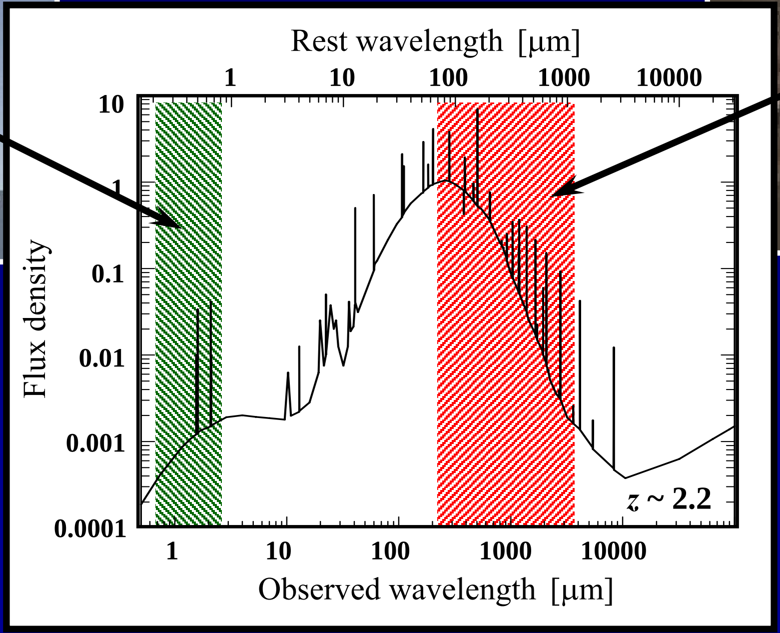
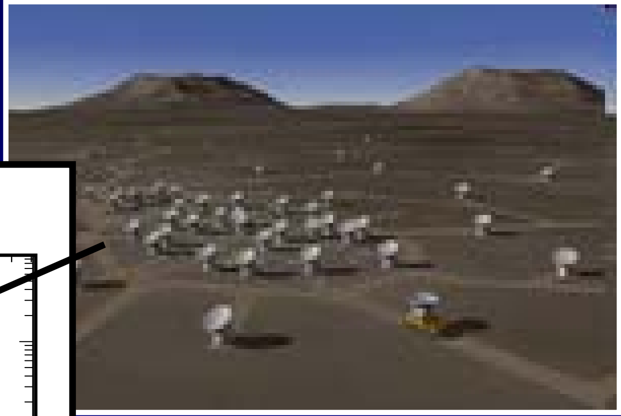
ISM and Galaxy Evolution – the ALMA View

Linda Tacconi, MPE Garching

E-ELT, GMT, TMT

Stars, Black Holes, Warm ISM





ALMA

Cold Gas & Dust: Building Blocks for Stars & Black Holes,

ALMA and ELTs: A Deeper, Finer View of the Universe, ESO Garching
March 25, 2009

Some Important Questions for ISM and and Galaxy Evolution:

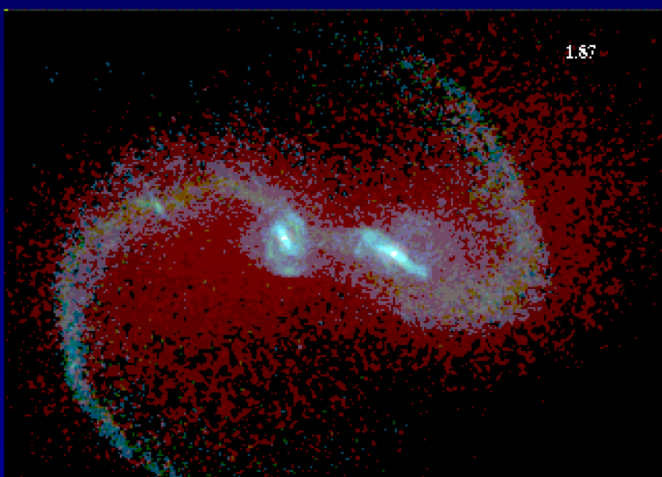
- *Early galaxy evolution: what fraction of star formation is due to to major mergers vs minor mergers and steady accretion?*

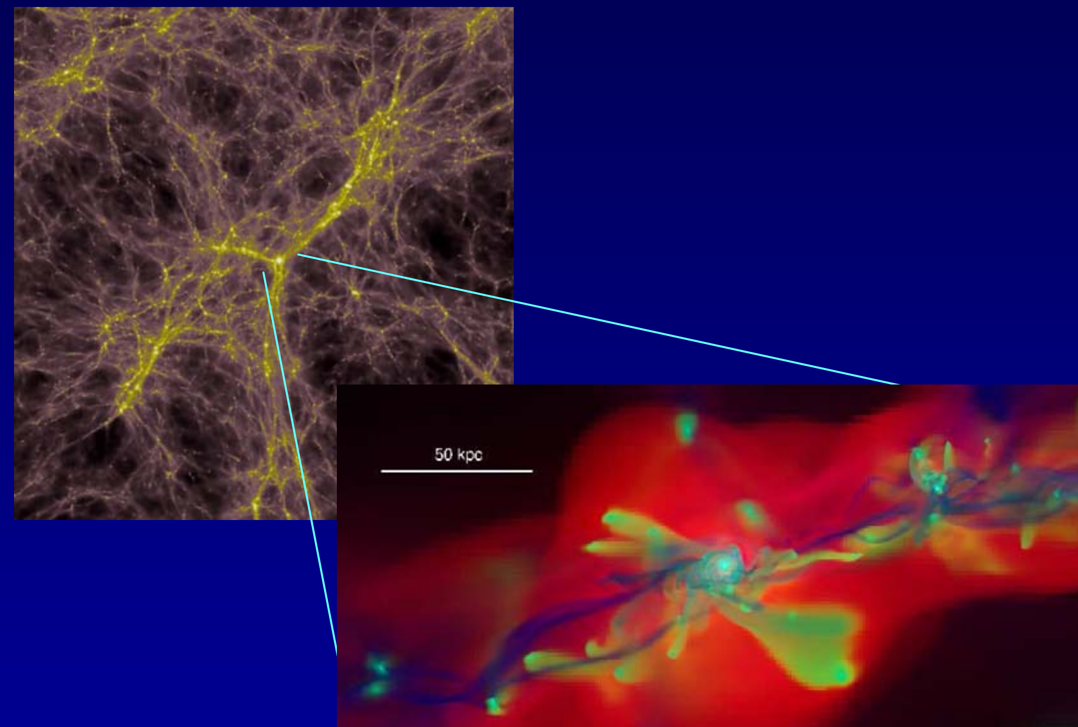
- *How do galaxies get their gas ? What are gas fractions in galaxies as a function of mass, redshift, environment…? Effect on on star formation efficiency?*

- *What drives the internal evolution in high-z star forming galaxies? How important is feedback?*

- *Black hole - galaxy coevolution: is M_{BH}/M_{gal} (z, t)?*

What drives galaxy and star formation at at high-z ?





