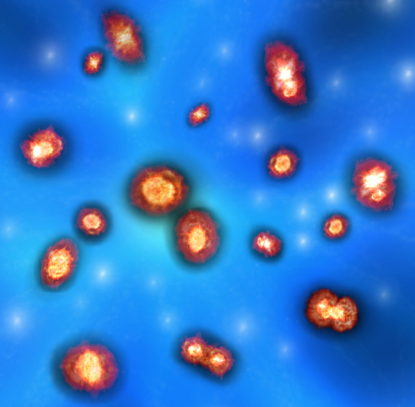
Challenges at the CMB Frontier at Chino
Jul. 3, 2026

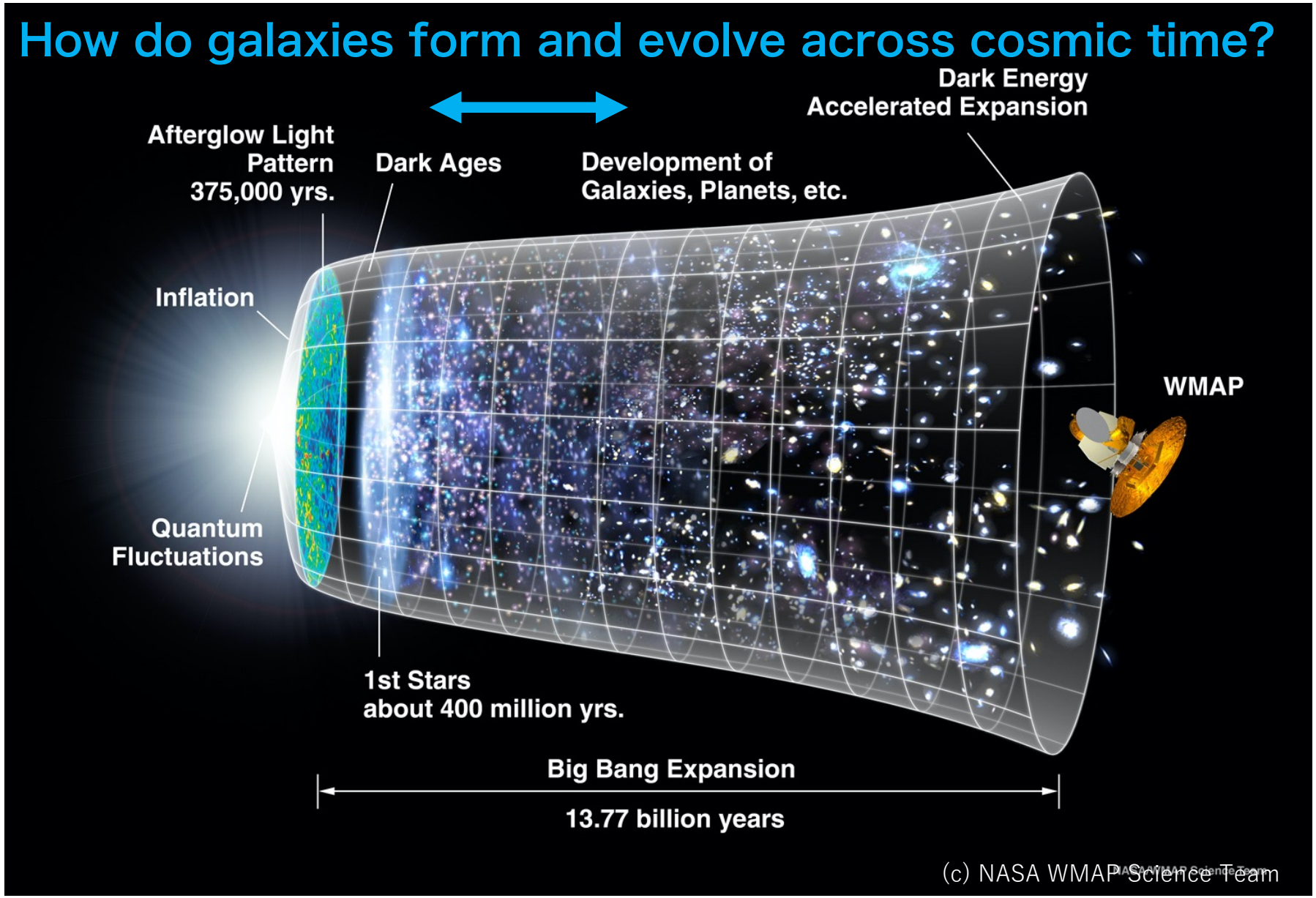
Galaxy Formation in Cosmic Large-Scale Structures



Hideki Umehata (Nagoya Univ.)

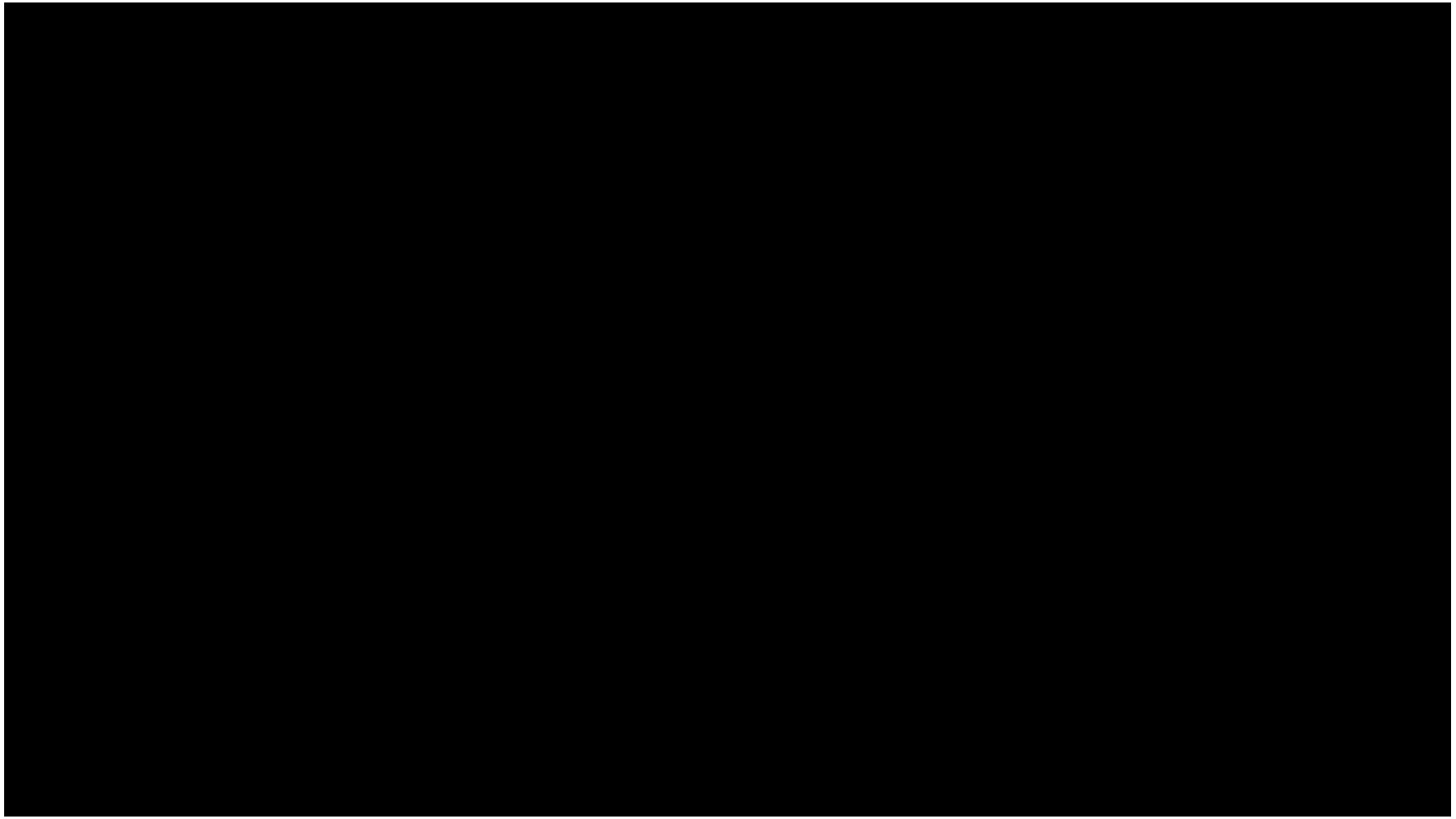
NAGOYA UNIVERSITY
名古屋大学 高等研究院

From primordial fluctuations to galaxies



Cosmological simulation view

Gas Dark Matter Stellar Magnetic Field https://www.tng-project.org/

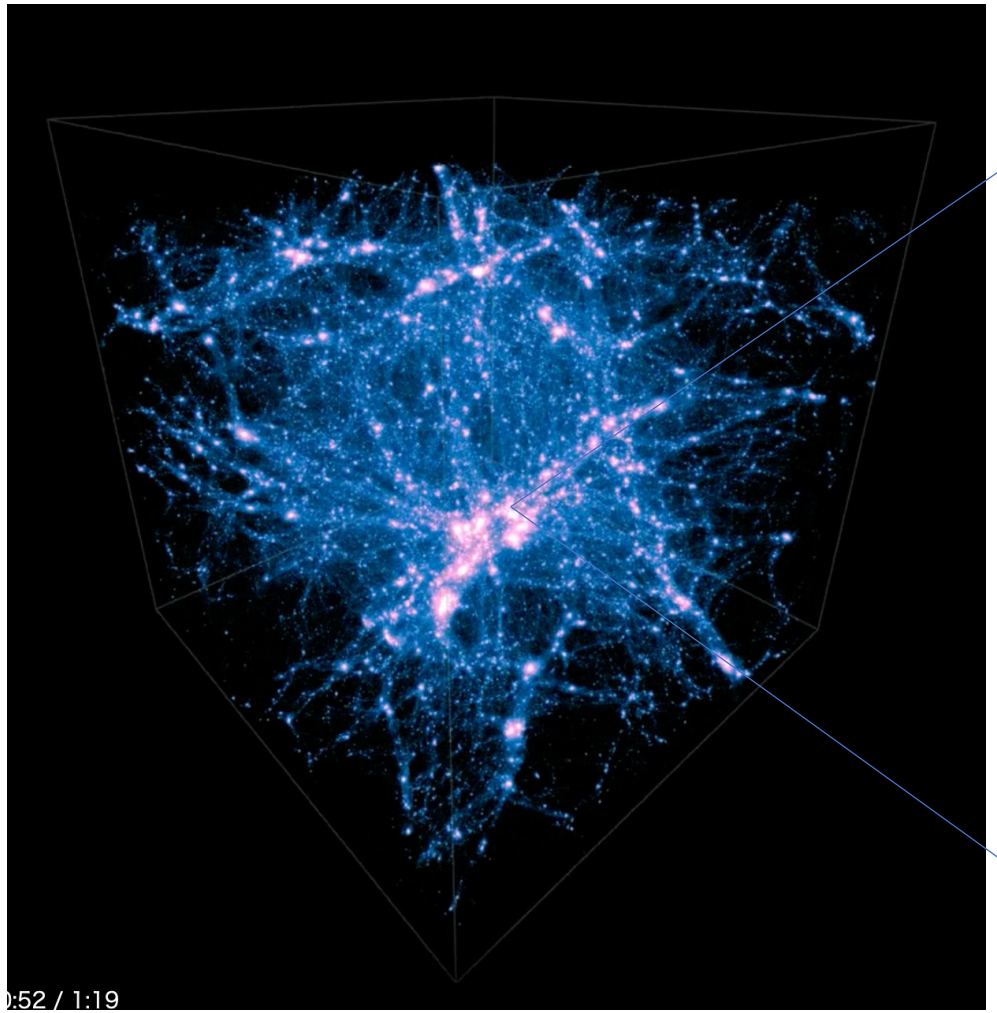


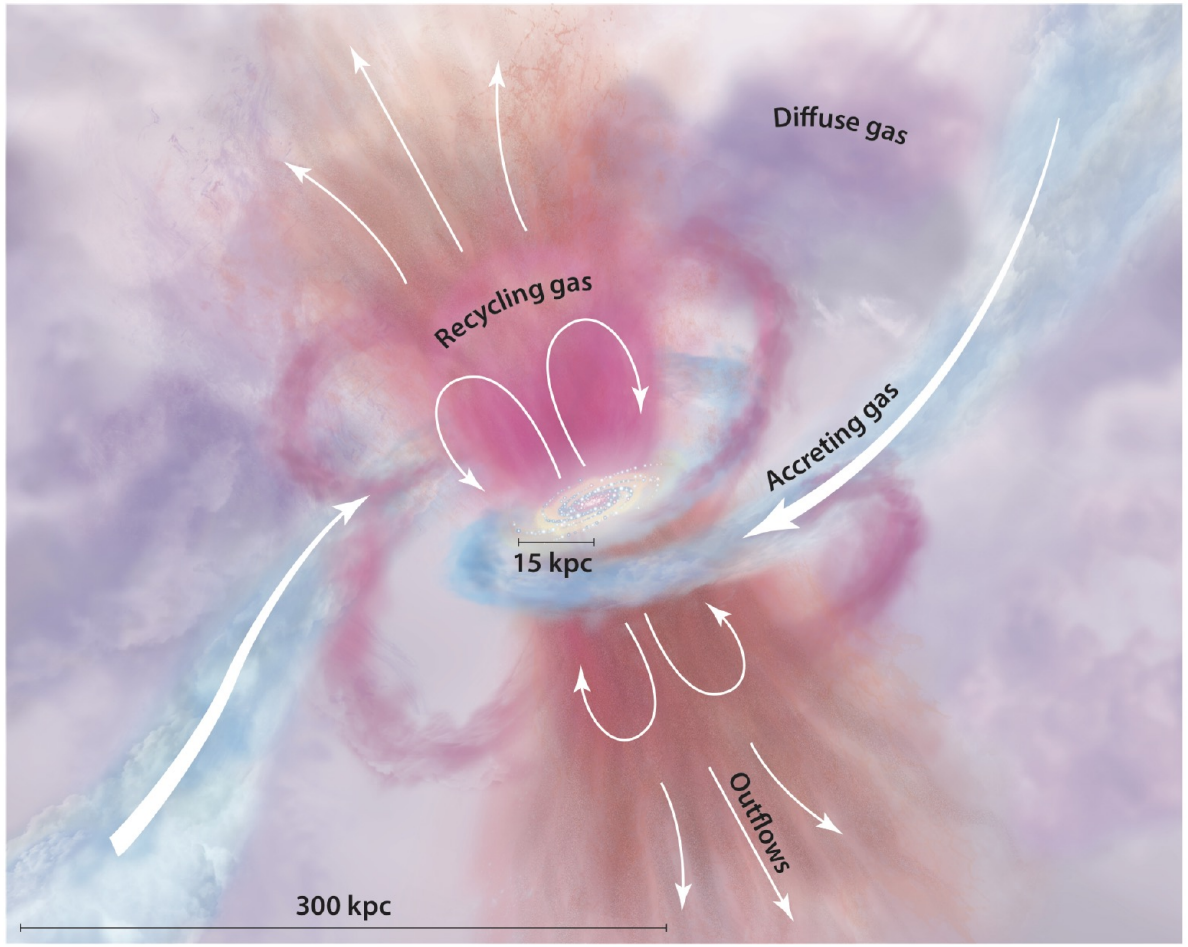
Temperature Gas Metallicity Gas Velocity Field OVI Column Density

- Primordial density fluctuations evolve into the cosmic web through gravitational instability.
- Galaxies form and evolve within the evolving large-scale structure.

