Insights into the star formation and dust properties of galaxies from integrated spectral energy distributions

Jacopo Chevallard

Collaborators: Stephane Charlot, Ben Wandelt, Vivienne Wild
Stephane Arnouts, Emeric Le Floc'h

Outline (1)

1) **Introduction**

(a) The key role of dust in shaping galaxy SEDs

(b) Formalism

2) Radiative transfer models of dust attenuation in galaxies

(a) Description of the models

(b) General properties of dust attenuation curves form RT models

3) The data: the Wild et al. (2011) sample

(a) How to compute attenuation curves from integrated photometry?

4) The model:

a) The parameters of the model

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5) Fitting the data

a) Results of the fit

6) Discussion of the results

7) Examples / applications

8) **SF and dust attenuation:** how to reliably infer the SFR from UV-to-near infrared colors, in absence of MIR/FIR observations?

a) The data

b) Encoding the infrared excess IRX into the (NUV-R) vs (R-K) diagram

c) Modeling and discussion

9) Future developments

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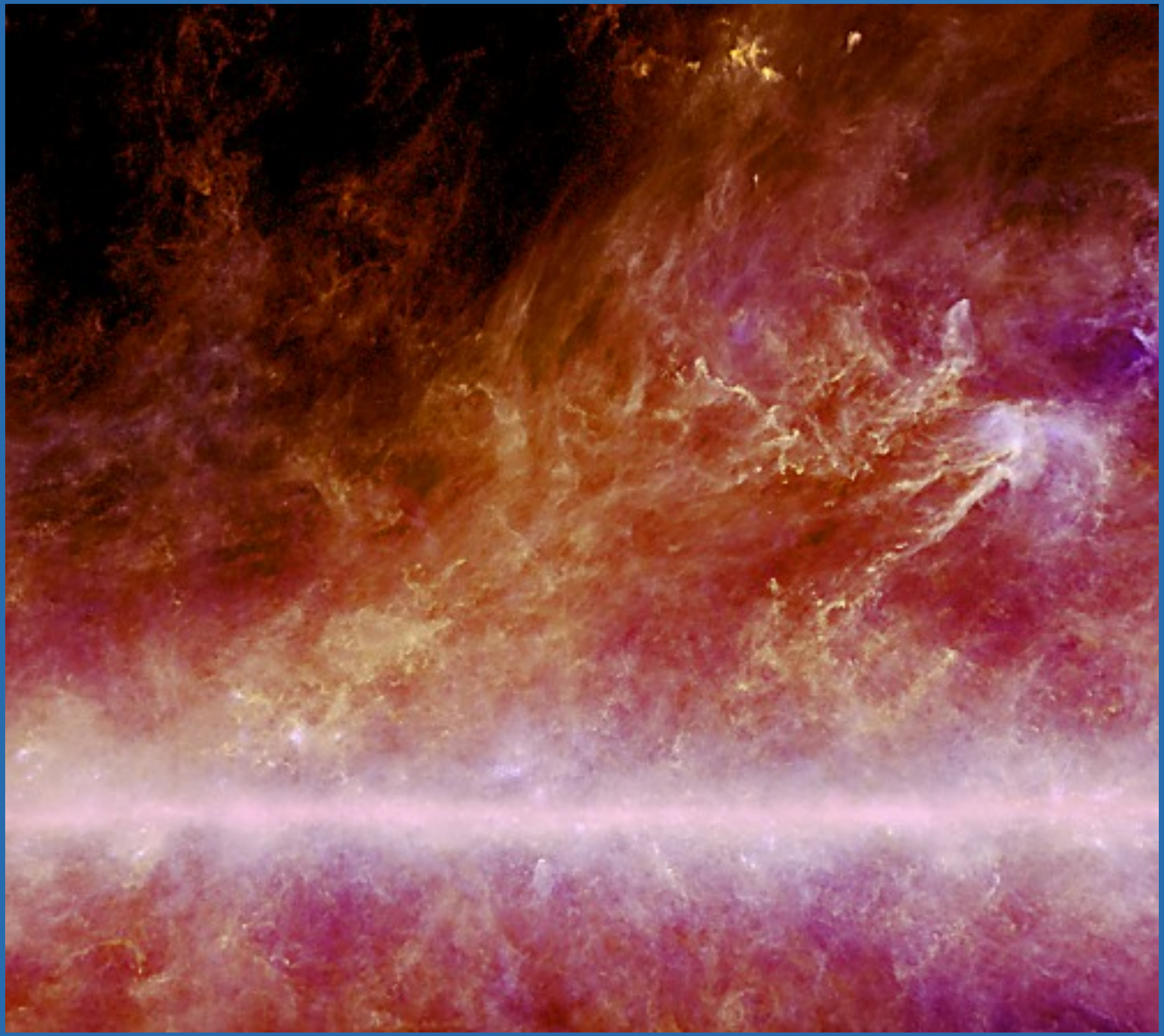
- Dust is an ubiquitous component of the ISM



Credits: ESA and the HFI Consortium IRAS

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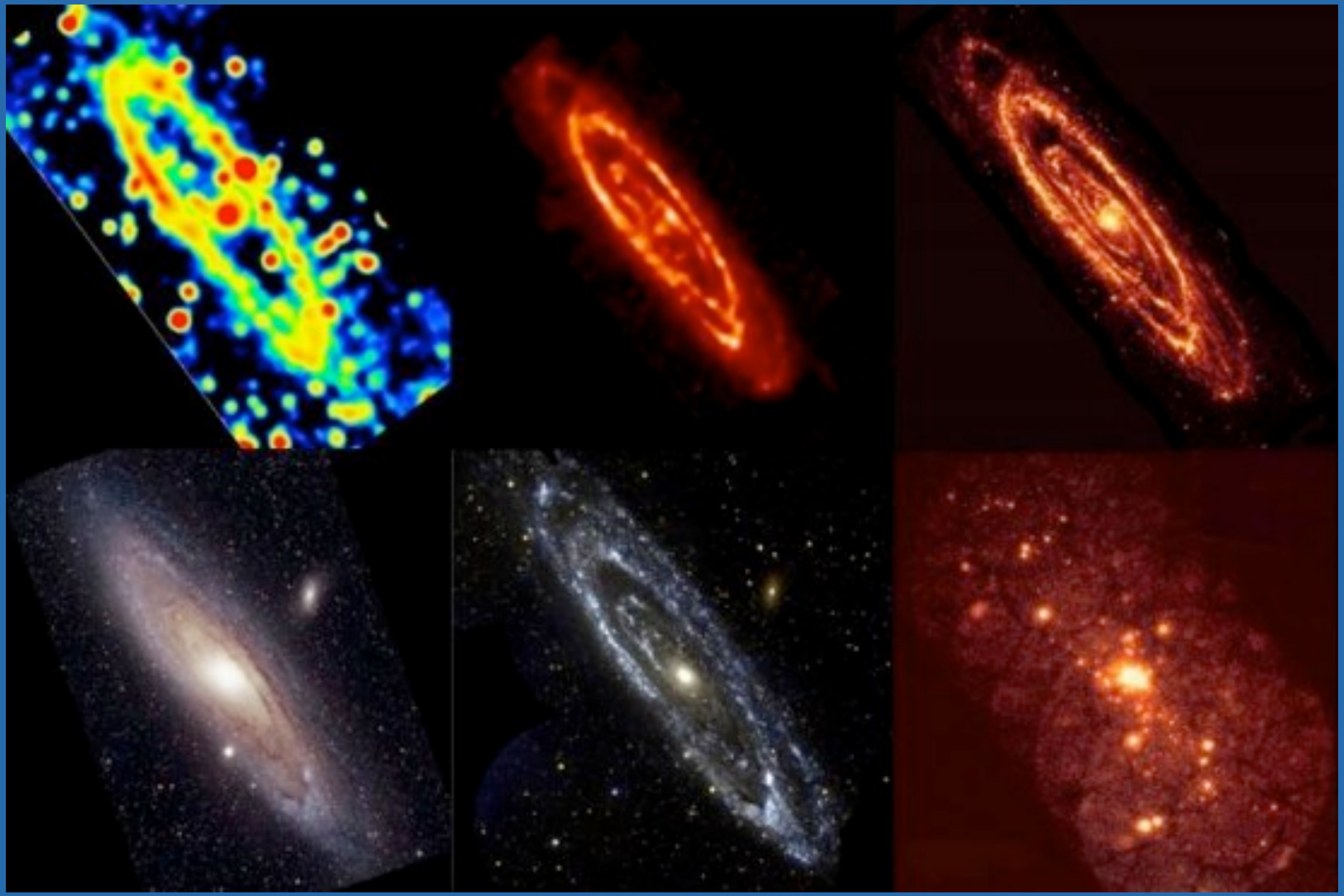
- Dust absorbs nearly half the UV-to-optical starlight, re-emitting the absorbed energy in the FIR

