

East Asian ALMA Community Workshop: ALMA2040 Science and Technology Perspectives
July 15 (pm) – July 17, 2026, NAOJ, Japan

Direct Observations of Warm Molecular Hydrogen at $z > 10$: A Unique Discovery Space for ALMA2040

DAY2 (July 16), 15:50 – 16:10 (15-minutes talk + 5-minutes Q&A)

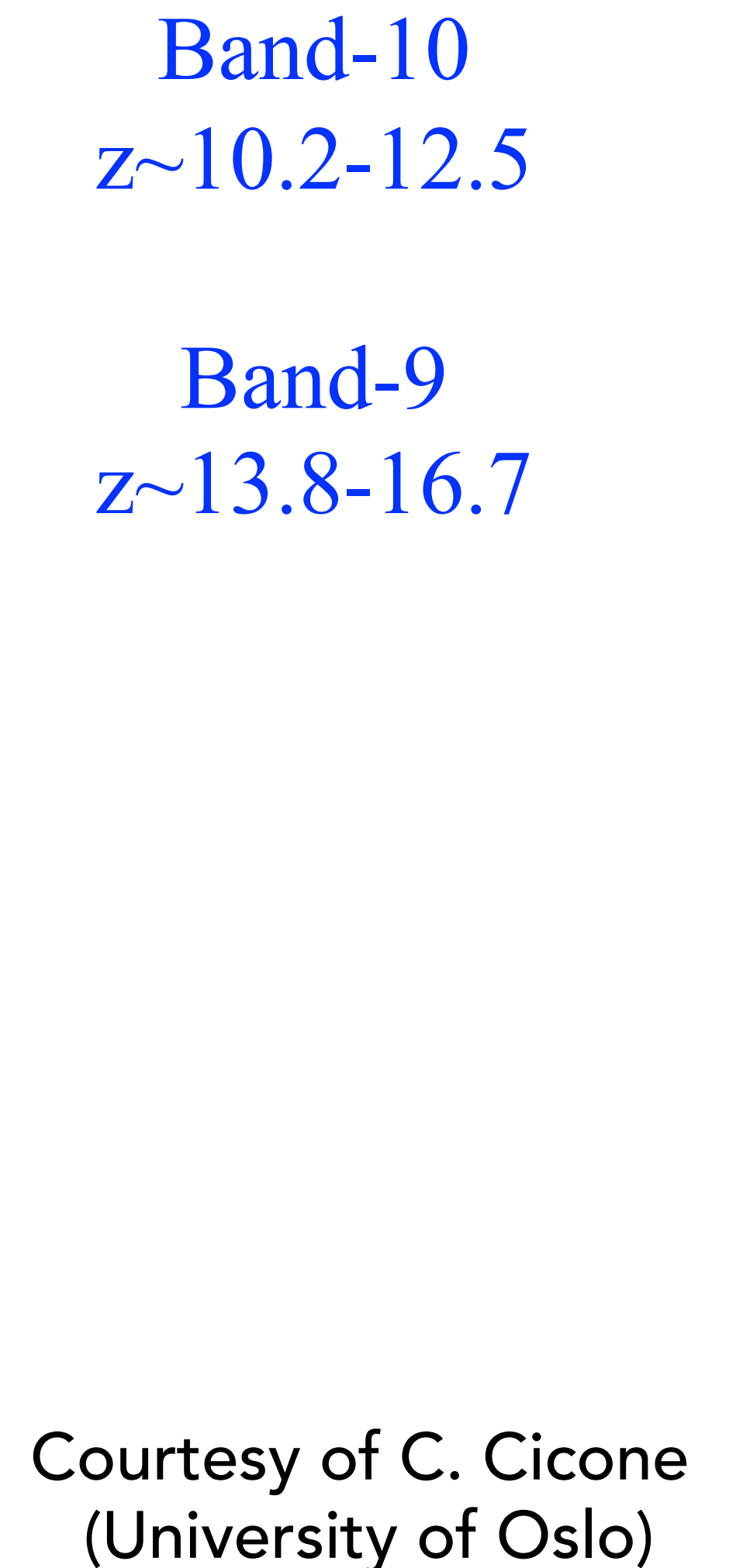
With thanks to Enrico Garaldi (IPMU/UTokyo), Erika Ogata (RESCEU/UTokyo), Kana Moriwaki, Naoki Yoshida (UTokyo, RIKEN), Yoichi Tamura (Nagoya Univ.), and Fumiya Maeda (Osaka Electro-Communication Univ.) for fruitful discussions

KOHNO Kotaro (IoA/UTokyo)



ALMA's Unique Window on Warm H₂ at Cosmic Dawn

- **Molecular hydrogen is the dominant baryonic component of galaxies**, yet it **remains essentially unconstrained in the first billion years of cosmic history**.
 - At very high redshift, conventional tracers such as CO, dust continuum, and even [C II] 158 μm become increasingly uncertain because of low metallicity and rapidly evolving interstellar-medium conditions.
- A remarkable opportunity arises from **the H₂ 0-0 S(0) rotational transition at 28.2 μm** .
- This line is redshifted into ALMA **Bands 10** and **9** over the redshift range **$z \sim 10.2-12.5$** and **$13.8-16.7$** .
- ALMA is the **only existing or foreseeable facility capable of directly probing warm (100-300 K) molecular hydrogen that traces the bulk of the molecular gas mass throughout Cosmic Dawn**.
 - Warm molecular hydrogen plays a key role in the thermal balance of the ISM and in the coupling between star formation, feedback, and gas accretion.
- No other planned observatory offers comparable access to this parameter space.
 - PRIMA Far-Infrared Survey Spectrometer (FIRES) provides 24 – 235 μm spectroscopy → H₂ S(0) can be accessible up to $z=7.3$, i.e., the last phase of the cosmic reionization.

