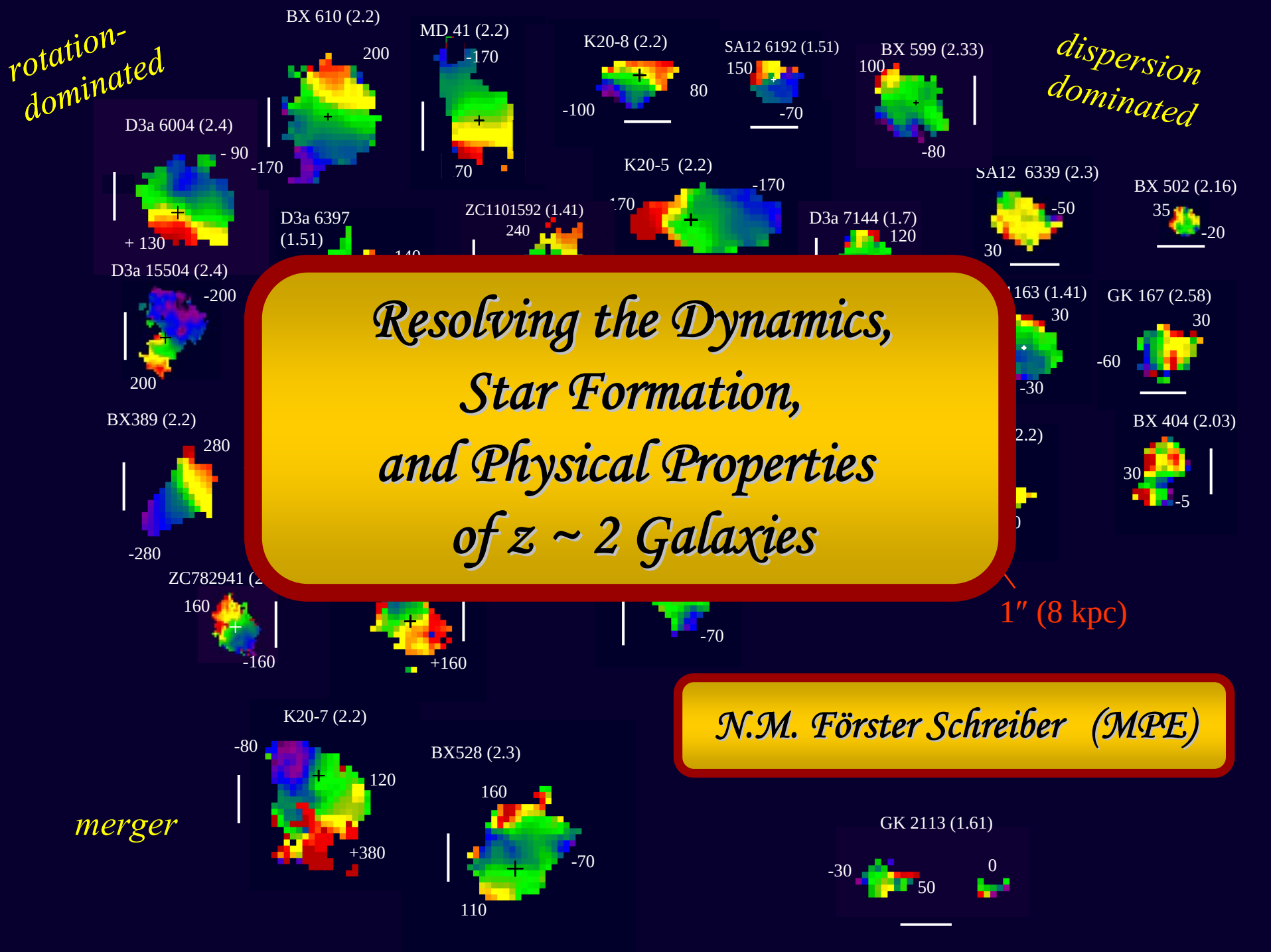

rotation-dominated
dispersion dominated
merger
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
D3a 6004 (2.4)
K20-5 (2.2)
SA12 6339 (2.3)
BX 502 (2.16)
D3a 6397 (1.51)
ZC1101592 (1.41)
D3a 7144 (1.7)
D3a 15504 (2.4)
GK 167 (2.58)
BX389 (2.2)
BX 404 (2.03)
ZC782941 (2
K20-7 (2.2)
BX528 (2.3)
GK 2113 (1.61)
Resolving the Dynamics, Star Formation, and Physical Properties of z ~ 2 Galaxies
1″ (8 kpc)
N.M. Förster Schreiber (MPE)

The Team and Collaborations

N.M. Förster Schreiber, R. Genzel, N. Bouché, G. Cresci,
R. Davies, K. Shapiro, P. Buschkamp, S. Genel, E.K.S. Hicks,
J. Kurk, L.J. Tacconi, D. Lutz, A. Sternberg, A. Verma,
F. Eisenhauer, S. Gillessen, R. Abuter,

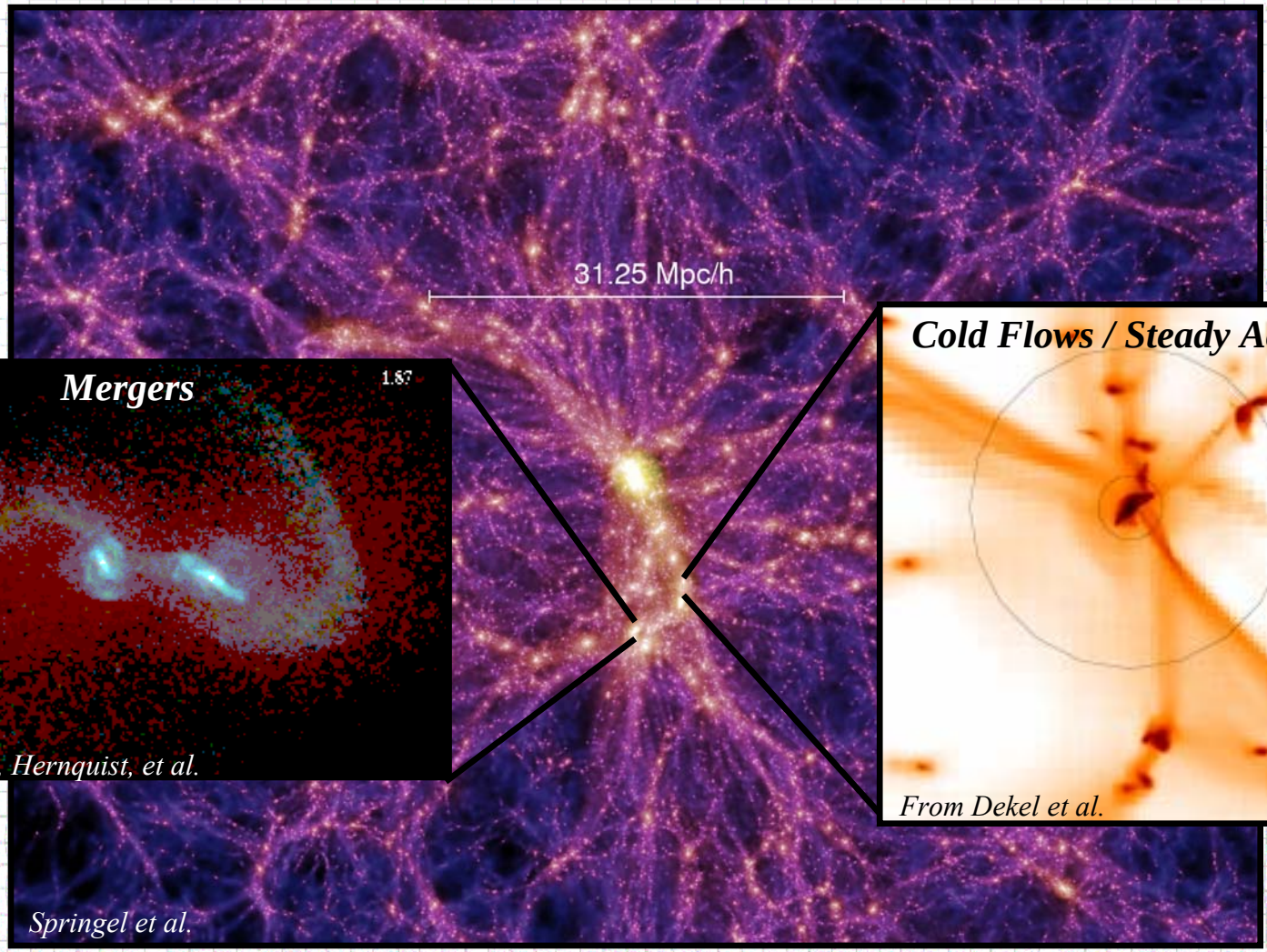
MPE/Berkeley/Tel Aviv/Oxford

A. Renzini, S. Lilly, A. Cimatti, E. Daddi, C. Mancini, Y. Peng, D. Vergani,
G. Zamorani, L. Pozzetti, P. Oesch, M. Mignoli, & zCOSMOS, GMASS, Deep3a Teams
Padova/ETH Zürich/Bologna/CEA Saclay/...

A.E. Shapley, D. K. Erb, C.C. Steidel
UCLA/UCSB/Caltech

A. Burkert, T. Naab, P. Johansson
USM

Star Formation and Mass Assembly at Early Stages of Galaxy Evolution

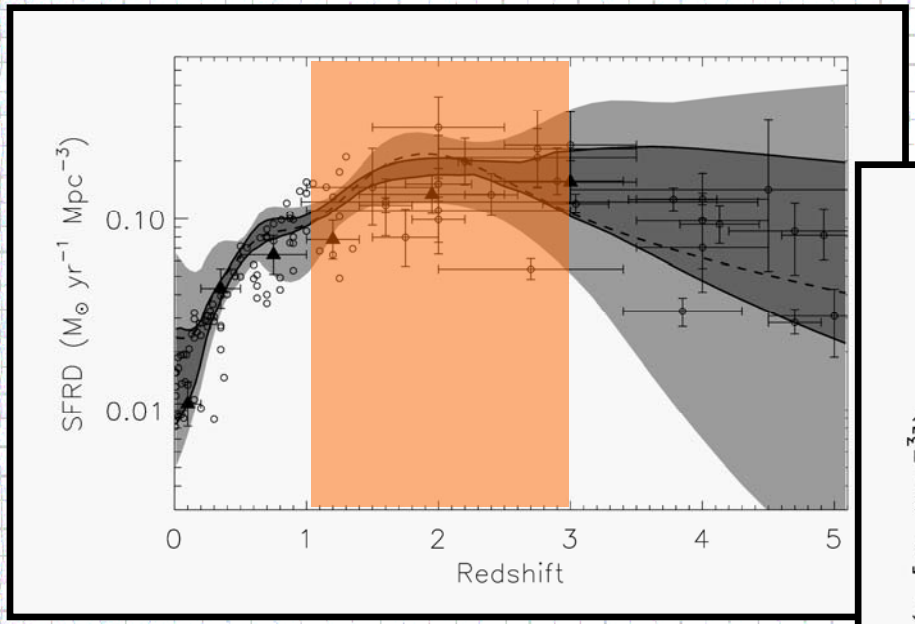


Springel et al.

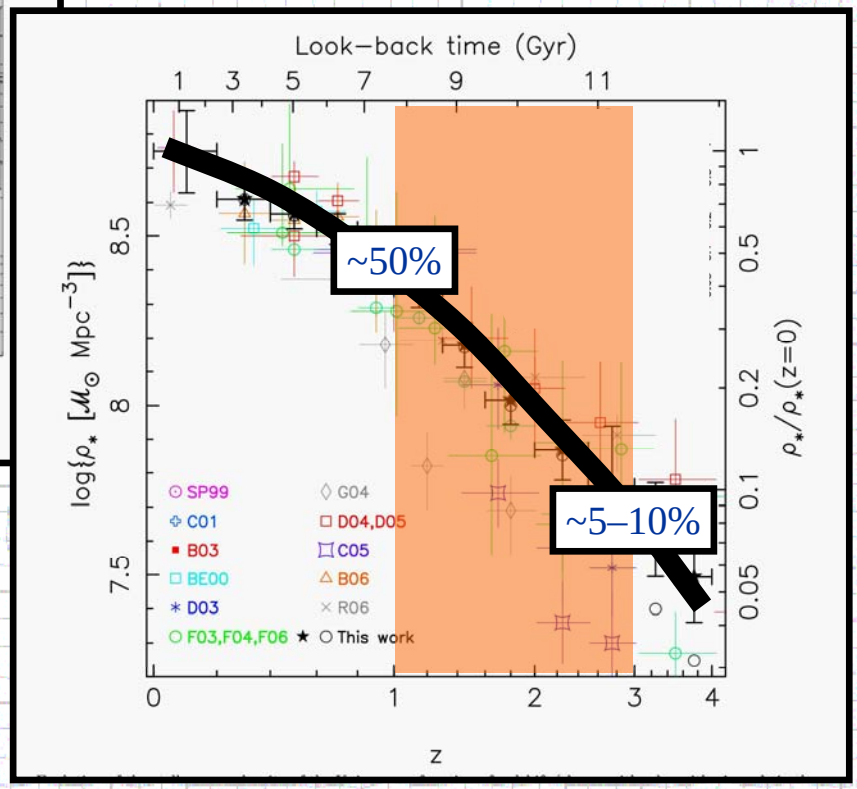
From Mihos, Hernquist, et al.

From Dekel et al.

