A resolved look at stars and gas in distant galaxies

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Apr 21, 2017

University of Sussex

OUTLINE

A Resolved Look at Stars and Gas in Distant Galaxies

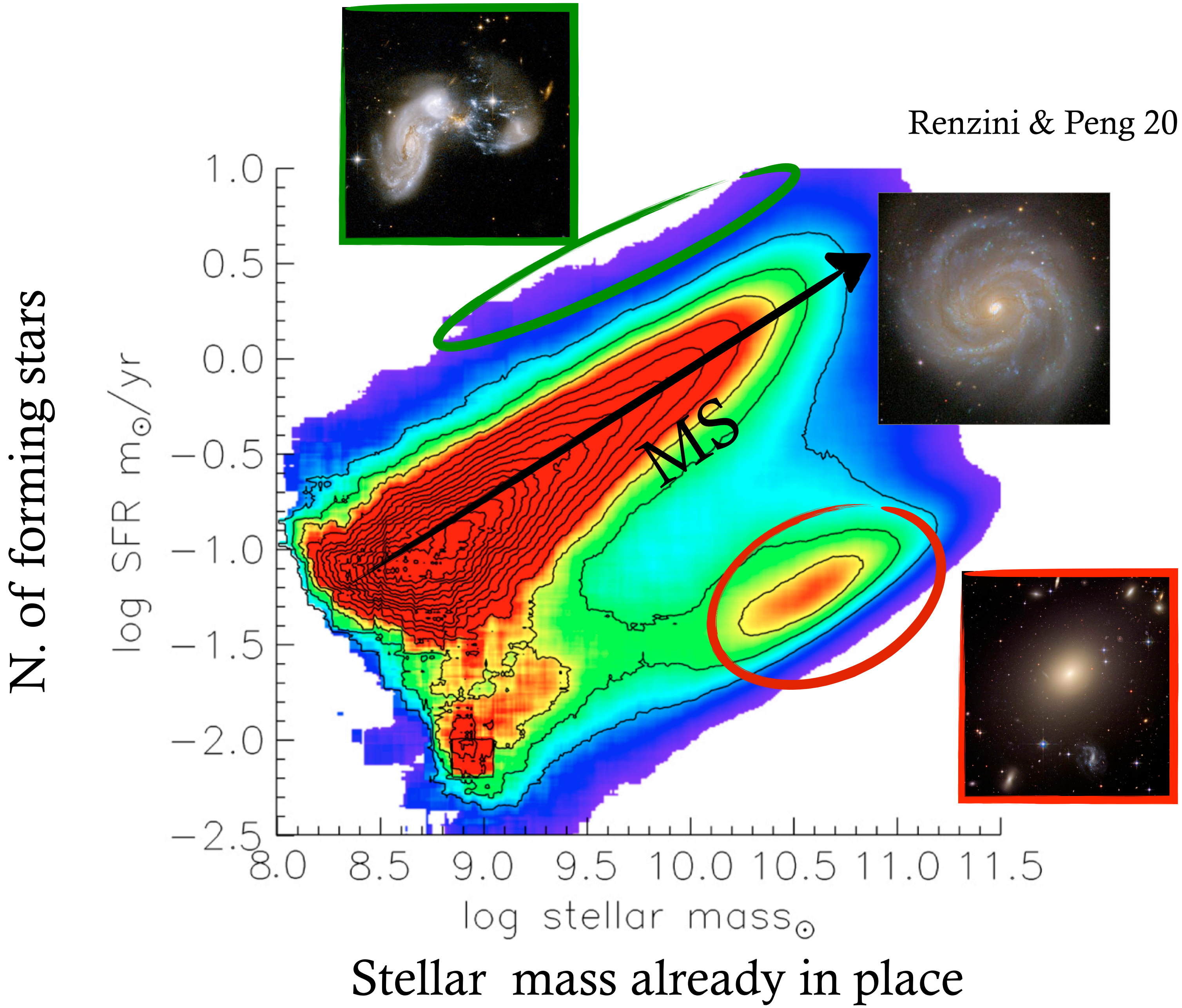
Part 1: Identification of high-z mergers through resolved mass distributions in $1.5<z<3$ galaxies

Part 2: Distribution of stars, star-formation and dust in $1.5<z<3$ galaxies

Part 3: Molecular gas and star formation efficiency at clump scale in a $z=1.5$ clumpy disk

General Introduction

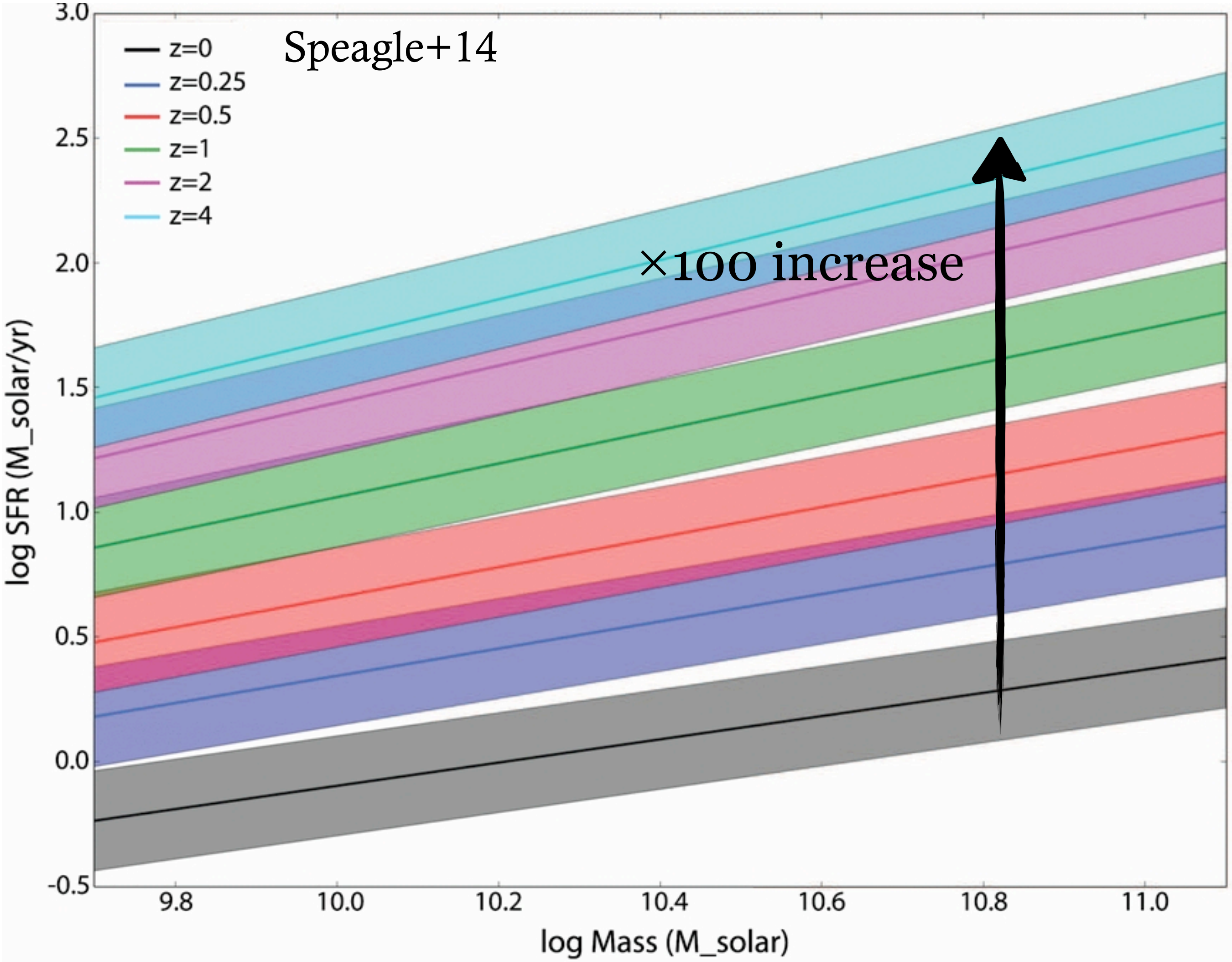
BACKGROUND: THE z=0 MAIN SEQUENCE (MS)



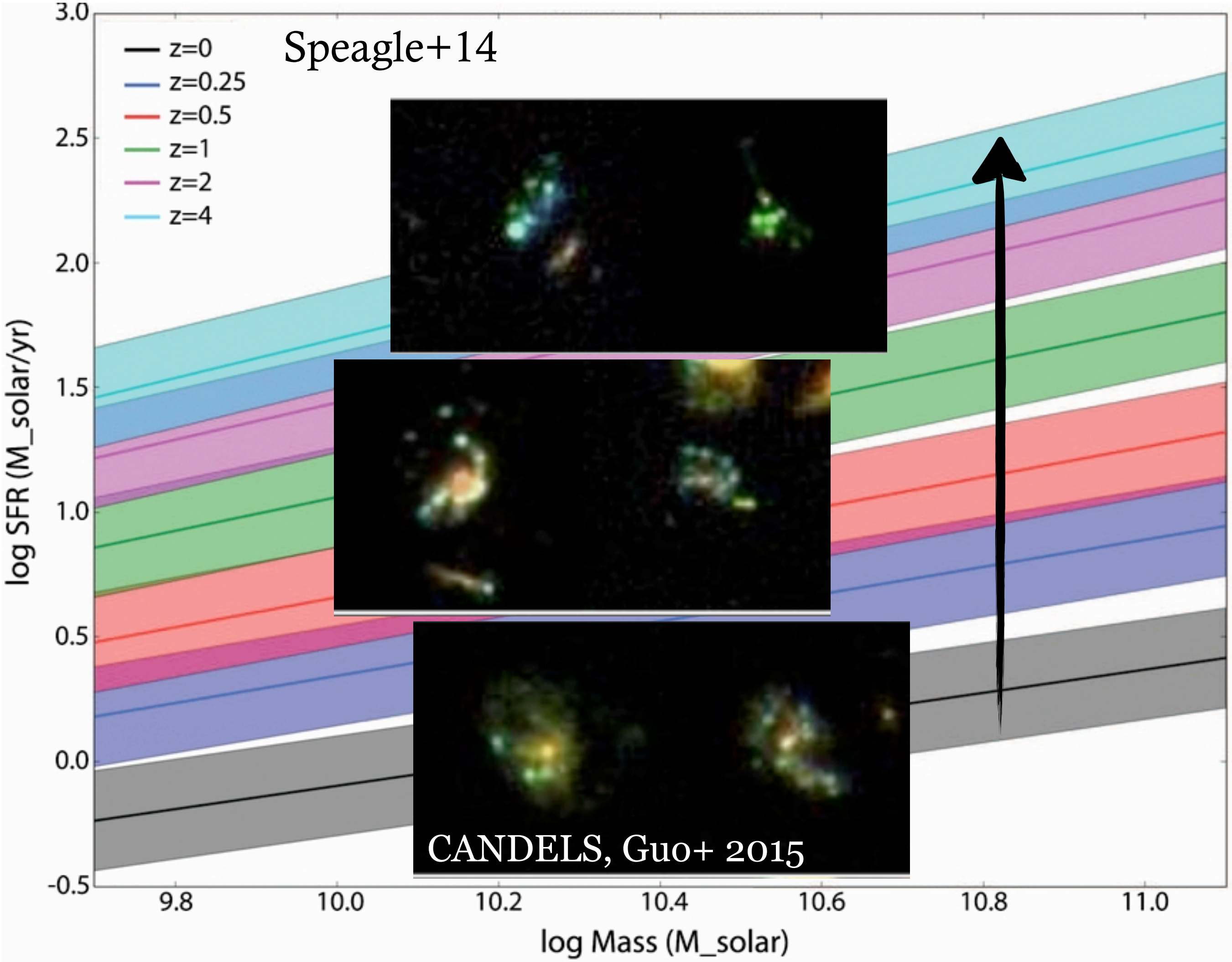
Renzini & Peng 2015

but see also
- Noeske+07
- Daddi+07
- Elbaz+07
- Pannella+09
- Oliver+10
- Peng+10
- Karim+11
- Whitaker+12
- Speagle+14,
- …

BACKGROUND: EVOLUTION OF THE MS



BACKGROUND: EVOLUTION OF THE MS



Increase with z in the degree of morphological disturbance in MS galaxies.

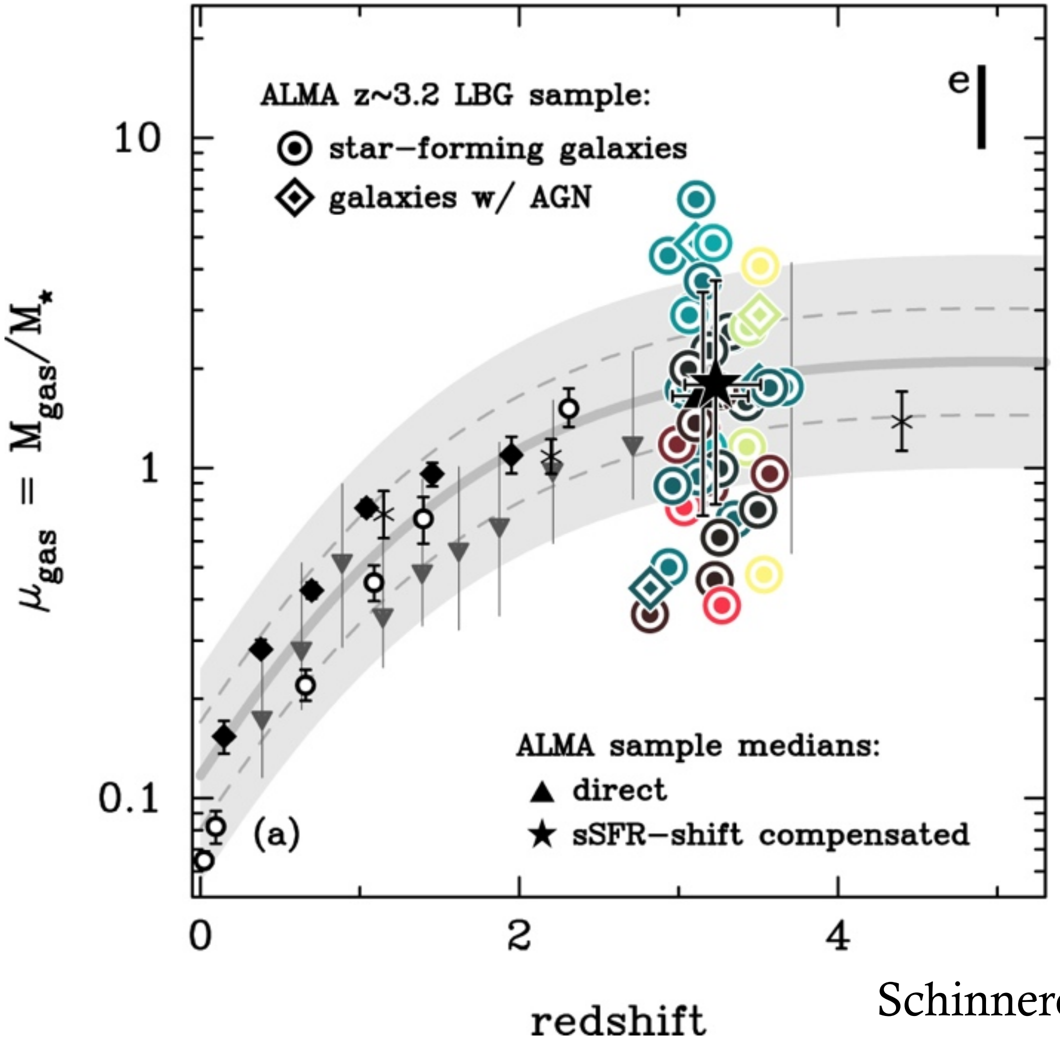
Galaxy morphology characterised by giant, SF clumps

$M \sim 10^{8\text{-}9} M_\odot$, $r \sim 0.1\text{-}1$kpc

Increased merger rate? Not necessarily….

BACKGROUND: EVOLUTION OF THE MS

Also the average gas fraction in galaxies also increases with redshift



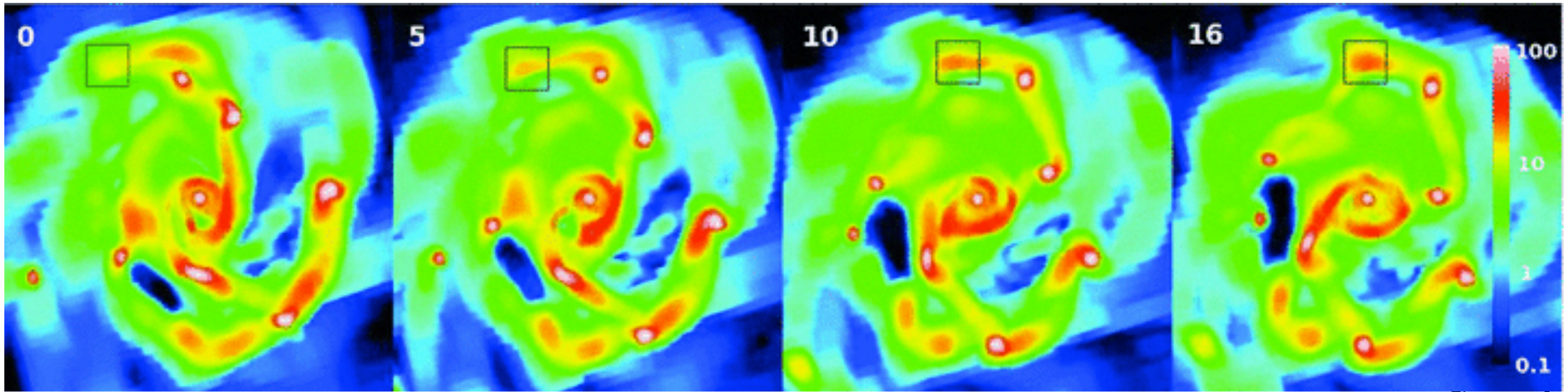
Schinnerer+16

BACKGROUND: GIANT CLUMPS (GC) IN HIGH-Z GALAXIES

Disturbed morphology can be explained by disk instability due to high gas fractions

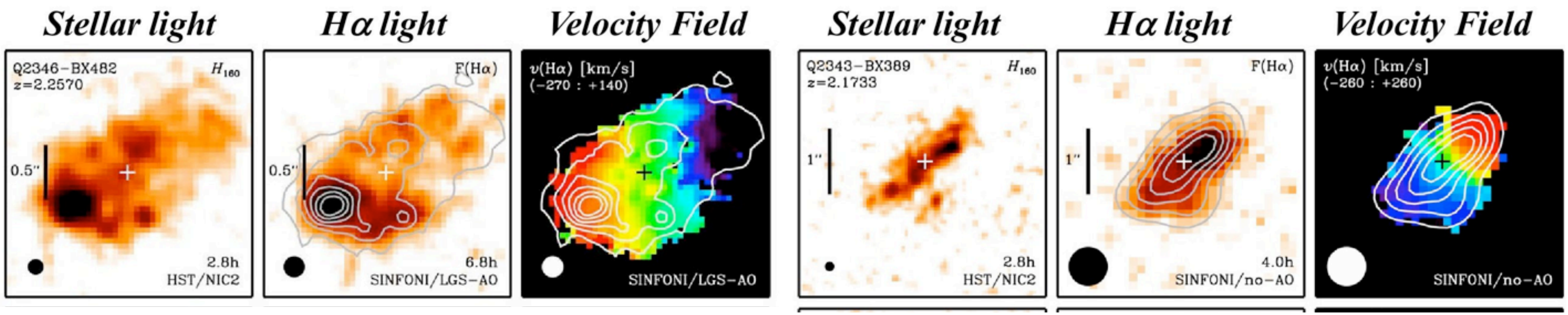
Formation of giant clumps and disturbed morphology in **non interacting** disks is theoretically expected in gas-rich/fed high-z galaxies

e.g. Bournaud+08, Agertz+09, Dekel+09,...



