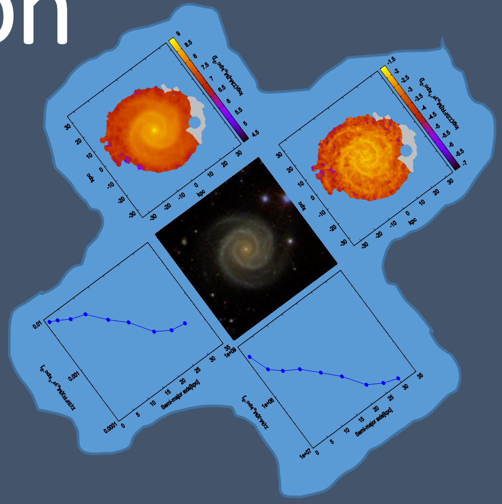
Spatially-resolved Star Formation Rate and Stellar Mass of Spiral Galaxies in the Local Universe : Quantifying the Inside-out Scenario of Disk Galaxies Formation



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Galaxy Evolution Workshop : June 2, 2016

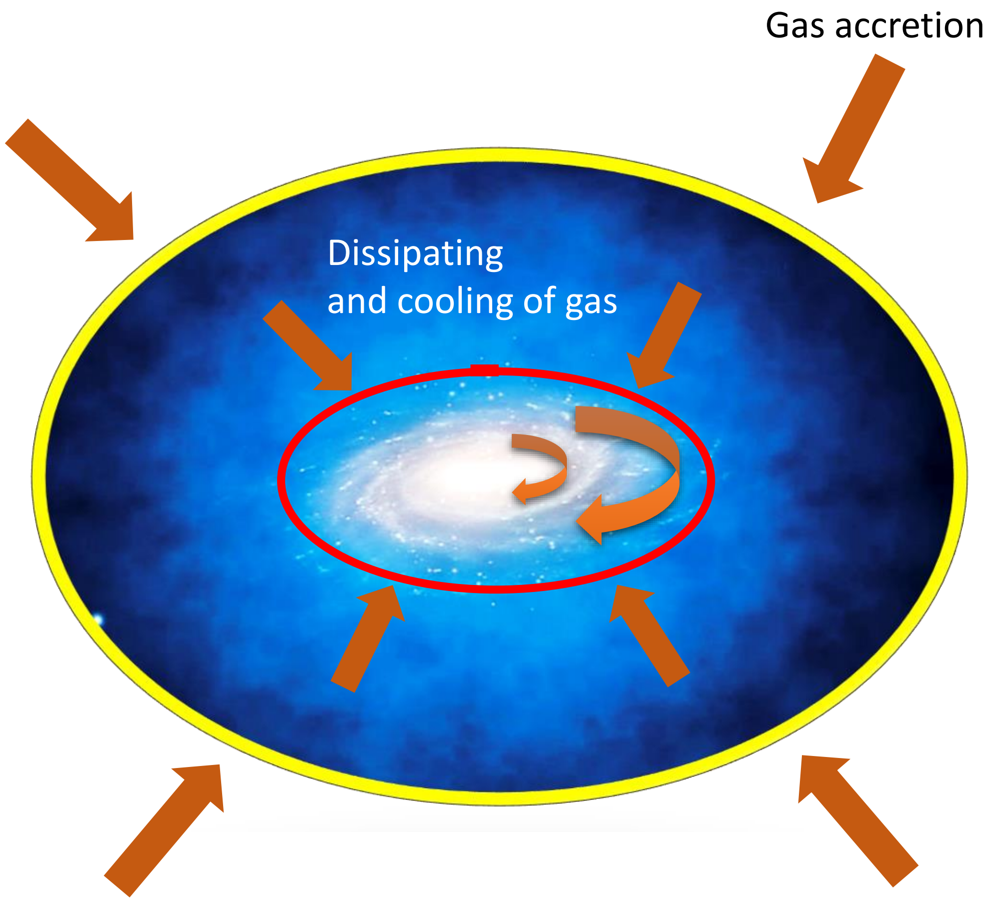
Outline

- Introduction
- Methodology
- Result & Discussion
- Conclusion

Model of Disk Assembly : Inside-out Scenario

- Galaxies assembled their disk by accreting gas from cosmic web through gas accretion to their host DMH
- The disk accretion rate is set by the rate at which the DMH accretes mass, and the rate of gas cooling
- The gas cools onto the disk and form stars with a radial distribution set by angular momentum distribution of the halo
- Gas accreted at later time and has high angular momentum will resides in the outer region of the disk

- This lead to the **"inside-out" scenario of disk assembly** (e.g. Kauffmann, 1996; Cole et al., 2000; van den Bosch, 2002; Dutton & van den Bosch, 2009)



(Mo, H., van den Bosch, F., White, S., 2010)

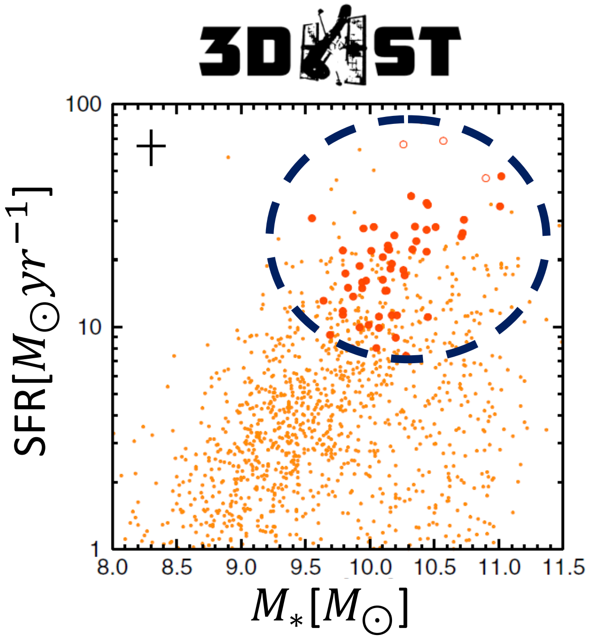
Testing the Inside-out Scenario of Disk Galaxy Formation

- The inside-out growth of disk galaxy should imprint some radially distributed properties (e.g. age, metallicity, stellar mass, and star formation activity)
- Inside-out disk galaxy assembly → SF activity is centrally concentrated in the past and gradually less concentrated/extended at later time
- Two parameters can be used as test for the scenario :
    - $\boldsymbol{M_*}$ **distribution** → past record of star formation activity distribution
    - **SFR distribution** → current distribution of star formation activity
- **Inside-out scenario → SFR distribution is going to be more extended than $\boldsymbol{M_*}$ distribution at later time**

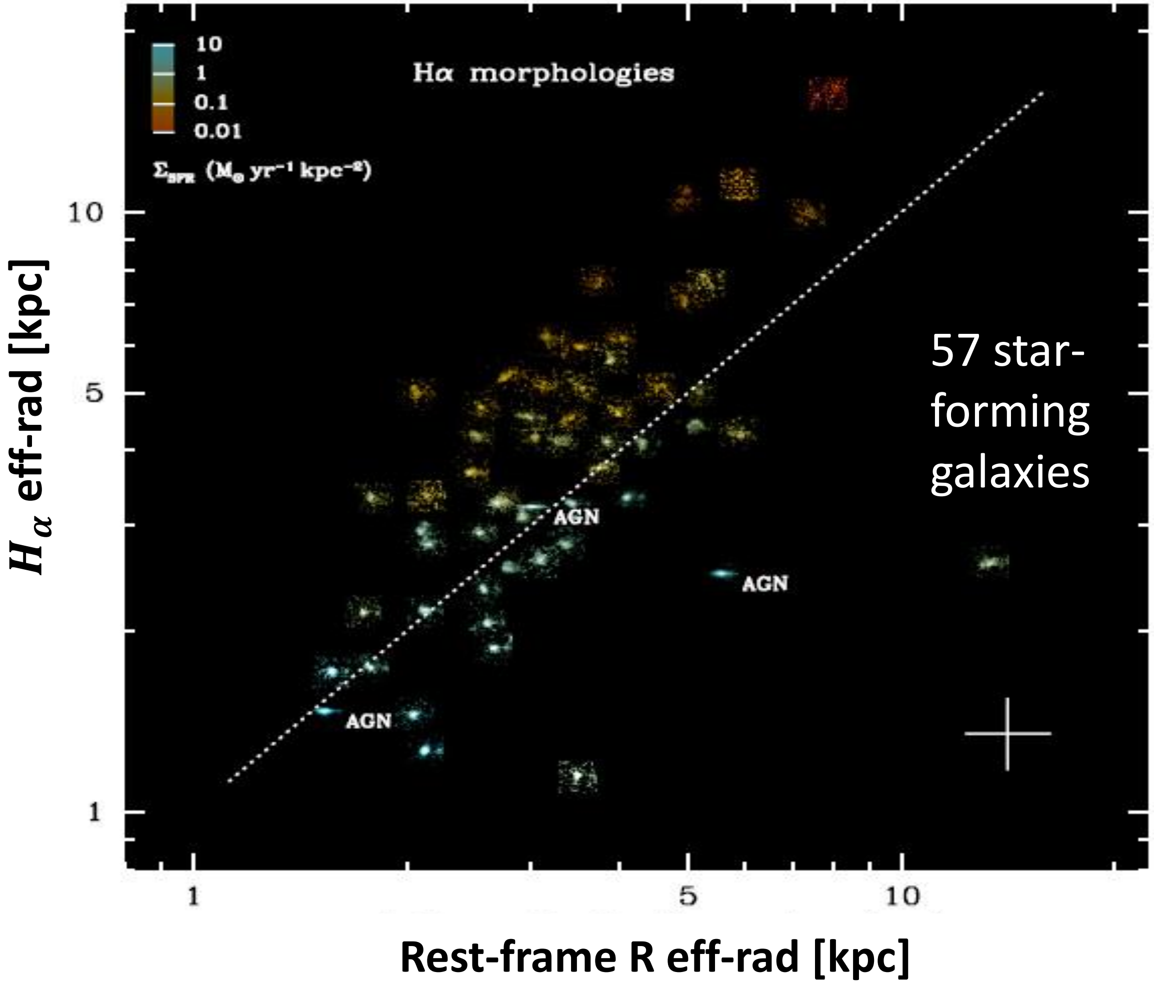
Observational Result at $z\sim1$: H_α Sizes vs Stellar Continuum Sizes

- H_α sizes generally track the F140W (rest-frame R band) sizes but with typically larger (~1.3 time)

(Nelson, E. J., et al. 2012, ApJ, 747, 28)



0.8 < z < 1.3



No dust-correction is applied in this result

Motivation : How SFR and M_* Distribution of Local Spiral Galaxies ?

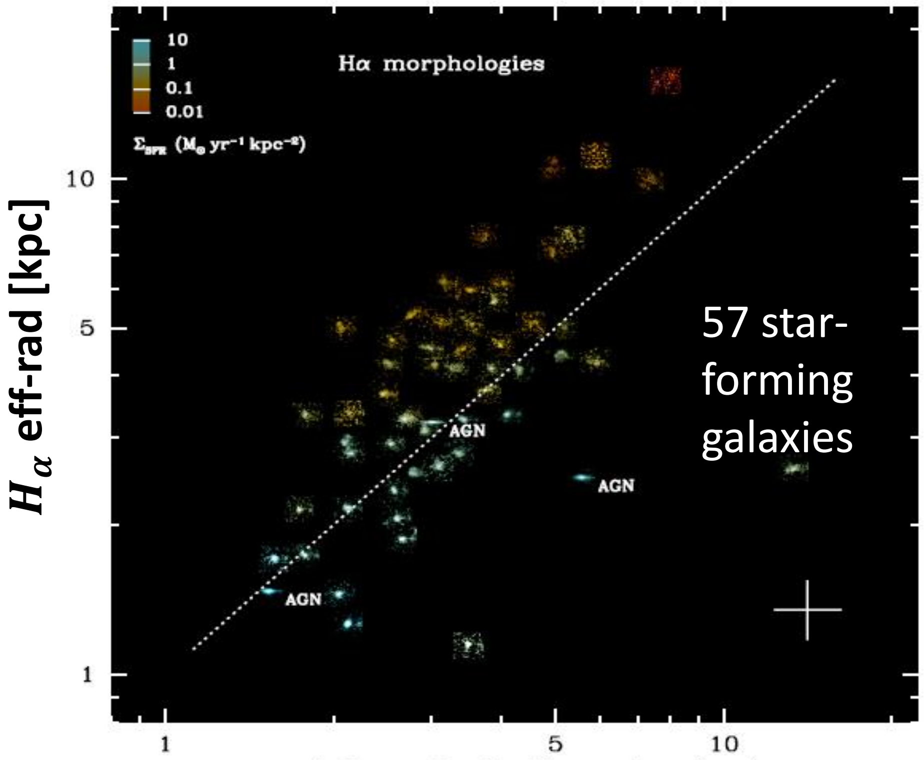
- Establishing method to resolve SFR and M_* in the galaxies→ pixel-to-pixel SED Fitting
- Massive local spiral galaxies might highly experienced inside-out growth in the past

- **Future work** : with currently established method and by mean of large number of photometric data, then calculating SFR and M_* distribution of large number of galaxies over large redshift range, to deeply study their evolution

Statistic is the key

How it looks like at z∼0 ?

