The *Chocolate Chip Cookie* Model: dust geometry of disk galaxies

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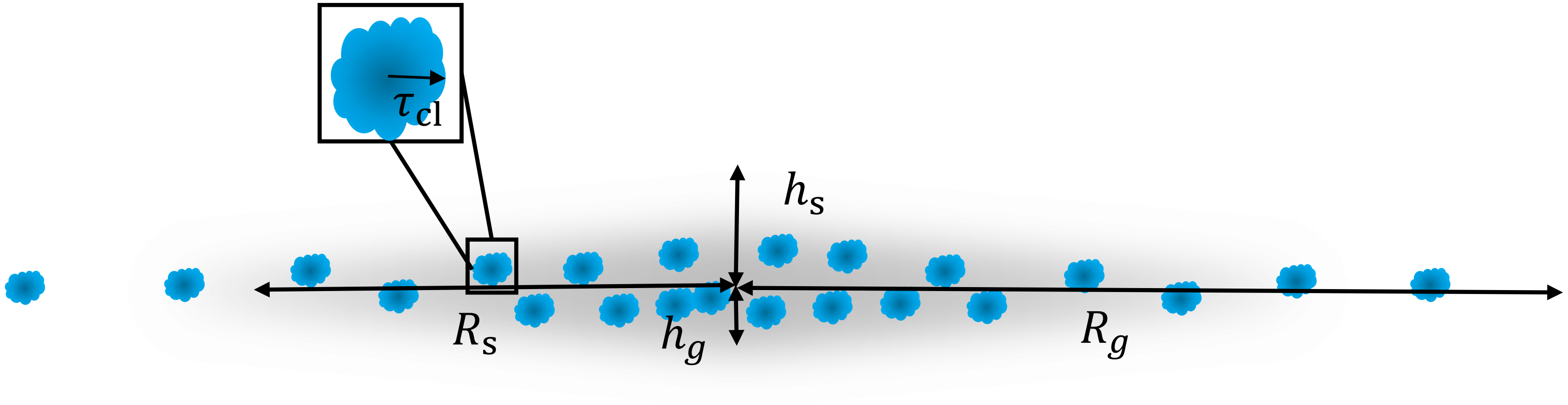
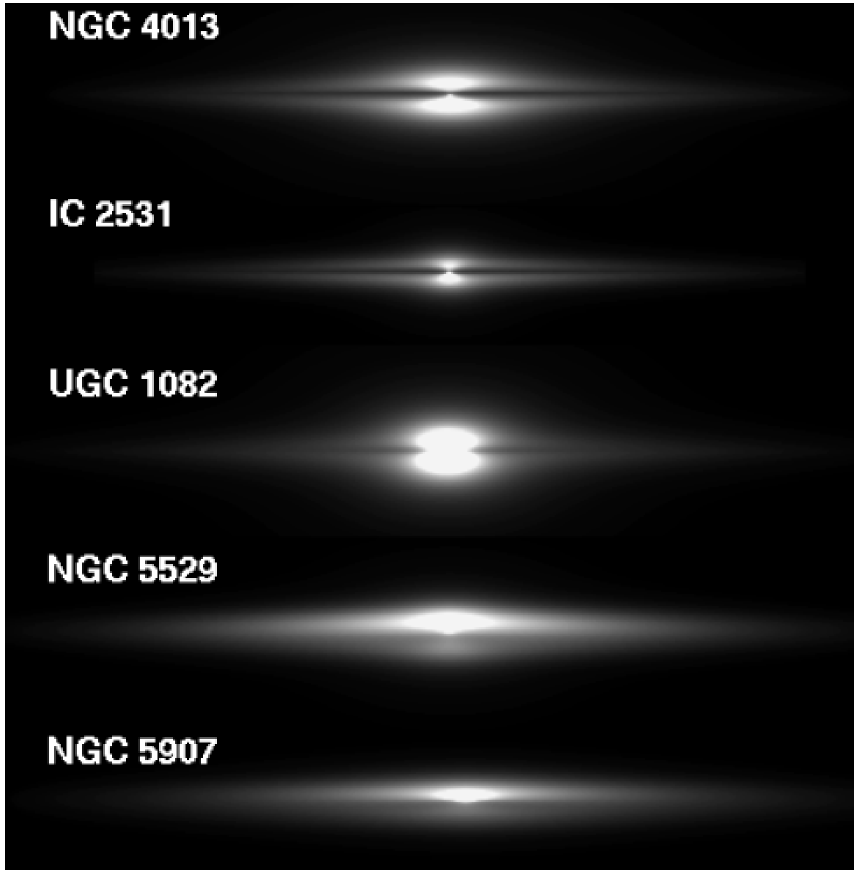
Lu et al. 2022,2023



Simple dust geometry model (Xilouris 1999)

- Exponential disks
  - Dust disks are thinner and more extended than stellar disk
    - $h_d \sim 0.5 h_s$
    - $R_d \sim 1.4 R_s$
  - Under-estimate IR emission

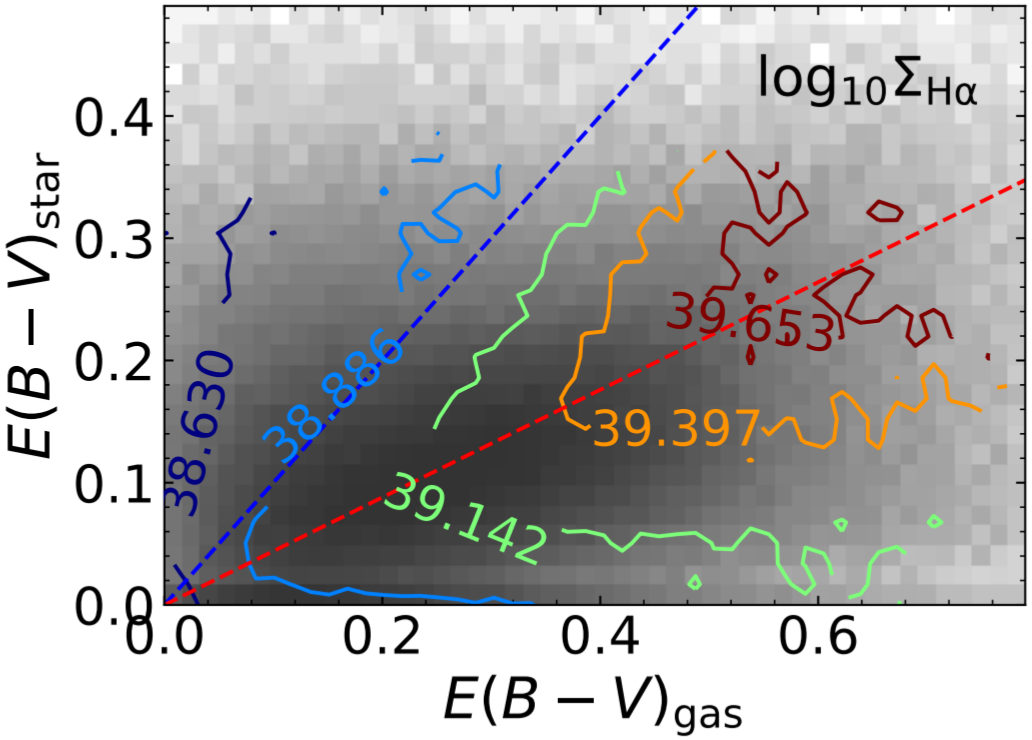
- Milky-Way model from dust extinction of a large sample of stars
  - Li, Shen+ 2018

