Spatially Resolved SFR and M_* of Local Massive Spiral Galaxies : Understanding the Scatter in Spatially Resolved SFMS

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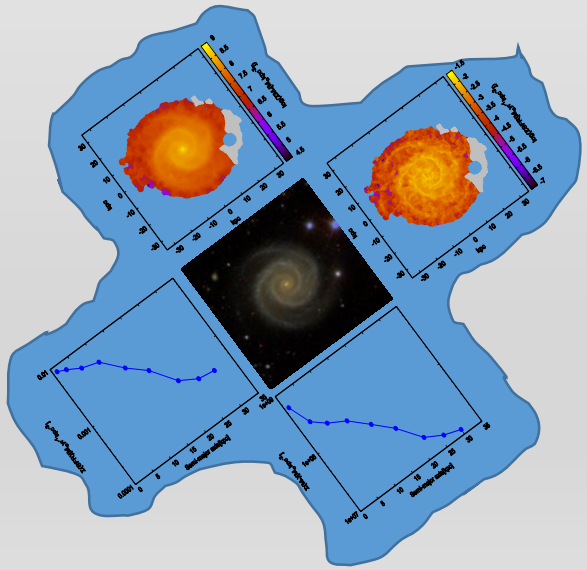


How Galaxies Form Stars Conference
Stockholm, 25 August 2016

Outlines

- Introduction
- Methodology
- Result and Discussion
- Summary

Global/Integrated Star Formation Main Sequence (SFMS)

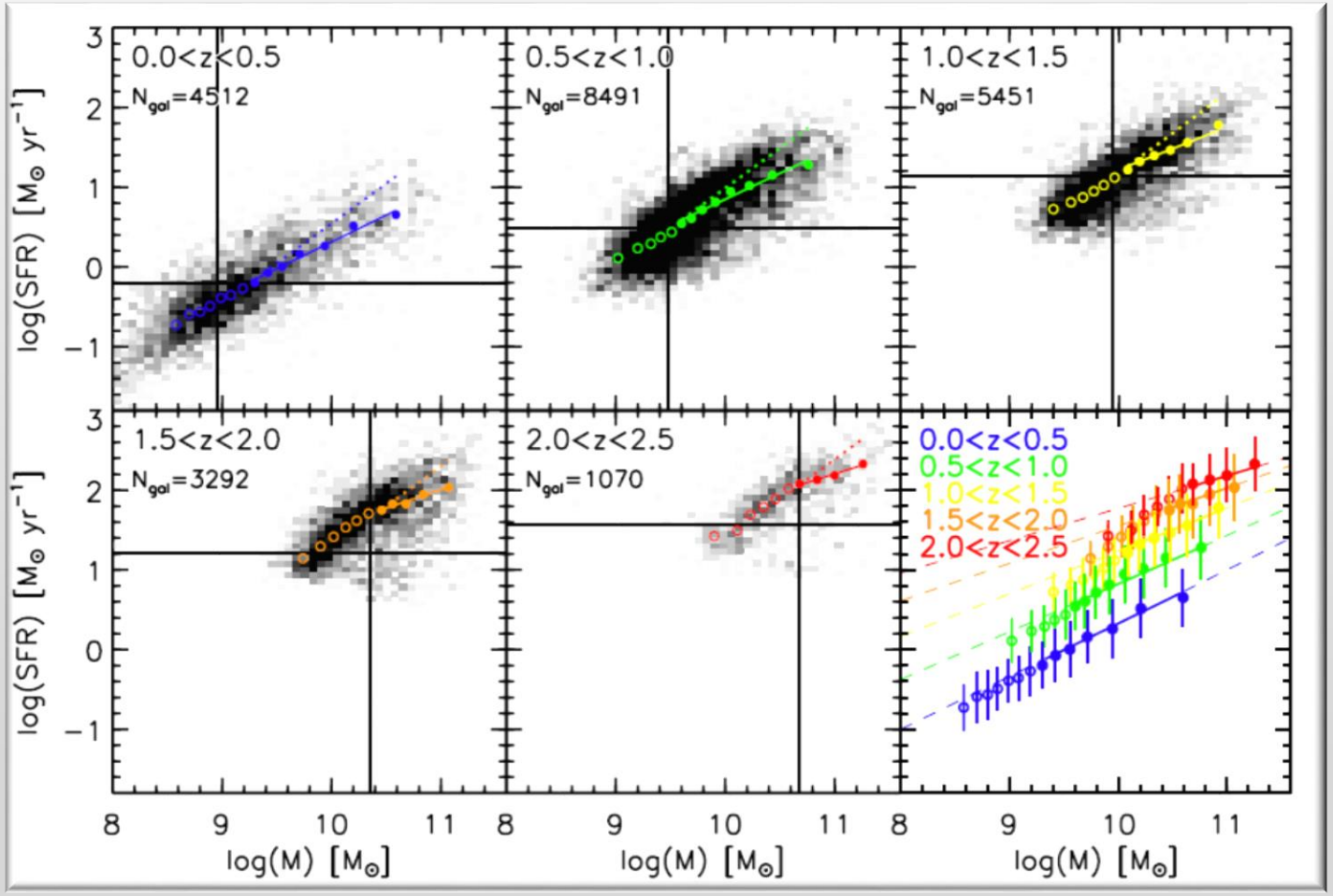
- The tight SFR – M_* relation is hold up to high redshift
- The scatter is roughly constant ~ 0.34 dex, independent of redshift and M_*
- SFMS has nearly-linear slope with flattened trend in massive end

SFMS relation :

$$\log(\mathrm{SFR}) = \alpha(z)(\log M_\star - 10.5) + \beta(z)$$

with $\alpha(z) = 0.70 - 0.13z$ **(slope)**

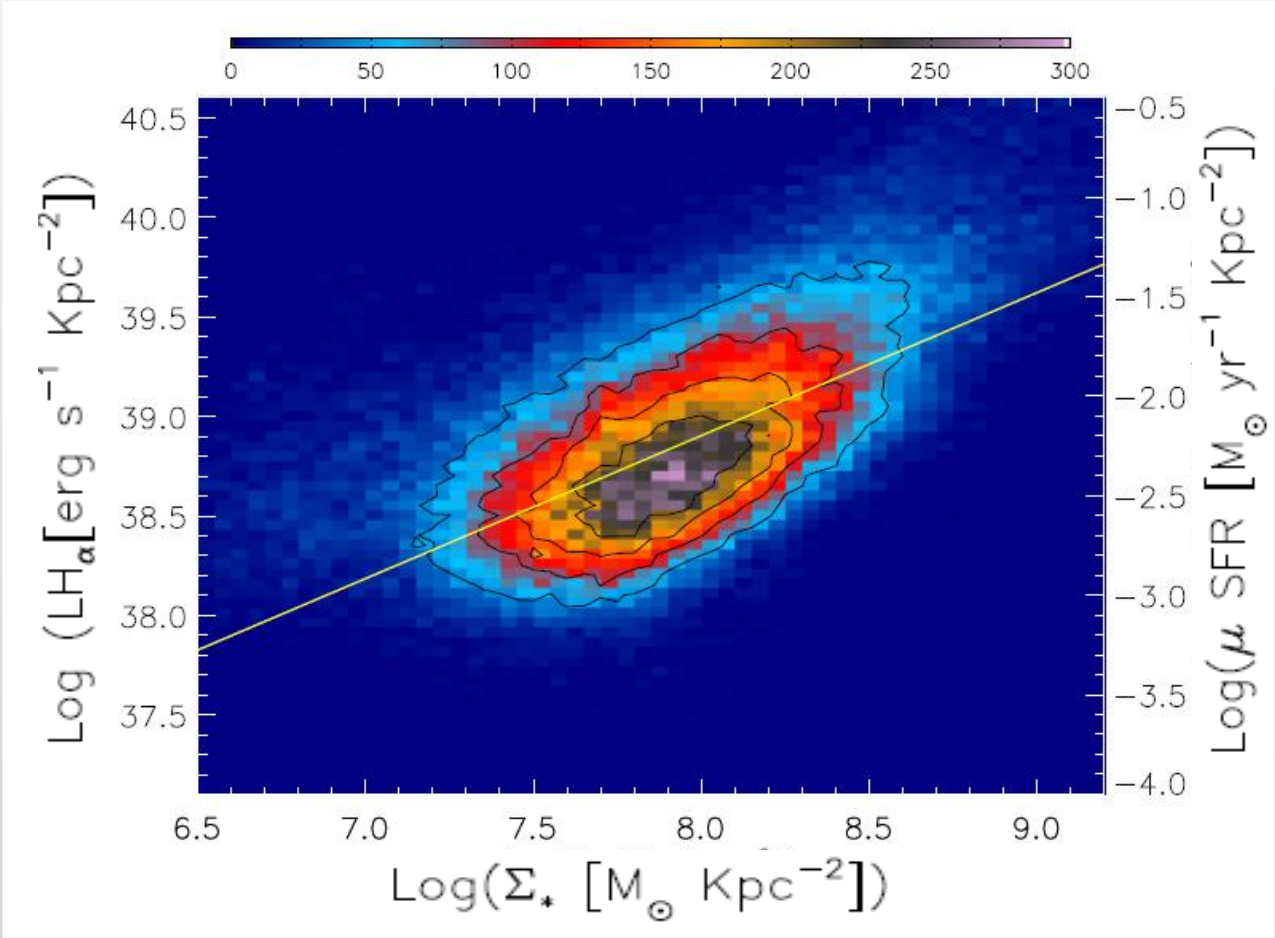
$\beta(z) = 0.38 + 1.14z - 0.19z^2$ **(normalization)**



Whitaker *et al* 2012 *ApJ* **754** L29

Spatially Resolved SFMS Relation

- SFMS relation is preserved in kpc scale
- Spatial scale 0.5-1.5kpc
- Integrated and resolved SFMS have similar characteristic slope and tightness
- Sample : local spiral galaxies (0.005<z<0.03)



CALIFA Survey

$$\log(\mathrm{SFR}) = 0.72\log(\mathrm{M}*) - 7.95$$

Cano-Díaz *et al* 2016 *ApJ* **821** L26

Motivations

* Study the local variations of sSFR and to understand the origin of scatter in spatially resolved SFMS

* Study the local variations of sSFR in barred and unbarred galaxies and to look for the indication of secular evolution promoted by bars

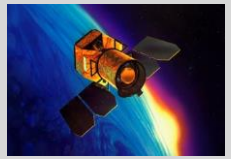
* Establish the method to derive spatially-resolved SFR and M_* (in pixels space) of galaxy based on SED fitting → pixel-to-pixel SED fitting

Data Sample

- We use data from **GALEX and SDSS** (7bands, $1344 \leq \lambda \leq 10000$ Å)
- Data sample : 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>40 in 7 bands
- Resulted in 93 galaxies sample