$z \sim 1$



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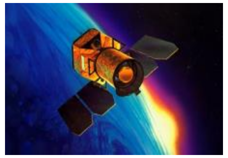
Data Sample

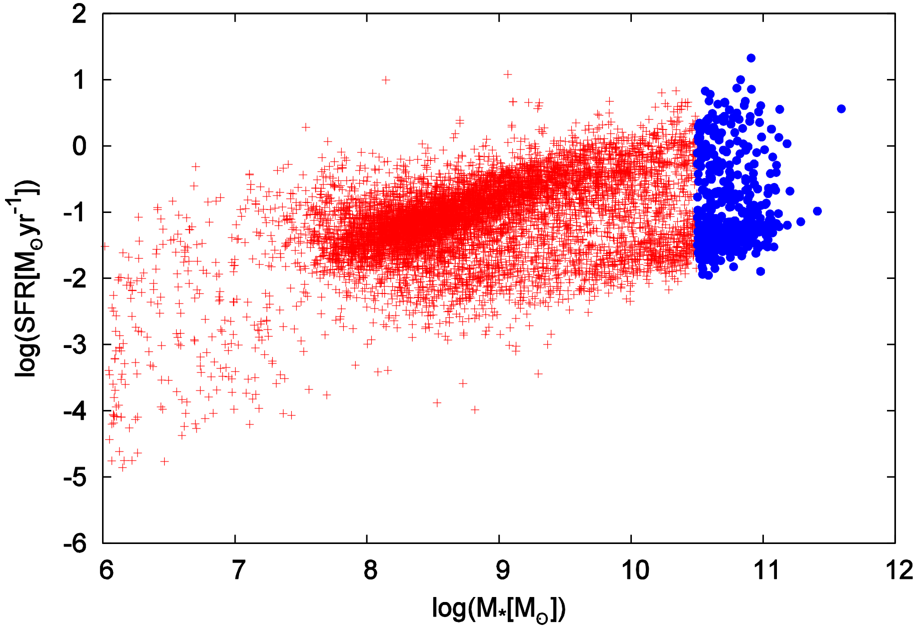
- We use data from **GALEX and SDSS** (7bands, $1344 \leq \lambda \leq 10000$ Å)
- Data sample : 118 relatively face-on **spiral galaxies**, located at **0.01<z<0.02**, more massive than $\log(M_*[M_\odot])$>10.5, with total S/N>10 in 7 bands

GALEX

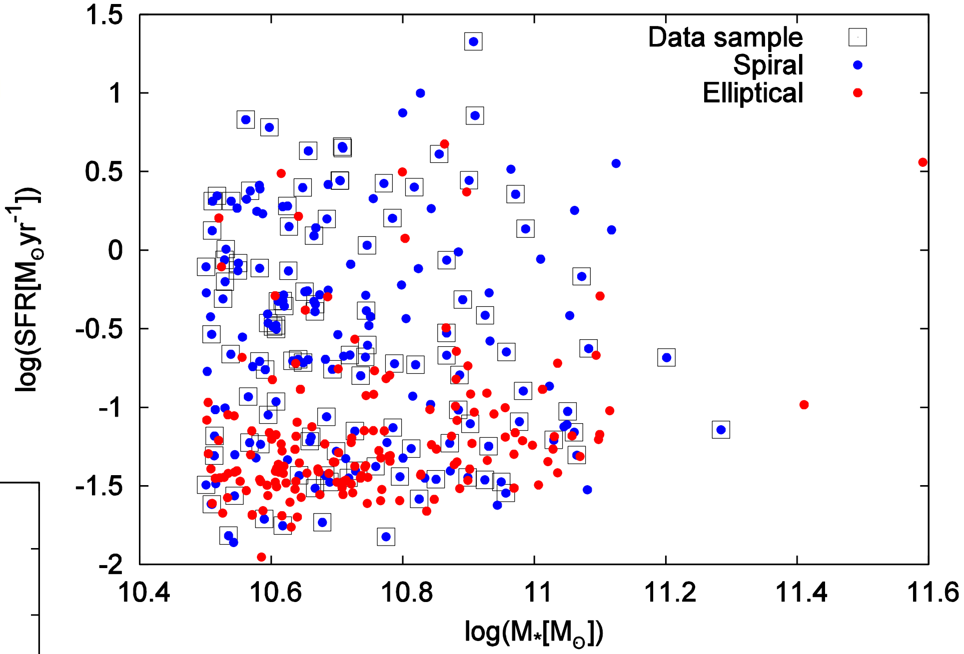


Edge-on Face-on

MPA/JHU Catalog for 0.01<z<0.02

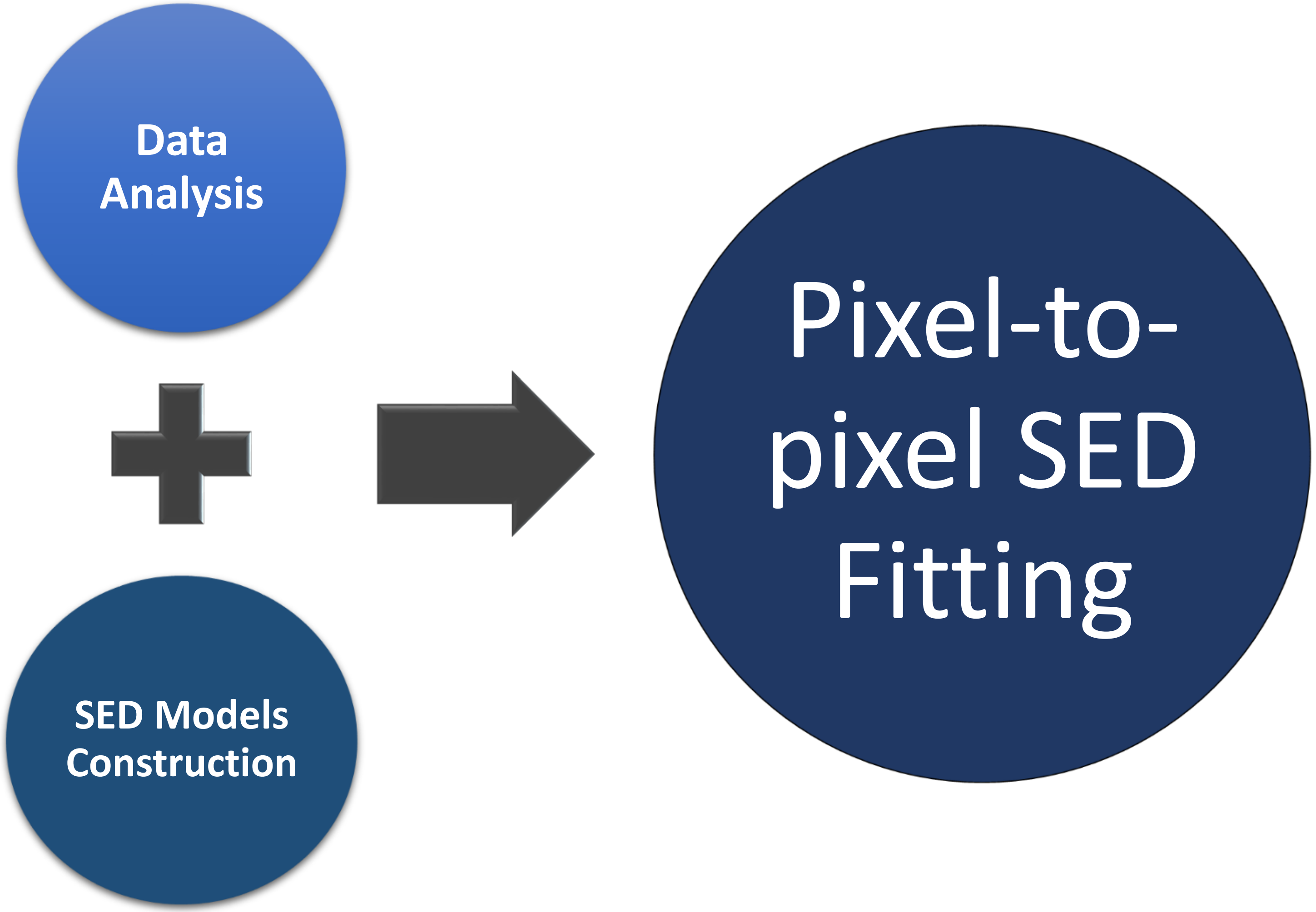


Galaxies at 0.01<z<0.02 with $\log(M_*[M_\odot])$>10.5

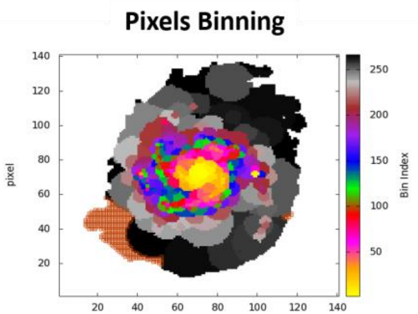


SDSS Galaxy Zoo's based Morphological Classification

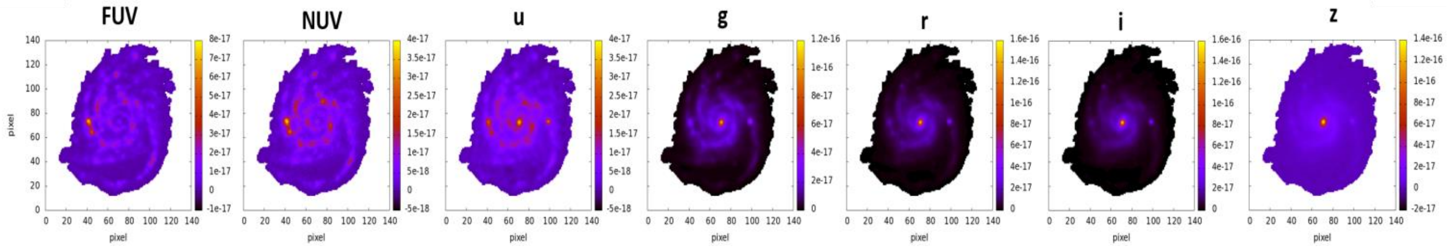
Methodology



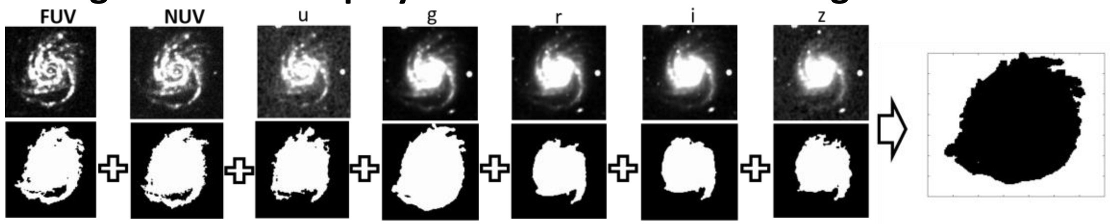
Methodology(1) : Data Analysis

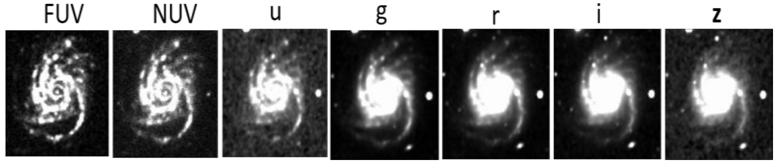


7 bands resolved photometric fluxes



7 segmentation map by SEXTRACTOR → summing





PSF Matching using convolution kernels created using PSFMATCH Iraf

New pixels binning method with 3 criteria : "closeness"; similarity of SED's shape; s/N

Pixels binning

Masking forground stars

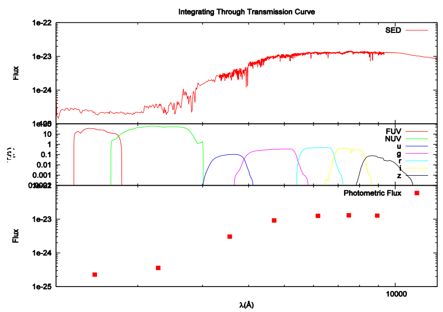
Get 7 bands fluxes and their uncertainties

Defining galaxy's region

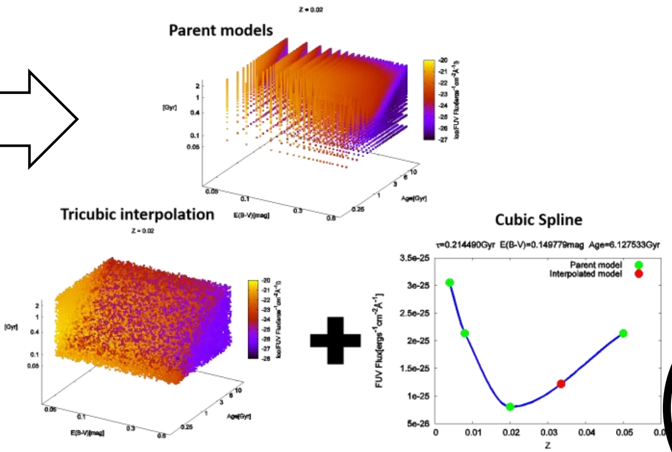
PSF Matching

Methodology(2) : SEDs Models Construction

$$f_{mod,i} = \frac{\int f_\lambda(\lambda)\lambda T_i(\lambda)d\lambda}{\int \lambda T_i(\lambda)d\lambda}$$

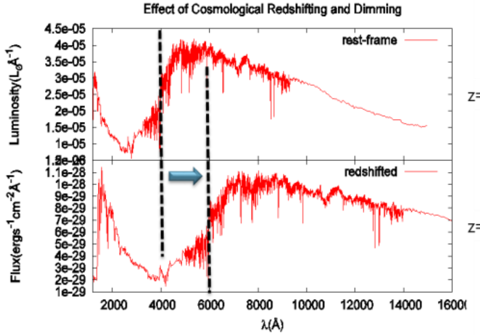


7 bands filtering



Model interpolation

Redshifting



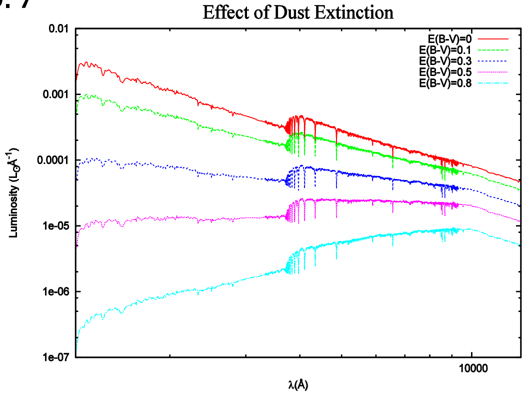
$$F_\lambda(\lambda_e(1+z)) = \frac{L_\lambda(\lambda_e)}{4\pi {d_L}^2(1+z)}$$

$H_0 = 70\text{kms}^{-1}\text{Mpc}^{-1}$

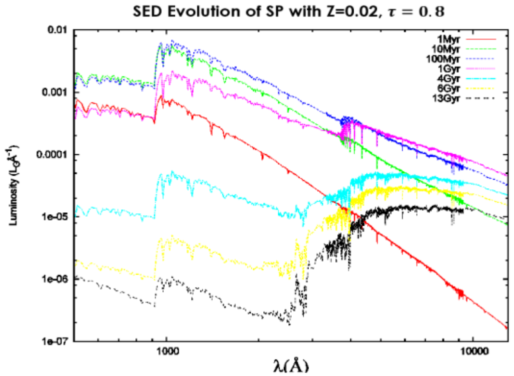
$\Omega_m = 0.3$

$\Omega_\Lambda = 0.7$

Calzetti 2000



GALAXEV



Random 4 parameters (Z,τ,E(B-V),age)

Interpolate models for random parameters

Number of generated random models : 200000

Integrating through filter transmission curves

Number of parent models : 193600

Cosmological redshifting

Reddening by dust using Calzetti 2000

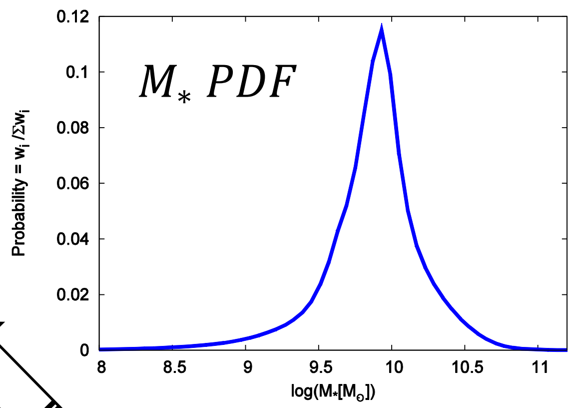
Rest-frame spectral models using GALAXEV (Bruzual & Charlot 2003)

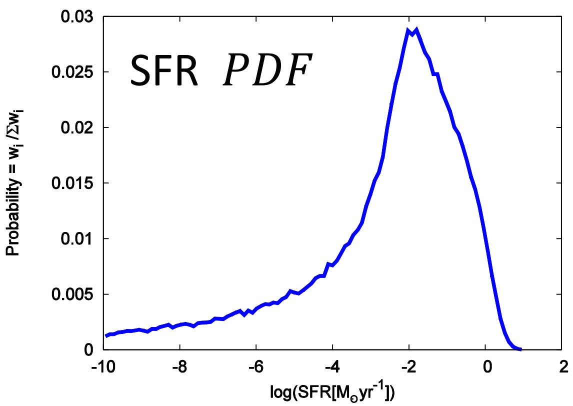
Methodology(3) : Pixel-to-Pixel SED Fitting

