EVIDENCE FOR REDUCED SPECIFIC STAR FORMATION RATES IN THE CENTERS OF MASSIVE GALAXIES AT Z = 4

Accepted for publication in ApJ, November 8, 2016
Preprint typeset using LaTeX style AASTeX6 v. 1.0

EVIDENCE FOR REDUCED SPECIFIC STAR FORMATION RATES IN THE CENTERS OF MASSIVE GALAXIES AT $z = 4$

Intae Jung[1,†], Steven L. Finkelstein[1], Mimi Song[2], Mark Dickinson[3], Avishai Dekel[4], Henry C. Ferguson[5], Adriano Fontana[6], Anton M. Koekemoer[5], Yu Lu[7], Bahram Mobasher[8], Casey Papovich[9], Russell E. Ryan Jr.[5], Brett Salmon[5], and Amber N. Straughn[2]

[1]Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA
[2]Astrophysics Science Division, Goddard Space Flight Center, Code 665, Greenbelt, MD 20771, USA
[3]National Optical Astronomy Observatory, Tucson, AZ 85719, USA
[4]Center for Astrophysics and Planetary Science, Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
[5]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[6]INAF–Osservatorio Astronomico di Roma, via di Frascati 33, I-00040, Monte Porzio Catone, Italy
[7]The Observatories, The Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA
[8]Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA
[9]George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
[†]itjung@astro.as.utexas.edu

CHARLIE BONFIELD
ASTR 503/703
NOVEMBER 30[TH], 2016

TERMINOLOGY/ACRONYMS

- "spatially-resolved": refers to the ability of the observers to study spatially distinct regions of galaxies (inner vs. outer, radial bins - more later!)
  - Authors use "integrated" in situations where this cannot be done.
- star formation rate (SFR): total mass of stars formed per year ($M_\odot$ yr^{-1})
- specific star formation rate (sSFR): star formation rate divided by galaxy stellar mass

Acronyms

- CANDELS: *Hubble Space Telescope* **C**osmic **A**ssembly **N**ear-infrared **D**eep **E**xtragalactic **L**egacy **S**urvey
  - S-CANDELS: *Spitzer*-CANDELS
- GOODS: **G**reat **O**bservatories **O**rigins **D**eep **S**urvey
- IRAC: **I**nfrared **A**rray **C**amera

MOTIVATION

- The SFR density peaks close to z~2 and declines to the present-day.
- The physical mechanisms responsible for the evolution of the SFH of the universe remain a mystery, but it is thought that bulge formation is associated with the star-formation quenching process.
- *Inside-out growth* scenario: start small, grow outward
  - Net result: spatially extended star-formation
- *Inside-out quenching* scenario: quench star formation at center, actively form stars out at large distances from the center
- The quenching process has been well-observed in the nearby universe, but we still do not have a clear view on when star-formation reduction began in the earlier universe (z~3 and further back).
- Spatially-resolved studies are necessary to disentangle composite phenomena that may contribute differently to galaxy evolution.

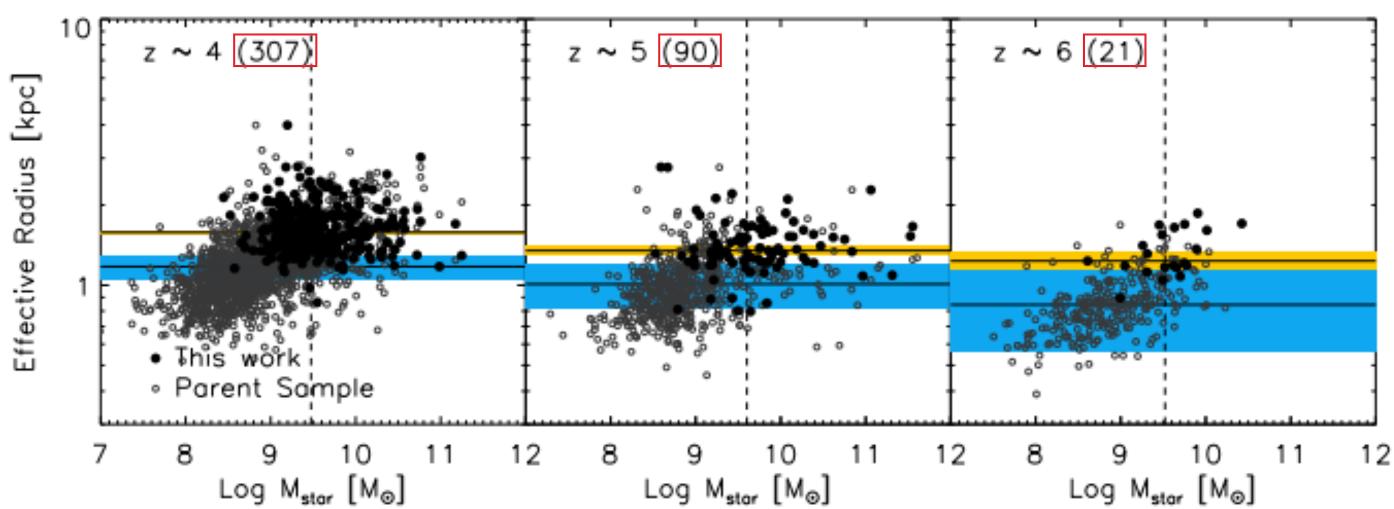
OBSERVATIONS

- Uses data from*:
  - CANDELS (in the southern field of GOODS)
  - *HST* (ERS, HUDF09, UDF12 surveys)
    - Bands: B_{435}, V_{606}, i_{775}, I_{814}, z_{850}, Y_{098}, Y_{105}, J_{125}, JH_{140}, H_{160}
  - *Spitzer Space Telescope* IRAC (from S-CANDELS)
    - Bands: 3.6 and 4.5 μm
- The IRAC fluxes are not actually used during spatially-resolved analysis because of a larger PSF, but the integrated fluxes are instead used to constrain the composite stellar populations of the galaxies in the study.

