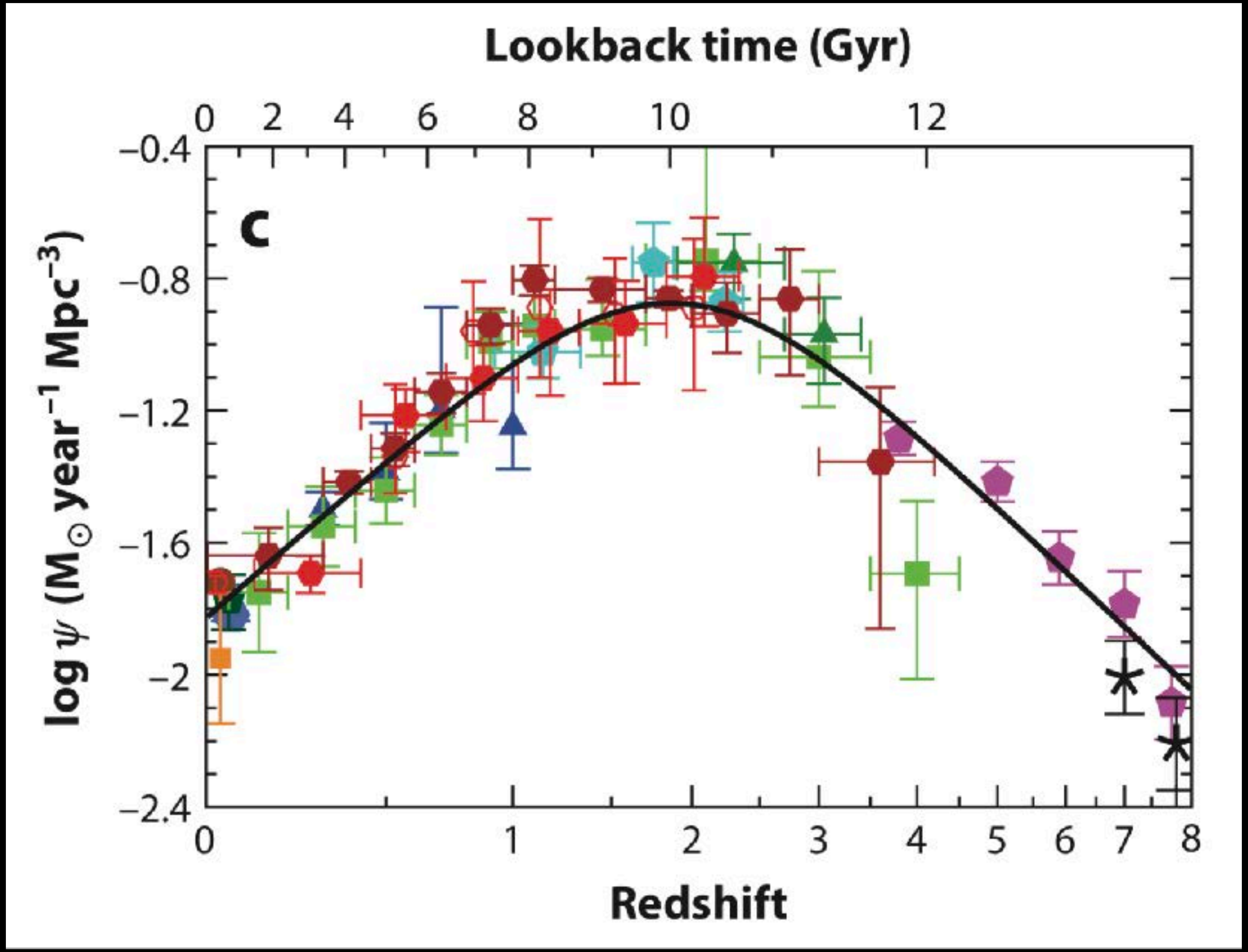
Obscured Star Formation at z~7 Observed with the REBELS ALMA Large Program

Hanae Inami
Hiroshima University

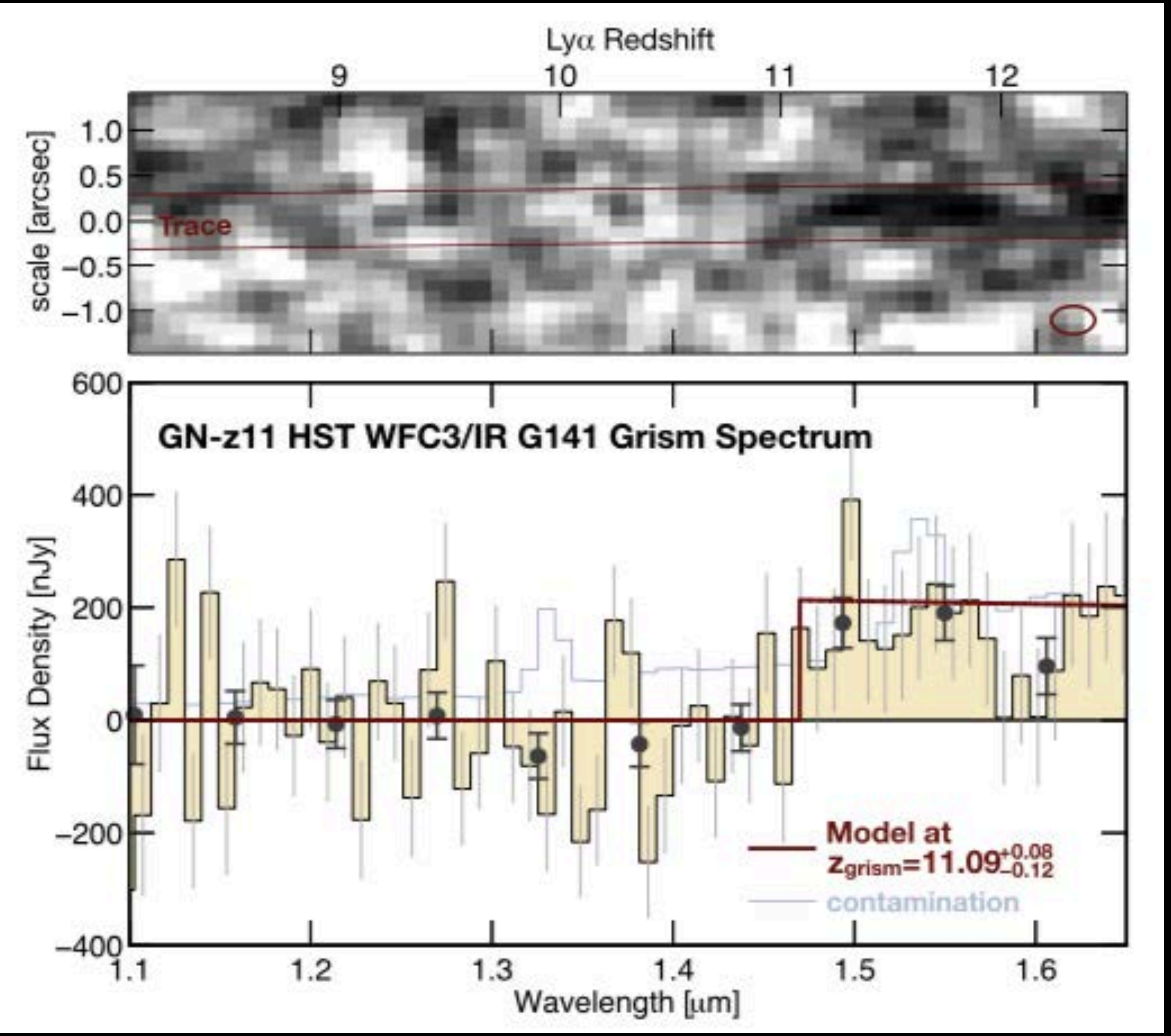
Star formation density across cosmic time

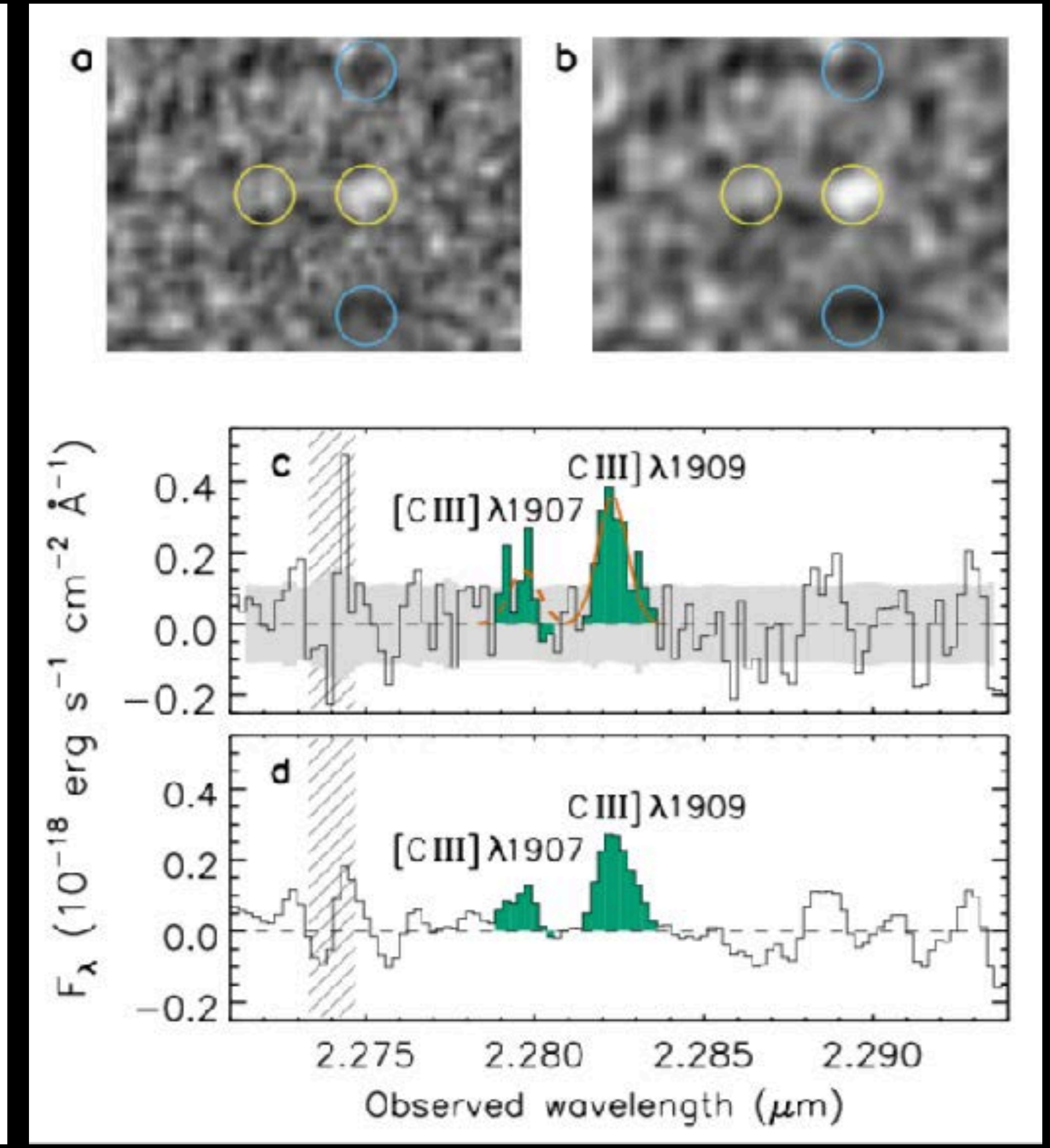


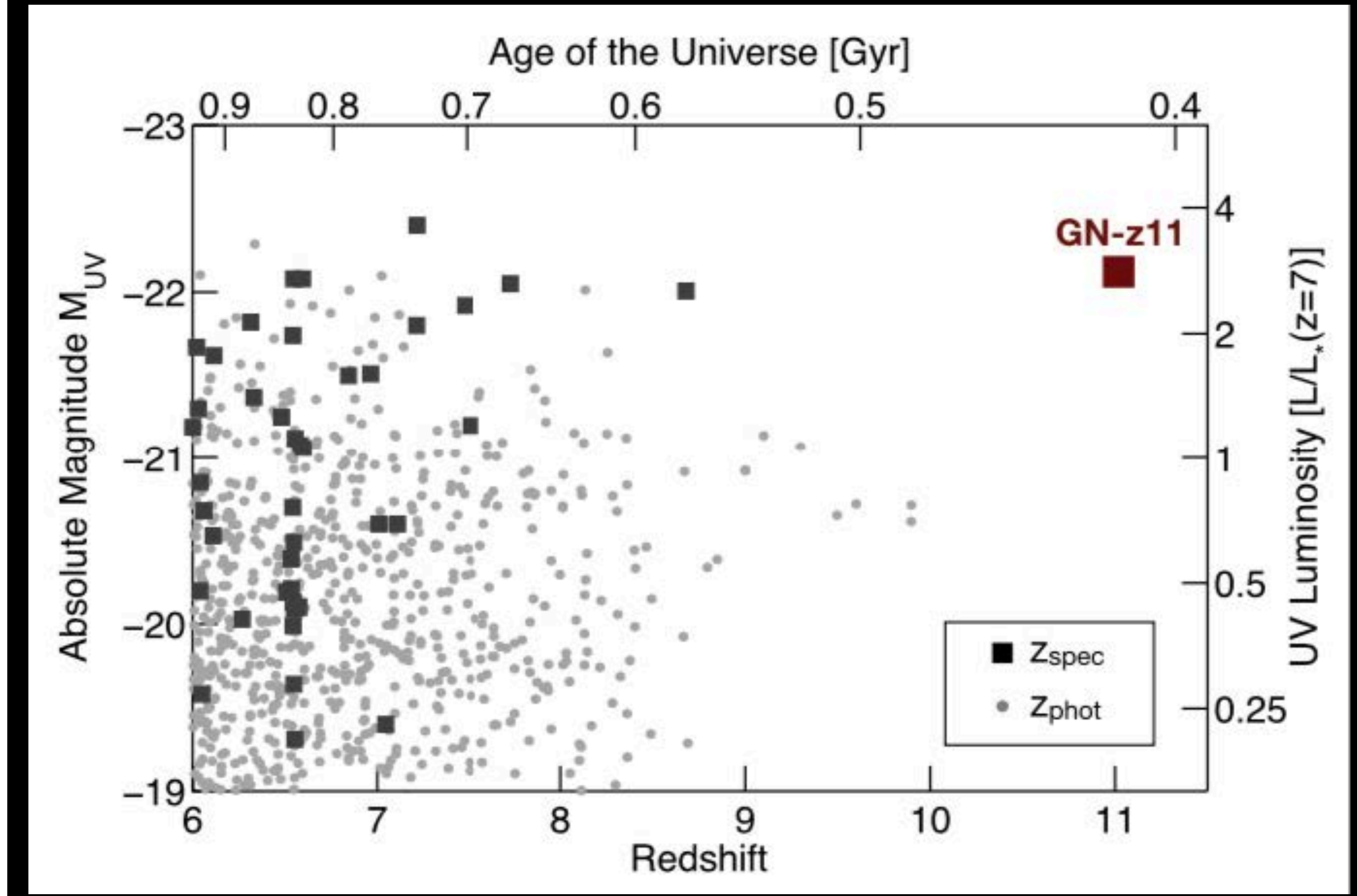
Madau & Dickinson 2014

A massive galaxy at z=10.957

GN-z11







Stellar mass = $(1.3 \pm 0.6) \times 10^9\, M_\odot$

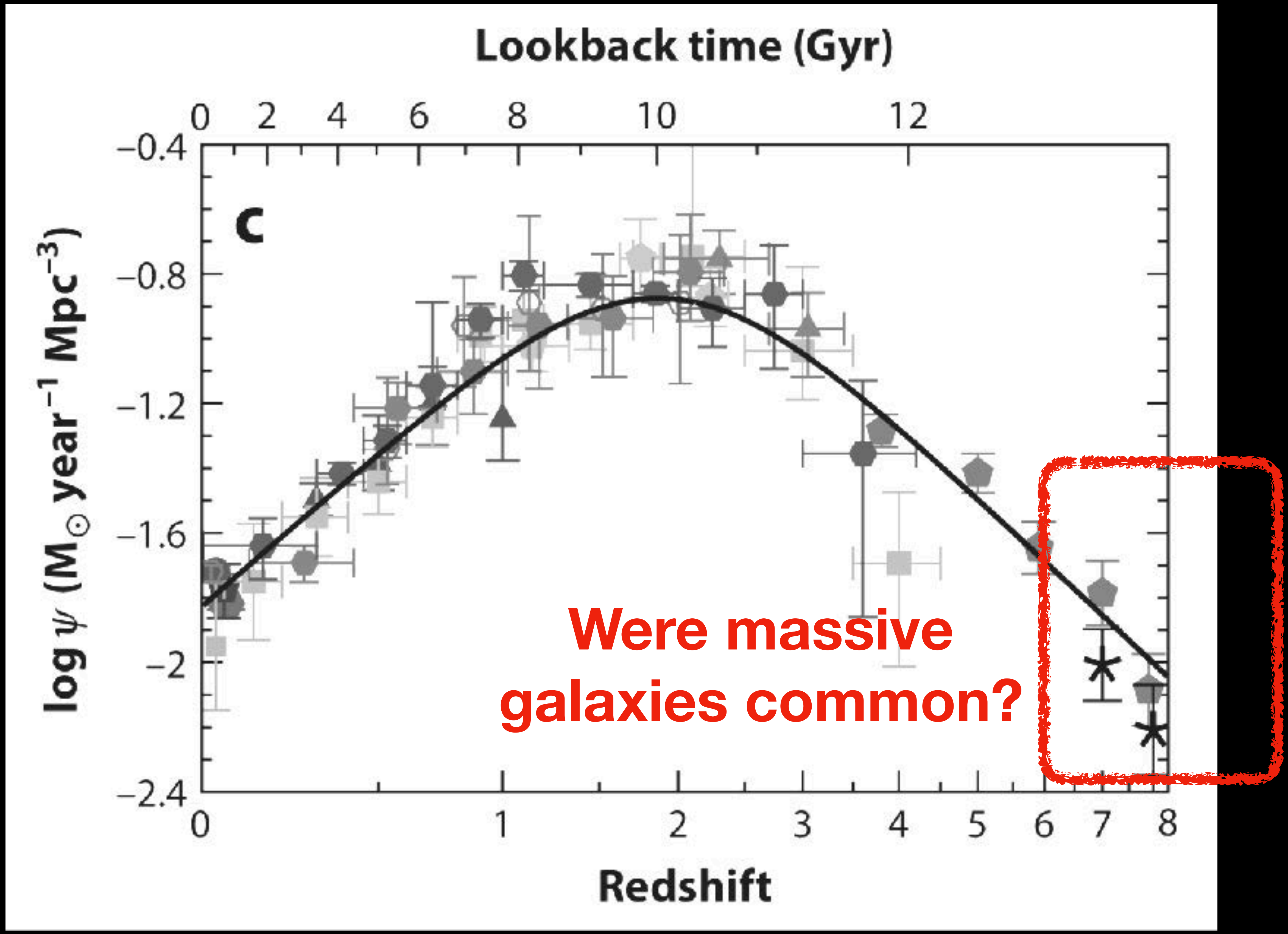
Two populations: very young + evolved populations?

High CIII] EQW Relatively high stellar mass

Oesch et al. 2016, Jiang, L. et al. 2021

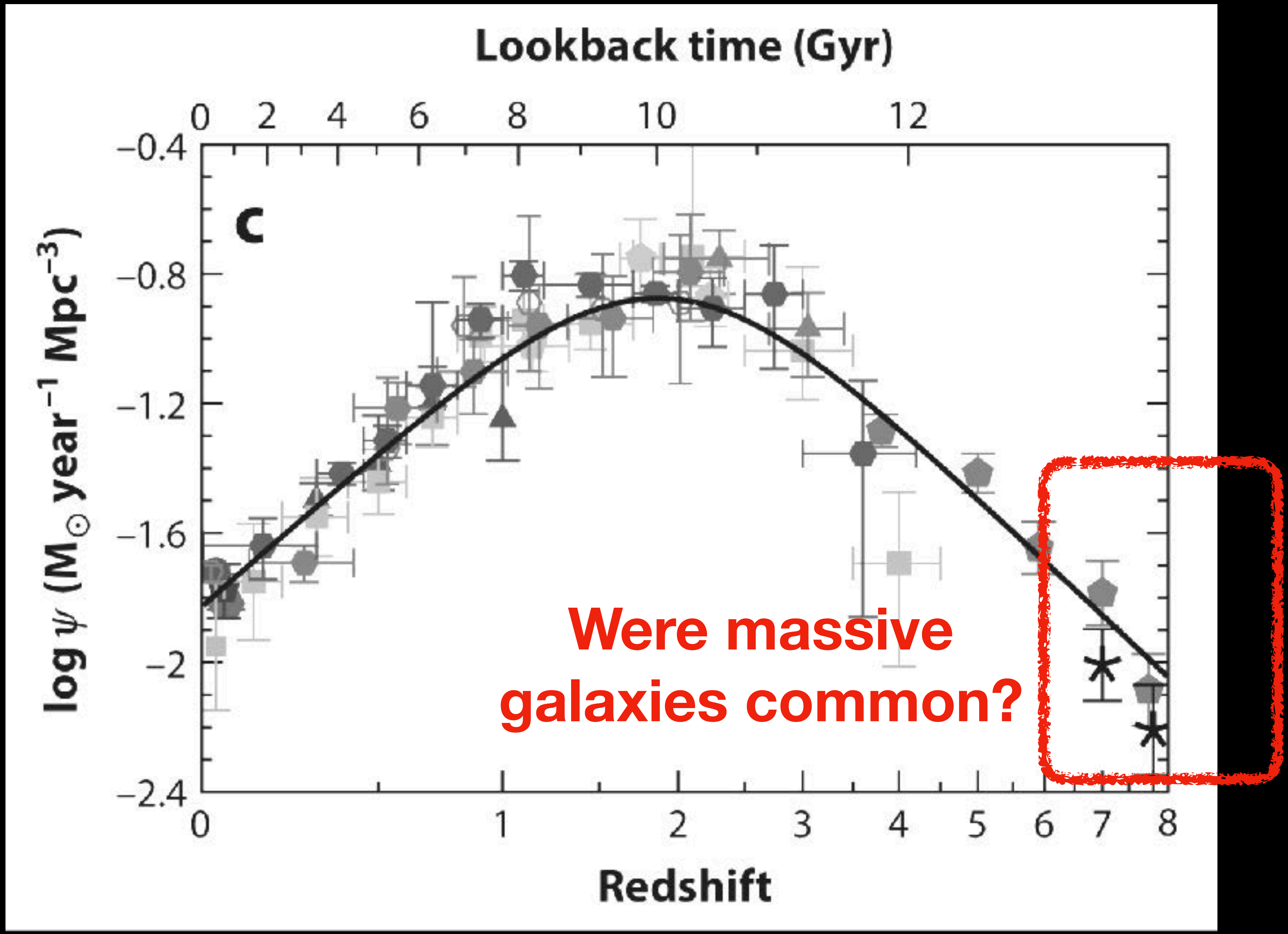
(See also Harikane et al. 2022 for z~13 SF galaxy candidates)

Star formation density across cosmic time

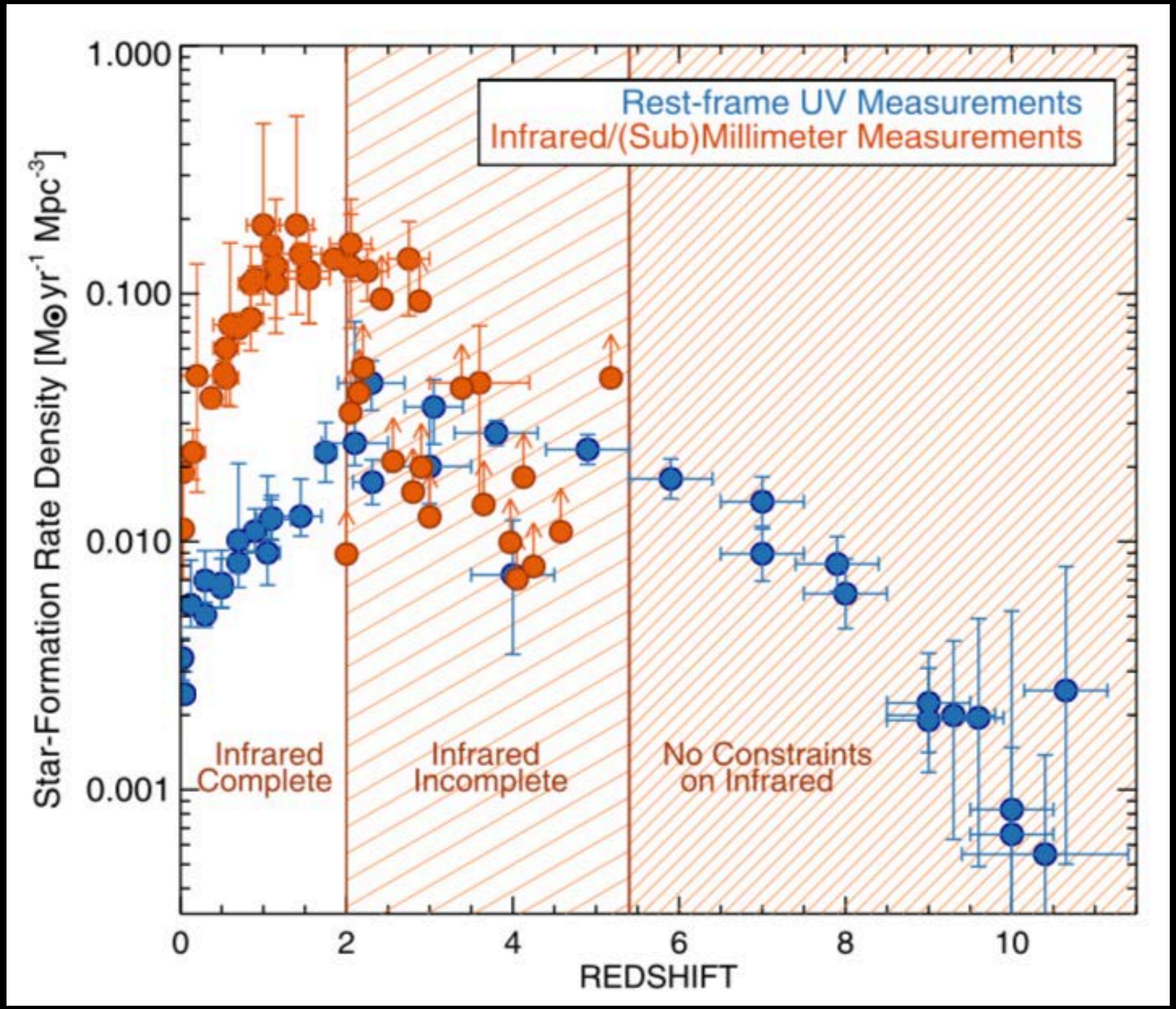


Madau & Dickinson 2014

Star formation density across cosmic time

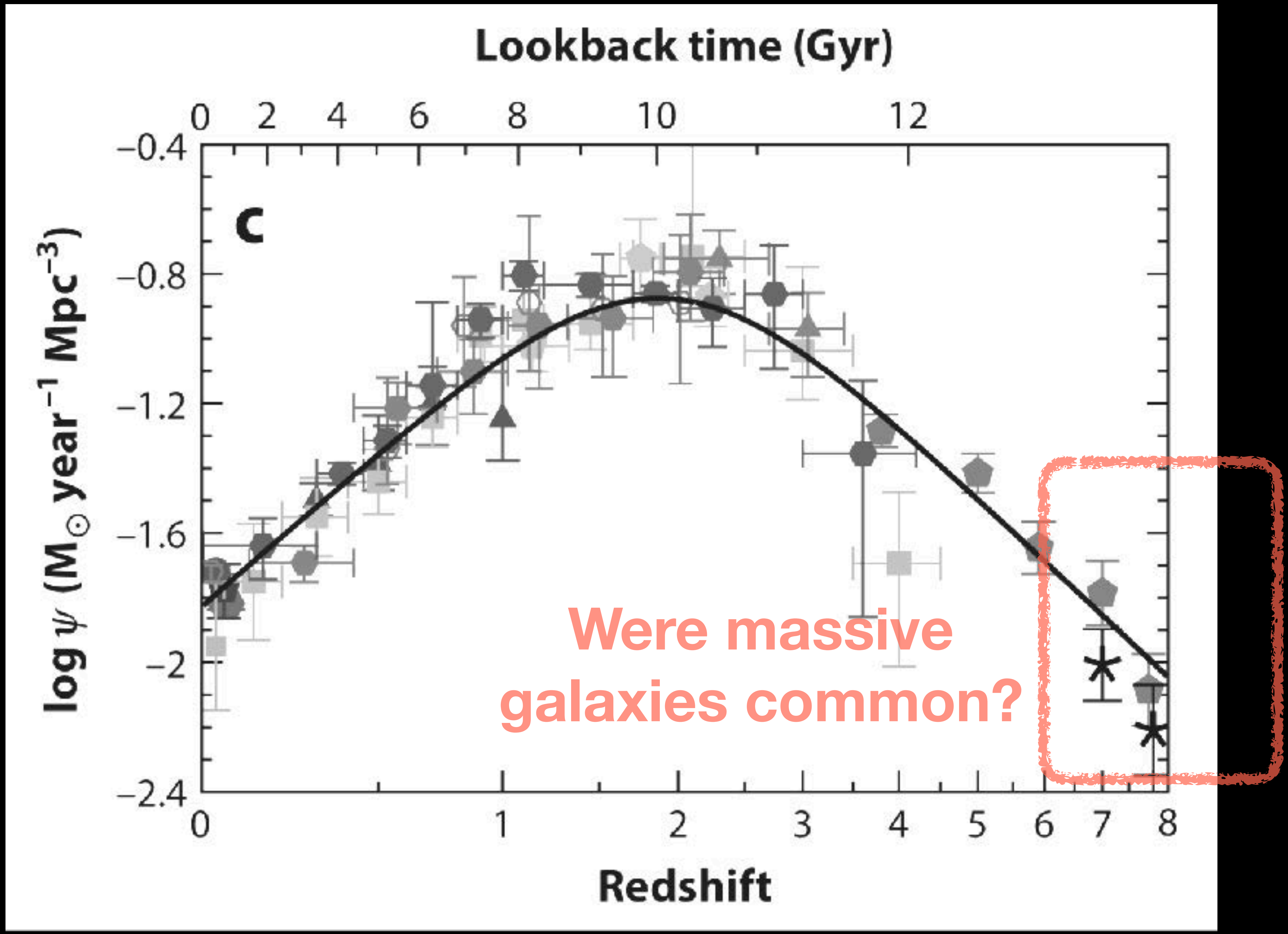


Madau & Dickinson 2014

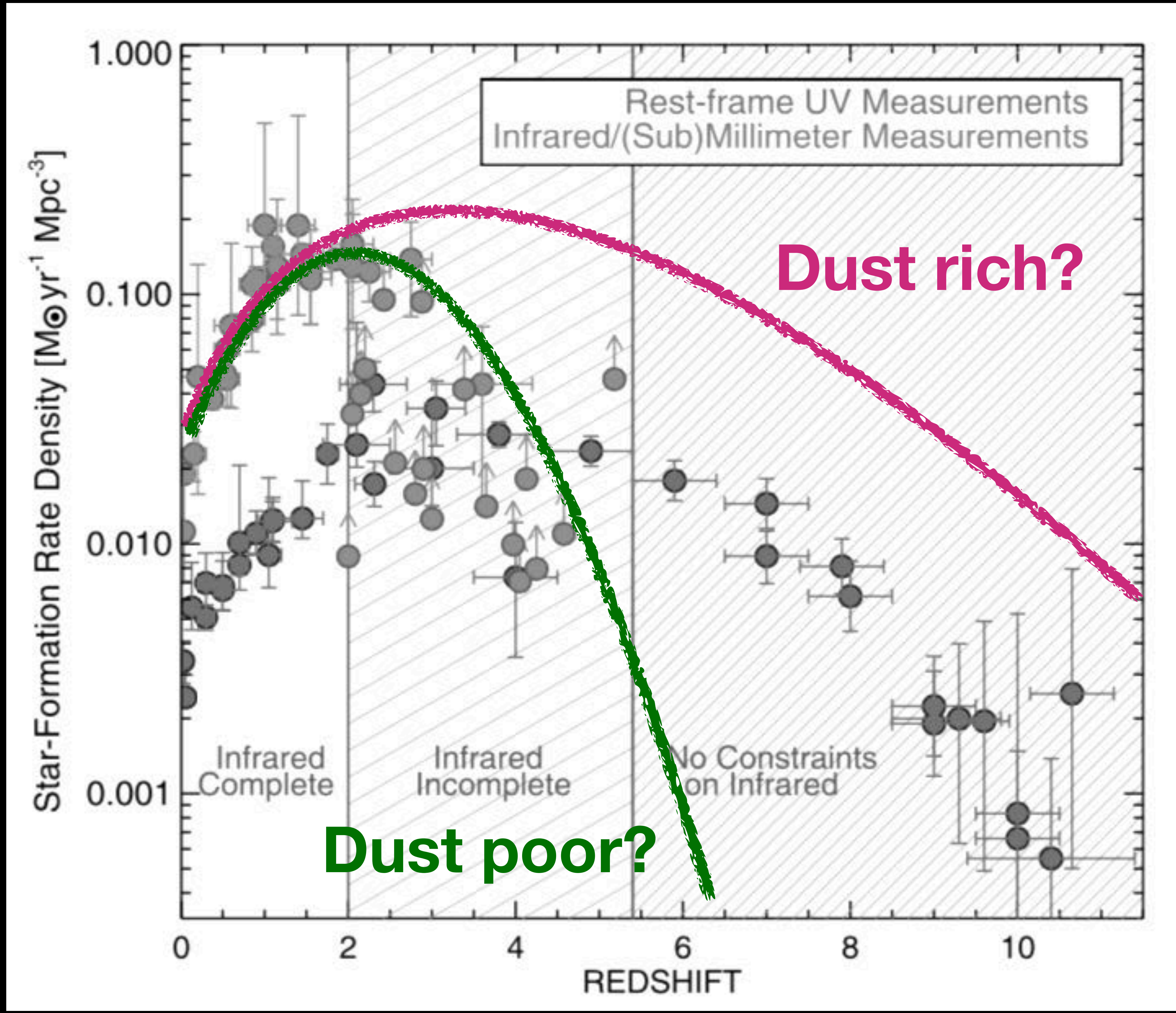


Casey et al. 2018

Star formation density across cosmic time



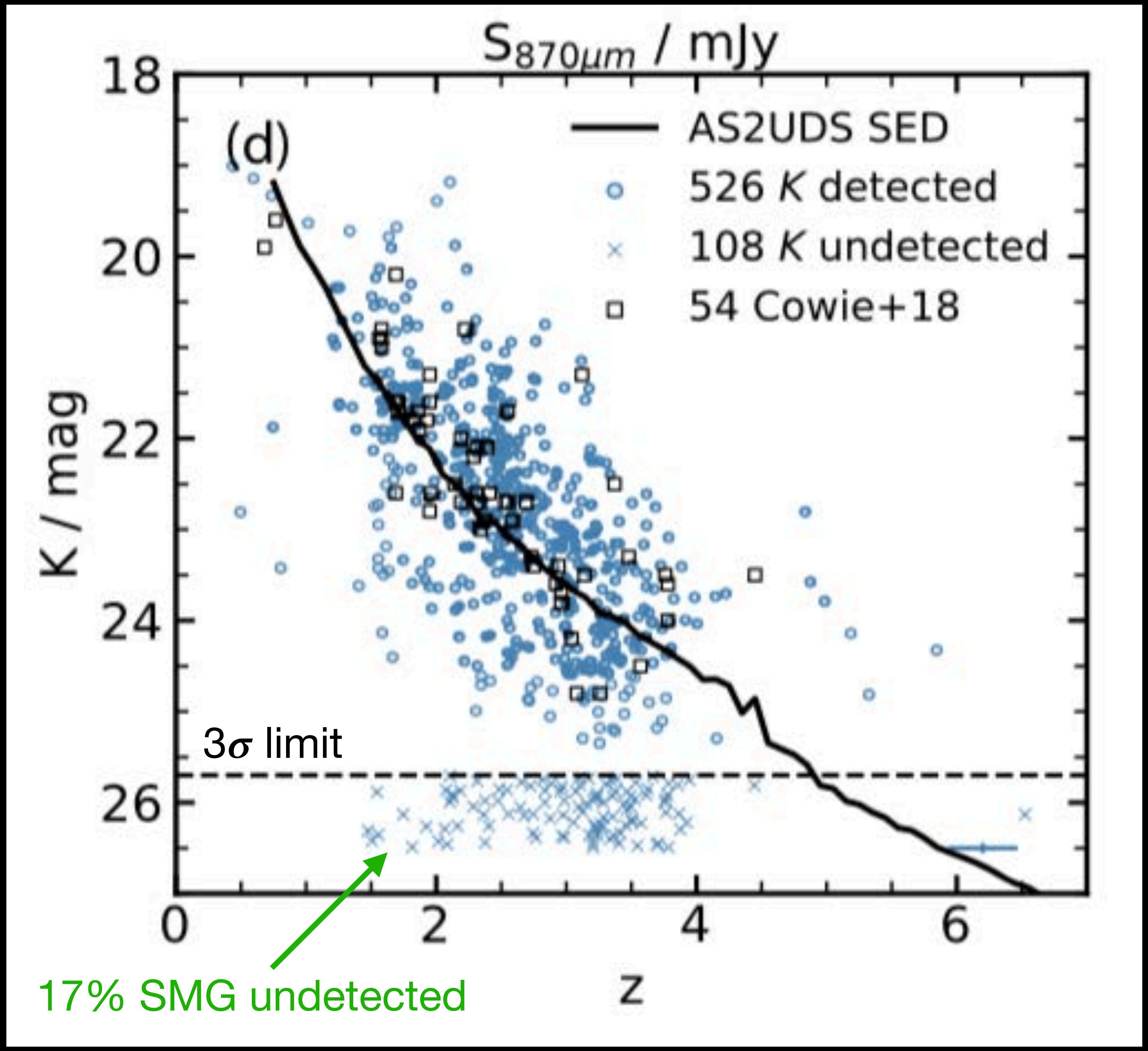
Madau & Dickinson 2014



Casey et al. 2018

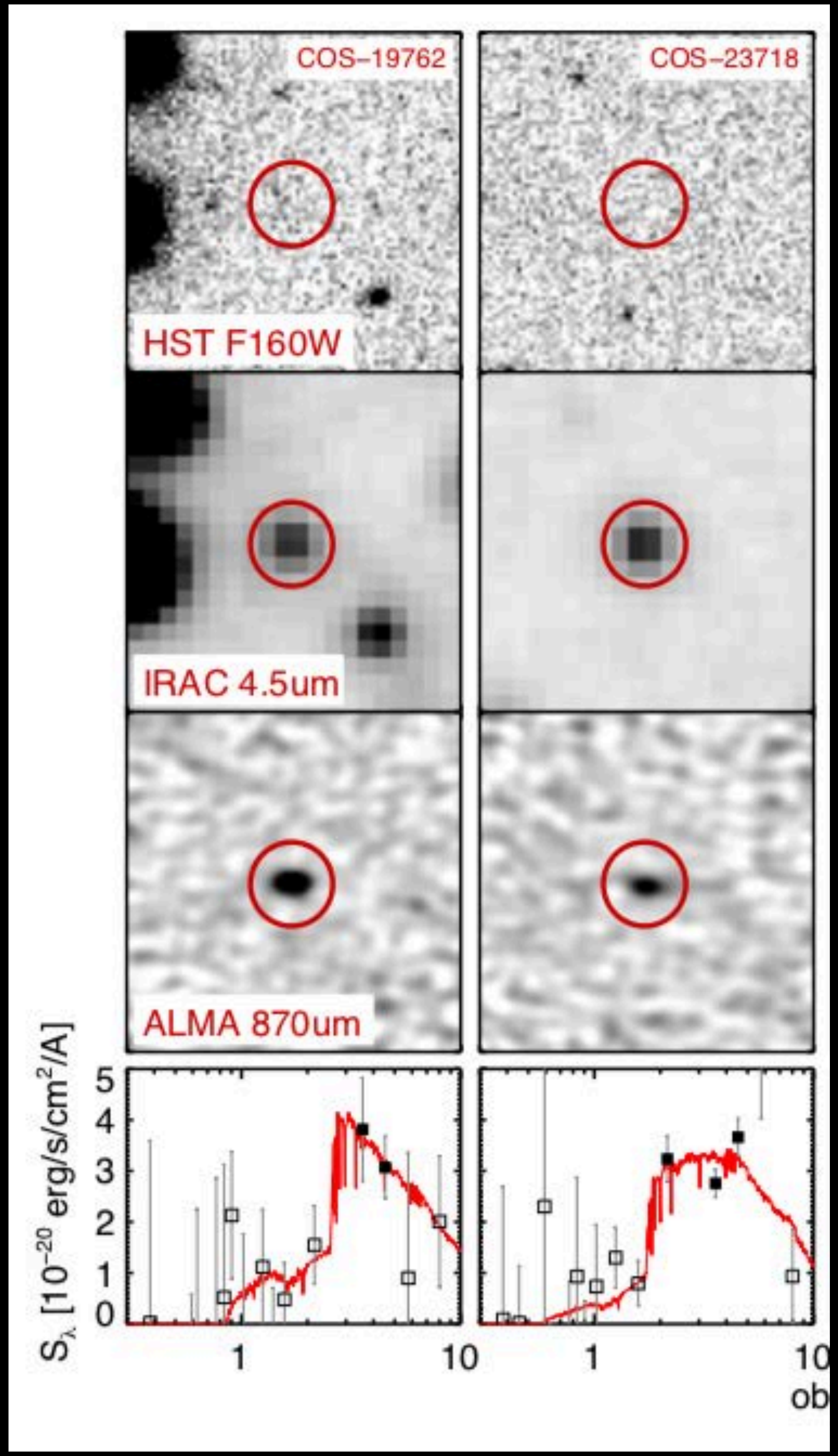
Dust embedded star-forming galaxies at high redshift

