Star formation in high-redshift galaxies

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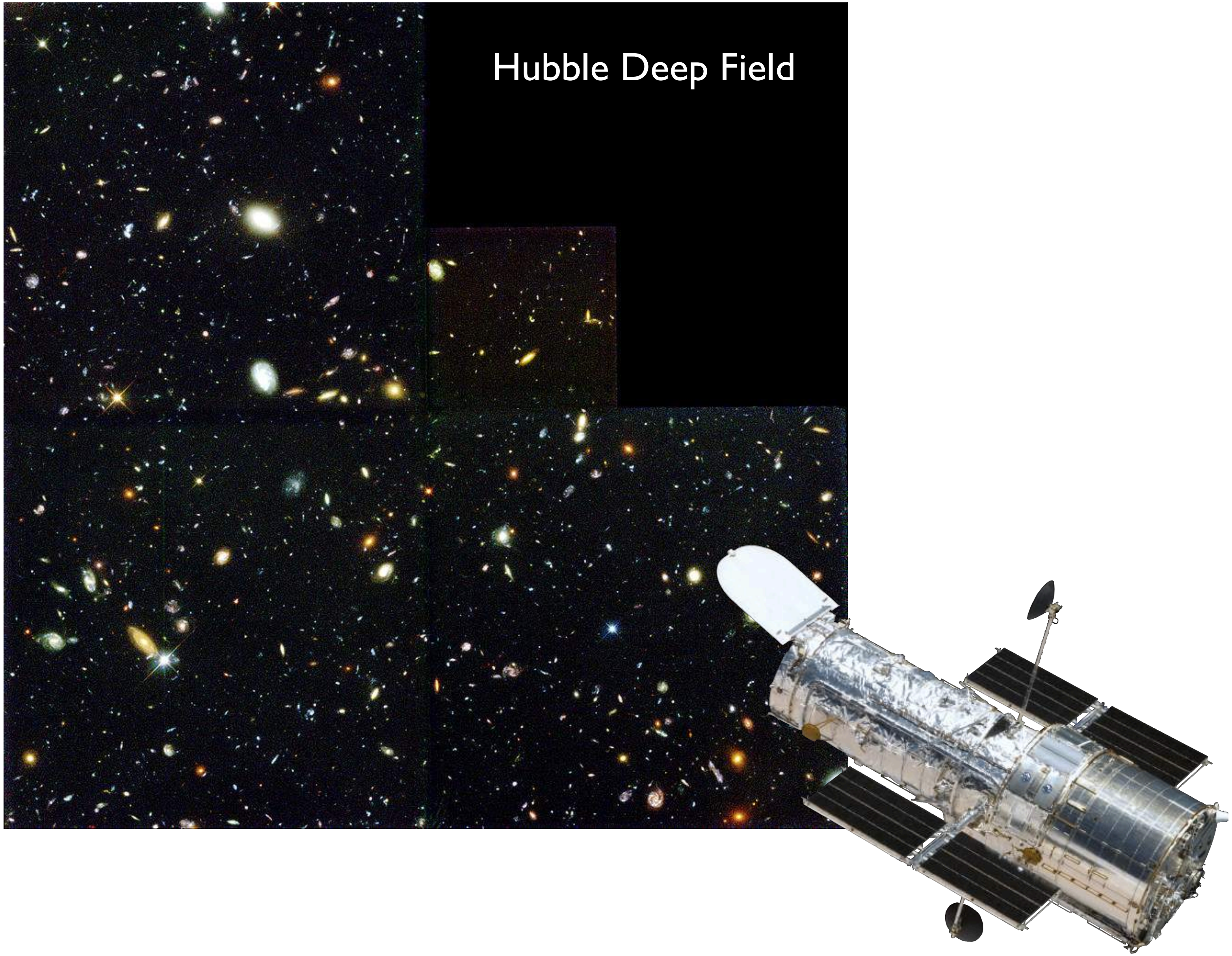
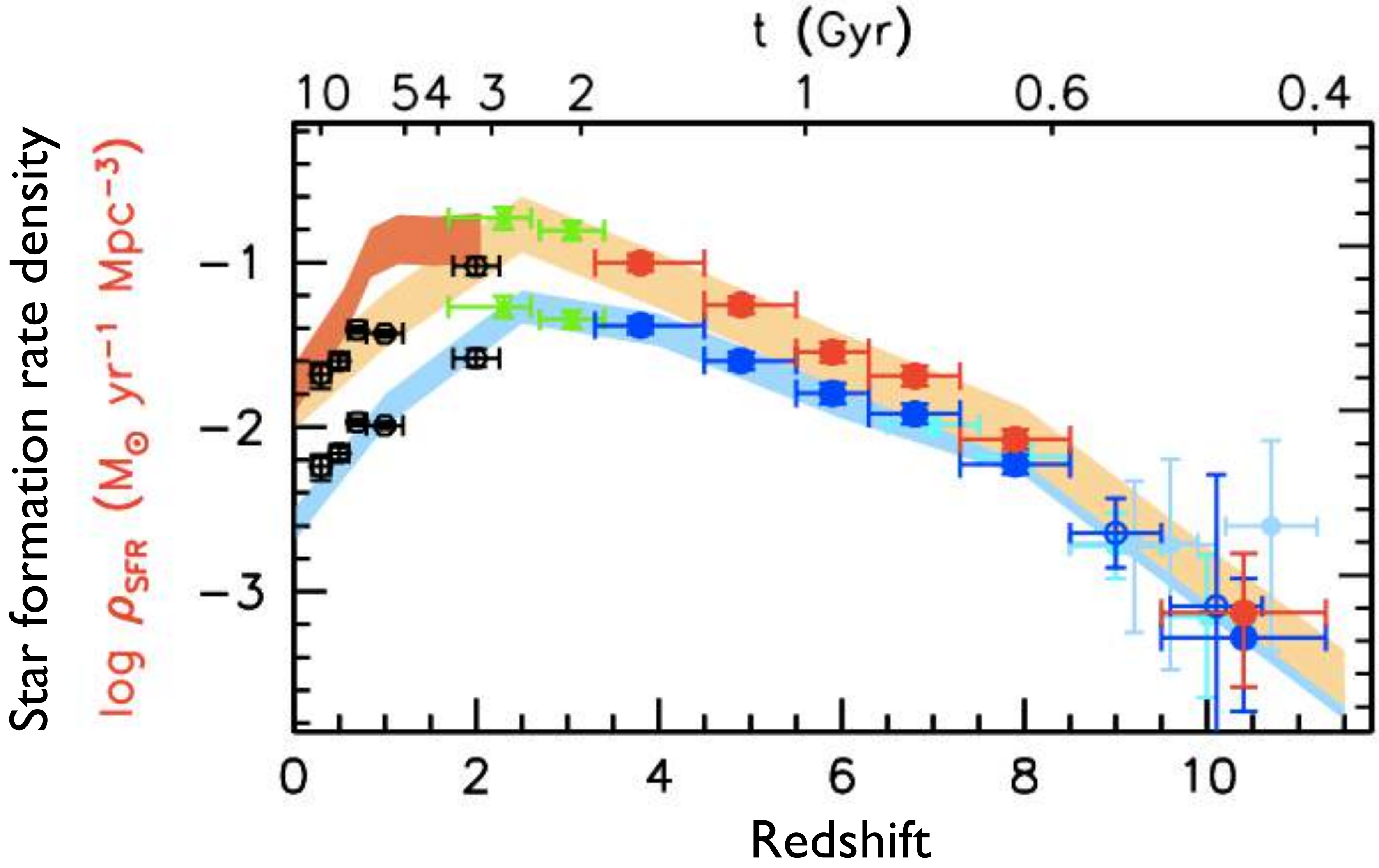
Observing the distant Universe



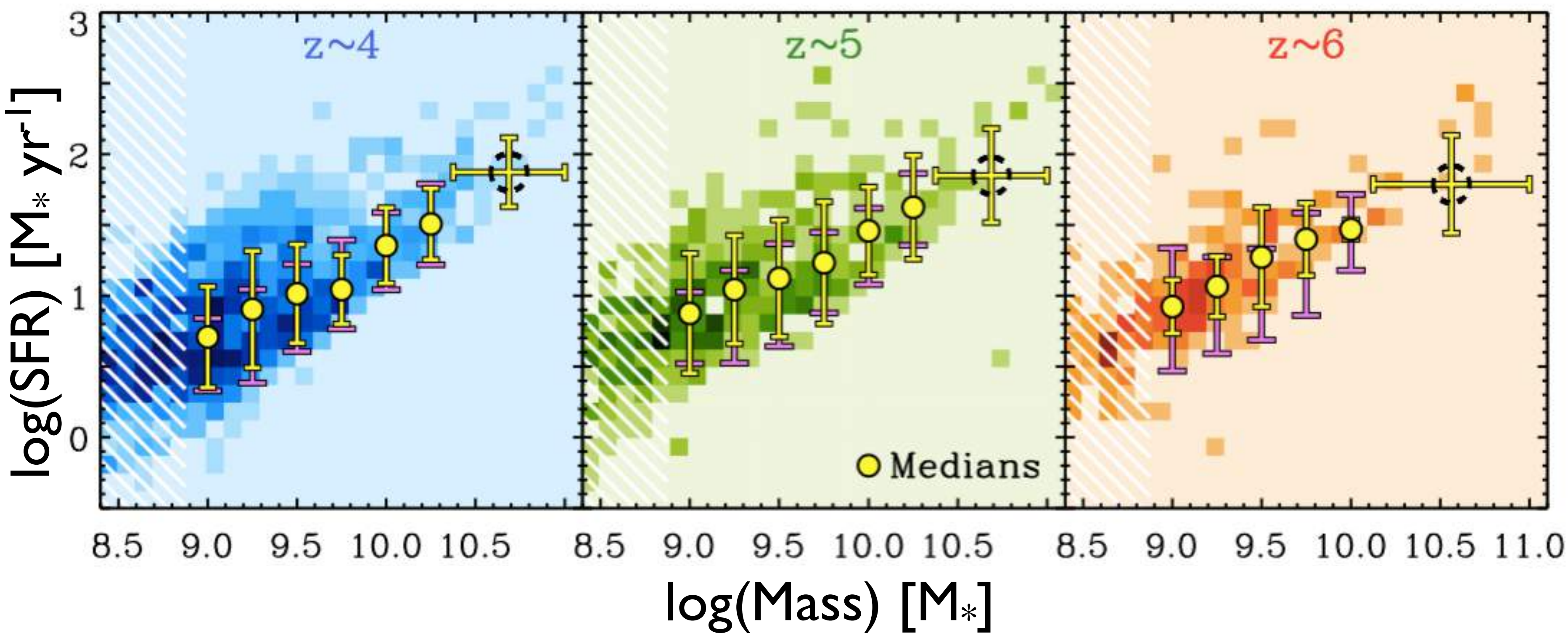
Star Formation History of the Universe



e.g., Bouwens+2015

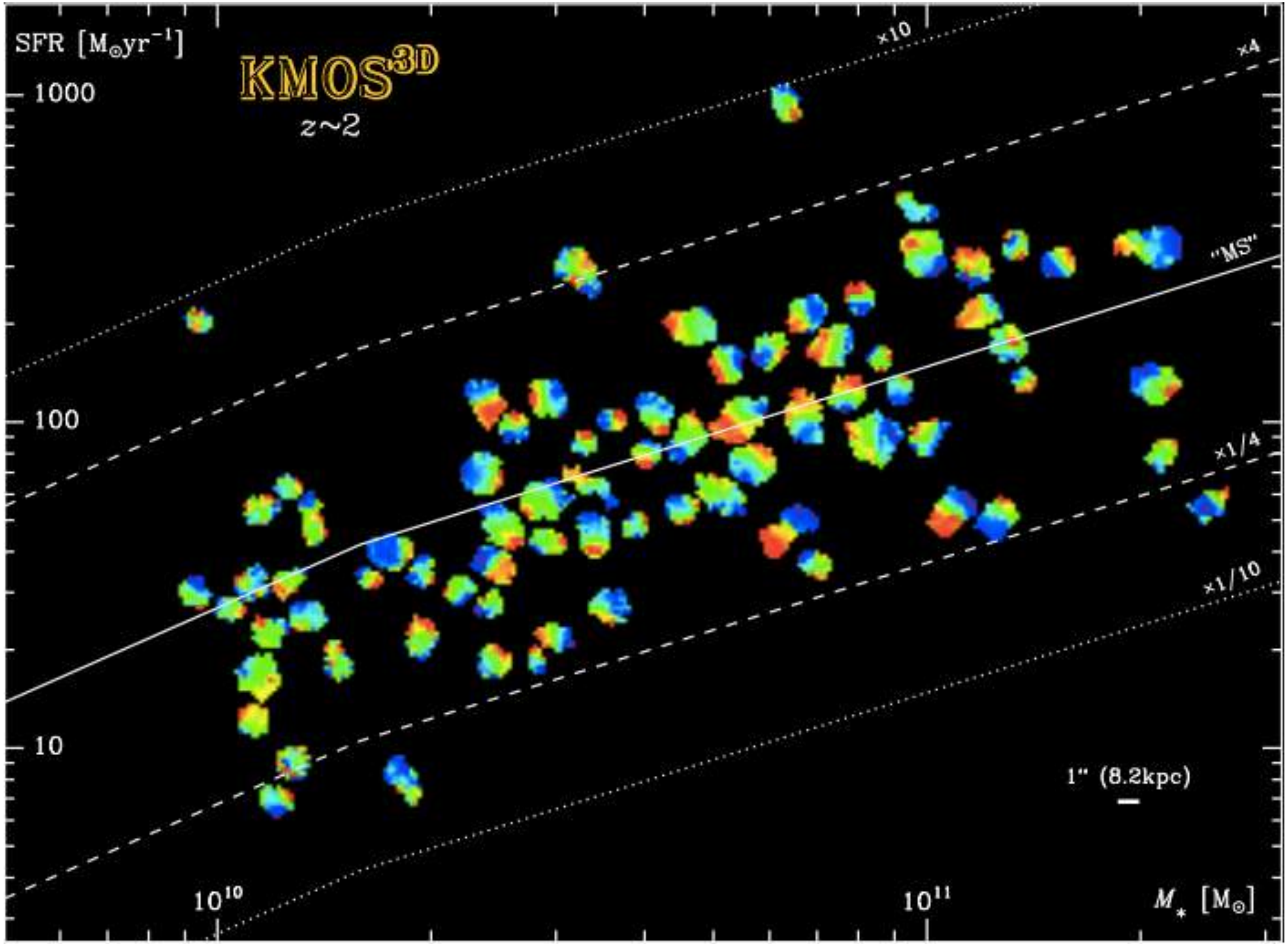
How did galaxies form their stars?