Posterior mean :

$$\bar{\theta} = \int \theta \, P(\theta | X) d\theta$$

with θ : $SFR \ and \ M_*$





$$M_* = Model's \ stellar \ mass \ \times s$$

$$SFR = \frac{M_*}{(1-\exp(-age/\tau))} \times \frac{\exp(-age/\tau)}{\tau}$$

weight of model :

$$w_i = 1/{\chi_i}^2$$

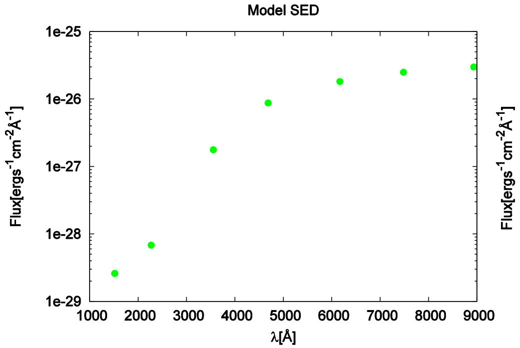
Probability of model :

$$P(\theta|X) = \frac{w_i}{\sum_i^N w_i} \quad N = 200000 \text{ models}$$

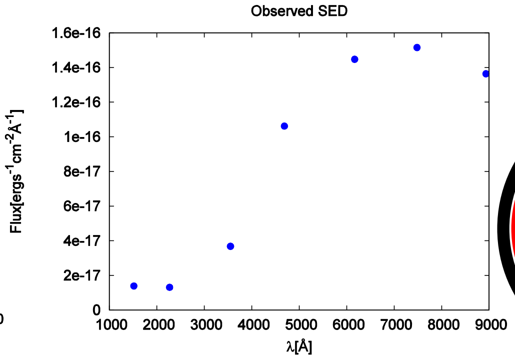
$${\chi_i}^2 = \sum_i \left(\frac{f_{d,i} - s f_{m,i}}{\sigma_i}\right)^2$$

with normalization (s), random-uniform around :

$$s_{least} = \frac{\sum_i \frac{f_{d,i} f_{m,i}}{\sigma_i^2}}{\sum_i \frac{f_{m,i}^2}{\sigma_i^2}}$$



Model SED

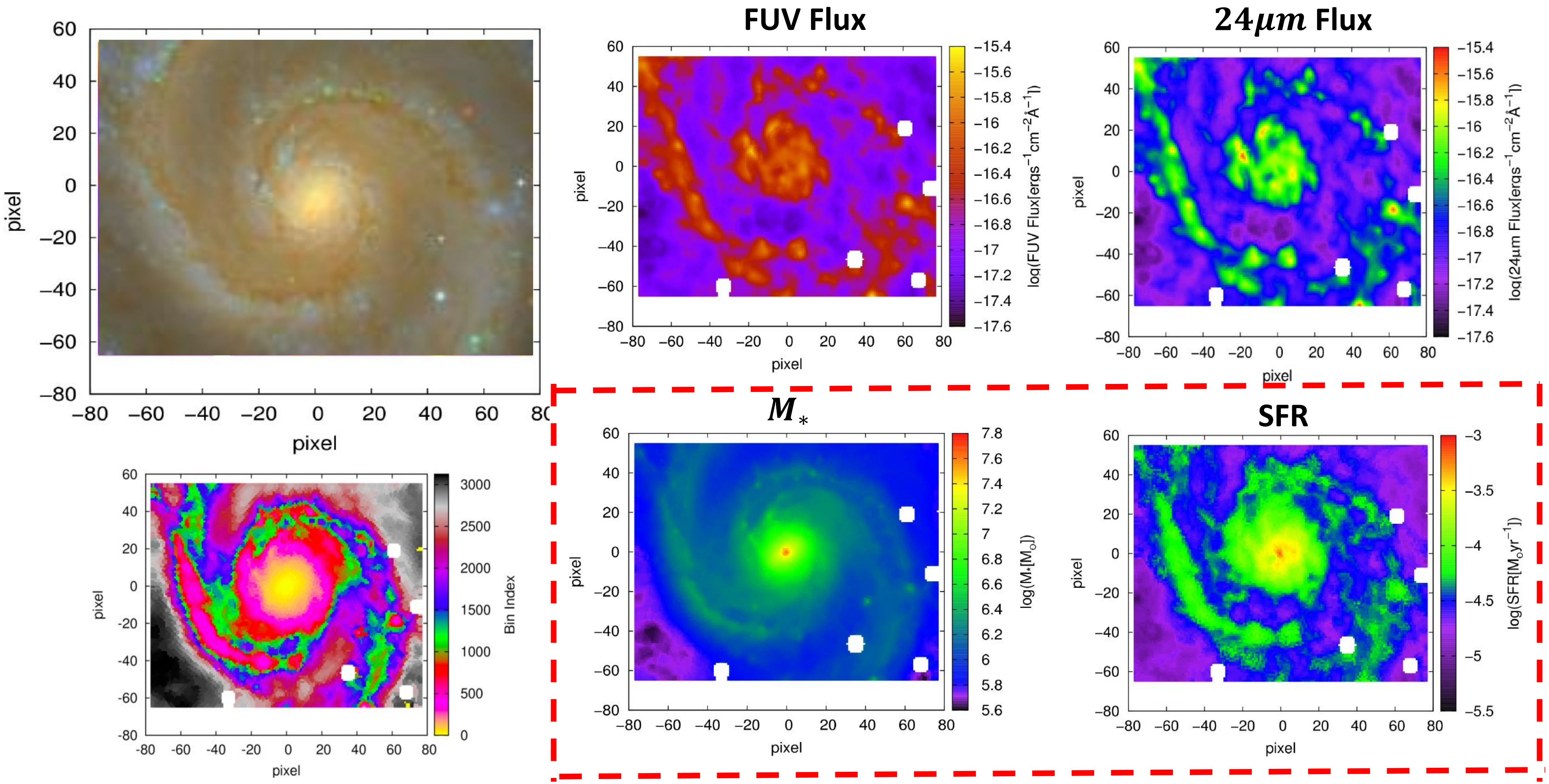


Observed SED

- Calculate ${\chi_i}^2$ of each model
- Calculate weight of each model, w_i
- Calculate posterior mean of SFR and M_*
- Calculate SFR and M_* uncertainties using Monte-Carlo method
- **Generate 100 random SEDs following Normal distribution around observed SED**

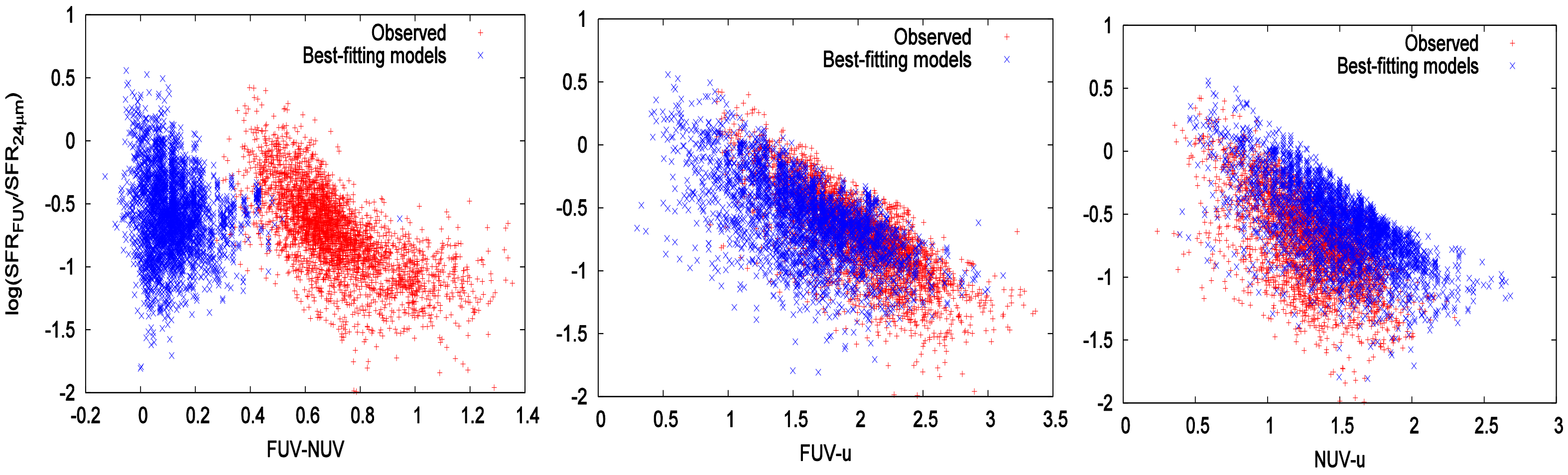
with Bayesian Statistic

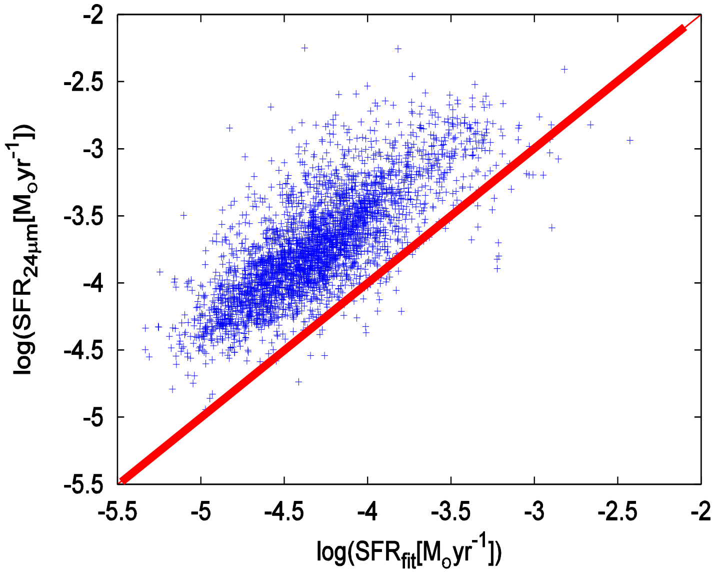
Case Example : M51 Galaxy



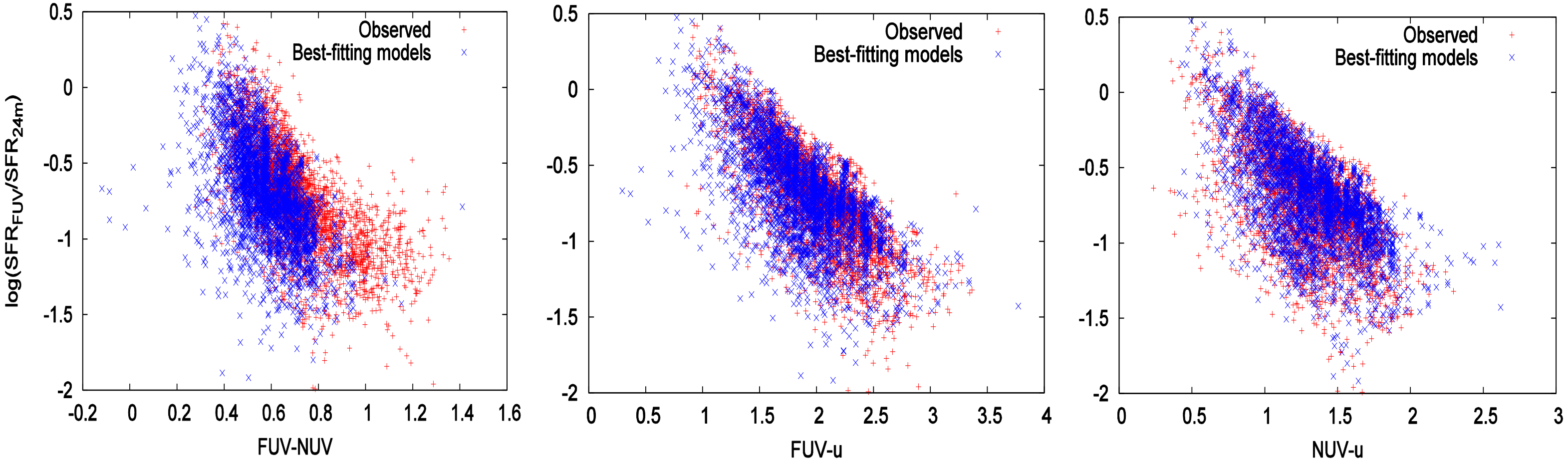
Case Example M51 : Why Calzetti (2000) Dust Extinction Law ?

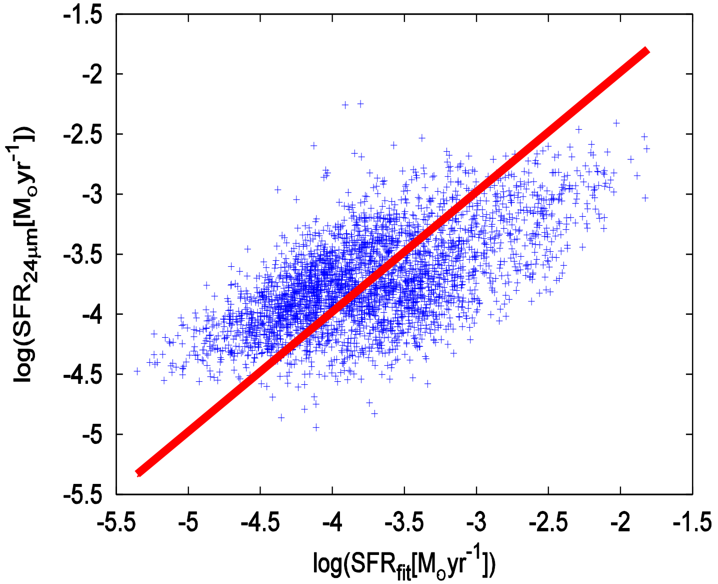
Milky Way dust-extinction law (Seaton(1979) + Cardelli(1989))





Calzetti (2000)





