Dissecting Galaxies in the Heart of Galaxy Clusters over Cosmic Time

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LIneA Webinar
Primary Goal: Understanding the Anatomy of a Galaxy

Credit: SPICA
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Primary Goal: Understanding the Anatomy of a Galaxy

Gas Accretion/Mode of Star Formation
continuous or stochastic?

Efficiency of Star Formation
relationship between gas surface density and SFR

Quenching of Star Formation
AGN or environment?

Role of Dark Matter

Growth of Massive Galaxies
cooling flows or mergers?

Large-Scale Structure
clustering properties

spatially-resolved studies of gas and star formation in galaxies &
statistical studies of global galaxy parameters
Galaxy properties dictated by:

Environment

Mass

Time
Galaxy properties dictated by:

- Environment
  - Field galaxy (HUDF)
  - Cluster galaxy (Abell 1689)

- Mass

- Time
Galaxy properties dictated by:

Environment
- field galaxy versus cluster galaxy
  - HUDF
  - Abell 1689

Mass
- dwarf galaxy versus dominant galaxy
  - NCG 5264
  - Abell 2261

Time
Galaxy properties dictated by:

- **Environment**
  - field galaxy versus cluster galaxy
    - HUDF
    - Abell 1689

- **Mass**
  - dwarf galaxy versus dominant galaxy
    - NCG 5264
    - Abell 2261

- **Time**
  - low redshift versus cosmic noon

- The Big Bang
- Expansion
- Galaxy evolution
- Dark matter
- Cosmology
- The early universe
Galaxy properties dictated by:

**Environment**
- Field galaxy (HUDF) versus cluster galaxy (Abell 1689)

**Mass**
- Dwarf galaxy (NCG 5264) versus dominant galaxy (Abell 2261)

**Time**
- Low redshift versus cosmic noon
Galaxy properties dictated by:

Environment
- field galaxy versus cluster galaxy
- HUDF versus Abell 1689

Mass
- dwarf galaxy versus dominant galaxy
- NCG 5264 versus Abell 2261

Time
- low redshift versus cosmic noon
- The Big Bang
How do environment/mass/time influence galaxy evolution?

- Field vs. cluster
- Lower mass vs. higher mass
- Early times vs. later times

![Diagram of galaxy evolution](Credit: HST/CFHT/NOAO)

- Red sequence
- Blue cloud

![Stellar Mass vs. u-r Colour plot](Credit: SDSS, Kevin Schawinski)
Outline

Part 1

Part 2
Outline

Part 1

ALMA Observations of Gas-rich Galaxies in z~1.6 Galaxy Clusters

molecular gas and star formation

Environment

Part 2

Brightest Cluster Galaxies over Cosmic Time (with ALMA)

dust continuum and molecular gas

230 GHz
Galaxy Clusters in a Nutshell

- total masses of $> 10^{14} \, M_\odot$
Galaxy Clusters in a Nutshell

- total masses of $> 10^{14} \, M_\odot$
- 3 basic matter components
Galaxy Clusters in a Nutshell

- total masses of $> 10^{14} \, M_\odot$

- 3 basic matter components
  - $\sim 3\%$ galaxies (stars+gas)

Credit: HST - Abell 2261, $z=0.224$
Galaxy Clusters in a Nutshell

- total masses of $> 10^{14} \, M_\odot$
- 3 basic matter components
  - $\sim 3\%$ galaxies (stars+gas)
  - $\sim 12\%$ intracluster medium (hot gas of electrons)

Credit: Chandra/HST/Spitzer - IDCS 1426, z=1.75; Brodwin et al. 2016
Galaxy Clusters in a Nutshell

- total masses of $> 10^{14} \, M_\odot$
- 3 basic matter components
  - $\sim 3\%$ galaxies (stars+gas)
  - $\sim 12\%$ intracluster medium (hot gas of electrons)
  - $\sim 85\%$ dark matter

Credit: NASA/ESA/JPL-Caltech/Yale/CNRS - Abell 1689, z=0.1832
Why study galaxy cluster environments?

Life is tough:
- harassment
- tidal truncation
- ram-pressure stripping
- thermal evaporation
- galaxy-galaxy encounter
- starvation

Illustrated by Aree Chung
Why study higher redshift?