*Audience members who are interested in the specifics of each survey are encouraged to peruse the corresponding papers cited in Jung et al. (2016).

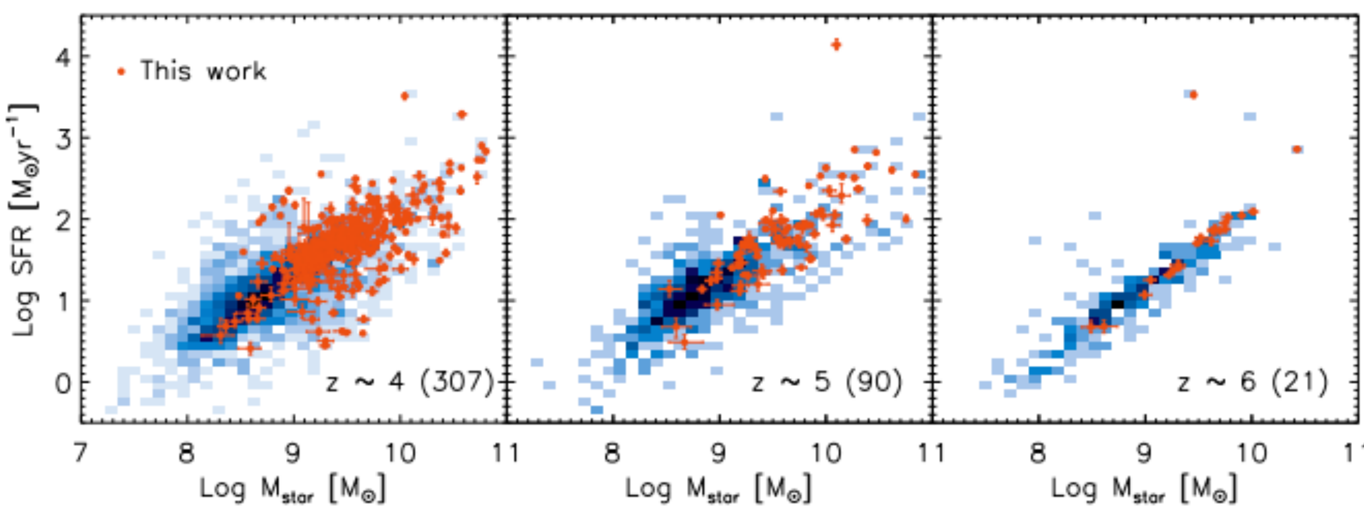
GALAXY SAMPLE (SELECTION CRITERIA)

- First, use the effective radius (R_{eff}) to characterize galaxy sizes.
- Next, preferentially select extended galaxies to allow for area binning.
- <u>Result</u>: 418 bright galaxies between z=3.5 and z=6.5 from catalog of ~8000 galaxies presented in Finkelstein et al. (2015).



GALAXY SAMPLE (SELECTION CRITERIA)

- Galaxies will naturally have smaller angular sizes at higher redshifts, therefore biasing the selection in favor of large values of R_{eff}.
- The influence of this bias is shown below.
- Authors state that this bias is ultimately unavoidable given the goal of the project and technical limitations.



SED FITTING METHODS

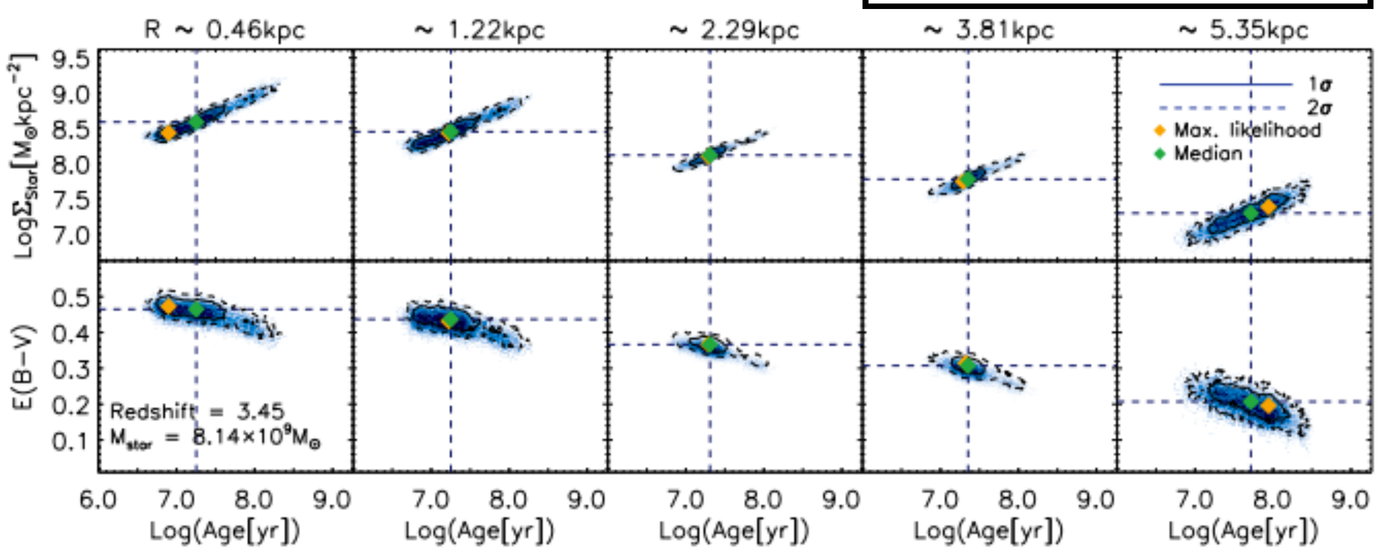
- Fit updated Bruzual-Charlot stellar population synthesis models to observed photometry.
- **IMF**: Salpeter (0.1 $M_\odot$ to 100 $M_\odot$)
- **Metallicity**: Z=0.01 to Z=1.0
- Star-formation histories include exponential models with SFHs that increase, decrease, or stay the same in time.
- Add dust attenuation.
- Add nebular emission lines to the model spectra.
- Add attenuation due to neutral hydrogen in the interstellar medium.
- Ready to work!

