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Star formation quenching and mass assembly of galaxies

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PKU

Bi-Modal Distribution of Galaxies

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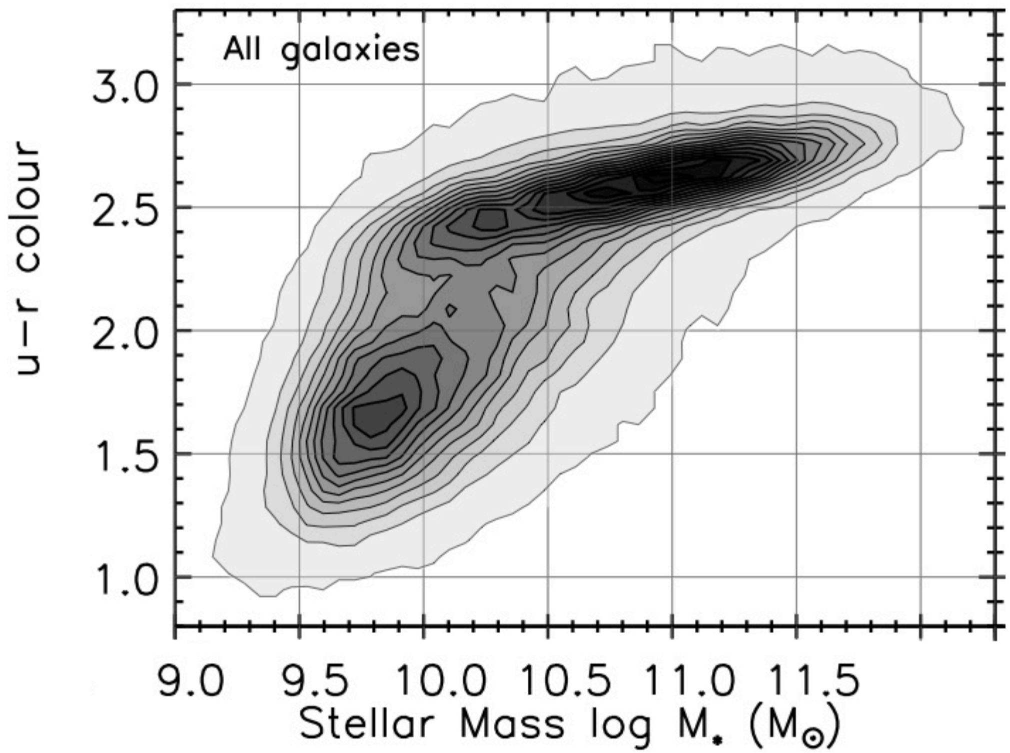
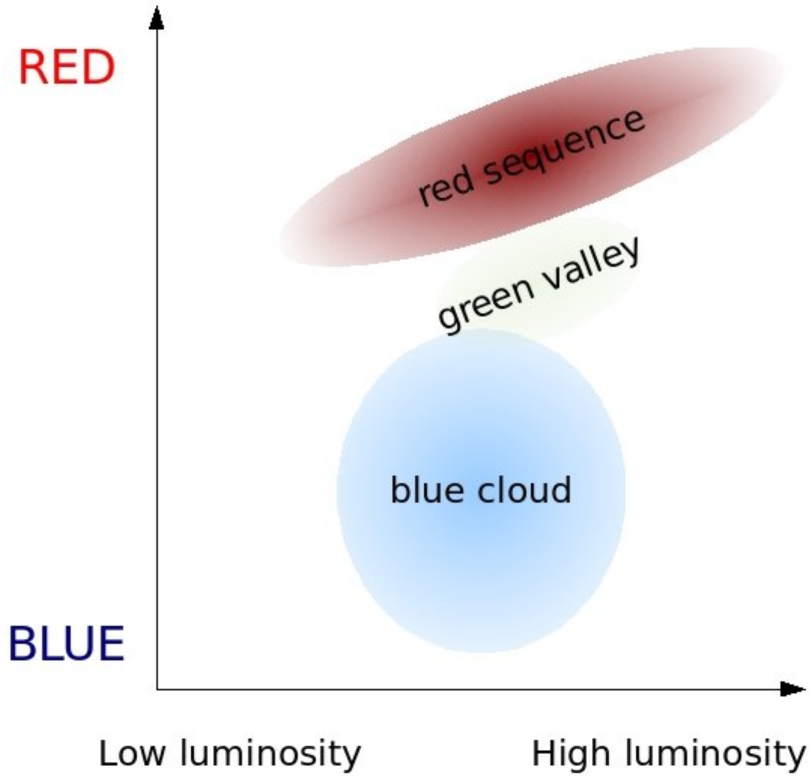


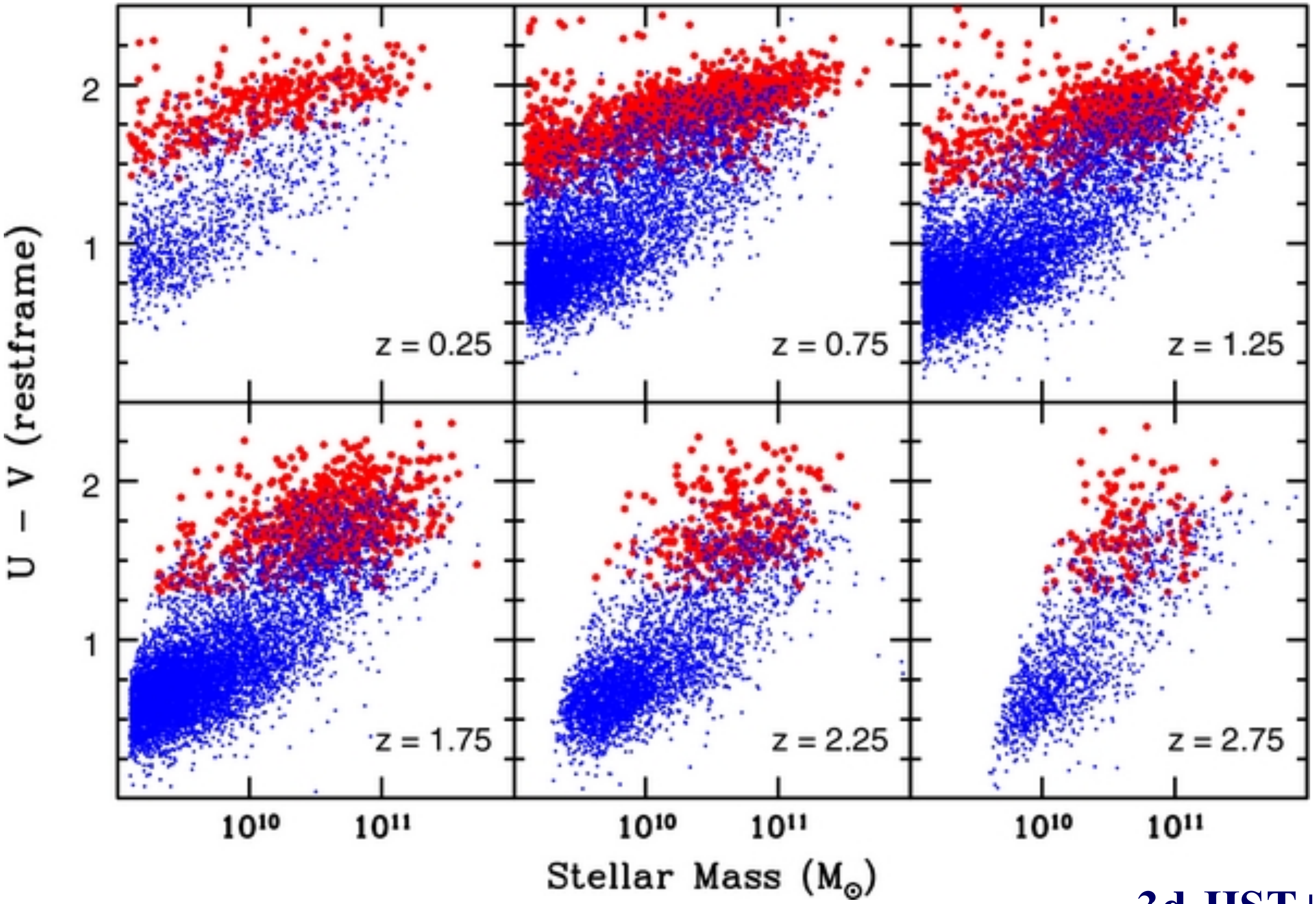
Early Type:
E/S0 Morphology;
Old Stellar Populations;
No or Little Cold Gas;
Red Colors

Late Type :
Abundant Cold Gas
Young Stellar Populations
Disk-Like Morphology
Blue color



Galaxies located in the joint region are called "green valley (GV)" galaxies.

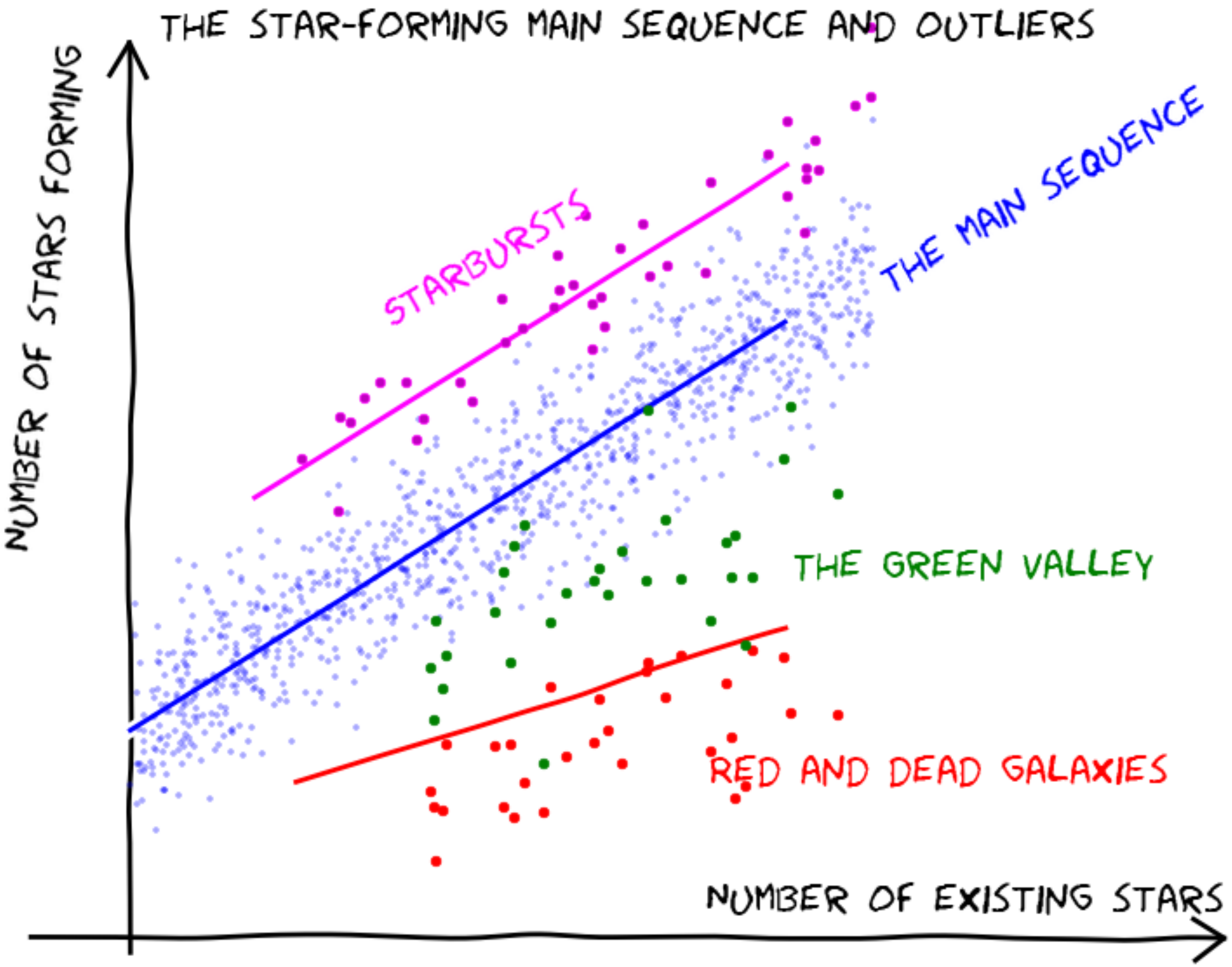
Rest-frame $U - V$ color vs. stellar mass in six redshift bins



3d-HST+CANDELS

A clearly defined red sequence is seen up to $z = 3$

Star-Forming Main Sequence (SFMS)



- **The intensity of <u>current star formation</u> (SFR) scales with its <u>product</u> (M*) over the cosmic time:**

$$SFR \propto M_*^{\alpha}$$

e.g., Brinchmann et al. 2004; Elbaz et al. 2007; Noeske et al. 2007.

