

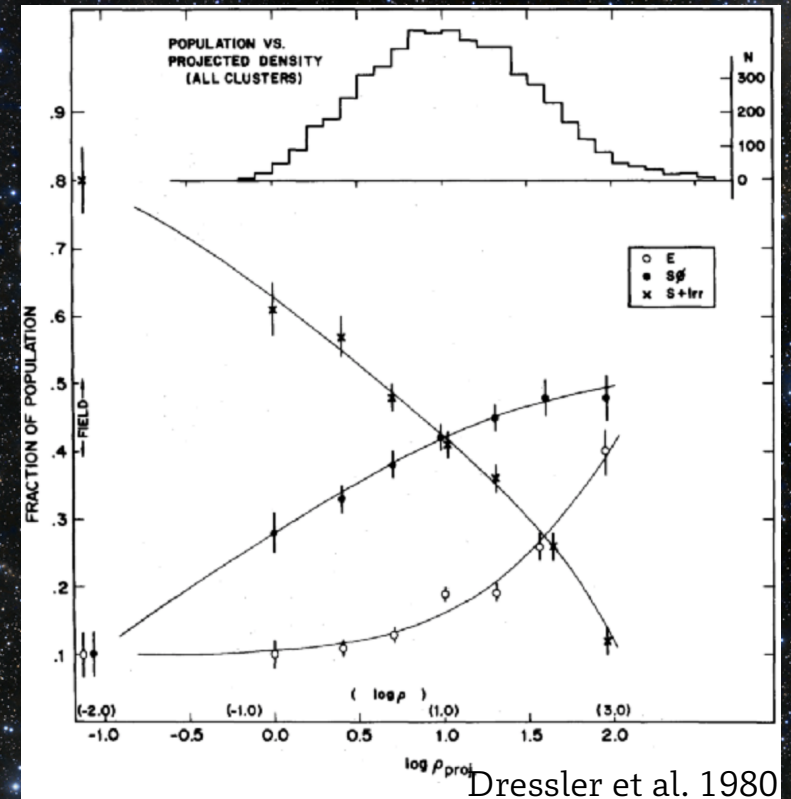
The average MIR-FIR properties of protoclusters at $z \sim 4$

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Introduction

Environmental dependence of galaxies today



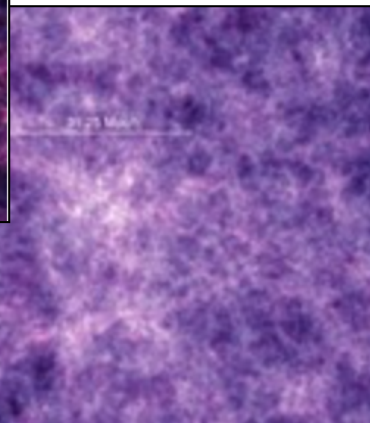
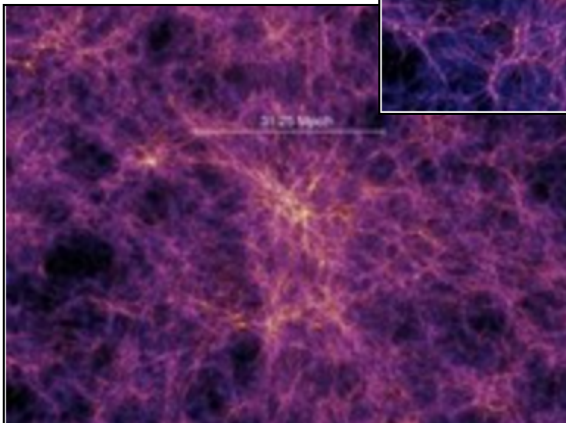
How the environmental dependences of galaxies today have formed?

Introduction

Protoclusters

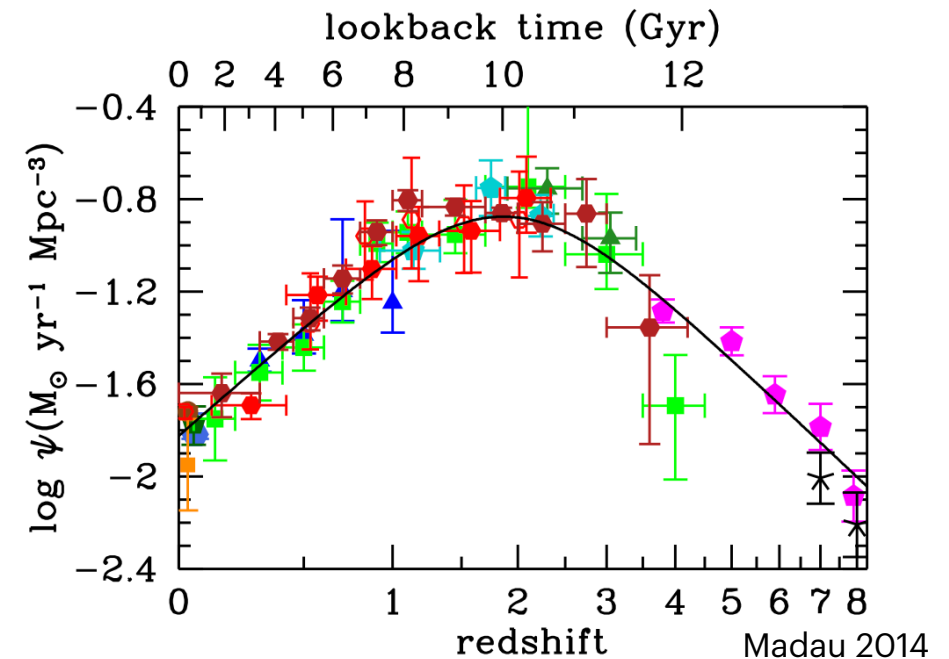


Overdense regions at high redshift evolve into clusters of galaxies today



From Millennium simulation

Cosmic SFR density peaks at $z=2-4$
(Passively evolving galaxies have also appeared)

