November 27, KASI, Daejeon, Korea

East-Asia ALMA Science workshop 2017

ALMA VIEW OF HIGH-REDSHIFT GALAXIES

Ken-ichi Tadaki (NAOJ)

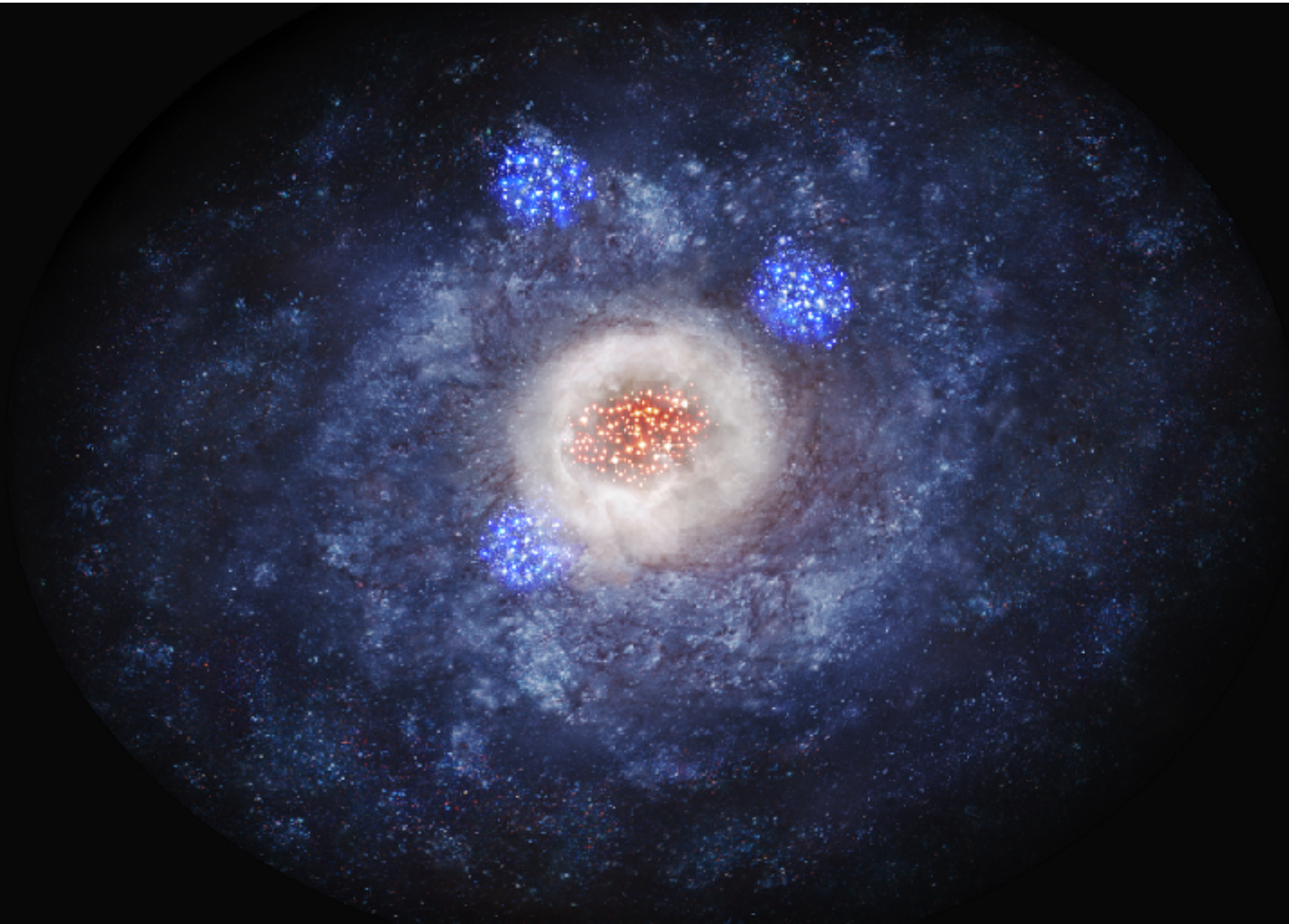
I. Our ALMA results about bulge formation in massive galaxies

II. A review of recent ALMA studies for high-z galaxies

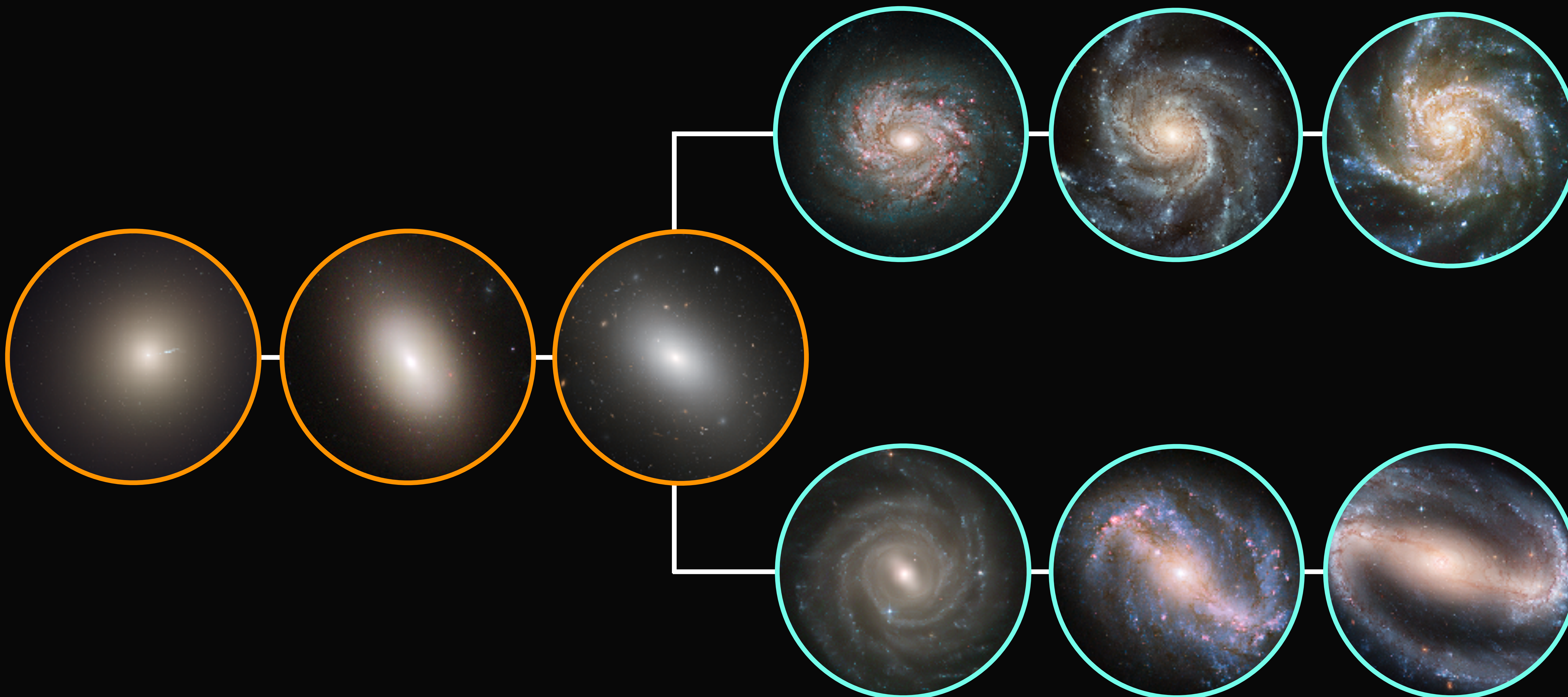
The Astrophysical Journal, 834:135 (10pp), 2017 January 10
doi:10.3847/1538-4357/834/2/135

BULGE-FORMING GALAXIES WITH AN EXTENDED ROTATING DISK AT $z \sim 2$

Ken-ichi Tadaki[1], Reinhard Genzel[1,2,3], Tadayuki Kodama[4,5], Stijn Wuyts[6], Emily Wisnioski[1], Natascha M. Förster Schreiber[1], Andreas Burkert[1,7], Philipp Lang[1], Linda J. Tacconi[1], Dieter Lutz[1], Sirio Belli[1], Richard I. Davies[1], Bunyo Hatsukade[4], Masao Hayashi[4], Rodrigo Herrera-Camus[1], Soh Ikarashi[8], Shigeki Inoue[9,10], Kotaro Kohno[11,12], Yusei Koyama[13], J. Trevor Mendel[1,7], Kouichiro Nakanishi[4,5], Rhythm Shimakawa[5], Tomoko L. Suzuki[5], Yoichi Tamura[11], Ichi Tanaka[13], Hannah Übler[1], and Dave J. Wilman[1,7]



Hubble sequence



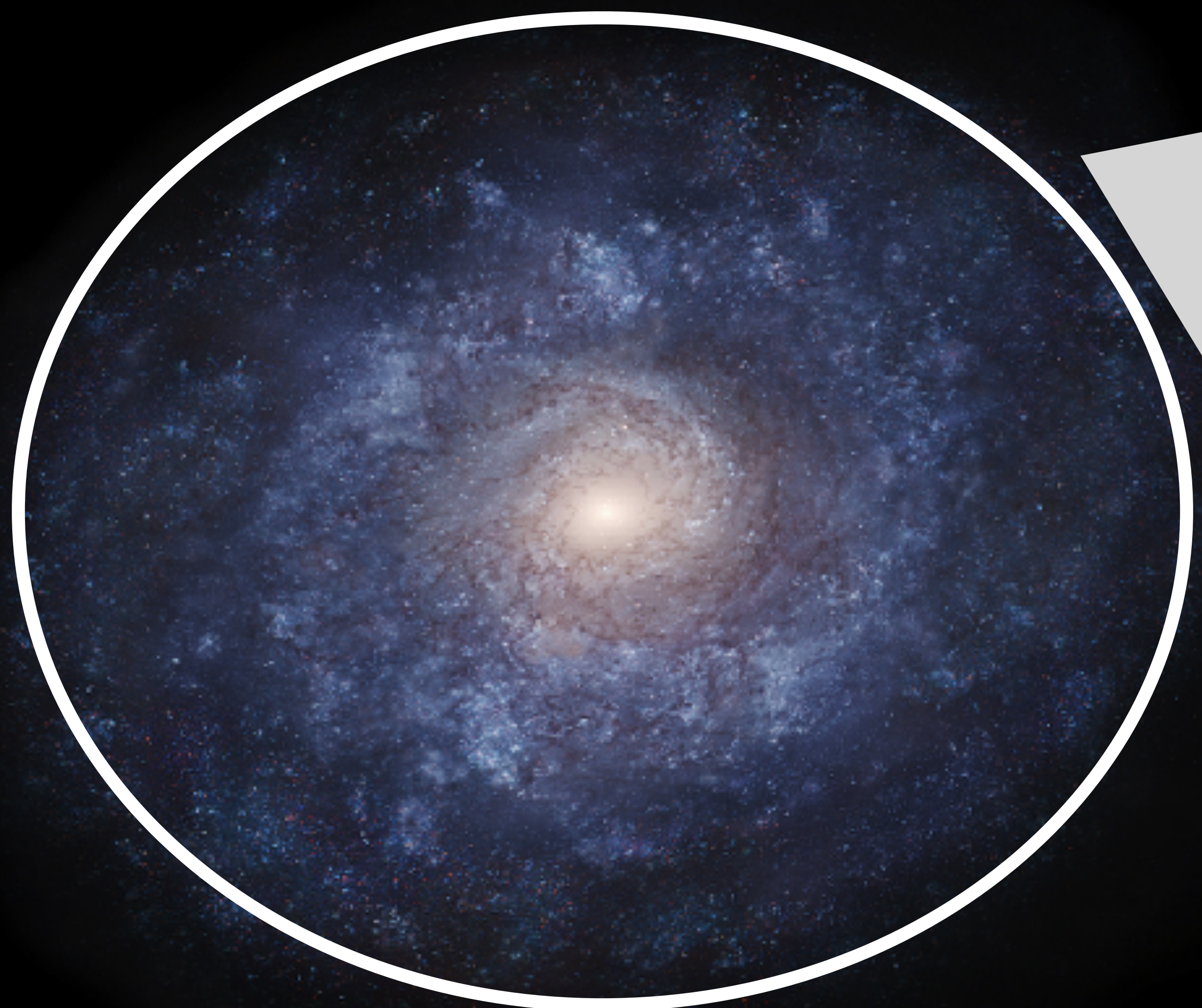
bulge-dominated
$n>2$

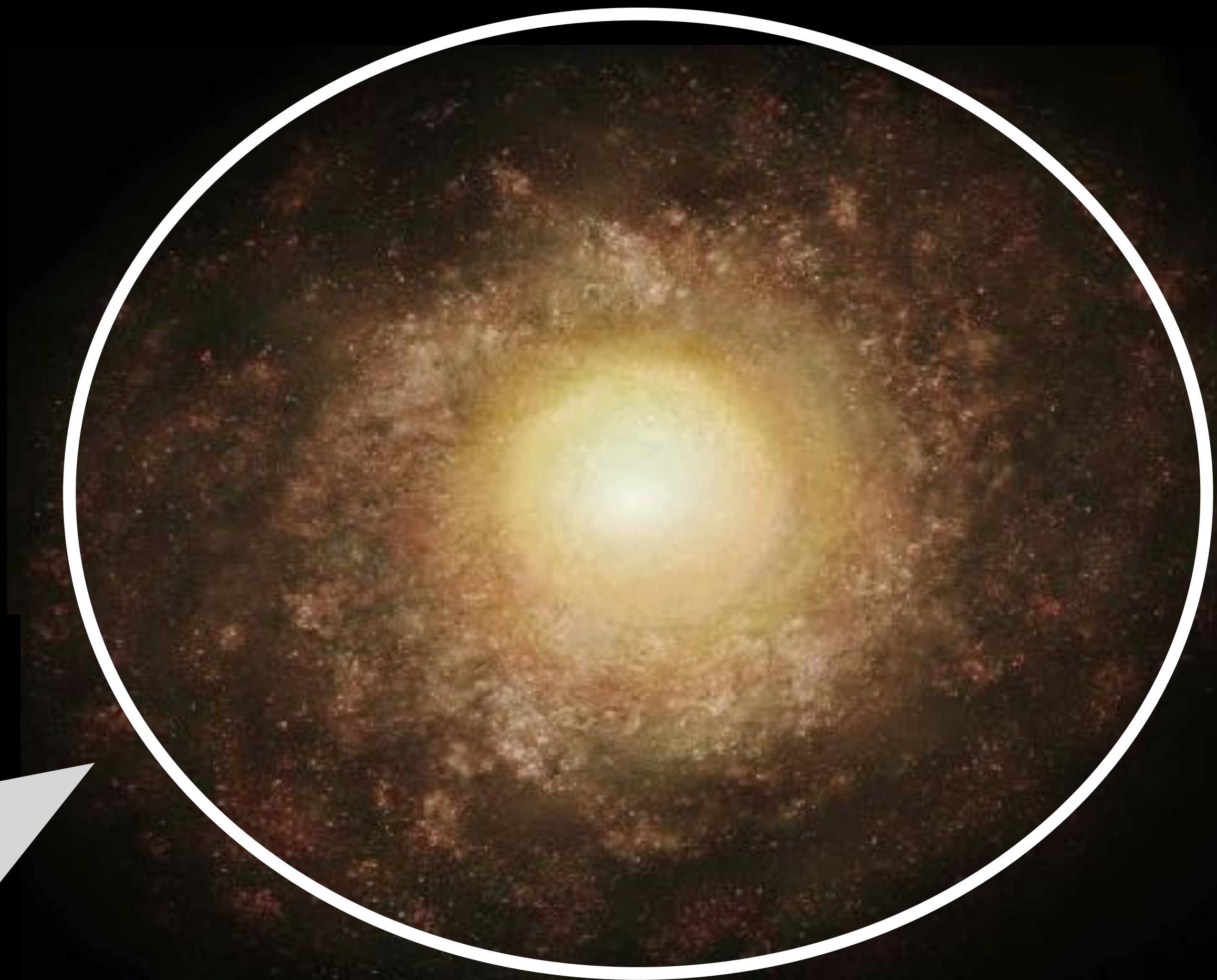
disk-dominated
$n<2$

NASA, ESA, M. Kornmesser

Galaxy evolution

disk-dominated star-forming galaxies





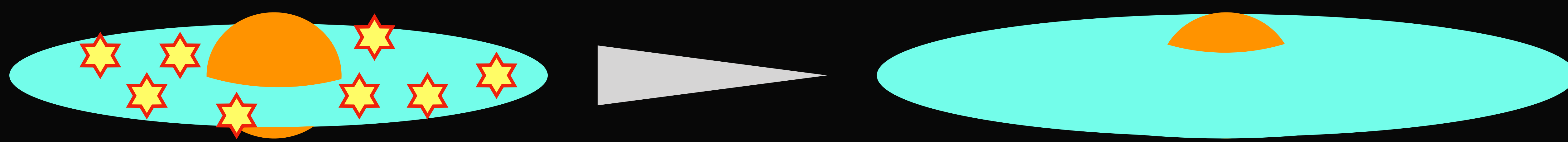
bulge-dominated quiescent galaxies

How did galaxies change morphologies?

Our approach:

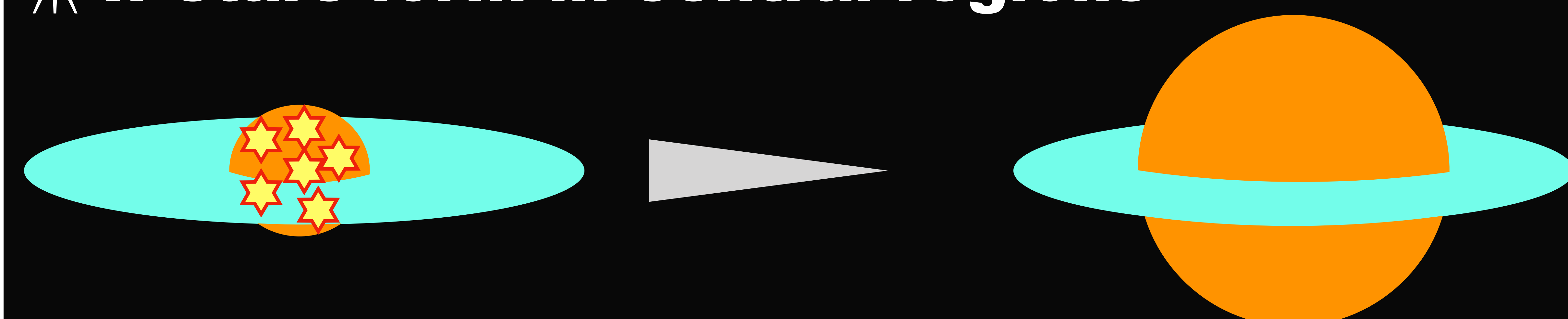
Study the spatial distribution of star formation

If stars form in disks



disk-dominated　　　　　more disk-dominated

If stars form in central regions

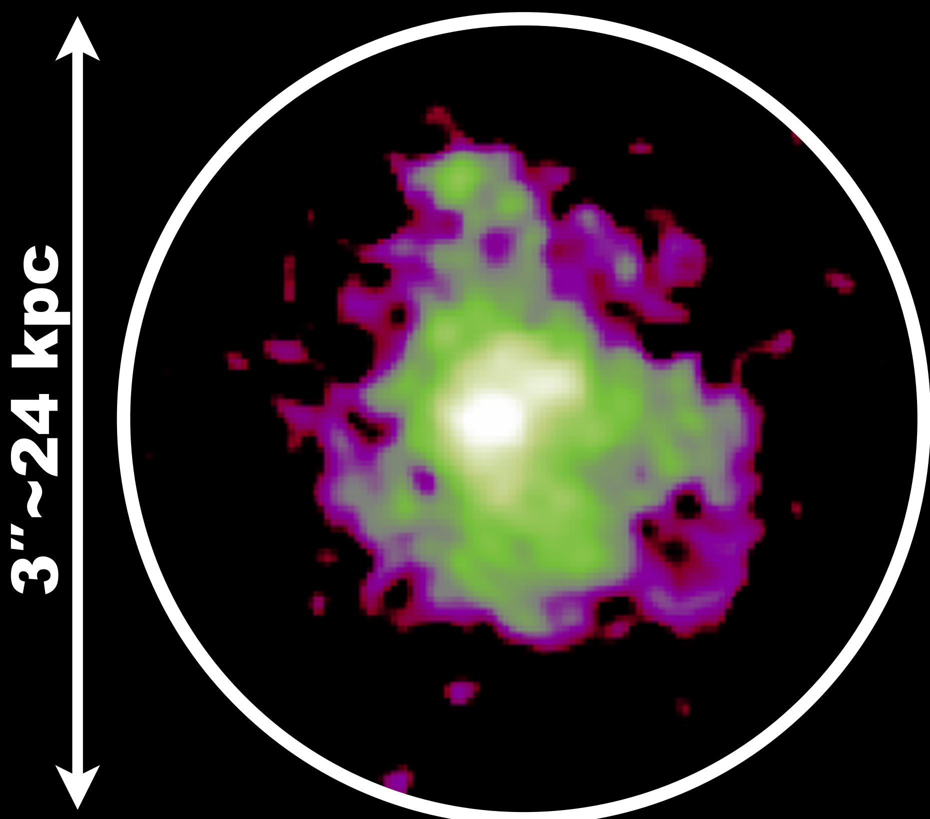


disk-dominated　　　　　bulge-dominated

Where do stars form?