The 'main sequence' of galaxy formation



e.g., Salmon+2015

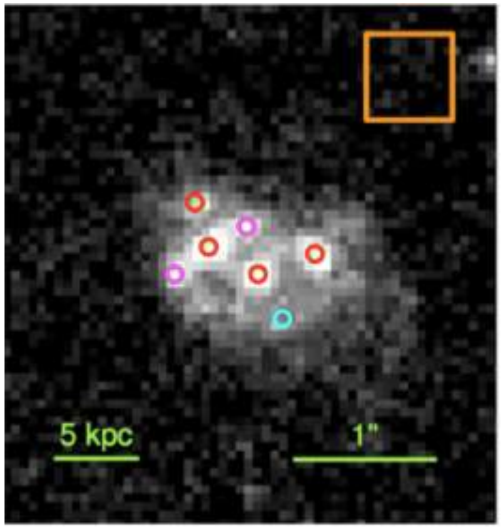
MS galaxies are rotation dominated



e.g., Wisnioski+16

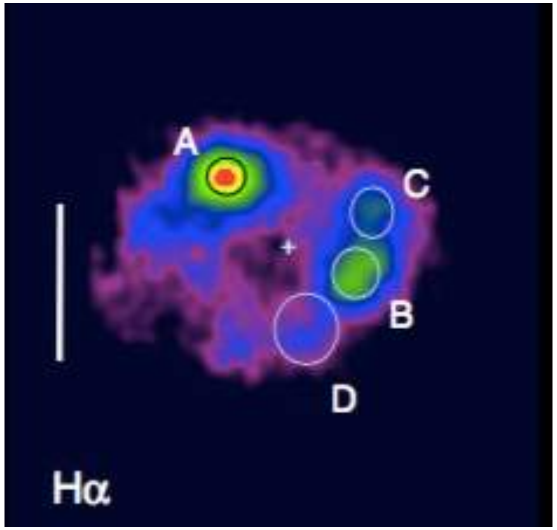
Morphology of MS galaxies: Clumps

UV imaging



e.g., Guo+2015

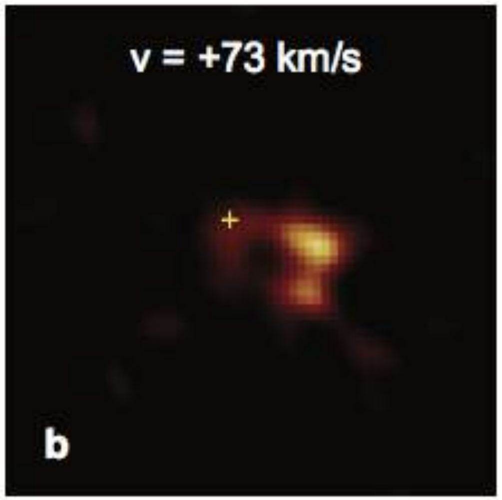
IFU spectroscopy



e.g., Genzel+2011

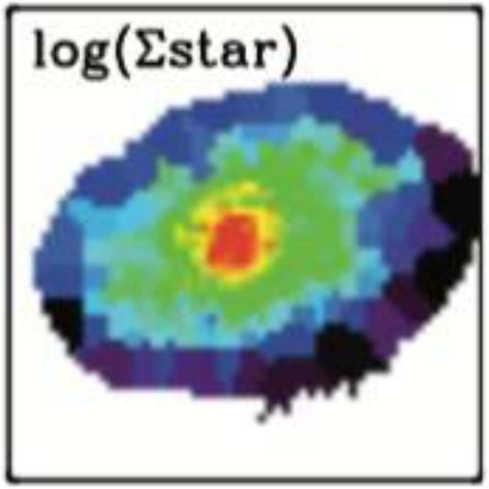
Molecular gas

e.g., Tacconi+2010



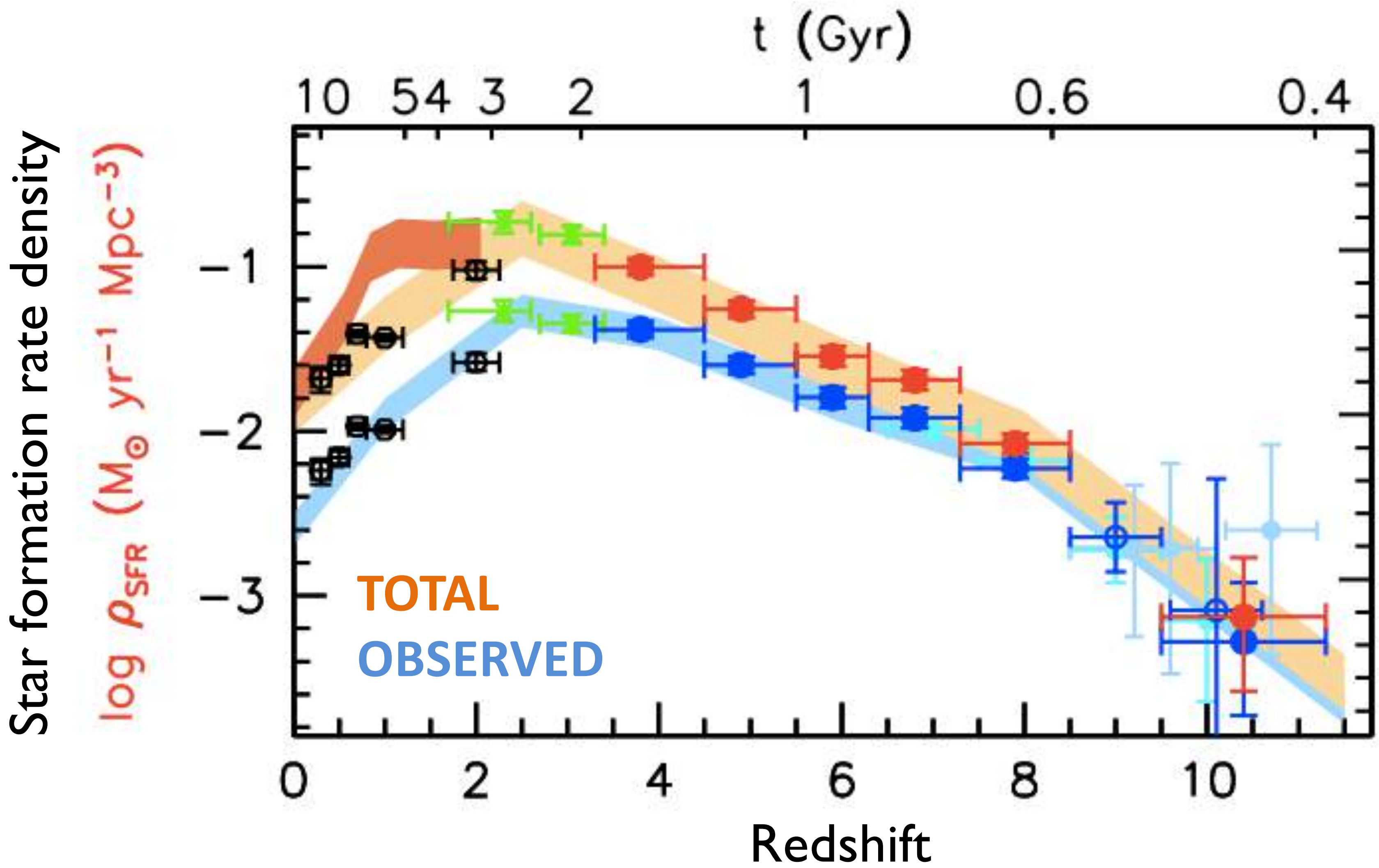
c.f.

Stellar Mass



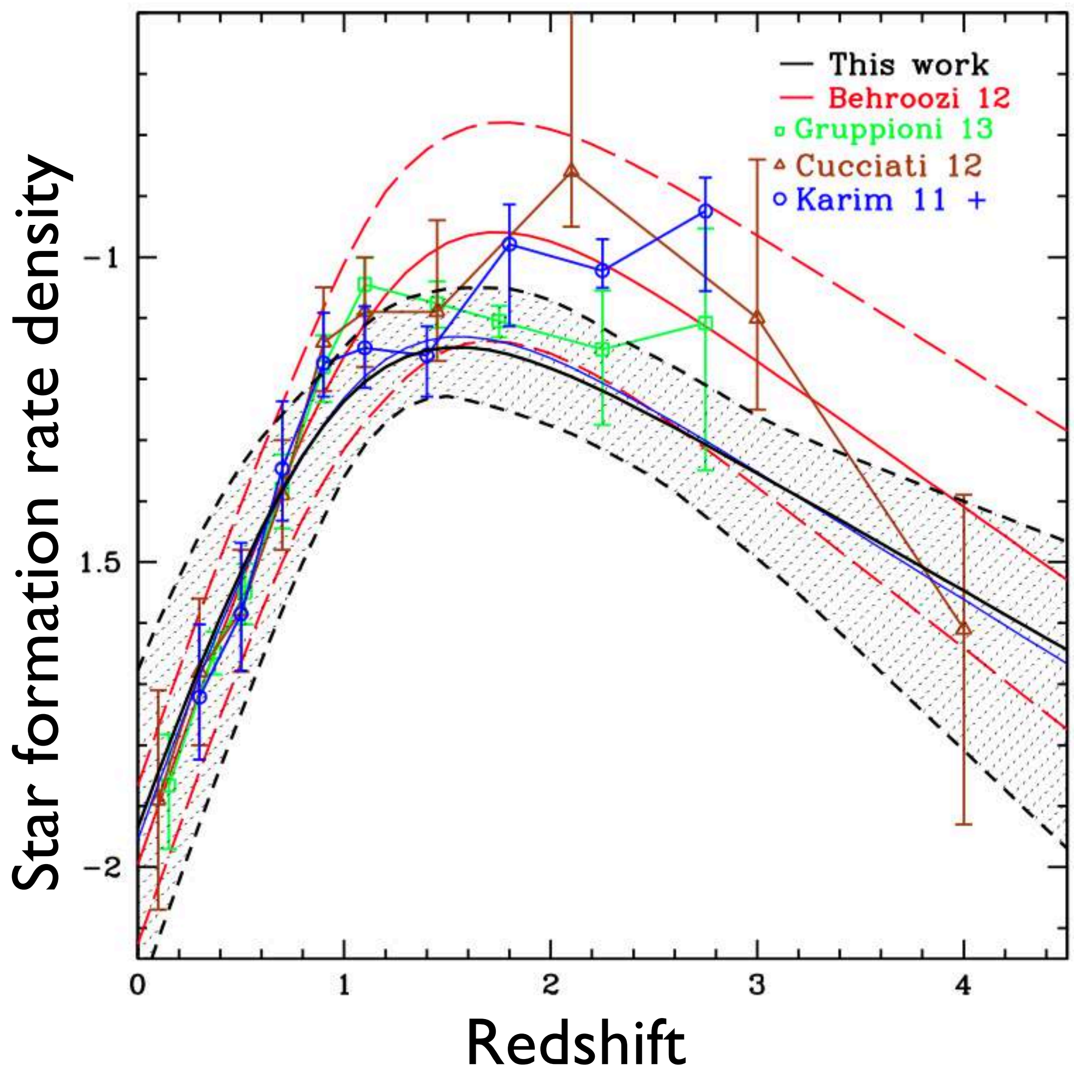
Wuyts+2012

Star Formation History of the Universe



e.g., Bouwens+2015

Long-wavelengths trace dust-obscured star formation

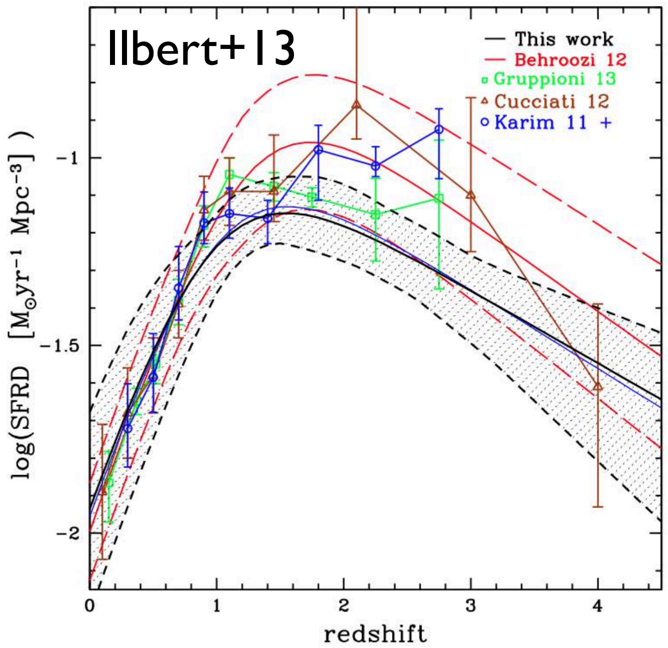


Near-IR
UV
IR
Radio

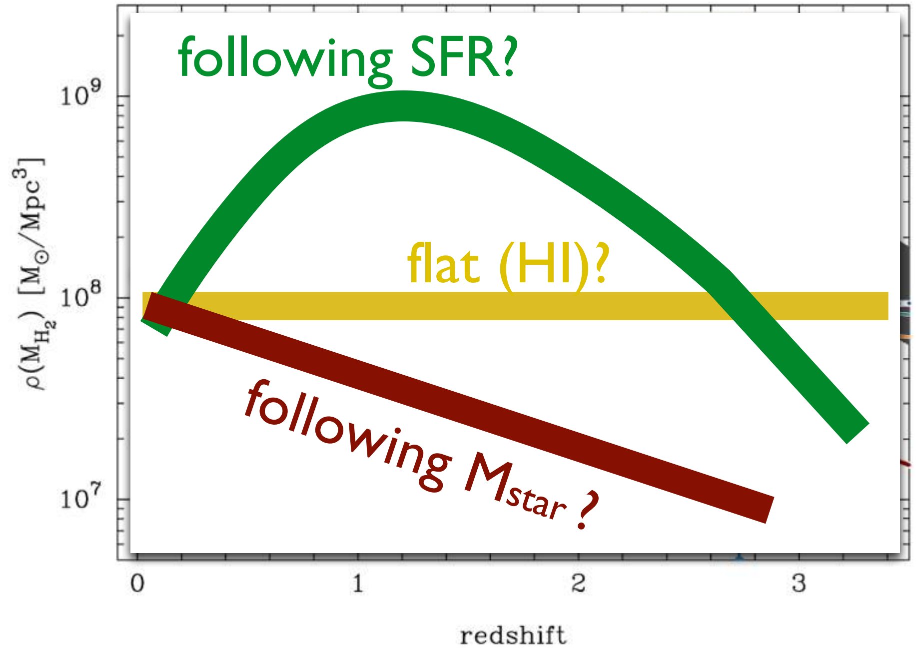
Ilbert+2013

The cosmic molecular gas density

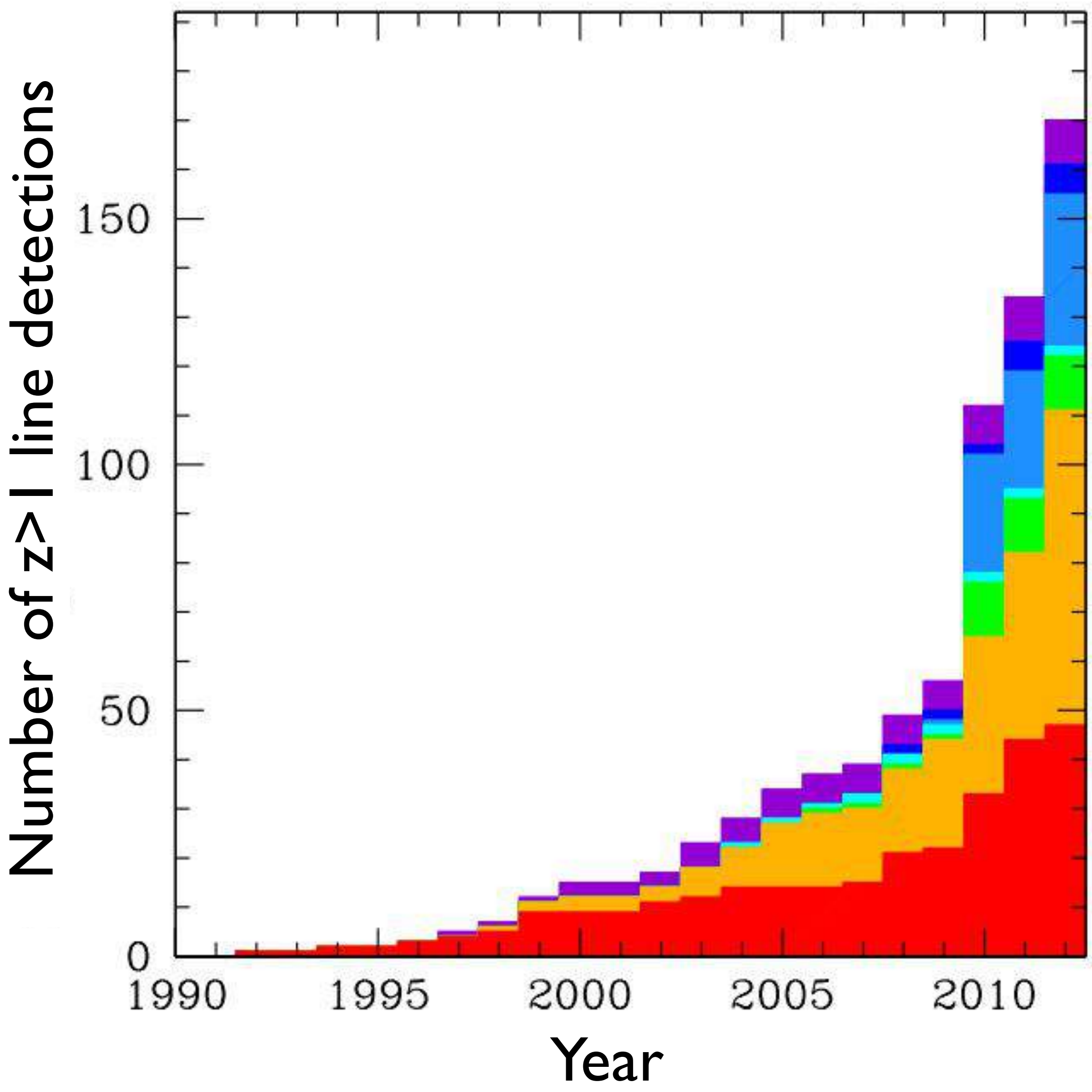
Ω(SFR)



$\Omega(H_2)$



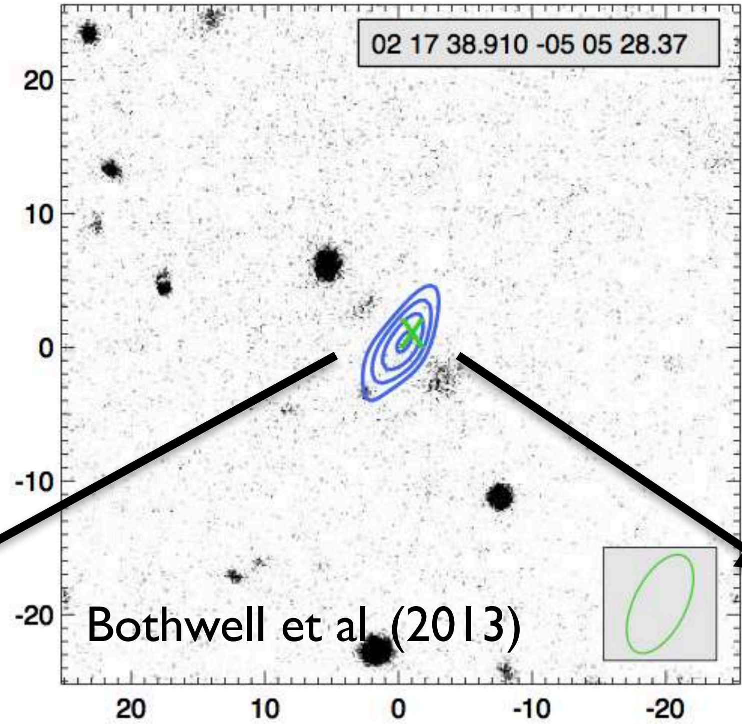
High-z molecular gas detections



Most are SMGs/ QSOs

Carilli & Walter 2013

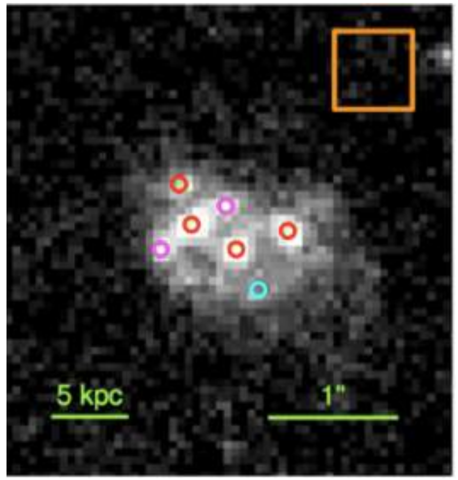
Most high-z gas/dusty SF unresolved



Bothwell et al. (2013)

