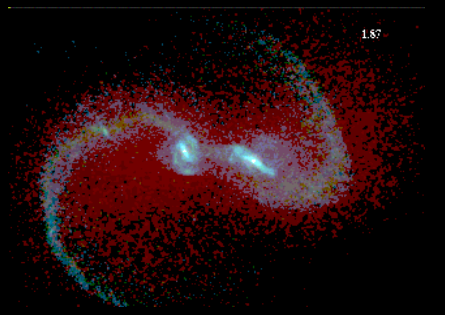
the formation & evolution of massive star forming disks at z~1-2

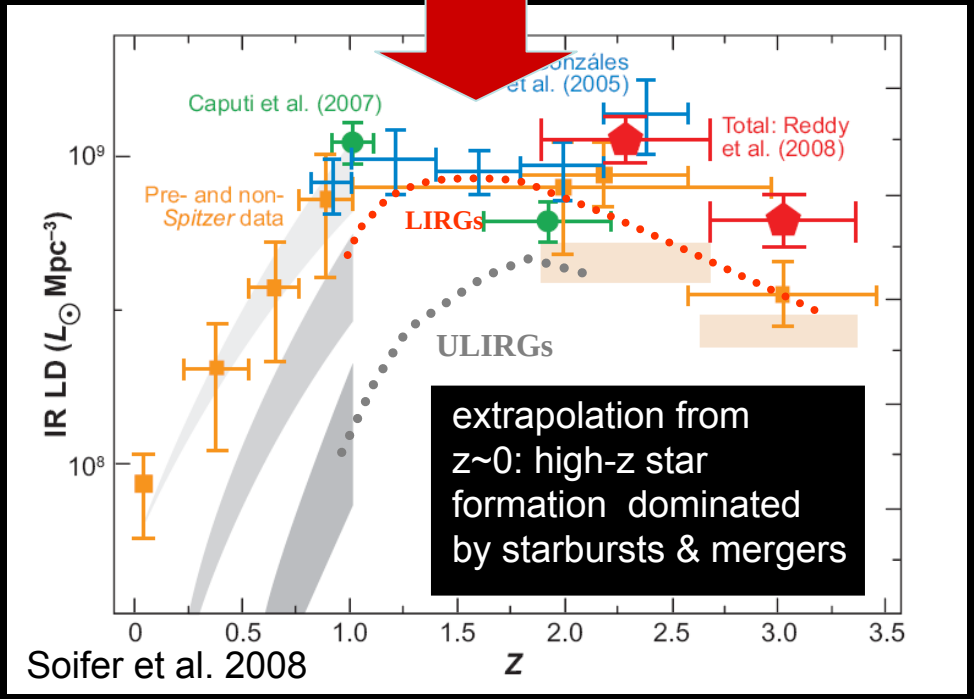
Reinhard Genzel
MPE & UCB

star formation and feedback at the peak of the galaxy formation epoch

ELBAZ TALK

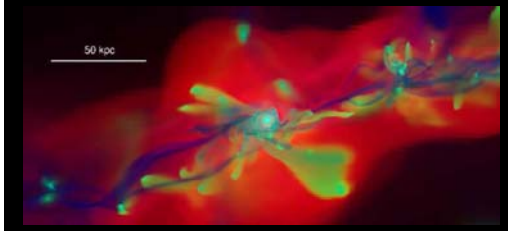


(major) mergers & starbursts



Soifer et al. 2008

continuous accretion from halo & disk instabilities



Lilly et al. 1996, Steidel et al. 1996, Hopkins & Beacom 2006, Soifer et al. 2008, Rees & Ostriker 1977, Silk 1977, White & Rees 1978, Kauffmann et al. 1993, Steinmetz & Navarro 2003, Hernquist, Springel, di Matteo, Hopkins et al. 2003-2009, Robertson & Bullock 2008, Sanders & Mirabel 1996, Dekel & Birnboim 2003,2006, Keres et al. 2005, 2009, 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, Guo et al. 2009, Teyssier et al. 2010, Bournaud 2010, Davè et al. 2011a,b, Kauffmann et al. 2010

Galactic star formation in equilibrium with cosmic accretion

$$\propto M_{halo}^{1.1}(1+z)^{2.3} \qquad \dot{M}_{out} = \eta \dot{M}_*$$

$$\dot{M}_{gas} = \dot{M}_{gas,accretion} - (1-R)\dot{M}_* - \dot{M}_{out}$$

$$f_{gas} \sim 0.5 \frac{\varepsilon_{acc}}{(1+\eta-R)} f_{baryon,0.18} \left(\frac{t_{depletion}}{1\ Gyr}\right)(1+z)_{3.2}^{\gamma} \quad \gamma > 0.8$$

$$\dot{M}_* \sim 100 \frac{\varepsilon_{acc}}{(1+\eta-R)} f_{baryon,0.18}\ \mathrm{M}_{*,11}(1+\mathrm{z})_{3.2}^{2.7} \quad \mathrm{M}_\odot yr^{-1}$$