Peak in cosmic **star formation rate** density

Evolution of star-forming main sequence

What drives these trends?

Madau & Dickinson 2014

Whitaker et al. 2014
Why study molecular gas?

Peak in cosmic molecular gas mass density

Dependence on star-forming main sequence

Decarli et al. 2017

Gas Regulation

credit: A. Saintonge
The Power of ALMA

**JVL**

*Radio Interferometer*
- $\lambda = 0.6 \text{ cm} - 410 \text{ cm}$
- $\nu = 74 \text{ MHz} - 50 \text{ GHz}$
- 27 25-meter dishes
- baselines of 1km - 36km
- 7,000 ft high in New Mexico

200 JVL hours = 2 molecular gas detections at $z \sim 1.6$

**ALMA**

*Submillimeter Interferometer*
- $\lambda = 0.3 \text{ mm} - 3.6 \text{ mm}$
- $\nu = 85 \text{ GHz} - 950 \text{ GHz}$
- 50 12-meter dishes
- baselines of 0.16km - 16km
- 16,000 ft high in Chile

13 ALMA hours = 11 molecular gas detections at $z \sim 1.6$

Rudnick et al. 2018

Noble et al. 2017
3 SpARCS Clusters at z~1.6

- ~115 spectroscopically confirmed cluster members
- richness-based masses >10^{14} M_☉
- 11-band photometry for stellar masses (ugrizYK[3.6][4.5][5.0][8.0])
- MIPS and Herschel imaging (24/250/350/500 um) for infrared-SFRs
- HST imaging for size and morphology of stellar components
ALMA Molecular Gas Observations

- 13 hours of ALMA time to detect CO (2-1) in z~1.6 cluster galaxies
- first molecular gas detections in z>1.5 cluster galaxies!

rms ~ 0.17 mJy/beam in 100 km/s
beam ~ 4.4” x 2.2”

SpARCS J022545–035517, Z_{spec} = 1.598
SpARCS J033056–284259, Z_{spec} = 1.626
SpARCS J022426–032330, Z_{spec} = 1.633

Noble et al. 2017
ALMA Data Cube

Noble et al. 2017
ALMA CO (2-1) Observations

**HST:**
- stars

**ALMA:**
- gas

Infrared (Spitzer/Herschel): dust (SFR)

Noble et al. 2017
Gas Fractions in $z\sim 1.6$ Cluster Galaxies

$\frac{(\text{SFR} - \text{SFR}_{\text{MS}})}{\text{SFR}_{\text{MS}}}$ vs. $f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{gas}} + M_{\text{stellar}}}$

(field: scaling relation tracks (Genzel et al. 2015))

Noble et al. 2017; 2019
Gas Fractions in $z \sim 1.6$ Cluster Galaxies

$z \sim 1.6$ cluster galaxies are at systematically higher gas fractions than field galaxies.
Gas Fractions in $z \sim 1.6$ Cluster Galaxies

- $z \sim 1.6$ cluster galaxies are at systematically higher gas fractions than field galaxies

Possible Explanations
- selection effect? Gopal, Noble++ in prep
- high cluster-to-cluster variation? ALMA Cycle 8?
- environmental-specific process? Noble et al 2019
- require different $\alpha_{\rm CO}$?

$M_{\rm mol} = \alpha_{\rm CO} \times L_{\rm CO}$

see e.g., Bolatto et al. 2013; Narayanan et al. 2012

Noble et al. 2017; 2019
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Noble et al. 2017; 2019
Spatially Resolving Molecular Gas

deep and higher spatial resolution observations

rms \approx 0.1 \text{ mJy/beam in } 50 \text{ km/s}

HST 160

J0225–371

1"

Noble et al. 2019
Spatially Resolving Molecular Gas

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rms ~ 0.1 mJy/beam in 50 km/s

previous resolution

Noble et al. 2019
Spatially Resolving Molecular Gas

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previous resolution

new ALMA resolution (0.4″ x 0.5″ or ~3 kpc)

HST 160
ALMA CO(2–1) S/N

J0225–371

Noble et al. 2019
Spatially Resolving Molecular Gas

- Deeper and higher spatial resolution observations
- $\text{rms} \sim 0.1 \text{ mJy/beam in 50 km/s}$
- Previous resolution
- New ALMA resolution (0.4” x 0.5” or ~3 kpc)
- 2.7 integration hours on ALMA in single $z \sim 1.6$ cluster
- 8 detections!

