A massive quiescent galaxy and type 2 QSO in a protocluster at z=3.09 in the SSA22 field

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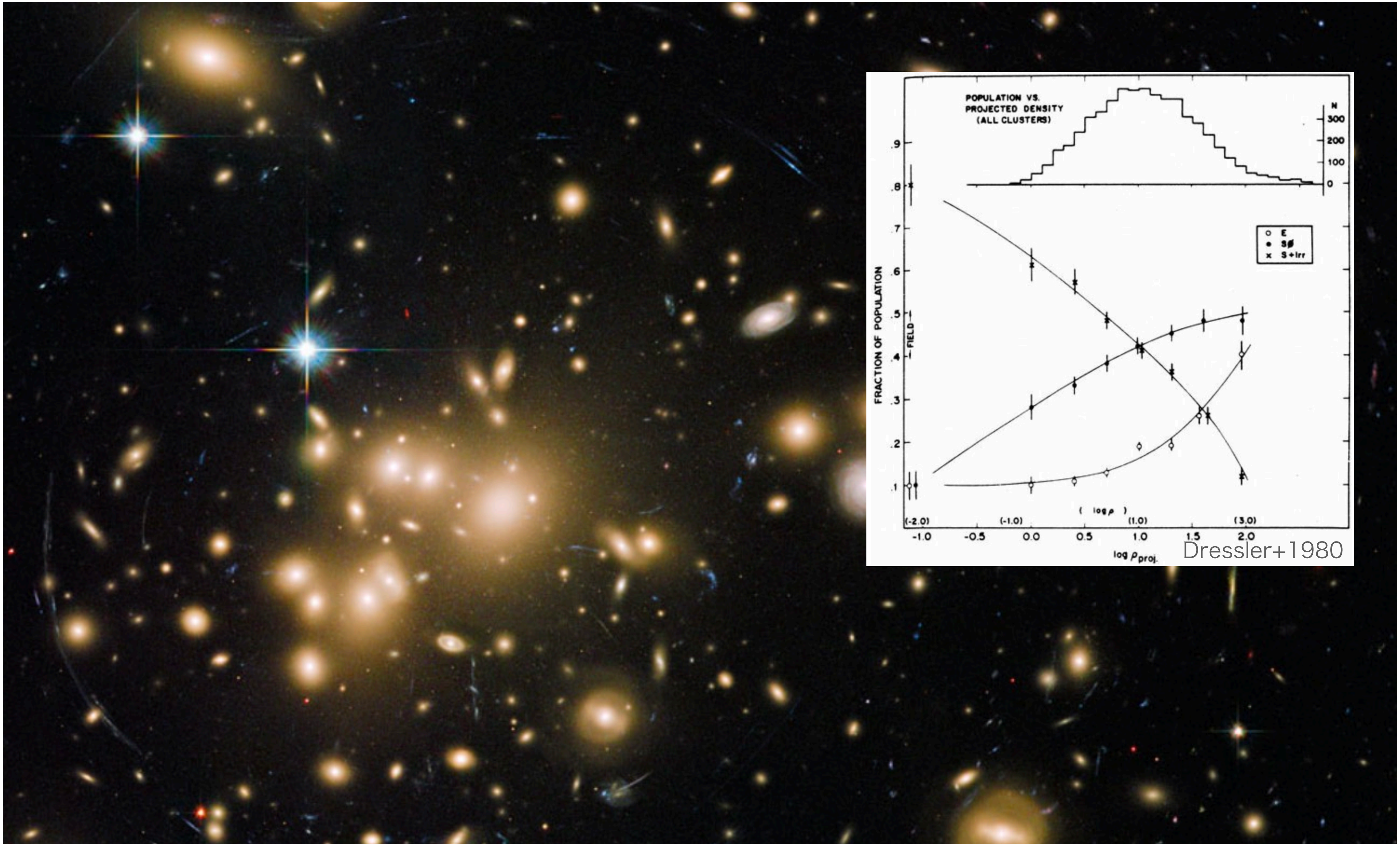
Subaru UM FY2021 1/11-13

INTRODUCTION

Environmental dependence of galaxy formation



NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Blakeslee (NRC Herzberg Astrophysics Program, Dominion Astrophysical Observatory), and H. Ford (JHU)

INTRODUCTION

Environmental dependence of galaxy formation

- ✦ When giant ellipticals appeared in our Universe? "Typical" formation history?(Massive QGs have been discovered at $z \leq 4$ in general fields, e.g., Tanaka+2018, Ito-san's talk)
- ✦ How they have been quenched and maintaining quiescence of star formation at such a high redshift?

➡ **Study massive quiescent galaxies and AGNs (related with quenching?) in protoclusters!**

I. Confirmation of a massive quiescent galaxy（Kubo+2021),
and
II. A detailed study for a type-2 QSO（Kubo+in prep）
in the SSA22 protocluster at z=3.09.