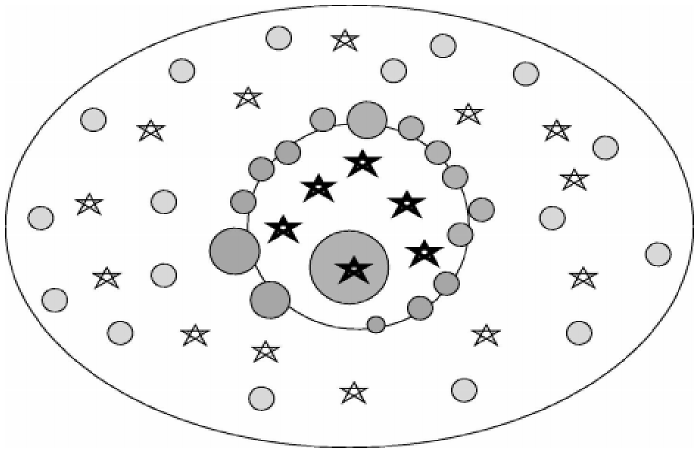


Dust attenuation: nebular VS stellar continua

- Nebular emissions are heavier attenuated than stellar continua
  - E_g : from Balmer decrement
  - E_s : from stellar population synthesis
  - $E_s(B-V) \sim 0.44 E_g(B-V)$ (Calzetti 1997)

MaNGA spaxels (Li, Li & Mo+ 2022)



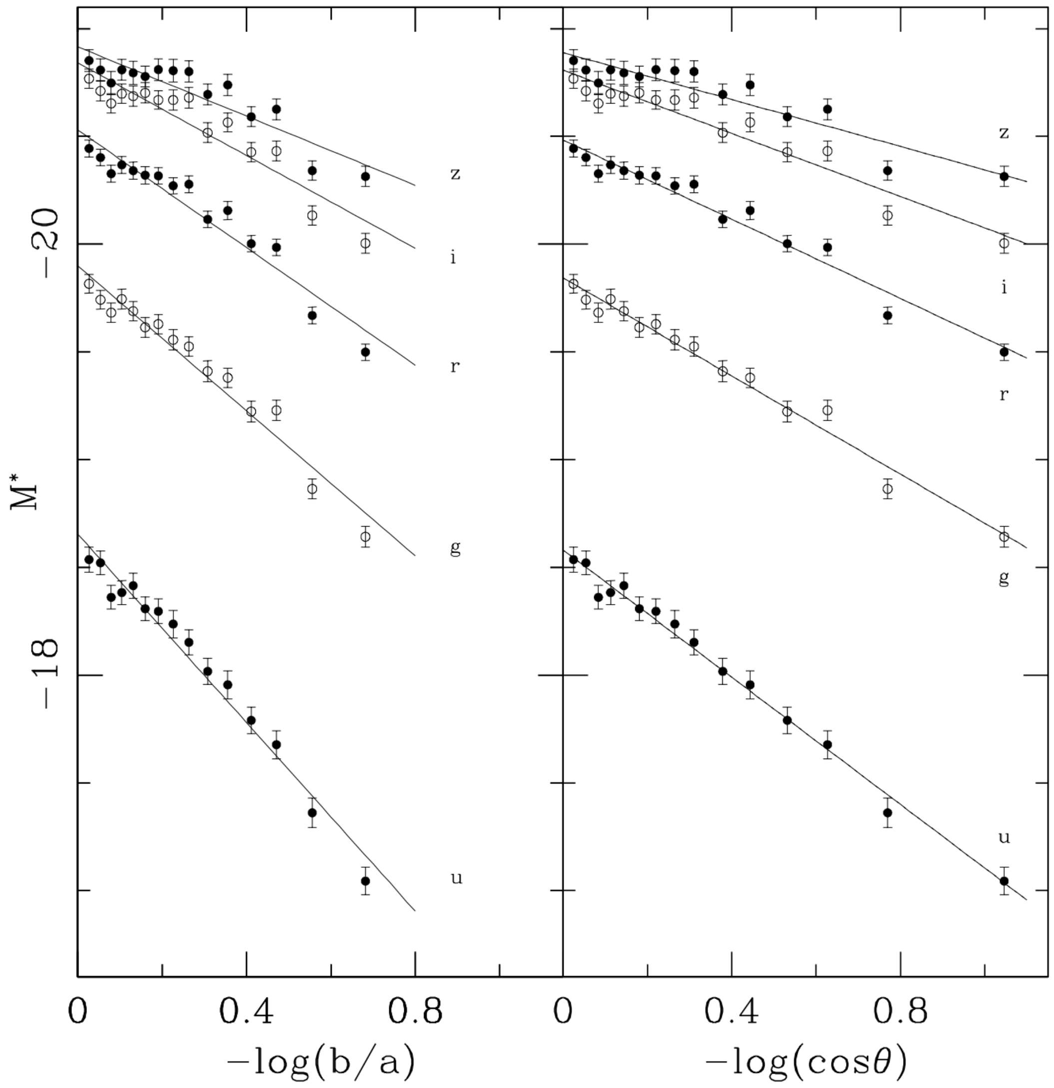


Charlot & Fall 2000

Dust attenuation: inclination dependence

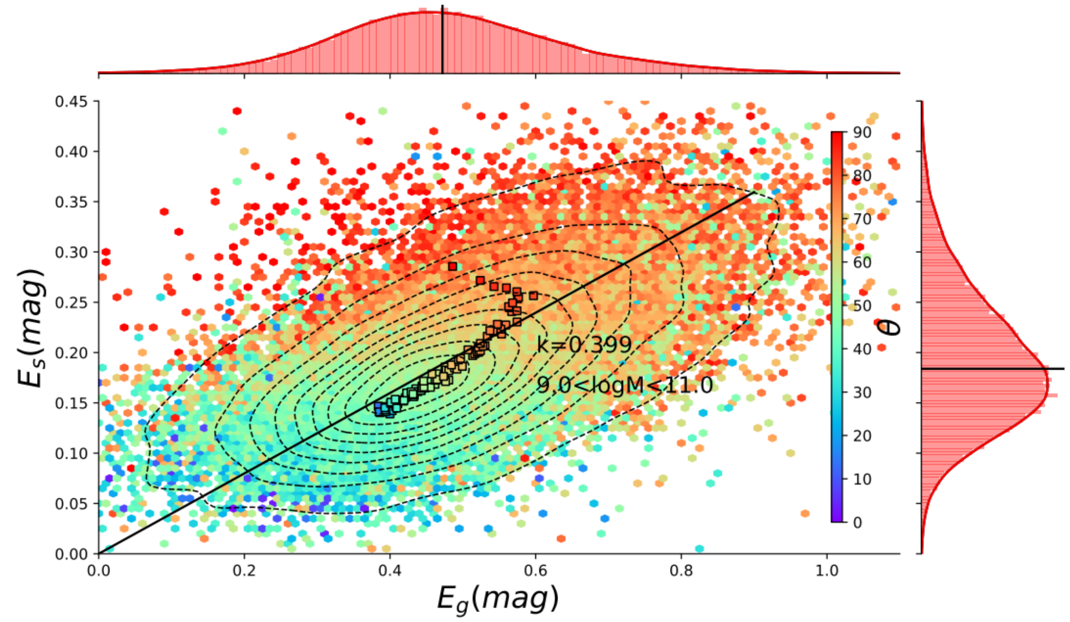
- Luminosity function (Shao et al. 2007)
  - Muti-wavelength, Constraints on extinction curve

