Caltech ipac

Marseille, July 2022

# ALPINE:

## *A Large Survey to Understand Teenage Galaxies*

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Collage of *ALPINE* galaxies imaged in $C^{+}$ at 158μm with ALMA
Background: II Zw 40 (similar to high-*z* galaxies?)

# The Big Picture of Galaxy Evolution

Hubble Deep Field

# The Universe is diverse …

Star Forming Galaxies
(t = 13.7 Gyrs; z = 0)

Hubble Deep Field

# The Universe is diverse …


Hubble Deep Field

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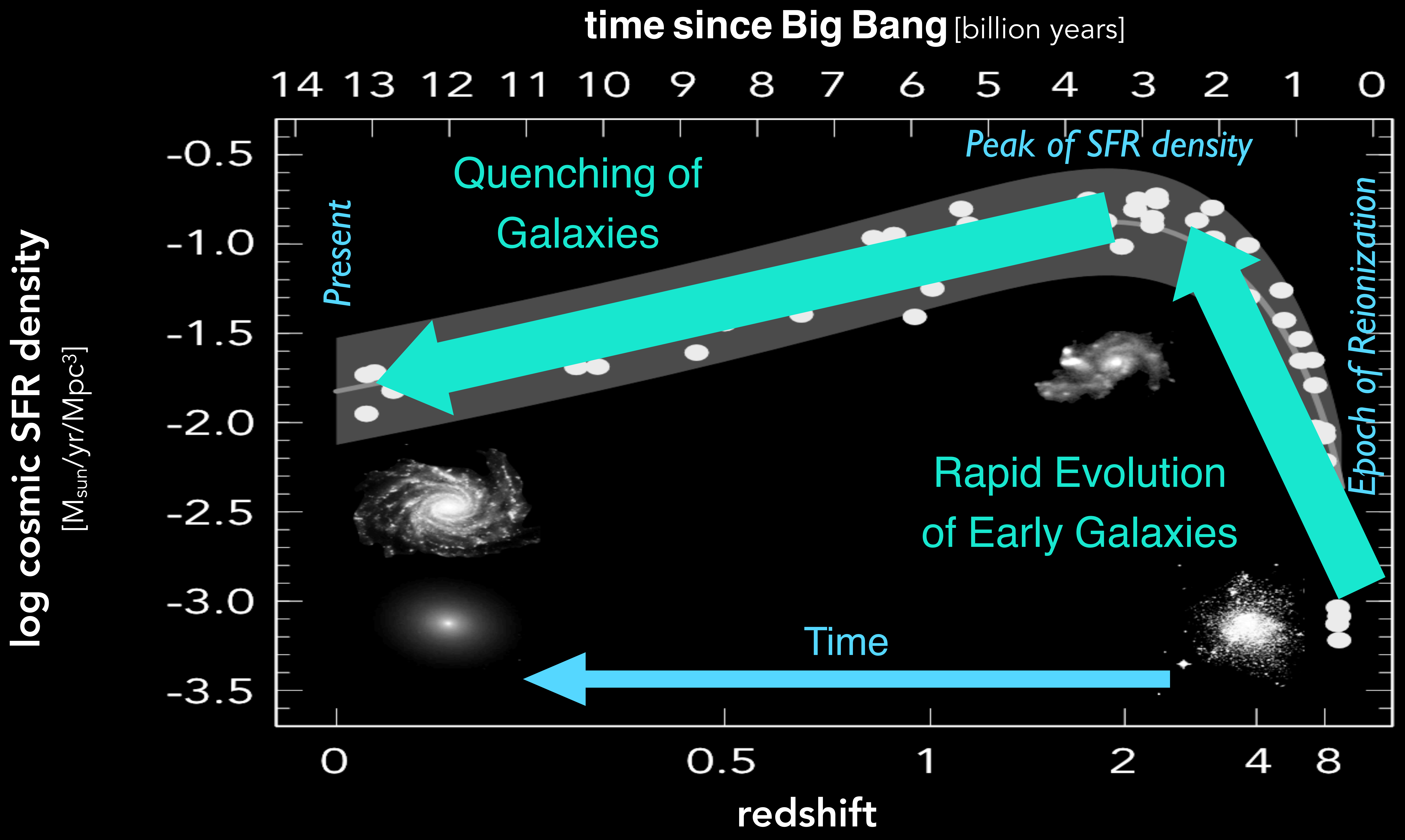
Primordial Galaxy in
the Early Universe
(t = 700 Myrs; z = 7)

Hubble Deep Field

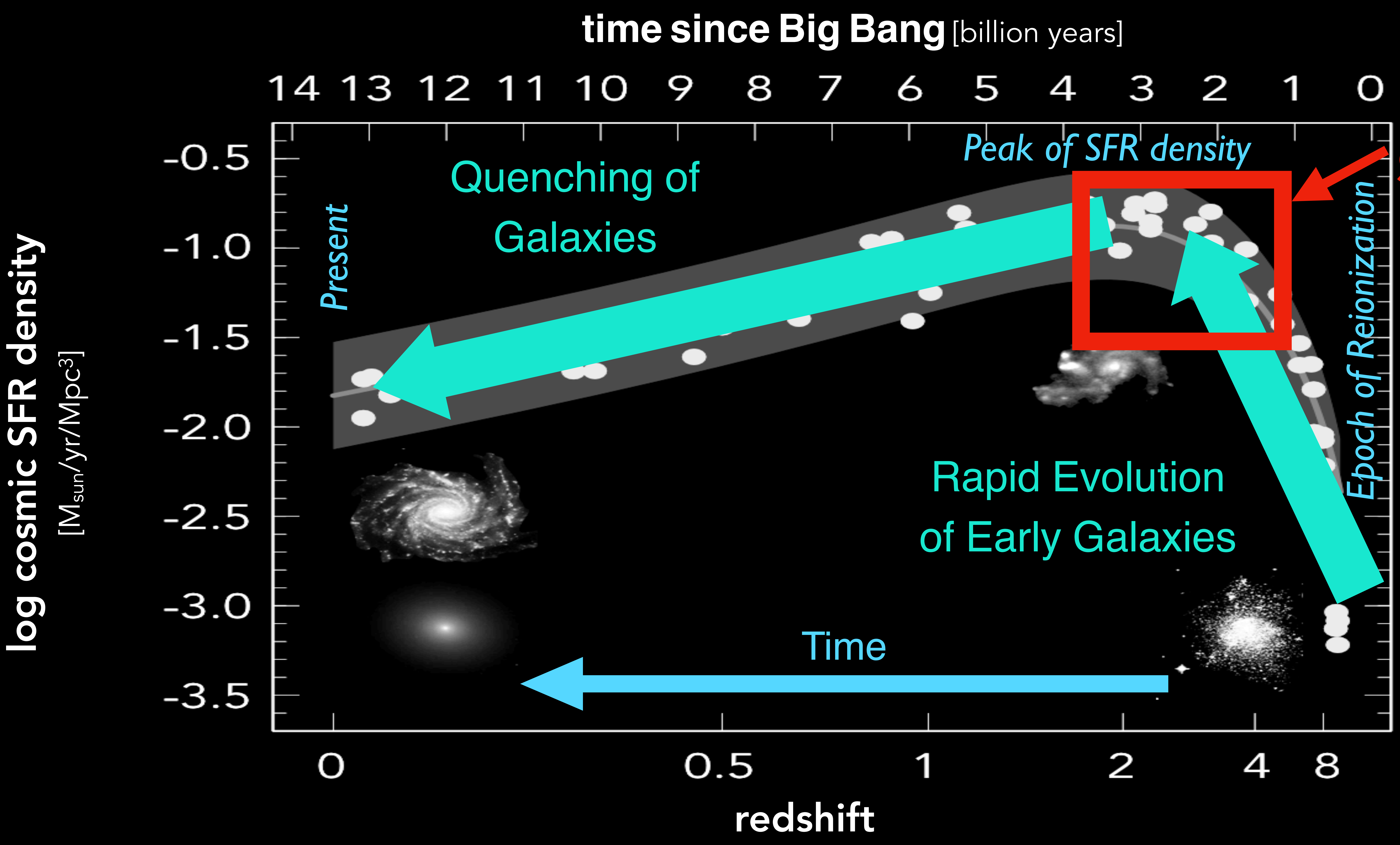

Goal: Find a Coherent physical picture to explain the evolution of galaxies, their interiors, and environment through cosmic time
Time
13.7 Gyrs
(z = 0)
3.2 Gyrs
(z = 2)
700 Myrs
(z = 7)

# Production of Stars and Structure over Cosmic Time




*Data from: Madau & Dickinson (2014); Bouwens et al. (2015)*

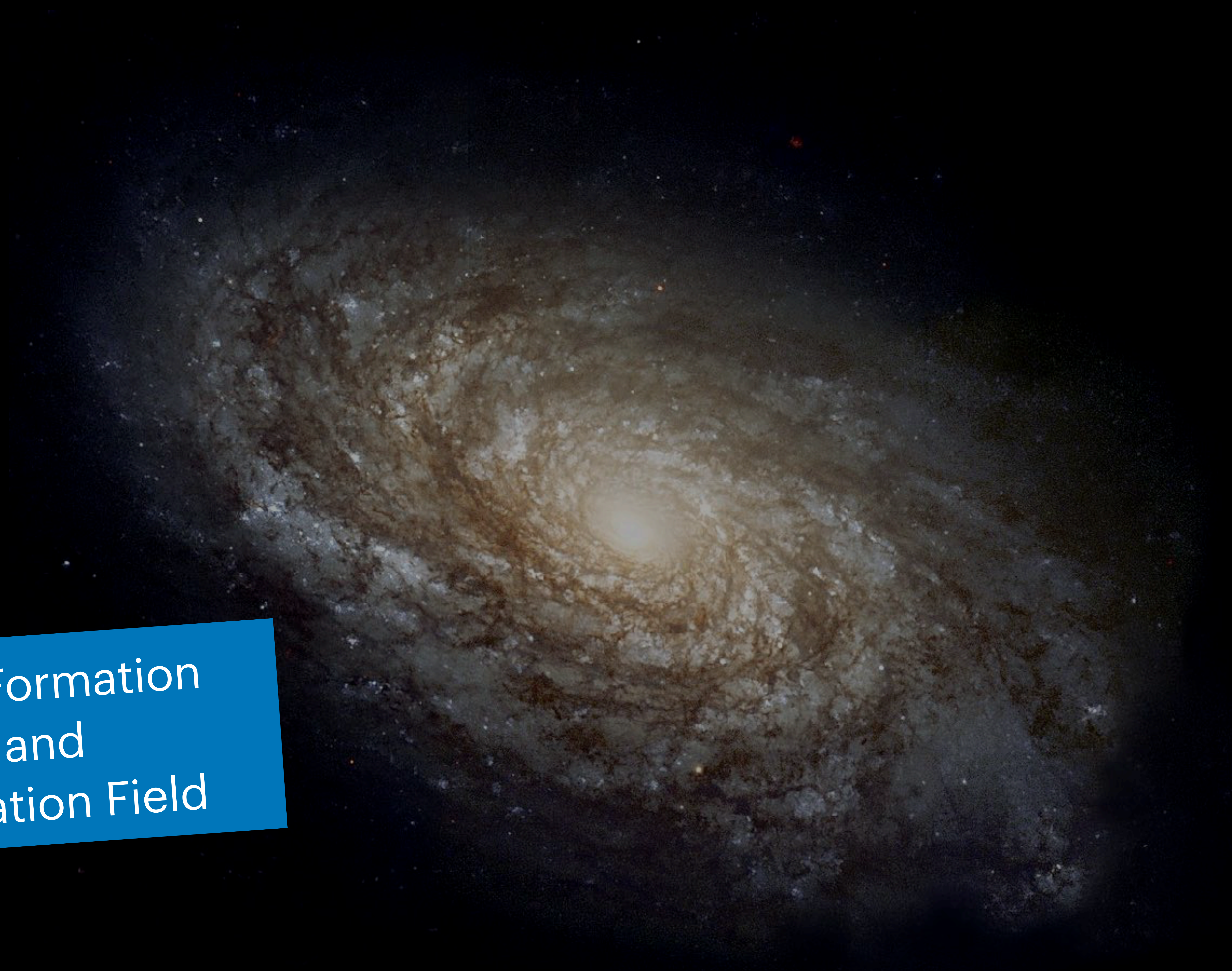
# Production of Stars and Structure over Cosmic Time




How do Galaxies get here?

Data from: Madau & Dickinson (2014); Bouwens et al. (2015)

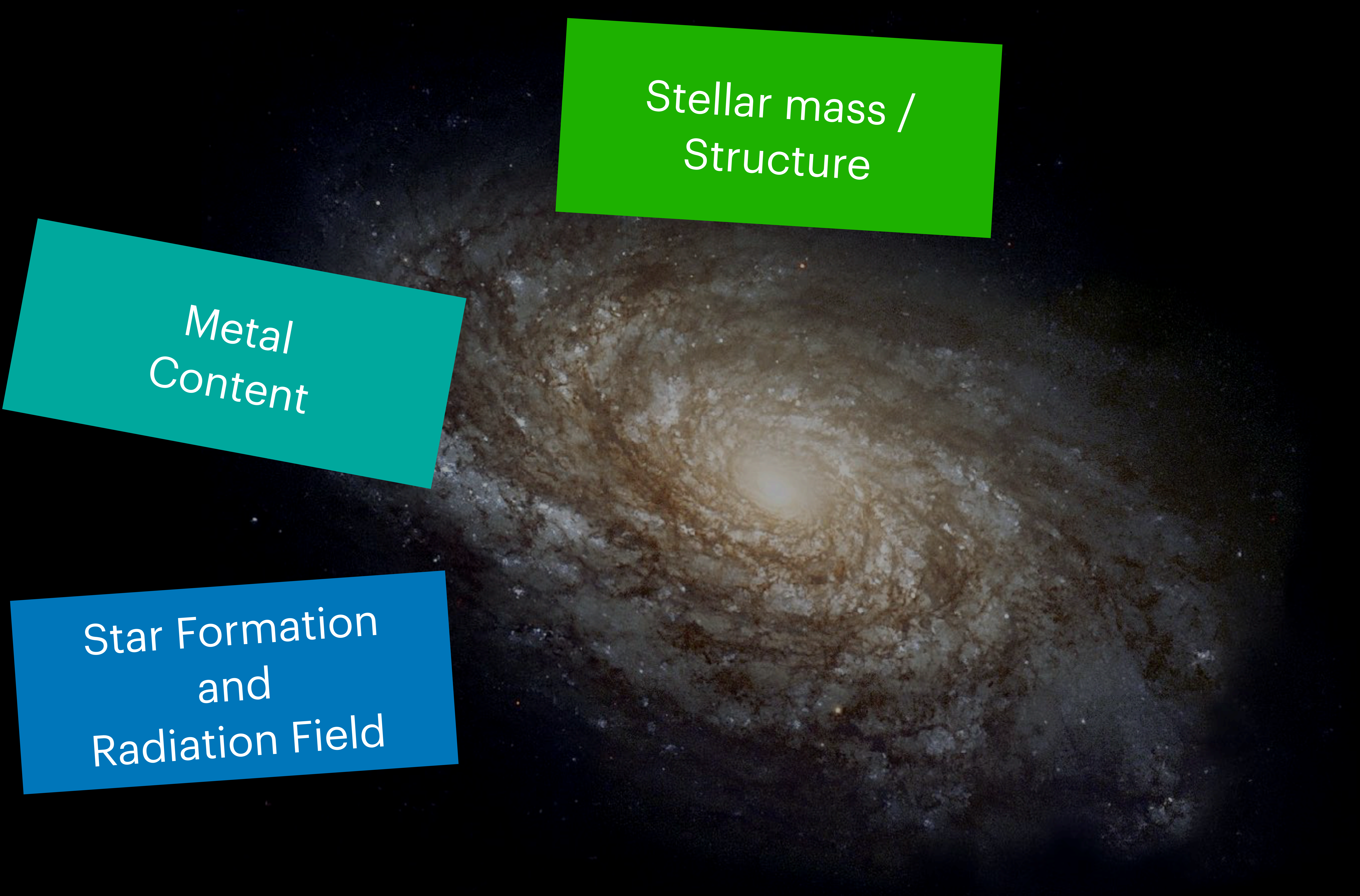
# What characterizes a galaxy?

