Environmental Quenching seen in CO Emitting Galaxies in a Massive Cluster SPT-CL J0615−5746

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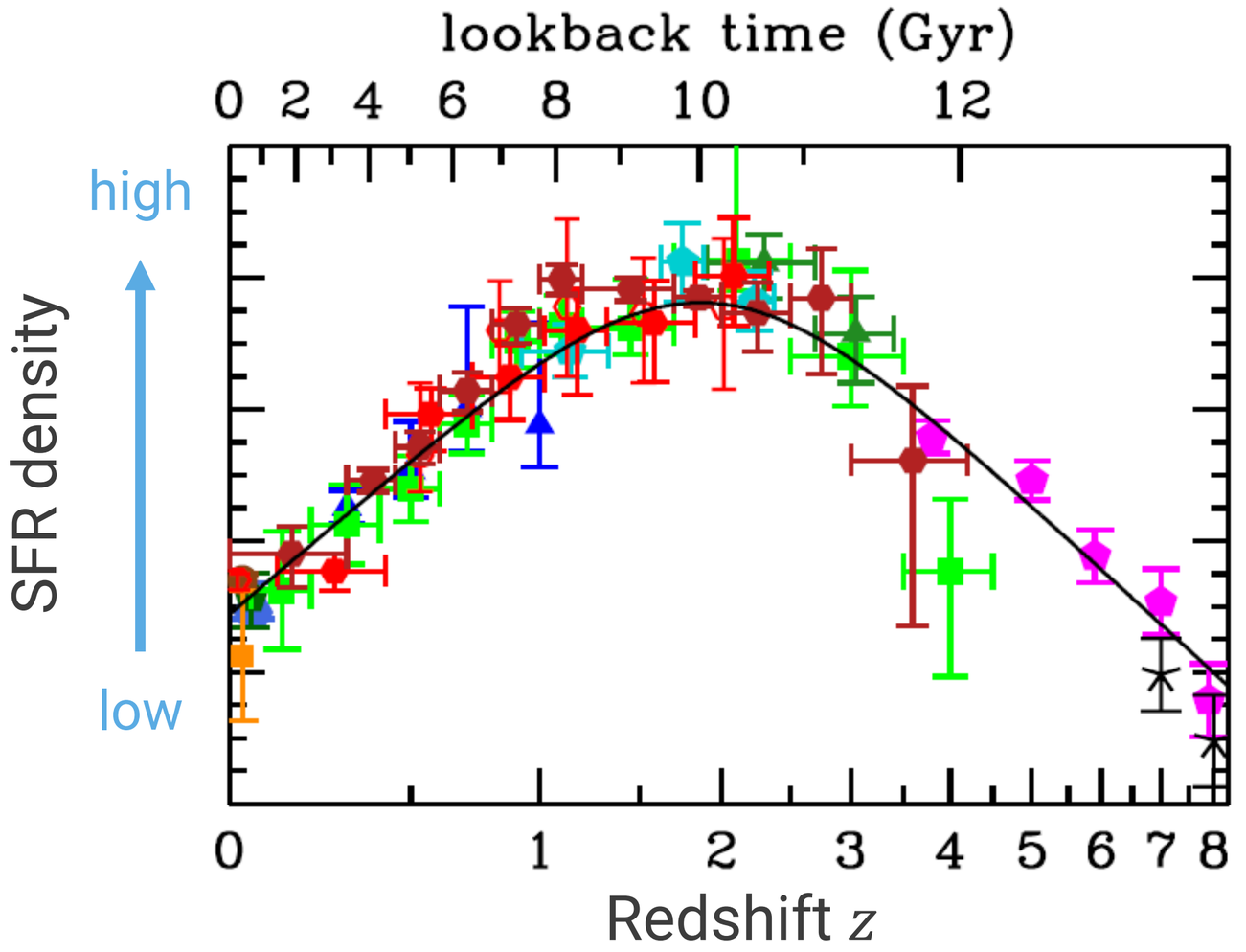
Introduction