Rapid Growth of Galaxies at z ~ 1 – 3



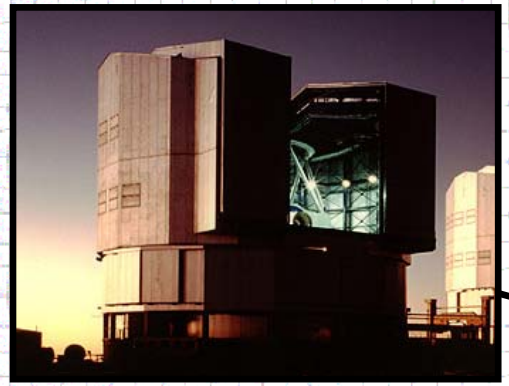
Le Borgne et al. (2009)



Perez-Gonzalez et al. (2009)

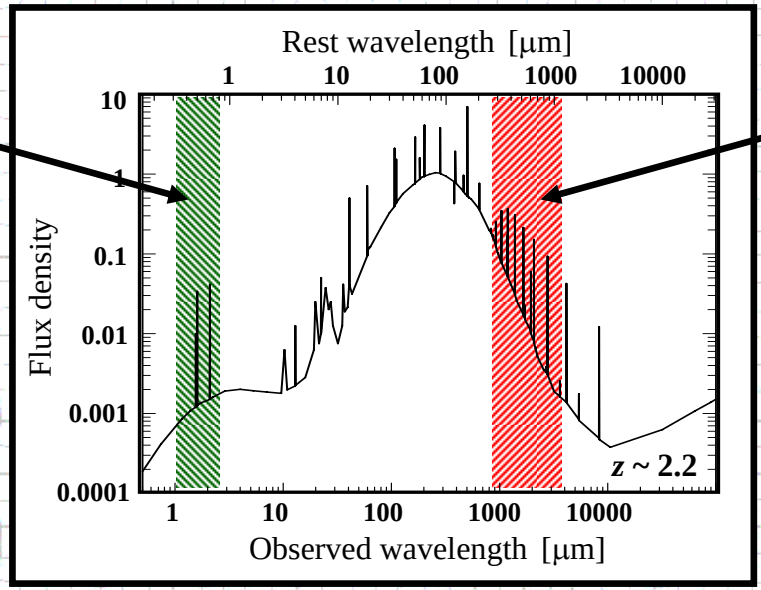
Spatially-resolved Studies of z~1–3 Star-forming Galaxies

Dynamics, morphologies, star formation, physical properties



Rest-frame optical

Stellar & nebular components



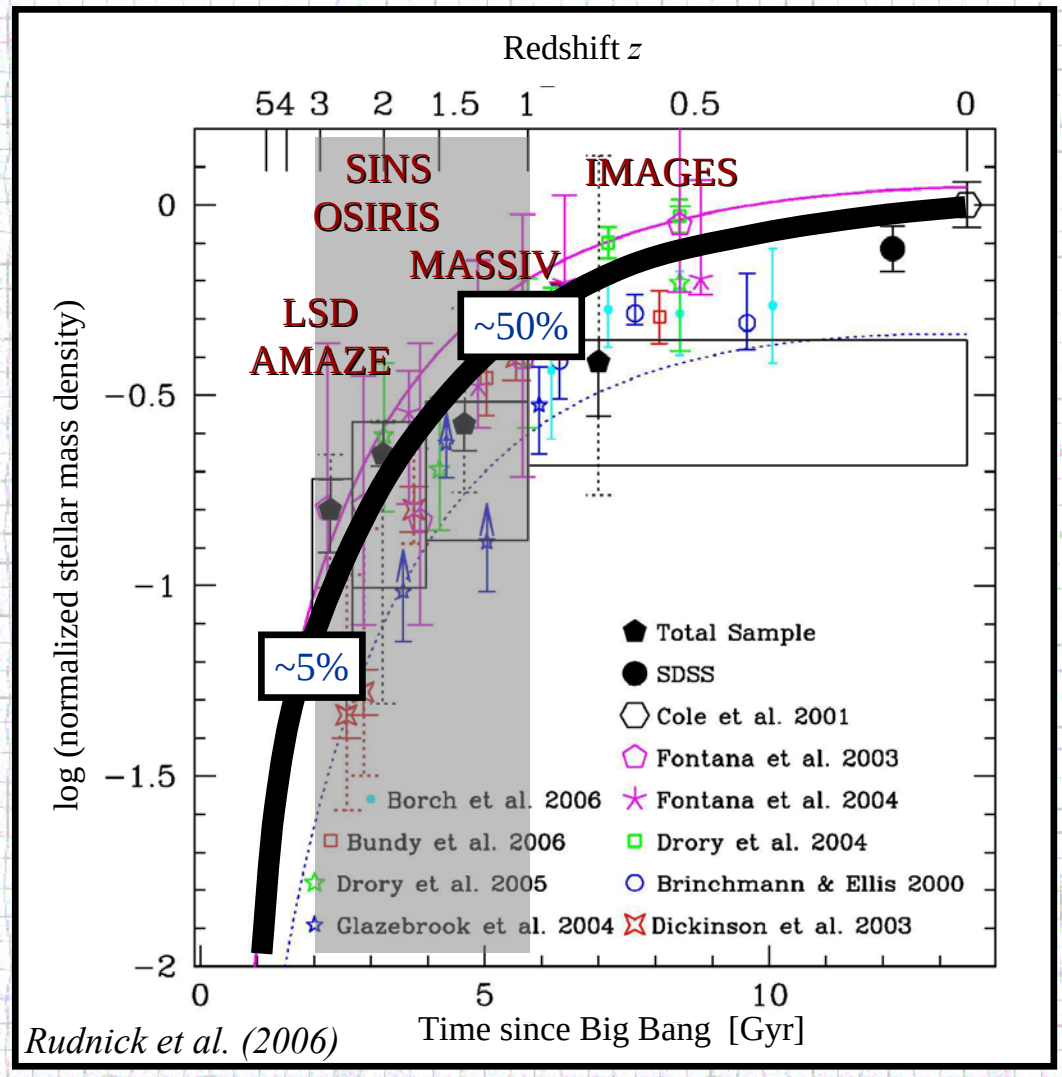
Rest-frame submm

Molecular gas & cold dust

Integral field spectroscopy and imaging
in the near-IR

Interferometry mapping
in the mm

Spatially-resolved Studies of Galaxy Dynamics and SF at z ~ 1 – 3



Rudnick et al. (2006)

Förster Schreiber et al. 2006, 2009;
Genzel et al. 2006, 2008;
Bouché et al. 2007; Shapiro et al. 2008;
Genel et al. 2008; Cresci et al. 2009

Wright et al. 2007, 2009;
Law et al. 2007,2009;

Épinat et al. 2009; Queyrel et al. 2009

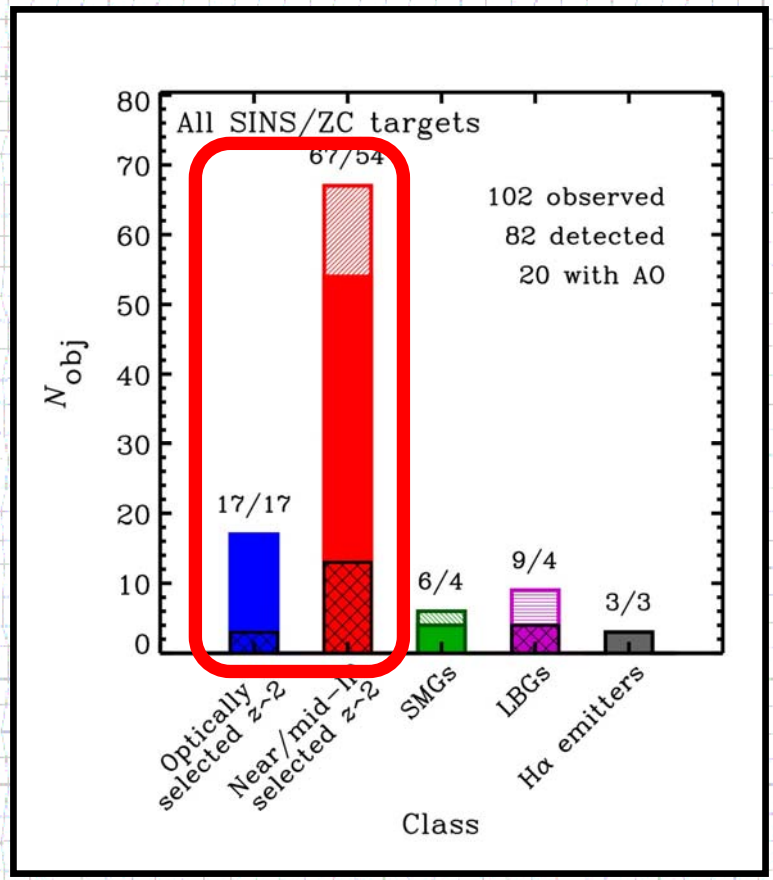
Maiolino et al. 2008;
Mannucci et al. 2009

Hammer, Puech, Flores, Yang, Neichel et al. 2005-2009

Nesvadba et al. 2006a,b; 2007; 2008
Swinbank et al. 2006, 2007, 2009;
Kriek et al. 2007; vStarkenburg et al. 2008;
Stark et al. 2008; Bournaud et al. 2008;
Lehnert et al. 2009; Jones et al. 2009;
Lemoine-Busserolle et al. 2010a,b

... Among others ...

SINS/ZC Survey

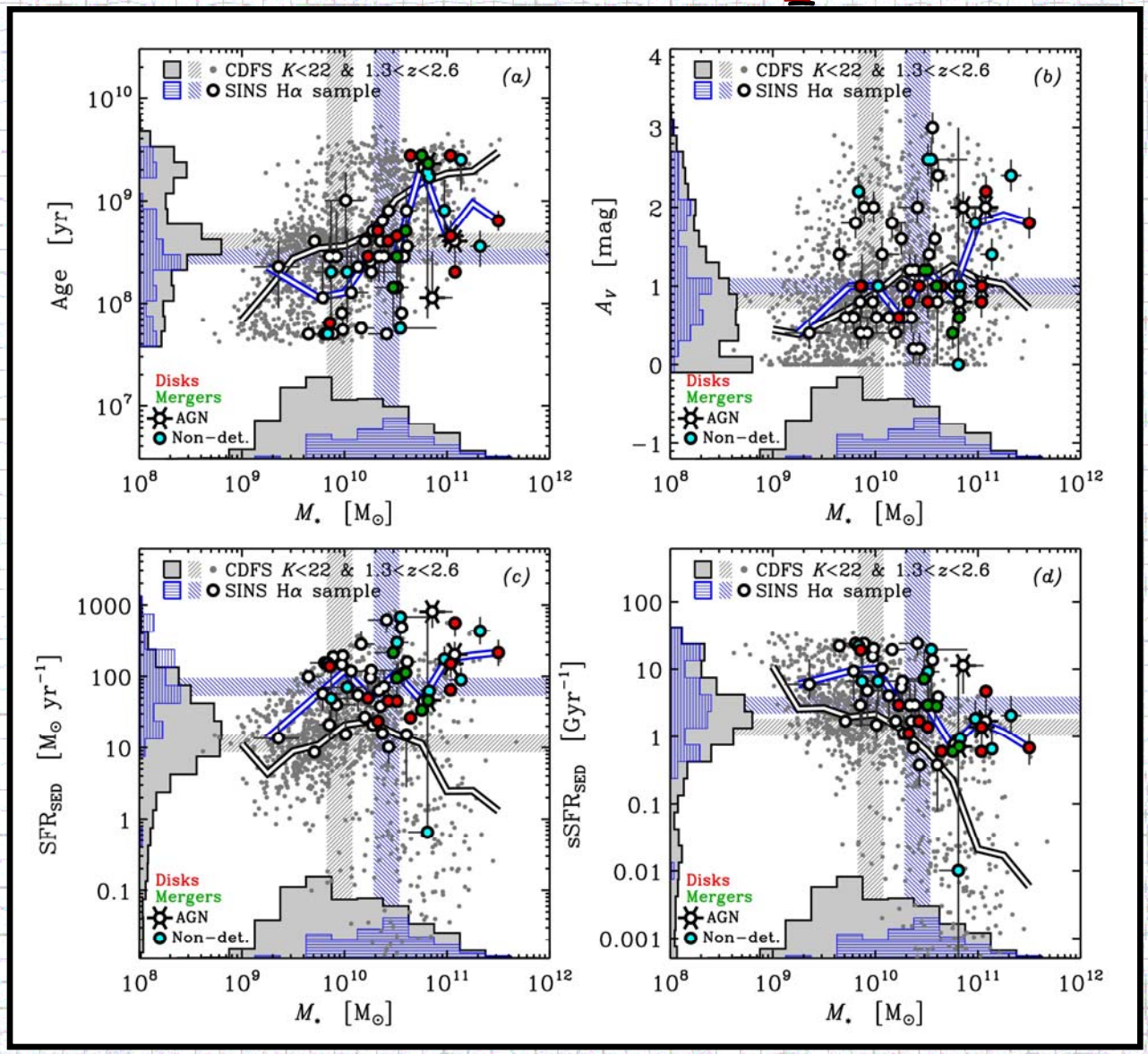


Near-IR
integral field spectroscopy
with SINFONI (AO/no-AO)
at the VLT

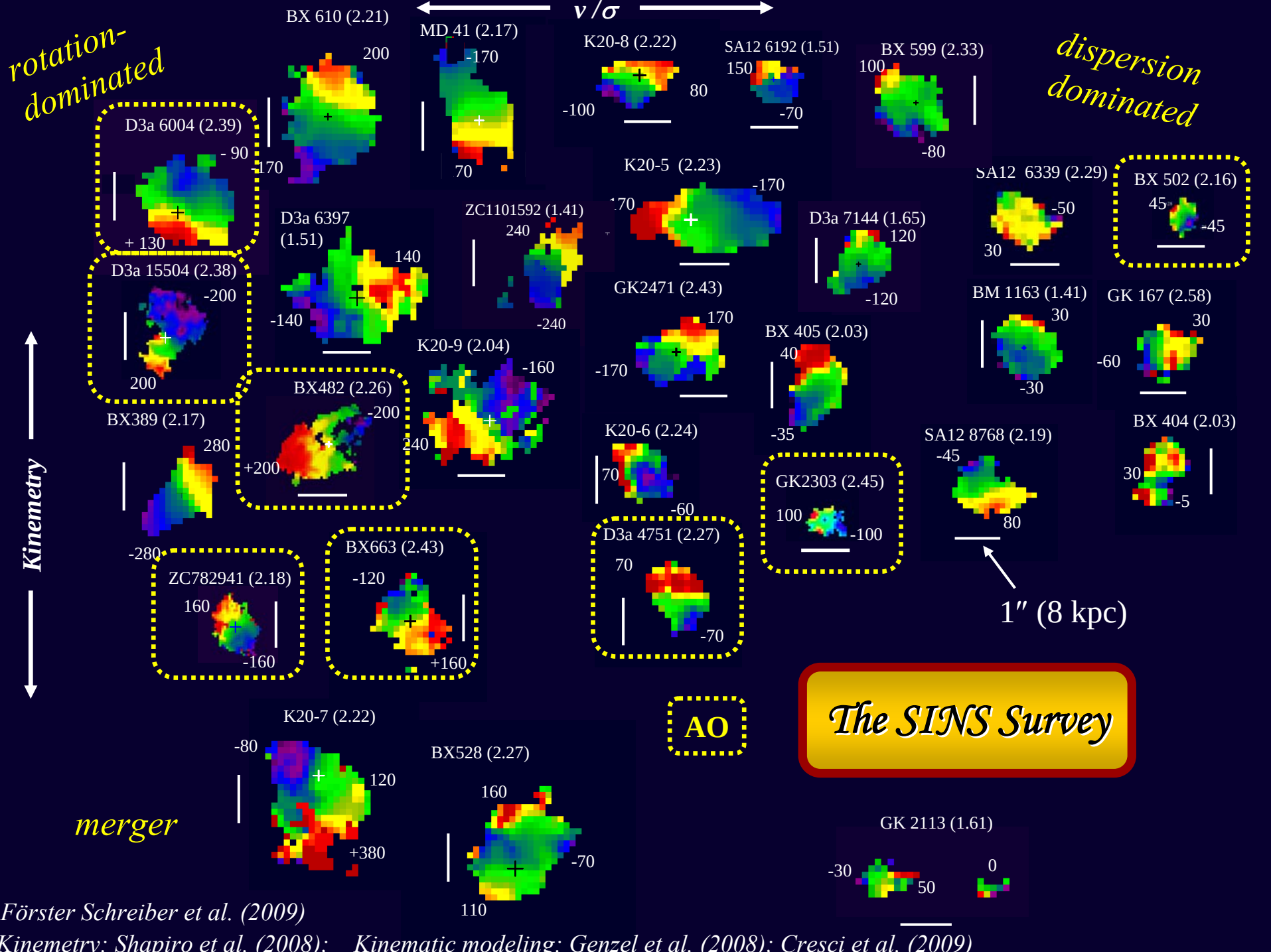
Complemented with near-IR imaging with HST/NICMOS-NIC2 and VLT/NACO+AO