SF Main Sequence

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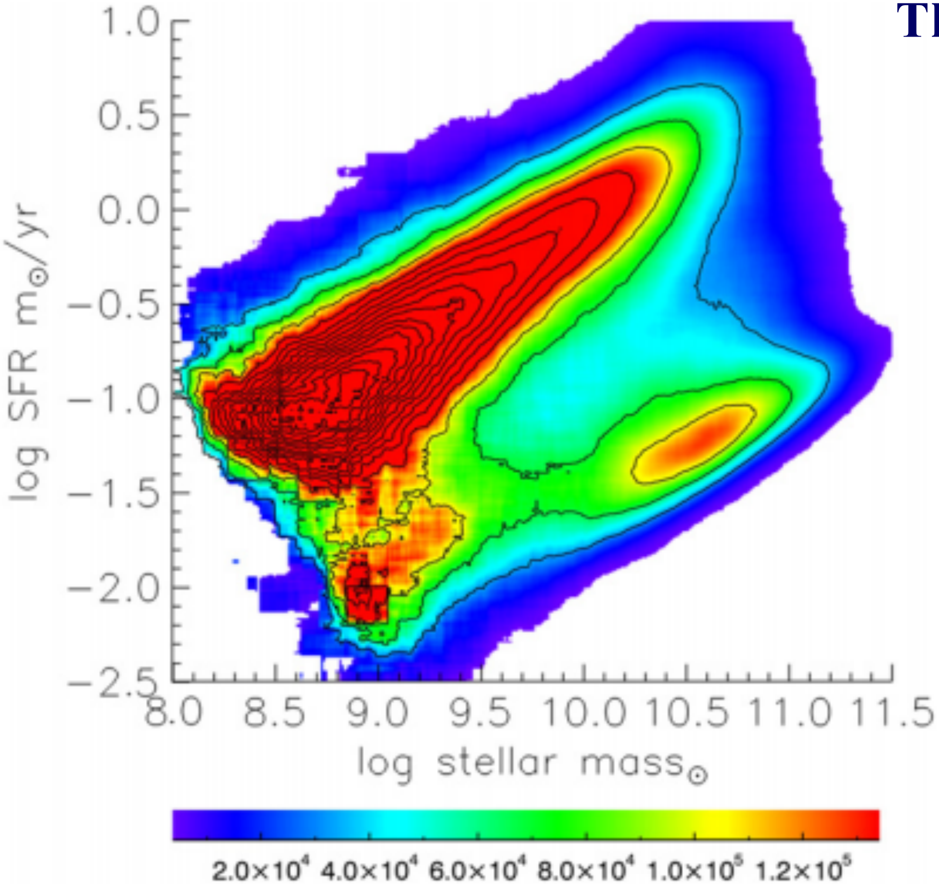
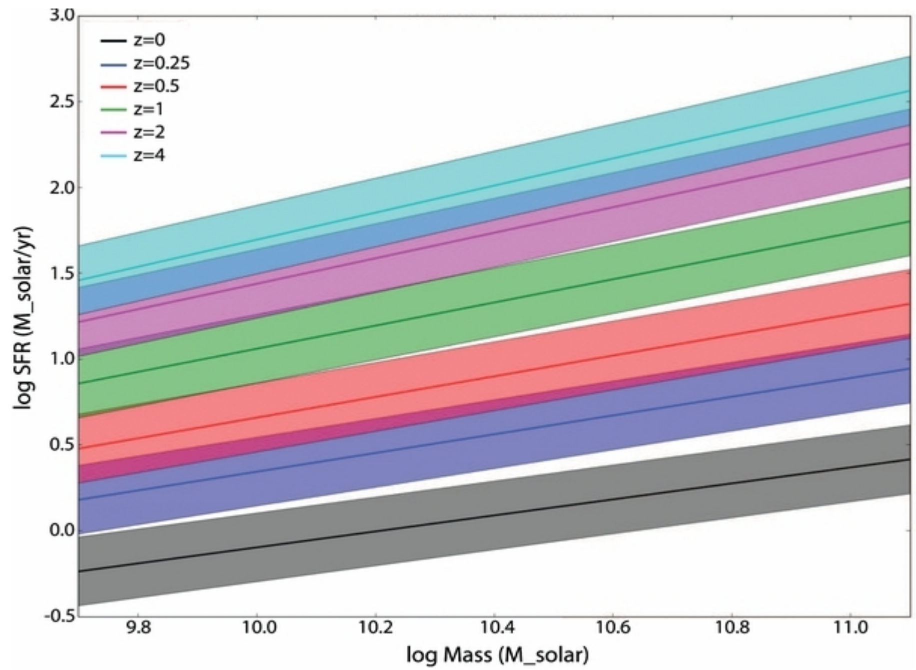
The Star-forming Main Sequence - Bimodality

: two populations of galaxies (SFGs and QGs) on the basis of their specific star formation rates (sSFR = SFR/M*)

Renzini & Peng (2015)

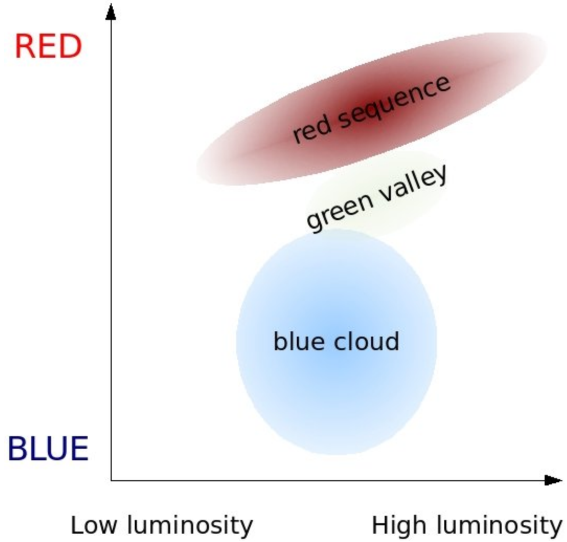


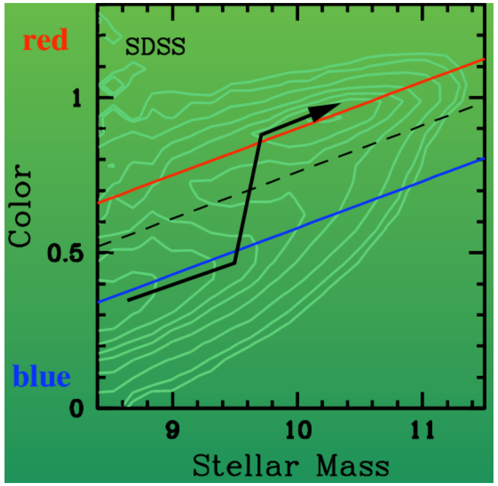


Evolution of the Star-Forming "Main Sequence"

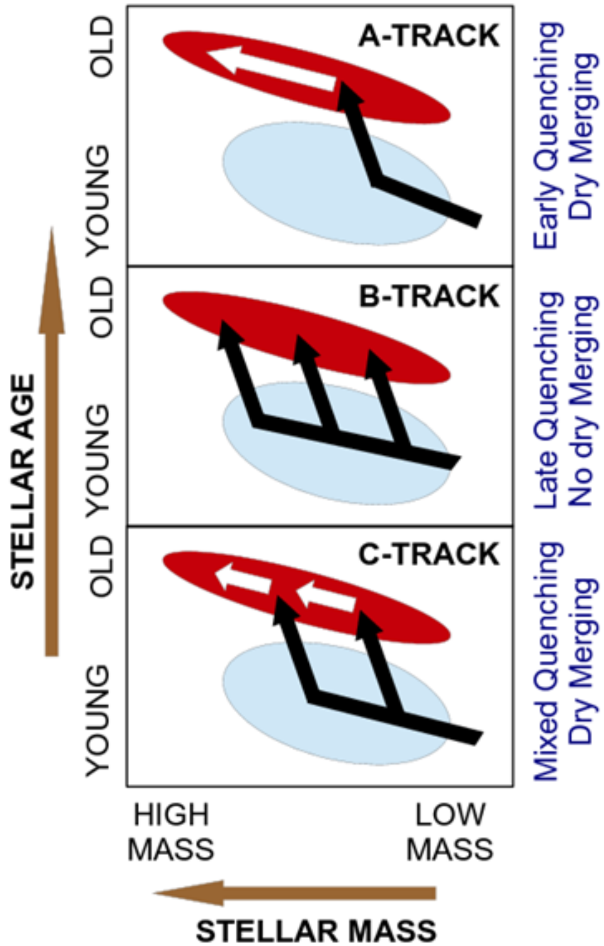
Speagle et al. (2014)

What is the origin of this bimodality?



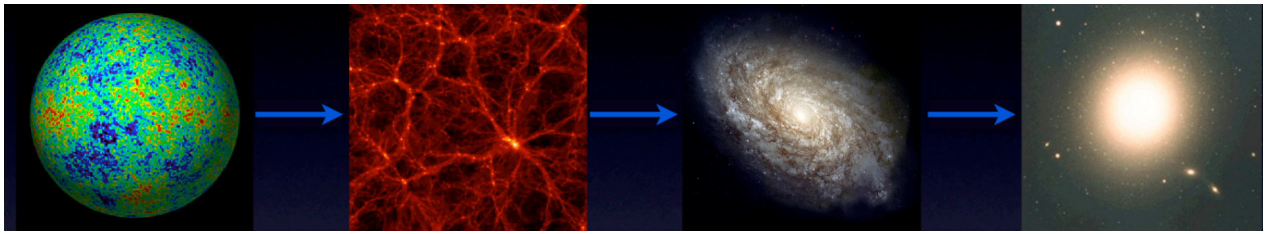


Faber et al.(2007)



Star formation quenching: why & how?

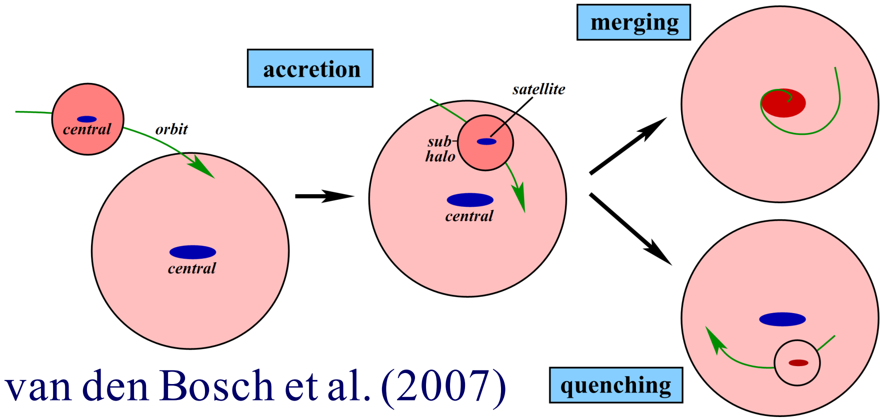
Evolution from blue cloud to red sequence



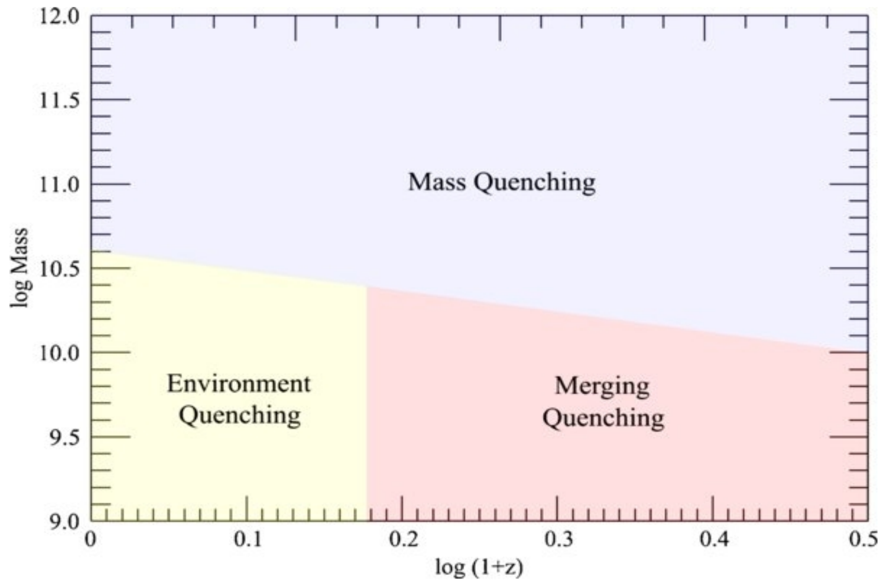
Standard Paradigm

All Galaxies Originally form as Central Disk Galaxies

Mechanisms for SF Quenching -- Why?