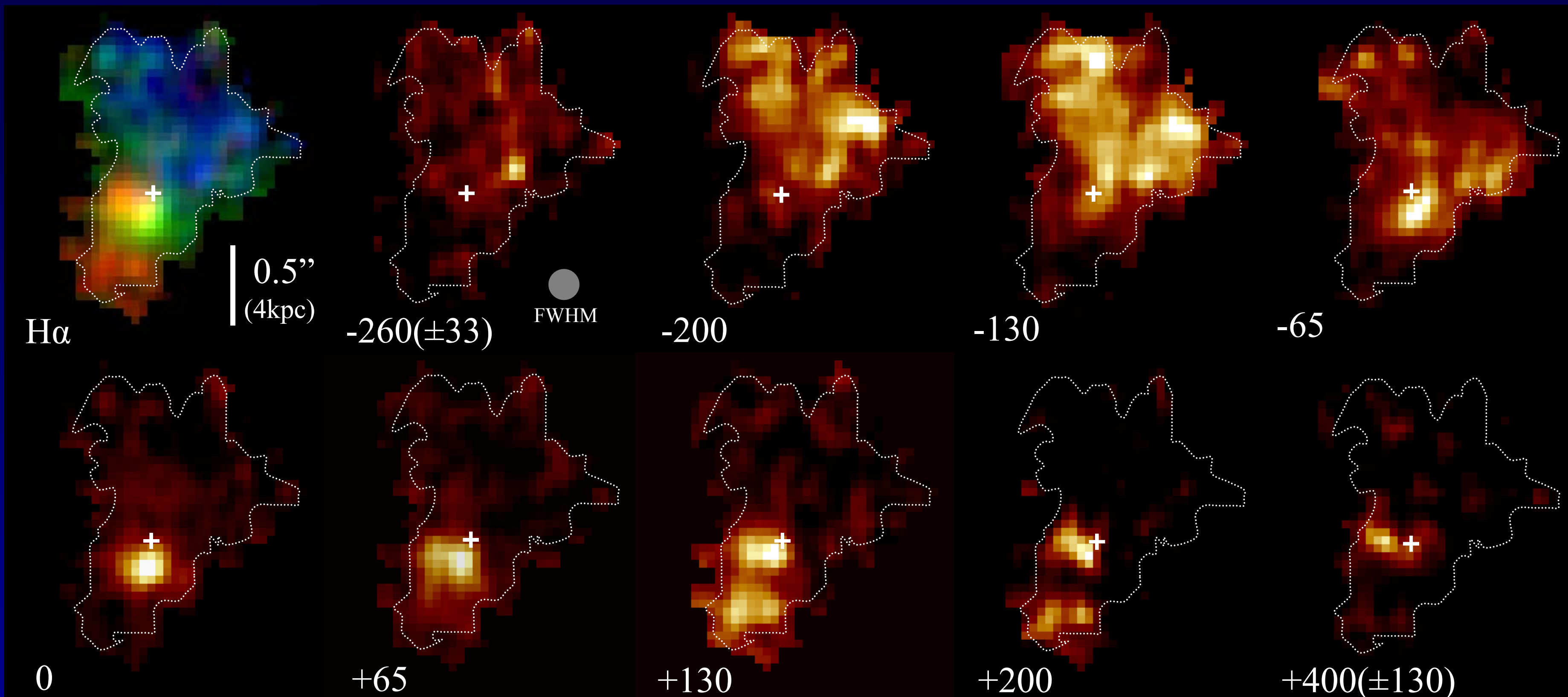
Major mergers

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

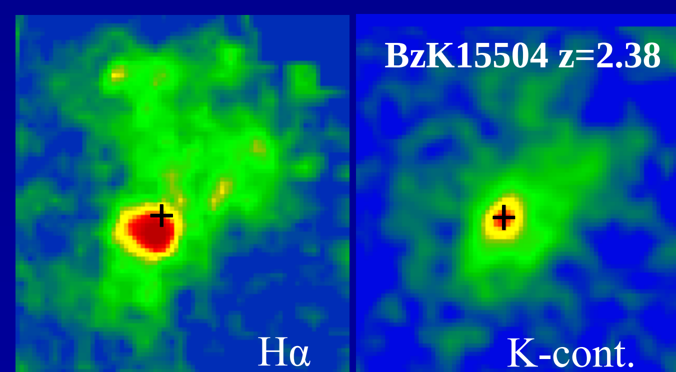
BzK 15504 z=2.38: A Thick, Clumpy & Globally Unstable Disk

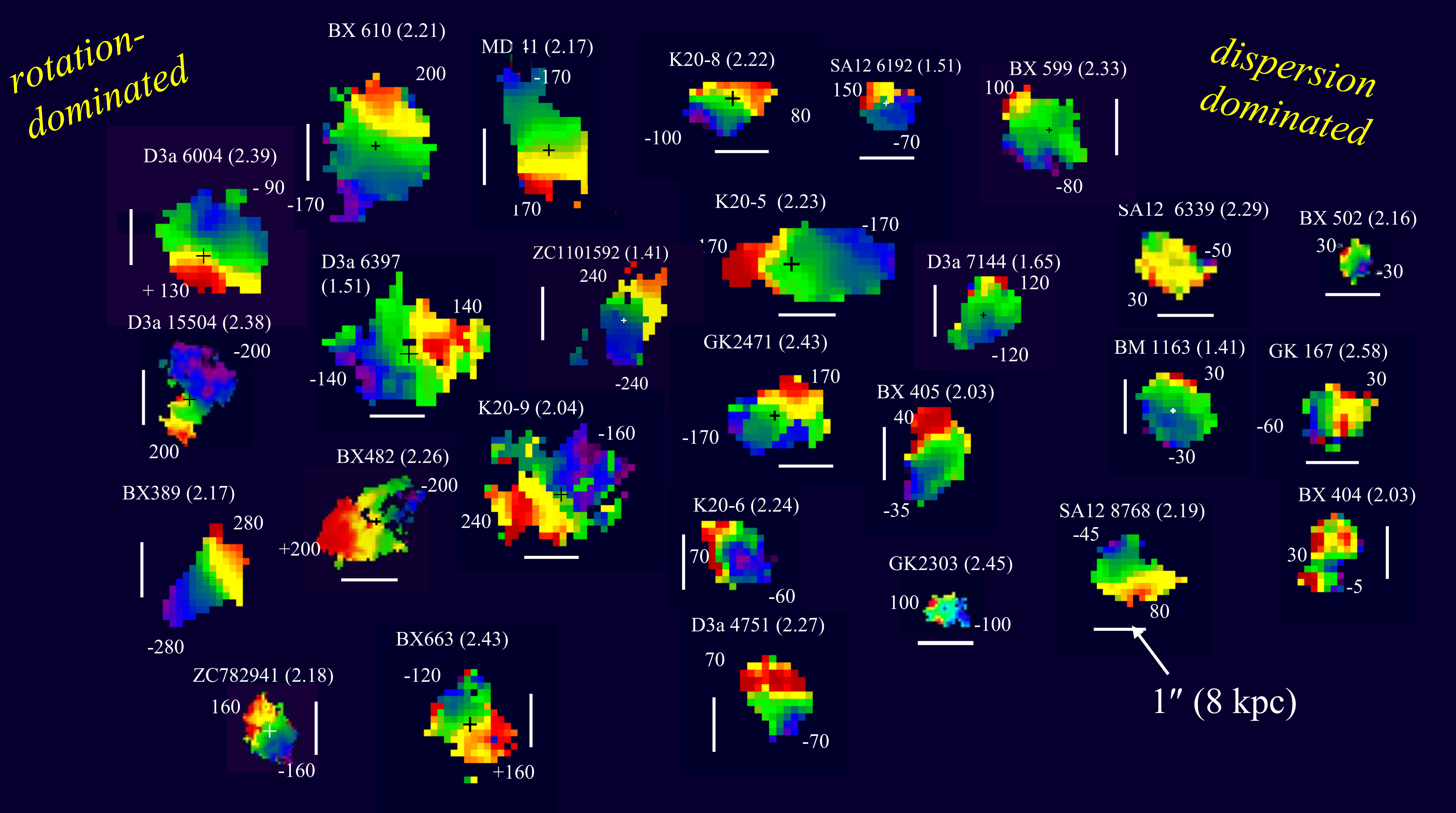


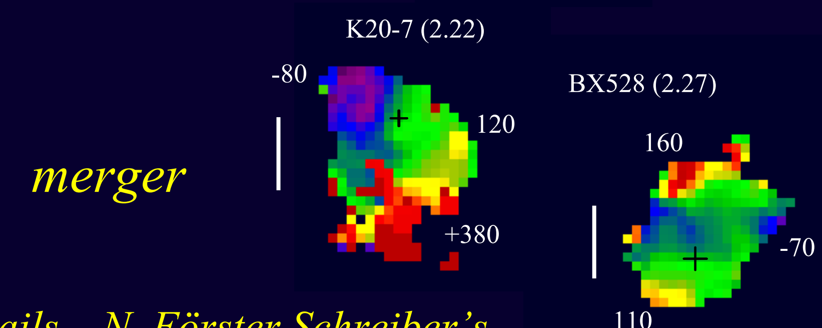
M_{dyn}(<10 kpc) ~10^{11} $M_\odot$
v_c=230 km/s, σ = 50 km/s,
R_d=4 kpc, Q=0.8
SFR = 150 $M_\odot yr^{-1}$, f_{gas}~0.3

Genzel et al.

SINFONI +AO (VLT):
0.2” (1.6 kpc)







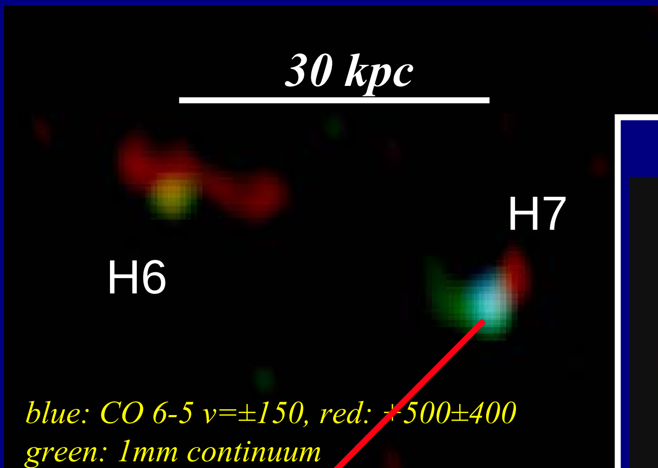
Galaxy Kinematics surveys:

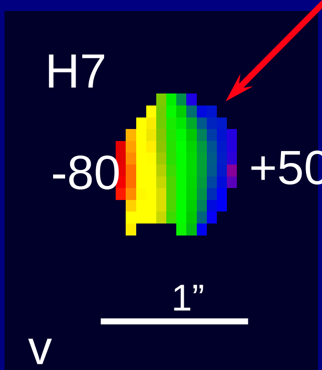
SINFONI (z~1.5-2.5): Förster Schreiber et al. (2009)
van Starkenburg et al. (2008)
z~1: Epinat et al. (2009)
OSIRIS(z~1.5-2.5): Law et al. (2009), Wright et al. (2009)
FLAMES (z~0.5): Hammer, Puech et al. (2009)