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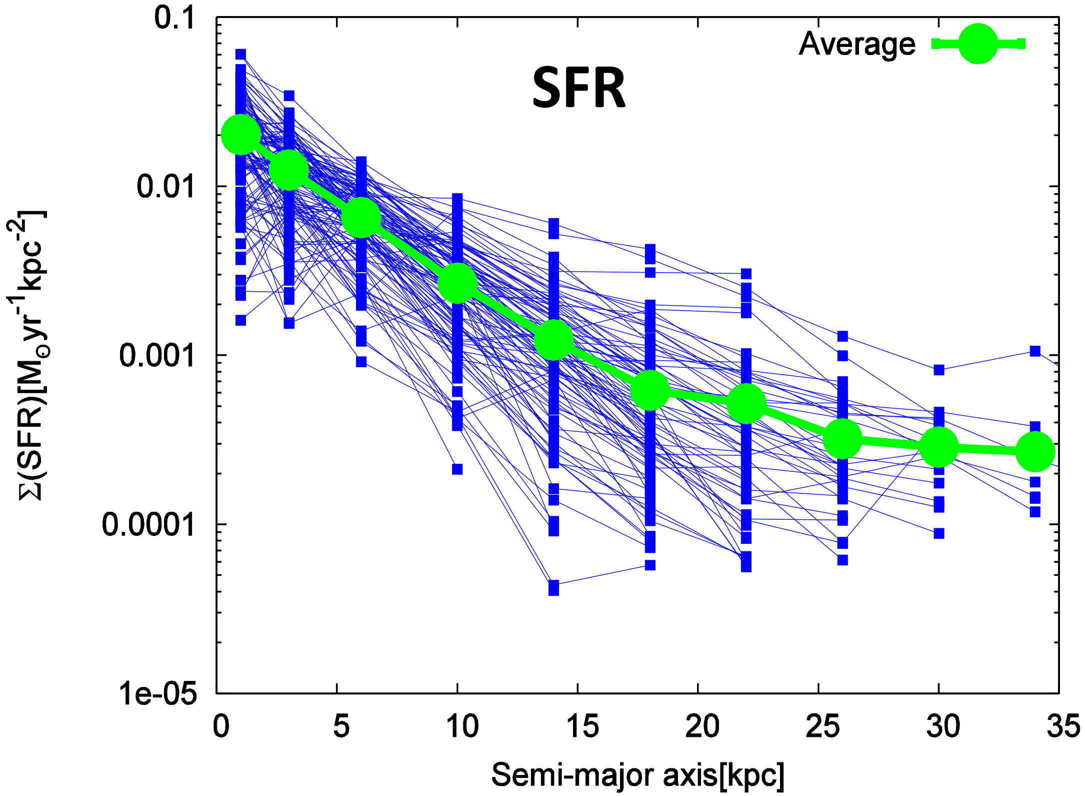
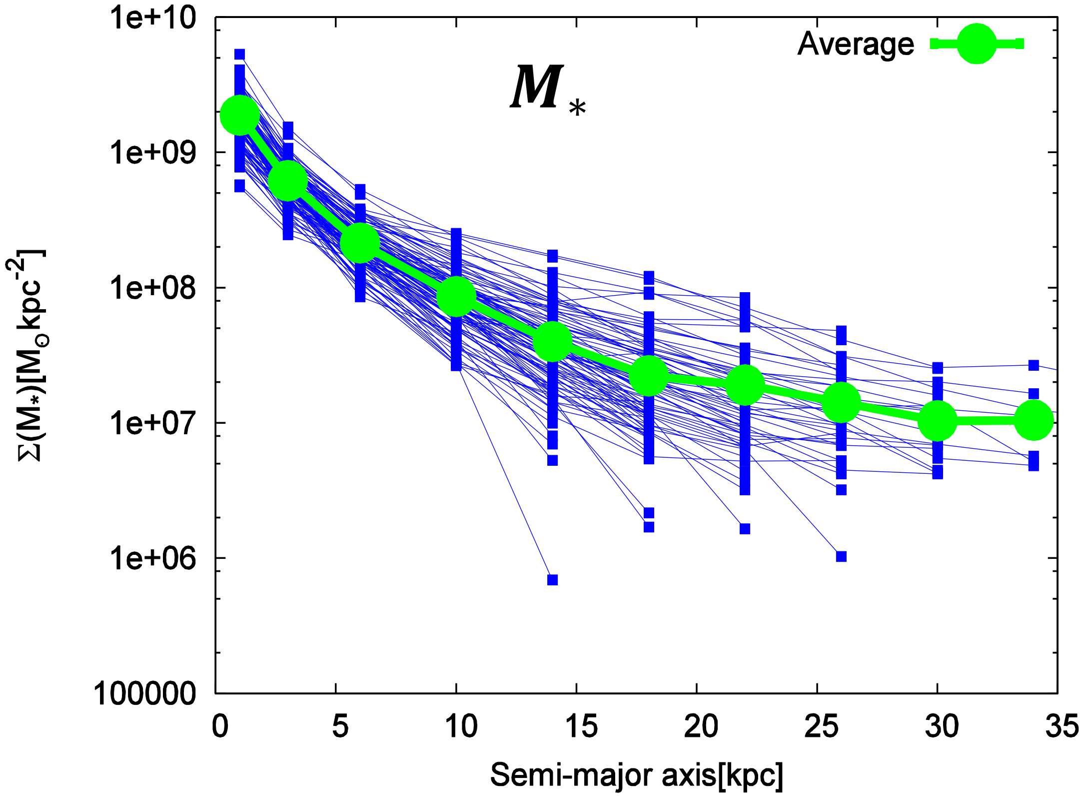
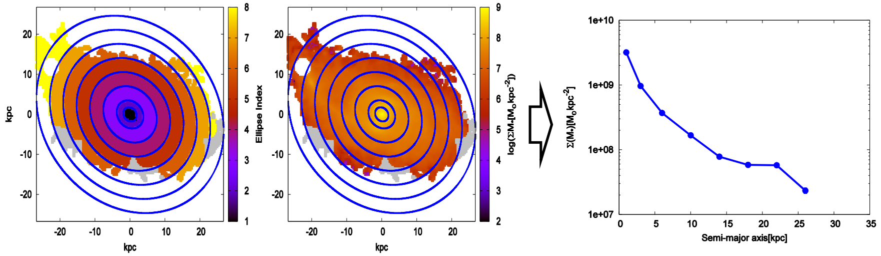
M_* and SFR Density Radial Profiles





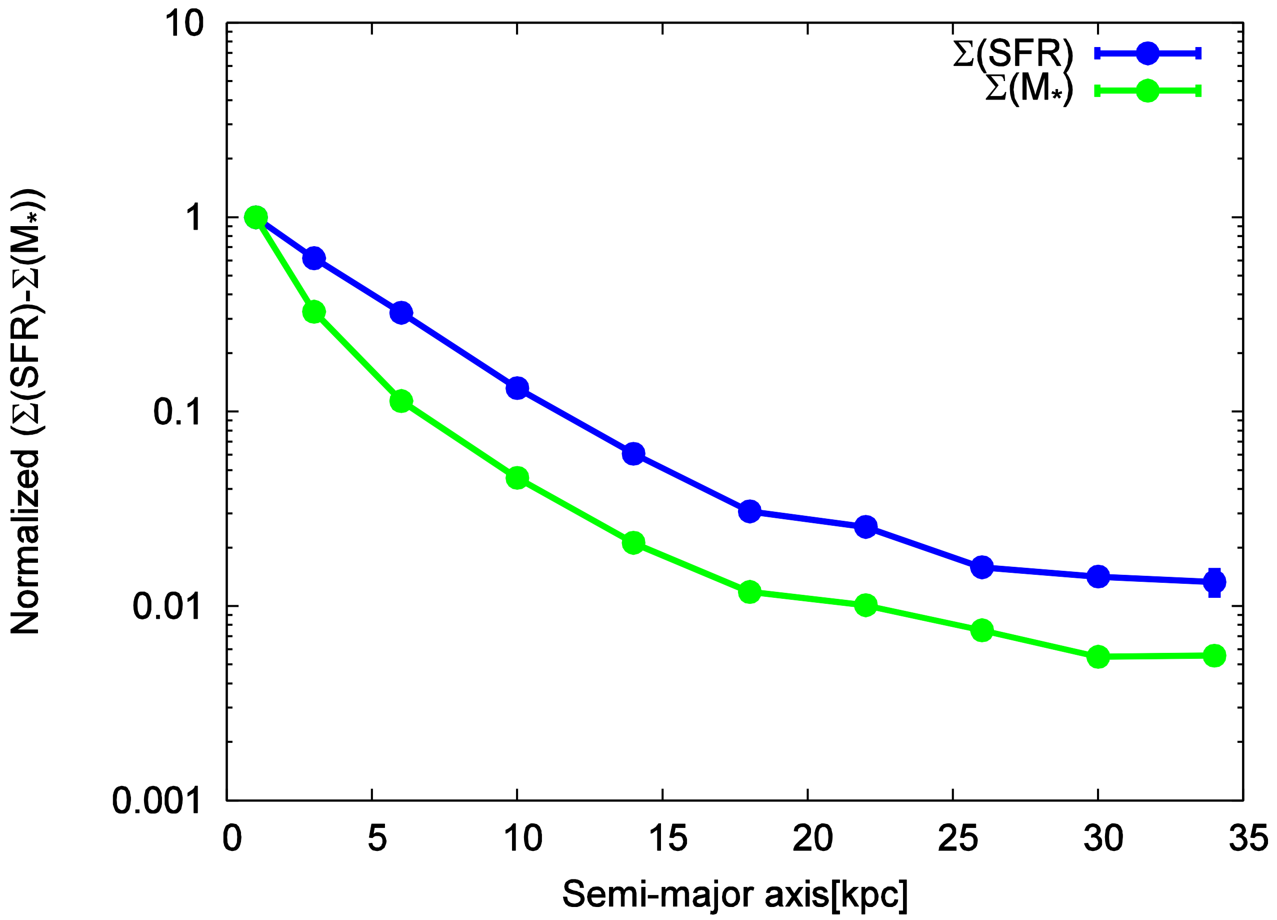
M_*density and SFR density radial profile of galaxies sample show declining toward the outskirt

Elliptical annuli **Radial profile**



SFR Radial Profile vs M_* Radial Profile

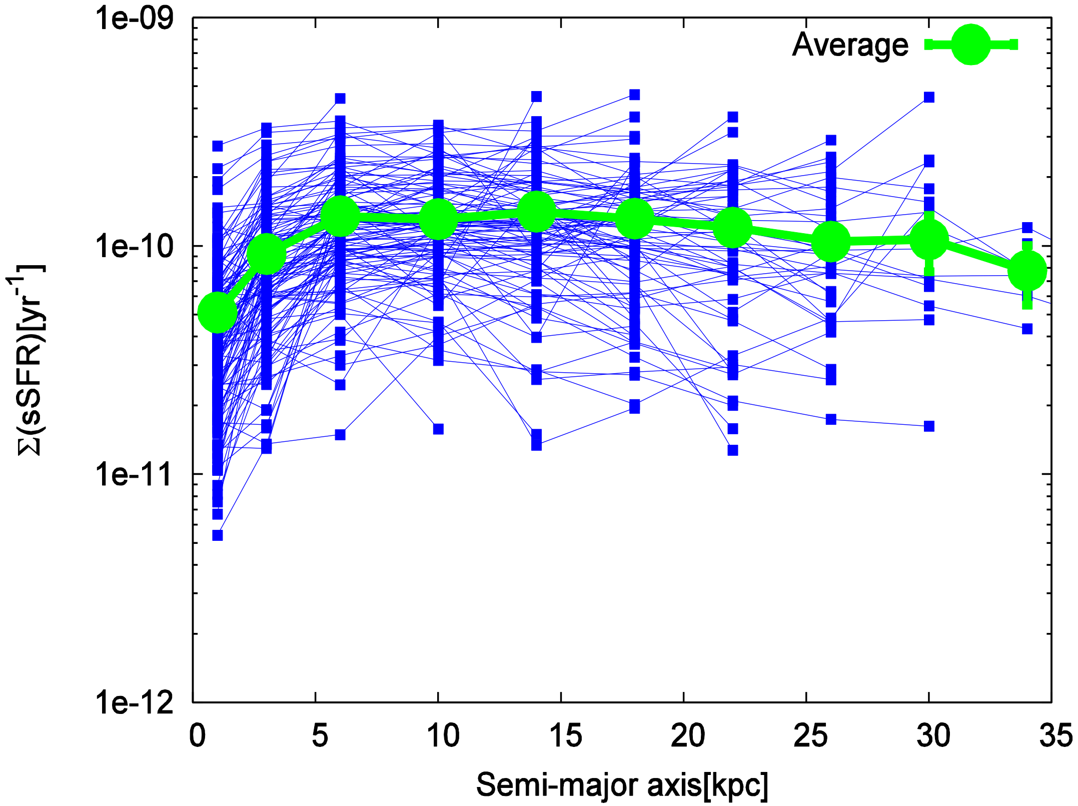
- The average SFR density radial profile follows the average M_*density radial profile, but with rather extended profile
- **This results may confirm the inside-out scenario of disk galaxy formation**, which suggests that present star formation in the galaxies occurs in rather extended (more outskirt) than past star formation



sSFR Radial Profiles

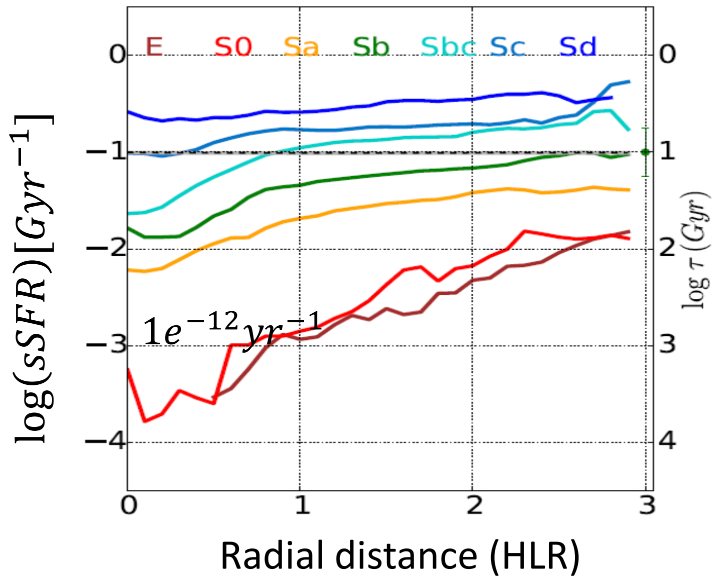
- sSFR radial profile of spiral galaxies in the sample show relatively flat radial profile outside of about 5kpc, but suppress in the central region
- This profile shows that SFR being suppressed from inside-to-outside → inside-out quenching

This research (Spiral at 0.01<z<0.02)



CALIFA Survey

IFU Survey (0.005<z<0.03)