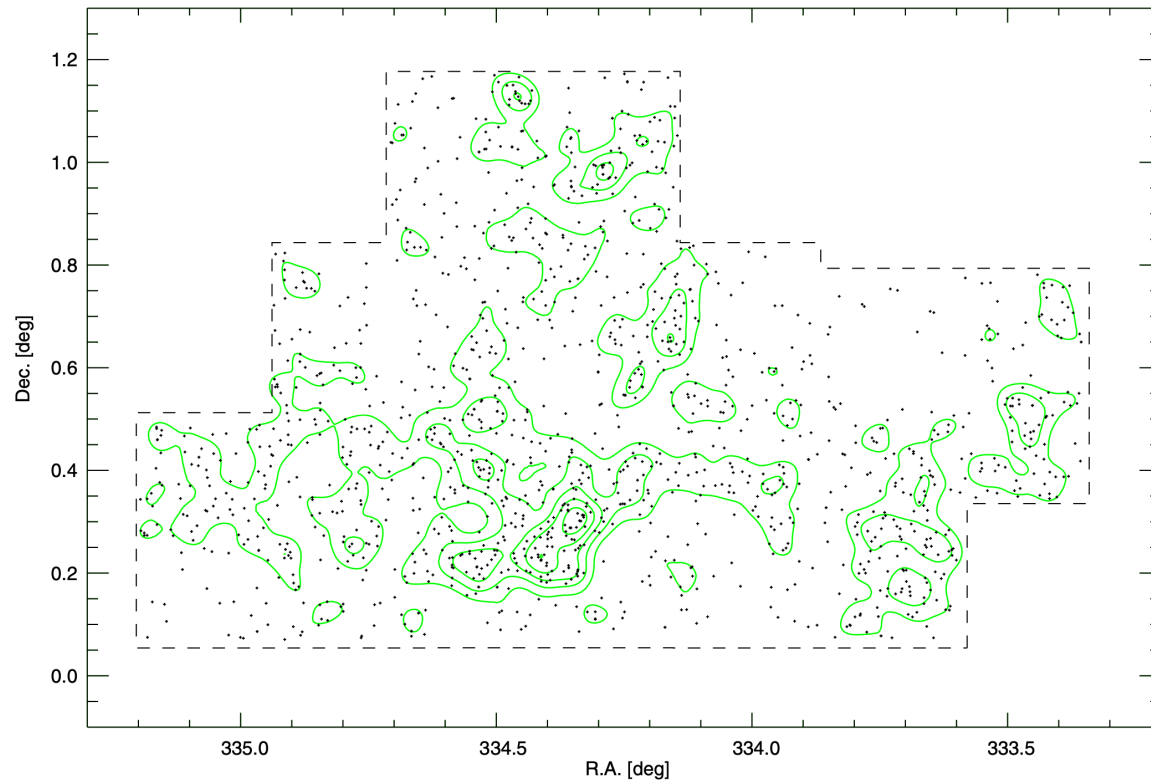


Protoclusters at $z=2-4$ are important laboratories.

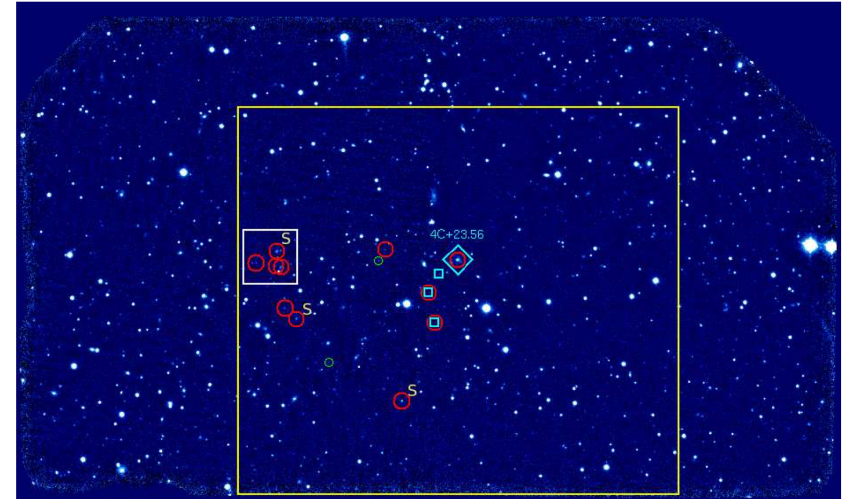
Introduction

Protoclusters

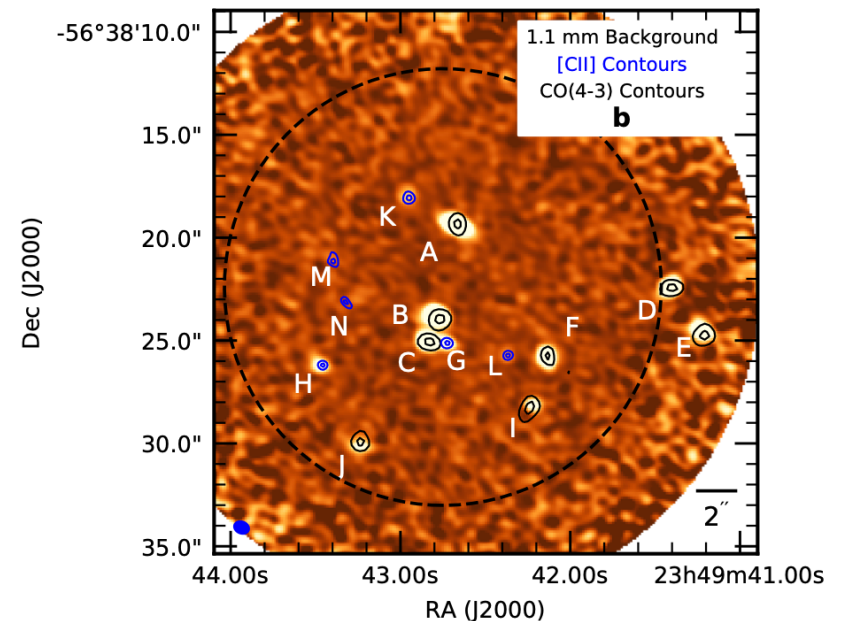
Many protoclusters have been discovered.
The selection methods and
the observed properties range widely.



Large scale structure of LAEs at $z=3.09$ protocluster (Yamada et al. 2012)
Originally found as LBG overdensity in general field.