Details – N. Förster Schreiber's

Sub-millimeter Galaxies Are Dissipative Gas Rich Rich Mergers

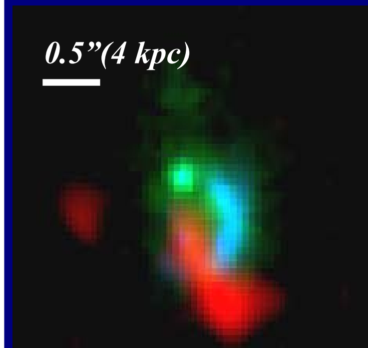
SMMJ09431+4700 z=3.35





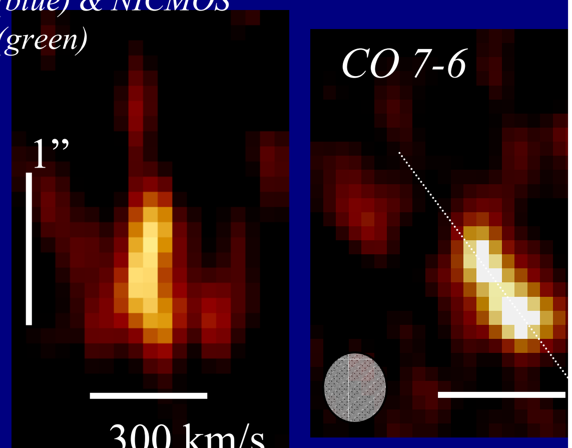
- *CO 6-5*
- *~0.5" resolution*

SMMJ163650+4057 z=2.39

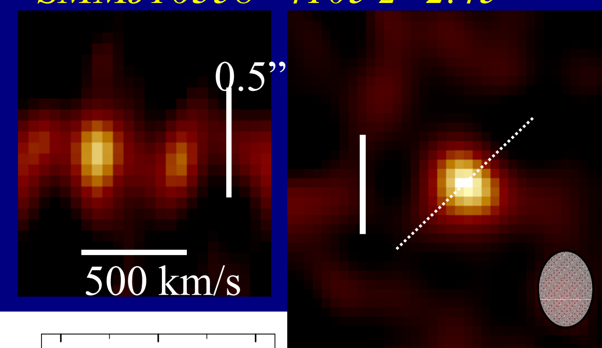


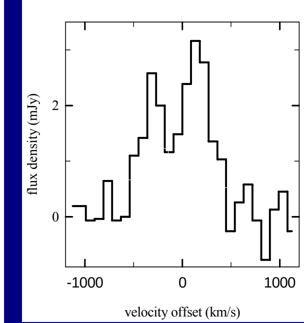
CO 7-6 (red) on ACS (blue) & NICMOS (green)

- *projected separation ~4 kpc*
- *velocity difference 200 km/s*



SMMJ16358+4105 z=2.45





- *CO 7-6*
- *CO Size ~0.25" FWHM (1.6 kpc)*

Neri et al. 2003, Greve et al. 2005, Tacconi et al. 2006, 2008, Engel et al. 2009, Smail et al. 2009

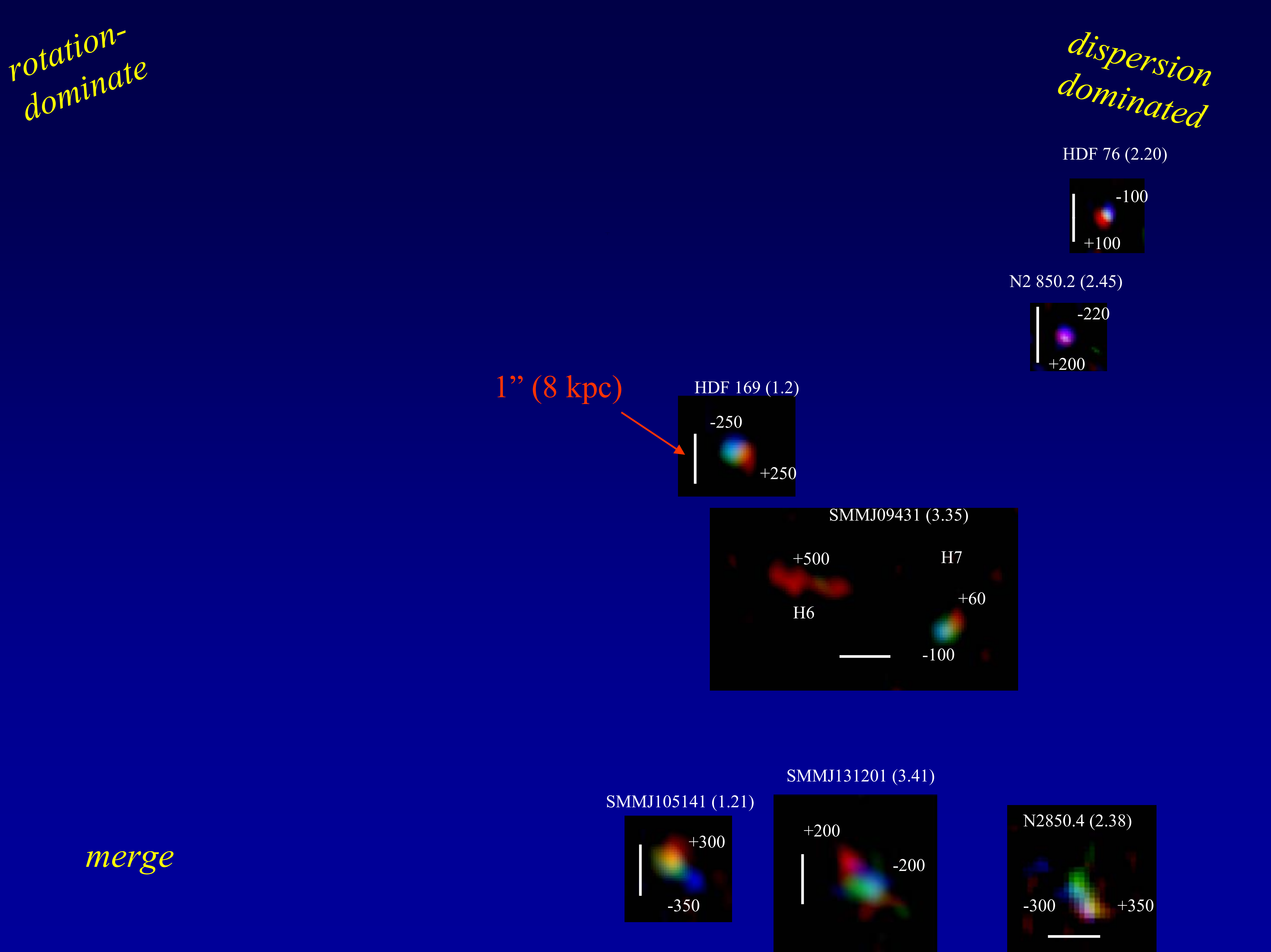
Sub-millimeter Galaxies Are Dissipative Gas Rich Rich Mergers

SMG Properties:

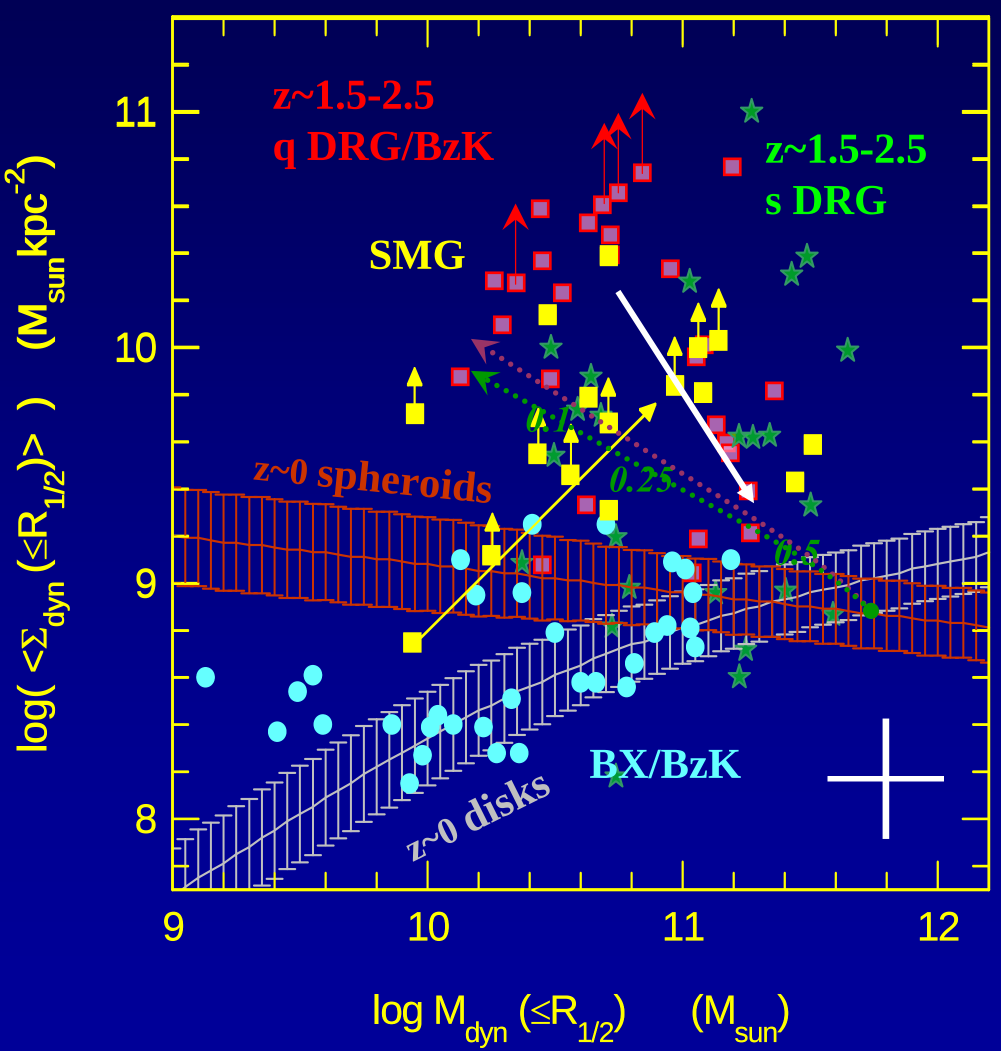
- $<v_c>=400$ km/s
- M_{dyn}~10^{11} $M_{\odot}$ within CO regions
- f_{gas} ~ 0.2-0.5
- $<R>_{1/2}$ < 0.25” (2 kpc)
- $<\Sigma_{dyn}>$ ~ $10^{3.7}$ $M_{\odot} pc^{-2}$ ~ $\Sigma_{bulges/Es}$
- SFR ~ 500 – 1000 $M_{\odot}$/yr