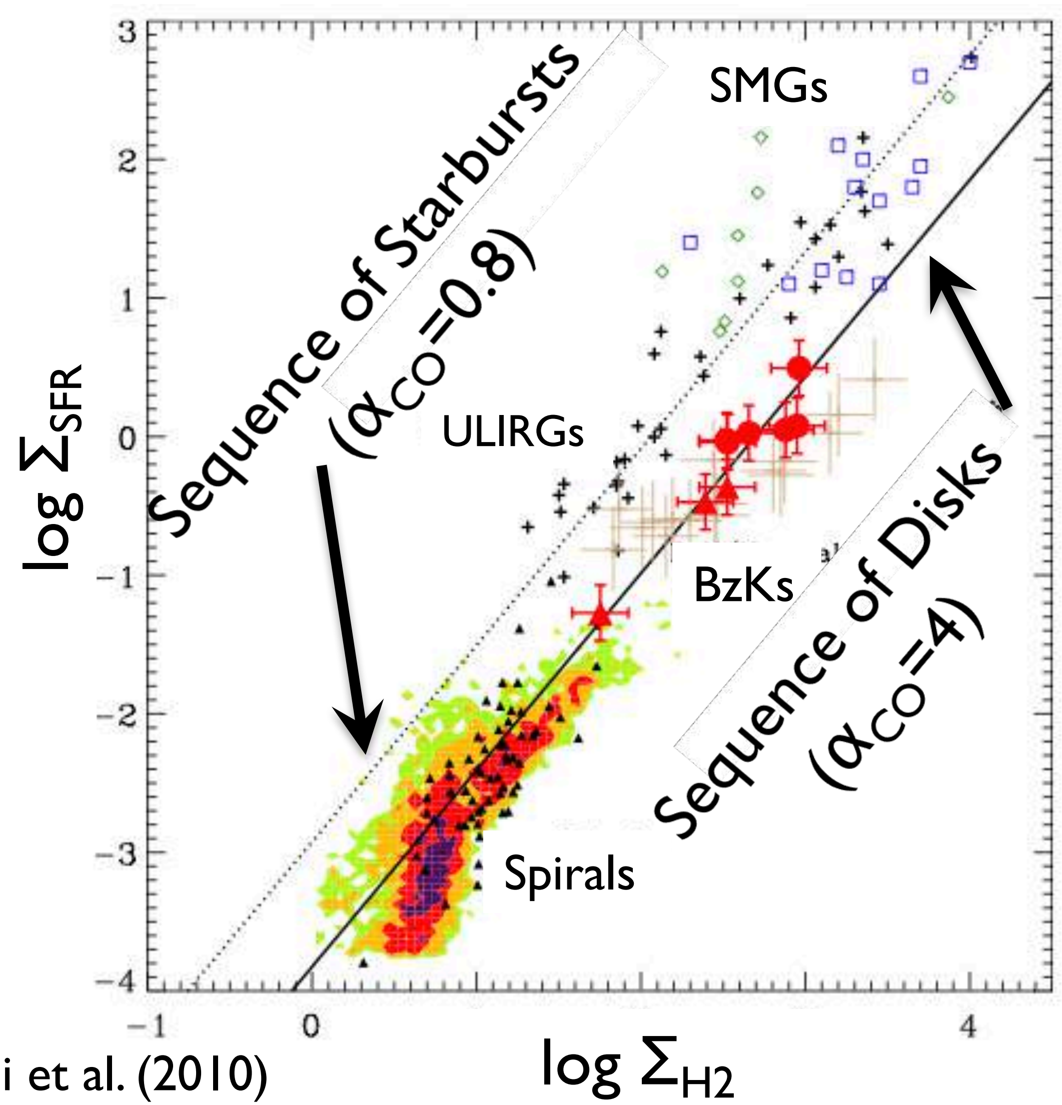
Merger?

Clumpy rotating disk?



Star formation law

Evidence for two sequences out to high-z – is it real?



Daddi et al. (2010)

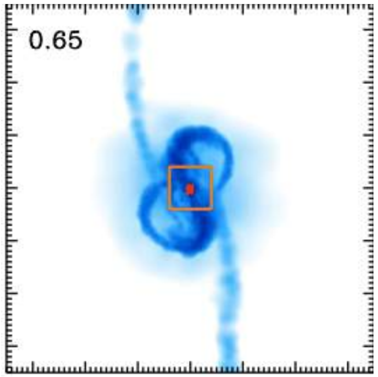
- A CO-to-H_2 conversion factor (α_{CO}) is assumed
- The size of the galaxies is also often assumed

Star formation at high-redshift
Recent results

- Submillimeter-selected
- Color-selected
- (Sub-)millimeter deep fields

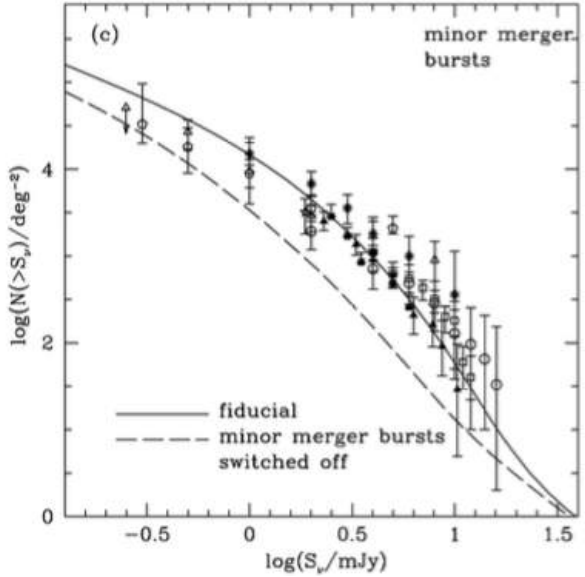
SMG formation challenges theorists

Major mergers



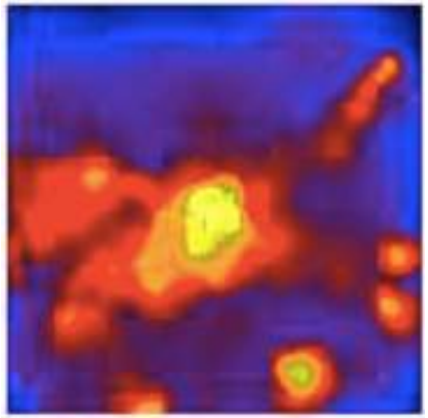
E.g., Narayanan+09,10a,b

Major+minor mergers



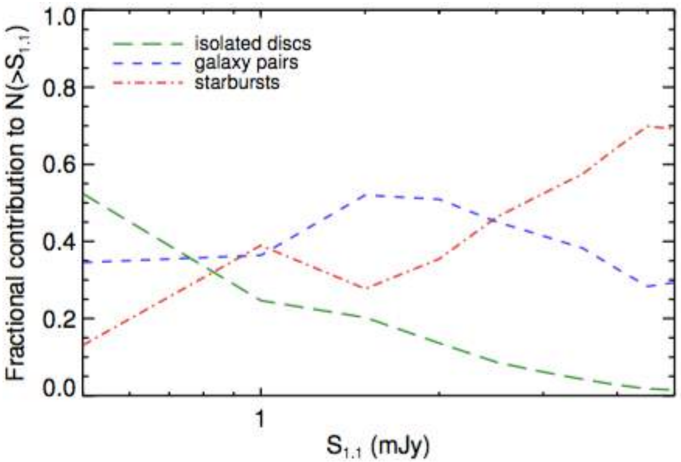
E.g., Baugh+05, Lacey+16 with modified IMF; c.f. Safarzadeh+17

Supersized ordinary galaxies



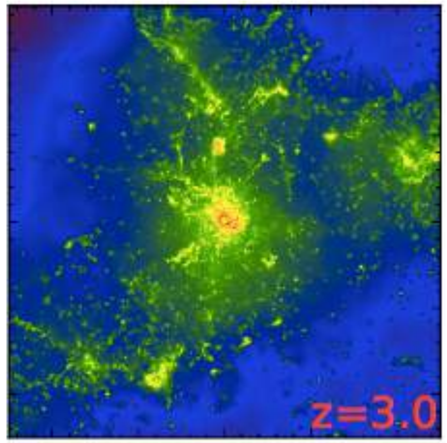
E.g., Dave+10

SBs+blends+disks



E.g., Hayward+11,12,13

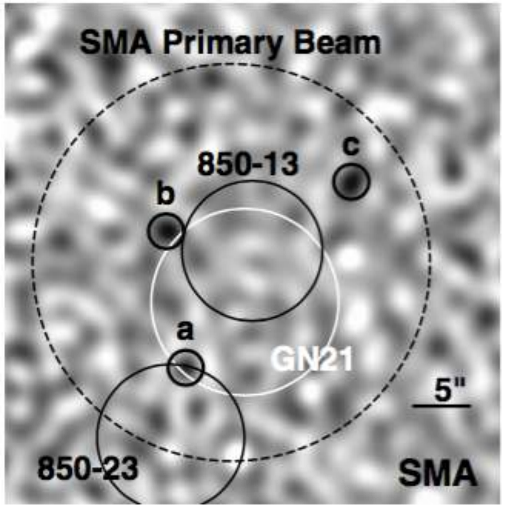
Early proto-clusters



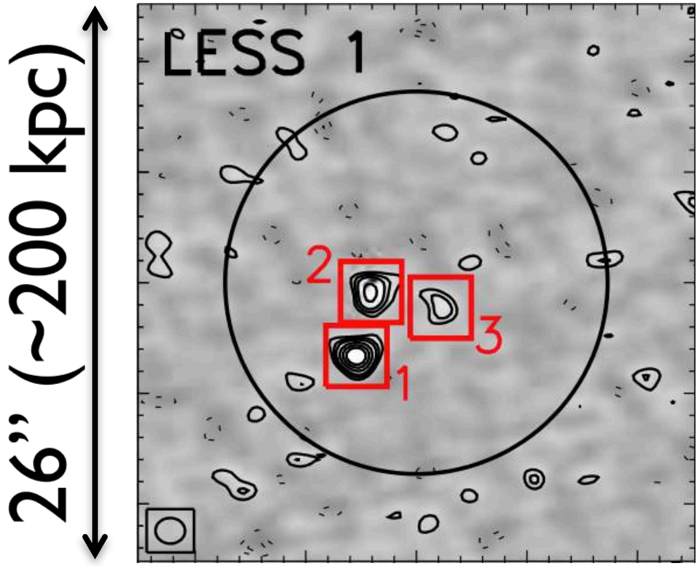
E.g., Narayanan+15

Many SMGs contain multiple galaxies

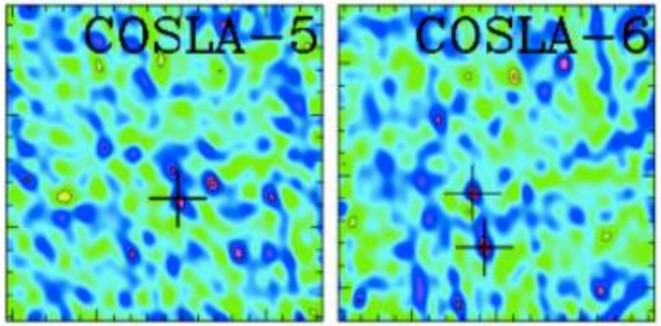
SMA Wang+11



ALMA ('ALESS') Hodge+13



PdBI

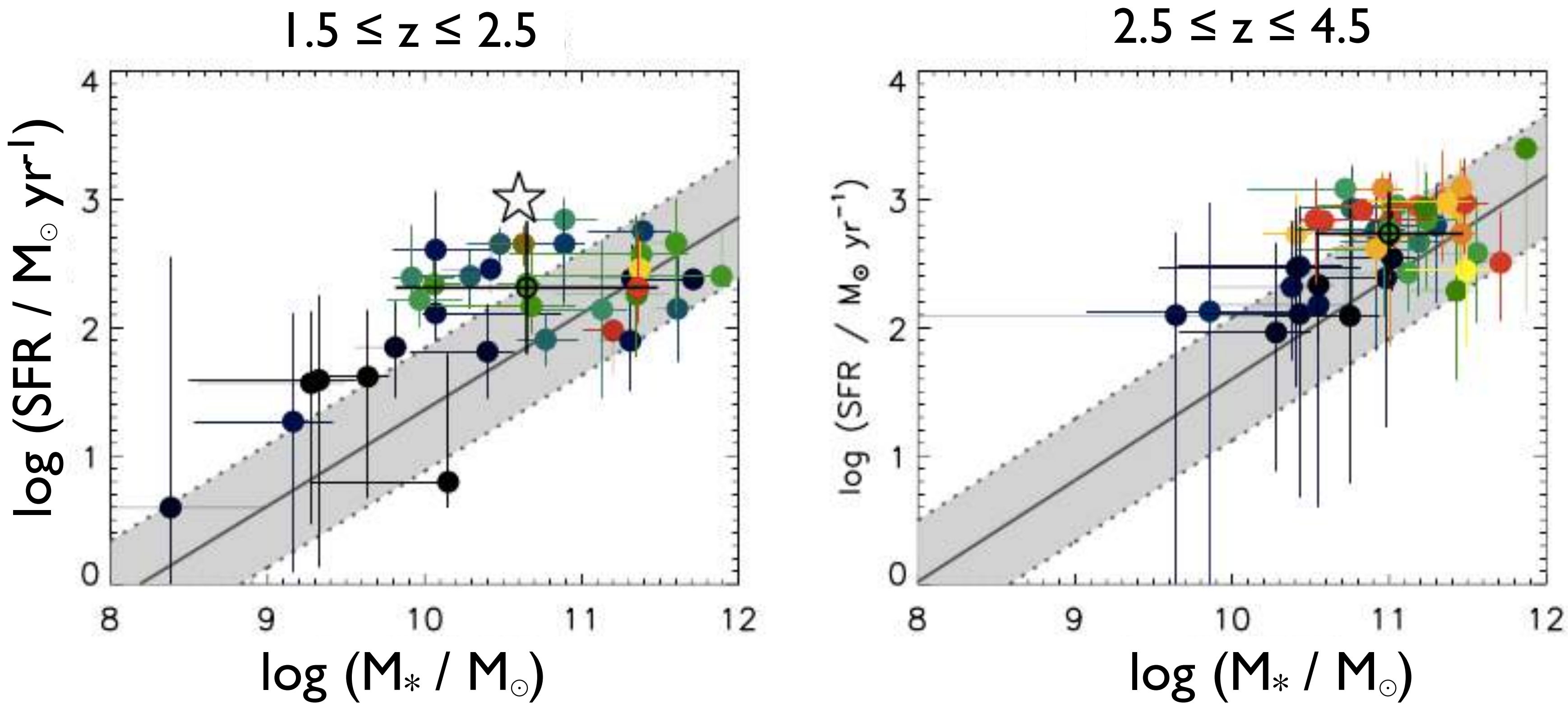


Smolcic+12

- A significant fraction (~30%) of single-dish submillimeter sources are multiples
- Precisely locating the submm emitters is key for getting redshifts (a prerequisite for studying physical properties!)

Many on galaxy main sequence

Da Cunha+15 (using ALMA ID's):

