Quenching and AGN activity for distant galaxies revealed by multi-wavelength surveys in the COSMOS field

Kei Ito
University of Tokyo, JSPS postdoctoral Fellow

Self-introduction

Name: **Kei Ito**

Positions:

2017/04 - 2022/03: **Ph.D. student at SOKENDAI/NAOJ**
- supervisors: Nobunari Kashikawa (U. Tokyo), Masayuki Tanaka (NAOJ)

2022/04 - Present: **JSPS post-doc fellow at U. Tokyo**
- host researcher: Kazuhiro Shimasaku

Research interests:
- Observation astronomy
- Galaxy evolution
- Star formation activity of galaxies including quenching
- Connection between environment and galaxy properties

Research interests

A few papers related to "**quenching**" at high redshift
→I will mainly introduce the latest paper published in April

Ito et al., 2022, ApJ, 929, 53

COSMOS2020: Ubiquitous AGN Activity of Massive Quiescent Galaxies at $0 < z < 5$ Revealed by X-Ray and Radio Stacking

Kei Ito[1,2], Masayuki Tanaka[1,2], Takamitsu Miyaji[3], Olivier Ilbert[4], Olivier B. Kauffmann[4], Anton M. Koekemoer[5], Stefano Marchesi[6,7], Marko Shuntov[8], Sune Toft[9,10], Francesco Valentino[9,10], and John R. Weaver[9,10]

Ito et al., 2021, ApJ, 916, 35

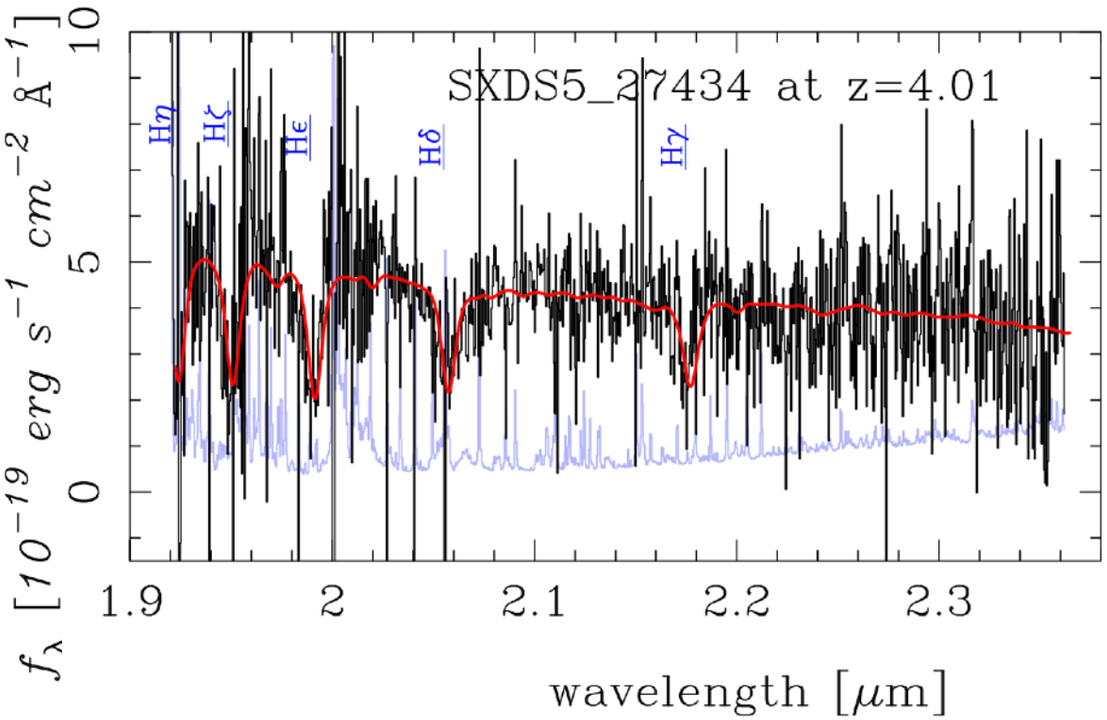
Interrelation of the Environment of Lyα Emitters and Massive Galaxies at $2 < z < 4.5$

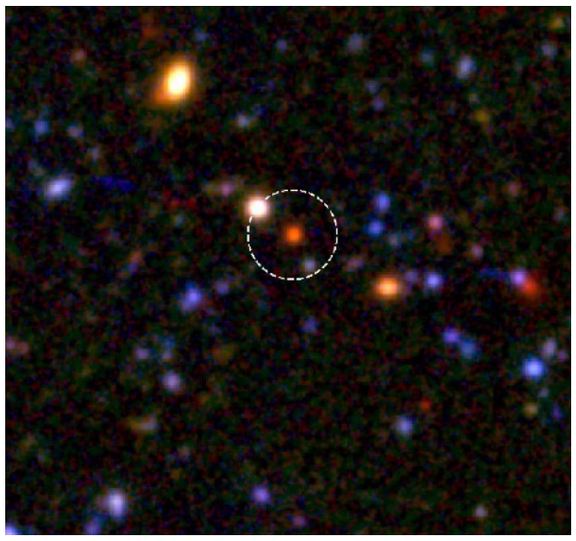
Kei Ito[1,2,3], Nobunari Kashikawa[3,4], Masayuki Tanaka[1,2], Mariko Kubo[5], Yongming Liang[1,2,3], Jun Toshikawa[6,7], Hisakazu Uchiyama[2], Rikako Ishimoto[3], Takehiro Yoshioka[3], and Yoshihiro Takeda[3]

※Introducing some results briefly

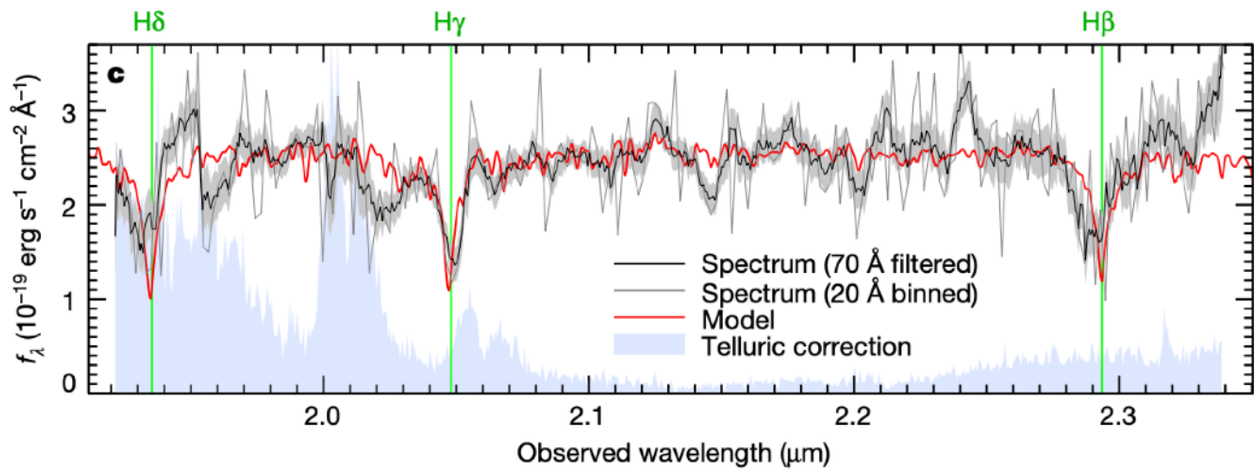
High-redshift quiescent galaxies

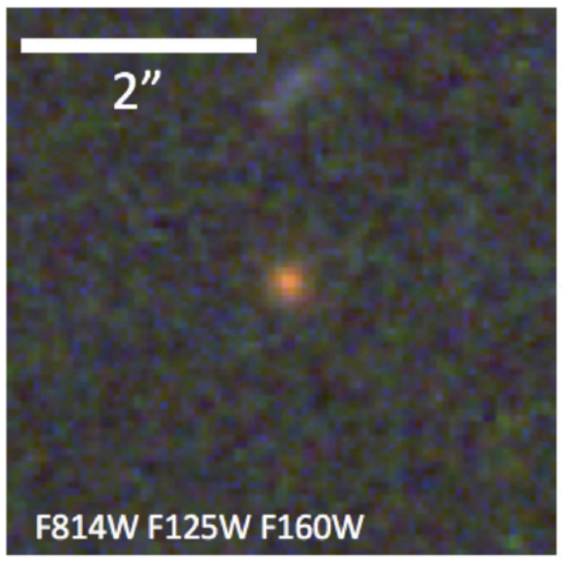
- Galaxies can be quenched even at high redshift
  - Multi-band survey have found low-SFR massive galaxy
- Photometrically, candidates are found up to **z~6 (e.g., Mawatari+20)**
- Spectroscopically, they are confirmed up to **z=4.01 (Tanaka+19)**





Tanaka et al. (2019)





Glazebrook+17

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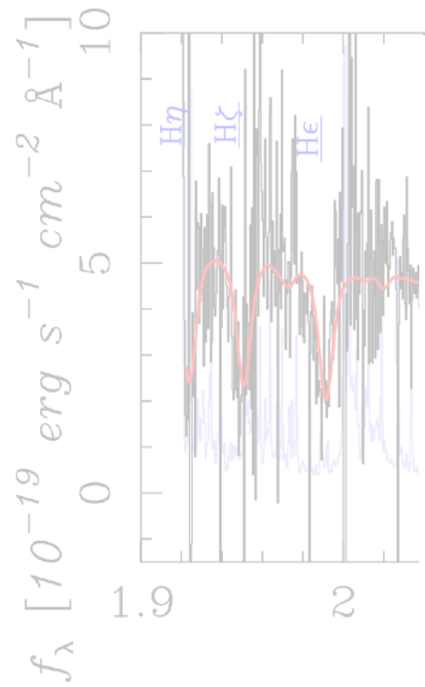

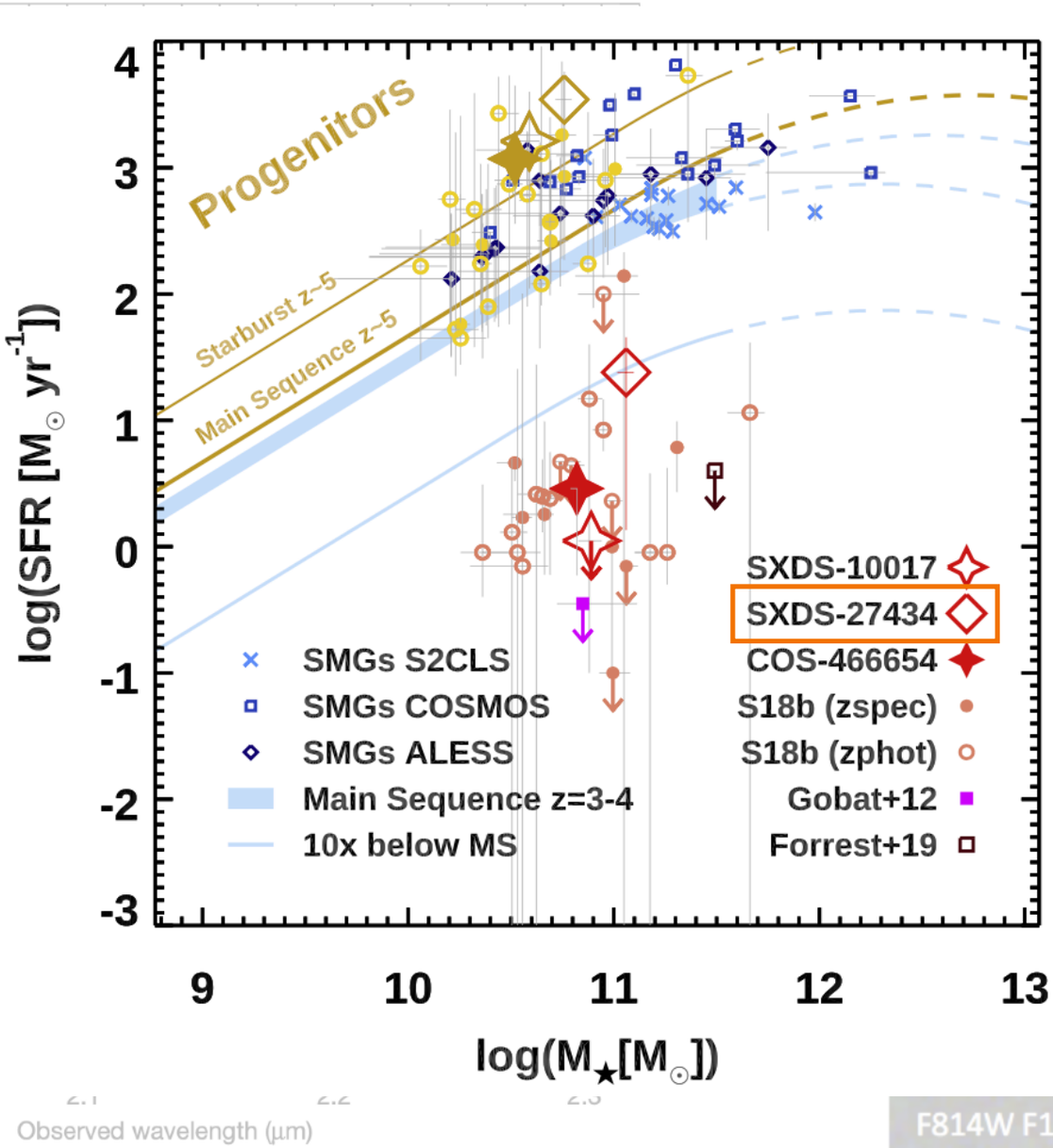

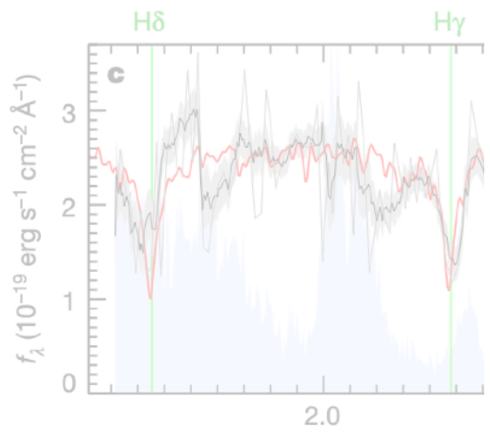

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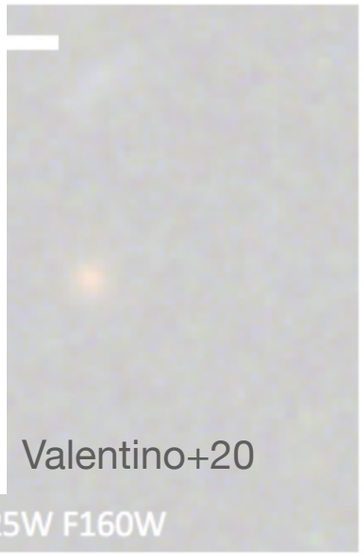
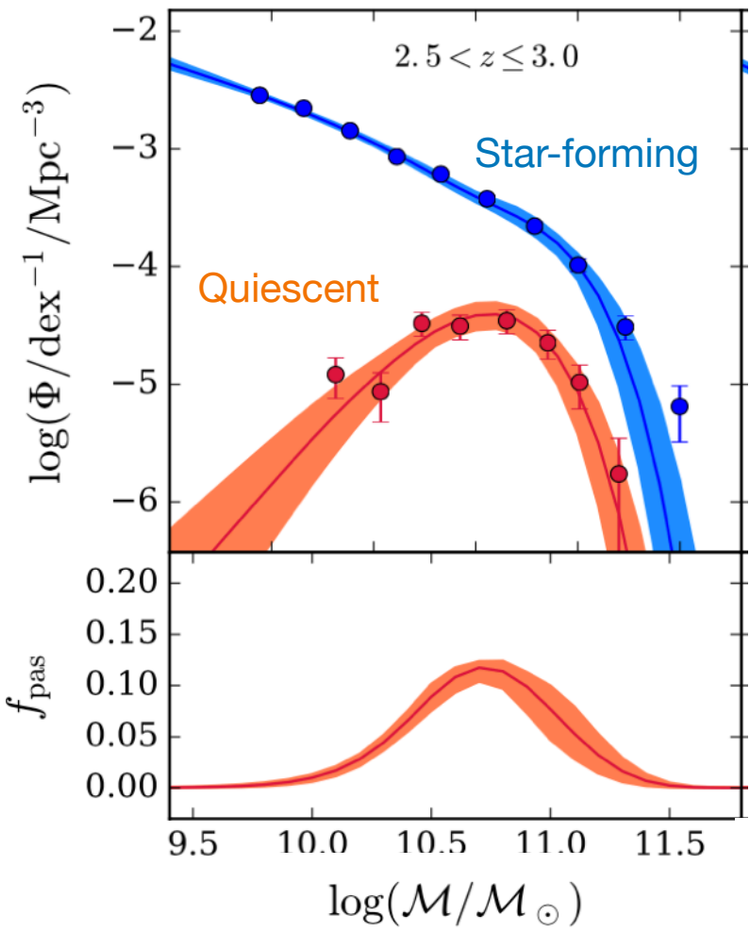


Valentino+20

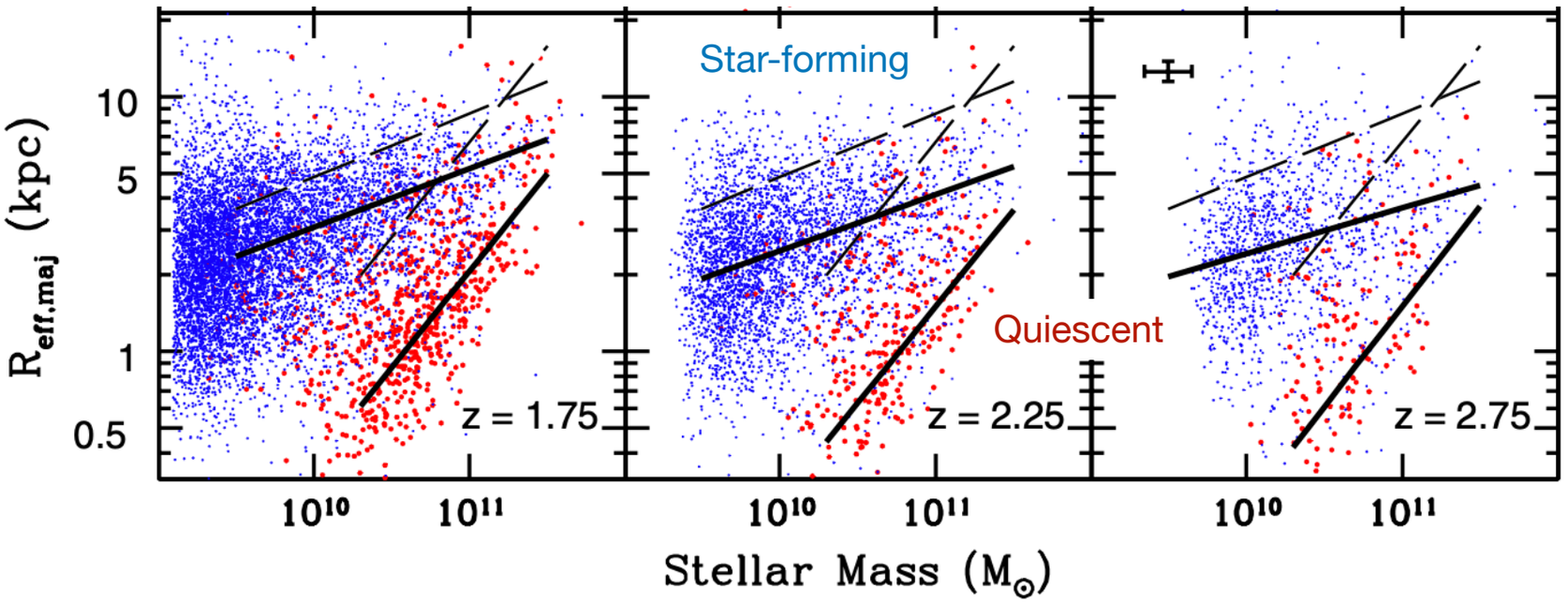
Glazebrook+17

Photometric properties

- Quiescent galaxies are…
  1. **Already massive**
     - typically $\log M_\star/M_\odot > 10.5$ at z> 2 (e.g., Davidzon+17)
  2. **Compact morphology**
     - ~1kpc at z>2 (e.g., van der Wel+14)



