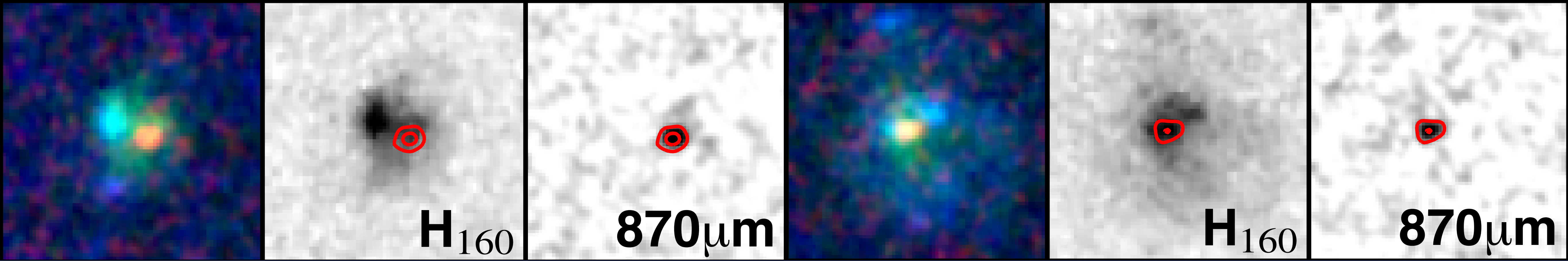
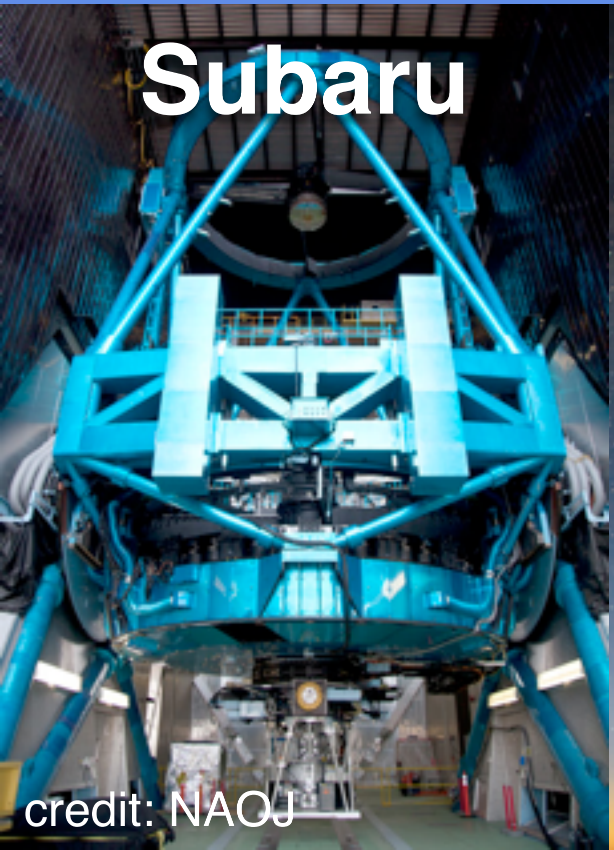


Panoramas of the Evolving Cosmos, November 29th, Hiroshima, Japan

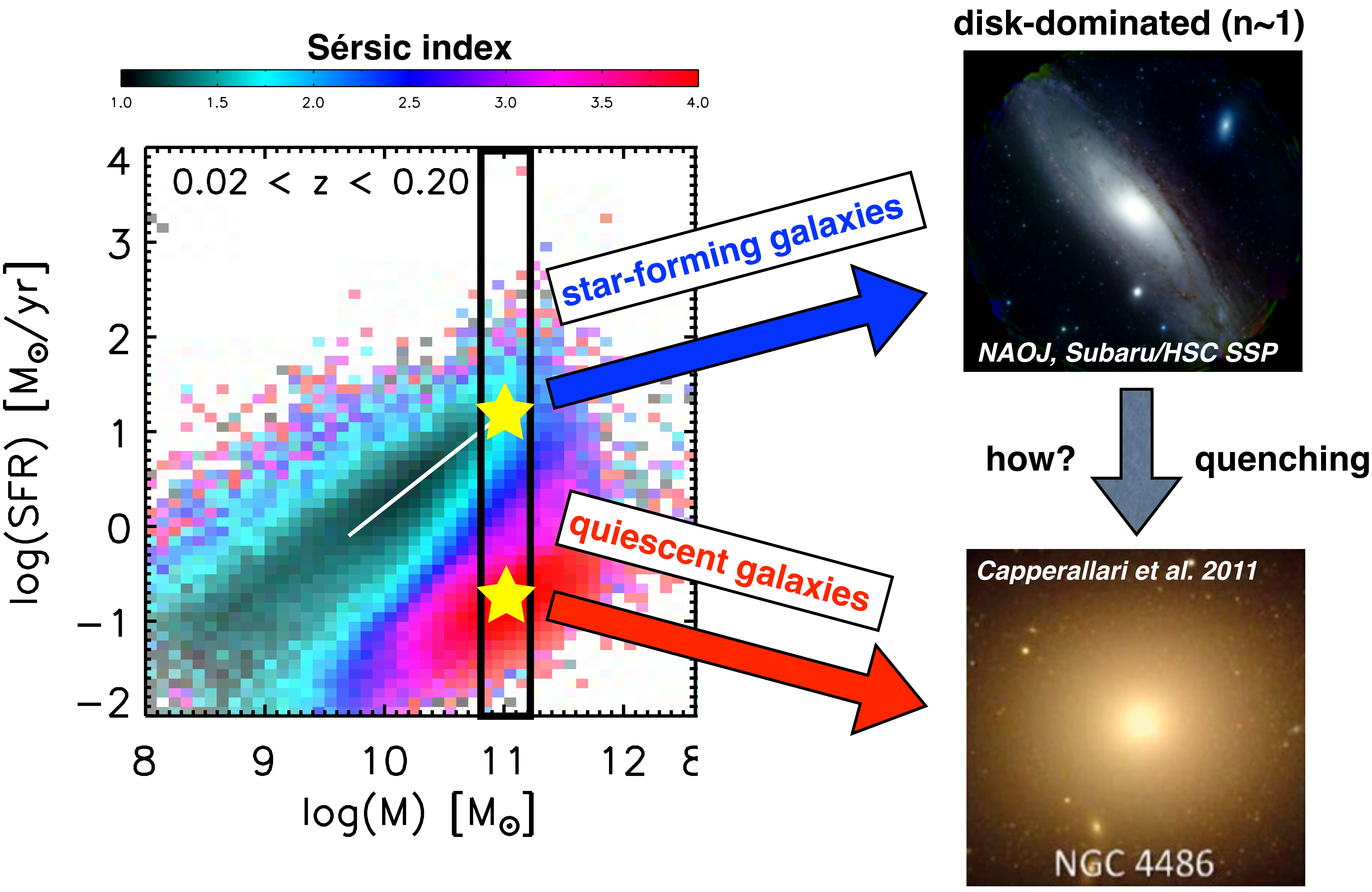
Rapid formation of a central bulge in massive galaxies at z~2: from Subaru to ALMA

Ken-ichi Tadaki (Max-planck Institute for Extraterrestrial Physics)

R. Genzel, T. Kodama, S. Wuyts, E. Wisnioski, N. M. Förster Schreiber, A. Burkert, P. Lang, L. J. Tacconi, D. Lutz, and the **MAHALO-Subaru** and **KMOS^{3D}** Teams