I. Massive quiescent galaxy in the SSA22 protocluster at z=3.09

SSA22 protocluster at z = 3.09

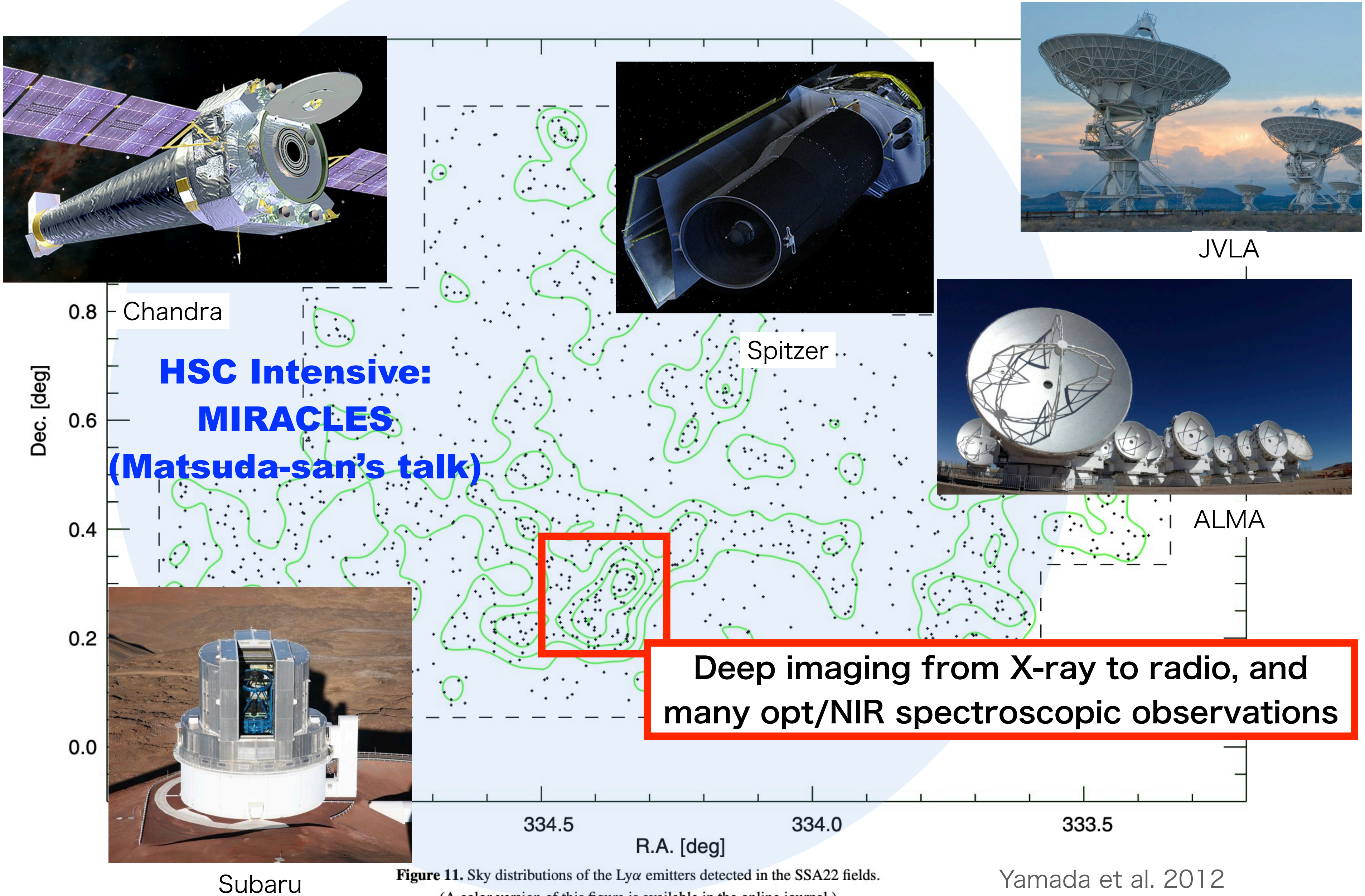
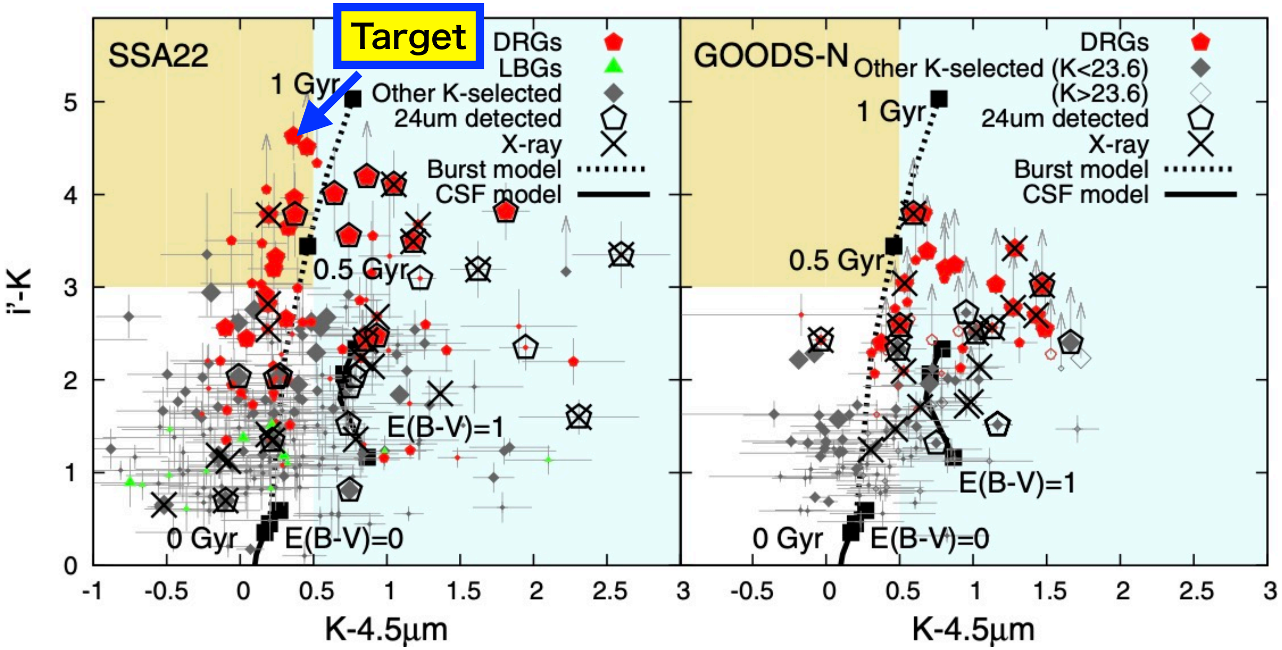


Figure 11. Sky distributions of the Lyα emitters detected in the SSA22 fields. (A color version of this figure is available in the online journal.)

