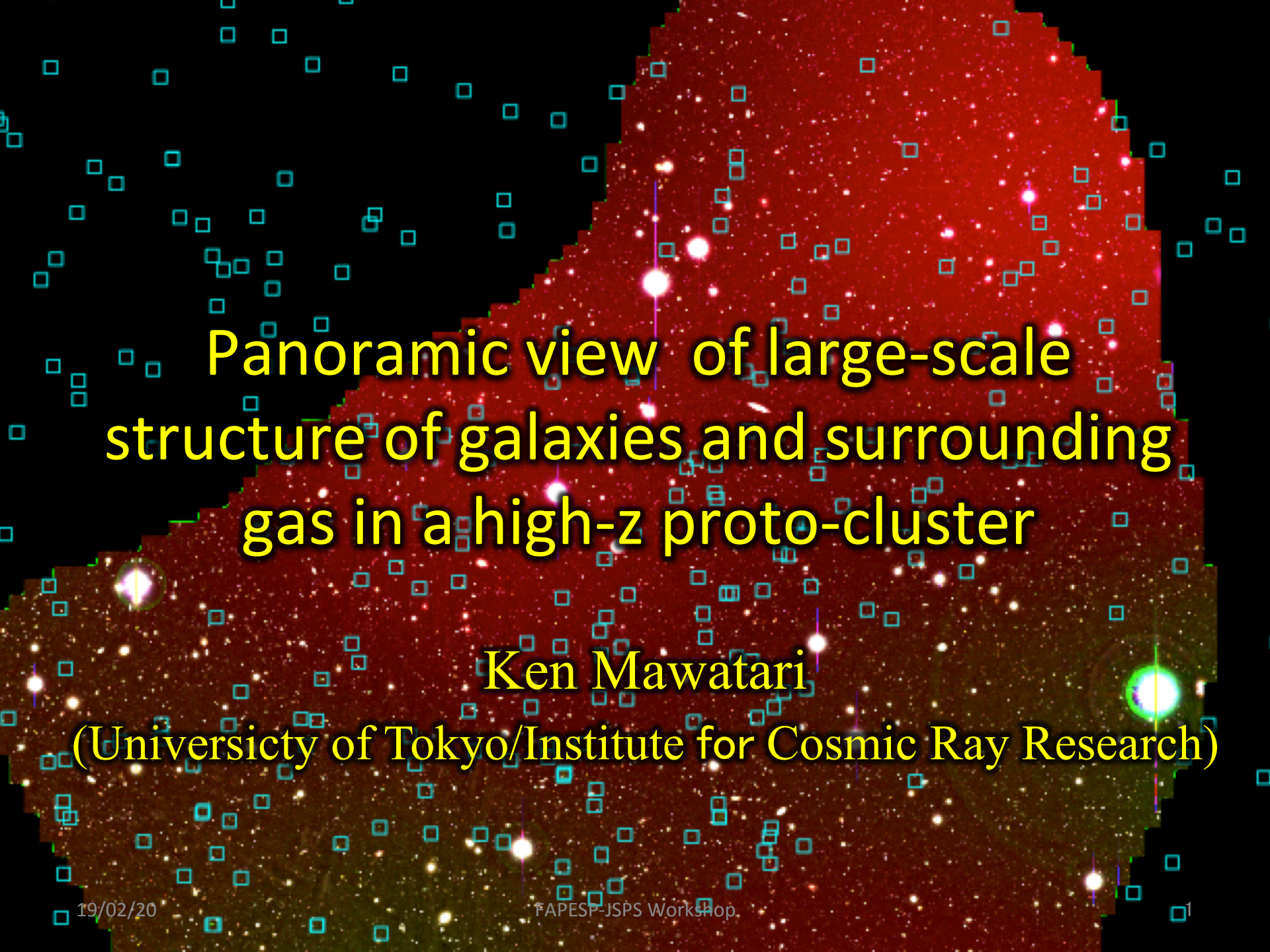


Panoramic view of large-scale structure of galaxies and surrounding gas in a high-z proto-cluster

Ken Mawatari
(Universicty of Tokyo/Institute for Cosmic Ray Research)

Aim of this presentation

Overview the proto-cluster (PC) studies focusing on a well-investigated “SSA22 PC” at z = 3.1

Topics

- ✓ Significance evaluation of the large-scale structure
- ✓ Environmental dependency of the galaxies
- ✓ Proto-cluster gas

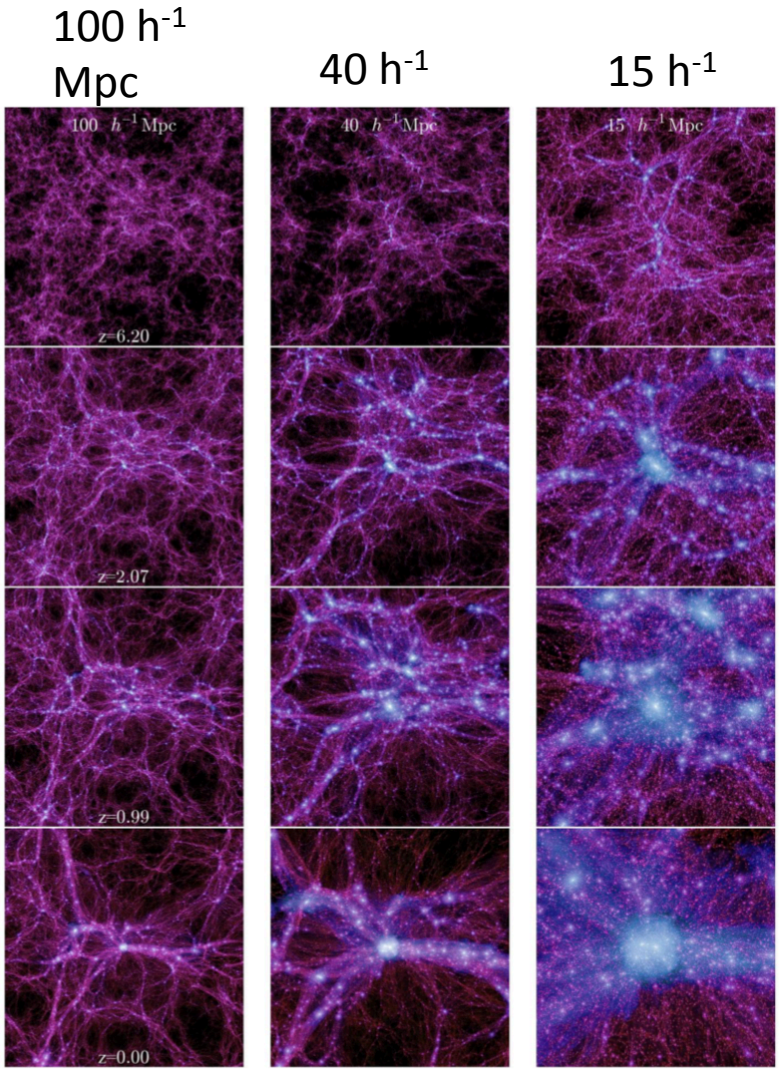
Introduction: Importance of proto-clusters