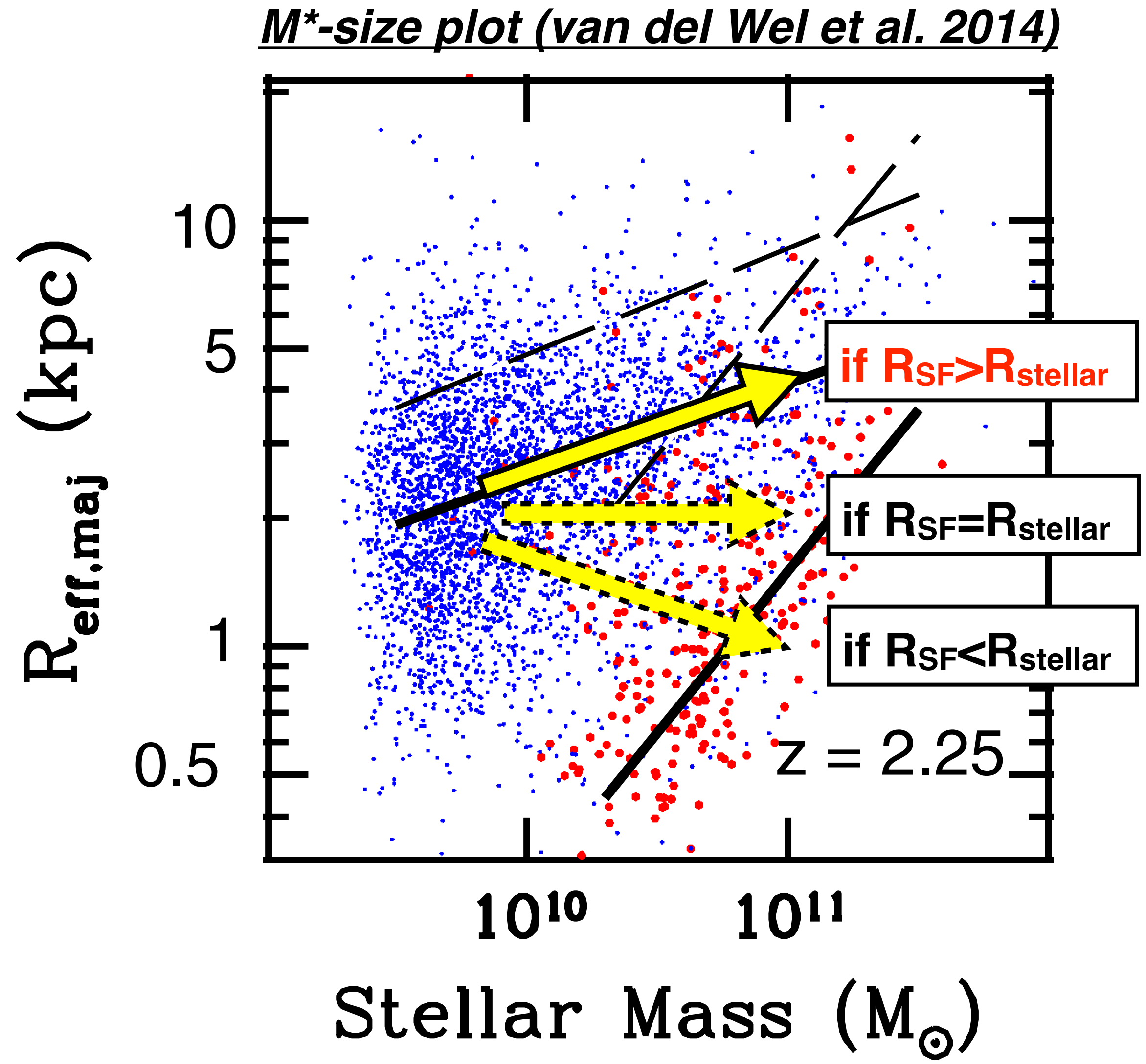


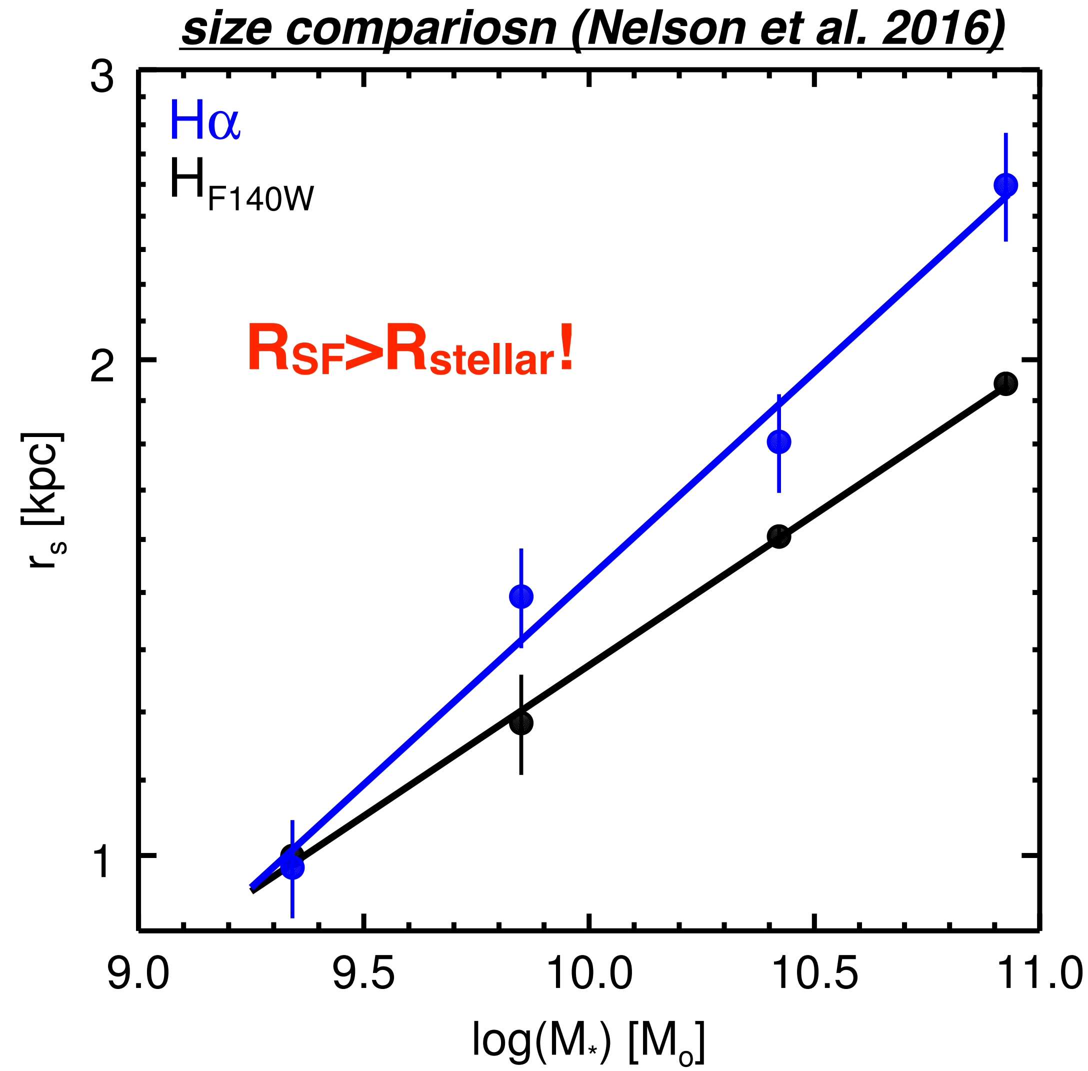
A modern version of the Hubble sequence



Wuyts+2011

Inside-out growth of galaxies



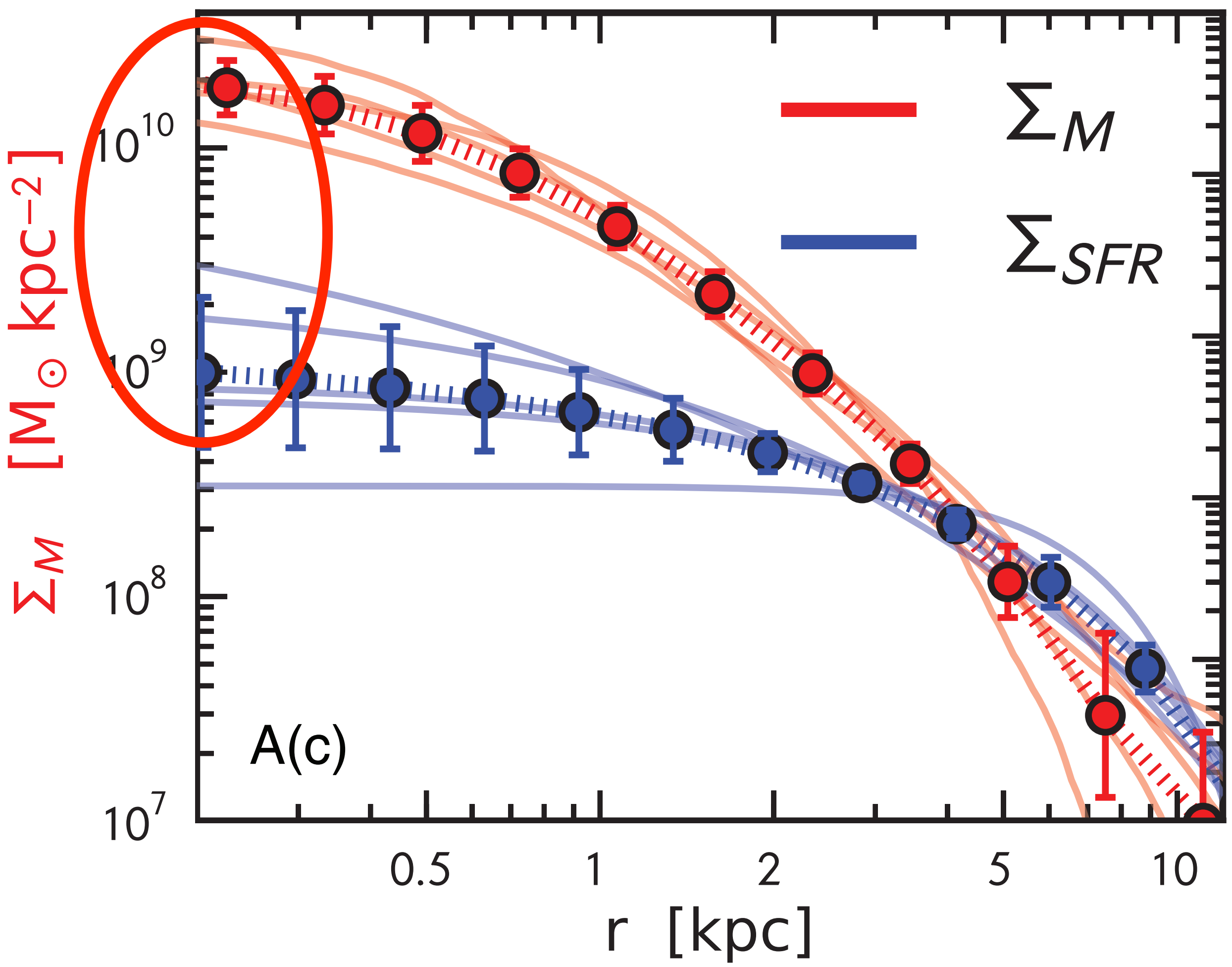


In an early evolutionary stage of star-forming galaxies,
- galaxies grow in size with increasing stellar mass
- they are forming stars in larger disks than stellar continuum (inside-out growth)
- they never form a bulge component!

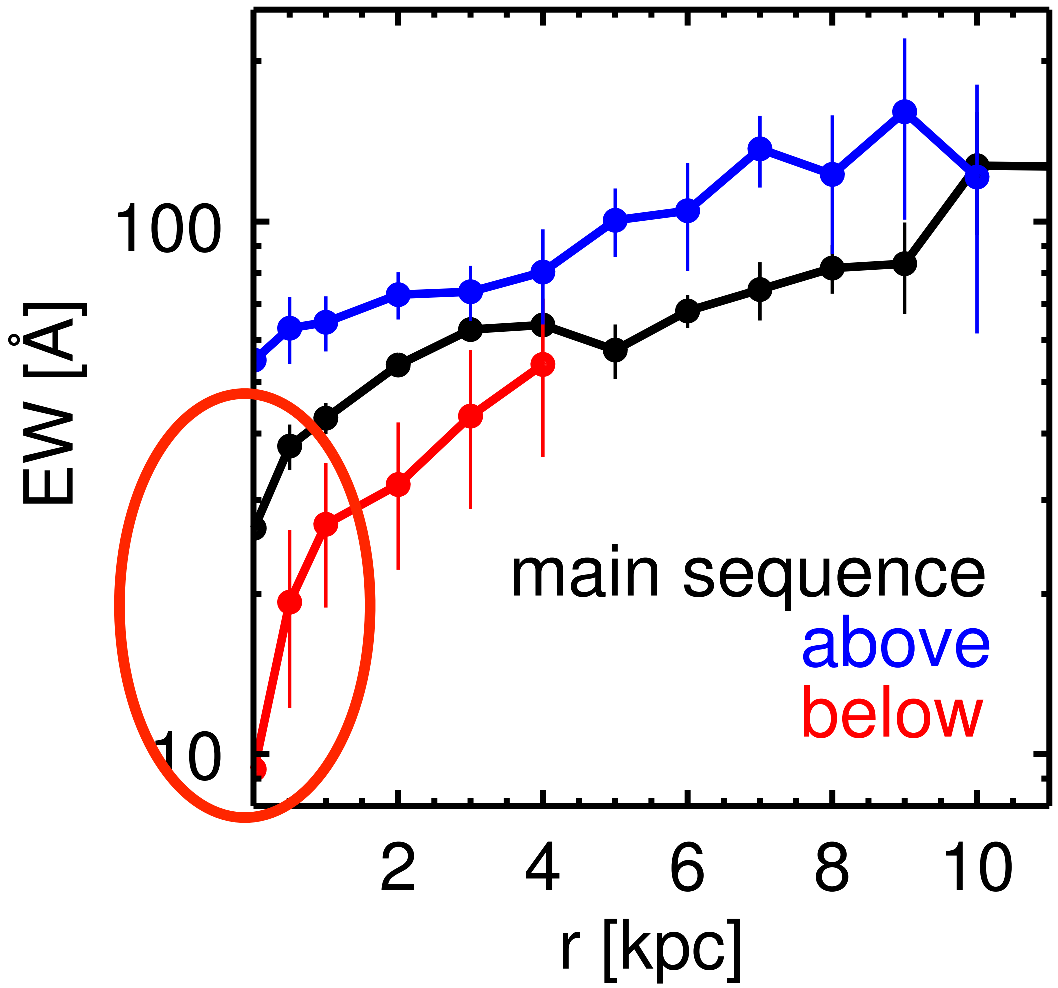
At some point (probably around the Schechter mass),
- star-forming region should become more compact than stellar continuum

Inside-out quenching of galaxies

Massive star-forming galaxies at z~2
(Tacchella et al. 2015)



Massive star-forming galaxies at z~1
(Nelson et al. 2016)



In a late evolutionary stage of star-forming galaxies,
(after a dense core is formed)
- central region has lower specific star formation rates
- the suppression is more significant in galaxies below the main-sequence
- star formation is likely quenched from the inside out

