# Properties of High-Redshift Galaxies Revealed with the Subaru/HSC Survey


Yuichi Harikane

ObsCos Group, ICRR (6/1~)

JSPS Fellow at NAOJ and University College London (~5/31)

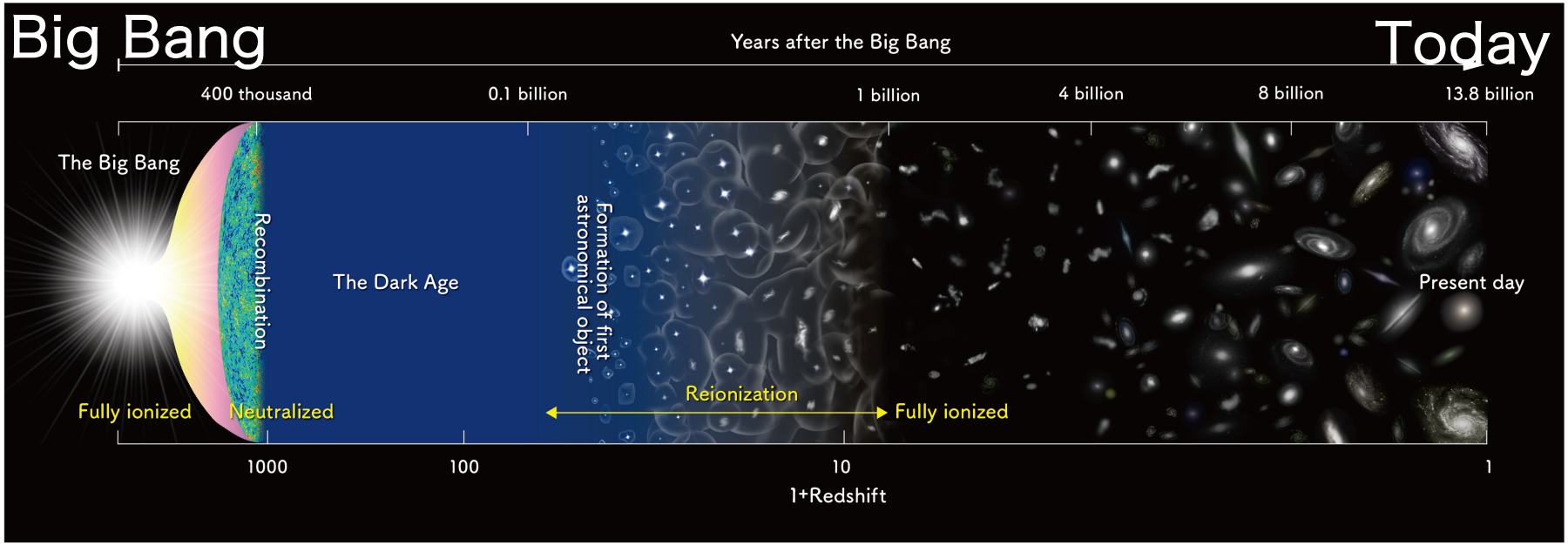
# Outline

- Introduction
  - galaxy formation and cosmic star formation history
- Subaru/Hyper Suprime-Cam Survey
  - Our high redshift galaxy projects
- Results:
  - Origin of the cosmic star formation history (Harikane+18a)
  - High-redshift Protoclusters (Harikane+19)