SED FITTING METHODS

- Perform actual SED fitting using MCMC algorithm.
  - Most efficient way to explore multi-dimensional parameter space to determine posterior probability distribution function.
- Likelihood: $P(D|x) = \prod_{i=0}^{n_m} e^{-\chi^2/2}$, where:

$$\chi^2_{\rm tot} = \chi^2_{\rm res} + \chi^2_{\rm int} = \sum_{i=1}^{N_{\rm bin}} \sum_{j=1}^{N_{\rm res,bands}} \frac{(D_{i,j}-M_{i,j})^2}{\sigma^2_{i,j}} + \sum_{j=1}^{N_{\rm int,bands}} \frac{(D_j - \sum_{i=1}^{N_{\rm bin}} M_{i,j})^2}{\sigma^2_j}$$

- 10,000 steps through parameter space are found to be sufficient.
- Use medians from marginalized posterior distributions for physical properties.



STAR FORMATION RATE

- Traditionally, star formation rates are calculated using SPS models and are therefore sensitive to model parameter selection.
- Here, the authors chose to do the following:

$$\mathrm{SFR_{UV}} = f_{\mathrm{CB}} \cdot \frac{4\pi D_L^2}{1+z} \cdot 10^{0.4A_{\mathrm{UV}}} \cdot \kappa(t,\tau)$$

flux density from closest band to 1500 Å

luminosity distance

dust attenuation

"conversion factor" (comes from SPS model)

$$\kappa(t,\tau) = \mathrm{SFR_{UV}}/\mathrm{L_{1500\AA}}$$

- In truth, this still requires input from the SPS models in the form of the conversion factor.

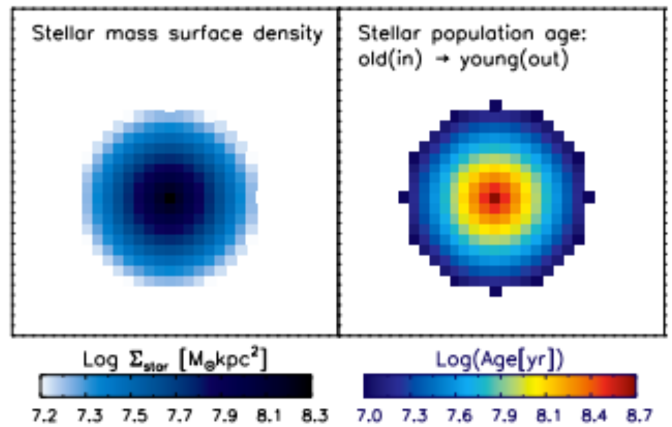
http://people.virginia.edu/~dmw8f/astr5630/Topic11/Lecture_11.pdf

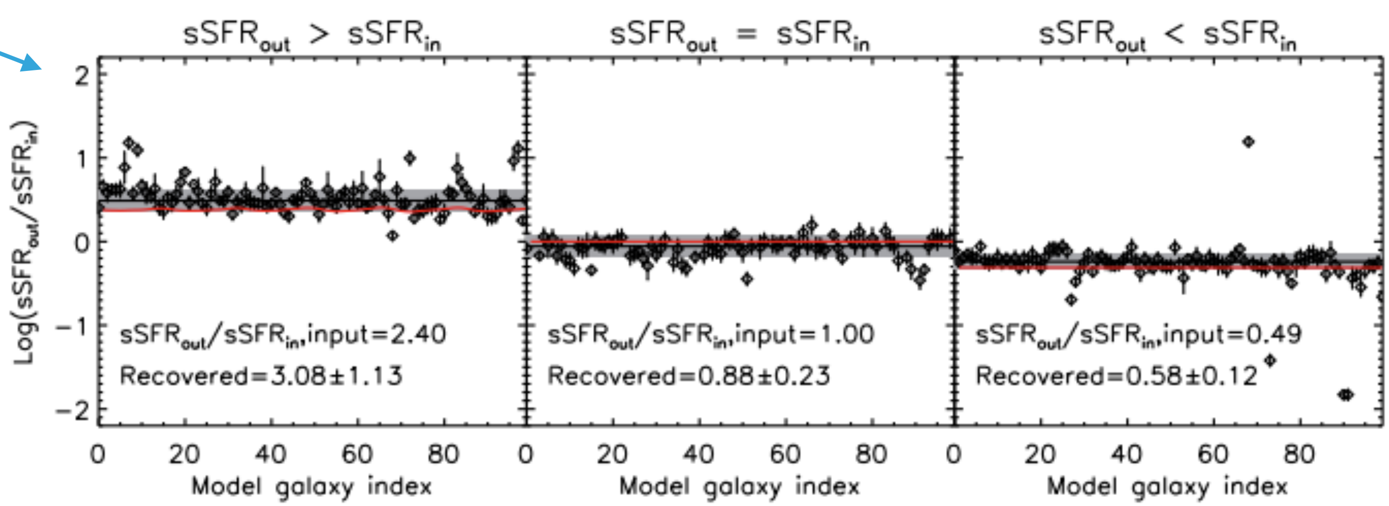
ANALYSIS: GALAXIES AT Z~4 (WITH K-BAND DATA)