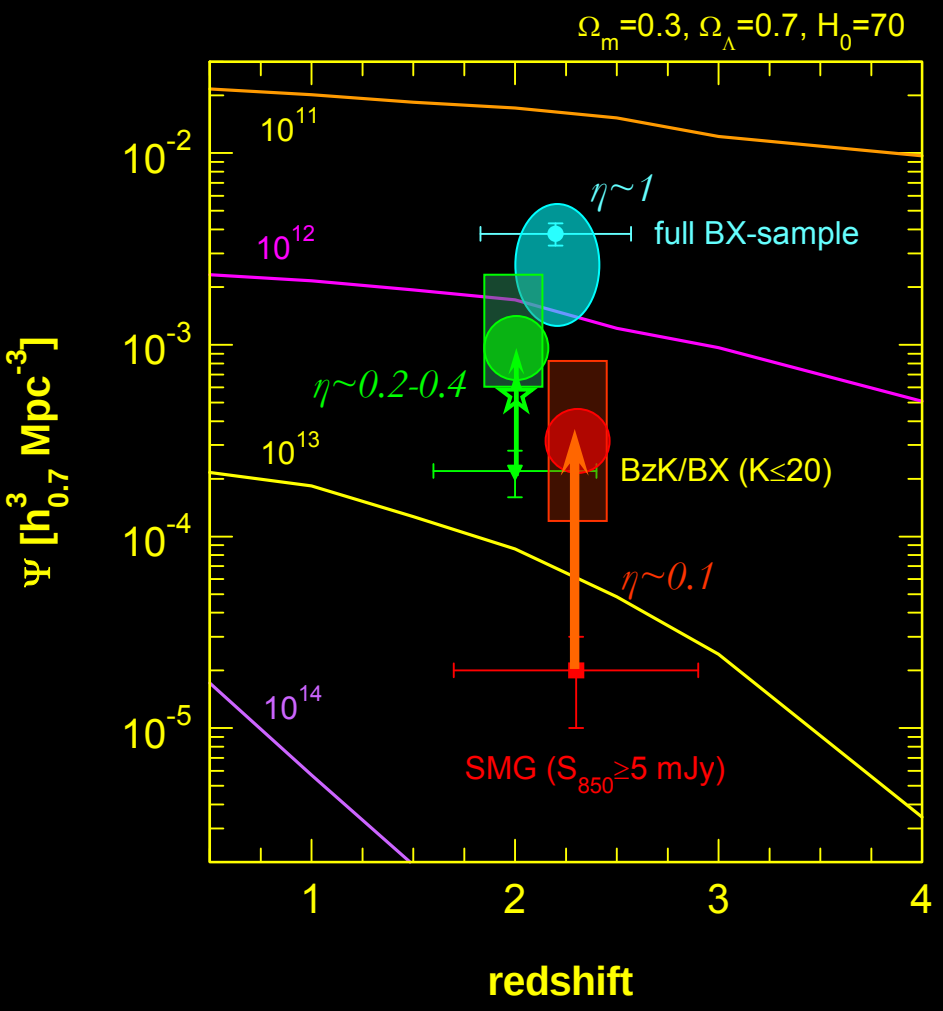
$\varepsilon_{acc} \rightarrow 1$ requires low star formation efficiency

at earlier times, when $\mathrm{M}_* << 10^{11} M_\odot$

LILLY & DAVÈ TALKs

Kereš et al. 2005, 2009, Neistein et al. 2006, Genel et al. 2008, Guo et al. 2009, Oppenheimer & Davè 2006, Dekel et al. 2009, Davè et al. 2010, 2011, Dutton et al. 2009, Bouchè et al. 2010

How bursty are the z> SFGs ?



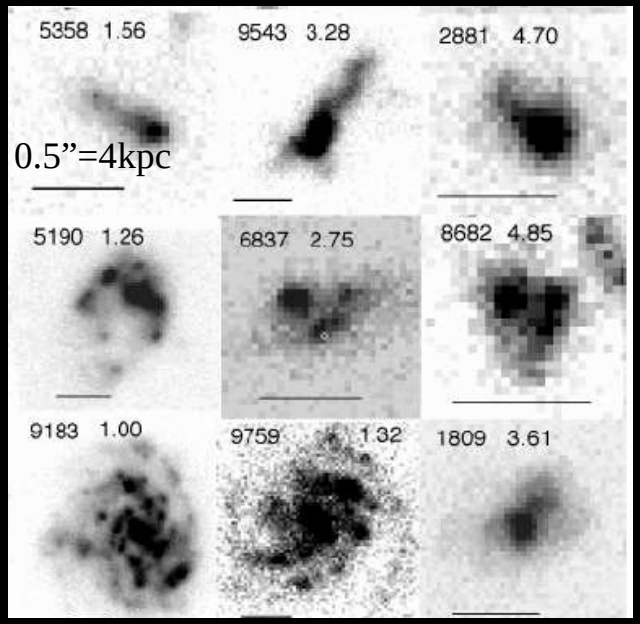
from ratio passive to star forming gals & scatter of ms relation

from clustering

from kinematics $M_{halo} \sim v_c^3 (1+z)^{-1.5}$

Adelberger et al. 2004, Daddi et al. 2004, 2005, 2007, Blain et al. 2004, Reddy et al. 2005, 2007, Grazian et al.2006, Kong et al.2006, Noeske et al. 2007, Conroy et al. 2008, McCracken et al. 2009, Amblard et al. 2011