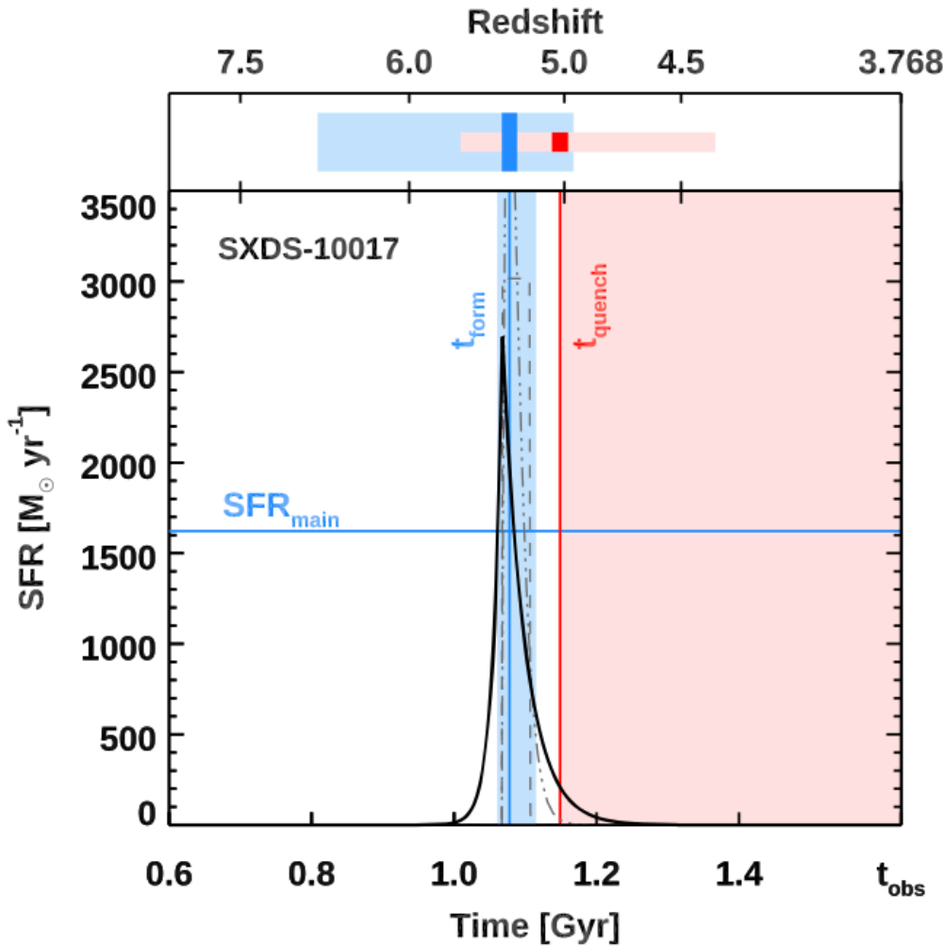
Davidzon+17



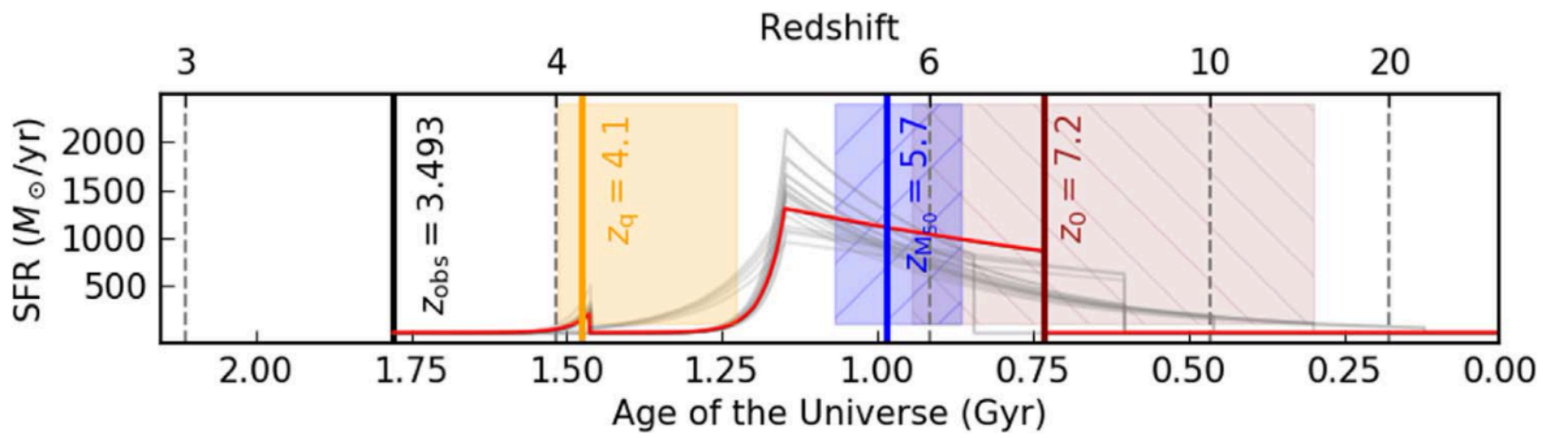
Van der Wel+14

Spectroscopic Properties

- Combining spectrum and multi-photometry can estimate star formation history
- Quiescent galaxies should have
  (1) intense starburst (~ 2000-6000 Msun/yr)
  - dusty star forming galaxy-like formation (c.f. compact shape)
  (2) rapid quenching (declining time scale 10-100 Myr)



Valentino+20



Forrest+20

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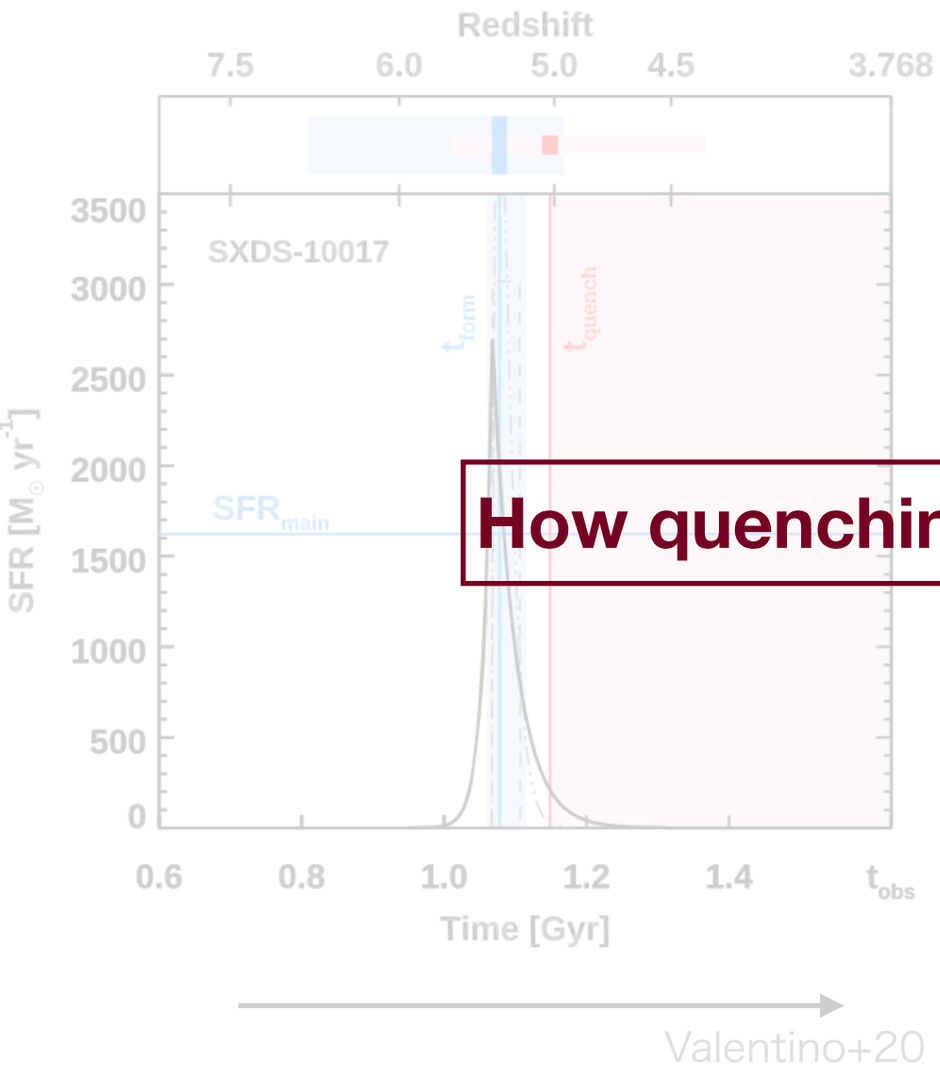
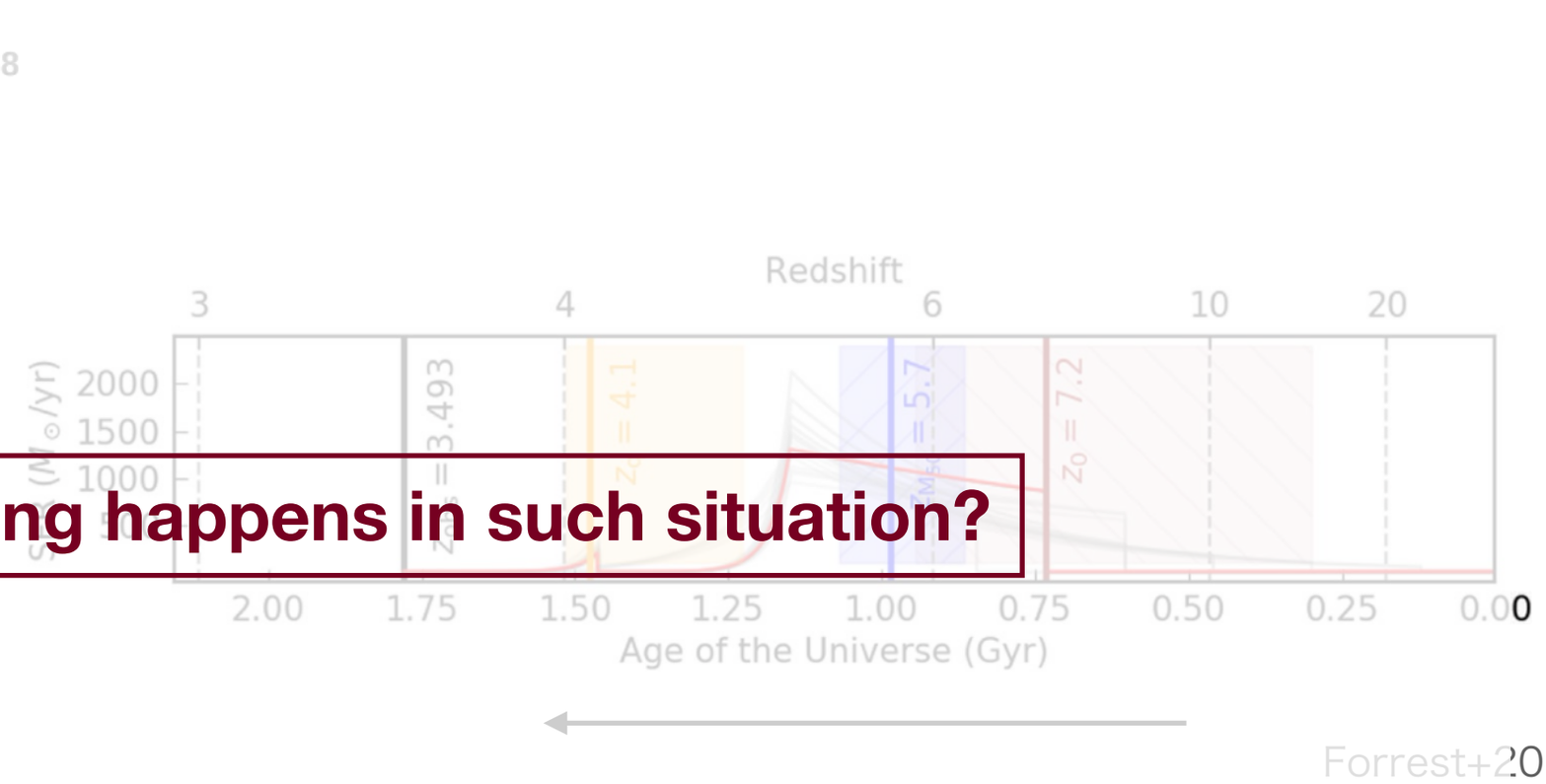


Valentino+20

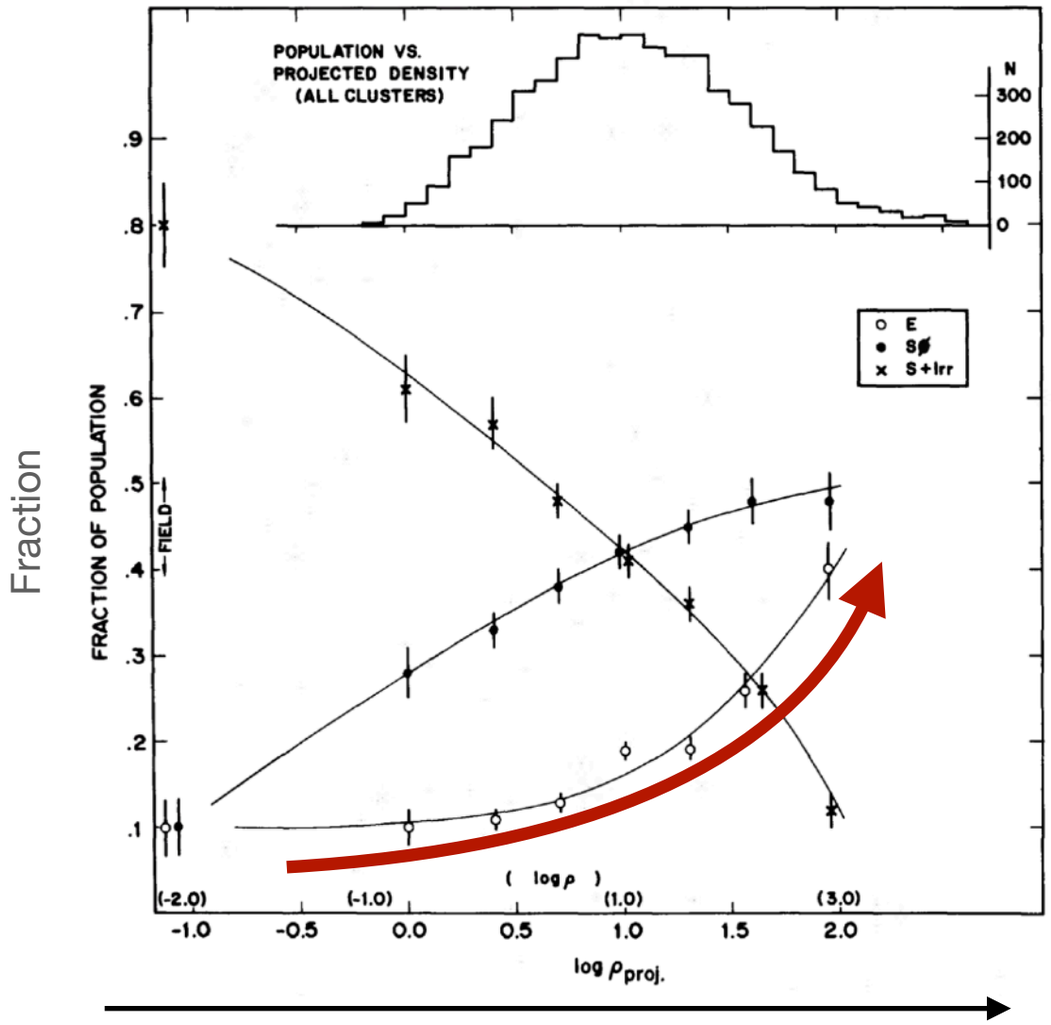
How quenching happens in such situation?