Definition

: an overdense structure
that collapses into a galaxy cluster
with M > 10^{14} Msun by z~0.

1. cosmological context

- Assembly and gravitational collapse of (proto-)clusters are of great interest in constraining cosmology model.



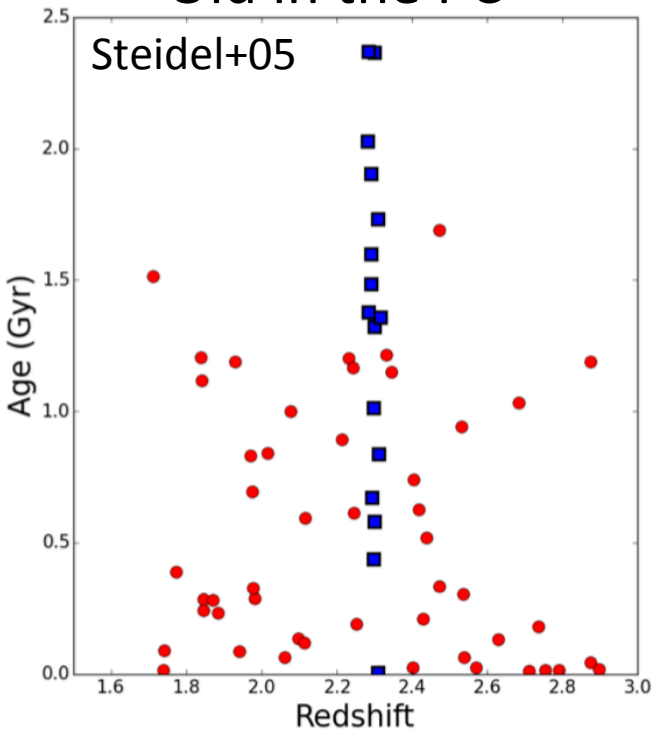
evolution of a cluster in dark matter
(Overzier+14, Boylan-Kolchin+09)

Introduction: Importance of proto-clusters

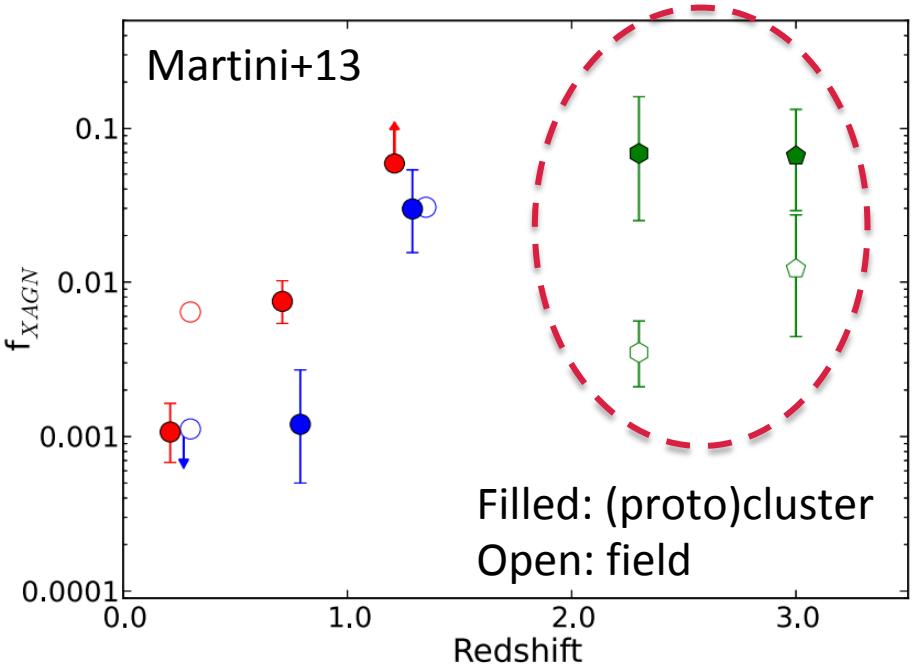
2. Environmental effect on the galaxy formation and evolution

- Did galaxies form and evolve faster in the PC? (due to frequent merger or efficient gas inflow or galaxy formation bias)

Old in the PC

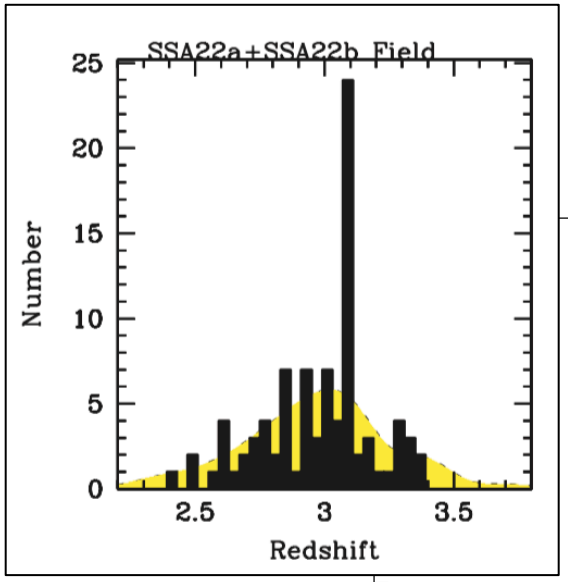


More AGNs in the PC



- Still not clear because of small sample size…

The SSA22 proto-cluster field at z = 3.1



Originally discovered as the significant overdensity region of Lyman break galaxies (LBGs; Steidel+98~+03)