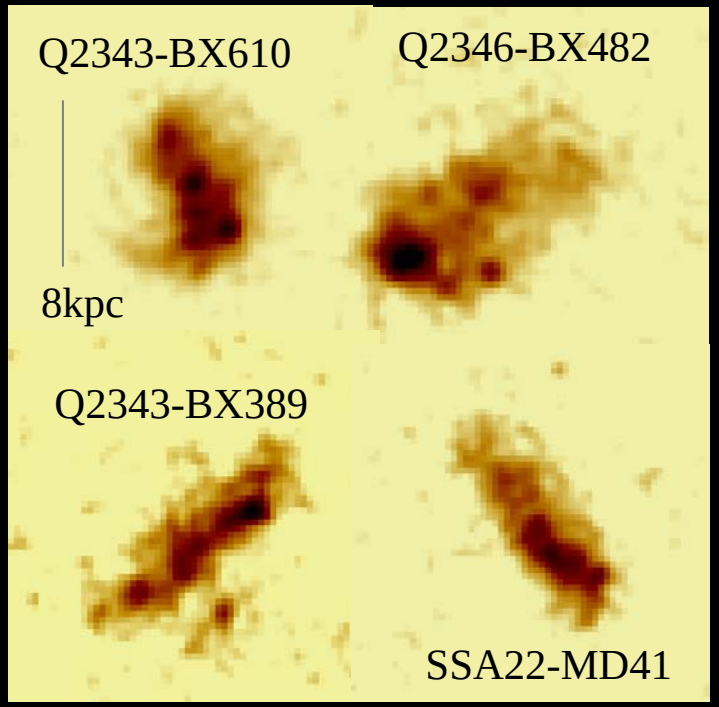
clumpy high-z SFGs: mergers or clumpy disks ?



HST UDF

3-10 clumps, 20-40% of light
average surface density distribution
of high-z SFGs flat: n_{Sersic}~ 1