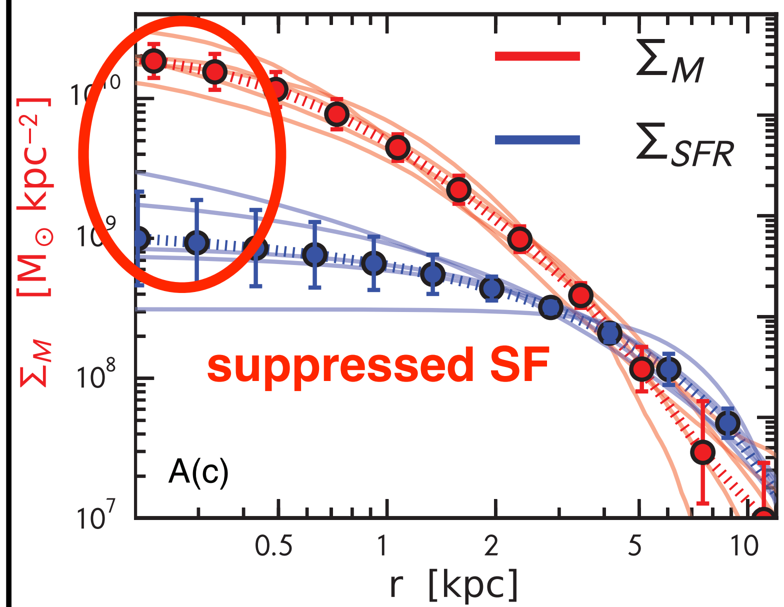
Missing link

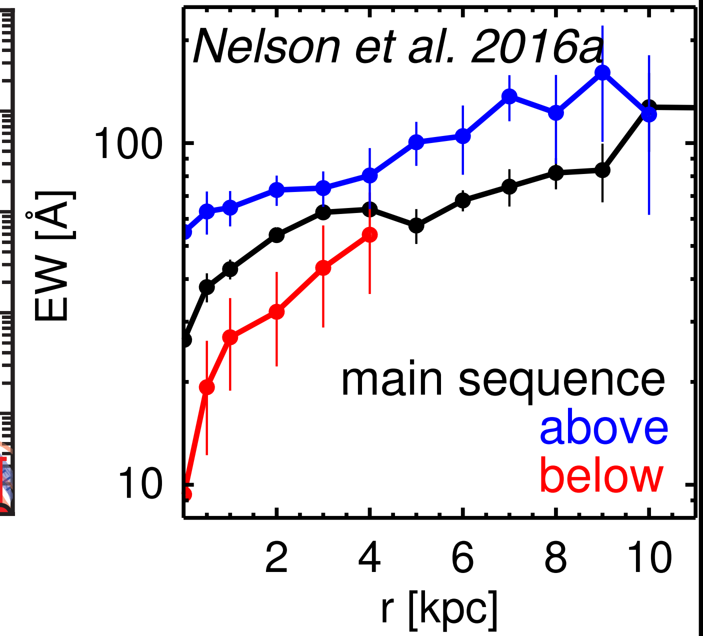
2. ????????????

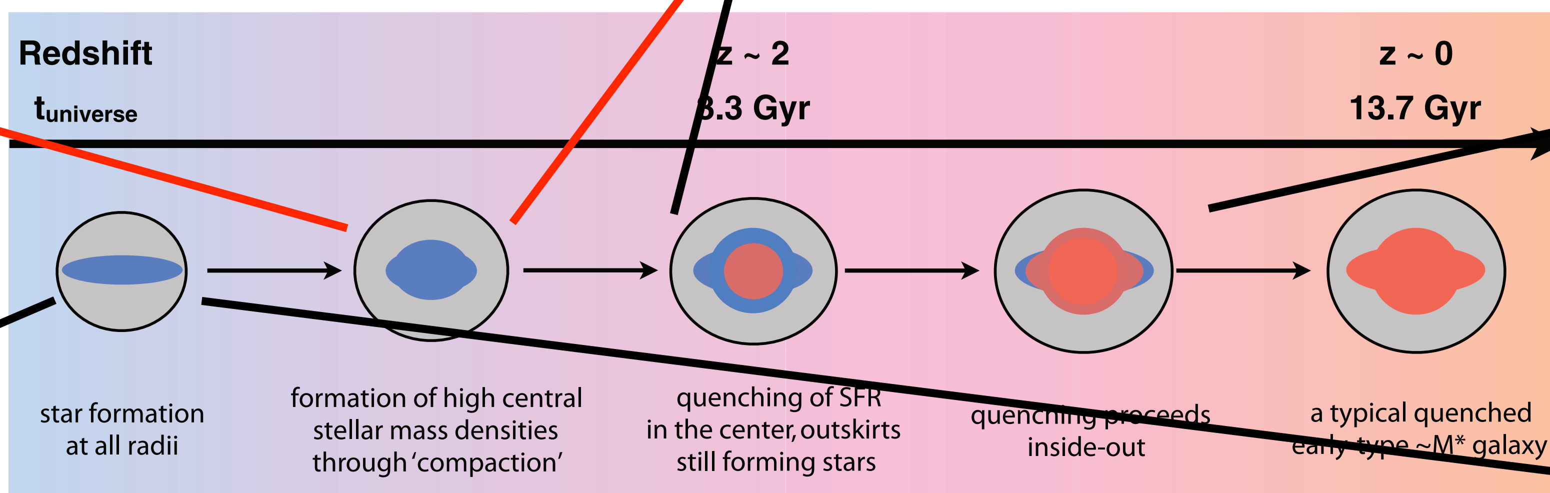
question: how did galaxies form a bulge component?

method: study the spatial distribution of star formation for massive galaxies at z~2

3. inside-out quenching

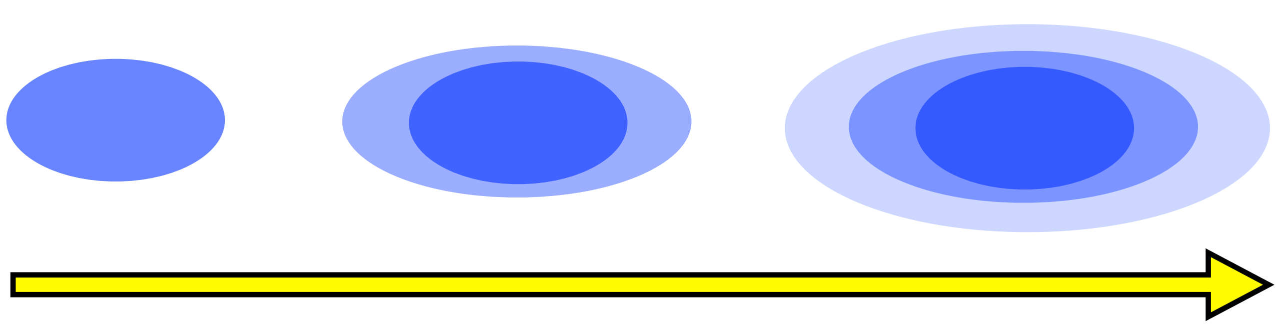




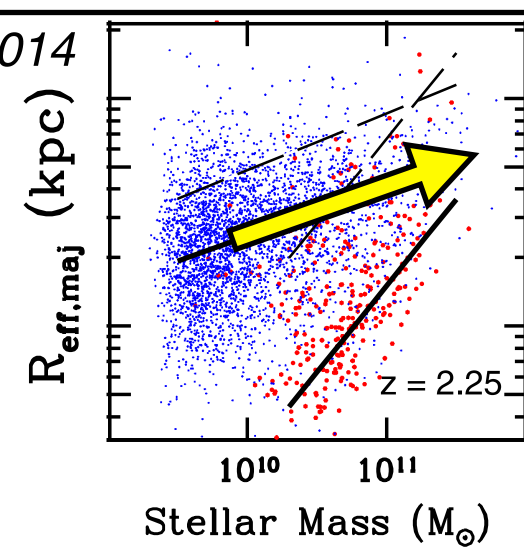


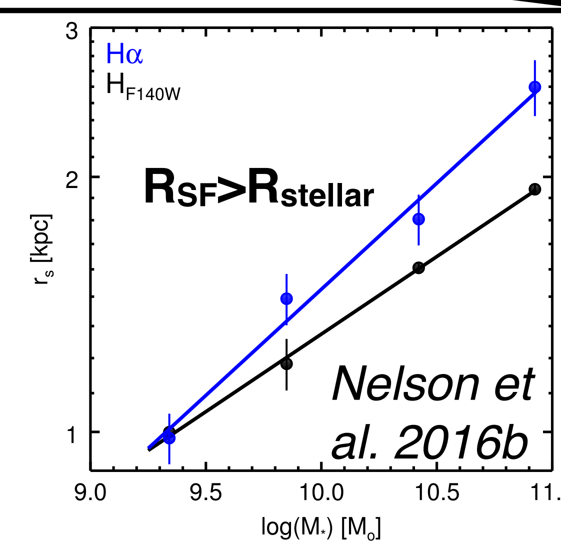
Tacchella et al. 2015

1. inside-out growth



van del Wel et al. 2014

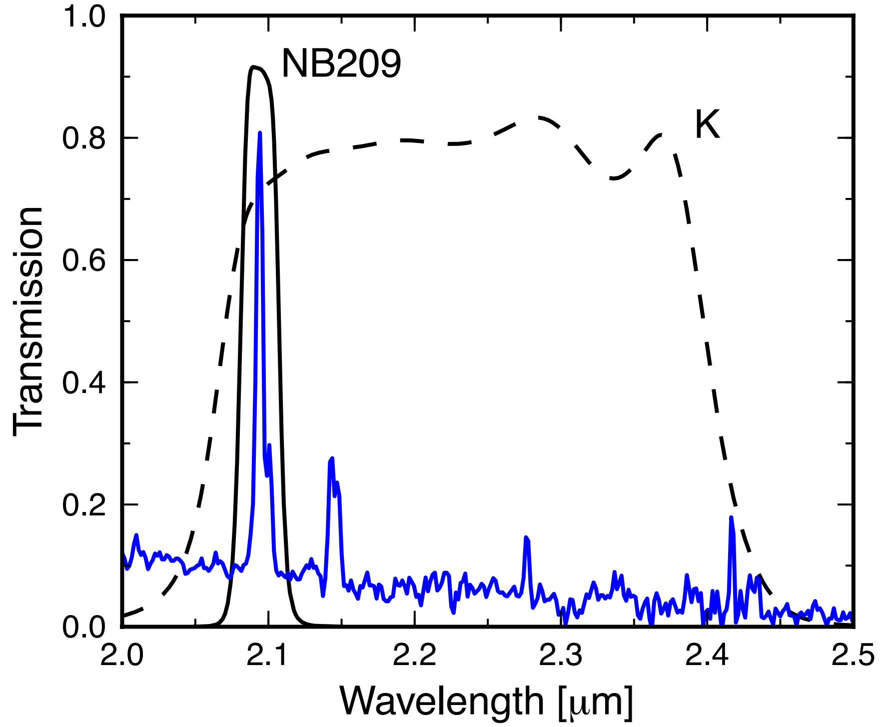


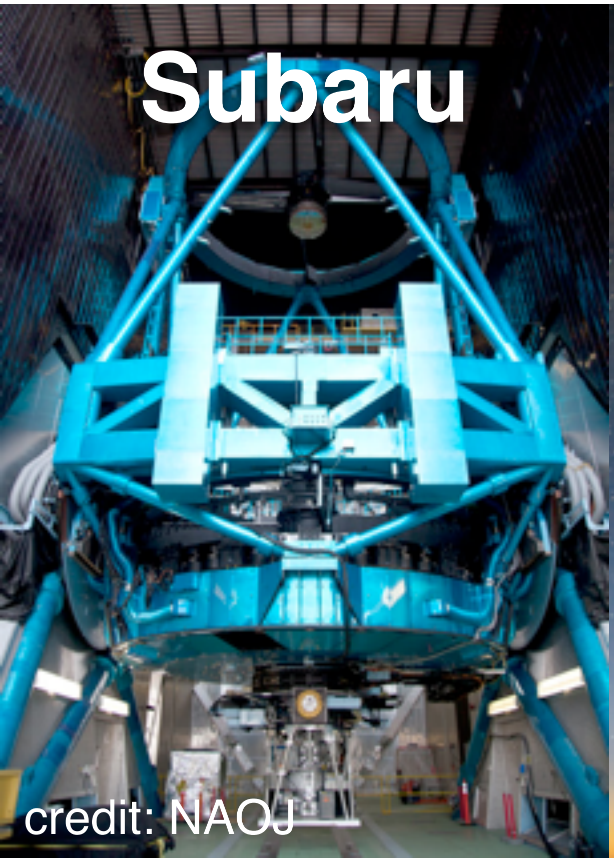


Sample and data in SXDF-UDS (CANDELS/3D-HST)

Subaru/ MOIRCS	Hα narrow-band imaging	MAHALO-Subaru (Tadaki+13, Kodama+13)
VLT/ KMOS	kinematics of ionized gas	KMOS^{3D} (Wisnioski+15)
HST/ WFC3	optical morphology	CANDELS/3D-HST (Skelton+14, Grogin+11, Koekemoer+11)
ALMA/ band7	FIR morphology	GRACIAS-ALMA (Tadaki+16)