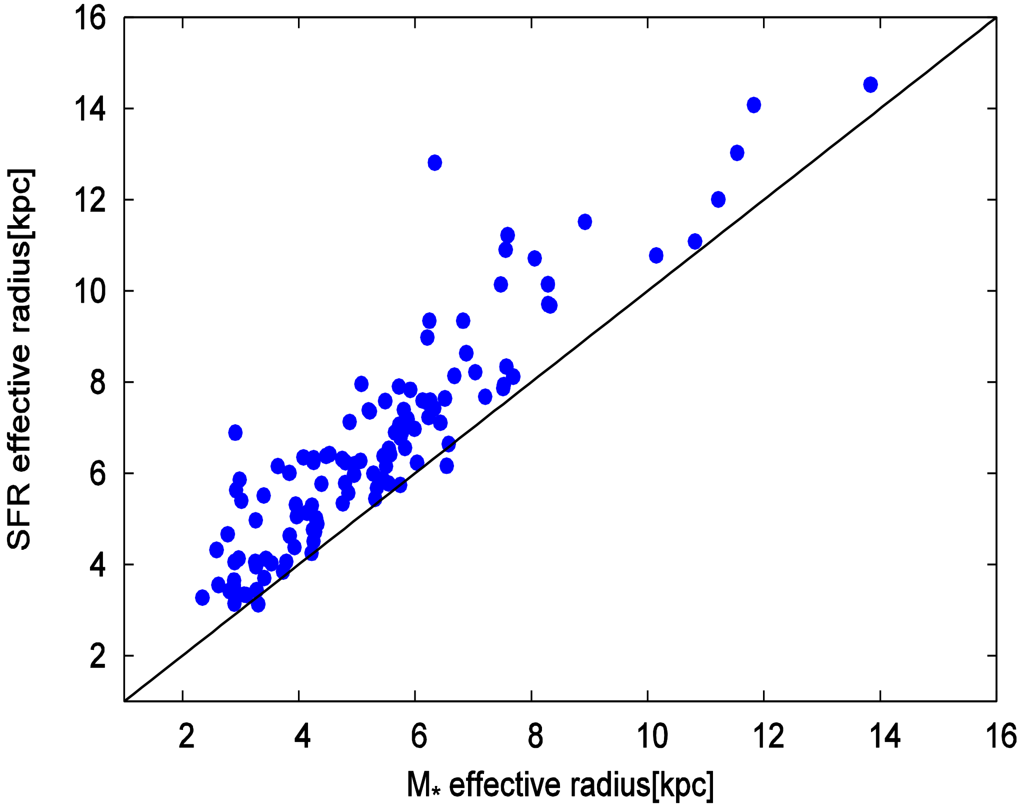


R. M. González Delgado, et al. 2016, A&A 590, A44

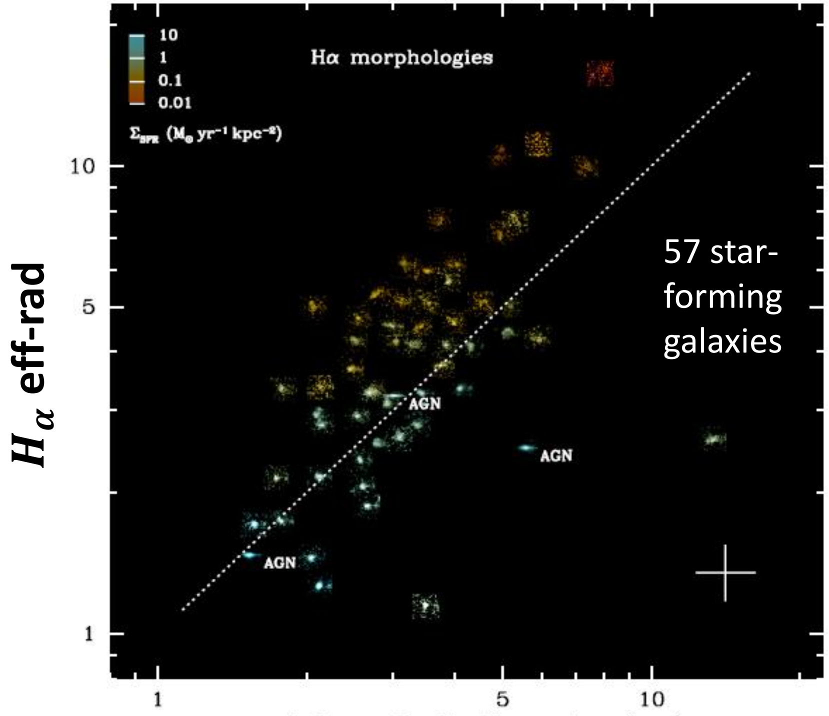
SFR eff-radius vs M_* eff-radius

- Almost all of the galaxies in the sample (spiral galaxies, 0.01<z<0.02) have SFR effective radius larger than M_* effective radius
- Majority of galaxies at z~1 have SFR eff-rad > M_*eff-rad, but some of the galaxies show SFR eff-rad < M_*eff-rad (Nelson, E. J., et al. 2012, ApJ, 747, 28)

This research (at 0.01<z<0.02)



at z~1

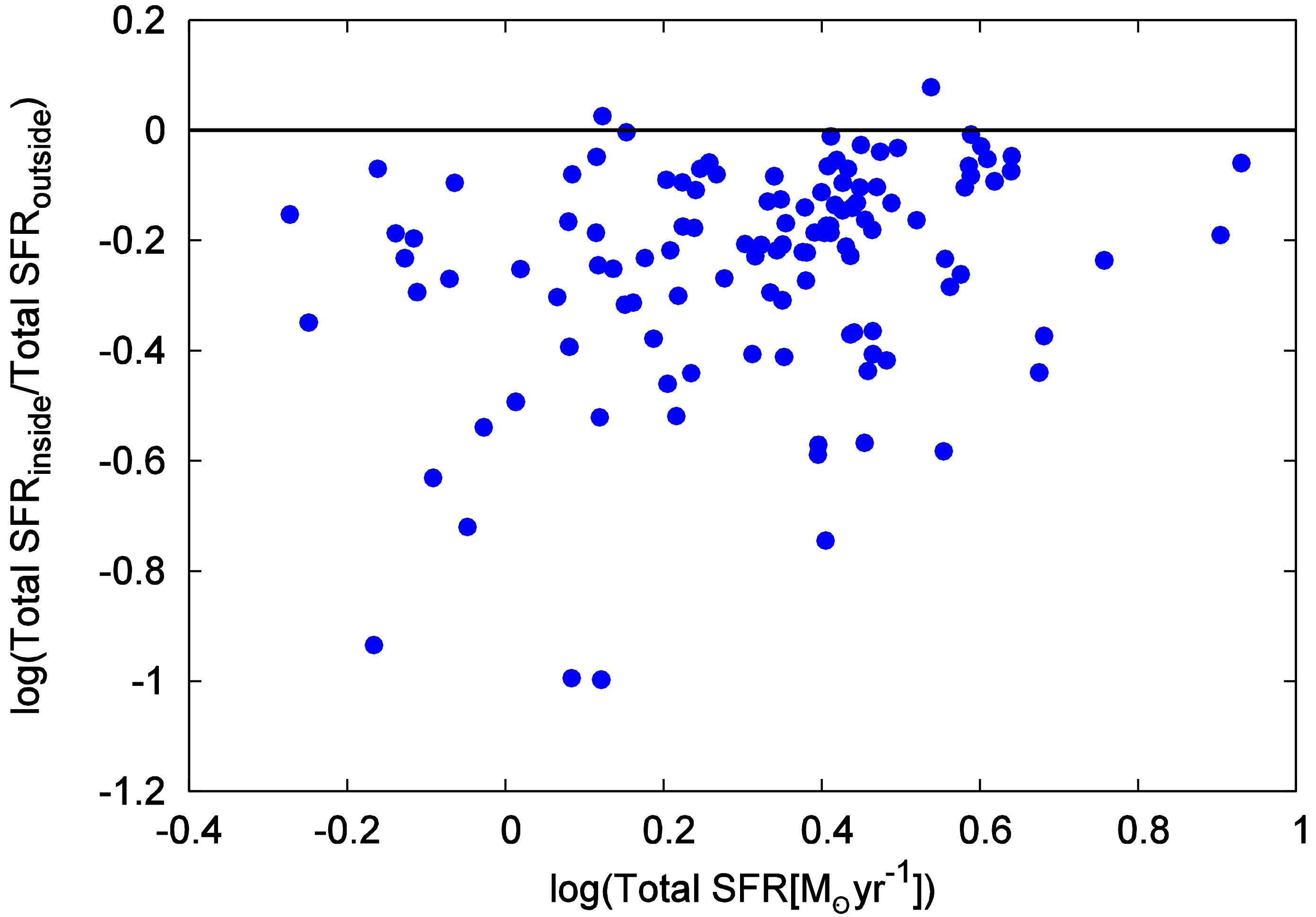


Rest-frame R eff-rad

(Nelson, E. J., et al. 2012, ApJ, 747, 28)

SFR_inside vs SFR_outside of Half-Mass Radius

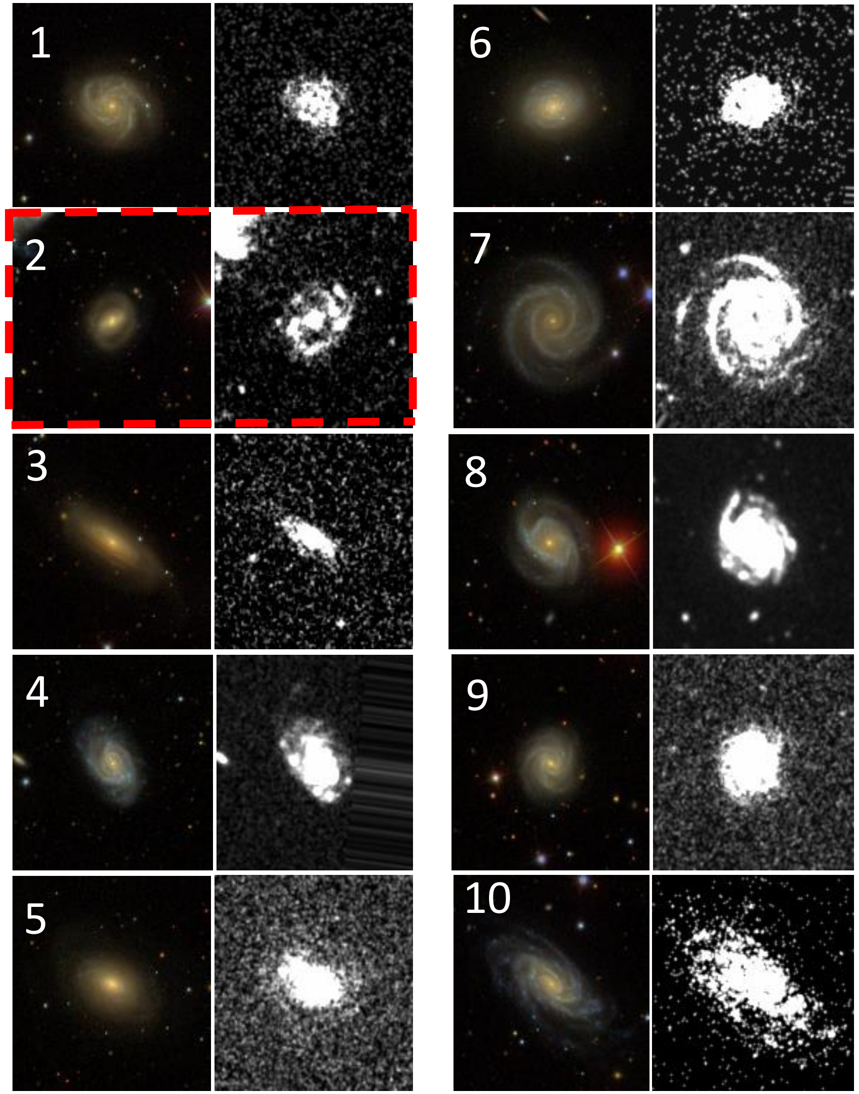
- Majority of galaxies in the sample (0.01<z<0.02) have SFR-outside larger than SFR-inside of M_* effective radius (half-mass radius)



Galaxy with High and Low (SFR_inside/SFR_outside)

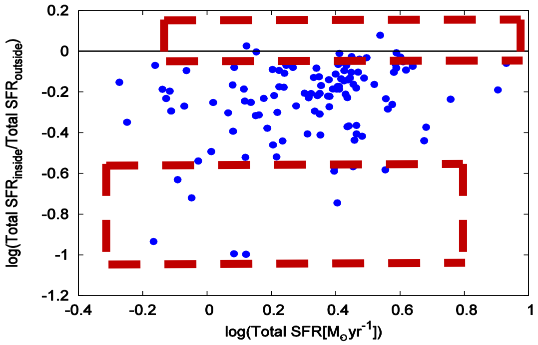
optic FUV

High (SFR_inside/SFR_outside)

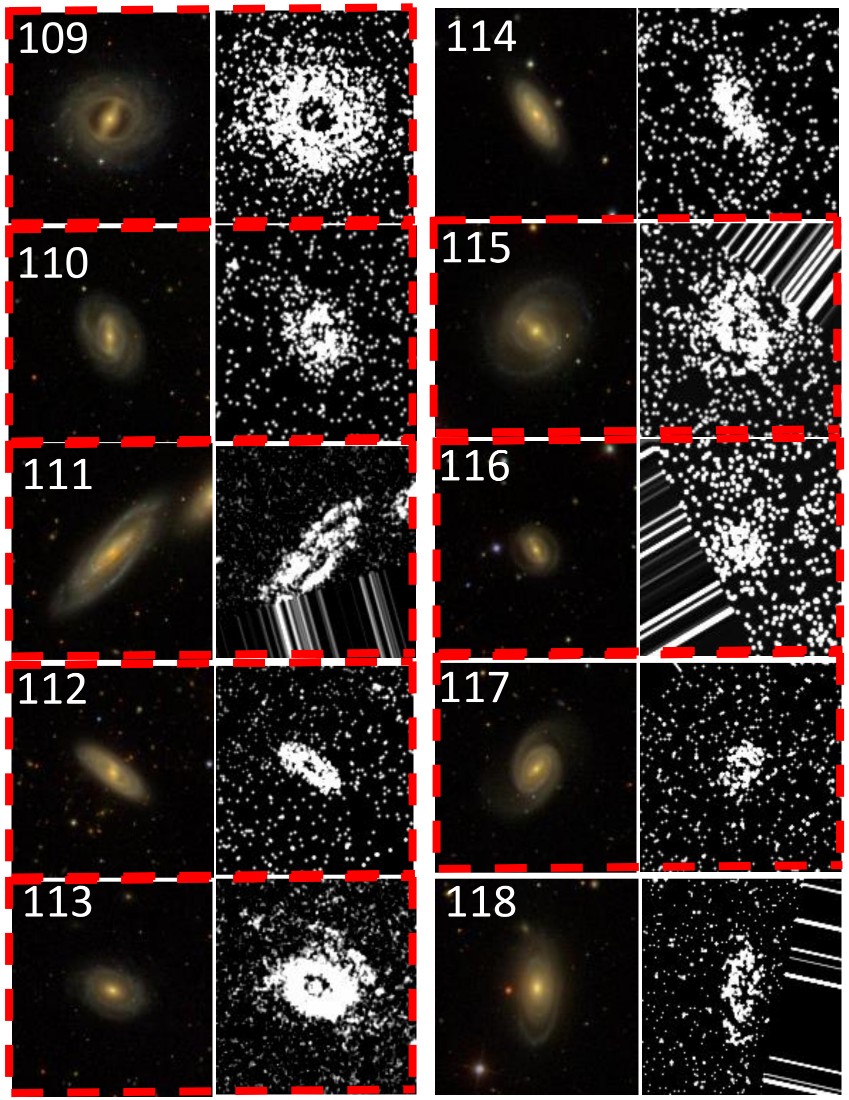


Sorted from highest to lowest of (SFR_in/SFR_out)

Some of the galaxies in 10 lowest ratio are Bar-galaxies



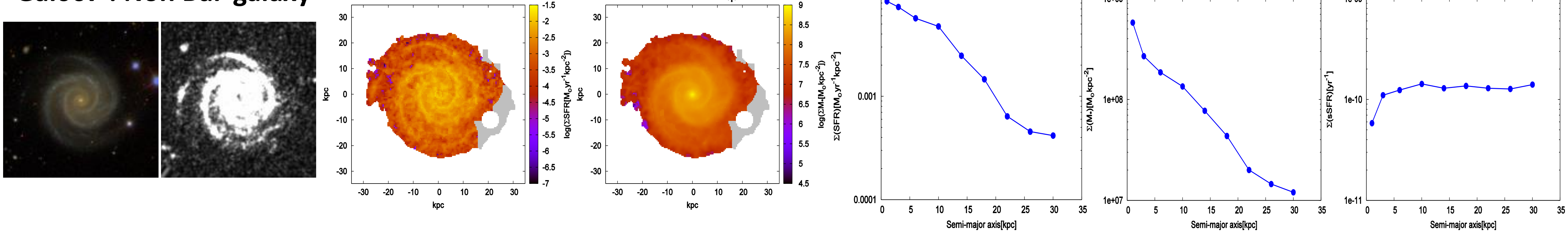
Low (SFR_inside/SFR_outside)



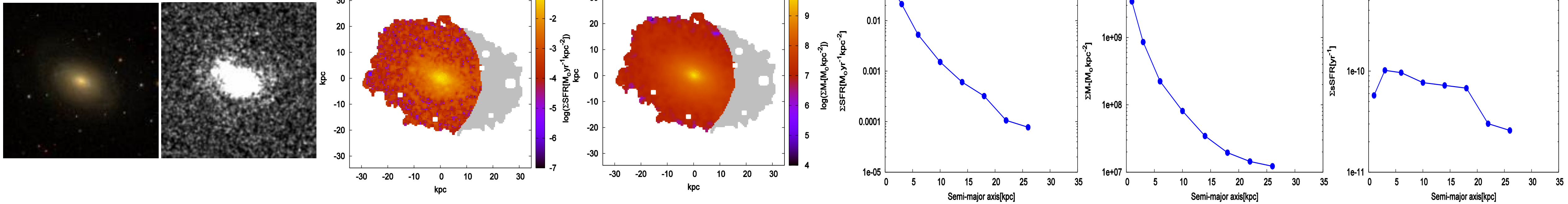
Bar- and Non Bar-Galaxies(1)

