2021.10.15 IPMU Postdoc Colloquium

(Dust and) Gas content in galaxies at z > 3 revealed with ALMA

Tomoko Suzuki

Collaborators: T. Kodama, M. Onodera, Y. Koyama, K. Tadaki, R. Shimakawa, I. Tanaka
I. Smail, E. Daddi, D. Sobral, S. Tacchella
K. Glazebrook, and the ZFOURGE team

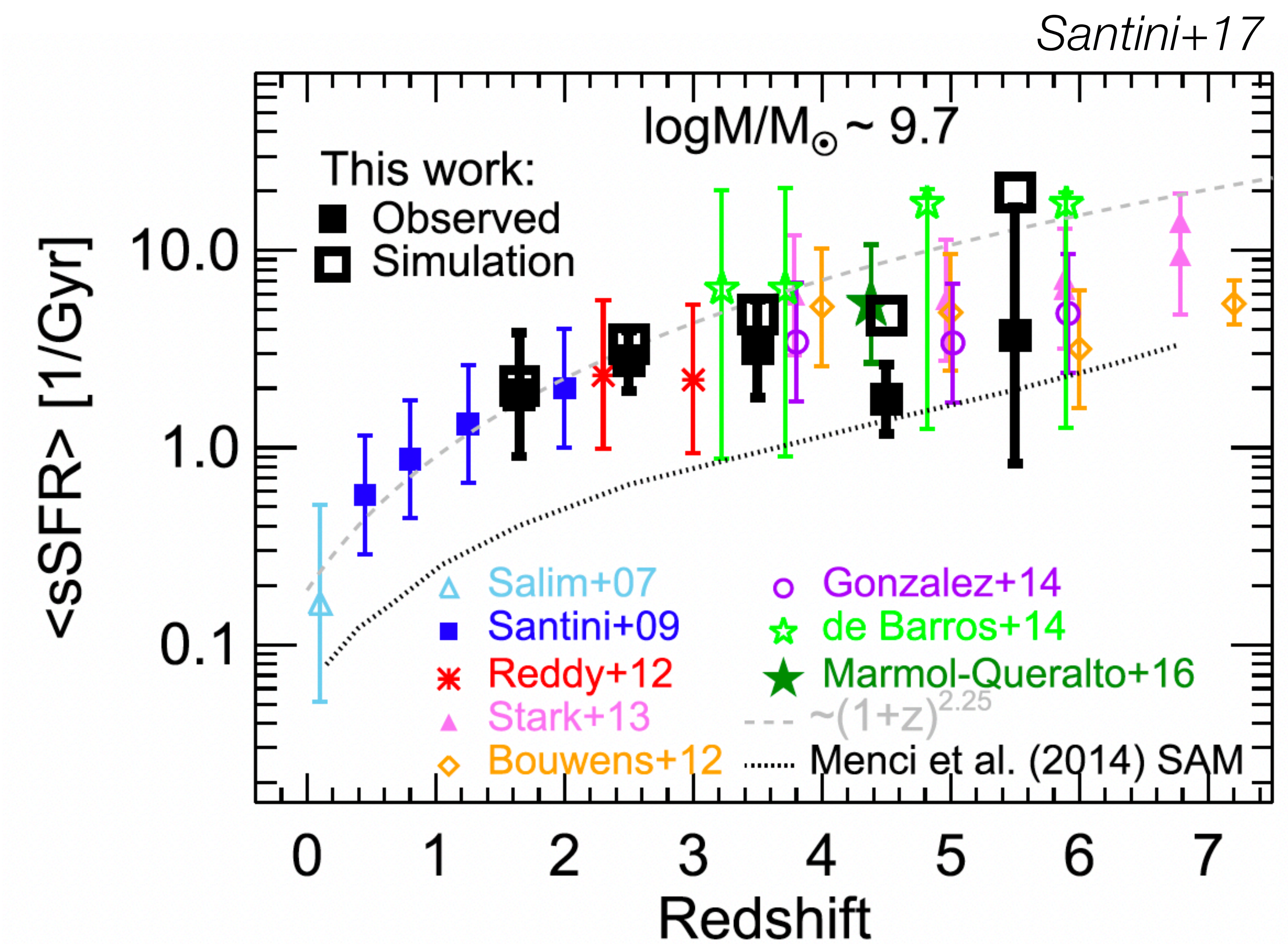
Today's talk

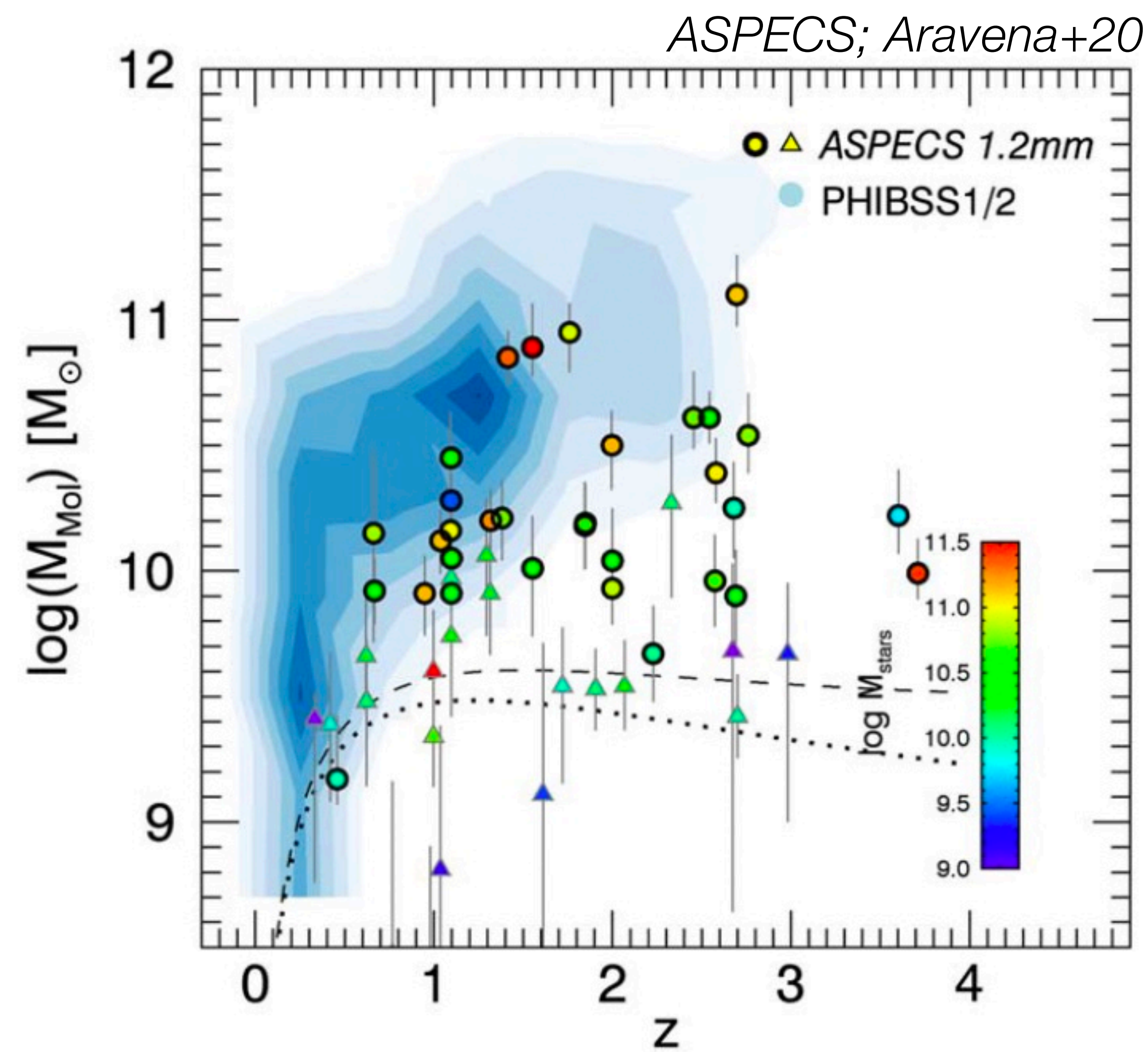
Gas properties of galaxies at z = 3-4

- **Star-forming galaxies** (Suzuki et al. 2021, ApJ, 908, 15)
  - Individual dust/gas mass measurements
  - Dependence on gas-phase metallicity

- **Quiescent galaxies** (Suzuki et al. in prep.)
  - First gas measurements at $z > 3.5$
  - How massive galaxies stop their star-formation?

Molecular gas: fuel of star-formation in galaxies





- High star-formation activity at high-z is supported by a large amount of gas

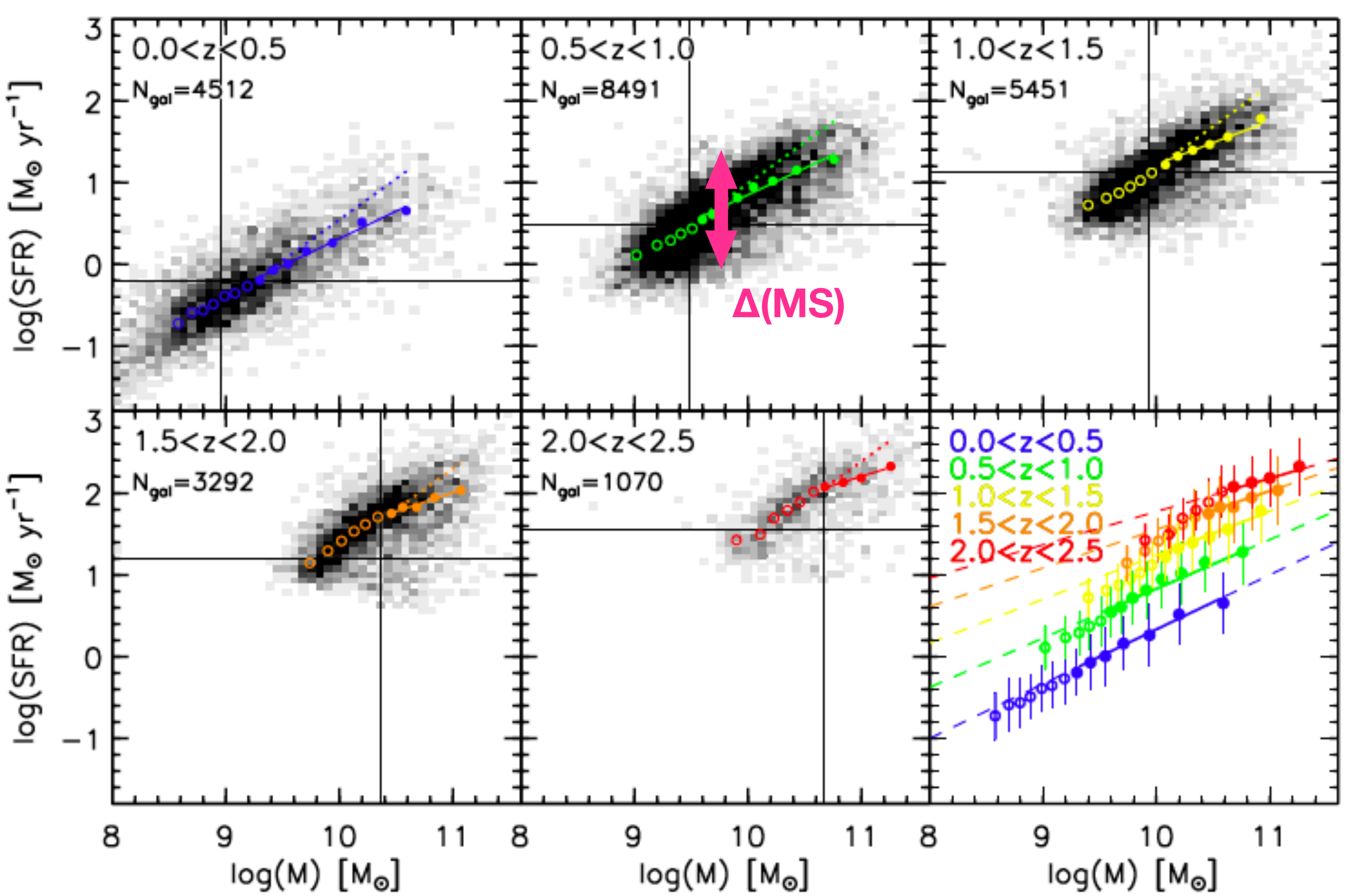
- **Molecular gas observations with CO lines and/or dust emission reaches up to z ~ 4 or even higher-z (but sample size is still limited)**

“Main sequence” of star-forming galaxies

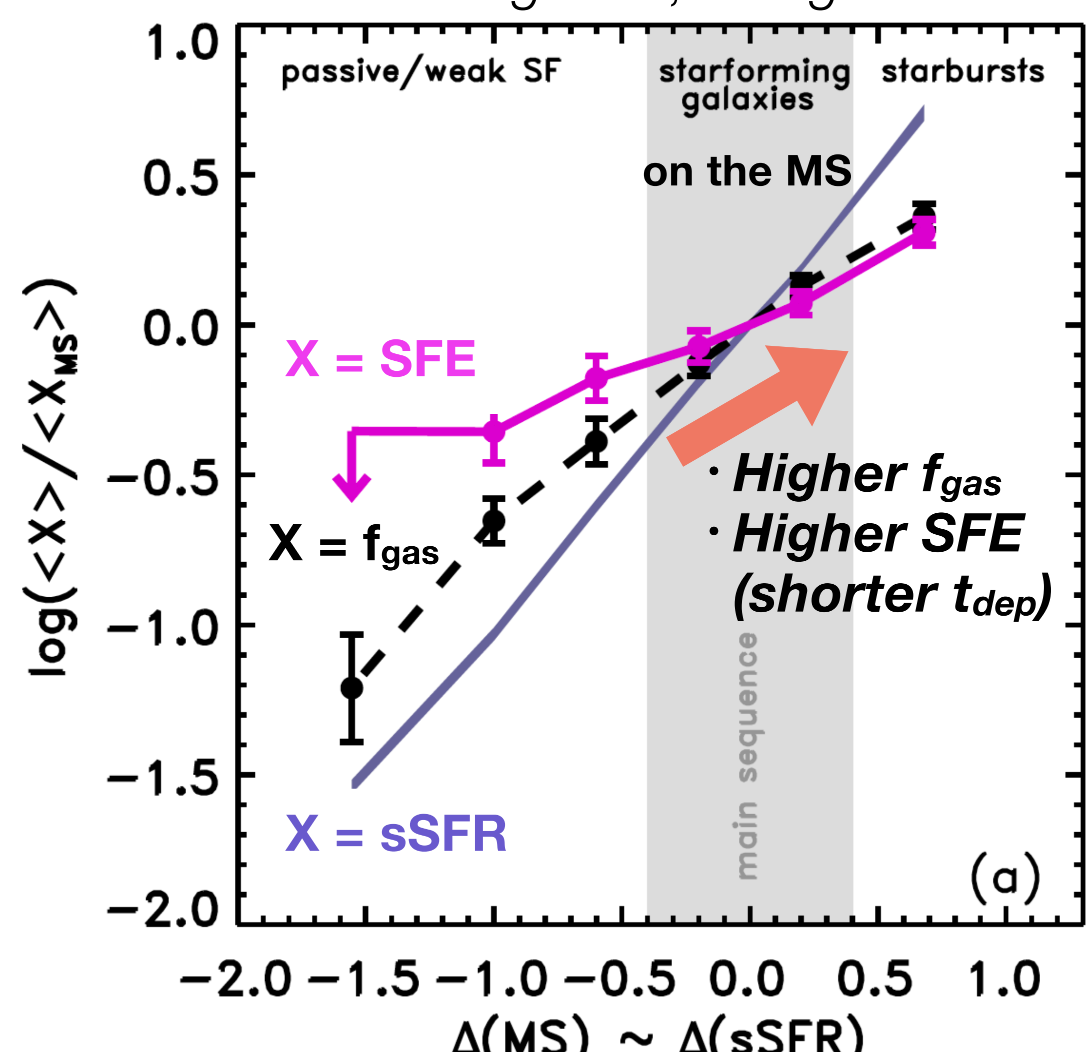
- Tight and positive correlation between M_{star} and SFR
  : “Main sequence" of star-forming galaxies

- Correlation between Δ(MS) and gas properties
  → Galaxies above the MS are more gas-rich and have higher SFE

Whitaker+14



Saintonge+12; z~0 galaxies



e.g., Sargent+14; Scoville+16; Tacconi+18; Liu+19ab

Importance of gas-phase metallicity?