Section 1

Star formation continue to decline



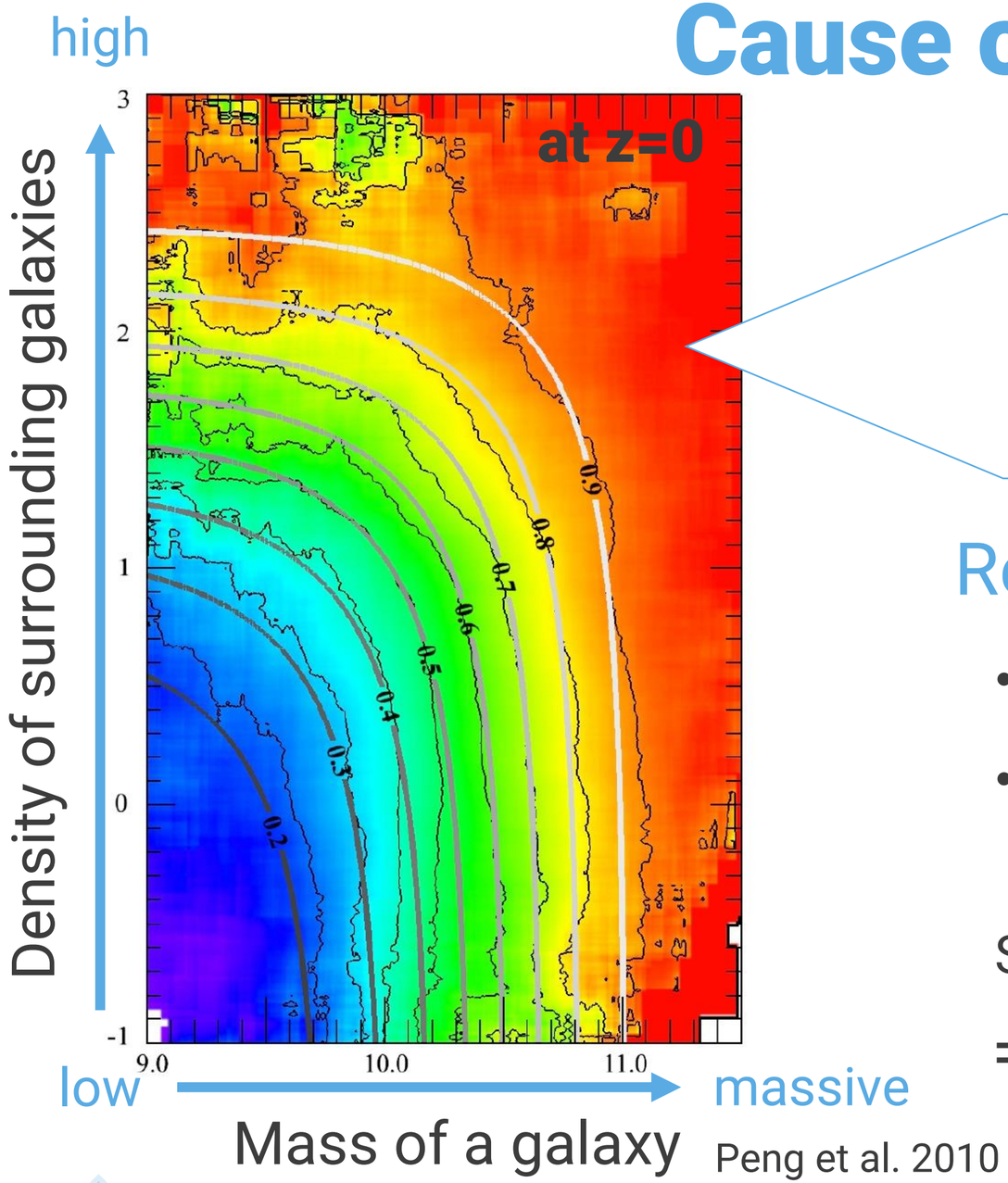
Madau & Dickinson 2014

Relationship of SFR density to redshift

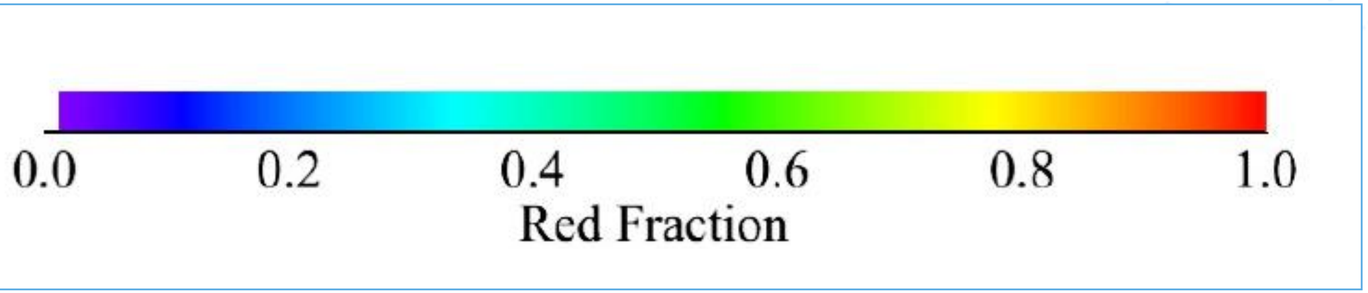
- The peak of star formation is $z \sim 2$
- Current SFR density is 1/20 of the peak

⇒ **Why did the SFR decline?**

Cause of declined SFR



Peng et al. 2010



Red fraction and environment at $z = 0$

- Massive galaxies stop star formation
- If the density of surrounding galaxies is high, stops star formation even in low-mass galaxies

Surrounding galaxies' density ··· **Environmental effect**

⇒ **Is the decline of SFR caused by environmental effect?**

Unresolved problem

What is the process of environment quenching?

Ex.1 Ram pressure / Viscous stripping

Ex.2 Tidal stripping / Galaxy harassment

Ex.3 Strangulation

… But we still don't know what the main process is for each cluster

We need the physical information of the galaxies which is just quenching

However, the detailed information of the molecular gas in cluster galaxies is almost **limited to the local galaxies ($z < 0.1$)**

Purpose of this study

Problems

- The process of environment quenching in individual clusters and galaxies remains to be determined
- Little information about spatially resolved molecular gases especially in cluster galaxies with $z > 0.1$

Purposes

- Obtain detailed information on the molecular gas of galaxies located in the center of a distant ($z \sim 1$) cluster
- Clarify the effect of cluster environment on galaxies from the physical information of galaxies obtained

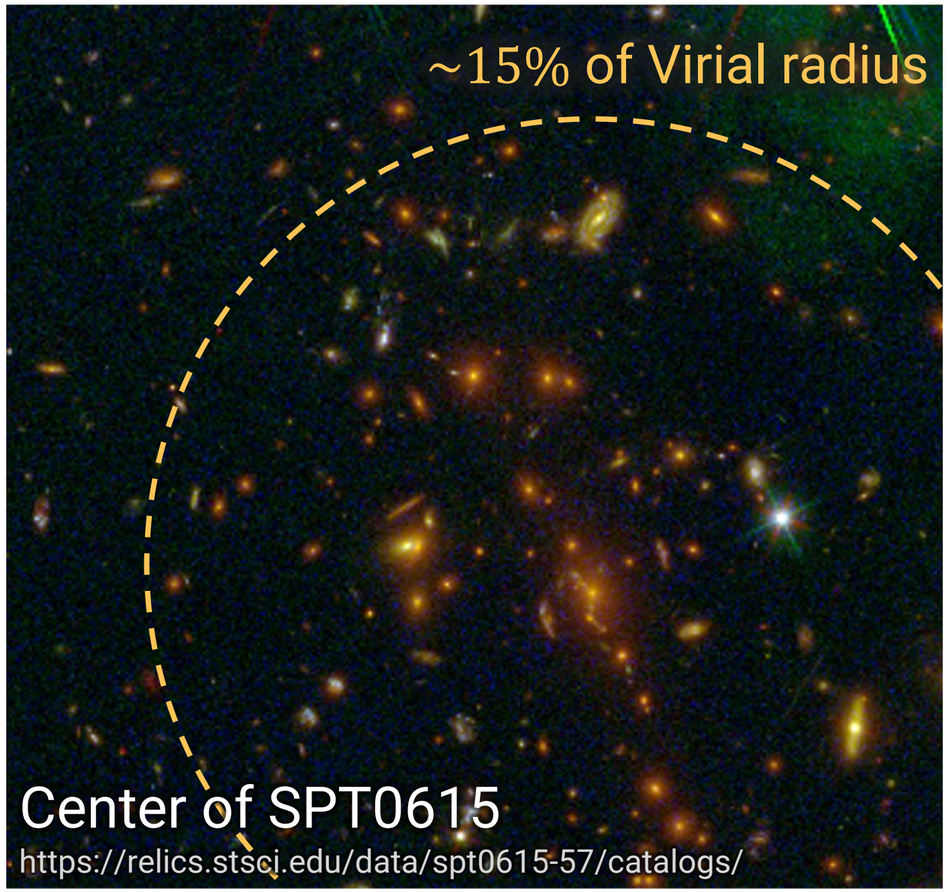
Methods

Analyze the observation results of **CO($J = 5-4$)** and **dust continuum** by Atacama Large Millimeter/submillimeter Array; ALMA

→ Get information about molecular gases and star formation

Target : SPT-CL J0615−5746

SPT0615; one of the farthest observed to cause gravitational lensing



	R_{500}	M_{500}	ICM temperature
Properties of cluster	~ 1 Mpc	$\sim 10^{15}\ M_{\odot}$	$\sim 10^{8}$ K

