The deep and high resolution imaging of an extremely dense group of galaxies at the core of the SSA22 protocluster at z=3.09 by using Subaru IRCS with AO188

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Mariko Kubo (ICRR)
Toru Yamada(ISAS, JAXA), Takashi Ishikawa (Tohoku Univ), M. Kajisawa (Ehime Univ), Y. Matsuda , I. Tanaka (NAOJ), H. Umehata (IOA, ESO)

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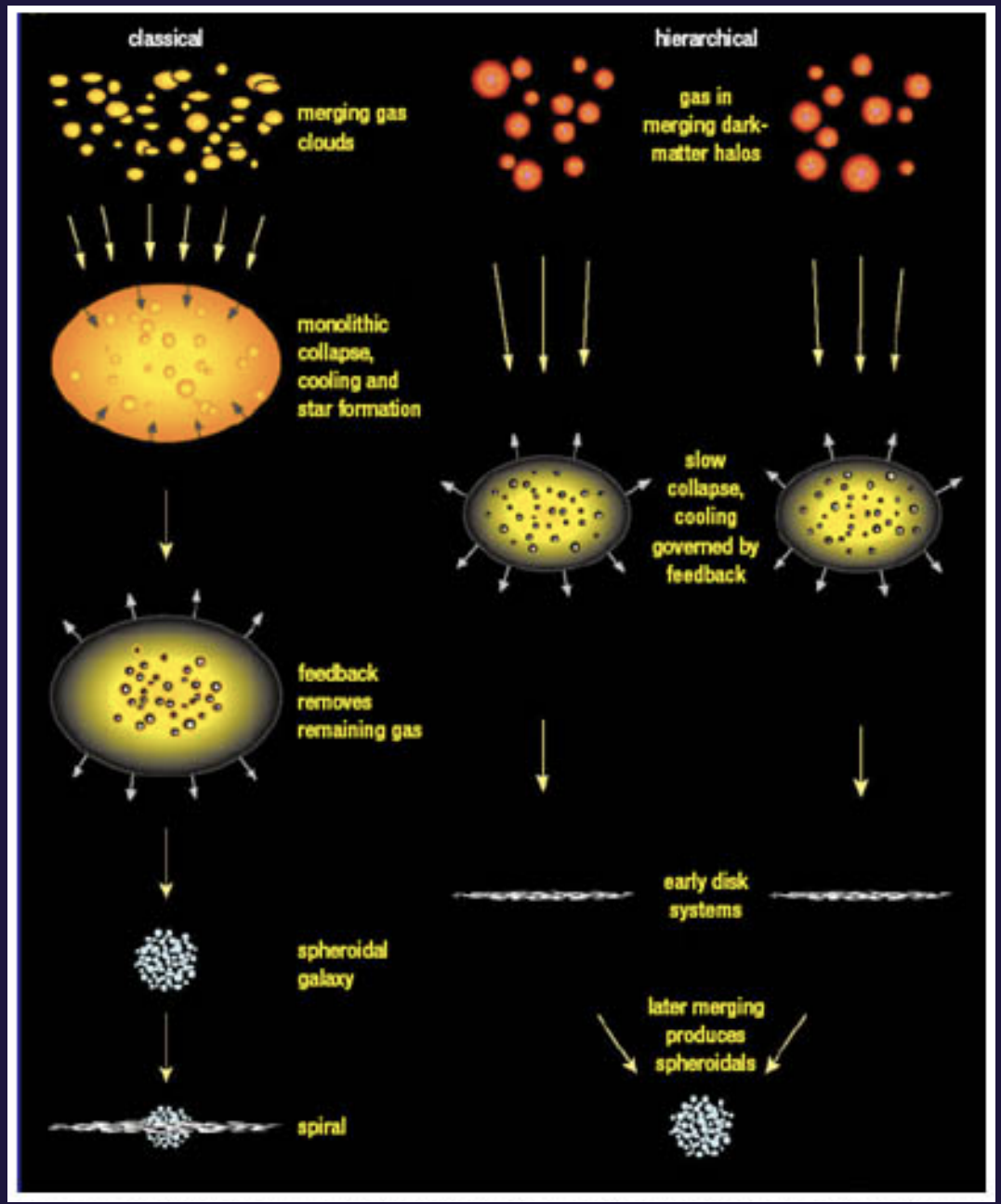
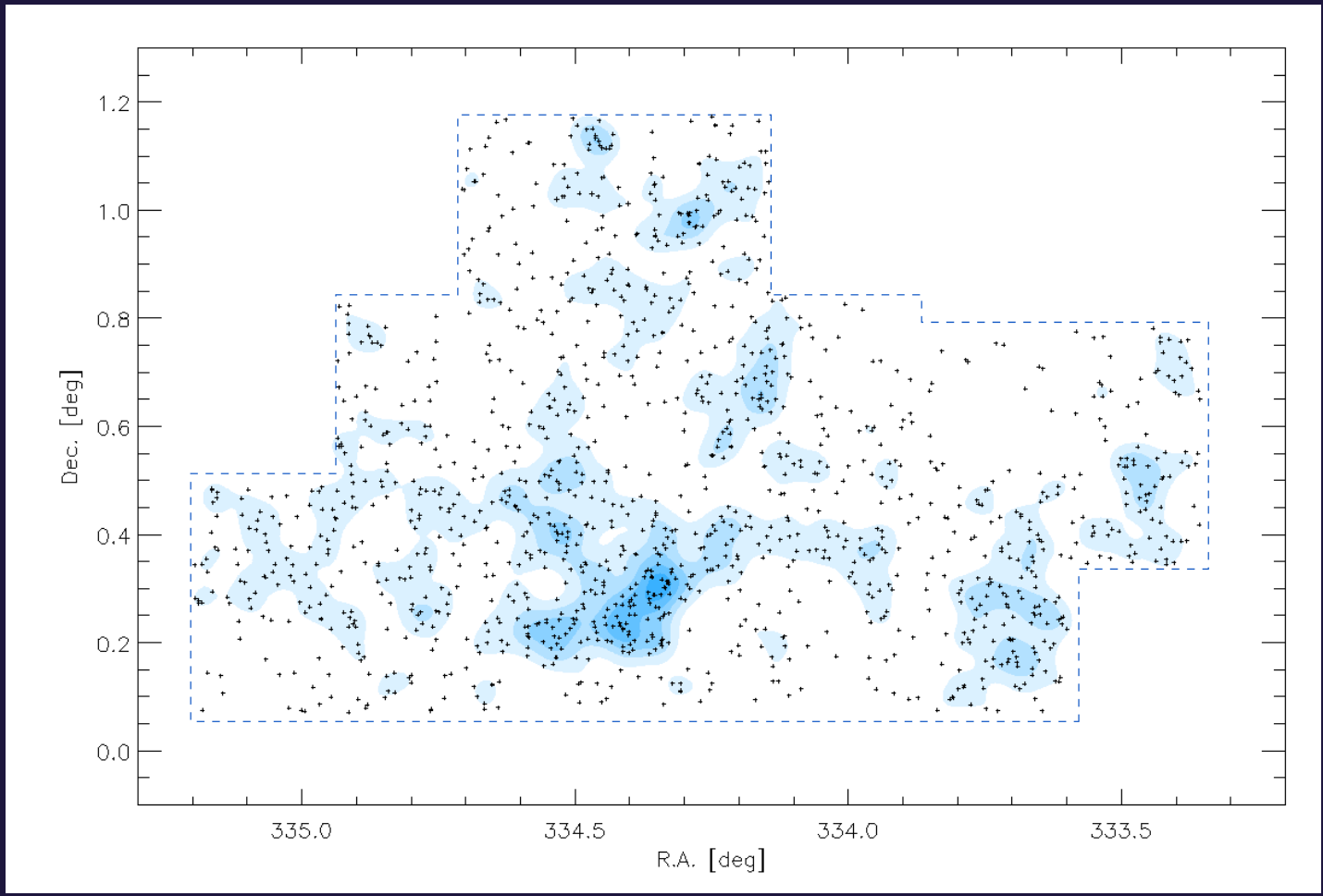
1.1 Formation of Massive elliptical galaxies



- Monolithic collapse, major mergers
- Cosmological numerical simulations in the ΛCDM Universe … hierarchical multiple mergers
- Two-phase formation (e.g., Oser+10) … in situ rapid formation of massive compact spheroids at z>2 ->growing by many mergers