# Introduction

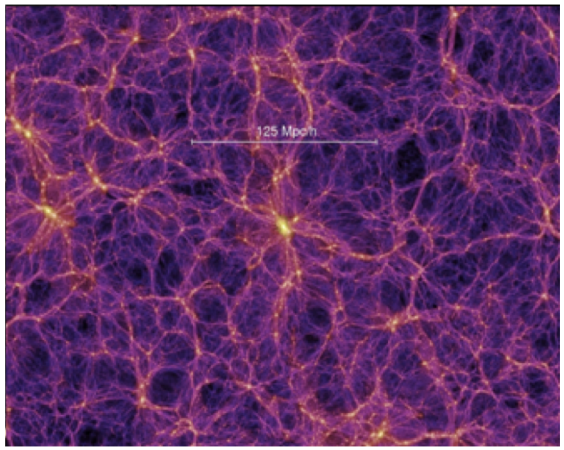
# Cosmic History

- We do not fully understand how galaxies form and evolve in the cosmic history…

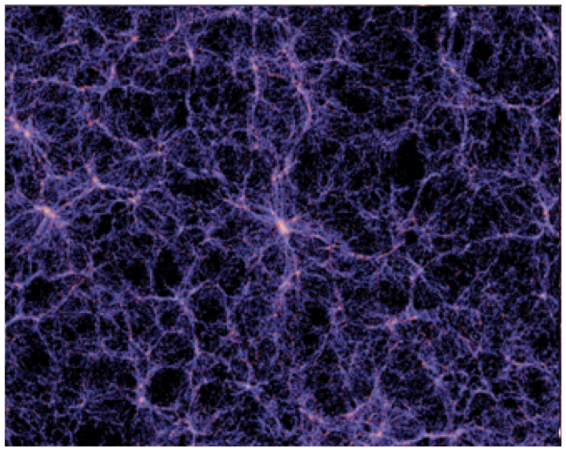


# Galaxy Formation

Galaxy = Structure Formation (Dark Matter) × Baryon Physics



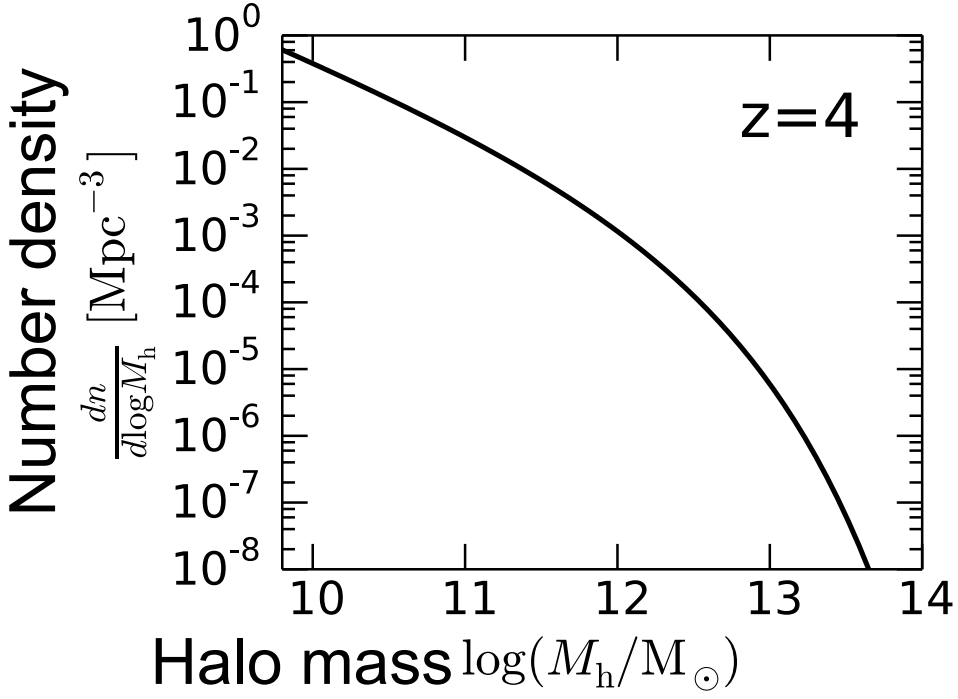

200 Mpc Springel+05



200 Mpc Springel+05

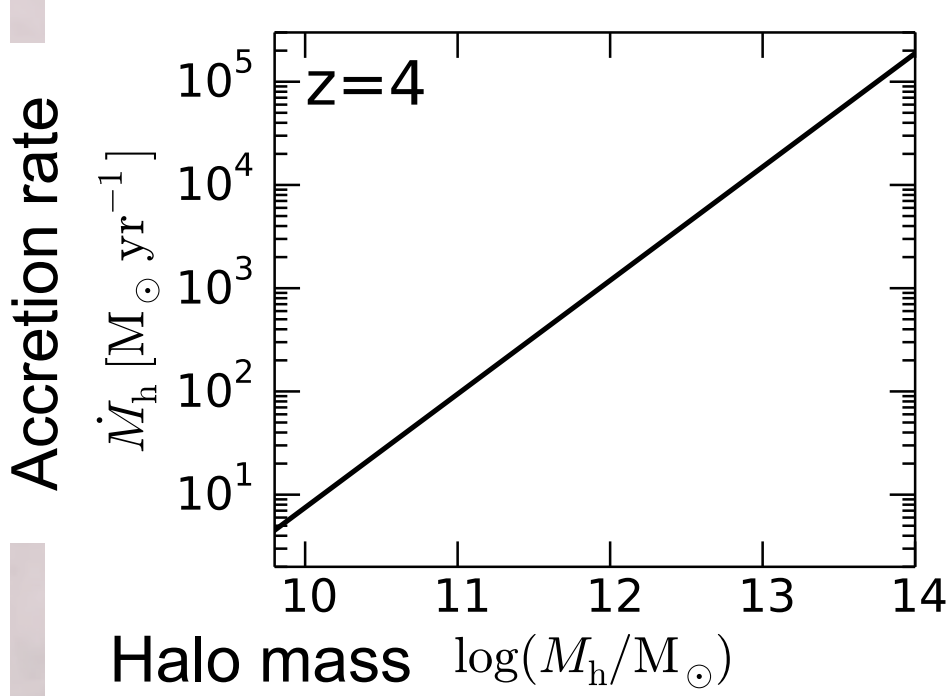
# Structure Formation

## Halo mass function




Behroozi+13

## Mass accretion rate



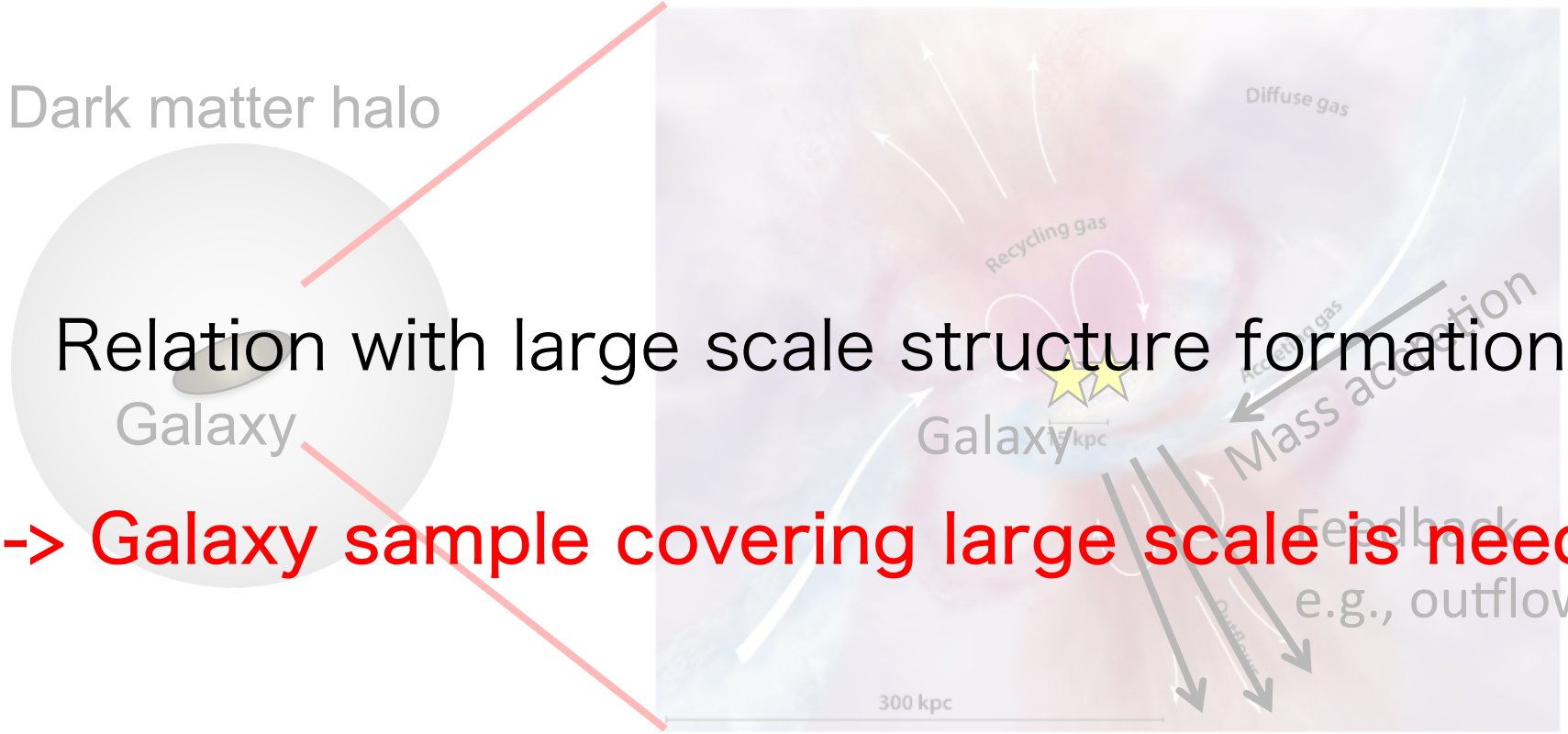

Fakhouri+10

Springel+05

50 Mpc

# Baryon Physics

Mass accretion -> Gas cooling -> Star formation
-> Feedback

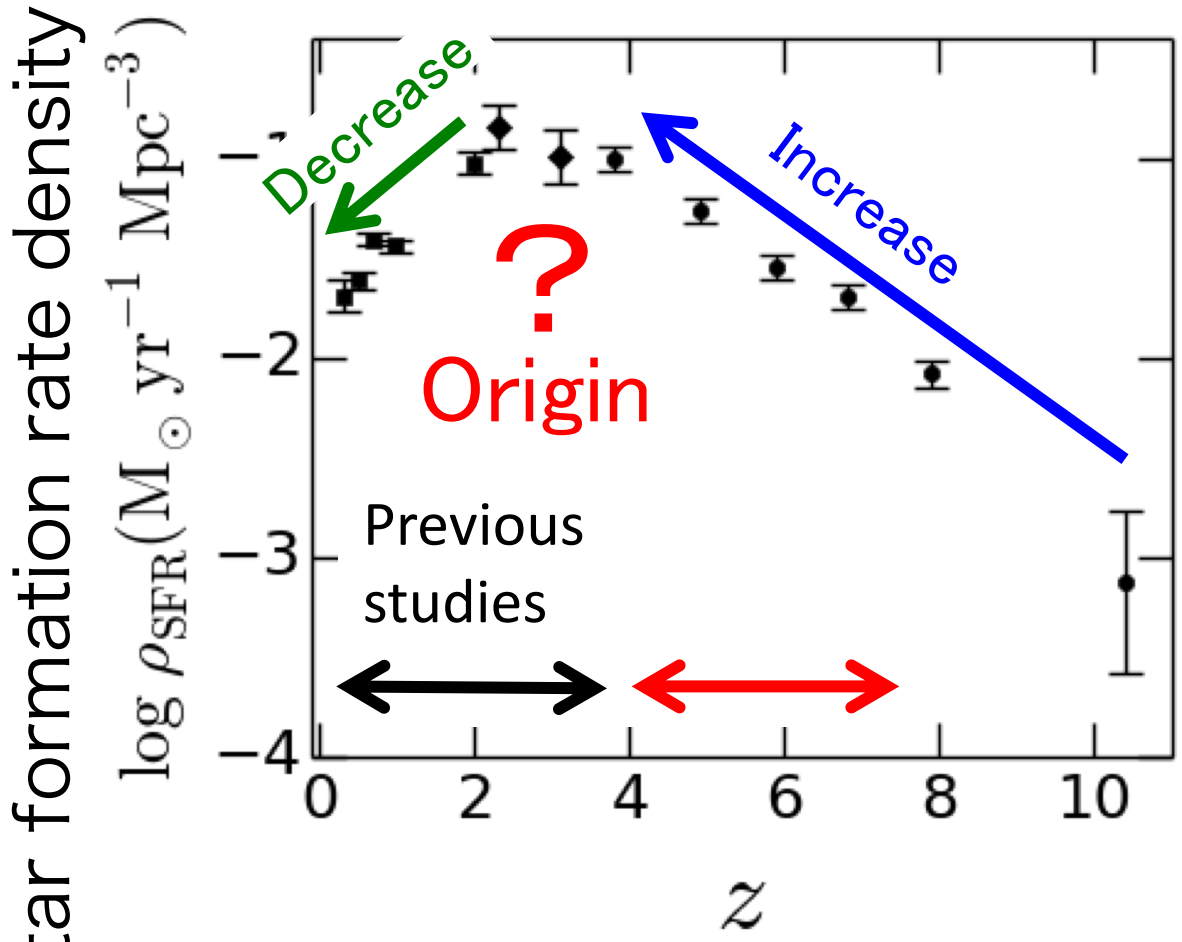



Relation with large scale structure formation?

-> Galaxy sample covering large scale is needed

Tumlinson17

# Cosmic Star Formation History




-> Observation at high redshift (high-z)

# This Talk

High-z galaxy sample covering large scale structures using Subaru/Hyper Suprime-Cam

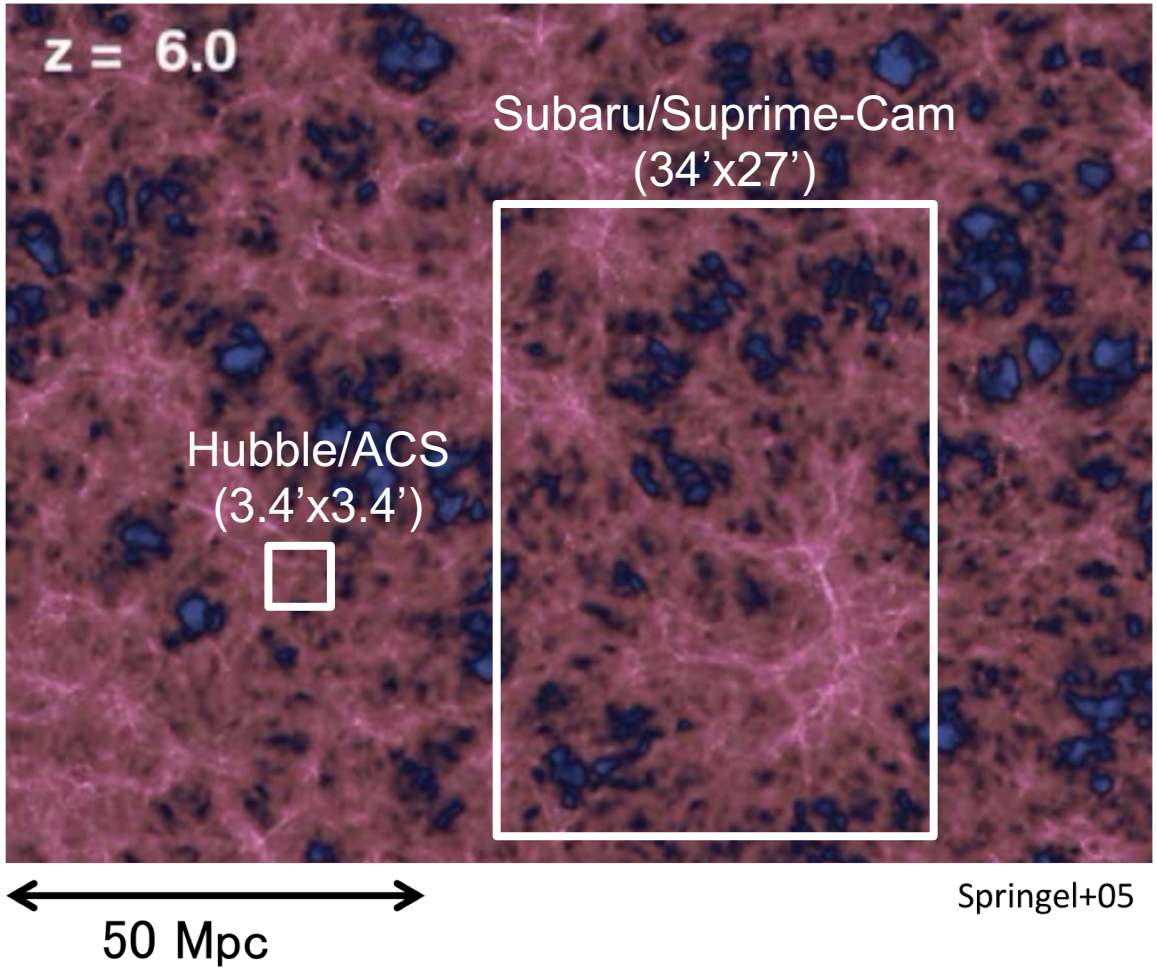
1. Origin of the cosmic star formation history (**average**)
2. Star formation in protoclusters (**special regions**)

# Subaru/Hyper Suprime-Cam Survey

# HSC (1.75 deg$^2$)

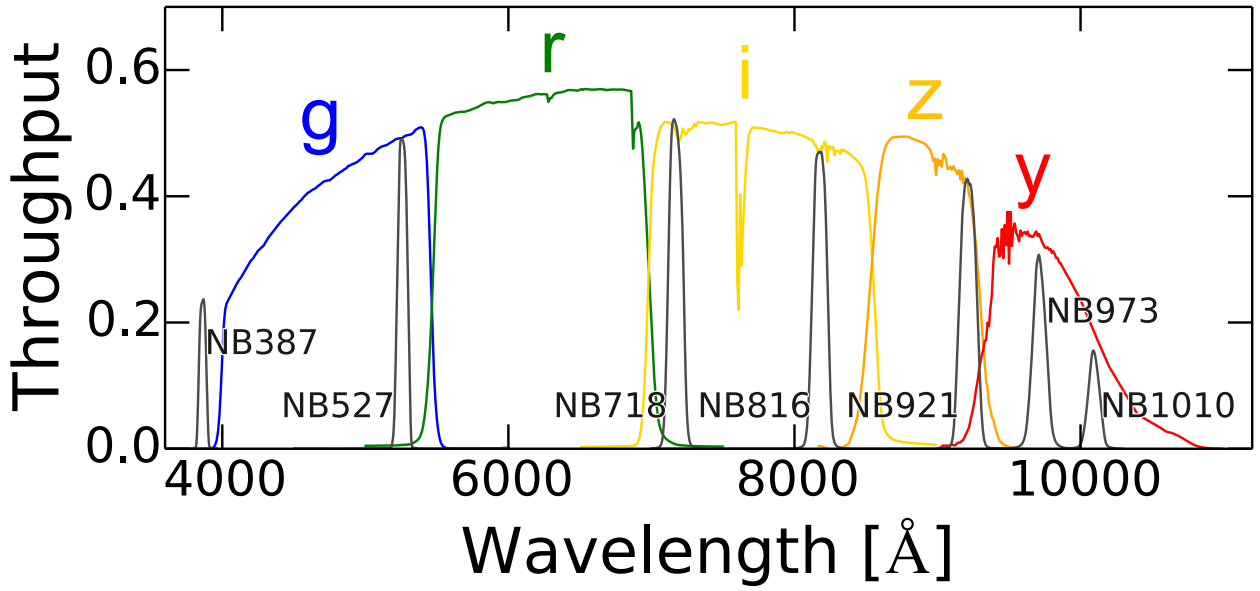
# Subaru/Hyper Suprime-Cam (HSC)

- 4000-11000Å, **wide field of view** (1.75 deg$^2$)



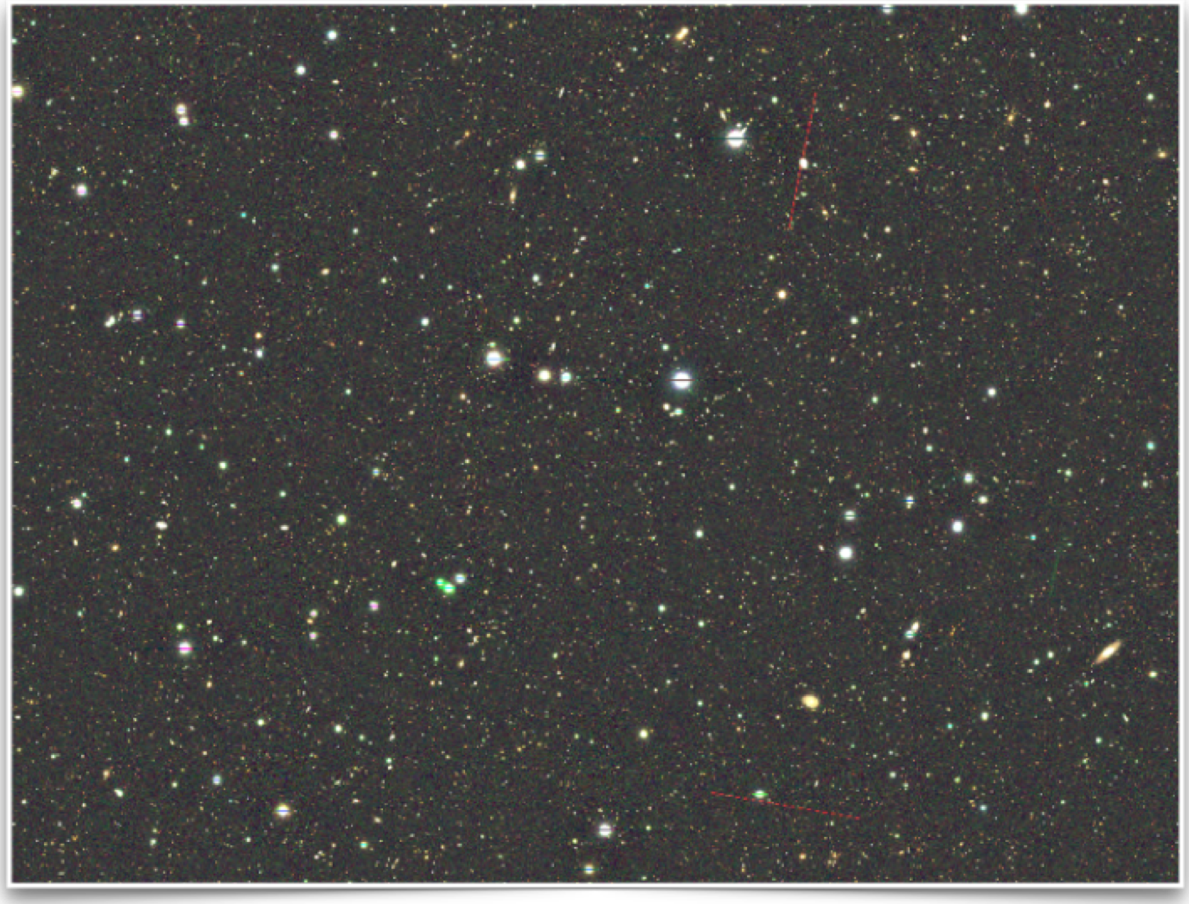
# Subaru/HSC Survey

- Started 2014 March, 300 nights (PI: Miyazaki)
- 5 broad bands + several narrow-bands



