ZFOURGE catalogue of AGN candidates: an enhancement of 160-μm-derived star formation rates in active galaxies to z = 3.2

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Abstract

- ZFOURGE — AGN with multiwavelength-selected (radio, X-ray, and infrared)
  - AGN Hosts: 235, z = 0.2–3.2, $\log(M_*/M_{\odot})$ > 9.75,
  - Mass-matched Control samples (non-AGN CSs)

- UVJ diagnostics:
  - AGN hosts: A lower fraction of quiescent galaxies and a higher fraction of dusty galaxies than control samples

- 160 µm Herschel PACS data:
  - sSFR of AGN hosts is 0.34 ± 0.07 dex higher than control samples
  - Infrared-selected have the most obvious offset with about 0.7 dex (a factor of 5)
  - The remaining population, comprised predominantly of X-ray AGN hosts, exhibits only a marginal elevation

Introduction

- Previous works about SMBH and AGN
  - During periods of rapid accretion, the galactic nuclei of these systems release an immense amount of energy into the surrounding environment of the host galaxy.
  - → negative feedback: heating or driving out gas to suppress star formation
  - → positive feedback: AGN outflows trigger star formation by compressing cold dense gas
- Reconciliation: understand the complex interplay between AGN activity and star formation

- Optical spectra to select AGN from large parent samples of galaxies

  → The restriction of low redshifts ($z < 0.3$), miss a key phase of AGN evolution
- X-ray emission (push to high-z):
  - Suggesting only minor or no difference in star formation activity between AGN and non-AGN
  - Miss a key phase when AGN are hosted in dust-rich, X-ray-obscured galaxies

- This paper:
  - A diverse sample of AGN over z = 0.2–3.2
  - Parent sample: ZFOURGE Ks-band imaging
  - Cross-matching the Ks-band imaging with radio, X-ray, and infrared (IR) data sets
  - Gauging star formation activity: Herschel — 160 µm

ZFOURGE and ancillary Data Sets

1. Galaxy catalogues: ZFOURGE (CDFS, COSMOS, UDS)

2. Radio data [Not all of them are AGN, cross-matching results]
    - VLA 1.4 GHz Survey of the Extended Chandra Deep Field South (119)
    - VLA-COSMOS Survey IV Deep Data (116)
    - Subaru/XMM–Newton Deep Field-I 100 μJy catalogue (31)
    - A total of 266 radio counterparts

3. X-Ray Data
    - Chandra Deep Field-South Survey: 4 Ms Source catalogue (X11, 422)
    - Chandra COSMOS Survey (E09, 93)
    - Subaru/XMM–Newton Deep Survey III. X-Ray Data (U08, 77)
    - A total of 592 X-ray counterparts

4 Far-infrared Data
- Spitzer/MIPS and Herschel/PACS FIR imaging

5. Photometric redshifts, rest-frame colours, stellar masses and star formation rates

- Photo-z: EAZY
- Stellar mass: FAST (solar metallicity, Calzetti00 dust extinction law, Chabrier03 IMF and exponentially declining star formation histories)
- SFRs: UV+IR $\Psi_{\rm IR+UV}\,[{\rm M_\odot\ yr^{-1}}] = 1.09 \times 10^{-10}(3.3L_{\rm UV} + L_{\rm IR})$,

■ 'pure' galaxy templates in SED fits, not using power-law template

6. Reliability of AGN photometric redshifts

- 3D-HST + ZFIRE

$$\sigma_{\rm NMAD} = 1.48 \times {\rm median}\left(\frac{|\Delta z - {\rm median}(\Delta z)|}{1 + z_{\rm spec}}\right),$$

