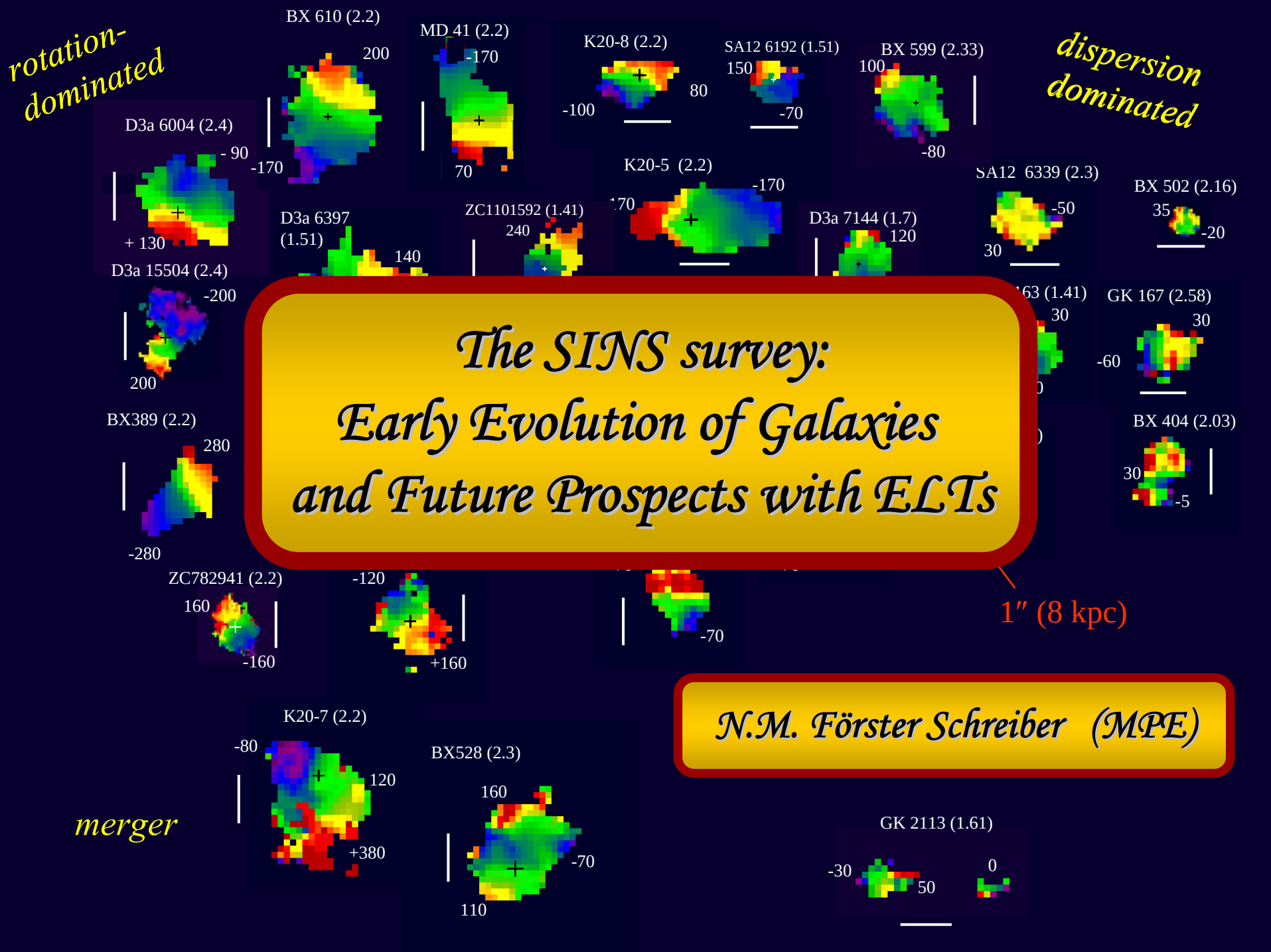

rotation-dominated
dispersion dominated
BX 610 (2.2)
200
-170
MD 41 (2.2)
-170
70
K20-8 (2.2)
80
-100
SA12 6192 (1.51)
150
-70
BX 599 (2.33)
100
-80
D3a 6004 (2.4)
- 90
+ 130
K20-5 (2.2)
-170
170
SA12 6339 (2.3)
-50
30
BX 502 (2.16)
35
-20
D3a 6397 (1.51)
140
ZC1101592 (1.41)
240
D3a 7144 (1.7)
120
D3a 15504 (2.4)
-200
200
GK 167 (2.58)
30
-60
BX389 (2.2)
280
-280
BX 404 (2.03)
30
-5
The SINS survey:
Early Evolution of Galaxies
and Future Prospects with ELTs
1″ (8 kpc)
ZC782941 (2.2)
160
-160
-120
+160
-70
N.M. Förster Schreiber (MPE)
K20-7 (2.2)
-80
120
+380
BX528 (2.3)
160
-70
110
merger
GK 2113 (1.61)
-30
50
0

The Team and Collaborations

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

MPE/Berkeley/Tel Aviv/Oxford/USM

A.E. Shapley, D. K. Erb, C.C. Steidel

UCLA/CfA/Caltech

A. Renzini, S. Lilly, A. Cimatti, E. Daddi, J. Kurk, X. Kong, & zCOSMOS, GMASS, Deep3a Teams

Padova/ETH Zürich/Bologna/CEA Saclay/MPIA/Hefei China/NAO Japan

A. Burkert, T. Naab, P. Johansson

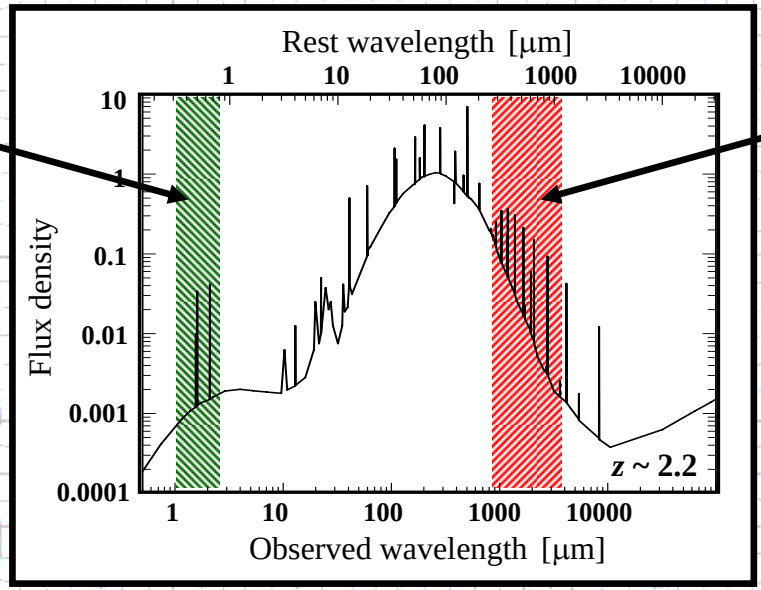
USM

Spatially-resolved Studies of z~1–4 Star-forming Galaxies

Dynamics, morphologies, physical properties

Rest-frame optical

Stellar & nebular components



Rest-frame submm

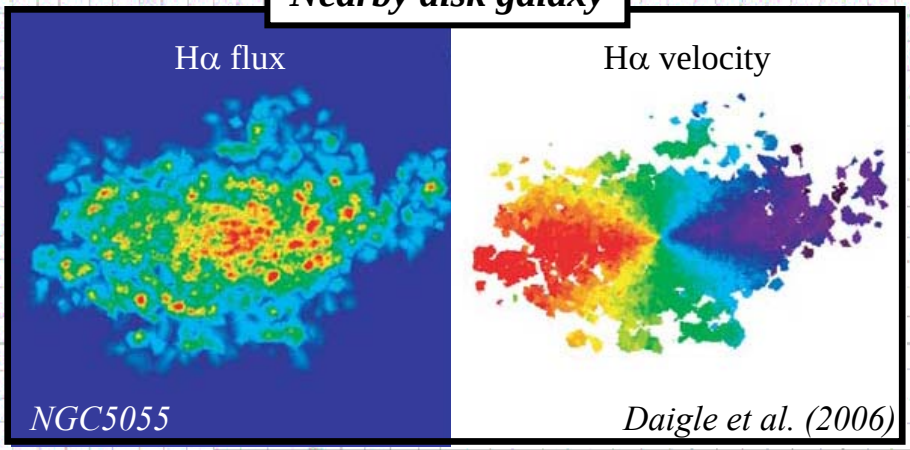
Molecular gas & cold dust

SINS survey
in the near-IR with
SINFONI at the VLT

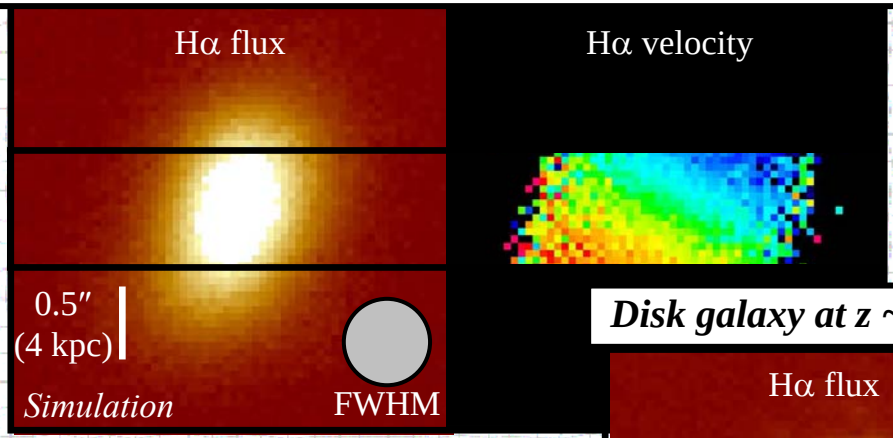
CO survey with the
IRAM/Plateau de Bure
mm-interferometer