# Subaru/HSC Data

- Total: 202,869,535 objects
  >99% are low-redshift interlopers



# Subaru/Hyper Suprime-Cam Survey

**Lyman break galaxies (LBGs; dropouts)**

Ref: Ono+18, YH+18a, Toshikawa+18

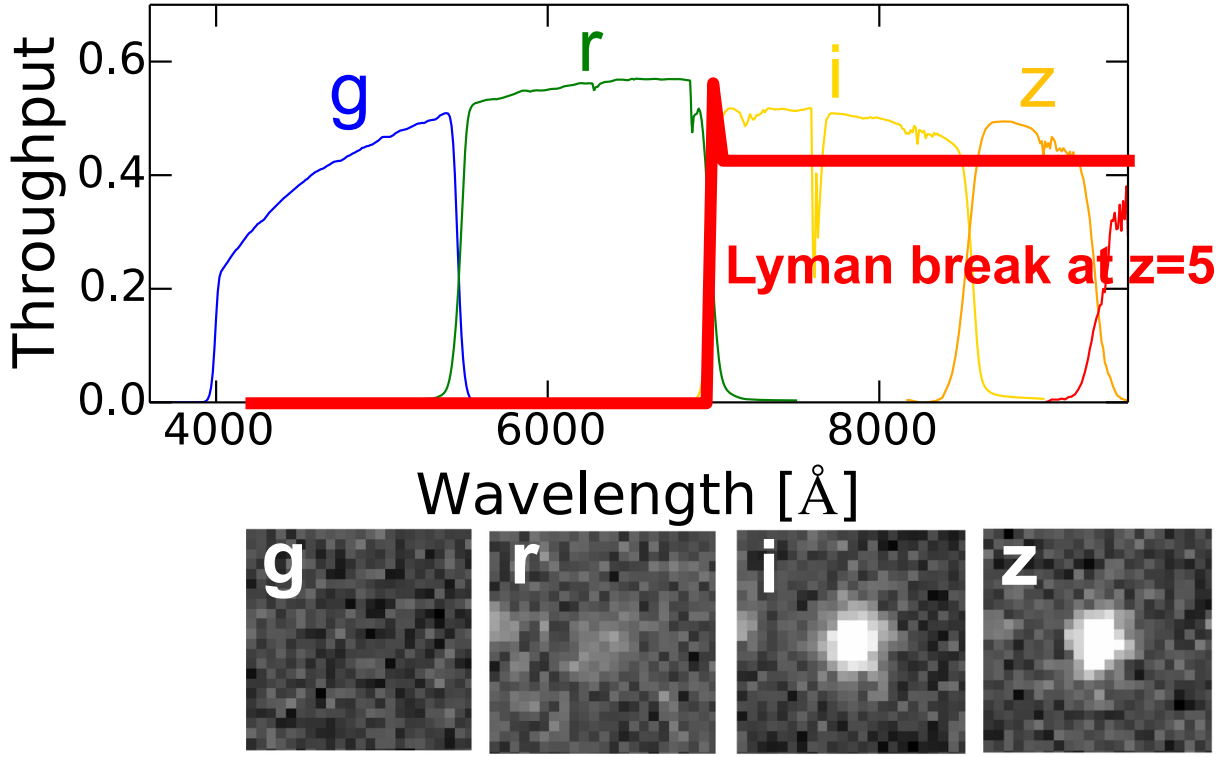

**Lyman alpha emitters (LAEs)**

Ref: Ouchi+18, Shibuya+18ab, Konno+18, Higuchi+18, YH+18a,19

# Lyman Break Selection

GOLDRUSH
Great Optically Luminous Dropout Research Using Subaru HSC

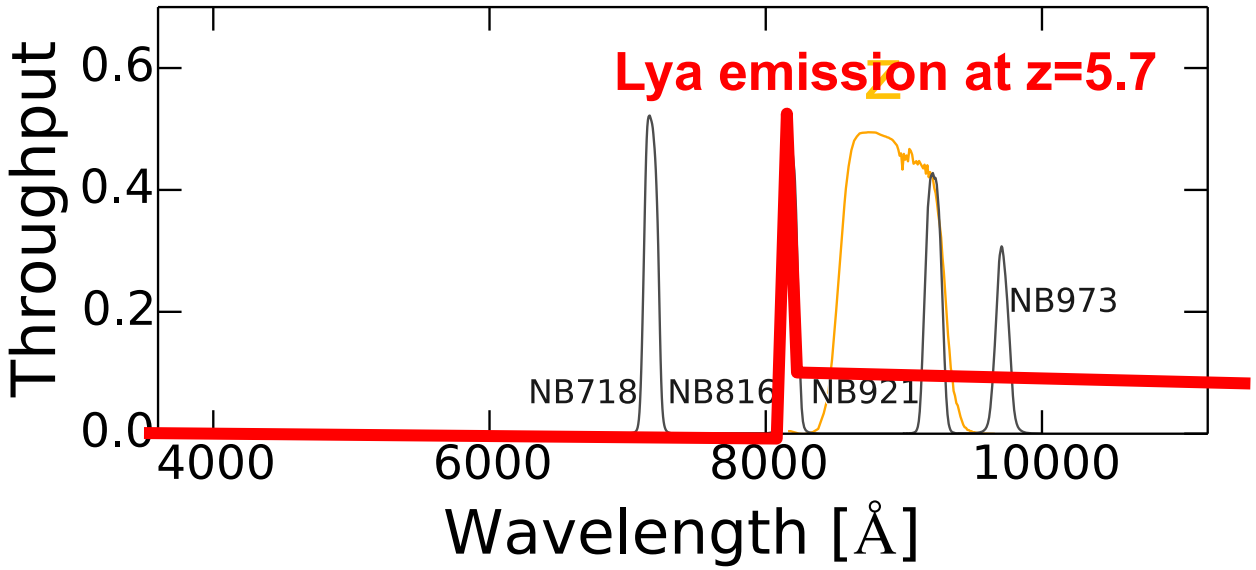
- Lyman break by neutral hydrogen absorption
  - Lyman break galaxy (LBG)

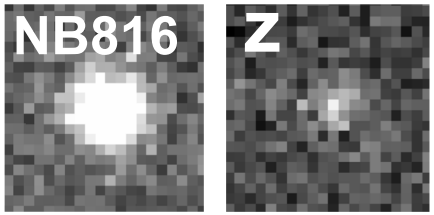


# Narrow-band Selection

SILVERRUSH
Systematic Identification of LAEs for Visible Exploration and Reionization Research Using Subaru HSC

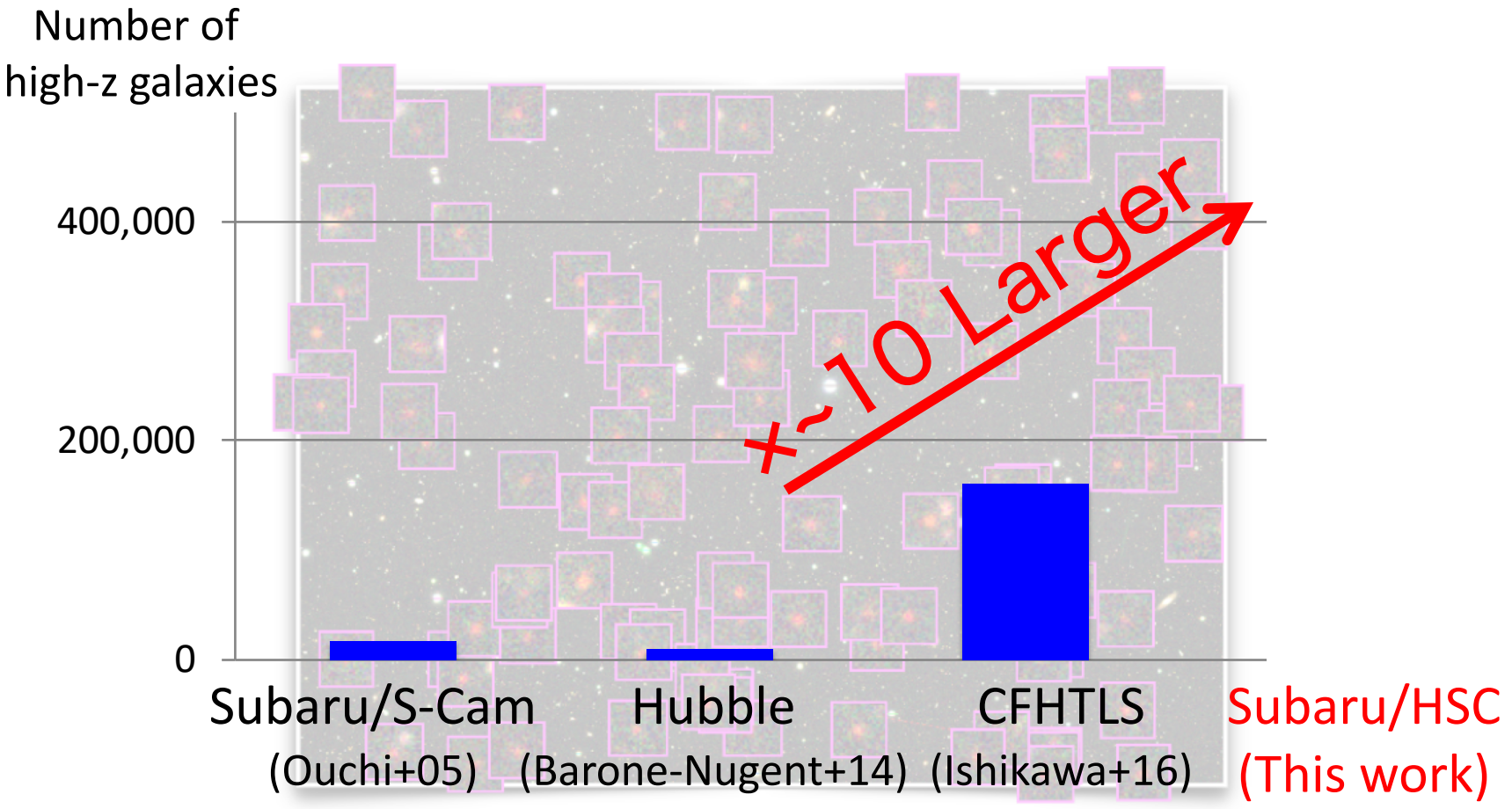
- Redshifted Lya line in narrow-band filter
  - Lya emitter (LAE)