Protocluster around a radio galaxy at $z=2.48$
found with HAEs (Tanaka et al. 2011)

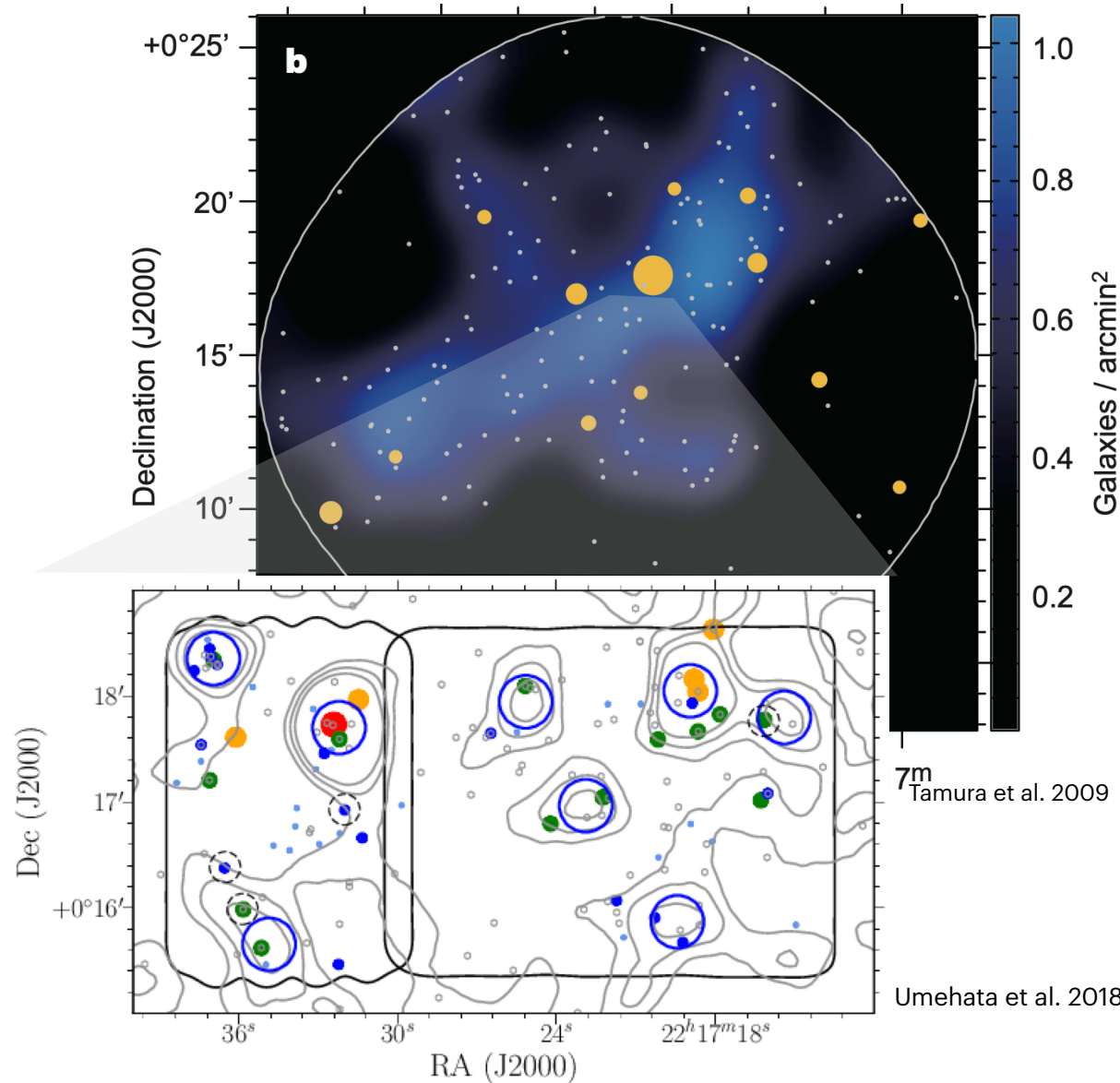


Dusty protocluster at $z \sim 4.3$ selected
with SPT (Miller et al. 2018)

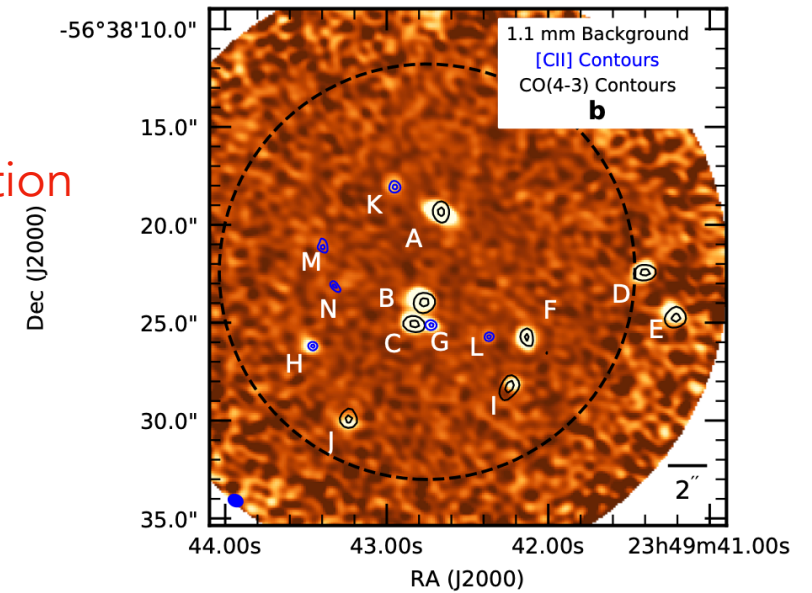
Introduction

Protoclusters: dusty galaxies

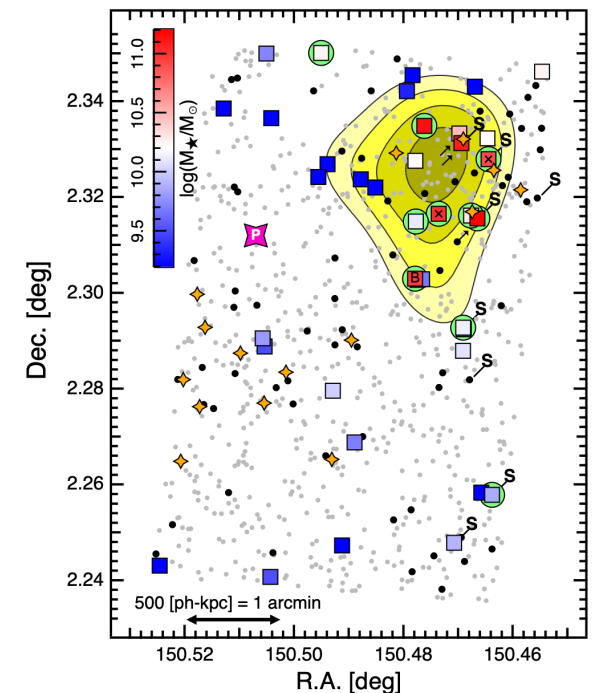
IR luminous dusty starburst galaxies are the key population



SMG overdensity in the SSA22 protocluster at $z=3.09$



Dusty protocluster at $z\sim 4.3$ selected with SPT (Miller et al. 2018)



Protocluster at $z=2.16$ selected with Planck (Koyama et al. in arXiv) 5/15

Introduction

What we need?...Uniform selection, large statistics, and IR

Protoclusters have a wide range of properties even at the same redshift. Number of the known protoclusters are limited. In addition, selection methods is not uniform...It is hard to compare them.