Ellis+2000

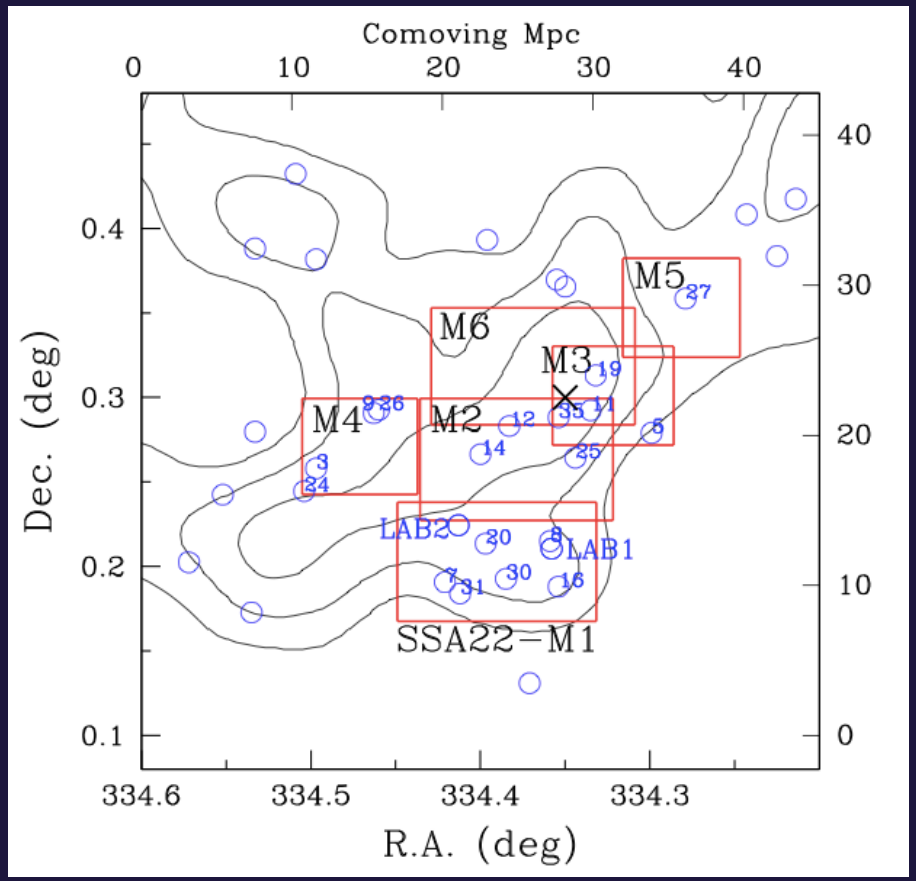
1.2 Discovery of an extreme dense group of galaxies at the centre of the SSA22 protocluster



LAEs at z=3.09(Yamada+12)

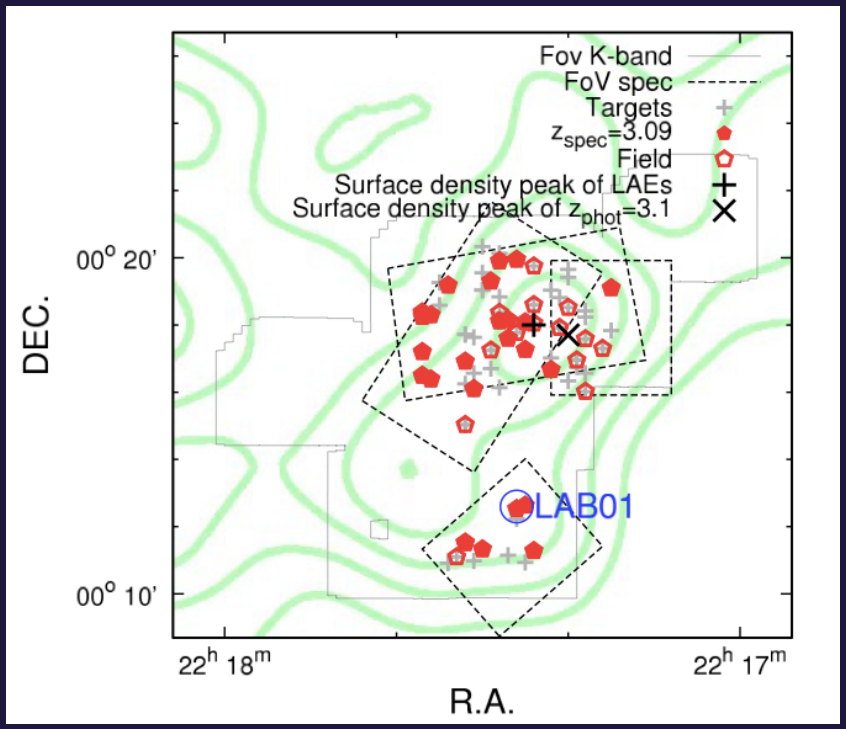
The SSA22 protocluster at z=3.09

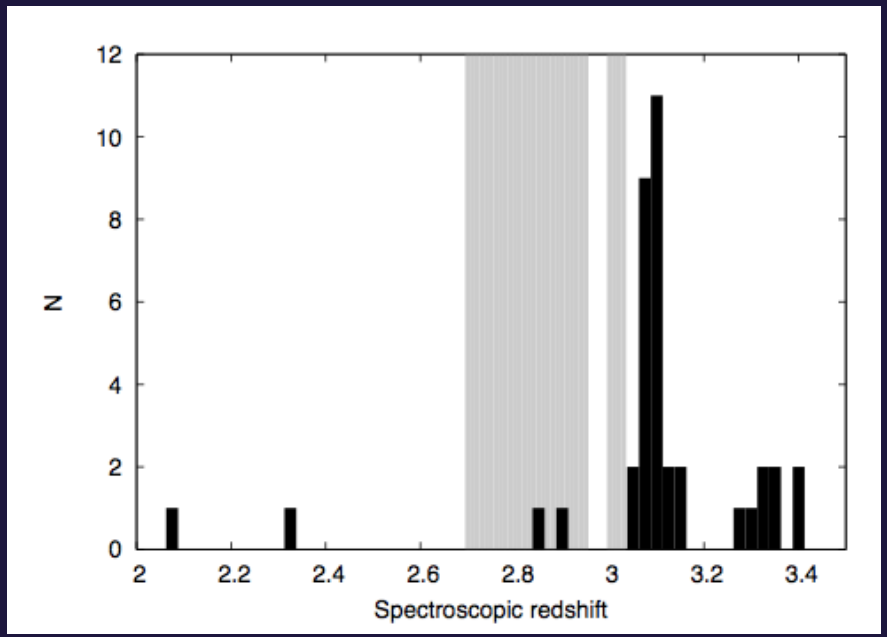
=very plausible progenitor of one of the most massive clusters



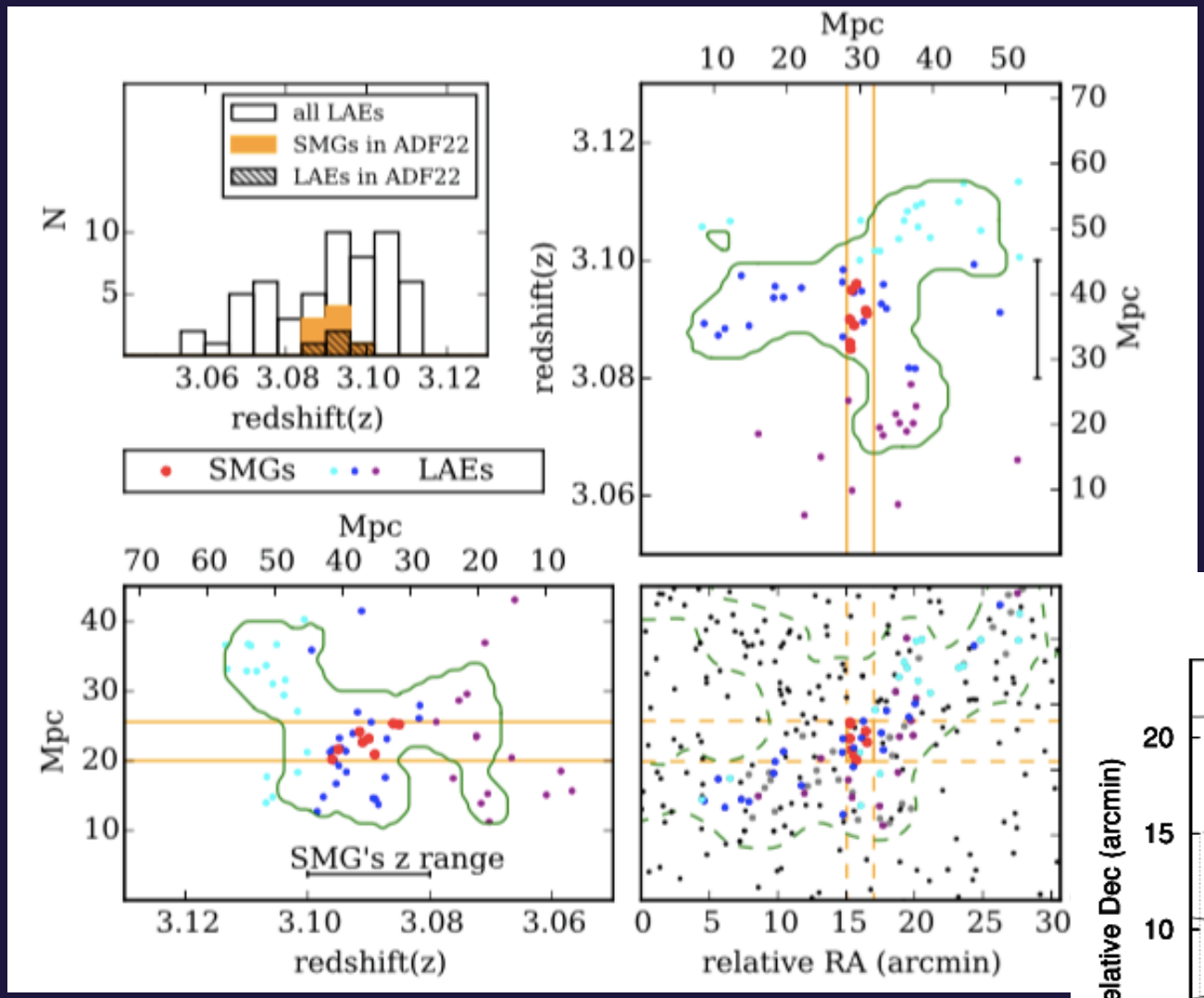
Uchimoto+12

MOIRCS deep imaging (KAB=24 at 5σ) and spectroscopic observations (Uchimoto+08,12, Kubo+13,15,16):
-> Overdensities of QGs, DRGs and K-band selected massive galaxies.