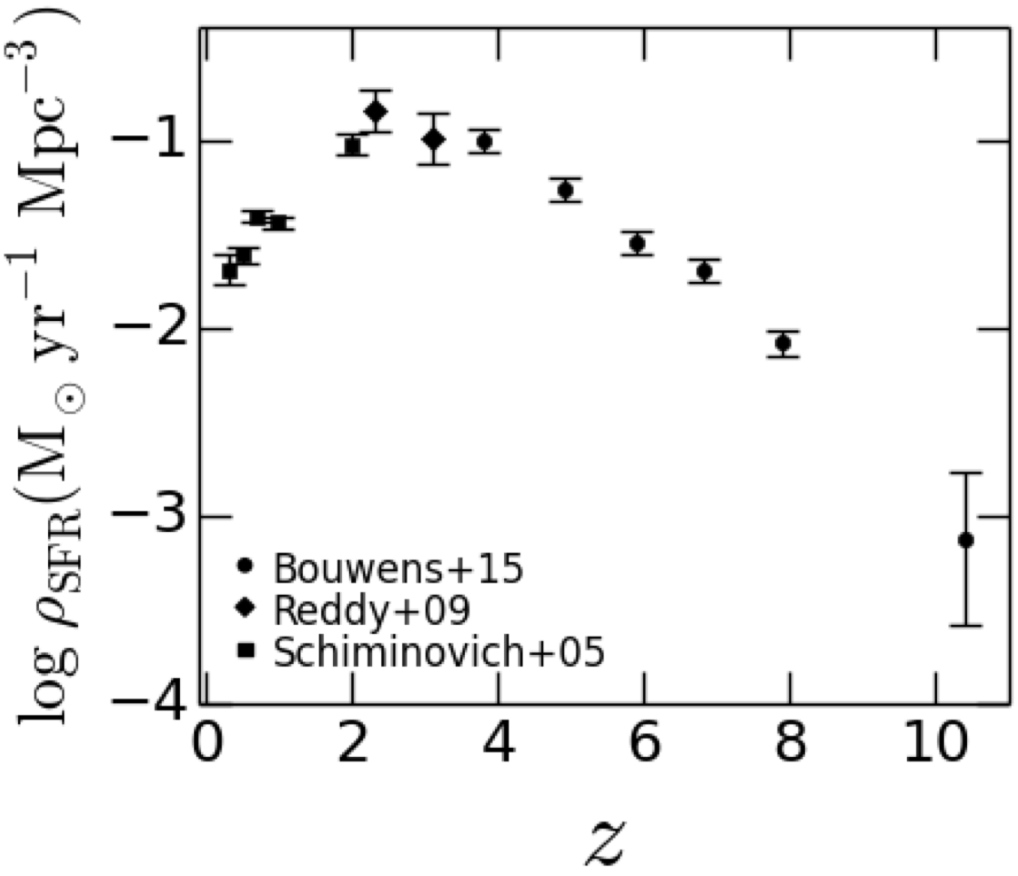


# The Largest High-z Galaxy Sample

- 554,051 LBGs and 2,230 LAEs at z~4-7



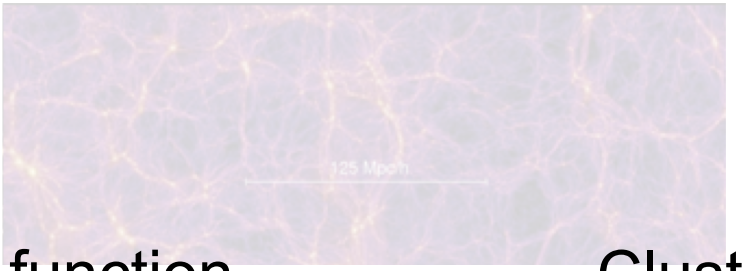


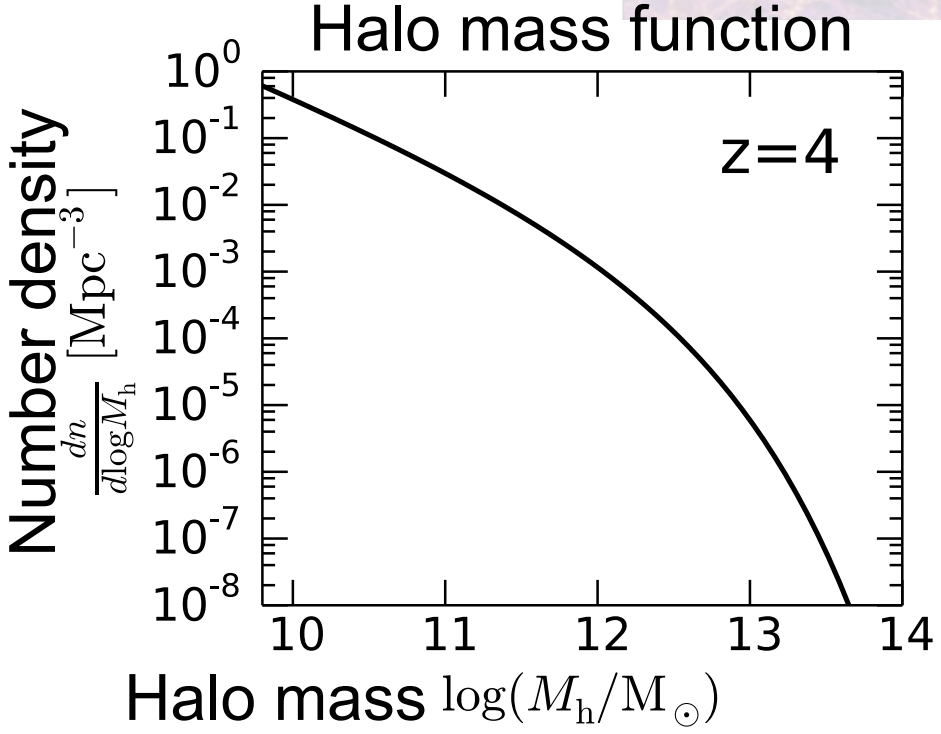

# 1. Origin of the Cosmic Star Formation History

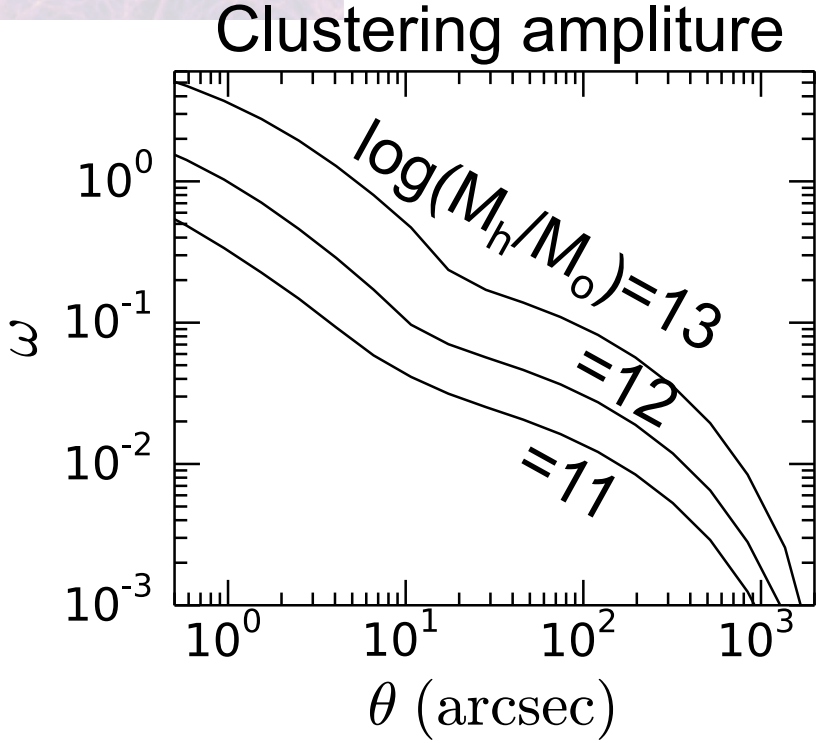
(Harikane+18a)

# Structure Formation and Halo Mass

Structure Formation Model
(Halo mass is important)





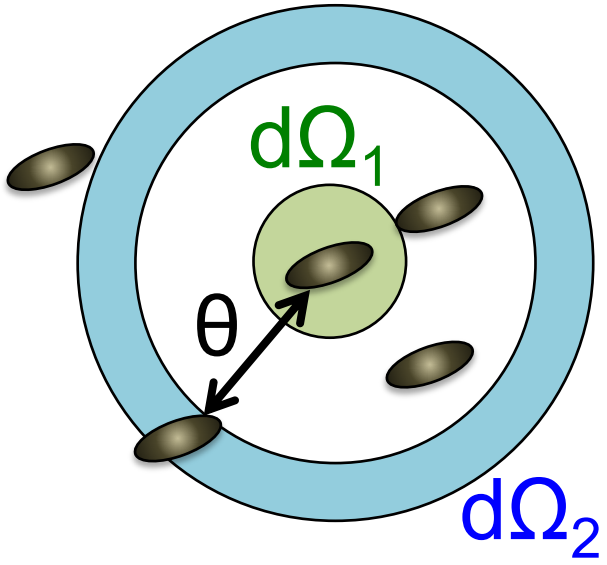
# Angular Correlation Function

Angular correlation function $\omega(\theta)$

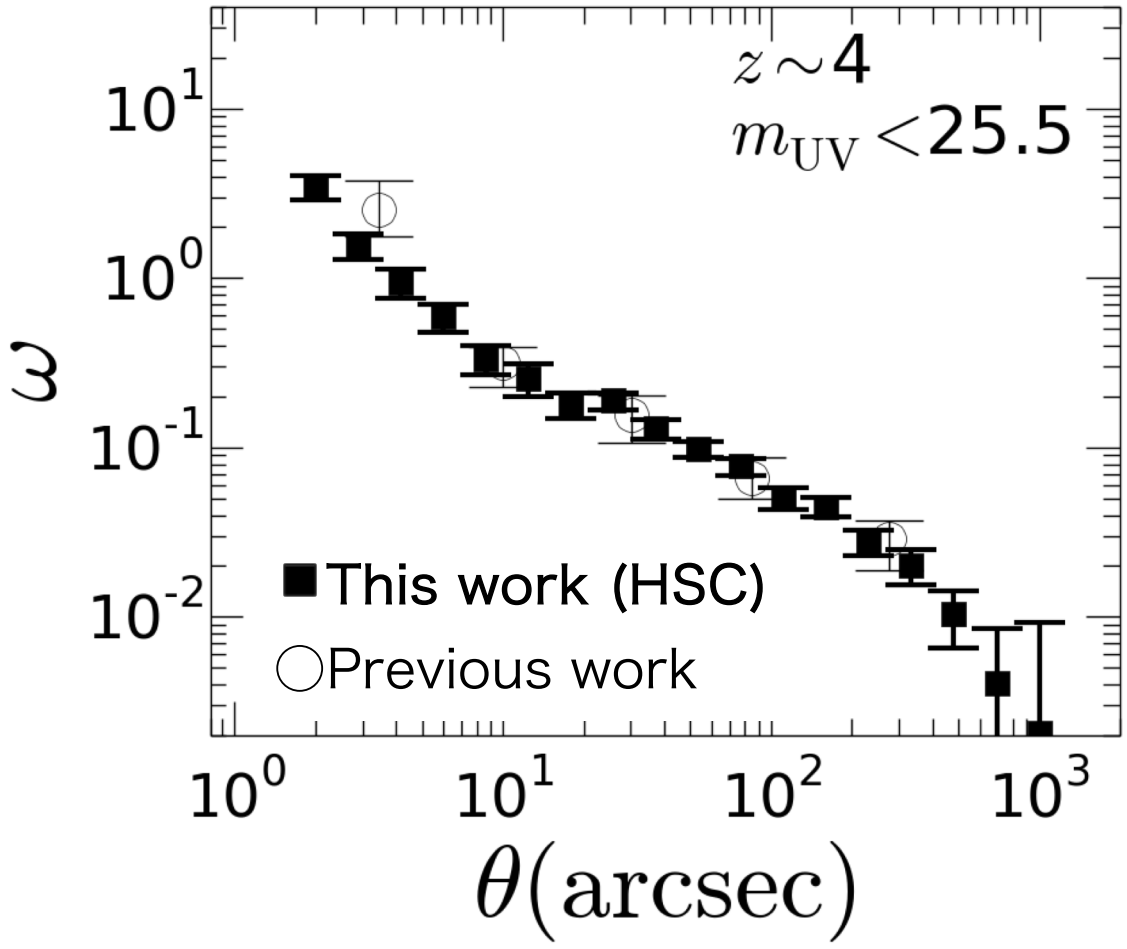
$$dP=n^2(1+\omega(\theta))d\Omega_1 d\Omega_2$$

dP: Probability of finding a galaxy pair

n : Surface number density

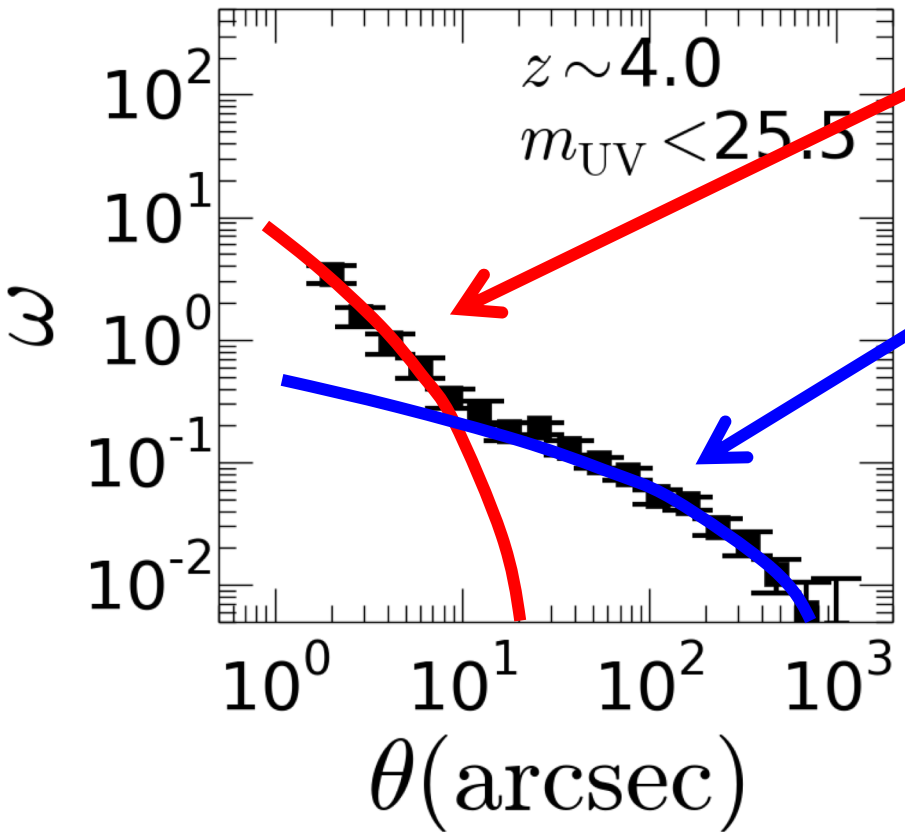


# Angular Correlation Function




- Redshift and magnitude subsamples

# Obtained Correlation Function

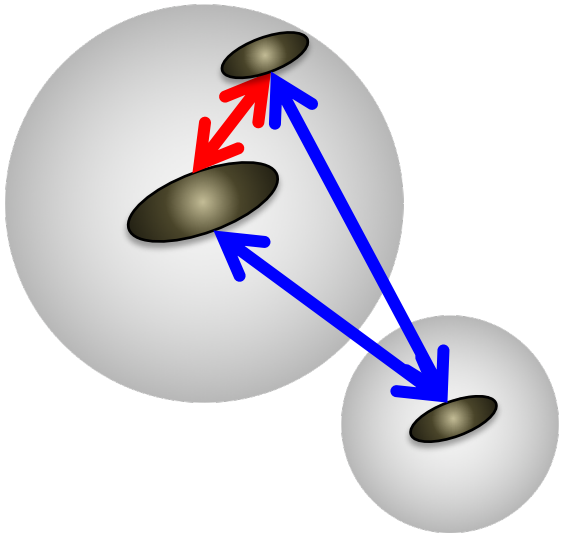



1 halo term:

Pair in the same halo

2 halo term:

Pair in distinct halos



# Halo Occupation Distribution (HOD) Model

## 1 halo term

$$P_{\rm g}^{\rm cs}(k,z) = \frac{2}{n_{\rm g}^2}\int dM_{\rm h}\,\langle N_{\rm c}N_{\rm s}\rangle\,(M_{\rm h})\frac{dn}{dM_{\rm h}}(M_{\rm h},z)u(k,M_{\rm h},z)$$

$$P_{\rm g}^{\rm ss}(k,z) = \frac{1}{n_{\rm g}^2}\int dM_{\rm h}\,\langle N_{\rm s}(N_{\rm s}-1)\rangle\,(M_{\rm h})\frac{dn}{dM_{\rm h}}(M_{\rm h},z)u^2(k,M_{\rm h},z)$$