- In addition to the photometric data from HST/Spitzer, the authors had access to K-band data from two other surveys (HUGS, GOODS) for galaxies near z~4.
- Divide galaxies into central and outer regions.
  - Central: same as the K-band PSF size (physical radius: ~1.5 kpc)
- Compare sSFR in central/outer regions.

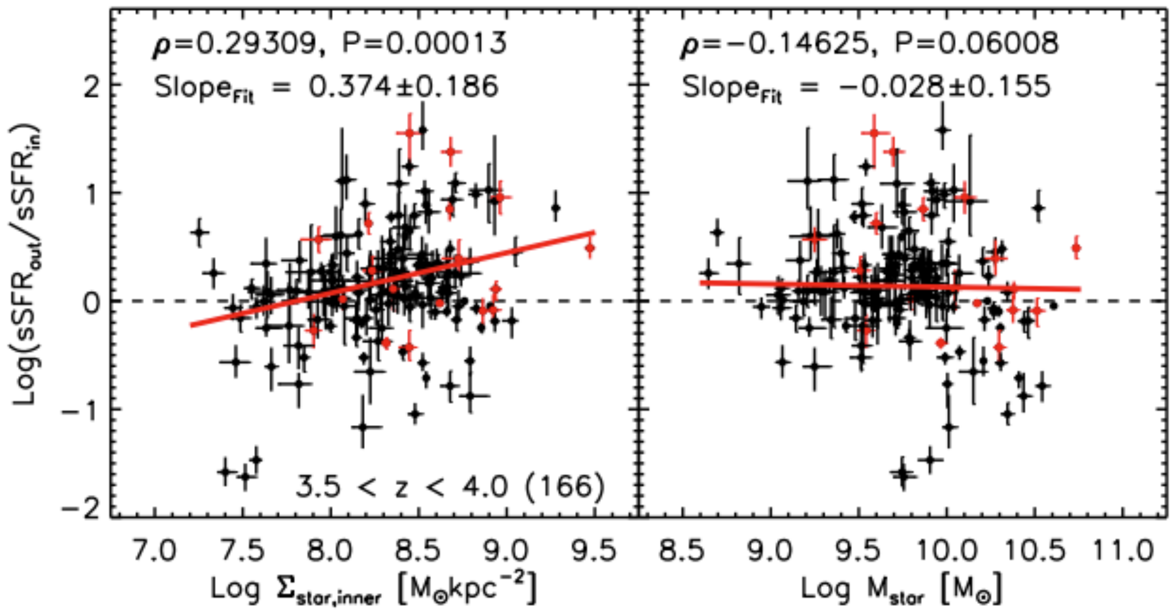
ANALYSIS: GALAXIES AT Z~4 (WITH K-BAND DATA)

- Prior to performing analysis, authors tested ability to recover sSFRs with mock images of simulated galaxies.
- Occasional outliers, but good agreement overall.

