Sub-kpc ALMA Imaging of Compact Star-forming Galaxies at z~2.5: Revealing the Formation of the Dense Galactic Cores in the Progenitors of Compact Quiescent Galaxies (Barro et al. 2016, accepted to ApJ Letters)

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ABSTRACT

We present spatially-resolved Atacama Large Millimeter/sub-millimeter Array (ALMA) 870 μm dust continuum maps of six massive, compact, dusty star-forming galaxies (SFGs) at $z \sim 2.5$. These galaxies are selected for their small rest-frame optical sizes ($r_{e,F160W} \sim 1.6$ kpc) and high stellar-mass densities that suggest that they are direct progenitors of compact quiescent galaxies at $z \sim 2$. The deep observations yield high far-infrared (FIR) luminosities of $L_{IR} = 10^{12.3-12.8}$ $L_\odot$ and star formation rates (SFRs) of SFR $= 200 - 700$ $M_\odot$ yr^{-1}, consistent with those of typical star-forming "main sequence" galaxies. The high-spatial resolution (FWHM$\sim$ 0\".12 – 0\".18) ALMA and HST photometry are combined to construct deconvolved, mean radial profiles of their stellar mass and (UV+IR) SFR. We find that the dusty, nuclear IR-SFR overwhelmingly dominates the bolometric SFR up to $r \sim 5$ kpc, by a factor of over 100× from the unobscured UV-SFR. Furthermore, the effective radius of the mean SFR profile ($r_{e,SFR} \sim 1$ kpc) is ∼30% smaller than that of the stellar mass profile. The implied structural evolution, if such nuclear starburst last for the estimated gas depletion time of $\Delta t = \pm 100$ Myr, is a 4× increase of the stellar mass density within the central 1 kpc and a 1.6× decrease of the half-mass radius. This structural evolution fully supports dissipation-driven, formation scenarios in which strong nuclear starbursts transform larger, star-forming progenitors into compact quiescent galaxies.

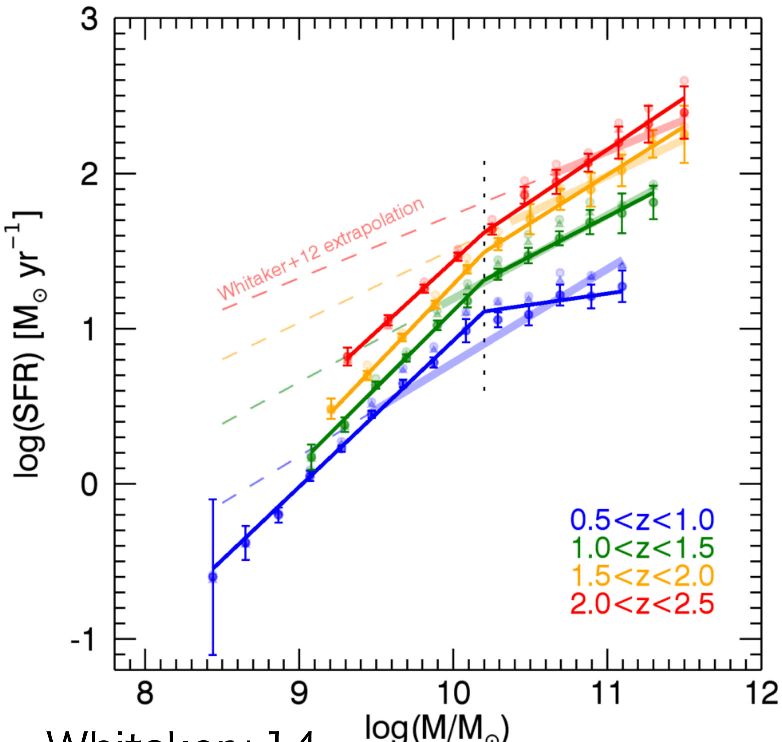
Subject headings: galaxies: photometry — galaxies: high-redshift — galaxies: evolution

- z~2.5の6個のmassive compact dusty SF 銀河のALMA観測 (870um, con)
  - ✓ rest opticalで小さく(re~1.6kpc), stellar-mass densityが高い

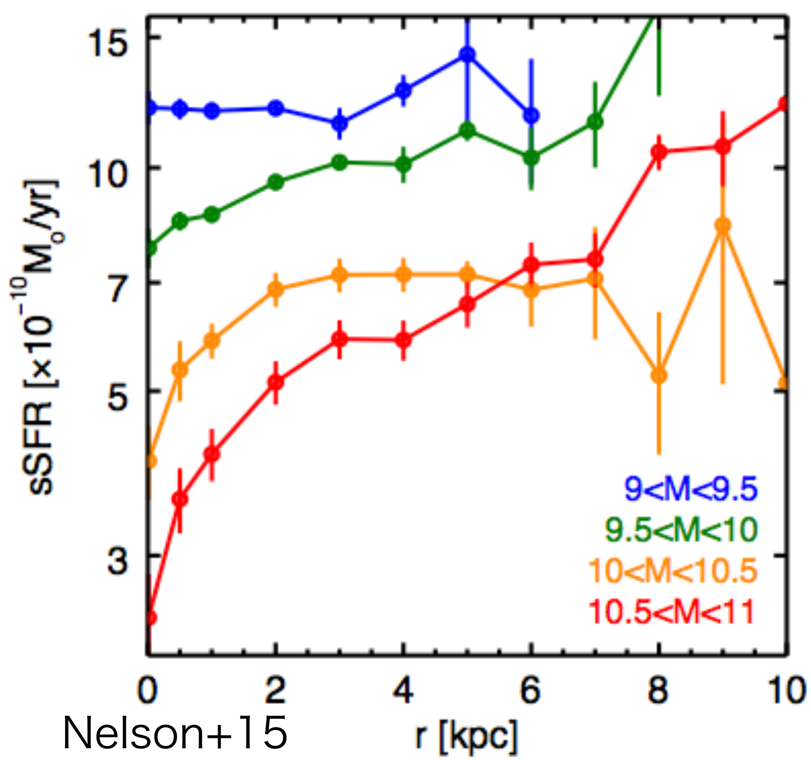
    →z~2のcompact quiescent銀河のprogenitors??
  - ✓ L_{IR}~$10^{12.3-12.8}$Lsun, SFR~200-700 Msun/yrのSFMS銀河
- r<~5kpc の中心でdusty なSF, IR-SFR~100×UV-SFR
- re(SFR)~1kpcでre(stellar)よりも30%小さい
- SFがgas depletion time scale Δt=±100Myr程度続けば、中心1kpcのstellar-mass densityが4倍高くなり、re(stellar)が1.6倍小さくなる