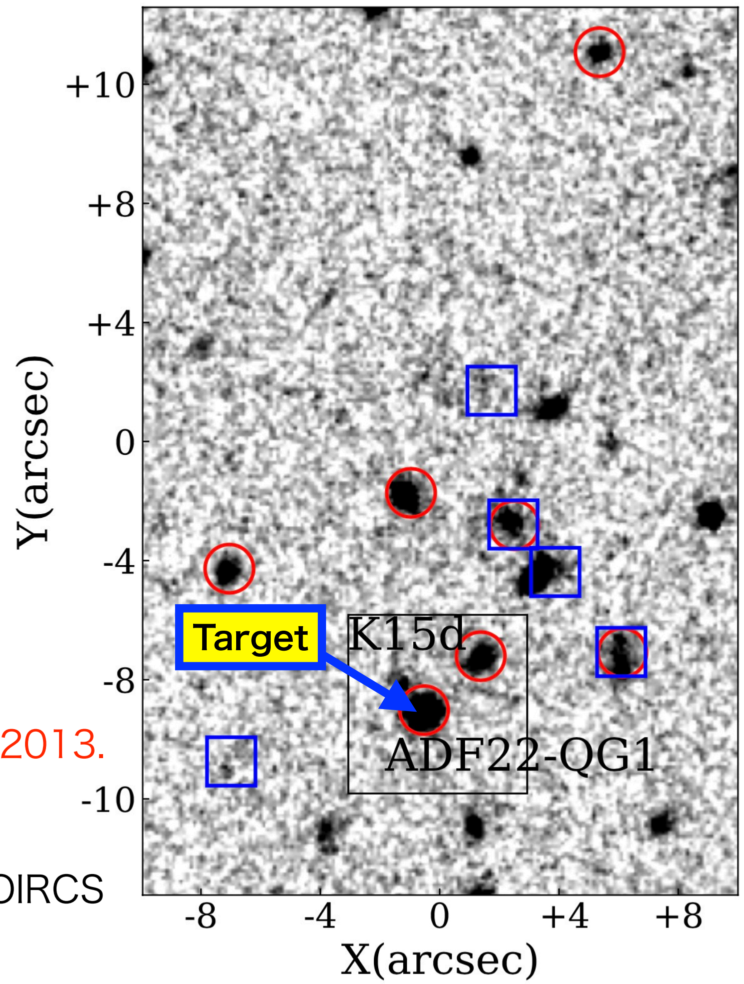
Yamada et al. 2012

I. Massive quiescent galaxy in the SSA22 protocluster at z=3.09

Target



Kubo+2013



- Overdensity of quiescent galaxies at zphot~3.1 is reported in Kubo+2013.
- The target is the brightest ($K_{AB} = 21$) one among them.
- Confirmed at z~3.1 with the 4000 Å break detected with HK500 MOIRCS on Subaru (Kubo+2015).
- Compact: Reff = 1.01 ± 0.04 kpc using IRCS+AO188 (Kubo+2017)
- In an extremely dense group of massive galaxies and SMGs at zspec=3.09 (Kubo+2016; a proto-BCG formed via mergers?)

I. Massive quiescent galaxy in the SSA22 protocluster at z=3.09

Target

Observation

✦u*BVRizJHK+IRAC photometry (described in Kubo+2013)

✦ALMA 1.2 mm (upper limit<75uJy a 3σ; Umehata+2018)

✦MOSFIRE H (2.5 h) and K (6.5 h) spectroscopy

Data analysis

✦ Redshift is $z = 3.0922^{+0.0008}_{-0.0004}$ based on the [O II]$\lambda\lambda$3727,3729 using SLINEFIT

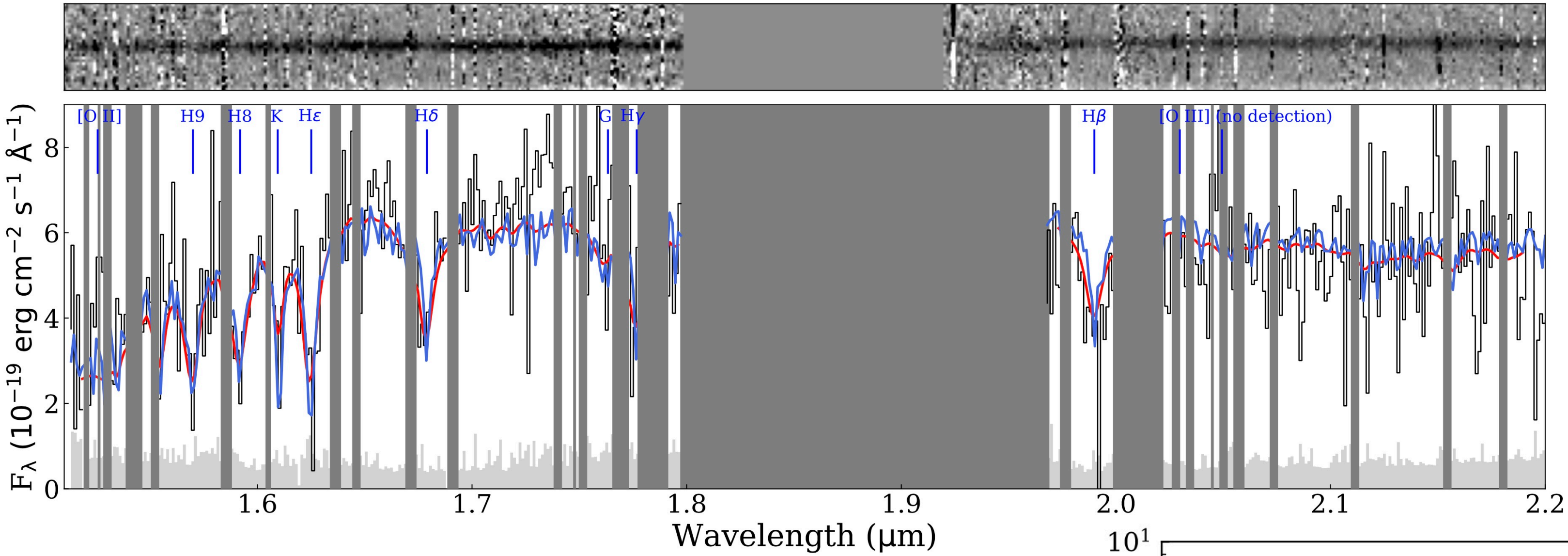
✦ Photometric and spectroscopic SEDs are fitted simultaneously using