SFR | M_* | SFR | M_* | sSFR

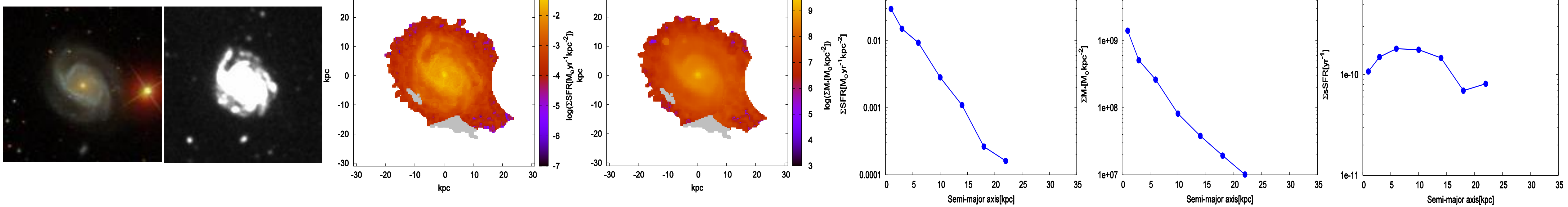
Gal067 : Non Bar-galaxy



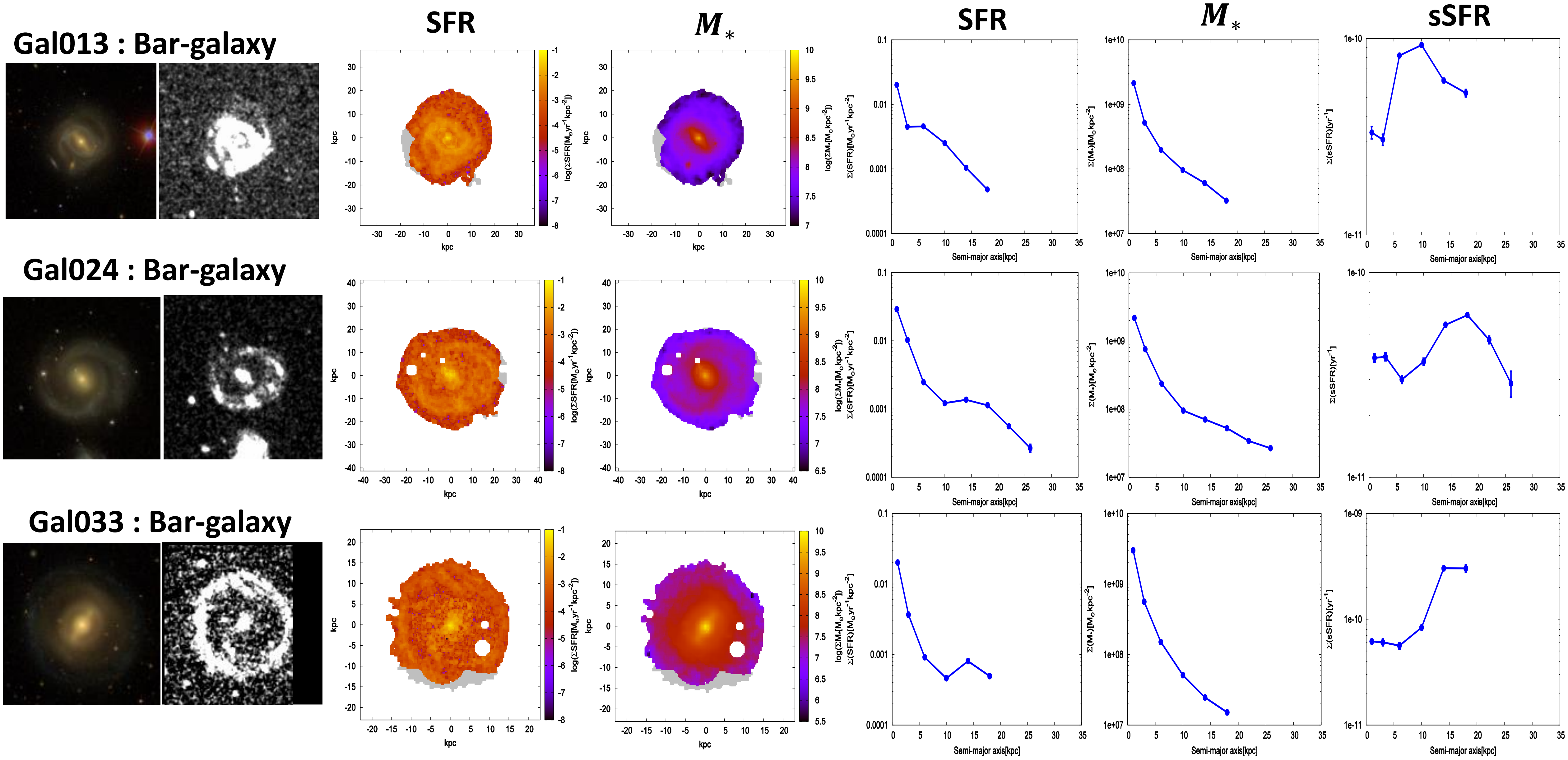
Gal179 : Non Bar-galaxy



Gal179 : Non Bar-galaxy



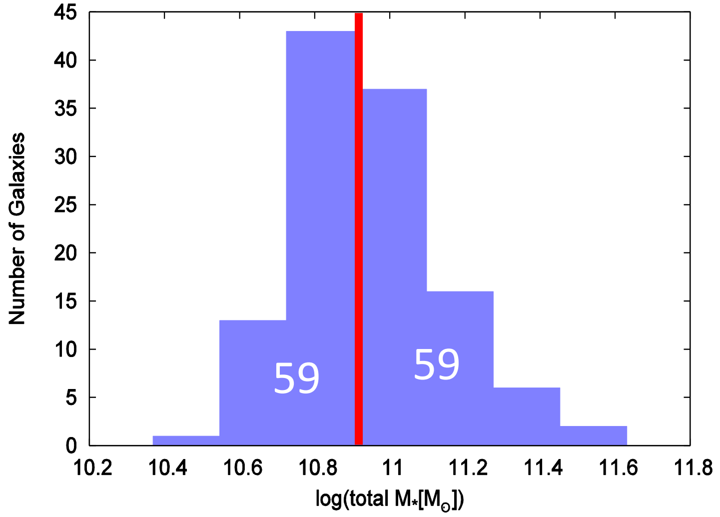
Bar- and Non Bar-Galaxies(2)



Higher and lower mass bin : Resolved “Downsizing” ?

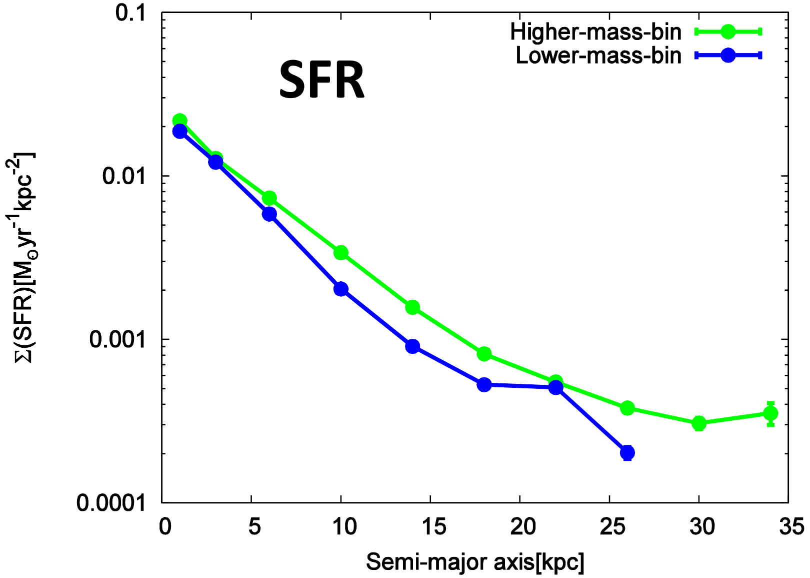
SFR density of higher mass bin galaxies typically higher at all radii

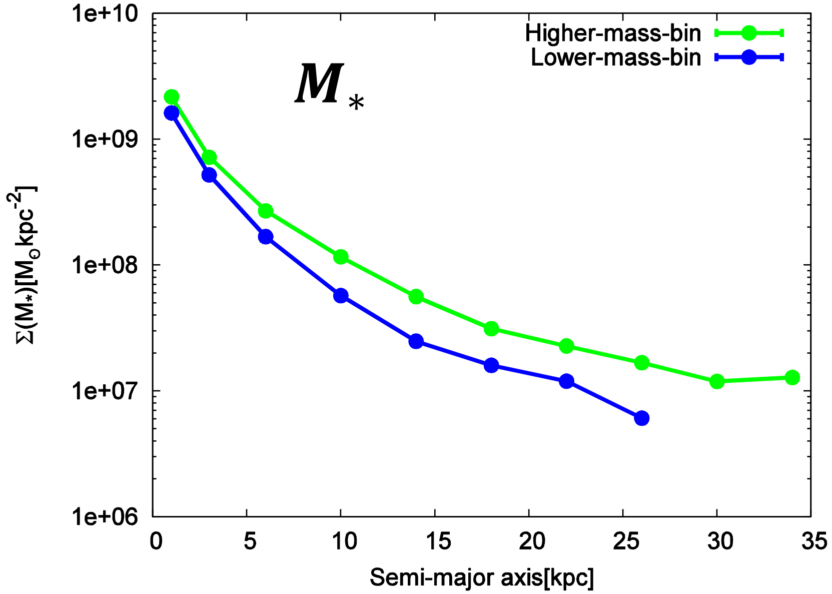
M_*density of higher mass bin Galaxies typically higher at all radii

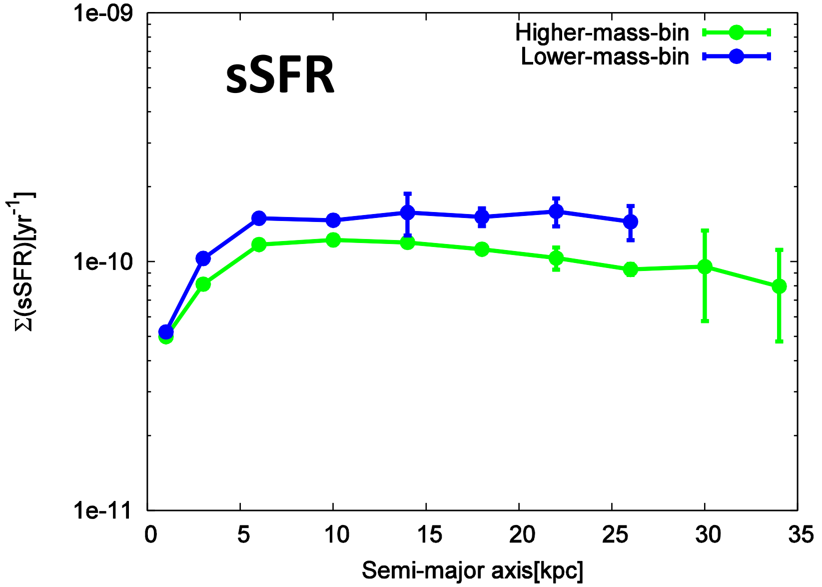


Both stellar mass bins have similar sSFR profile

sSFR profile of higher mass bin typically lower in all radius→ “Downsizing” in spatial scale





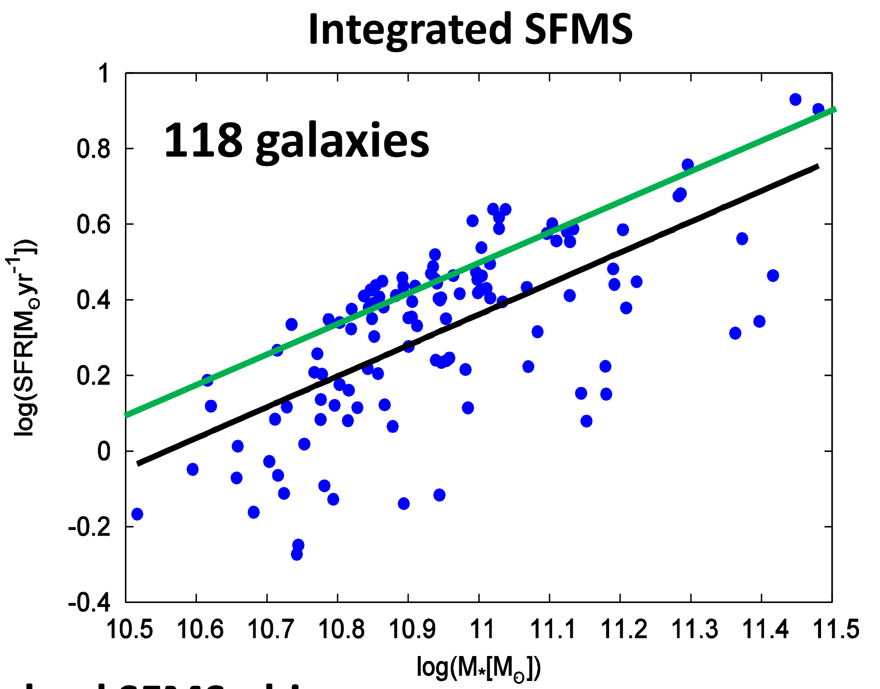


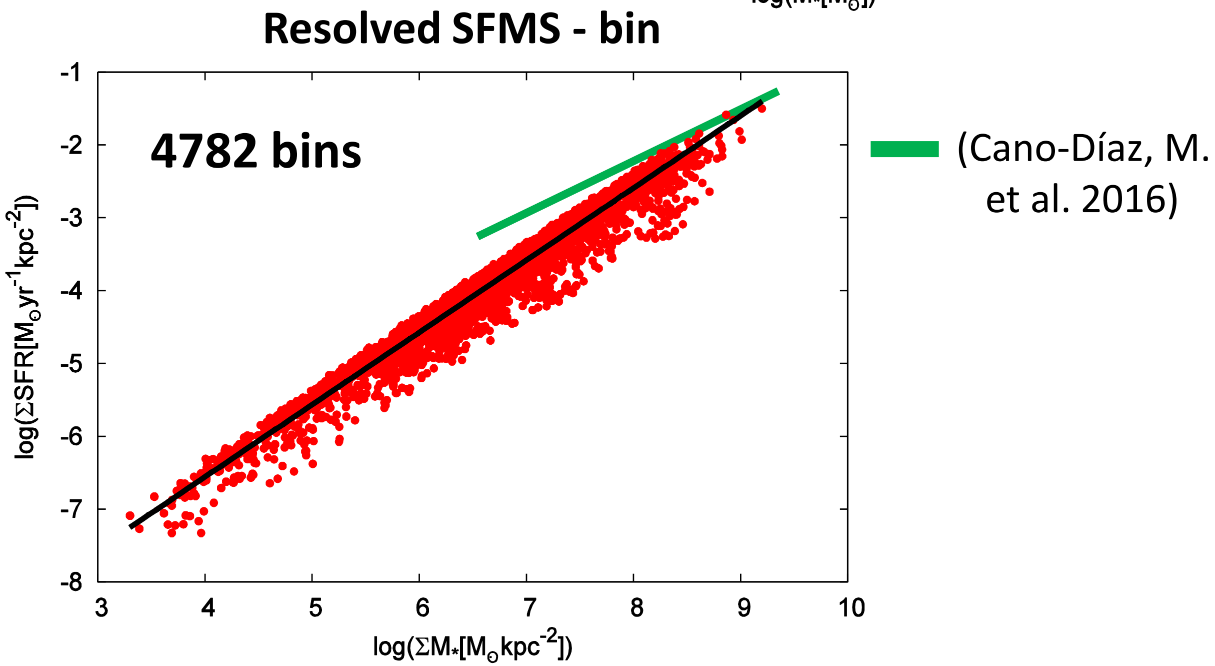
Integrated SFMS vs Resolved SFMS

- Integrated SFMS and resolved SFMS have very similar characteristic (slope, zero-point, and scatter) → SFMS is preserved up to the spatial scale
- Cano-Díaz, M. et al. (2016) also found the similarity between integrated and resolved SFMS of local galaxies (integrated : $\alpha = 0.81$ $\beta = -8.34$ $\sigma = 0.20$; resolved : $\alpha = 0.72$ $\beta = -7.95$ $\sigma = 0.16$) → global SFMS may be derived from local SFMS

$$\log SFR\left(M_{\odot} yr^{-1}\right) = \alpha \log M_{*}\left(M_{\odot}\right) + \beta$$

