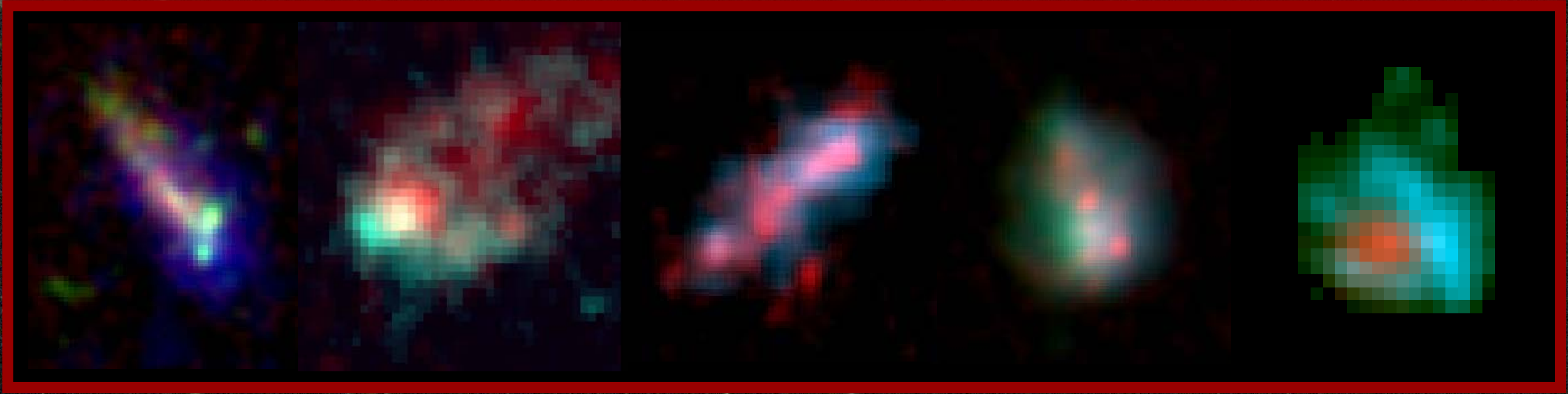
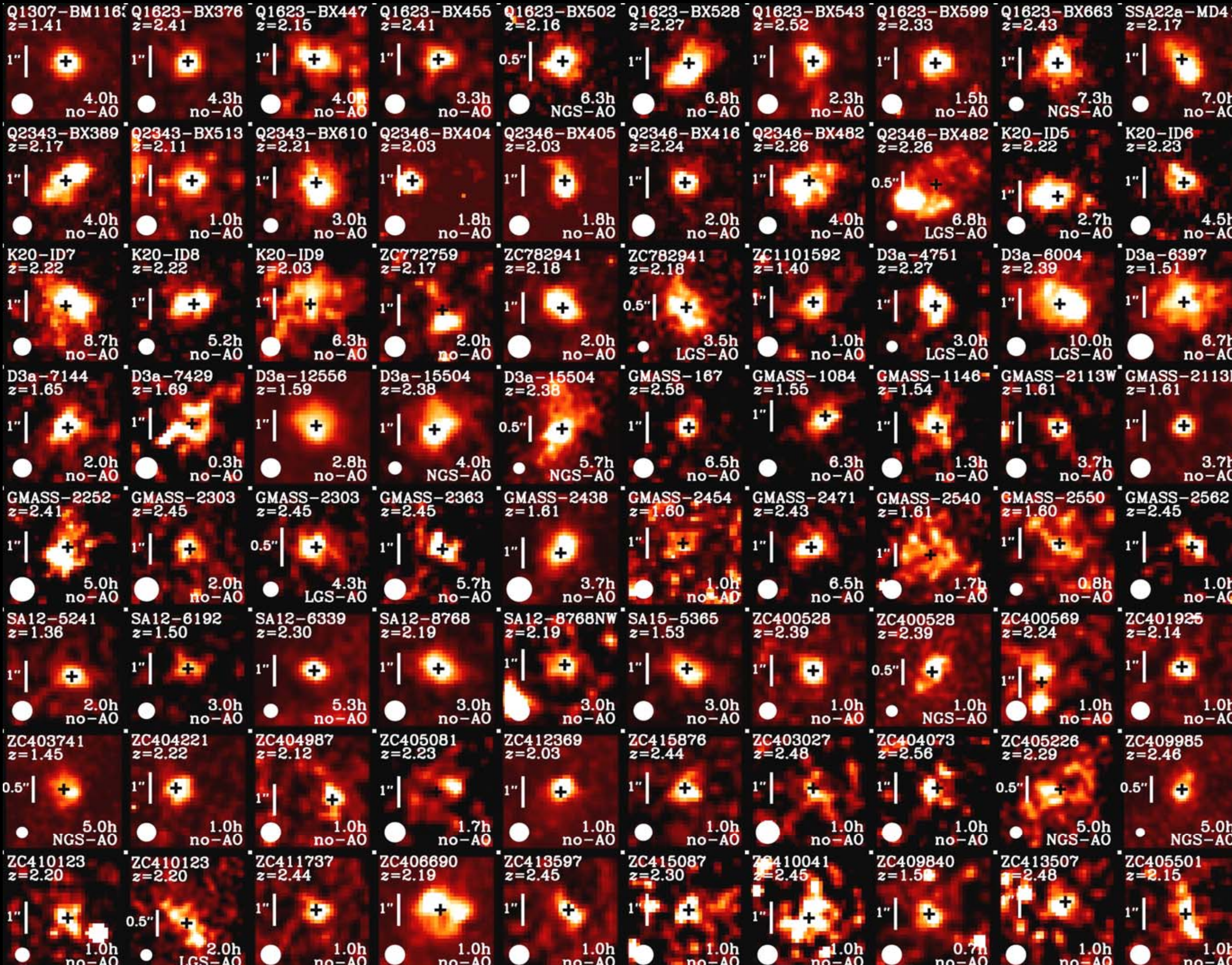
# The Growth of Galaxies at z ~ 2




N.M. Förster Schreiber (MPE)
The SINS Team
The zCOSMOS-SINFONI Team
and collaborations with GMASS/Caltech UV/Theory Teams

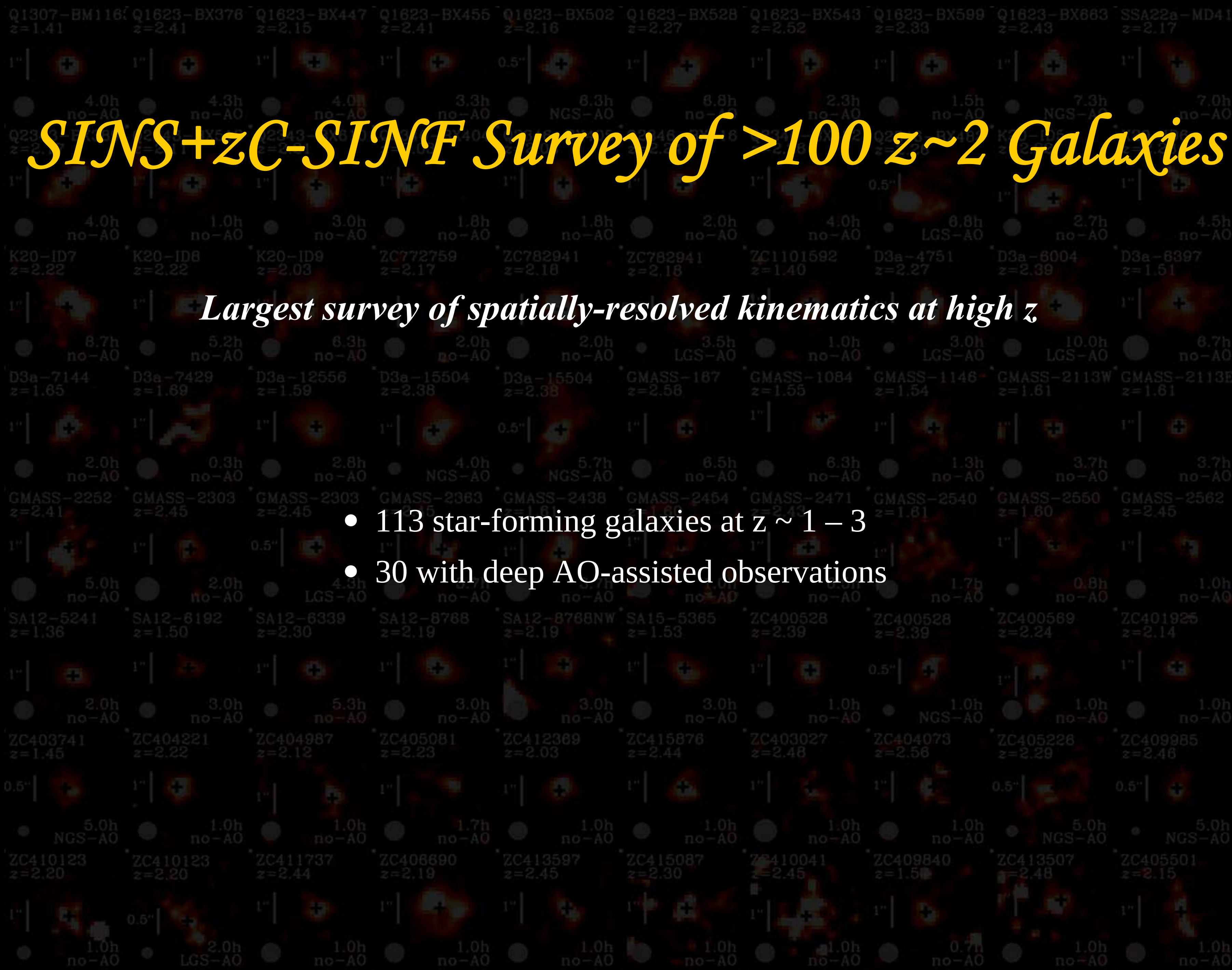
R. Genzel, L.J. Tacconi, N. Bouché, P. Buschkamp, G. Cresci, R.I. Davies, F. Eisenhauer, S. Genel, E.K.S. Hicks, S. Gillessen, J. Kurk, D. Lutz, S. Newman, K.L. Shapiro, A. Sternberg, A. Verma, S. Wuyts
A. Renzini, S. Lilly, C.M. Carollo, C. Mancini, Y. Peng, D. Vergani, G. Zamorani, A. Cimatti, E. Daddi, O. Le Fèvre, C. Maier, V. Mainieri, H.J. McCracken, M. Mignoli, P. Oesch, L. Pozzetti, M. Scodeggio
A.E. Shapley, D.K. Erb, C.C. Steidel
A. Burkert, T. Naab, P. Johansson, A. Dekel, D. Ceverino, O. Gerhard, S. Khochfar, F. Bournaud, G. de Lucia



Q1307-BM116 z=1.41 1" 4.0h no-AO
Q1623-BX376 z=2.41 1" 4.3h no-AO
Q1623-BX447 z=2.15 1" 4.0h no-AO
Q1623-BX455 z=2.41 1" 3.3h no-AO
Q1623-BX502 z=2.16 0.5" 6.3h NGS-AO
Q1623-BX528 z=2.27 1" 6.8h no-AO
Q1623-BX543 z=2.52 1" 2.3h no-AO
Q1623-BX599 z=2.33 1" 1.5h no-AO
Q1623-BX663 z=2.43 1" 7.3h NGS-AO
SSA22a-MD41 z=2.17 1" 7.0h no-AO
Q2343-BX389 z=2.17 1" 4.0h no-AO
Q2343-BX513 z=2.11 1" 1.0h no-AO
Q2343-BX610 z=2.21 1" 3.0h no-AO
Q2346-BX404 z=2.03 1" 1.8h no-AO
Q2346-BX405 z=2.03 1" 1.8h no-AO
Q2346-BX416 z=2.24 1" 2.0h no-AO
Q2346-BX482 z=2.26 1" 4.0h no-AO
Q2346-BX482 z=2.26 0.5" 6.8h LGS-AO
K20-ID5 z=2.22 1" 2.7h no-AO
K20-ID6 z=2.23 1" 4.5h no-AO
K20-ID7 z=2.22 1" 8.7h no-AO
K20-ID8 z=2.22 1" 5.2h no-AO
K20-ID9 z=2.03 1" 6.3h no-AO
ZC772759 z=2.17 1" 2.0h no-AO
ZC782941 z=2.18 1" 2.0h no-AO
ZC782941 z=2.18 0.5" 3.5h LGS-AO
ZC1101592 z=1.40 1" 1.0h no-AO
D3a-4751 z=2.27 1" 3.0h LGS-AO
D3a-6004 z=2.39 1" 10.0h LGS-AO
D3a-6397 z=1.51 1" 6.7h no-AO
D3a-7144 z=1.65 1" 2.0h no-AO
D3a-7429 z=1.69 1" 0.3h no-AO
D3a-12556 z=1.59 1" 2.8h no-AO
D3a-15504 z=2.38 1" 4.0h NGS-AO
D3a-15504 z=2.38 0.5" 5.7h NGS-AO
GMASS-167 z=2.58 1" 6.5h no-AO
GMASS-1084 z=1.55 1" 6.3h no-AO
GMASS-1146 z=1.54 1" 1.3h no-AO
GMASS-2113W z=1.61 1" 3.7h no-AO
GMASS-2113E z=1.61 1" 3.7h no-AO
GMASS-2252 z=2.41 1" 5.0h no-AO
GMASS-2303 z=2.45 1" 2.0h no-AO
GMASS-2303 z=2.45 0.5" 4.3h LGS-AO
GMASS-2363 z=2.45 1" 5.7h no-AO
GMASS-2438 z=1.61 1" 3.7h no-AO
GMASS-2454 z=1.60 1" 1.0h no-AO
GMASS-2471 z=2.43 1" 6.5h no-AO
GMASS-2540 z=1.61 1" 1.7h no-AO
GMASS-2550 z=1.60 1" 0.8h no-AO
GMASS-2562 z=2.45 1" 1.0h no-AO
SA12-5241 z=1.36 1" 2.0h no-AO
SA12-6192 z=1.50 1" 3.0h no-AO
SA12-6339 z=2.30 1" 5.3h no-AO
SA12-8768 z=2.19 1" 3.0h no-AO
SA12-8768NW z=2.19 1" 3.0h no-AO
SA15-5365 z=1.53 1" 3.0h no-AO
ZC400528 z=2.39 1" 1.0h no-AO
ZC400528 z=2.39 0.5" 1.0h NGS-AO
ZC400569 z=2.24 1" 1.0h no-AO
ZC401925 z=2.14 1" 1.0h no-AO
ZC403741 z=1.45 0.5" 5.0h NGS-AO
ZC404221 z=2.22 1" 1.0h no-AO
ZC404987 z=2.12 1" 1.0h no-AO
ZC405081 z=2.23 1" 1.7h no-AO
ZC412369 z=2.03 1" 1.0h no-AO
ZC415876 z=2.44 1" 1.0h no-AO
ZC403027 z=2.48 1" 1.0h no-AO
ZC404073 z=2.56 1" 1.0h no-AO
ZC405226 z=2.29 0.5" 5.0h NGS-AO
ZC409985 z=2.46 0.5" 5.0h NGS-AO
ZC410123 z=2.20 1" 1.0h no-AO
ZC410123 z=2.20 0.5" 2.0h LGS-AO
ZC411737 z=2.44 1" 1.0h no-AO
ZC406690 z=2.19 1" 1.0h no-AO
ZC413597 z=2.45 1" 1.0h no-AO
ZC415087 z=2.30 1" 1.0h no-AO
ZC410041 z=2.45 1" 1.0h no-AO
ZC409840 z=1.52 1" 0.7h no-AO
ZC413507 z=2.48 1" 1.0h no-AO
ZC405501 z=2.15 1" 1.0h no-AO

