Dissecting Galaxies in the Heart of Galaxy Clusters over Cosmic Time

Allison G. Noble

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Adam Muzzin, Michael McDonald, Greg Rudnick, Jasleen Matharu, Mike Cooper, William Cramer, Ricardo Demarco, Delaney Dunne, Mrudula Gopal, Chris Lidman, Kyle Massingill, Julie Nantais, Anjali Ramish, Eelco van Kampen, Tracy Webb, Gillian Wilson, Howard Yee, and the SpARCS Collaboration

September 24, 2020

LIneA Webinar

Meet the Students and Postdocs

Mrudula Gopal
ASU PhD Student

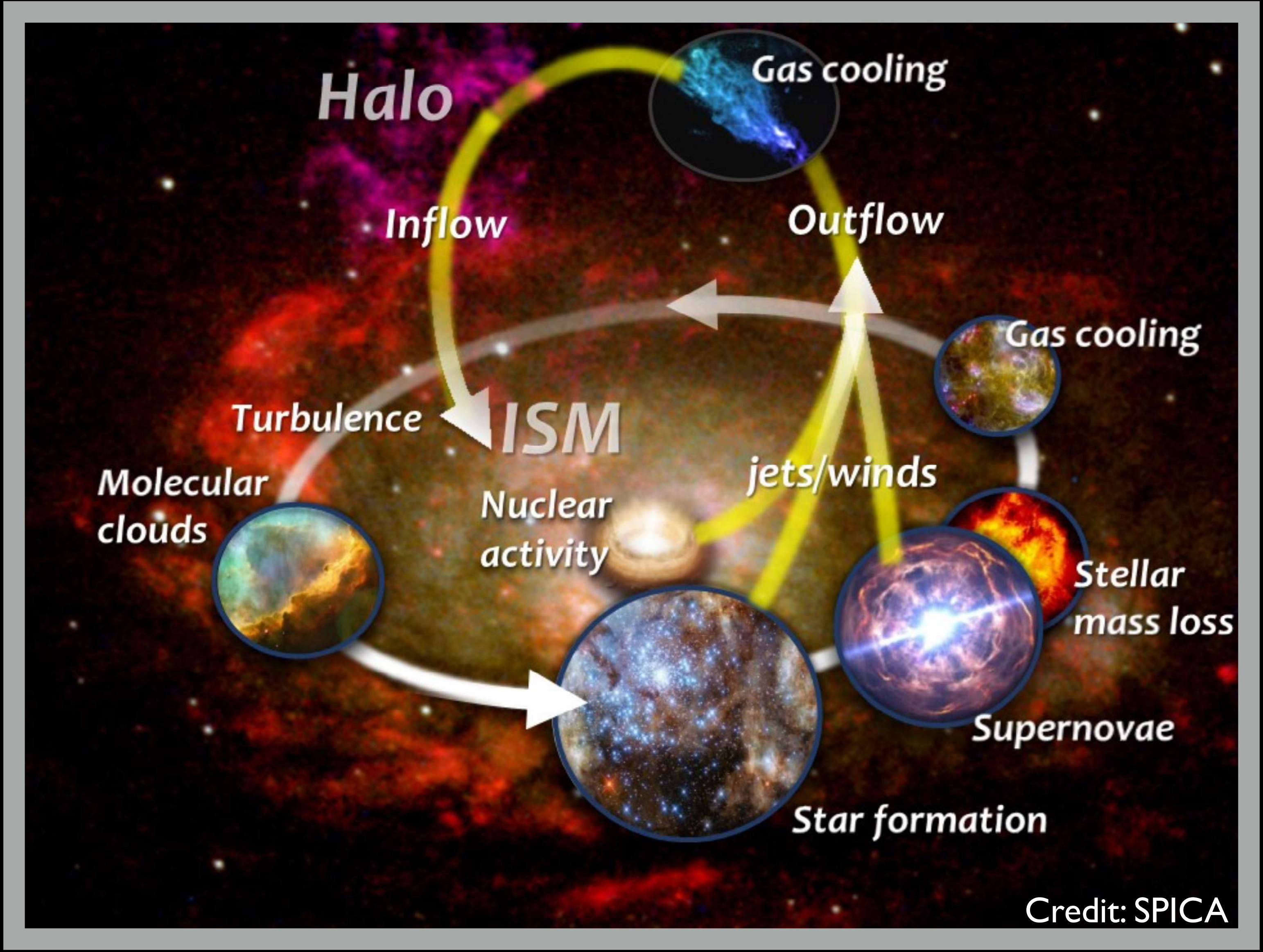
William Cramer
ASU Postdoc

Anjali Ramesh
ASU PhD Student

Kyle Massingill
ASU PhD Student

Delaney Dunne
McGill Undergrad

Primary Goal: Understanding the Anatomy of a Galaxy



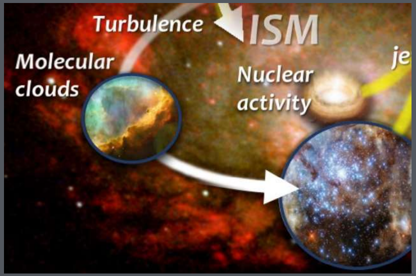
Credit: SPICA

Primary Goal: Understanding the Anatomy of a Galaxy

Gas Accretion/Mode of Star Formation

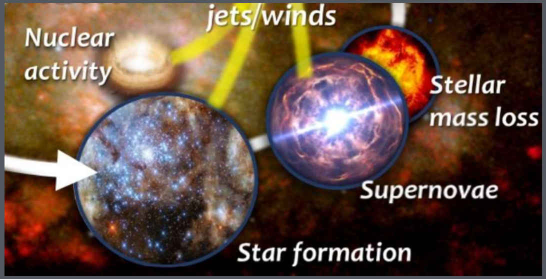
continuous or stochastic?

Efficiency of Star Formation



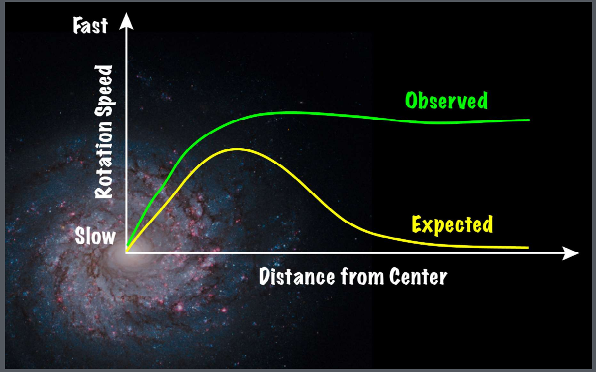
relationship between gas surface density and SFR

Quenching of Star Formation



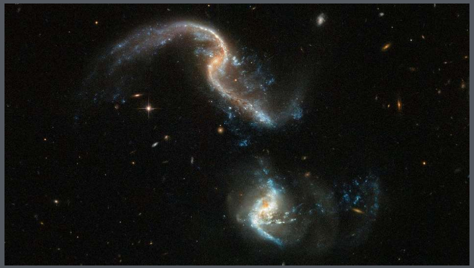
AGN or environment?

Role of Dark Matter



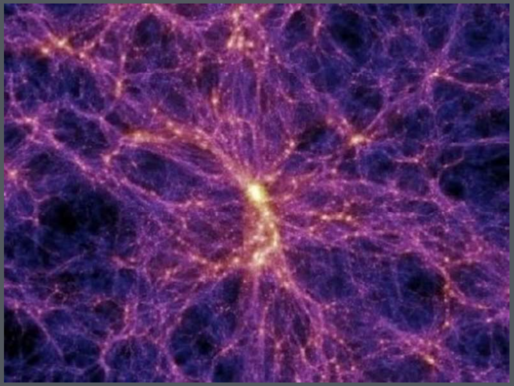
kinematic properties of gas

Growth of Massive Galaxies



cooling flows or mergers?

Large-Scale Structure



clustering properties

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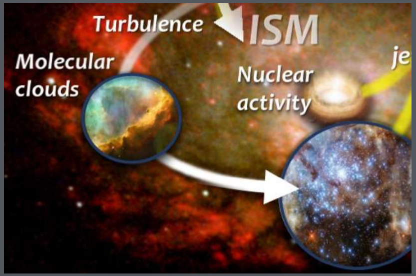

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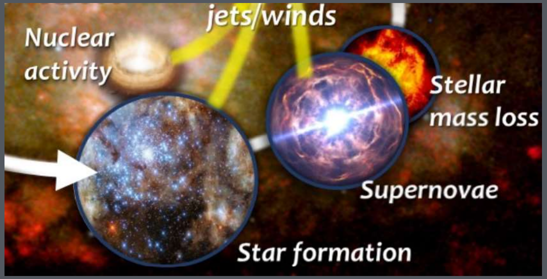

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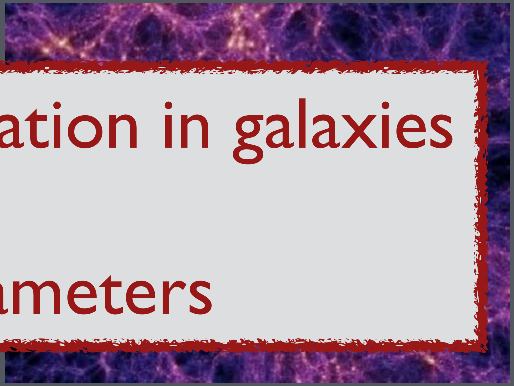


clustering properties

spatially-resolved studies of gas and star formation in galaxies
&
statistical studies of global galaxy parameters

Galaxy properties dictated by:

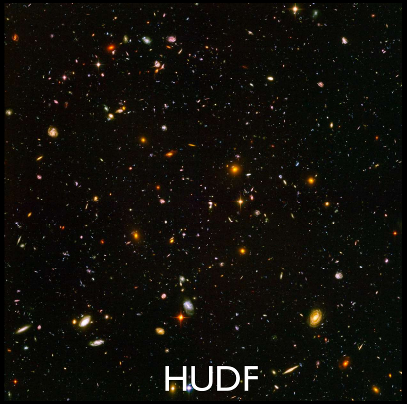
Environment

Mass

Time

Galaxy properties dictated by:

Environment



field galaxy

versus

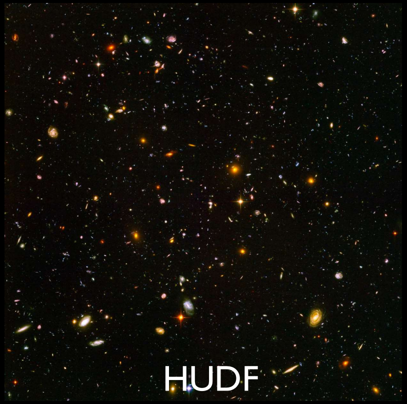
cluster galaxy

Mass

Time

Galaxy properties dictated by:

Environment


HUDF

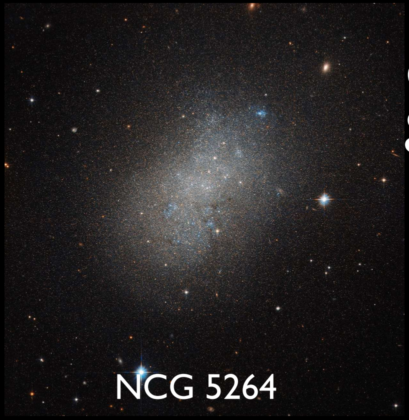
field galaxy

versus

cluster galaxy


Abell 1689

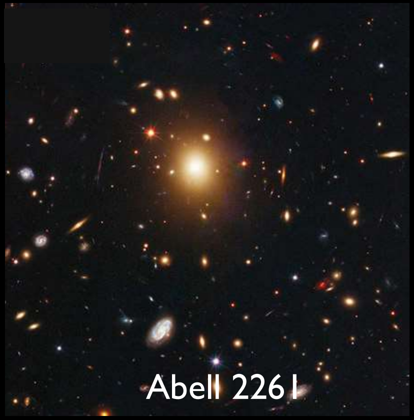
Mass


NCG 5264

dwarf galaxy

versus

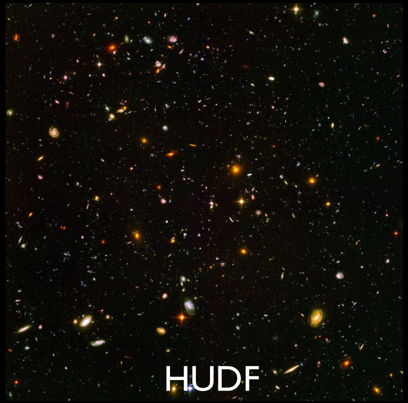
dominant galaxy


Abell 2261

Time

Galaxy properties dictated by:

Environment



field
galaxy

versus

cluster
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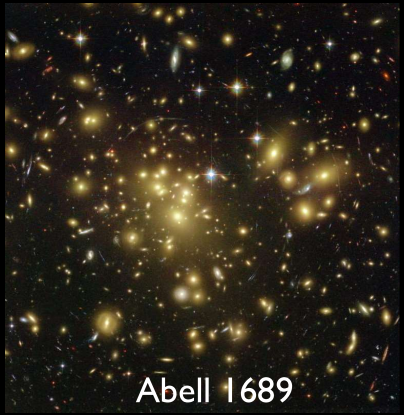

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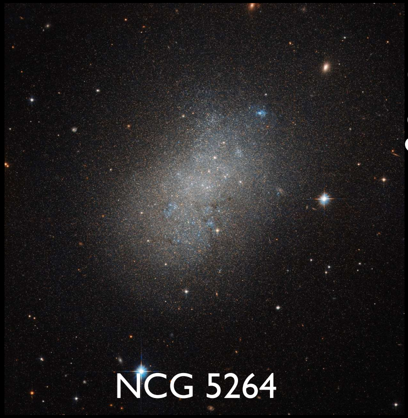

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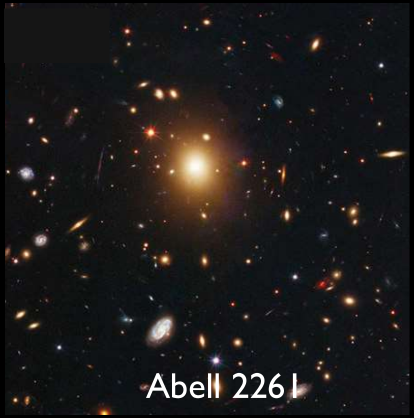
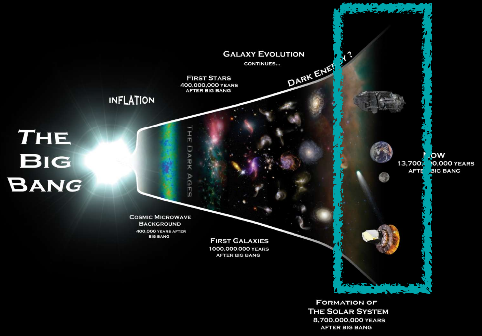


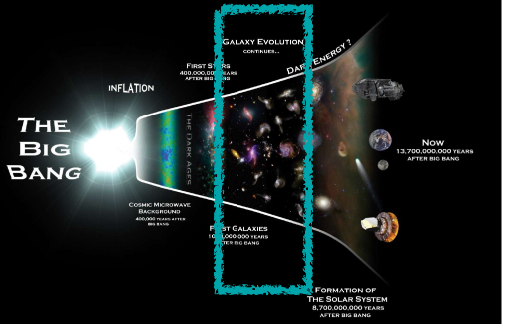
Time



low
redshift

versus

cosmic
noon



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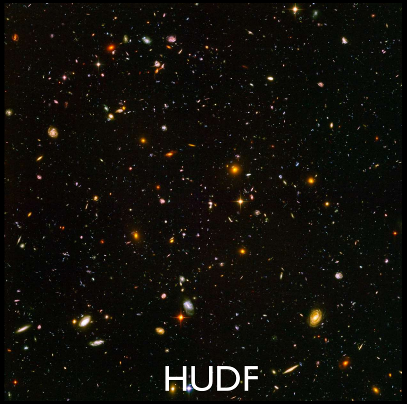
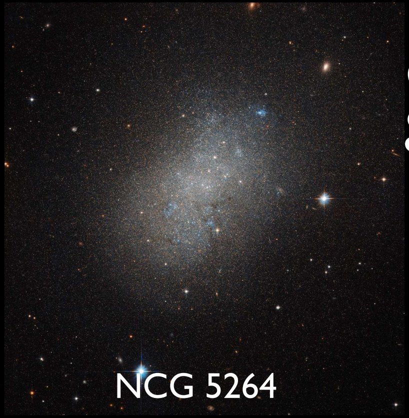


field galaxy

versus

cluster galaxy

Mass



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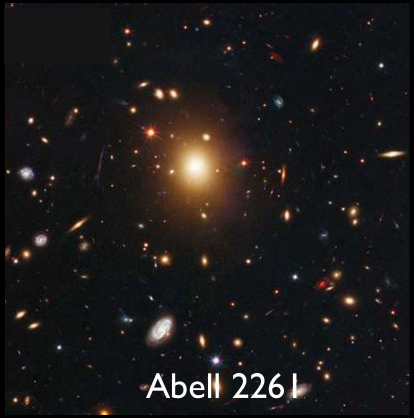

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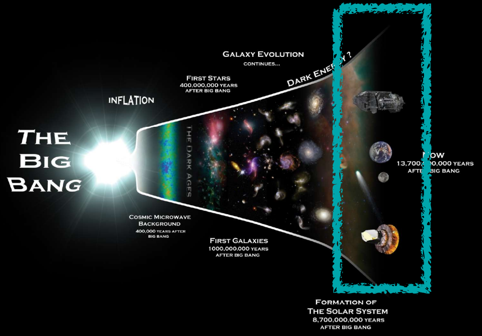

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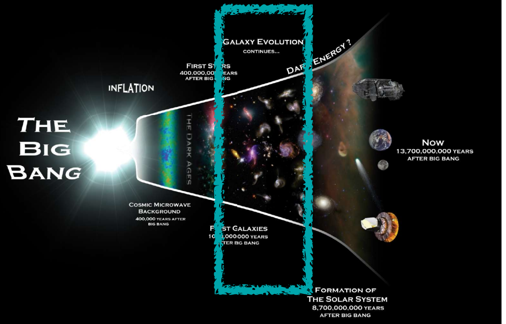

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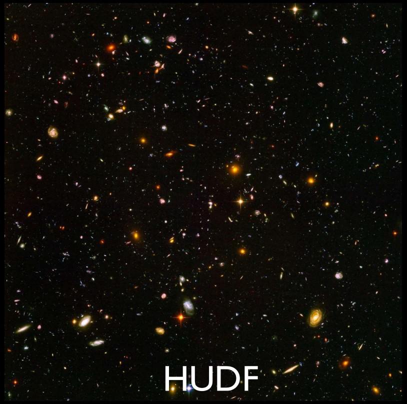

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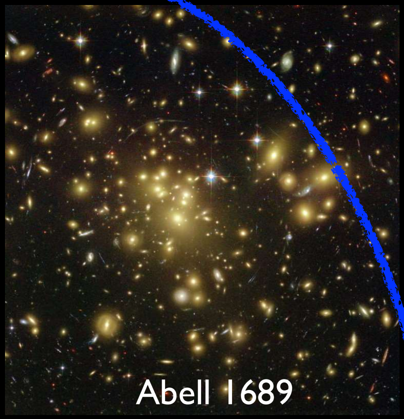
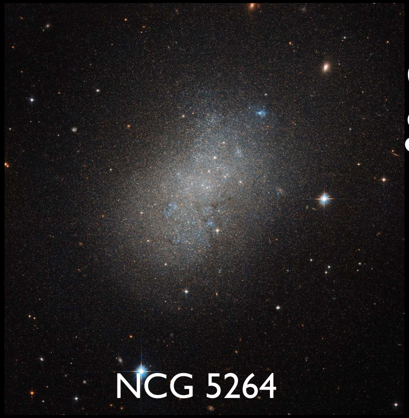


Mass



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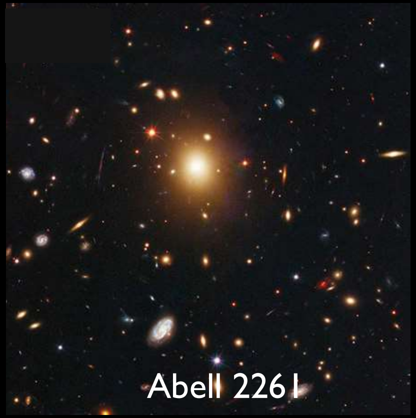
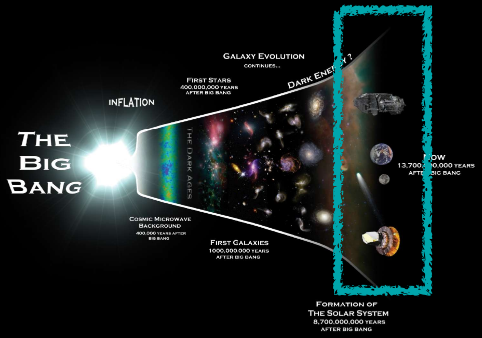


Time



low redshift

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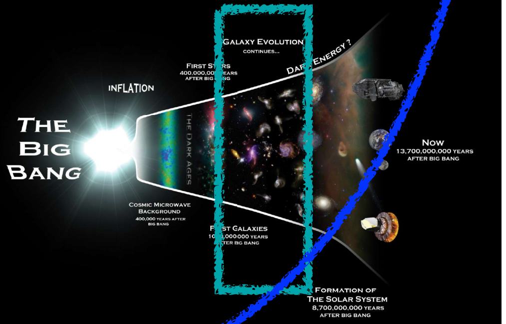


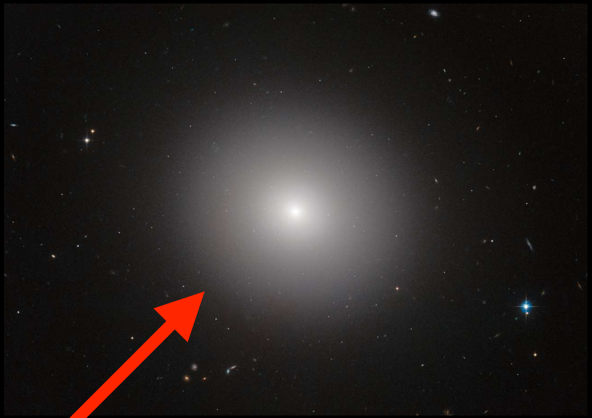
How do environment/mass/time influence galaxy evolution?

