

rotation-dominated

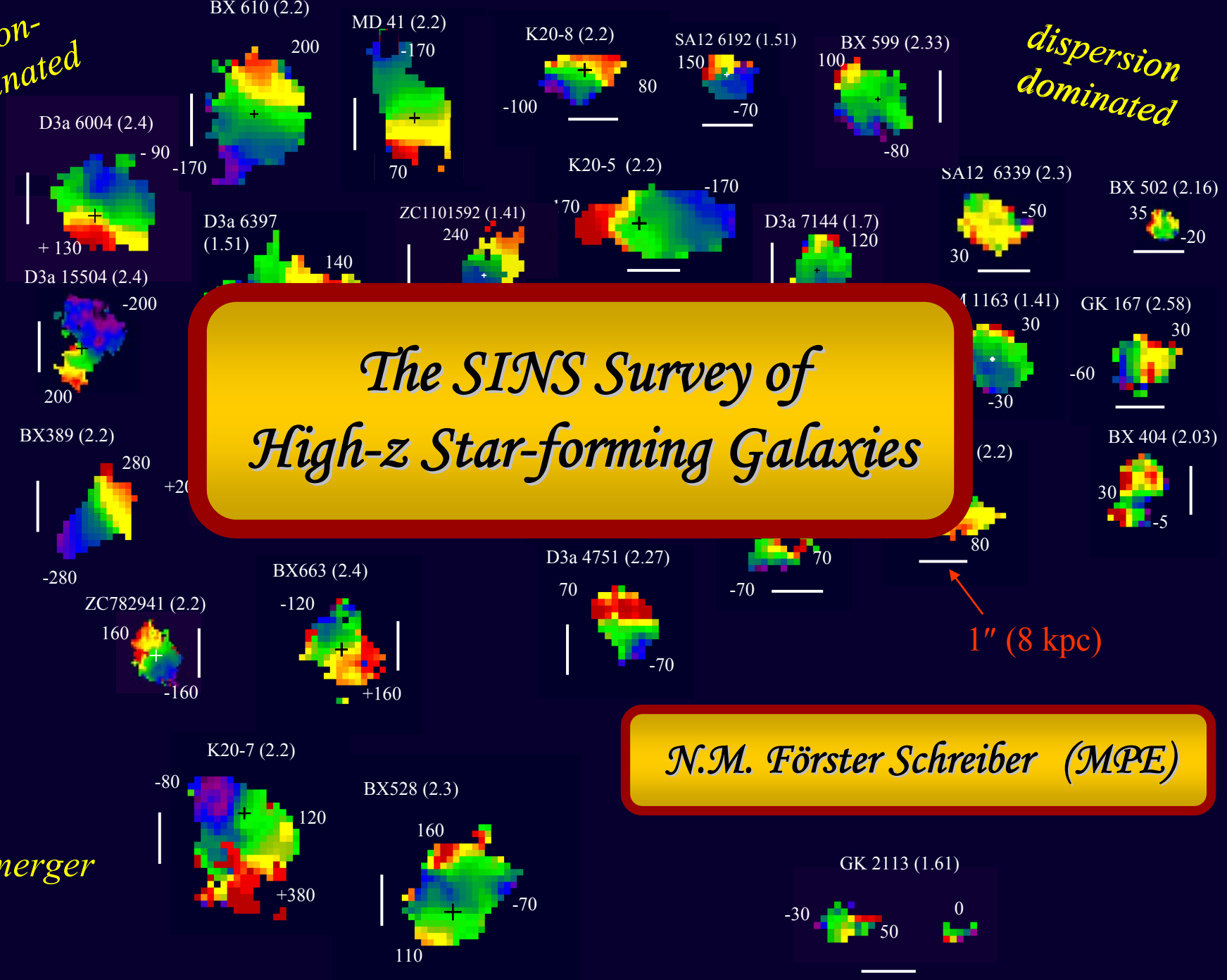
dispersion dominated

The SINS Survey of High-z Star-forming Galaxies

N.M. Förster Schreiber (MPE)

merger

1" (8 kpc)



The Team and Collaborations

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USM

Spatially-resolved Studies of $z \sim 1-4$ Star-forming Galaxies

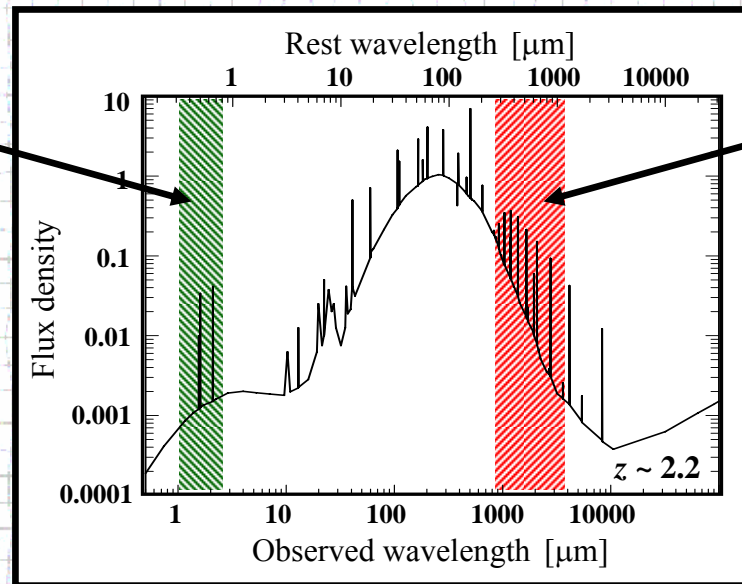
Dynamics, morphologies, physical properties



Spectroscopic **I**maging survey
of high redshift galaxies in the
Near-IR with
SINFONI at VLT

GTO program

Rest-frame UV/optically selected
star-forming galaxies



Sub**M**m **G**alaxy **S**urvey
with the IRAM
Plateau de Bure
mm-interferometer

Long-term program

Submillimeter-selected
luminous dust-rich galaxies

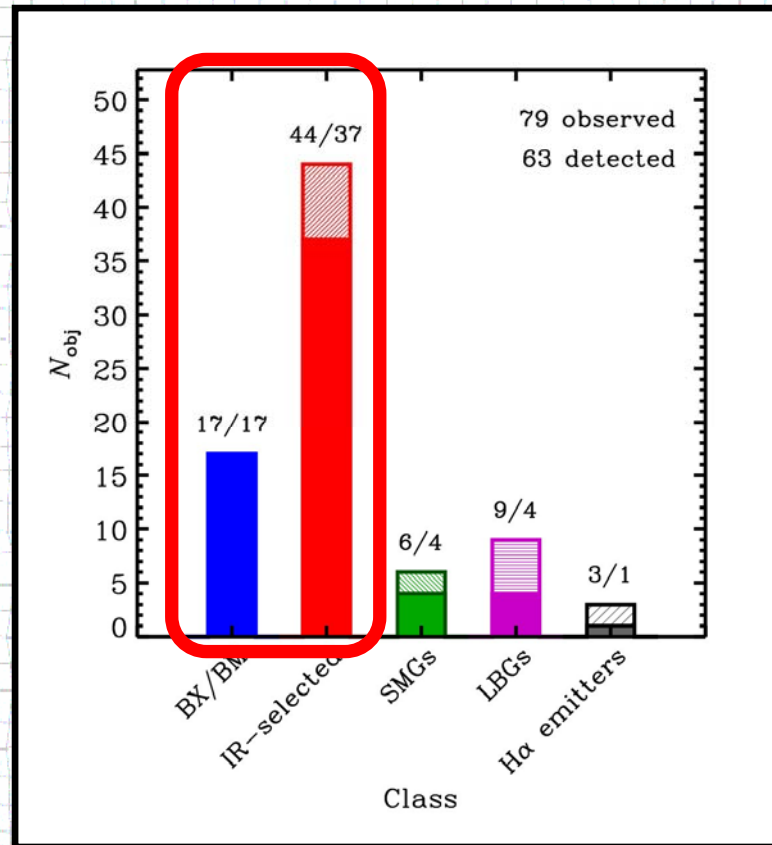


SINS Survey



Near-IR
integral field spectroscopy
with SINFONI, +AO,
at the VLT

(15 w/ AO observations,
+ 8 more pending)