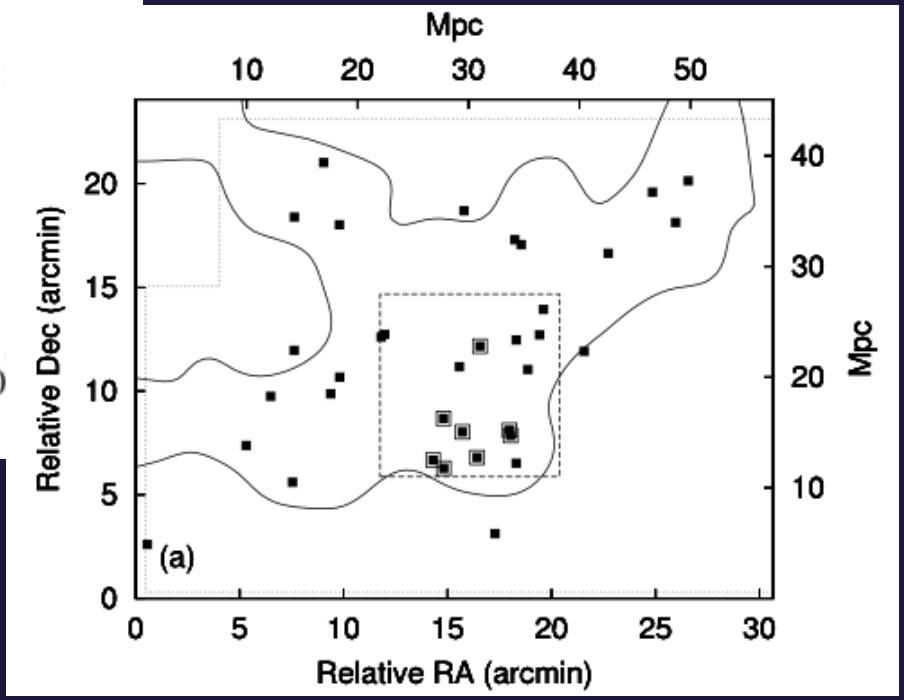




Kubo+15



SMGs in the SSA22 protocluster (Umehata+16)



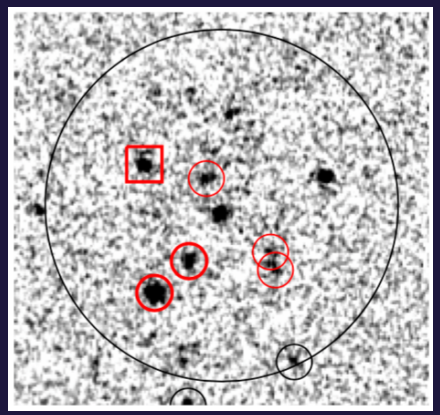
LABs at z=3.09(Matsuda+05)

Overdensity of starburst galaxies like LABs, SMGs and DRGs

= on-going formations of massive galaxies

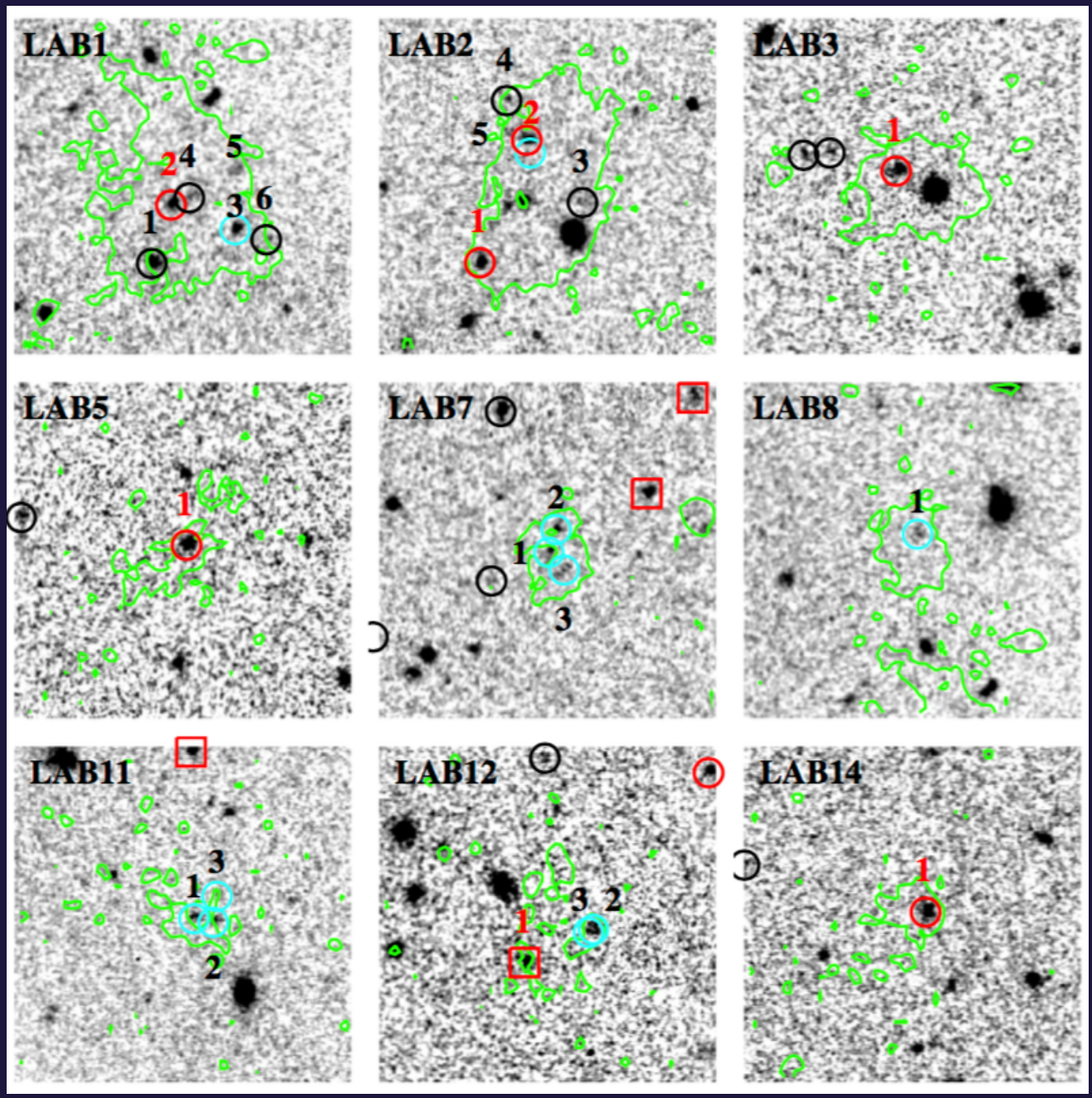
Multiple massive counterparts of LABs and SMGs …

multiple hierarchical mergers at the early-phase of formation of massive elliptical galaxies?



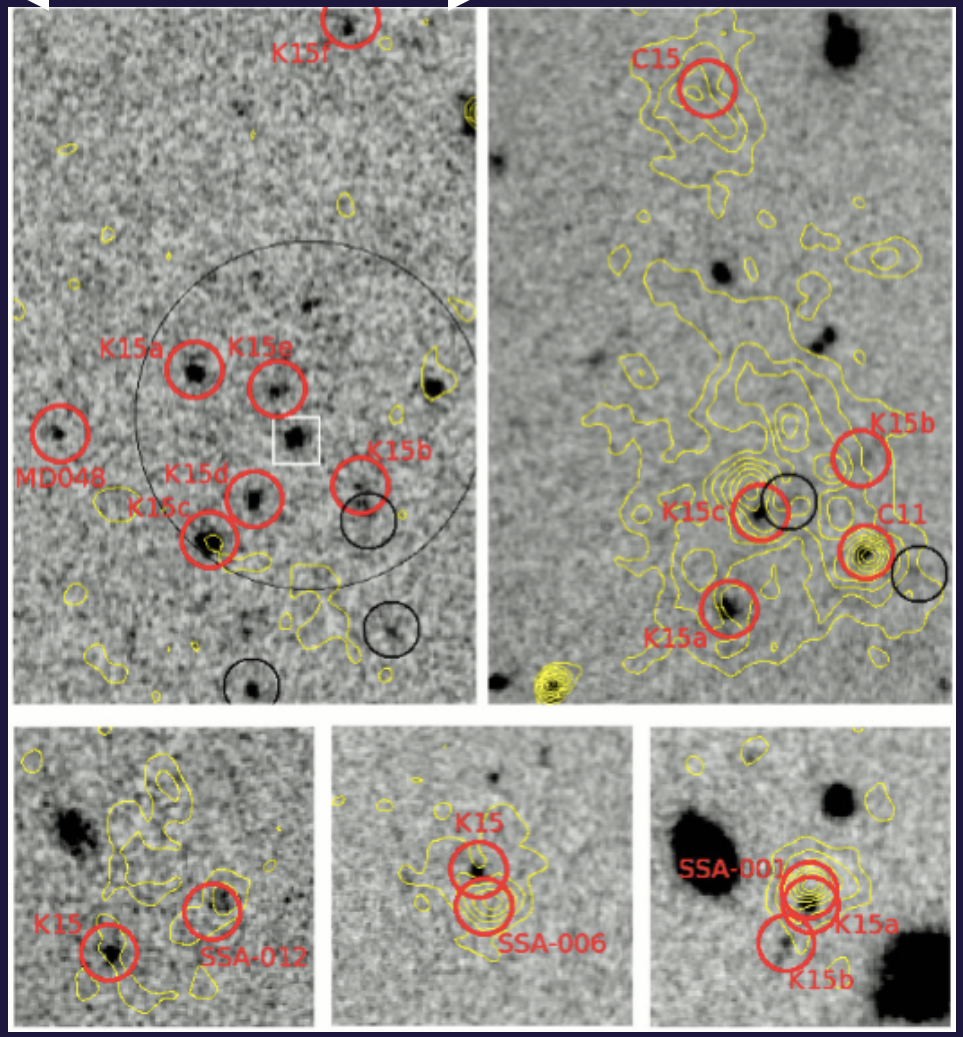
Counterparts of AzTEC 1.1 mm (Uchimoto+12)