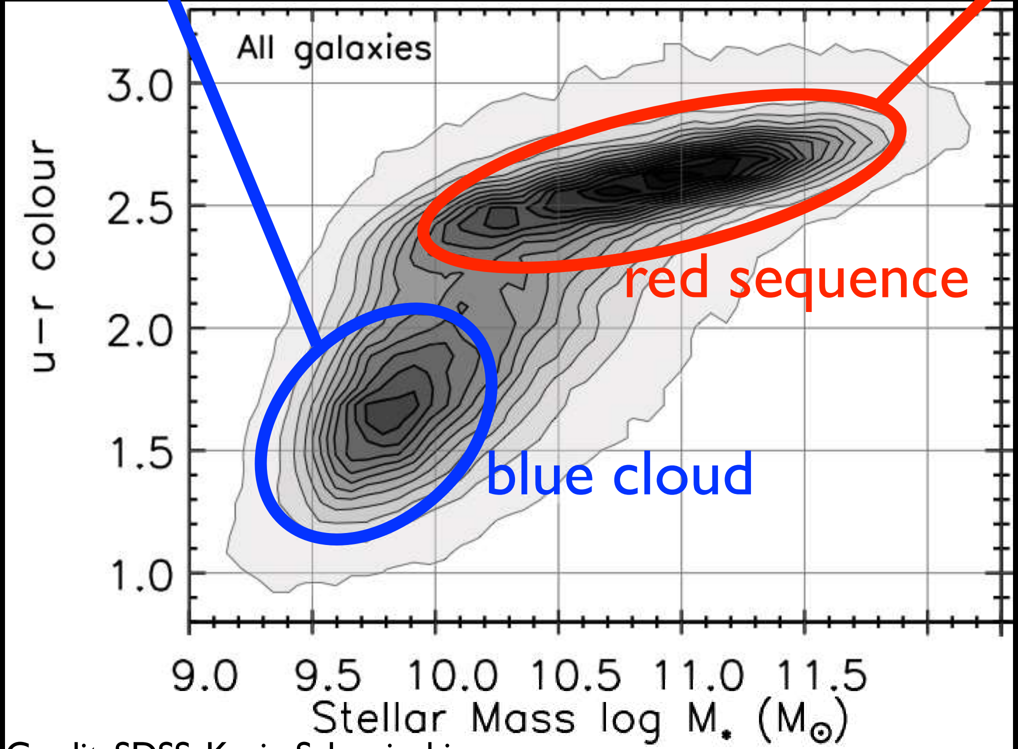

Credit: HST/CFHT/NOAO

field → cluster

lower mass → higher mass

early times → later times


Credit: HST



Credit: SDSS, Kevin Schawinski

Outline

Part 1

Part 2

Outline

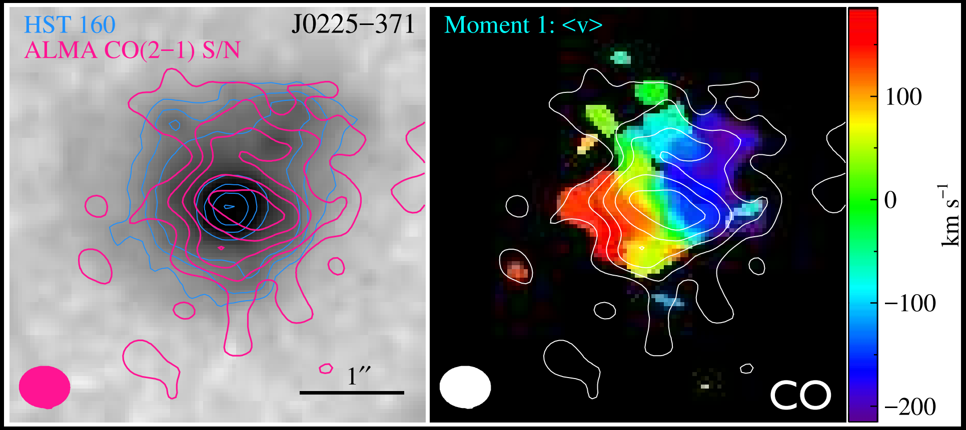
Part 1

Part 2

Environment →

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

molecular gas and star formation



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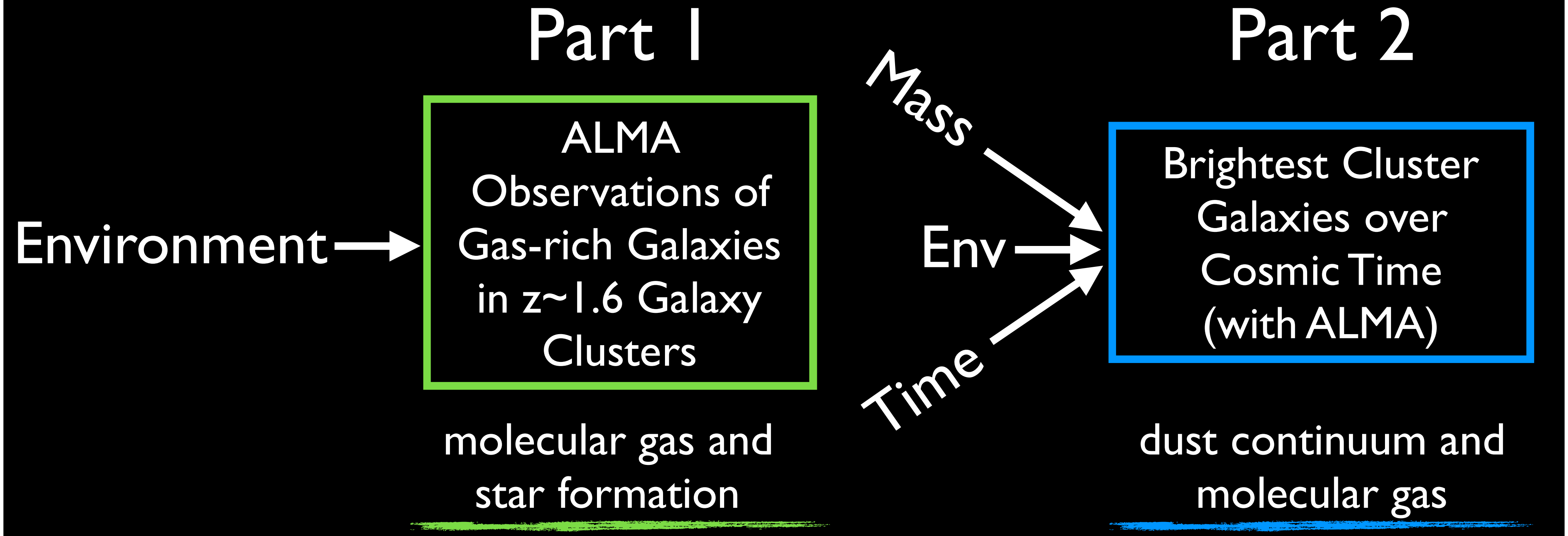


Part 1

Environment →

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

molecular gas and star formation

Part 2

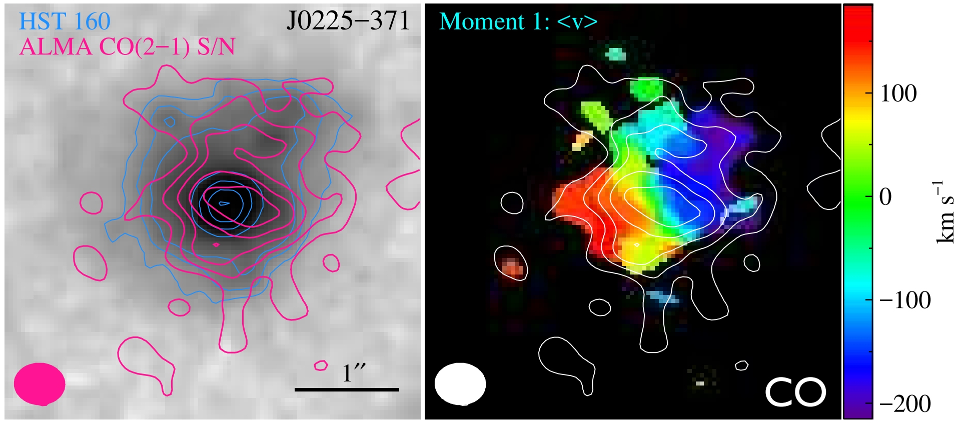
Mass →

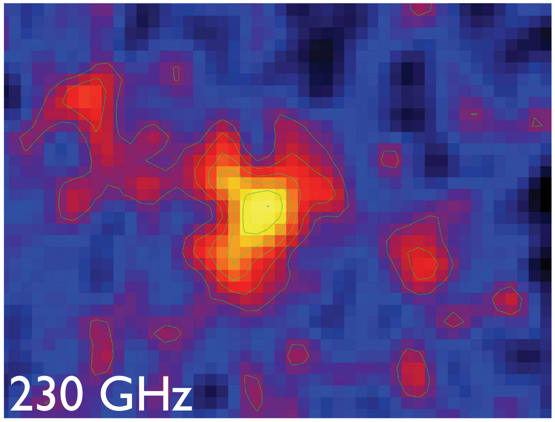
Env →

Time →

Brightest Cluster Galaxies over Cosmic Time (with ALMA)

dust continuum and molecular gas





Galaxy Clusters in a Nutshell

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

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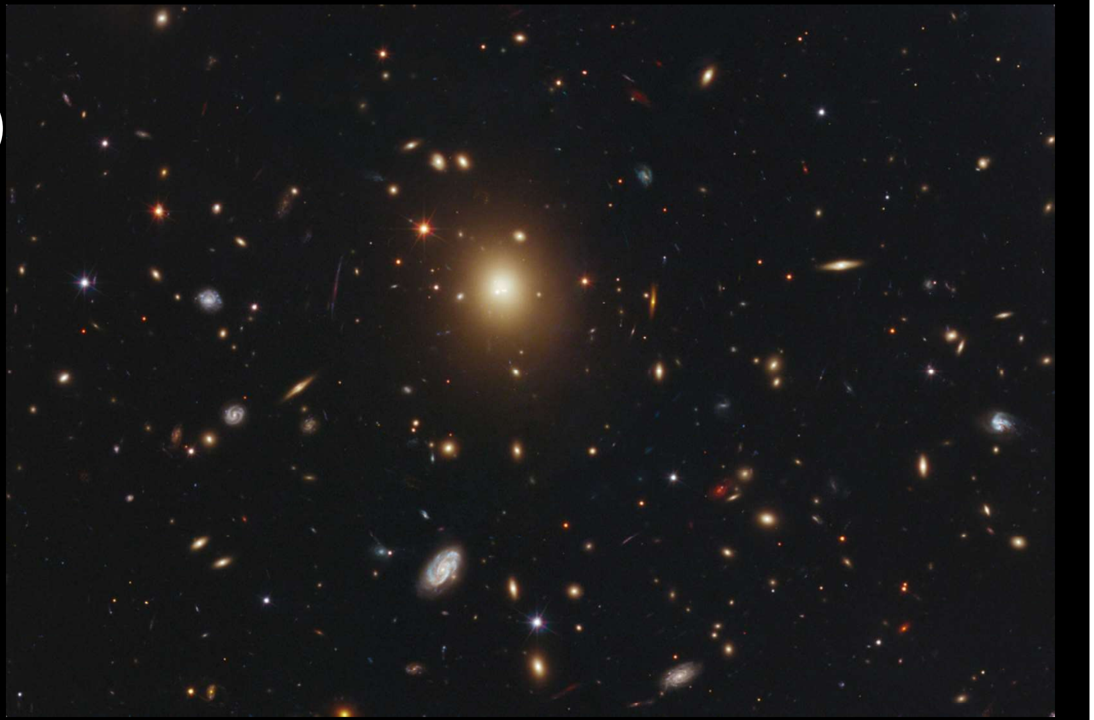
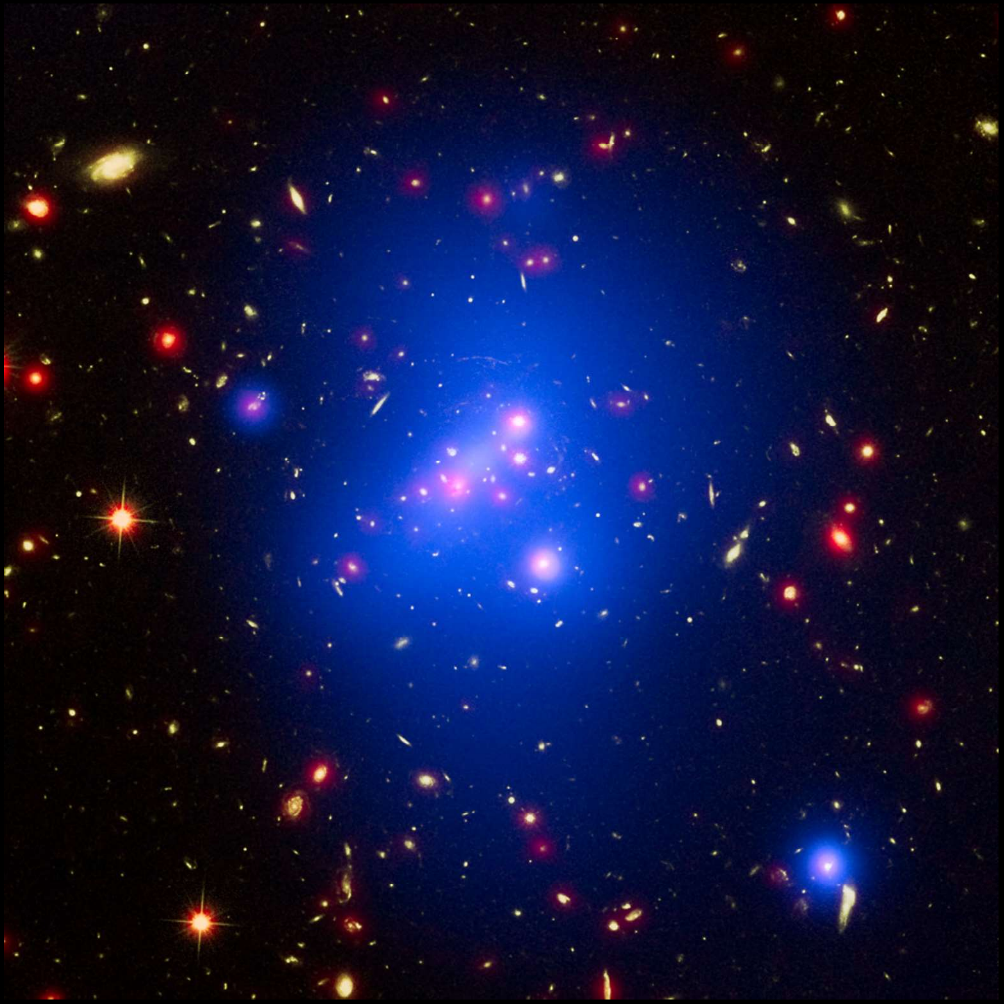


Credit: HST - Abell 2261, z=0.224

Galaxy Clusters in a Nutshell

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



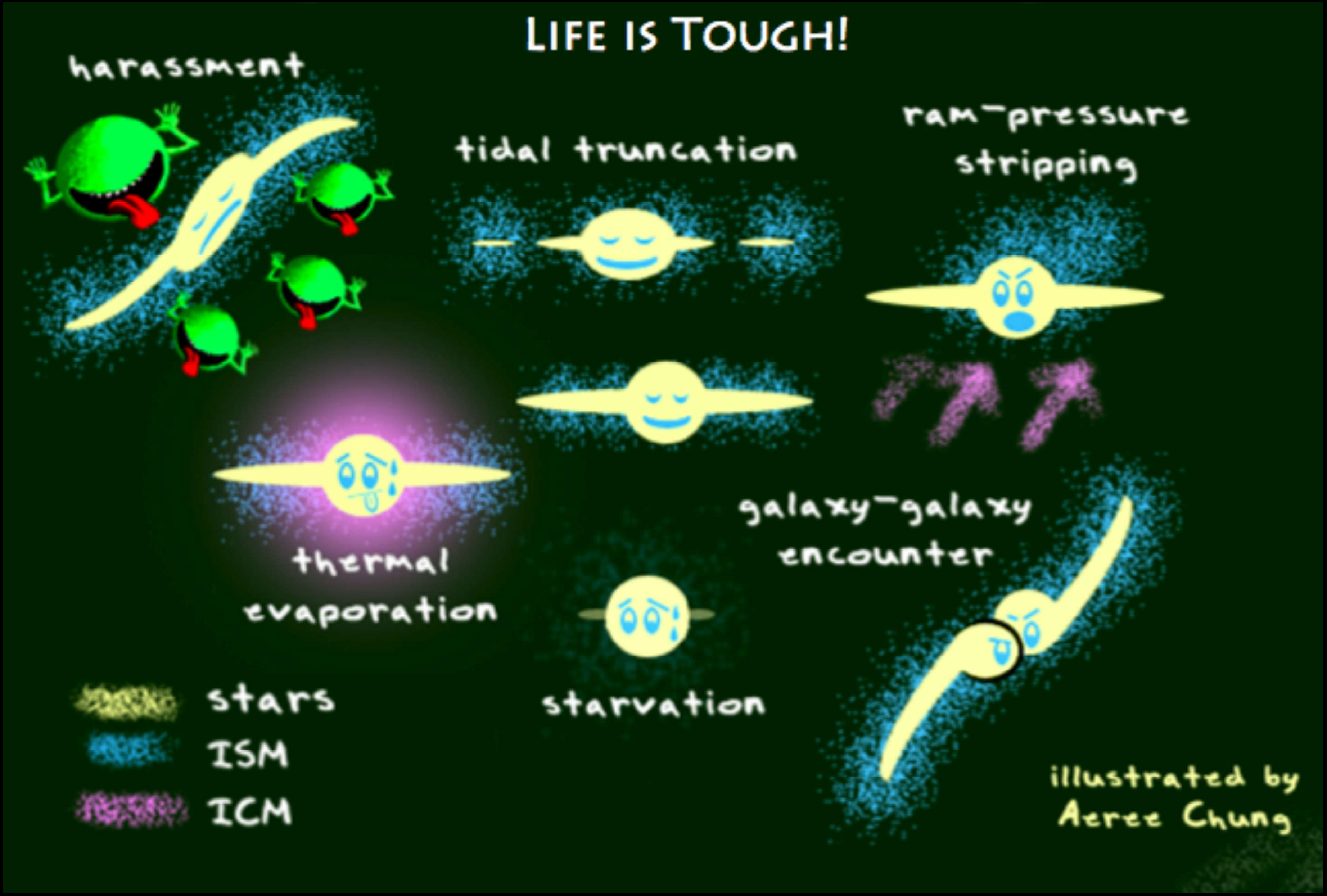
Credit: Chandra/HST/Spitzer - IDCS 1426, z=1.75; Brodwin et al. 2016

Galaxy Clusters in a Nutshell

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

Credit: NASA/ESA/JPL-Caltech/Yale/CNRS - Abell 1689, z=0.1832

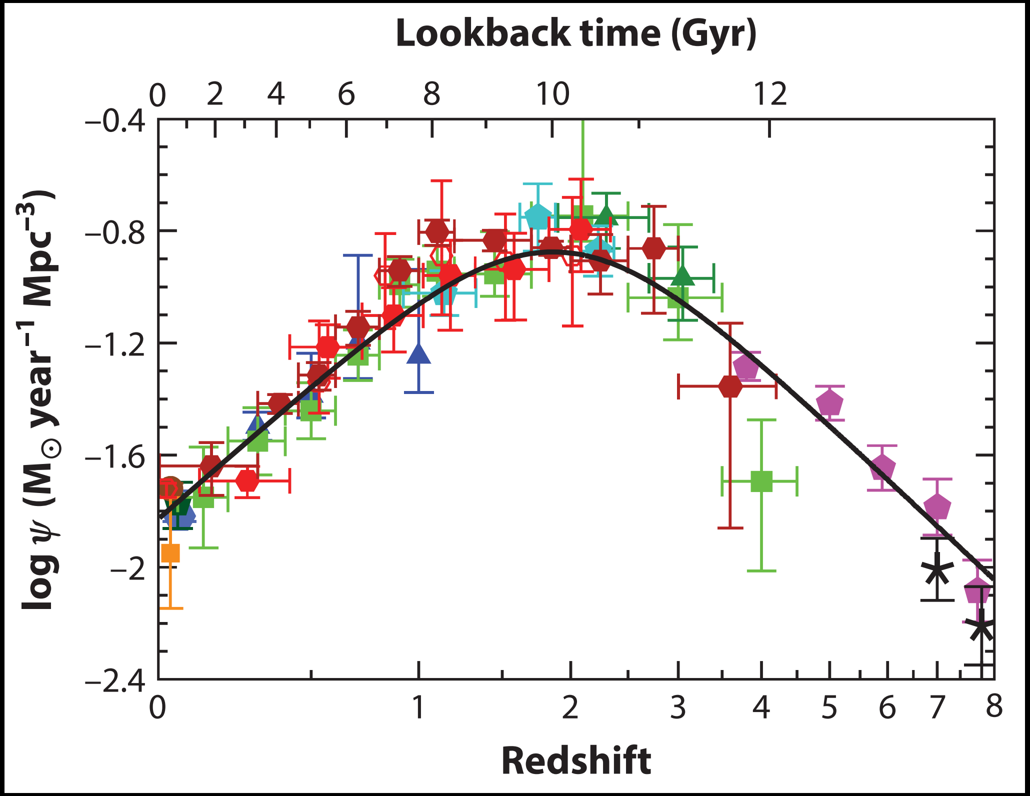
Why study galaxy cluster environments?



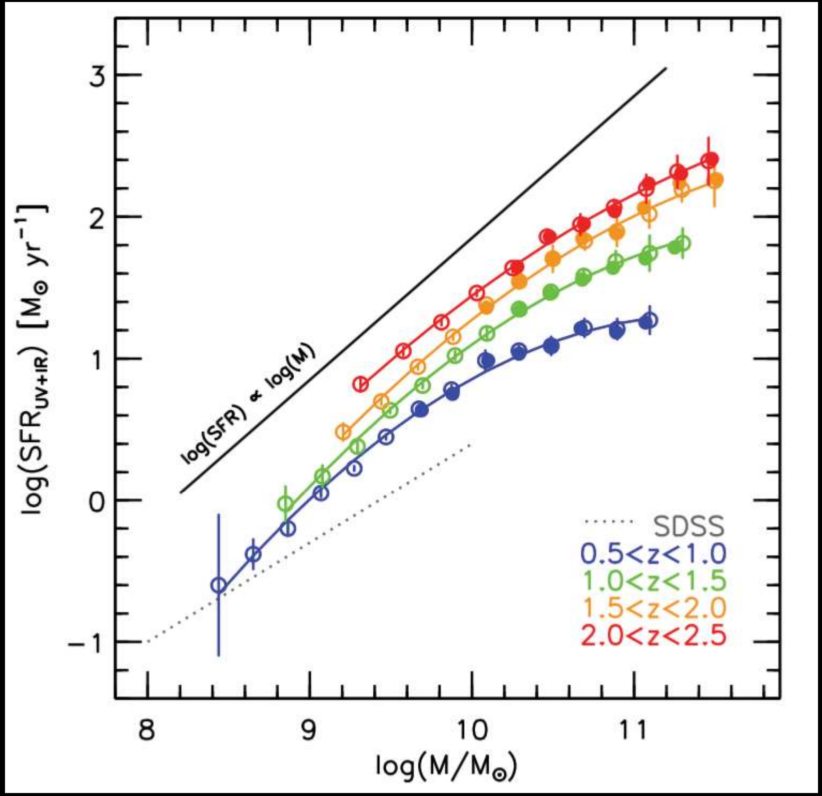
Why study higher redshift?