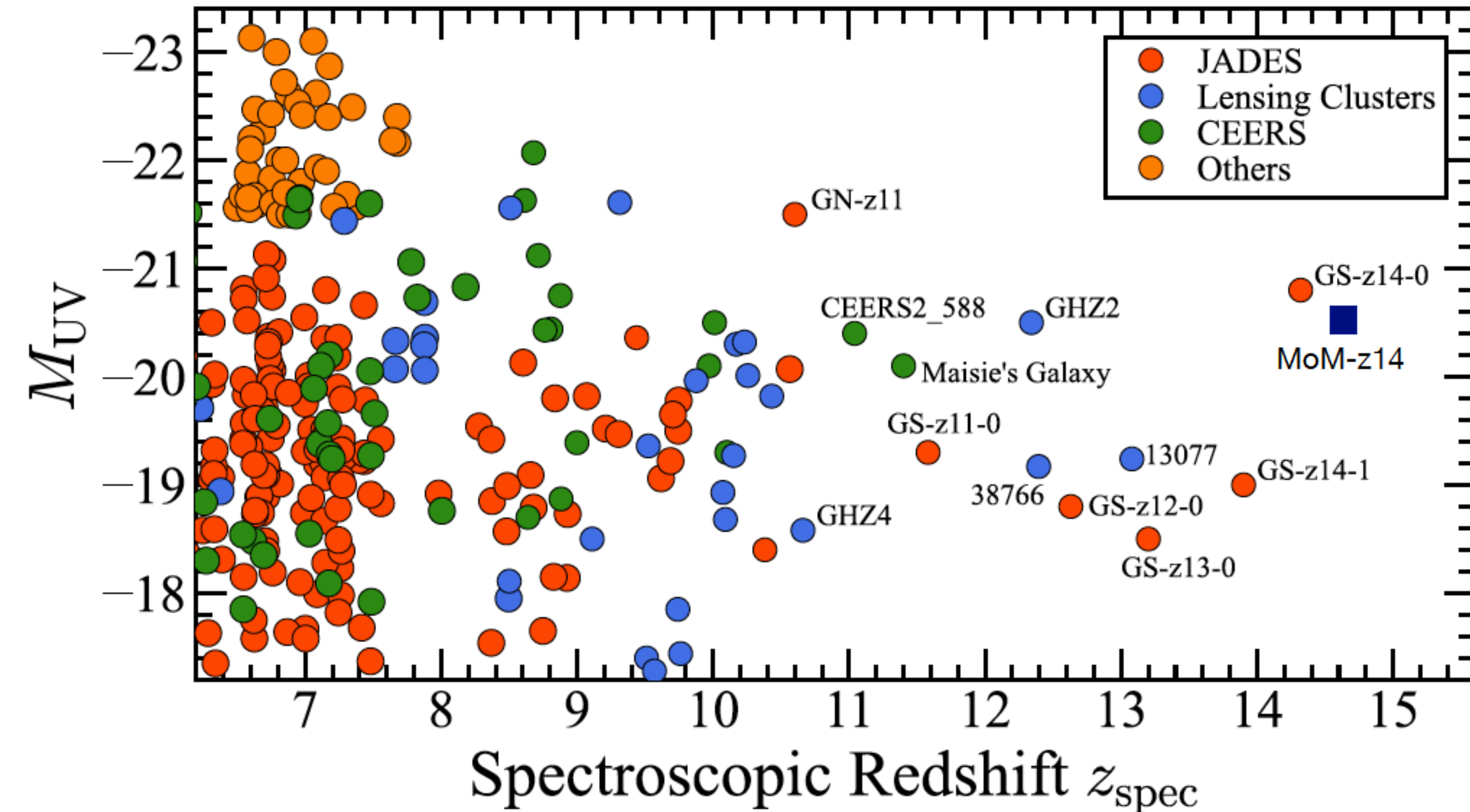


The Missing Piece: Warm Molecular Hydrogen Tracing the Dominant Baryonic Component of Star-Forming Galaxies at Cosmic Dawn

- The discovery of the spectroscopically confirmed galaxy JADES-GS-z14-0 at $z = 14.179$ has opened a new window on galaxy formation only ~ 300 Myr after the Big Bang.
- Despite its extreme redshift, this source already exhibits clear signatures of rapid chemical enrichment, including detections of [O III] $88\ \mu\text{m}$ emission (Schouws et al. 2025, ApJ, 988, id.19), as well as a stringent upper limit on [C II] $158\ \mu\text{m}$ (Schouws et al. 2025, arXiv:2502.01610).
- These observations indicate that metal-enriched gas can assemble remarkably early, challenging our understanding of the timing and efficiency of star formation and feedback in the first galaxies.
- However, existing observations probe only specific phases of the interstellar medium (ISM), primarily ionized gas [O III] and neutral gas traced by fine-structure lines [C II] or dust.
- The major baryonic component of gas-rich star-forming galaxies – i.e., molecular hydrogen (H_2) – remains entirely unconstrained.

Key questions: Can warm molecular hydrogen cooling become energetically important in the first massive galaxies? Can H_2 cooling rival or even exceed metal-line cooling in a massive galaxy at cosmic dawn?

Incredibly high abundance of massive star-forming galaxies at $z > 10$



See also MoM-z14
@ $z=14.44$
Naidu et al. 2026,
arXiv: 2505.11263

Harikane et al. 2025,
ApJ, 980, 138

ALMA Detection of [O III] 88 μm at $z=14.2$

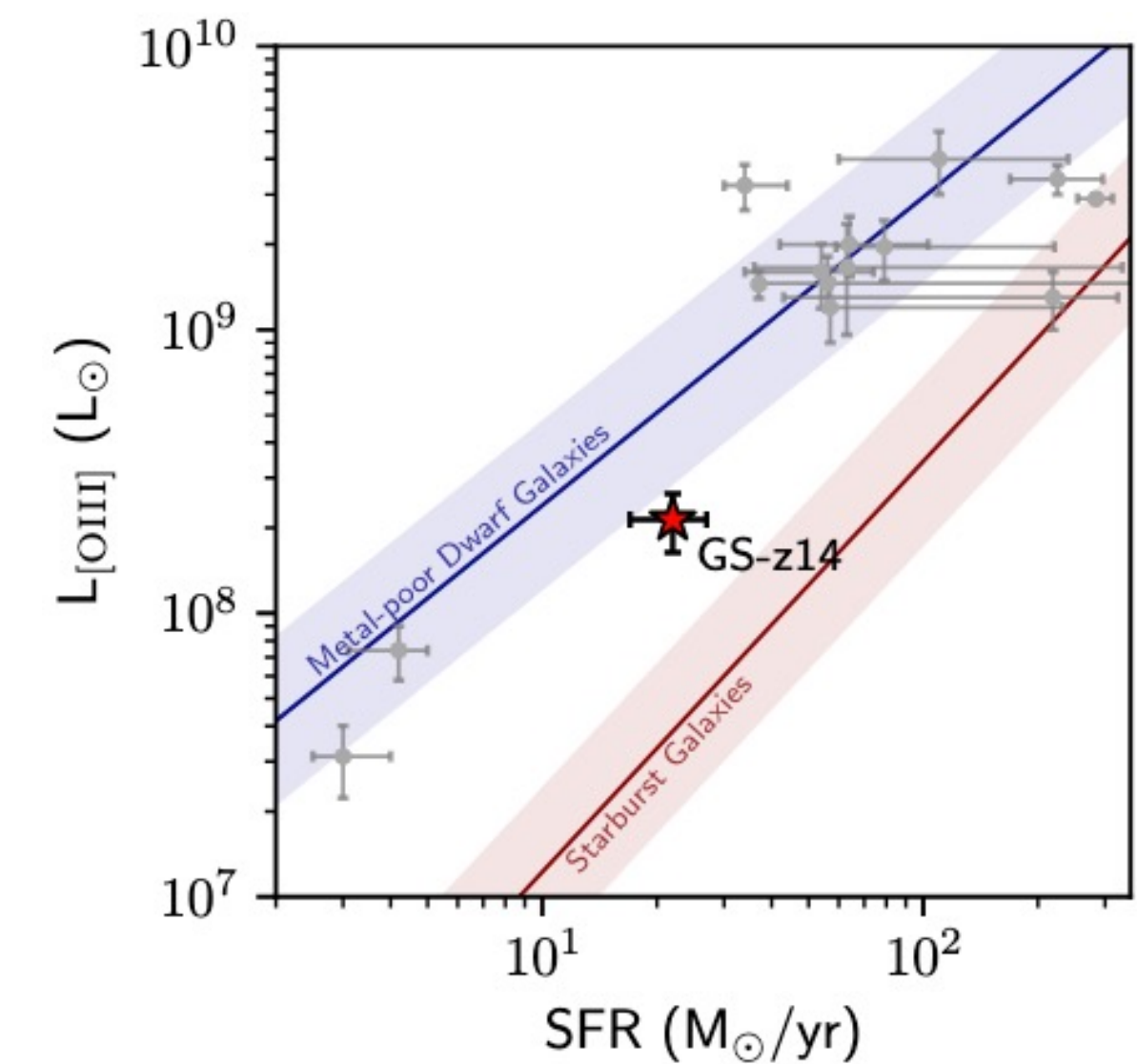
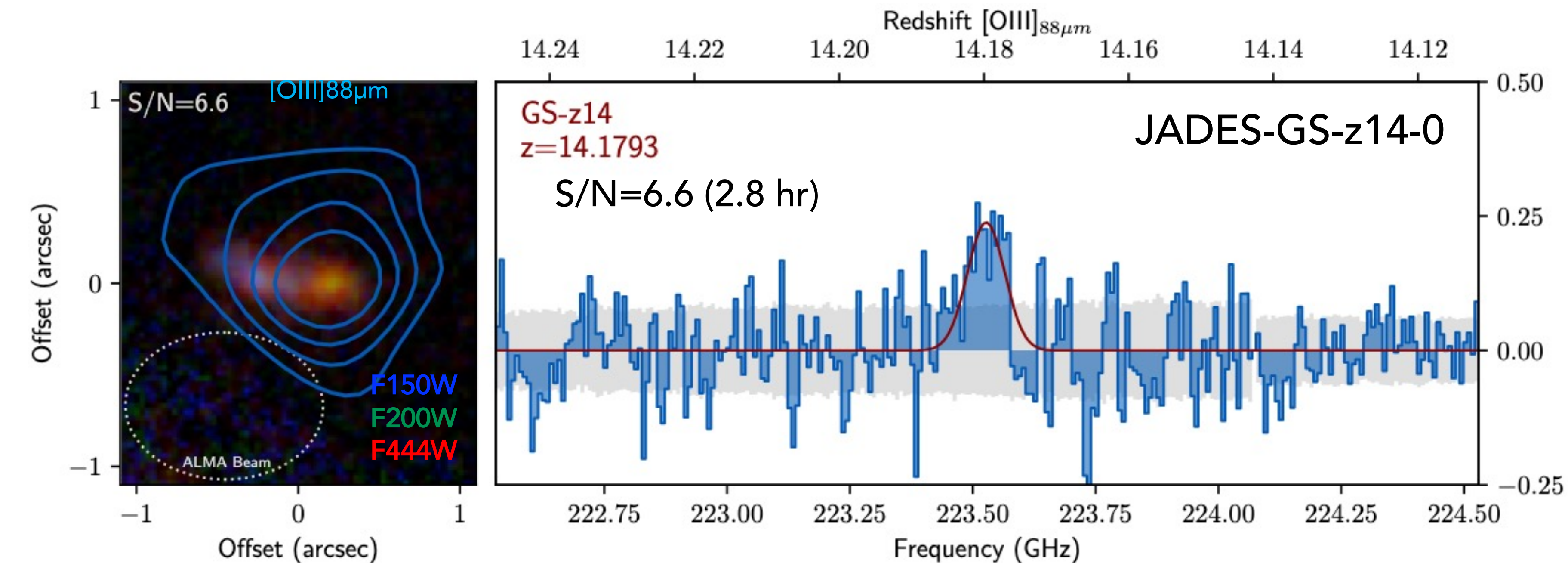