8-10m (+AO) /HST: Resolving on kpc scales

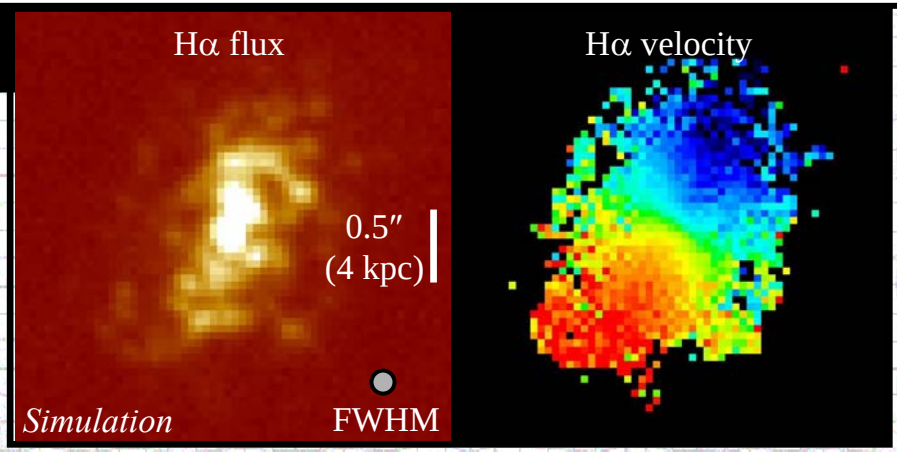
Nearby disk galaxy



Disk galaxy at z ~ 2: seeing-limited long-slit spectroscopy



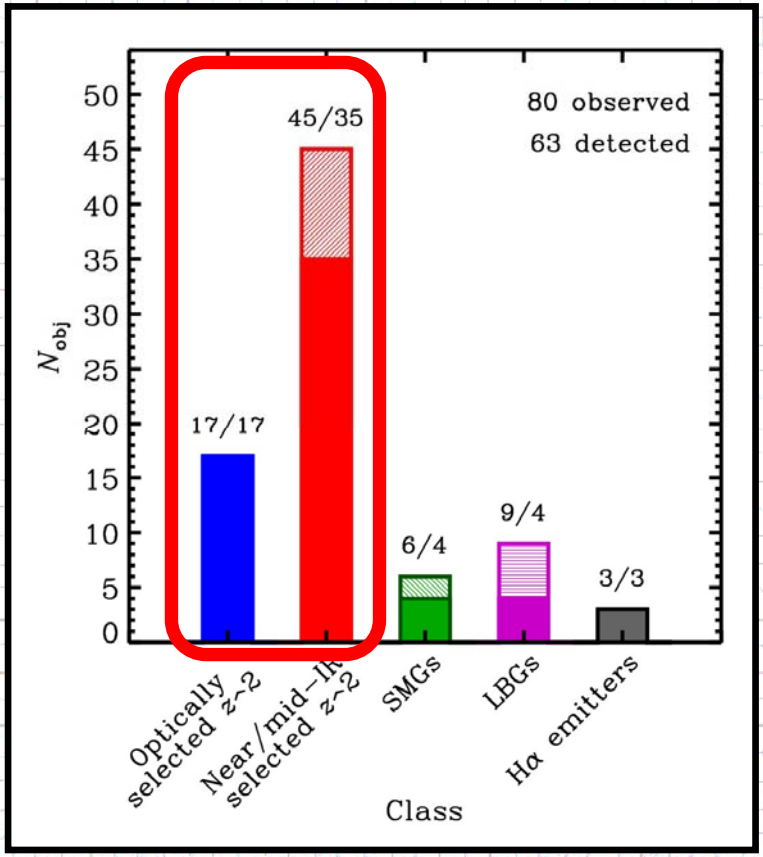
Disk galaxy at z ~ 2: integral field spectroscopy + AO



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

Also, e.g., Tecza et al. 2004; Swinbank et al. 2006,2007;
Nesvadba et al. 2006a,b,2007,2008; Law et al. 2007,2009;
Wright et al. 2007,2009; van Starkenburg et al. 2008;
Stark et al. 2008; Épinat et al. 2009; Mannucci et al. 2009

SINS Survey

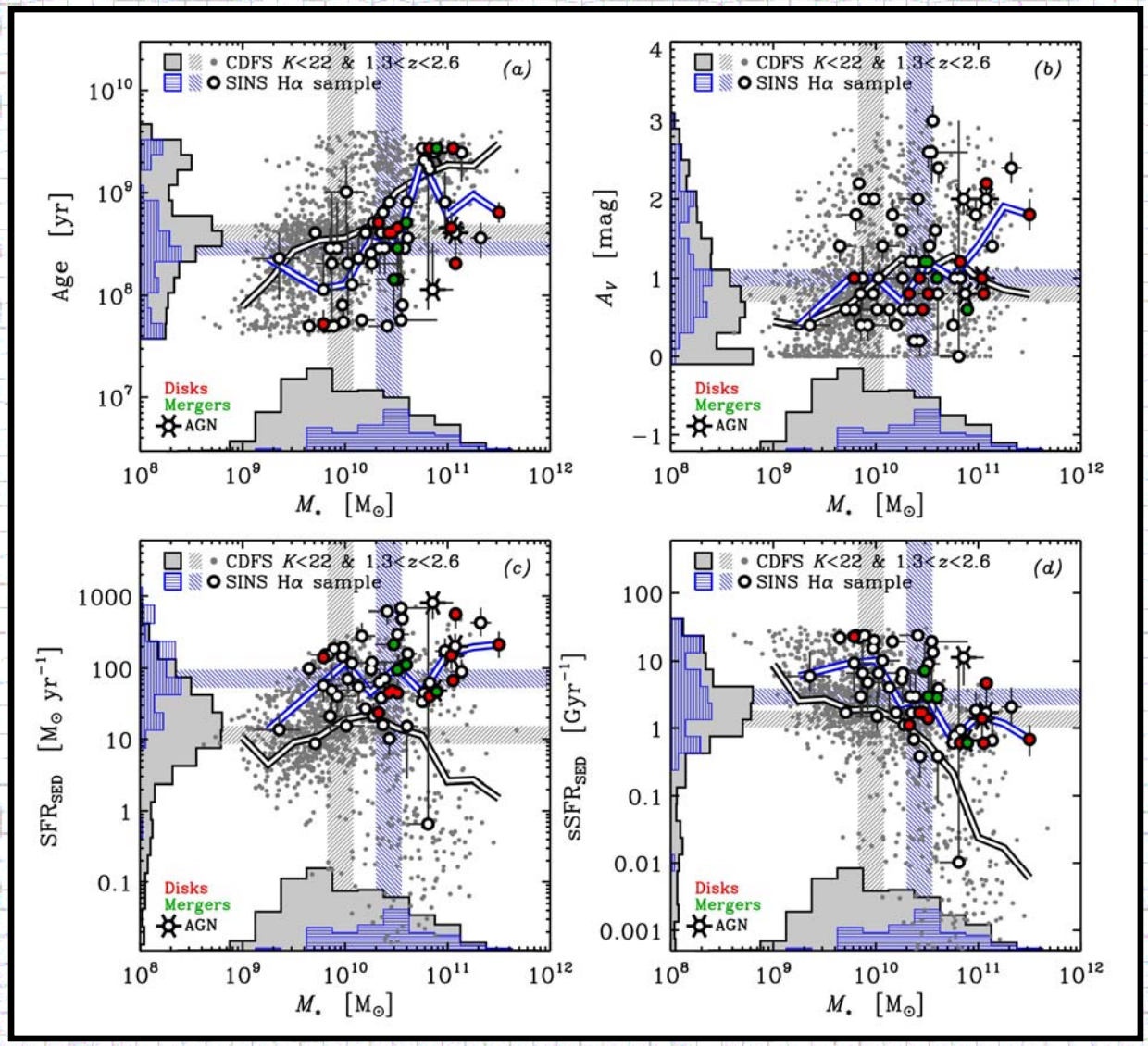


Near-IR
integral field spectroscopy
with SINFONI (+AO)
at the VLT

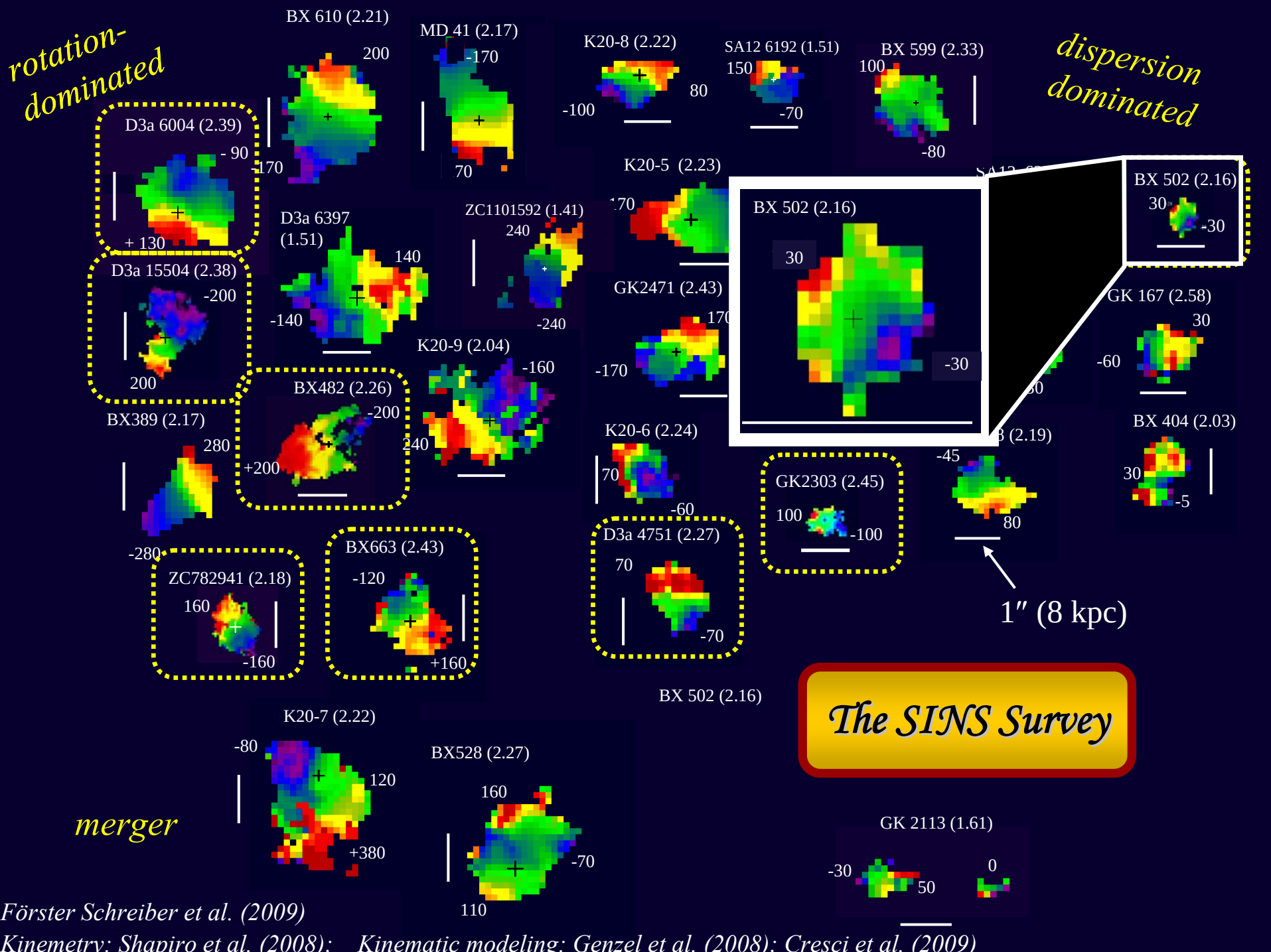
Complemented with near-IR imaging with HST/NICMOS-NIC2 and VLT/NACO+AO