Peak in cosmic **star formation rate** density

Evolution of star-forming main sequence



Madau & Dickinson 2014



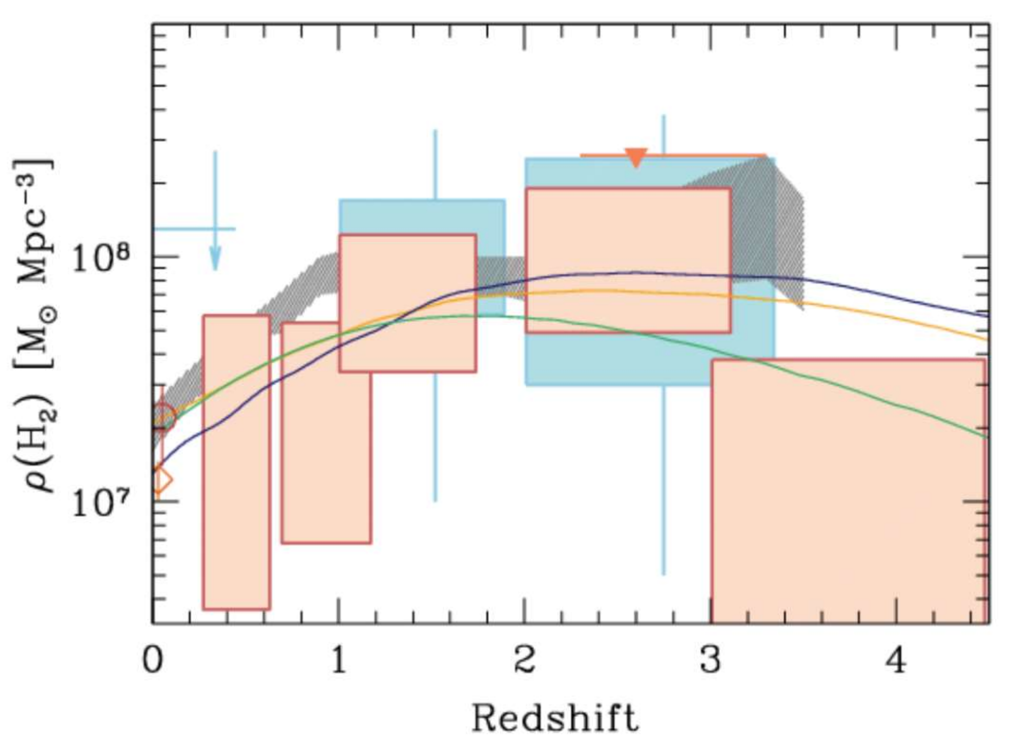
Whitaker et al. 2014

What drives these trends?

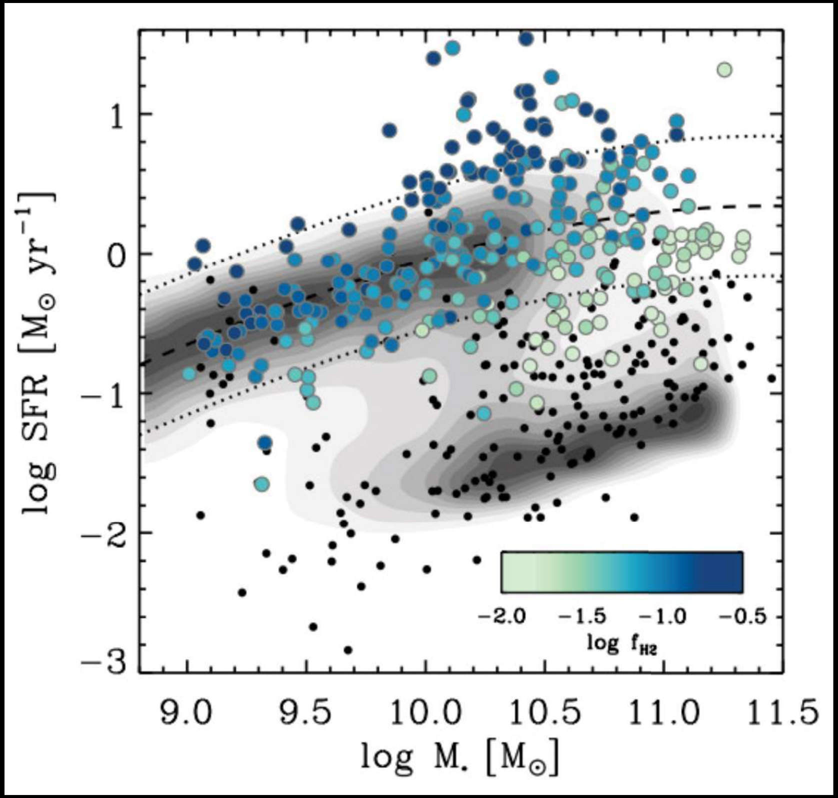
Why study molecular gas?

Peak in cosmic **molecular gas mass** density

Dependence on star-forming main sequence



Decarli et al. 2017



credit: A. Saintonge

Gas Regulation

The Power of ALMA

Radio Interferometer

λ = 0.6 cm - 410 cm

ν = 74 MHz - 50 GHz

27 25-meter dishes

baselines of 1km - 36km

7,000 ft high in New Mexico

Submillimeter Interferometer

λ = 0.3 mm - 3.6 mm

ν = 85 GHz - 950 GHz

50 12-meter dishes

baselines of 0.16km - 16km

16,000 ft high in Chile

200 JVLA hours = 2 molecular gas detections at z~1.6

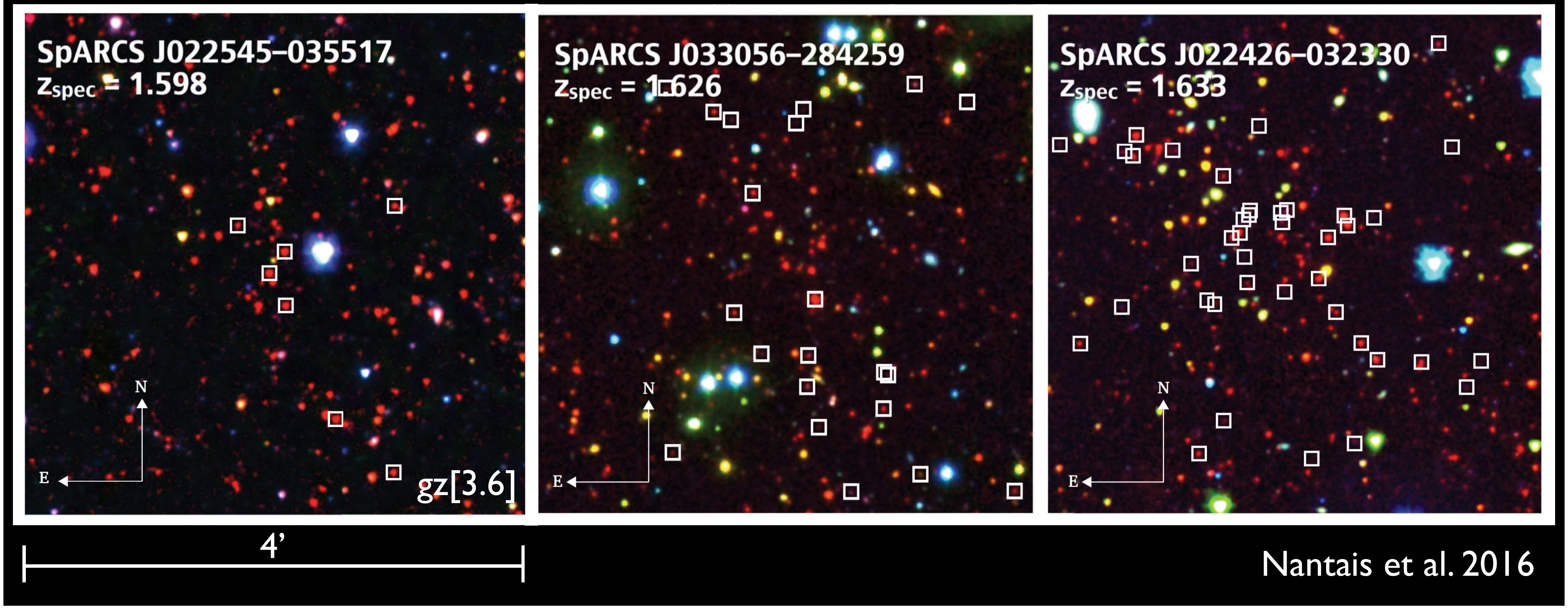
13 ALMA hours = 11 molecular gas detections at z~1.6

Rudnick et al. 2018

Noble et al. 2017

3 SpARCS Clusters at z~1.6

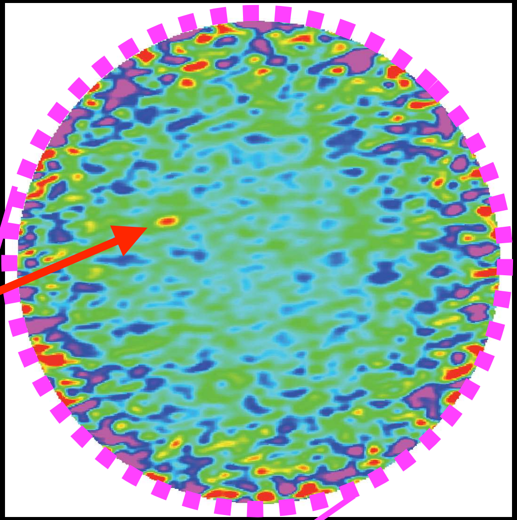
- ~115 spectroscopically confirmed cluster members
- richness-based masses >10^{14} $M_\odot$
- 11-band photometry for stellar masses (*ugrizYK*[3.6][4.5][5.0][8.0])
- MIPS and *Herschel* imaging (24/250/350/500 um) for infrared-SFRs
- HST imaging for size and morphology of stellar components



Nantais et al. 2016

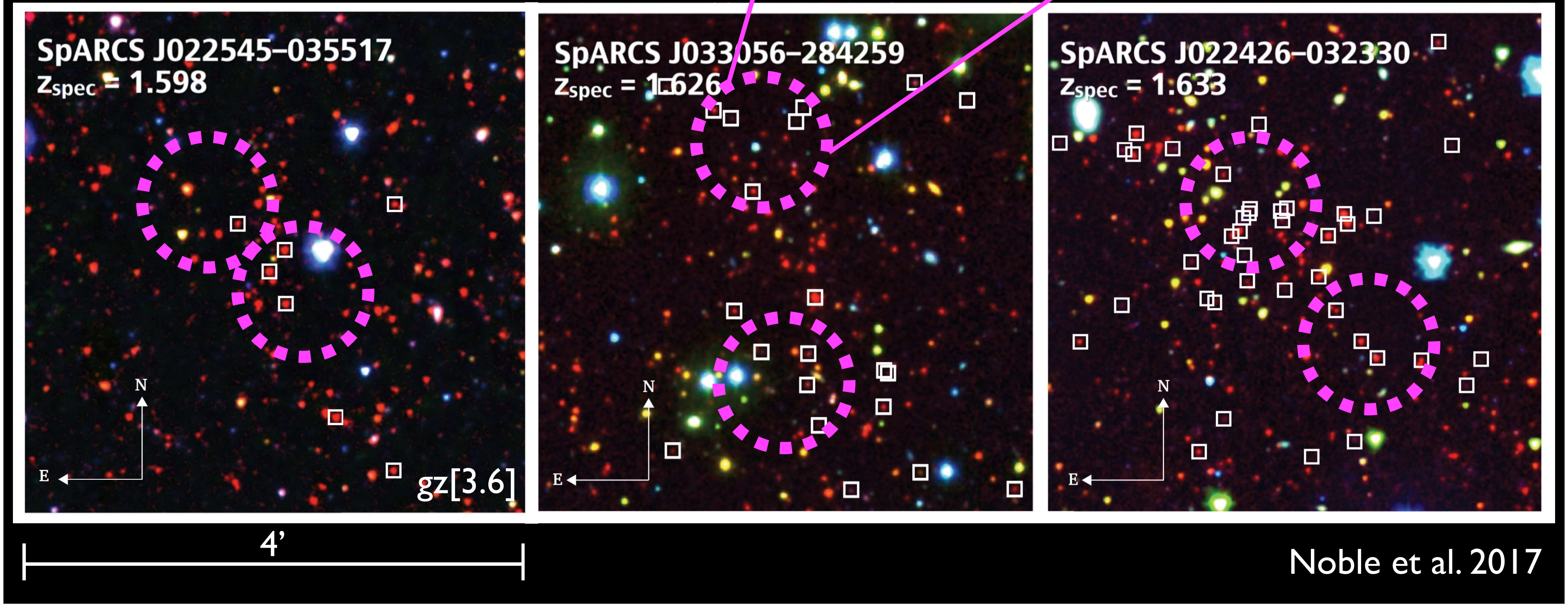
ALMA Molecular Gas Observations

- 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!



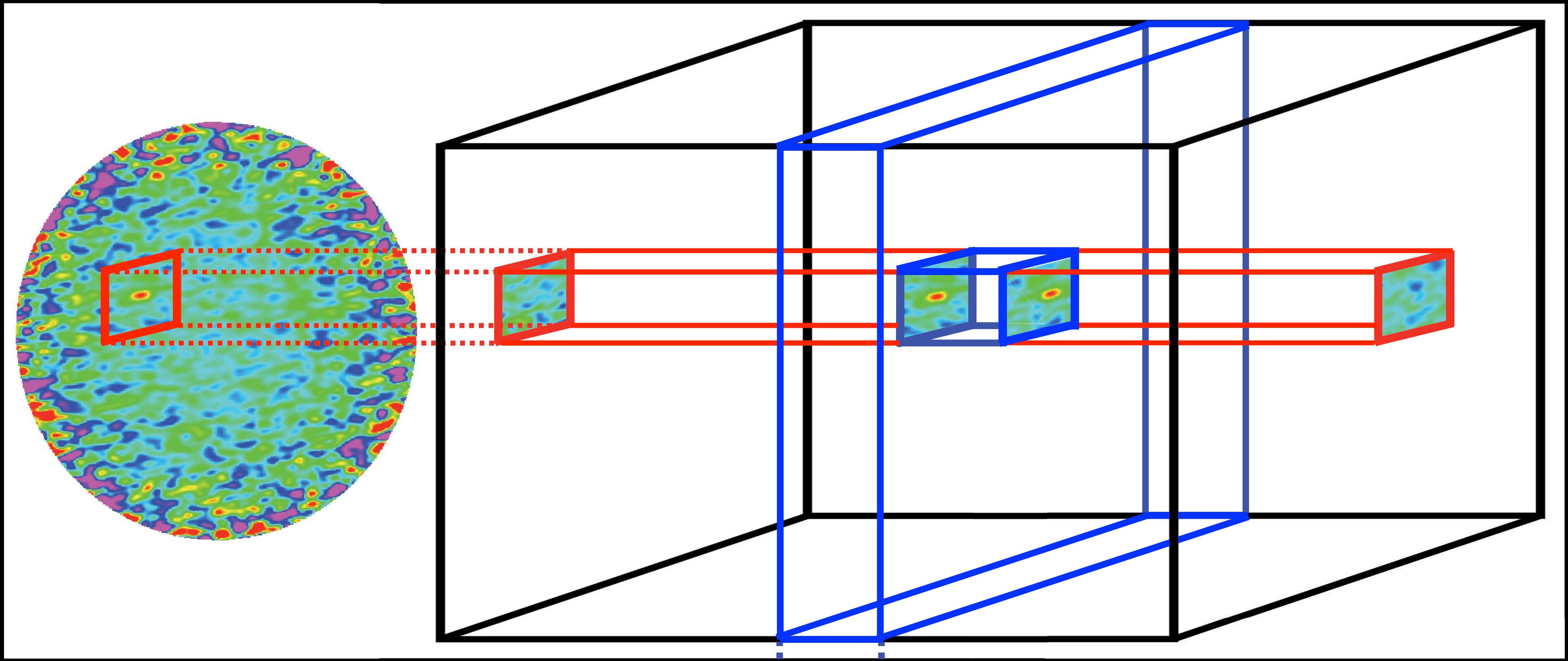
rms ~ 0.17 mJy/beam in 100 km/s

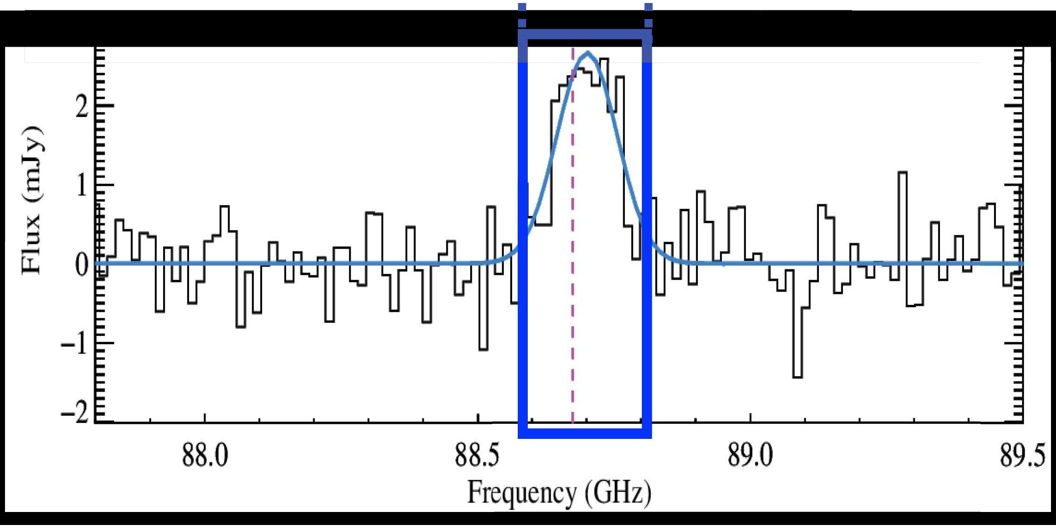
beam ~ 4.4" x 2.2"



Noble et al. 2017

ALMA Data Cube



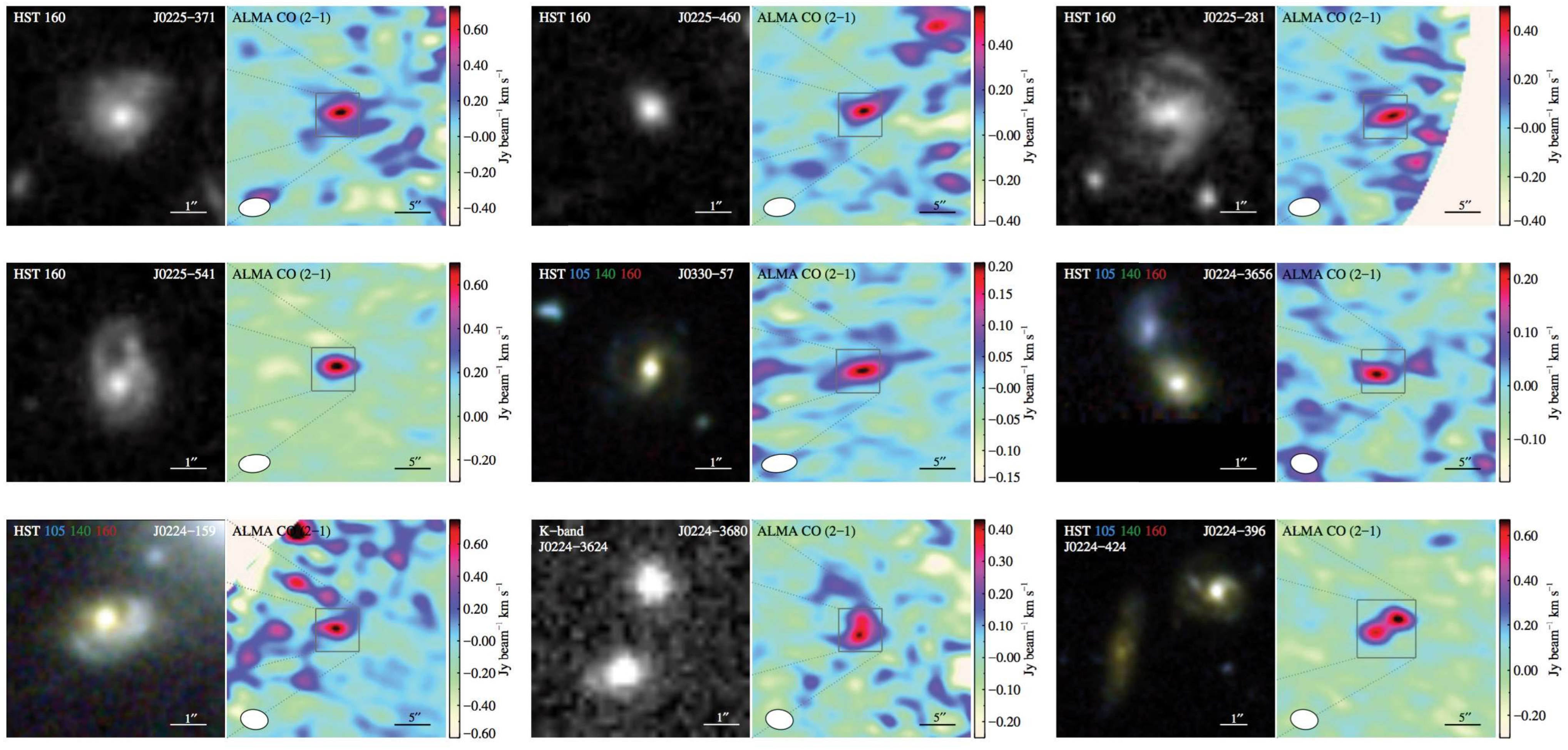


Noble et al. 2017

ALMA CO (2-1) Observations

HST: stars

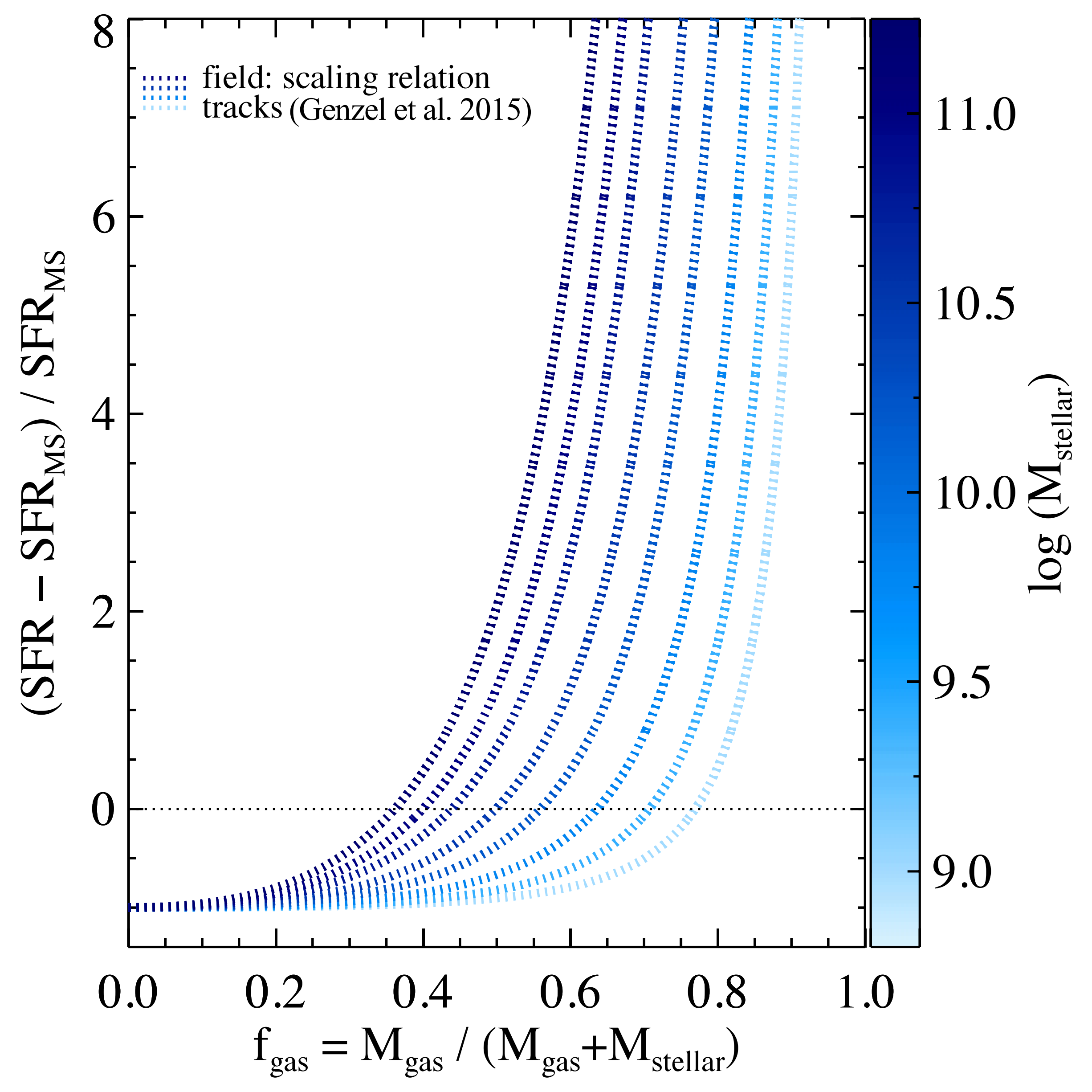
ALMA: gas



Infrared (Spitzer/Herschel): dust (SFR)

