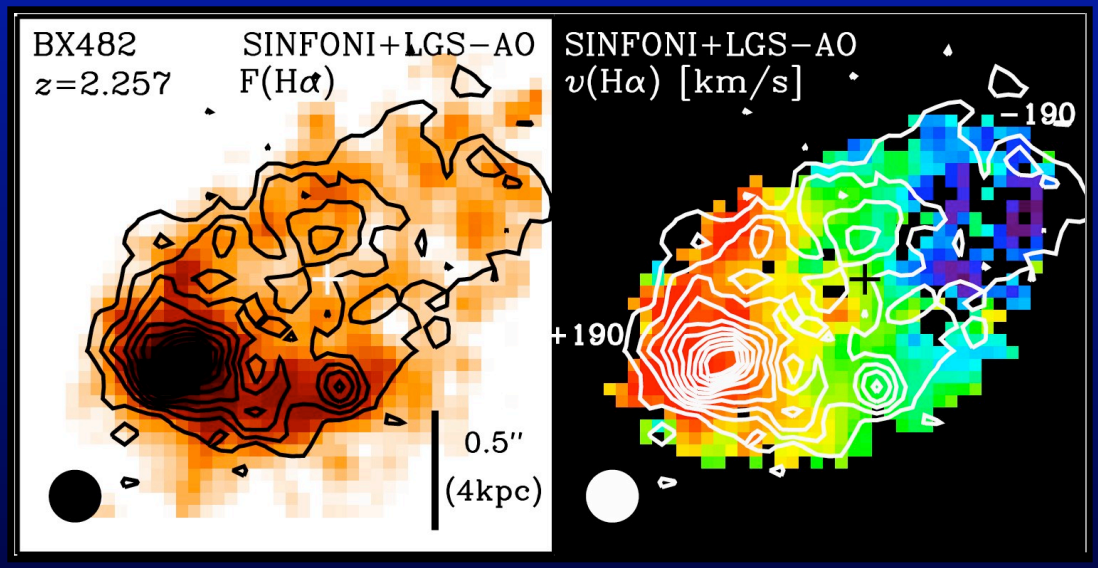
Galaxy Assembly at z~2: Recent Progress and Remaining Questions



Kristen Shapiro

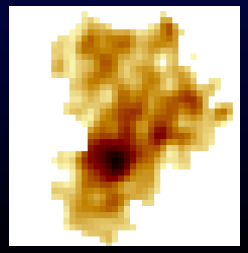
Some Important Questions for Galaxy Evolution

- *What is the role of major mergers / minor mergers / steady accretion in driving the bulk of star formation in galaxies?*

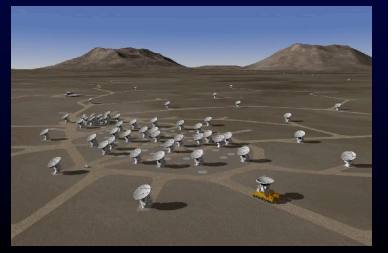
- *What are gas fractions in galaxies as a function of mass, redshift, environment, … ? What is the effect on star formation efficiency?*

- *What drives the evolution of high-z star-forming galaxies? What is the structure of the ISM and how does it affect this evolution?*

- *How is the evolution of black holes connected to that of their host galaxy? Is this process a function of redshift?*



Recent Results and
Opportunities with Upcoming Facilities



SINS Survey

Hα IFU observations of >80 z~2 star-forming galaxies

Spatially-resolved dynamics and star-forming properties

SINS/zCOSMOS Large Program

Very deep Hα IFU observations on several sources

Map at kpc scale, isolating individual star-forming regions

PIs: Genzel, Förster Schreiber, Renzini

SMG Survey

CO observations of ~10 z~1-3.5 sub-millimeter galaxies

Spatially-resolved dynamics and molecular gas properties

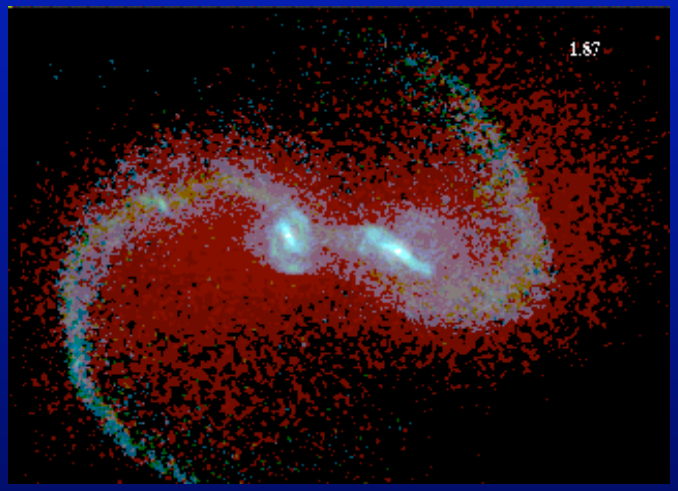
IRAM Large Program

CO 3-2 mapping of z~1 and z~2 normal galaxies

Synergies with ionized gas and stellar data: f_{gas} , SF, dynamics

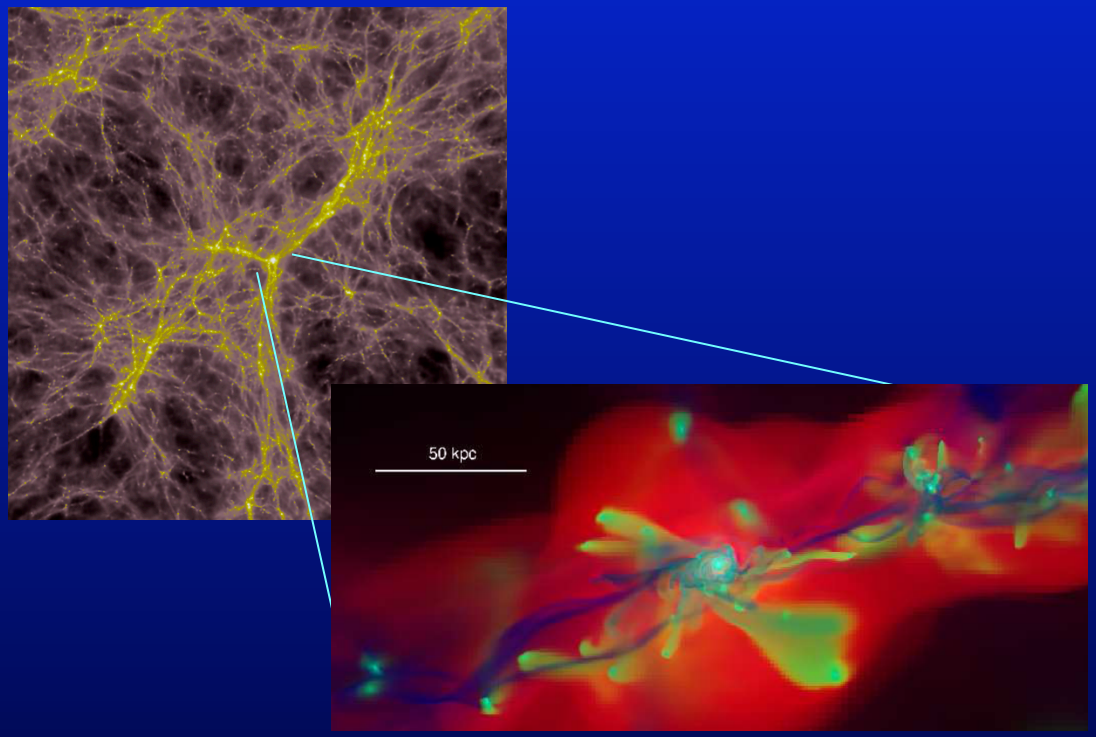
PIs: Genzel, Ivison, Tacconi

What drives galaxy and star formation at high-z?