Table 1. Properties of GS-z14

Parameter	Value
RA	03:32:19.9049
Dec	-27:51:20.265
Redshift	$z = 14.1793(7)$
M_{UV}	-20.81 ± 0.16
Stellar Mass ($\log(M_{\odot})$)	$8.7^{+0.5}_{-0.4}$
Star Formation Rate ($M_{\odot}/\text{yr}$)	25^{+6}_{-5}
[O III] 88 μm Luminosity ($10^8 L_{\odot}$)	2.1 ± 0.5
FWHM [O III] 88 μm (km s^{-1})	136 ± 31
Dynamical Mass ($M_{\odot} (\sin i)^2$)	$(1.0 \pm 0.5) \times 10^9$
90- μm continuum flux ($\mu\text{Jy}/\text{beam}$)	$< 15.1 (3\sigma)$
Dust Mass ($\log(M_{\odot})$)	< 6.0

Notes: M_{UV} from Carniani et al. (2024); stellar mass and SFR from Helton et al. (2024). Values have been corrected for a lensing magnification of $1.17 \times$ (Carniani et al. 2024).

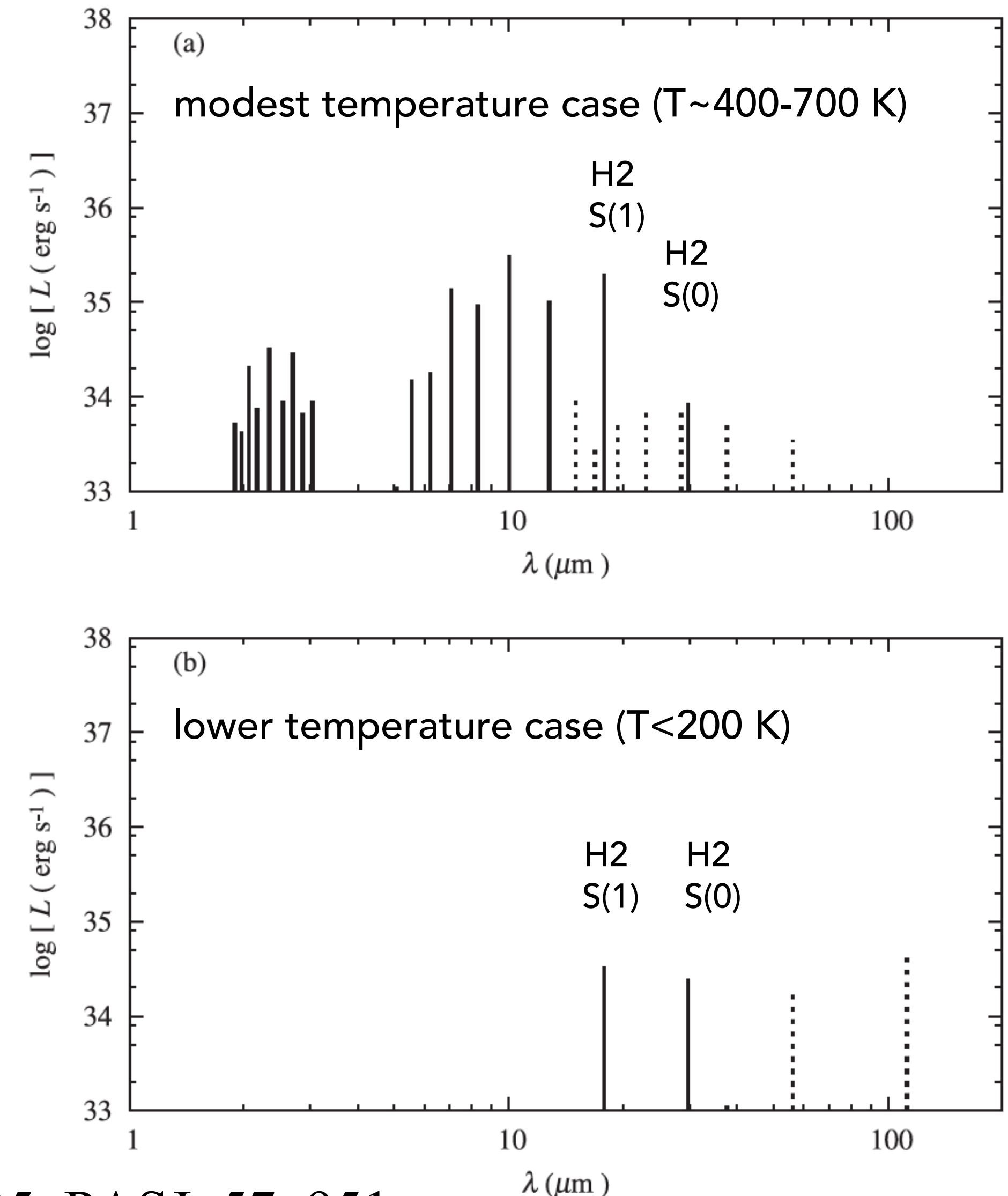
Schouws, S., et al. 2025, ApJ, 988, id.19