· **FAST++ (parametric SFH**; https://github.com/cschreib/fastpp)

· **Prospector (nonparametric SFH**; Leja+2017;2019)

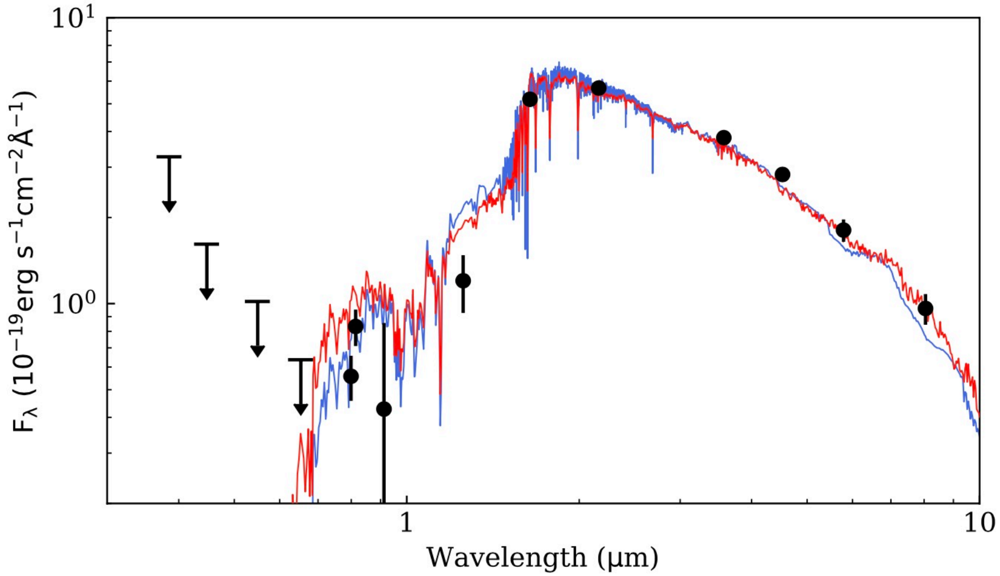
I. Massive quiescent galaxy in the SSA22 protocluster at z=3.09

Result



Red: FAST++

Blue: Prospector

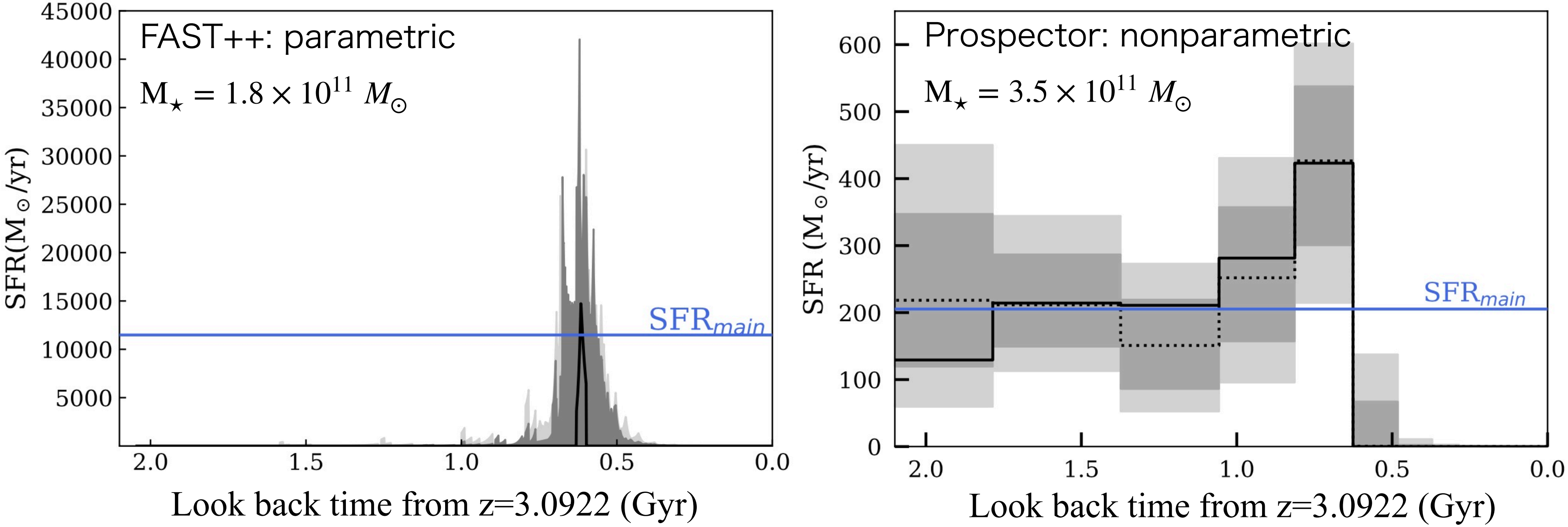


- Significant Balmer break
- Significant Balmer absorption

→Dominated by moderately old stars

I. Massive quiescent galaxy in the SSA22 protocluster at z=3.09

Discussion: SFH



- FAST++ ··· Short starburst and quenching at ~0.6 Gyr ago (Is it realistic to have a peak SFR>1E+4 Msun/yr??). According to SFH, progenitors are SMGs? **This SFH is similar to those of massive quiescent galaxies at z=3-4 in general fields** (e.g., Schreiber+2018; Forrest+2020; Valentino+2020).
- Prospector ··· Continuous modest star formation + starburst and quenching at similar look back time as FAST++. According to SFH, more general SFGs are allowed as their progenitors than that suggested from parametric models.