Radio FIR FIR



Optical UV X-ray

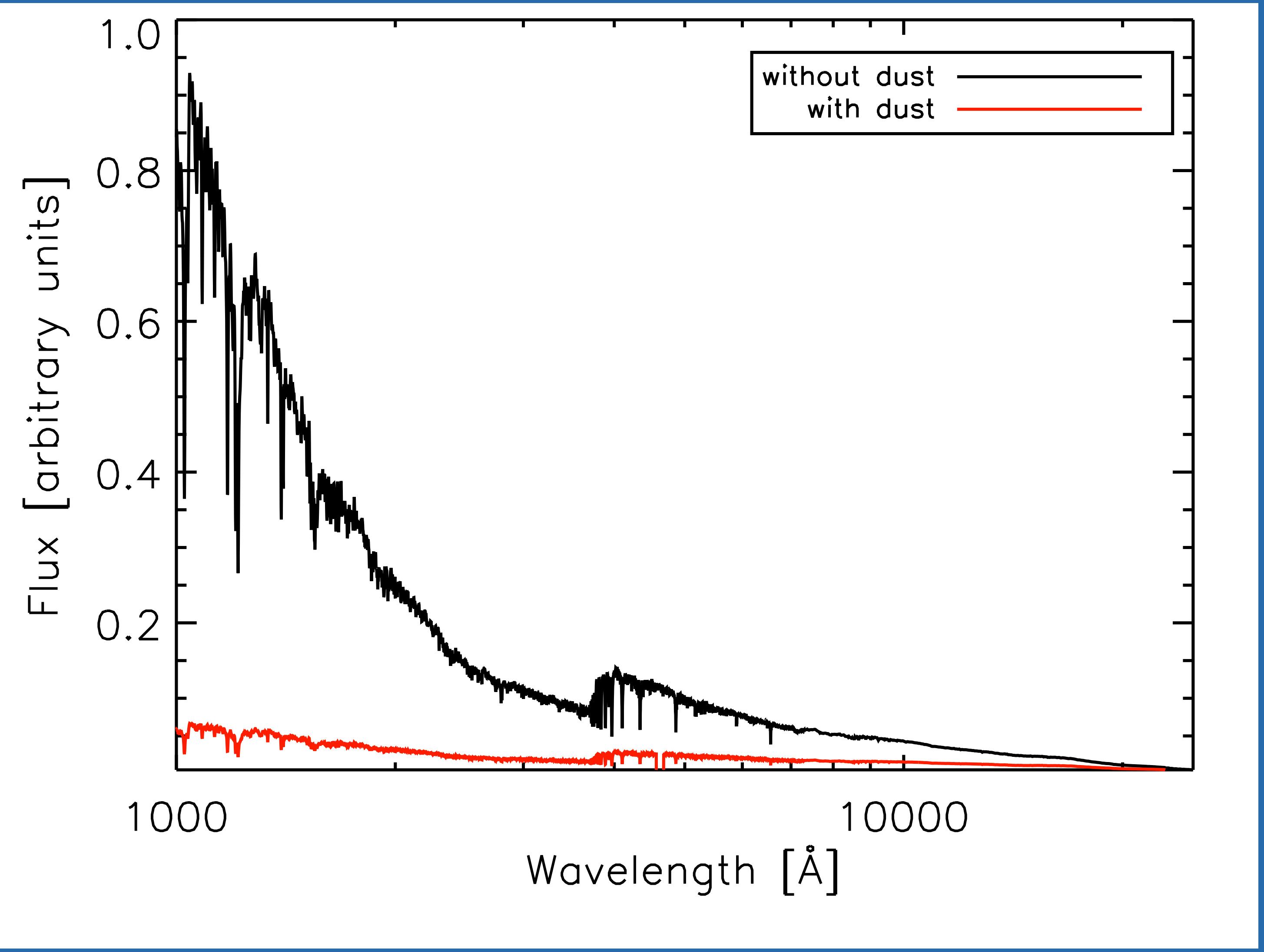
Andromeda (M31)

The key role of dust in shaping galaxies SEDs

- Dust is an ubiquitous component of the ISM

- Dust absorbs nearly half the UV-to-optical starlight, re-emitting the absorbed energy in the FIR

- To reliably estimate physical quantities (masses, SFR, SFH, ages, metallicities) from stellar and gas emission, modeling the effect of dust is critical



Dust attenuation: formalism

$$I_\lambda(\theta) = I_\lambda^0 \exp\left[-\hat{\tau}_\lambda(\theta)\right]$$

$I_\lambda(\theta)$: intensity emerging at wavelength λ in a direction θ from the normal to the equatorial plane of a galaxy

I_λ^0 : intensity produced by stars at wavelength λ (assumed isotropic)

$\hat{\tau}_\lambda(\theta)$: effective absorption optical depth at wavelength λ and inclination θ