Basic picture in the current paradigm

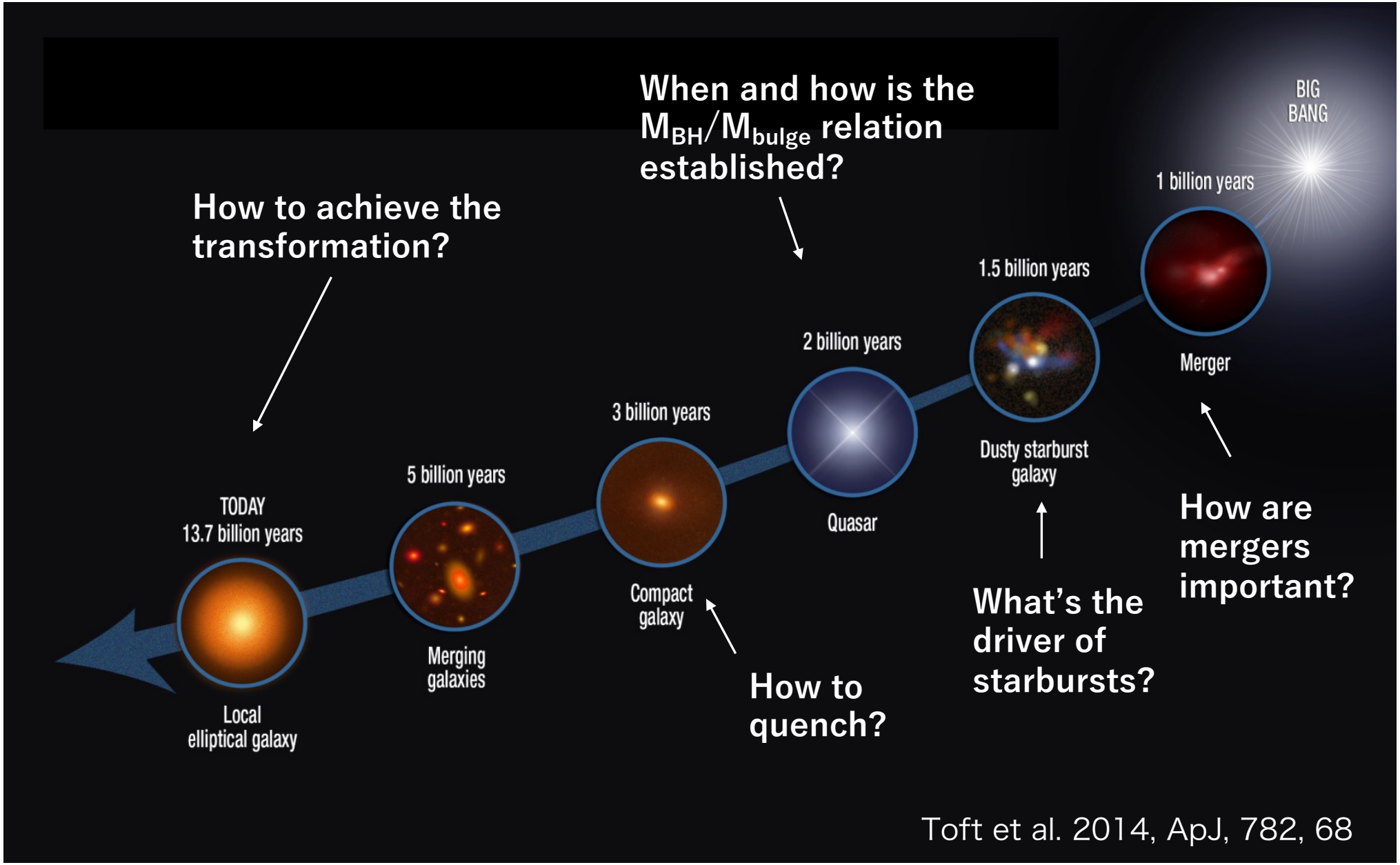
Tumlinson et al. 2017, ARAA, 1, 46



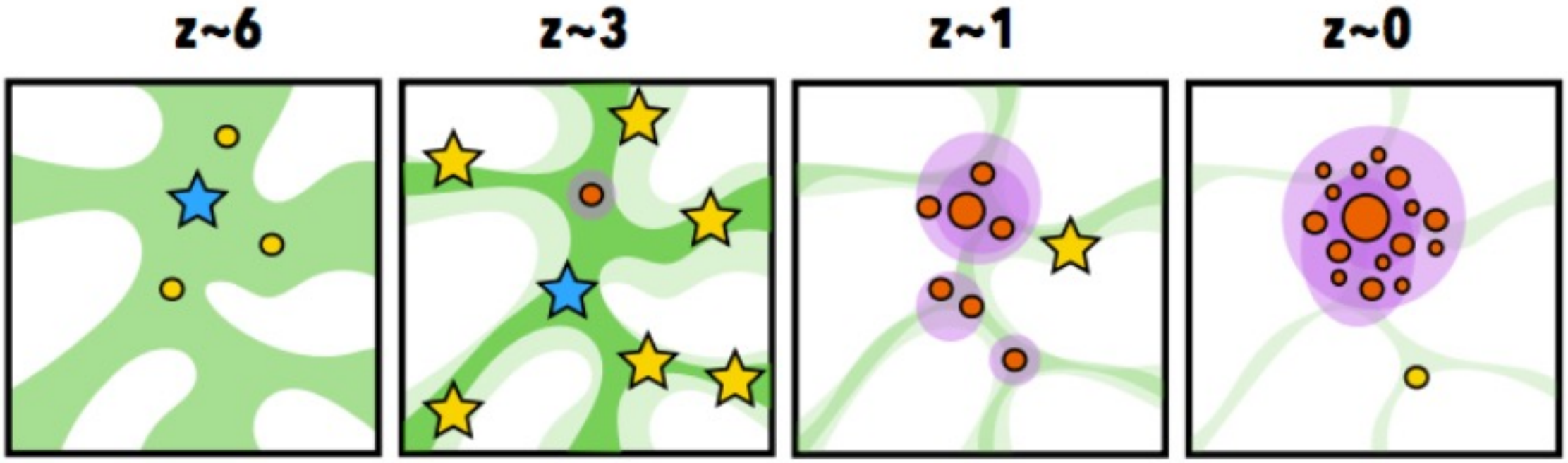


- Galaxies form at the nodes of the cosmic web.
- Gas continuously cycles between galaxies and their surrounding medium.

The evolution of massive galaxies



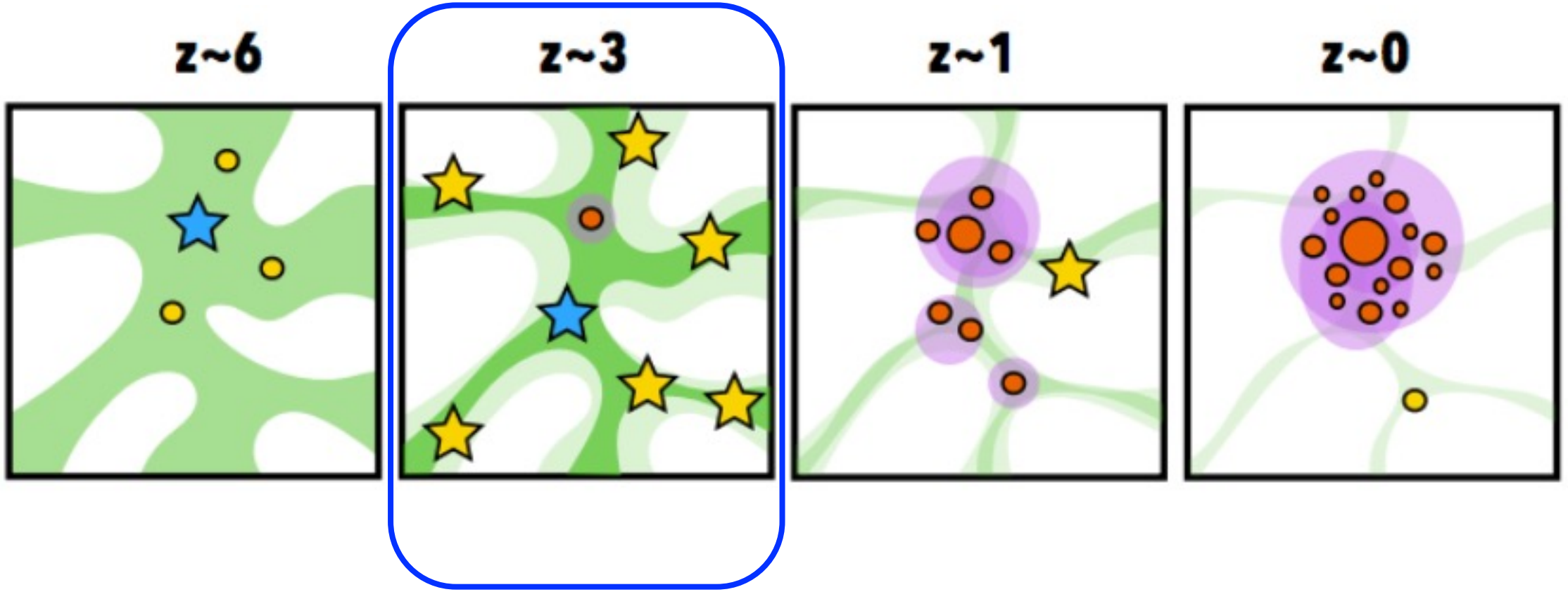
Galaxy evolution and the LSS



COLD GAS / HOT GAS / GALAXIES (QSOs, SFGs, QGs)

- Galaxies and large-scale structures have co-evolved throughout cosmic history.
- Today I will highlight three recent advances, primarily enabled by ALMA (+JWST, …).
  - I. Galaxy assembly along cosmic web filaments (at z~3).
  - II. Emergence of the hot intracluster medium (at z~2-4).
  - III. Proto-clusters at Cosmic dawn (at z~7-8).

I. Galaxy assembly along cosmic web filaments

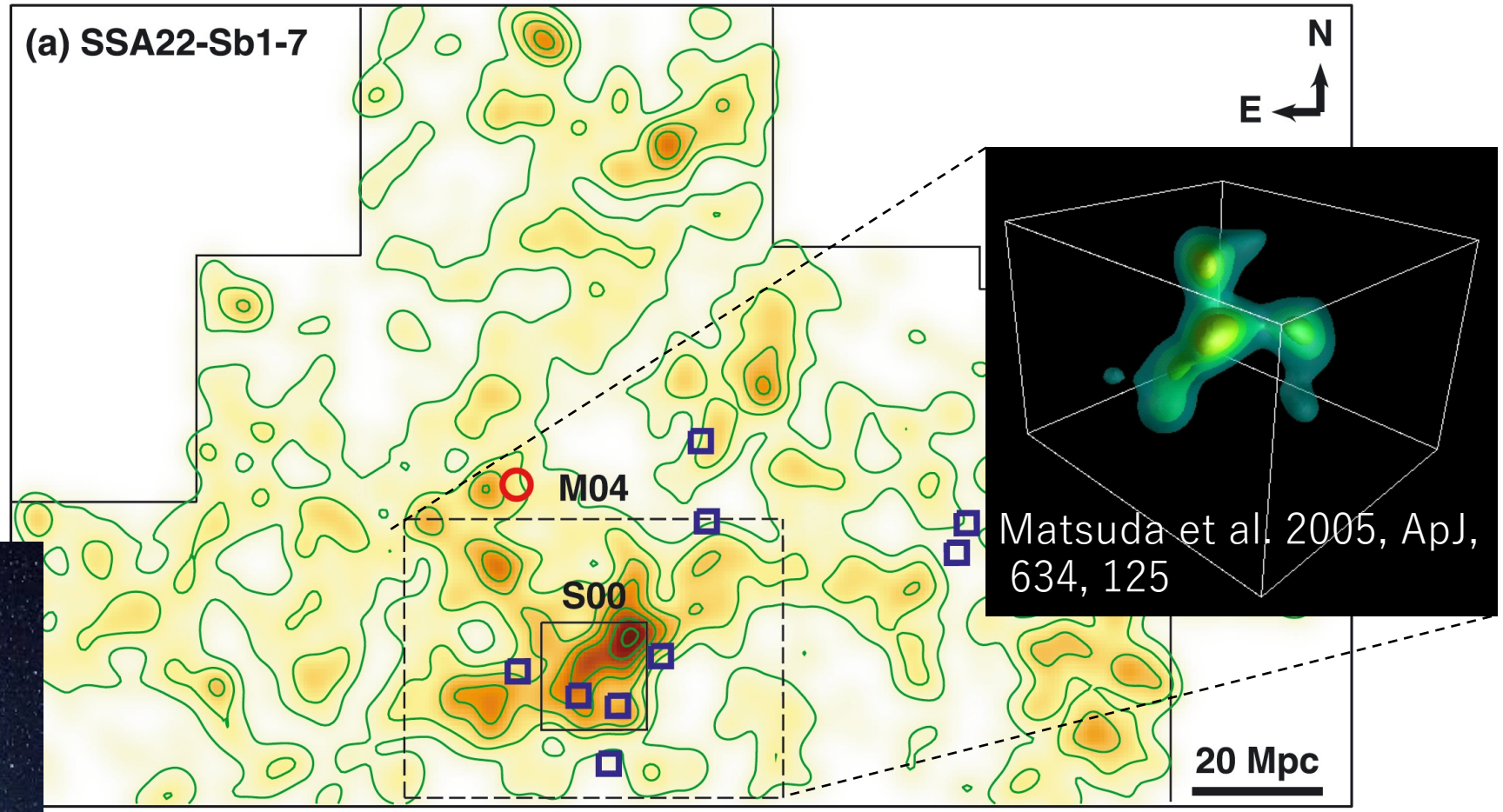


COLD GAS / HOT GAS / GALAXIES (QSOs, SFGs, QGs)

- The peak epoch of galaxy assembly.
- What drives this active phase?

SSA22 Proto-cluster at z=3.1

Matsuda et al. 2011, MN, 410, 13



- Subaru performed a panoramic census of Lyα emitters (LAEs).
- Cosmic large-scale structure has been found at z=3.1 (“proto-great wall”).

ADF22: ALMA Deep Field in SSA22

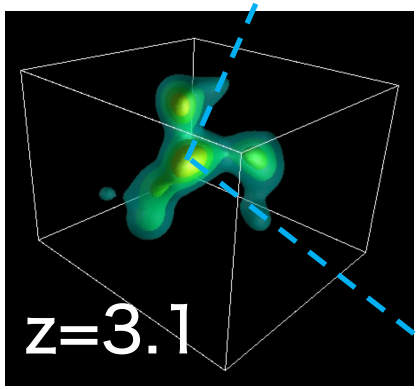
Umehata et al. 2019, Science, 366, 97 (cf: Umehata+15)

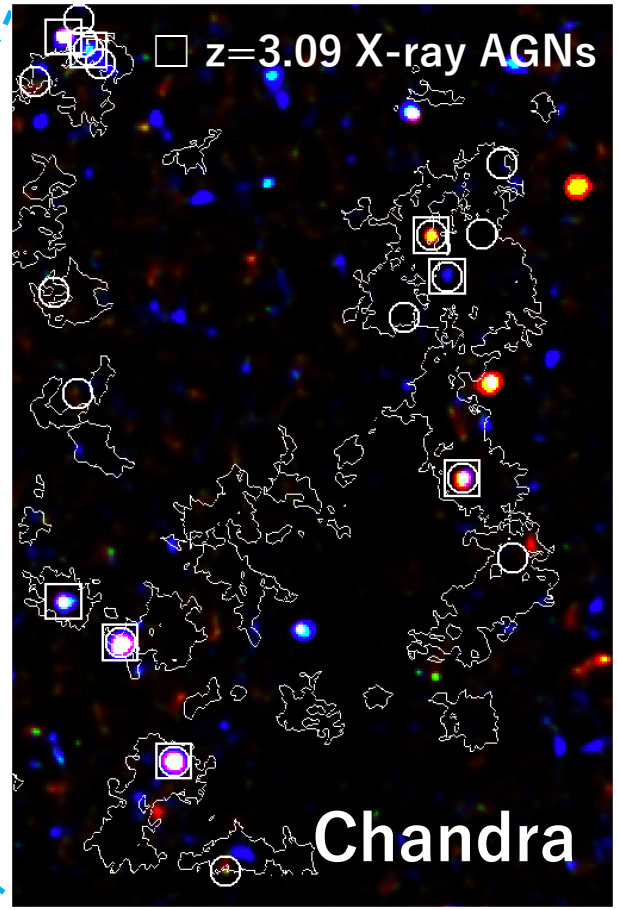
X-ray: AGNs

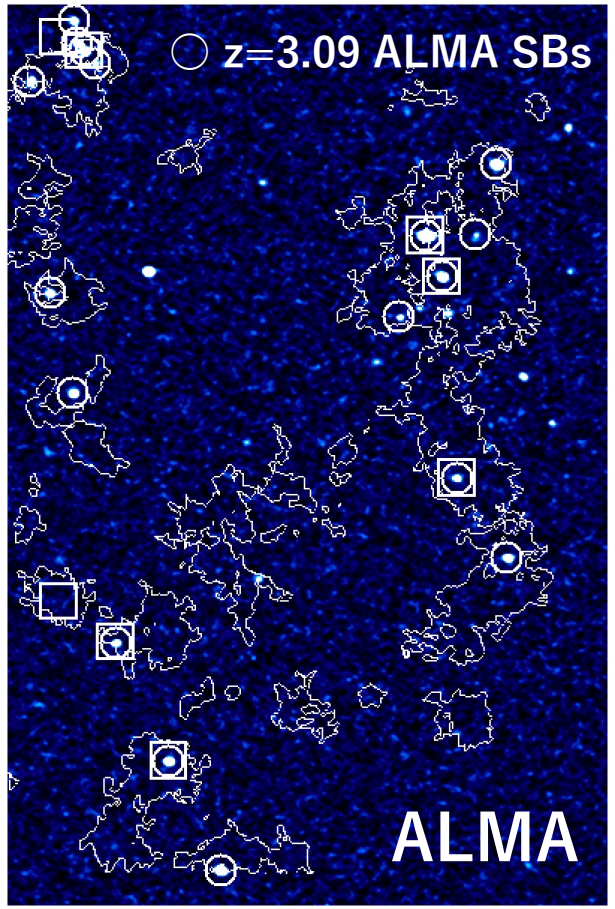
mm: DSFGs

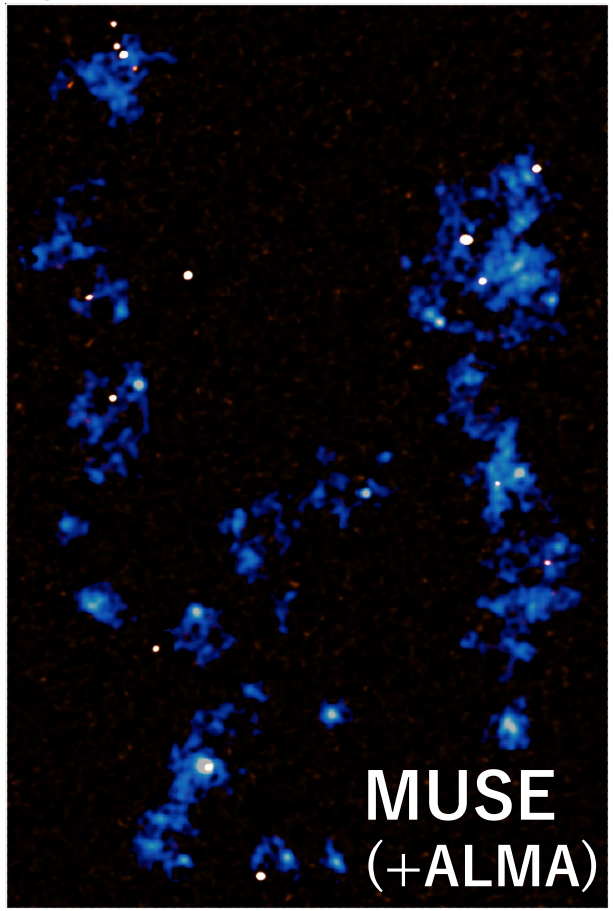
Lyα: Cosmic Web

Large-scale structure in 3D









1 pMpc

- **The most massive, active galaxies (DSFGs/QGs, M*~10^{11}Msun) are ubiquitously found along cosmic web gas filaments in the protocluster.**

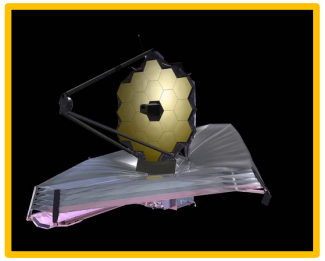
(cf: Tranvascio+24;25, Vito+24 for other examples of X-ray AGNs in proto-cluster DSFGs at z>3)

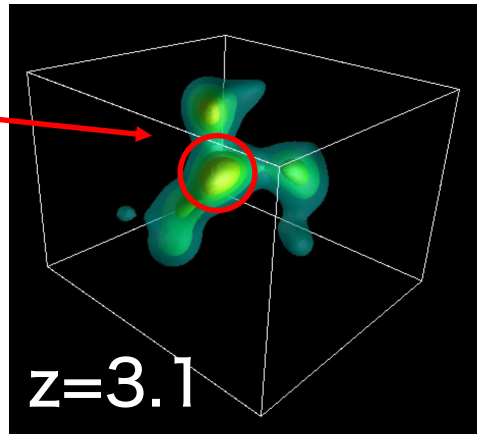
“ADF22-WEB” Project

ADF22-WEB

Hideki Umehata (Nagoya, JP, PI), David Alexander (Durham, UK), Bret Lehmer (Arkansas, US), Mariko Kubo (Tohoku, JP), Chuck Steidel (Caltech, US), David Rosario (New Castle, UK), Ian Smail (Durham, UK), Erik Monson (Pen State, US), Kouichiro Nakanishi (NAOJ, JP), Kotaro Kohno (Tokyo, JP), Yoichi Tamura (Nagoya, JP), Yuichi Matsuda (NAOJ, JP), Shuo Huang (Nagoya, JP), and more.