- ◆ **Statistical study is needed to know the typical properties of protoclusters at each epoch.**
- ◆ **Wide and systematic survey is required:** ~ 1 protocluster in 1 deg^2

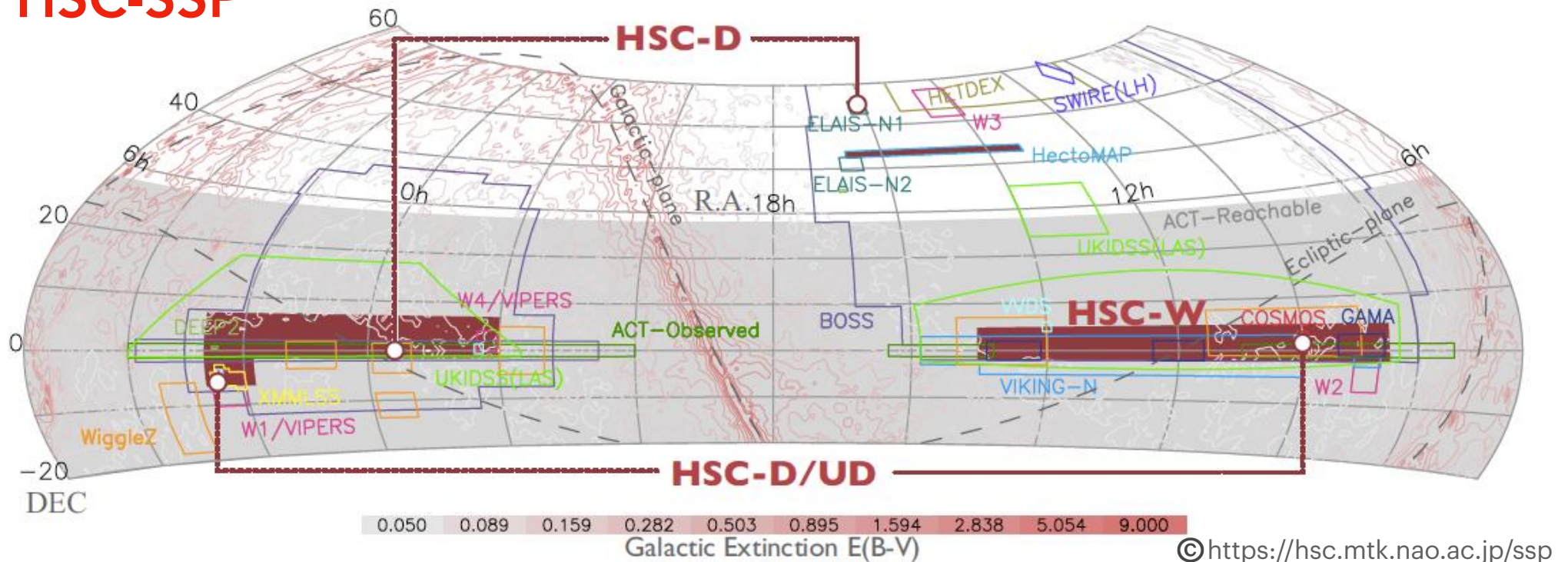
Properties in optical do not give the whole picture even at $z \sim 3$ (dusty starburst, quiescent galaxies, AGNs etc...).

- ◆ **Multi-wavelength observations are needed.**
- ◆ Especially, dust re-emission in IR is very important. But there is no working telescope capable for high- z galaxies at MIR-FIR.

How to study protoclusters statistically in IR?

Large and uniform catalog of protoclusters:

HSC-SSP



Wide wavelength coverage in IR:

**Full or wide IR sky surveys "in archive",
Planck, IRAS, AKARI, WISE and H-ATLAS**

Planck (and other archives) stacking analysis of HSC protoclusters

Planck stacking analysis of HSC protoclusters

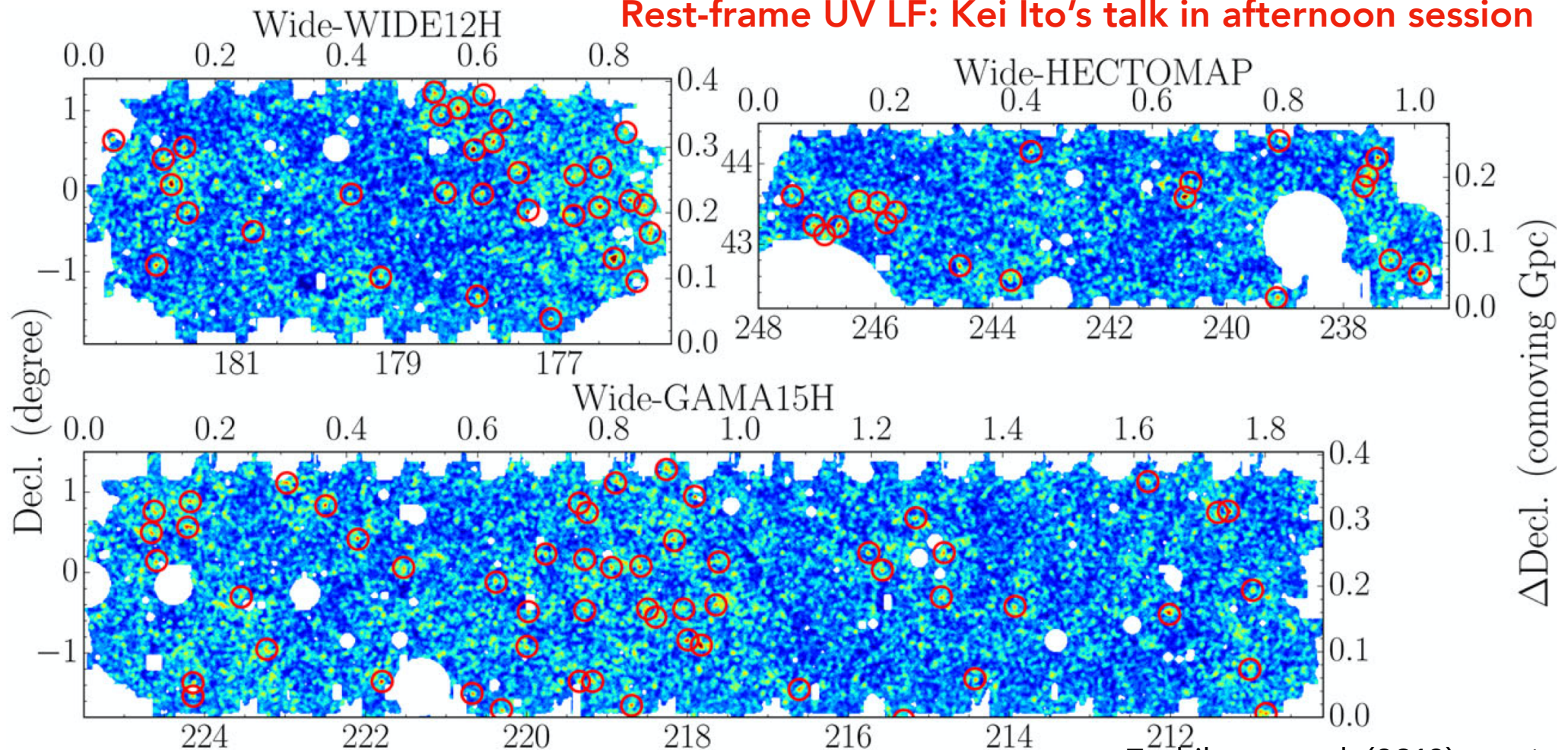
Sample: The first systematic protocluster survey in optical