HOD　　Halo profile

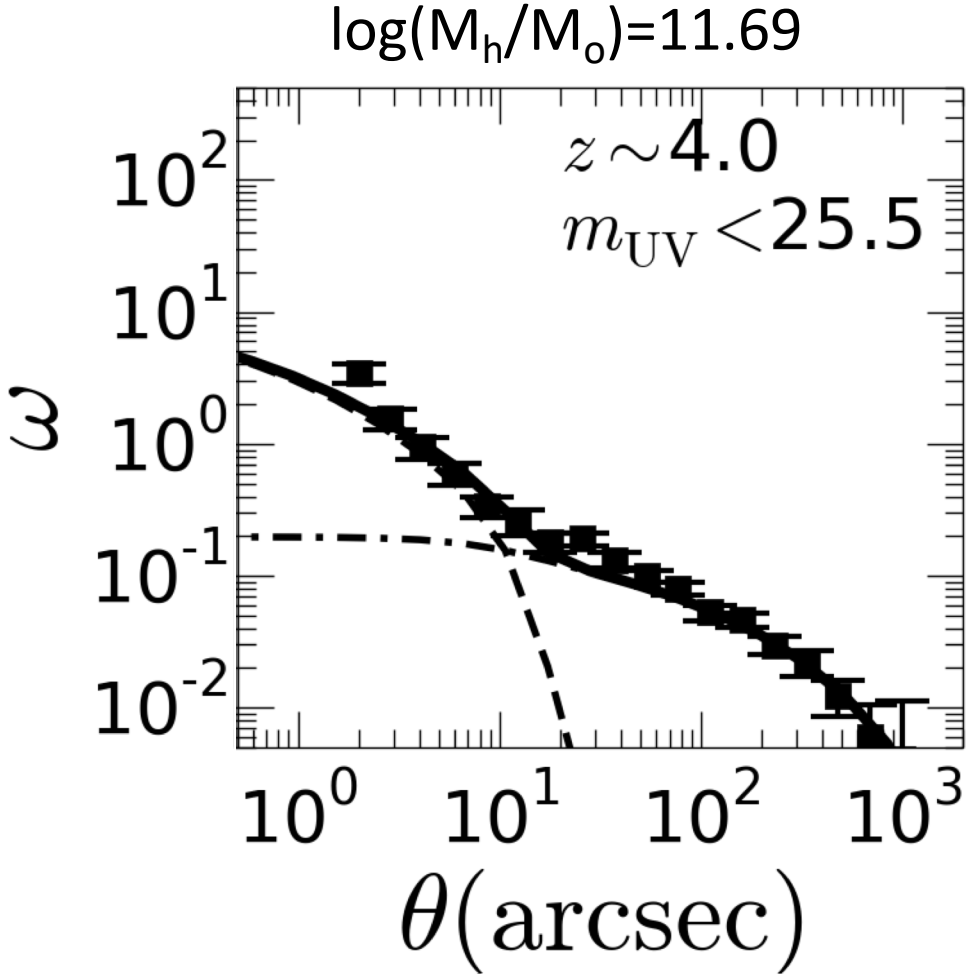
## 2 halo term

$$P_{\rm g}^{\rm 2h}(k,z) = P_{\rm m}(k,z)\left[\frac{1}{n_{\rm g}}\int dM_{\rm h}\,N(M_{\rm h})\frac{dn}{dM_{\rm h}}(M,z)b_{\rm h}(M_{\rm h},z)u(k,M_{\rm h},z)\right]^2$$

HOD　　Halo bias

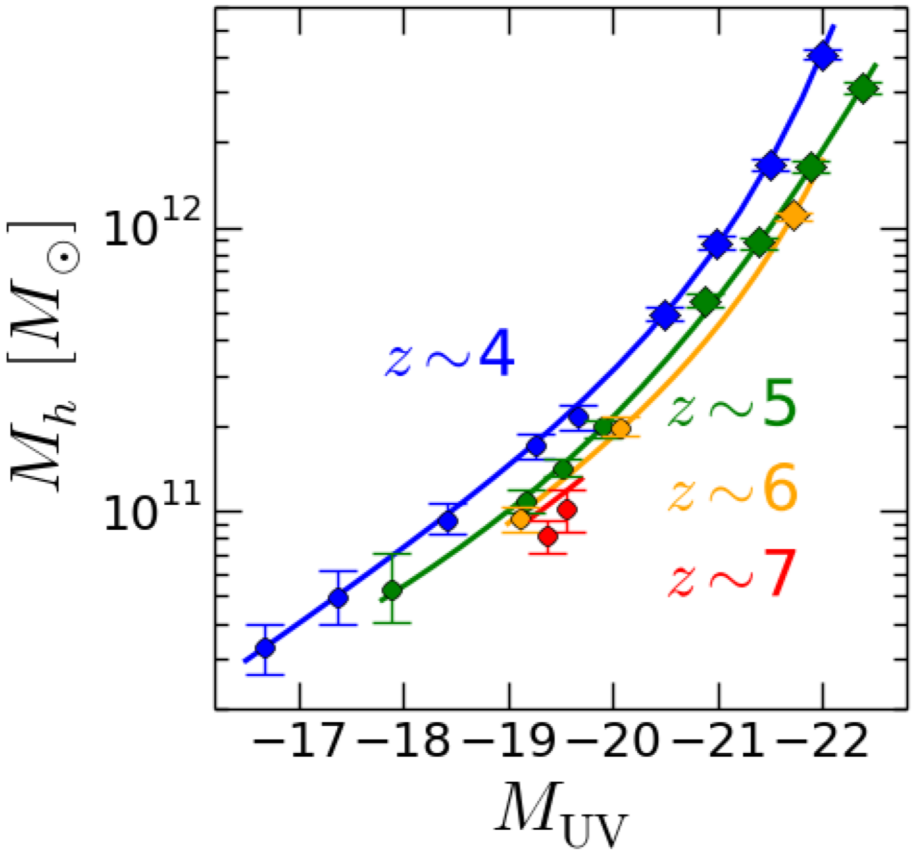
$$\omega(\theta) = \int dz N^2(z)\left(\frac{dr}{dz}\right)^{-1}\int dk\frac{k}{2\pi}P_{\rm g}(k,z)J_0[r(z)\theta k]$$

# HOD Model Fitting



# Results: Halo Mass

$M_h$=4x$10^{10}$ $M_o$ – 4x$10^{12}$ $M_o$

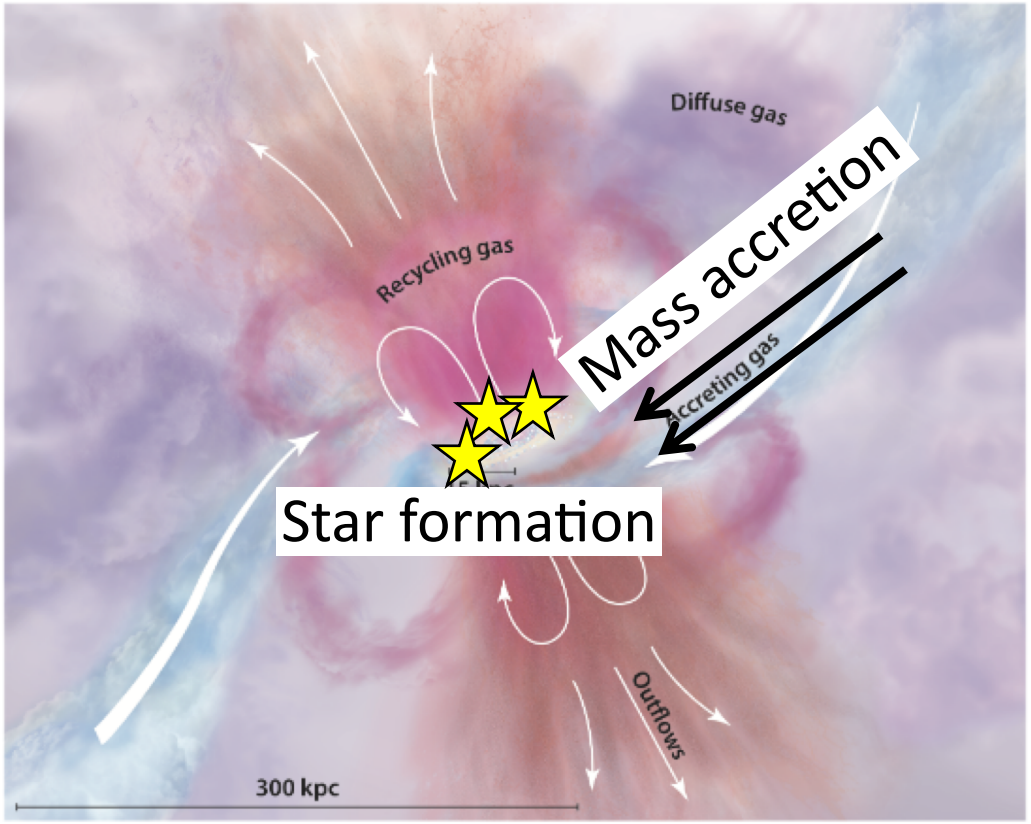


# Star Formation-Accretion Fundamental Relation

- $M_h$, SF
- $\dot{M}_h$ - M

$$\frac{SFR}{\dot{M}_h} = \frac{2 \times 1.7 \times 10^{-2}}{(M_h/10^{11.35})^{-1.1} + (M_h/10^{11.35})^{0.3}}$$

Star Formation Rate / Mass Accretion Rate $\mathrm{SFR}/\dot{M}_h$




Tumlinson17

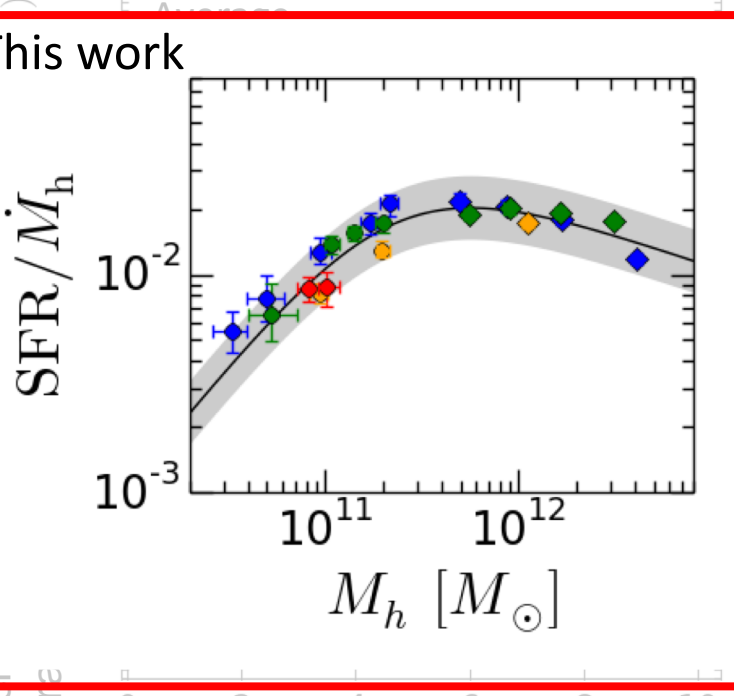
# Cosmic Star Formation History

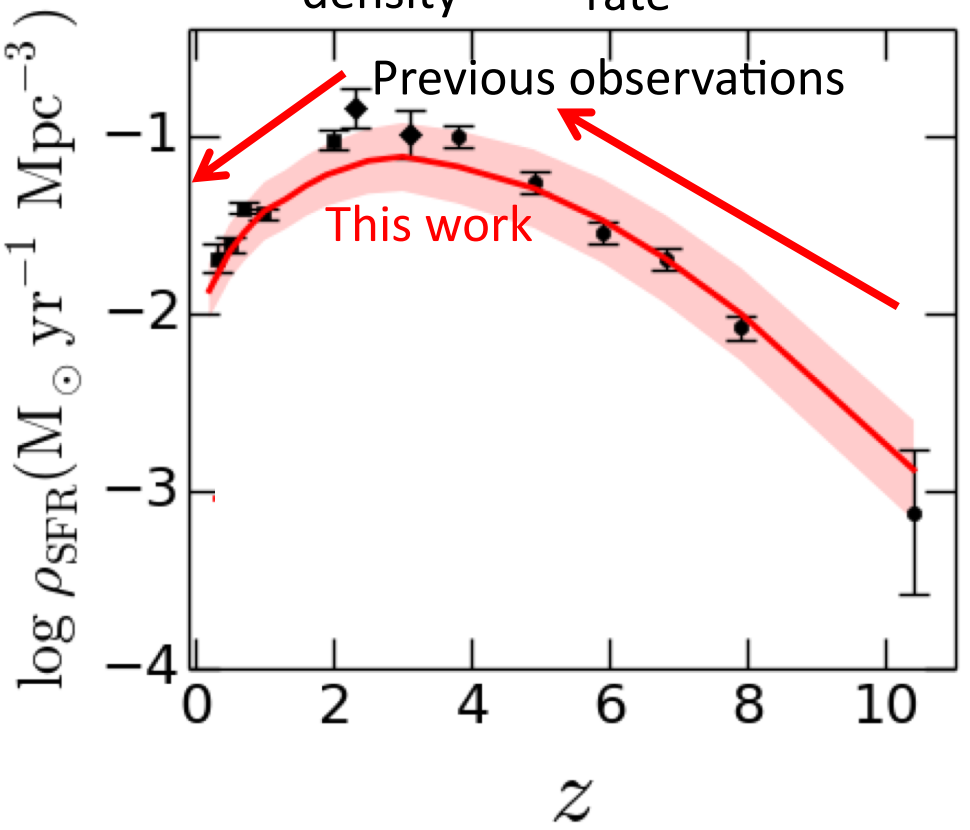
$$\rho_{\rm SFR} = \int dM_{\rm h} \frac{dn}{dM_{\rm h}} SFR = \int dM_{\rm h} \frac{dn}{dM_{\rm h}} \dot{M}_{\rm h}(M_{\rm h}, z) \frac{SFR}{\dot{M}_{\rm h}}$$