Förster Schreiber et al. 06/9; Genzel et al. 06/8; Bouché et al. 07; Shapiro et al. 08/09; Cresci et al. 09; Mancini et al. 10
Also: e.g., Swinbank et al. 06/7; Nesvadba et al. 06-08; Wright et al. 07/9; Law et al. 07/9; Stark et al. 08;
Bournaud et al. 08; van Starkenburg et al. 08; Epinat et al. 09; Mannucci et al. 09; Jones et al. 09; Lemoine-Busserolle et al. 10

SINS Hα Sample



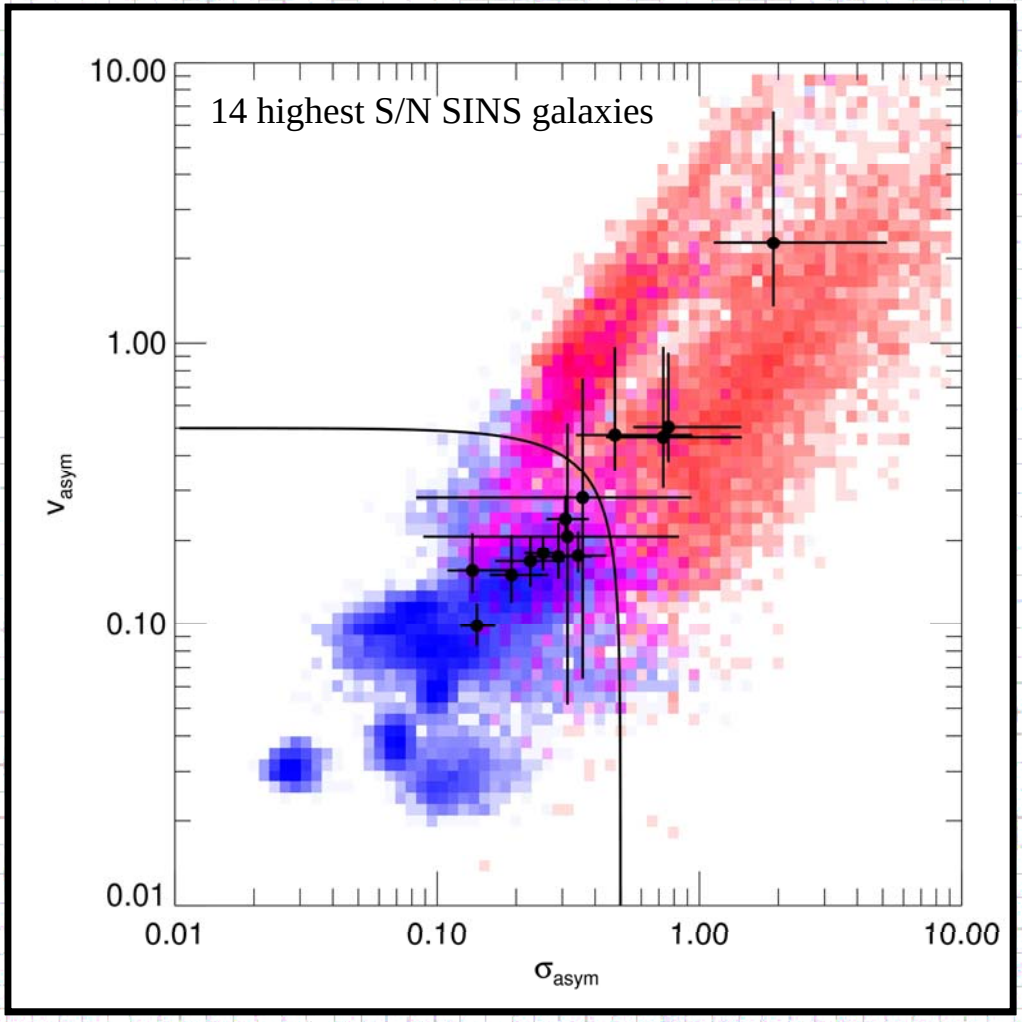
Förster Schreiber et al. (2009); CDFS/FIREWORKS: Wuyts et al. (2008)



Förster Schreiber et al. (2009)

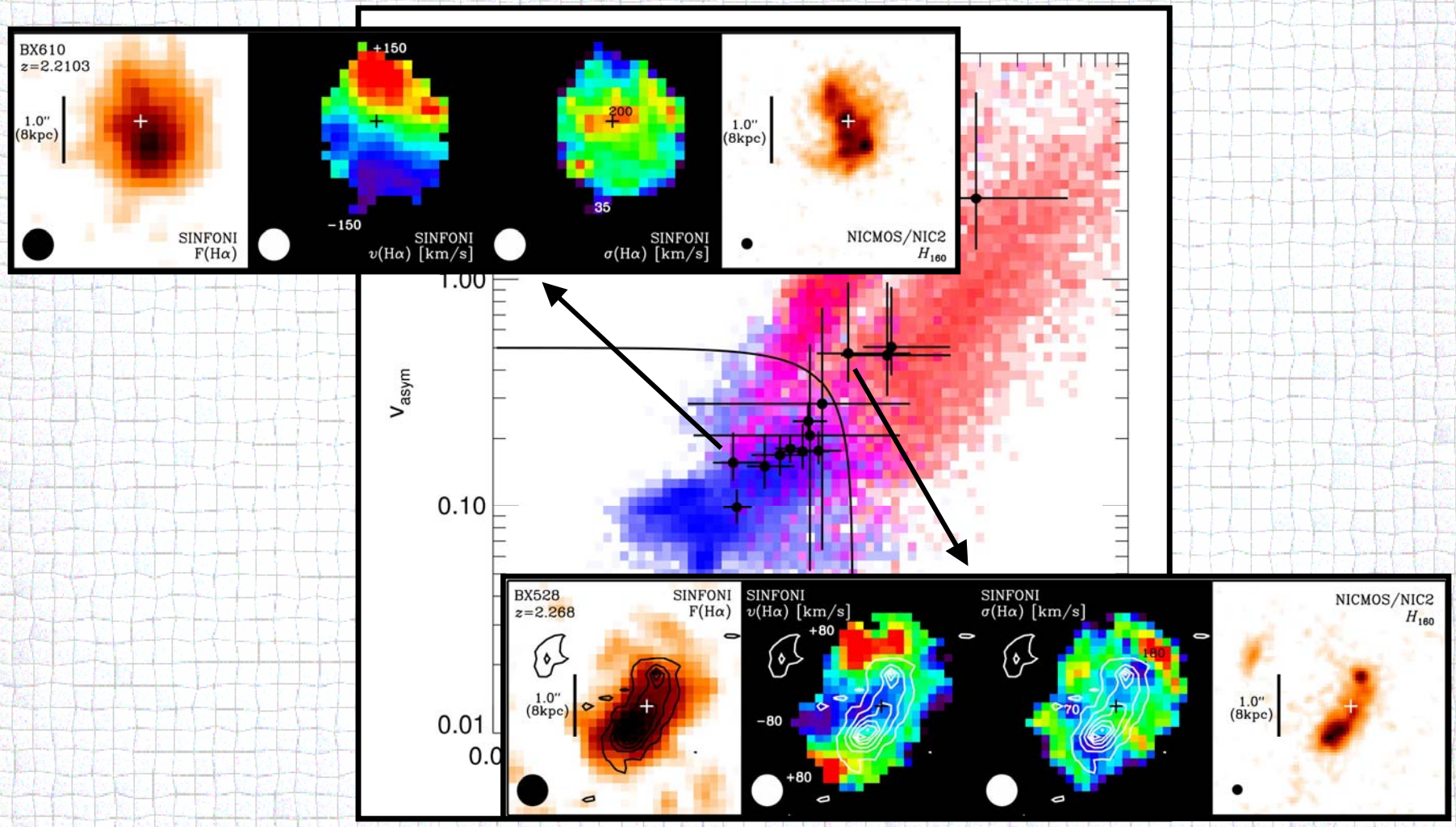
Kinemetry: Shapiro et al. (2008); Kinematic modeling: Genzel et al. (2008); Cresci et al. (2009)

Disks vs Mergers: Quantitative Discrimination

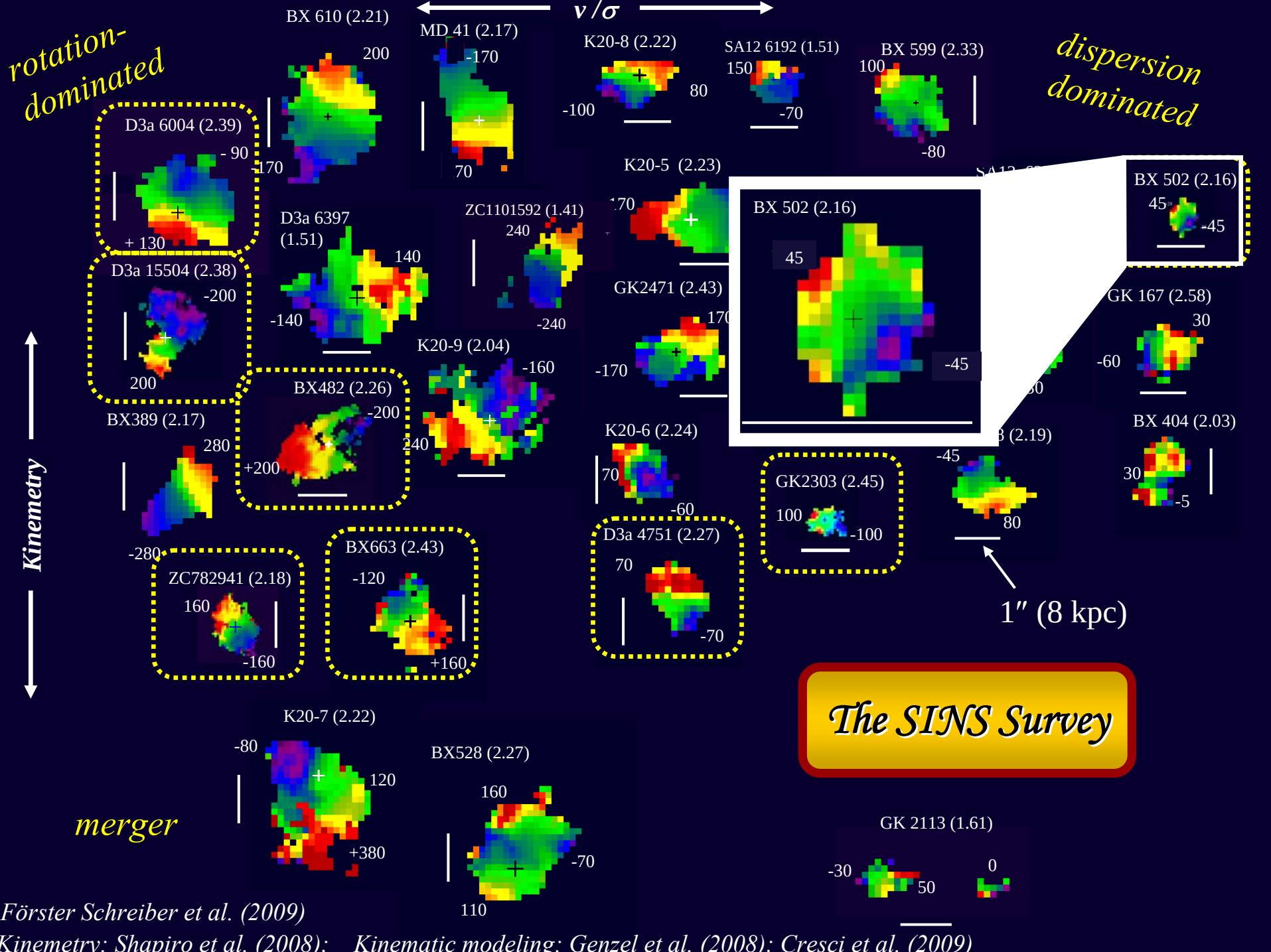


Shapiro et al. (2008); Kinemetry: Krajnović et al. (2006)
Template data: Daigle et al. (2006), Colina et al. (2005), Naab et al. (2007), Johansson et al. (2008).