- Detailed variation with inclination
  - Constraints on dust geometry

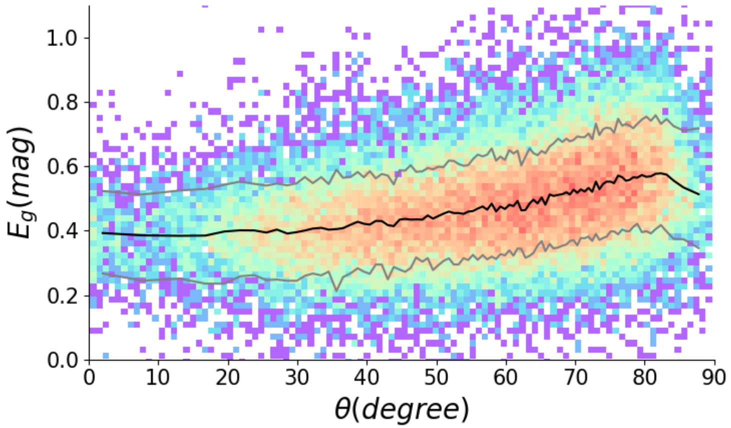


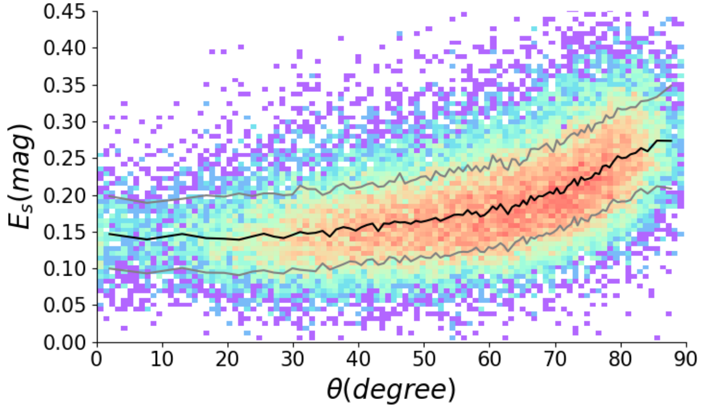
Observational results

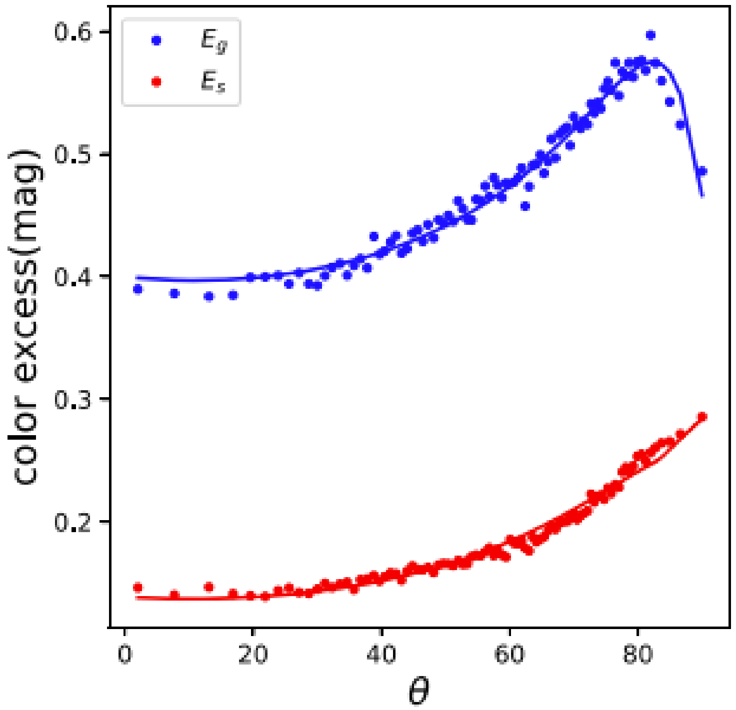
- MW-like star-forming galaxies in SDSS main galaxy sample