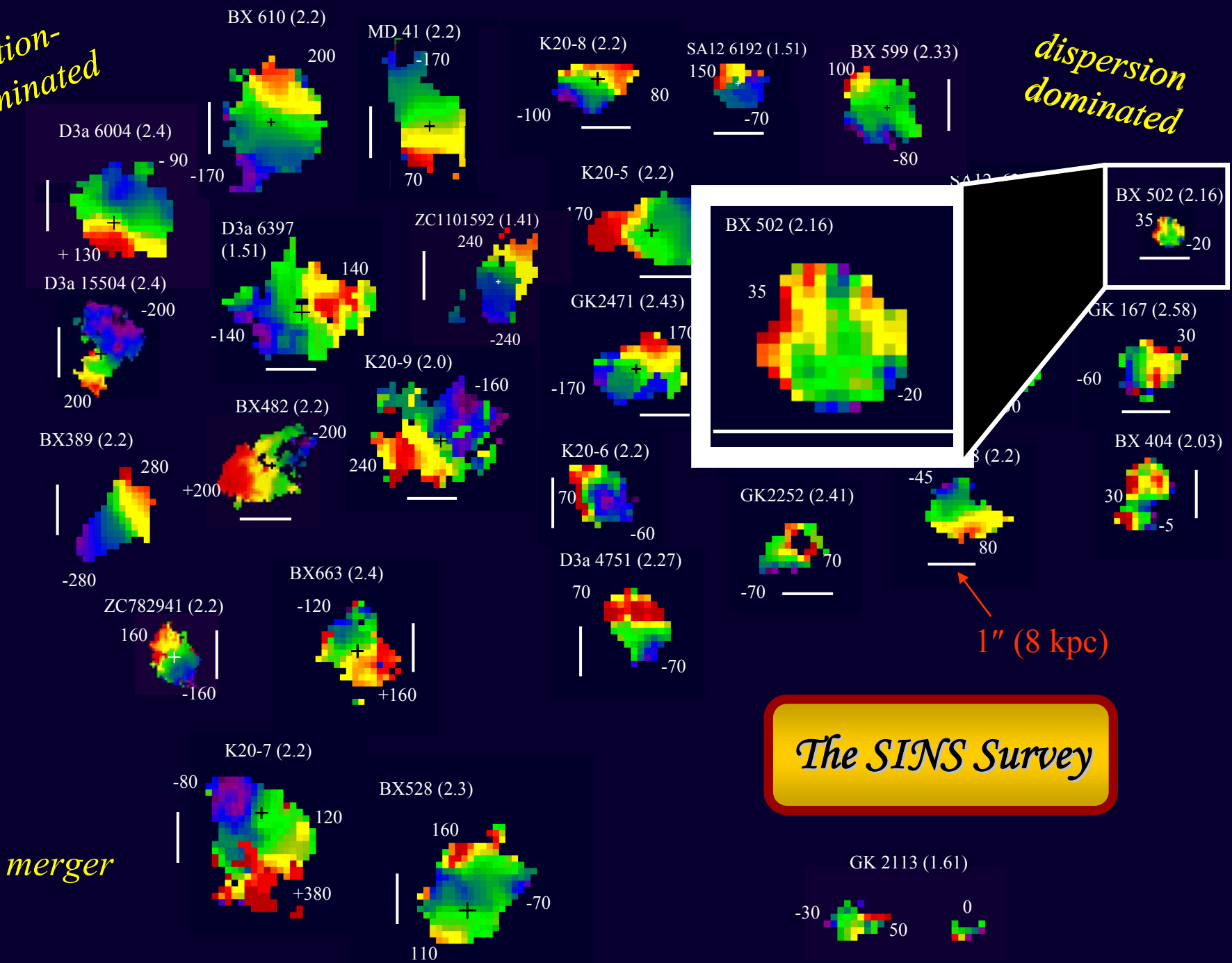


Complemented with
near-IR imaging
with HST/NICMOS-NIC2
and VLT/NACO+AO

Submm galaxies: with I. Smail, S. Chapman, F. Bertoldi, A. Blain, P. Cox, T. Greve, R. Ivison, R. Neri, A. Omont
See also: Tecza et al. (2004); Nesvadba et al. (2006a,b; 2007; 2008)