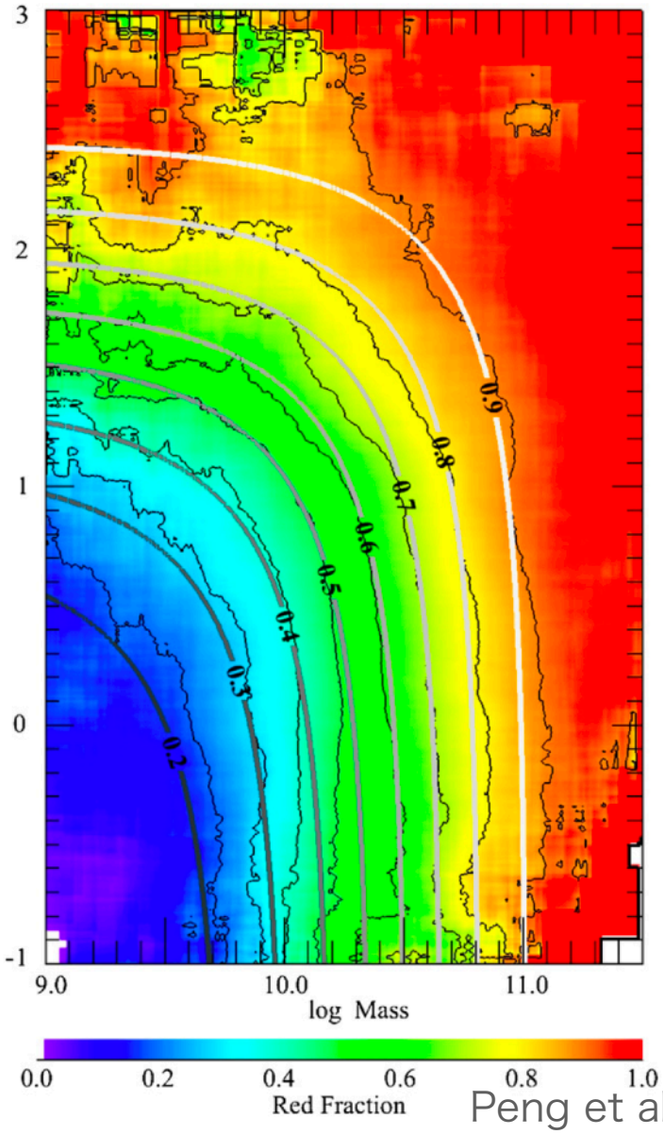
Forrest+20

Environment of quiescent galaxies

- Elliptical galaxies (≒quiescent galaxies) are in **denser environments** in local universe
- Quenching preferentially occurs in dense region (**environmental quenching**)
  - ram pressure, tidal stripping can explain enhanced quenching



Dressler 1980



Peng et al. 2010

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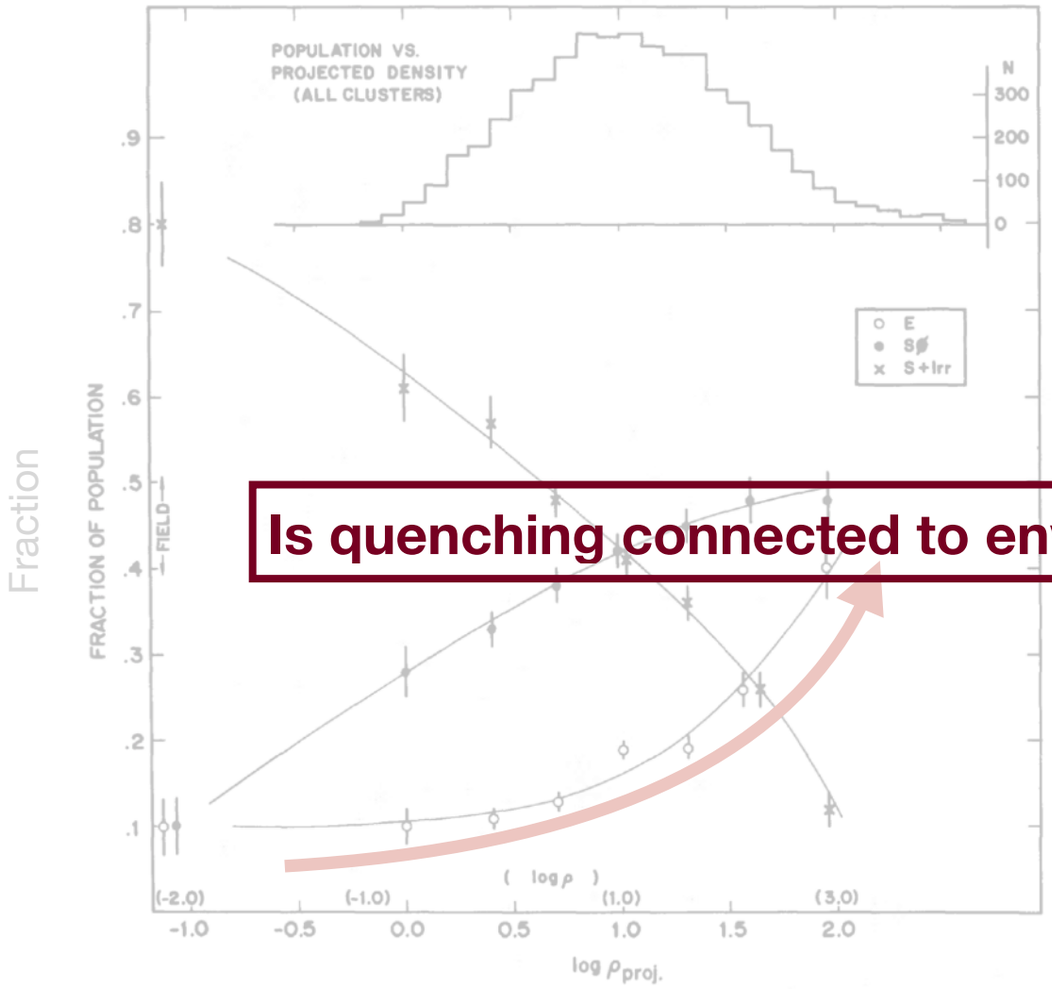

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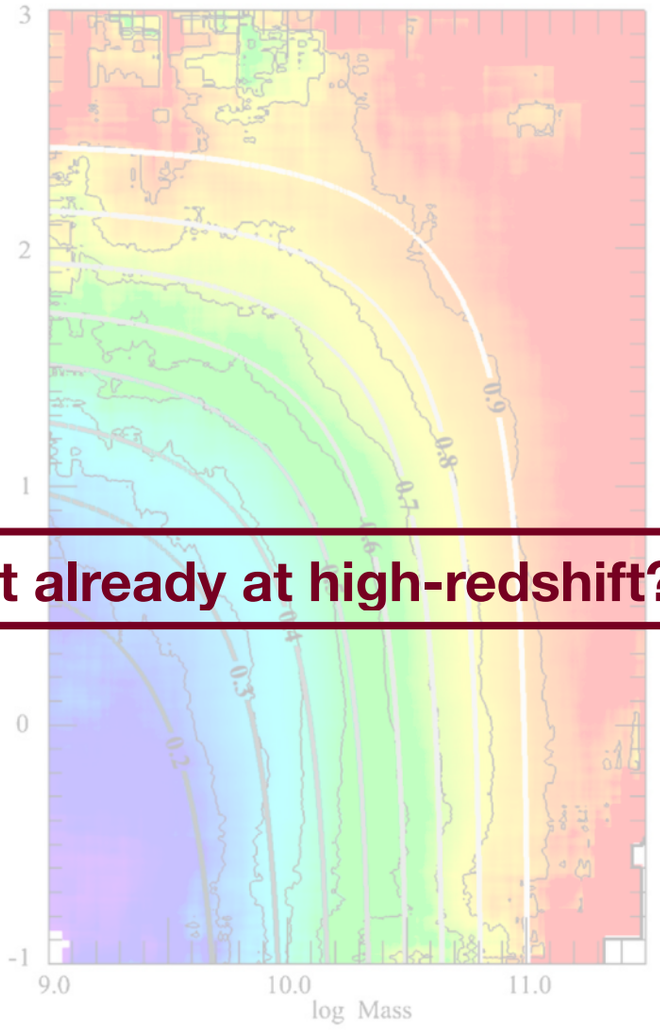


Peng et al. 2010

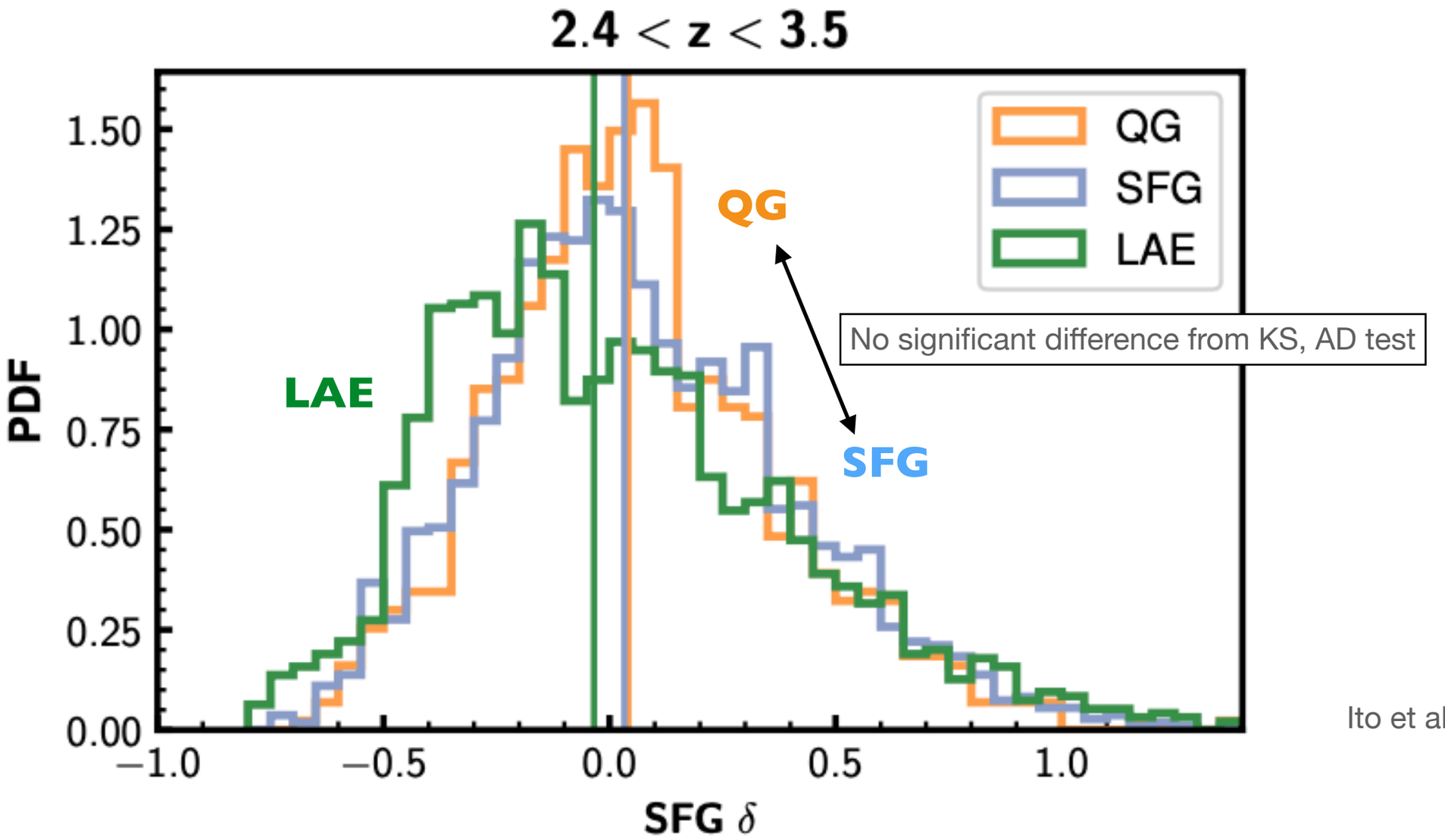
Is quenching connected to environment already at high-redshift?

Examining distribution difference among different galaxy populations

- Ito et al. (2021), ApJ, 916, 35

Environment of quiescent galaxies at high redshift

- Deriving cross-correlation function and overdensity for different galaxy populations
  - Lyman alpha emitters (SC4K, Sobral et al. 2016)
  - Massive star-forming galaxies (SFGs, from photo-z, Laigle et al. 2016)
  - Massive quiescent galaxies (QGs, from photo-z, Laigle et al. 2016)
  → ~2200 LAEs, ~8000 SFGs, ~1400 QGs in **COSMOS** field at 2<z<4.5
- Quiescent galaxies have similar overdensity distribution to star-forming galaxies



Ito et al. (2021)

Environment of quiescent galaxies at high redshift

- Deriving ratio between cross-/auto-correlation function

cross-correlation ⟶ $\xi^2_{\mathrm{SFG-QG}}/\xi_{\mathrm{SFG}}\xi_{\mathrm{QG}}$ ⟵ autocorrelation

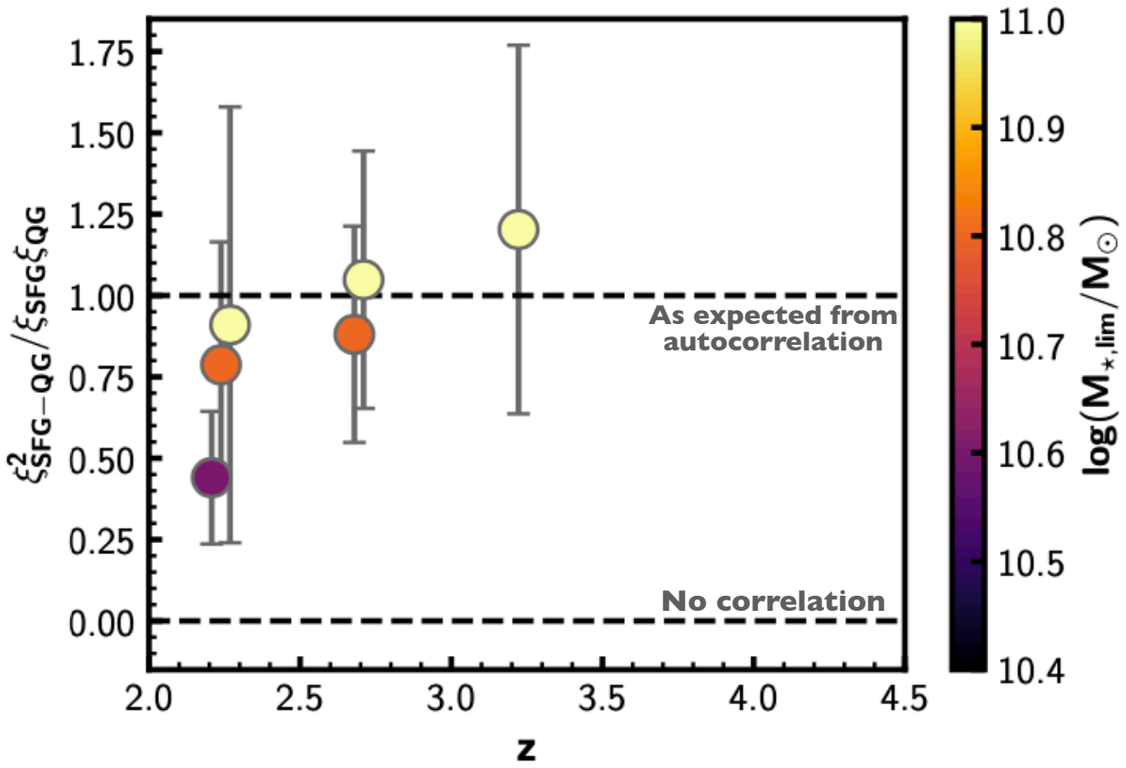
- If ratio is equal to one, cross-correlation is as expected from auto-correlation
- If ratio is less than one, cross-correlation is lower than expected

→**Distribution between two is more different than expected from halo mass difference**

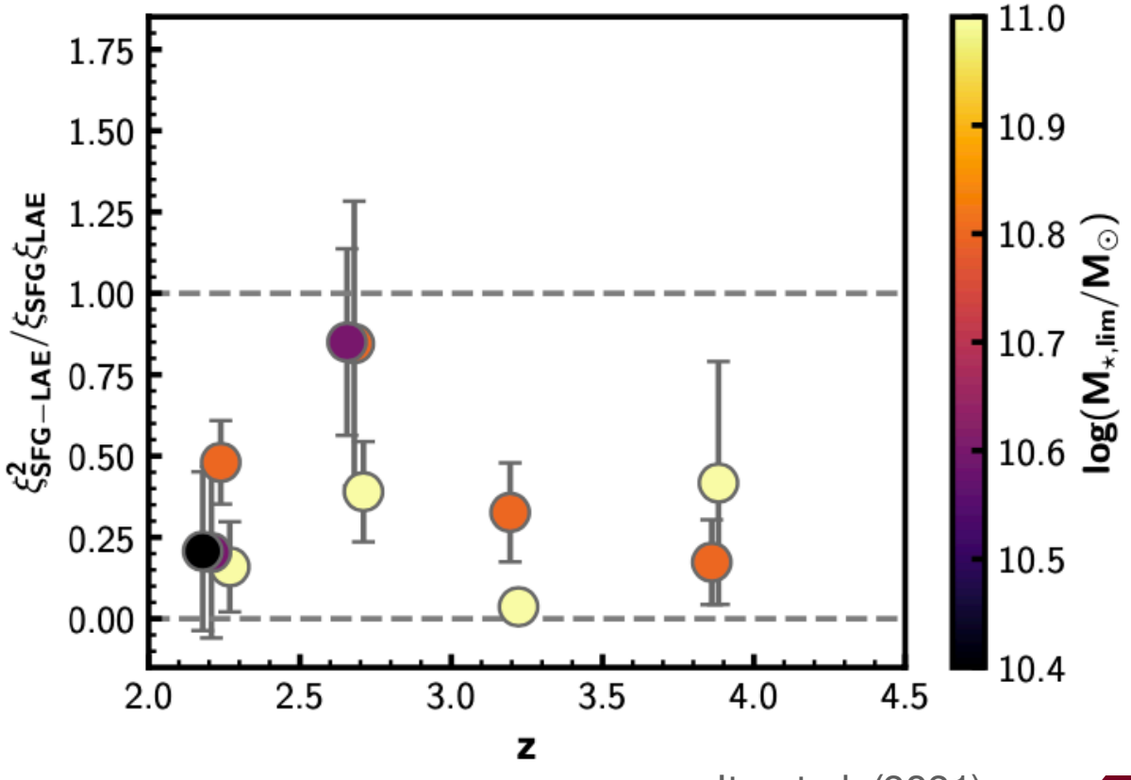
- No significant difference between SFG and QG (c.f., SFG-LAE)