van den Bosch et al. (2007)

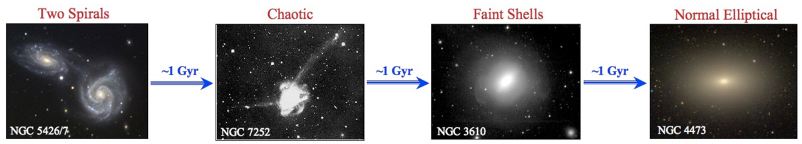


Peng et al. (2010, ApJ);

- **Dry mergers** increase the stellar mass of a galaxy, but leave its color unchanged
- Star Formation Quenching
  - Stellar mass (or structure)
    - SNe feedback/AGN feedback
    - Disk instability / bar / bulge
  - External (environment)
    - Tidal/Ram-pressure (stripping of cold gas)
    - Strangulation (stripping of hot gas atmosphere)
    - Harassment (impulsive encounters with other satellites)
    - Halo shock heating

- **Environmental effects** may be crucial for quenching star formation activities in $\log(M*/M_{\odot}) < 10.0$ galaxies at $z < 0.7$
- For more **massive** galaxies, quenching does not show clear dependence on local galaxy environment (**mass** quenching).

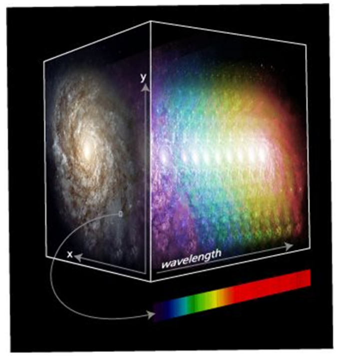
Pan et al. (2013, ApJ)

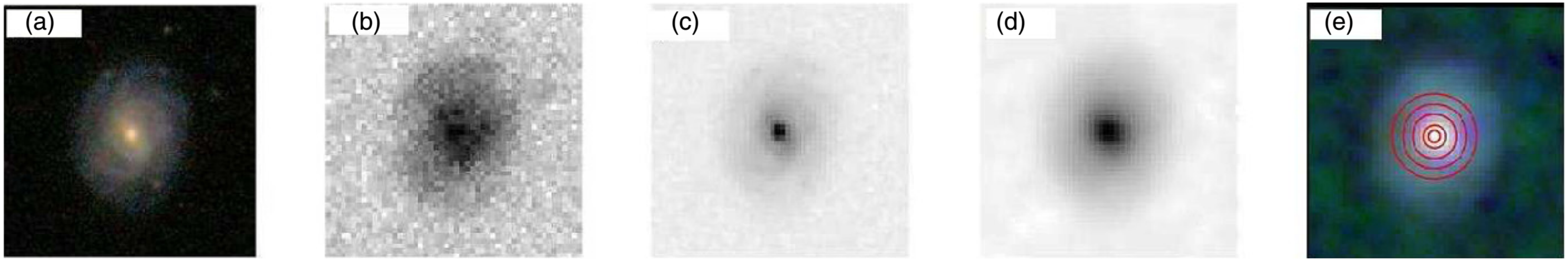


Major mergers/interaction between disk galaxies trigger AGNs (or starburst) and feedback

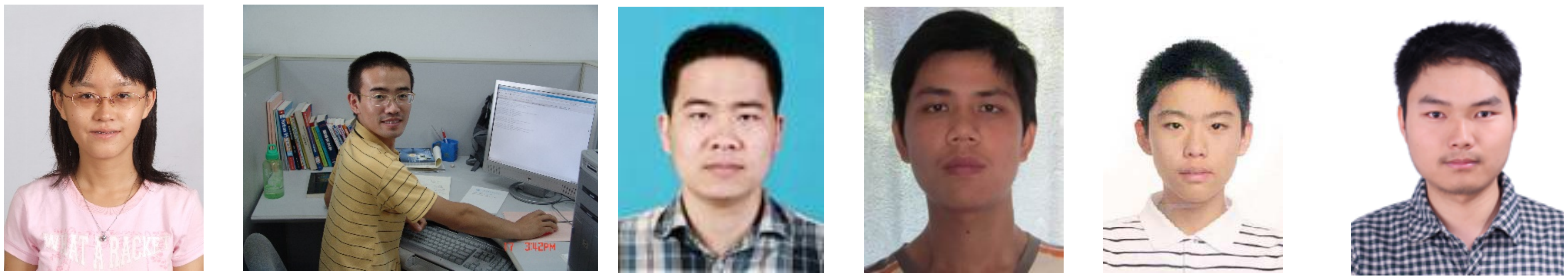
We are interesting …   How?

- **How fast** does the galaxy SFR have to decline to turn quiescent (SFH)?
- **How** galaxy mass **assembly mode** depends on stellar mass?

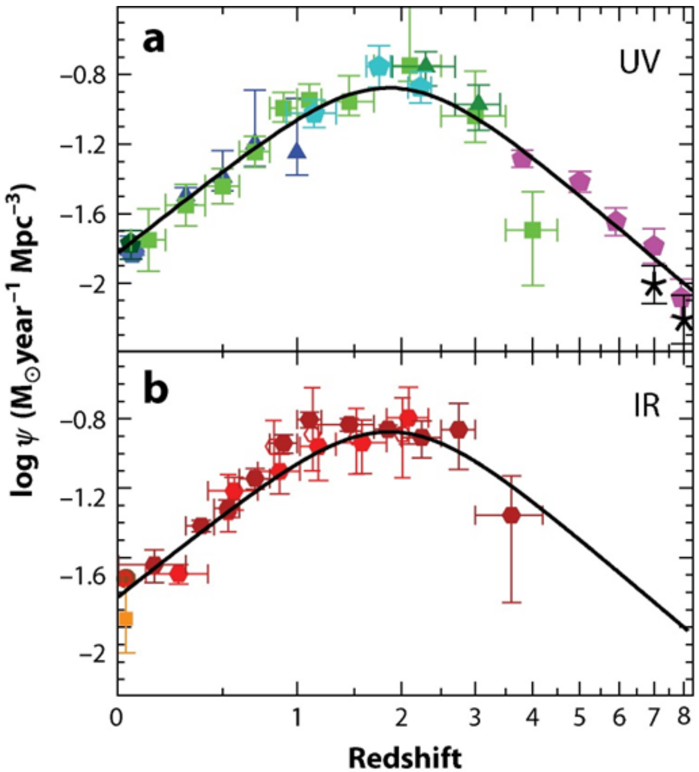


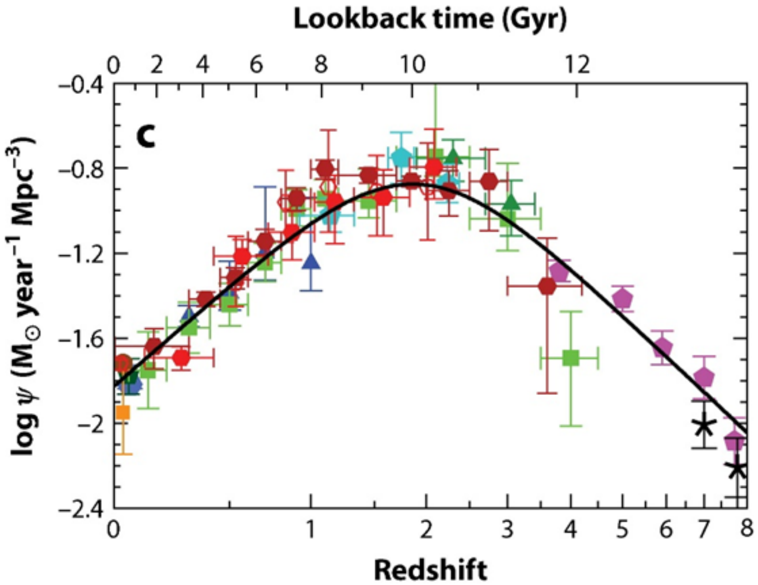


PSF-matched GALEX+SDSS images: a) SDSS gri color image; b) NUV image; (c) registered SDSS r-band image, interpolated to the GALEX resolution; (d) convolved with NUV PSF; (e) RGB color image, generated by NUV (blue), SDSS u band (green) and r band (red) PSF-matched images.



Cosmic SFH





Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

The average SFR in galaxies has been declining since z ~ 2: a fraction of galaxies quench and become quiescent.

- **To discern potential quenching mechanisms, it is critical to constrain quenching properties, such as quenching time scale and quenching rate by observations.**

How to constrain quenching time scale ?

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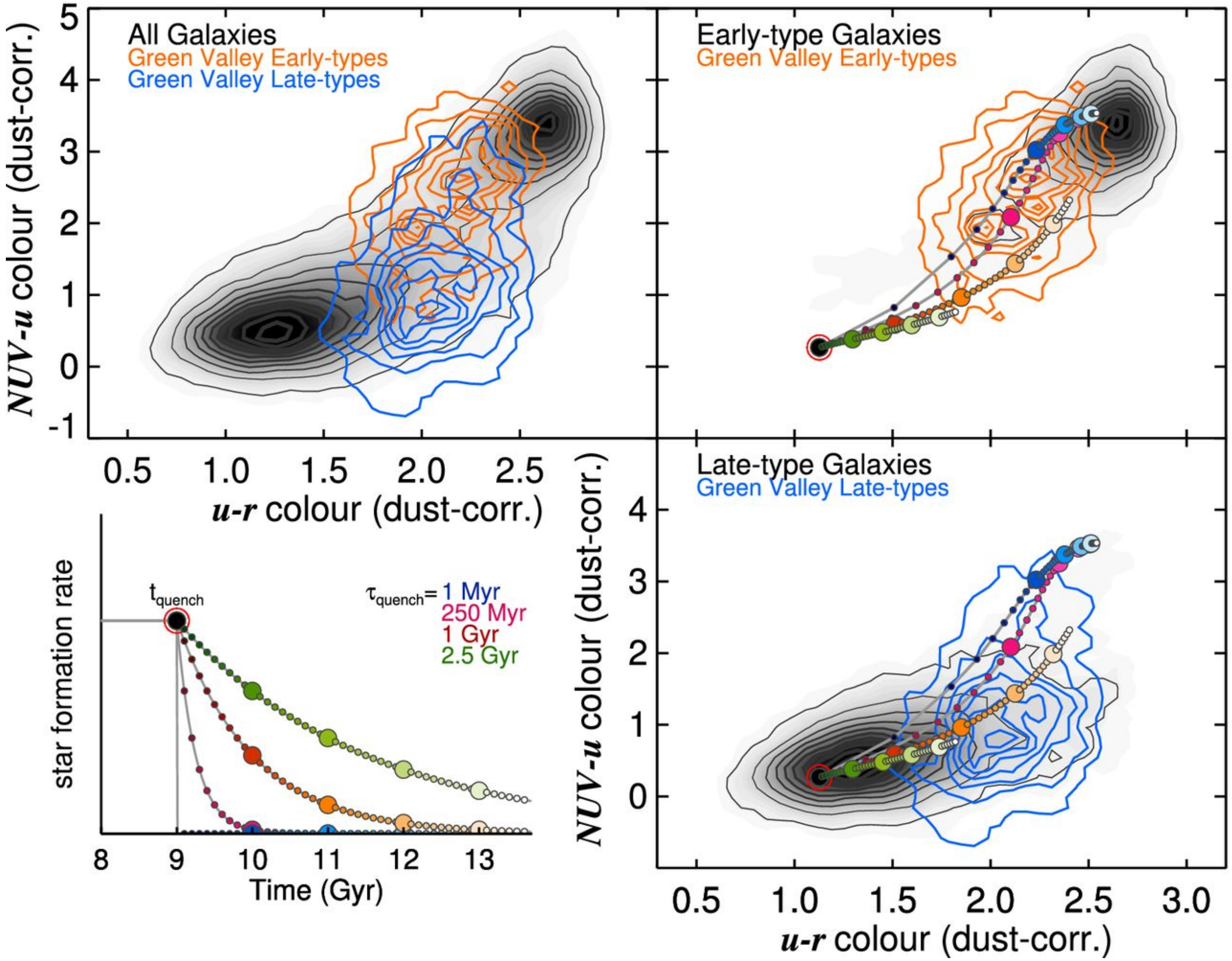
NUV-optical colors of green valleys in different morphology categories