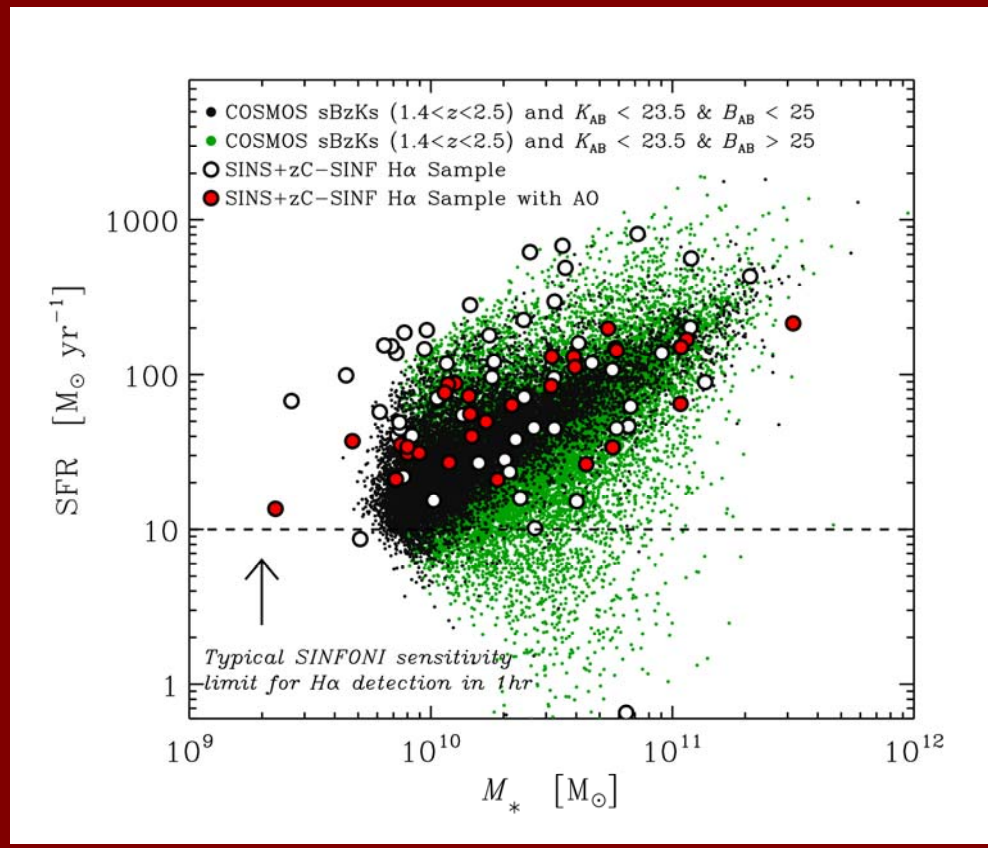
# *SINS+zC-SINF Survey of >100 z~2 Galaxies*

***Largest survey of spatially-resolved kinematics at high z***



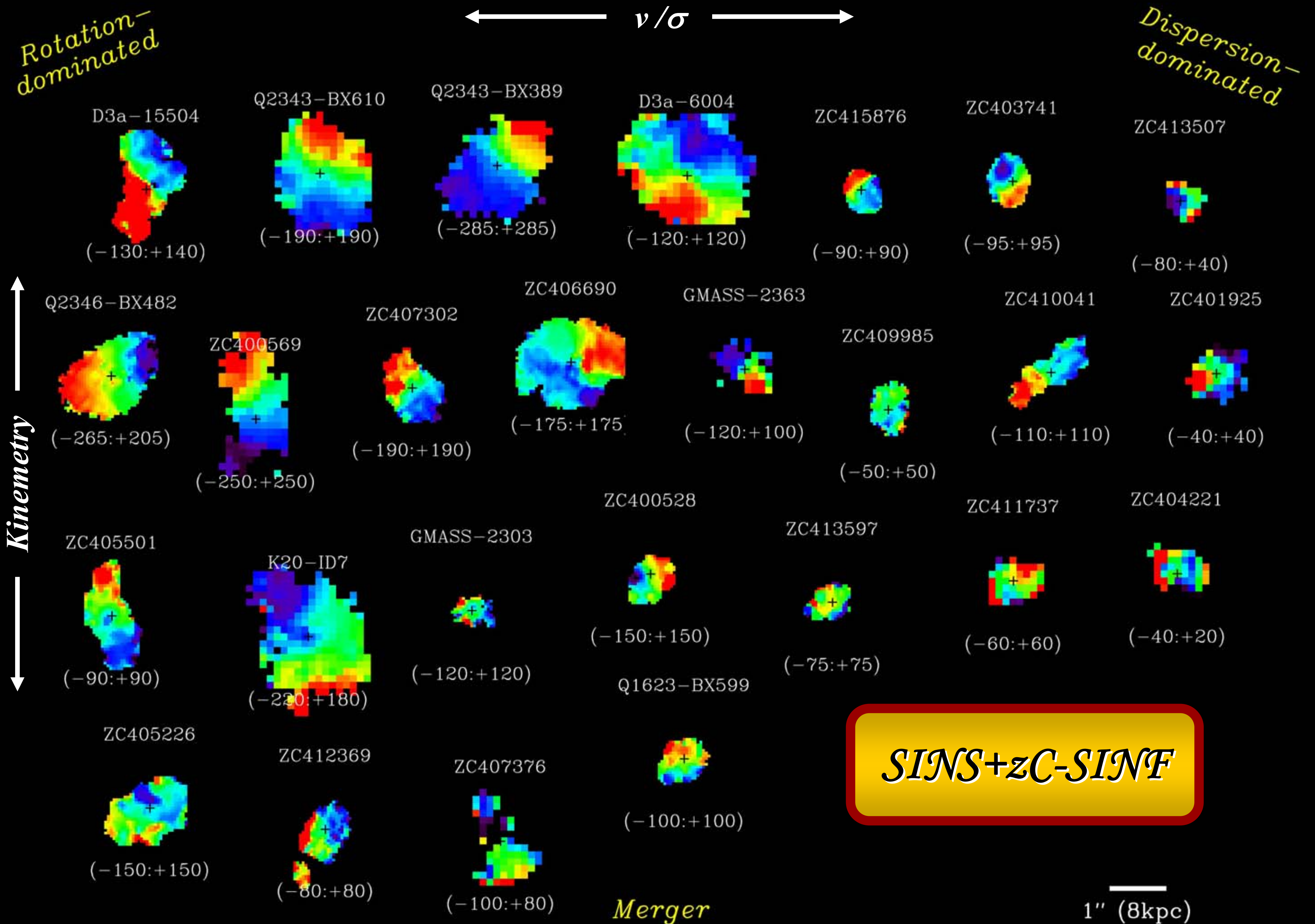
- 113 star-forming galaxies at z ~ 1 – 3
- 30 with deep AO-assisted observations

# *SINS+zC-SINF Survey of >100 z~2 Galaxies*



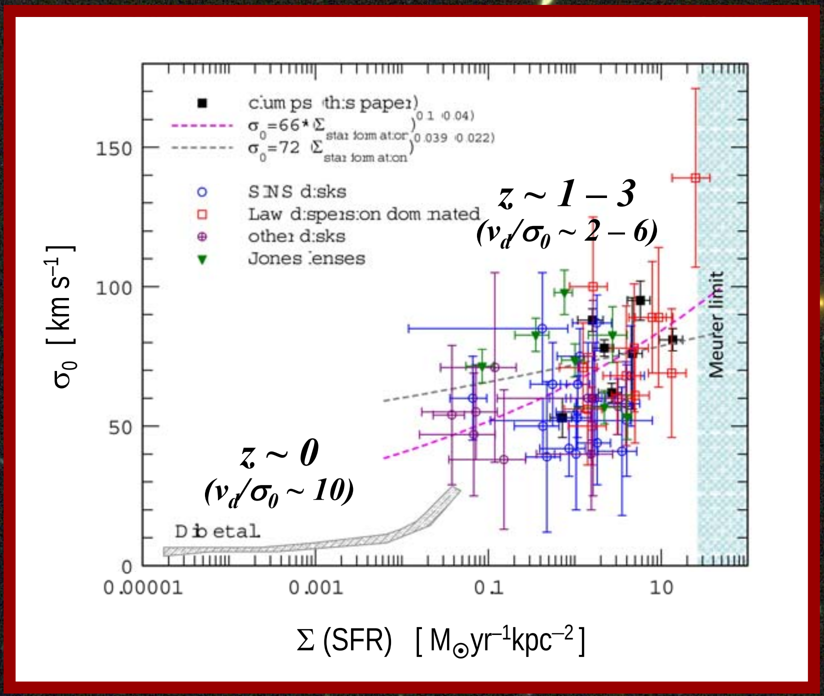

*NMFS et al. (2009); Mancini et al. (2011); and refs. therein*

*Other IFU samples at z~1-3: e.g., Law+07/09; Wright+07/09/10; Épinat+09; Jones+10; Gnerucci+10/11; Cresci+10; Wisnioski+11; Contini+11*




*NMFS et al. (2009); Mancini et al. (2011); and SINS+zCOSMOS (in prep.)*
*Kinemetry: Shapiro et al. (2008); Kinematic modeling: Genzel et al. (2008,2011); Cresci et al. (2009)*

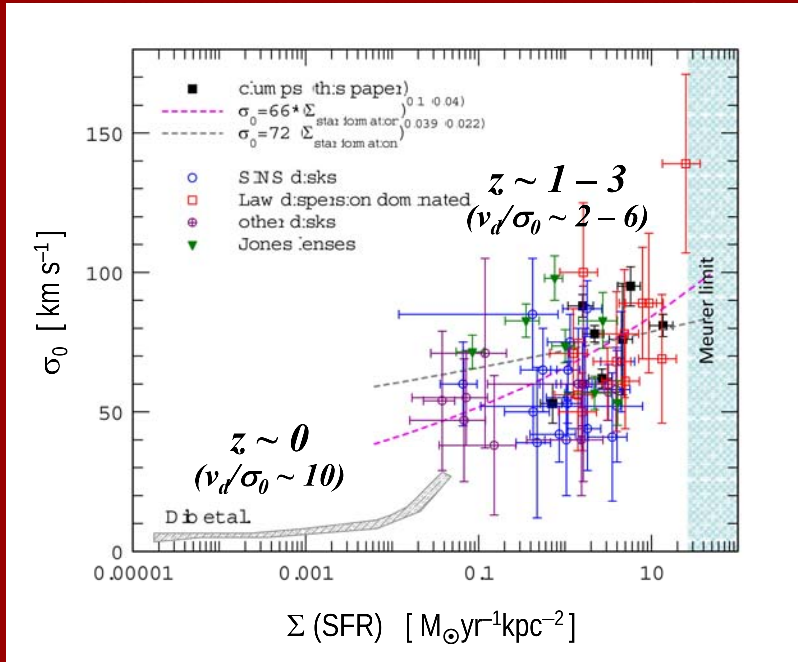
# Turbulent Gas-Rich Clumpy Disks at High z



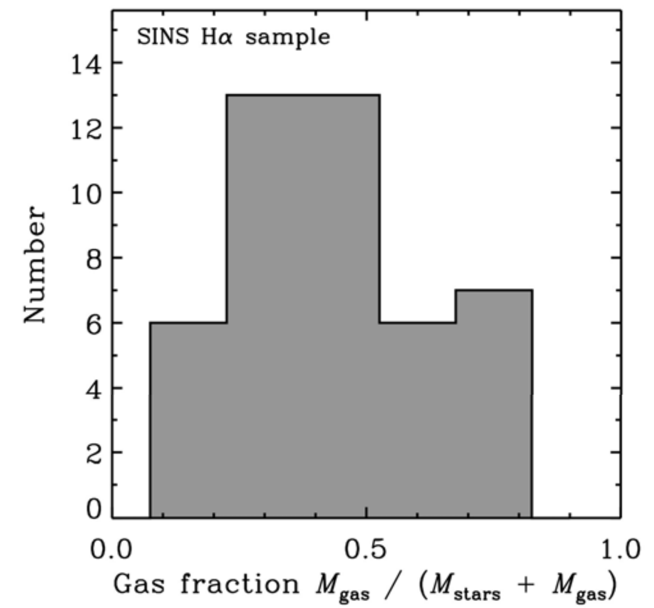

*SINS+zC-SINF / Genzel+06/08/10/11; Cresci+09; Tacconi+08/10; Daddi+10; Erb+06; NMFS+06/09/11*

*Also, e.g., Elmegreen+04-09; Law+07/09; Wright+07/09; Stark+08; Epinat+09; Jones+10; Swinbank+10;Wisnioski+11; Contini+11 Burkert+10; Aumer+10; Puech+06; Dib+06; Baker+04; Elmegreen+05-10; Overzier+09/10; Basu-Zych+09; Green+10*