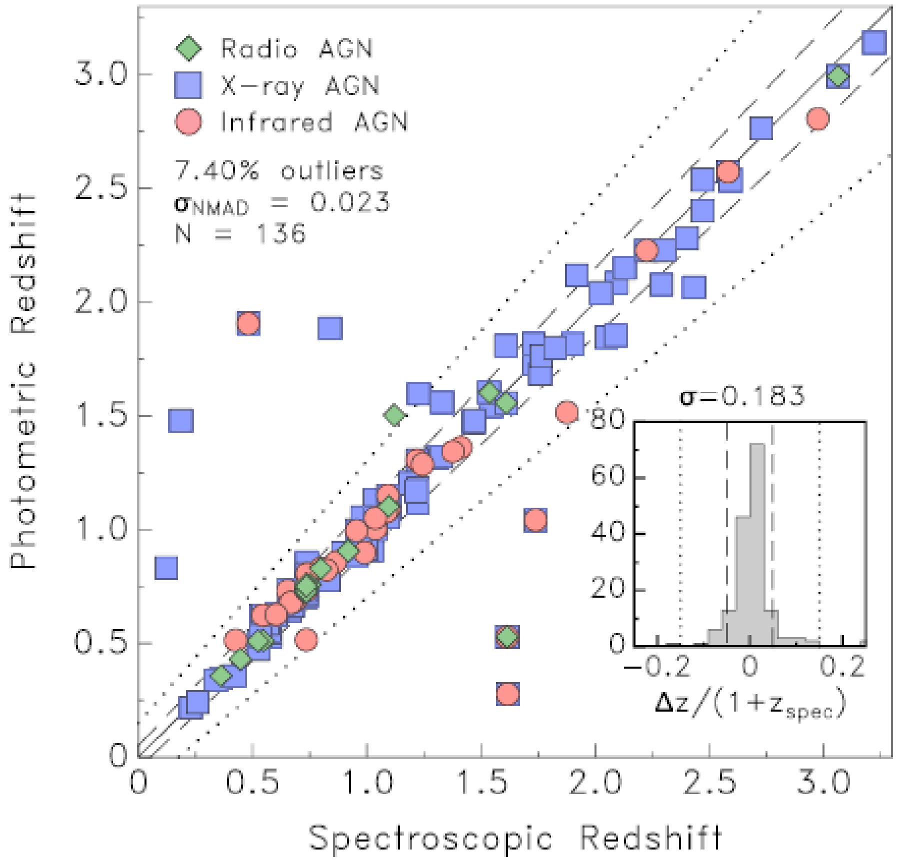
- 136 cross-matches with Zspec,

  $\sigma_{\rm NMAD} = 0.023$ (0.018 for all ZFOURGE objects)

- Type-2 AGN: negligible contamination to host
- Type-1 AGN: impact SED fits,

  compare with SWIRE type-1 QSO template (UVJ color ±0.5 mag)

  low error in photometric redshift



Multiwavelength AGN selection

- Minimize the selection bias of AGN from multiwavelength data

1. Radio-AGN selection
   - Relativistic jets that propagate perpendicular to the plane of the accretion disc of SMBH
   - Radio-AGN ⟷ Inactive, star-forming galaxies (how to distinguish)
   - Radio-AGN Activity Index of Rees et al. (2015):

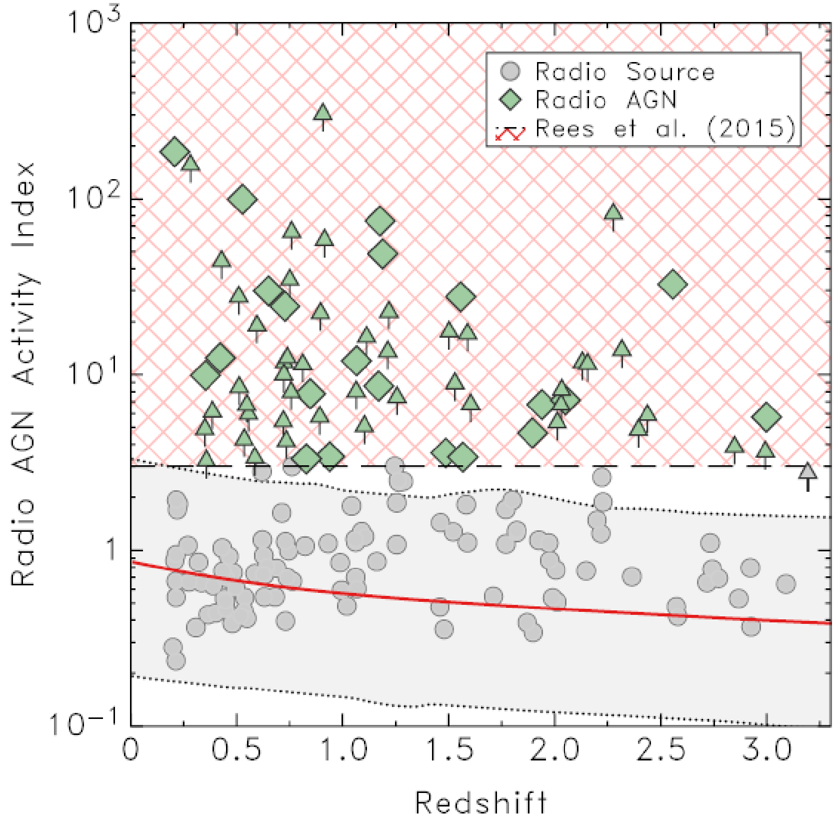
$$\mathrm{SFR_{RADIO}/SFR_{IR+UV}} = \text{Radio-AGN Activity Index} > 3.$$