➢ compact quiescent銀河のformation はdissipation-driven scenarioを支持

1. イントロ: structural growth & SFMS



Whitaker+14



Nelson+15

- z~5-6からz~0までのstar-forming（SF）銀河のrelation: SF main sequence（SFMS）→星形成の大半はsmoothな**secular mode**？(e.g., Noeske+07)
- 星の大半はdiskで形成され、diskはinside outでsmoothに成長 (e.g.,Nelson+15)
- SFMSにおけるstructural growthはΛCDMとconsistent (e.g., Mo+98)

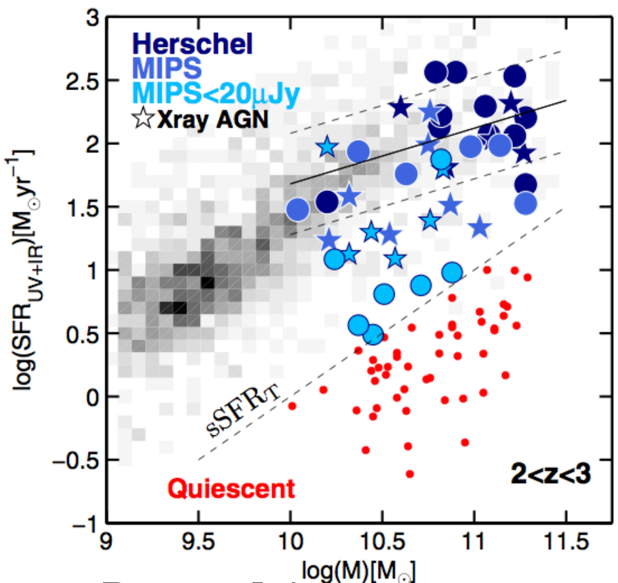
1. イントロ: compact massive quiescent

- simpleな描像へのchallenge:
  z~1.5-3のthe first massive quiescent galaxiesの小さなサイズ(re~1kpc)
  1) より初期のdenseな宇宙におけるより小さなSF progenitors: **secular mode**
  2) mergerやinteraction-driven disk instabilitiesによる**dissipative process**
     gas-rich starburstでnuclear stellar densityが増加
  ✓ どちらのscenarioもquenchingの直前にcompactなSFGsとなることを示唆
  ✓ 1)と2)はSFRのprofileが異なる
     1)はinside out的なextended SFR profile
     2)compactなSF region (starburst)

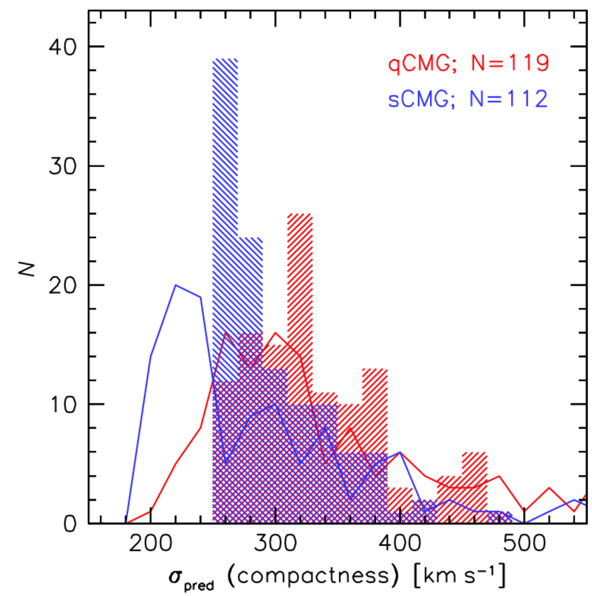
➢ **SFRとstellar mass**の相対的な**profileのdirect measurement**が必要

1. イントロ: compact SFGs

- 多くのcompact SFGsを発見済み
  45個(z~2-3; Barro+14), 112個(z~2-2.5; van Dokkum+14)
- 小さなstellar size, steepなmass profile, obscured SFR profileで確認済み
  (Barro+13,14, van Dokkum +15)



Barro+14



van Dokkum+15

1. イントロ: HST + ALMA

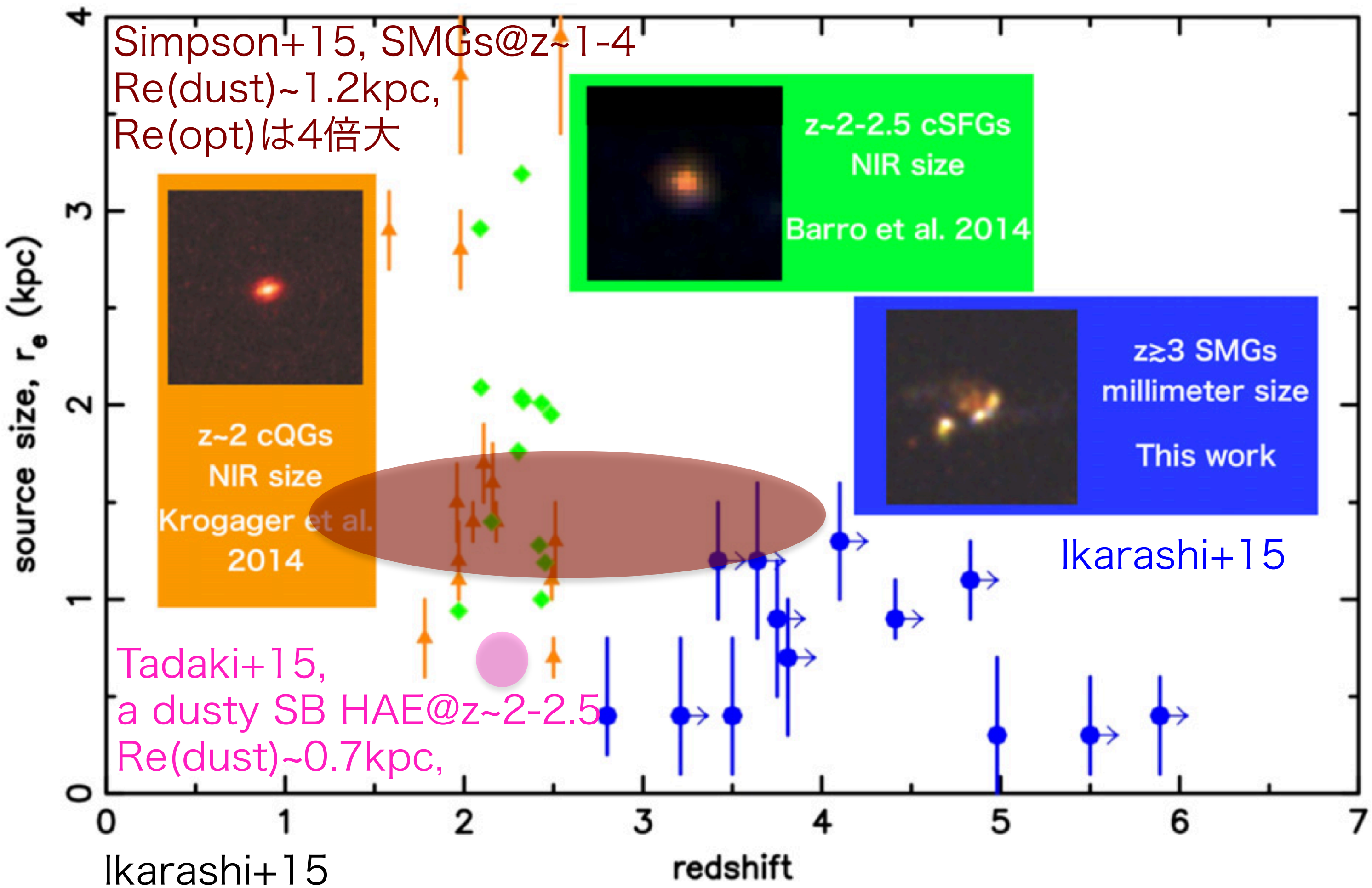
- SFRとstellar massの相対的なprofileのdirect measurementは容易じゃない
  - ✓ UVやopticalのSFR indicators(HST)はdust減光の影響大(特に銀河中心)
  - ✓ FIRの観測はresolutionが不十分