Log M* ~10.5

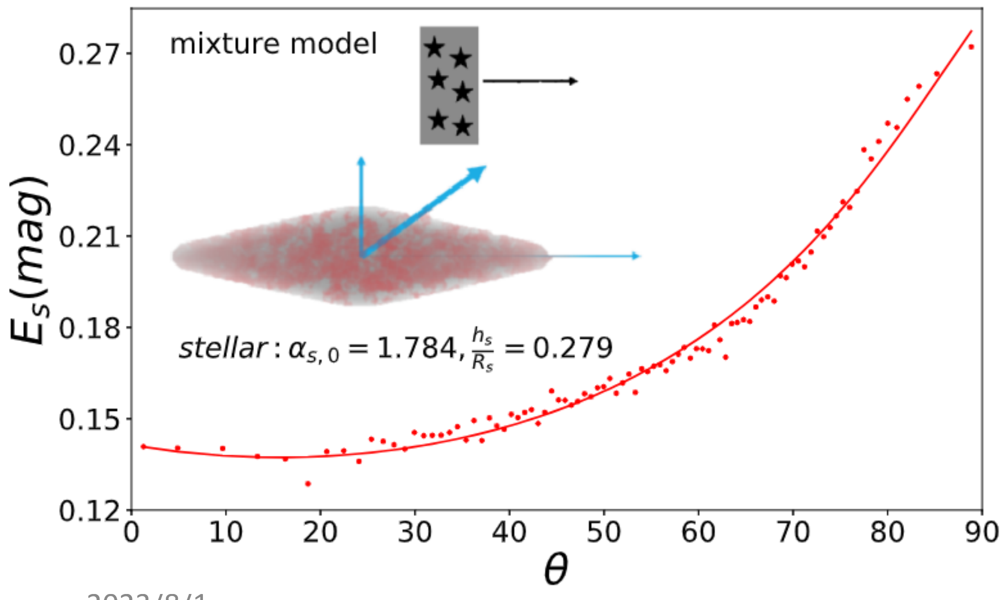




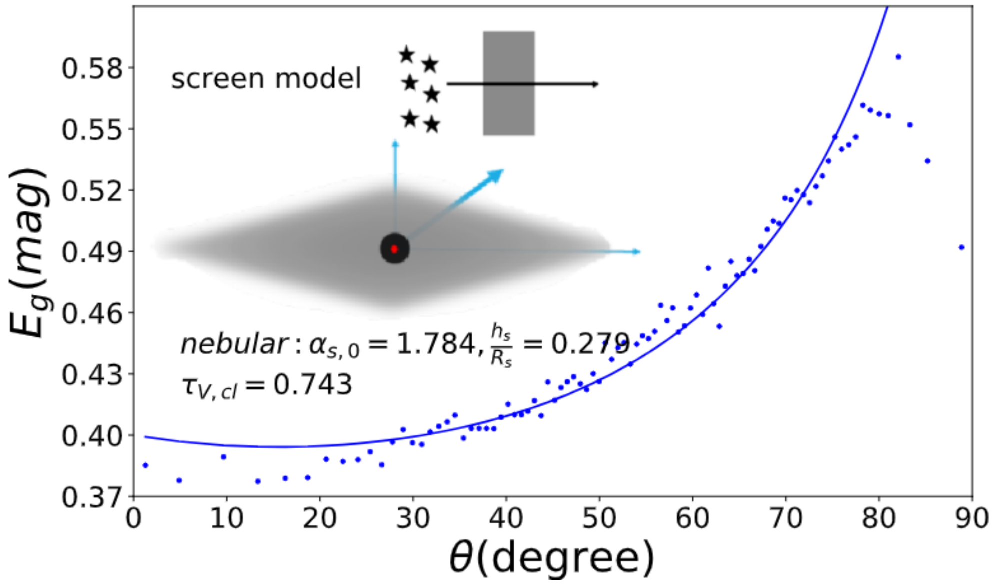


Simple dust geometry models

- Uniformly mixing model
  - stellar attenuation
  - dust in diffuse ISM
  - Exponential disk

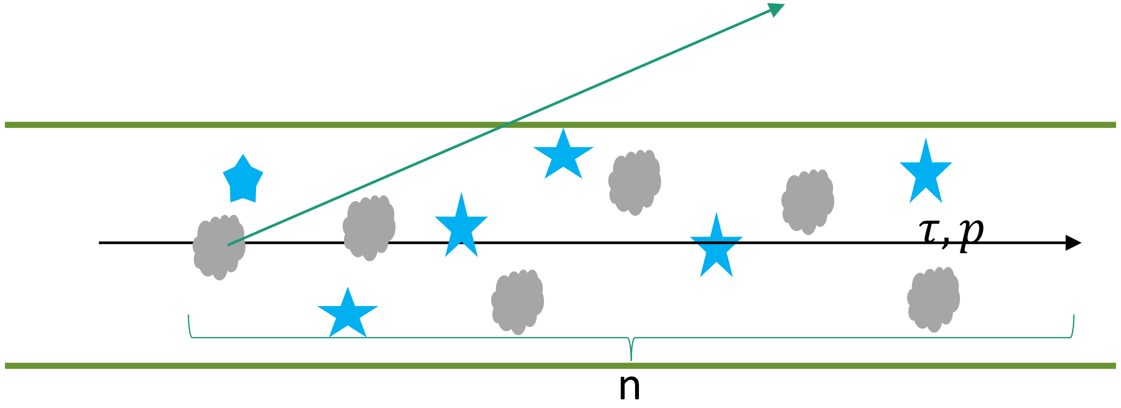


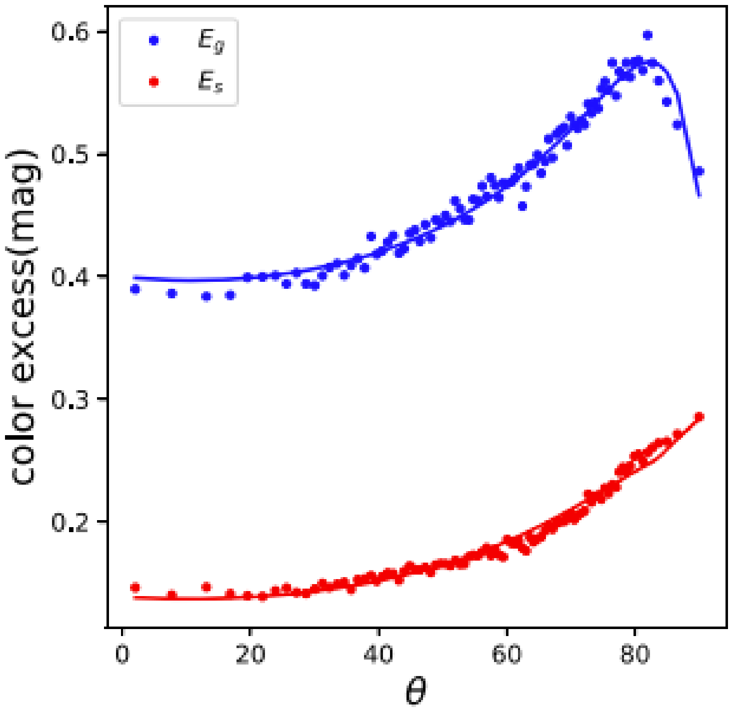
- Screen model
  - Nebular attenuation
  - Single star forming region along the line-of-sight



Motivation of Chocolate Chip Cookie model

- Highly inclined disk
  - More than one nebular region along the line of sight
- Difficulties
  - model the clumpy distribution of nebular regions





“Chocolate Chip Cookie” model

- Stellar disk: exponential disk
  - Diffuse ISM (dust) uniformly mixed

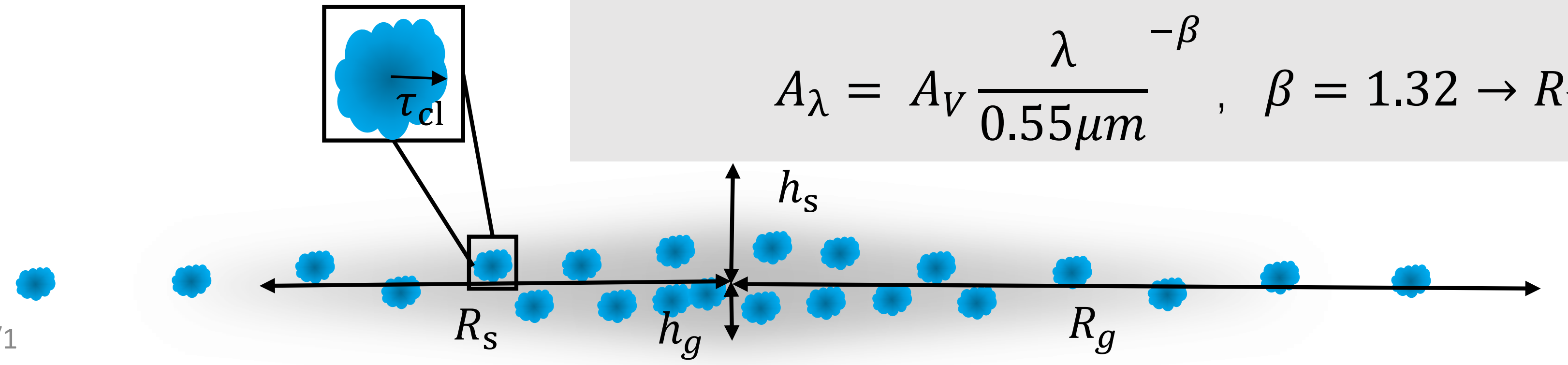
  - Geometry : R_s,h_s
  - Central dust density: $\rho_{s,0}$
  - Central stellar emission: $I_{s,0}$