The most massive SFGs at z=2.5 (Tadaki+17)

HST (H-band)

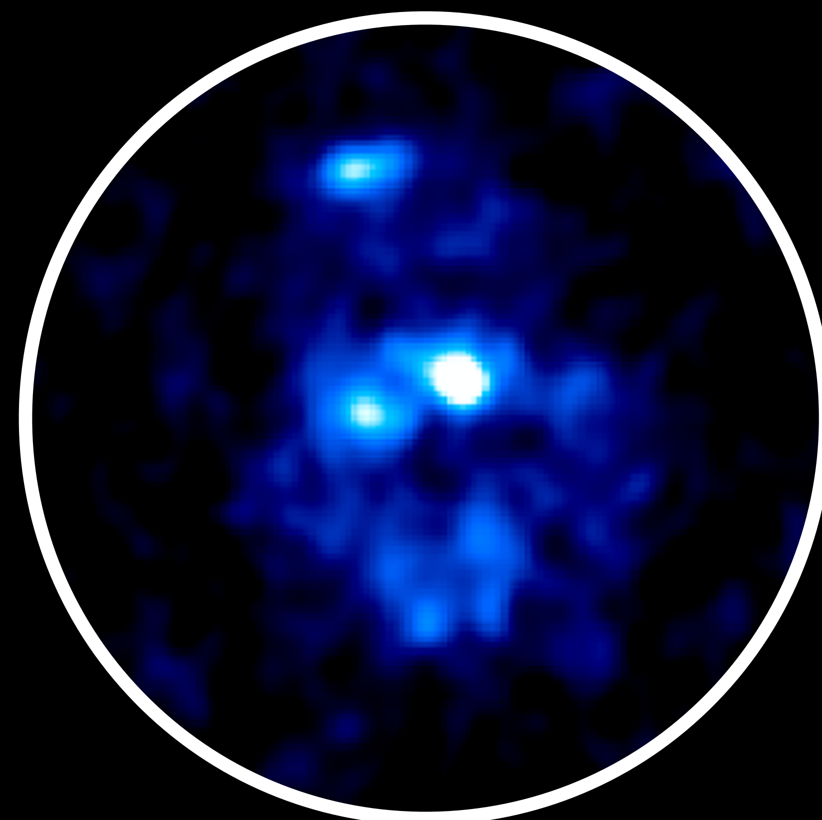


stellar mass

↓

extended disk

HST (I-band)

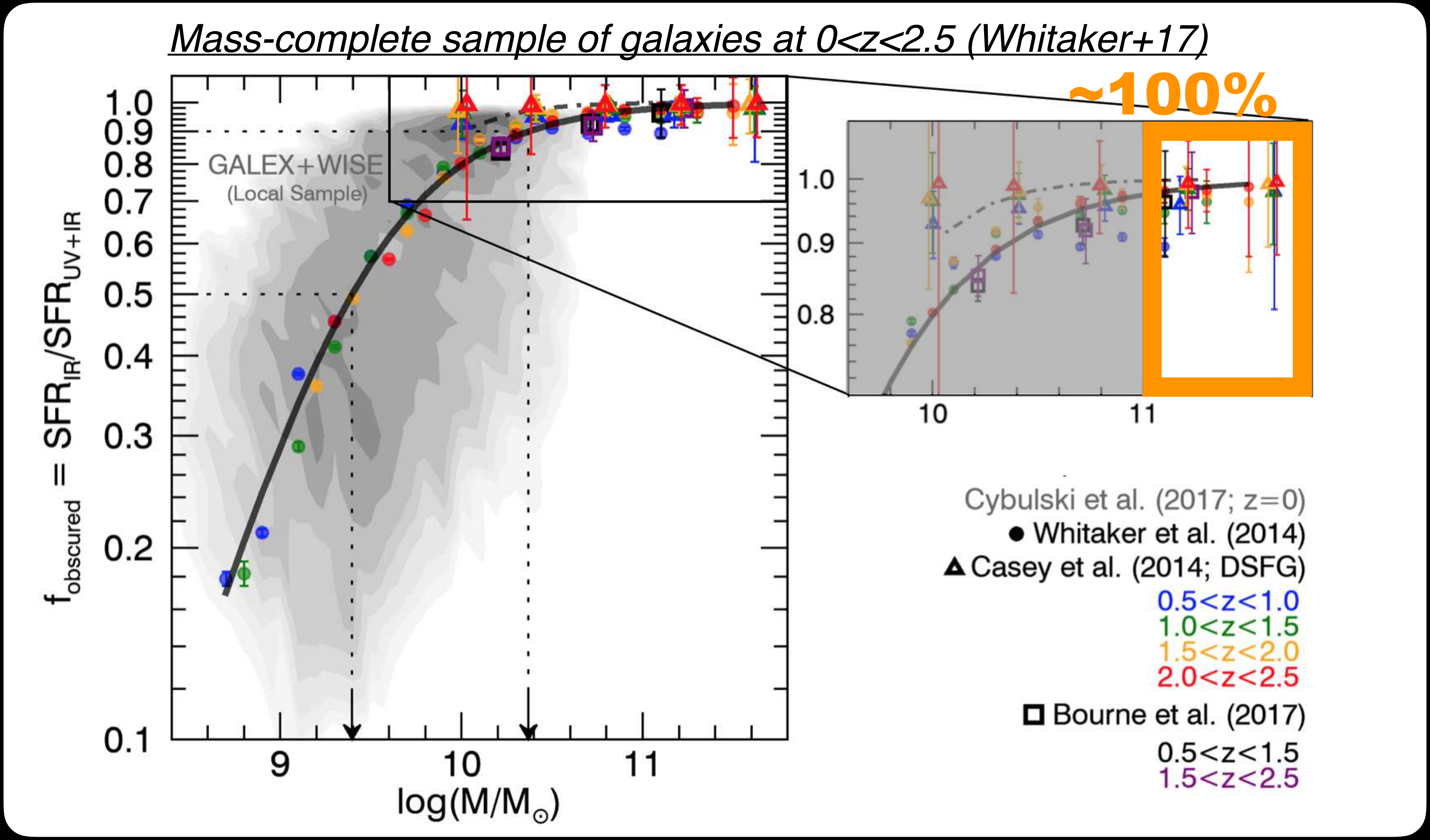


unobscured star formation

↓

clumpy

Dust extinction problem



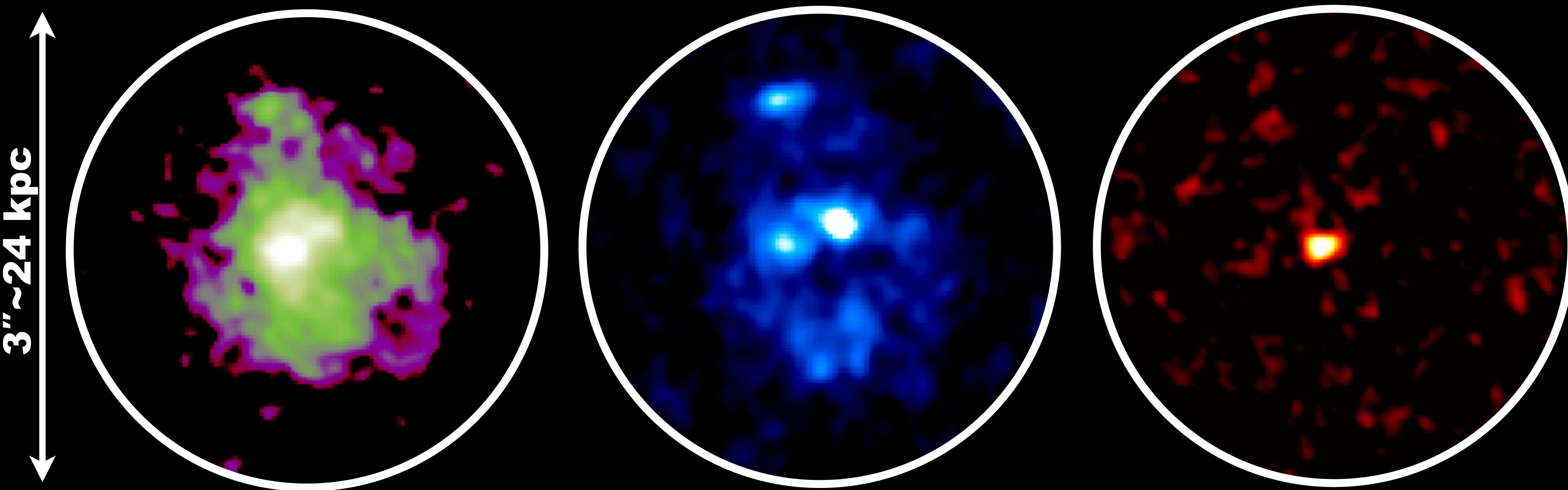
For the most massive star-forming galaxies

▸IR light traces ~100% of total star formation

Where do stars form?

The most massive SFGs at z=2.5 (Tadaki+17)

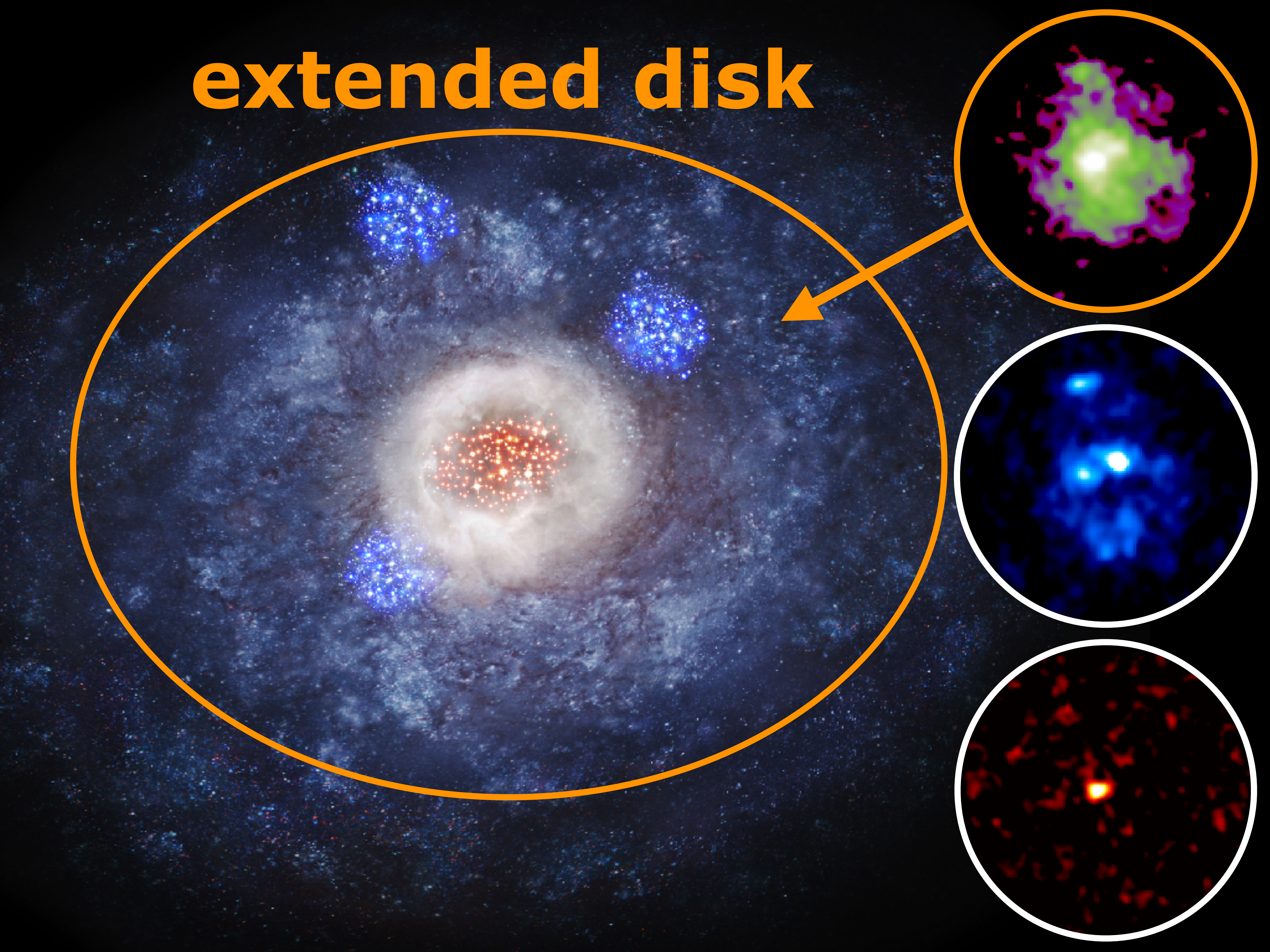
HST (H-band) | **HST (I-band)** | **ALMA (870μm)**

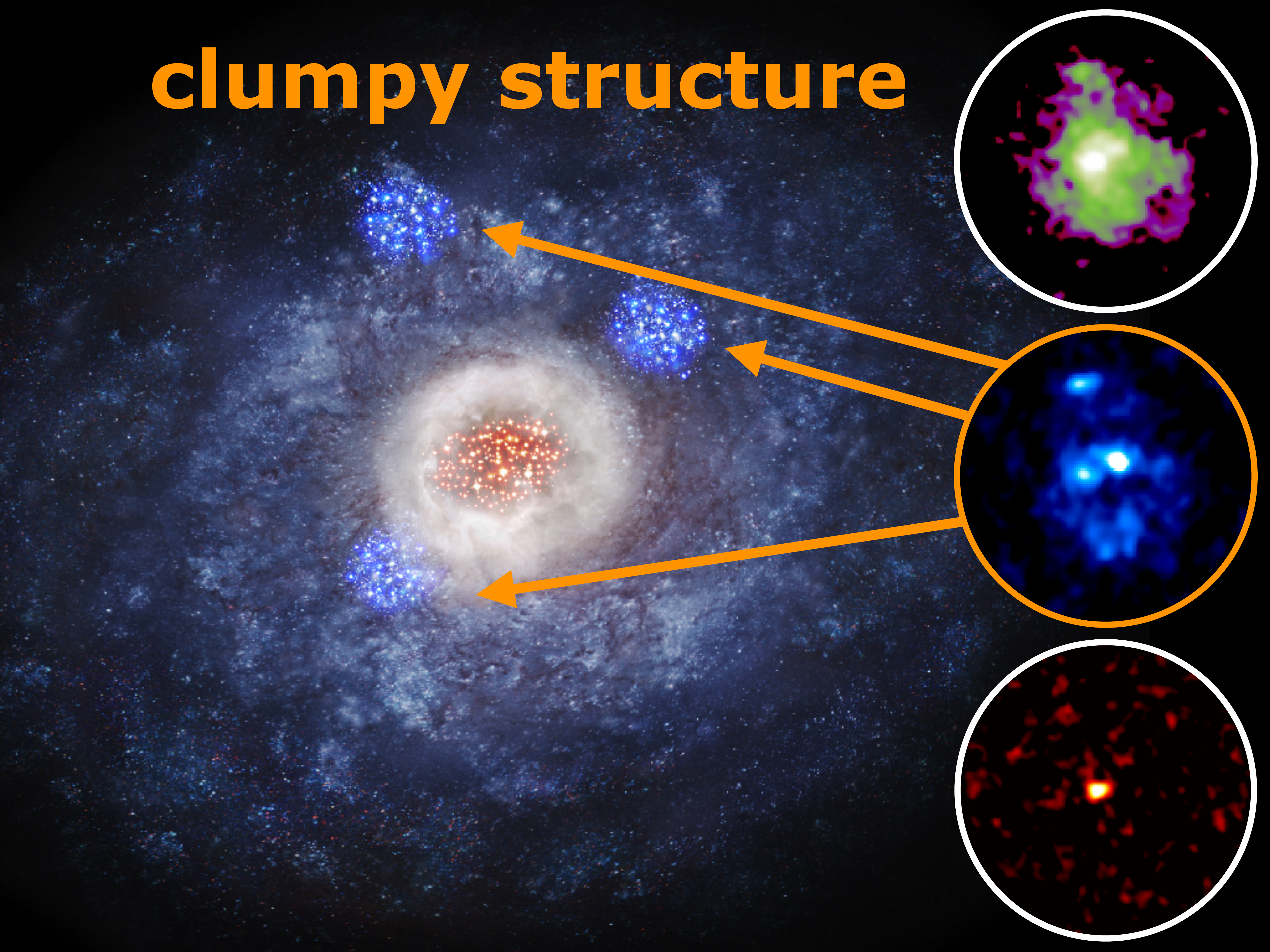


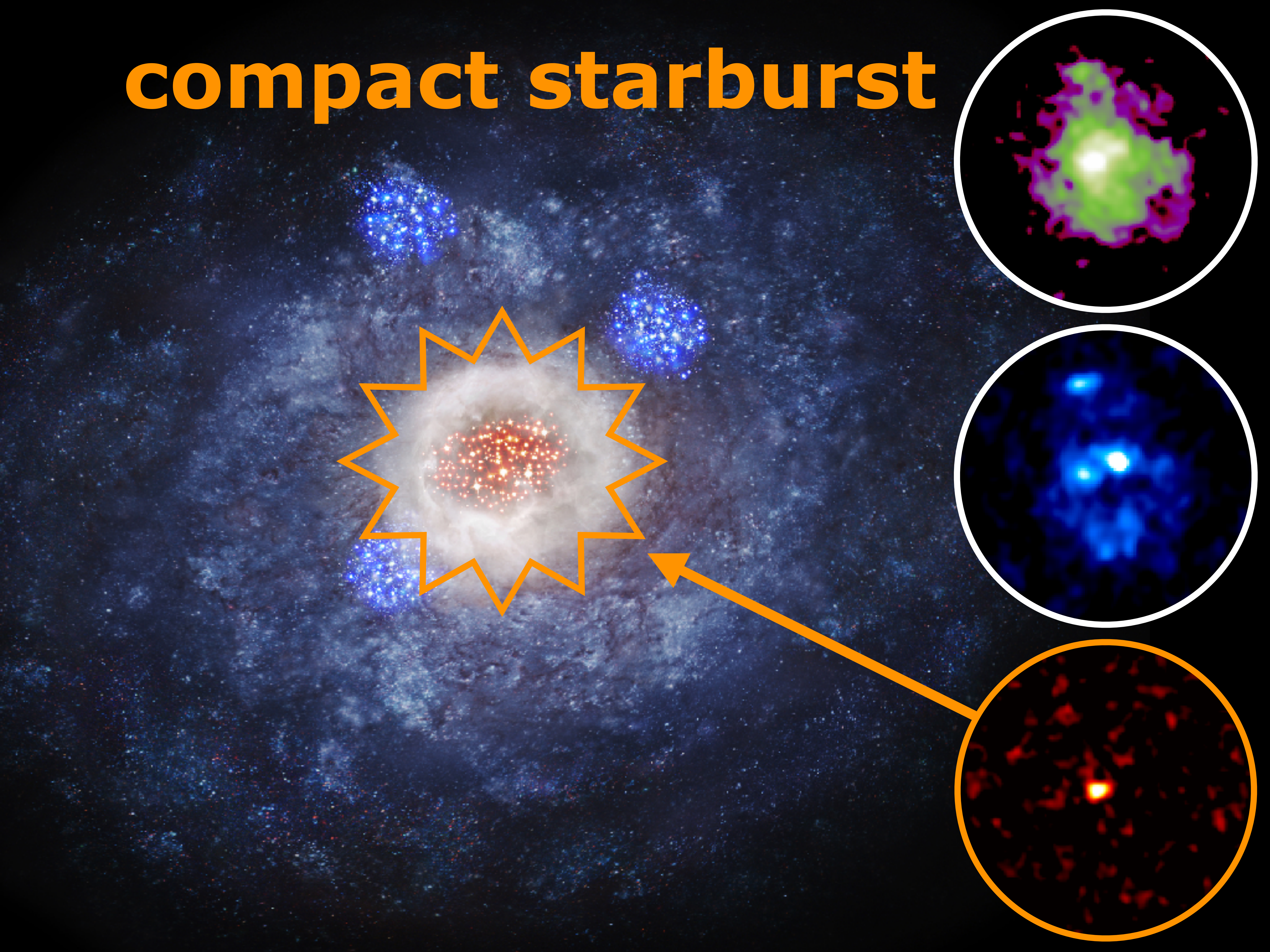
stellar mass → **extended disk**

unobscured star formation → **clumpy**

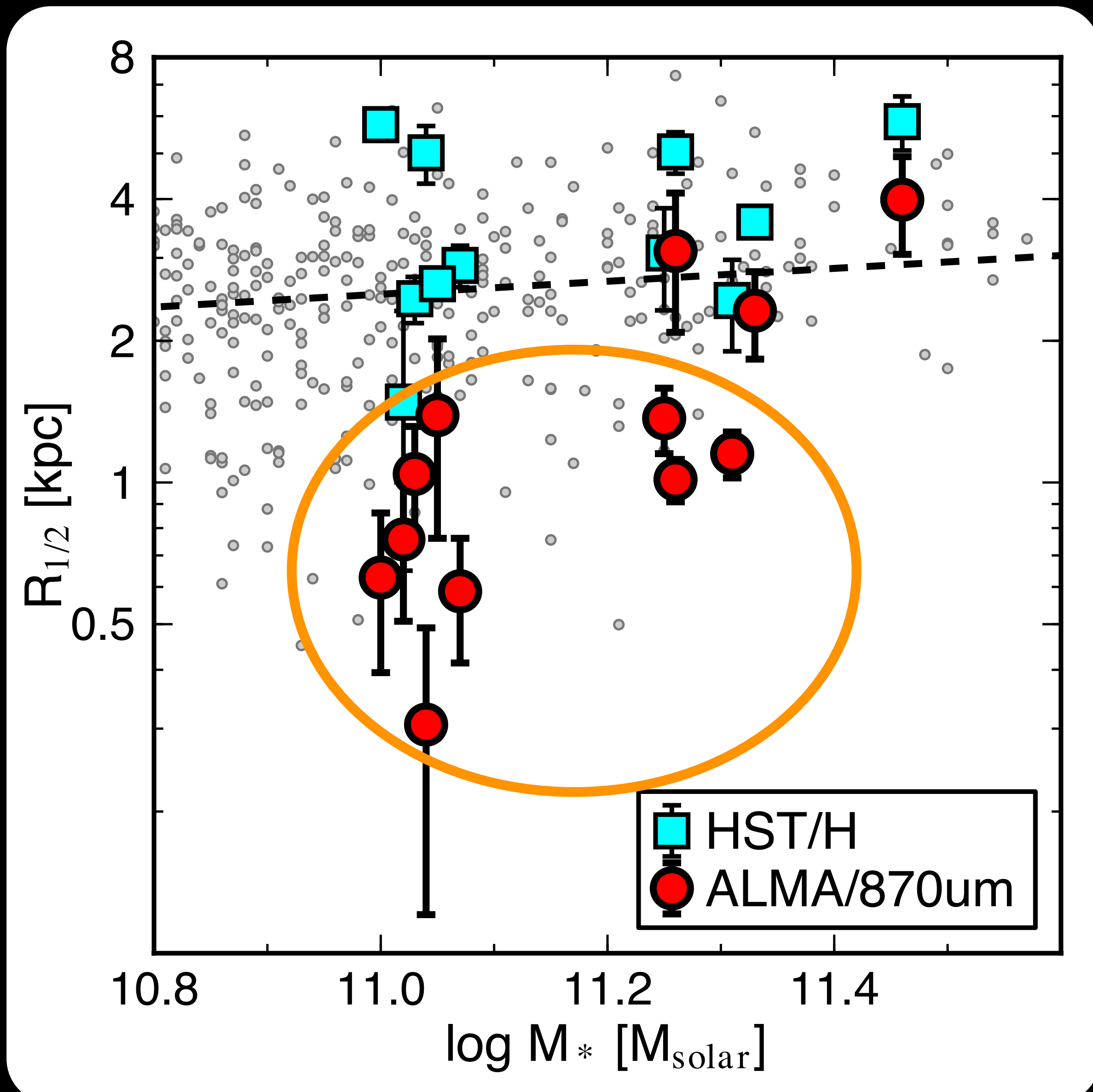
dust-obscured star formation → **centrally-concentrated**