A. Pascut & T. J. Ponman 2015; Bartalucci et al. 2017; Bulbul et al. 2019

- Exists at $z = 0.972$; when clusters are just accumulating
- Filled with hot ICM ($\sim 10^{8}$ K)

→ a distant but relatively developed cluster

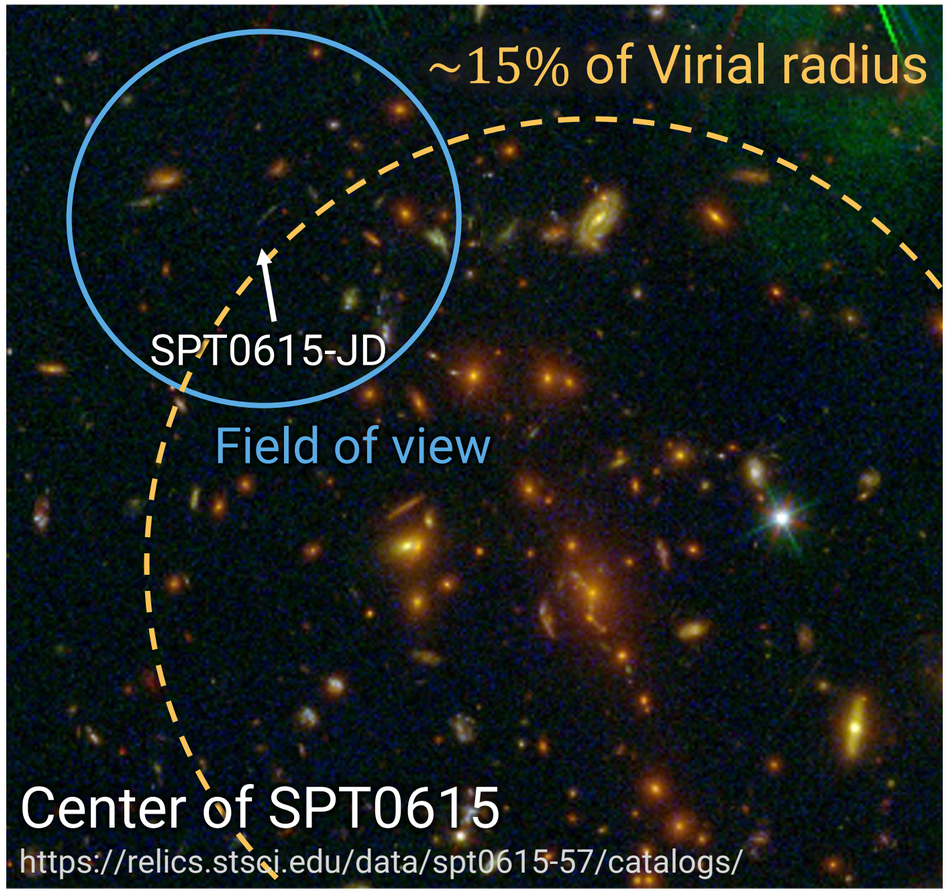
→ **It is expected that central star formation is relatively inactive**

Observations and Results

Section 2

ALMA Band 7 data

Contains CO(5—4) line at $z = 0.972$ (292.23 GHz)



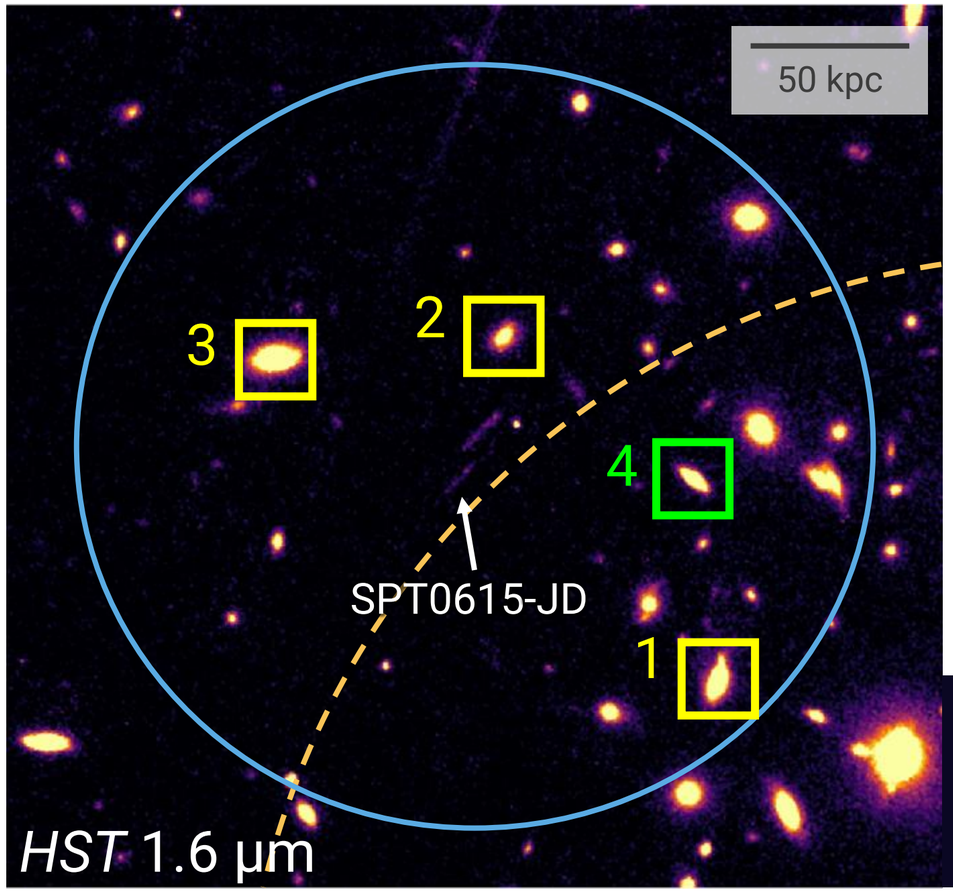
Date (UT)	23rd, November— 5th, December, 2018 (Cycle 6)
Frequency	290.31 GHz — 323.97 GHz
Target (RA / Dec)	SPT0615−JD (06:15:55.03 / −57:46:19.56)

Results of imaging

Dust continuum	
RMS noise	~ 8.3 μJy beam^{-1}
Beam size	0”.29 × 0”.26 (~2.2 kpc)
CO(5—4) data cube	
RMS noise	~ 0.10 mJy beam^{-1}
Beam size	~ 0”.34 × 0”.30 (~2.5 kpc)
Frequency resolution	93.75 MHz (~96.2 km s^{-1})

Observations results

Four star-forming galaxies located in the center of the cluster SPT0615 were detected