Systematic protocluster survey with HSC-SSP (Toshikawa et al. 2018)

179 protocluster candidates at $z \sim 4$ are selected based on the overdensities of g-dropout galaxies in 121 deg² of HSC SSP PDR1 Wide.

Expected to be the progenitors of $M_{\text{halo}} > 10^{14} M_{\text{sun}}$ clusters.

Rest-frame UV LF: Kei Ito's talk in afternoon session



Planck stacking analysis of HSC protoclusters

Method

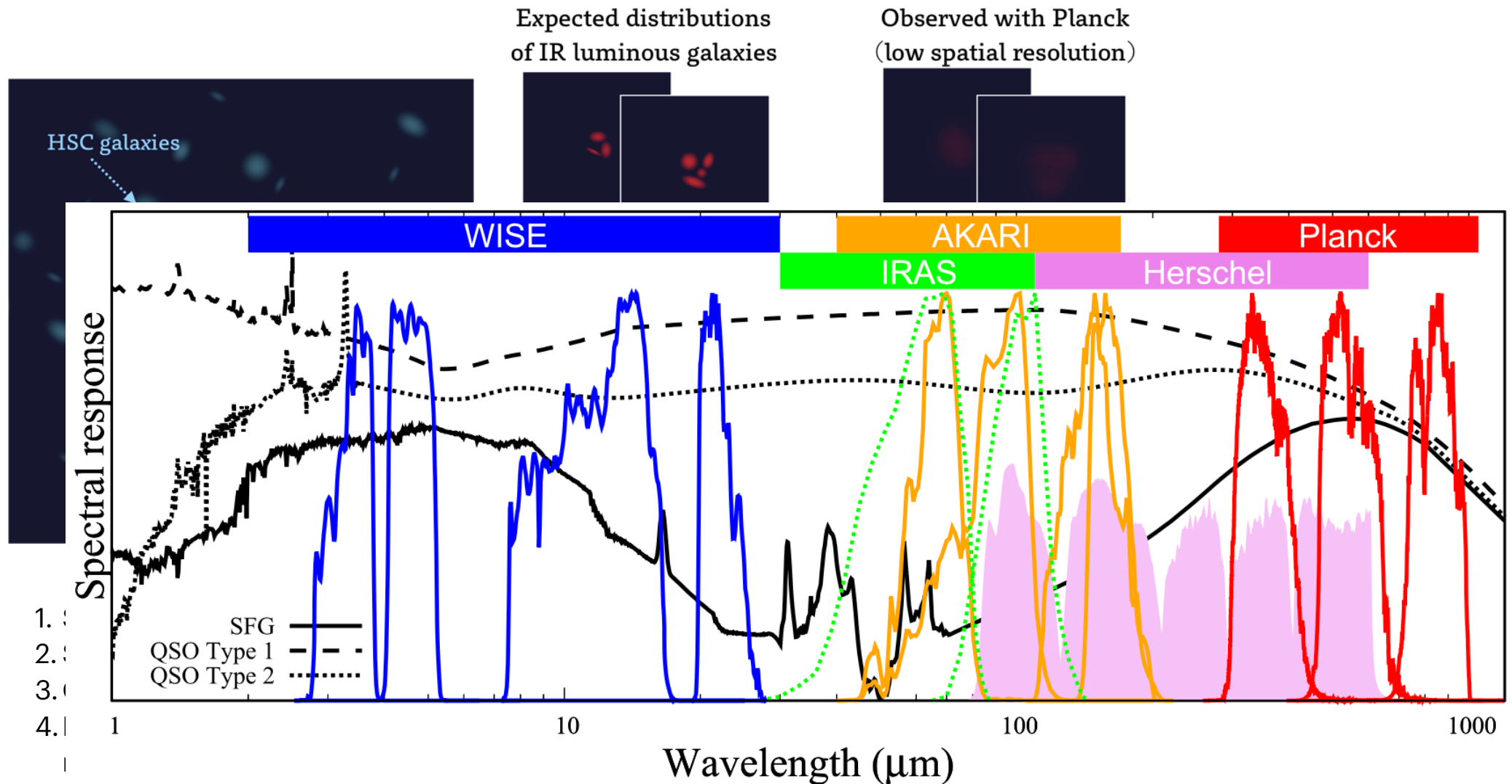
Planck, IRAS, AKARI, WISE and H-ATLAS

Size of protoclusters ... several arcmin

= low ($<5'$) spatial resolution sky maps in IR

Planck stacking analysis of HSC protoclusters

Method

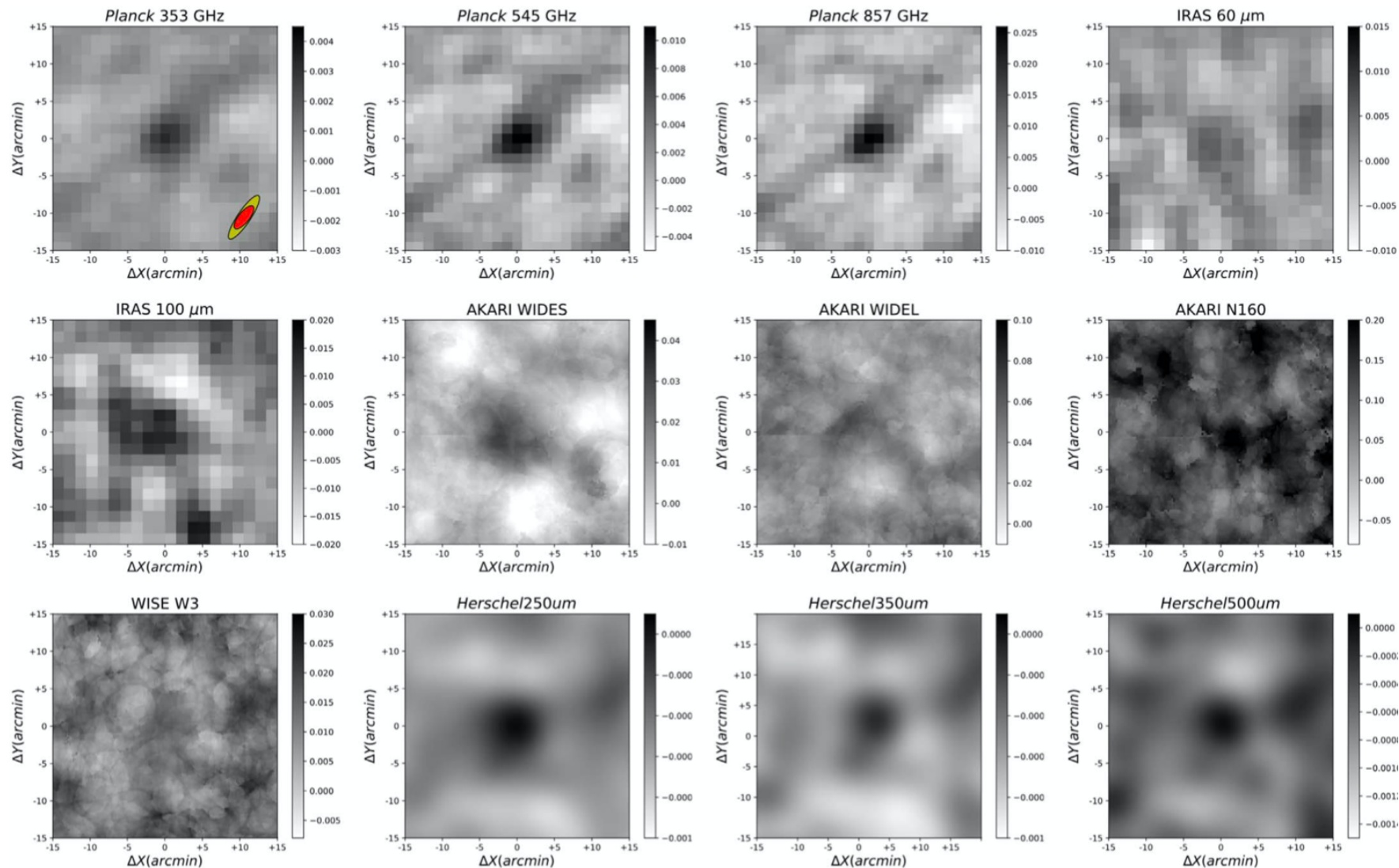


5. Taking the average and standard deviation of aperture photometry of bootstrap resampling as the value and noise.
6. Finally, the aperture flux is converted into total flux with the aperture correction factor evaluated by using the H-ATLAS image.