An ALMA-JWST joint project toward the core





ALMA+JVLA (PI. Umehata)

- Dust continuum in B3, B6, B7, B8.
- CO(1-0), CO(3-2), CO(8-7), CO(9-8), CO(12-11), [C II], H_2O, OH+, CH+, …

JWST (PI. Umehata)

- NIRCam: F115W, F200W, F356W, F444W.
- MIRI: F770W, F2100W

Aim: To uncover galaxy formation and evolution along the cosmic web filaments.

SED and ALMA/JWST

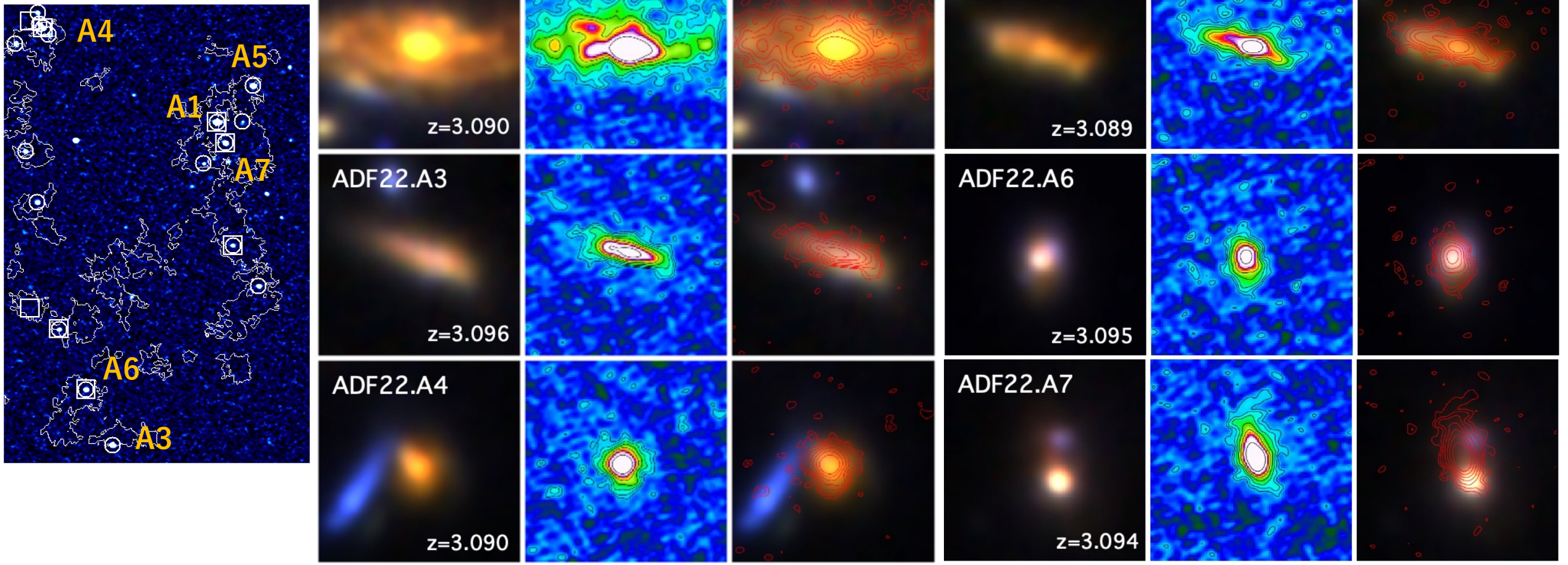
Herrera-Camus et al. 2026, NatAs, 10, 34

JWST

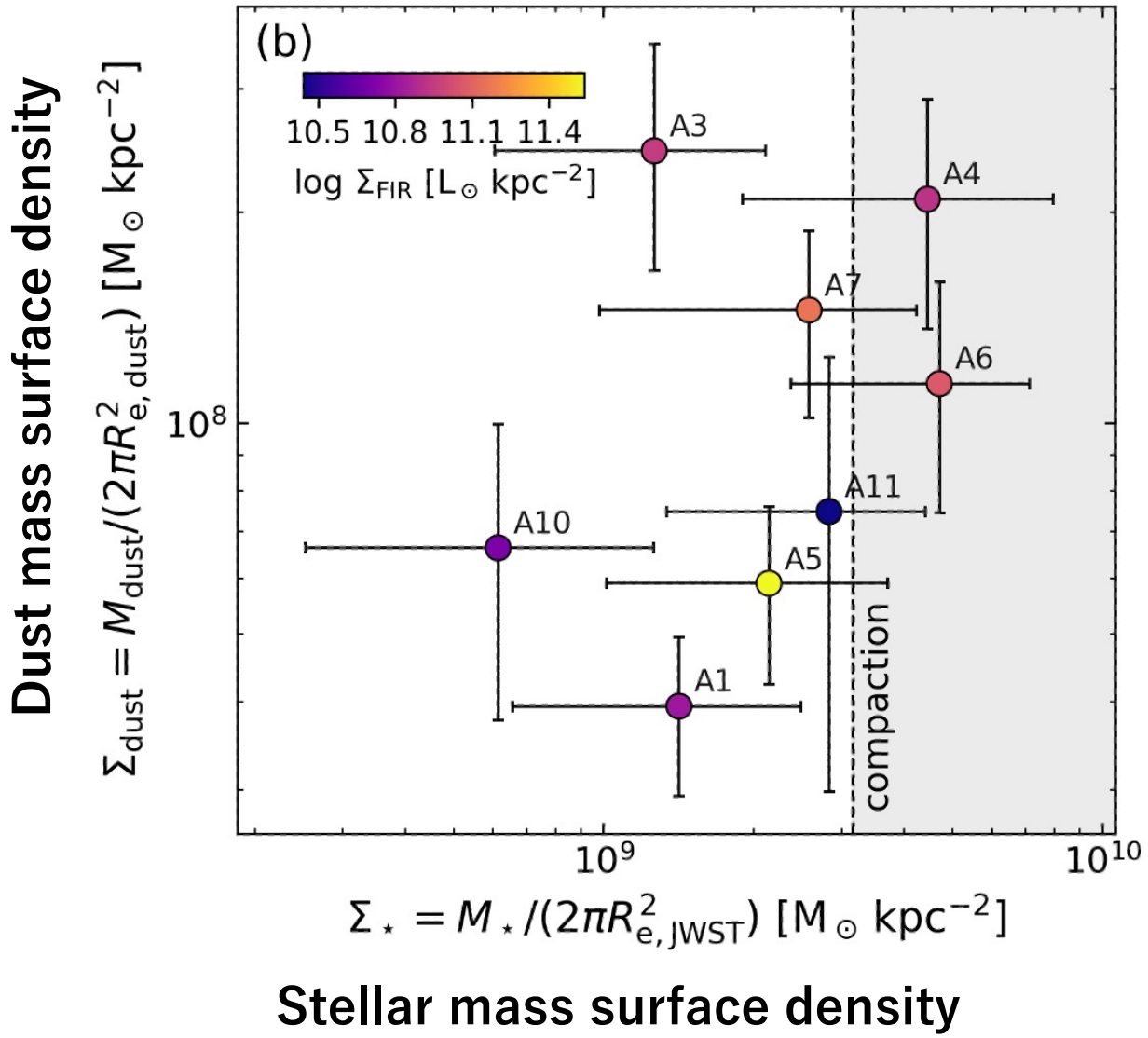
ALMA

Morphologies of DSFGs

Umehata et al. 2026a, ApJ, 997, 79

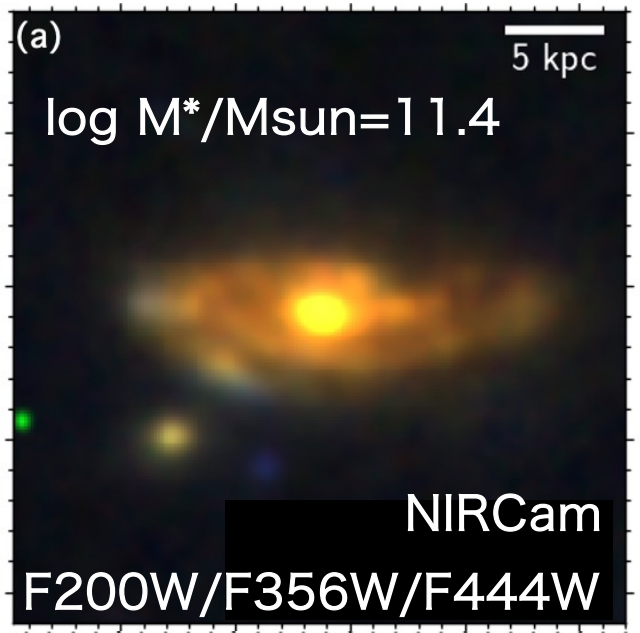


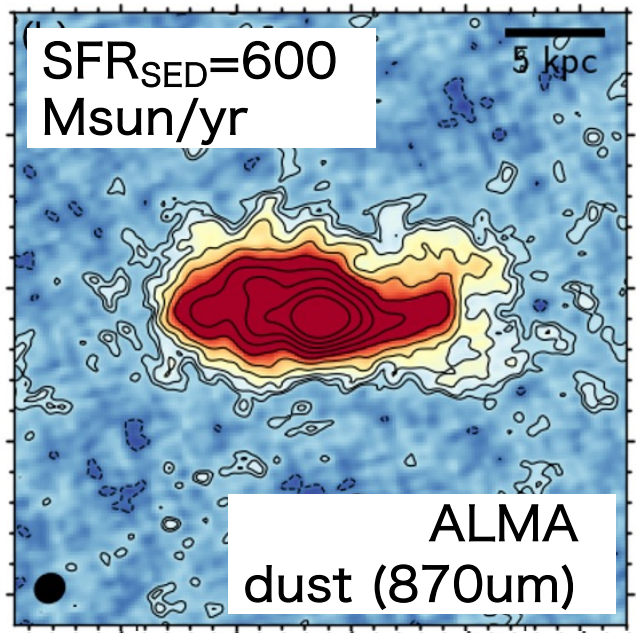
Mass assembly in DSFGs

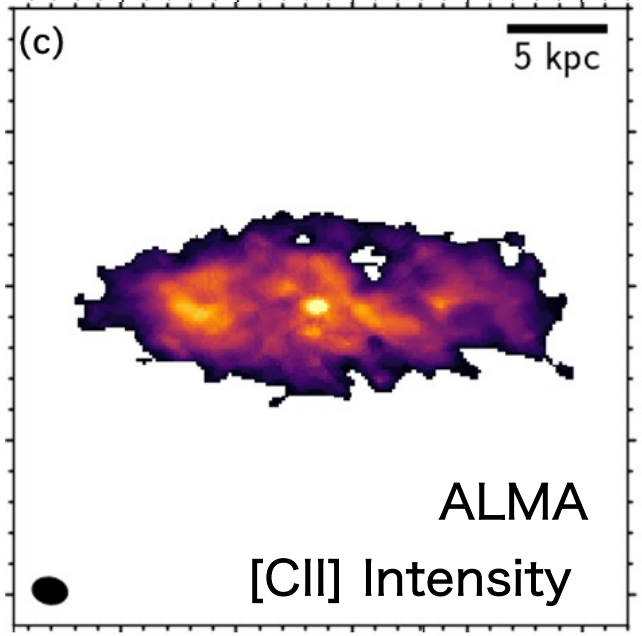


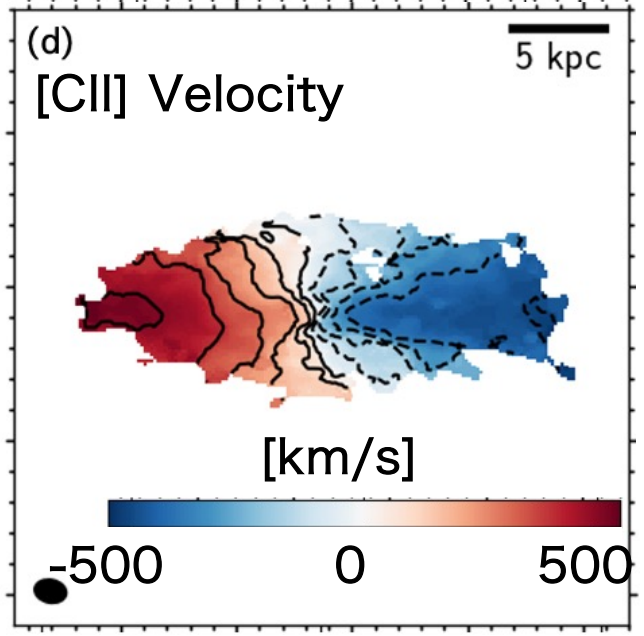
- The stellar and dust surface densities are correlated.
- Both profiles are described by disk and bulge components.
- Stellar growth and ISM build-up proceed together, suggesting continuous gas supply from the cosmic web filaments.