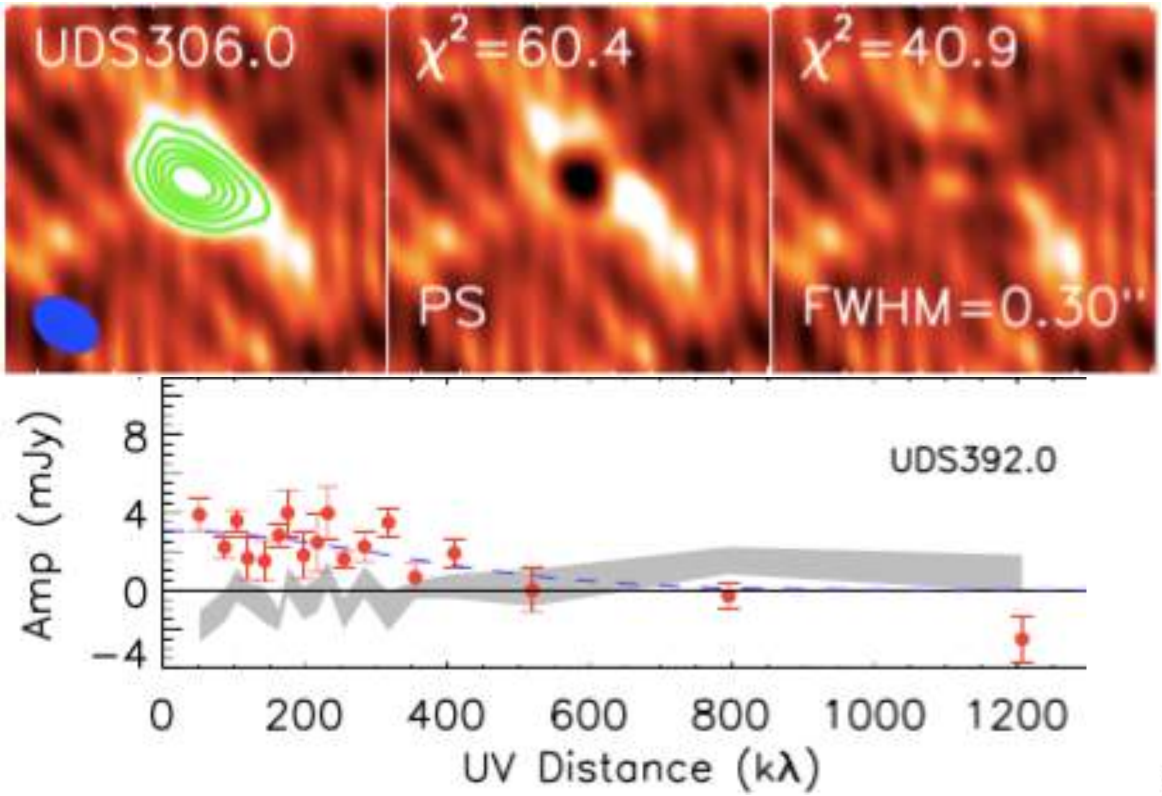


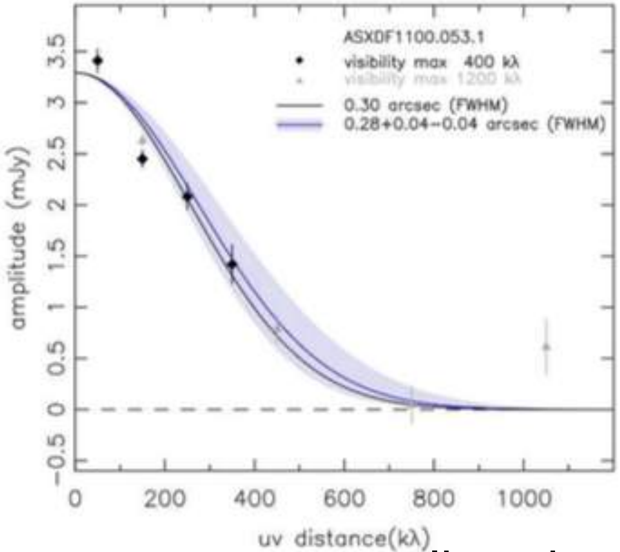
Fraction on MS increases with z

See also Michalowski+17; Koprowski+16

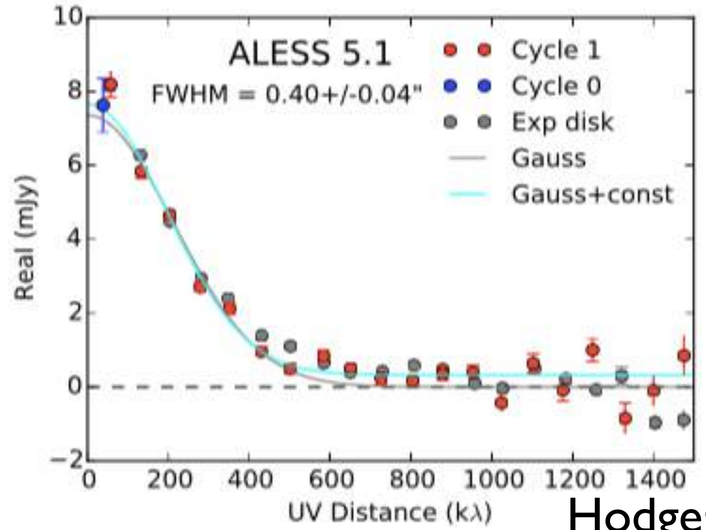
Dusty SF is compact

Simpson+15





Ikarashi+15



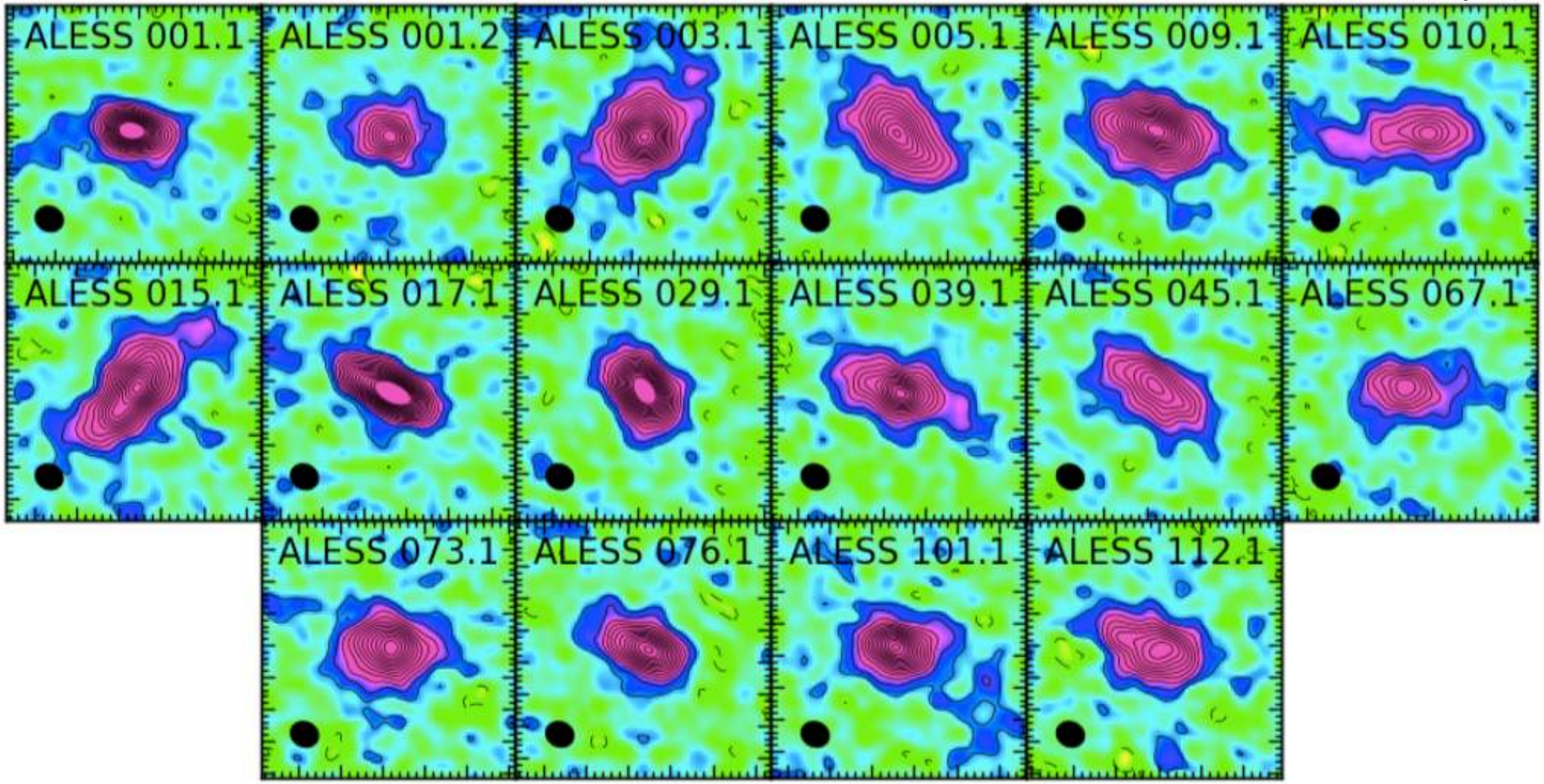
Hodge+16

- Typical R_{eff} ~ 0.24" (~1.8 kpc) at 870um
- Implies SFRSD ~ 100 $M_{\odot}$/yr/kpc^2

Dusty SF is disky

Hodge+16

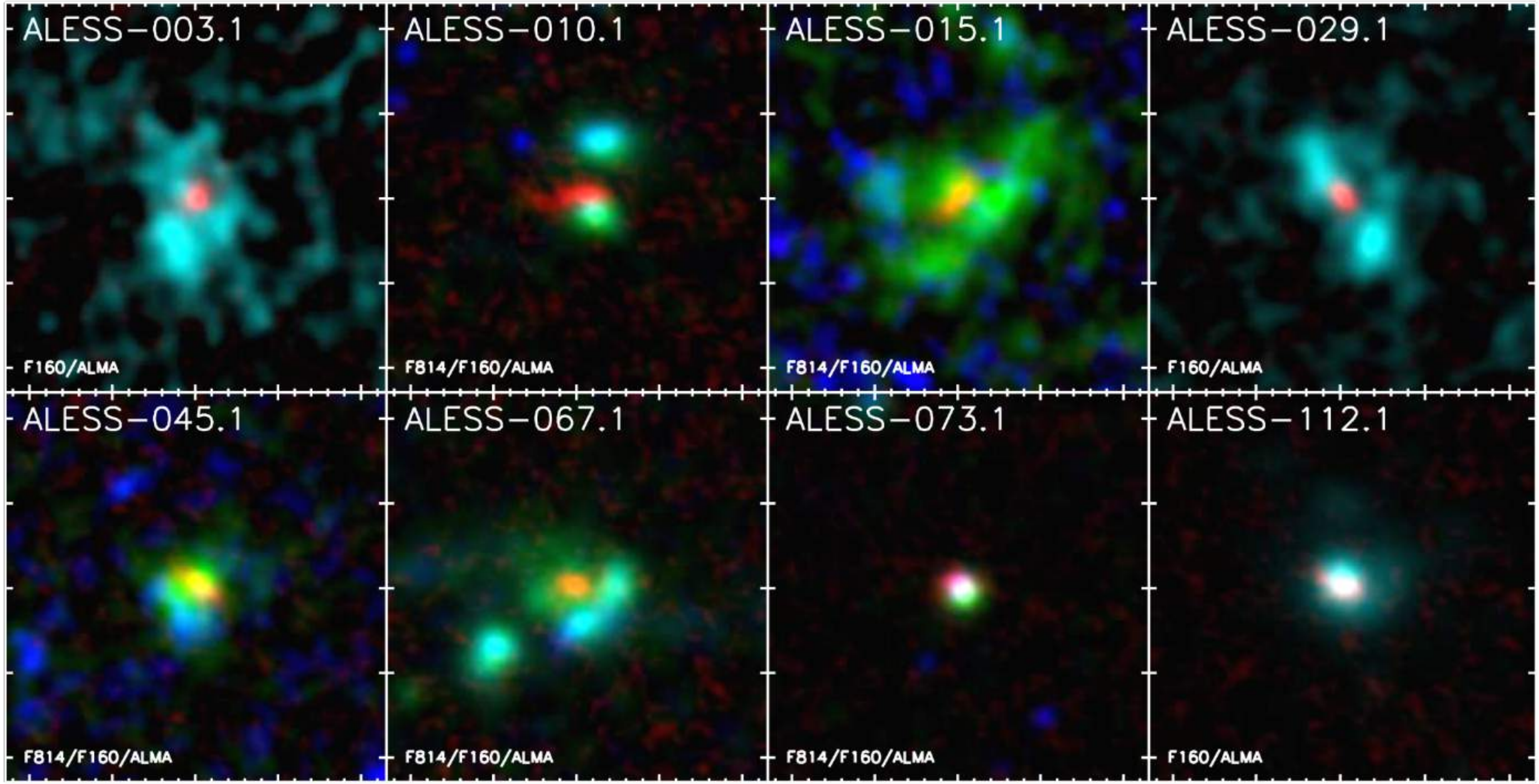
ALESS; resolution 0.16” (1.3 kpc)



Median Sersic index n = 0.9±0.2

Stark contrast with existing stellar populations

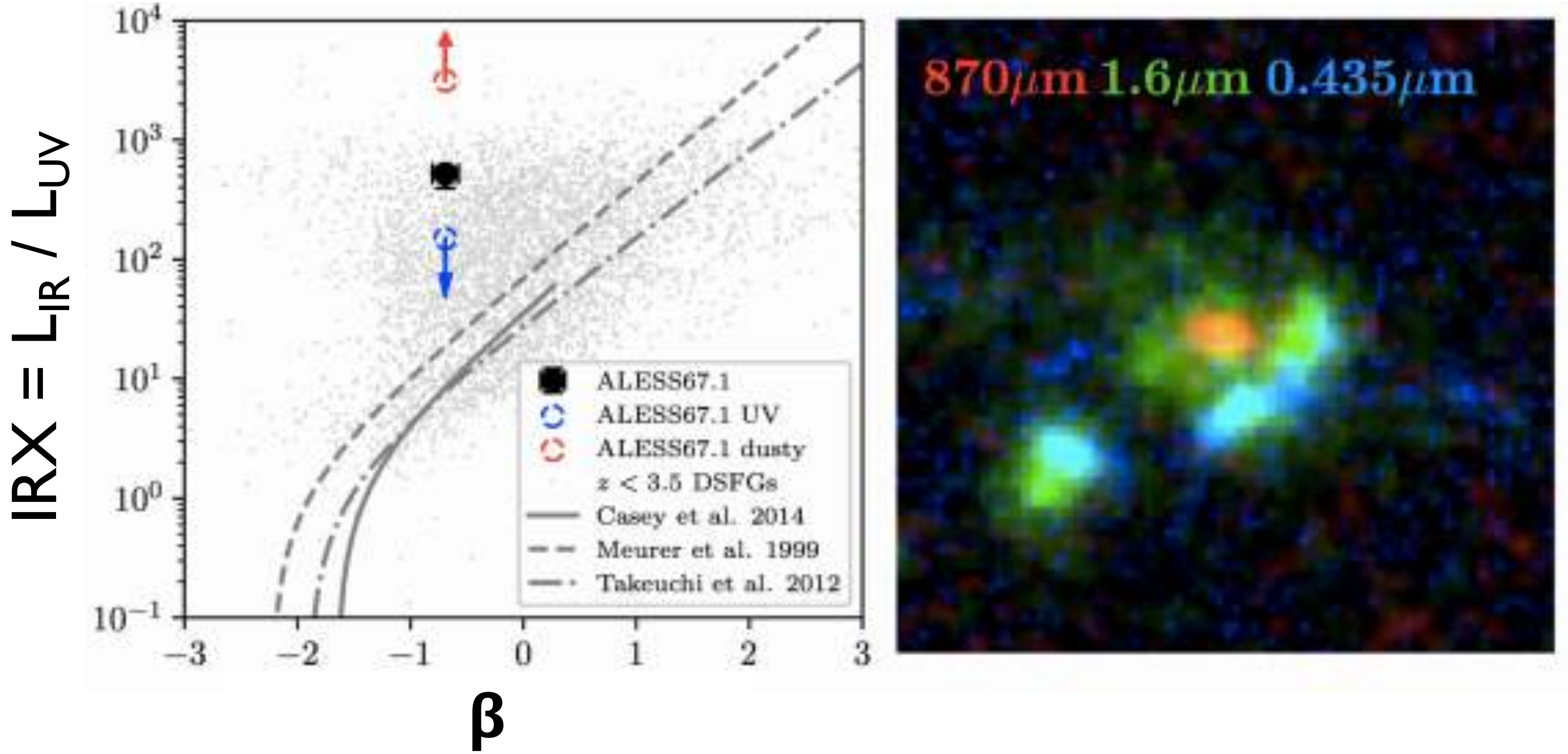
Hodge+16



May have implications for SED fitting routines assuming co-located dust

Stark contrast with existing stellar populations

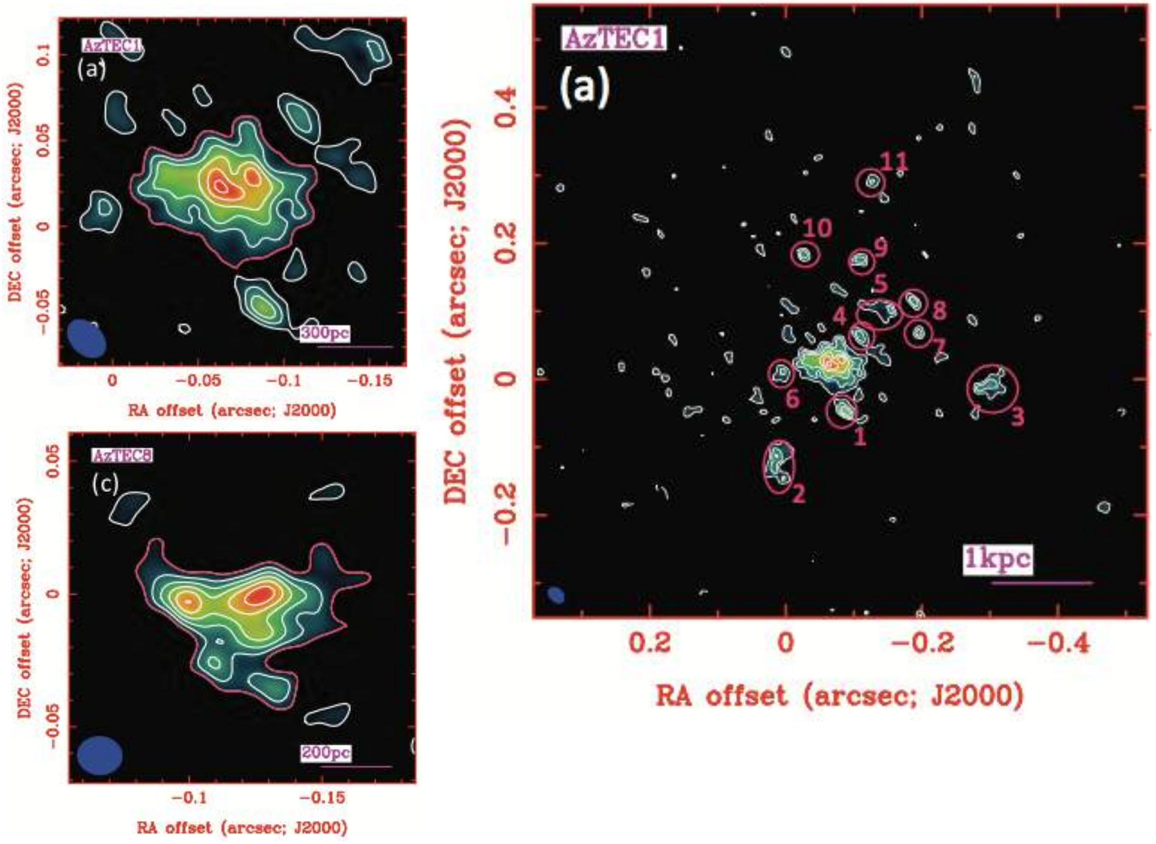
Chen, JH+17



Implies geometrical effects may be partly responsible for offset from local IRX-β relation

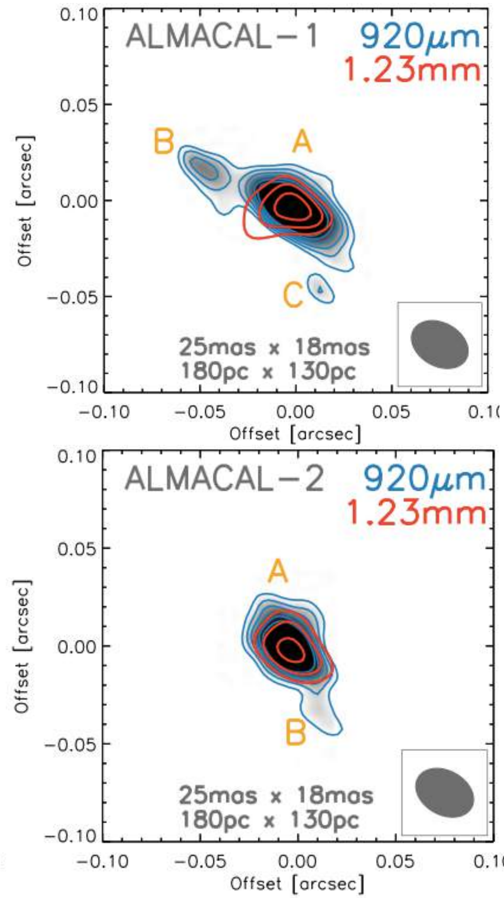
Is the dusty SF clumpy?