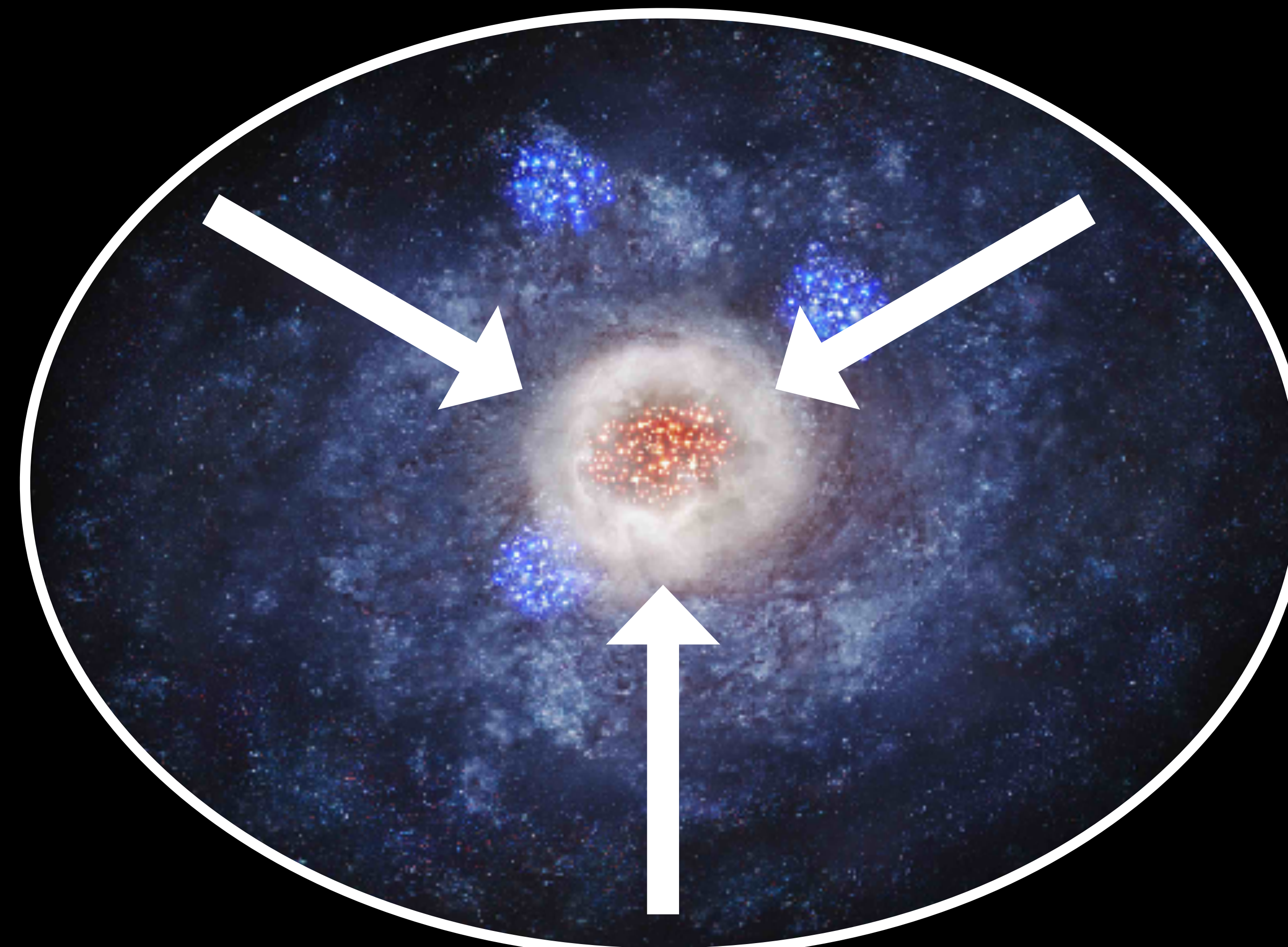

extended disk


clumpy structure


compact starburst

ALMA & HST view

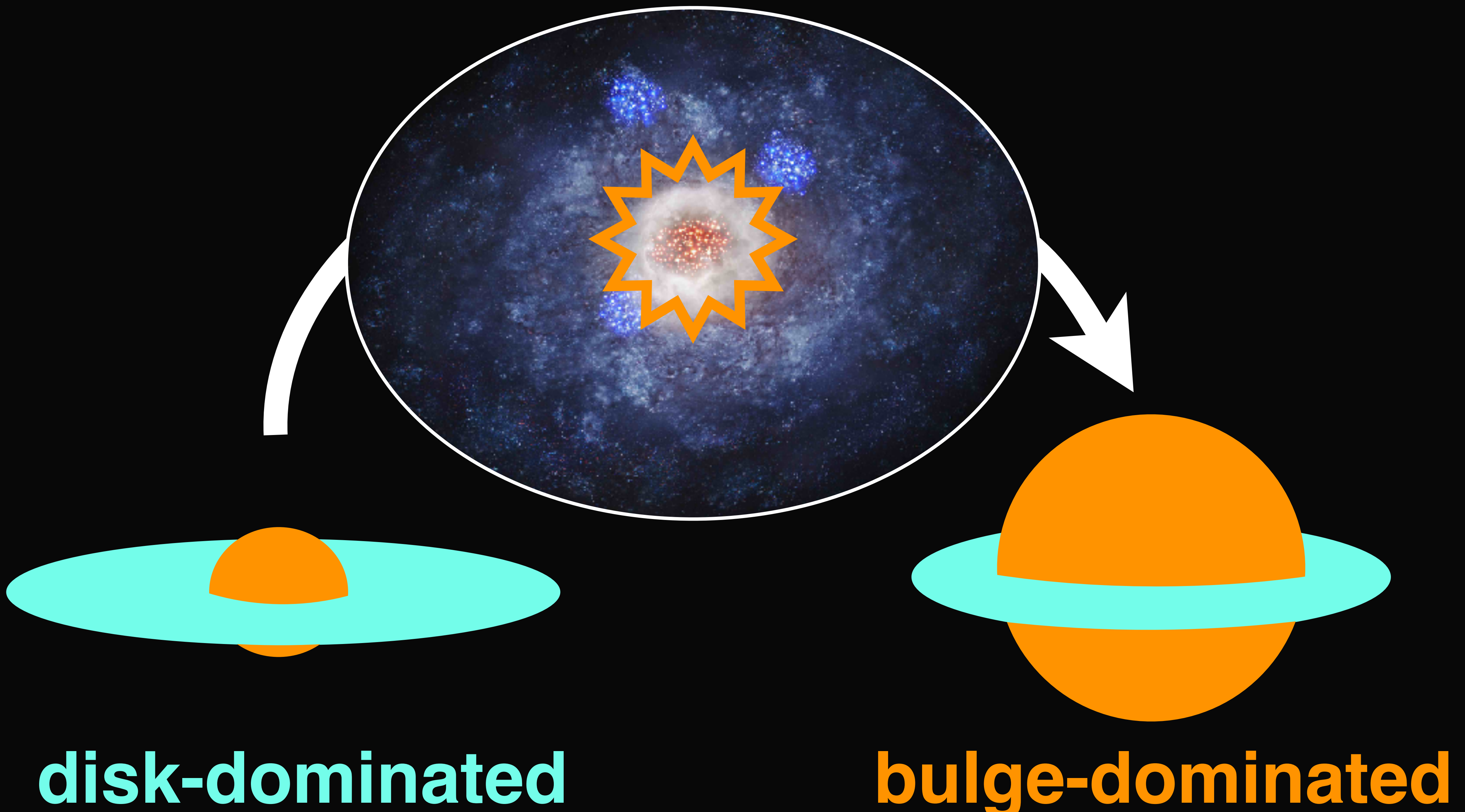




- they have an extended, exponential disk
- star-forming regions are extremely compact

suggesting **radial transport of gas**

Conclusion



Massive SFGs are transforming through compact dusty starbursts at z~2.5

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I. Our ALMA results about bulge formation in massive galaxies

II. A review of recent ALMA studies for high-z galaxies

- ✓ **Dust continuum distributions**
- ✓ **Gas mass measurements**
- ✓ **Fine structure lines**

Dust continuum distributions

The Astrophysical Journal, 799:81 (14pp), 2015 January 20 doi:10.1088/0004-637X/799/1/81

THE SCUBA-2 COSMOLOGY LEGACY SURVEY: ALMA RESOLVES THE REST-FRAME FAR-INFRARED EMISSION OF SUB-MILLIMETER GALAXIES

J. M. Simpson[1], Ian Smail[1], A. M. Swinbank[1], O. Almaini[2], A. W. Blain[3], M. N. Bremer[4], S. C. Chapman[5], Chian-Chou Chen[1], C. Conselice[2], K. E. K. Coppin[4], A. L. R. Danielson[1], J. S. Dunlop[7], A. C. Edge[1], D. Farrah[8], J. E. Geach[6], W. G. Hartley[2,9], R. J. Ivison[7,10], A. Karim[11], C. Lani[2], C.–J. Ma[1], R. Meijerink[12,13], M. J. Michałowski[7], A. Mortlock[2,7], D. Scott[14], C. J. Simpson[15], M. Spaans[12], A. P. Thomson[1], E. van Kampen[10], and P. P. van der Werf[13]

The Astrophysical Journal, 810:133 (12pp), 2015 September 10 doi:10.1088/0004-637X/810/2/133

COMPACT STARBURSTS IN $z \sim 3$–6 SUBMILLIMETER GALAXIES REVEALED BY ALMA

Soh Ikarashi[1,2,3], R. J. Ivison[1,4], Karina I. Caputi[3], Itziar Aretxaga[5], James S. Dunlop[4], Bunyo Hatsukade[6], David H. Hughes[5], Daisuke Iono[6,7], Takuma Izumi[2], Ryohei Kawabe[2,6,7], Kotaro Kohno[2,8], Claudia D. P. Lagos[1], Kentaro Motohara[2], Kouichiro Nakanishi[6,7,9], Kouji Ohta[10], Yoichi Tamura[2], Hideki Umehata[2], Grant W. Wilson[11], Kiyoto Yabe[6], and Min S. Yun[11]

The Astrophysical Journal Letters, 827:L32 (7pp), 2016 August 20 doi:10.3847/2041-8205/827/2/L32

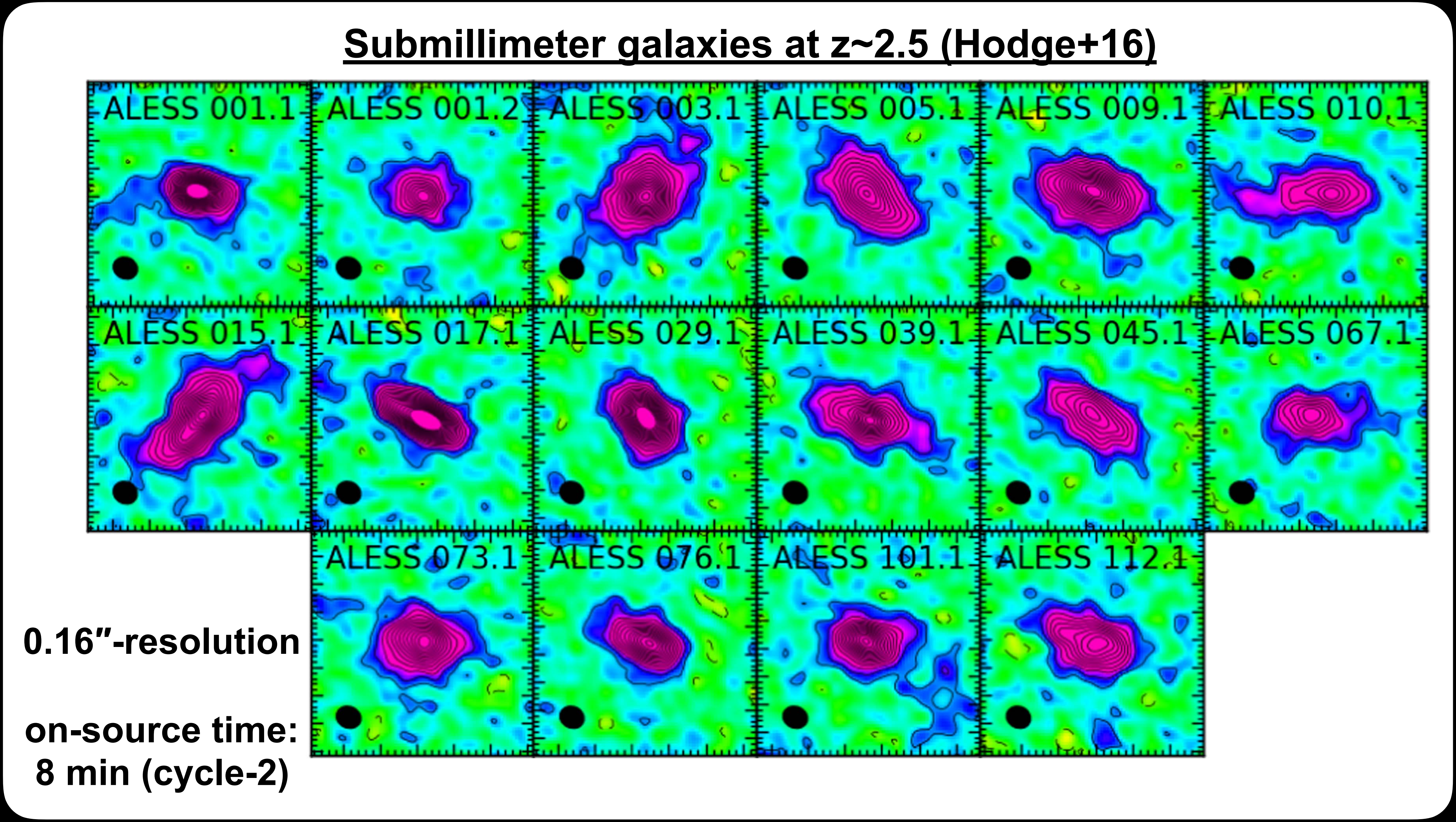
CrossMark

SUB-KILOPARSEC ALMA IMAGING OF COMPACT STAR-FORMING GALAXIES AT $z \sim 2.5$: REVEALING THE FORMATION OF DENSE GALACTIC CORES IN THE PROGENITORS OF COMPACT QUIESCENT GALAXIES

G. Barro[1], M. Kriek[1], P. G. Pérez-González[2], J. R. Trump[3,12], D. C. Koo[4], S. M. Faber[4], A. Dekel[5], J. R. Primack[6], Y. Guo[3], D. D. Kocevski[7], J. C. Muñoz-Mateos[8], W. Rujoparkarn[9,10], and K. Seth[11]

Consensus: dust continuum is very compact (R_e=1-2 kpc)

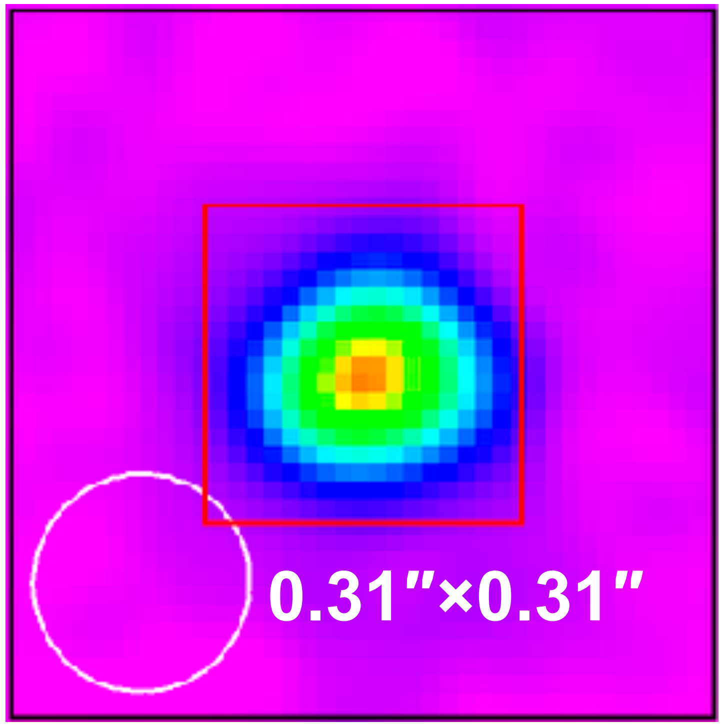
Dust continuum distributions



They have an exponential disk
median Sersic index of 0.9±0.2

Dust continuum distributions

The brightest submillimeter galaxy at z=4.3 (Iono+16)



on-source time: ~20 min (cycle-1)

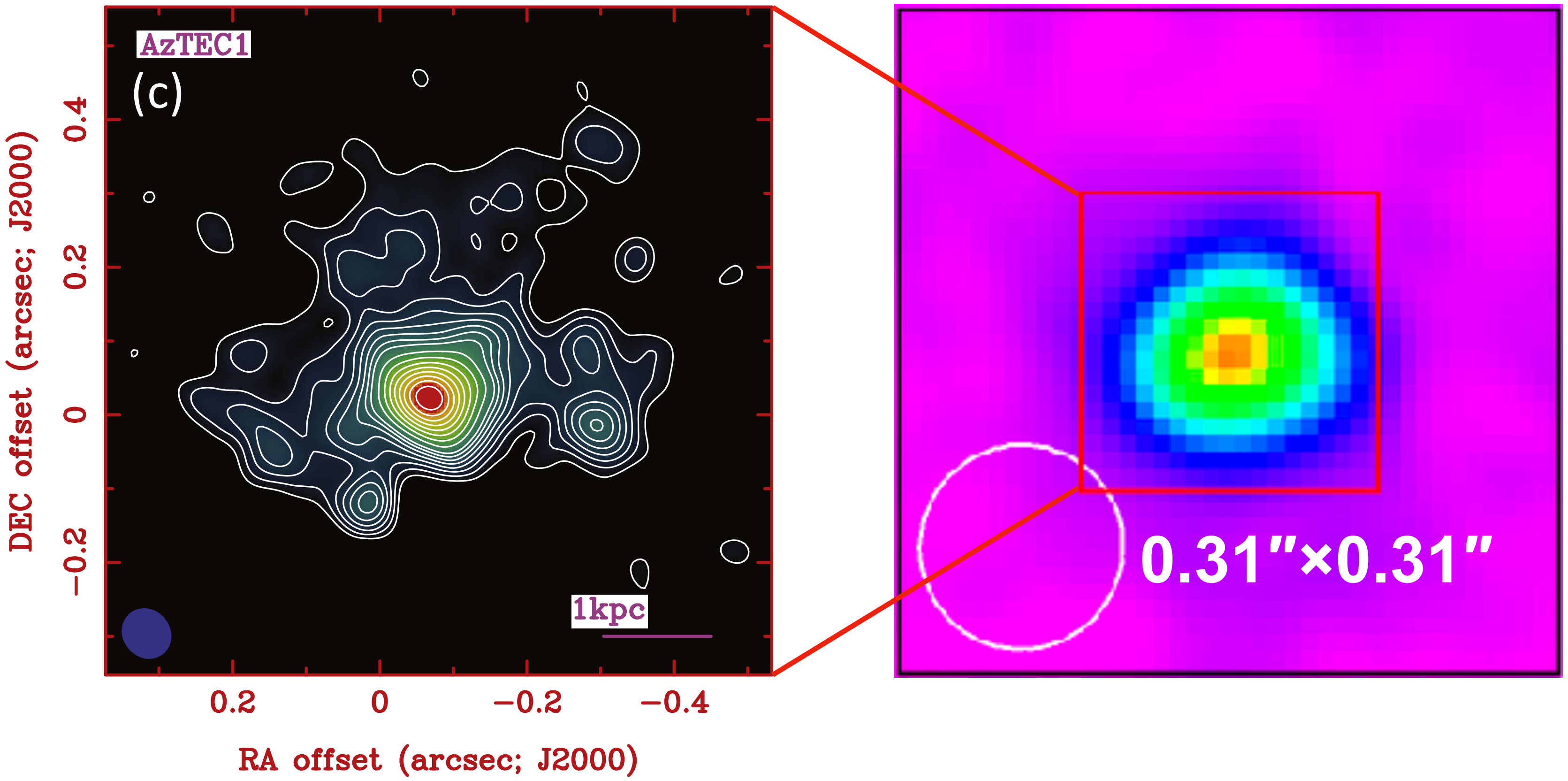
dust emission is very compact

R_e ~ 1 kpc

Dust continuum distributions

The brightest submillimeter galaxy at z=4.3 (Iono+16)

resolution: 0.07″×0.063″ 0.31″×0.31″



on-source time: ~30 min (cycle-3)