23”.4 ~180 kpc in physical



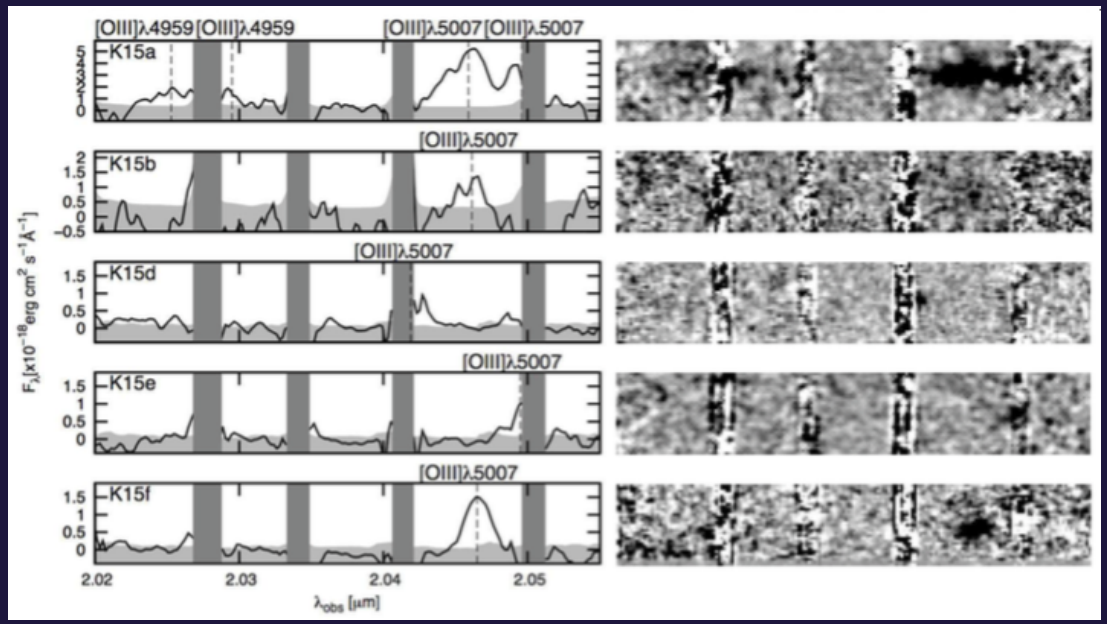
K-band images of LABs in the SSA22 protocluster (Uchimoto+12)

20”.0 ~160kpc

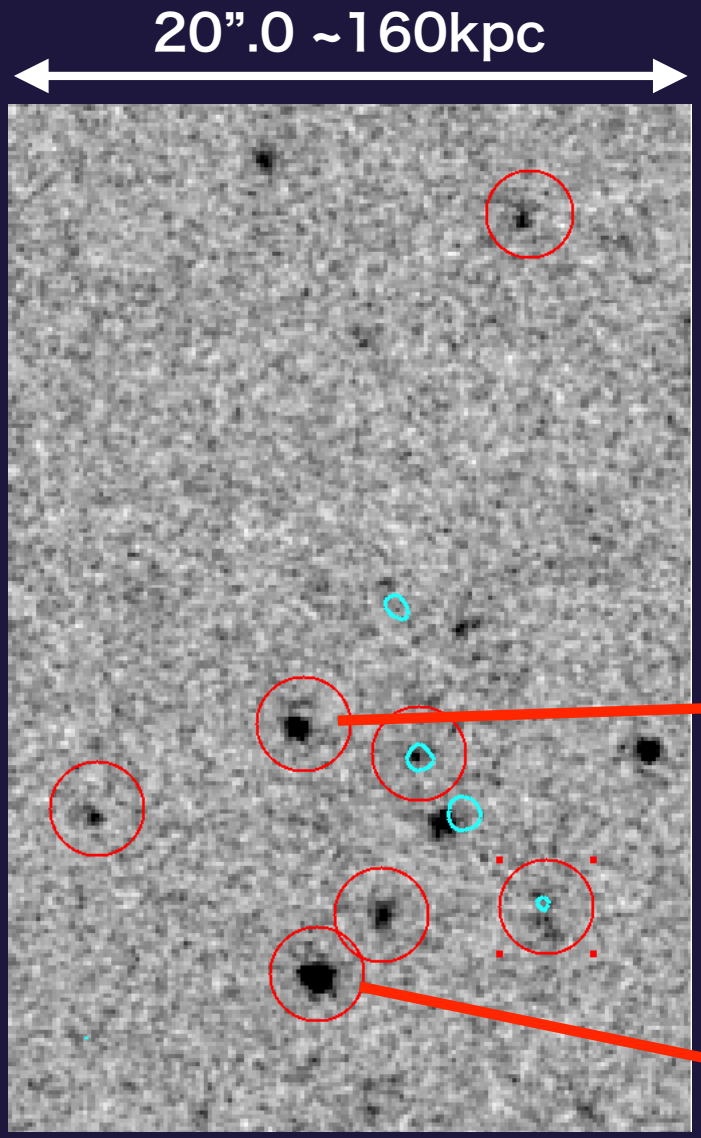


K-band image of the AzTEC14 group left top) and LABs.
Red circles: zspec=3.09
Black circles: zphot~3.1

- Follow-up spectroscopy with Subaru MOIRCS (Kubo+2015 & 2016)
- The most extreme case:
  The AzTEC14 group: 7 galaxies at zspec=3.09. 5 are $M^{*}>10^{10.5}$ Msun

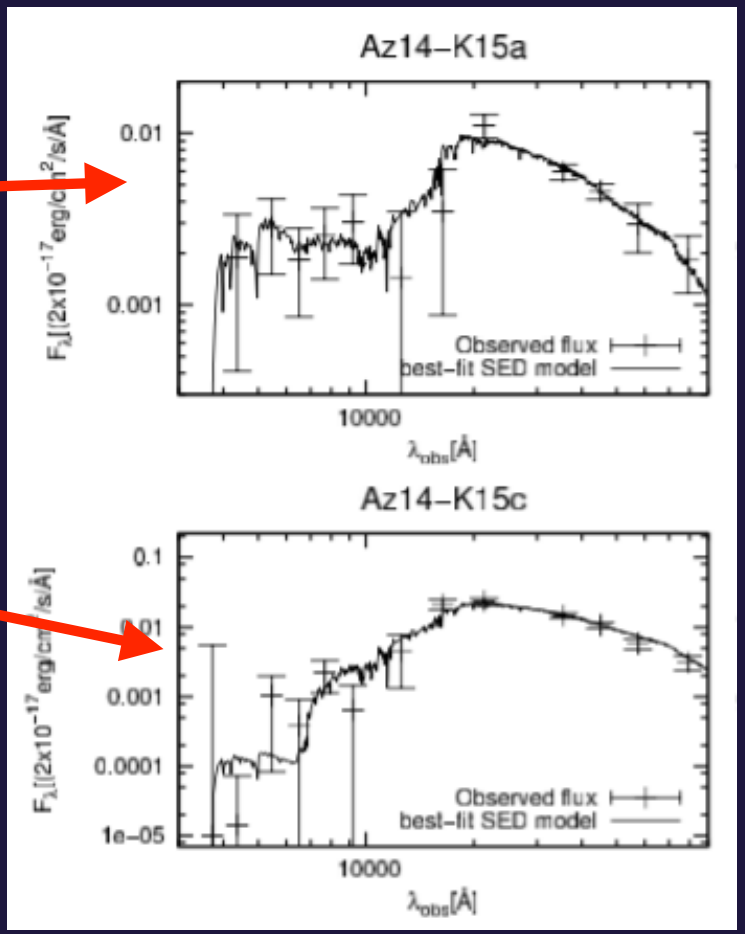


The NIR spectra of the AzTEC14 group (Kubo+2016)