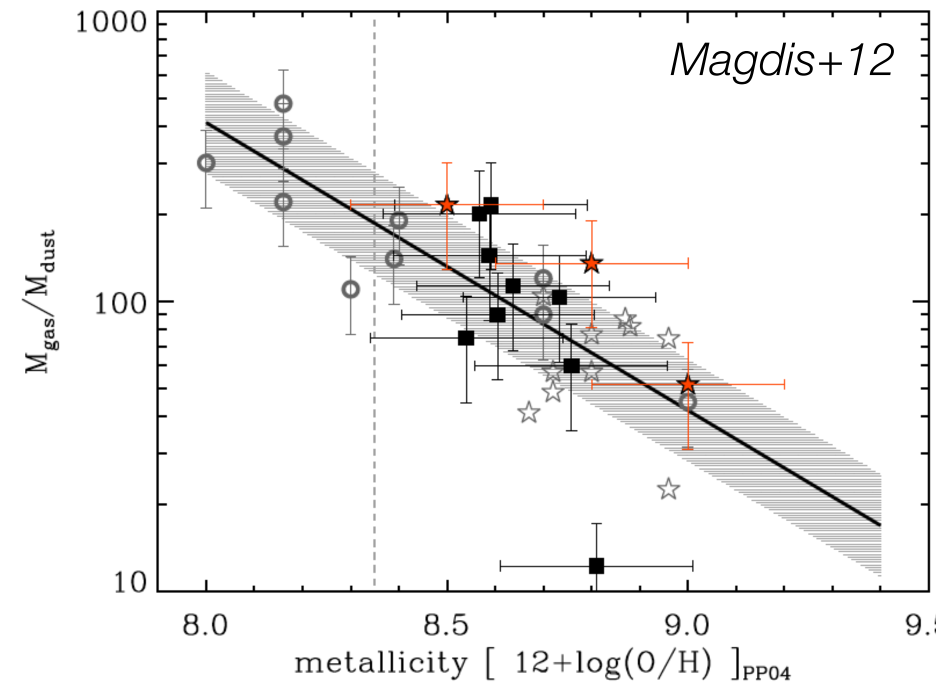
- **Metallicity dependence appears when estimating gas mass**

  - **CO-to-H2 conversion factor**

    : CO line flux —> M_{gas} (e.g., Daddi+10; Genzel+10)

  - **Gas-to-dust mass ratio**

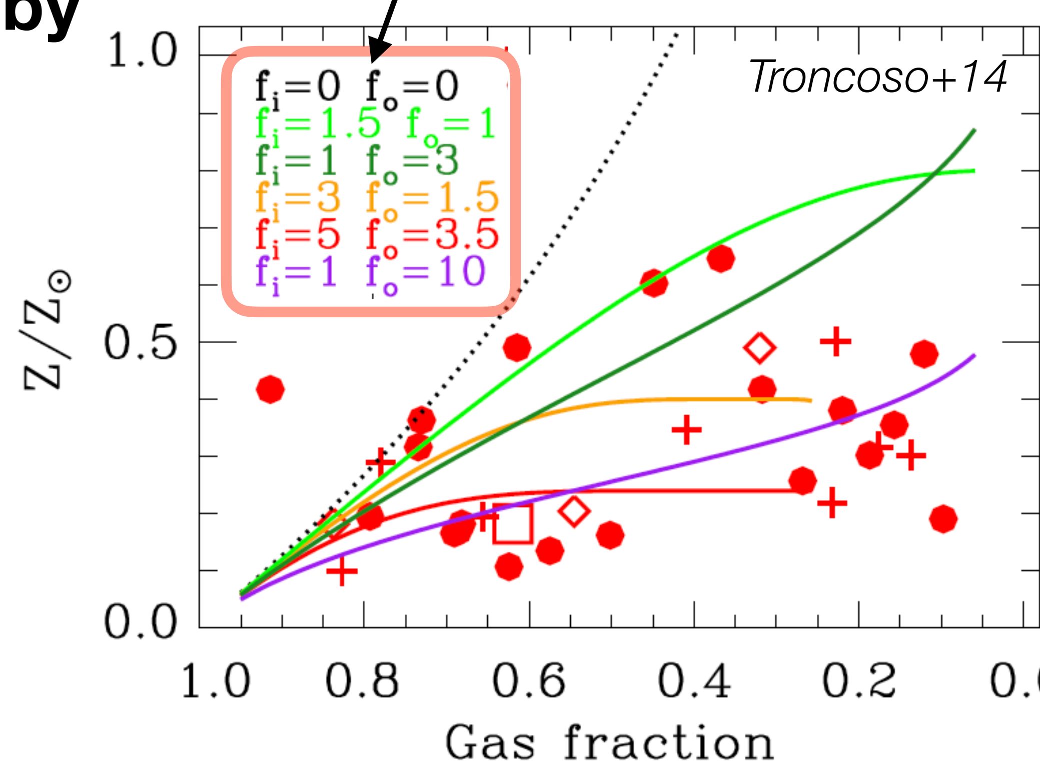
    : M_{dust} —> M_{gas} (e.g., Santini+10; Bethermin+15)



- **Gas mass and metallicity could change by star-formation, gas inflow and outflow**

  → Used to give a constraint on inflow/outflow rate by combining with the chemical evolution models

Inflow rate, Outflow rate



e.g., Erb+06; Cresci+10; Troncoso+14; Yabe+15; Seko+16

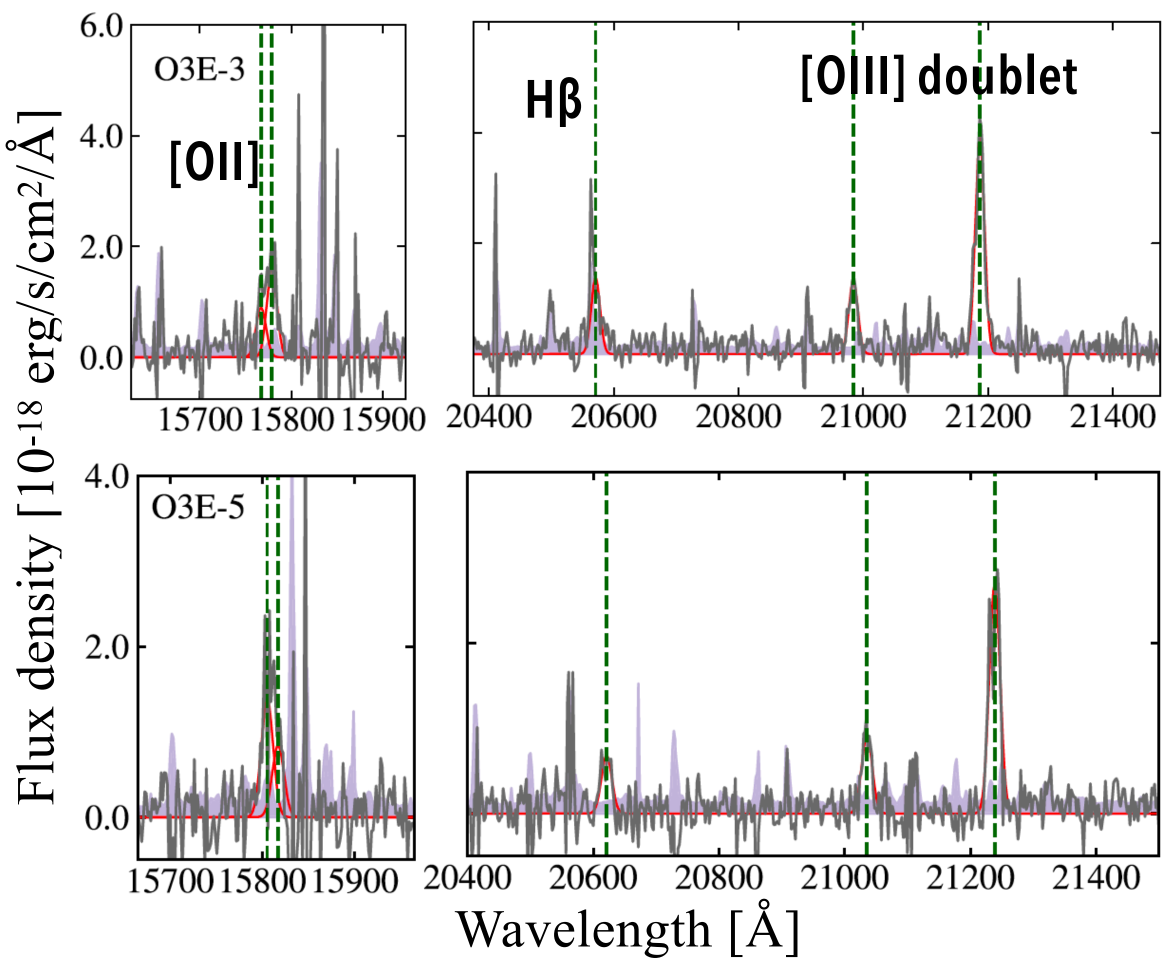
Previous works: NIR spectroscopy for SFGs at z = 3-4

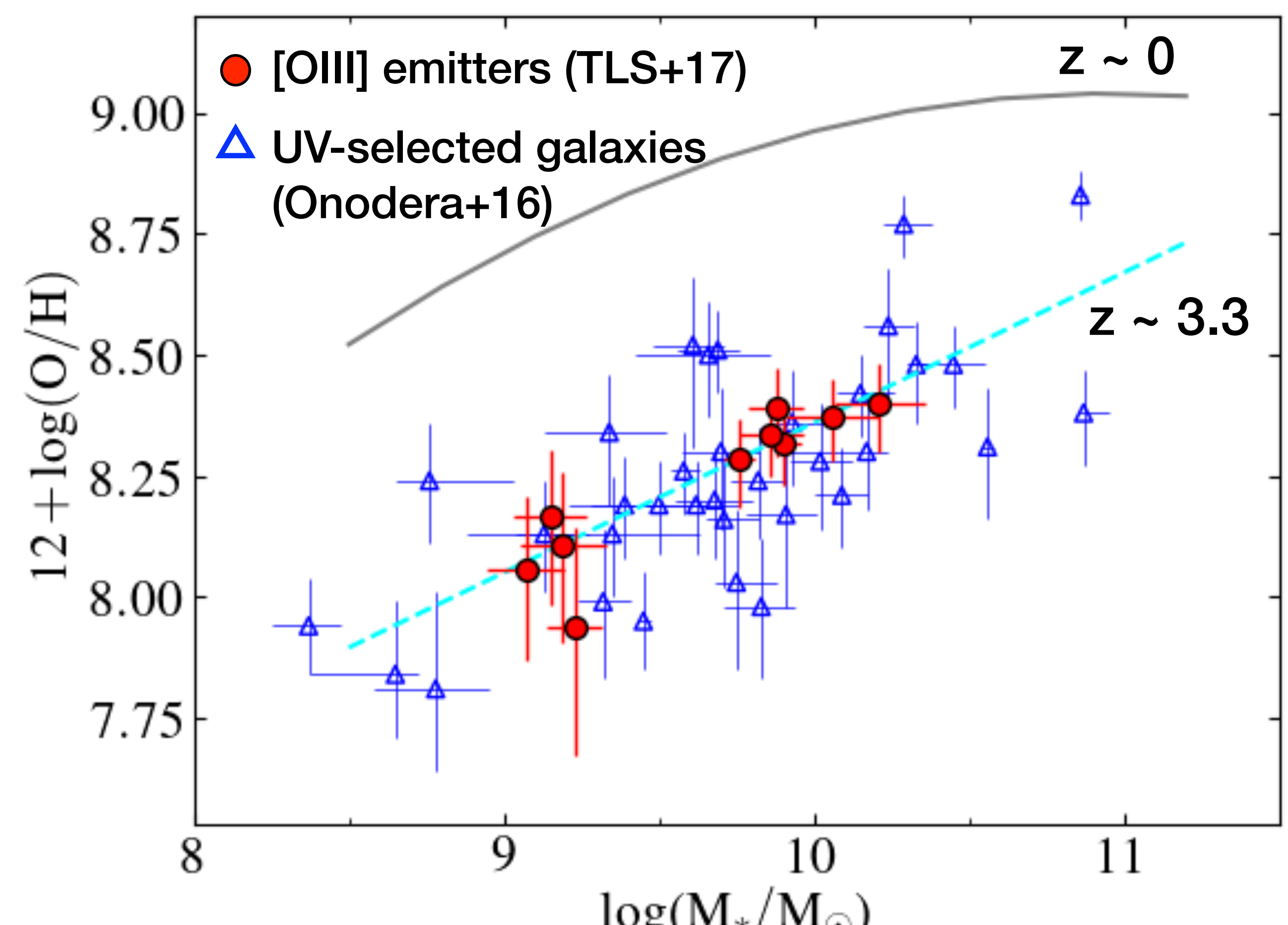
- Onodera et al. (2016) & Suzuki et al. (2017)

: H+K band spectroscopy with Keck/MOSFIRE

- Metallicity calibration with [OIII], Hβ, and [OII] lines (Curti+17)

  : Individual measurement of gas-phase metallicity

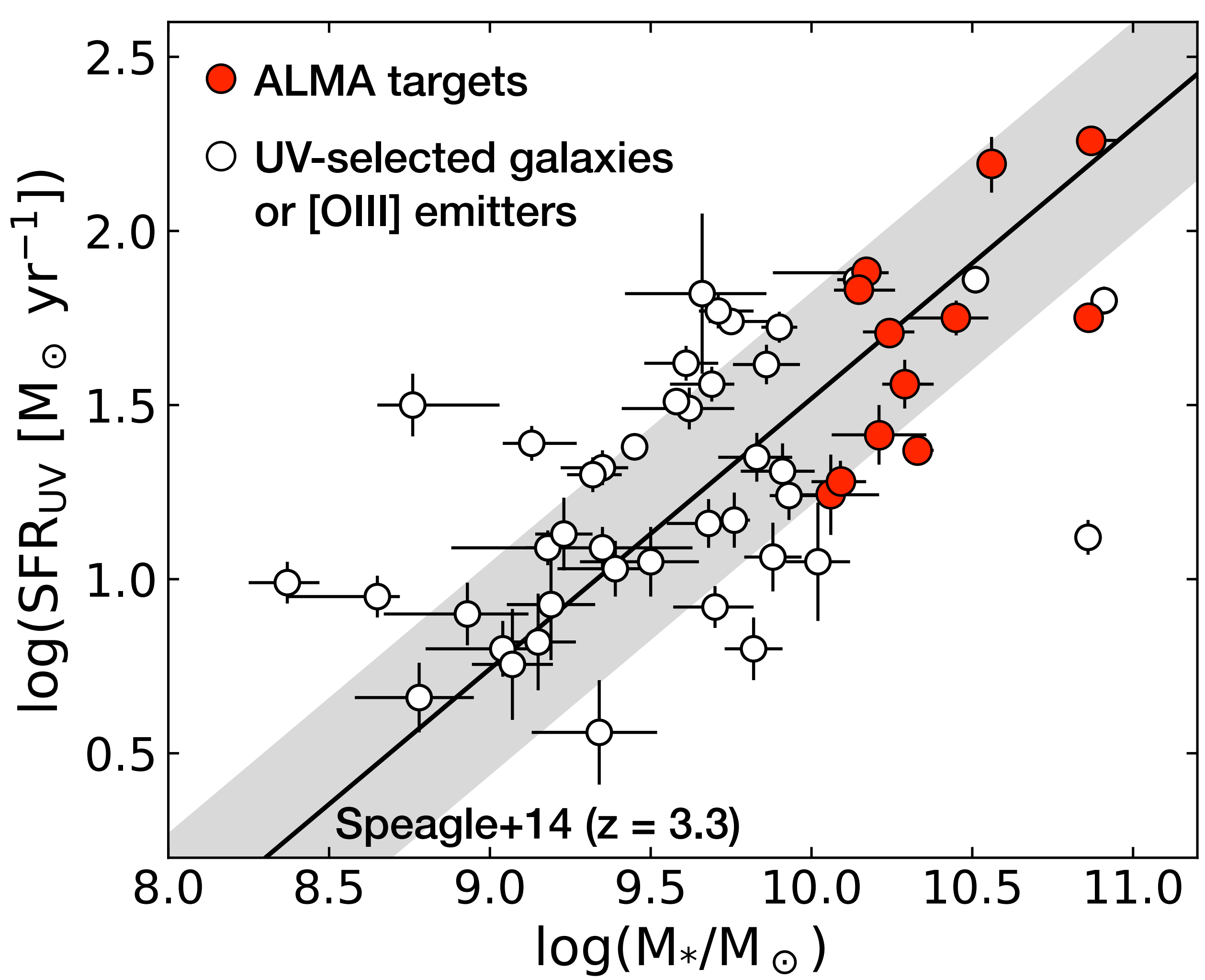




TLS+17

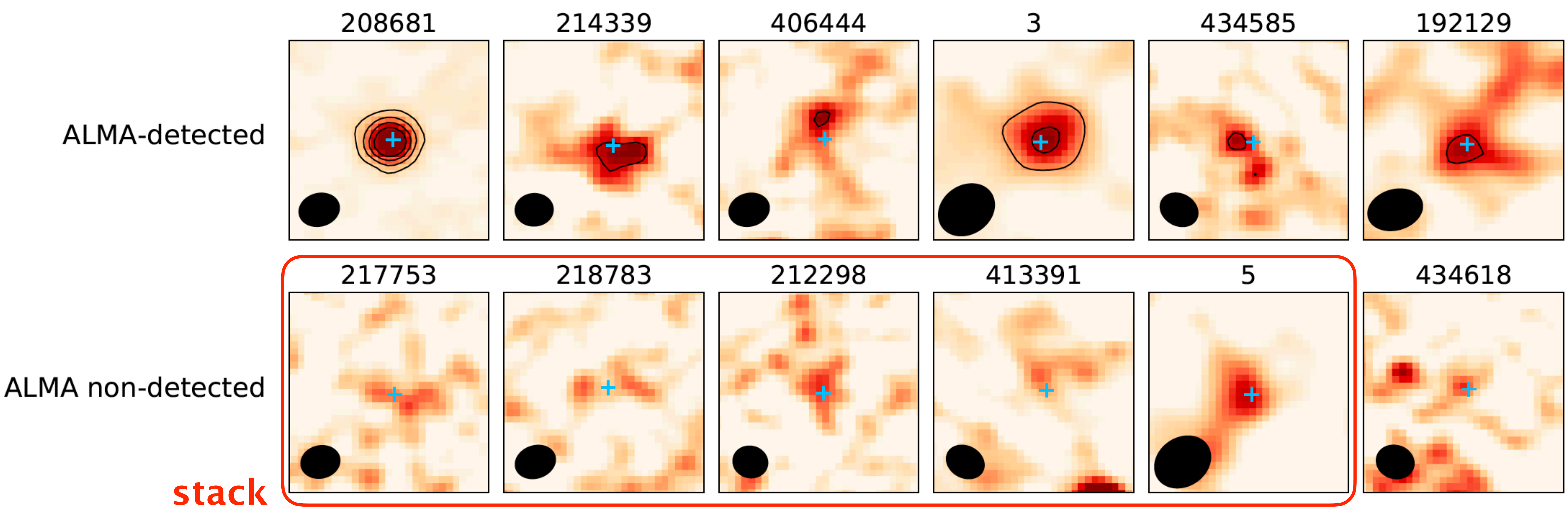
ALMA Band-6 observation

- Cycle-6 (2018.0.00681.S, PI: T. Suzuki)
- **12 galaxies with log(M_{star}/M_{sun}) > 10 and [OIII]λ5007, Hβ, and [OII] >= 3σ**
- Dust continuum emission at ~ 1.1mm
- Beam size: ~ 1.5 arcsec x 1.3 arcsec