Major mergers

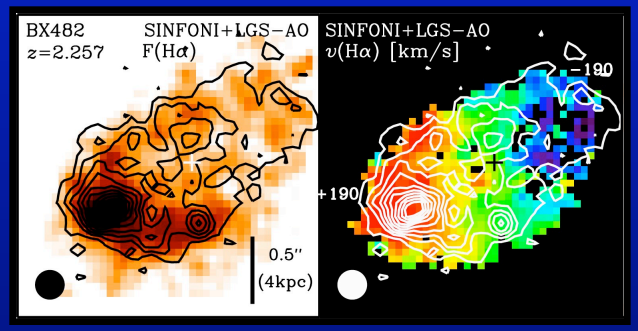
Kauffmann et al. 1993,
Steinmetz & Navarro 2003,
Hernquist, Springel,
di Matteo, Hopkins et al. 2003-2006,
Robertson & Bullock 2008

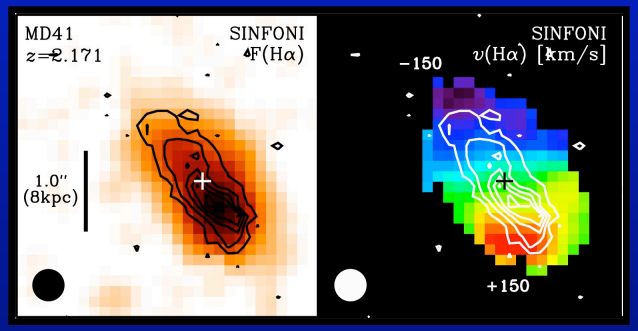


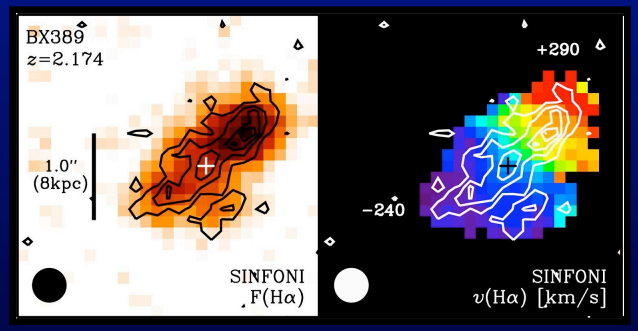
Minor mergers and steady accretion

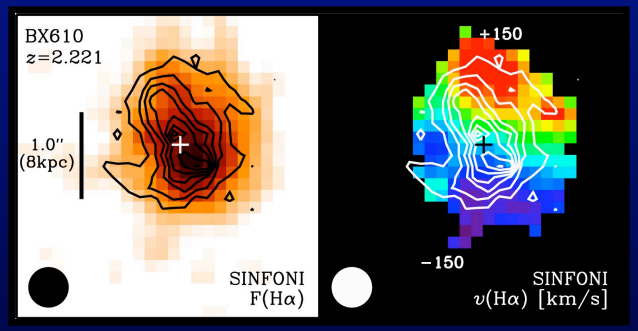
Dekel & Birnboim 2003,2006, Keres et al. 2005,
Nagamine et al. 2005, Davé 2007,
Kitzbichler & White 2007, Naab et al. 2007,
Governato et al. 2008, Ocvirk et al. 2008,
Dekel et al. 2009, Agertz et al. 2009

Star-Forming Galaxies in a Clumpy, Thick Disk Phase









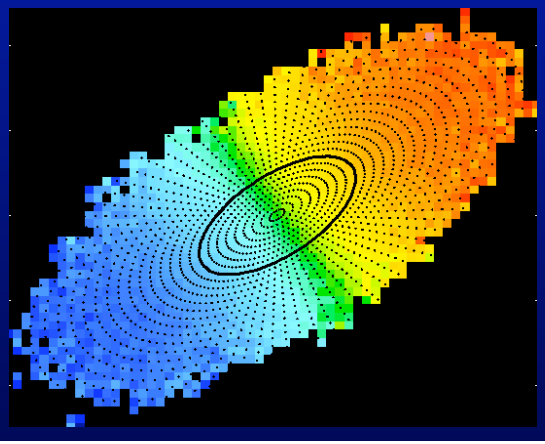
V ~ 200 km/s
R ~ 10 kpc

5-10 clumps / gal
M_{clump} ~ 10^8-10^9 $M_\odot$

Förster Schreiber 2006, 2009b, Genzel et al. 2008, Cresci et al. 2009, see also Elmegreen & Elmegreen 2007

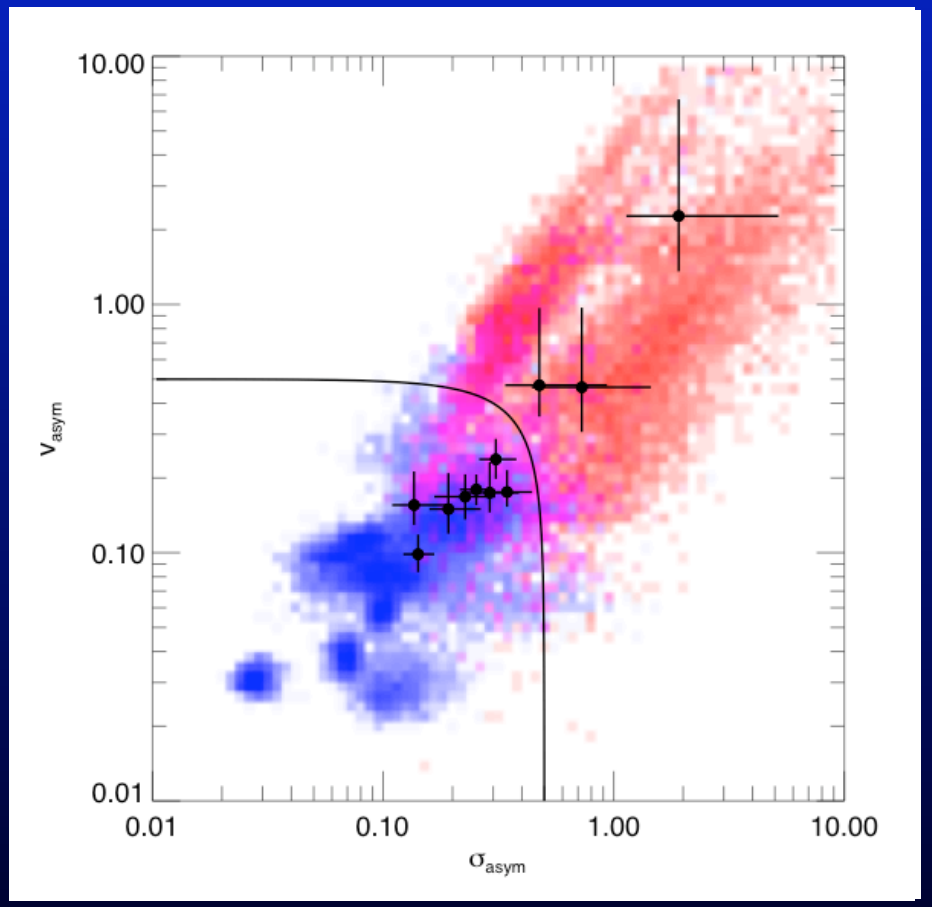
Regular Rotation in Massive High-z Galaxies

Fourier analysis of first and second velocity moment for highest quality SINS data