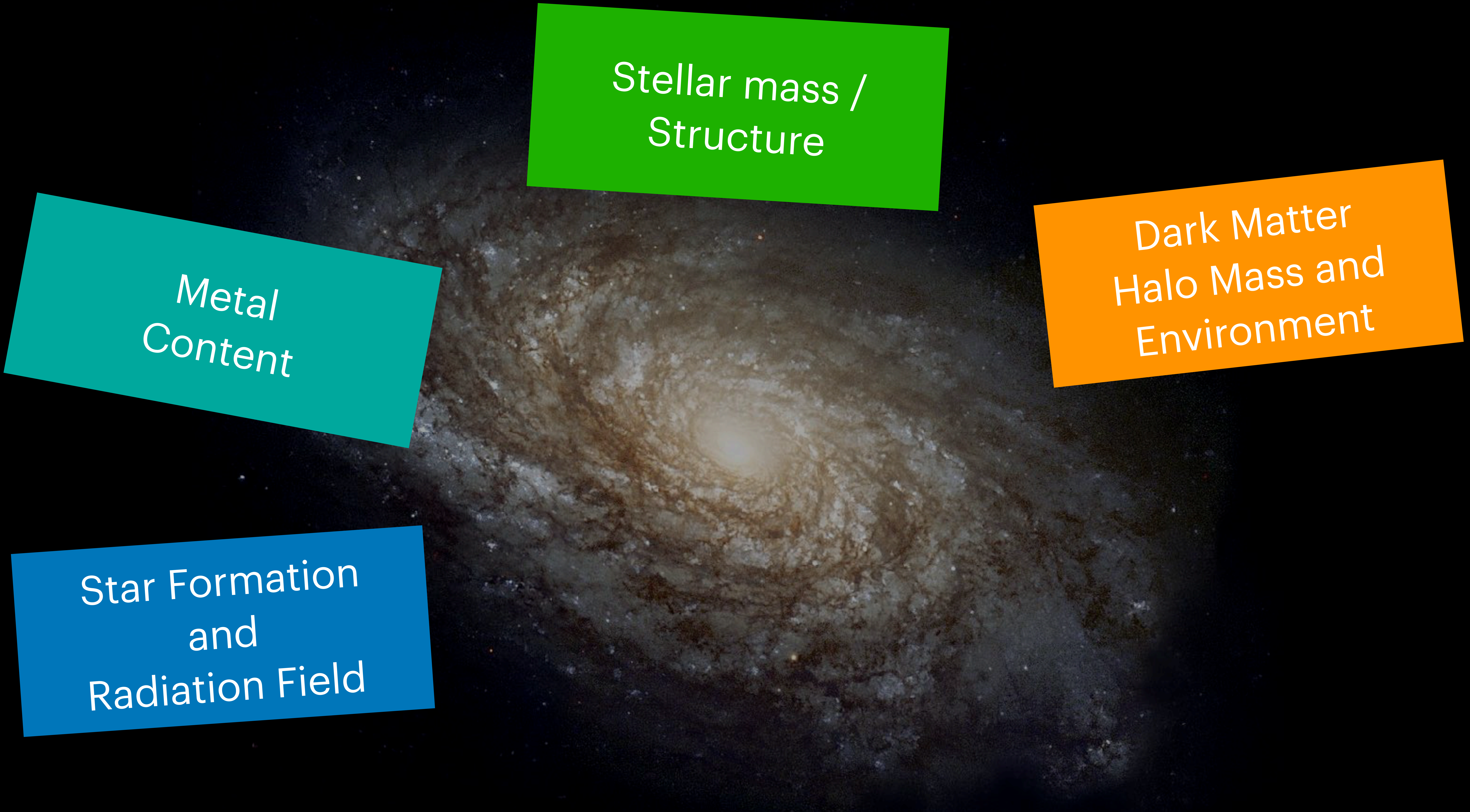


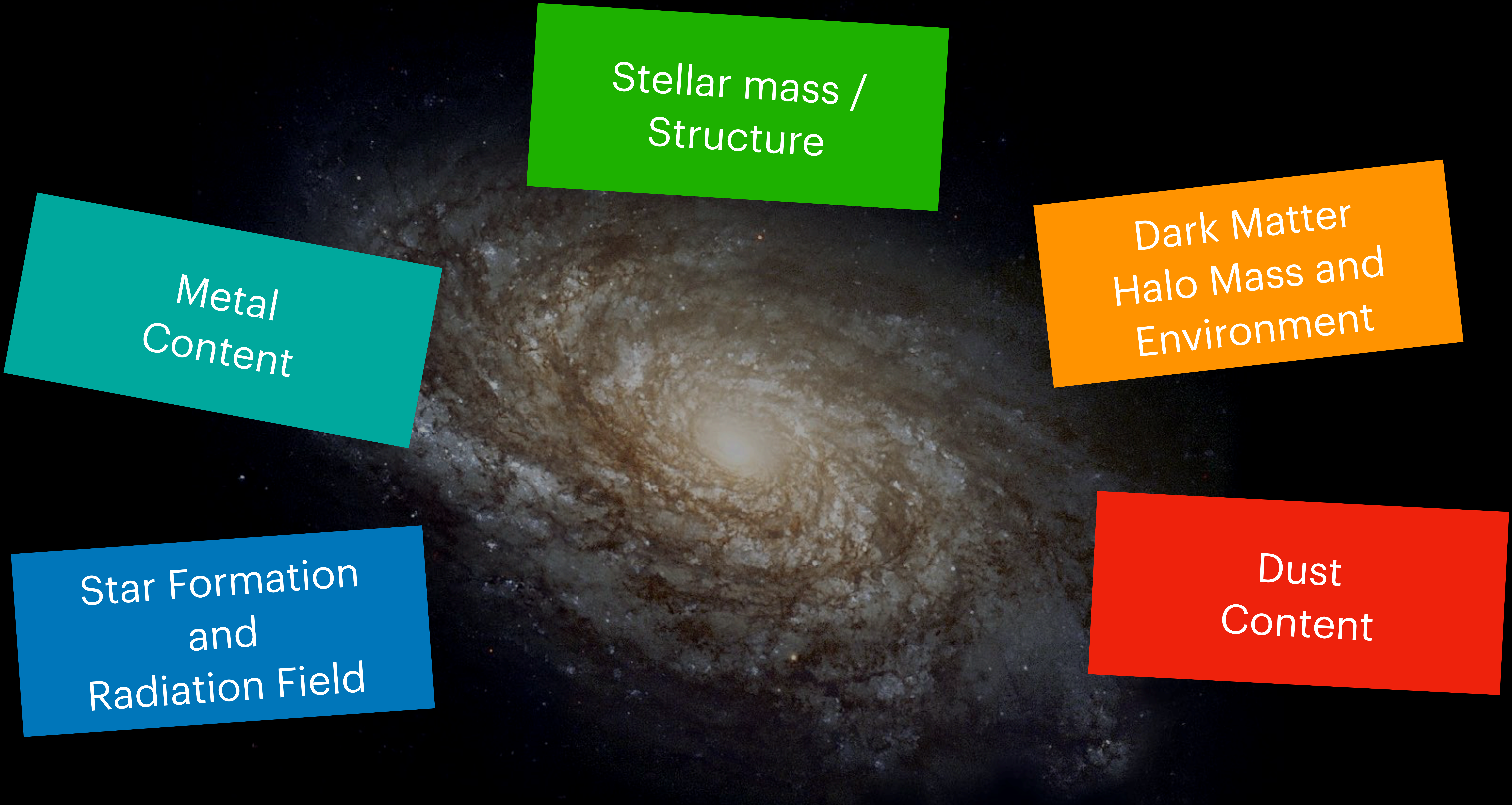
# Star Formation and Radiation Field

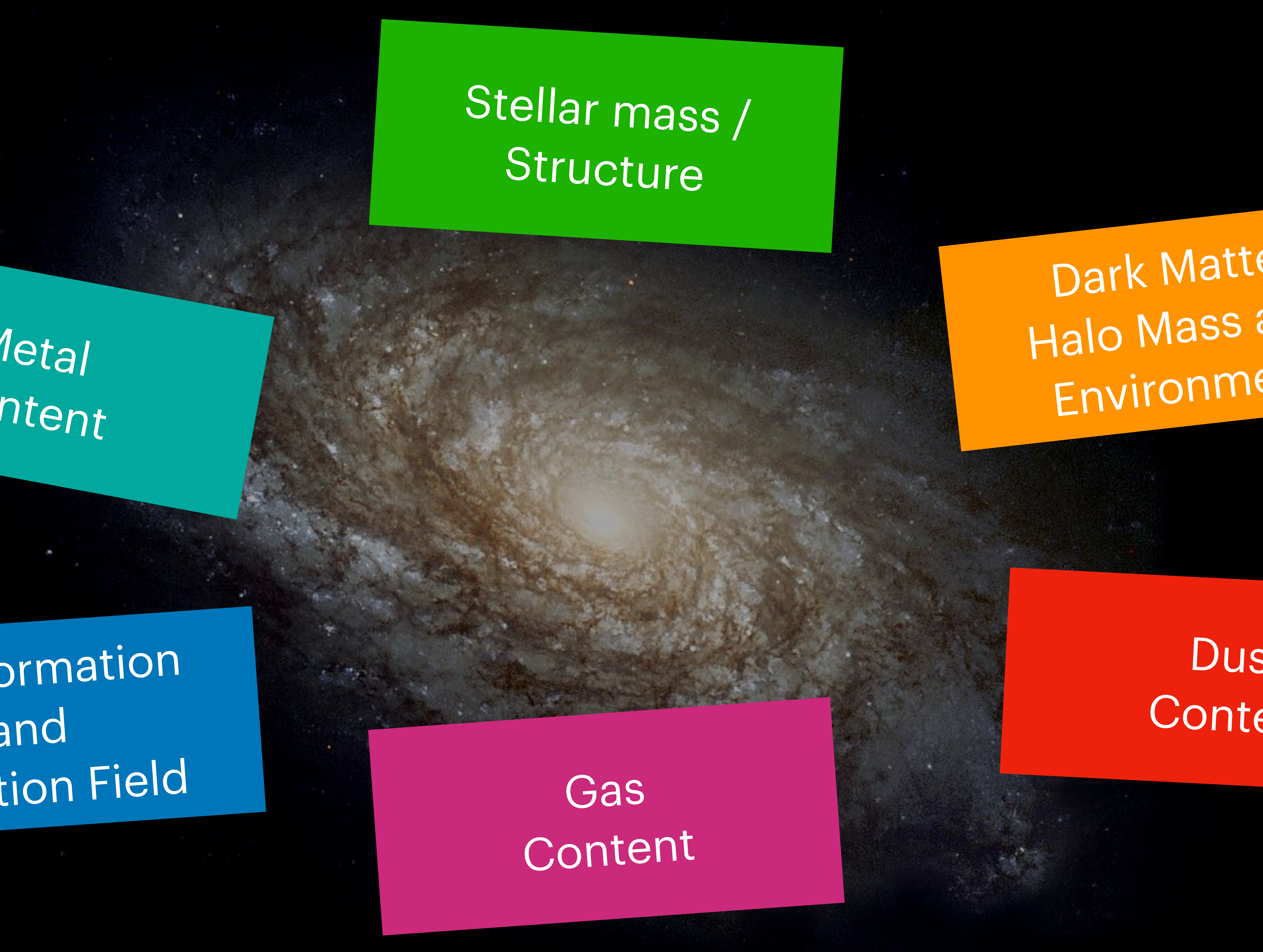
Metal Content

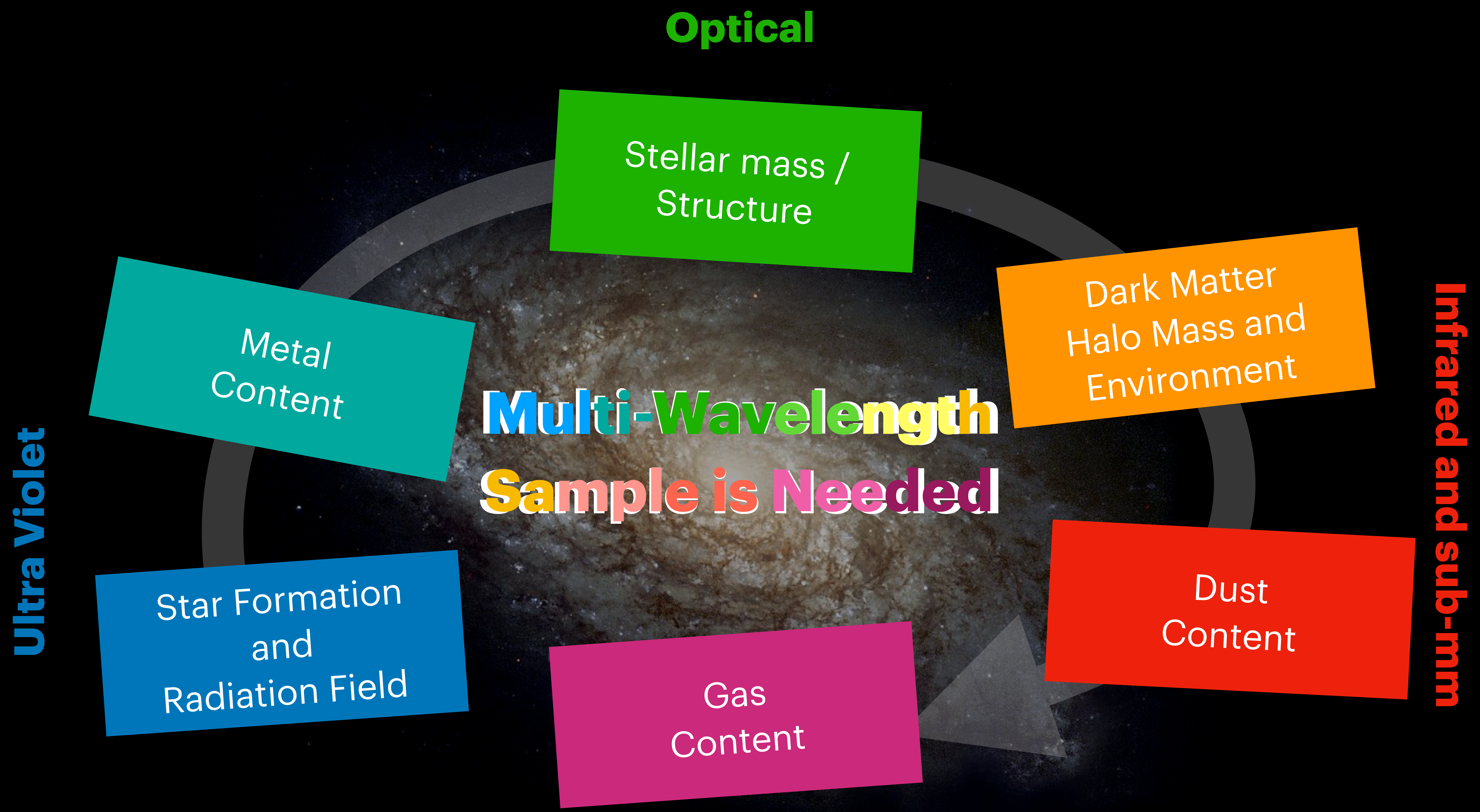
Star Formation and Radiation Field


Stellar mass /
Structure
Metal
Content
Star Formation
and
Radiation Field


Stellar mass / Structure
Metal Content
Dark Matter Halo Mass and Environment
Star Formation and Radiation Field


Stellar mass / Structure
Metal Content
Dark Matter Halo Mass and Environment
Star Formation and Radiation Field
Dust Content


Stellar mass /
Structure
Metal
Content
Dark Matter
Halo Mass and
Environment
Star Formation
and
Radiation Field
Dust
Content
Gas
Content


Optical
Stellar mass / Structure
Dark Matter Halo Mass and Environment
Infrared and sub-mm
Dust Content
Gas Content
Star Formation and Radiation Field
Ultra Violet
Metal Content
Multi-Wavelength Sample is Needed

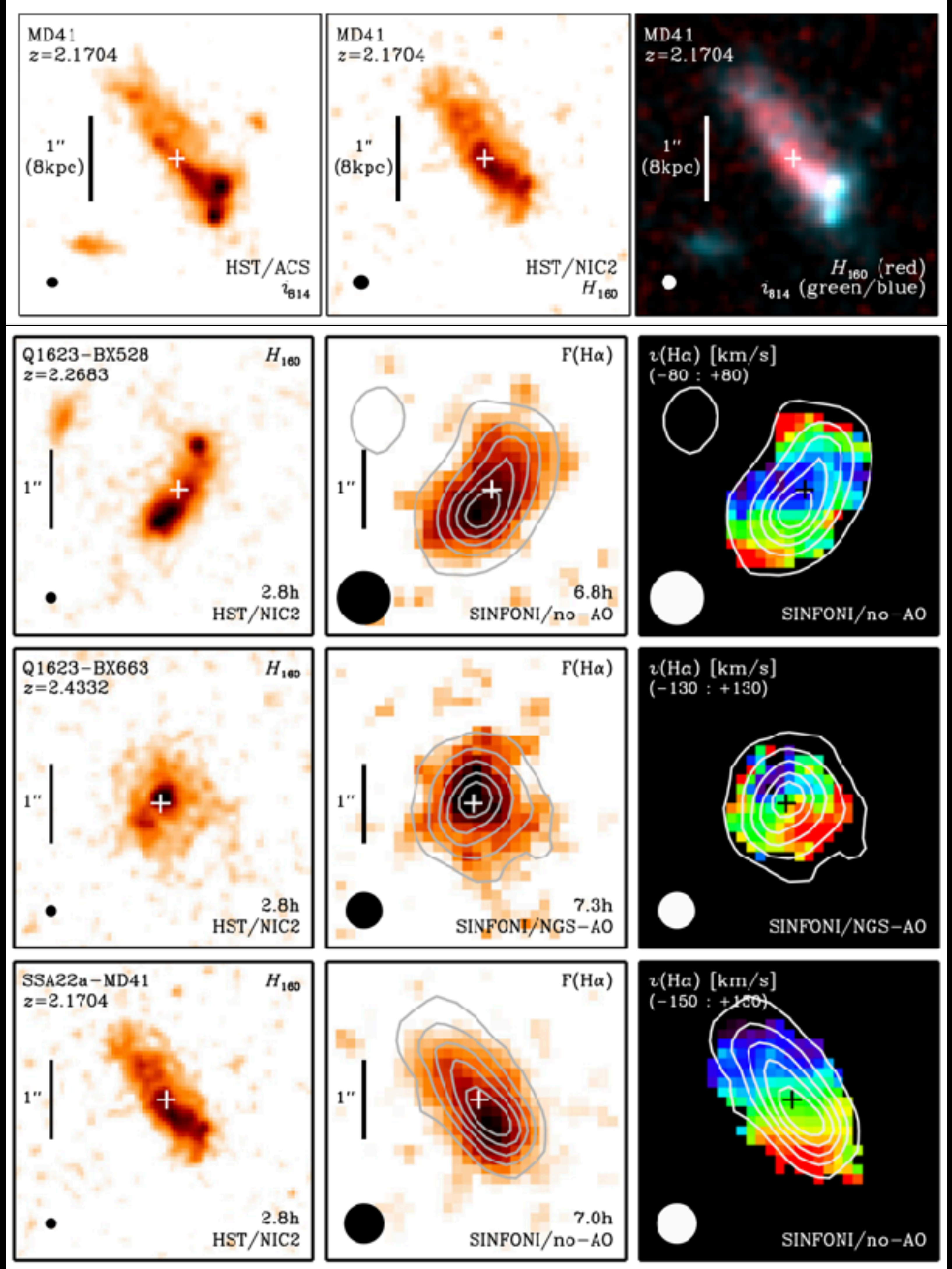
# Can we extrapolate from lower redshifts?

# Extrapolation from Lower Redshifts

We can (maybe?) extrapolate the properties of high-z galaxies from galaxies at lower redshifts (z < 3)

- Irregular structure, suggesting turbulent gas accretion and growth, and possible lack of "disk galaxies"


z = 2



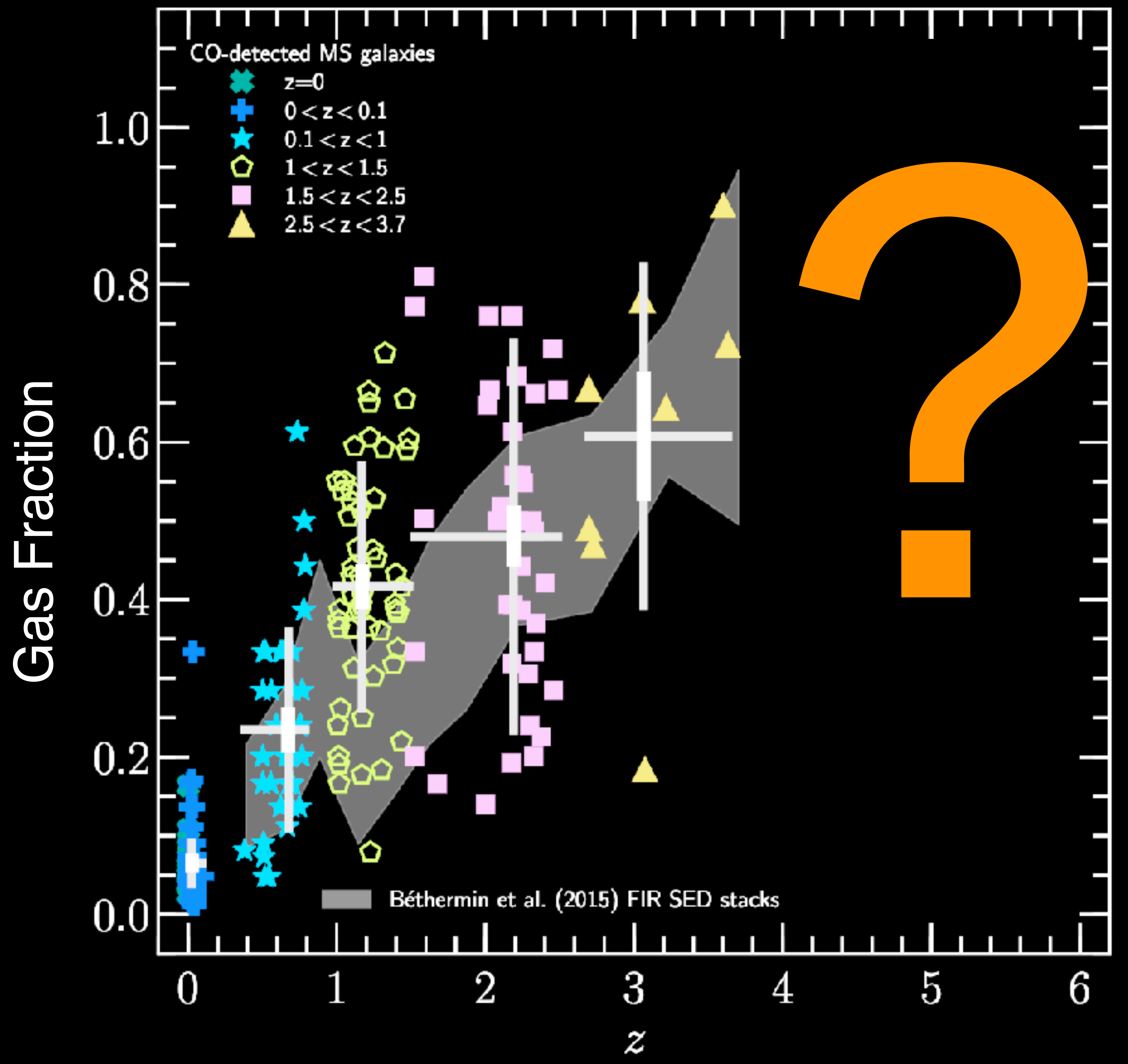

Förster-Schreiber et al. (2011)

# Extrapolation from Lower Redshifts

We can (maybe?) extrapolate the properties of high-z galaxies from galaxies at lower redshifts (z < 3)

- Irregular structure, suggesting turbulent gas accretion and growth, and possible lack of "disk galaxies"
- Galaxies are rich in gas, suggesting high star formation rates

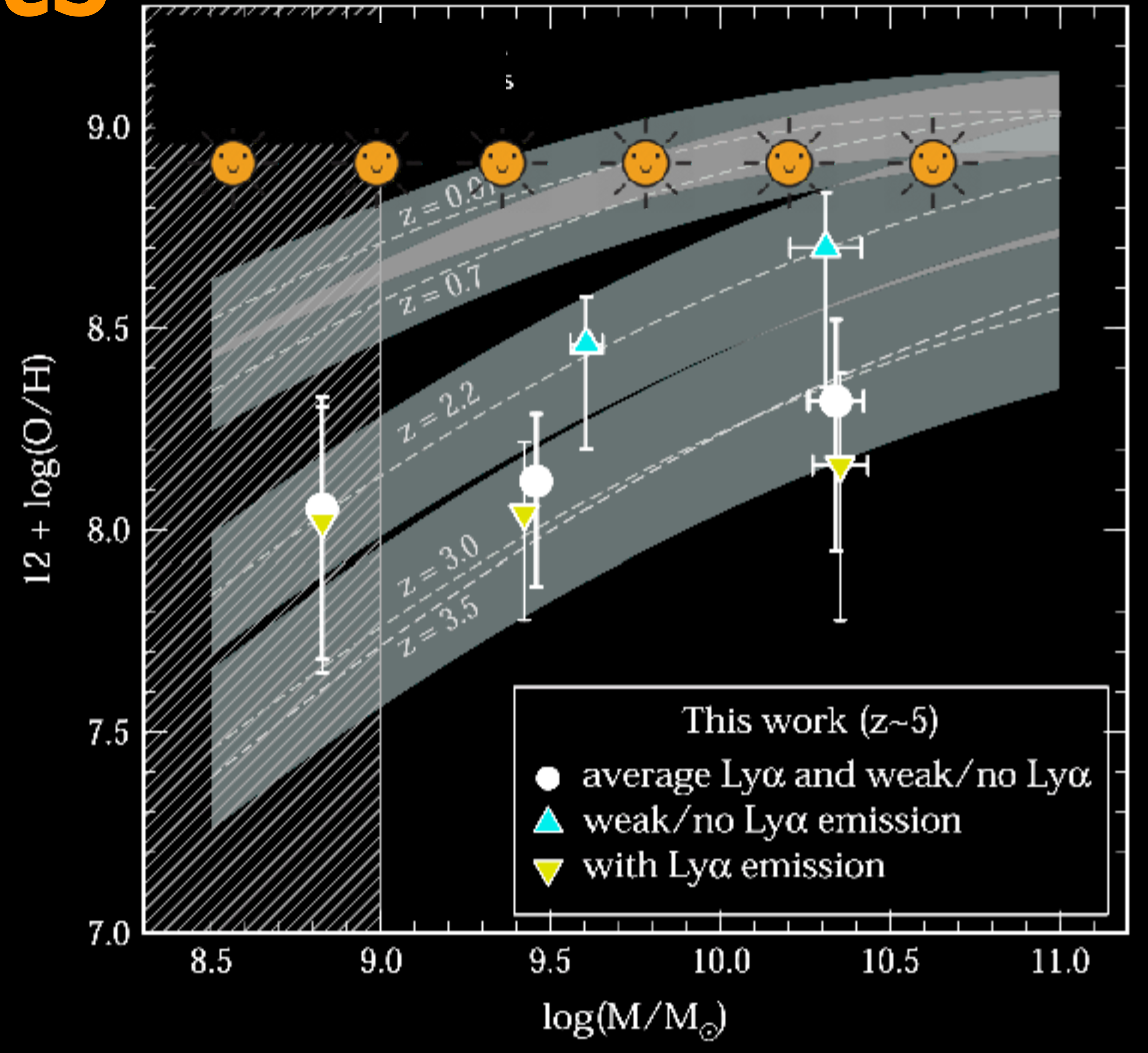
*Dessauges-Zavadsky et al. (2020)*
*see also Tacconi et al.*



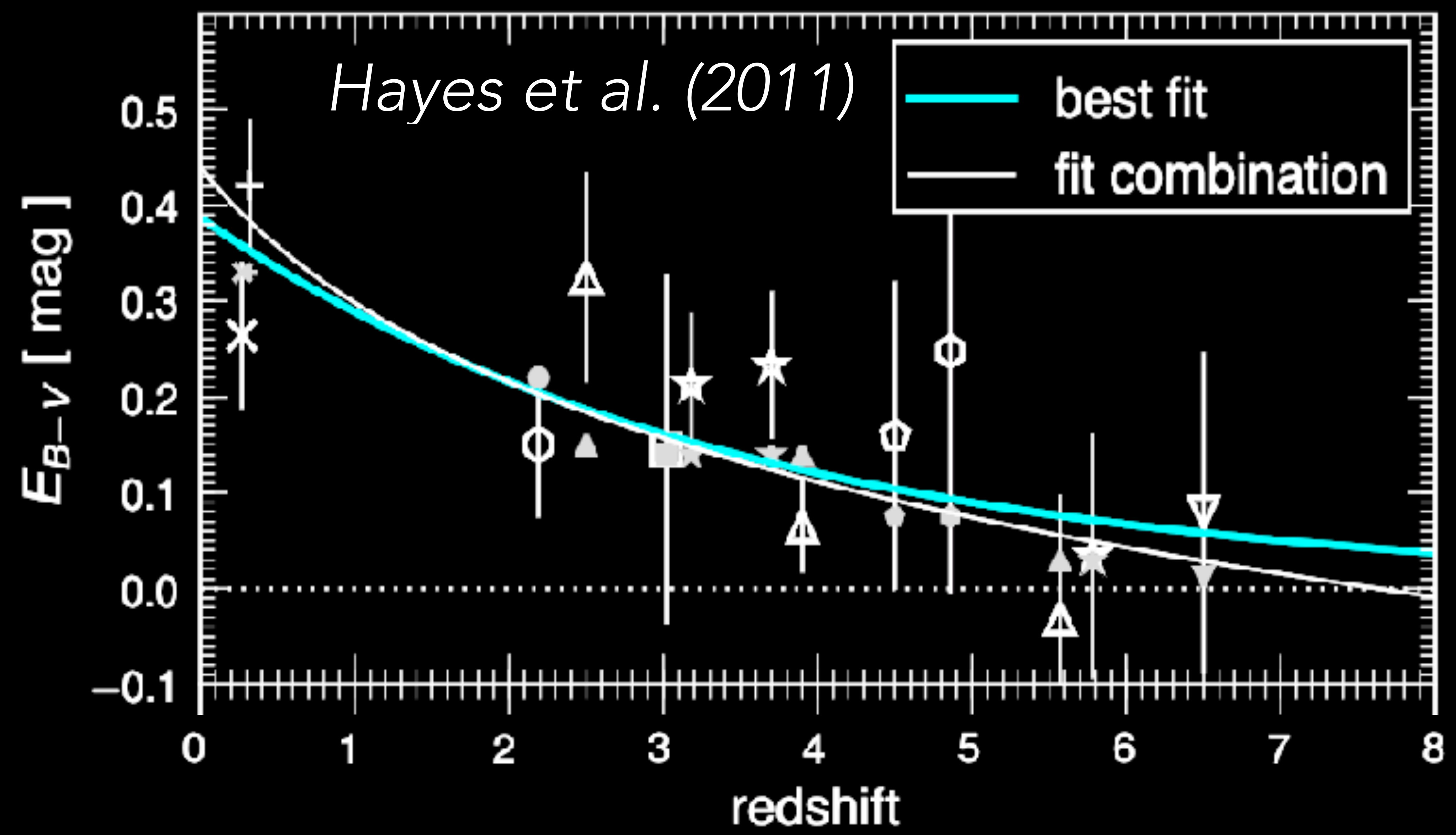
# Extrapolation from Lower Redshifts

We can (maybe?) extrapolate the properties of high-z galaxies from galaxies at lower redshifts (z < 3)

- Irregular structure, suggesting turbulent gas accretion and growth, and possible lack of "disk galaxies"
- Galaxies are rich in gas, suggesting high star formation rates
- Galaxies have less metals and probably very little dust




***Faisst** et al. (2016b)*



# So, are we done?

# The Role of ALMA

Large samples of $z > 4$ galaxies have been observed **mostly** at rest-frame UV (e.g., luminosity functions).

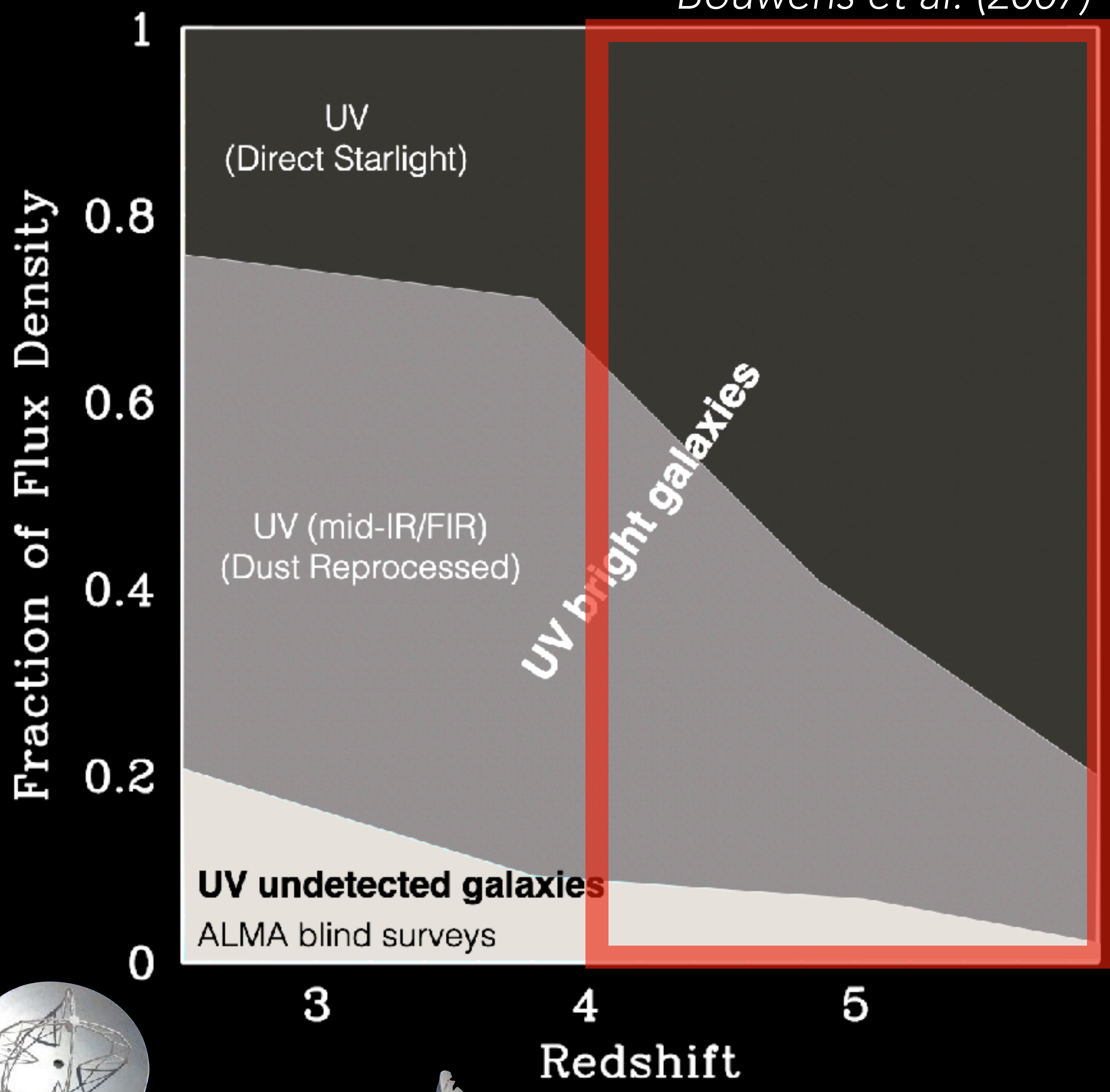
# The Role of ALMA

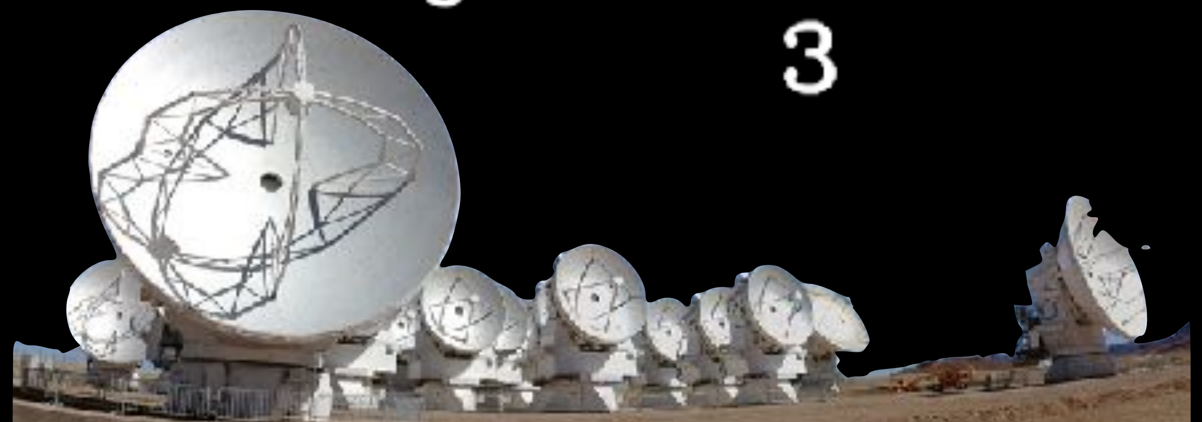
Large samples of z > 4 galaxies have been observed **mostly** at rest-frame UV (e.g., luminosity functions).