A gigantic z=3 spiral hosting an X-ray AGN

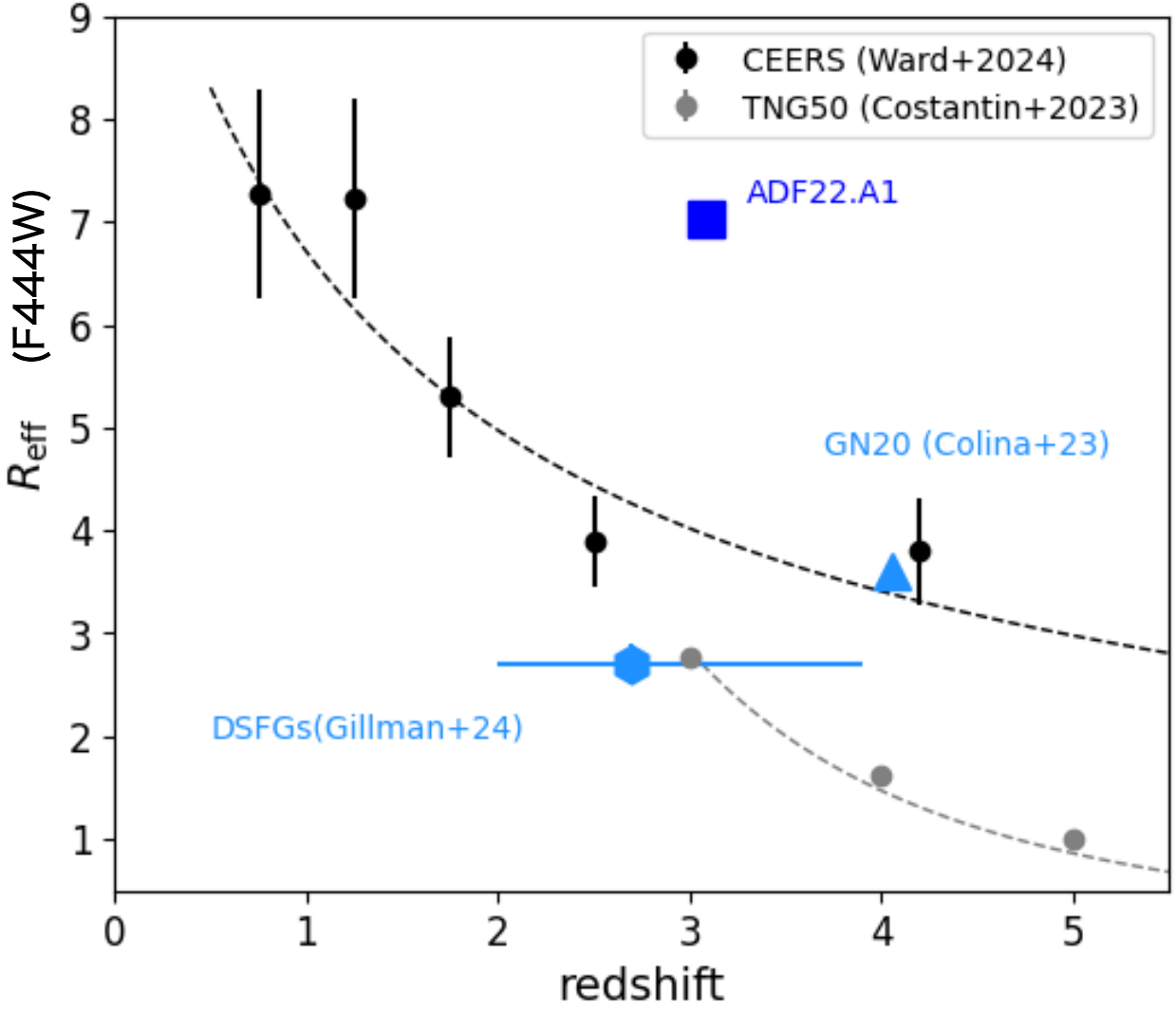








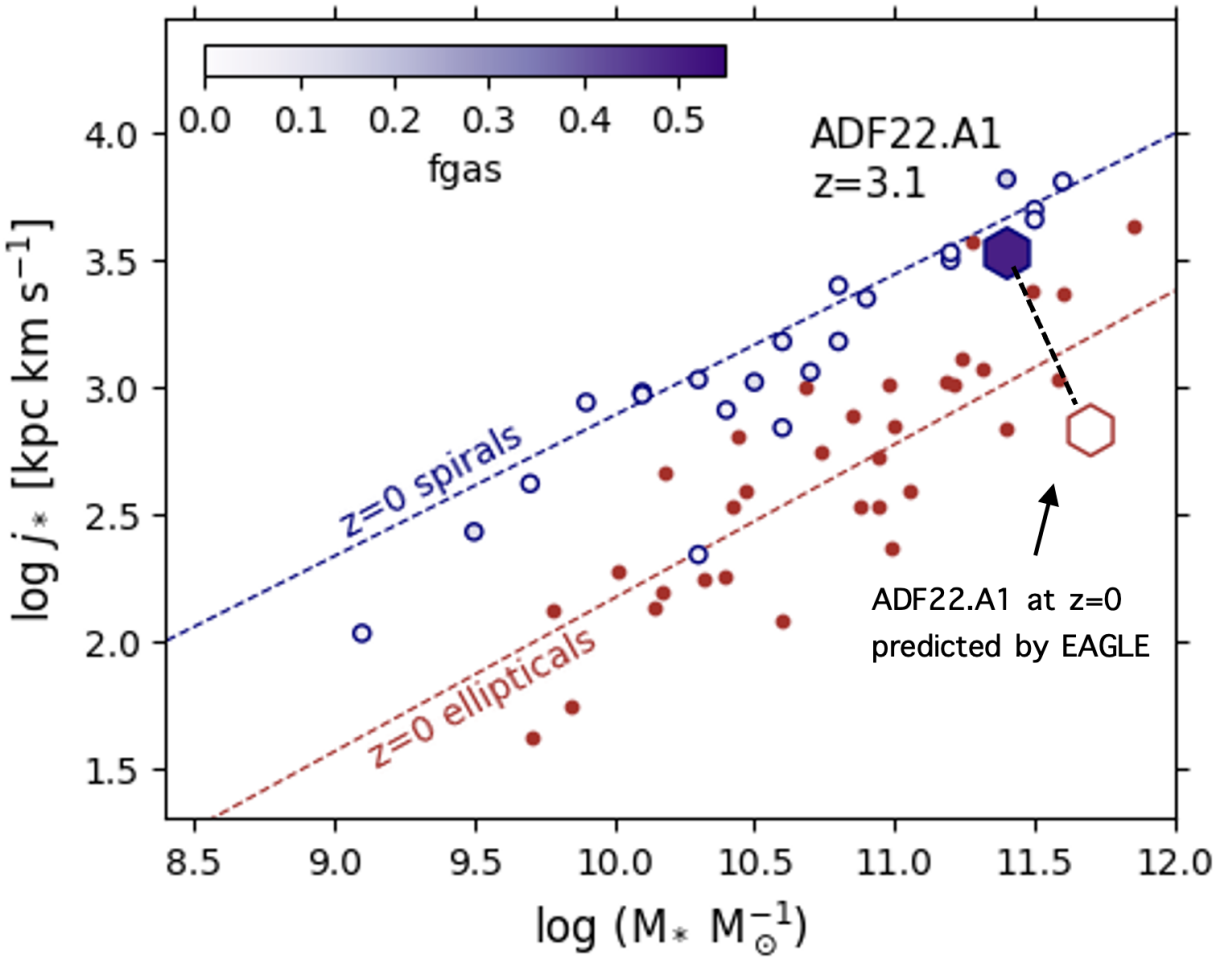
Umehata et al. 2025a, PASJ, 77, 432



(cf: Wu+2023 and Wang+2025 for other “big” galaxies at z~3)

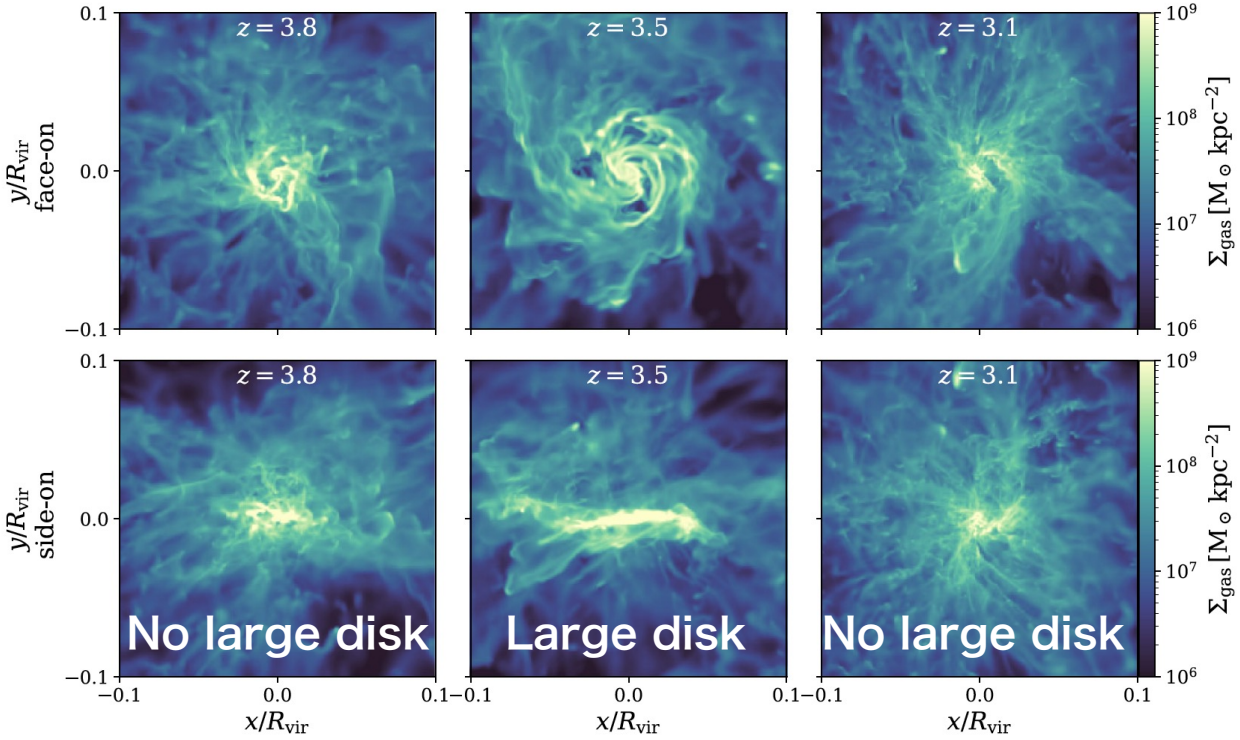
Origin of large angular momentum

Umehata et al. 2025a, PASJ, 77, 432



Intense gas accretion

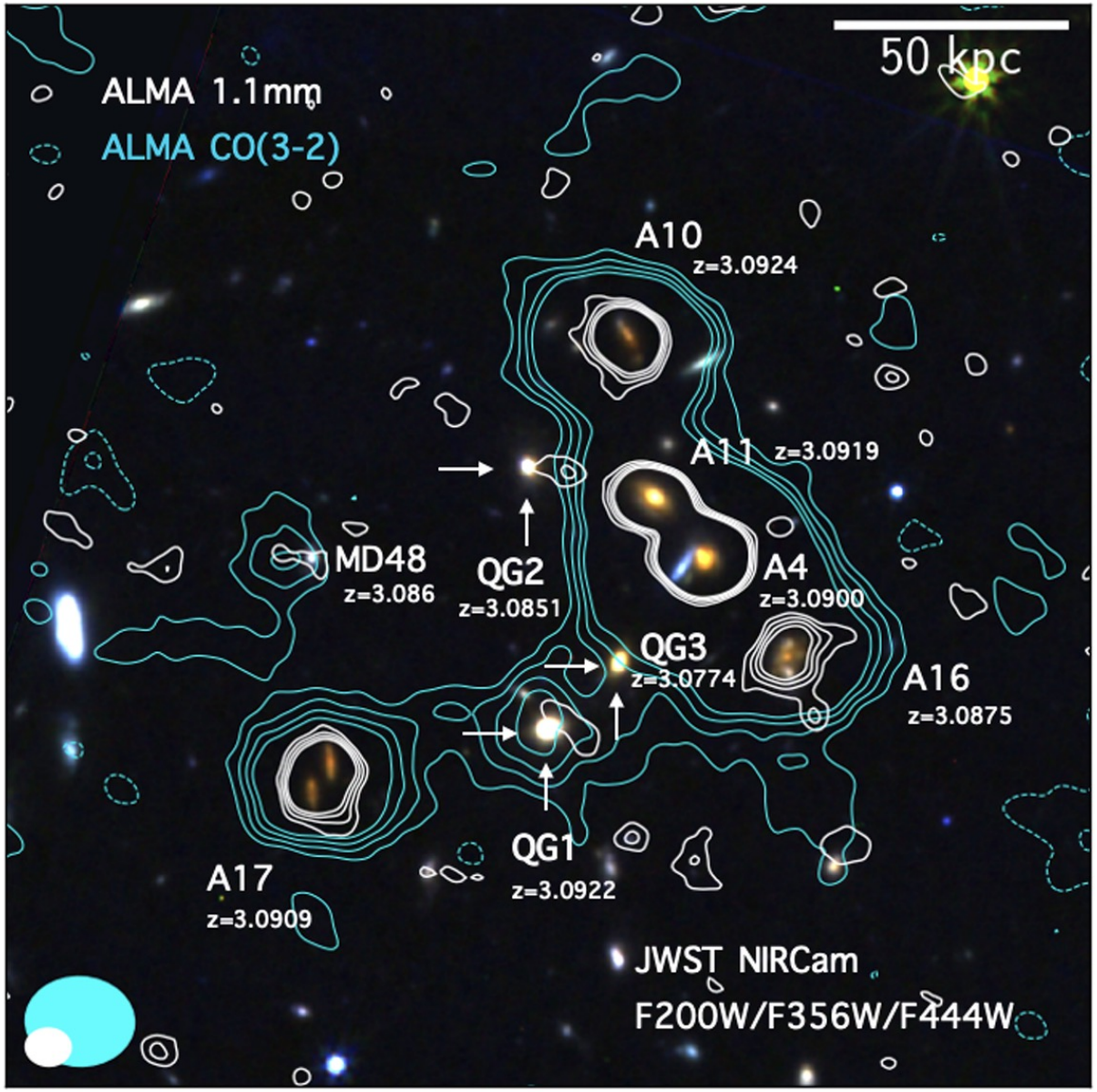
time

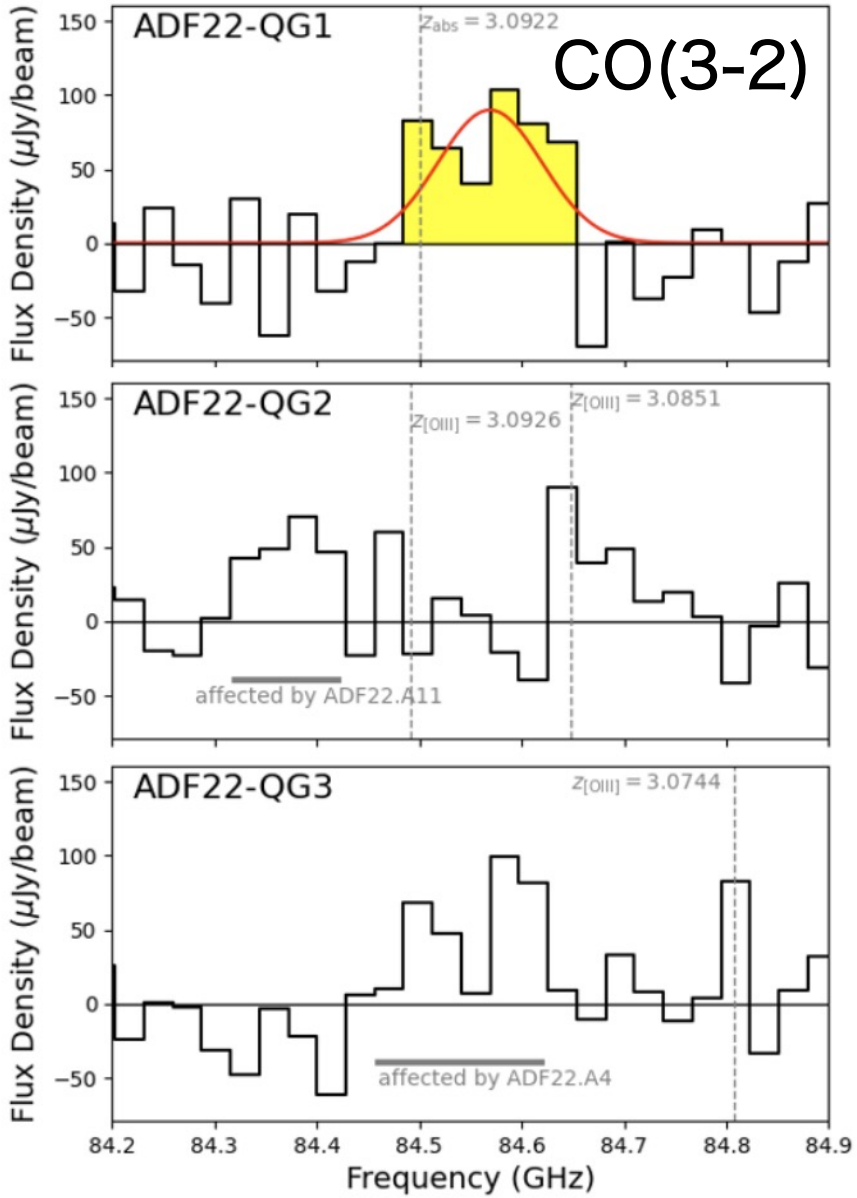


Kretschmer et al. 2022, MNRAS, 3266, 3275

- Intense accretion of coplaner, co-rotating gas via cold stream may be a key to form such a gigantic gas disk at z~3.