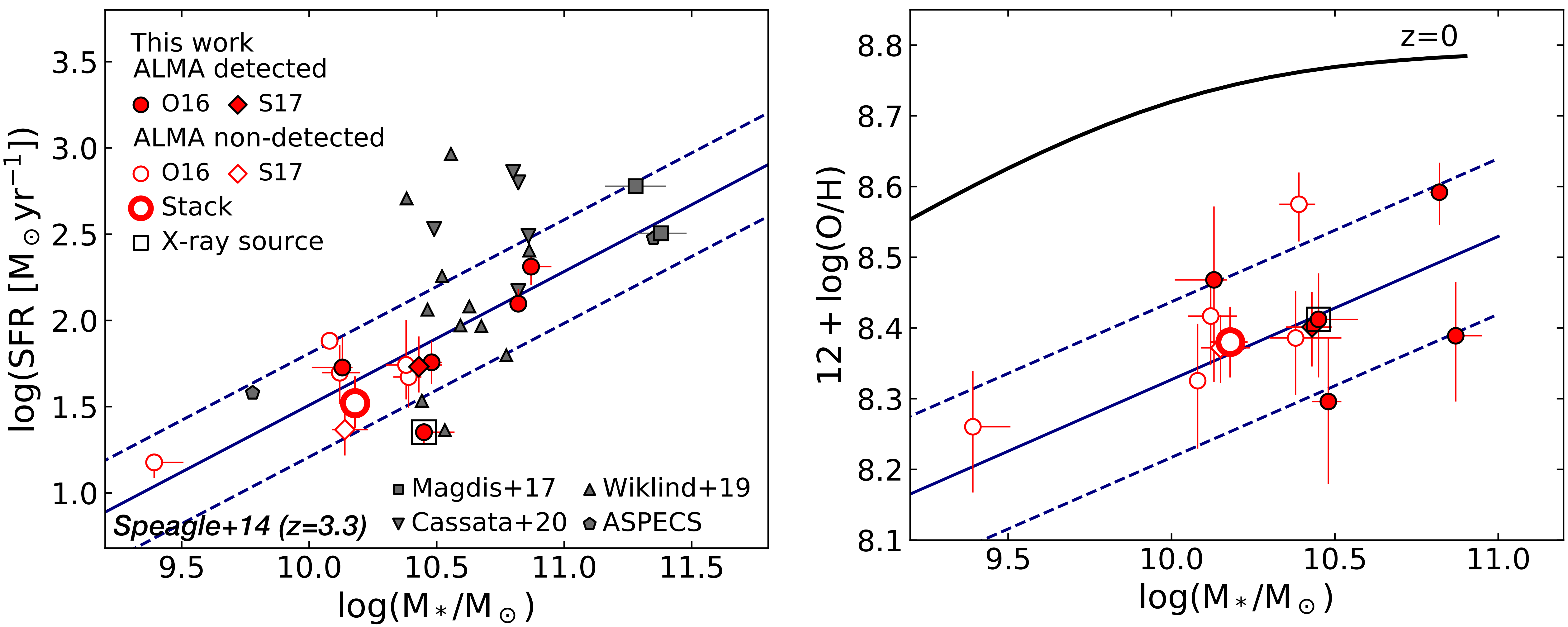


Continuum detection and stacking analysis

- **6 galaxies are detected with S/N$_{\text{peak, IMFIT}}$ > 3** (@ Ks-band centroid)
- Staking 5 non-detected sources —> ~5sigma detection
- ID 19129 turns out to be an *Chandra*-detected X-ray source
  → Type-2 AGN? (Kalfountzou+14)



Star-forming activity and gas-phase metallicity

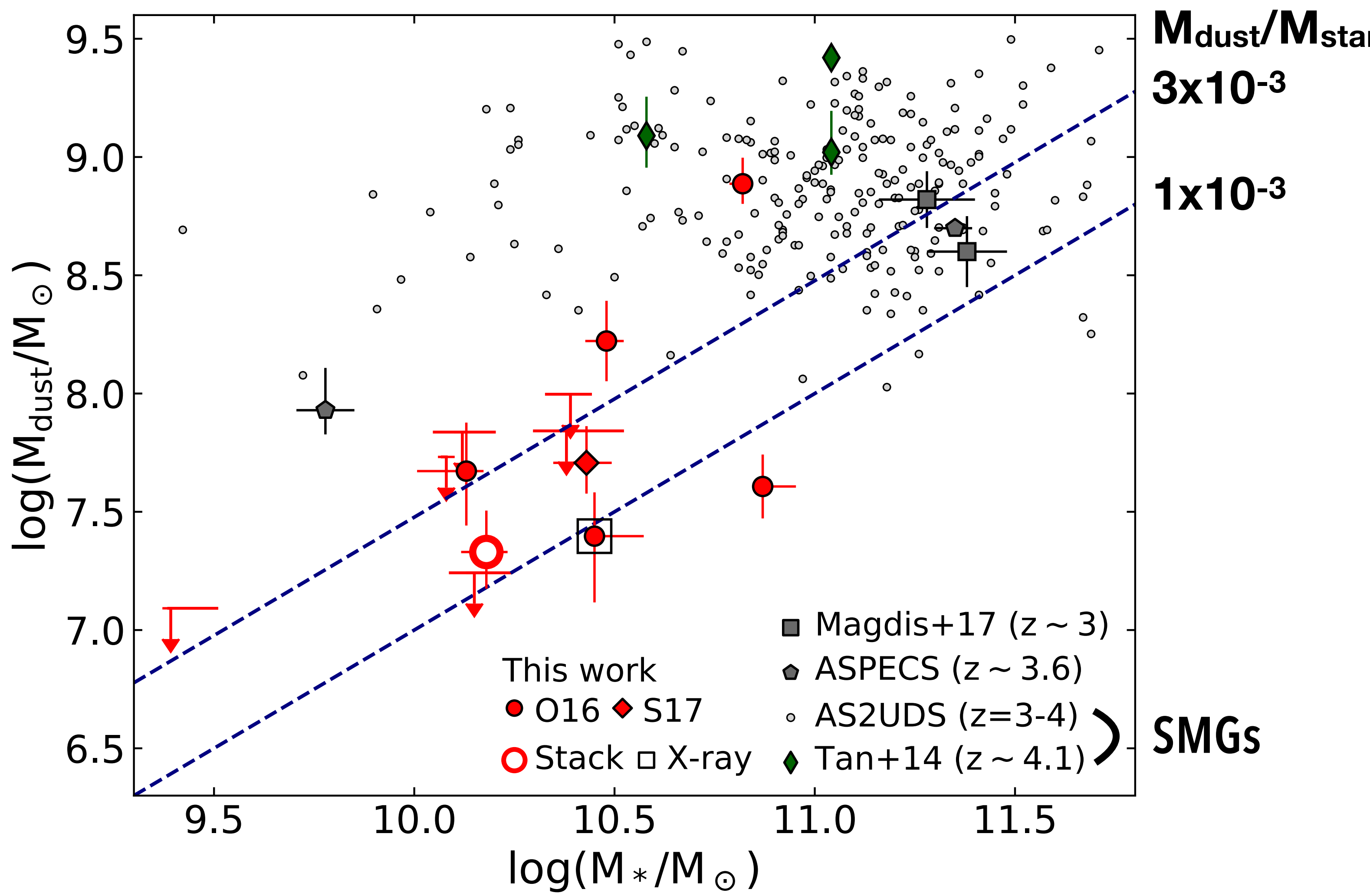


- SED fitting with MAGPHYS (da Cunha+08,15) inc. ALMA photometry

  → Re-estimate stellar mass and SFR

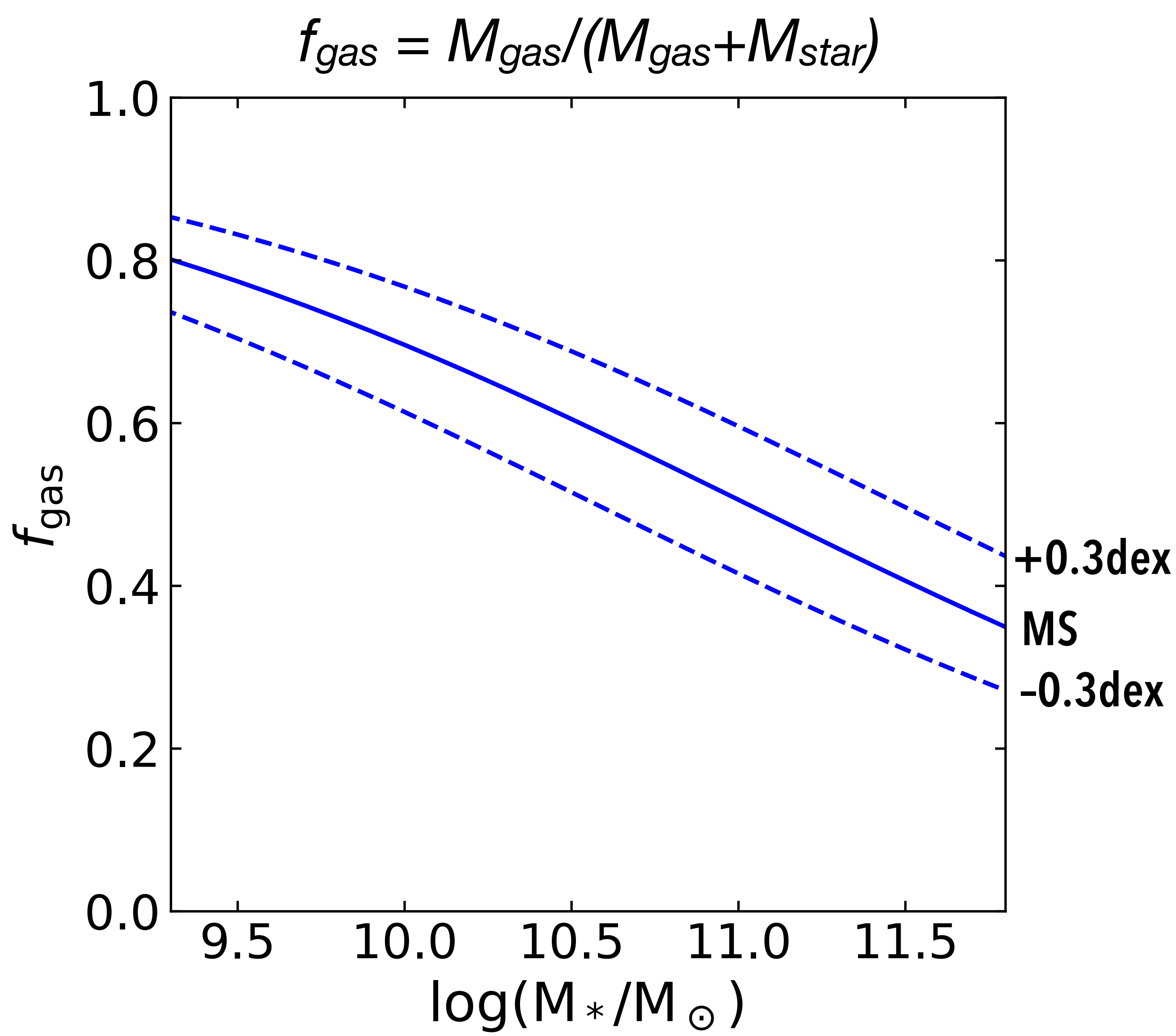
- **Tight distribution around the main sequence at z~3.3**

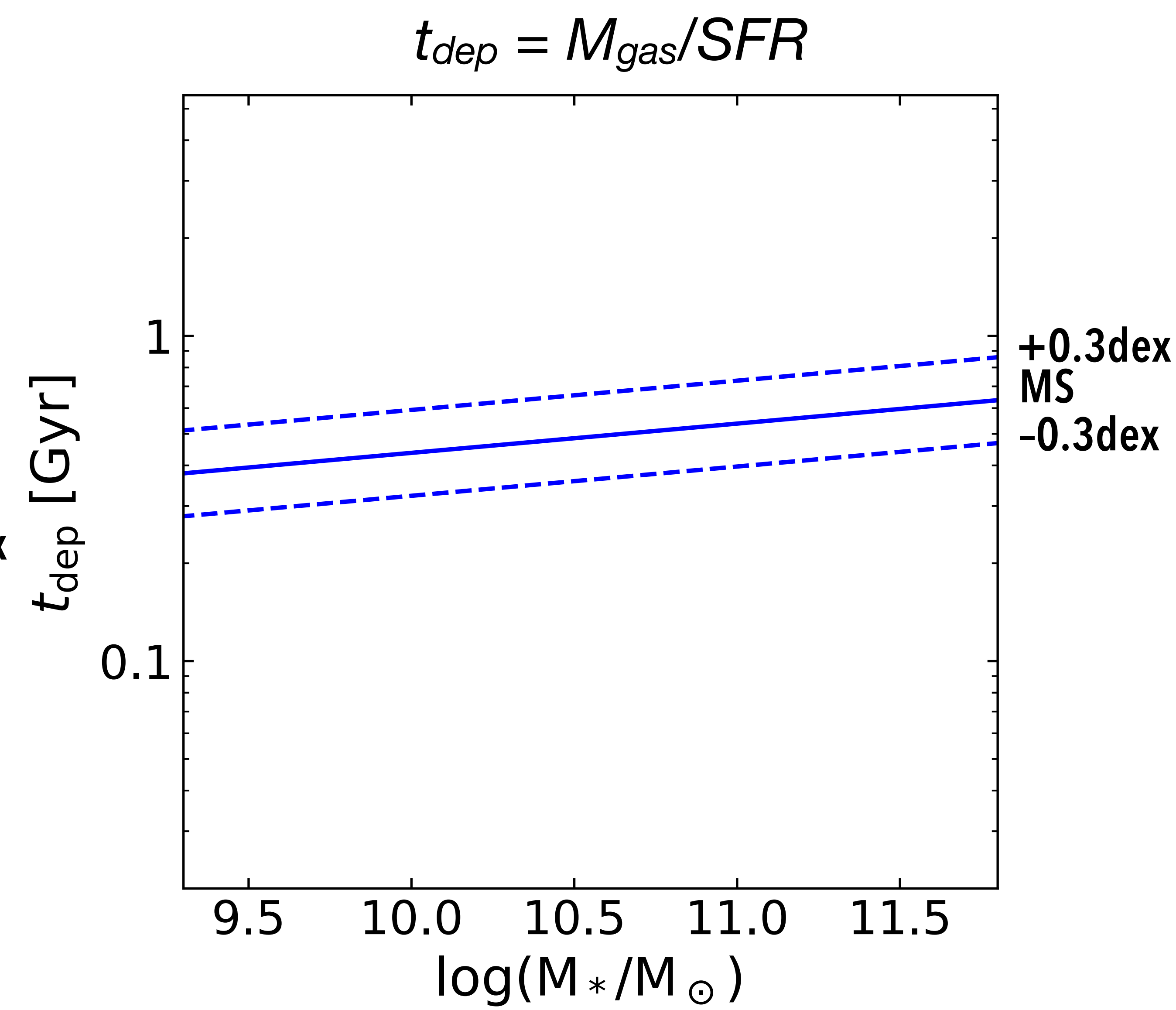
Dust mass in galaxies at z = 3-4



- Dust mass from MAGPHYS
- $M_{dust}/M_{star} = 1\text{-}5 \times 10^{-3}$
- Convert M_{dust} to M_{gas} with the relation between gas-phase metallicity and gas-to-dust mass ratio (Magdis+12)