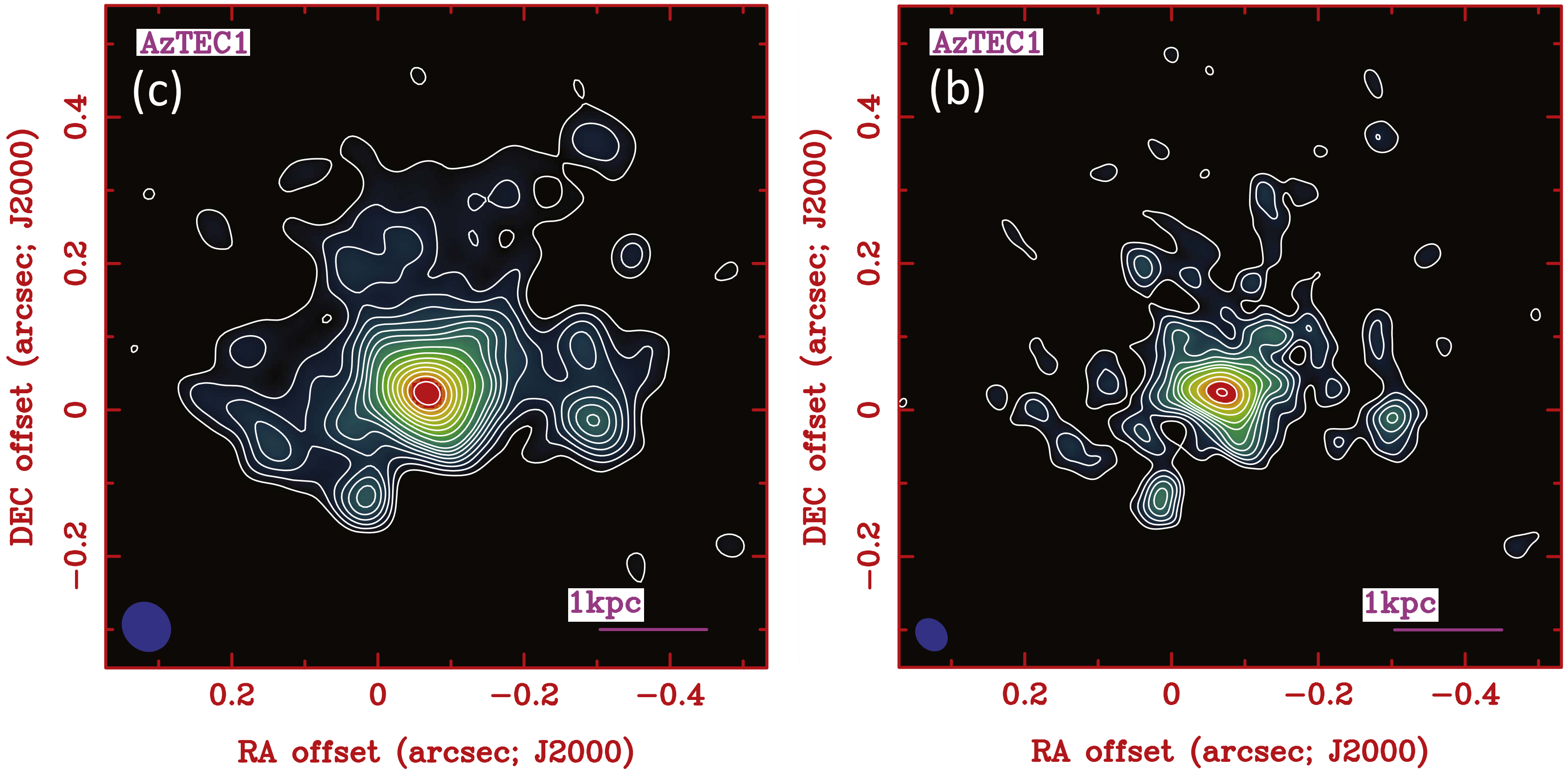
dust emission is very compact

R_e ~ 1 kpc

Dust continuum distributions

The brightest submillimeter galaxy at z=4.3 (Iono+16)

resolution: 0.07″×0.063″ **0.048″×0.039″**

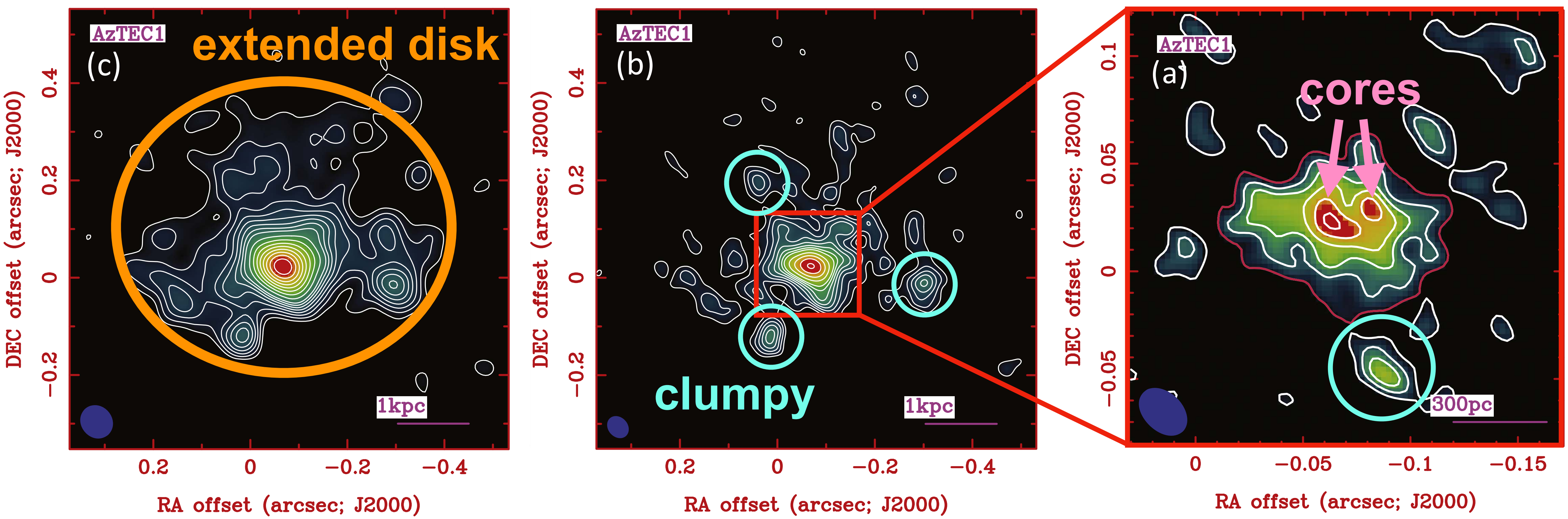


on-source time: ~30 min (cycle-3)

Dust continuum distributions

The brightest submillimeter galaxy at z=4.3 (Iono+16)

resolution: 0.07″×0.063″ 0.048″×0.039″ 0.026″×0.018″



on-source time: ~30 min (cycle-3)

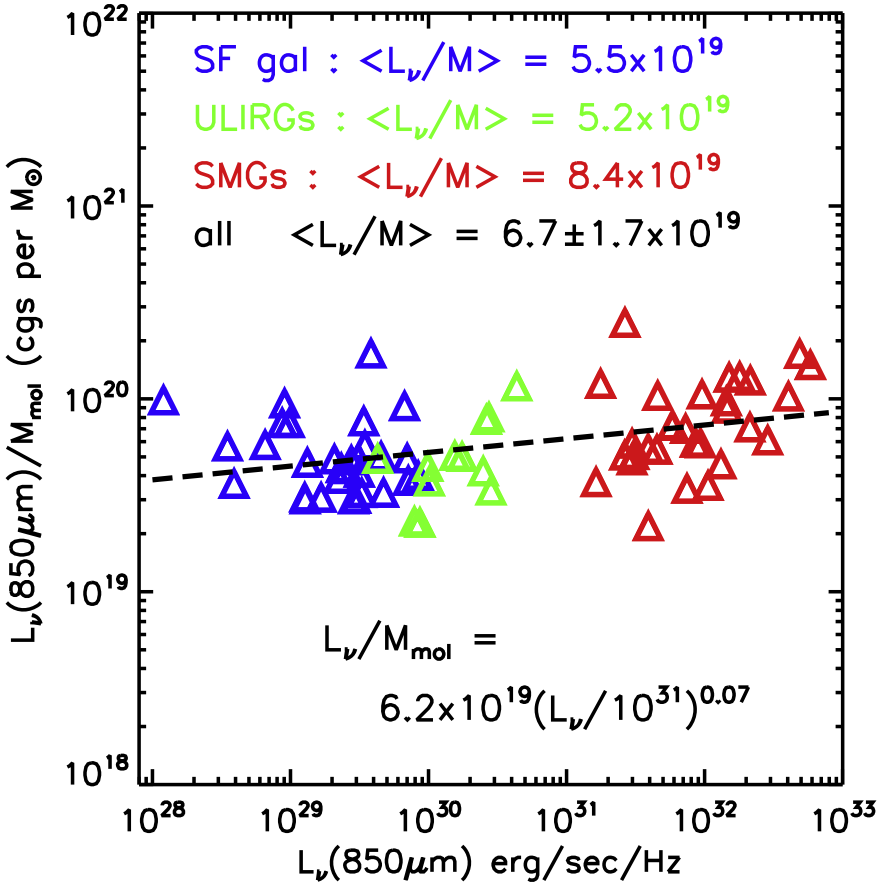
Dual cores +
extended disk + clumpy structure
3-4 kpc 200-300 pc

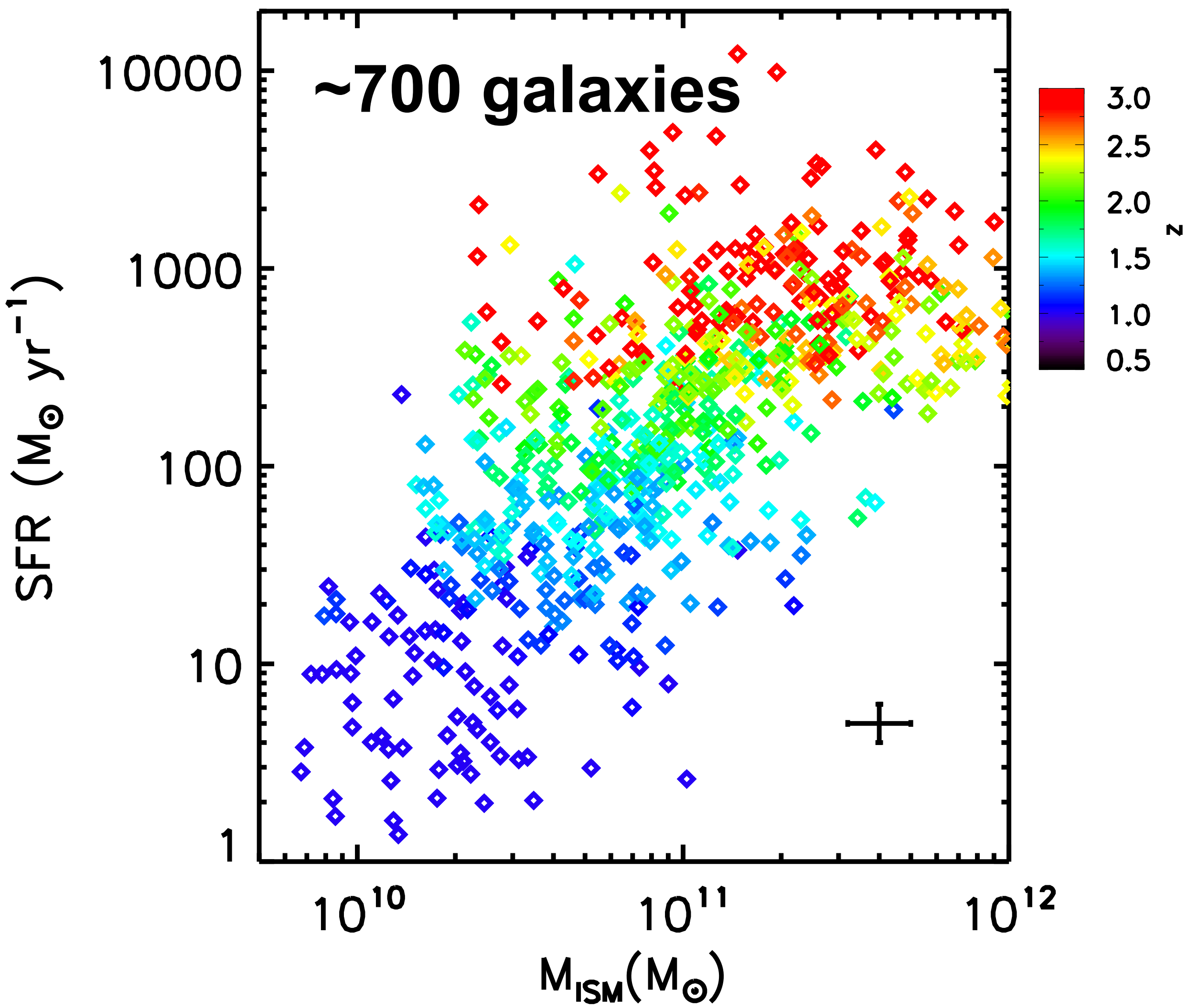
- ✓ Dust continuum distributions
- ✓ **Gas mass measurements**
- ✓ Fine structure lines

Gas mass measurements

1. **Dust continuum**
2. CO line
3. CI line

Scoville's recipe (Scoville+15,16,17)





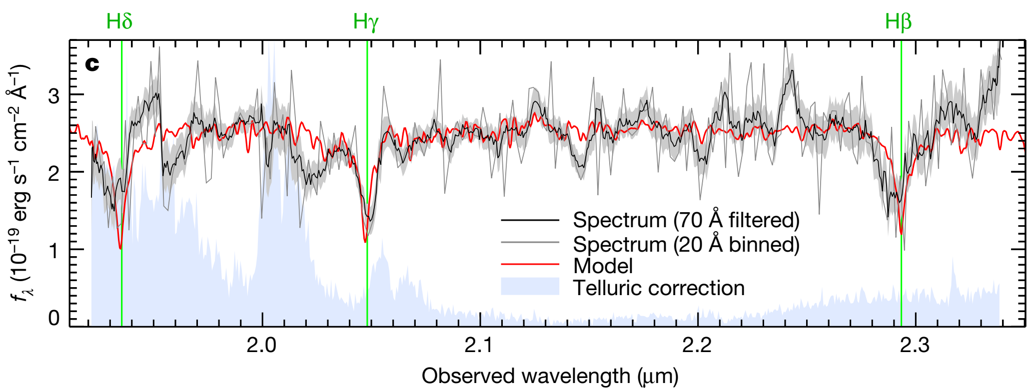
$$M_{\rm ISM} = 1.78\, S_{\nu_{\rm obs}}[{\rm mJy}]\ (1+z)^{-4.8} \left(\frac{\nu_{850\mu{\rm m}}}{\nu_{\rm obs}}\right)^{3.8} ({\rm d}_L[{\rm Gpc}])^2 \times \left\{\frac{6.7 \times 10^{19}}{\alpha_{850}}\right\} \frac{\Gamma_0}{\Gamma_{\rm RJ}}\ 10^{10}\, M_\odot.$$

on-source time: ~2 min (cycle-2)

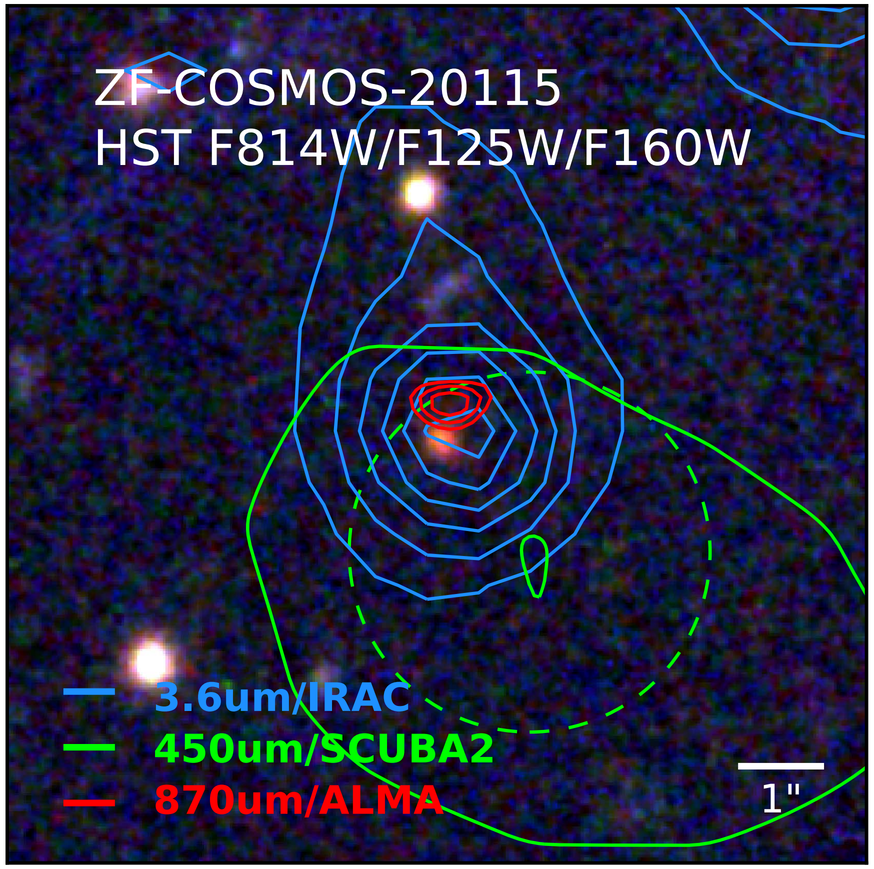
Gas mass measurements

1. **Dust continuum**
2. **CO line**
3. **CI line**

A quiescent galaxy at z=3.7 (Glazebrook+17, Nature)

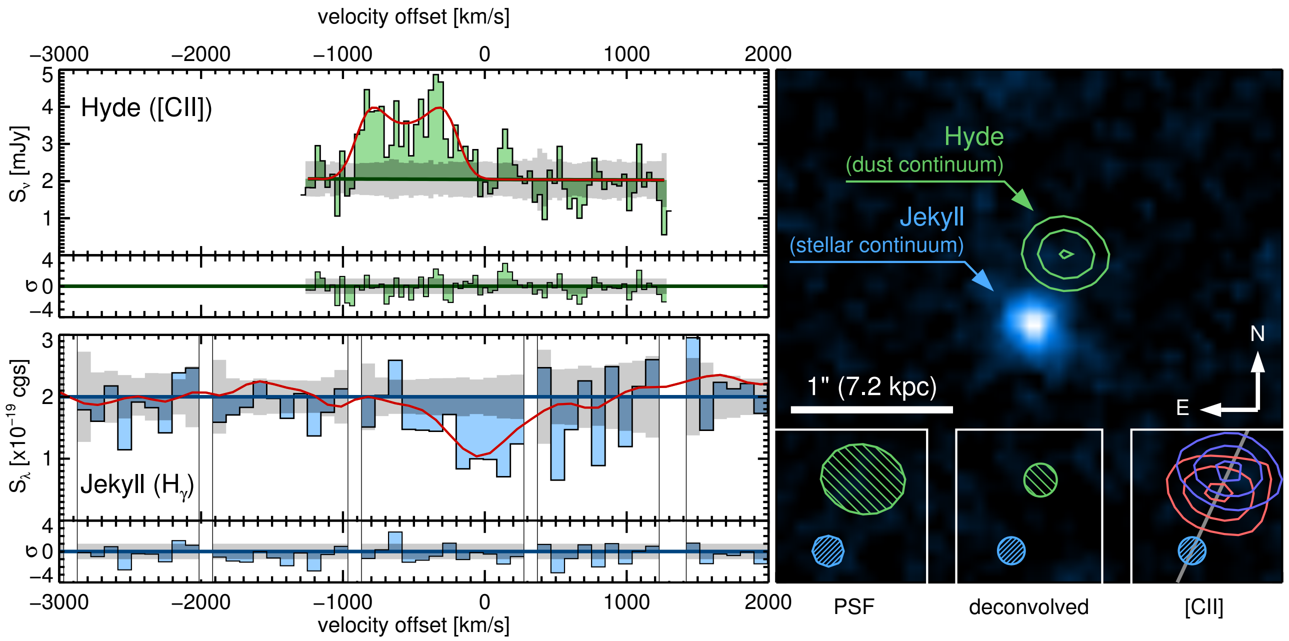


Dust cont. detection (Simpson+17)



on-source time: 1.4 min (cycle-3)

[CII] detection (Schreiber+17)