Resolution ~0.015”-0.05” (200 pc)



Iono+16

Resolution 0.025”
(150 pc)



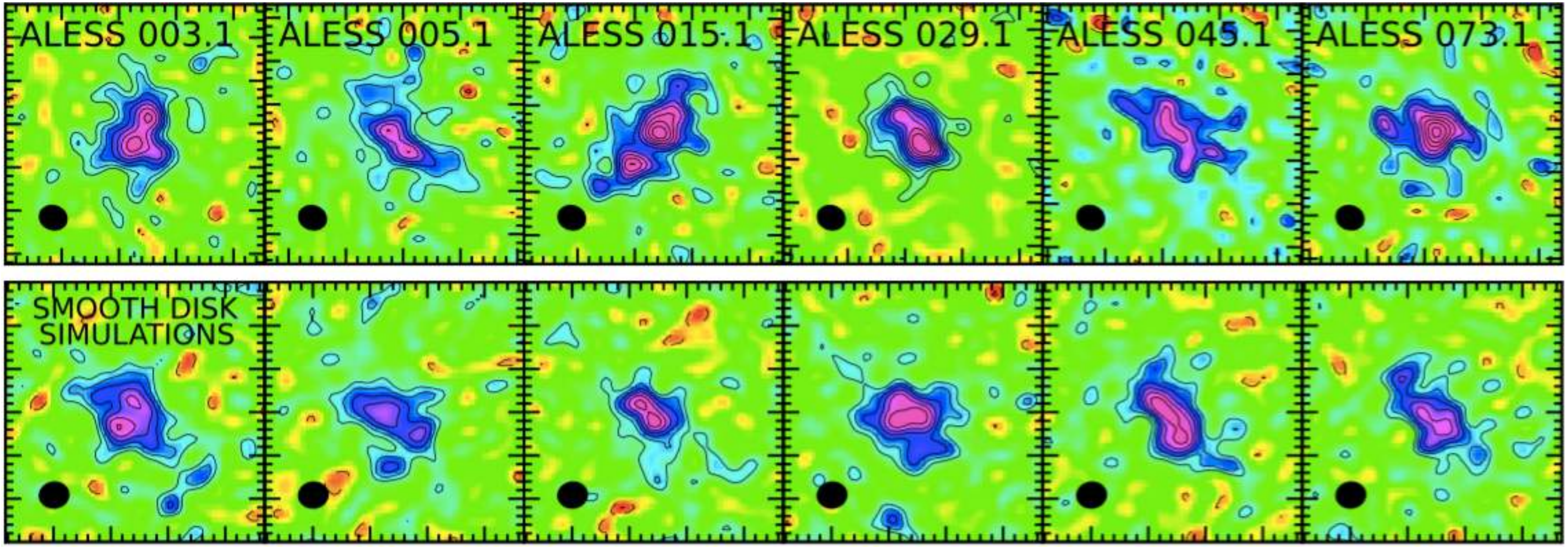
Oteo+17

Would imply extreme SFRSDs
of up to 6000 M yr^{-1} kpc^{-2}

Is the dusty SF clumpy?

Hodge+16

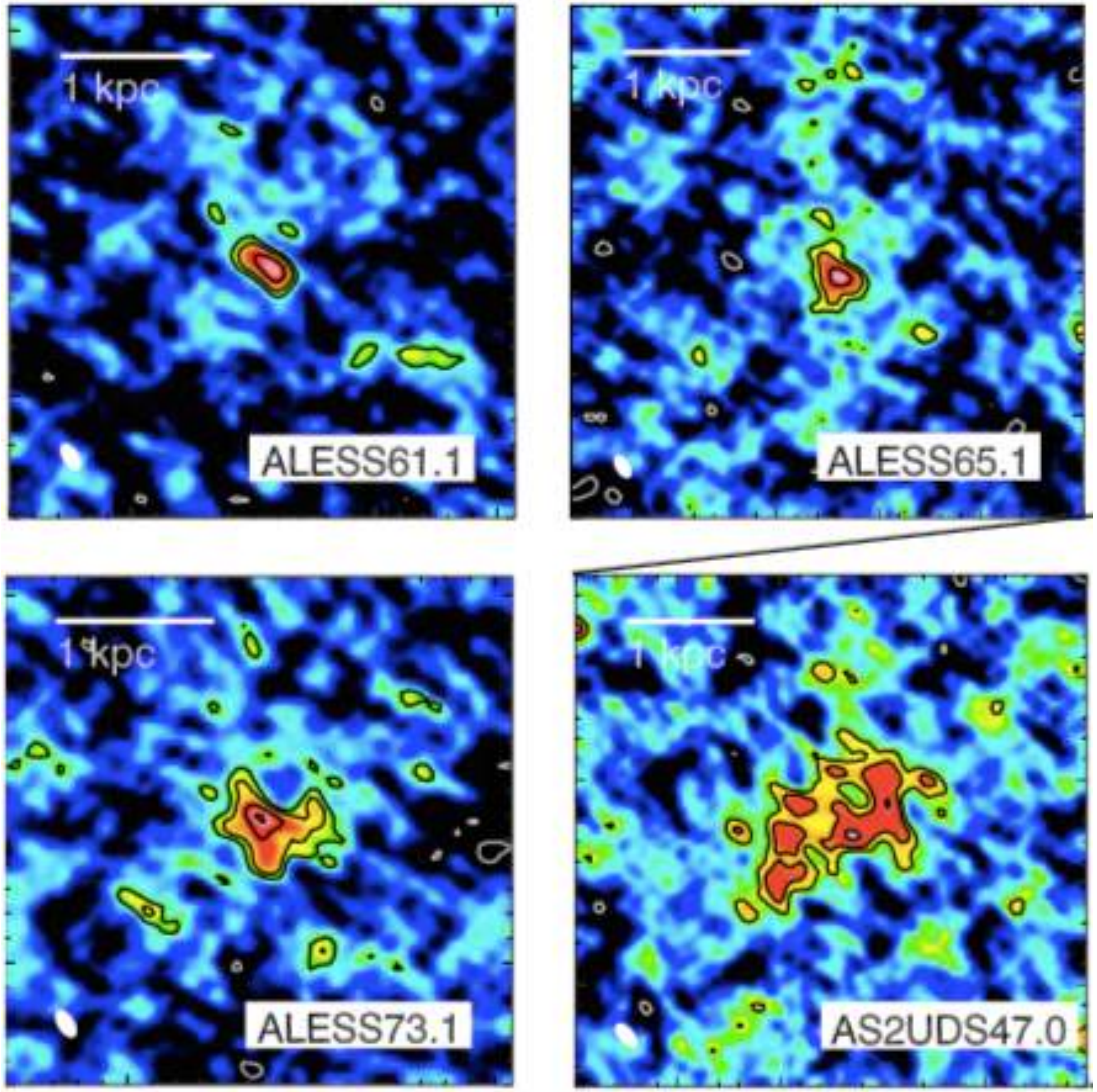
Resolution 0.12” (1.0 kpc)



Consistent with smooth exponential disks

Is the dusty SF clumpy?

Resolution 0.03" (200pc) Gullberg+17 (in prep)



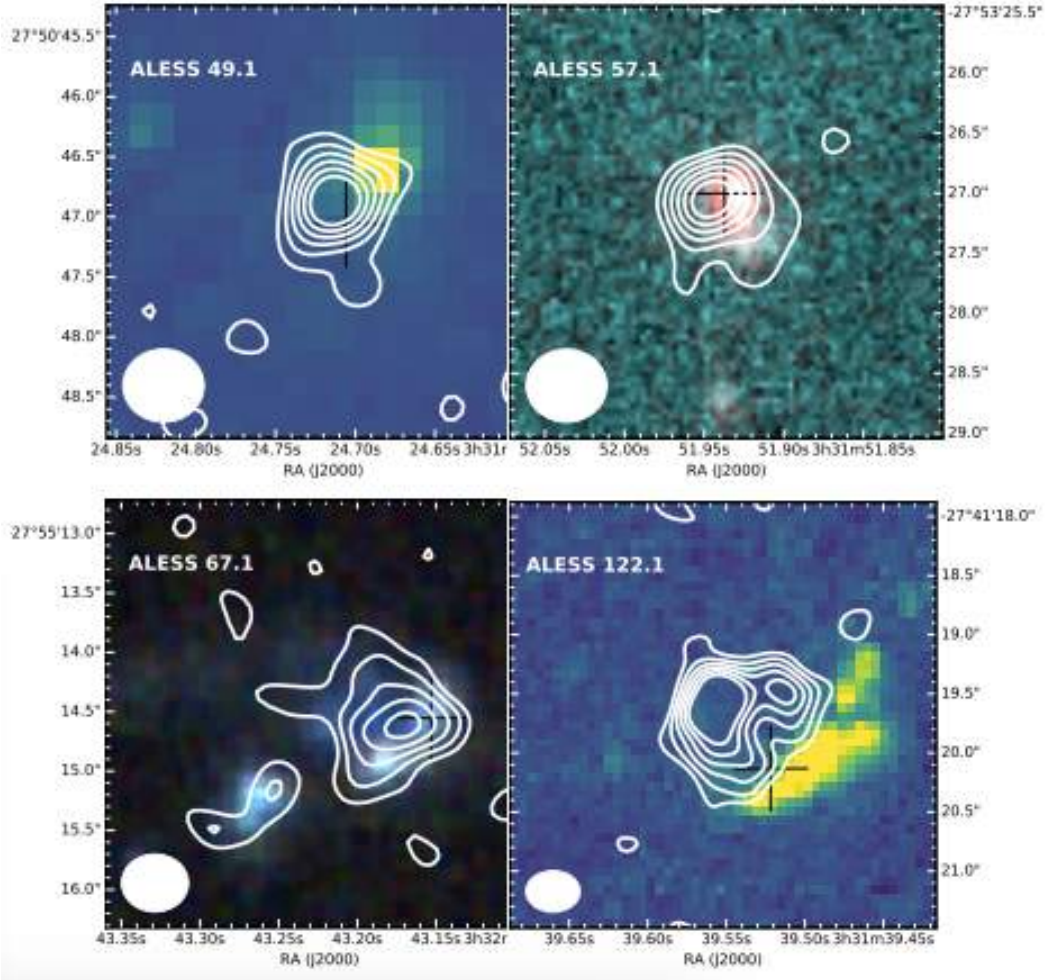
Also consistent with smooth exponential disks

Caution should be exercised when identifying clump candidates in interferometric data of such S/N

Cold gas extends further than dust

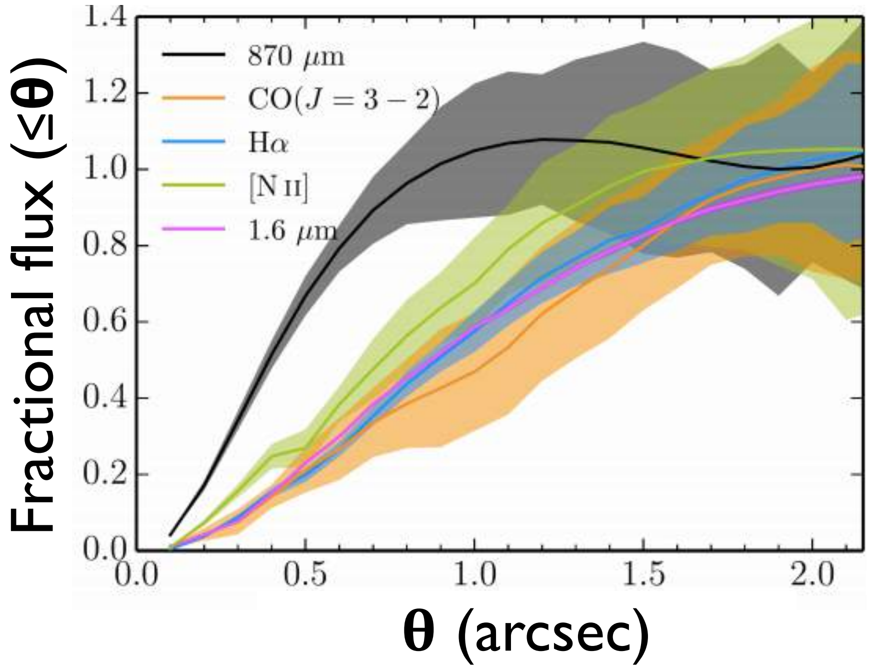
Calistro Rivera, JH+17 (in prep)

CO(3-2) contours on HST-WFC3/ACS



$R_{eff,CO}$ range from 2.5-7 kpc

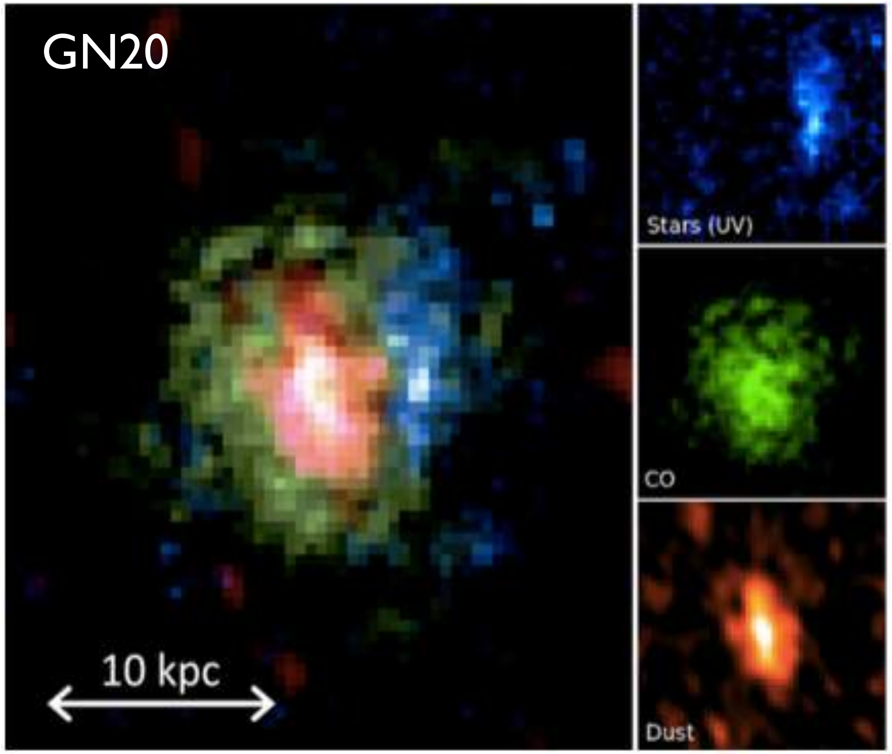
(And can show large offset to stars)