# *Turbulent Gas-Rich Clumpy Disks at High z*

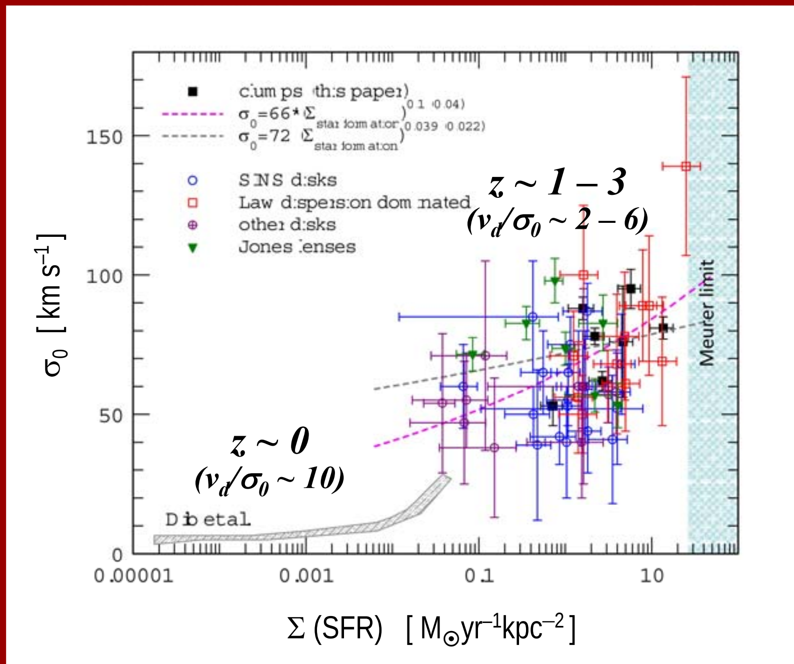


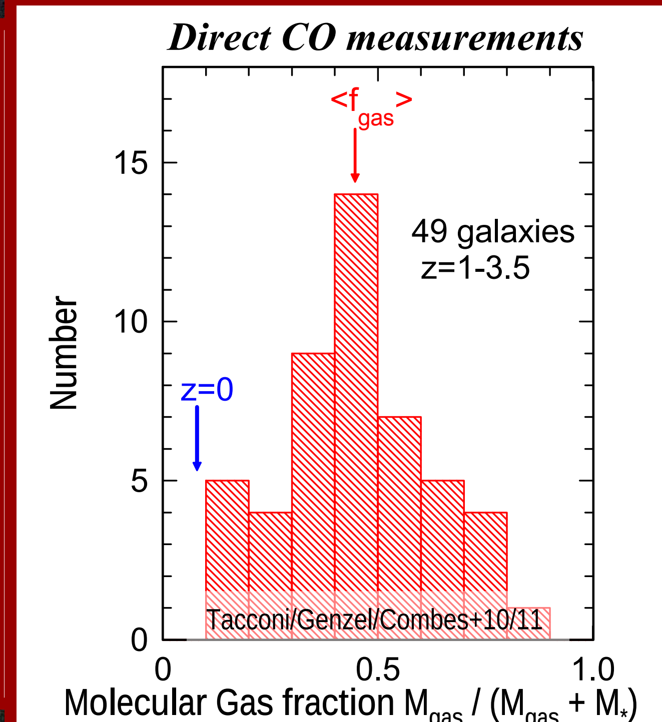

***Hα + Gas – Star formation relation***




*SINS+zC-SINF / Genzel+06/08/10/11; Cresci+09; Tacconi+08/10; Daddi+10; Erb+06; NMFS+06/09/11*
*Also, e.g., Elmegreen+04-09; Law+07/09; Wright+07/09; Stark+08; Epinat+09; Jones+10; Swinbank+10;Wisnioski+11; Contini+11 Burkert+10; Aumer+10; Puech+06; Dib+06; Baker+04; Elmegreen+05-10; Overzier+09/10; Basu-Zych+09; Green+10*

# Turbulent Gas-Rich Clumpy Disks at High z

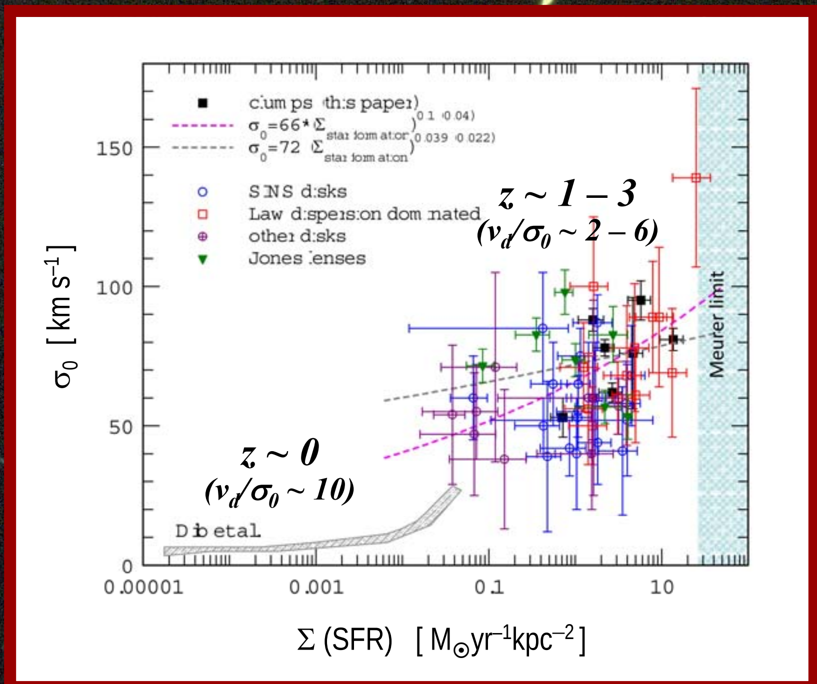


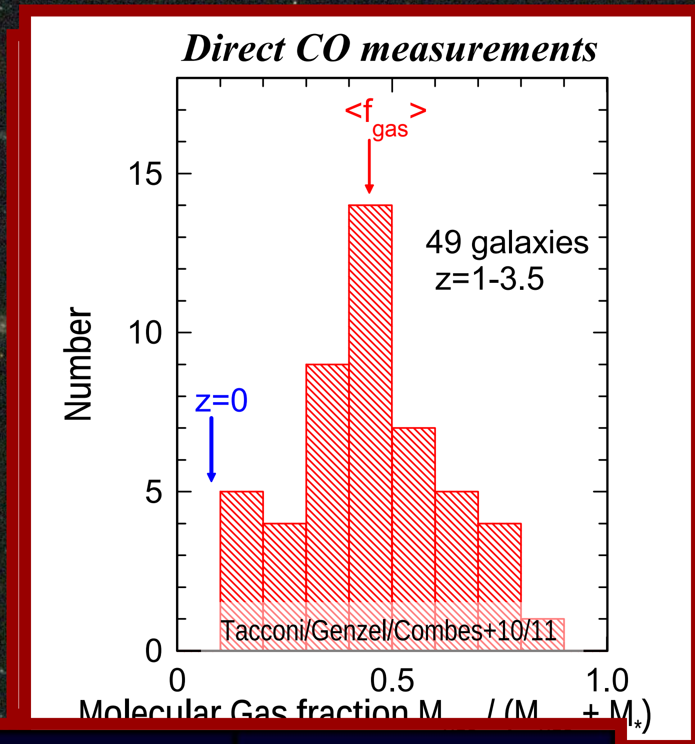



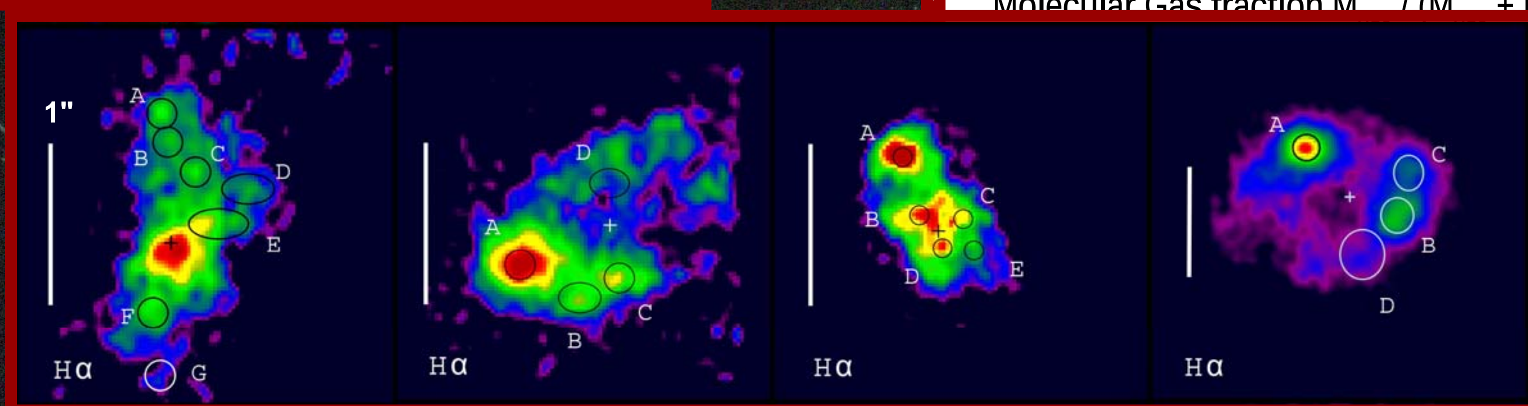

*SINS+zC-SINF / Genzel+06/08/10/11; Cresci+09; Tacconi+08/10; Daddi+10; Erb+06; NMFS+06/09/11*

*Also, e.g., Elmegreen+04-09; Law+07/09; Wright+07/09; Stark+08; Epinat+09; Jones+10; Swinbank+10;Wisnioski+11; Contini+11 Burkert+10; Aumer+10; Puech+06; Dib+06; Baker+04; Elmegreen+05-10; Overzier+09/10; Basu-Zych+09; Green+10*

# *Turbulent Gas-Rich Clumpy Disks at High z*



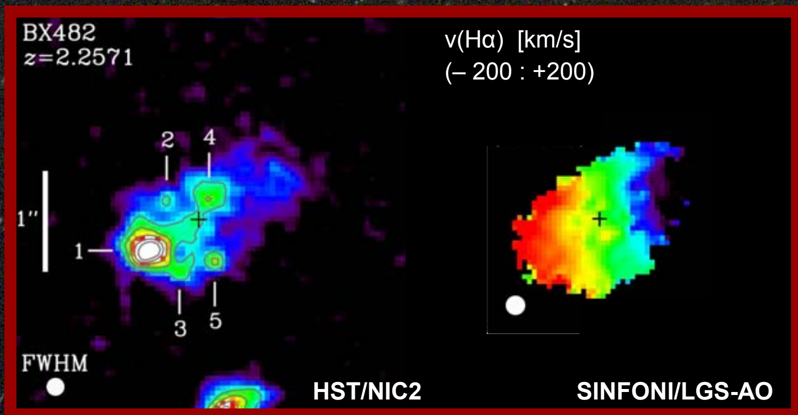



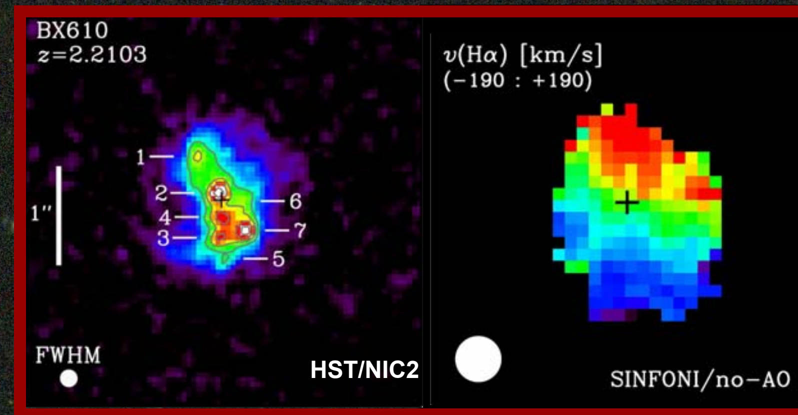



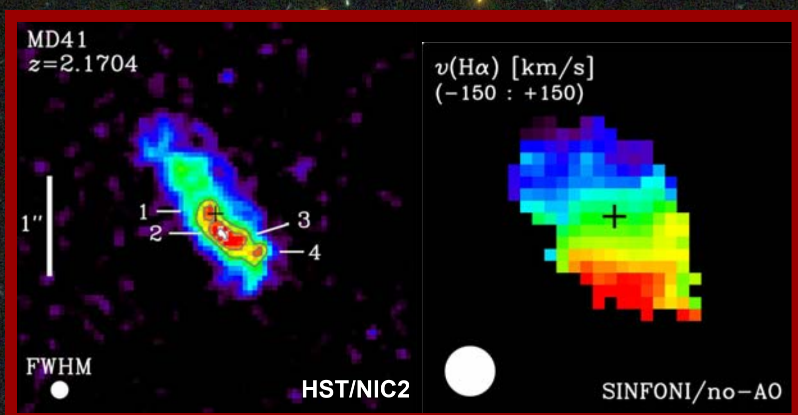

*SINS+zC-SINF / Genzel+06/08/10/11; Cresci+09; Tacconi+08/10; Daddi+10; Erb+06; NMFS+06/09/11*
*Also, e.g., Elmegreen+04-09; Law+07/09; Wright+07/09; Stark+08; Epinat+09; Jones+10; Swinbank+10;Wisnioski+11; Contini+11*
*Burkert+10; Aumer+10; Puech+06; Dib+06; Baker+04; Elmegreen+05-10; Overzier+09/10; Basu-Zych+09; Green+10*

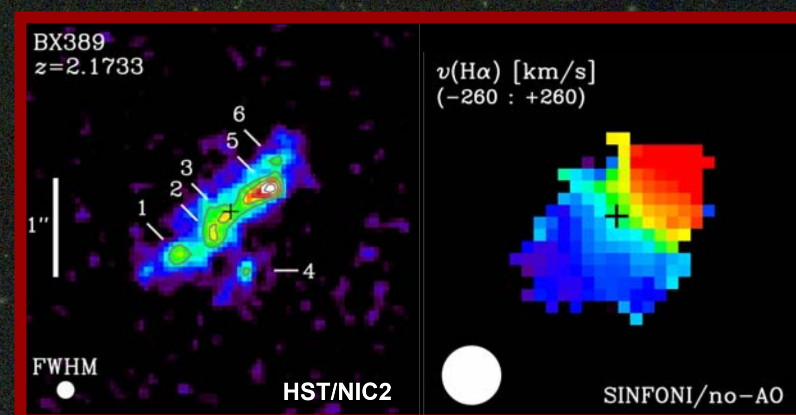
# *Clumpy Morphologies of Disks at High z*