Noble et al. 2017

Gas Fractions in z~1.6 Cluster Galaxies



Noble et al. 2017; 2019

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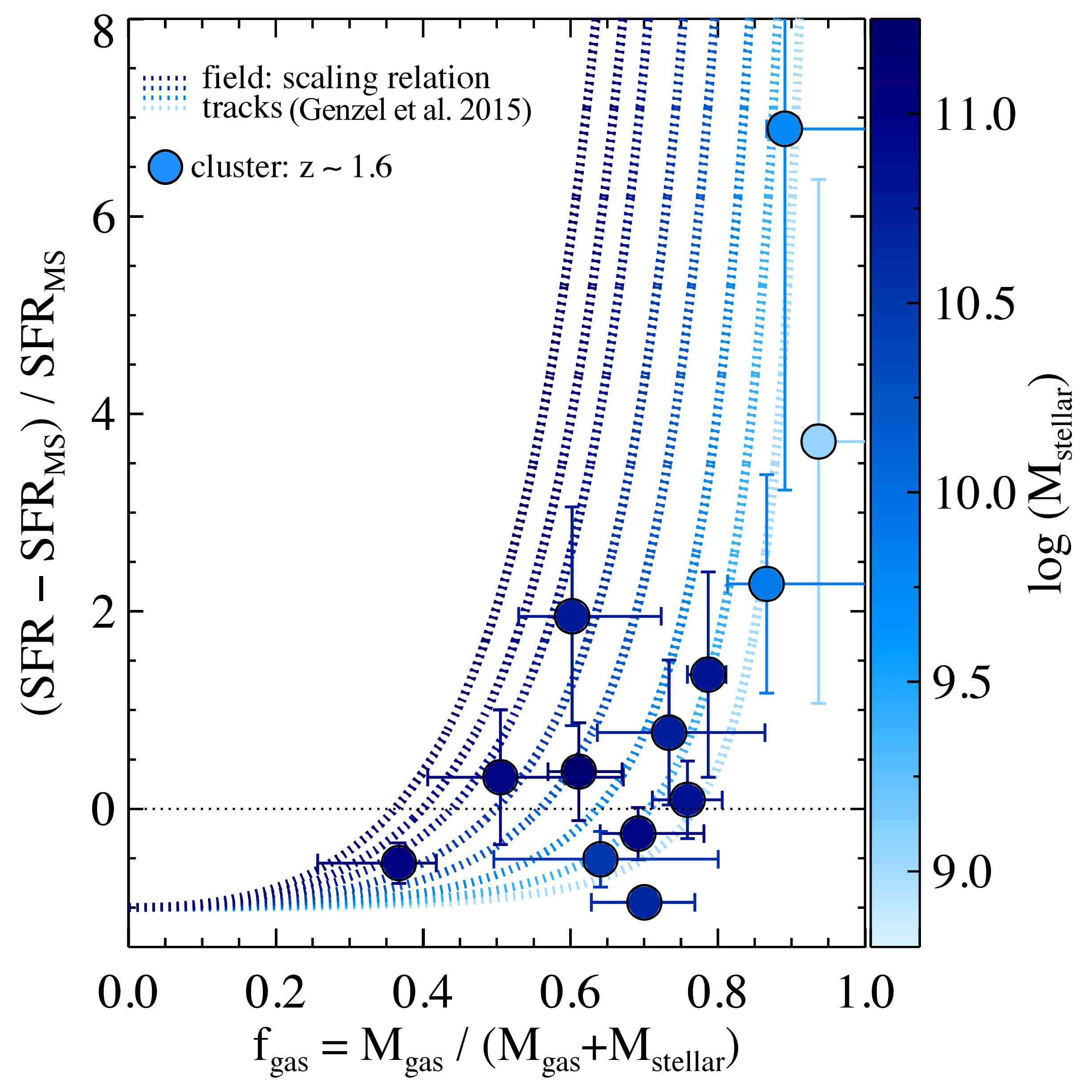

Noble et al. 2017; 2019

z~1.6 cluster galaxies are at systematically higher gas fractions than field galaxies

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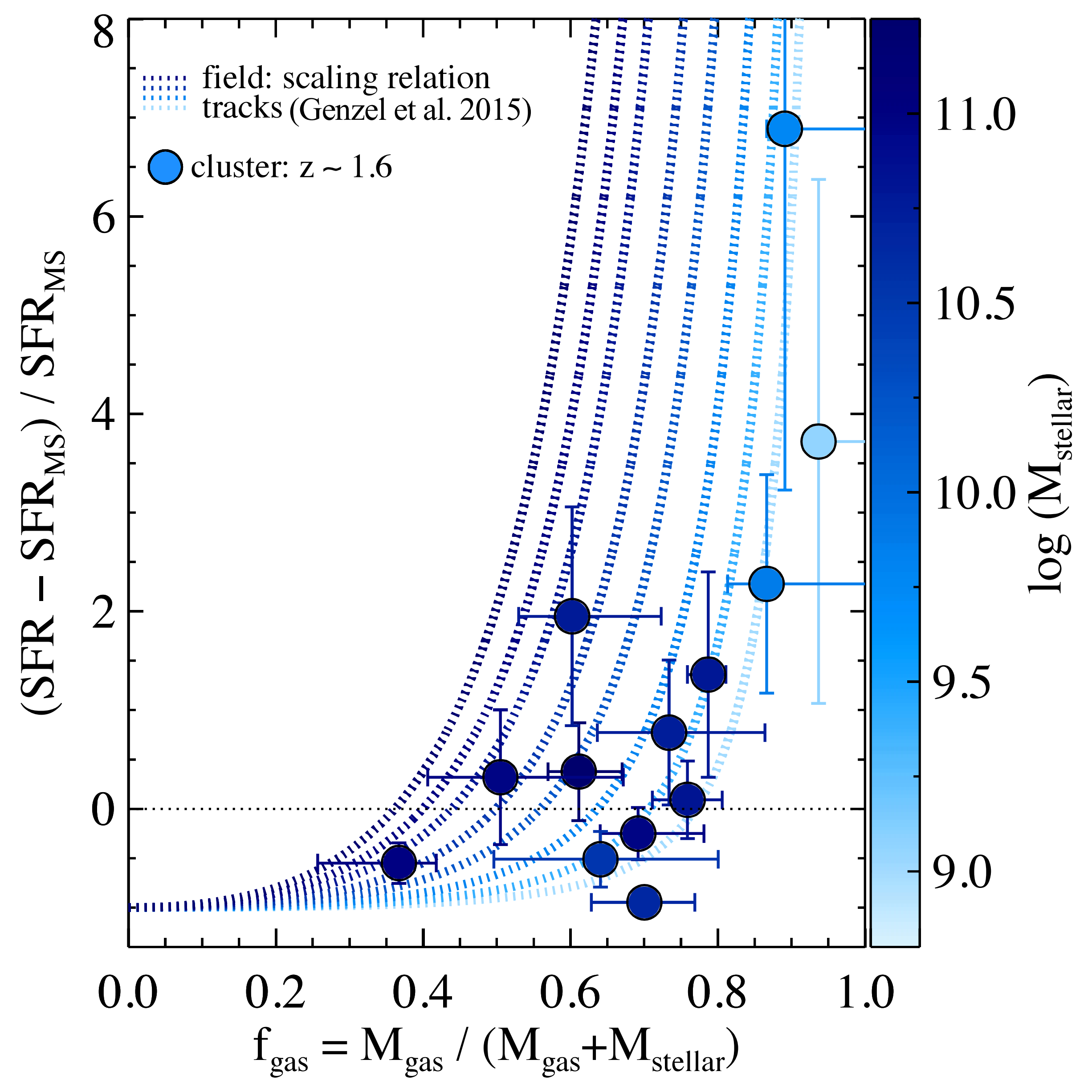


Noble et al. 2017; 2019

z~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

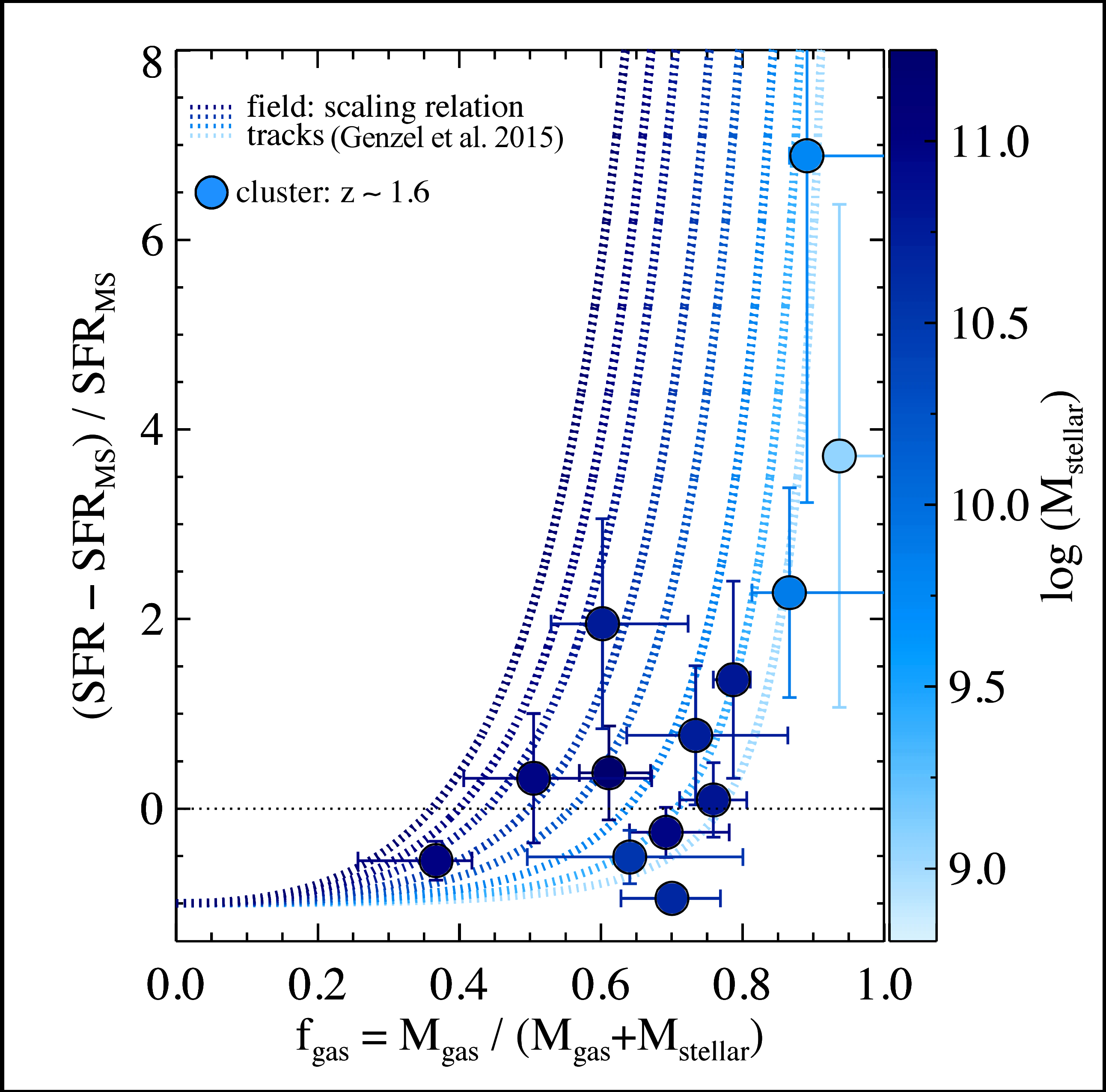
Massingill, Noble++ in prep

- require different α_{CO}?

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

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

Gas Fractions in z~1.6 Cluster Galaxies



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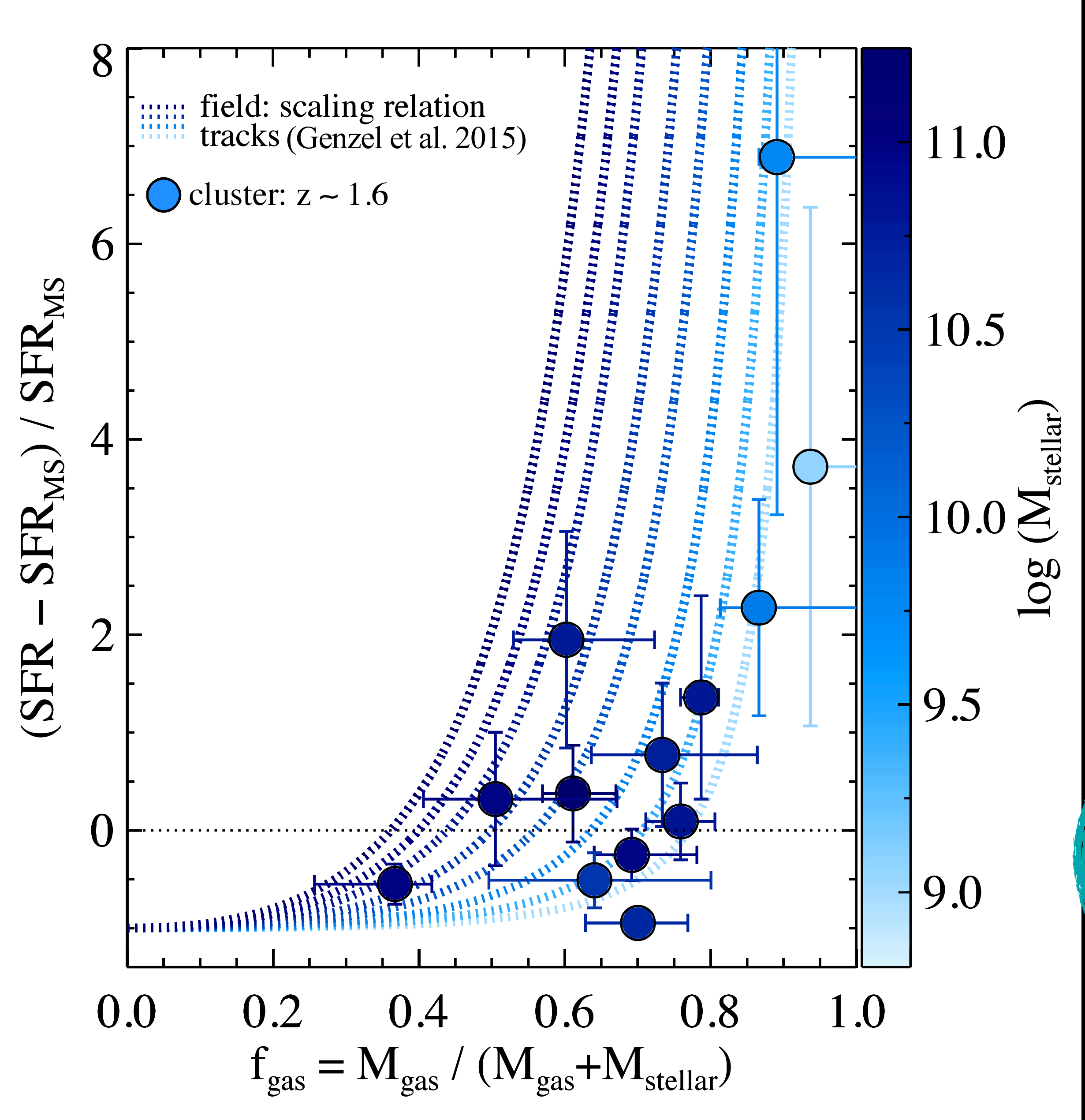

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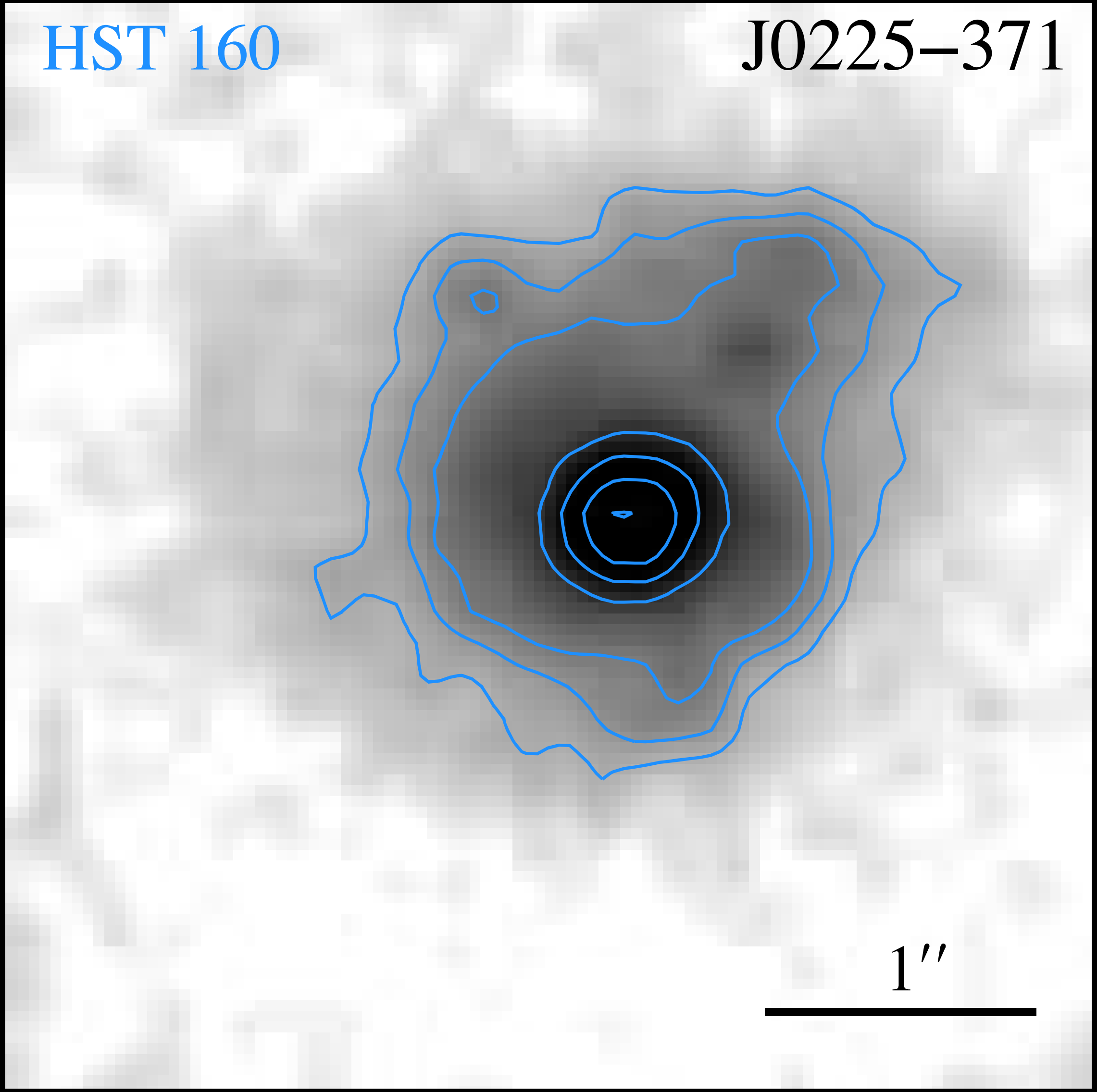
Spatially Resolving Molecular Gas