→Supporting no enhanced quenching due to environment at z>2

SFG-QG



SFG-LAE



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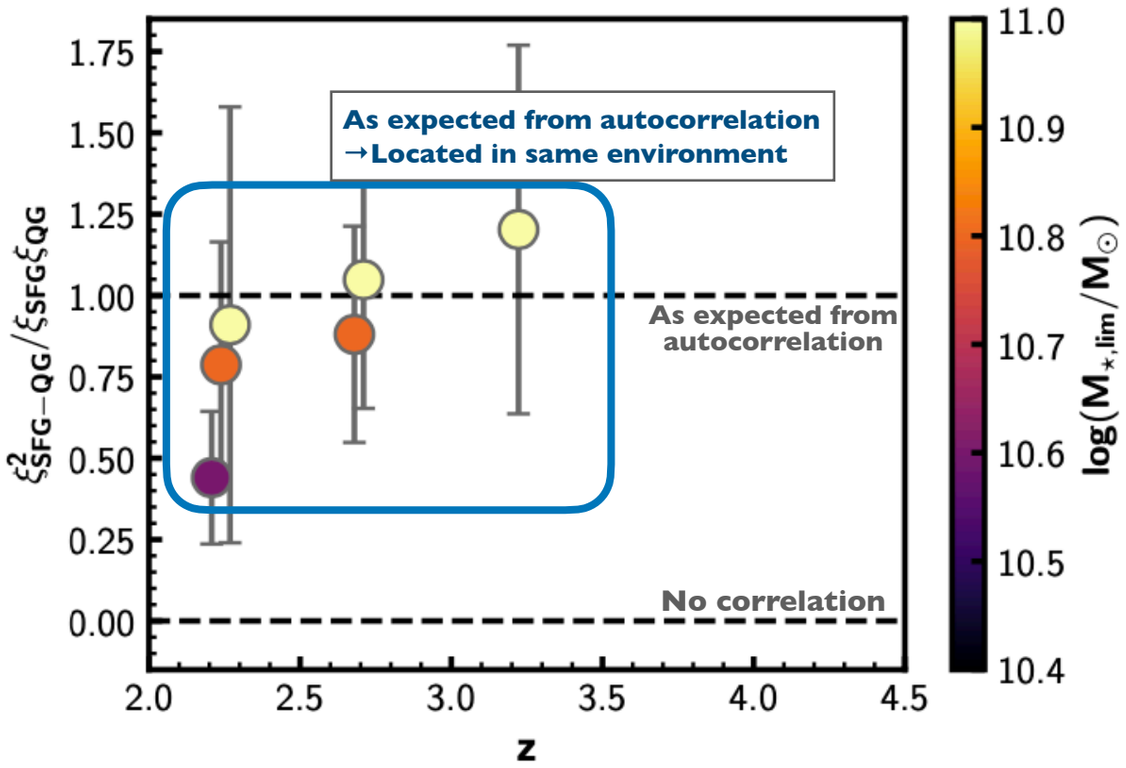
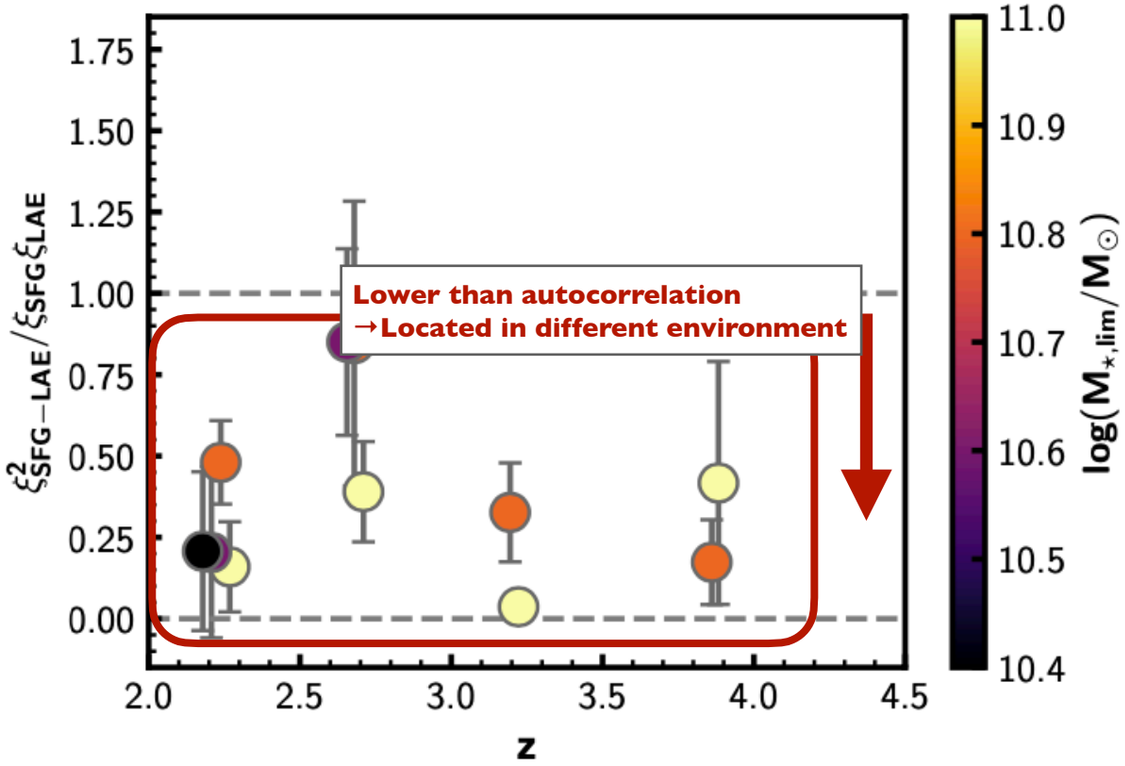


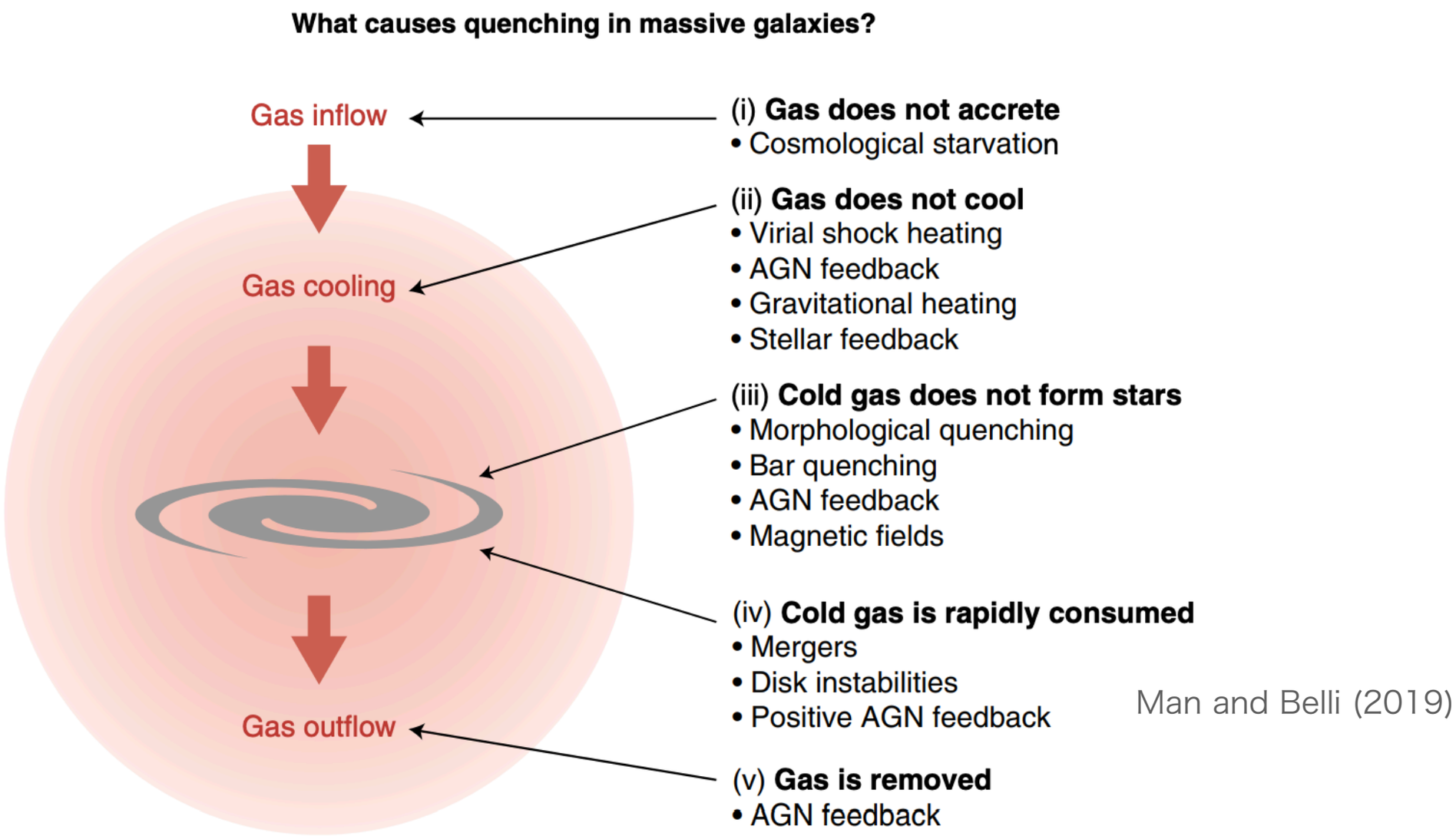
SFG-LAE



Ito et al. (2021)

Quenching mechanism?

- Various mechanisms are proposed for quenching
  - Preventing gas to transforming into stars
- Two mechanisms are needed for quenching
  - Reducing star formation
  - Keeping star formation stopped
- One of the most preferable mechanism : AGN feedback



Man and Belli (2019)

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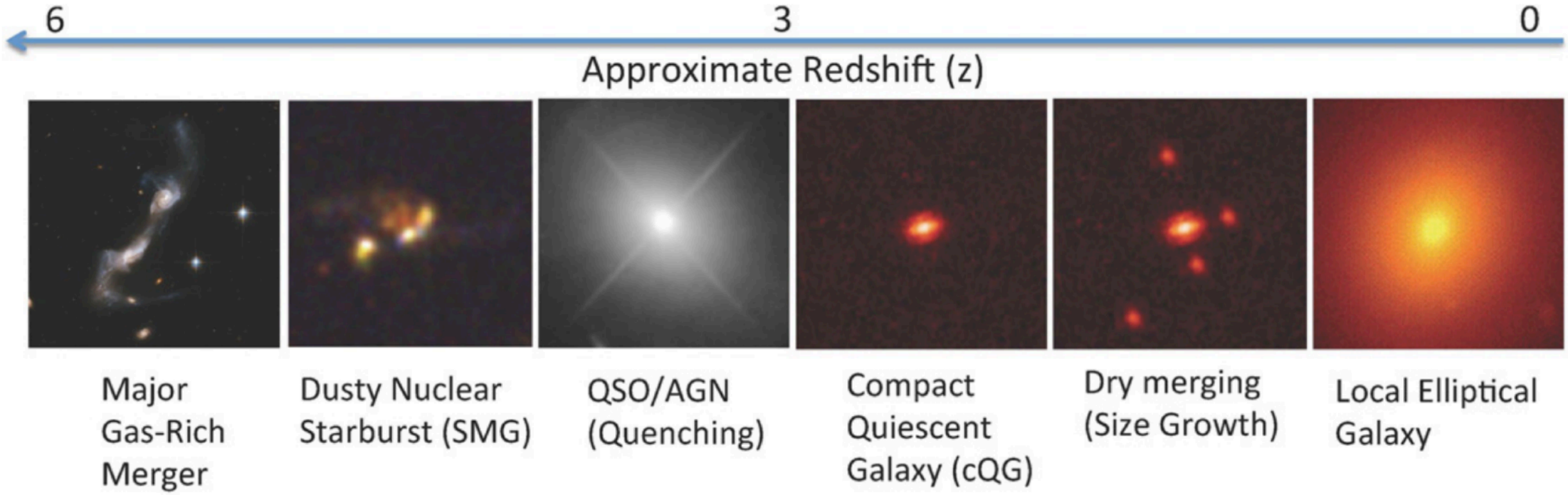
Expected evolution history of quiescent galaxies



Toft et al. (2014)

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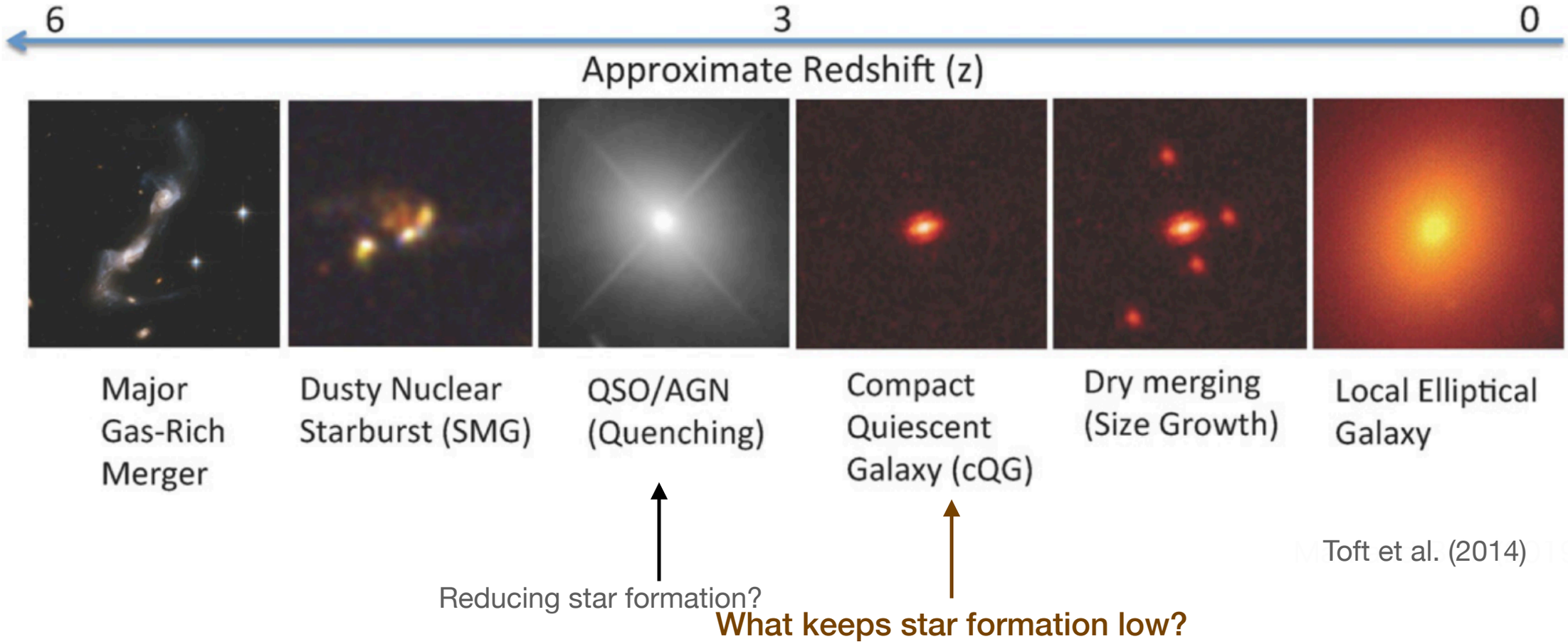
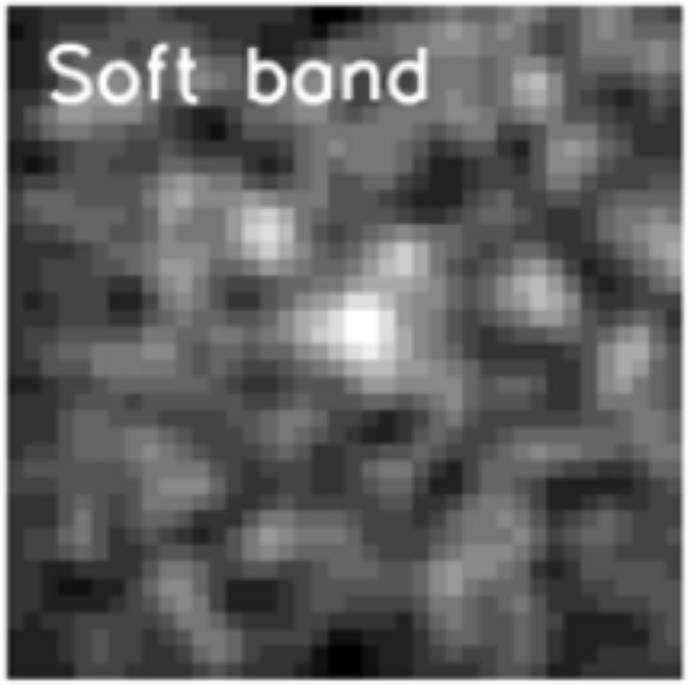


Toft et al. (2014)

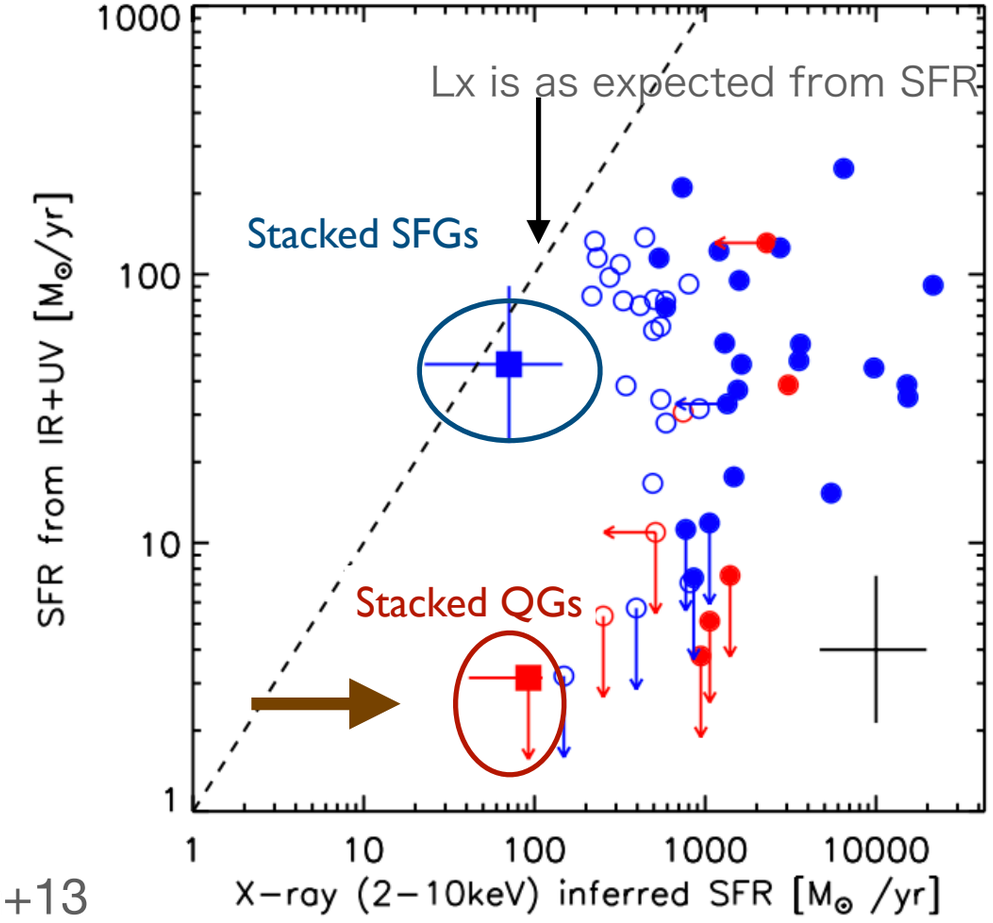
AGN and quiescent galaxies

- **Observational connection between high-z quenching and AGNs**
- **X-ray:** tracing black hole accretion
- Olsen et al. (2013)
  - Stacking typical z~2 UVJ selected quiescent galaxies in Chandra Deep field-South
  - typical: individually non-detection in X-ray
- Detecting average X-ray signal
  - X-ray luminosity is higher than expected from SFR (X-ray binary)