- **Our work: constrain quenching time scale and quenching rate by revisiting NUV-optical color-color diagram without morphology classification**



- **Sample selection criteria: $0.02 < z < 0.05$, $M^* > 10^9 M_\odot$, $b/a > 0.7$**

NUV-u v.s. u-r color-color diagram (Schawinski et al. 2014)

Two-phase SFH

Lian et al. (2016, ApJ)

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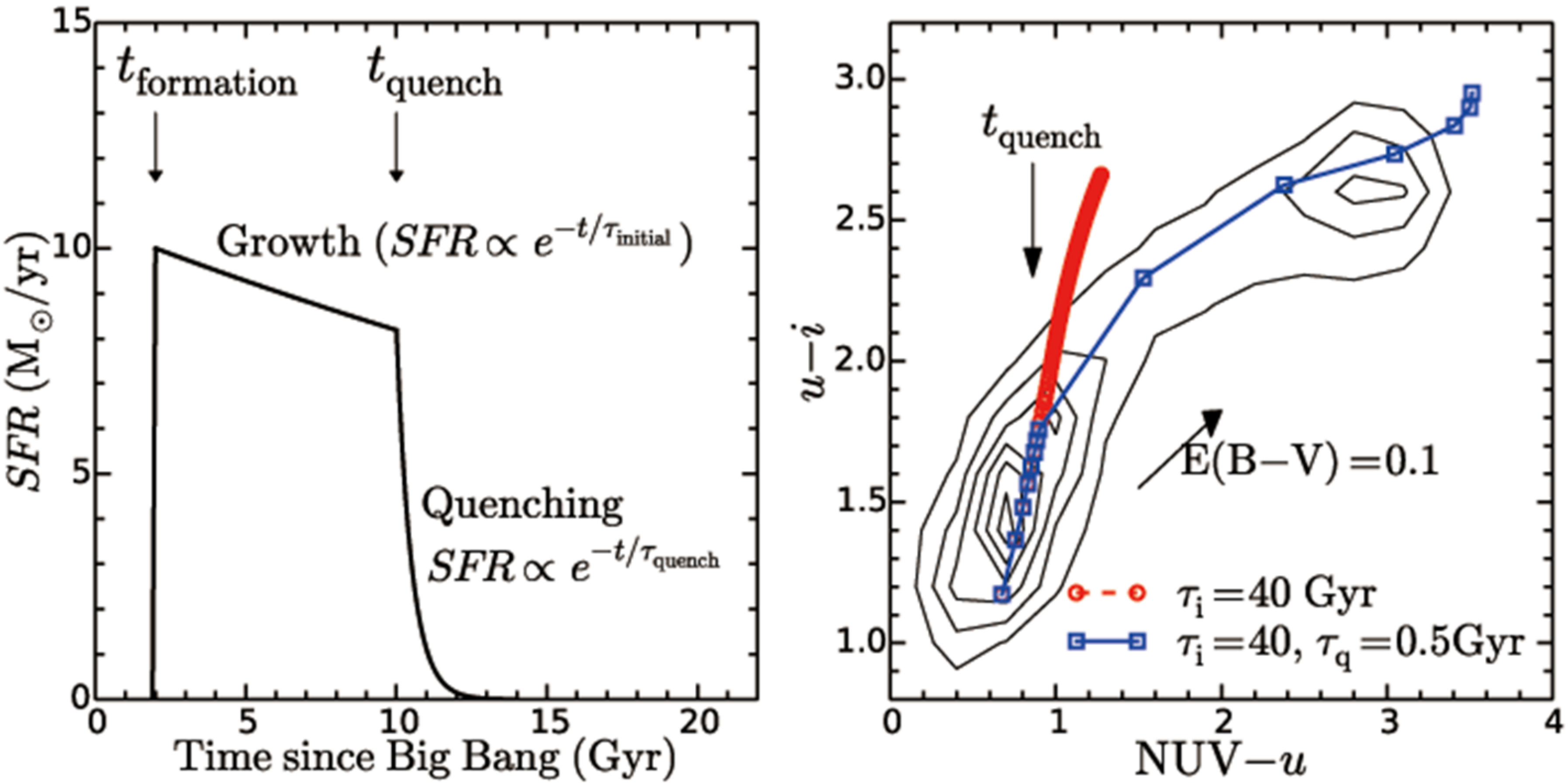
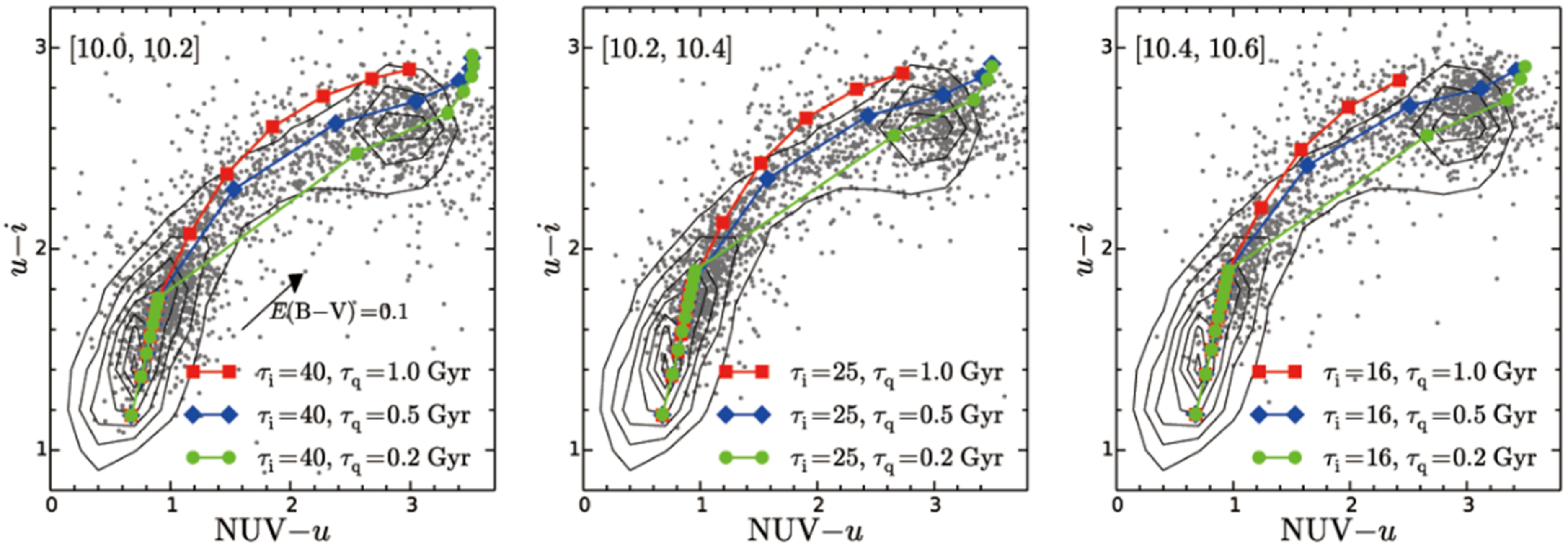


- Investigate both one-phase and two-phase ($\tau_{initial} + \tau_{quench}$) star formation histories (SFHs) based on stellar population synthesis models (BC03).
- Two-phase SFH supported by: curved distribution, non-flat density distribution (drop at NUV-u ~ 1.4)

Quenching time scale

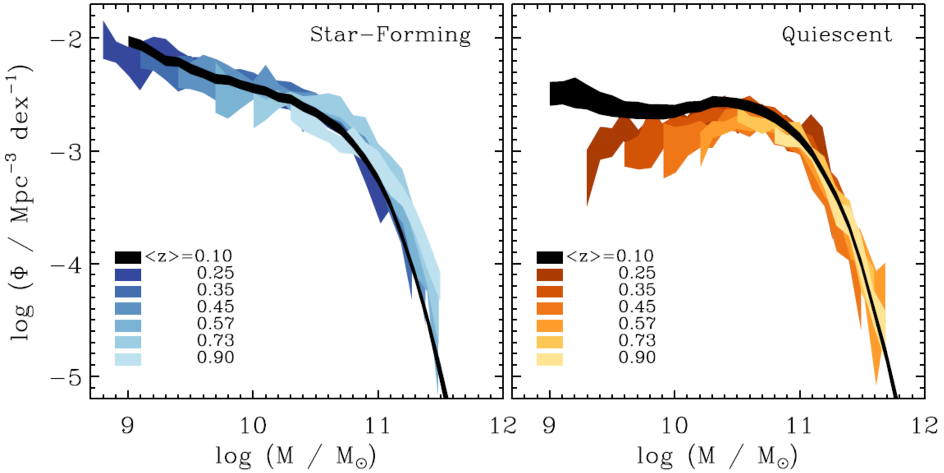


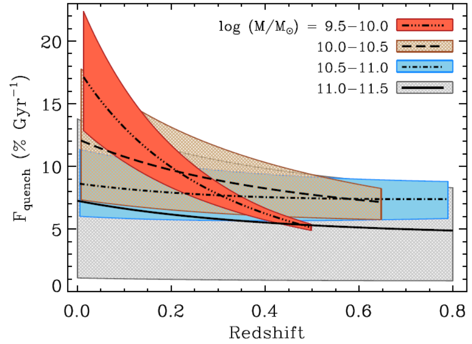
- **E-folding time of growth stage is taken from Noeske et al. (2007)**
- **Quenching time scale should be within [0.2, 1] Gyr.**
- **The model with τ_q = 0.5 Gyr best-fits the data.**

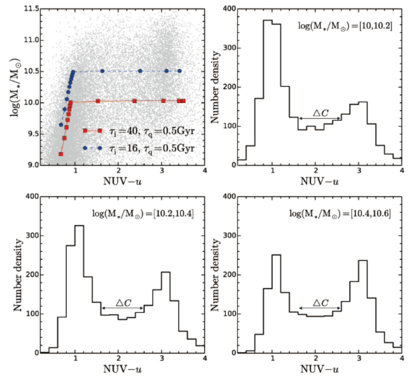
How to constrain the quenching rate ?

- **Mass function evolution v.s. number density profile**
  - **Strength**: insensitive to dust extinction and rejuvenated activity; quenching rate at different epoches
  - **Weakness**: limited by sample variance and observation accuracy at high redshift; subject to systematical errors when comparing two large surveys

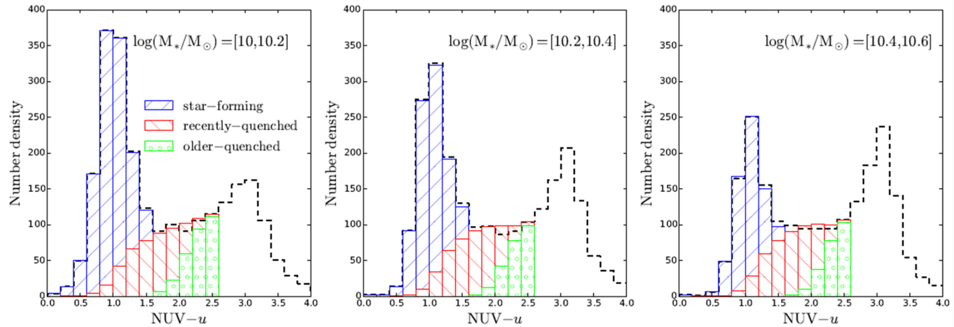
Moustakas et al. (2013)



