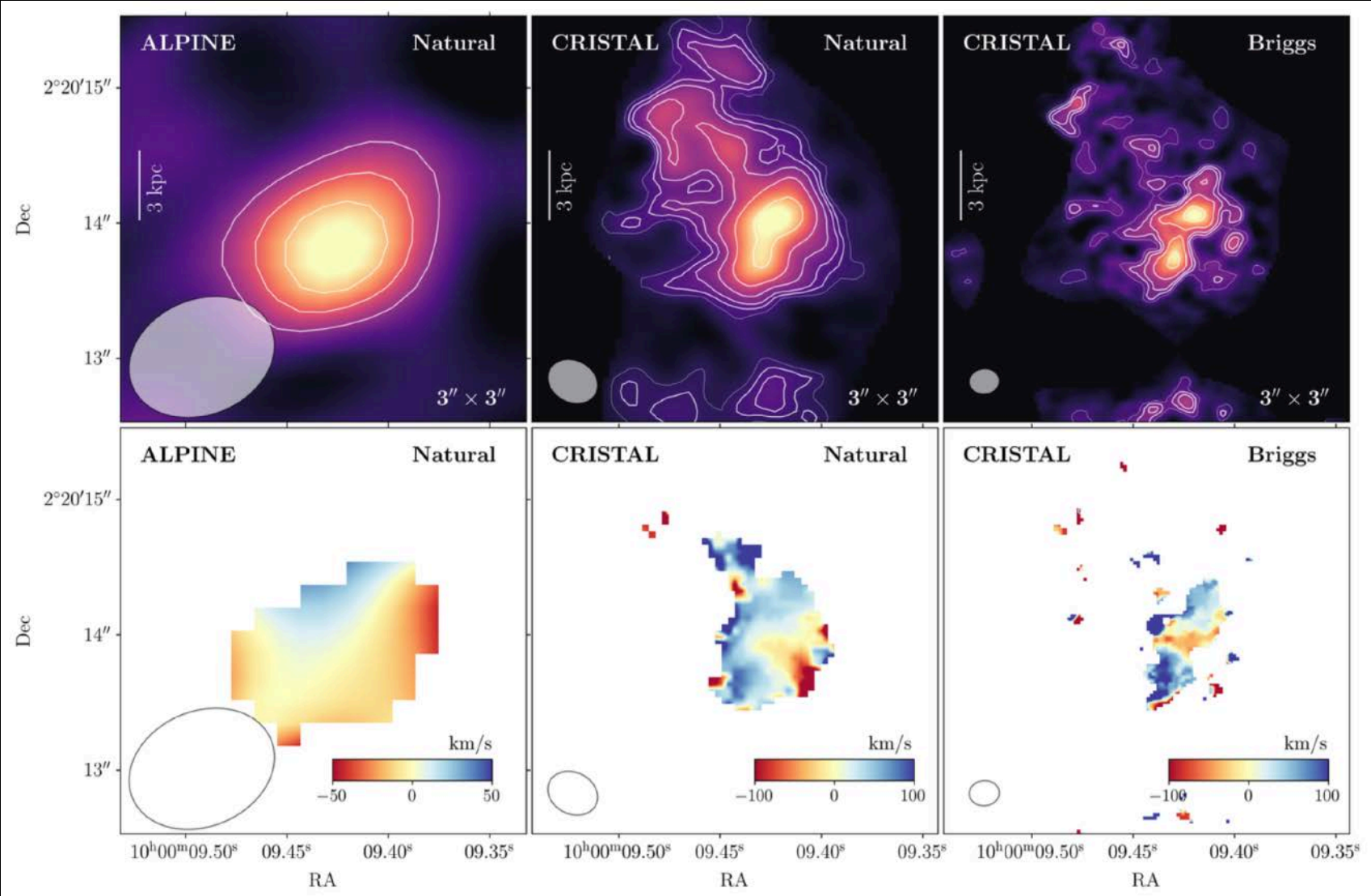


Hodge et al. 2016

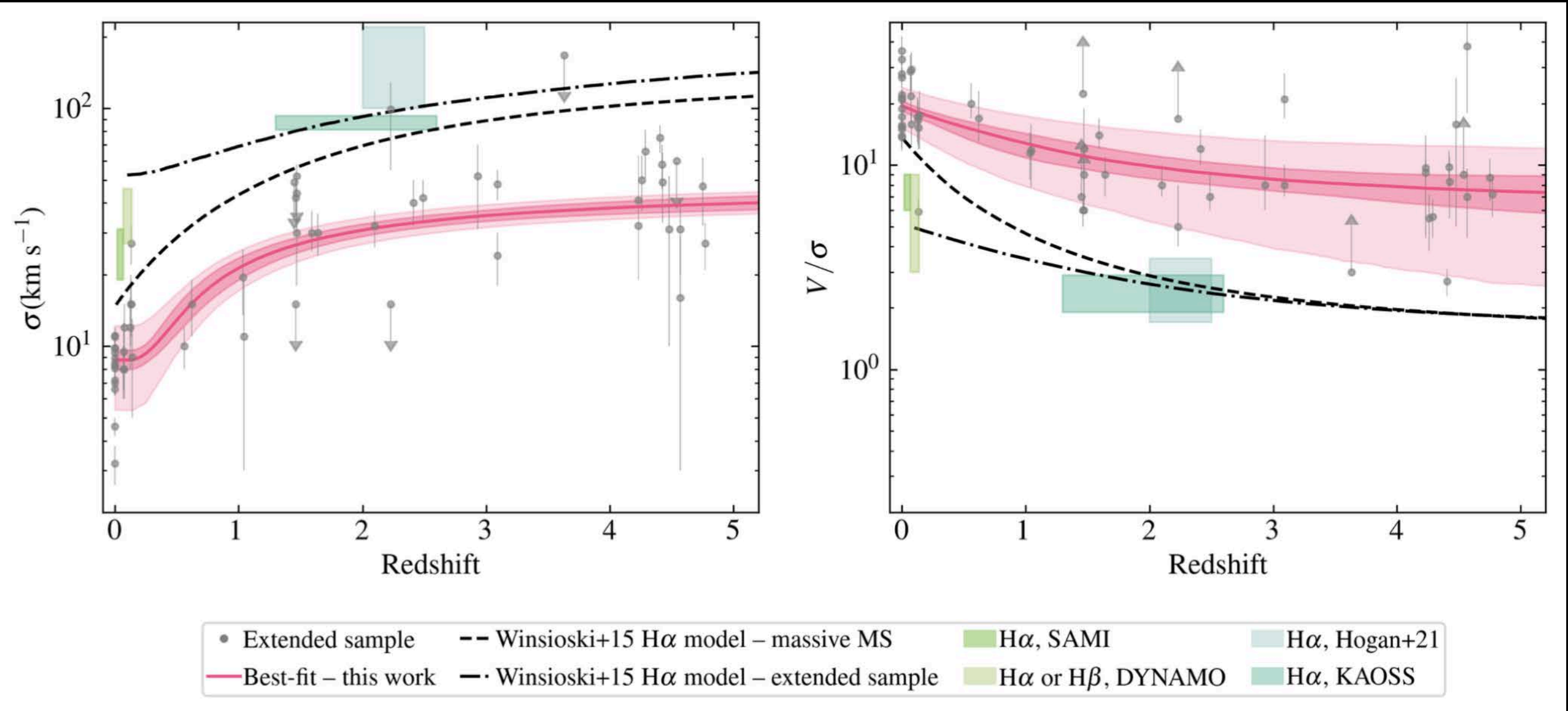
- **Complicated structure**
- **Outflows, mergers**
- **Mature dynamics in the early Universe**



ALMA (ESO/NAOJ/NRAO) / Rowland et al. 2024



Herrera-Camus et al. 2025

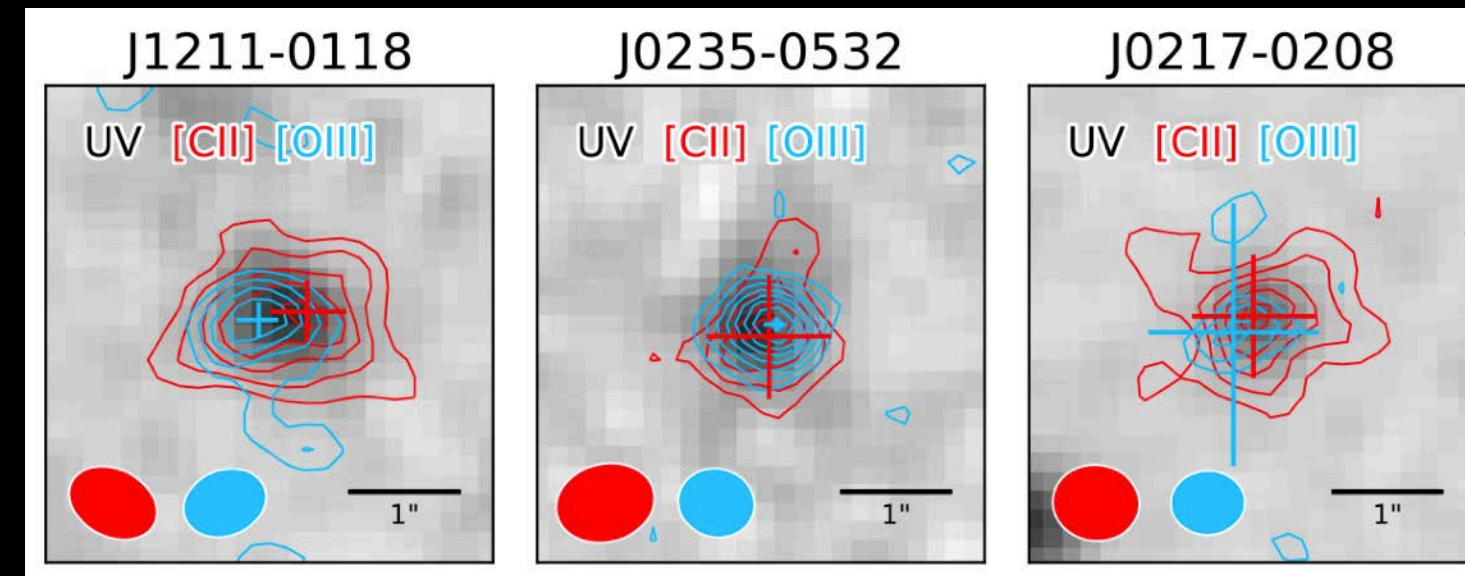
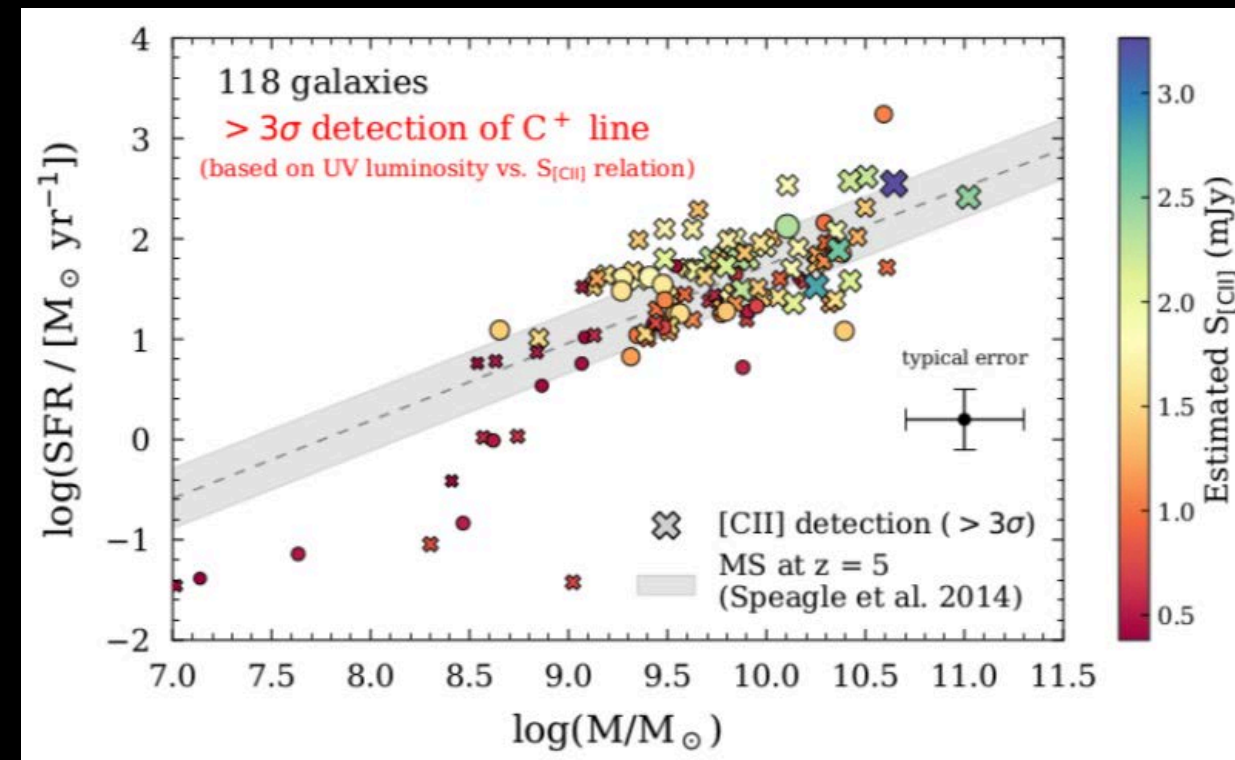


Rizzo et al. 2024

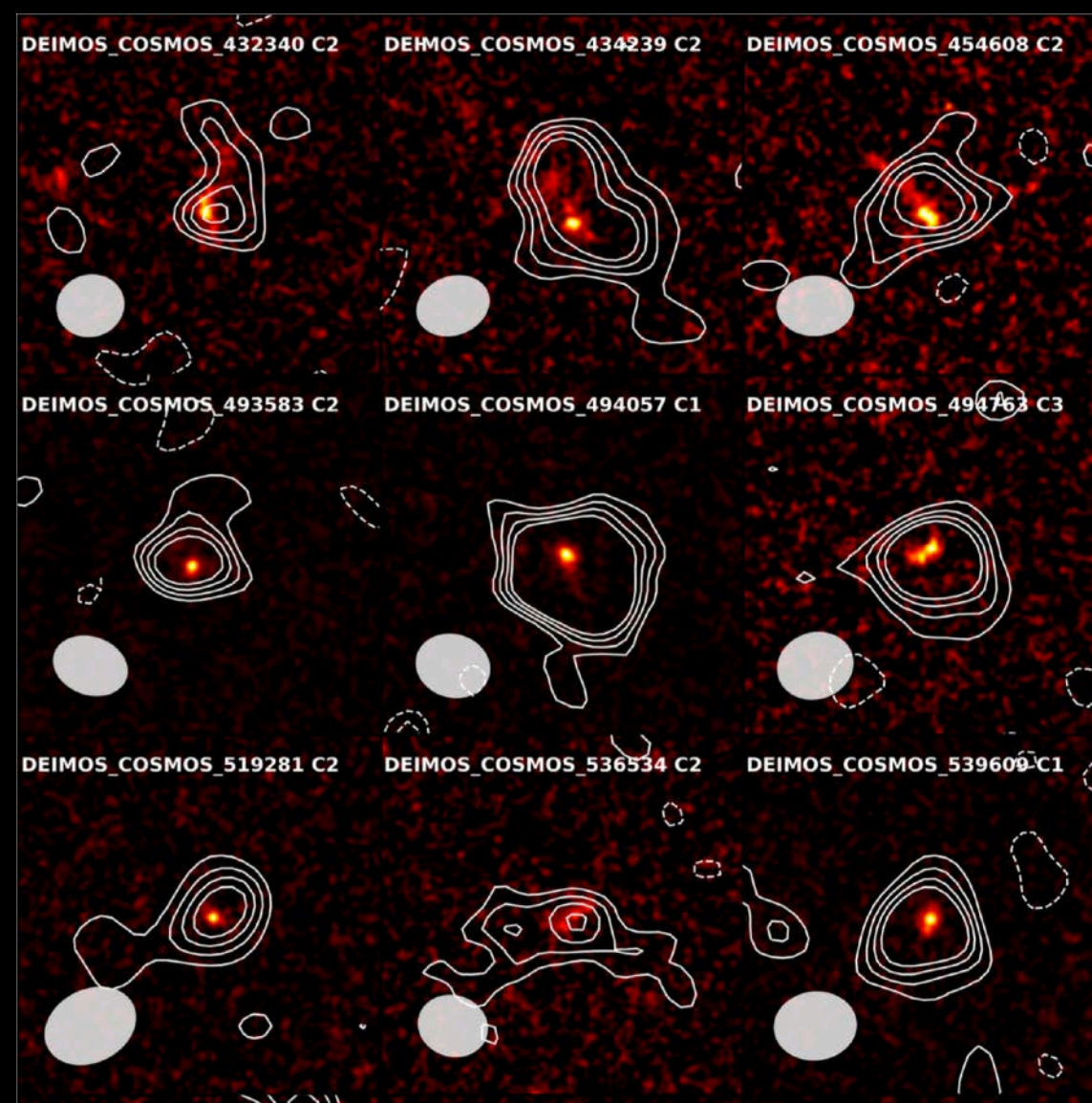
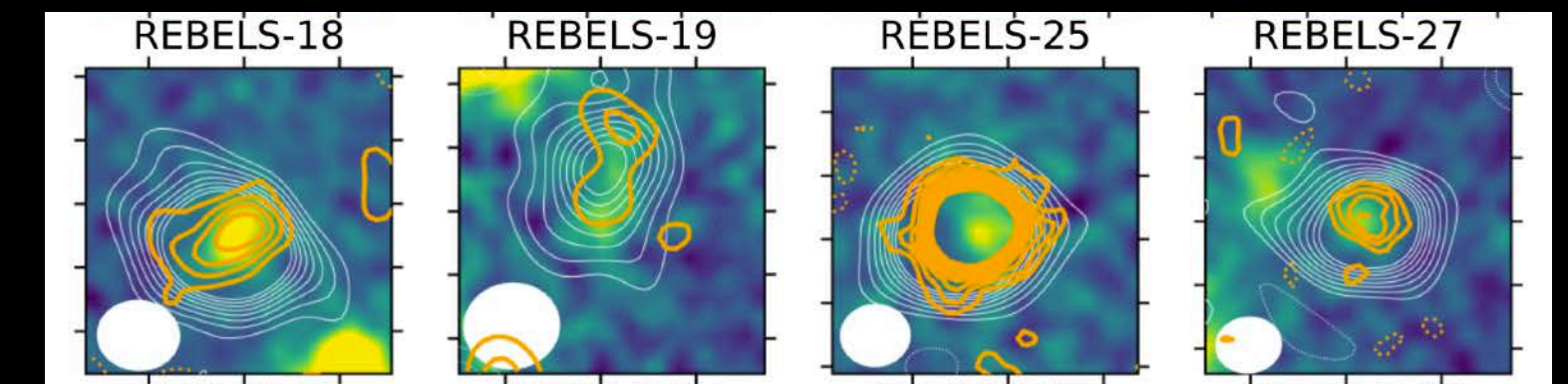
Galaxies at $4 < z < 6$ and in the EoR