z~3



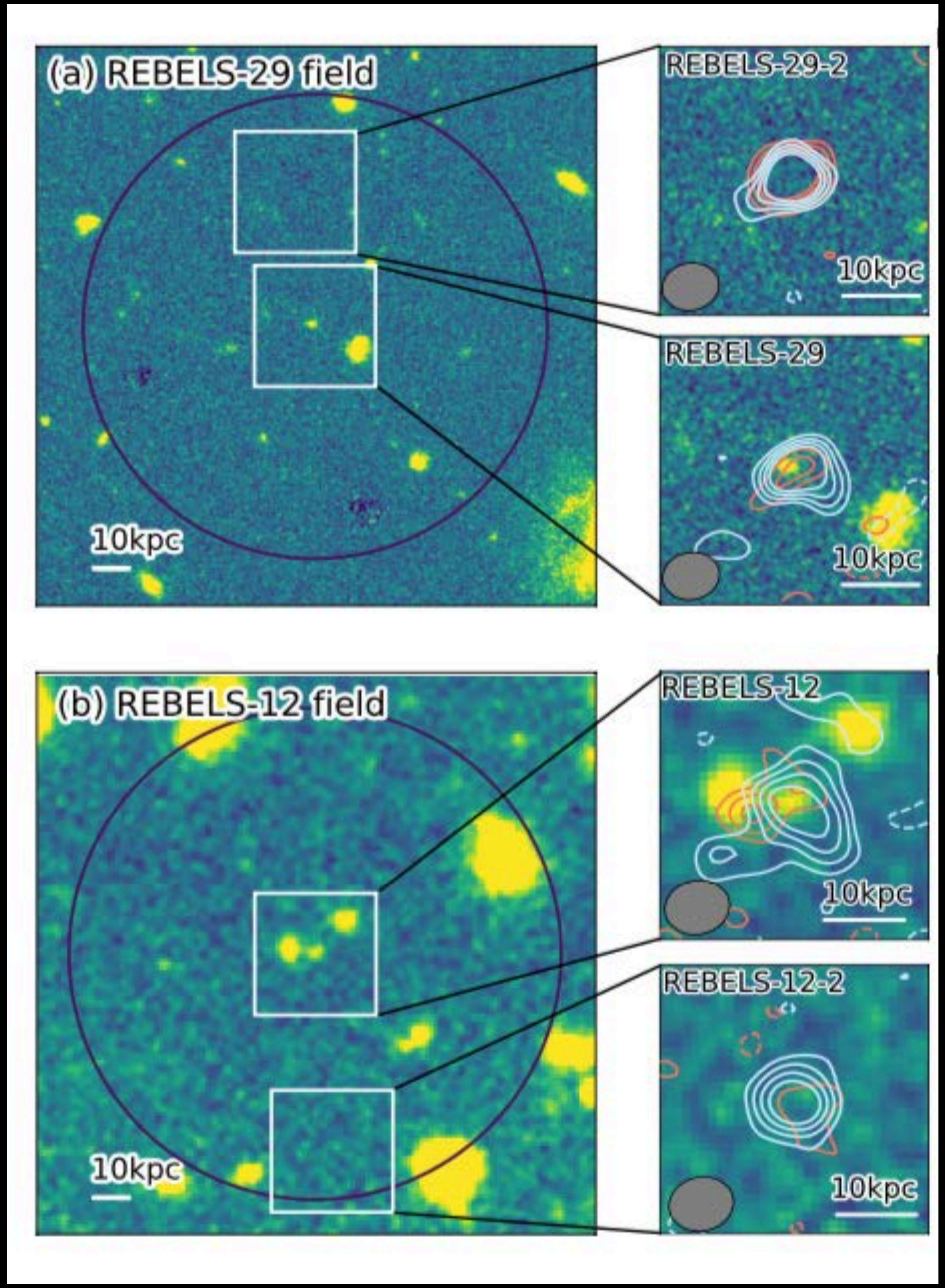
Dudzeviciute et al. 2020

z~4



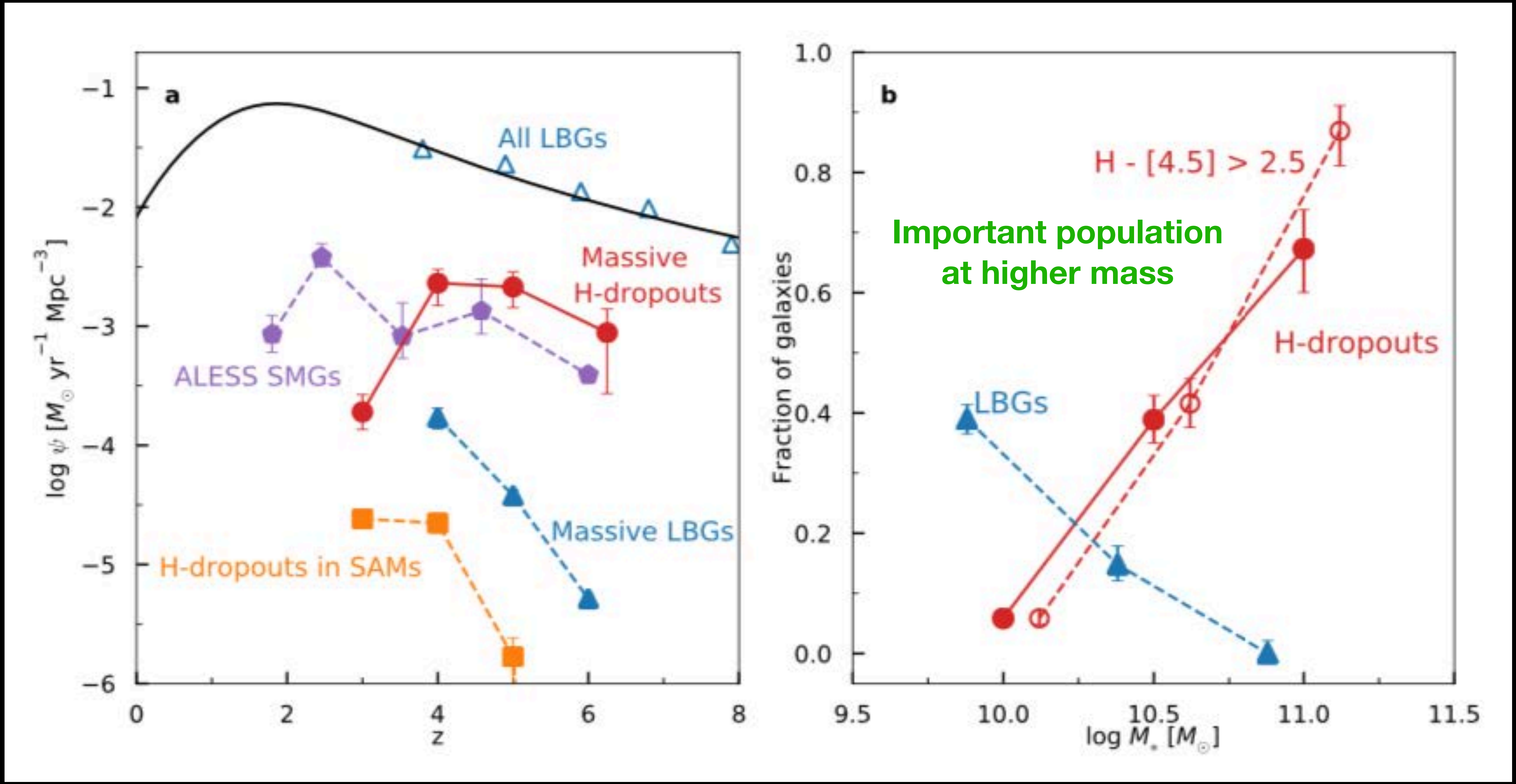
Wang, T. et al. 2019

z~7



Fudamoto et al. 2021

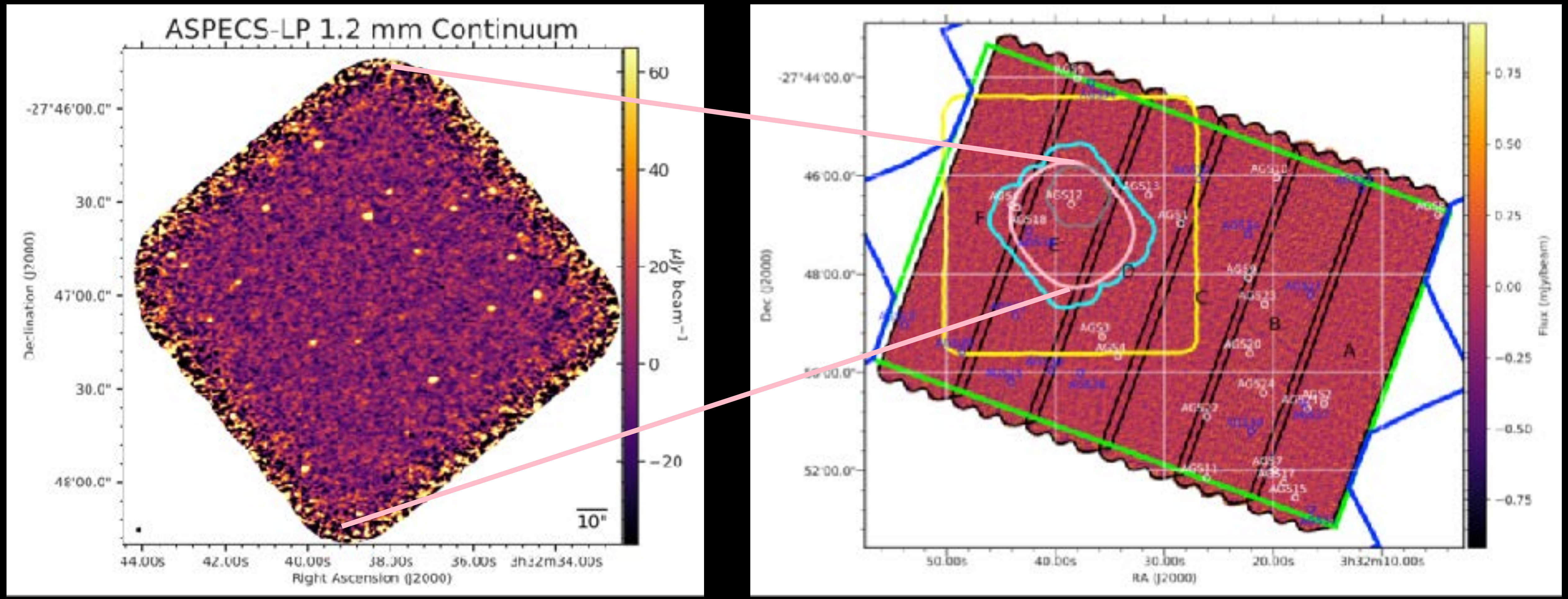
Dust embedded galaxies in the distant universe



Wang, T. et al. 2019

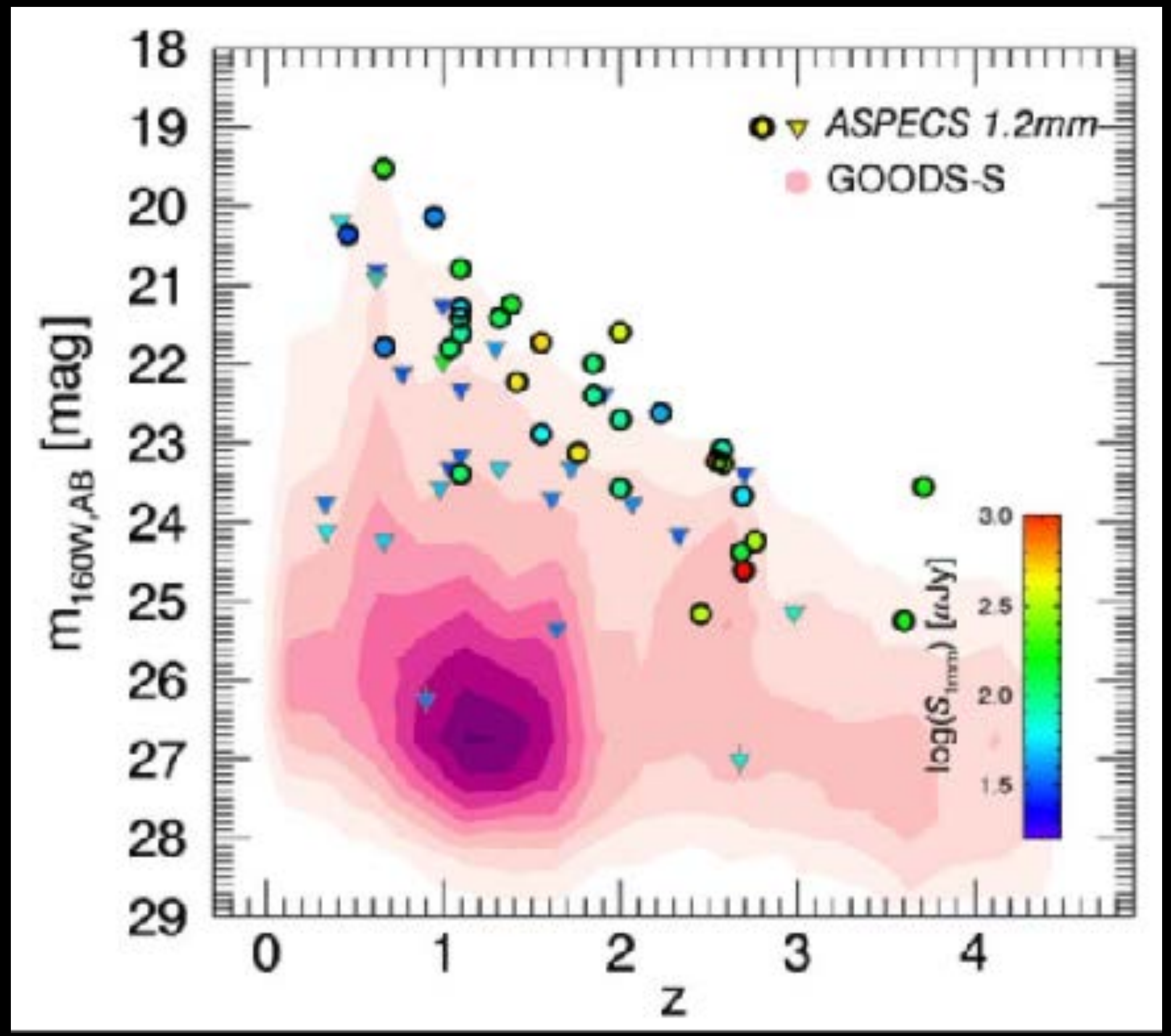
ALMA dust continuum surveys

González-López et al. 2020

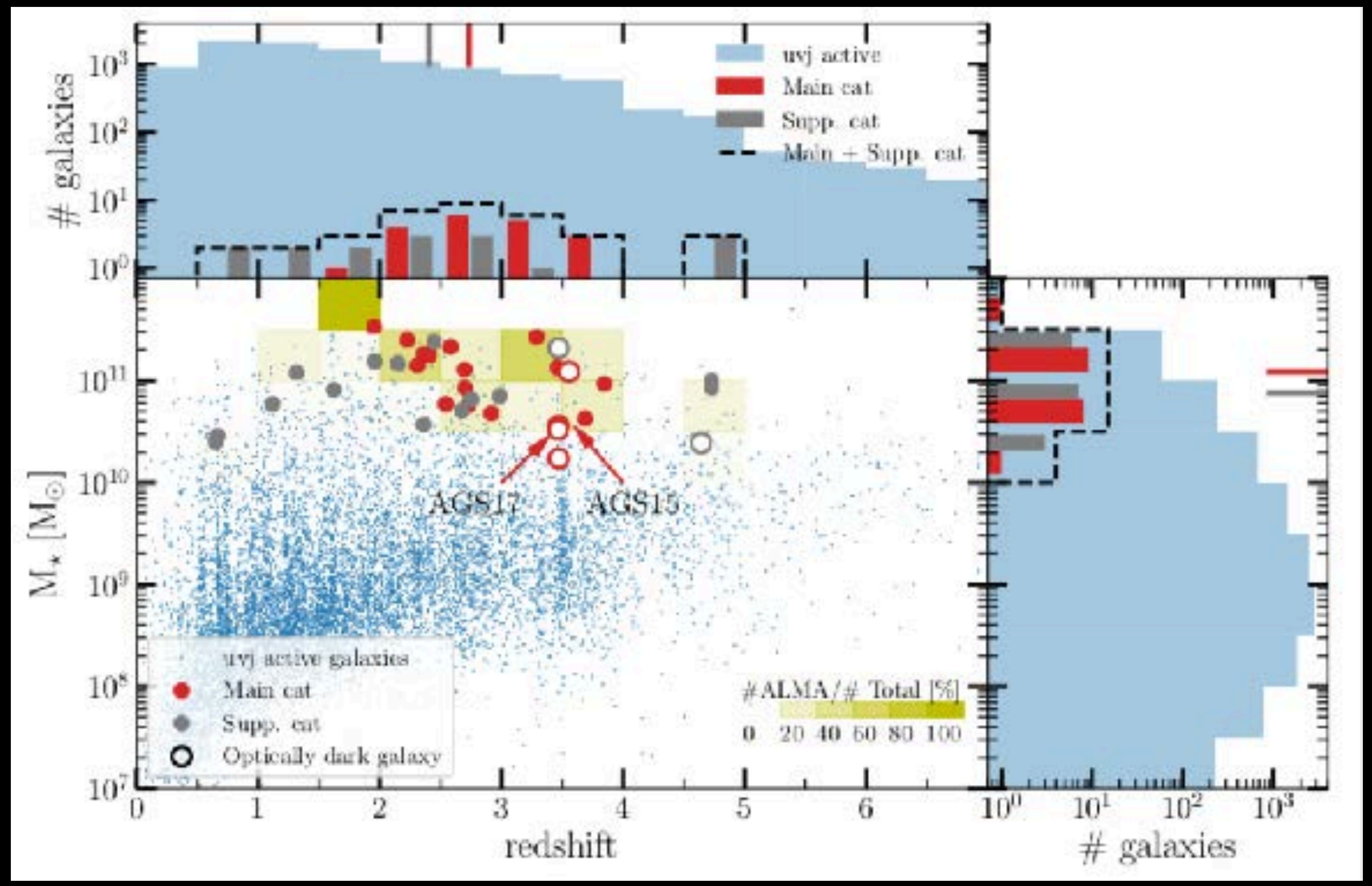


See also:
Dunlop et al. 2016
Aravena et al. 2016
Hatsukade et al. 2018
Franco et al. 2018
Gómez-Guijarro et al. (submitted)

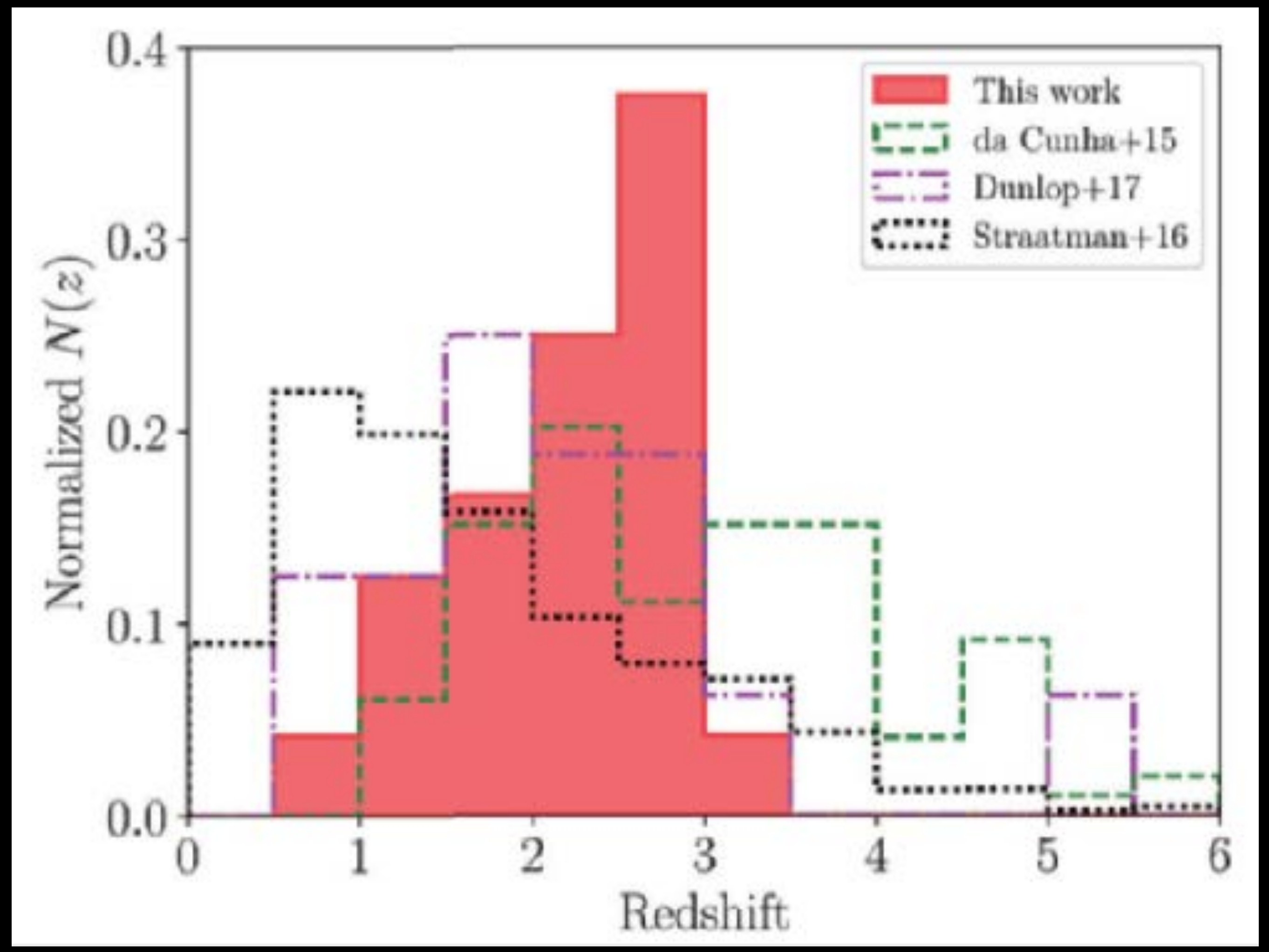
Aravena et al. 2020



Franco et al. 2020

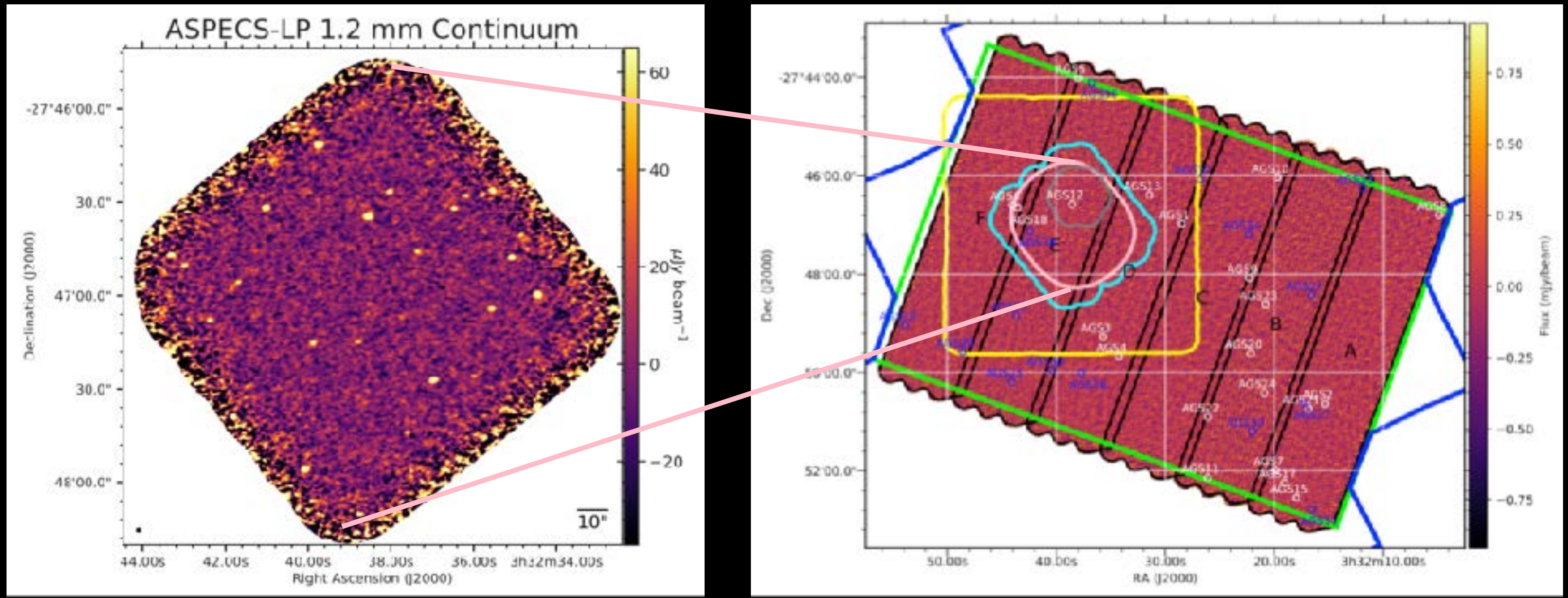


Yamaguchi et al. 2020



ALMA dust continuum surveys

González-López et al. 2020



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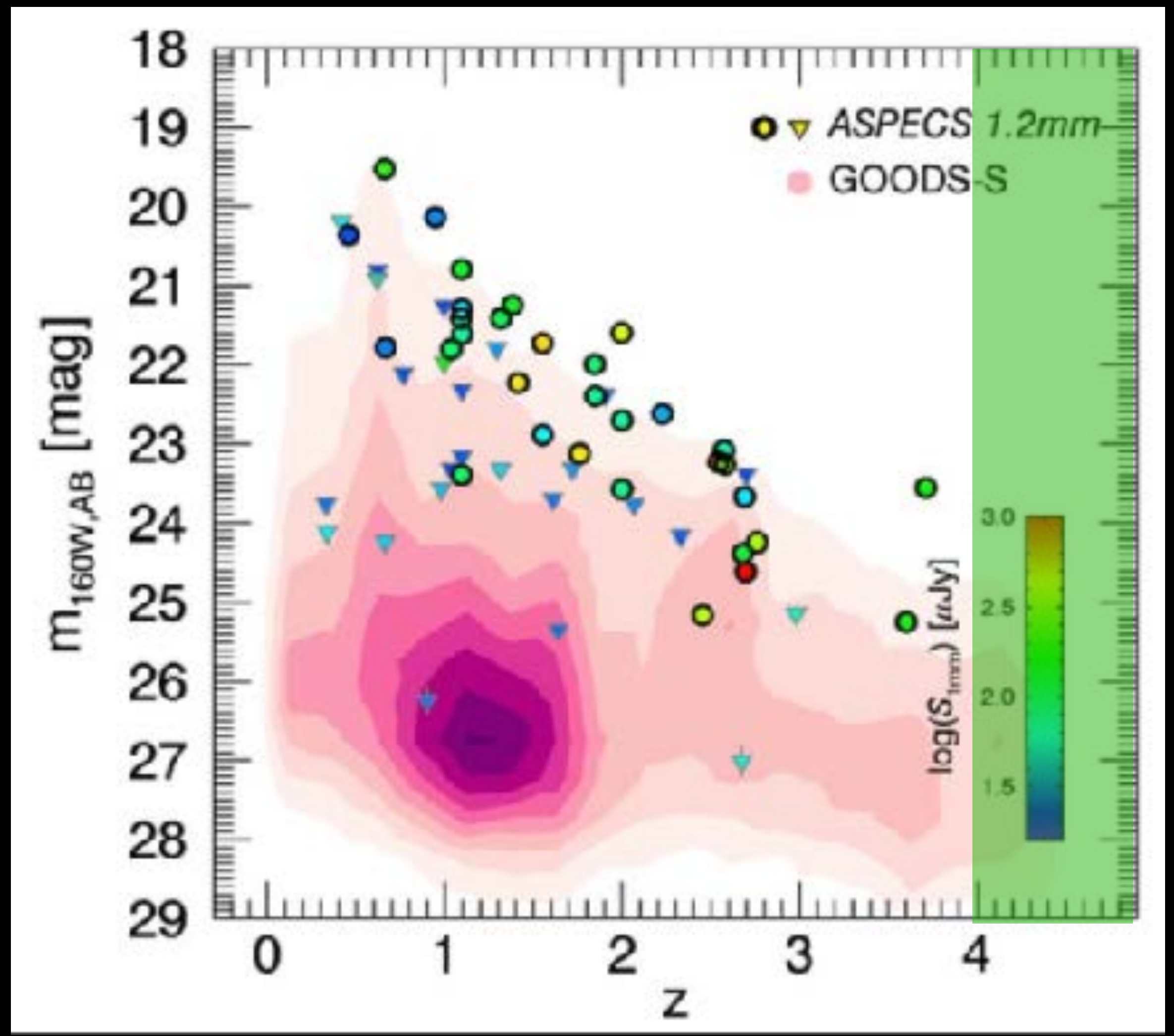
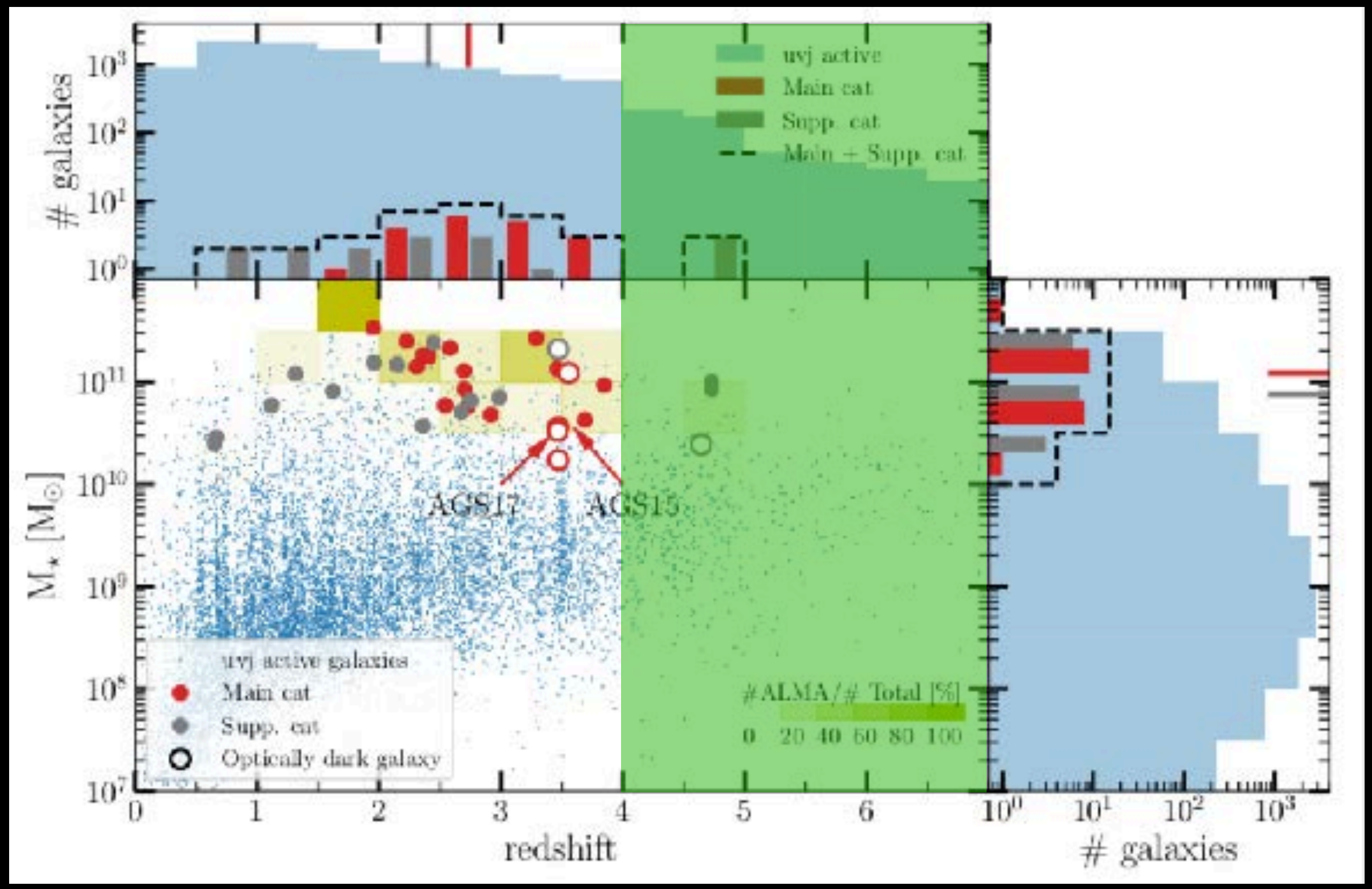
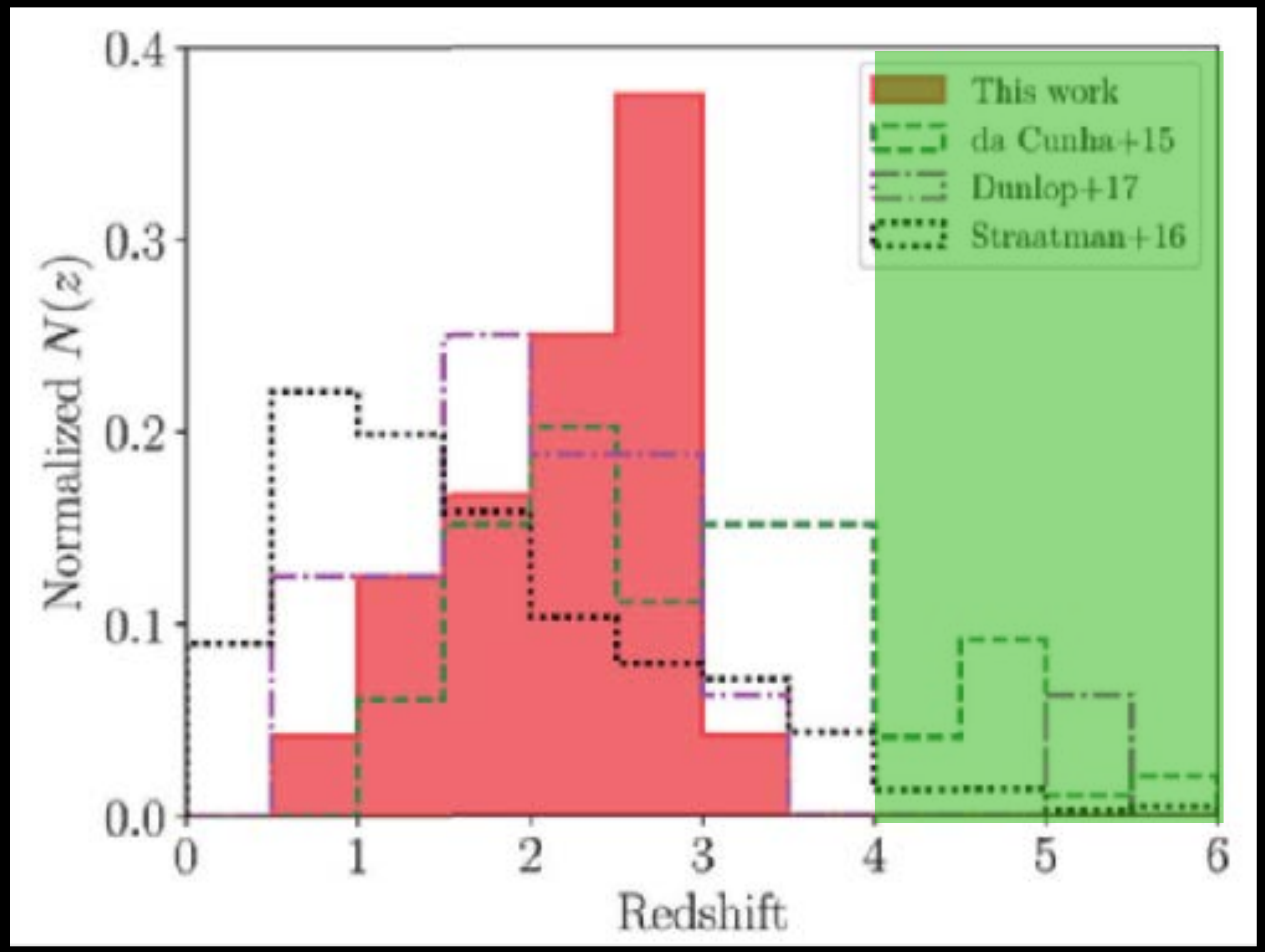