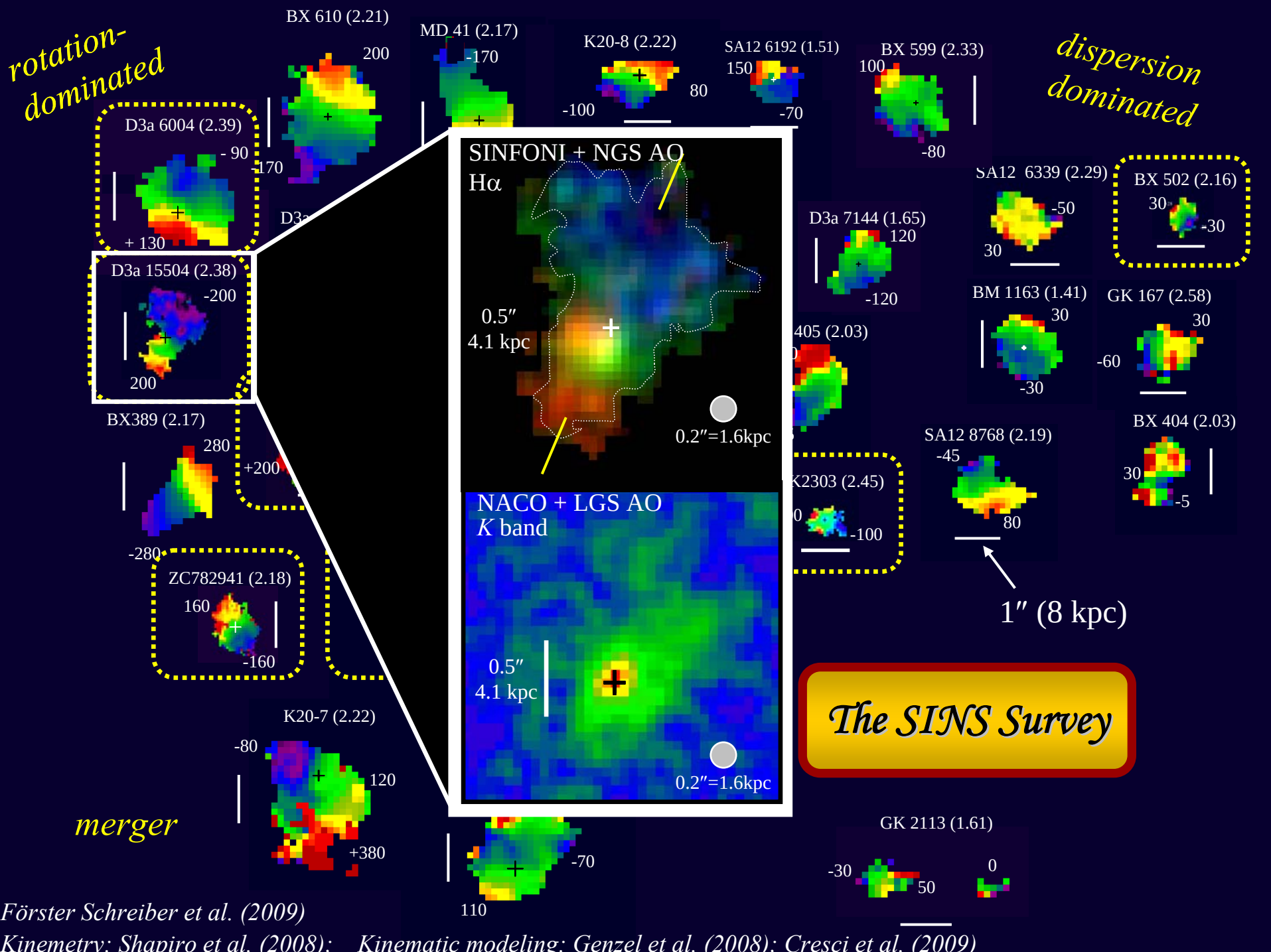
Förster Schreiber et al. 2006, 2009; Genzel et al. 2006, 2008; Bouché et al. 2007; Cresci et al. 2009; Shapiro et al. 2009
Also: e.g., Tecza et al. 2004; Nesvadba et al. 2006a,b; 2007; 2008; Swinbank et al. 2006, 2007; Wright et al. 2007, 2009; Law et al. 2007,2009; Stark et al. 2008; Bournaud et al. 2008; van Starkenburg et al. 2008; Epinat et al. 2009; Mannucci et al. 2009

SINS Hα Sample



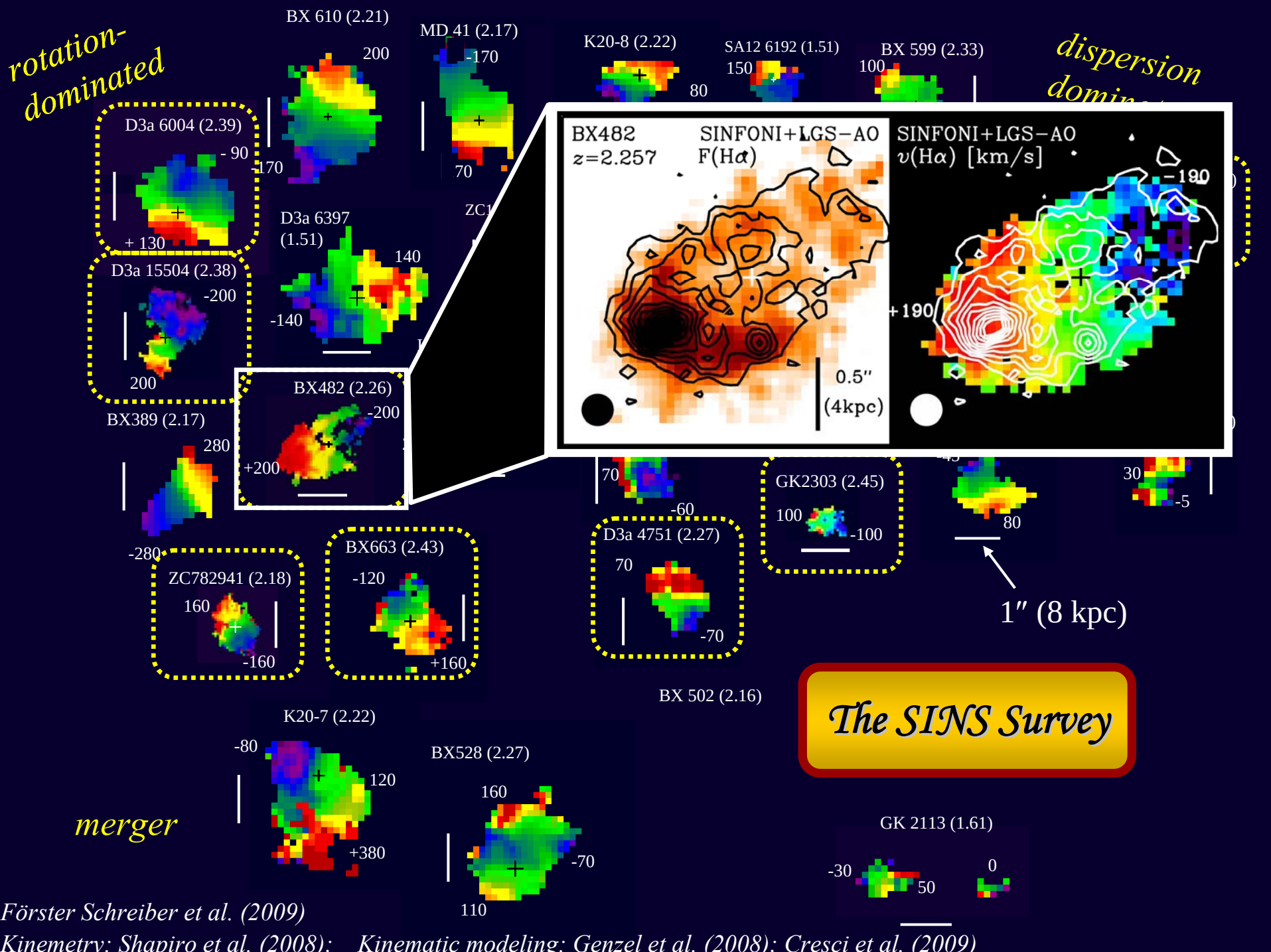
Förster Schreiber et al. (2009; arXiv:0903.1872)


rotation-dominated
dispersion dominated
merger
BX 610 (2.21)
200
170
MD 41 (2.17)
-170
70
K20-8 (2.22)
-100
80
SA12 6192 (1.51)
150
-70
BX 599 (2.33)
100
-80
D3a 6004 (2.39)
- 90
+ 130
K20-5 (2.23)
170
BX 502 (2.16)
30
-30
BX 502 (2.16)
30
-30
D3a 6397 (1.51)
140
-140
ZC1101592 (1.41)
240
-240
D3a 15504 (2.38)
-200
200
GK2471 (2.43)
170
-170
GK 167 (2.58)
30
-60
K20-9 (2.04)
-160
240
BX482 (2.26)
-200
+200
BX389 (2.17)
280
-280
K20-6 (2.24)
70
-60
GK2303 (2.45)
100
-100
D3a 4751 (2.27)
70
-70
BX 404 (2.03)
30
-5
-45
80
BX663 (2.43)
-120
+160
ZC782941 (2.18)
160
-160
1″ (8 kpc)
BX 502 (2.16)
The SINS Survey
K20-7 (2.22)
-80
120
+380
BX528 (2.27)
160
-70
110
GK 2113 (1.61)
-30
50
0
Förster Schreiber et al. (2009)
Kinemetry: Shapiro et al. (2008); Kinematic modeling: Genzel et al. (2008); Cresci et al. (2009)