  ~ε M_{gas}/t_{dyn} - maximal starbursts

Neri et al. 2003, Greve et al. 2005, Tacconi et al. 2006, 2008, Engel et al. 2009, Smail et al. 2009


rotation-
dominate
dispersion
dominated
HDF 76 (2.20)
-100
+100
N2 850.2 (2.45)
-220
+200
1” (8 kpc)
HDF 169 (1.2)
-250
+250
SMMJ09431 (3.35)
+500
H7
+60
H6
-100
SMMJ131201 (3.41)
SMMJ105141 (1.21)
+300
-350
+200
-200
N2850.4 (2.38)
-300
+350
merge

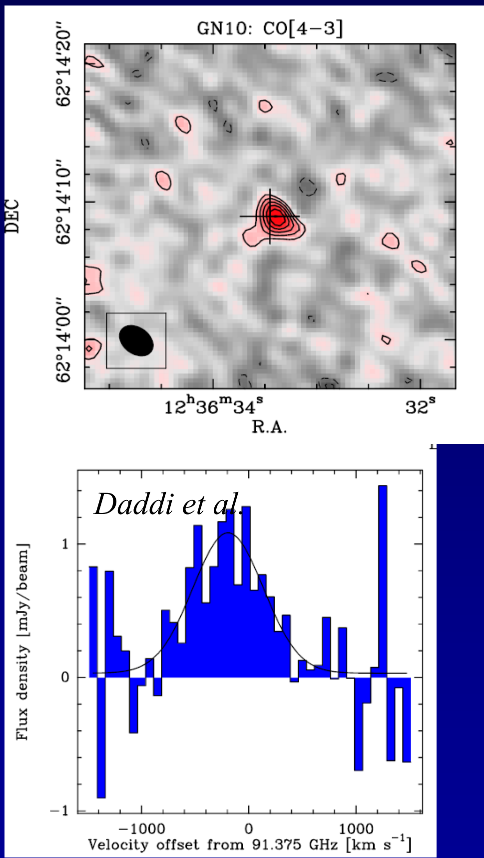
Evolution of High-z Galaxy Populations



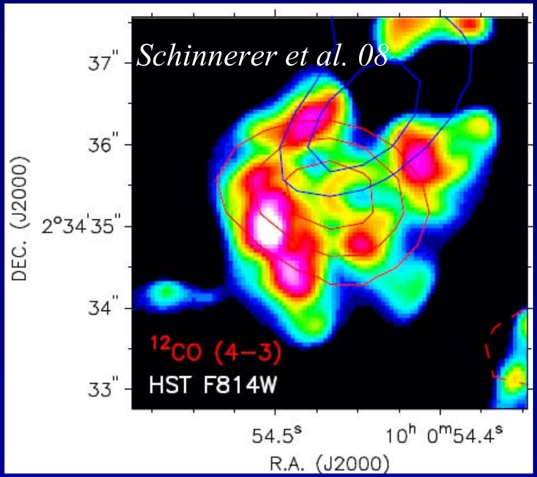
Daddi et al. 2005, Trujillo et al. 2006, Zirm et al. 2007, Toft et al. 2007, Bouche et al. 2007, Shen et al. 2003, Tacconi et al. 2008, Younger et al. 2008, Naab et al. 2009, Hopkins et al. 2009

z≥4 SMGs

GN 10 z=4.09



COSMOS J100054+023436 z=4.5



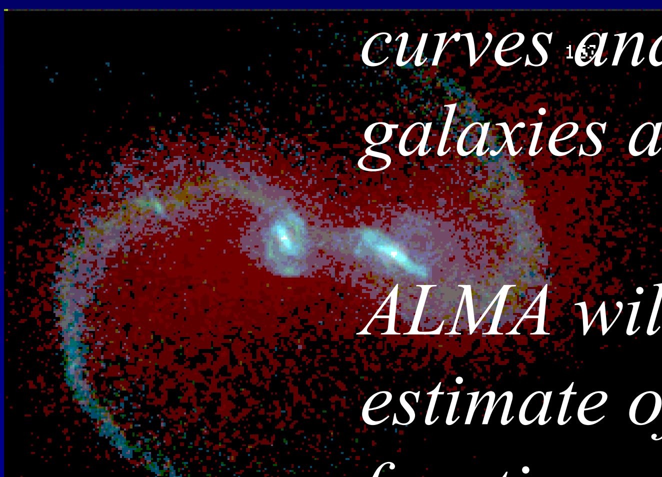
- *SFR ~1000 $M_\odot$/yr*
- *linewidths ~ z=2 SMGs*
- *M_{gas} ~ fewx10^{10} $M_\odot$*
- *likely progenitors of z=2-3 quiescent, "red and dead" compact galaxies*

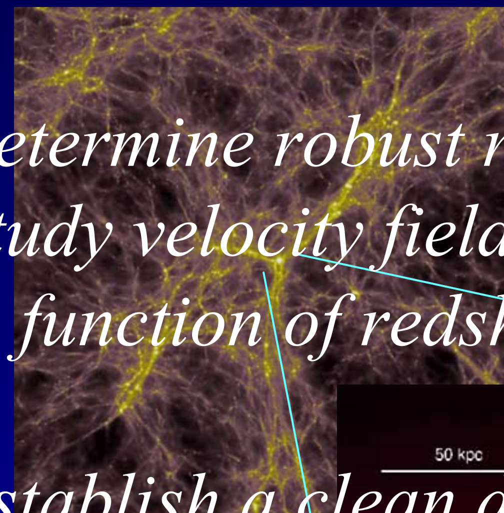
Still very rough estimates of number densities

Dannerbauer et al. 2002, 2004, 2008, Wang et al. 2007, Younger et al. 2007, 2008a,b,c, Capak et al. 2008, Daddi et al 2008, 2009, Schinnerer et al. 2008, Coppin et al. 2009

See also talks by J. Dunlop, van Kampen, T. Greve…

What drives galaxy and star formation at at high-z ?





ALMA will determine robust rotation curves and study velocity fields for distant galaxies as a function of redshift and mass

ALMA will establish a clean dynamical estimate of galaxy merger fractions as a function of redshift and mass

Major mergers

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***Minor mergers and steady accretion**:*

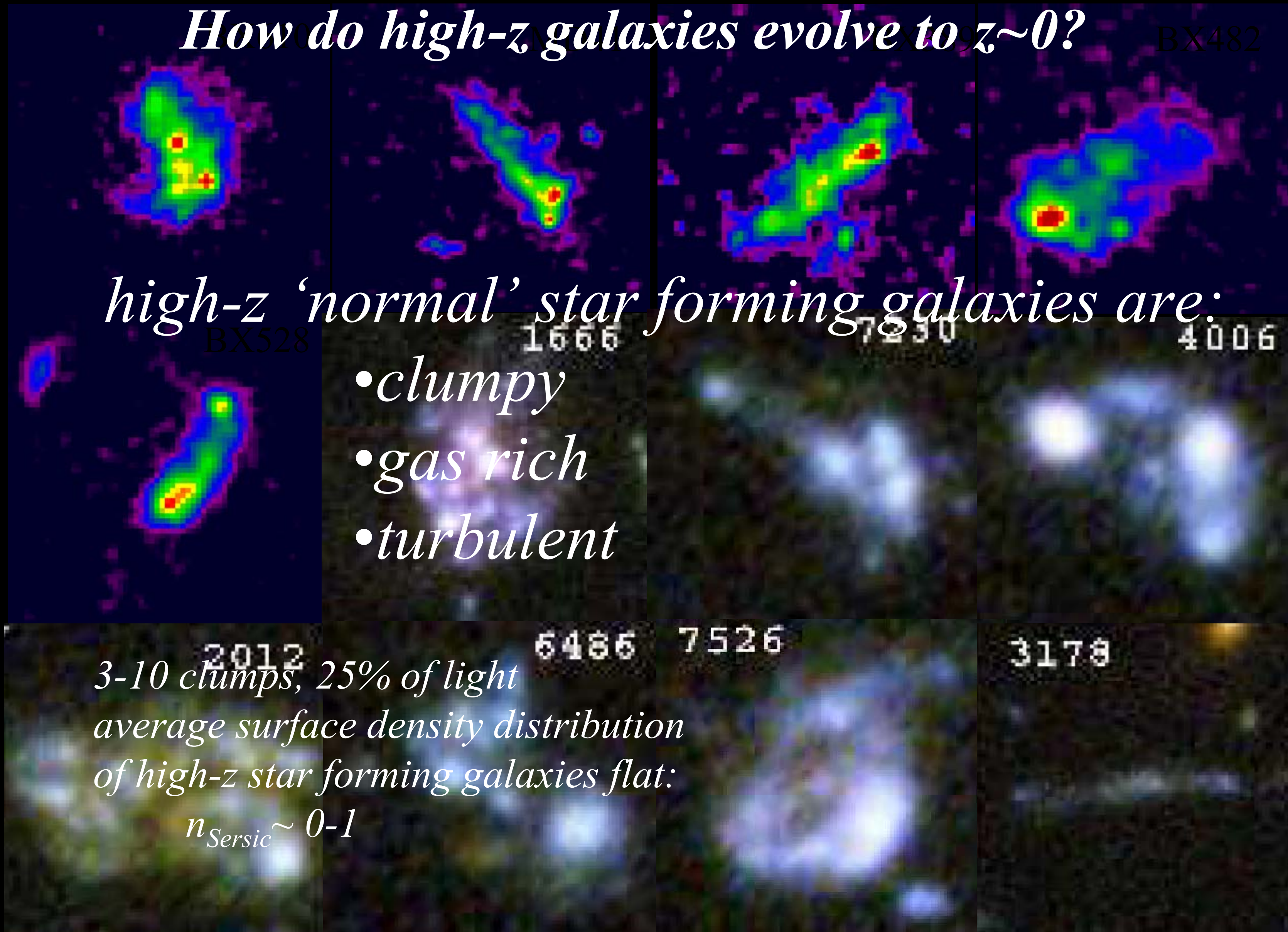
Dekel & Birnboim 2003,2006, Keres et al. 2005, Nagamine et al. 2005, Davé 2007, Kitzbichler & White 2007, Naab et al. 2007, Governato et al. 2008, Ocvirk et al. 2008, Dekel et al. 2009, Agertz et al. 2009

What Are Gas Fractions of High-z Galaxies?