Planck stacking analysis of HSC protoclusters

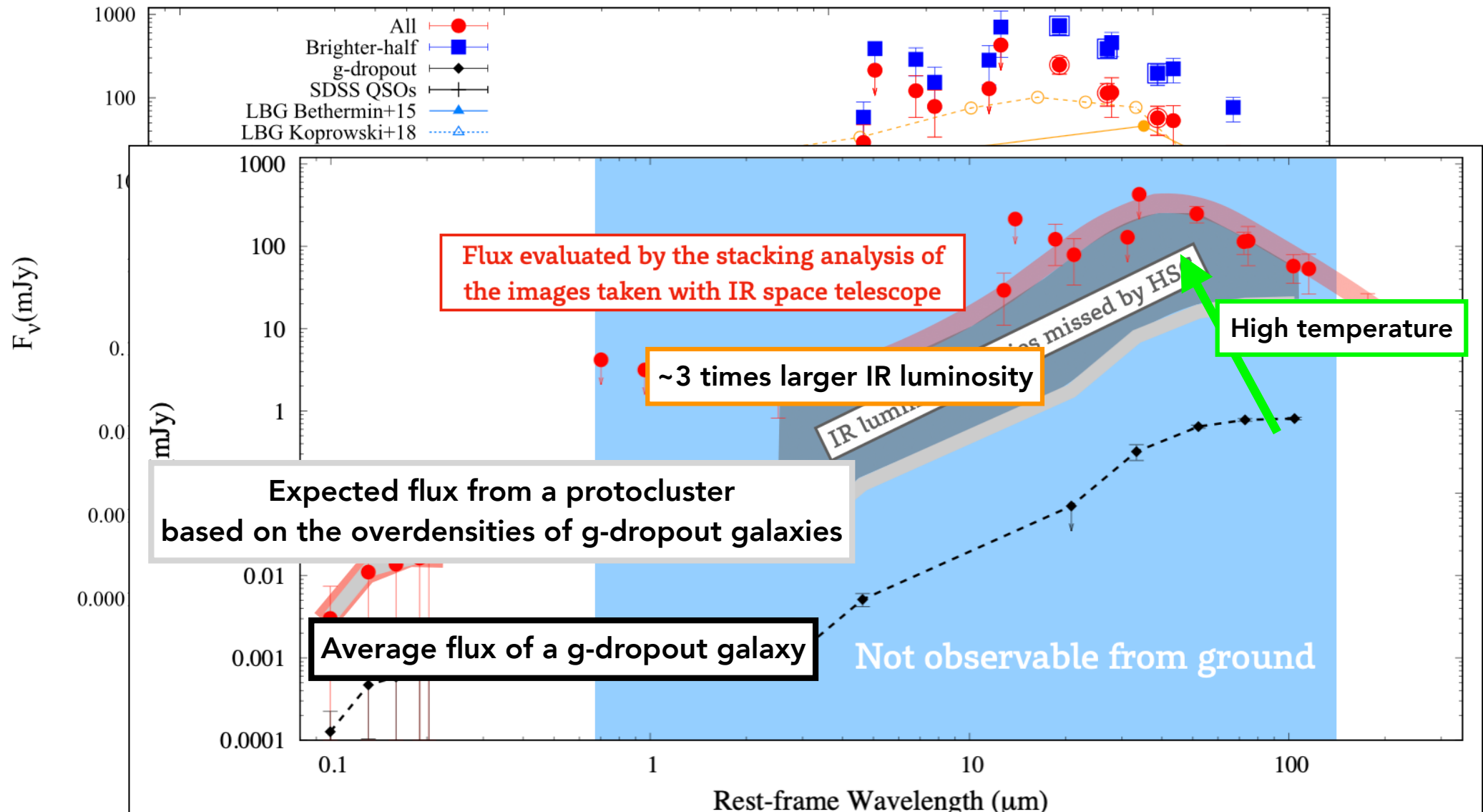
Result

Stacked images of protoclusters (PSF matched to Planck)



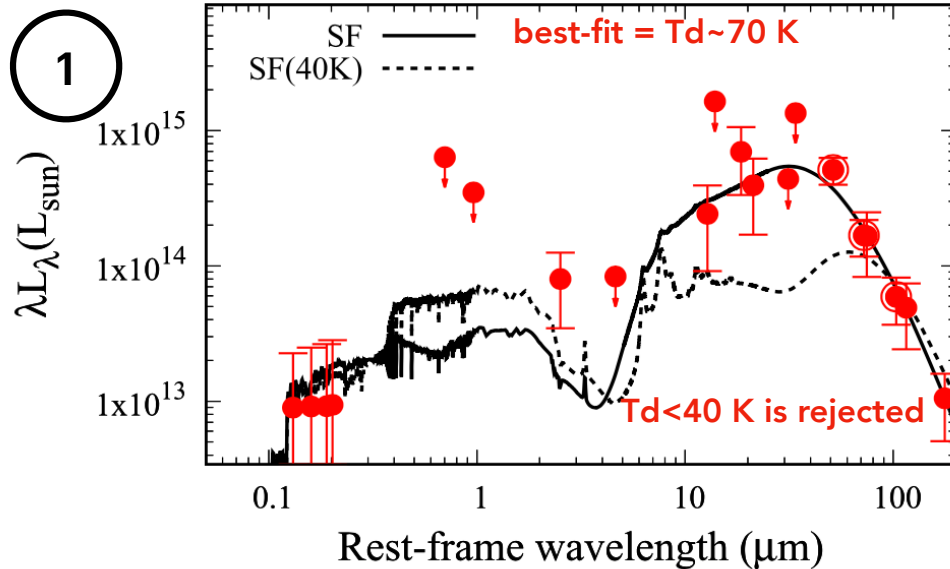