Coefficient	Integrated SFMS	Resolved SFMS
Slope (α)	0.82	0.99
Zero-point (β)	-8.63	-10.52
Standard deviation (σ)	0.17	0.20





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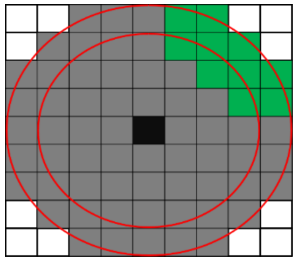
Conclusion

- From analyzing 118 spiral galaxies at 0.01<z<0.02, we found that :
  - SFR distribution generally follow M_* distribution, but slightly more extended
  - Average sSFR radial profile is relatively flat in the outskirt (outside of about 5kpc) but suppress in the center
  - Majority of galaxies show that total SFR outside larger than total SFR inside of half-mass radius
  - More massive galaxies tend to be quenched faster in all radius compare to less massive galaxies → resolved “Downsizing”
  - Integrated SFMS and resolved SFMS characteristics are similar → global SFMS may be derived from more fundamental relation in the spatial scale (local SFMS)
- Overall, this results may confirm other observation results, for galaxies at local universe (Munoz-Mateos, J. C. et al. 2007; Wang, J. et al. 2011; Perez, E. et al. 2013) as well as for galaxies at $z{\sim}1$ (Nelson, E. J. et al. 2012), which were said to be supporting **the inside-out scenario of disk galaxy formation**

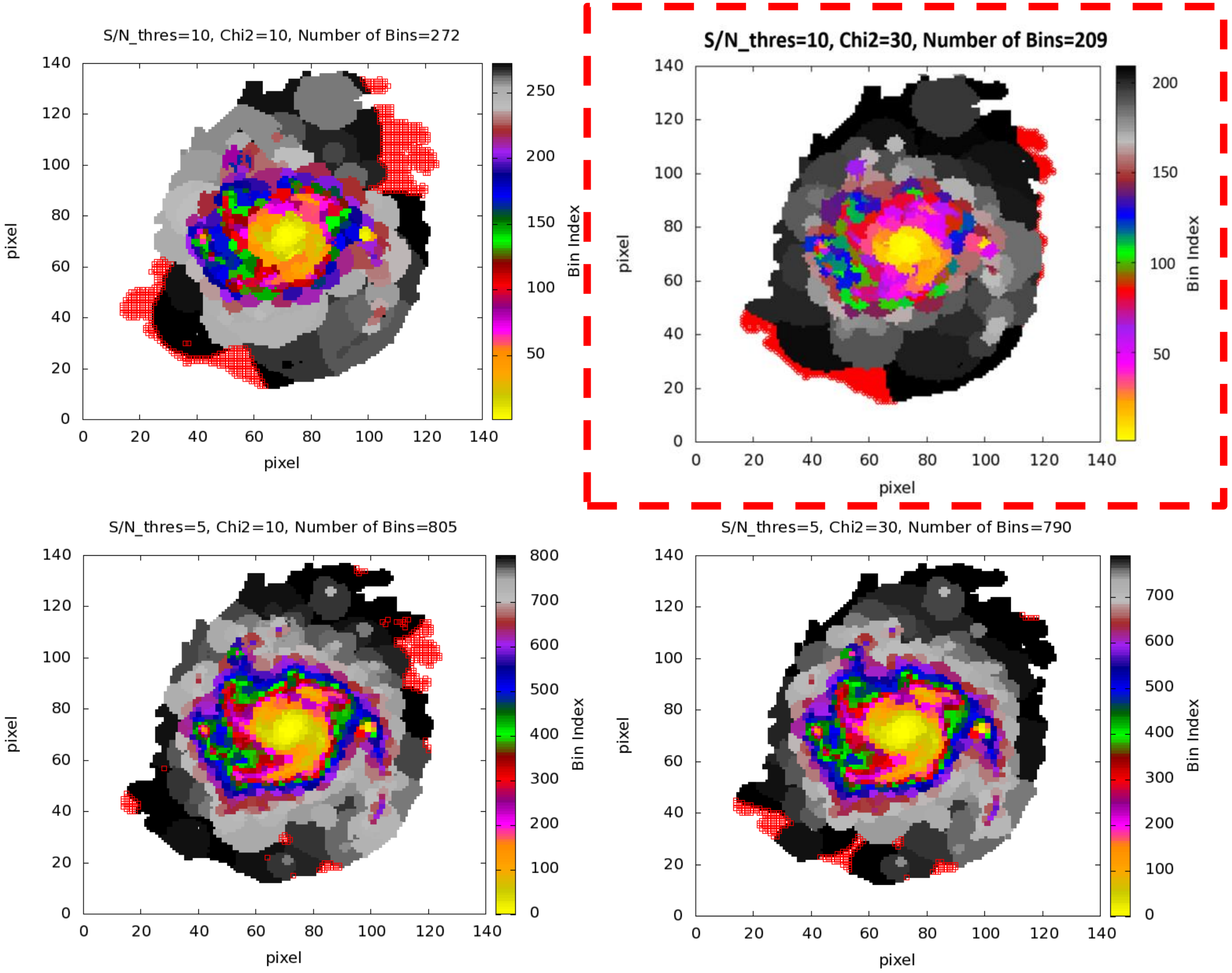
Thank you for your attention !!!

Pixels Binning Technique



- This research used new pixels binning technique which considers 3 criteria :
  - “closeness”
  - “similarity SED’s shape” among bin’s members ($\chi_{12}^2 < \chi_{\mathrm{thresh}}^2$)
  - Total S/N of bin > S/N_thresh
- Throughout this research, binning with S/N_thresh=10 and chi-square limit of 30 is used
- Chi-square equation to test similarity of SED’s shape :

$$\chi_{12}{}^2 = \sum_i \left(\frac{\left(f_{2,i} - s_{12} f_{1,i}\right)^2}{\sigma_{1,i}{}^2 + \sigma_{2,i}{}^2} \right) \quad \text{with} \quad s_{12} = \frac{\sum_i \frac{f_{2,i} f_{1,i}}{\sigma_{1,i}{}^2 + \sigma_{2,i}{}^2}}{\sum_i \frac{f_{1,i}{}^2}{\sigma_{1,i}{}^2 + \sigma_{2,i}{}^2}}$$



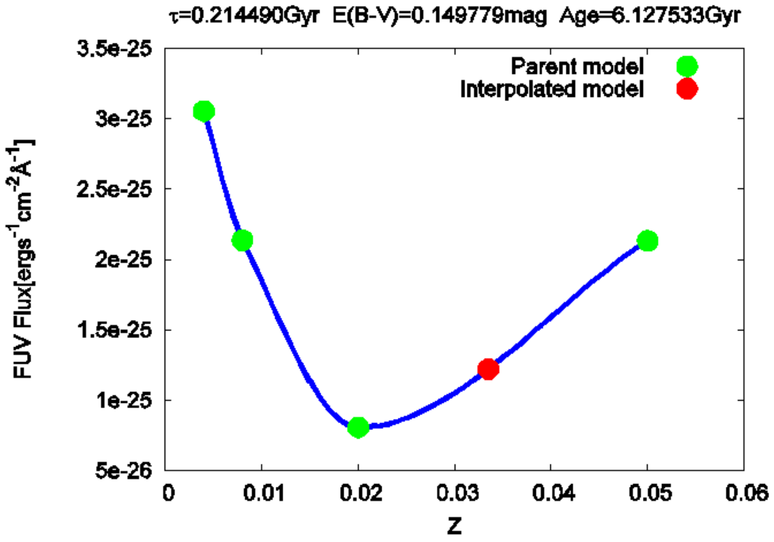
Model Interpolation – in 4D (Z,tau,E(B-V),age)

- Parent models (193600) are generated using GALAXEV (Bruzual & Charlot 2003), with parameters :
  - Z : 0.004, 0.008, 0.02, and 0.05
  - Tau : [0.05:2] with delta_tau=0.05
  - E(B-V) : [0:0.6] with delta_color_excess=0.05
  - Age : [0.25:13.75] with delta_age=0.25
- For each metallicity, Model's flux and stellar mass are interpolated using method of **tricubic interpolation** (in 3 dimension: Tau, E(B-V), and Age), then for some fix values of (tau, E(B-V), and age), **cubic spline interpolation** is done to interpolate for random metallicity

Cubic Spline interpolation : 1D (Z)

$$f(x) = \sum_{i=0}^{3} a_i x^i$$

$$\begin{matrix} 1 & x_1 & {x_1}^2 & {x_1}^3 \\ 1 & x_2 & {x_2}^2 & {x_2}^3 \\ 0 & 1 & 2x_1 & 3{x_1}^2 \\ 0 & 1 & 2x_2 & 3{x_2}^2 \end{matrix} \quad \begin{matrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{matrix} \quad = \quad \begin{matrix} f(x_1) \\ f(x_2) \\ f_x(x_1) \\ f_x(x_2) \end{matrix}$$



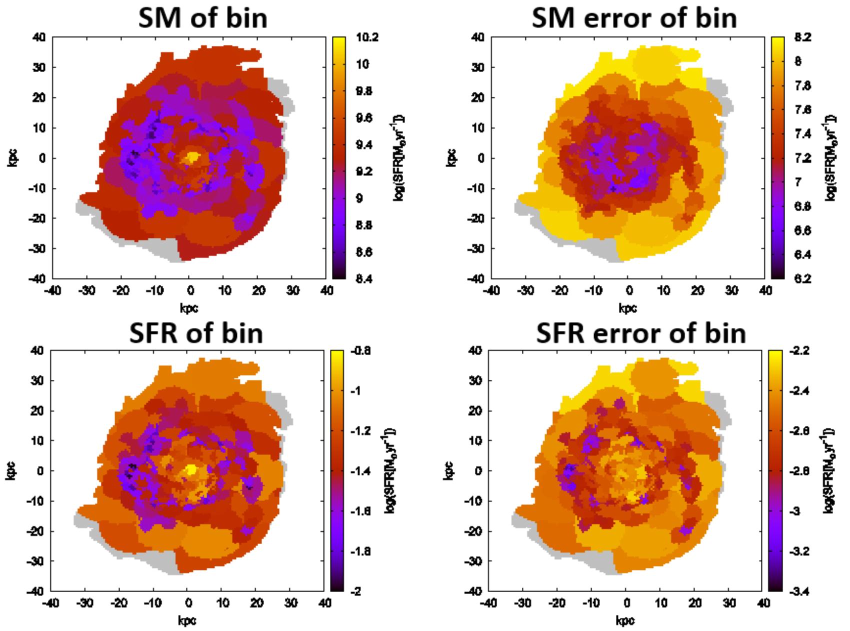
Methodology(4) : Distribution of SFR and M_* among Galaxy's Pixels

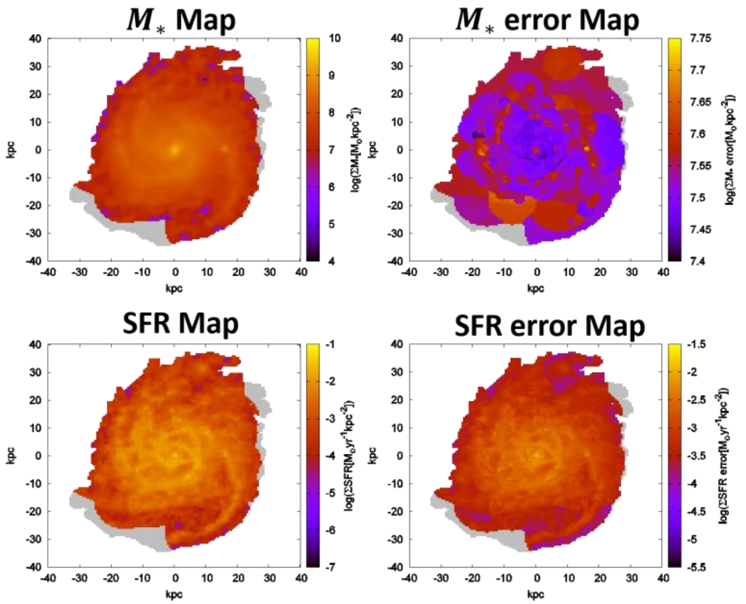
$$M_{*pixel} = \frac{Flux_{z,pixel}}{Flux_{z,bin}} \times M_{*bin}$$

$$SFR_{pixel} = \frac{Flux_{FUV,pixel}}{Flux_{FUV,bin}} \times SFR_{bin}$$

$$\delta M_{*pixel} = M_{*pixel}\sqrt{\left(\frac{\delta M_{*bin}}{M_{*bin}}\right)^2 + \left(\frac{\delta Flux_{z,pixel}}{Flux_{z,pixel}}\right)^2 + \left(\frac{\delta Flux_{z,bin}}{Flux_{z,bin}}\right)^2}$$

$$\delta SFR_{pixel} = SFR_{pixel}\sqrt{\left(\frac{\delta SFR_{bin}}{SFR_{bin}}\right)^2 + \left(\frac{\delta Flux_{FUV,pixel}}{Flux_{FUV,pixel}}\right)^2 + \left(\frac{\delta Flux_{FUV,bin}}{Flux_{FUV,bin}}\right)^2}$$