- Clumpy HII regions
  - Identical
  - Number density: another exponential disk

  - Geometry: R_g,h_g
  - HII region: τ_{cl}, $\rho_{cl,0}$

Extinction curve:

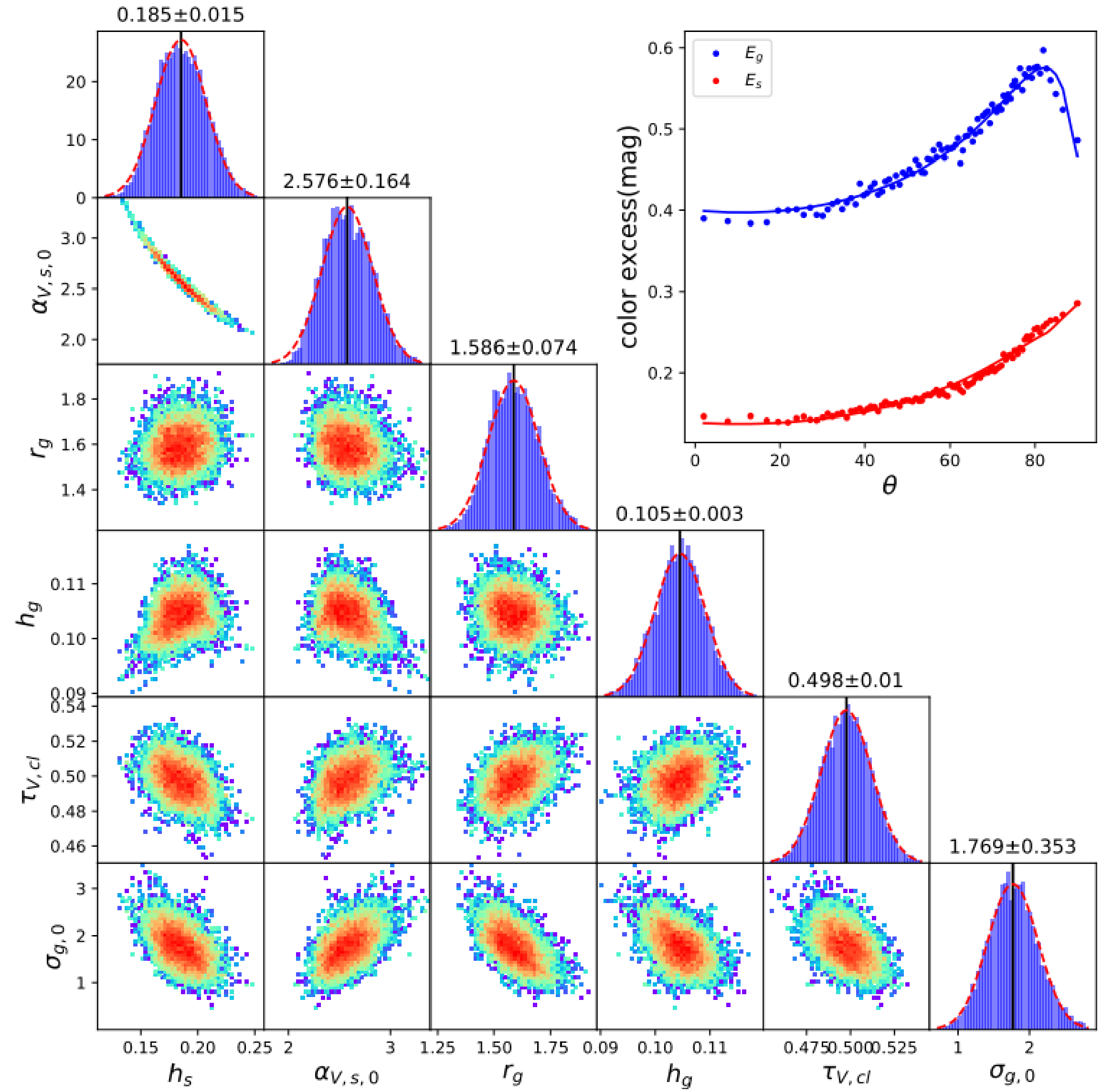
$$A_\lambda = A_V \left(\frac{\lambda}{0.55\mu m}\right)^{-\beta}, \quad \beta = 1.32 \rightarrow R_V = 3.1$$



Model parameters for MW-like galaxies

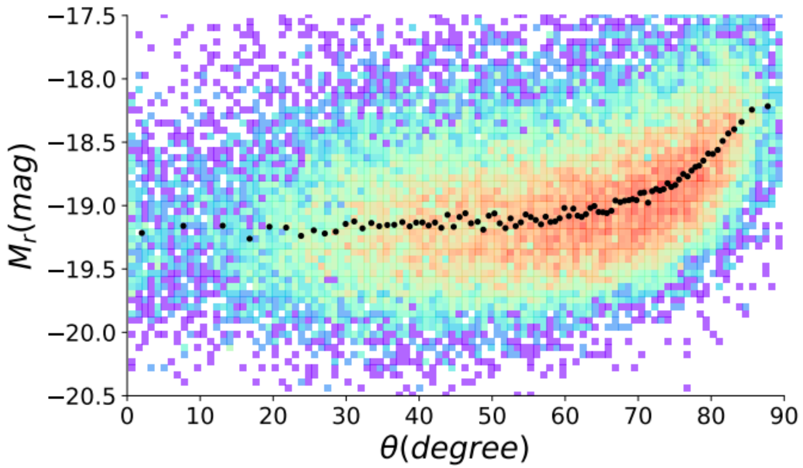
- Constrained by E_g and E_s as function of disk inclination
  - the only successful model~
- h_s / R_s ~ 0.19
  - ~0.1-0.15
- h_g / h_s ~0.57
  - ~0.5
- R_g / R_s ~1.59
  - ~1.4-1.8
- $\tau_{cl,V}$ ~ 0.5
  - ~0.5 (MW), 1-2 (extragalactic)

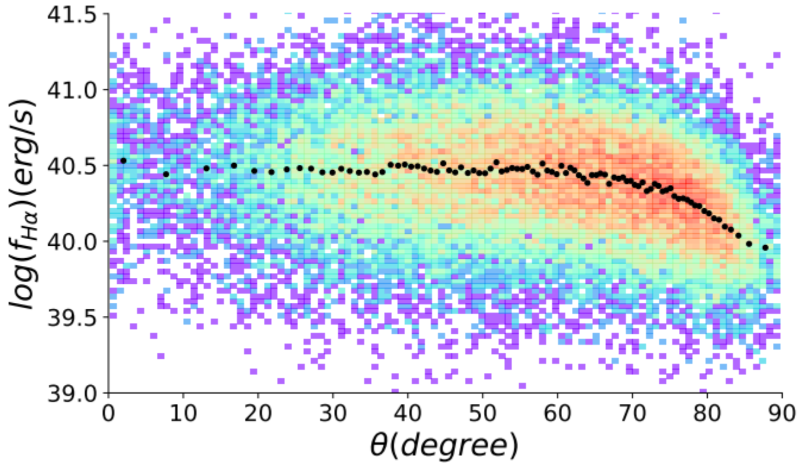
h_s	$\alpha_{s,0}$	R_g	h_g	$\tau_{cl,V}$	$\sigma_{g,0}(\rho\pi R_{cl}^2)$
$0.19\ R_s$	$2.58 R_s^{-1}$	$1.59\ R_s$	$0.105\ R_s$	0.50	$1.77 R_s^{-1}$