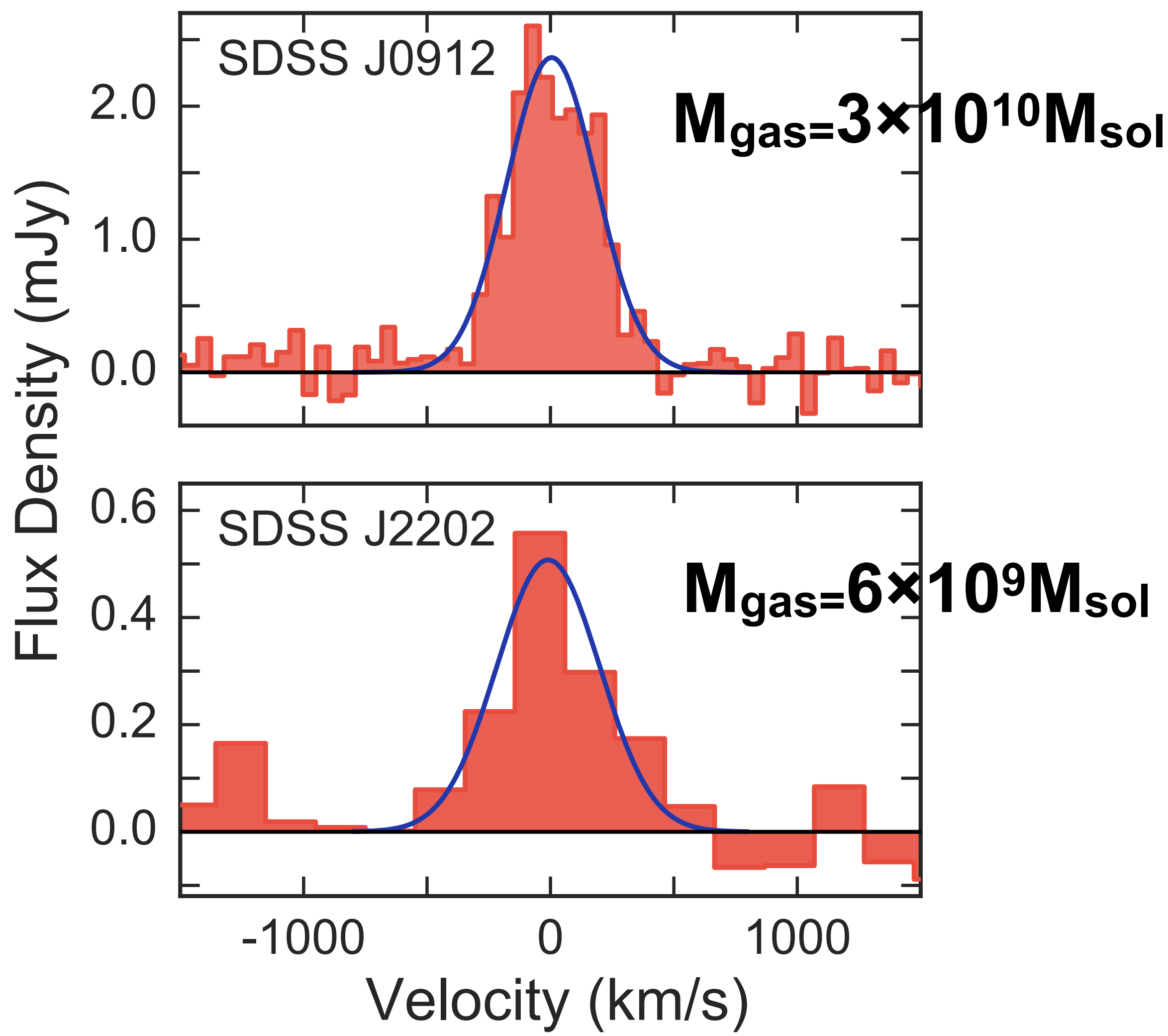


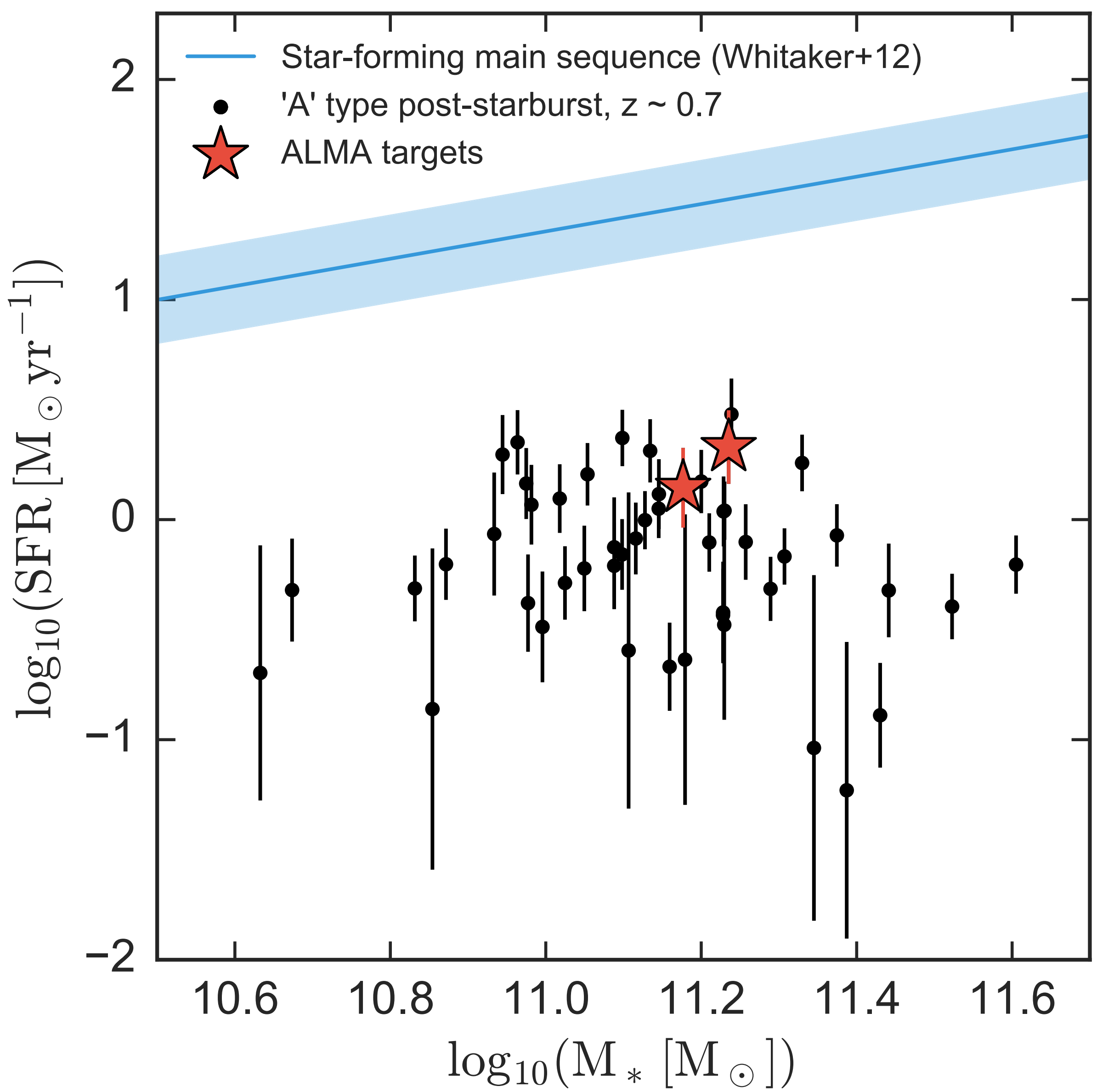
on-source time: 1.4 hours (cycle-4)

Gas mass measurements

1. Dust continuum
2. **CO line**
3. CI line

Large molecular gas reservoirs in quenched galaxies at z=0.7 (Suess+17)



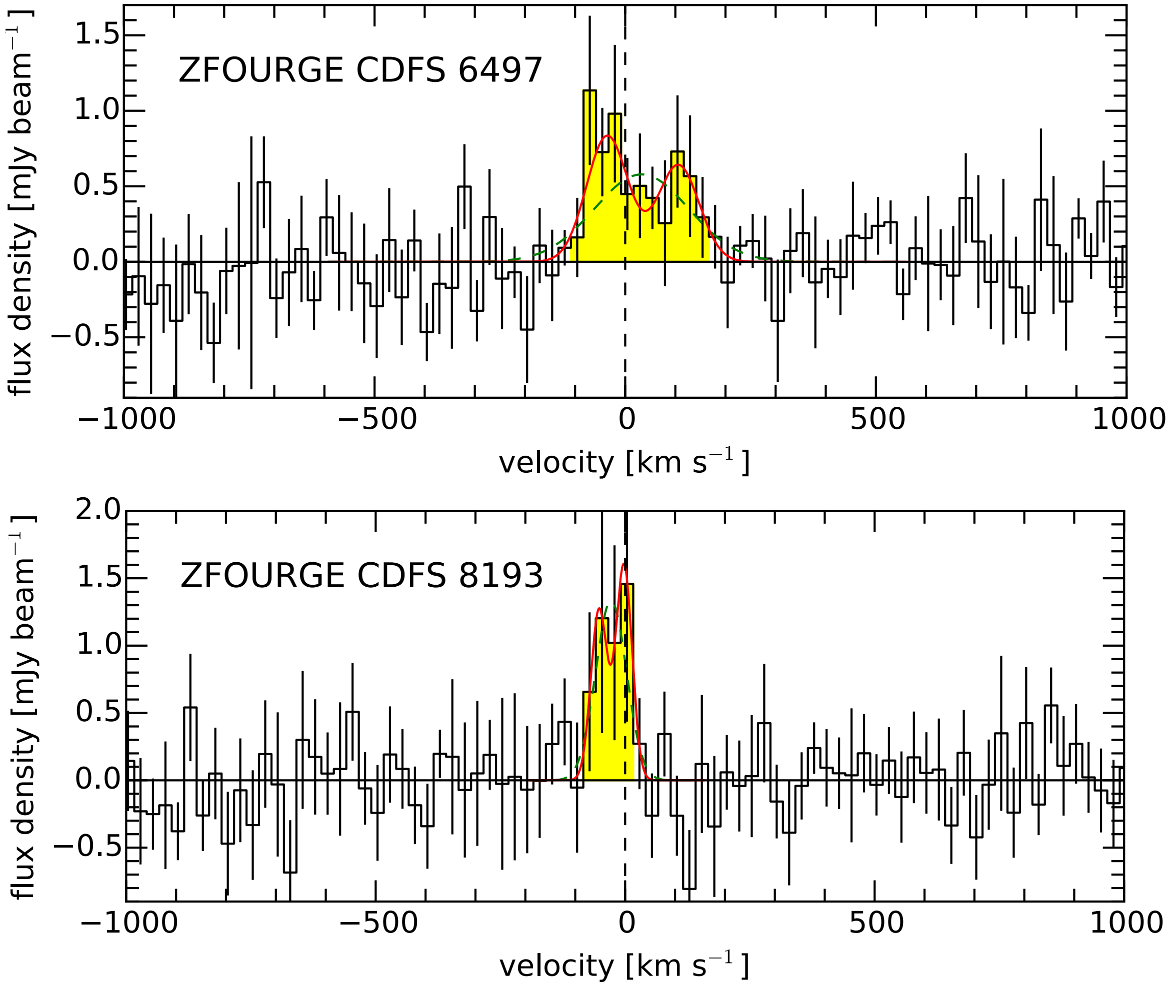


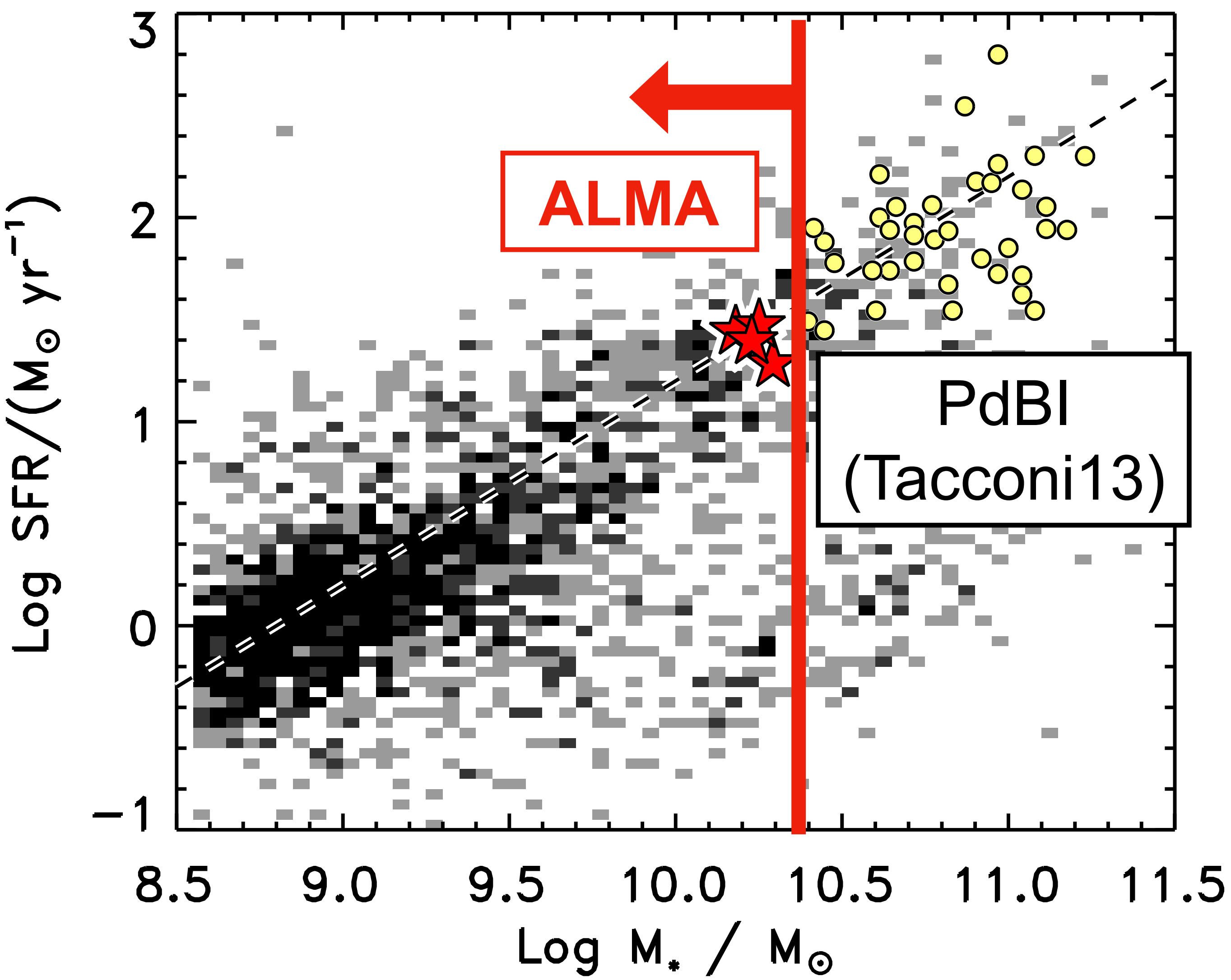
on-source time: 100 min (cycle-5)

Gas mass measurements

1. Dust continuum
2. CO line
3. CI line

Ancestors of MW-mass galaxies (z=1.2-1.3, Papovich+16)



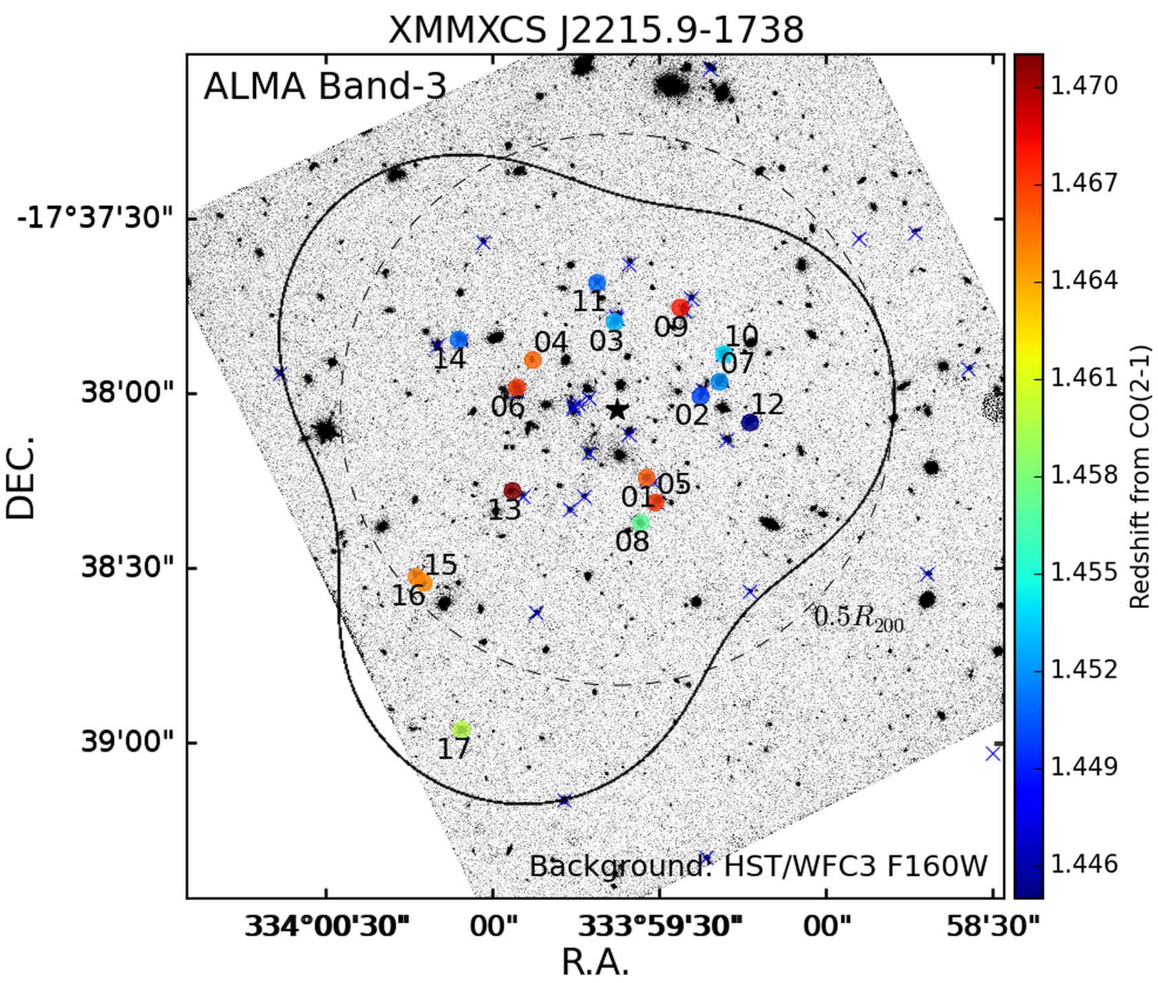


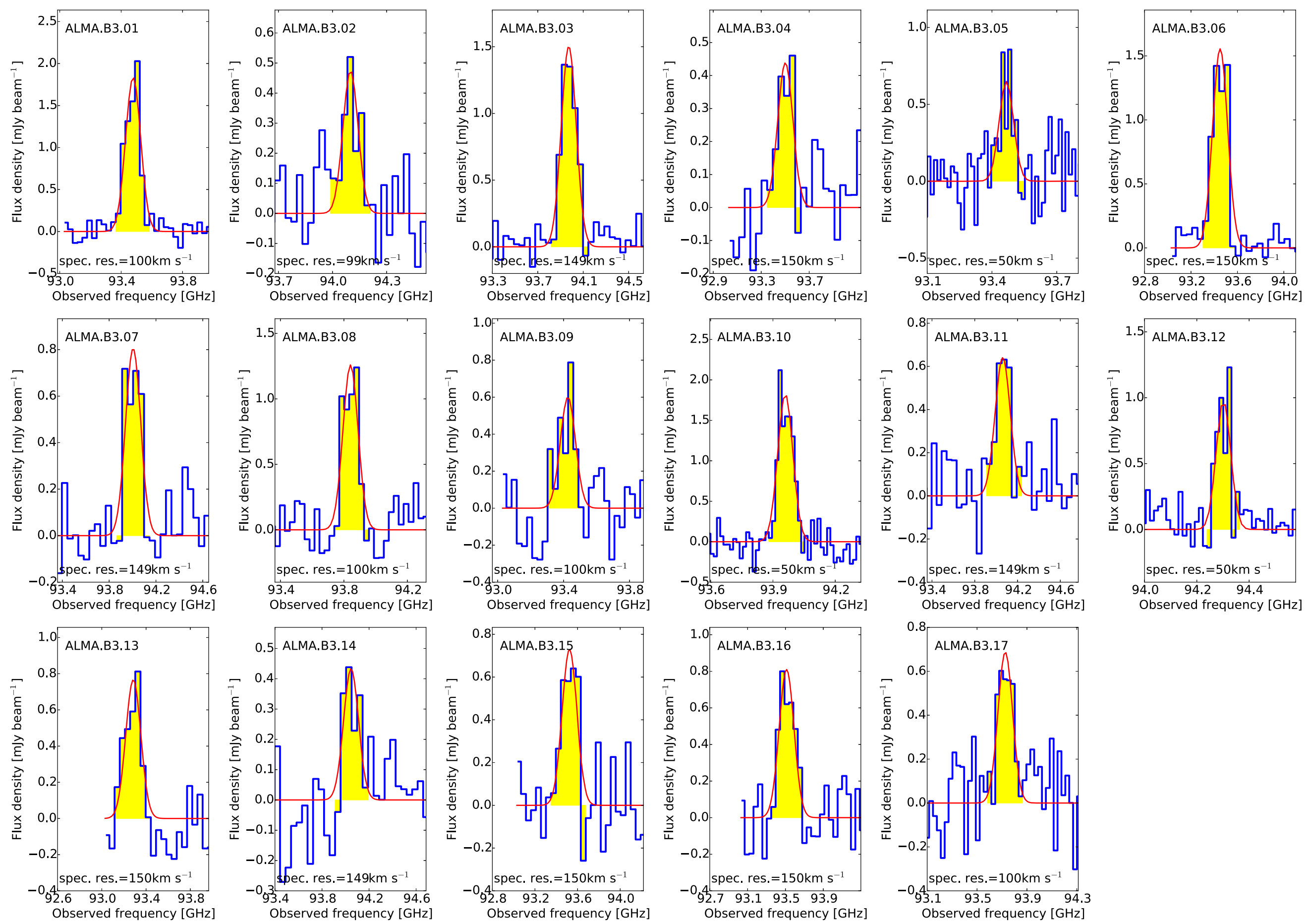
on-source time: 40 min (cycle-2)