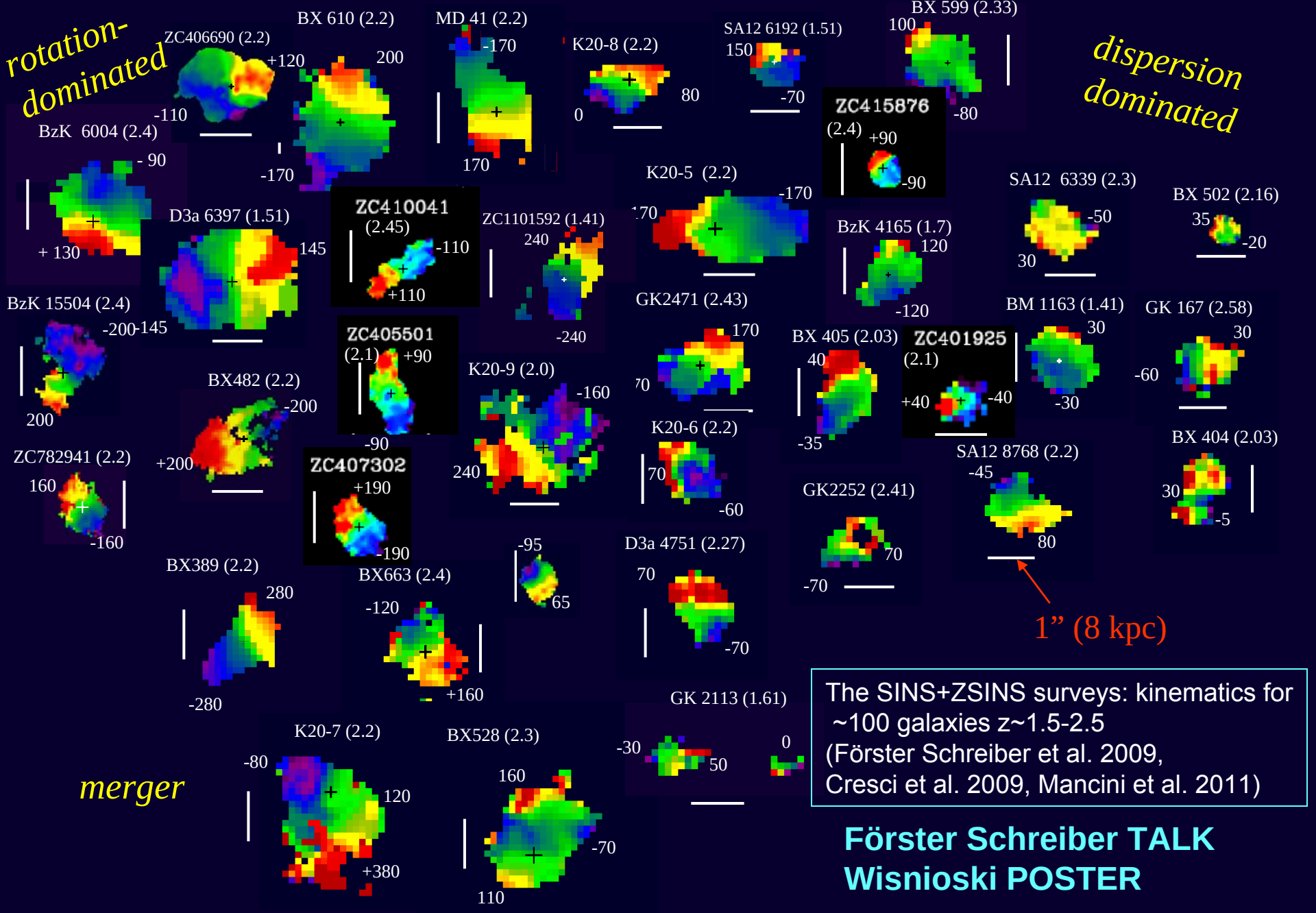
Elmegreen et al. 2005, 2007



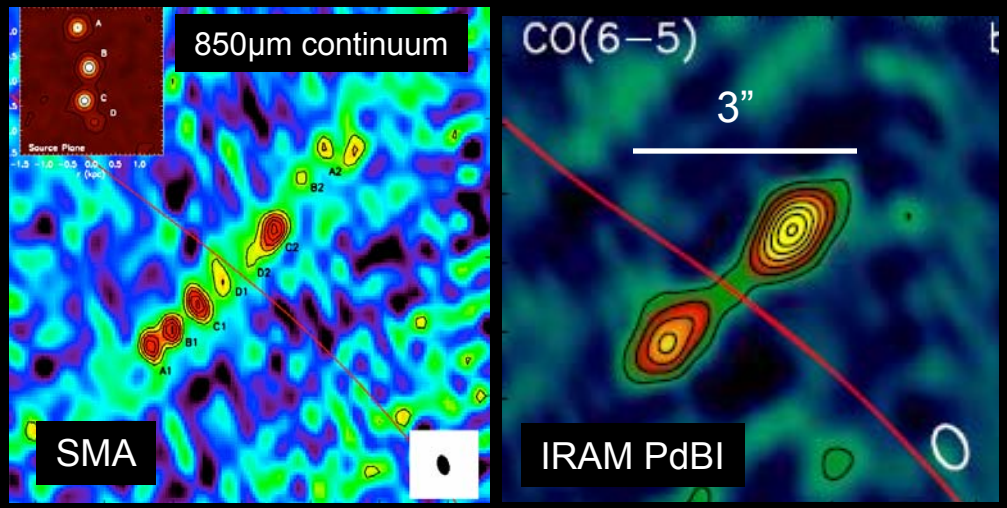
BX: NICMOS H_{160}

Foerster Schreiber et al. 2011 a,b

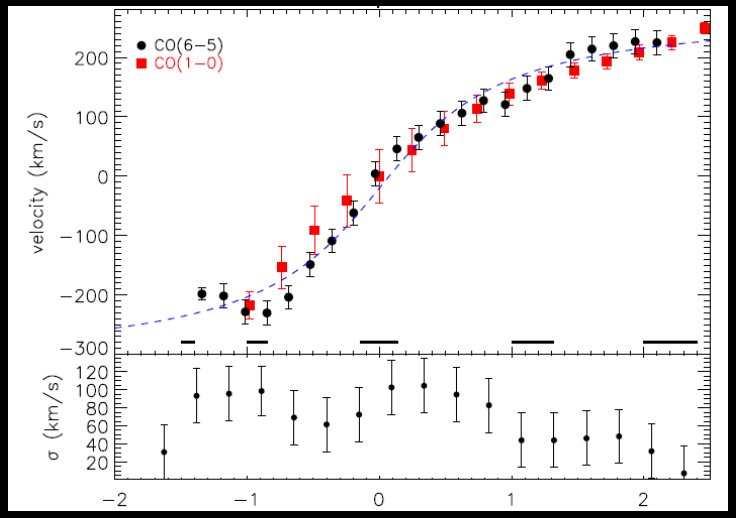
Cowie, Hu, Giavalisco, van den Bergh, Elmegreen & Elmegreen, Labbé, Stockton 1995-2007, Lotz, Conselice 2000-2008, Kriek et al. 2009


rotation-dominated
dispersion dominated
merger
ZC406690 (2.2)
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
ZC415876 (2.4)
BzK 6004 (2.4)
K20-5 (2.2)
SA12 6339 (2.3)
BX 502 (2.16)
D3a 6397 (1.51)
ZC410041 (2.45)
ZC1101592 (1.41)
BzK 4165 (1.7)
BzK 15504 (2.4)
GK2471 (2.43)
BM 1163 (1.41)
GK 167 (2.58)
ZC405501 (2.1)
BX 405 (2.03)
ZC401925 (2.1)
BX482 (2.2)
K20-9 (2.0)
K20-6 (2.2)
BX 404 (2.03)
ZC782941 (2.2)
ZC407302
SA12 8768 (2.2)
GK2252 (2.41)
BX389 (2.2)
BX663 (2.4)
D3a 4751 (2.27)
1” (8 kpc)
GK 2113 (1.61)
K20-7 (2.2)
BX528 (2.3)
The SINS+ZSINS surveys: kinematics for ~100 galaxies z~1.5-2.5
(Förster Schreiber et al. 2009, Cresci et al. 2009, Mancini et al. 2011)
Förster Schreiber TALK
Wisnioski POSTER
further ~50 z~1-3 SFGs: Erb et al. 2003, 2006, Law et al. 2007, 2009, Wright et al. 2007, 2010, Epinat et al. 2010, Lemoine Busserolle 2010, van Starkenburg et al. 2008, Stark et al. 2008, Jones et al. 2010, Wisnioski +11