  →Quiescent galaxies have AGNs at z~2



4.9sigma detection

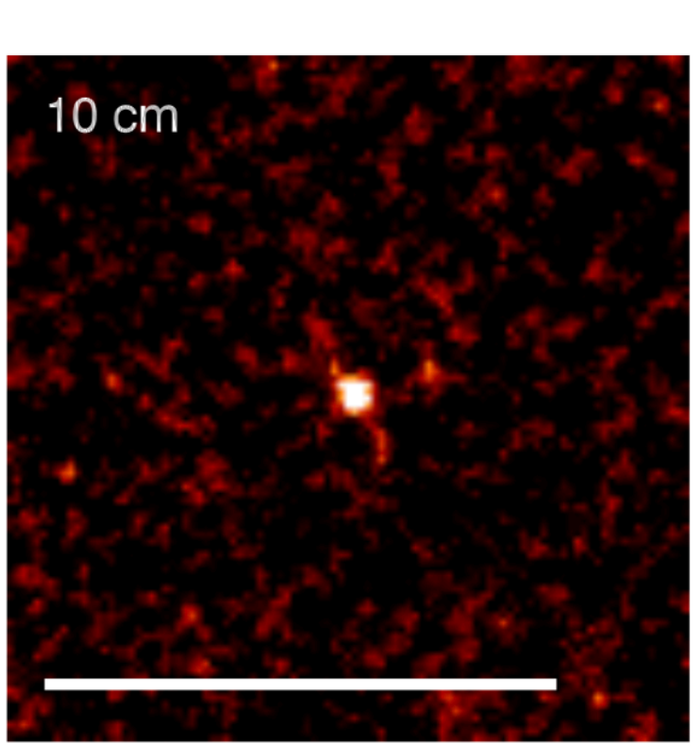


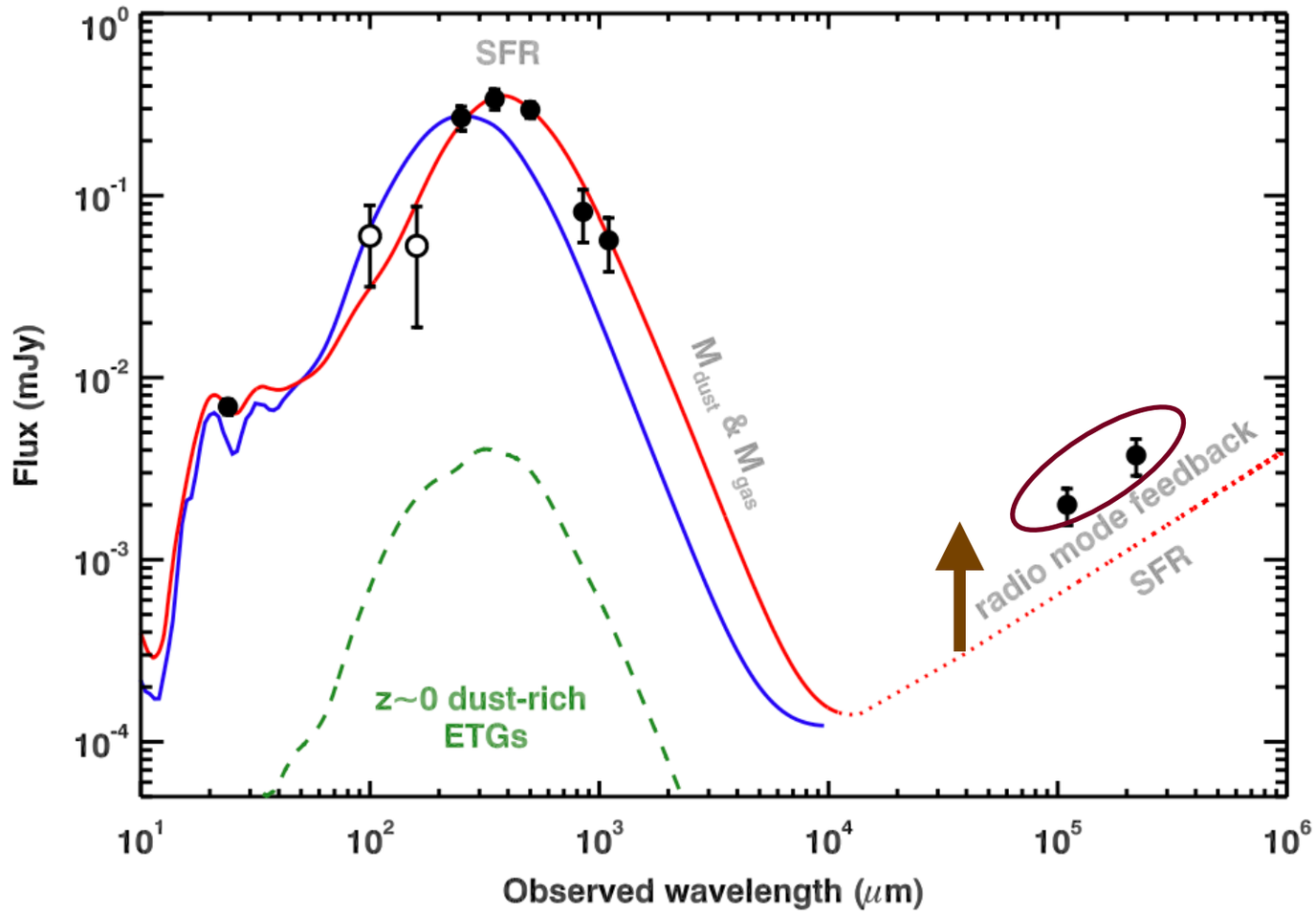
Olsen+13

AGN and quiescent galaxies

- **Radio:** Tracing jet emission from AGN
- Gobat et al. (2018)
  - Stacking z~2 BzK selected quiescent galaxies in COSMOS
- Detecting average radio signal
  - Radio luminosity is higher than expected from SFR

  →**Quiescent galaxies have AGNs at z~2**



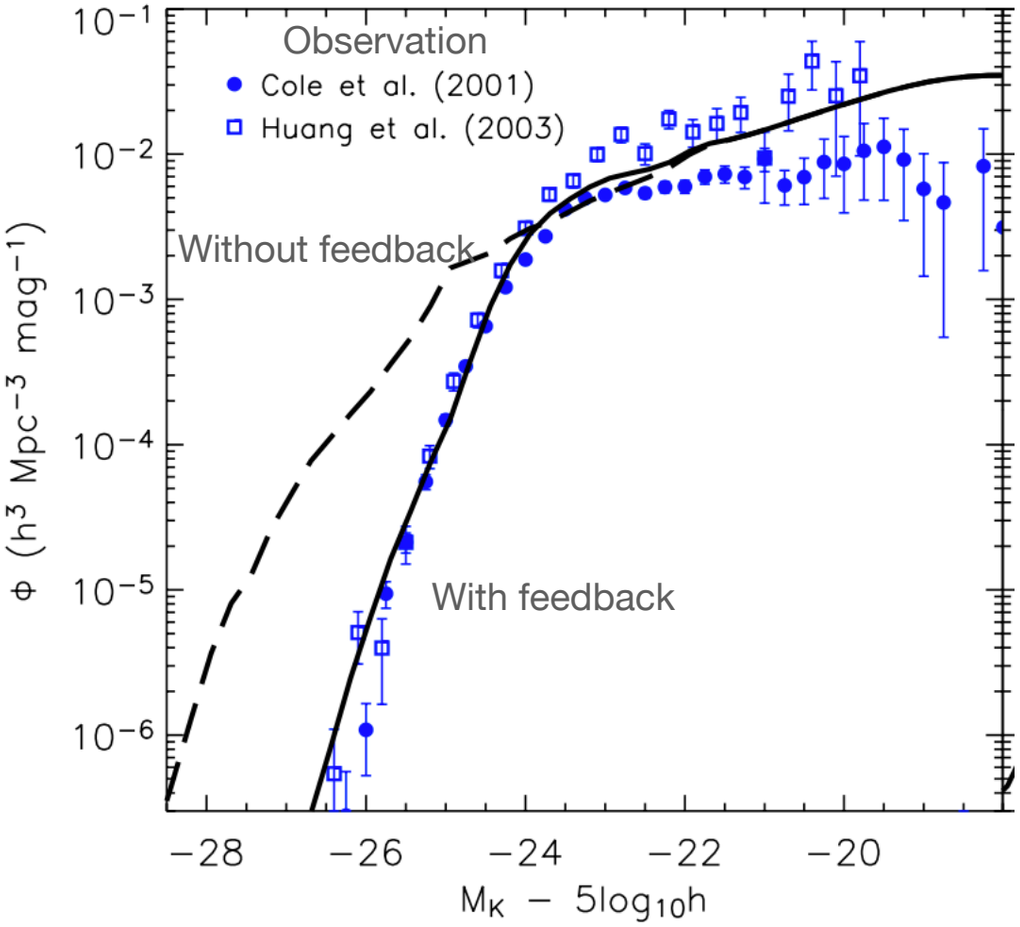


Gobat+18

AGN feedback in simulations

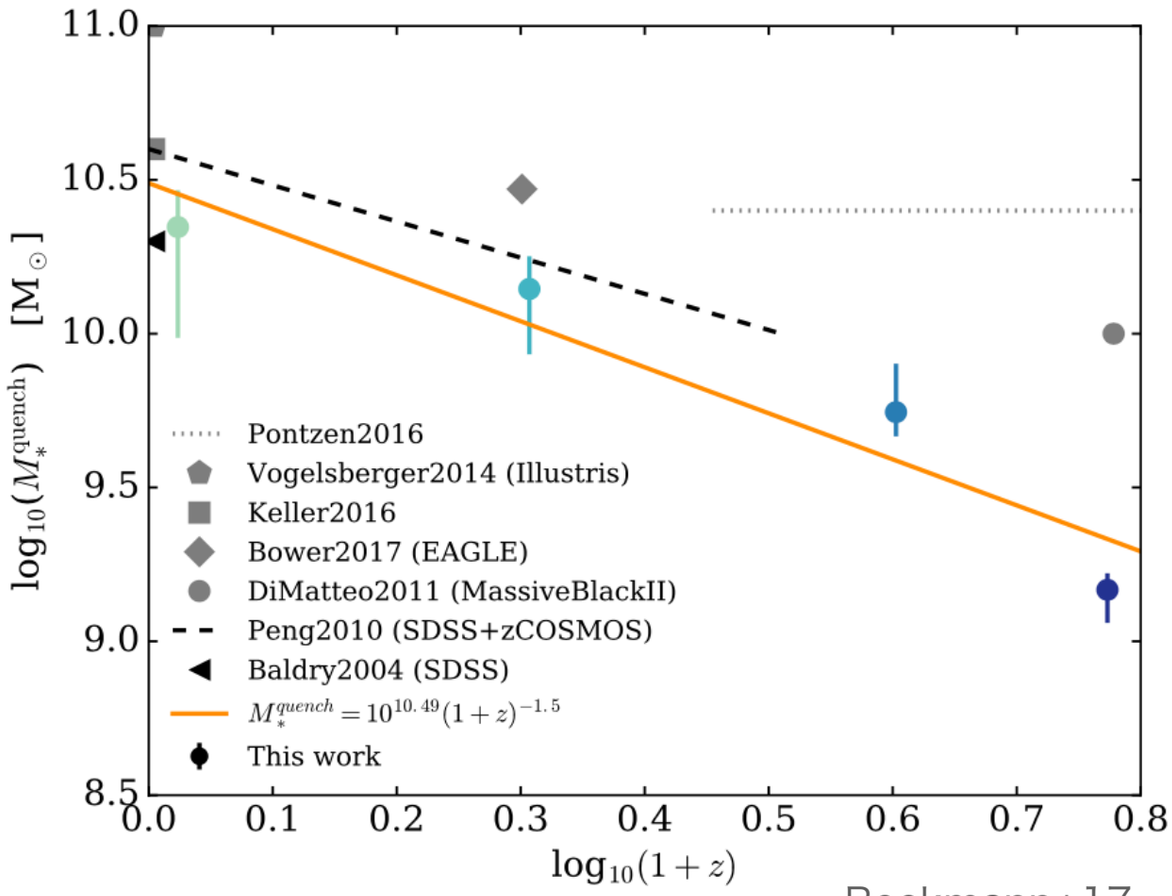
- AGN feedback is needed for explaining stellar mass function
  (e.g., Benson+03, Croton+06)
- Recent simulations shows its **more** significant contribution to high-z
  (Beckmann+17)

  →How about in real universe?



Croton+06

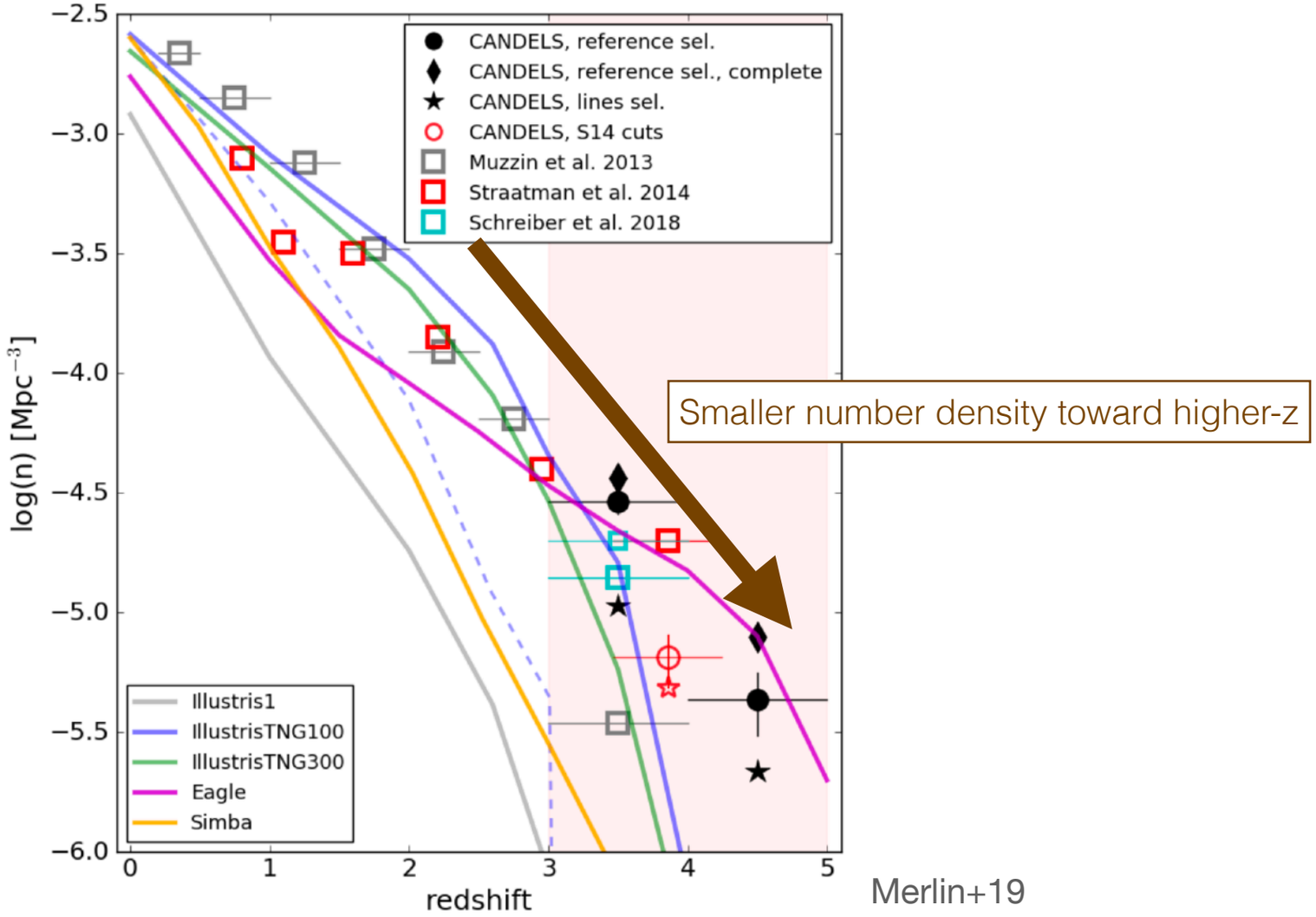
Stellar mass where stellar mass ratio
between w/ and w/o AGN feedback is less than 0.85



Beckmann+17

AGN and quiescent galaxies

- Higher redshift (z>2)?
  - Only limited for detected objects or including bright sources
- Carraro et al. (2020)
  - Deriving average flux for all NUVrJ selected quiescent galaxies
  - Including detection → How represent this average flux is?
  - Is NUVrJ selection correct, even if AGN emission can be significant?
- **Problem**: Smaller number density of quiescent galaxies at higher redshift
  →Wider field and deep X-ray/radio survey is needed to detect their faint signal

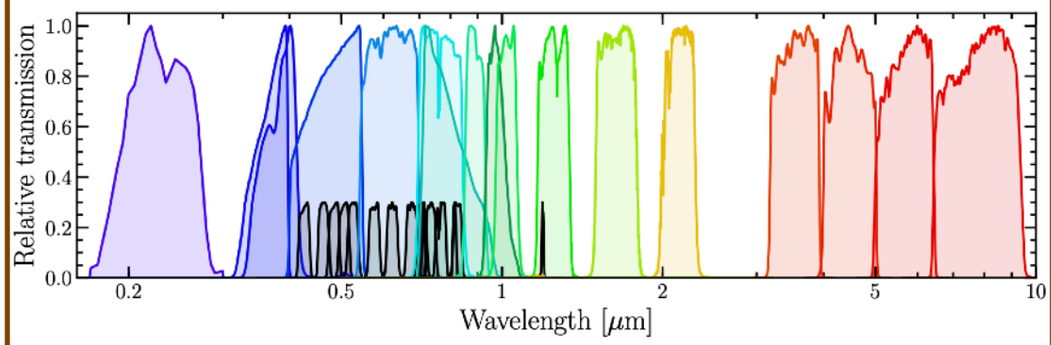


Merlin+19

This work

- Aiming to connect quenching with AGN activity at the highest redshift
- Combining multi-wavelength data of Cosmic Evolution Survey (COSMOS) over ~2deg2
  - COSMOS2020 (Weaver+21)
  - Chandra COSMOS Legacy Survey (Civano+16)
  - VLA-COSMOS survey (Schinnerer+07, Smolcic+17)

Plenty quiescent galaxy sample



COSMOS2020 (Weaver+21)

Deep multi-wavelength data

Chandra COSMOS Legacy Survey (Civano+16)