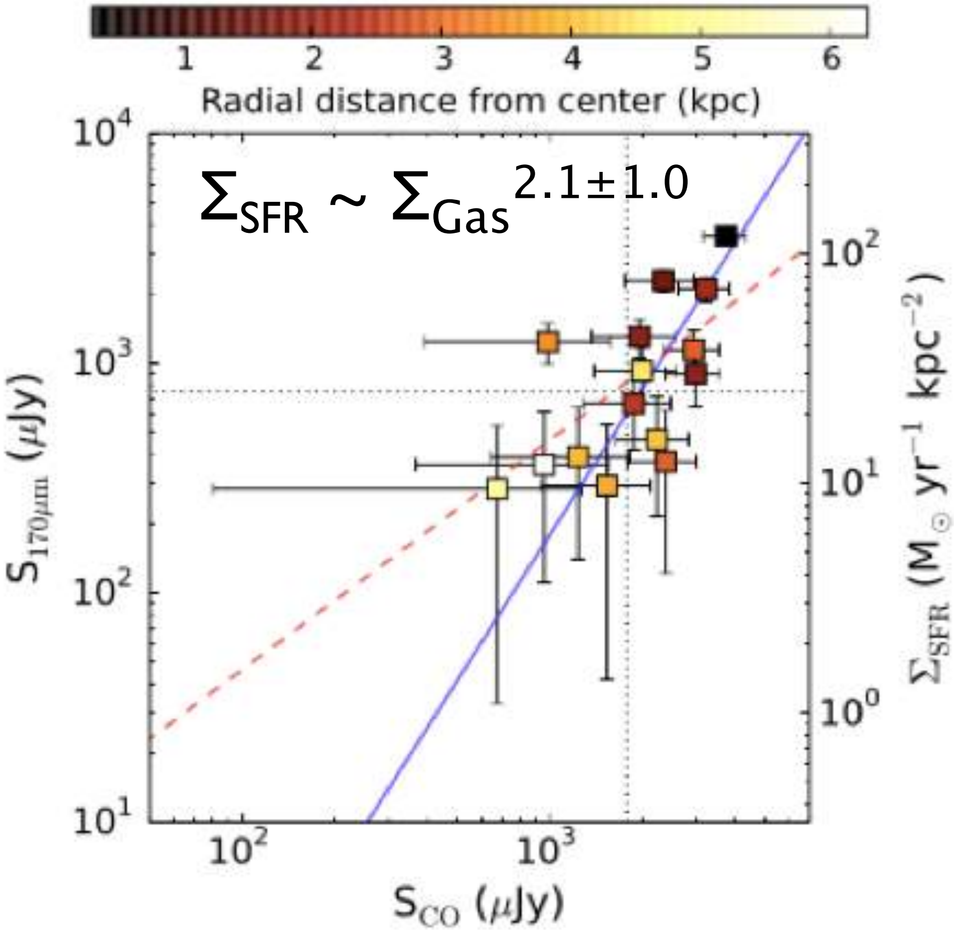


Chen, JH+17

Implies higher SFE in center

With
VLA/PdBI:
132 hours

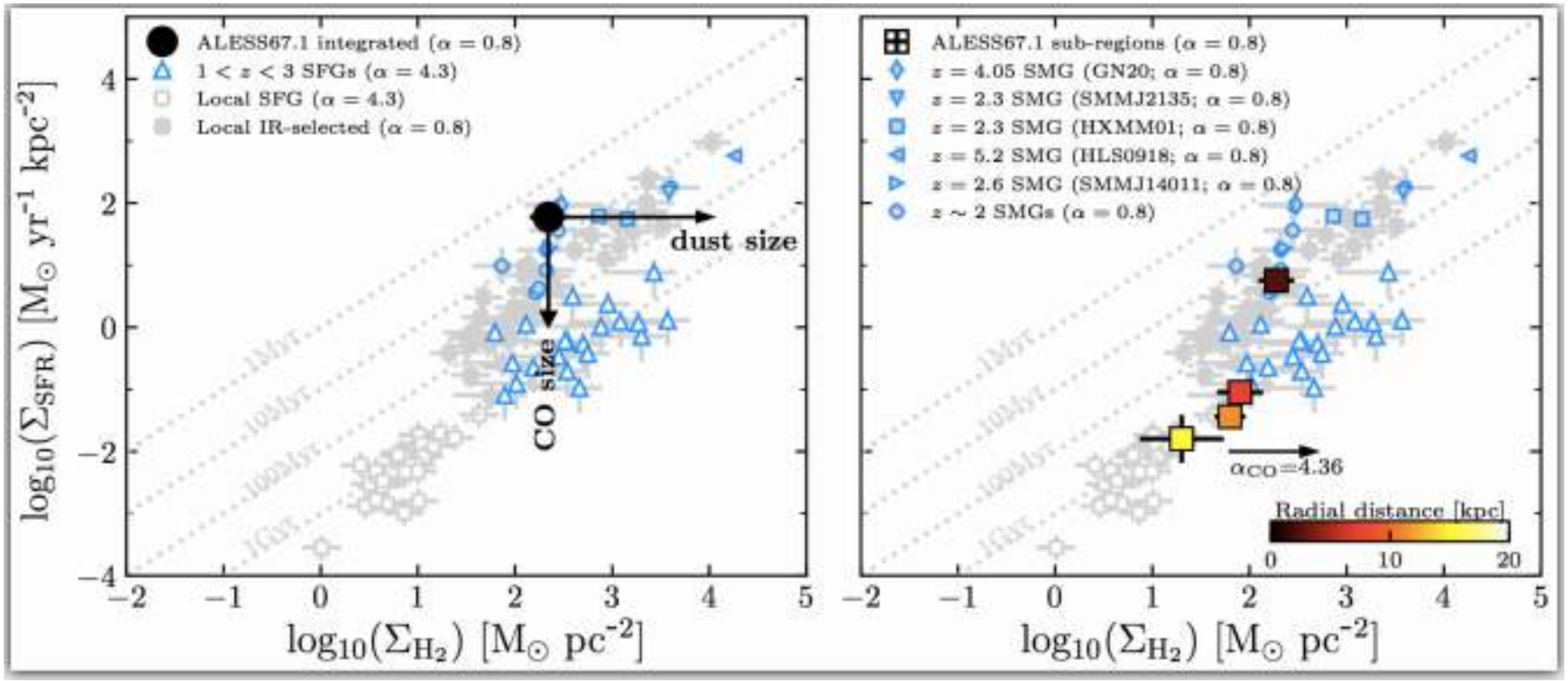




Hodge+15

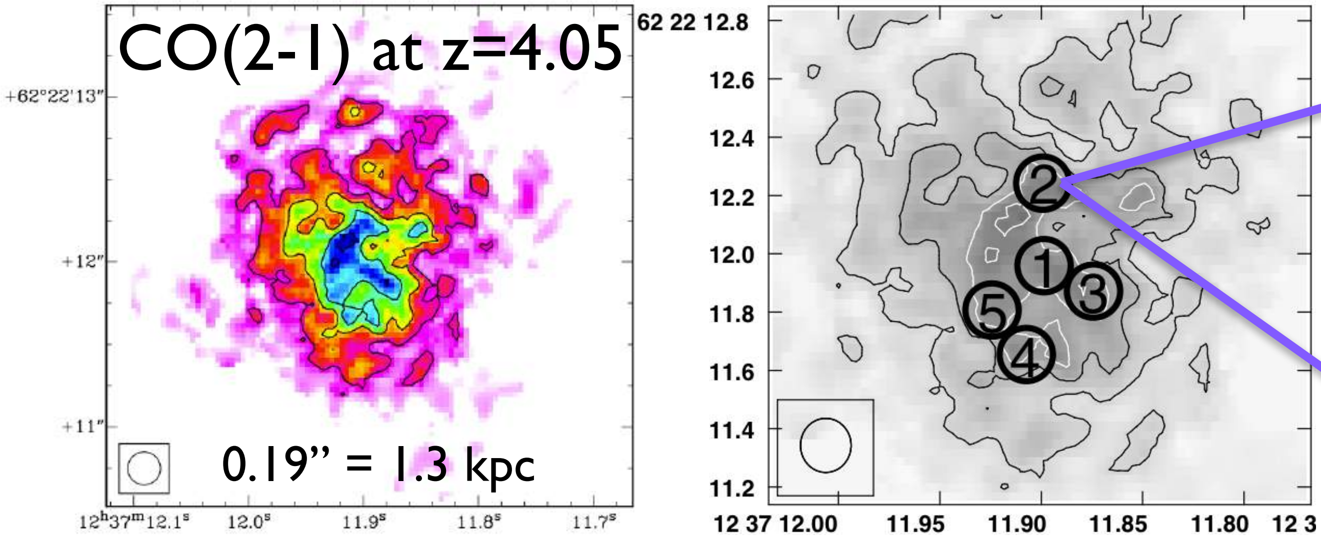
Implies higher SFE in center

With ALMA:
0.6 hours

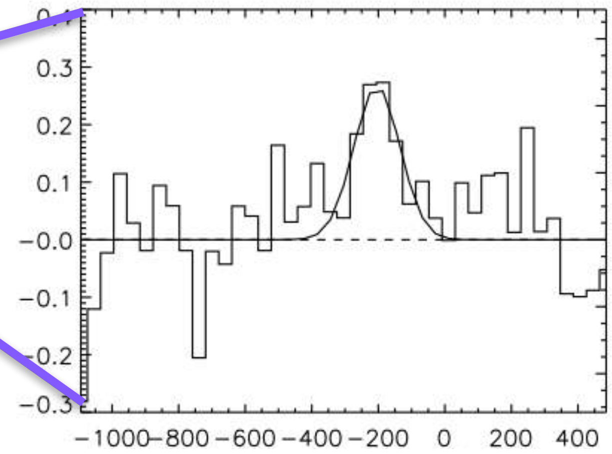


Chen, JH+17

Is the gas clumpy?

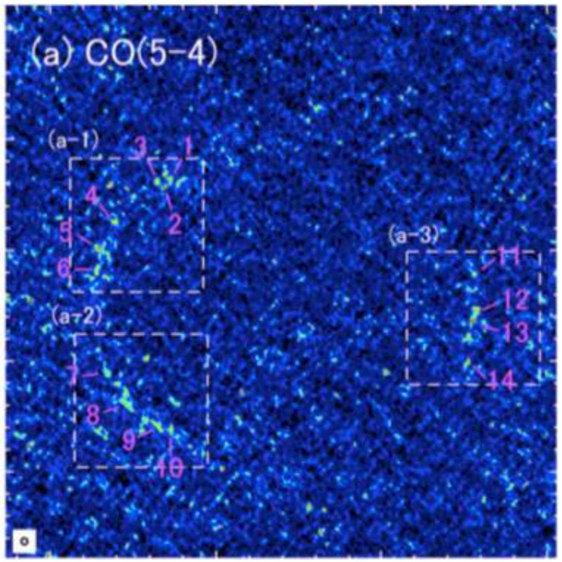


Hodge+12,13c,15

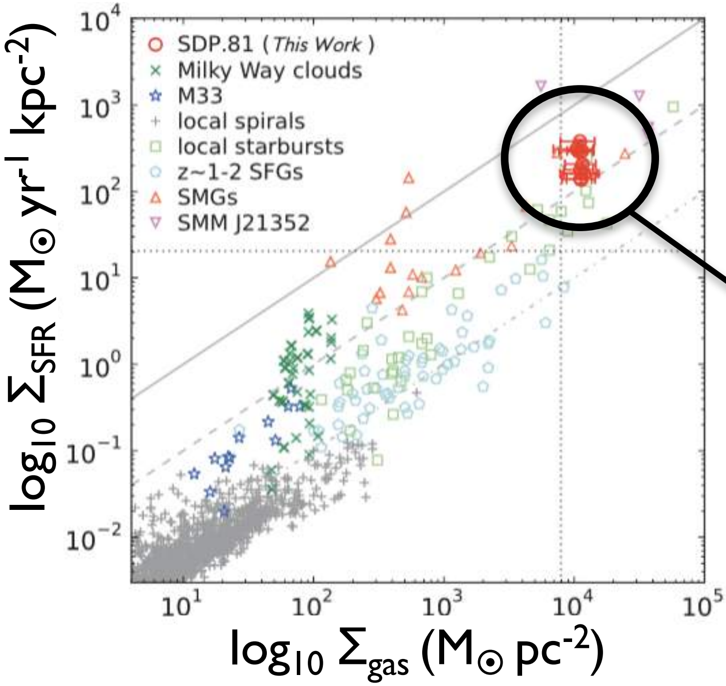


Clump properties:

- T_B = 16-32 K ~ T_{dust}
- Size ~ 1 kpc
- Mass ~ 10^9 $M_\odot$
- Densities ~ 100 cm^{-3}



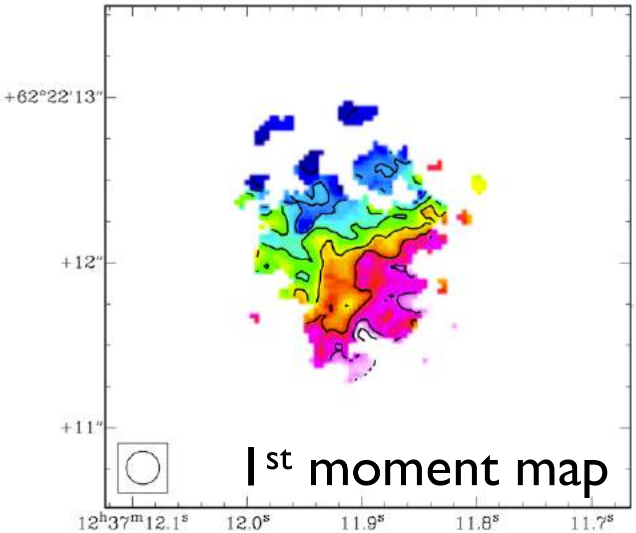
Hatsukade+15

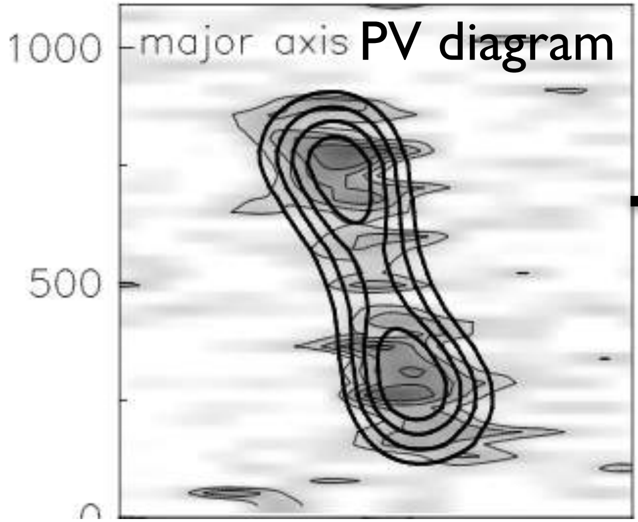


Fall on SB sequence… with SB α_{CO}!

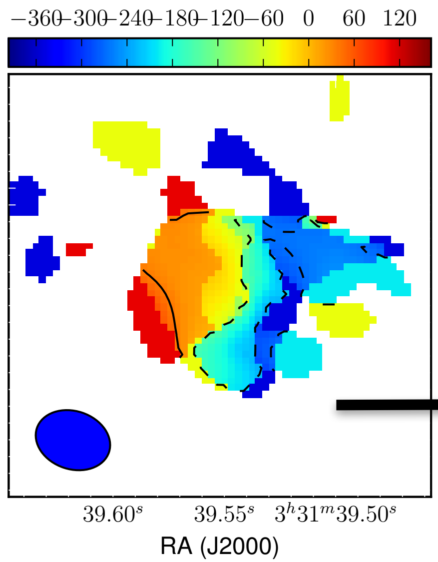
Dynamically constraining α_{CO}

Hodge+12,13c,15

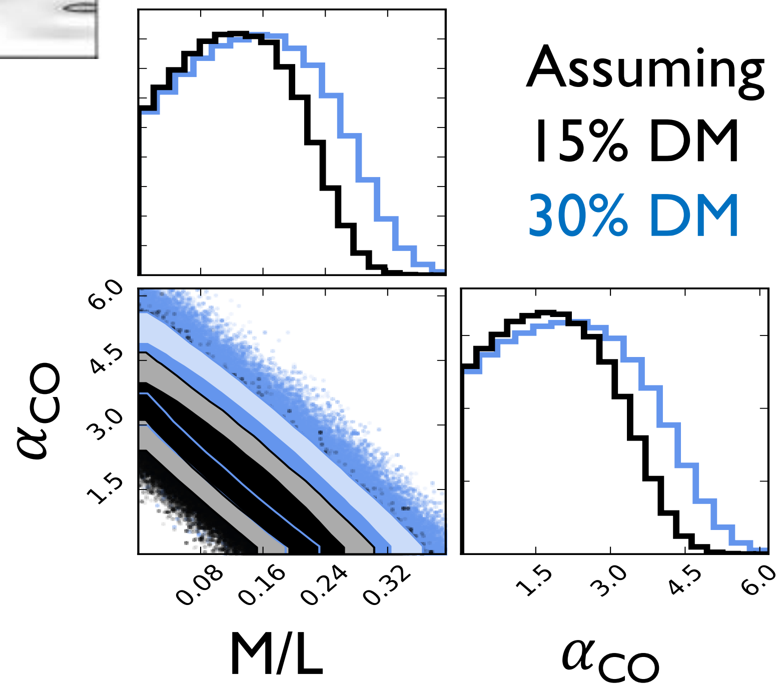




α_{CO} = 1.1 ± 0.6 (K km s^{-1} pc^2)$^{-1}$



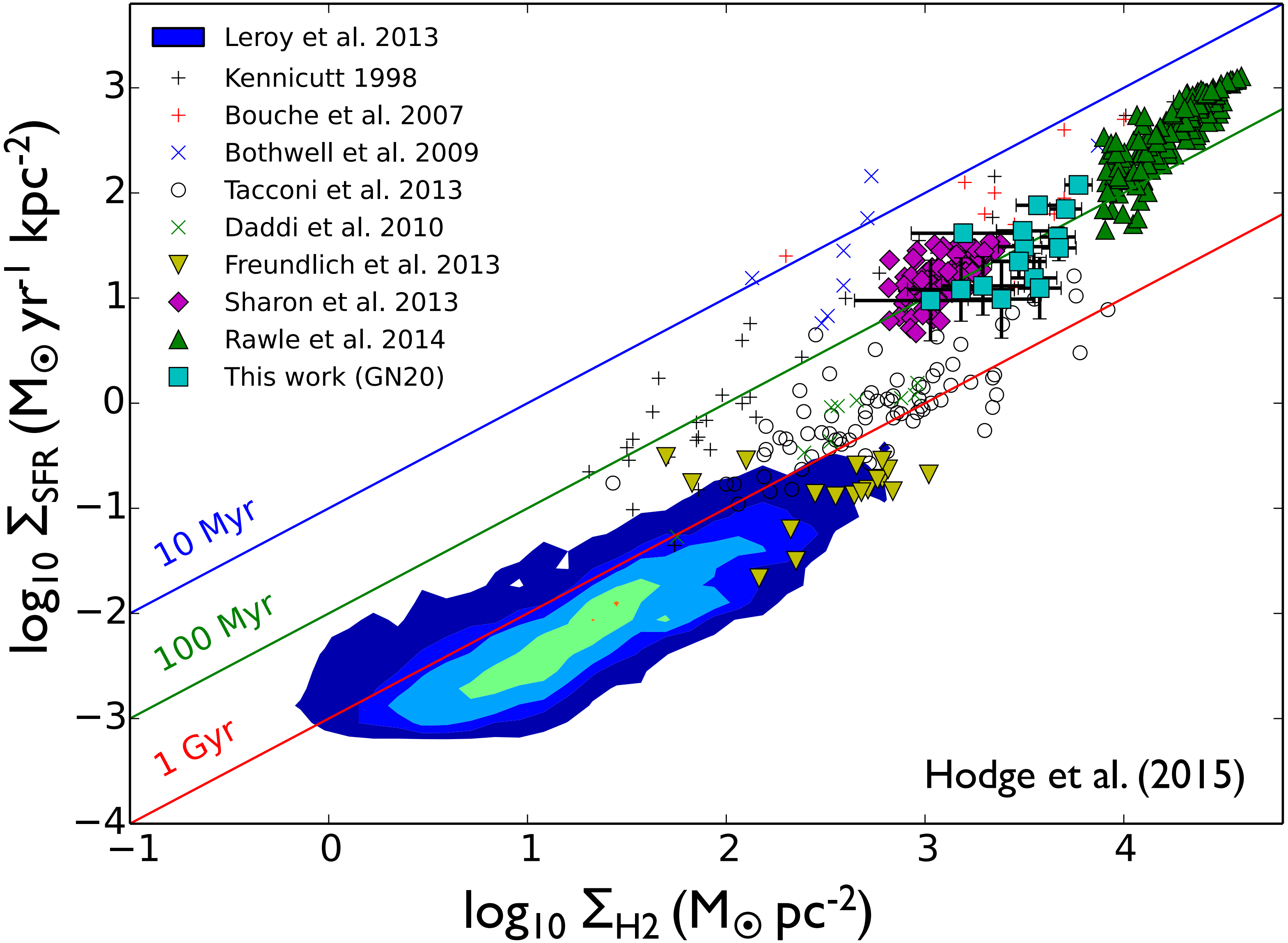
α_{CO} = 2.7 ± 0.9 (K km s^{-1} pc^2)$^{-1}$