   - Radio-SFR:

$$L_{\mathrm{RADIO}}\,[\mathrm{W\ Hz^{-1}}] = 4\pi d_l^2 (1+z)^{-(\alpha+1)} f_{\mathrm{RADIO}}, \qquad \alpha = -0.3$$

$$\Psi_{\mathrm{RADIO}}\,[\mathrm{M_{\odot}\ yr^{-1}}] = 3.18 \times 10^{-22} L_{\mathrm{RADIO}}.$$

   - 67 radio-AGN (CDFS: 20 + COSMOS: 32 + UDS: 15)



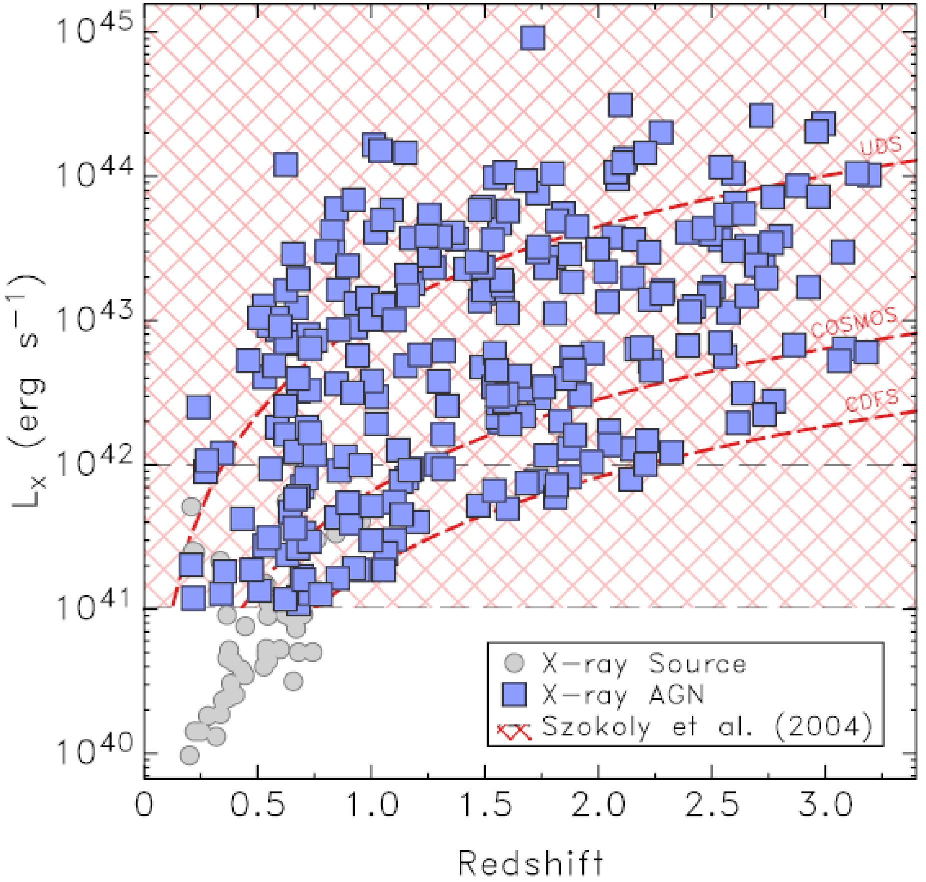
2. X-ray AGN selection

- X-ray emission from sources at high Galactic latitudes are predominantly AGN and outshine the highest star-forming galaxies
- Distinguish the dusty system:

  hardness ratio (HR): (hard − soft)/(hard + soft) → dusty system appear harder spectrum (larger HR)
- X-ray luminosity: (0.5 — 8 keV,)

  $L_X[\mathrm{erg\ s^{-1}}] = 4\pi d_l^2 (1+z)^{\Gamma-2} f_x, \quad \Gamma = 1.4$
- X-ray AGN: $L_X \geq 10^{41}\ \mathrm{erg\ s^{-1}}$ and $\mathrm{HR} > -0.2$