Ceverino+ 2010

And observationally confirmed

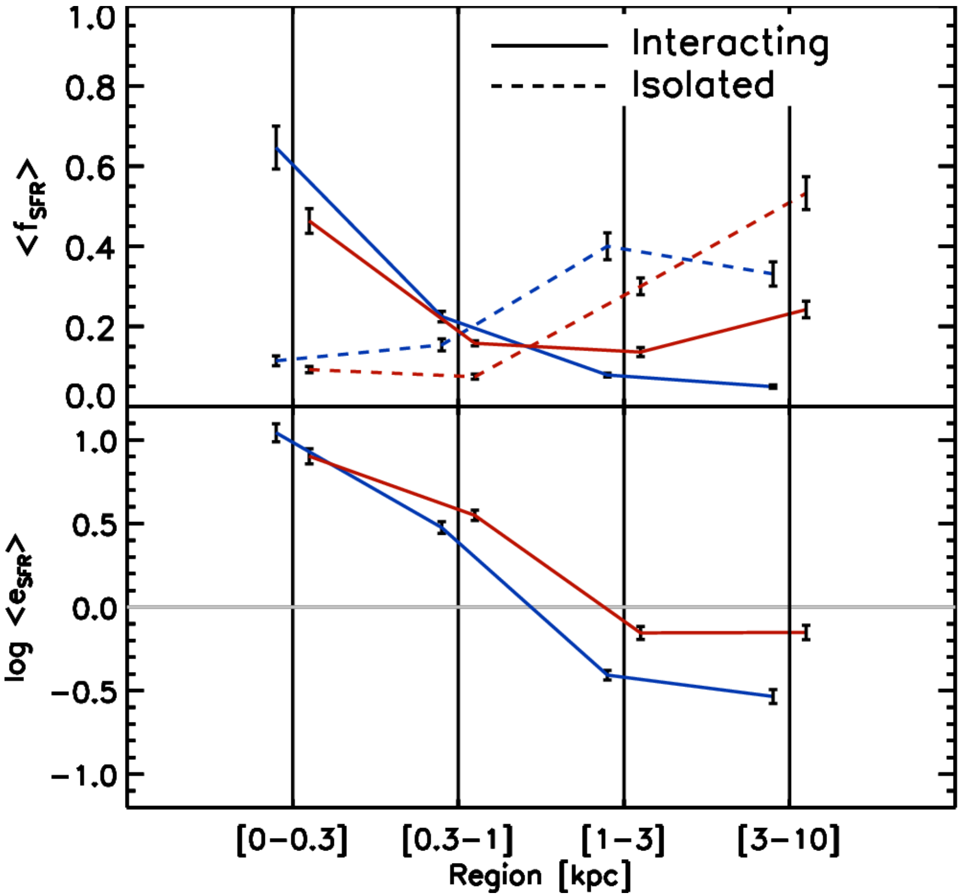


Forster-Schreiber et al. 2011
Genzel+06, Bournaud+08, ...

BACKGROUND: EVOLUTION OF THE MS

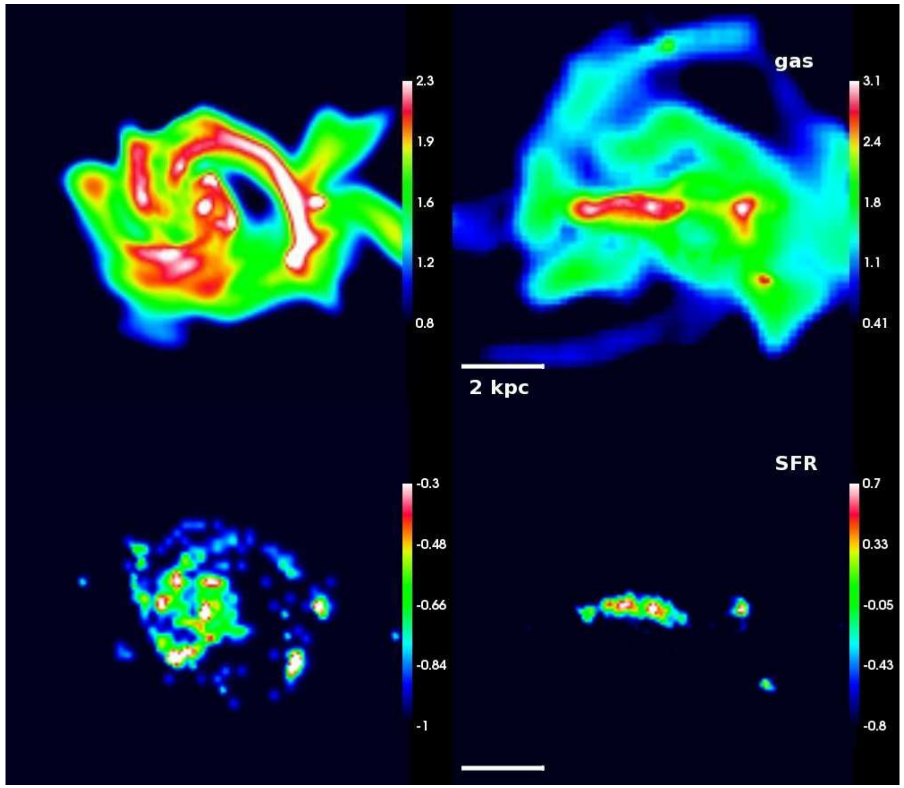
The spatial distribution of star formation holds insights into the processes driving MS evolution.

centrally concentrated in mergers

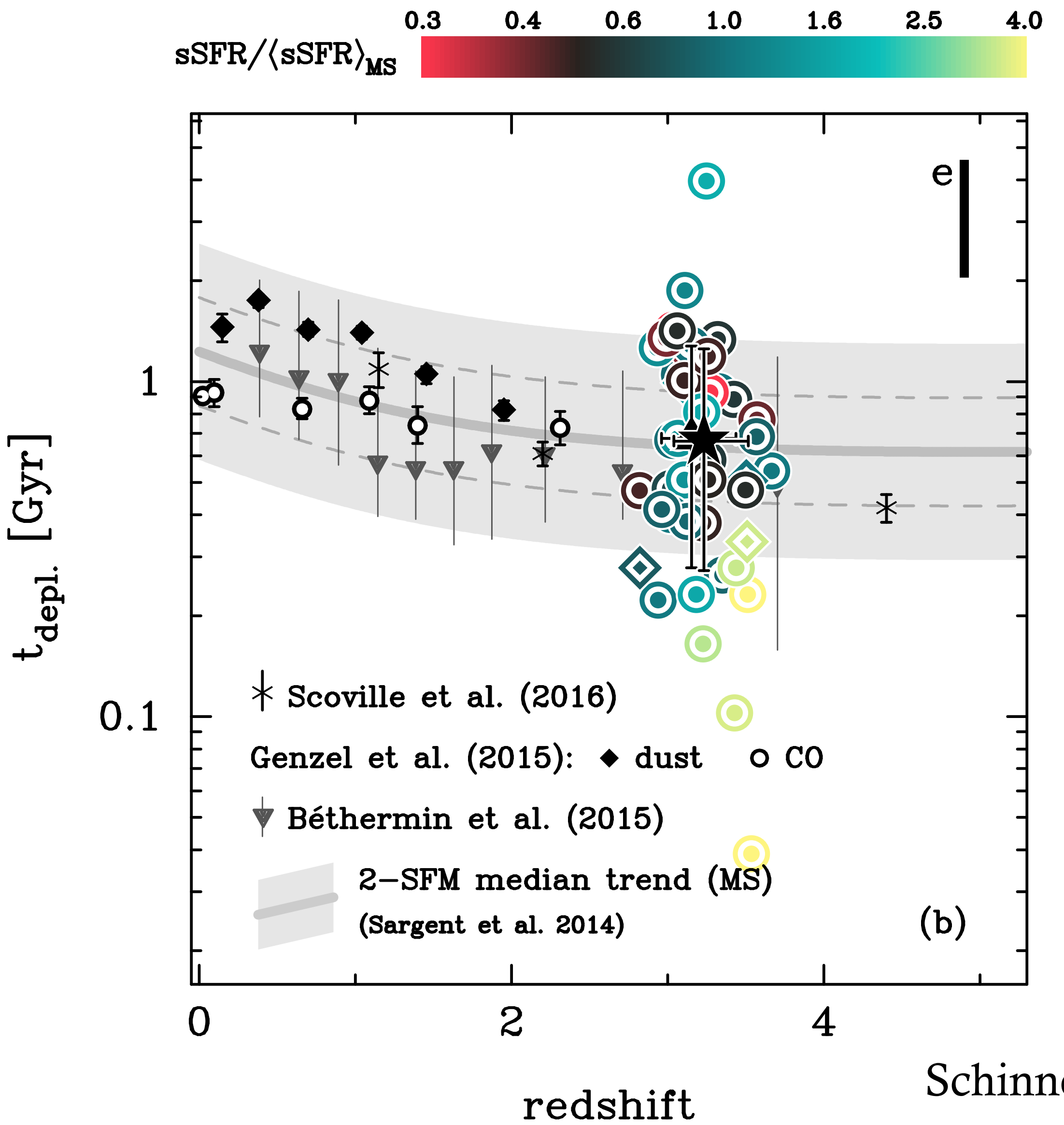


Moreno+15

more widespread in gas-fed clumpy galaxies



Ceverino+10



Schinnerer+16

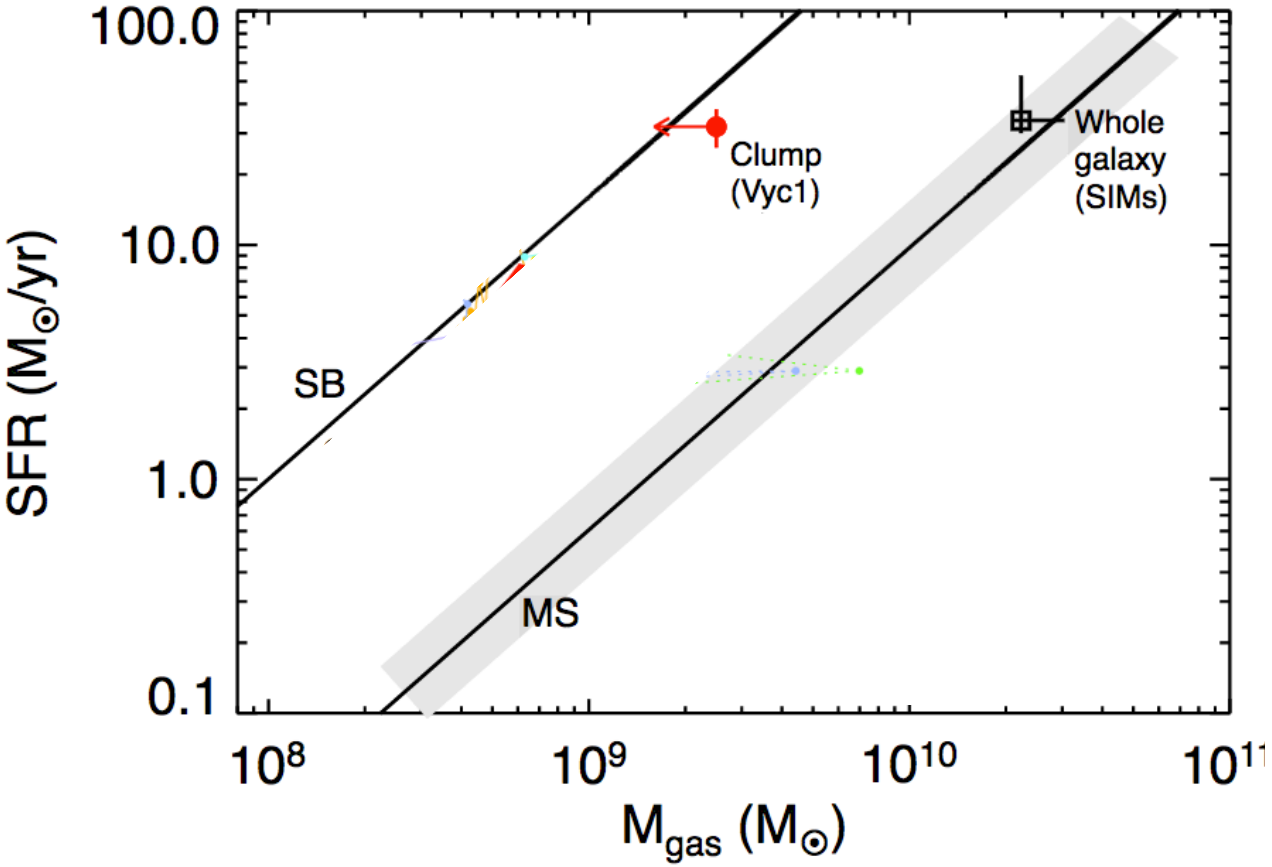
Moreover there is mild evolution of SFE

$SFE = SFR/M_{gas}$
$= 1/\tau_{depl}$

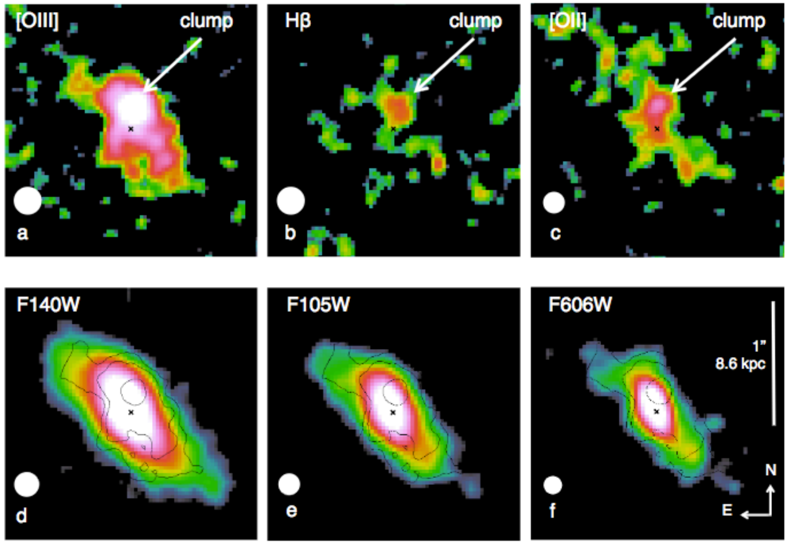
Could SFE evolution be related to clumps?

BACKGROUND: EVOLUTION OF THE MS

Indirect evidence for SB-like, high SFE in one extremely young (<10Myr) clump at z~2

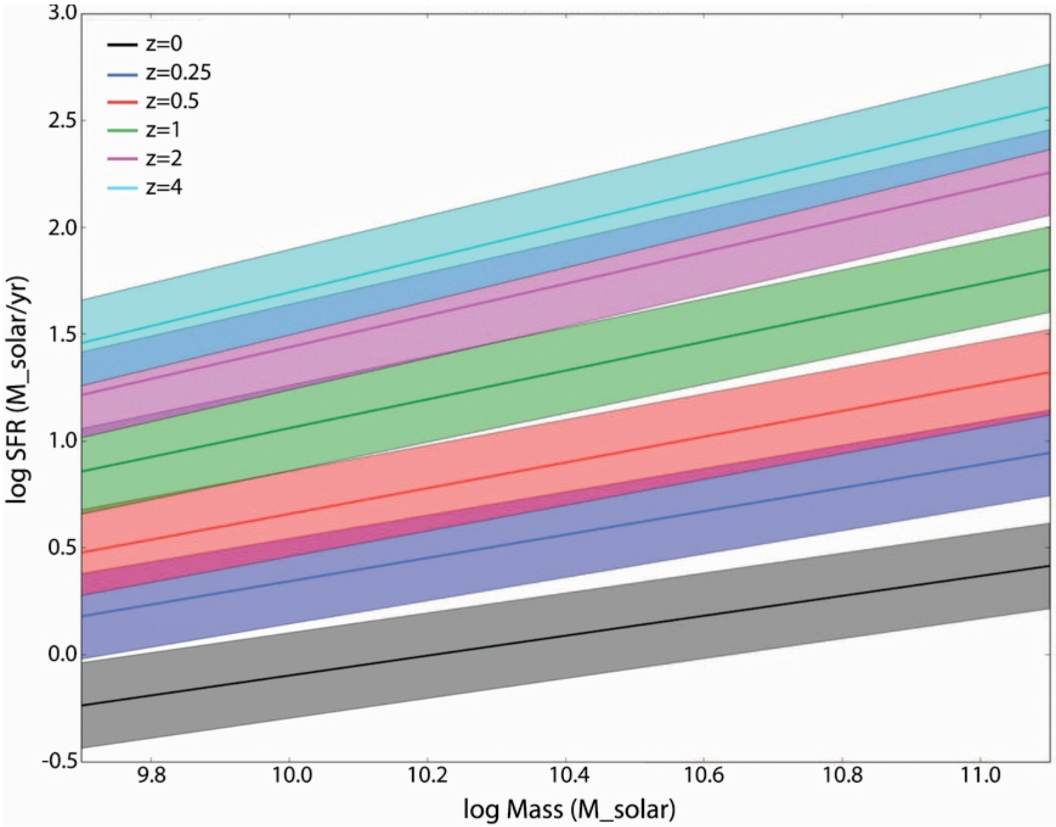


$SFE=SFR/M_{gas}=1/\tau_{depl}$



Zanella, …, AC+ 2015

BACKGROUND: EVOLUTION OF THE MS



Speagle+14

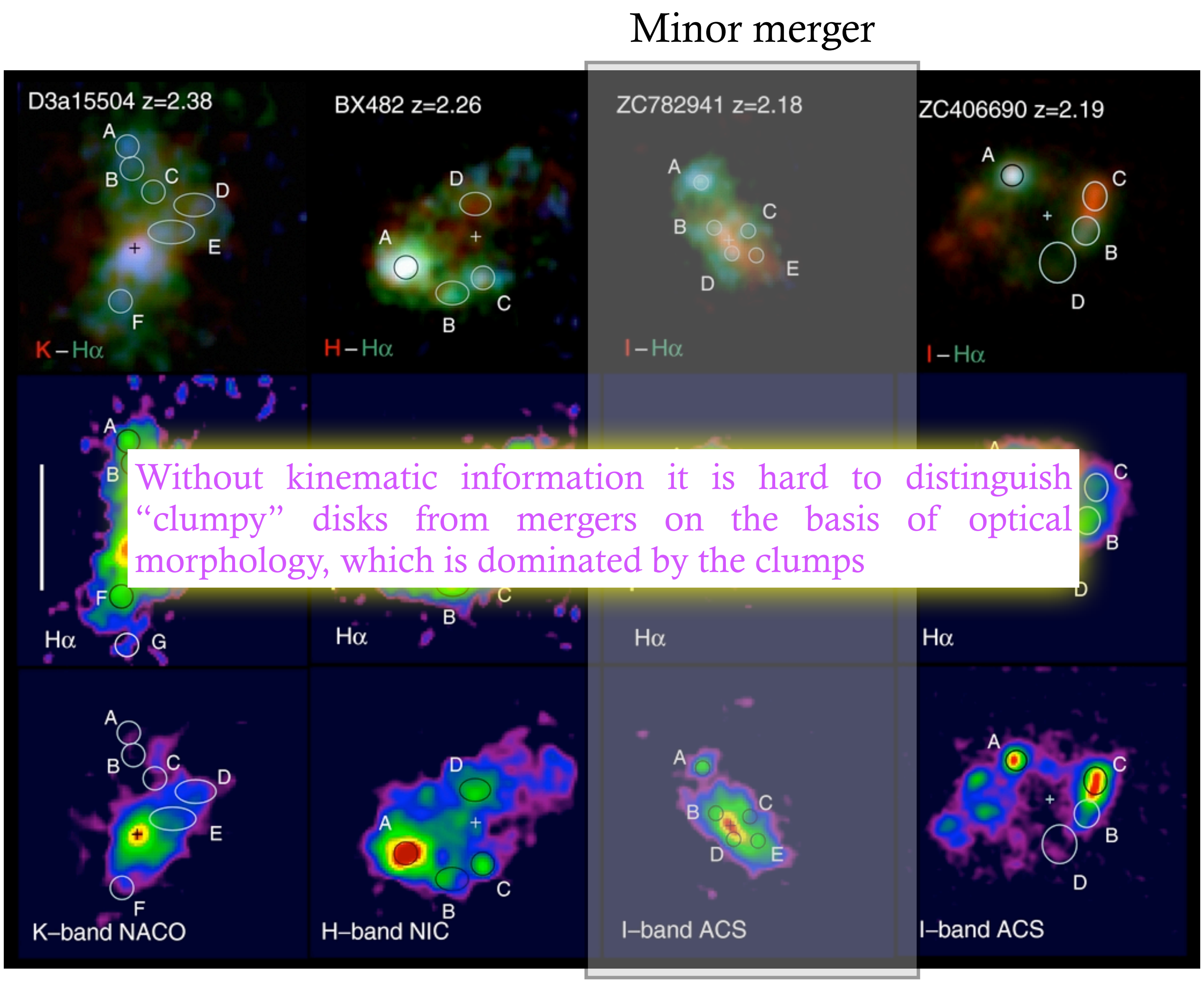
What is the role of mergers vs. instabilities in MS evolution?