Shift to statistical studies of normal galaxies at $z \sim 4-6$

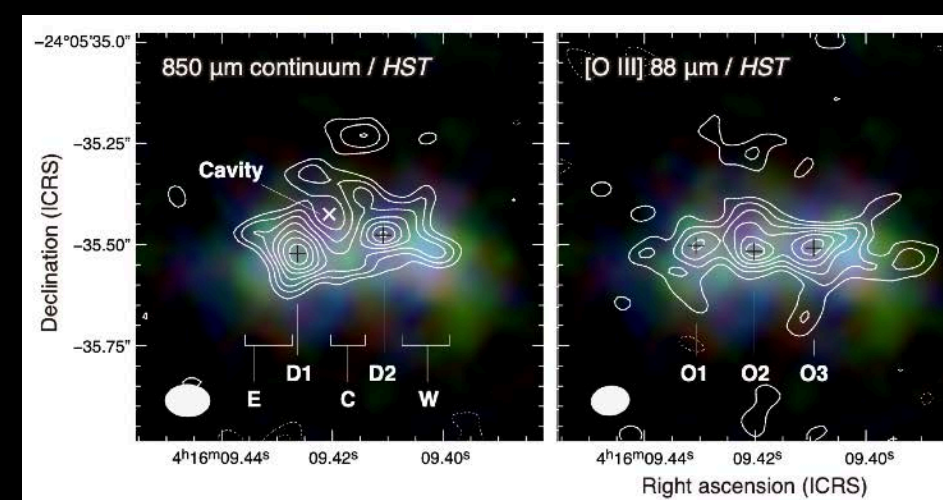
Routine observations of galaxies at $z > 6$



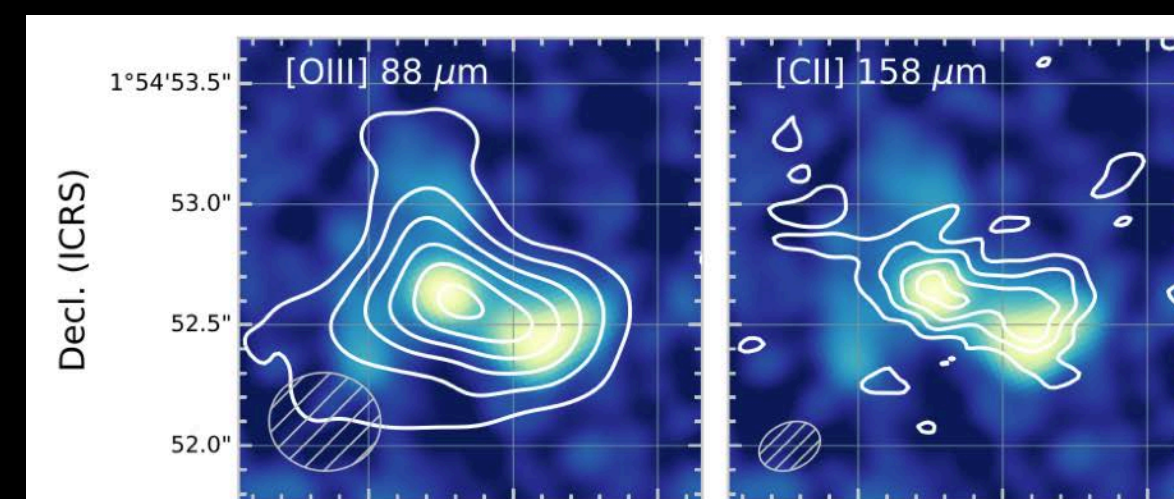
Harikane et al. 2020



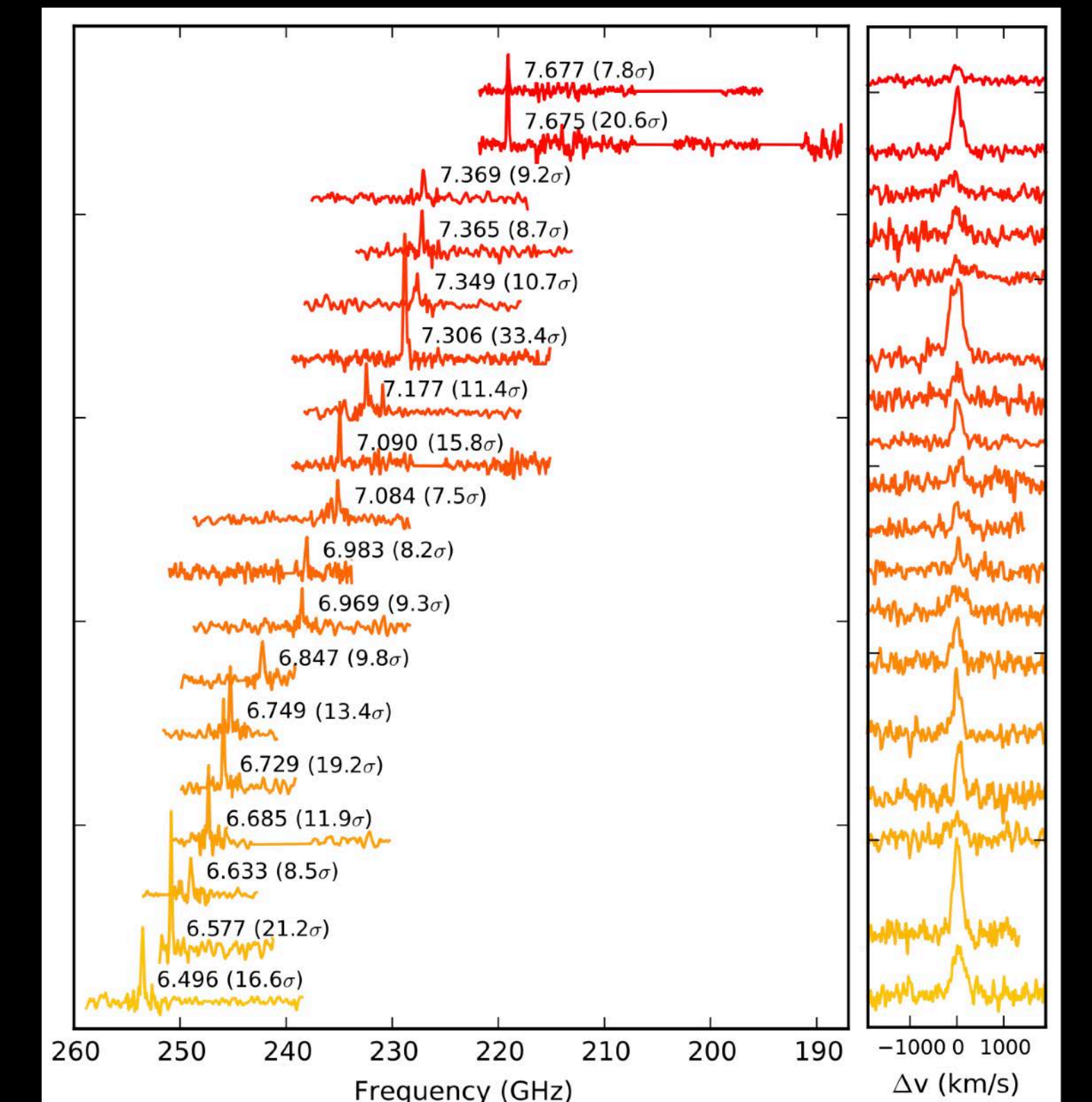
Le Fèvre et al. 2020



Tamura et al. 2023



Sugahara et al. 2024



Bouwens et al. 2022, Inami et al. 2022

Pre-ALMA to ALMA

- Before ALMA, we could detect only the brightest galaxies.
- With ALMA, we began to study galaxy properties and evolution.

Pre-ALMA

Can we detect molecular gas?

Are galaxies dusty?

Can we detect the cool ISM?

What happened during reionization?

ALMA

What are the gas properties of galaxies?

What are the dust properties?

What are its structures and dynamics?

How are early galaxies assembled?

What's next?

ALMA with the Wideband Sensitivity Upgrade

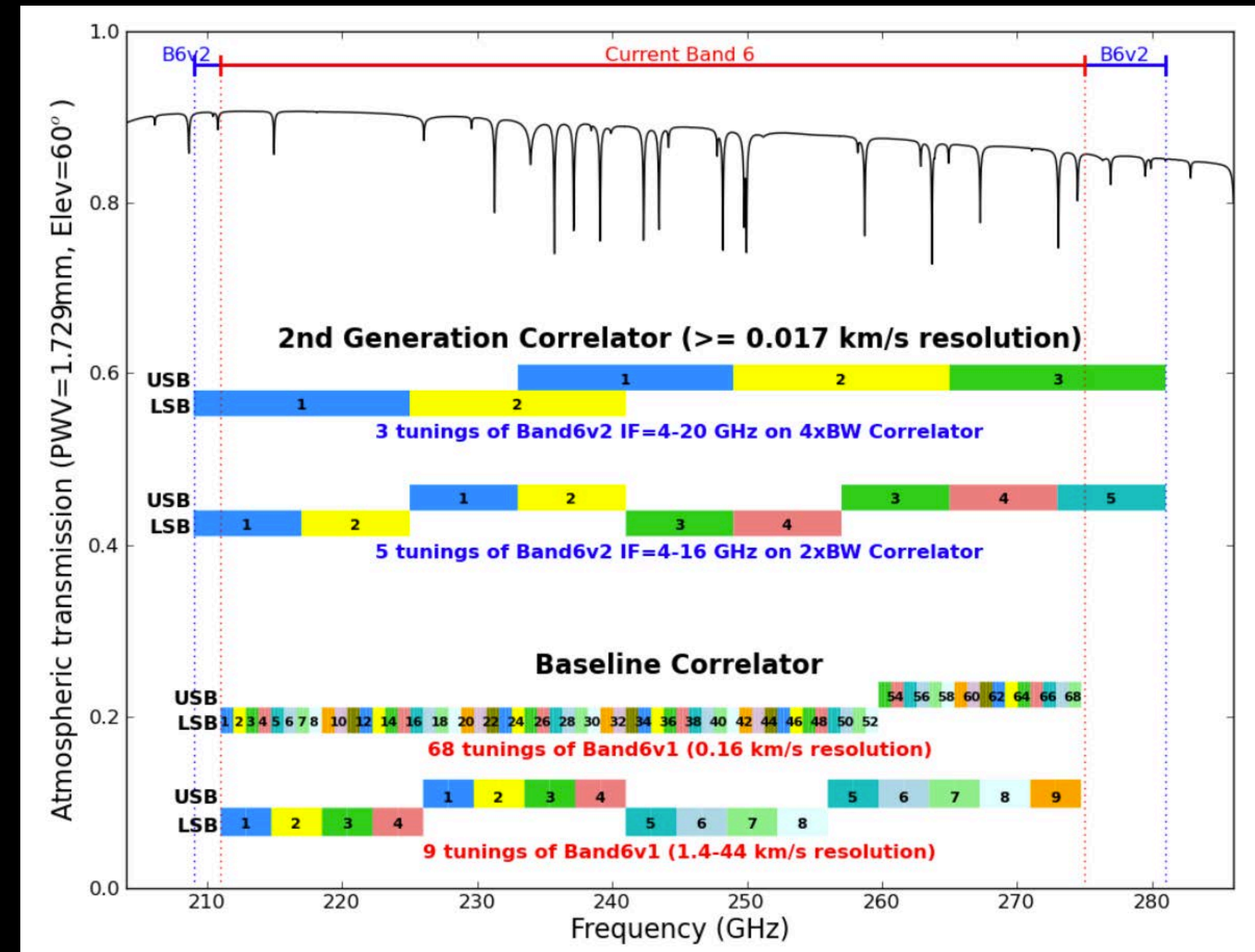
What are expected to be *routine* in the 2030s?