Dust attenuation: effect on galaxy SED

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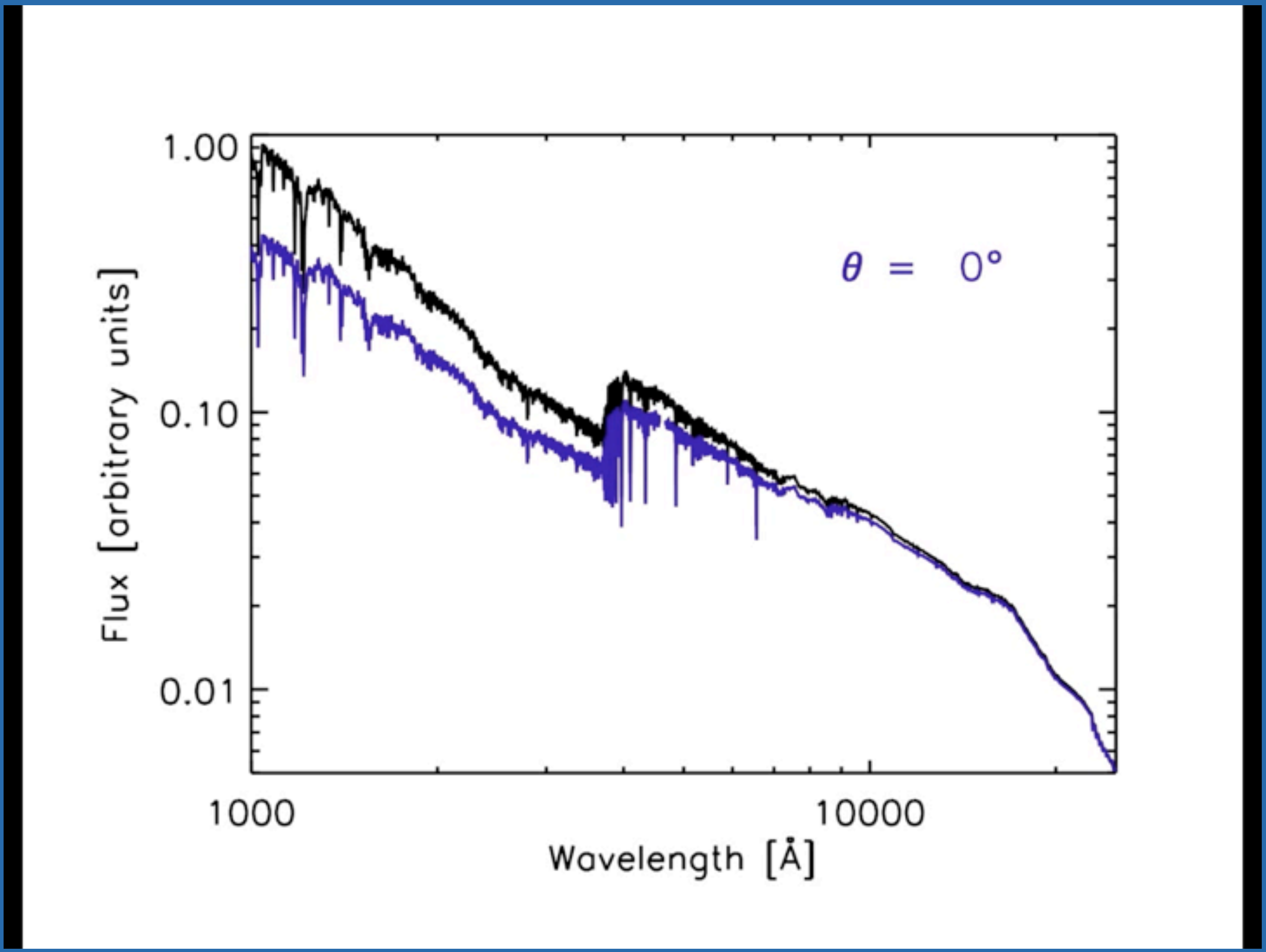

Dust attenuation: modeling

$\hat{\tau}_\lambda(\theta)$: absorption + scattering + geometry

Same dust properties, but different **distributions** of dust and stars → Different attenuation laws in the **bulge**, **thick** and **thin** disks.

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Aim of my work: use general conclusions from **radiative transfer** (RT) models to improve dust attenuation prescriptions used in spectral analyses

↓

Includes **galaxy inclination** and different **spatial components**

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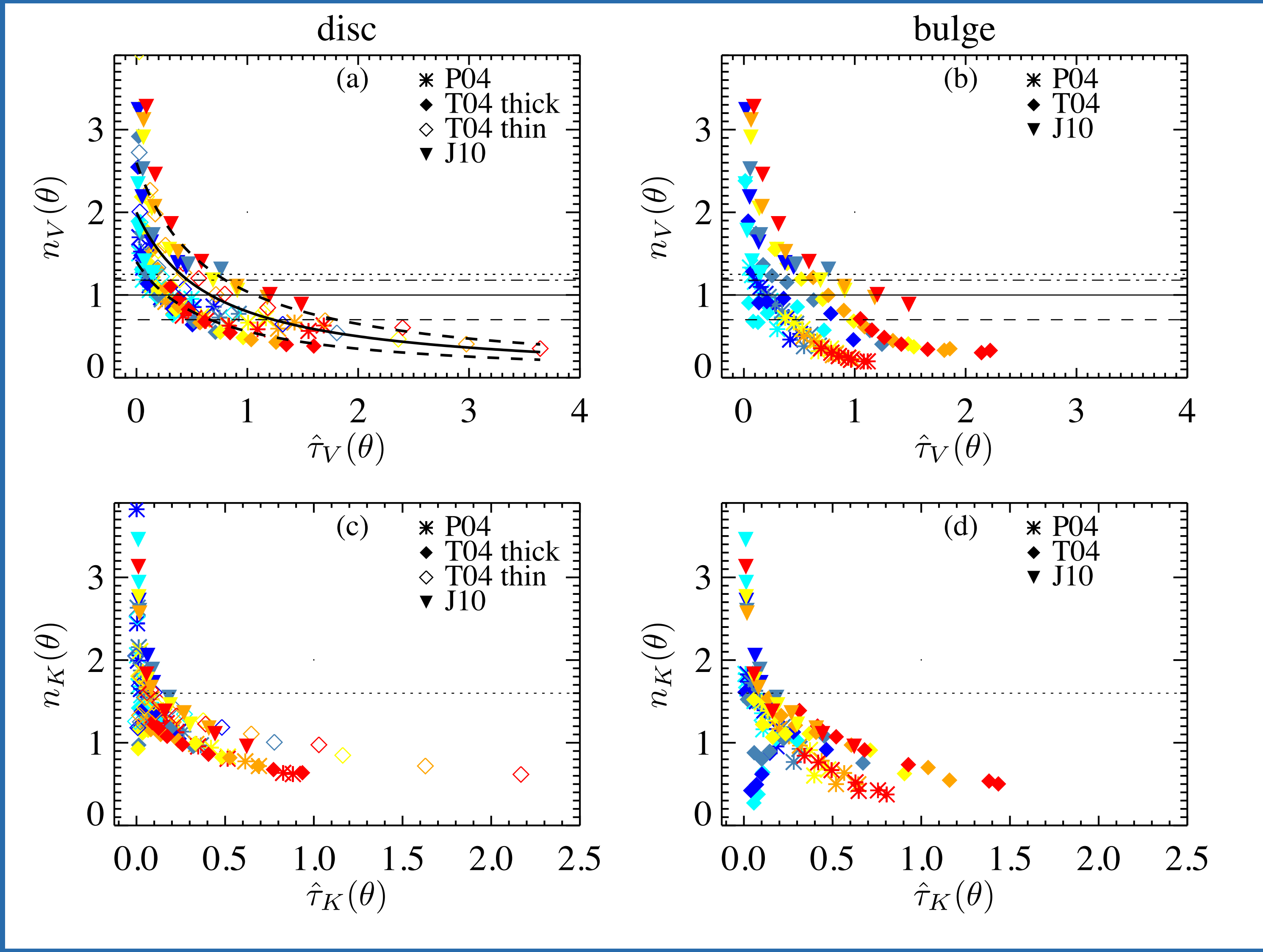
Dust attenuation: modeling