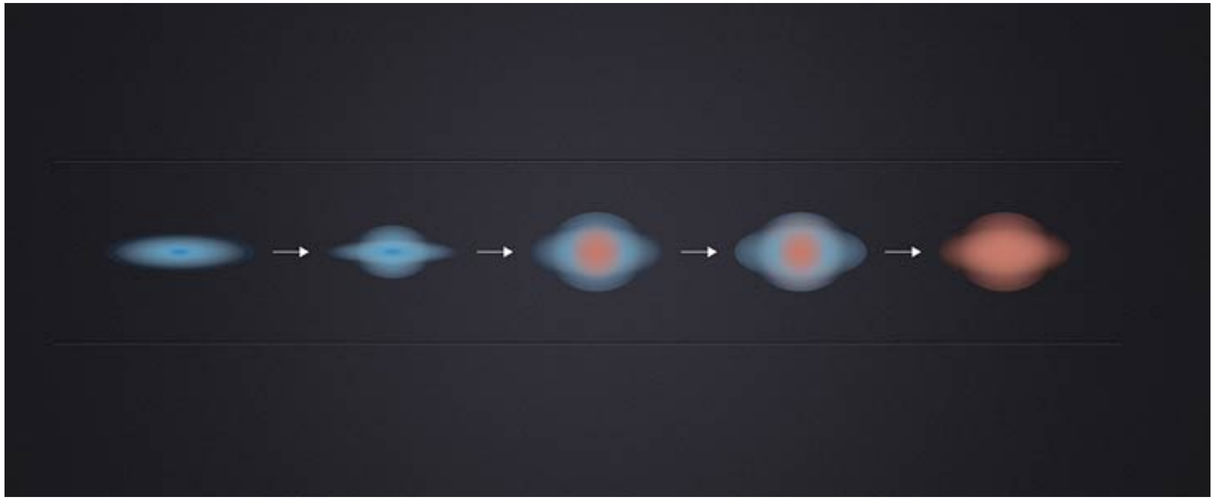


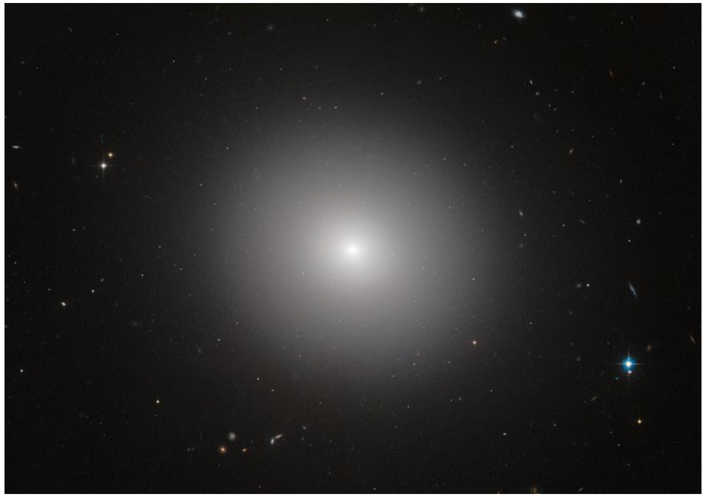


- **Quenching fraction: : iterative 5-step process or simple method**
  - **Quenching fraction**: 28% (28%), 35% (31%), and 45% (40%).
  - **Quenching rate** (τq = 0.5 Gyr): 19%/Gyr, 25%/Gyr, and 33%/Gyr.

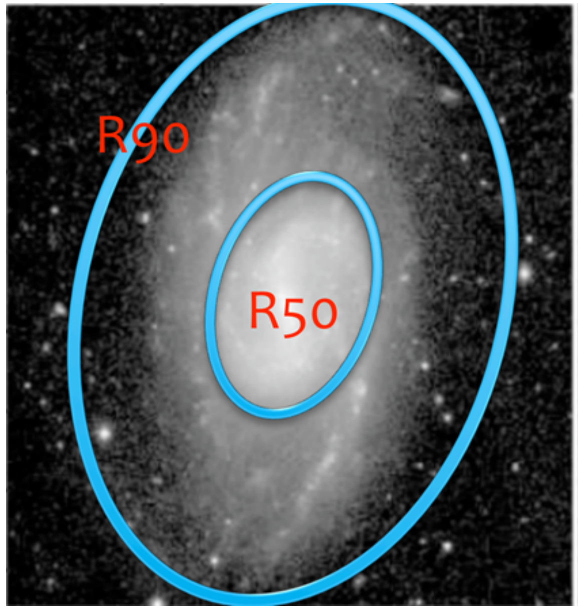


Galaxy Assembly Mode





- M*, is one of the most fundamental properties of galaxies.
- Assembly mode: inside-out or outside-in
  - Inside-out : galaxies still made stars on their outskirts, but no longer in their interiors.
  - Inside-out : the quenching of star formation seems to have started in the cores of the galaxies and then spread to the outer parts.



Mass assembly mode

Pan et al. (2015, ApJ)

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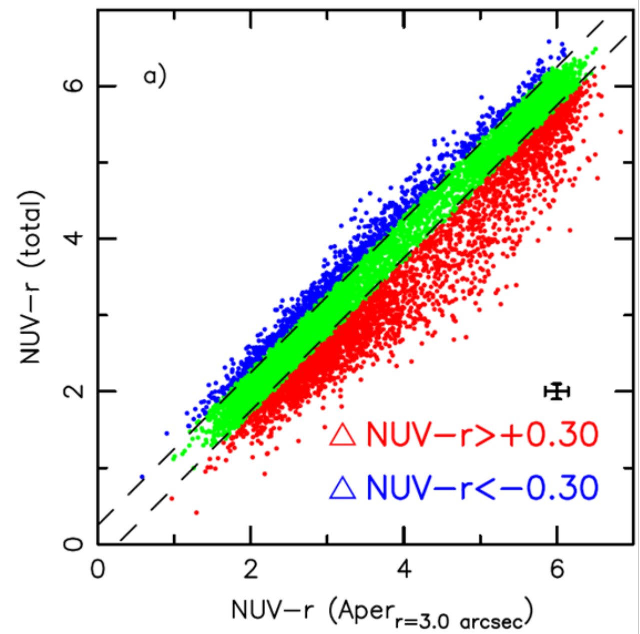
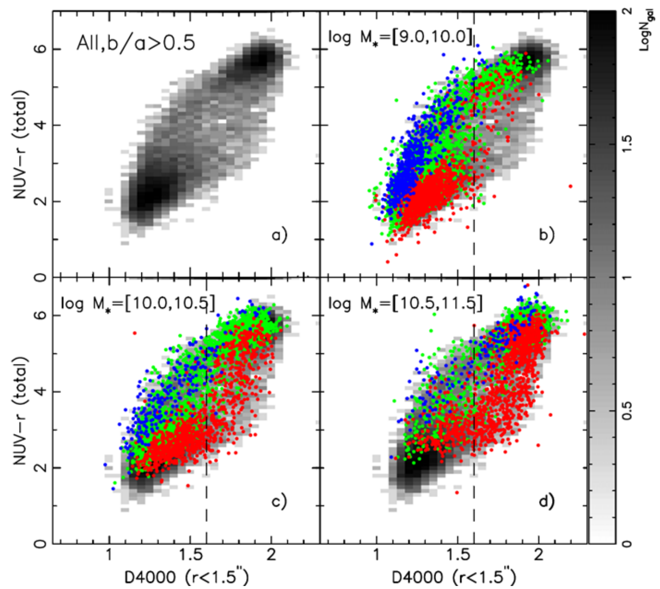
- **How galaxy mass assembly mode depends on stellar mass M*?**
- **~10,000 large ($R_{90} > 5.''0$), face on, low-redshift galaxies.**
- **Measures of both the integrated and the central NUV–r color indices, also D4n**
- **D4n > 1.6:**
  - **$M^* < 10^{10} M_\odot$ galaxies have moved to the UV red sequence**
  - **$M^* > 10^{10.5} M_\odot$: a large fraction of galaxies still lie on the UV blue cloud or the GV region.**
- **Main galaxy assembly mode is transiting from "outside-in" mode to "inside-out" mode at $M^* < 10^{10} M_\odot$ and at $M^* > 10^{10.5} M_\odot$.**



$$\Delta NUV-r = (NUV-r_{r=3''0})-(NUV-r_{total})$$



Gradients in oxygen abundance

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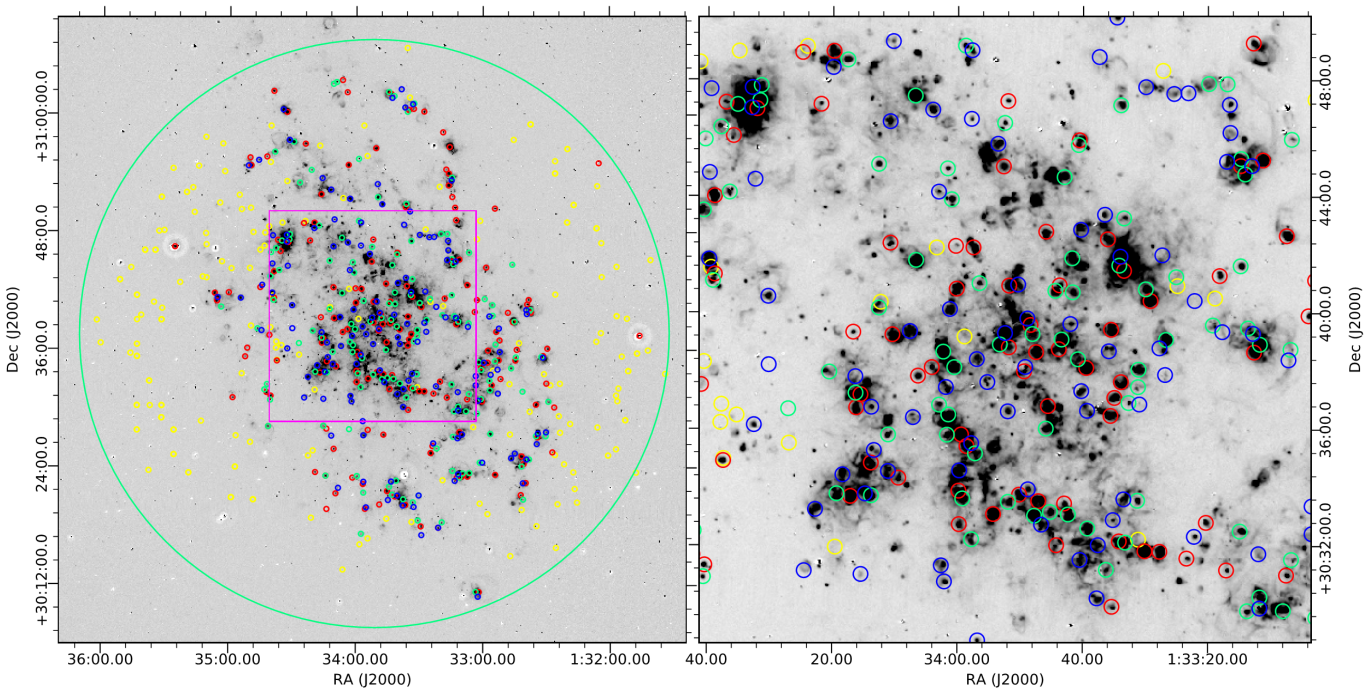
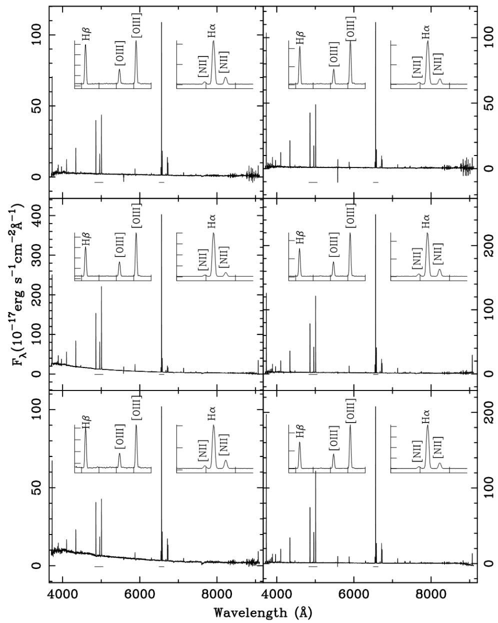
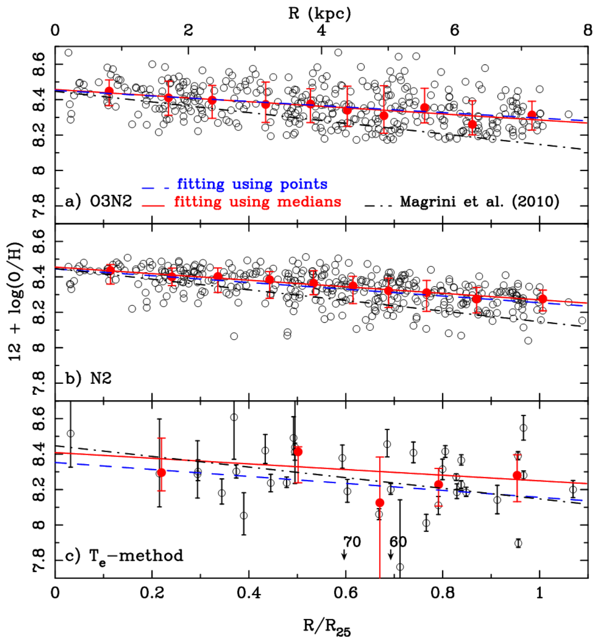