- Metal-enriched ($Z \sim 0.05 - 0.2 Z_{\odot}$) a mere 300 Myr after the Big Bang
- Detection of [O III] 88 μm itself challenges the current galaxy formation models (e.g., Kohandel, Pallottini, & Ferrara 2025, A&A, 704, A39)
- A large gas fraction $f_{\text{gas}} = M_{\text{gas}}/(M_{\text{star}}+M_{\text{gas}}) \sim 0.7-0.9$ is suggested (Heintz et al. 2025, ApJL, 987, L2)

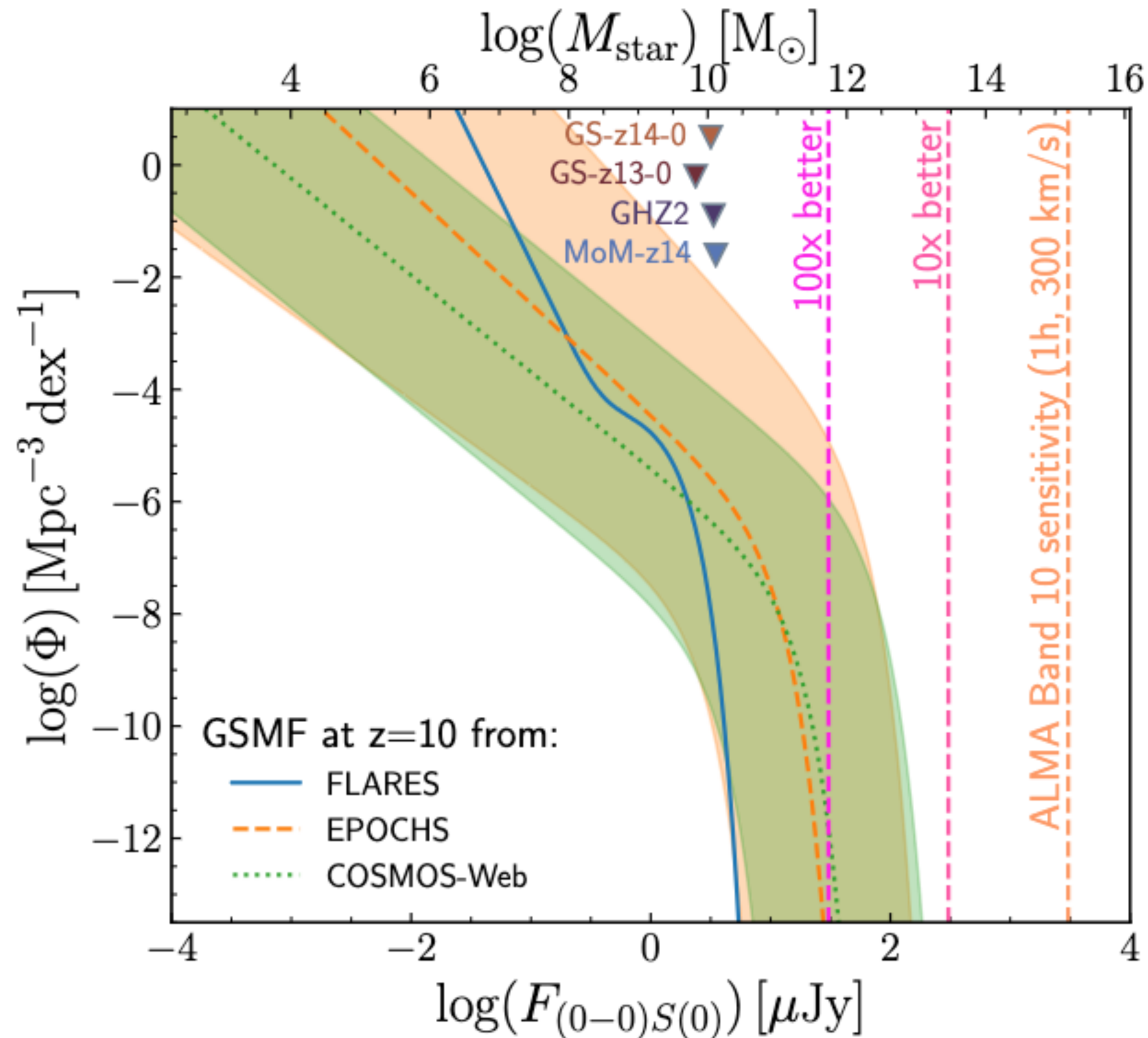
**Question: can we expect
powerful H₂ cooling in
such $z > 10$ galaxies?**

Warm H₂ from low-metallicity and Pop III galaxies

- H₂ forms mainly through the H⁻ channel, in which a hydrogen atom first captures a free electron to form the negative hydrogen ion, H⁻
 - e.g., Abel, T., et al. 1997, *New Astronomy*, 2, 181
- Three-body formation becomes dominant at high densities, $n_{\text{H}} > 10^8 \text{ cm}^{-3}$
 - e.g., Palla, F., et al. 1983, *ApJ*, 271, 632
- The theoretical study of primordial molecular cloud formation: a traditional stronghold of astrophysical research in Japan
 - Omukai & Nishi 1998, *ApJ*, 508, 141
 - Omukai 2001, *ApJ*, 546, 635
 - Yoshida et al. 2006, *ApJ*, 652, 6
 - etc..