Disks vs Mergers: Quantitative Discrimination

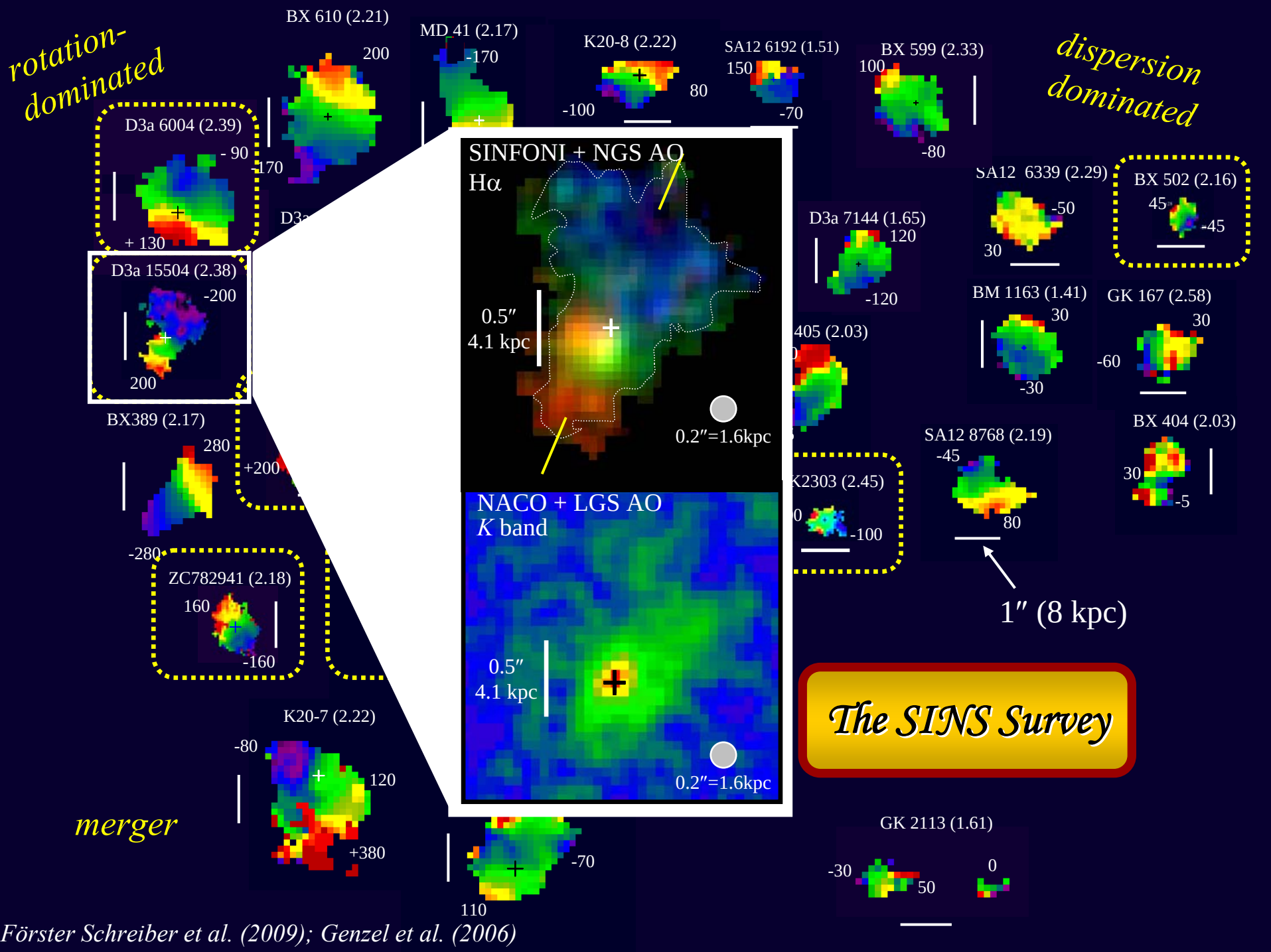


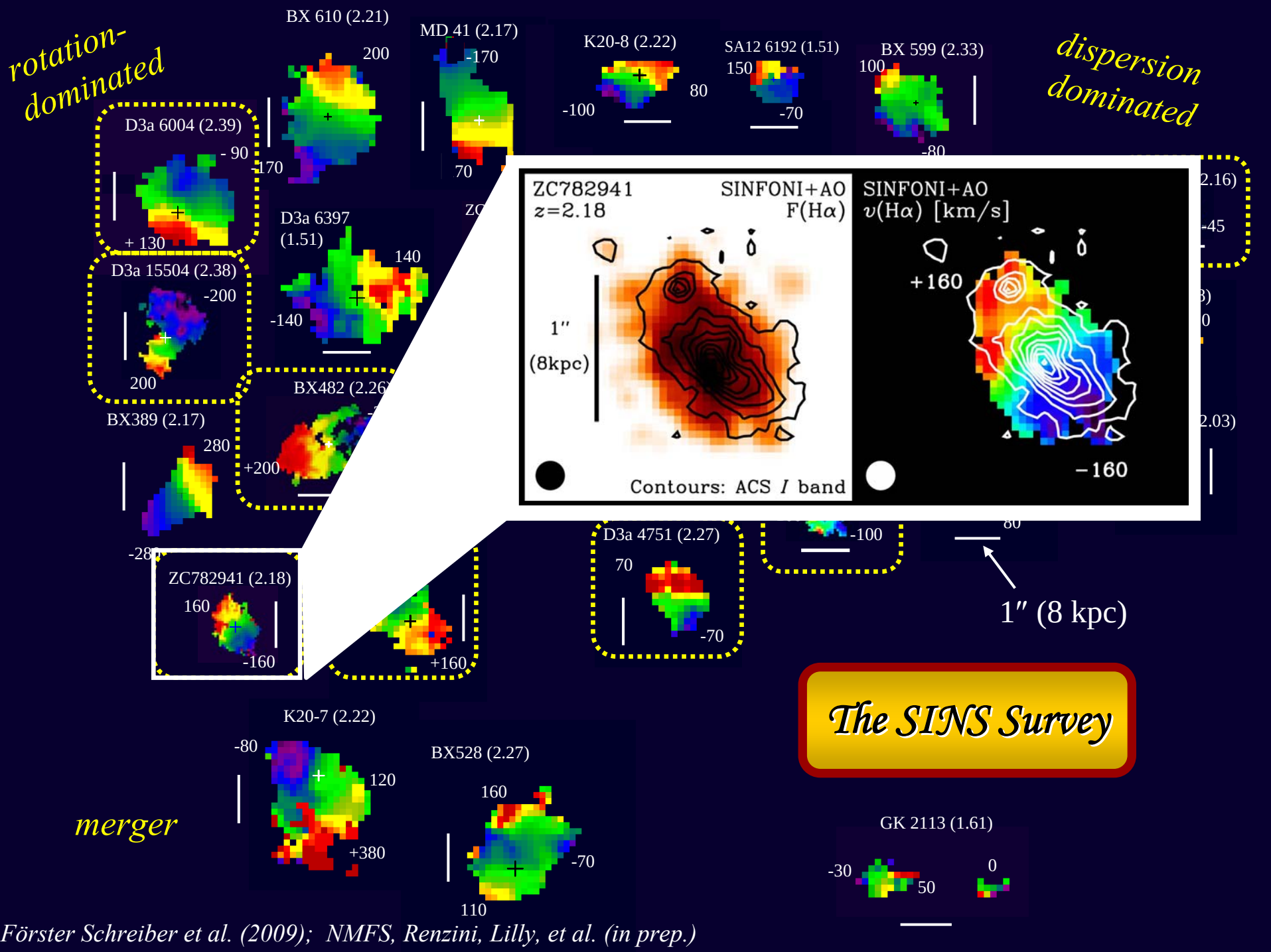
Shapiro et al. (2008); Kinemetry: Krajnović et al. (2006)
Template data: Daigle et al. (2006), Colina et al. (2005), Naab et al. (2007), Johansson et al. (2008).



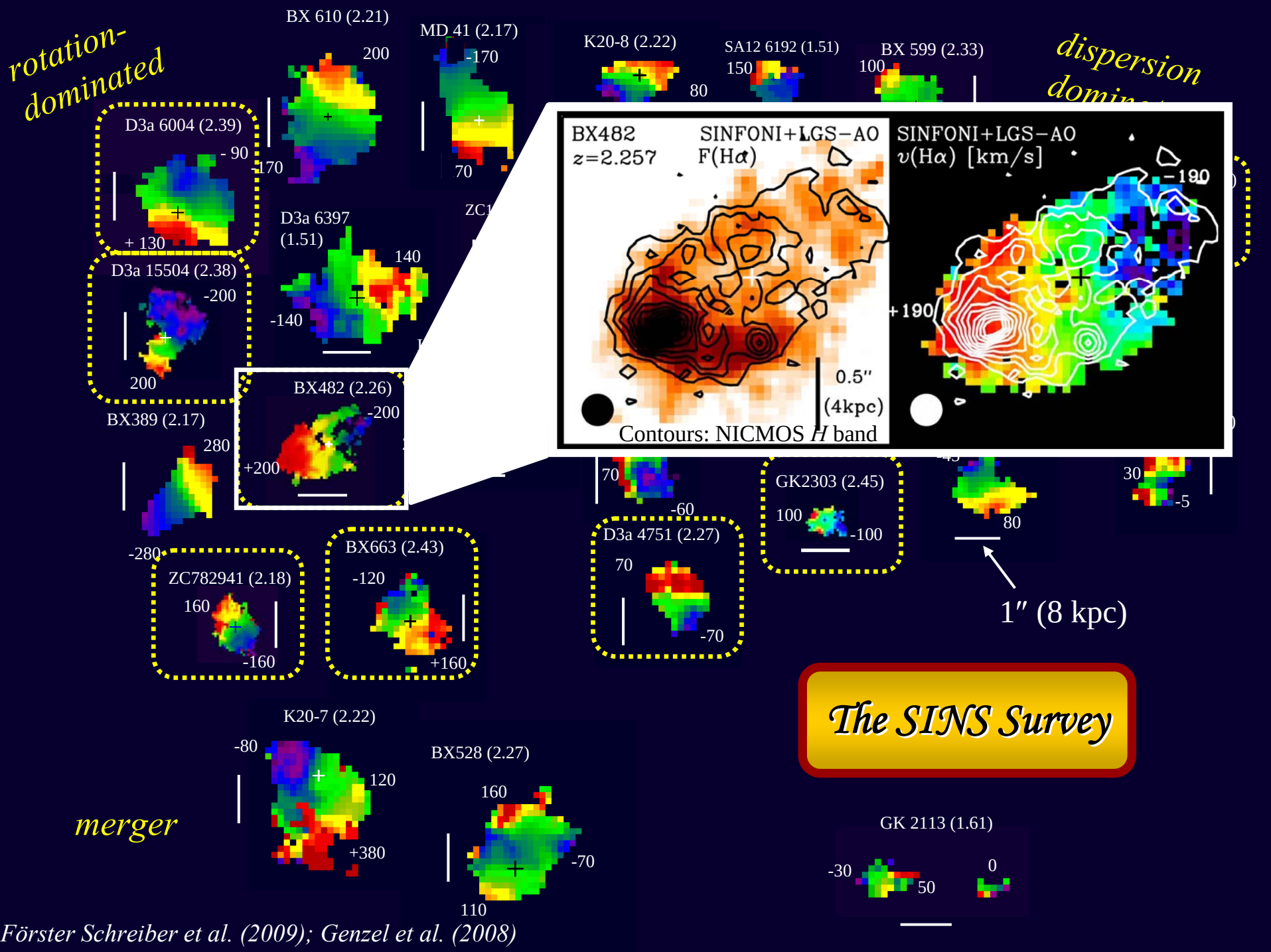
Förster Schreiber et al. (2009)

Kinemetry: Shapiro et al. (2008); Kinematic modeling: Genzel et al. (2008); Cresci et al. (2009)

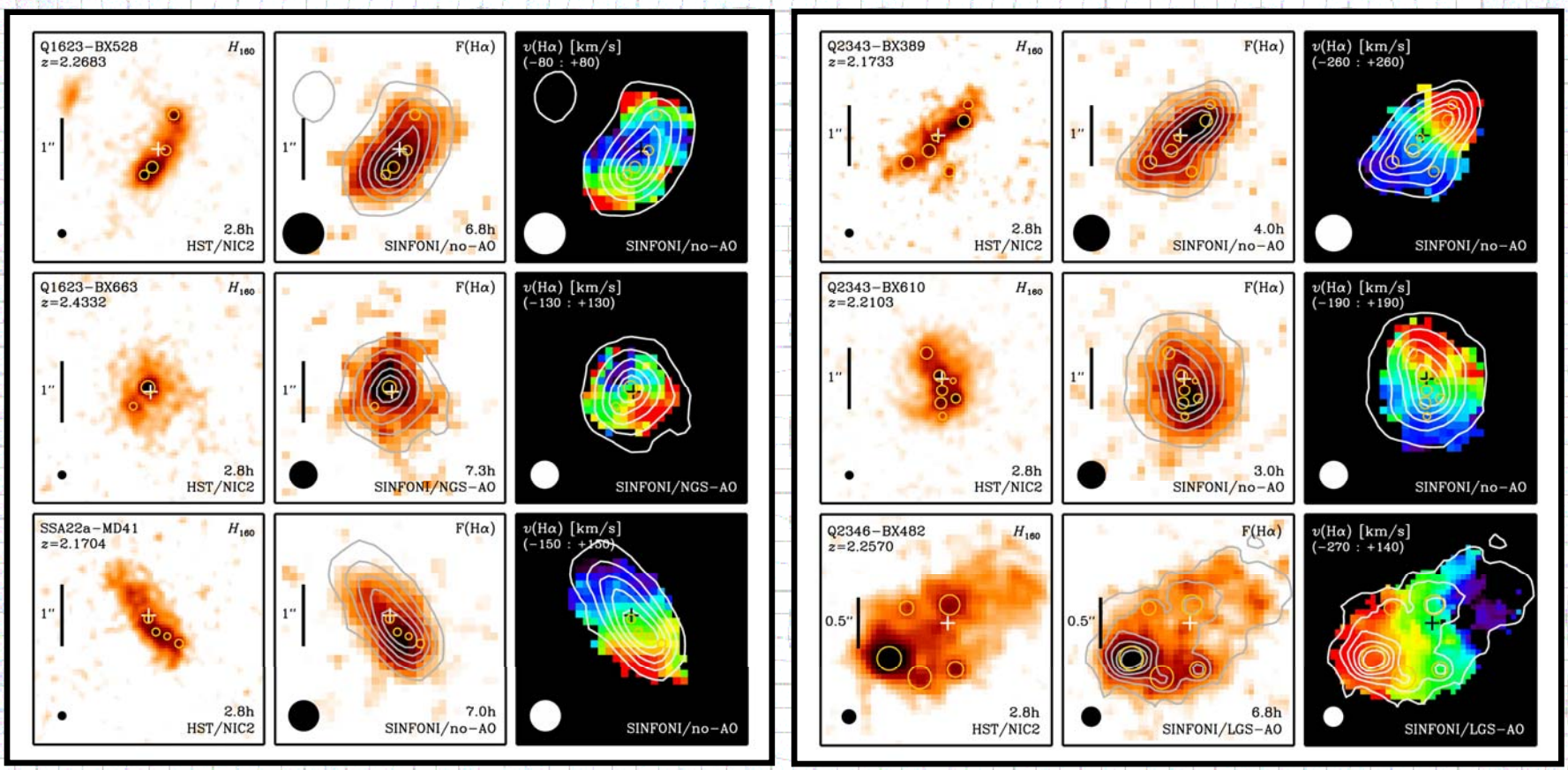

rotation-dominated
dispersion dominated
merger
SINFONI + NGS AO
Hα
0.5″
4.1 kpc
0.2″=1.6kpc
NACO + LGS AO
K band
0.5″
4.1 kpc
0.2″=1.6kpc
1″ (8 kpc)
The SINS Survey
BX 610 (2.21)
MD 41 (2.17)
K20-8 (2.22)
SA12 6192 (1.51)
BX 599 (2.33)
D3a 6004 (2.39)
D3a 15504 (2.38)
D3a 7144 (1.65)
SA12 6339 (2.29)
BX 502 (2.16)
BM 1163 (1.41)
GK 167 (2.58)
BX389 (2.17)
SA12 8768 (2.19)
BX 404 (2.03)
ZC782941 (2.18)
K20-7 (2.22)
GK 2113 (1.61)
Förster Schreiber et al. (2009); Genzel et al. (2006)



Förster Schreiber et al. (2009); NMFS, Renzini, Lilly, et al. (in prep.)