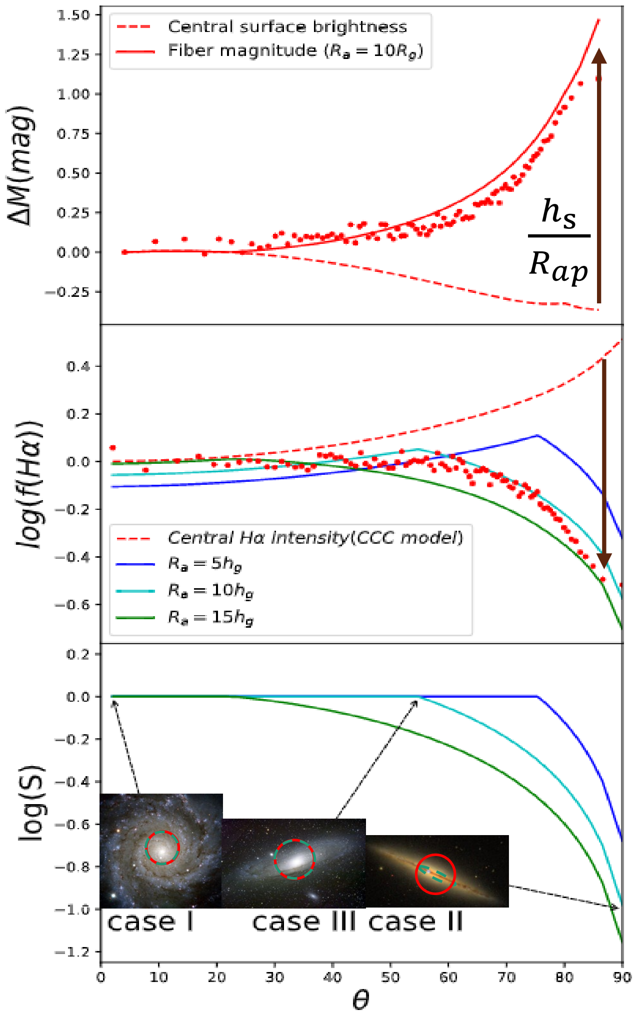


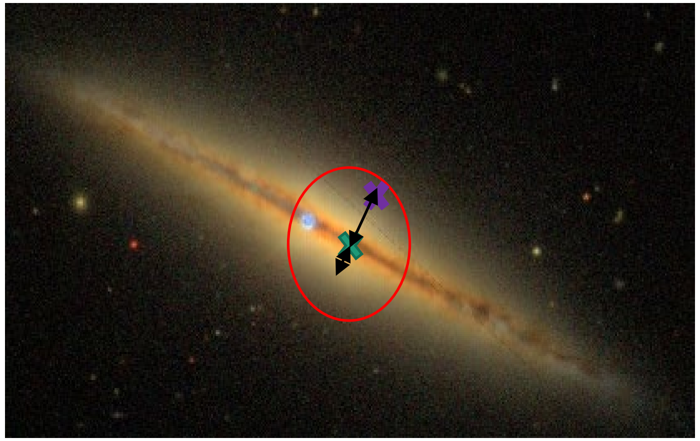
Application of CCC model：

I. Ha flux and fibermag as function of disk inclination





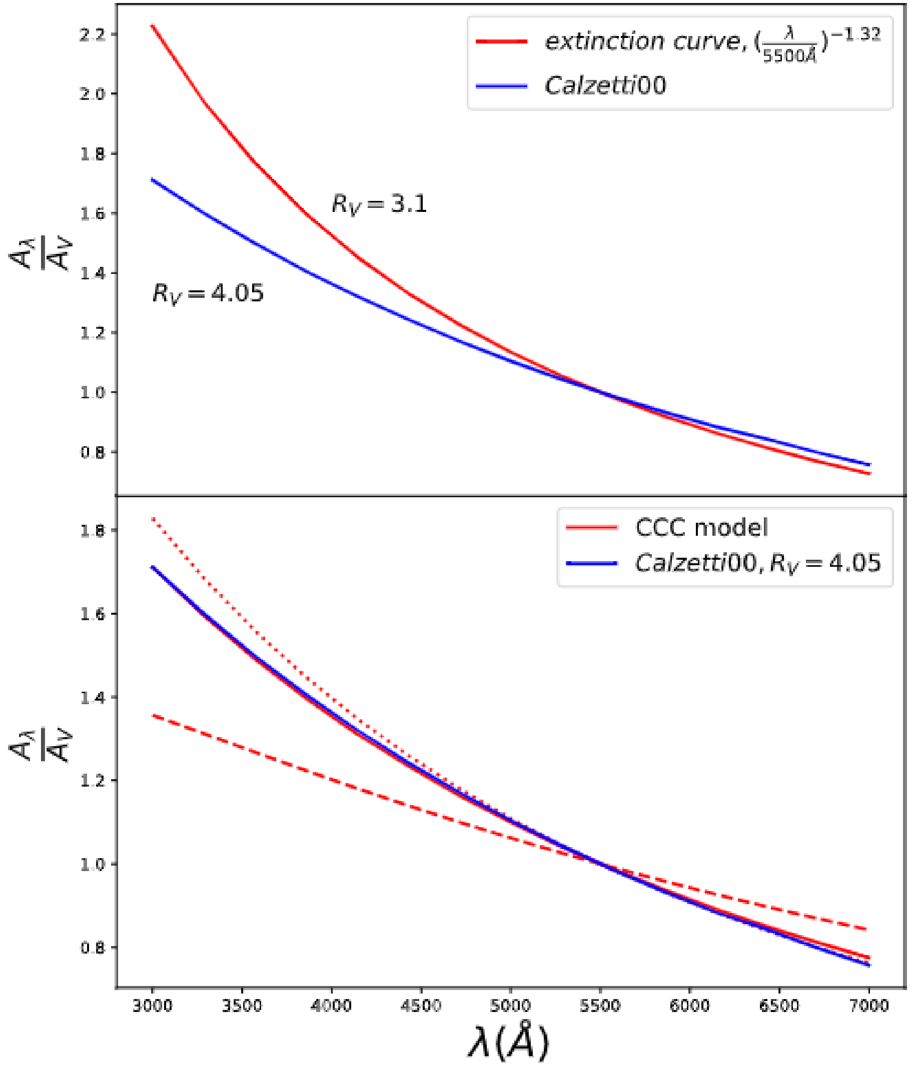




R_{ap}	2.2 kpc
h_s	0.41 kpc
R_s	2.1 kpc
$\alpha_{s,0}$	1.22 kpc^{-1}
R_g	3.33 kpc
h_g	0.22 kpc
$\sigma_{g,0}$	0.84 kpc^{-1}