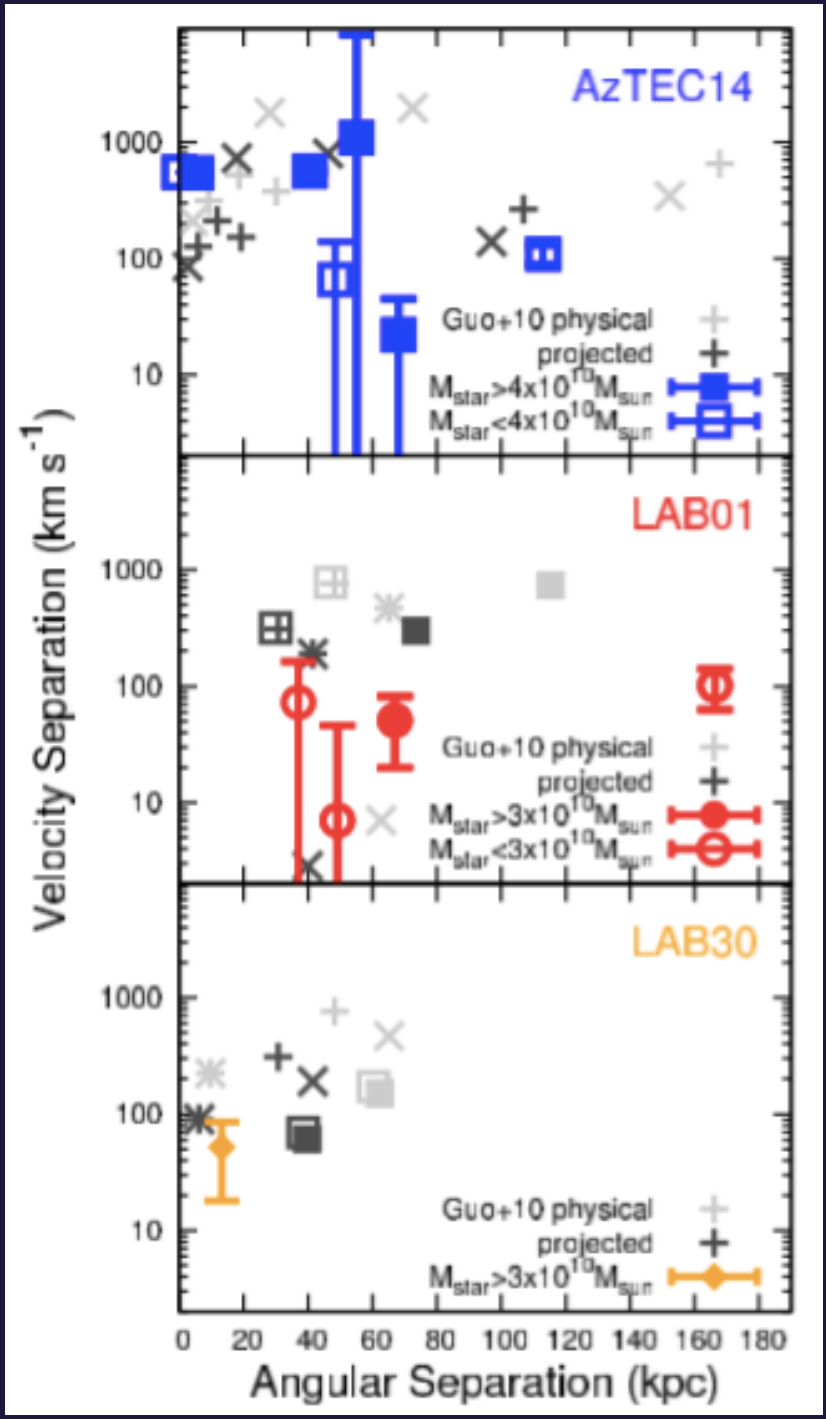


Cyan contours: ALMA 1.1 mm sources >0.25 mJy (Umehata et al. in prep)

- Total M^* ~ 5×10^{11} M_{sun}
- **The two most massive members have SEDs of quiescent galaxies.**
- 4 sub-mm sources with $S_{1.1mm}$>0.25mJy (2 are z_[OIII] λ 5007 =3.09)

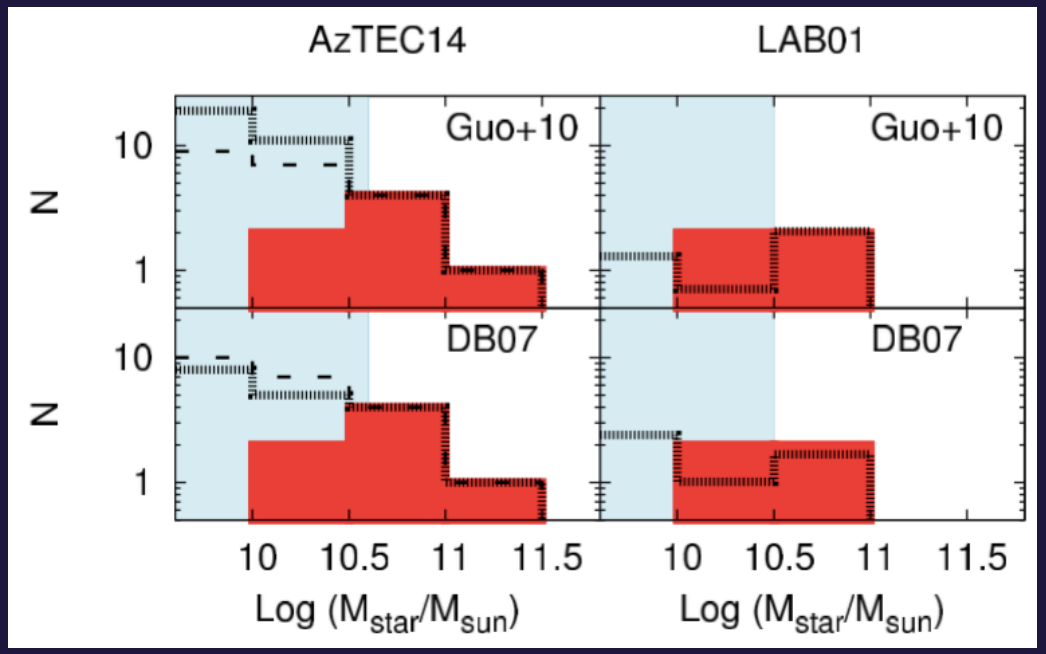


Kubo+2016



Kubo+2016

Comparing with galaxy formation models based on the Millennium simulation … similar velocity distribution and stellar mass distributions as those of the progenitors of BCGs (AzTEC14).



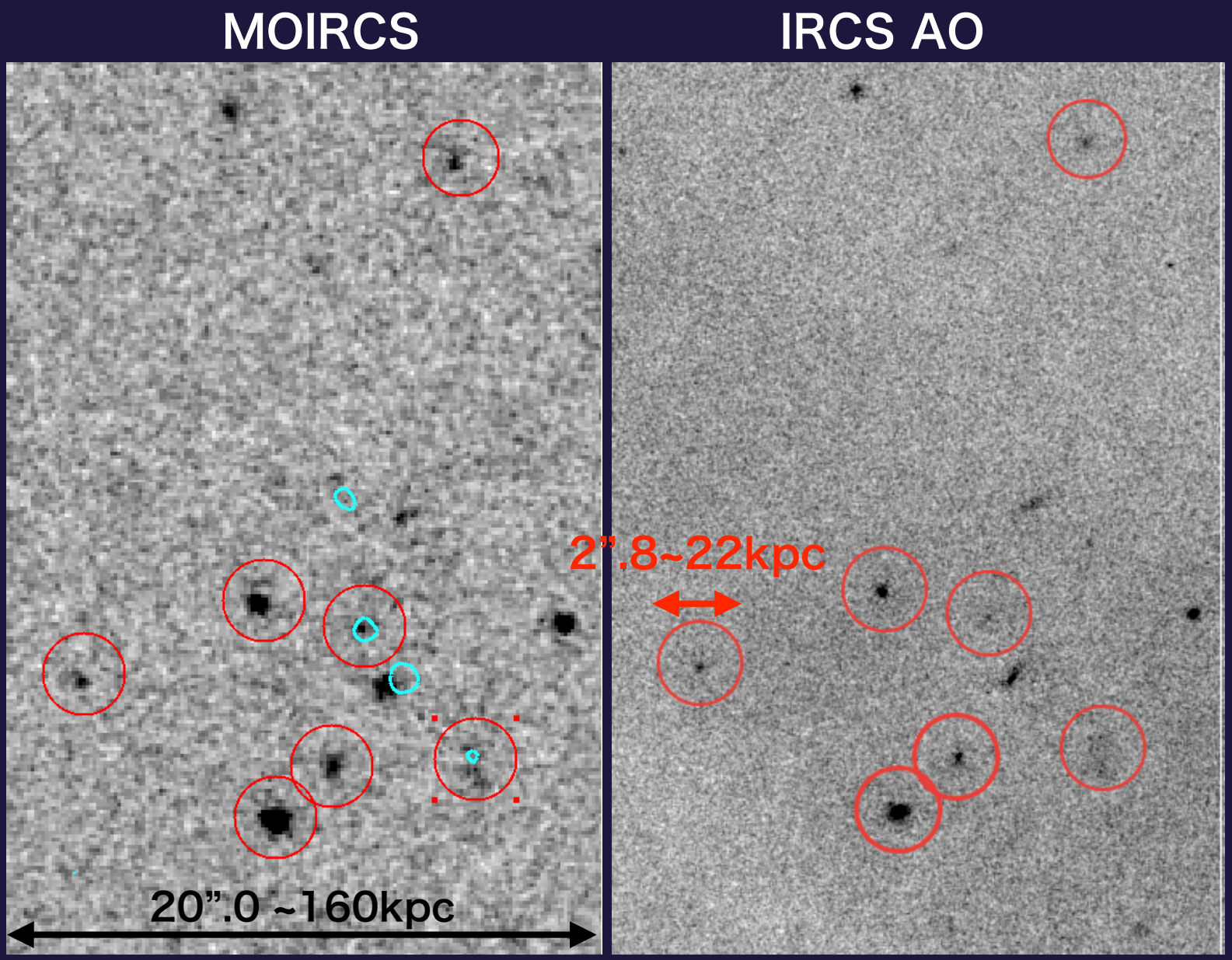
… Very suitable targets to study the early-phase morphological evolutions of massive ellipticals.