- Comparison of different **radiative transfer models**:
  - ➡ Tuffs et al., 2004 (analytic, 3 comp.)
  - ➡ Pierini et al., 2004 (analytic, 2 comp.)
  - ➡ Jonsson et al., 2010 (SPH)

➡ Predictions from different models are roughly consistent with each other (esp. optical)



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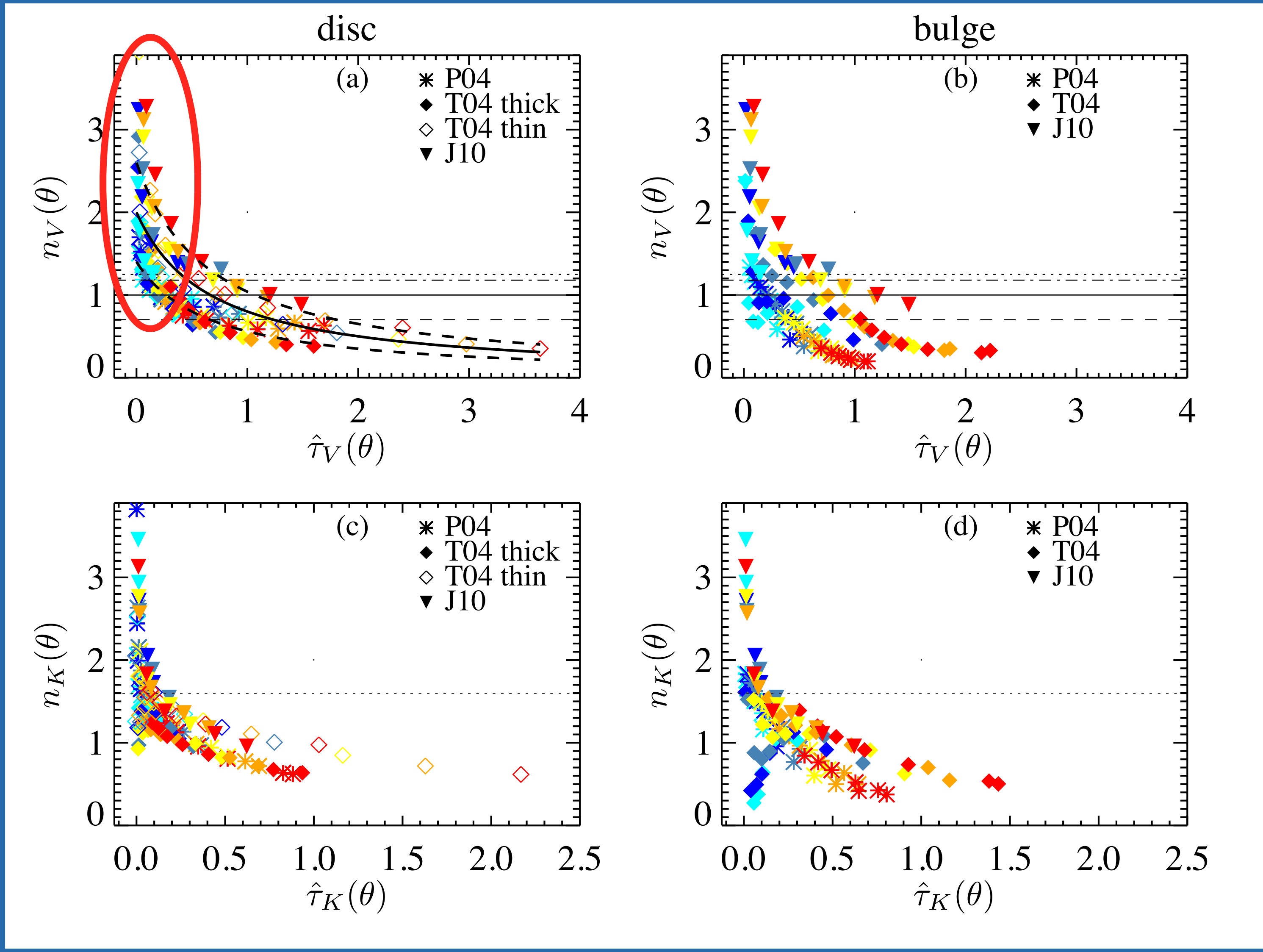

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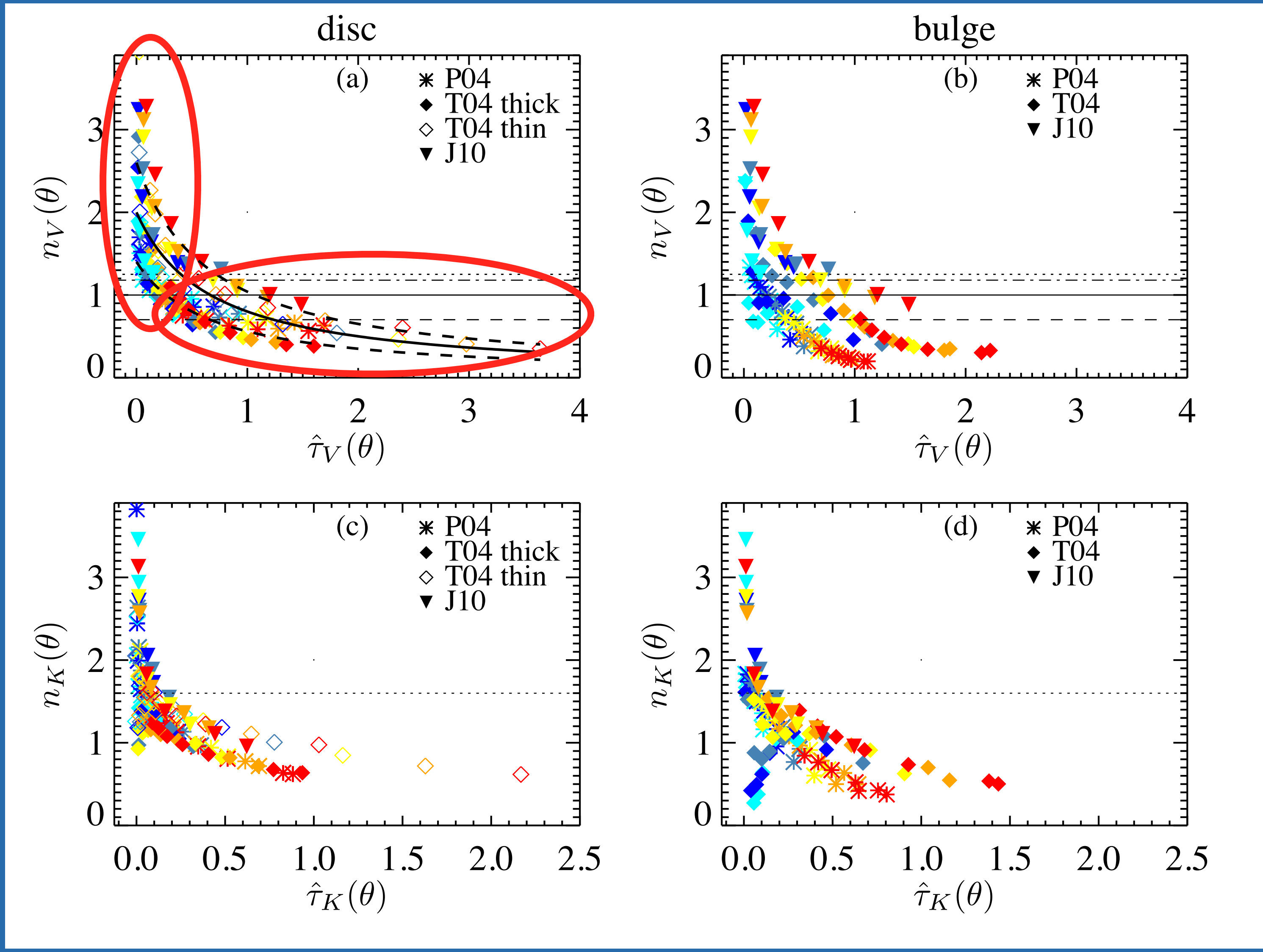