Numerical simulations predict ">100 times ALMA" is necessary



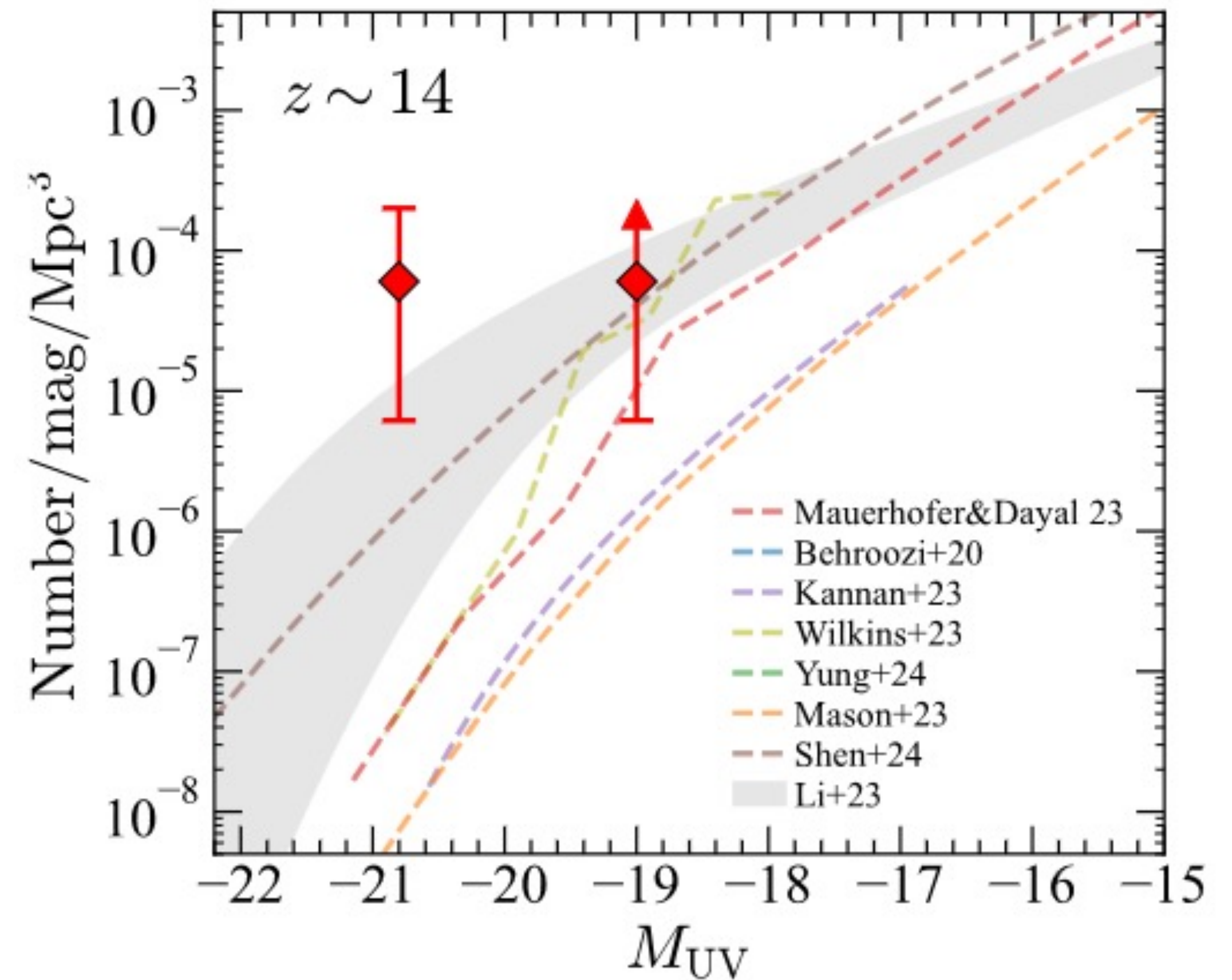
- Estimated luminosity function of the S(0) line from the stellar mass function.
- Lines show the predictions using galaxy stellar mass function (GSMF) from the FLARES simulations (Lovell et al. 2021), the COSMOS-Web (Shuntov et al. 2025) JWST observations and the EPOCHS (Harvey et al. 2025) compilation of observed fields.
- **Combination of "10 times ALMA" & gravitational lensing ($\mu > 10$) may provide a viable route**

Garaldi, E., Ogata, E., Yoshida, N., et al. in prep.

BUT remember: Current models struggle to reproduce GS-z14-0-like “monsters” at $z > 10$!

- While these objects may not necessarily violate the Lambda-CDM framework itself, it is fair to say that **current galaxy-formation models still have difficulty explaining the observed abundance of such luminous and massive galaxies at $z > 10$.**
- For the brightest galaxies, **the discrepancy can reach a few orders of magnitude** (e.g., Harikane et al. 2025, ApJ, 980, 138).
- **Detection of [O III] 88 μ m itself challenges the current galaxy formation models** (e.g., Kohandel, Pallottini, & Ferrara 2025, A&A, 704, A39)
- Many ideas have been proposed to explain these objects, but there is currently no consensus and no clear evidence that any model can reproduce all of their observed properties.

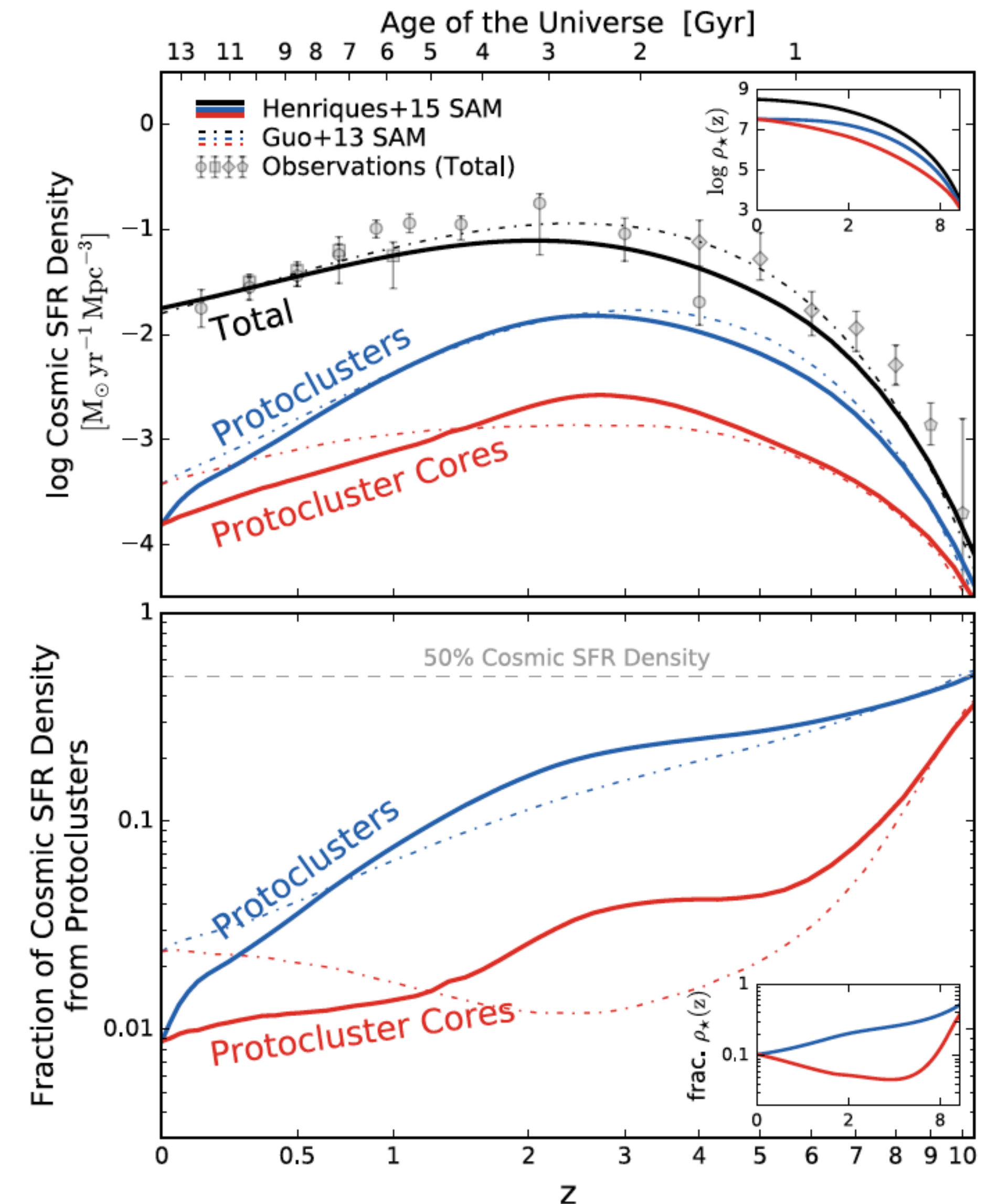
UV luminosity functions: Observations vs. theoretical models