➢ ALMA & JVLA！
深いdust観測とHSTと同程度のresolution

- 本研究では、z~2.5の６個のcompact SFGsについてHST/ACS, WFC3 + ALMAを用いてUV とIRのSFR とstellar mass profileを求める

1. イントロ: HST + ALMA

- 最近のSMGsやIR-bright銀河のdust continuumの大きさ論文
z~2のcompact quiescent galaxies (cQGs)のprogenitor ??



Ikarashi+15

1. イントロ: HST + ALMA

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- 本研究では、z~2.5の６個のcompact SFGsについてHST/ACS, WFC3 + ALMAを用いてUV とIRのSFR とstellar mass profileを求める
  - ✓ HSTとコンパラなspatial resolutionのALMA観測
  - ✓ opticalもcompactなmassive SF銀河がターゲット
  - ✓ rest UV- FIRまで使ってSED fit (Ms, photo-z, SFR)

2. データ & サンプルセレクション

- サンプルは6個のcompact SFG @CANDELS GOODS-S (Barro+14)
  U – 8um+ Spitzer/MIPS 24 & 70um, Herschel/PACS 70, 100 & 160um, SPIRE 250, 350 & 500um
- selection criteria
  - ✓ massive: Ms > $10^{10.5}$Msun, SF: sSFR > 10^{-1}/Gyr
  - ✓ compact: Ms/π $re^{1.5}$ > $10^{10.4}$Msun/$kpc^{1.5}$ quiescentと似たprofile@z~1.5~3
  - ✓ FIR bright: SpitzerとHerschelで受かっていてALMA/870um >~1mJyと推定

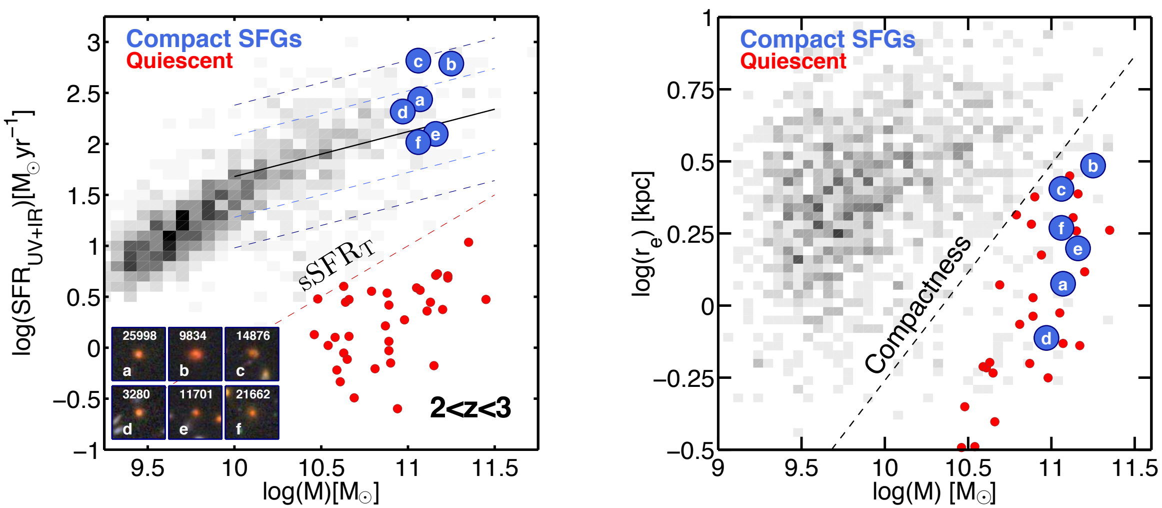


FIG. 1.— *Left:* SFR–mass diagram for galaxies in CANDELS GOODS-S at $2 < z < 3$. The grey-scale density bins map the location of the SFR-MS. The solid black and dashed blue lines depict the best fit and 2.5× and 5× limits above and below the SFR-MS. The blue circles depict the compact SFGs observed with ALMA. The subpanels in the bottom-left corner show the $5'' \times 5''$ ACS/WFC3 zJH images of the ALMA galaxies. The red dashed line marks the threshold in sSFR ($\log(\mathrm{sSFR/Gyr^{-1}}) < -1$) used to identify quiescent galaxies (red circles). *Right:* mass–size distribution for the same galaxies as in the left panel. The dashed line marks the *compactness* threshold, $\log(\Sigma_{1.5}) = 10.4\ M_{\odot}\mathrm{kpc}^{-1.5}$.