ALMA-WSU

- 2-4x bandwidth expansion
- Increased continuum (and line) sensitivity
- higher spectral resolution

Science benefits

- Blind redshift searches
- Multi-line observations
- Fainter galaxies
- Much larger galaxy samples
- Better legacy surveys

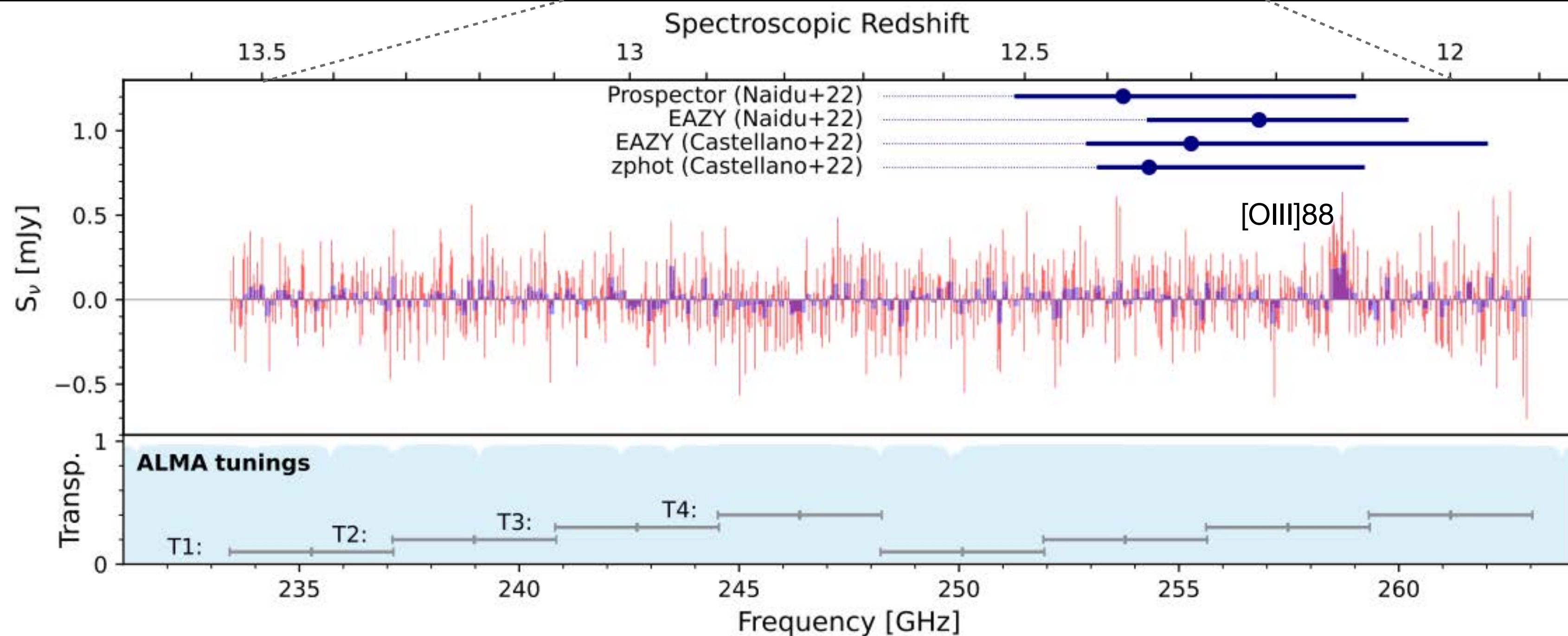
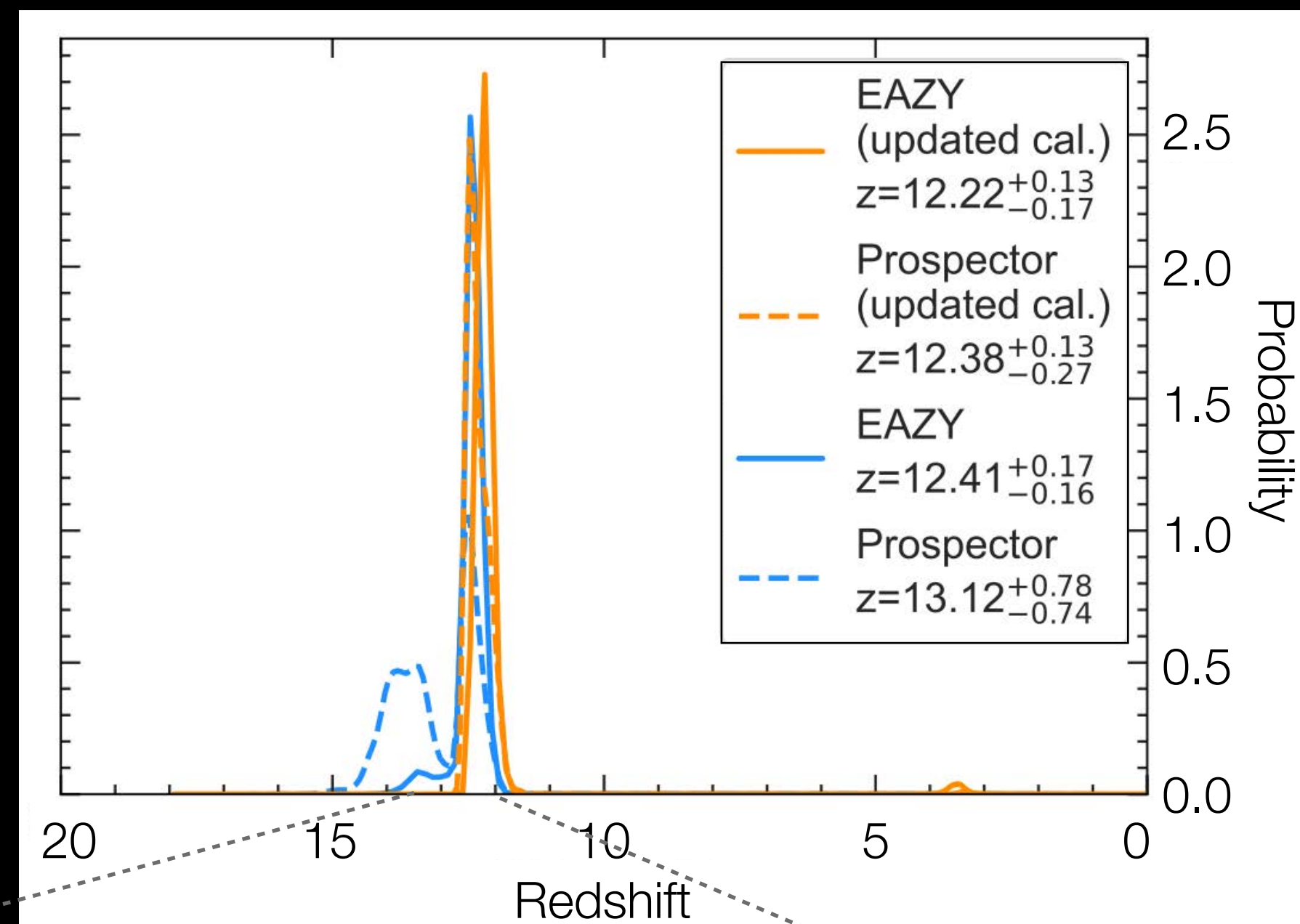


Carpenter et al. 2022

More efficient studies of the high-redshift Universe

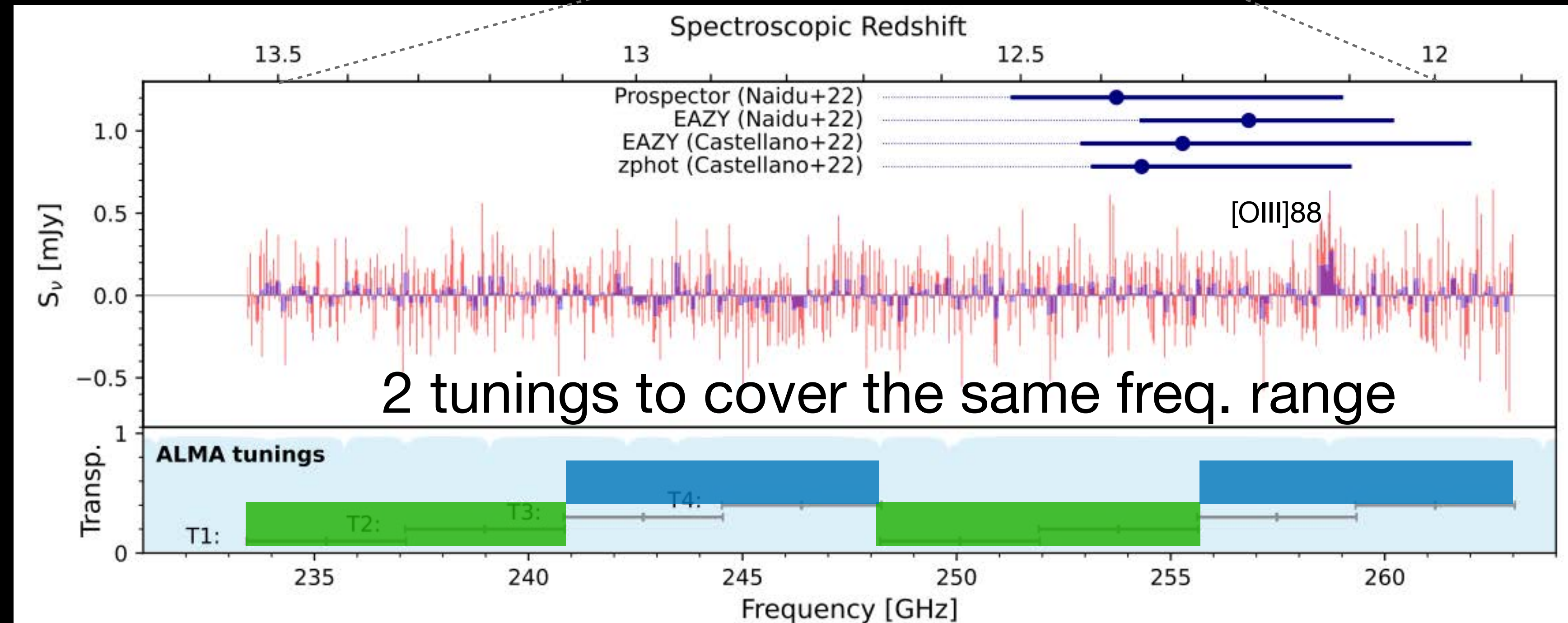
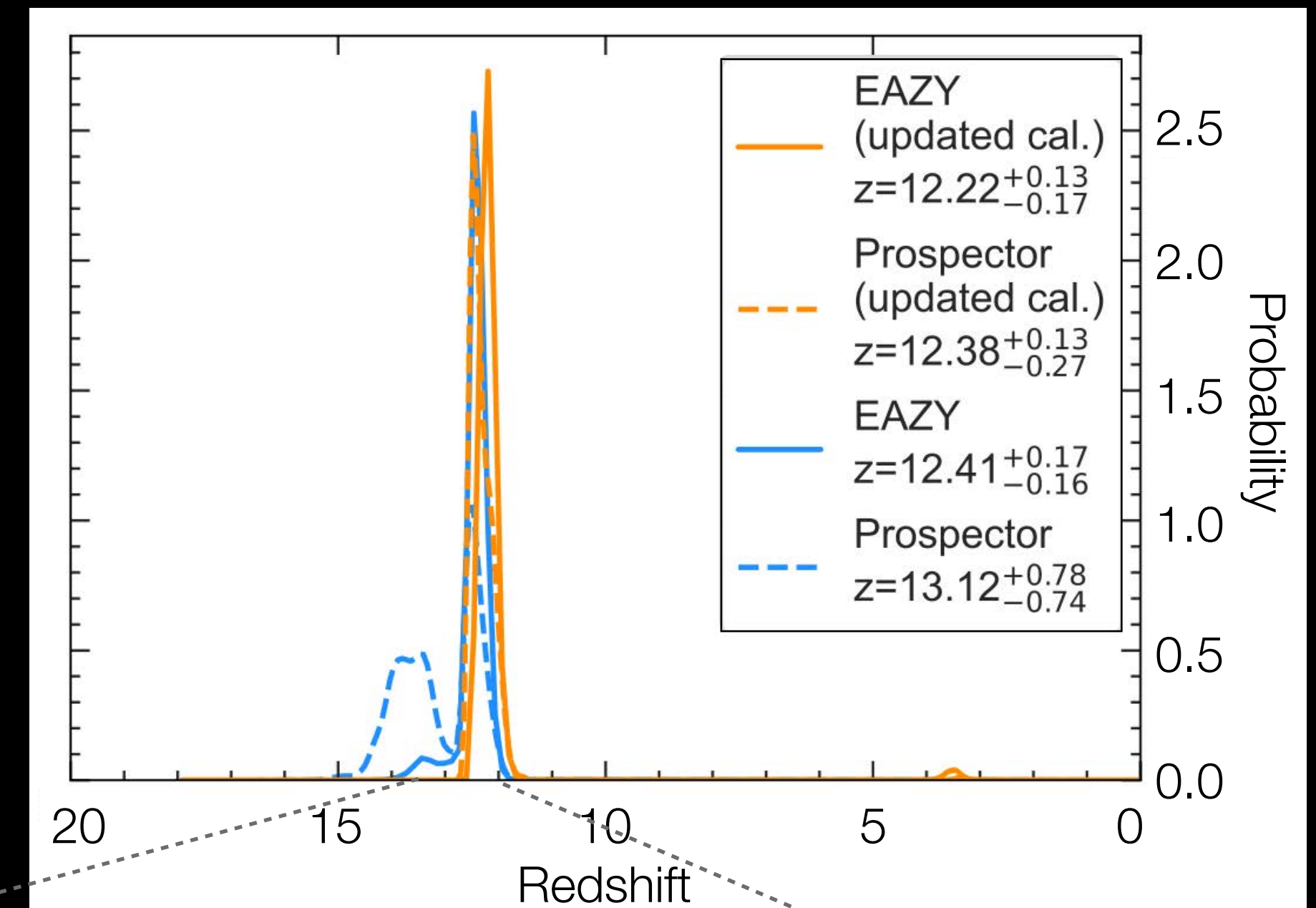
Blind Redshift Searches

- Current ALMA
2.2 hrs x 4 tunings = 8.8 hours
- ALMA-WSU
2.2 hrs x 2 tunings = 4.4 hours



Blind Redshift Searches

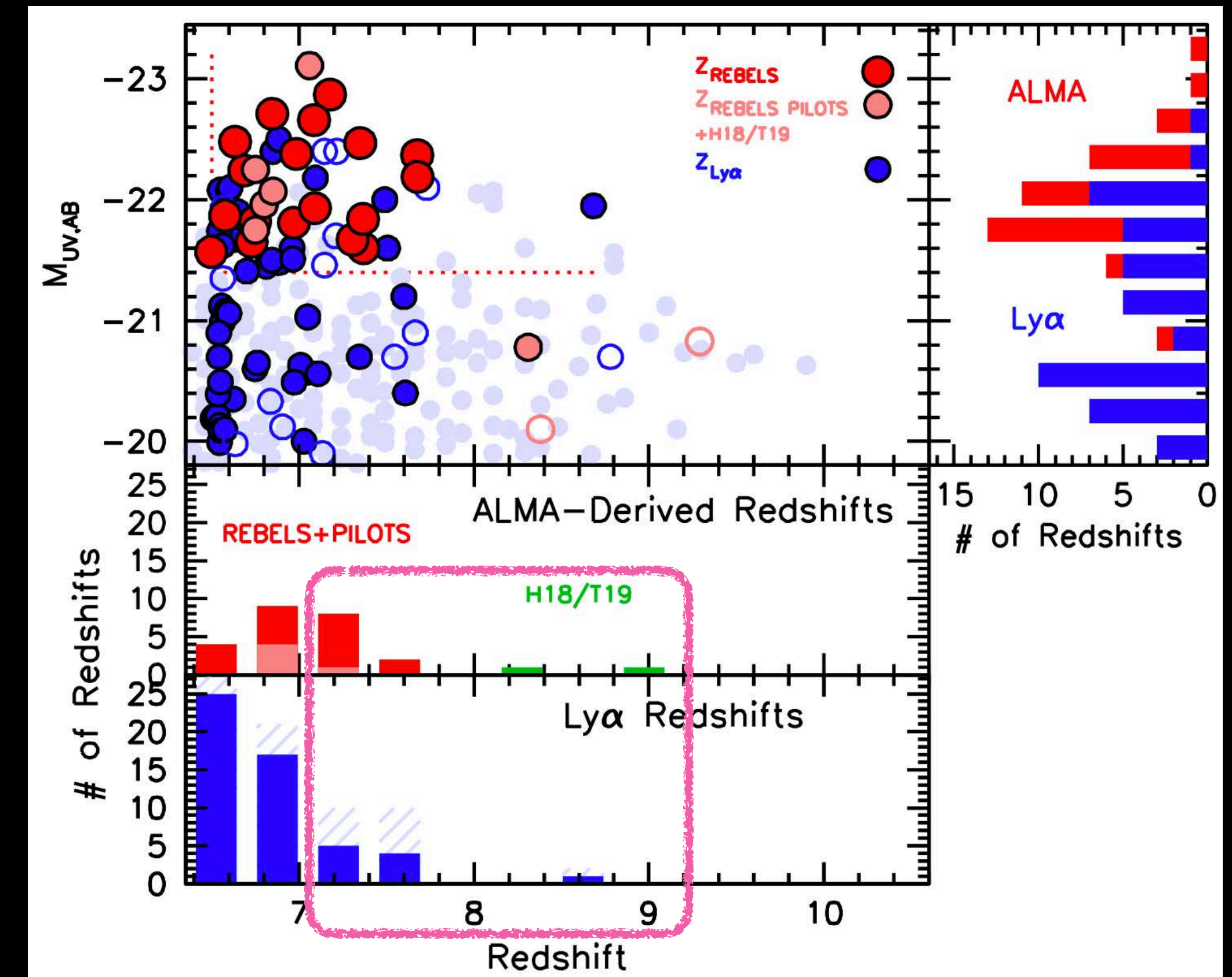
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Blind Redshift Searches

- Current ALMA
2.2 hrs x 4 tunings = 8.8 hours
- ALMA-WSU
2.2 hrs x 2 tunings = 4.4 hours
- **Larger (dusty) galaxy samples**
- **Fewer optical selection biases**
- **More complete censuses**

Bouwens et al. 2022



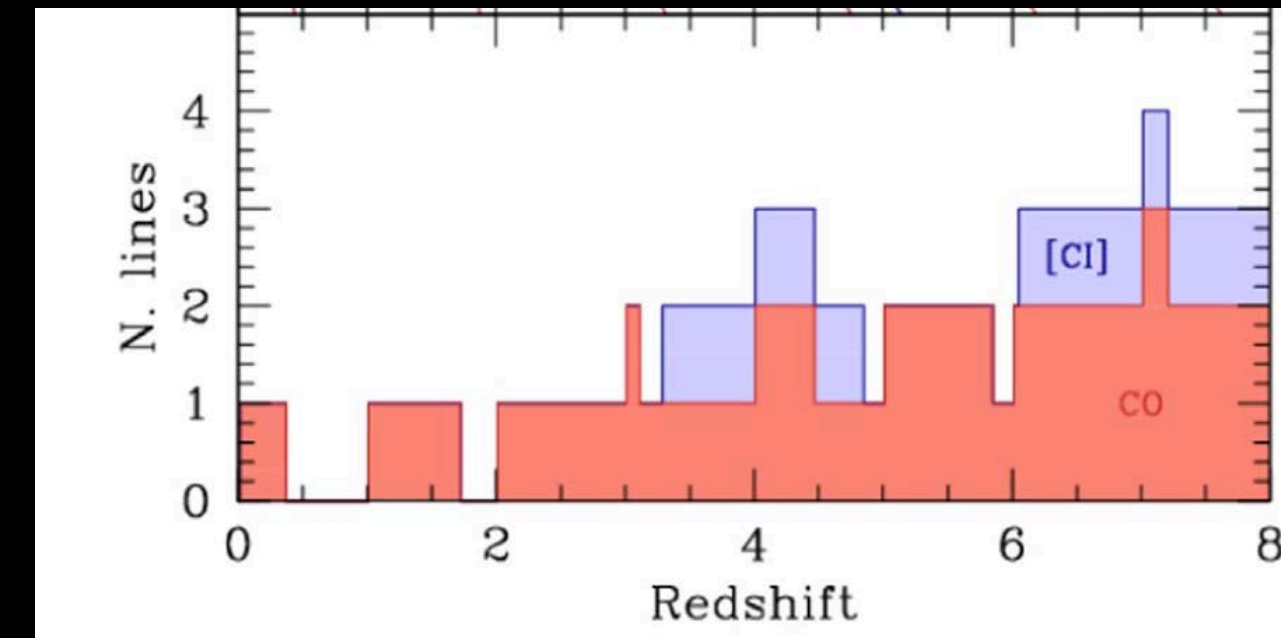
- $> 3\times$ ISM-cooling lines known at $z > 6.5$
- A larger number of $z > 7$ galaxies were found by [CII] and/or [OIII] than $Ly\alpha$ (before JWST)

How representative are the galaxies that drive reionization?