high-z SFGs under the microscope: lenses



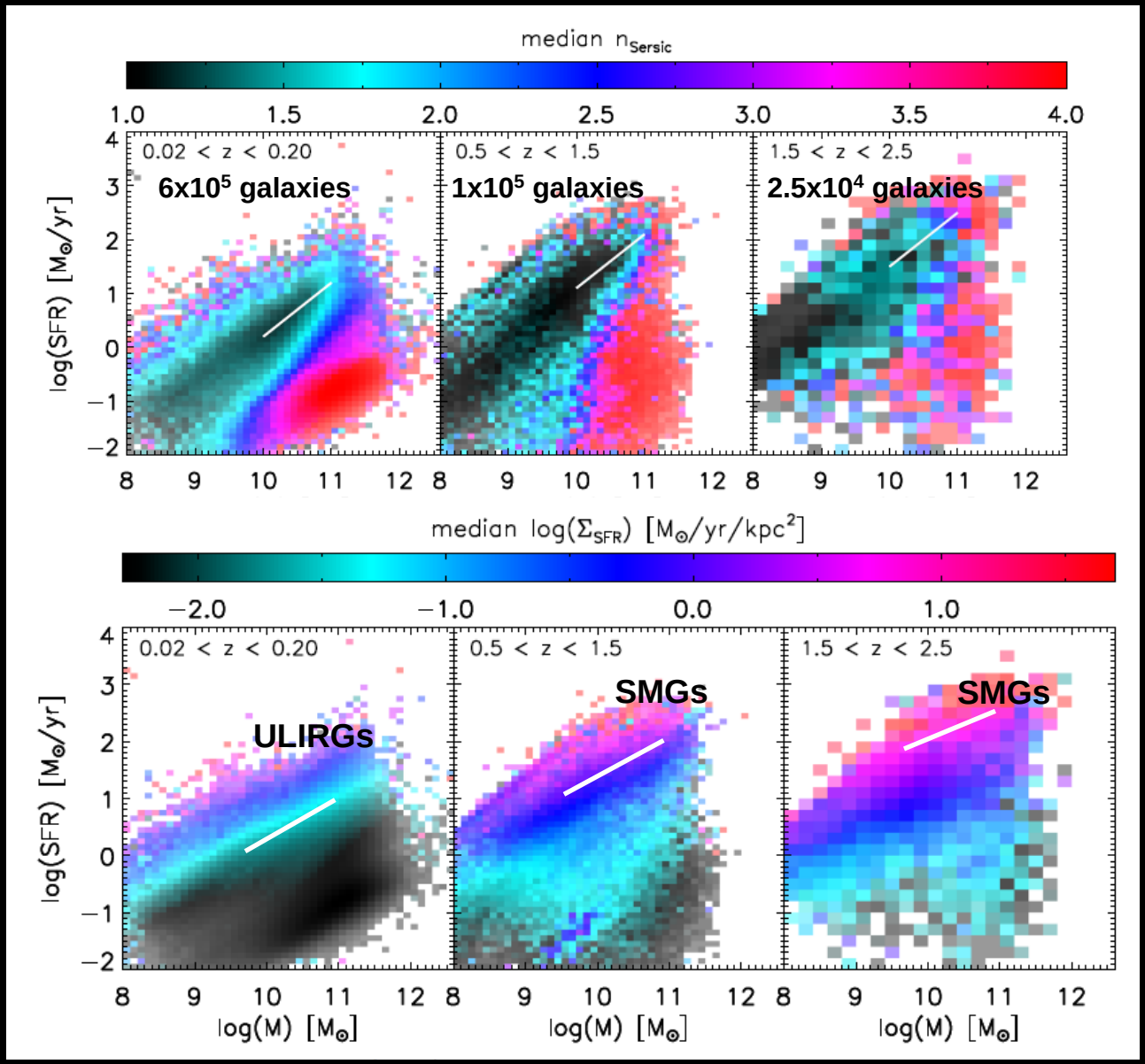
‘cosmic eyelash’
z=2.3



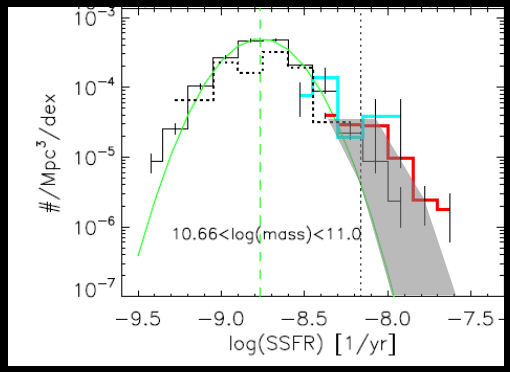
- confirmation of rotation & large vel. dispersion to ~10^2 pc
- large star forming clumps diameter ~a few 10^2 pc
- $n(H_2)$~$10^{3...4}$ cm^{-3}

Nesvadba et al. 2006, Stark et al. 2008, **Jones** et al. 2010 (**POSTER**), Swinbank et al. 2010, 2011, **Danielson** et al. 2011 (**POSTER**)

galaxies on 'star forming (main) sequence' are disks with $\Sigma_{\text{star form}}$ & n_{Sersic} increasing above sequence



ELBAZ TALK

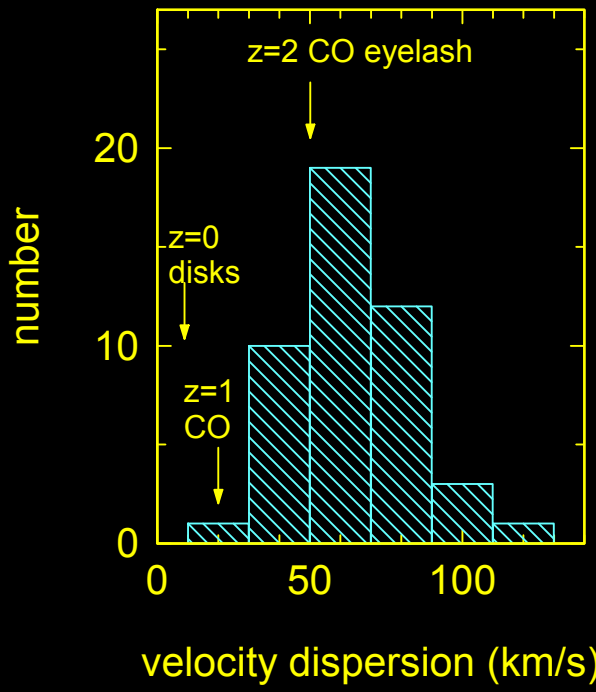


Rodighiero et al. 2011 (PEP):
off-ms galaxies account for ~10% of cosmic star formation at z~2