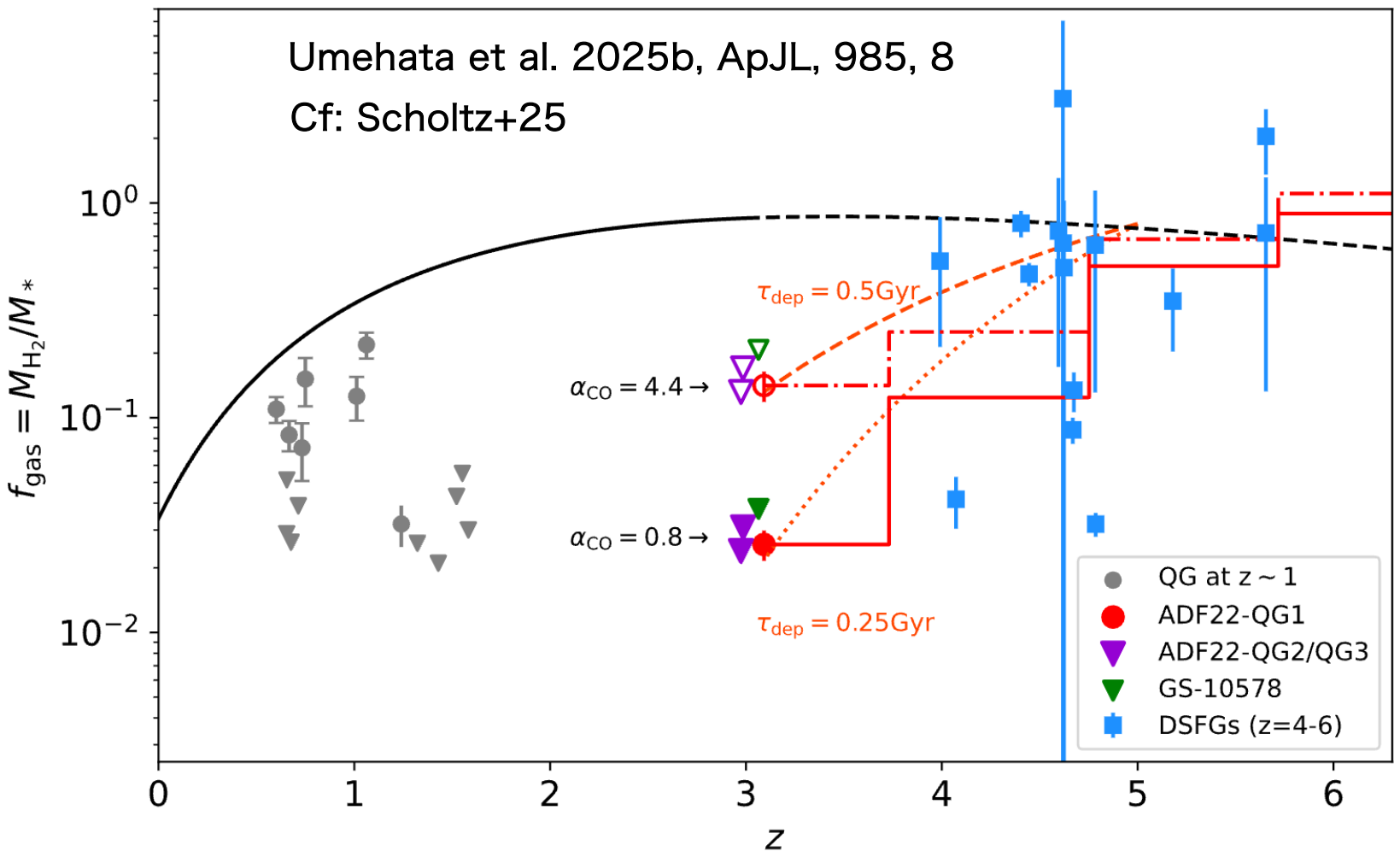
First CO detection from a QG at z>2

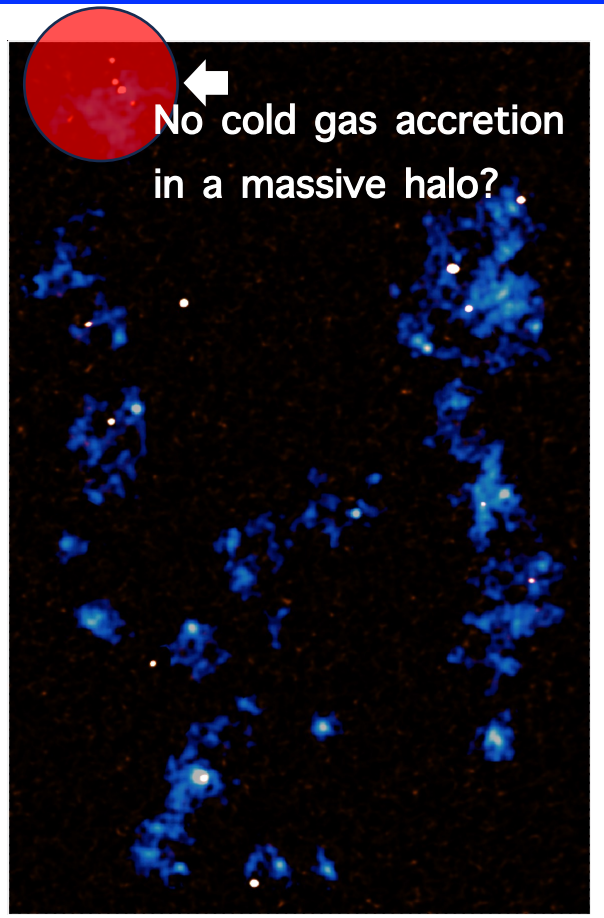




Umehata et al. 2025b, ApJL, 985, 8

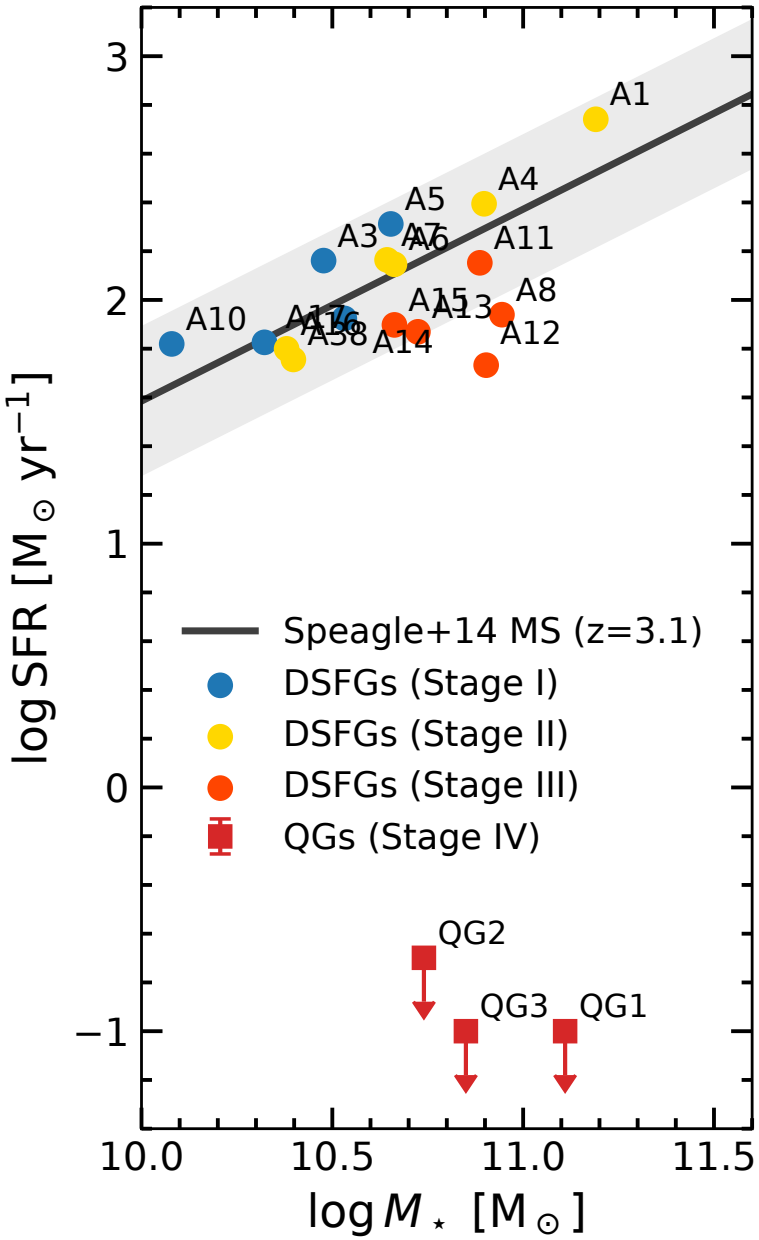
How to quench QG1?

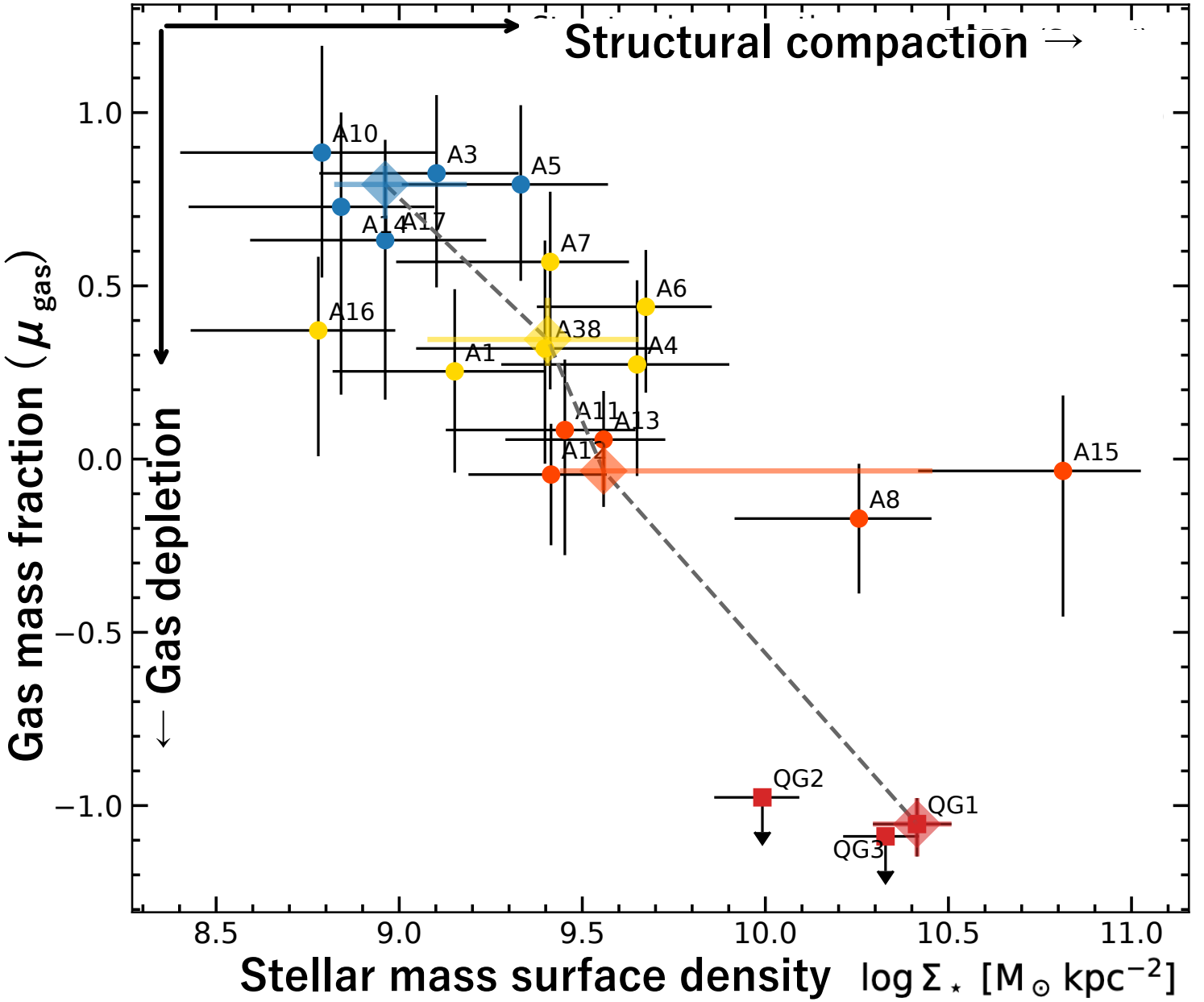




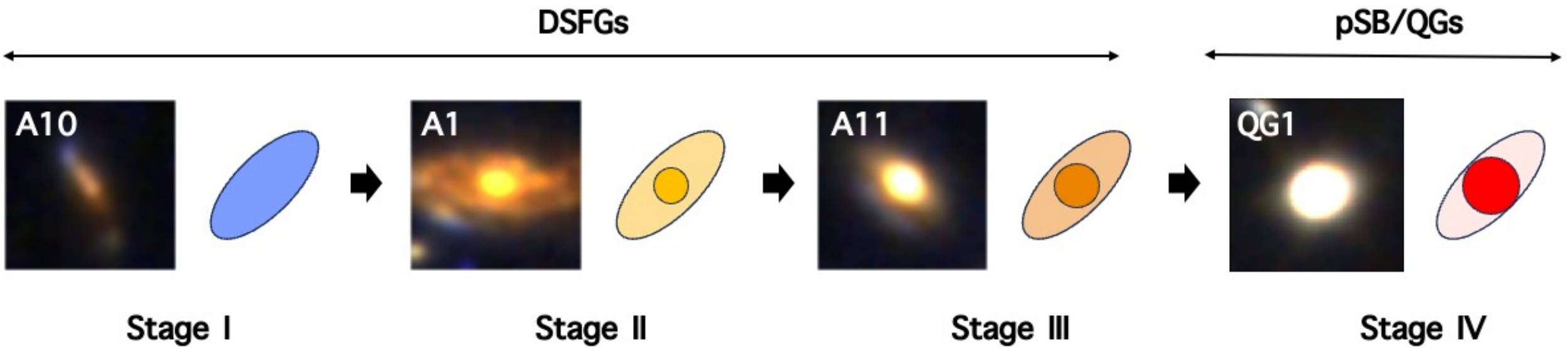
- Gas accretion from the cosmic web may be halted (e.g., heating by shocks or AGNs).
- Molecular gas consumption and morphological quenching may suppress further star formation.

Gas depletion and structural compaction





Gas depletion and structural compaction

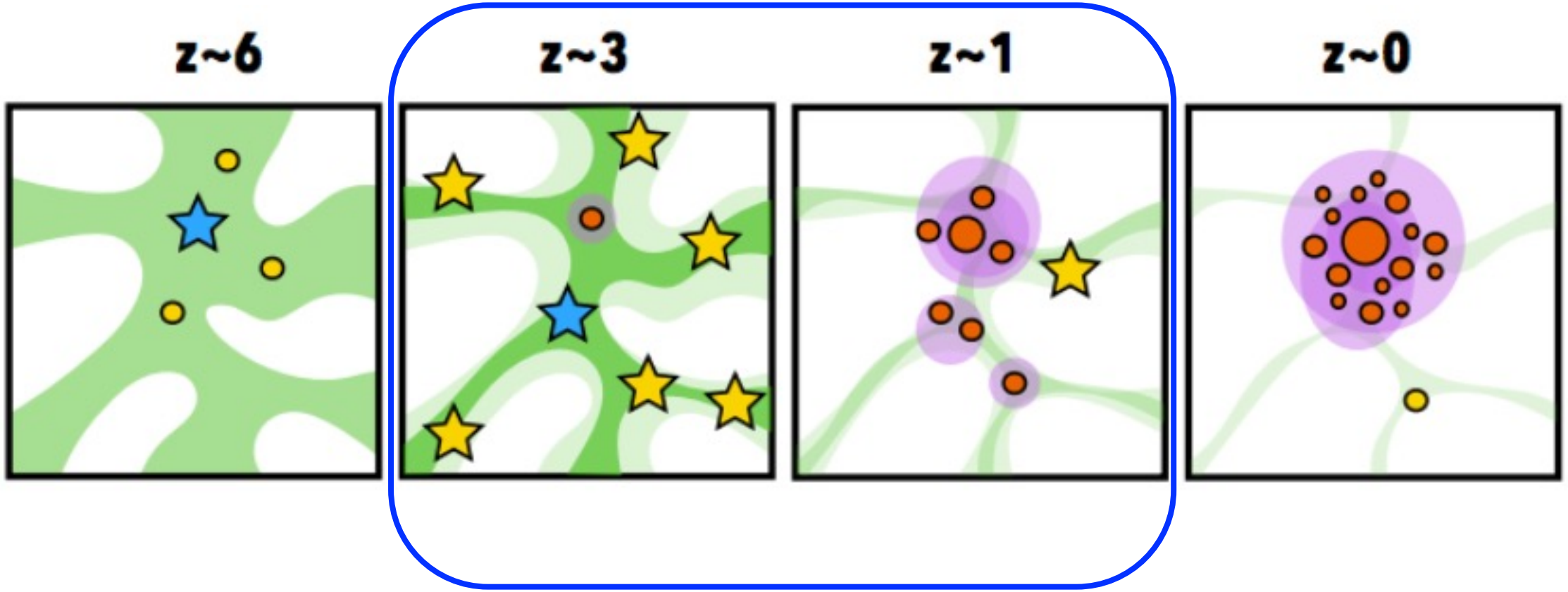


- DSFGs and QGs likely represent an evolutionary sequence from gas-rich extended systems to compact gas-poor galaxies.
- Gas depletion and structural compaction appear to proceed together.

Summary: galaxy assembly in filaments

- Massive galaxies are embedded within cosmic web gas filaments.
- Ordered disk morphology favors secular growth sustained by filaments rather than major-merger driven starburst.
- A giant disk with exceptionally large angular momentum has been discovered. Gas accretion along cosmic web filaments may efficiently transport angular momentum into galaxies.
- Gas depletion and structural compaction appear to proceed together, which may drive the evolution from gas-rich star-forming galaxies to quiescent galaxies.

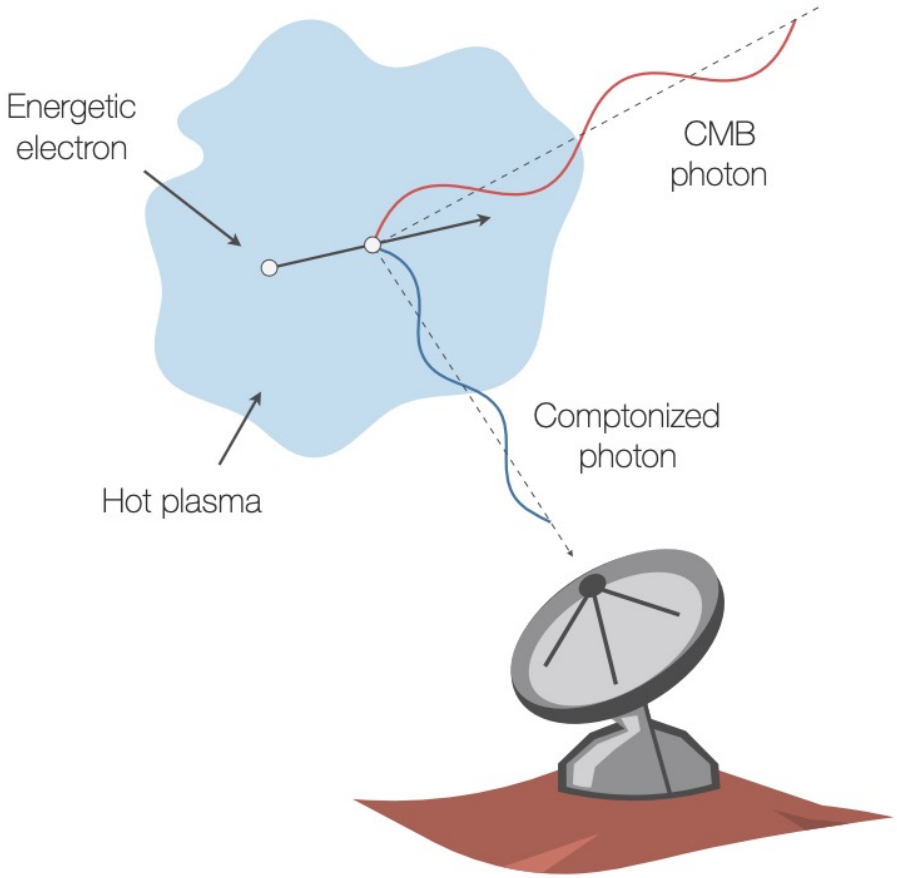
II. Emergence of the hot intracluster medium



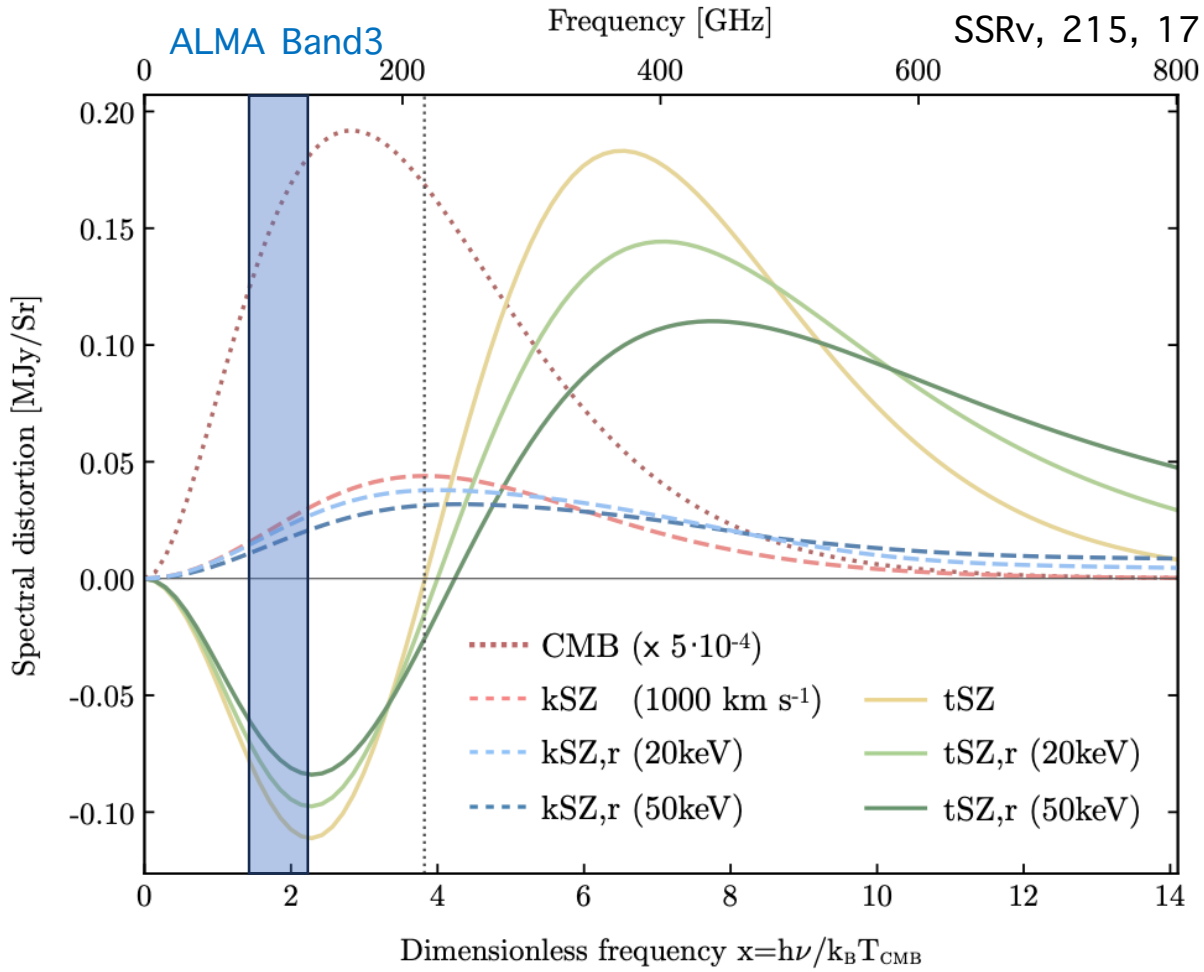
COLD GAS / HOT GAS / GALAXIES (QSOs, SFGs, QGs)

- Tracing the thermal state of baryons using CMB photons.
- A key question is: when does hot intracluster gas emerge during cluster assembly?