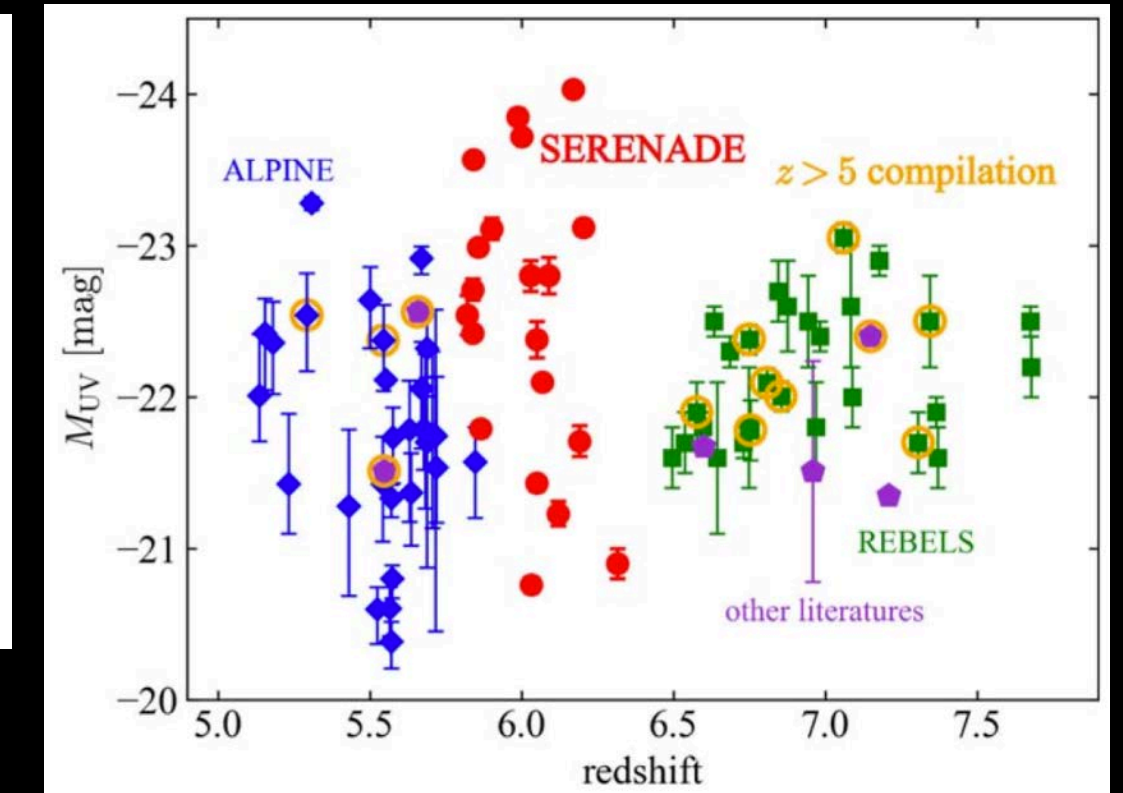
Large, representative surveys

Current sample sizes: *Case studies*

- A few tens of galaxies
- Biased towards massive galaxies



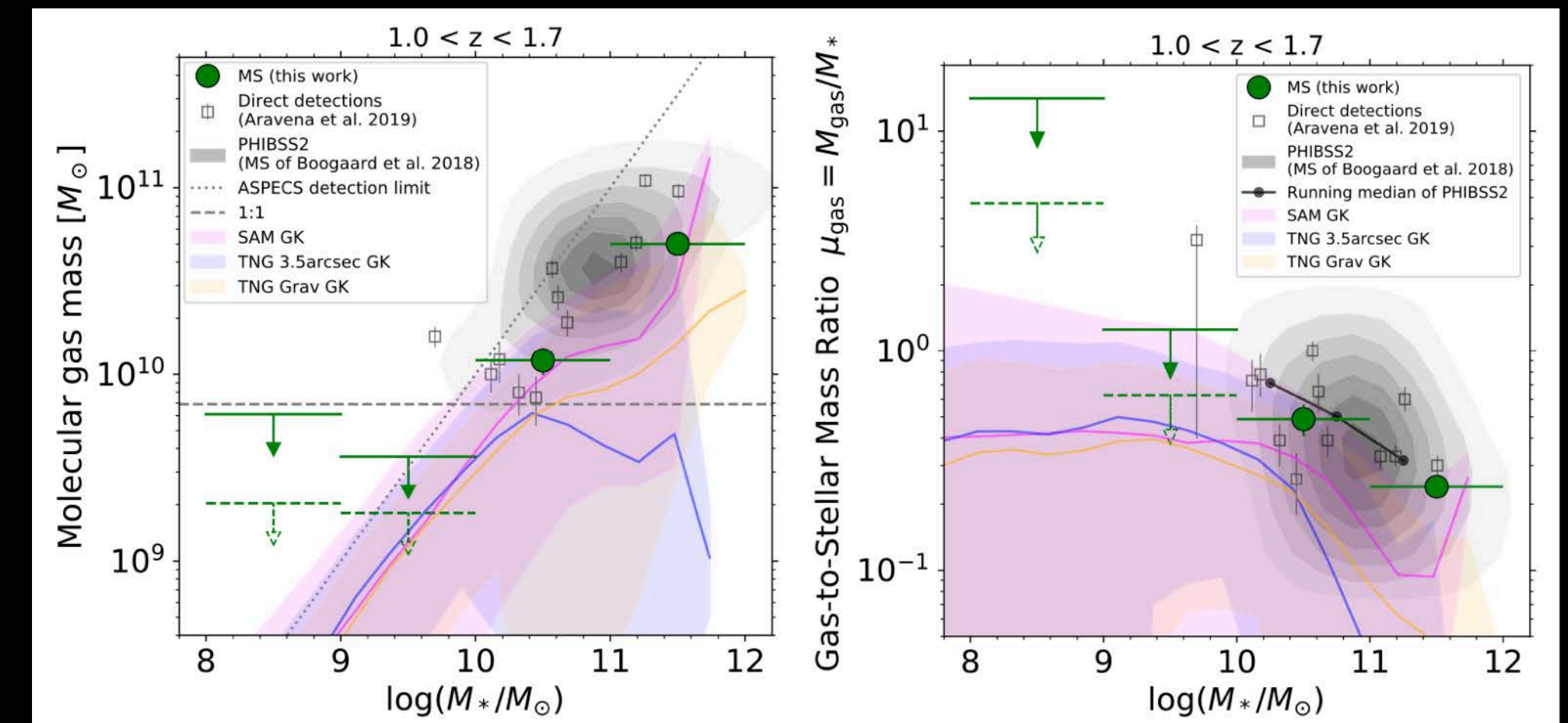
Decarli et al. 2019



Mitsuhashi et al. 2024

Larger samples (~100s of galaxies): *Statistics*

- More representative MS galaxies (with lower M^* and SFR)
- Robust scaling relations
- Population statistics
- Environmental studies



Inami et al. 2020

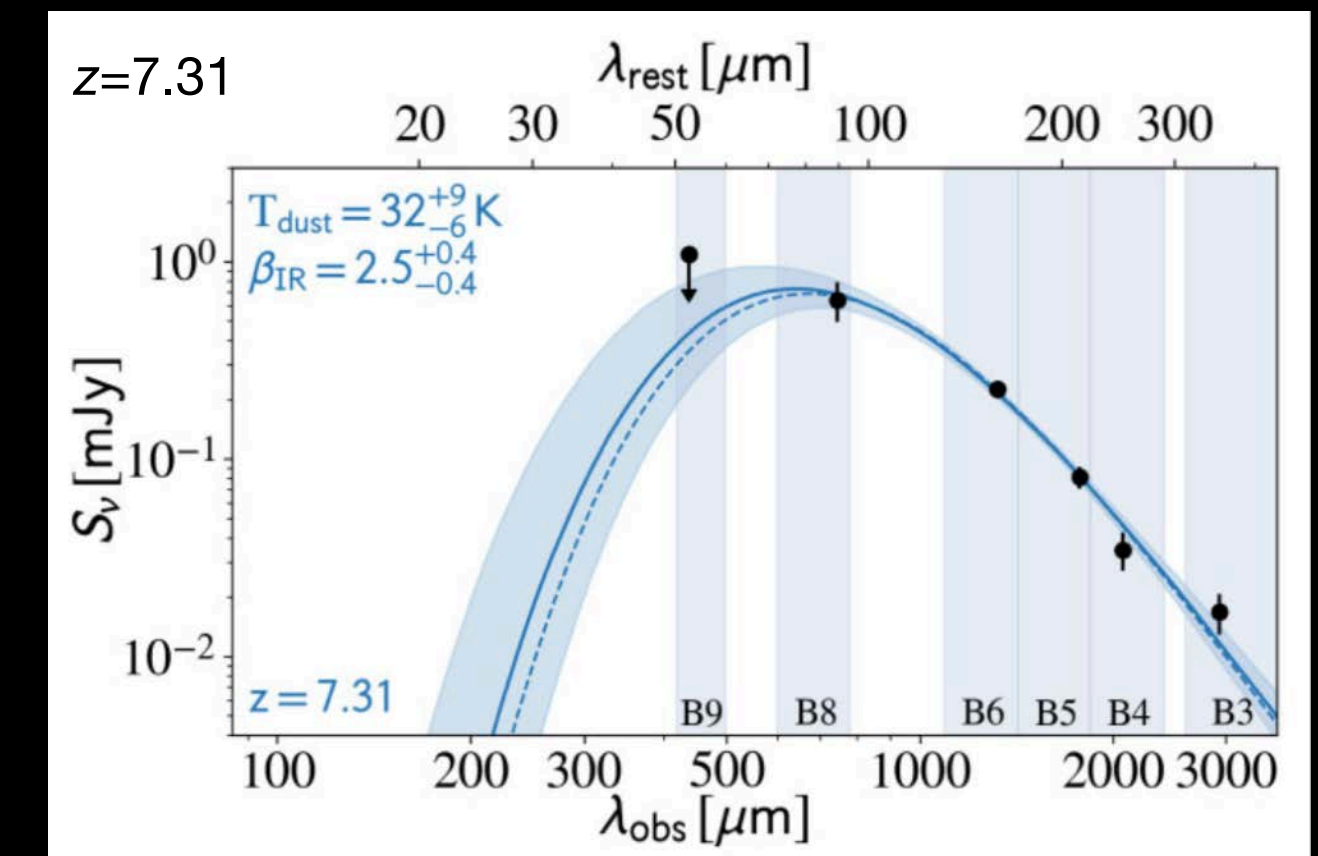
What drives the evolution of gas across galaxy populations?

Routine multi-line/dust observations

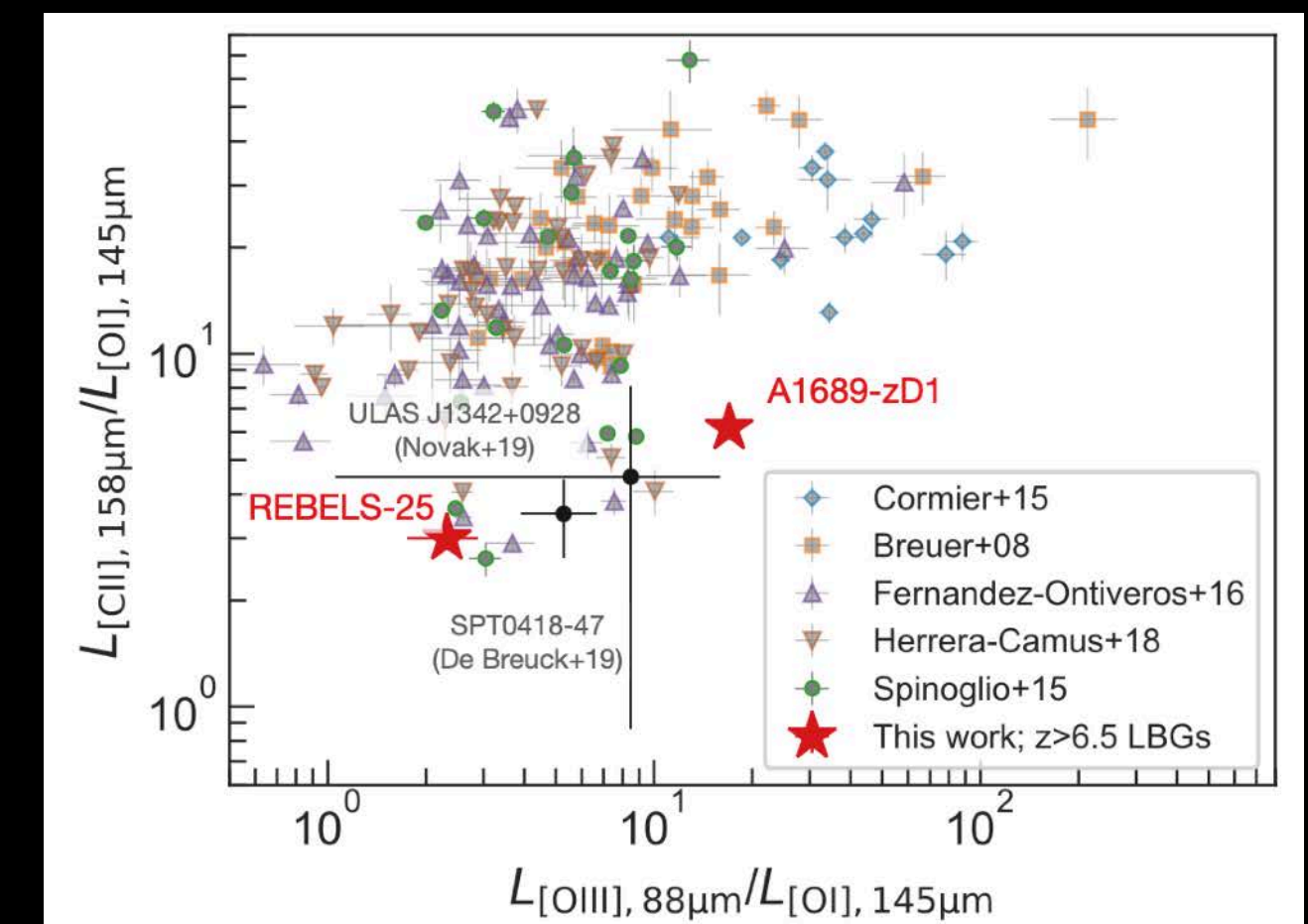
- Current: Often one spectral line per proposal
 - Detection experiments
 - Need a few observing cycles for physical studies
- ALMA-WSU: Multi-cont/line observations in a single proposal

Rich scientific products in a single observation package:

- **Dust SED (multiple dust continuum)**
- Gas excitation (e.g., high- and low-J CO, [O III]/[C II])
- Ionized vs. neutral gas (e.g., [C II], [O III], [N II], [O I])
- Electron density (e.g., [O III]52/[O III]88)
- Abundance (e.g., [NIII]57/[OIII]88)



Algera et al. 2024b



Fudamoto et al. 2026

How does the cool ISM regulate galaxy evolution?
How does dust evolve from the first galaxies onward?