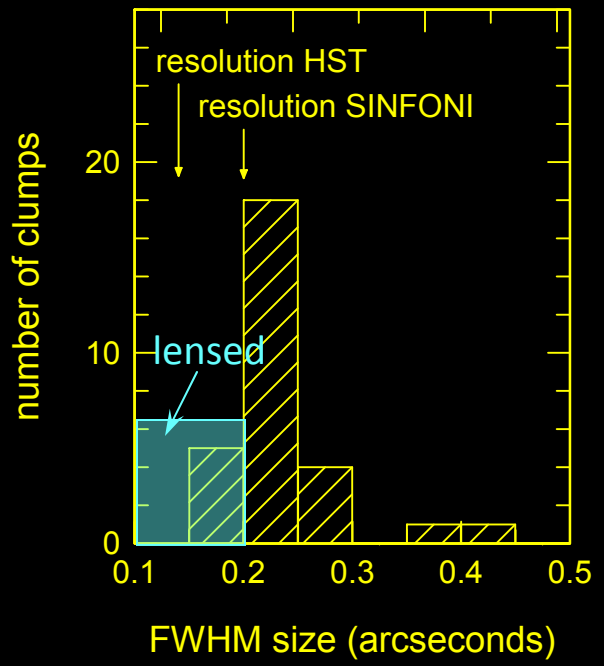
Wuyts et al. 2011 (PEP):
SDSS/GALEX, COSMOS,GOODS

WUYTS POSTER

internal structure: large vel. dispersion, big clumps, thick disks

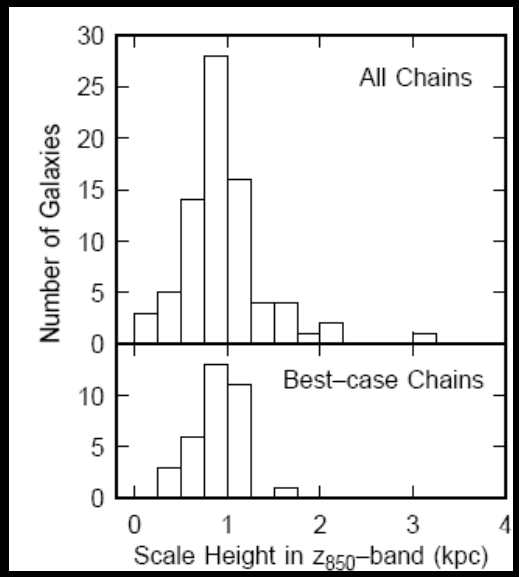


large turbulent
gas velocities



large star formation clumps

is the MW 'thick disk' the remnant of this phase ?

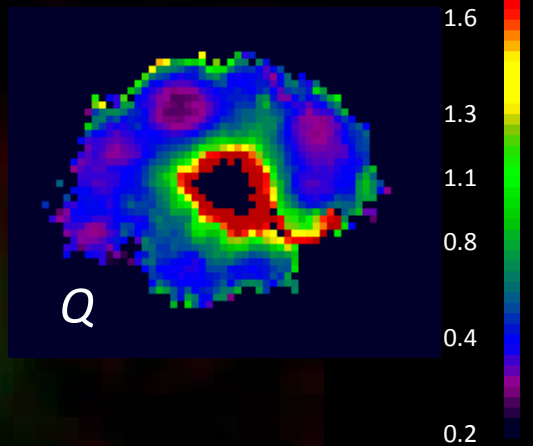


large stellar z-scale heights

HELMI, GLAZEBROOK TALKS

Elmegreen & Elmegreen 2005, Elmegreen et al. 2007, Kassin et al. 2007, Genzel et al. 2006, 2008, Förster Schreiber et al. 2006, 2009, 2011, Cresci et al. 2008, Stark et al. 2008, Swinbank et al. 2009, 2011, Jones et al. 2010, Dekel et al. 2009, Law et al. 2011, WIsnioski et al. 2011

large clumps from fragmentation in gas-rich, Q ≤ 1 disks



R ~ 1kpc

$$\left(\frac{\sigma}{v_d}\right) = \left(\frac{h_z}{R_{disk}}\right) \underset{Q\sim1}{=} \frac{Q f_{gas}}{\sqrt{2..3}}$$

$$L_{Toomre} \sim f_{gas} R_{disk}$$

$$M_{Toomre} \sim f_{gas}^2 M_{disk}$$

5 kpc

largest star formation clumps in high-z 'main-sequence' disks are the largest scale of gravitational fragmentation, scaled up to the 5-10 times greater gas fraction & $10^{1.5...3}$ greater interstellar pressure than at z~0

Noguchi 1999, Immeli et al. 2004, Bournaud et al. 2007, Elmegreen et al. 2008, Dekel et al. 2009b, Genzel et al. 2008, 2011, Krumholz & Burkert 2010