rotation-dominated

dispersion dominated

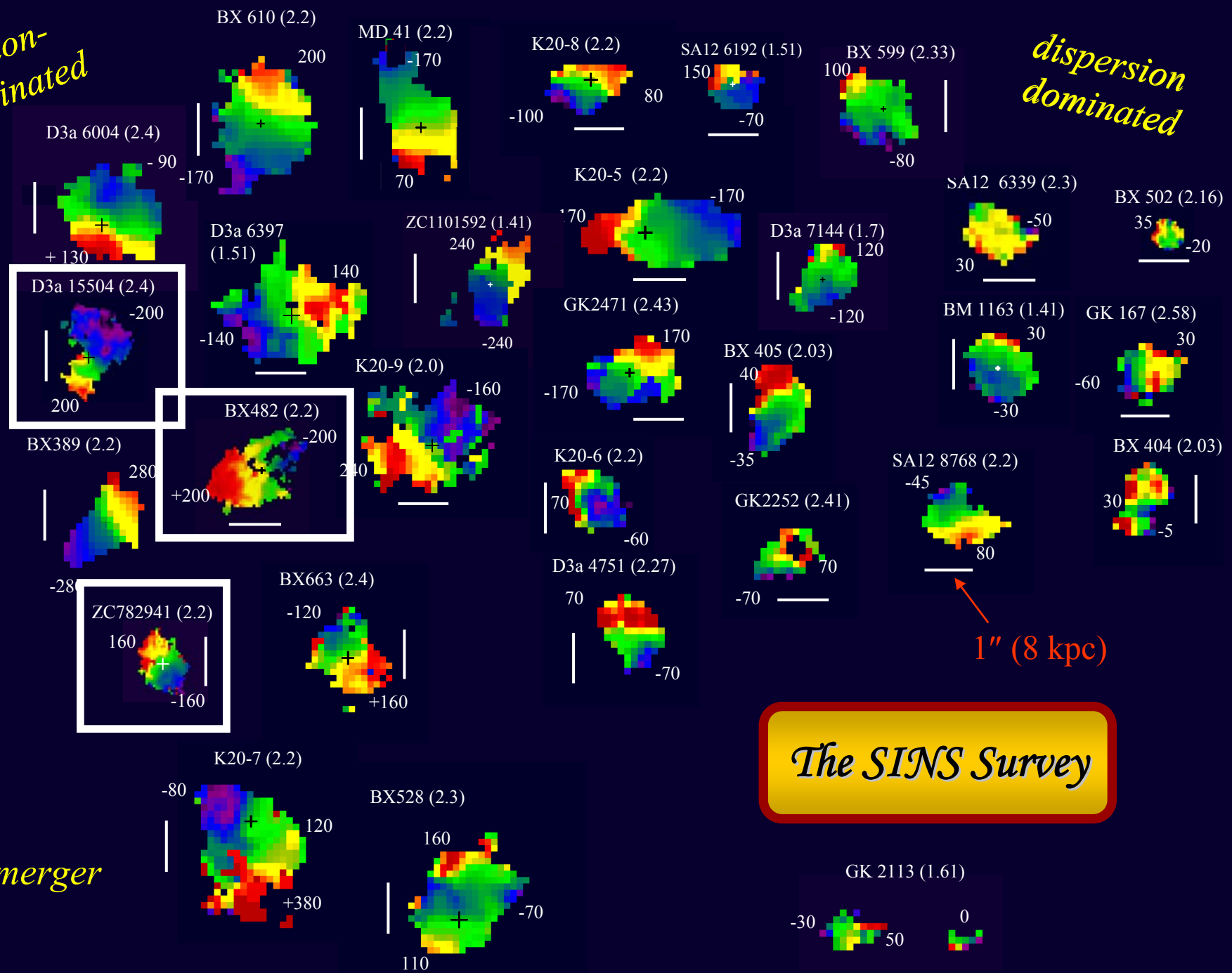


merger

The SINS Survey

rotation-dominated

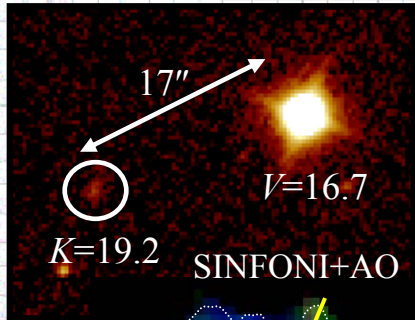
dispersion dominated



merger

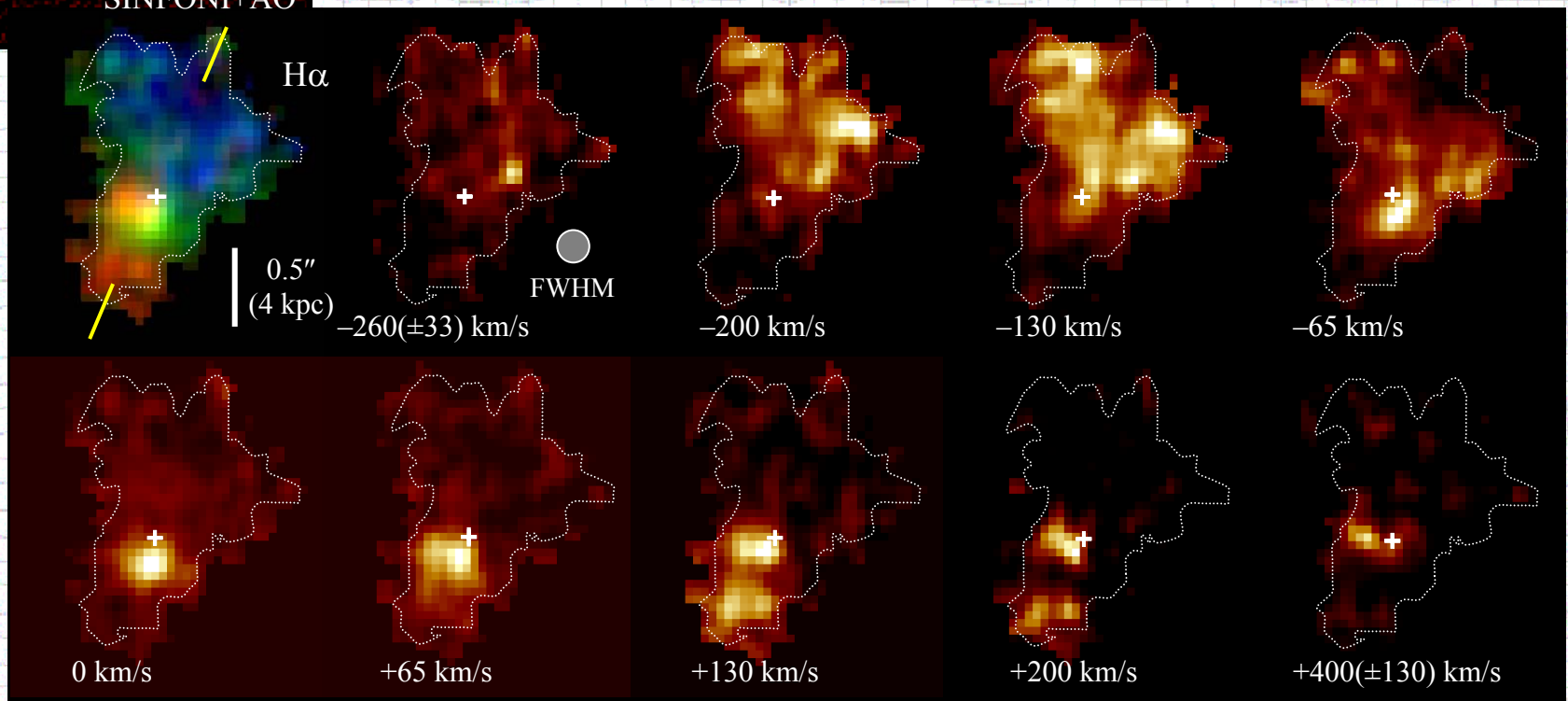
The SINS Survey

1st Detailed View of a $z \sim 2$ Galaxy with Integral Field Spectroscopy + AO



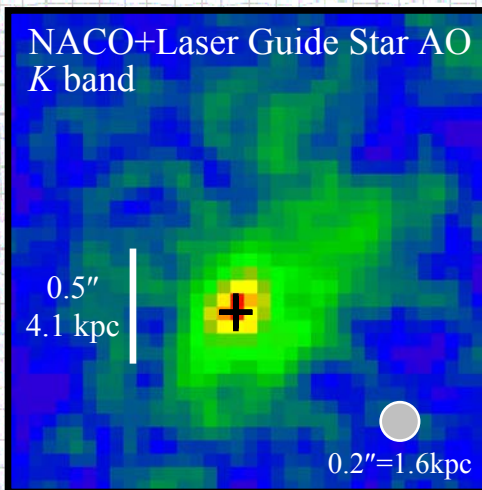
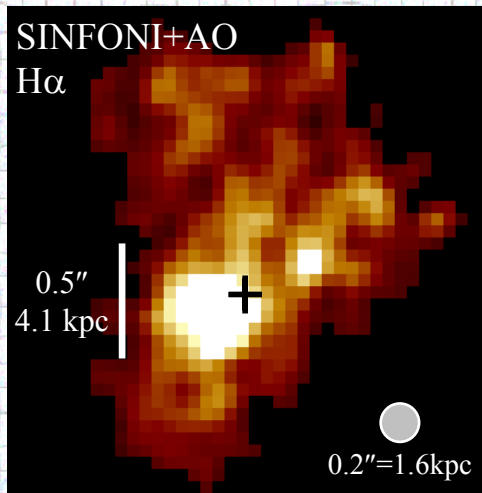
BzK-15504 at $z = 2.38$

$\text{FWHM} \approx 0.15'' \rightarrow \approx 1.2 \text{ kpc}$



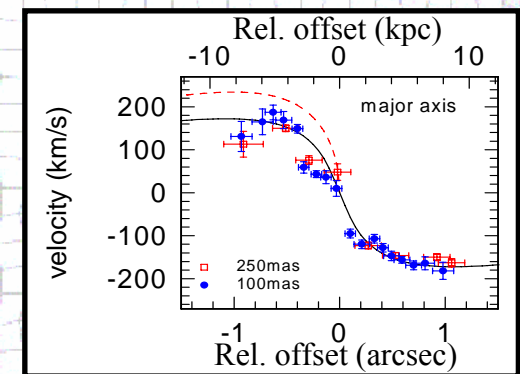
Physical Properties

BzK-15504 at $z = 2.38$



- ➔ Large, massive, turbulent, gas-rich rotating disk
- ➔ Stellar disk + nascent stellar bulge
- ➔ Rapidly converting a significant fraction of its baryonic mass into stars
- ➔ No obvious evidence of major merger

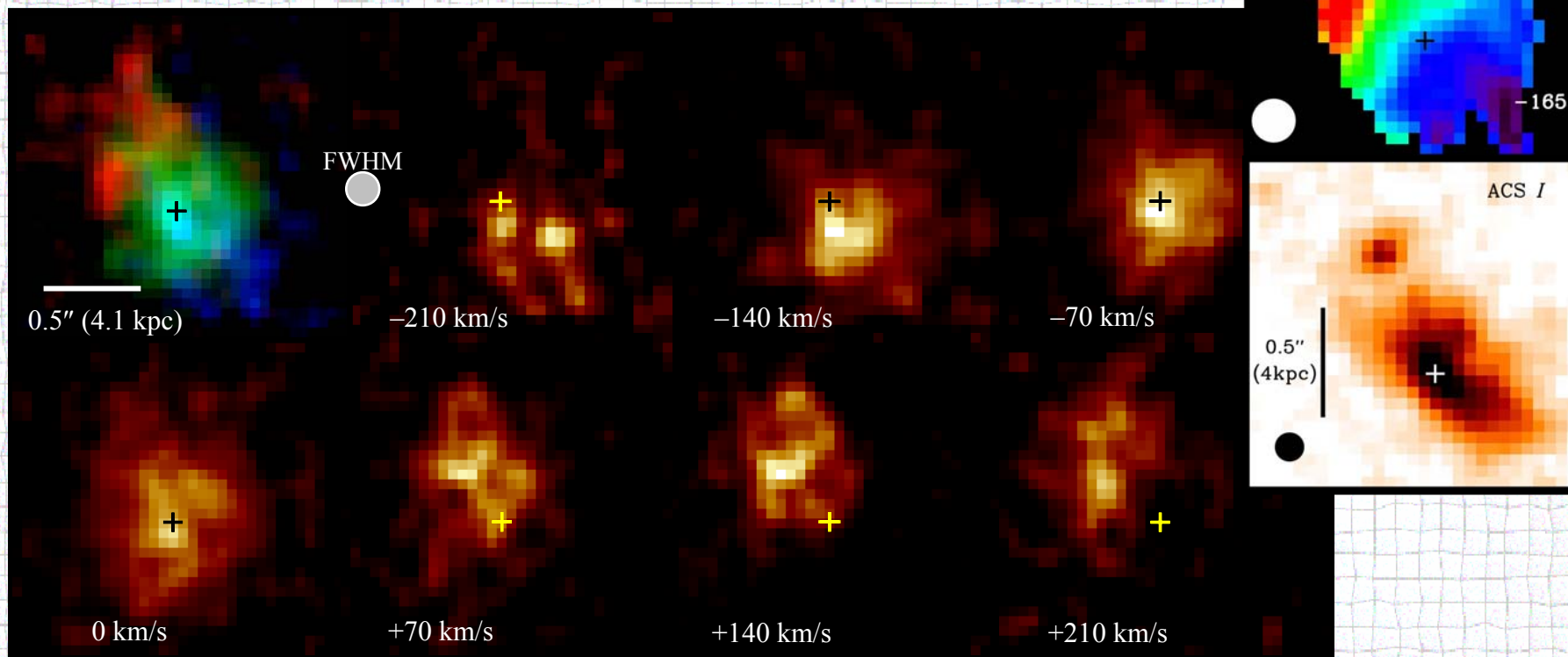
-
- $v_c = 230 \text{ km s}^{-1}$
 - $r_{1/e} \approx 4.5 \text{ kpc}$
 - $v_c/\sigma \approx 5$
-
- $M_{\text{dyn}} \approx 1.1 \times 10^{11} M_{\odot}$
 - $M_* \approx 0.8 \times 10^{11} M_{\odot}$
 - $M_{\text{gas}} \approx 0.4 \times 10^{11} M_{\odot}$
-
- $\tau_* \sim \tau_{\text{gas}} \sim 500 \text{ Myr}$
 - $\text{SFR} \sim 150 M_{\odot} \text{ yr}^{-1}$
-



SINFONI+Laser Guide Star AO Reveal Massive Star-forming Disk at $z \sim 2$

ZC782941 at $z = 2.18$

FWHM $\approx 0.2'' \rightarrow \approx 1.6$ kpc

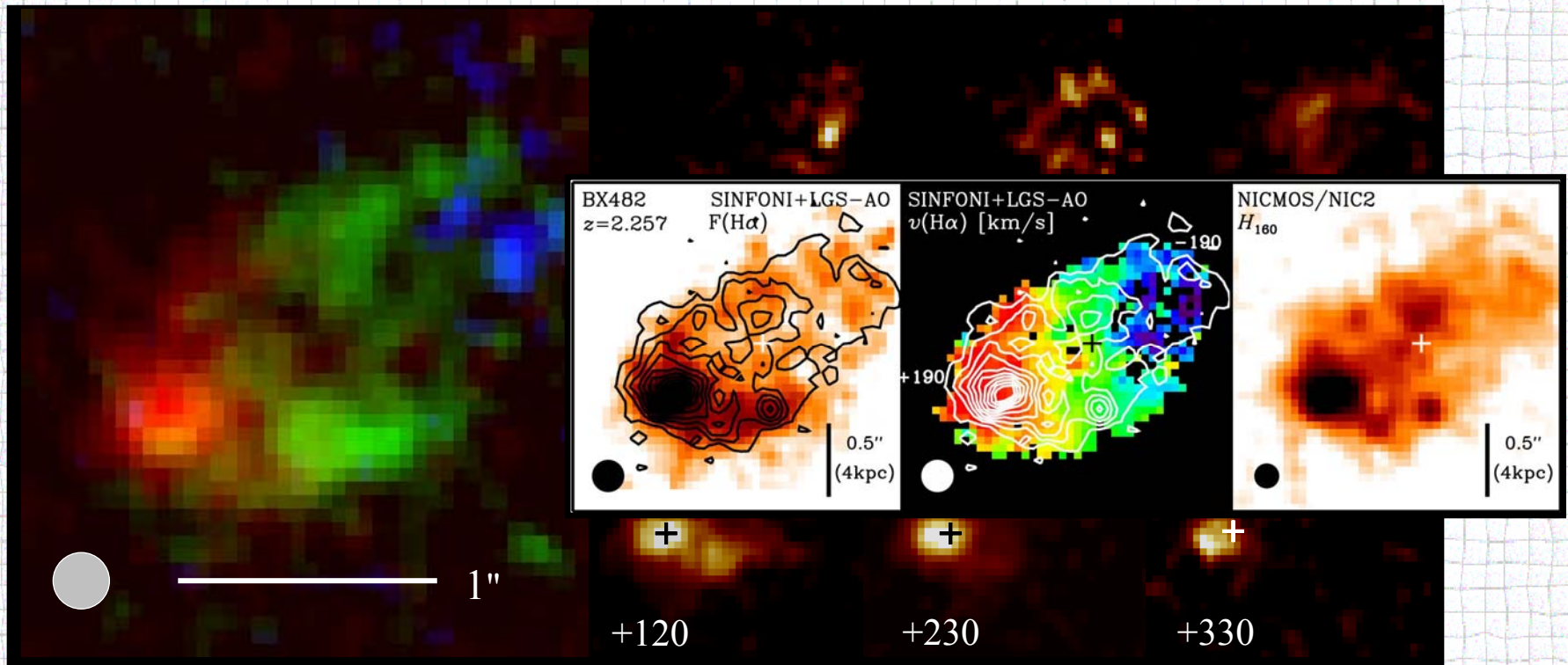


SINS & zCOSMOS teams; in prep.