Where is the SF occurring in MS galaxies?

How is star-formation regulated in high-z, MS clumpy galaxies?

Part -1: Identification of High-z Mergers

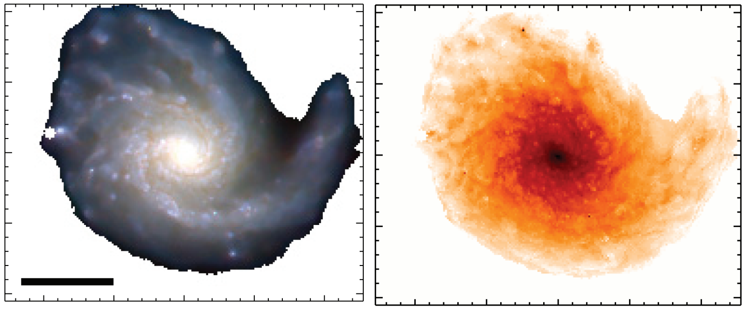
Morphological Classification of High-z Galaxies



Genzel+11

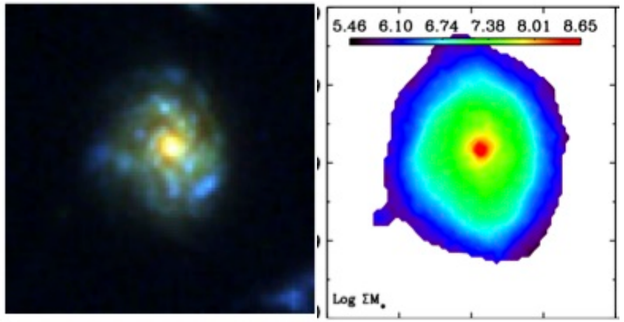
Clumps are typically UV-bright, but not very massive.
→ display lower contrast in (stellar) mass maps than in optical images

z~0



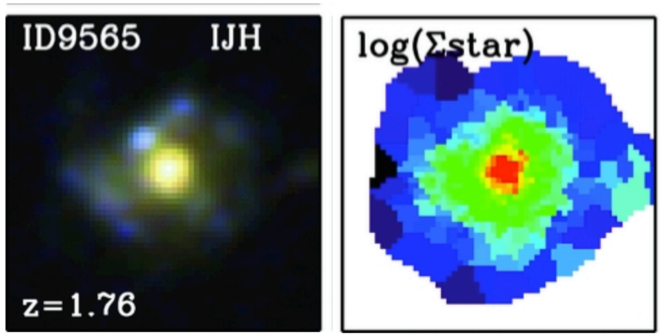
Zibetti+09

z~1



Hemmati+2014

z~2

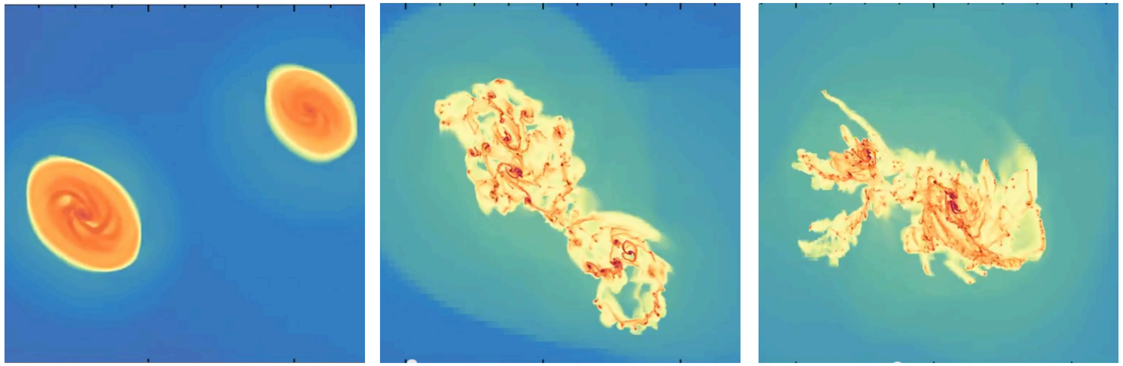


Wuyts+2012

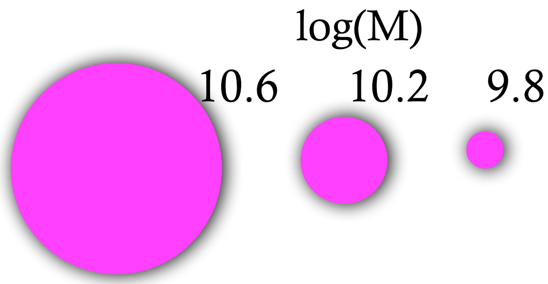
Can we use the distribution of mass as a kinematic proxy?

Perform morphological classification (using standard techniques) on mass maps rather than optical images

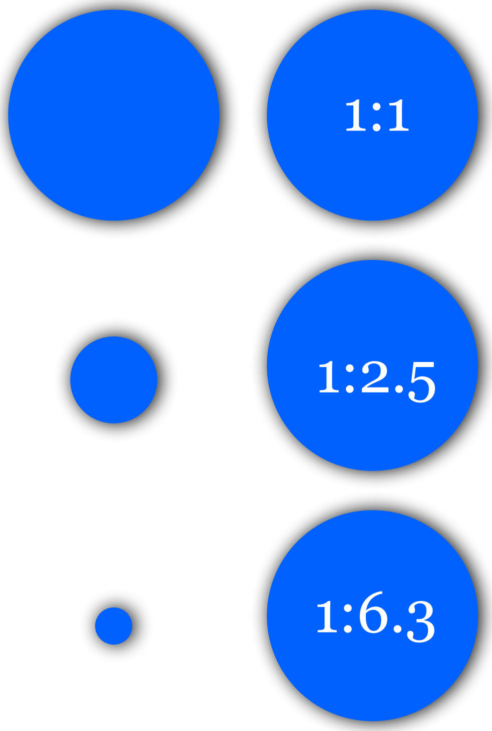
CALIBRATION ON SIMULATIONS



3 isolated disks



combined in minor/major mergers

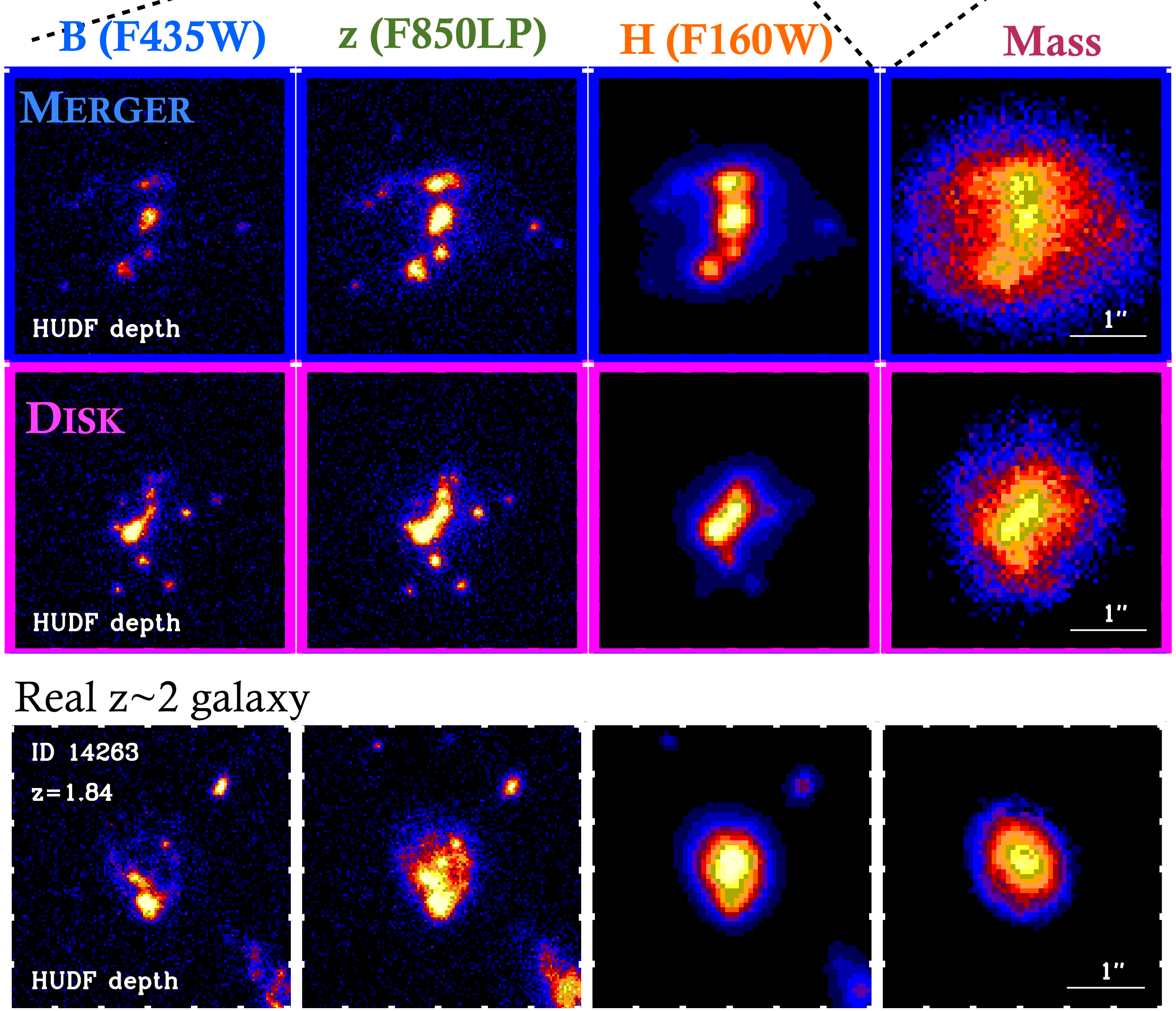


The MIRAGE Simulations (Perret+14)

1. RAMSES AMR simulations
2. Gas rich, **f_{gas}=0.65** (as observed, Daddi+10, Tacconi+10)
3. Moderate stellar feedback
4. Tailored to MASSIV z~2 sample (Contini+12)
5. Reproduce **clumpy structure** also in isolated disks

CALIBRATION ON SIMULATIONS

From simulations, generated mock images (Starburst99) and mass maps at HUDF depth



Caveats

- no cosmological context
- no dust included in sims
- possibly lower f_{gas} than real galaxies

↓

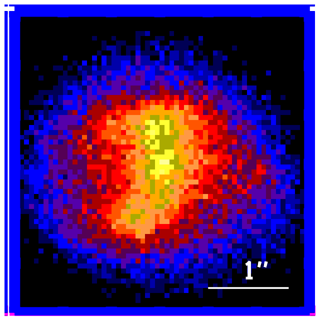
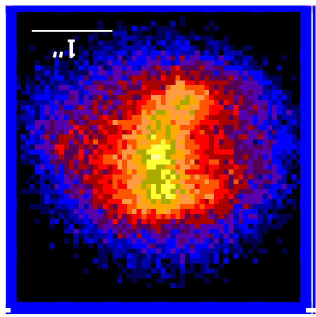
Flux maps in real galaxies likely to be clumpier

Cibinel+15

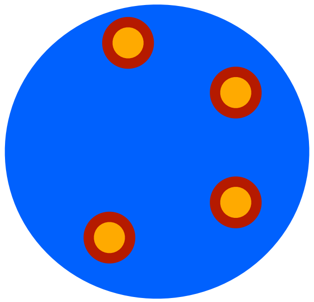
CALIBRATION OF THE MASS-BASED CLASSIFICATION

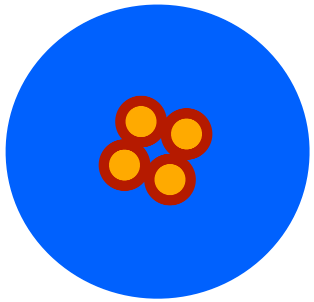
Measured standard structural parameters on simulated **mass maps**

180°

Asymmetry =  −  and calculate fractional residual flux

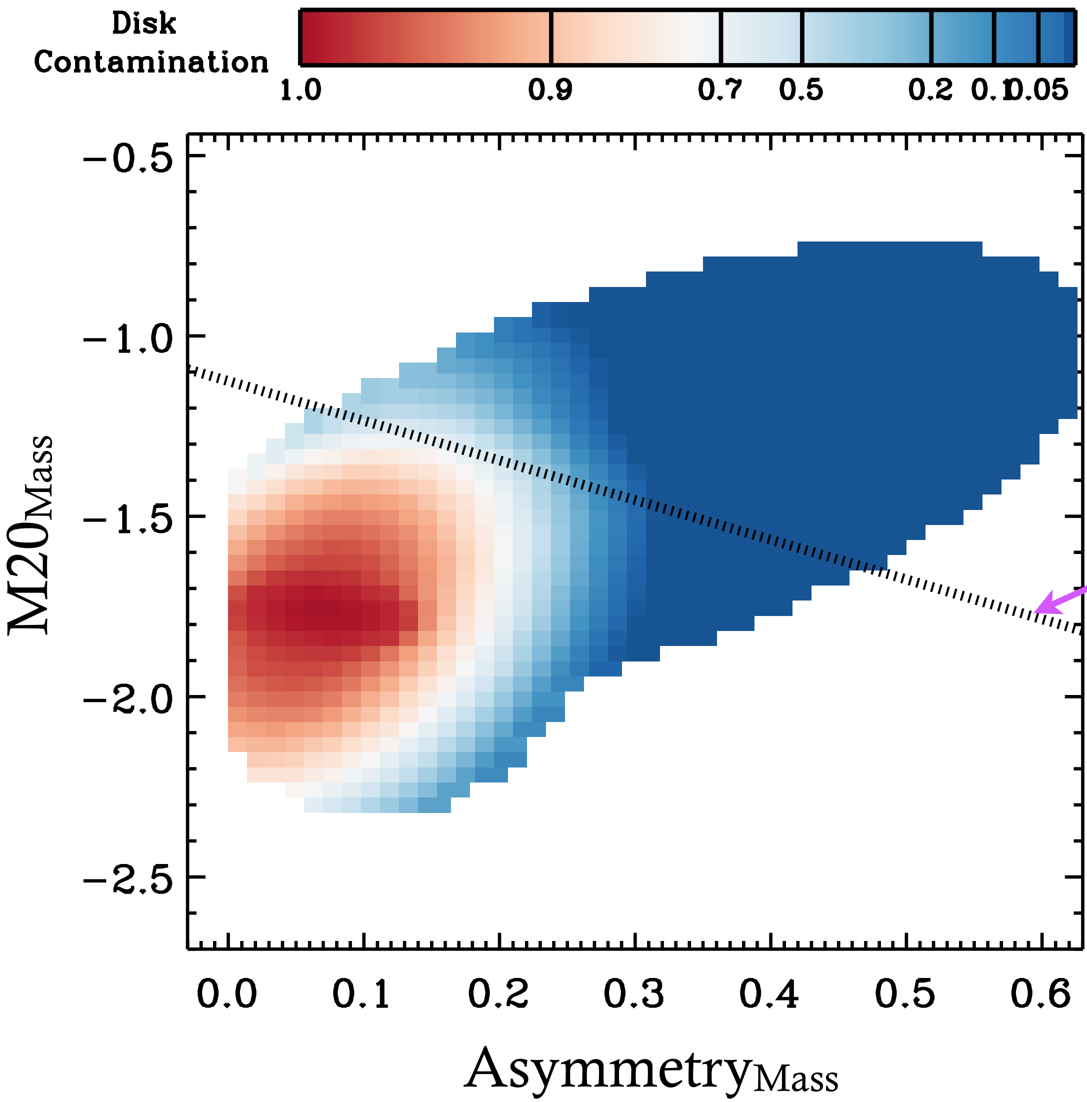
M20 (second-order moment of the 20% brightest regions)





Calibration of the Mass-Based Classification

Calculated the parameters on entire simulation suite to determine parameter space for disks & mergers



Operational dividing line between mergers and normal galaxies based on simulations

(ask me later the reason for this specific cut)

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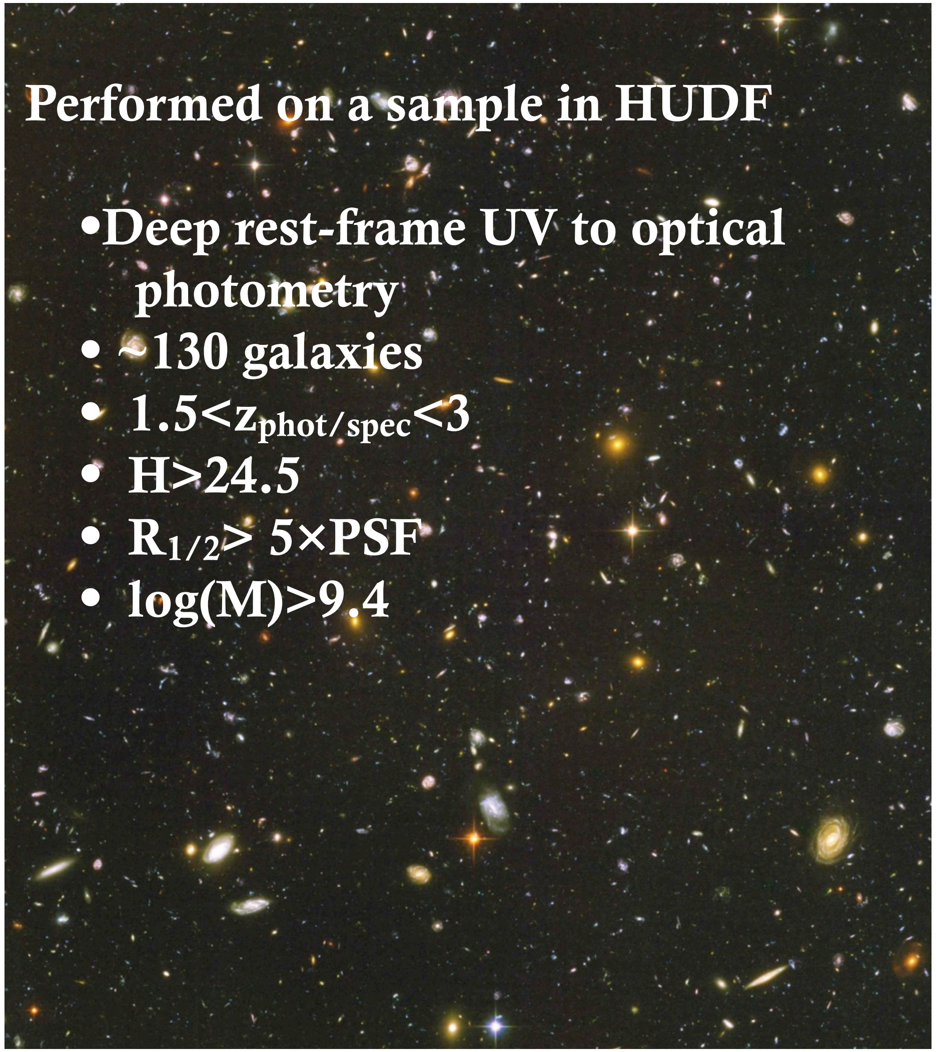
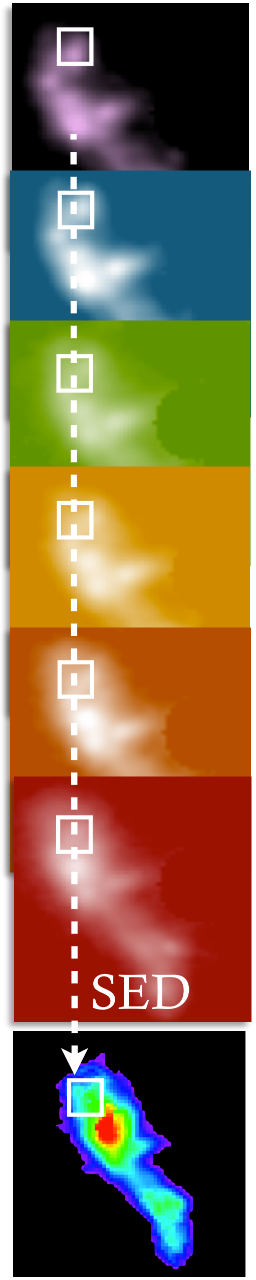
Classification On Real Galaxies