***Rest-optical continuum emission***



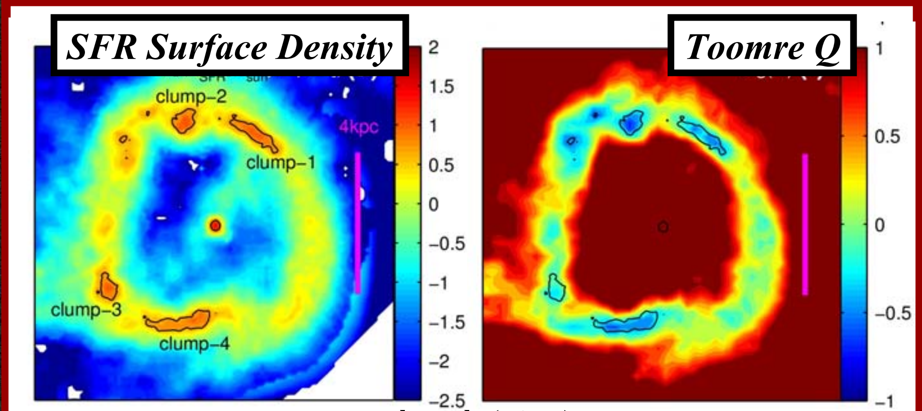




*NMFS et al. (2011a,b)*

*Also, e.g., Cowie+95; Colley+96; van den Bergh+96; Giavalisco+96; Conselice+04; Lotz+04; Papovich+05; Toft+07; Law+07; Carollo+07; Bournaud+08; Law+11 Elmegreen+04-09; Genzel+08/11; Overzier+10; Cameron et al. (2010); Tacconi+10; Swinbank+10/11; Wuyts et al. (2011)*

# Clumps and Disk Instabilities

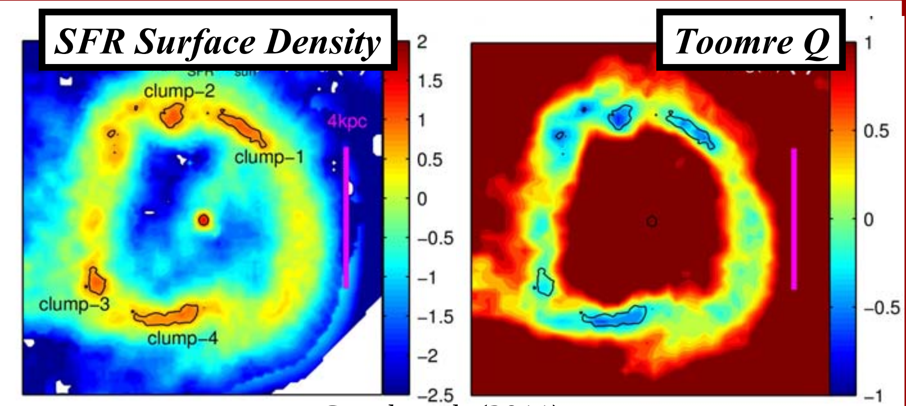
$$Q_{gas} = \frac{\sigma_0 \kappa}{\pi G \Sigma_{gas}}$$



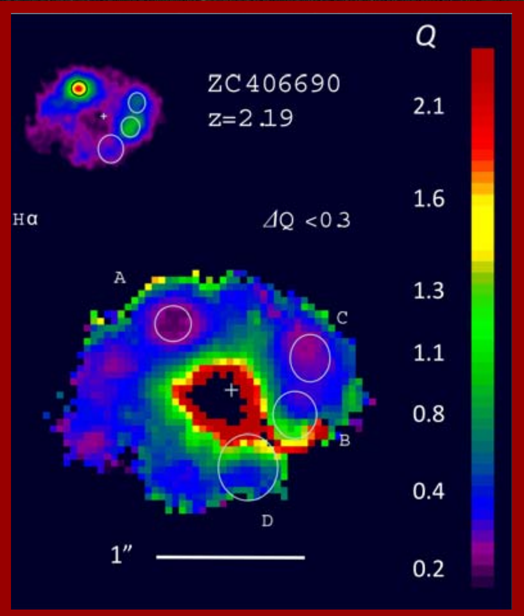

Genel et al. (2011)

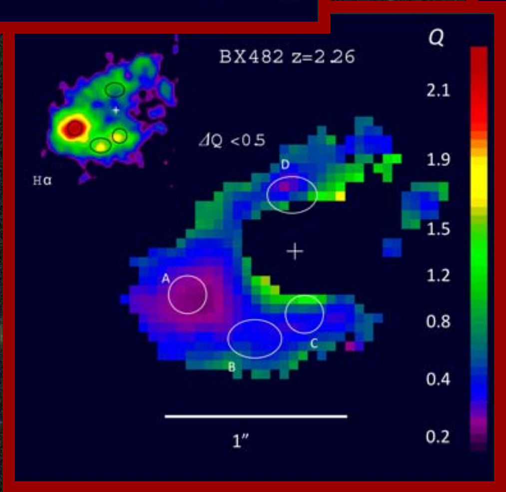
# *Clumps and Disk Instabilities*

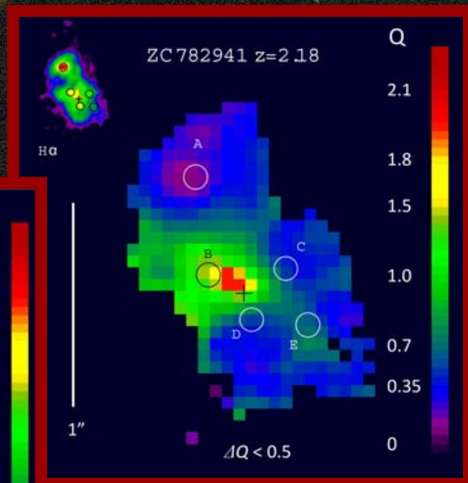
$$Q_{gas} = \frac{\sigma_0 \kappa}{\pi G \Sigma_{gas}}$$

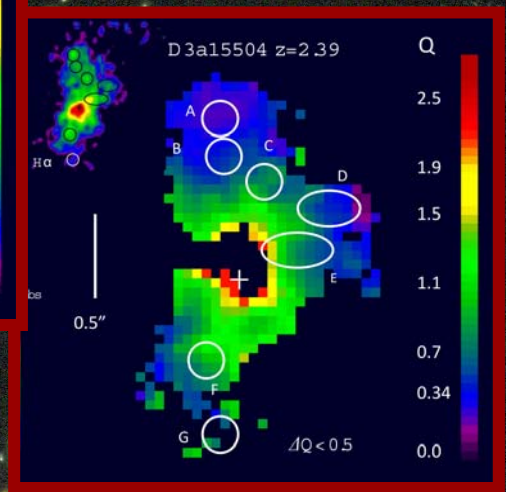



Genel et al. (2011)



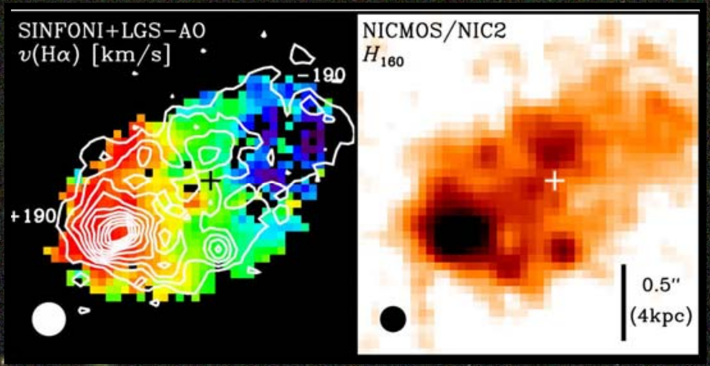



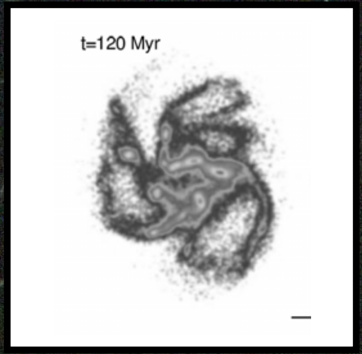

Genzel et al. (2011)

# Bulge Formation in Gas-rich High z Disks

**In-situ Observations**




**Numerical Simulations**



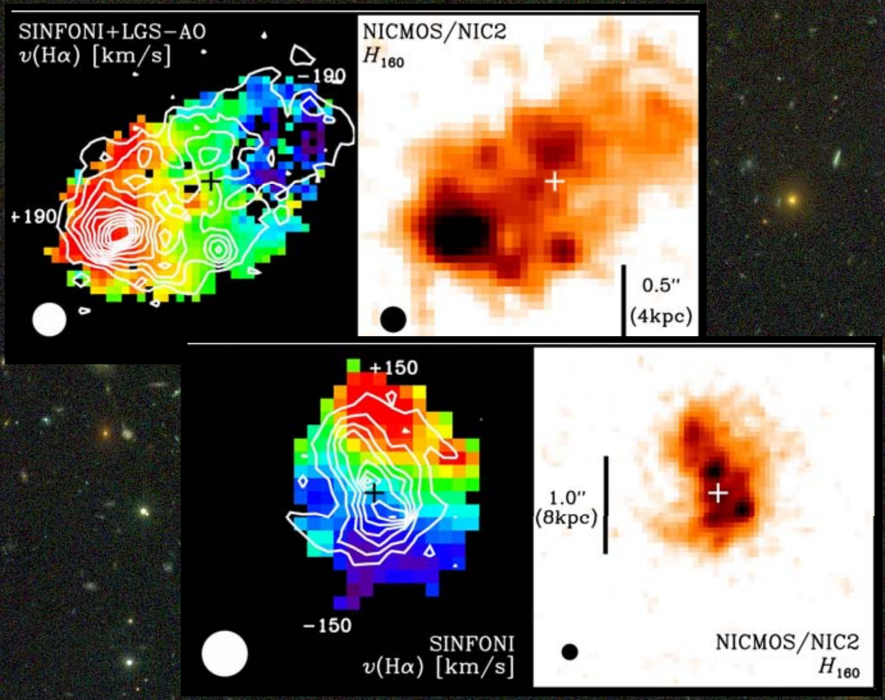

Genzel et al. (2008/11); NMFS et al. (2011b)

Bournaud et al. (2007-2009)

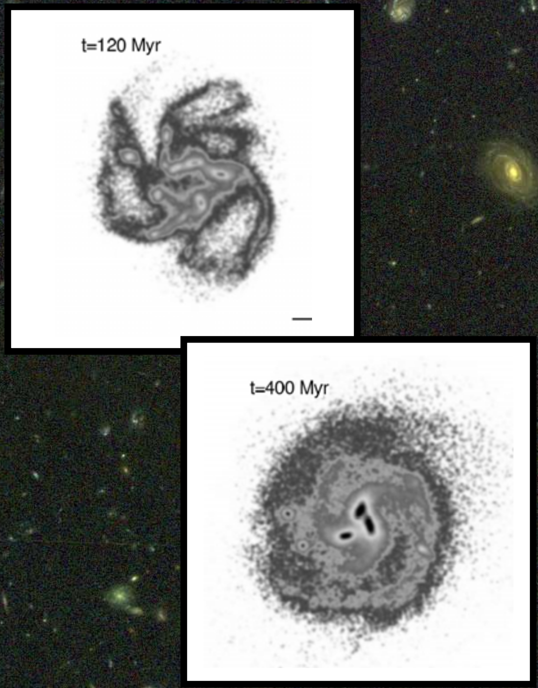
Also, e.g., Noguchi99; Immeli+04; Governato+06/07; Carollo+07; Burkert+09; Dekel+09; Aumer+10; Ceverino+10; Genel+11

# Bulge Formation in Gas-rich High z Disks

## In-situ Observations




## Numerical Simulations



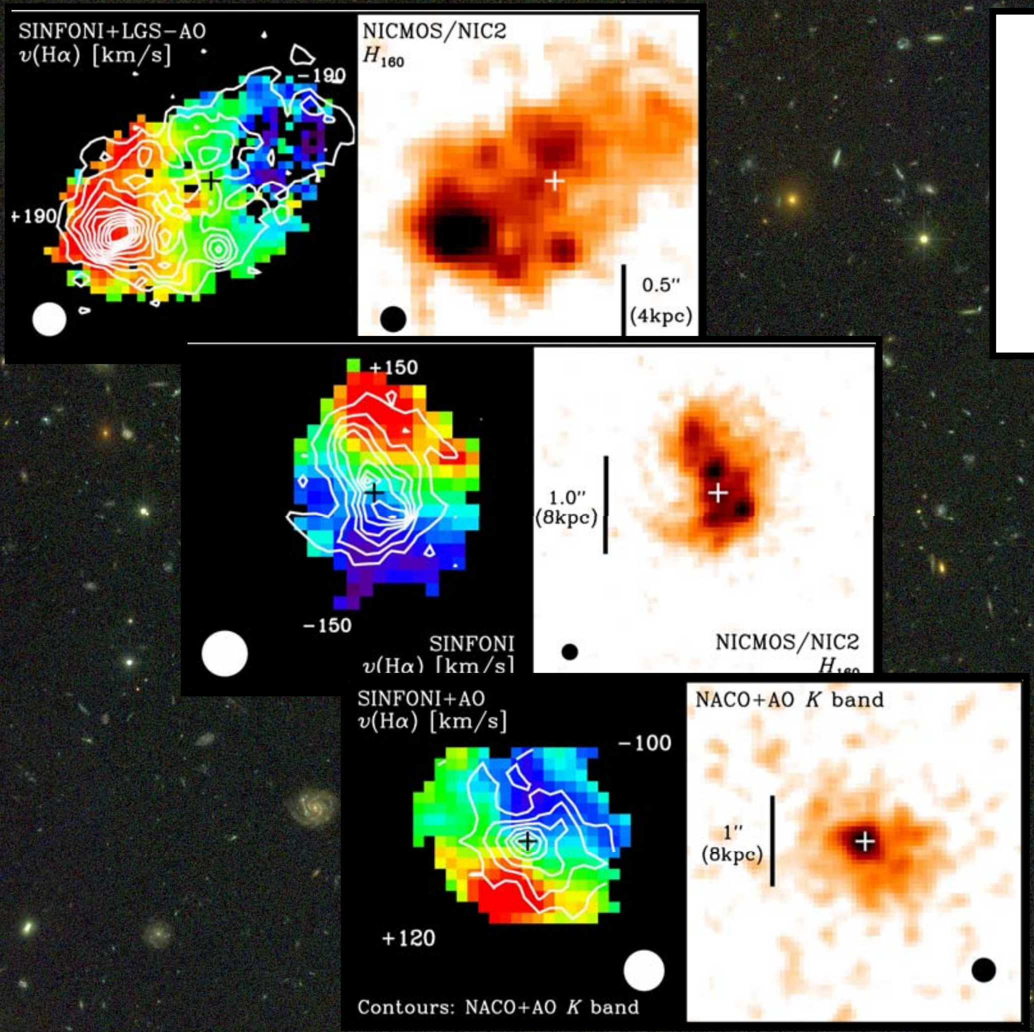

*Genzel et al. (2008/11); NMFS et al. (2011b)*

*Bournaud et al. (2007-2009)*

*Also, e.g., Noguchi99; Immeli+04; Governato+06/07; Carollo+07; Burkert+09; Dekel+09; Aumer+10; Ceverino+10; Genel+11*