Förster Schreiber et al. (2009)

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


rotation-dominated
dispersion
BX 610 (2.21)
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SA12 6192 (1.51)
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BX 599 (2.33)
100
D3a 6004 (2.39)
- 90
+ 130
D3a 15504 (2.38)
-200
200
D3a 6397
(1.51)
140
-140
ZC1
BX482 (2.26)
-200
+200
BX389 (2.17)
280
-280
BX482
z=2.257
SINFONI+LGS-AO
F(Hα)
0.5″
(4kpc)
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)
ZC782941 (2.18)
160
-160
BX663 (2.43)
-120
+160
BX 502 (2.16)
The SINS Survey
K20-7 (2.22)
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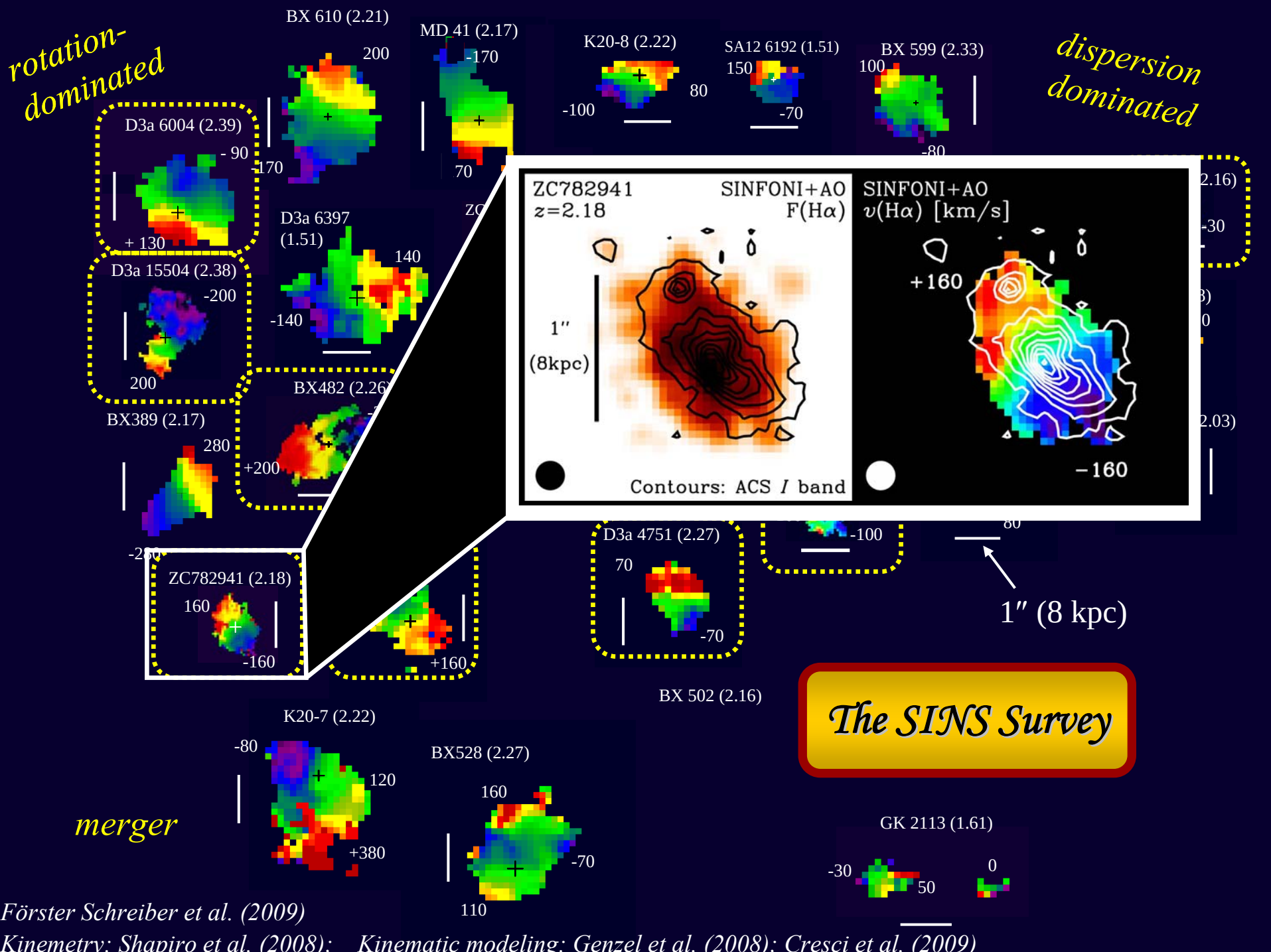
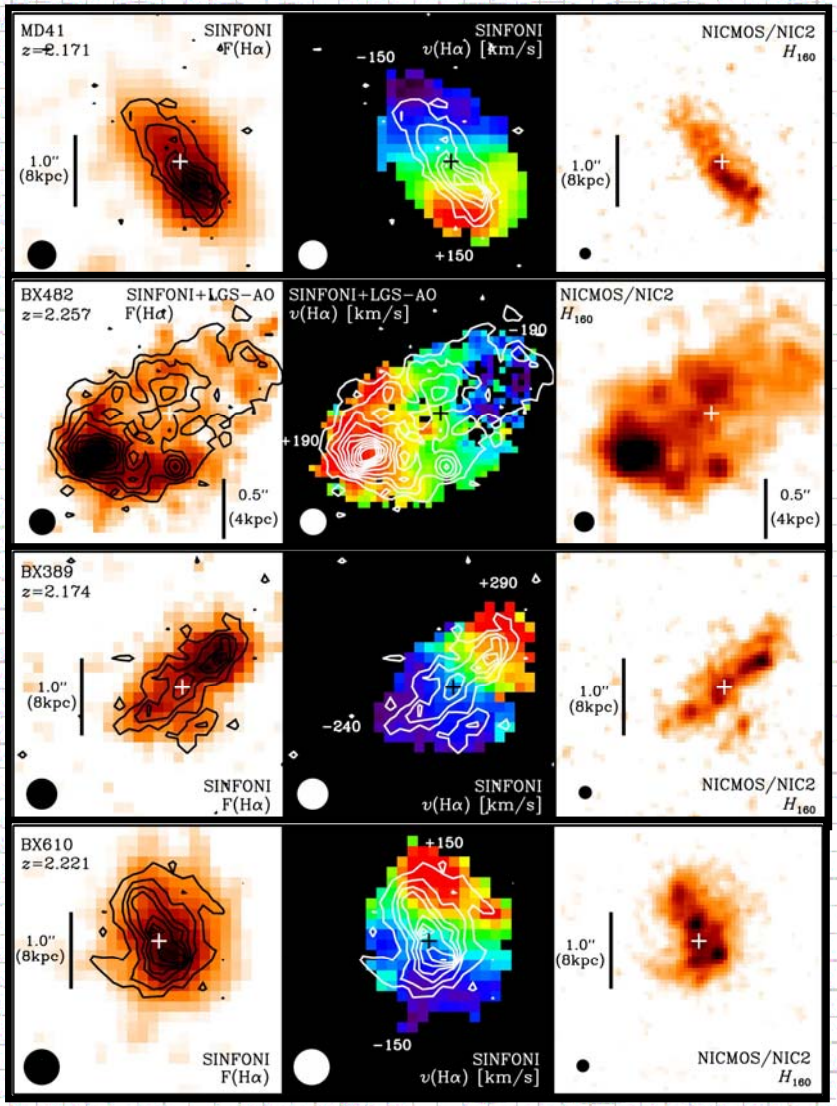
Kinemetry: Shapiro et al. (2008); Kinematic modeling: Genzel et al. (2008); Cresci et al. (2009)



Förster Schreiber et al. (2009)