Performed on a sample in HUDF

- Deep rest-frame UV to optical photometry
- ~130 galaxies
- $1.5<z_{phot/spec}<3$
- H>24.5
- $R_{1/2}>5\times$PSF
- log(M)>9.4



Stellar mass maps for real galaxies obtained via pixel-by-pixel SED fitting (e.g. Welikala+08, Zibetti+09 Wuyts+12):

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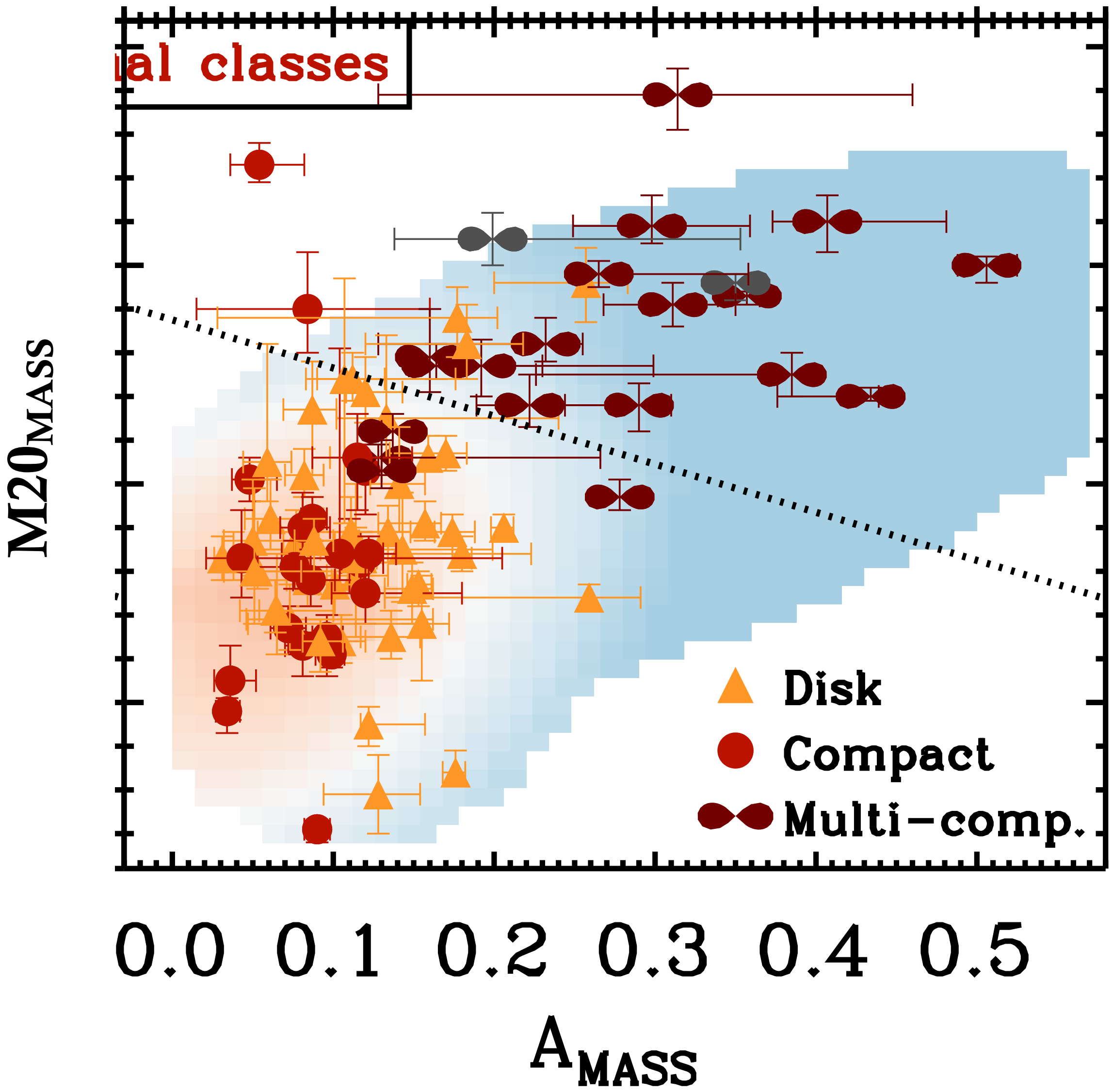
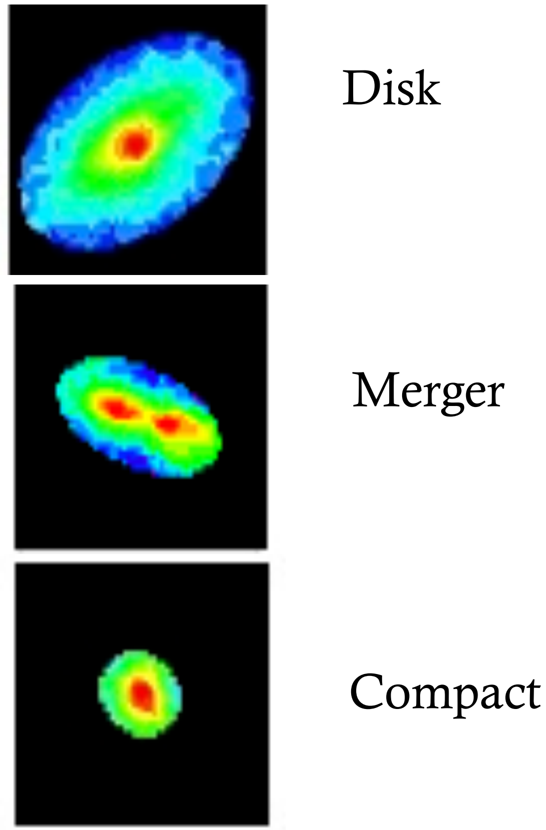
Real Galaxies Follow the Same Distribution



Visual classification of mass maps



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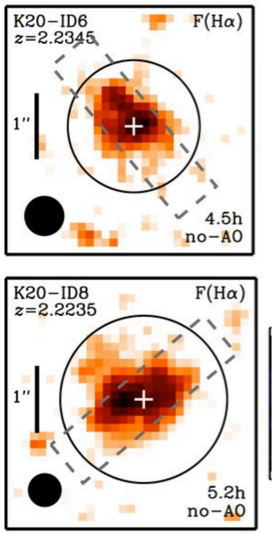
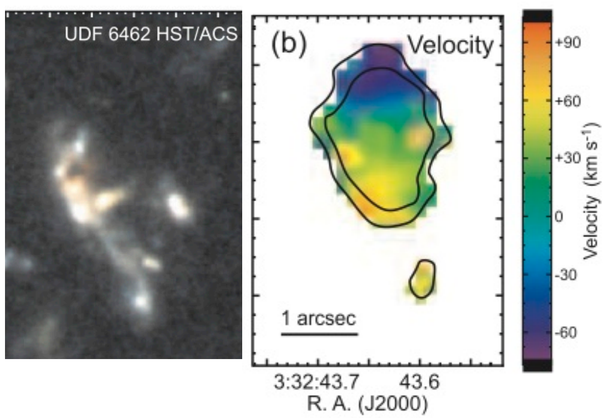
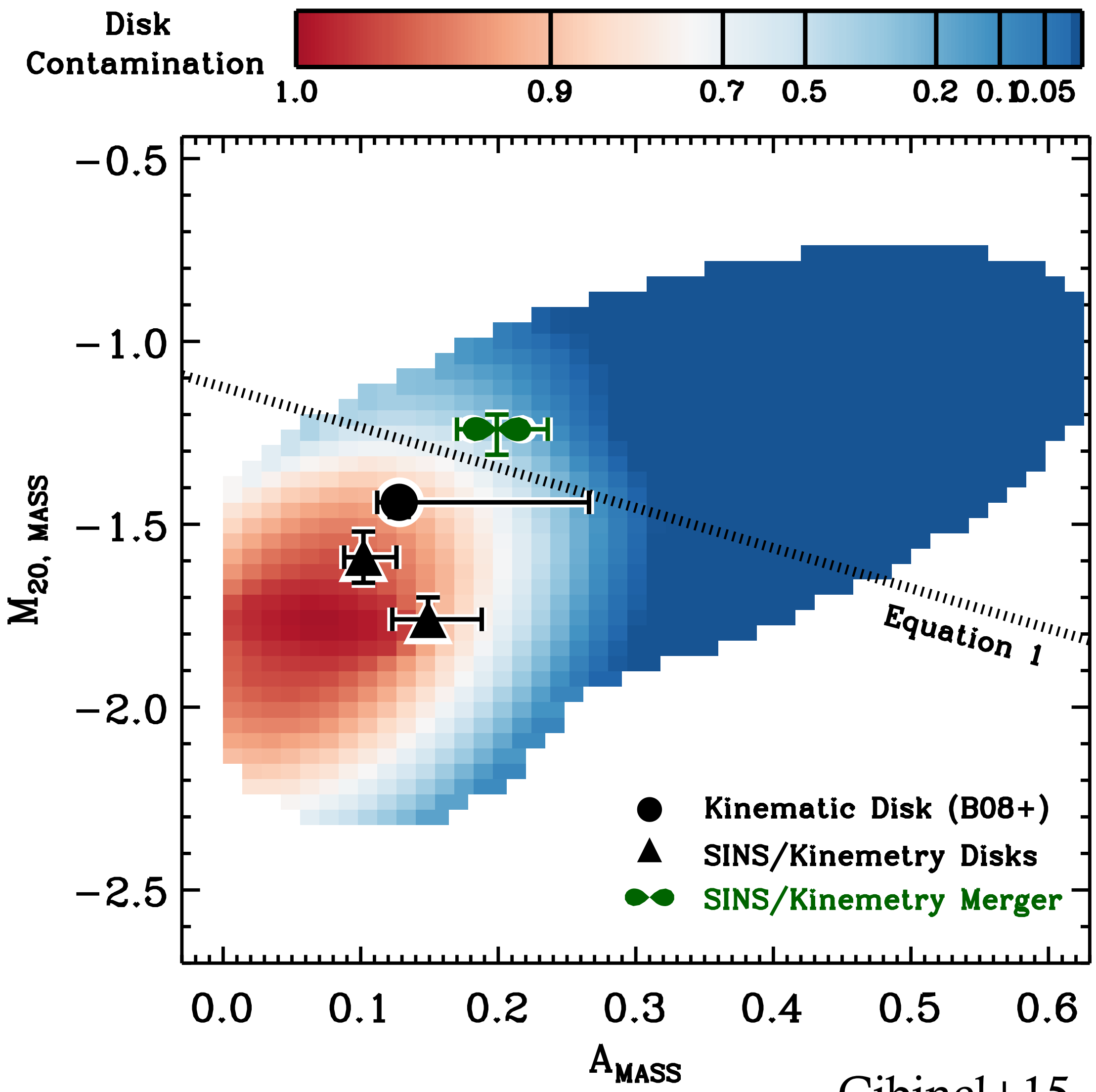
TEST ON GALAXIES WITH KNOWN KIN. CLASS

SINS galaxies w. kinemetry classification (Forster-Schreiber+09)



Clumpy Disk (Bournaud+08)





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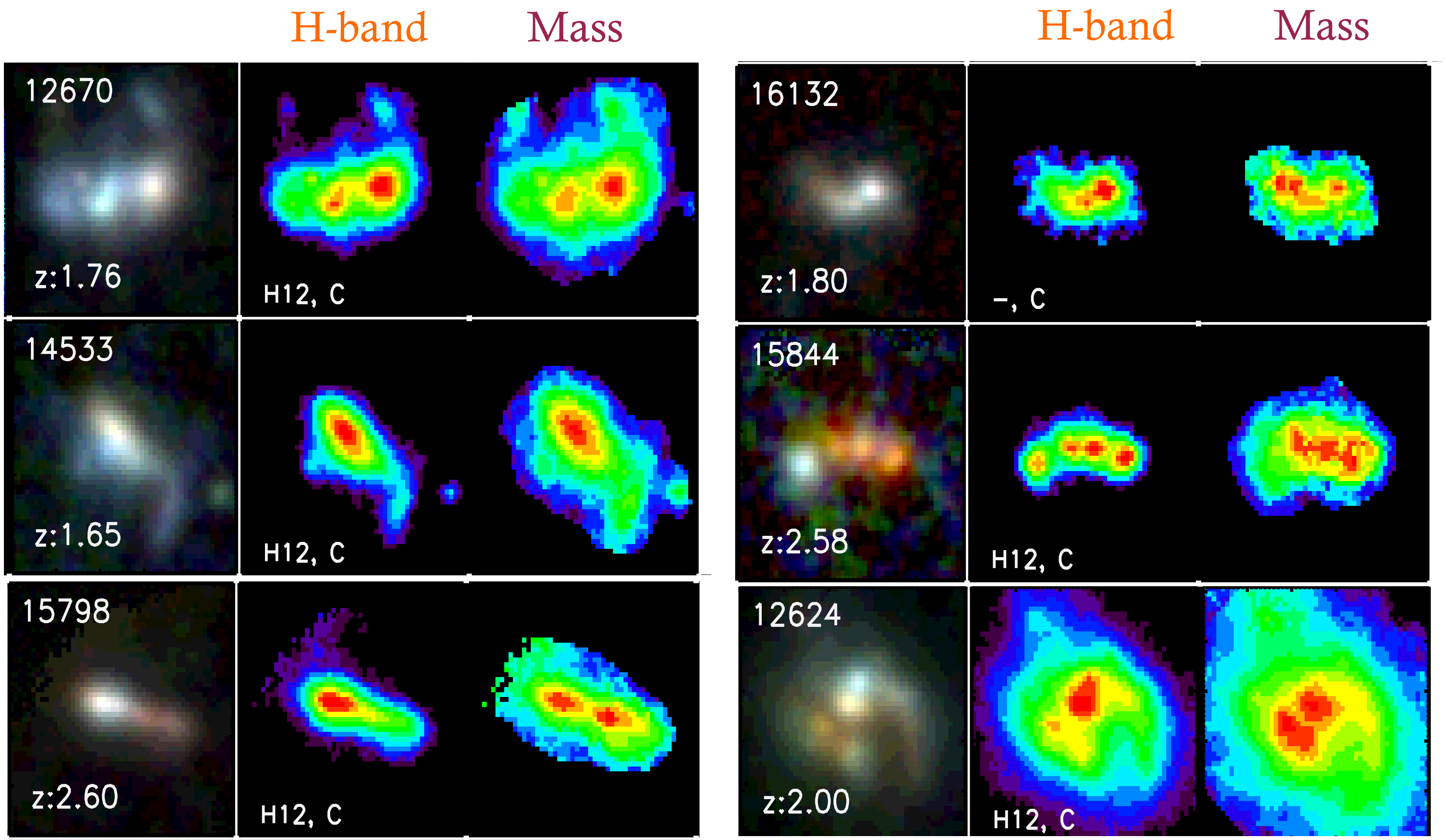
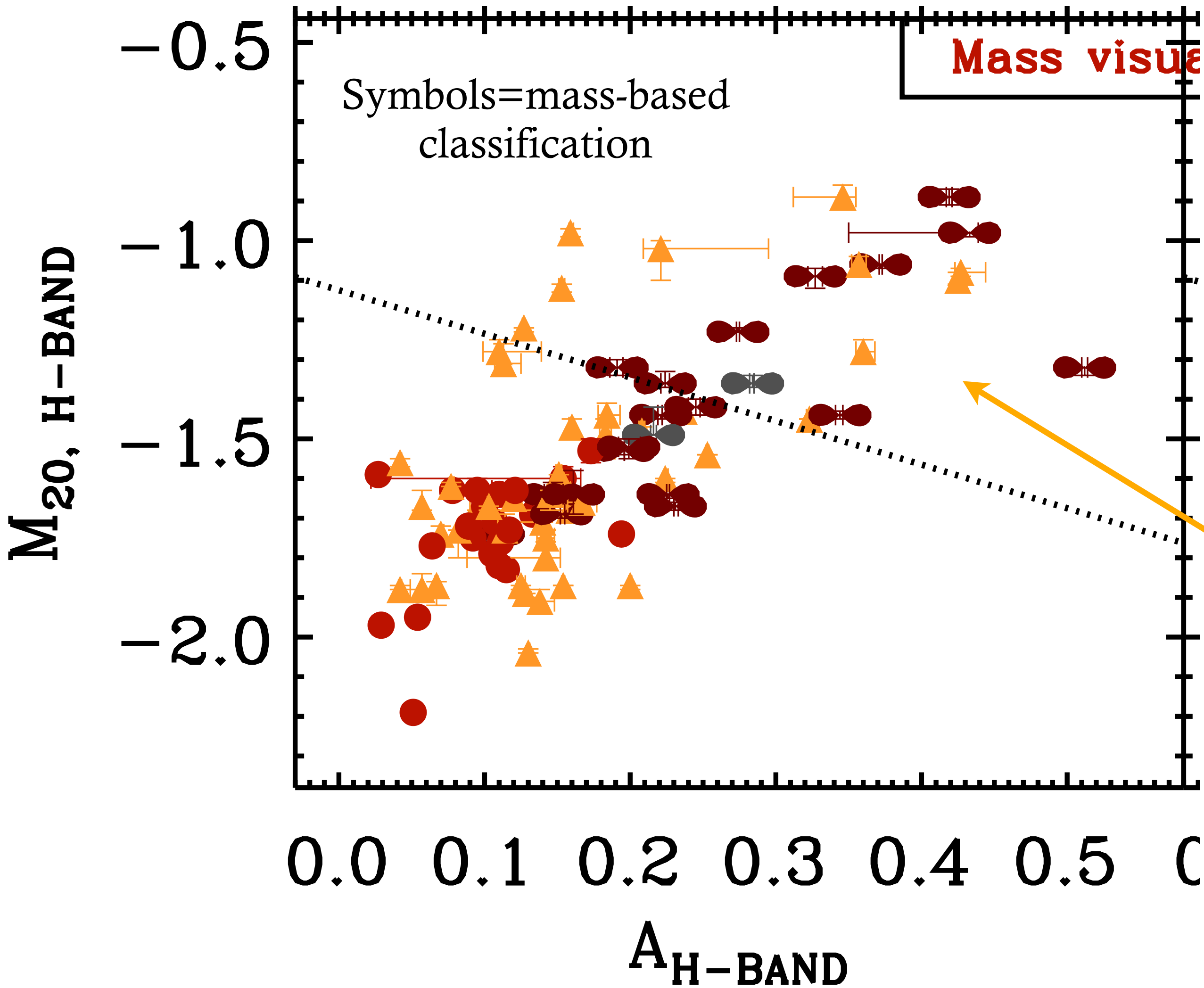
Mass Selected Mergers

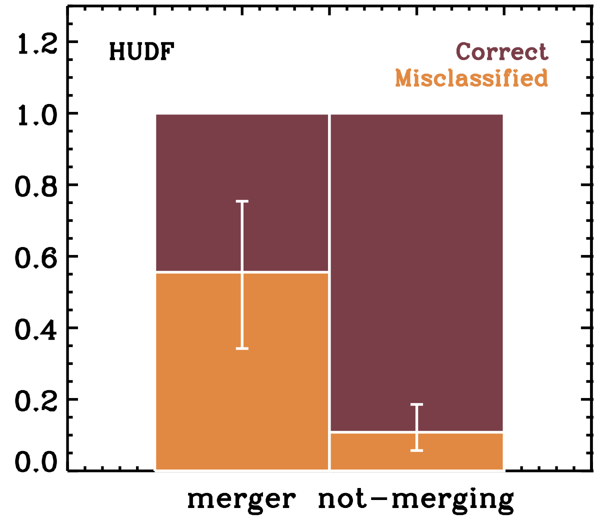


Cibinel+15

Is the Distinction Disk vs. Merger Improved?