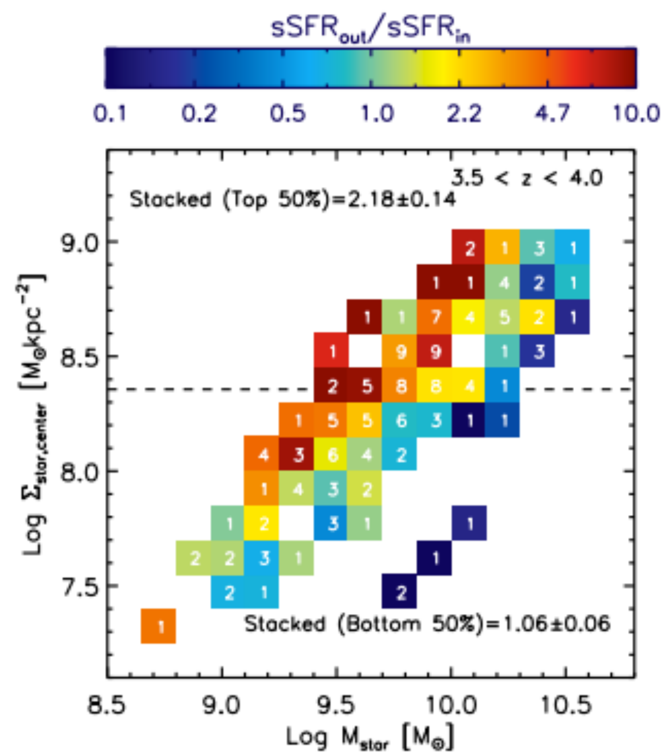


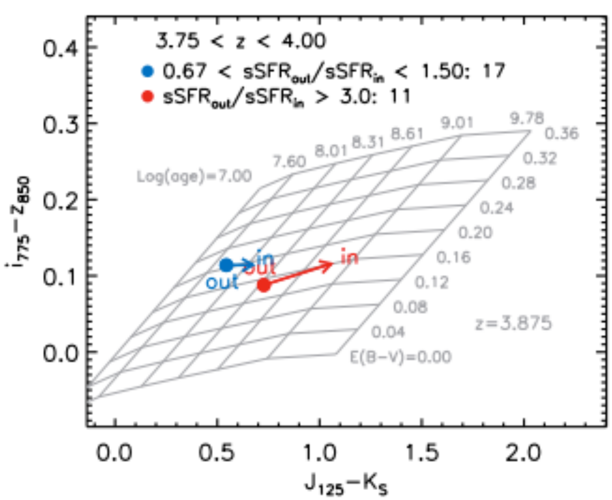


RESULTS: GALAXIES AT Z~4 (WITH K-BAND DATA)



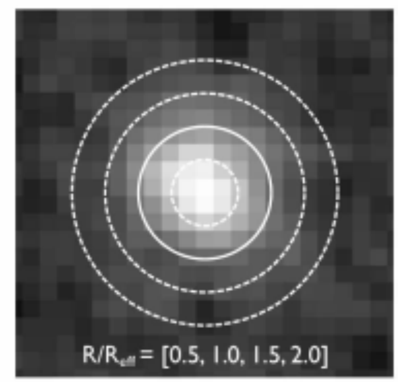
$$\mathrm{sSFR_{stack,in/out}} = \frac{\sum_{i=1}^{N_{\rm gal}} \mathrm{SFR_{i,in/out}}}{\sum_{i=1}^{N_{\rm gal}} \mathrm{M_{star,i,in/out}}}$$





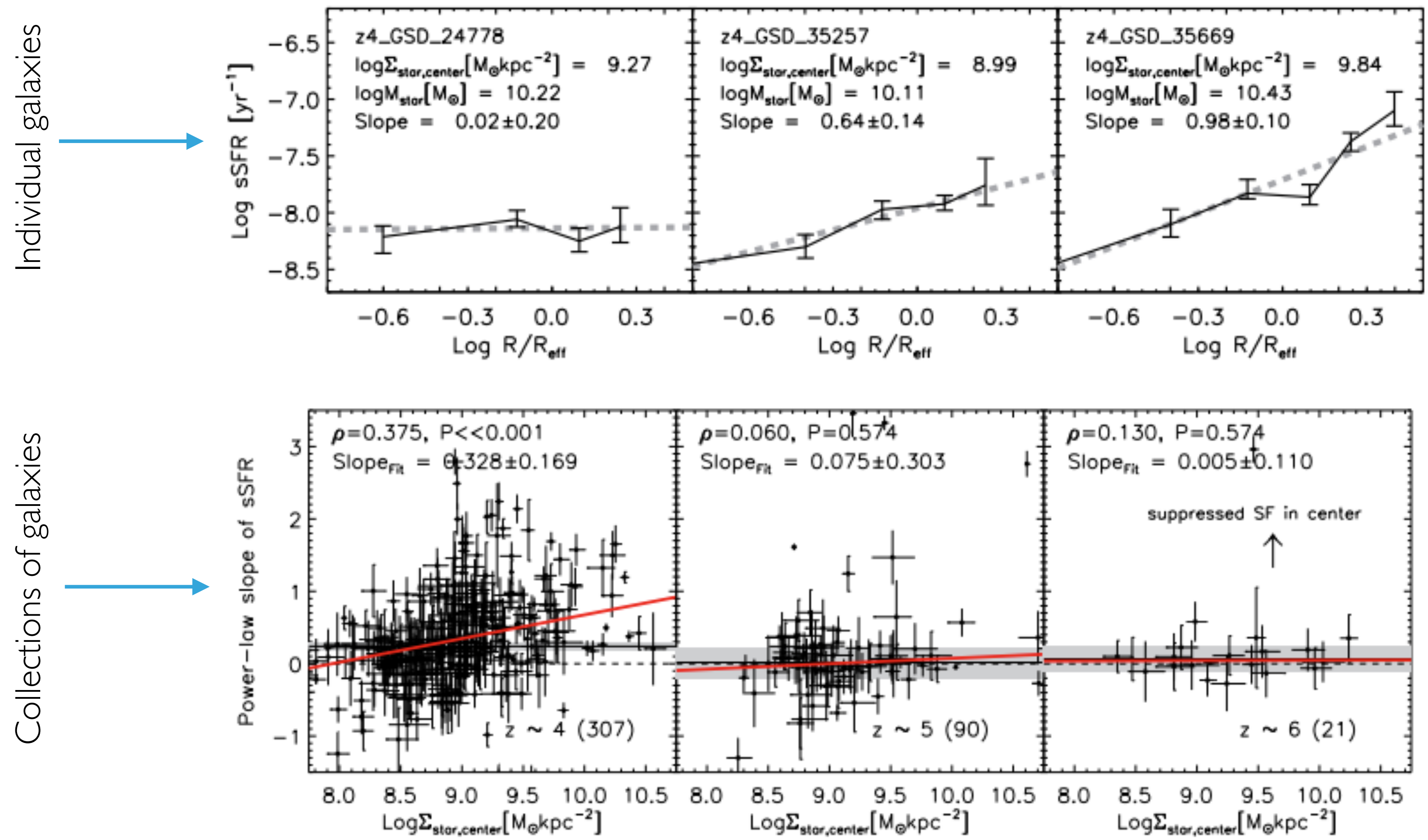
ANALYSIS: GALAXIES AT Z~4-6

- Pixel-based stellar population synthesis modeling is the norm, but is difficult to do at high z.
- Authors used radial binning method dependent upon galaxy size (R_{eff}).
- Flux measurements are based on aperture photometry using SExtractor.
- Once fluxes have been computed, they are run through resolved SED fitting pipeline (discussed earlier).