  $L_X \geq 10^{42}\ \mathrm{erg\ s^{-1}}$ and $\mathrm{HR} \leq -0.2.$
- 270 X-ray AGN (CDFS: 187 + COSMOS: 57 + UDS: 26)

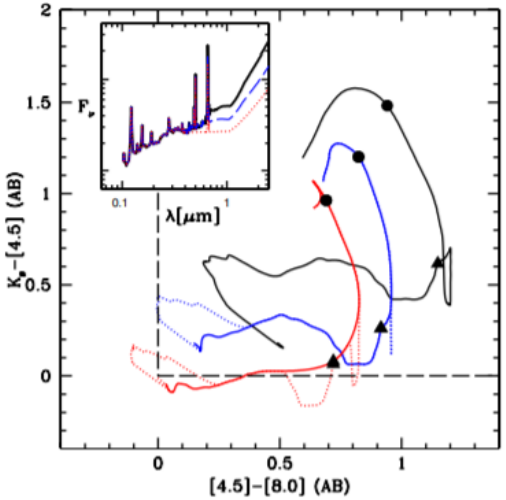


3. Infrared-AGN selection

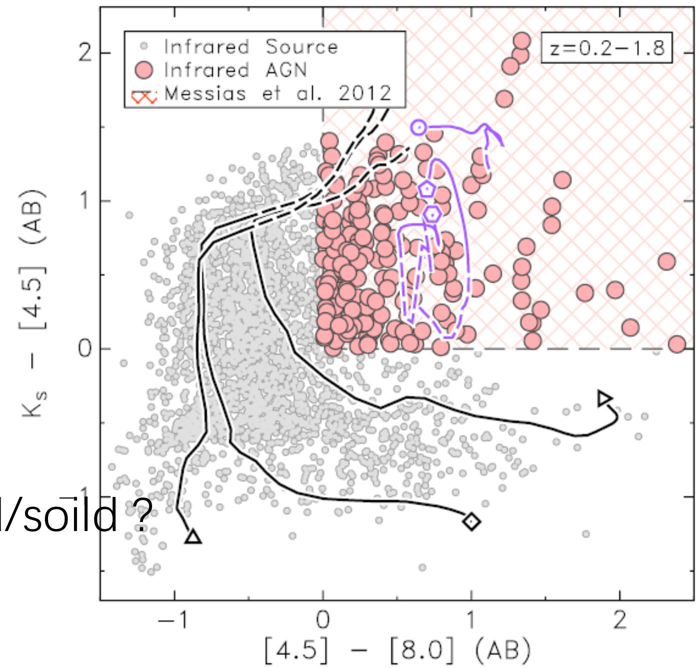
- X-ray detection can still miss heavily obscured AGN
- IR observations: dust radiating the reprocessed nuclear emission in the mid-IR regime
- For AGN: domination of thermal continuum in MIR
- Only with IRAC bands is not able to identify AGN at z > 2.5 because of the similar shape of rest-frame 1.6μm bump of galaxies
- IRAC + Additional wavebands (IRAC + Ks, IRAC + 24μm) from Messias et al. (2012)

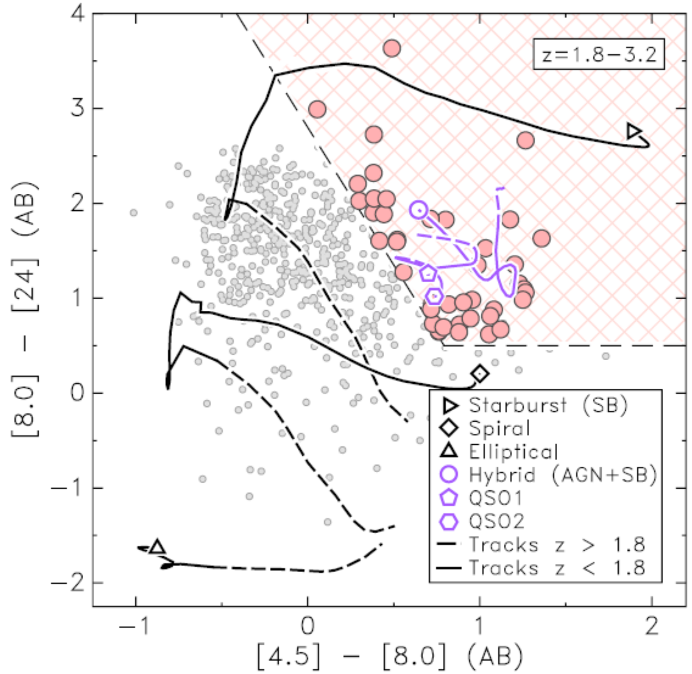
$$z < 1.8 \begin{cases} K_s - [4.5] > 0 \\ [4.5] - [8.0] > 0 \end{cases} \qquad z > 1.8 \begin{cases} [8.0] - [24] > 2.9 \times ([4.5] - [8.0]) + 2.8 \\ [8.0] - [24] > 0.5 \end{cases}$$