ALMA to ALMA-WSU

- The WSU will change how efficiently we study the high-redshift Universe
- It will transform detailed studies of individual galaxies
into population-scale studies of the high- z galaxies

Pre-ALMA

Can we detect molecular gas?

Are galaxies dusty?

Can we detect the cool ISM?

What happened during reionization?

With ALMA

What are the gas properties of galaxies?

What are the dust properties?

What are its structures and dynamics?

How are early galaxies assembled?

The WSU

What drives the evolution of molecular gas across galaxy populations?

How does dust evolve from the first galaxies onward?

How does the cool ISM regulate galaxy evolution?

How representative are the galaxies that drive reionization?

Frontiers in the 2040s

The remaining missing pieces

First molecular clouds

Earliest dust

Environmental effects

Low-mass galaxies

Circumgalactic Medium

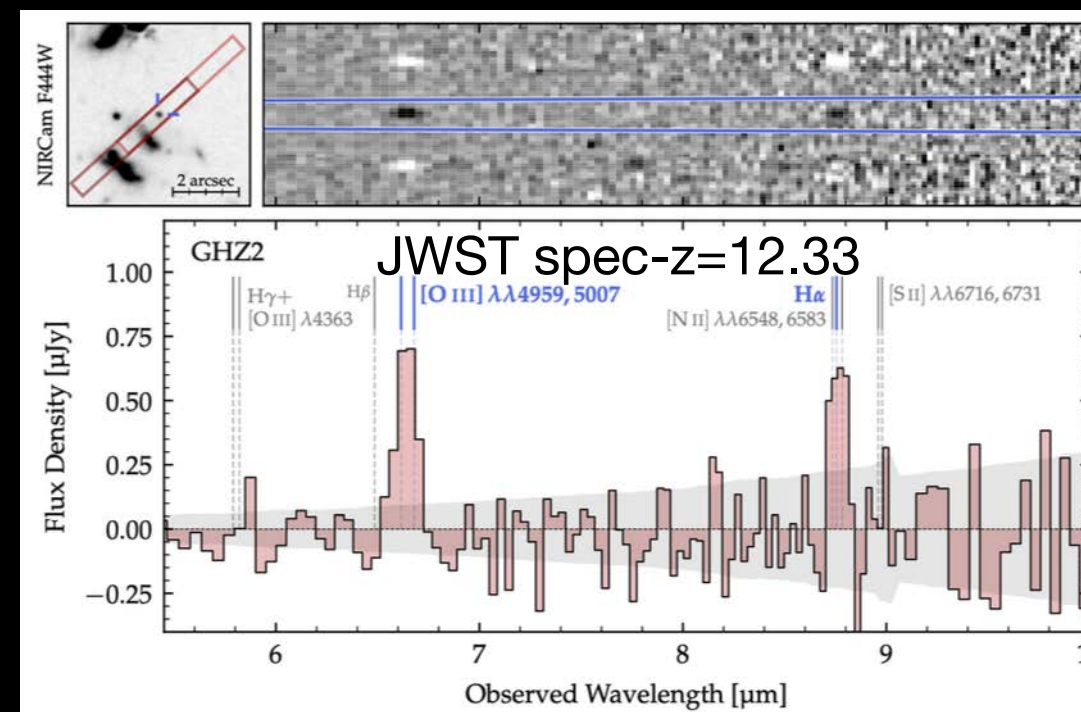
Resolved ISM

Proto-clusters

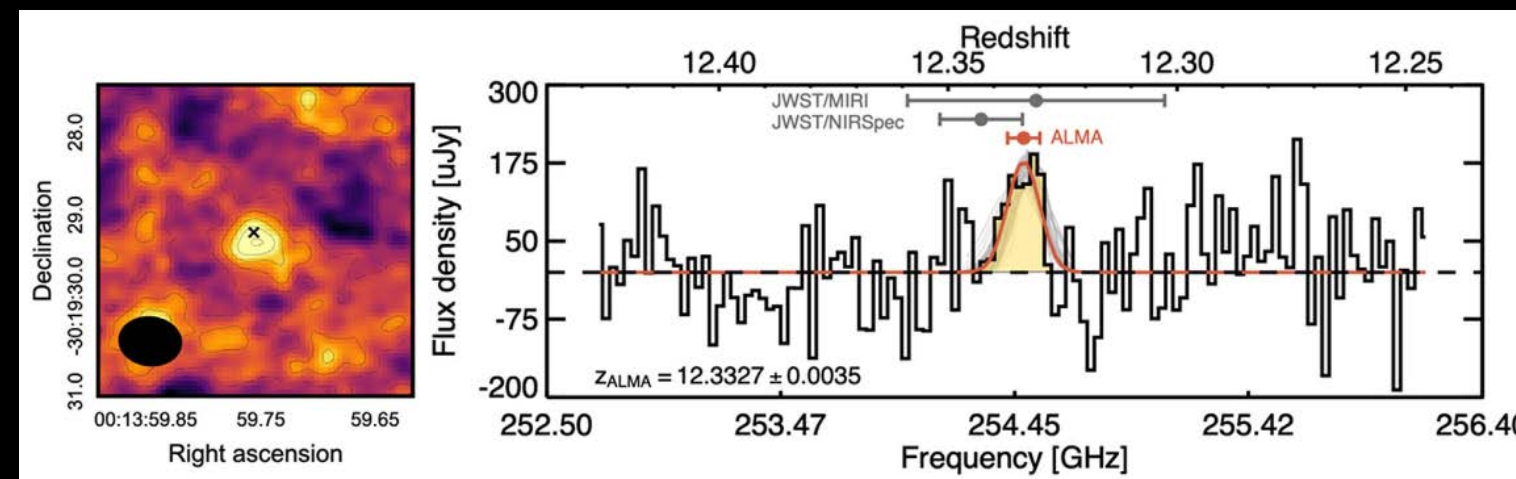
How does the baryon cycle evolve across cosmic time?

When do the first baryons condense into stars and dust?

GHZ2 / GLASS-z12



ALMA [O III]88 detection



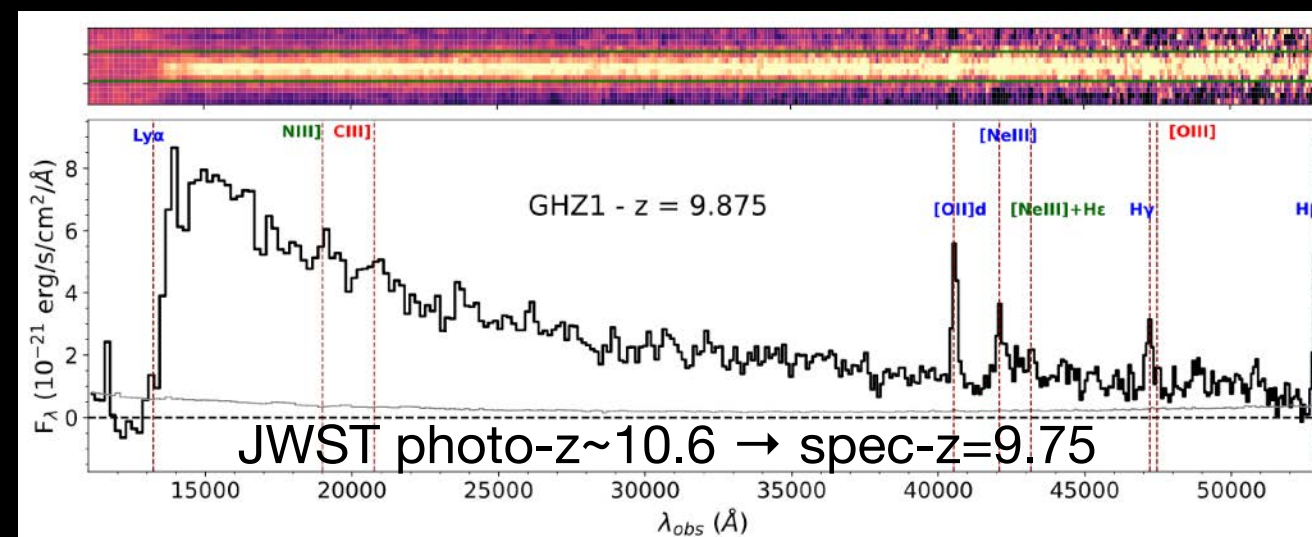
Zavala et al. 2024,2025, Bakx et al. 2023, Castellano et al. 2024, Calabro et al. 2024, Mitsuhashi et al. 2026

No detection with ALMA?

- **Low metallicity:** too young to have metals and dust
- **Embedded:** Highly dense dust suppresses line emission
- **Dust removal:** Strong radiation pressure blows produced dust out of the galaxies

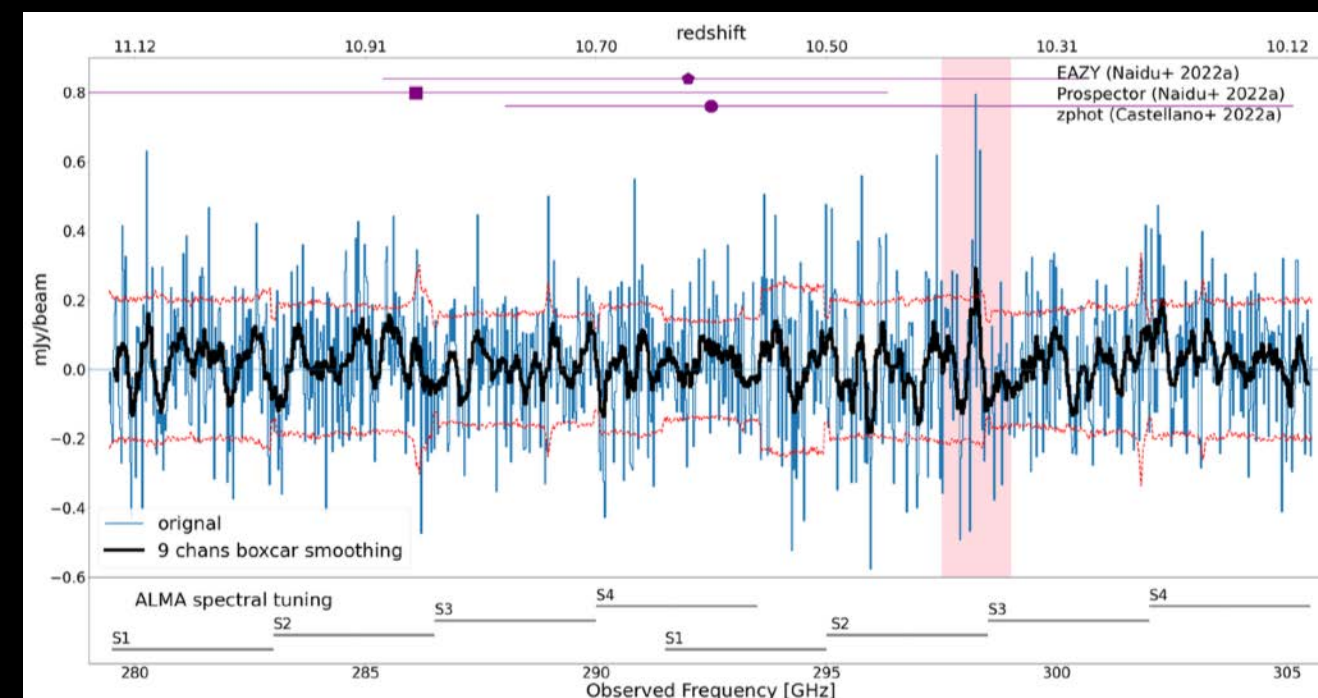
Tsuna et al. 2023, Kohandel et al. 2023, Nakazato et al. 2025

GHZ1 / GLASS-z10



Yoon et al. 2023, Castellano et al. 2022, Naidu et al. 2022, Napolitano et al. 2025

Later confirmed with spec-z=9.875
Expecting ALMA followup...



With JWST, it is now *not* about finding galaxies, but characterizing their baryonic content

Science question:

Characterize the cool ISM in typical galaxies

Capability needed:

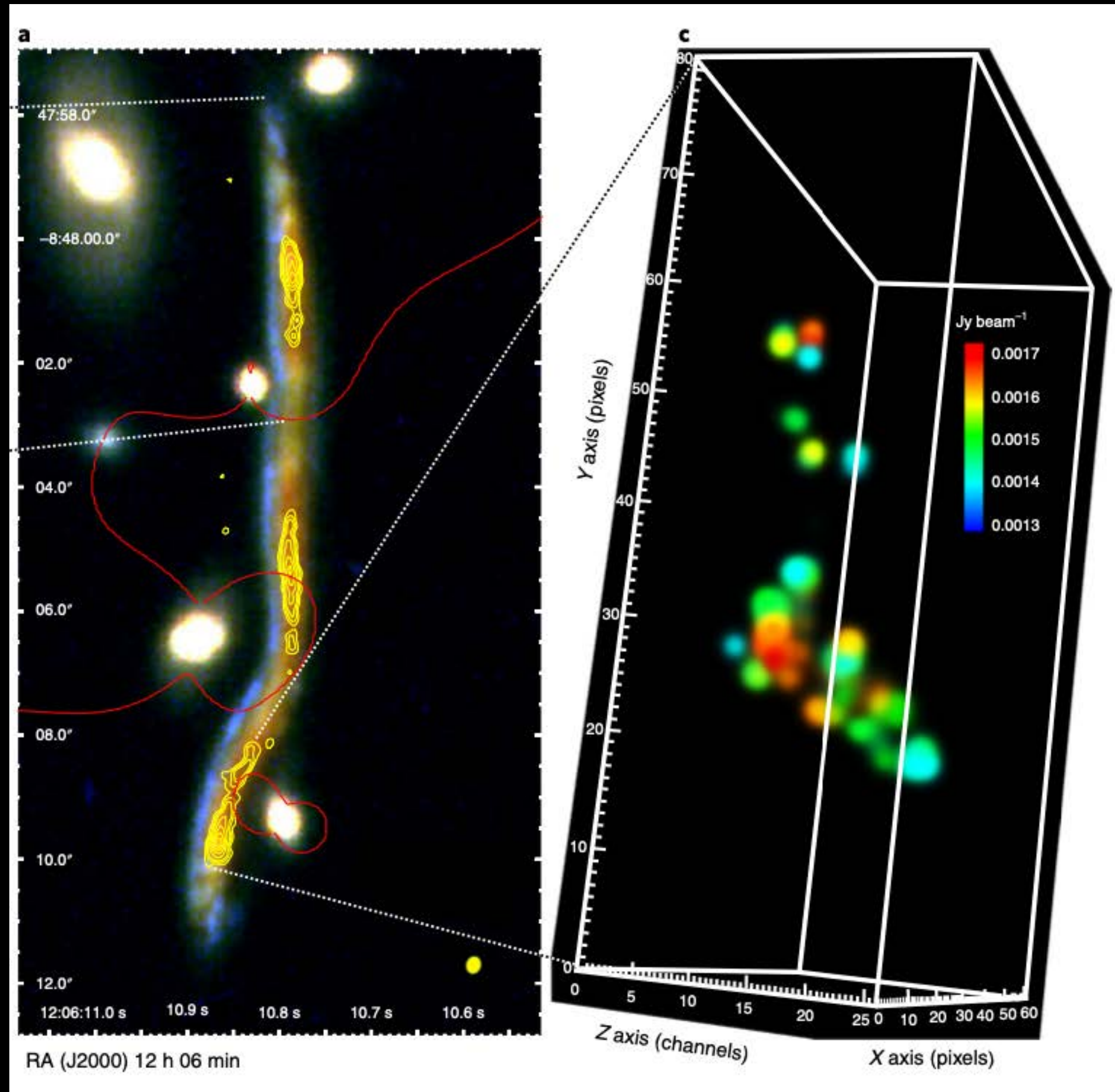
Greater sensitivity (more collecting area)