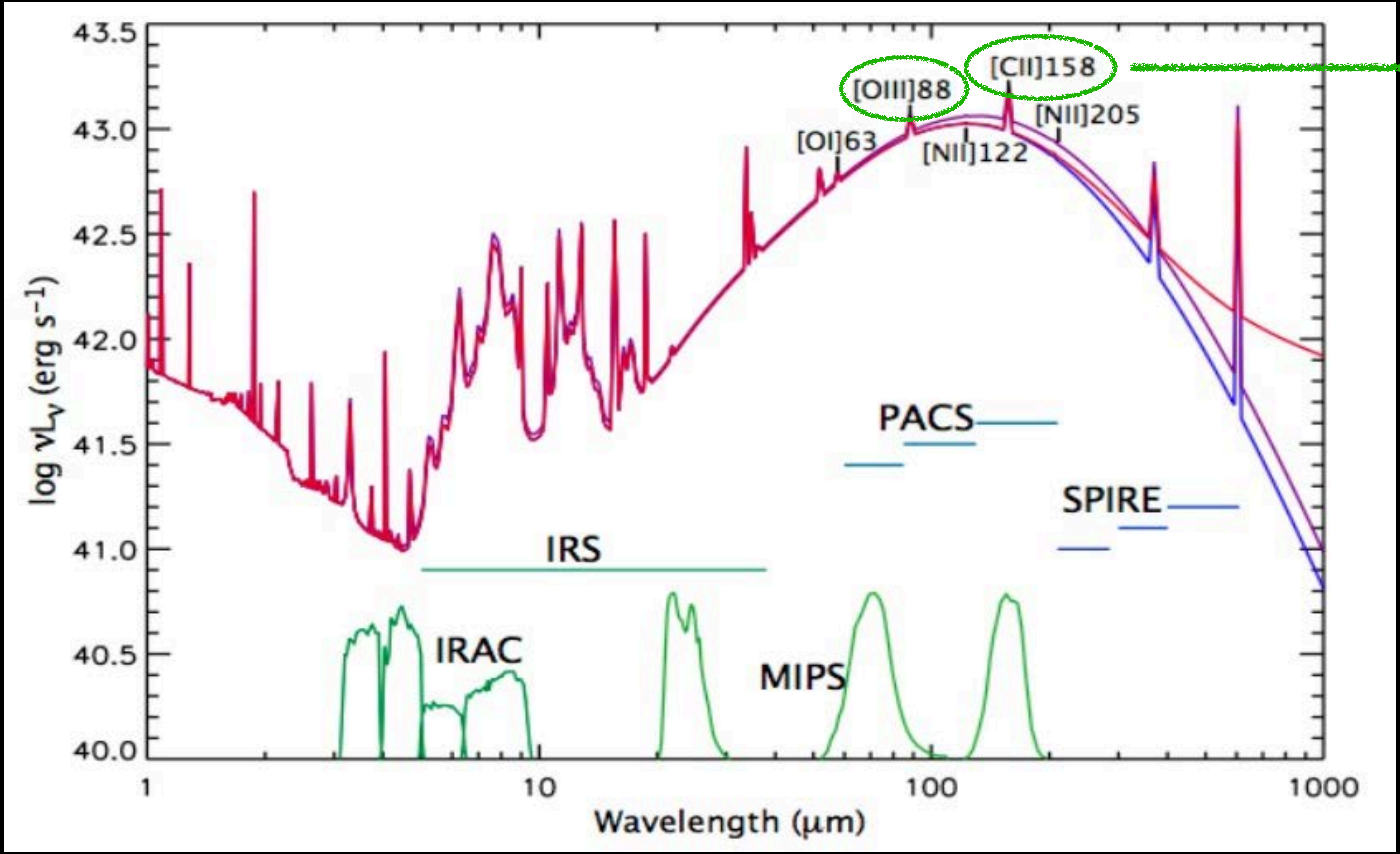
Franco et al. 2020



Yamaguchi et al. 2020



[CII] and [OIII], instead of dust continuum

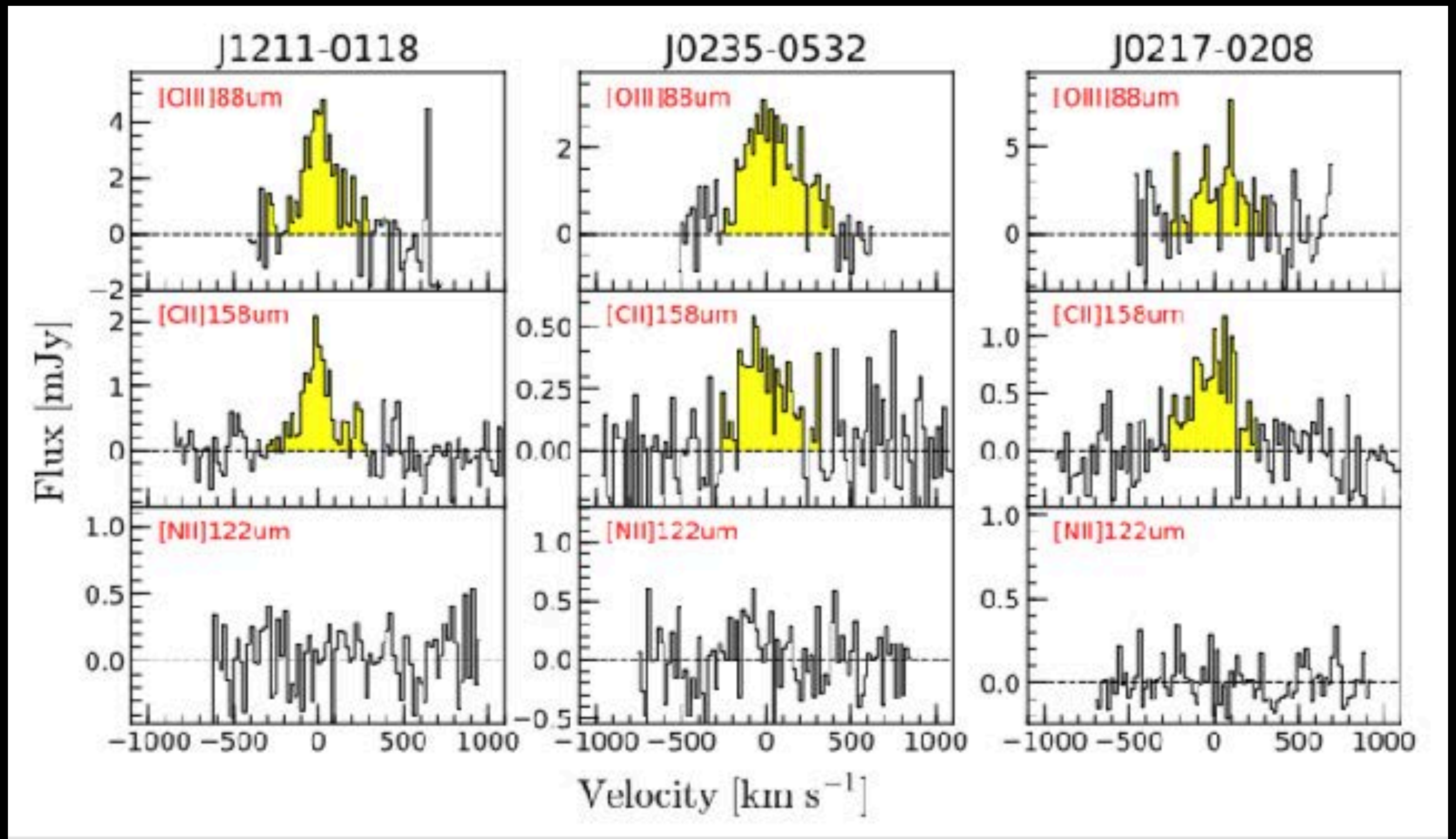


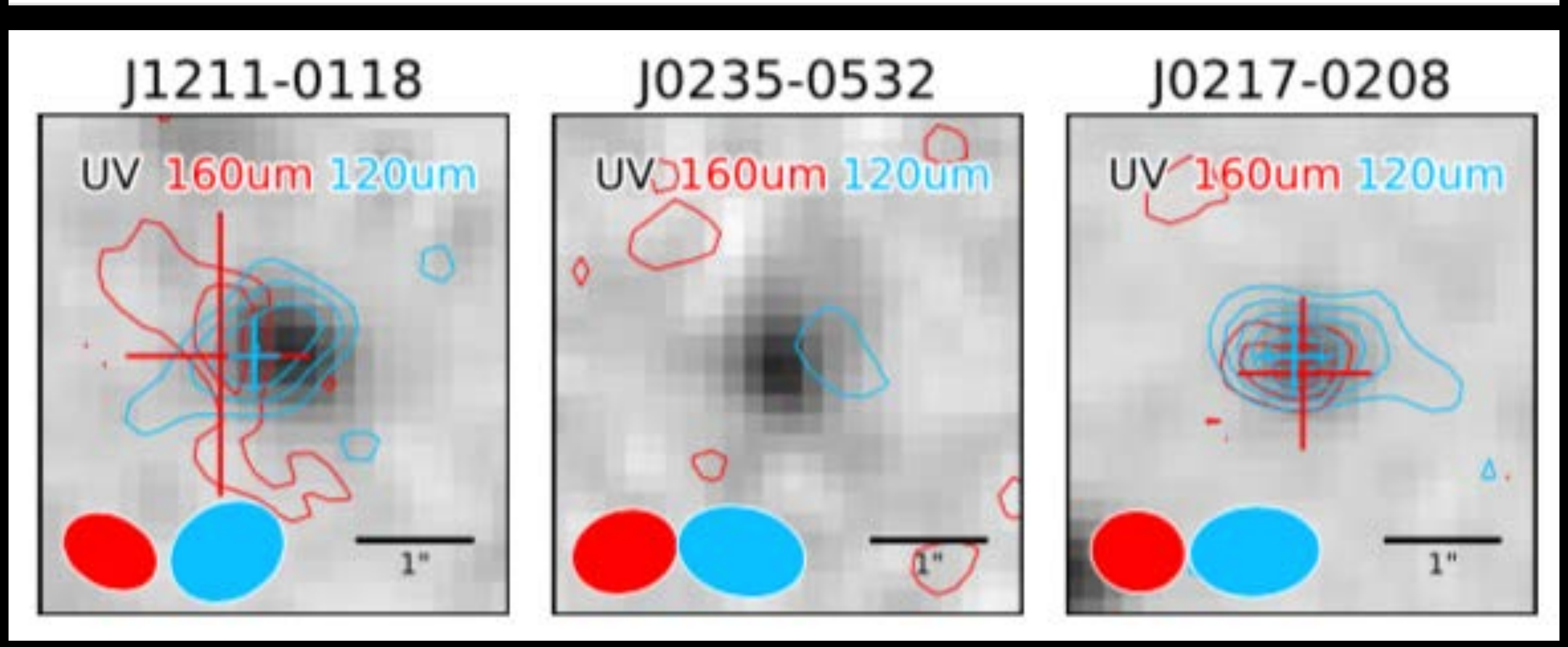
Redshift to ALMA bands

KINGFISH survey

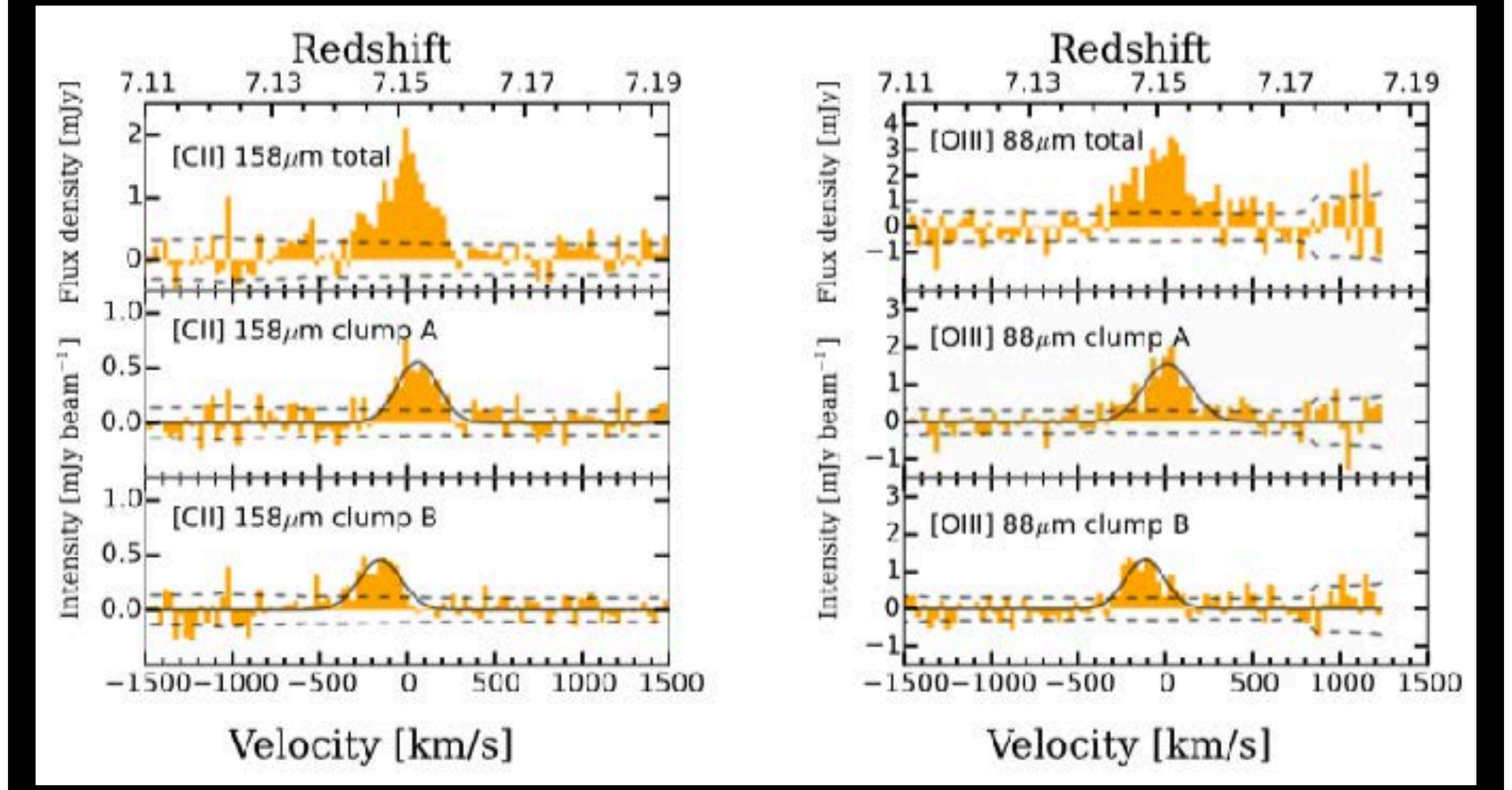
ALMA to observe beyond z~4

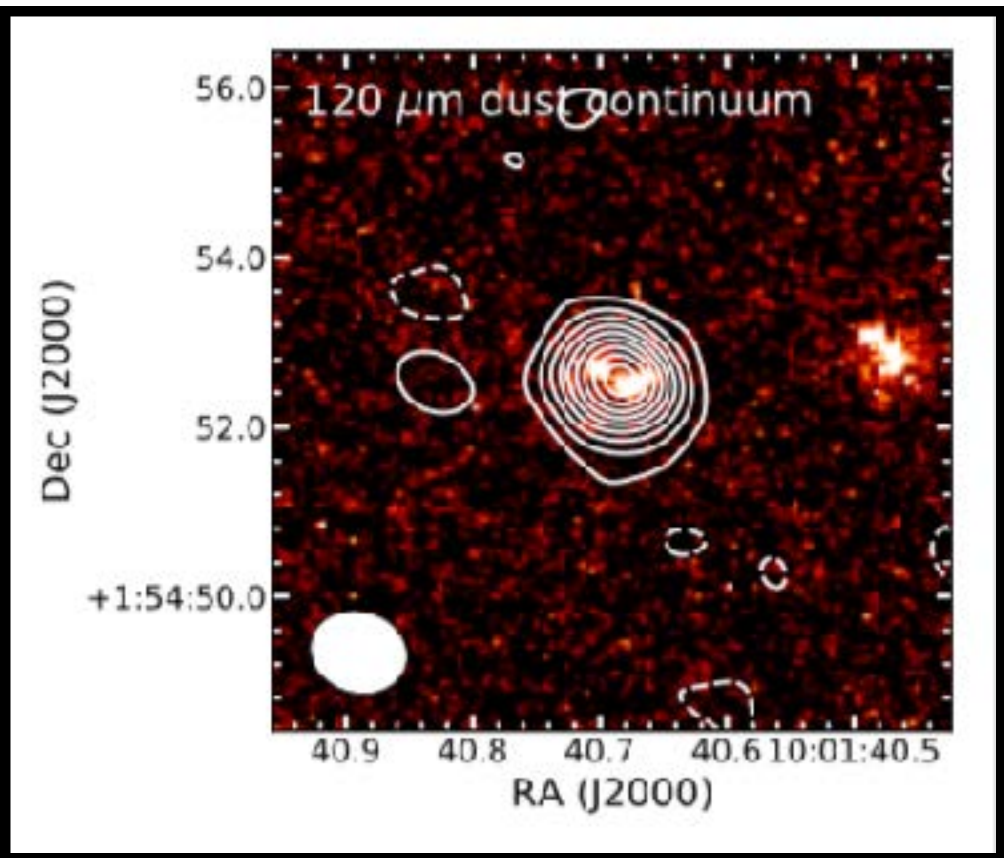
Targeted observations: [CII], [OIII], dust continuum



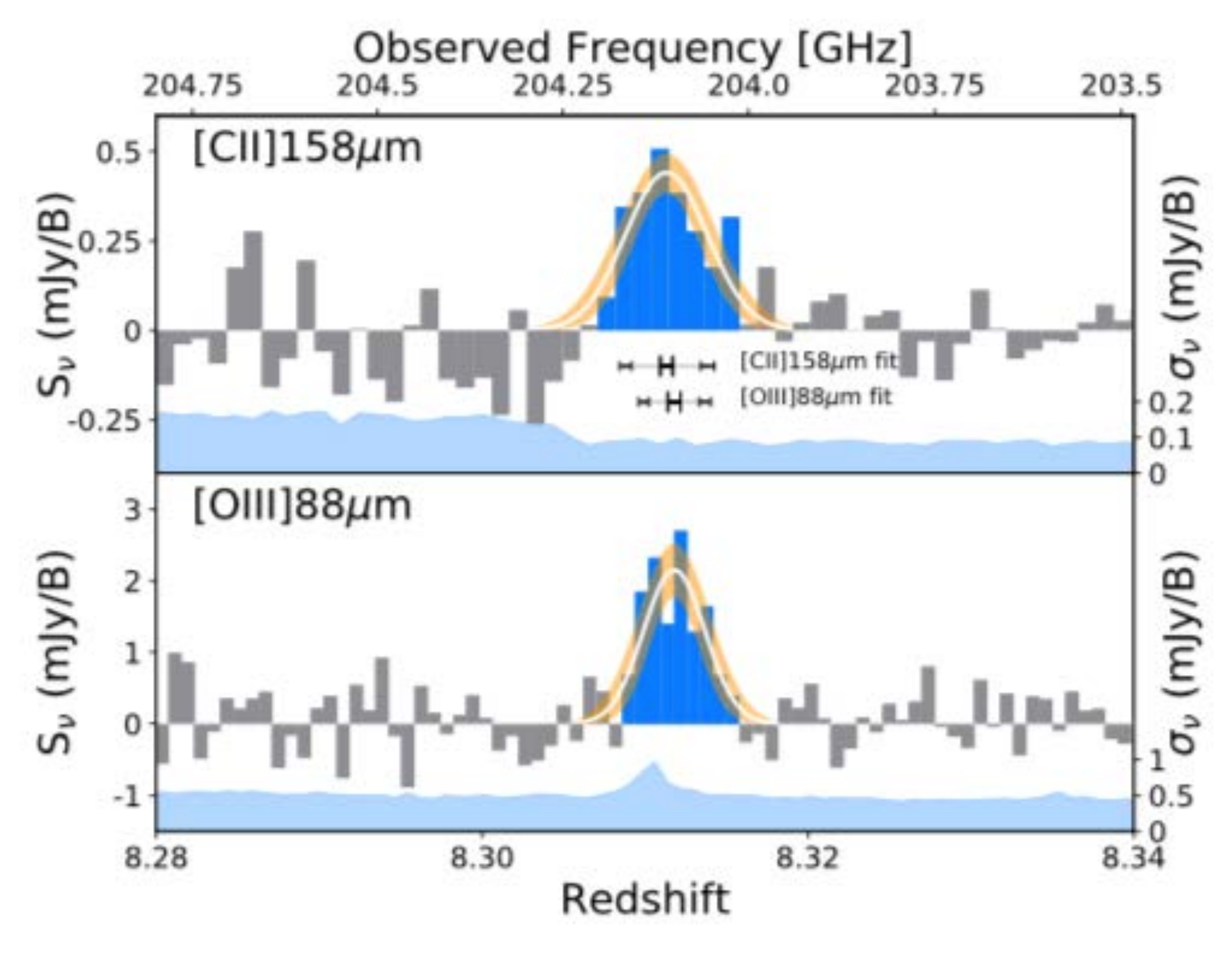


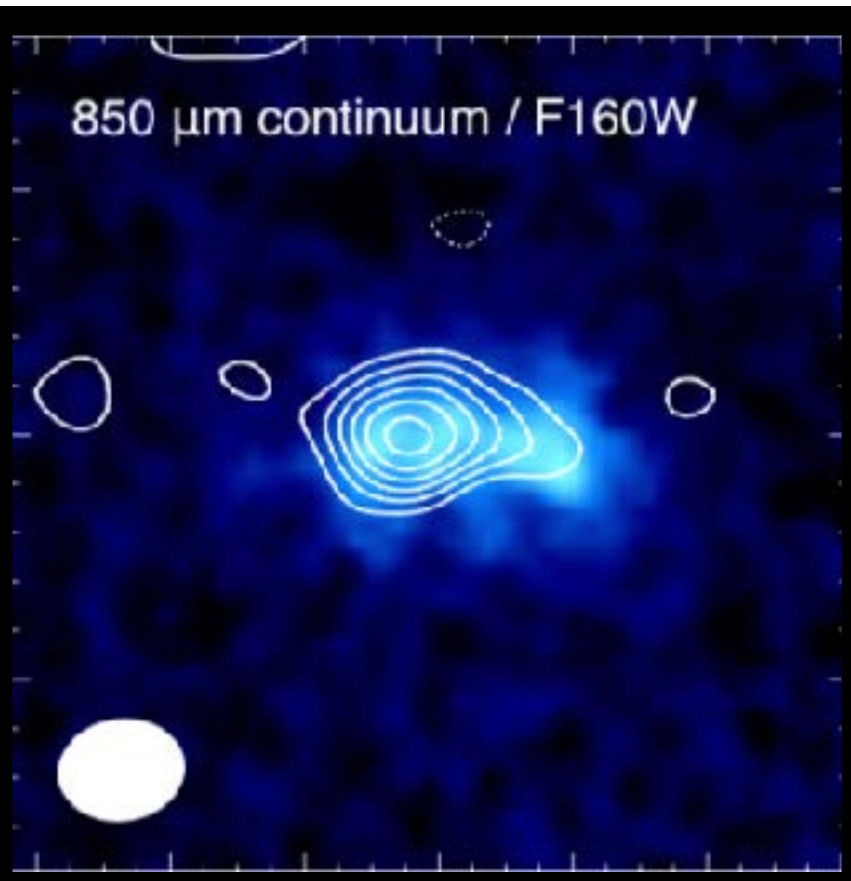
z~6 (Harikane et al. 2020)





z=7.15
(Hashimoto et al. 2019, Sugahara et al. 2021, Bowler et al. 2018)



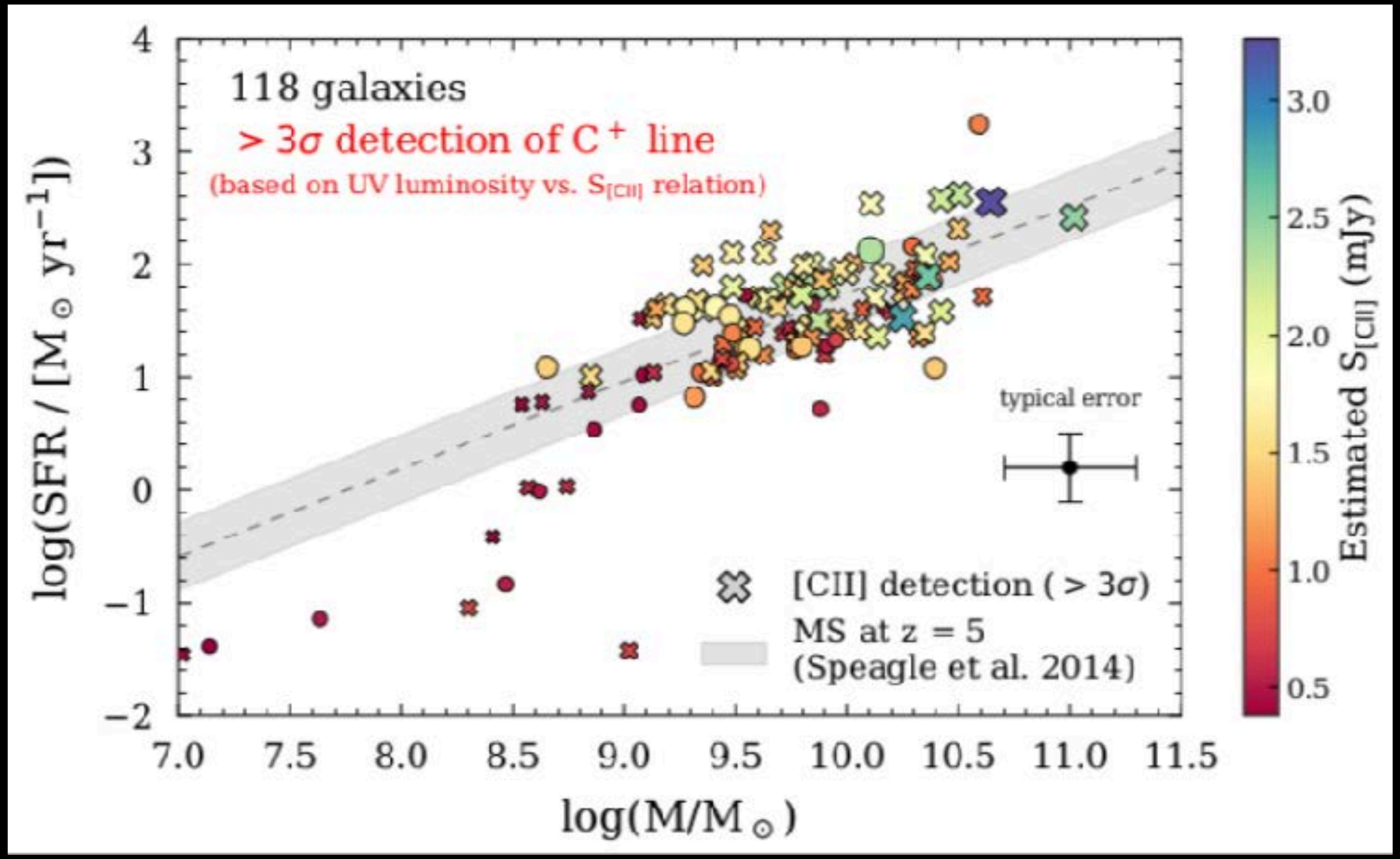


z=8.31 (Tamura et al. 2019, Bakx et al. 2020)

ALMA to observe beyond z~4

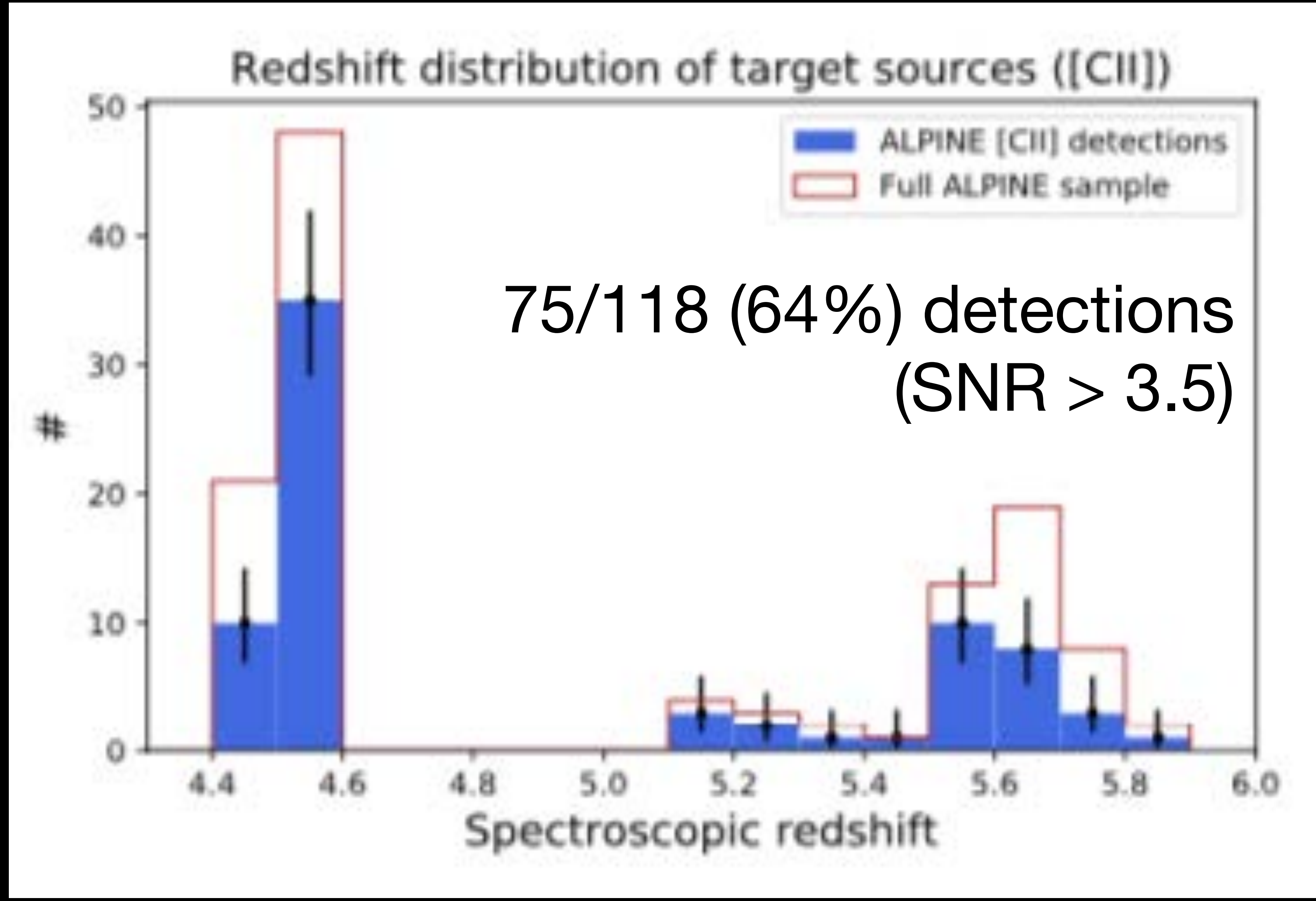
ALPINE: ALMA Large Program to INvestigate CII at Early Times

4 < z < 6, 118 galaxies with UV spec-z



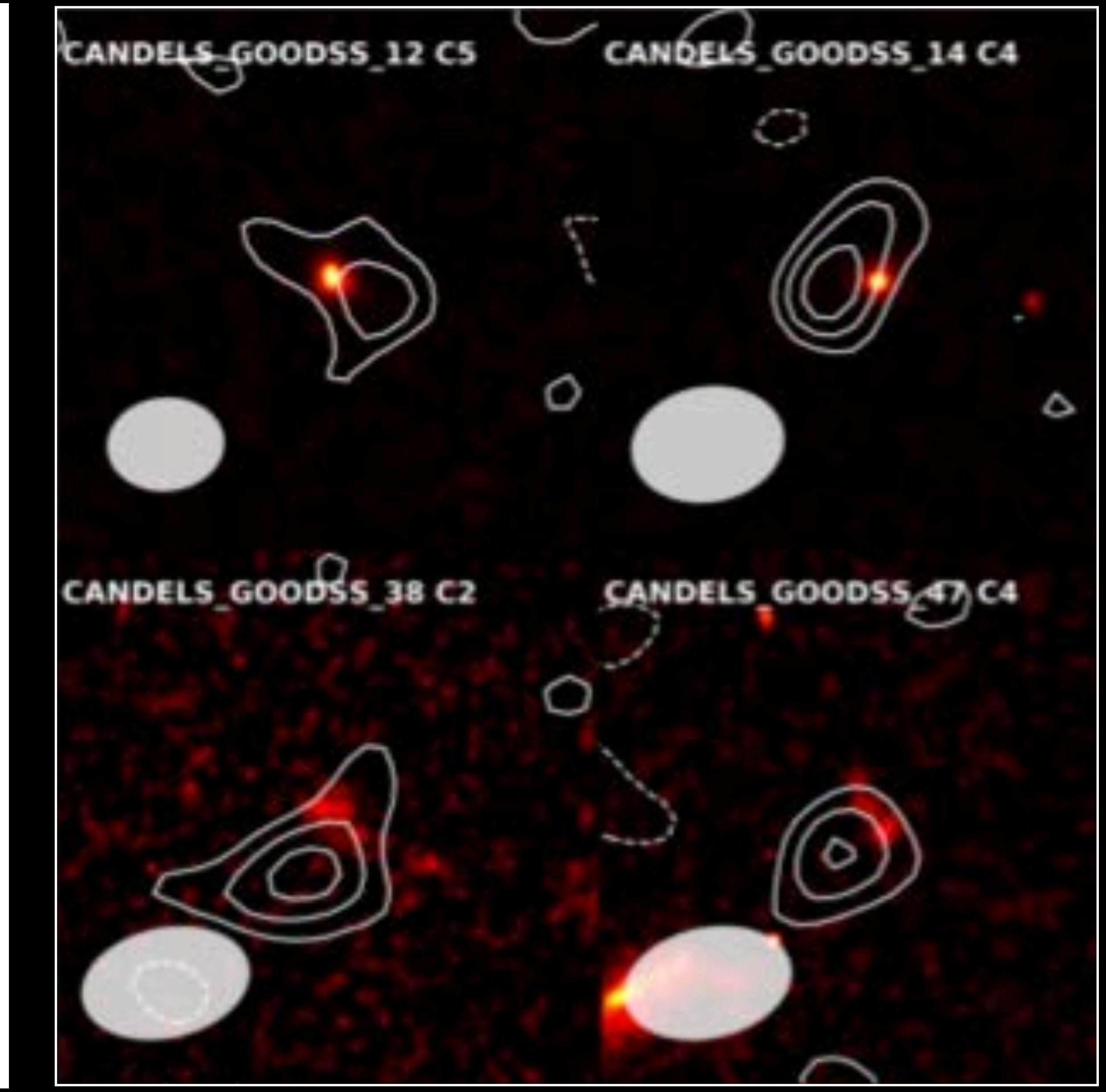
Le Fèvre et al. 2020

ALPINE galaxies with [CII]