- 234 Infrared-AGN
  (CDFS: 66 COSMOS: 50 UDS: 118)



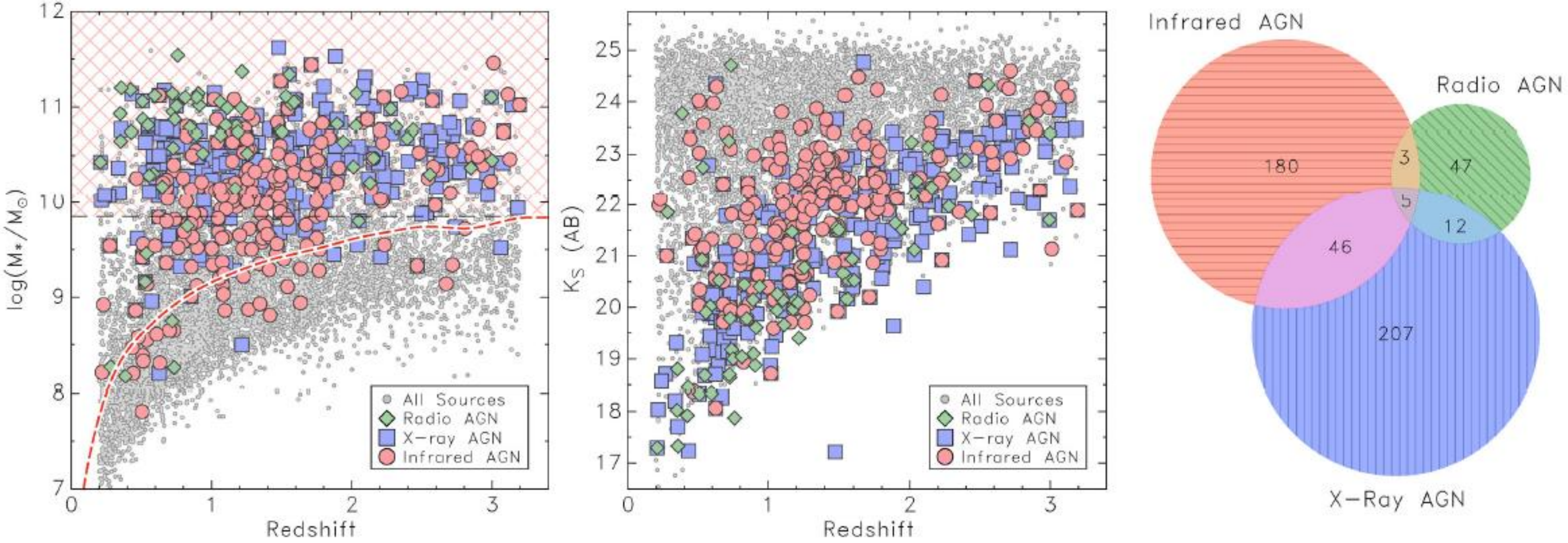
Messias et al. (2012)
Circle: z = 1
Triangle: z = 3
Fig 4 annotation: dashed/soild ?
curve: SWIRE templates





4. Summary of AGN samples

- The overlap between radio and X-ray AGN hosts is low, while the overlap between IR and X-ray AGN hosts is significantly large (similar to former studies)



Mass-Limited Sample

- Control sample, based on redshift, stellar mass and luminosity limits (UDS excluded)

1. Redshift, mass, and luminosity cuts
   - Mass cut: $\log(M_*/M_\odot) > 9.75$
   - 3 redshift bins: z = [0.2, 0.8], [0.8, 1.8], [1.8, 3.2]