2. データ & サンプルセレクション

- ALMA cycle-2 campaign (ID: 2013.1.00576.s; PI: G. BARRO)
  band 7, continuum, 最長で1800sec/source, 合計3時間

- FWHM 0.”14 - 0.”11, rms~49uJy/beam or 2.4mJy/arcsec^2
  surface brightnessを3σでALMAのclean beamのHWHMの5倍まで

- ALMAとHSTのastrometryは平均ΔRA=-0.”08, ΔDEC=0.”27, rms~0.”06

3. Opt-NIR, MIR/Submm SED fit

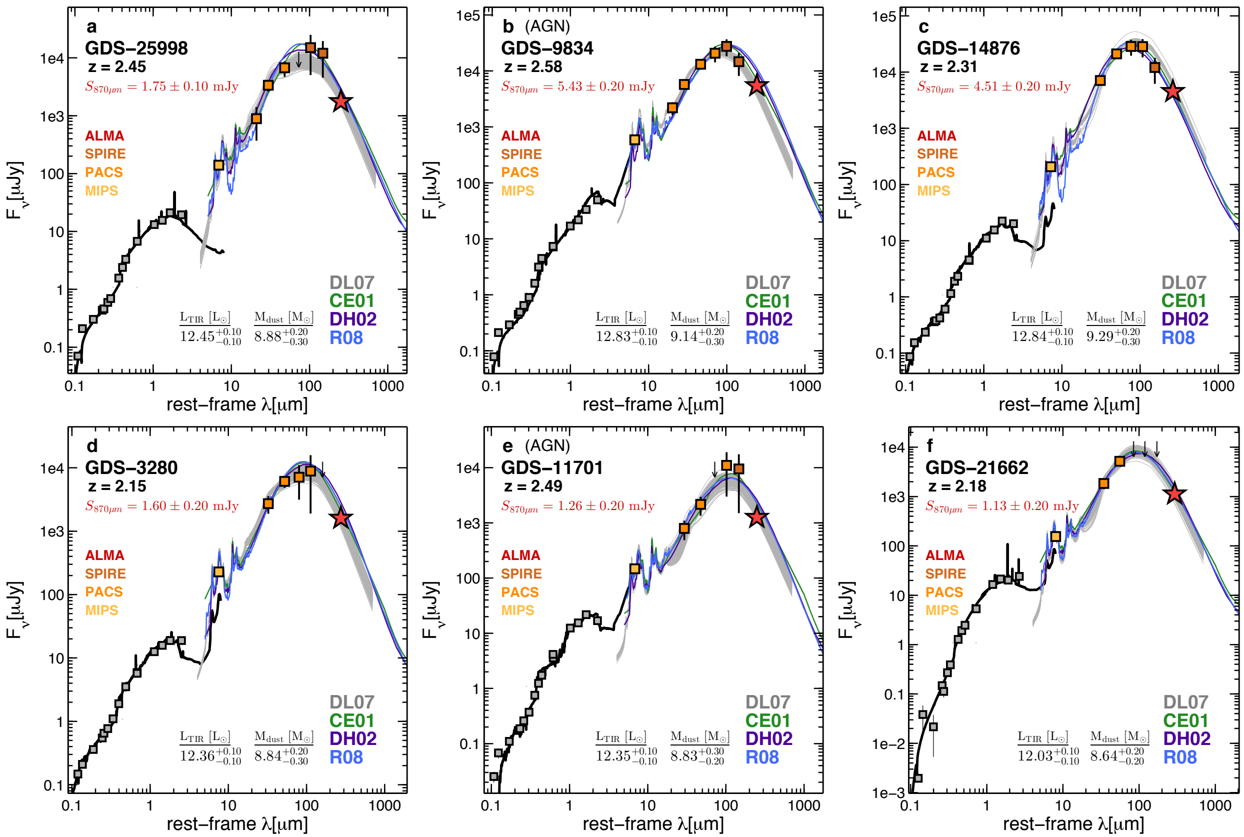


FIG. 2.— UV-to-FIR SEDs of the compact SFGs. The black lines show the best-fit BC03 stellar population models for the photometry up to 8μm rest-frame (gray squares), which provide an estimate of the stellar population properties and the dust attenuation. The orange squares show the mid-to-far IR data from *Spitzer* MIPS and *Herschel* PACS and SPIRE; the red star shows the ALMA 870 μm flux. The green, purple and blue lines show the best-fit dust emission models from the libraries of Chary & Elbaz (2001), Dale & Helou (2002), Rieke et al. (2009). The grey regions depict 300 models drawn from the posterior probability distribution of the `emcee` fit to the Draine & Li (2007) models. The median values and confidence intervals for L_{TIR} and M_{dust} are indicated.

- Opt-NIR fit: FAST BC03 + calzetti + exp-decline SFH (Santini+15)
- MIR-FIR fit: CE01, DH02, Rieke09, & DL07
- gas mass: gas to dust ratio~100 ←MZR relation + Md Z~8.57
- SFR:

$$= 1.09 \times 10^{-10}(L_{\rm IR} + 3.3 L_{2800})[M_\odot/{\rm yr}] \quad (1)$$

(Kennicutt+98)

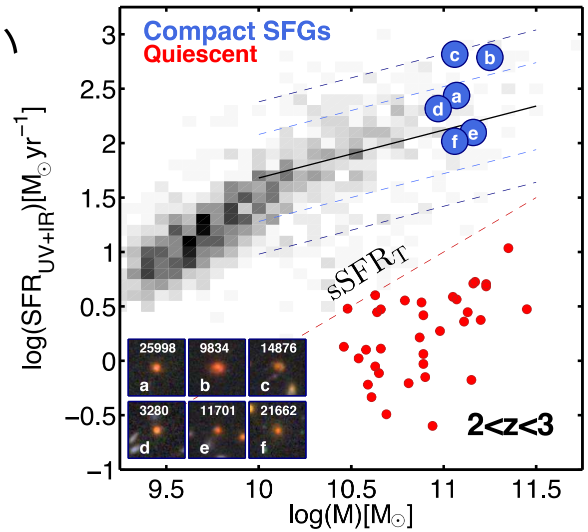
3. Opt-NIR, MIR/Submm SED fit

- L_{IR} = $10^{12.03\text{-}12.80}$Lsun, SFR= 150- 730Msun/yr (SFMS@Ms~10^{11}Msun)
  cとbはSFRがやや高いがSFMSの5倍程度 (結構高い…)

- SFR_{IR}/SFR_{UV}~70-100, A_V>~2mag(A_V from SED fit ~1.3-1.6mag)