Bethermin et al. 2020

[CII] contours

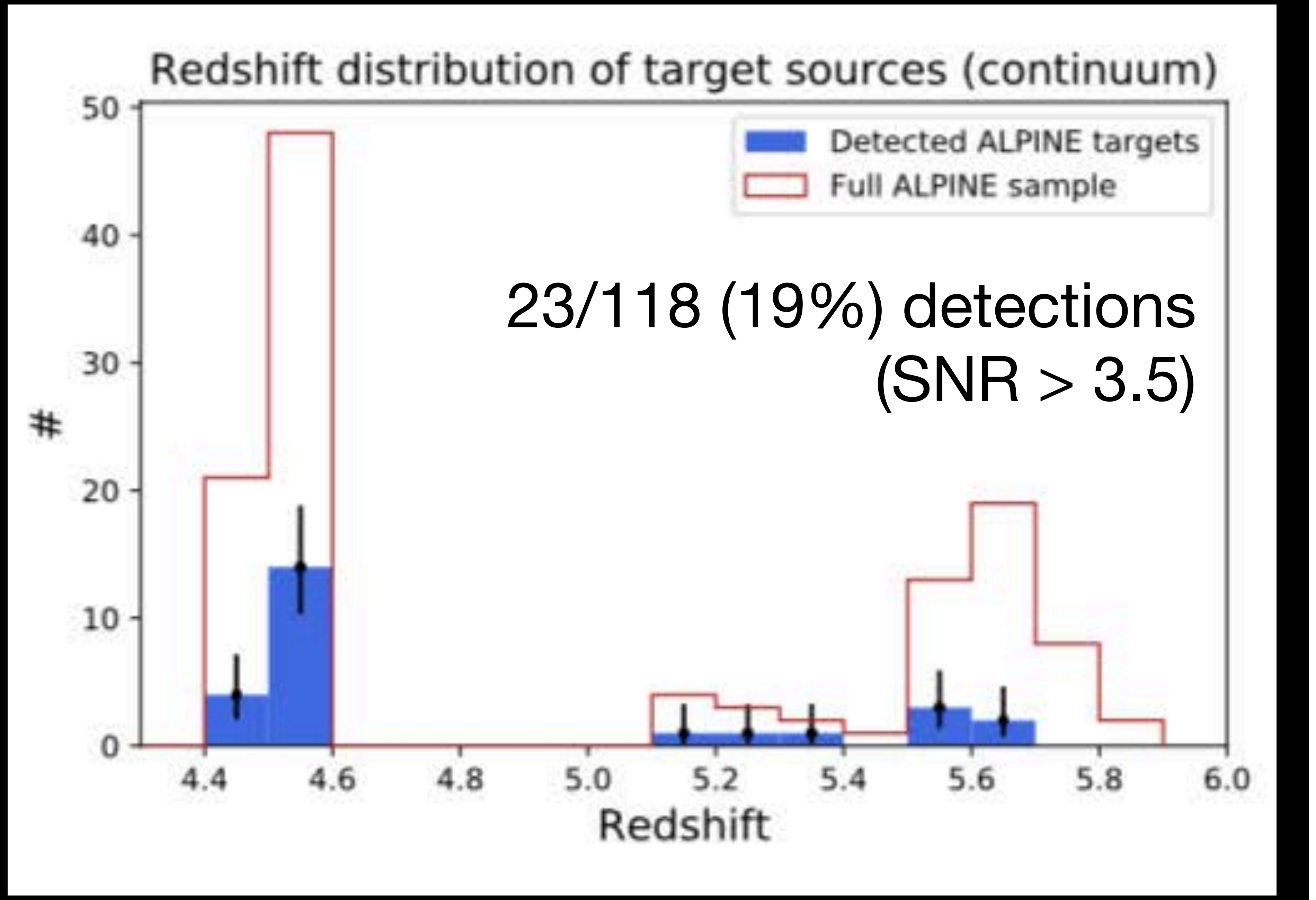


Le Fèvre et al. 2020

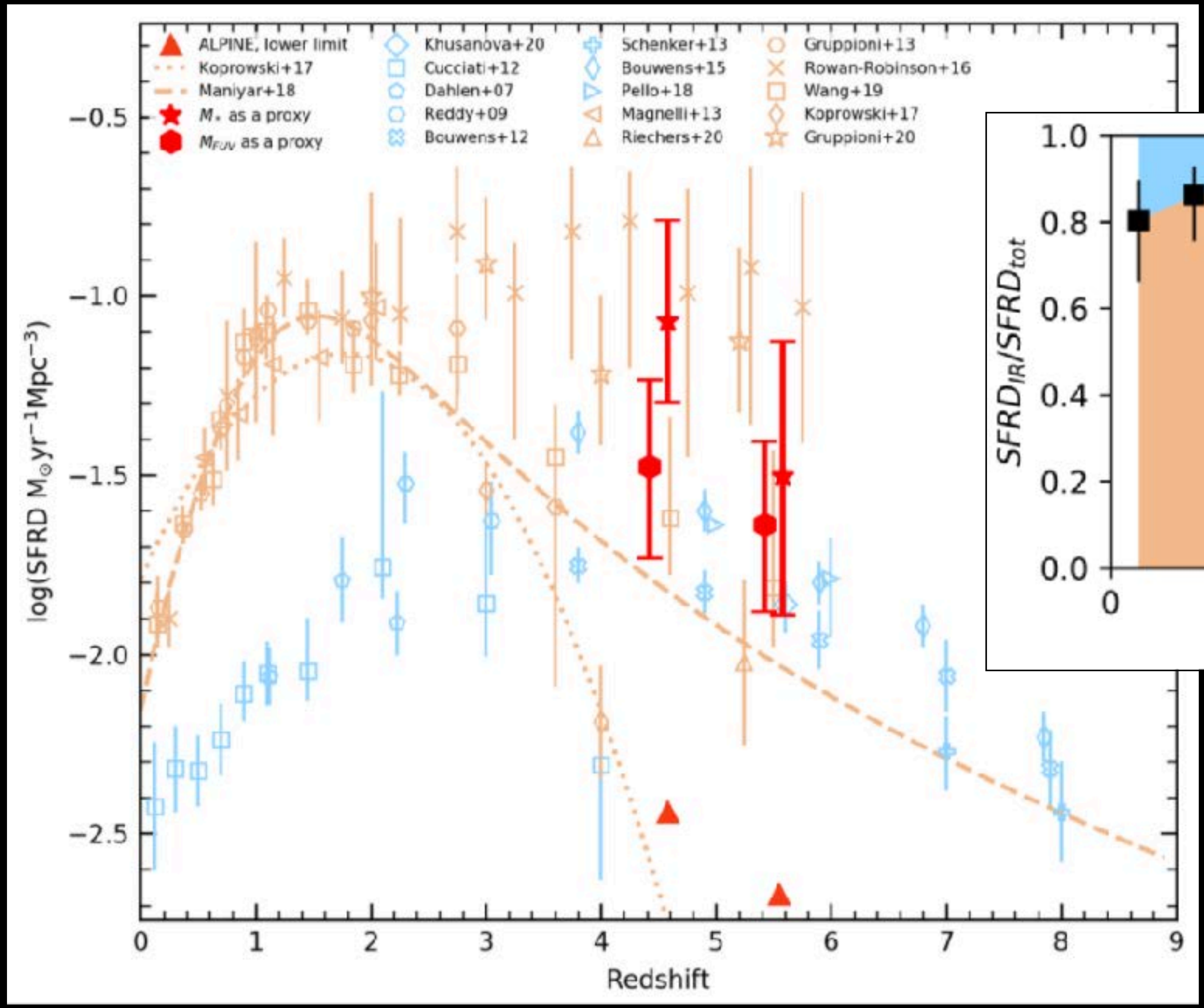
ALMA to observe beyond z~4

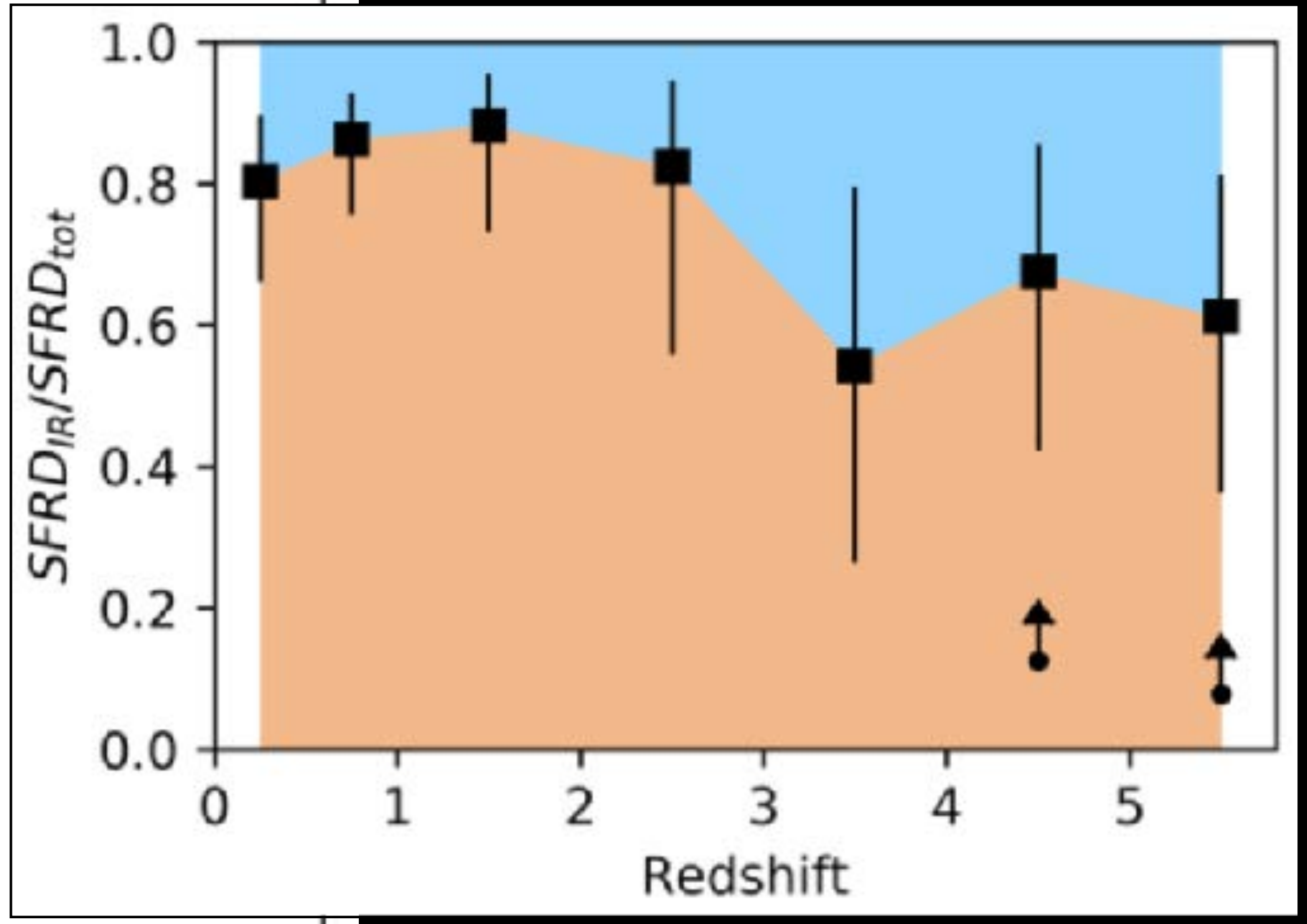
ALPINE: ALMA Large Program to INvestigate CII at Early Times

ALPINE dust detections



Bethermin et al. 2020





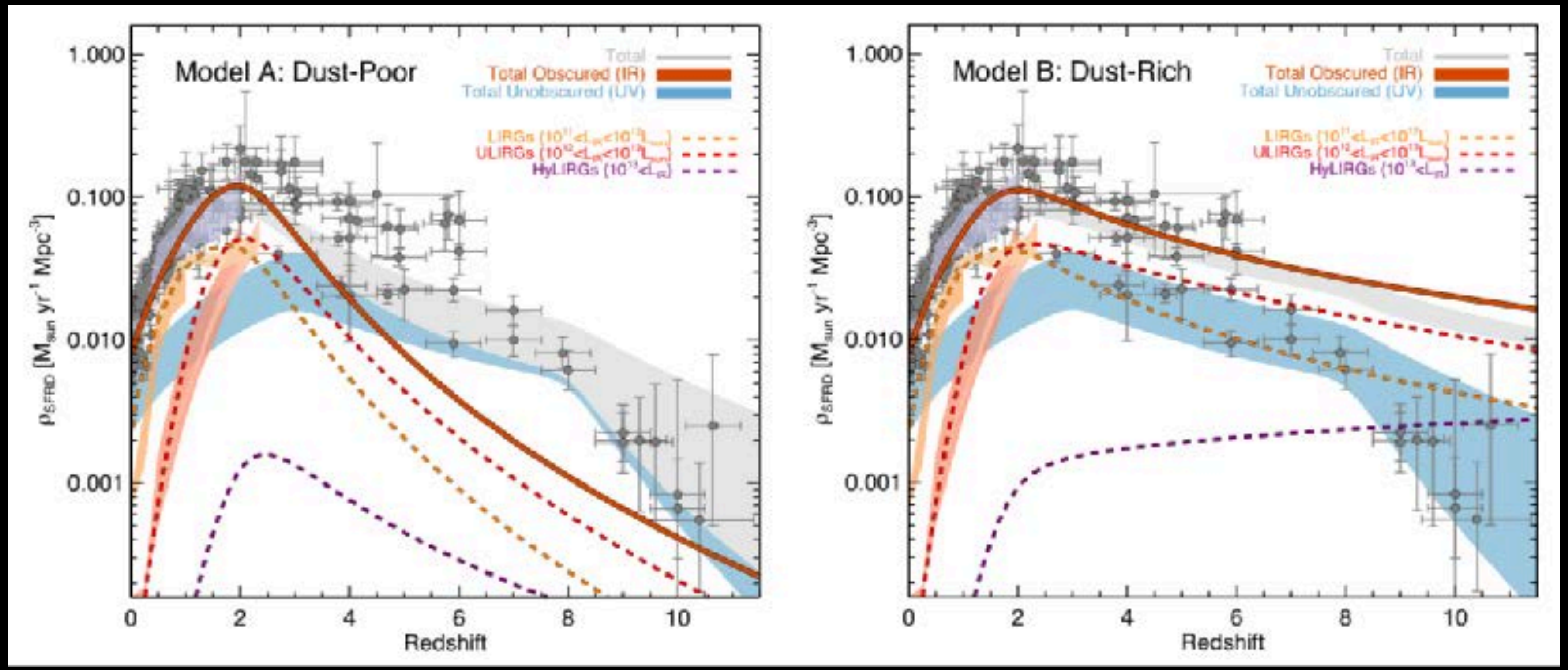
Khusanova et al. 2021

See also Gruppioni et al. 2020, Yan et al. 2020, Loiacono et al. 2021

ALMA to observe beyond z~4

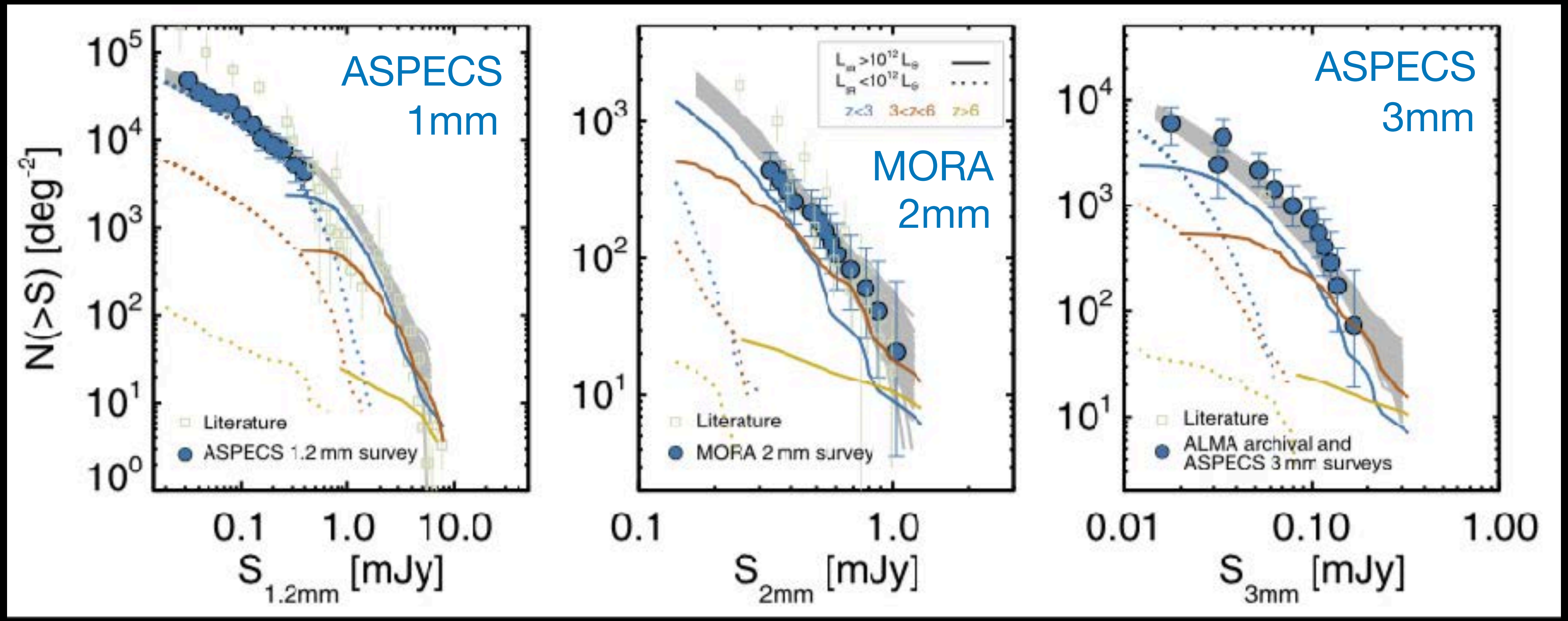
MORA: Mapping Obscuration to Reionization with ALMA

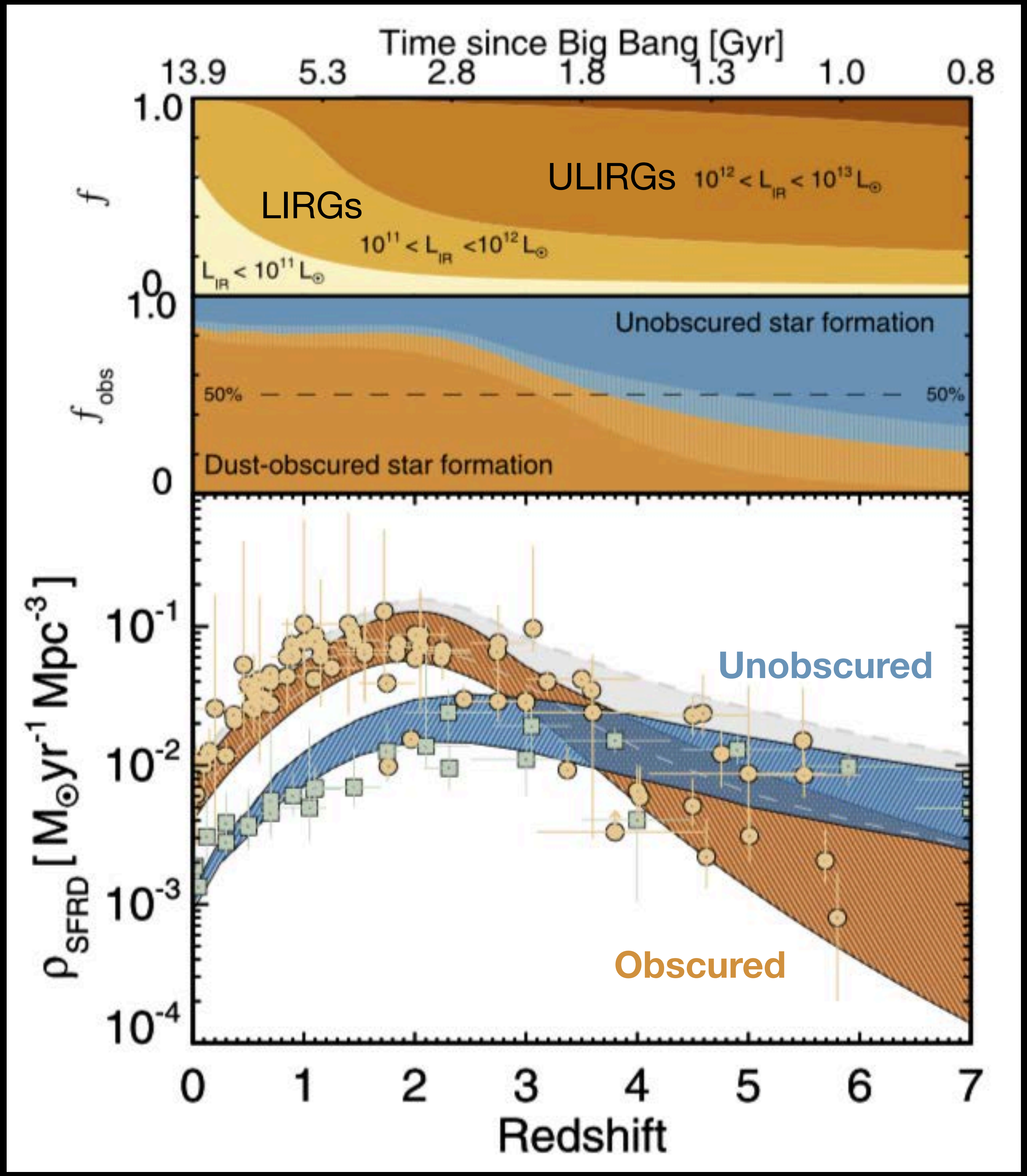
Star formation rate density



Casey et al. 2018

Find a model that agrees with the data

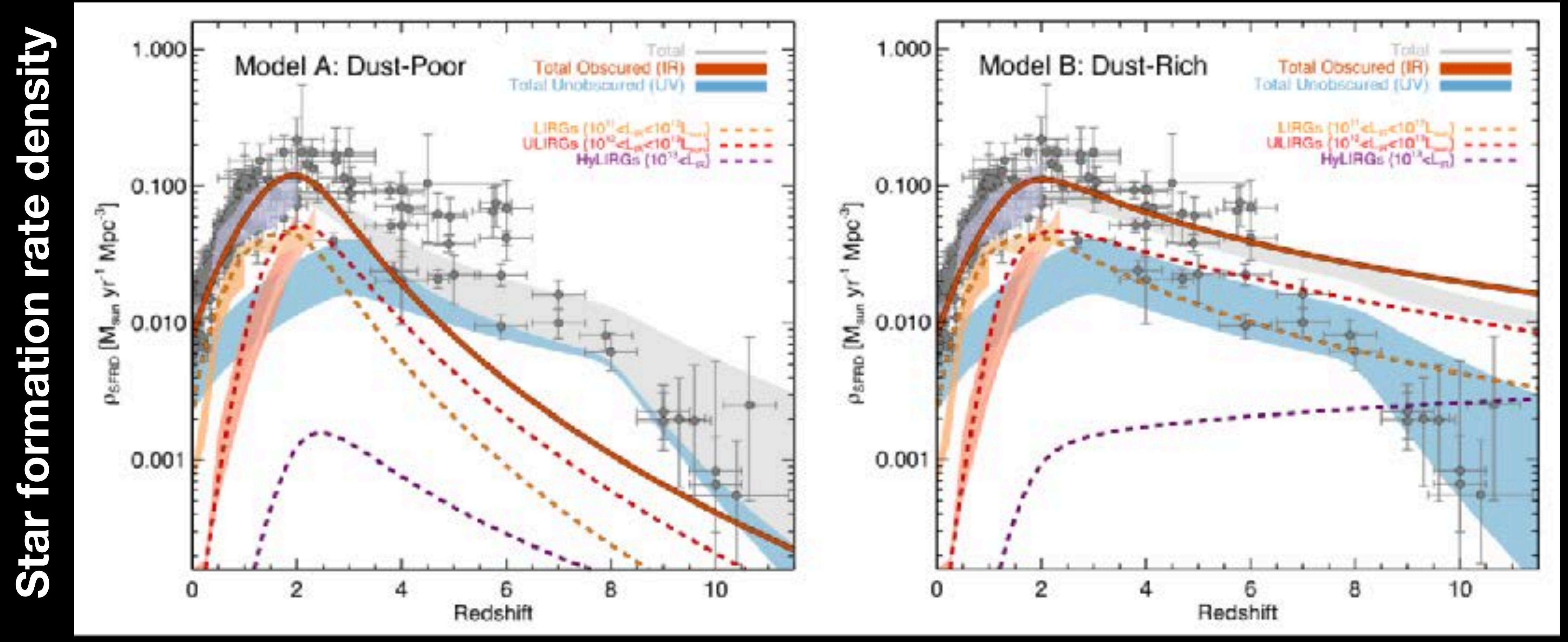




Zavala et al. 2018,2021

ALMA to observe beyond z~4

MORA: Mapping Obscuration to Reionization with ALMA



Casey et al. 2018

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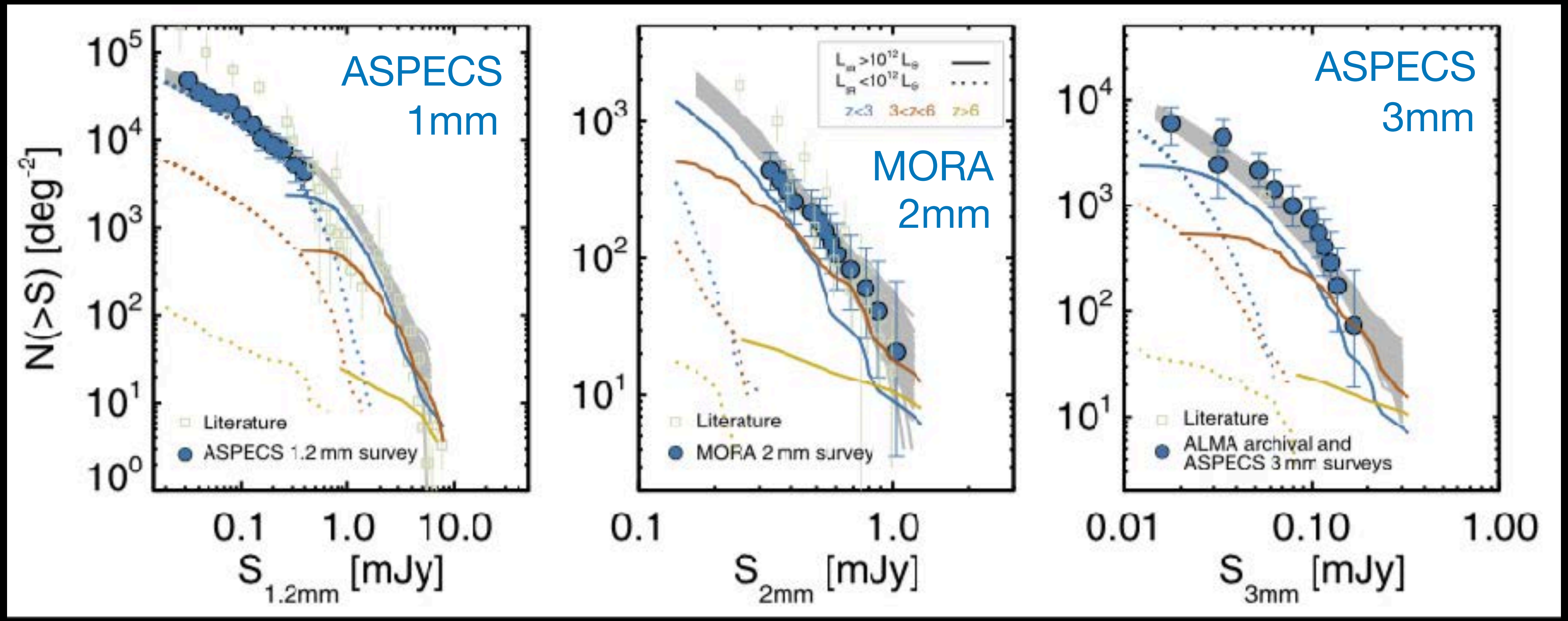
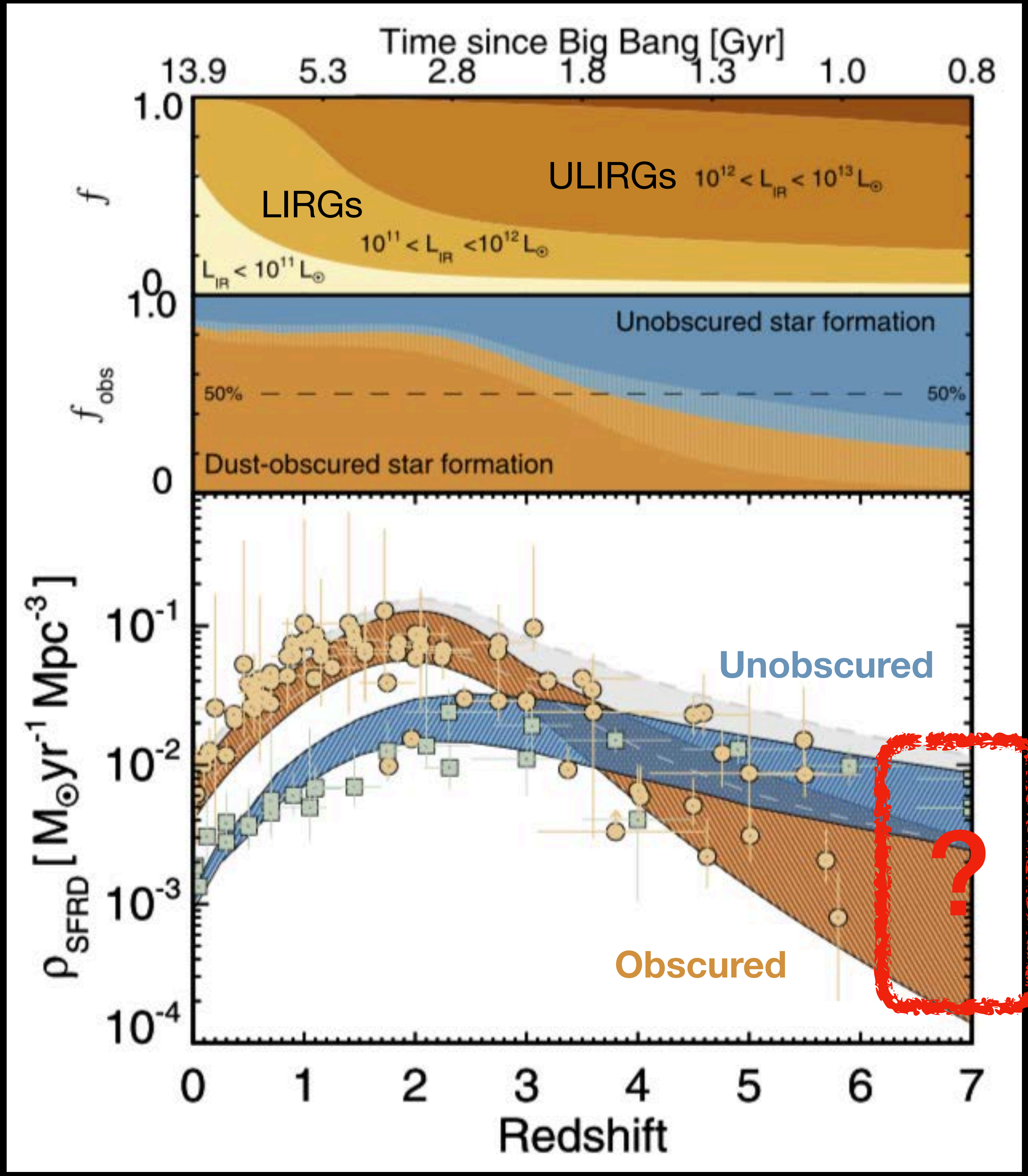
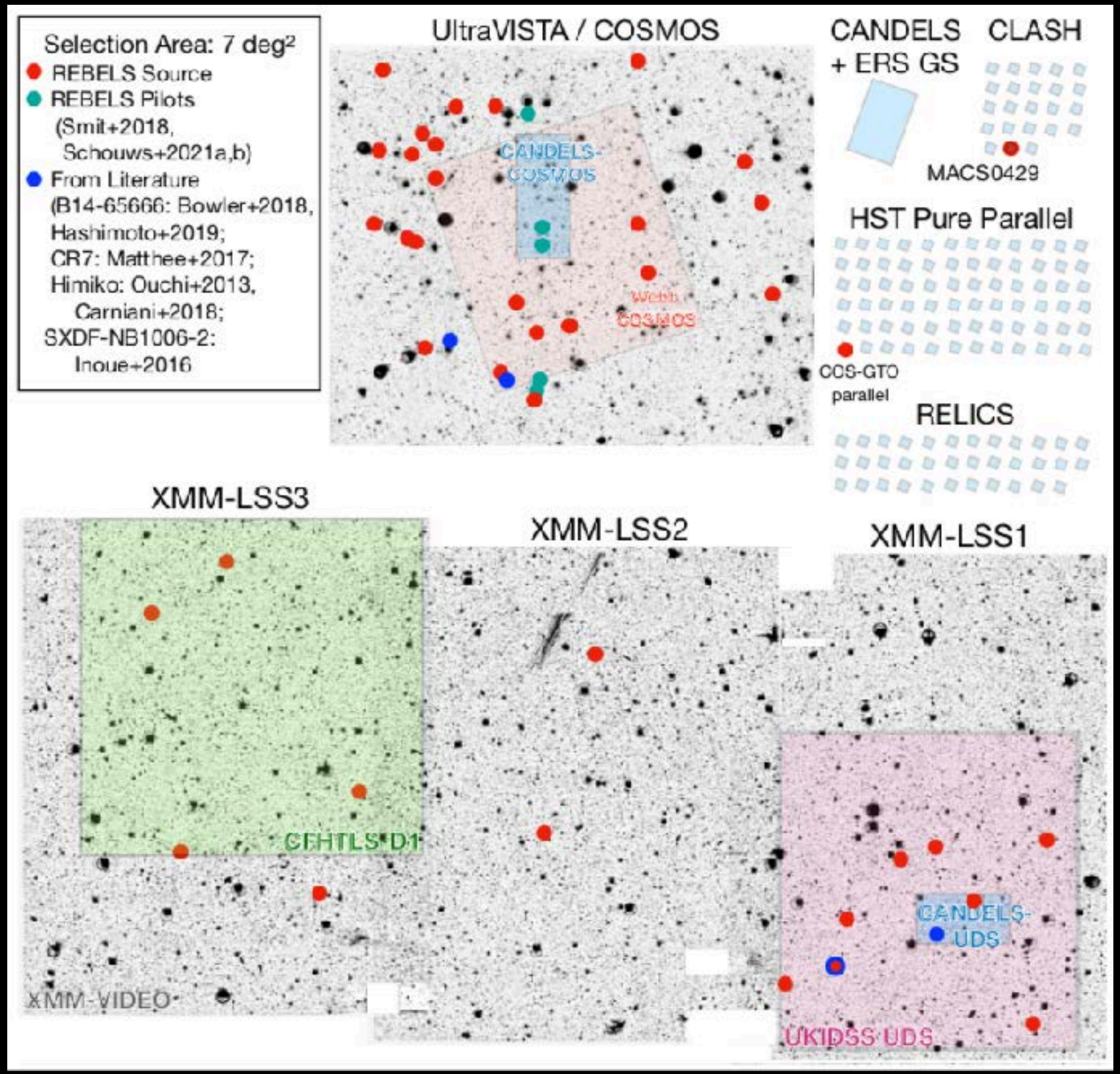




Zavala et al. 2018,2021

REBELS: Reionization Era Bright Emission Line Survey

ALMA Large Program



- Targeted survey of 40 sources in ~7deg^2
- 6.5 < photo-z < 9.5
- UV-luminous Lyman break galaxies
- Spectral scans for $[CII]_{158\mu m}$ or $[OIII]_{88\mu m}$