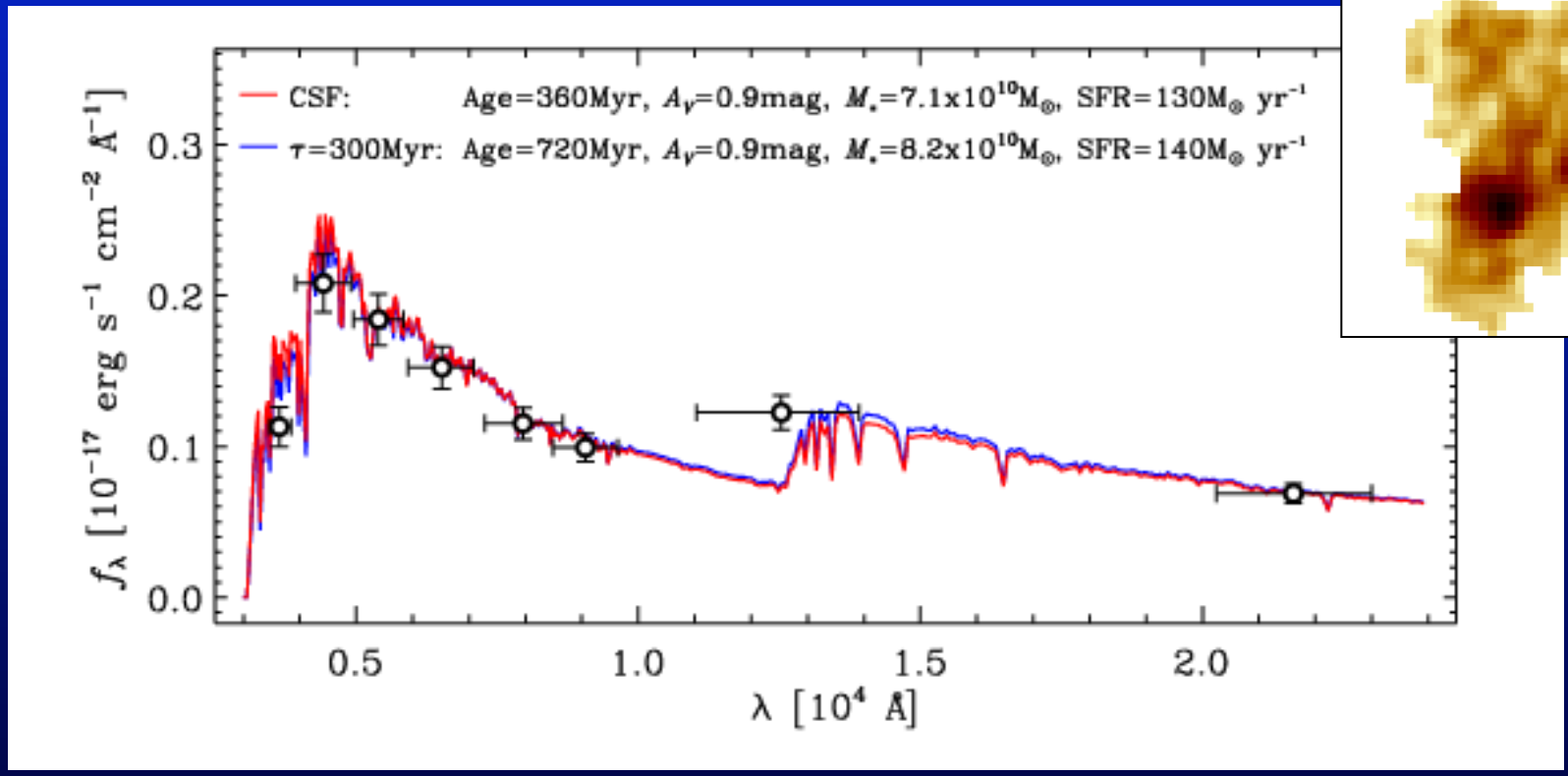
$$K(\psi) = A_0 + A_1 \sin(\psi) + B_1 \cos(\psi) + A_2 \sin(2\psi) + B_2 \cos(2\psi) + A_3 \sin(3\psi) + B_3 \cos(3\psi) \ldots$$

Krajnović et al. 2006



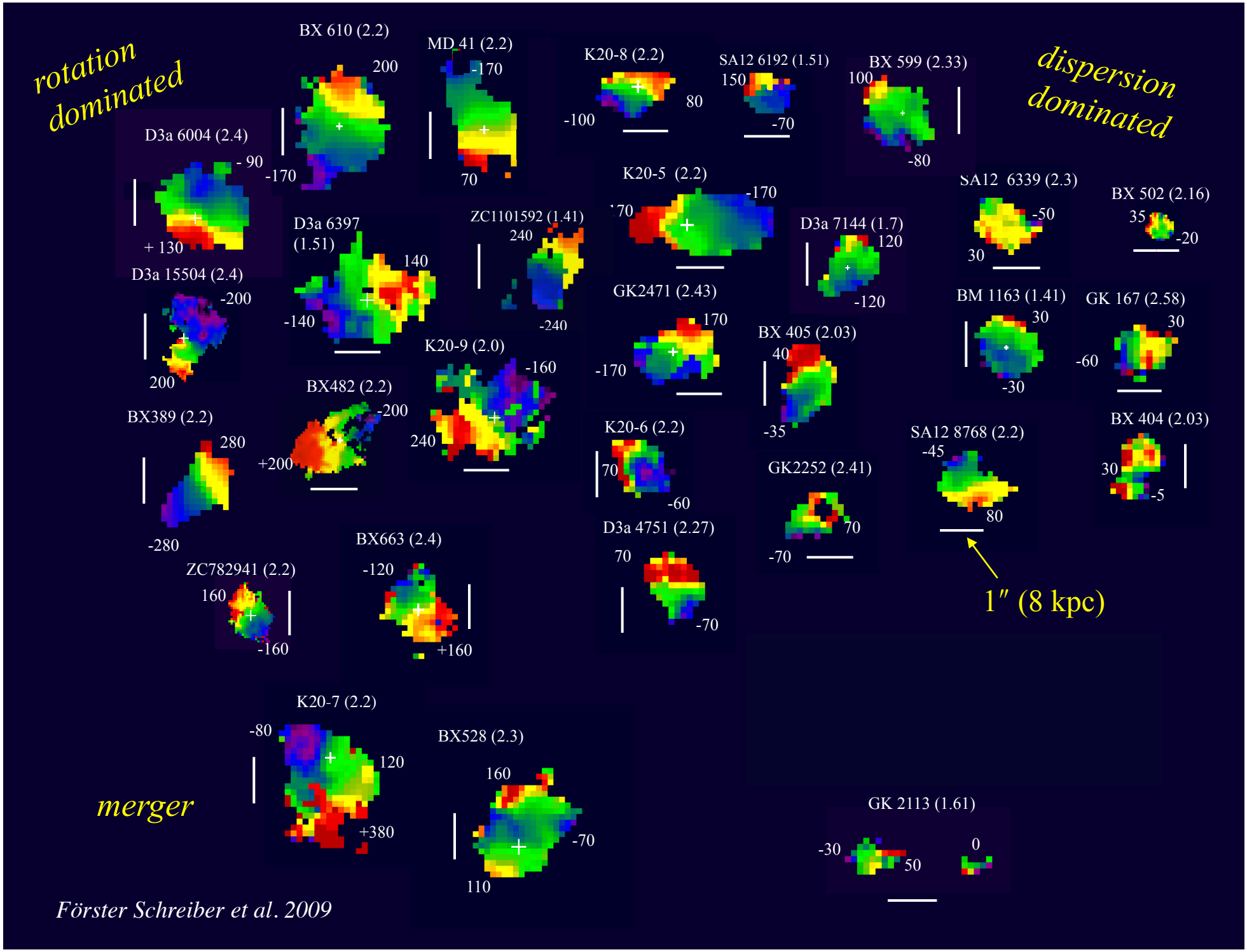
Shapiro et al. 2008

Star Formation Rate is High and Constant



$M_* \sim 8 \times 10^{10}\ M_\odot$
$SFR \sim 100\text{-}200\ M_\odot/yr$ → Age ~ 500 Myr