Comparison with classification performed on the H-band images





Merger region highly contaminated by disks in A-M20 plane measured on the H-band

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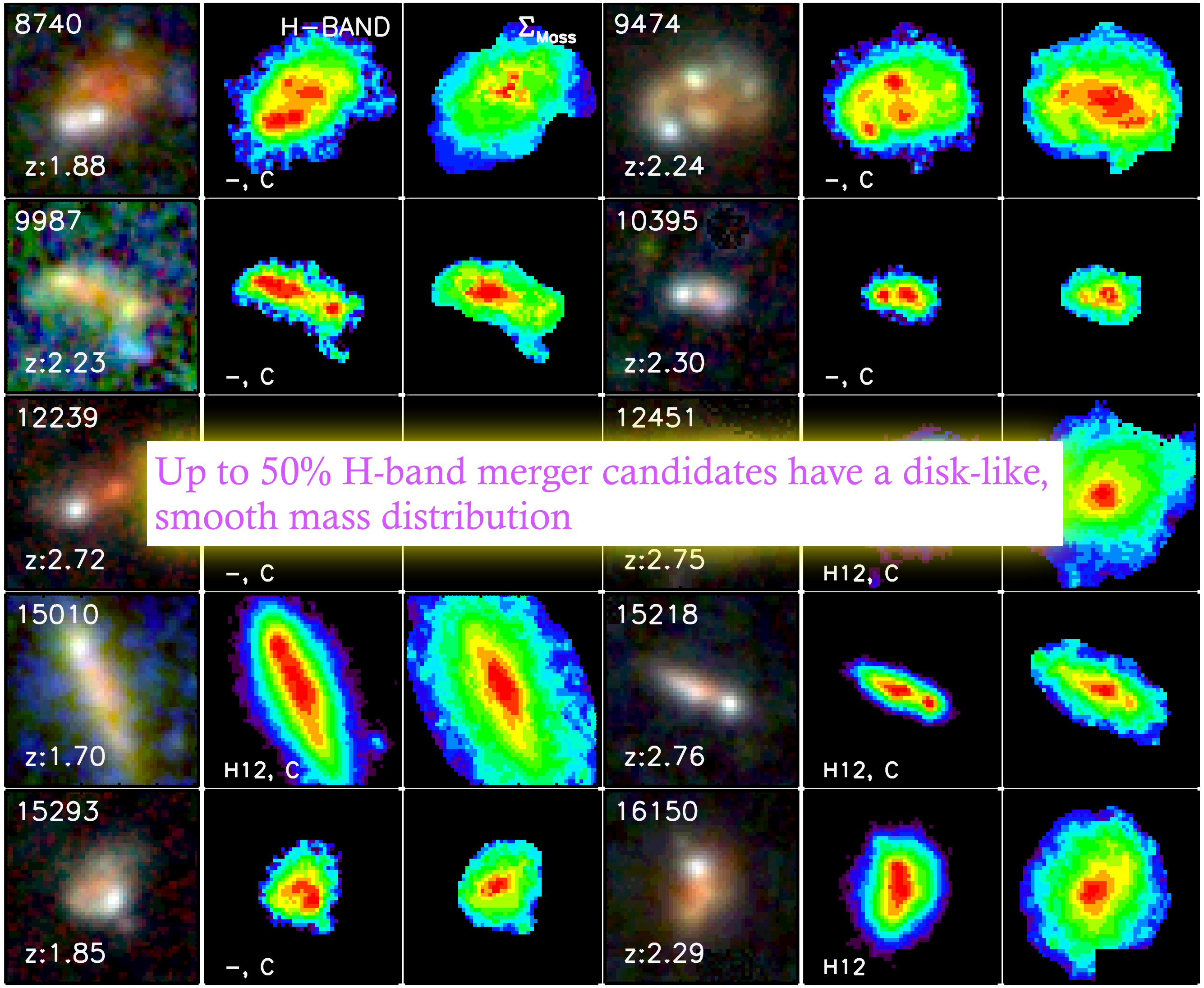
Is the Distinction Disk vs. Merger Improved?



Up to 50% H-band merger candidates have a disk-like, smooth mass distribution

Cibinel+15

CONCLUSIONS - PART 1

- The identification of merger candidates based on asymmetries in the mass maps provides a useful alternative to a kinematic analysis

- Regardless of the imaging depth (e.g. CANDELS vs. HUDF), the mass-based classification always results in a lower contamination from clumpy disks than an H-band classification.

Part -2: Distribution of Stars & SF in MS Galaxies

VLA and ALMA Imaging of Star Formation at z~2

Combine mass maps for z~2 MS galaxies with long wavelength high-resolution follow-ups in HUDF

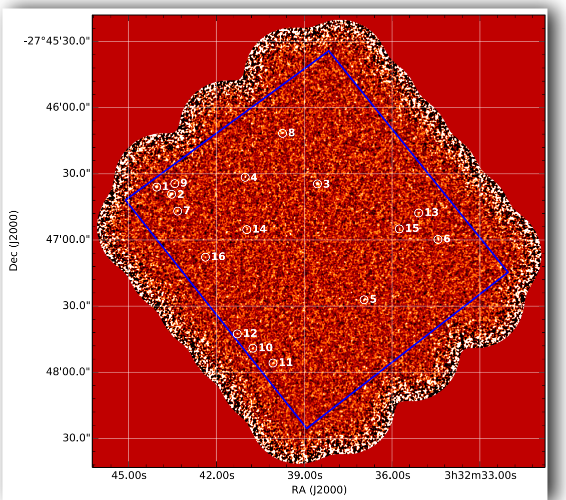
Image courtesy of NRAO/AUI

VLA 6GHz (~5cm), Rujopakarn+16

Tracing radio synchrotron emission from relativistic e- from SNe

→ probes $\lesssim 10^8$yr SF (but can be affected by AGN)

Credit: Clem & Adri Bacri-Normier



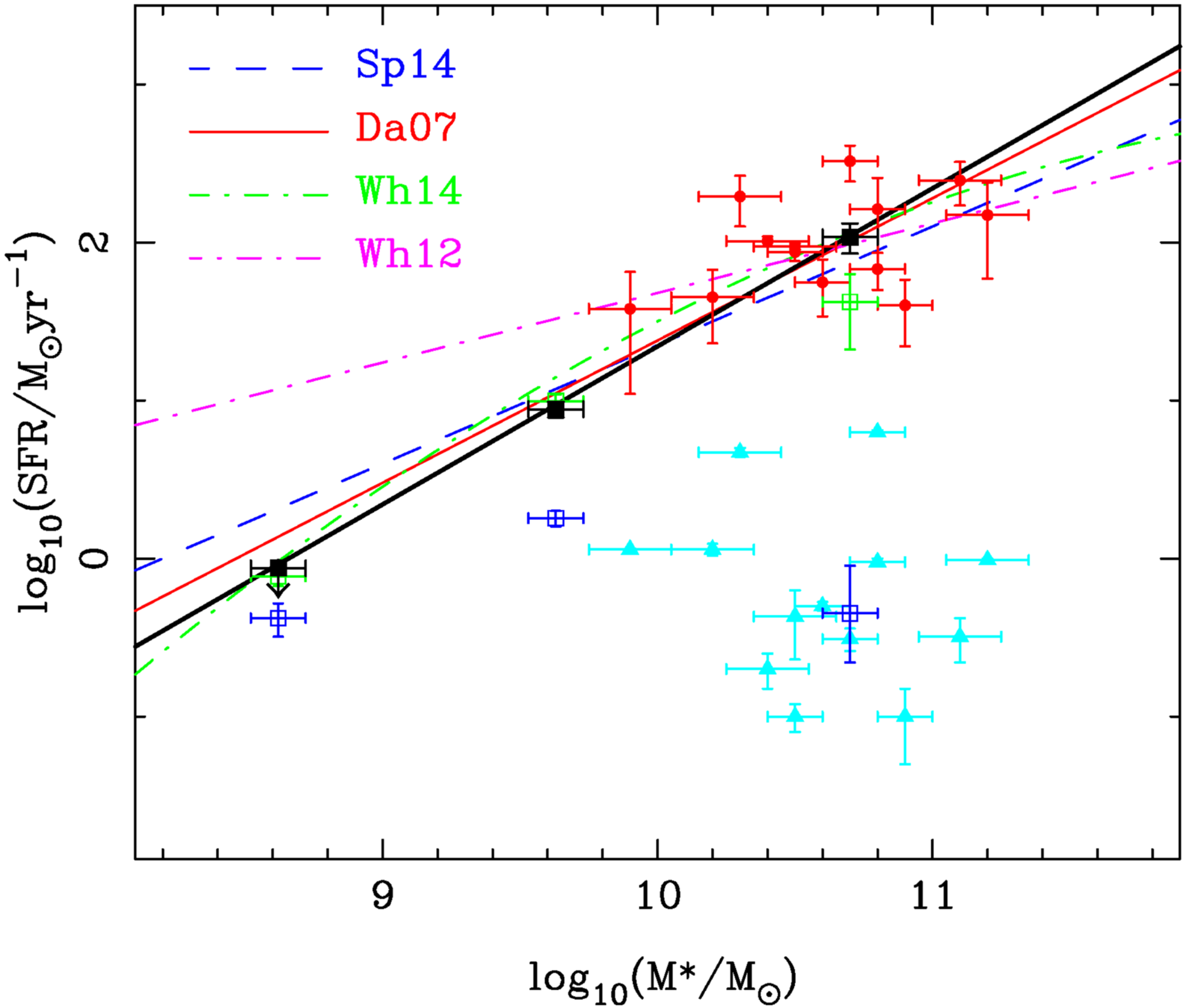
ALMA 1300μm, Dunlop+17

Tracing emission of cold dust (indirectly gas/SF)

Rujopakarn,..,AC+16

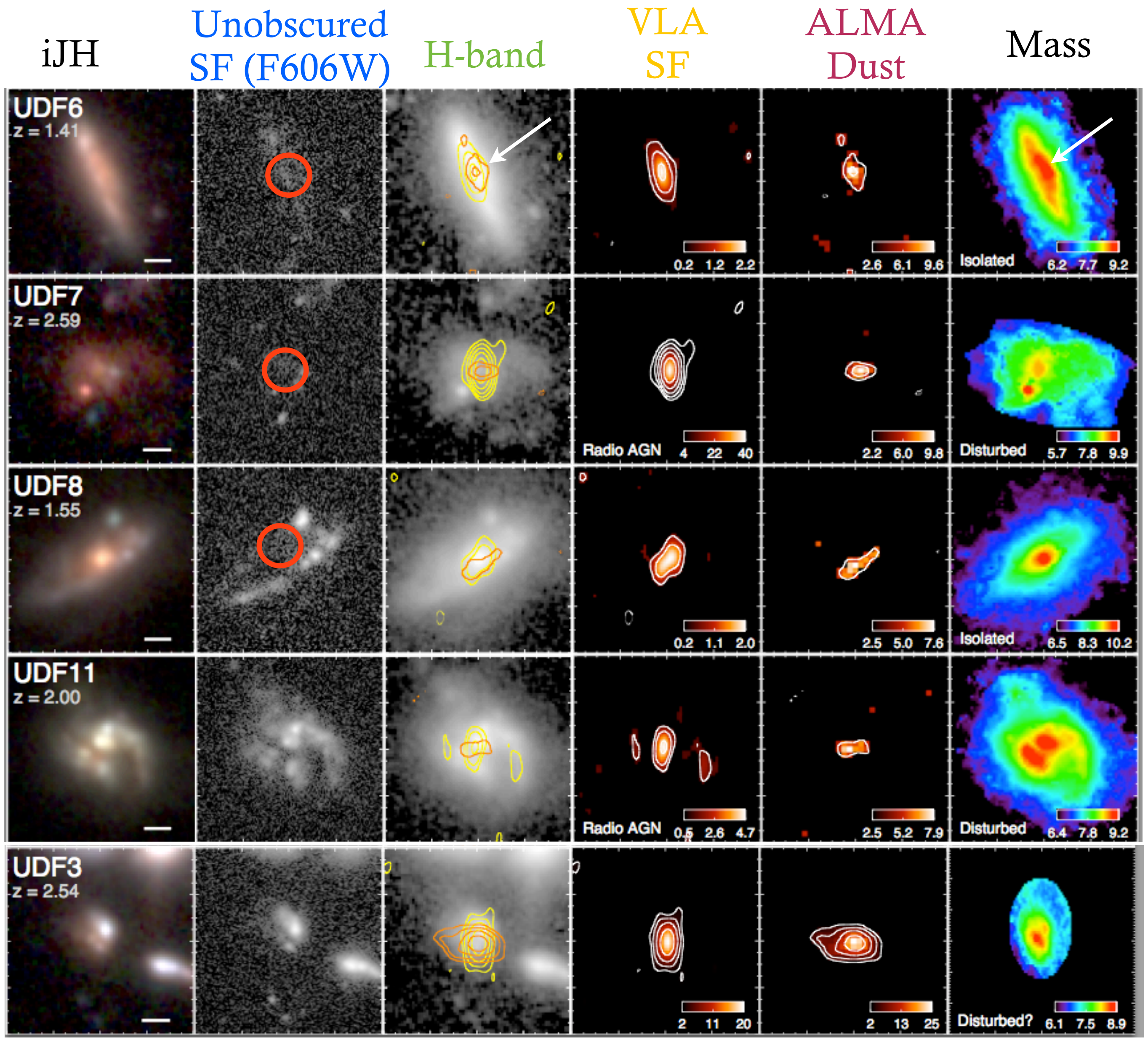
VLA AND ALMA IMAGING OF STAR FORMATION AT Z~2

Combine mass maps for z~2 MS galaxies with long wavelength high-resolution follow-ups in HUDF



Dunlop+17

VLA and ALMA Imaging of Star Formation at z~2



Peak of SF & central mass concentration co-spatial

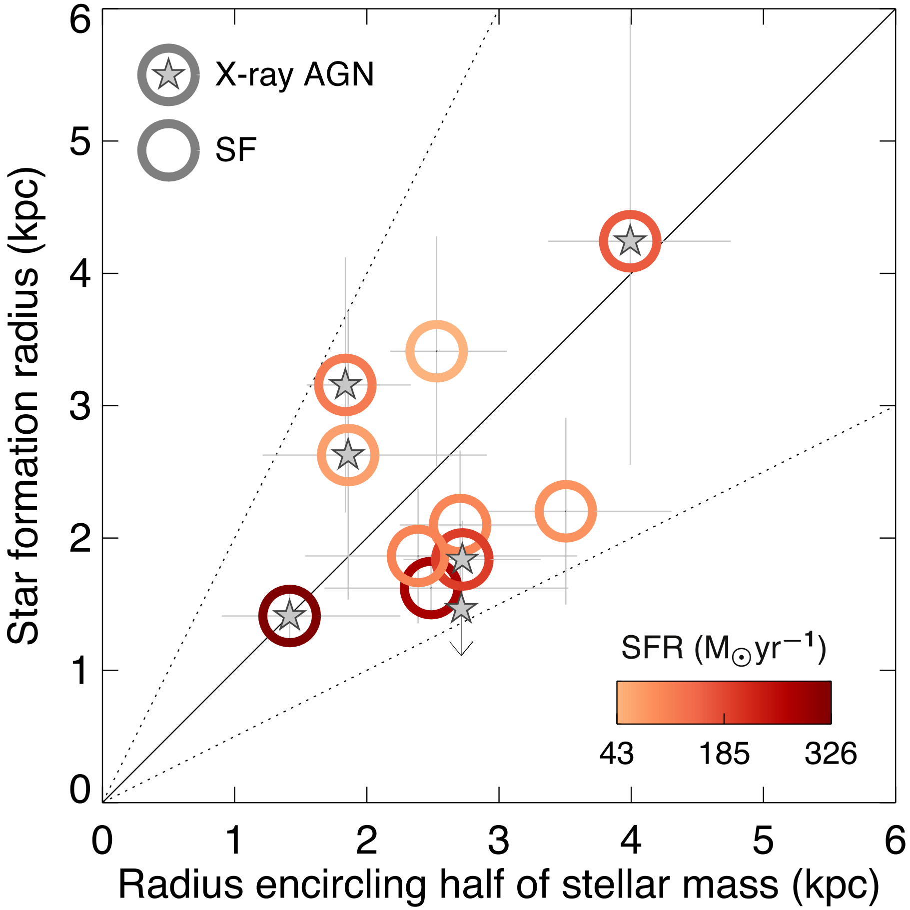
Dust (hence gas) too

(Not surprisingly,) SF mostly invisible in the rest-frame UV

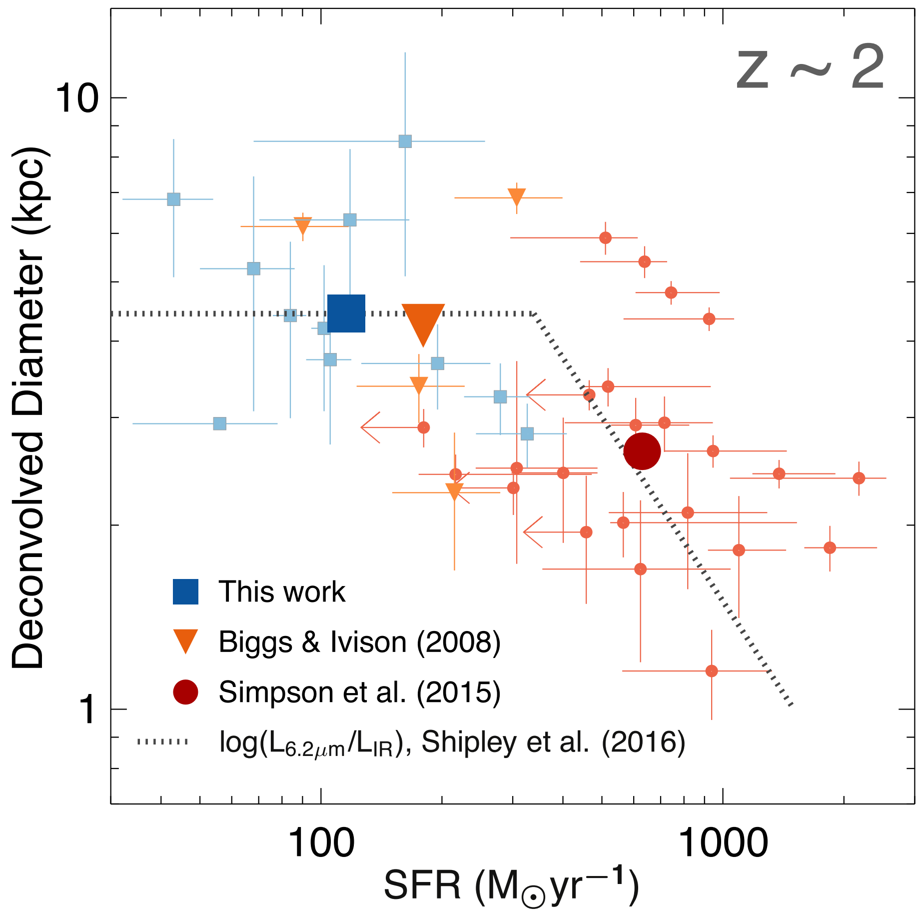
Rujopakarn,..,AC+16

Size of Star Formation at z~2

SF is as extended as already existing stars (~2kpc)



and not as compact as in sub-mm galaxies ($\lesssim$ 1kpc)



Rujopakarn,..,AC+16

Conclusions - Part 2

- $z \sim 2$ MS galaxies host, at times intense, star formation at the position of the central mass concentration (see also e.g., Nelson+16) → Bulge formation?

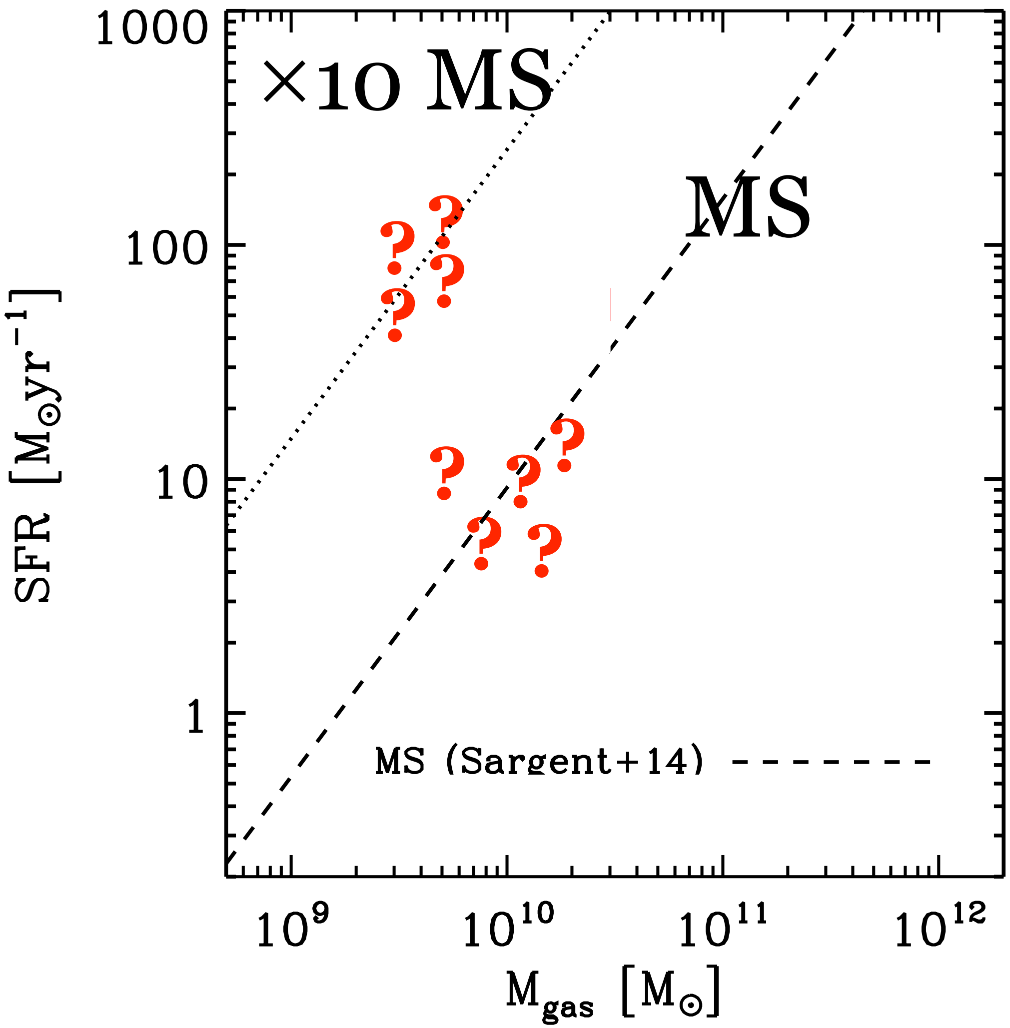
- Star formation is wide spread in MS galaxies. Different mechanisms or conditions for star formation in MS and sub-mm galaxies?