**BUT: at z=4-6 still > 40% of UV light is reprocessed by dust! And ~10% is missed completely!**

**ALMA is necessary to study the "missing" light!**

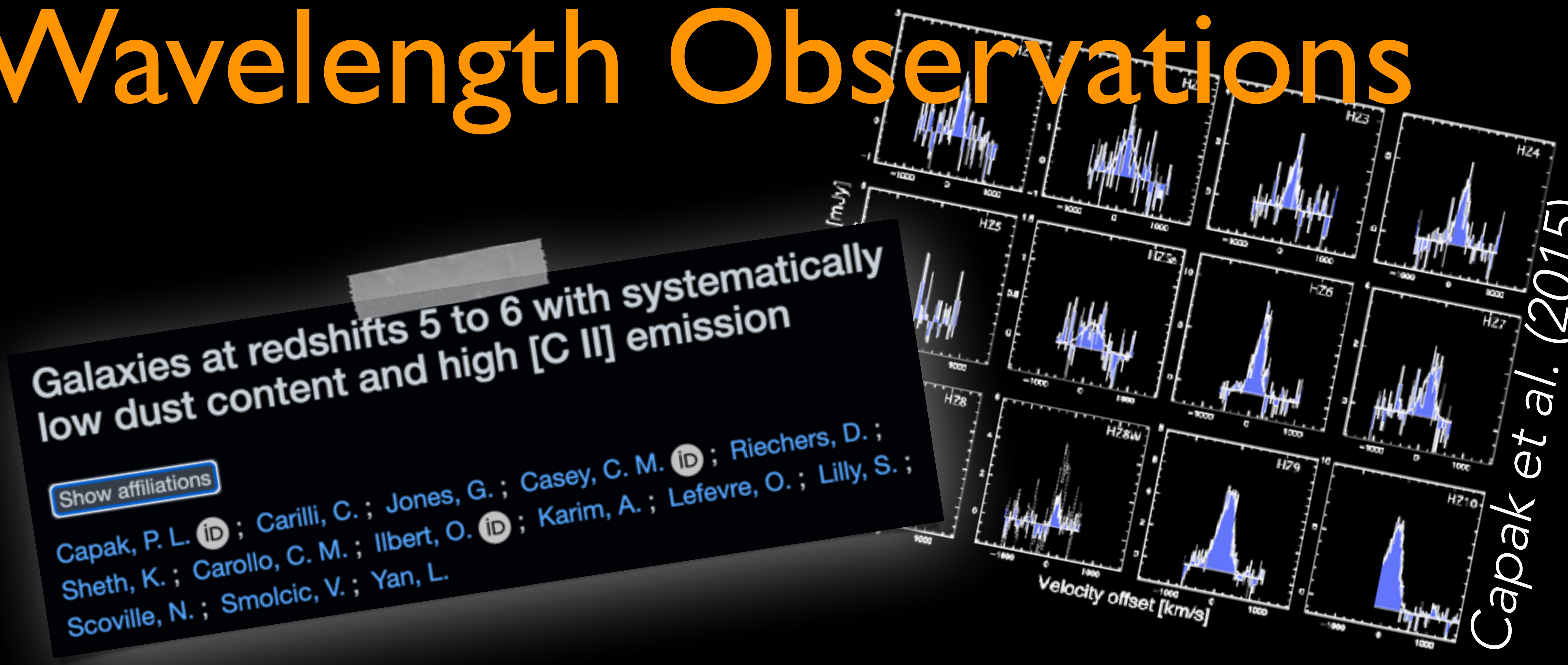
Bouwens et al. (2007)



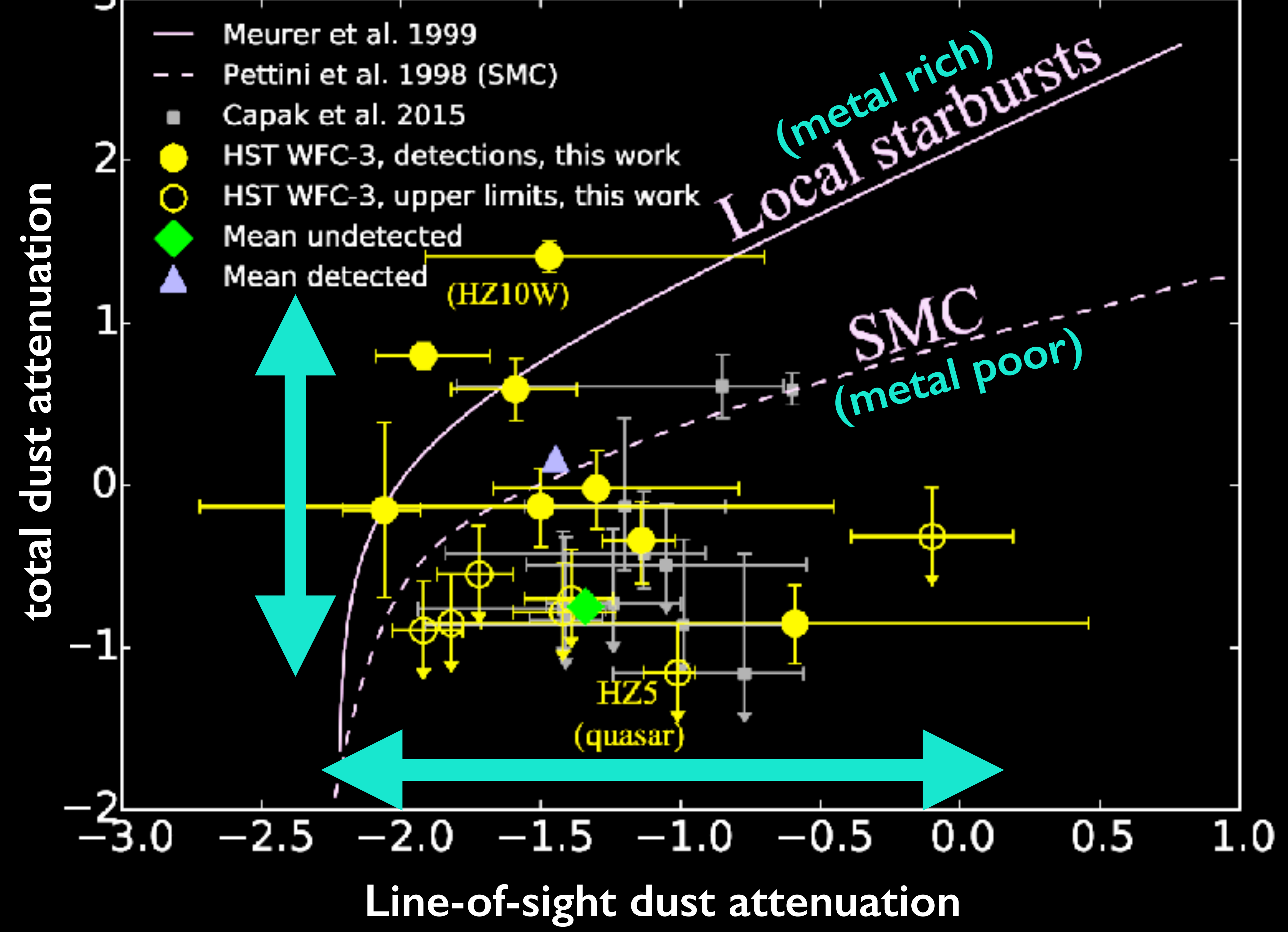
# Small Sample with Multi-Wavelength Observations

- Bright sub-mm galaxies at z > 4 have been observed with ALMA
- Pre-2017: only 10 ***typical* galaxies at z > 4** with ALMA measurements (Capak et al. 2015)

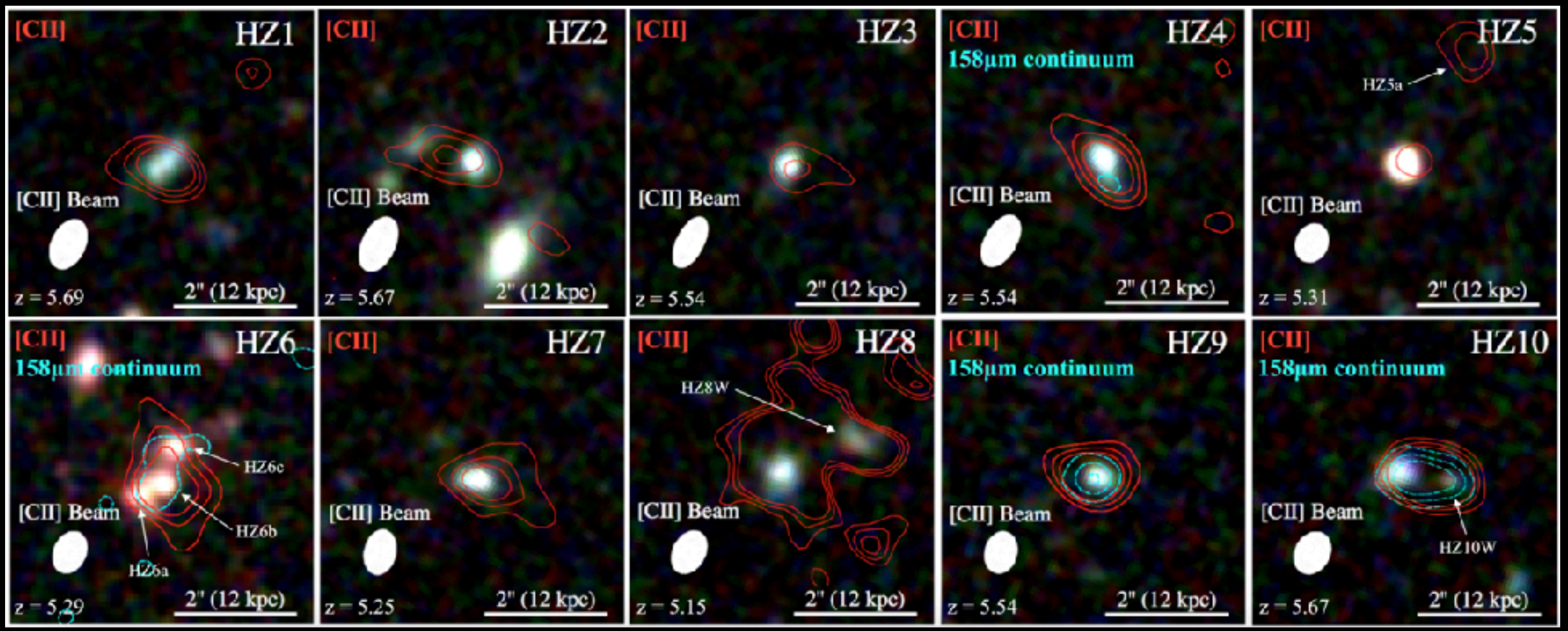



Capak et al. (2015)

Barisic et al. (2017)




Faisst et al. (2017)



# We Need Larger Samples!

What about going for a large ALMA proposal?

… the birth of *ALPINE*

http://alpine.ipac.caltech.edu
https://cesam.lam.fr/a2c2s/data_release.php

# The ALPINE Survey

**ALPINE** = **A**LMA **L**arge **P**rogram to **IN**vestigate $C^+$ at **E**arly times

*PIs: LeFèvre, **Faisst**, Béthermin, **Cassata**, **Schaerer**, **Silverman**, Yan, Capak*

- 70 hours of ALMA observations (cycle 5, Band 7) of **singly ionized Carbon** emission ($C^+$) at 158μm and surrounding **dust continuum**
- **118 average teenage galaxies** in total (largest sample so far!)
- Redshifts **z = 4 - 6** (1- 1.5 billion years after the Big Bang)
- **First true multi-wavelength survey at z > 4!**

27 Papers since 2019!!

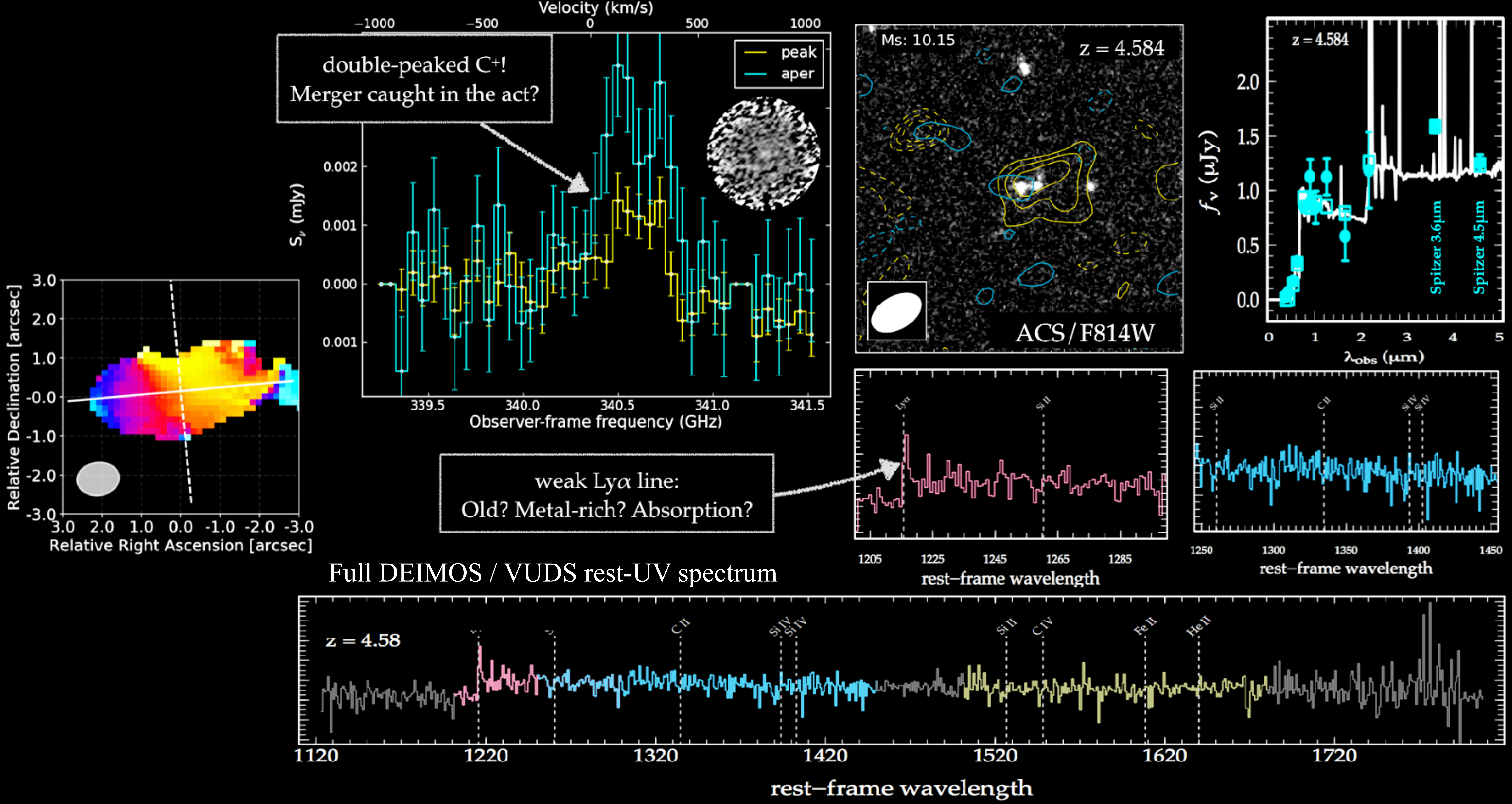
## Measure $C^+$ emission (gas)

- Kinematics (disk galaxies!)
- Gas fractions
- Outflows & Mergers

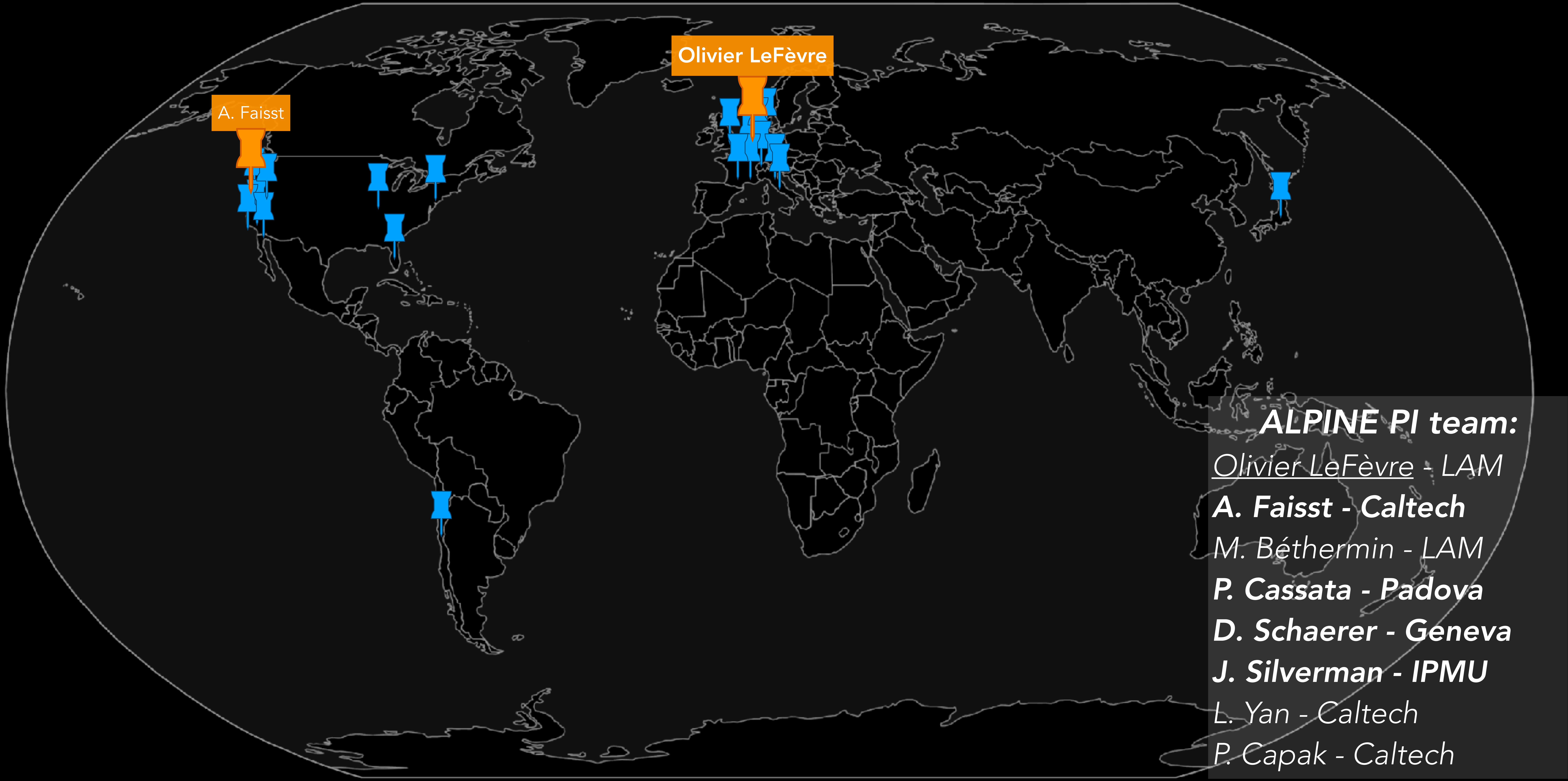
## Measure 150μm continuum (dust)

- Hidden star formation
- Dust content
- Finding dust-obscured galaxies

# ALPINE: the First Large Multi-Wavelength Study of z > 4 Galaxies



# ALPINE is Global




***ALPINE PI team:***

*<u>Olivier LeFèvre</u> - LAM*

***A. Faisst - Caltech***

*M. Béthermin - LAM*

***P. Cassata - Padova***

***D. Schaerer - Geneva***

***J. Silverman - IPMU***

*L. Yan - Caltech*

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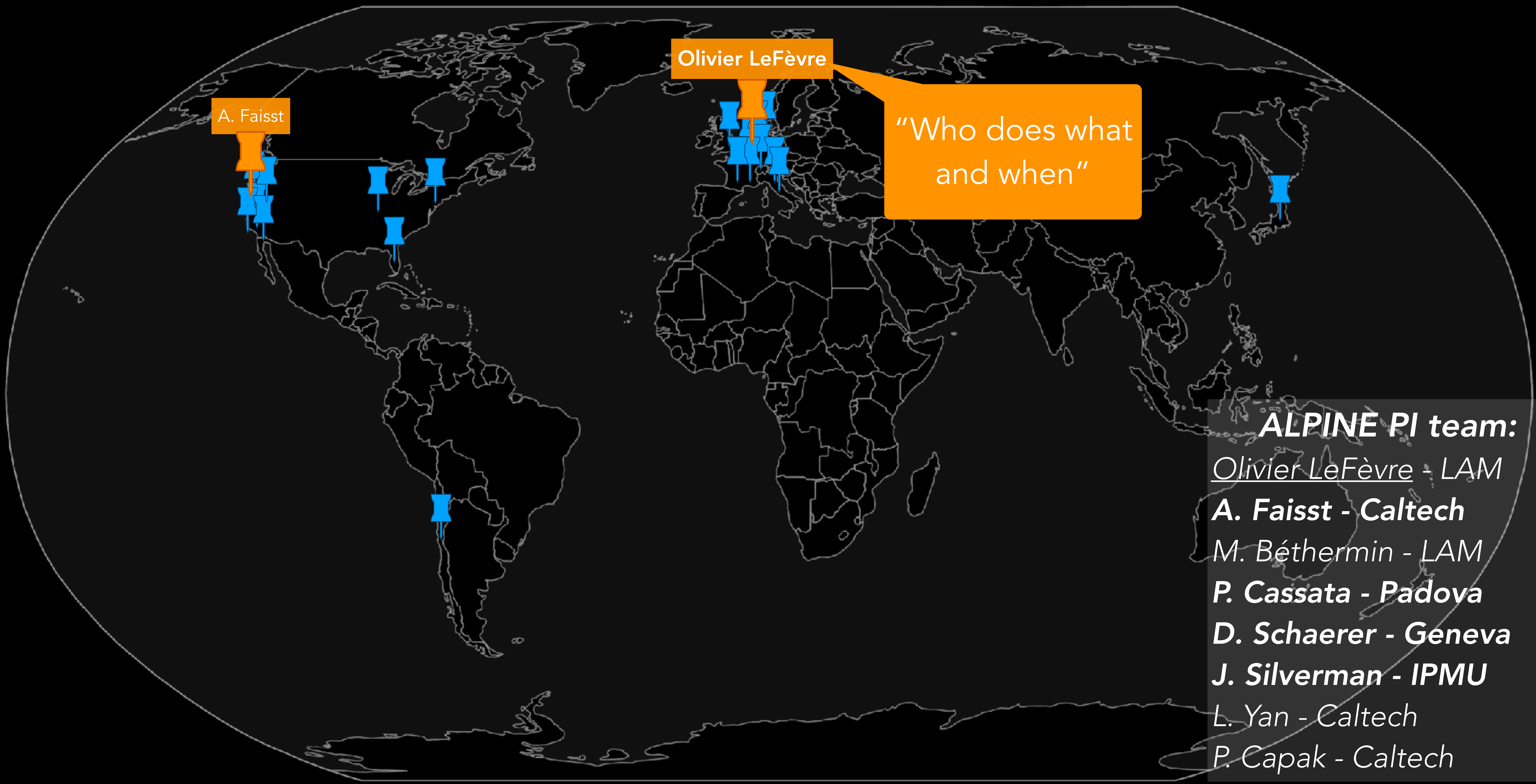


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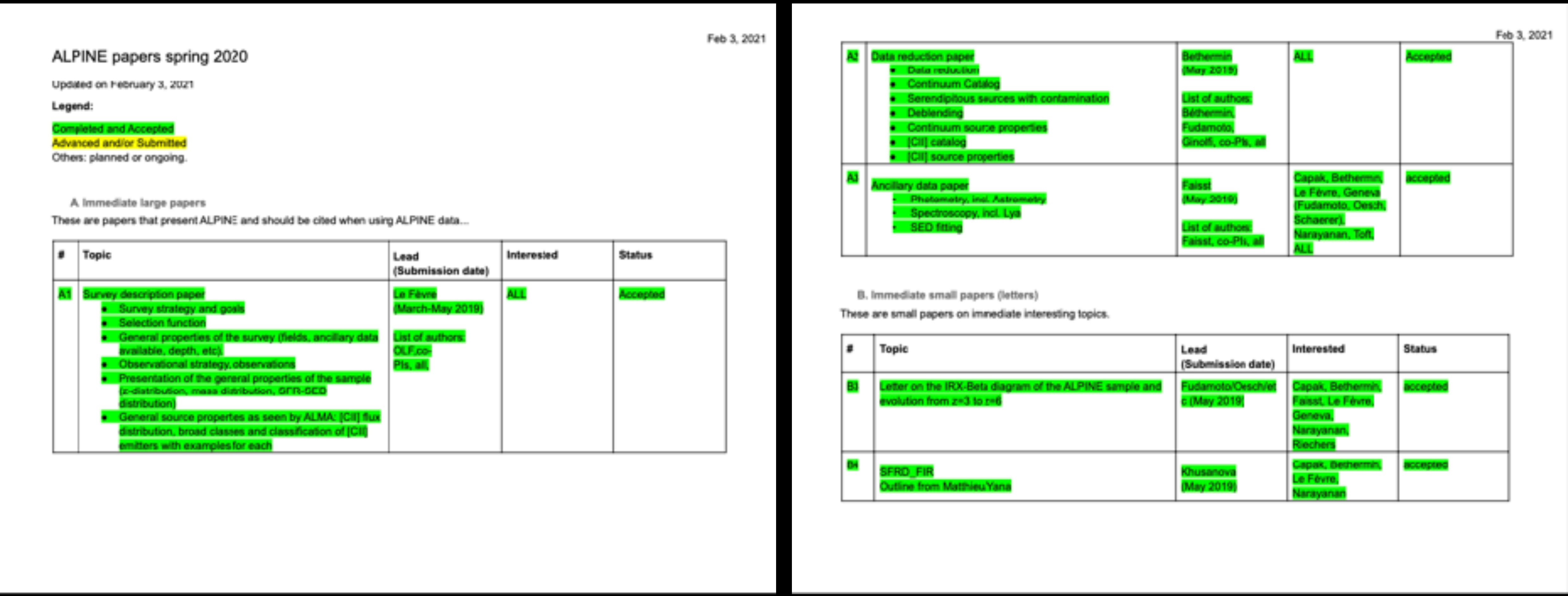
# Original Google Doc listing ALPINE papers

(Olivier's favorite document)




# Inclusive Spectroscopic Selection

ALPINE galaxies are selected from various spectroscopic programs to mitigate (as well as possible) spectroscopic selection biases.