HST 160
ALMA CO(2–1) S/N

Noble et al. 2019
Spatially Resolving Molecular Gas

Noble et al. 2019
Cramer, Noble et al. in prep
Spatially Resolving Molecular Gas

possible gas tails?  direction to cluster center

see also: Dasyra et al. 2012; Jachym et al. 2014; 2017; Verdugo et al. 2015; Lee et al. 2017; Moretti et al. 2018

Noble et al. 2019
Cramer, Noble et al. in prep
Stellar-to-CO Radii

Noble et al. 2019

Tacconi et al. 2013; Daddi et al. 2010

high-z: ~1σ offset in mean
Stellar-to-CO Radii

Noble+ 2019
Tacconi+ 2013; Daddi+ 2010

High-z: $\sim 1\sigma$ offset in mean
Low-z: $\sim 3\sigma$ offset in mean

Kenney & Young 1988
Regan+ 2001

Gas stripping
Noble et al. 2019
Stellar-to-CO Radii

- **z=1.6 cluster**
  - Noble+ 2019

- **z~1–1.6 field**
  - Tacconi+ 2013; Daddi+ 2010

- **Virgo cluster**
  - Kenney & Young 1988

- **low-z field**
  - Regan+ 2001

**high-z: \( \sim 1\sigma \) offset in mean**

**low-z: \( \sim 3\sigma \) offset in mean**

Noble et al. 2019
Stellar-to-CO Radii

20 more hours on ALMA to spatially-resolve molecular gas in an additional ~15 $z=1.6$ cluster galaxies!

high-z: $\sim 1\sigma$ offset in mean

low-z: $\sim 3\sigma$ offset in mean

Noble et al. 2019
Massingill, Noble et al. in prep
How does environment influence galaxy evolution?

Life is tough!

- Harassment
- Tidal truncation
- Ram-pressure stripping
- Thermal evaporation
- Galaxy-galaxy encounter
- Starvation

Illustrated by Aeruz Chung
How does environment influence galaxy evolution?

LIFE IS TOUGH!

- harassment
- tidal truncation
- ram-pressure stripping
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Illustrated by Aeree Chung
How does environment influence galaxy evolution?

gas tails: evidence for molecular gas stripping at $z \sim 1.6$?
Evidence for Molecular Gas Stripping at z~1.6?

**Similarities to field galaxies**
- rotating gas disks
- main-sequence SFRs

**Differences from field galaxies**
- gas tails, gas & stellar centroid offsets
- higher gas fractions

*Images and text credit: Aree Chung*
Evidence for Molecular Gas Stripping at z~1.6?

Similarities to field galaxies

- rotating gas disks
- main-sequence SFRs

Differences from field galaxies

- gas tails, gas & stellar centroid offsets
- require lower $\alpha_{CO}$ in cluster galaxies due to ram-pressure stripping?

higher gas fractions
Evidence for Molecular Gas Stripping at z~1.6?

Similarities to field galaxies
- rotating gas disks
- main-sequence SFRs

Differences from field galaxies
- gas tails, gas & stellar centroid offsets

High-z clusters are exciting prospects for detecting gas-rich galaxies!

αCO in cluster galaxies due to ram-pressure stripping?

Higher gas fractions
What's Next?