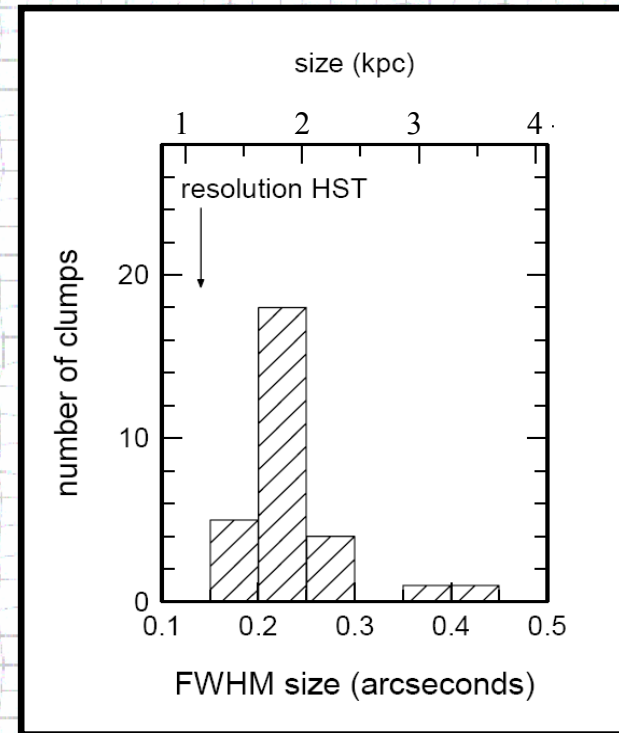
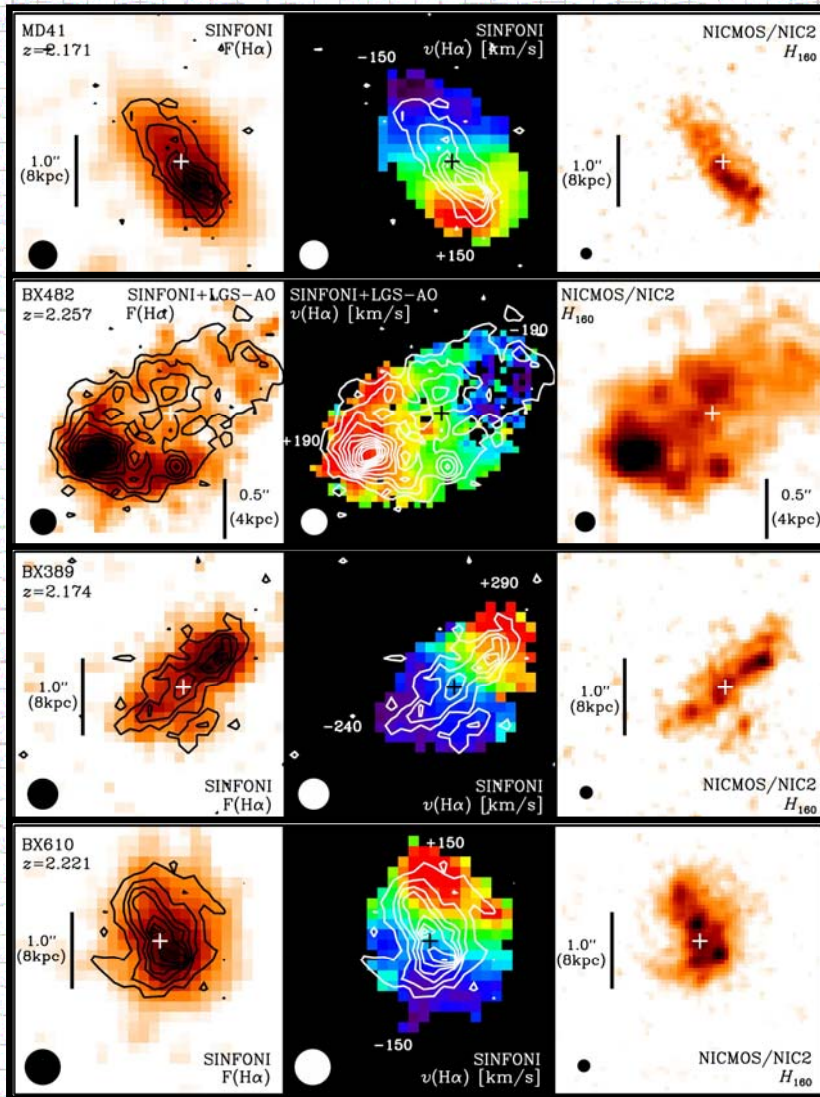
SINFONI+Laser Guide Star AO Reveal Massive Star-forming Ring at $z \sim 2$

Q2346-BX482 at $z = 2.26$

FWHM $\approx 0.2'' \rightarrow \approx 1.6$ kpc

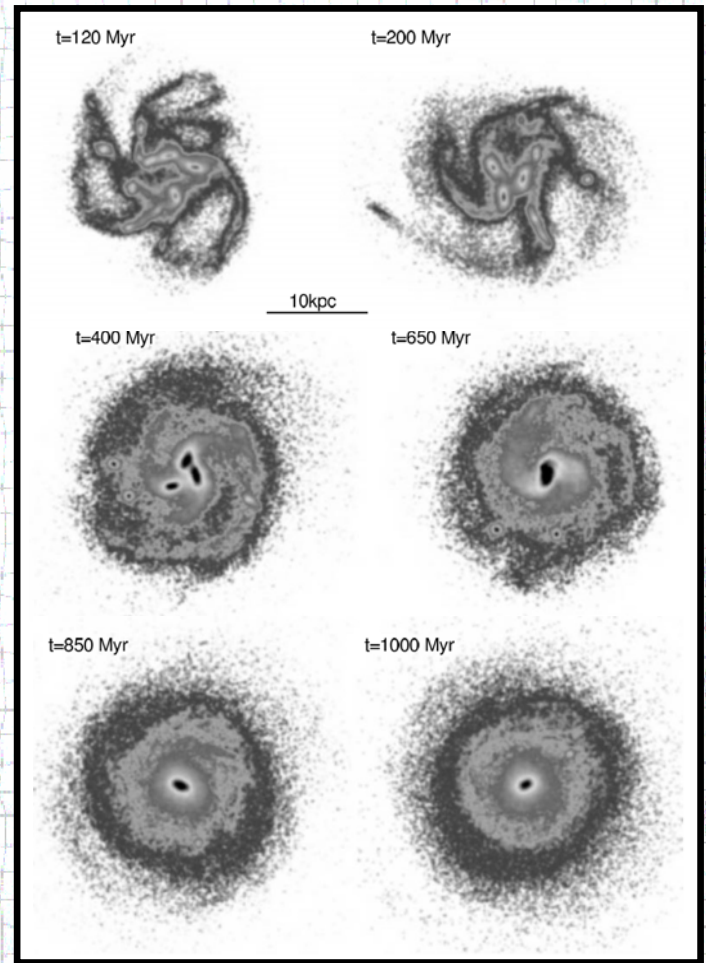
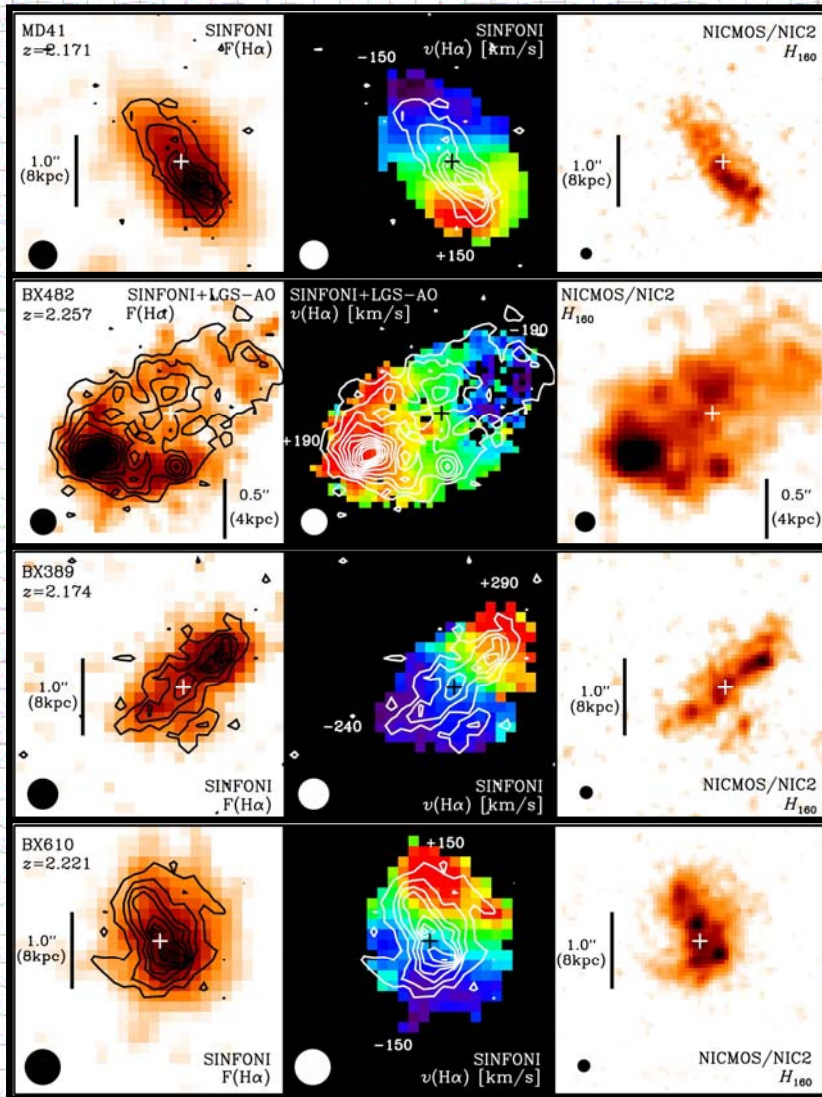