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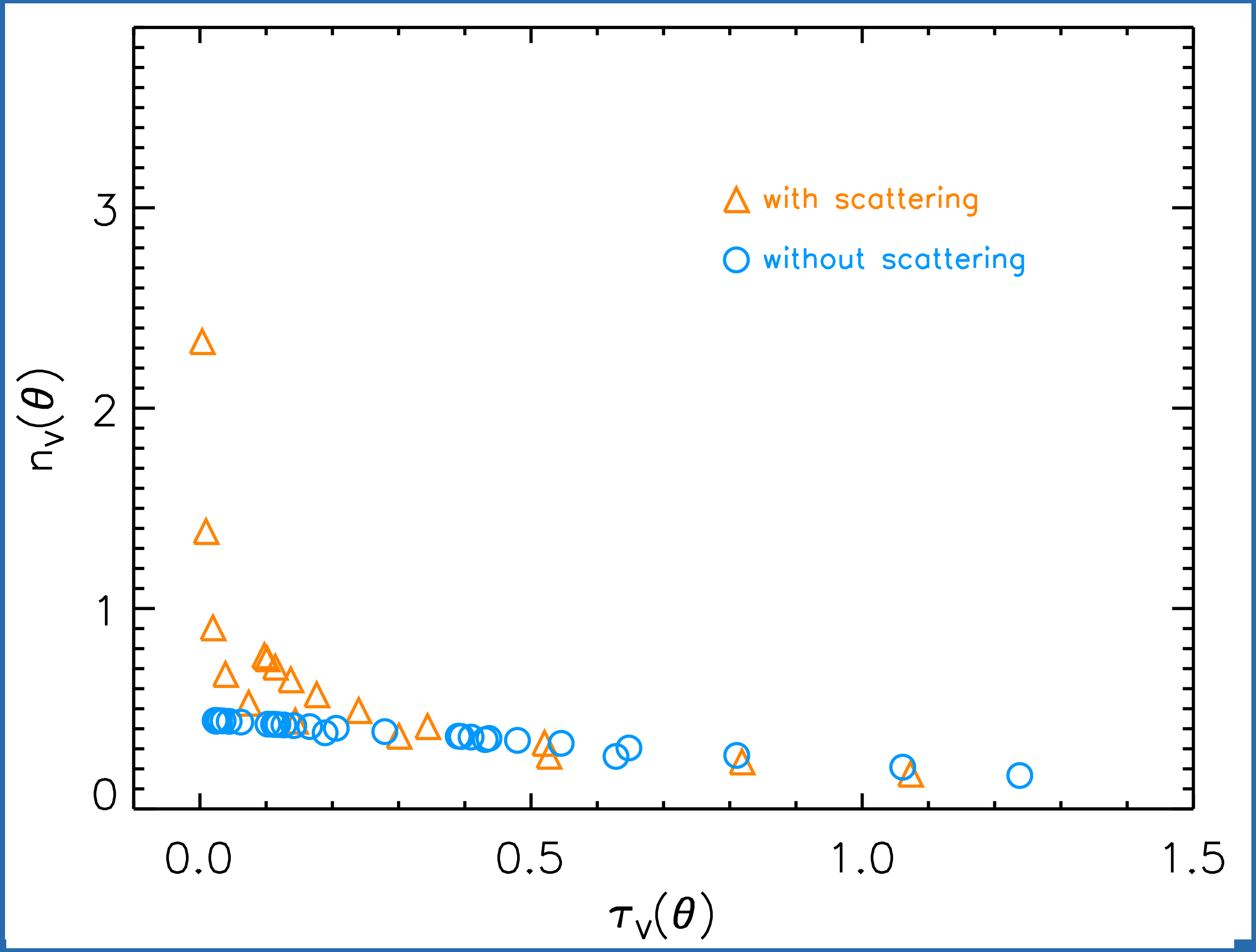

MacLachlan, private communication

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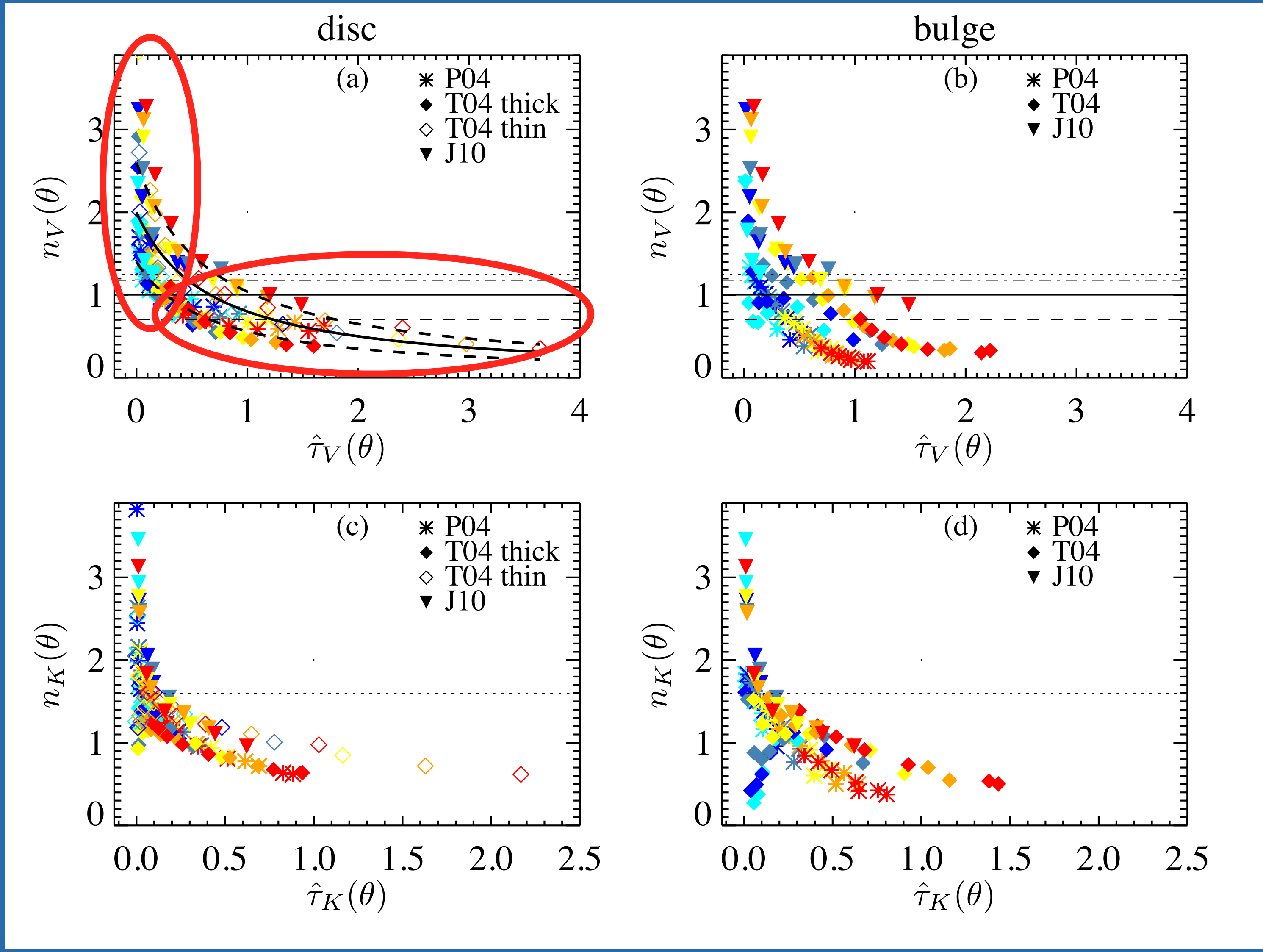