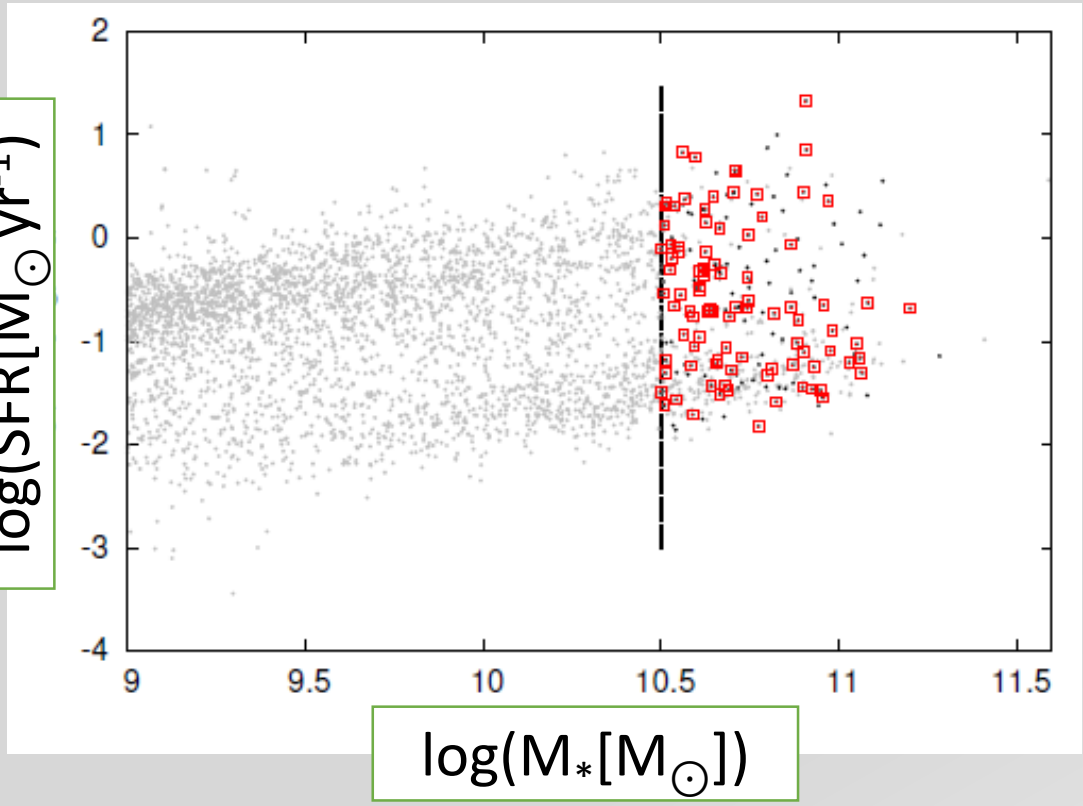
Edge-on Face-on

GALEX



SDSS

MPA/JHU Galaxy Catalog for 0.01<z<0.02

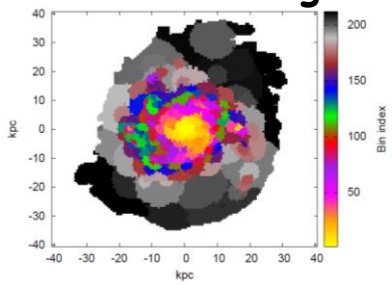


Methodology(1) : Data Analysis

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

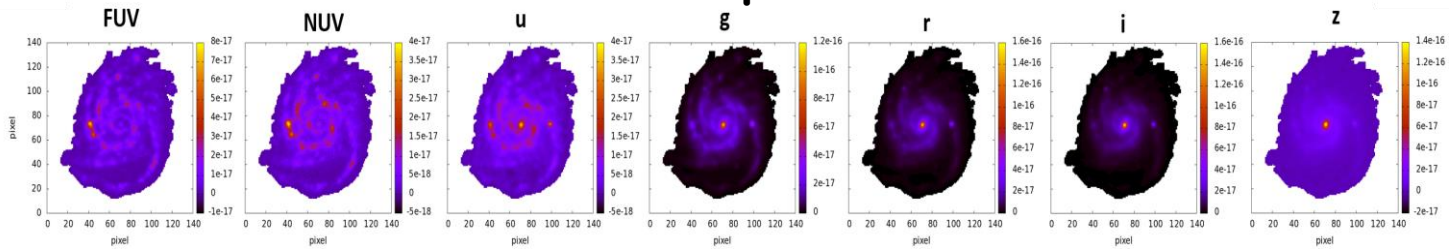
Pixels binning

Pixels Binning



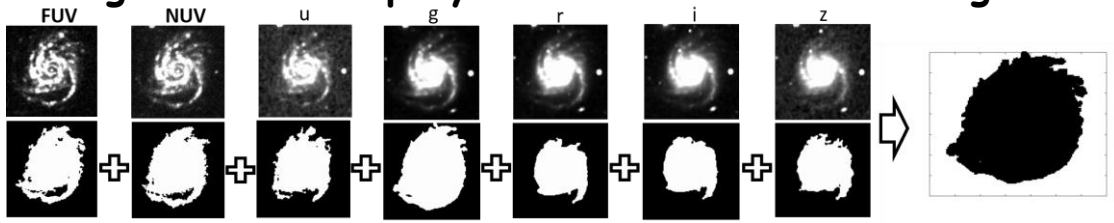
Masking forground stars

7 bands resolved photometric fluxes

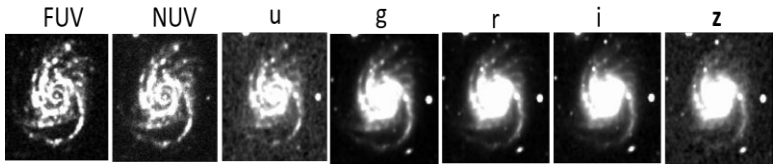


Get 7 bands fluxes and their uncertainties

7 segmentation map by SEXTRACTOR → summing



Defining galaxy's region



PSF Matching using convolution kernels created using PSFMATCH Iraf

PSF Matching

Methodology(2) : SEDs Models Construction

"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)"
"Chabrier (2003) IMF"
"exponentially declining SFH"

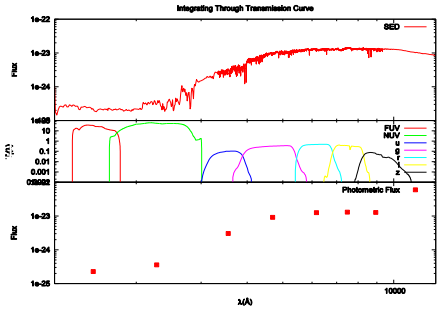
Parent models

Tricubic interpolation

Cubic Spline

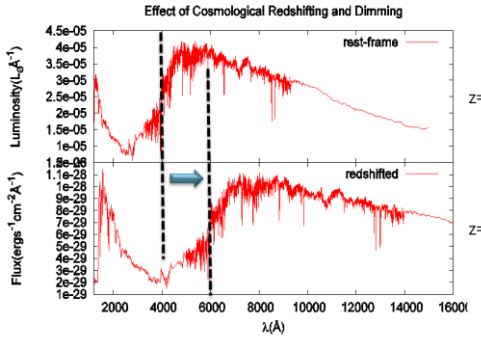
Model interpolation

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



7 bands filtering

Redshifting



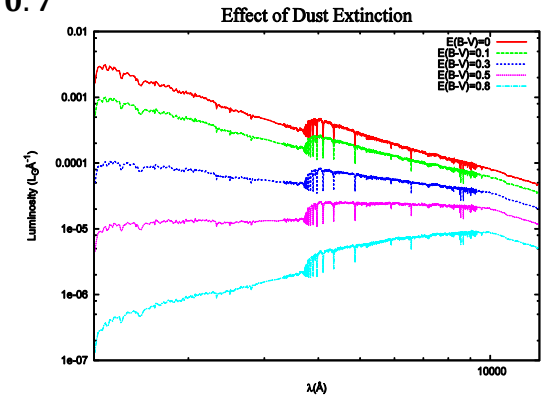
$$H_0 = 70 \mathrm{km s^{-1} Mpc^{-1}}$$

$$\Omega_m = 0.3$$

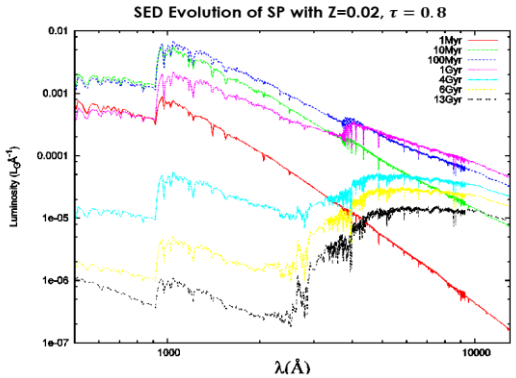
$$\Omega_\Lambda = 0.7$$

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

Calzetti 2000



GALAXEV

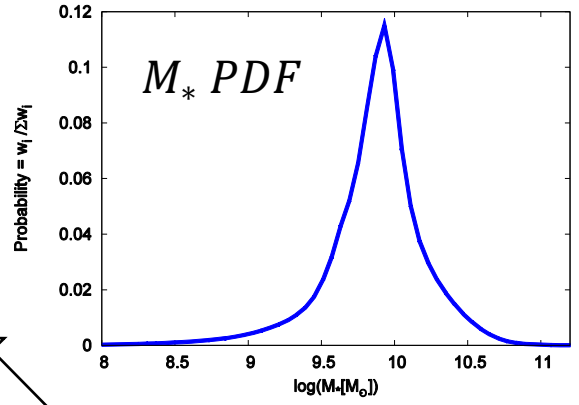


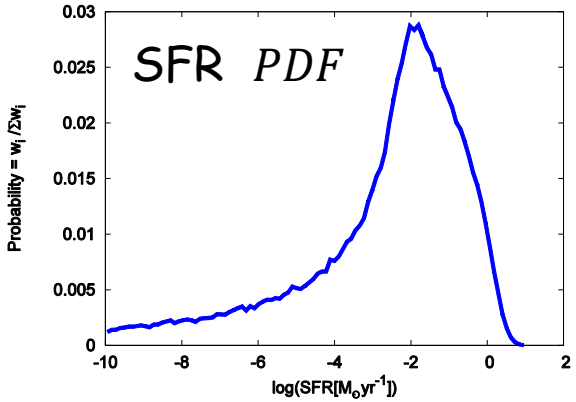
Methodology(3) : Pixel-to-Pixel SED Fitting

Posterior mean :

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

with θ : SFR and M_*





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

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

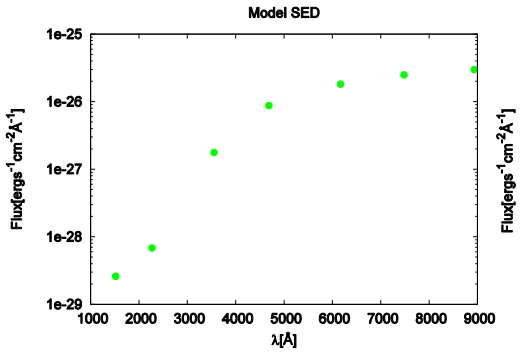
Model's weight : (Student's t distribution)

$$W_{\theta i} = \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\sqrt{\nu\pi}\Gamma\left(\frac{\nu}{2}\right)}\left(1+\frac{(\chi_i^2)^2}{\nu}\right)^{-\frac{\nu+1}{2}}$$

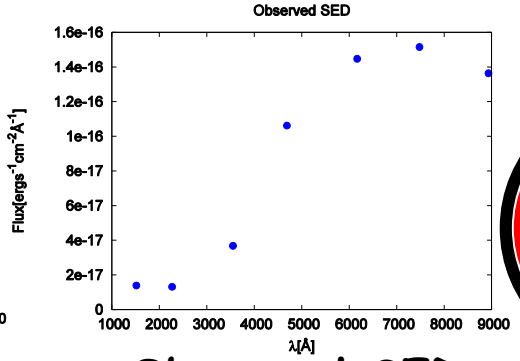
$$\chi_i{}^2 = \sum_i \left(\frac{f_{d,i} - s f_{m,i}}{\sigma_i}\right)^2$$

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

"Generate 100 random SEDs following Normal distribution around observed SED"

Calculate SFR and M_* uncertainties using Monte-Carlo method

Calculate posterior mean of SFR and M_*

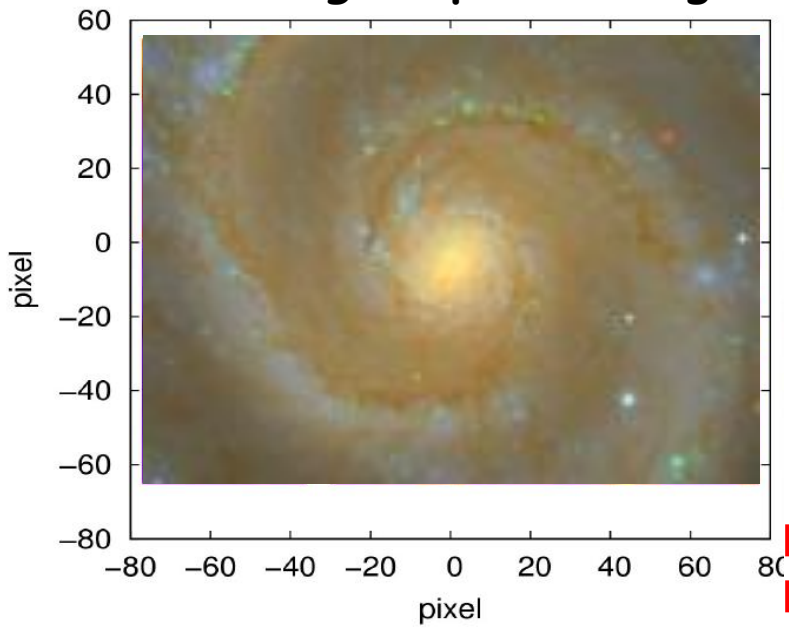
Calculate weight of each model, w_i

Calculate $\chi_i{}^2$ of each model

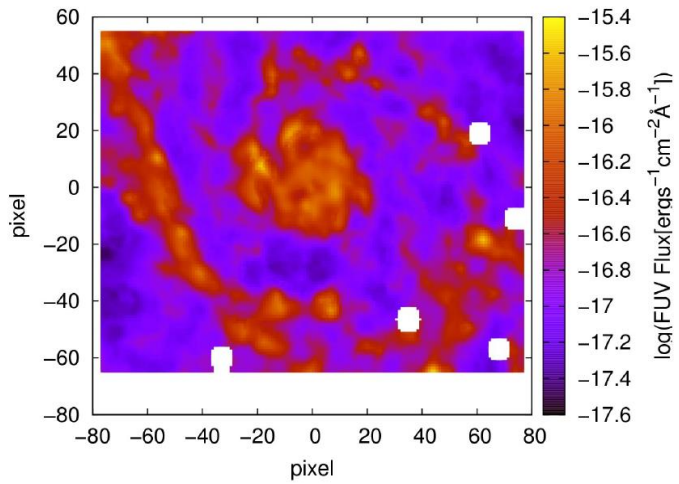
"with Bayesian Statistic"