High-frequency bands

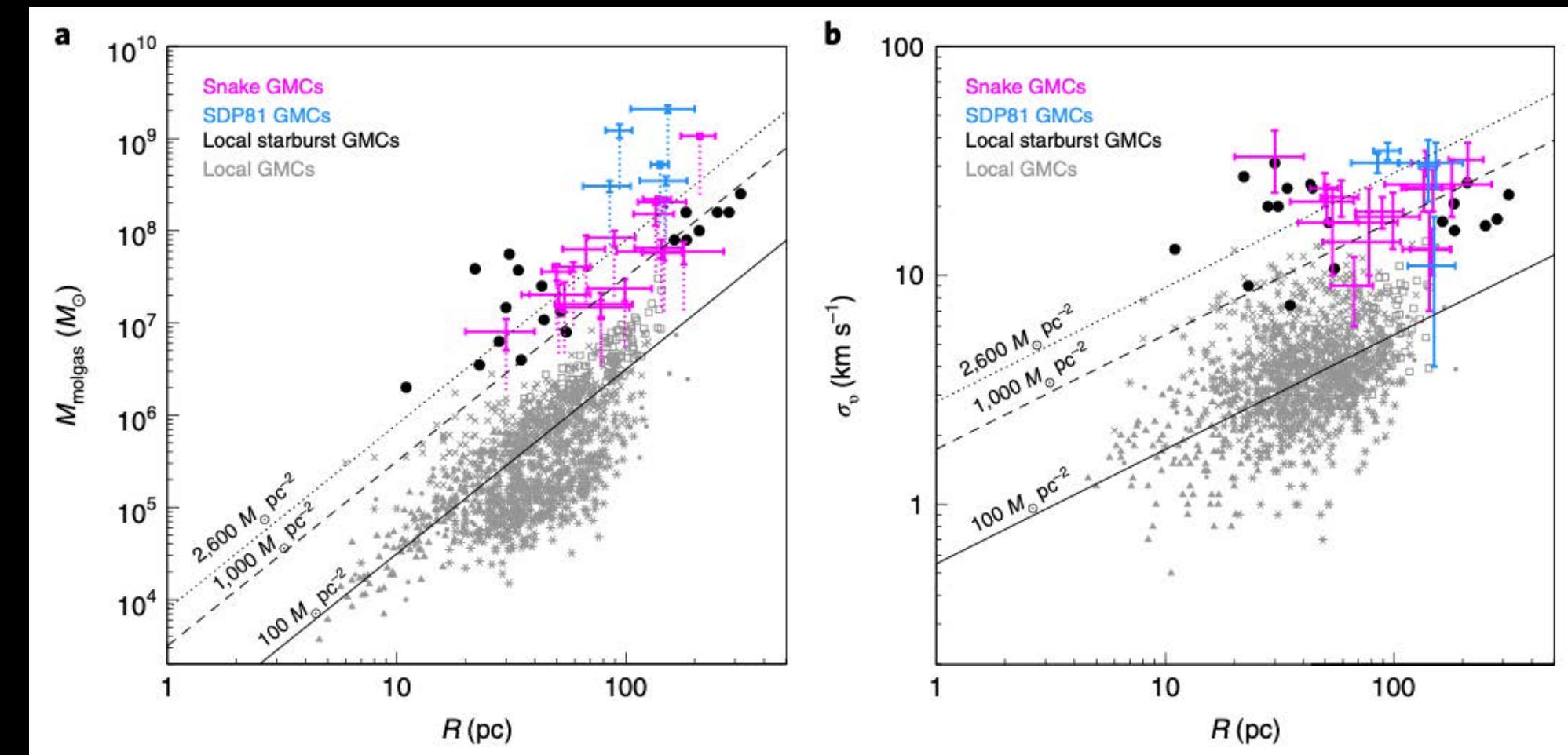
Multi-band capabilities

How is gas converted into stars?

Cosmic Snake galaxy (lensed) $z=1.036$



Dessauges-Zavadsky et al. 2019



Currently, rare gravitational lenses are needed

Science question:

Resolve giant molecular clouds in representative galaxies

Capability needed:

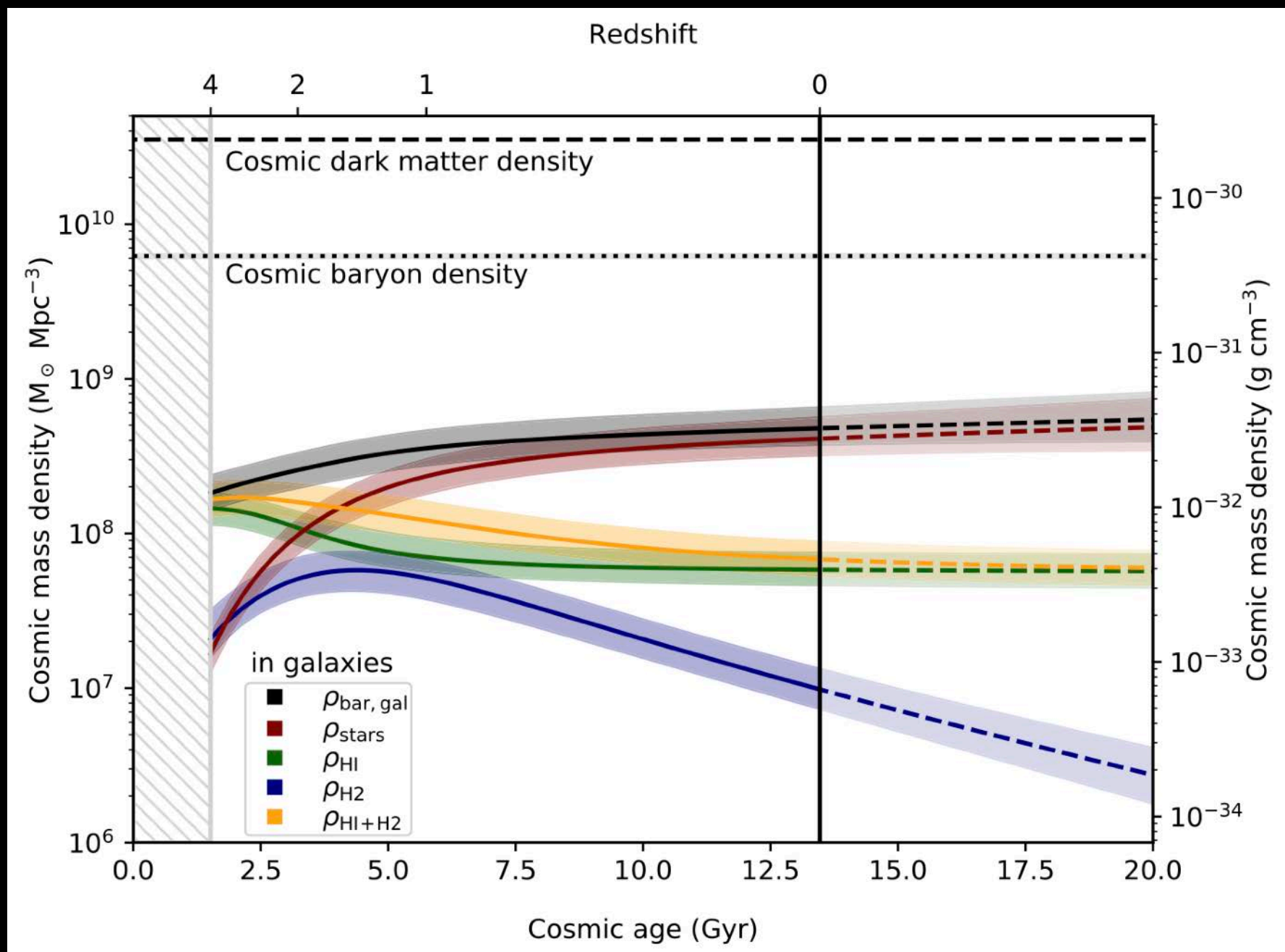
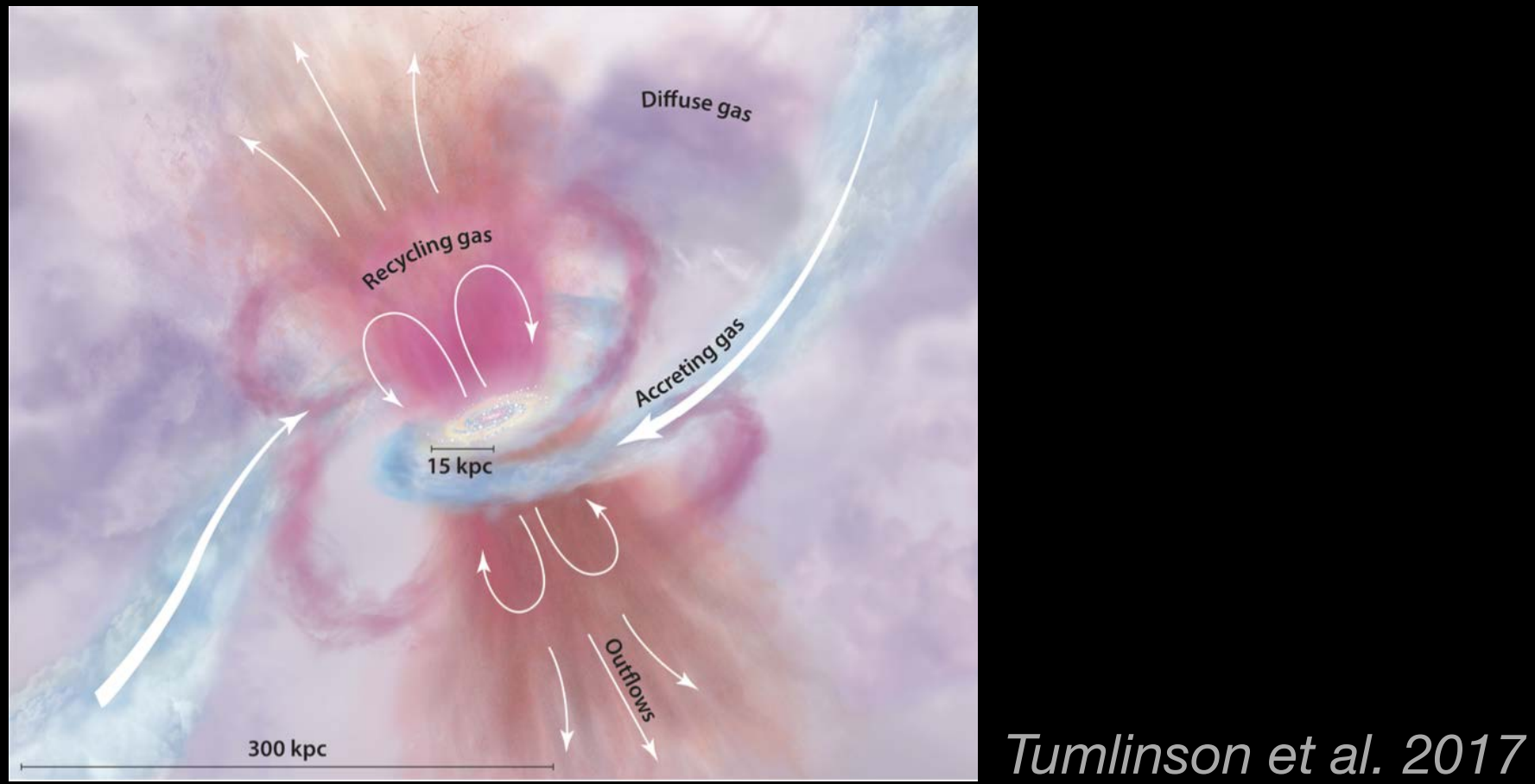
Greater sensitivity

Higher brightness sensitivity

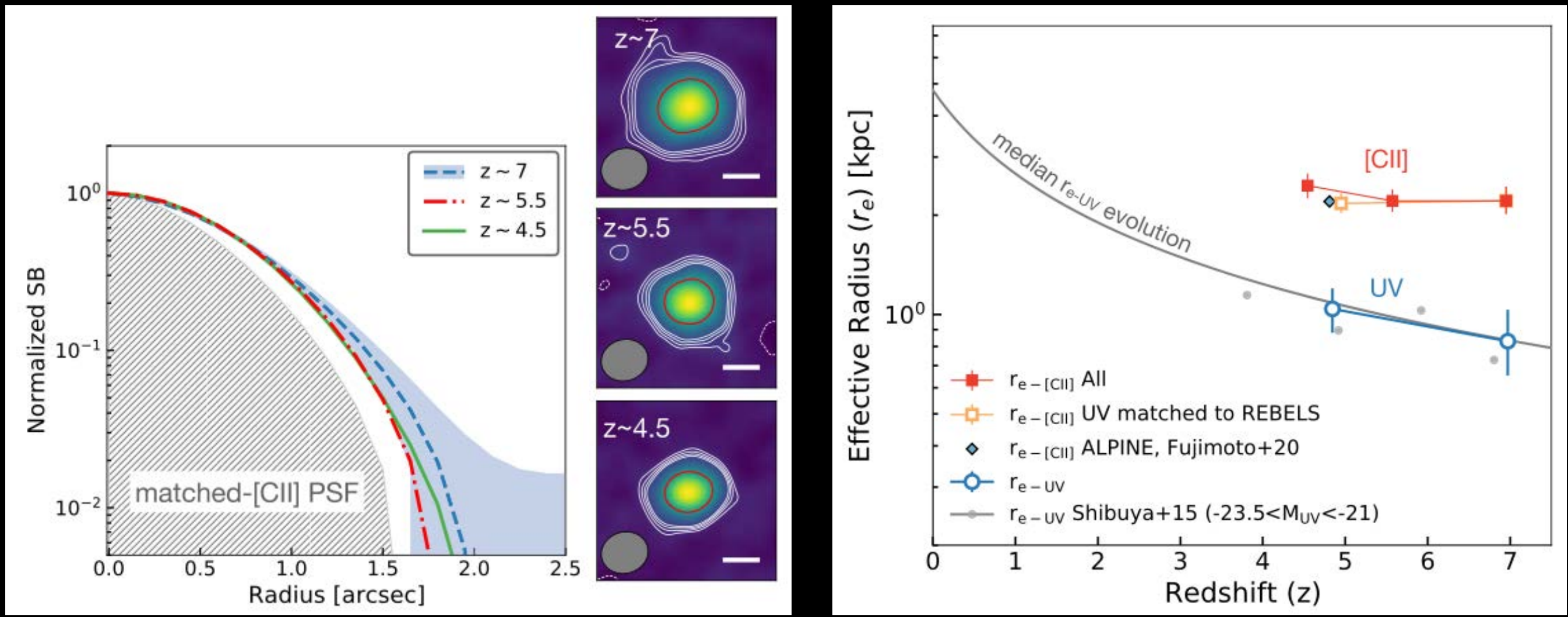
Reliable recovery of cloud morphology

E.g., Swinbank et al. 2015, Paraficz et al. 2018

How do galaxies acquire, expel, and recycle their baryons?