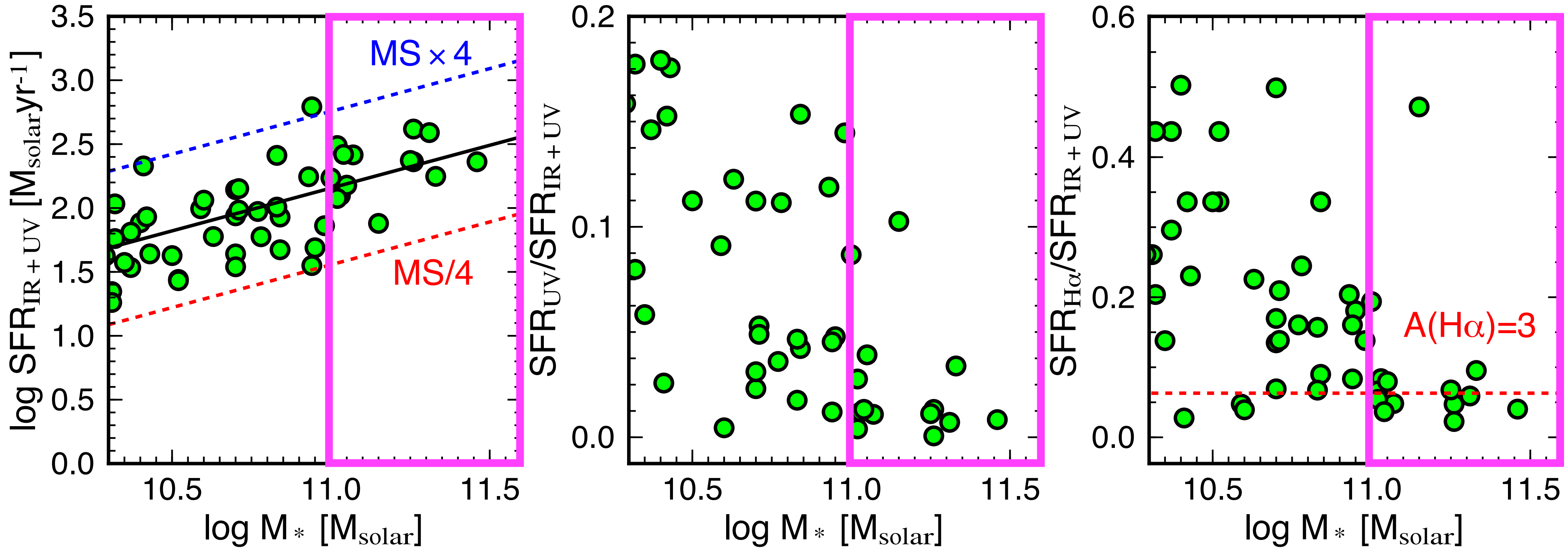
Narrow-band filter to trace Hα emission at z=2.19





Why ALMA?

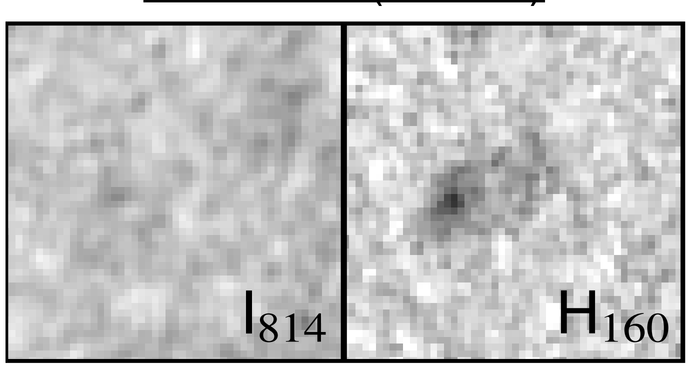
Galaxy properties of Hα-selected SFGs at z~2



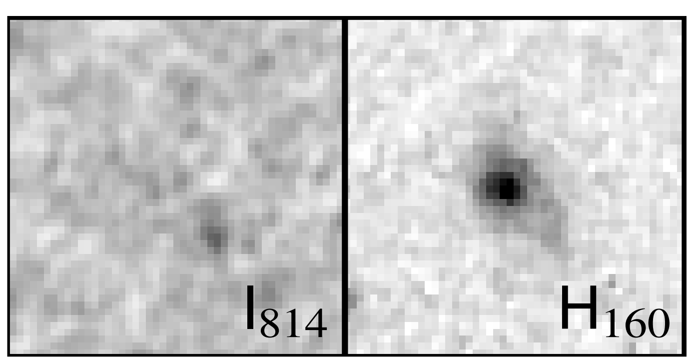
UV light traces ~1% of total star formation

even Hα trace ~5% A(Hα)~3 mag

U4-16795 (z=2.53)



U4-28473 (z=2.53)



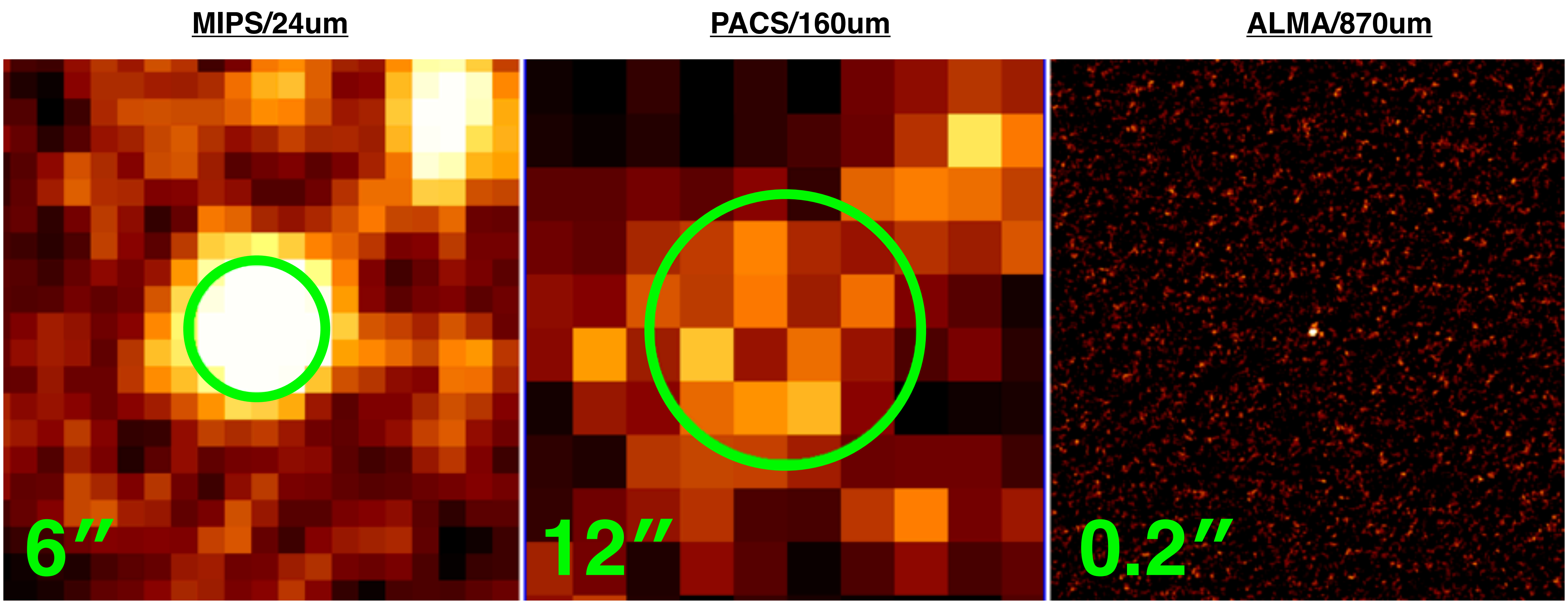
- what we want to know is the spatial distribution of star formation within galaxies
- UV/Hα light is strongly attenuated by dust extinction for massive galaxies

we need to spatially resolve the dust emission

Tadaki et al. 2016, arXiv:1608.05412

Why ALMA?

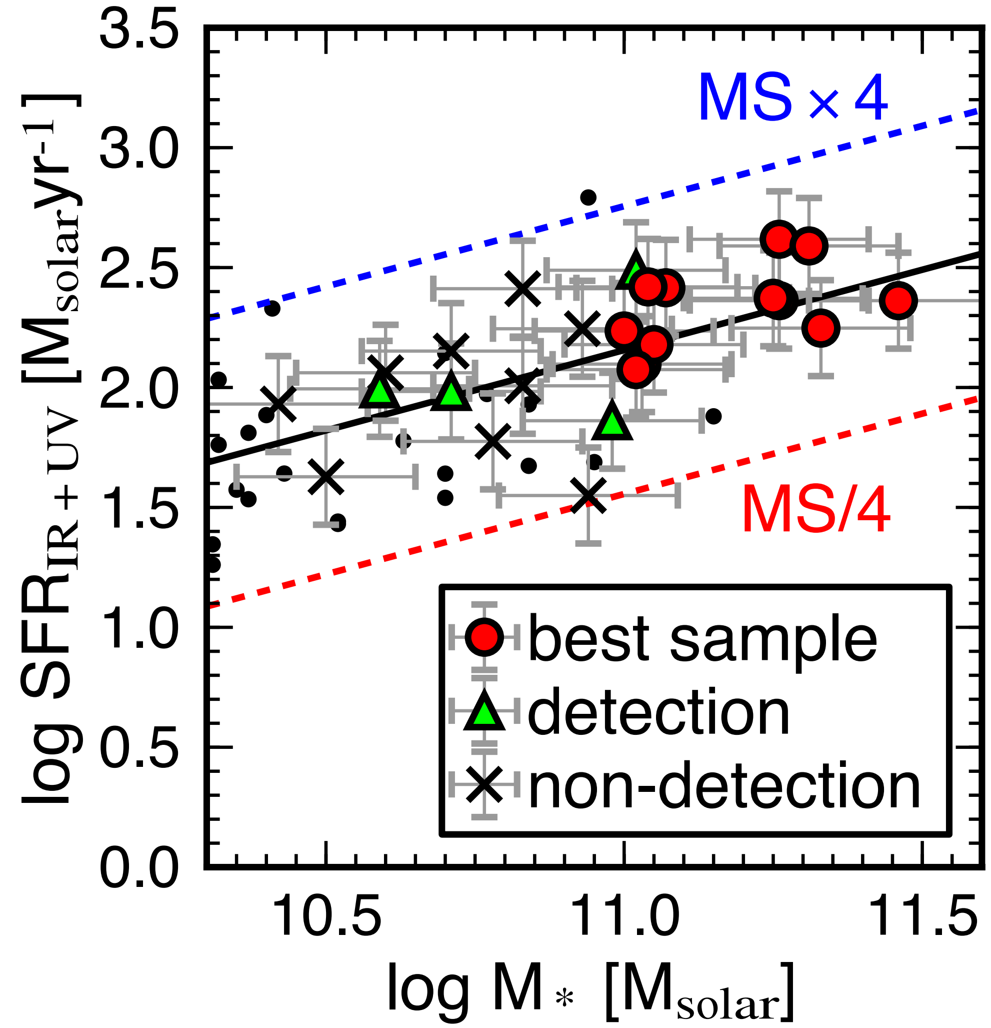
ALMA is the most powerful tool for resolving dust emission