Lya emitter (LAE) density map (Yamada+12, Hayashino+04)

Highest density "proto-cluster"

Size ~ 50Mpc (comoving)

~ 200 cMpc

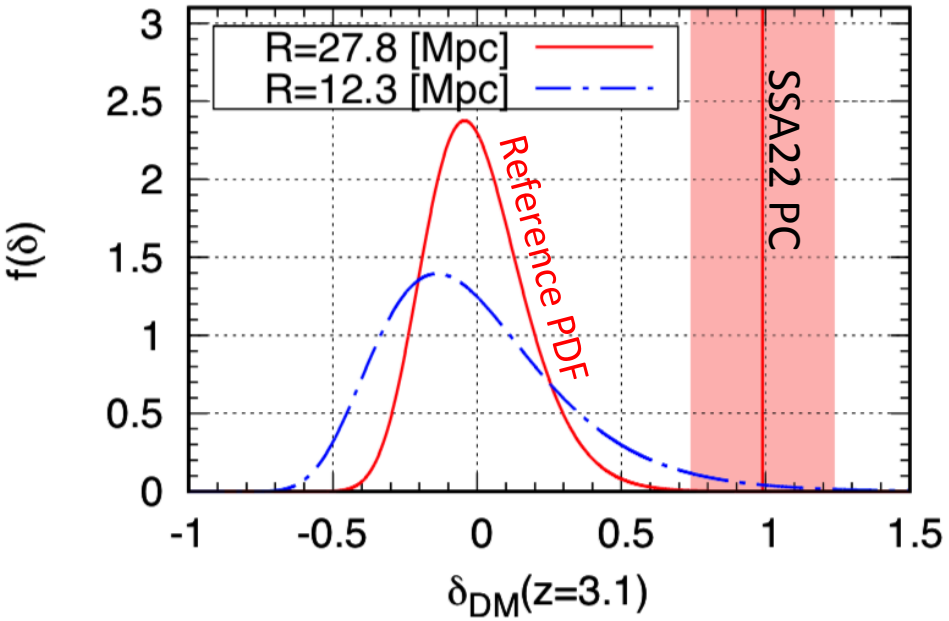
Dec. [deg]

R.A. [deg]

Cosmological view of the SSA22 proto-cluster

- ✓ N-body simulation with semi-analytic galaxy formation model (Millenium sim used in Yamada+12)
  : No structure similar to the SSA22 PC (LAE density ~ 4 σ @60 Mpc scale) is found in the 5000 realizations of $(500h^{-1})^3$ Mpc^3 simulation boxes.

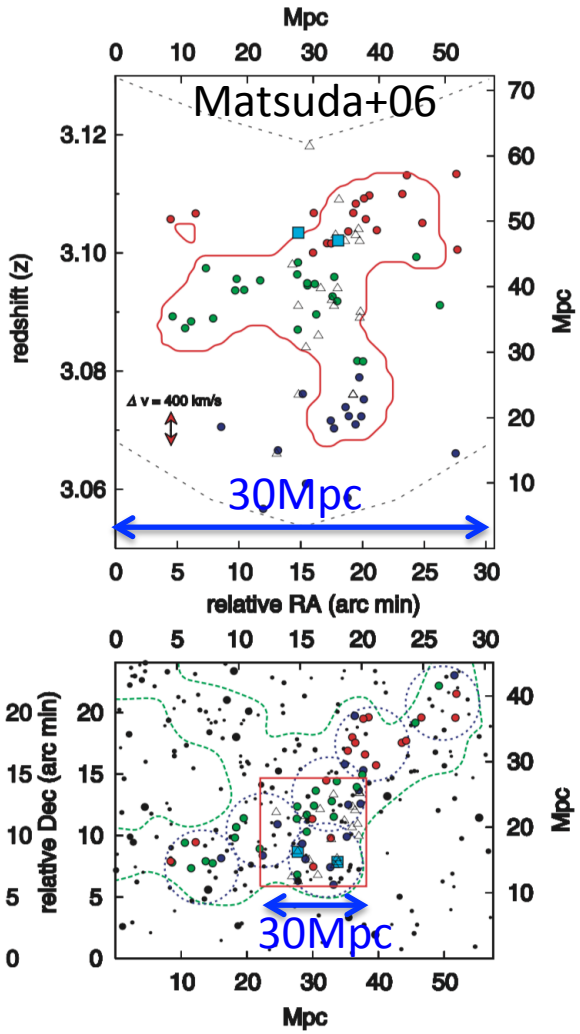
- ✓ Analytical evaluation with dark matter probability distribution function and galaxy bias (Mawatari+12, Hayashino+19)
  : Finding probability of the SSA22 PC is only 0.002 %.



δ = Density_obs / Density_average -1

Cosmological view of the SSA22 proto-cluster

The SSA22 PC's uniqueness is its very large size (~ 50Mpc).
It seems to be an ancestor of local super-cluster (great wall).



Similar?