I. Massive quiescent galaxy in the SSA22 protocluster at z=3.09

Summary

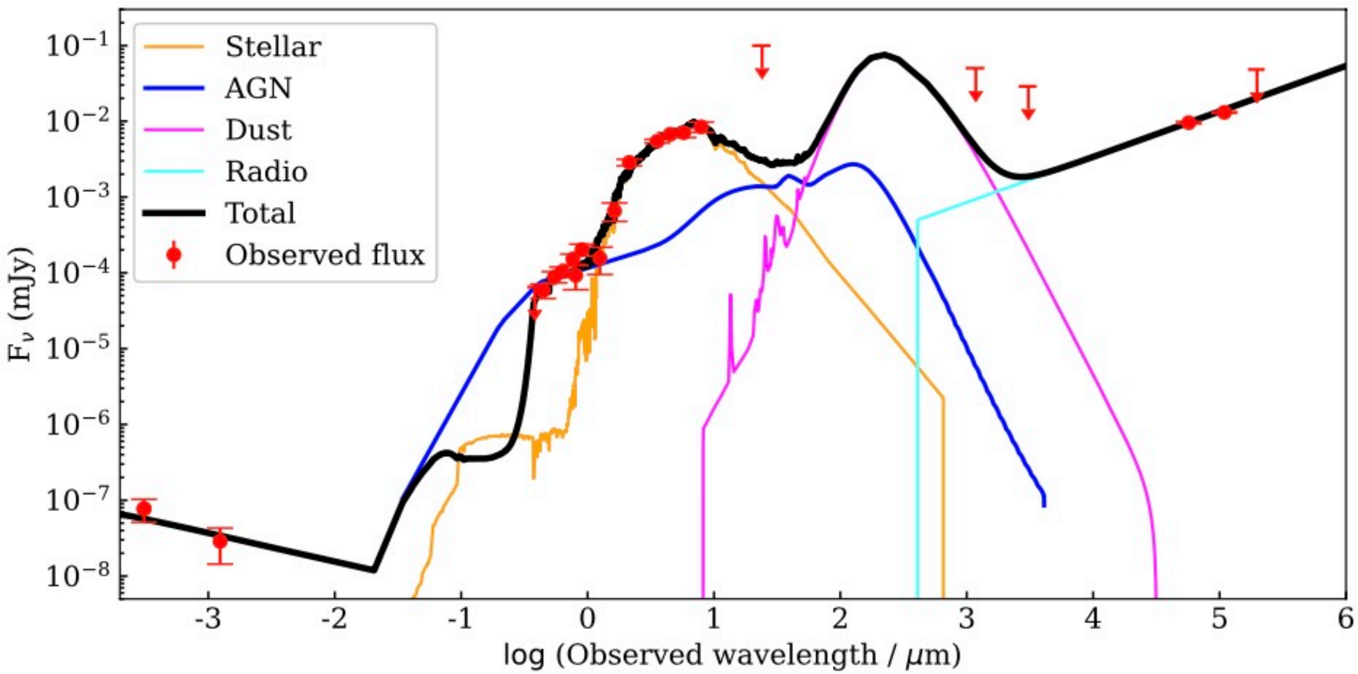
- A massive QG has already appeared in a protocluster at z=3.09 (Recently, QGs in a protocluster at z=3.37 is confirmed spectroscopically in McConachie et al. in arXiV).
- According to the SFH, it is formed via starburst and quenching at ~0.6 Gyr ago.
- SFH is similar to QGs at z=3-4 found in general fields.
- Non parametric modeling may give more realistic SFH than parametric modeling.

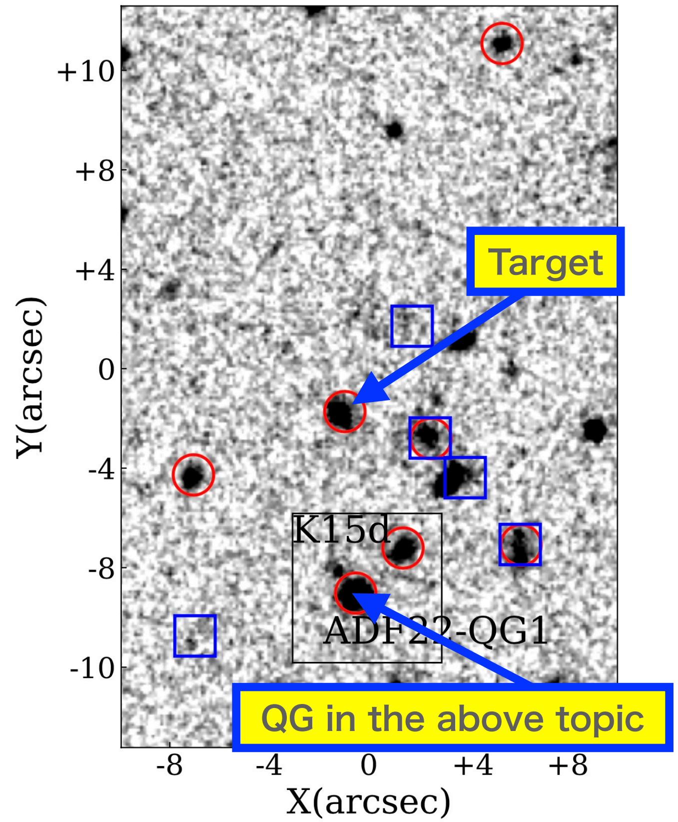
Quenching and maintenance mechanism??