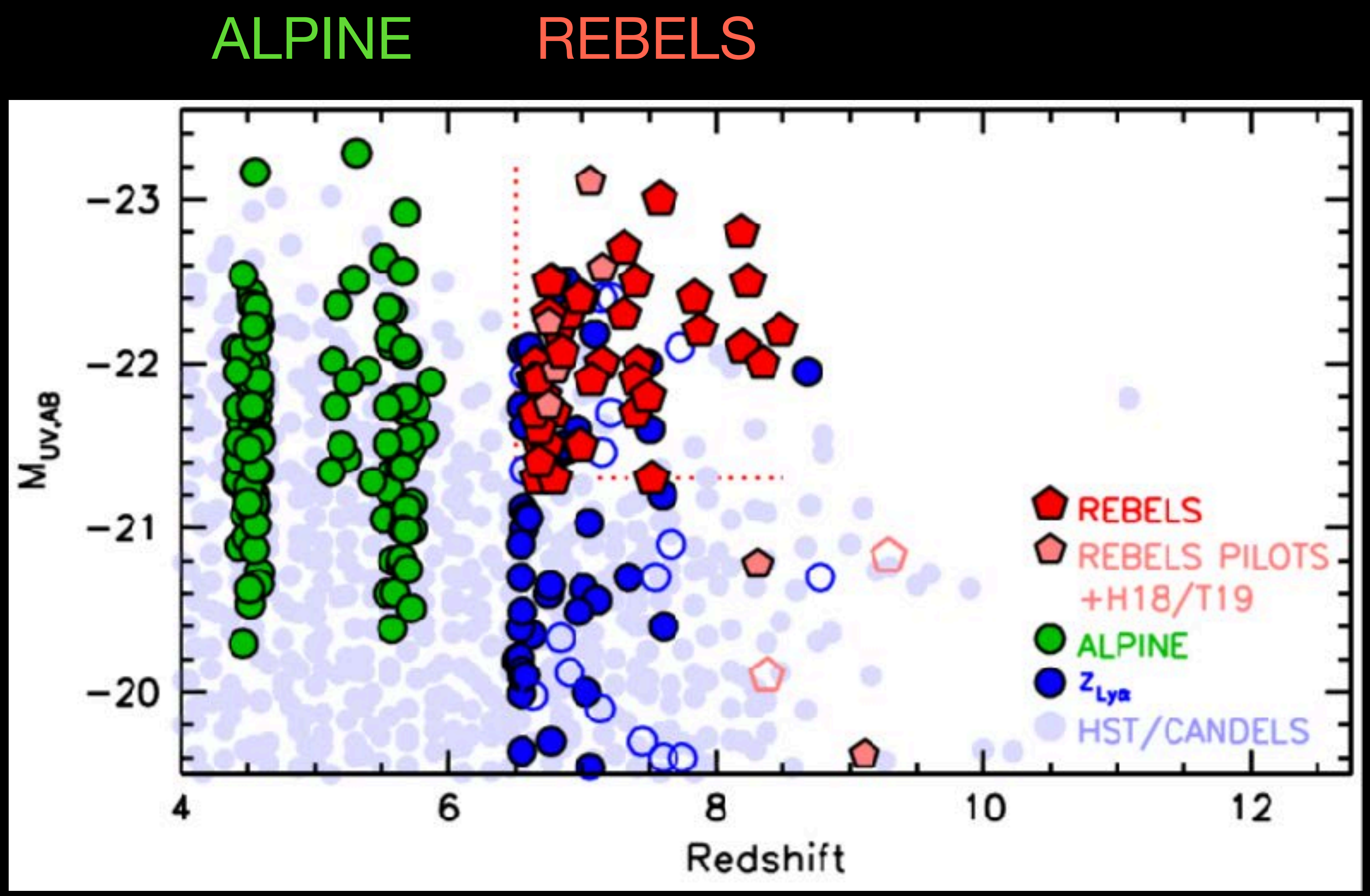
- 60.6/70 hours of data acquired to date
- 34/40 targets observed

PI: Bouwens, co-PIs: Gonzalez, Stark, Inami

Bouwens et al. 2022

REBELS: Reionization Era Bright Emission Line Survey

ALMA Large Program



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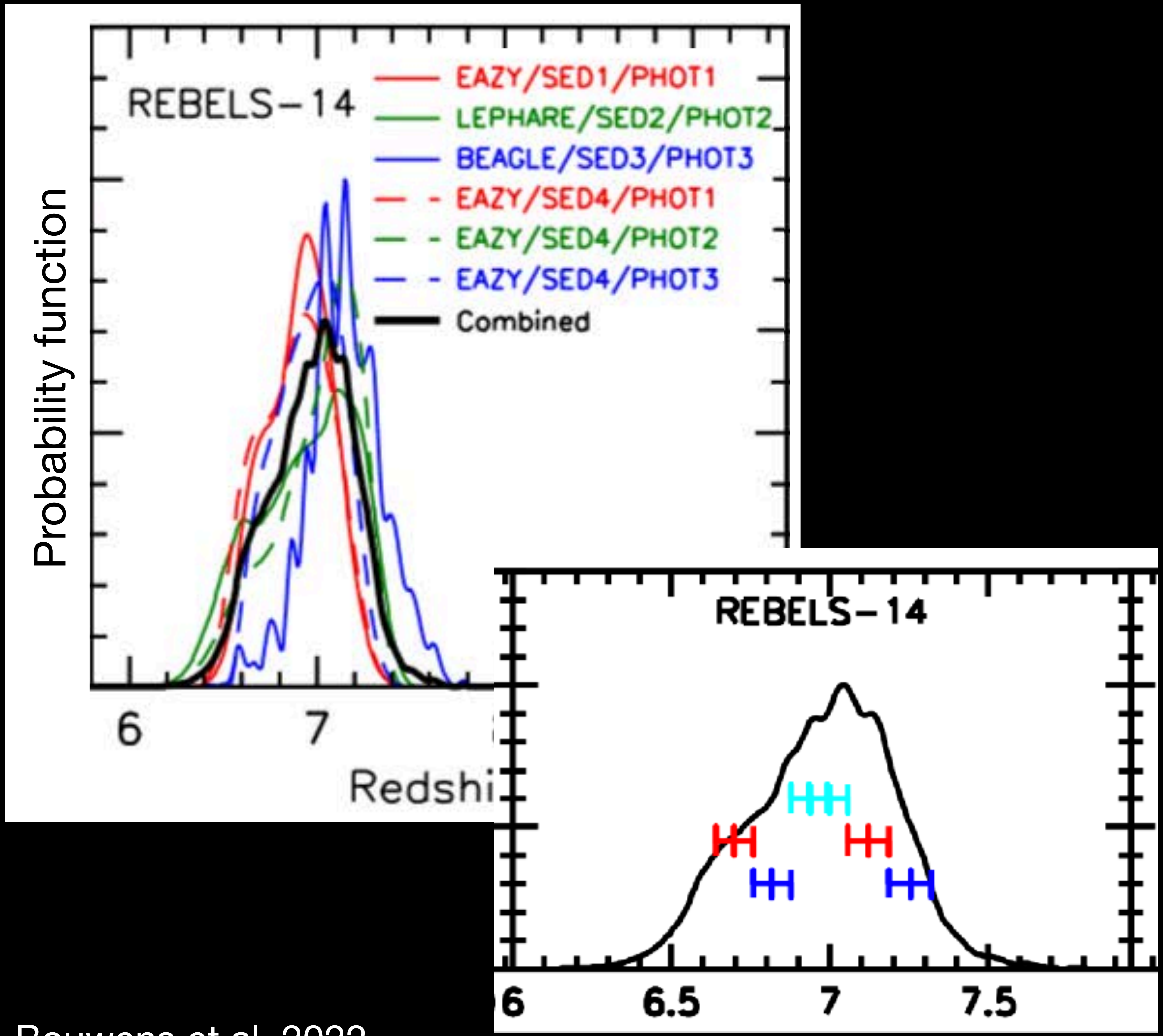
Bouwens et al. 2022

Line scan strategy

Predict a redshift with combined photometric redshifts



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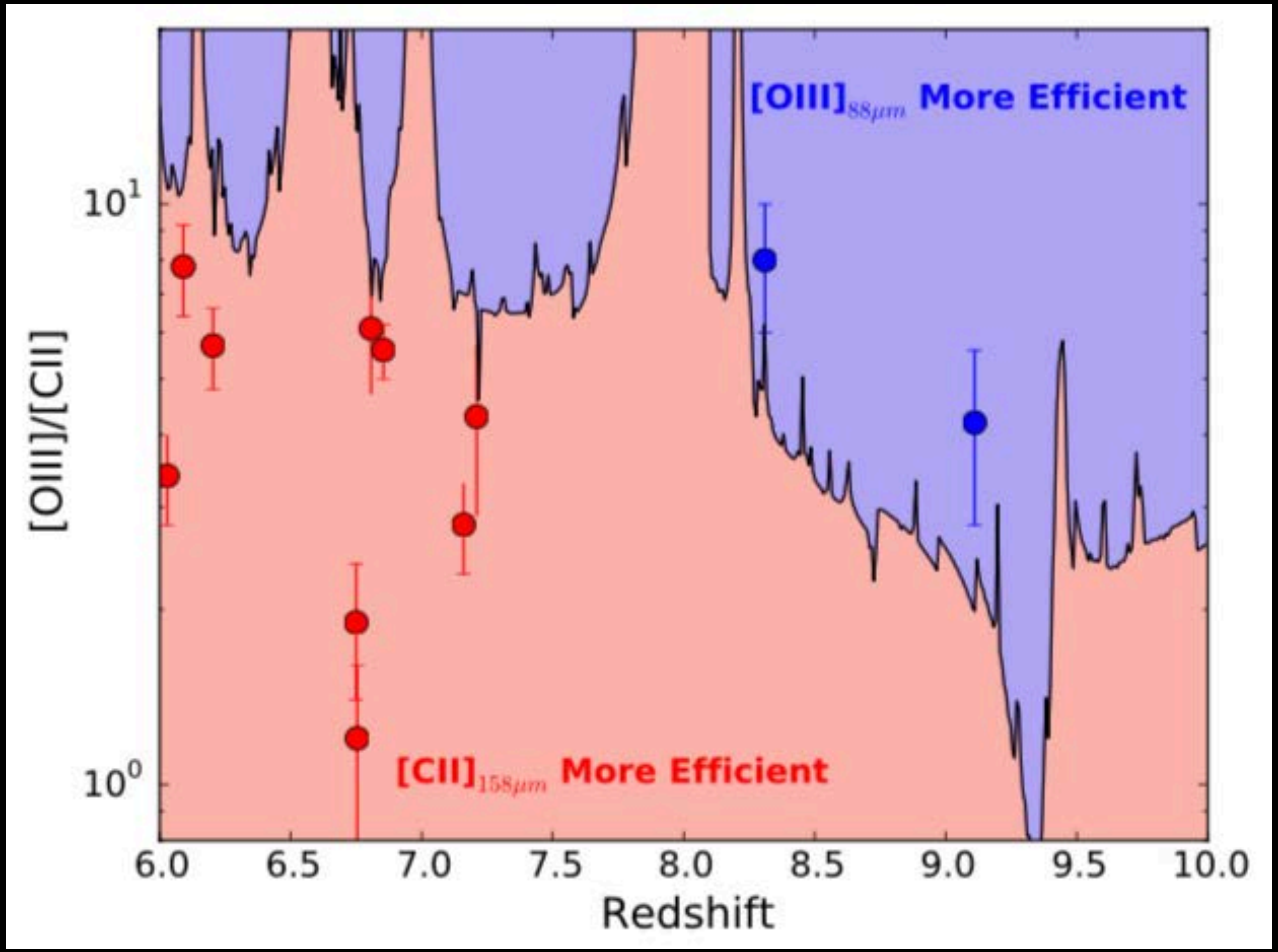
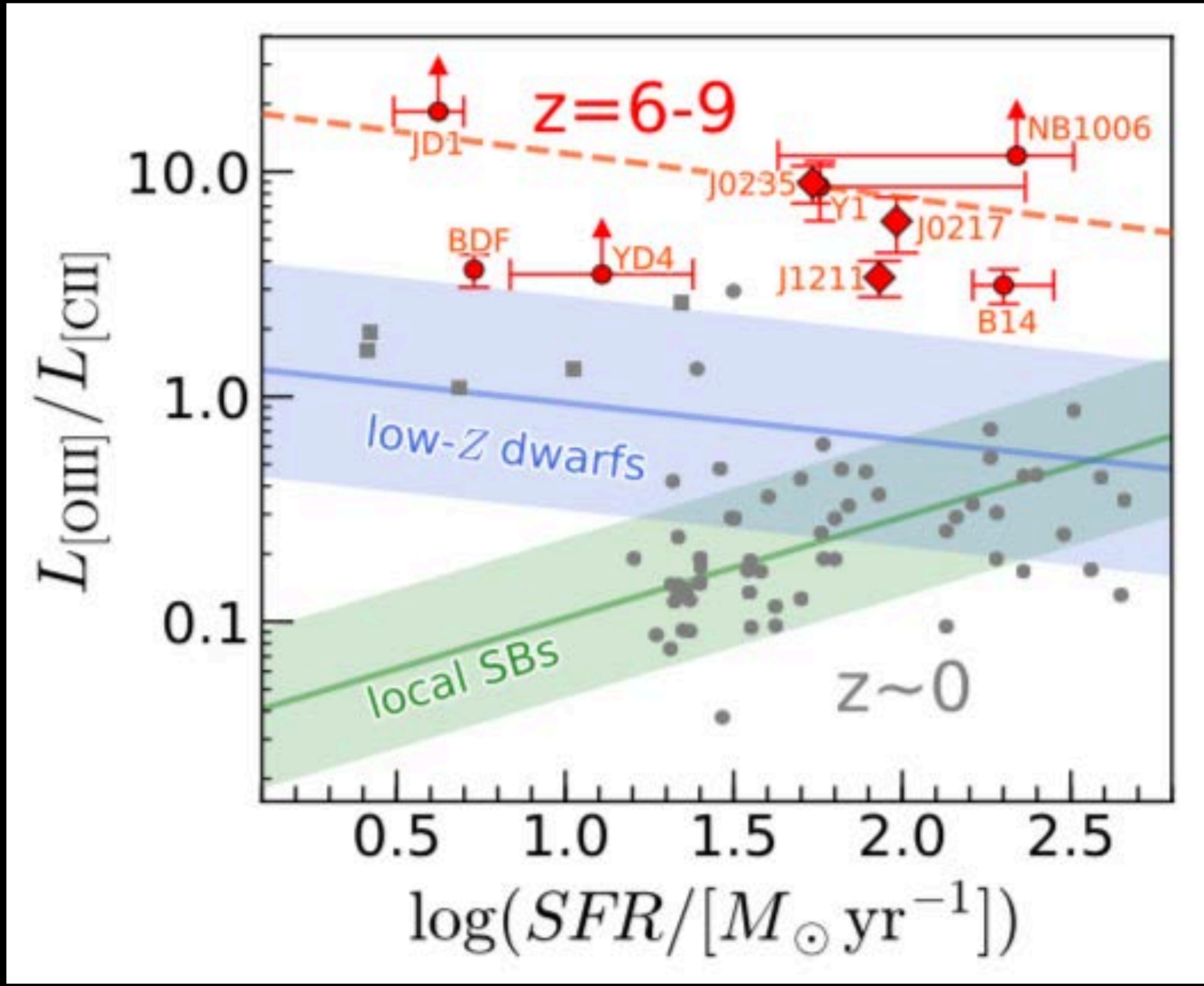
Bouwens et al. 2022

Line scan strategy

Line scan efficiency with [CII] and [OIII]



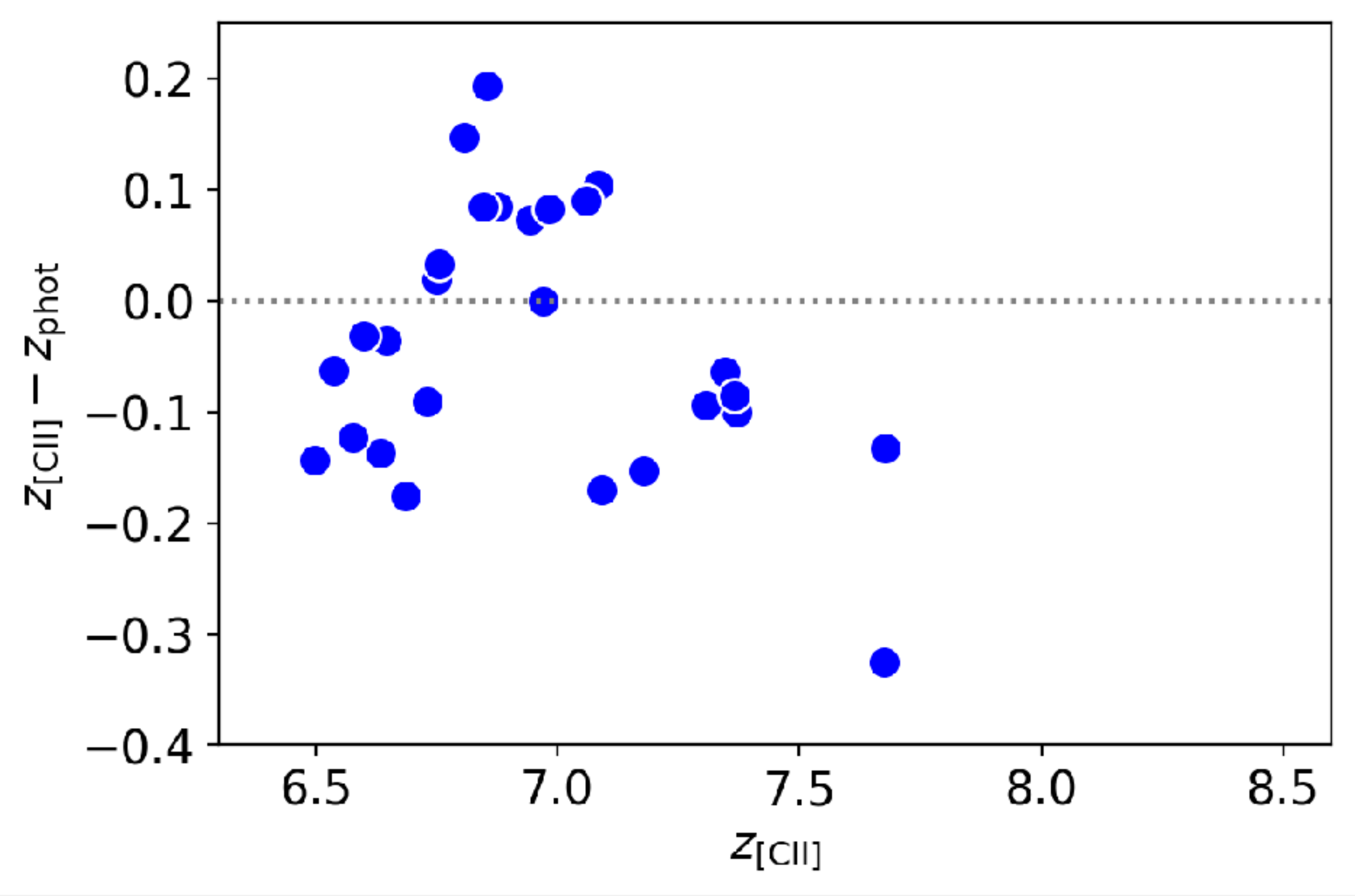
Bouwens et al. 2022



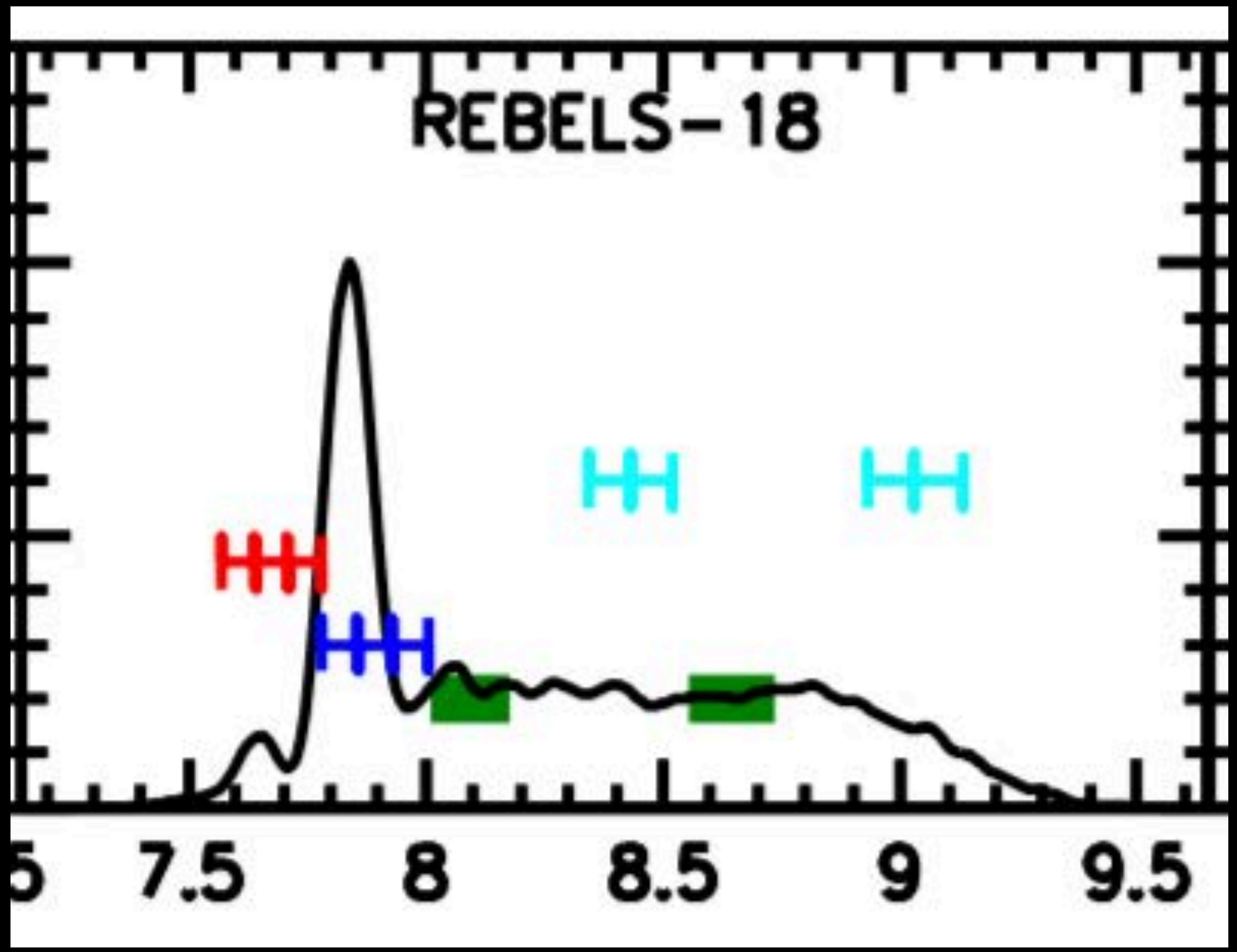
Harikane et al. 2020

Line scan strategy

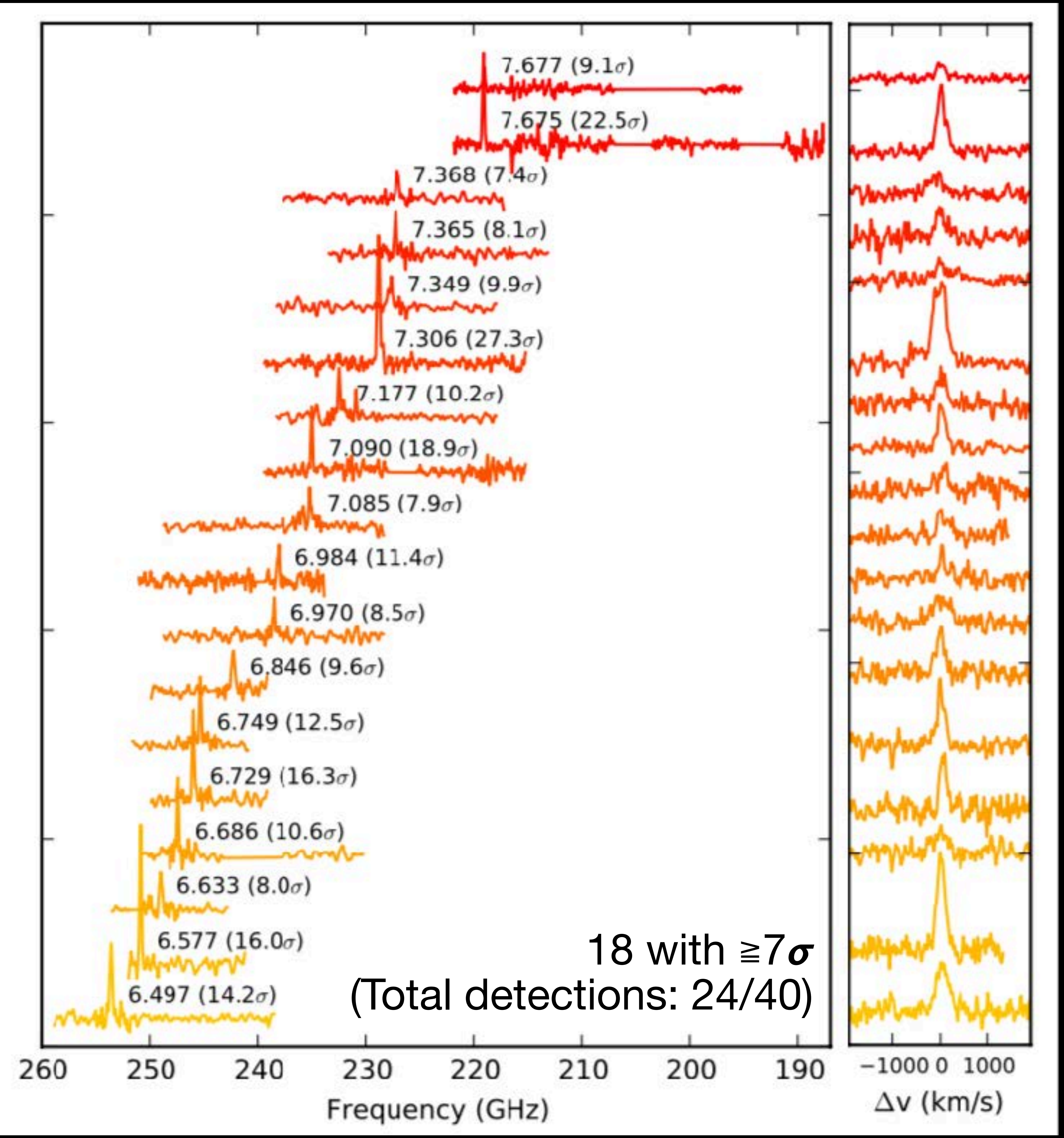
[CII] spec-z vs. photo-z

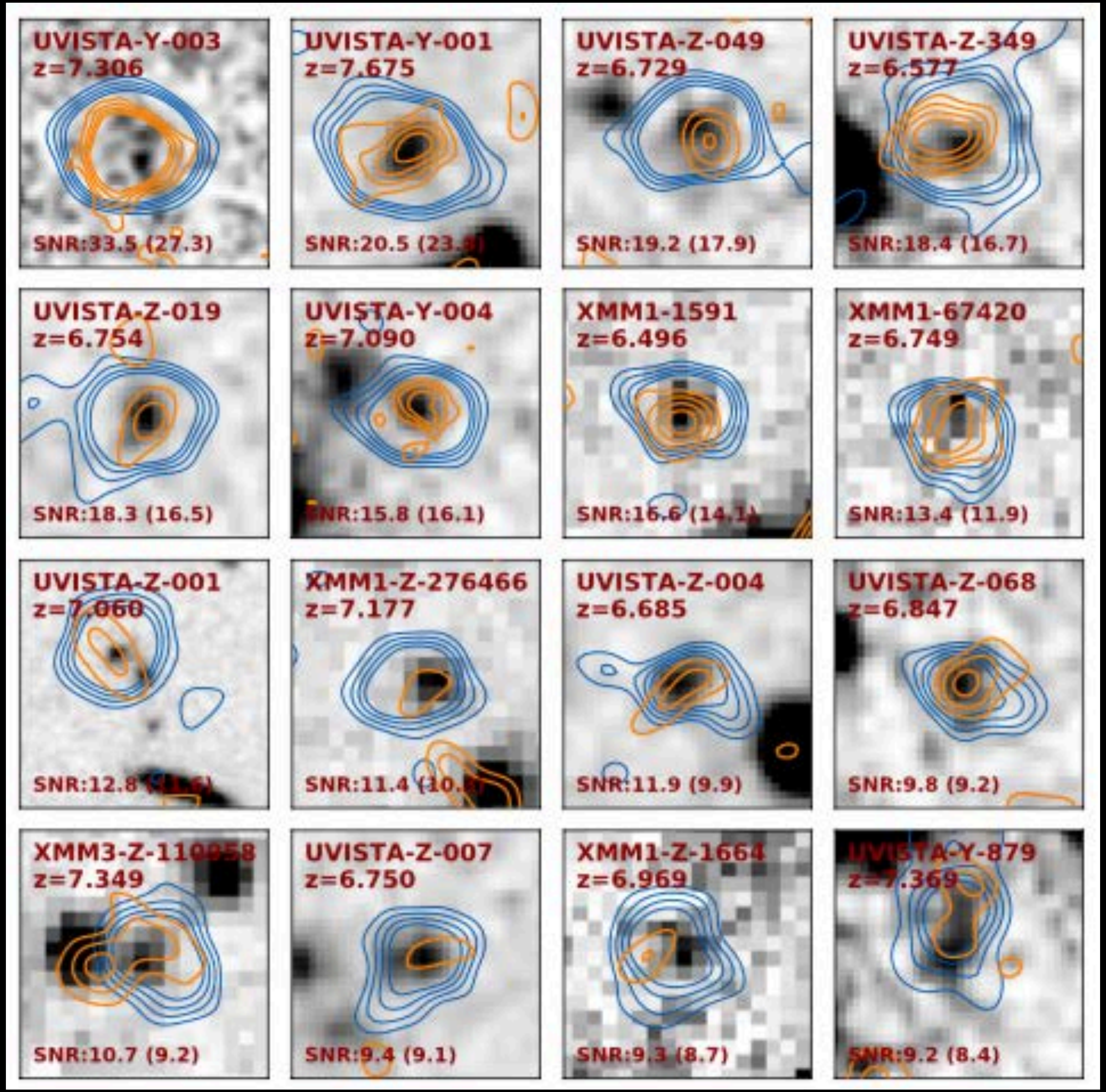


- Most of photo-z were well predicted within +/- 0.2 of spec-z
- The sources at z > 7 tend to have a long tail in the redshift probability function



[CII] detections in REBELS

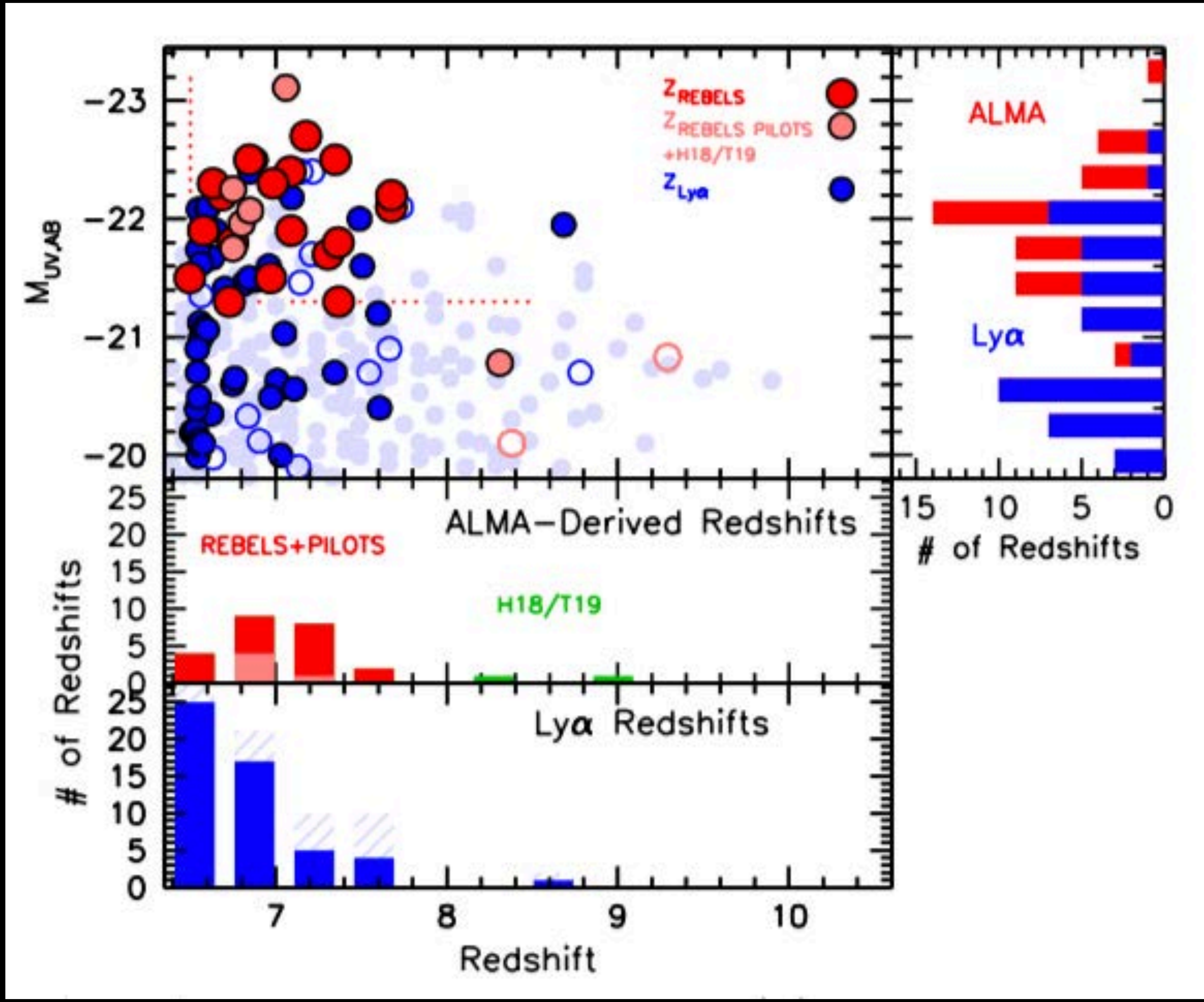




[CII]
Dust

Bouwens et al. 2022

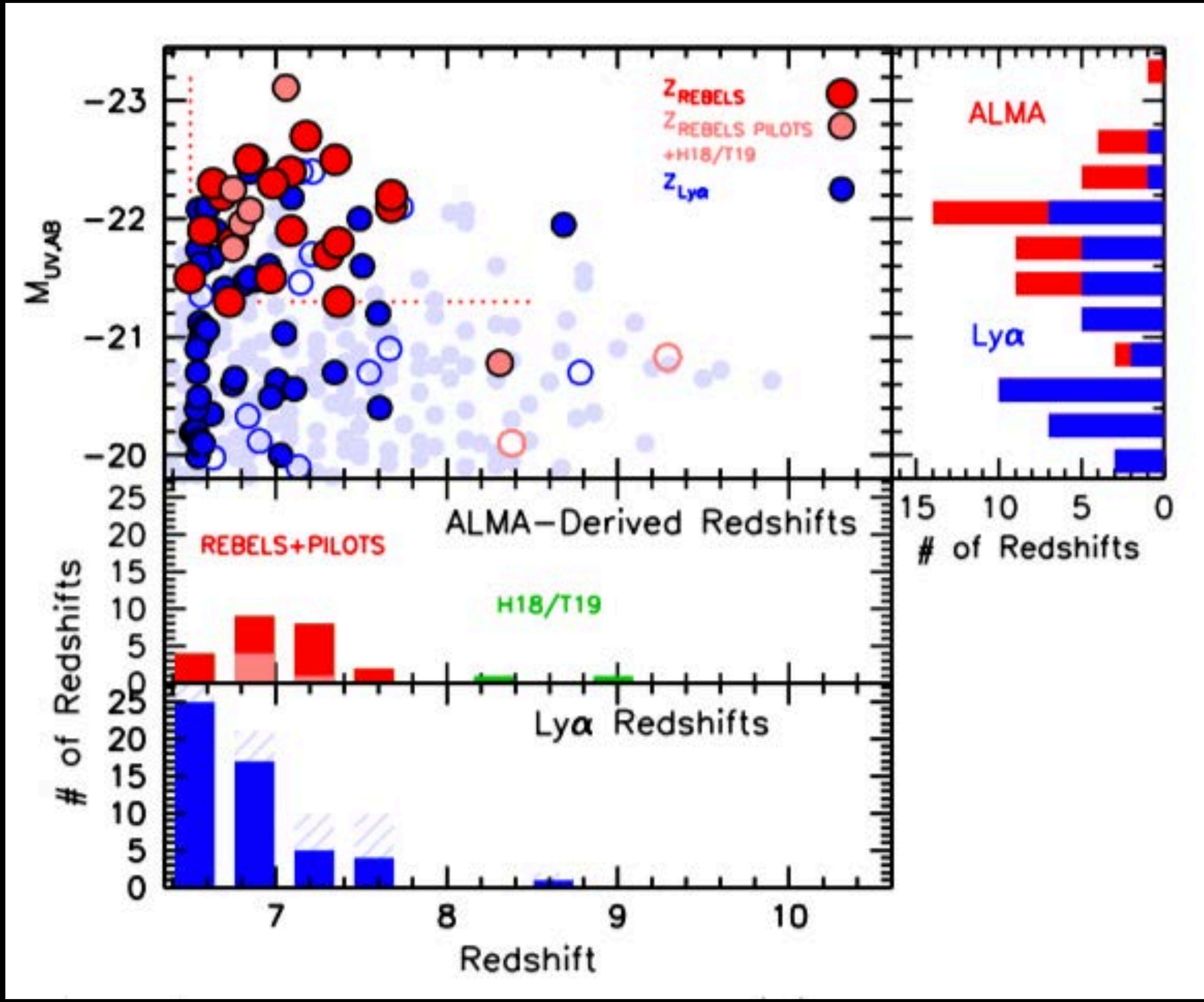
[CII] detections in REBELS



- Total detections: 24/40 (60%)
  - 6 more to be complete
- > 3x of bright ISM-cooling lines known at z > 6.5
- The spec-z confirmed z > 6.5 galaxies with ISM-cooling lines already compete with Lyα