Gas mass measurements

1. Dust continuum
2. CO line
3. CI line

A massive cluster at z=1.5 (Hayashi+17)





on-source time: 1 hour (cycle-3)

17 CO(2-1) detections

ISM mass measurements

1. Dust continuum
2. CO line
3. **CI line**

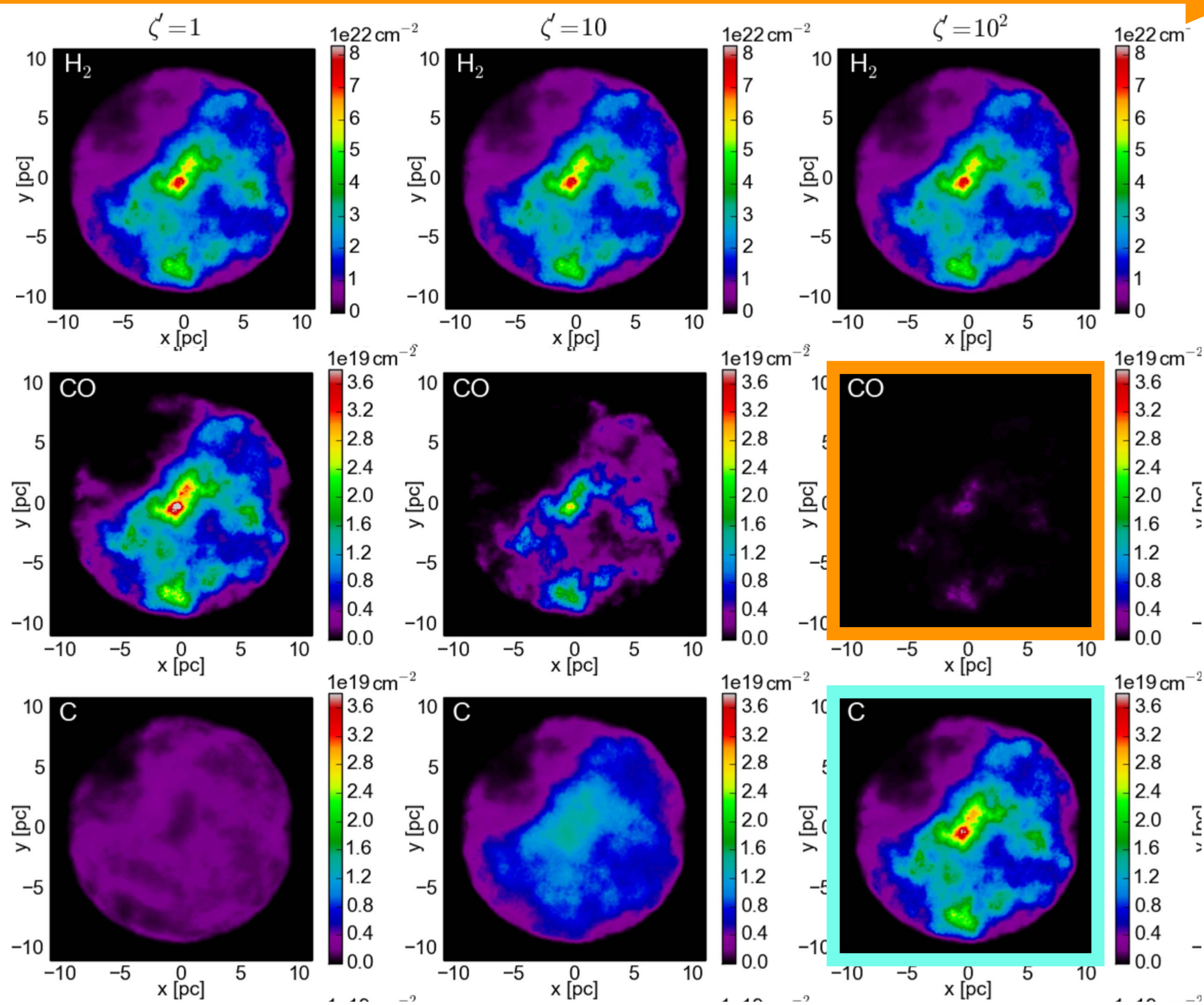
CO-dark gas (Bisbas+17)

stronger cosmic ray field

H_2

CO

C



CO destruction

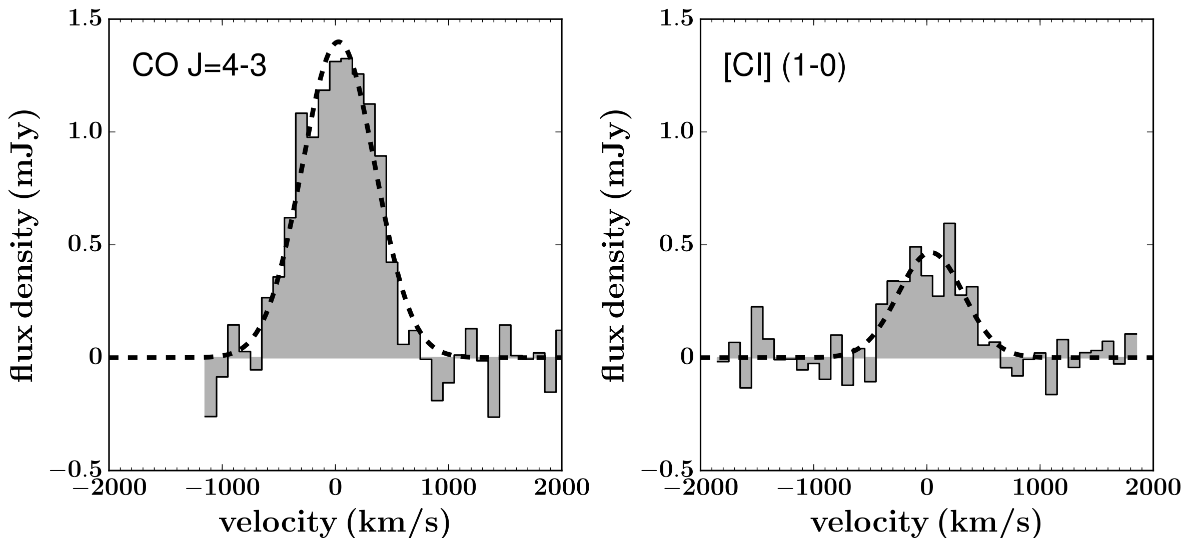
C abundance increases

Gas mass measurements

1. Dust continuum
2. CO line
3. **CI line**

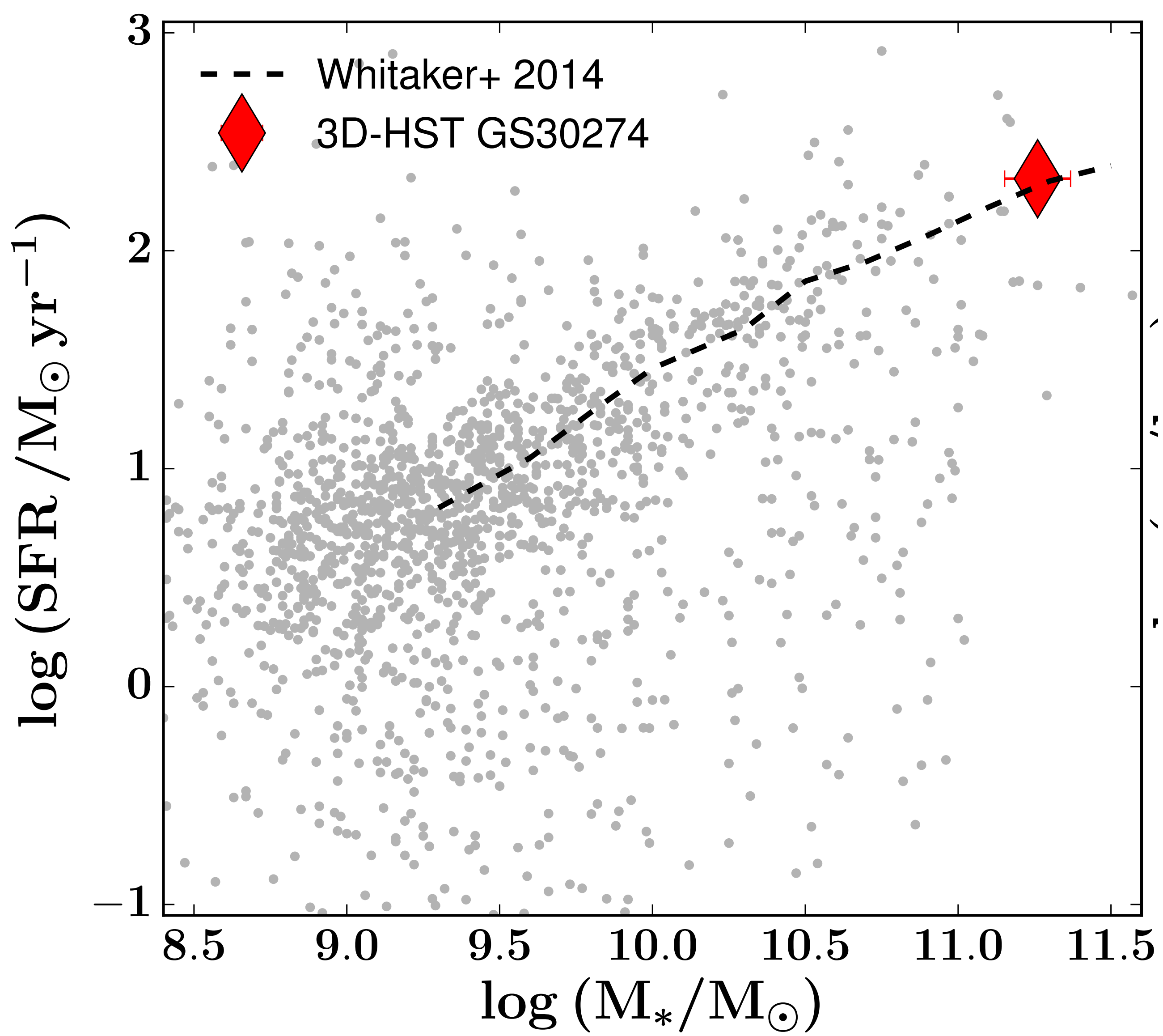
A massive star-forming galaxy at z=2.2 (Popping+17)

on-source time: 90 min (cycle-4)



at z~2, CO(4-3) and [CI](1-0) can be simultaneously observed

$$M_{[CI]}(M_{\odot}) = 5.706 \times 10^{-4} Q(T_{ex}) \frac{1}{3} e^{23.6/T_{ex}} L'_{[CI](1-0)}$$



Gas mass measurements

fast | uncertain

1. Dust continuum
2. CO line
3. CI line

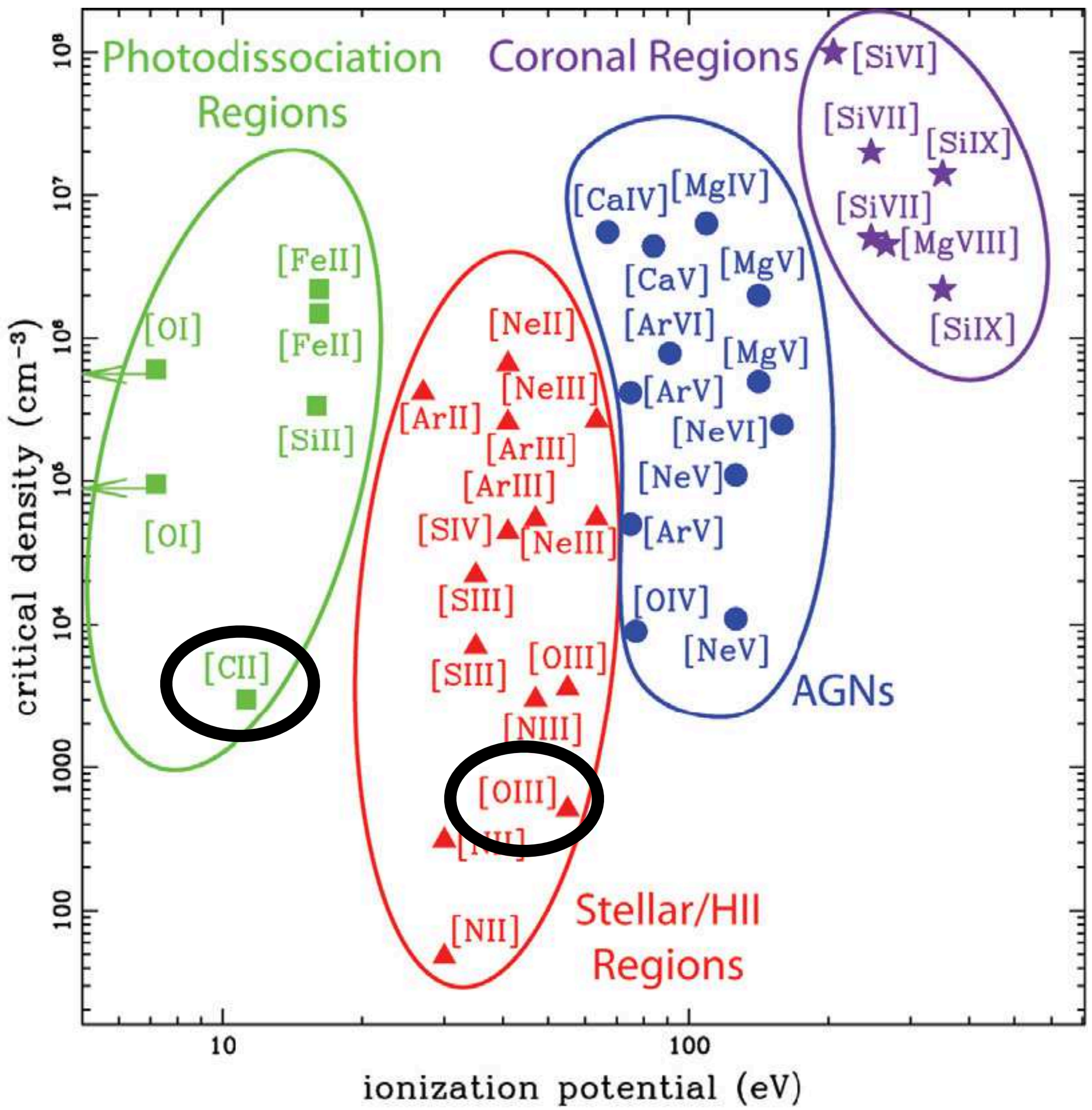
time-consuming | reliable

Also need to check dynamical mass

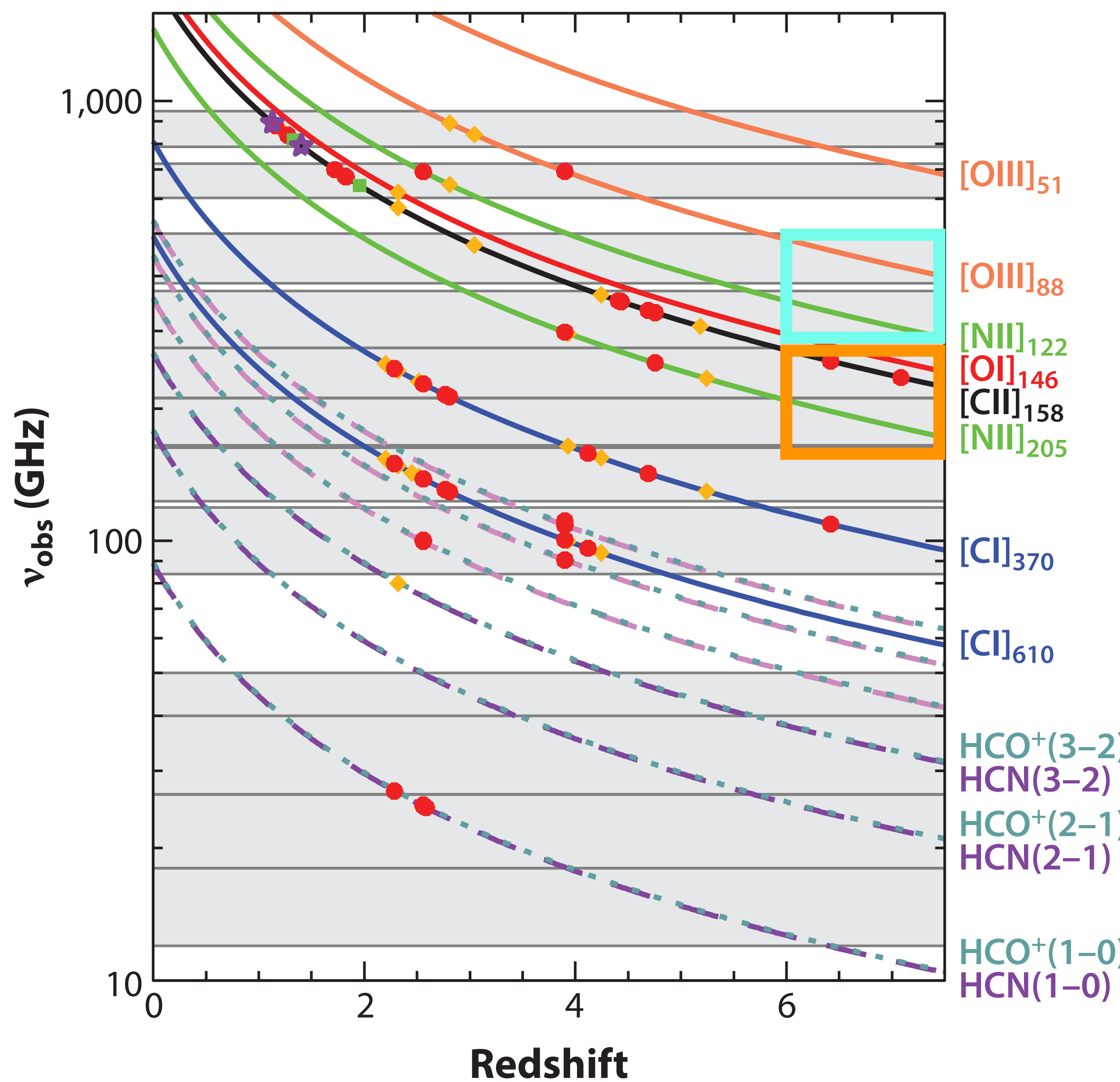
- ✓ Dust continuum distributions
- ✓ Gas mass measurements
- ✓ **Fine structure lines**