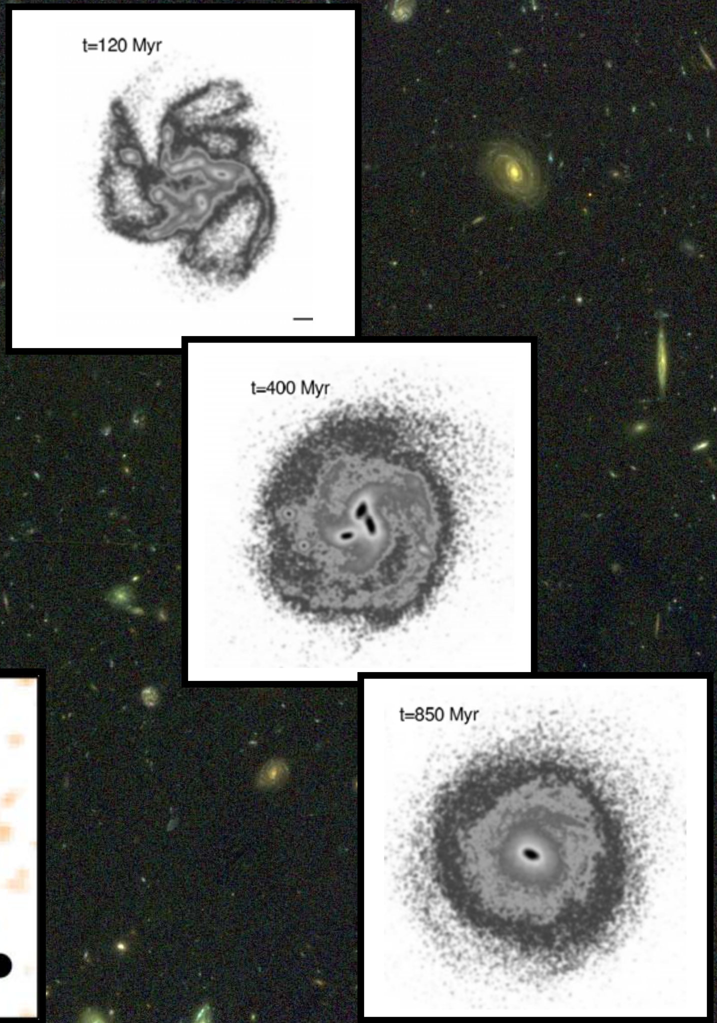
# *Bulge Formation in Gas-rich High z Disks*

## *In-situ Observations*




Genzel et al. (2008/11); NMFS et al. (2011b)

## *Numerical Simulations*

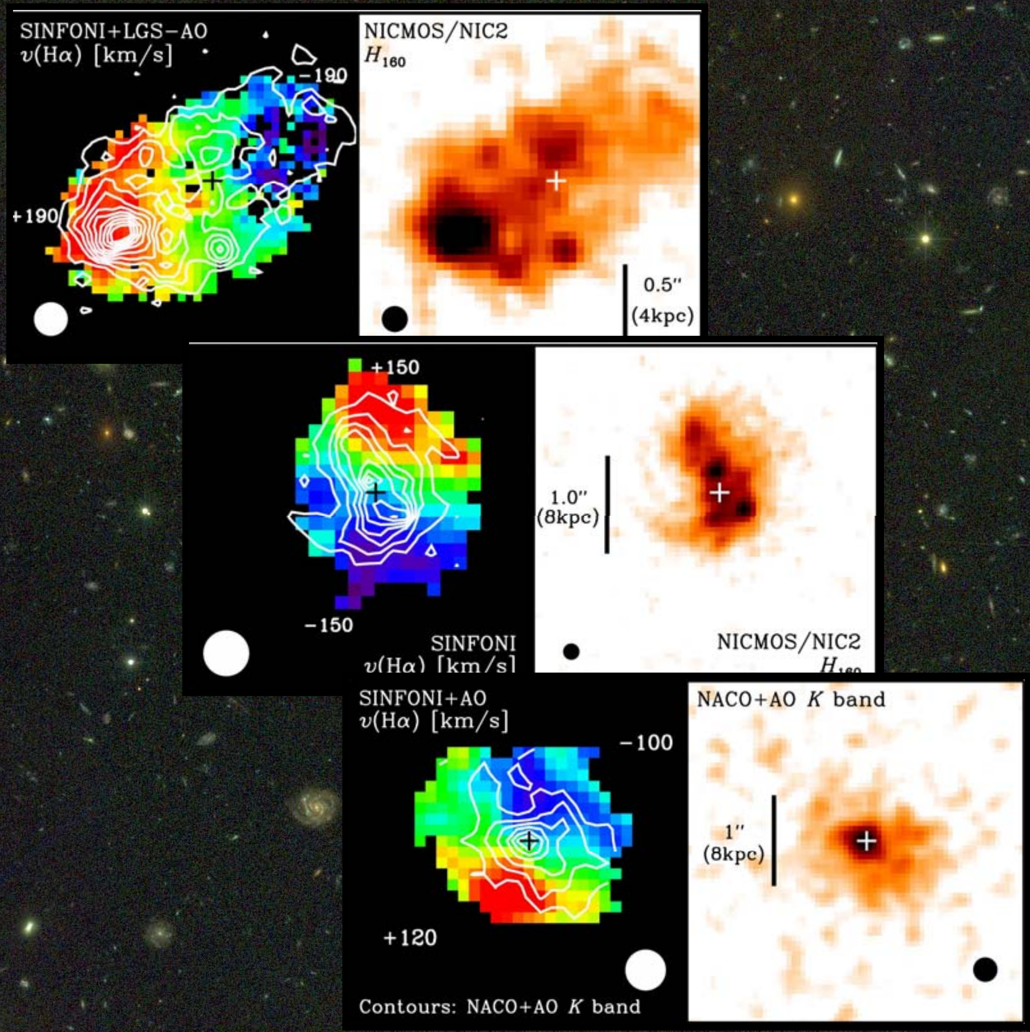


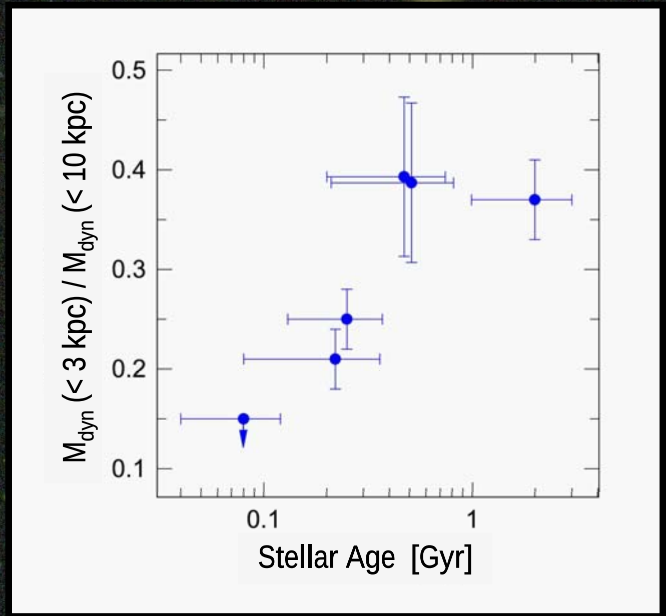

Bournaud et al. (2007-2009)

*Also, e.g., Noguchi99; Immeli+04; Governato+06/07; Carollo+07; Burkert+09; Dekel+09; Aumer+10; Ceverino+10; Genel+11*

# Bulge Formation in Gas-rich High z Disks

***In-situ Observations***

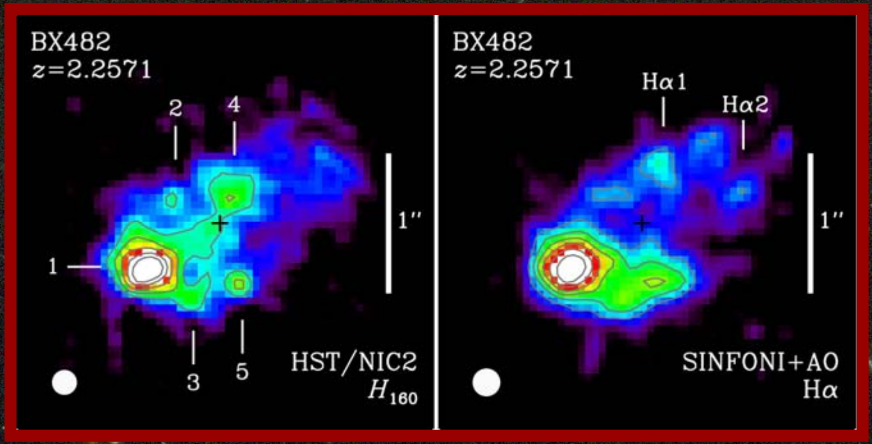


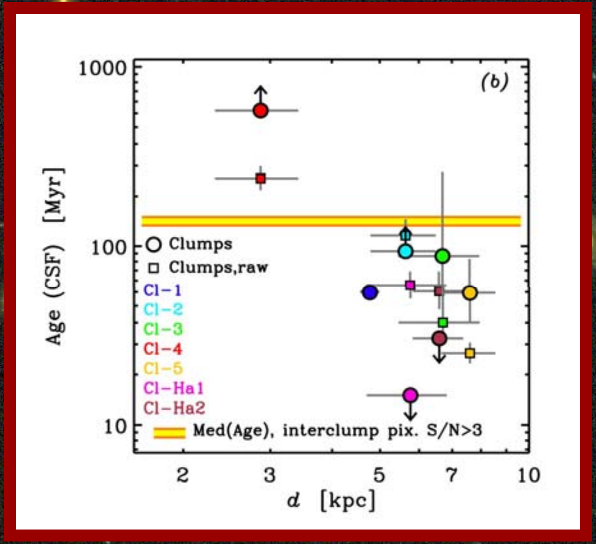




*Genzel et al. (2008/11); NMFS et al. (2011b)*

*Also, e.g., Noguchi99; Immeli+04; Governato+06/07; Carollo+07; Burkert+09; Dekel+09; Aumer+10; Ceverino+10; Genel+11*

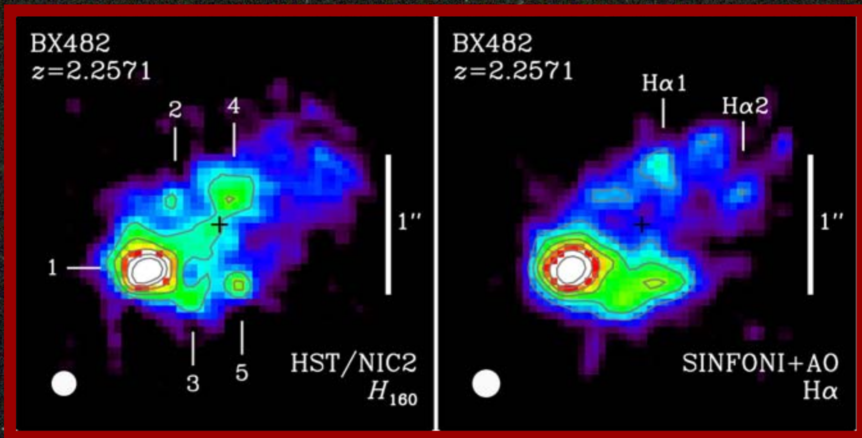
# Radial Trends in Clump Evolutionary Stage

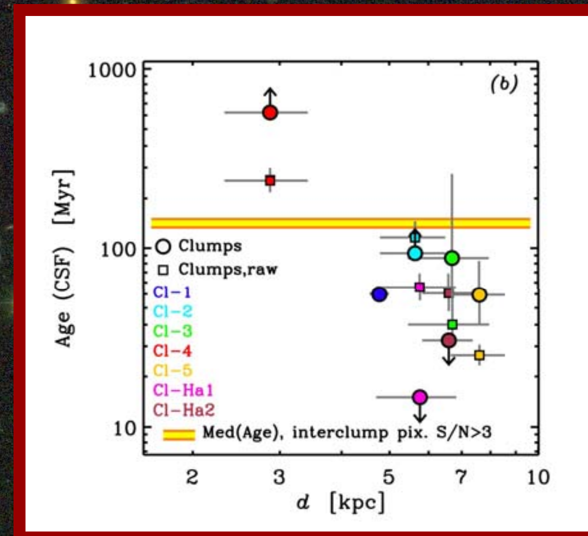


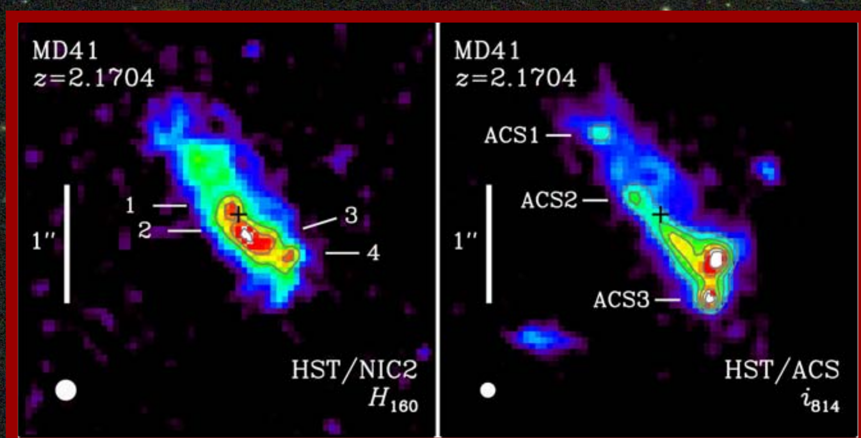



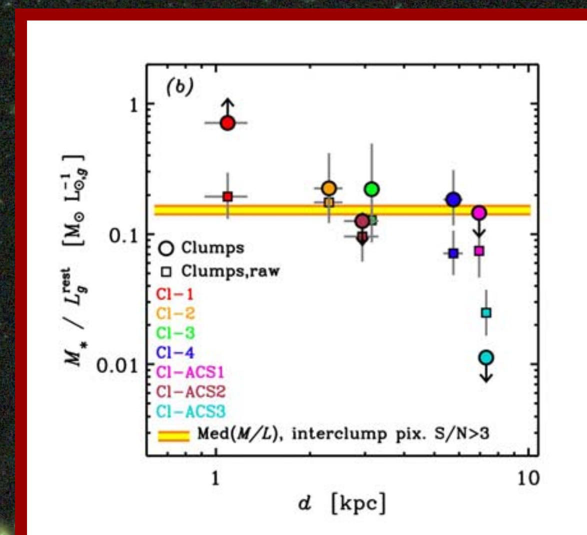

NMFS et al. (2011b)
Also: Elmegreen, Elmegreen, et al. (2004-2009); Genzel et al. (2008,2011)