Case Example : M51 Galaxy

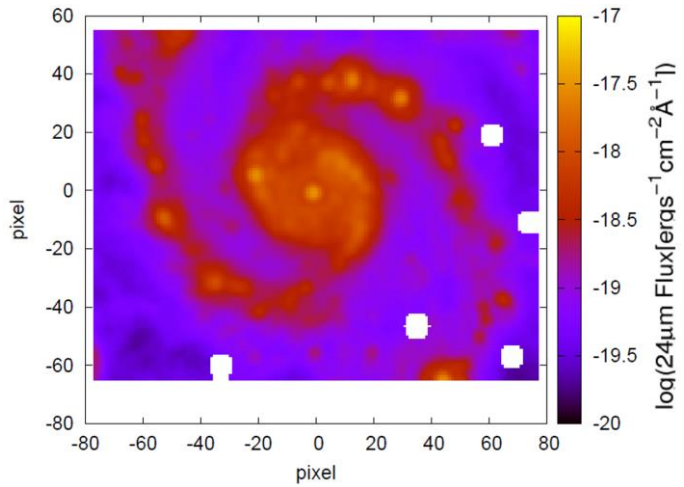
SDSS *gri* Optical Image



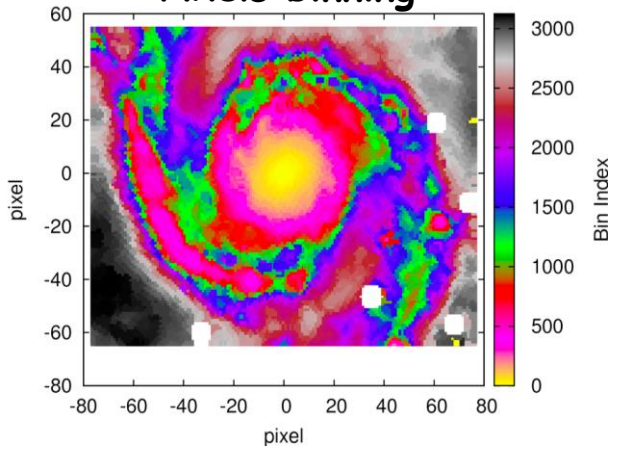
FUV Flux



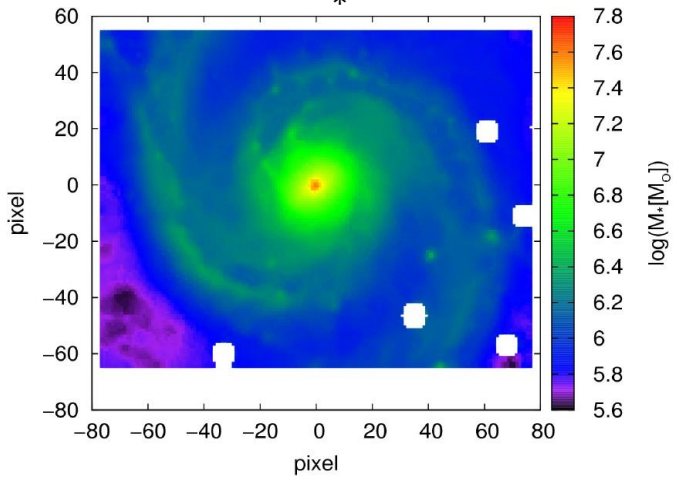
$24\mu m$ Flux



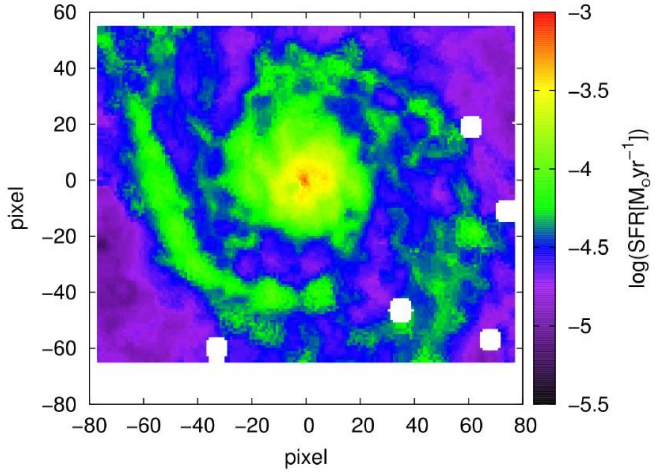
Pixels binning



M_*



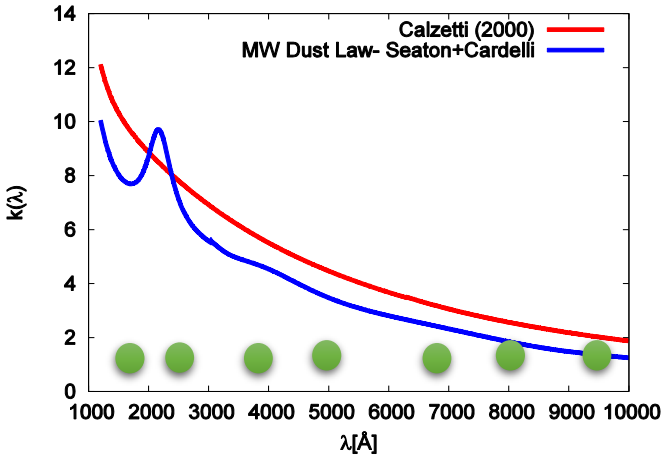
SFR



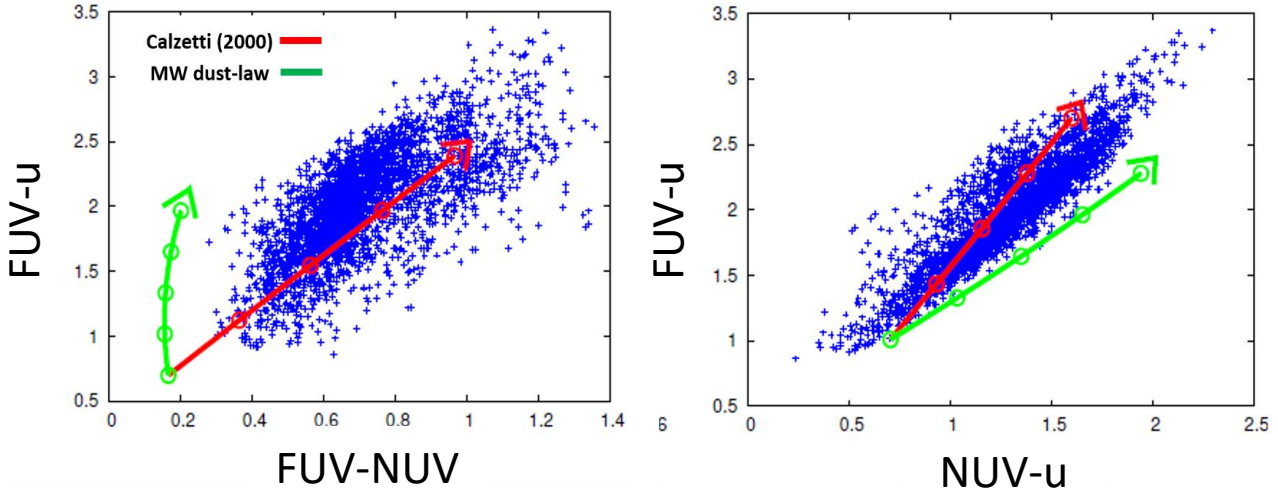
Dust Extinction Law : Why Calzetti (2000)?

- MW dust-law (Seaton(1979)+Cardelli(1989)) has "curvy" dust extinction track along FUV-NUV
- Calzetti (2000) is better fitted to spatially resolved SEDs of M51 and our galaxies sample

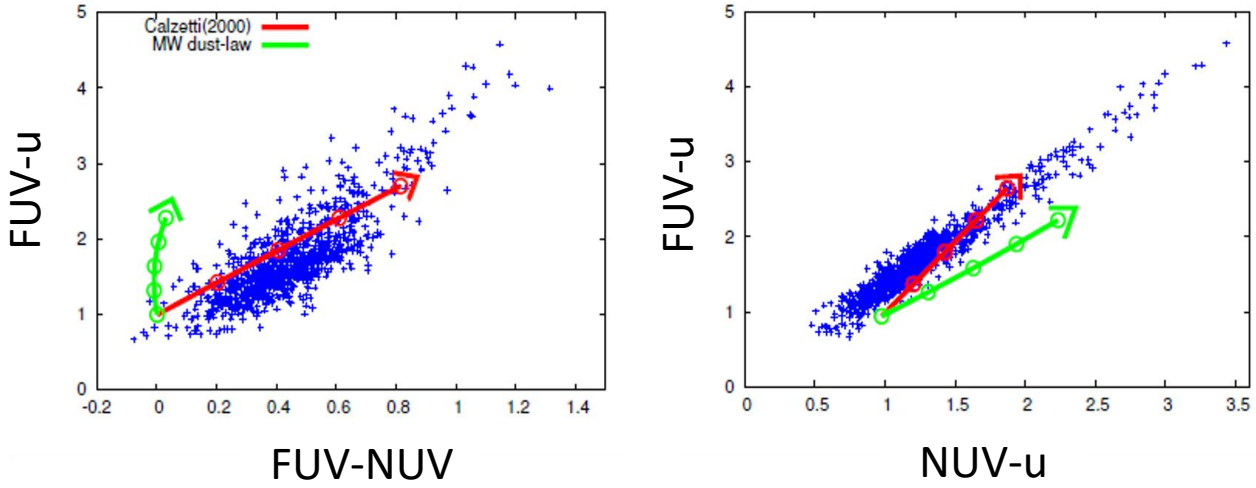
Dust extinction curve



M51's photometry (bin space)



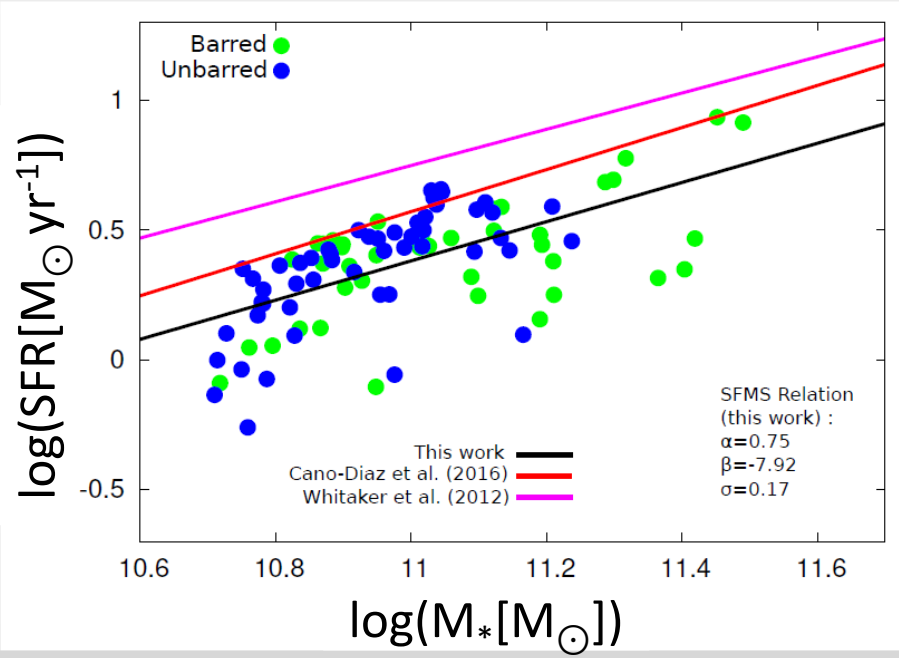
10 galaxies from data sample (bin space)