Local great wall

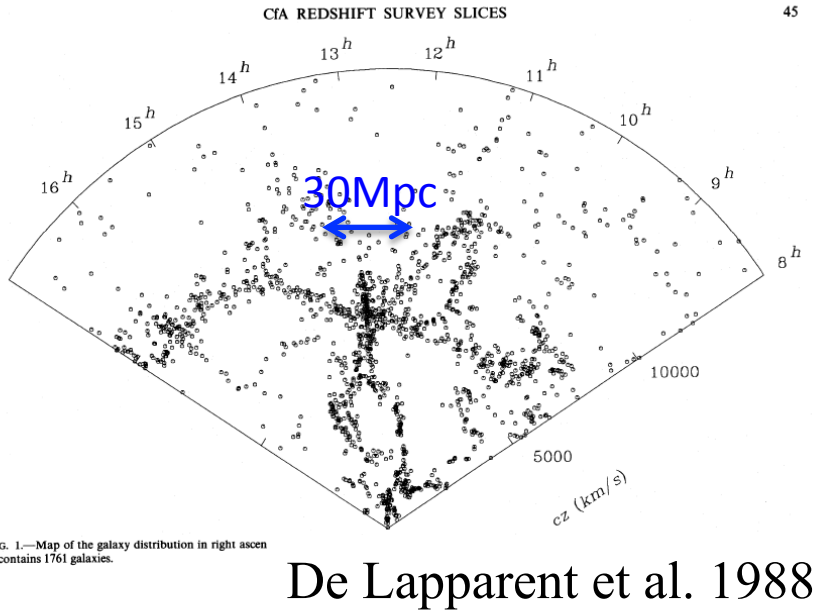


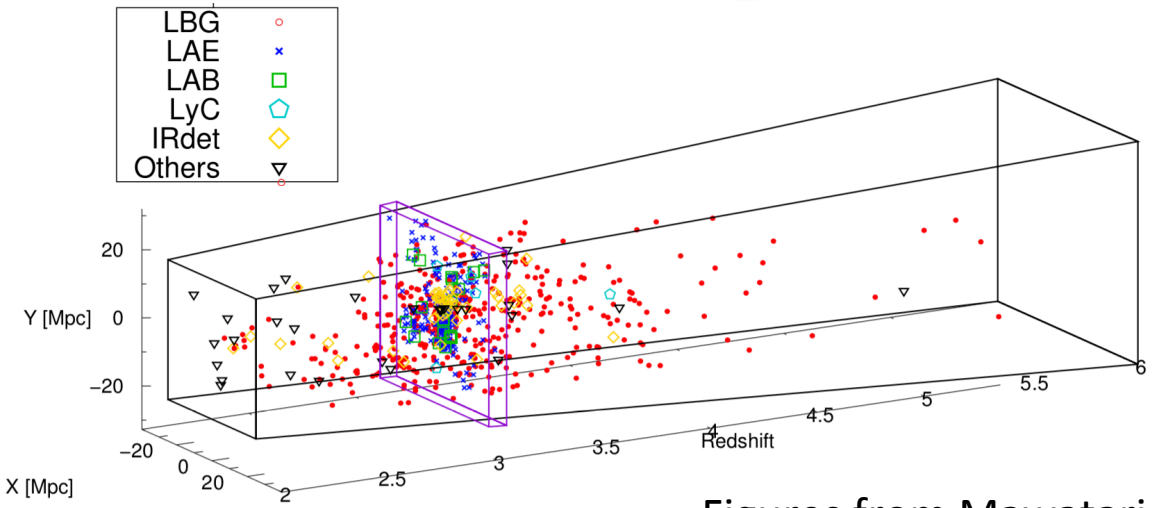
FIG. 1.—Map of the galaxy distribution in right ascen
map contains 1761 galaxies.

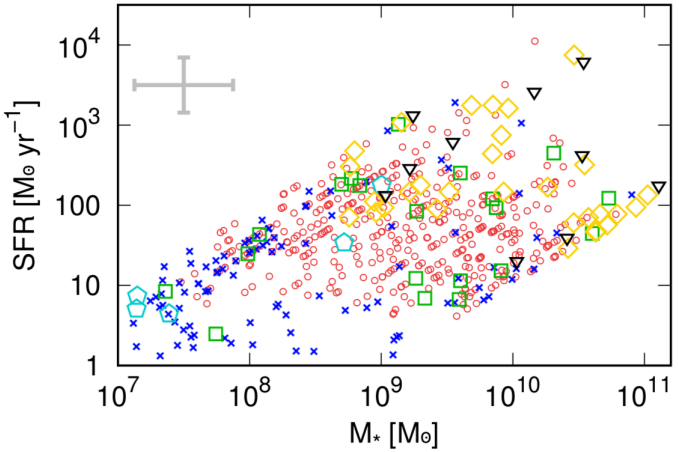
De Lapparent et al. 1988

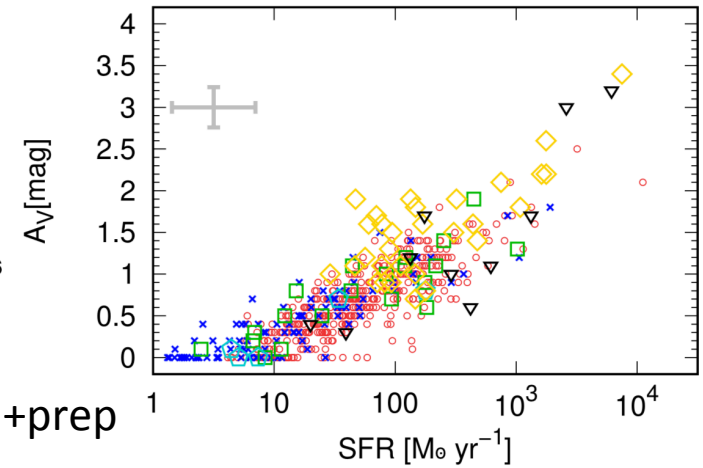
Galaxy formation and evolution in the SSA22 PC

- ✓ Overdensity of wide variety of galaxies
  - LBGs: typical galaxies at high-z
  - LAEs: less massive, less dusty
  - Lya blobs (LABs; Matsuda+04,12)
  - NIR-detected massive red galaxies (DRGs; Kubo+13,15,16)
  - Submm sources (SMGs; Umehata+15,17)