Gas properties of SFGs at z~3.3

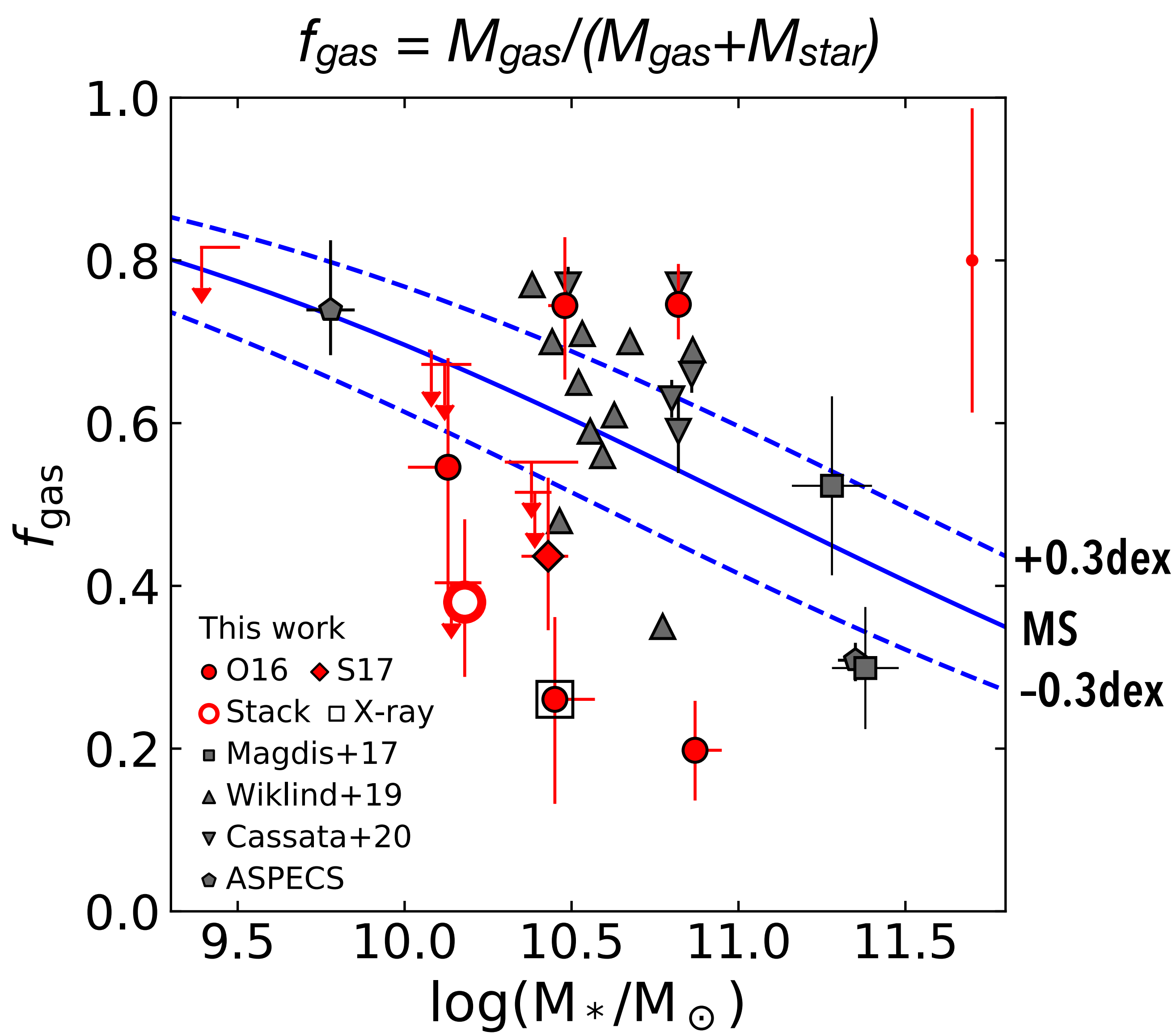


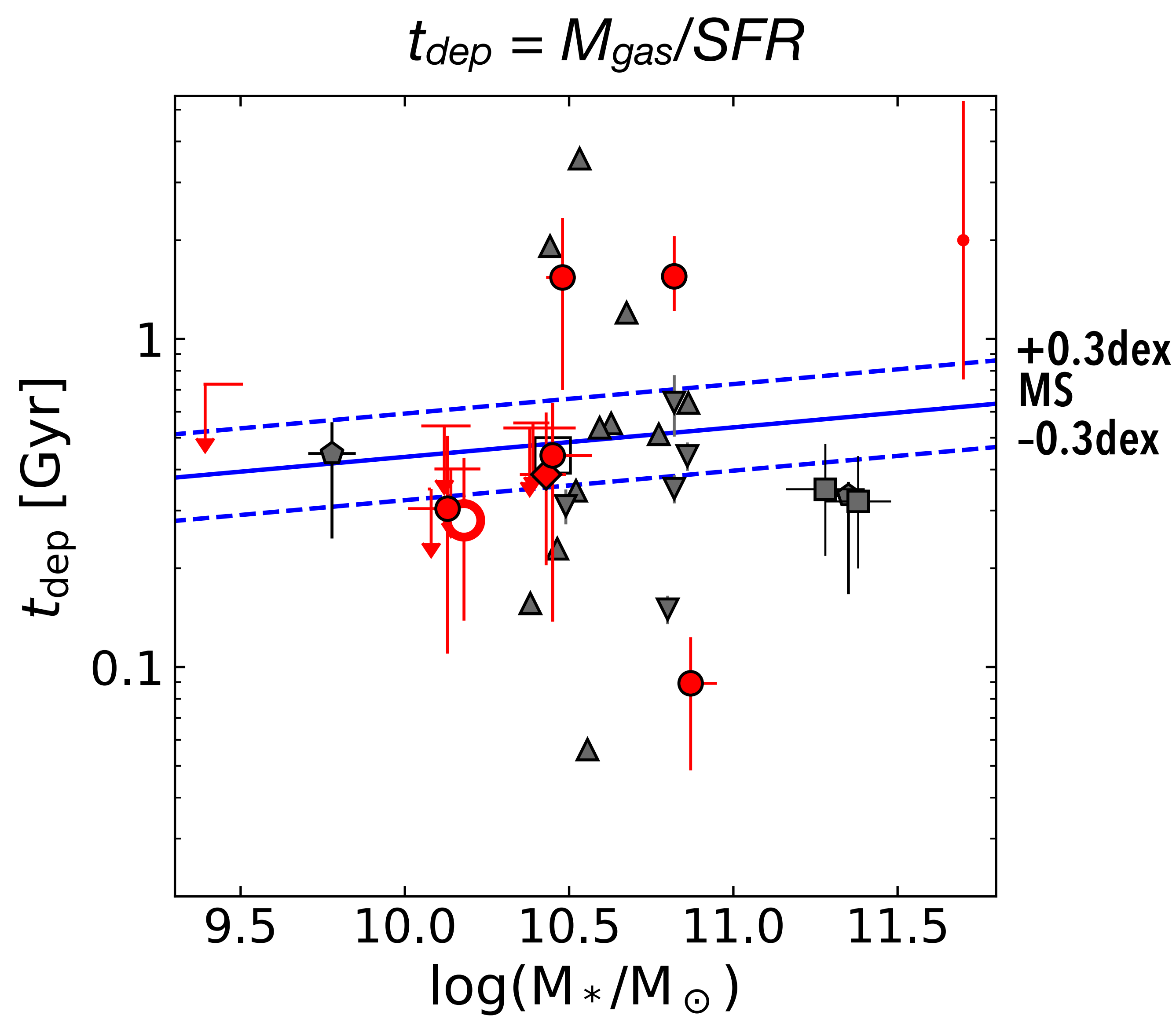


- Tacconi et al. (2018)

  Establish a scaling relation between M_{gas}, M_{star}, SFR, and redshift by compiling available observational data

Gas properties of SFGs at z~3.3



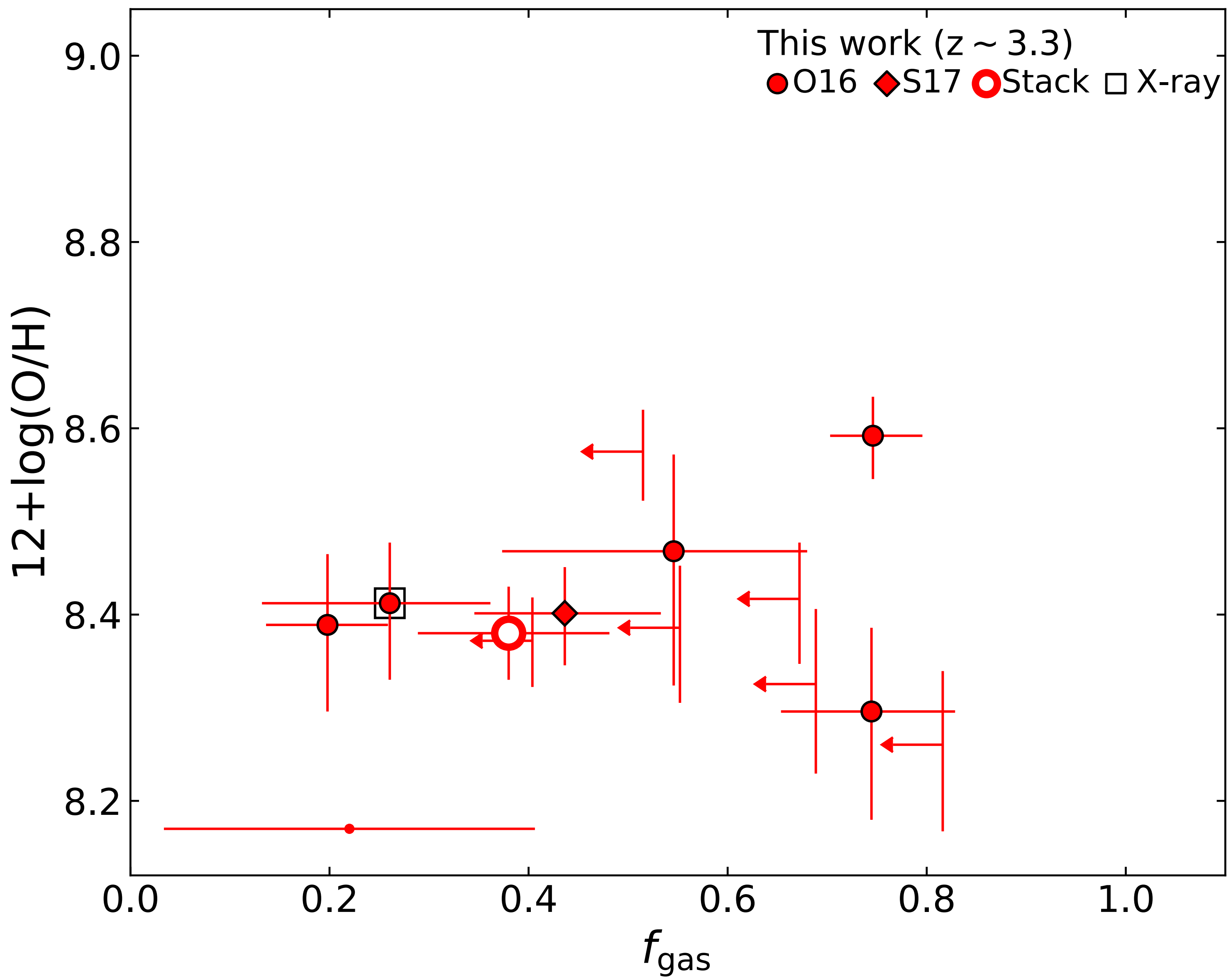


- Large scatter of f_{gas} and t_{dep} at a fixed stellar mass

  : Cannot be explained by the scatter around the main sequence

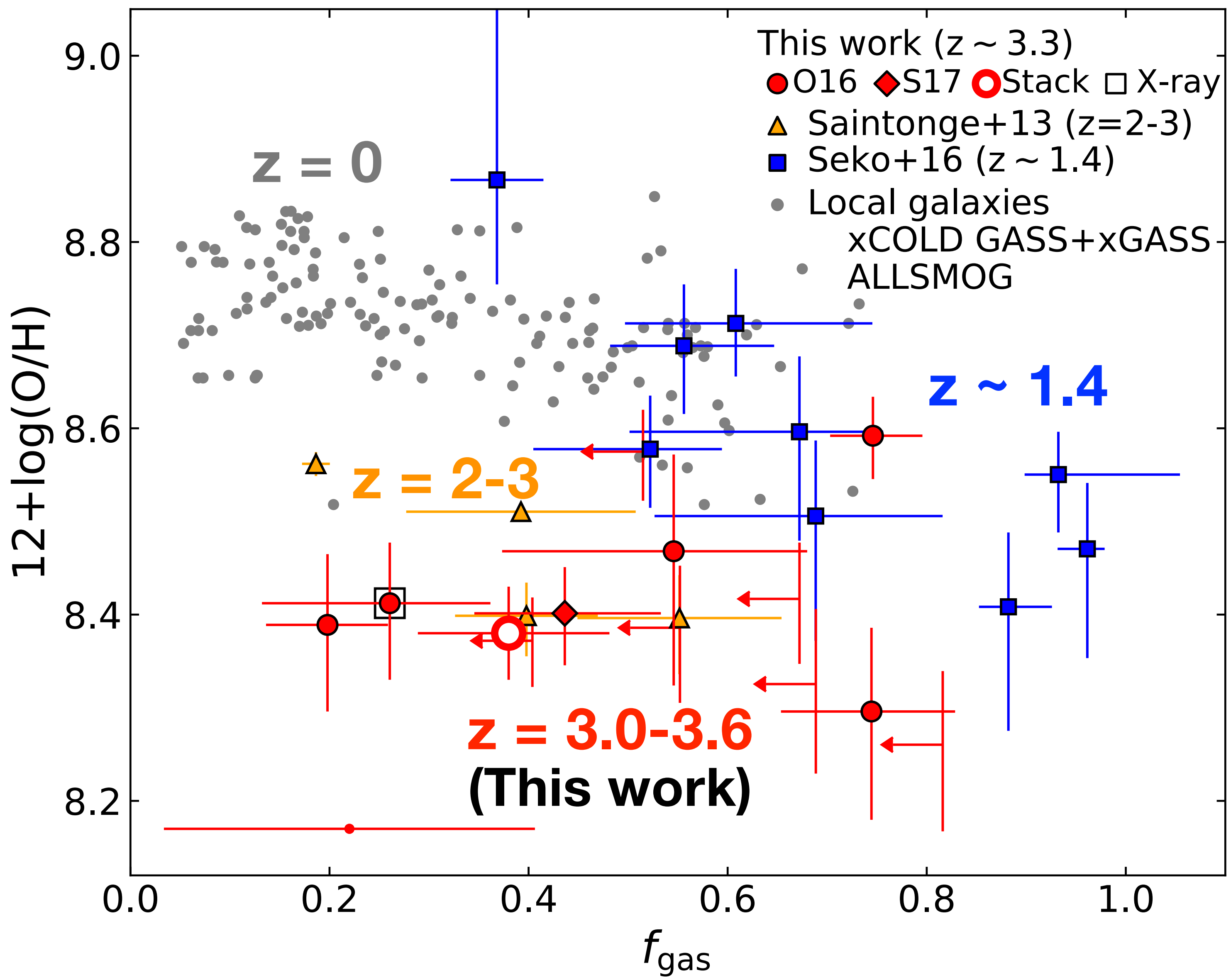
→ Gas properties have a large variety even when galaxies have similar M_{star} and SFR (e.g., Elbaz+18)

Gas mass fraction versus metallicity



- No clear correlation between gas mass fraction and metallicity

Comparison with galaxies at lower redshifts



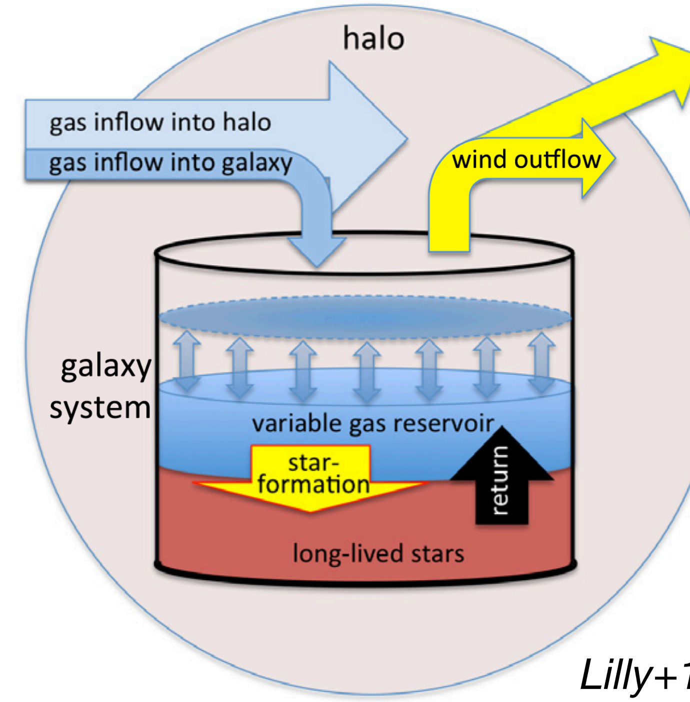
- Star-forming galaxies at z > 2 have lower gas-phase metallicities than local galaxies at a fixed gas mass fraction

Gas regulator model: Peng & Maiolino (2014)

Analytic formula to track the evolution of galaxies

- **Input parameters**

  : Inflow rate (Φ), star formation efficiency (ε), mass-loading factor(λ), return mass fraction (R)



Lilly+13

$$f_{\rm gas}(t) = \frac{1}{1+\varepsilon(1-R)\left(\frac{t}{1-e^{-\frac{t}{\tau_{\rm eq}}}} - \tau_{\rm eq}\right)}$$

$$Z_{\rm gas}(t) = [Z_0 + y\tau_{\rm eq}\varepsilon(1-e^{-\frac{t}{\tau_{\rm eq}}})][1-e^{-\frac{t}{\tau_{\rm eq}(1-e^{-t/\tau_{\rm eq}})}}]$$