Application II. Dust attenuation curve

- Extinction curve (input)
  - $R_V = 3.1$
- Stellar attenuation curve (output)
  - Face-on : $R_V = 3.7$
  - Edge-on : $R_V = 7.0$
  - Medium (60°) : $R_V = 4.1$
    - Calzetti law(4.05)

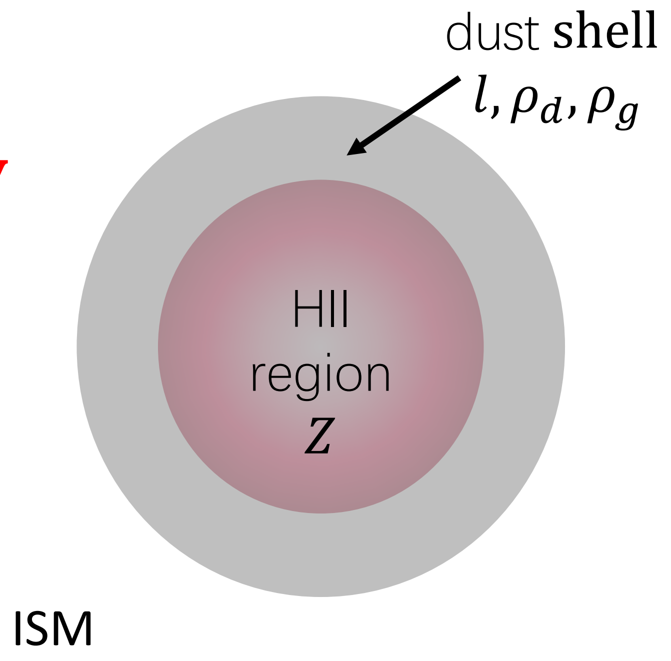


Application III. Dust-to-Metal ratio of HII regions

- $\tau_{\rm cl}$ ~ 0.5 in CCC model
  - **function of nebular metallicity and host galaxy stellar mass**

$$\tau_{\rm cl} = \kappa_{\rm V}\rho_{\rm dust}l$$

$$\tau_{\rm cl} = \kappa_{\rm V}\rho_{\rm gas}l \cdot {\rm DGR}$$

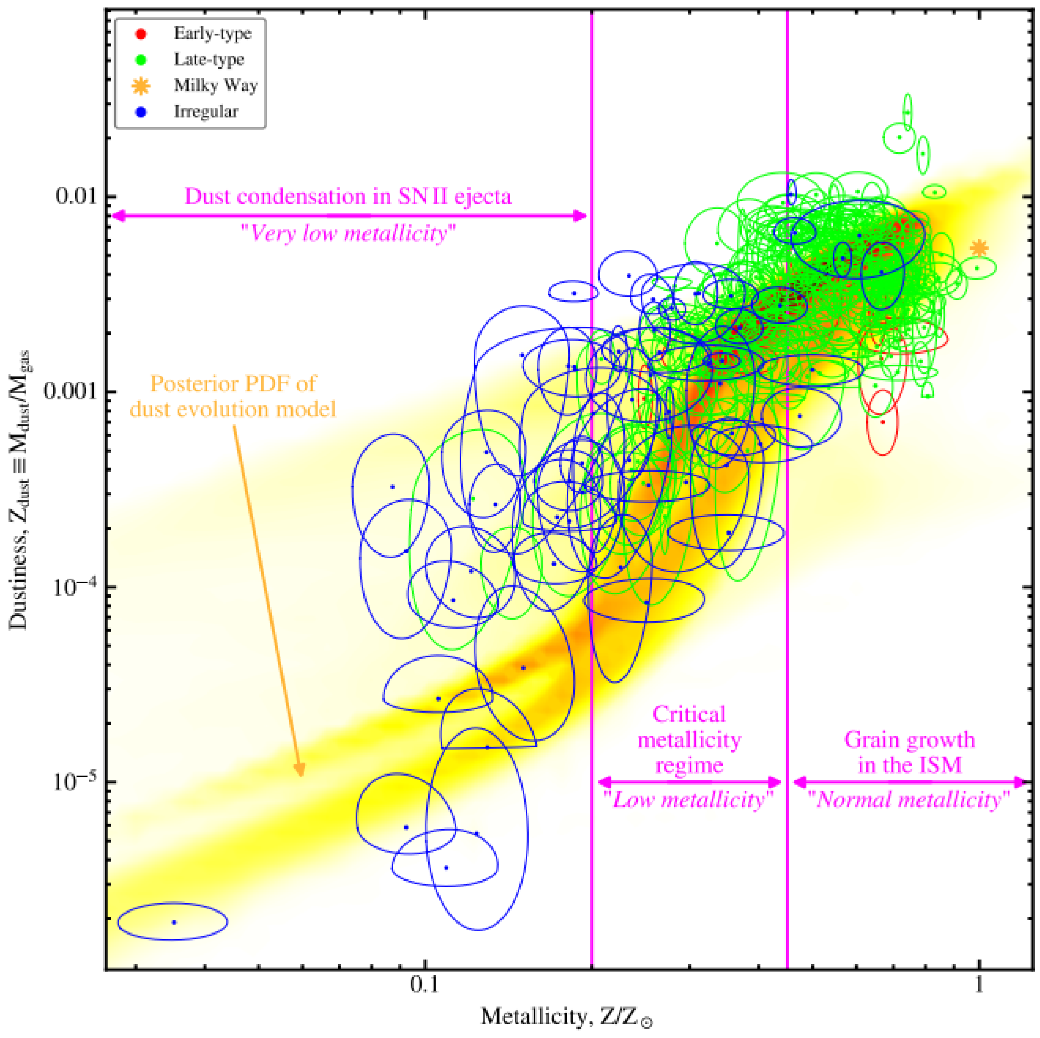


- $\tau_{\rm cl}$ → DGR: dust-to-gas ratio

- DGR/metallicity → Dust-to-Metal ratio(DTM)