deeper and higher spatial resolution observations

rms ~ 0.1 mJy/beam in 50 km/s



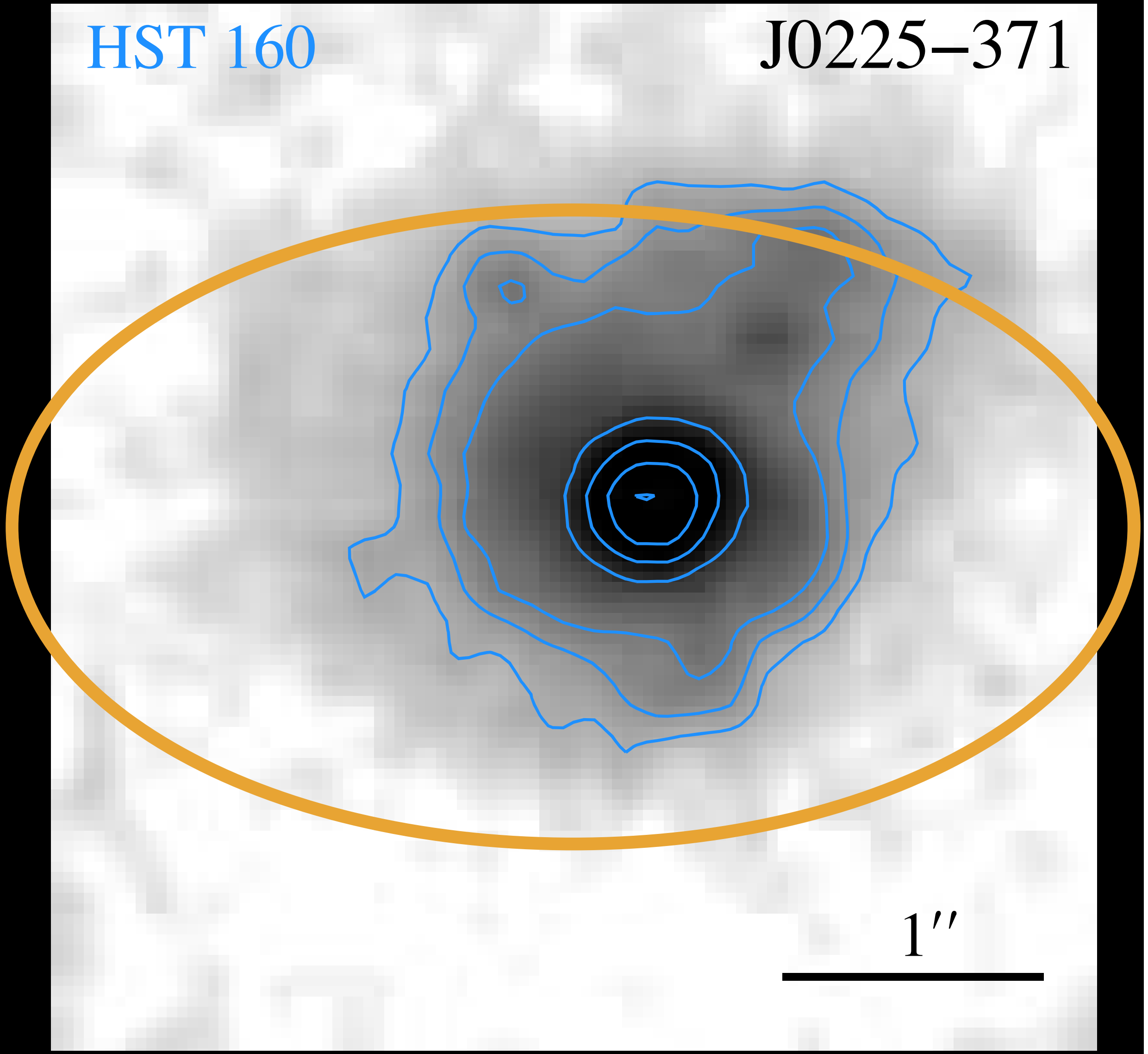
Noble et al. 2019

Spatially Resolving Molecular Gas

deeper and higher spatial resolution observations

rms ~ 0.1 mJy/beam in 50 km/s

previous resolution



Noble et al. 2019

Spatially Resolving Molecular Gas

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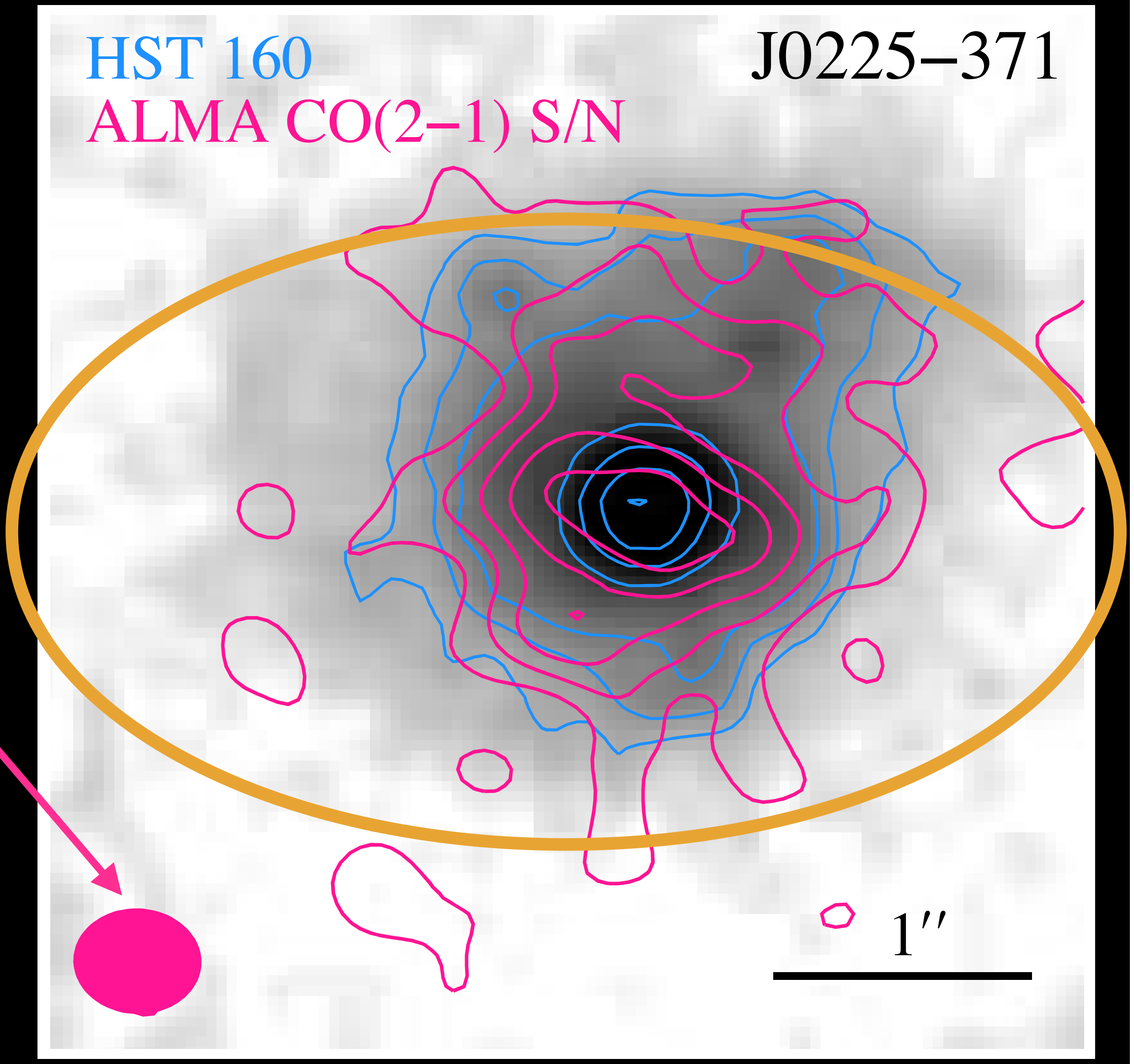
previous resolution

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



Noble et al. 2019

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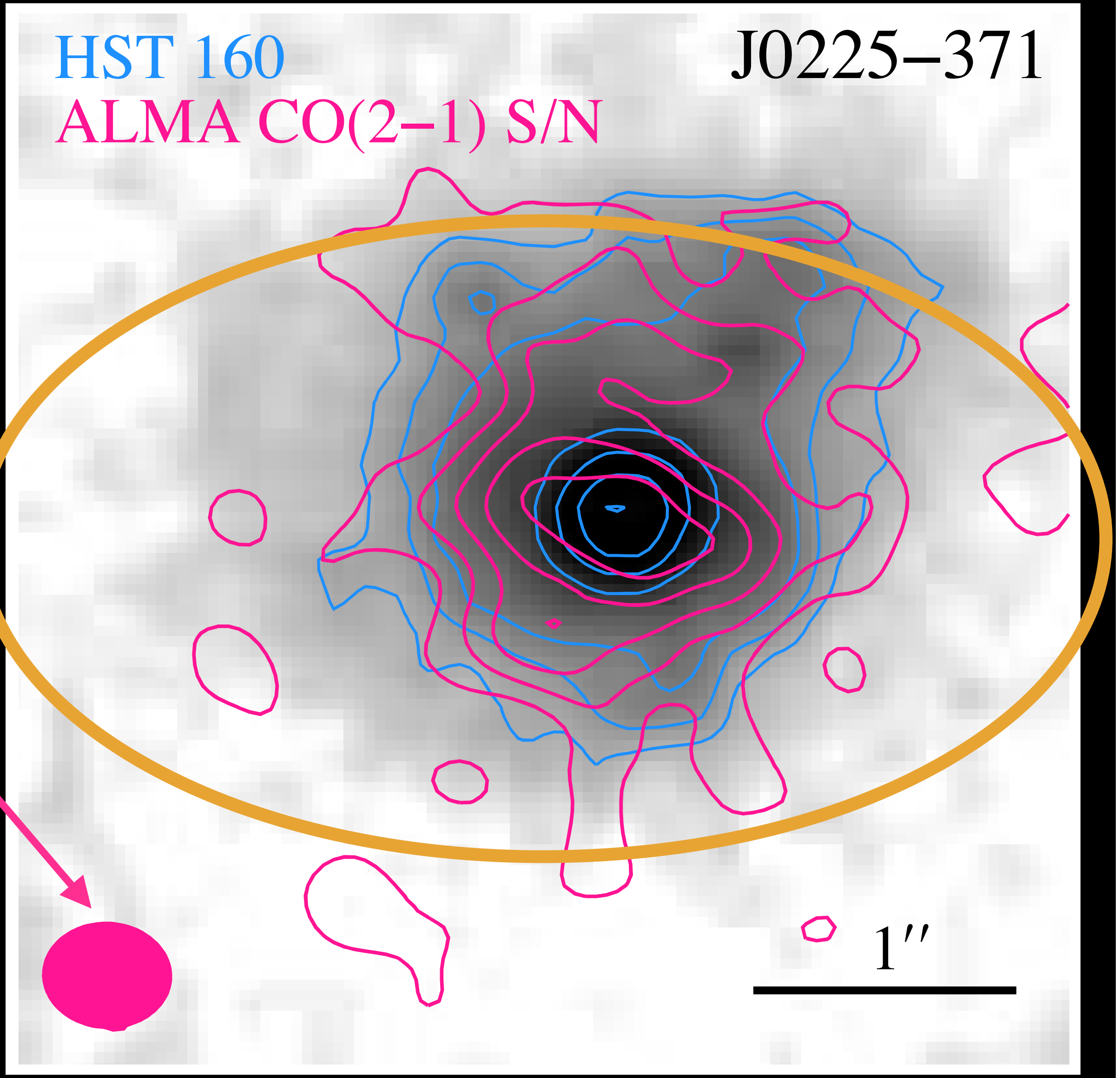


2.7 integration hours on ALMA in single z~1.6 cluster

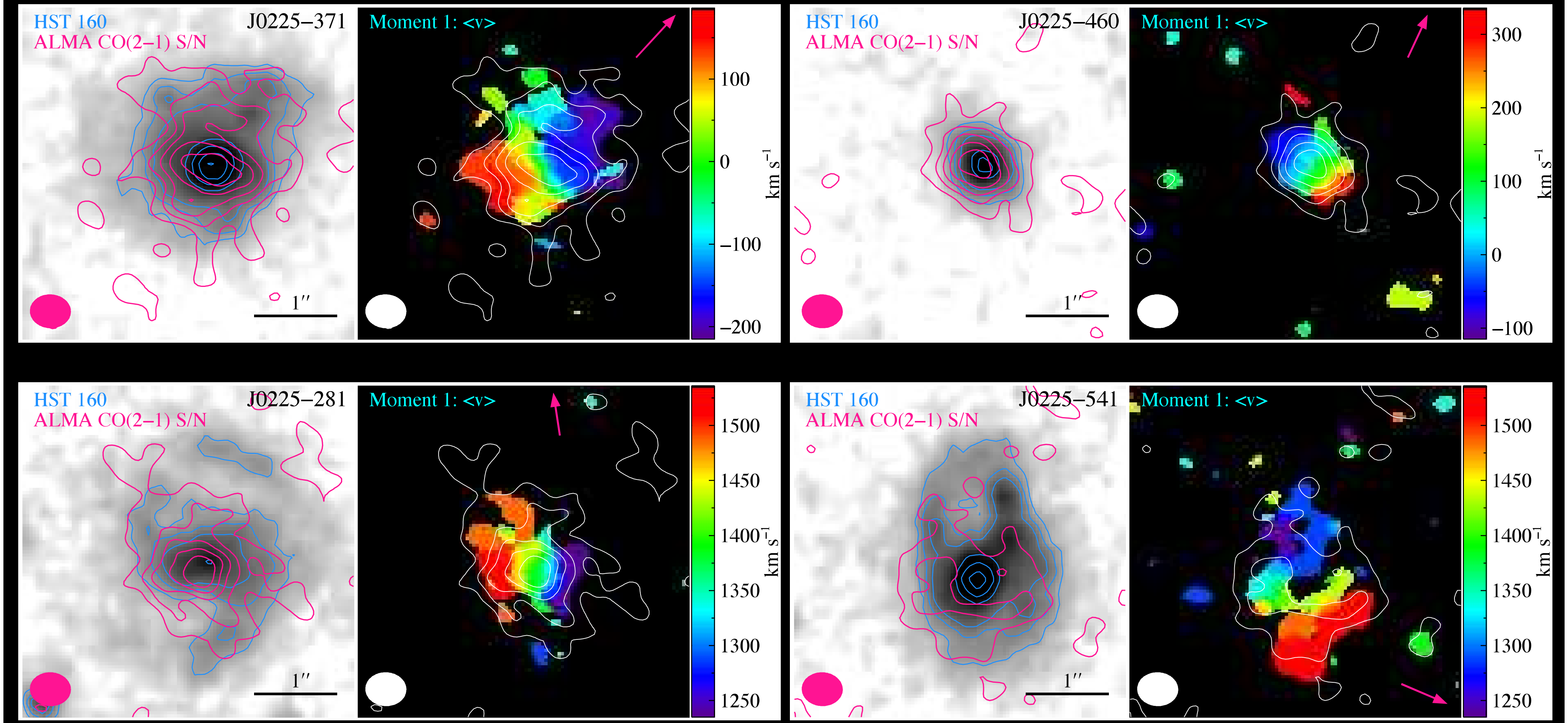
↓

8 detections!

Noble et al. 2019

Spatially Resolving Molecular Gas

velocity maps!