rotation-dominated
dispersion
BX 610 (2.21)
200
170
MD 41 (2.17)
-170
70
K20-8 (2.22)
80
SA12 6192 (1.51)
150
BX 599 (2.33)
100
D3a 6004 (2.39)
- 90
+ 130
D3a 6397 (1.51)
140
-140
ZC1
D3a 15504 (2.38)
-200
200
BX482 (2.26)
-200
+200
BX389 (2.17)
280
-280
BX482
z=2.257
SINFONI+LGS−AO
F(Hα)
0.5″
(4kpc)
Contours: NICMOS H band
SINFONI+LGS−AO
v(Hα) [km/s]
-190
+190
70
-60
GK2303 (2.45)
100
-100
80
30
-5
D3a 4751 (2.27)
70
-70
1″ (8 kpc)
BX663 (2.43)
-120
+160
ZC782941 (2.18)
160
-160
The SINS Survey
K20-7 (2.22)
-80
120
+380
BX528 (2.27)
160
-70
110
merger
GK 2113 (1.61)
-30
50
0
Förster Schreiber et al. (2009); Genzel et al. (2008)

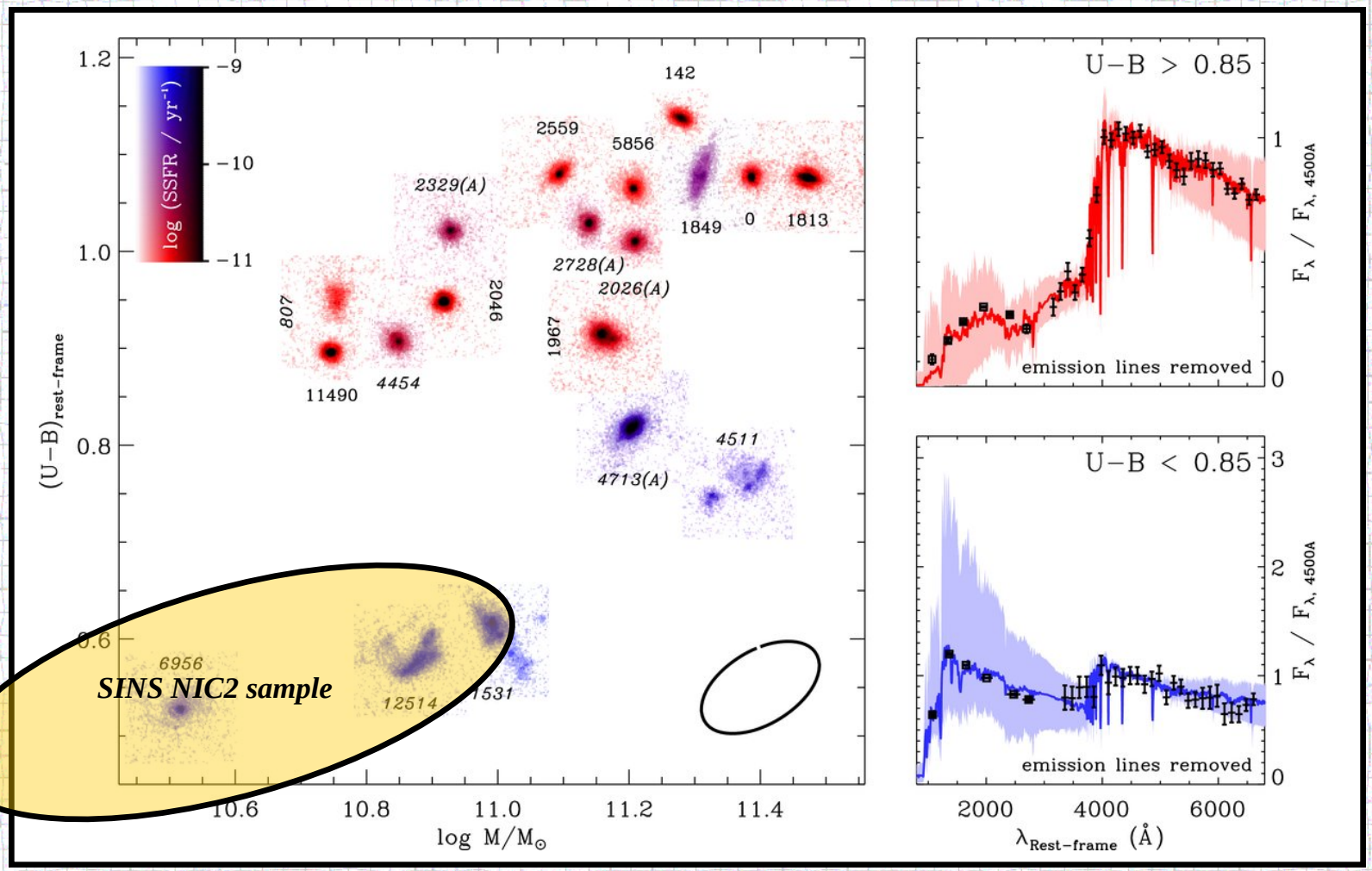
Clumps in High-z Star-forming Galaxies



Förster Schreiber, Shapley, et al. (2010)

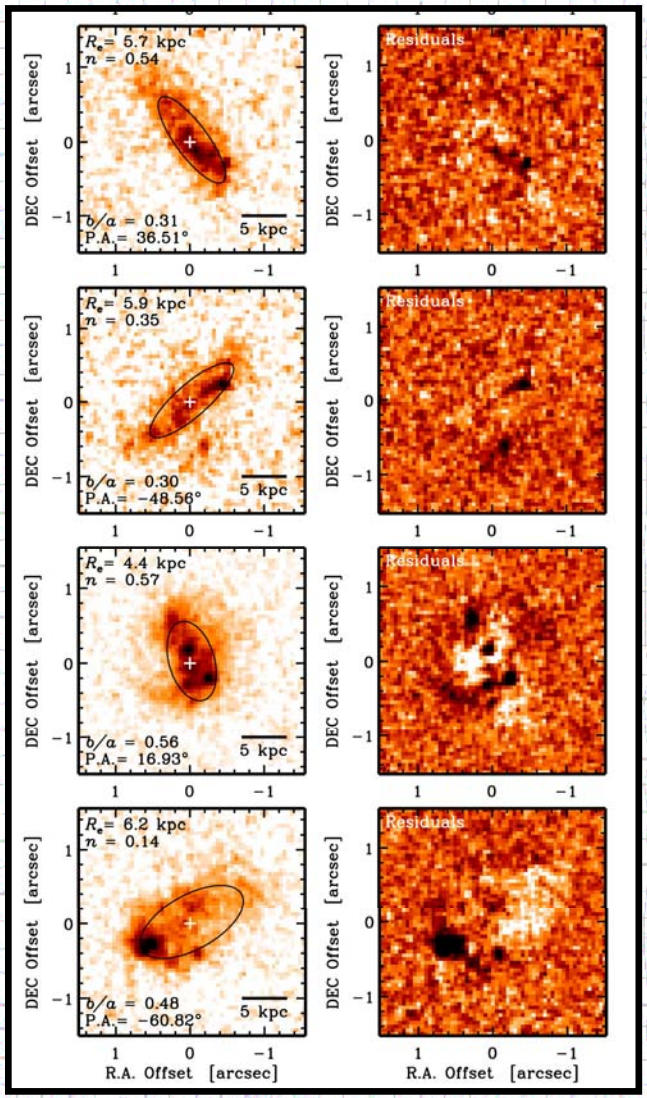
Also, Cowie et al. 1995; van den Bergh et al. 1996; Giavalisco et al. 1996; Conselice et al. 2004; Lotz et al. 2004; Papovich et al. 2005; Toft et al. 2007; Law et al. 2007; Carollo et al. 2007; Elmegreen, Elmegreen, et al. 2004-2009; and others

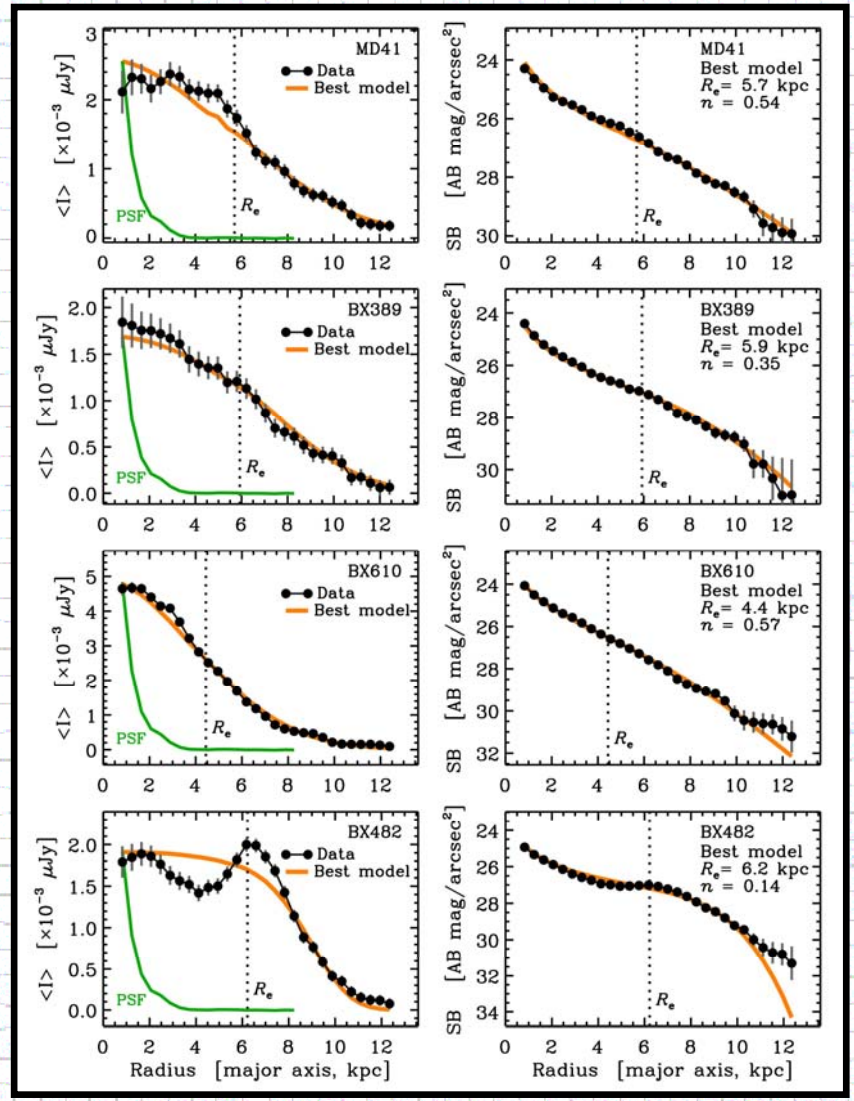
Hubble Sequence at z ~ 2



Kriek et al. (2009); SINS NIC2 NMFS, Shapley, et al. (2010)

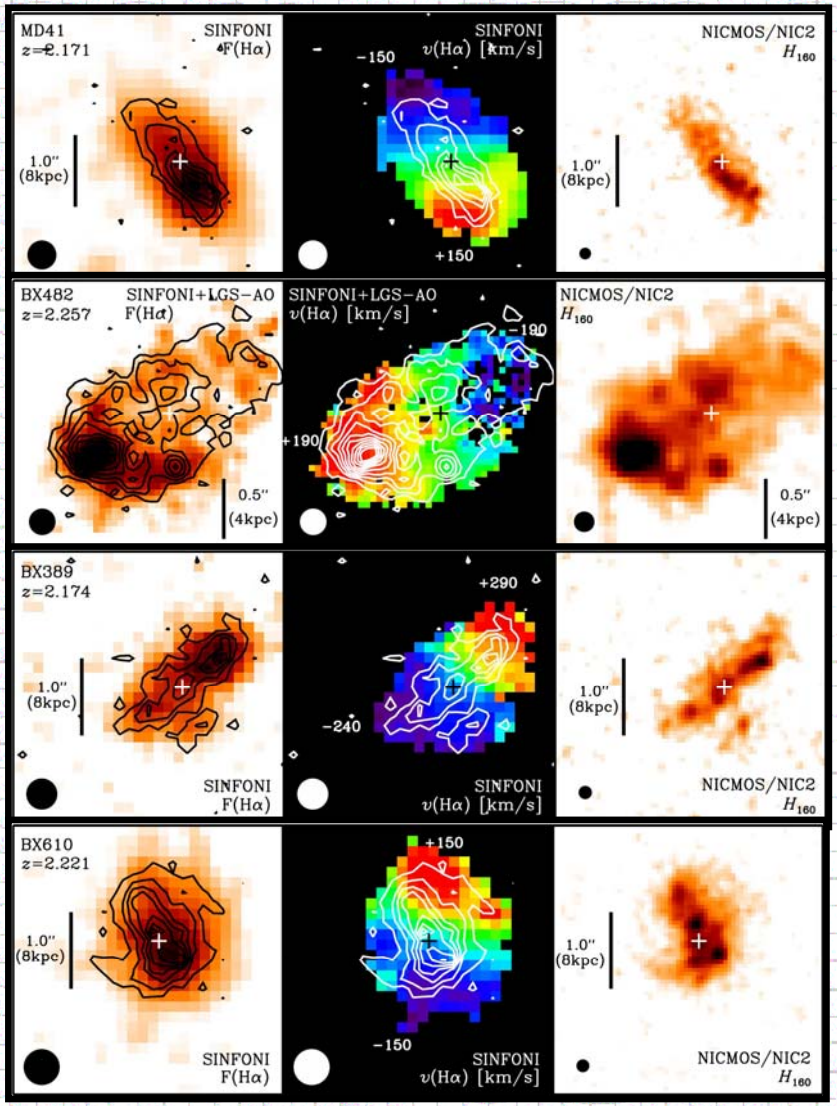
Shallow Profiles for z~2 Clumpy Disks





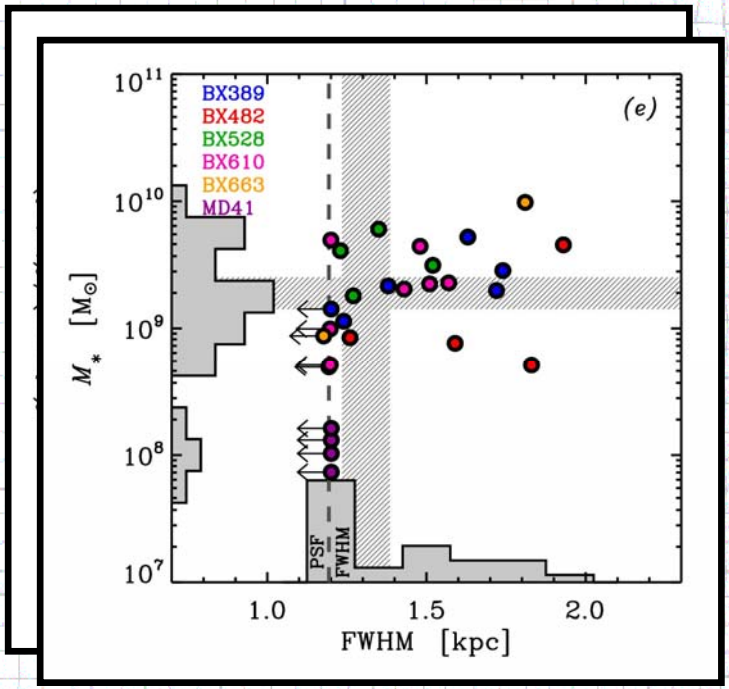
Förster Schreiber, Shapley, et al. (2010)