RESULTS: GALAXIES AT Z~4-6

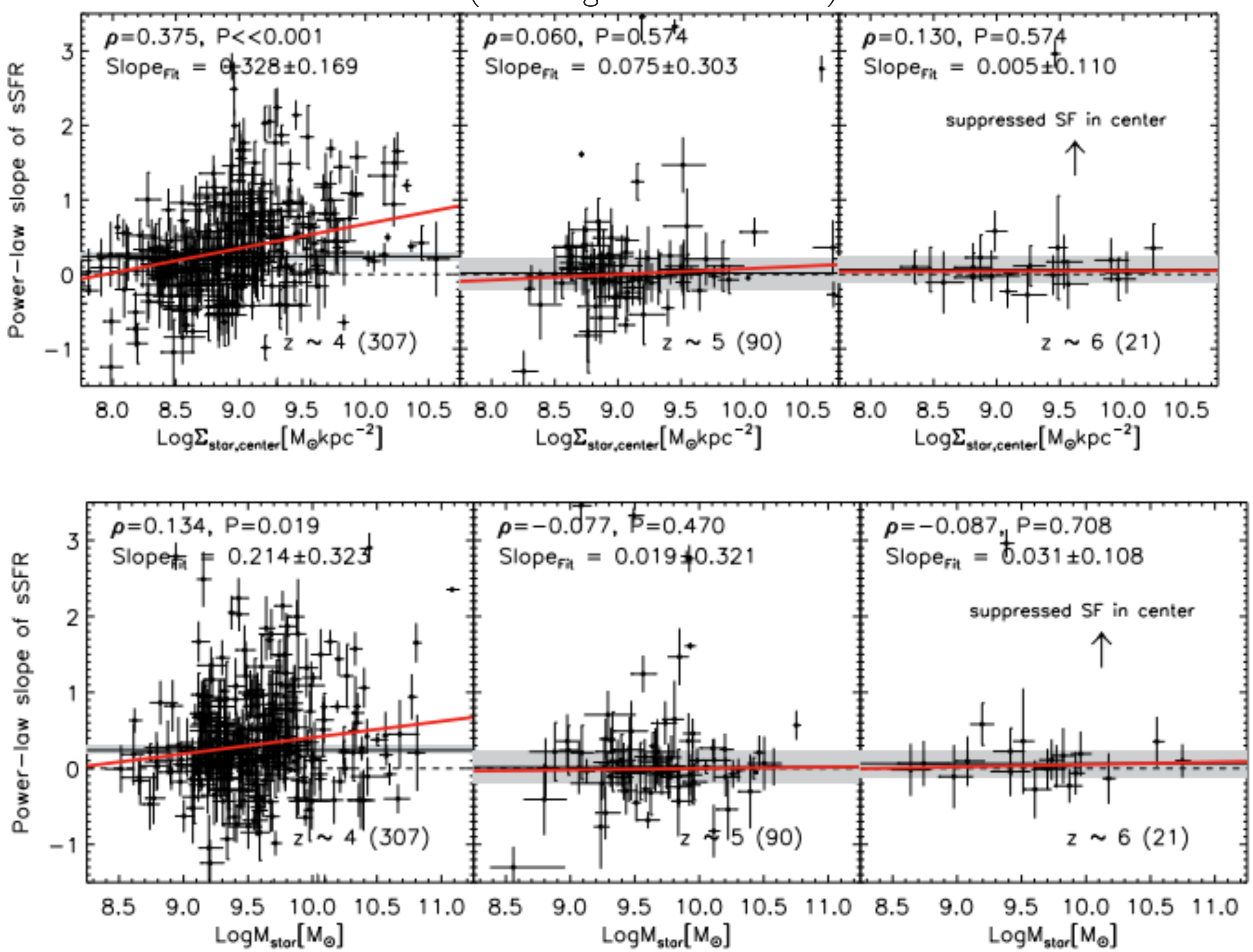
- Authors fit a single power-law slope to the sSFR as a function of radius for each galaxy.