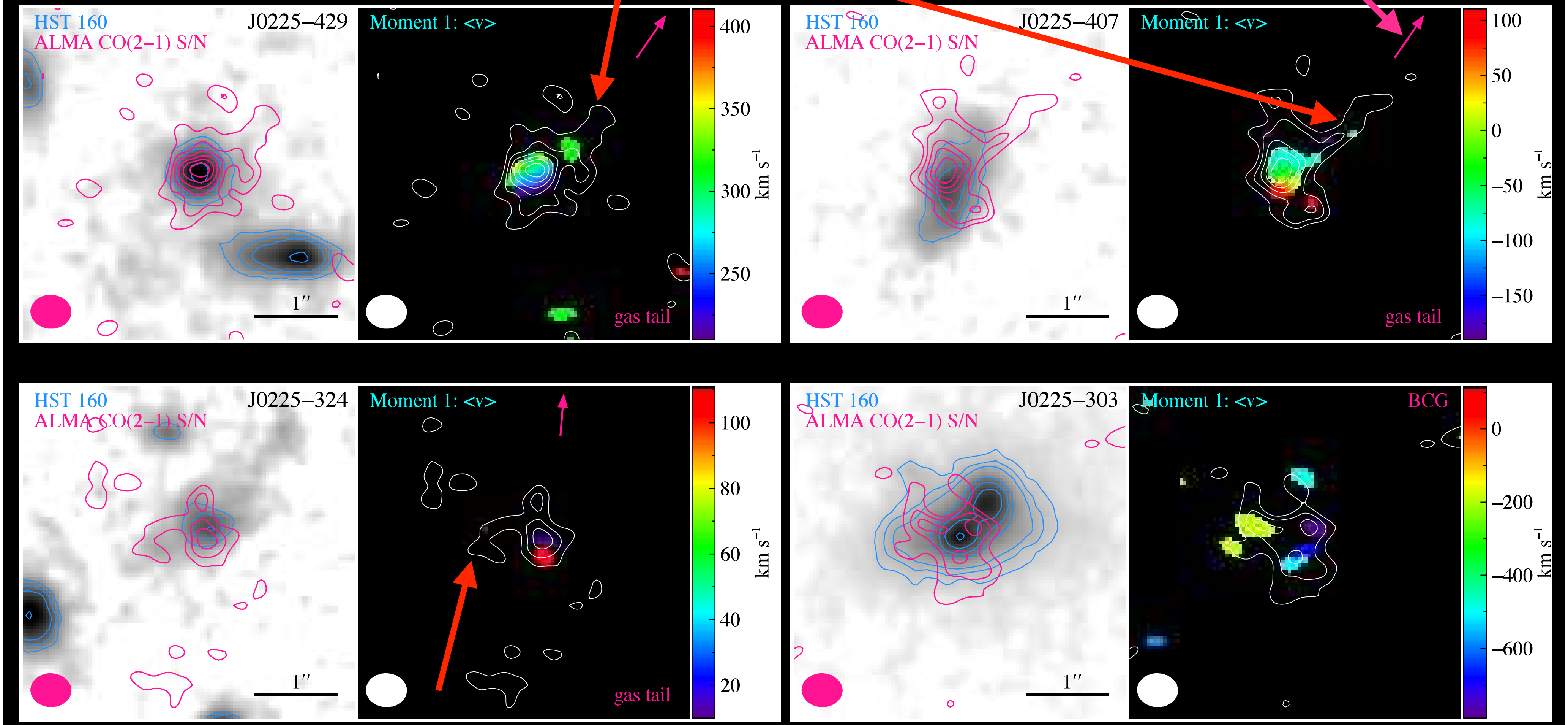
Noble et al. 2019

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

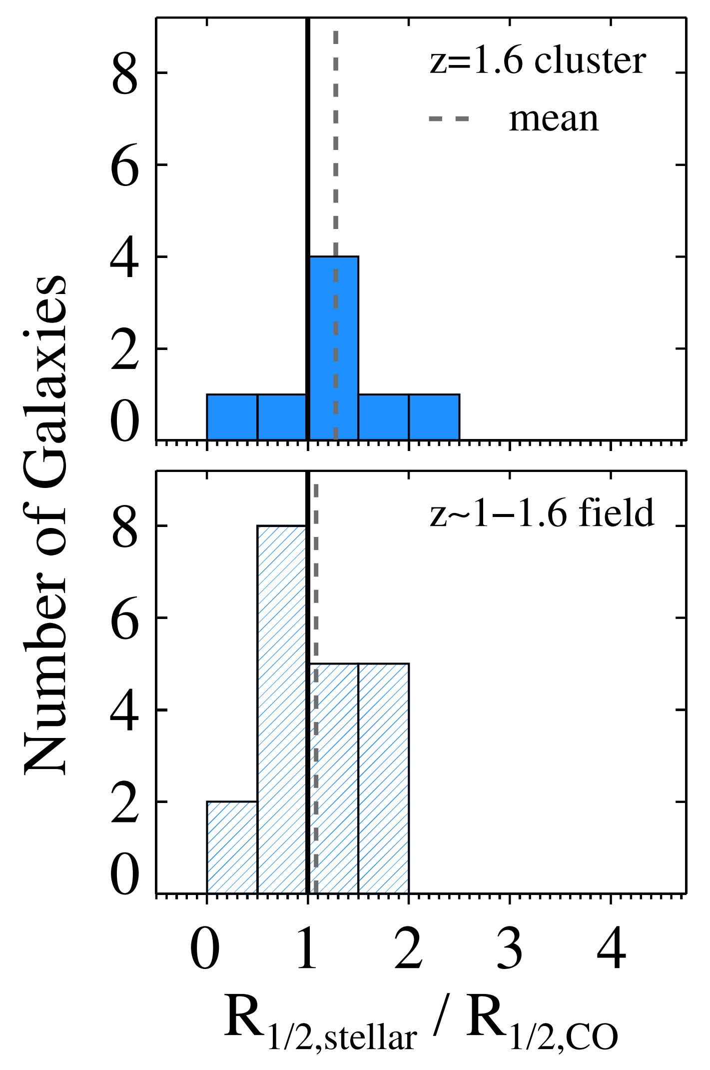
Noble et al. 2019

Cramer, Noble et al. in prep

Stellar-to-CO Radii

Noble+ 2019

Tacconi+ 2013; Daddi+ 2010



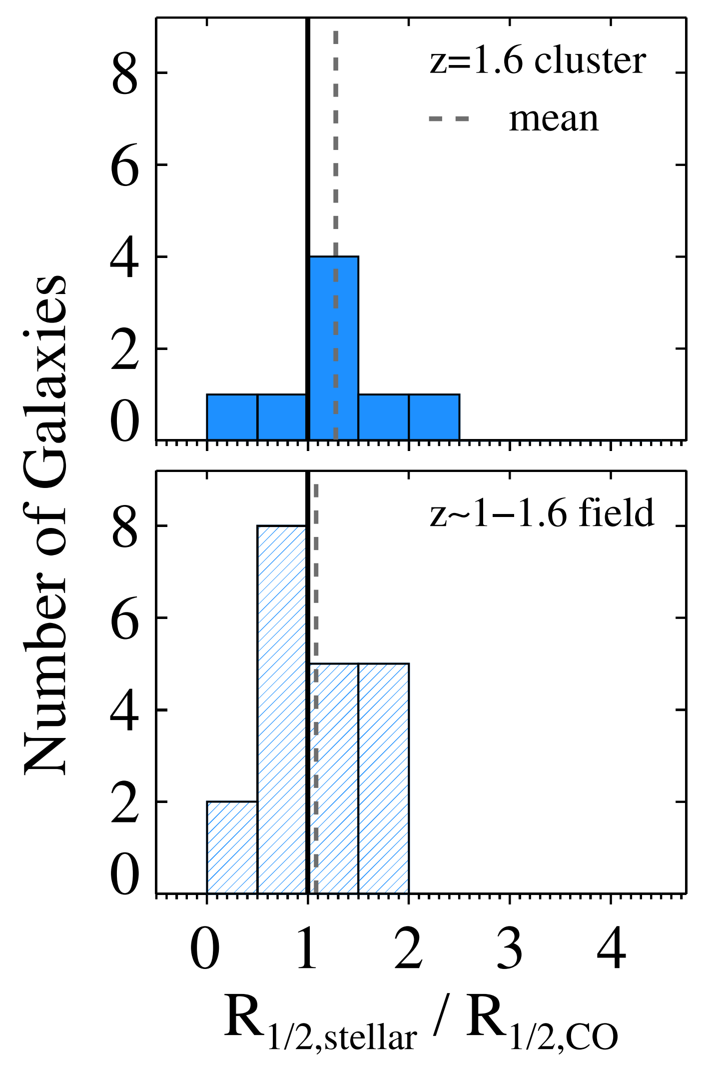
high-z: ~1σ offset in mean

Noble et al. 2019

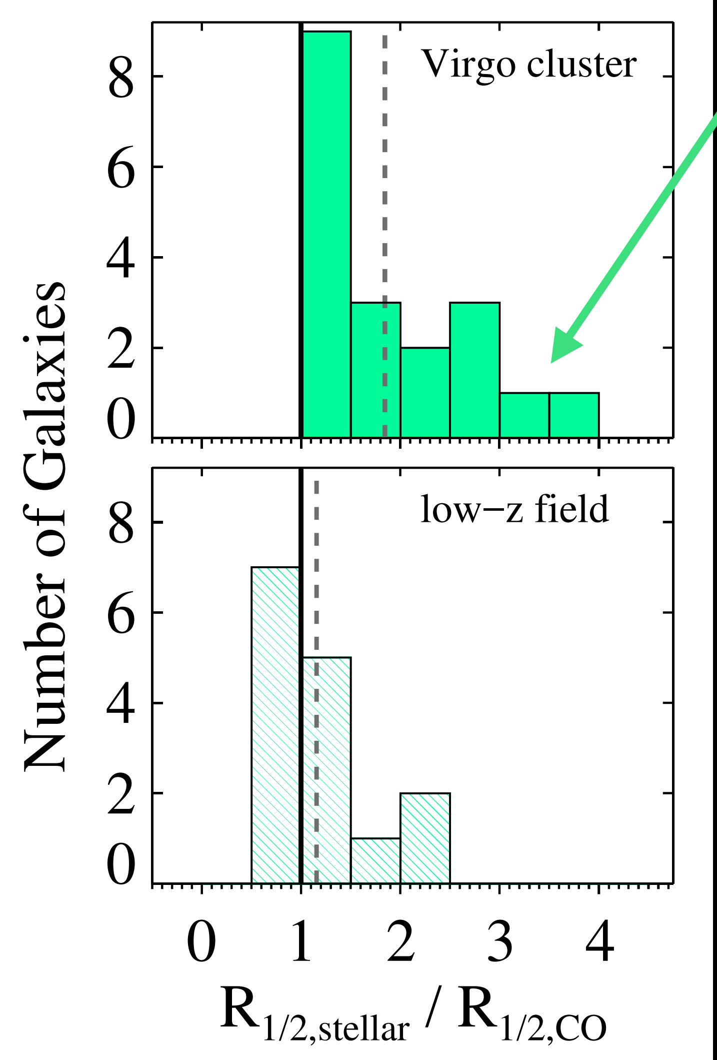
Stellar-to-CO Radii

Noble+ 2019

Tacconi+ 2013; Daddi+ 2010



gas stripping



Kenney & Young 1988

Regan+ 2001

high-z: ~1σ offset in mean   low-z: ~3σ offset in mean

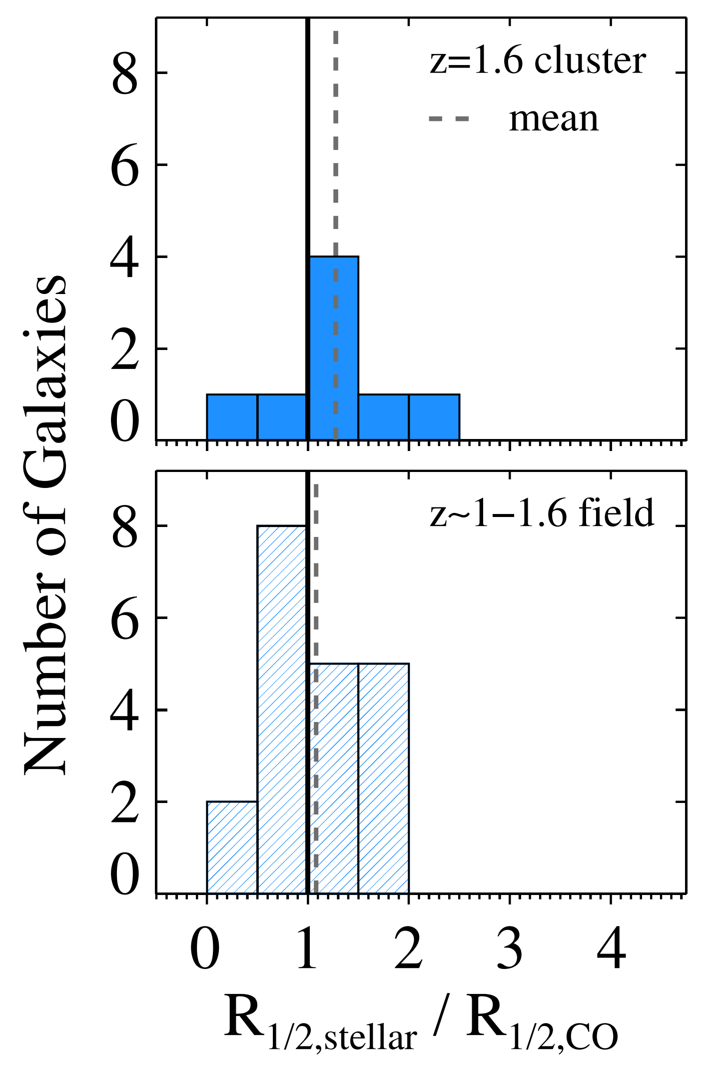
Noble et al. 2019

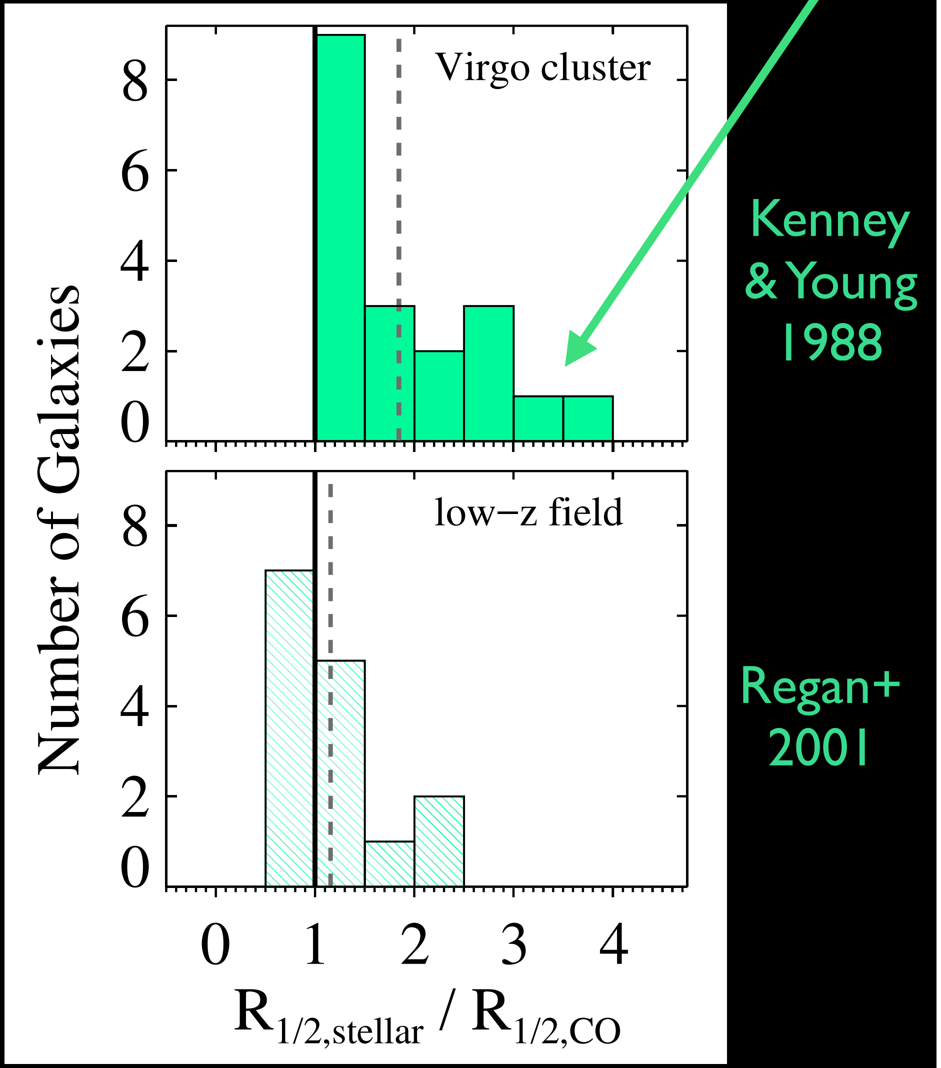
Stellar-to-CO Radii

gas stripping

Noble+ 2019

Tacconi+ 2013; Daddi+ 2010





Kenney & Young 1988

Regan+ 2001

high-z: ~1σ offset in mean

low-z: ~3σ offset in mean

Noble et al. 2019

Stellar-to-CO Radii

gas stripping

Noble+
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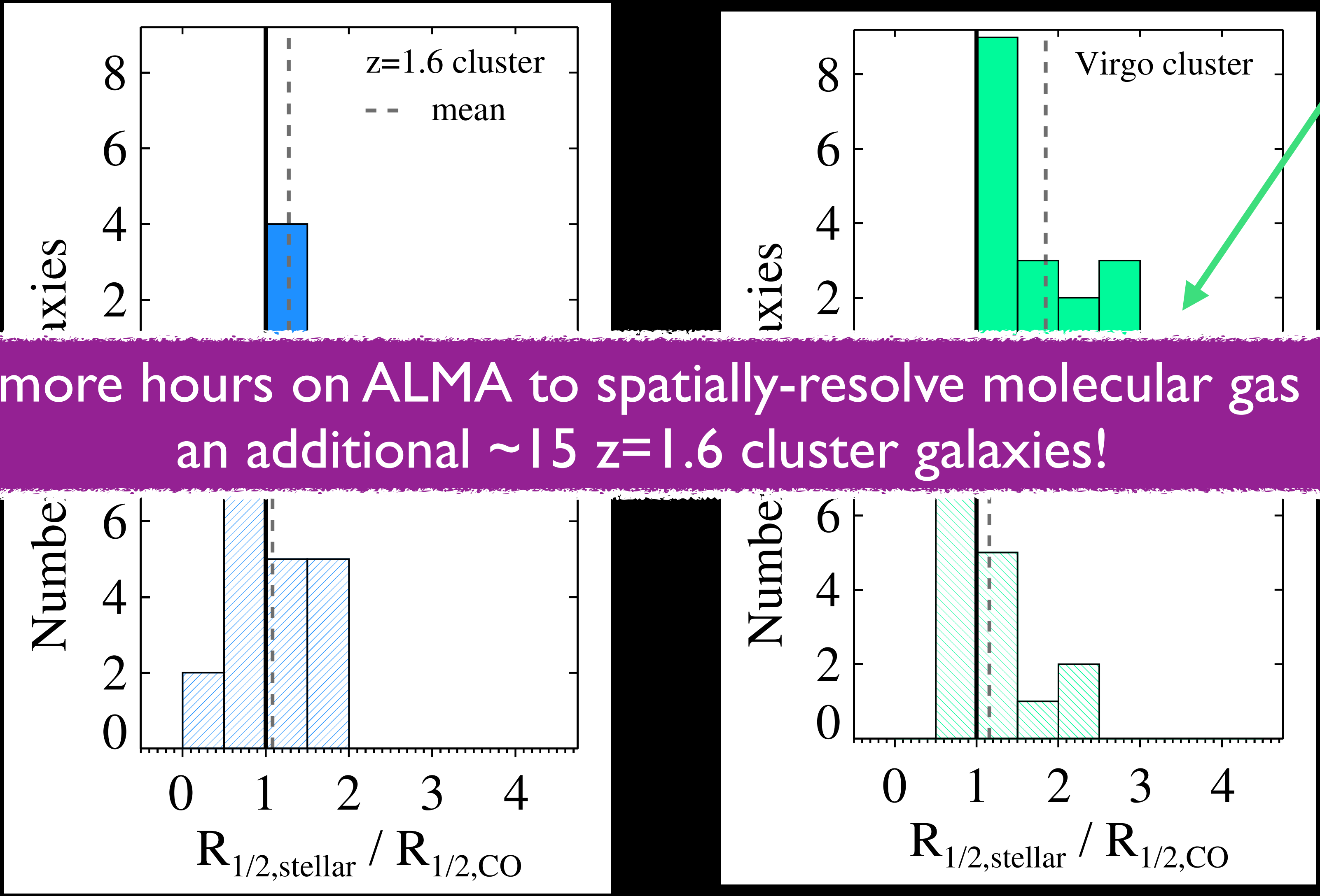


20 more hours on ALMA to spatially-resolve molecular gas in an additional ~15 z=1.6 cluster galaxies!

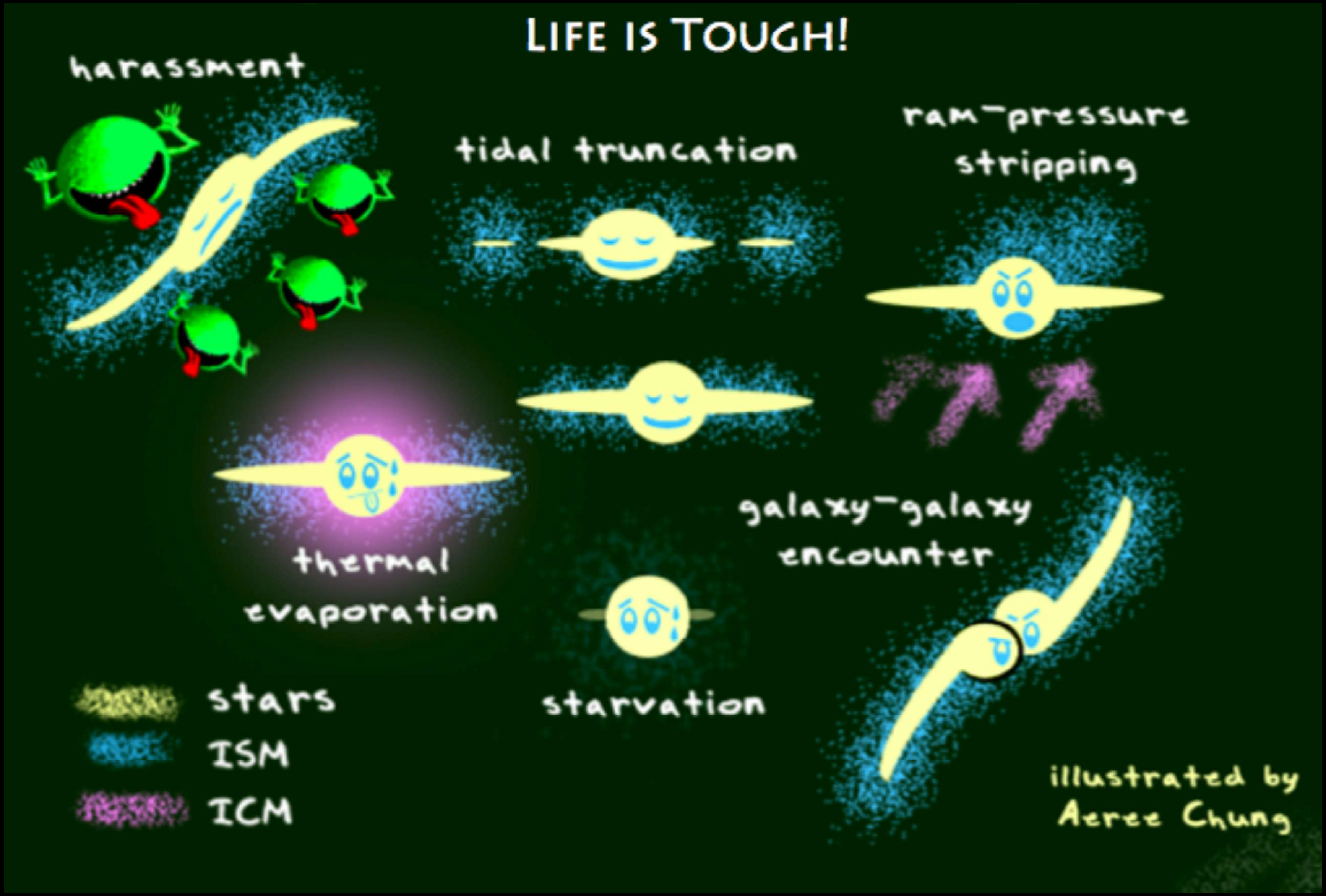
high-z: ~1σ offset in mean

low-z: ~3σ offset in mean

Noble et al. 2019

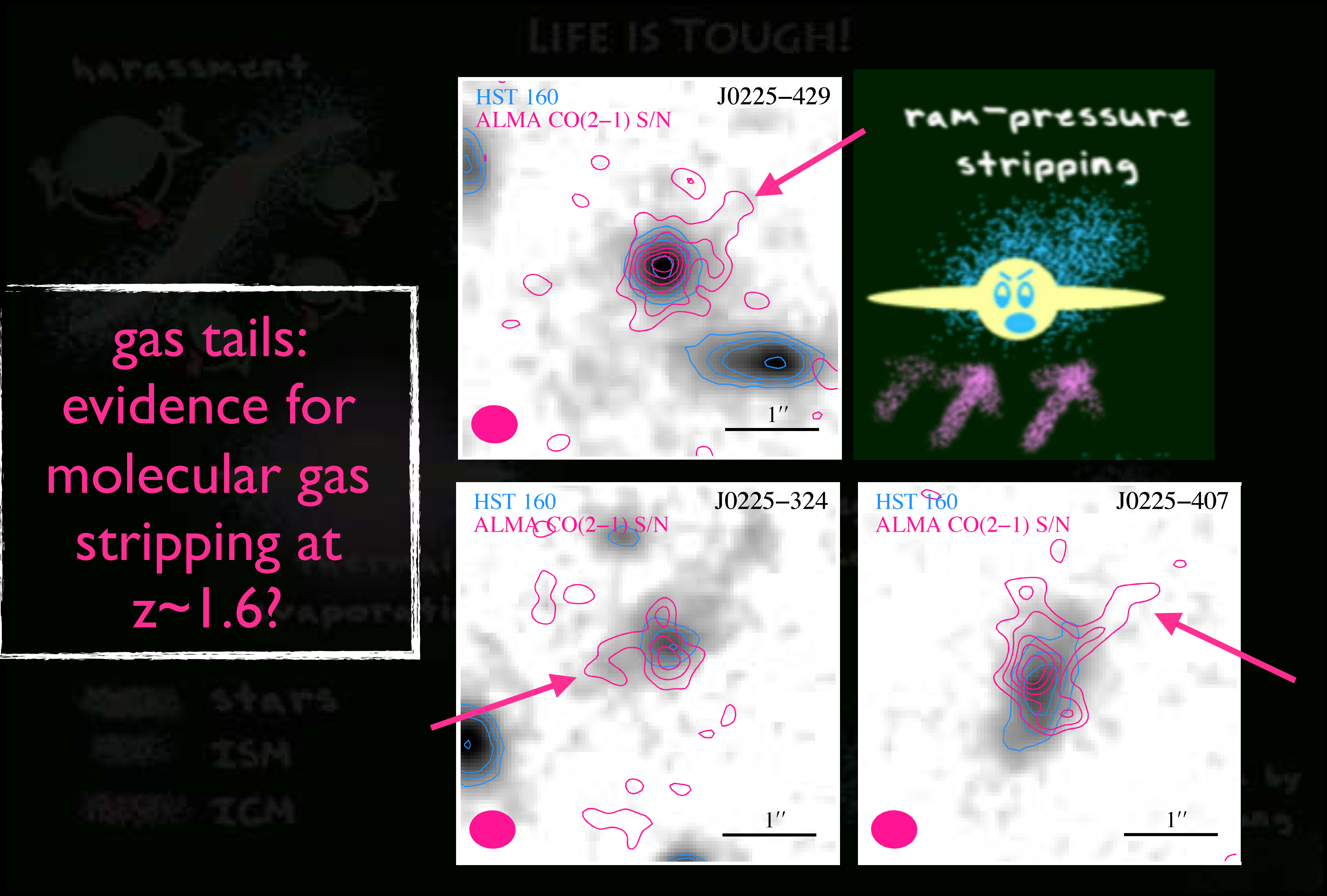
Massingill, Noble et al. in prep

How does environment influence galaxy evolution?



How does environment influence galaxy evolution?

How does environment influence galaxy evolution?

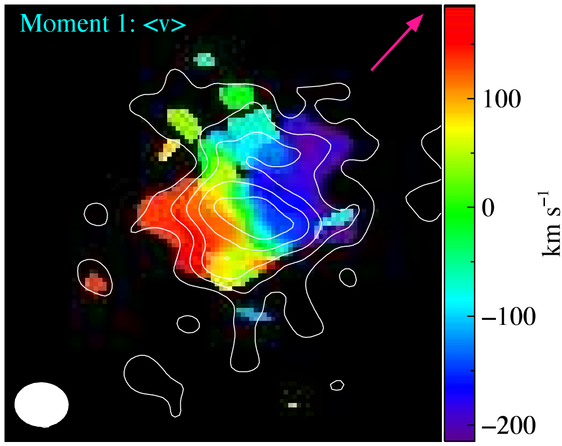


gas tails: evidence for molecular gas stripping at z~1.6?

Evidence for Molecular Gas Stripping at z~1.6?

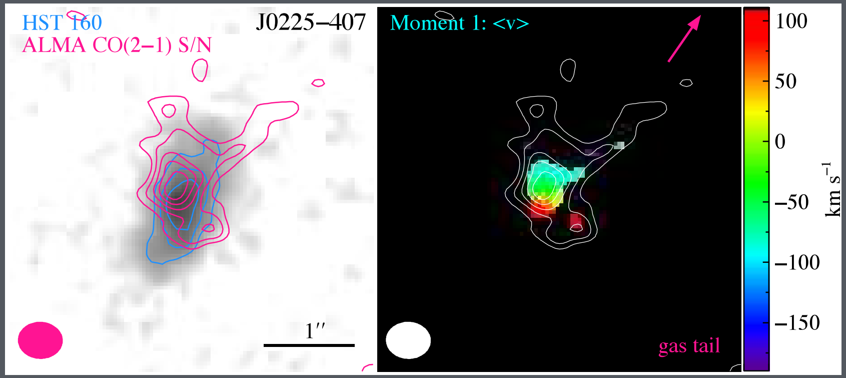
Similarities to field galaxies

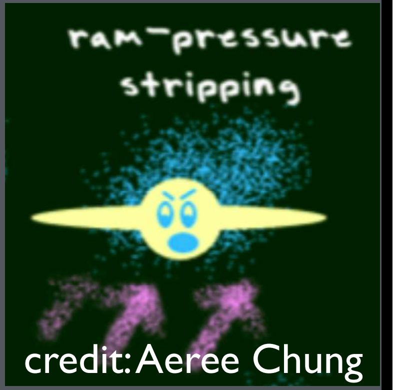
rotating gas disks



main-sequence SFRs

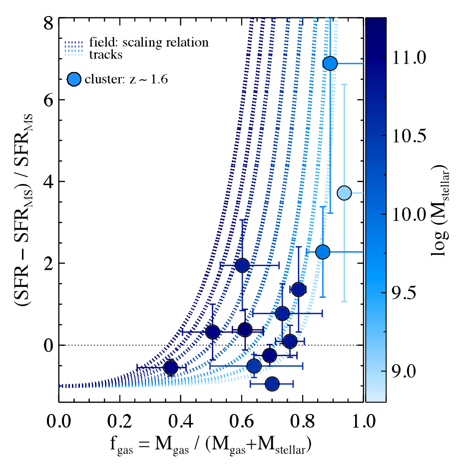
Differences from field galaxies





credit: Aeree Chung

gas tails, gas & stellar centroid offsets

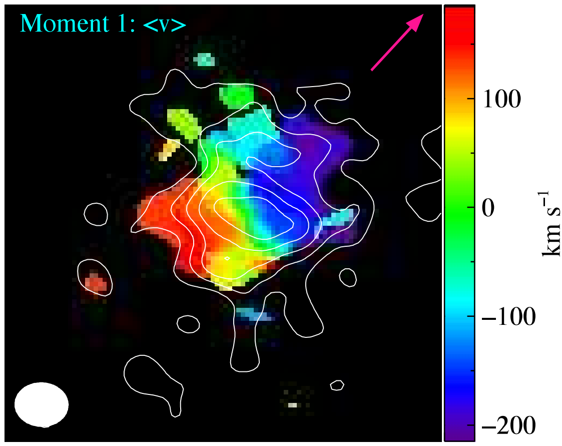


higher gas fractions

Evidence for Molecular Gas Stripping at z~1.6?