Result and Discussion

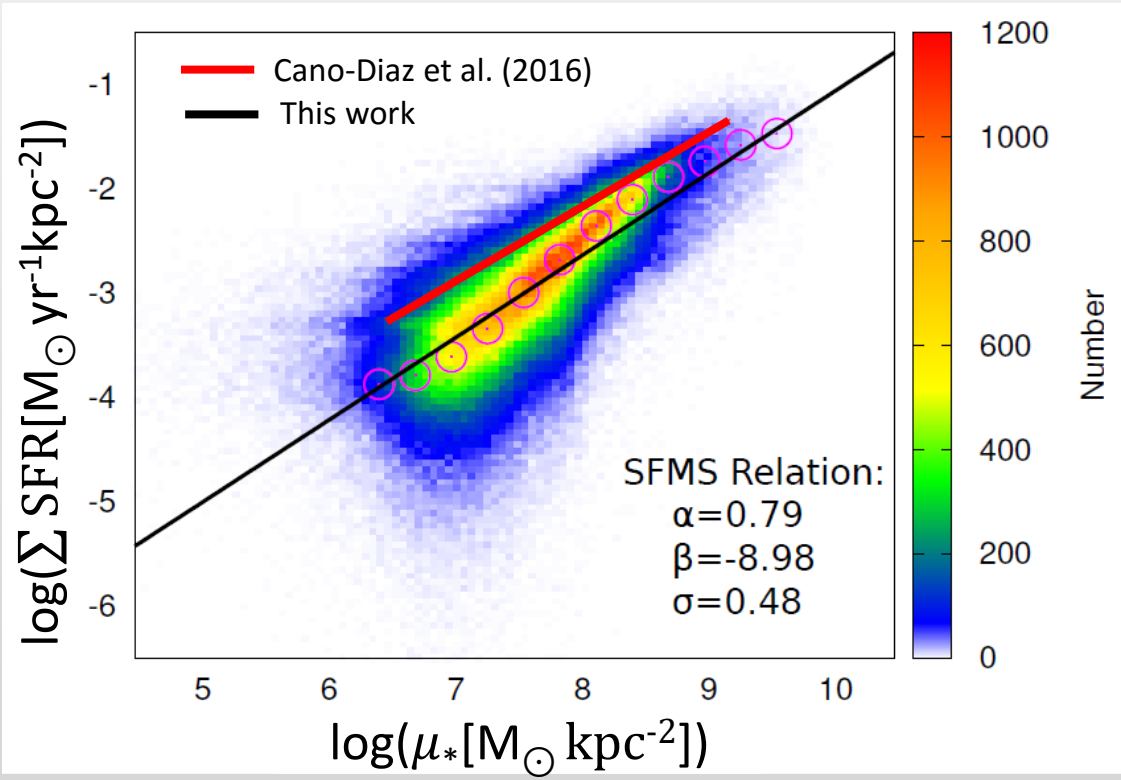
Integrated and Spatially Resolved SFMS

Integrated SFMS



- Star formation main sequence (SFMS) is spatially preserved (in pixels space, 1pixel : 0.3-0.6 kpc)
  - Characteristic SFMS relation of integrated and resolved SFMS are similar (in slope)
- Average resolved SFMS profile show tendency toward flatten in massive end

Spatially resolved SFMS (pixels space)



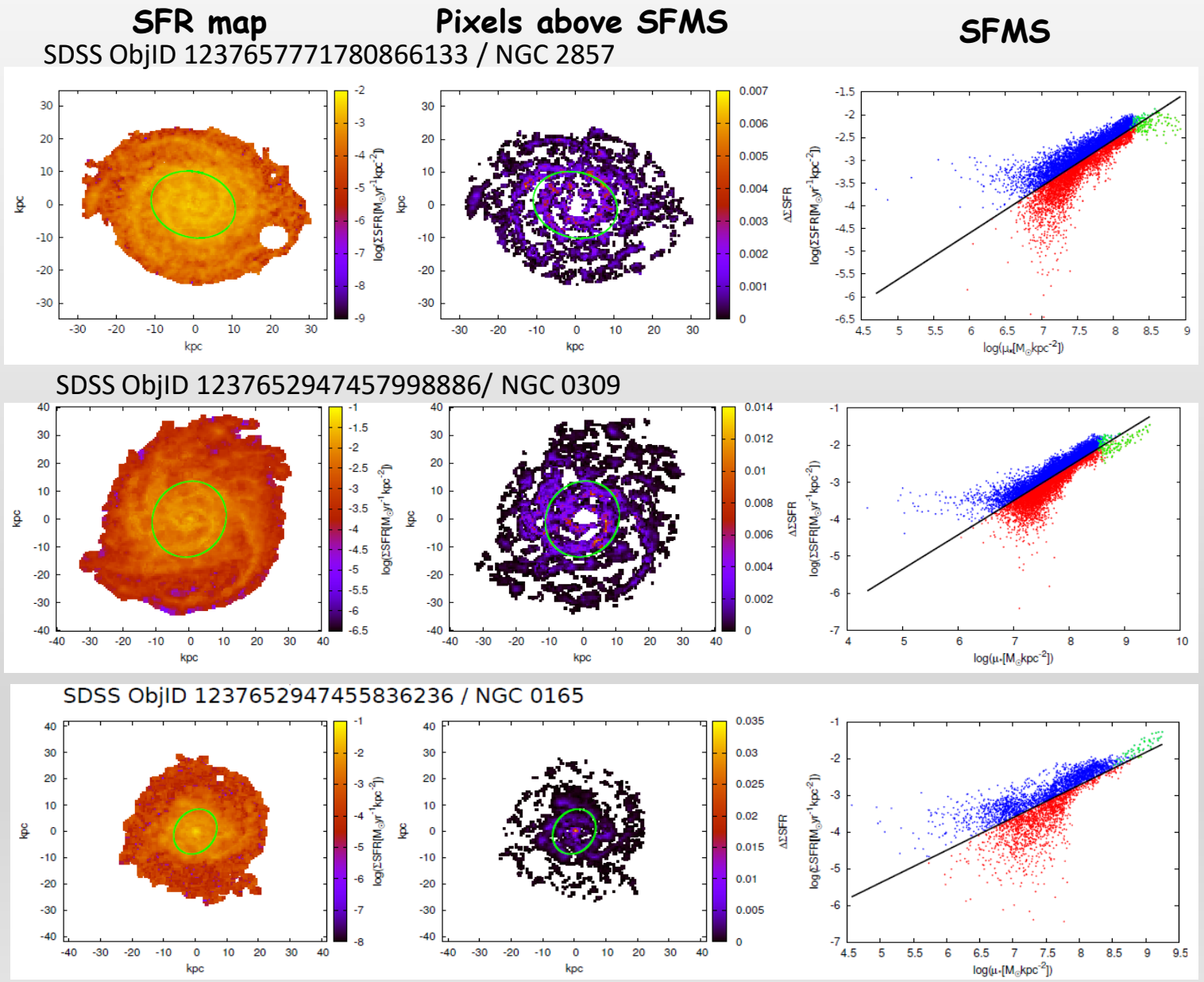
$$\log(SFR) = \alpha \log(M_*) + \beta$$

accounted all galaxies pixels : 375089 pixels

Resolved SFMS in Individual Galaxy : Local Variation of sSFR

- Pixels above SFMS line roughly located in spiral arms region
- While pixels located in underlying disks are residing below SFMS line

- Green points correspond to pixels located in "core" ($r<10^{-0.5}$ half-mass radius)
- Green ellipse correspond to half-mass radius

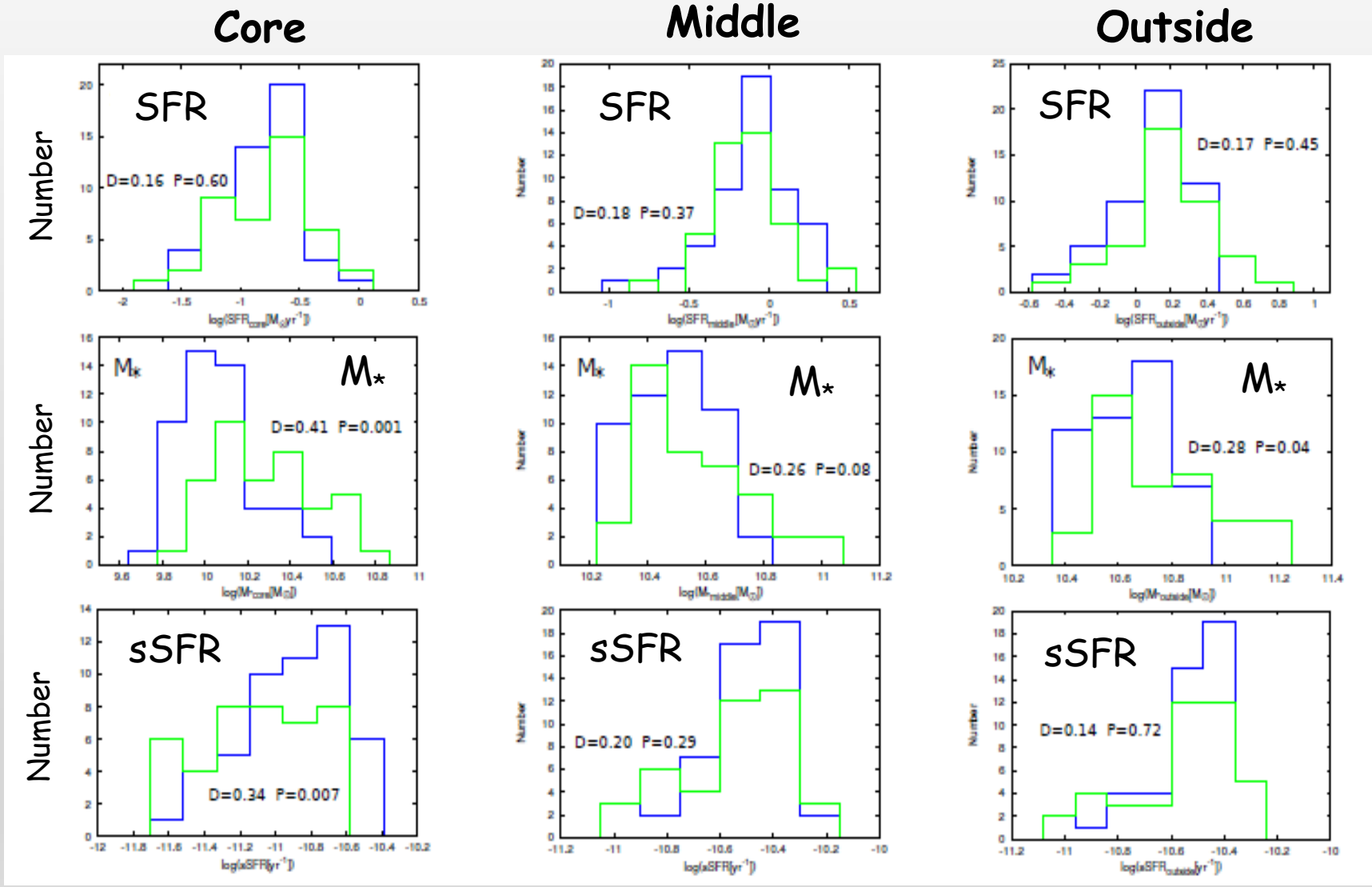


Local Variation of SFR, M_*, and sSFR in Barred and Unbarred Galaxies : Their Role on the Scatter of Resolved SFMS