PART -3: MOLECULAR GAS AND STAR FORMATION EFFICIENCY IN A Z=1.5 CLUMPY DISK

Paper recently submitted:
Cibinel+17 - arxiv:1703.02550

GIANT CLUMPS - STAR FORMATION EFFICIENCY

Does star formation in clumps occurs in a "sustained" mode as observed in MS galaxies or in an intense and rapid mode as observed in some SB? (Daddi+2010, Genzel+2010).



$SFE = SFR/M_{gas} = 1/\tau_{depl}$

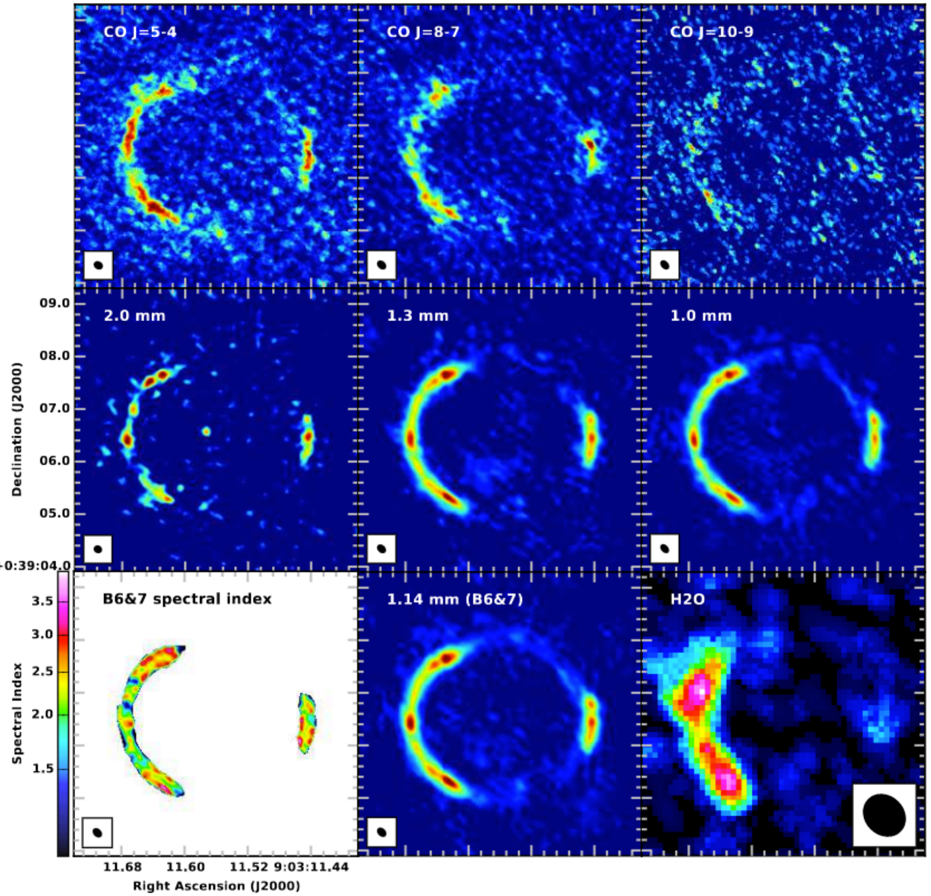
→ Position of clumps in the Schmidt-Kennicutt plane?

Need to measure M_{gas} for clumps → molecular gas (CO) observations at clump scale

GIANT CLUMPS - MOLECULAR GAS OBSERVATIONS

Resolved observations of molecular gas content in z>1 galaxies are difficult!
Available for:

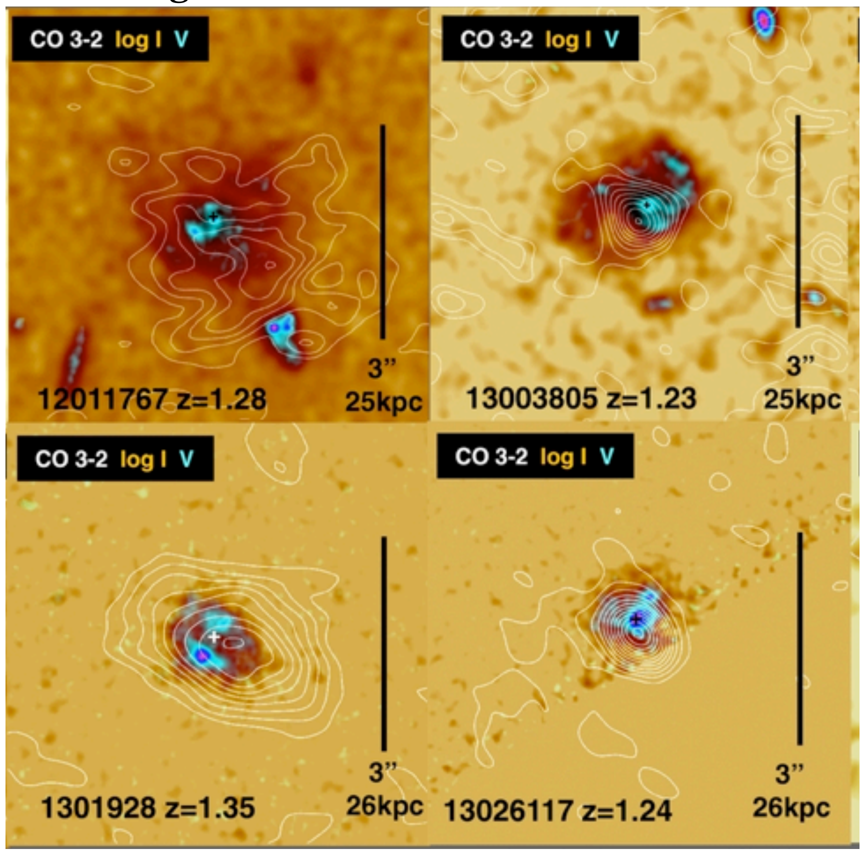
bright/lensed, sub-mm, starburst galaxies…



Vlahakis+ 2014, Genzel+13, Hatsukade 2015

…or at ~1" arcsec resolution

PHIBBS galaxies



Tacconi+ 2013, Aravena 2015, Freundlich+13

PUSHING ALMA CAPABILITIES

We observed a z=1.5 clumpy, MS galaxy with ALMA in Cycle 2

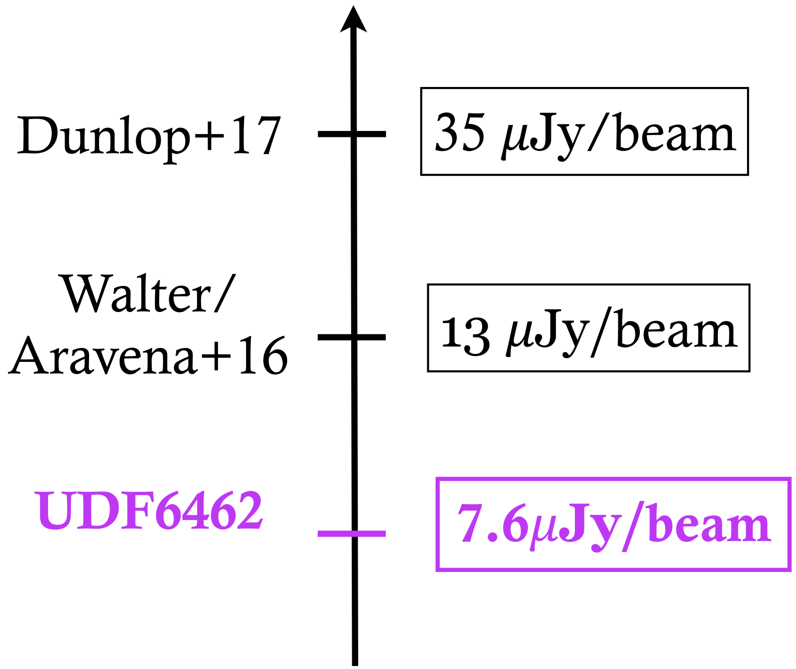
ALMA Band 6 Observations, CO(5-4) line

~4.5h on source integration

Beam: 0.6”x0.4”

Sensitivity:
- continuum (~1.3mm)= 7.6μJy
- line= 0.11mJy (35km/s)

Continuum Sensitivity @ ~1.3mm



Observations of molecular gas content at clump scales is very difficult even with ALMA

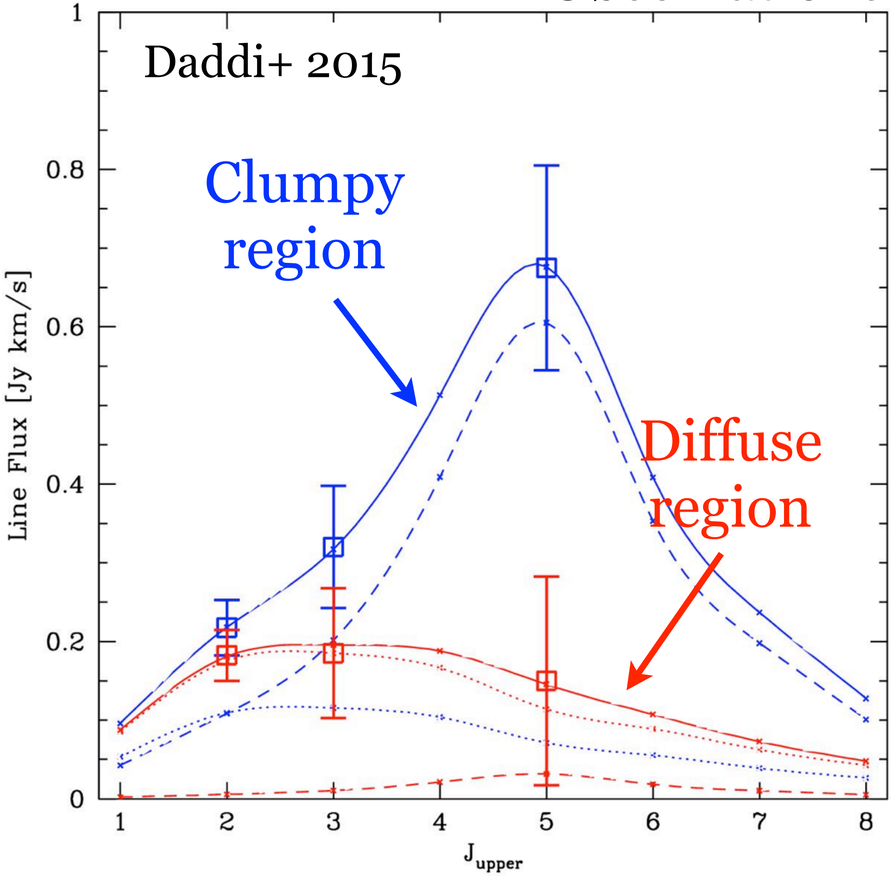
Cibinel+17

CO(5-4): WHY NOT LOWER TRANSITION?

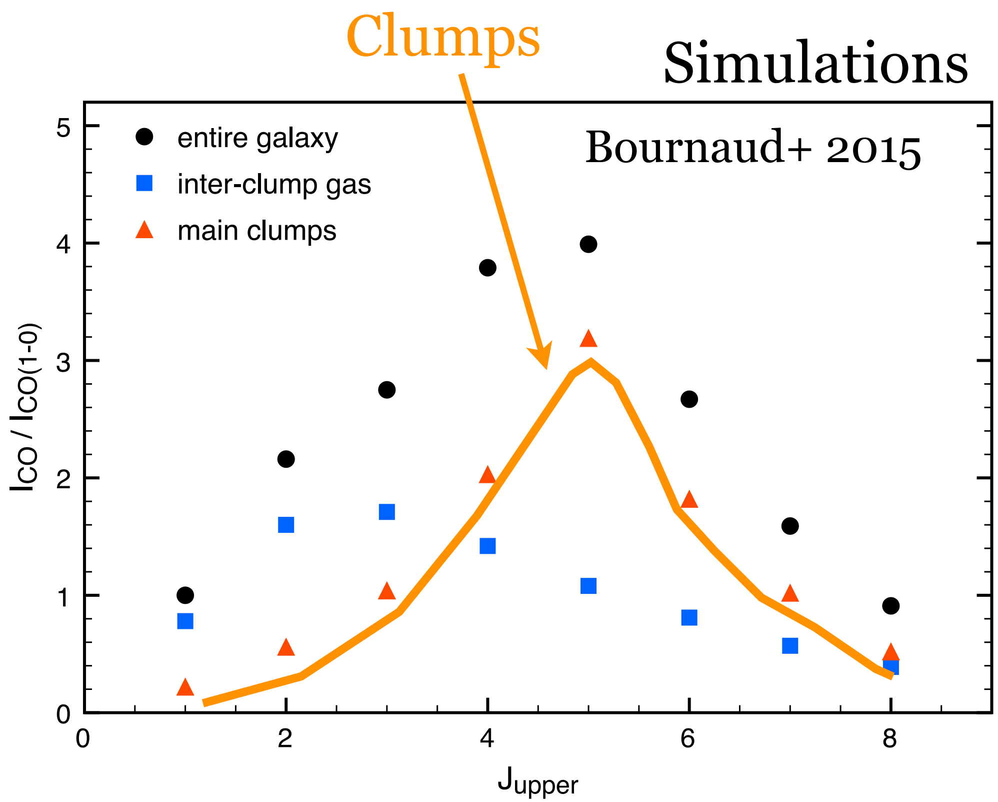
1) Easier to observe (because of ν^2 dependency of line flux for thermally excited gas)

2) Is a tracer of the high-density, star-forming gas → clumps

Observations



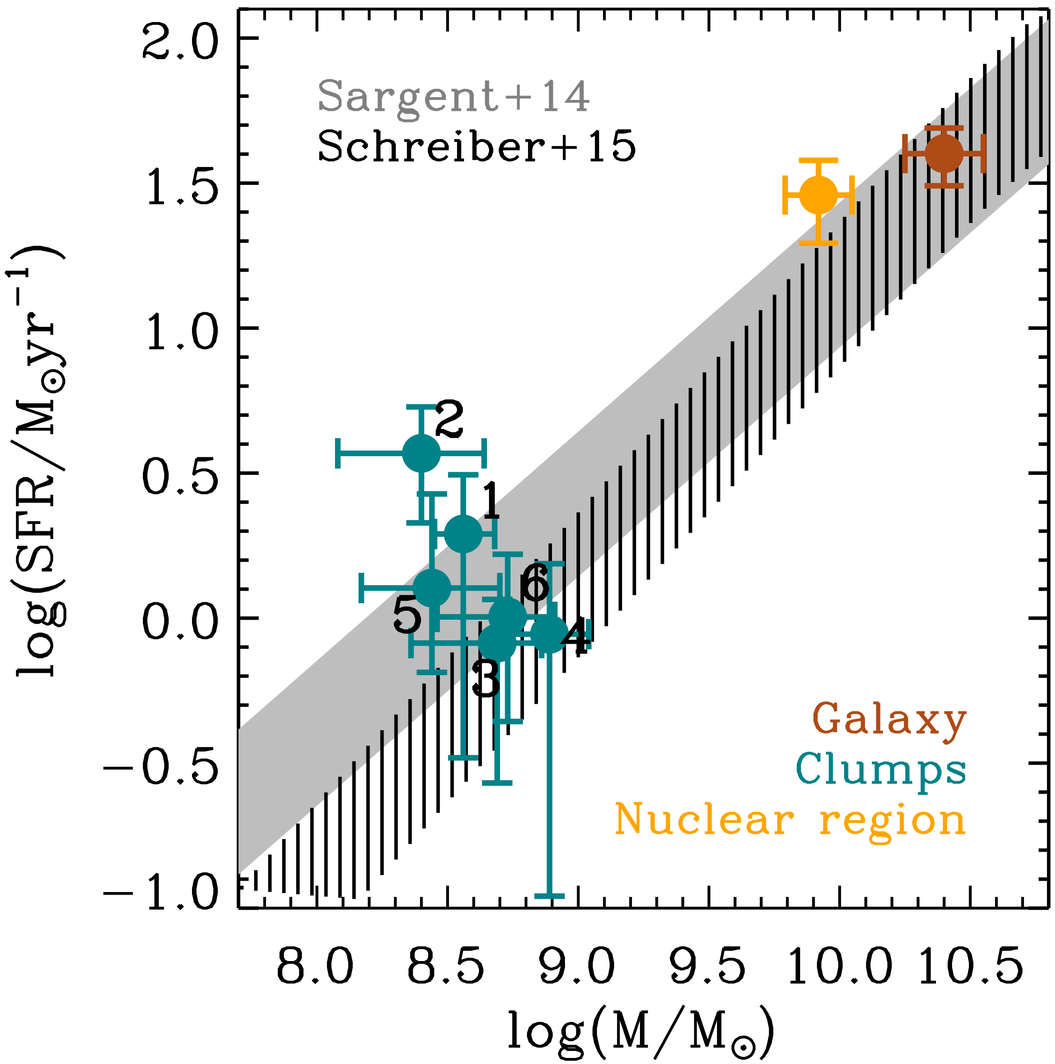
Simulations



Drawback: gas masses and SFE derived from CO will depend on the assumed line excitation (together with α_{CO}).