2. Control sample of inactive galaxies
   - Mass-matched control sample of inactive galaxies $\Delta M_* = 0.2$ dex

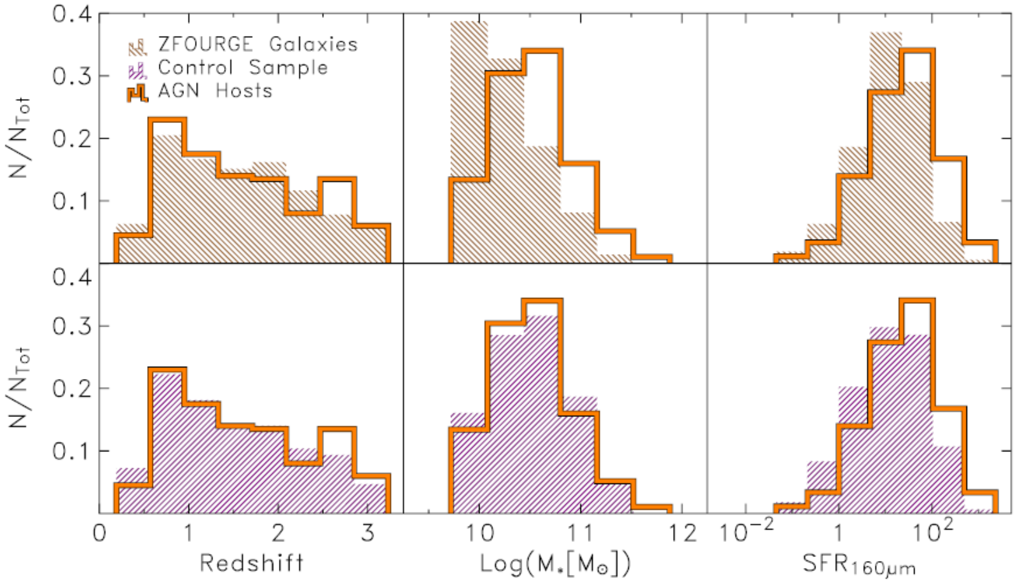


Table 1. Luminosity limits of mass-limited AGN sample.

Waveband	$L_{1.4GHz}$ (W Hz^{-1})	L_X (erg s^{-1})	L_{IR}^a	z_{min}	z_{max}	N_{AGN}^b
Radio	1.0×10^{23}	–	–	0.2	0.8	10
	6.0×10^{23}	–	–	0.8	1.8	11
	1.9×10^{24}	–	–	1.8	3.2	5
X-ray	–	4.0×10^{41}	–	0.2	0.8	31
	–	2.0×10^{42}	–	0.8	1.8	60
	–	7.0×10^{42}	–	1.8	3.2	50
Infrared	–	–	6.0×10^{27}	0.2	0.8	7
	–	–	3.0×10^{28}	0.8	1.8	39
	–	–	1.0×10^{27}	1.8	3.2	22

Notes. [a] $L_{IR} = L_{8\mu m}$ at $z = 0.2$–1.8 and $L_{24\mu m}$ at $z = 1.8$–3.2.
[b] Number of AGN hosts within the specified limits.

Results

1. Comparison of Rest-frame Colors

UVJ-diagrams

- CS: grey-scale density, open marks
- Low-z

IR AGN: exclusively in star-forming

radio AGN: in quiescent galaxies

X-ray AGN: in both (29% QGs)