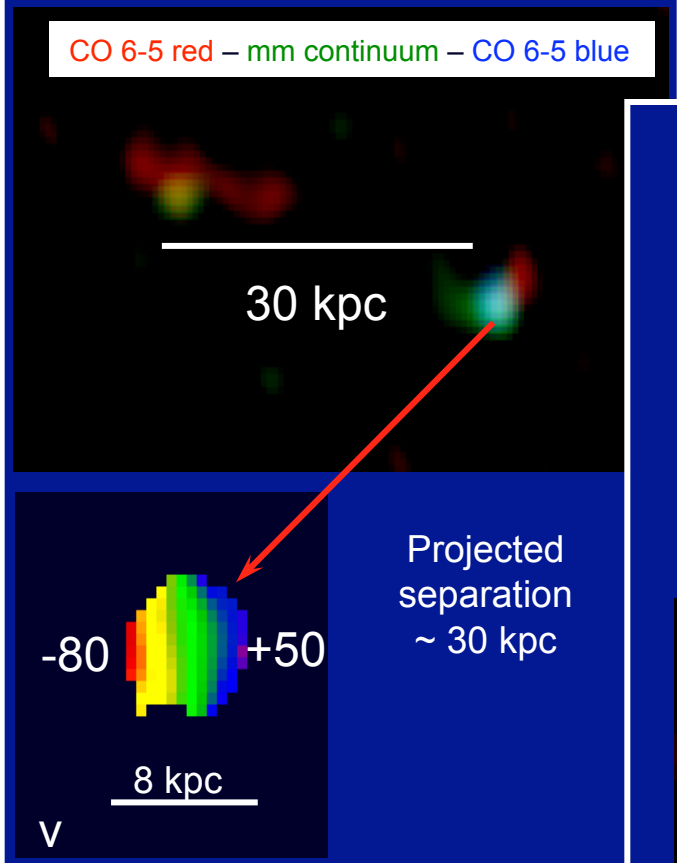
Förster Schreiber et al. 2006, 2009, Genzel et al. 2006,2008, Shapiro et al. 2008, see also Daddi et al. 2007


rotation dominated
dispersion dominated
merger
BX 610 (2.2)
200
-170
MD 41 (2.2)
-170
70
K20-8 (2.2)
-100
80
SA12 6192 (1.51)
150
-70
BX 599 (2.33)
100
-80
D3a 6004 (2.4)
- 90
+ 130
K20-5 (2.2)
-170
170
SA12 6339 (2.3)
-50
30
BX 502 (2.16)
35
-20
D3a 6397 (1.51)
140
-140
ZC1101592 (1.41)
240
-240
D3a 7144 (1.7)
120
-120
D3a 15504 (2.4)
-200
200
GK2471 (2.43)
170
-170
BM 1163 (1.41)
30
-30
GK 167 (2.58)
30
-60
BX482 (2.2)
-200
+200
K20-9 (2.0)
-160
240
BX 405 (2.03)
40
-35
BX389 (2.2)
280
-280
K20-6 (2.2)
70
-60
SA12 8768 (2.2)
-45
80
BX 404 (2.03)
30
-5
GK2252 (2.41)
70
-70
D3a 4751 (2.27)
70
-70
ZC782941 (2.2)
160
-160
BX663 (2.4)
-120
+160
1″ (8 kpc)
K20-7 (2.2)
-80
120
+380
BX528 (2.3)
160
-70
110
GK 2113 (1.61)
-30
50
0
Förster Schreiber et al. 2009

Sub-Millimeter Galaxies are Gas-Rich Major Mergers

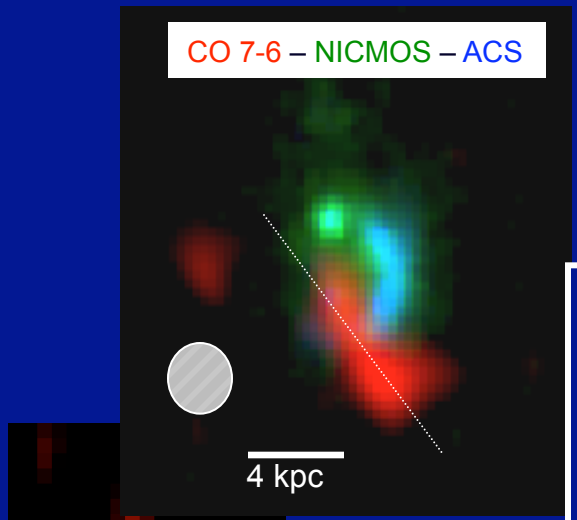
SFR ~ 1000 $M_\odot$ / yr = 10 x SFR_{SINS}
M ~ M_{SINS}
R ~ 0.25 R_{SINS}