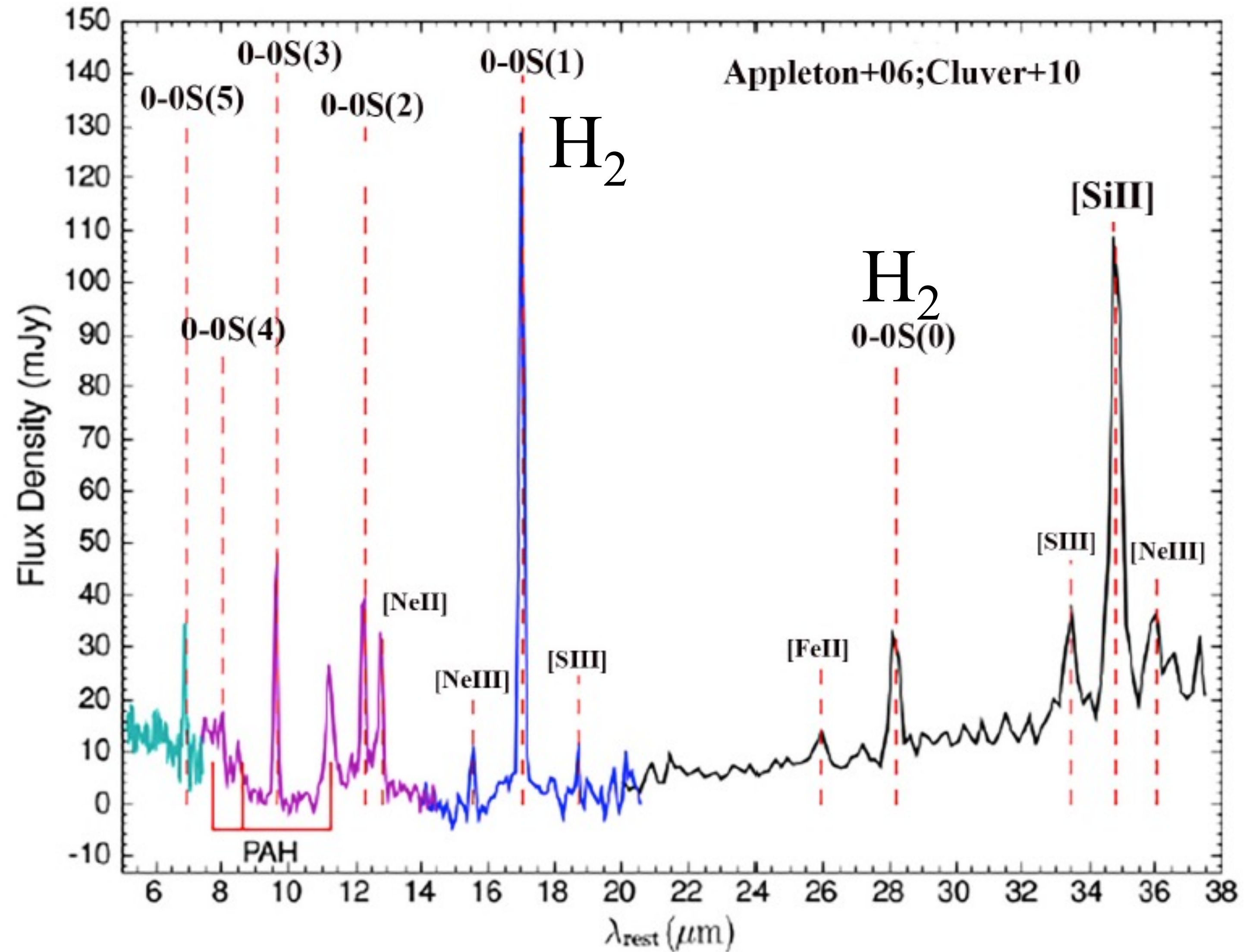
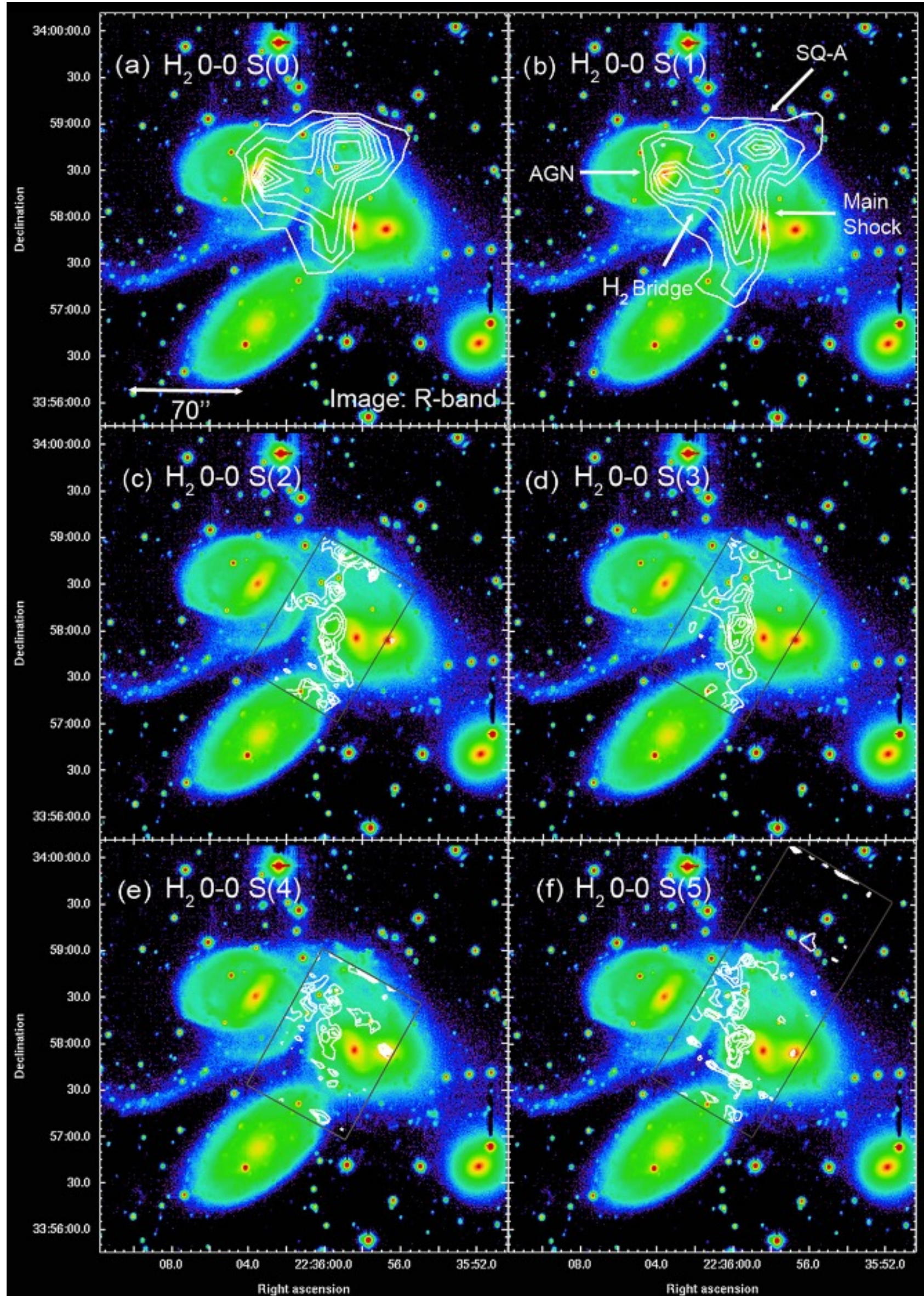
Harikane et al. 2025, ApJ, 980, 138

Do GS-z14-0-like “Monsters” Reside in Overdense Environments?