ALMA will measure gas fractions as a function of redshift, mass, environment and galaxy morphology

ALMA will explore the dependence of star formation rates on galaxy

How do high-z galaxies evolve to z~0?



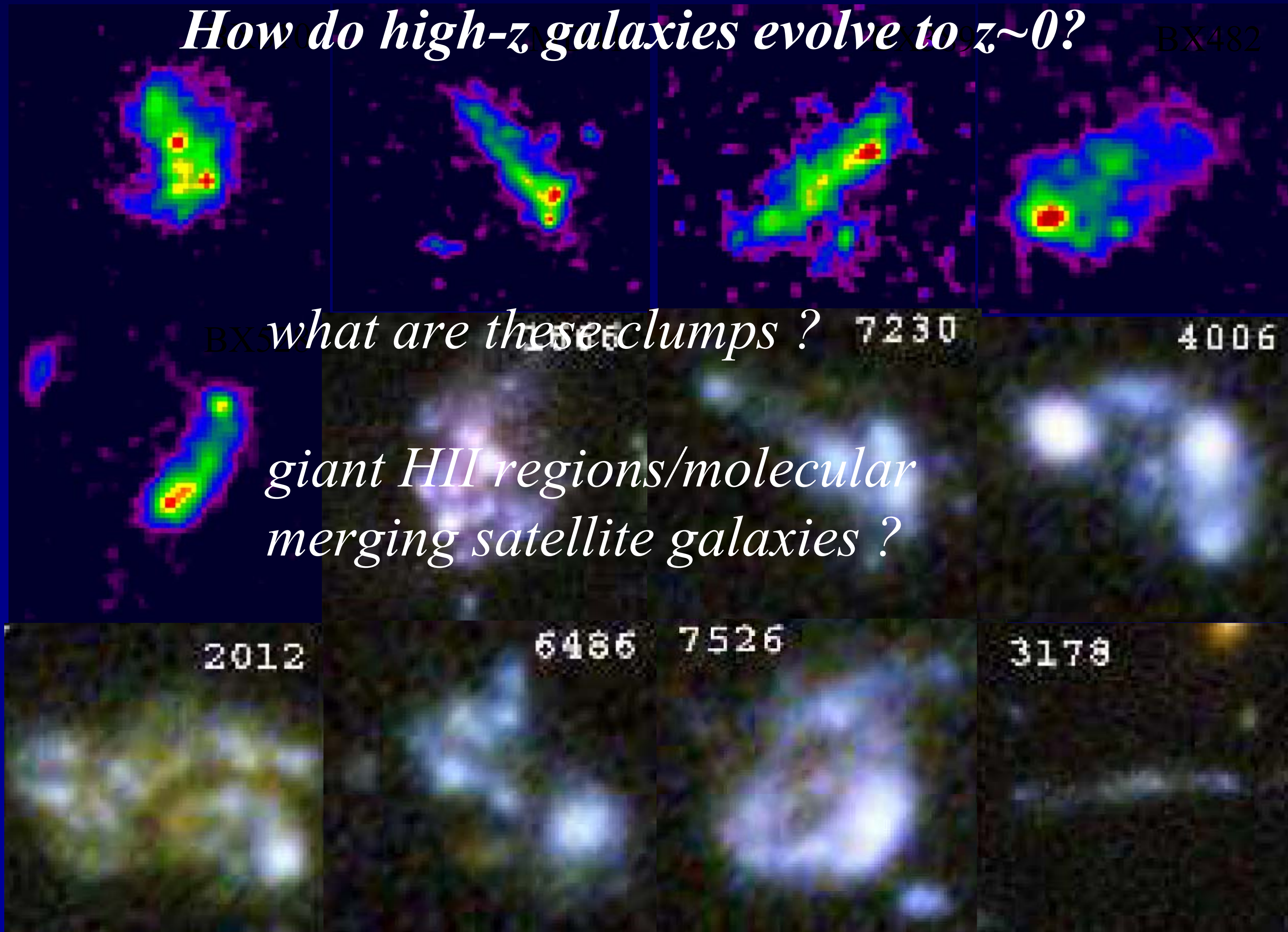
high-z 'normal' star forming galaxies are:

- *clumpy*
- *gas rich*
- *turbulent*

3-10 clumps, 25% of light
average surface density distribution of high-z star forming galaxies flat:
$n_{Sersic} \sim 0\text{-}1$

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

How do high-z galaxies evolve to z~0?



what are these clumps ?

giant HII regions/molecular
merging satellite galaxies ?

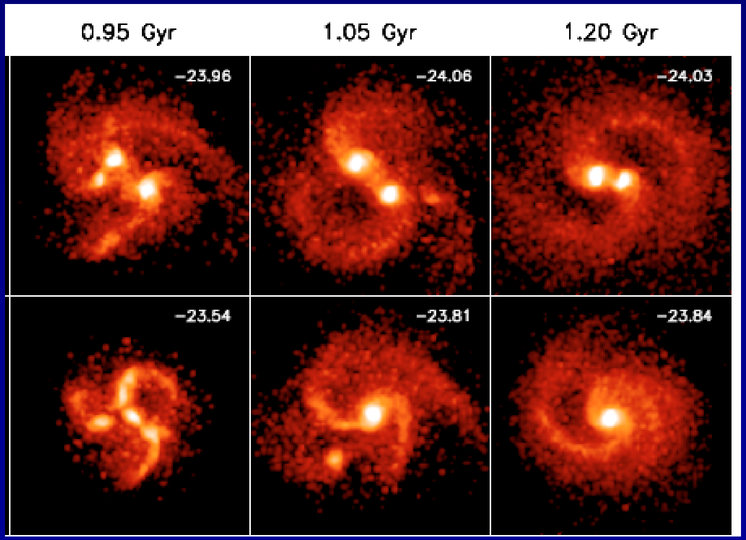
Cowie et al. 1996, Elmegreen, Elmegreen et al. 2005-2009, Förster Schreiber et al.

Do most galaxies go through a phase of rapid rapid secular evolution at z~2-4 ?

for a self-regulated disk ($Q_{Toomre} \sim 1$)

$$\frac{L_{Jeans}}{R} \sim \frac{\sigma}{v_c} \sim f_{gas}$$

the higher gas fractions at high-z result in turbulent systems with large fragmentation lengths



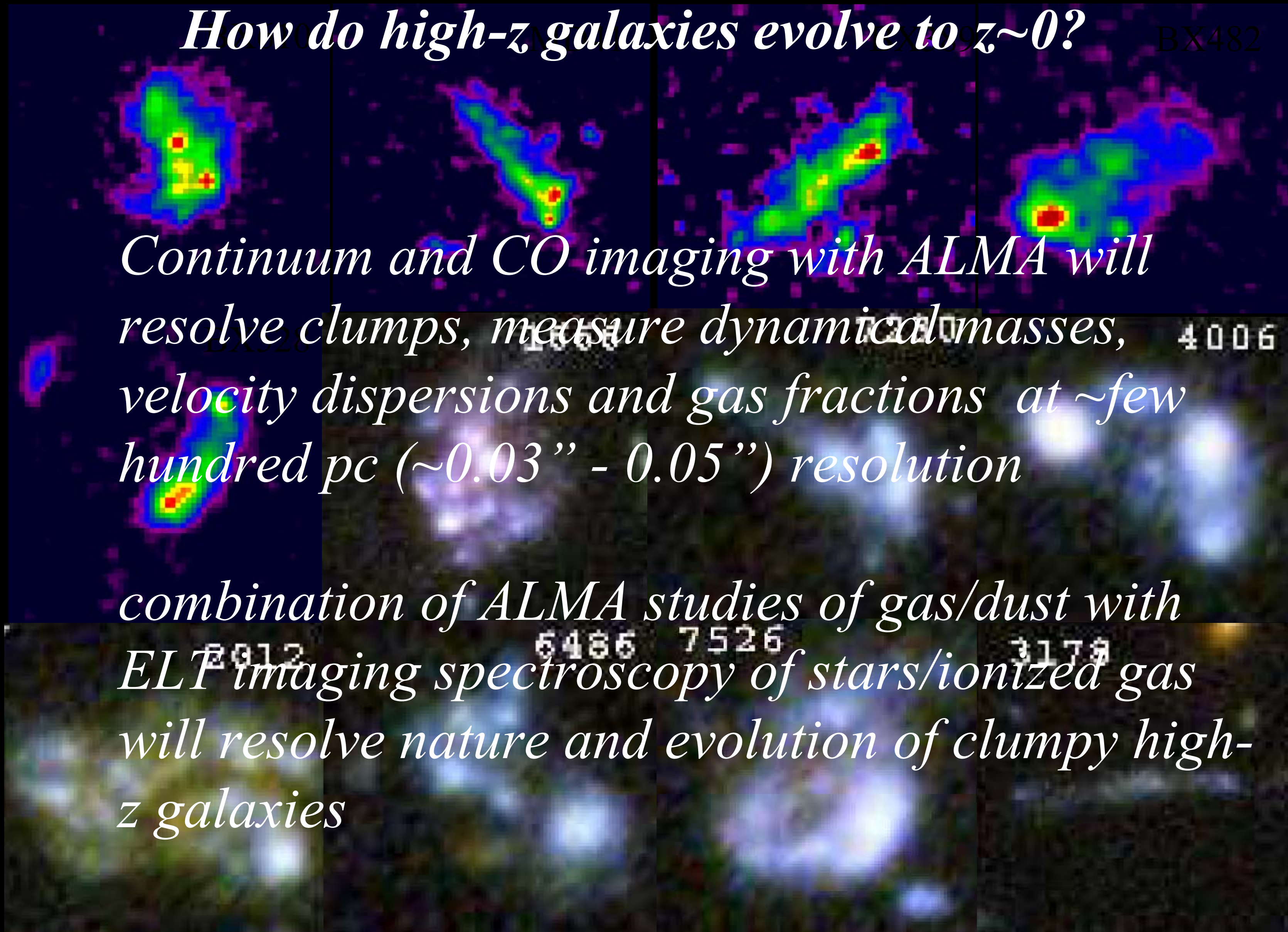
$$t_{visc} \sim t_{df} \sim \left(\frac{v_d}{\sigma_0}\right)^2 t_{dyn}(R)$$