Walter et al. 2020



Fudamoto et al. 2022

Cf. Fujimoto et al. 2019, Ginolfi et al. 2020, Fudamoto et al. 2023

Science requirement:

Trace the cool baryons beyond galaxies

Capability needed:

Greater sensitivity (collecting area)

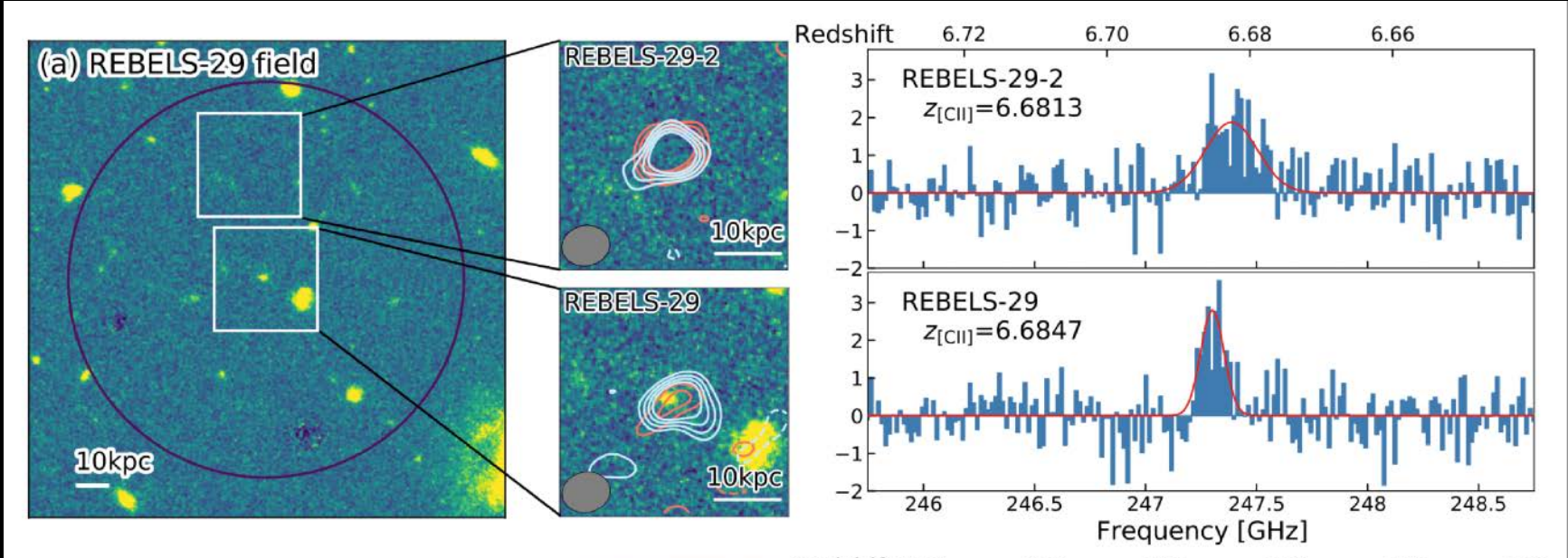
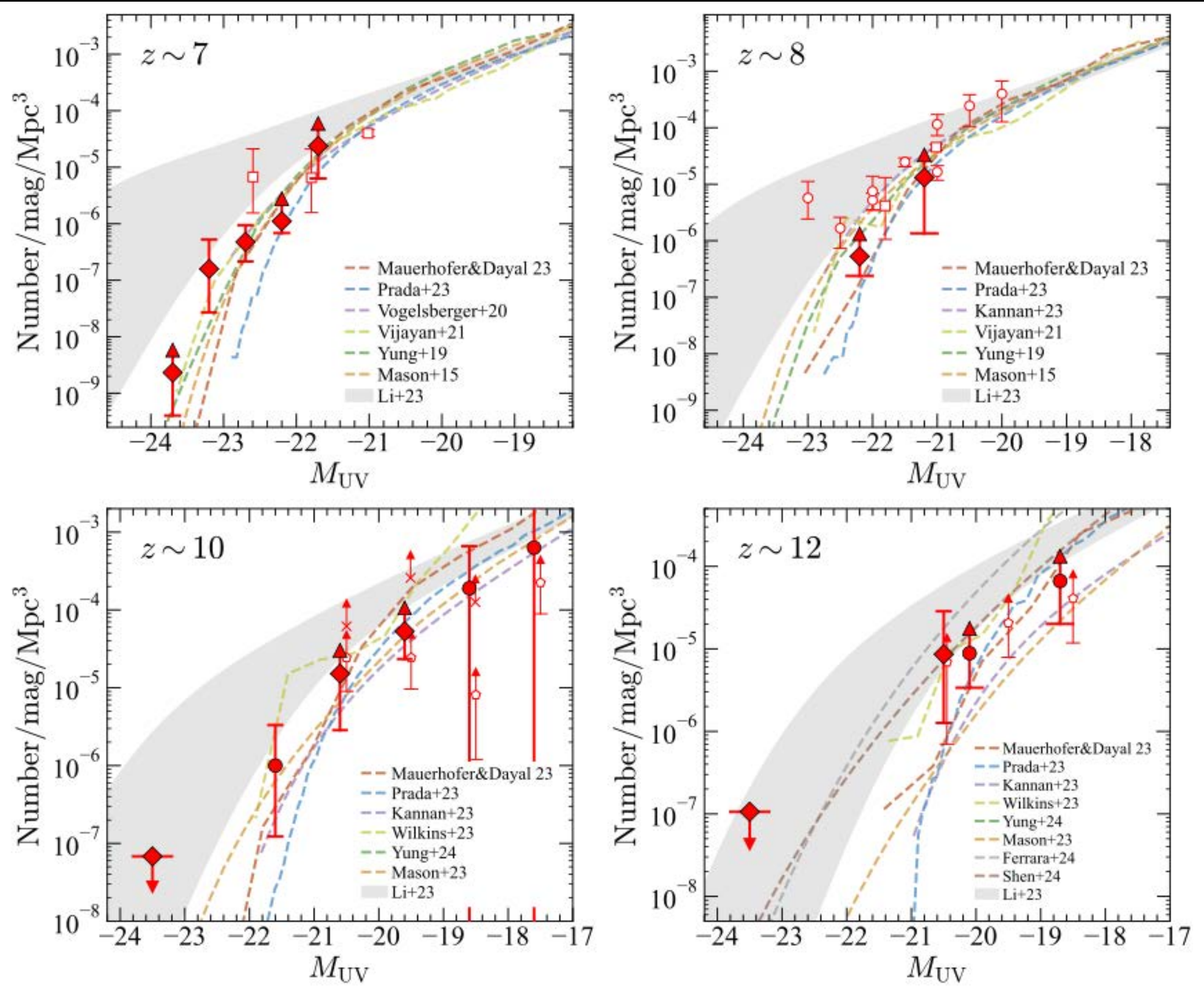
Higher brightness sensitivity

Simultaneous recovery of compact and diffuse emission

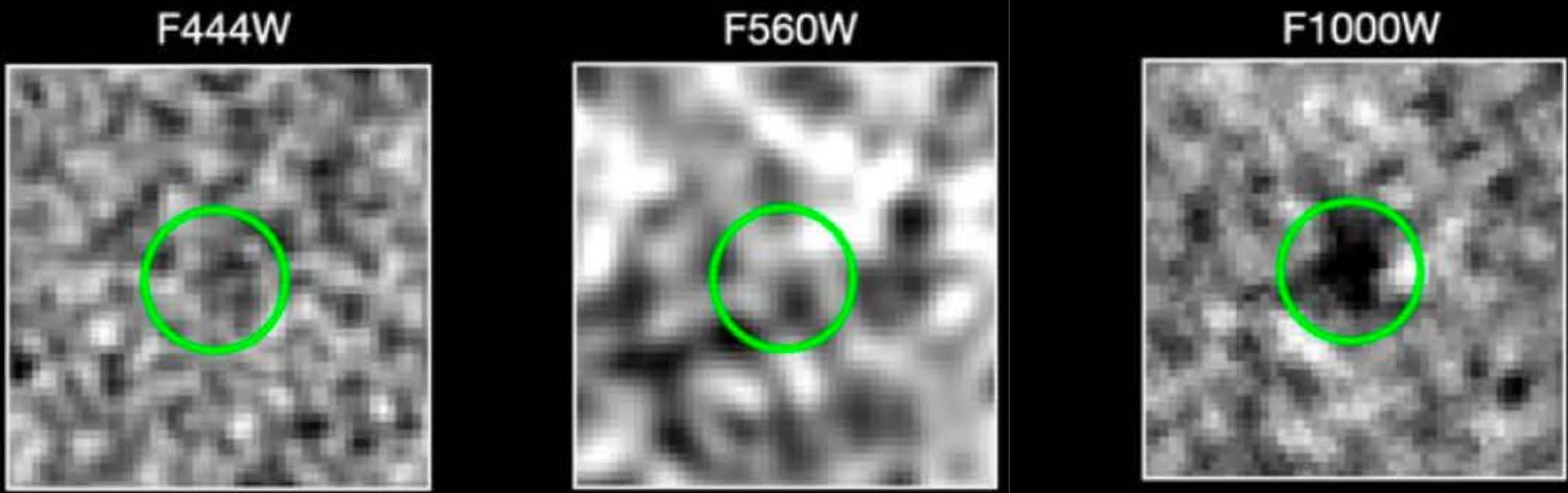
Which galaxy populations dominate the baryon budget and reionization?

Most baryons are likely processed by fainter galaxies

Missing (dusty) populations?



Fudamoto et al. 2021



Pérez-González et al. 2024

Science requirement:

Surveys of representative galaxy populations

Capability needed:

Greater sensitivity (collecting area)

Efficient mapping & High-speed surveys

High-frequency bands

Evolution of Key Questions

From Pre-ALMA to ALMA2040

Pre-ALMA	ALMA	The WSU	ALMA2040
Can we detect molecular gas?	What are the gas properties of galaxies?	What drives the evolution of molecular gas across galaxy populations?	How is gas converted into stars under the conditions of the early Universe?
Are galaxies dusty?	What are the dust properties?	How does dust evolve from the first galaxies onward?	When do the first baryons condense into stars and dust?
Can we detect the cool ISM?	What are its structures and dynamics?	How does the cool ISM regulate galaxy evolution?	How do galaxies acquire, expel, and recycle their baryons?
What happened during reionization?	How are early galaxies assembled?	How representative are the galaxies that drive reionization?	Which galaxy populations dominate the baryon budget and reionization?
<i>Extreme galaxies</i>	<i>Normal massive galaxies</i>	<i>Representative galaxies</i>	<i>Typical galaxies across all environments</i>

Key observational capabilities for high- z galaxies

¹ **Sensitivity**

² **Brightness sensitivity**

³ **Recovery of morphology**

When do the first baryons condense into stars and dust?

Greater sensitivity
Multi-band capabilities
High-frequency bands

How is gas converted into stars under the conditions of the early Universe?

Greater sensitivity on cloud scales
Higher brightness sensitivity
Reliable recovery of cloud morphology

How do galaxies acquire, expel, and recycle their baryons?

Greater sensitivity
Higher brightness sensitivity
Simultaneous recovery of compact and diffuse emission

Which galaxy populations dominate the baryon budget and reionization?

Greater sensitivity
Efficient mapping & High-speed surveys
High-frequency bands

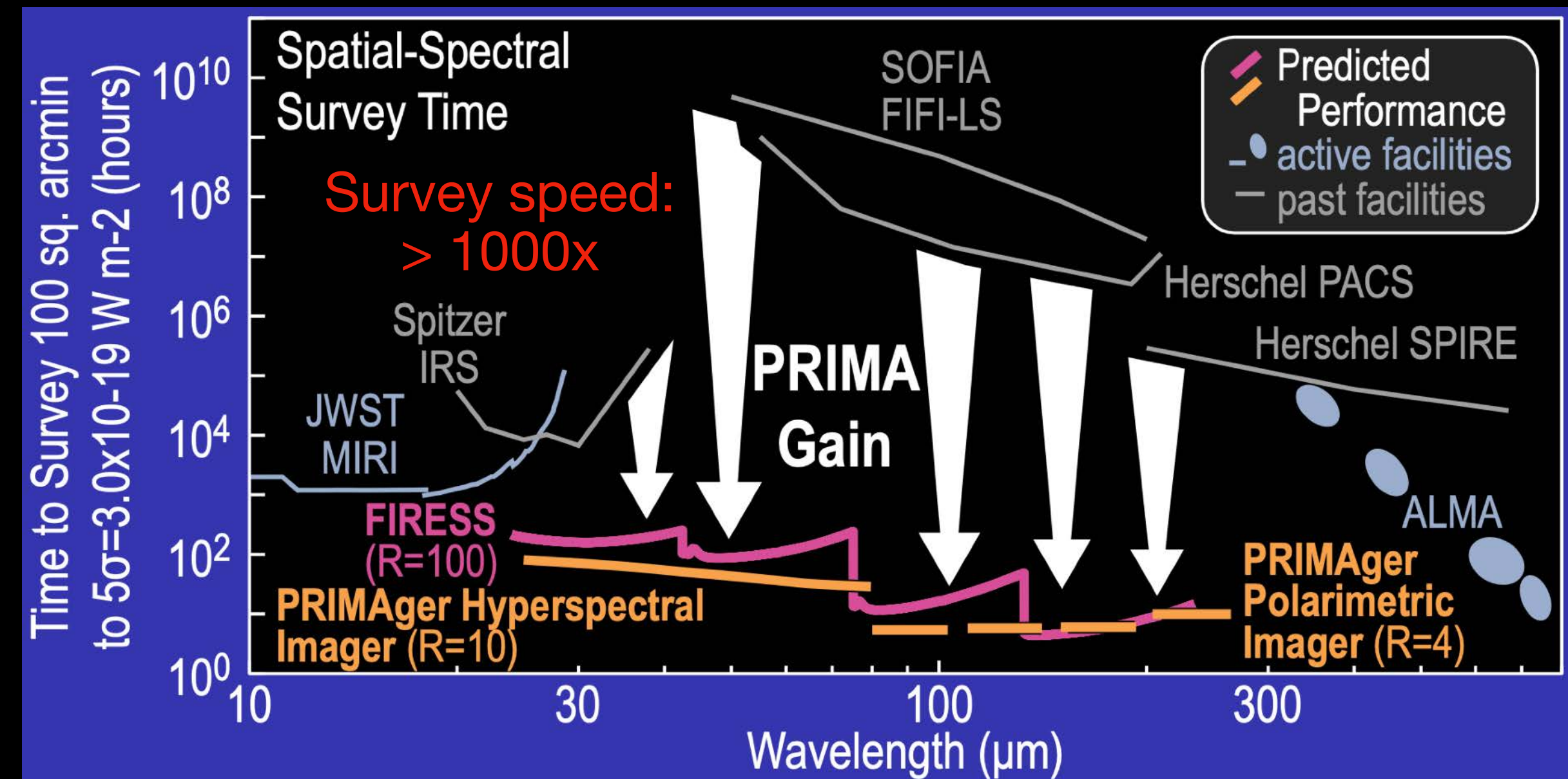
ALMA2040 in the Multi-Wavelength Era

PRIMA: Probe far-Infrared Mission for Astrophysics

- NASA's Far-IR Probe mission candidate
- **D=1.8m** far-infrared cryo-telescope (4.5K)
 - The first far-infrared telescope since *Herschel*
 - Cover **~25-250 μm** , filling the gap between JWST and ALMA
- Launch: **2032**

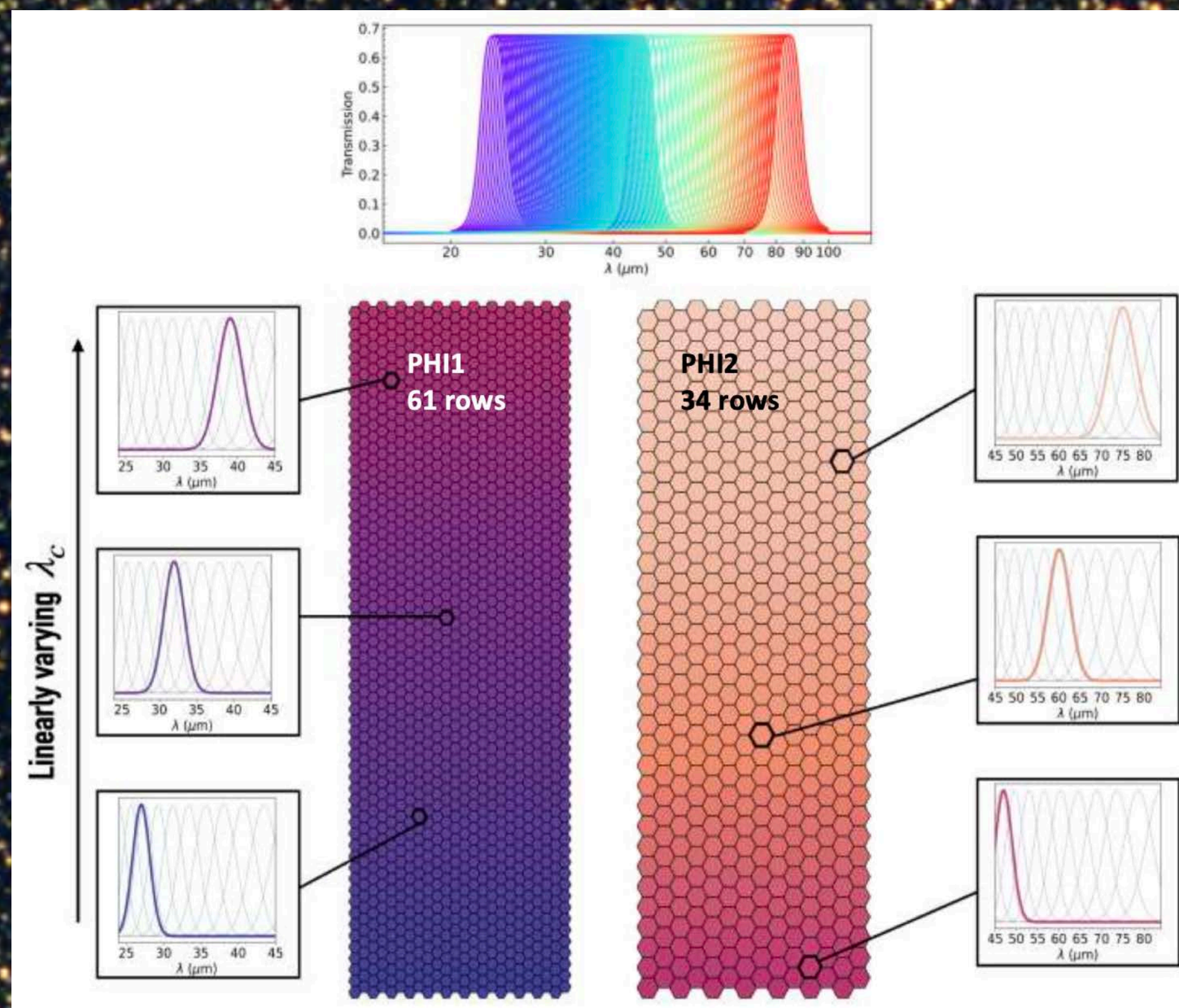
Outstanding sensitivity + survey capability