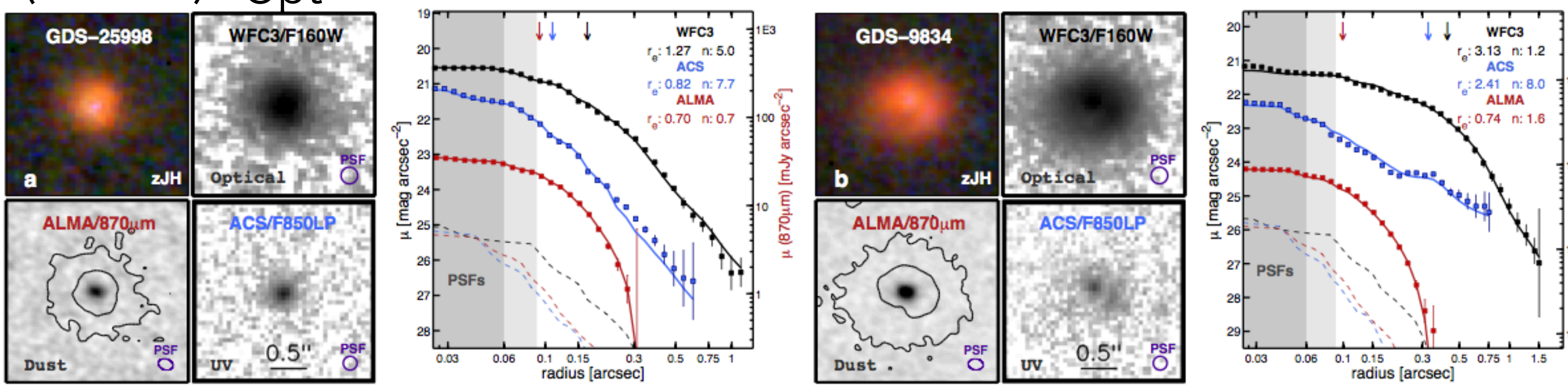
- SFR_{IR}のtmpによる差は、ΔSFR=0.01±0.13dex
  MIPS24umからのSFR(Wuyts+11)との差は、ΔSFR=0.02±0.26dex
  bとeはx-ray detected AGNで、MIPSのSFRがやや高いが、fitから抜けば同程度

- Md = $10^{8.05\text{-}9.29}$Msun, SFRが高い２天体(b,c)はMdも高い
  fgas = $0.47^{+0.19}_{-0.15}$ (Tacconi+10とconsistent)
  t_{dpl} = Mg/SFR = 230^{+90}_{-120} Myr



4. Structural Properties

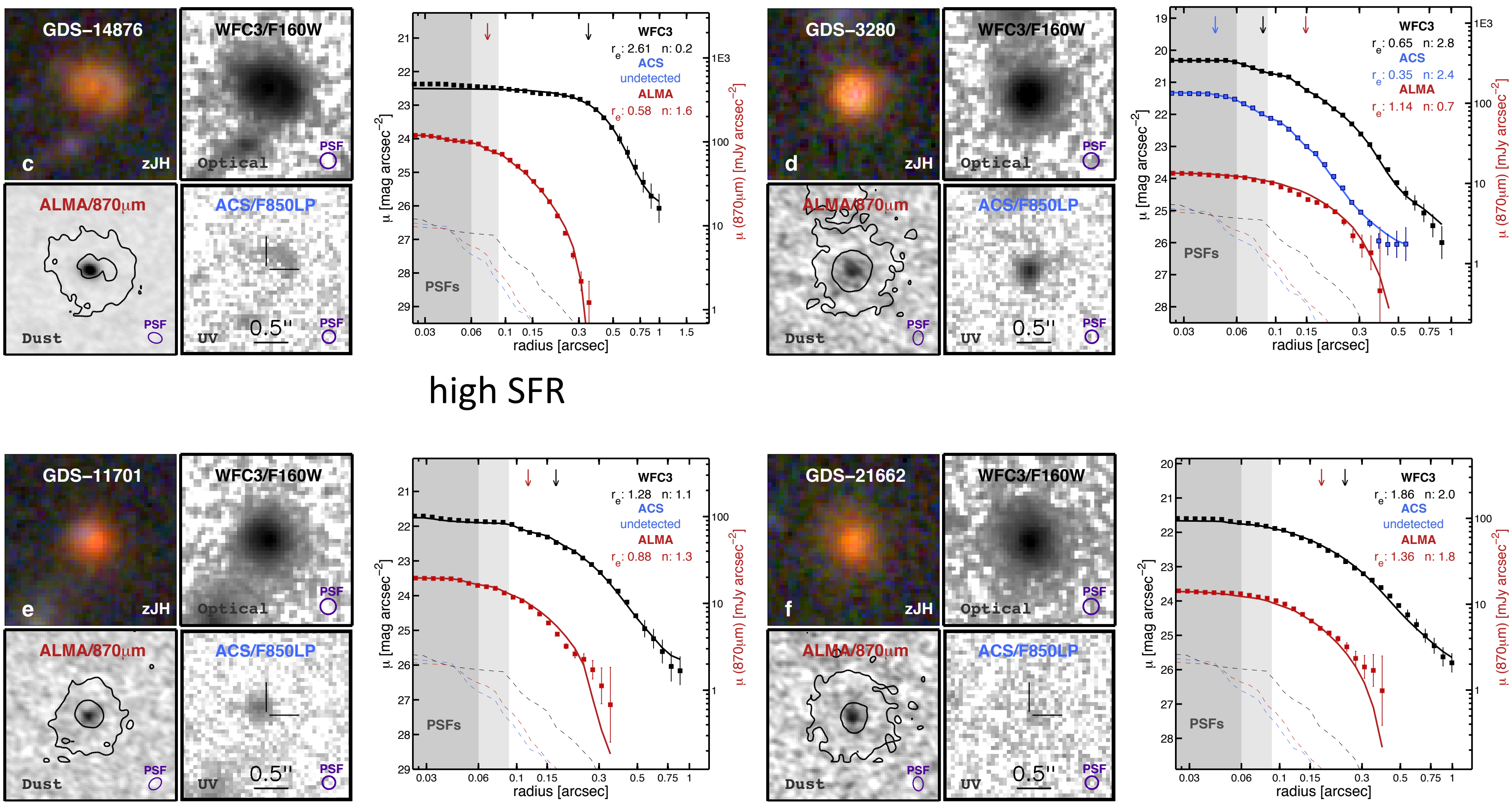
(GALFIT) Opt



FIR UV AGN/ high SFR

FIG. 3.— $2''.5 \times 2''.5$ images and surface brightness profiles (un-corrected for the PSF) of the compact SFGs in ACS/F850LP, WFC3/F160W and ALMA 870 μm (with the F160W contours shown in black). The surface brightness profiles (squares) are measured along concentric ellipses which follow the geometry of the best-fit Sérsic model (solid lines). The ALMA 870 μm profiles are scaled down arbitrarily with respect to the HST data (see right y-axis). The ALMA and ACS images have similar spatial resolution (FHWM $\sim 0''.12$) and are slightly smaller than for WFC3 (FHWM $\sim 0''.18$). The dashed lines show the PSF profiles and the shaded regions show the extent of their HWHM in F850LP and ALMA (dark grey) and F160W (light grey). The deconvolved GALFIT effective radii in kpc are indicated with arrows. The profiles are shown up to the radius where the errors become significant, typically $\sim 1''$ in F160W and $\sim 0''.4$ in ALMA.

