Draft version December 1, 2019
Typeset using LaTeX **modern** style in AASTeX63

How Do Galaxies Evolve into the Forms They Have Today?

Zhiwei Pan[1]

[1]*Kavli Institute for Astronomy and Astrophysic*
Peking University
Beijing 100871, China

ABSTRACT

This paper is a naive "review" on galaxy formtion by introducing some backgrounds and summarizing Susan Kassin's colloquim. This colloqium is about thier recent study on the formation and evolution of disk and spheroidal galaxies, which will challenge the classic scenarios. They use Hubble images and Keck spectroscopy at $z = 0 - 2.5$ to study the kinematic evolution of disk galaxies and find that disks are gradually settling from disordered motion at high redshift to rotation dominance at low redshift. They also find that the massive galaxies evolve faster and the low-mass galaxy below a typical mass even can't form a disk. As for the spheriodal formation problem, they measure the star formation histories by fitting models and find mainly three scenarios, which indicates that the evolution of high redshift and high mass is faster. At last, they demonstrate that the spectroscopy of JWST in the future will help them a lot, such as creating the kinematic maps of the earliest galaxies.

Keywords: disk galaxy — kinematics — SFH — JWST

1. INTRODUCTION

Galaxy is a gravitational surported system with gas, stars, Dark matter, which has mainly two types in univserse: disk galaxy and early-type galaxy. Disk galaxy is rotationally supported, which means that stars and gas rotate around the center of disk; While early-type galaxy with many old and low-mass stars is dispersion dominated.

However, the formation and evolution of galaxy is far from understood. People are always tring to solve out such problems: How and when are disks assembled? How and when do disks obtain their current well-ordered state? How and when do quiescent spheriods form? In history there existed some theoretical models such as the gas-collapsing model to interprete these questions, but in this colloquim, the

1901110222.pku.edu.cn

observation results of this speaker challenge the physical picture of typical model. In this summary, I aim to follow the logic of this colloquim and introduce its three parts.

In Section 2, I will introduce their new understanding of disk formation process. In Section 3, I will discuss spheriod formation with their fitted star formation history. In Section 4, I will do the outlook about what JWST can do in the future. In Section 5, I will present the conculsions of this colloquim. They adopt a ΛCDM cosmology defined with $(h, \Omega_m, \Omega_\Lambda) = (0.7, 0.3, 0.7)$.

2. DISK FORMATION

In this part, I will firstly introduce some analytical models and their predictions in Section 2.1. Then I will show the observation results and measurements of some galaxy physical properties. At last, I will discuss the critical mass below which the disk will not form in Section 2.3 and the characteristics of disks assembly over cosmic time in Section 2.4

2.1. *Models of Disk Formation and Evolution*

We know that the over-density regions of dark matter will cluster and collapse into a galaxy and White & Rees (1978) found that baryonic gas dissipation must play a significant role in the formation of disc galaxies. While Fall & Efstathiou (1980) argued that White & Rees (1978) didn't discuss the angular momentum problem, so they firstly consider a gas-collapsing model in extended dark matter halo with hierarchical clustering. The key assumption here is that these systems get their angular momentum by tidal torques and the angular momentum is conserved through galaxy collapse, which is very crucial to disk forming. Dalcanton et al. (1997) extended previous models and developed a scenrio that links the surface brightness of the resultant disk to the mass and angular momentum of its protogalaxy: Low surface brightness galaxies form from low-mass and high angular momentum protogalaxies. These models predict that disks start off well-ordered and they grow in radius in an regular manner called "onion skin".

Tully-Fisher relation (TFR) is an empirical relation between the rotation velocity and luminosity of disk galaxies: $L \propto V^{2.5}$ (Tully & Fisher 1977). The analytic and numerical theory can also reproduce a tight TFR as shown in Figure.1.

There are also some dynamical theories of isolated disk evolution, which predict that stars start off in a well-ordered and thin disk. However, their velocity dispersion will increase with cosmic time (Aumer et al. 2016) as shown in Figure and the disk will gradually thicken.2 via lots of possible mechanisms including: molecular clouds (Aumer et al. 2016), merging satellites (Velazquez & White 1999), buckling of bars (Debattista et al. 2006), minor mergers (Moster et al. 2011)(I checked this paper and found that ppt may make a mistake: not minor mergers, but major mergers) and so on.

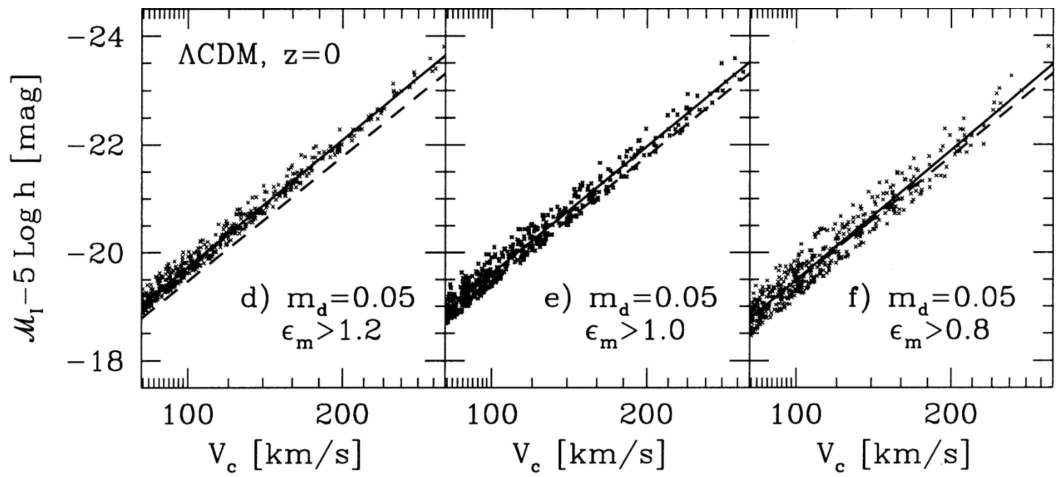

Figure 1. Tully-Fisher relation for stable disks at z=0. Black dots are predictions from model (Mo et al. 1998). The dashed lines show the observed TFR as given by Giovanelli et al. (1997). We can find that disks lie on a tight TFR.