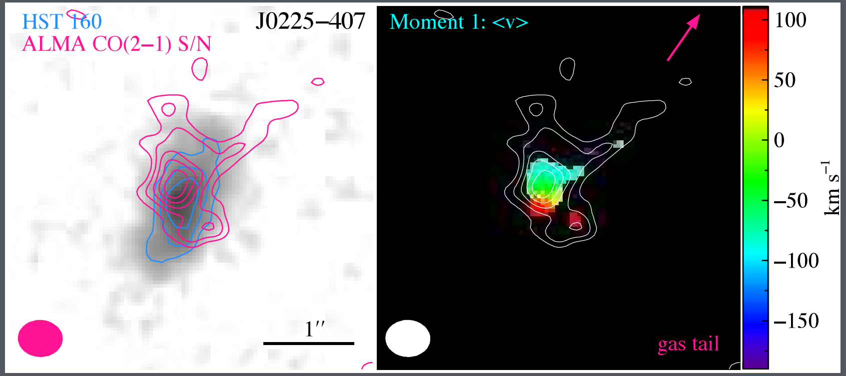
Similarities to field galaxies

rotating gas disks



main-sequence SFRs

Differences from field galaxies



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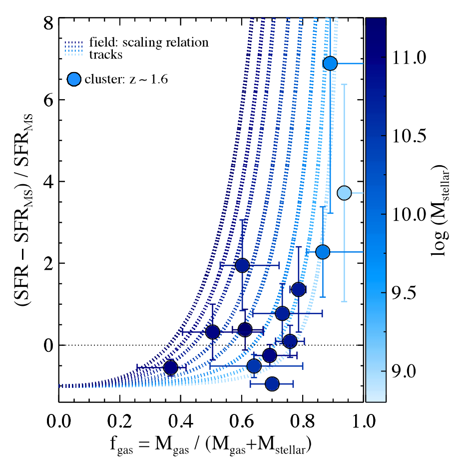


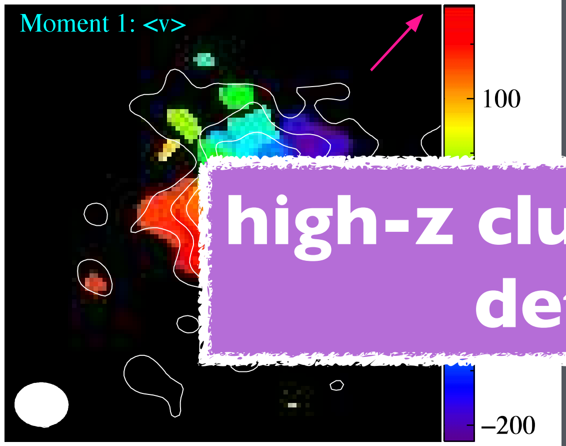
require lower α_{CO} in cluster galaxies due to ram-pressure stripping?

higher gas fractions

Evidence for Molecular Gas Stripping at z~1.6?

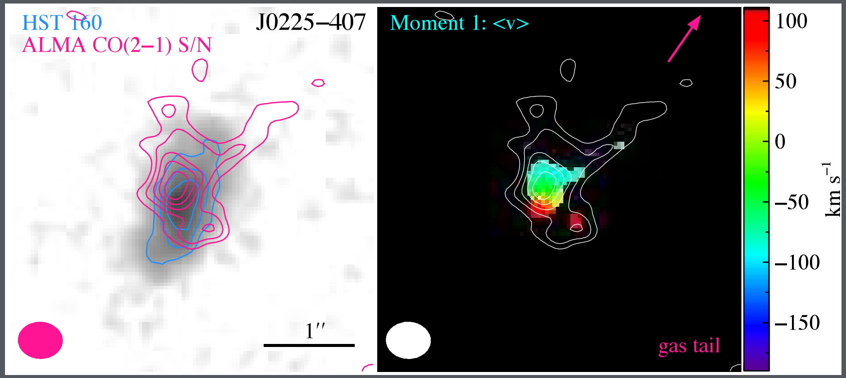
Similarities to field galaxies

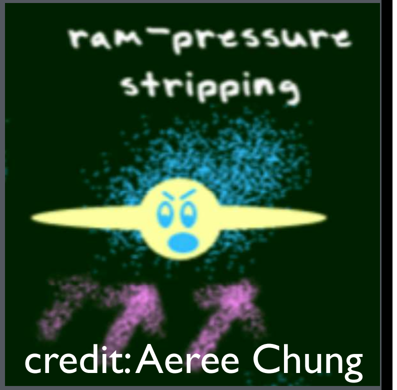
rotating gas disks



main-sequence SFRs

Differences from field galaxies

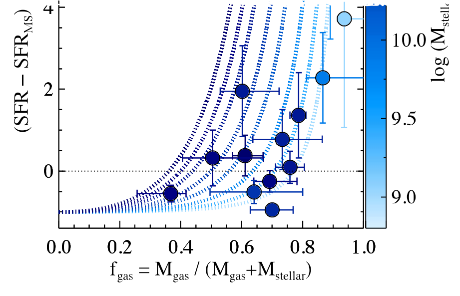




credit: Aeree Chung

gas tails, gas & stellar centroid offsets

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



ver α_{CO} 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

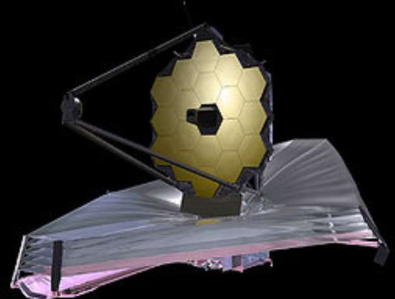
Spatially-resolved Kennicutt-Schmidt

- 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


ALMA


HST


VLT

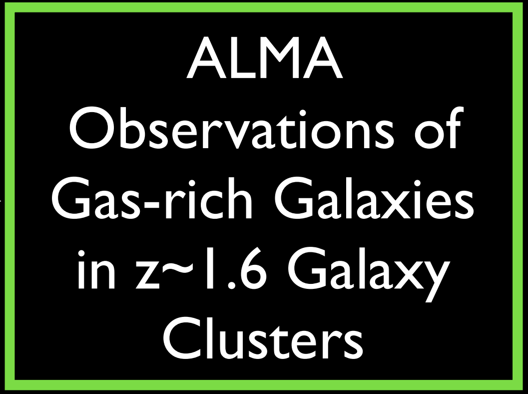

JWST

Outline

Part 1

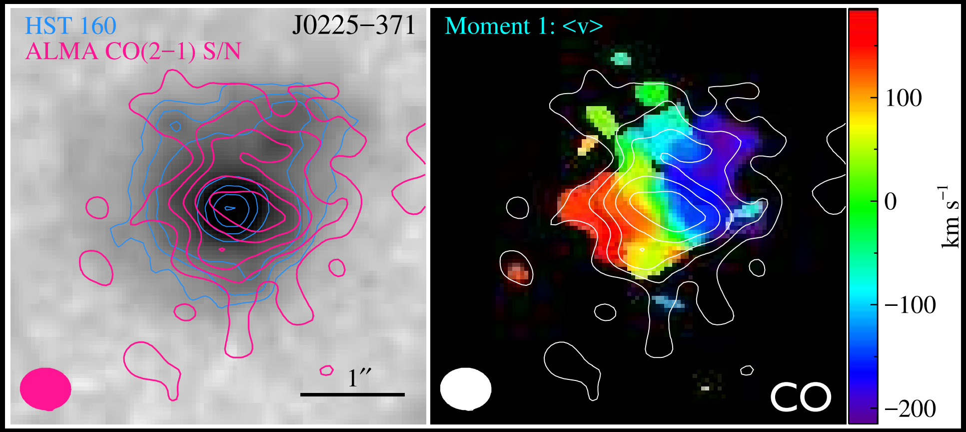
Part 2

Environment →



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

molecular gas and
star formation



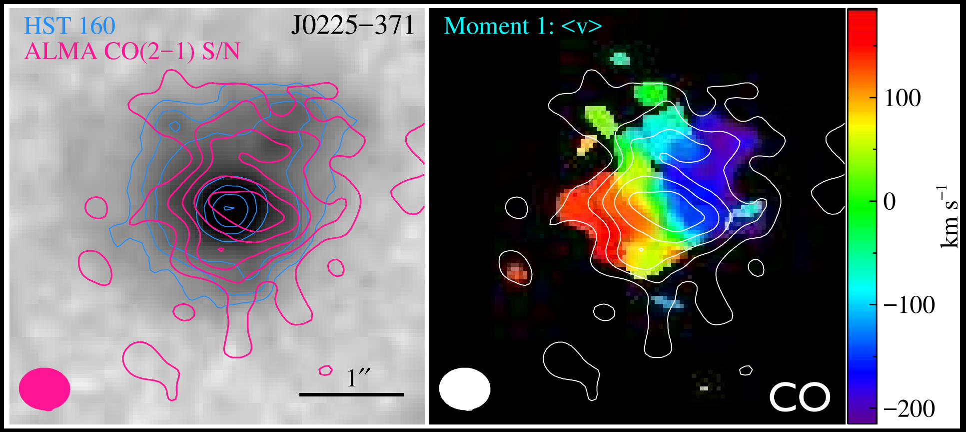
Outline

Part 1

Environment →

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

molecular gas and star formation



Part 2

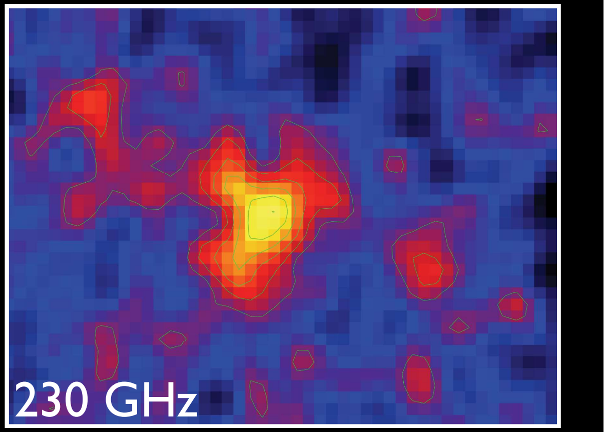
Mass →

Env →

Time →

Brightest Cluster Galaxies over Cosmic Time (with ALMA)

dust continuum and molecular gas



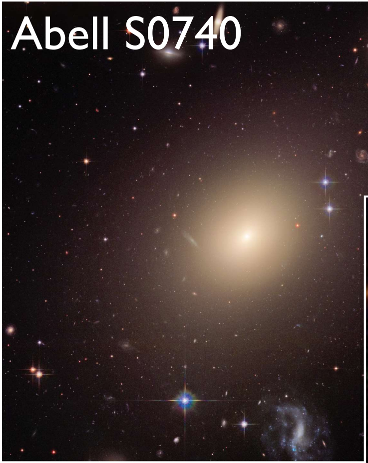
Brightest Cluster Galaxies (BCGs)

Mass growth linked to:

- gas cooling
- star formation
- energy feedback
- galaxy accretion

A Diversity of BCGs over Cosmic Time

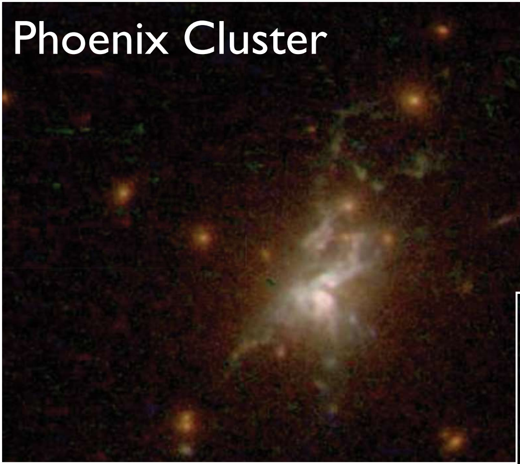
z = 0.03



Abell S0740

Credit: J. Blakeslee

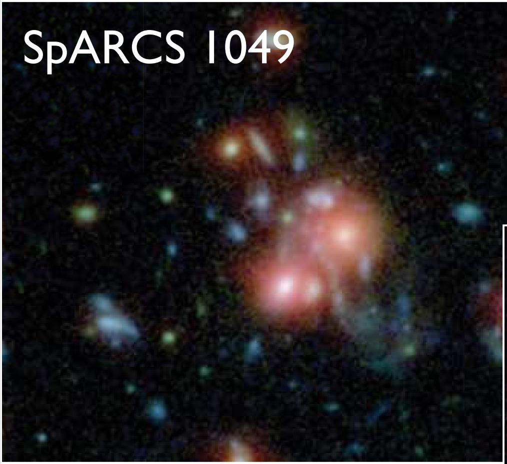
z = 0.60



Phoenix Cluster

McDonald et al. 2013

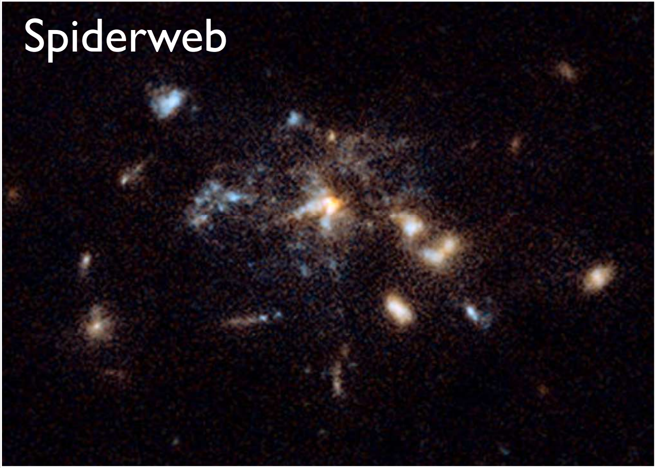
z = 1.70



SpARCS 1049

Webb, Noble et al. 2015a

z = 2.16



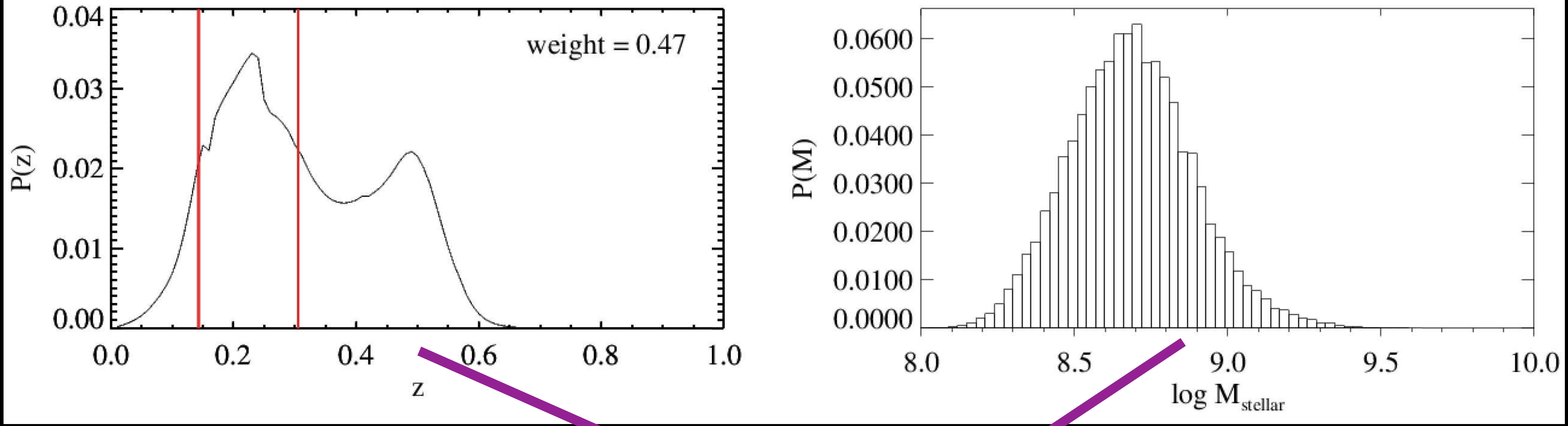
Spiderweb

Miley et al. 2006

time

When does the BCG become the dominant galaxy?

A probabilistic approach to identifying the BCG

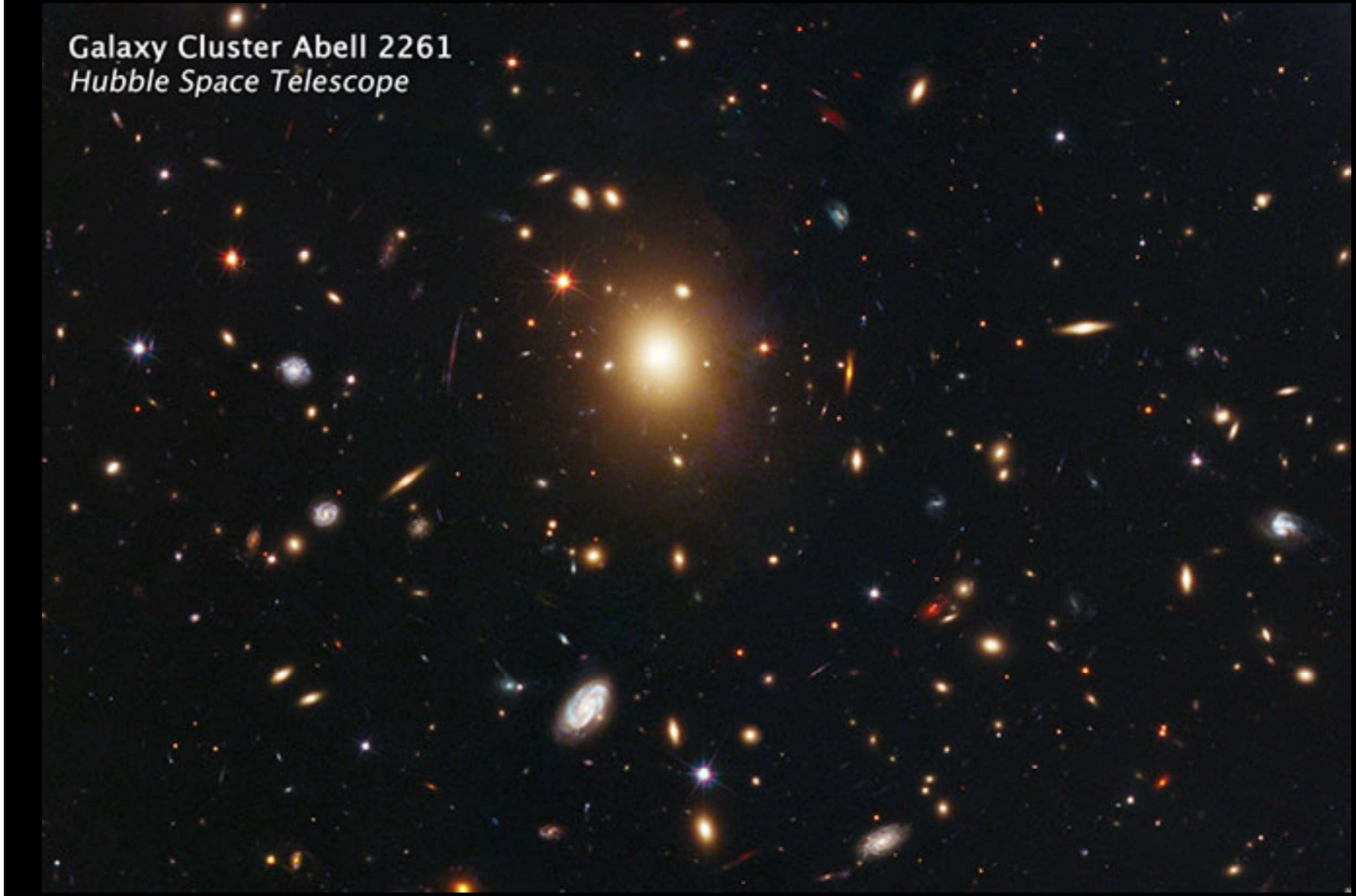


P(z) P(M)

monte carlo and find most massive cluster member in each iteration

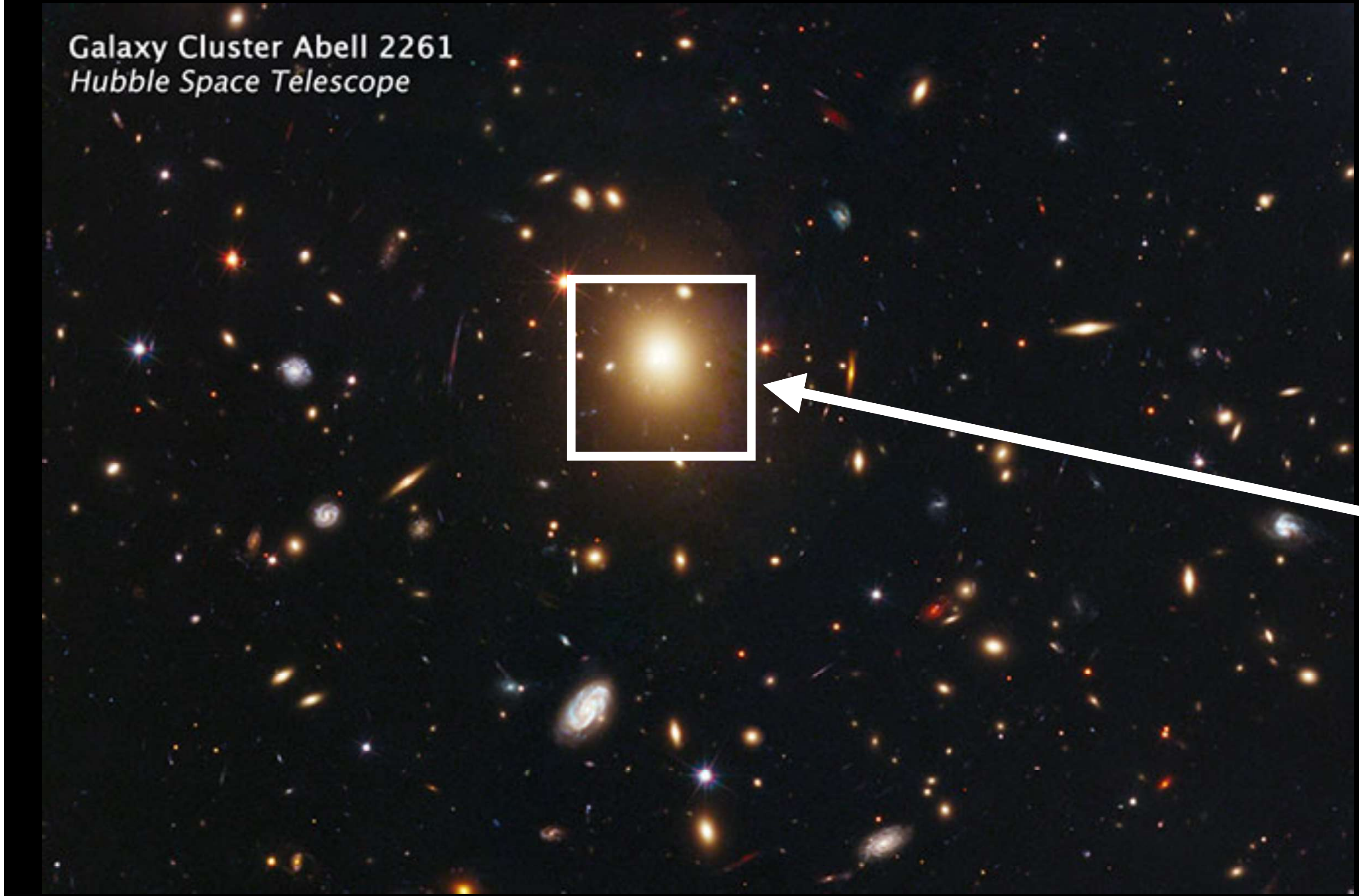
build up a BCG likelihood for each galaxy