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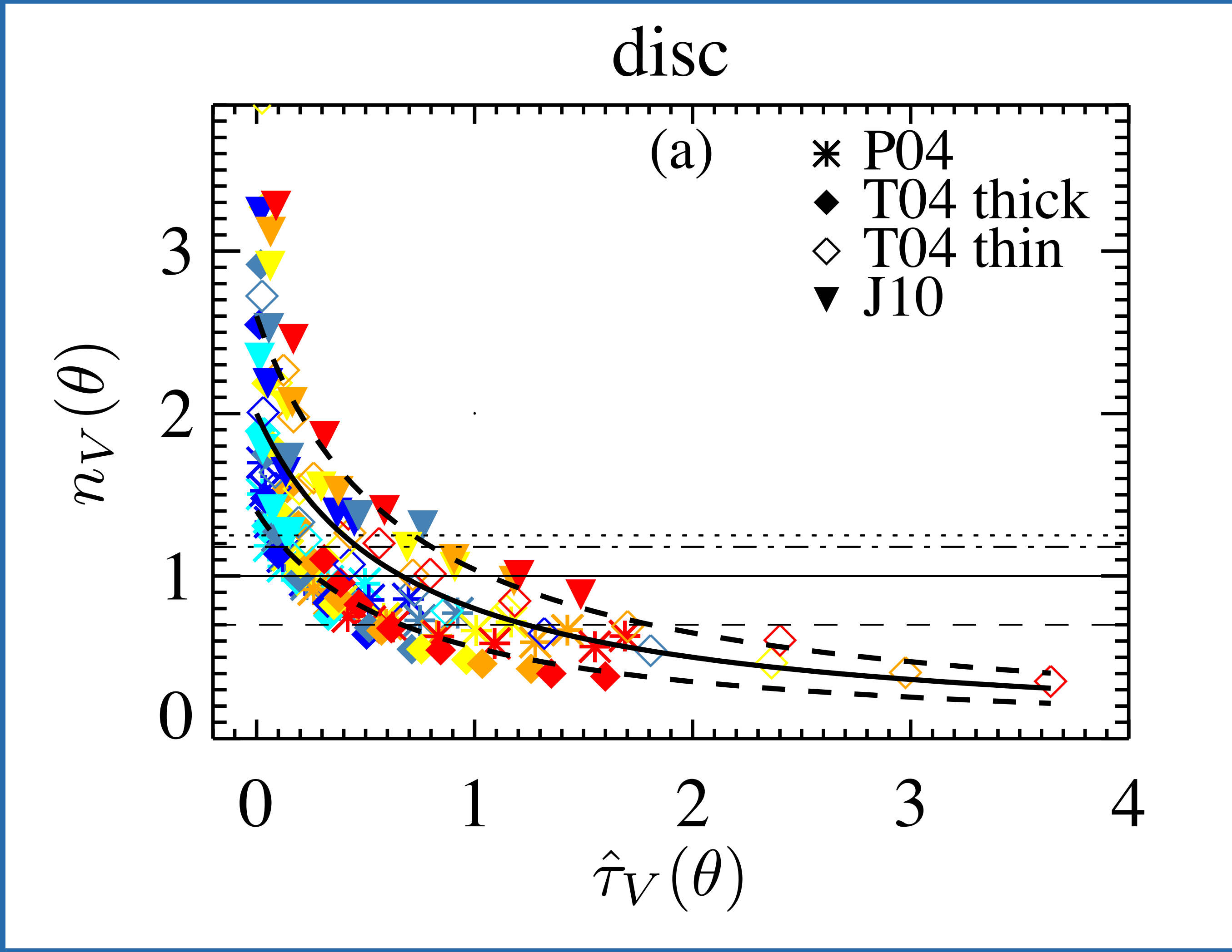
Dust attenuation: modeling

We can fit the relation between optical slope $n_V(\theta)$ and V-band effective optical depth $\hat{\tau}_V(\theta)$



$$n_V(\theta) = \frac{2}{1+1.5\hat{\tau}_V(\theta)}$$

+

dispersion of 30 % at fixed $\hat{\tau}_V(\theta)$ to account for the dispersion in the models

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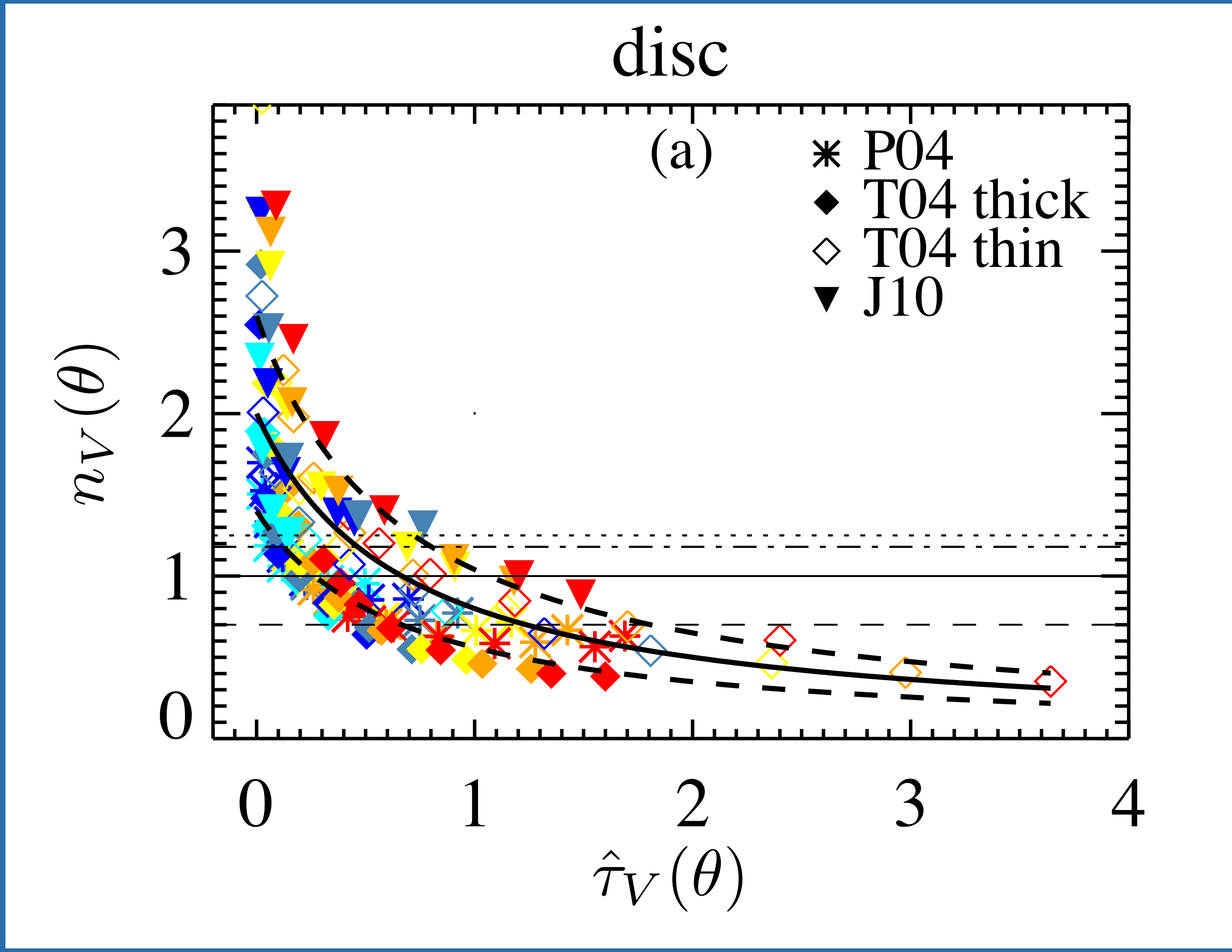