Bouwens et al. 2022

[CII] detections in REBELS



Bouwens et al. 2022

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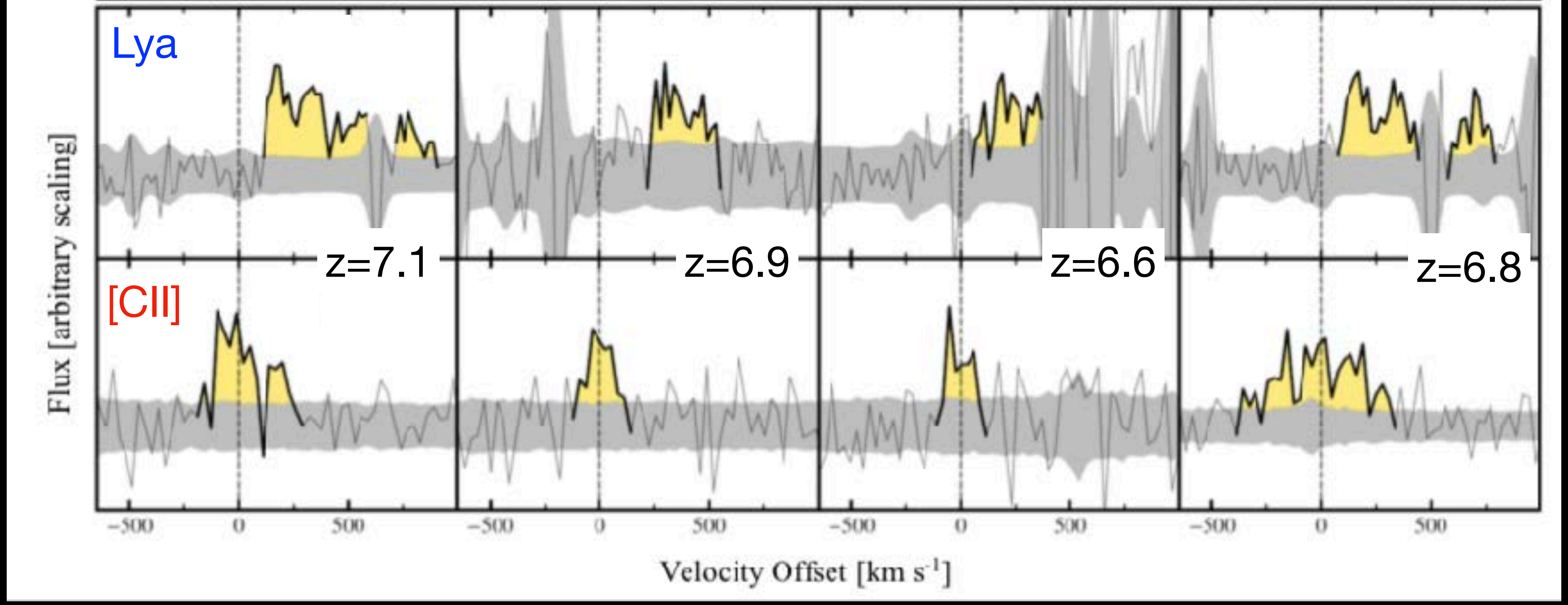
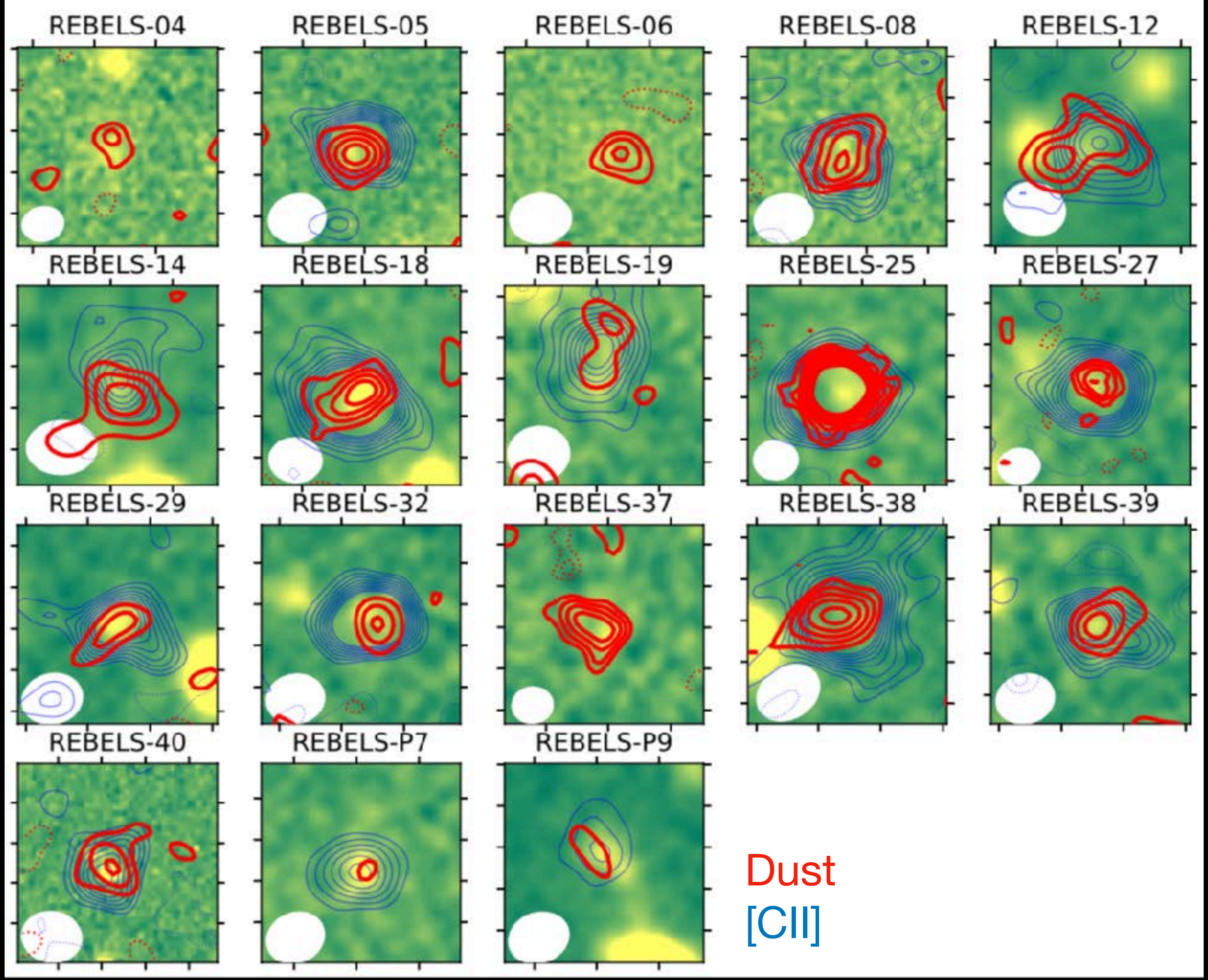
Lyα followup observations



Endsley et al. 2022, Algera et al. (in prep.)
Followup: Subaru/FOCAU IFU observations of Lya

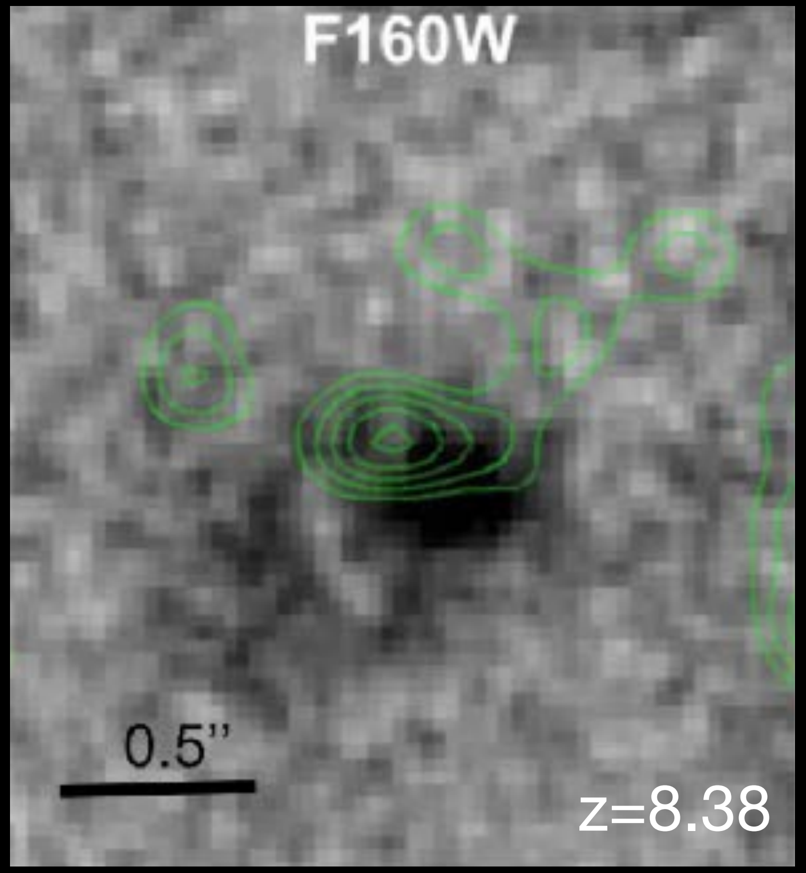
Dust continuum detections in REBELS



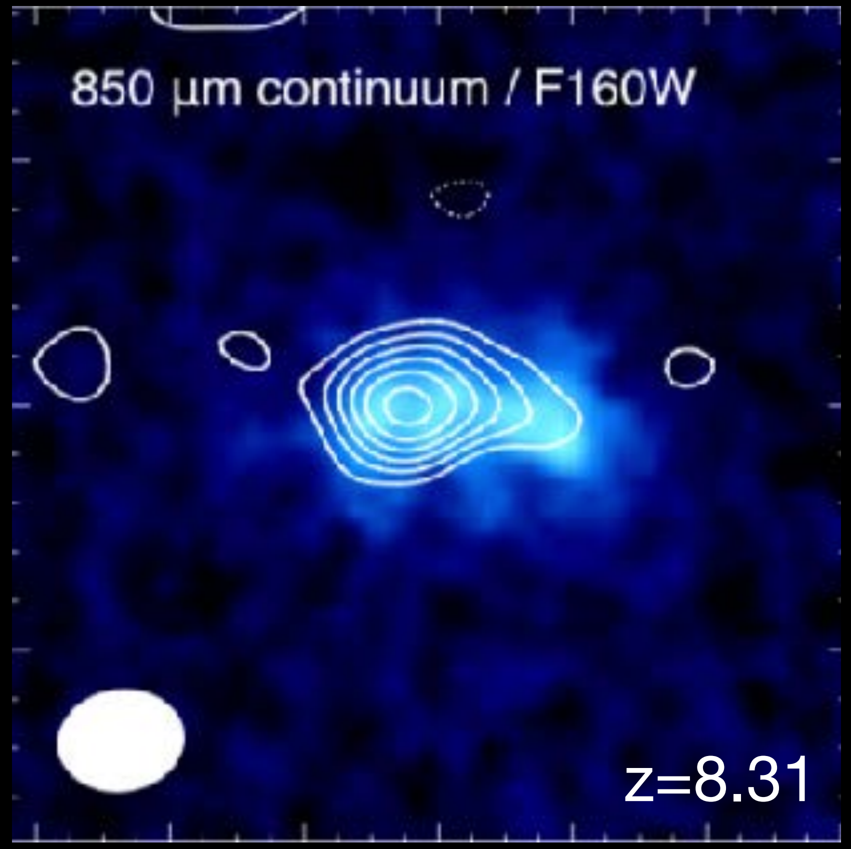
- 16 out of the 40 targets in REBELS (≧40%)
  - 6 more sources to complete the observations!
- 2 out of the 9 targets in the pilot program (22%)
- Deeper observations from Bowler et al. 2021 added 2 more REBELS detections
- **Detection rate: ≧41%**
  - (16+2+2)/49

Inami et al. (arXiv:2203.15136)

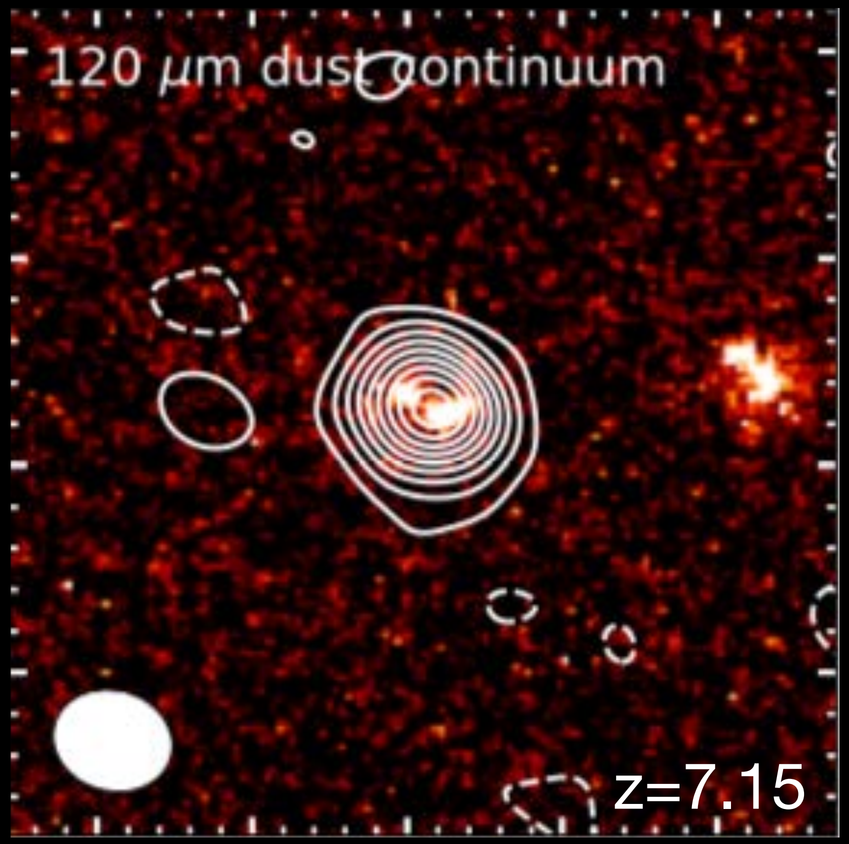
Dust continuum detected sources at z~7



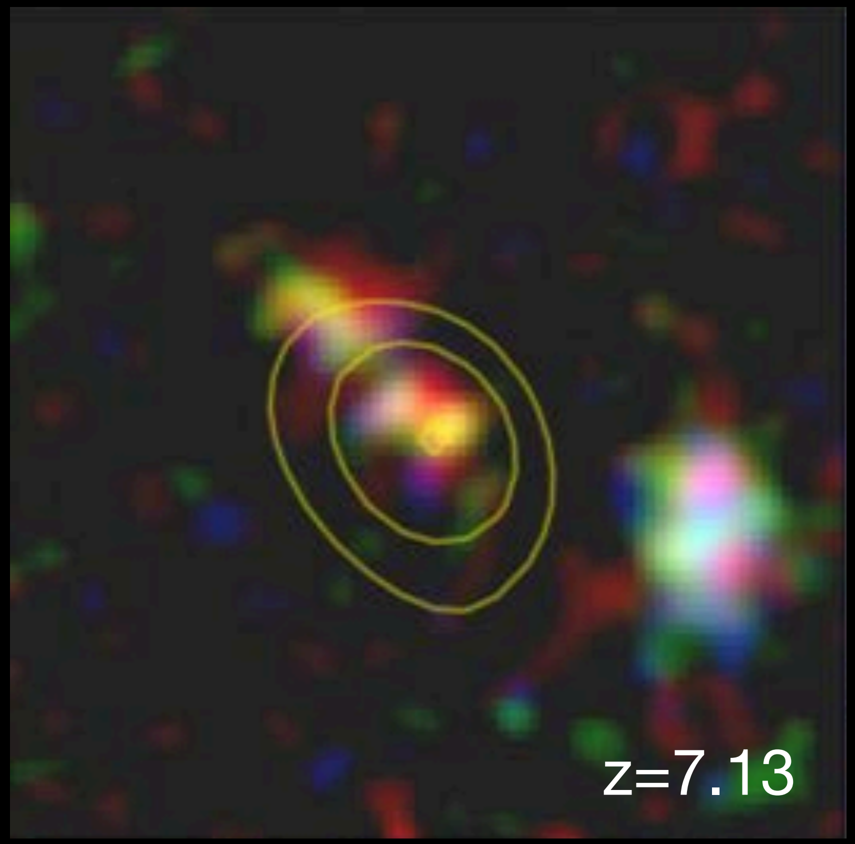
Laporte et al. 2017



Tamura et al. 2019
Bakx et al. 2020



Bowler et al. 2018
Hashimoto et al. 2019
Sugahara et al. 2021



Watson et al. 2015, Inoue et al. 2020
Knudsen et al. 2017, Bakx et al. 2021

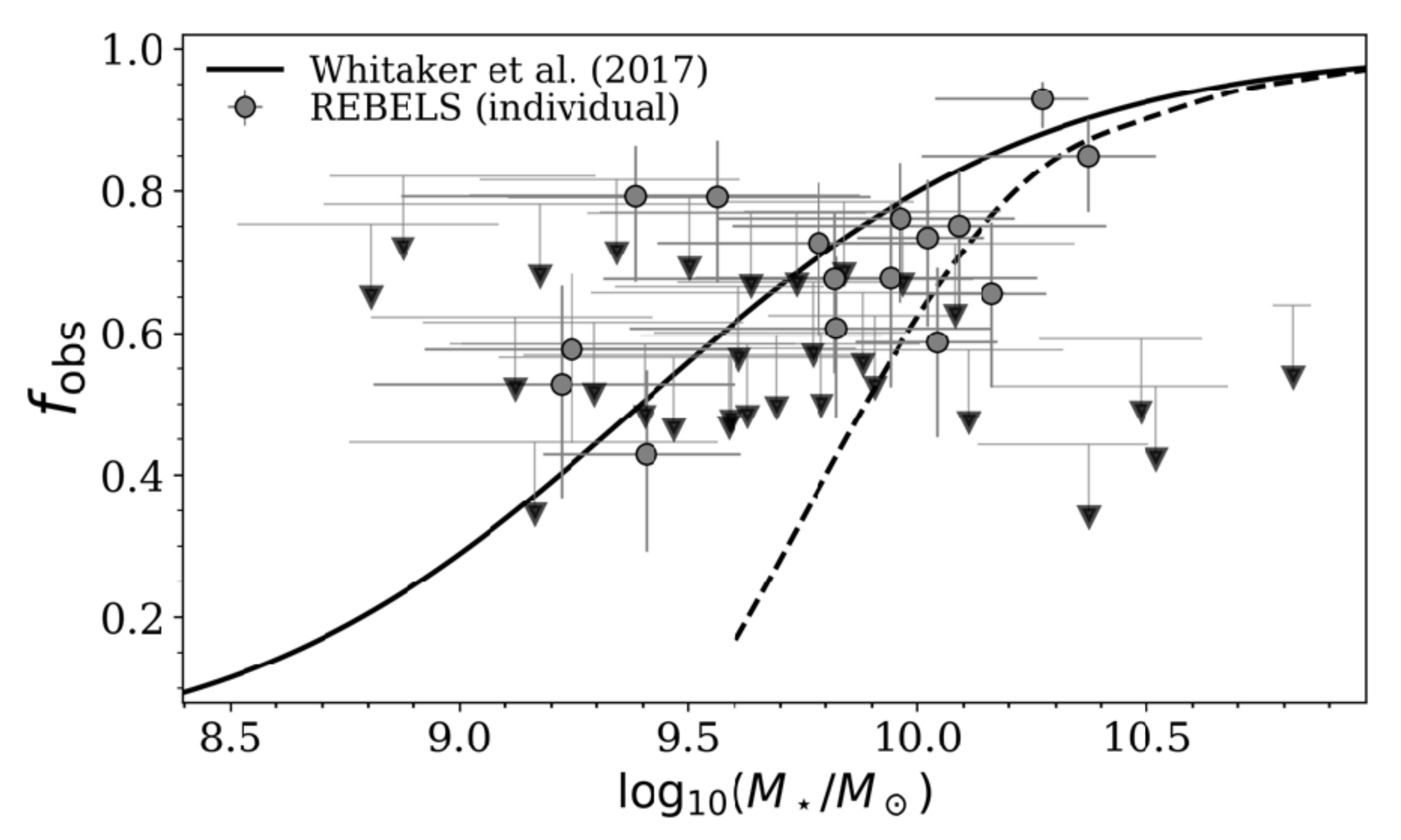
Source name	Redshift	References
REBELS-04	8.57†	This work
A2744_YD4	8.38	Laporte et al. (2017)
MACS0416_Y1	8.31	Tamura et al. (2019); Bakx et al. (2020)
REBELS-37	7.75†	This work
REBELS-18	7.67	Schouws et al. (2022a); This work
REBELS-19	7.37	This work
REBELS-40	7.36	This work
REBELS-12	7.35	This work
REBELS-25	7.31	Schouws et al. (2022a); Hygate et al. (in prep.); This work
B14-65666	7.15	Bowler et al. (2018); Hashimoto et al. (2019); Sugahara et al. (2021)
A1689-zD1	7.13	Watson et al. (2015); Knudsen et al. (2017); Inoue et al. (2020); Bakx et al. (2021)
REBELS-27	7.09	Schouws et al. (2022a); This work
REBELS-14	7.08	This work
REBELS-P9	7.06	Bowler et al. (2021); Schouws et al. (2022a); This work
ID238225* (REBELS-30)	6.98	Bowler et al. (2021)
REBELS-P8	6.85	Schouws et al. (2022a)
REBELS-39	6.84	This work
REBELS-06	6.80†	This work
REBELS-08	6.75	This work
REBELS-P7	6.75	Schouws et al. (2022a); This work
REBELS-32	6.73	This work
REBELS-29	6.68	Bowler et al. (2021); This work
ID169850* (REBELS-34)	6.63	Bowler et al. (2021)
REBELS-38	6.58	This work
REBELS-05	6.50	This work

5x more dust samples at z~7!
(3x for the new discoveries)

Inami et al. 2022; see also Schouws et al. 2022a and Bowler et al. 2021

Dust obscuration at z~7

Fraction of obscured star formation: $f_{\rm obs} = SFR_{\rm IR}/SFR_{\rm IR+UV}$



- $f_{\rm obs}$ of the REBELS dust detected galaxies is ~50-90%.
- Despite the REBELS targets being UV-selected, $f_{\rm obs}$ is relatively high

Algera et al. (to be submitted)

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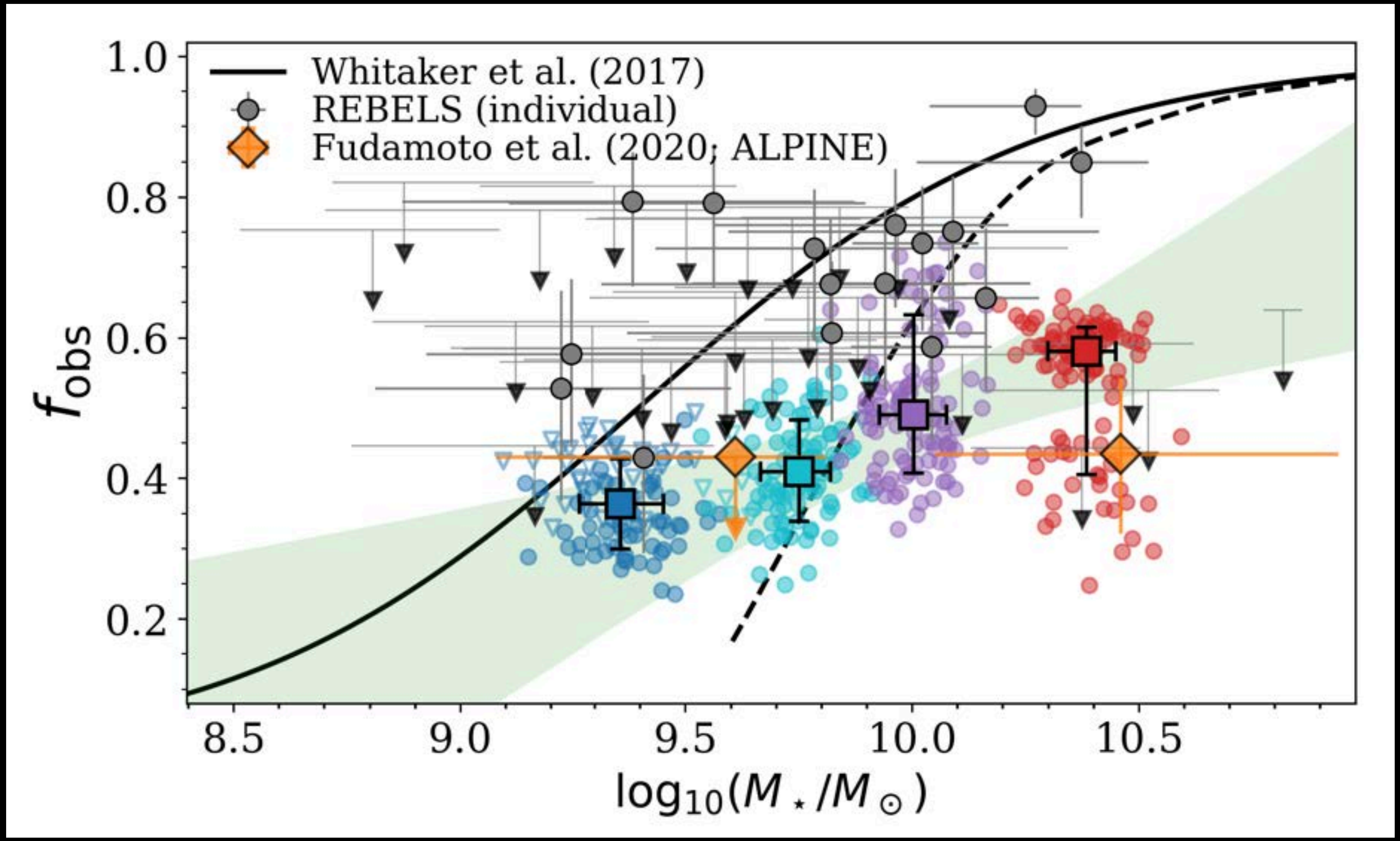
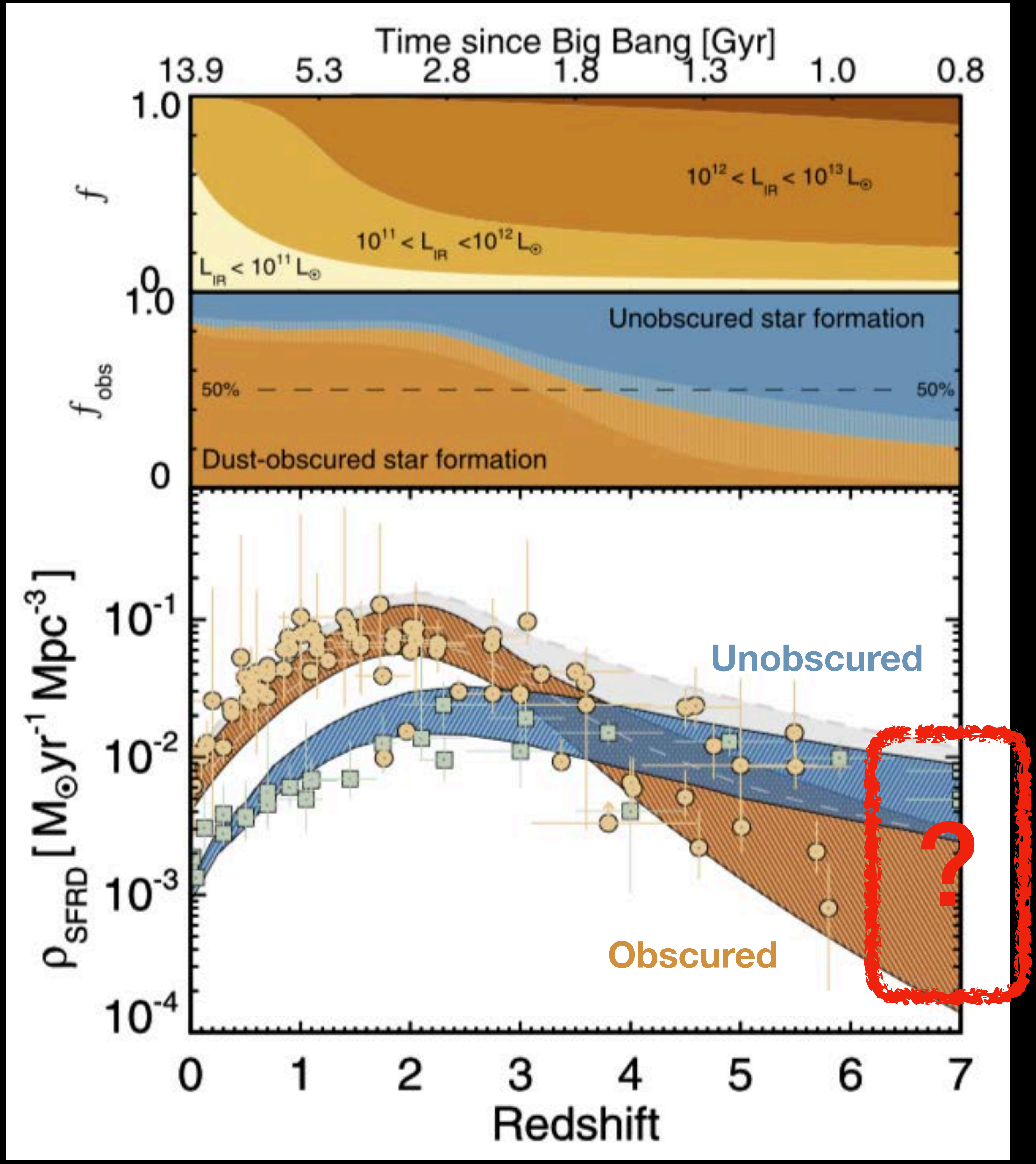


- $f_{\rm obs}$ of the REBELS dust detected galaxies is ~50-90%.
- Despite the REBELS targets being UV-selected, $f_{\rm obs}$ is relatively high
- Agrees well with the ALPINE sample (z~5)

Algera et al. (to be submitted)

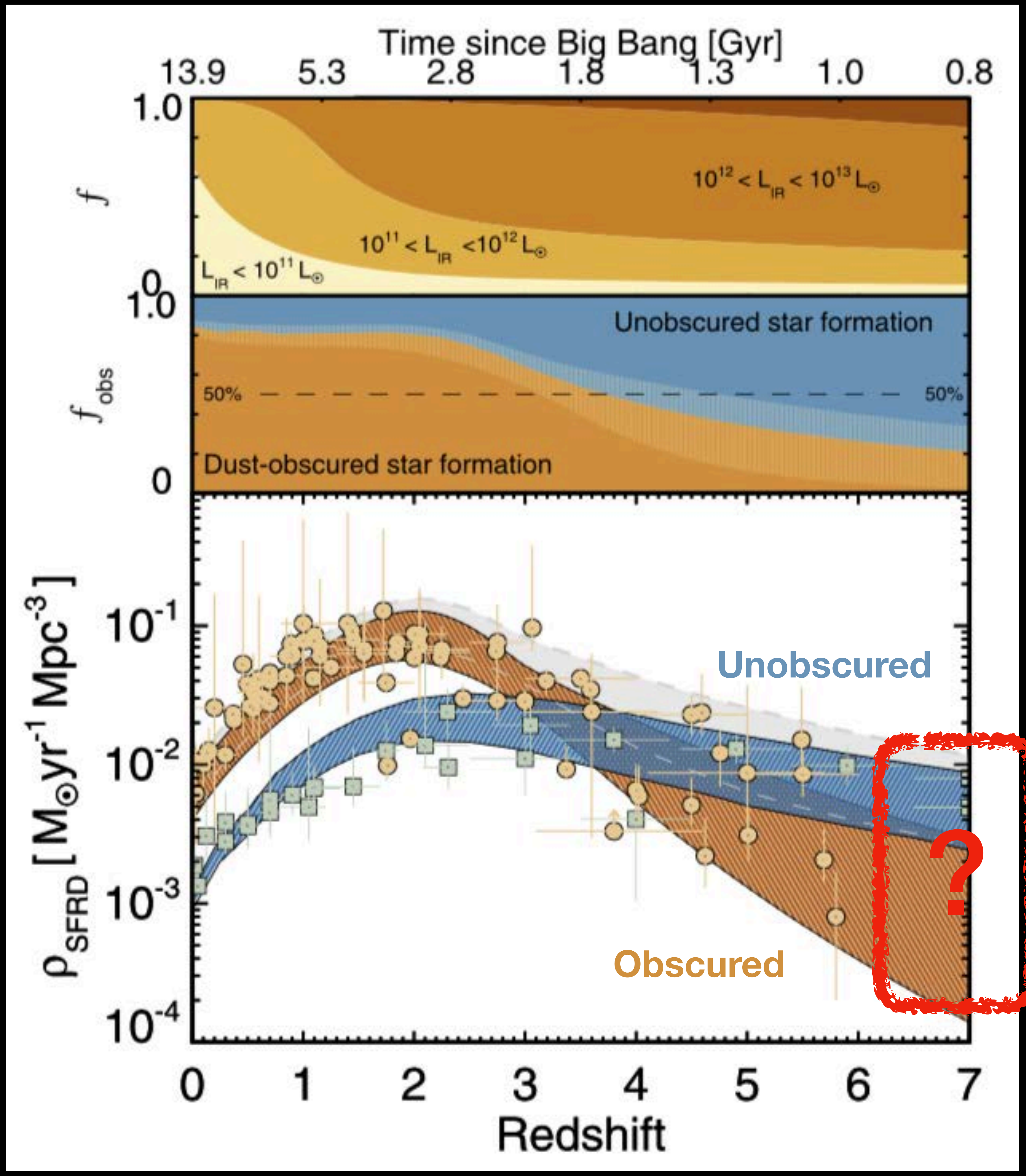
Obscured star formation rate density at z~7

Zavala et al. 2018,2021

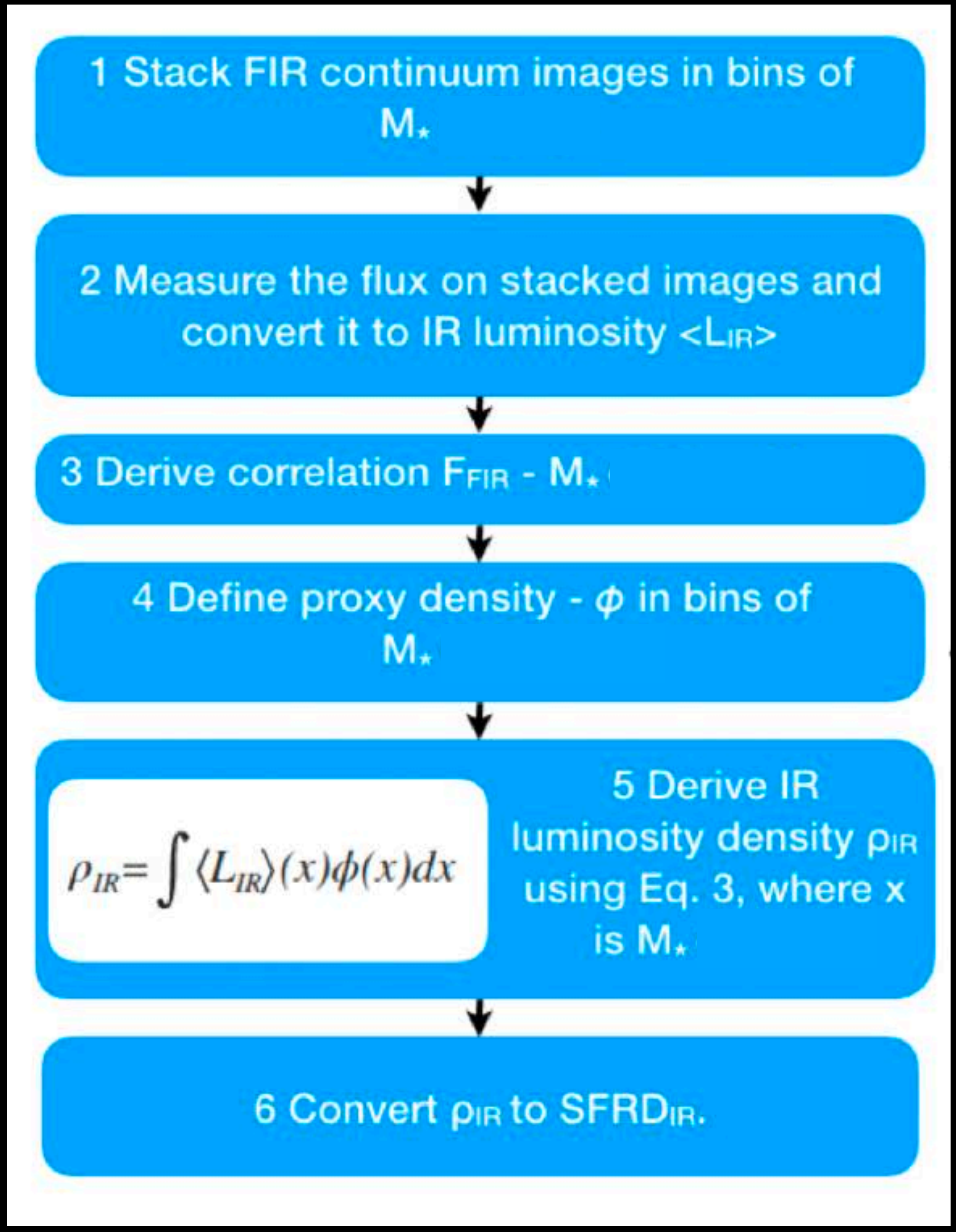


Obscured star formation rate density at z~7

Zavala et al. 2018,2021

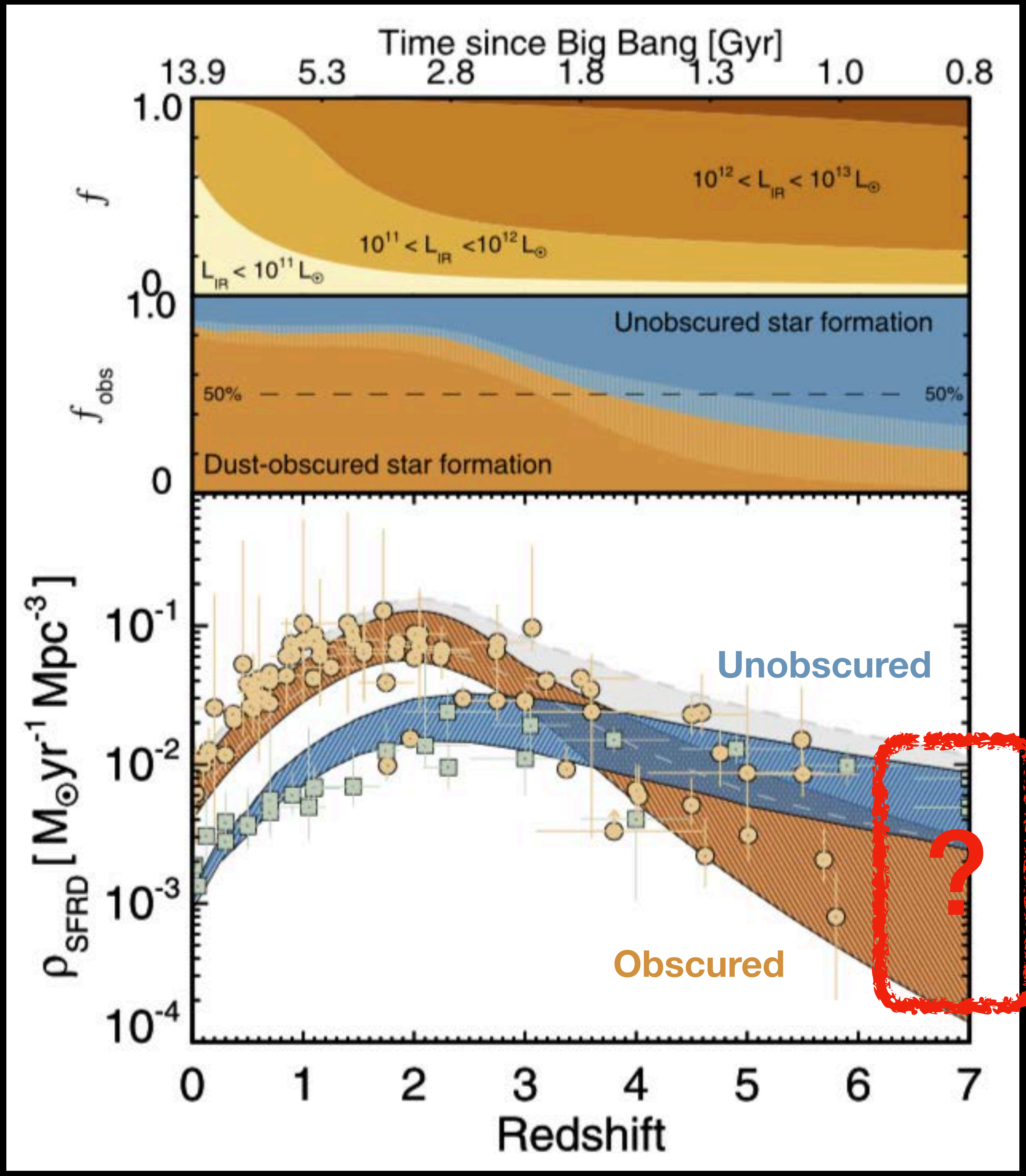


Adopt the same method of Khusanova et al. 2021 (ALPINE)