Local Variation of SFR, M*, and sSFR

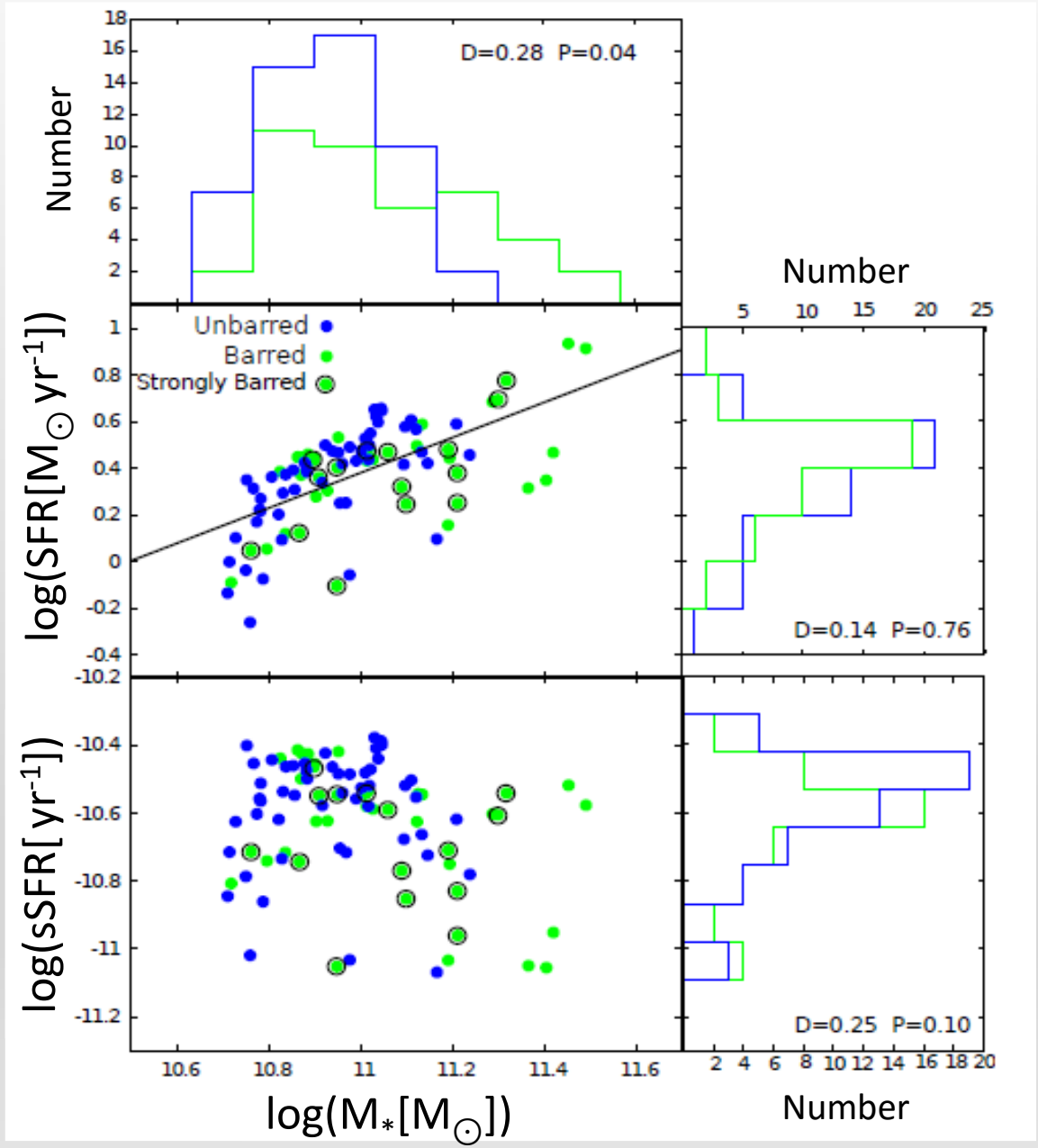
- Barred galaxies have more massive core than unbarred galaxies
- Barred galaxies have core sSFR lower than those of unbarred galaxies
- Barred and unbarred galaxies have similar local variation of SFR in all 3 regions

Core : $r < 10^{-0.5} r_e(M_*)$
Middle : $10^{-0.5} r_e(M_*) < r < r_e(M_*)$
Outside : $r > r_e(M_*)$



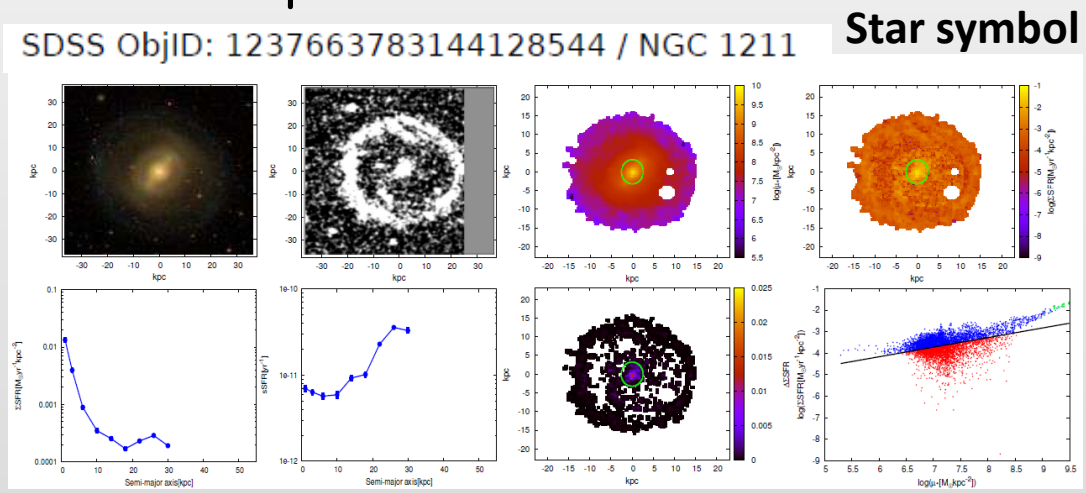
Effect of Local Variation of SFR, M_*, and sSFR on Global Values

- Integrated SFR of barred and unbarred galaxies are similar
- There is no significant different of integrated sSFR between barred and unbarred galaxies
- Lower sSFR in core region of barred galaxies doesn't give significant effect toward integrated sSFR
- Barred galaxies are in average more massive than unbarred galaxies

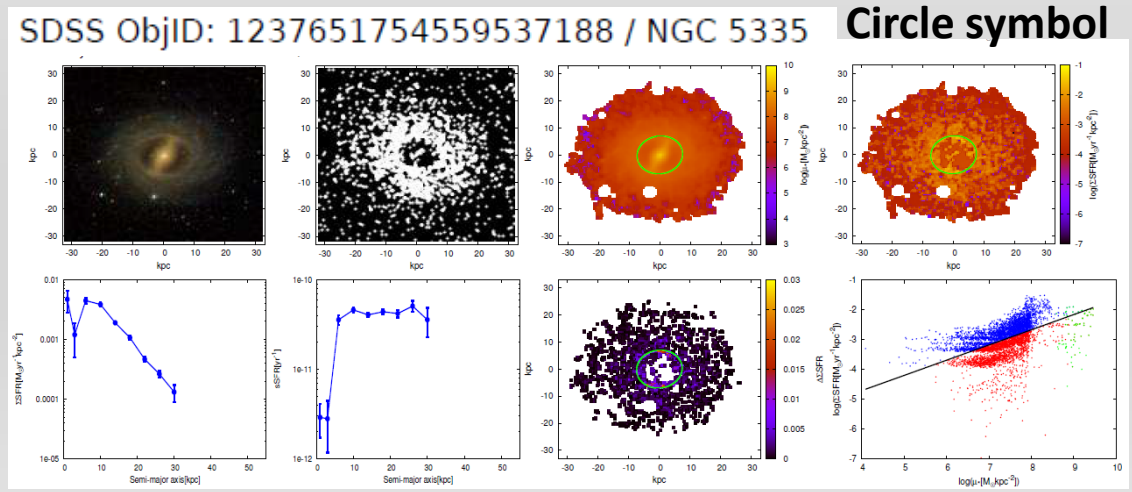


Bar-driven Secular Evolution

- We find a sign of evolutionary epoch of bar-driven secular evolution in our strongly-barred galaxies sample