Equilibrium timescale

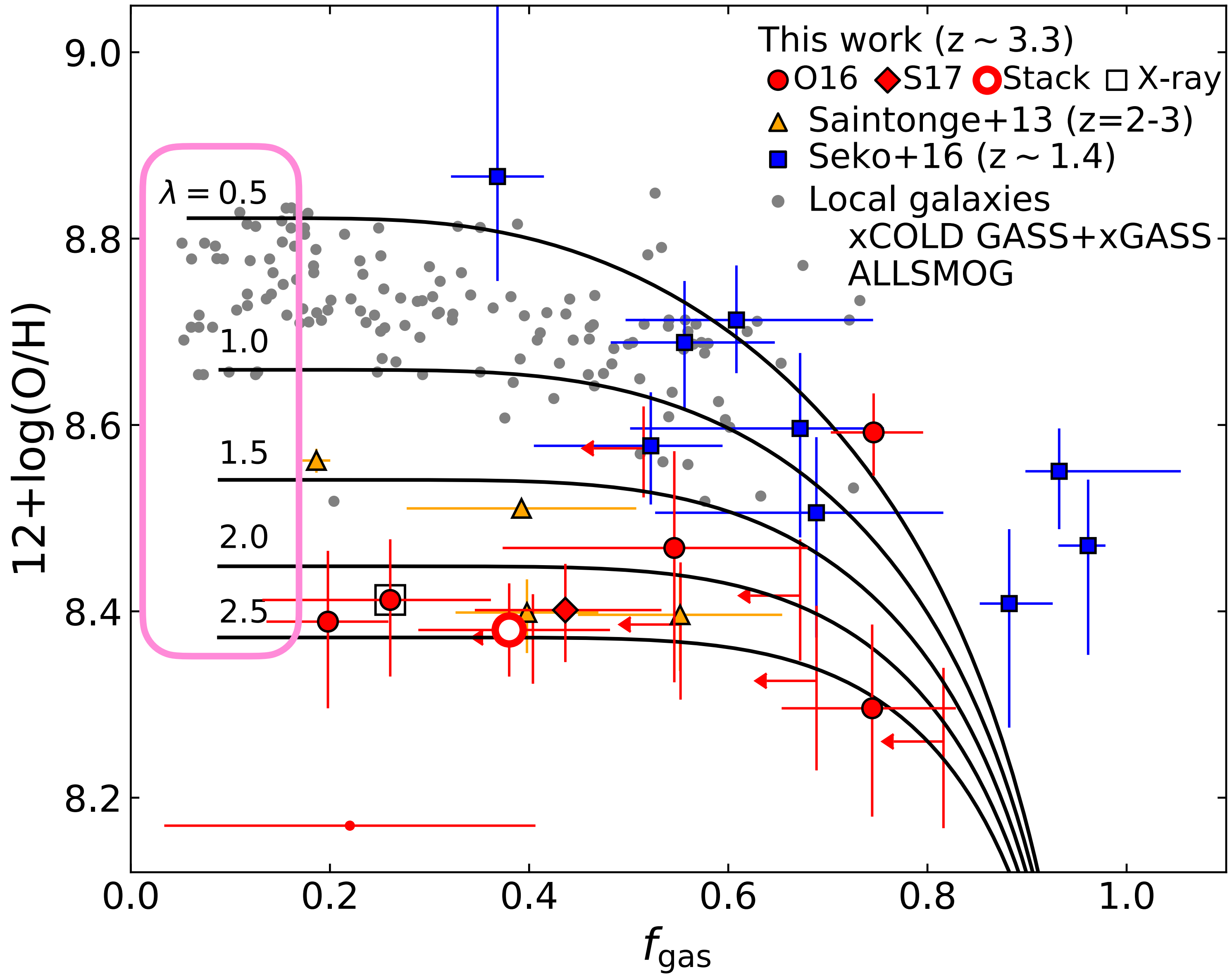
$$\tau_{\rm eq} = \frac{1}{\varepsilon(1-R+\lambda)}$$

y: average yield

Z0: Metallicity of inflowing gas

- **Assumptions**
  - Gas accretion scales with the growth rate of DM halo
  - Outflow rate is proportional to SFR
  - Input parameters are constant with time or change slowly with time

Higher mass-loading factors for high-z galaxies



1/ε = 0.8 Gyr

y = 1.5 Zsun

R = 0.4

Z0 = 0

+ Different mass-loading factors

- **The offset can be explained with the model tracks with higher mass-loading factor λ~2-2.5**

—> Redshift evolution of mass-loading factor

(e.g., Barai+14; Hayward & Hopkins 2017; Sugahara+17)

Part 1 - Summary

We conducted ALMA Band-6 observations of star-forming galaxies at z~3.3 with individual gas-phase metallicity measurements

- A large scatter of f_{gas} and t_{dep} in contrast to the tight distribution about the main sequence at z ~ 3.3

—> **Large variety of gas properties of galaxies with similar M_{star} and SFR**

- Lower metallicities of star-forming galaxies at z ~ 3.3 at a given f_{gas} can be explained with model tracks assuming higher mass-loading factors

—> **Star-forming galaxies at higher redshifts seem to have more powerful outflow with higher mass-loading factors**

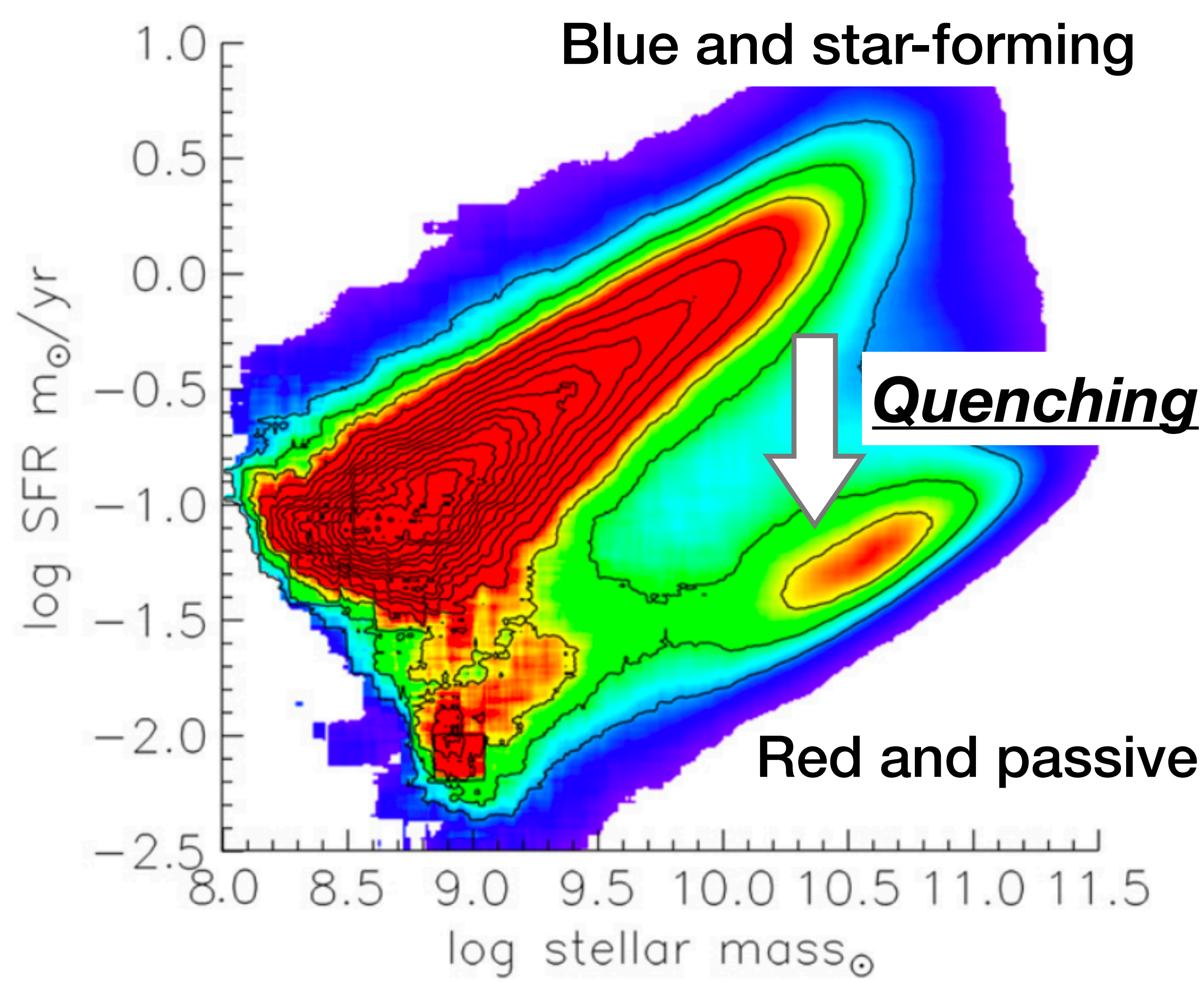
Today's talk

Gas properties of galaxies at z = 3-4

- **Star-forming galaxies** (Suzuki et al. 2021, ApJ, 908, 15)
  - Individual dust/gas mass measurements
  - Dependence on gas-phase metallicity

- **Quiescent galaxies** (Suzuki et al. in prep.)
  - First gas measurements at $z > 3.5$
  - How massive galaxies stop their star-formation?

How massive galaxies stop their star-formation?



z = 0, Renzini & Peng (2015)

- **Low gas fraction?**

  e.g., AGN feedback, mergers, halo quenching

- **Low star-formation efficiency?**

  e.g., Morphological quenching

Different quenching mechanisms

→ Different gas properties of quiescent galaxies

e.g., Sargent+15; Gobat+18; Spilker+18; Belli+21; Magdis+21; Williams+21; Whitaker+21…

Our targets: quiescent galaxies from ZFOURGE

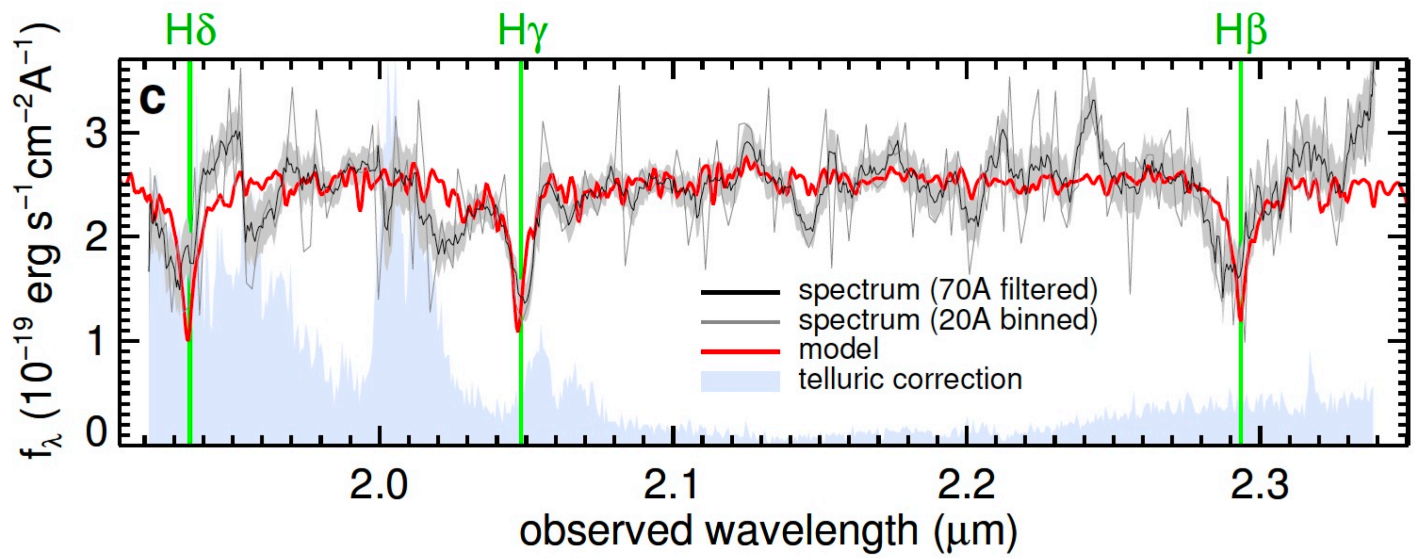
- **Four quiescent galaxies at z = 3.5-4** from the ZFOURGE survey (Glazebrook+17; Schreiber+18b)

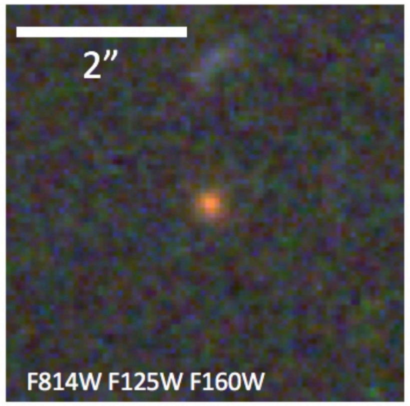
- ALMA Band-3 observations to observe [CI] line in Cycle 7

- All the targets are not detected with [CI] → 3σ upper limit

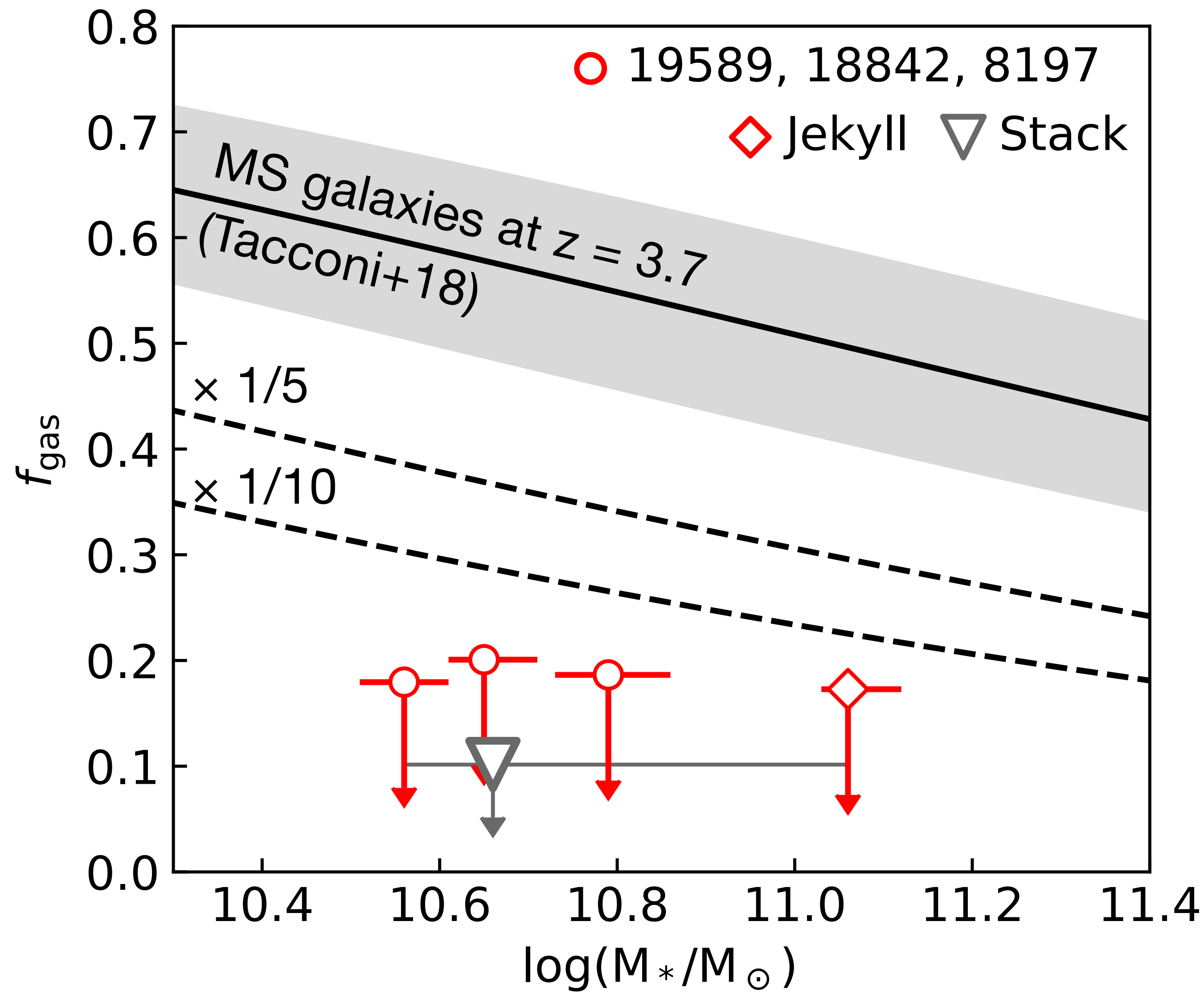
ID	$z_{\rm spec}$	$\log(M_*/M_\odot)$	$S_{\rm [CI]}\Delta v^a$ [Jy km s^{-1}]
ZF-COS-19589	3.715[c]	$10.79^{+0.07}_{-0.06}$	< 0.06
ZF-COS-18842	3.782[c]	$10.65^{+0.06}_{-0.04}$	< 0.05
ZF-UDS-8197	3.543	$10.56^{+0.05}_{-0.05}$	< 0.04
Jekyll[d]	3.715	$11.06^{+0.06}_{-0.03}$	< 0.11