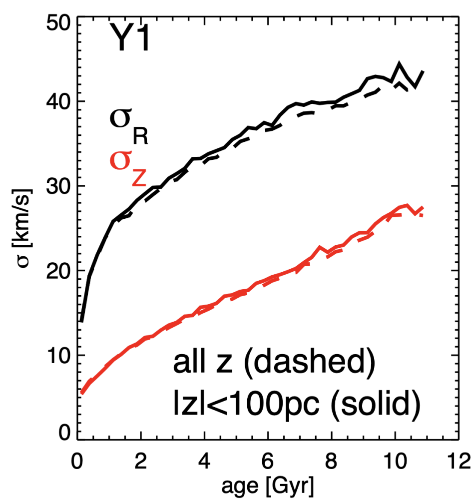

Figure 2. The velocity dispersions in radial (black) and vertical (red) directions increase with time. (Aumer et al. 2016)

2.2. *observations*

They did observations of galaxy kinematics at a range of redshifts aimming to examine the picture discribed by models. To study the evolution of galaxy kinematics from z=3 to now, they need spectra and Hubble images for a hundreds of representative galaxies over a significant range in redshift and stellar mass. They firstly selected some star-forming galaxies on the "main sequence" as observation targets with no cuts on morphology, which can reduce selection bias. Then they did spectroscopy and multi-band photometry in DEEP2 & SIGMA Surveys (Simons et al. 2017) and got Hubble images from AEGIS & CANDELS (Davis et al. 2007; Grogin et al. 2011).

They used multi-band photometry to measure the total stellar mass of each individual galaxy and use emission lines of spectrum to mearsure the galaxy kinematics

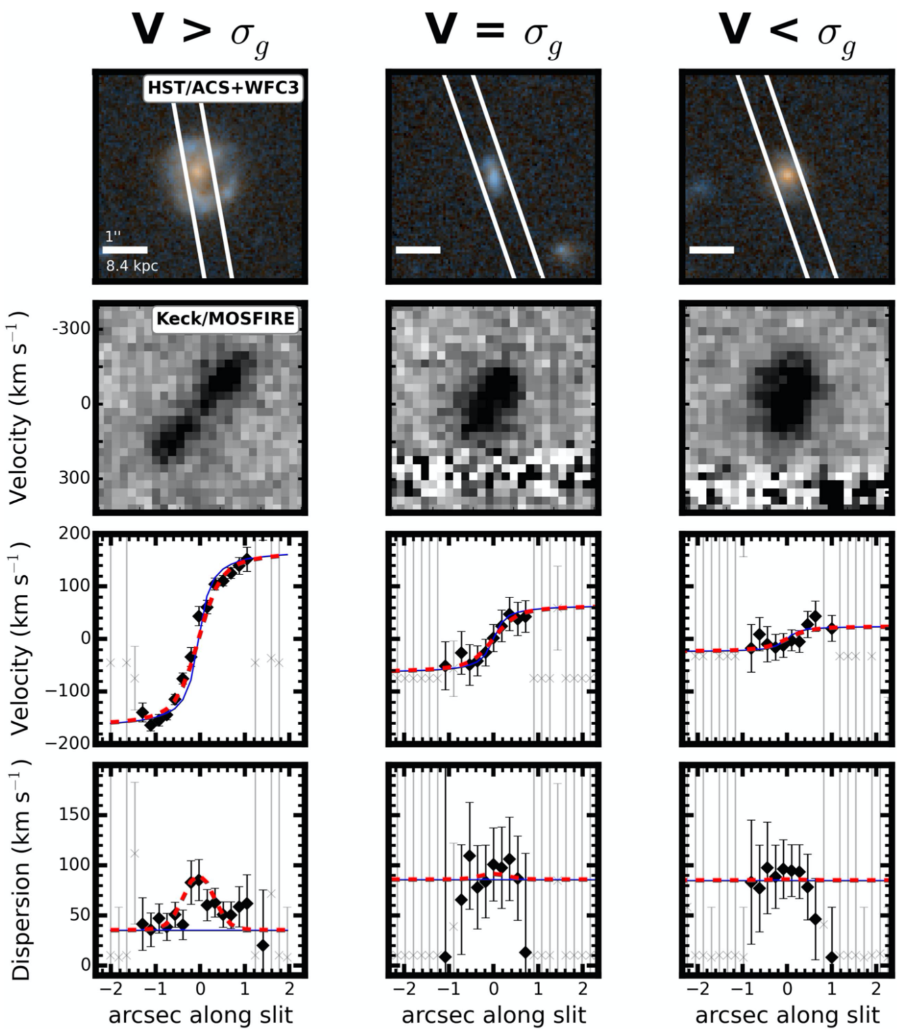

Figure 3. Example single-slit observations are presented for three SIGMA galaxies, which span three kinematic types: a rotation dominated galaxy (left column), a galaxy with equal contributions of rotation and dispersion (middle column), and a dispersion-dominated galaxy (right column). The top two rows are the I+H-band HST/ACS-WFC3 color images with the MOSFIRE slit placement and the 2D spectra centered around the Hα line. In the bottom two rows, they show the kinematic model fits to the emission lines.(Simons et al. 2016)

including the rotation velocity V_{rot} and the velocity dispersion σ (Simons et al. 2016) as shown in Figure.3. The team of this speaker is the first one to measure σ and also the first one to correct both V_{rot} and σ for the effects of seeing. They also correct V_{rot} for inclination using Hubble image.