A Bayesian Probabilistic Approach to Identifying the BCG



Abell 2261
z = 0.22

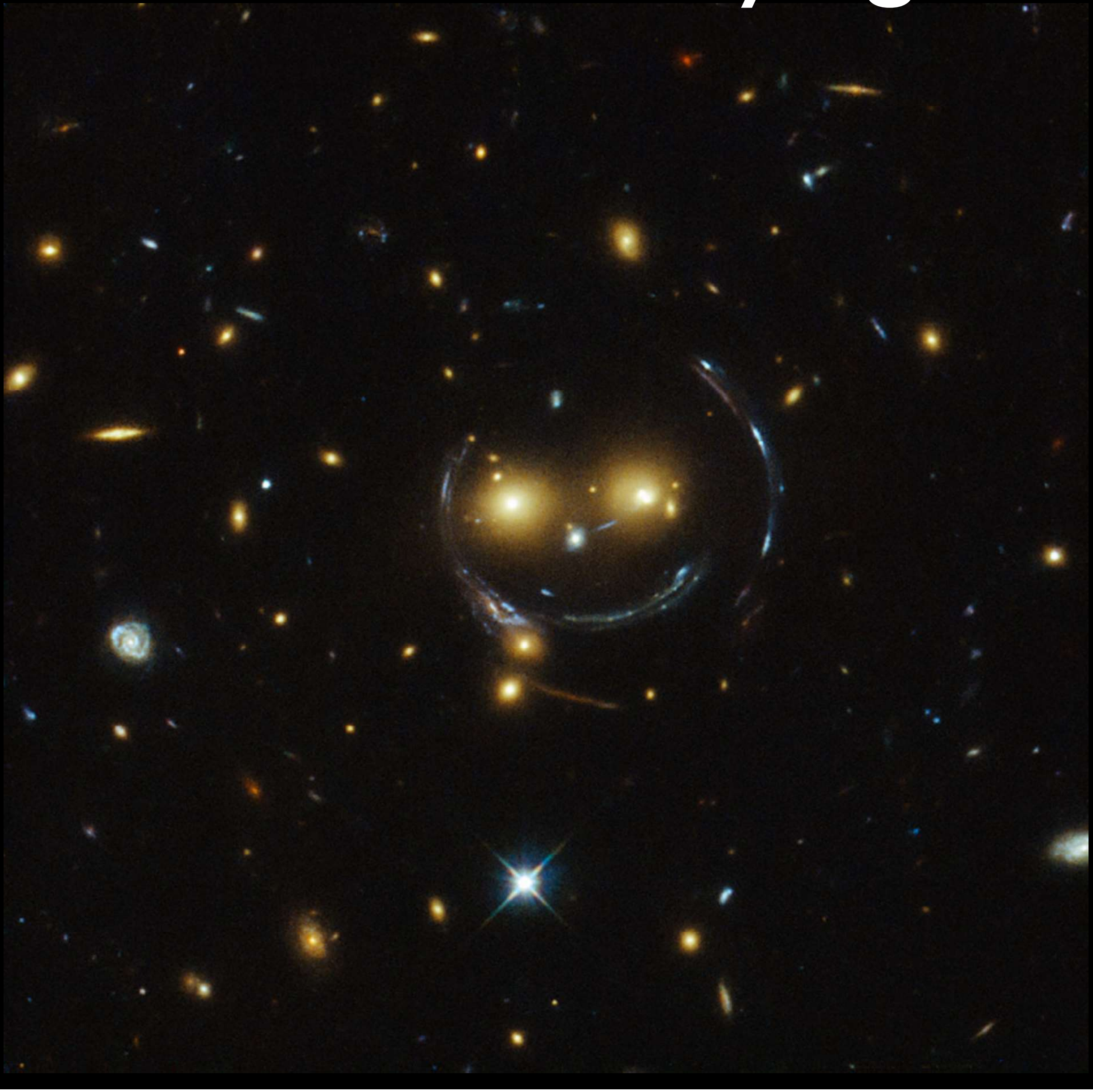
A Bayesian Probabilistic Approach to Identifying the BCG



Abell 2261
z = 0.22

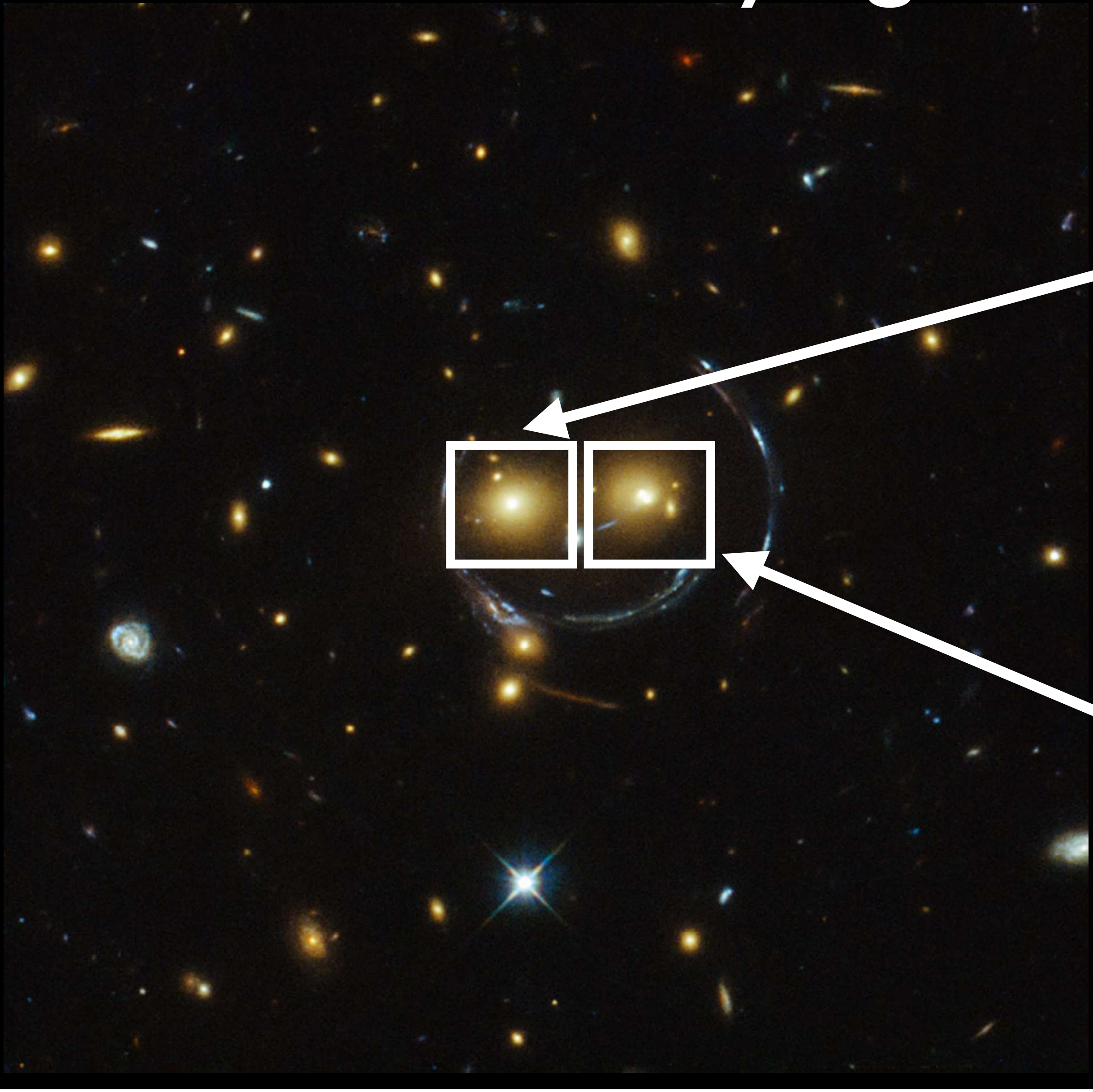
99.99% probability of being the BCG

A Bayesian Probabilistic Approach to Identifying the BCG



SDSS 1038
z = 0.43

A Bayesian Probabilistic Approach to Identifying the BCG



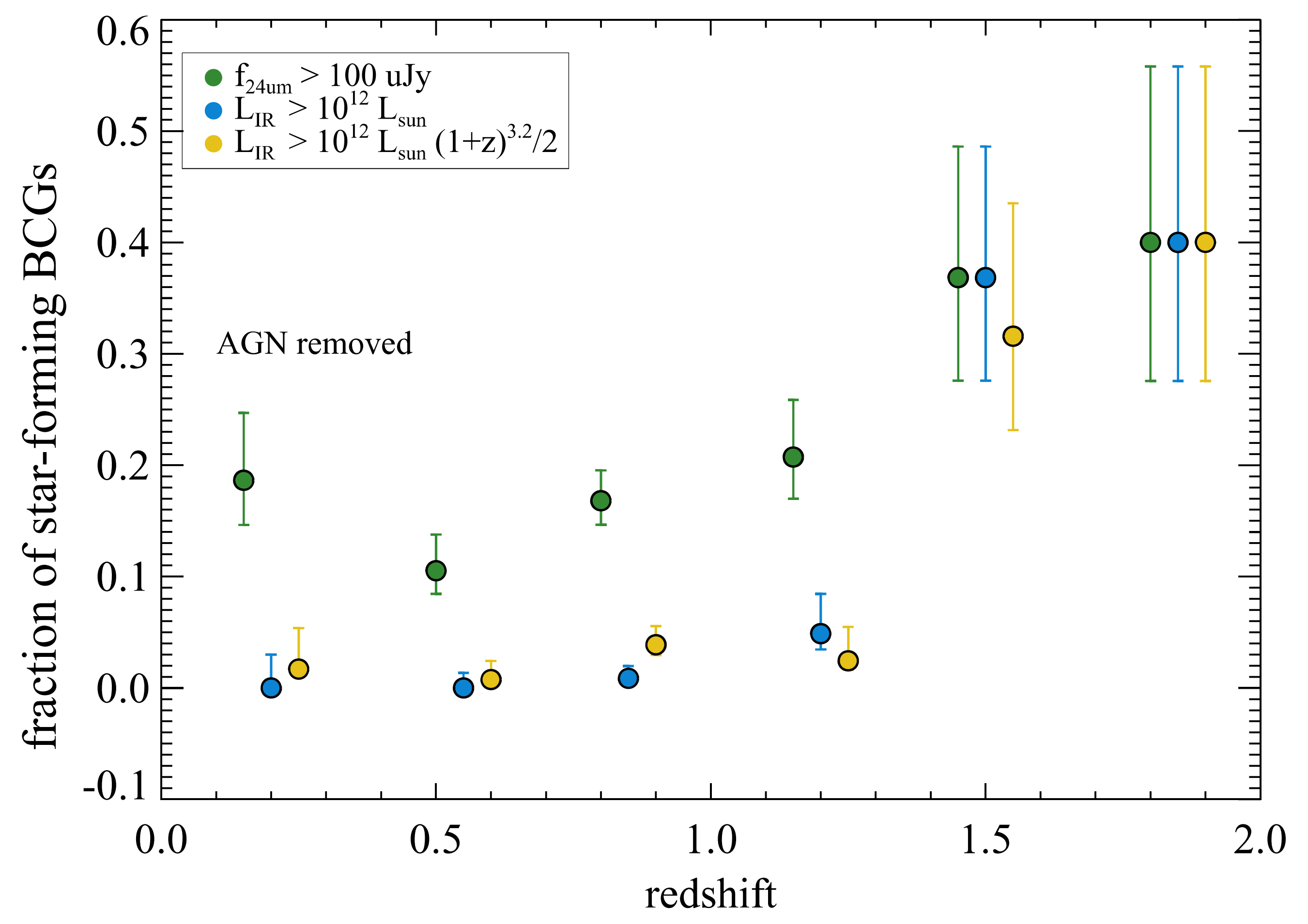
SDSS 1038
z = 0.43

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?

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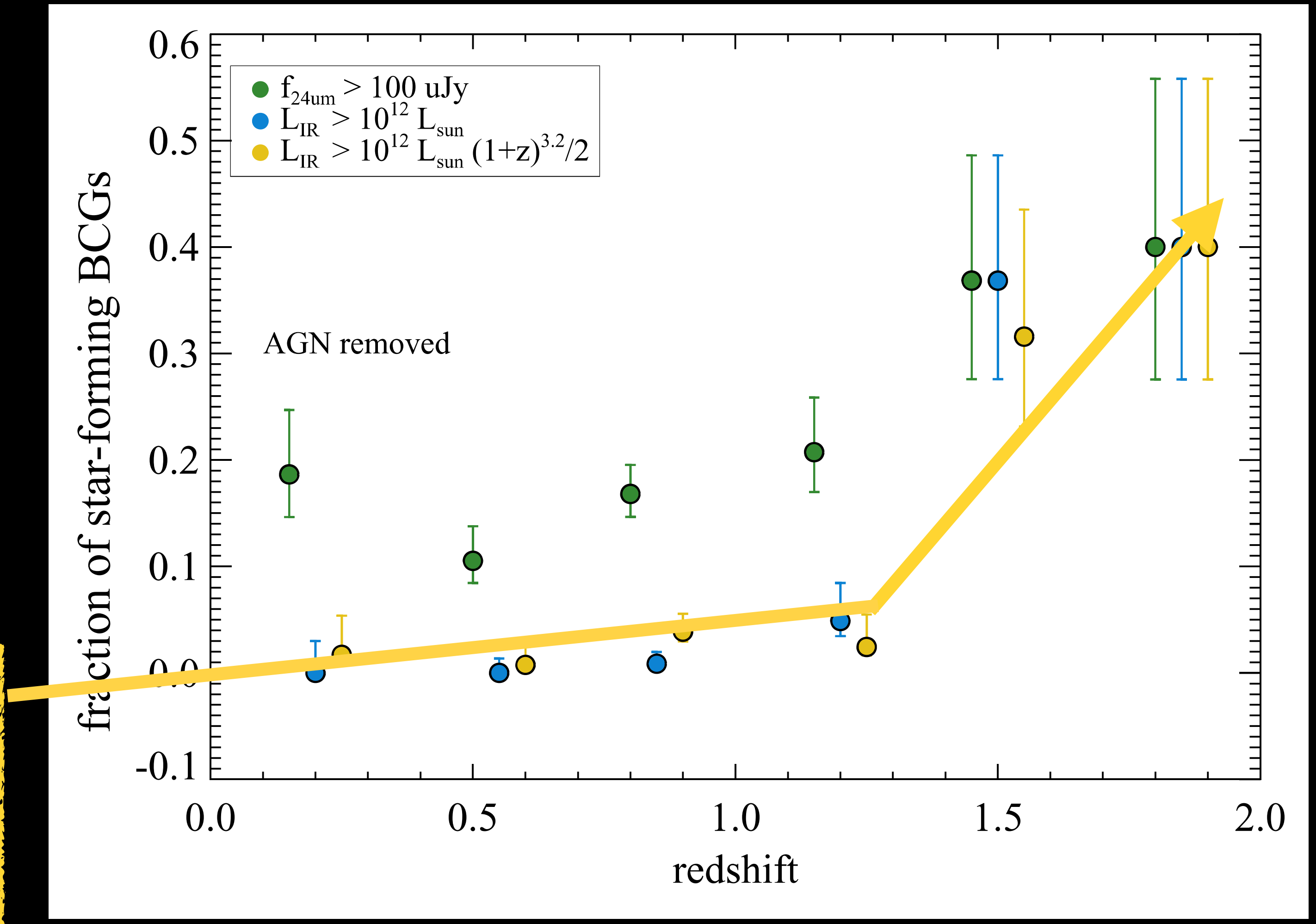


fraction of star-forming BCGs increases beyond z~1

Webb+Noble et al. 2015b

see also:

Lidman+Noble et al. 2012

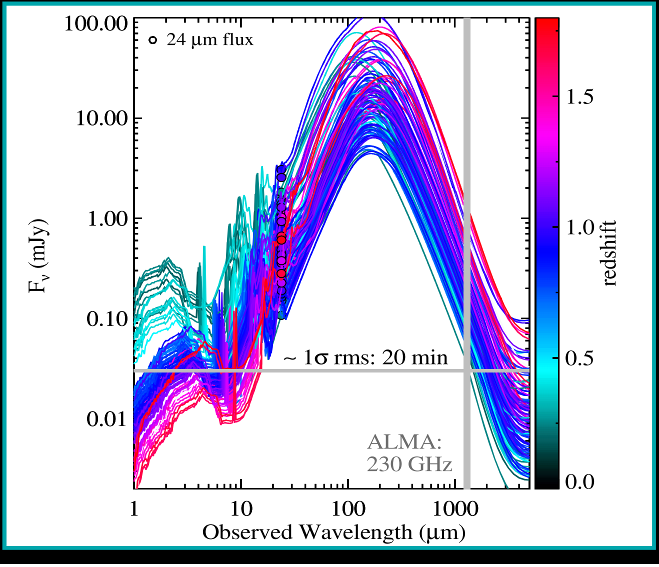
Lidman+Noble et al. 2013

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?

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

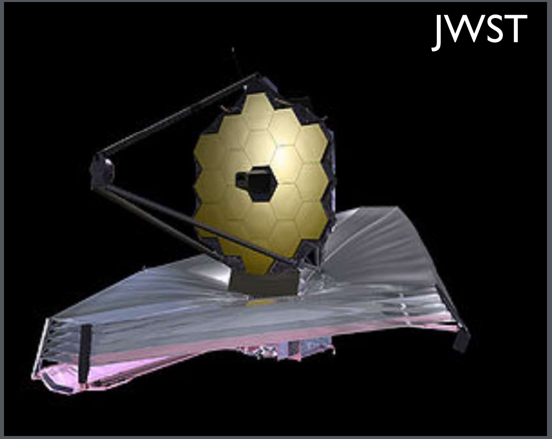

ALMA


SKA


ngVLA

+

Space-based Sensitivity


JWST

+

30-meter Telescopes


Giant Magellan Telescope


Thirty Meter Telescope

The Future of Galaxy Evolution

Interferometry

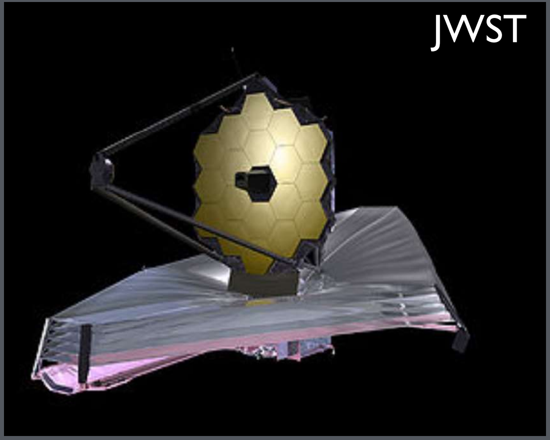

ALMA


SKA

ngVLA

+

Space-based Sensitivity


JWST

+

30-meter Telescopes


Giant Magellan Telescope

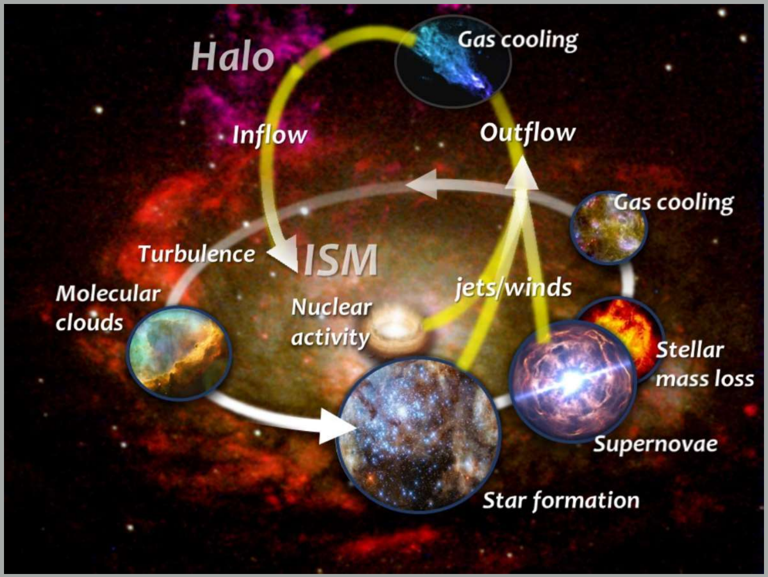

Thirty Meter Telescope

=

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

The Future of Galaxy Evolution

Interferometry

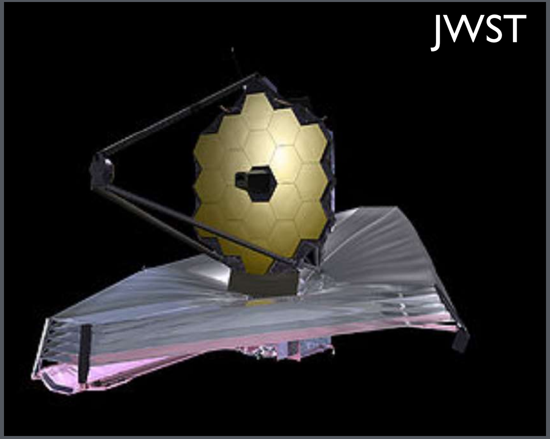
Gas Accretion/Mode of Star Formation

Efficiency of Star Formation

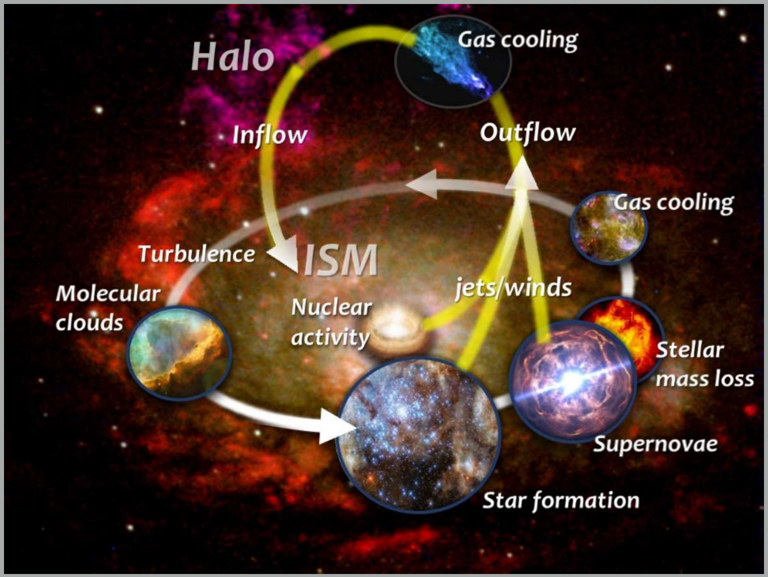
Quenching of Star Formation

+

Space-based Sensitivity



Thank you!



+

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