RESULTS: GALAXIES AT Z~4-6

(same figure on last slide)

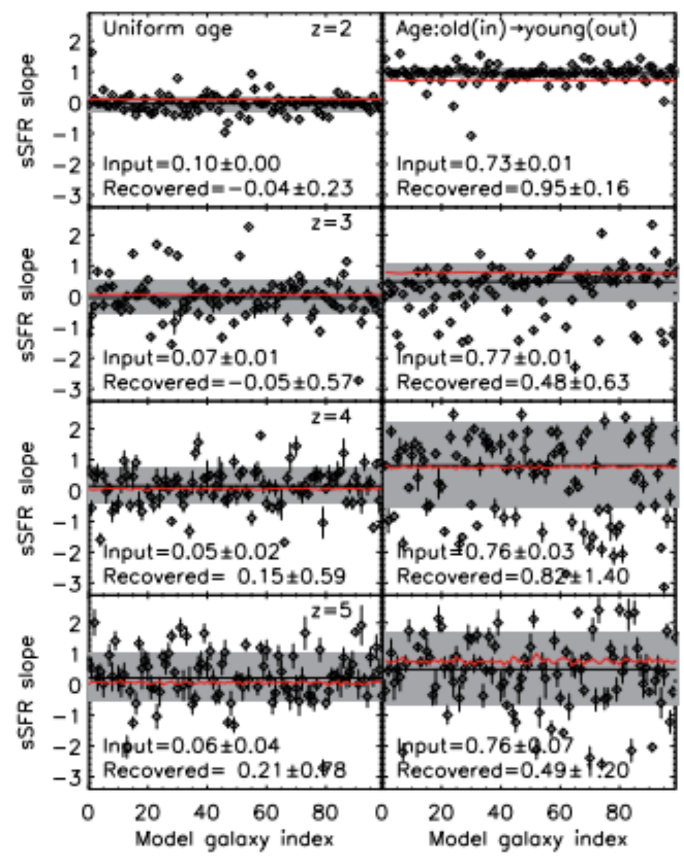
Collections of galaxies



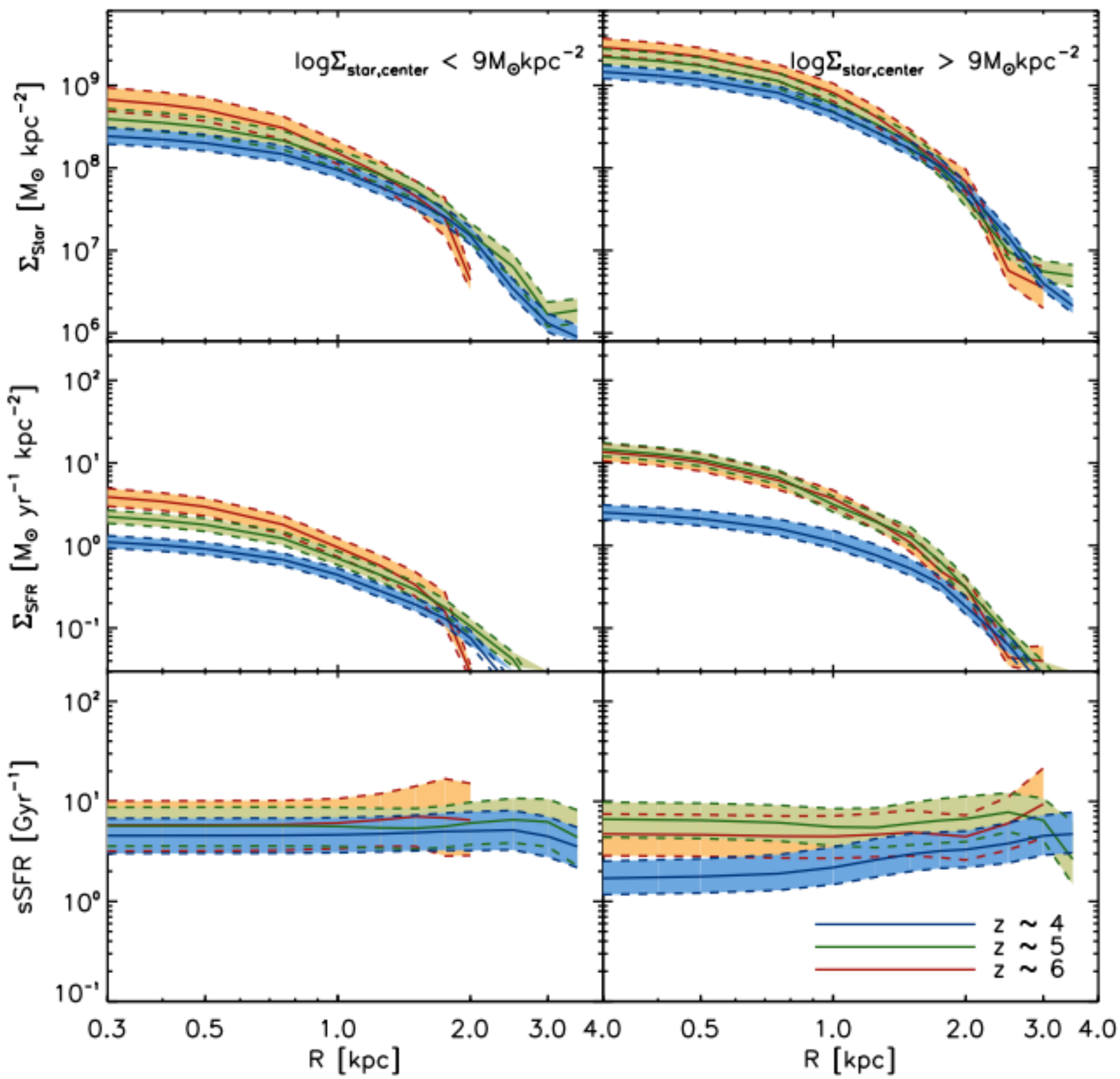
Collections of galaxies

CHECKING RESULTS: GALAXIES AT Z~4-6

- Earlier in the paper, the authors expressed concern about the following issues:
  - **Bias:** Galaxy sample favors bright/massive galaxies with large radii.
  - **Mass uncertainty:** Difficulty encountered constraining stellar mass without rest-frame optical data for z>4.