→ Next topic: Type 2 QSO in the SSA22 protocluster

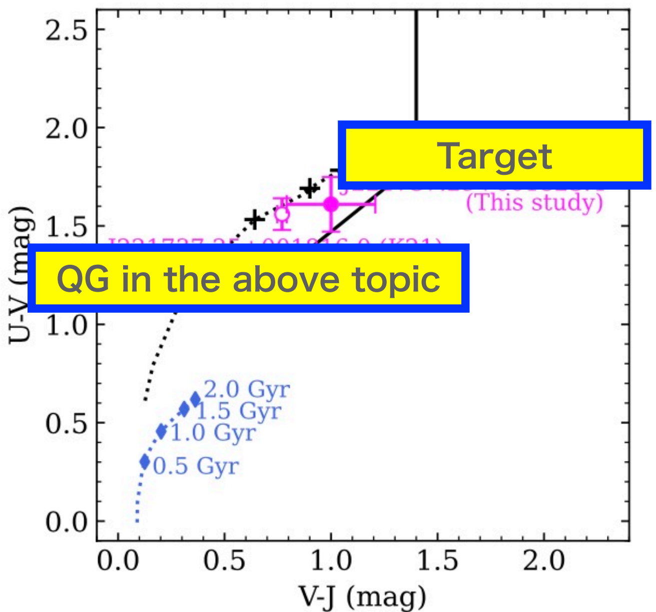
II. A detailed study for an AGN in the SSA22 protocluster at z=3.09

Target



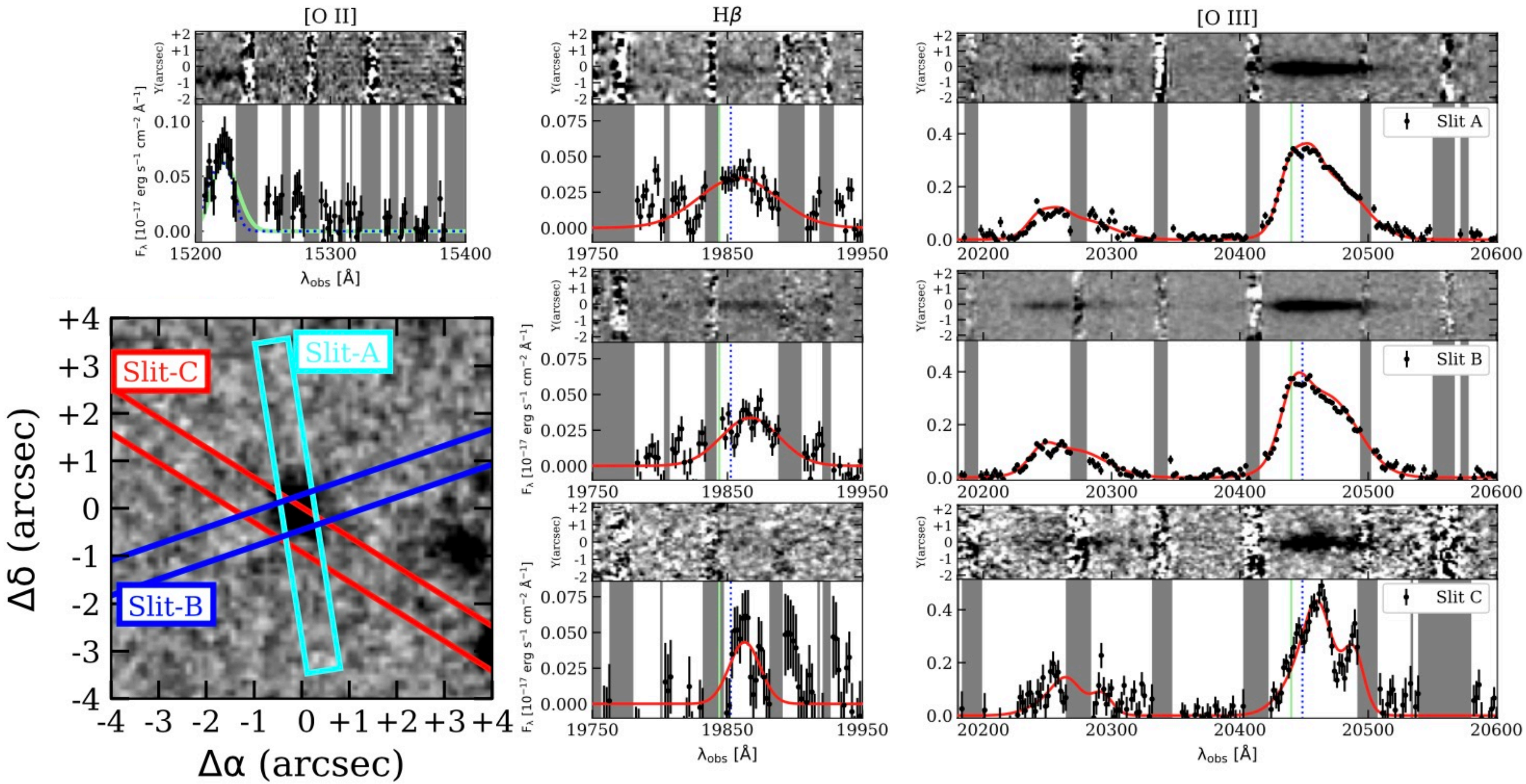


- X-ray AGN with strong [O III] λ λ 4959,5007 at z=3.085 (using MOIRCS; Kubo+2015). Also detected with JVLA 3 and 6 GHz.
- Further spectroscopy with MOSFIRE and SED re-analysis using X-CIGALE (Yang+2020; Top panel).
- Faint in rest-frame UV. SED is dominated by galaxy.
- Hosted in a massive ($M_\star = 0.6 - 1 \times 10^{11}\ M_\odot$) quiescent galaxy (mass weighted age = 0.6-1.8 Gyr)