- At higher redshift, **galaxies in protoclusters** are an important and even dominant population, as **their expected contribution to the cosmic star formation rate density** rises from 1% at $z = 0$ to 20% at $z=2$ and then **50% at $z=10$** (Chiang, Y-K., et al. 2017, ApJL, 844, L23)
- Based on cosmological hydrodynamic simulations with radiative transfer, **GS-z14-0** and **GS-z14-1**, two of the earliest spectroscopically confirmed galaxies, are **likely progenitors of Coma-type clusters** (Morokuma-Matsui, K., Yajima, H., & Abe, M. 2025, MNRAS, 539, 1834)
- Could such environments generate **galaxy-wide or group-wide shocks** analogous to Stephan’s Quintet?



Powerful H₂ Line Cooling in galaxy-group-wide shocks



Cluver, Appleton, et al. 2010, ApJ, 710, 248

H₂ cooling vs [O III] 88um line in Stephan's Quintet

- H₂ S(0) line luminosity: $L_{\text{H}_2 \text{ S}(0)} \sim 3.3 \times 10^{40} \text{ erg/s} \sim 8.5 \times 10^6 L_{\odot}$
 - Cluver, Appleton, et al. 2010, ApJ, 710, 248
 - S(0) – S(5) in total reaches $L_{\text{H}_2 \text{ S}(0)\text{-S}(5)} \sim 10^{42} \text{ erg/s}$
- Although there is no direct [O III] 88 um line observations, H₂ S(0) line luminosity can become comparable to the [O III] 88 um line luminosity; $L_{\text{H}_2 \text{ S}(0)} / L_{[\text{O III}] 88 \text{um}} \sim 0.3\text{-}1.2$ (see below)
 - Optical [O III] 5007Å line flux in the shocked region $F_{[\text{O III}] 5007} = (5.19 \pm 0.09) \times 10^{-13} \text{ erg/s/cm}^2$ (Arnaudova et al. 2024, MNRAS, 535, 2269) ➔ $L_{[\text{O III}] 5007} = 5.5 \times 10^{41} \text{ erg/s} = 1.4 \times 10^8 L_{\odot}$
 - Then [O III] 88um line luminosity can be estimated to be $L_{[\text{O III}] 88 \text{um}} \sim \text{a few} \times 10^7 L_{\odot}$
 - $L_{[\text{O III}] 88 \text{um}} \sim L_{[\text{O III}] 5007} / (5\text{-}20)$ for $n_e \sim 300\text{-}600 \text{ cm}^{-3}$, $T_e \sim 10^4 \text{ K}$
 - consistent with an electron density $n_e \sim 480 \text{ cm}^{-3}$, which is inferred from an optical [S II] line ratio

A Reality Check: H₂ S(0) Observations of "the monster" GS-z14-0 at $z = 14.2$ using ALMA, 10xALMA, and ..?

- With current ALMA capabilities:
 - Consider a "modest" integration time at Band-9, say ~4 hours
 - ➔ 1 sigma = 1.0 mJy/beam at 130 km/s
 - It gives an upper limit of $L_{\text{H}_2 \text{ S}(0)}/L_{[\text{OIII}]88\mu\text{m}} \sim 30$ ➔ Placing the first limit on the ratio $L_{\text{H}_2 \text{ S}(0)}/L_{[\text{OIII}]88\mu\text{m}}$ and testing whether very exceptional, extreme molecular cooling can exist
 - $L_{\text{H}_2 \text{ S}(0)}/L_{[\text{OIII}]88\mu\text{m}} \sim 1$ with an observing time of ~4,000 hours ➔ Placing stringent limits on the ratio $L_{\text{H}_2 \text{ S}(0)}/L_{[\text{OIII}]88\mu\text{m}}$ and testing whether molecular cooling can rival the already observed metal-line cooling.
- It becomes a ~40 hours business if "**10 × ALMA**" is implemented
- "**>100 × ALMA**" will be necessary for galaxies in the current numerical simulations (Garaldi, E., Ogata, E., Yoshida, N., et al. in prep; see Page 9)

"Normal simulated galaxies" in the current state-of-the-art simulations require "**>100 × ALMA**", while *the monsters* revealed by JWST & ALMA observations could be tested with "**10 × ALMA**".

The ALMA2040 Era: GREX-PLUS wide-area searches for $z > 10$ targets

- An infrared surveyor with $D=1.0\text{m}$ (PI: Inoue, A., Waseda Univ.)
- <https://arxiv.org/abs/2304.08104>
- Proposed wide-field surveys will drastically expand the sample of $z>10$ galaxies