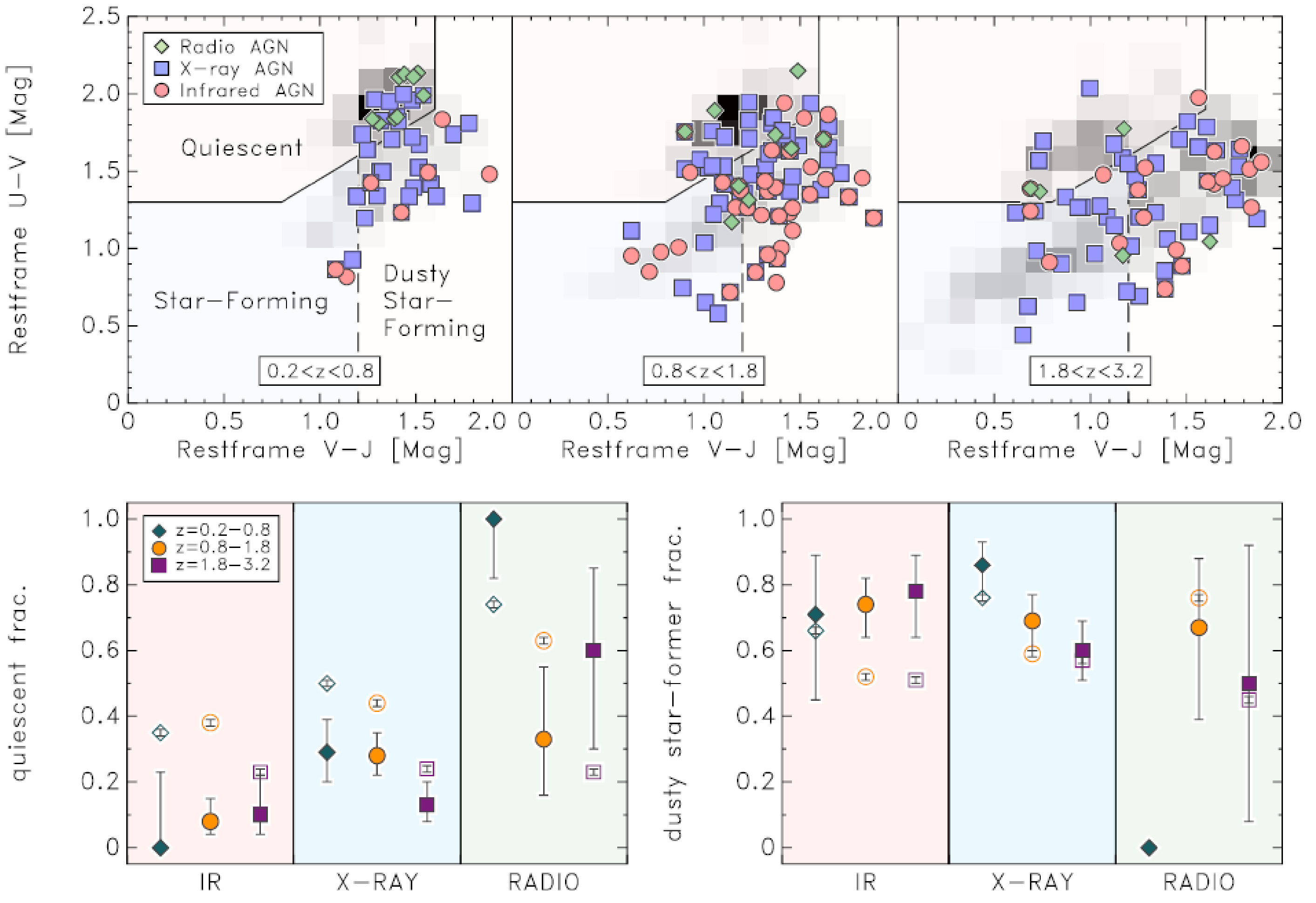
- High-z

The trend above weakens

All AGN are predominantly in star-forming region

- AGN and non-AGN

Over all redshifts, the dusty fraction is found to be slightly elevated over the control samples, while the quiescent fraction is lower.