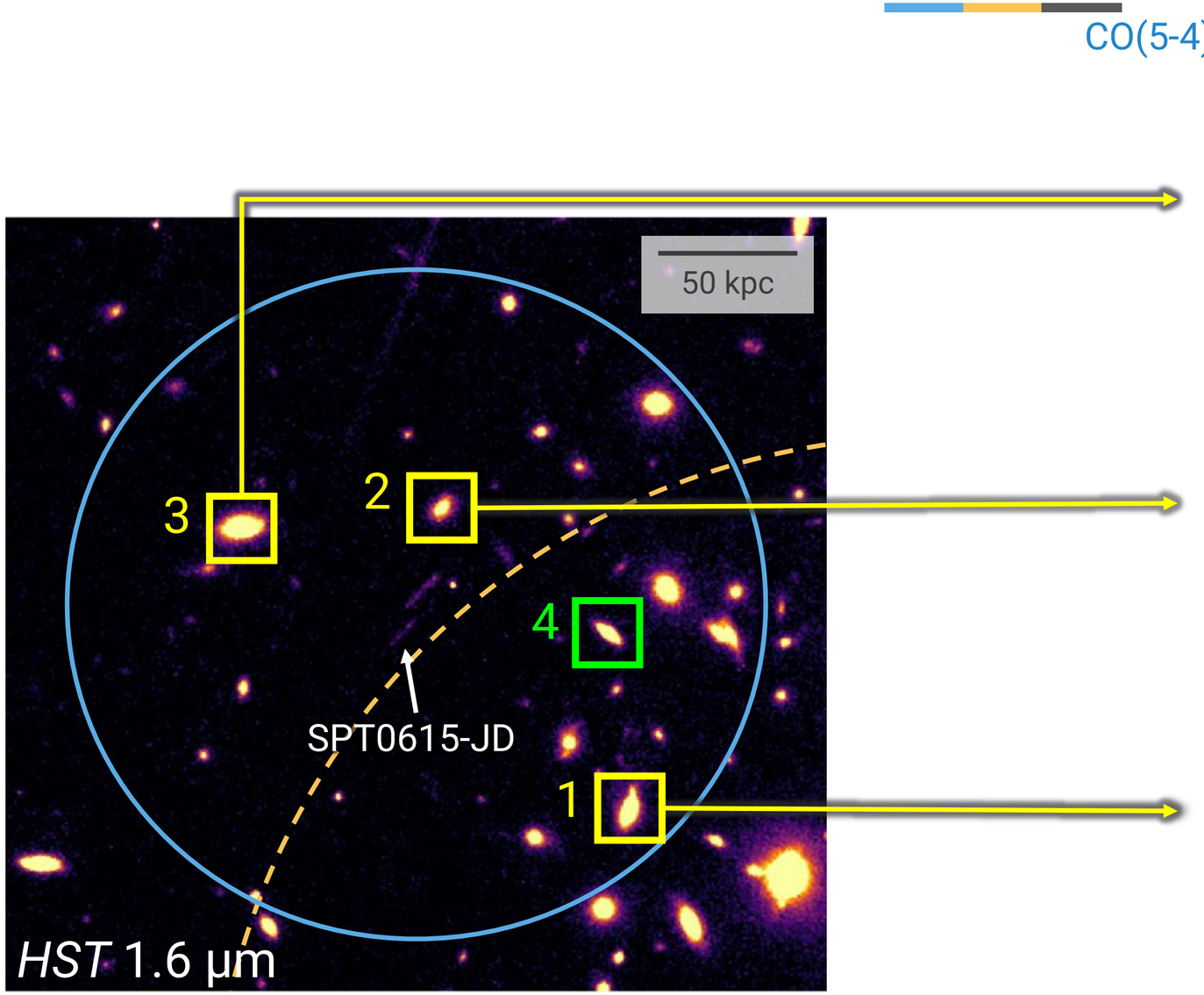
- Dust continuum was detected in 4 objects, and CO(5—4) line was detected in 3 of them
- Although located in the center of the cluster, the 3 member galaxies have CO(5—4) lines, suggesting star-forming activity

⇒ **We can say that these galaxies are going to be quenched**

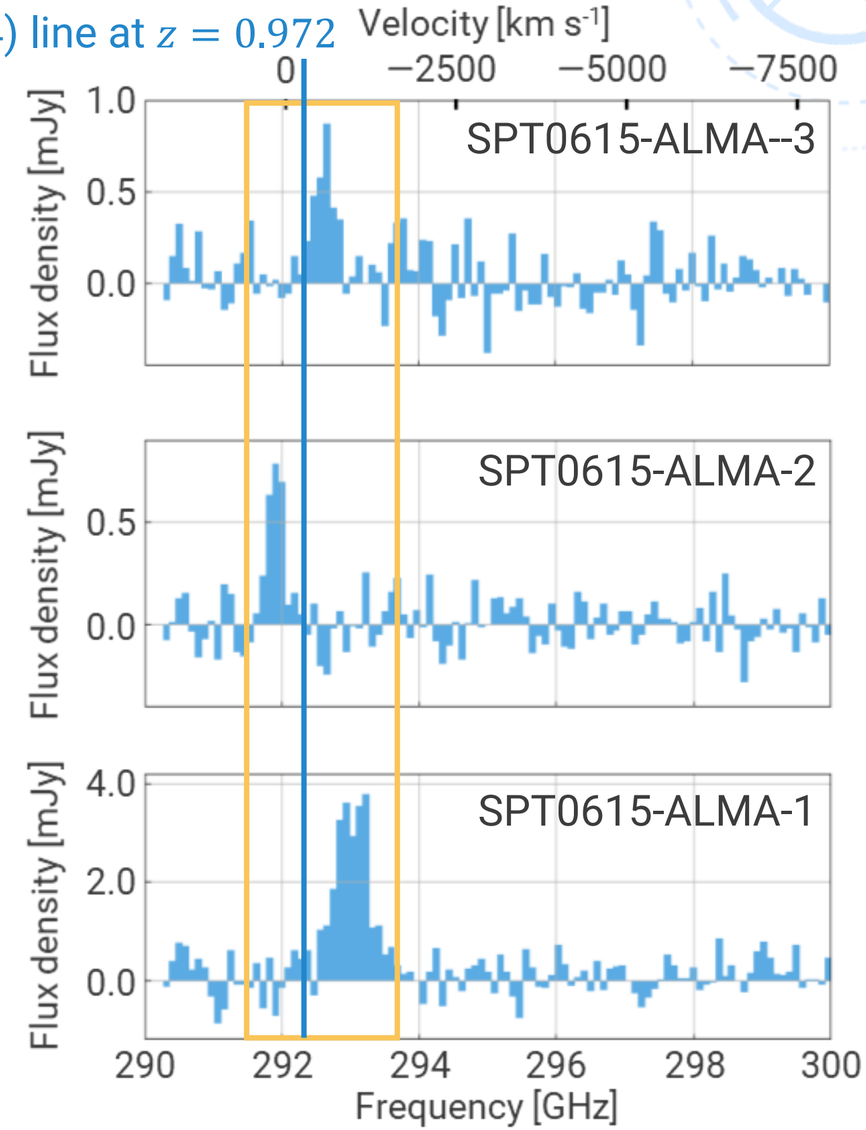
□ : Dust and CO(5-4) detected

□ : Dust only detected ($\mathrm{photo}z = 0.85^{+0.14}_{-0.12}$)