4. Structural Properties



high SFR

AGN

opt sizeが最小
nが高い

4. Structural Properties

- $R_{95\%}$ (FIR) ~ 1/ 4 $R_{95\%}$ (Opt)
  5 /6個の銀河はdeconvolvedしたFIR profileはよりcompact
  残りの1天体(d)はopt sizeが最小でnが高く、ALMAで少し非対称な形態

- <Re(Opt)> / < Re(UV)> ~ 1.9

- FIR profileはUVよりもdisk-like
  (lower sersic index: n~1, UVはn~2)
- Re(FIR)とRe(Opt)には相関がない
- Re(FIR)は分布の幅が狭い
  - ➢ nuclearのcompact, dusty, starburstはhomogeneousなpop?
- nuclear starburst: <ΣSFR>=SFR/πRe²は SFMS銀河(Re~5kpc)の25倍

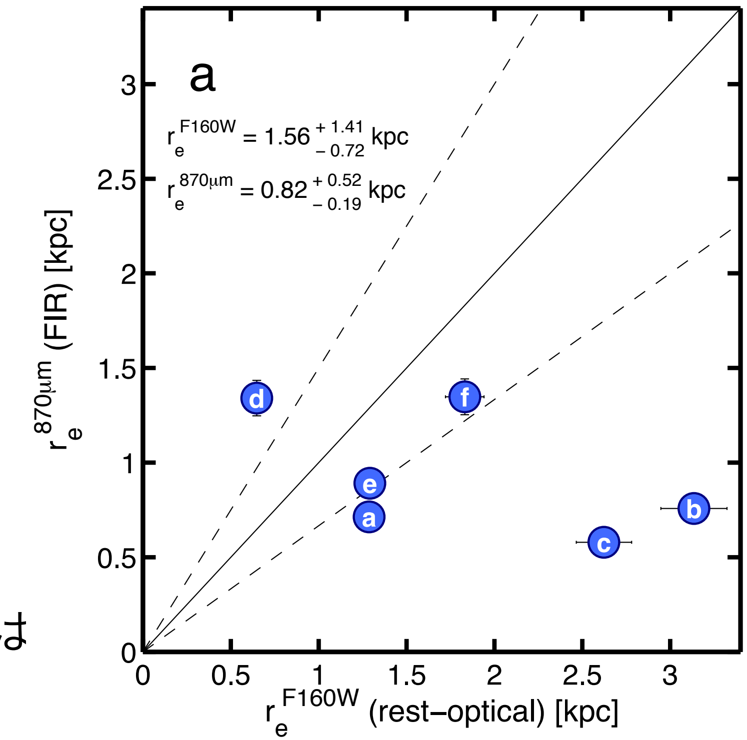


FIG. 4.— *Left:* Comparison of the rest-frame optical (WFC3/F160W) and FIR (ALMA 870 μm) effective radii of compact SFGs. The solid line indicates the 1:1 relation, the dashed lines show the 1.5× size ratios. The FIR sizes are ∼1.6× smaller than the optical sizes and they exhibit a tighter distribution around $r_e \sim 1$ kpc. *Right:* Mean de-convolved stellar mass (black line) and SFR (blue and red lines)

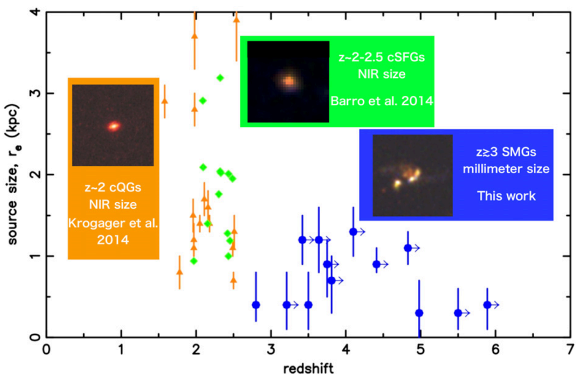
4. Structural Properties

- 最近のSMGsやIR-bright銀河のdust continuumの小さなサイズとconsistent
  典型的なz~2-3のSFGsのrest-optの大きさと比べて

✓ Simpson+15
  - 23個のSMGs@z~1-4のサイズを測定(reso~0."35×0."25),
  - Re(dust)=1.2kpc~z~2のQGsのRe(opt)~1.5kpc, Re(opt)~4.4kpc

  →SMGs@z>2がz~2のquiescent galaxiesのprogenitor?

✓ Ikarashi+15
  - 13個のSMGs@z~3-6のサイズを測定(reso~0."2)
  - Re~0.7kpcでz<3のSMGsよりも二倍ほどcompact,
    z~2のcompact QGsのサイズRe(opt)~1kpcと一致
    →SMGs@z>3がz~2のQGsのprogenitor?