More massive, more dusty



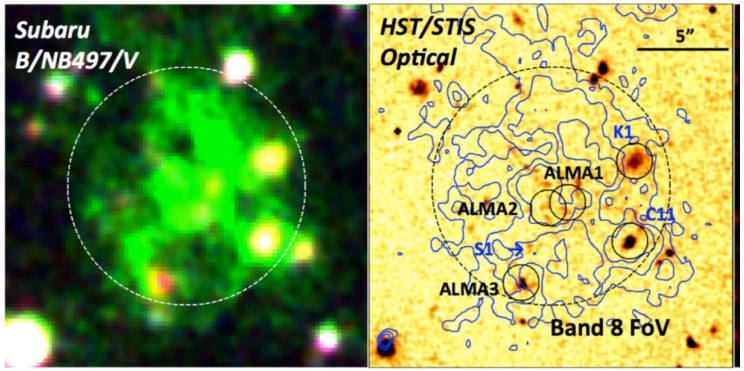


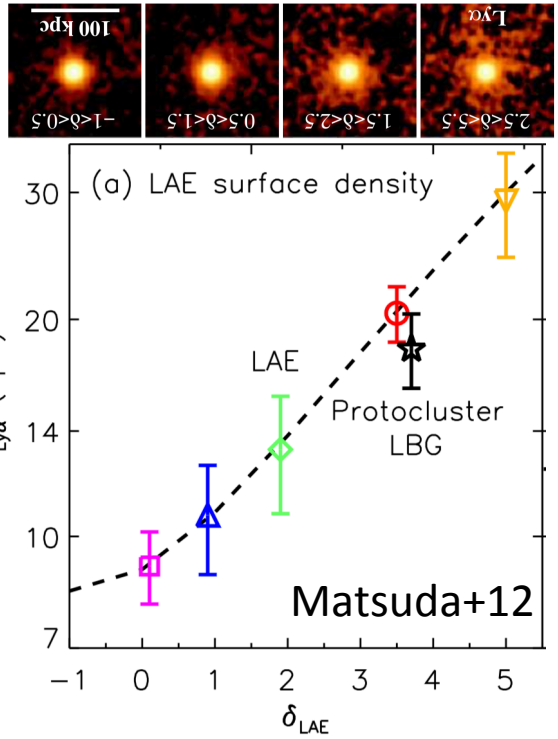


Figures from Mawatari+prep

Galaxy formation and evolution in the SSA22 PC

- ✓ LAEs generally have diffuse Lya halo, of which size depends on their environment.
- ✓ LABs often contain multiple massive red galaxies (Kubo+16,Umehata+17)





- ✓ Preliminarily, Mpc-scale Lya filament is found in the PC core region.
  Interestingly, SMGs lie in their nodes (Umehata+prep).

It seems that galaxy evolution and diversification are accelerated in the PC. What cause it? The key physics may be “galaxy-gas connection”.

Gas in the SSA22 PC

- ✓ Gas is important component in local clusters, owing ~40% of total baryon mass in the Universe in form of Intra-Cluster Medium (ICM) and Warm Hot IntraCluster Medium (WHIM).
- ✓ Proto-clusters also should have significant amount of gas, but they may be in pre-heated phase.
- ✓ Cool HI gas can be investigated via the Lya absorption imprinted in the background objects' spectra.

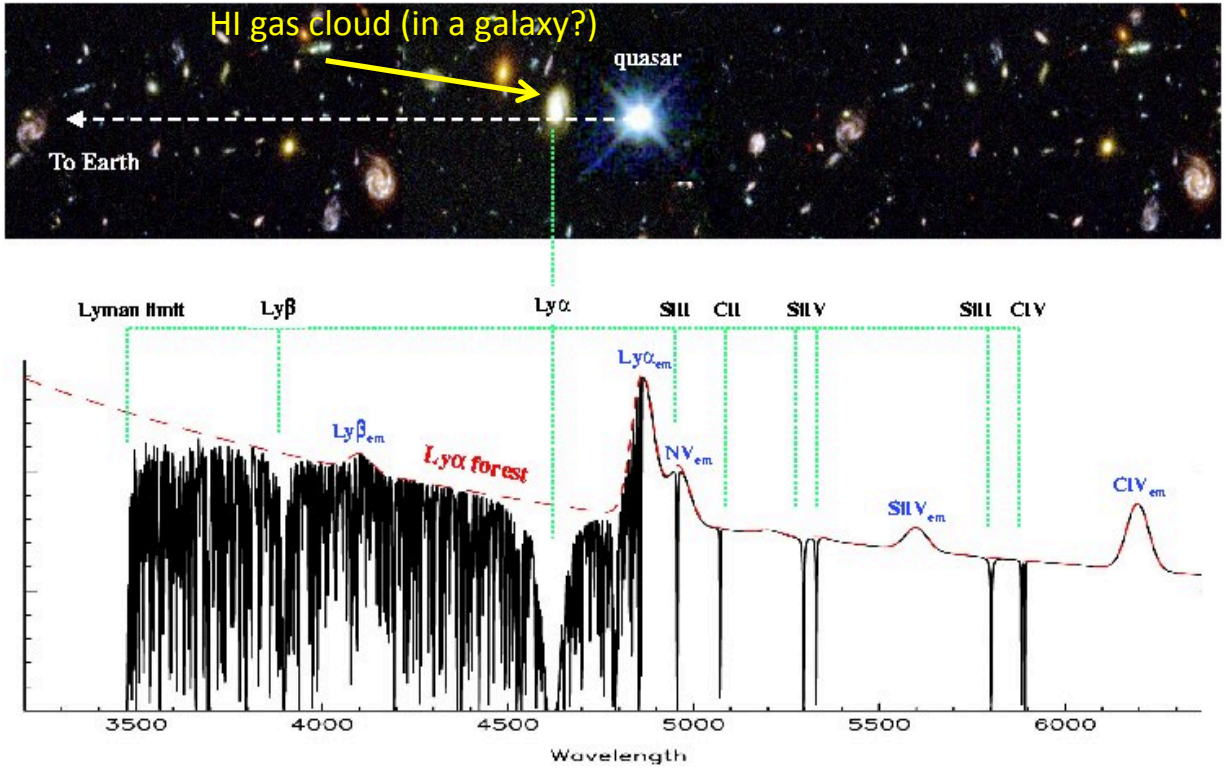
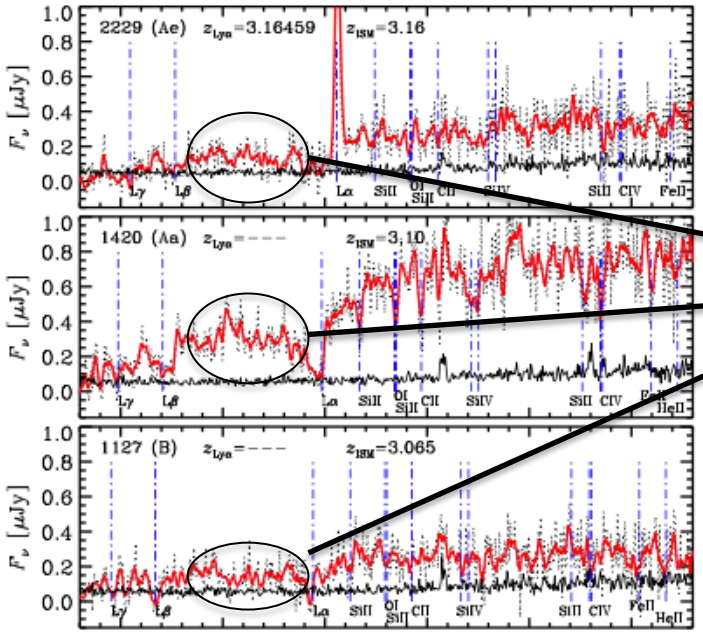