Dynamical Evolution of Gas-rich Disks



(Also, Cowie et al. 1995; van den Bergh et al. 1996; Giavalisco et al. 1996; Conselice et al. 2004; Lotz et al. 2004; Papovich et al. 2005; Toft et al. 2007; Law et al. 2007; Elmegreen, Elmegreen, et al. 2004-2008; and others)

Dynamical Evolution of Gas-rich Disks

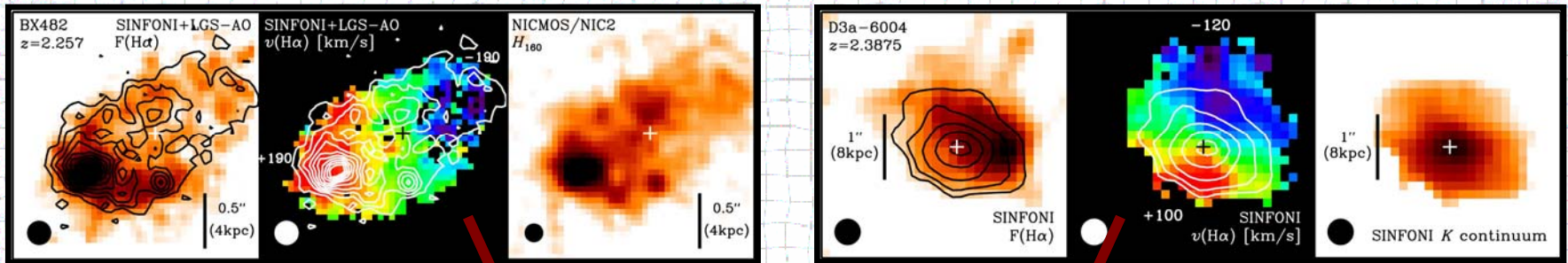


Bournaud et al. (2007; 2008)

Also, e.g., Noguchi (1999); Immeli et al. (2004a, b); Semelin & Combes (2002); Naab et al. (in prep.)

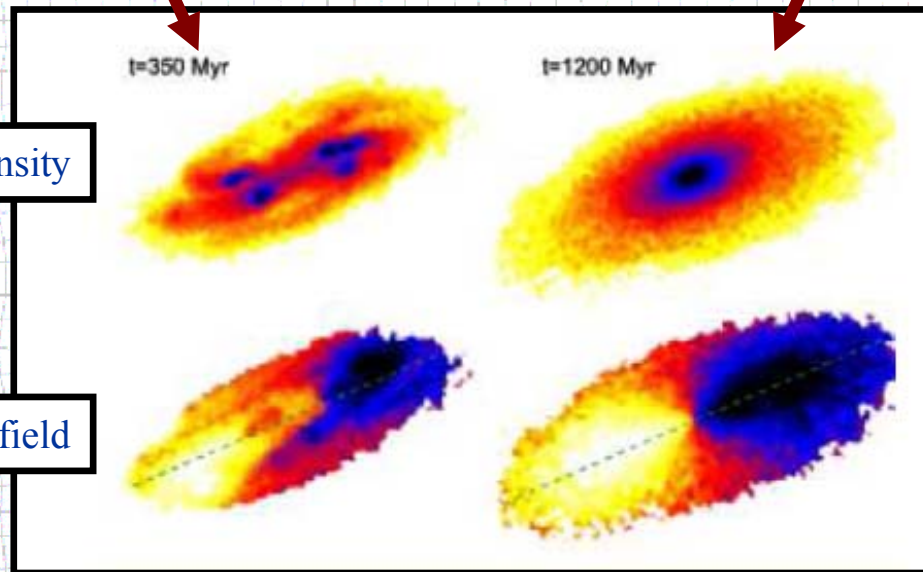
Förster Schreiber, Shapley, et al. (2008); Genzel et al. (2008)

Dynamical Evolution of Gas-rich Disks



Stellar surface density

Velocity field



Evidence for Bulge Growth

D3a6004
 $z=2.39$

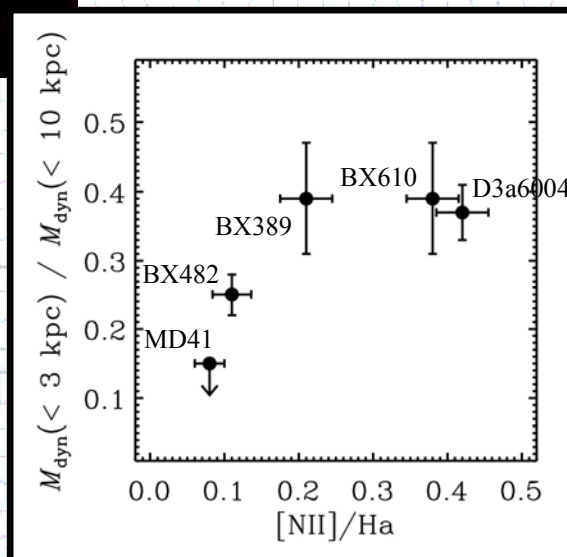
BX610
 $z=2.21$

BX389
 $z=2.17$

BX482
 $z=2.26$

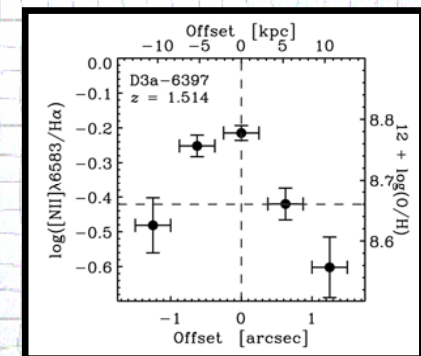
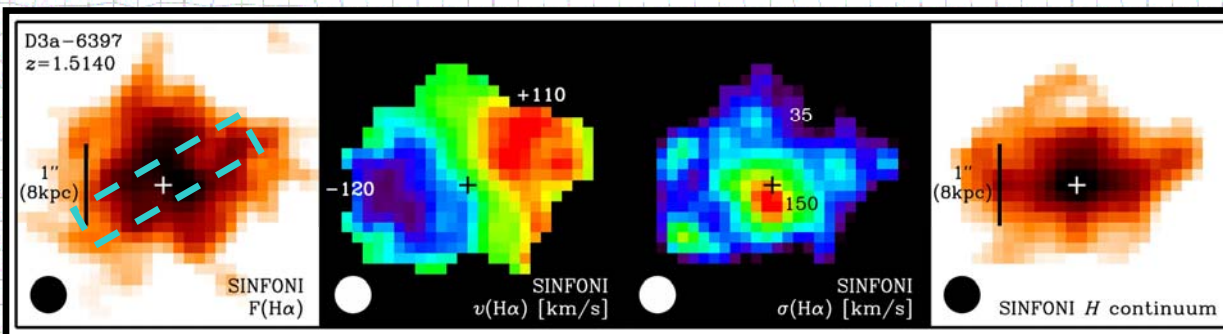
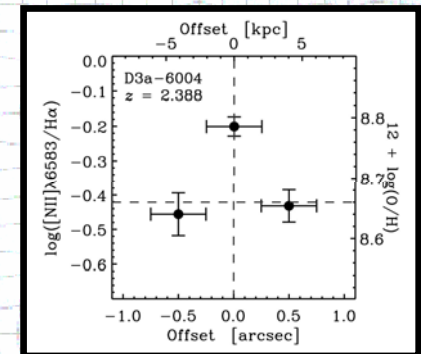
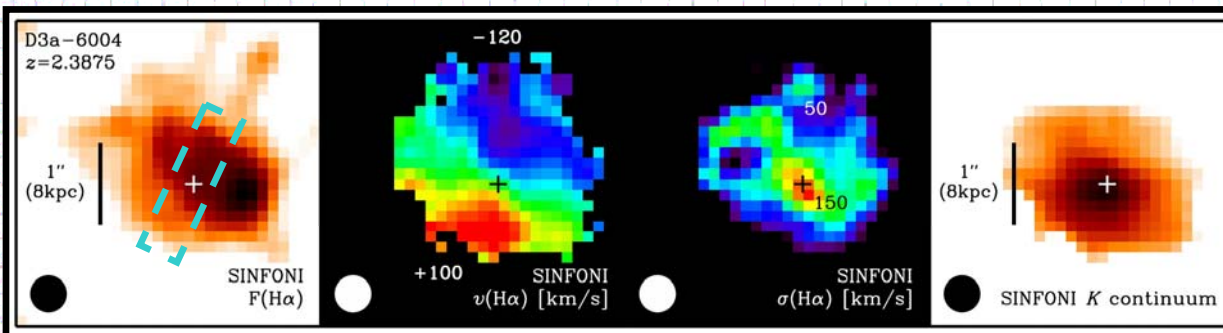
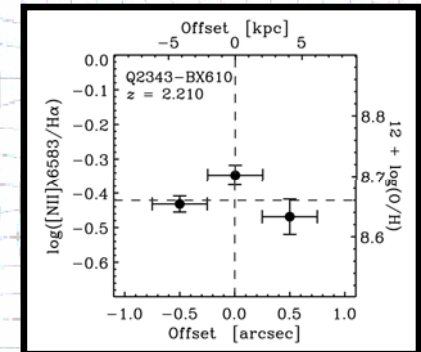
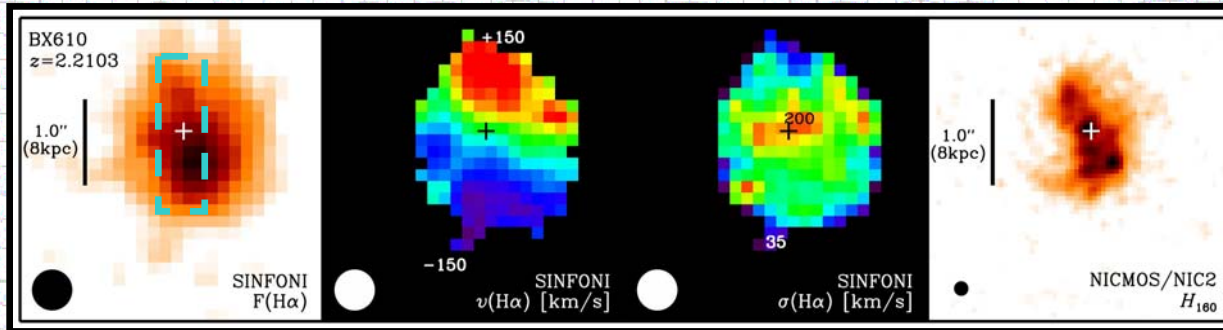
MD41
 $z=2.17$