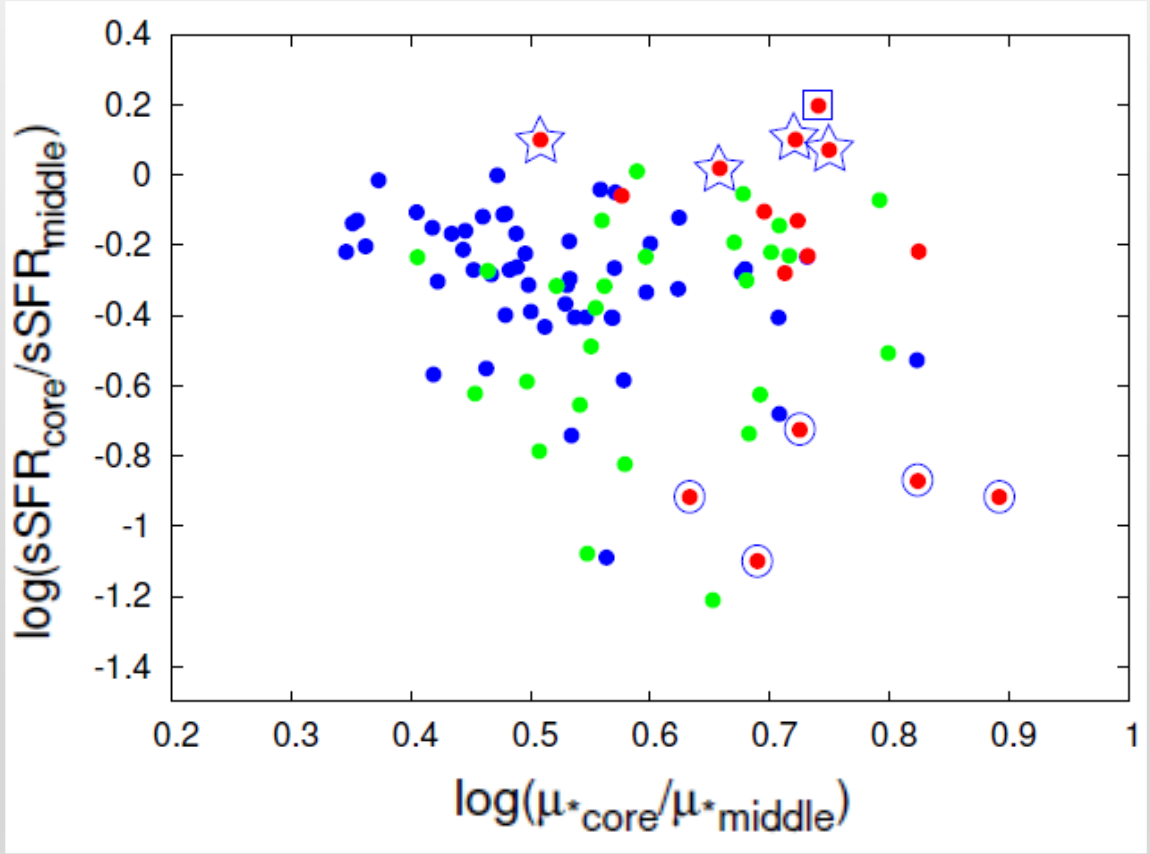


Star symbol



Circle symbol

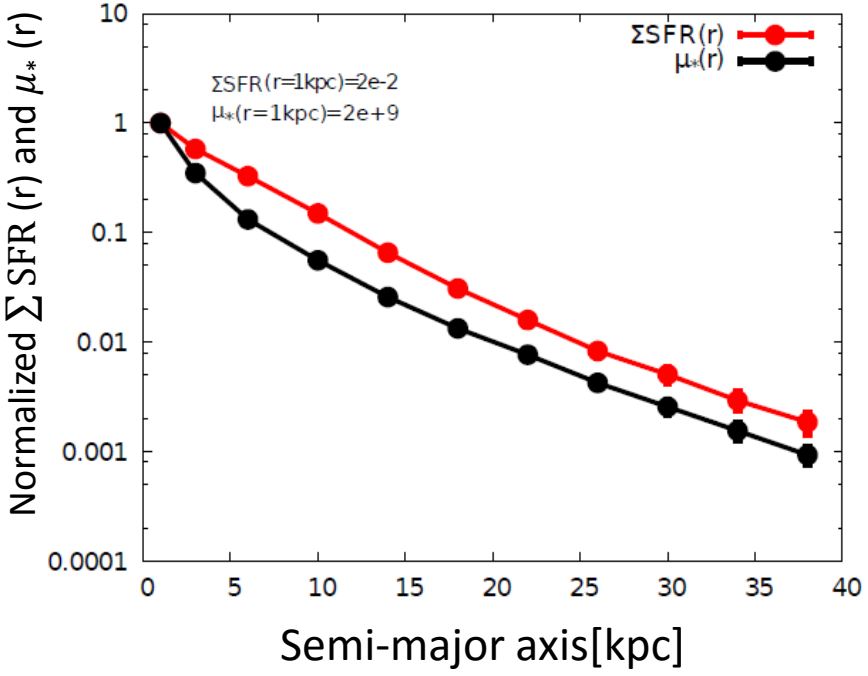
Unbarred Weakly-barred Strongly-barred



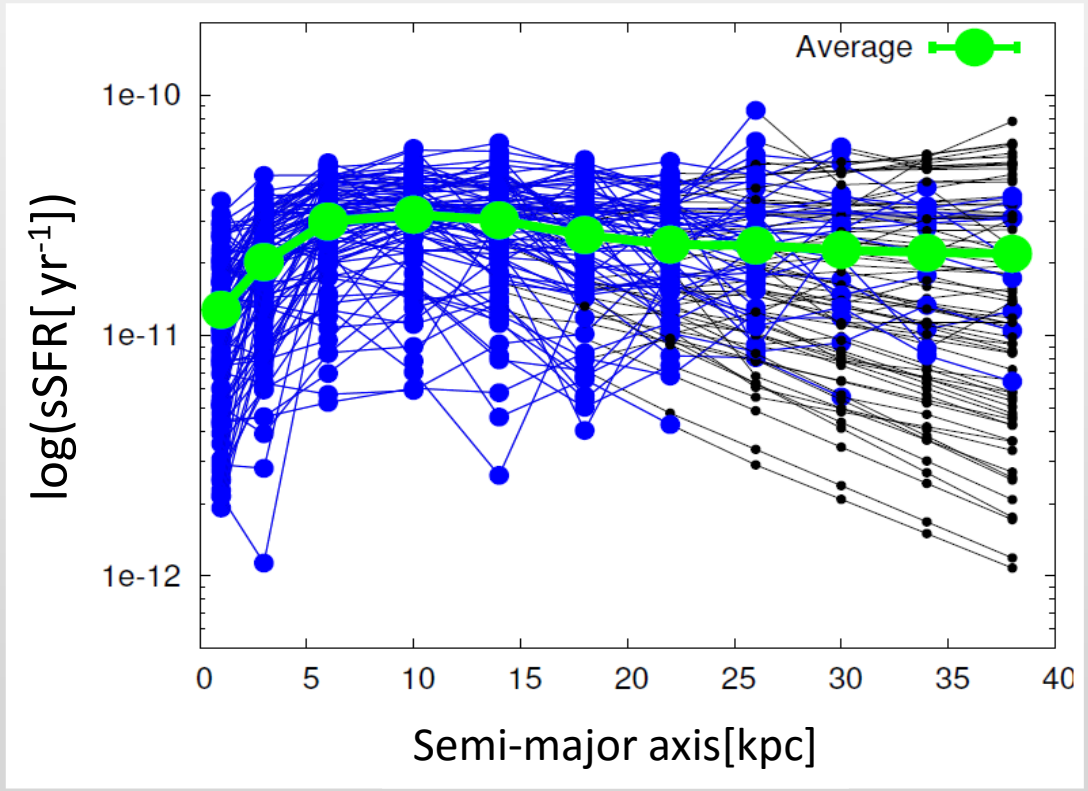
Effect of Global/Integrated M_* on the Scatter of Spatially Resolved SFMS

Radial Profile of SFR, M*, and sSFR

Normalized radial profile of SFR and SM



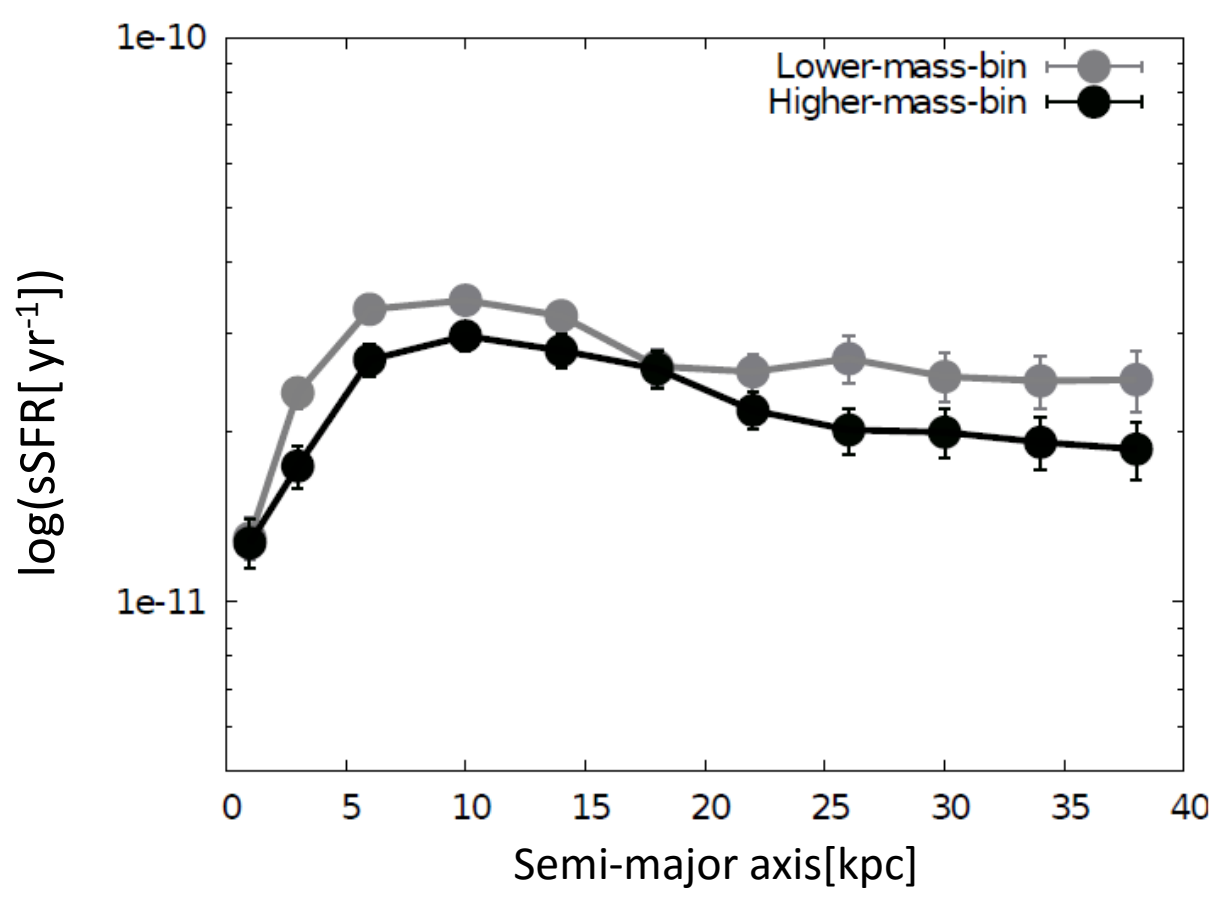
- $\sum$SFR(r) in average following $\mu_*(r)$ but slightly more extended
- sSFR(r) profiles in average is flat in the outskirt, while suppressed ($\sim$0.4 dex) in the central region



- This result may be consistent with "inside-out" scenario of disk galaxies formation (e.g., White & Frenk 1991; Kauffmann 1996; Mo et al. 1998; Cole et al. 2000)

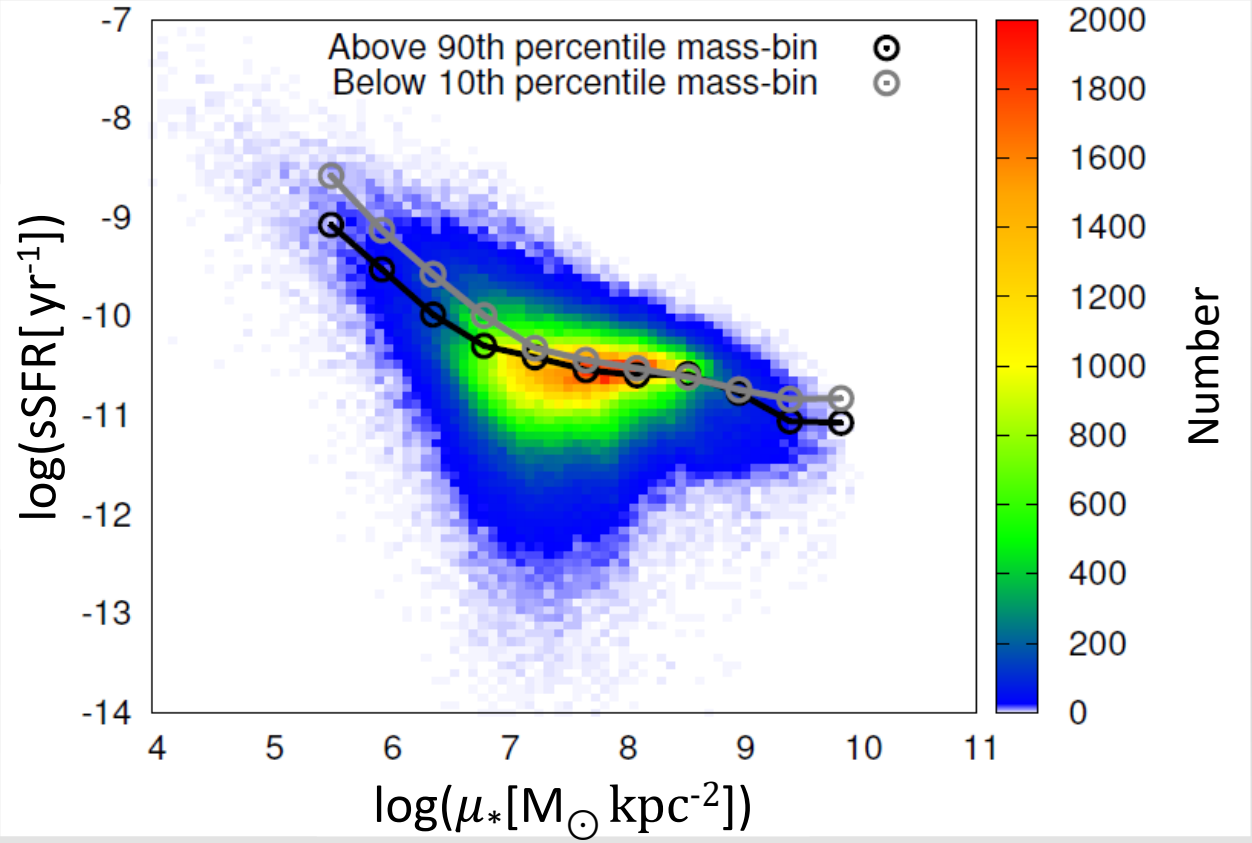
Effect of Global M_* on the sSFR(r) Profile

- sSFR tells about relative ratio of current and past star formation rate
- More massive galaxies have sSFR(r) lower than less massive galaxies in all radius→ Spatially resolved "Downsizing"?