Figure from
http://enki.phyast.pitt.edu
qso_abs.html
(courtesy John Webb)

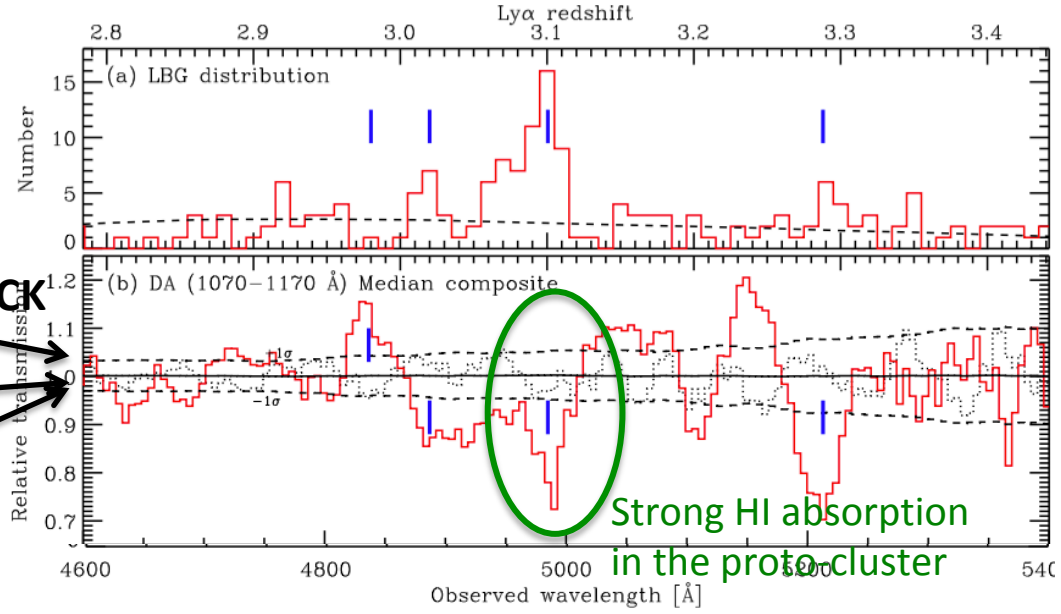
Gas in the SSA22 PC

- ✓ Stacking analysis to measure the average absorption strength by the PC HI gas (Hayashino+19)