H α : blue
ACS: green
NICMOS: red



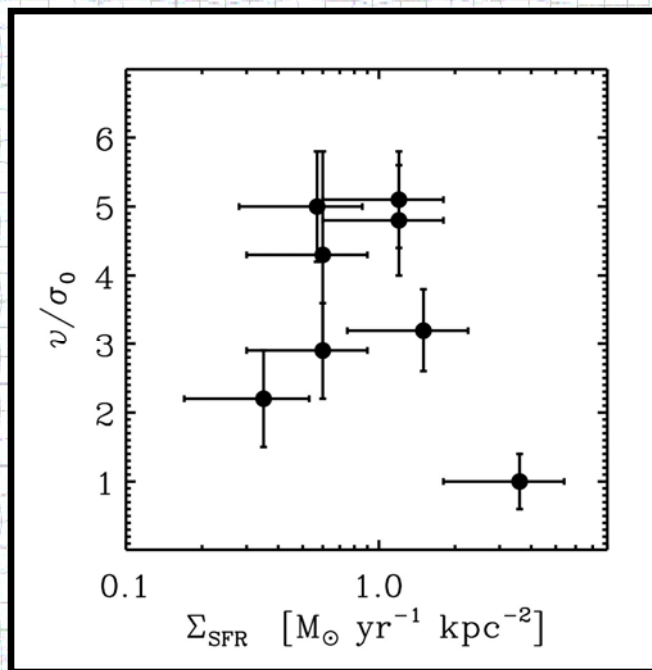
Genzel et al. (2008)

Metallicity Gradients in $z \sim 2$ Disks

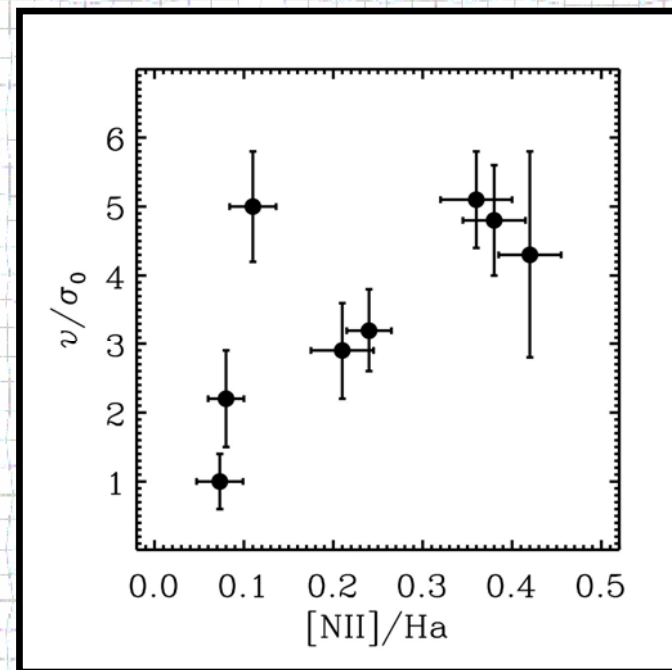


Origin of the Large Velocity Dispersion in $z \sim 2$ Gas-rich Star-forming Disks

Star formation feedback?



Gas accretion?

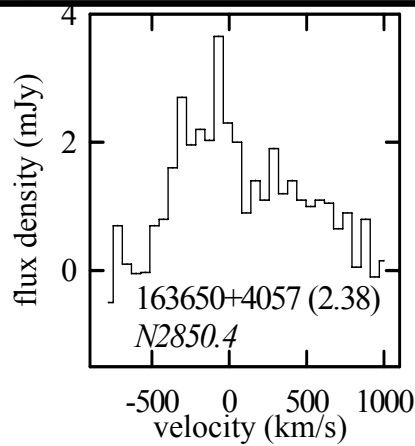


IRAM Plateau de Bure Interferometry of SMGs Reveal Compact Mergers

SMMJ163650+4057 (N2 850.4)
 $z=2.39$

0.5"

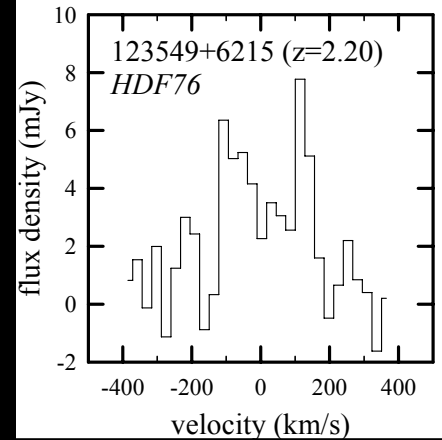
CO 7-6 (red; 0.45" FWHM)
ACS (blue), NICMOS (green)



SMMJ123549+6215
 $z=2.2$

0.5"

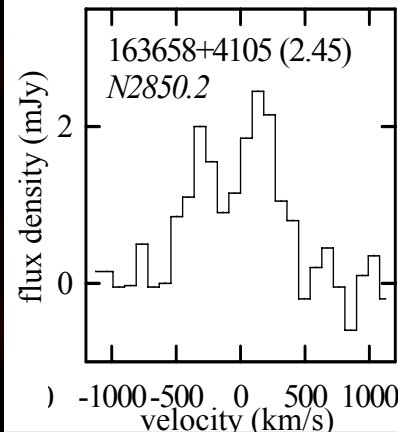
CO 7-6 blue/red components
(0.3" FWHM)



SMMJ163658+4105
 $z=2.45$

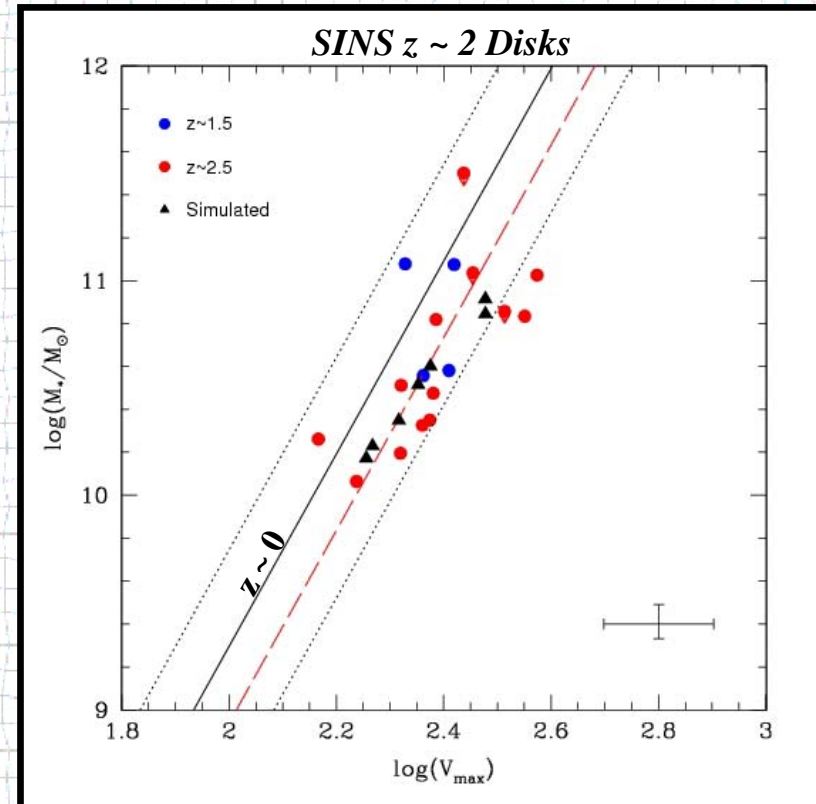
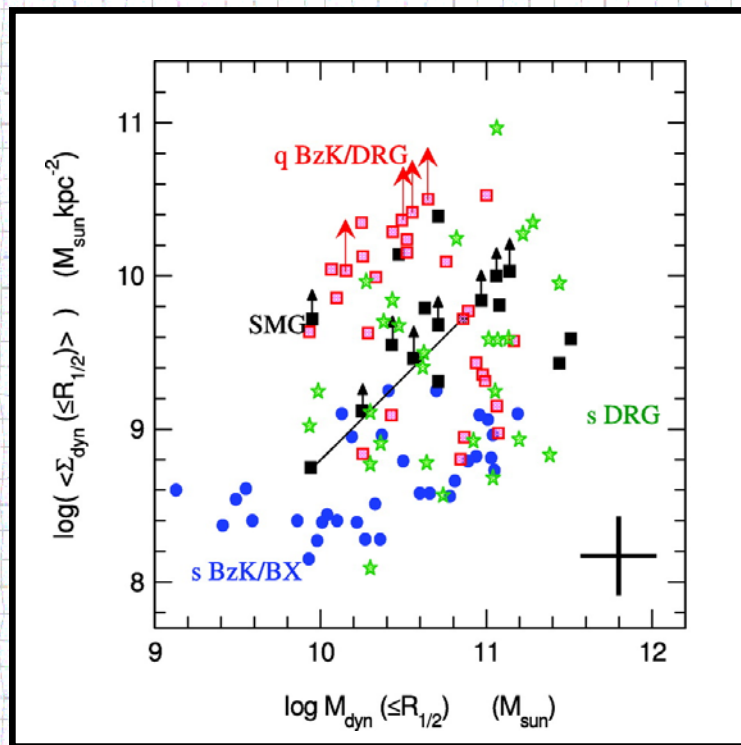
0.5"