Planck stacking analysis of HSC protoclusters

Result



Discussion

1. What is the origin of the IR emission?

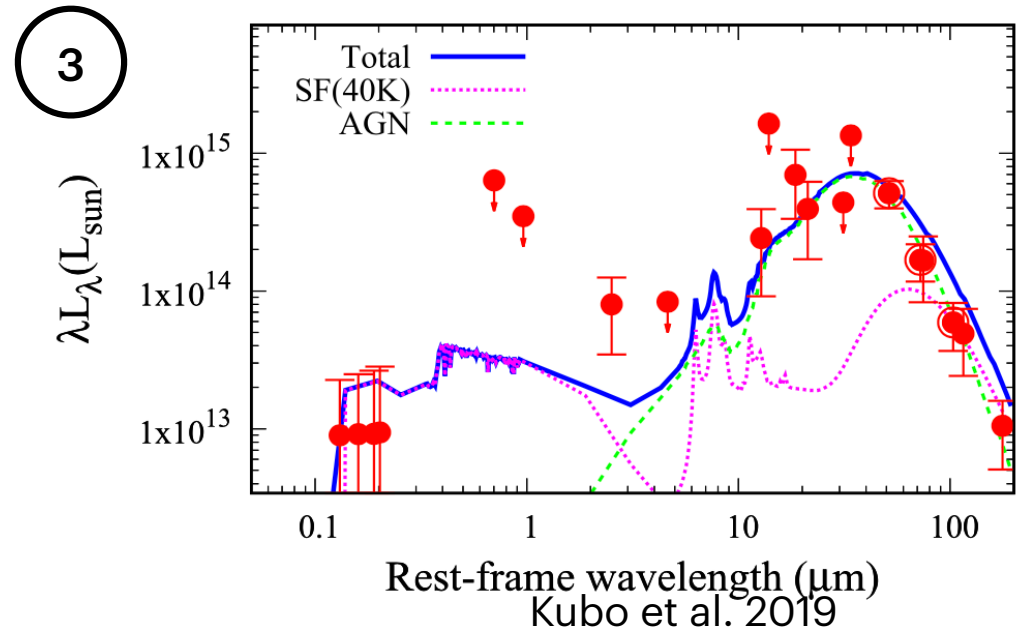
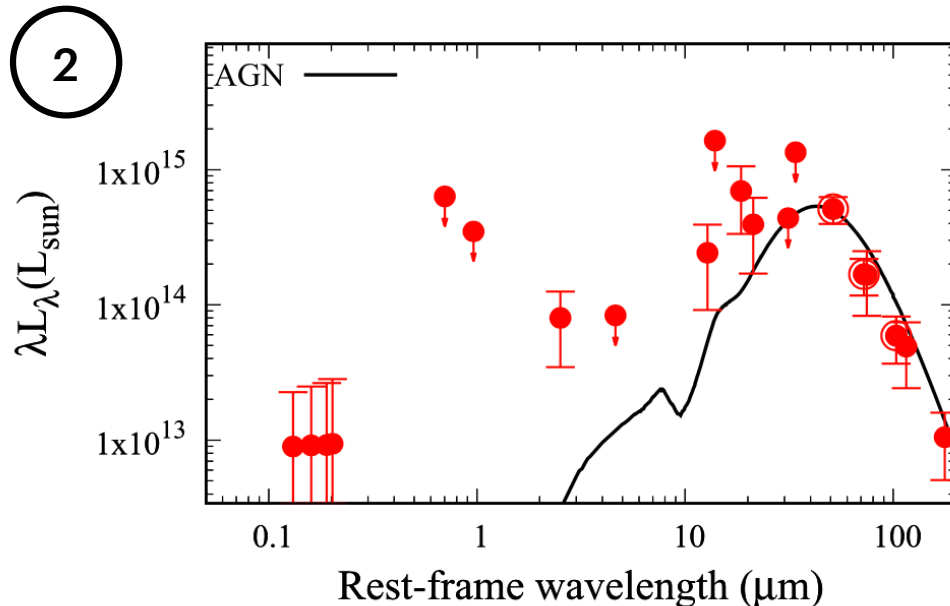