VLT VIMOS spec obs (R=180)
=> 80 LBG spectra



STACK

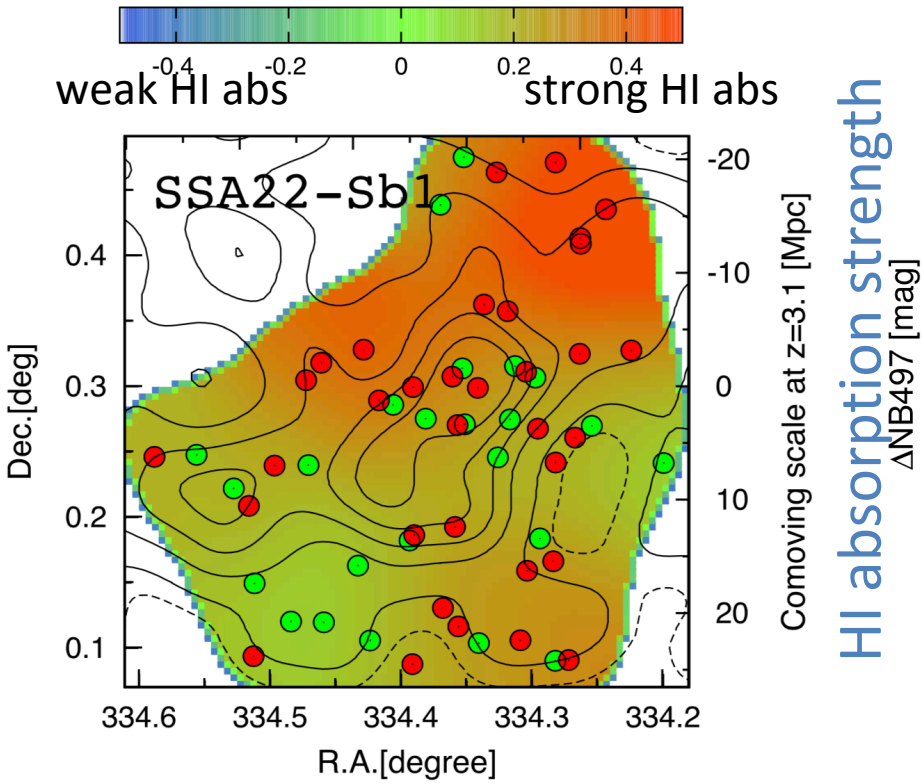


※Each spectrum contains the foreground HI absorbers information

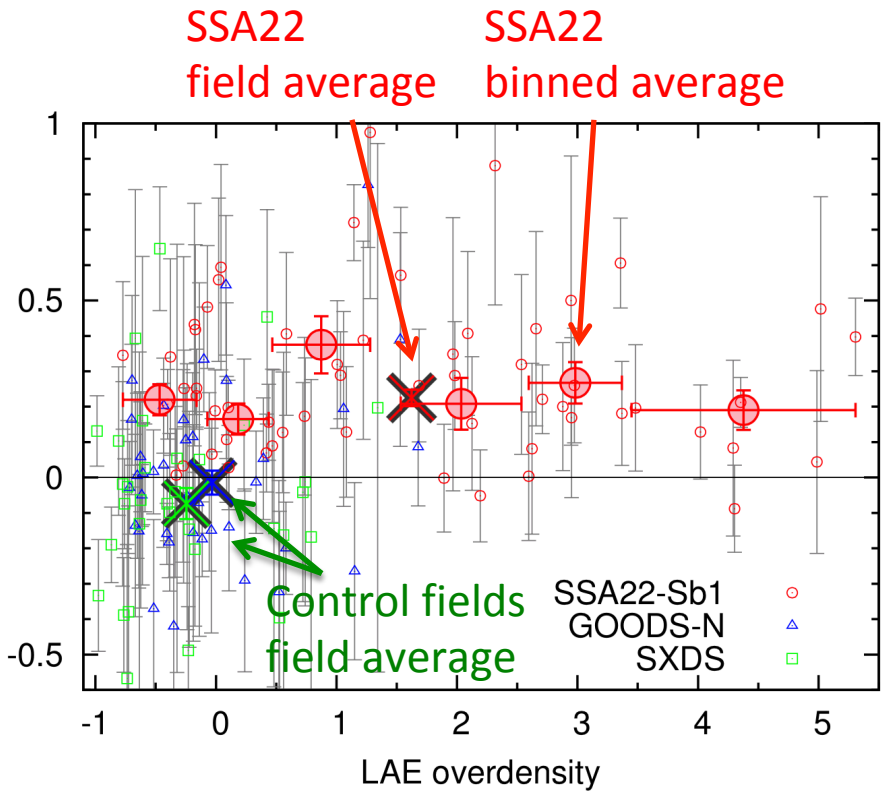
- ✓ There is indeed rich gas in the SSA22 PC
- ✓ Galaxies – HI abundance relation is found

Gas in the SSA22 PC

- ✓ Narrow-band survey of z=3.1 HI absorption to resolve the HI gas 2D structure at z = 3.1 (Mawatari+17).