*Faisst et al. (2020)*

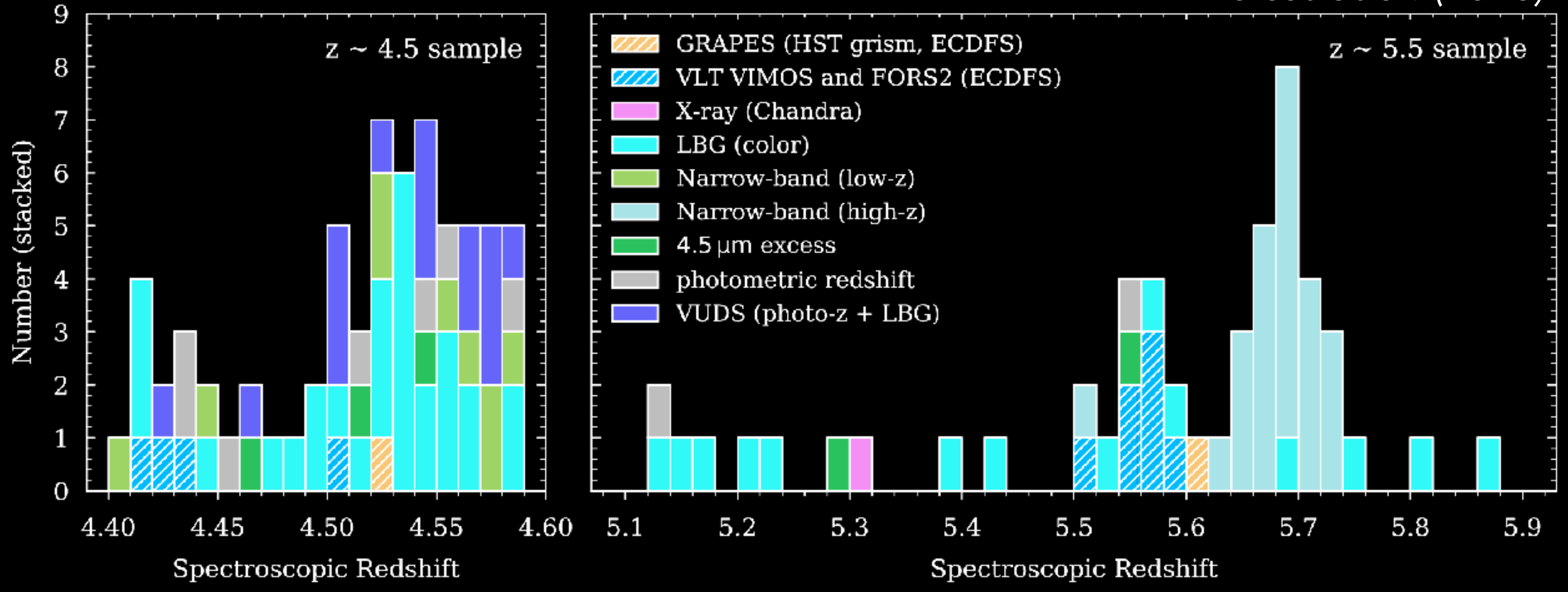


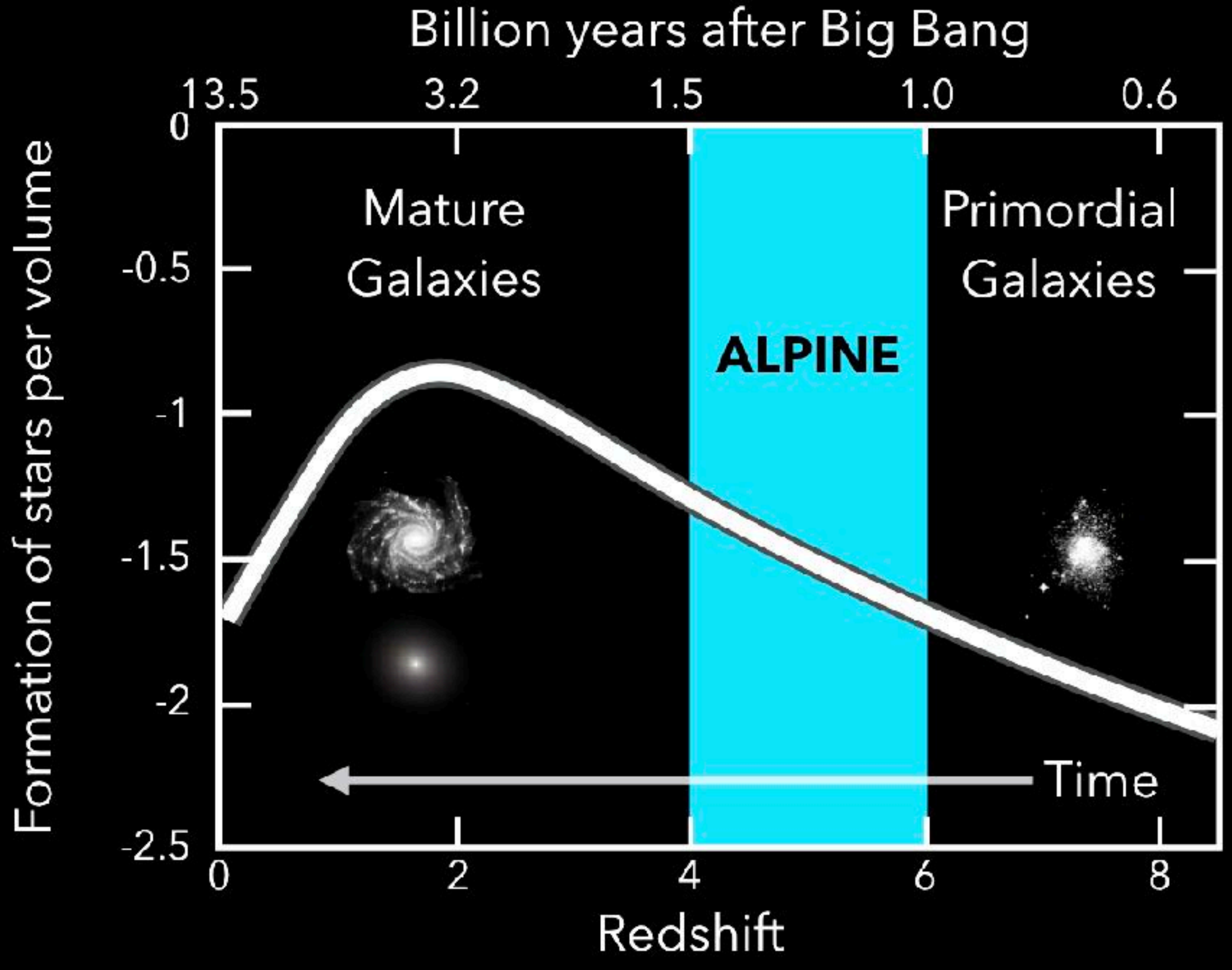

**Table 1**
Spectroscopy and Selection of ALPINE Galaxies

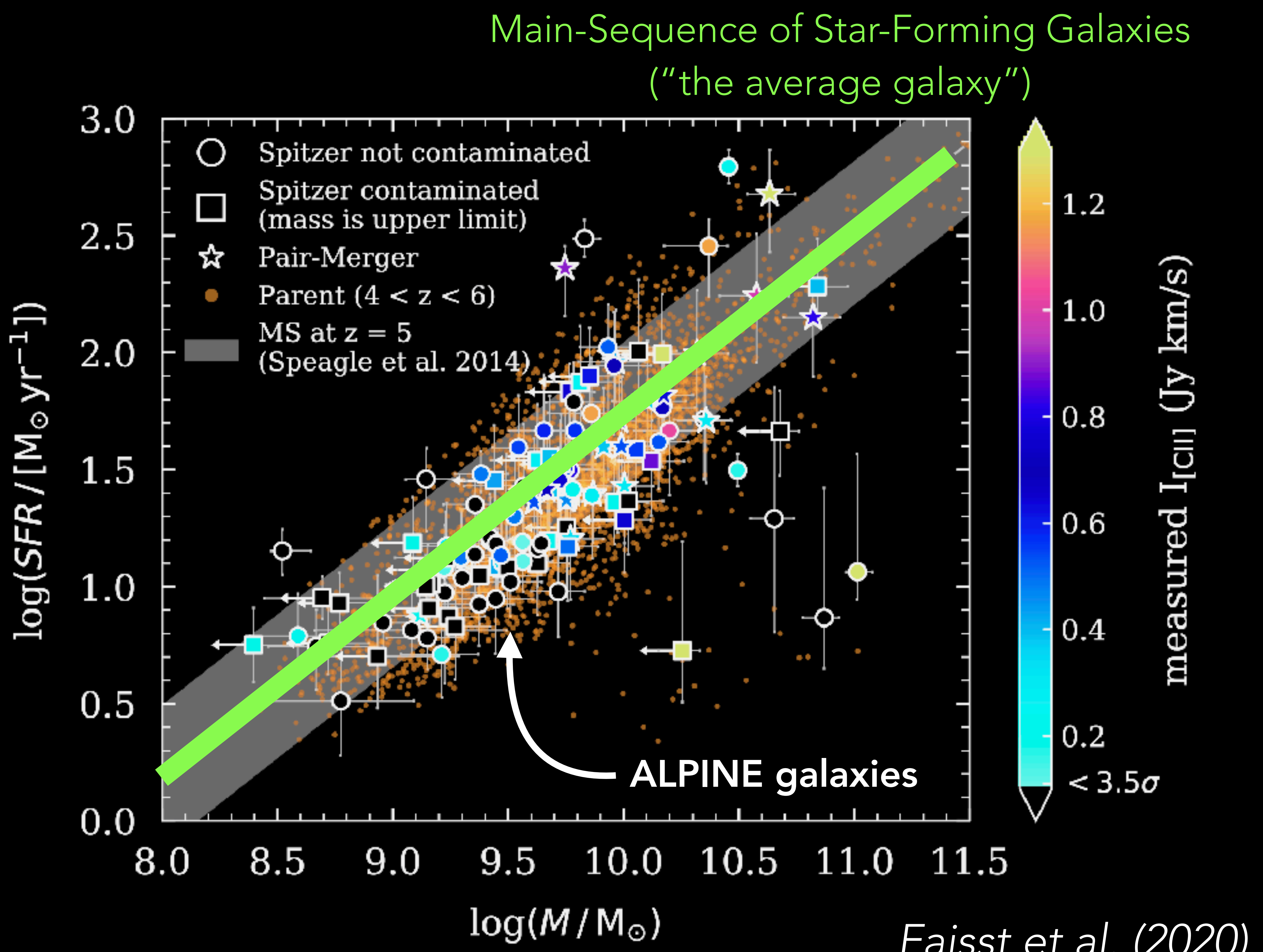
| Survey | Selection | Number | Ref. |
|---|---|---|---|
| | COSMOS field (105 galaxies) | | |
| Keck/DEIMOS[a] | | 84 | 1 |
| | narrowband ($z \sim 4.5$)[c] | 6 | |
| | narrowband ($z \sim 5.7$)[d] | 23 | |
| | LBG (color)[e] | 41 | |
| | pure photo-$z$[f] | 9 | |
| | 4.5 $\mu$m excess | 4 | |
| | X-ray (*Chandra*) | 1 | |
| | with Ly$\alpha$ emission | 66 | |
| | weak Ly$\alpha$ emission or absorption | 18 | |
| VUDS | | 21 | 2 |
| | photo-$z$ + LBG | 21 | |
| | [narrowband ($z \sim 4.5$) | 3][b] | |
| | [narrowband ($z \sim 5.7$) | 1][b] | |
| | [LBG (color) | 1][b] | |
| | [4.5 $\mu$m excess | 1][b] | |
| | with Ly$\alpha$ emission | 16 | |
| | weak Ly$\alpha$ emission or absorption | 5 | |
| | ECDFS field (13 galaxies) | | |
| VLT GOODS-S | | 11 | 3 |
| | primarily LBG (color) | 11 | |
| | total with Ly$\alpha$ emission | 6 | |
| | total without Ly$\alpha$ emission | 5 | |
| *HST*/GRAPES | | 2 | 4 |
| | Grism (no a priori selection) | 2 | |
| | with Ly$\alpha$ emission | 2 | |
| | weak Ly$\alpha$ emission or absorption | 0 | |

Olivier!!

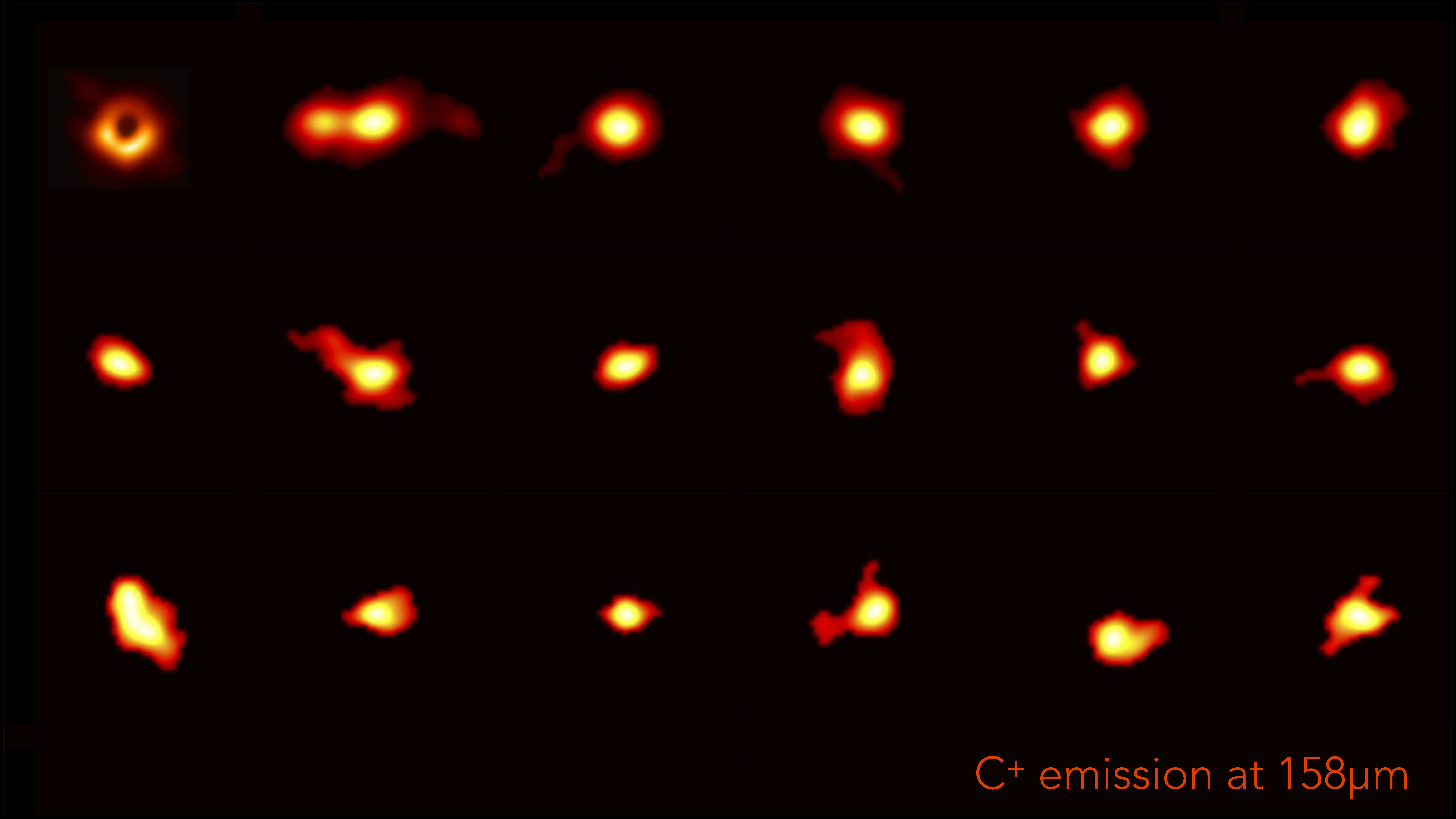
# Typical Galaxies at High Redshifts

ALPINE galaxies are main-sequence galaxies living during the early growth phase at z = 4 - 6.

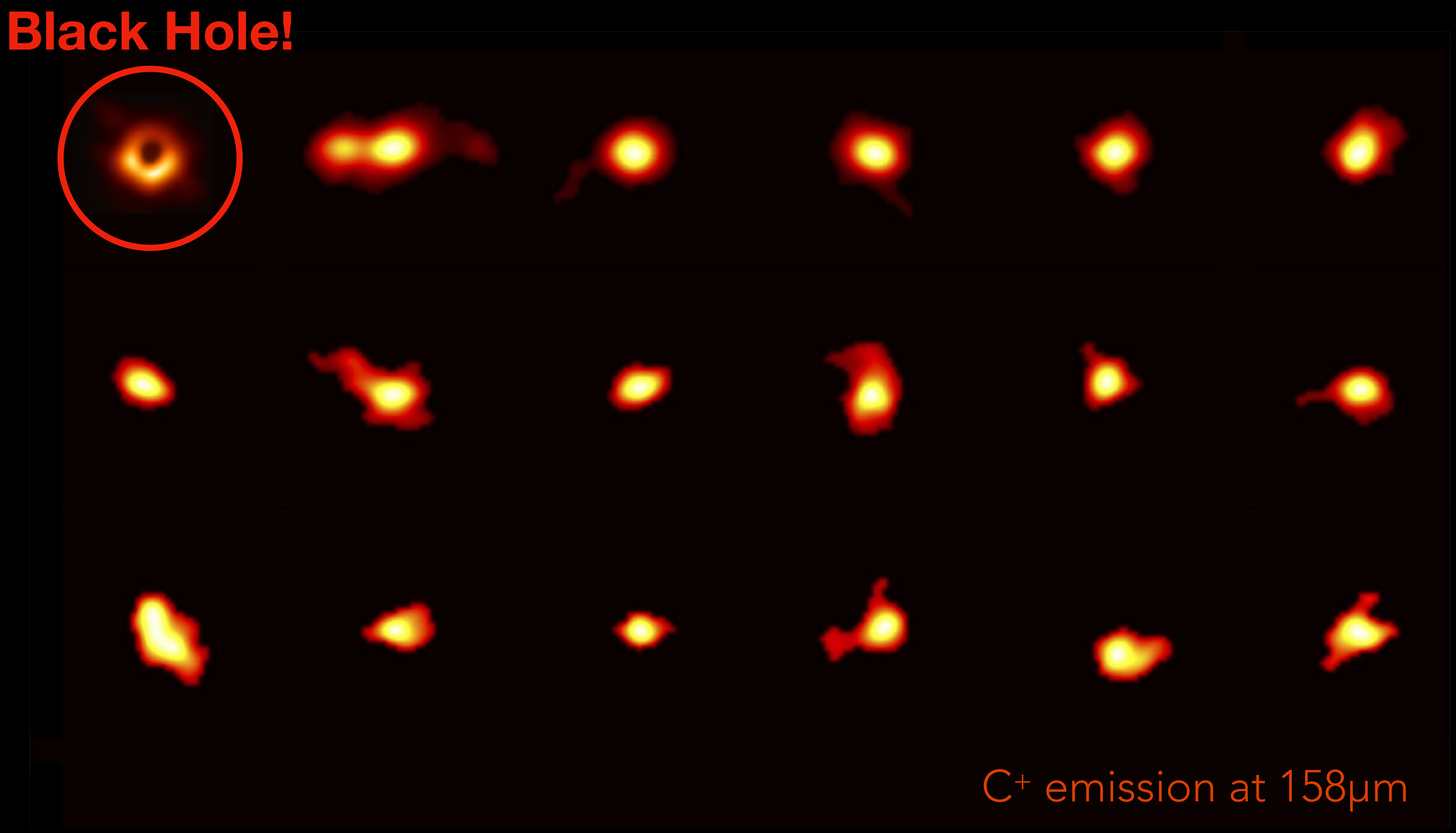



*Faisst et al. (2020)*




*LeFèvre et al. (2020) + M. Ginolfi*



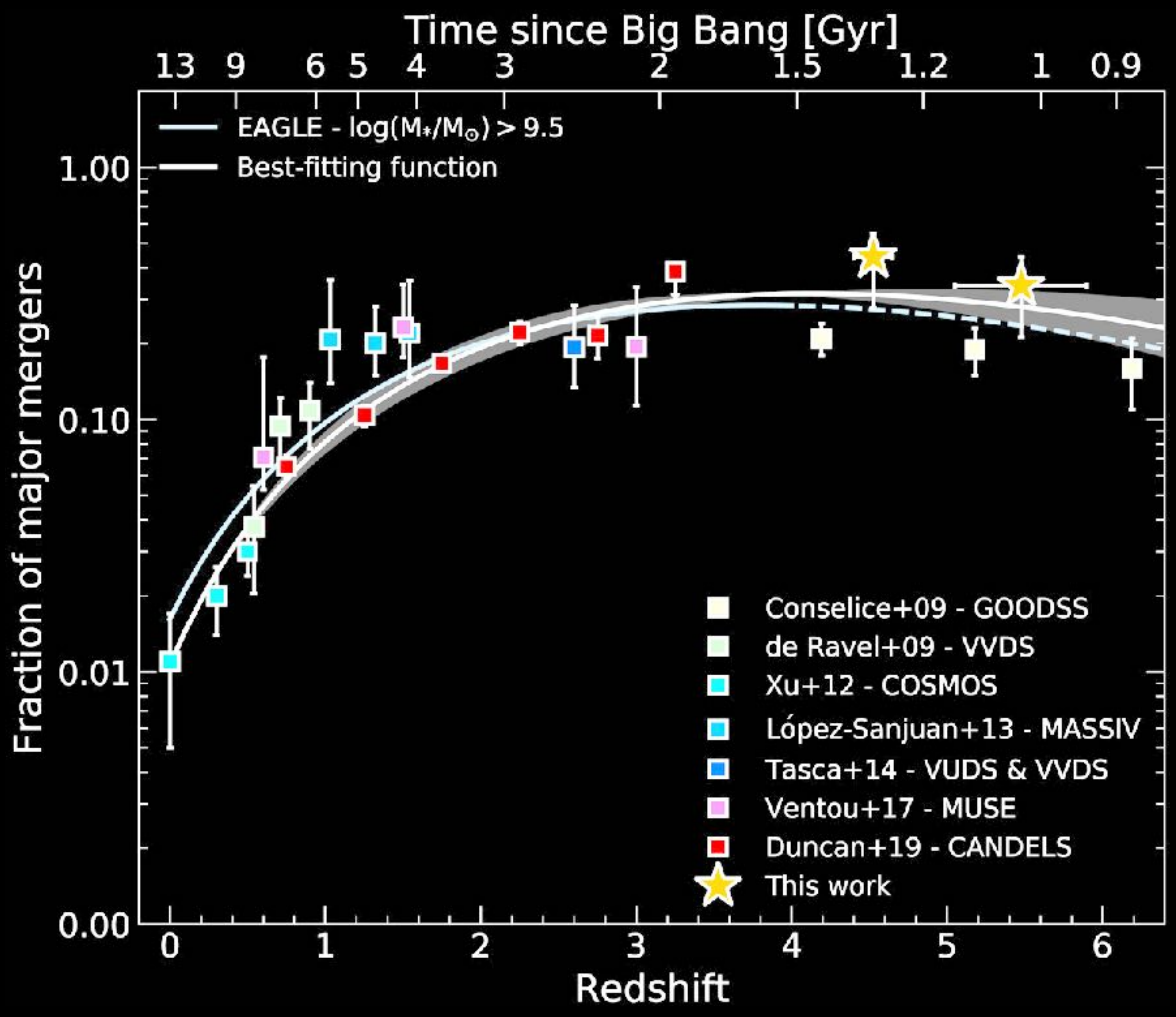

*LeFèvre et al. (2020) + M. Ginolfi*

# What does *ALPINE* tell us about high-z (post-reionization) galaxies?

# What Is ALPINE Telling Us About Early Galaxies?

## Fraction of Major Mergers

- Michael Romano's talk




*Romano et al. (2021)*

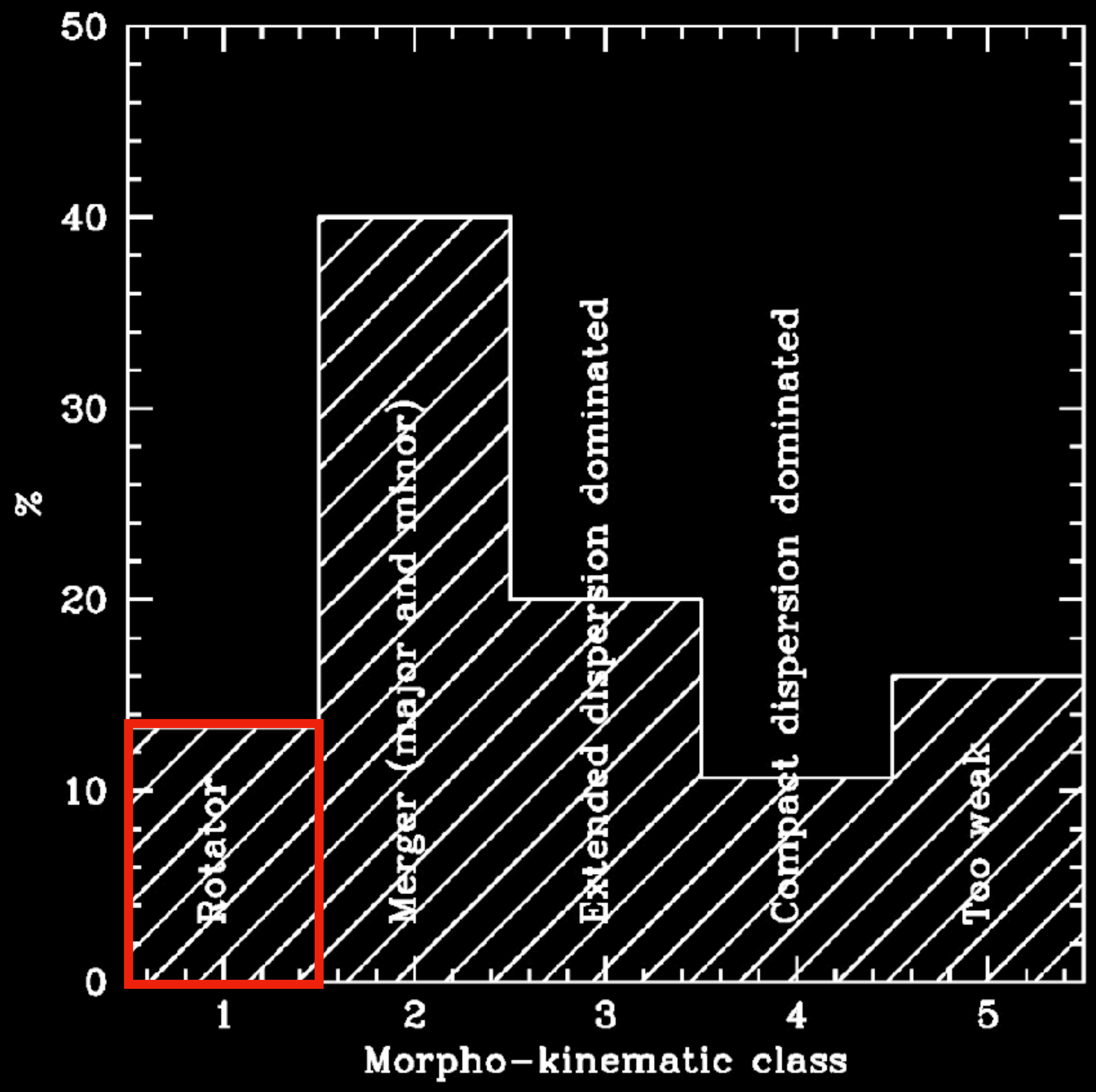
# What Is ALPINE Telling Us About Early Galaxies?