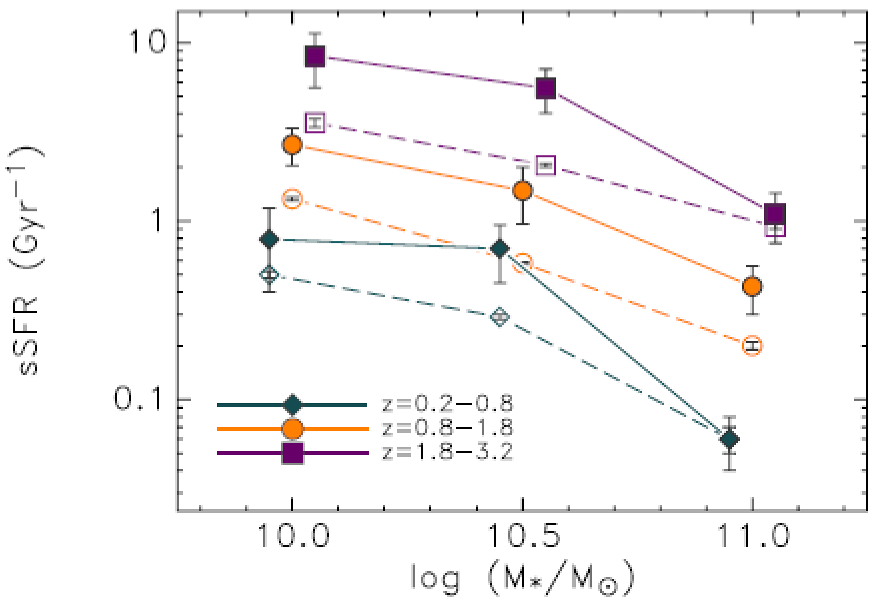


2. Comparison of star formation activity

sSFR: the relative strength of star formation activity

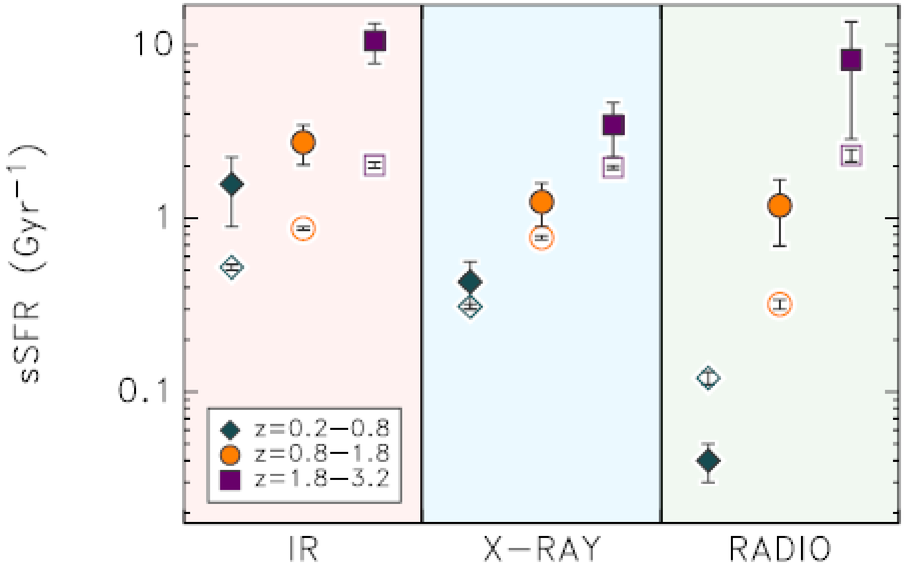
Split with stellar mass:

- Decrease with increasing stellar mass
- With the exception of the highest mass bins at low and high redshifts, AGN hosts show an elevated level of star formation activity with respect to the control sample.



Split with detection technique:

- With the exception of low-redshift radio AGN, all AGN hosts show an elevated level of star formation activity, at all redshifts, with respect to their control sample.



3. AGN contamination

■ ‘pure’ galaxy templates in SED fits, not using power-law template

SFRs (UV + IR luminosities):

- Check the impact to the UV by removing the UV contribution to the SFRs of the AGN sample
  Negligible impact (offsets increase 0.01 dex)
- The FIR regime is thought to be mostly immune to the effects of AGN

Stellar mass:

- Type-I AGN can lead to an overestimation in mass by as much as 150 percent
- Type-II AGN can overestimate ~ 50 percent (dominate in this study) (Ciesla et al. 2015)

→ Reduce mass by 150 percent overestimation and reselect control sample

- sSFR elevation 0.34±0.07 dex → 0.25±0.07 dex

Discussion

- Conflicting results in AGN hosts and inactive galaxies:

  Early studies (Low-z, low sample sizes, no control samples) → Suppression of star-forming

  Recent studies → star formation activity is more similar or elevated over inactive galaxies

  - **This work supports the latter**
- Elevation of star-forming is almost existing, except **low redshift, radio AGN**

  low redshift, radio AGN

  - Hosted by quenched galaxies, similar to the early perception of AGN
- The elevation of X-ray AGN is small
  - Similar to Bongiorno et al. (2013) and Mullaney et al. (2015), which present the identity of AGN and non-AGN
  - Slight elevation in this study can possibly be explained away by the different approach and selection effects
- IR-AGN hosts have an elevation of a factor of 5
  - Strong link between IR-AGN and its host

- UVJ diagnostics at **low redshifts** → hosts have different stellar properties
  - Consistent with former studies of multiwavelength AGN
  - Evolutionary sequence: dusty IR AGN → unobscured X-ray AGN → early-type galaxy with radio AGN
- This trend weakens at z > 0.8 → AGN are resided in star-forming galaxies
  - Support Rees et al. (2015) who find the majority of radio AGN at z > 1.5 are hosted by star-forming galaxies
- UVJ diagnostics shows that IR AGN is the most dusty
  - Support the evolutionary sequence, large amounts of gas and dust can fuel both a period of high star formation and AGN.
- Explanation of enhanced SFR
  - Major Merger scenario
  - Positive feedback from AGN
    (gravitationally collapsed cold gas from Accretion disk winds or Jets)
- No direct evidence ANG contributes to suppression.
- AGN quenching ???