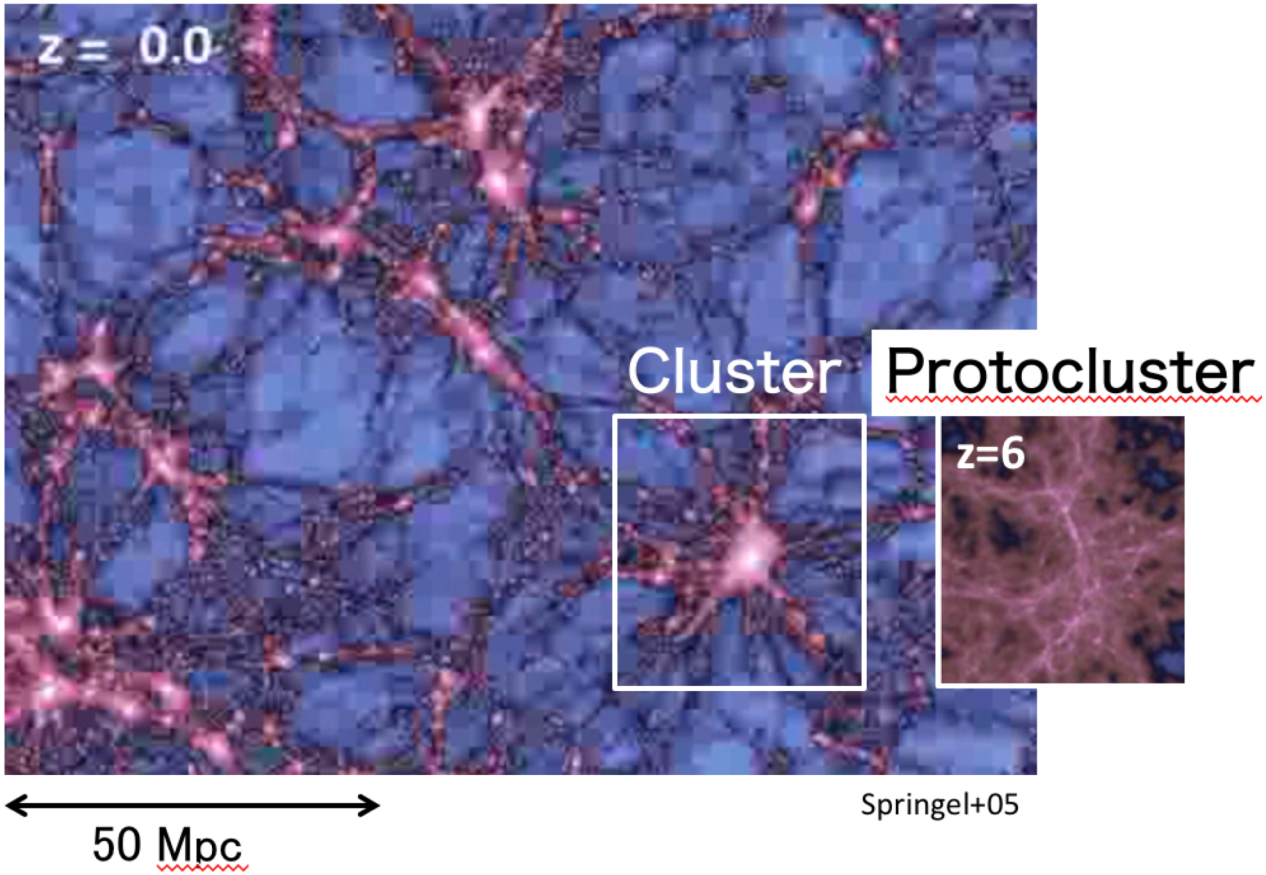
Number density | Accretion rate | This work

N-body simulation

This work



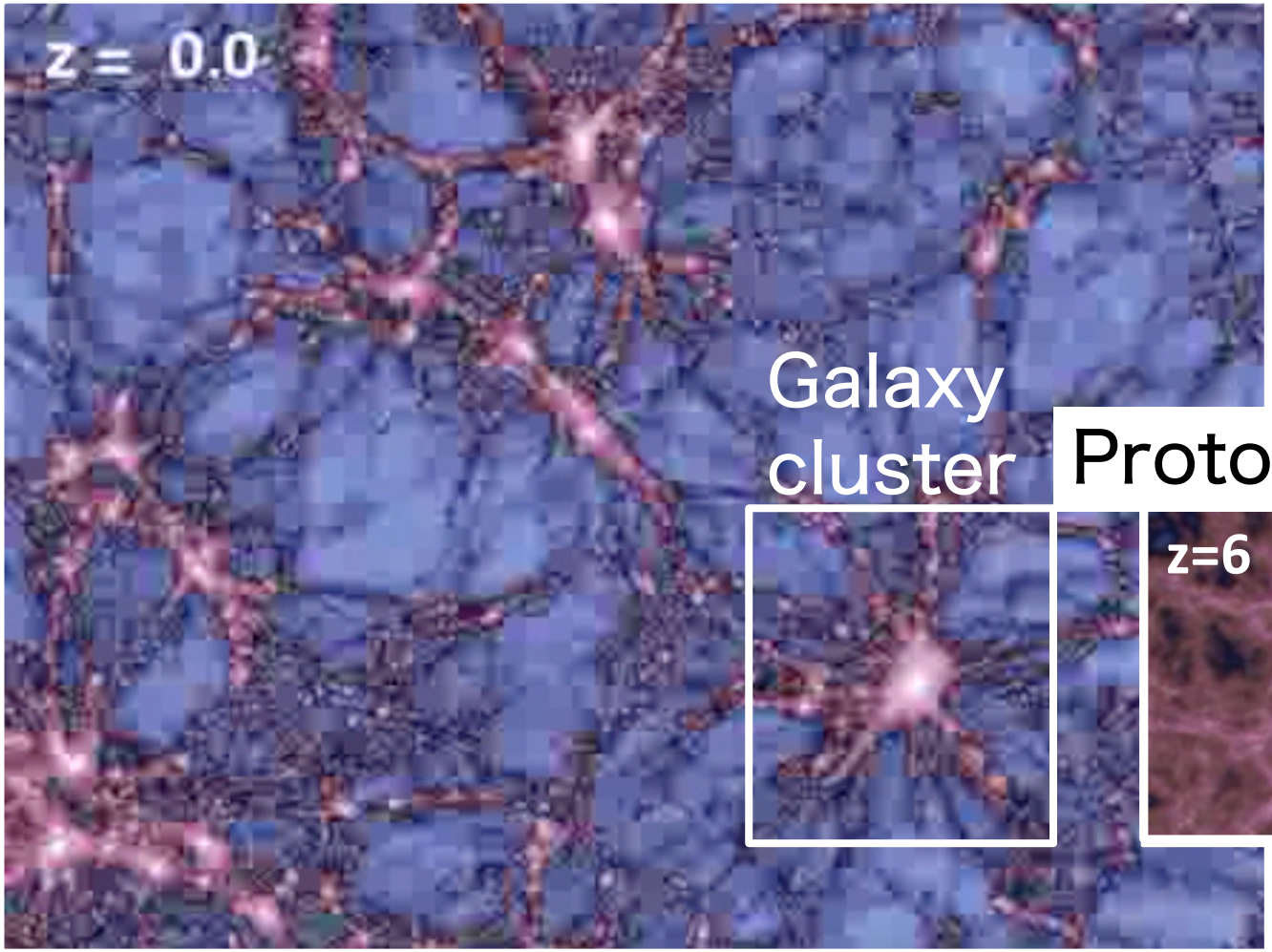






# 2. Star Formation in Protoclusters

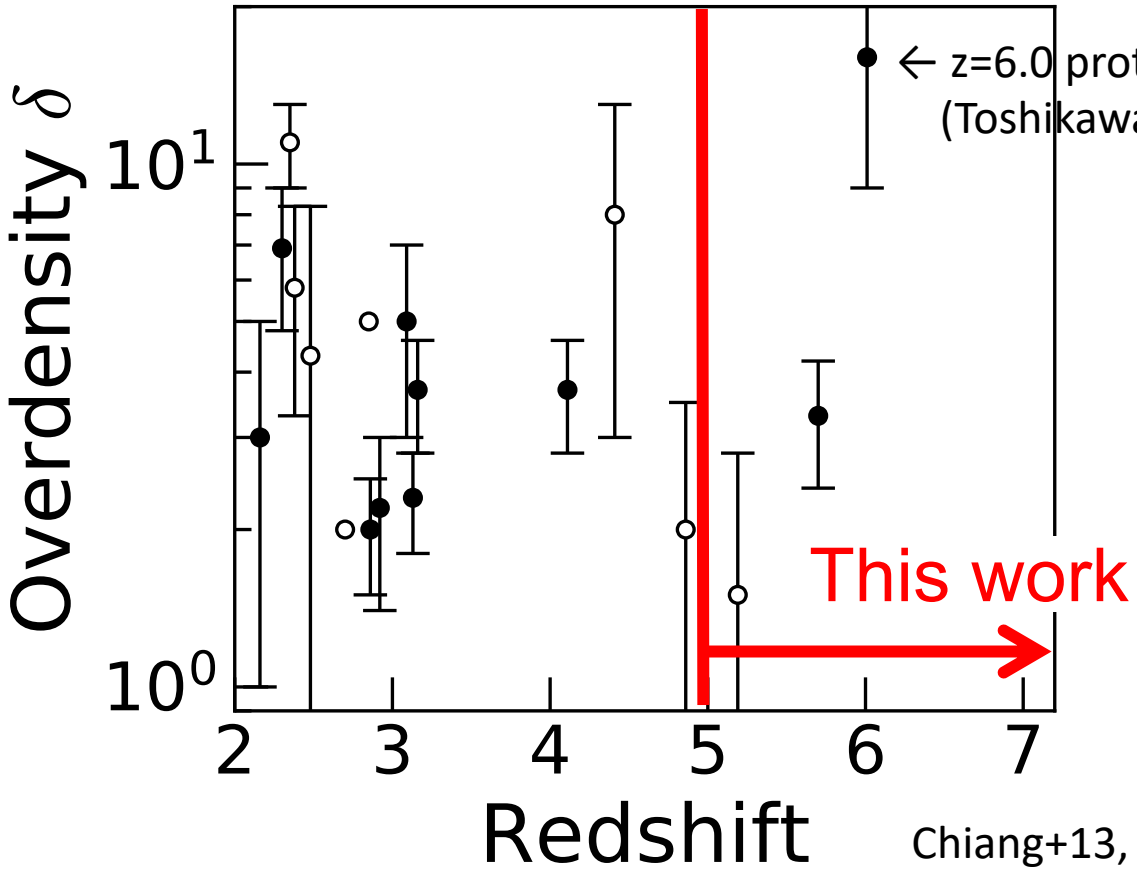
(Harikane+19)

# Protoclusters



# High Redshift Protoclusters

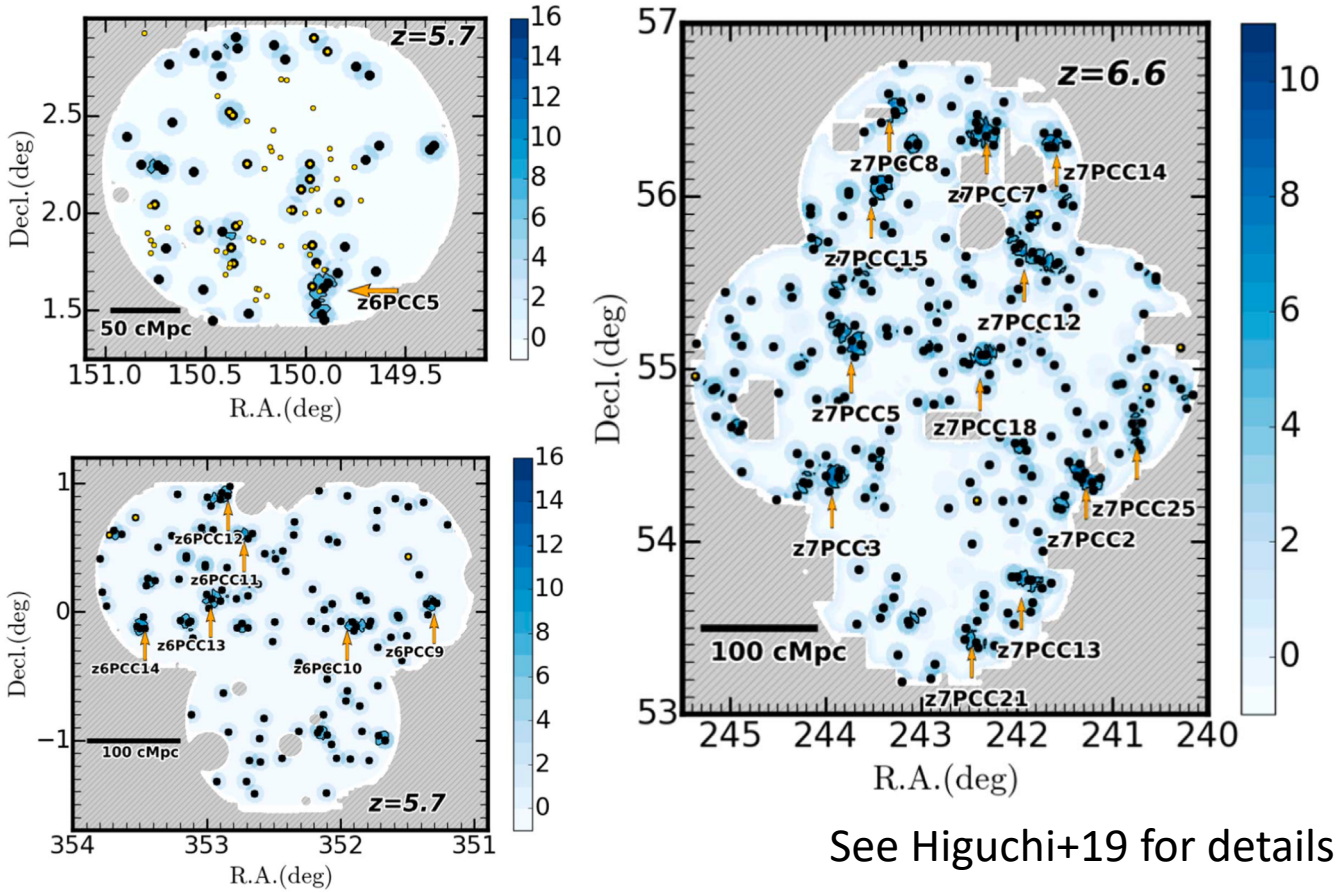
- Only a few protoclusters are identified at z>5
- Large area deep survey is needed -> Subaru/HSC