origin of large turbulent velocities

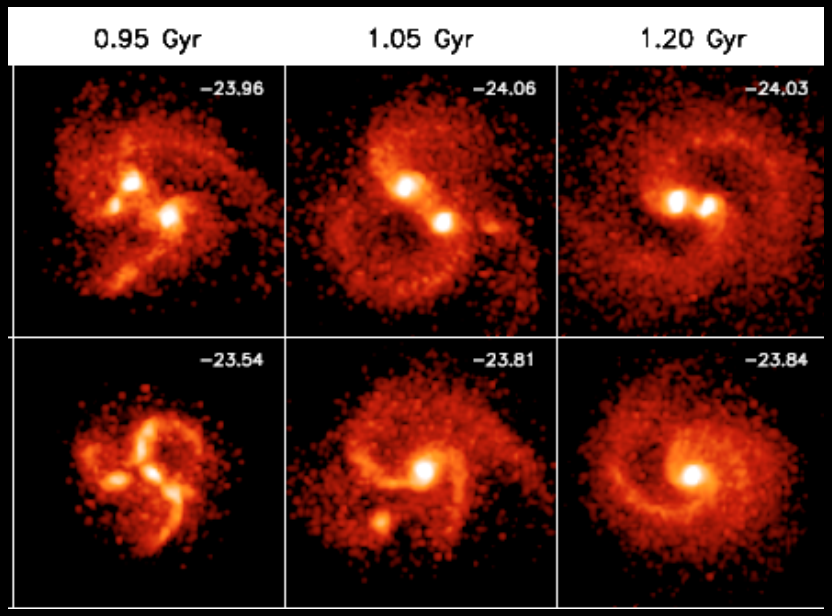
- feedback from SN/winds/radiation
- dynamical instabilities in the disk
- gravitational energy of accreting gas

GLAZEBROOK TALK

Förster Schreiber et al. 2006, Dib, Bell & Burkert 2006, Genzel et al. 2008, Immeli et al. 2004, Bournaud et al. 2007, Dekel & Birnboim 2003, 2006, Keres et al. 2005, Ocvirk et al. 2008, Dekel, Sari & Ceverino 2009, Murray et al. 2009, Lehnert et al. 2009, Bournaud et al. 2009, Green et al. 2010

violent disk instability

$$t_{vis} \sim t_{df} = \beta \left(\frac{R}{\lambda_{Jeans}} \right)^2 t_{dyn}(R) = \beta \left(\frac{v_d}{\sigma_0} \right)^2 t_{dyn}(\mathrm{R})$$

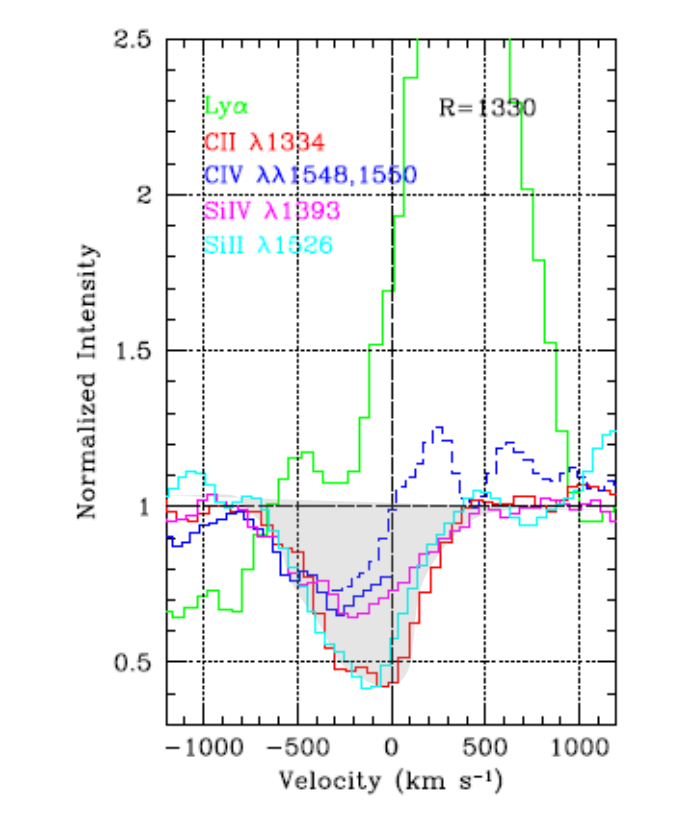


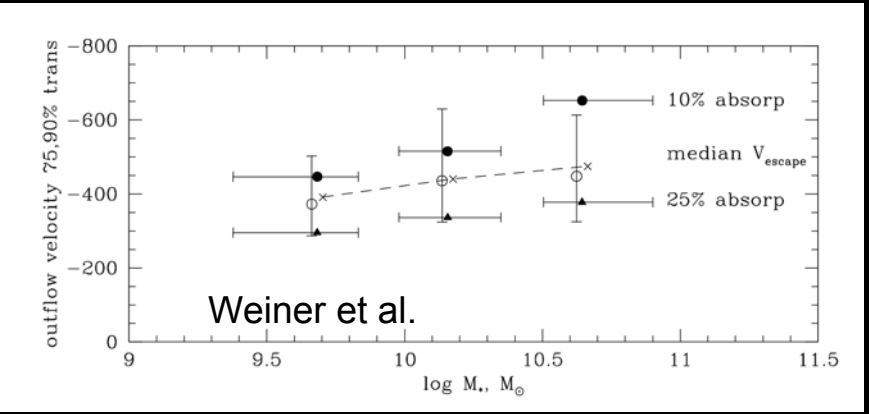
at z~0: $t_{vis,df}$~5-10 Gyrs
at z~2: $t_{vis,df}$~ a few 10^2 Myrs

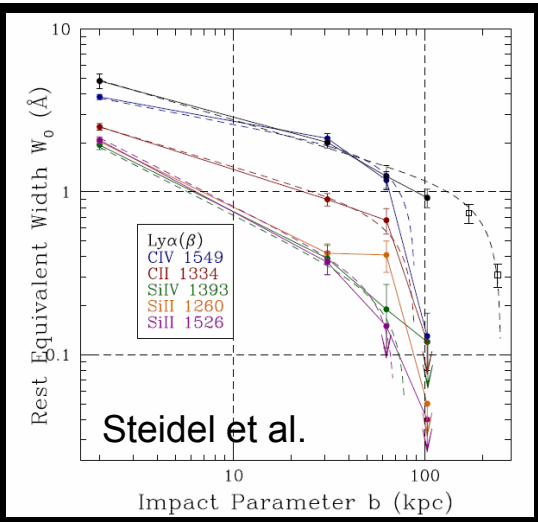
inward transport of gas (clumps)
formation of bulges
feeding of central BH ?