Excellent for statistical studies of a wide range of galaxy populations



3D Hyperspectral surveys: for every galaxy we get a full IR spectral energy distribution

PRIMAger: 25-250 μ m imaging with $R=8$



30

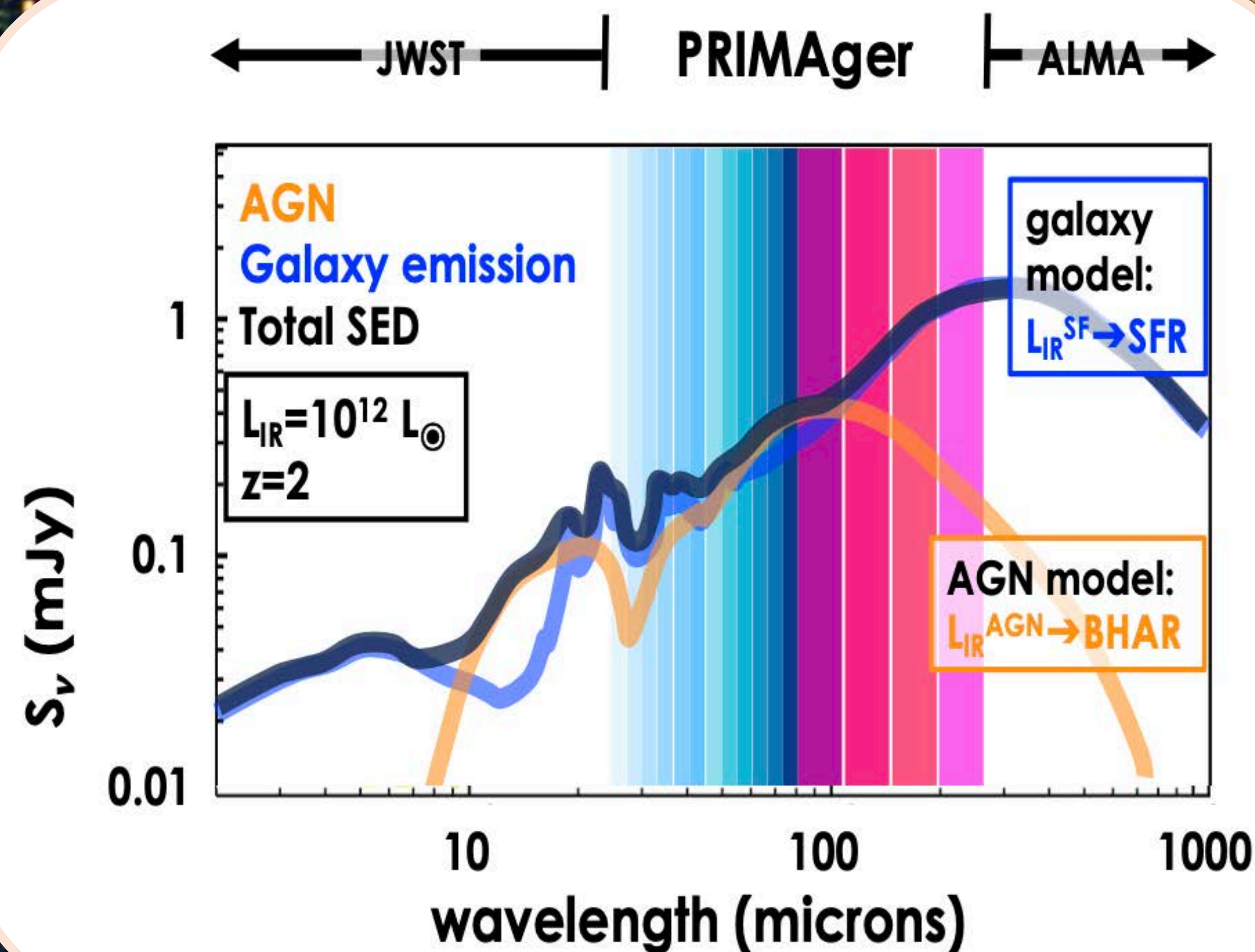
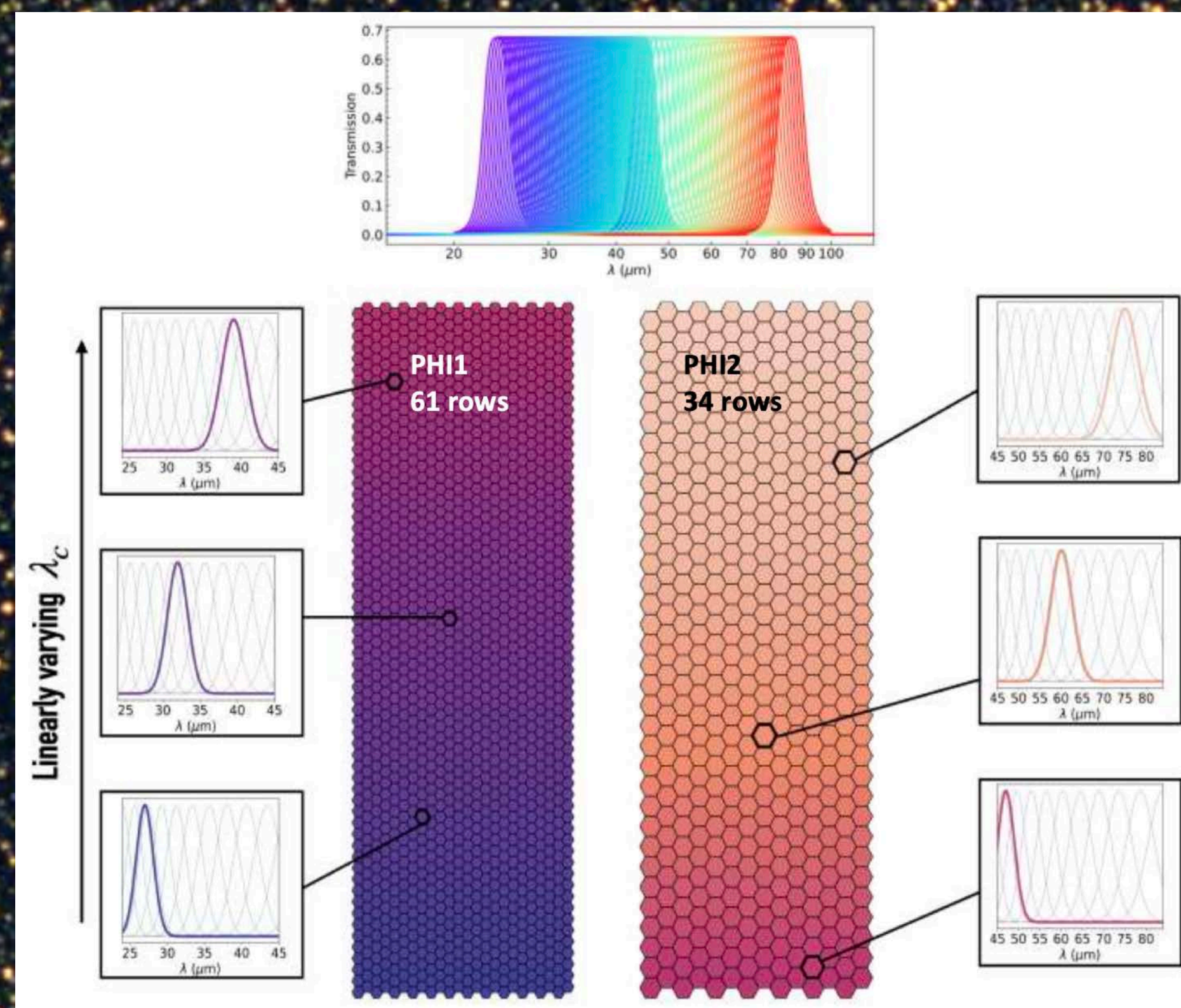
200

1 deg

Simulated PRIMAger 3-color image from SIDES (Bethemin+24)

3D Hyperspectral surveys: for every galaxy we get a full IR spectral energy distribution

PRIMAger: 25-250 μ m imaging with $R=8$

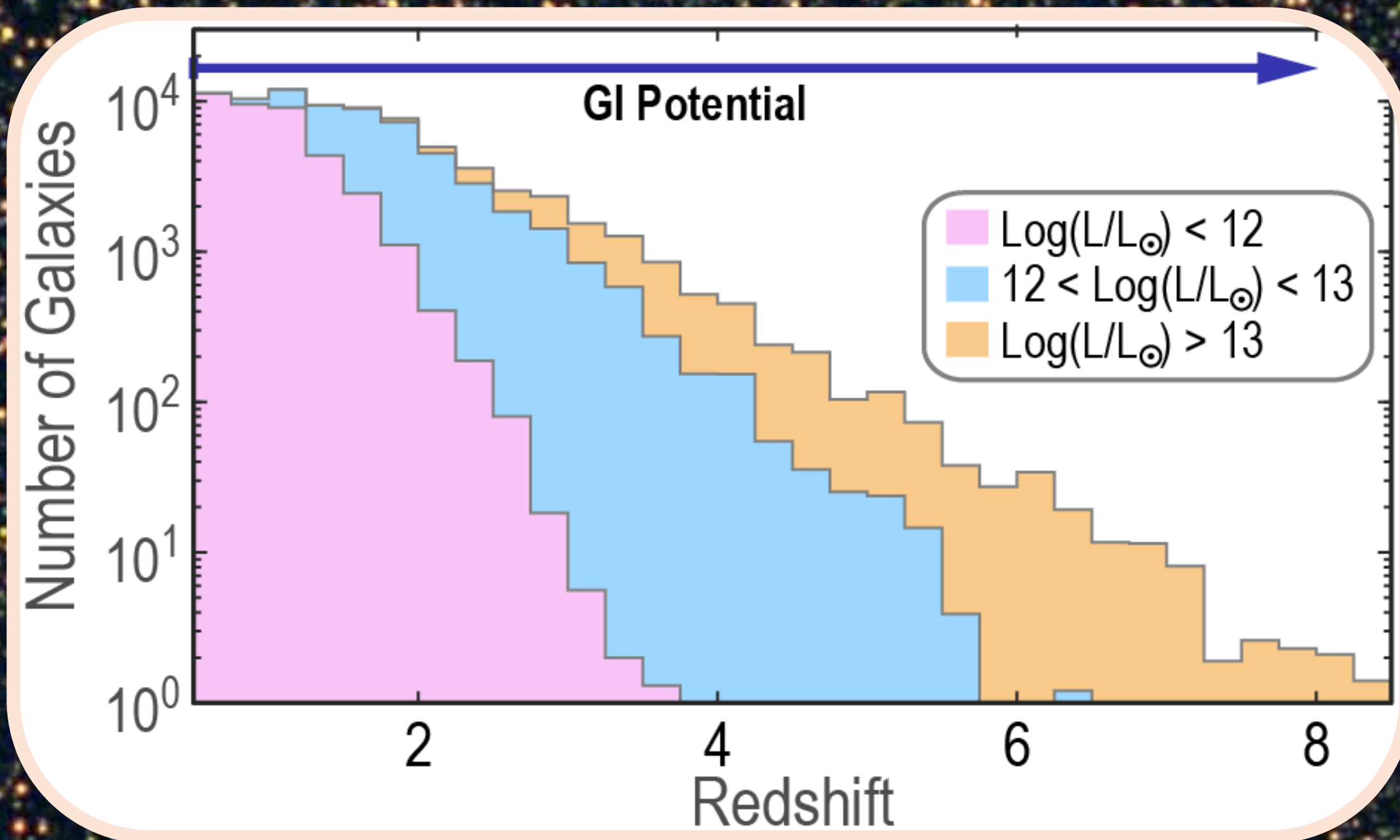


1 deg

Simulated PRIMAger 3-color image from SIDES (Bethemin+24)

3D Hyperspectral surveys: for every galaxy we get a full IR spectral energy distribution

1 deg² + 10 deg² surveys



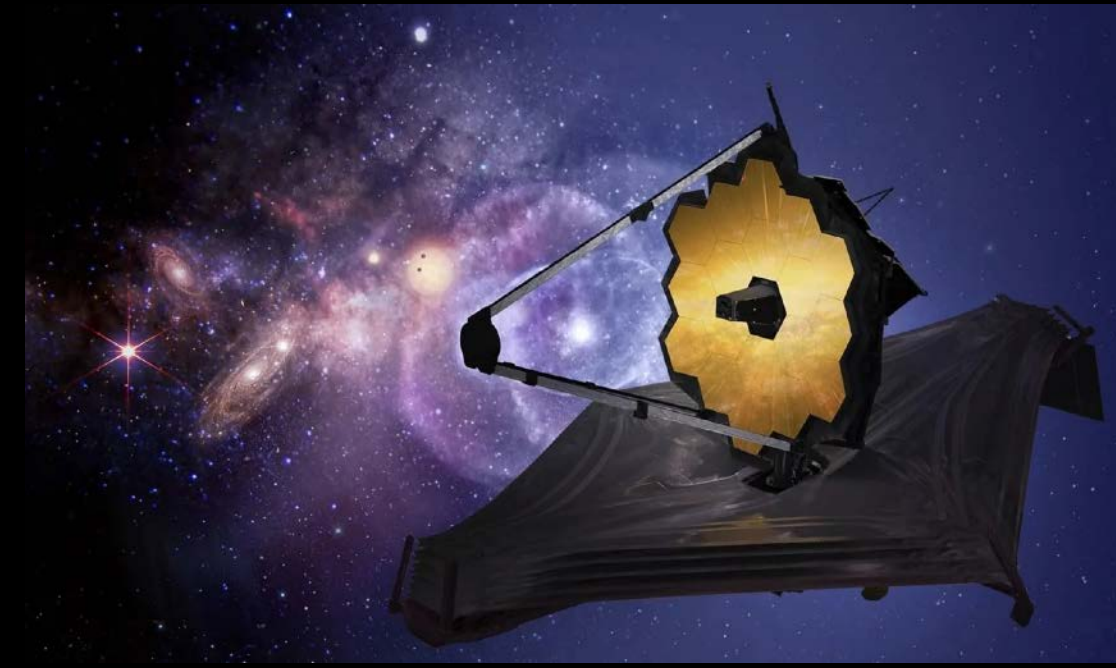
PRIMA:

- Detect dusty galaxies over large volumes
- Measure FIR luminosities
- Provide statistical samples
- Identify "typical" galaxies

ALMA2040:

- transforms the census into physics

1 deg



Extending the view of the cold ISM

SKA

- HI (lower z)
- radio continuum
- reionization

ngVLA

- low- J CO
- free-free emission
- dust

Connecting baryons to stars

JWST

- stellar populations
- nebular emission
- metallicity

ELTs

- morphologies
- kinematics
- stellar spectroscopy

Together with **ALMA2040**, we will obtain a complete picture of

- molecular gas excitation
- gas reservoir
- star formation
- multi-phase ISM
- metal abundance
- baryon cycle

to answer the question *how the gas forms stars and evolve*

ALMA2040: the Next Frontier

Pre-ALMA	ALMA	The WSU	ALMA2040
Can we detect?	What are the properties?	What governs galaxy populations?	What are the fundamental baryon cycles of galaxy formation?
<i>Extreme galaxies</i>	<i>Normal massive galaxies</i>	<i>Representative galaxies</i>	<i>Typical galaxies across all environments</i>

- ALMA has transformed high-redshift galaxy studies
- WSU will make many currently difficult observations routine
- ALMA2040 should be able to
reveal the cold baryon cycle in the multi-wavelength era

How does the baryon cycle evolve across cosmic time?