- Spectra of > 400 star-forming regions in M33 were observed by using Hectospec/MMT
- Physical parameters, such as electron temperatures, electron densities, and metallicities.
- Inside-out picture of galaxy formation is supported by the gradients in oxygen abundance of H II regions



Lin et al. (2017, ApJ)

12 galaxies @ P-MaNGA

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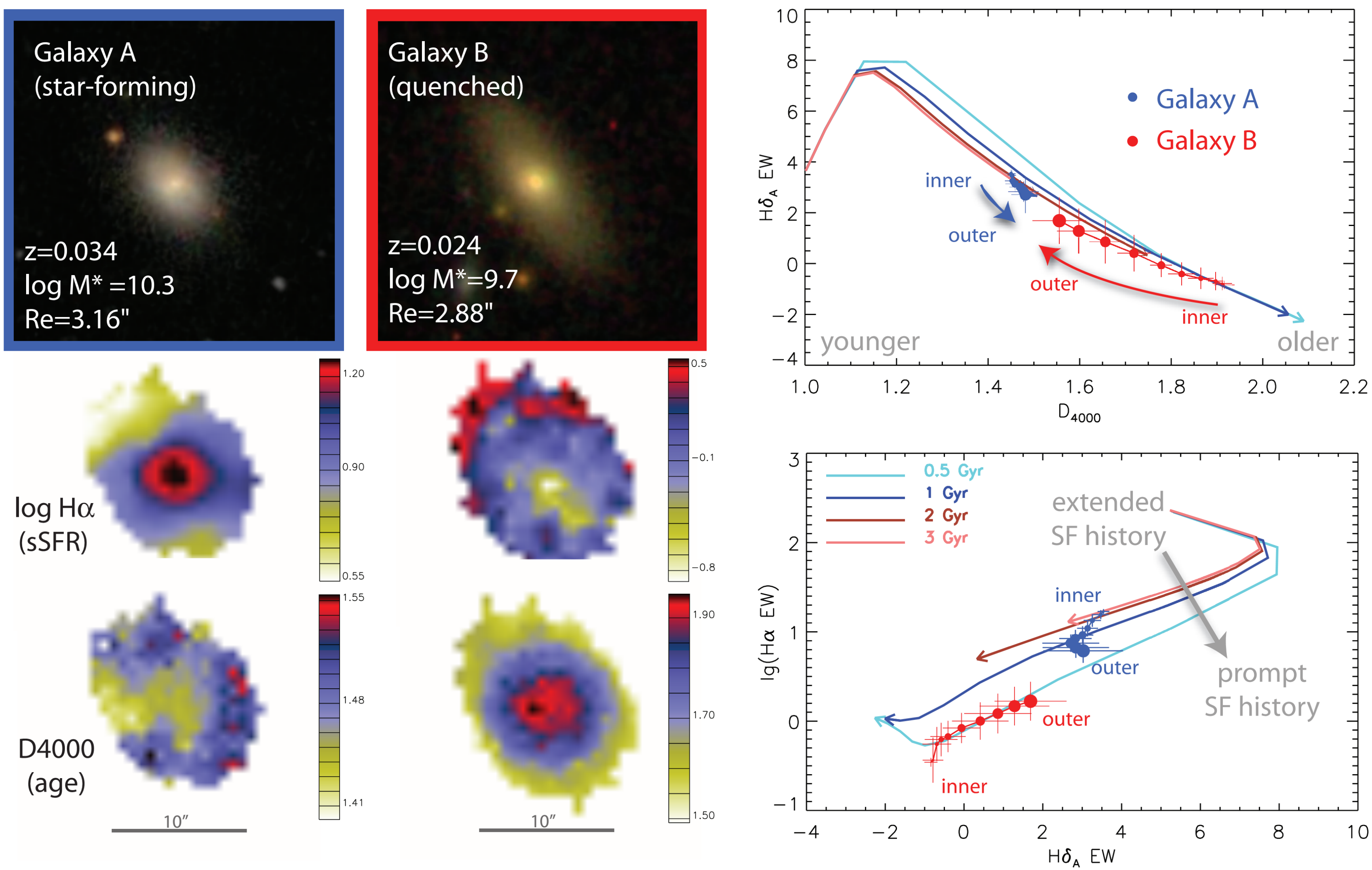

The cessation of star formation propagates from the center of a galaxy outward as it moves to the red sequence (inside-out mode): Li et al. (2015, ApJ)

Bulge

Pan et al. (2016, ApJ)

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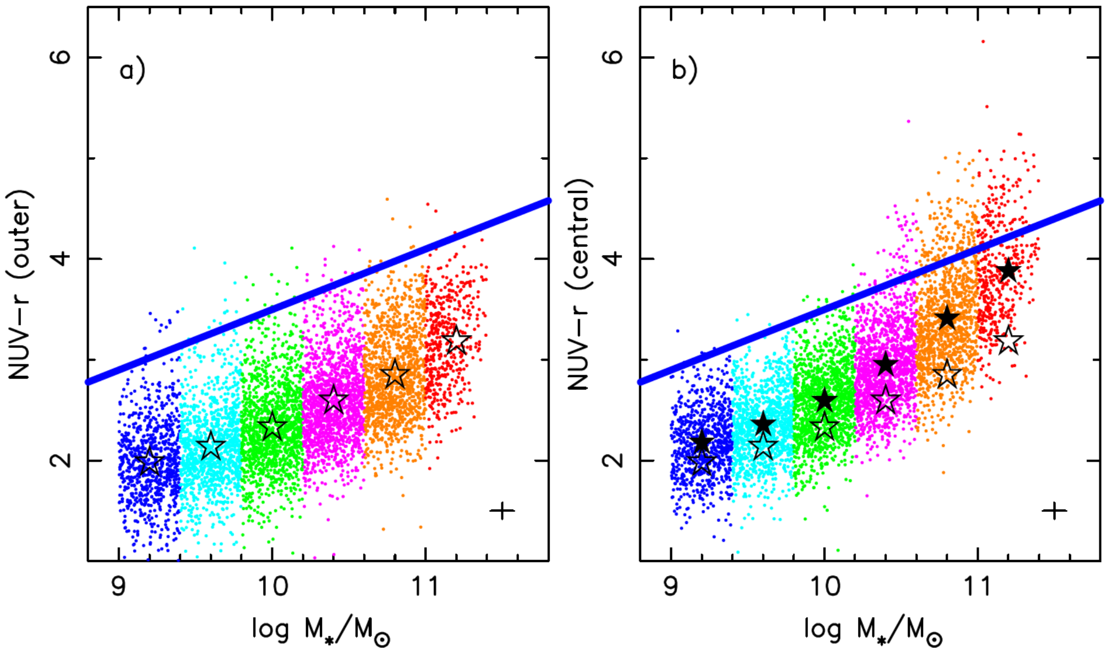
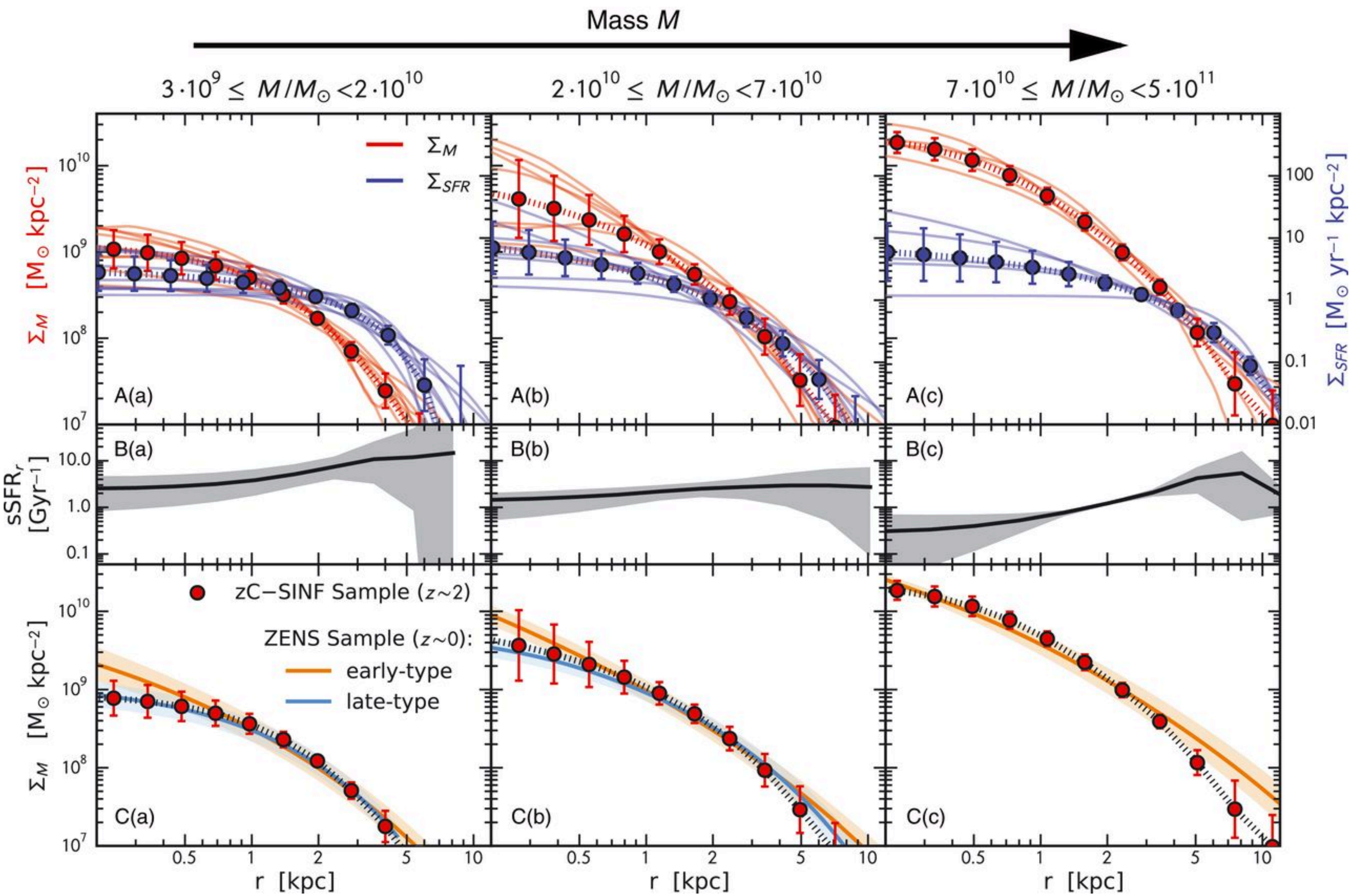
- To understand how the quenching of star formation is linked to **galaxy structure**.
- ~ 6000 local face-on SFGs: the NUV–r colors inside and outside R_{50} vs. stellar mass M*
- $M < 10^{10.2}$Msun : (NUV–r)c ~ (NUV-r)o
- $M > 10^{10.2}$Msun : the central NUV–r becomes **much redder** than the outer NUV–r



a) $(NUV\text{-}r)_{outer}$ as a function of M*.
b) similar to (a), but shown in $(NUV\text{-}r)_{central}$.
The large symbols denote the median NUV-*r* in that mass bin.

Galaxies with $M < 10^{10.2}$ Msun : exhibit **similar** star formation activity from the inner region to the $R > R_{50}$ region. In contrast, a considerable fraction of the $M > 10^{10.2}$Msun galaxies have a relatively **inactive (quenching) bulge** component.