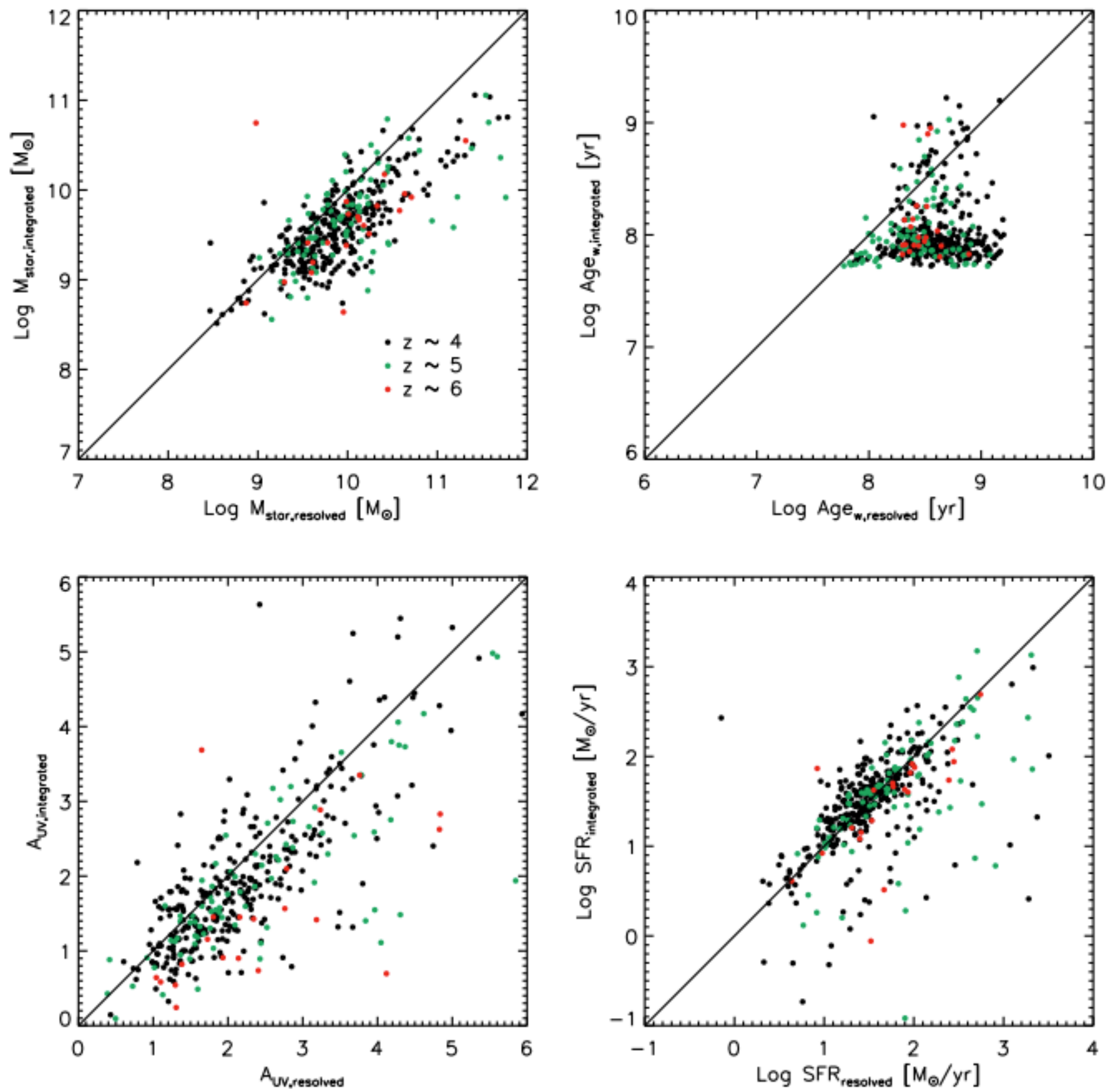
RESULTS: GALAXIES AT Z~4-6



SUMMARY

- Evidence for reduced star-formation in centers of massive galaxies between z~3.5 and z~4.5 (using sSFR ratios and power-law slope of the sSFRs).
- Galaxies at z~5 and z~6 are forming stars uniformly throughout, contrary to the findings for z~4 (power-law slope of the sSFRs).
- SFR and sSFR in central regions are lower for high central mass density galaxies at z~4 than similar galaxies at z~5 or z~6 (stacked radial density profiles).
- Authors warn that the interpretability of results may be difficult to ascertain due to selection bias and lack of optical-band data for z>4.
- Analysis does not shed any light on causation for observed phenomena.

APPENDIX FIGURE (INTEGRATED VS. RESOLVED)



REFERENCES

- **Bruzual, G., & Charlot, S.**, MNRAS 344, 1000 (2003).
- **Finkelstein et al.,** ApJ 810, 71(2015).
- **Jung et al.**, arXiv:1611.02713 (to appear in ApJ).
- **Kennicutt, R. C., Jr.**, ARA&A 36, 189 (1998).
- **Madau, P. & Dickinson, M.**, ARA&A 52, 415 (2014).
- **Salmon et al.**, ApJ 799, 183 (2015).