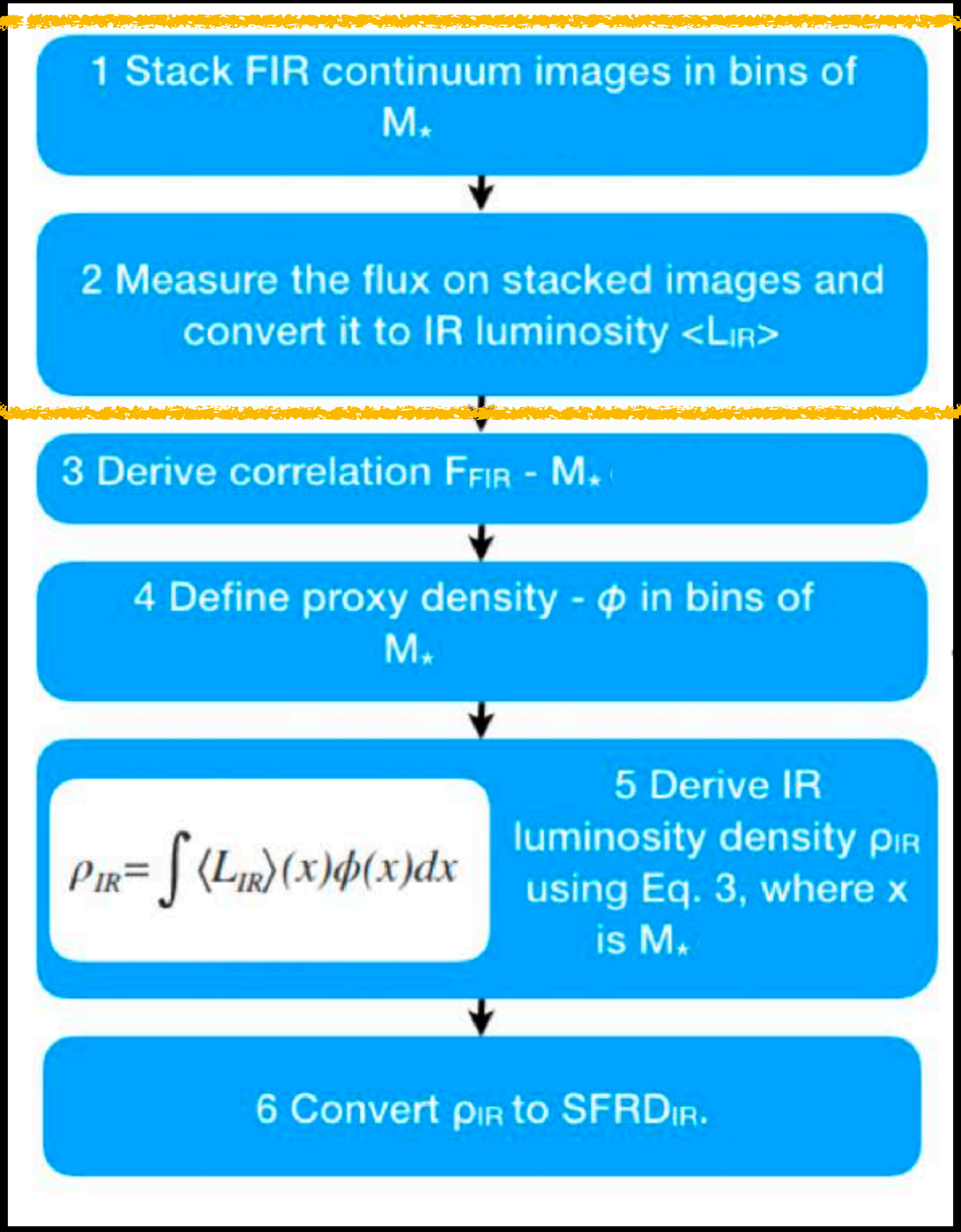


Obscured star formation rate density at z~7

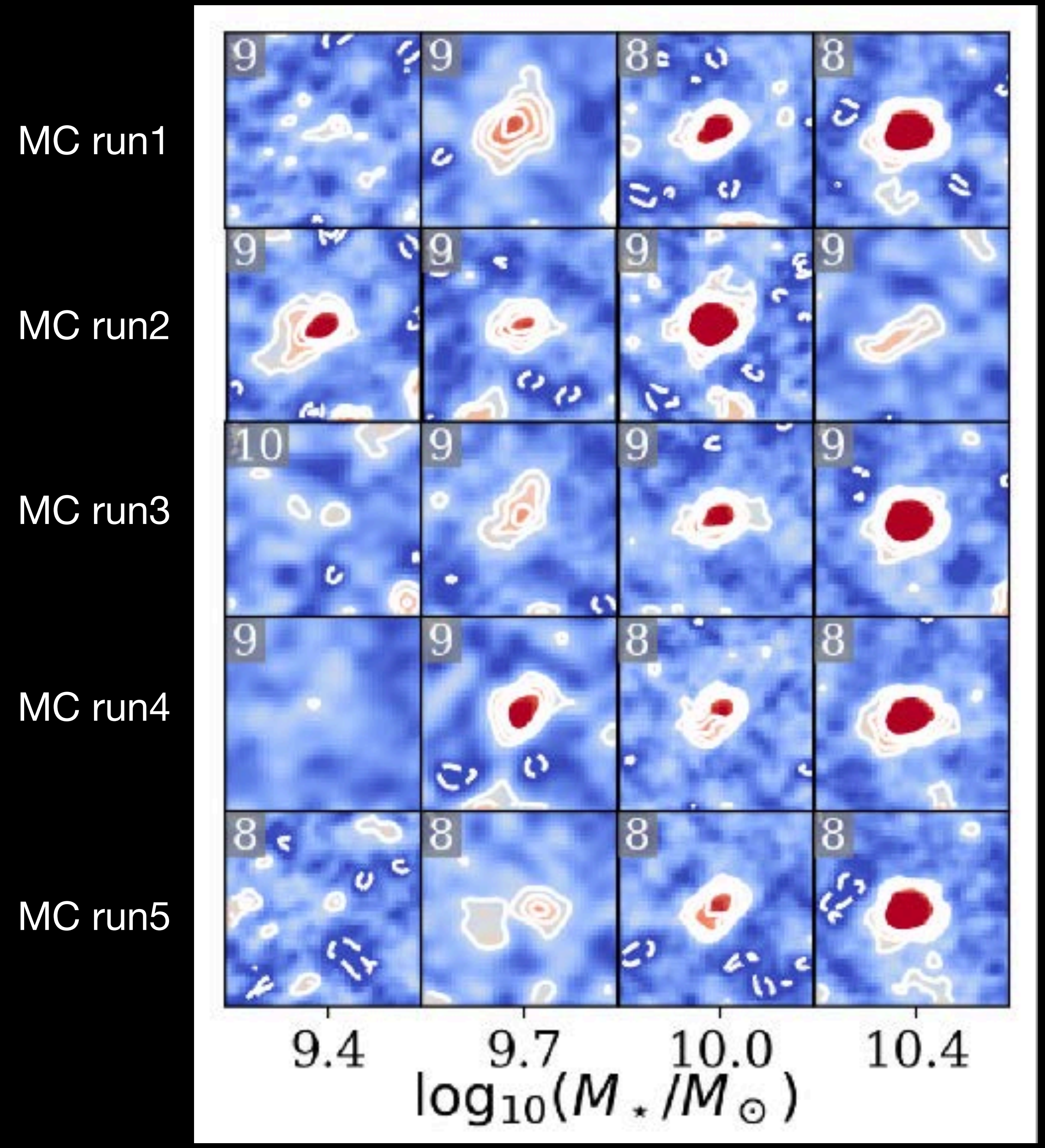
Zavala et al. 2018,2021



Adopt the same method of Khusanova et al. 2021 (ALPINE)



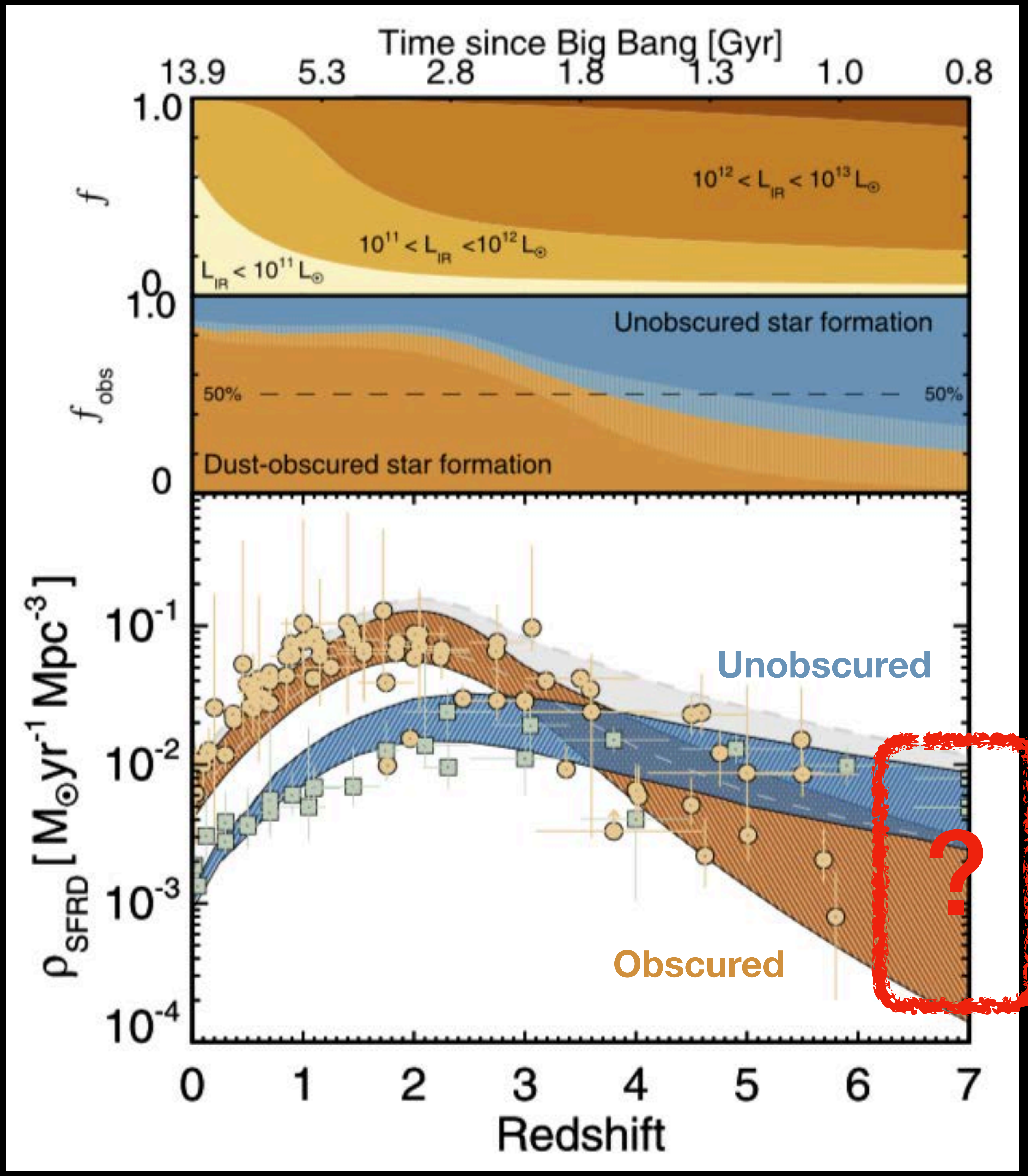
ePoster at EAS



Algera et al. (to be submitted)

Obscured star formation rate density at z~7

Zavala et al. 2018,2021



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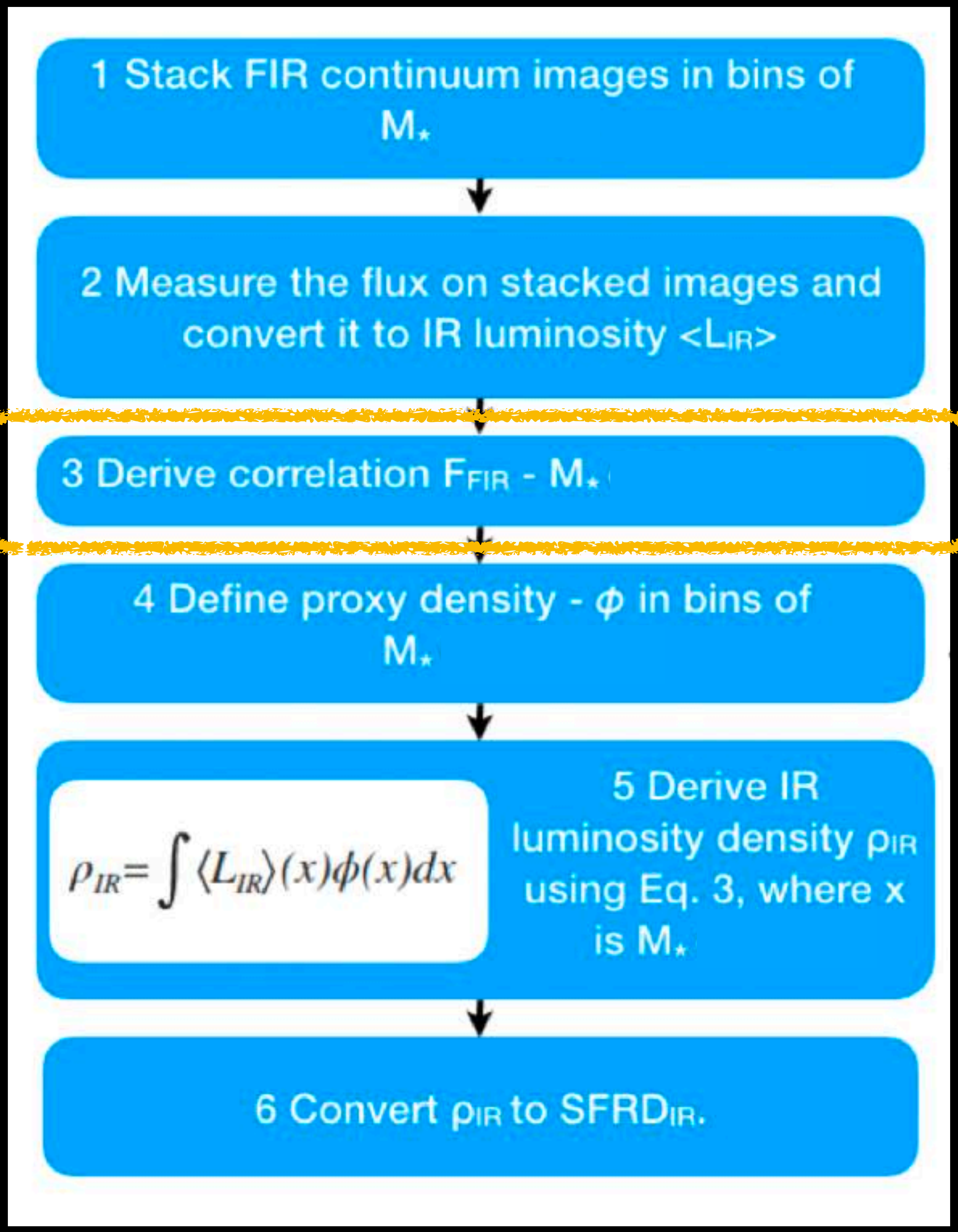
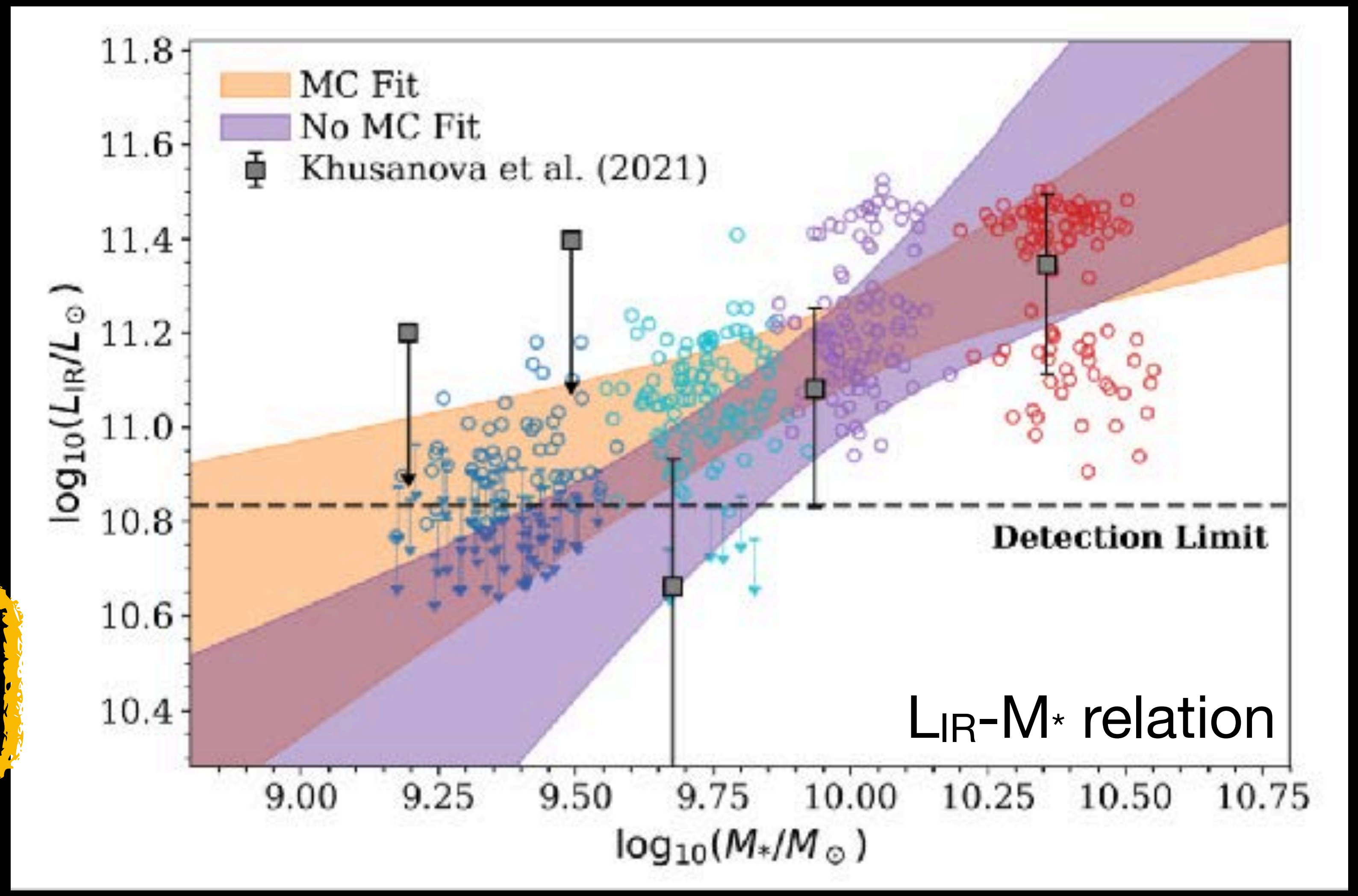
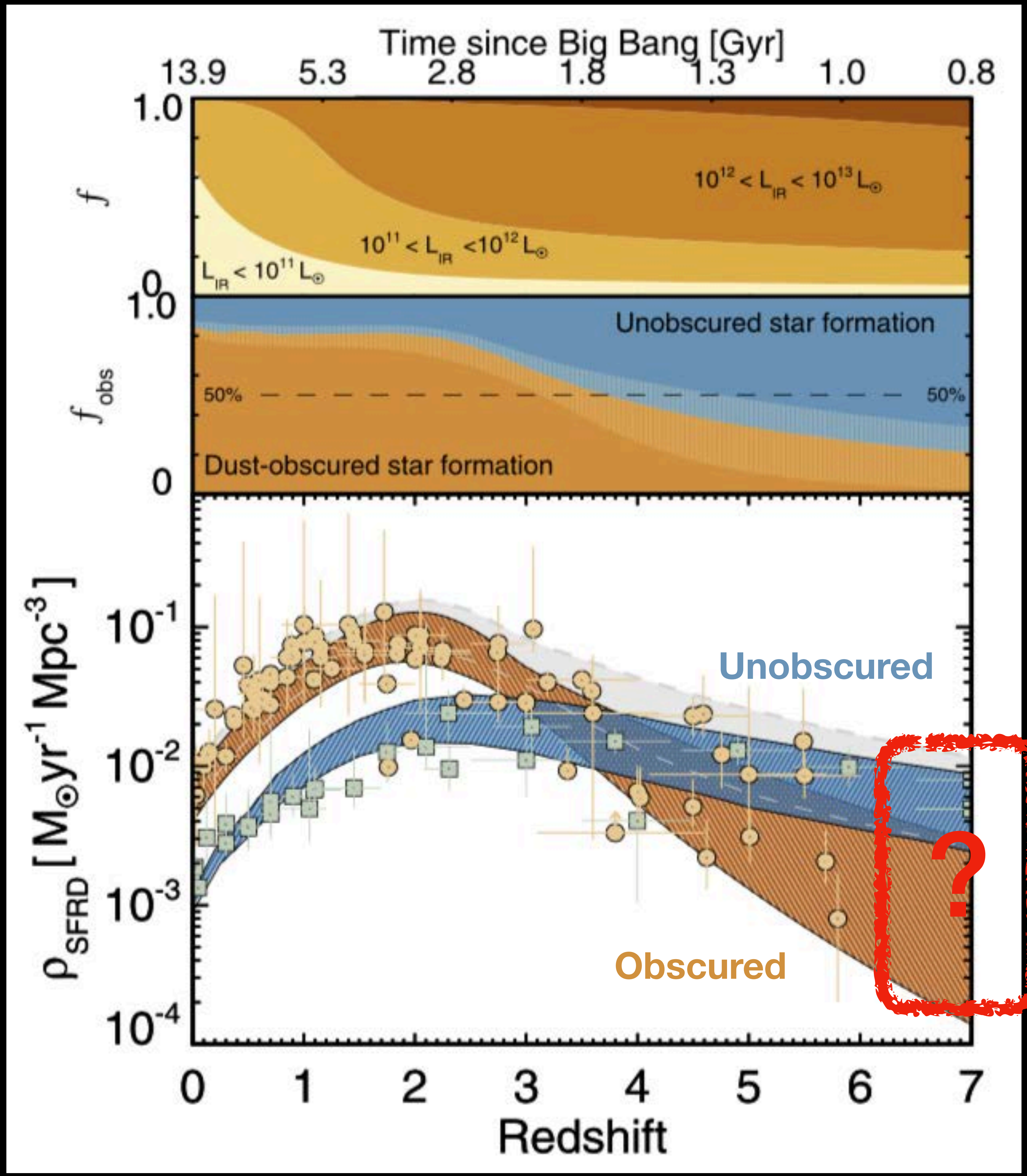


Algera et al. (to be submitted)



Obscured star formation rate density at z~7

Zavala et al. 2018,2021



Adopt the same method of Khusanova et al. 2021 (ALPINE)

1 Stack FIR continuum images in bins of M_*

2 Measure the flux on stacked images and convert it to IR luminosity $\langle L_{IR} \rangle$

3 Derive correlation F_{FIR} - M_*

4 Define proxy density - ϕ in bins of M_*

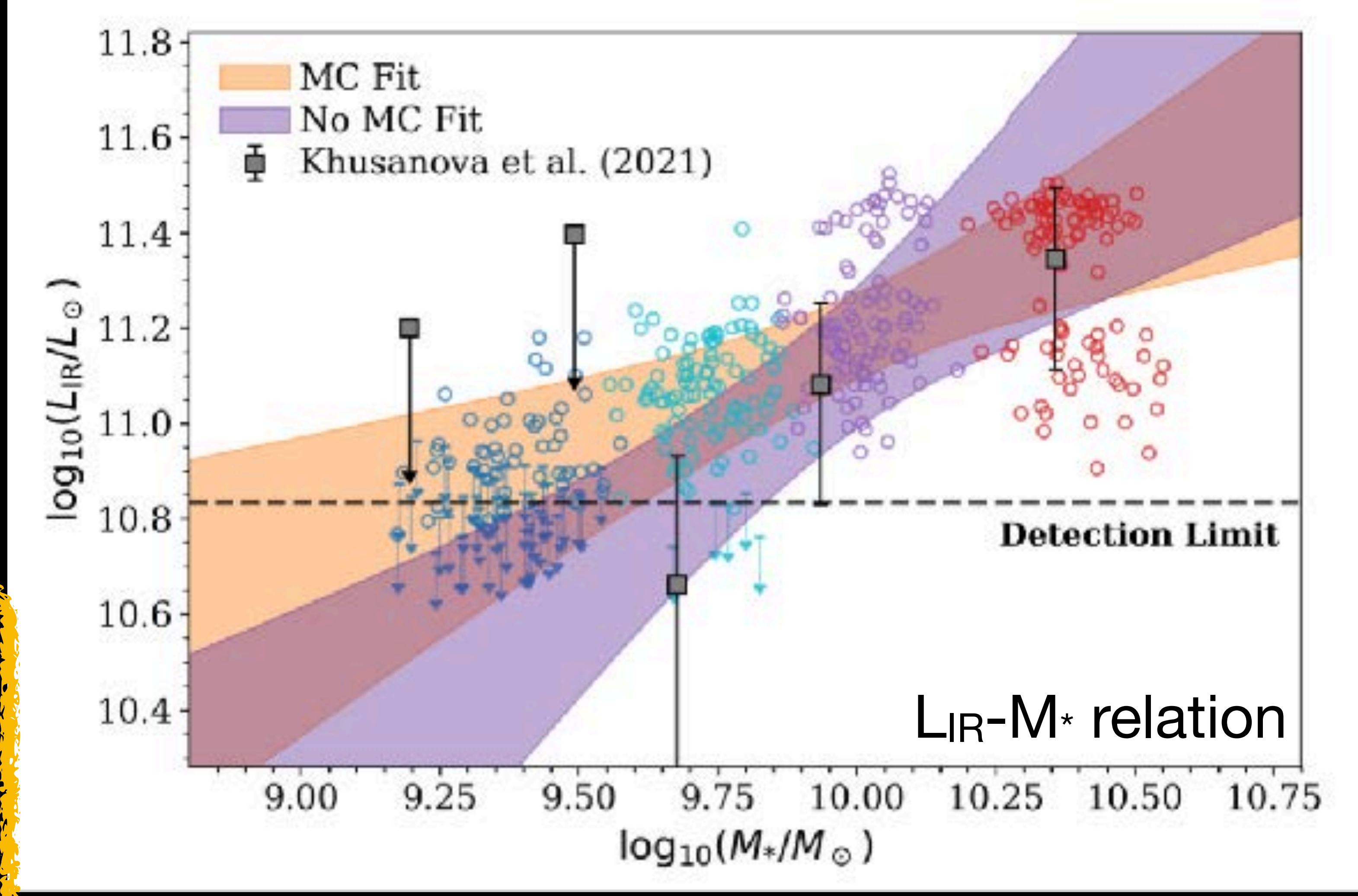
Proxy

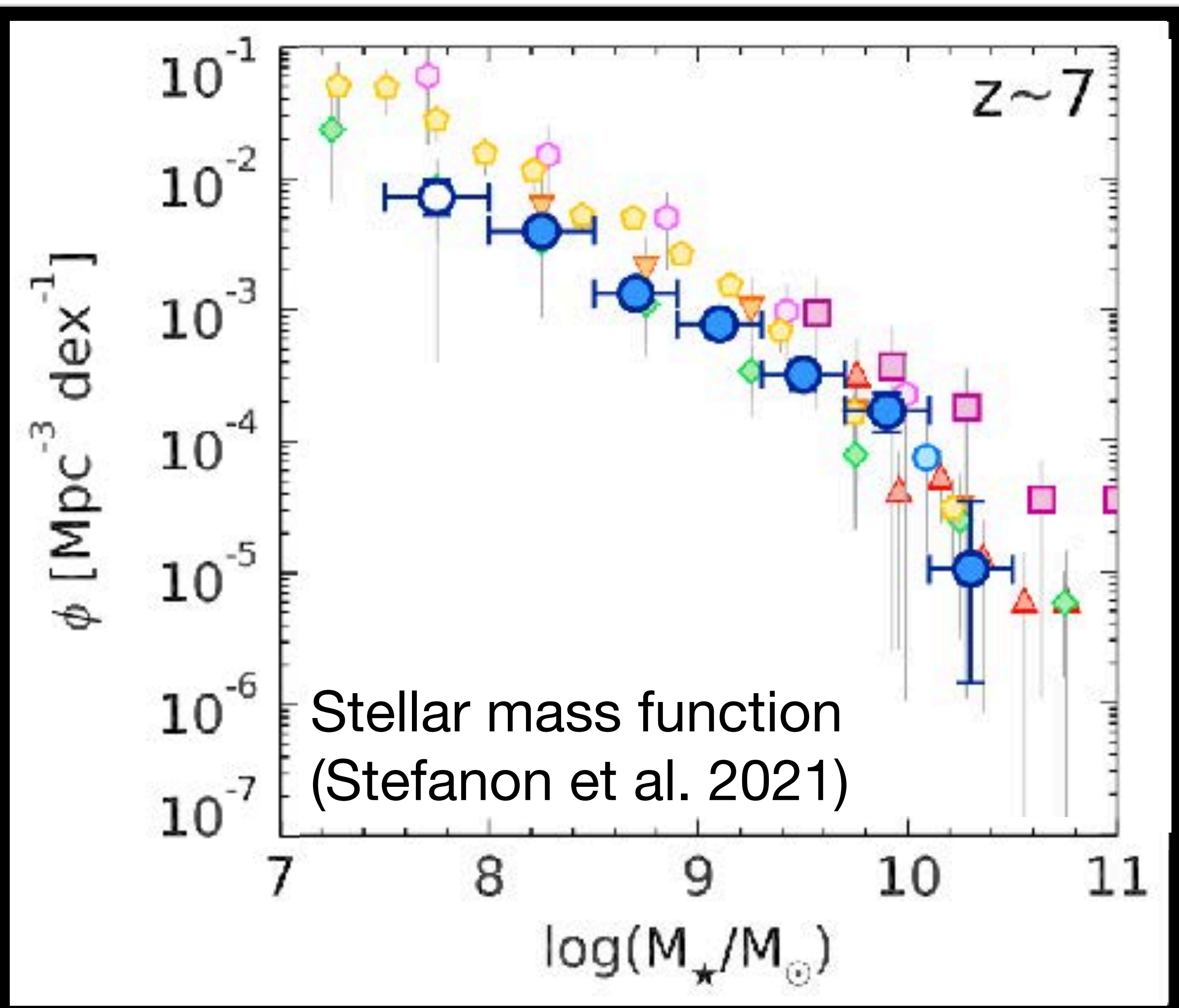
5 Derive IR luminosity density ρ_{IR} using Eq. 3, where x is M_*

$$\rho_{IR} = \int \langle L_{IR} \rangle (x) \phi(x) dx$$

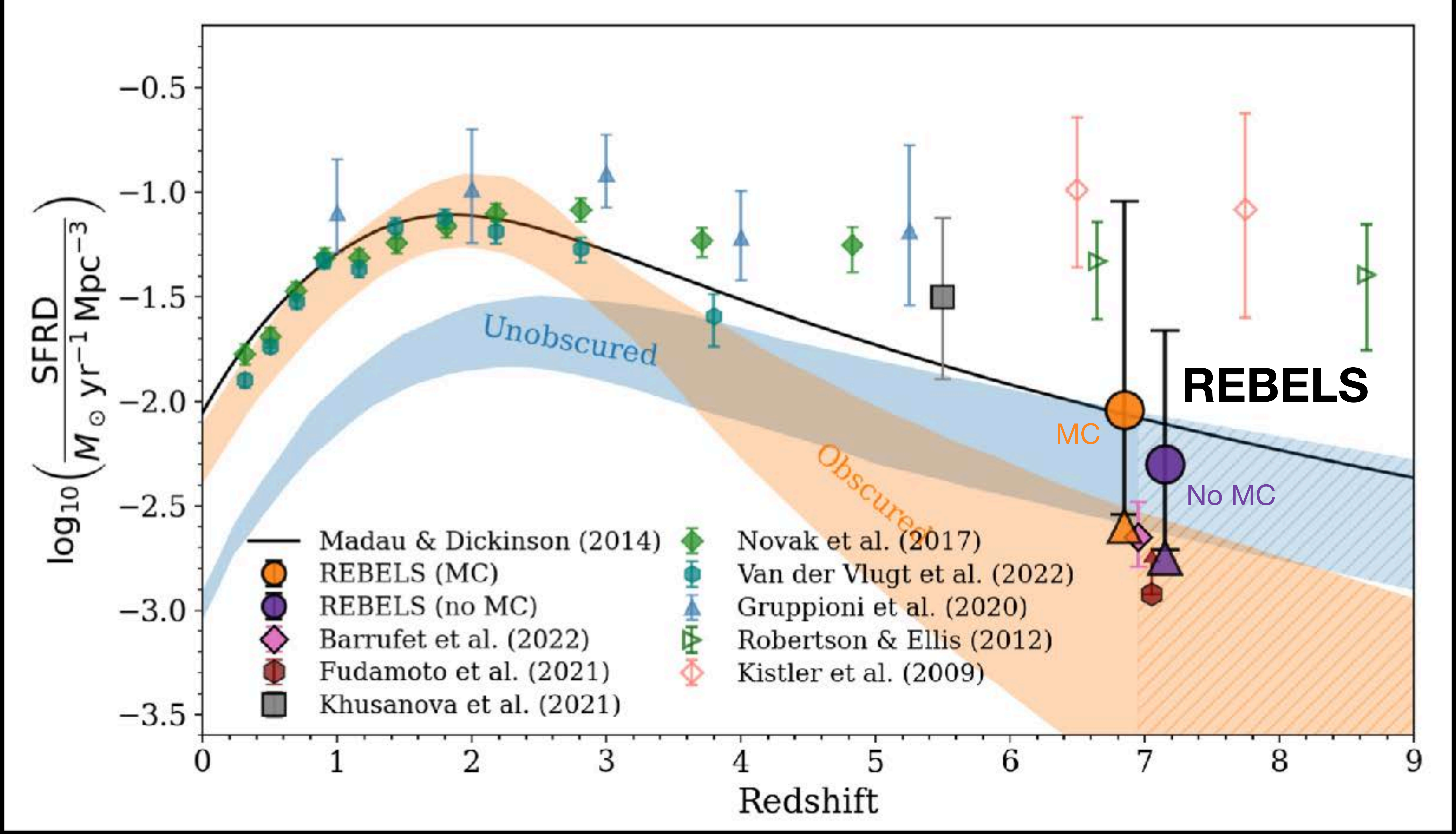
6 Convert ρ_{IR} to $SFRD_{IR}$.