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

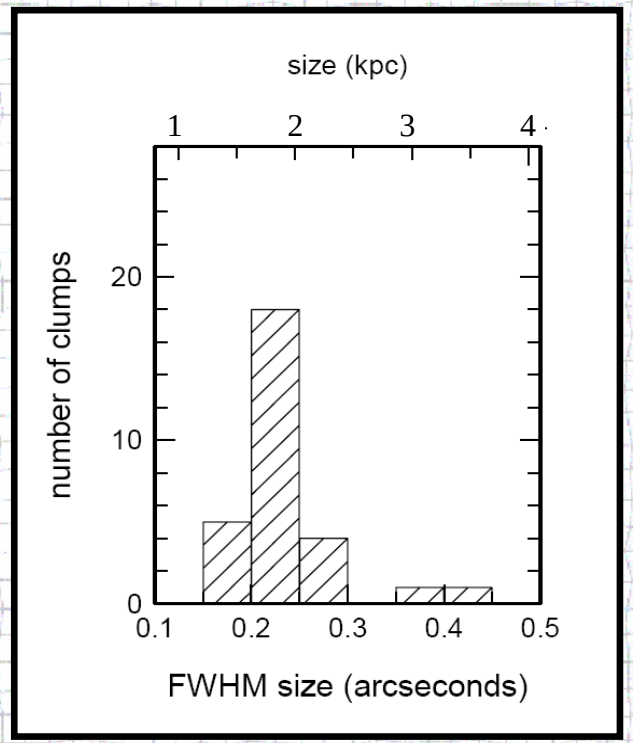
Dynamical Evolution of Gas-rich Disks



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

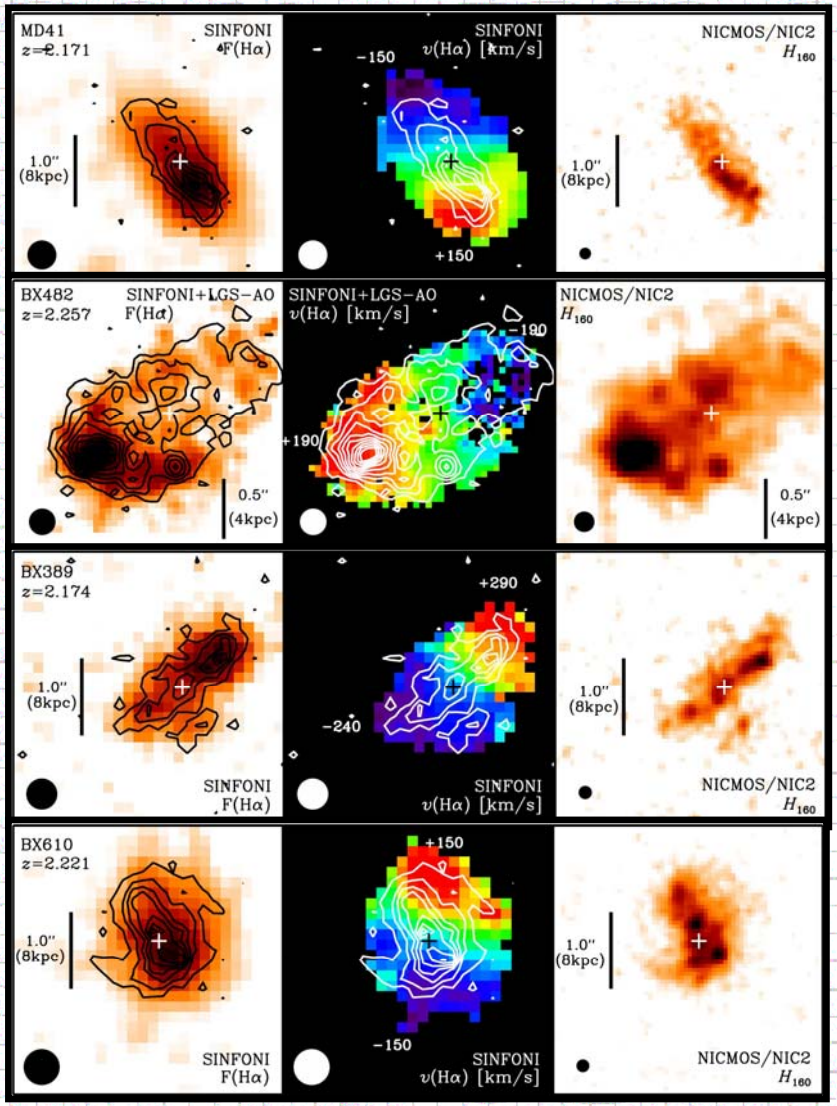
For $Q \approx 1$:

- $L_J \propto (\sigma_0/v_c)R_d \sim 2.5$ kpc
- $M_{cl} \propto (L_{cl}\, v_c)^2/R_d \sim 10^{9.4}\ M_\odot$

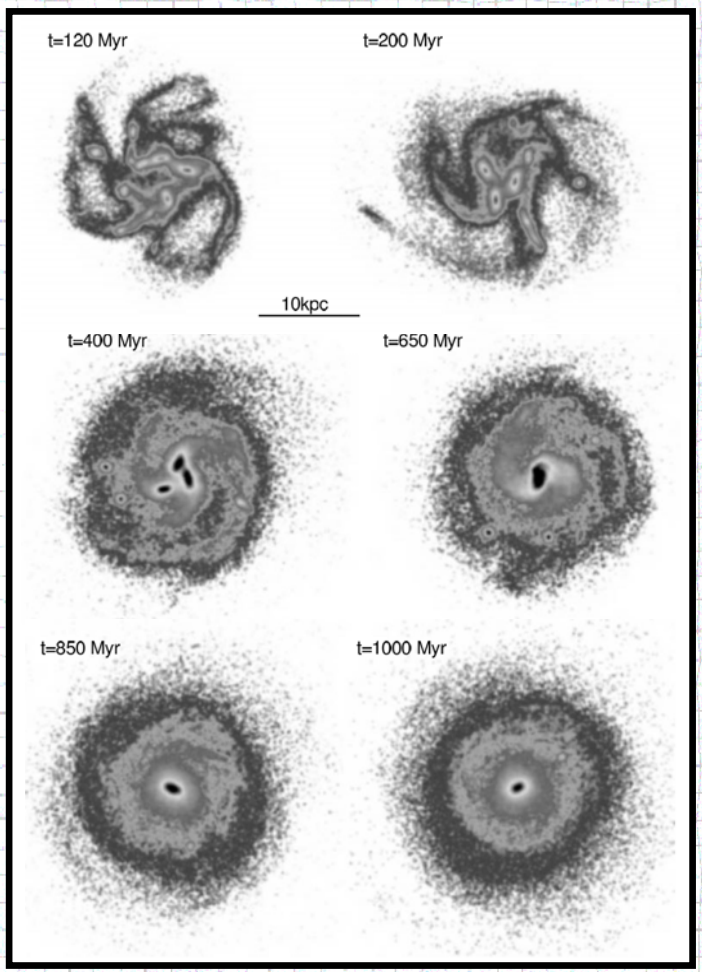


(Also, Cowie et al. 1995; van den Bergh et al. 1996; Giavalisco et al. 1996; Conselice et al. 2004; Lotz et al. 2004; Papovich et al. 2005; Toft et al. 2007; Law et al. 2007; Elmegreen, Elmegreen, et al. 2004-2009; and others)

Dynamical Evolution of Gas-rich Disks

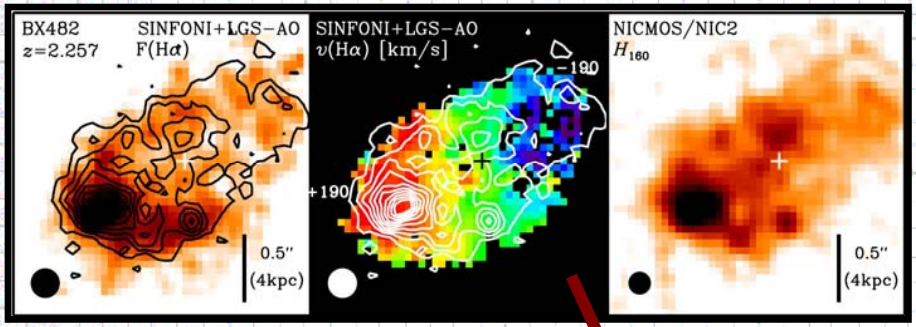


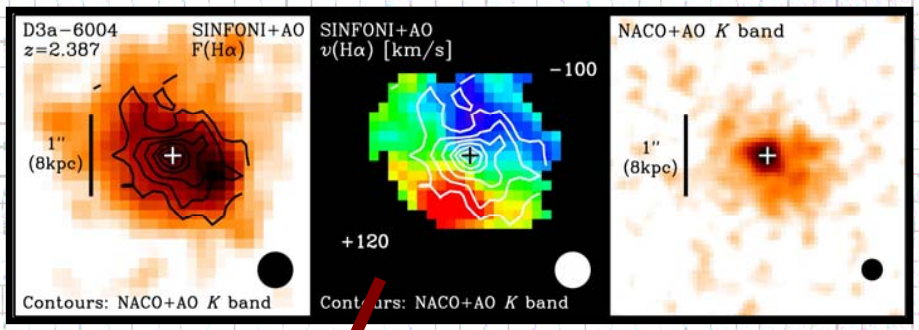
Förster Schreiber, Shapley, et al. (2009); Genzel et al. (2008)



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

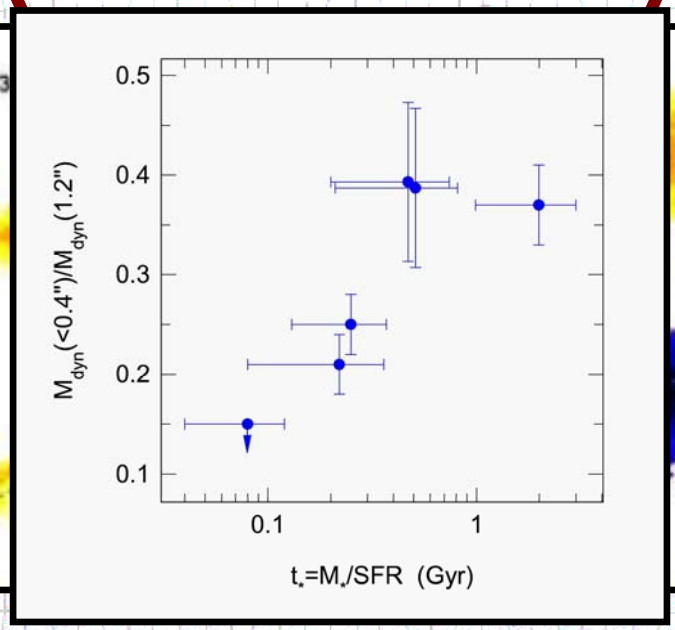
Dynamical Evolution of Gas-rich Disks





Stellar surface density

Velocity field

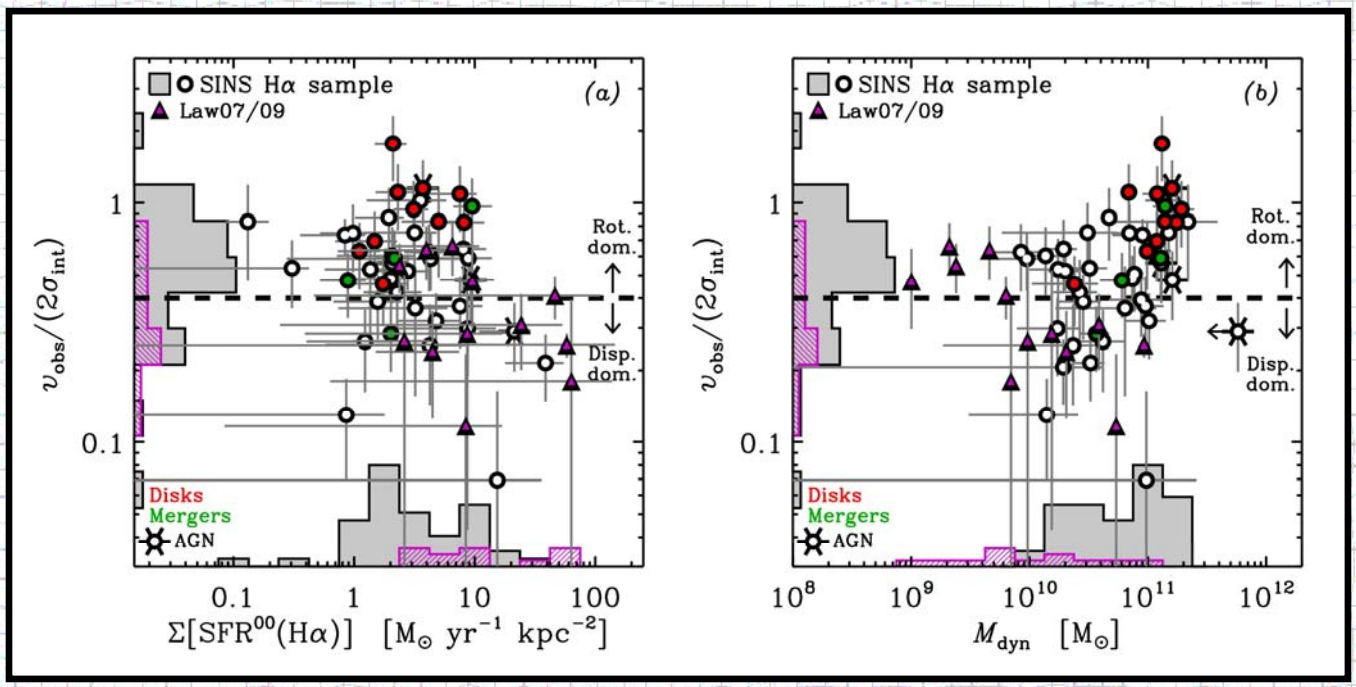


Förster Schreiber, Shapley, et al. (2009); Genzel et al. (2008)