The Target Galaxy: UDF6462

UDF6462: a typical (~sub M★) z~1.6 clumpy disk galaxy in HUDF

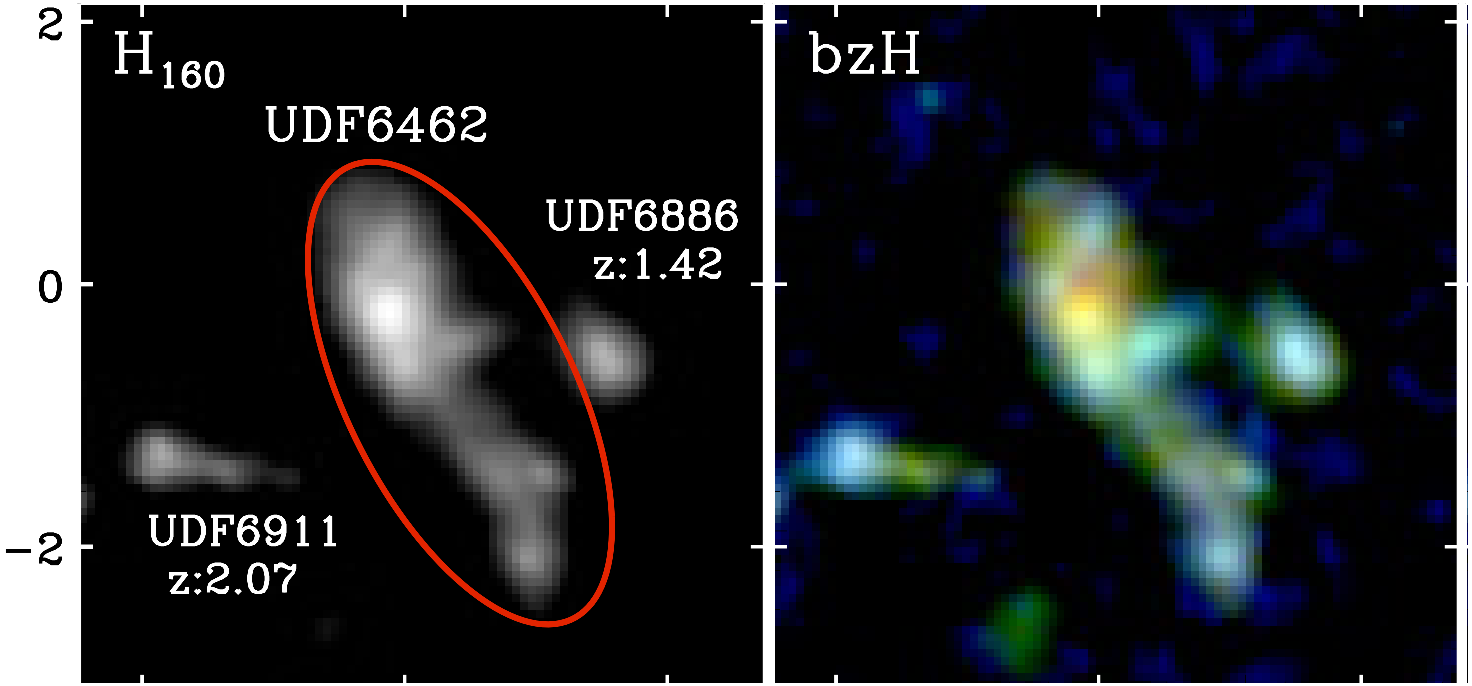


$SFR_{UV+IR} \approx 40 M_*/yr$

$L_{IR} \approx 3 \times 10^{11} L_\odot$

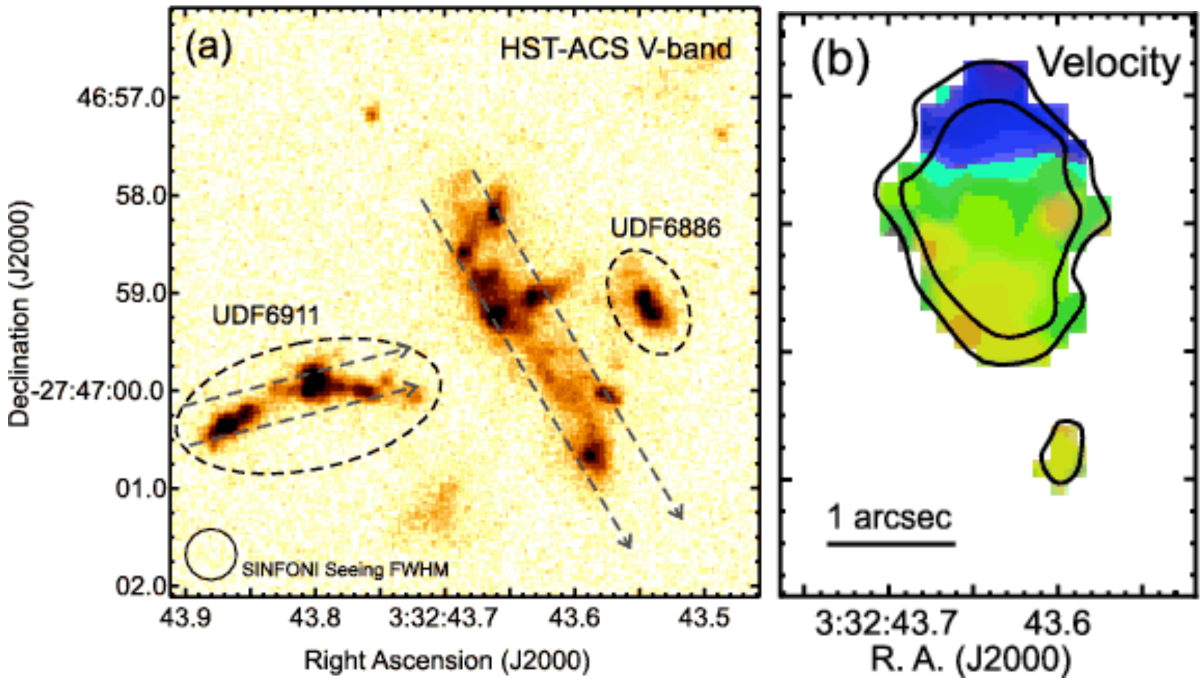
THE TARGET GALAXY: UDF6462

UDF6462: a typical z~1.6 clumpy disk galaxy in HUDF



The Target Galaxy: UDF6462

UDF6462: a typical z~1.6 clumpy disk galaxy in HUDF



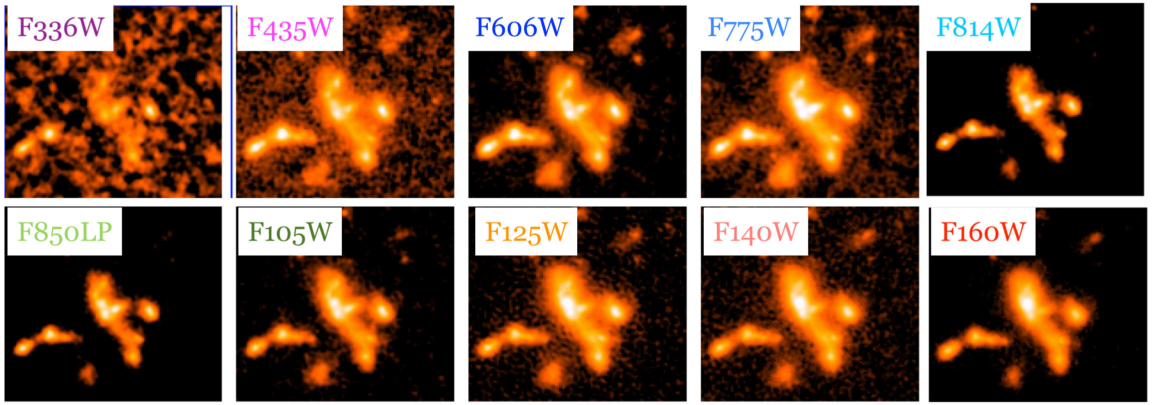
Kinematically classified as a disk from
SINFONI Hα observations (Bournaud+ 2008)

And also using the mass-map method

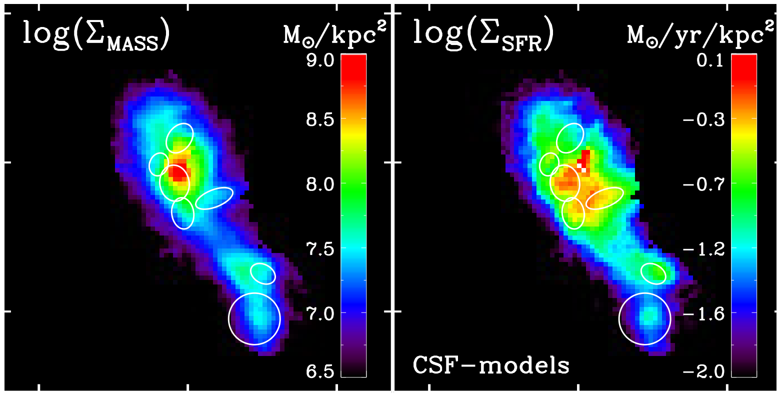
THE TARGET GALAXY: UDF6462

UDF6462: a typical z~1.6 clumpy disk galaxy in HUDF

Extremely deep HST observations at rest FUV to optical (XDF area)



Resolved stellar mass, SFR, extinction, maps



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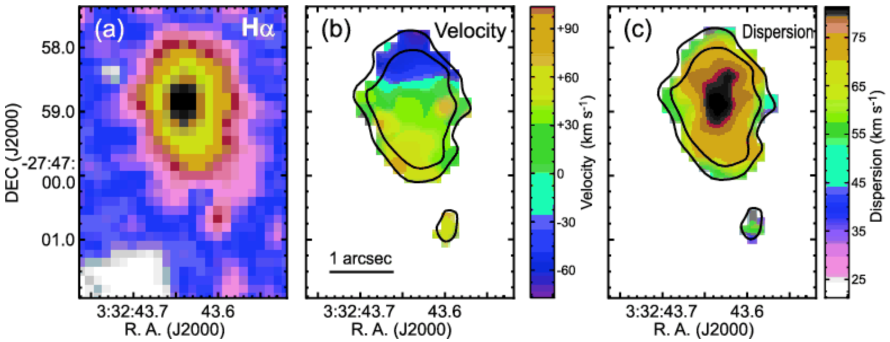
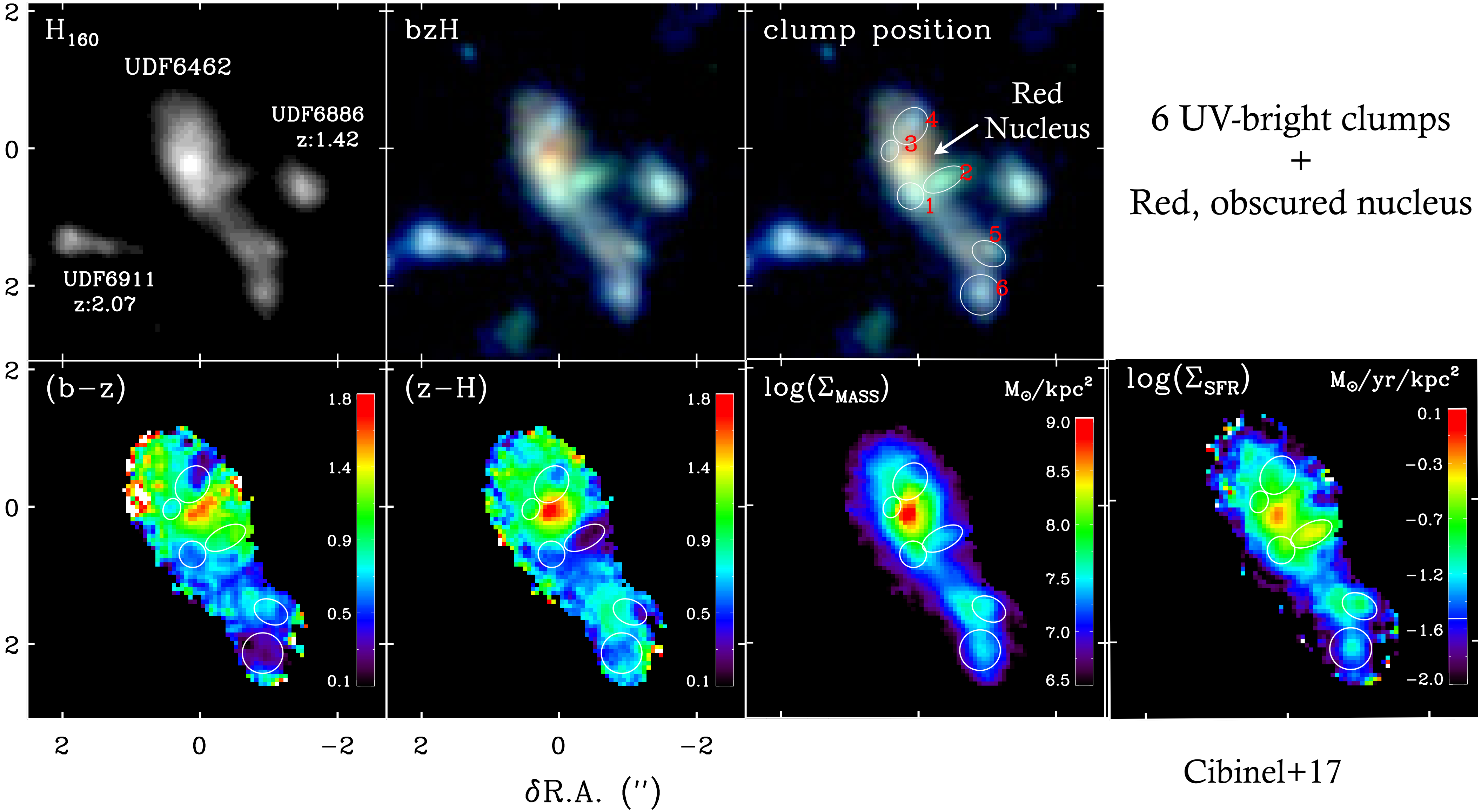
SINFONI Hα, metallicity maps



Bournaud+ 2008

+ FIR & Radio VLA observations

THE TARGET GALAXY: UDF6462



6 UV-bright clumps
+
Red, obscured nucleus

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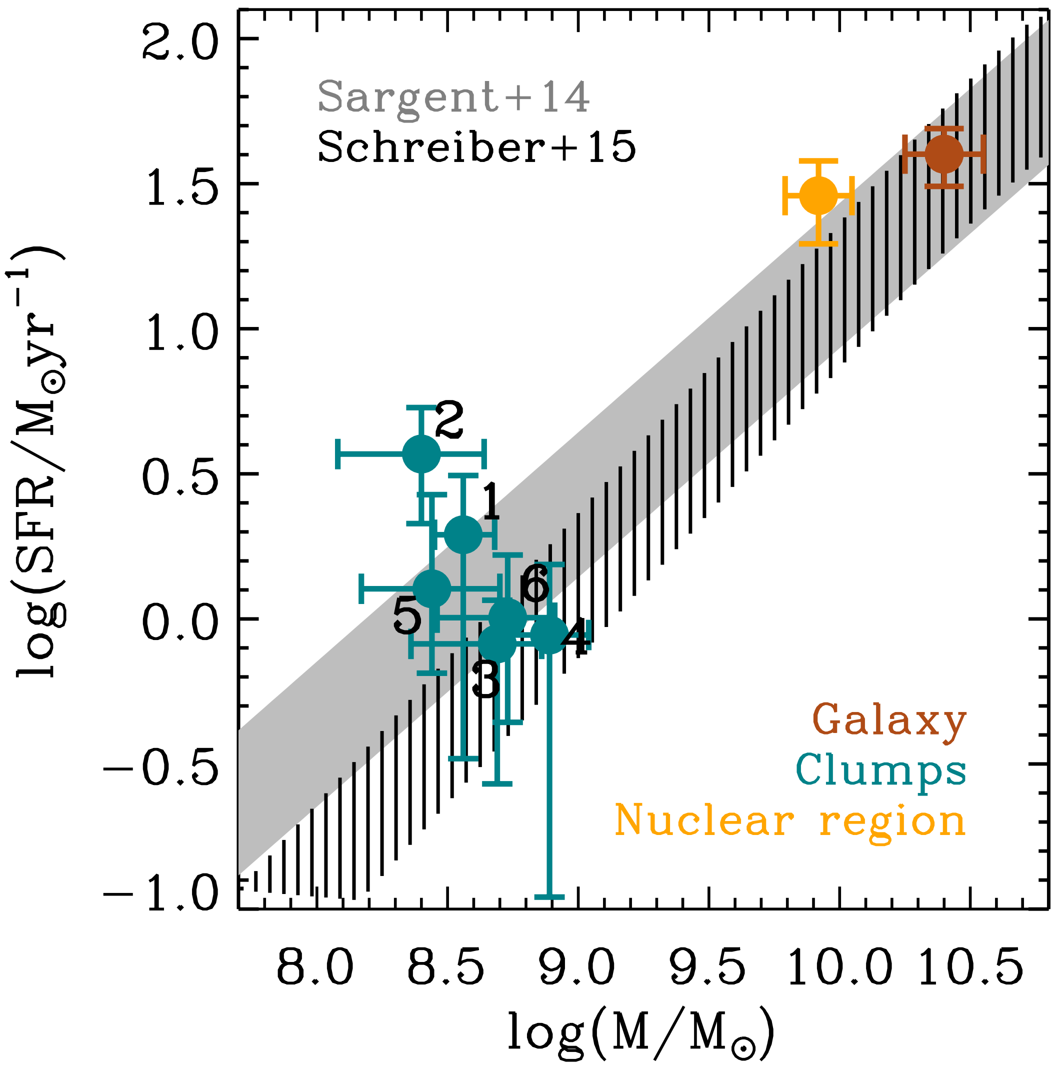
The Target Galaxy: UDF6462



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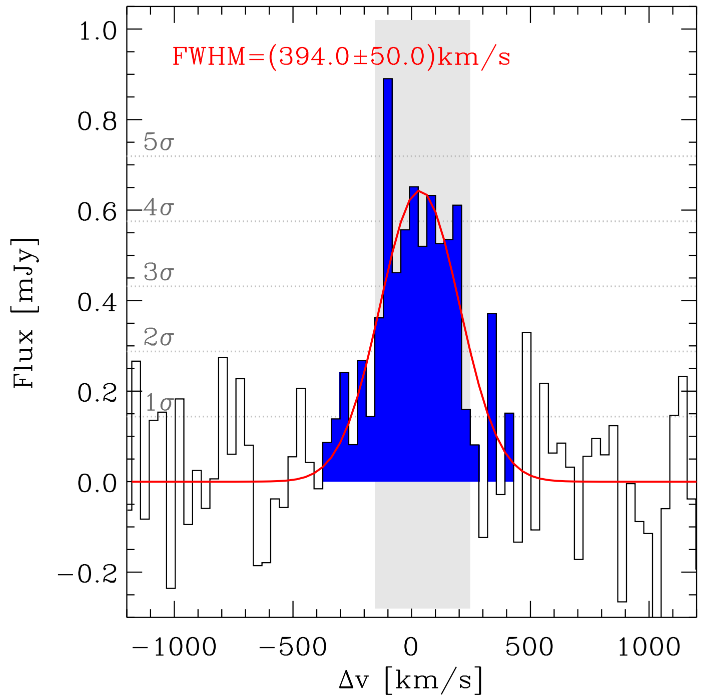
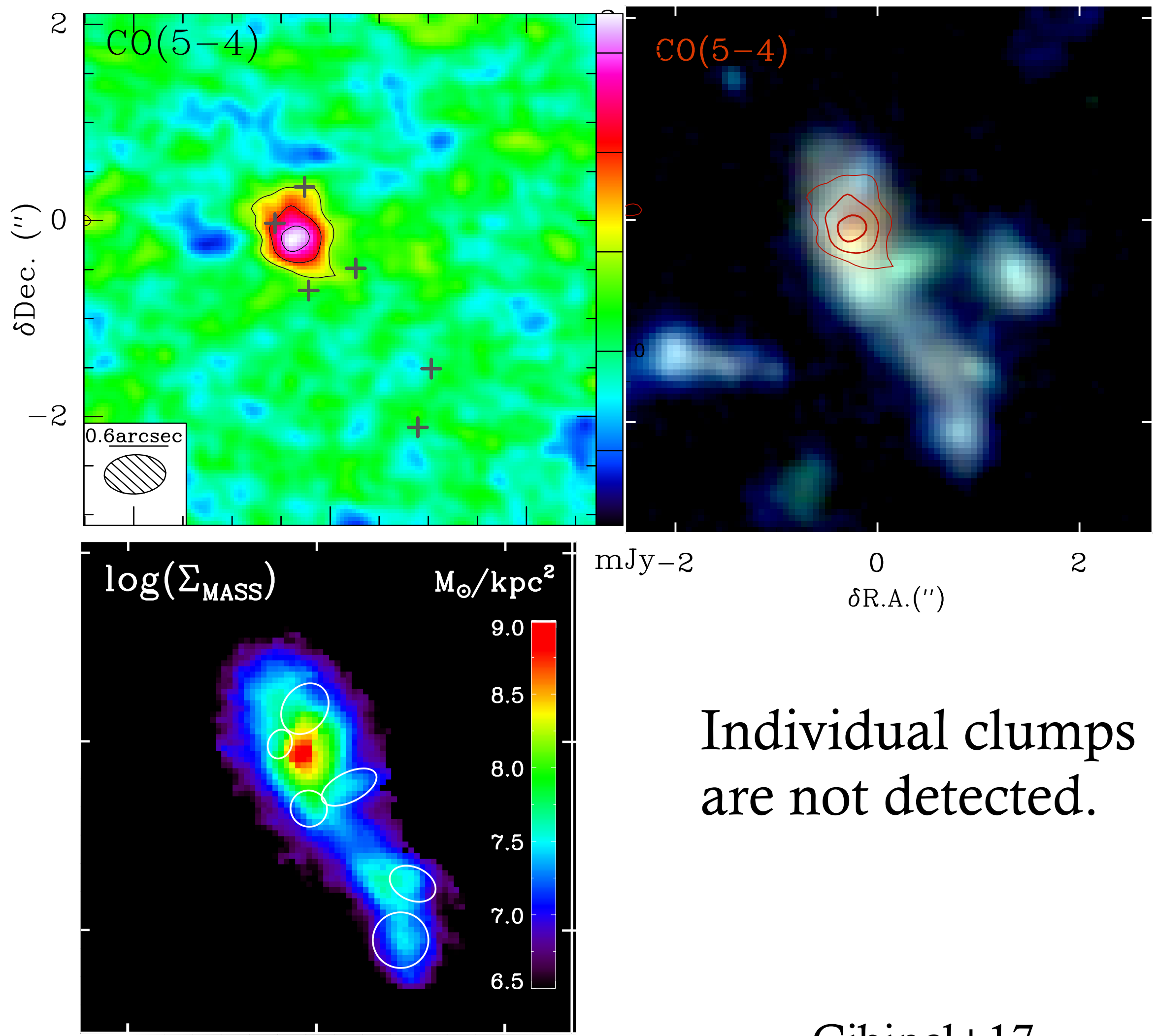
ALMA CO(5-4) DATA

Detected CO(5-4) emission confined to the red, central region ⟷ central mass concentration (see part 2)





Individual clumps are not detected.