2.3. *mass of disk formation*

By using series of observations introduced above, they studied the TFR at local galaxies ($0.1 < z < 0.375$) (Simons et al. 2015) as shown in Figure.4. They found a transition stellar mass in the TFR, $\log M_\star/M_\odot = 9.5$. Above this mass, nearly all galaxies are rotation dominated disk galaxies and lie on a relatively tight TFR. While

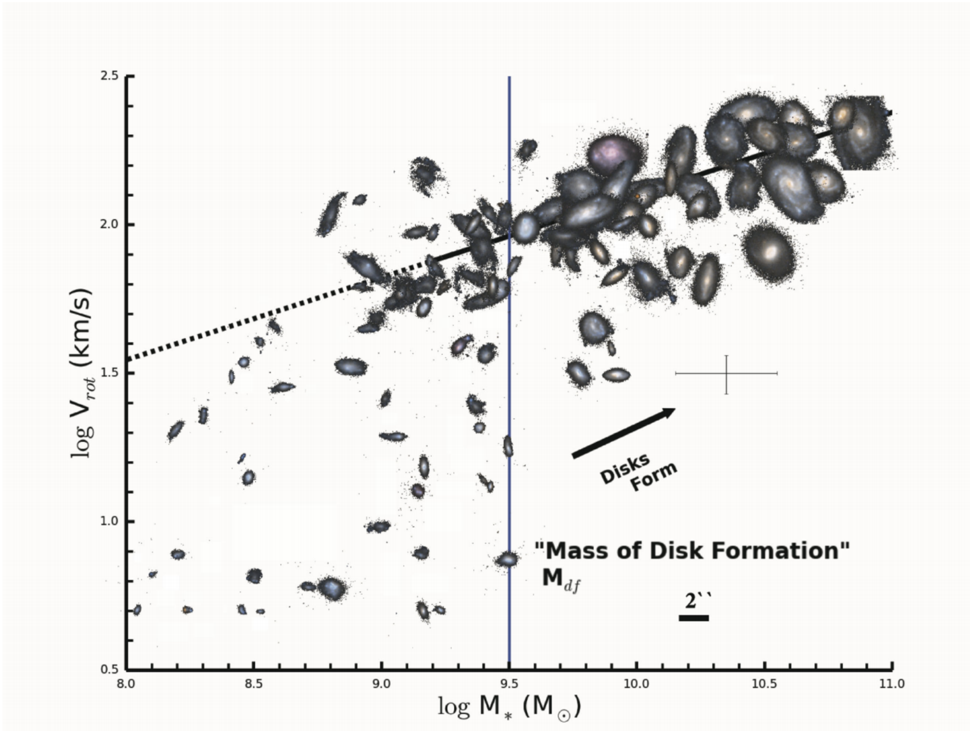

Figure 4. The TFR for a morphologically unbiased sample of blue galaxies over $0.1 < z < 0.375$. They find that below the mass of disc formation, a galaxy may not have formed a disc.(Simons et al. 2015)

below this mass, the TFR has significant scatter to low rotation velocity and galaxies will not form discks.

2.4. *Assembly of disks over cosmic time*

After concluding that Tully-Fisher relation falls apart for local low mass galaxies and local low-mass star-forming galaxies are often not disks galaxies, Kassin et al. (2007) keep on showing the TFR at different redshift as shown in Figure.5. They found that even massive galaxies deviate from TFR at high-redshift, which may indicate that even the disks of massive galaxies haven't formed at early epoch. Then they defined $S_{0.5}^2 = 0.5V_{rot}^2 + \sigma^2$ to combines dynamical support from ordered motion with that from disordered motions (Weiner et al. 2006) and found TFR much tighter, which may indicate that velocity dispersion can result in the deviation from TFR. Based on TFRs from high-redshift to now, they got a picture that many massive galaxies without disks at high-redshift eventually form into well-disk galaxies.

Another important question is that whether V_{rot} and σ evolve with time, so the team of speaker explore the evolution of the internal gas kinematics of star-forming galaxies from the peak of cosmic star formation at $z \sim 2$ to today as shown in Figure.6.

They further studied the evolution of the disk galaxies fraction over cosimc time as shown in Figure.7. Simons et al. (2017) found that galaxies were undergoing disk assembly at $z \sim 2.5$, which means that most of galaxies didn't have formed the disks and disks settling happened at $z \sim 0.5$ because of the high disks fraction. The key