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

Large Velocity Dispersion of Star-forming Disks at z ~ 2

- Star formation feedback? Gas accretion? Internal dynamics?
- For $Q \approx 1$, $v_c/\sigma_0 \propto 1/f_{gas}$



Rotation- vs Dispersion-dominated:

$v_c/\sigma_0 \sim 1$

$\leftrightarrow$

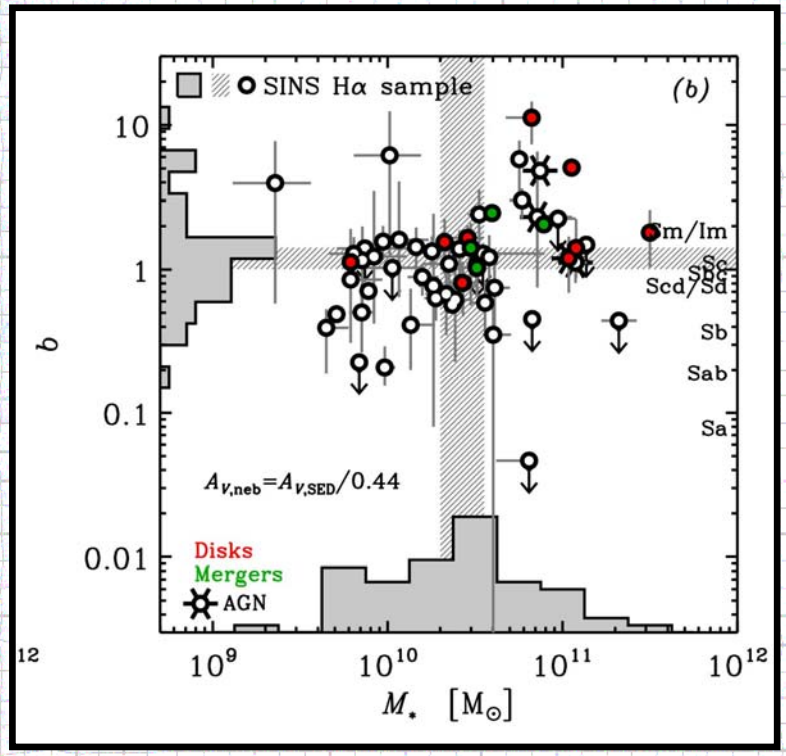
$0.5 v_{obs}/\sigma_{int} \sim 0.4$

Förster Schreiber et al. (2006; 2009); Genzel et al. (2006, 2008); Cresci et al. (2009)

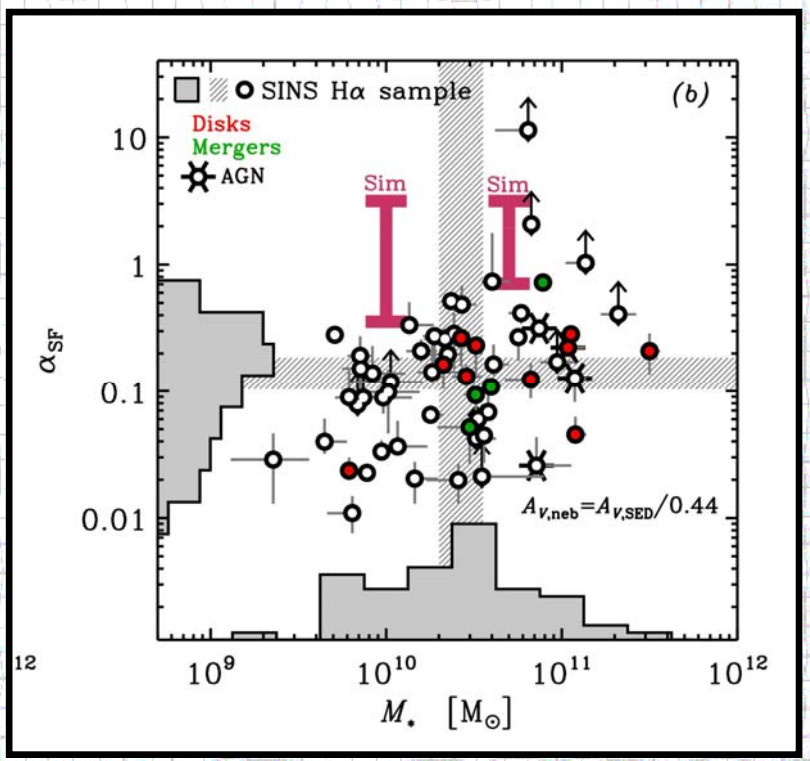
also: Law et al. (2007, 2009); Wright et al. (2007); van Starkenburg (2008); Stark et al. (2008); Épinat et al. (2009)

Star Formation Activity and Timescales

$\tau_\star \sim \tau_{gas} \sim 500\,\mathrm{Myr} \sim \text{several } \tau_{dyn} << t_{Hubble}$



b = $SFR_{current}$ / $\langle SFR \rangle_{past}$



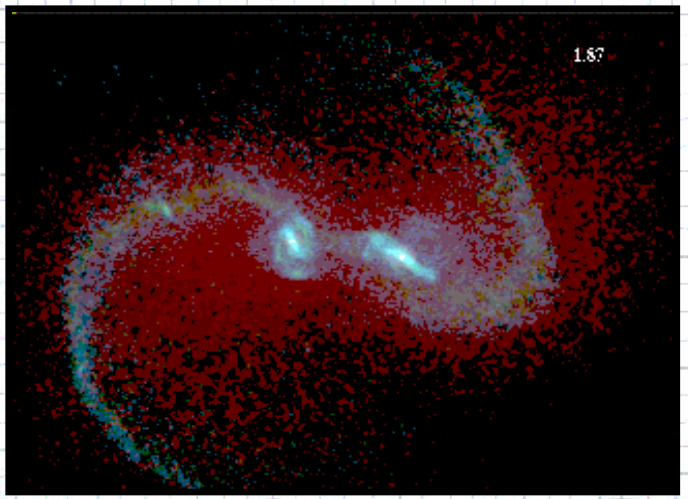
α = (1/sSFR) / (t_H – 1 Gyr)

Förster Schreiber et al. (2006; 2009); Genzel et al. (2008); Bouché et al. (2009)
see also, e.g., Kennicutt et al. (1994); Daddi et al. (2007); Davé (2008); Chen et al. (2009)

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

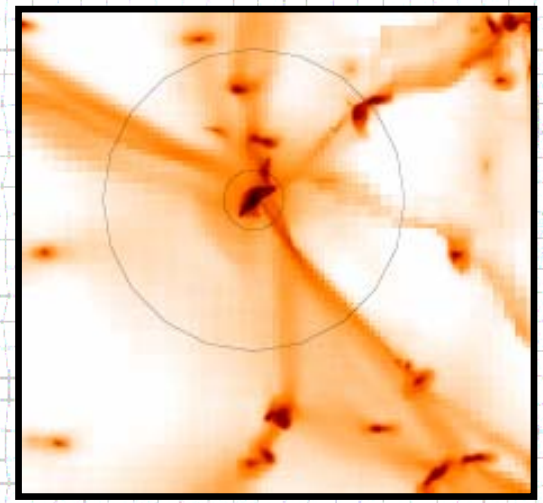
$\tau_\star \sim \tau_{gas} \sim 500\,\mathrm{Myr} \sim$ several $\tau_{dyn} \ll t_{Hubble}$

Major 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 Robertson et al. 2008)

Cold flows/minor mergers



(e.g., Dekel & Birnboim 2003,2006; Kereš et al. 2005; d'Onghia et al. 2006; Kitzbichler & White 2007; Guo & White 2008; Davé 2008; Noeske et al. 2007; Elbaz et al. 2007; Daddi et al. 2007; Dekel et al. 2008, 2009; Genel et al. 2008, 2009)

SINS Key Results

- Kinematics of SINS massive star-forming galaxies at $z \sim 2$

  ~ 1/3 rotation-dominated, ~ 1/3 compact dispersion-dominated, ~ 1/3 mergers

  Fraction of rotation-dominated systems increase at higher masses

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

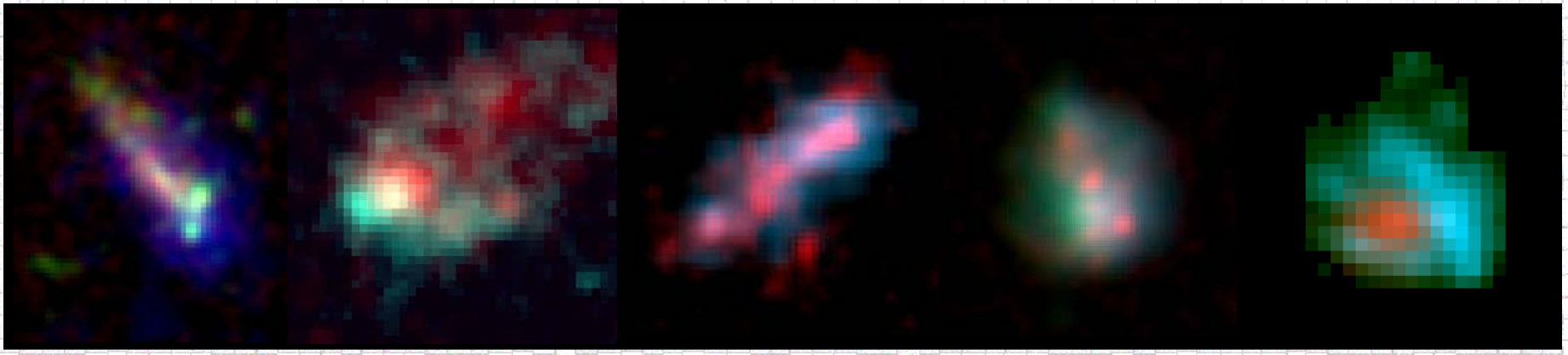
  Significantly more turbulent and gas-rich than local disks