Scatter in the Spatially Resolved SFMS : Effect of Integrated M_* on Local sSFR

- There is tendency of local sSFR (of galaxies sample) to have flat trend with local stellar mass density → consistent with spatially resolved SFMS
- There is tendency of local sSFR of more massive galaxies to have lower value than local sSFR of less massive galaxies with the same local stellar mass density



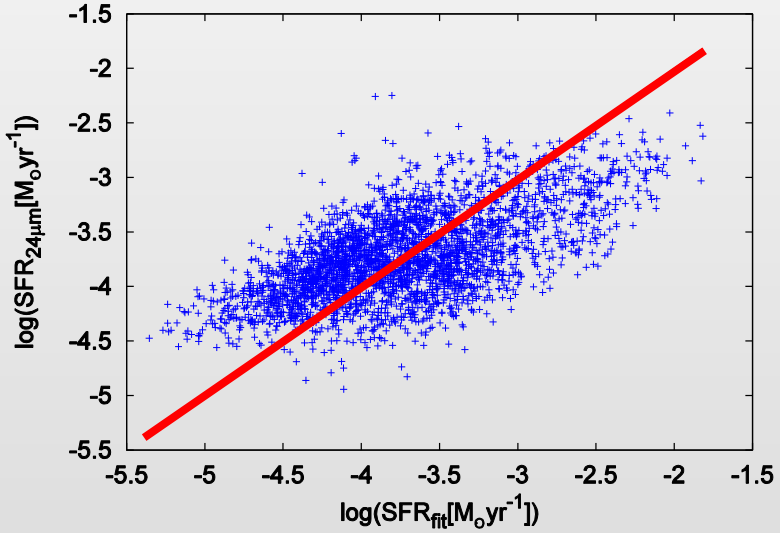
Summary

* Star formation main sequence relation is locally preserved, with similar slope and scatter (same order) as those of global
* Local variation of sSFR and global/integrated M_* give contribution to the scatter in spatially resolved SFMS
* Barred galaxies have more massive core and lower sSFR in core than unbarred galaxies
* Barred galaxies don't show systematic offset in integrated sSFR compare to unbarred galaxies

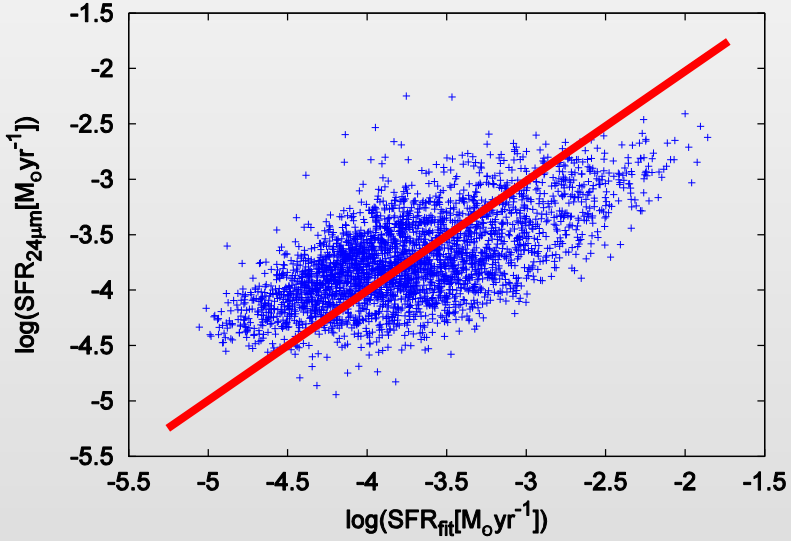
Thank you very much for your attention

Robustness of Fitting Method – M51 Case

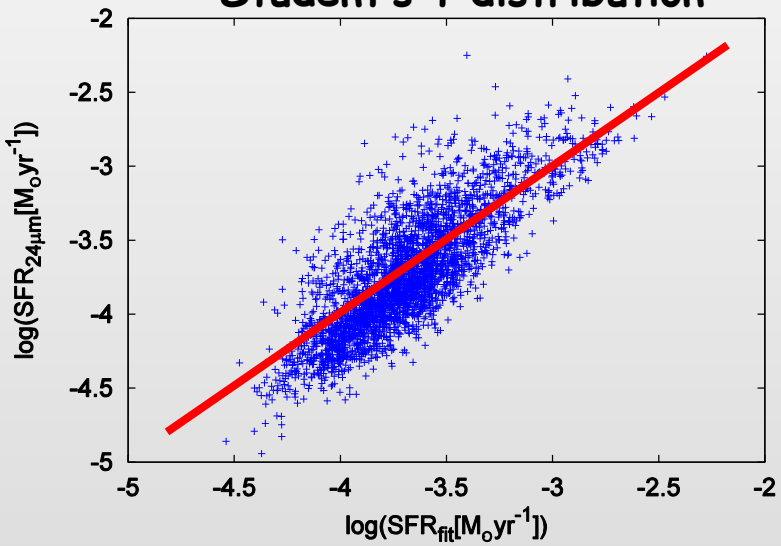
Maximum likelihood

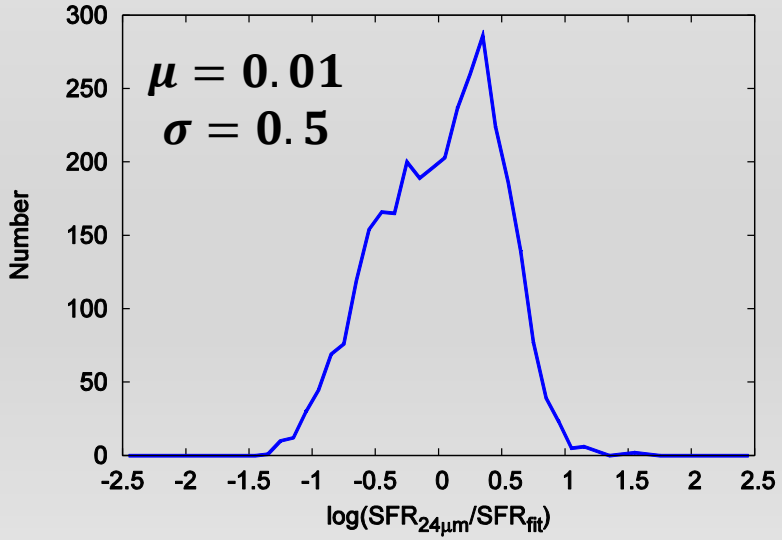


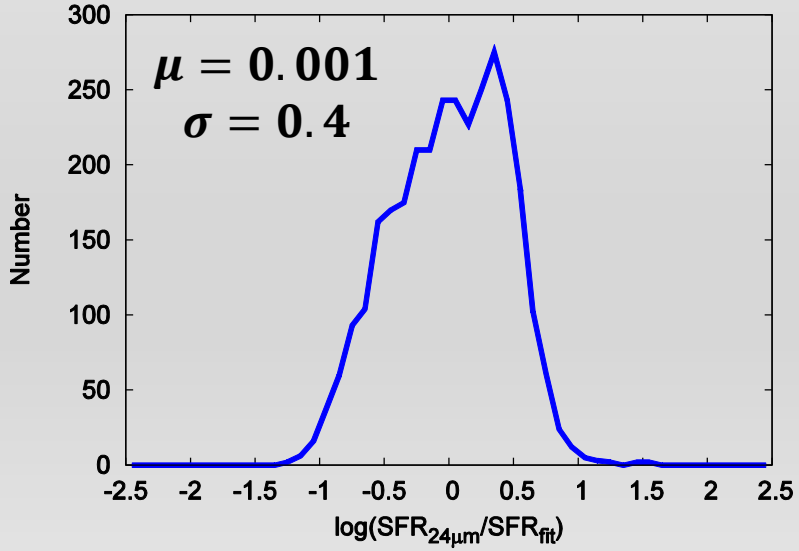
Bayesian with $P(\theta|X) \propto exp\,(-\chi^2/2)$

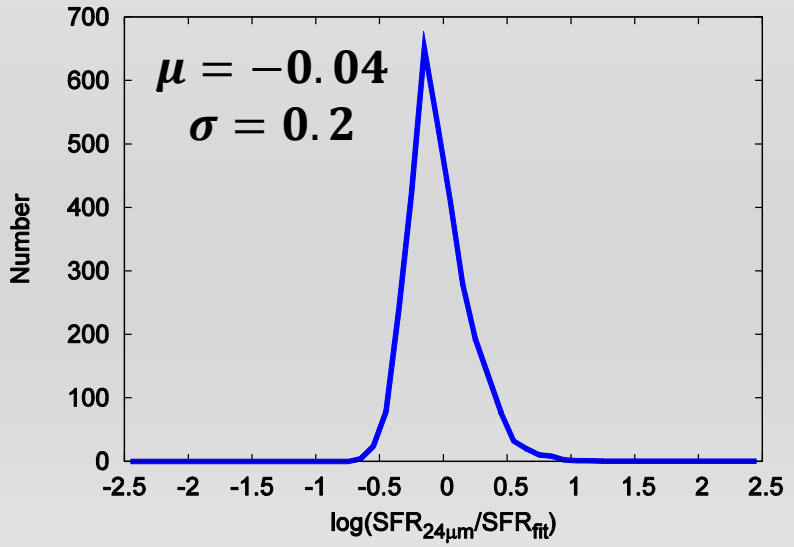


Bayesian with $P(\theta|X)$ following Student's t distribution



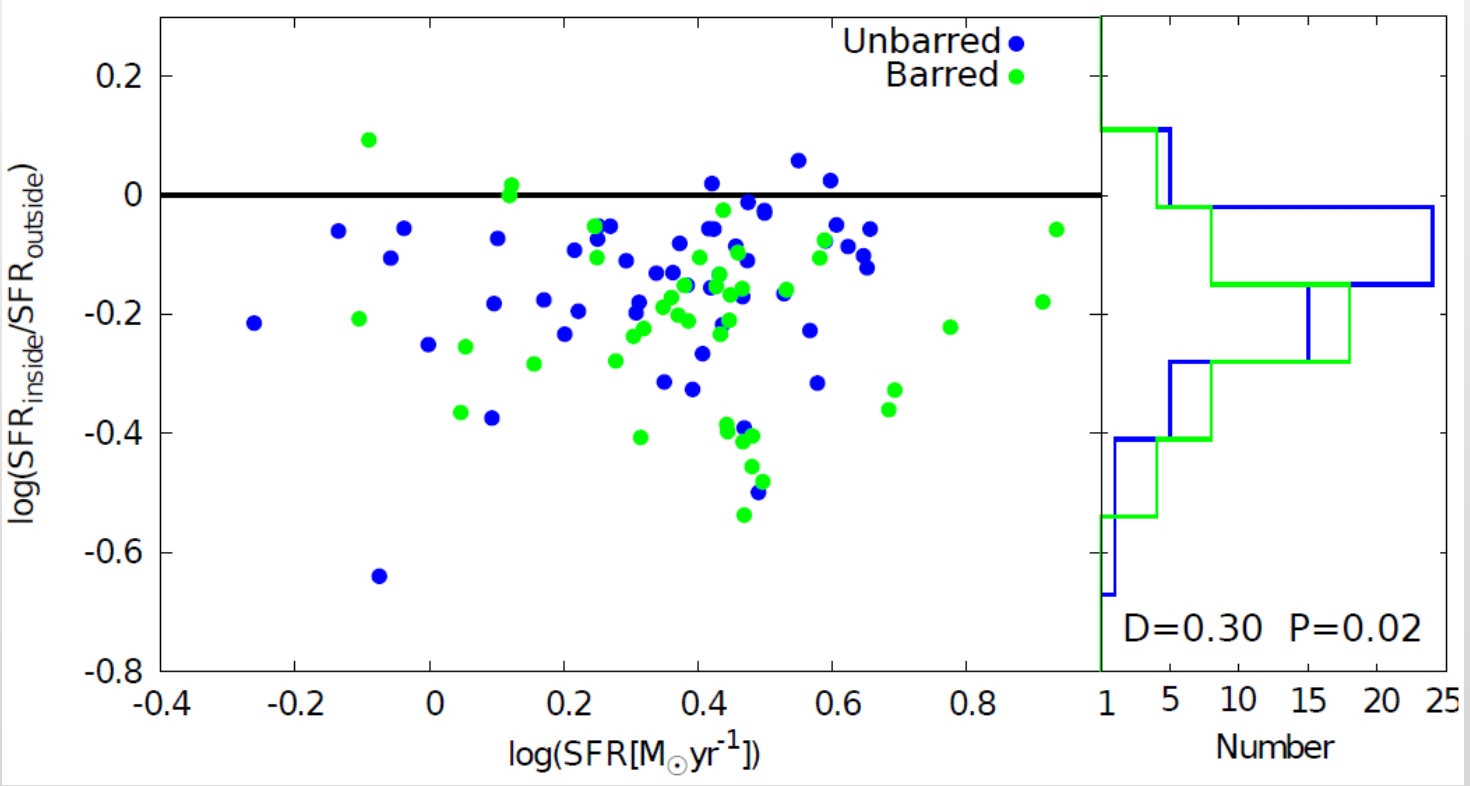






Local Variation of SFR, M_*, and sSFR (1)