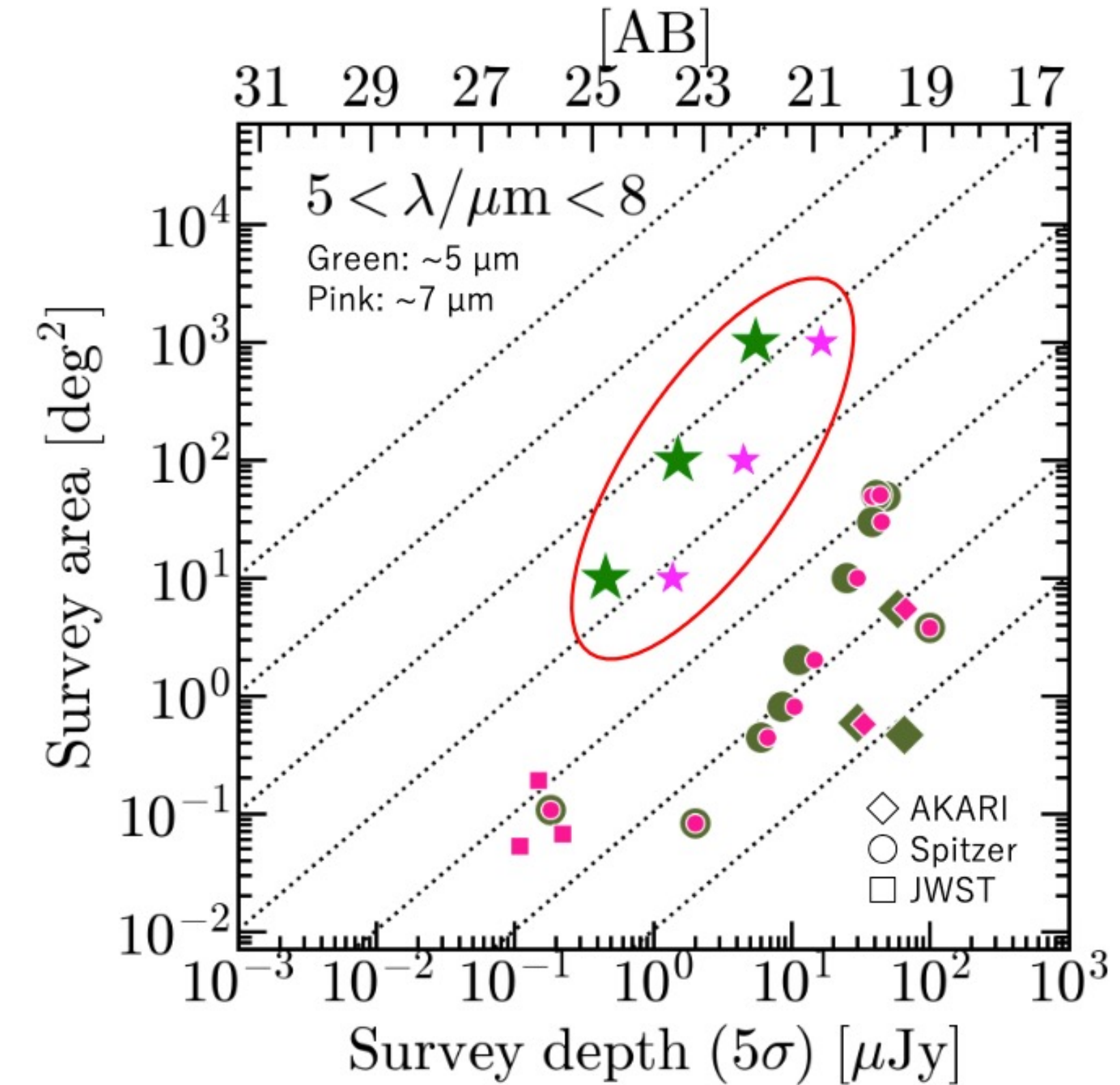
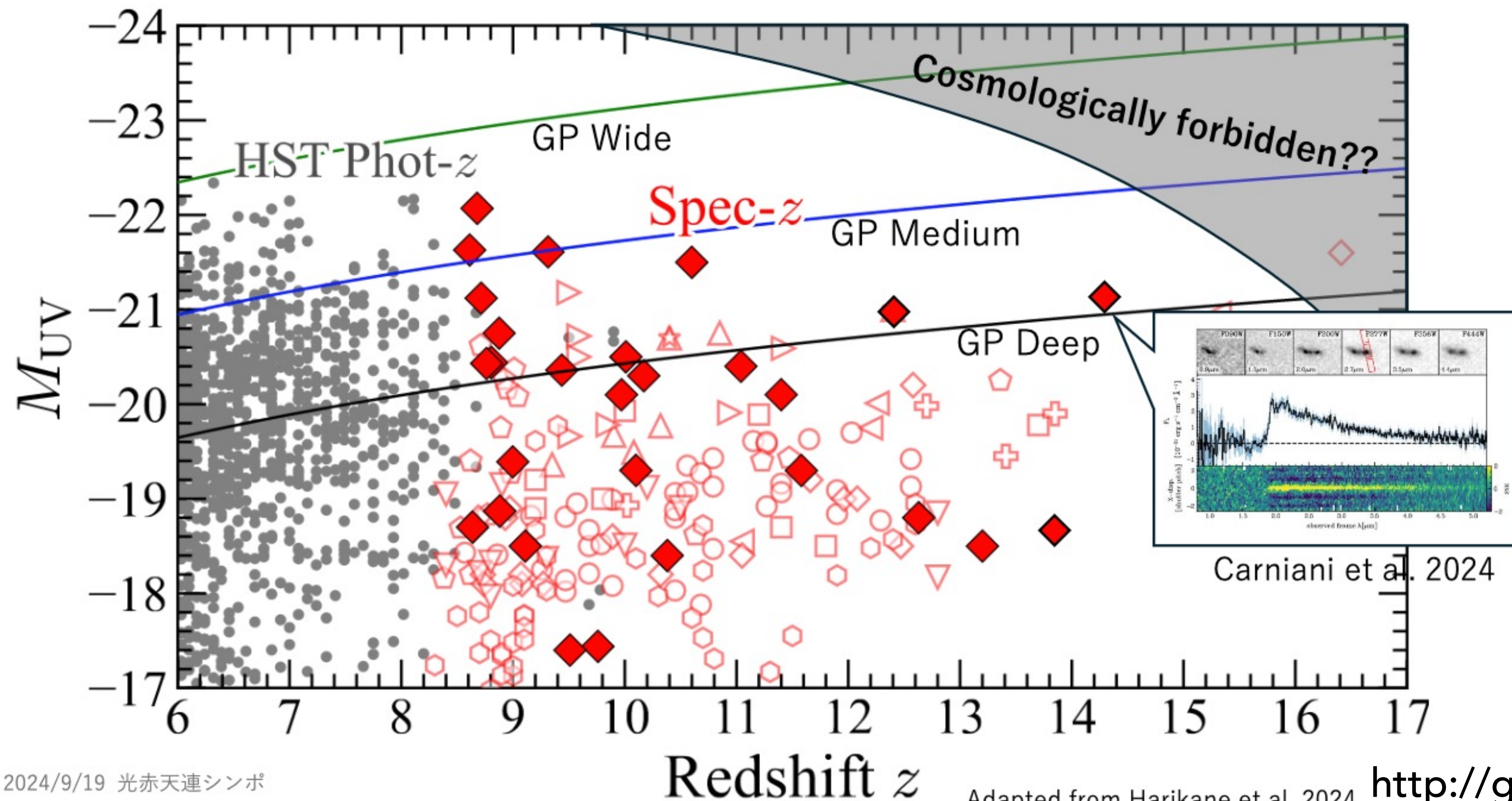


Table 1.3: GREX-PLUS wide-field survey plan.

	Deep	Medium	Wide
Area [deg^2]	10	100	1000
F232 [ABmag, 5σ]	26.9	25.6	24.2
F303 [ABmag, 5σ]	27.0	25.7	24.3
F397 [ABmag, 5σ]	27.1	25.8	24.4
F520 [ABmag, 5σ]	25.2	23.9	22.5
F680 [ABmag, 5σ]	24.0	22.7	21.3

Summary and implications for ALMA2040

- H_2 S(0) 28.2 μm provides a unique ALMA window on warm molecular gas at cosmic dawn.
 - It enters ALMA Bands 10 and 9 over $z \sim 10.2\text{-}12.5$ and $13.8\text{-}16.7$.
- For "normal simulated $z > 10$ galaxies", the line is far beyond current ALMA capabilities. Robust detections of normal galaxies in simulations would require sensitivity improvement of $> 100\times$.
- However, GS-z14-0-like "monster" galaxies challenge the current galaxy formation models.
 - Current models struggle to reproduce their abundance
- Shock-powered warm H_2 emission offers a physically motivated possibility.
 - Stephan's Quintet suggests that $L_{\text{H}_2\text{S}(0)}/L_{[\text{OIII}]\lambda 88} \sim 1$ is plausible in extreme shock-dominated systems.
 - GS-z14-0-like "monster" galaxies may reside in overdense, dynamically active environments.
- Current ALMA Band-9 reaches only $L_{\text{H}_2\text{S}(0)}/L_{[\text{OIII}]\lambda 88} \sim 30$ in a few hours.
 - Reaching ratio $L_{\text{H}_2\text{S}(0)}/L_{[\text{OIII}]\lambda 88} \sim 1$ would require several 1,000 hours today, but becomes a ~ 40 -hourish, feasible experiment with "10 $\times$ ALMA".
 - Stringent test whether molecular cooling can rival the already observed metal-line cooling.
- Implication for ALMA2040: high-frequency sensitivity in Bands 9/10 is not incremental. It opens a new and unique probe of molecular cooling, shocks, and gas assembly in the first massive galaxies.