Massive Clumps in High-z Star-forming Disks



For $Q \approx 1$:

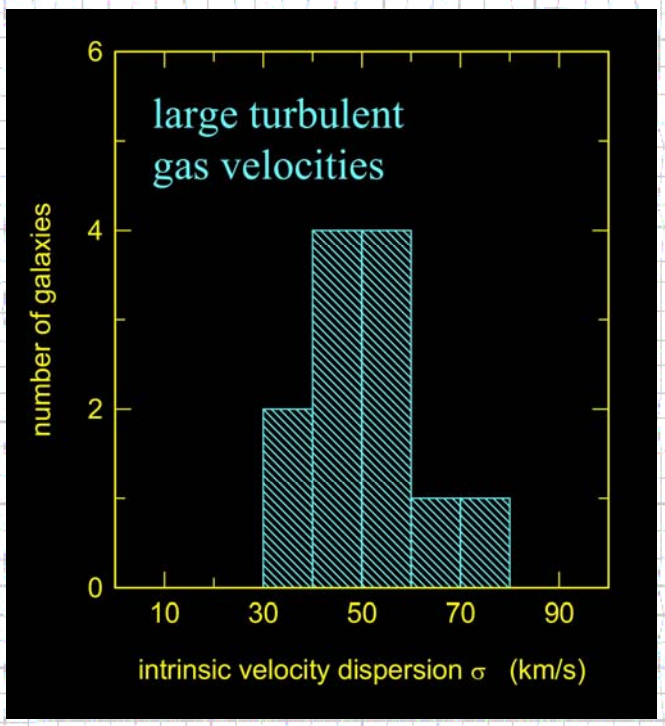
- $L_J \propto (\sigma_0/v_c)R_d \sim 1 - 2$ kpc
- $M_{cl} \propto (L_{cl}\, v_c)^2/R_d \sim 10^{7.5} - 10^{9.5}\ M_\odot$

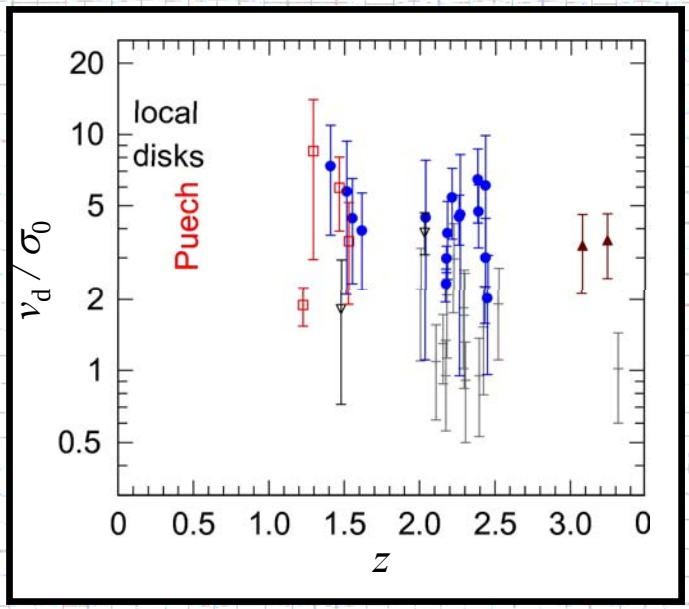


Förster Schreiber, Shapley, et al. (2010); Genzel et al. (2008)

Large Velocity Dispersion in High-z Disks

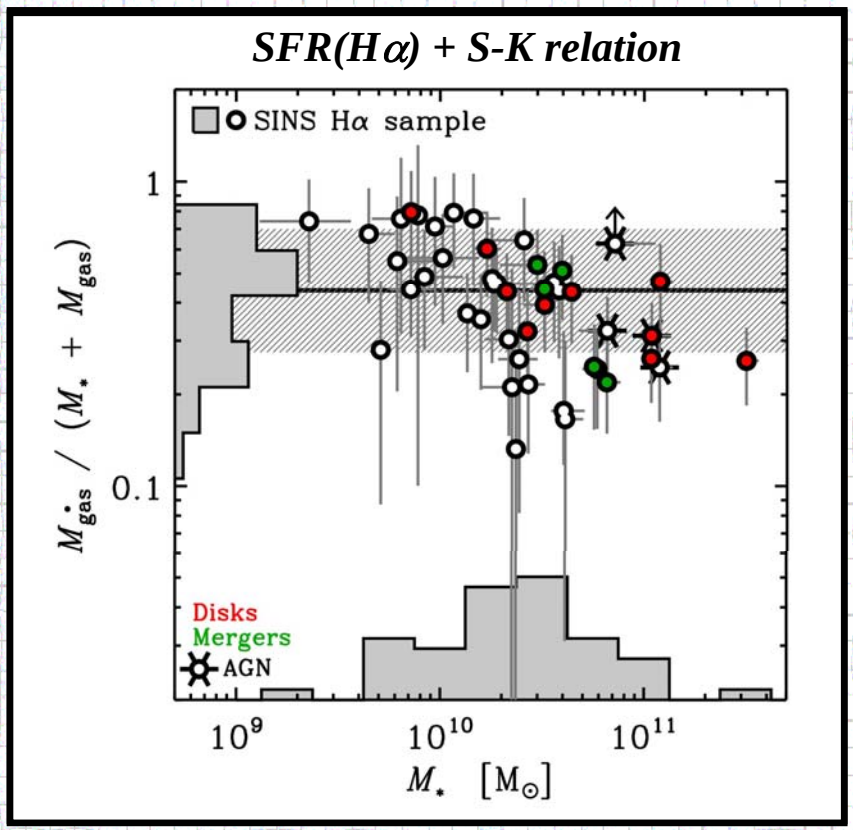
- For disks with $Q \approx 1$, $v_c/\sigma_0 \propto 1/f_{gas}$



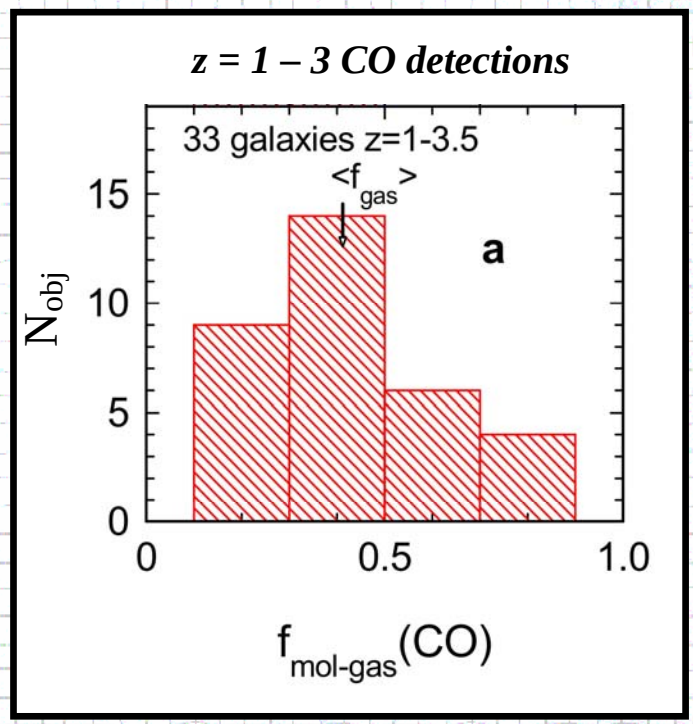


NMFS et al. (2006, 2009); Cresci et al. (2009); Genzel et al. (2008); Nesvadba et al. (2006); Stark et al. (2008); Law et al. (2007,2009); Wright et al. (2007,2009); van Starkenburg et al. (2008); Epinat et al. (2009); Puech et al. (2006); Dib et al. (2006); Jones et al. (2009) Khochfar & Silk (2009); Burkert et al. (2009)

High Gas Mass Fractions in High-z Star-forming Galaxies



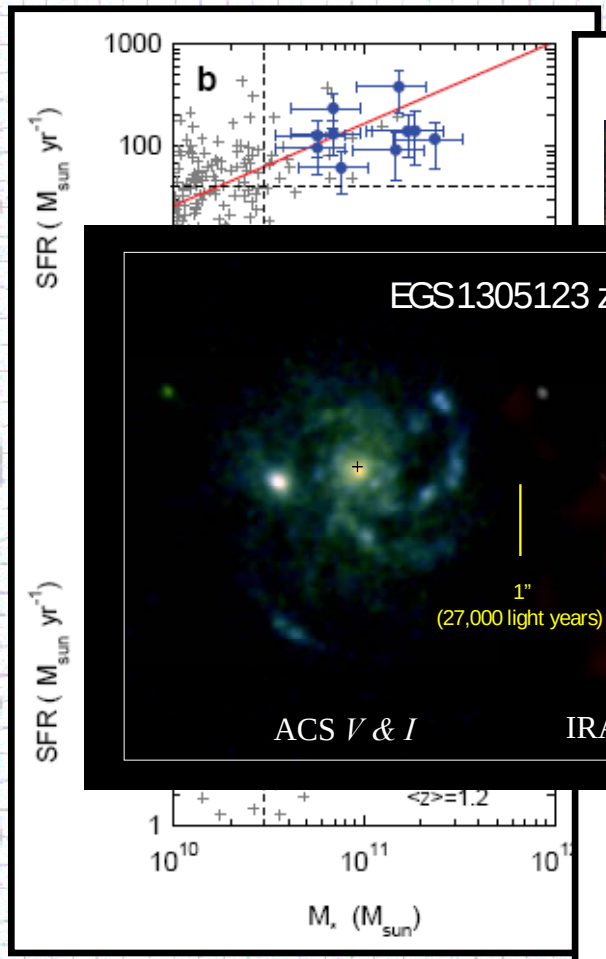
NMFS et al. (2009); Cresci et al. (2009)
Cf. also Erb et al. (2006b)

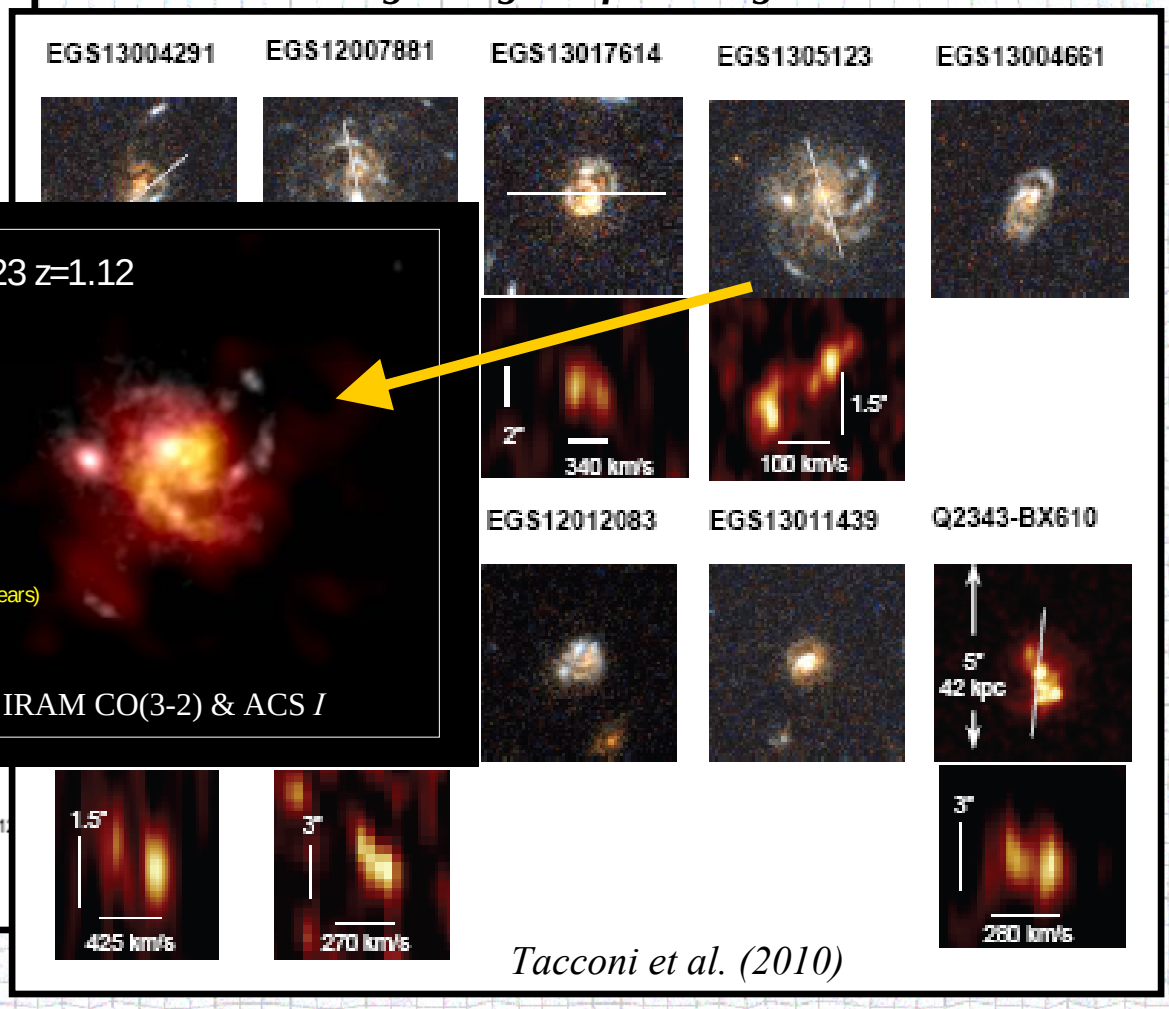


Tacconi et al. (2008, 2010);
Baker et al. (2004); Coppin et al. (2007);
Daddi, Dannerbauer, et al. (2007,2008,2009)