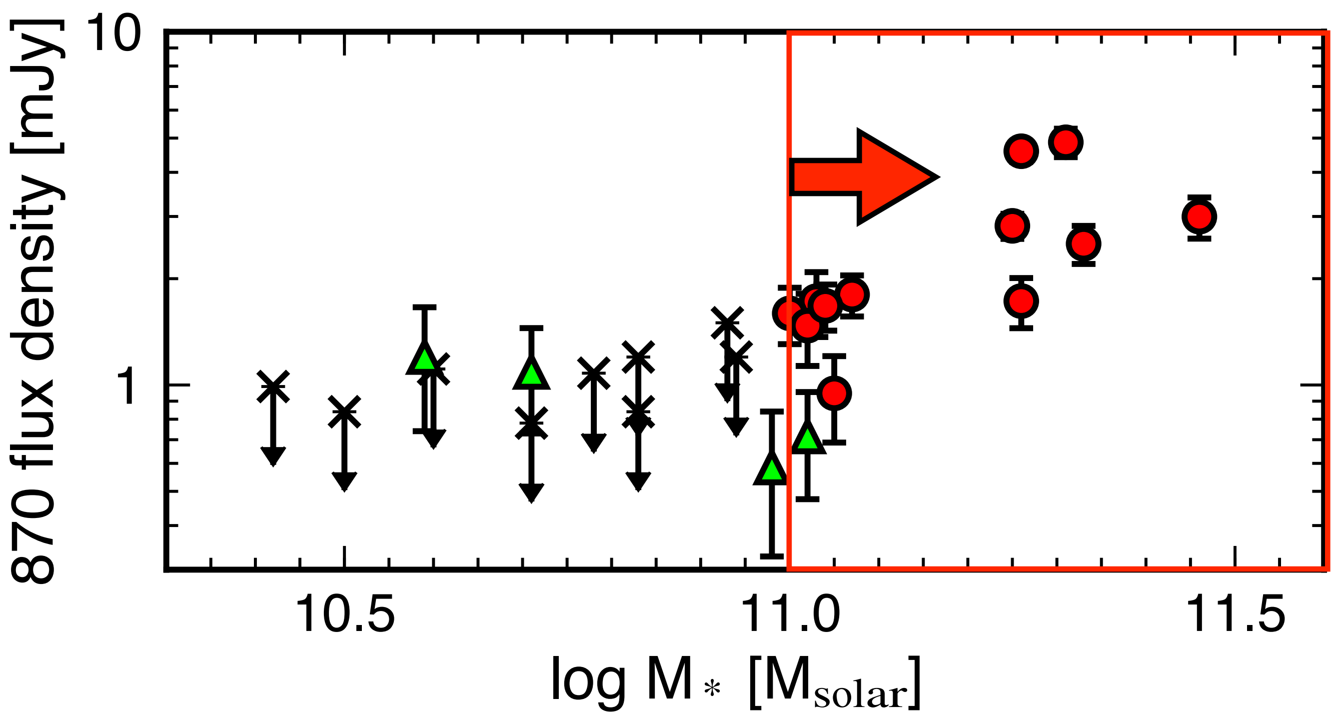


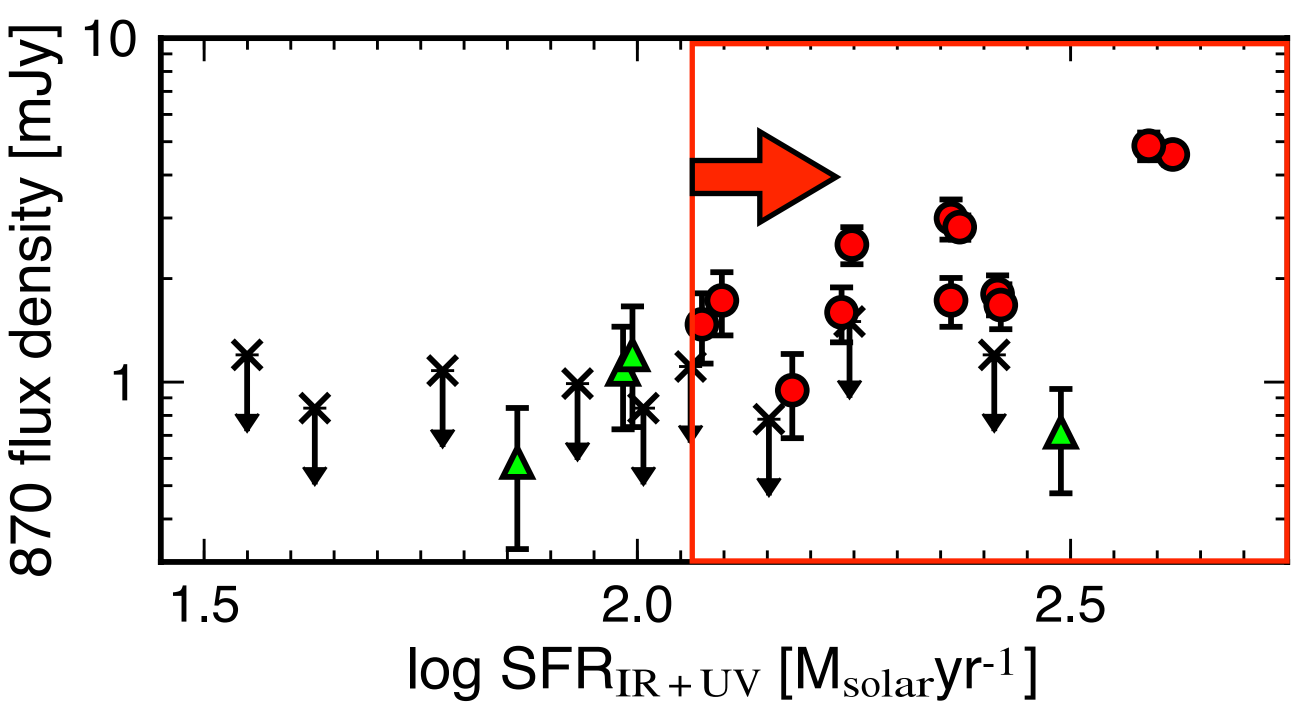
Tadaki et al. 2016, arXiv:1608.05412

ALMA Band-7 observations

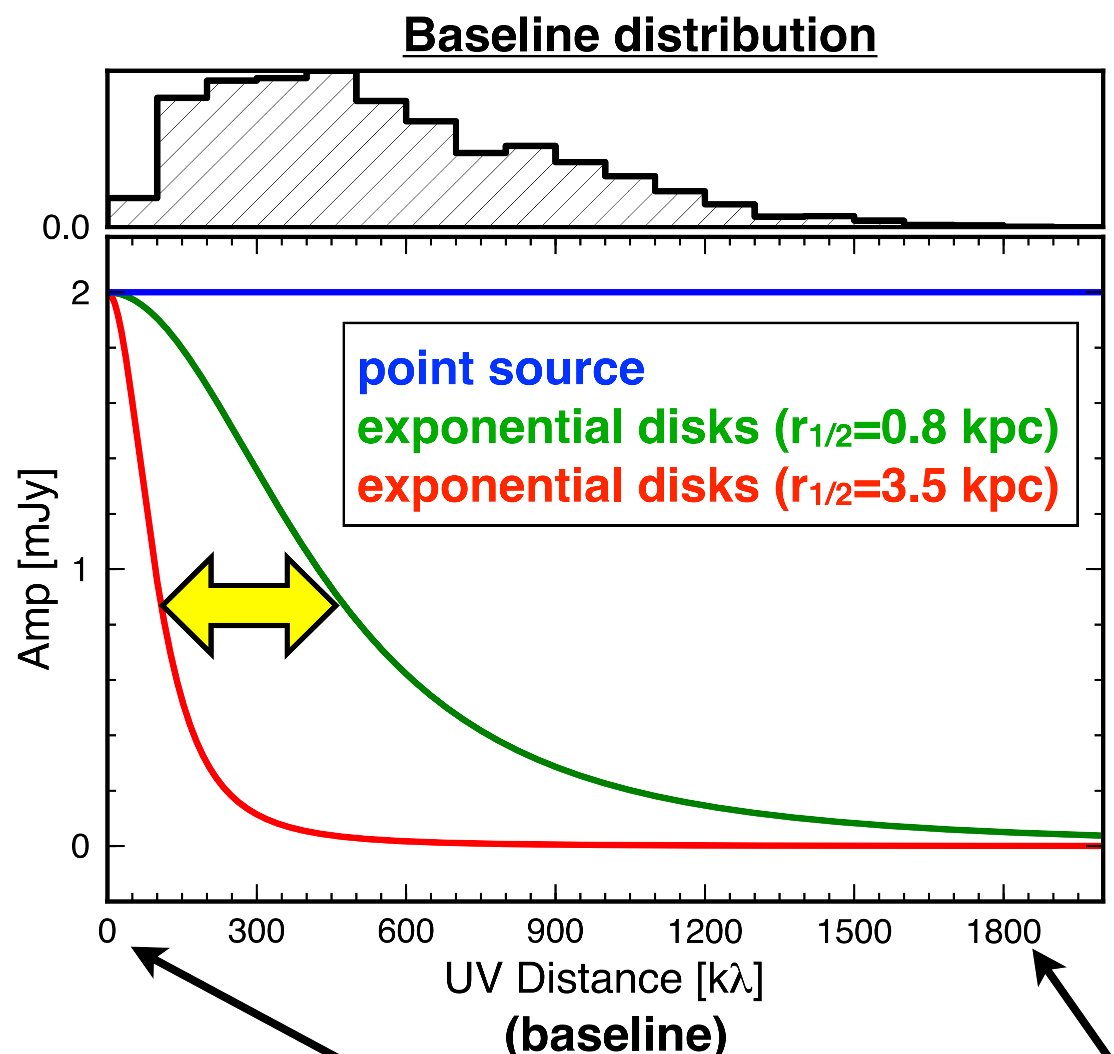
Target	25 SFGs on main-sequence at z~2
Frequency	345 GHz (870 um)
On-source time	6-8 minutes
Spatial resolution	0.18″
Result	16/25 are detected 12 have reliable size measurements







Size measurements of 870 μm emission



Our data is sensitive to emission in uv the range of 100-900 kλ

the best configuration to identify dust emission with $r_{1/2}$=1-2 kpc

visibility plane:

$$g(u) = S_{\rm model} \times \frac{k_0^3}{(u^2 + k_0^2)^{3/2}}$$

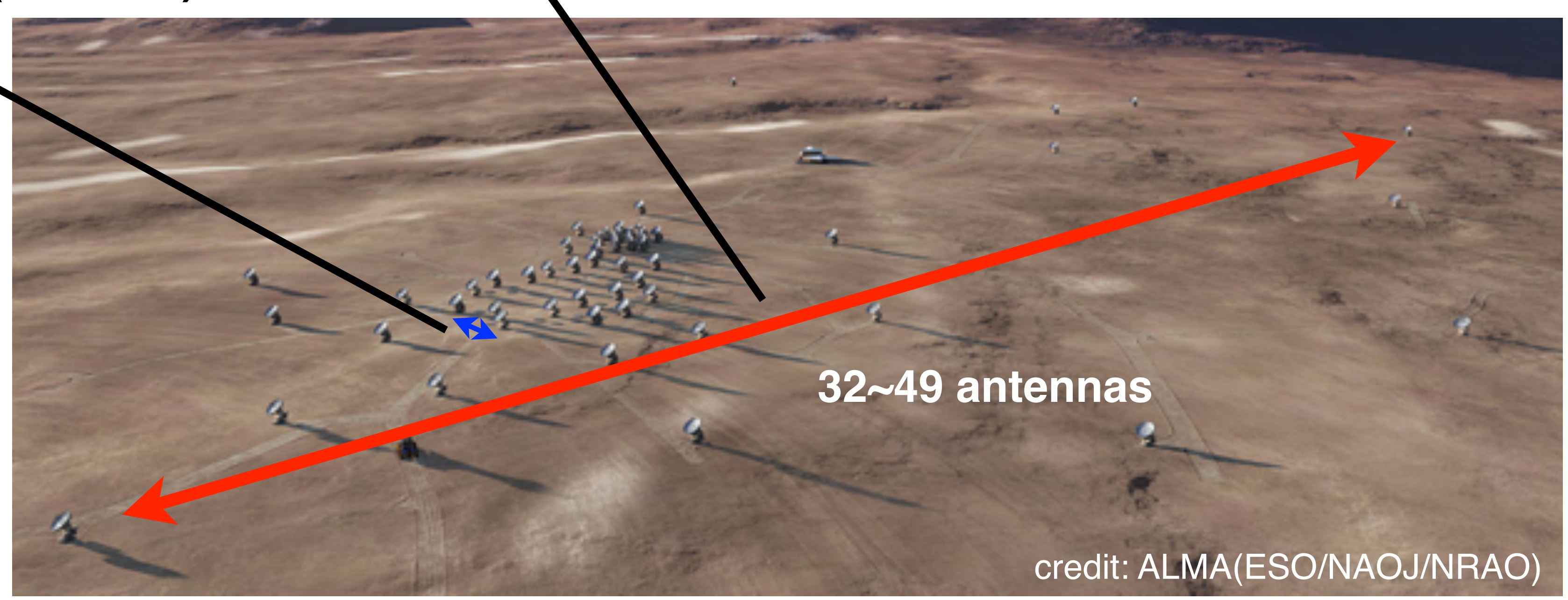
2D Fourier transform

image plane:

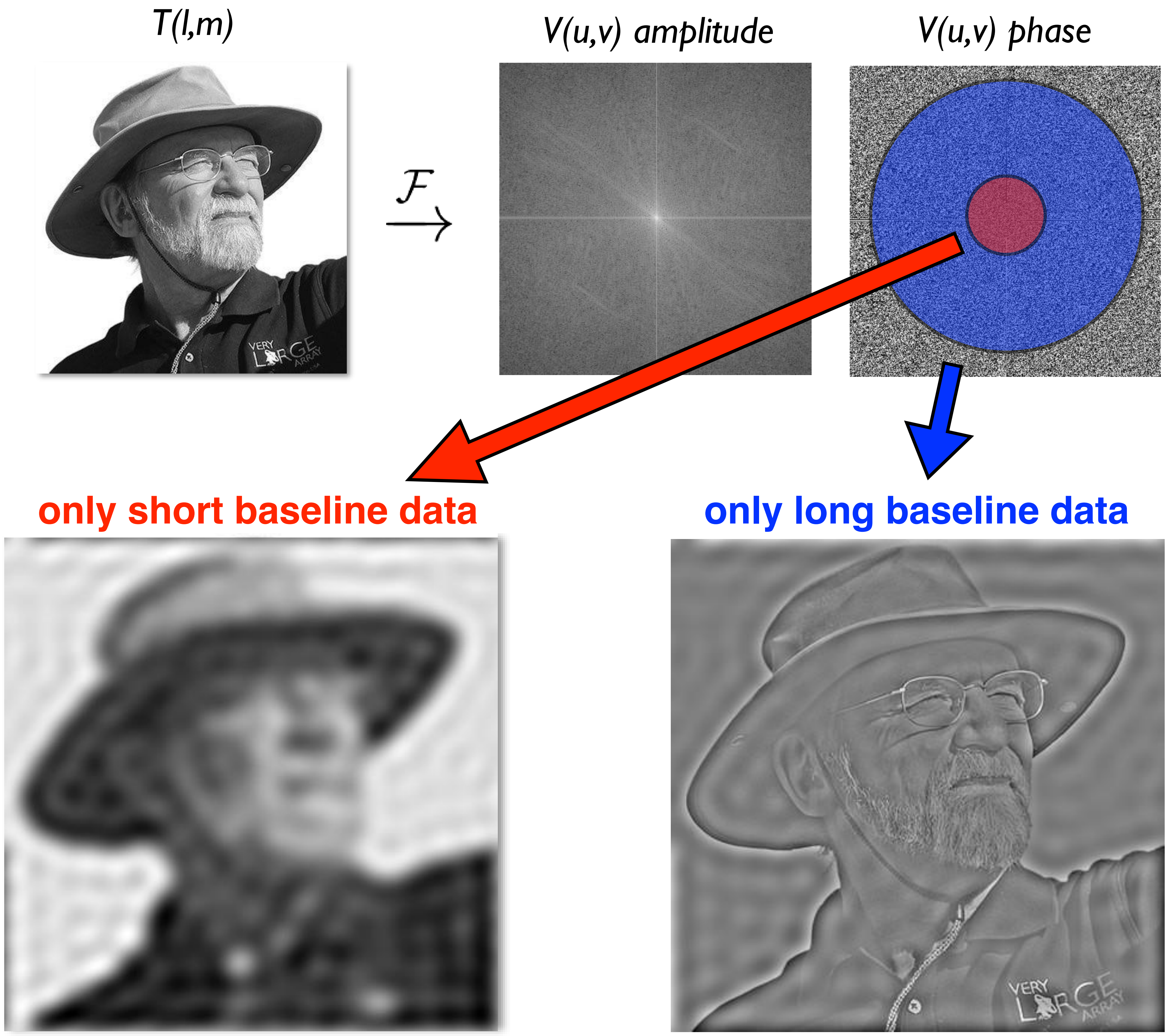
$$f(R) \quad = \quad \exp(-1.678R/R_{1/2})$$

max. baseline=1600m
corresponding to ~1840 kλ

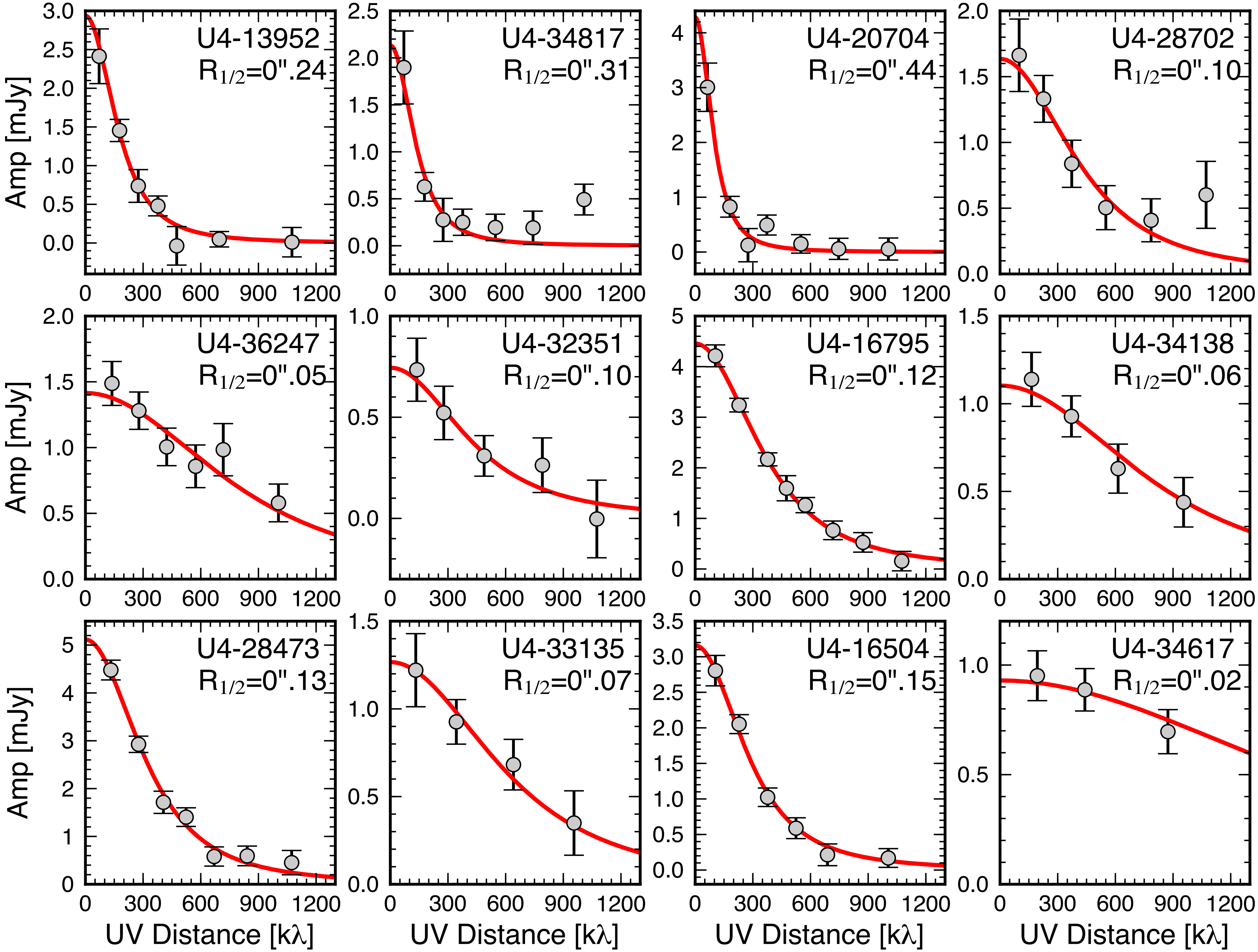
min. baseline=20m
corresponding to 23 kλ



Why not size measurements in image plane?