# Radial Trends in Clump Evolutionary Stage



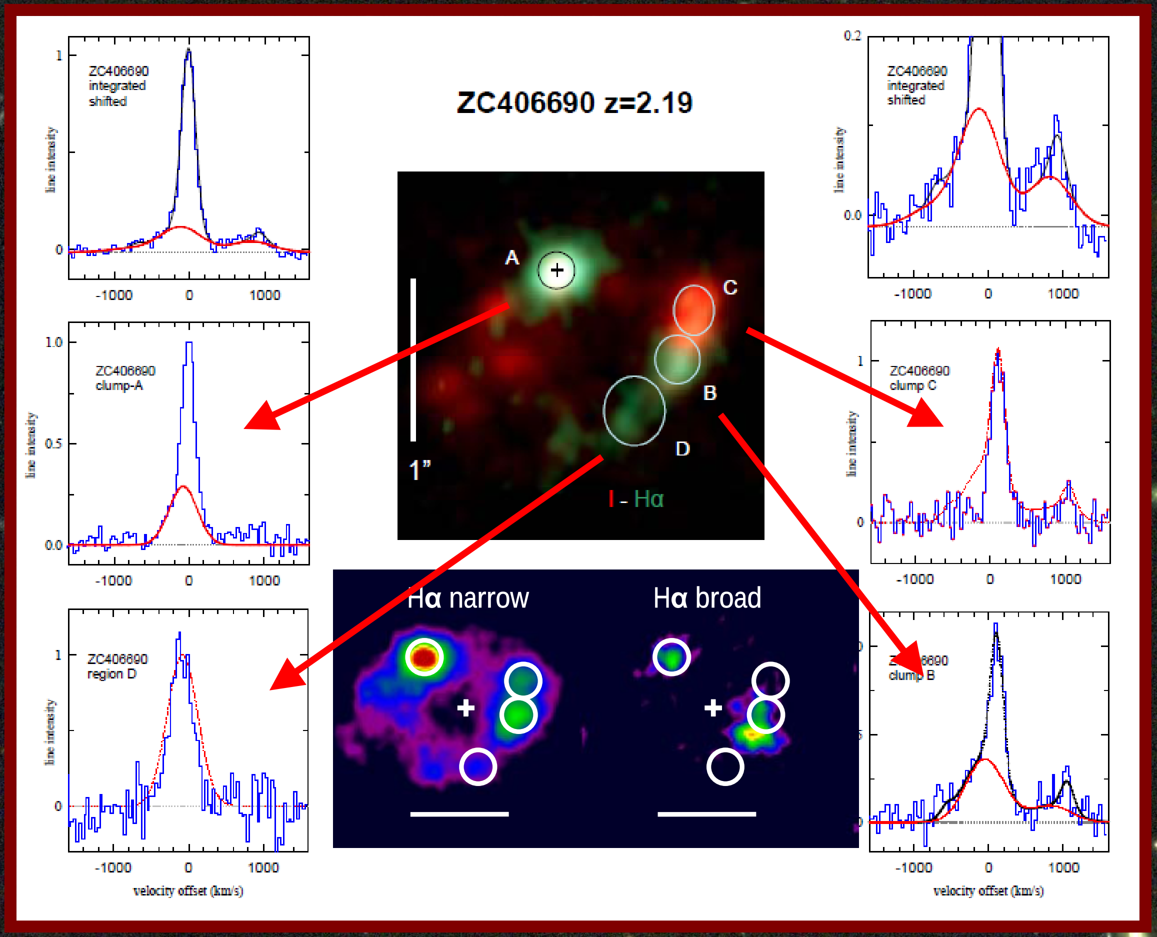




*NMFS et al. (2011b)*

*Also: Elmegreen, Elmegreen, et al. (2004-2009); Genzel et al. (2008,2011)*

# *Vigorous Stellar Feedback in Clumps*

- ***Clump mass outflow rates ~ 1 – 10 x SFRs***
- ***Lifetimes of most actively star-forming clumps limited to a few 100 Myrs***

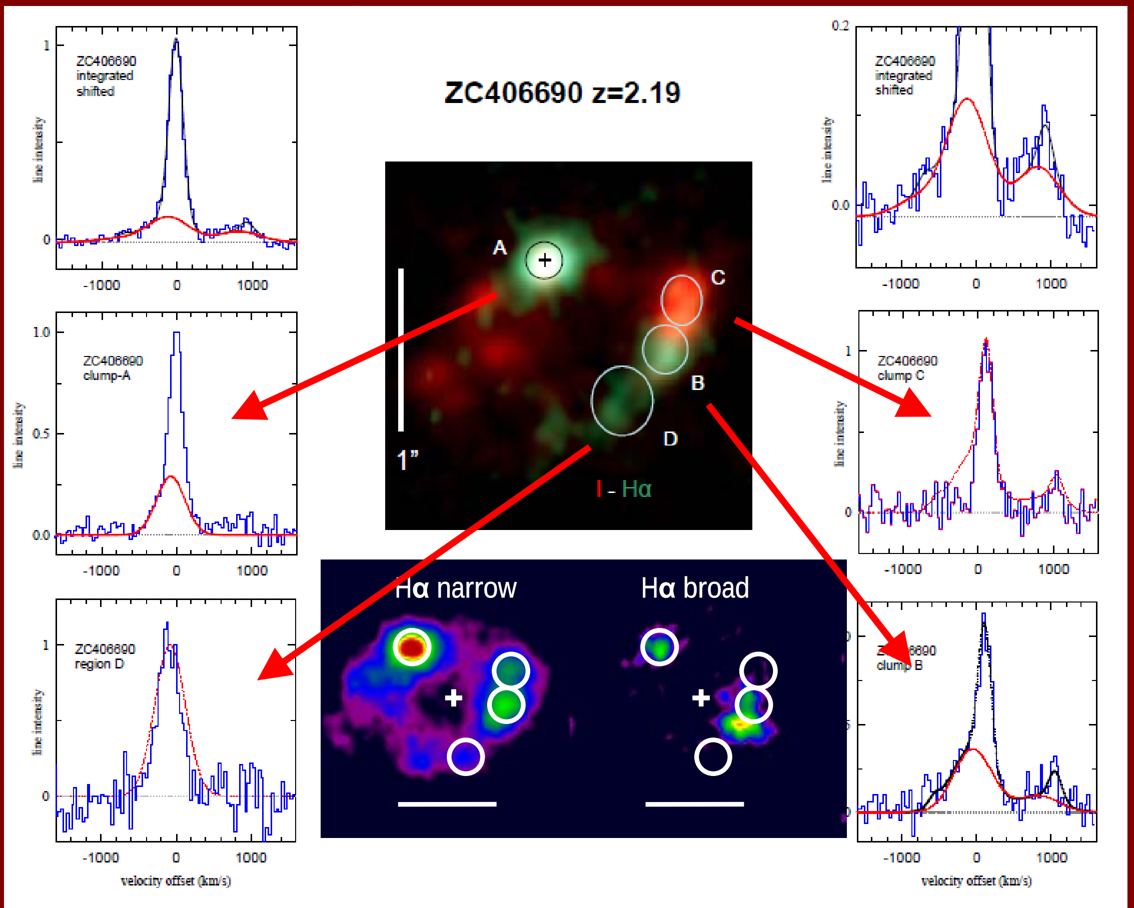


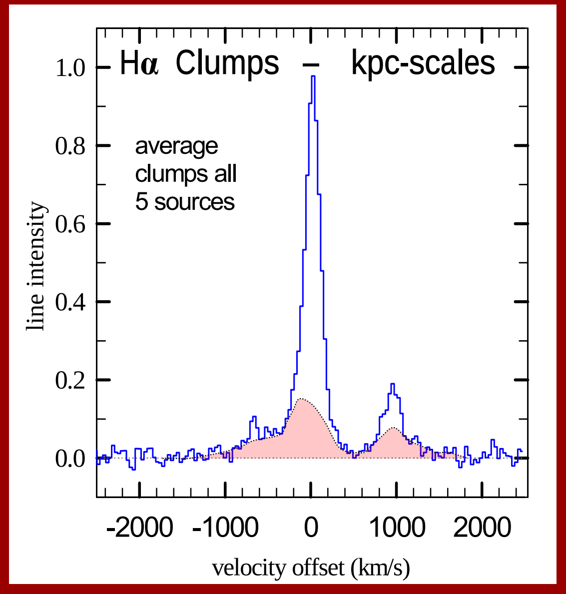

*Genzel et al. (2011); Newman et al. (in prep.)*

*Large-scale galactic winds at high z: e.g., Pettini et al. (2000); Shapley et al. (2003); Erb et al. (2006/08); Shapiro et al. (2009); Weiner et al. (2010); Steidel et al. (2010); Law et al. (2011)*

# *Vigorous Stellar Feedback in Clumps*

- ***Clump mass outflow rates ~ 1 – 10 x SFRs***
- ***Lifetimes of most actively star-forming clumps limited to a few 100 Myrs***



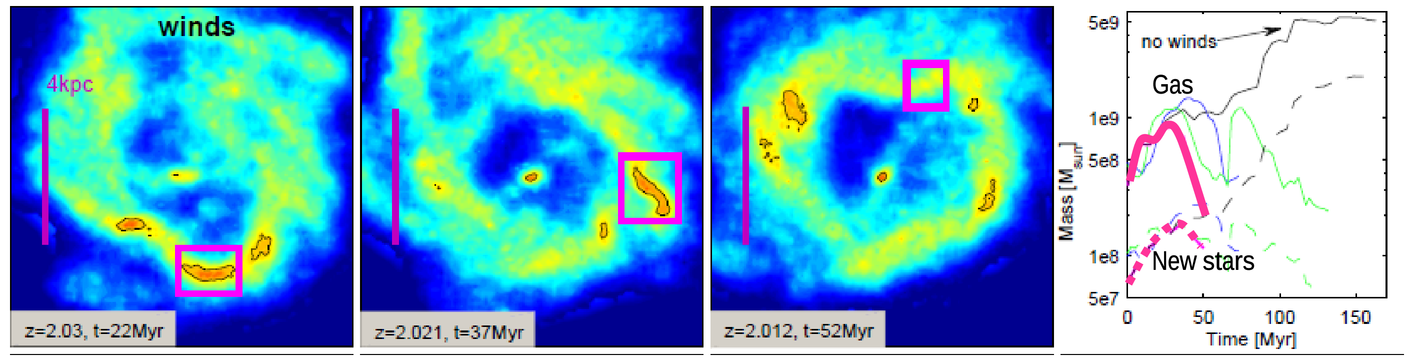




*Genzel et al. (2011); Newman et al. (in prep.)*

*Large-scale galactic winds at high z: e.g., Pettini et al. (2000); Shapley et al. (2003); Erb et al. (2006/08); Shapiro et al. (2009); Weiner et al. (2010); Steidel et al. (2010); Law et al. (2011)*

# *Clumps Evolution and SF Feedback*

***Gas Surface Density; Time Span ~ 50 Myr; Momentum-driven mass-loaded feedback***

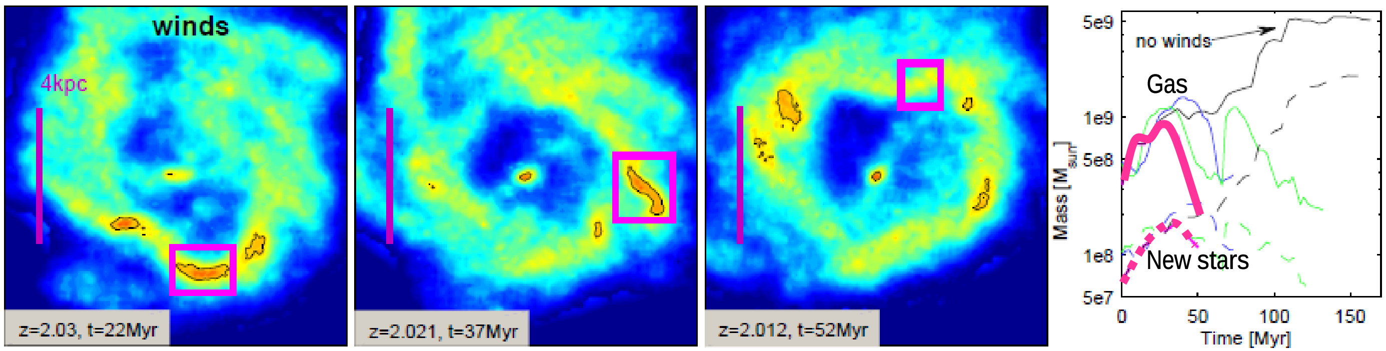



*Genel et al. (2011)*

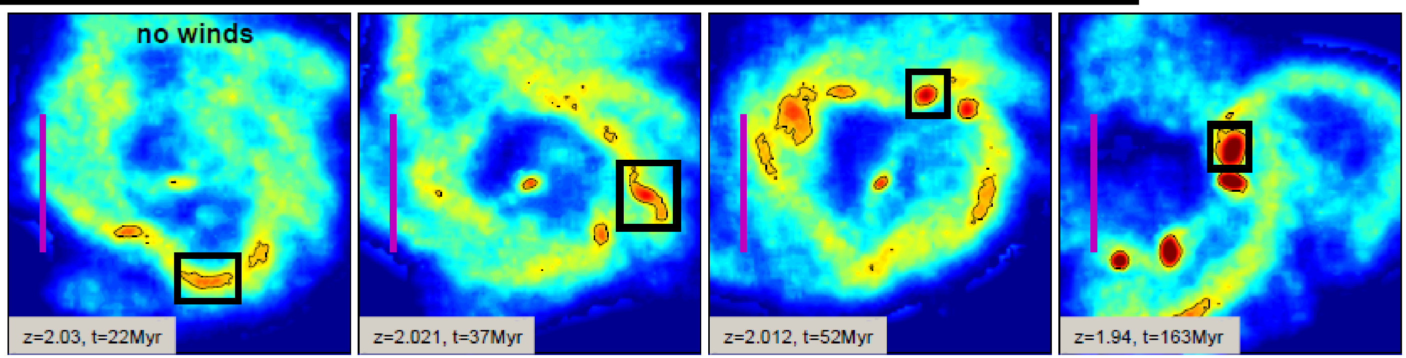
*Also, e.g., Noguchi99; Immeli+04a,b; Bournaud+07-10; Ceverino+10; Krumholz & Dekel 2009; Murray+10*