## Fraction of Major Mergers

- Michael Romano's talk

## Structure of high-z galaxies

- 5 morpho-kinematic classes
- See Gareth Jones' talk!




*Le Fèvre et al. (2020)*

PECULIAR MORPHOLOGY OF THE HIGH-REDSHIFT RADIO GALAXIES 3C 13 AND 3C 256 IN SUBARCSECOND SEEING

O. LE FÈVRE[1]
Canada-France-Hawaii Telescope Corporation; and Meudon Observatory
F. HAMMER,[1] L. NOTTALE, AND A. MAZURE[1]
Meudon Observatory
AND
C. CHRISTIAN[1]
Canada-France-Hawaii Telescope Corporation and University of Hawaii
*Received 1987 June 19; accepted 1987 October 8*

ABSTRACT

We report high spatial resolution imaging of two radio galaxies from the 3C catalog, 3C 13 and 3C 256 with redshifts of 1.351 and 1.819, respectively. The excellent image quality obtained at CFHT, 0".6 FWHM for 3C 13 and 0".7 for 3C 256 in the *R* band, over long integration times, allowed us to resolve these distant galaxies into complex structures. As suggested by Le Fèvre and colleagues in 1987 for another source, the

# Le Fèvre et al. (1987)

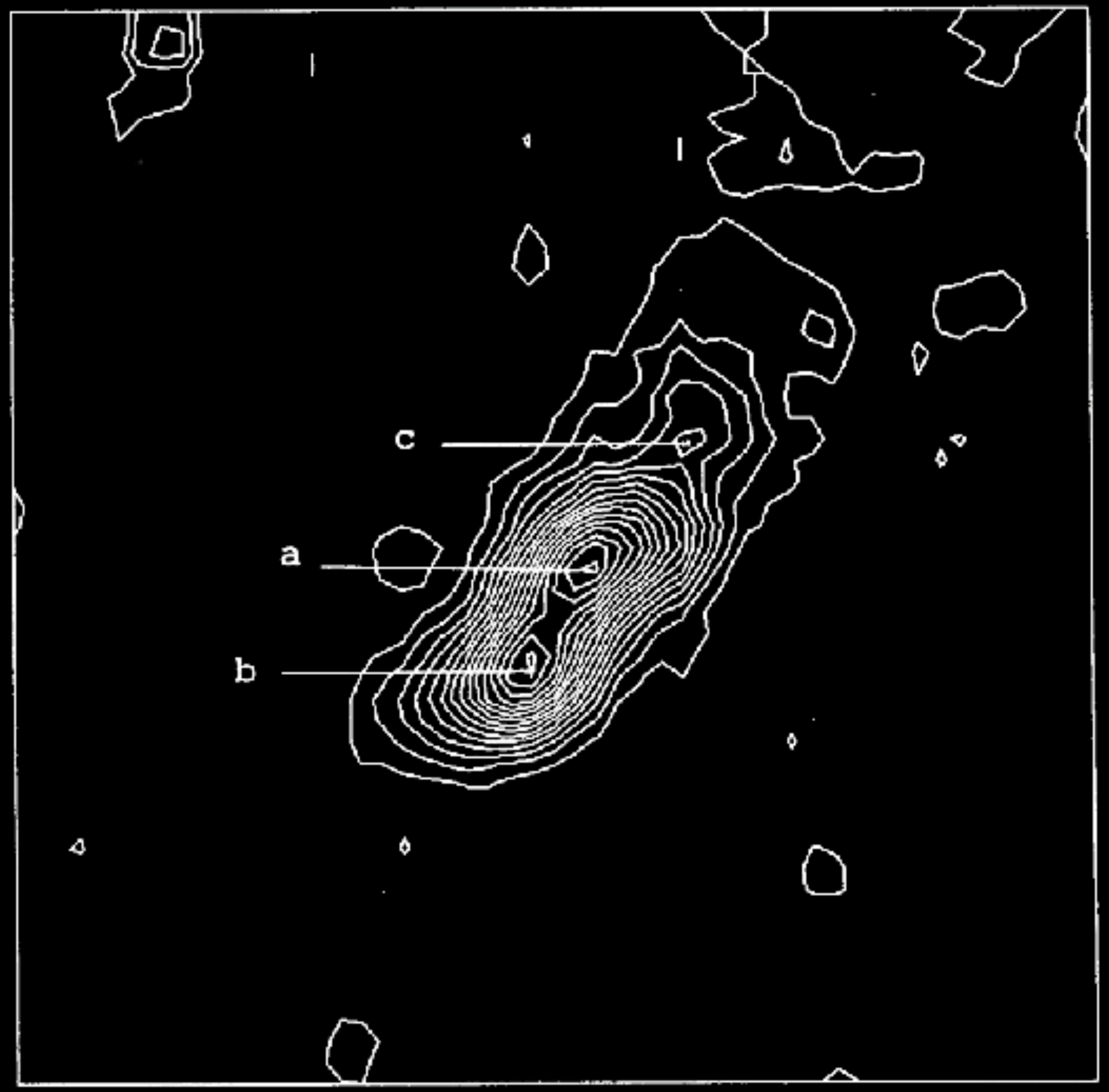



FIG. 2.—3C 256 ($z = 1.819$): 1 hr exposure in *R* band at CFHT prime focus. FWHM is 0".7. The multiple component structure is aligned on a common axis. North is up, and the image is 10.5 × 10.5 arcsec$^2$.

*"The excellent image quality obtained at CFHT, [...] allowed us to resolve these distant galaxies into complex structures."*

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O. Le Fèvre[1]
Canada-France-Hawaii Telescope Corporation; and Meudon Observatory
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A&A 643, A1 (2020)
https://doi.org/10.1051/0004-6361/201936965

Astronomy & Astrophysics

**Survey strategy, observations, and sample properties of 118 star-forming galaxies at $4 < z < 6$**

O. Le Fèvre[1], M. Béthermin[1], A. Faisst[2], G. C. Jones[15,16], P. Capak[2,27,28], P. Cassata[4,5], J. D. Silverman[6,32], D. Schaerer[7,8], L. Yan[23], R. Amorin[12,13], S. Bardelli[11], M. Boquien[14], A. Cimatti[9,10], M. Dessauges-Zavadsky[7],

ABSTRACT

The ALMA-ALPINE [CII] survey is aimed at characterizing the properties of a sample of normal star-forming galaxies (SFGs). The ALMA Large Program to INvestigate (ALPINE) features 118 galaxies observed in the [CII]-158 $\mu$m line and far infrared (FIR) continuum emission during the period of rapid mass assembly, right after the end of the HI reionization, at redshifts of $4 < z < 6$. We present the survey science goals, the observational strategy, and the sample selection of the 118 galaxies observed with ALMA, with an average beam minor axis of about 0.85", or ~5 kpc at the median redshift of the survey. The properties of the sample are described, including spectroscopic redshifts derived from the UV-rest
for a signal-to-noise ratio (S/N) threshold larger than 3.5 corresponding to a 95% purity (40% detection rate for $S/N > 5$). Based on a visual inspection of the [CII] data cubes together with the large wealth of ancillary data, we find a surprisingly wide range of galaxy types, including 40% that are mergers, 20% extended and dispersion-dominated, 13% compact, and 11% rotating discs, with the remaining 16% too faint to be
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# Le Fèvre et al. (1987)

# Le Fèvre et al. (2020)

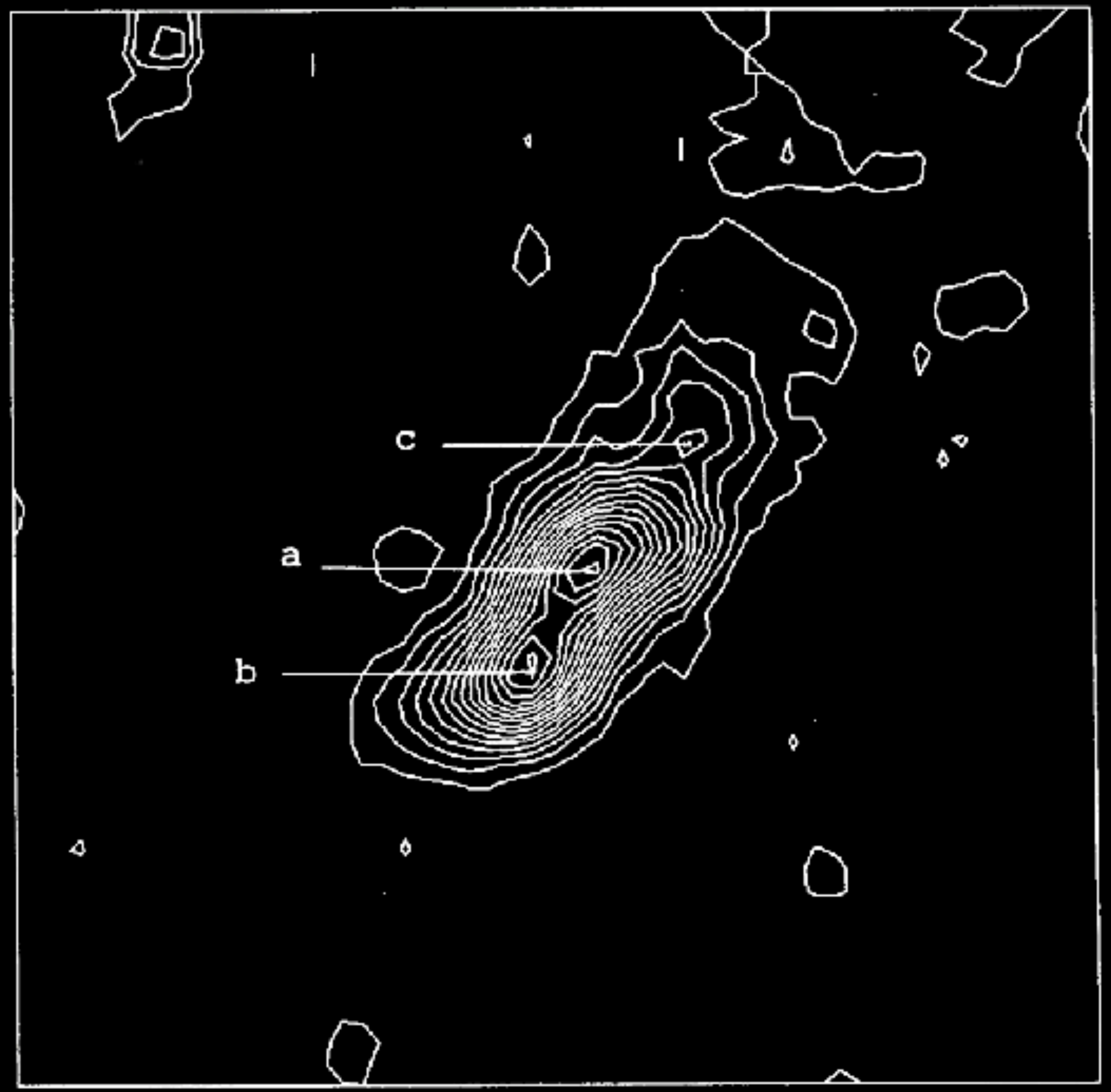
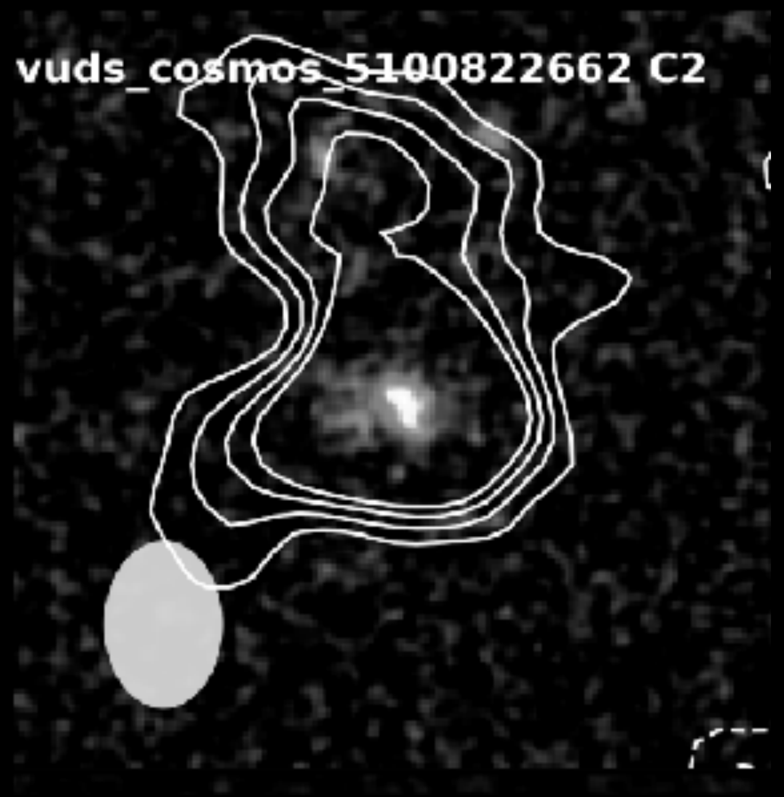



Fig. 2.—3C 256 ($z = 1.819$): 1 hr exposure in *R* band at CFHT prime focus. FWHM is 0".7. The multiple component structure is aligned on a common axis. North is up, and the image is 10.5 × 10.5 arcsec$^2$.

*"The excellent image quality obtained at CFHT, […] allowed us to resolve these distant galaxies into complex structures."*

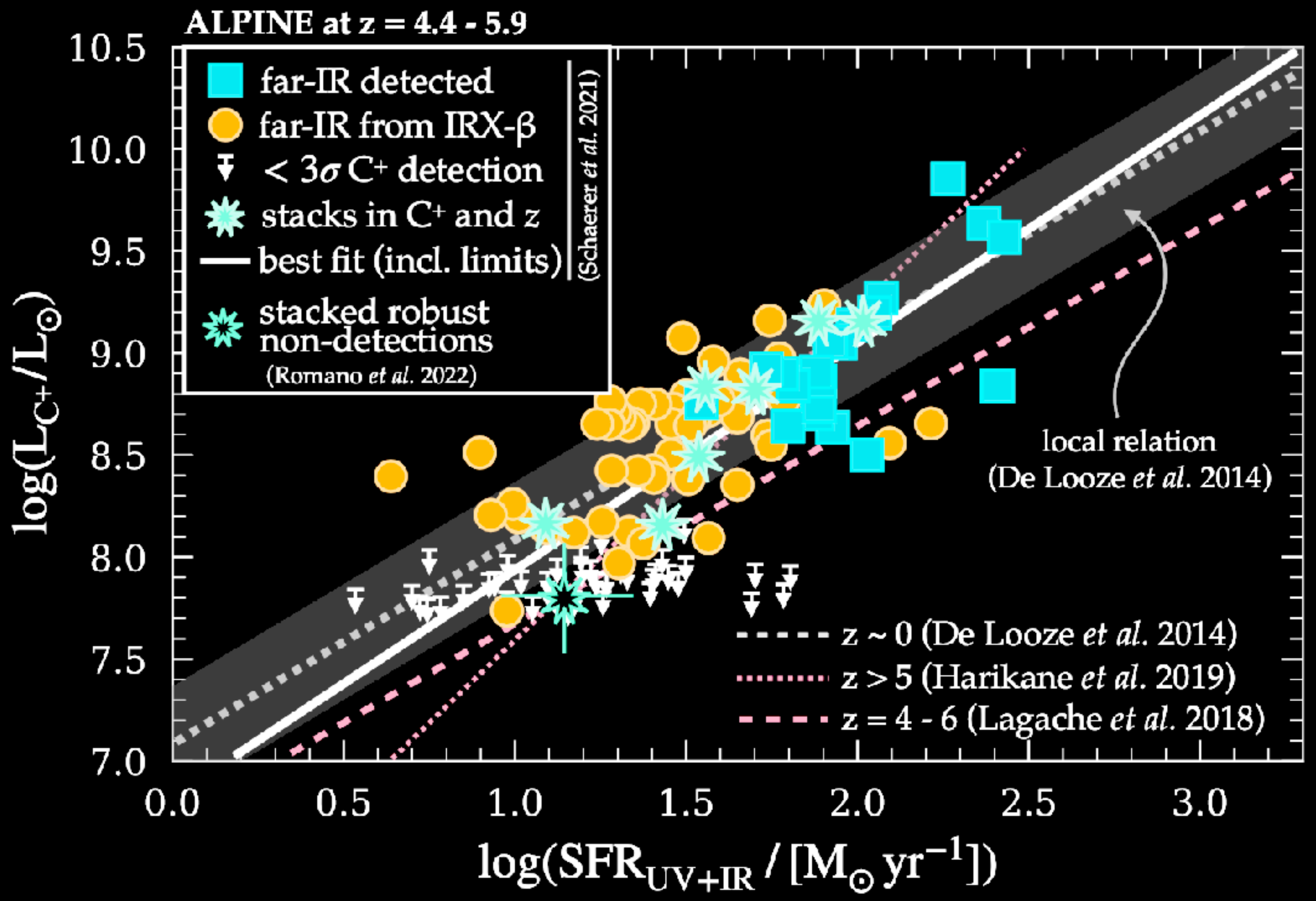



*"Based on a visual inspection of the [CII] data cubes together with the large wealth of ancillary data, we find a surprisingly wide range of galaxy types […]"*

# What Is ALPINE Telling Us About Early Galaxies?

## The SFR vs. C$^+$ relation and C$^+$ deficit

- No deviation found with respect to local SFR-C$^+$ relation
- No deficit in C$^+$ found
- C$^+$ is a reasonable tracer of SFR at z=4-6 for relatively massive galaxies




*Schaerer et al. (2021); Romano et al. (2022)*

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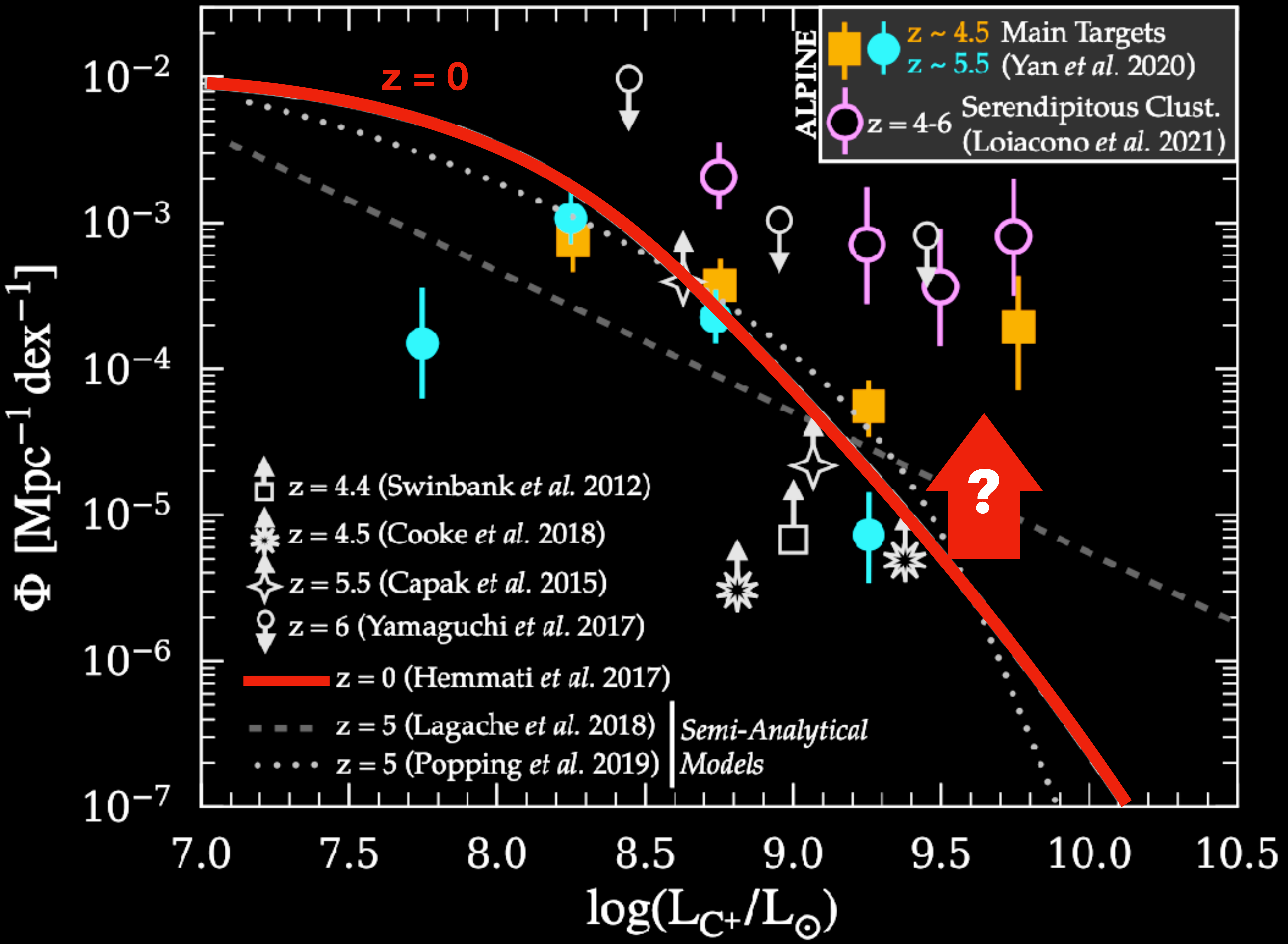
- $C^+$ overdensity compared to z = 0 LF??




*Yan et al. (2020); Loiacono et al. (2021)*

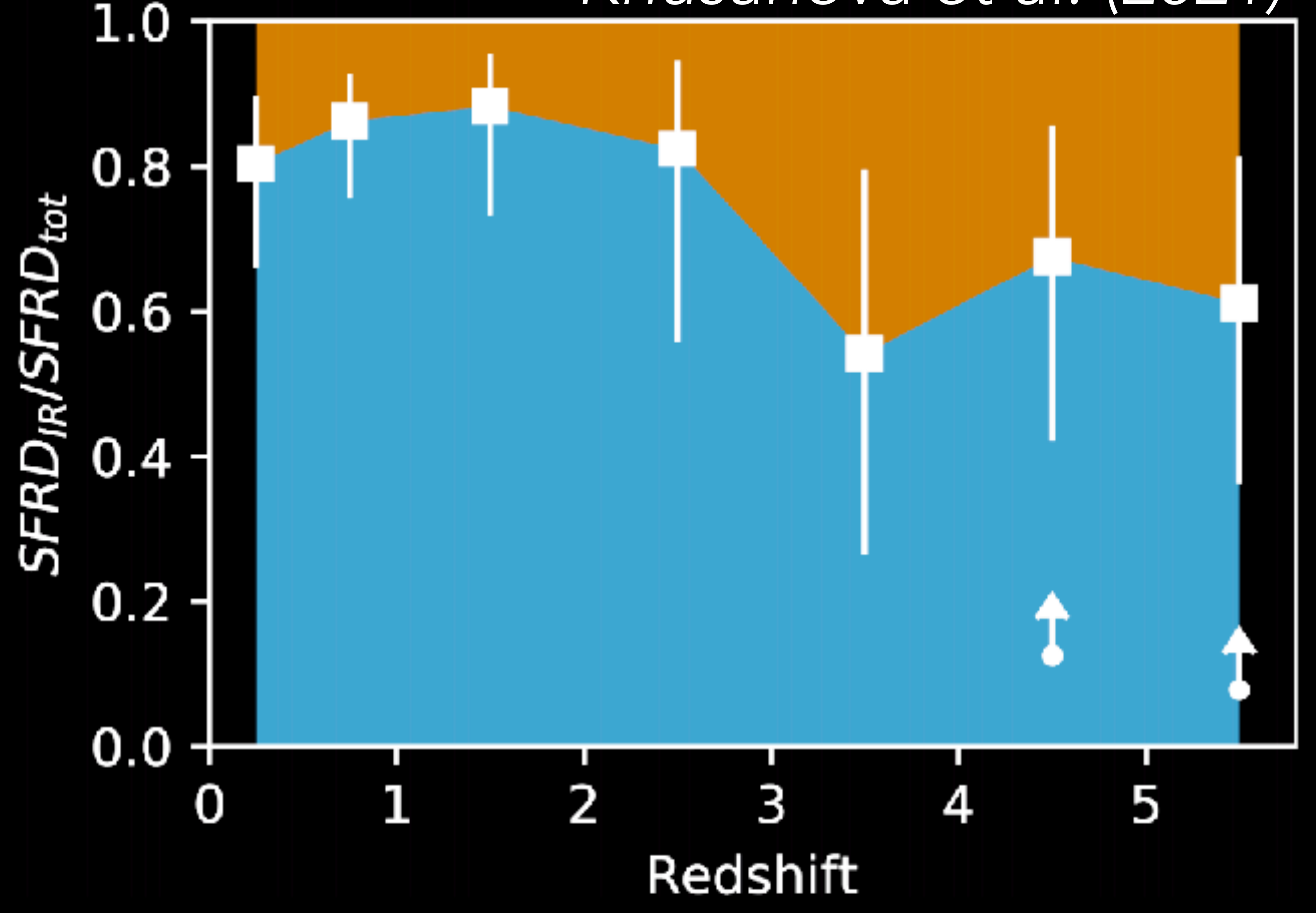
# What Is ALPINE Telling Us About Early Galaxies?