Calculate pixel's SFR and M_* uncertainties

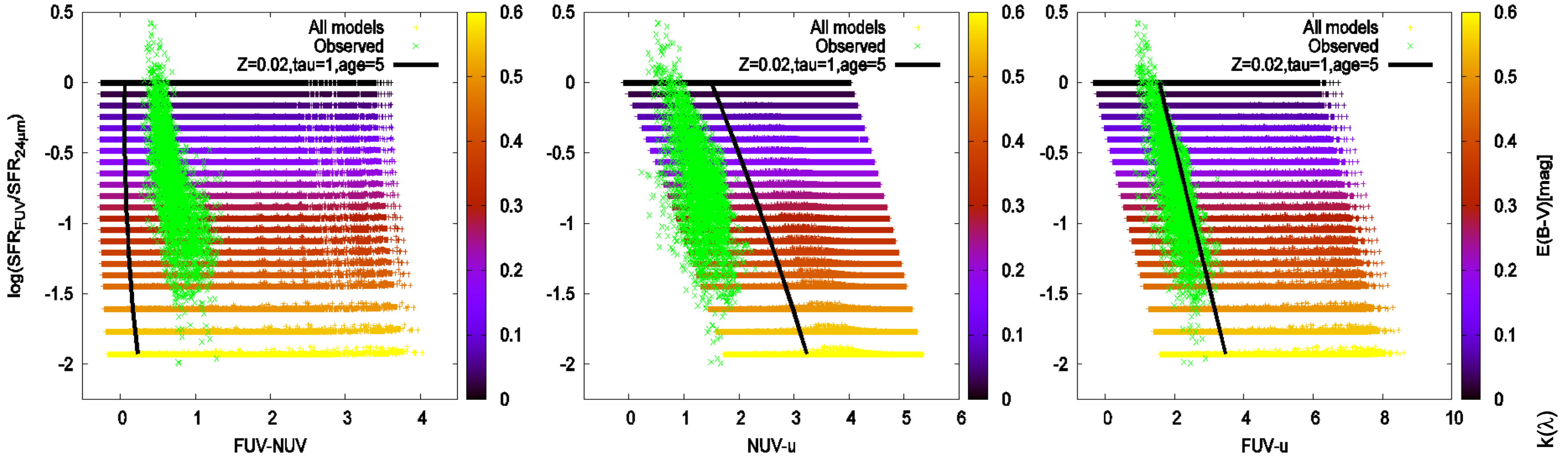
Distribute SFR and M_* of each bin into its constituent pixels

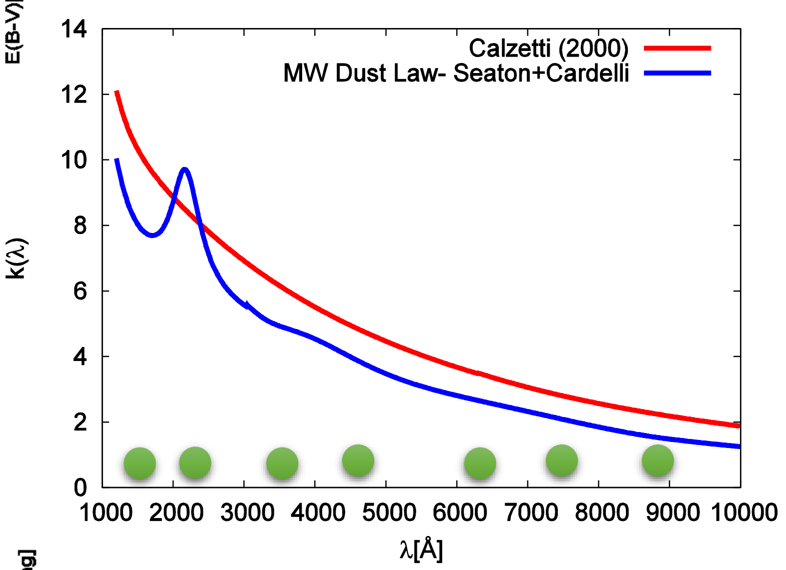
Assuming :

$SFR_i \propto FUV\ Flux_i$ and $M_{*i} \propto z\ Flux_i$

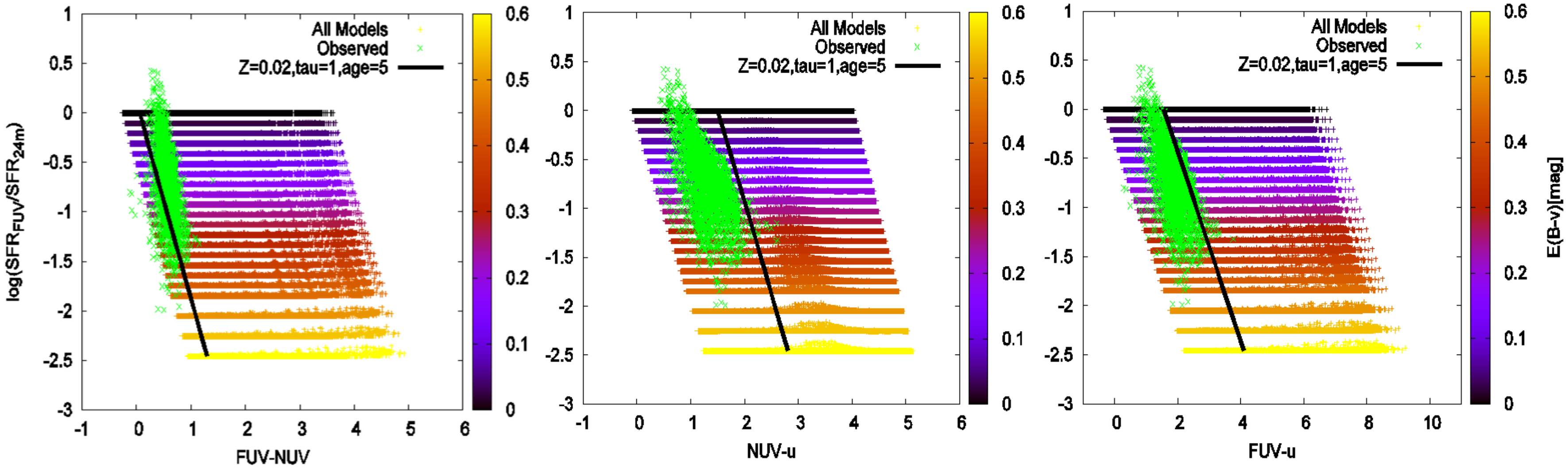
Case Example M51(1) : Why Calzetti (2000) Dust Extinction Law ?

Milky Way dust-extinction law (Seaton(1979) + Cardelli(1989))



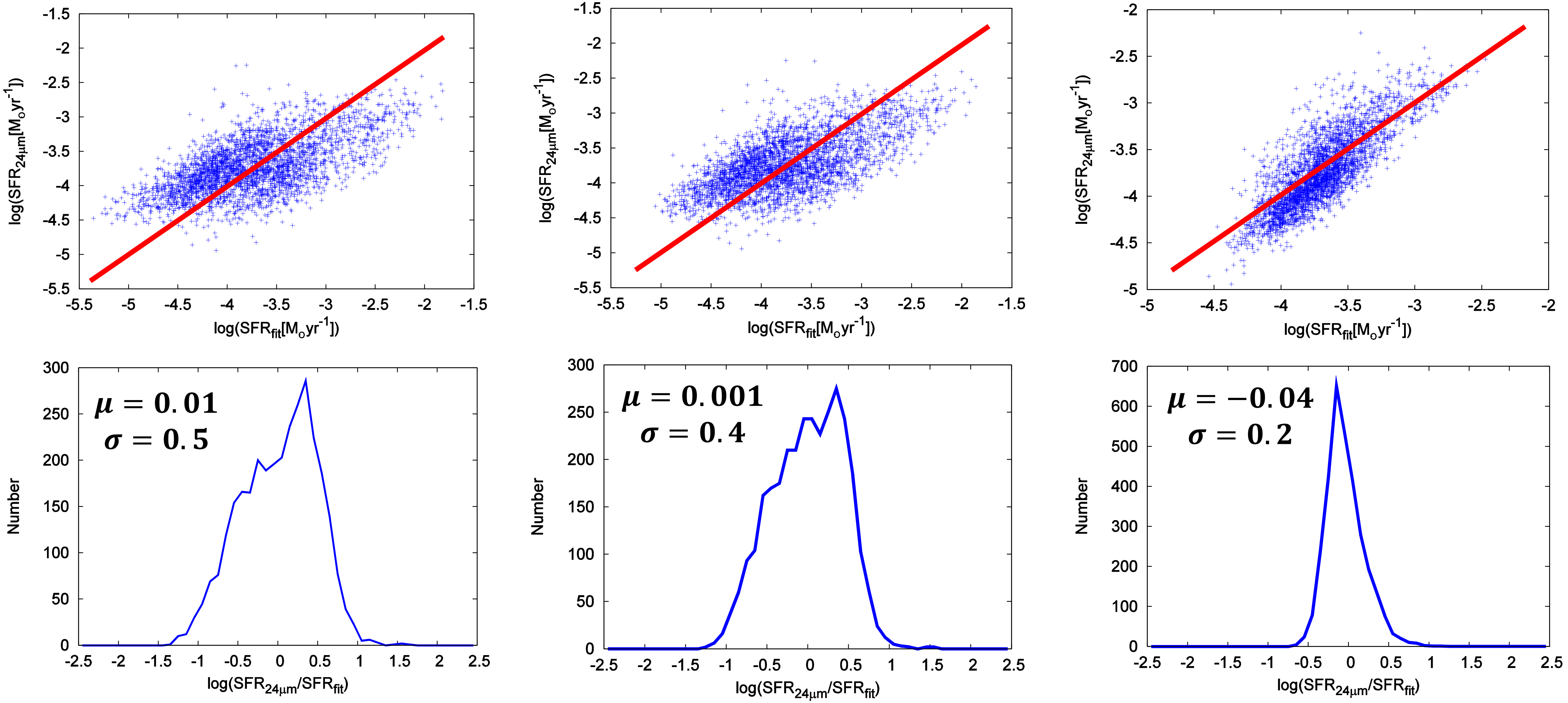


Calzetti (2000)



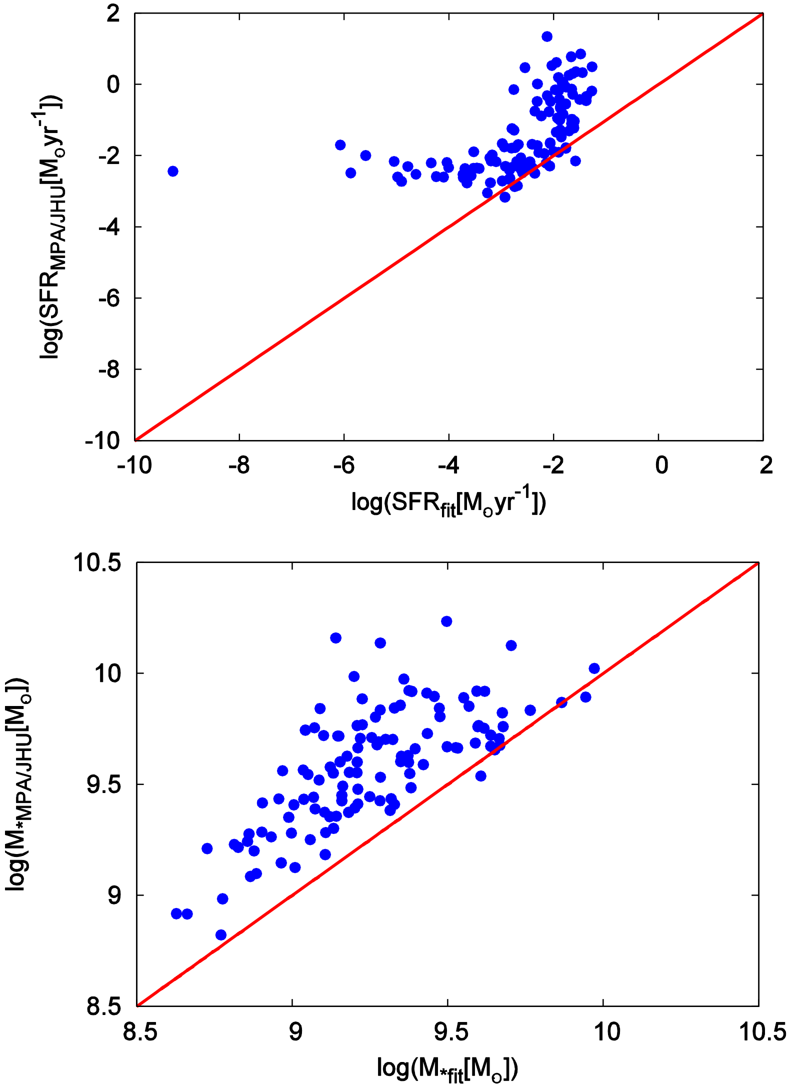
Bayesian SED Fitting : Model's Weight – M51 Case

Maximum likelihood | **Bayesian with $P(\theta|X) \propto exp\,(-\chi^2/2)$** | **Bayesian with $P(\theta|X) \propto 1/\chi^2$**

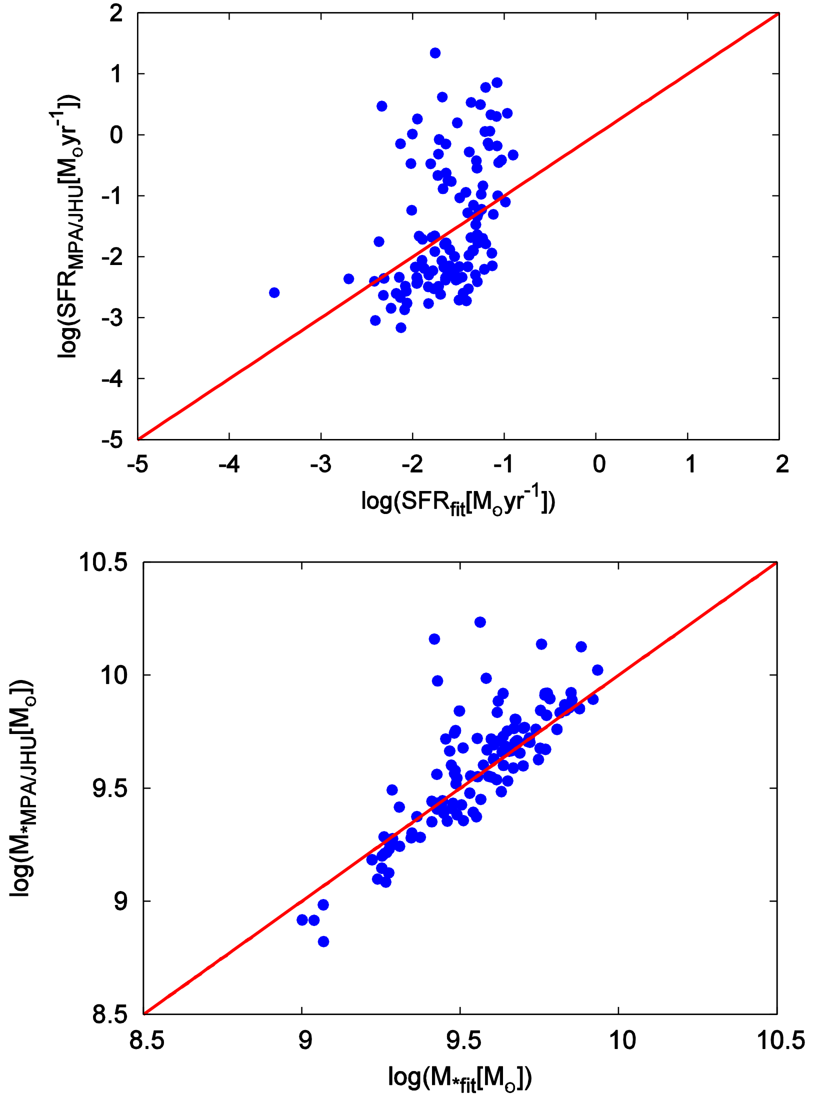


Bayesian SED Fitting : Model's Weight – This Sample

Bayesian with $P(\theta|X) \propto exp\,(-\chi^2/2)$



Bayesian with $P(\theta|X) \propto 1/\chi^2$



SFRs and stellar masses of 118 spiral galaxies sample

The SFRs and stellar masses are total within SDSS fiber diameter (3 arcsec=2 pixel)

Better consistency found for $P(\theta|X) \propto 1/\chi^2$