A similar trend at z~2.2



Evidence for mature bulges and an inside-out quenching phase 3 billion years after the Big Bang

Tacchella et al. (Science 2015;348:314 317)

Quenching picture of massive galaxies

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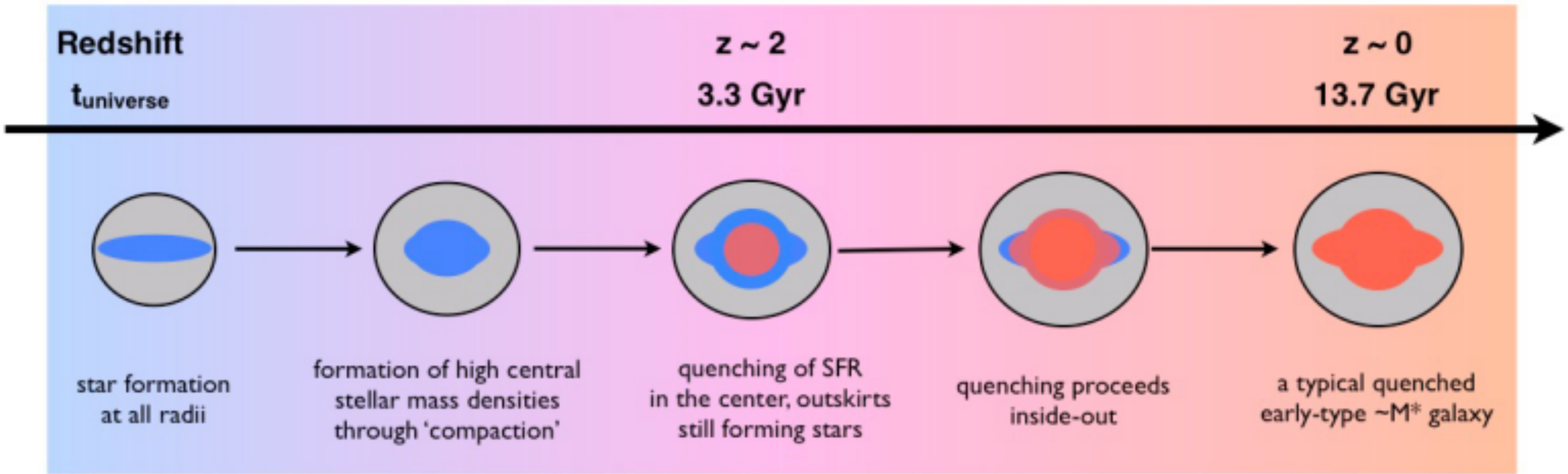
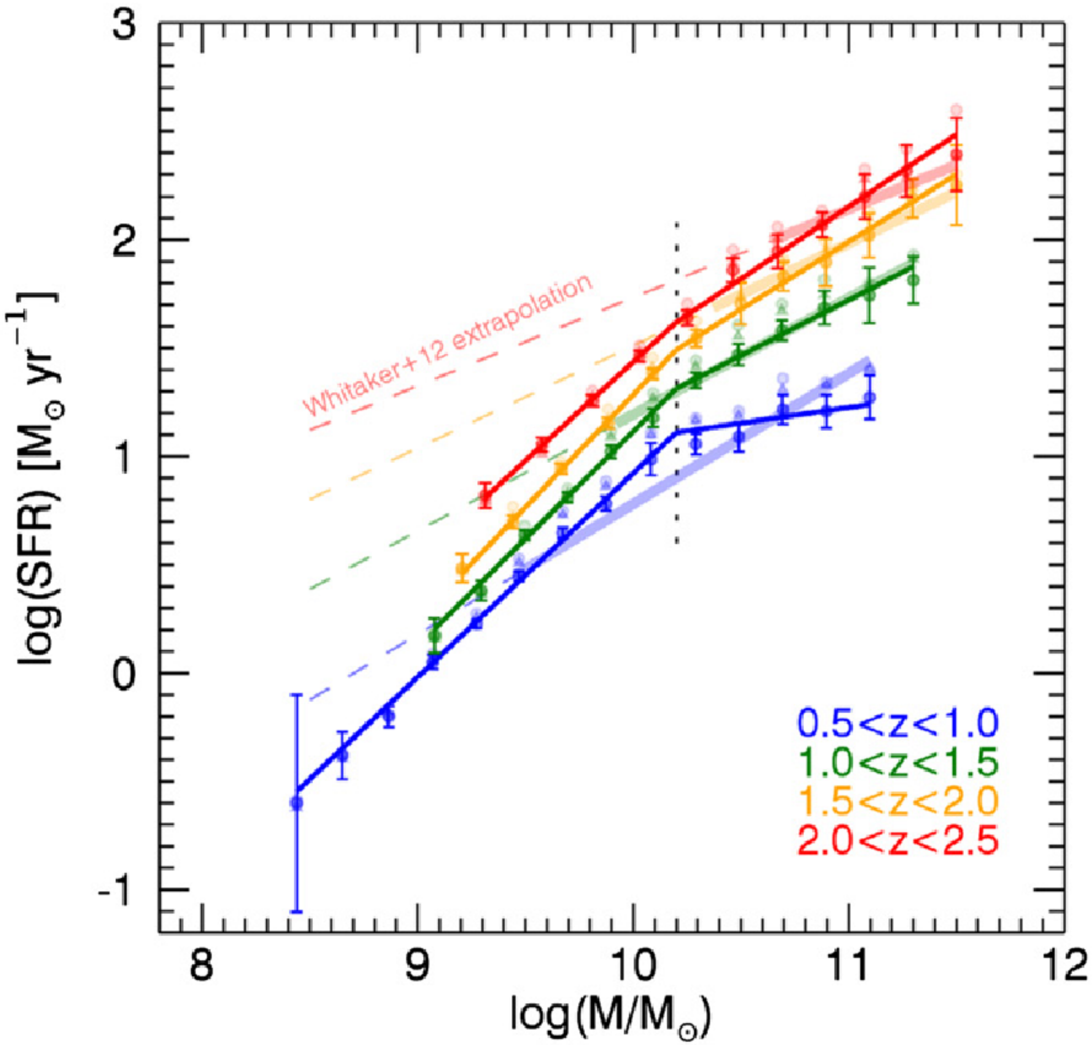


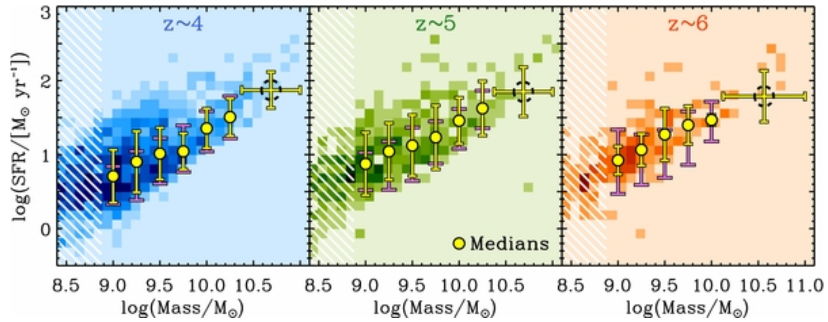
Fig. 4. Proposed sketch of the evolution of massive galaxies. Our results suggest a picture in which the total stellar mass and bulge mass grow synchronously in z~2 main sequence galaxies, and quenching is concurrent with their total masses and central densities approaching the highest values observed in massive spheroids in today's universe.

Tacchella et al. (2015, Science)

A considerable fraction of quenched mass is hidden in massive SFGs . The presence of old bulges in massive galaxies naturally explains the flattened slope of the SFR–M* relation seen at the massive end. How to quantify it ?

Turnover in MS





$$\log \Psi = a \left[\log \left(\frac{M_\star}{M_\odot} \right) - 10.2 \right] + b$$

The value of *a* is different above (~0.2-0.7) and below (~1.0) the characteristic mass (knee mass) of $M_K = 10^{10.2}$ Msun.

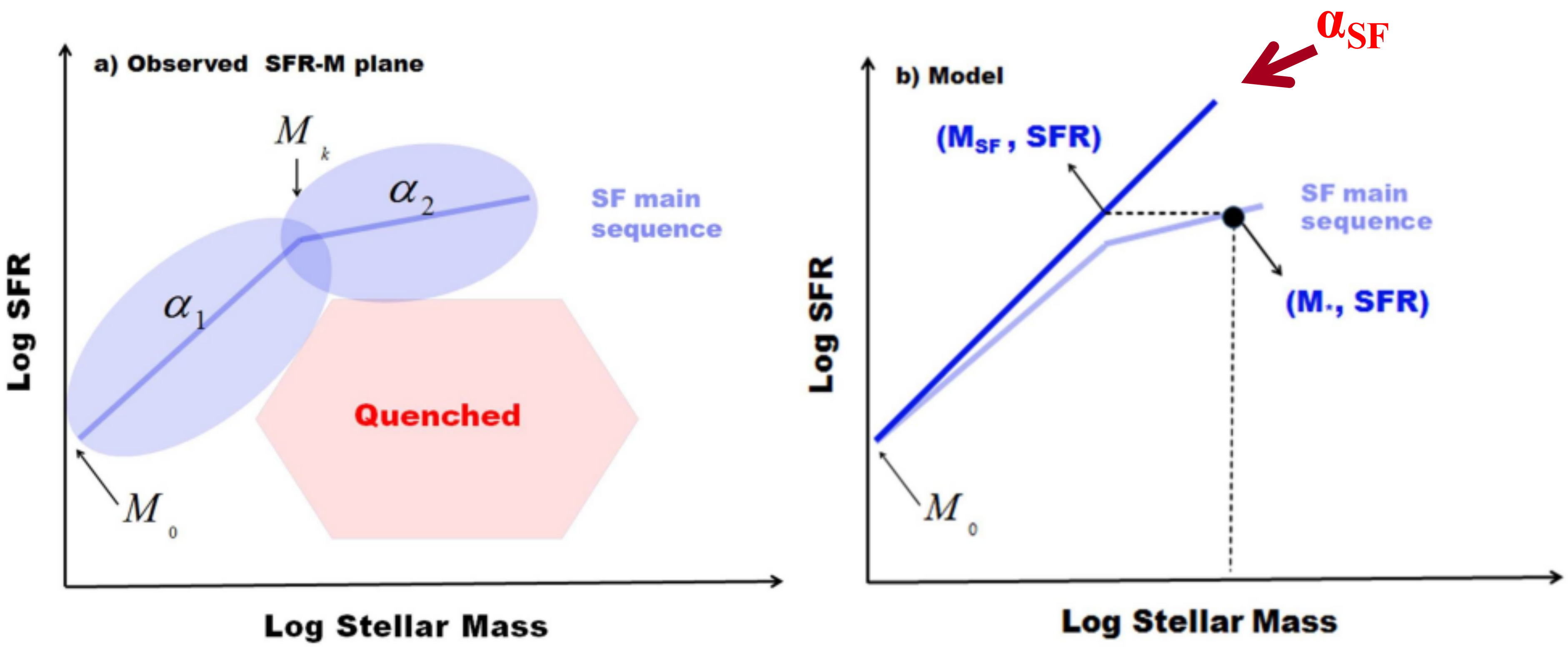
Whitaker et al. (2014): the slope of SFG MS is dependent on stellar mass, in a broken power-law form.

Why the star formation main sequence has a shallow slope at high masses?

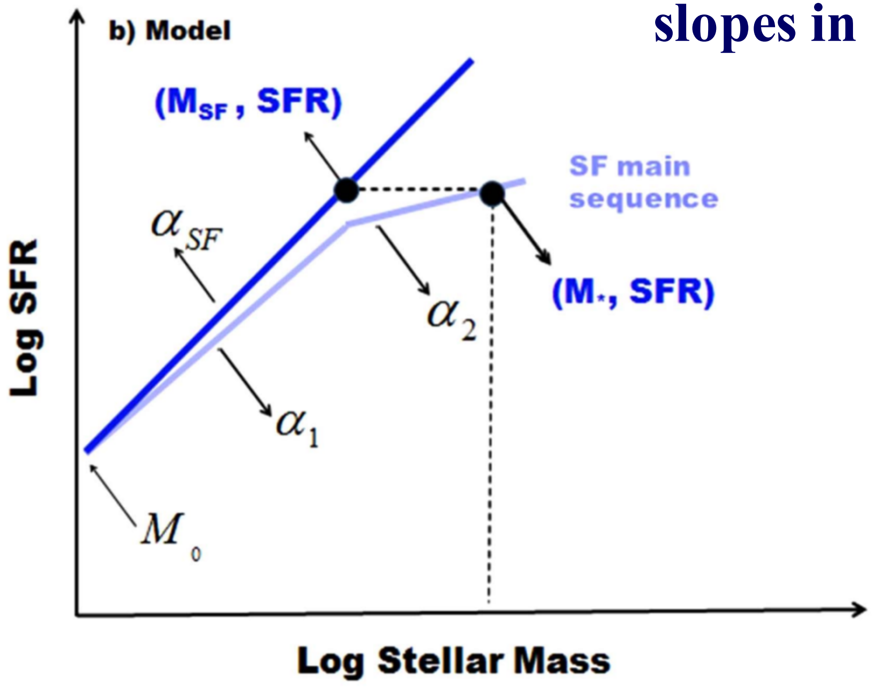
a massive disk galaxy can harbor a bulge (quiescent) component

Toy model

- Scientific goal: to quantify quenched mass portion of SFGs.
- The model: a SFG is composed by a star formation component + a quenched component, where the SF component always has $a_{SF} \sim a_1 \sim 1.0$.