Observations results

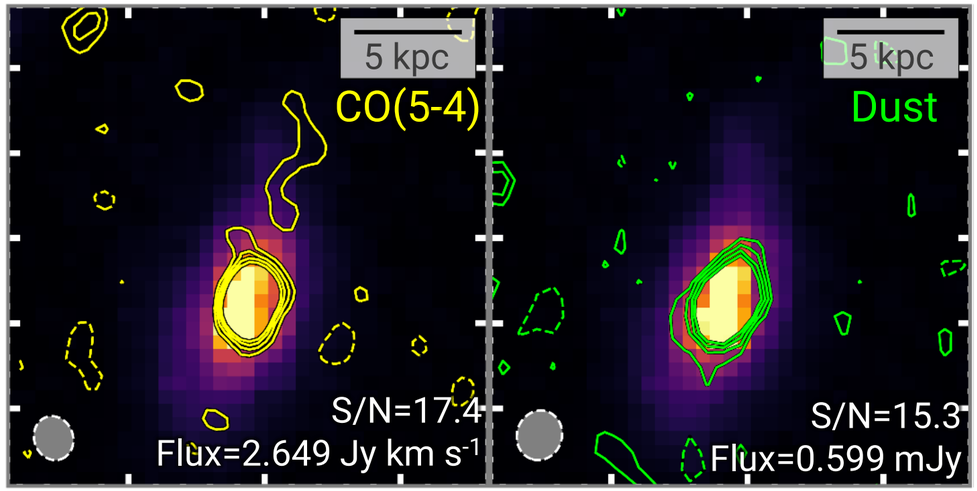


CO(5-4) line at $z = 0.972$

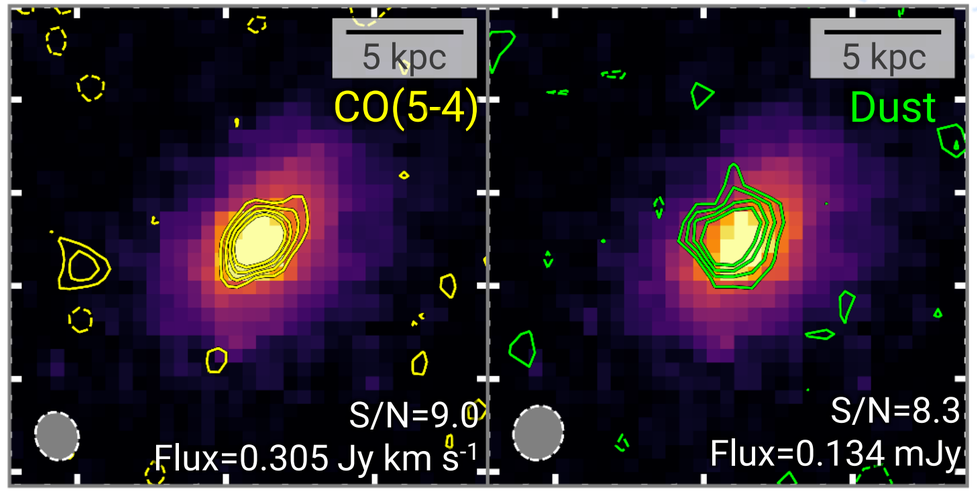


Observations results

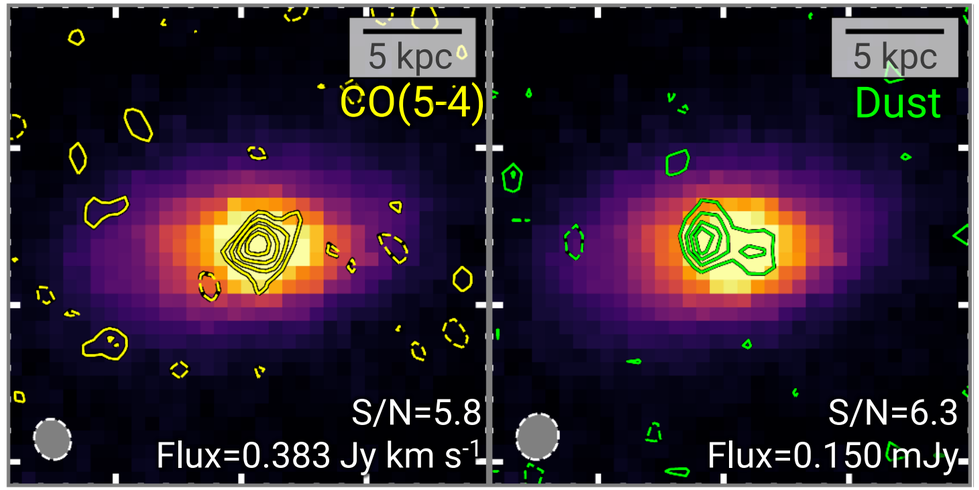
SPT0615-ALMA-1



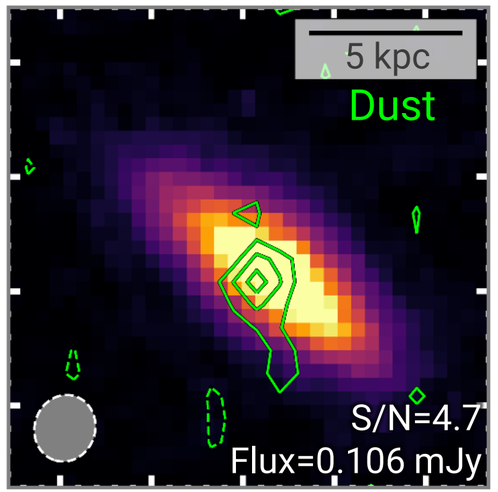
SPT0615-ALMA-2



SPT0615-ALMA-3



SPT0615-ALMA-4



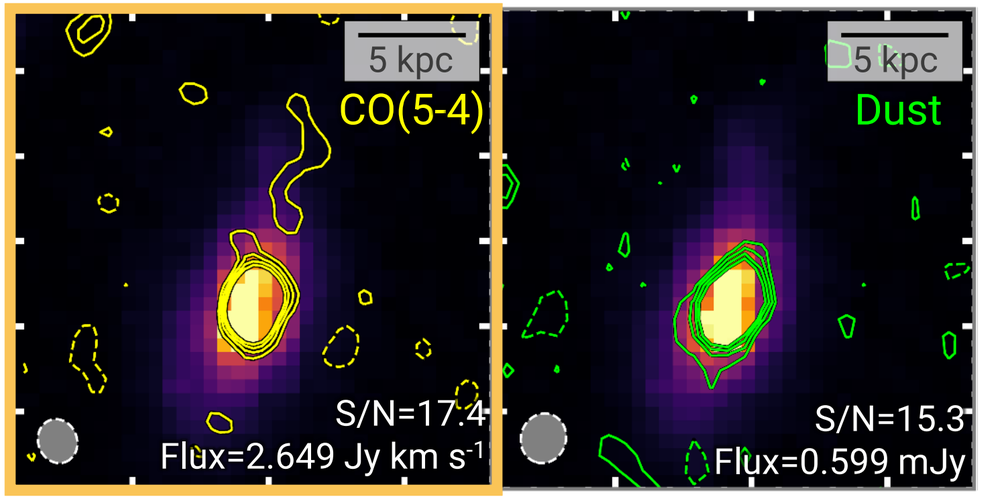
Background :
HST 1.6 μm
Contour :
drawn at
2σ, 3σ, 4σ, 5σ