2. OBSERVATION

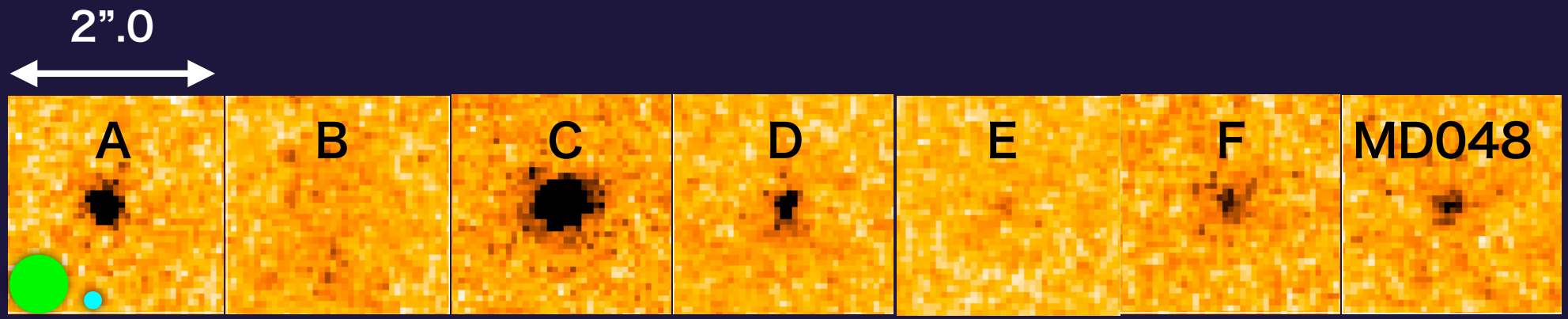
To study the morphologies of the group members, we conducted the deeper and higher resolution imaging observation of the AzTEC14 group in K-band. **For galaxies at z=3, K-band with AO is more recommended than H-band with HST.**

- Instrument: Subaru IRCS with AO188, LGSAO mode
- FoV: 52".0 x 52".0 (Fully covers the AzTEC14 group)
- Filter: K'-band
- DATE: 2015 July (a half night with good weather)
- Total EXPTIME= 2.8 h (~2 times of that with MOIRCS K)
- **FWHM of PSF size =0".16** (~0".55 for MOIRCS K)
- **Limiting magnitude: K_{AB}=25.6 at 5σ** with 0".3 diameter aper (K_{AB}=24 at 5σ with 1".1 diameter aper for MOIRCS K)
- Calibrated to MOIRCS K-band magnitudes and wcs.
- HST/ACS f814w (GDDS, 7000sec, i=28.3 at 5σ) can also be used but some sources are too red to detect with f814w.

3. RESULTS

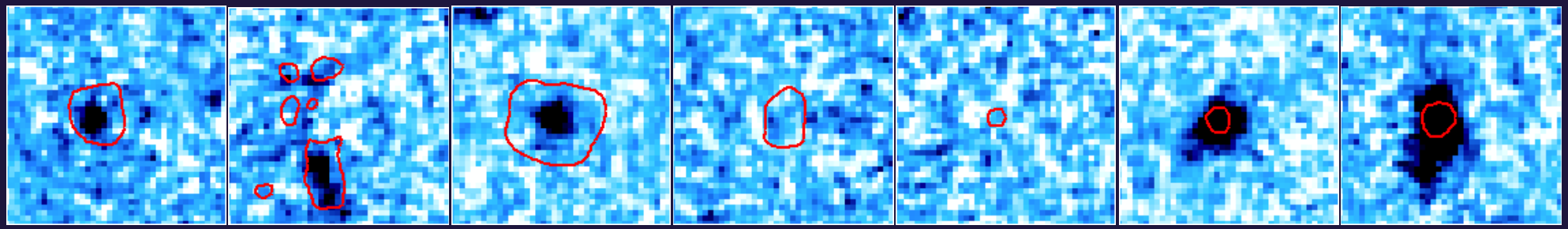


3. 1 The morphologies of members of the AzTEC14 group



↑FWHM PSF of
MOIRCS & IRCS AO

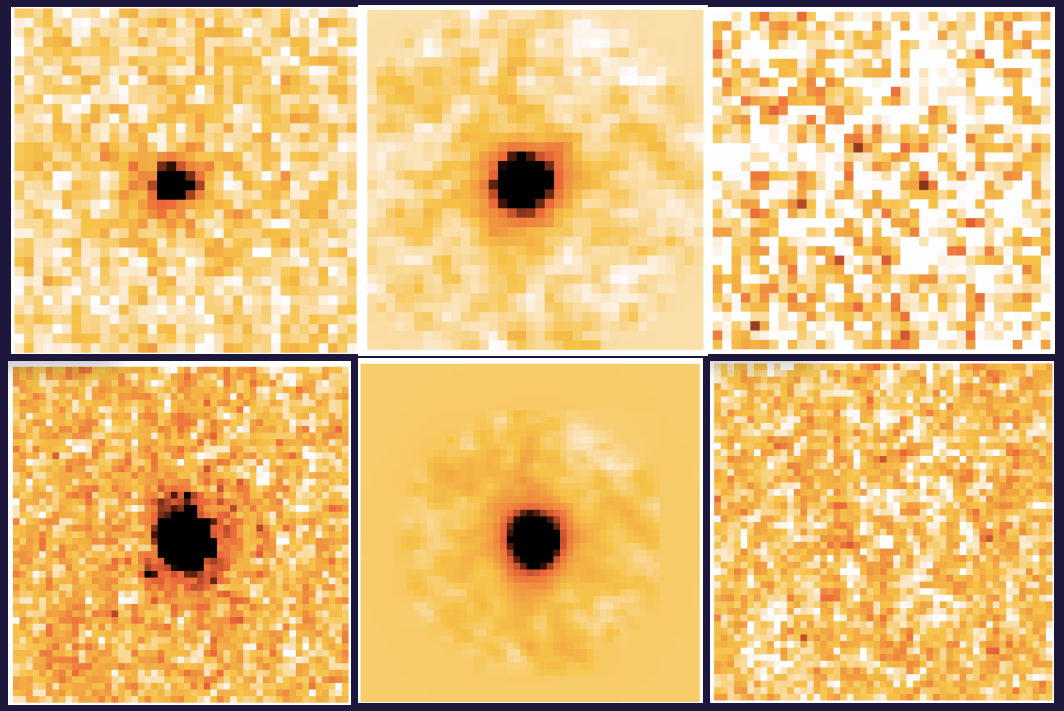
Subaru IRCS K



HST ACS F814W (Red contour=IRCS K)

A: Ktot=22.8
(QG with AGN)

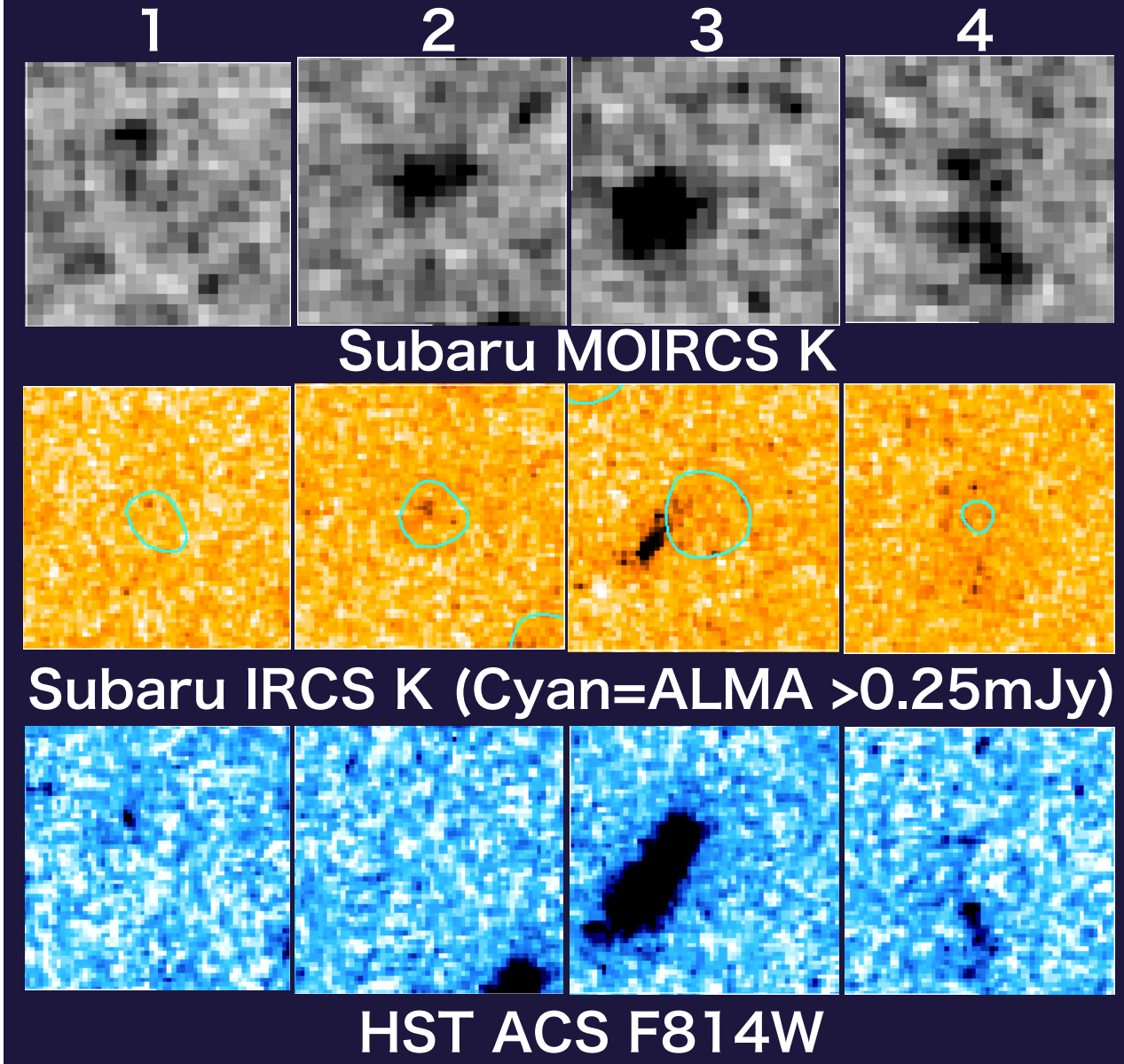
C: Ktot=21.8
(The most massive
& old QG)