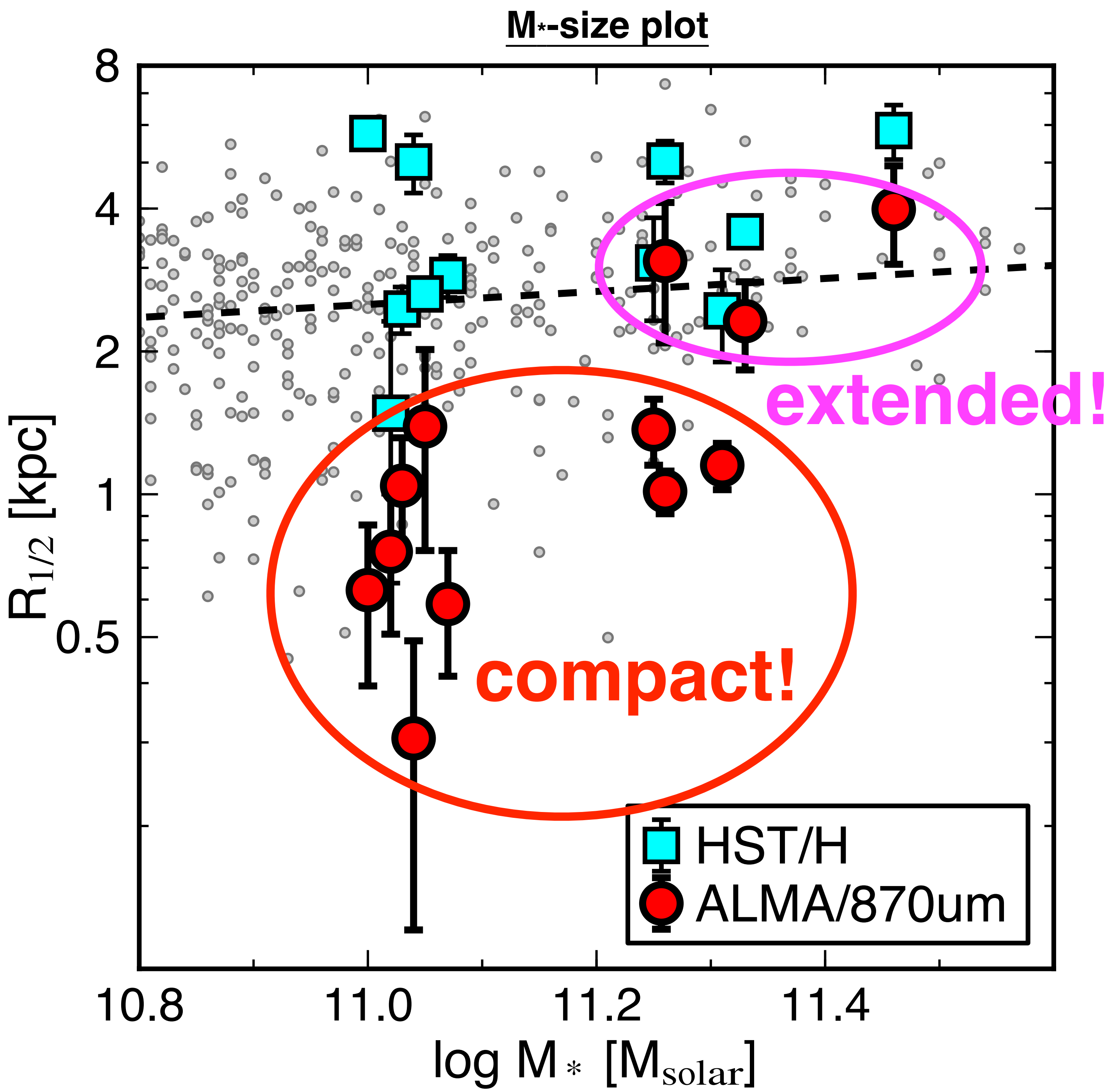


Size measurements of 870 μm emission

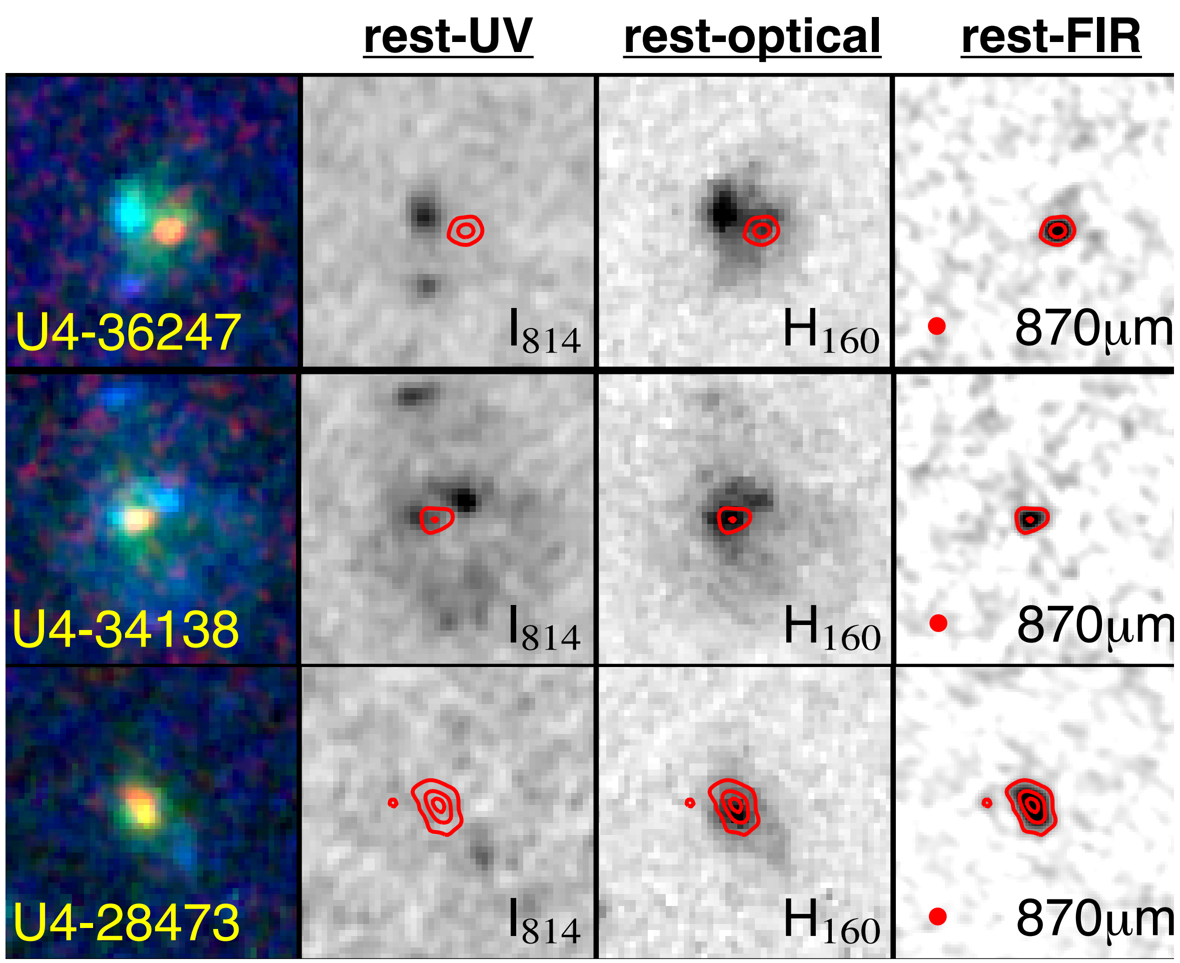


Tadaki et al. 2016, arXiv:1608.05412

Bulge-forming galaxies with an extended disk



small dots:
3D-HST sample of SFGs at z~2
(*Momcheva+15*)



- **They have an extended, exponential disk ($R_{1/2}$~3 kpc, n~1)**
- **Star-forming regions are extremely compact ($R_{1/2}$<1.5kpc)**

When are bulges formed?

HST map: stellar mass surface density within a central 1 kpc ($\Sigma M_{*,\mathrm{1kpc}}$)

ALMA map: SFR surface density within a central 1 kpc ($\Sigma \mathrm{SFR}_{\mathrm{1kpc}}$)

Bulge formation timescale

$$\tau_{\mathrm{bulge}} = \frac{10^{10} - \Sigma M_{*,\mathrm{1kpc}}}{w \times \Sigma \mathrm{SFR}_{\mathrm{1kpc}}}$$

w: mass loss (~0.6)

versus

Gas depletion timescale

$$\tau_{\mathrm{depl}} = \frac{M_{\mathrm{gas}}}{\mathrm{SFR}(1+\eta)}$$

η: outflow mass loading (~1)

τ_{bulge} = 300 Myr, $\tau_{\mathrm{bulge}}/\tau_{\mathrm{depl}}$=1.2 for $R_{1/2,870\mathrm{um}}$<1.5 kpc

- they can complete bulge formation by z~2
- it does not necessarily require additional gas accretion
- they can naturally quench star formation soon after the dense core is formed

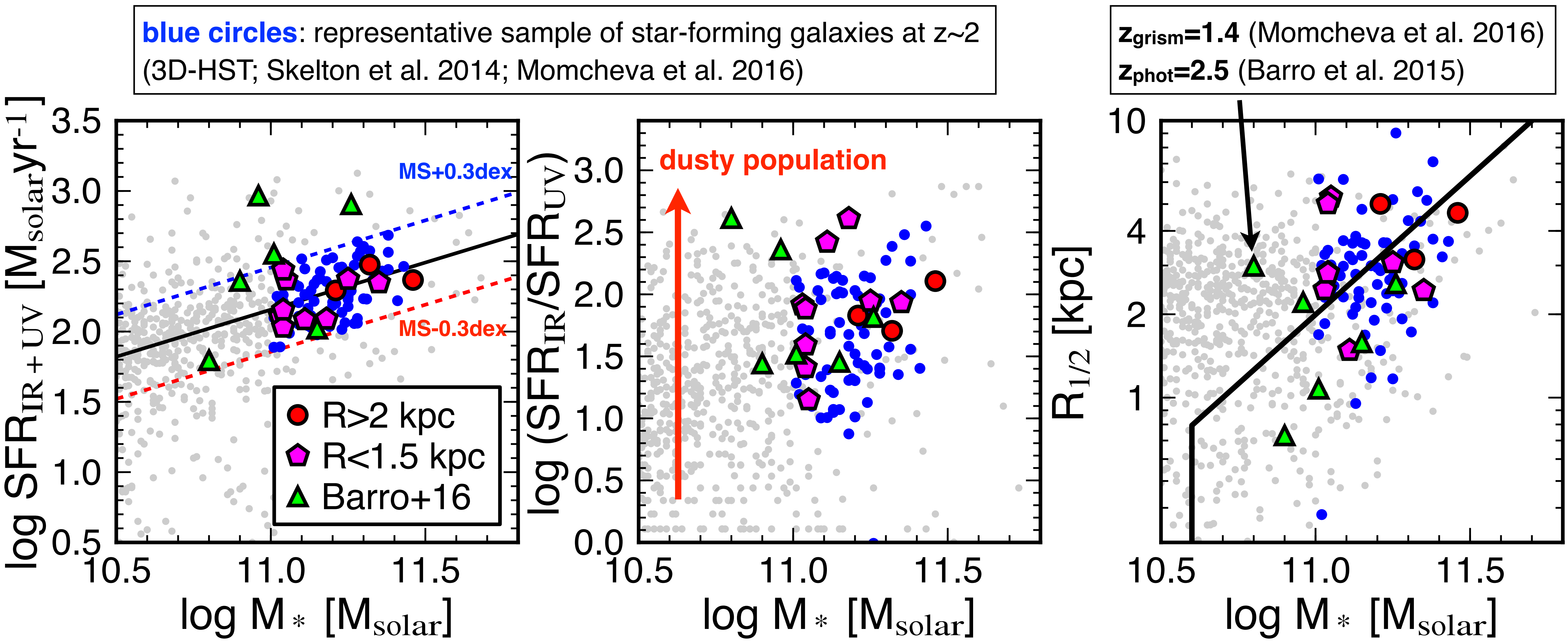
Sample bias

- recent ALMA works for high-resolution dust continuum observations

Simpson+15, Hodge+16: pick up only submm-bright galaxies

Barro+16: mainly compact galaxies

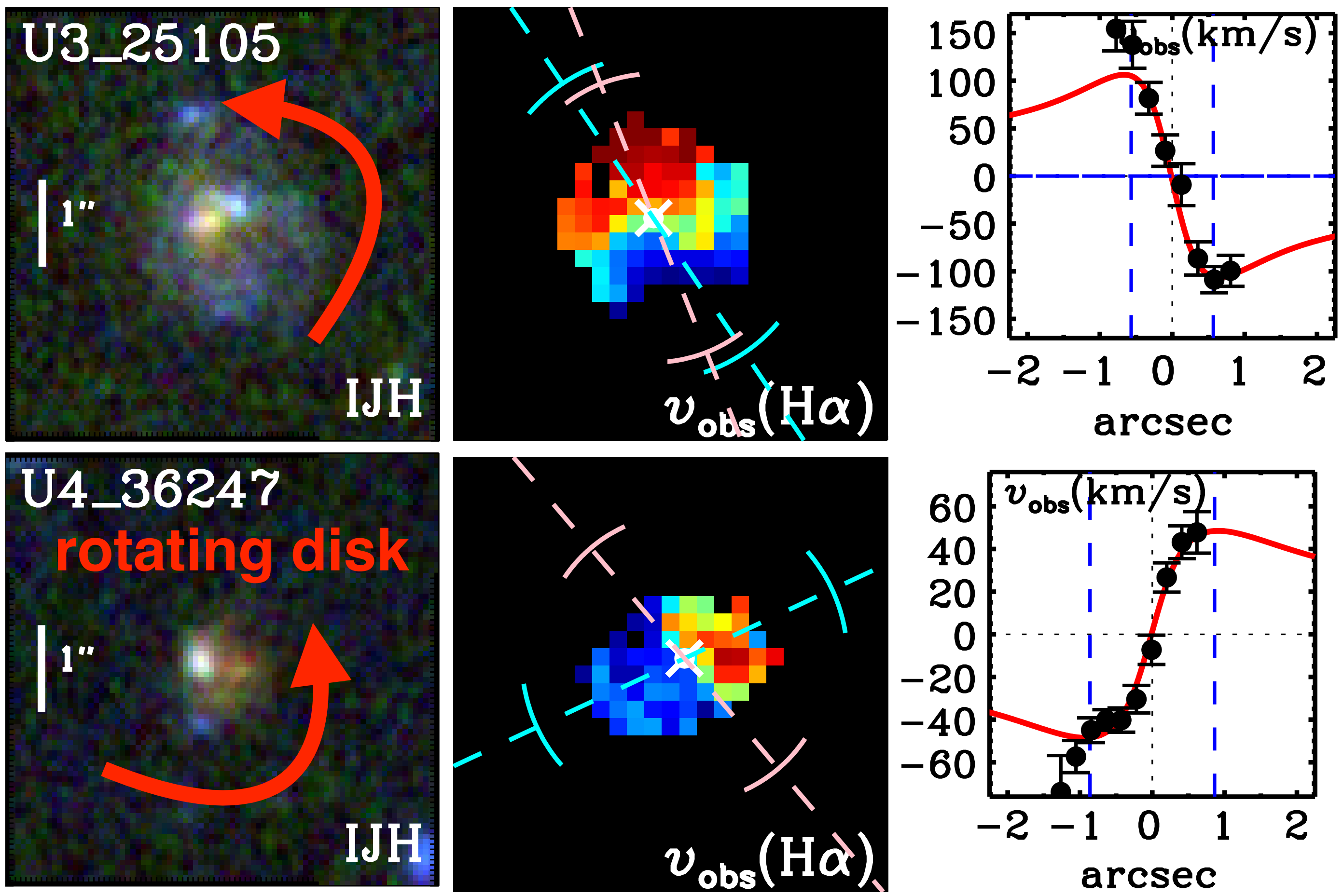
Tadaki+16: on main sequence (±0.3 dex), no selection on optical size