## Are high-z galaxies really dust poor?

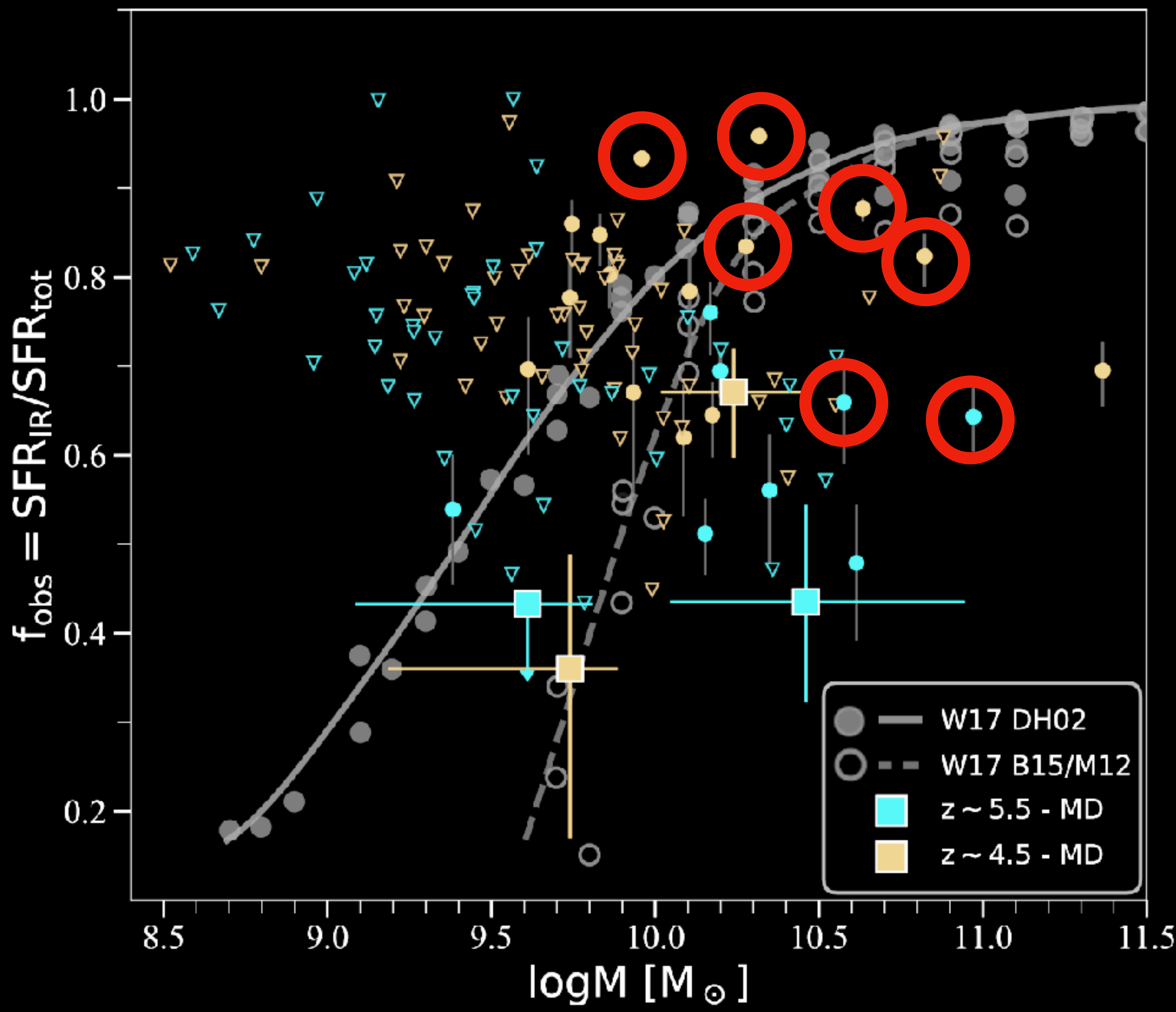
- Generally high-z galaxies do have a lower dust content
- Most massive galaxies, however can be quite dust-rich

POSTER!

Khusanova et al. (2021)




Fudamoto et al. (2020)

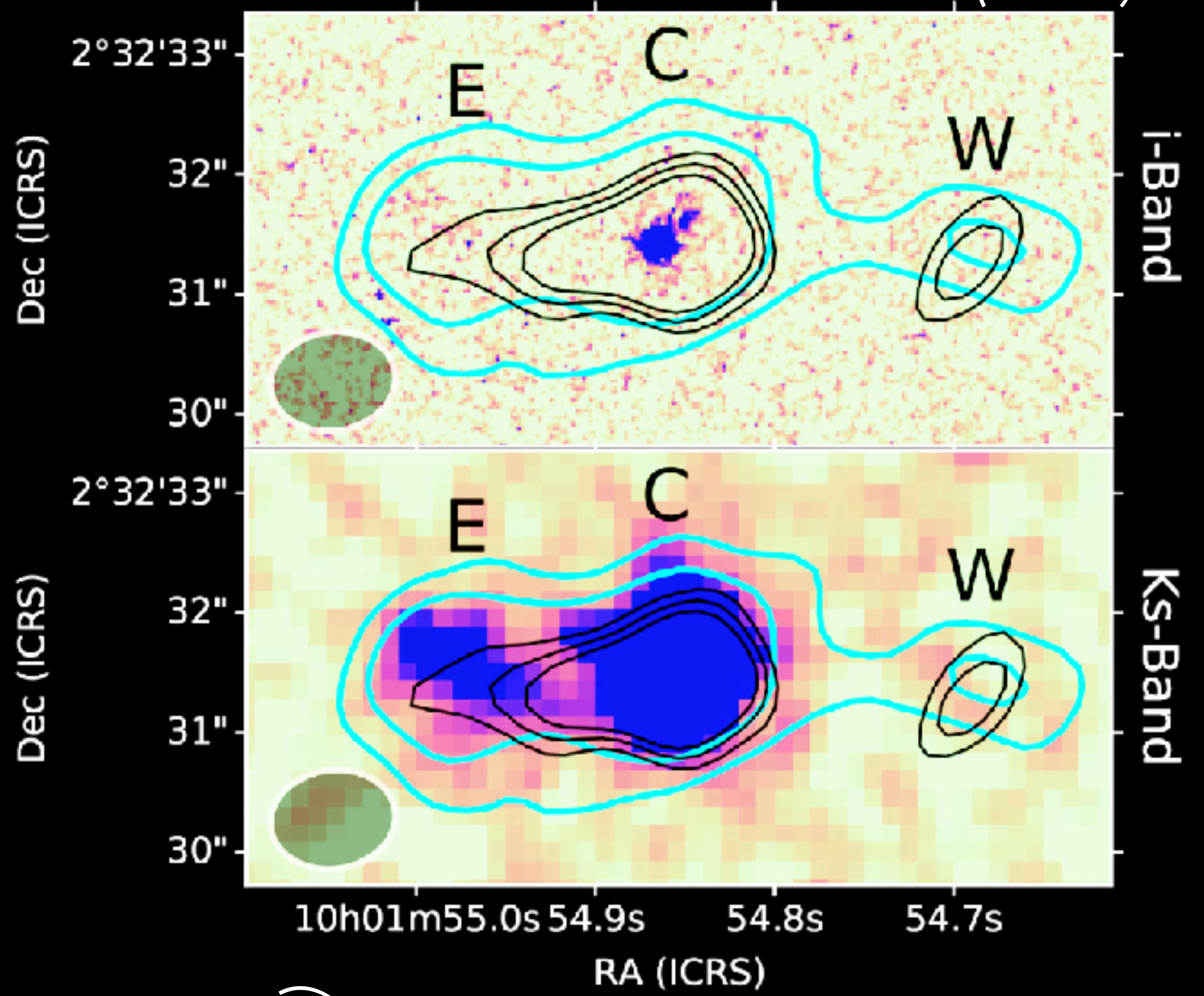


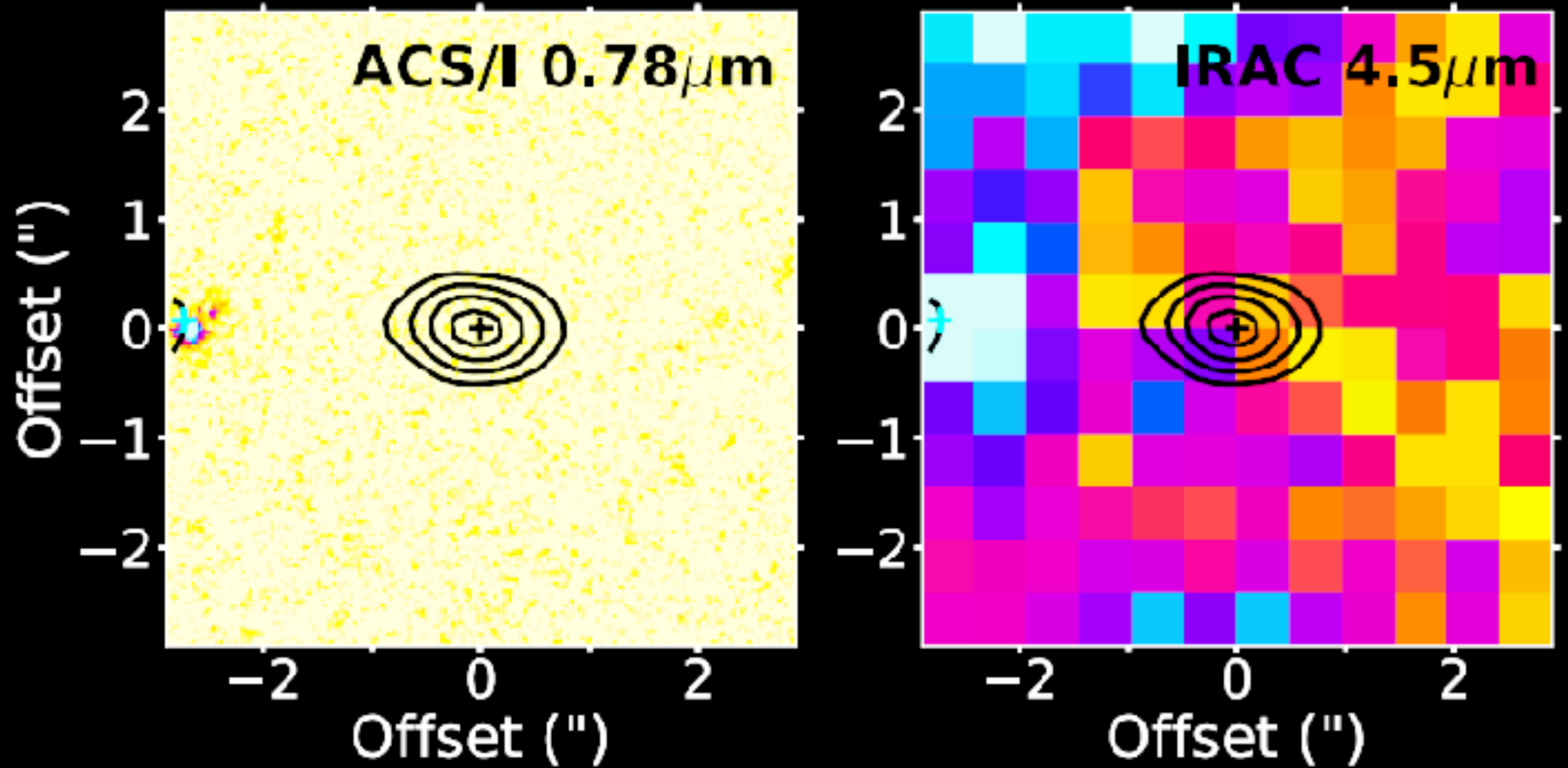
# What Is ALPINE Telling Us About Early Galaxies?

## Are high-z galaxies really dust poor?

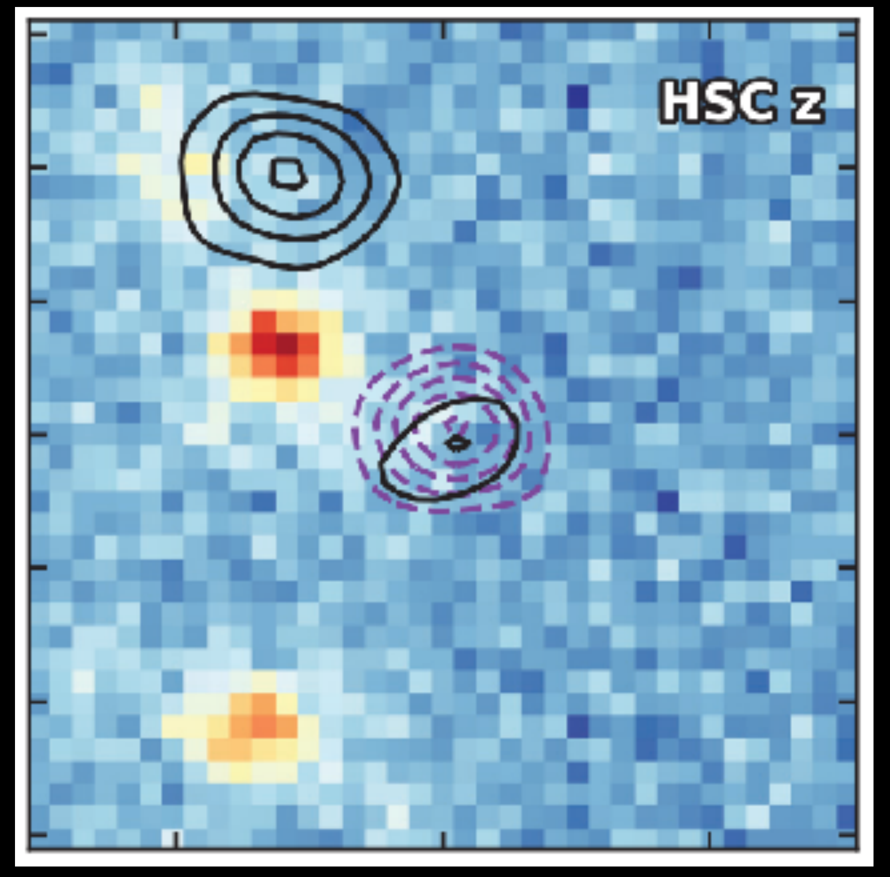
- Generally high-z galaxies do have a lower dust content
- Most massive galaxies, however can be quite dust-rich
- Significant amount of dust obscured ("UV/optical-dark") galaxies!

*Jones et al. (2020)*




*Loiacono et al. (2021)*
*Gruppioni et al. (2020)*



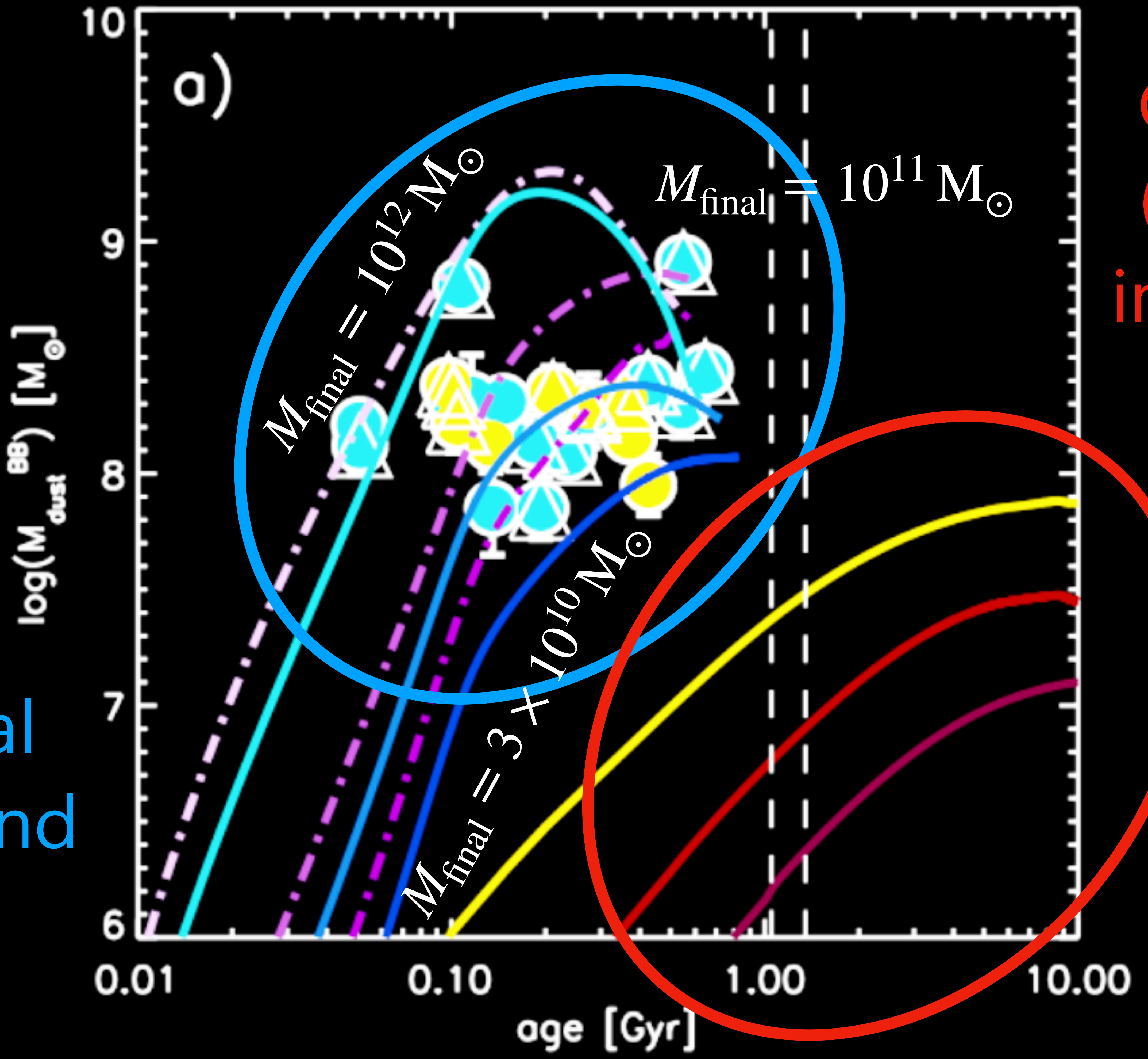

*Romano et al. (2020)*

# What Is ALPINE Telling Us About Early Galaxies?

## Total dust mass and age can constrain evolutionary stage

- Statistically, ALPINE galaxies are likely progenitors of local elliptical galaxies (spheroids) as opposed to local disk galaxies.
- Consistent with high fraction of merging galaxies?

*Pozzi et al. (2021)*




Proto-Spheroidal (collapse and burst)

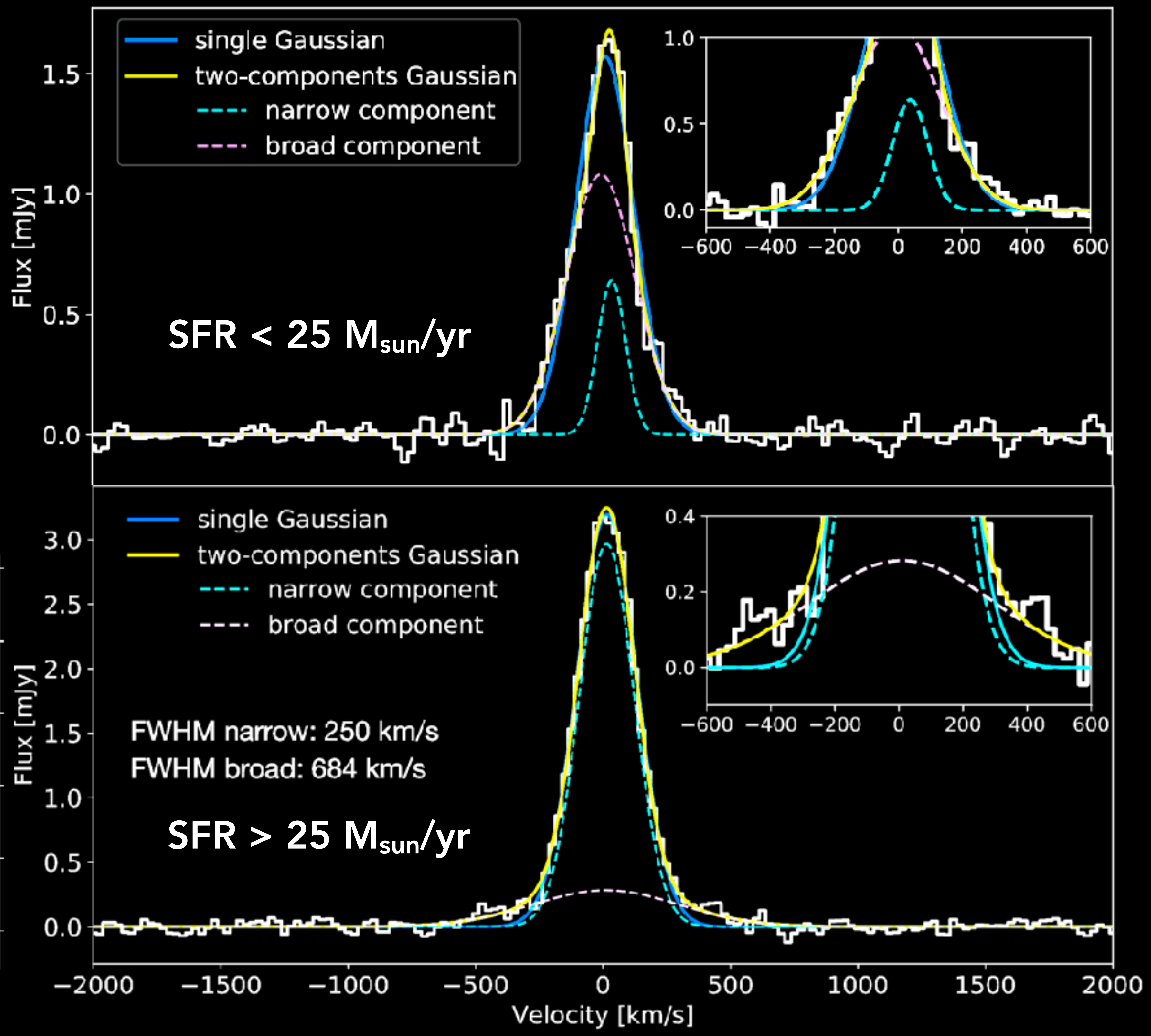
Disk Galaxies (smooth inside-out growth)

# What Is ALPINE Telling Us About Early Galaxies?

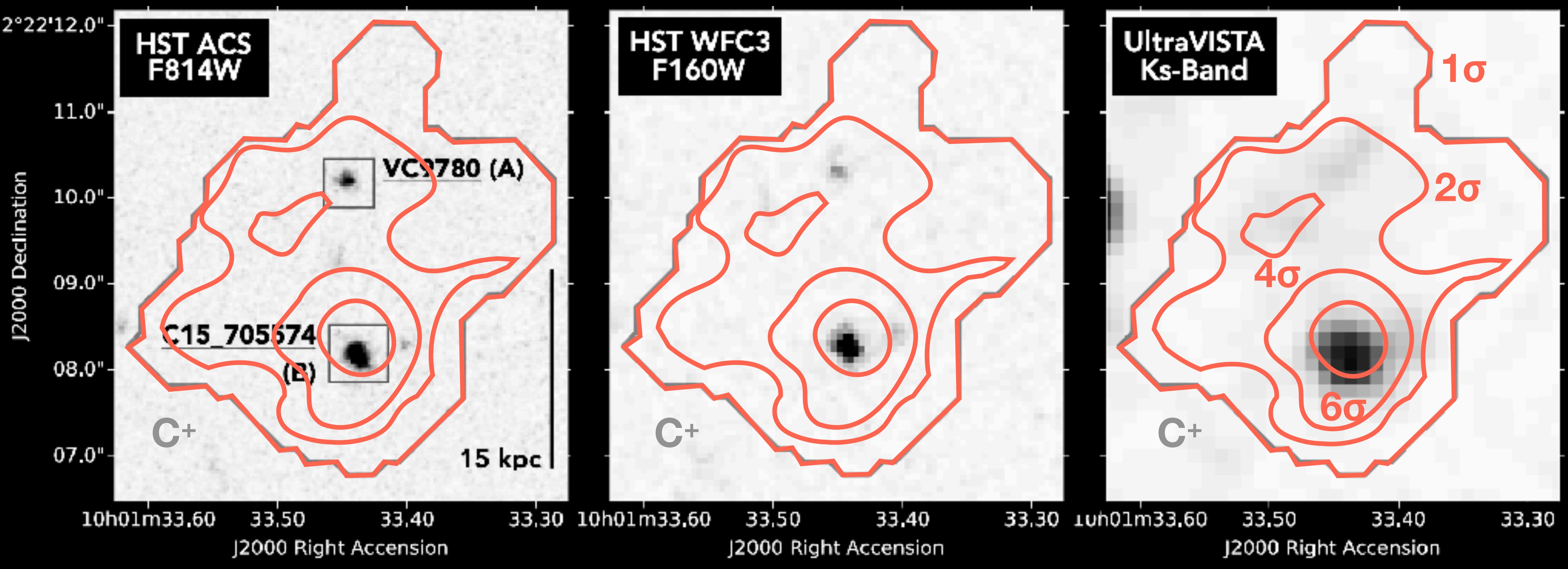
## How do high-z galaxies interact with their environment?