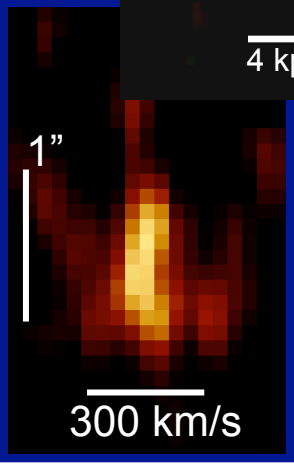
SMMJ09431+4700 z=3.35



Projected separation ~ 30 kpc

SMMJ163650+4057 z=2.39

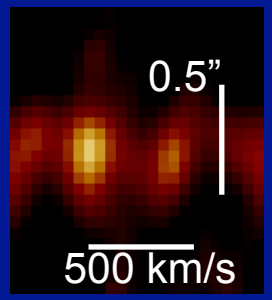


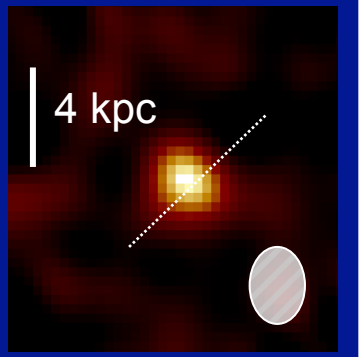


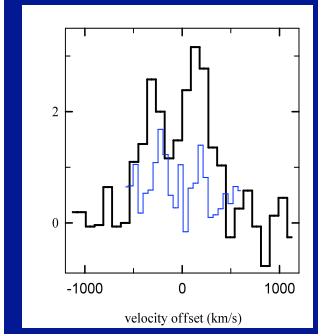
Projected separation ~4 kpc

Velocity difference 200 km/s

SMMJ16358+4105 z=2.45



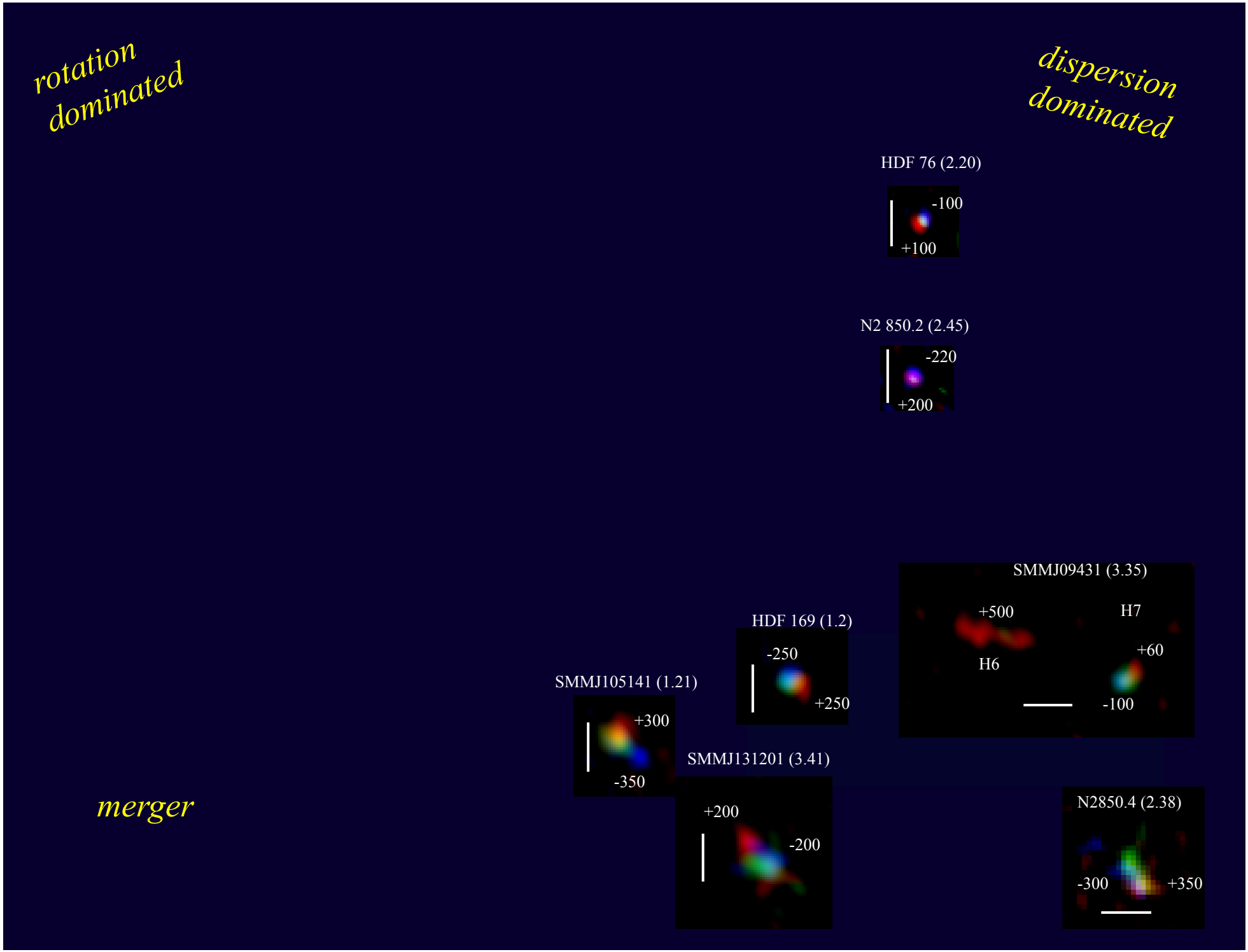


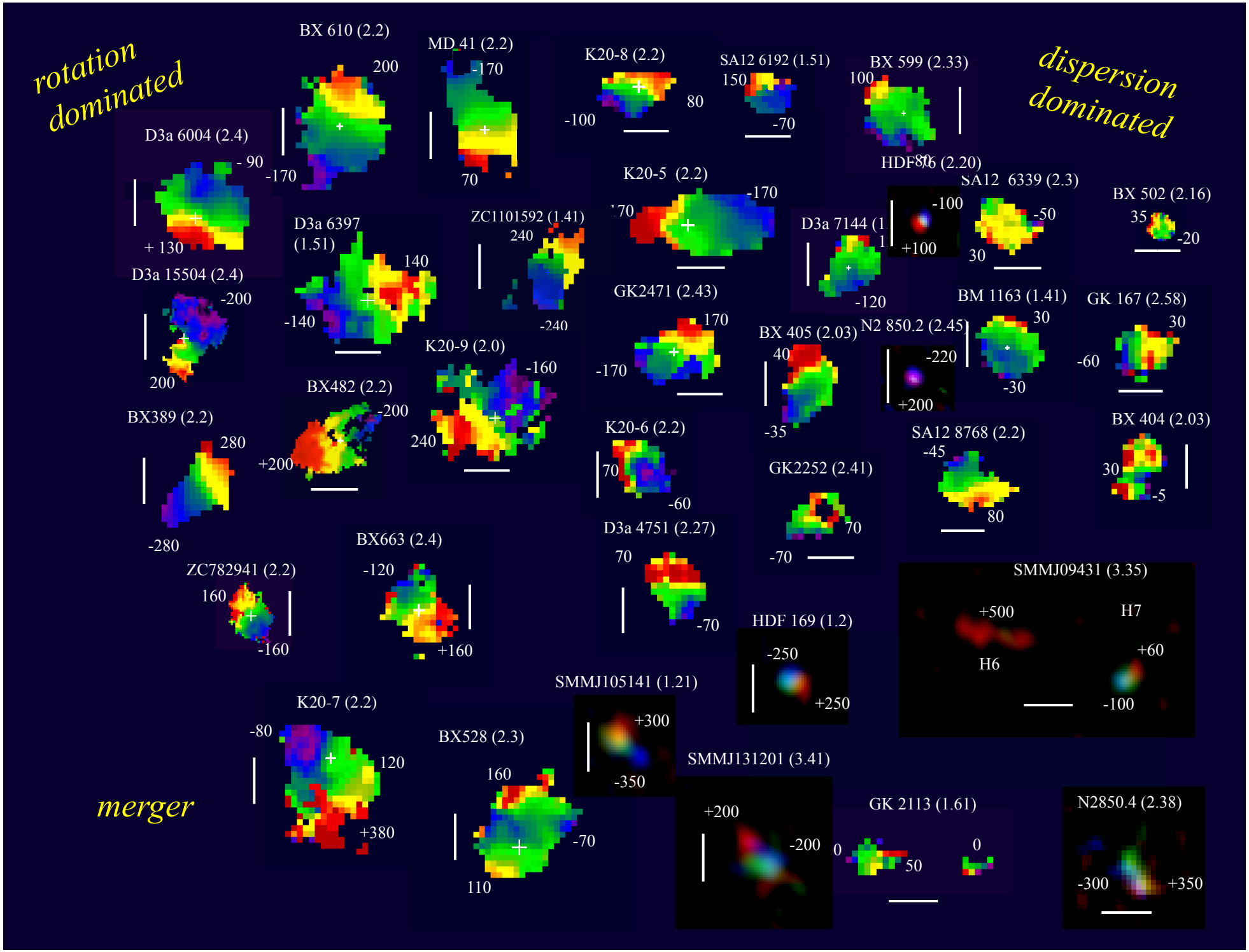


Unresolved to 1.6 kpc

Velocity FWHM ~500 km/s

Neri et al. 2003, Greve et al. 2005,
Tacconi et al. 2006, 2008,
Engel et al. 2010, Smail et al. 2010


rotation dominated
dispersion dominated
HDF 76 (2.20)
-100
+100
N2 850.2 (2.45)
-220
+200
SMMJ09431 (3.35)
+500
H7
+60
H6
-100
HDF 169 (1.2)
-250
+250
SMMJ105141 (1.21)
+300
-350
SMMJ131201 (3.41)
+200
-200
N2850.4 (2.38)
-300
+350
merger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-240
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-120
D3a 15504 (2.4)
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-70
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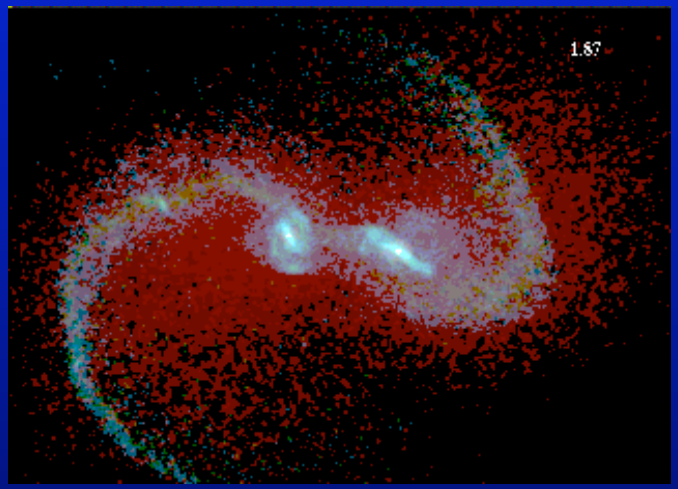
SMMJ131201 (3.41)
+200
-200
GK 2113 (1.61)
0
50
0
N2850.4 (2.38)
-300
+350

What drives galaxy and star formation at high-z?