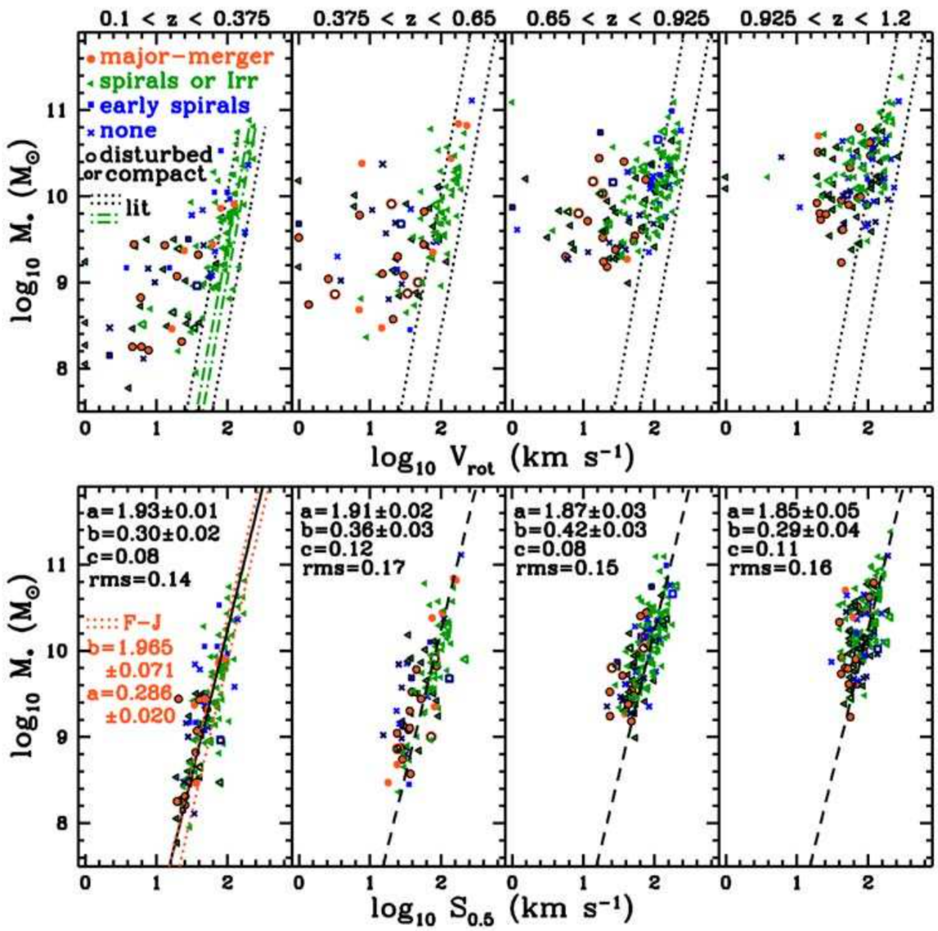

Figure 5. The $S_{0.5}$ and V_{rot} TFR for $0.1 < z < 1.2$ in bins of z. Using $S_{0.5}$, which combines the dynamical support from ordered motion with that from disordered motions, results in a tighter TFR, independent of morphology, and non-evolving to $z = 1.2$ (Kassin et al. 2007).

assumption here is they assume that galaxy whose $V_{rot}/\sigma > 3$ must be disk galaxy. They also confirmed "kinematic downsizing" (Kassin et al. 2012) that massive galaxies develope strong rotational support and form disks fisrt.

2.5. *comparisions between models and observations*

In this subsection, I will make a little review to compare the difference between predictions from models and conclusion of this colloquim as shown in Table.1.

3. SPHERIOD FORMATION

3.1. *theories of spheriod formation*

After discussing the formation of star-forming disk galaxies, in this section the speaker focus on the problem that how and when galaxies become "red and dead" spheriod galaxies.

The classical picture for red, early-type galaxies is that they form in a single-burst very early in the universe (Larson 1975). However, Faber et al. (1995) have already

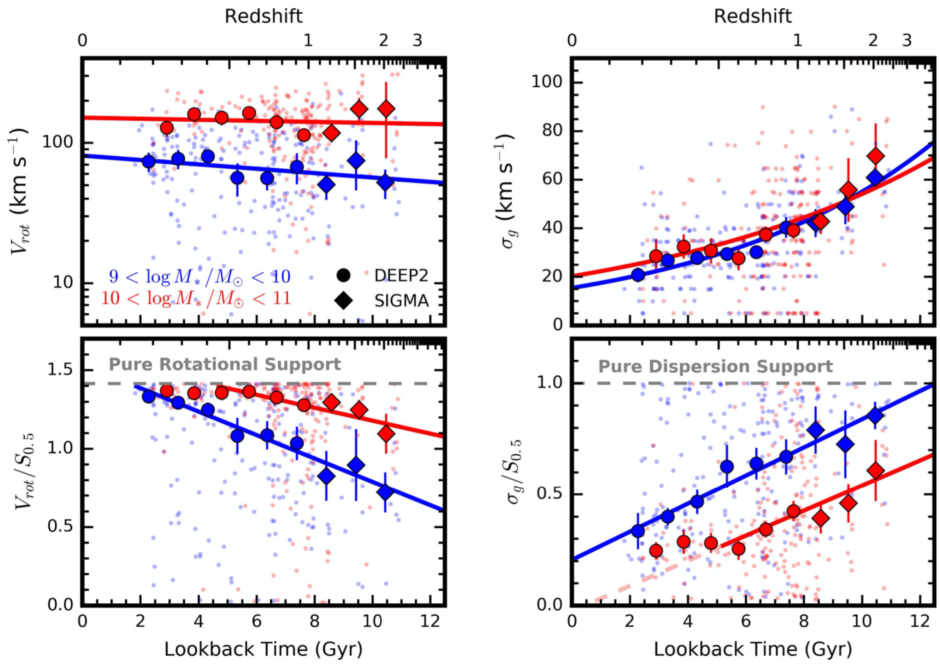

Figure 6. Star-forming galaxies evolve in V_{rot} and σ with time. The small faint background points are measurements for individual galaxies. The large points and associated error bars show medians of the individual points in bins of lookback time and their standard error. Solid lines are the best-fit relations to the median points. Low-mass and high-mass galaxies are shown in blue and red, respectively. Top left: V_{rot} increases with time since z = 2.5 for low-mass galaxies but shows no evolution for high-mass galaxies. Top right: the gas velocity dispersion σ decreases precipitously from z = 2.5 to today for both low-mass and high-mass galaxies. In the bottom panels, V_{rot} and σ are normalized by $S_{0.5}$, which allows us to examine the fraction of total dynamical support that V_{rot} and σ provide to galaxies. At $z \sim 2$, low-mass galaxies have a significant fraction of their total support in disordered motions. With time, all galaxies on average increase in rotational support and decrease in dispersion support. (Simons et al. 2017).