Jekyll at z = 3.72
(Glazebrook+17)





Low gas mass fractions in QGs at z > 3.5



[CI] line flux → M_{gas}

- Bothwell+17
- Assume line width of 400 km/s

Stacking result of the four QGs

- **Low gas fraction of < 20 %** (<~ 10% from the stacking analysis)
- **Massive galaxies at z > 3.5 stop star-formation by consuming or expelling all the gas** rather than reducing star-formation efficiency

Part 2 - Summary

We analyzed the ALMA Band-3 data of massive quiescent galaxies at $z > 3.5$ found from the ZFOURGE survey

- All the quiescent galaxies at $z > 3.5$ are confirmed to have **low gas fraction of f_{gas} < 20 %**

- **Massive galaxies at $z > 3.5$ stop star-formation by consuming or expelling all the gas** rather than reducing star-formation efficiency

Summary of this talk

We investigate the gas properties (gas mass fraction and depletion timescale) of different galaxy populations at $z > 3$ with ALMA

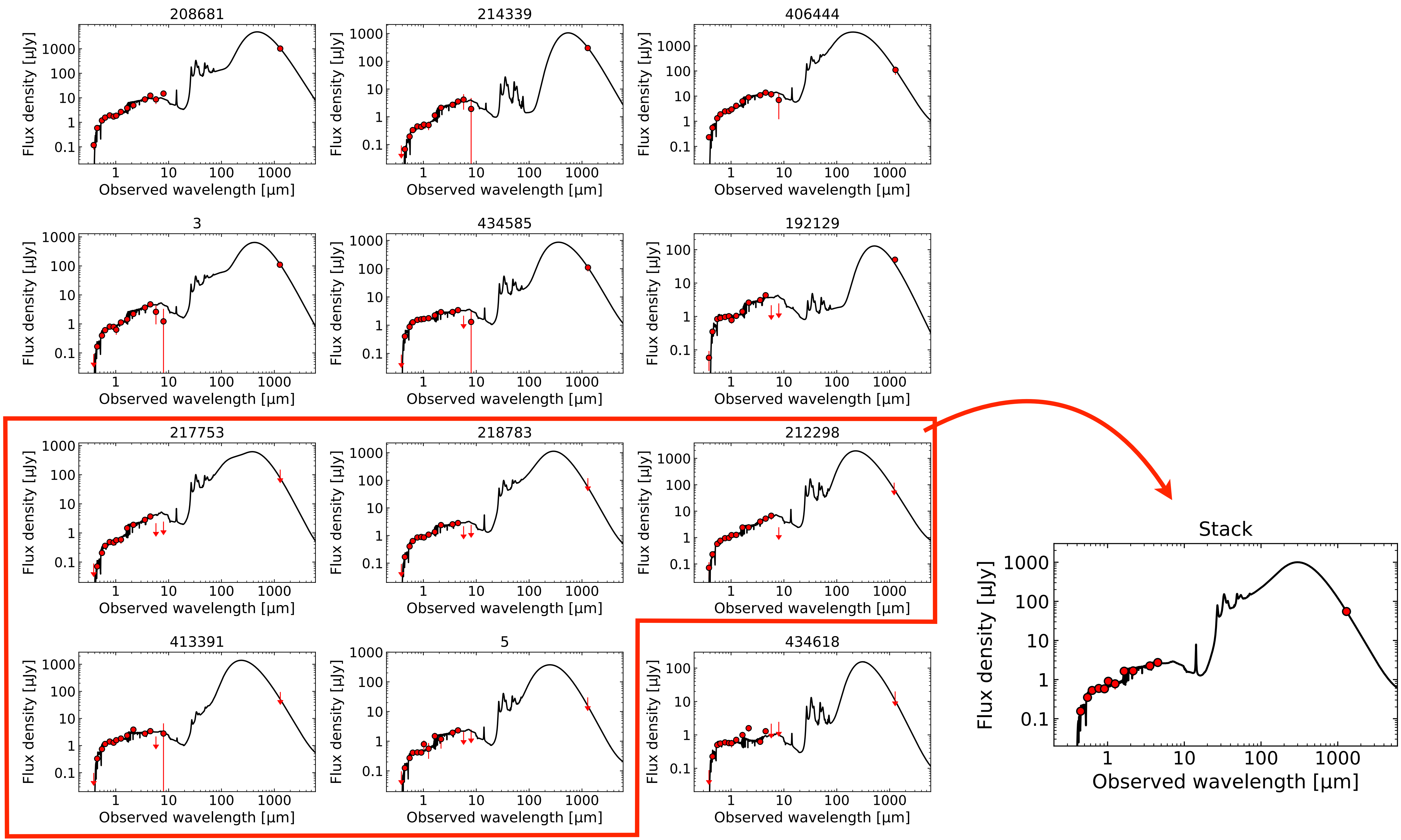
- **Star-forming galaxies**
  - Large variety of f_{gas} and t_{dep} in contrast to tight distribution around the main sequence
  - Suggested to have more powerful outflows with higher mass loading factors

- **Quiescent galaxies**
  - Low gas mass fractions of < 20%
  - Stop their star-formation by consuming/expelling all the gas rather than by reducing star-formation efficiency

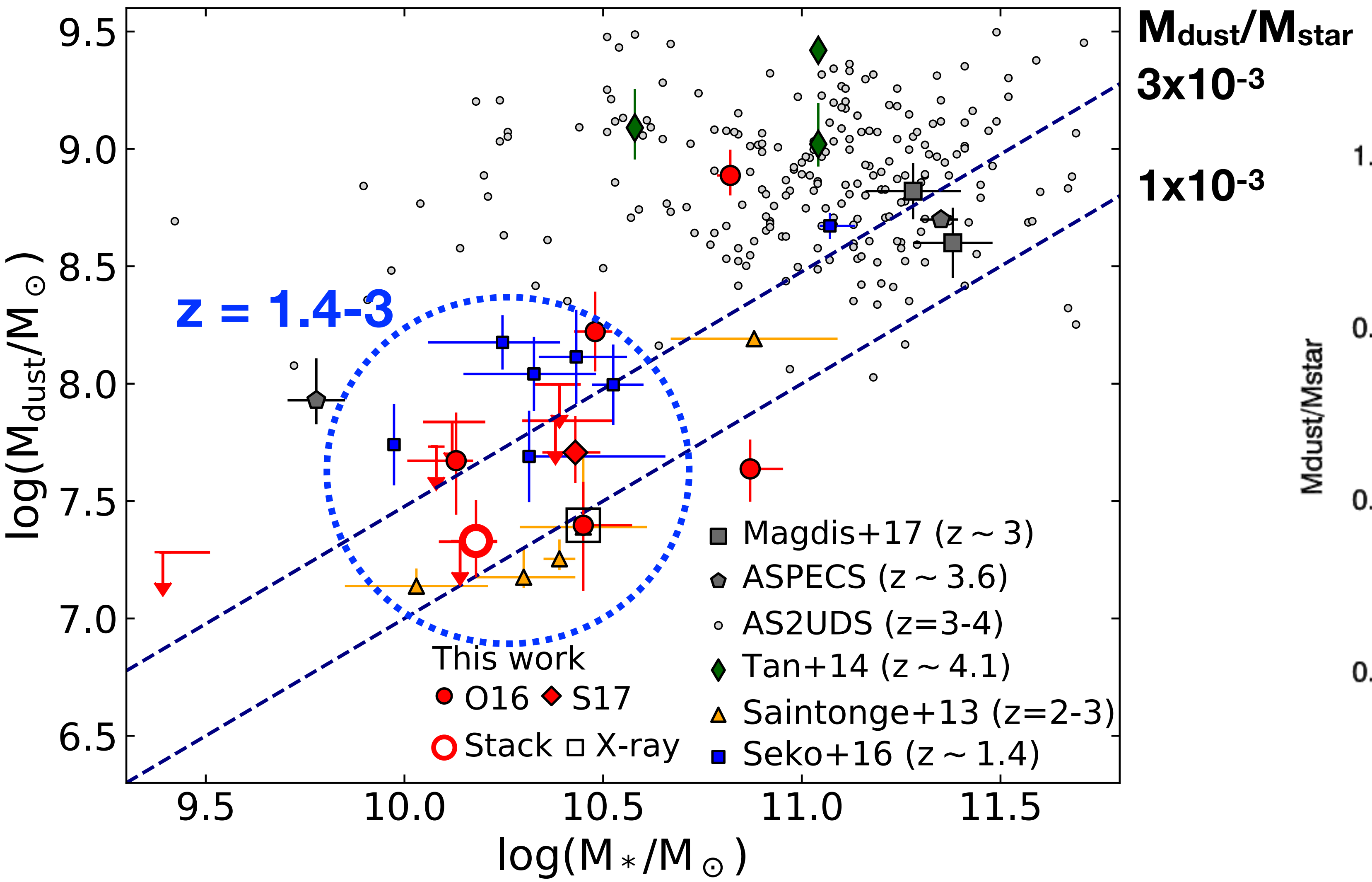
SED fitting with MAGPHYS (da Cunha+15)

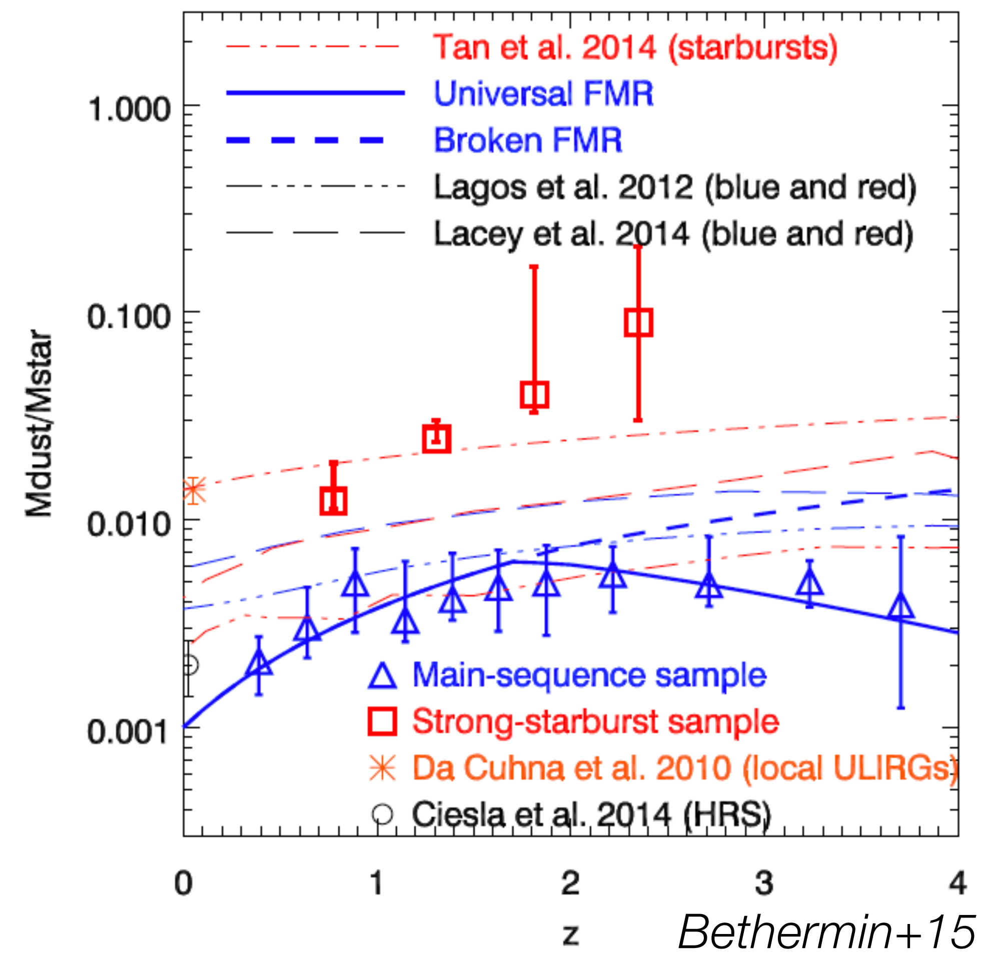
Optical-NIR photometric catalog (COSMOS2015) + ALMA Band-6

—> Stellar mass, SFR, and dust mass



Similar M_{dust}/M_{star} as lower-z SFGs



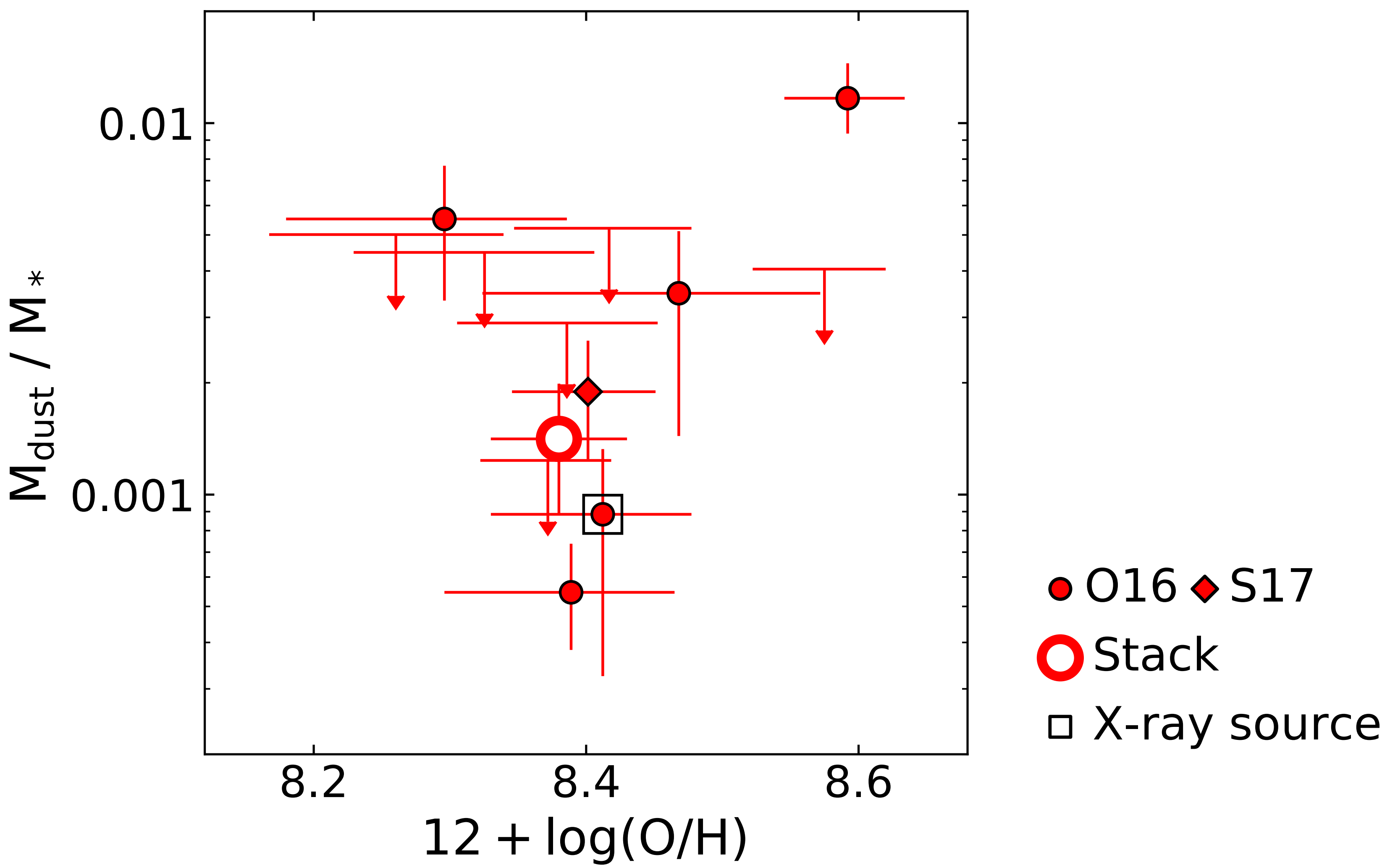


- Similar M_{dust}/M_{star} with star-forming galaxies at z ~ 1.5-3

  : Mild (or flat) evolution of dust content in galaxies since z ~ 1.4 to z ~ 3.3? (Bethermin+15)