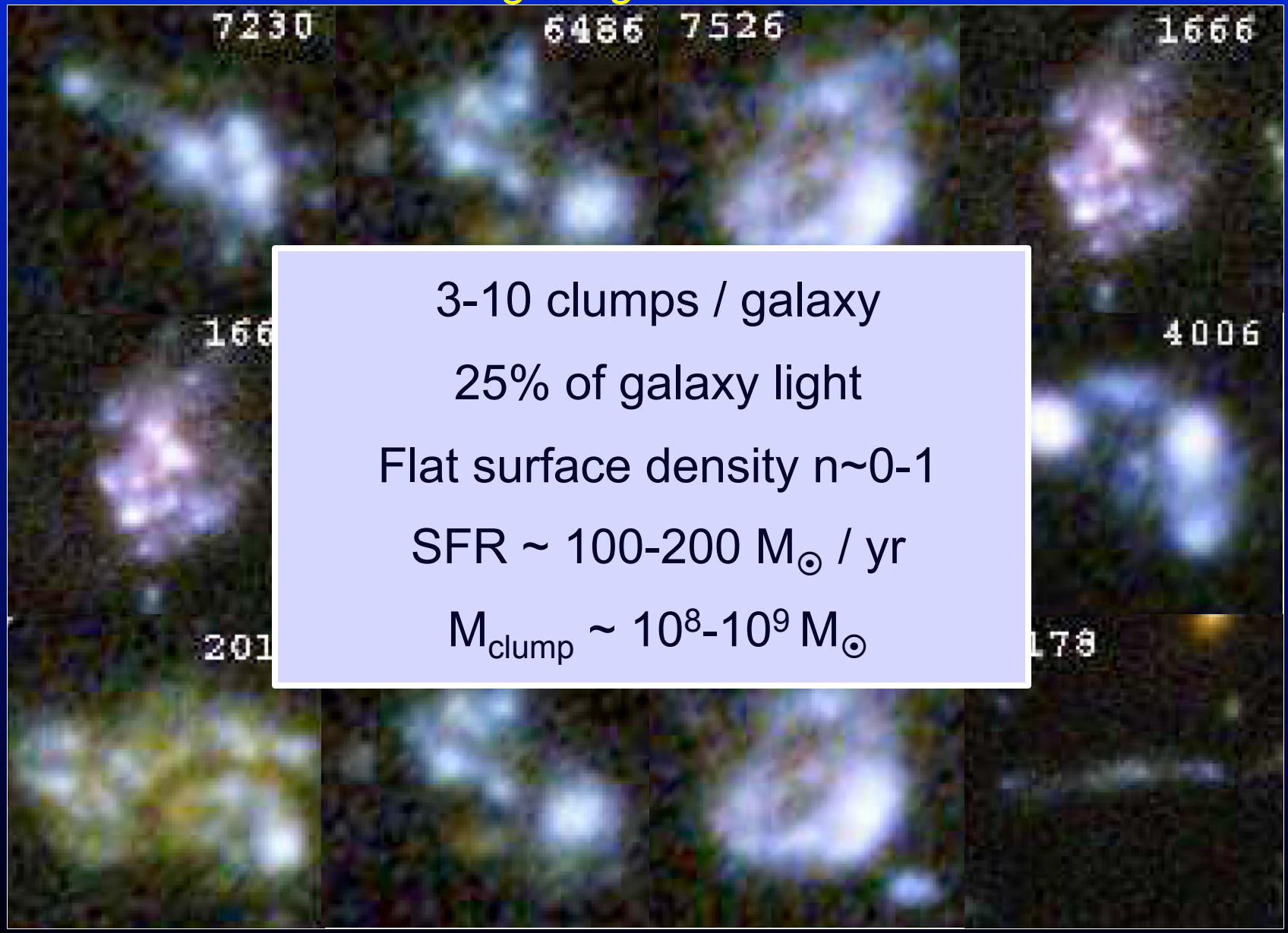
SMGs

Normal Star-Forming Galaxies

ALMA and EVLA will trace the dynamics of the cold gas reservoirs of normal, star-forming galaxies as a function of mass and redshift

- Clean dynamical estimate of galaxy merger fraction as f(mass, z)
- Link gas to star formation via synergies with Opt/IR facilities

How do high-z galaxies evolve?



3-10 clumps / galaxy

25% of galaxy light

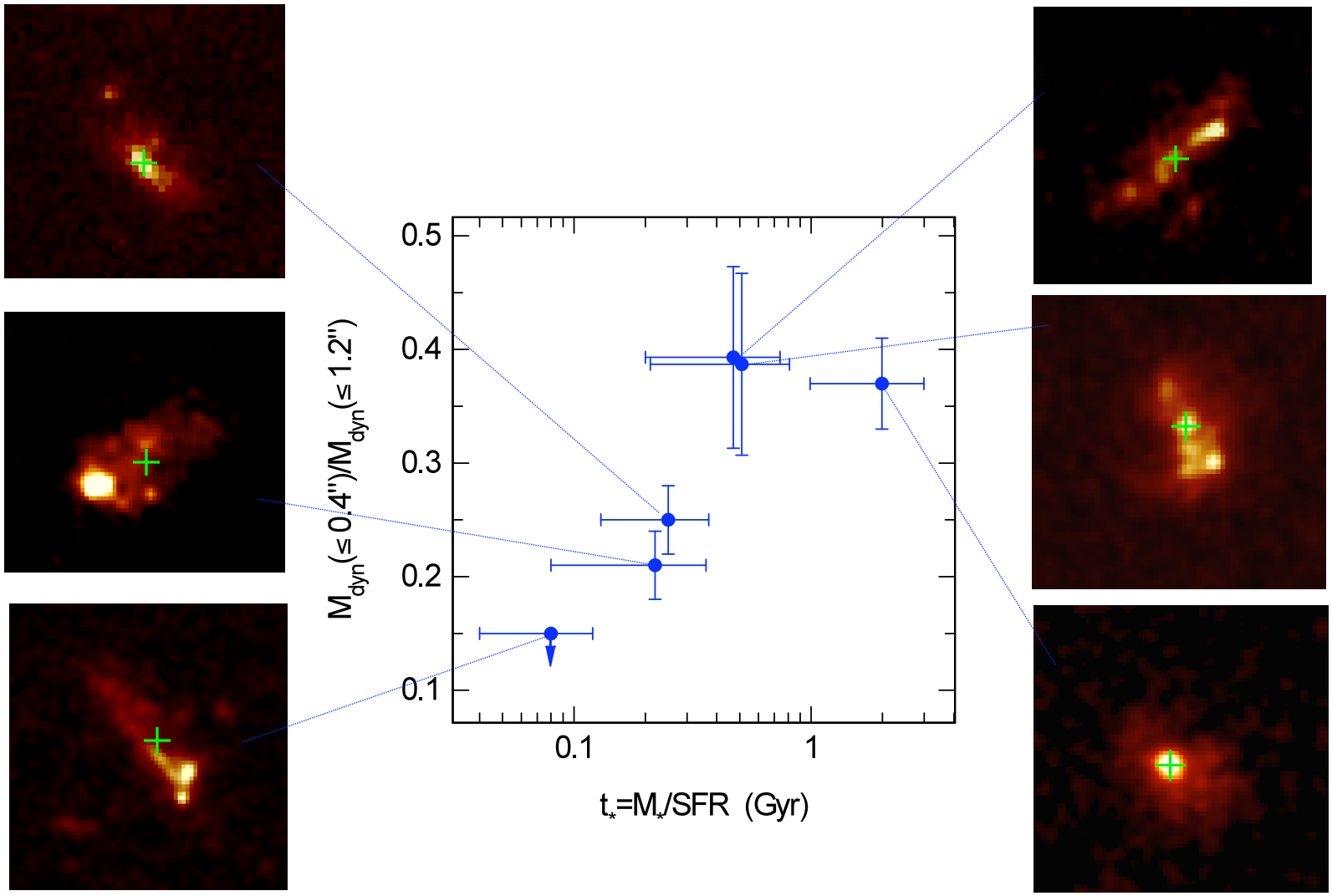
Flat surface density n~0-1

SFR ~ 100-200 $M_{\odot}$ / yr

M_{clump} ~ 10^{8}-10^{9} $M_{\odot}$

Cowie et al. 1996, Elmegreen, Elmegreen et al. 2005-2009, Förster Schreiber et al. 2009b