Algera et al. (to be submitted)



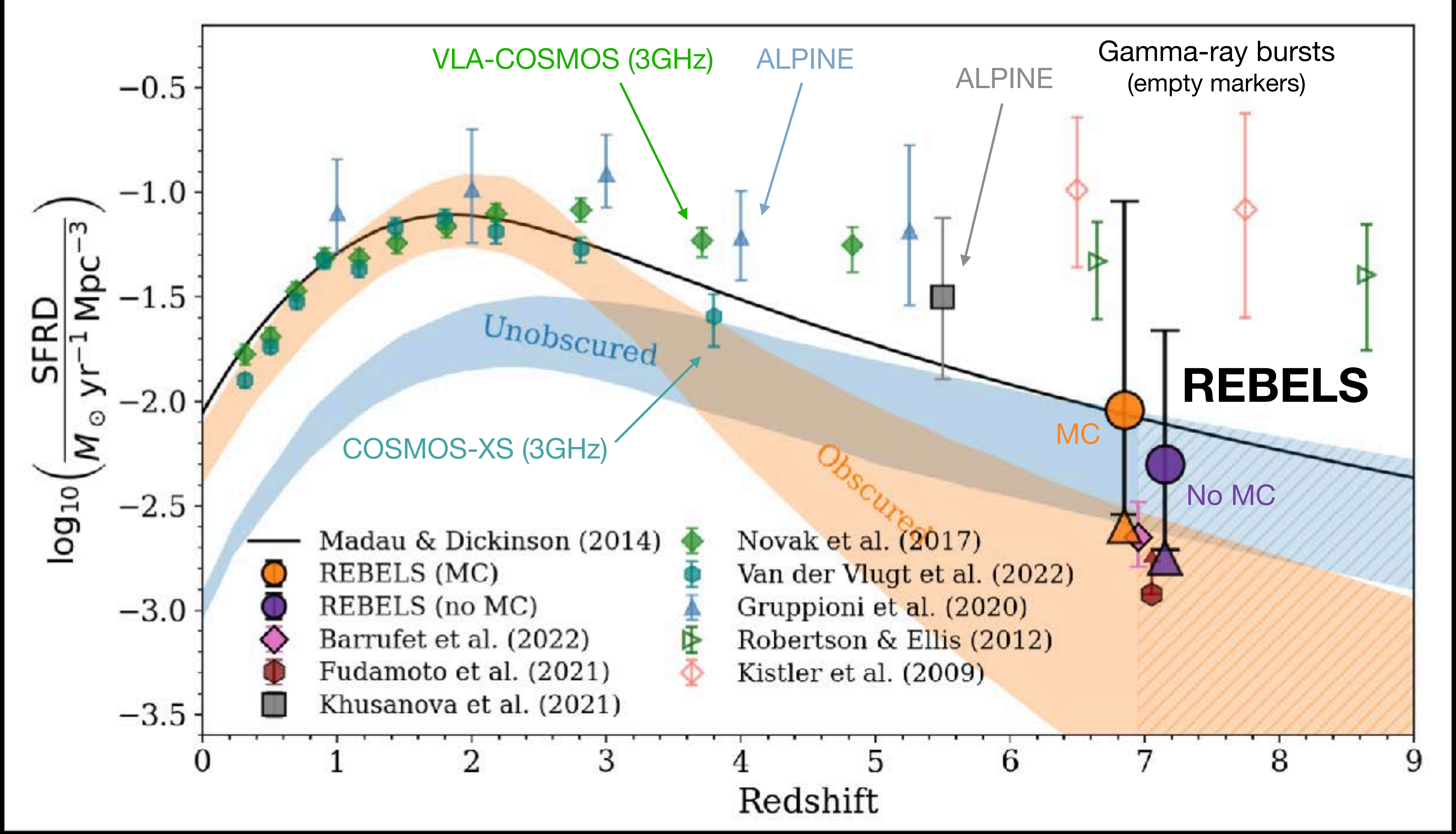


Obscured star formation rate density at z~7



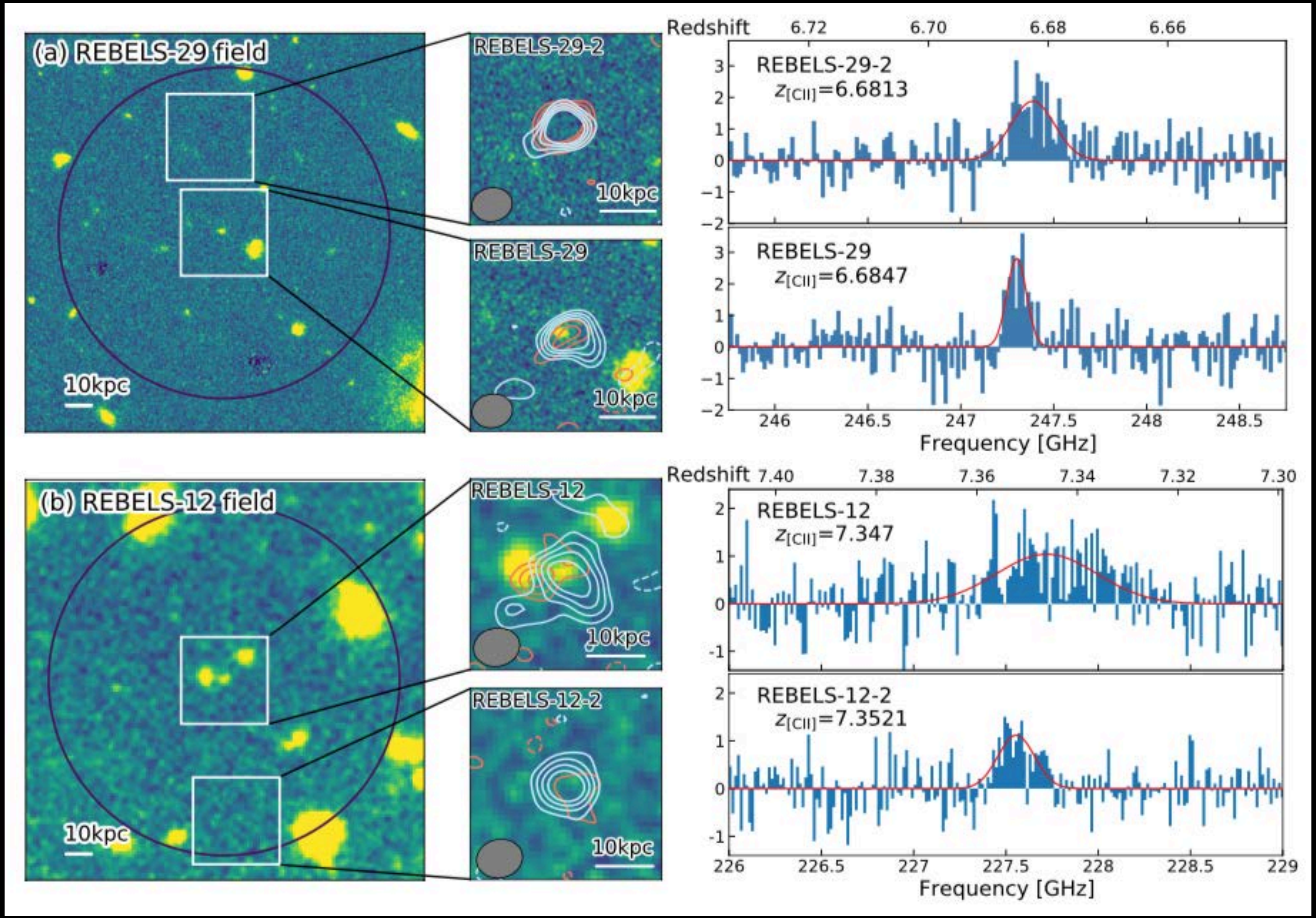
Algera et al. (to be submitted)

Obscured star formation rate density at z~7



Algera et al. (to be submitted)

Missing dusty "normal" populations?



Fudamoto et al. 2021

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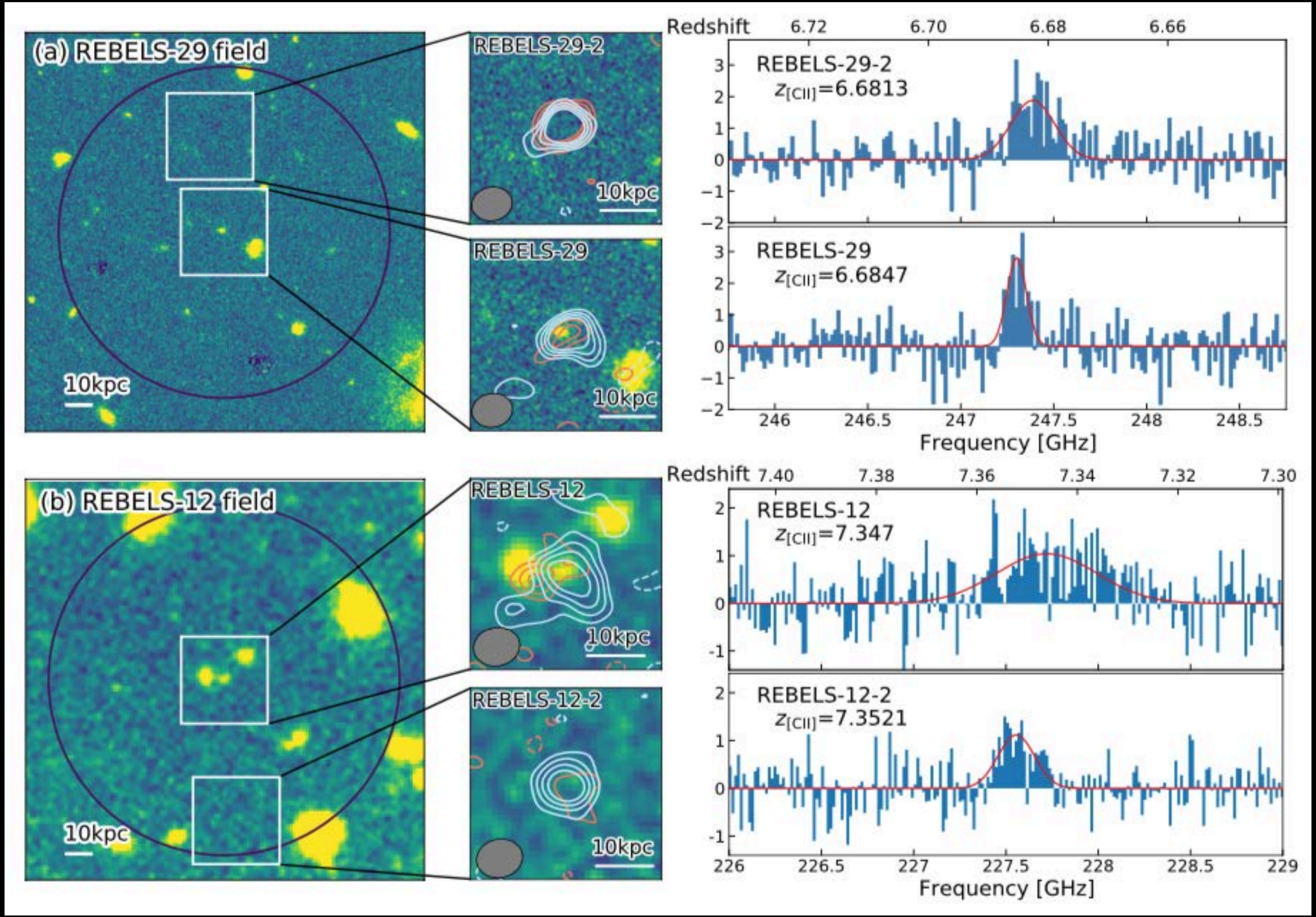
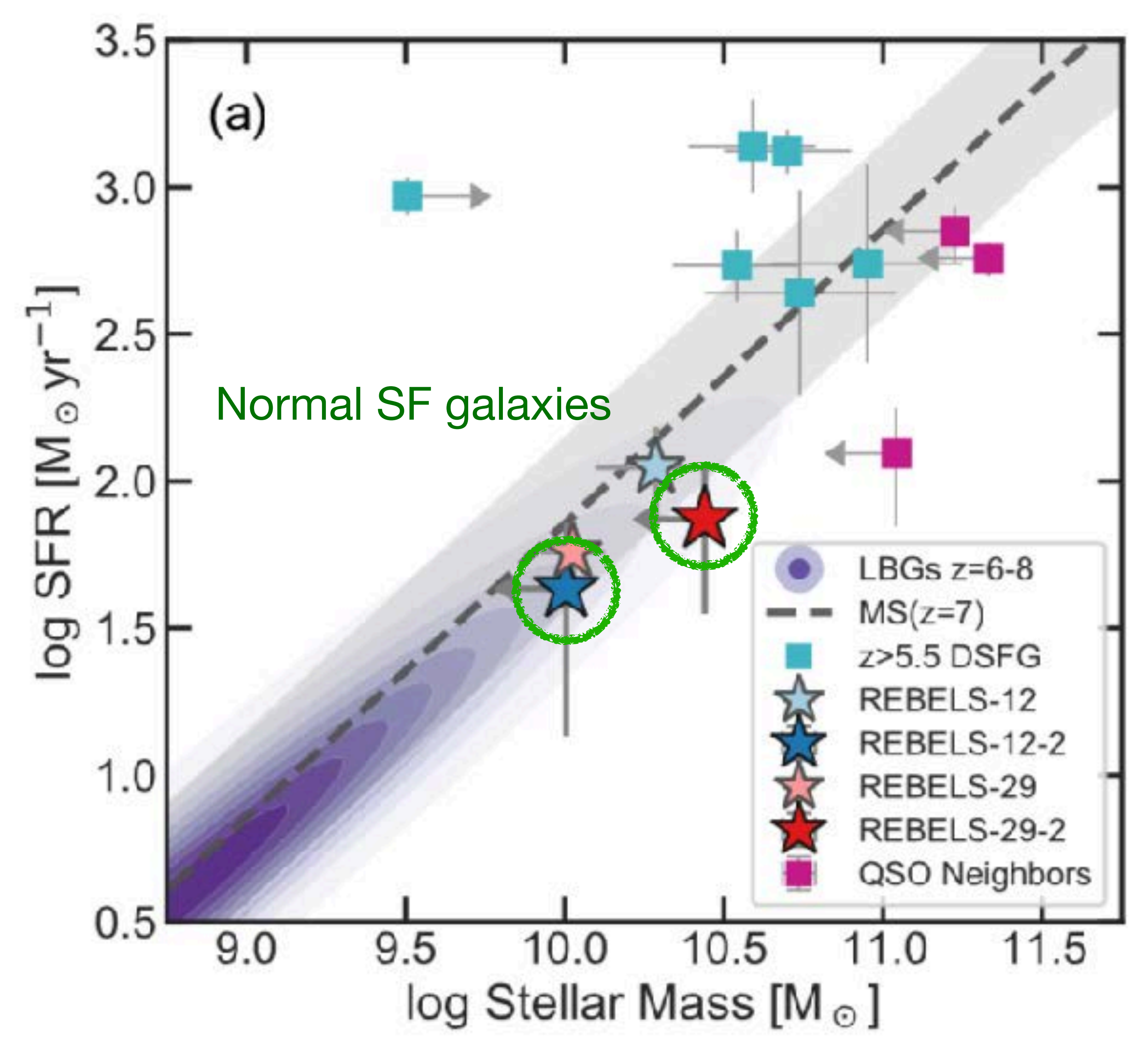
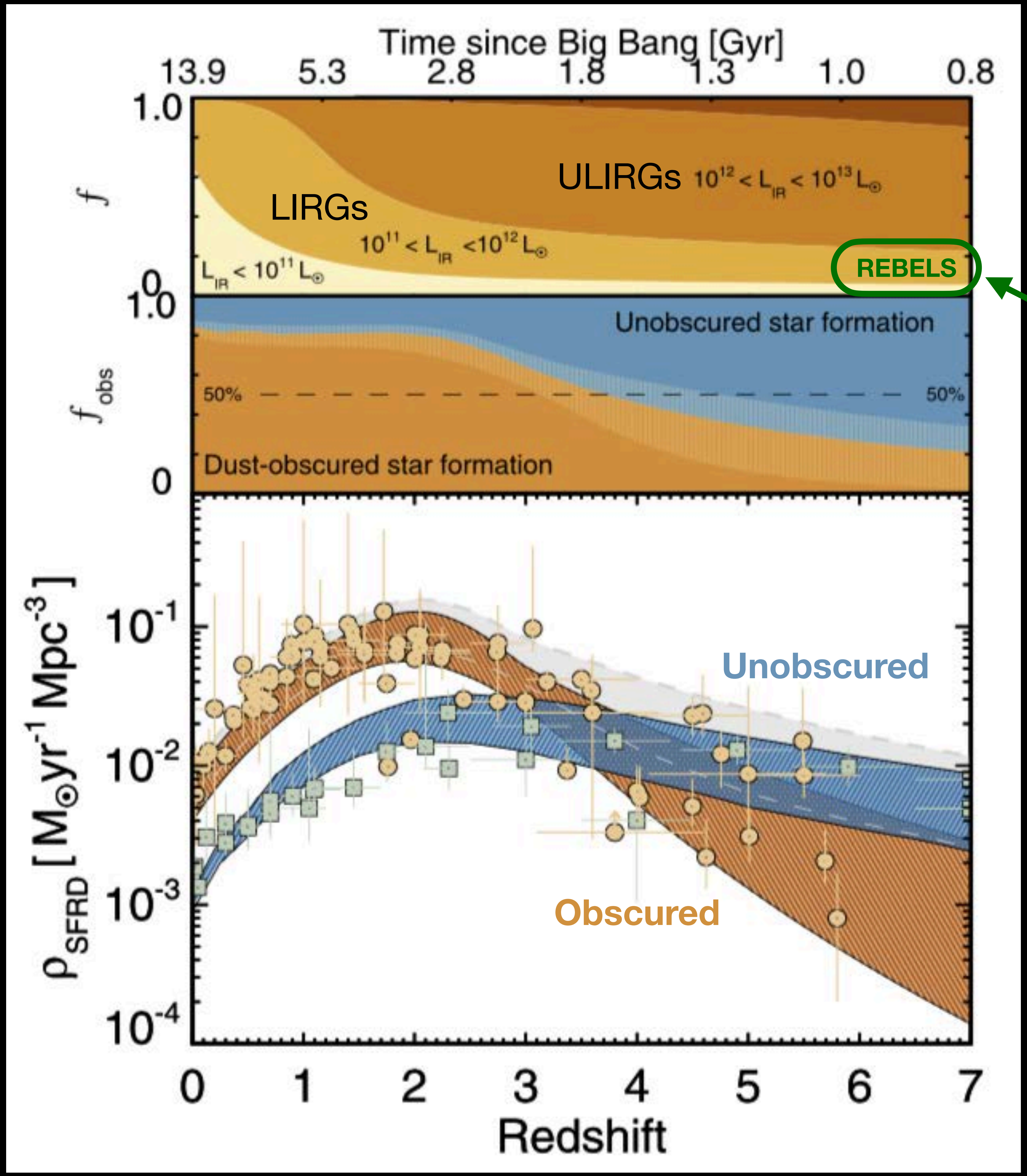


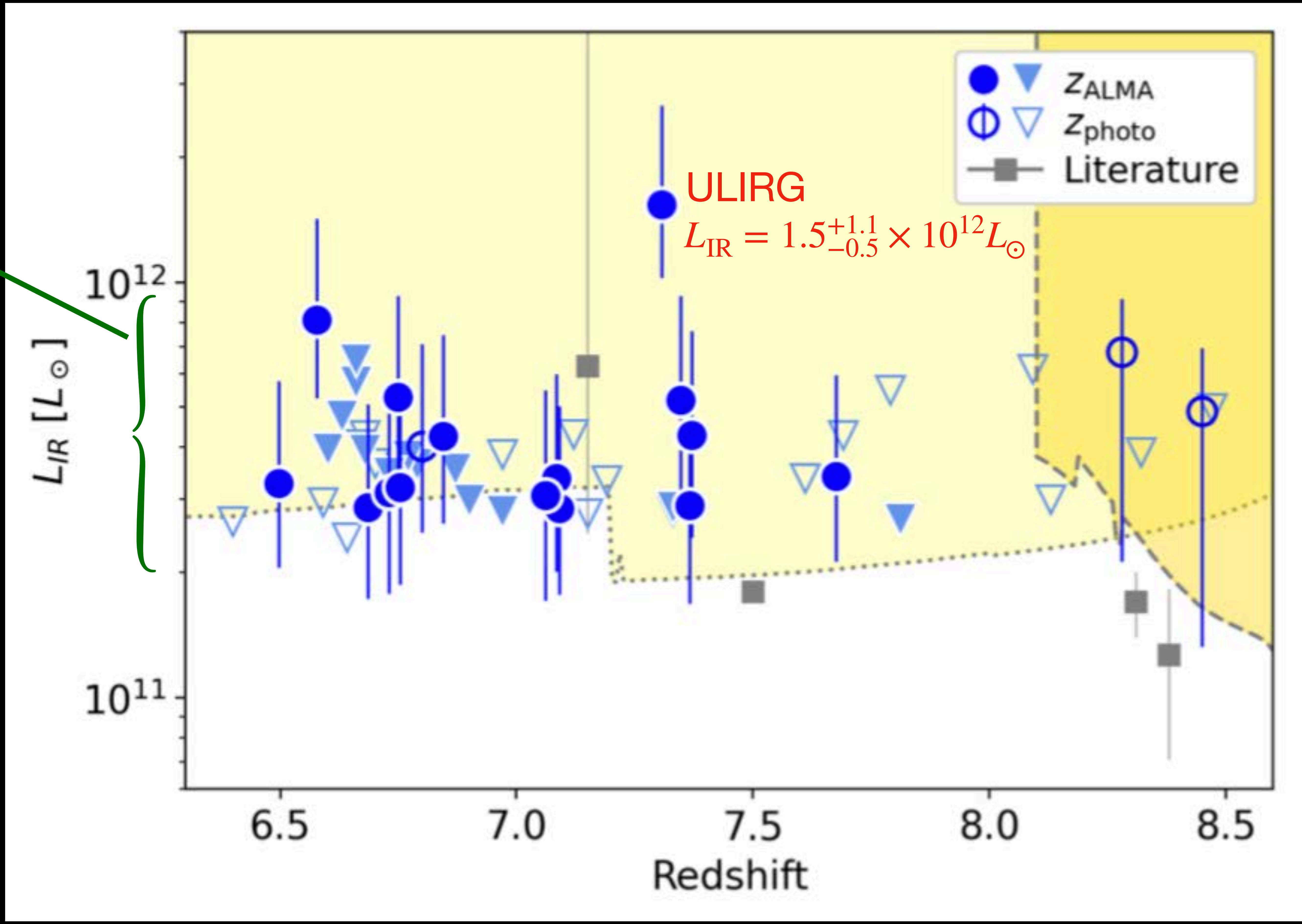


Fudamoto et al. 2021

Most are Luminous Infrared Galaxies

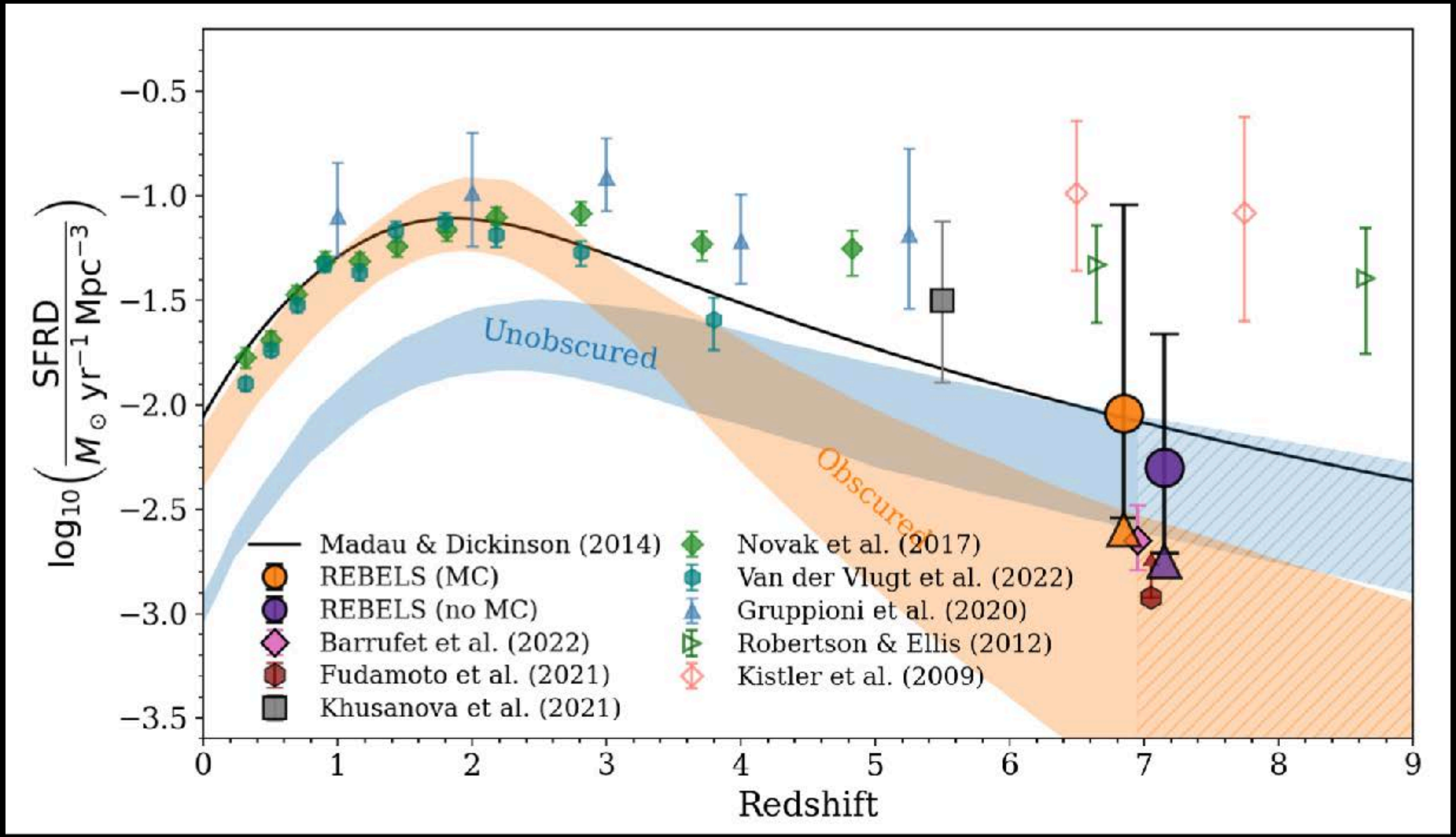


Zavala et al. 2021



Inami et al. (arXiv:2203.15136)

Obscured star formation rate density at z~7

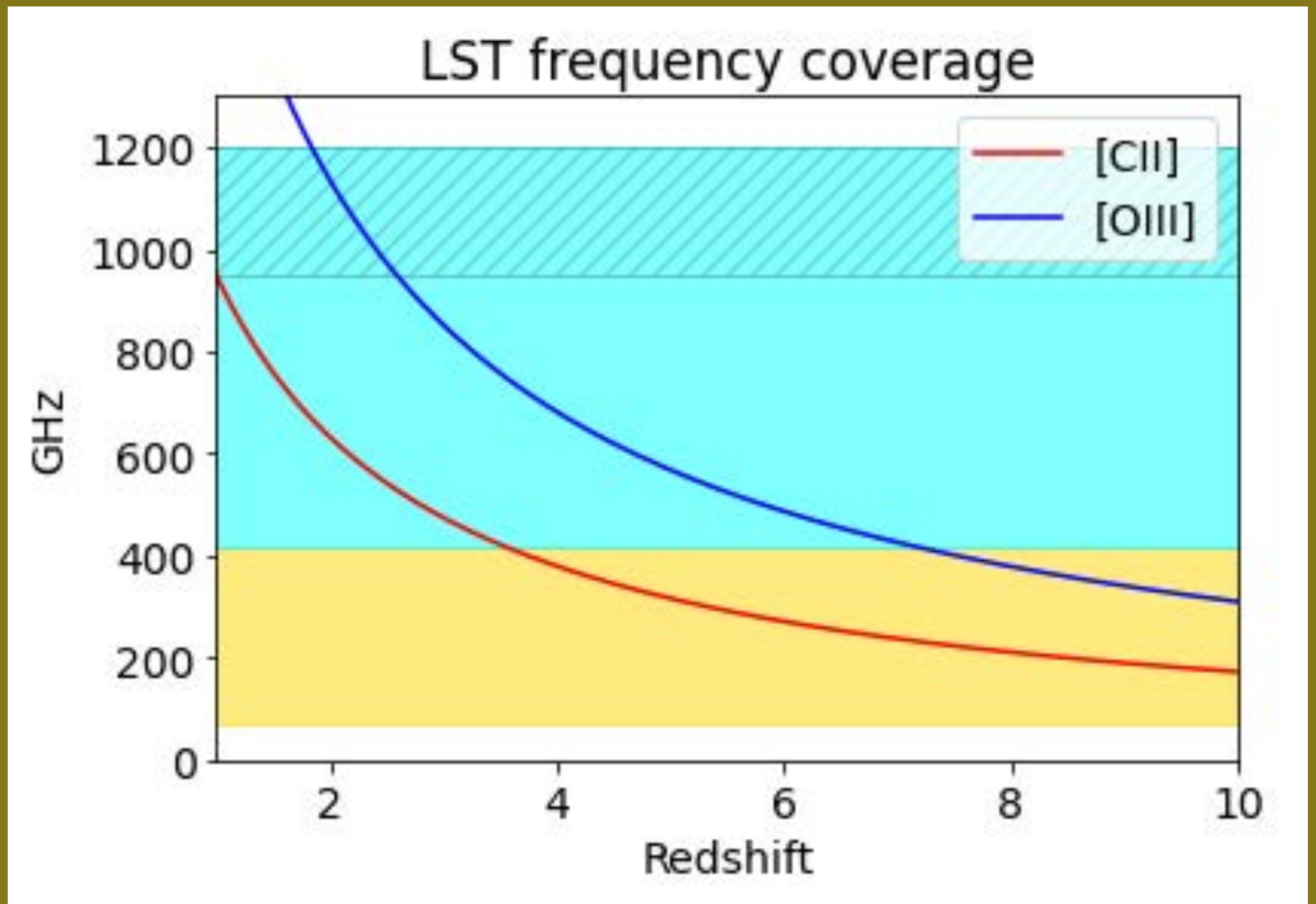


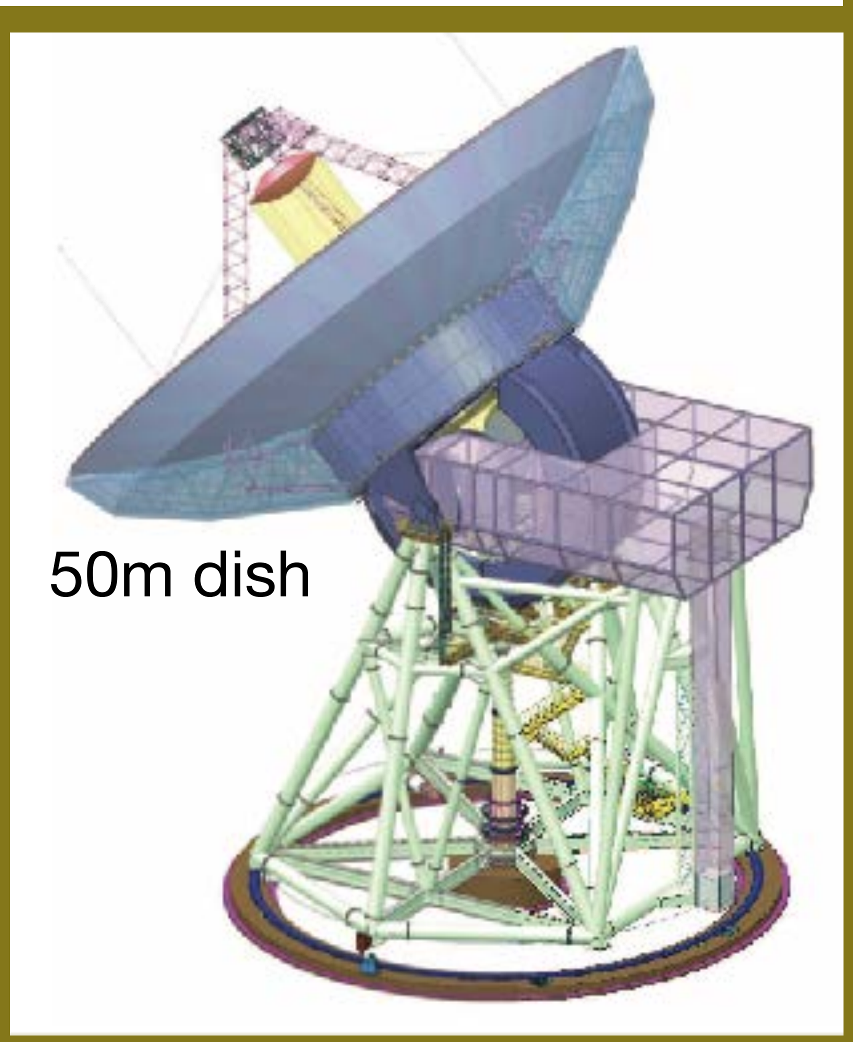
- Large submm blind surveys are needed to fully understand obscured star formation in the early universe
- ALMA:
  - Targeting potential over-density regions (e.g., quasar fields)
- Future large survey telescopes:
  - Large Submillimeter Telescope (LST; Kawabe et al. 2016)
  - Atacama Large Aperture Submillimeter Telescope (AtLAST; Klaassen et al. 2020)

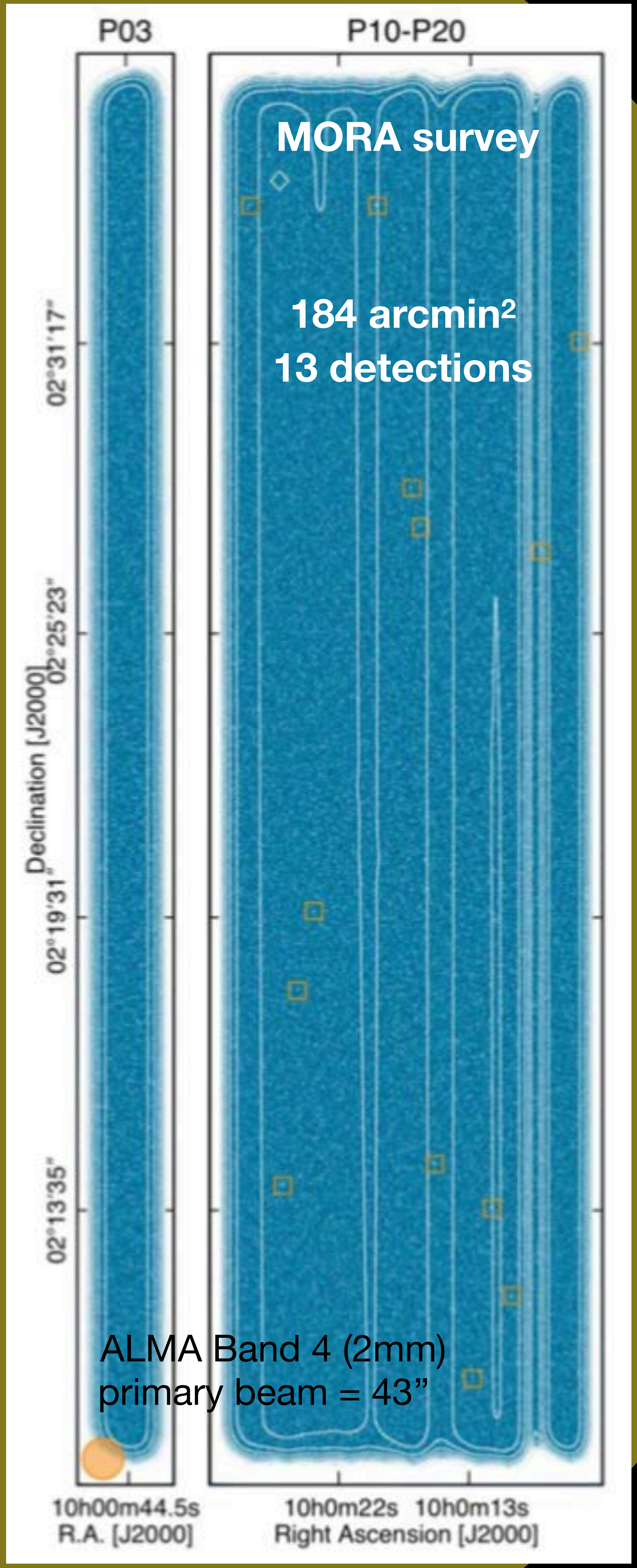
Algera et al. (to be submitted)

Large Submillimeter Telescope

- Large FoV (0.5-1 deg^2)
- Wide wavelength coverage (70-950/1200 GHz)
- High sensitivity
- High mapping speed
- High spatial resolution (for a single dish)







LST's 1 deg^2 FoV

Kawabe et al. 2016

Zavala et al. 2021

Summary

ALMA Cycle-7 Large Program, REBELS

- Systematic survey with detection rates of
  - **[CII]: 24/40 (≧60%)**
    - The spec-z confirmed z > 6.5 galaxies already compete with Lyα
  - **Dust: 16/40 (≧40%)**
    - Increased by 3x at z~7

  Note: spectral scans of 6 galaxies are still incomplete

- **Fraction of obscured star formation is > 50%** for the dust continuum detected galaxies (despite being UV-selected galaxies)

- **Modest decrease of obscured SFR density towards z~7** (Algera et al., Barrufet et al.)
  - All are luminous infrared galaxies (LIRGs) with $10^{11} < L_{IR}/L_{\odot} < 10^{12}$, except one
  - Discovery of two heavily dust obscured galaxies missed by the UV selection, suggesting an incomplete view of cosmic star formation in the early universe (Fudamoto et al. 2021)
  - Need large submm blind surveys to obtain the full picture

More results to come this year!