Discussions

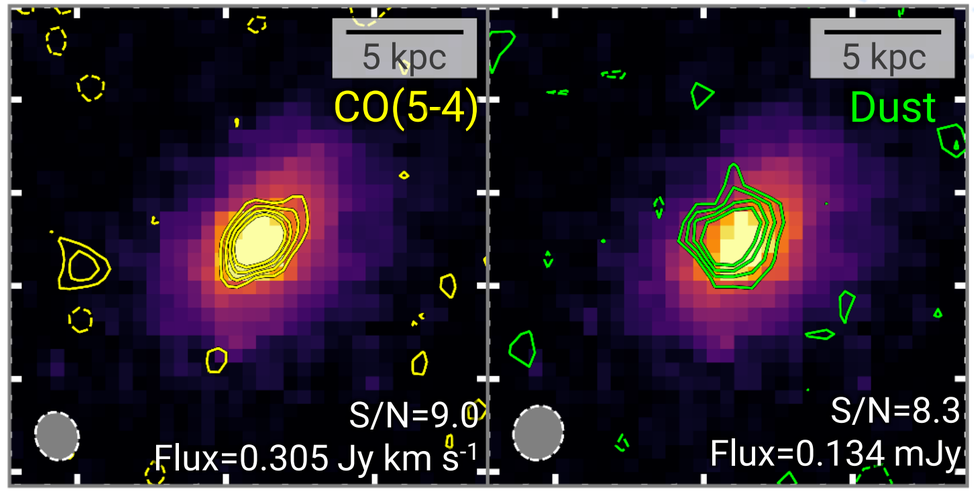
Section 3

Tail structure of ALMA-1

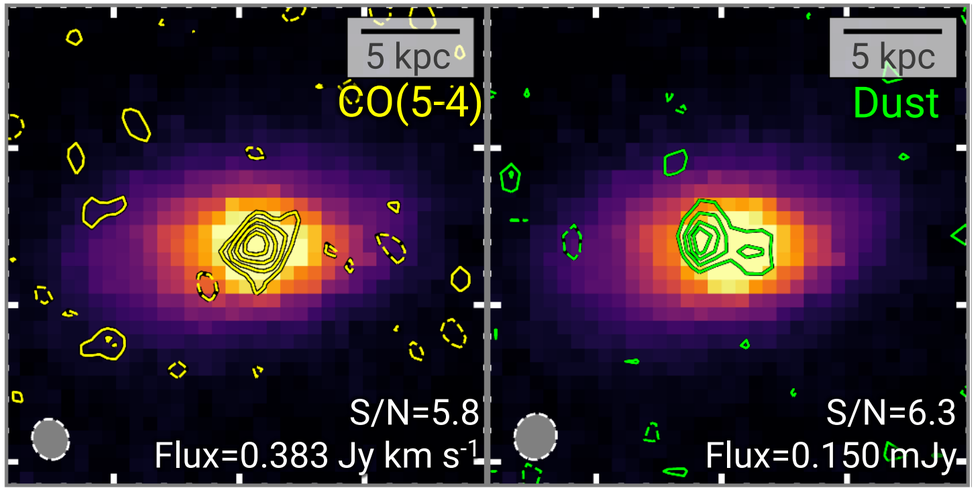
SPT0615-ALMA-1



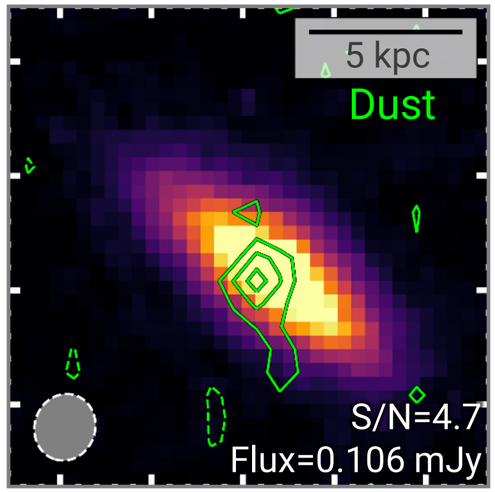
SPT0615-ALMA-2



SPT0615-ALMA-3

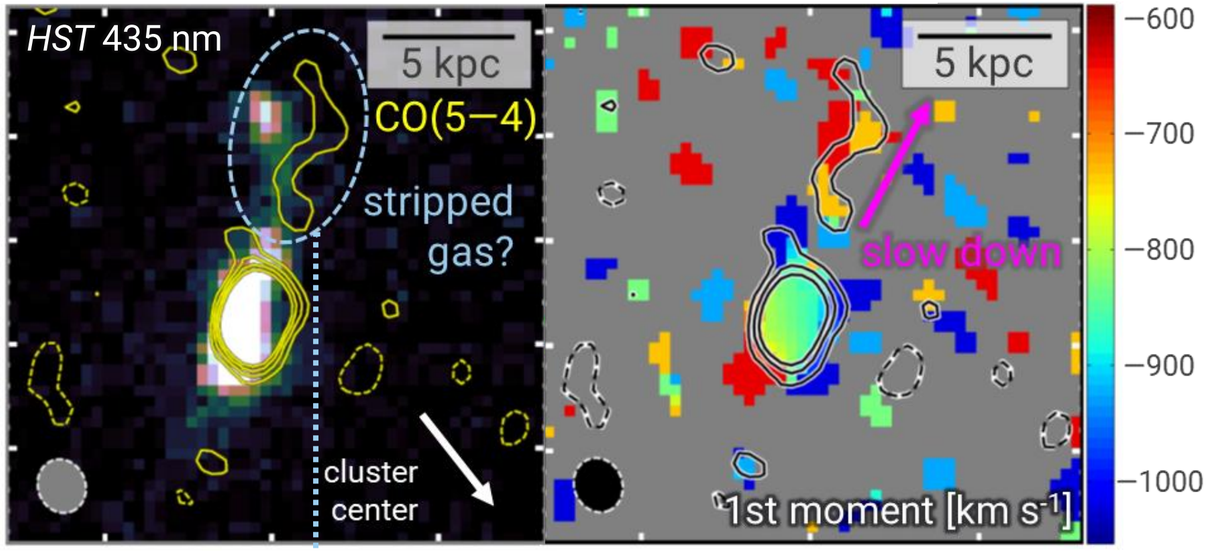


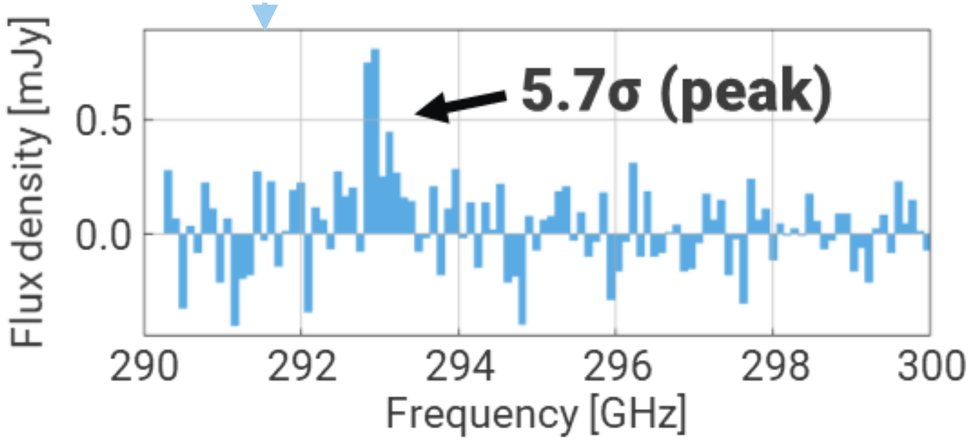
SPT0615-ALMA-4



Background :
HST 1.6 μm
Contour :
drawn at
2σ, 3σ, 4σ, 5σ

Tail structure of ALMA-1





Gas stripping at the center of the cluster

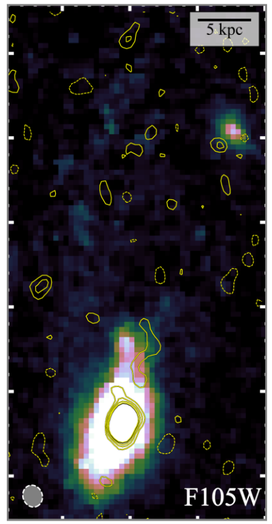
- Tail structure extending to the top of the image

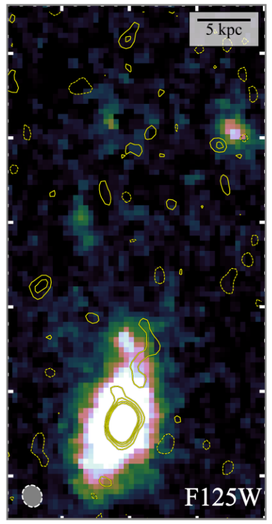
⇒ **Molecular gas stripping in which a multi-wavelength counterparts exists, first detected at $z\sim1$**

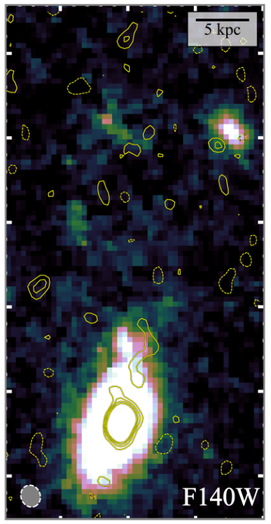
- Located near cluster center ($0.134R_{200}$)