Table 1. Models v.s. Observations

Predictions from models	Conclusions of colloqium
Disks star off well-ordered and thin	Disks start off with lots of disordered motions
Disks grow in radius in an "onion skin" manner	Disks grow in radius, but not in an orderly manner
The Tully-Fisher relation has little scatter	Tully-Fisher has large scatter to low rotation velocity
They thicken with time	They lose disordered motions and "thin out" with time

successfully challenged this picture, finding that quiescent galaxies increase in numbers by a factor of 2-4 over the last 8 billion years since z 1, so all could not have formed in a single burst in the early universe. Trager et al. (2000) also found that early-type galaxies span a large range of ages and thus showed that blue galaxies can become red via different mechanisms occurring at different times and masses.

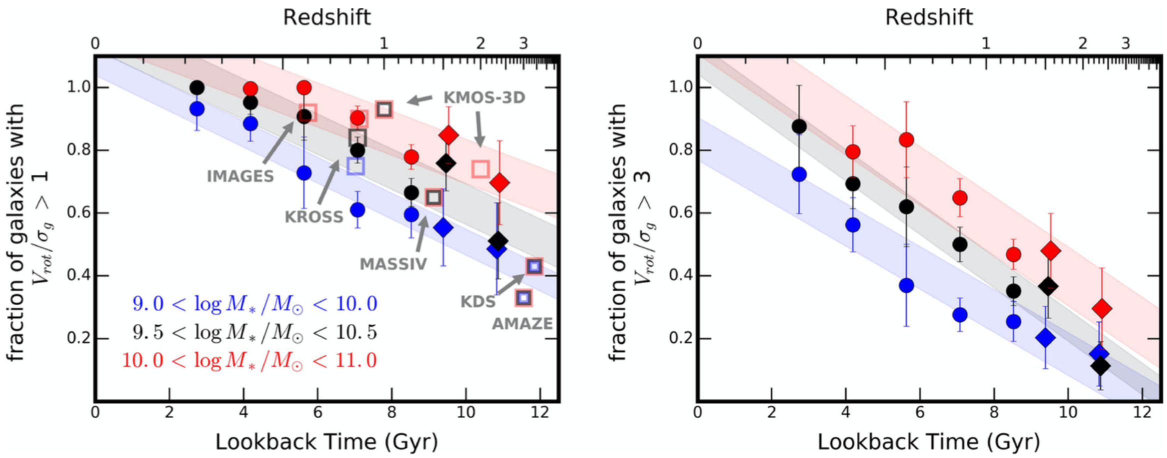

Figure 7. The fraction of star-forming galaxies with disk-like kinematics declines with increasing redshift and decreasing mass. In the left panel, the fractions of galaxies with $V_{rot}/\sigma > 1$ are shown as a function of lookback time and redshift and galaxy stellar mass. The solid points show measurements from DEEP2 (circles) and SIGMA (diamonds). In the right panel, the fractions of galaxies with $V_{rot}/\sigma > 3$ are shown. They confirm that the disk fraction of massive galaxies (red) is higher than that of low-mass galaxy (blue) at $z \sim 2$, which is called "kinematic downsizing" (Simons et al. 2017).

Besides, there exist some theories that mergers of disks can also form an early type (Toomre 1977).

One of the most important way to study the path from star-forming disks to quiescent spheroids ("quenching") is to infer galaxy formation histories (SFHs) from their past stellar populations (e.g. McDermid et al. 2015). So the speaker investigate this quenching path problem with measurements of the SFHs of quiescent glaxies. (Pacifici et al. 2016)

3.2. *measurements of SFHs*

They used HST/WFC3-F160W-selected catalogs from CANDELS (Koekemoer et al. 2011) and fitted the photometry of 845 quiescent galaxies with a library of 500,000 galaxy SED models that vary in terms of SFH, metallicity, stellar mass, age, etc. Then they determined the best-estimate SFH for each galaxy by averaging all the model SFHs weighted by their likelihoods as shown in Figure.8. They divided the sample into six redshift bins and for each further divide tha galaxies into six stellar-mass bins. Finally, they could calculate the median SFH of galaxies in each bin as shown in Figure.9 and Figure.10

After some theoretical analysis and considering the observational constraints from literature, they proposed three probable scenarios (Pacifici et al. 2016) as shown in Figure.11. For high-mass and high-z galaxies, they form fast and quench fast. The short dynamical timescale ($\sim$ 1 Gyr at $z = 2$)is consistent with gas accretion being stopped quickly and residual gas being used up. In terms of high-mass and low-z galaxies, they form fast and quench slowly, which indicates that the gas accretion is stopped but galaxies use up their residual gas slowly. As for low-mass and low-z