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- Account for the effect of inclination and spatial distribution of dust and stars
- Based on MW-type dust
- Valid for quietly star-forming disc

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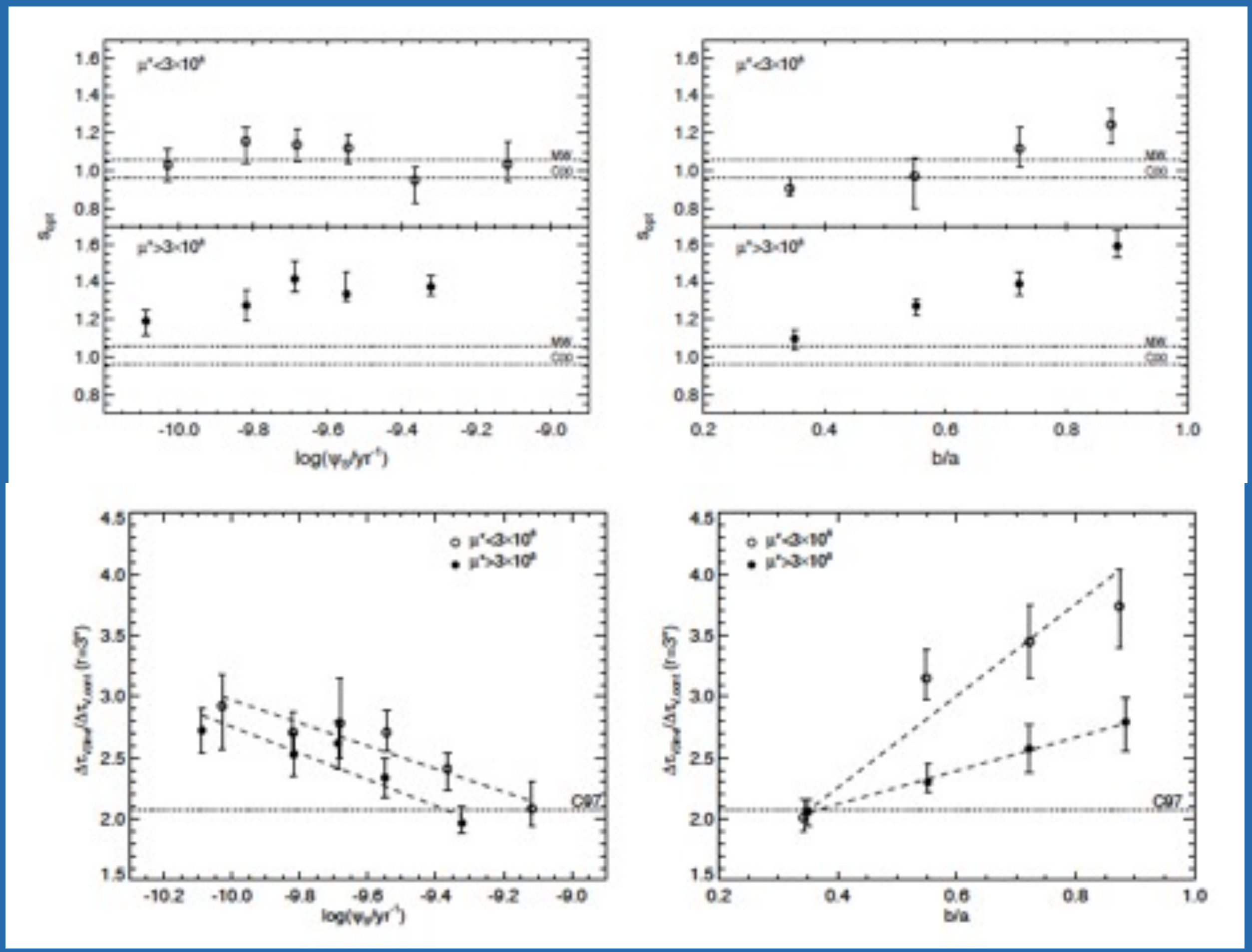

Wild et al., MNRAS 2011

- 23 000 star forming galaxies
- Optical through NIR photometry and optical spectra (SDSS + UKIDSS)
- Wild et al. used pair matching of galaxies with different Balmer ratios to obtain attenuation curves
- Find trends between attenuation slopes and SSFR / axis ratio
- Valid only if attenuation curves are independent on τ_V
- RT models show that this is not the case