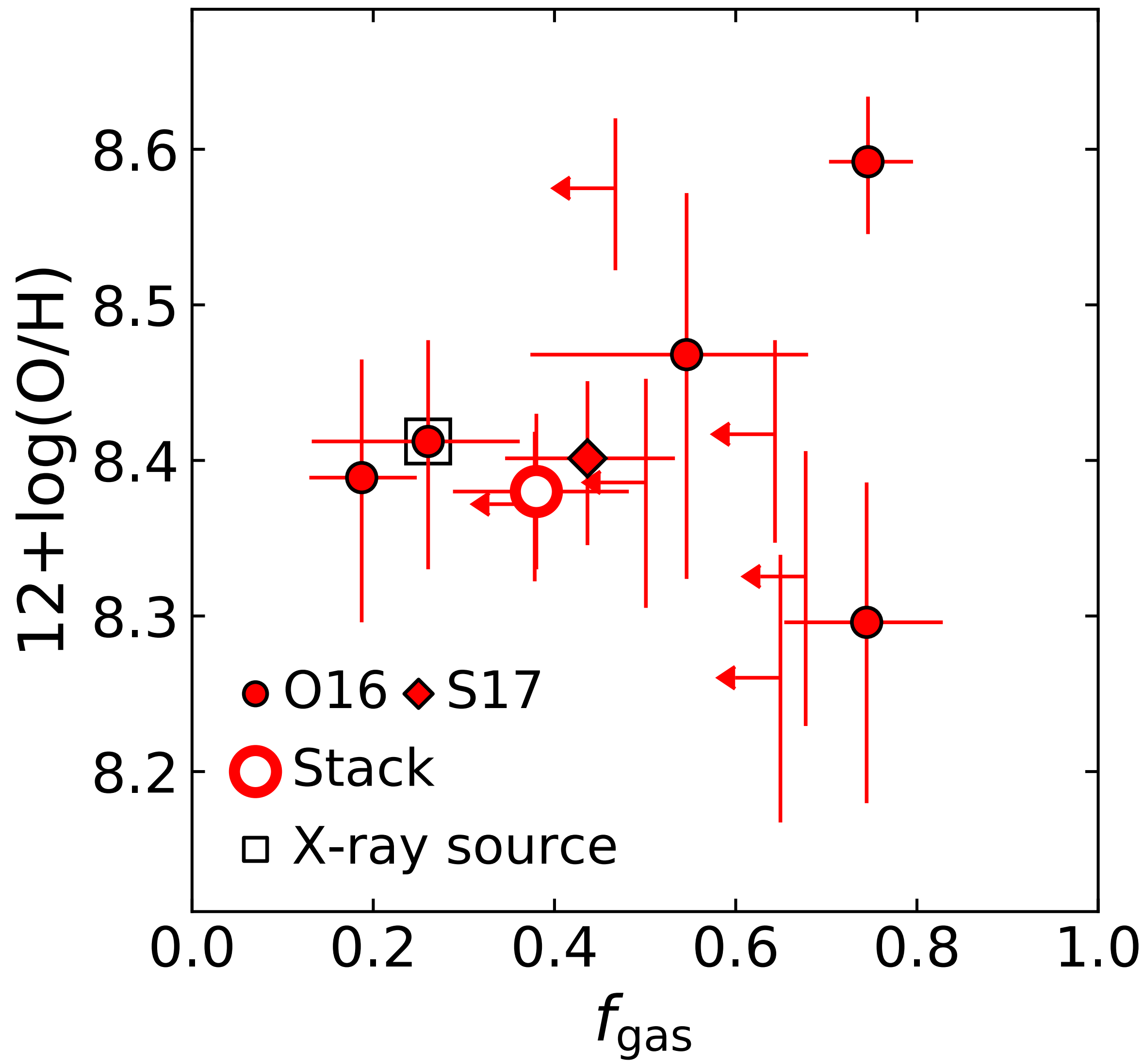
Dependence on gas-phase metallicity?

Dust-to-stellar mass ratio vs metallicity



- **No clear correlation between M_{dust}/M_{star} and metallicity**
  (Positive correlation would have been expected)
- Need a larger sample covering a wider stellar mass range…

No clear correlation between f_{gas} and 12+log(O/H)



- No clear correlation between gas mass fraction and metallicity

→ **Reflect stochastic star-formation histories of star-forming galaxies at high redshifts?** (e.g., Guo+16; Tacchella+20)

= More difficult to identify a global trend between the physical quantities

Quiescent galaxies confirmed at z > 3

- Increasing the number of spectroscopically confirmed quiescent galaxies at z > 3

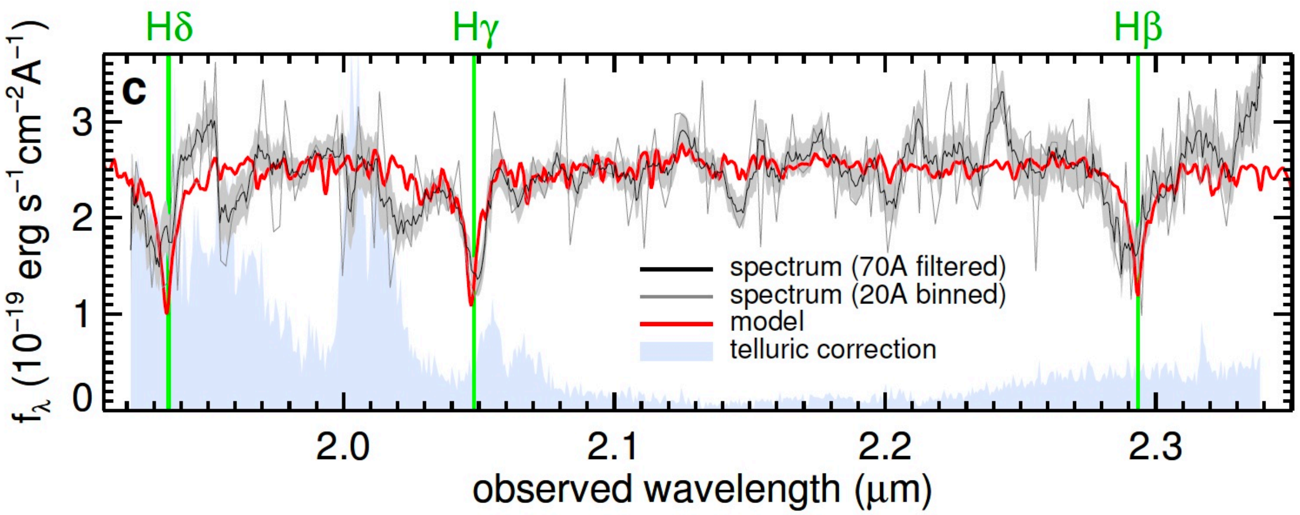
  : Glazebrook+17; Schreiber+18b; Tanaka+19; Valentino+20; Kubo+21…

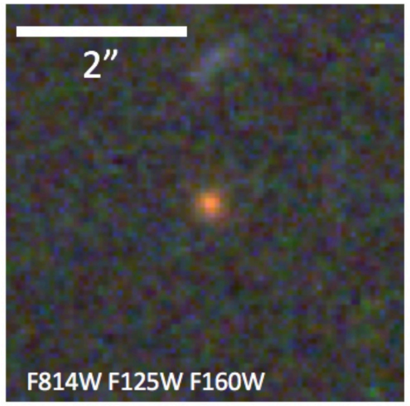
- Closer to the epoch of quenching

  → Stronger constraint on the quenching mechanisms

z = 3.72

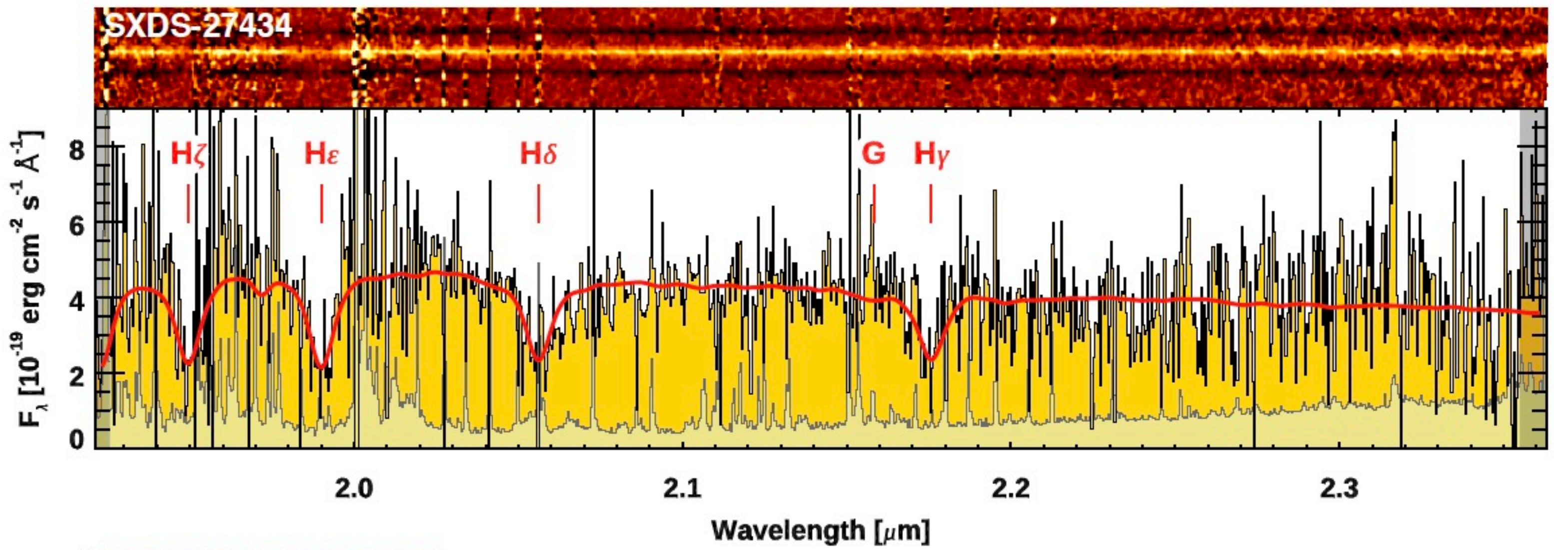
(Glazebrook+17)





z = 4.01

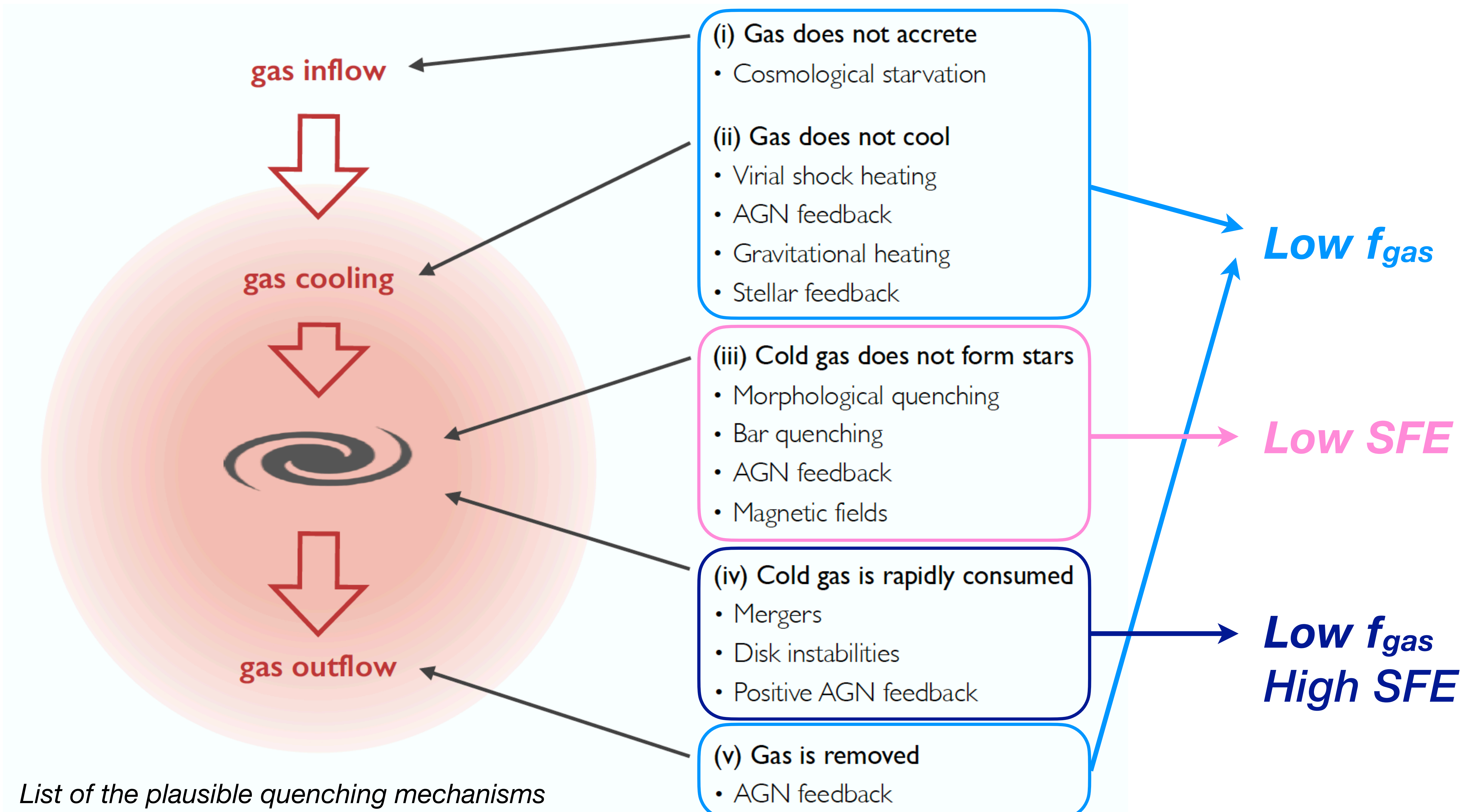
(Tanaka+19; Valentino+20)



Gas properties and quenching processes

Gas mass fraction and star-formation efficiency

: Change depending on quenching processes



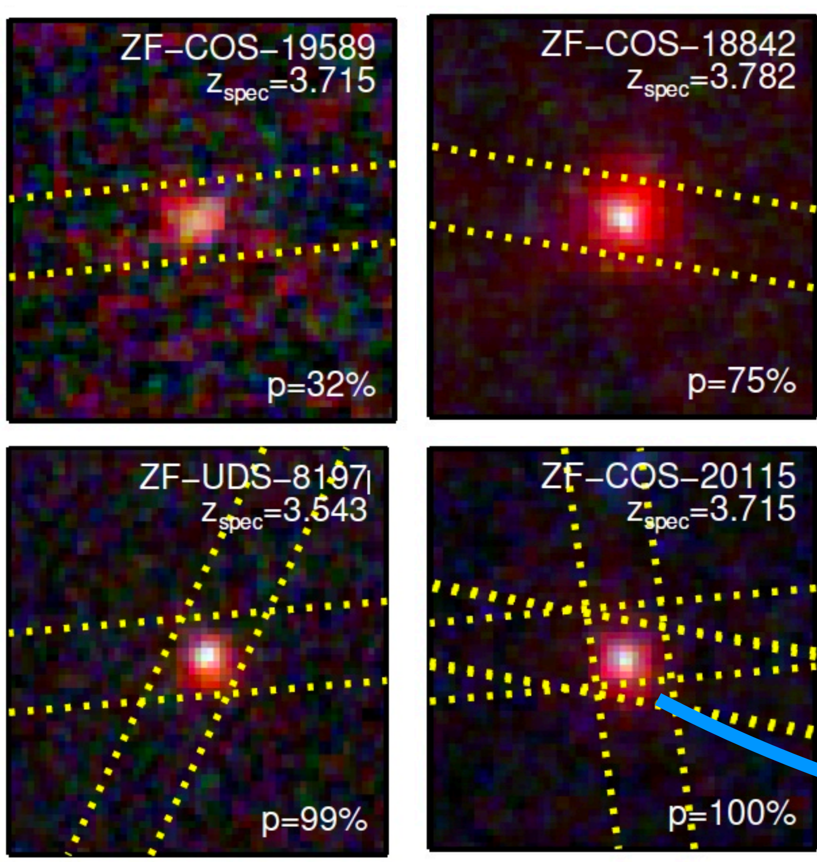
List of the plausible quenching mechanisms from Man & Belli (2018)

Our targets: quiescent galaxies from ZFOURGE

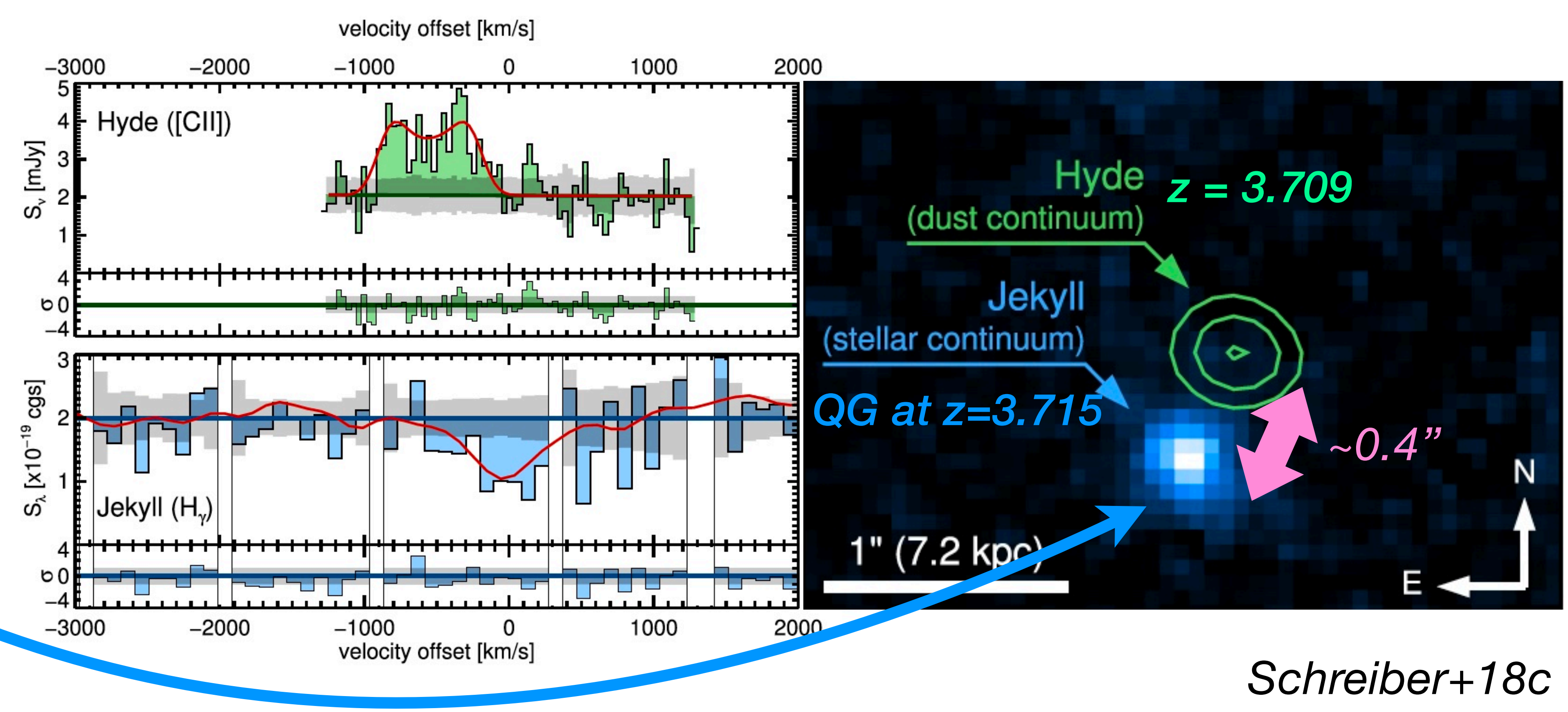
- **Four quiescent galaxies at z = 3.5-4** from the ZFOURGE survey (Glazebrook+17; Schreiber+18b)