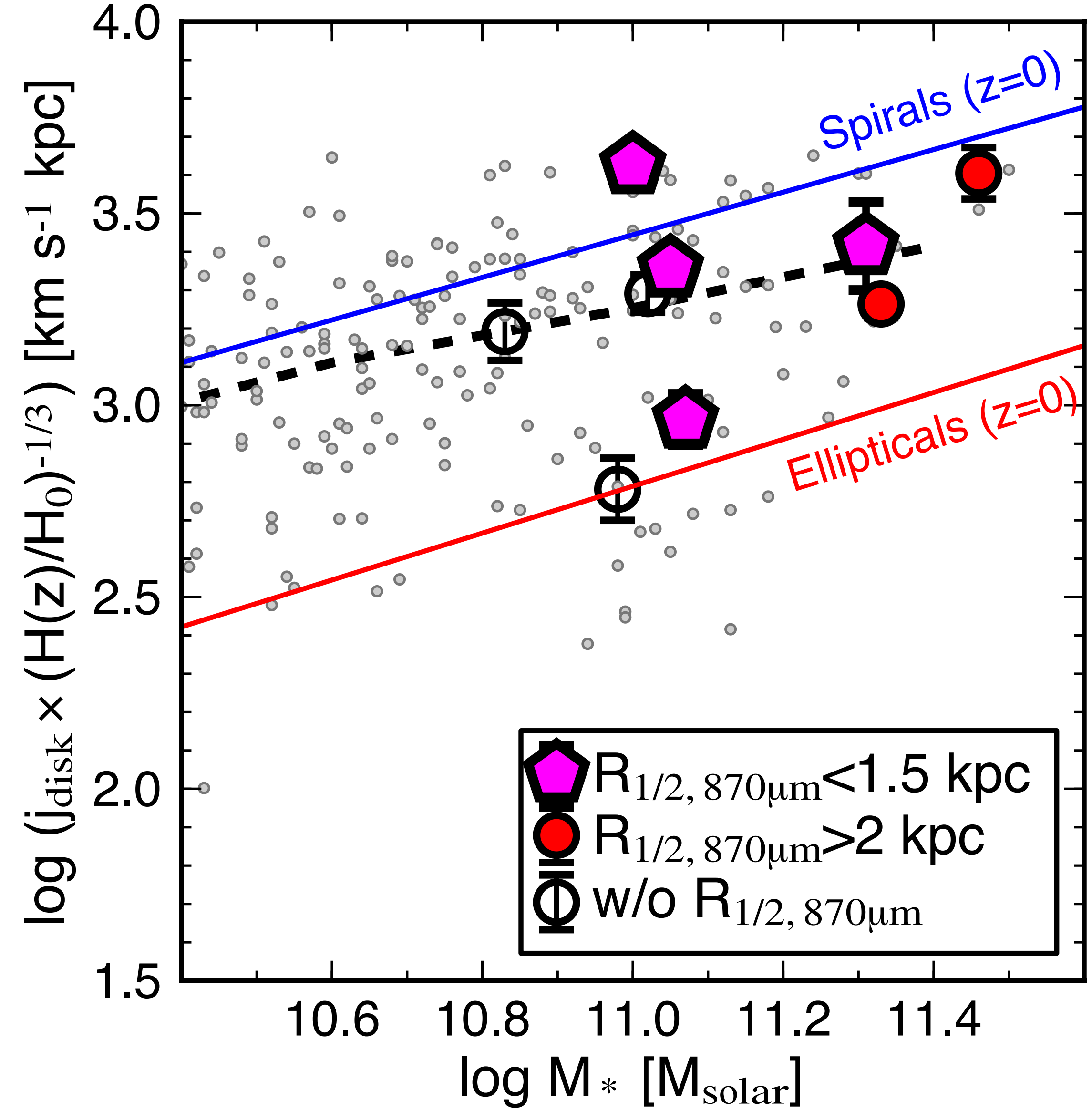
massive star-forming galaxies are commonly form stars in the central compact region

Ionized gas kinematics with VLT/KMOS

The KMOS^{3D} survey (Wisnioski+2015)



Disk angular momentum (Burkert+2016)



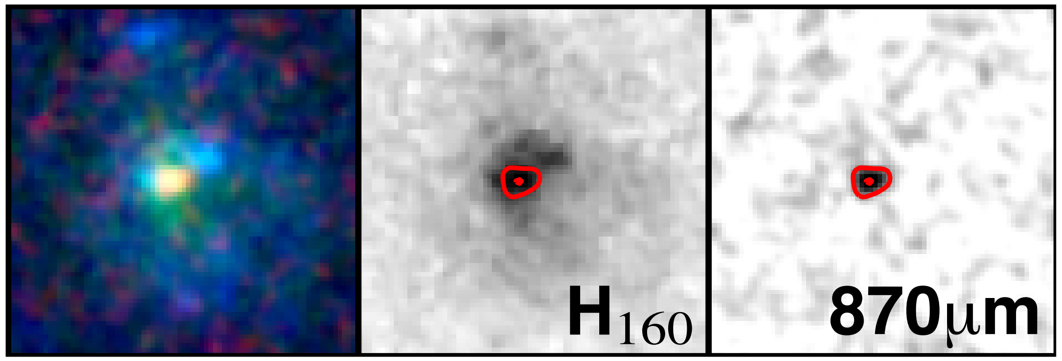
- they are all rotation-dominated
- their angular momenta are broadly consistent with those of mass-limited galaxies in the KMODS^{3D} sample

Tadaki et al. 2016, arXiv:1608.05412

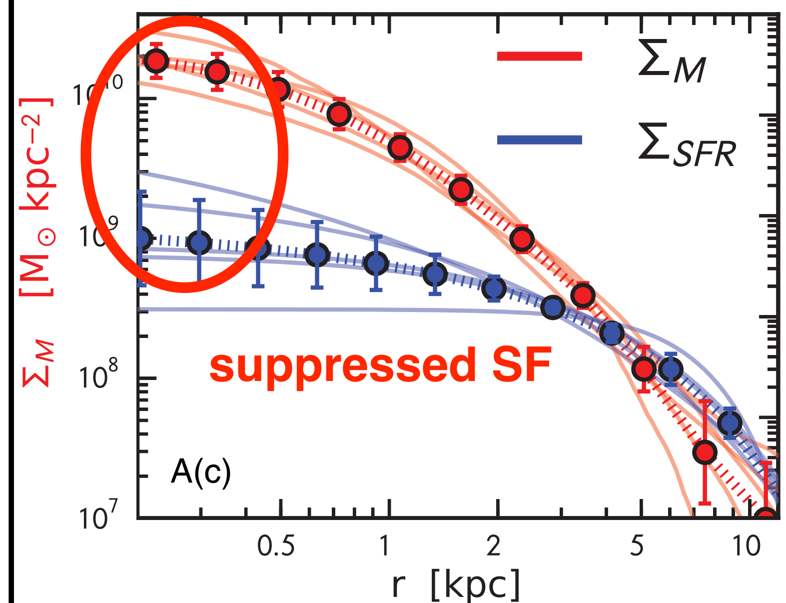
Summary

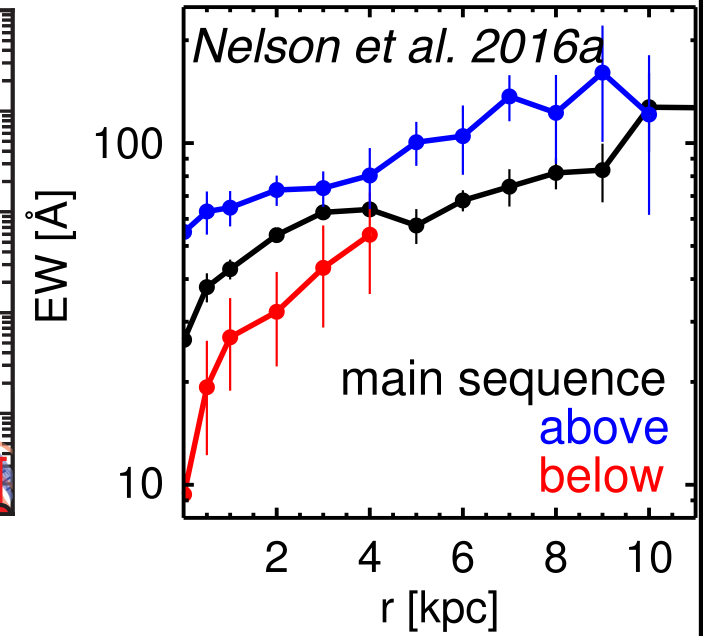
2. extreme starburst!

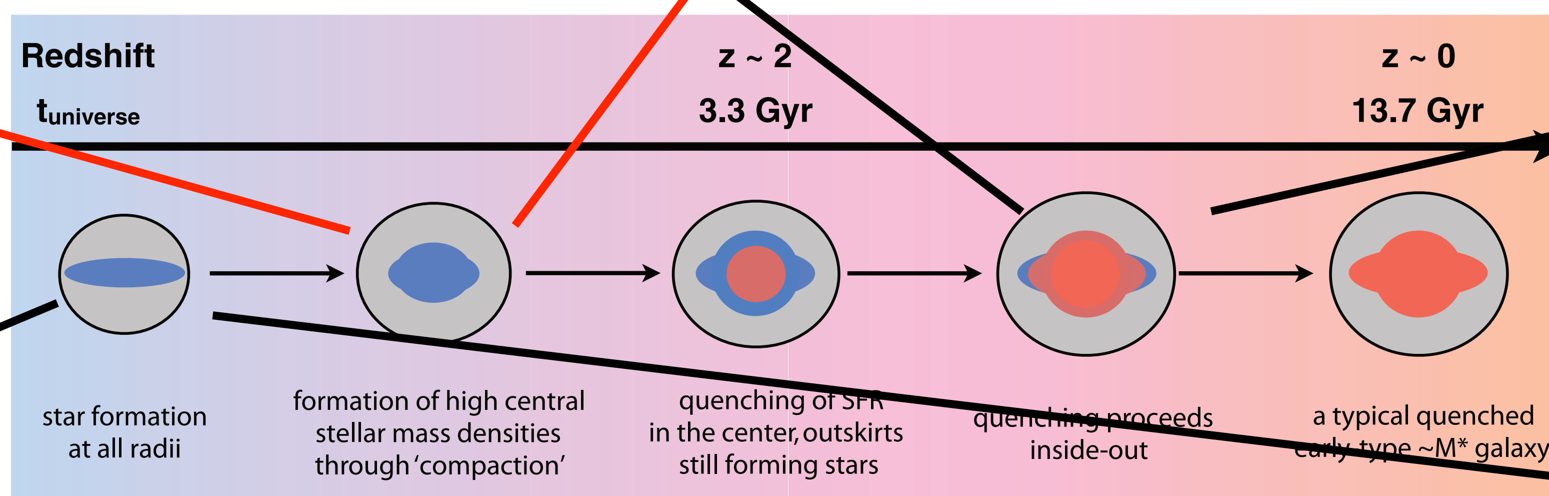
preferred for
(1) morphological transformation from n=1 to n=4
(2) BH growth?
(3) bottom heavy IMF in local ellipticals?
(4) enhanced α/Fe in local ellipticals?



3. inside-out quenching







Tacchella et al. 2015

1. inside-out growth

van del Wel et al. 2014