The thermal SZ effect

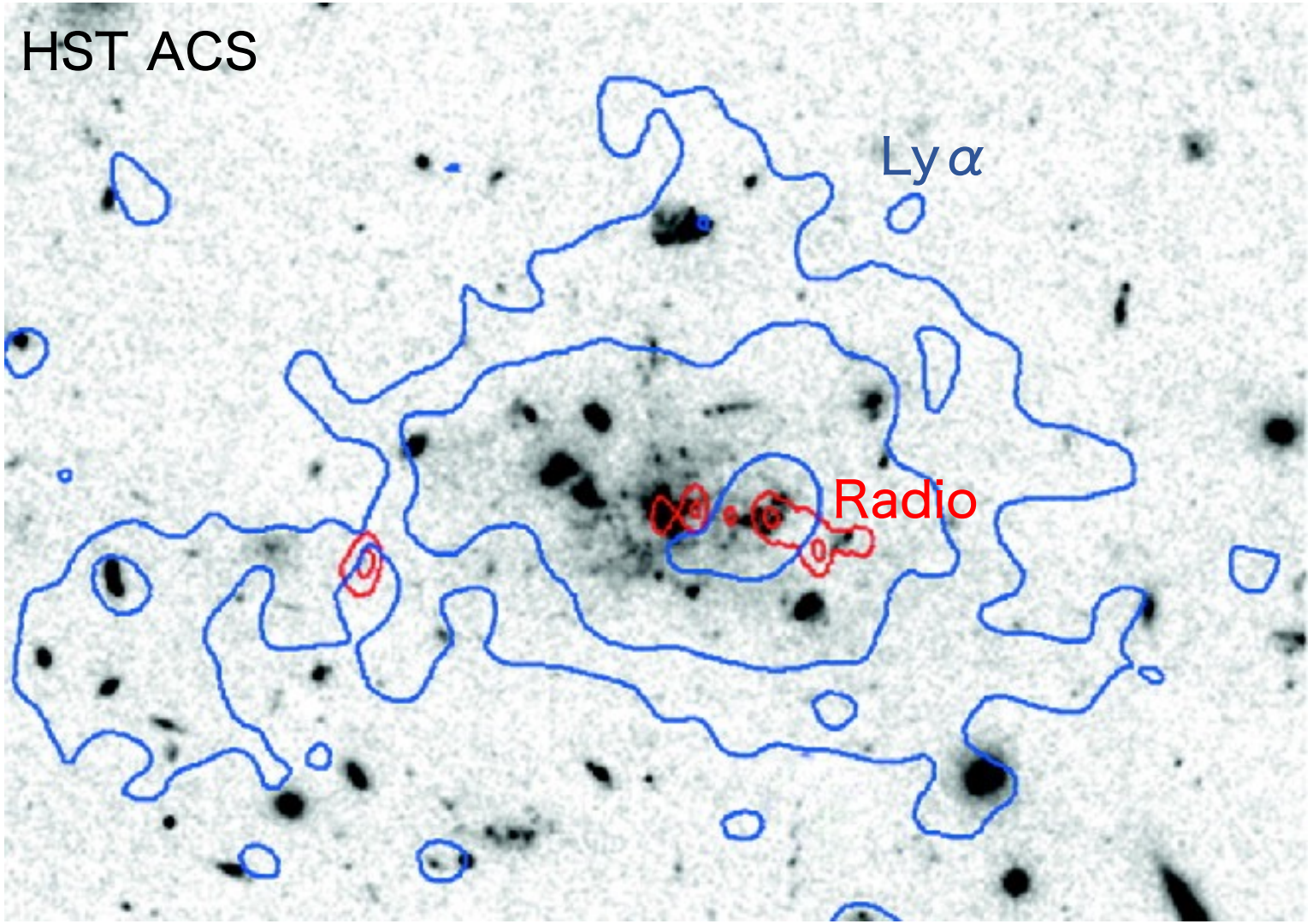


Mroczkowski+2019, SSRv, 215, 17



- **The thermal SZ effect arises when CMB photons gain energy through inverse Compton scattering by hot electrons.**
- **The tSZ effect directly probes the thermal pressure of ionized gas.**

The tSZ effect in the z=2 proto-cluster

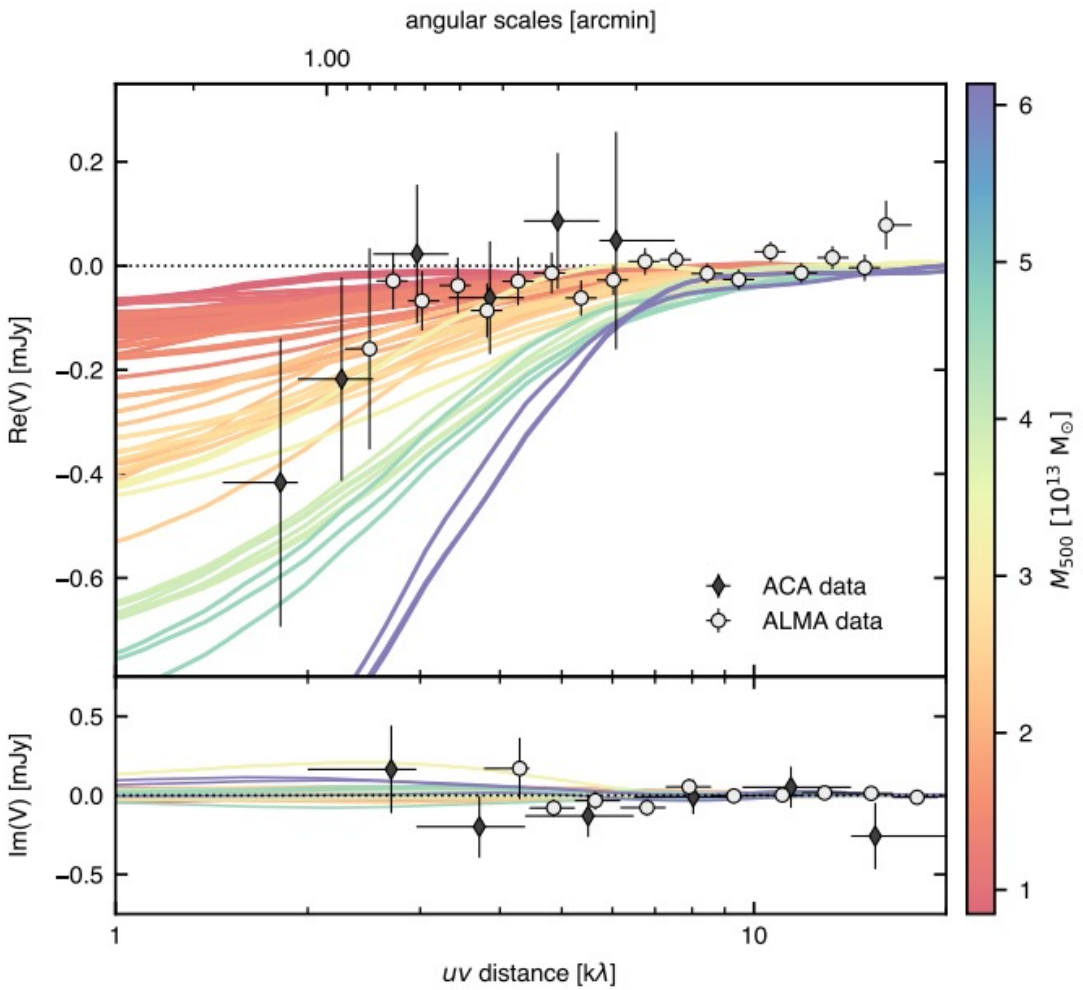


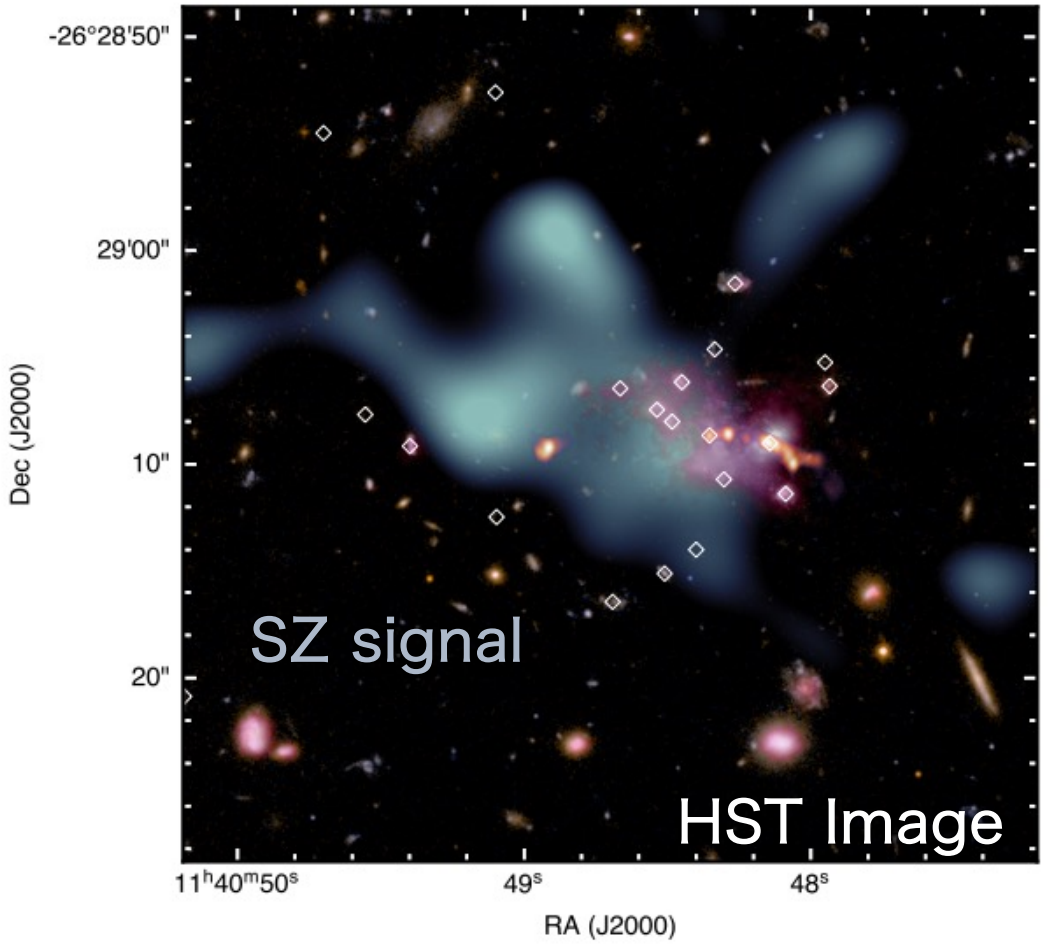
Miley et al. 2006, ApJ, 650, 29

- **The Spiderweb protocluster is the benchmark system for studying the transition from a galaxy overdensity to a mature galaxy cluster.**