Fine structure line studies

Spinoglio+09



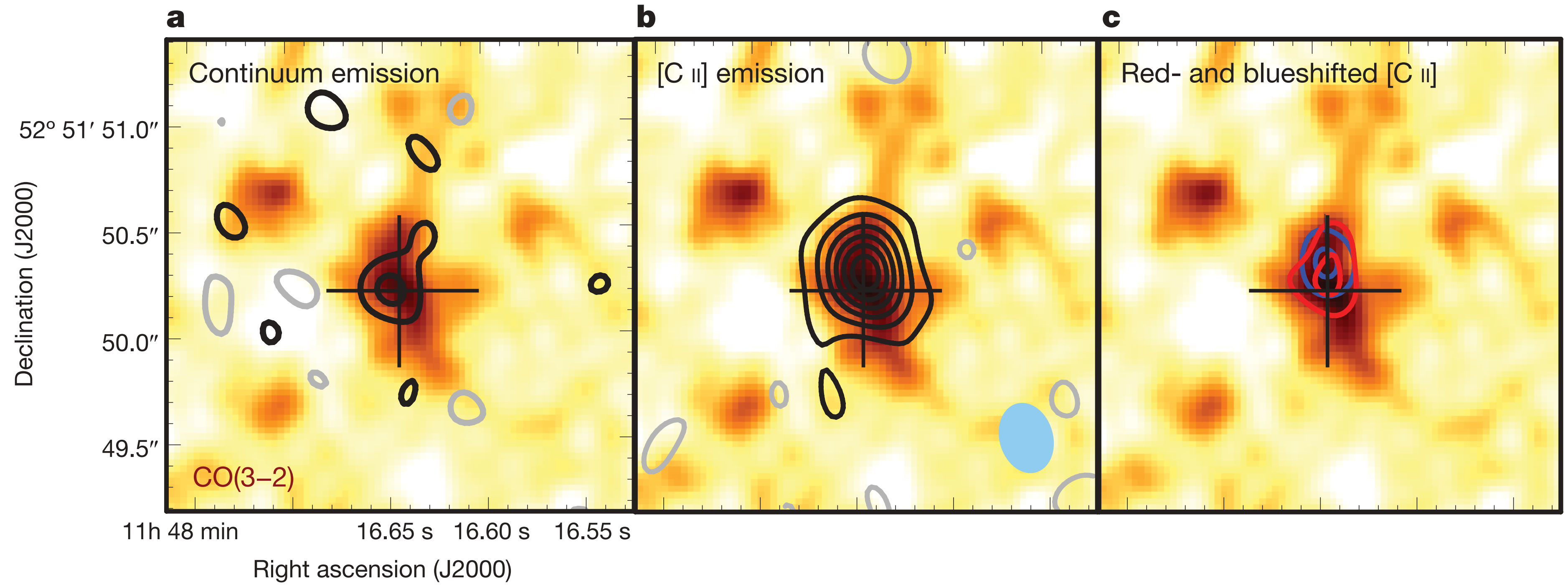
Carilli+13

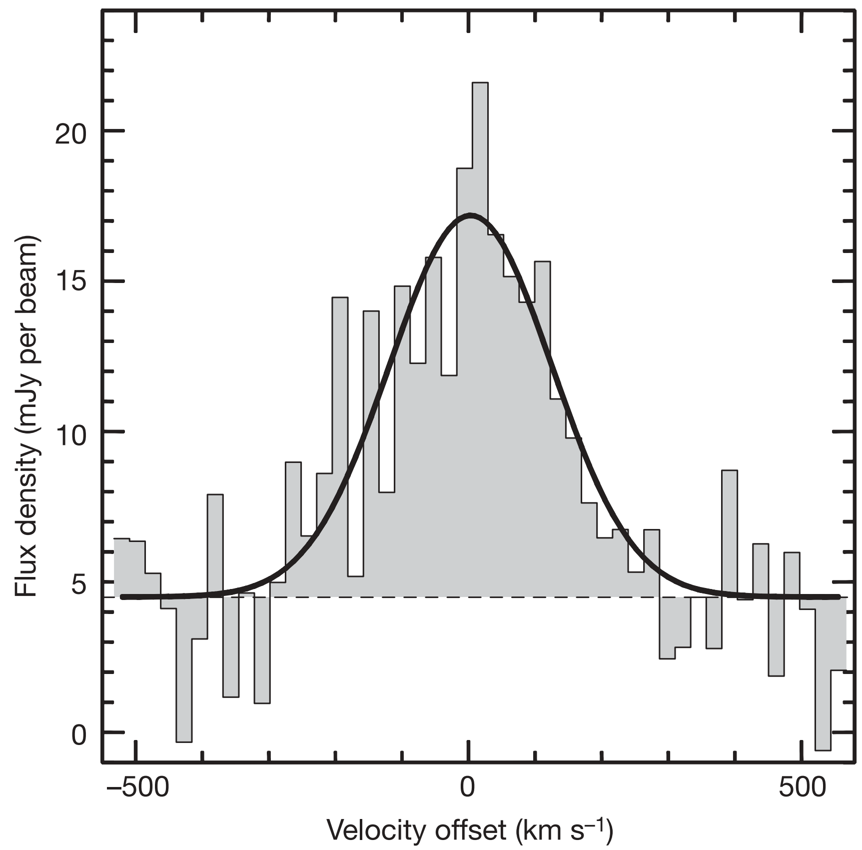


	[CII]158um	[OIII]88um
z=6-7.5	Band-8	Band-6
z~8	Band-7	Band-5

[CII] 158um detections before ALMA

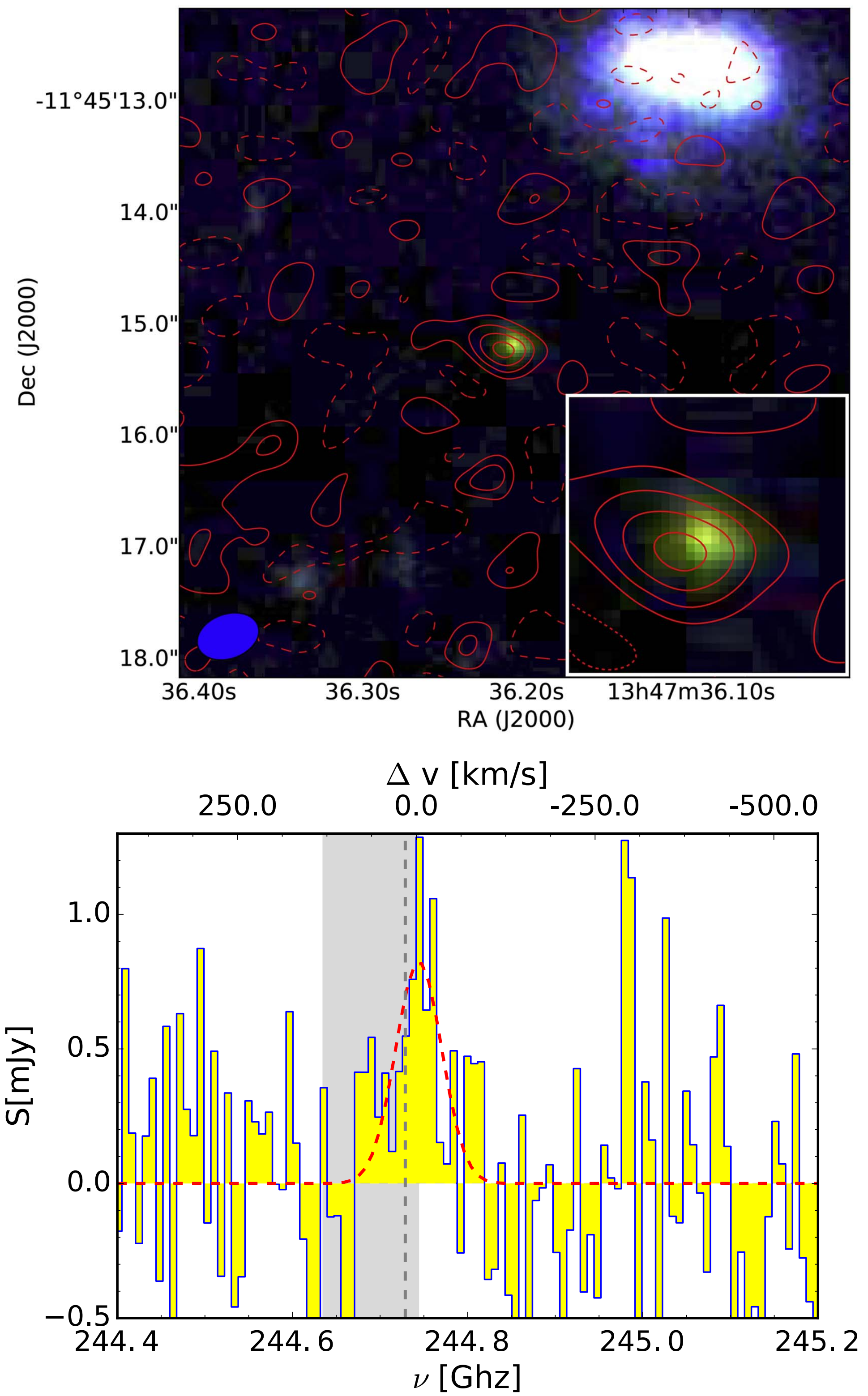
A galaxy at z=6.4 (Walter+13, Nature)



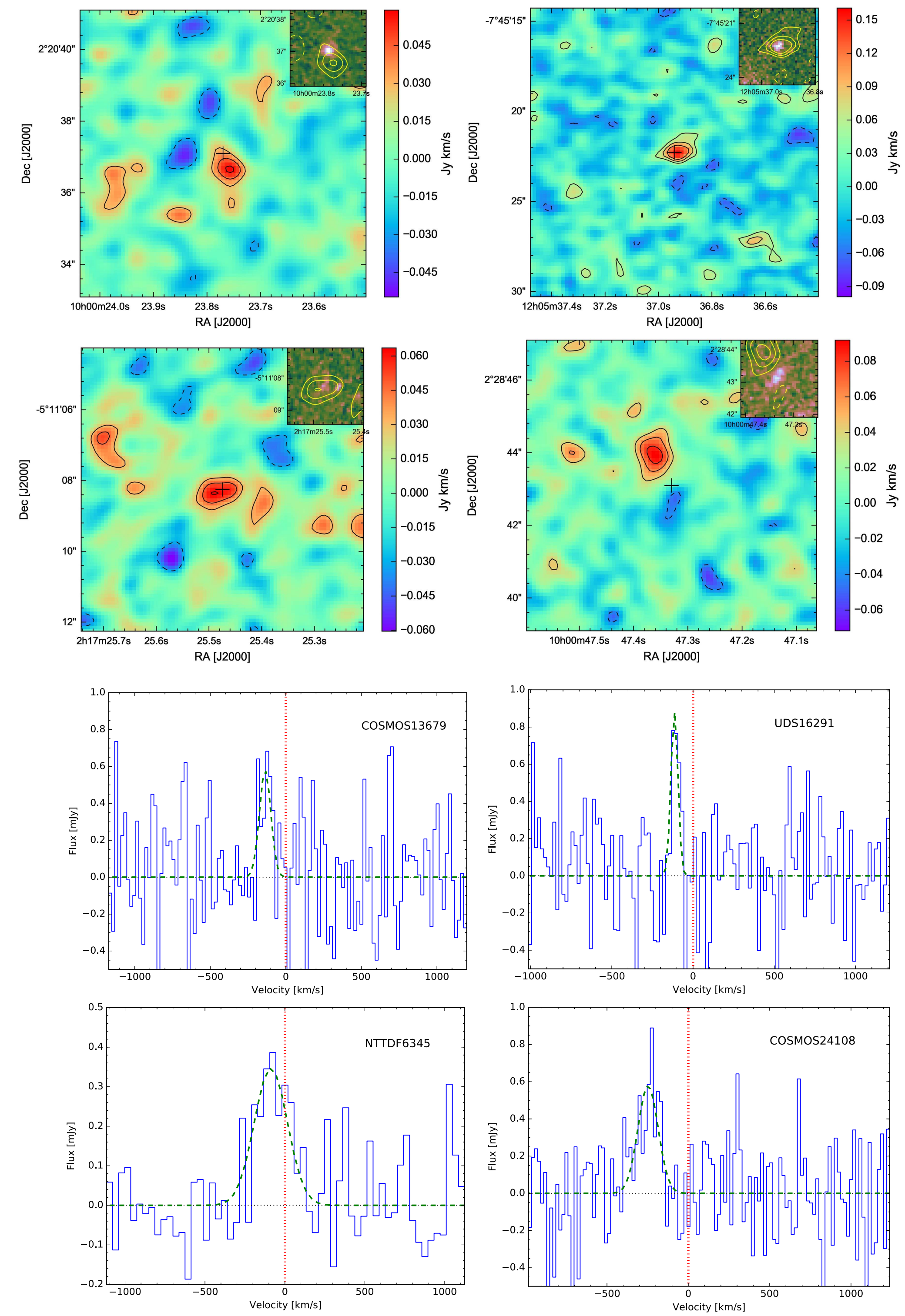


[CII] 158um detections in ALMA era

A galaxy at z=6.8 (Bradac+17)

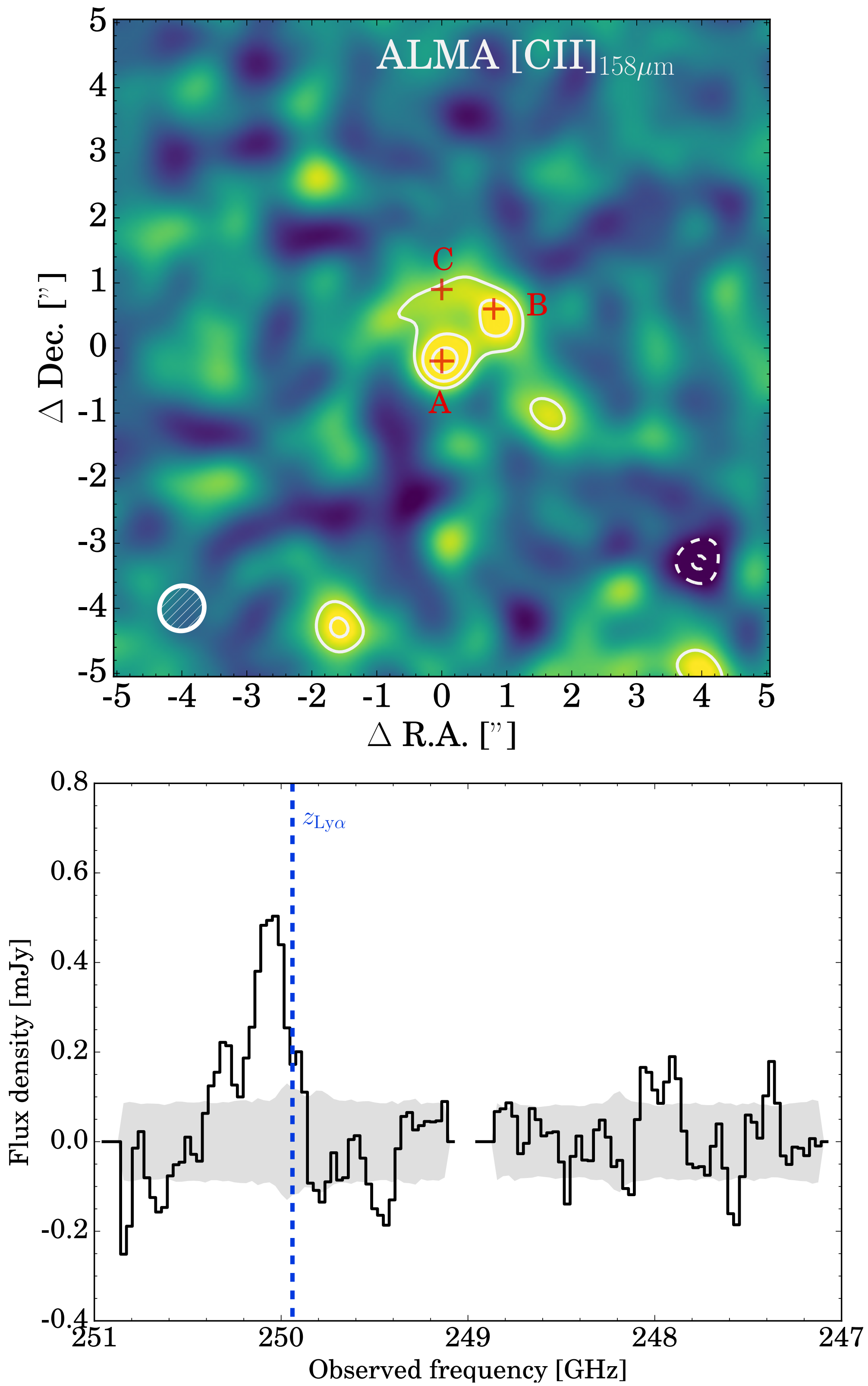


Four galaxies at z=6.6-7.2 (Pentericci+17)

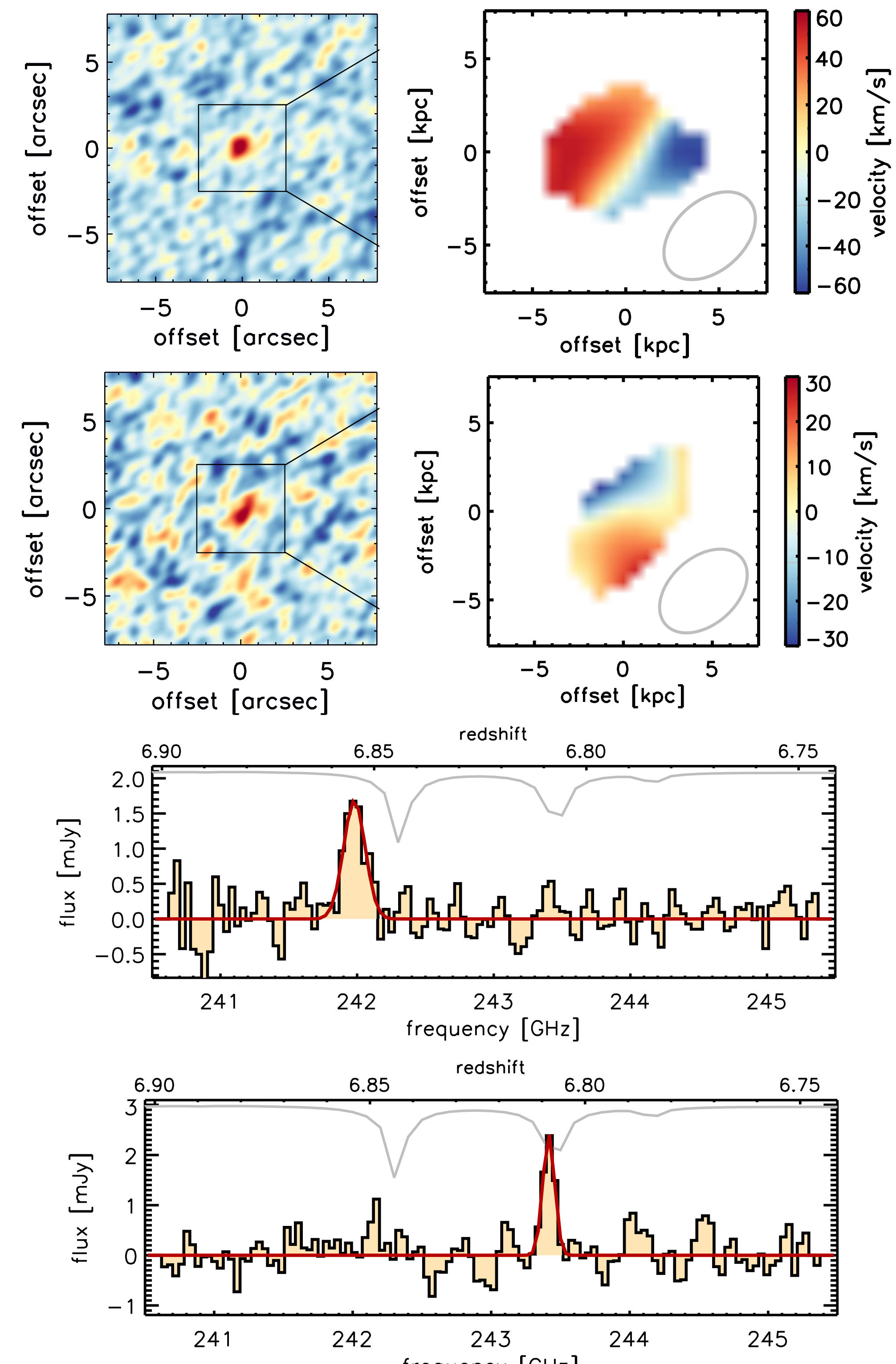


[CII] 158um detections in ALMA era

A galaxy at z=6.6 (Matthee+17)



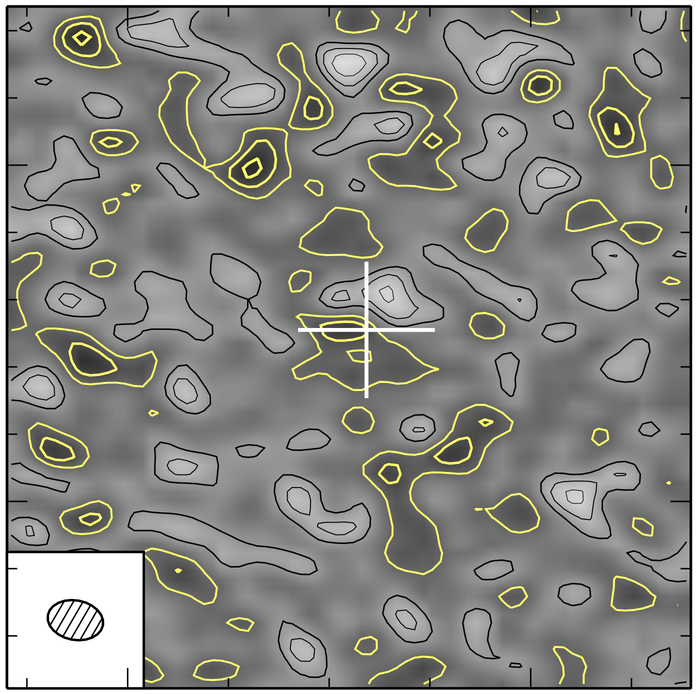
Two galaxies at z=6.8-6.9 (Smith+17)



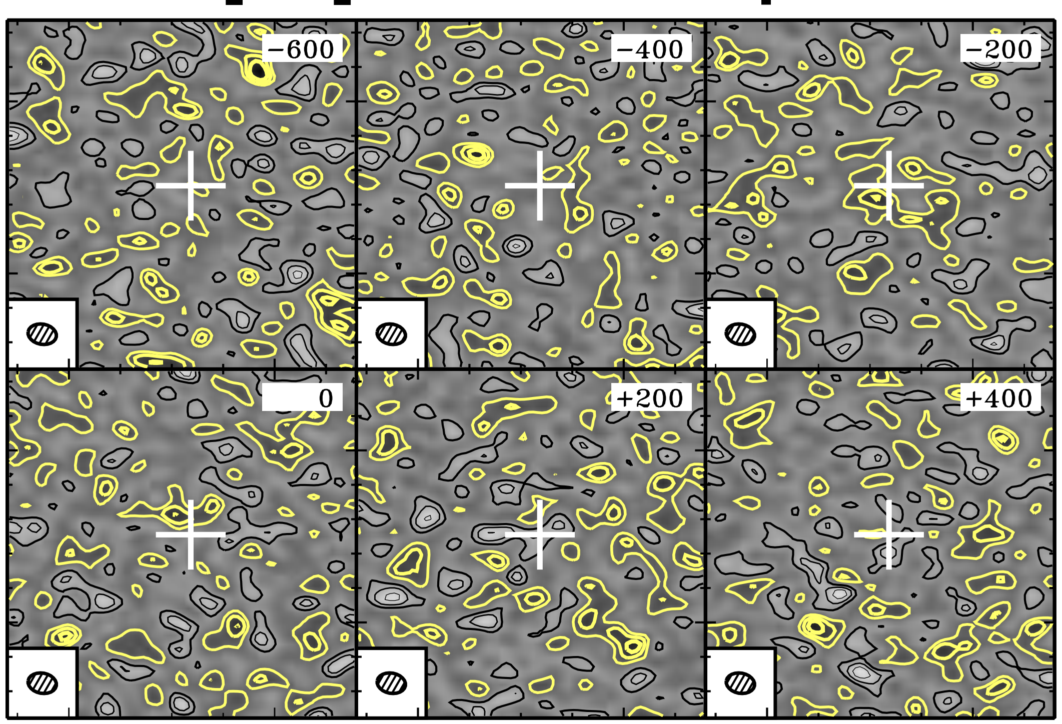
[CII] 158um non-detections

A galaxy at z=6.6 (Ouchi+13)

dust cont.