- Outflows and distribution of gas in merging systems enrich the surrounding IGM
- Outflows likely dominated by star formation (not AGN)

*Ginolfi et al. (2020a)*



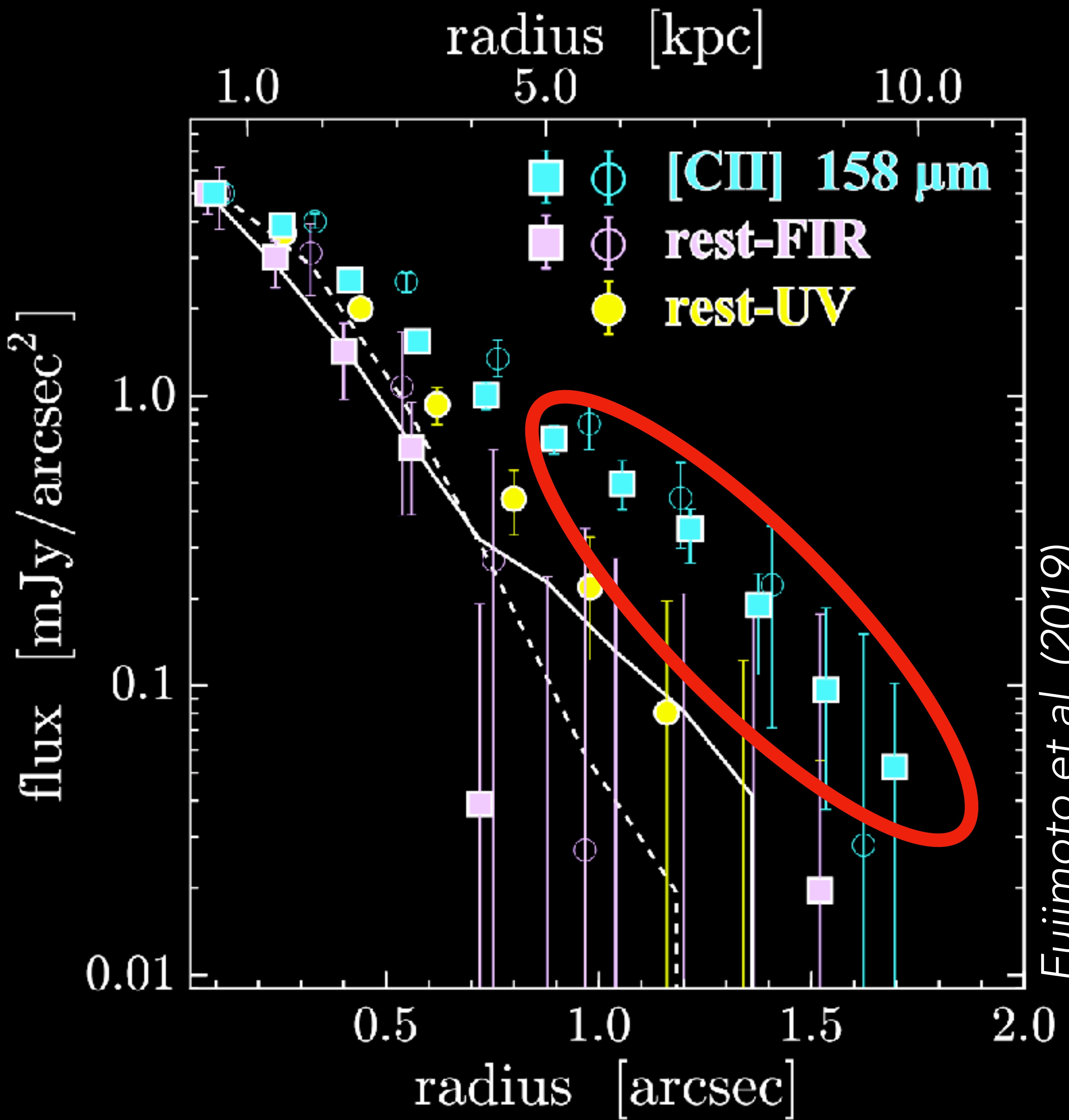

*Ginolfi et al. (2020b)*



# What Is ALPINE Telling Us About Early Galaxies?

## How do high-z galaxies interact with their environment?

- Outflows and distribution of gas in merging systems enrich the surrounding IGM
- Outflows likely dominated by star formation (not AGN)
- $C^+$ halos (likely common) produced by outflows, heating, gigantic disks, minor satellites (?)



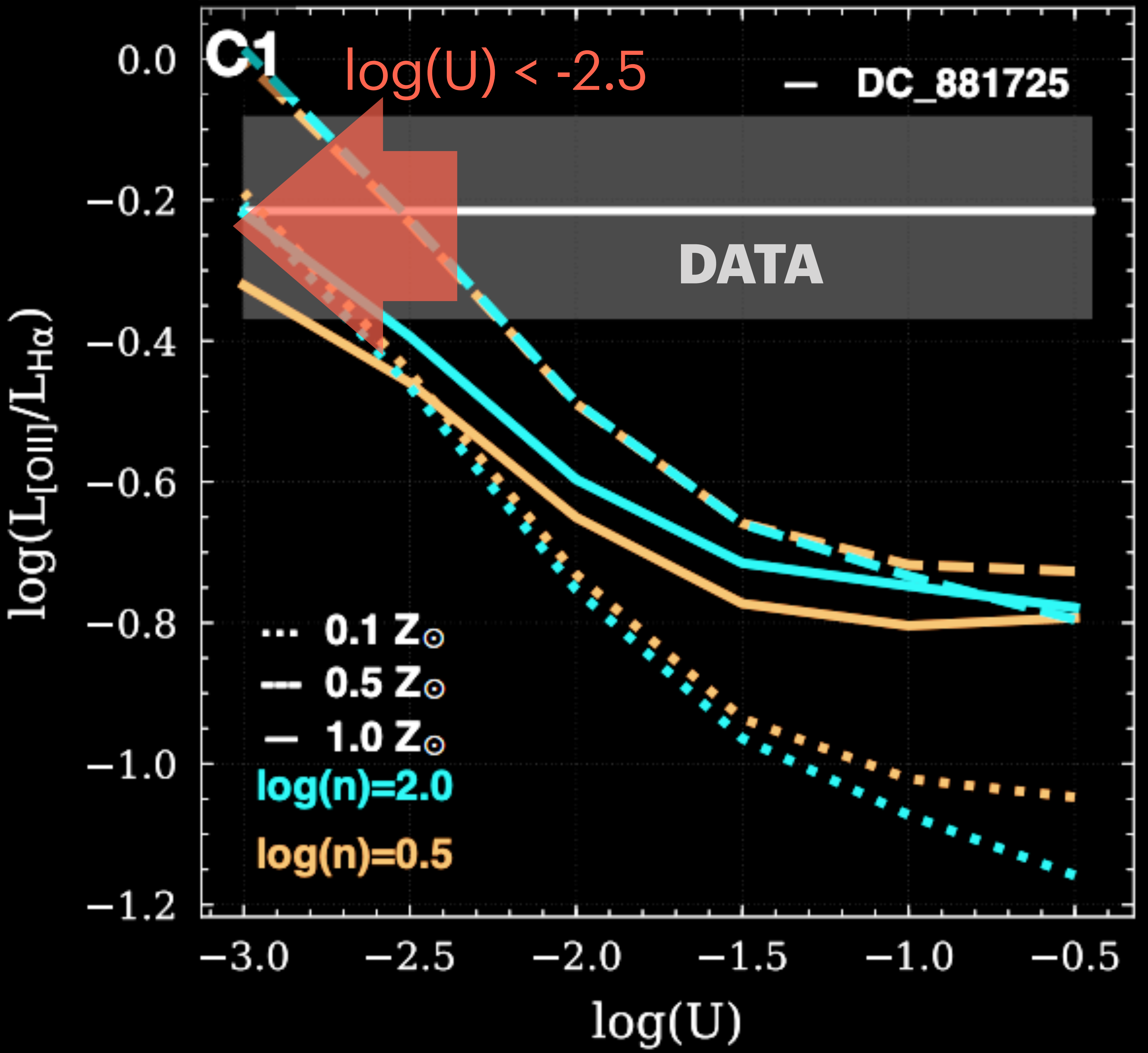

Fujimoto et al. (2019)

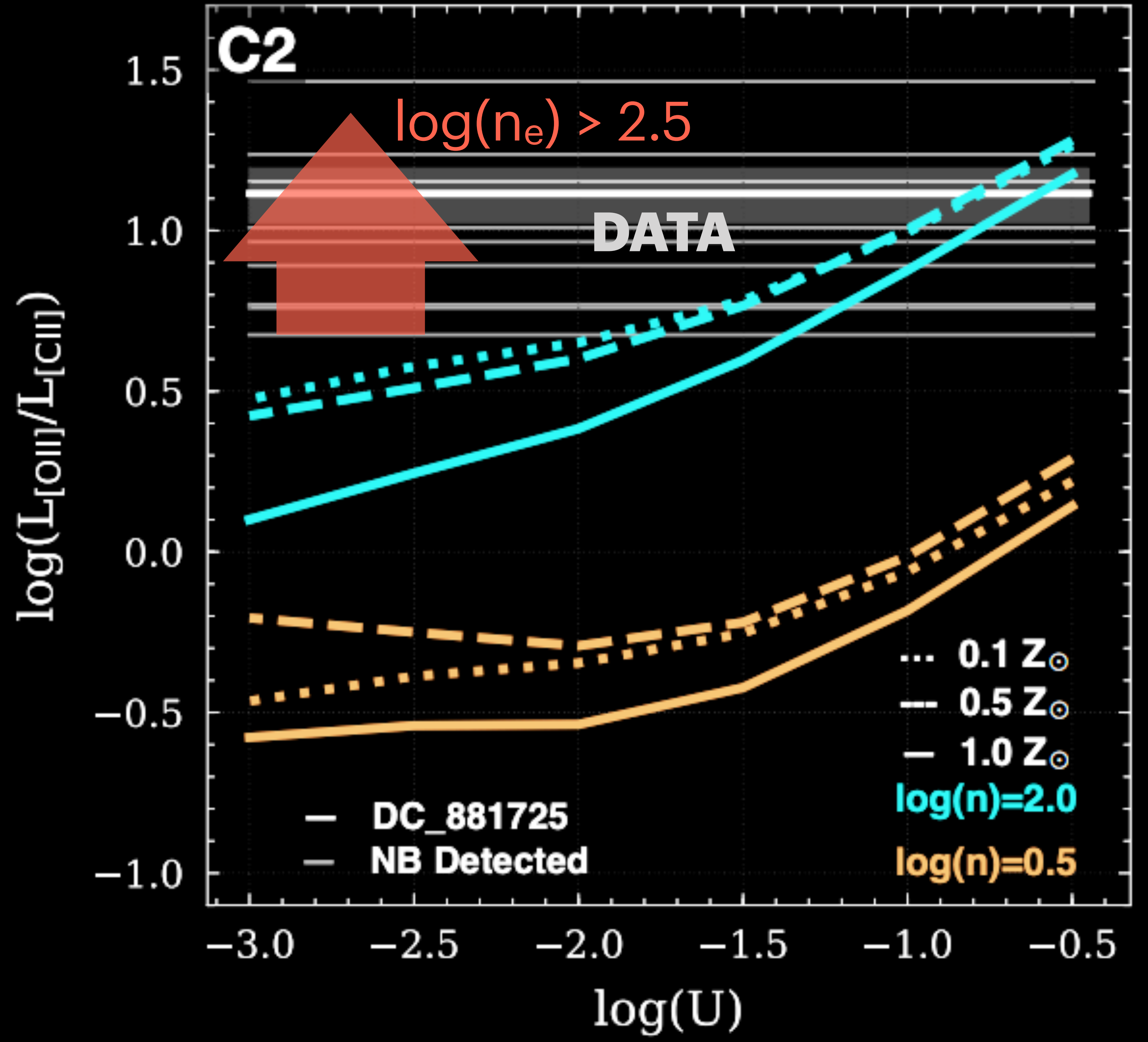
# What Is ALPINE Telling Us About Early Galaxies?

## Constraints on ISM properties of high-z galaxies

- 10 galaxies have $[OII]_{\lambda 3727}$ and $C^+$ measured: **ONLY** sample at z > 4.5!!
- $[OII]_{\lambda 3727}$ from MOSFIRE (1) and Subaru NB (9) observations of C3VO cluster (Lemaux et al. 2020; Shen et al. 2021)!
- Hα from Spitzer colors (Faisst et al. 2019)
- Results:
  - ➡ log(U) < -2.5 (consistent with z=2-3 galaxies)
  - ➡ $\log(n_e)$ = 2.5-3 (slightly higher than z=2-3 galaxies at same SFR)

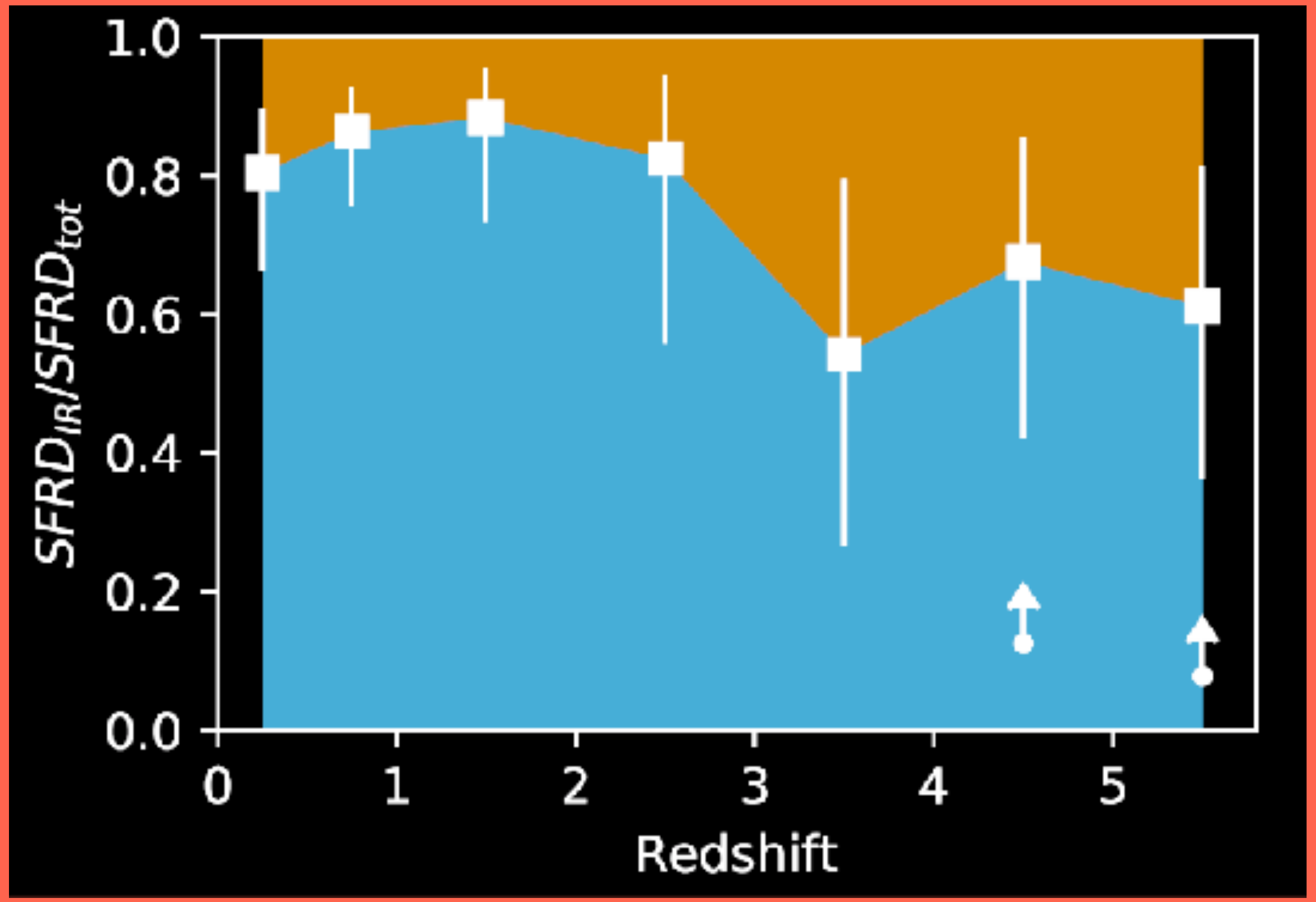
*Vanderhoof et al. (2022)*



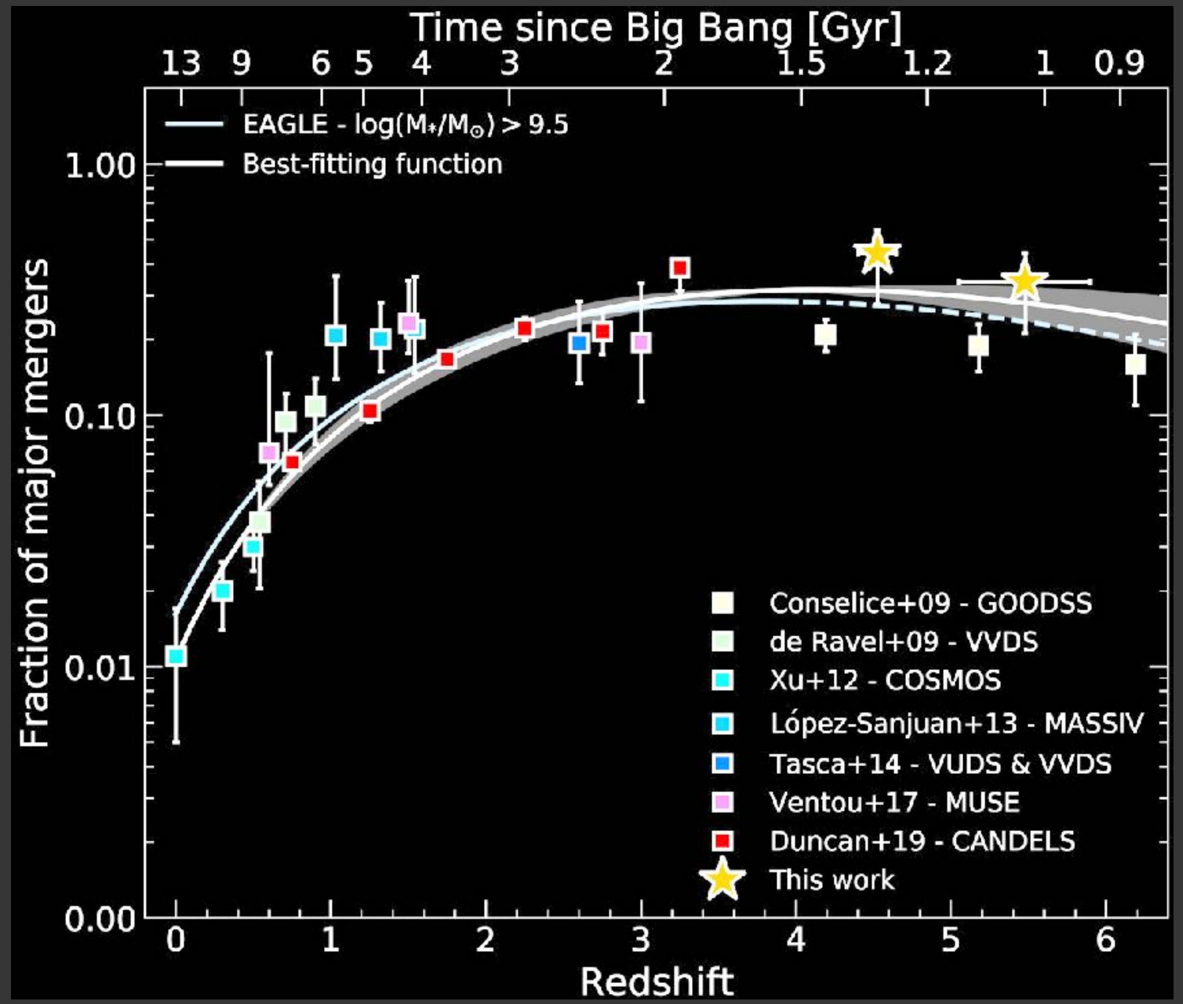
# More results in following presentations!