CO 7-6
(0.3" FWHM)



Tacconi et al. (2006, 2008)
(Also: Swinbank et al. 2006)

Disks vs Dissipative Mergers at $z \sim 2$



Bouché et al. (2007); Tacconi et al. (2006; 2008); Cresci et al. (2008)

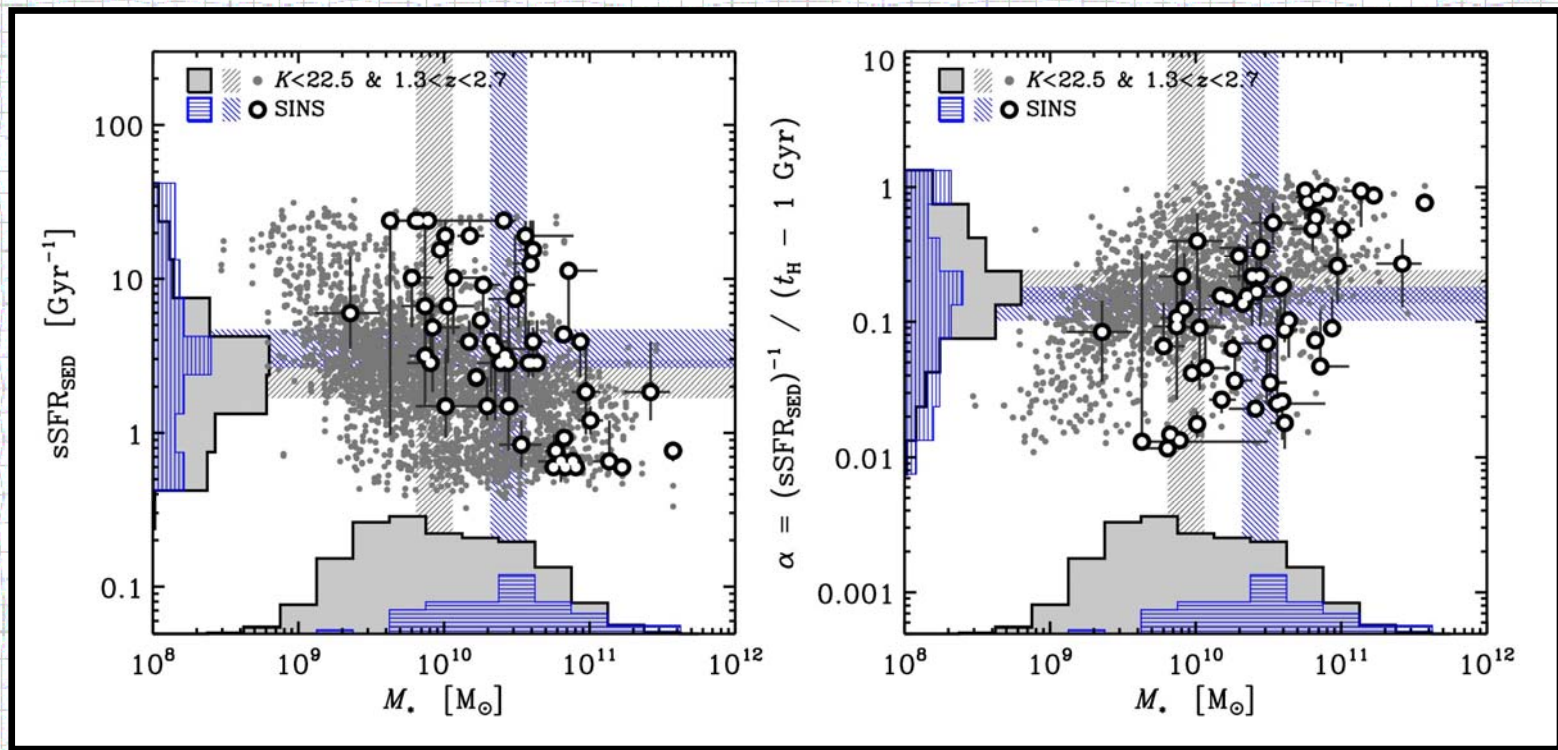
Daddi et al (2005); Trujillo et al (2006); Toft et al (2007); Zirm et al (2007); Cimatti et al (2008); van Dokkum et al (2008)

Bell & de Jong (2001); Conselice et al. (2005); Kassin et al. (2007); Somer-Larsen et al. (2008); Somerville et al. (2008)

Rapid Star Formation/Mass Accretion

For many SINS $z \sim 2$ star-forming galaxies:

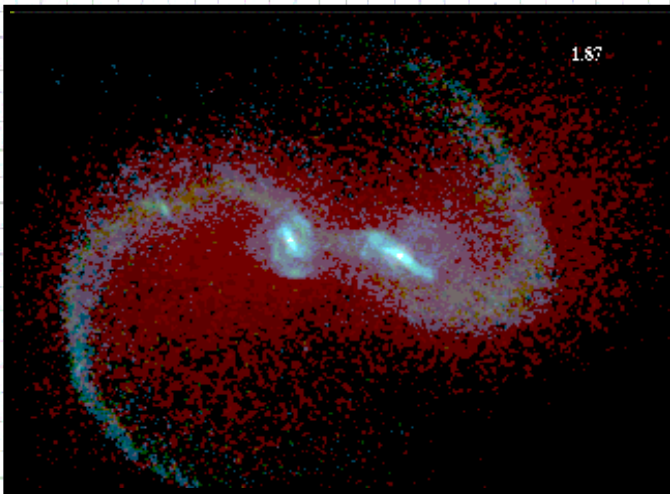
$$\tau_{\star} \sim \tau_{\text{gas}} \sim 500 \text{ Myr} \sim \text{several } \tau_{\text{dyn}} \ll t_{\text{Hubble}}$$



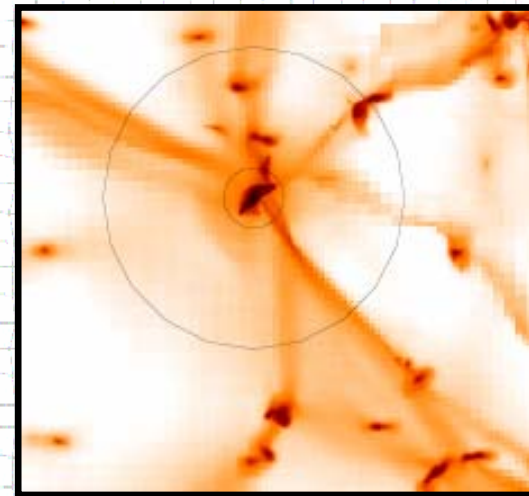
Förster Schreiber et al. (2006, 2008); Genzel et al. (2006, 2008)
(FIREWORKS/CDFS data: Wuyts et al. 2008)

Rapid Star Formation/Mass Accretion: Major Mergers or Smoother Infall?