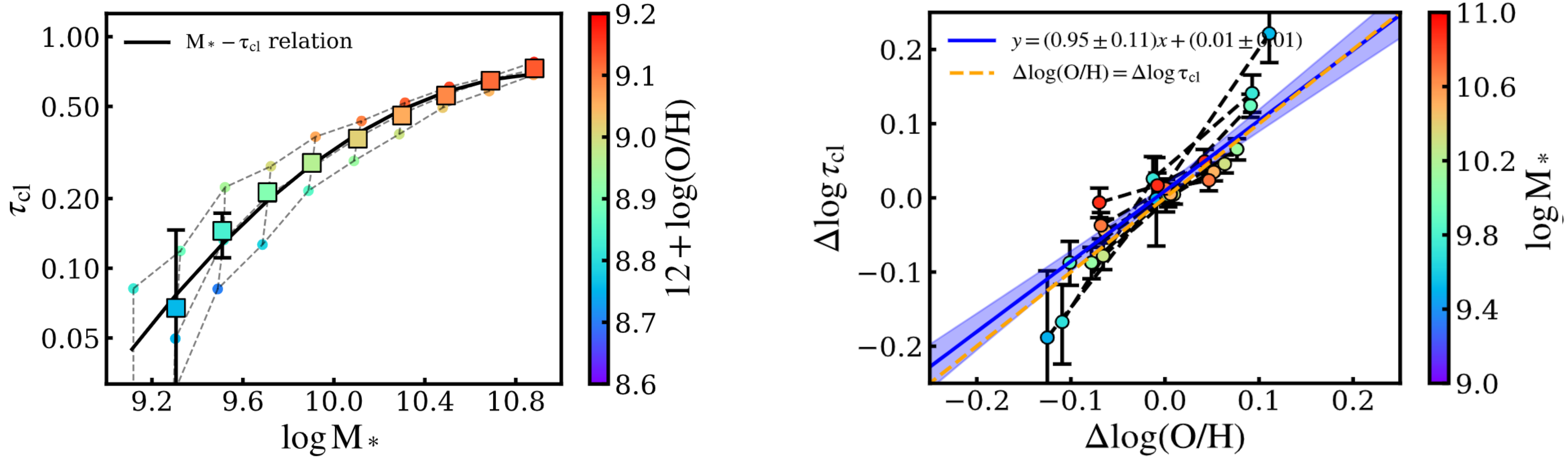
Dust-to-Metal ratio (DTM)

- Classical model： DTG is a function of gas-phase metallicity
  - Very Low Z
    - Inefficient dust growth
  - Low z
    - Dust growth
  - High z
    - Balance between dust growth and destroy by SN



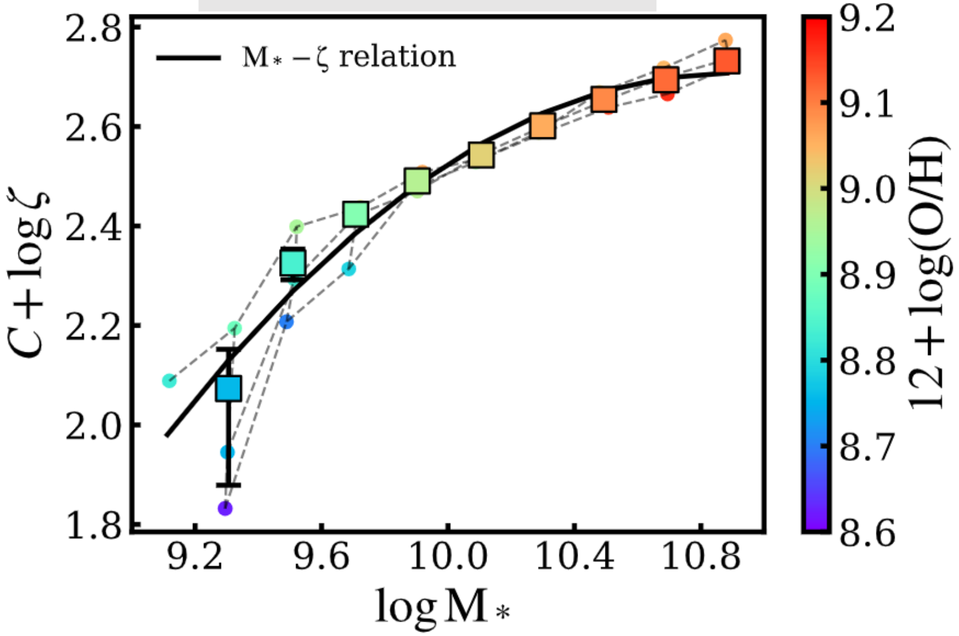
Galliano 2022

DTM: function of stellar mass/metallicity

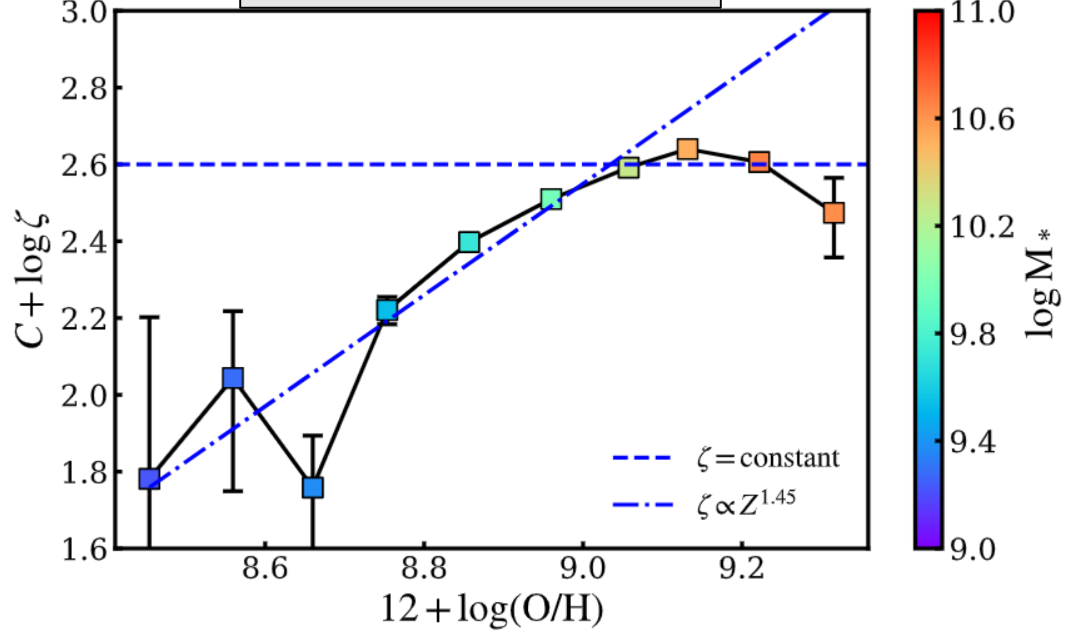


- Higher stellar mass， higher metallicity， higher τ_{cl} （DTG）
- τ_{cl} （DTG） increases faster with stellar mass than metallicity
- At given stellar mass, τ_{cl} proportional to metallicty
  - **Constant Dust-to-Metal ratio~**

Our new claim



classical model



Dust-to-Metal ratio is the primary function of stellar mass rather than metallicity

Why at given stellar mass: DTM is a constant?

- Dust growth timescale is longer than HII lifetime
- Gas inflow dilute metallicity and dust ratio

Other possible applications

- Dust geometry model for disk galaxies with different stellar masses
  - Need to include bulge component
- Dust emission from different components
  - Need to consider optical-thick HII regions
- Compare with IFS study of HII regions
  - Our model can separate the ISM dust extinction
- Incorporate into state-of-art semi-analytical model
  - Our model is analytical

Summary

- We have developed a two-component dust geometry model (CCC) for star-forming disk galaxies, which properly accounts for both the dust in
  - Clumpy HII regions (molecular gas)
  - Diffuse ISM