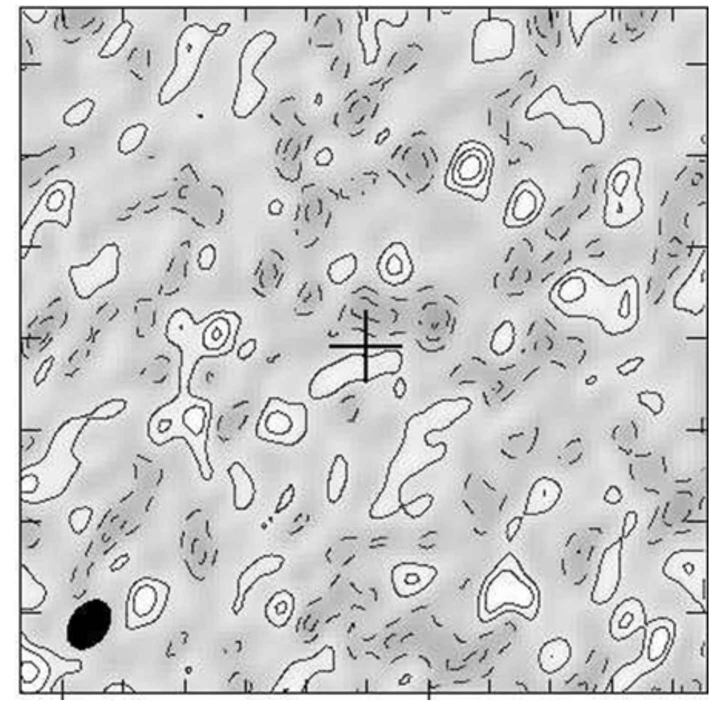


[CII] channel maps

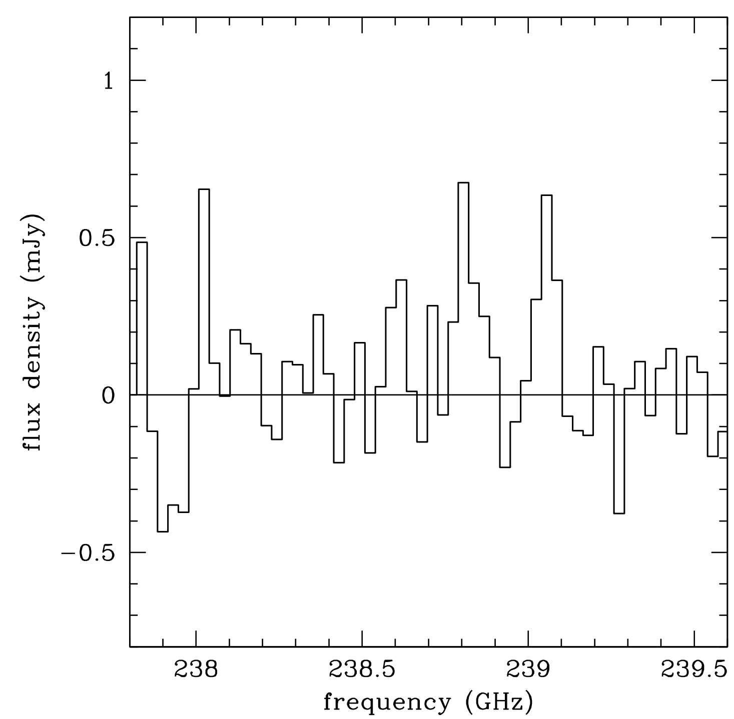


A galaxy at z=7.0 (Ota+14)

dust cont.



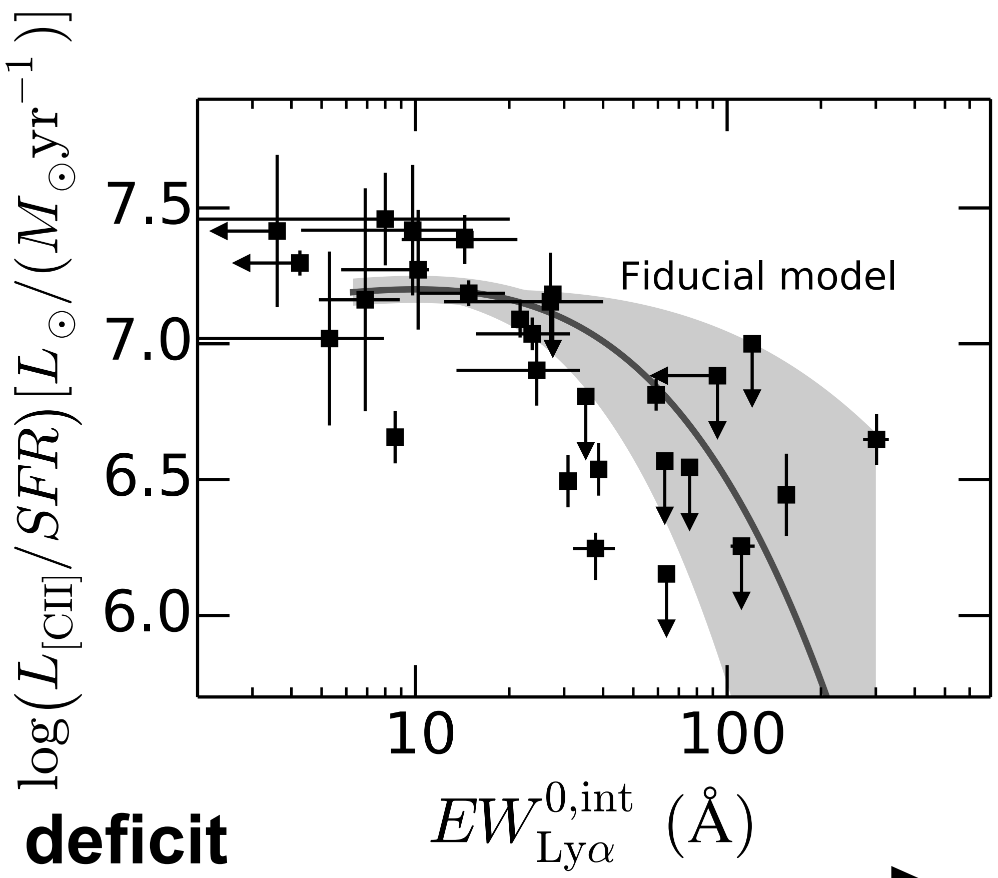
[CII] spectrum

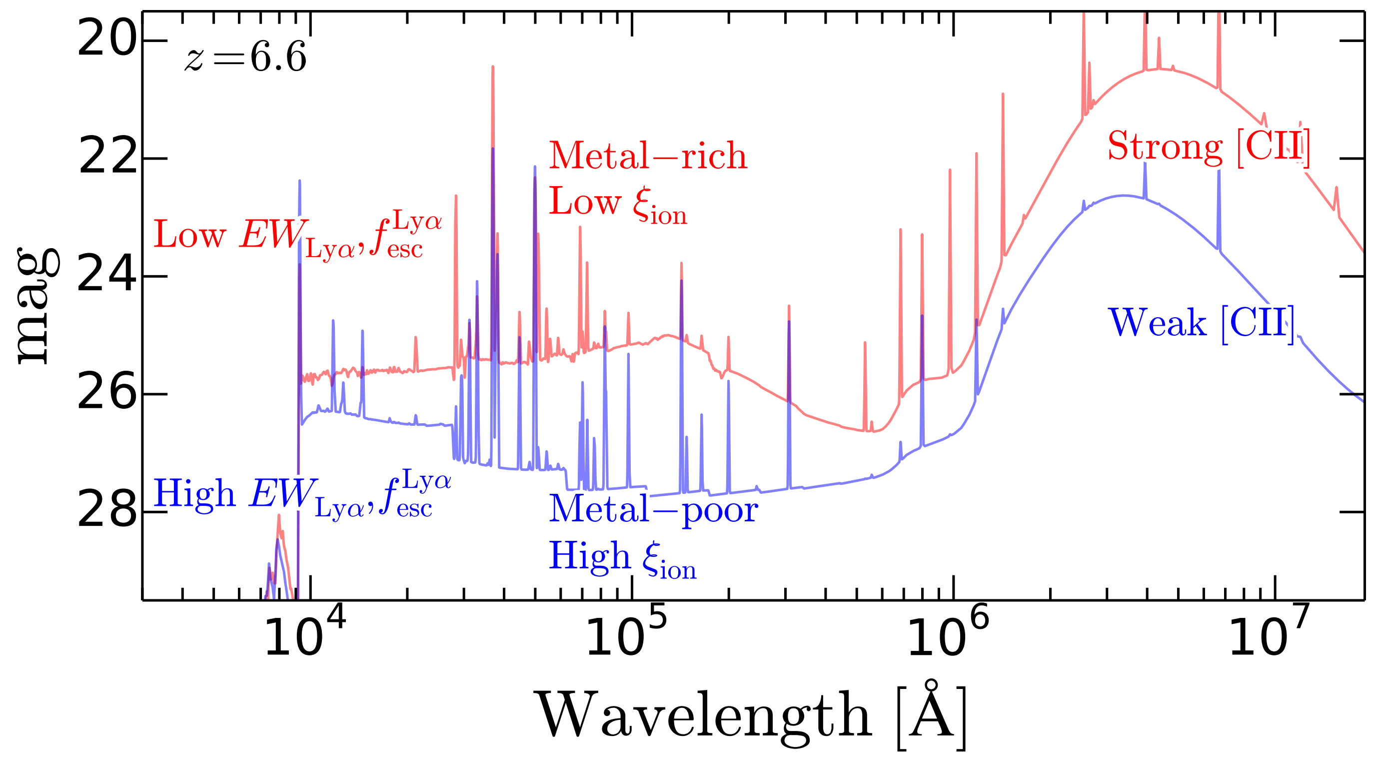


What is the difference between detections and non-detections?

What is the difference?

Compling [CII] sample (Harikane+17)





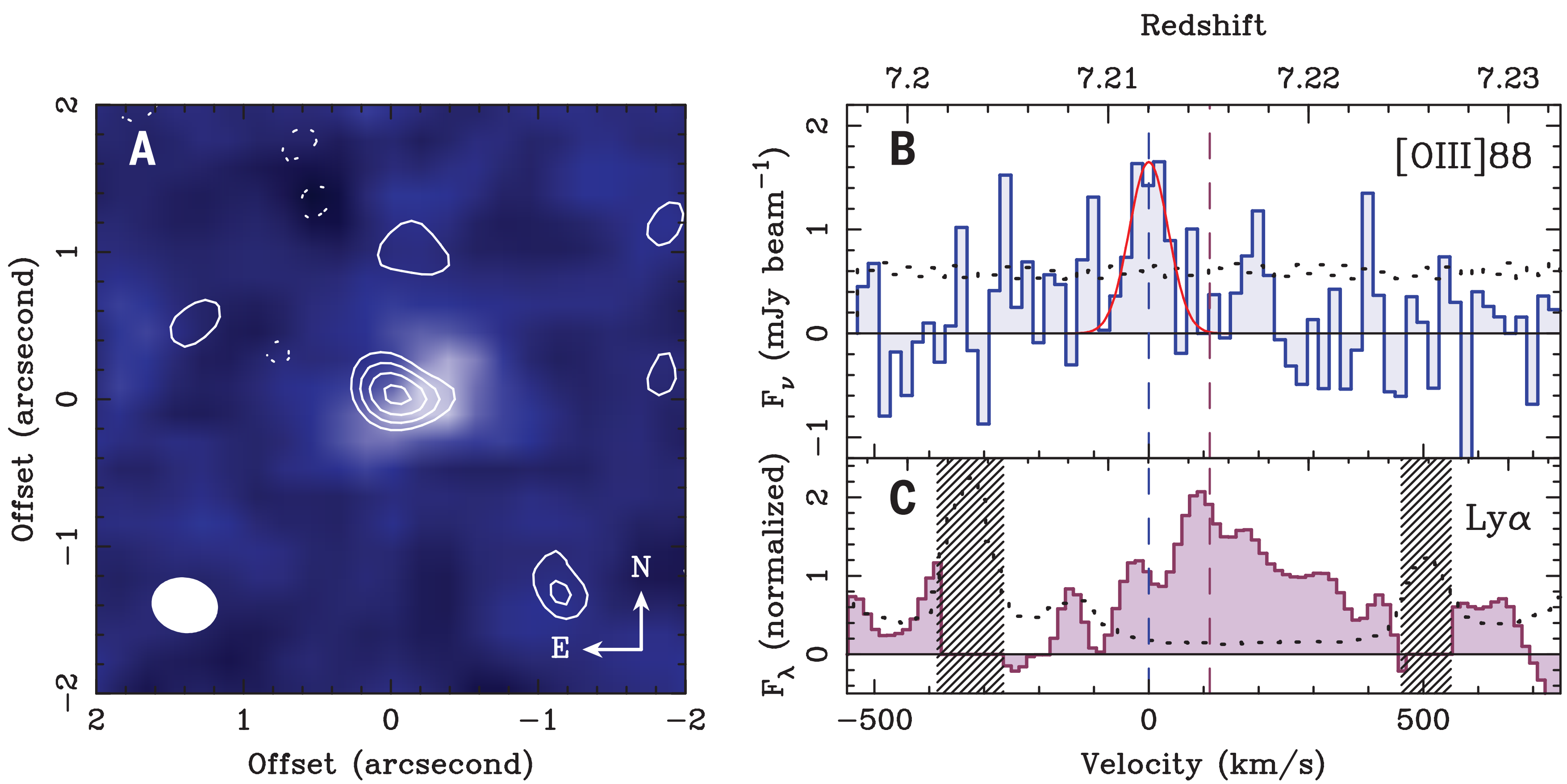
[CII] deficit

1. **more metal poor**
2. **higher ionizing photon production efficiency**

Galaxies in the very early stage are likely to have a weak [CII] line
[CII] line may not be a good probe of z=7-9 galaxies?

[OIII] 88um line

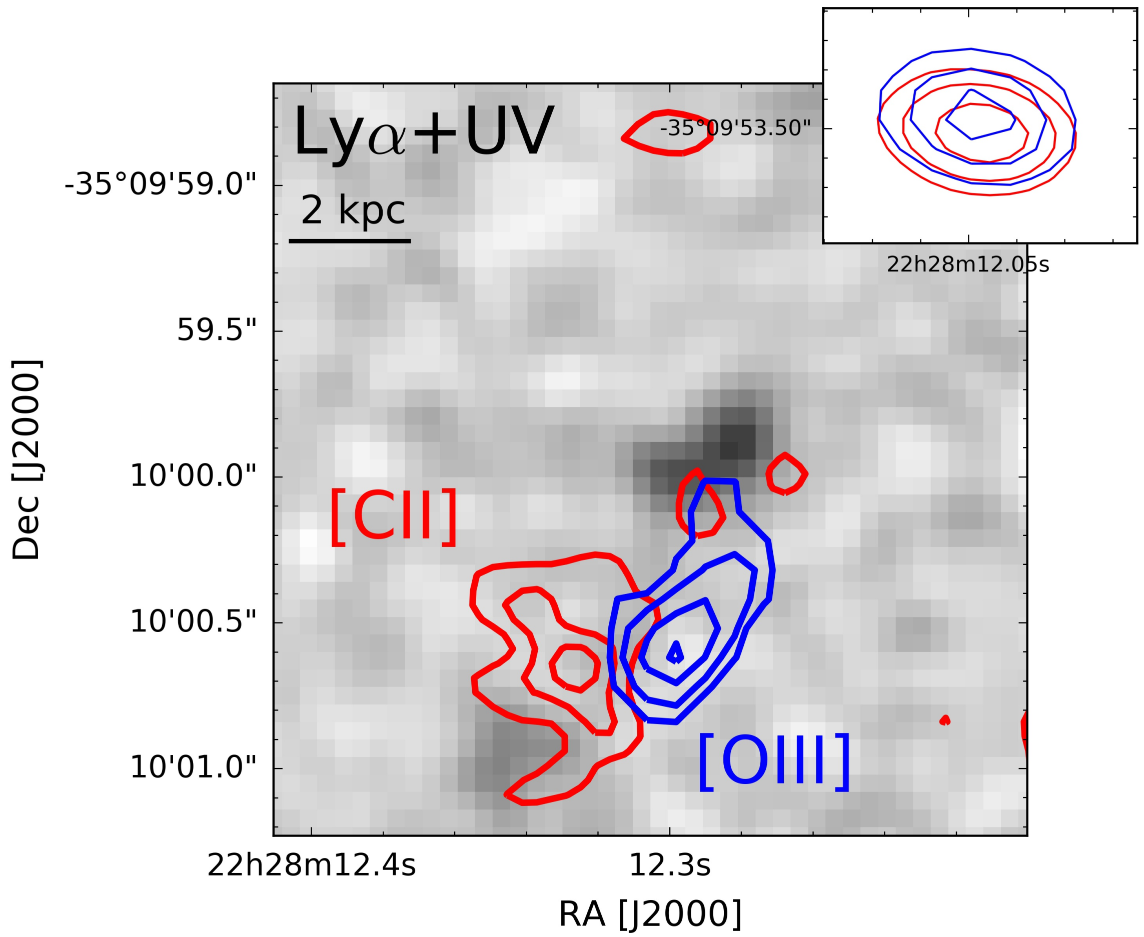
A galaxy at z=7.2 (Inoue+16, Science)



Band-8		Band-6
2 hours	on-source	1.8 hours
0.042 mJy	1σ (cont.)	0.014 mJy
[OIII] 88um	line	[CII] 158um
0.45 Jy km/s	line flux	<0.069Jy km/s

[OIII] 88um line

A galaxy at z=7.1 (Carniani+17)

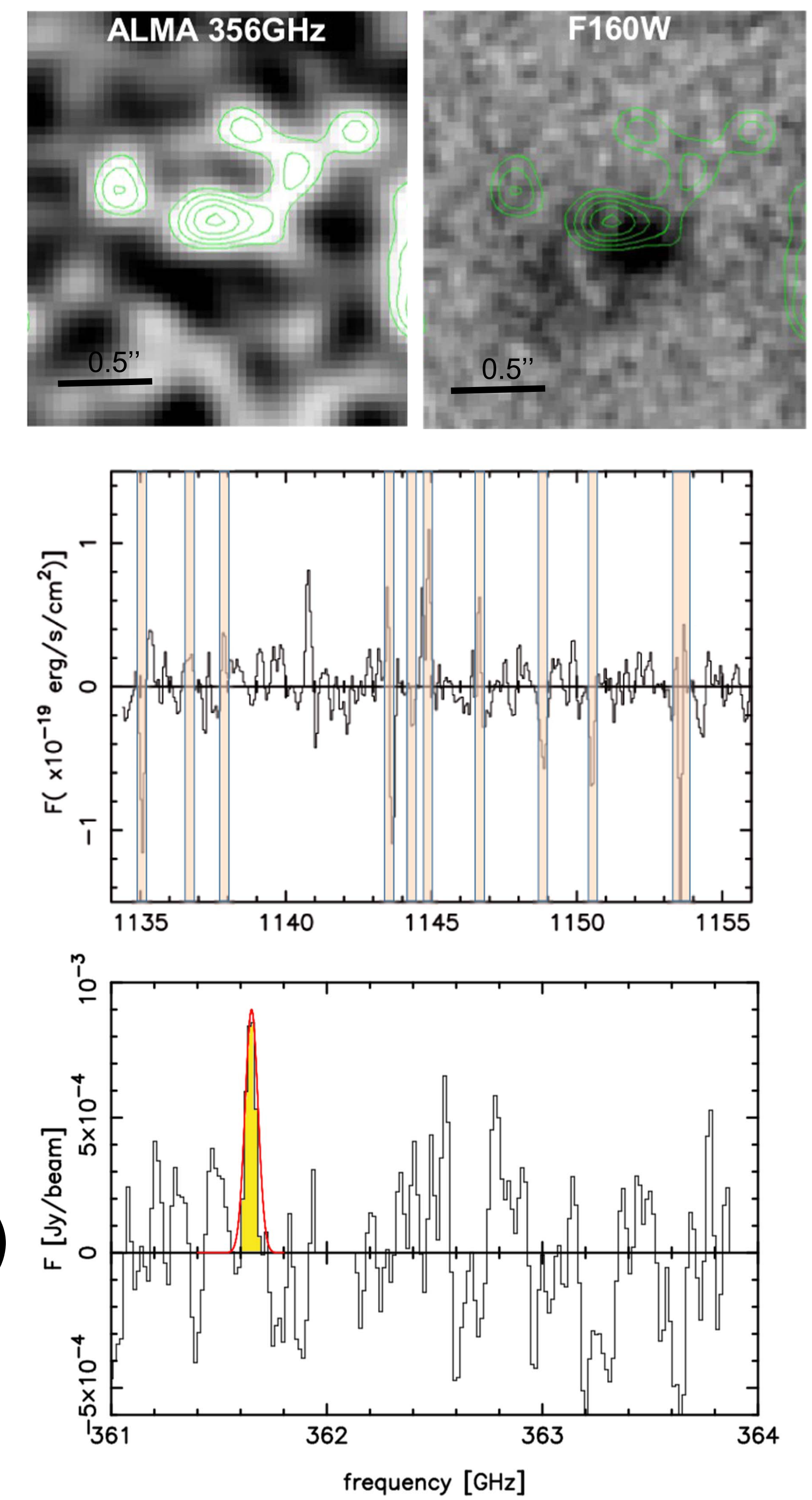


A galaxy at z=8.4 (Laporte+17)

dust cont.

Lyα (4σ,VLT)

[OIII] (4σ,ALMA)



Hot topics in high-z galaxy science

redshift

- ✓ It is now possible to measure gas masses even for quiescent galaxies or low stellar mass galaxies at z~1 through **CO observations**.

z~1

- ✓ 0.1-0.3" resolution observation revealed that the **dust continuum emission** is very compact for dusty star-forming galaxies at z=1-5. But higher resolution observations show more complex morphologies.

z=1-5

- ✓ **[OIII]88um line** will open the way for z>8 metal-poor galaxies. **[CII]158um line** is still useful for studying more metal-rich galaxies at z~6.

z=6-9

If you want to make creative works, following these trends is not a good way.

Thank you for your attention