Chiang+13, Overzier+16

# SILVERRUSH Protoclusters

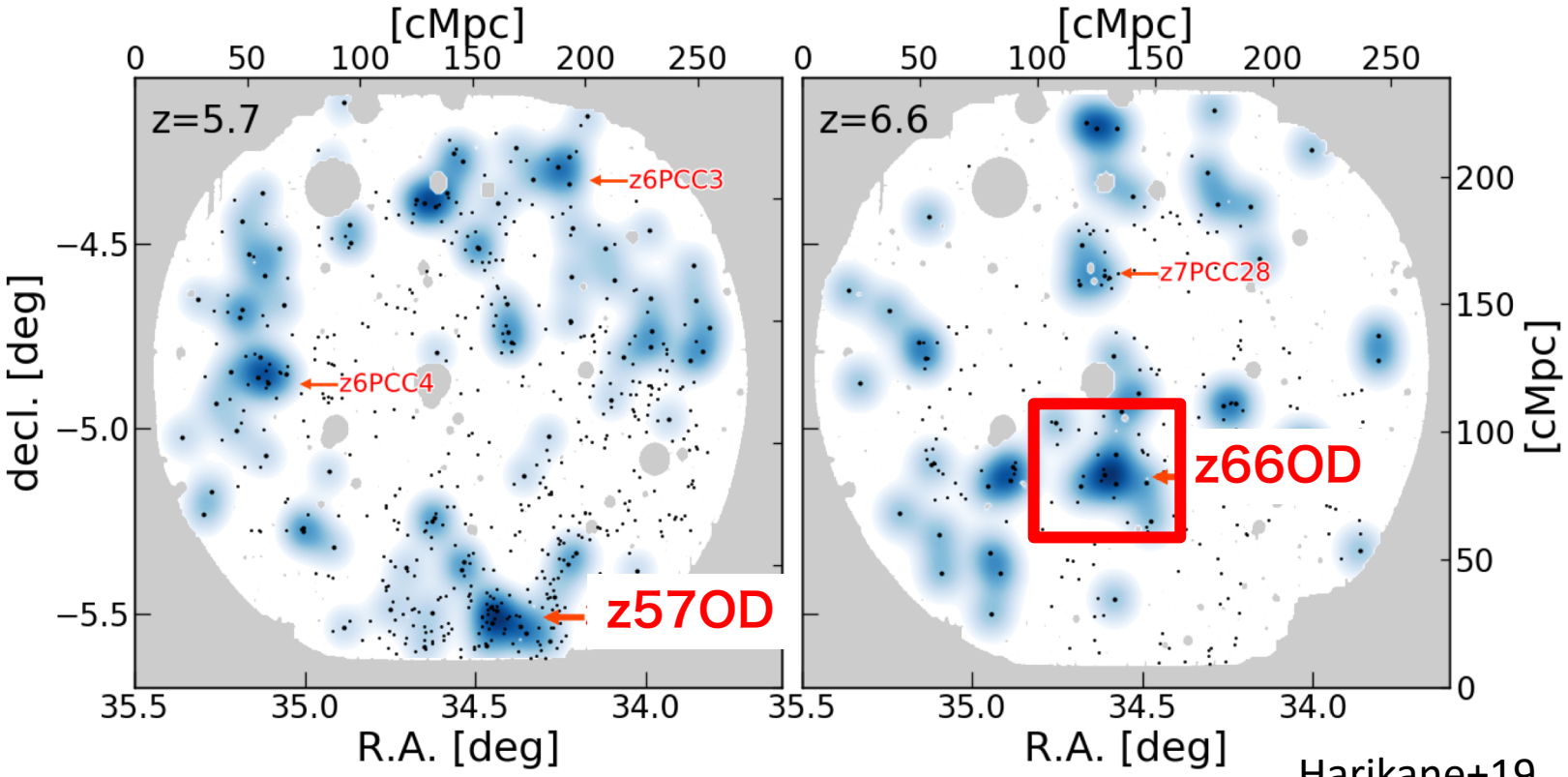
- ~2000 LAEs at z=5.7, 6.6 in 15 deg$^2$ (Shibuya+18)
- 40 protocluster candidates at z=5.7,6.6




See Higuchi+19 for details

# Protoclusters in the SXDS field

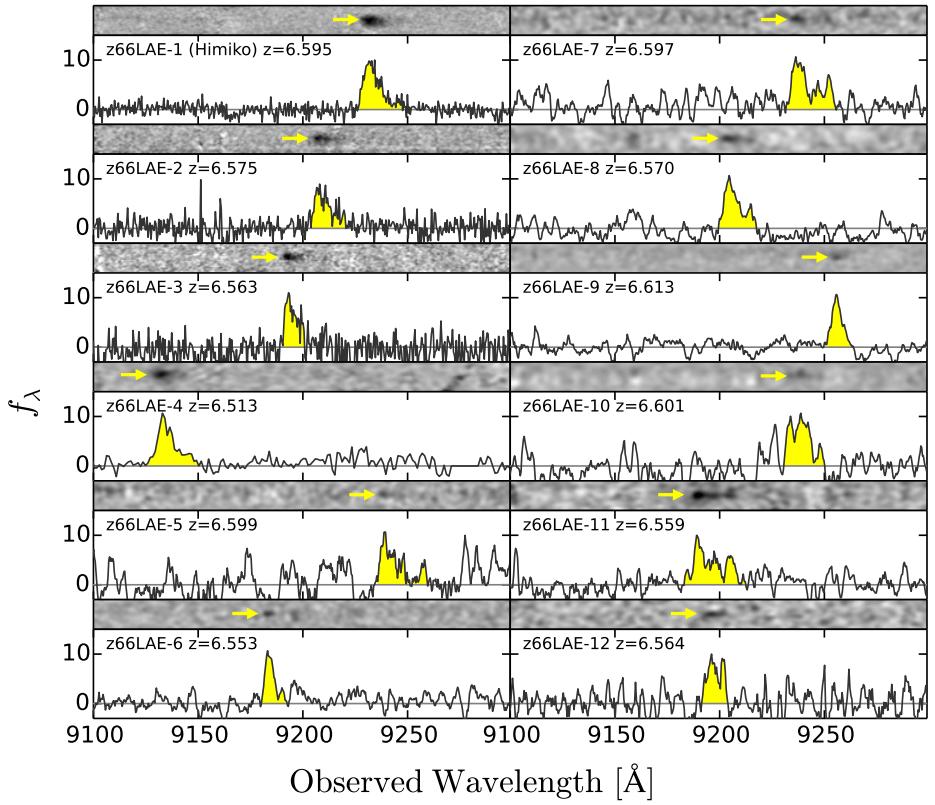
- 810 LAEs at z=5.7, 6.6 with NB816 & NB921
- Overdensity δ in 10cMpc $\delta = \frac{n - \overline{n}}{\overline{n}}$

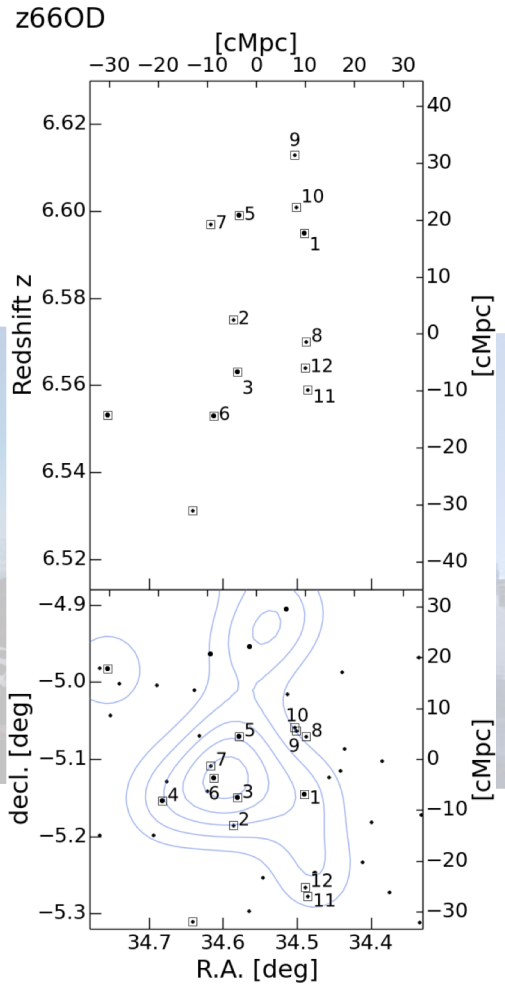



Harikane+19

# Spectroscopy for z66OD

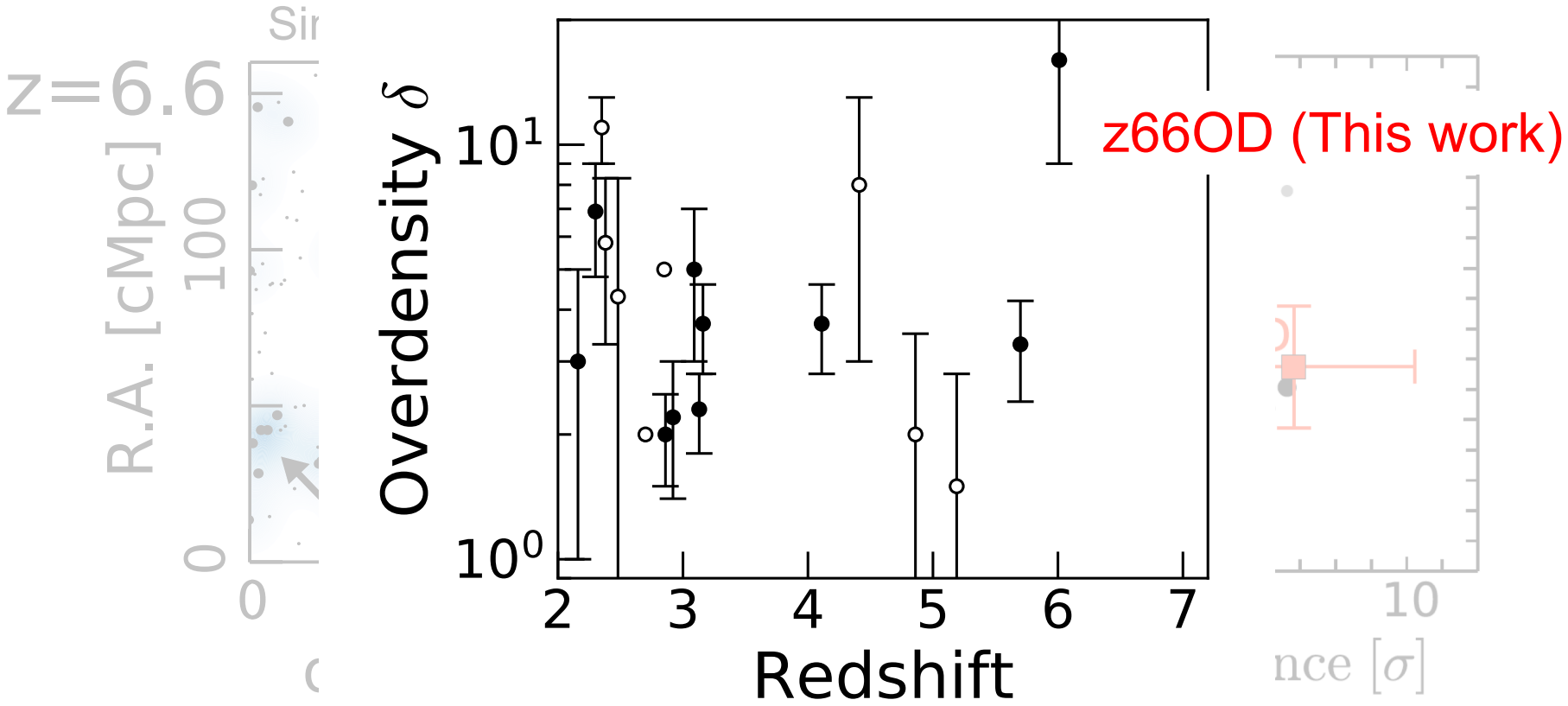
- Spectroscopic confirmation of z66OD at <z>=6.585 with $N_{spec}$=12