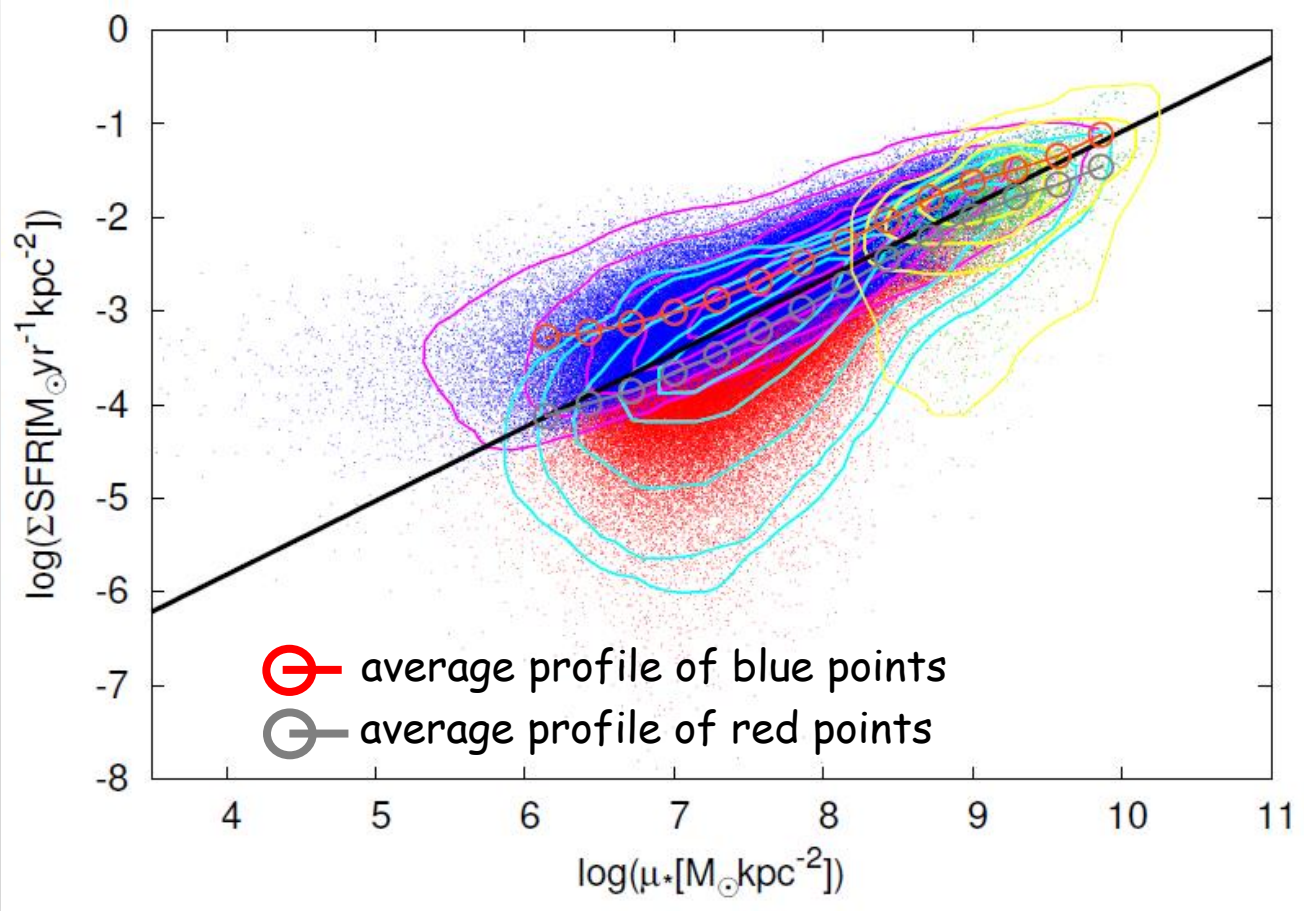
- Majority of galaxies sample (local massive spiral galaxies) have SFR_outside > SFR_inside
- The ratio (SFR_outside/SFR_inside) of barred galaxies is in average lower than those of unbarred galaxies, with KS-test show they are significantly different (within significant level of 0.05)



"inside" and "outside" regions are divided by effective radius (half-mass radius)

Scatter in the Spatially Resolved SFMS : Effect of Local Variation of SFR on the Scatter of Resolved SFMS

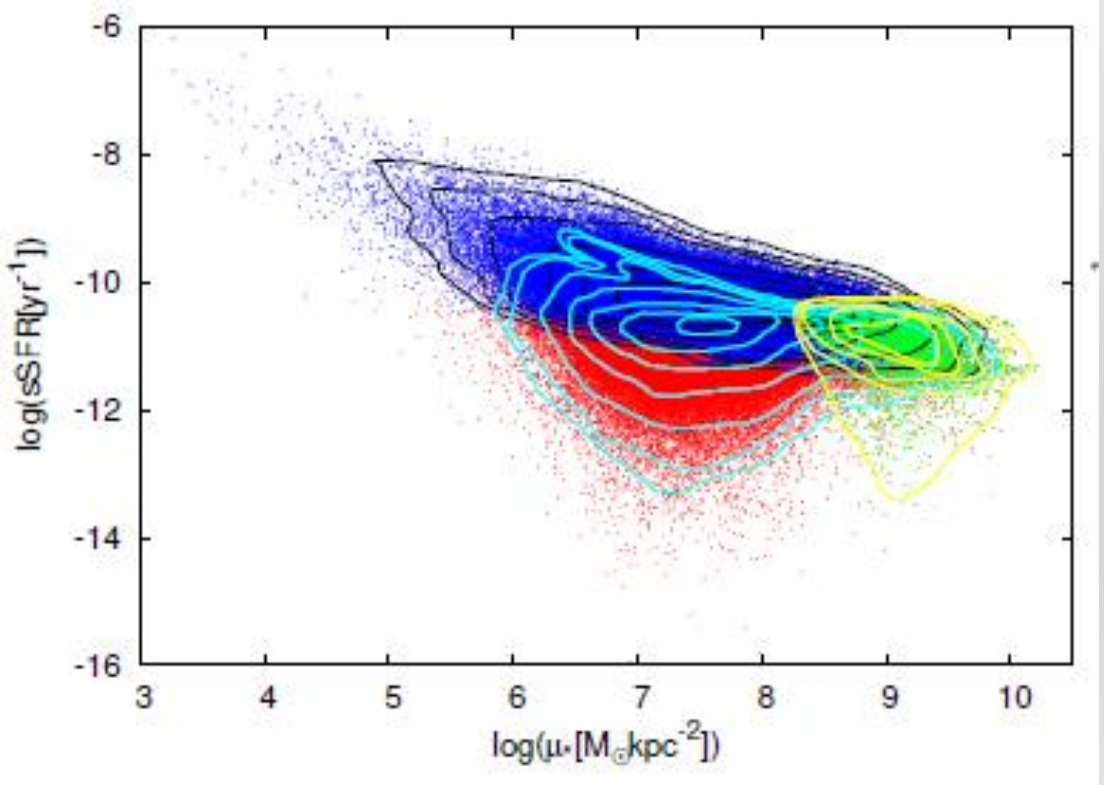
- Location of pixels relative to SFMS relation in each galaxy are maintained in resolved SFMS over all galaxies pixels
- It's local variation of SFR in each galaxy which responsible to the scatter of resolved SFMS over all galaxies pixels
- Relative ratio between SFR of blue points and red points is 0.52 dex

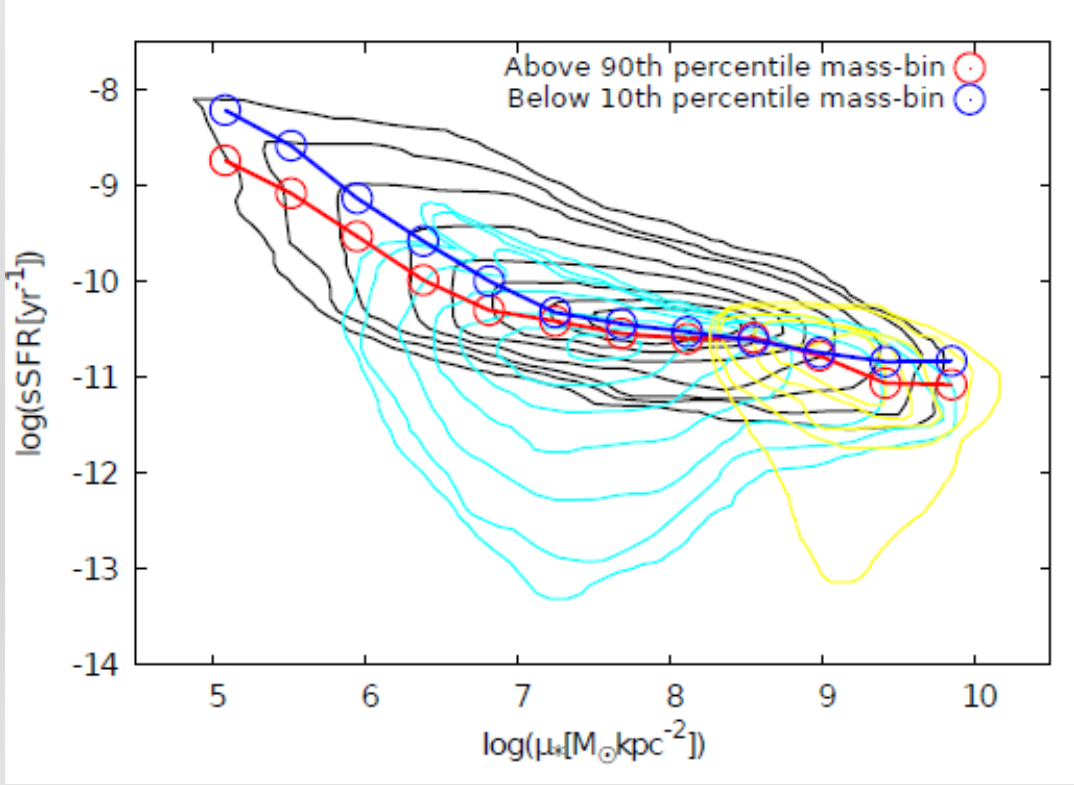


-**blue points** : pixels above SFMS relation in each galaxy
-**red points** : pixels below SFMS relation in each galaxy
-**green points** : pixels located in "core" ($r<10^{-0.5}$half-mass radius)

Scatter in the Spatially Resolved SFMS : Effect of Integrated M_* on Local sSFR

- There is tendency of local sSFR (of galaxies sample) to have similar value, flat trend with local stellar mass density → consistent with spatially resolved SFMS
- There is tendency of local sSFR of more massive galaxies to have lower value than local sSFR of less massive galaxies with the same local stellar mass density





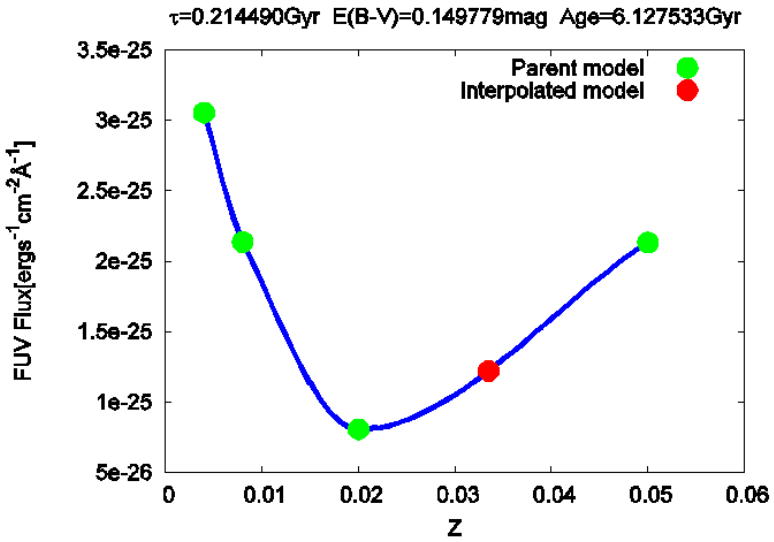
Model Interpolation – in 4D (Z,tau,E(B-V),age)

- 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

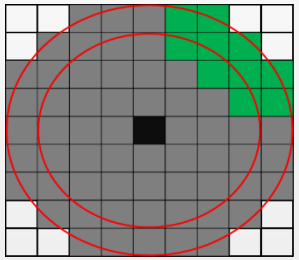
Cubic Spline interpolation : 1D (Z)

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

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



Pixels Binning Technique



- This research used new pixels binning technique which considers 3 criteria :
  - "closeness"
  - "similarity SED's shape" among bin's members ($\chi_{12}^2 < \chi_{\text{thresh}}^2$)
  - 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 :

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