# Clumps Evolution and SF Feedback

***Gas Surface Density; Time Span ~ 50 Myr; Momentum-driven mass-loaded feedback***



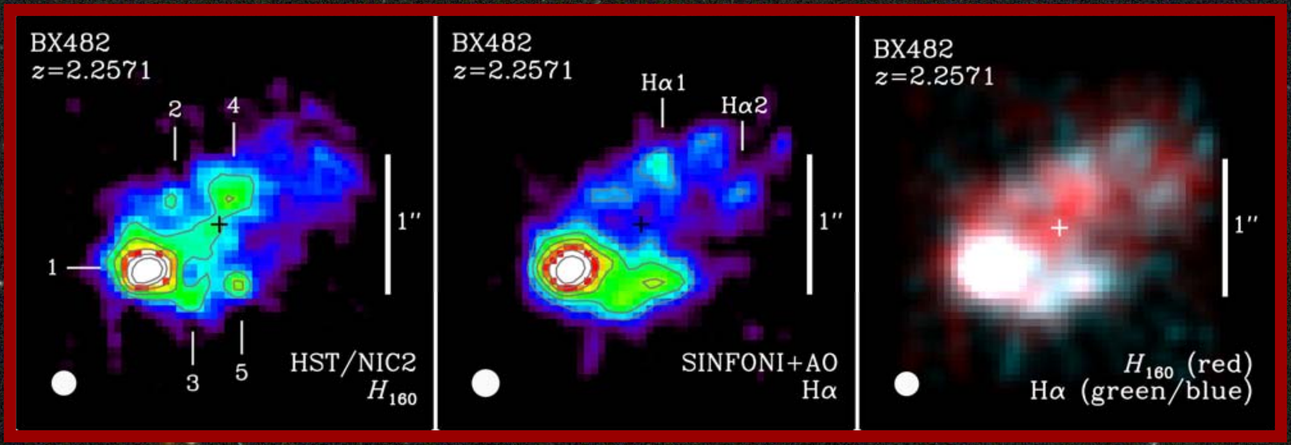

***Gas Surface Density; Time Span ~ 160 Myr; Feedback shut off at z = 2.03***




*Genel et al. (2011)*

*Also, e.g., Noguchi99; Immeli+04a,b; Bournaud+07-10; Ceverino+10; Krumholz & Dekel 2009; Murray+10*

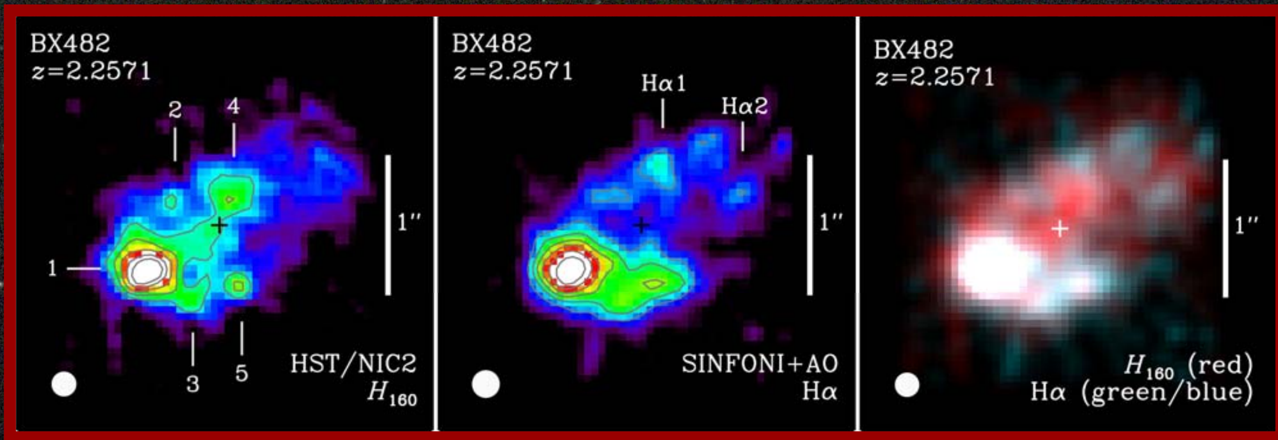
# Distribution of Star Formation vs Stars

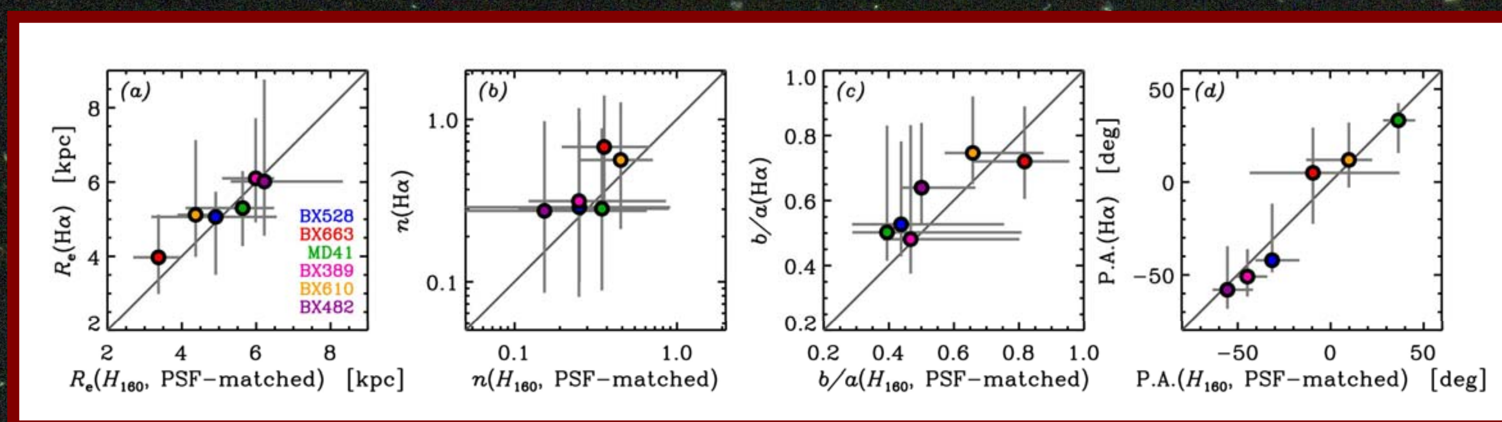



*NMFS, Shapley, et al. (2011a,b)*

*Also, e.g., Sales et al. (2009); Dutton et al. (2007-2010); Firmani & Avila-Reese (2009); Piontek et al. (2009)*

# Distribution of Star Formation vs Stars

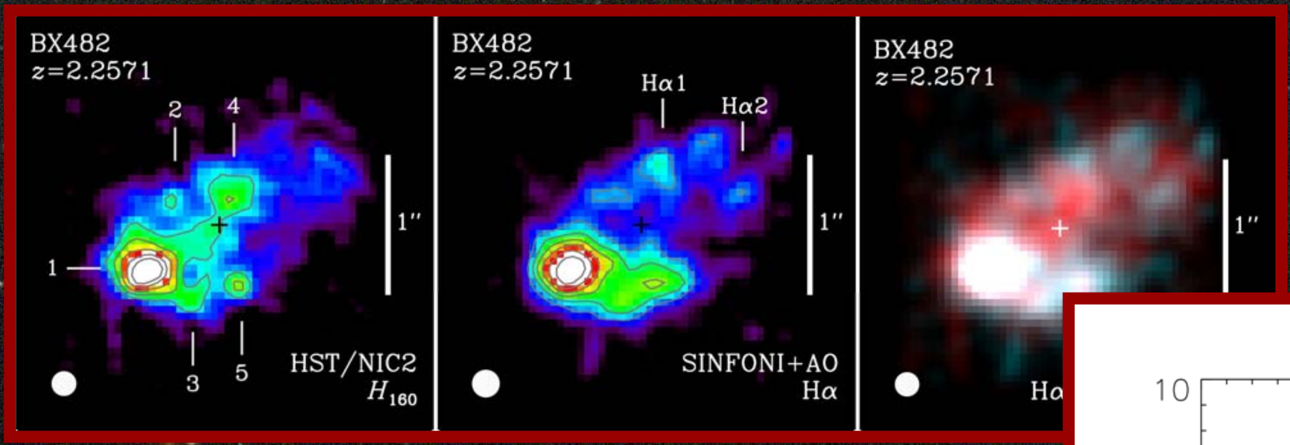


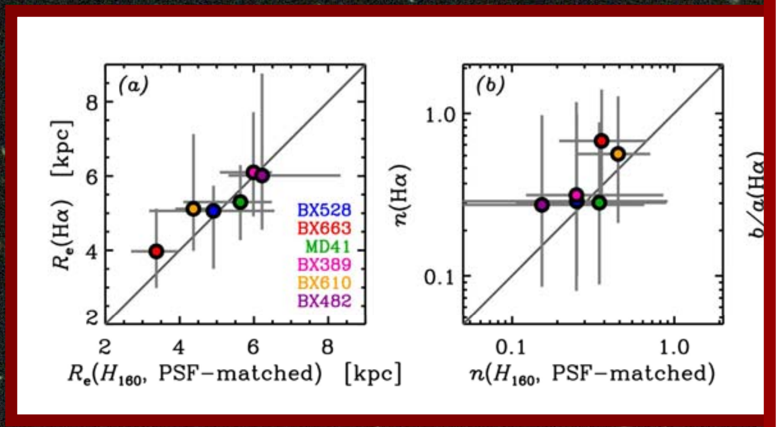



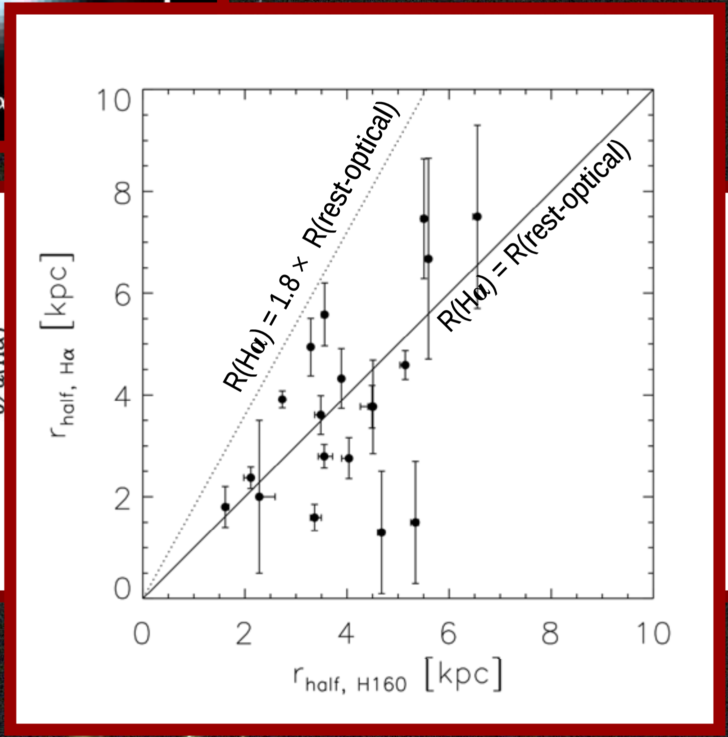

*NMFS, Shapley, et al. (2011a,b)*

*Also, e.g., Sales et al. (2009); Dutton et al. (2007-2010); Firmani & Avila-Reese (2009); Piontek et al. (2009)*

# Distribution of Star Formation vs Stars



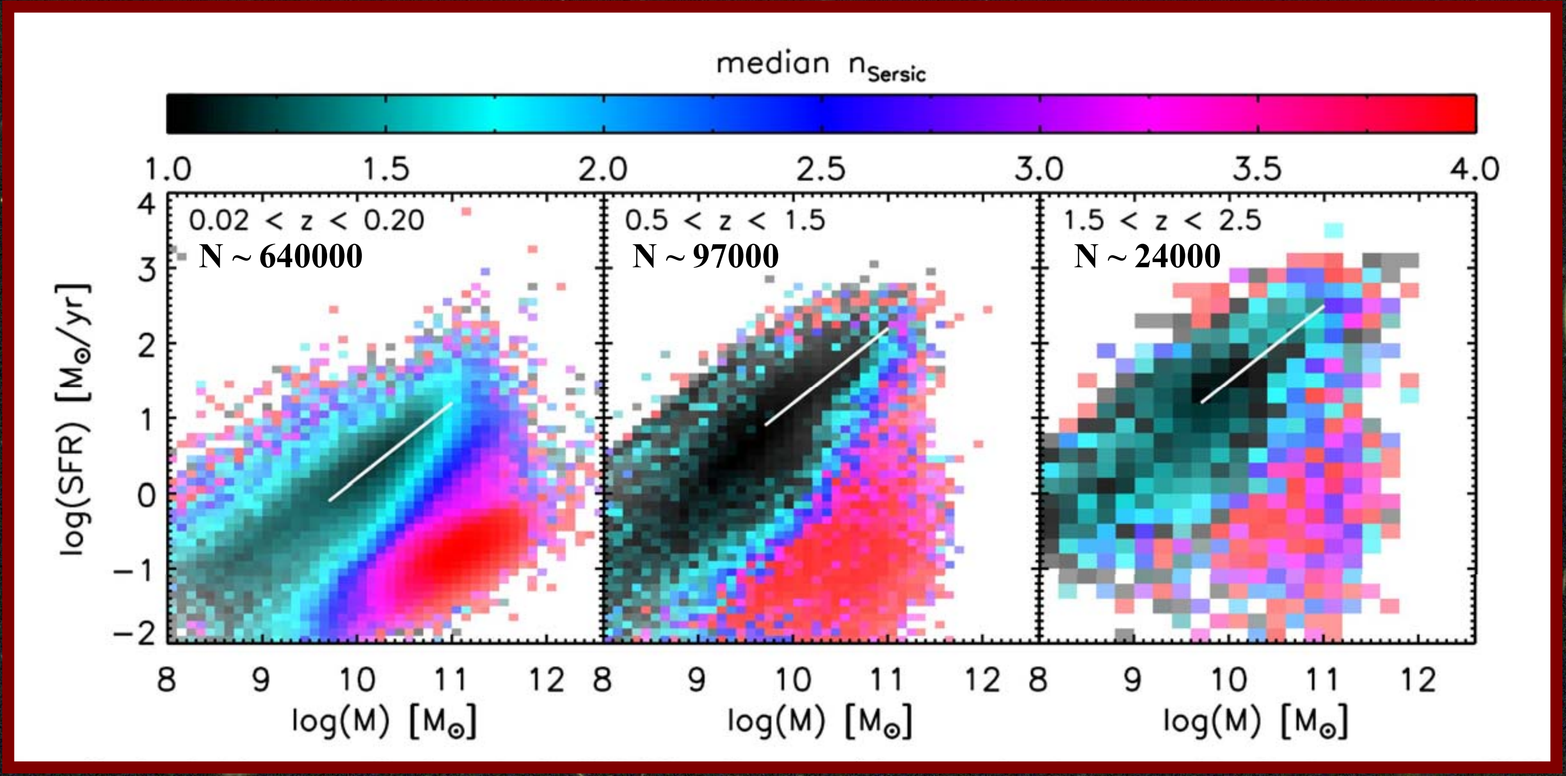




*NMFS, Shapley, et al. (2011a,b)*

*Also, e.g., Sales et al. (2009); Dutton et al. (2007-2010); Firmani & Avila-Reese (2009); Piontek et al. (2009)*