at z~0: $t_{vis,df}$~5-10 Gyrs
at z~2: $t_{vis,df}$~ a few 10^2 Myrs

we need size, velocity dispersion and age measurements for clumps

Lin & Pringle 1987, Noguchi 1999, Semelin & Combes 2002, Immeli et al. 2004, Bournaud et al. 2007, Genzel et al. 2008, Agertz et al. 2009, Dekel, Sari & Ceverino 2009

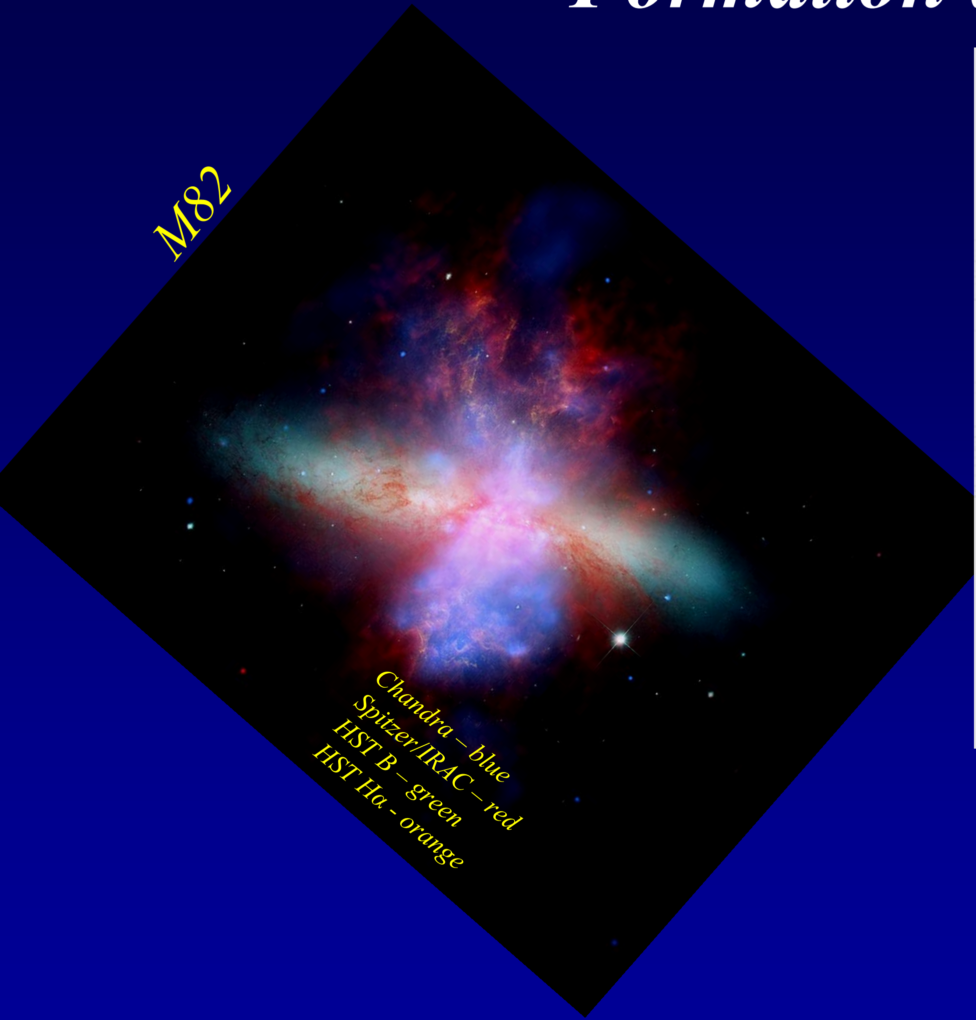
How do high-z galaxies evolve to z~0?

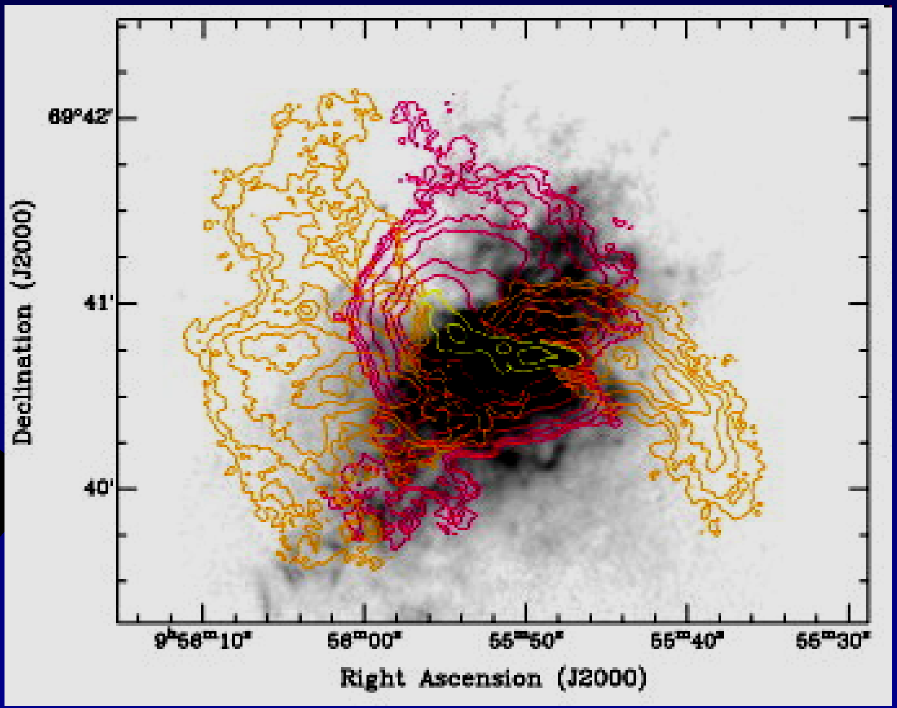


Continuum and CO imaging with ALMA will resolve clumps, measure dynamical masses, velocity dispersions and gas fractions at ~few hundred pc (~0.03" - 0.05") resolution

combination of ALMA studies of gas/dust with ELT imaging spectroscopy of stars/ionized gas will resolve nature and evolution of clumpy high-z galaxies

How Important Is Feedback Due to Star Formation and AGN?