Assuming
15% DM
30% DM

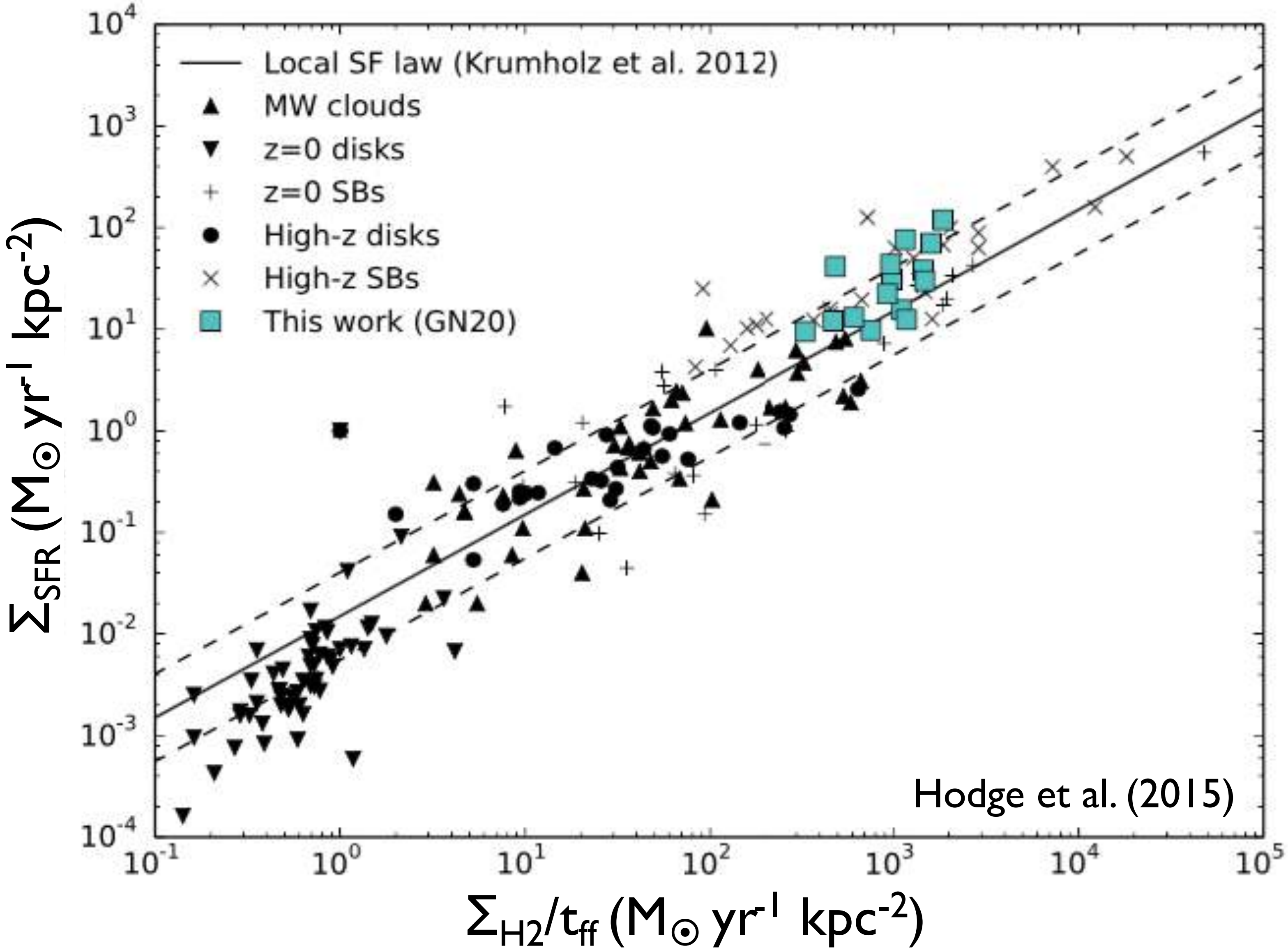
Calistro Rivera, JH+17 (in prep)

The resolved star formation law



➔ High-z SMGs have high SF efficiencies on small scales

A universal star formation law?



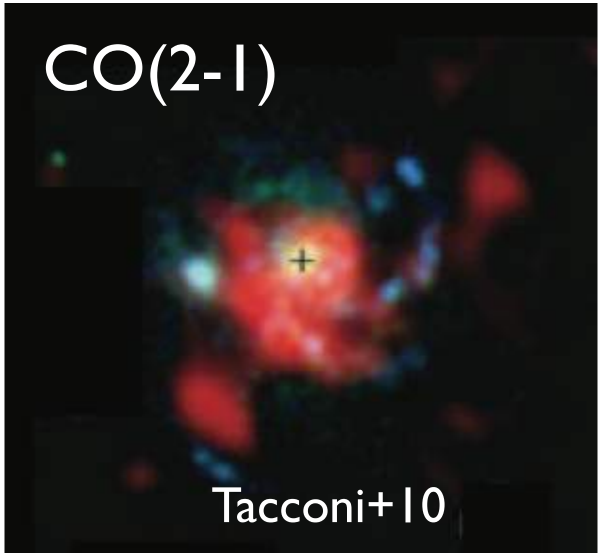
➔ Consistent with fixed SFE per t_{ff} of ϵ_{ff}=0.015

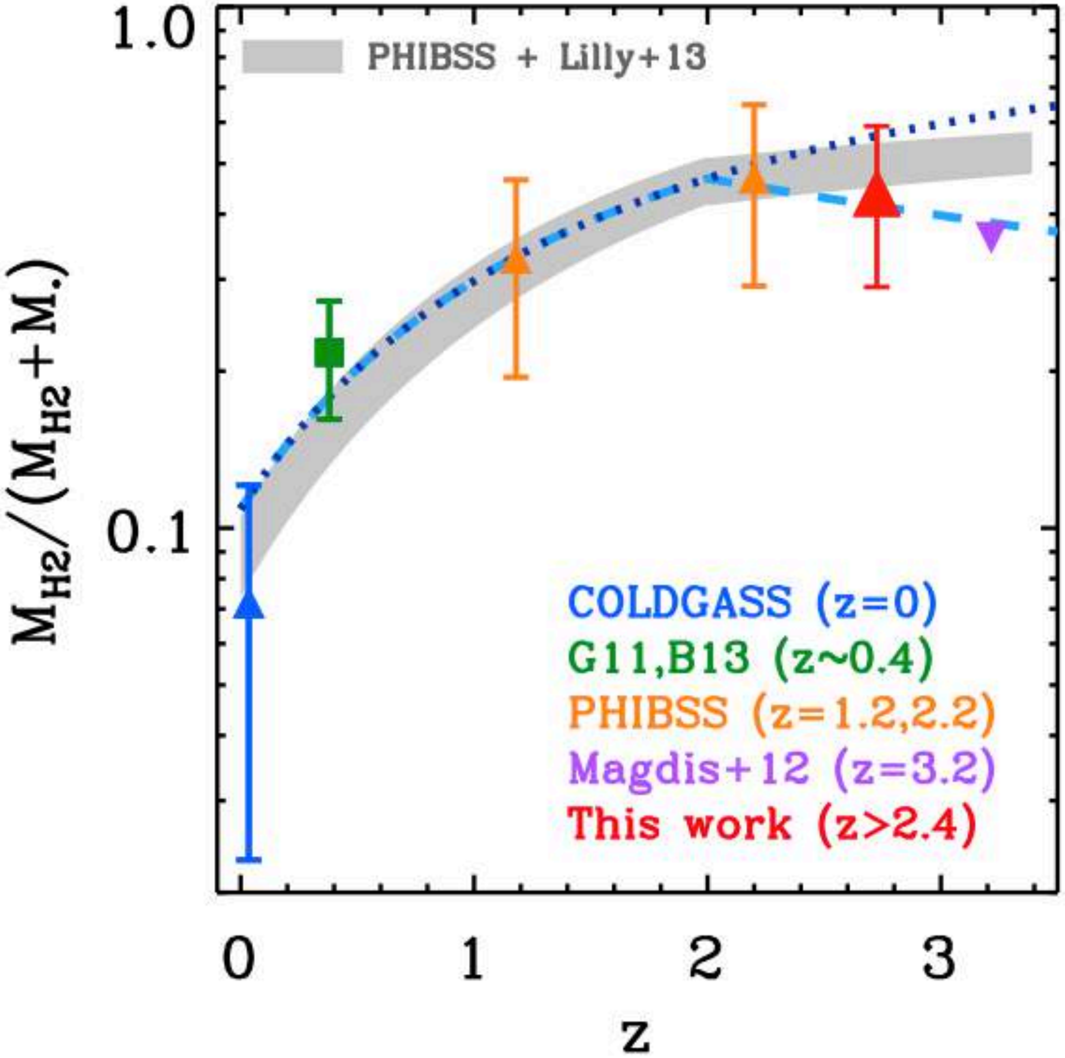
Star formation at high-redshift

Recent results

- Submillimeter-selected
- Color-selected
- (Sub-)millimeter deep fields

Evolving cold gas fraction

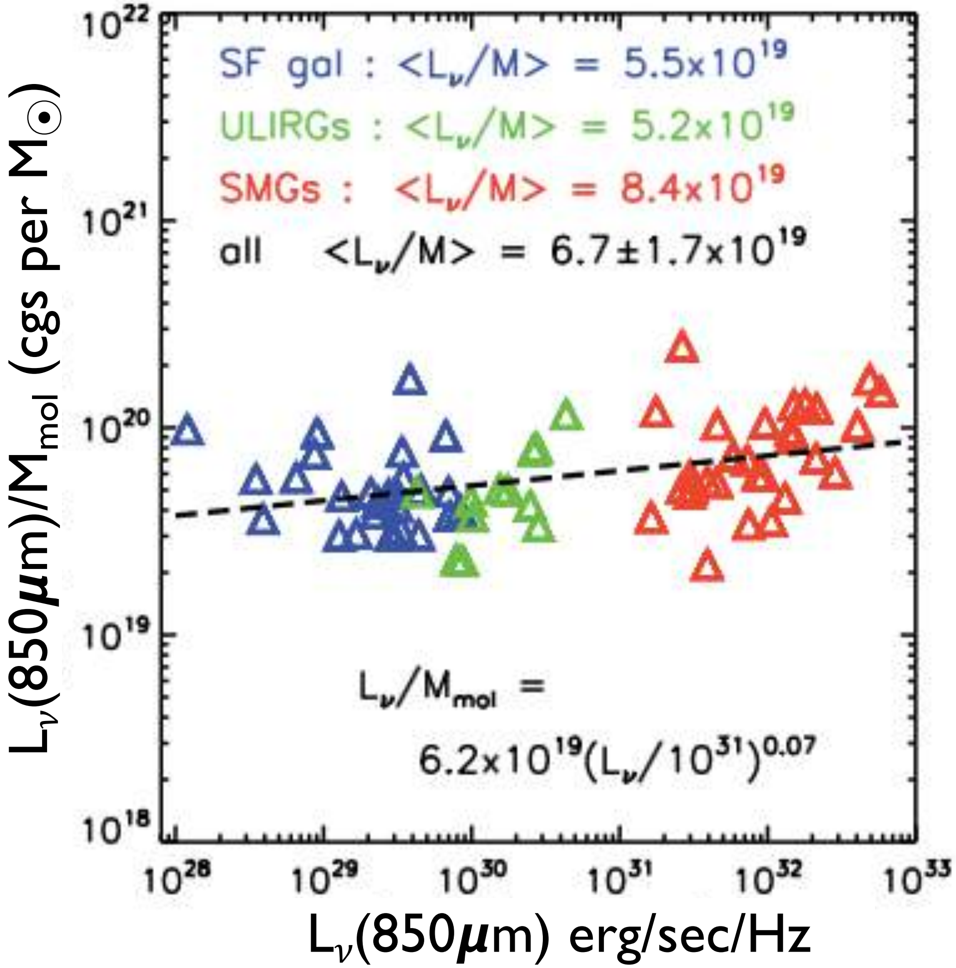




Saintonge+13
See also Magdis+12, Tacconi+13, etc

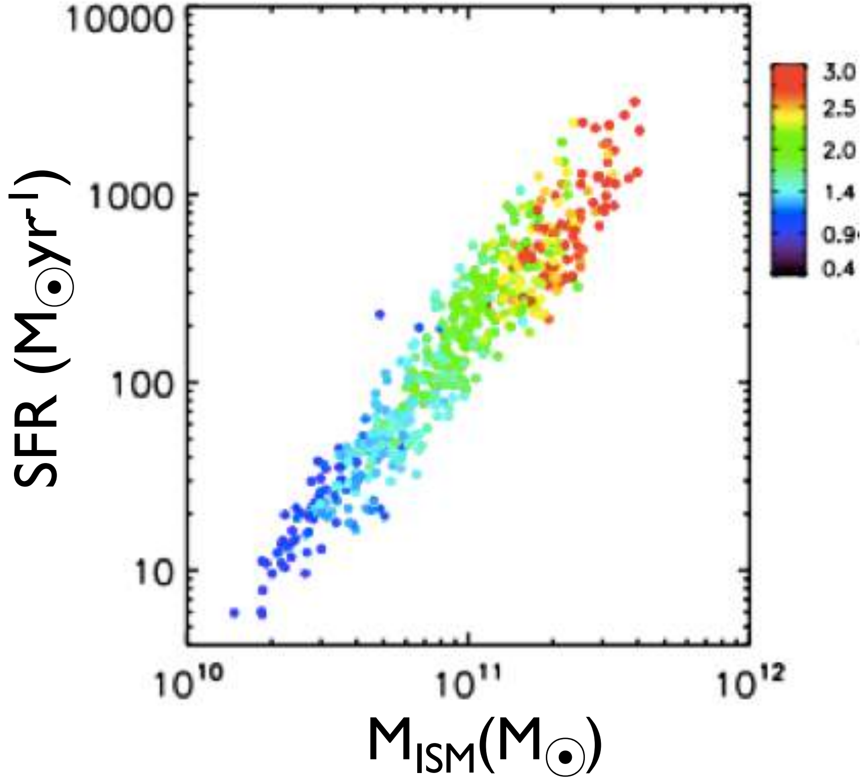
SFR/ISM content dependencies

Scoville+16



Ratio close to constant, implying dust emission probes ISM content

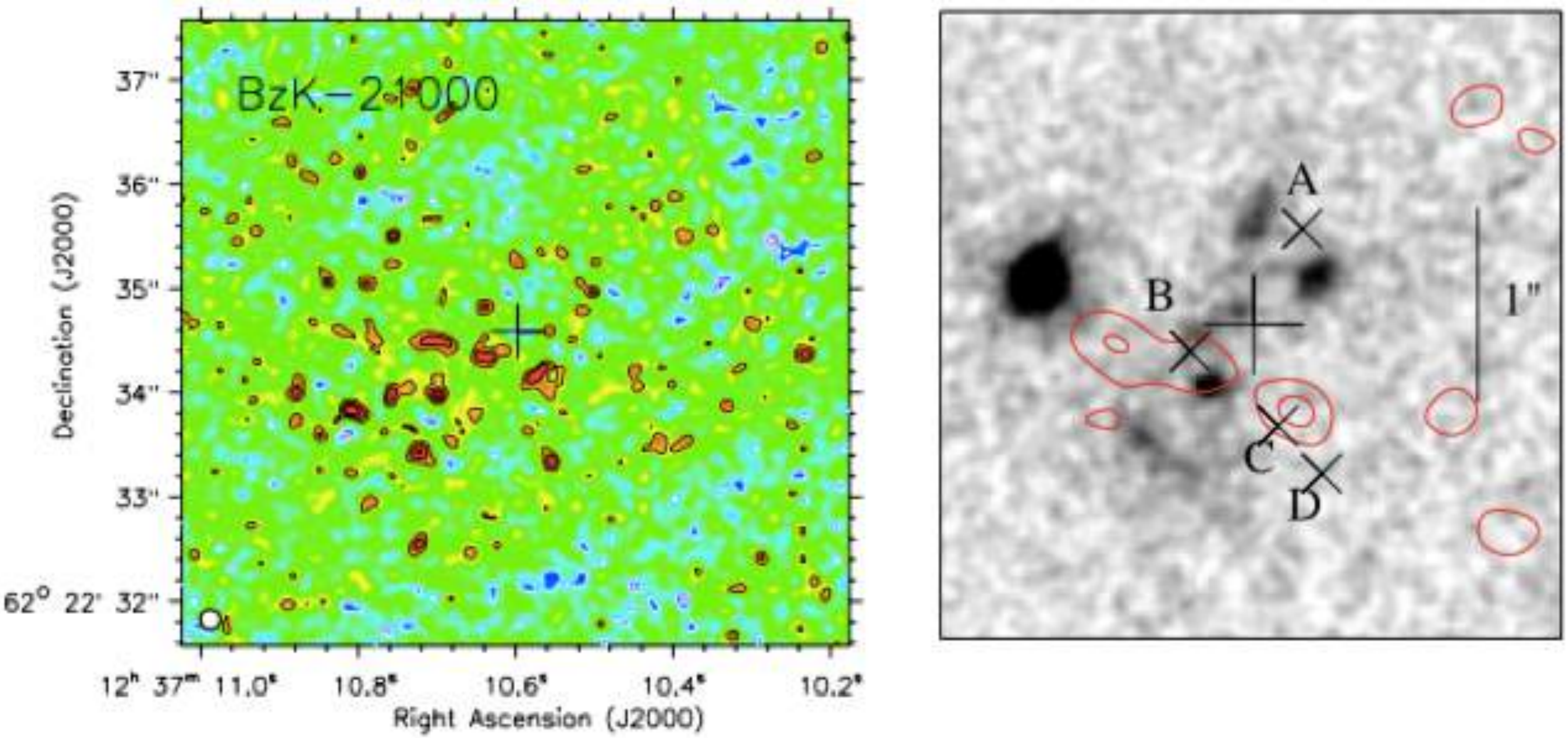
Scoville+17



$$\mathrm{SFR} = 0.31 \pm 0.01\ \mathrm{M_\odot\ yr^{-1}} \times \left(\frac{\mathrm{M_{ISM}}}{10^9 \mathrm{M_\odot}}\right) \times (1+z)^{1.05\pm0.05} \times (\mathrm{sSFR}/\mathrm{sSFR_{MS}})^{0.70\pm0.02} \times \left(\frac{\mathrm{M_*}}{10^{10}\mathrm{M_\odot}}\right)^{0.01\pm0.01}.$$