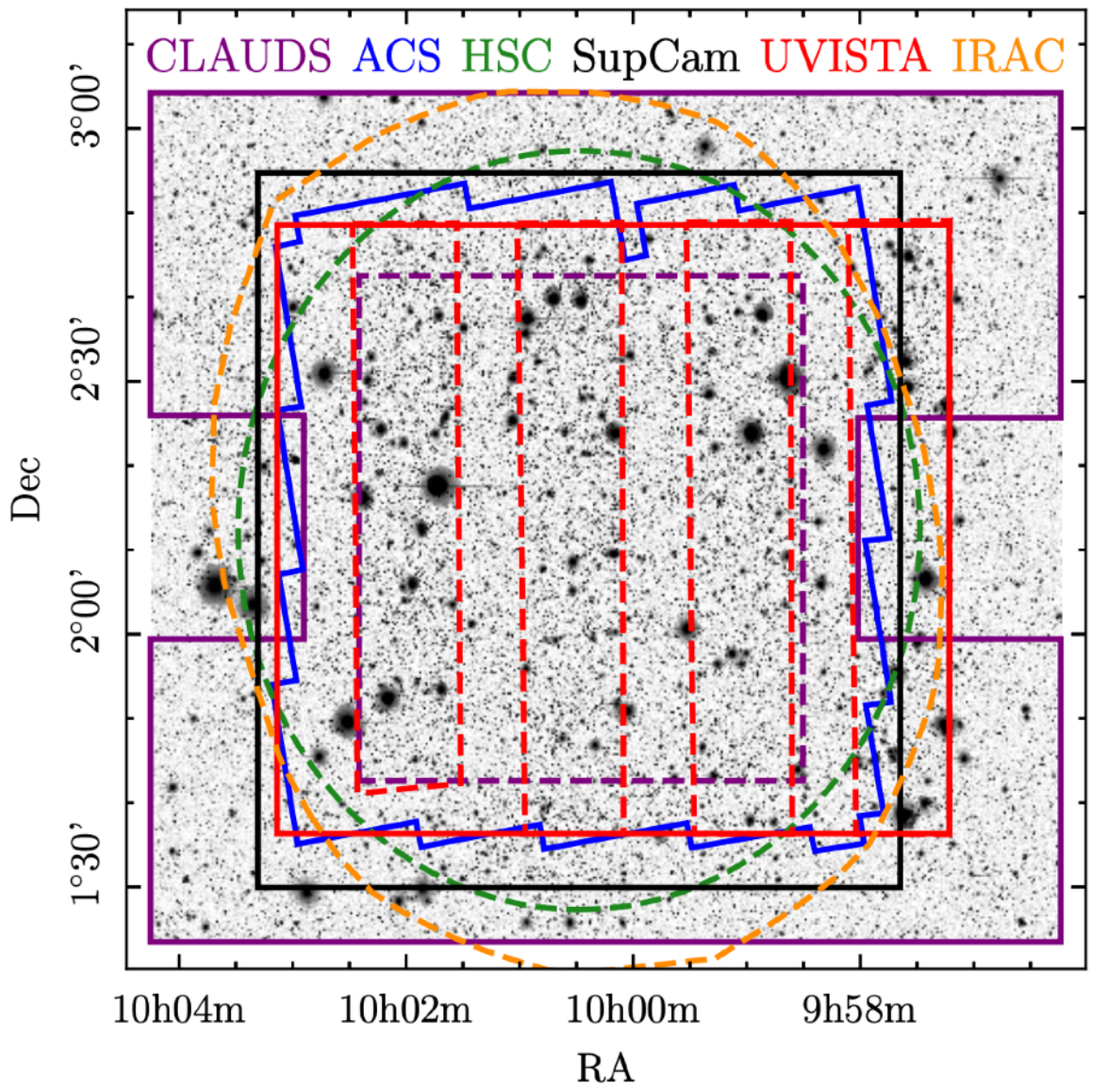
VLA-COSMOS Survey (Schinnerer+07, Smolcic+17)

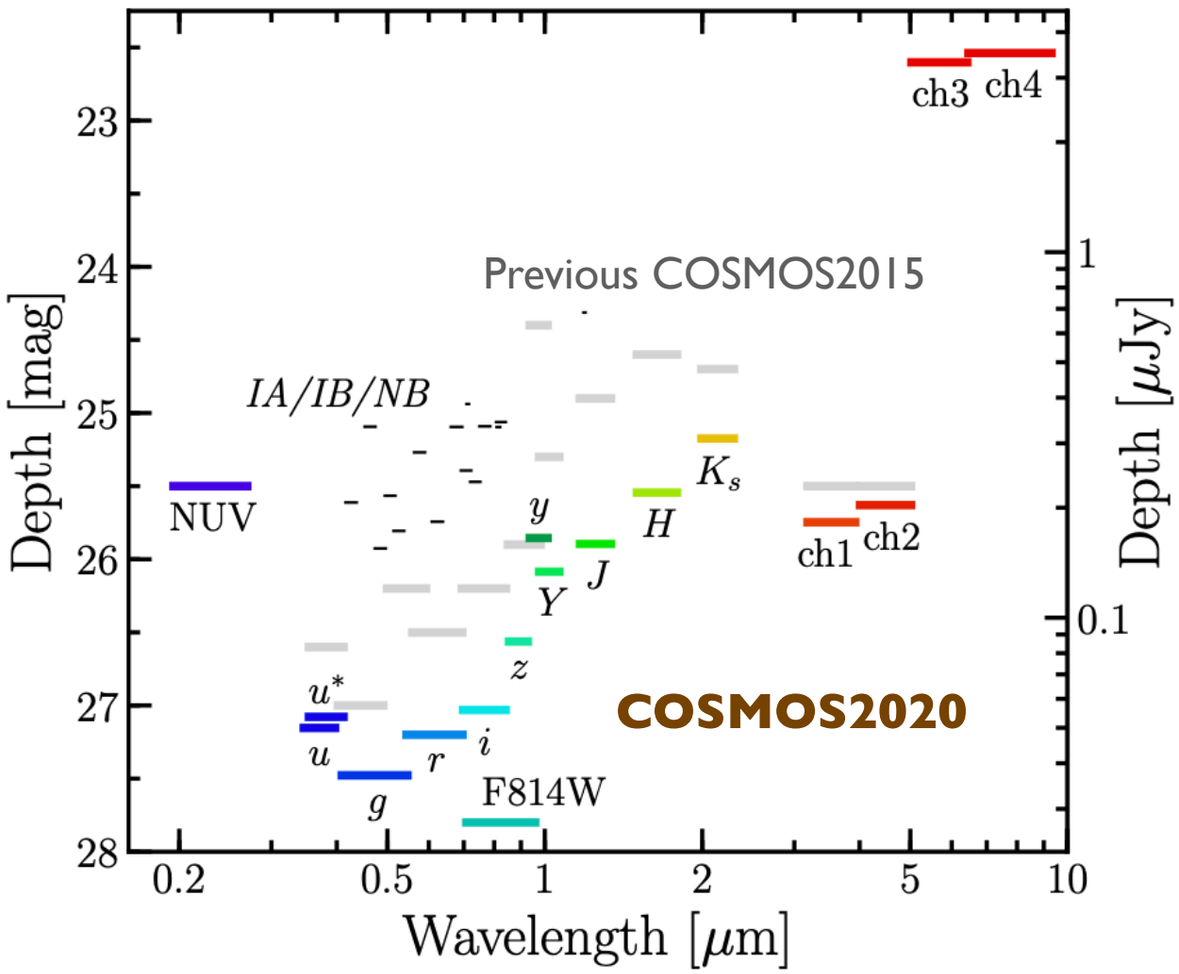
Stacking analysis for quiescent galaxies at 0<z<5

- Ito et al. (2022), ApJ, 929, 53

COSMOS2020

- **COSMOS2020 (Weaver+22)**
  - Latest multi-band catalog of COSMOS
  - Including HSC-SSP, CLAUDS, deeper UVISTA
- **Complete for lower-mass and higher-z galaxies**
  - 90% complete for $\log M_\star/M_\odot \sim 10$ even for quiescent galaxies at z~3





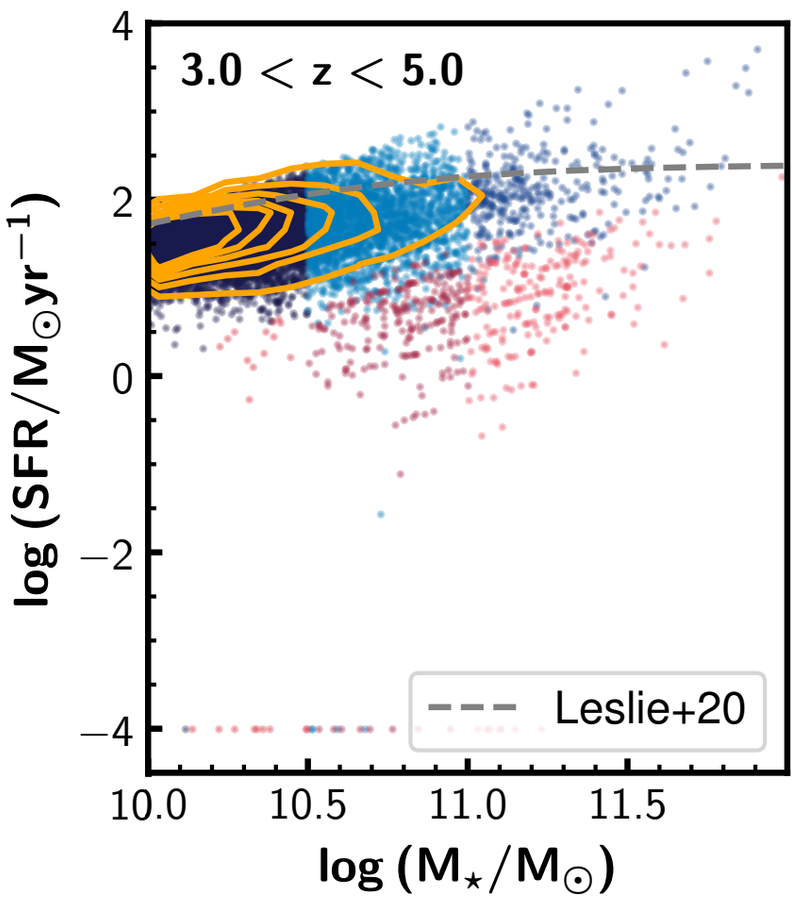
Weaver+21

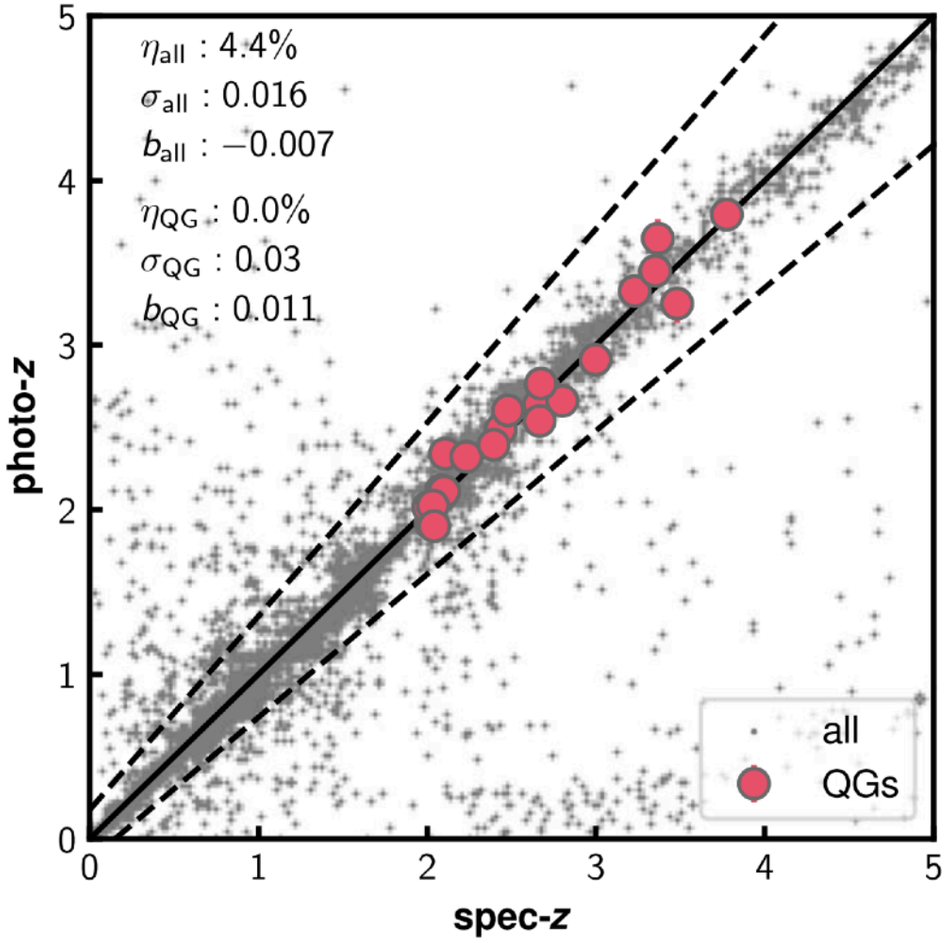
Quiescent Galaxy Sample

- **Definition of quiescent galaxies**
  - $0 < z < 5$ based on photo-z
  - quiescent galaxies have ~1dex lower sSFR than main sequence
  - $\log M_\star / M_\odot > 10$

  →selecting quiescent galaxies based on good quality photo-z
- **Stacking sample**
  - 7 redshift bins and 3 stellar mass bins
  - No individually X-ray detections (85-100% of the total)

    ∵to focus on typical properties of quiescent galaxies





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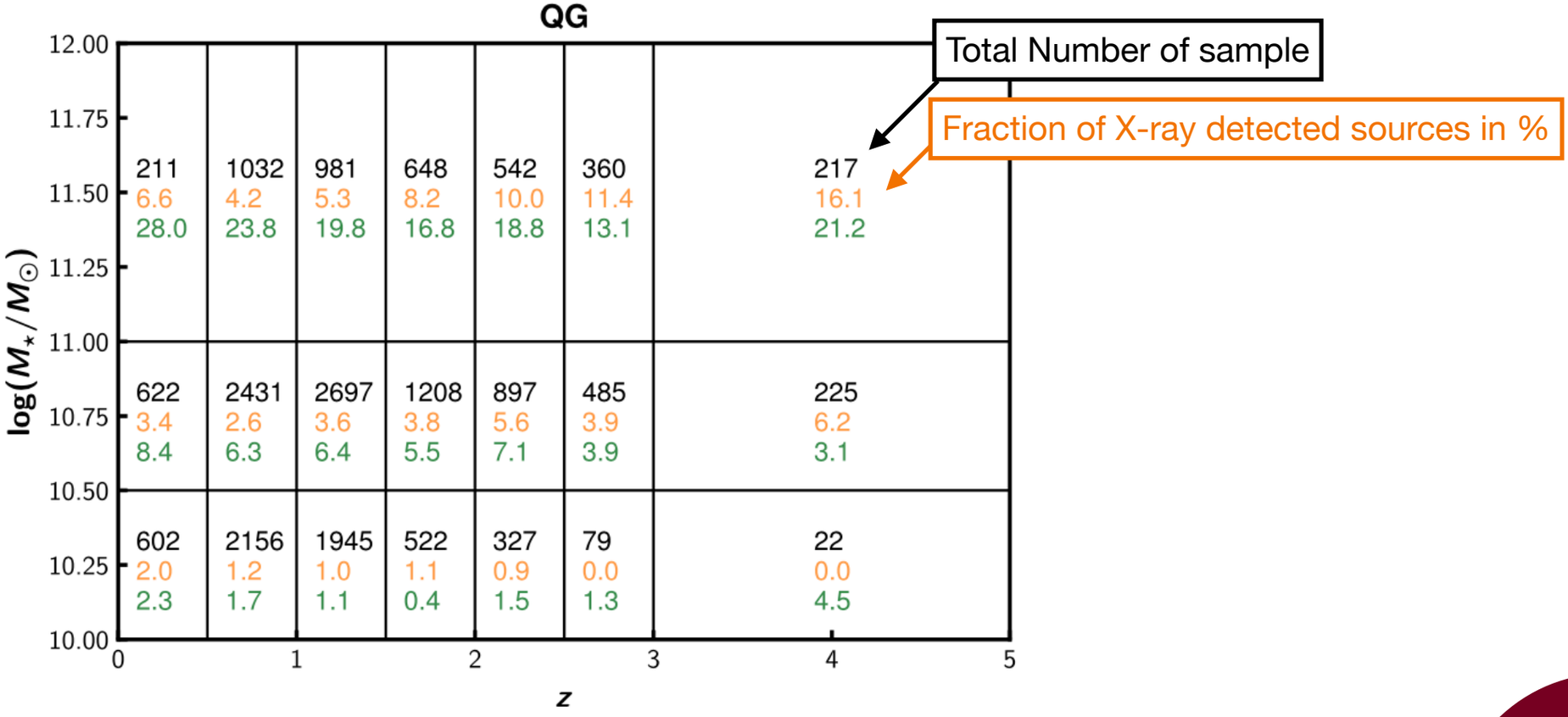
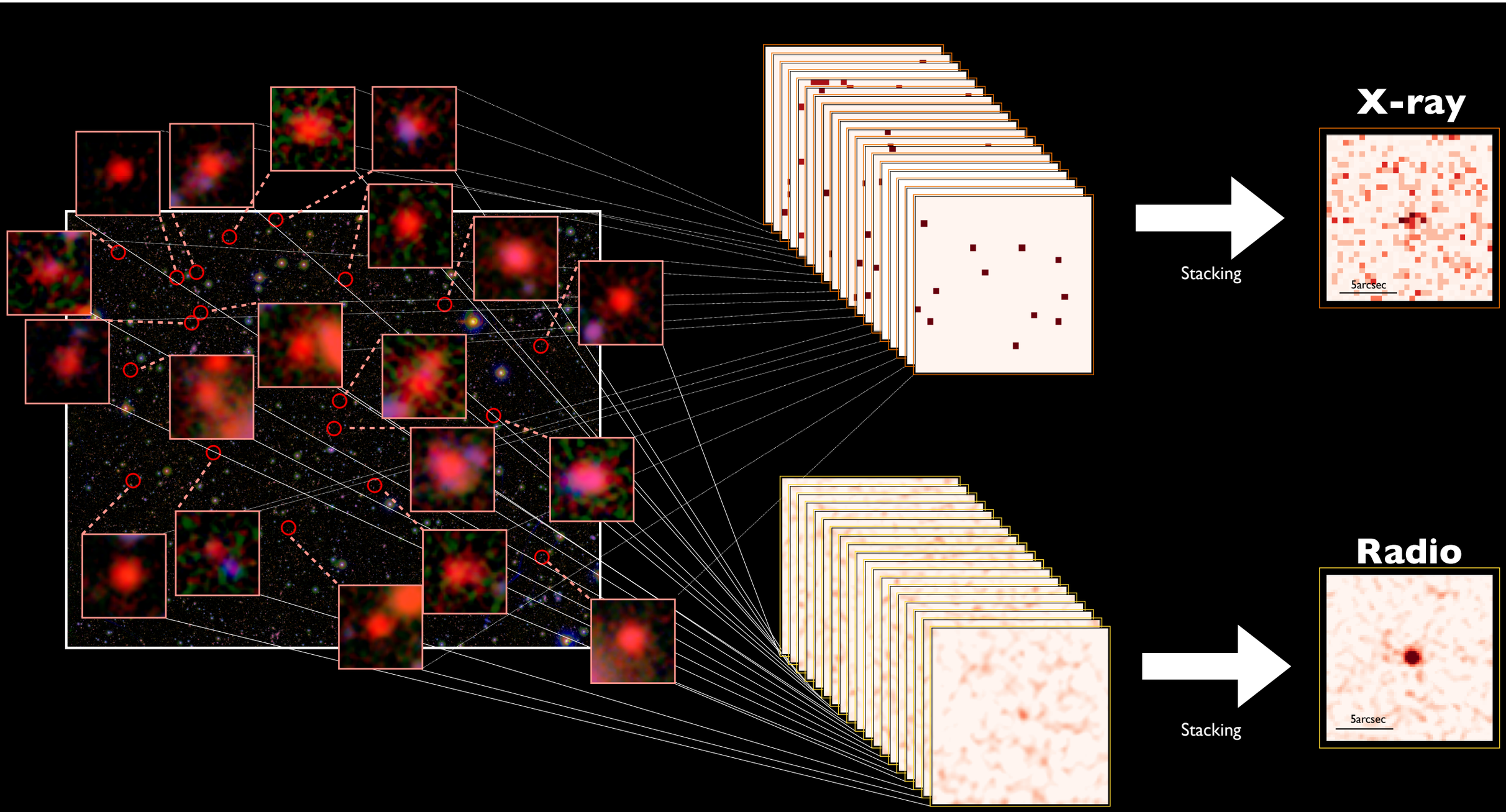