Lin & Pringle 1987, Noguchi 1999, Semelin & Combes 2002, Immeli et al. 2004, Bournaud et al. 2007, 2009, Genzel et al. 2008, Agertz et al. 2009, Dekel, Sari & Ceverino 2009, Ceverino et al. 2011, Genel et al. 2011

strong mass outflows from z>1 star forming galaxies



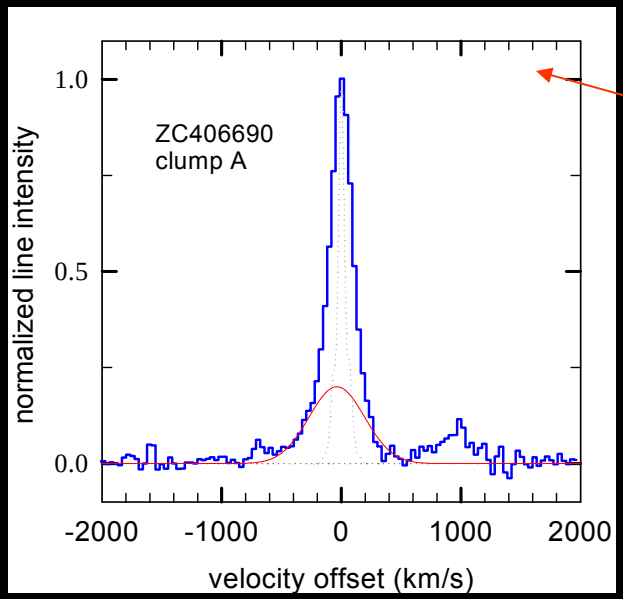


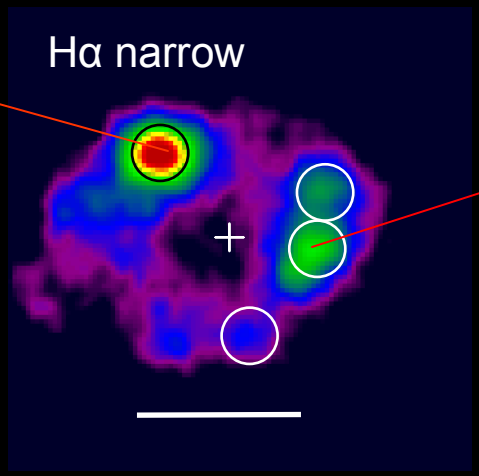


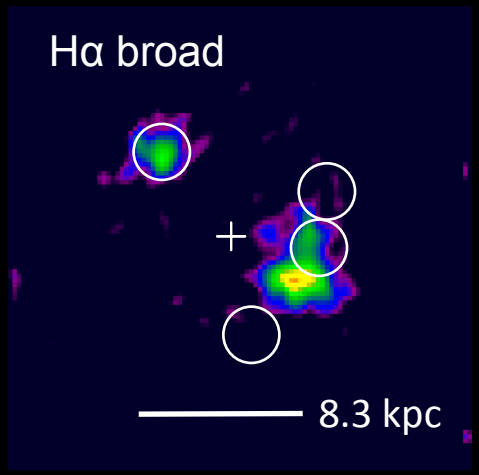
MARTIN & STEIDEL TALKS

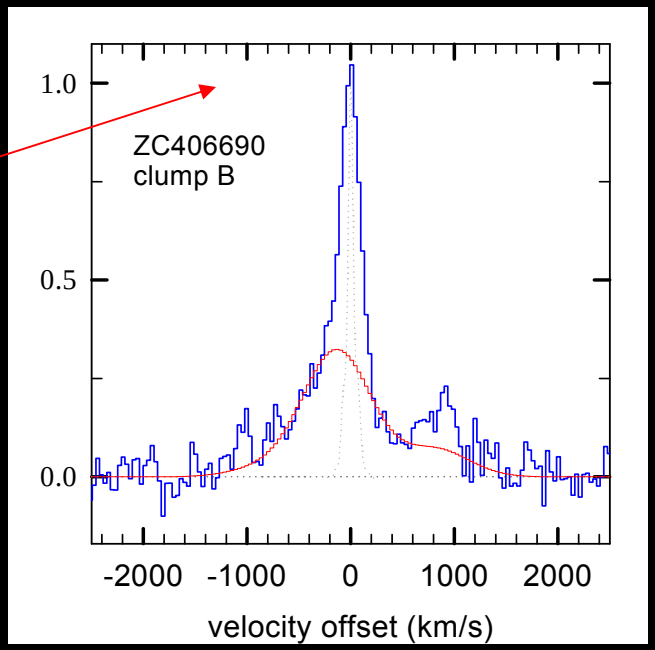
Pettini et al. 2000, Shapley et al. 2003, Steidel et al. 2010, Weiner et al. 2009

in situ observations of stellar feedback from SINFONI & AO Hα integral field spectroscopy









ZC406690
z=2.19

10hrs SINFONI
+LGSF

- outflow rates ~1-10 SFR,
- $v_{out} \sim v_{escape}$
- stellar feedback may limit life times of the most active clumps to a few 10^2 Myrs

Shapiro et al. 2009, Genzel et al. 2011, **Newman** et al. 2011 (**POSTER**)