Develop a toy model to reconcile the MS slopes in both the low- and the high-mass regimes.



$$\mathrm{SFR}(\mathrm{M}_*) = \begin{cases} C_1 M_*^{\alpha_1}, & M_* \leqslant M_k \\ C_2 M_*^{\alpha_2}, & M_* \geqslant M_k \end{cases} \quad (1)$$

$$\mathrm{SFR}(M_{\mathrm{SF}}) = C_{\mathrm{SF}} M_{\mathrm{SF}}^{\alpha_{\mathrm{SF}}}, \ \mathrm{SFR}(M_Q) = C_{\mathrm{Q}} M_{\mathrm{Q}}^{\alpha_{\mathrm{Q}}} \quad (2)$$

$$C_{\mathrm{Q}} \ll C_{\mathrm{SF}}. \quad M_{\mathrm{SF}} = f_{\mathrm{SF}} M_* \quad (3)$$

$$\mathrm{SFR}(M_*) \approx \mathrm{SFR}(M_{\mathrm{SF}}) = C_{\mathrm{SF}} f_{\mathrm{SF}}^{\alpha_{\mathrm{SF}}} M_*^{\alpha_{\mathrm{SF}}}. \quad (4)$$

Then at M_0

$$C_1 M_0^{\alpha_1} = C_{\mathrm{SF}} M_0^{\alpha_{\mathrm{SF}}}. \quad (5)$$

Similarly, at $M_* = M_{\mathrm{k}}$

$$C_1 M_{\mathrm{k}}^{\alpha_1} = C_2 M_{\mathrm{k}}^{\alpha_2}. \quad (6)$$

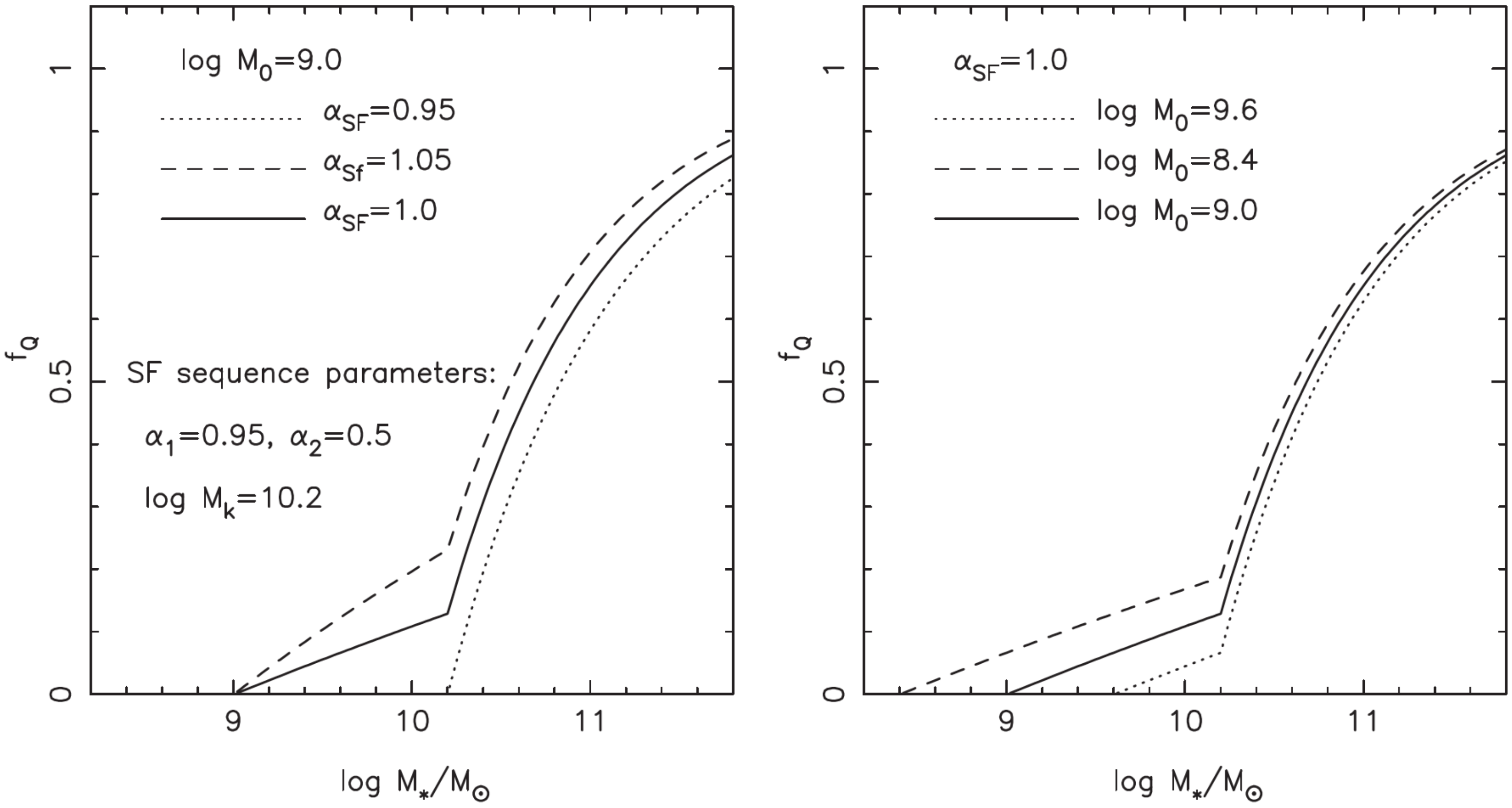
Combining Equations (1), (4), (5), and (6),

$$f_{\mathrm{SF}} = \begin{cases} \sqrt[\alpha_{\mathrm{SF}}]{M_0^{\alpha_{\mathrm{SF}}-\alpha_1} M_*^{\alpha_1-\alpha_{\mathrm{SF}}}}, & M_0 \leqslant M_* \leqslant M_k \\ \sqrt[\alpha_{\mathrm{SF}}]{M_0^{\alpha_{\mathrm{SF}}-\alpha_1} M_k^{\alpha_1-\alpha_2} M_*^{\alpha_2-\alpha_{\mathrm{SF}}}} & M_* \geqslant M_k \end{cases}. \quad (7)$$

The quenched mass portion f_{Q} is then easily derived as $f_{\mathrm{Q}} = 1 - f_{\mathrm{SF}}$.

α_1, α_2 and M_k can be determined from the MS

While only α_{SF} and M_0 are free parameters.



Left: dependence of the $f_Q - M_*$ relation on α_{SF}.

Right: dependence of the f_Q relation on M_0.

$M_* > M_k$: the f_Q–M_* relation is not very sensitive to both M_0 and α_{SF}, the f_Q estimation is robust at high masses as long as the MS parameters are well determined.

$M_* < M_k$: however, f_Q is strongly dependent on the choice of the free parameters, this method may be no longer valid in the low-mass regime.

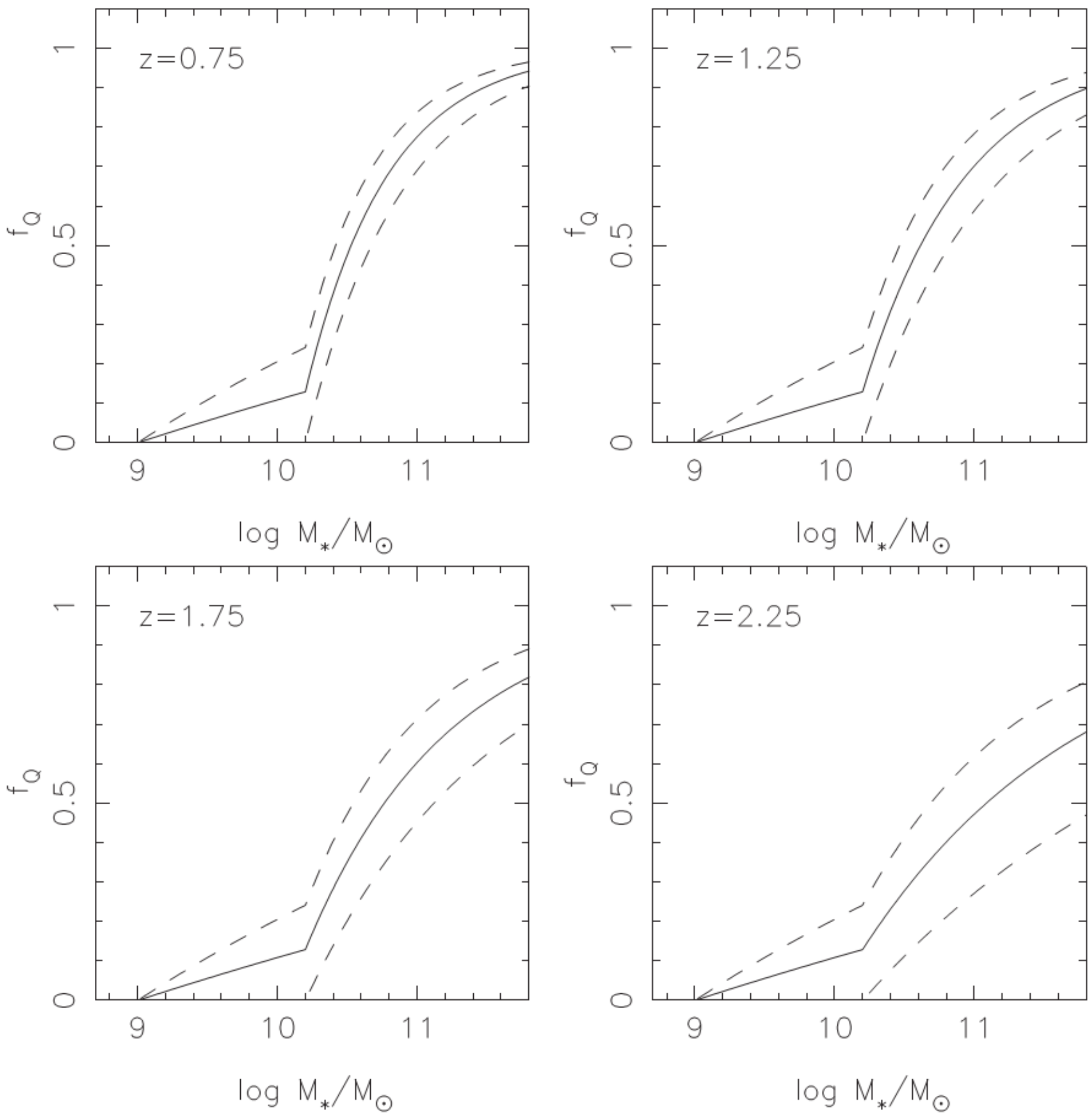
Evolution (z) of $f_Q - M_*$

Whitaker et al. (2014)

$$\alpha_1(z) = 0.95 \pm 0.05 + (0.02 \pm 0.04)z$$

$$\alpha_2(z) = 0.03 \pm 0.10 + (0.31 \pm 0.06)z.$$

- **The f_Q of a Milky Way like SFG (with $M^* \sim 10^{10.7}$Msun) is around 30% – 40% at z ~ 2.25, whereas it rapidly rises up to 70% – 80% at z ~ 0.75.**
- **The massive SFGs have been dominated by quenched mass since very high redshifts.**
- **Even at z = 2.25, the most massive SFGs have already contained a high fraction of quenched mass.**



Pan et al. (2017, ApJ)

Summary

- The distribution of galaxies in color-color diagram and the number density profile strongly support two-phase evolution scenario of galaxies, and the time scale of the quenching stage is within [0.2, 1] Gyr.

- The central regions of less massive SFGs are comparably active to the outer regions (outside-in). In contrast, the bulge of a portion of massive galaxies has been quenched (inside-out).

- The presence of old bulges in massive galaxies naturally explains the flattened slope of the SFR–M* relation seen at the massive end.

THANKs!