+ **Hyde** (Schreiber+18c,21)
: A massive optical-dark galaxy at z ~ 3.71 (~0.4” away from Jekyll)
Possibly in transition to quiescence

Quiescent galaxies at z > 3.5



Schreiber+18b

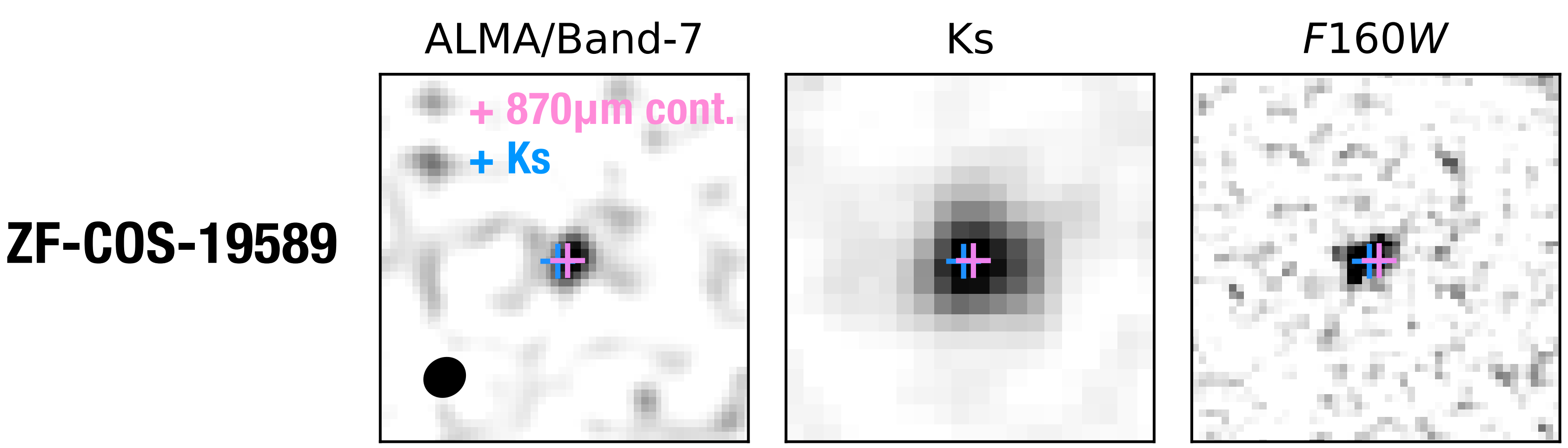


Schreiber+18c

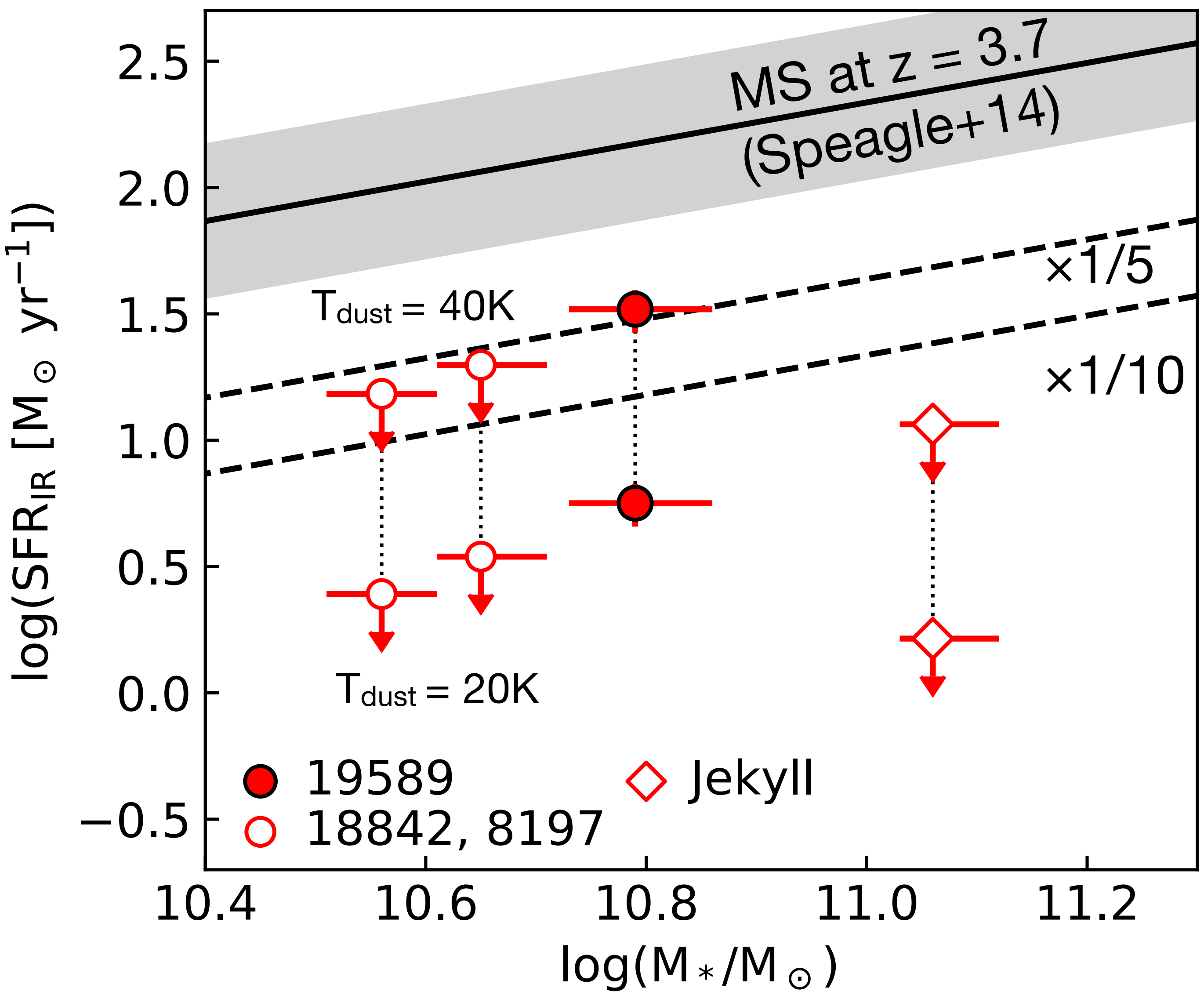
Our targets: quiescent galaxies from ZFOURGE

- **Four quiescent galaxies at z = 3.5-4** from the ZFOURGE survey (Glazebrook+17; Schreiber+18b)
- Band-7 (870μm continuum) and Band-3 ([CI]) data taken in Cycle 7 & 6
- Continuum emission is detected from one galaxy (~5σ)
- All the targets are not detected with [CI] → 3σ upper limit

ID	$z_{\rm spec}$	$\log(M_*/M_\odot)$	Band analyzed	$S_{870\mu m}$ [mJy]	$S_{\rm [CI]}\Delta v^a$ [Jy km s^{-1}]
ZF-COS-19589	3.715^c	$10.79^{+0.07}_{-0.06}$	7 & 3	0.21 ± 0.04	< 0.06
ZF-COS-18842	3.782^c	$10.65^{+0.06}_{-0.04}$	7 & 3	< 0.13	< 0.05
ZF-UDS-8197	3.543	$10.56^{+0.05}_{-0.05}$	7 & 3	< 0.10	< 0.04
Jekyll[d]	3.715	$11.06^{+0.06}_{-0.03}$	3	–	< 0.11



Low dust-obscured SF activity



870μm continuum flux → L_{IR}

- IR SED Library of Schreiber+18a
- **Assume T_{dust} = 20 K and 40 K**

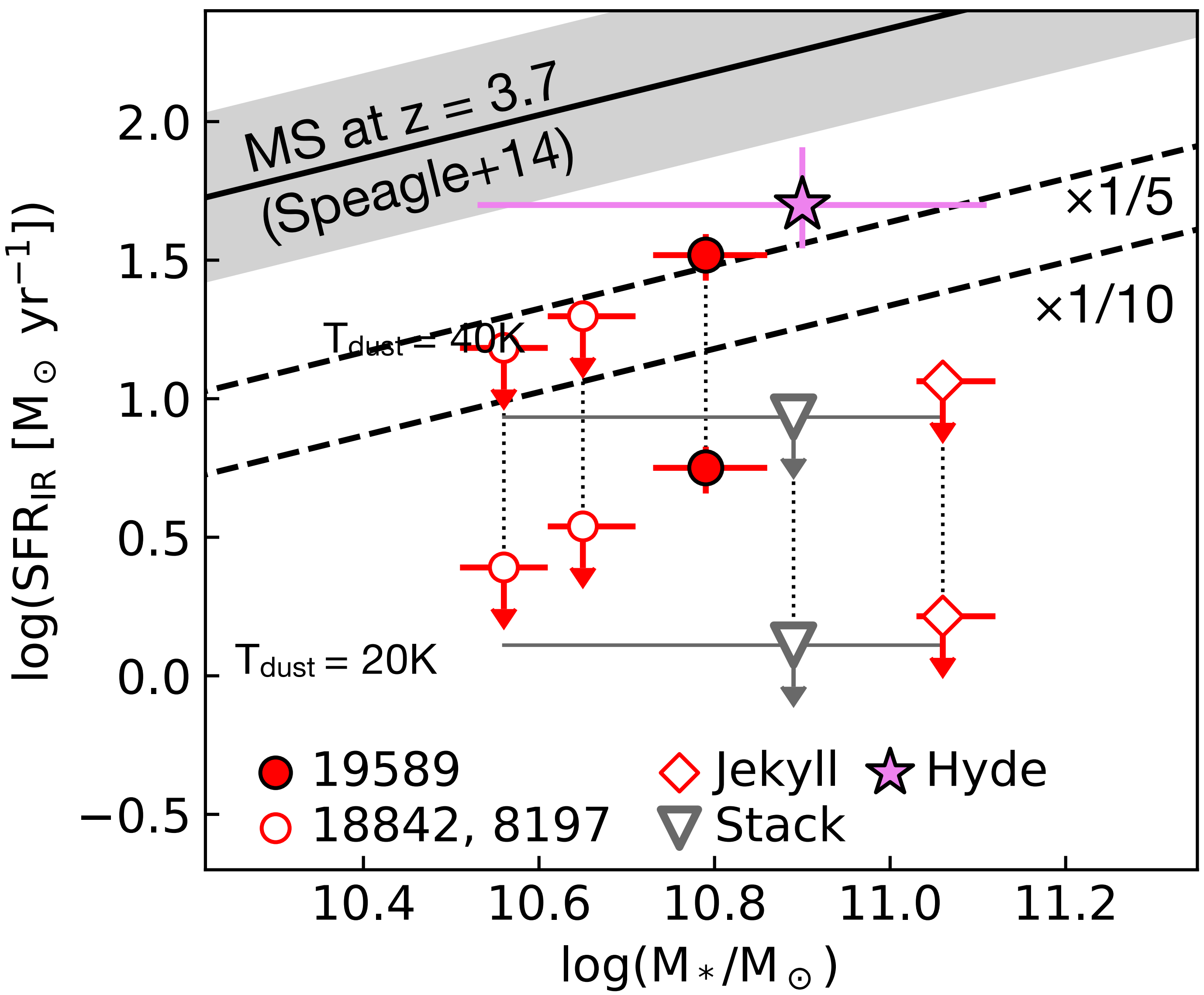
L_{IR} → SFR_{IR}

- Kennicutt (1998) relation

- **Confirm the low star-formation activity of the targets**

  : >~ 5 times below the main sequence of star-forming galaxies

Low dust-obscured SF activity



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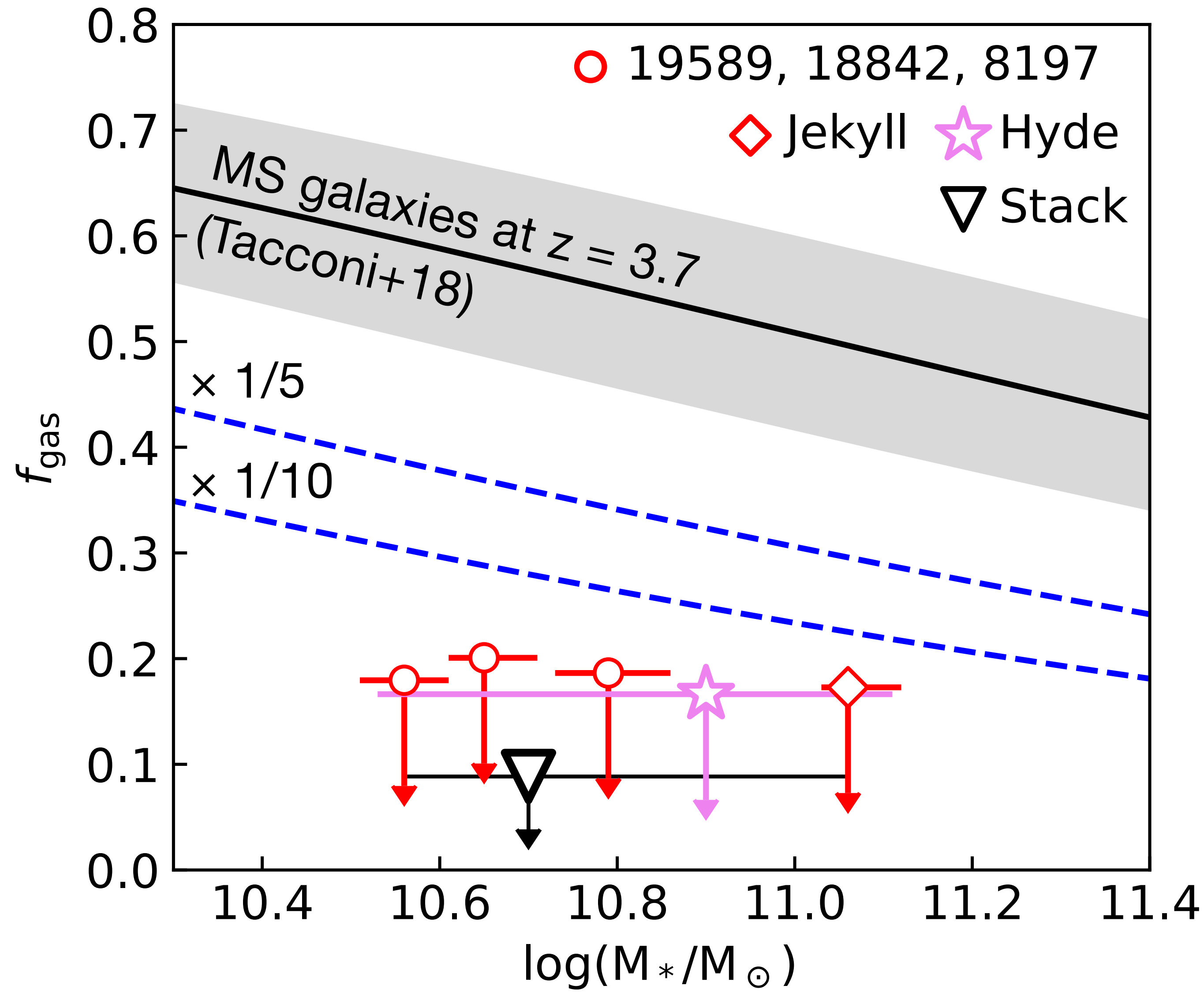
Low gas mass fractions in QGs at z > 3.5



Stacking result for all the five targets

[CI] line flux → M_{gas}

- Bothwell+17
- Assume line width of 400 km/s except for Hyde with 800 km/s

- **Low gas fraction of < 20 %** (< 10 % from the stacking result)
- Gas depletion timescale (M_{gas}/SFR) of Hyde

  —> t_{dep} < 0.32 Gyr (cf. 0.4-0.6 Gyr for SFGs at z ~ 3-4)