Kinematic Analysis in High-z Clusters

- measure rotational velocities, velocity dispersions, baryon fractions, dynamical masses
- 2022: ALMA Band 1 receiver
  - CO (1-0) at $z=1.1-2.2$
  - CO (2-1) at $z=3.5-5.5$

Spatially-resolved Kennicutt-Schmidt

- star formation efficiency on kpc scales
- HST - ACS/WFC F475W/F625W
  - rest-frame UV
- ALMA - Band 7
  - far-infrared dust continuum
- VLT - KMOS
  - Hα
- JWST - NIRSpec
Outline

Part 1

ALMA Observations of Gas-rich Galaxies in z~1.6 Galaxy Clusters

molecular gas and star formation

Environment

Part 2
Outline

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ALMA Observations of Gas-rich Galaxies in z~1.6 Galaxy Clusters

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Part 2

Mass

Brightest Cluster Galaxies over Cosmic Time (with ALMA)

dust continuum and molecular gas

Env

Time
Brightest Cluster Galaxies (BCGs)

Mass growth linked to:
- gas cooling
- star formation
- energy feedback
- galaxy accretion

Galaxy Cluster Abell 2261
Hubble Space Telescope
A Diversity of BCGs over Cosmic Time

Credit: J. Blakeslee

When does the BCG become the dominant galaxy?
A probabilistic approach to identifying the BCG

$P(z) \quad P(M)$

monte carlo and find most massive cluster member in each iteration

build up a BCG likelihood for each galaxy
A Bayesian Probabilistic Approach to Identifying the BCG

Abell 2261
$z = 0.22$
A Bayesian Probabilistic Approach to Identifying the BCG

Abell 2261
\[ z = 0.22 \]

99.99% probability of being the BCG
A Bayesian Probabilistic Approach to Identifying the BCG
SDSS 1038
$z = 0.43$
A Bayesian Probabilistic Approach to Identifying the BCG

SDSS 1038
z = 0.43

72% probability of being the BCG

26% probability of being the BCG
How do BCGs Grow over Cosmic Time?

BCGs grow in stellar mass by 2x between z~1 and z~0

Webb+Noble et al. 2015b
see also:
Lidman+Noble et al. 2012
Lidman+Noble et al. 2013
McDonald et al. 2016
How do BCGs Grow over Cosmic Time?

- BCGs grow in stellar mass by 2x between z~1 and z~0
- fraction of star-forming BCGs increases beyond z~1

Webb+Noble et al. 2015b
see also:
Lidman+Noble et al. 2012
Lidman+Noble et al. 2013
McDonald et al. 2016
What’s Next?

Statistical Morphological Analysis of BCGs

- hundreds of star-forming BCGs over 0.2<z<2
- perform quantitative morphological and molecular gas analysis to determine physical driver of emission (clumps vs filaments)
- What is the dominant growth mechanism of the most massive galaxies in the Universe?
- How is gas deposited onto BCGs over cosmic time?

Bayesian BCG Probability with LSST + SPT-3G

- SPT-3G will detect hundreds of high-redshift clusters
- LSST will provide 6-band photometry for redshifts and stellar masses
- perform probability analysis to identify BCG(s) in (proto)clusters
- When do BCGs become the dominant cluster galaxy?

South Pole Telescope

![South Pole Telescope Image]

LSST

![LSST Image]
Conclusions

Part 1

• evidence for systematically higher gas fractions in z~1.6 clusters compared to the field

• spatially-resolved molecular gas reveals evidence for gas stripping

• high-z clusters are exciting prospects for detecting gas-rich galaxies

Part 2

• BCGs can be statistically identified through a Bayesian analysis

• Ongoing ALMA programs to study the formation channel for stellar mass growth in BCGs over cosmic time
The Future of Galaxy Evolution

Interferometry

- ALMA
- SKA
- ngVLA

Space-based Sensitivity

- JWST

30-meter Telescopes

- Giant Magellan Telescope
- Thirty Meter Telescope
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Gas Accretion/Mode of Star Formation

Efficiency of Star Formation

Quenching of Star Formation

Halo
Gas cooling
Inflow
Outflow
Turbulence
Molecular clouds
Nuclear activity
ISM
Jets/winds
Stellar mass loss
Supernovae
Star formation

Role of Dark Matter

Growth of Massive Galaxies

Large-Scale Structure
The Future of Galaxy Evolution

- Interferometry
  - ALMA
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- Space-based Sensitivity
  - JWST

- 30-meter Telescopes
  - Giant Magellan Telescope
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Thank you!

- Gas Accretion/Mode of Star Formation
- Efficiency of Star Formation
- Quenching of Star Formation
- Role of Dark Matter
- Growth of Massive Galaxies
- Large-Scale Structure