The tSZ effect in the z=2 proto-cluster

Di Mascolo+2023, Nature, 615, 809

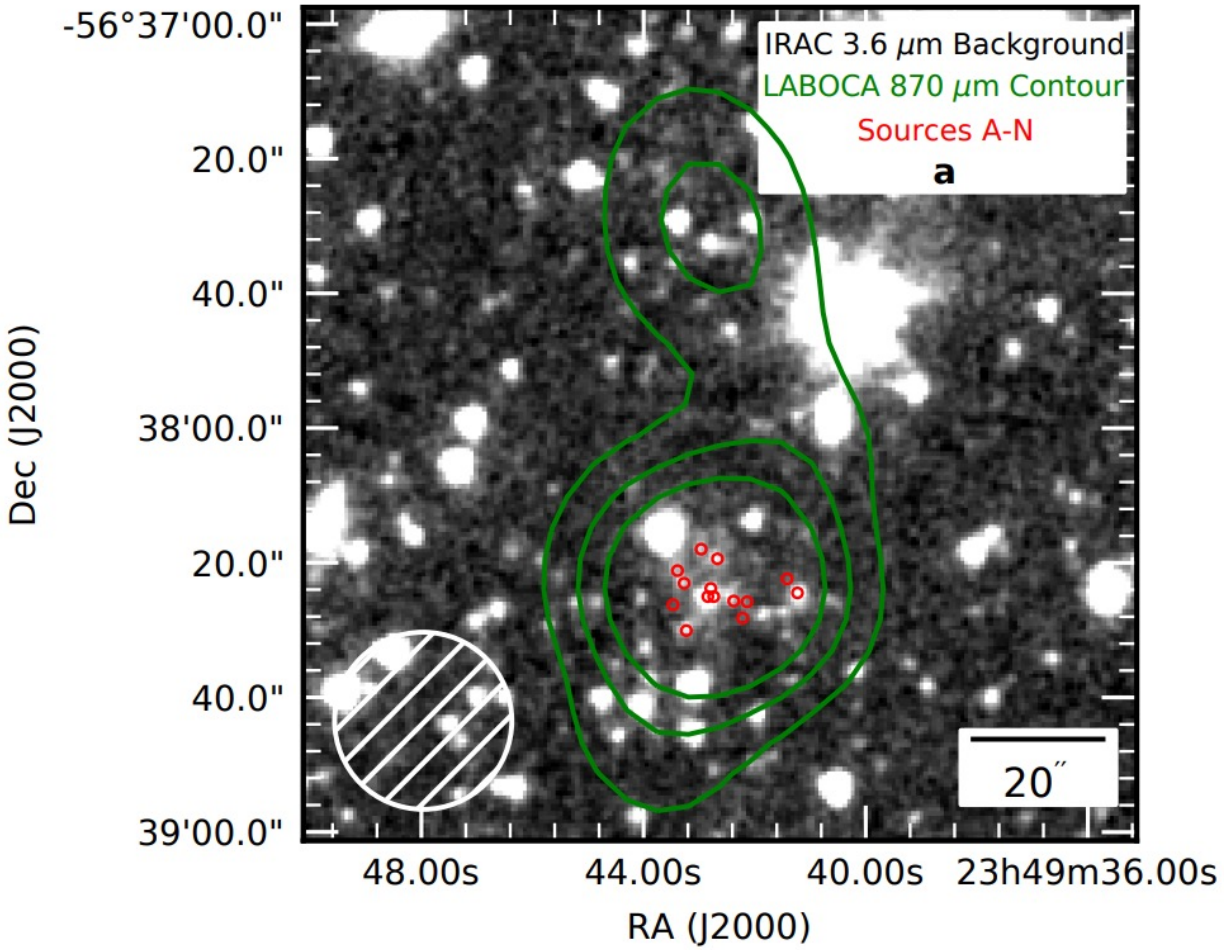


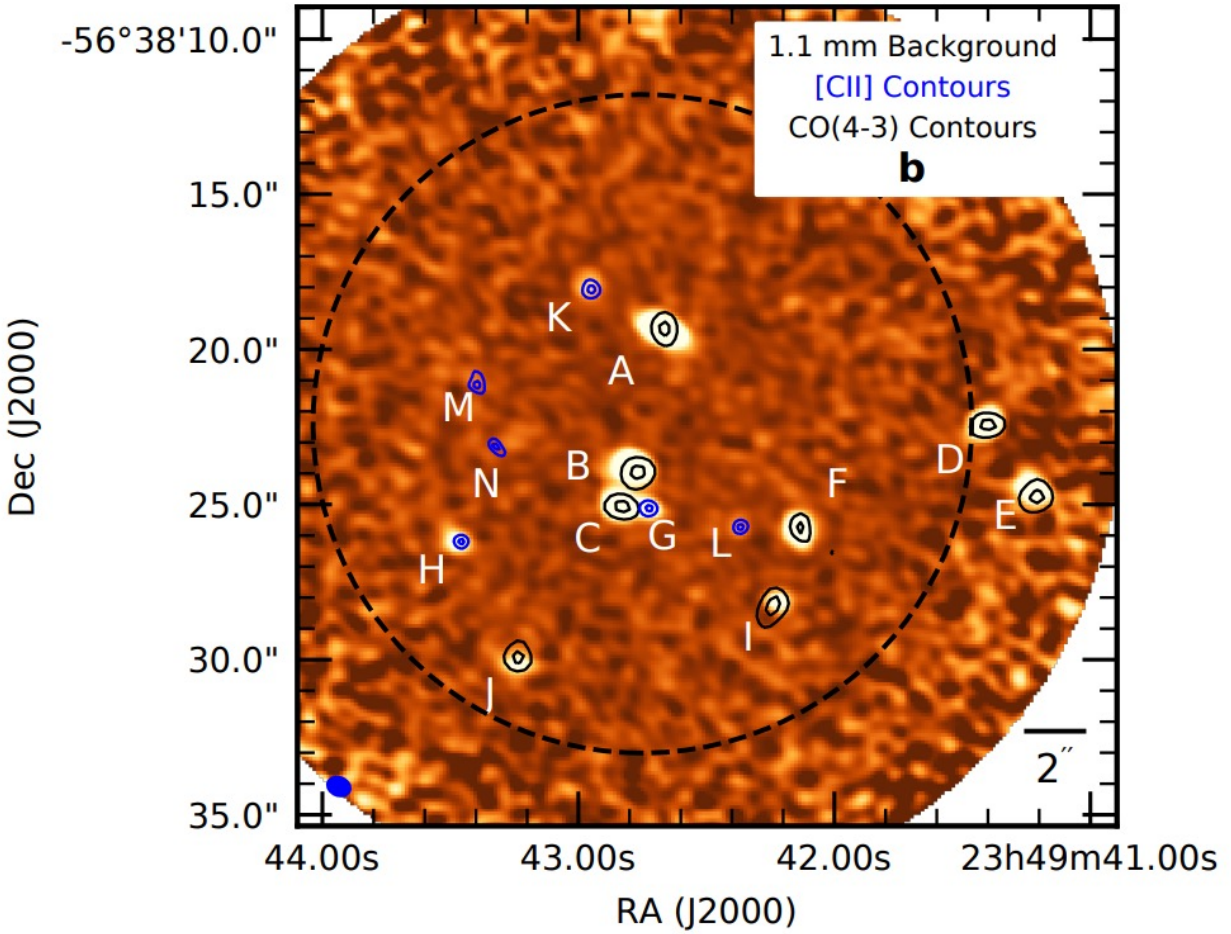


- A nascent hot intracluster medium is detected in the Spiderweb protocluster (z=2.16).
- The detected hot gas suggests that cluster-scale atmospheres are already emerging by z~2.

The tSZ effect in the z=4 proto-cluster

Miller+2018, Nature, 556,469

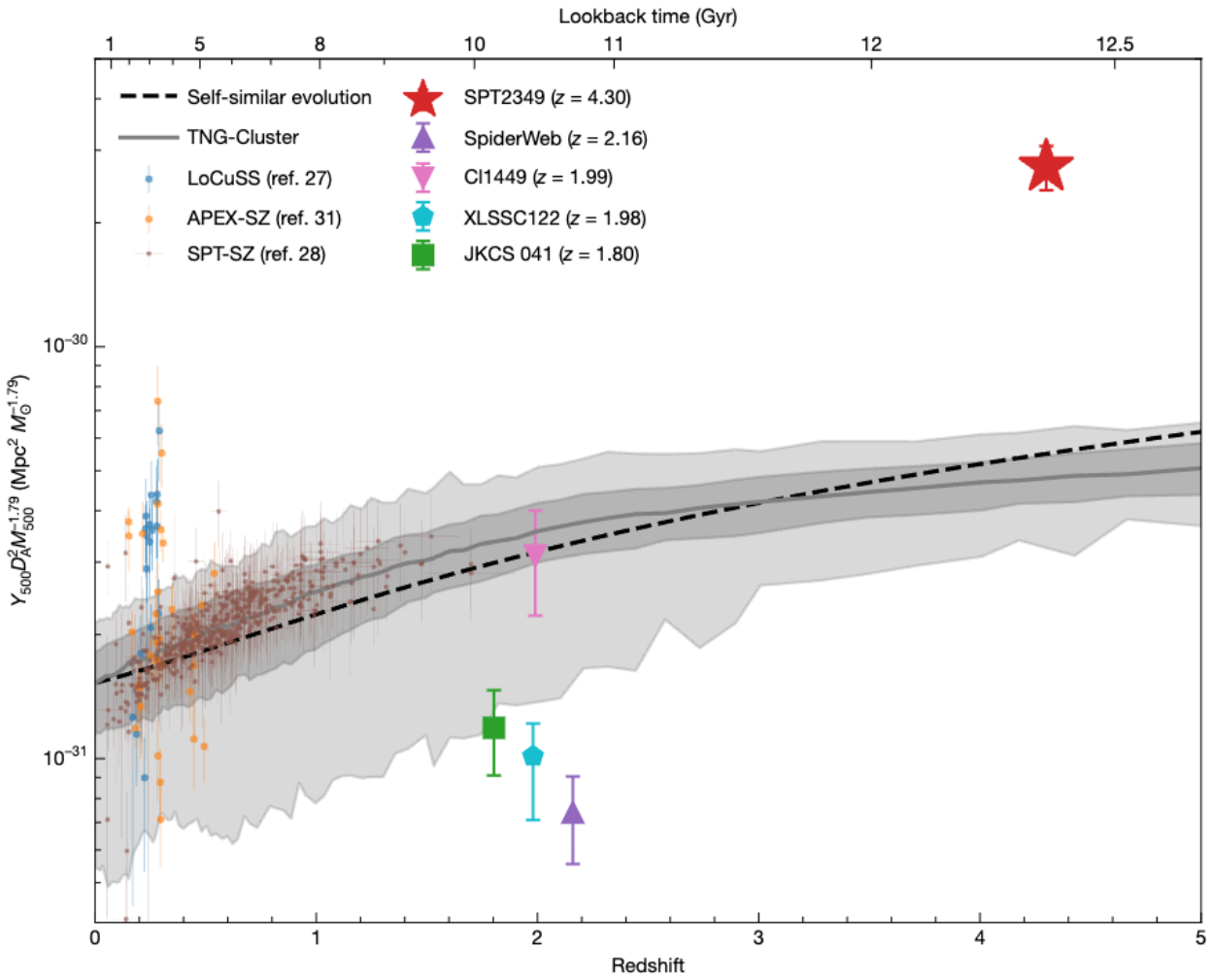


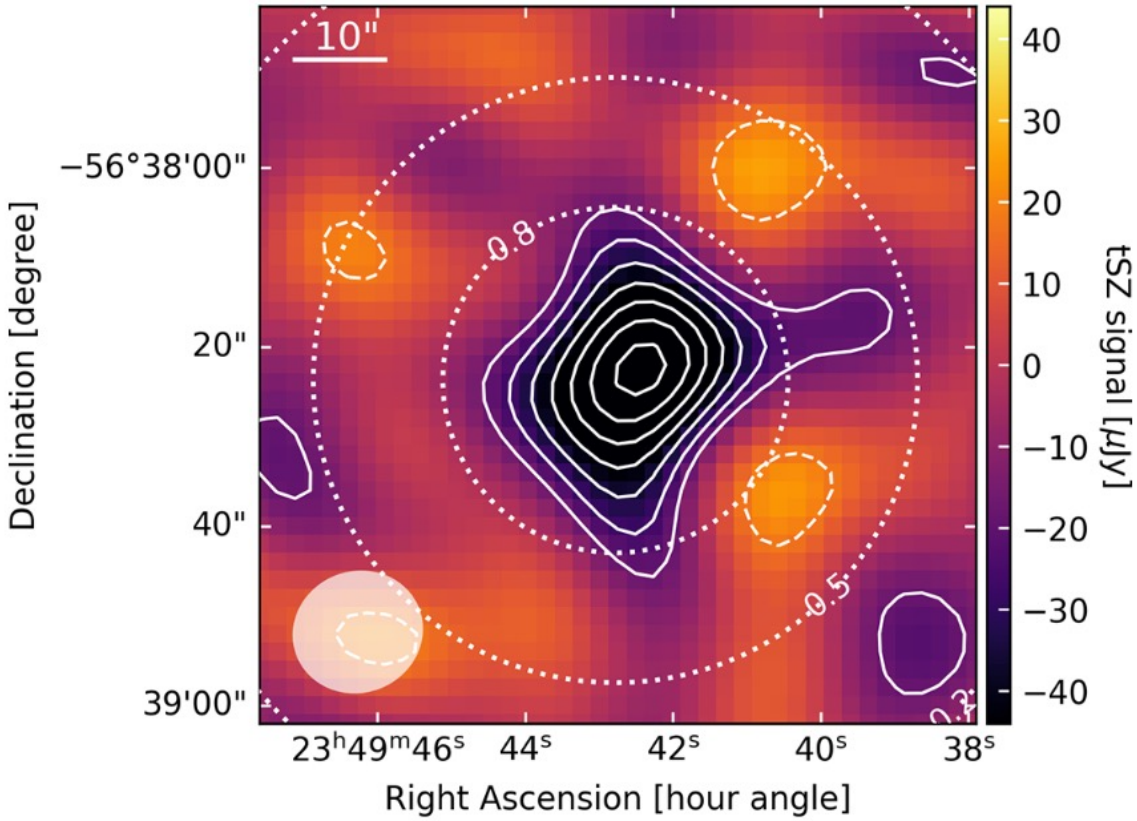


- One of the most remarkable proto-cluster core at z=4.3.

The tSZ effect in the z=4 proto-cluster

Zhou+2026, Nature, 649, 1130



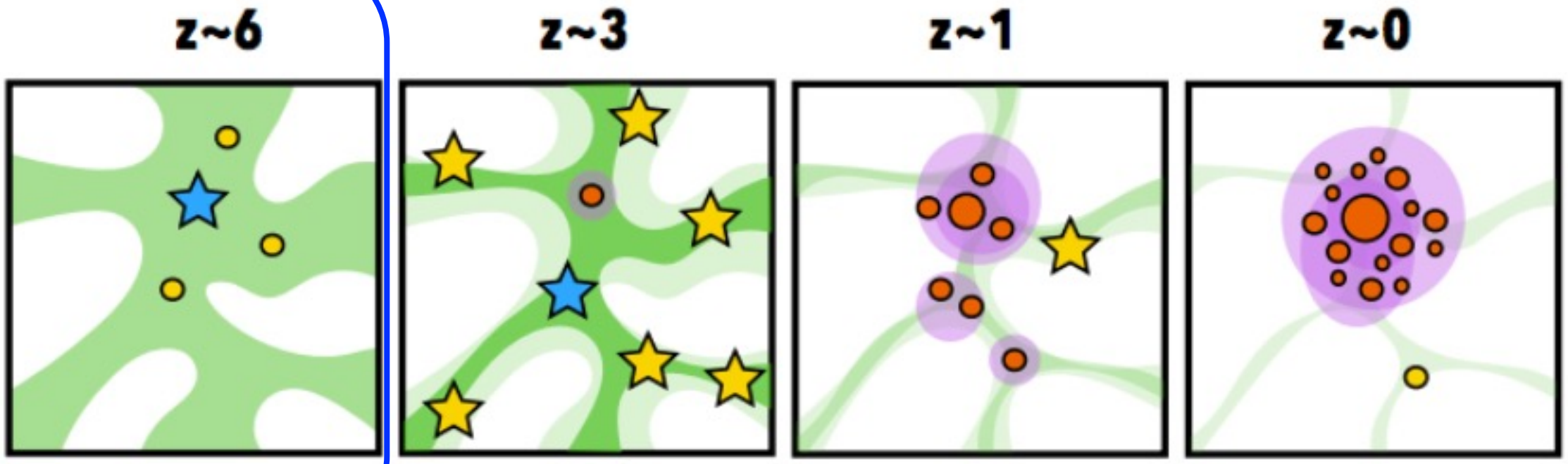


- A hot intracluster medium may already exit in the z=4.3 protocluster SPT2349−56.
- The observed thermal energy is substantially higher than predicted, implying efficient early heating by feedback.

Summary: hot gas at high-z

- The thermal SZ effect provides a unique probe of hot halo gas in high-redshift protoclusters.
- The thermal SZ effect has revealed the emergence of a nascent intracluster medium by z~2, suggesting that cluster-scale hot gas is already forming at this epoch.
- Hot halo gas may already be present by z~4, possibly owing to efficient early AGN feedback.

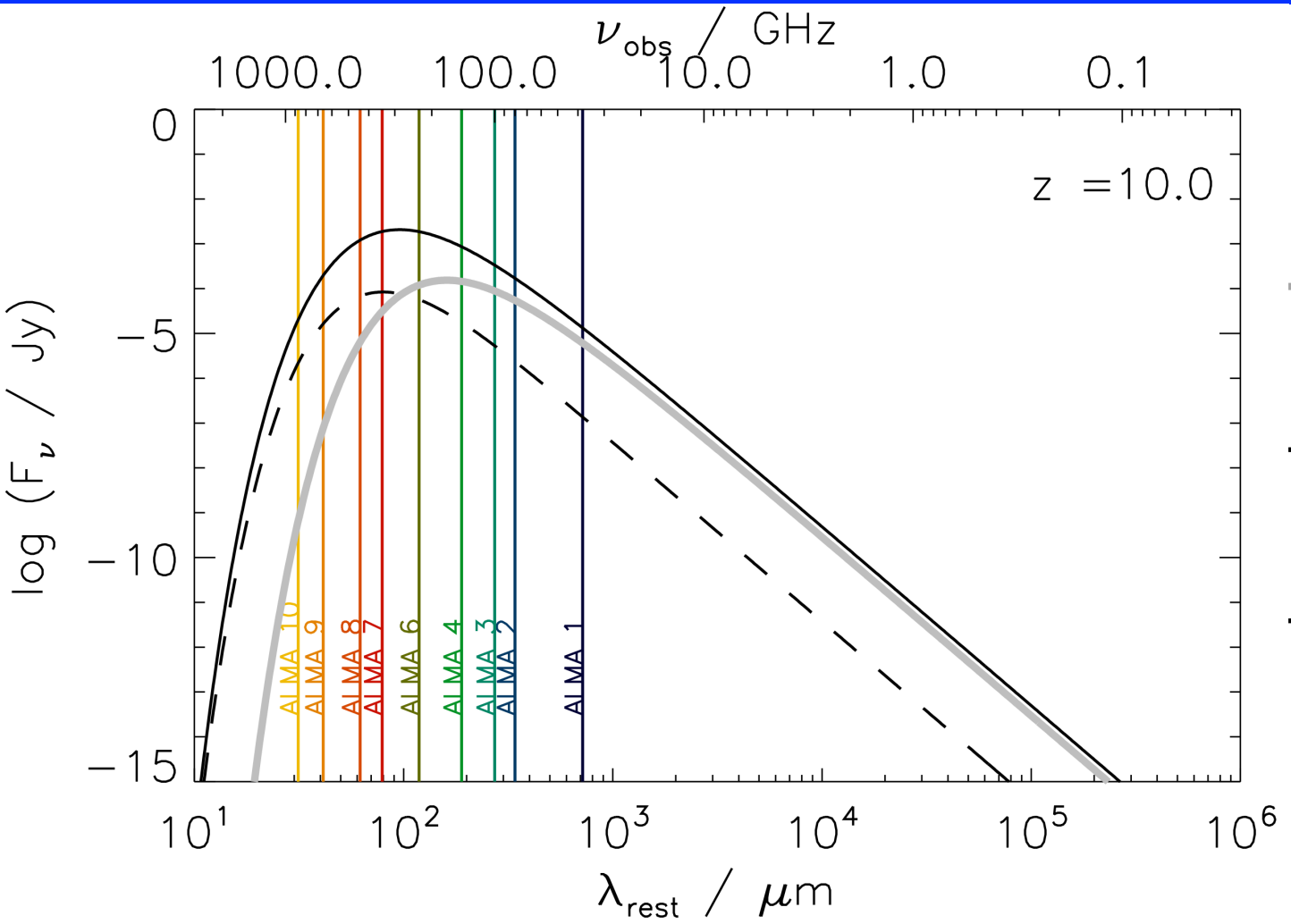
III. Proto-clusters at Cosmic dawn



COLD GAS / HOT GAS / GALAXIES (QSOs, SFGs, QGs)

- The increasing CMB temperature begins to affect ALMA observations.
- A key question is: When and how do dust grains form?