Clumps Migrate to Galaxy Centers and Form Bulges

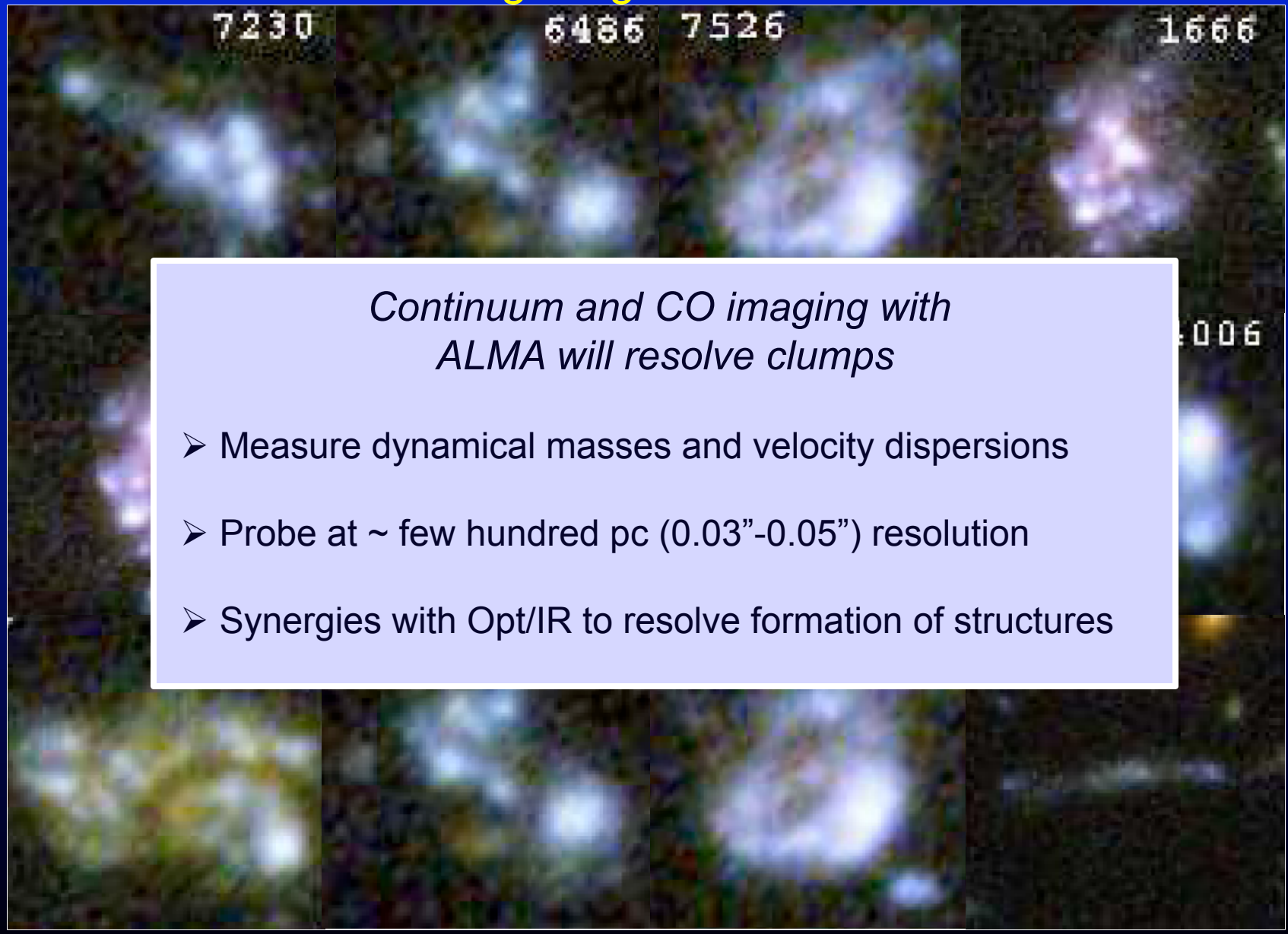


$M(\leq 3\ kpc)/M(\leq 15\ kpc) \sim 0.15\text{-}0.4$

ACS, NICMOS H
NACO K_s LGSF

Genzel et al. 2008, see also simulations by Noguchi 1999, Immeli et al. 2004, Bournaud et al. 2007

How do high-z galaxies evolve?

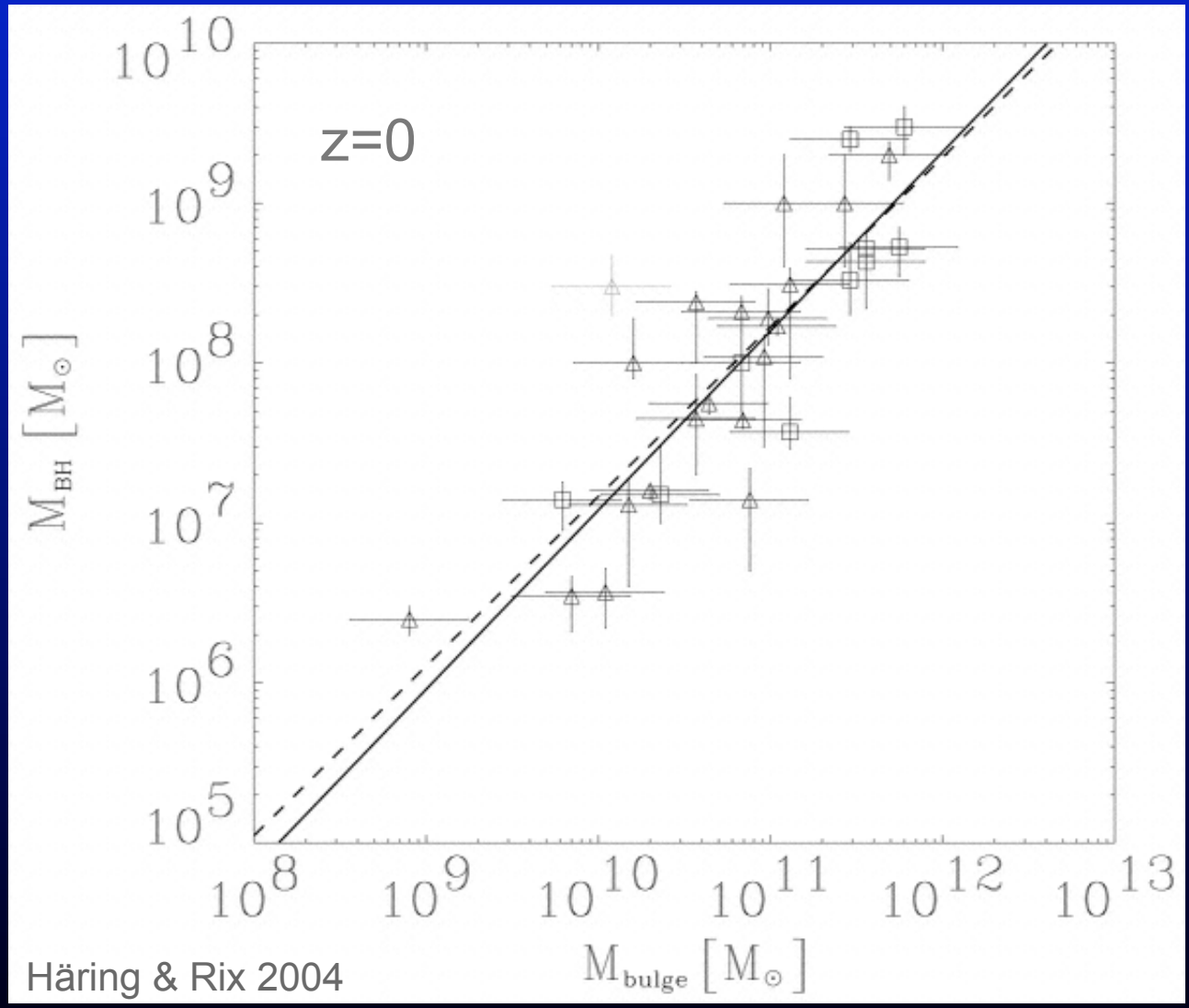


Continuum and CO imaging with ALMA will resolve clumps

- Measure dynamical masses and velocity dispersions
- Probe at ~ few hundred pc (0.03”-0.05”) resolution
- Synergies with Opt/IR to resolve formation of structures