II. A detailed study for an AGN in the SSA22 protocluster at z=3.09

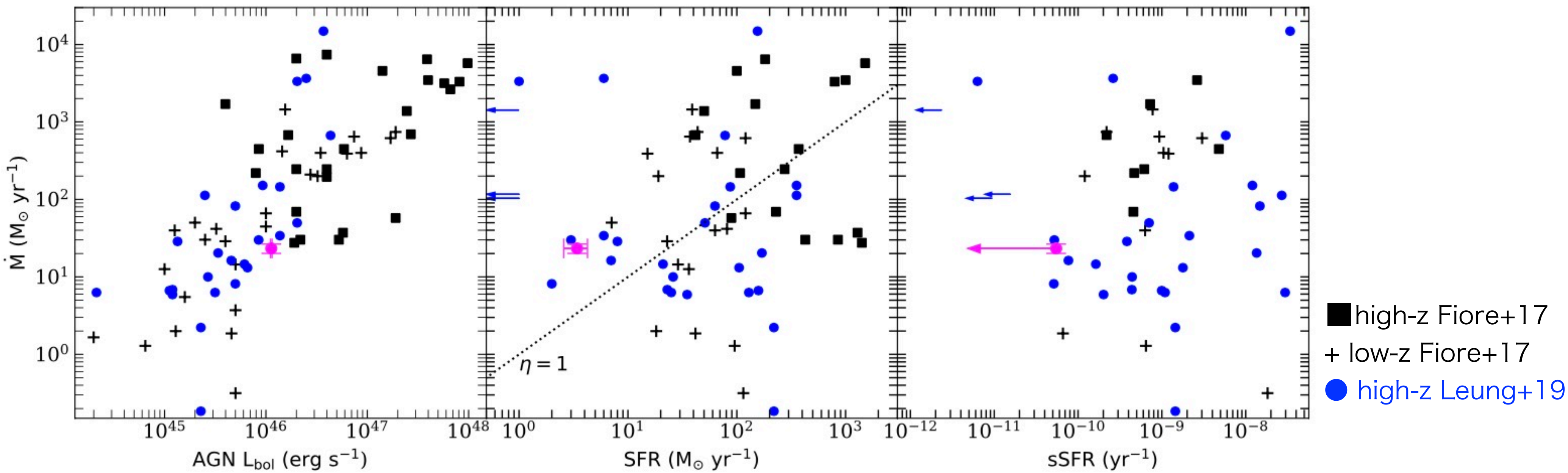
Results: line profiles



- Spectroscopy at three directions using MOIRCS x (1 in K) & MOSFIRE x (2 in K + 1 in H)
- Complex and broad [O III] with W80 =1015-1188 km/s (indicating strong outflows)
- [O III] luminosity of log (L[OIII]/erg/s) = 43.28±0.01. Using the empirical relations, it corresponds to $L_{AGN} \sim 10^{46}$ erg/s ⋯ moderately luminous QSO

II. A detailed study for an AGN in the SSA22 protocluster at z=3.09

Results: Ionized gas mass outflow rate



- Ionized gas mass outflow rate is $23 \pm 3\ M_{\odot}\ \mathrm{yr}^{-1}$ following Fiore+2017;

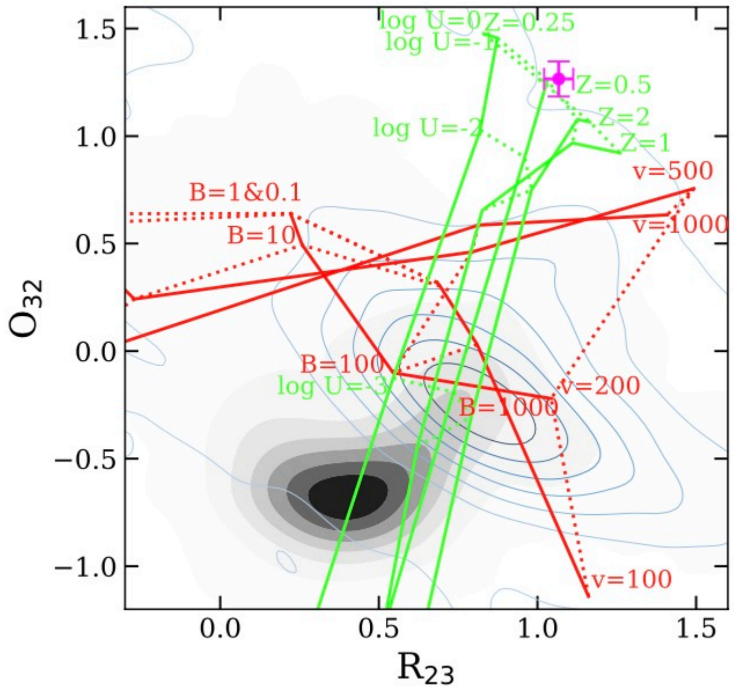
$$M_{\mathrm{H}\beta} = 7.8 \times 10^{8} C \left(\frac{L_{H\beta}}{10^{44}}\right)\left(\frac{\langle n_e \rangle}{10^{3}}\right)^{-1}, \dot{M} = 3 \times v_{max} \times M_{\mathrm{H}\beta}/R$$