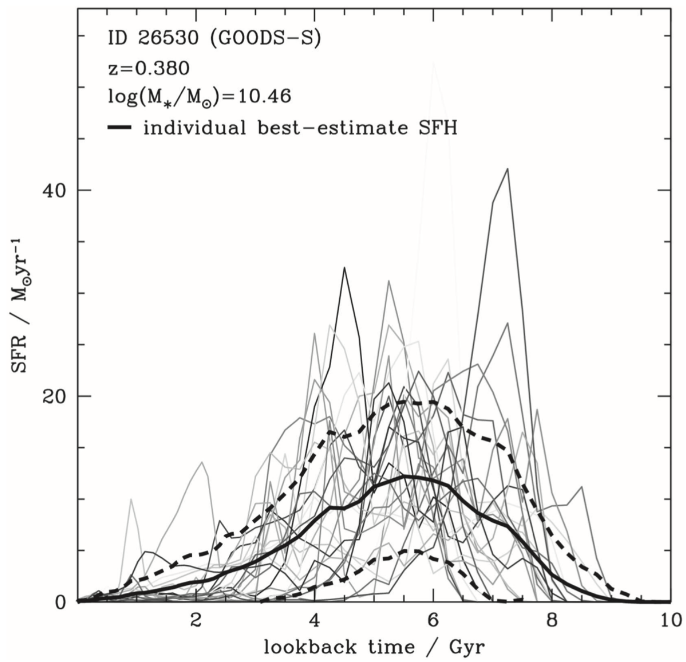

Figure 8. Best-estimate SFH of a single galaxy is the average of all the models weighted by their likelihoods. The thick black line is the best-estimate SFH and the thick dashed line is standard deviation. This figure only shows 25 best-fit results from 500,000 models and note that a lookback time of 0 corresonds to the lookback time at the redshift of observation (Pacifici et al. 2016).

galaxies, they form slowly and quench fast resulted from some catastrophic event such as stripping or strong feedback.

4. JWST

The James Webb Space Telescope (JWST) is a large (6.6 m), cold (¡50 K), infrared (IR)-optimized space observatory that will be launched early in the next decade into orbit around the second Earth Sun Lagrange point (Gardner et al. 2006). JWST will carry four scitenfic instruments: a Near-IR Camera (NIRCam). a Near-IR Spectrograpah (NIRSpec), a near-IR Tunable Filter Imager (TFI), and a Mid-IR Instrument (MIRI). The JWST sicence goals are divided into four themes, one of which is to study the assembly and evolution of galaxies from the epoch of reionization to the present day. Therefore, JWST will be very useful for the further and extended study of previous study introduced above. For example: How do the kinematics of the earliest galaxies ($z > 2$) evolve?

NIRSpec is a near-IR multiobject dispersive spectrograph capable of simultaneously observing more than 100 sources over a FOV larger than 3×3 arcmin (Gardner et al. 2006), witch can help them create kinematic maps of galaxies. Targets in the FOV are normally selected by opening groups of shutters in a microshutter assembly (MSA) to form multiple apertures as shown in Figure.12 and the fixed slits and IFU will also play an important role in spectroscopy.

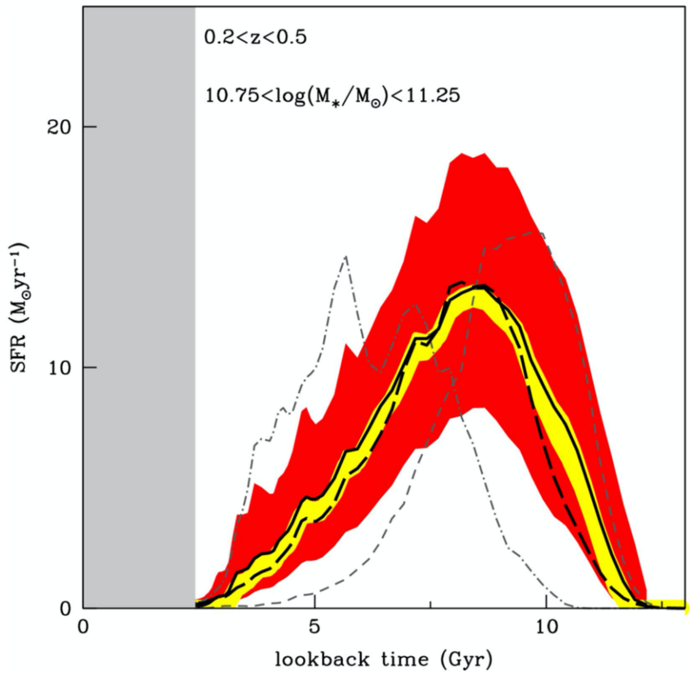

Figure 9. Calculation of the median SFH for 24 galaxies in an example bin of stellar mass and redshift. The thick black lines are median SFH. Thin dashed and dotted-dashed gray lines are two example individual galaxies (the other 22 are not shown). The yellow shade represents the sample variance and the red shade is interquartile range (Pacifici et al. 2016).

Her group had already used NIRSpec to test the mis-identifying ratio of disk galaxies in mock observations of merger at $z \sim 2$ and the low ratio indicates that NIRSpec of JWST will be a powerful tool. In the future, they are going to observe ~ 80 galaxies in 2 areas in the CANDELS field at $z = 2 - 6$ as a cycle 1 proposal, which will significantly help understand the evolution of earliest galaxies.

5. CONCLUSIONS

In this colloquim, the speaker mainly introduce three topics.

The first topic is about the disk formation. There is a critical mass of disk formation in the local universe, above which disks always form, but below which they find it hard to. They also found that at high z, galaxies are highly disordered and only just assembling. They later settle to disks. Besides, massive galaxies are always the earliest and fastest evolved.

Queicent spheriod formation is the second topic. She conclude that galaxy quenching time evolves with mass and redshift: it is faster at low mass and high redshift.

At last, She did an outlook about JWST, which will enable them to determine the dynamical state of galaxies soon after reionization and create kinematic maps.

ACKNOWLEDGMENTS

I thank to my roommate Yuxuan Pang.