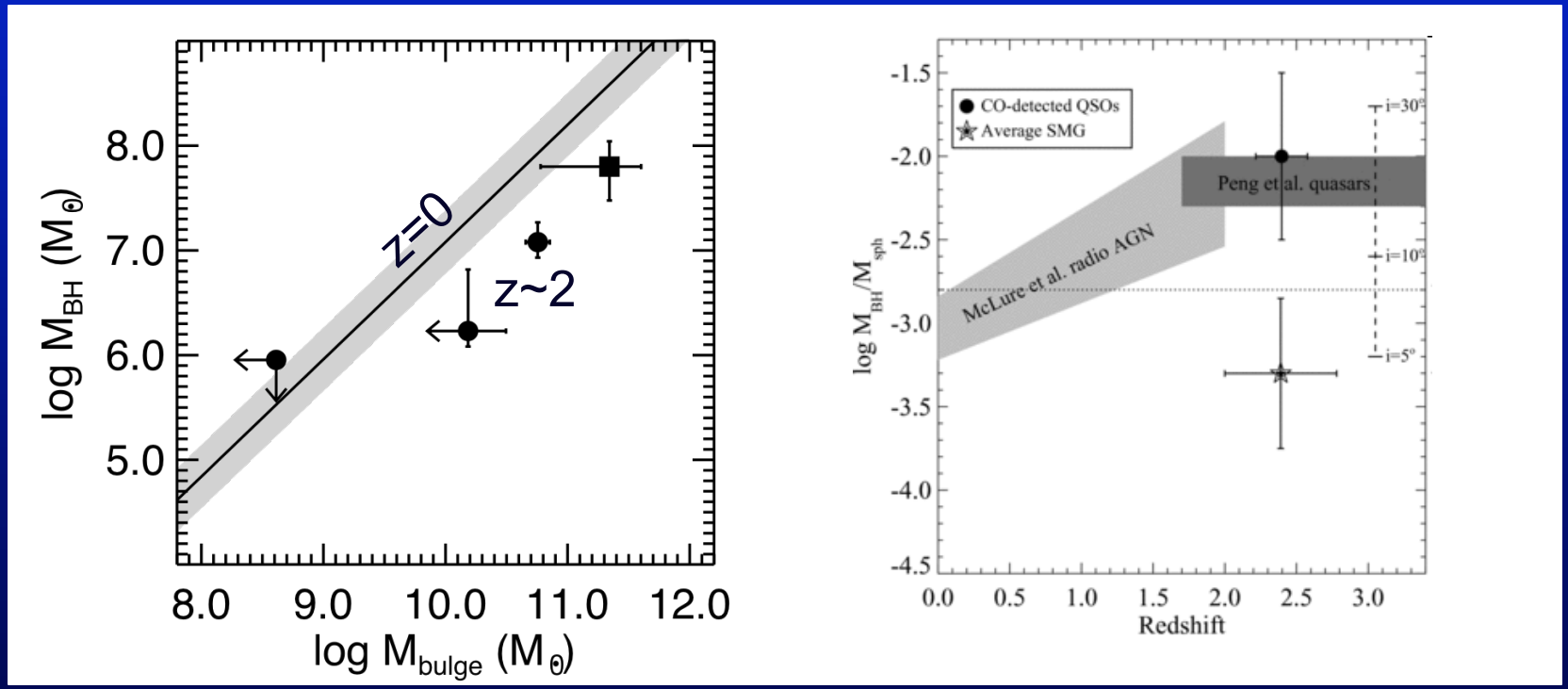
Cowie et al. 1996, Elmegreen, Elmegreen et al. 2005-2009, Förster Schreiber et al. 2009b

What is the galaxy – black hole evolutionary connection?



Häring & Rix 2004

Measurements of Black Holes at High-z



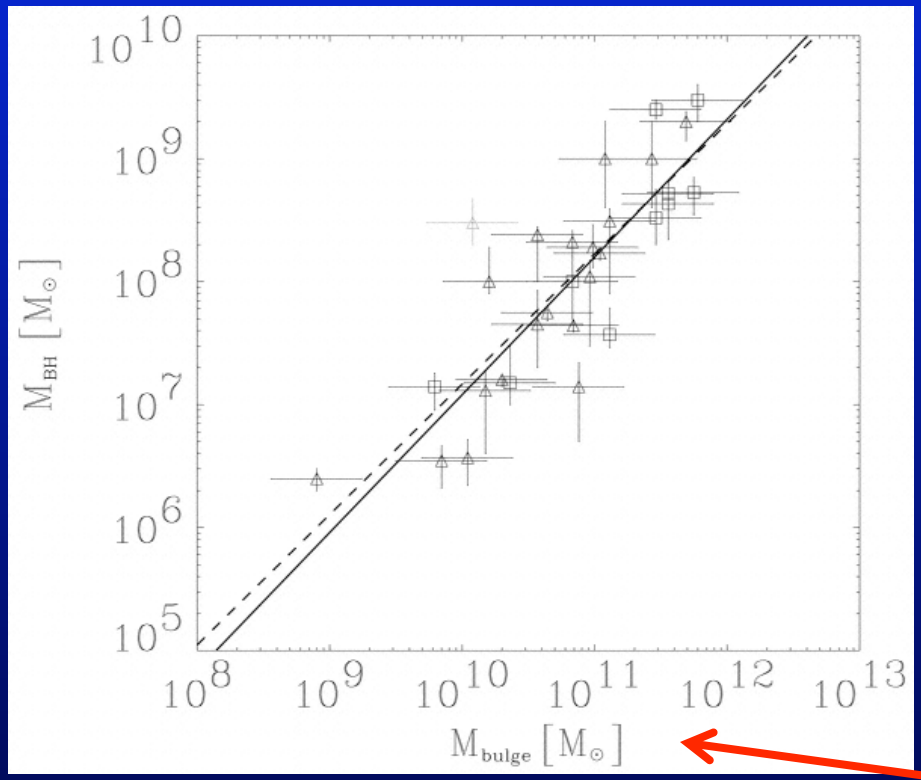
Normal Star-forming Galaxies: Shapiro et al. 2009

SMGs: Alexander et al. 2008

UNDER-massive BHs:
Normal star-forming galaxies
Sub-millimeter galaxies

OVER-massive BHs:
CO-detected quasars
High-redshift radio AGN and quasars

What is the galaxy – black hole evolutionary connection?



ALMA will determine robust host masses for AGN over all redshifts and AGN type

- Resolve bulges
- Probe much larger samples of galaxies
- Synergies with Opt/IR to measure BH masses

Summary: Where We Are and Where We're Going

- *KNOWN: SMGs driven by mergers, normal high-z galaxies by cold flows*
- *FUTURE: Clean dynamical estimate of merger fraction as f(mass, z)*

- *KNOWN: Giant clumps drive the evolution of high-z galaxies*
- *FUTURE: Resolving the structure of clumps and their effect on the galaxy*

- *KNOWN: Black holes at high-z diverge from local scaling relations*
- *FUTURE: Accurate bulge masses and systematic studies with mass, z*