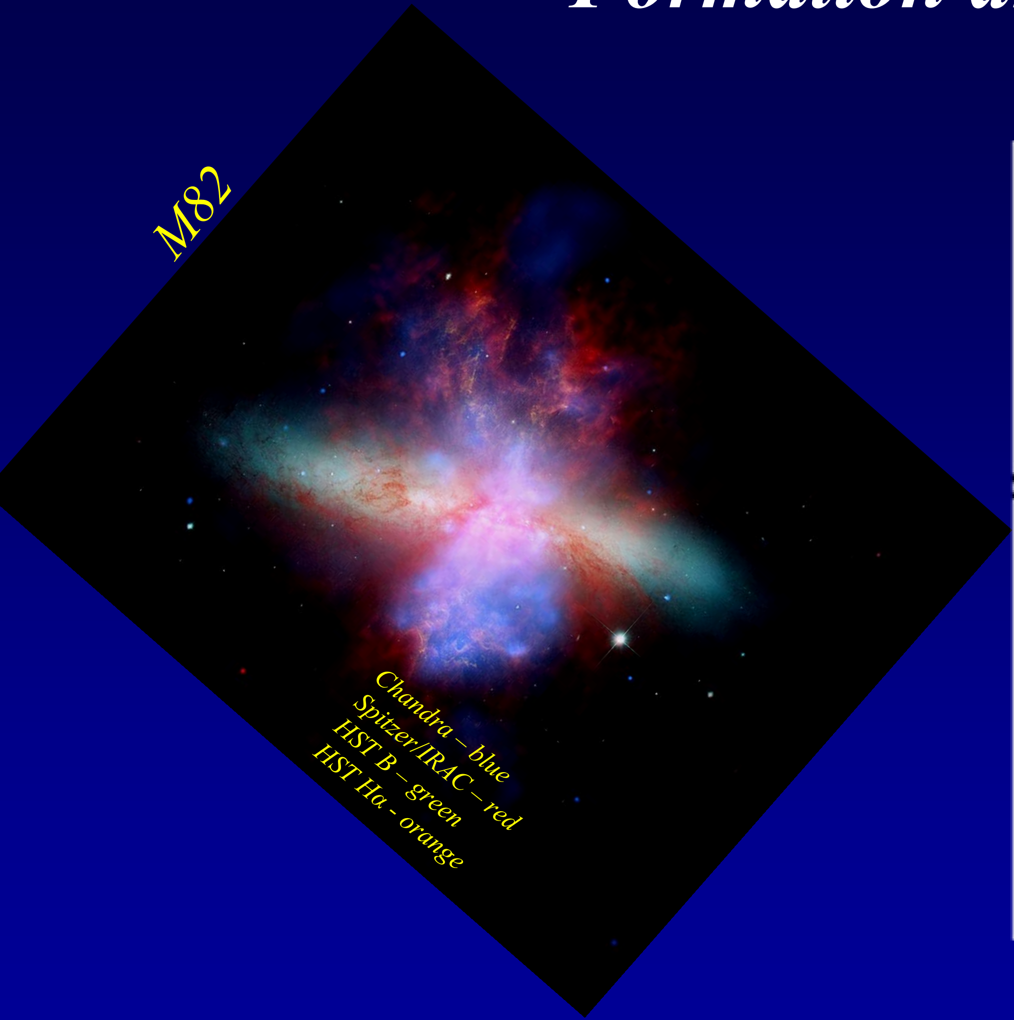
Walter, Weiss & Scoville 2002 - OVRO

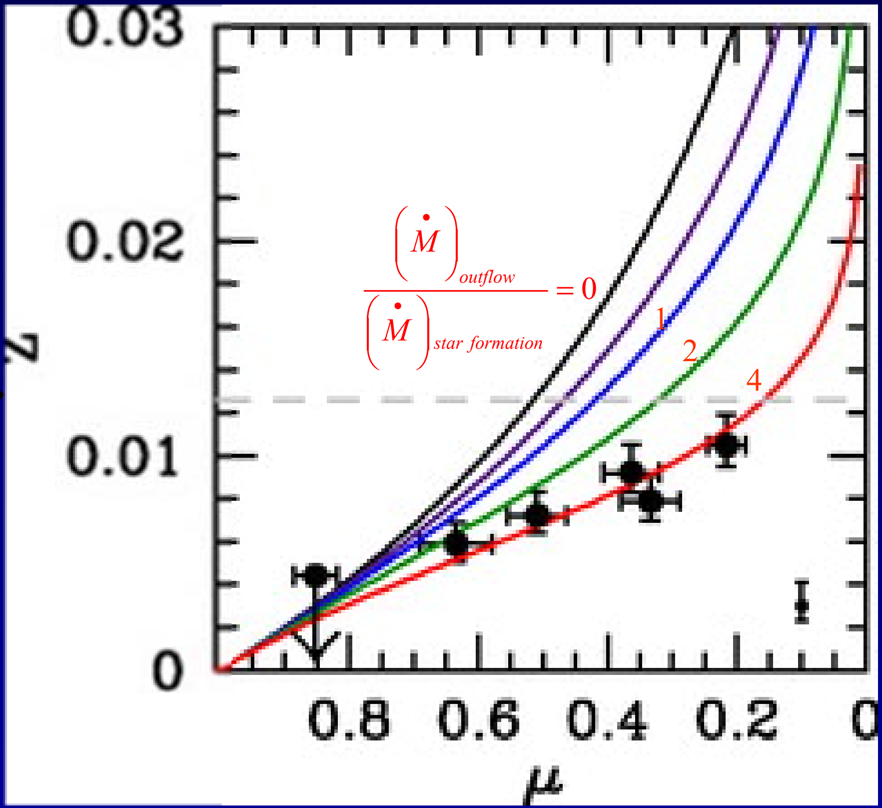
M82 Starburst Driven Wind

- *>20% $M(H_2)$ in outflow ($>10^8\ M_\odot$)*
- *~1 kpc out of disk*
- *v(flow) ~230 km/s*
- *$\sim 10^7\ M_\odot$ could escape the galaxy*

Also Sakamoto et al. 2006, Iono et al. 2007

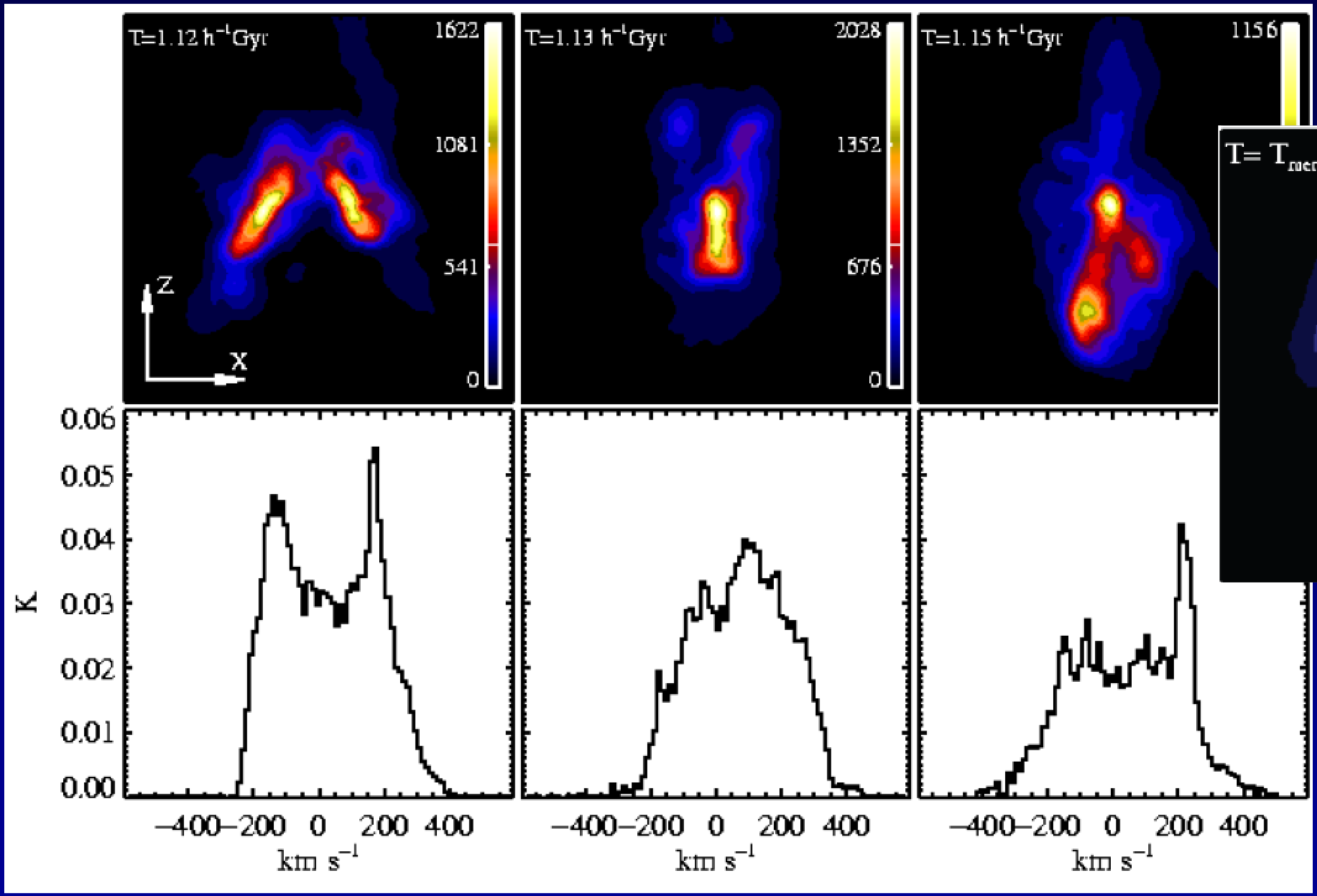
How Important Is Feedback Due to Star Formation and AGN?

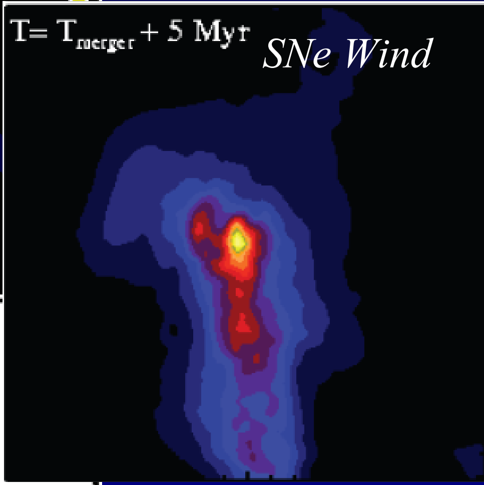




Erb et al 2006

AGN Feedback and Molecular Outflows





Narayanan et al. 2006, 2008

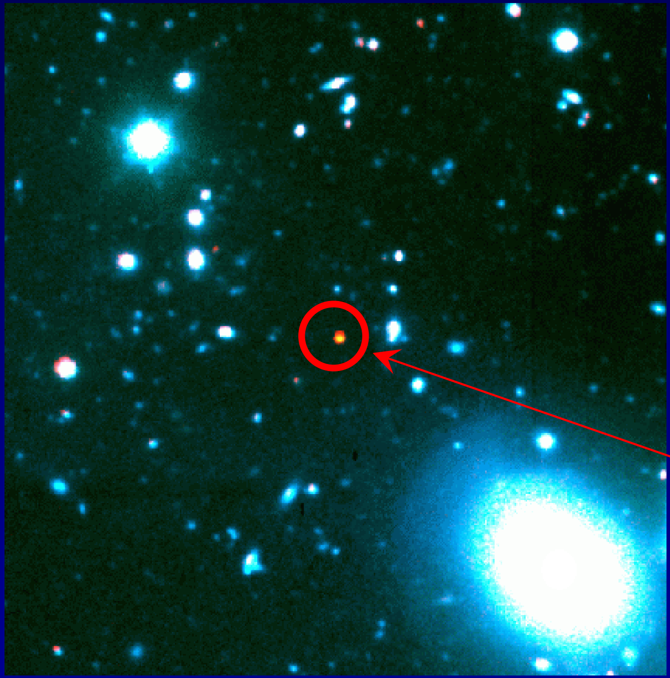
•Simulations of CO at 250 pc resolution,(~0.03" at z=2) Possible with ALMA at 1mm

How Important Is Feedback Due to Star Formation and AGN?