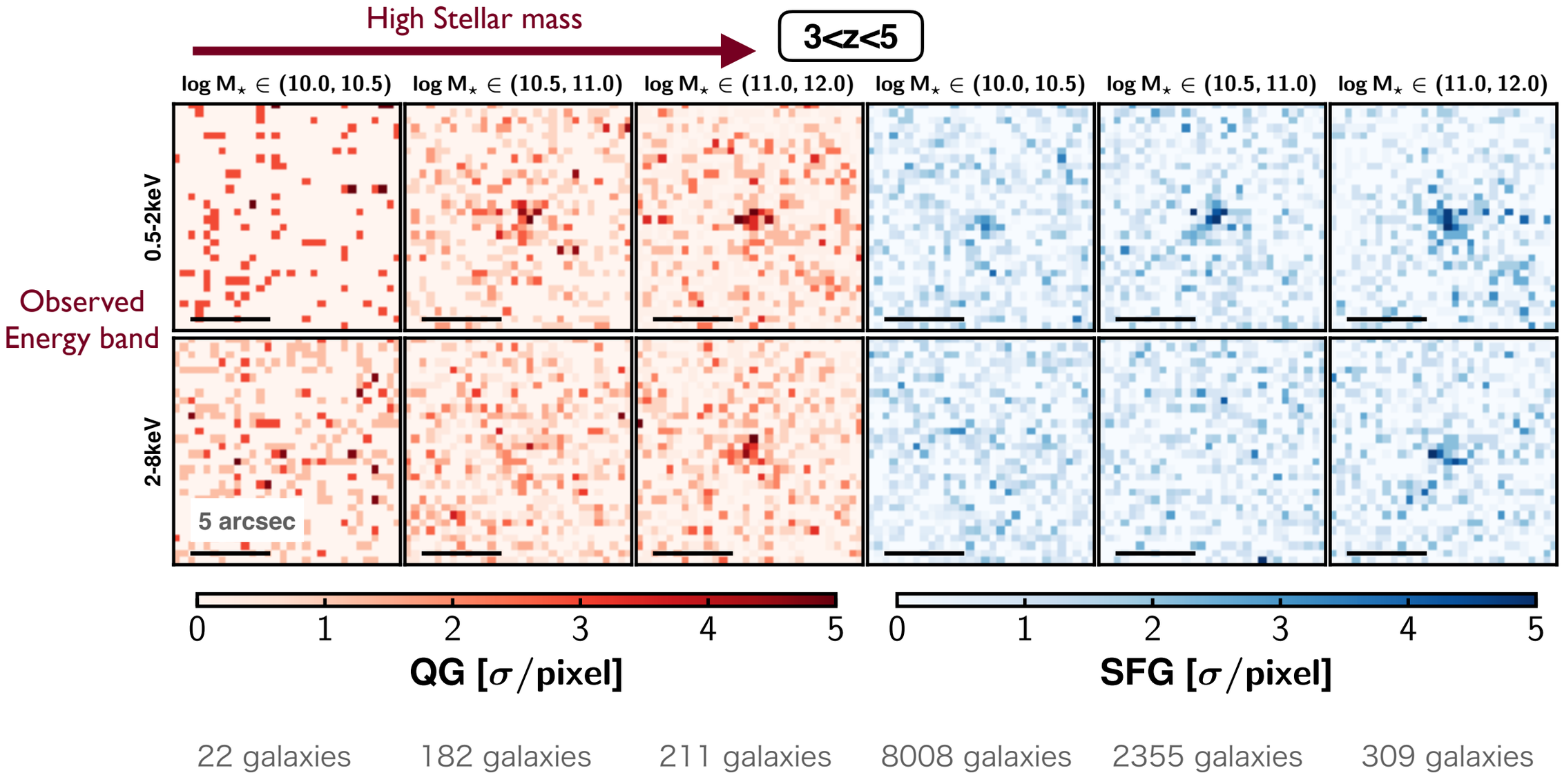
Stacking analysis



Press-release from Subaru Telescope (May 27th)

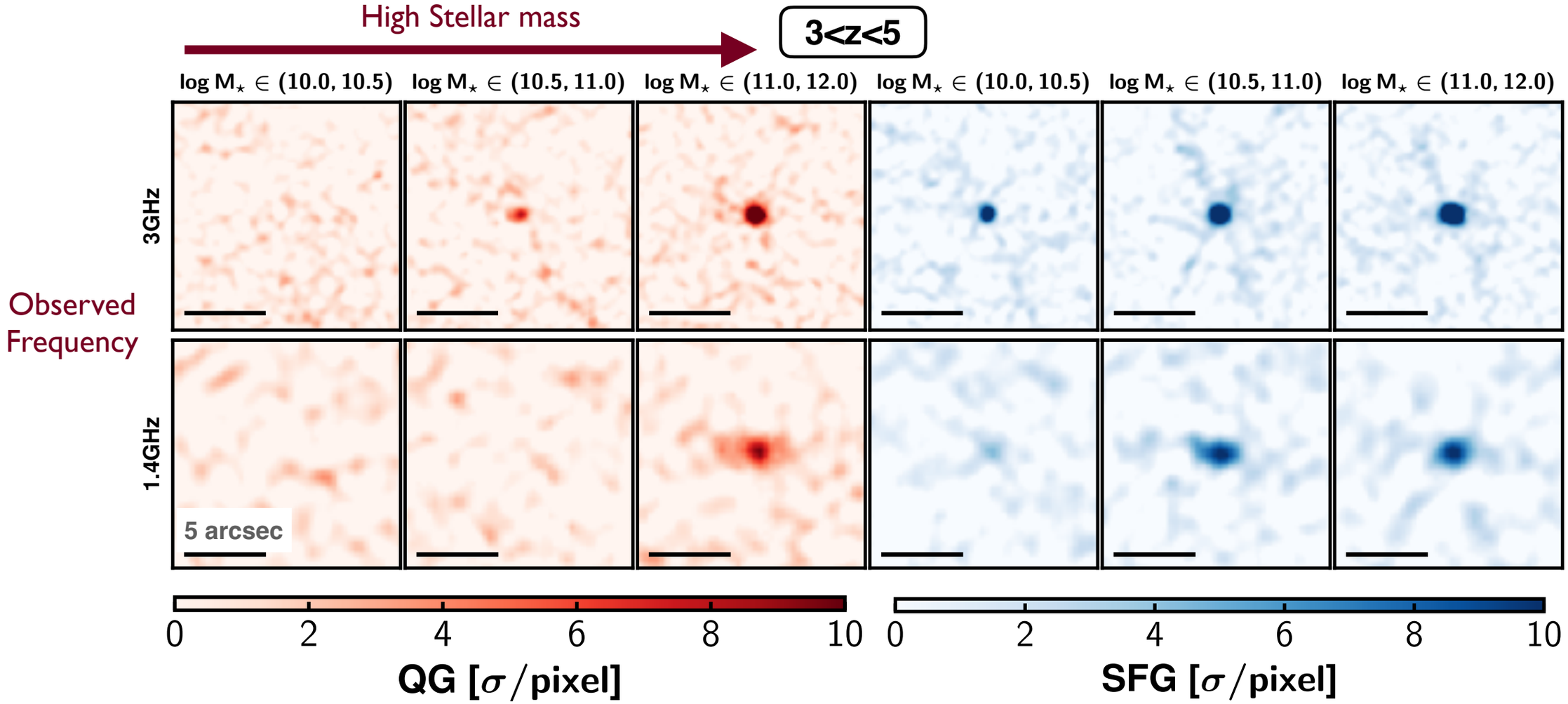
X-ray stacking analysis

- Stacking individual images (with CSTACK, Miyaji+08)
- Significant emission at any redshift in more than one band
  → First time to detect the average signal for typical quiescent galaxies at z>2-3

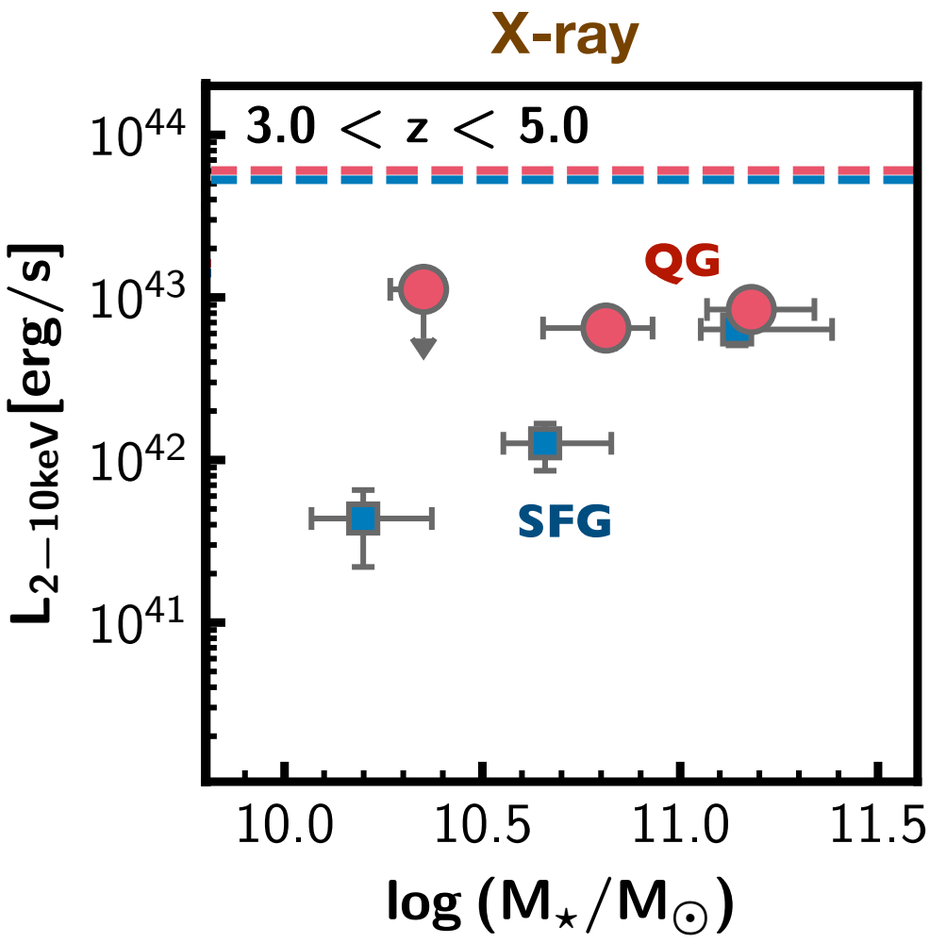


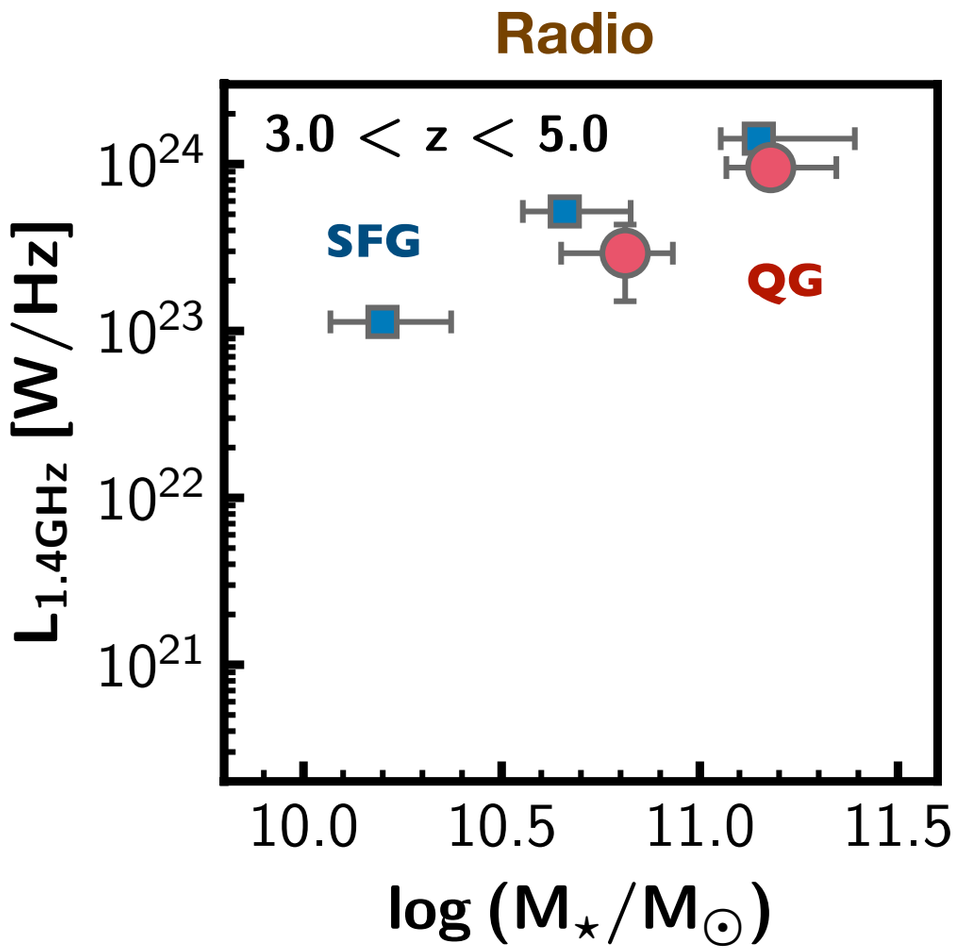
Radio stacking analysis

- VLA-COSMOS survey: two frequencies (1.4GHz, 3GHz)
- Successfully detect signals also for radio wavelength
  → First time to detect the average signal for typical quiescent galaxies at z>2-3



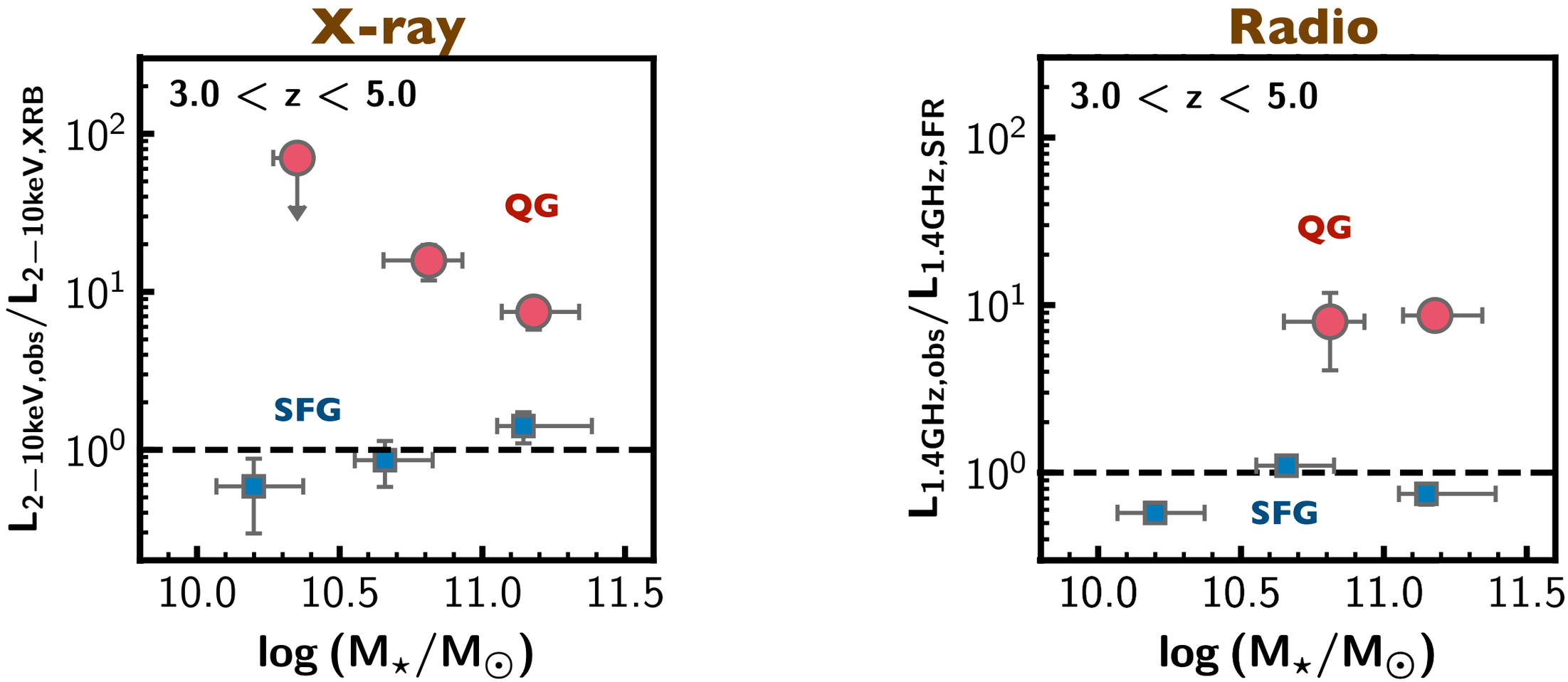
Average X-ray/radio luminosity





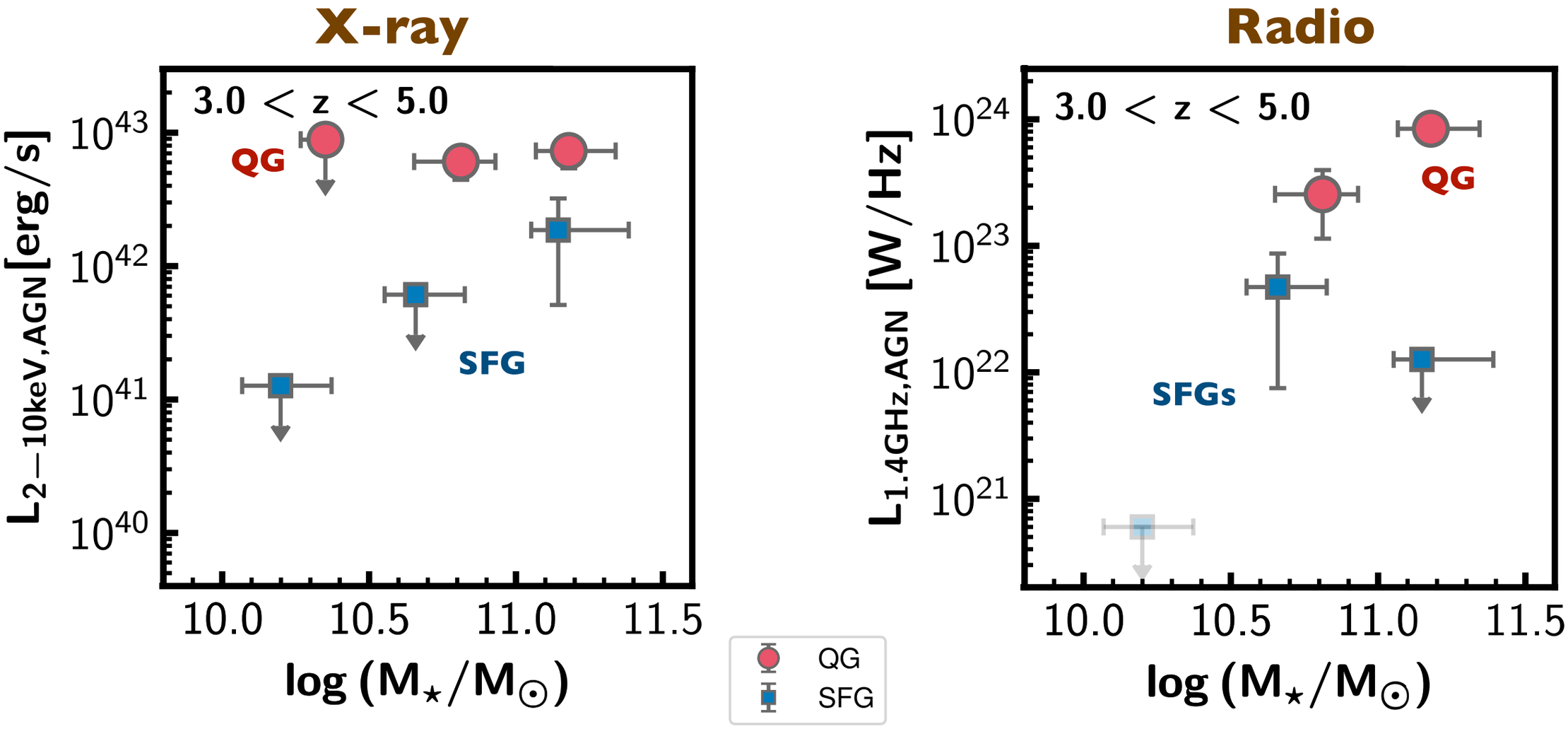
- Average luminosity is estimated from stacked flux
  - Absorption is corrected for X-ray luminosity
- No systematical difference between star-forming and quiescent galaxies
  - In X-ray, quiescent have slightly higher luminosity
  - In radio, star-forming have higher luminosity
- These can be due to different contribution from stellar related ones
  - How significant contribution AGNs have?