Molecular Gas in "Normal" z ~ 1 – 3 Massive Star-forming Galaxies

IRAM/PdBI Large Program for ~ 30 galaxies

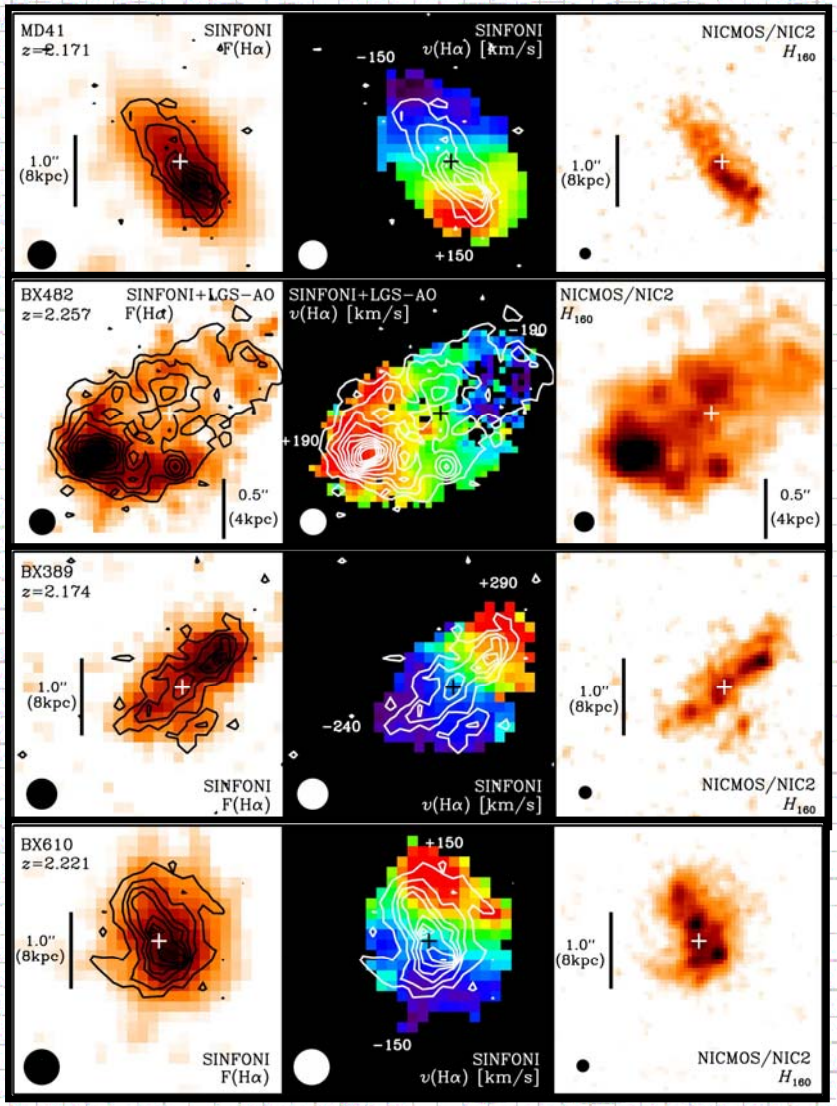




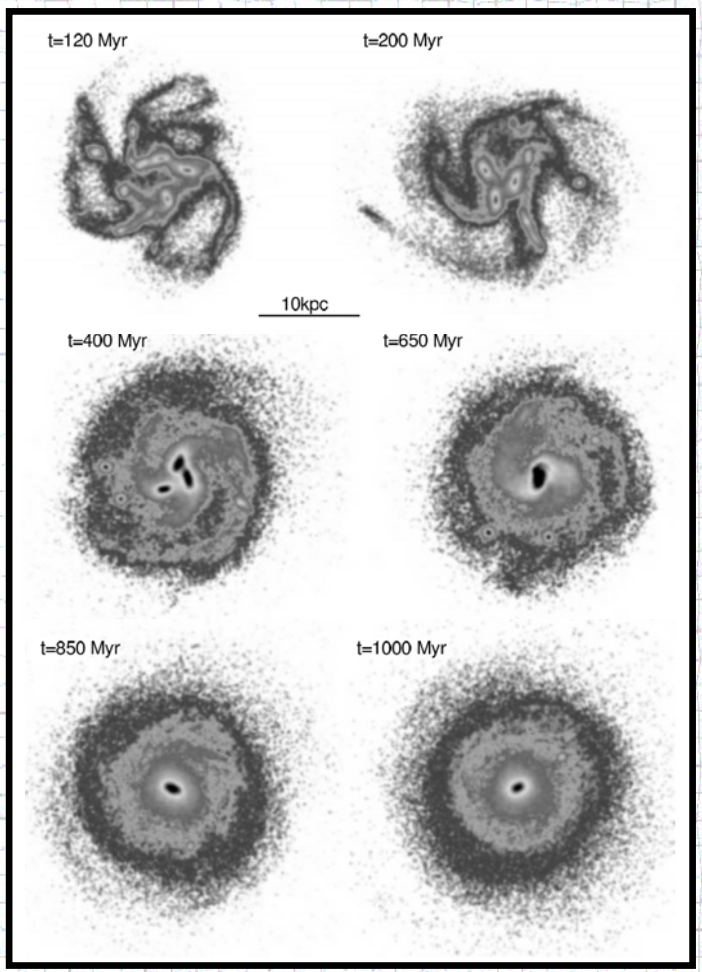
Tacconi et al. (2010)

Also: Baker et al. (2004); Coppin et al. (2007); Daddi, Dannerbauer, et al. (2007,2008,2009)

Dynamical Evolution of Gas-rich Disks

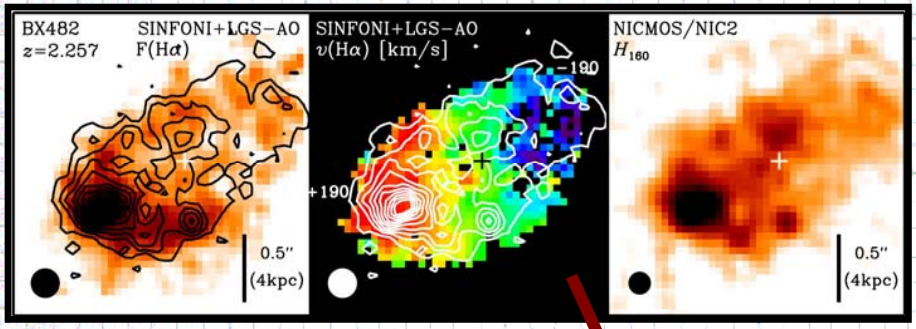


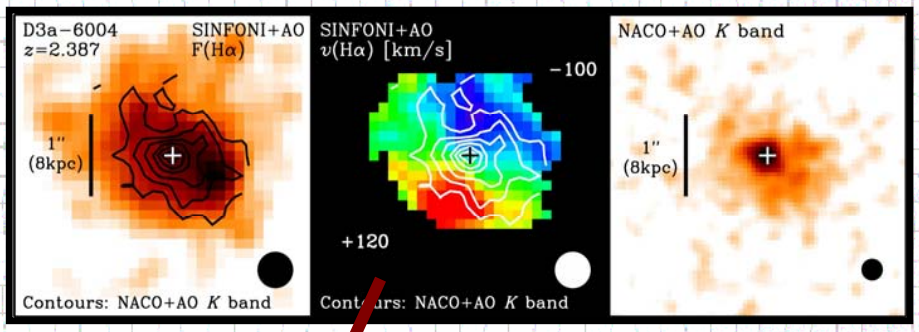
Förster Schreiber, Shapley, et al. (2009); Genzel et al. (2008)



Bournaud et al. (2007; 2008)
Also, e.g., Noguchi (1999); Immeli et al. (2004a, b); Semelin & Combes (2002); Naab et al. (in prep.)

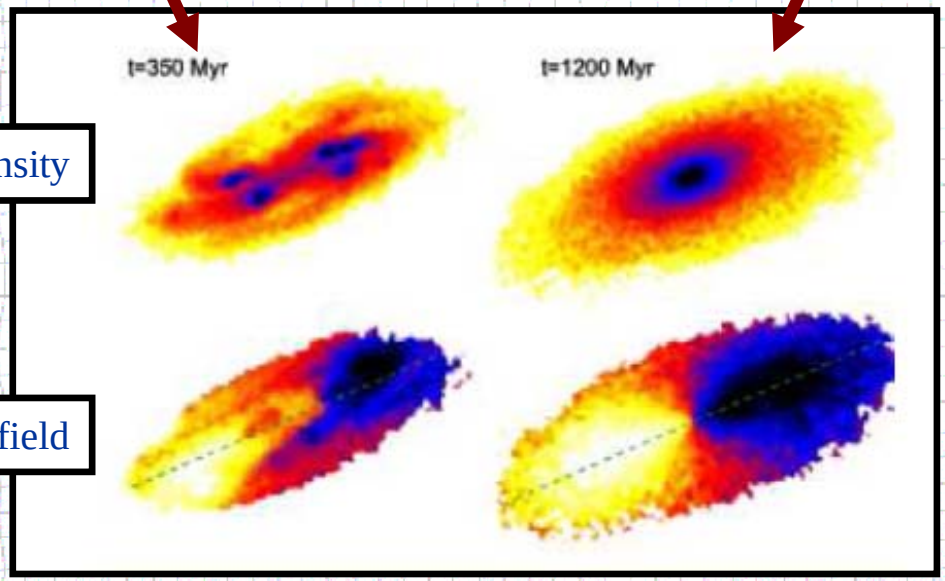
Dynamical Evolution of Gas-rich Disks





Stellar surface density

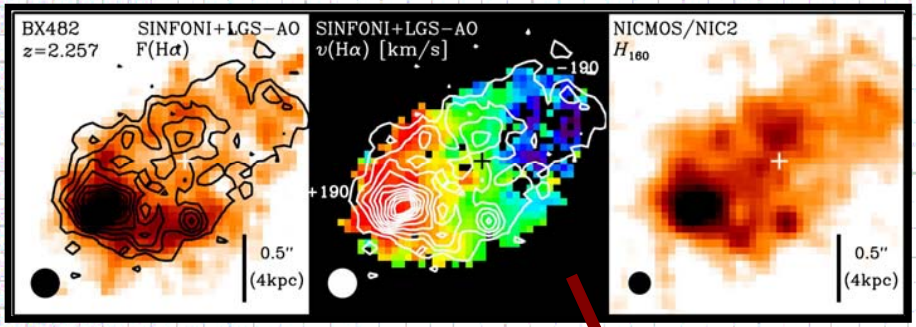
Velocity field

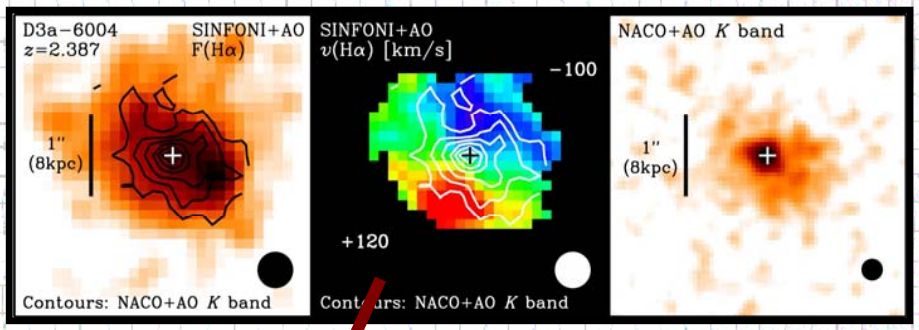


Förster Schreiber, Shapley, et al. (2009); Genzel et al. (2008)

Bournaud et al. (2007;2008; 2009)
Also: Immeli et al. (2004a,b); Naab et al. (in prep.)

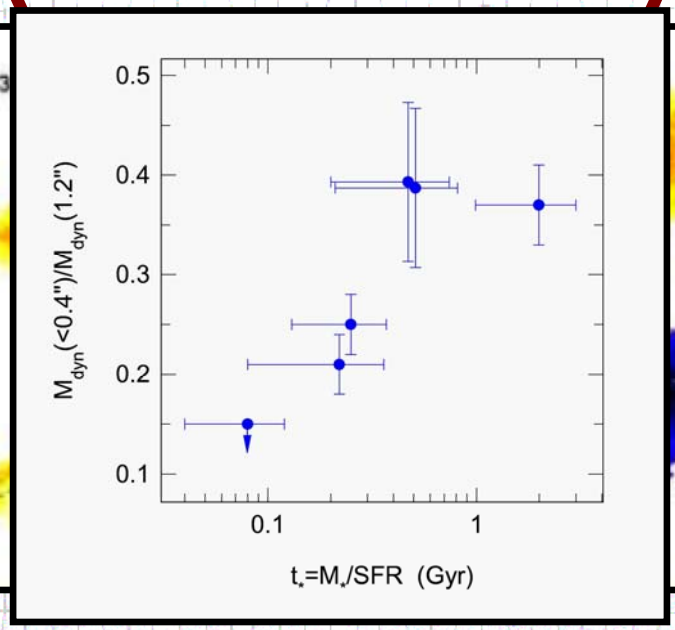
Dynamical Evolution of Gas-rich Disks





Stellar surface density

Velocity field

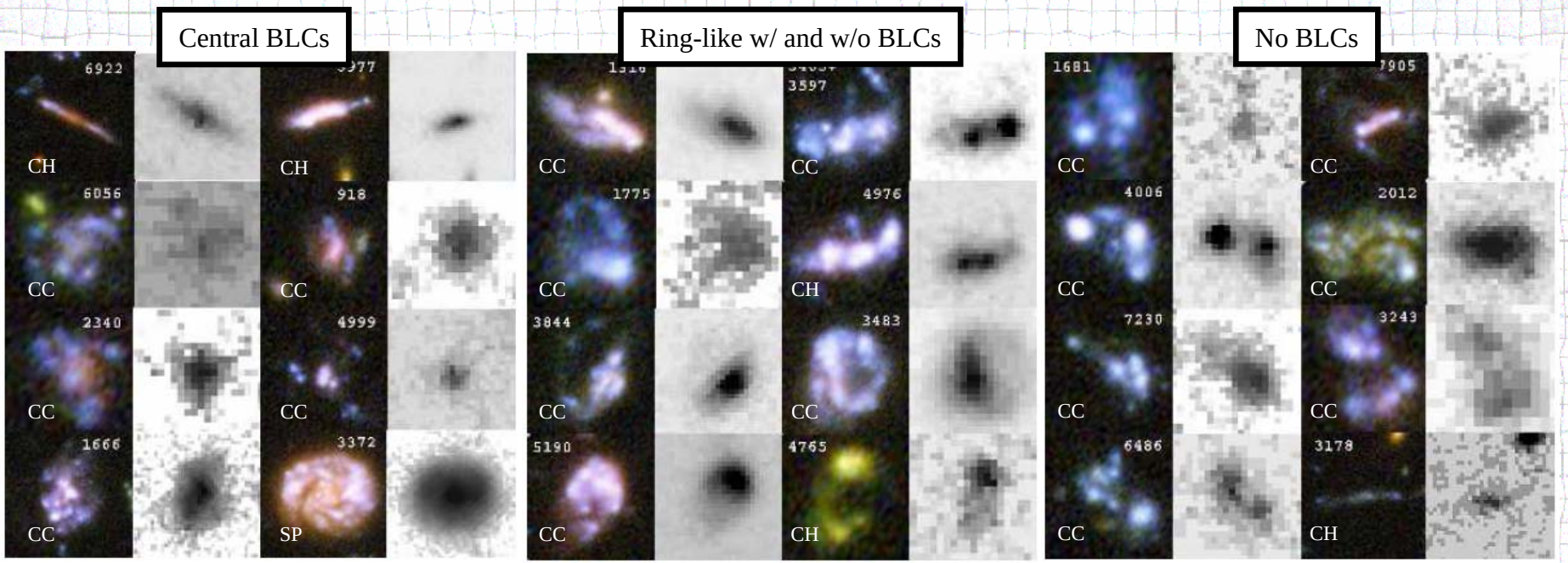


Förster Schreiber, Shapley, et al. (2009); Genzel et al. (2008)

Bournaud et al. (2007;2008; 2009)
Also: Immeli et al. (2004a,b); Naab et al. (in prep.)