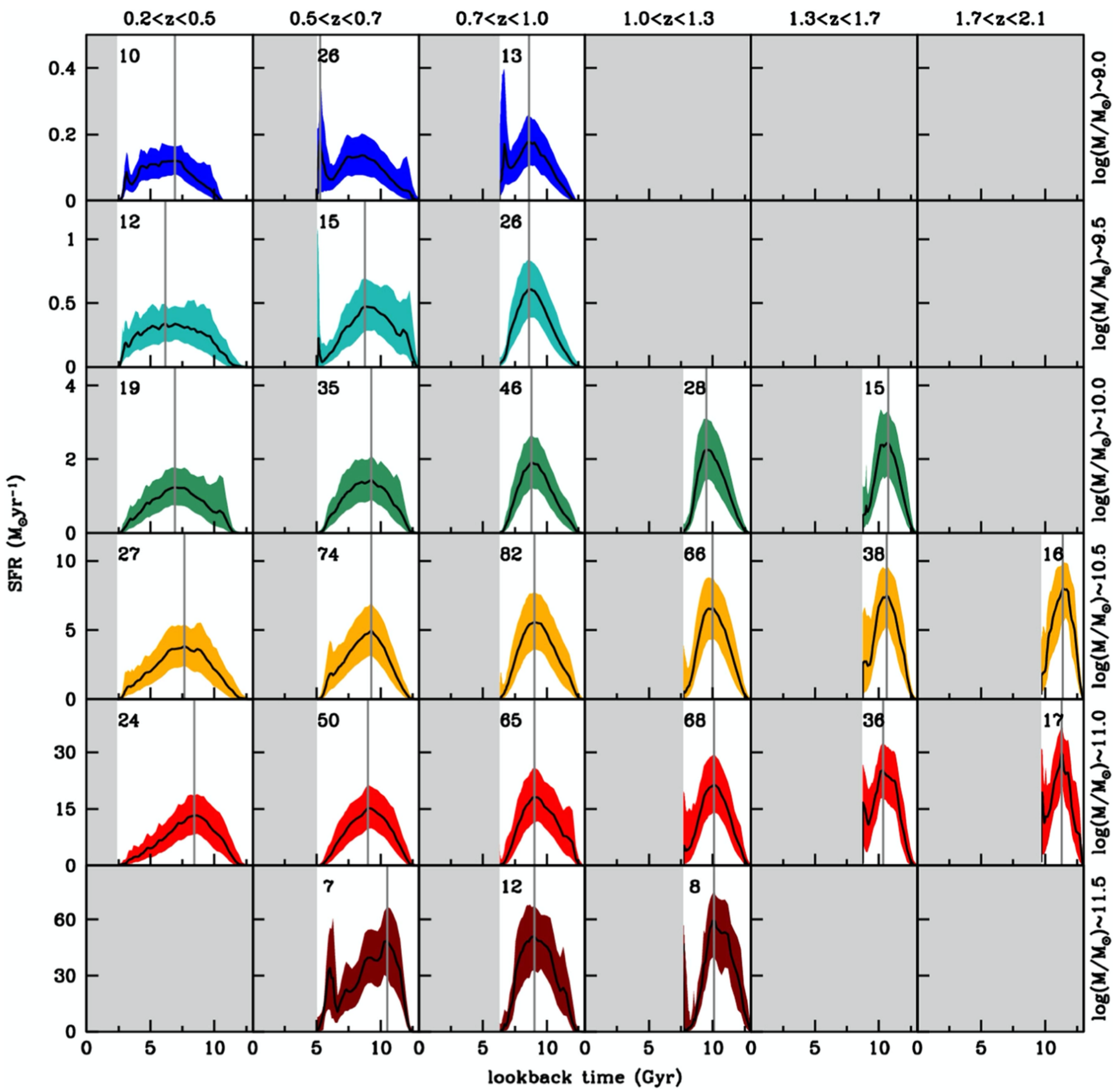

Figure 10. Median SFHs of quiescent galaxies in bins of stellar mass (rows) and redshift (columns). The vertical gray lines mark the peak of SFR (Pacifici et al. 2016).

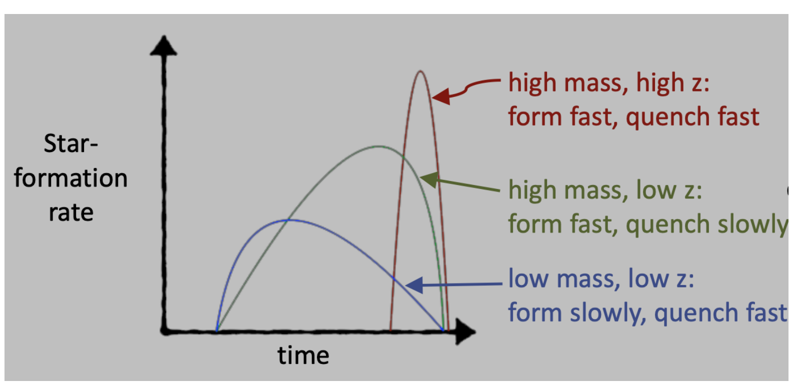

Figure 11. Three possible scenarios to explain the variety of shapes of quiescent galaxy SFHs (PPT, from "http://www.stsci.edu/contents/events/stsci/2018/november/how-do-galaxies-evolve-into-the-forms-they-have-today").