Observed model residual

- Fit the two brightest galaxies A and C with Sersic profiles by using GALFIT (Peng et al. 2002)
- **The most massive QG (C): n=2.9±0.3, re=1.18±0.06 kpc**
- Another massive QG (A): n=7.7±3.6, re=0.86±0.28 kpc
- **Other sources are diffuse** (central surface brightness are 2~6 times fainter than those of normals SFGs at z=3 w n=1.4 and re=1 kpc, from Shibuya+15).
- **Supporting the two-phase evolution scenario.**

3.2 The counterparts of SMGs in the AzTEC14 group

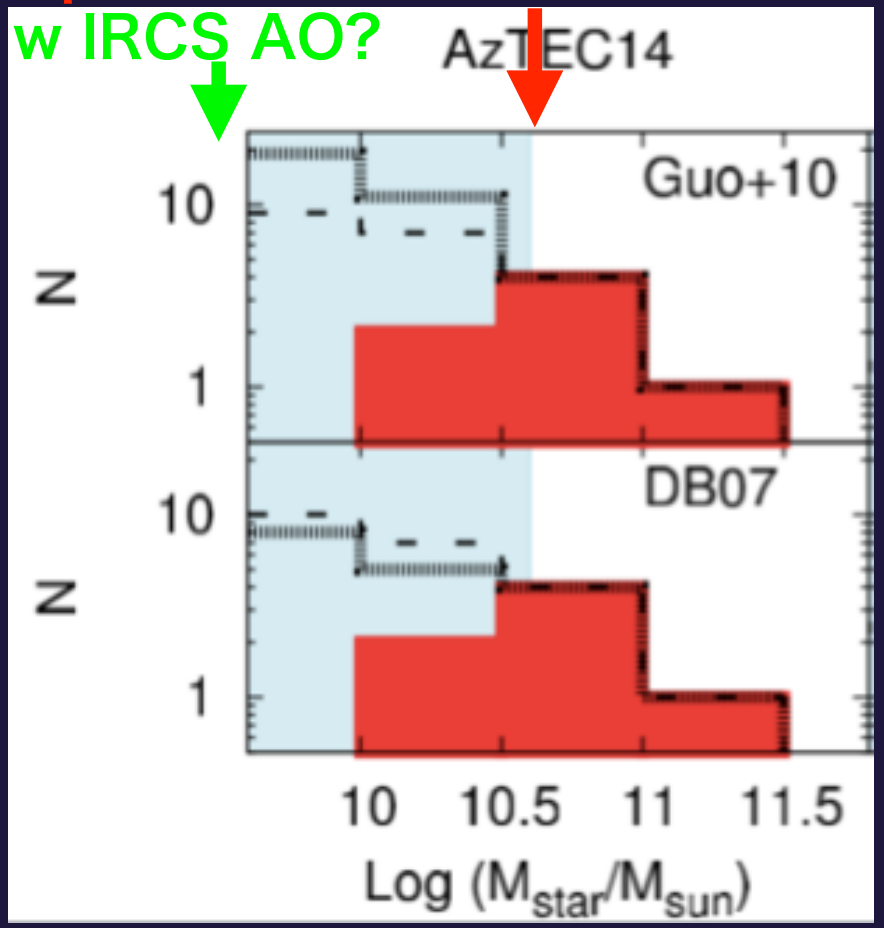


- There are four sub-mm sources identified by ALMA with $S_{1.1mm}$ >0.25 mJy (Umehata+ in prep)
- No counterparts for SMGs 1 & 3
- SMGs 2 & 4 are better identified by MOIRCS **=very diffuse**.
- Stellar distributions offset from dust and gas distribution?

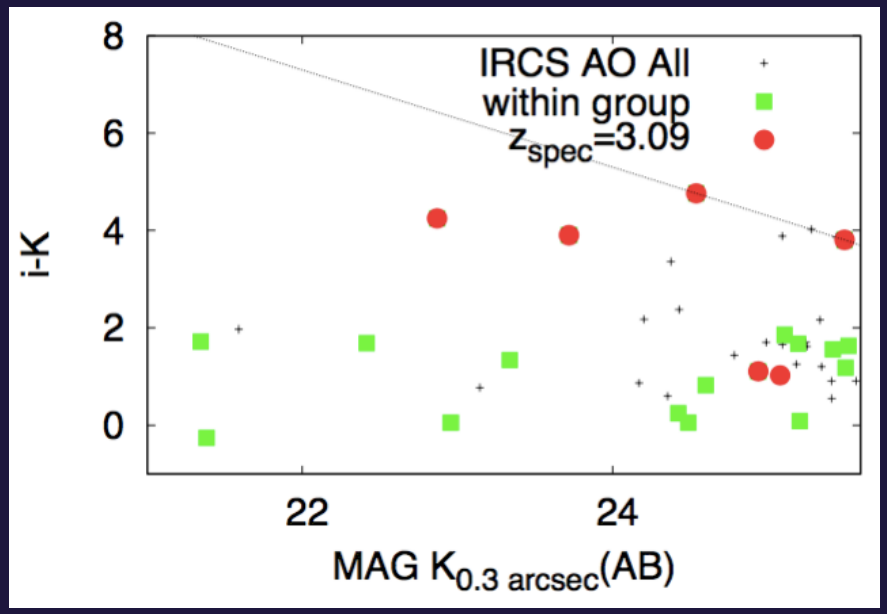
3.3 Faint-end of the group

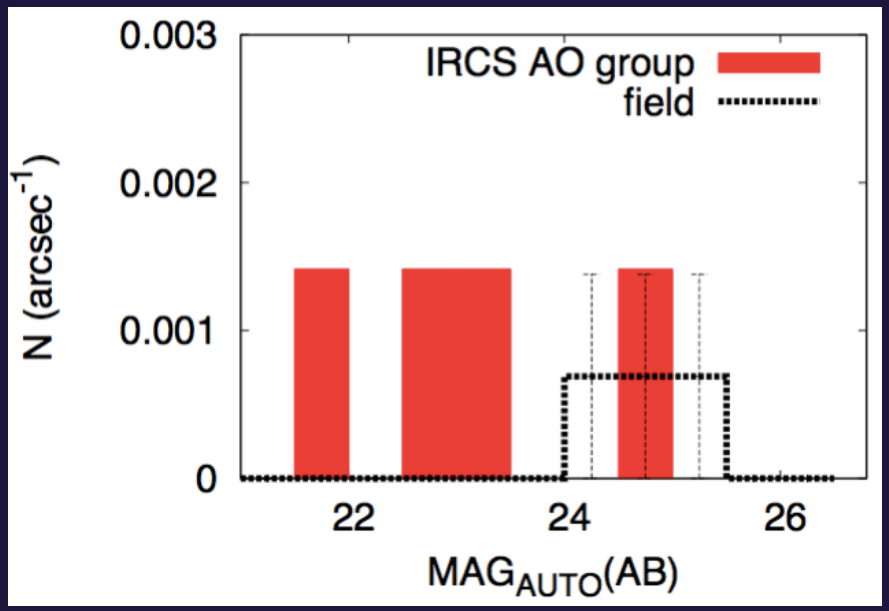
- 5σ detection limit… K_{AB}=24 (MOIRCS 1".1)
  → K_{AB}=25.6 (IRCS AO 0".3 diameter)
- This corresponds to stellar mass completeness limit M^*~2x10^9 M_{sun} in general.
- >10~30 new group members are expected from galaxy formation models based on the Millennium simulation.

Completeness limit w MOIRCS



Red: SMF confirmed with MOIRCS
Dash and dotted line: galaxy formation models based on Millennium simulation



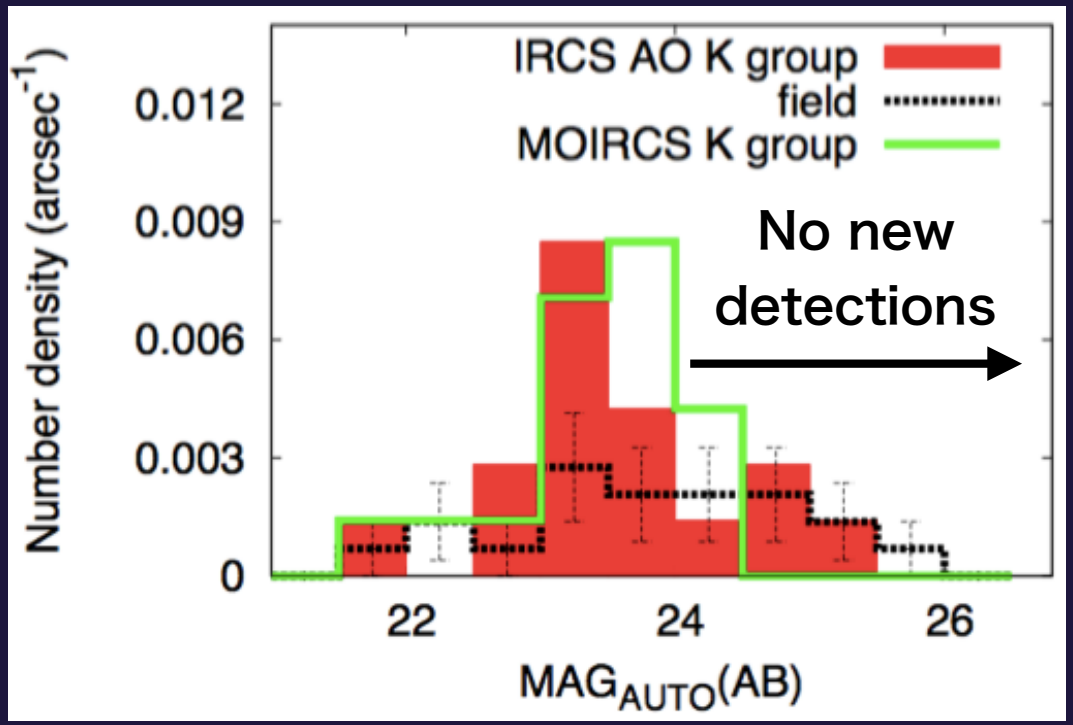


i-K v.s. K-mag diagram (top)
Number density of EROs (bottom)

Number densities of galaxies in the group (within 120 kpc of the most massive member) and the field.