Clumps and Bulges in Distant Galaxies

- ~ 30% / 50% of “chains” / “clump-clusters” have red bulge-like clumps
- ~ 20% of bulge-like clumps are off-center



Elmegreen et al. (2009)

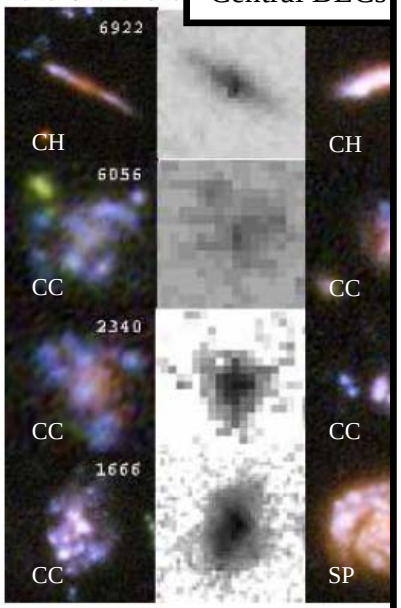
Clumps and Bulges in Distant Galaxies

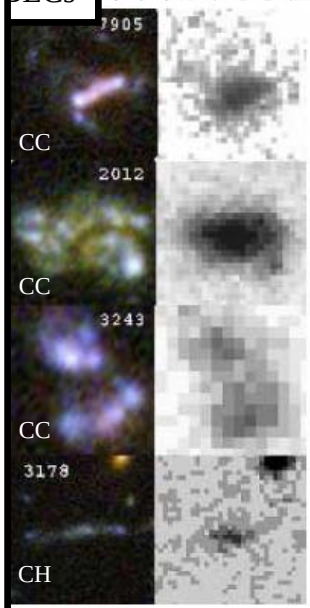
-
-

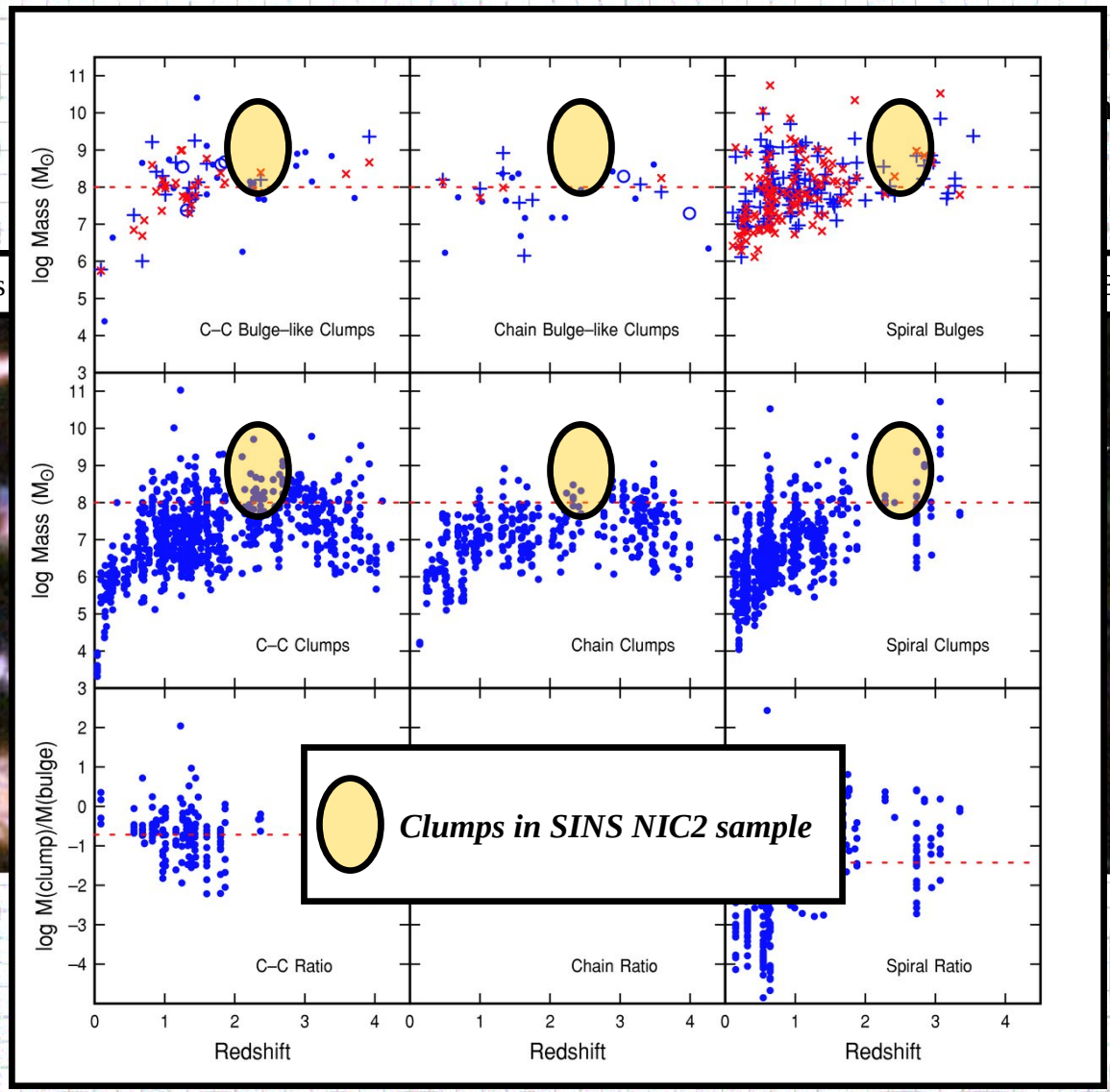
ps

Central BLCs

BLCs

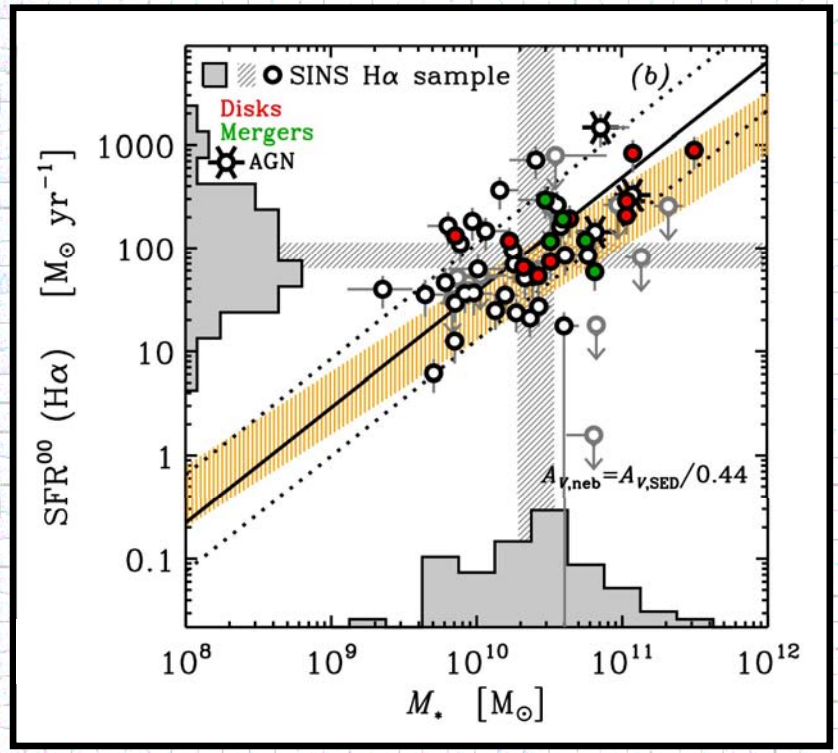


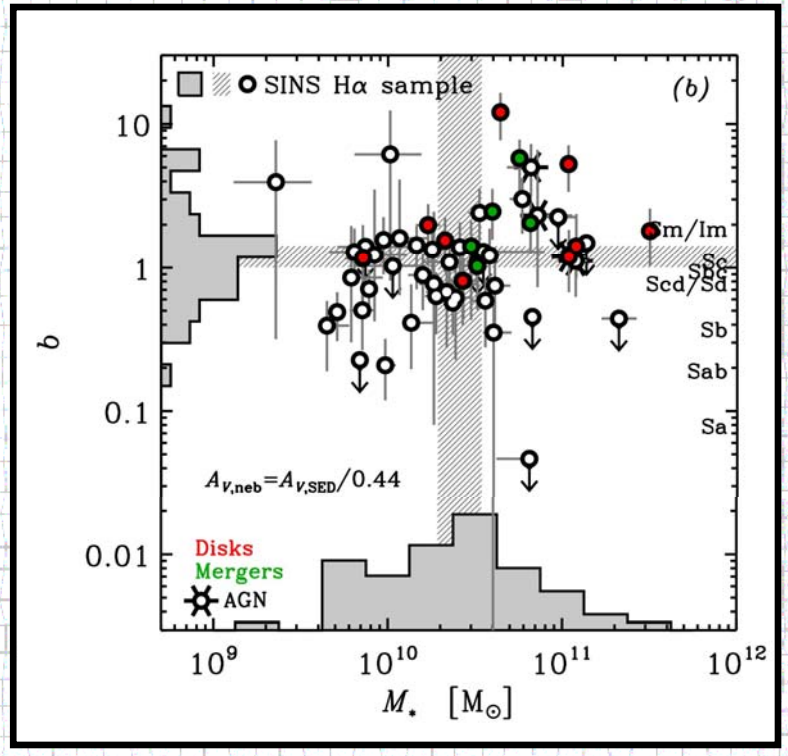




Elmegreen et al. (2009)

Star Formation Activity



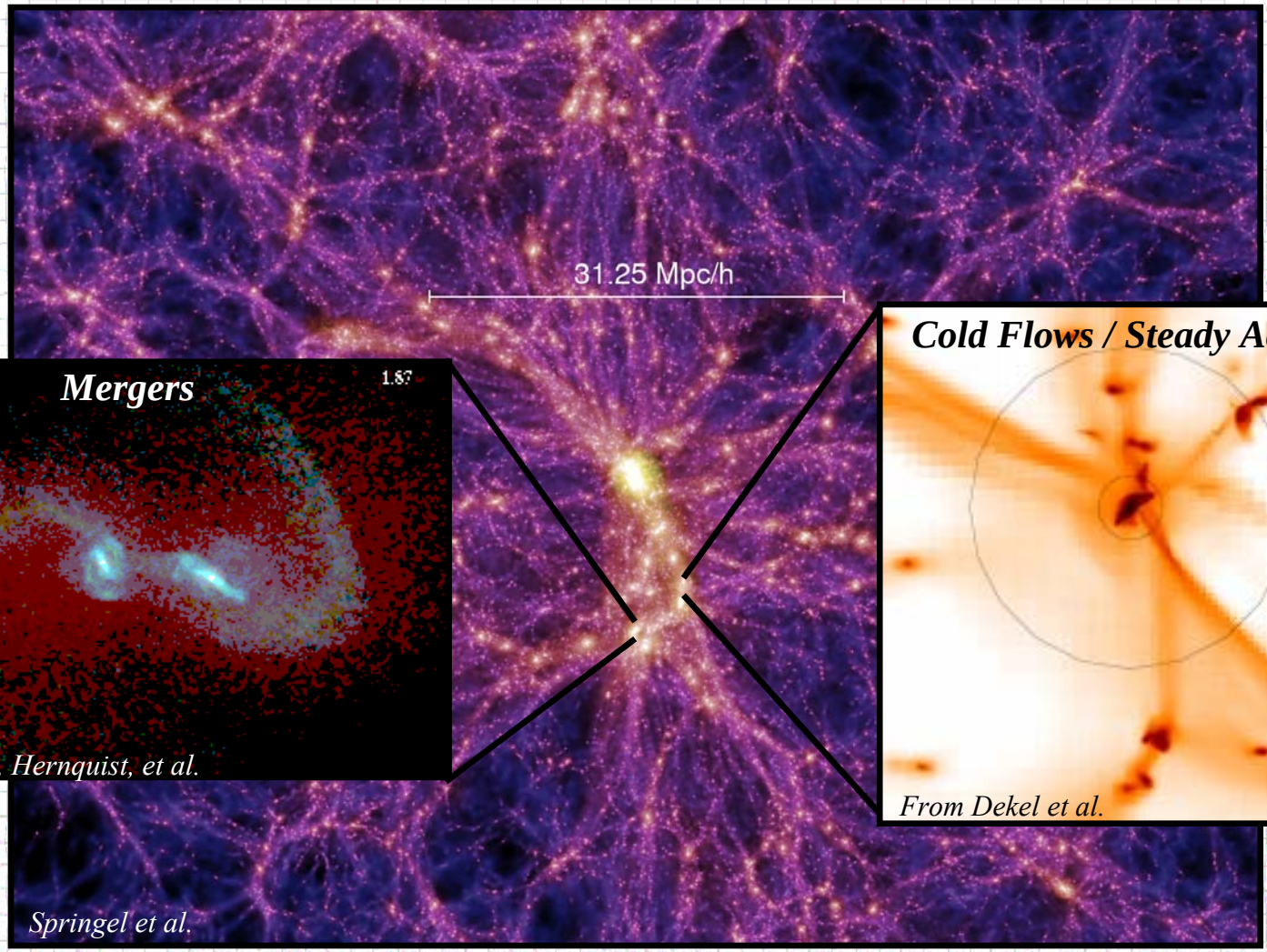


b = SFR$_{current}$ / <SFR>$_{past}$

Förster Schreiber et al. (2009); Bouché et al. (in prep.)

See also, e.g., Daddi et al. (2007); Noeske et al. (2007); Elbaz et al. (2007); Davé (2008); Genzel et al. (2008)
Kennicutt et al. (1994); Davé (2008); Chen et al. (2009); Damen et al. (2009)

Star Formation and Mass Assembly at Early Stages of Galaxy Evolution



Springel et al.

From Mihos, Hernquist, et al.

From Dekel et al.

Summary

- Diverse kinematics of massive star-forming galaxies at $z \sim 1 - 3$

  All Hα samples: ~ 150 objects

  SINS+ZC (~80): ~1/3 rotation-dominated, ~1/3 dispersion-dominated, ~1/3 mergers

  Fraction of rotation-dominated systems increase at higher masses

- Properties of massive $z \sim 2$ star-forming disks

  Significantly more turbulent and gas-rich than local disks

  Higher SFRs, large luminous/massive clumps in many

- Mass assembly, early evolution, and star formation activity

  Evidence for smooth+rapid mass accretion via cold flows/minor mergers

  Evidence for internal dynamical processes in gas-rich disks and rapid bulge formation