CMB Effects on ALMA Observations



Da Cunha et al. 2013, ApJ, 766, 13

intrinsic SED with no dust heating by the CMB

intrinsic SED with dust heating by the CMB

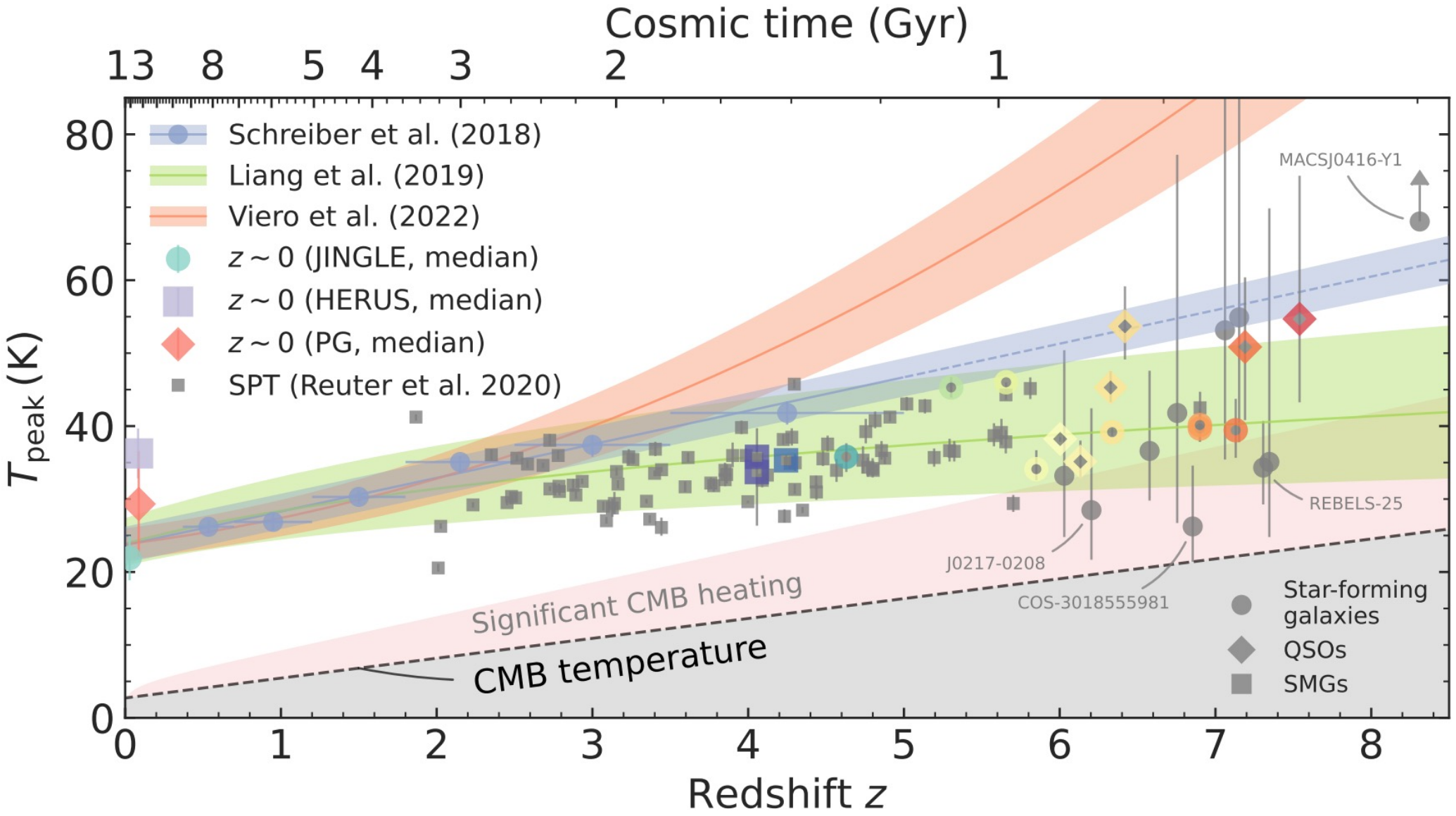
Observed SED (including the CMB background)

■ CMB affects ALMA observations in two ways

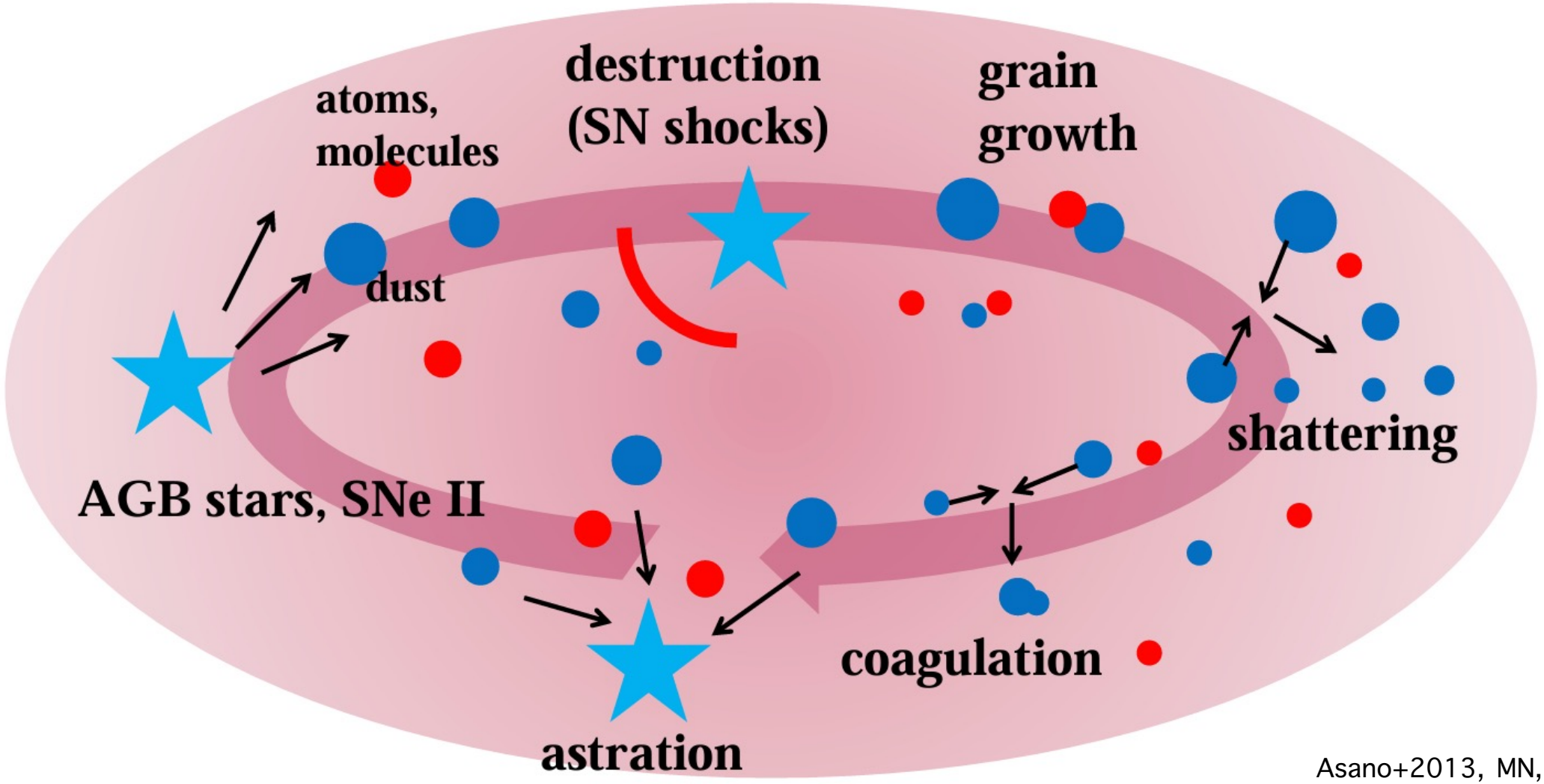
1. Heating: dust becomes warmer
2. Reduced contrast: dust continuum becomes fainter

CMB Effects on ALMA Observations

Witstok et al. 2023, MN, 523, 3119



How is dust formed?

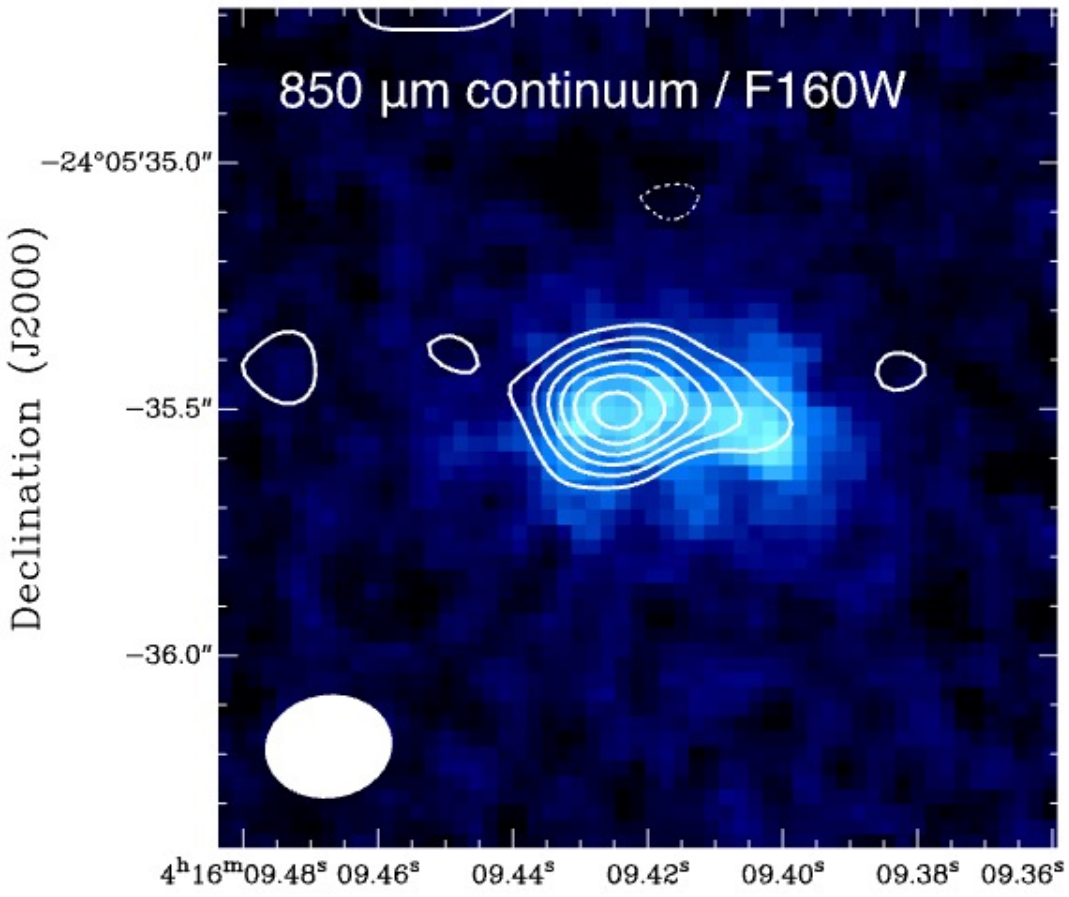


Asano+2013, MN, 432, 637

■ Dust is a key component of the baryonic cycle linking stars, gas, and metals.

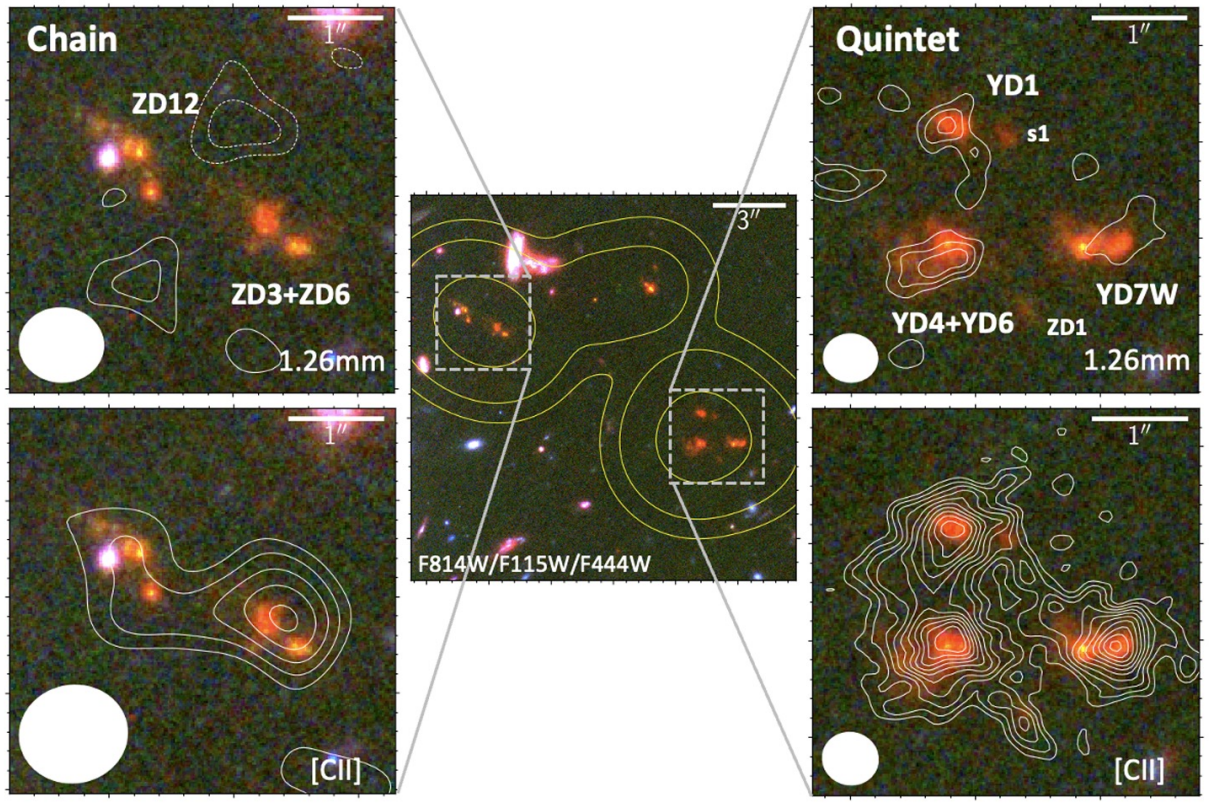
Results

MACS0416-Y1 at z=8.31



Tamura+2019, ApJ, 874, 27

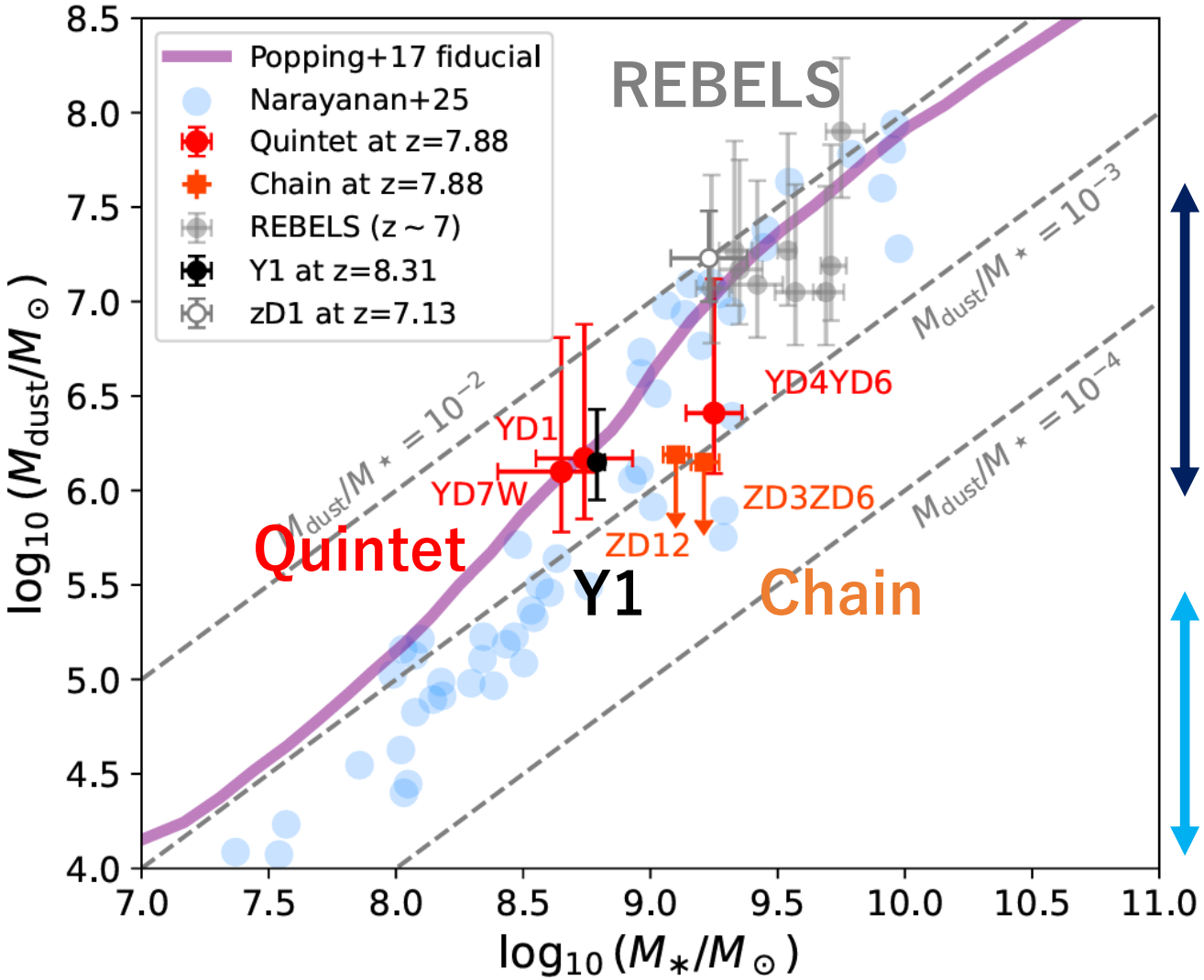
A2744-Quintet at z=7.88



Umehata et al. 2025c, ApJ, 993L, 50

- Dust continuum has now been detected in four galaxies residing in two z~8 proto-clusters.

Discussion: Dust-to-stellar mass ratio



SNe + grain growth

SNe

Umehata et al. 2025c, ApJ, 993L, 50

Cf: Popping+2017, Narayanan+2025, Bakx+2025, Algera+2026

■ **Some z~8 galaxies may be transitioning from SN-dominated dust production to grain growth.**

Summary: Proto-clusters at Cosmic dawn

- The CMB increasingly affects ALMA observations toward higher redshifts.
- Dust continuum has now been detected in galaxies residing in z~8 proto-clusters.
- Some z~8 galaxies may be transitioning from SN-dominated dust production to grain growth.

Take home messages

- Galaxies form and evolve within the cosmic large-scale structure.
- ALMA and JWST are revealing how baryons assemble into massive galaxies along cosmic web filaments.
- The thermal SZ effect is beginning to reveal the emergence of hot halo gas during cluster assembly.
- ALMA is now probing the cold ISM at Cosmic Dawn, despite the increasing impact of the CMB.