✓ Tadaki+15
  - 12個のHAE@z~2.19-2.53
  - brightでdusty SBな天体のサイズ Re(dust)=0.7kpc
    50Myr以内にQGsのstellar mass densityに達せる

  →compact dusty SFGsとQGsの間の進化段階？

4. Structural Properties

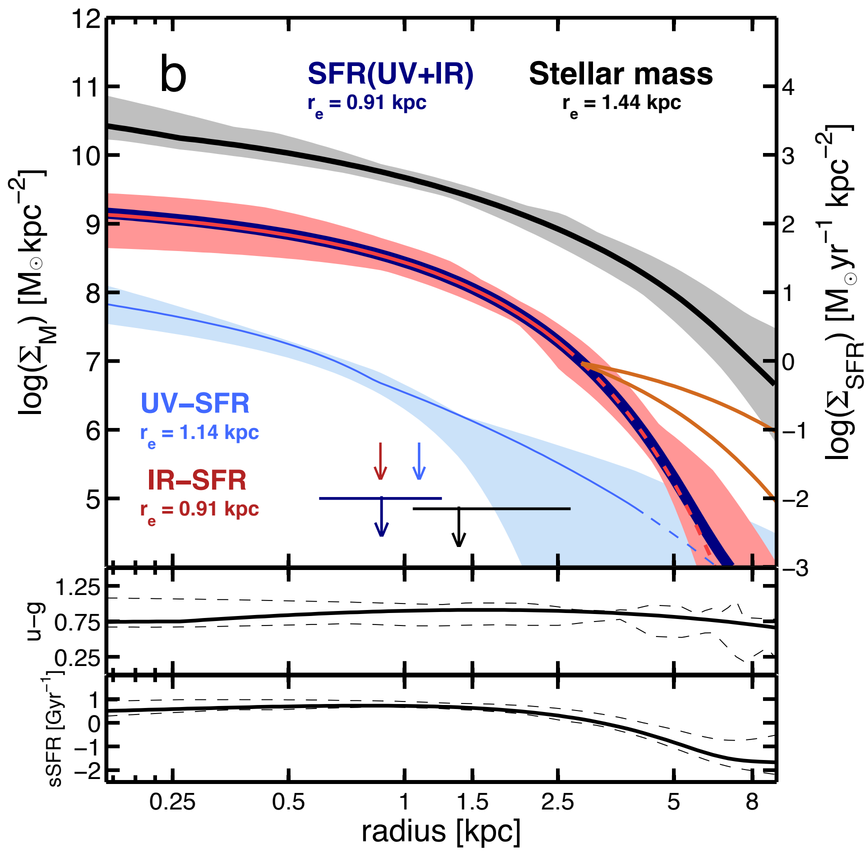
- SFRの平均profileは、stellar massの平均profileと比べて1.5倍以上concentrated
- R<5kpcまでUV/IR>~100
- sSFRはR<~2.5kpcまで高い

➢ stellar mass growthの大半は内側数kpcで

- R>5kpcでは、sSFRが~100倍低い

➢ 外側でのstellar mass growthへの寄与は無視できる

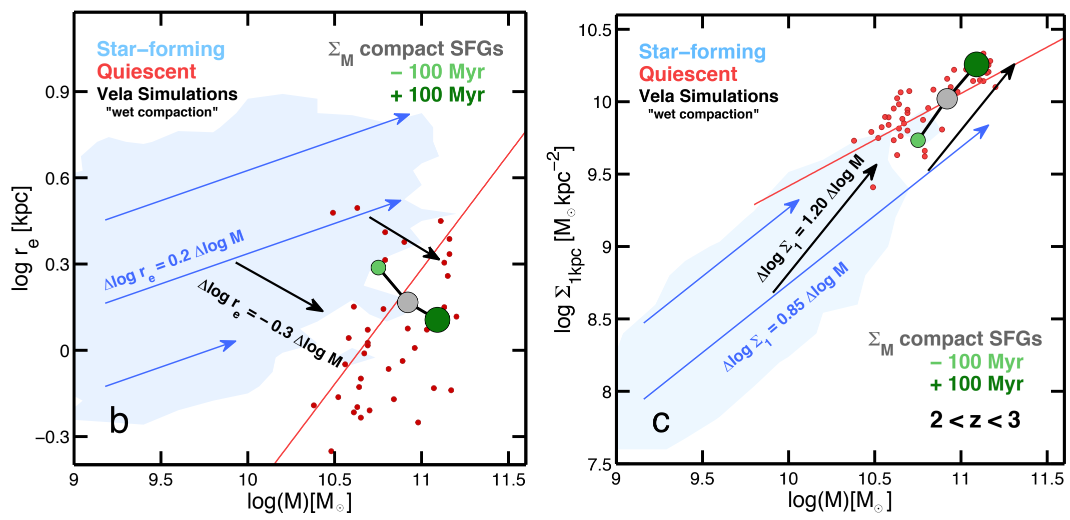
(注) R(SFR)は>~3-4kpcは非検出
(ΣSFR~1Msun/kpc^2, 0.1Msun/kpc^2)
R>3-4kpcはbest fit profileを元に議論
仮にIR-SFRが非検出のsecondary comp
(det limの100倍、10倍高い)
→Reは5%, 20%大きくなるだけ



they exhibit a tighter distribution around $r_e \sim 1$ kpc. *Right:* Mean de-convolved stellar mass (black line) and SFR (blue and red lines) density profiles of compact SFGs. The shaded regions indicate the 1σ dispersion. The dashed lines indicate the Sérsic fit to SFR profile below the UV and FIR detection limits. The orange lines show possible IR-SFR profiles undetected by ALMA. The arrows show the mean effective radii and the horizontal bars indicate their lower/upper limits determined from the $\pm1\sigma$ profiles. The bottom panels show the $u-g$ color profile and the sSFR profile.

5. Discussion

- SFGsの平均的なstructural evolutionはscaling relation上 (青矢印)
- z~1.5-3のmassive compact quiescent galaxies形成の主要processは(非排他的)？
  1) より初期のdenseな宇宙におけるより小さなSF progenitors
     secular mode, inside out的なextended SFR profile
  2) strong nuclear starburstでscaling relationから外れてconcentration増加
     dissipative process, compactなSF region (starburst)
     →◎compact SFGsのmass profileよりも内側のstrong nuclear starburst



Tacchella et al. (2015) at $z \sim 2$). The arrows indicate the r_e. *Middle:* The blue contour and the red points indicate the loci of star-forming and quiescent galaxies at $z \sim 2$, and the blue and red lines depict their best-fit scaling relations from van der Wel et al. (2014). The light-to-dark green circles indicate the size-mass evolution of the stellar mass profile in panel a. The black arrows show the direction of the structural evolution in the Vela simulations during the "wet compaction" phase. *Right:* Same as middle panel but showing the Σ_1-mass evolution. The average relations for SFGs and quiescent galaxies at $z \sim 2$ are from Barro et al. (2016b).