SED fitting with 3 models:

1. SFG(MAGPHYS: da Cunha et al. 2008)
2. AGN torus(Siebenmogen et al. 2015)
3. SFG(Td=40K or typical SFG)+AGN

Young dusty starburst with Td ~ 70 K and SFG(40K) + AGN are equally good.

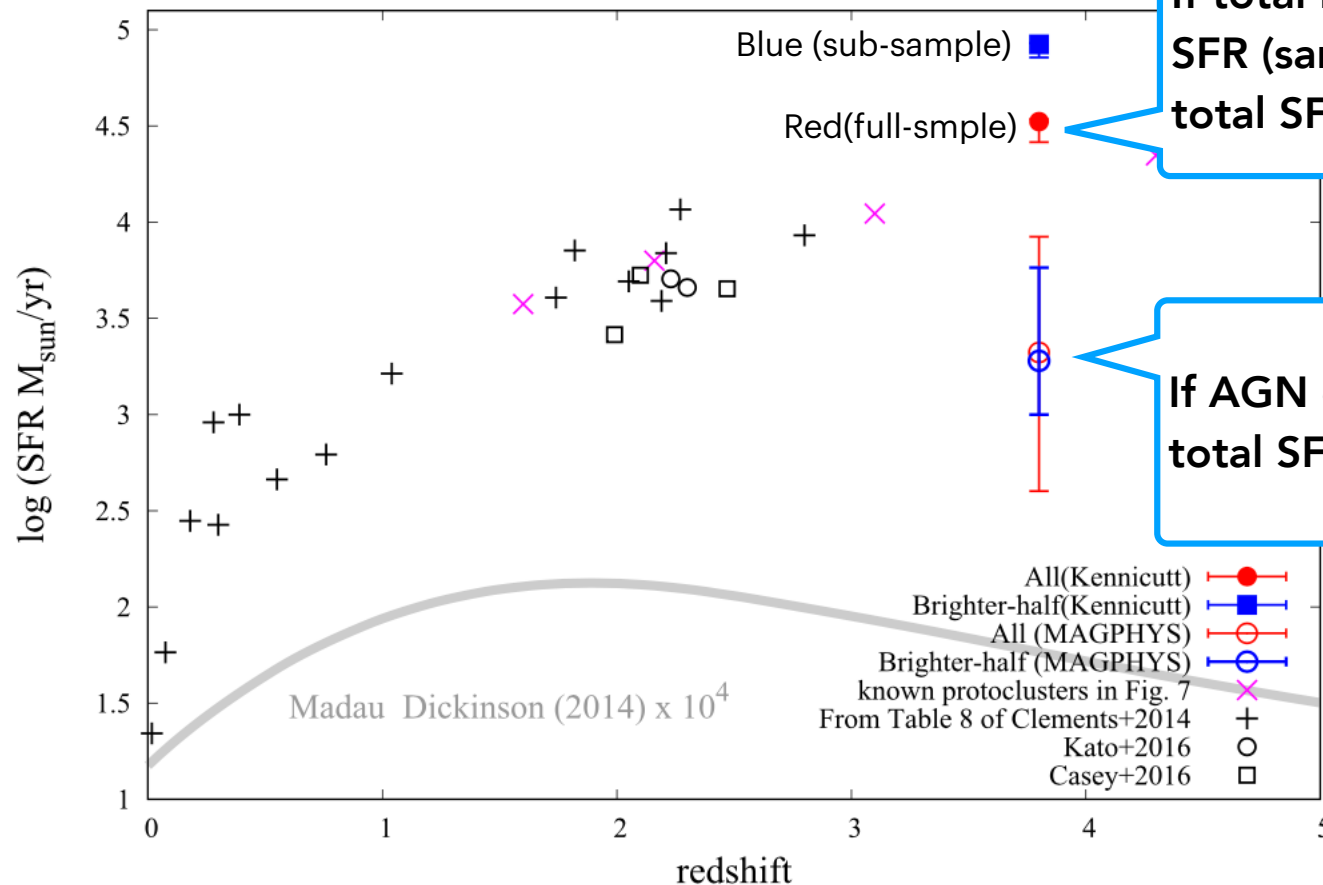
The total SFR of a protocluster is $16.3^{+1.0}_{-7.8}$ and $2.1^{+6.3}_{-1.7} \times 10^3$ Msun/yr for SFG and SFG+AGN models, respectively.



Discussion

2. Evolution of total SFR of protoclusters/clusters

Total SFR of protoclusters based on IR luminosity
(Rough SF history for massive clusters)



If total IR flux is just converted into SFR (same as other protoclusters), total SFR continues to increase.

If AGN contribution is subtracted, total SFR declines between $z=3-4$.

At least, the total IR luminosities of massive clusters continues to increase at up to $z \sim 4$.

Conclusion and future work

- ◆ We successfully show the average IR SED of a protocluster at $z \sim 4$ for the first time by stacking the IR archival images of HSC-SSP selected protoclusters.
- ◆ The total IR luminosity from a protocluster is ~ 3 times higher than that expected from optically selected galaxies.
- ◆ The average SED of a protocluster shows more warm dust component than that of typical SFGs. The over density of young hot SFGs with $T_d \sim 70$ K and/or AGNs is required.
- ◆ Though there is the uncertainty in the contribution of AGNs, at least, the IR luminosity of a protocluster continue evolves at up to $z \sim 4$
- ◆ **The MIR-FIR properties of protoclusters are quite essential !!**
- ◆ Future works:
 - ◆ SFG?AGN? Characterize them in individual protoclusters in NIR/mm
 - ◆ The average evolution across cosmic time? **Here we studied only 121 deg^2 of HSC-SSP.** Our study can be expanded with the later release of HSC-SSP, and future wide surveys with Rubin Observatory, Euclid and Roman Space telescope.