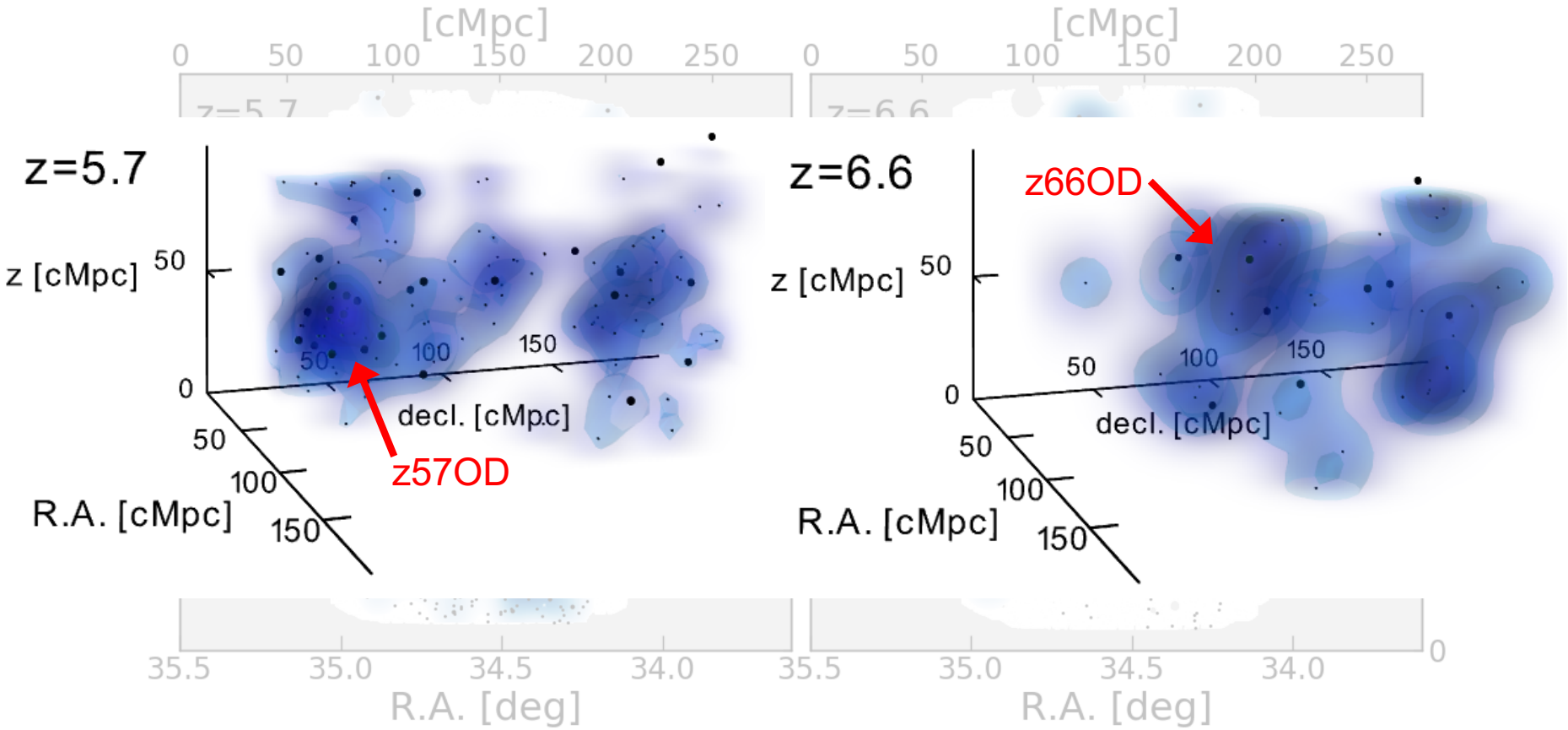
# Is z66OD Protocluster?

- simOD4: similar overdensity to z66OD
  - Halo mass $M_h$~$10^{12}$ $M_o$ → >$10^{14}$ $M_o$ at z=0



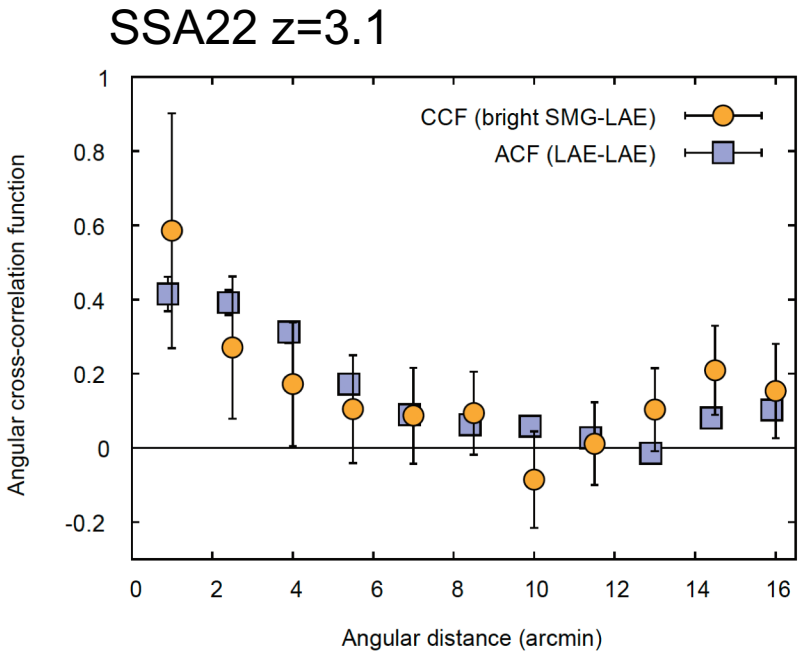
# 3D Map at z=5.7, 6.6

- 174 spec-z LAEs (>80% at $L_{Lya}>10^{43}$ erg/s)



# LAE-SMG Correlation

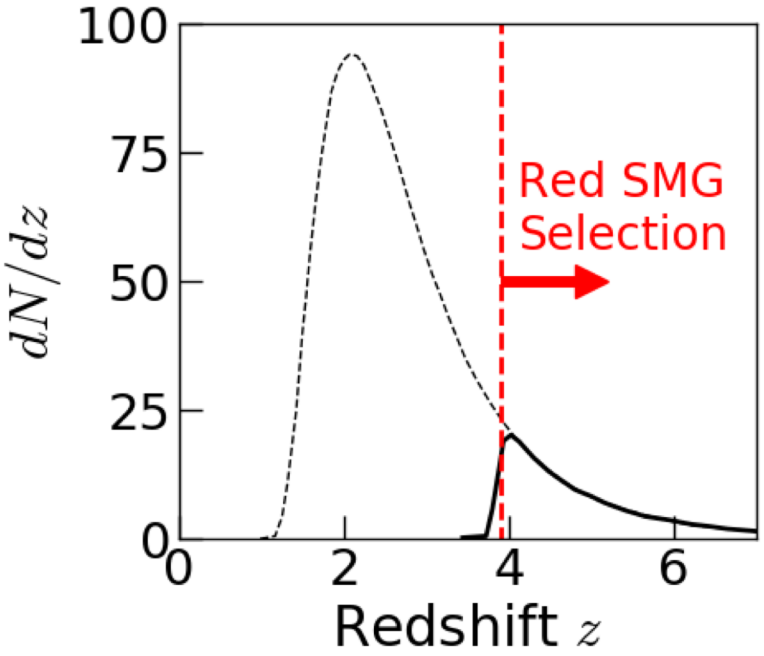
- LAE: dust-poor star-forming galaxies
- Submillimeter galaxies (SMGs): dusty star-forming
  - Cross-correlation reported at z=3.1 in SSA22 protocluster

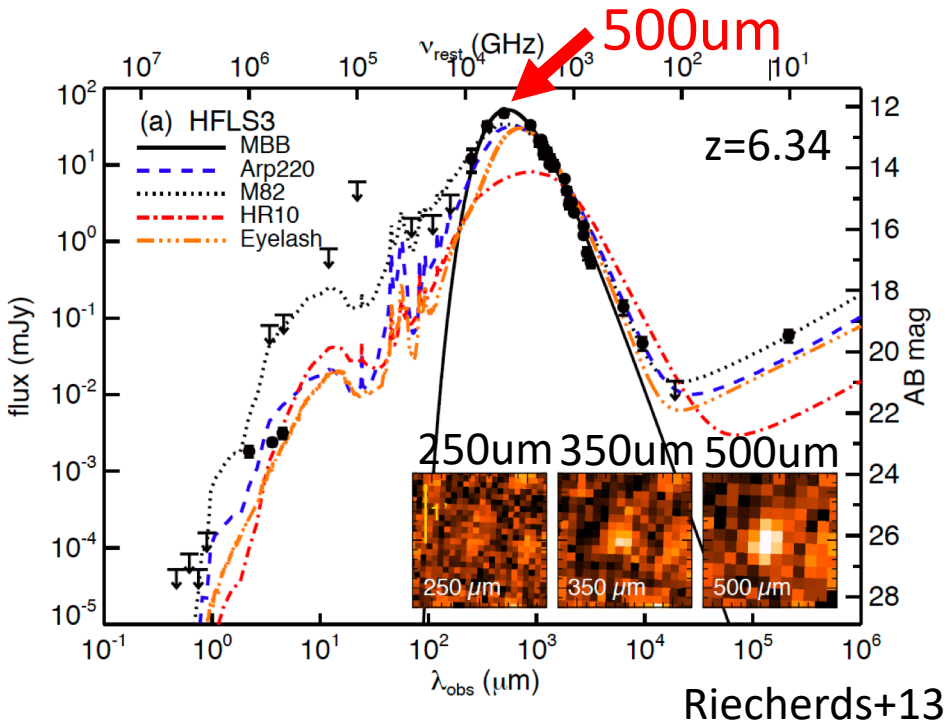



Tamura+09 Nature

# Red SMG Selection

- Submillimeter galaxy (SMG) catalog (Geach+17)
- Select ”Red SMG” (z>4) using Herschel color
  - $S_{250} < S_{350} < S_{500}$ (Donevski+18) -> 42 red SMGs

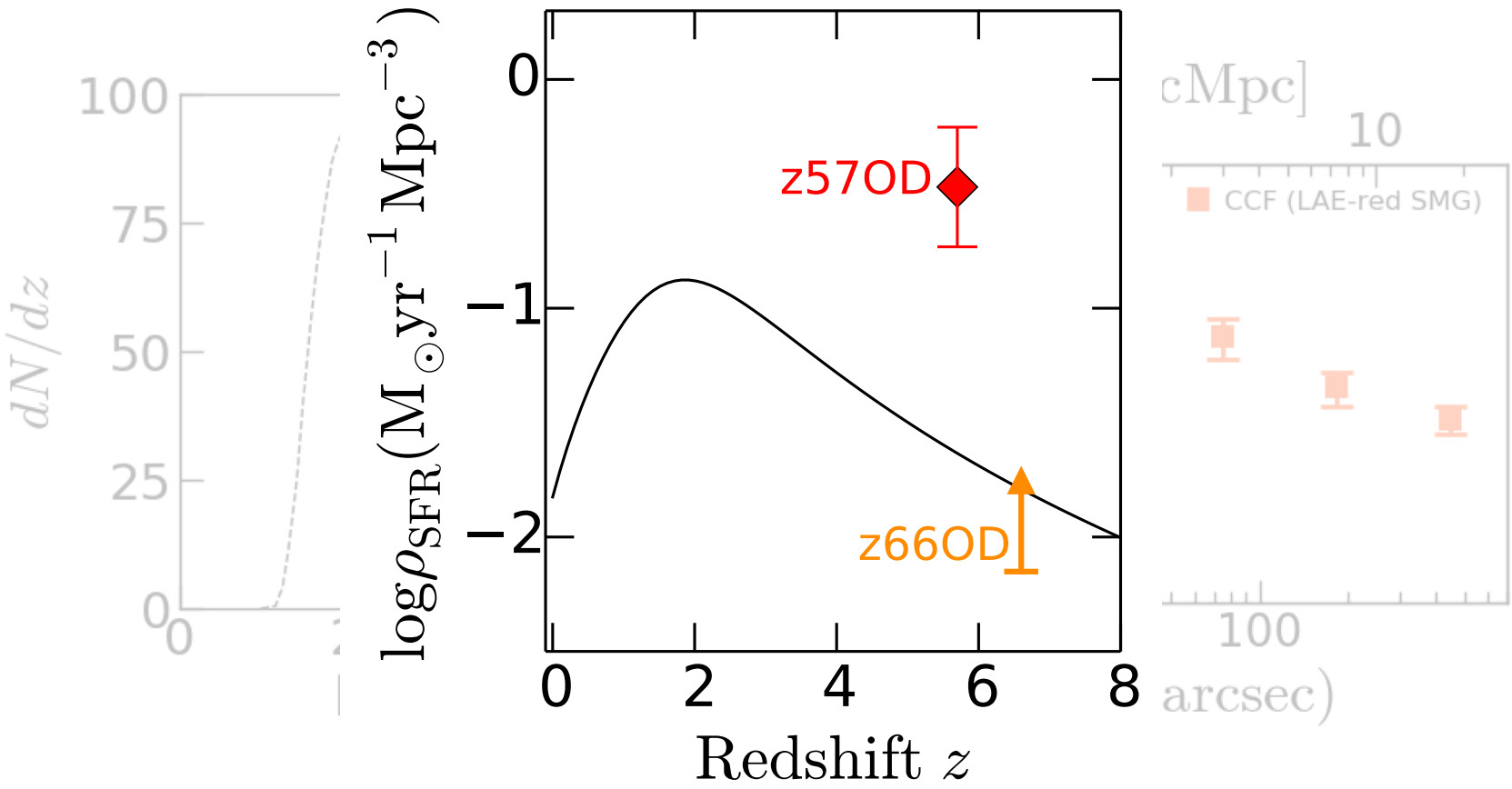



Riecherds+13

# LAE-SMG Correlation at z=5.7

- 99.97% cross correlation
  - z57OD: overdensity with both LAE and SMG



# Summary

- The largest sample of high-z galaxies from Subaru/HSC data
  - Cosmic star formation rate density
    = structure formation X cosmic expansion
  - Highest redshift protocluster
    Active star formation in protoclusters