What is the dominant source?



- Estimating expected luminosity from stellar related phenomena
  - Low/High-mass X-ray binary in X-ray (Lehmer+16)
  - Infrared-radio correlation (Delvecchio+21)
- Using best-fit value of stellar mass and SFR in SED fitting
- QGs' luminosity is ~10 times larger than expected luminosity
  →QGs typically have AGNs even to z~3-5

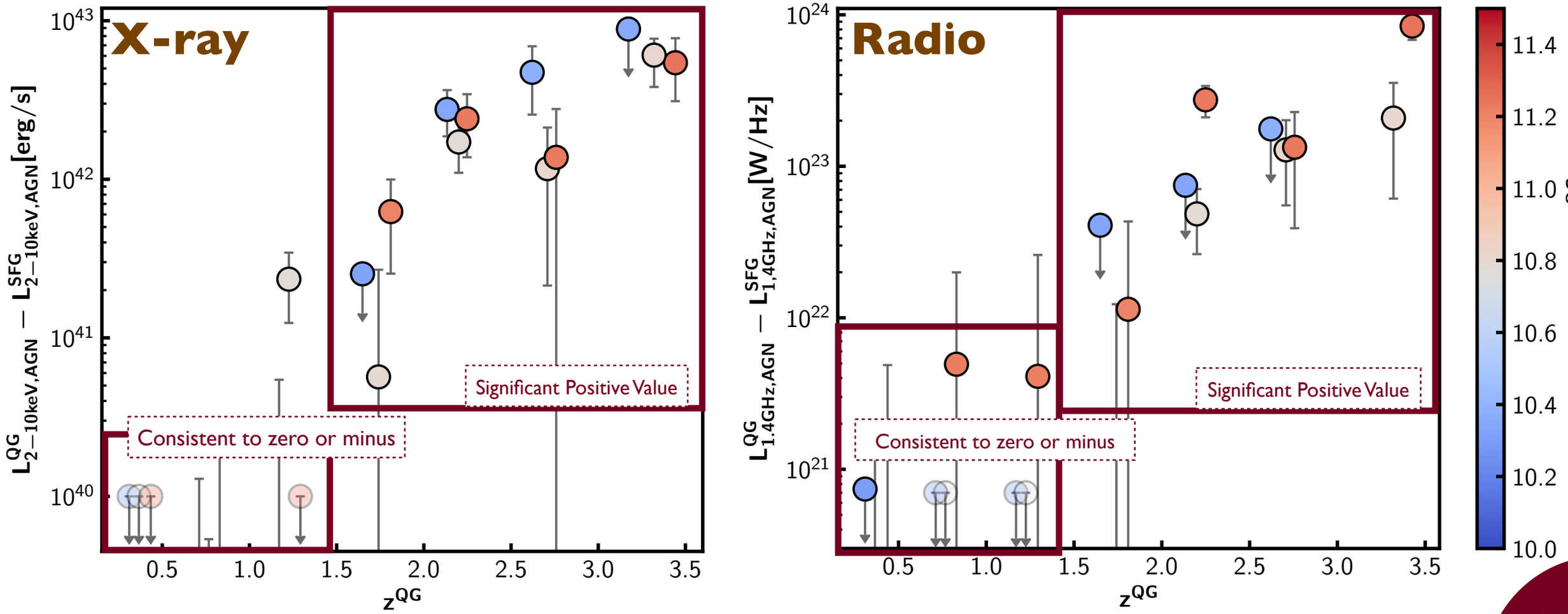
AGN X-ray/radio luminosity



- Deriving AGN luminosity as the difference of observed and expected
  - All bins trace low-luminosity AGN regime
- Quiescent have higher AGN luminosity in both X-ray and radio
  →Enhanced AGN activity in quiescent galaxies

AGN luminosity excess of QGs

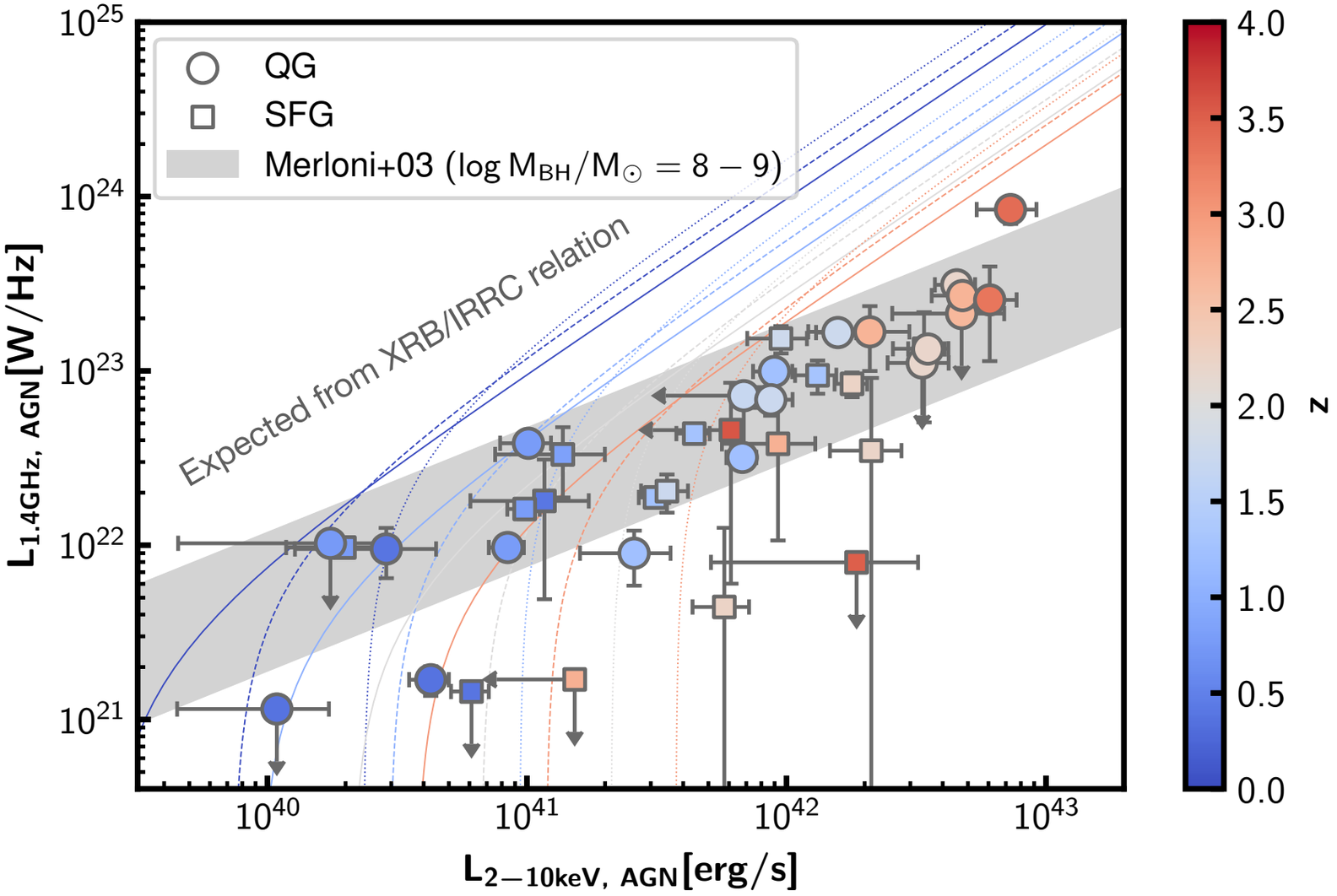
- Tracing redshift evolution of AGN luminosity difference
- AGN luminosity of quiescent is higher than star-forming at z>1.5.
  - both in X-ray and radio
- Difference disappears at z<1.5
  →AGN feedback is particularly important for high redshift?



Correlation of X-ray and radio AGN luminosity

- "Fundamental plane of black hole activity"
  - Correlation among black hole mass, radio and X-ray luminosity in local universe (e.g., Merloni+03)
- Our average luminosity have similar slope as local one
  - Similar amplitude to local one with black hole mass of $\log M_{\rm BH} \sim 8-9$

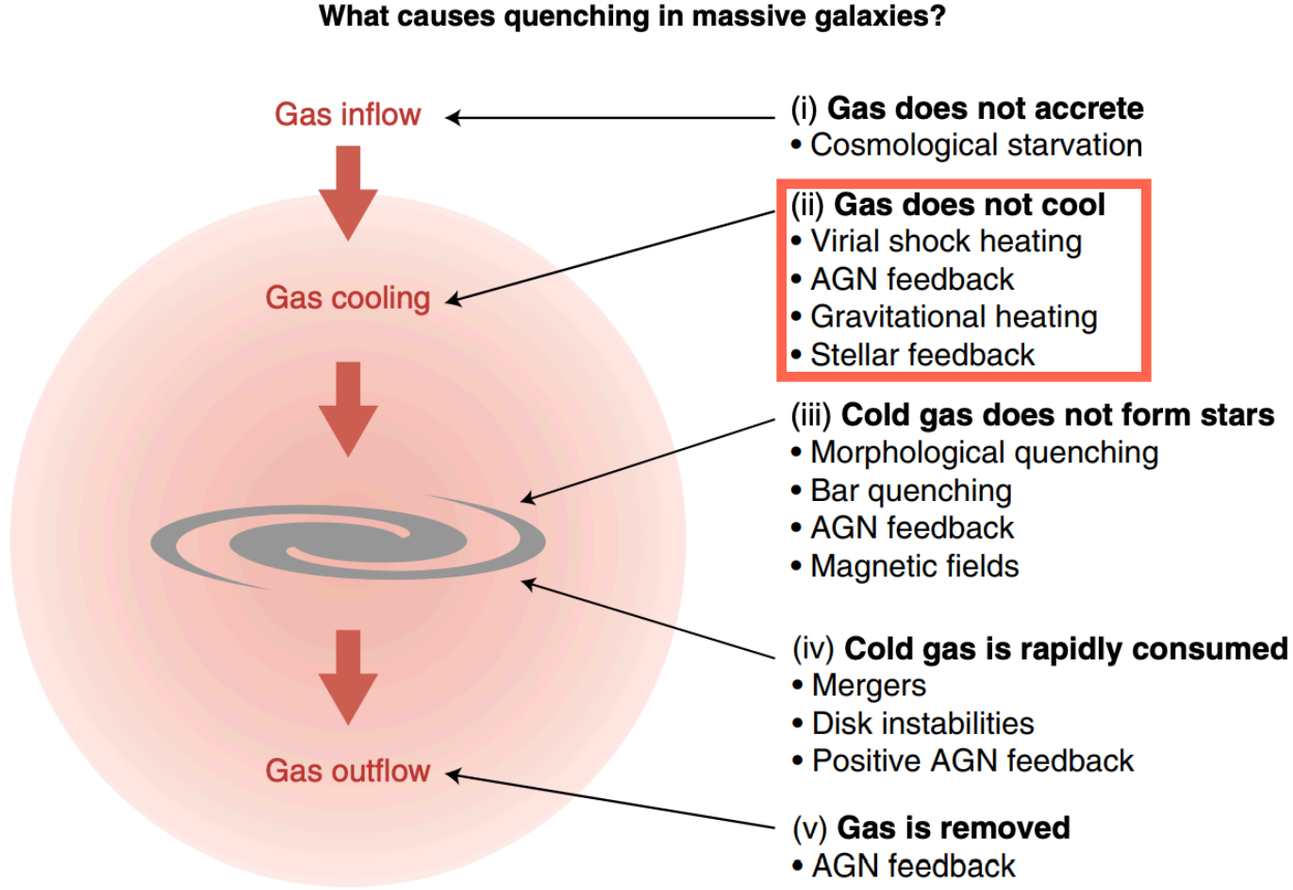
→Our luminosity comes from AGNs and relation is similar to z~3-5



AGN and quenching

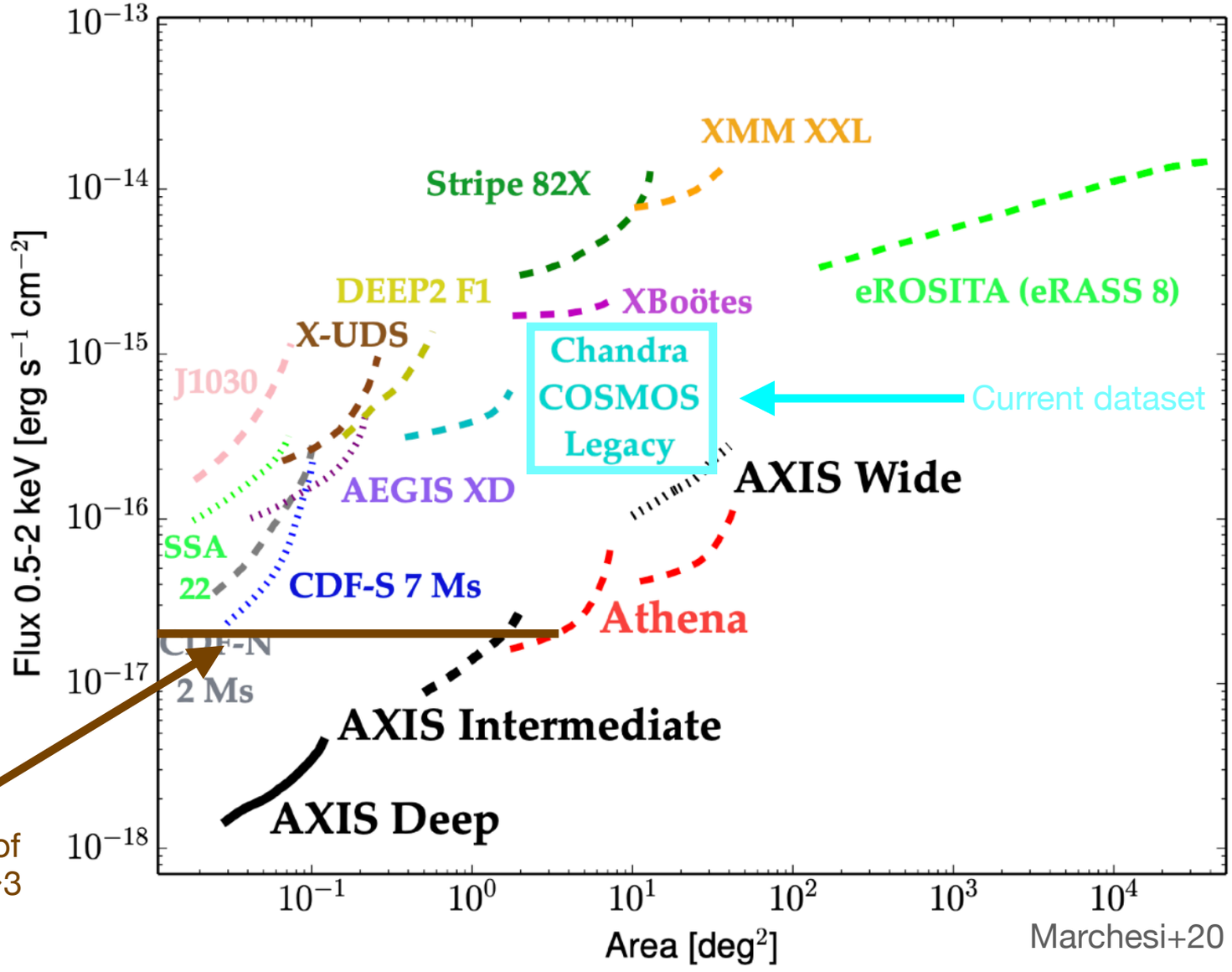
- Quiescent galaxies have low luminosity AGNs ($L_{\rm X} \sim 10^{42}{\rm erg/s}$)
- Quiescent galaxies have higher luminosity than star-forming galaxies
  →**Quenching are likely to be linked to activity of AGNs**

- **How AGNs quench galaxies?**
  - Our quiescent galaxies already have low sSFR
  - Their AGNs is low luminosity
  →"Radio-mode" feedback is occurring?
  …Gas does not cool and AGNs keep sSFR low



Future Prospects

- Upcoming X-ray satellites will detect quiescent galaxies' AGN individually!
  - **AXIS Intermediate** (0.3Ms) : covering ~1deg2
  - **Athena deep** (14Ms) : covering ~4deg2
- They will prove detailed connection between quenching and low-luminosity AGNs
  … distribution of BHAR, connection with sSFR, e.t.c….



Stacked soft band flux of quiescent galaxies at z~3

Summary

- Understanding quenching process through multi-wavelength data-set in COSMOS field

- **Distribution difference among LAEs, star-forming and quiescent galaxies at 2<z<4.5**
  →Quenching is not significantly linked to the environment at high-redshift

- **X-ray and radio stacking analysis for quiescent galaxies at 0<z<5**
  - Utilizing deeper photometry from COSMOS2020
  - Average X-ray/radio signal is detected for z>2 for individually non-detected quiescent galaxies
  - Their X-ray/radio emission are likely from AGNs
  - AGNs activity is higher in quiescent galaxies than in star-forming galaxies at z>1.5

→AGN feedback keeps SFR of quiescent galaxies low at high redshift?