  Higher SFRs, large luminous/massive clumps

- Mass assembly, early evolution, and star formation activity

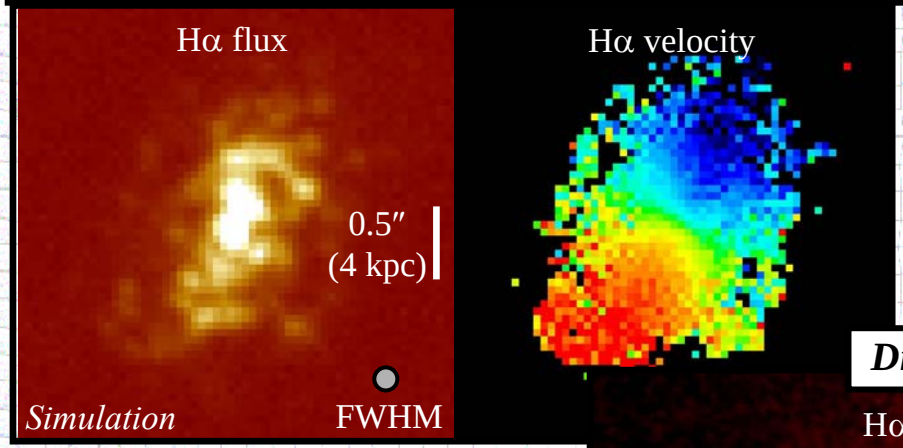
  Evidence for smooth+rapid mass accretion via cold flows/minor mergers

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

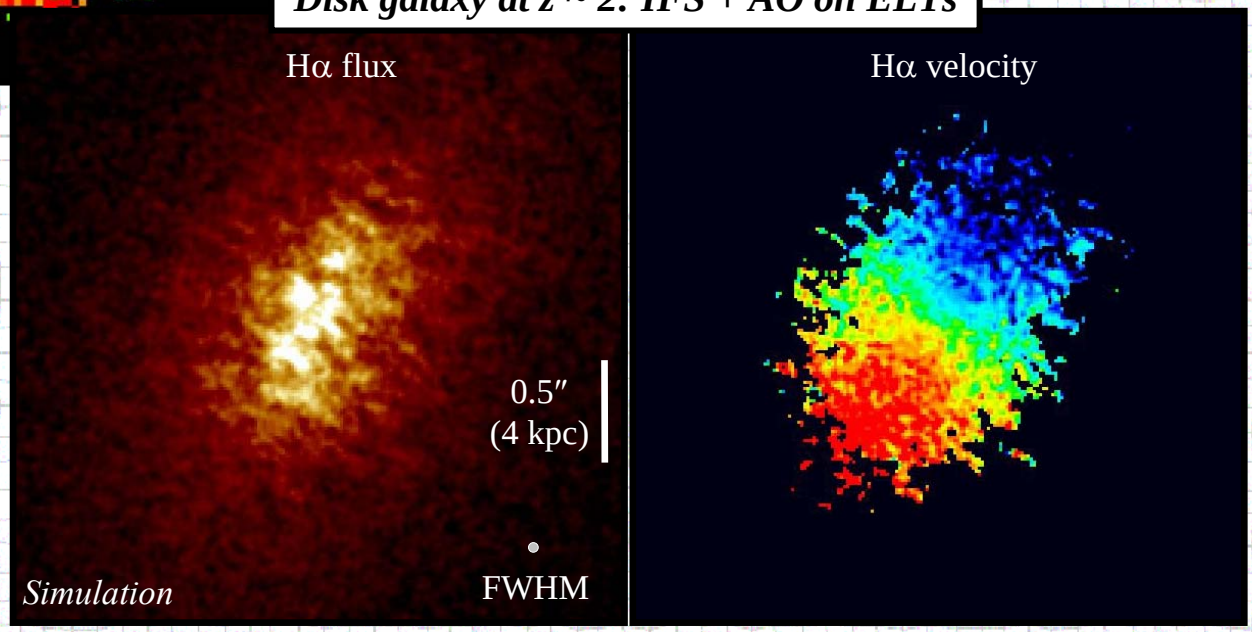


ELTs & ALMA: Resolving sub-kpc scales

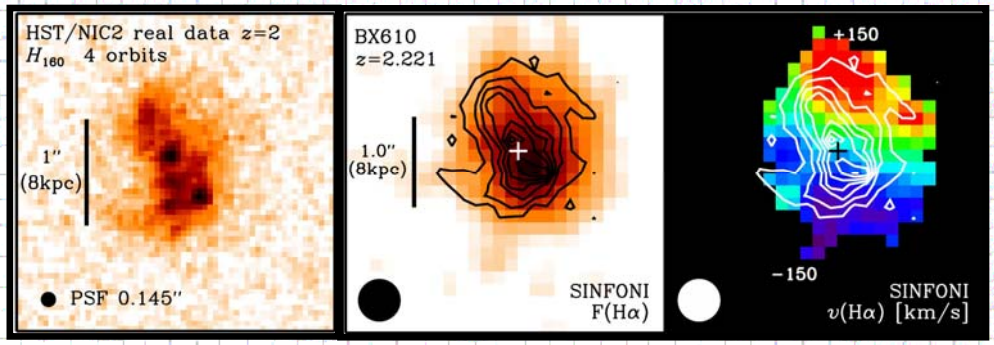
Disk galaxy at z ~ 2: IFS + AO on 8-10m telescopes



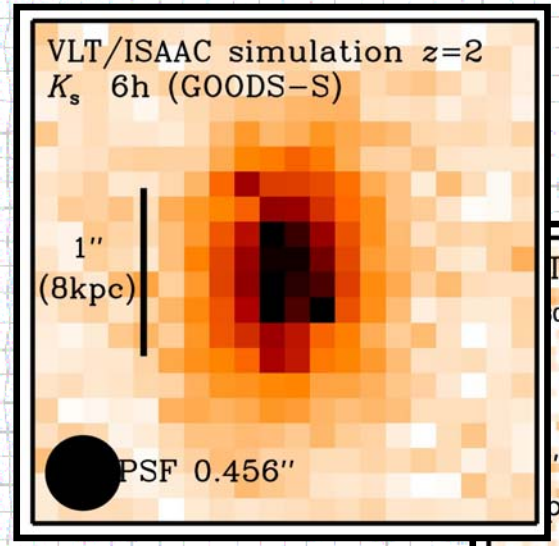
Disk galaxy at z ~ 2: IFS + AO on ELTs

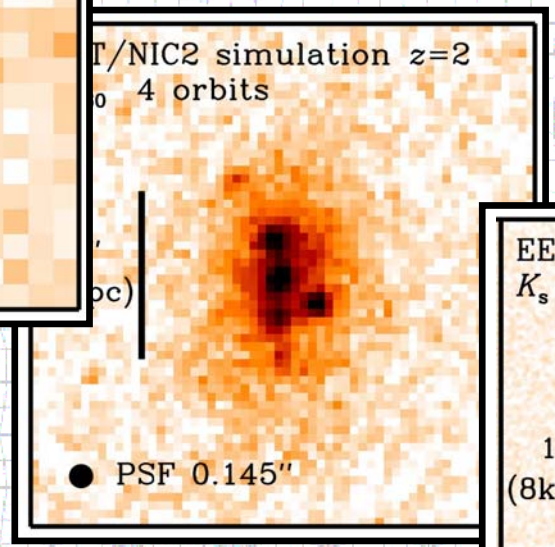


Simulations for E-ELT/MICADO

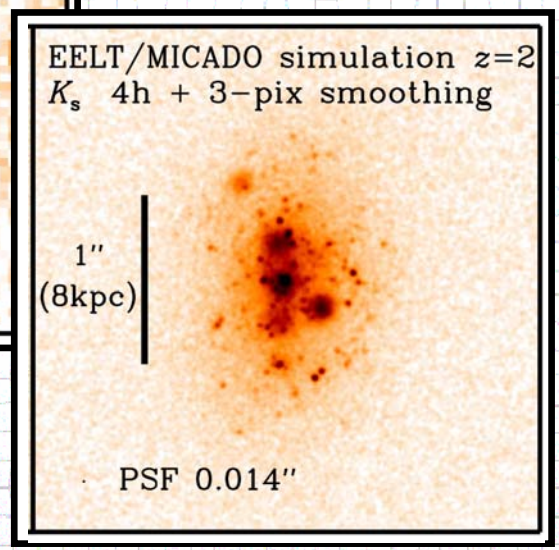


Real disk galaxy at z = 2.3
$R_{1/2}$ = 5 kpc, K_{AB} = 21.3





Mock disk galaxy at z = 2.3
$R_{1/2}$ = 5 kpc, K_{AB} = 21.3

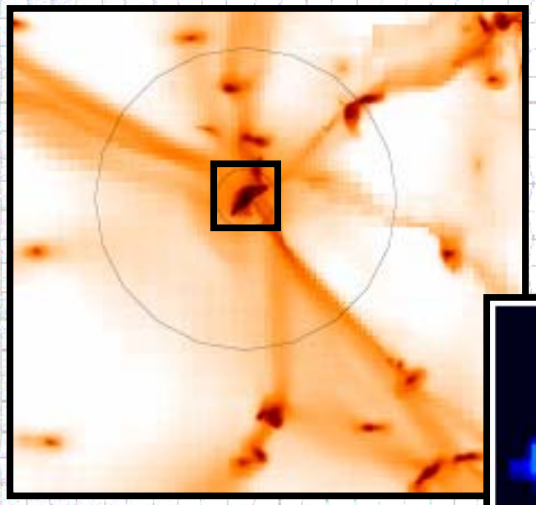


Resolution of ~ 100 pc at z ~ 2
Compact clusters detected to K_{AB} ~ 28.5

NMFS 2008; Förster Schreiber et al. (2009b)