5. Discussion

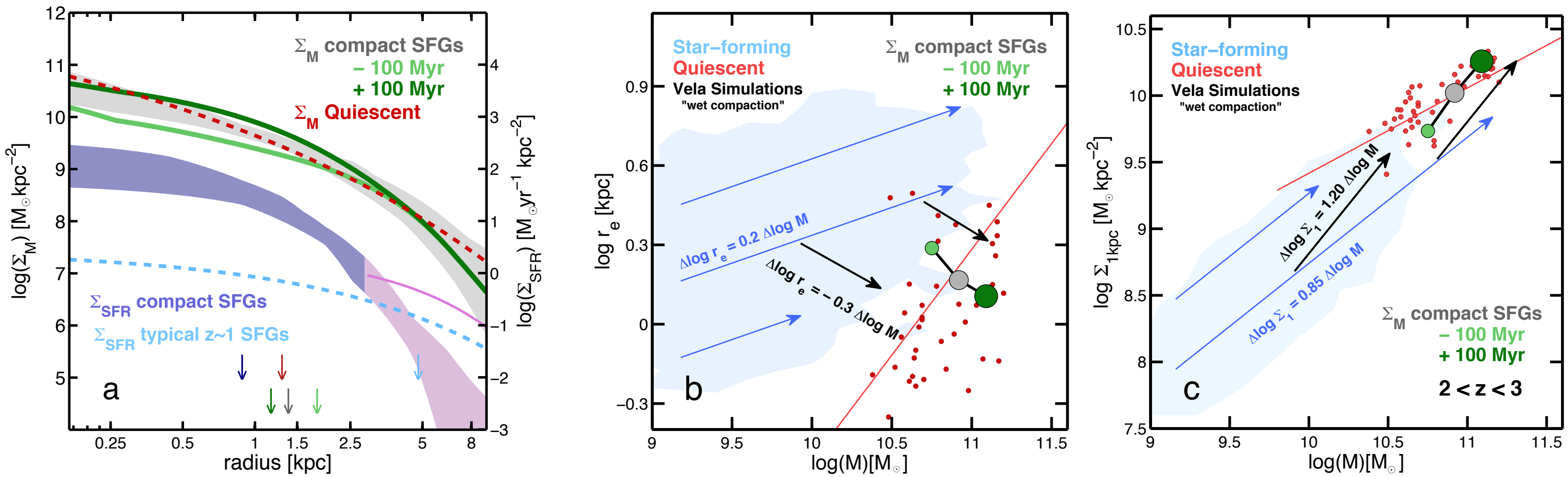
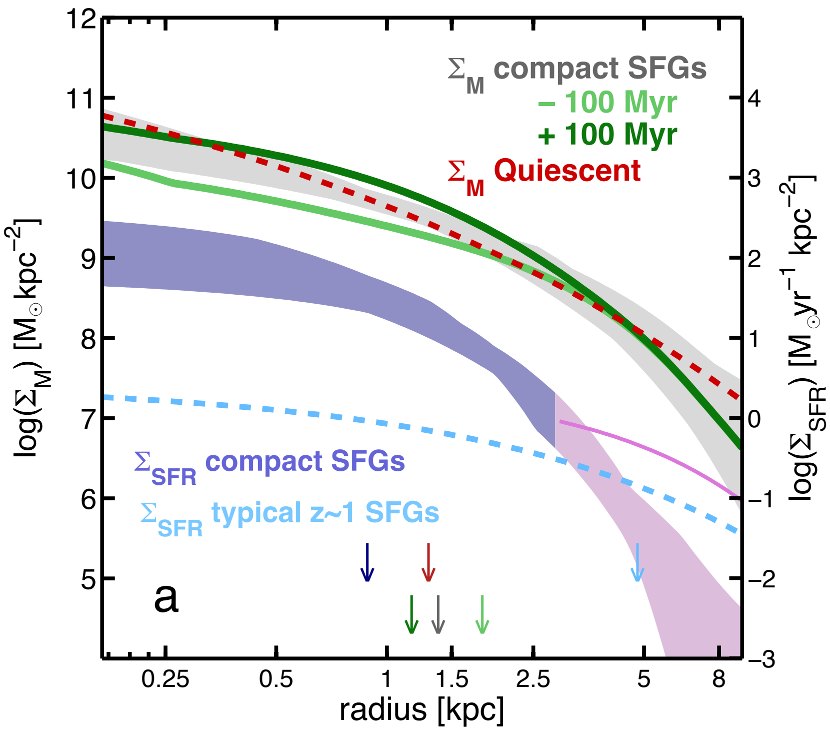


FIG. 5.— *Left:* Evolution of the $\Sigma_{\rm M}$ profile (grey contour) of compact SFGs assuming that their $\Sigma_{\rm SFR}$ (blue contour) remains constant during $\Delta t = \pm 100$ Myr (light-to-dark green lines). The magenta contour indicates the region below the ALMA detection limit. The magenta line shows a possible extended star-forming component (see § 4.2). The red dashed line shows the mean stellar mass profile of compact quiescent galaxies at $z \sim 2$. The cyan dashed line indicates the $\Sigma_{\rm SFR}$ of typical SFGs at $z \sim 1$ from Nelson et al. (2015) (see also Tacchella et al. (2015) at $z \sim 2$). The arrows indicate the $r_{\rm e}$. *Middle:* The blue contour and the red points indicate the loci of star-forming and quiescent galaxies at $z \sim 2$, and the blue and red lines depict their best-fit scaling relations from van der Wel et al. (2014). The light-to-dark green circles indicate the size-mass evolution of the stellar mass profile in panel a. The black arrows show the direction of the structural evolution in the Vela simulations during the "wet compaction" phase. *Right:* Same as middle panel but showing the Σ_1-mass evolution. The average relations for SFGs and quiescent galaxies at $z \sim 2$ are from Barro et al. (2016b).

- Δt=200Myr~$t_{\rm dpl}$の進化(薄緑→灰色→濃い緑)
  R<2kpcのstellar mass growthによりReが1.9→1.2kpcに1.6倍減少し、
  R<1kpcのΣ_1は$10^{9.7}$→$10^{10.3}$Msun/kpc^2 に4倍増加
  R>3kpcにextendedなSF componentがあるとReは7%減る
- Vera simulationのwet compaction phaseと似ている(黒矢印, Zolotov+15, Tachella+16)

5. Discussion



- compact SFGsの短いt_{dpl}～200Myr + compact quiescentと似たmass profile(赤点線)
- ➢ nuclear SBは数100Myrしか続かない (gasが銀河中心に降着しない、dense stellar compによるgasの安定化)
- ➢ quenching
- dense coreがquenchさせるscenarioとconsistent (Cheung+12; van Dokkum+14)
- ➢ quenchingとdense coreの形成はgas reservoirsを消費するnuclear SBの結果同時におこる