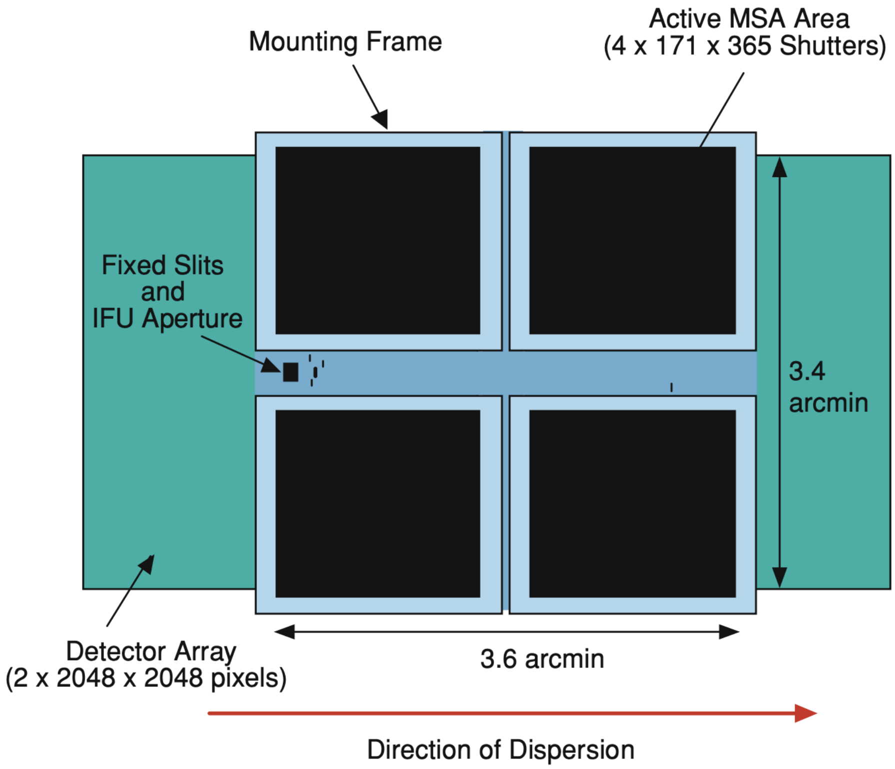

Figure 12. MSA (Gardner et al. 2006).

REFERENCES

Aumer, M., Binney, J., & Schönrich, R. 2016, MNRAS, 462, 1697, doi: 10.1093/mnras/stw1639

Dalcanton, J. J., Spergel, D. N., & Summers, F. J. 1997, ApJ, 482, 659, doi: 10.1086/304182

Davis, M., Guhathakurta, P., Konidaris, N. P., et al. 2007, ApJL, 660, L1, doi: 10.1086/517931

Debattista, V. P., Mayer, L., Carollo, C. M., et al. 2006, ApJ, 645, 209, doi: 10.1086/504147

Faber, S. M., Trager, S. C., Gonzalez, J. J., & Worthey, G. 1995, in IAU Symposium, Vol. 164, Stellar Populations, ed. P. C. van der Kruit & G. Gilmore, 249

Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189, doi: 10.1093/mnras/193.2.189

Gardner, J. P., Mather, J. C., Clampin, M., et al. 2006, SSRv, 123, 485, doi: 10.1007/s11214-006-8315-7

Giovanelli, R., Haynes, M. P., da Costa, L. N., et al. 1997, ApJL, 477, L1, doi: 10.1086/310521

Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, ApJS, 197, 35, doi: 10.1088/0067-0049/197/2/35

Kassin, S. A., Weiner, B. J., Faber, S. M., Koo, D. C., & Lotz, J. M. 2007, Astronomical Society of the Pacific Conference Series, Vol. 380, The Stellar Mass Tully-Fisher Relation to z=1.2, ed. J. Afonso, H. C. Ferguson, B. Mobasher, & R. Norris, 477

Kassin, S. A., Weiner, B. J., Faber, S. M., et al. 2012, ApJ, 758, 106, doi: 10.1088/0004-637X/758/2/106

Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, ApJS, 197, 36, doi: 10.1088/0067-0049/197/2/36

Larson, R. B. 1975, MNRAS, 173, 671, doi: 10.1093/mnras/173.3.671

McDermid, R. M., Alatalo, K., Blitz, L., et al. 2015, MNRAS, 448, 3484, doi: 10.1093/mnras/stv105

Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319, doi: 10.1046/j.1365-8711.1998.01227.x

Moster, B. P., Macciò, A. V., Somerville, R. S., Naab, T., & Cox, T. J. 2011, MNRAS, 415, 3750, doi: 10.1111/j.1365-2966.2011.18984.x

Pacifici, C., Kassin, S. A., Weiner, B. J., et al. 2016, ApJ, 832, 79, doi: 10.3847/0004-637X/832/1/79

Simons, R. C., Kassin, S. A., Weiner, B. J., et al. 2015, MNRAS, 452, 986, doi: 10.1093/mnras/stv1298

Simons, R. C., Kassin, S. A., Trump, J. R., et al. 2016, ApJ, 830, 14, doi: 10.3847/0004-637X/830/1/14

Simons, R. C., Kassin, S. A., Weiner, B. J., et al. 2017, ApJ, 843, 46, doi: 10.3847/1538-4357/aa740c

Toomre, A. 1977, in Evolution of Galaxies and Stellar Populations, ed. B. M. Tinsley & D. C. Larson, Richard B. Gehret, 401

Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 119, 1645, doi: 10.1086/301299

Tully, R. B., & Fisher, J. R. 1977, A&A, 500, 105

Velazquez, H., & White, S. D. M. 1999, MNRAS, 304, 254, doi: 10.1046/j.1365-8711.1999.02354.x

Weiner, B. J., Willmer, C. N. A., Faber, S. M., et al. 2006, ApJ, 653, 1027, doi: 10.1086/508921

White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341, doi: 10.1093/mnras/183.3.341