- There is no evidence of tidal interaction

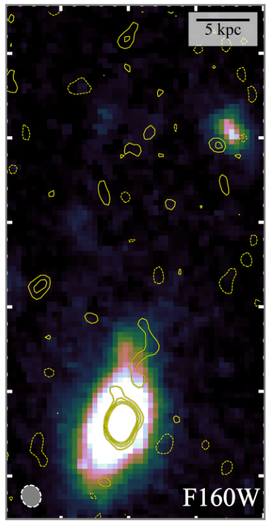
→ **Stripping by ram pressure** from dense ICM is suggested

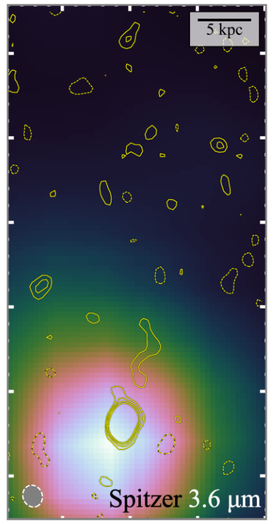
Size comparison

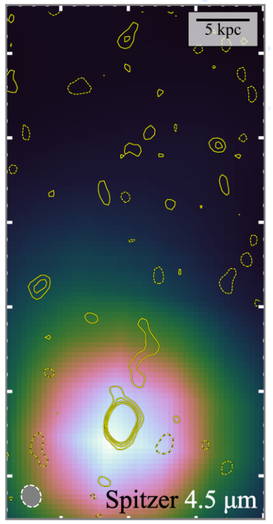


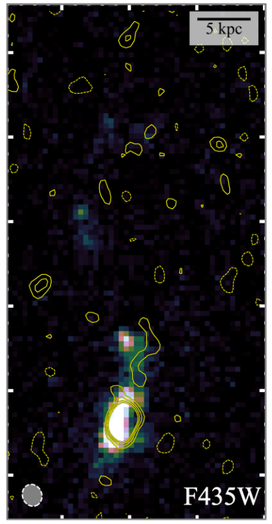


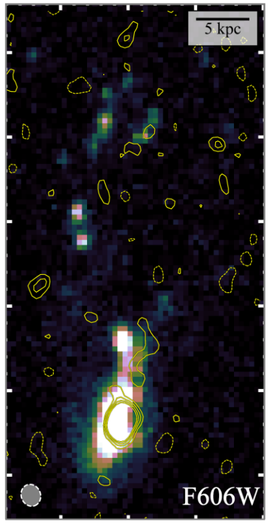


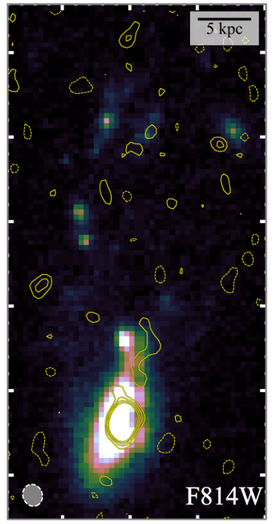












Size comparison

	Half light radius of 1.6 μm $R_{1/2,\mathrm{opt}}$ [kpc]	>	Half light radius of 435 nm $R_{1/2,\mathrm{UV}}$ [kpc]	>	Half light radius of CO(5−4) $R_{1/2,\mathrm{CO(5-4)}}$ [kpc]	≃	Half light radius of dust $R_{1/2,\mathrm{dust}}$ [kpc]
ALMA-1	2.027 ± 0.004		1.258 ± 0.012		0.67 ± 0.11		0.73 ± 0.12
ALMA-2	2.670 ± 0.018		$-$		0.81 ± 0.18		0.91 ± 0.21
ALMA-3	2.978 ± 0.006		$-$		1.35 ± 0.39		1.34 ± 0.37