Major mergers



Cold flow/minor mergers

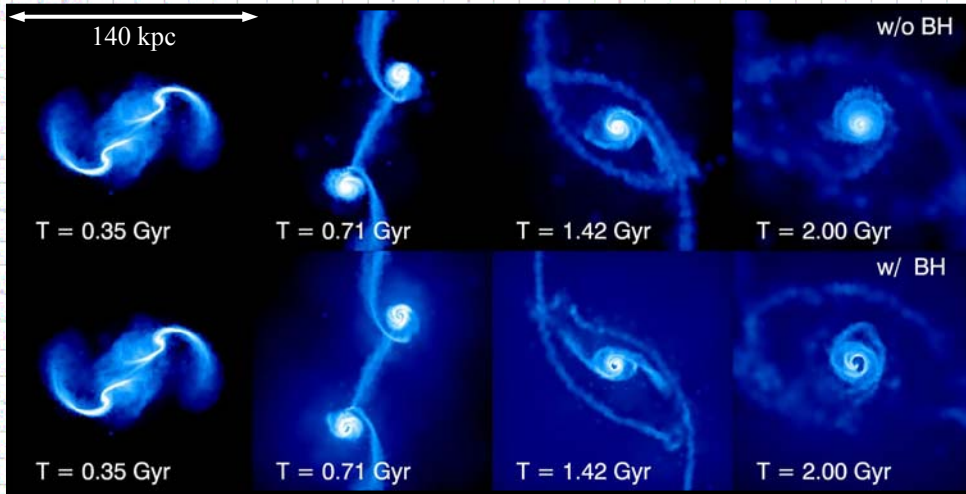


*(e.g., Toomre & Toomre 1972; Barnes & Hernquist 1996;
Springel & Hernquist 2005; di Matteo et al. 2005;
Naab & Burkert 2003,2006; Hopkins et al. 2006;
Tacconi et al. 2006,2008; Swinbank et al. 2006)*

*(e.g., Dekel & Birnboim 2003,2006; Kereš et al. 2005;
Kitzbichler & White 2007; Guo & White 2008;
Ocvirk et al. 2008; Genel et al. 2008;
Daddi et al. 2007; Noeske et al. 2007; Davé 2008)*

Subsequent Evolution

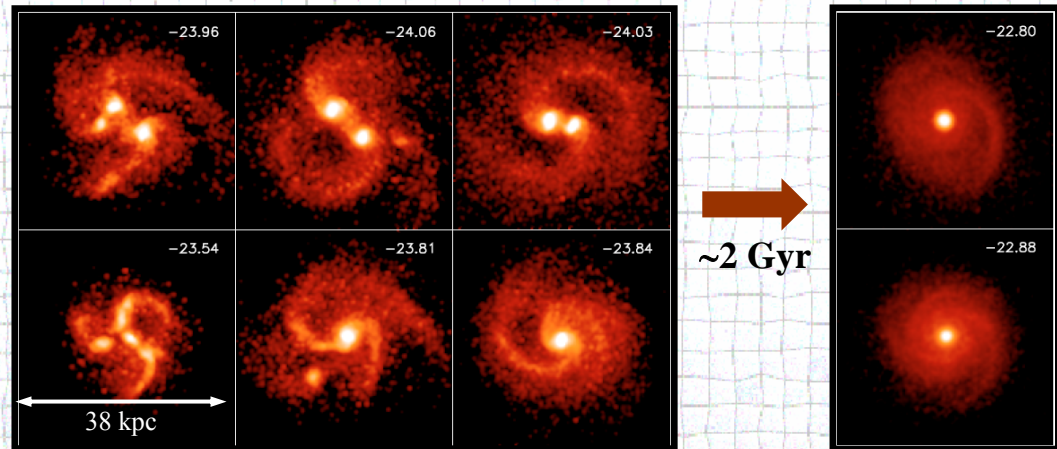
Gas-rich mergers + vigorous feedback



Robertson et al. (2005)

Major mergers?
Secular evolution?

Gas-rich star-forming disk: disk fragmentation + bulge formation



Immeli, Gerhard, et al. (2004)

(e.g., Noguchi 1999;
van den Bosch 2002;
Croton et al. 2005;
Governato et al. 2006, 2007;
Dekel et al. 2007;
Bournaud et al. 2007;
Genel et al. 2008;
and others)

Cold flows/minor mergers

Internal/secular processes

D3a6004
 $z=2.39$

BX610
 $z=2.21$

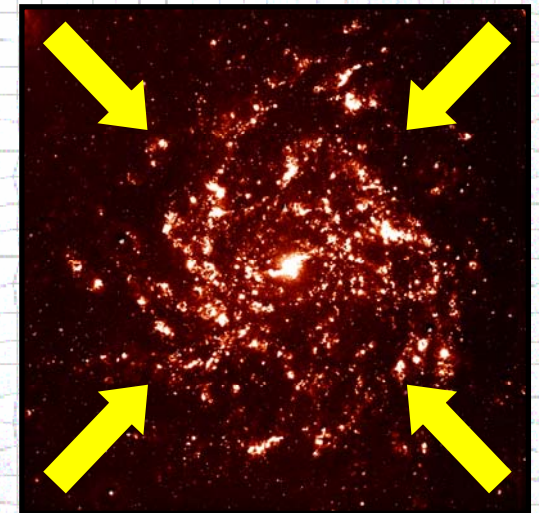
BX389
 $z=2.17$

BX482
 $z=2.26$

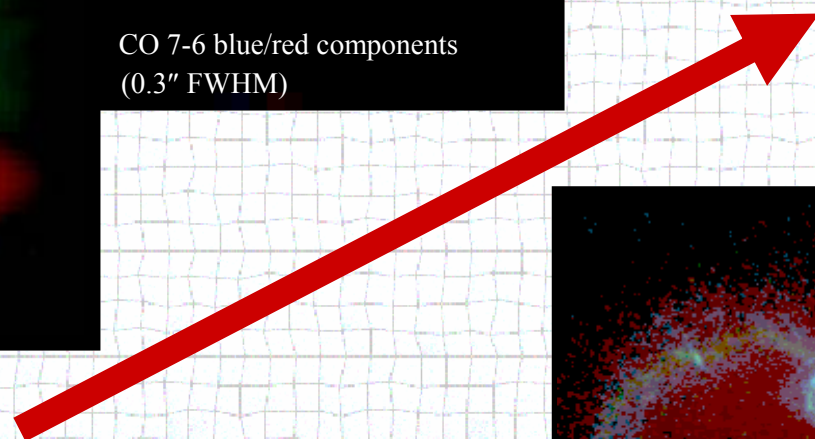
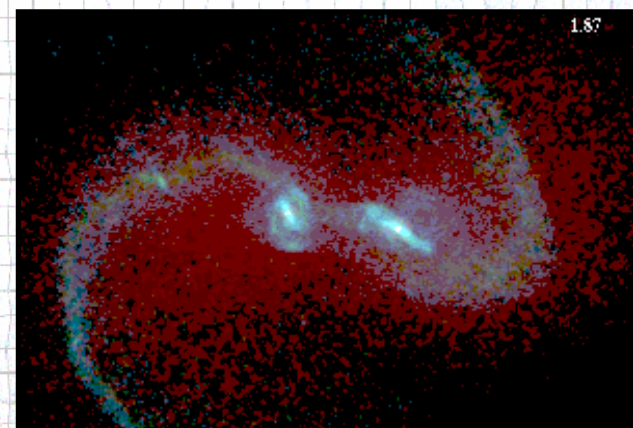
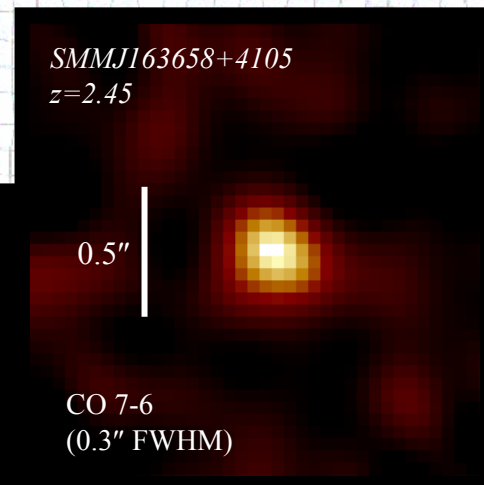
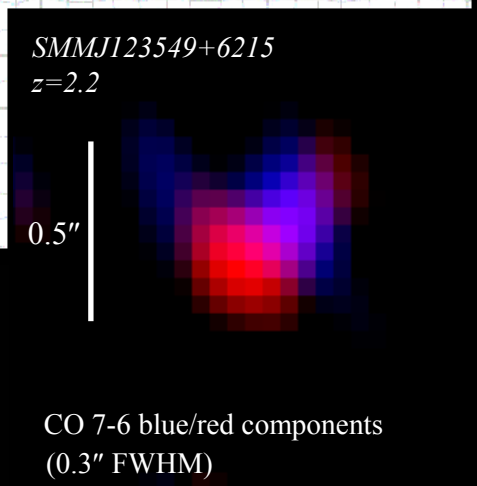
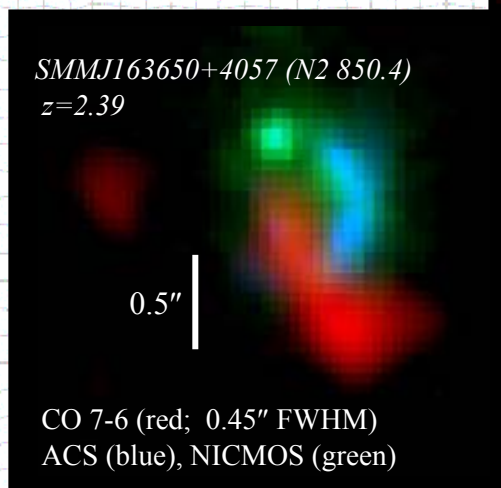
MD41
 $z=2.17$

Blue/green: young stars
Red: old stars

(e.g., Dekel & Birnboim 2003, 2006;
Kereš et al. 2005; Ocvirk et al. 2008;
Noguchi 1999; Semelin & Combes 2002;
Immeli et al. 2004; Bournaud et al. 2007, 2008)



Gas-Rich Major Mergers



(e.g., Toomre & Toomre 1972; Barnes & Hernquist 1996; Springel & Hernquist 2005; di Matteo et al. 2005; Naab & Burkert 2003, 2006)

SINS Highlights

- Spatially-resolved kinematics now possible at $z \sim 2$
 - Majority of disk-like systems among rest-UV/optically-selected galaxies*
 - Major mergers more important among more luminous submm-selected galaxies*
- Properties of massive $z \sim 2$ star-forming disks
 - Significantly more turbulent, gas-rich, with higher SFRs and large luminous clumps*
- Mass assembly, early evolution, and star formation activity
 - Evidence for smooth+rapid mass accretion via cold flows/minor mergers*
 - Evidence for internal/secular processes in gas-rich disks and rapid bulge formation*