- EROs (i-K>2.5)
- Simple K-band source count

No new source detection within the group!



Simple source count in K-band

4. DISCUSSION

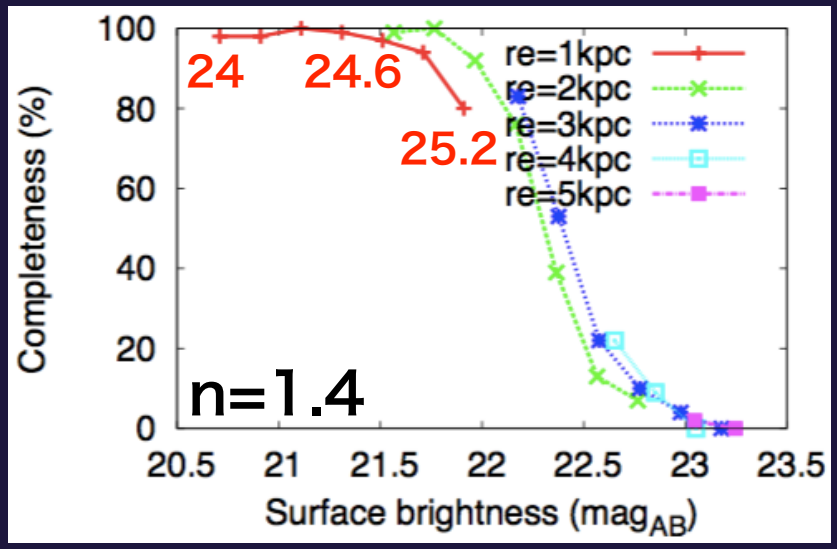
- The most massive quiescent galaxy in the AzTEC14 group is a massive compact elliptical galaxy. Diffuse morphologies of the other members implying frequent interactions and mergers of galaxies in the group. These results supports the two-phase evolution scenario.
- **The K-band image with AO is deeper than that with MOIRCS but no new group member are detected.**
- **Actual deficiency of low mass galaxies? Bad detectability owing to red colors and/or diffuse morphologies?**
- Simulating the dependence of detectability on colors and morphologies.

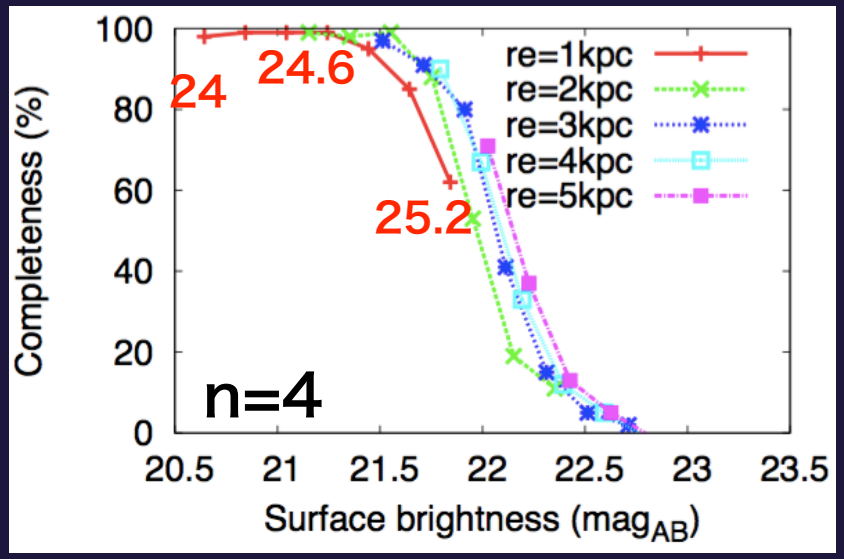
- **Dependence of completeness limit on colors**
  - In general ⋯ $M^* > 2 \times 10^9 M_{sun}$ at $K_{AB} < 25.6$
  - If QGs or dusty SFGs are dominant (following the stellar population of the confirmed members of the AzTEC14 group) ⋯ $M^* > 10^{10} M_{sun}$ at $K_{AB} < 25.6$
  - But still > 4~10 new members would be detectable.
- **Dependence of completeness on morphologies**
  - Diffuse objects are hard to detect.
  - Simulation:

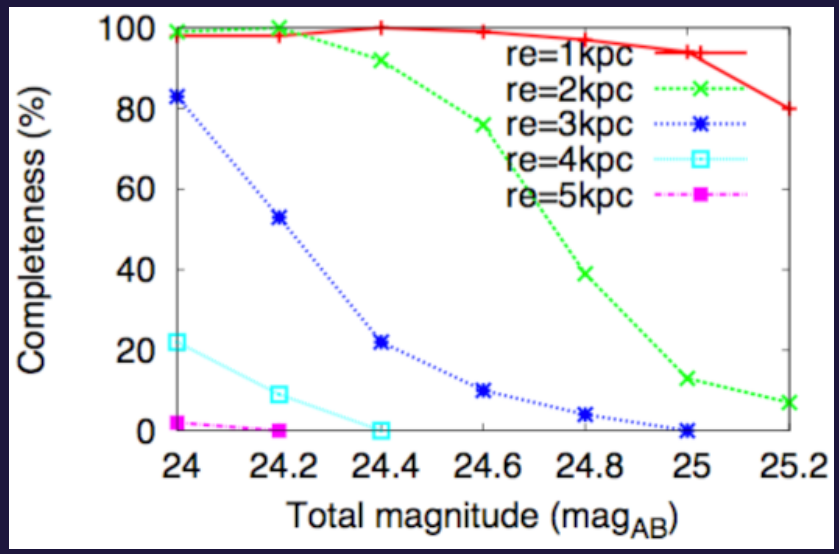
    -> Making model galaxies by using GALFIT (mocking diffuse objects by large re objects)

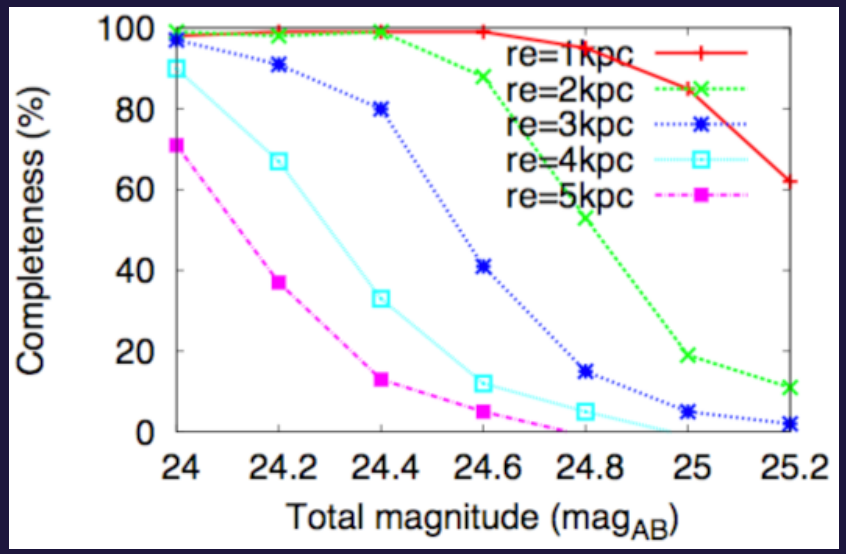
    -> embed models on the observed image

    -> run source extractor









- >80 % completeness for the objects with central surface brightness <~22 mag arcsec^{-2}
- Normal SFGs at z~3(with median re~1 kpc and n=1.4; Shibuya et al. 2015) with K<25.2 would be detectable at most.

What are the causes of the deficiency of faint galaxies?

- In the case QGs and dusty SFGs are dominant, complete for galaxies with $M^* > 10^{10}$ M_{sun} for $K_{AB}<25.6$.
- For normal SFGs (re~1 kpc, n=1.4), >80% completeness at $K_{AB}<25.2$.
- **Actual deficiency?** ⋯ Suppression of formation of low mass galaxies? (by feedback?)
- **Diffuse morphologies?**
  - Among the 7 members, the brightest two are compact but other members are more diffuse than normal SFGs.
  - Frequent interaction and mergers? But low mass galaxies would be less affected by interactions.
  - Expanded by feedback?

5. Summary

- We conducted the deep and high resolution imaging of an extreme dense group of galaxies at the center of the SSA22 protocluster. **It may be the first time to resolve how massive elliptical galaxies assembled at z>3.**
- The most massive quiescent galaxy in the group is a massive compact elliptical galaxy. The diffuse morphologies of other members suggesting frequent mergers and interactions of galaxies in the group. **Our results supports the two-phase formation scenario of massive elliptical galaxies.**
- **No new detection of faint galaxy. This may be caused by actual deficiency of low mass galaxies (by feedback?) and/or diffuse morphology (by feedback for low mass galaxies?).**
- **Deeper imaging with MOIRCS could show whether there is an actual deficiency of low mass galaxies or not.**