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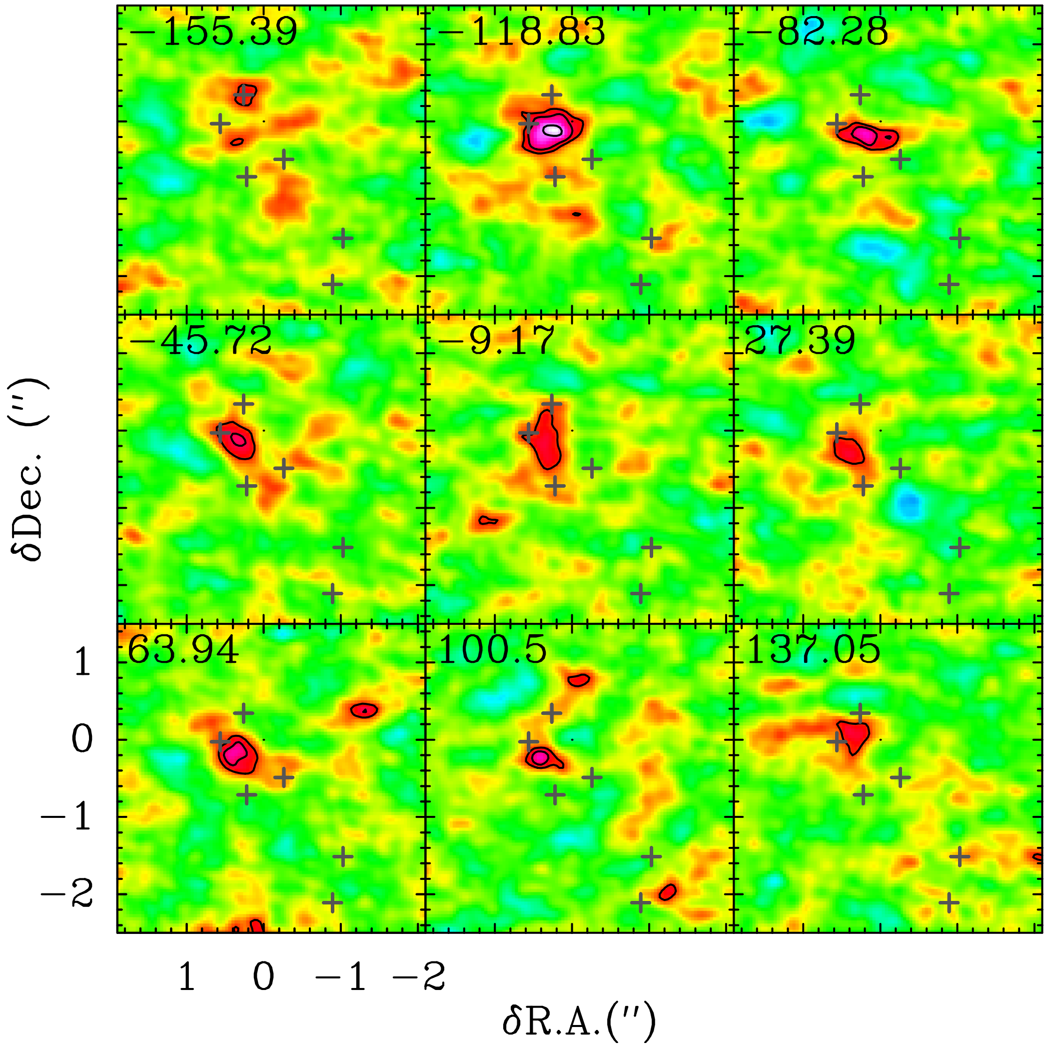
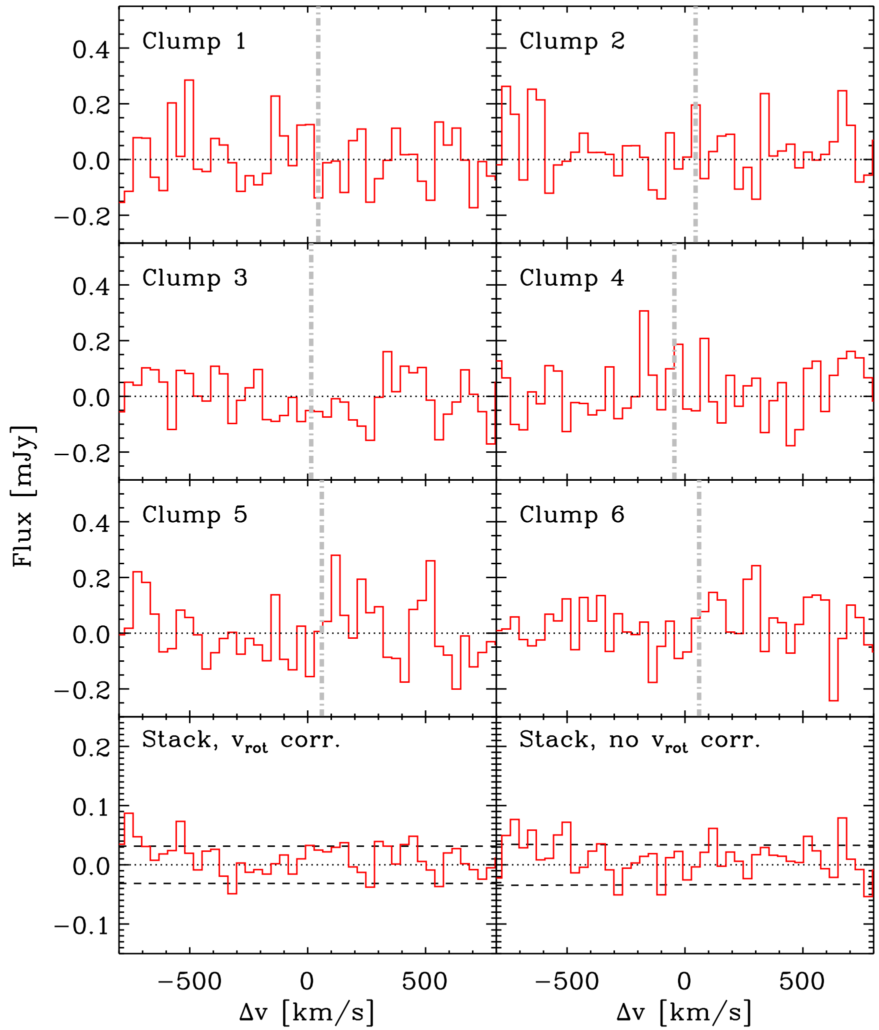
ALMA CO(5-4) DATA

Clumps undetected also at high spectral resolution & after stacking





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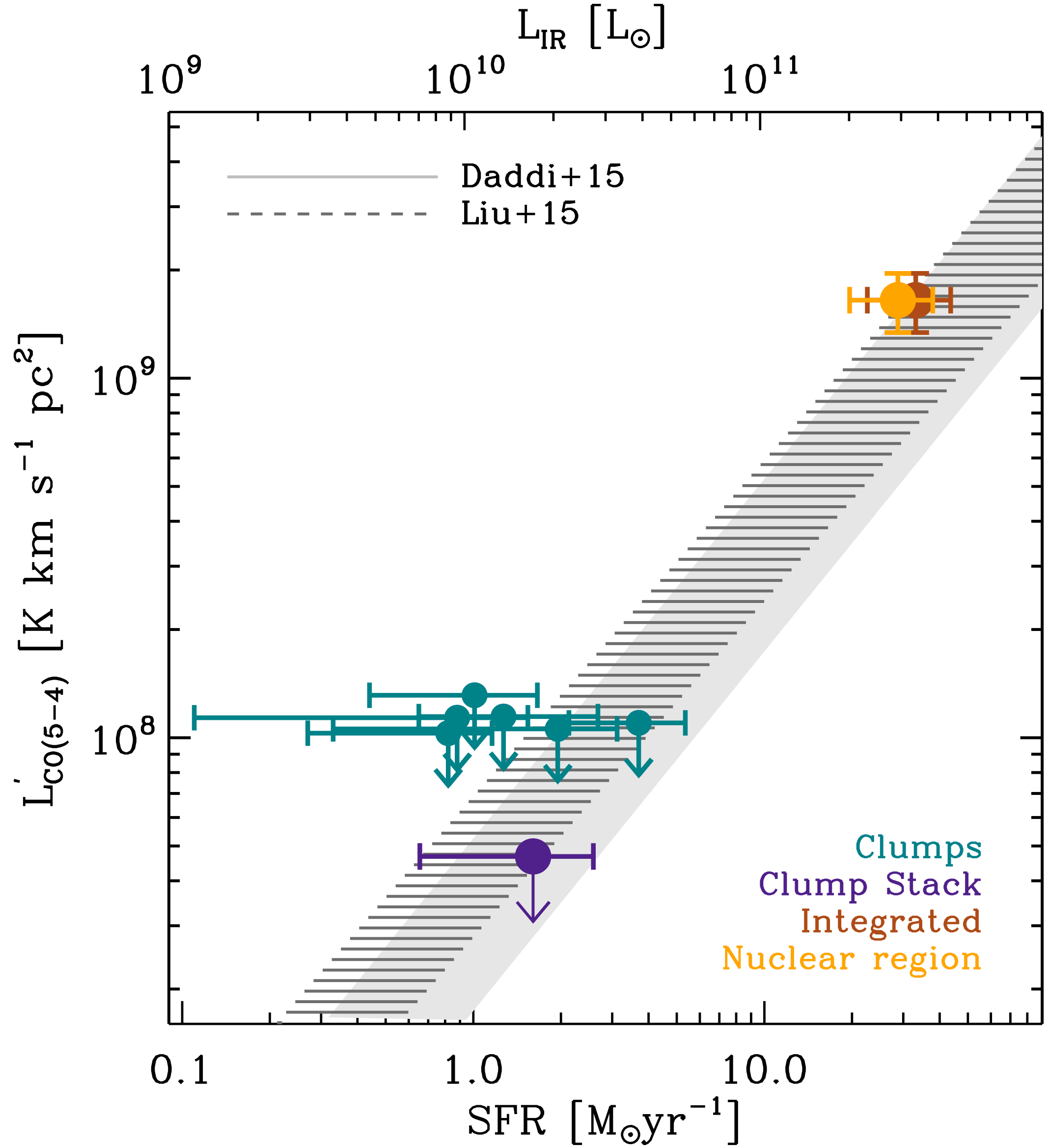
$L'_{CO(5\text{-}4)}$ - L_{IR} (SFR) Correlation



Clumps consistent with $L'_{CO(5\text{-}4)}$ - L_{IR} measured for integrated galaxies (both SB and MS)

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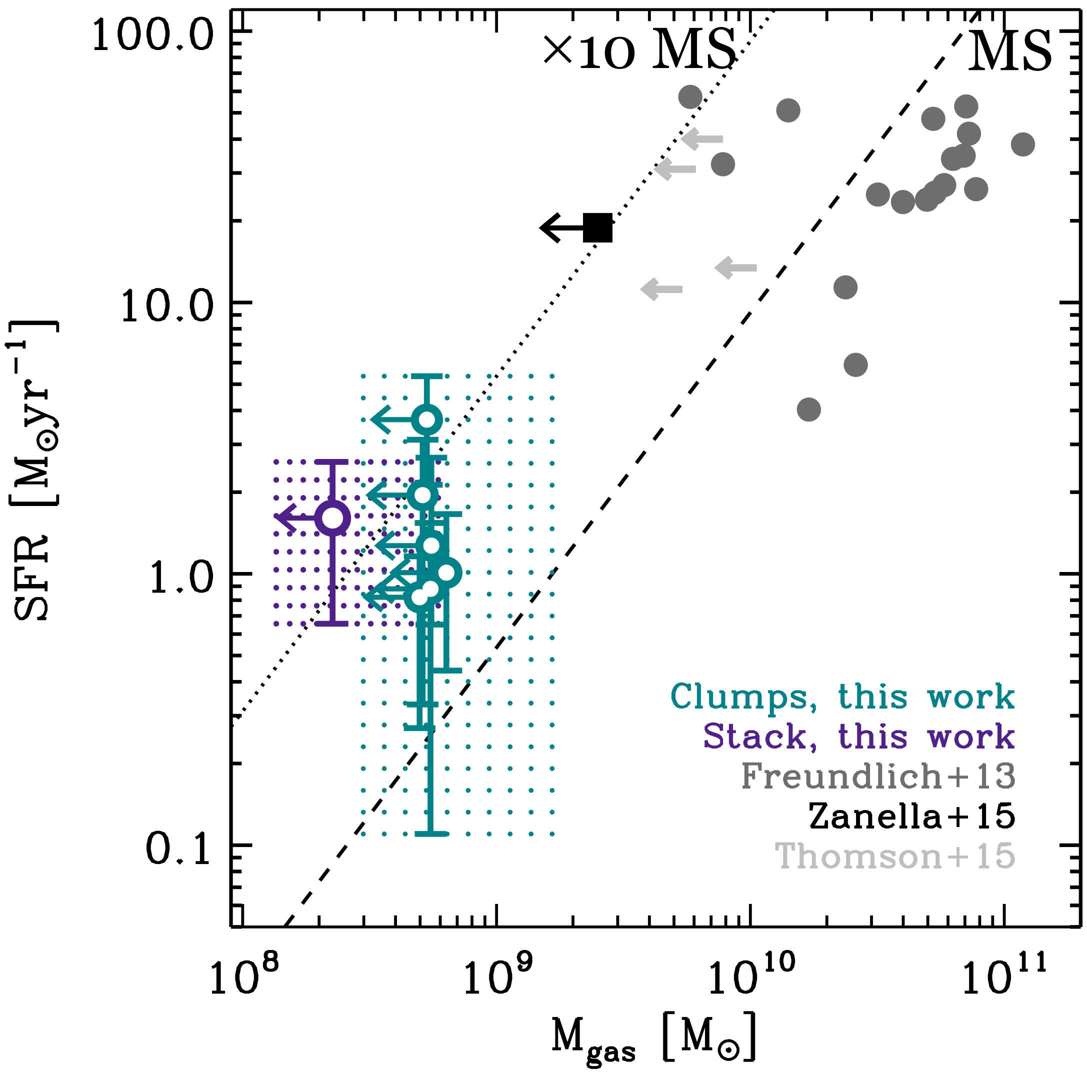
SFE: Schimdt-Kennicutt Plane



Probing ~1dex fainter clumps than other studies of gas content in resolved regions
→ Single out individual clumps

Clumps seem to deviate from MS locus

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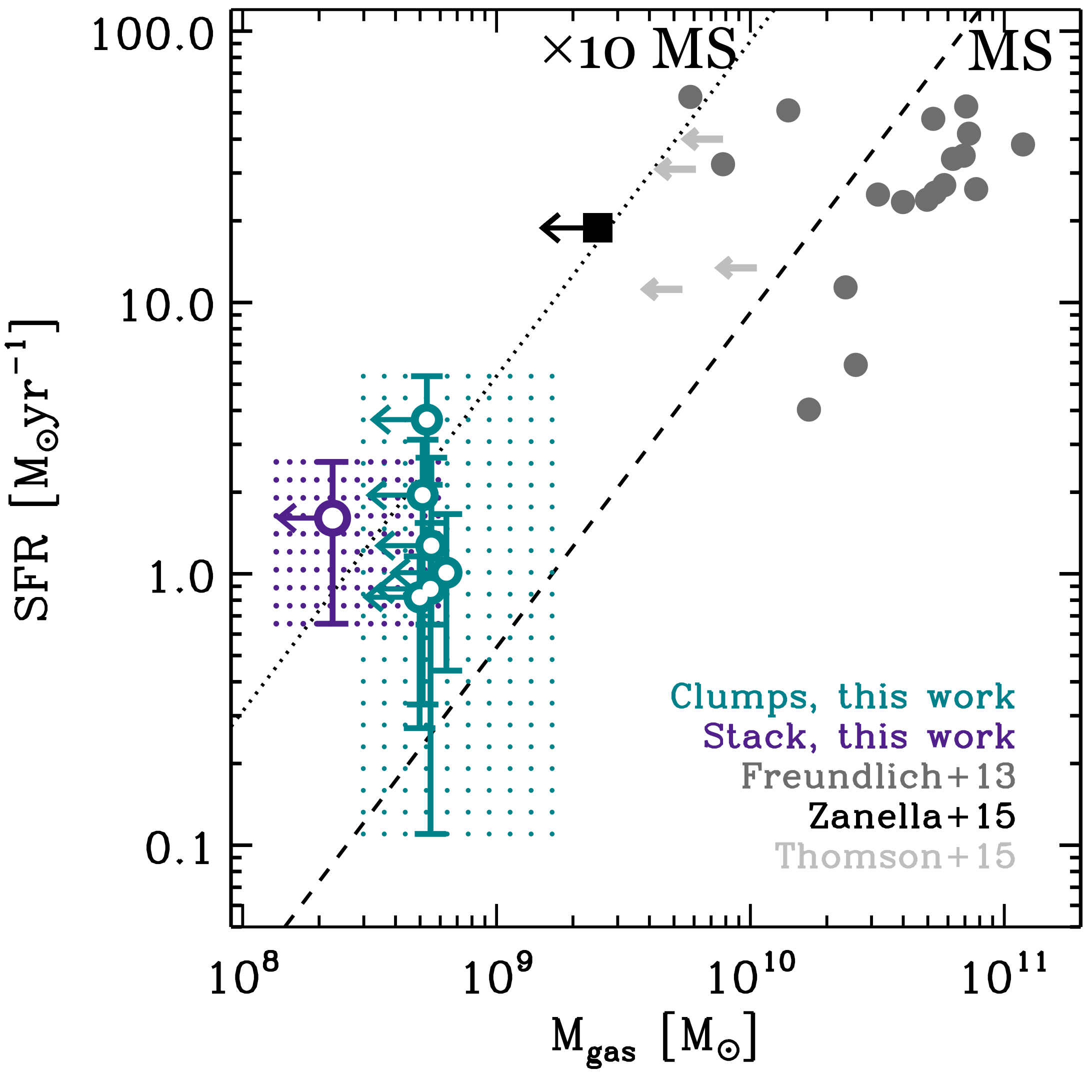
SFE: Schimdt-Kennicutt Plane



Possible Interpretations:

- genuine high efficiency in clumps (stellar feedback and disk instability torques funneling gas towards the galaxy centre could contribute too)

- late stage of gas consumption (100-300 Myr timescale for UV vs. instantaneous gas content tracer)

- UV-bright clumps may have lower SFR than anticipated

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CONCLUSIONS - PART 3

- In UDF6262, CO(5-4) tracing star forming gas is observed at the center of the galaxy extending over ~2kpc.
- Stacking analysis suggests high SFE in high SFR clumps.
- Studies of molecular gas on clump scales for $M_\star$, MS galaxies is highly challenging even in the ALMA area

Conclusions - Part 1 to 3

What is the role of mergers vs. instabilities in MS evolution?

- We have developed a classification schemes based on the resolved mass distribution in galaxies which can help distinguish mergers and clumpy disks in the lack of kinematic information

Where is the SF occurring in MS galaxies?

- In main sequence galaxies at z~2 star formation is co-spatial with central mass concentration but is extended (~2kpc)

How is star-formation regulated in high-z, MS clumpy galaxies?

- ALMA observations of 6 clumps in a z=1.5 in suggest that they could have a high efficiency of SF.

THANK YOU!