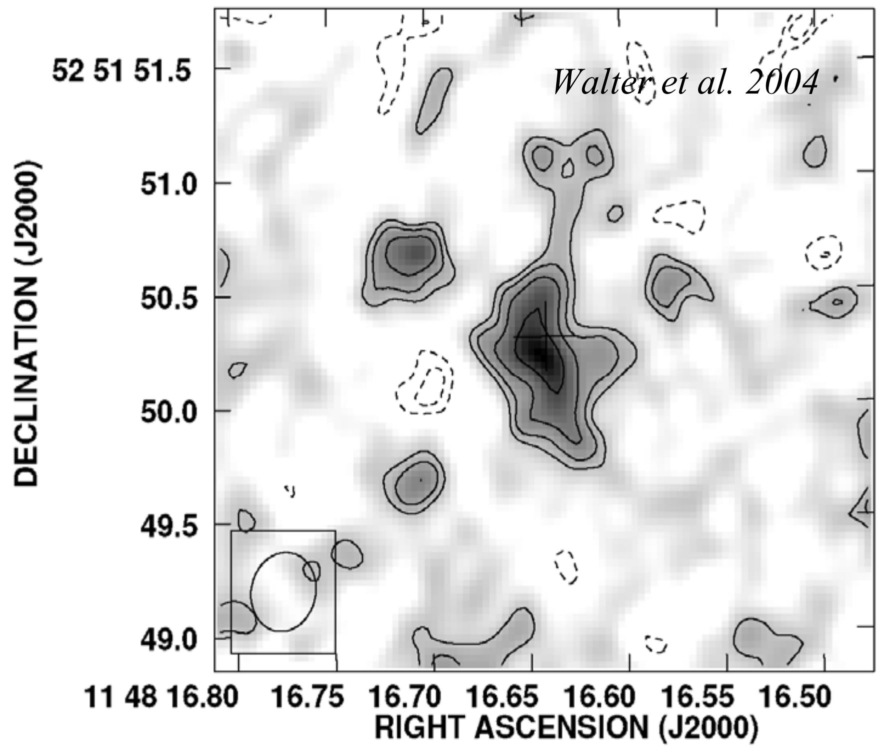
ALMA will measure outflow rates of cold gas and test feedback models

Cosmic Co-evolution of Massive Black Holes Holes & Galaxies

- $M_{gas} = 2 \times 10^{10}\ M_{sun}$
- $M_{dyn} \sim 6 \times 10^{10}\ M_{sun}$
- $M_{BH} = 3 \times 10^{9}\ M_{sun}$

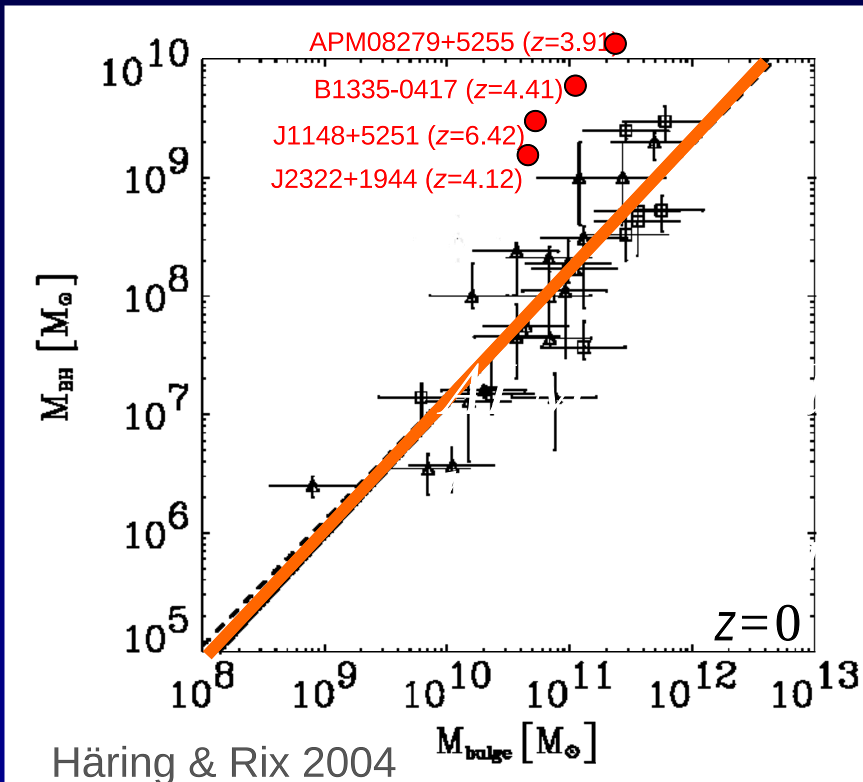


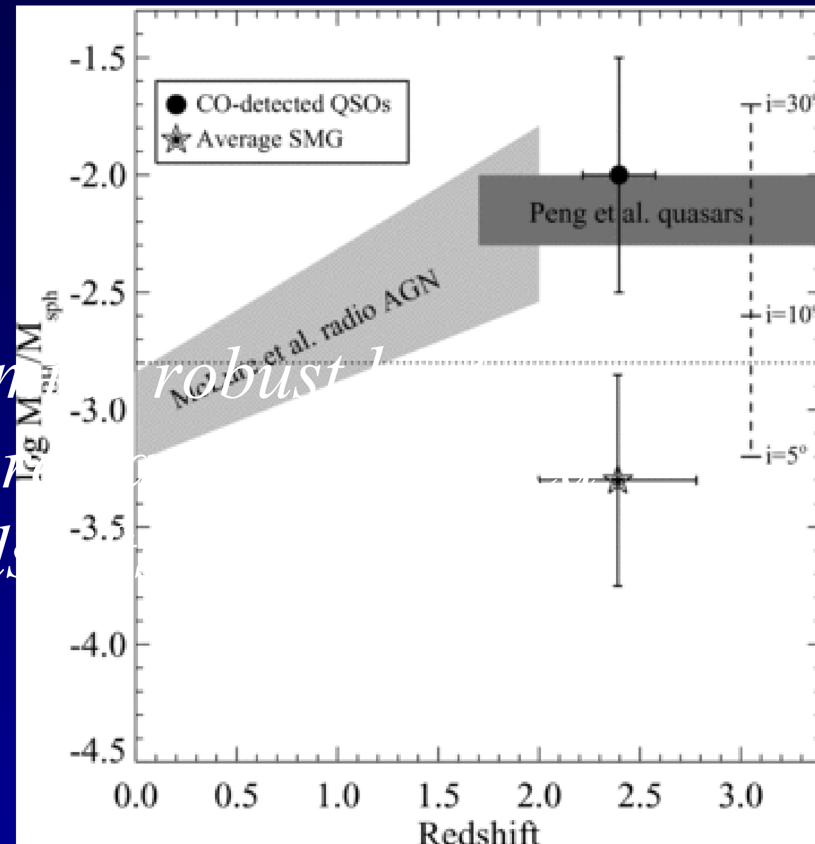
a 3 billion solar mass black hole, 800 million years after the Big Bang !



Steidel et al. 1996, Madau et al. 1996, Boyle et al. 2000, Fan et al. 2001, Hasinger et al. 2002, Chapman et al. 2003, 2005, Walter et al. 2003, 2004, Bertoldi et al. 2003

•*Black Hole - Galaxy Co-evolution: is M_{BH}/M_{gal} (z, t)?*





Walter et al. 2004, Peng et al. 2006, McClure et al 2006,Kurk et al 2007, Jiang et al 2007, Maiolino et al. 2007,Riechers et al 2007,2008, Alexander et al. 2008, Coppin et al 2008

Summary – What ALMA Will Do for ISM and and Galaxy Evolution:

•*Determine robust rotation curves and study velocity fields for distant galaxies as a function of redshift and mass*

•*Establish a clean dynamical estimate of galaxy merger fractions as a function of and mass*

•*Measure gas fractions as a function of redshift, mass, environment and galaxy morphology; explore the dependence of star formation rates on galaxy properties*

•*Resolve clumps, measure dynamical masses, velocity dispersions and gas fractions at ~few hundred pc (~0.03" - 0.05") resolution; together with ELTs, resolve nature and internal evolution of clumpy high-z galaxies*

•*Measure outflow rates of cold gas and test feedback models*

•*Together with ELTs, establish MBH/Mgal as a function of z, L for obscured and unobscured AGN population*