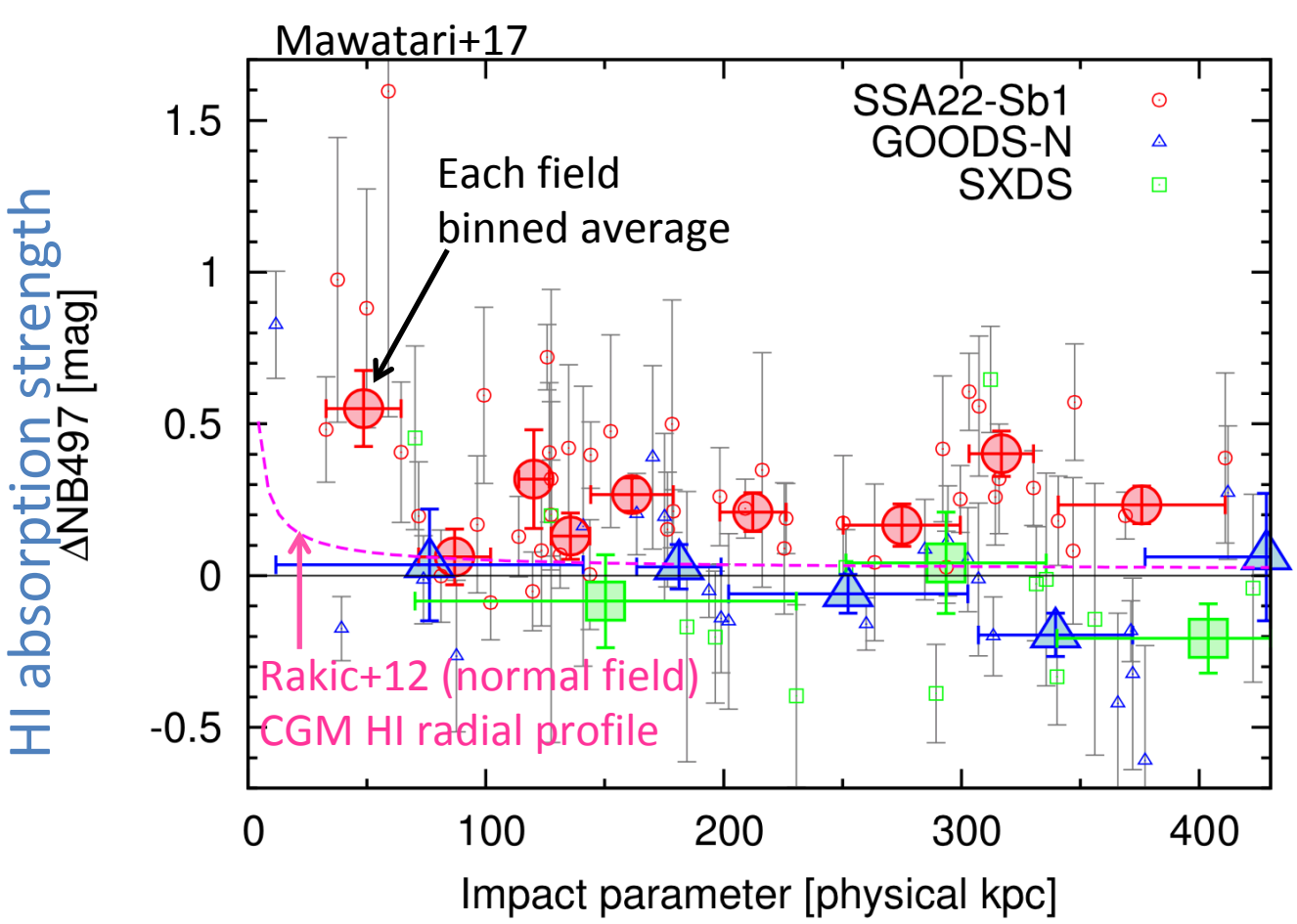


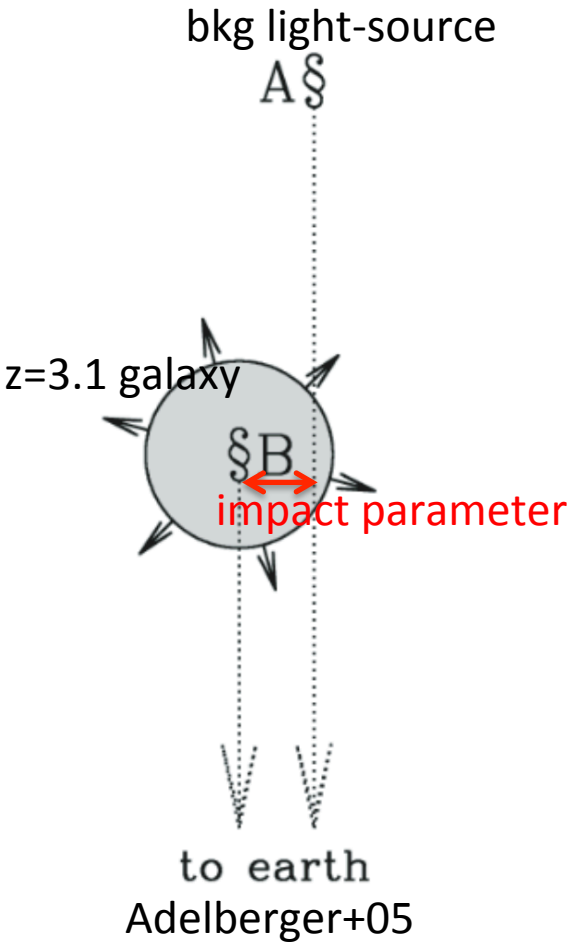
HI absorption strength ΔNB497 [mag]



- ✓ HI absorption enhancement spreads out over the entire PC (> 50 cMpc).
- ✓ This HI gas is not correlated with galaxy (LAE) density => Diffuse extended component, maybe Intra-Proto-Cluster Medium (IPCM)

Gas in the SSA22 PC

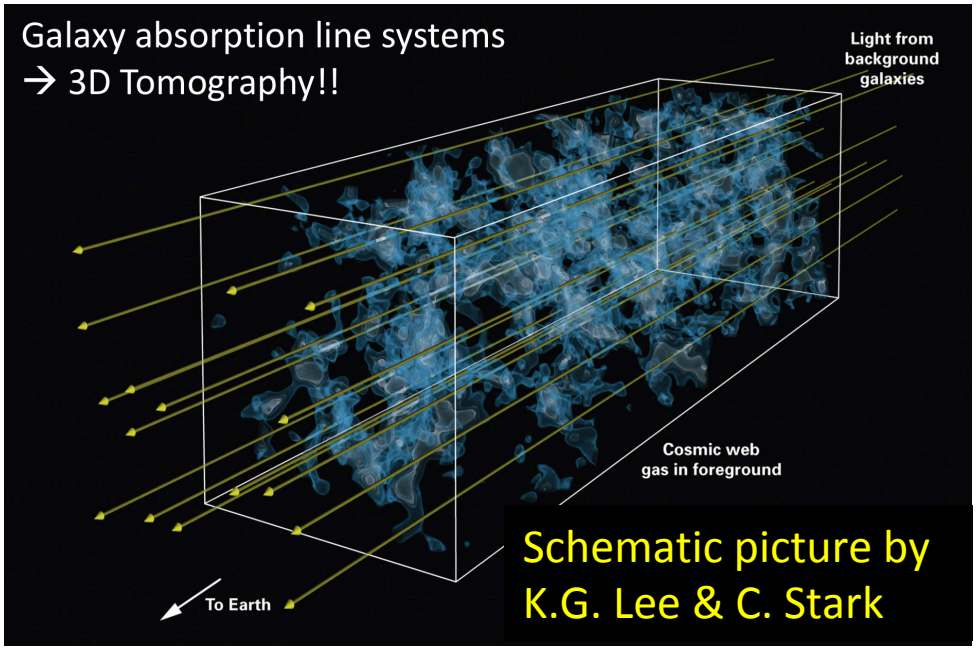




- ✓ Non-zero HI absorption at b > 200 kpc in SSA22 => IPCM HI gas
- ✓ HI absorption enhancement at b < 100 kpc is found. => CGM effect
- ✓ CGM HI absorption halos may be more thick in the high density environment.

On-going and Future works in the SSA22 PC

- ✓ Higher spatial resolution HI gas tomography
  On-going SSA22-HIT project
  with Keck/DEIMOS



- ✓ Metal absorbers
  to investigate gas nature:
  Outflow or inflow?

- ✓ Detailed SED analysis for PC member galaxies
  We'll constrain metallicity and escape fraction of ionizing photons by including spectral line flux in the SED fitting.

In any case, large and deep spectroscopic data are essential => Subaru PFS

Summary

- ✓ The SSA22 PC at z = 3.1, one of the most studied large-scale structure, is very rare object in the current cosmology.
- ✓ Galaxy evolution and diversification seems to be accelerated in the PC.
- ✓ Rich gas components are detected via emission and absorption. Such gas-rich environment should affect galaxy evolution.