*Bouché, Wuyts et al, in prep.*
*Also: 3D-HST: Nelson et al.; Schmidt et al. (in prep.)*

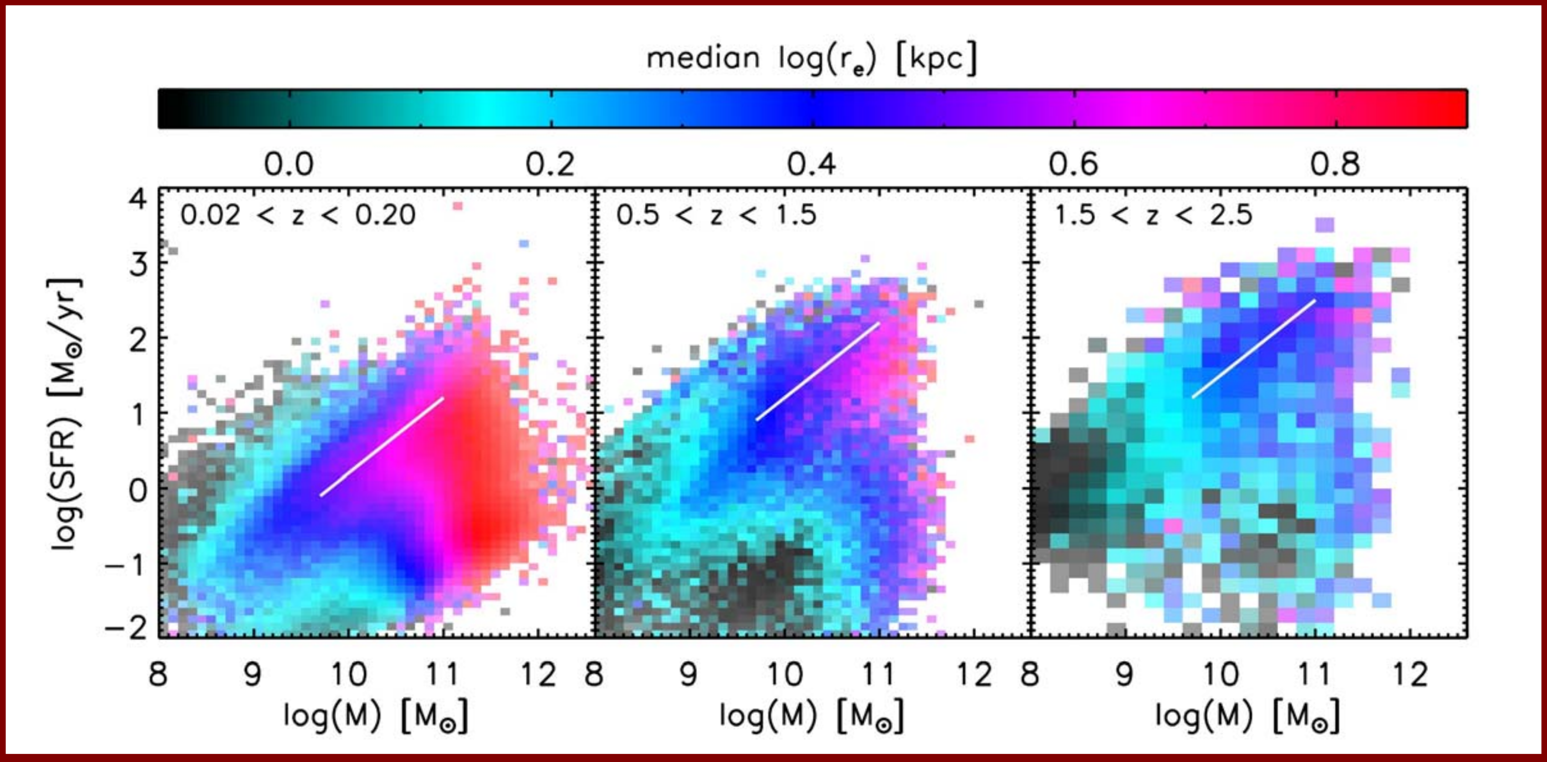
# *Structural Sequences out to z ~ 2*




*Wuyts et al. (2011b)*

*Also, e.g., Kauffmann+03; Shen+03; Brinchmann+04; Schiminovich+07; Franx+08; van Dokkum+08; Kriel+09; Toft+09; Williams+10; NMFS+11a; Szomoru+11; Elbaz+11; Law+11*

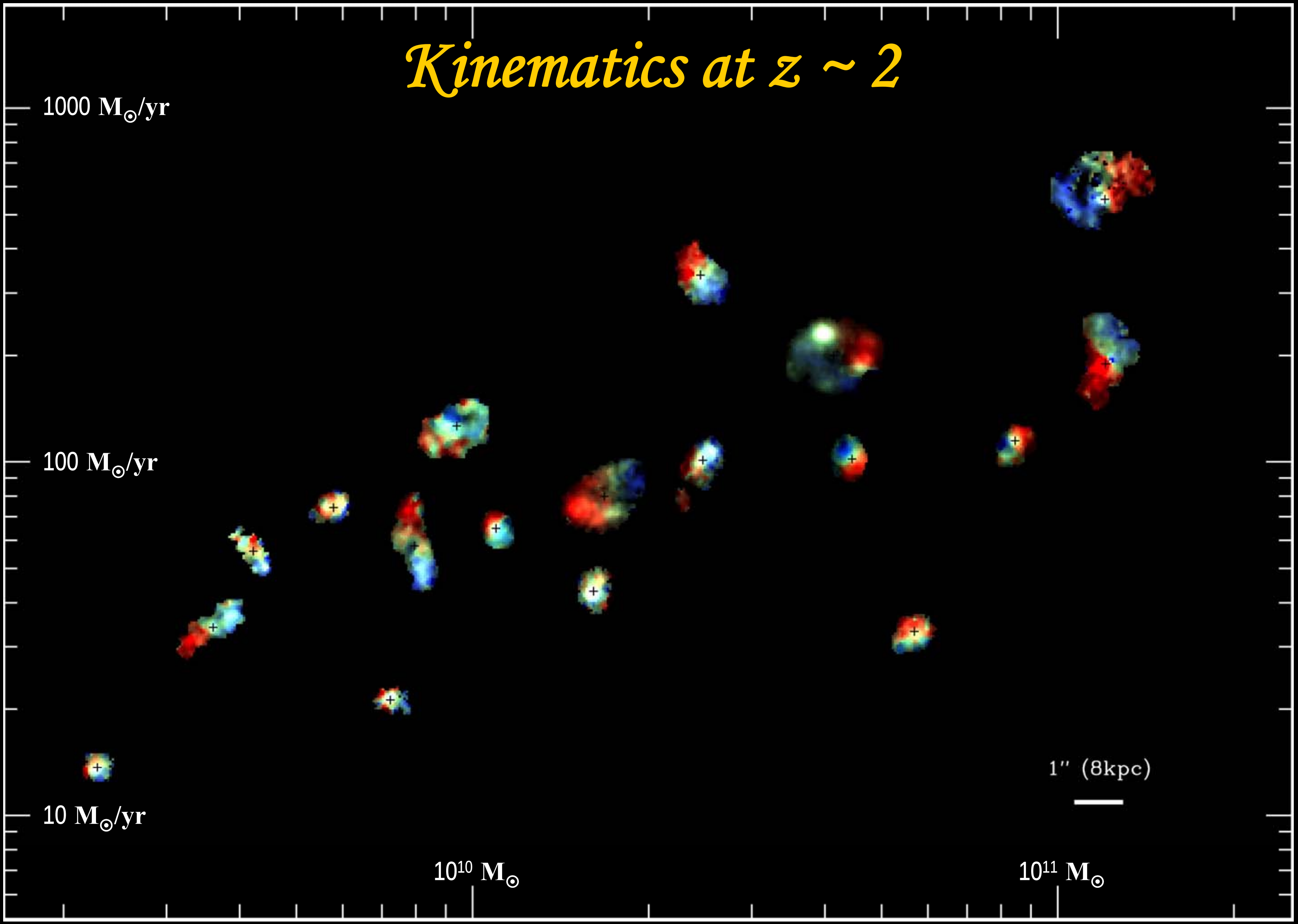
# Structural Sequences out to z ~ 2



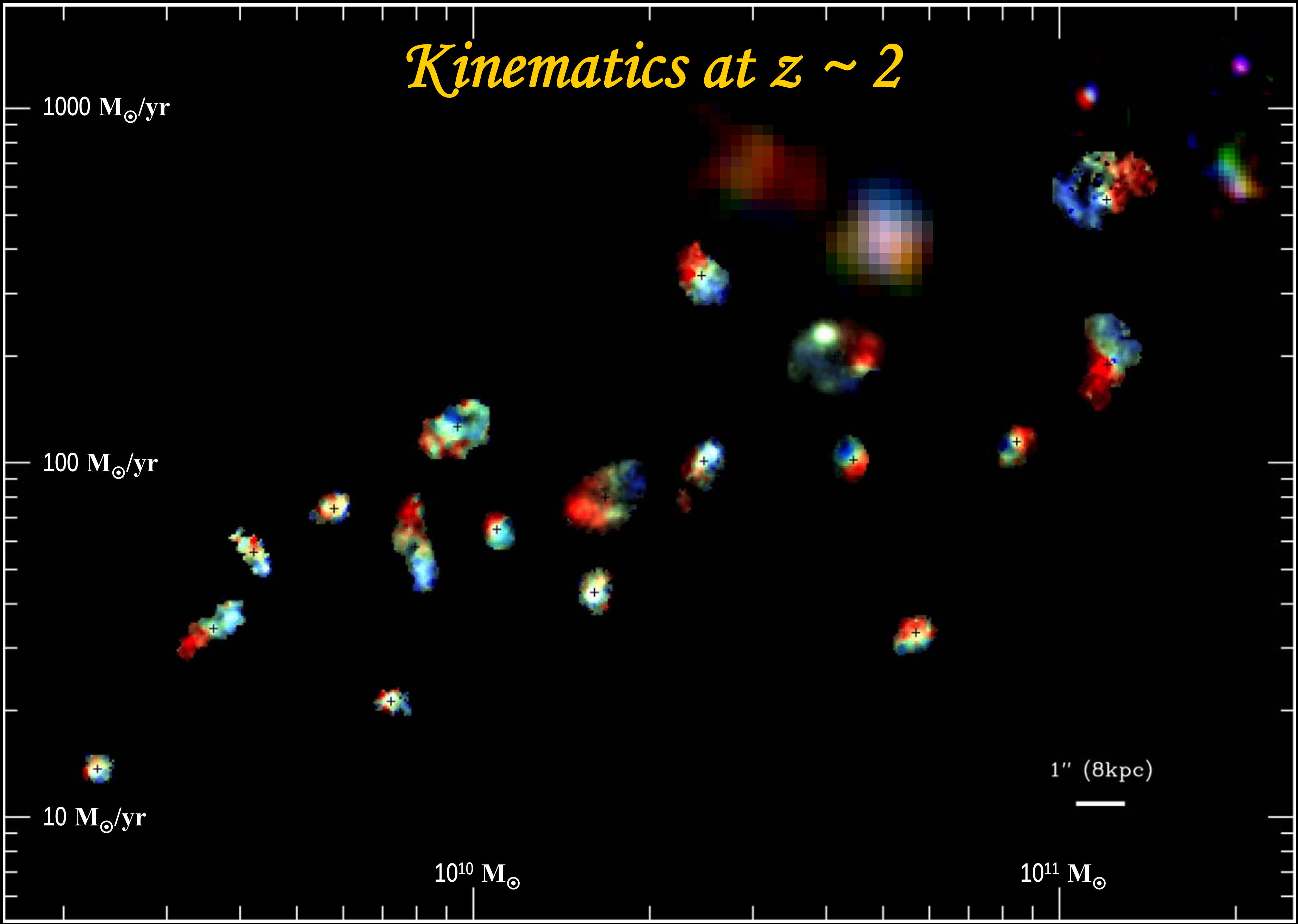

*Wuyts et al. (2011b)*

*Also, e.g., Kauffmann+03; Shen+03; Brinchmann+04; Schiminovich+07; Franx+08; van Dokkum+08; Kriel+09; Toft+09; Williams+10; NMFS+11a; Szomoru+11; Elbaz+11; Law+11*

# *Kinematics at z ~ 2*




*NMFS+09; in prep.; Tacconi+08*




*NMFS+09; in prep.; Tacconi+08*

# *Summary*

- ***Efficient internal dynamical/secular processes are important in driving star formation and the mass build-up in high z galaxies***

- ***Clumps can form from disk instabilities and drive vigorous outflows; clumps surviving feedback may spiral in to form a bulge***

- ***Kinematics are essential for a full understanding***