- In ALMA-1, the UV size is less than ~60% of the 1.6 μm size

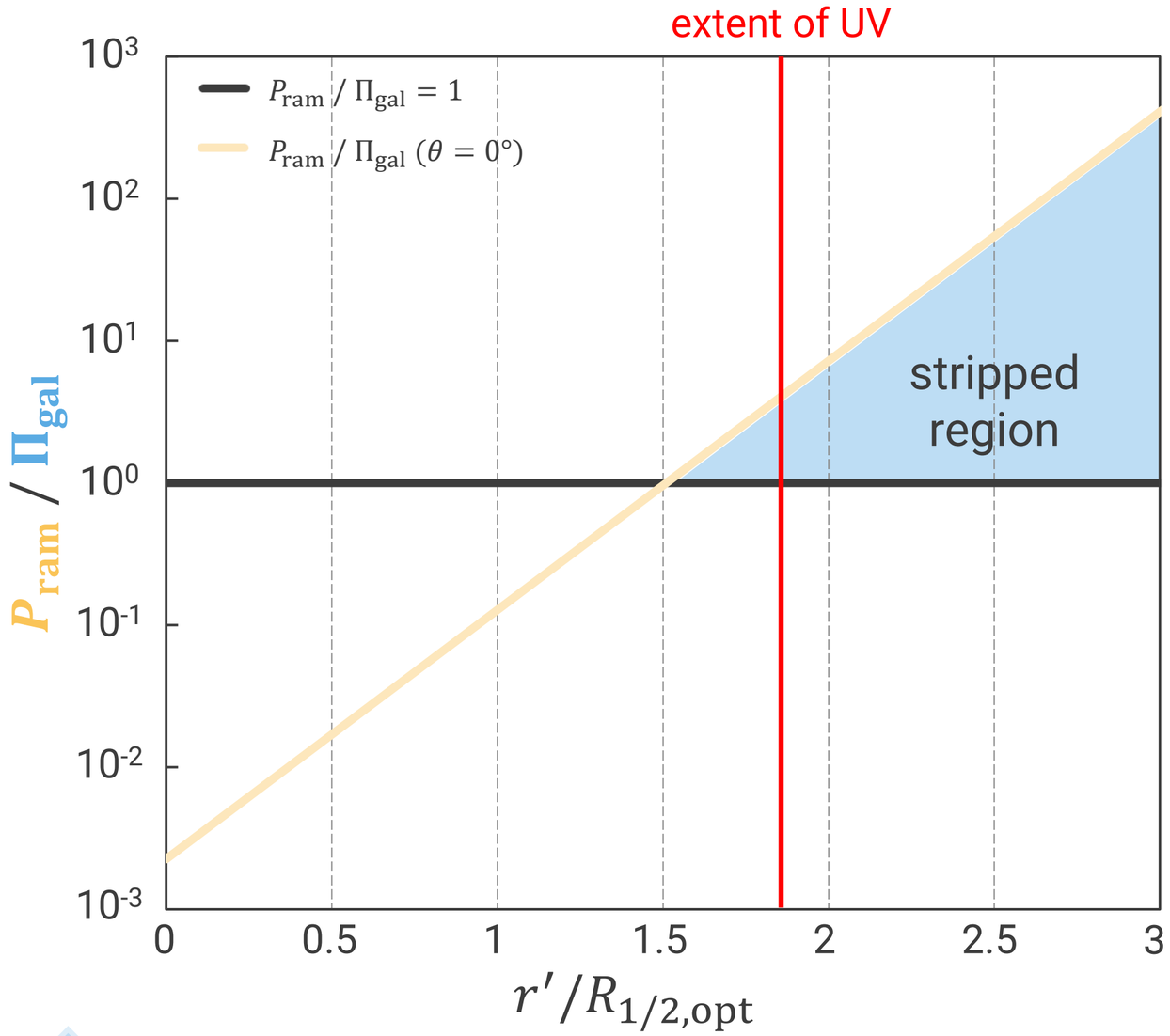
… But in field galaxies, UV sizes and optical sizes are almost identical (e.g., Barden et al. 2010; Dutton et al. 2011; Law et al. 2012)

→ In ALMA-1, star formation at the outer edge of the galaxy has stopped

⇒ **It may indicate that the gas at the outer edge of the galaxy is stripped**

- The sizes of CO(5—4) and dust are also small and are consistent with gas stripping

ALMA-1 : Ram pressure vs Gravity



Criteria for stripping by Gunn & Gott (1972)

$$P_{\rm ram} \geq \Pi_{\rm gal}$$

$P_{\rm ram} = \rho_{\rm ICM} v_{\rm gal}^2$ **(Ram pressure)**

- $\rho_{\rm ICM}$ … density o ICM
- $v_{\rm gal}$ … relative velocity of galaxy and cluster / $\cos\theta$
- θ … the angle between the line of sight and the direction in which the galaxy is moving

$\Pi_{\rm gal} = 2\pi G \Sigma_s \Sigma_g$ **(Gravity)**

$$\Sigma_i = \Sigma_0 \exp(-r'/R_{\rm d}),\ \ \Sigma_0 = \frac{M_{\rm d}}{2\pi R_{\rm d}^2}$$

- $R_{\rm d}$ … the radius of stellar or gas
- $M_{\rm d}$ … the mass of a stellar or gas
- r' … galactocentric distance

Summary

We analyzed galaxies in the center of the cluster SPT0615 ($z = 0.972$)

→ Dust was detected in 4 galaxies, and CO(5—4) was detected in 3 of them

→ CO(5—4) line indicate that these 3 galaxies are member galaxies of SPT0615

We showed indication of molecular gas stripping is observed in one galaxy

→ **Valuable sample of gas stripping with definite counterpart first captured at $z \sim 1$**

→ likely to be a galaxy that experience environmental effects for the first time, relatively recently fell into the cluster

We showed some possible evidence for environmental effects

→ The small star-forming region suggests that the outer molecular gas is stripped

→ In field galaxies, the sizes of the star-forming regions and stellar generally match