## Yana Khusanova (Poster)



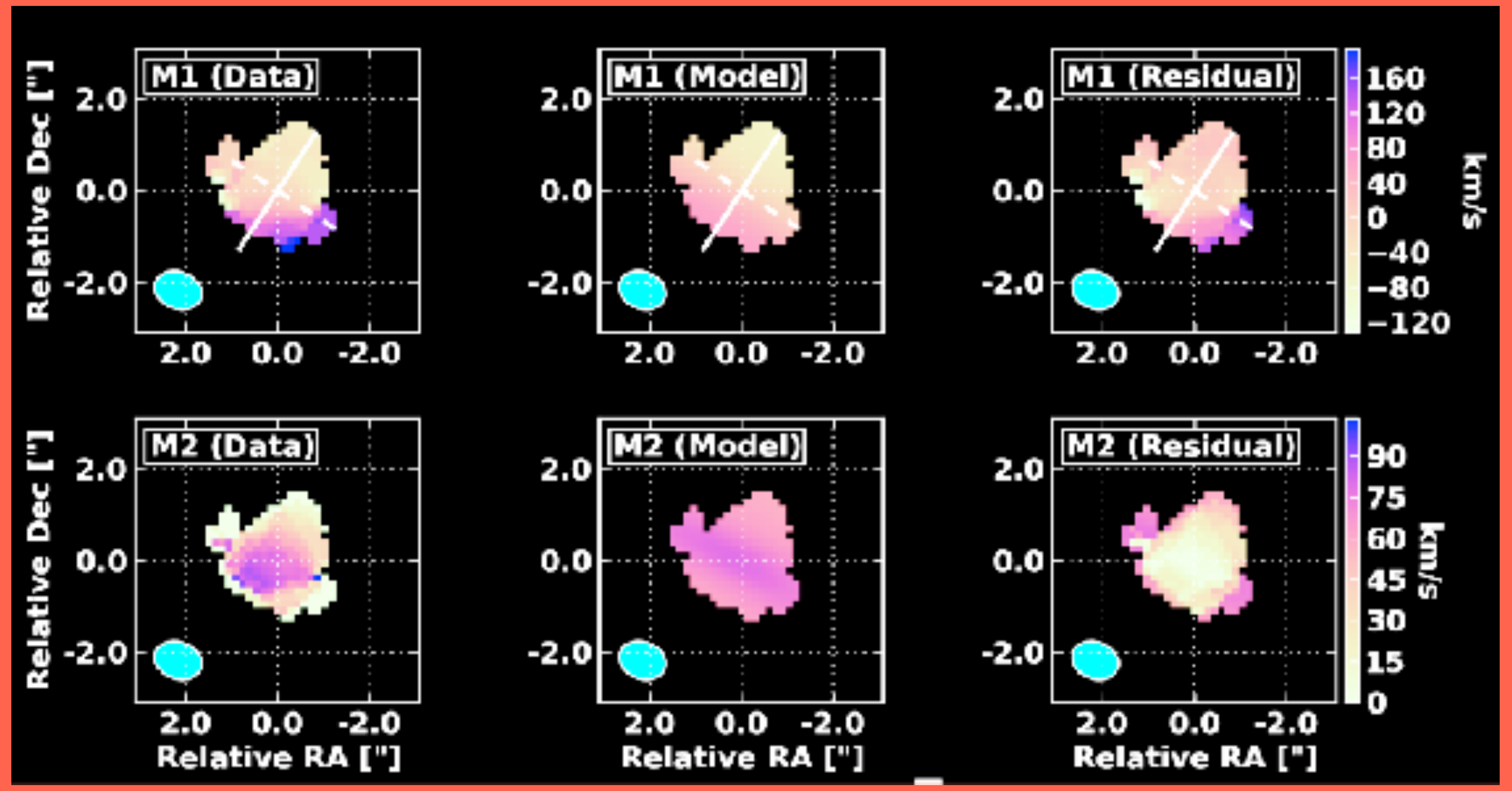

*Main sequence and SFR density*

## Michael Romano



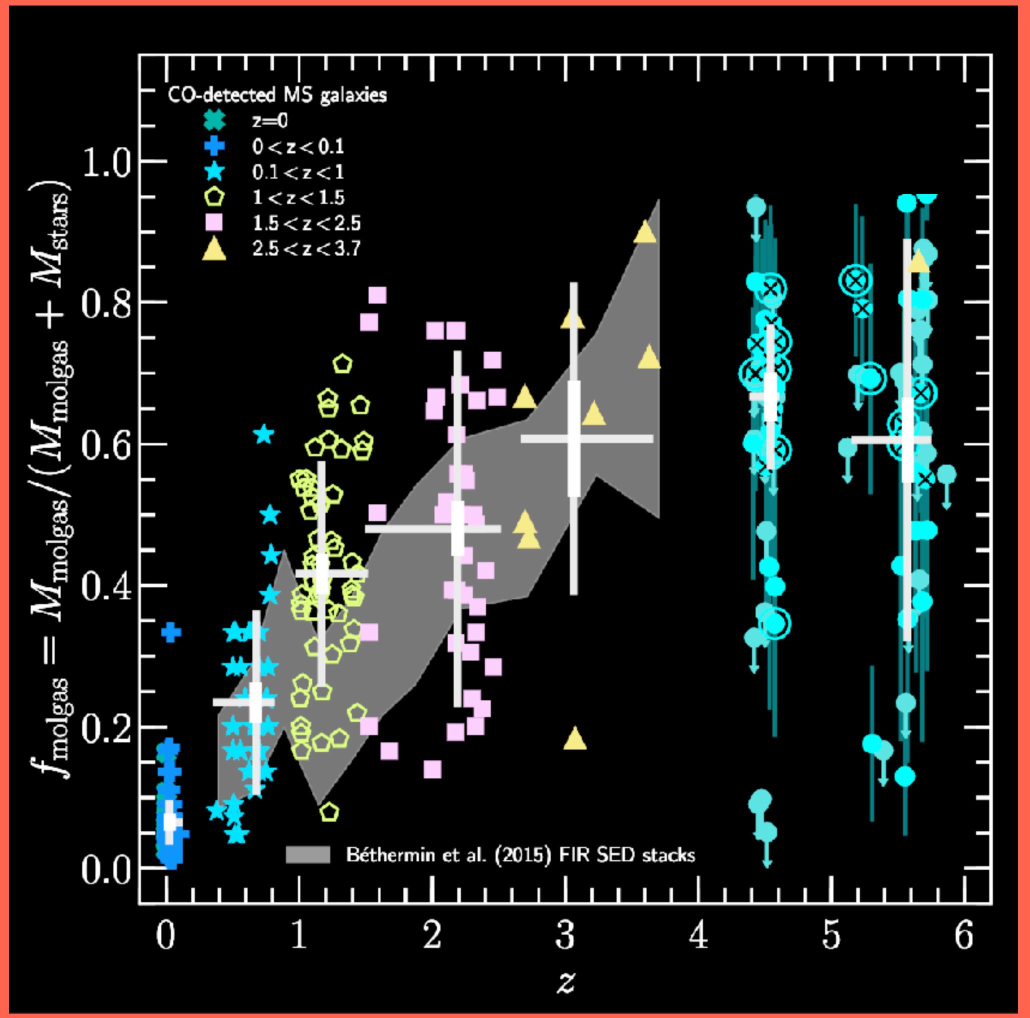

*Major mergers and obscured sources*

## Gareth Jones



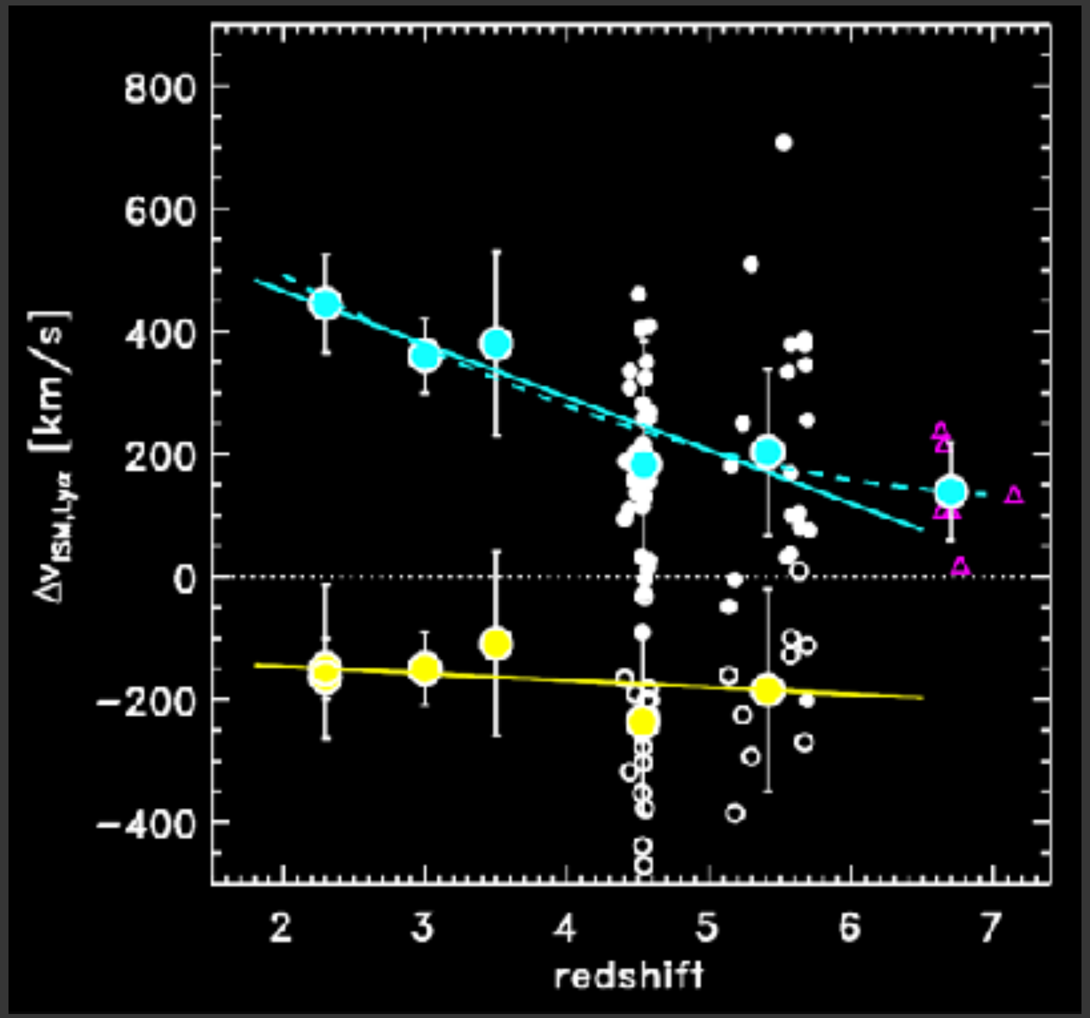

*Kinematic analysis*

## Mirka Dessauges-Zavadsky




*Molecular gas mass and depletion*

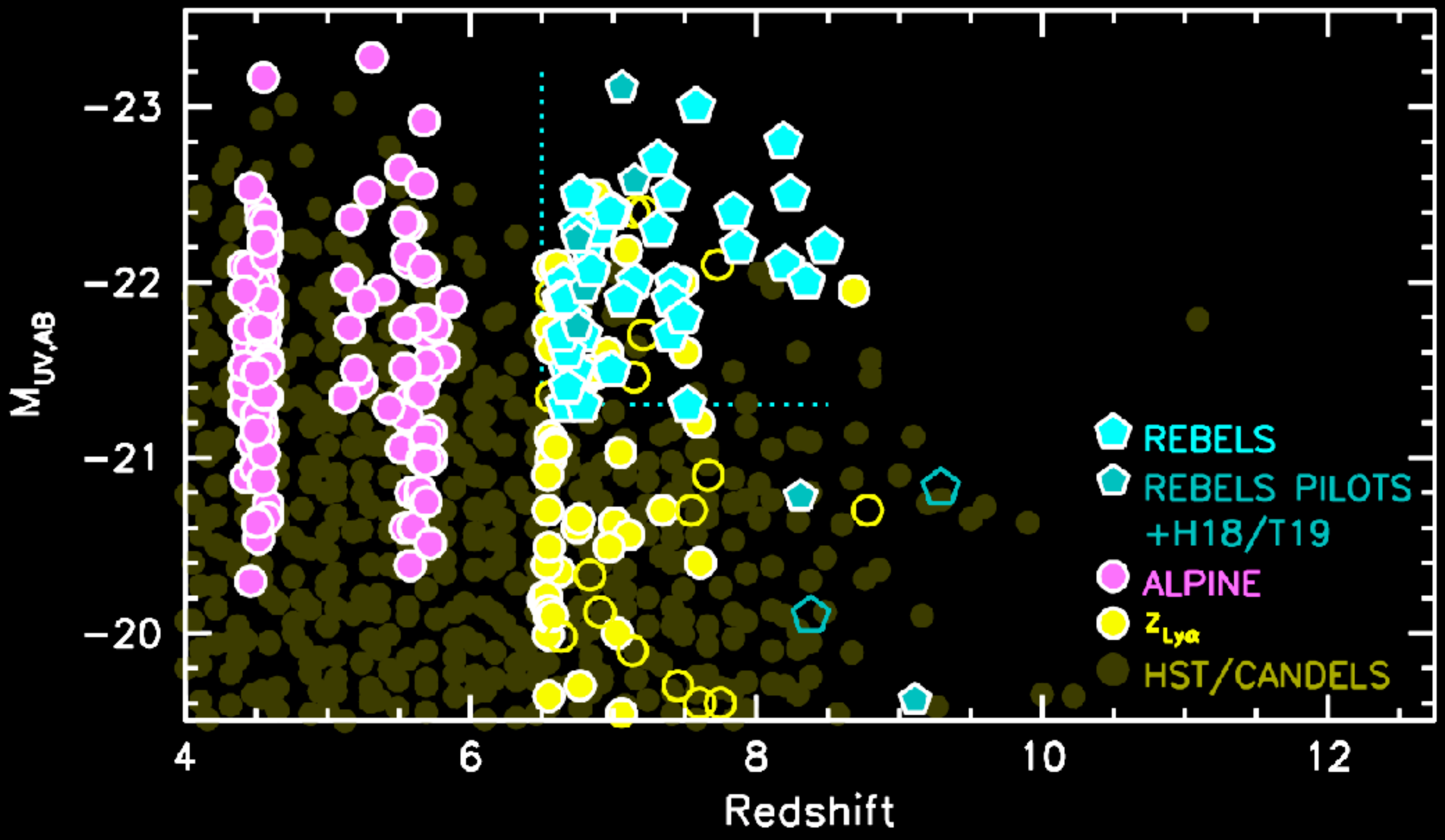
## Paolo Cassata

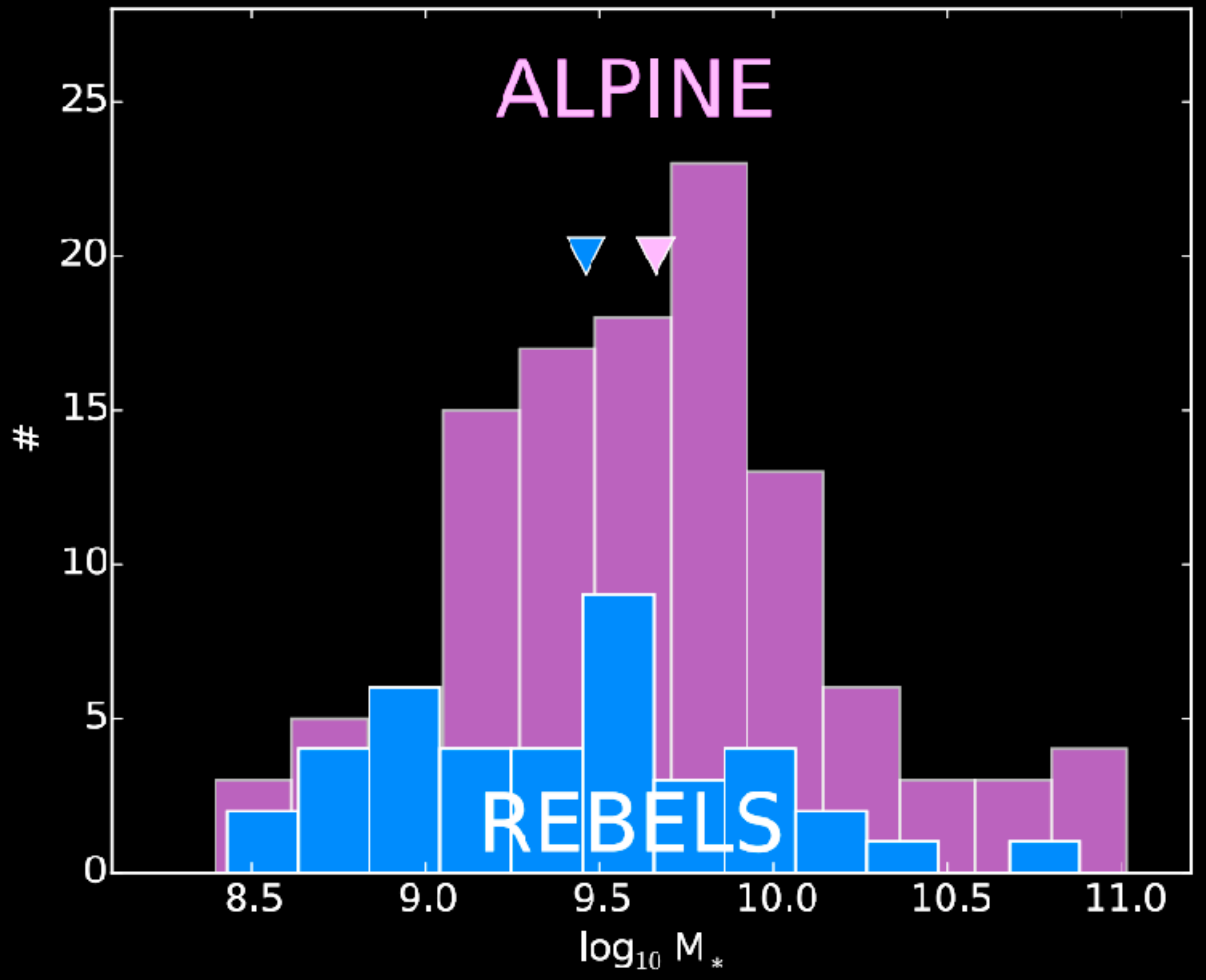


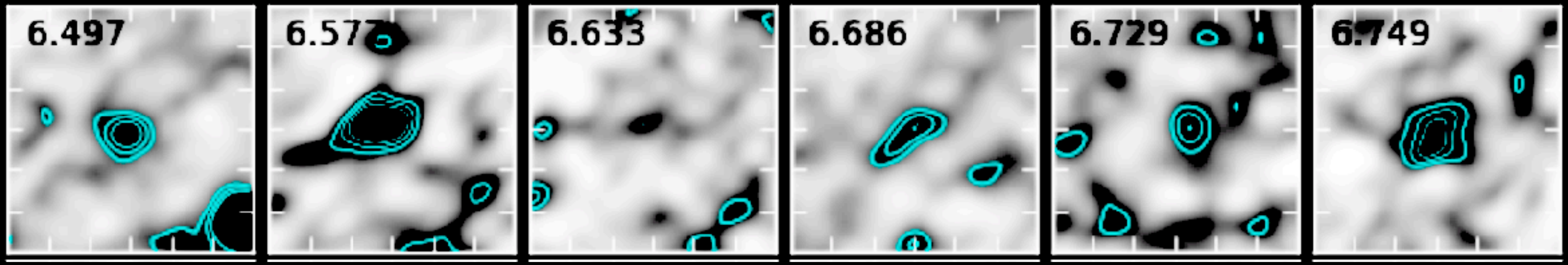

*Velocity offsets between Lya and C+*

# What About Higher Redshifts?

*REBELS* survey (Bouwens et al. 2021) is ALPINE continuation to $z > 7$



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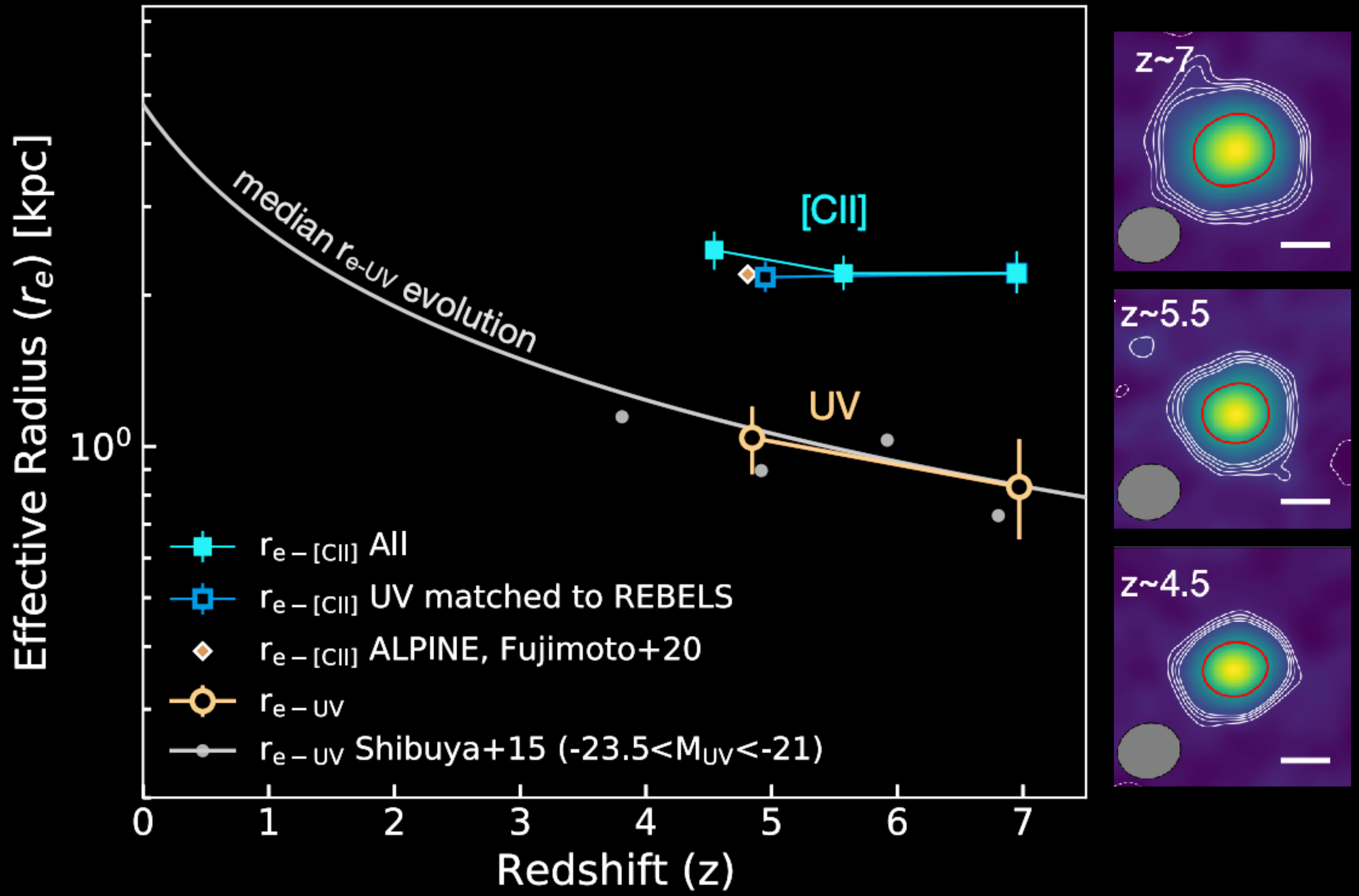
*REBELS* survey (Bouwens et al. 2021) is ALPINE continuation to z > 7

- Evolution of $C^+$ halo size from z = 7 to z = 4

*Fudamoto et al. (2022)*

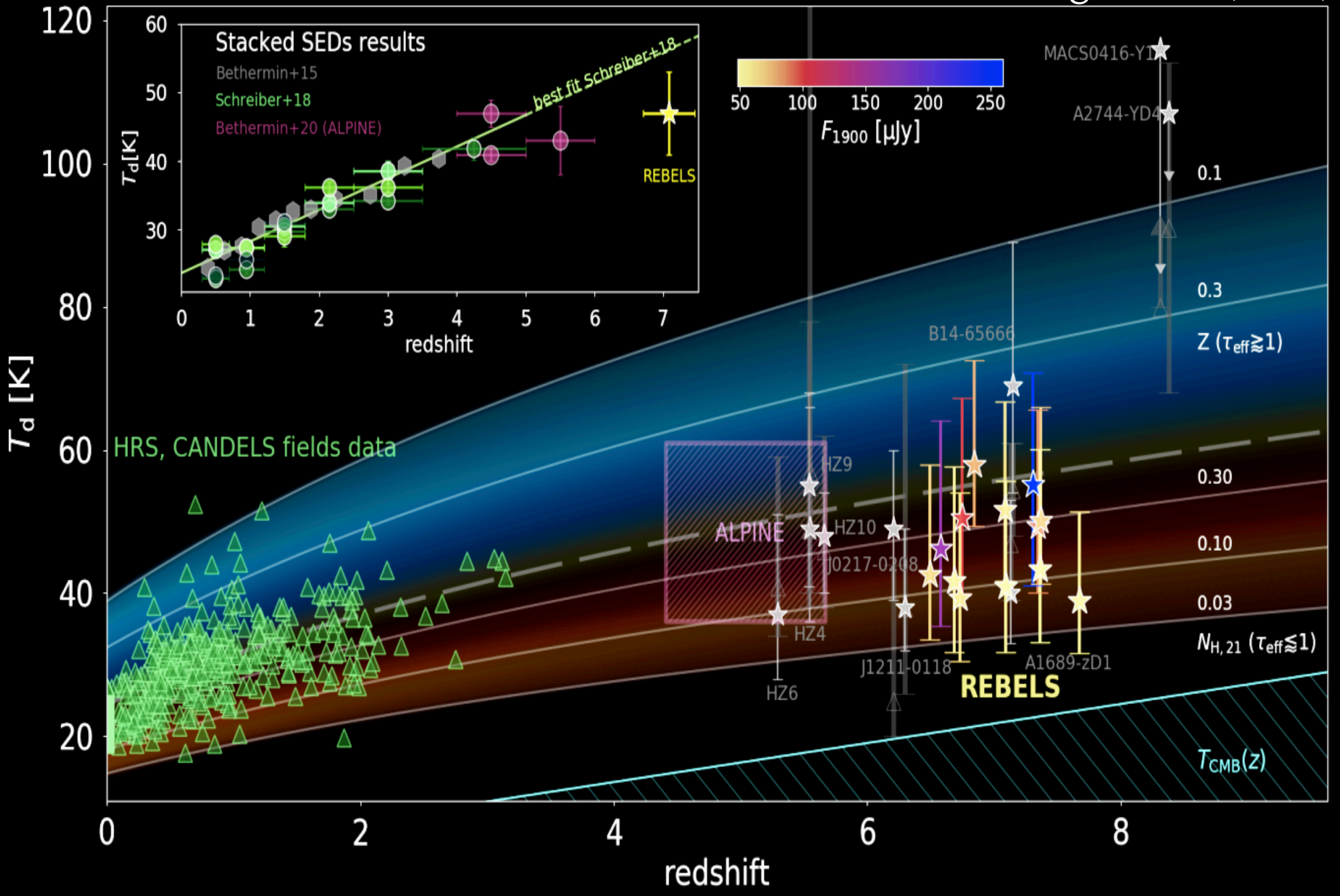


# What About Higher Redshifts?

*REBELS* survey (Bouwens et al. 2021) is ALPINE continuation to z > 7

- Evolution of $C^+$ halo size from z = 7 to z = 4
- Evolution of dust temperature from z = 7 to z = 4 (**<u>see Laura Sommovigo's talk</u>**)

*Sommovigo et al. (2022)*



# Conclusions

- ALPINE, providing the **first true multi-wavelength study**, has significantly improved our understanding of **how galaxies evolve in a post-reionization time**.

- ALPINE builds the necessary **baseline sample** that can be further expanded (by more galaxies and observations) and serves as **comparison sample** for other redshifts.

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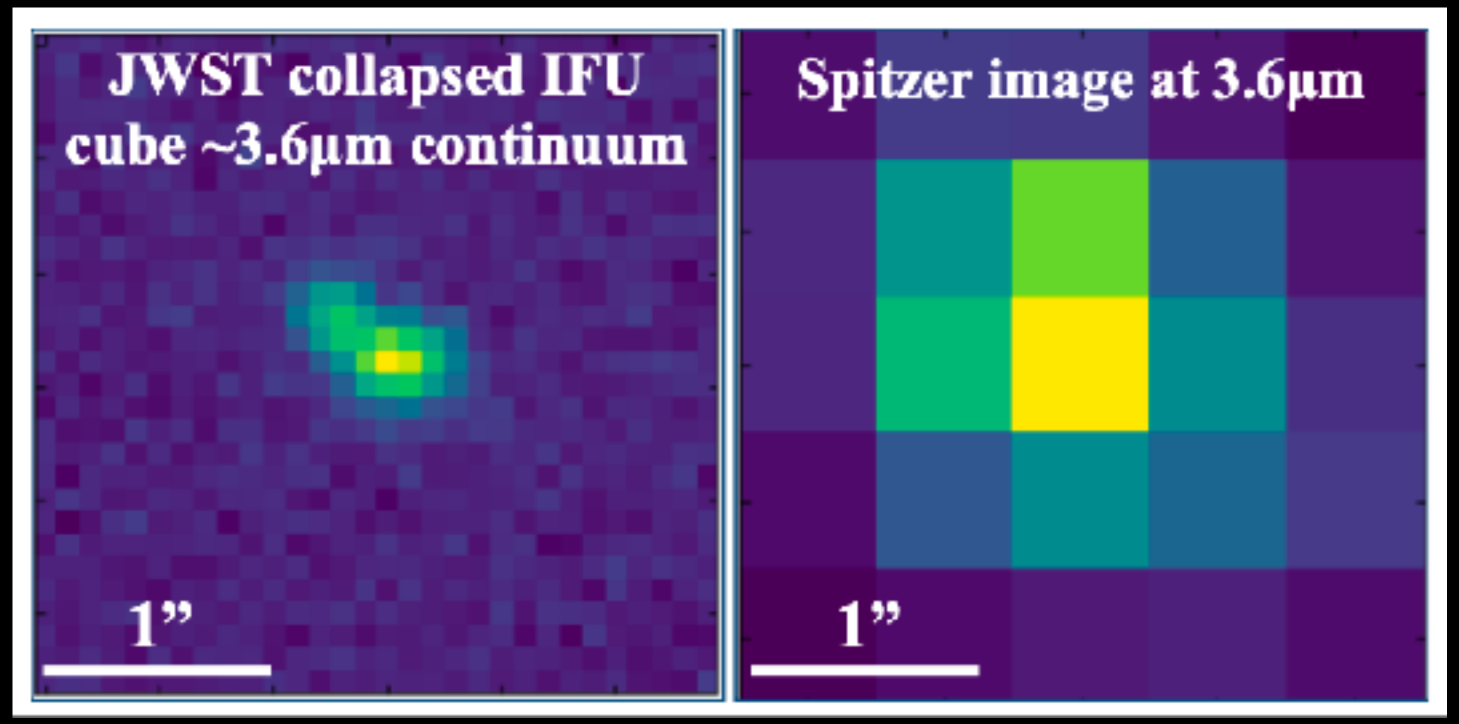


- **ALPINE is part of *COSMOS-Web***, a 208 hour JWST NIRCam + MIRI survey. Some galaxies will also be observed by NIRSpec.

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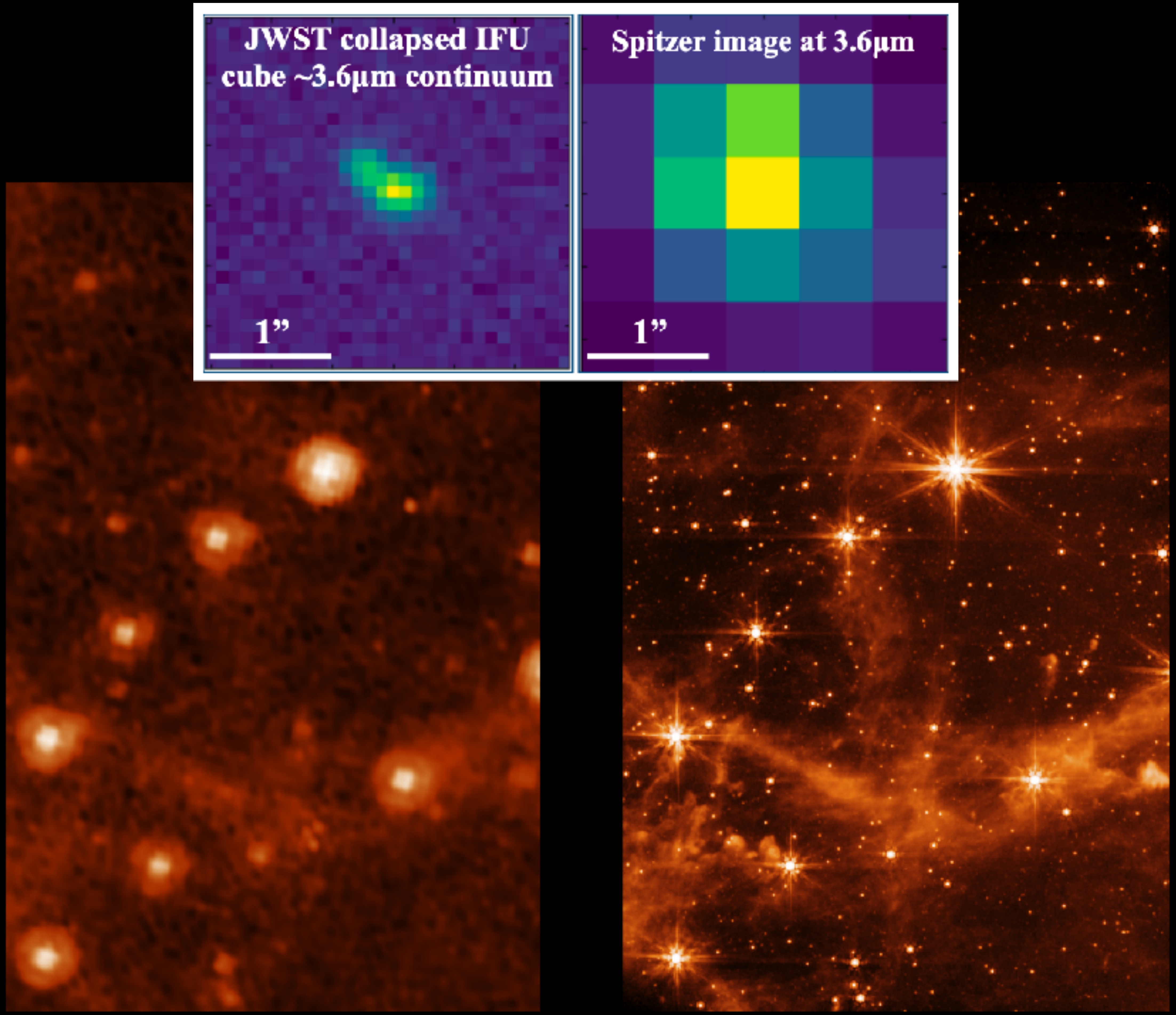


SPITZER IRAC 8.0μ    WEBB MIRI 7.7μ