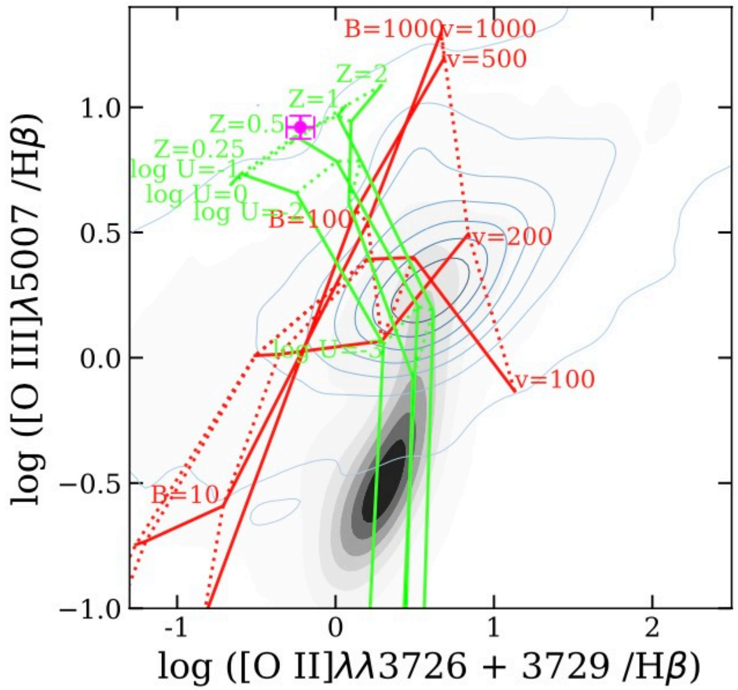
where $n_e = 200\ \mathrm{cm}^{-3}$, $v_{max} = W_{80,corr}/1.3$, & $R = 7.5\mathrm{kpc}$ (spatial extent along slit/2)

- On the same Lbol vs. ionized gas mass outflow rate relation.
- Including our target, several high-z QSOs are hosted by quiescent galaxies.

II. A detailed study for an AGN in the SSA22 protocluster at z=3.09

Results: Line ratio





- Compared with photoionization model (Green: Grove+2004) and shock excitation model (Red: Allen+2008) & SDSS (Black: SFGs, Blue; AGNs selected using BPT diagram)
- Our target is a radio galaxy but not like shock model (not ionized by radio-jets at most).
- Consistent with photoionization model. The central AGN may be the dominant ionizing source.

II. A detailed study for an AGN in the SSA22 protocluster at z=3.09

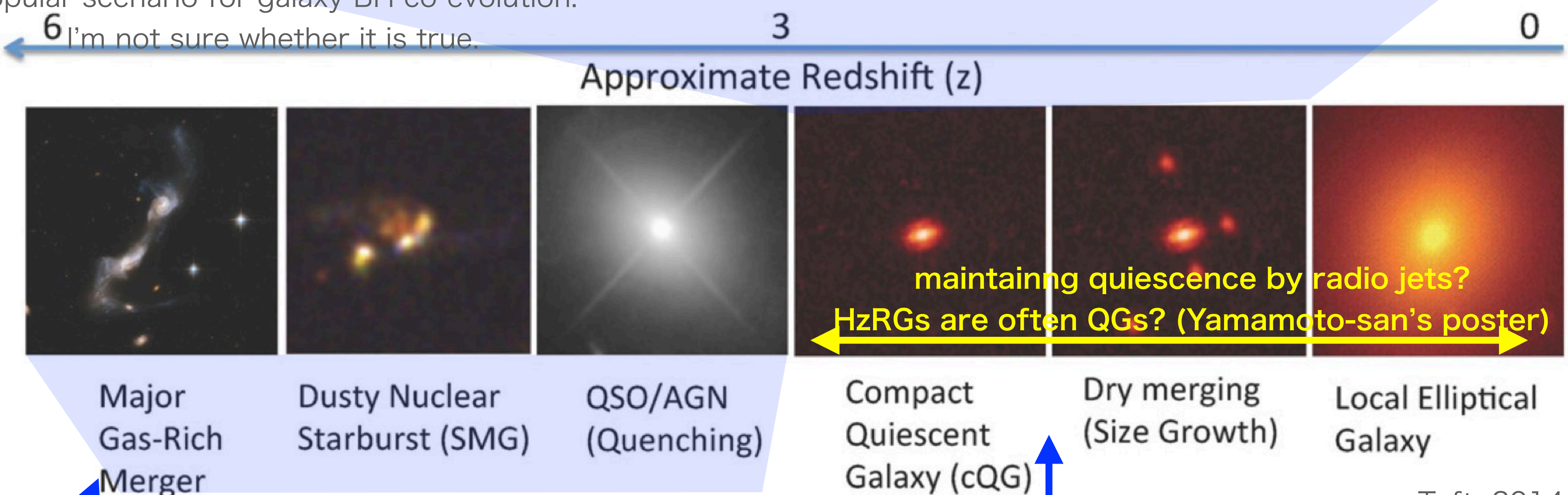
Discussion and summary

- We find a QSO with significant ionized gas outflows hosted by a quiescent galaxy in the SSA22 protocluster at z=3.09.
- According to the SED with a significant 4000 Å break, it may have stopped star formation by several 100 Myr ago.
- According to the line diagnostics, photoionization by the central AGN is likely the dominant ionizing mechanism.
- **This outflow may not quench the star formation. It may work to complete quenching and/or maintain the quiescence.**
- Such delaied QSOs are also reported in the local Universe (e.g., Davies et al. 2007; But our target is 10~100 times more luminous in L_{AGN}). How a QSO is fueled without further star formation? (mass loss from stars poviding gas? hot gas accretion?)

Conclusion (summary of SSA22 pcl)

Photo-z overdensity of QGs and a compact quiescent galaxy in a dense group.
SFH: Formed via starburst and quenching at ~0.6 Gyr ago.
Strong quenching and maintenance mechanisms are needed.

Popular scenario for galaxy-BH co-evolution.
I'm not sure whether it is true.



Toft+2014

AGNs, SMGs, IR luminous AGNs are found (Lehmer+2009; Kubo+2013; Umehata+2019).
But it is not known whether they have significant outflows at this point.

A QSO with strong outflows at several 100 Myrs "after" quenching. This QSO may work to complete and/or maintain quenching.

Merger fraction is not high in rest-frame UV.
Missed mergers at rest-frame UV and/or formed via gas flows through large scale filaments?