Resolving CO in 'normal' galaxies

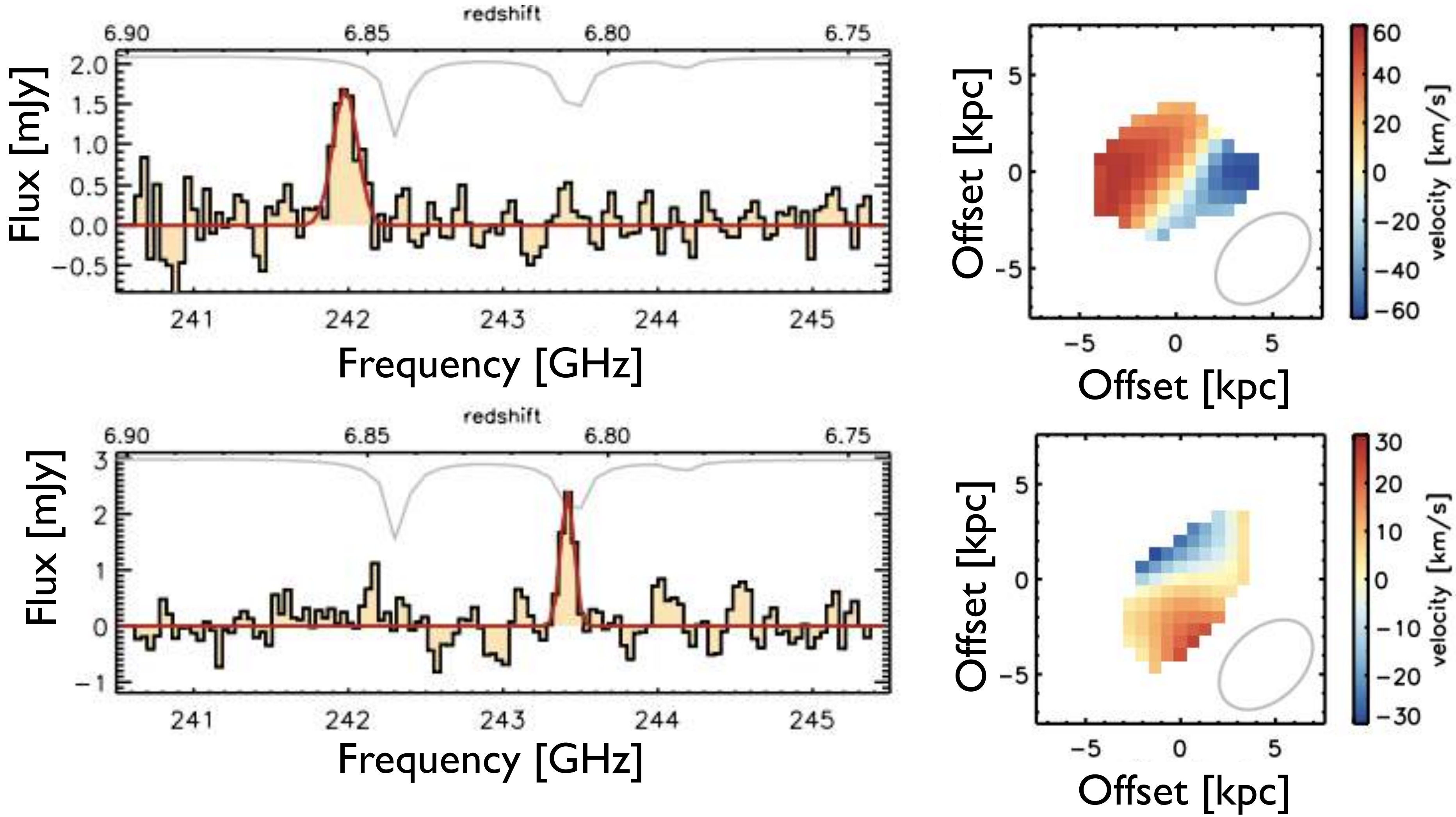
Aravena+14



Even with ALMA, this requires a substantial time investment

Resolved [CII] at z=7

Smit+17

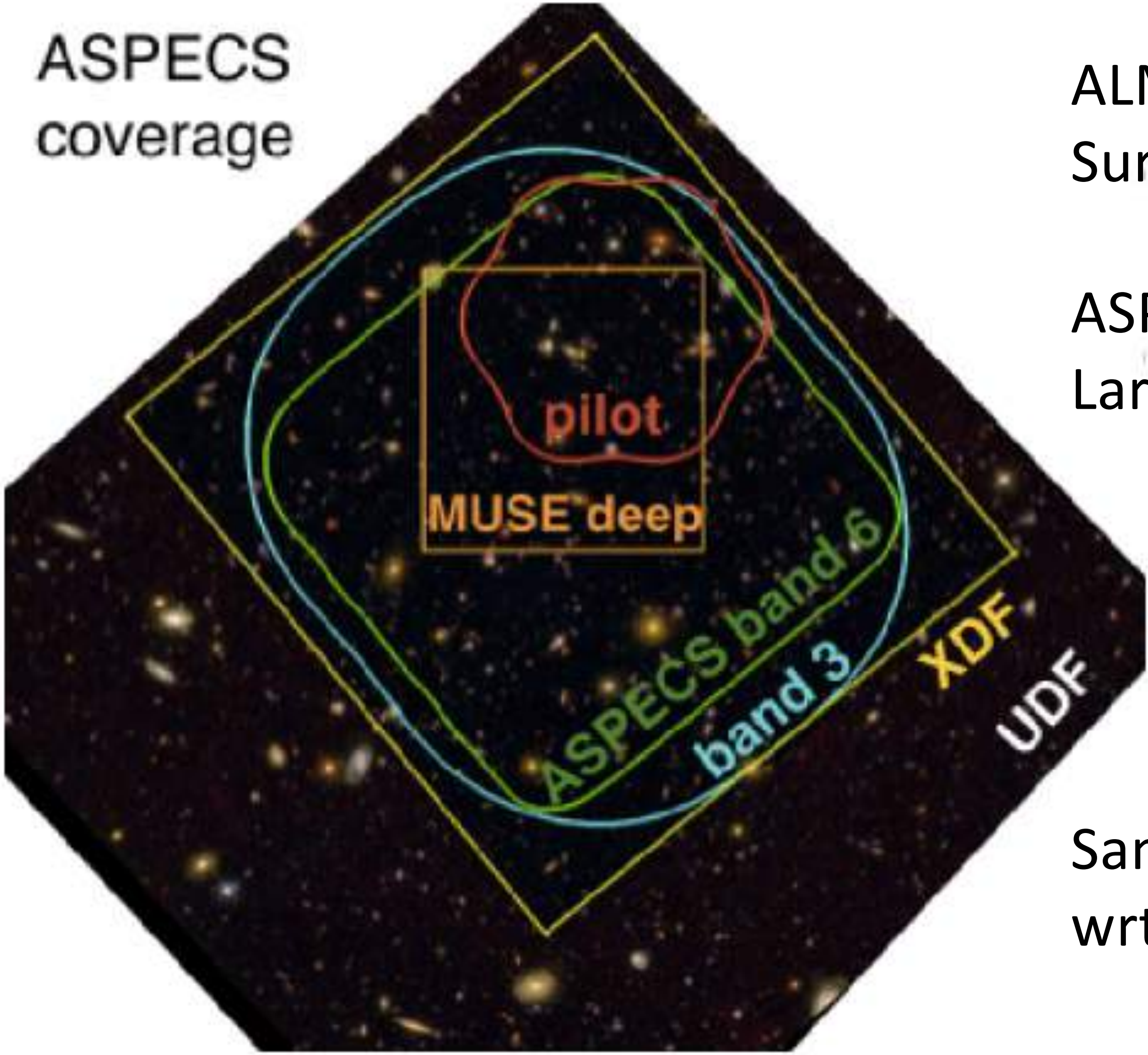


Star formation at high-redshift

Recent results

- Submillimeter-selected
- Color-selected
- (Sub-)millimeter deep fields

ASPECS

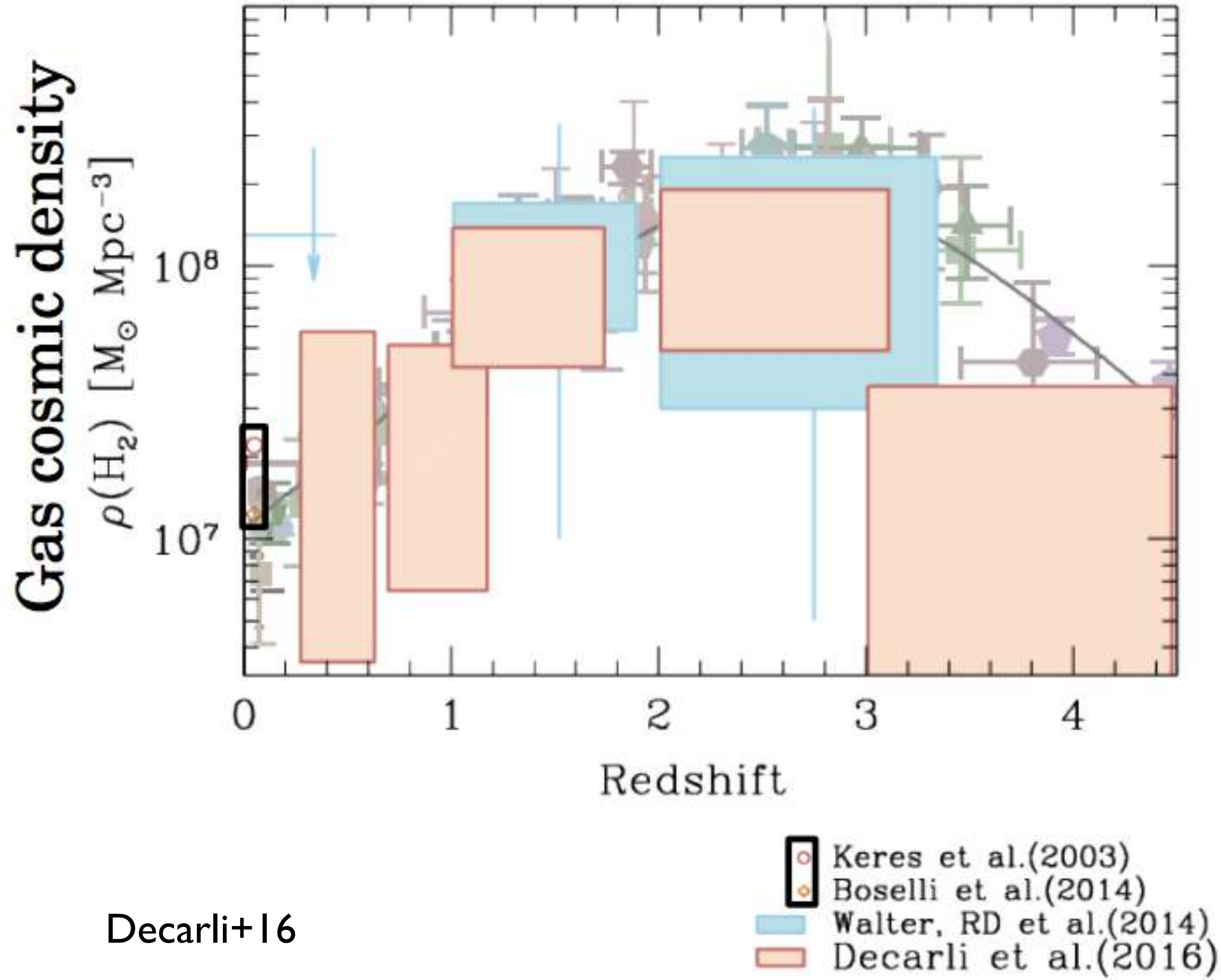


ALMA SPECtroscopic Survey in the HUDF

ASPECS LP: ALMA Large Program (150 hr)

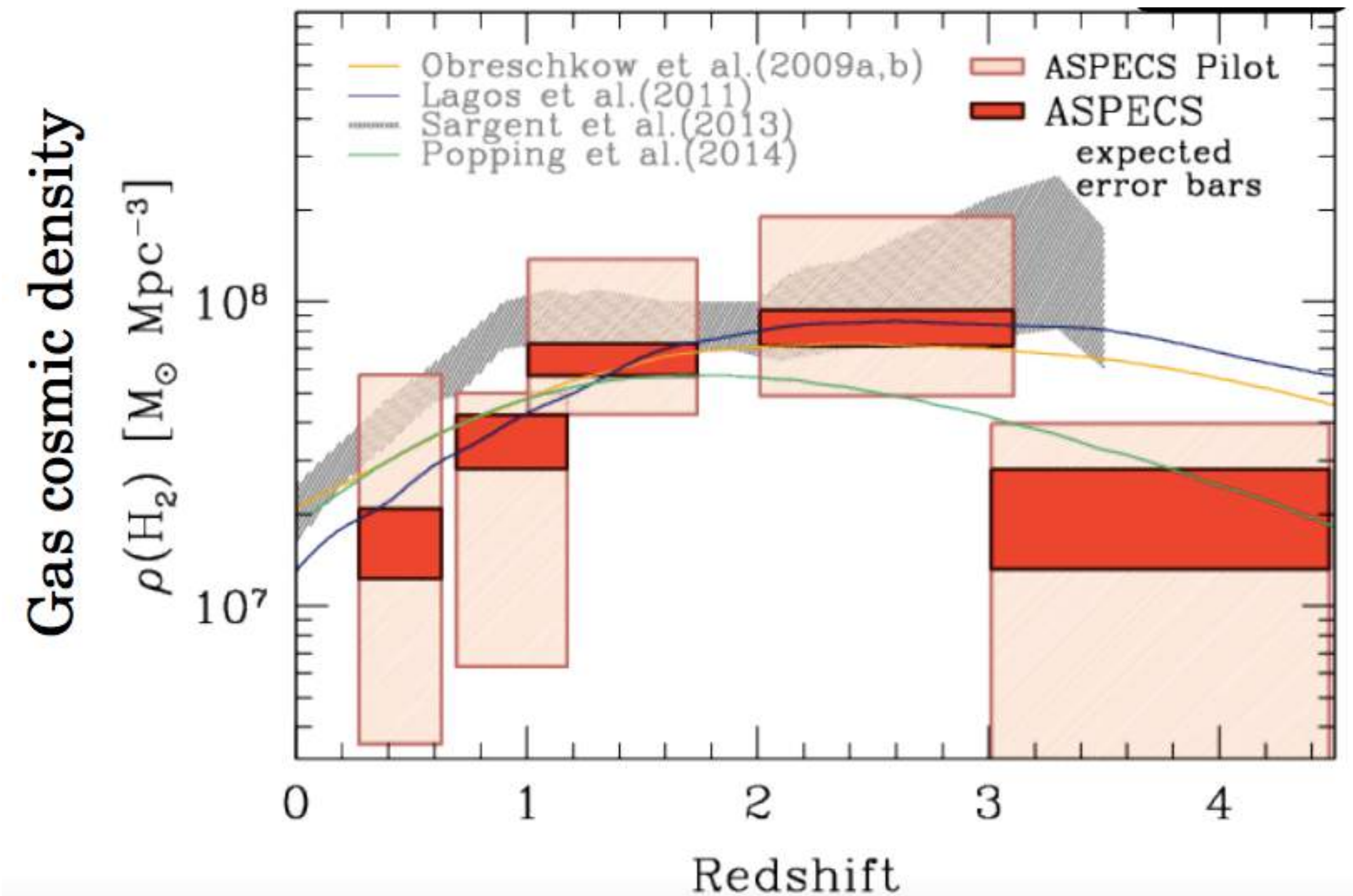
Same setup, 5x area wrt the pilot

Molecular gas content from ASPECS pilot



Decarli+16

What will ASPECS LP deliver?



Summary

- Huge progress in understanding star formation at high-redshift
- We can now not only correctly identify galaxies (not trivial!), but also resolve their cold gas and dust on ~kpc scales
- Recent efforts constrain both the evolution of the cold gas density, as well as its contribution to the shape of the cosmic SFRD
- ALMA will allow resolved studies of the gas/dusty SF in galaxies further down the LF