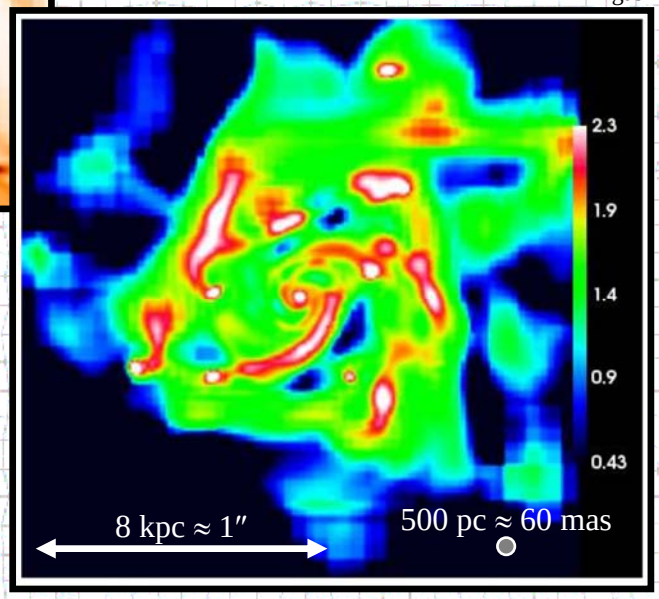
Sub-kpc structure at high-z: Simulations

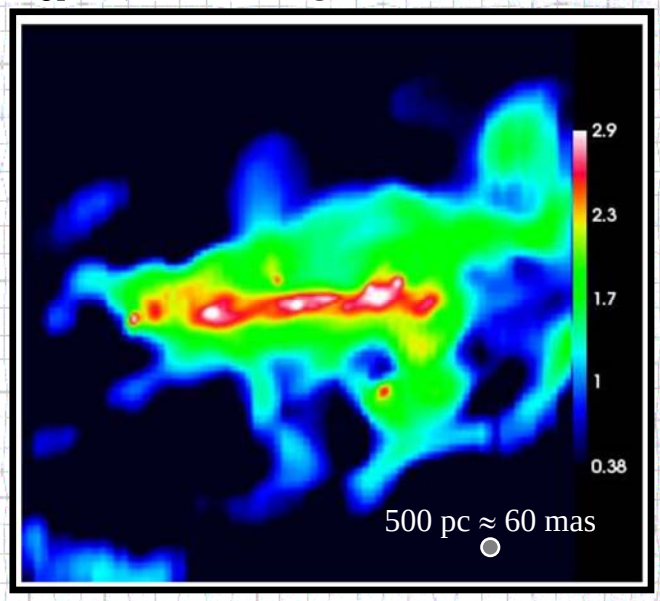
Cold flows/Streams



Example hydro-AMR cosmological simulation
Resolution: 70 pc ≈ 10 mas at $z \sim 2$

Face-on log (Σ_{gas} [$M_\odot pc^{-2}$]) Edge-on



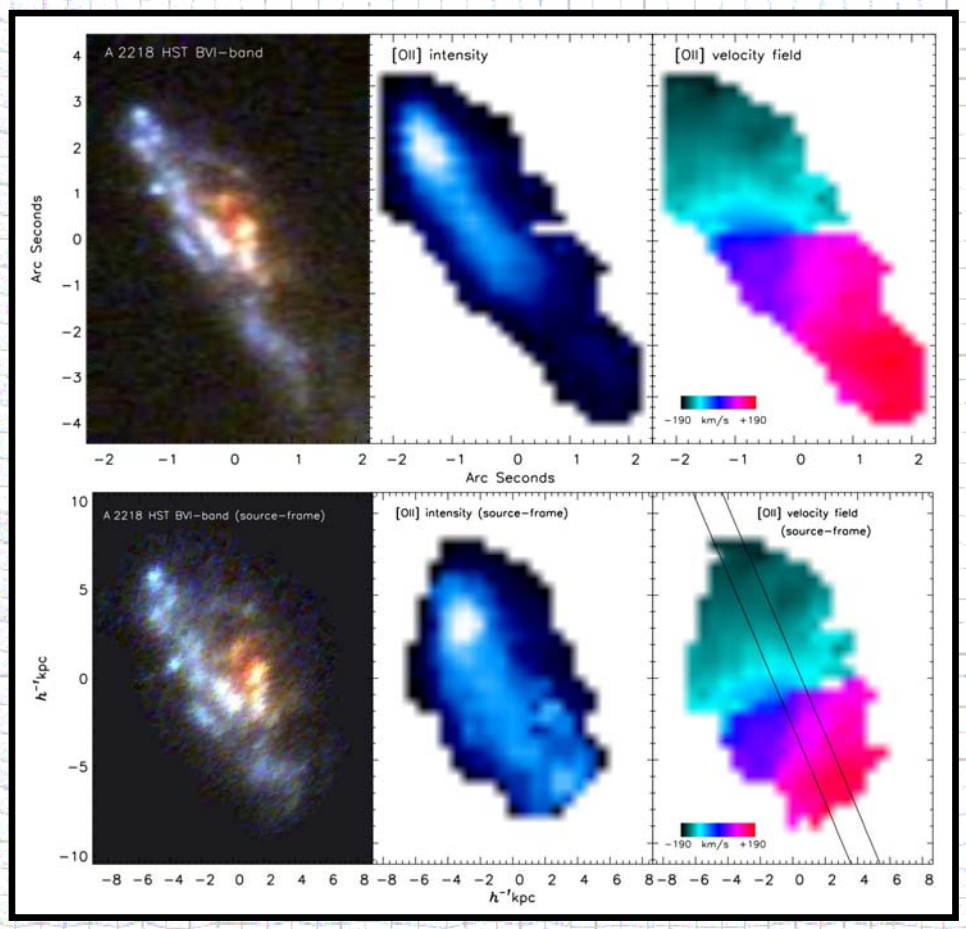


Disk galaxy at z = 2.3
fed by gas streams
$R_d = 6$ *kpc*, $v_d/\sigma_0 = 4.7$

Dekel et al. 2008; Dekel, Sari, & Ceverino 2009; Ceverino & Dekel, in prep.
also, e.g., Naab, Genel, et al., Bournaud et al. (in prep.), among others

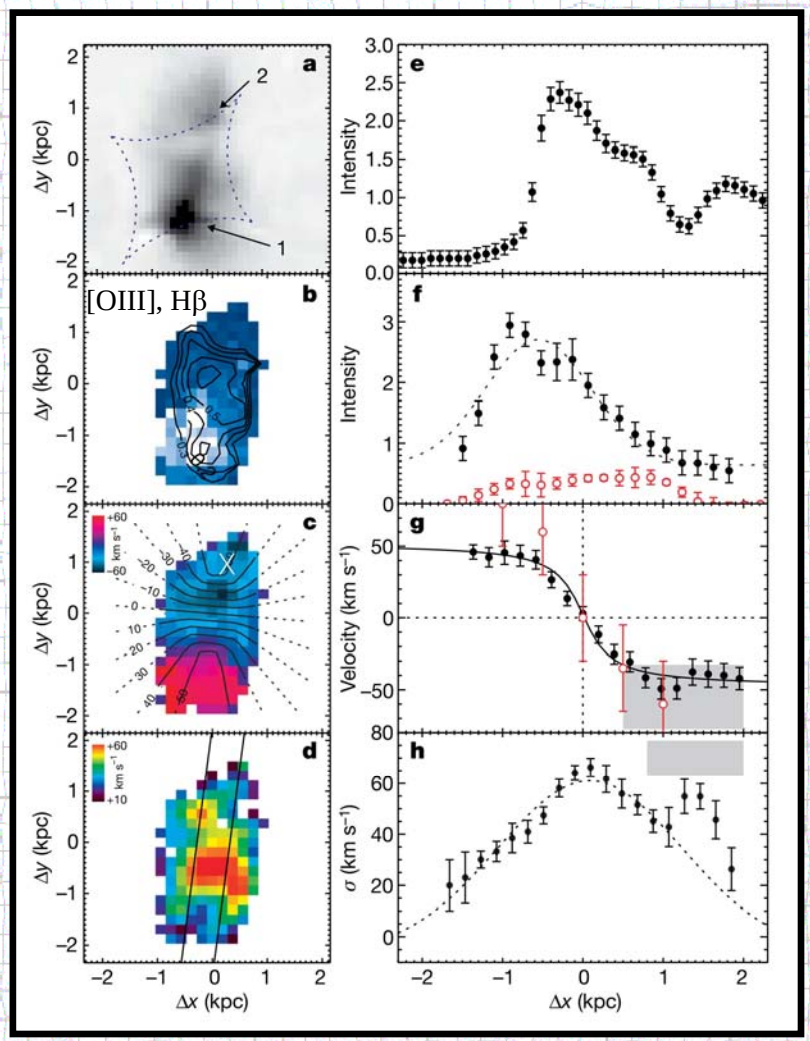
Sub-kpc structure at high z: Lensed Objects

Lensed galaxies at $z \sim 1$, $\mu \sim 10$;
HST resolution ~ 150 pc; GMOS resolution ~ 500 pc



Swinbank et al. (2003, 2006 + in prep.)

Lensed galaxy at $z \sim 3$, $\mu \sim 30$;
HST & OSIRIS+AO resolution ~ 150 – 300 pc



Stark et al. (2008)

Prospects for ELTs/ALMA

- Structural, dynamical, and stellar/physical properties on ~ 100 – 500 pc scales
  - ***Mass, density, metallicity, kinematics profiles***
  - ***Disk instabilities, properties and substruture of clumps***
  - ***Age, SFR, and dust distribution***
  - ***Formation of bulges, globular clusters***
  - ***Feedback from star formation and AGN***
  - ***SMBH / IMBH formation***
  - ***Push down the mass/luminosity function and to higher z***
- Synergies ELTs/ALMA
  - ***Gas mass fraction is key parameter for evolution of galaxies***
  - ***Cold gas distribution and dynamics***