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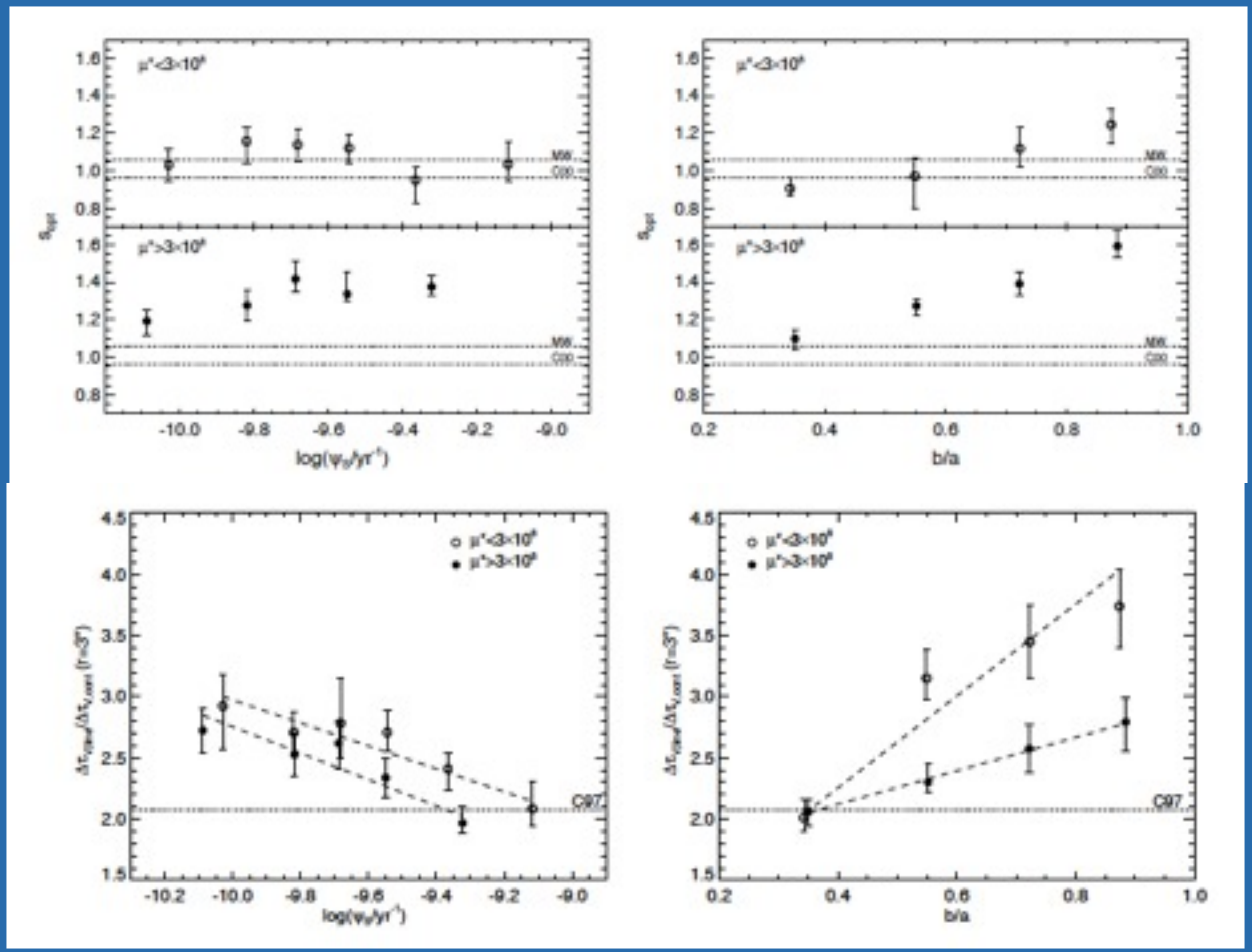

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Need of a different approach to get attenuation curves from galaxies SEDs

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Computing attenuation curves from data

- **Differential photometry** to compute attenuation curves (attenuation suffered by stars older than 10 Myr, due to the ambient ISM):
    - normalize all the SEDs to the K-band flux (small attenuation in the K-band)
    - divide in 10 b/a bins and compute the mean SED in each bin
    - compute the ratio of the SED in any bin to the face-on one
- This works if the intrinsic SEDs are the same across the b/a bins...

+

- $H\alpha/H\beta$ ratio, which traces the total attenuation suffered by starlight

Computing attenuation curves from data

- Are the unattenuated SEDs constant across the b/a bins? Not really...

- Systematic variation of SSFR, 12+log(O/H), z and radius across the b/a bins

- Correct these biases using a method based on importance sampling (see soon Chevallard +2012 for details!)

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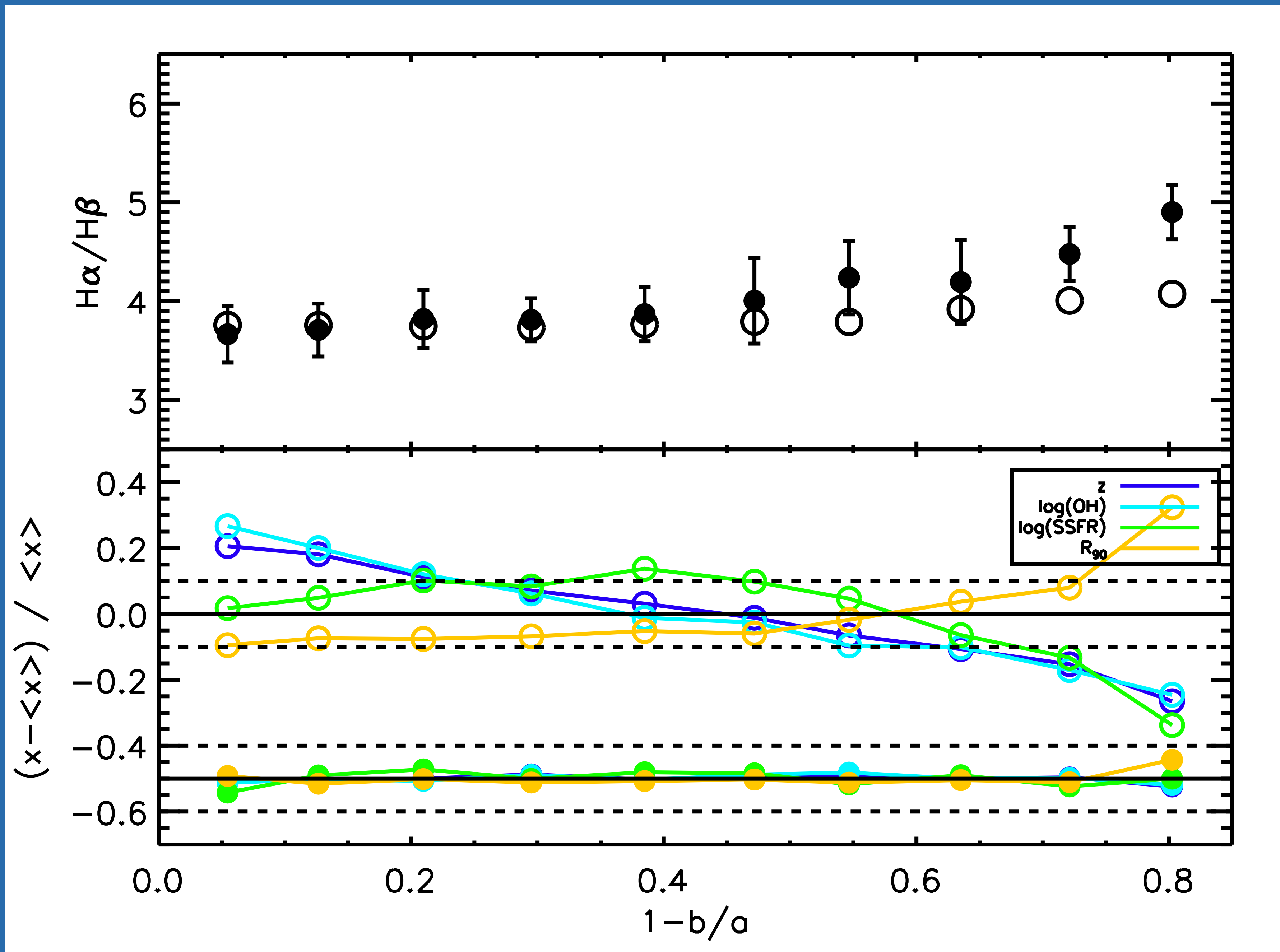

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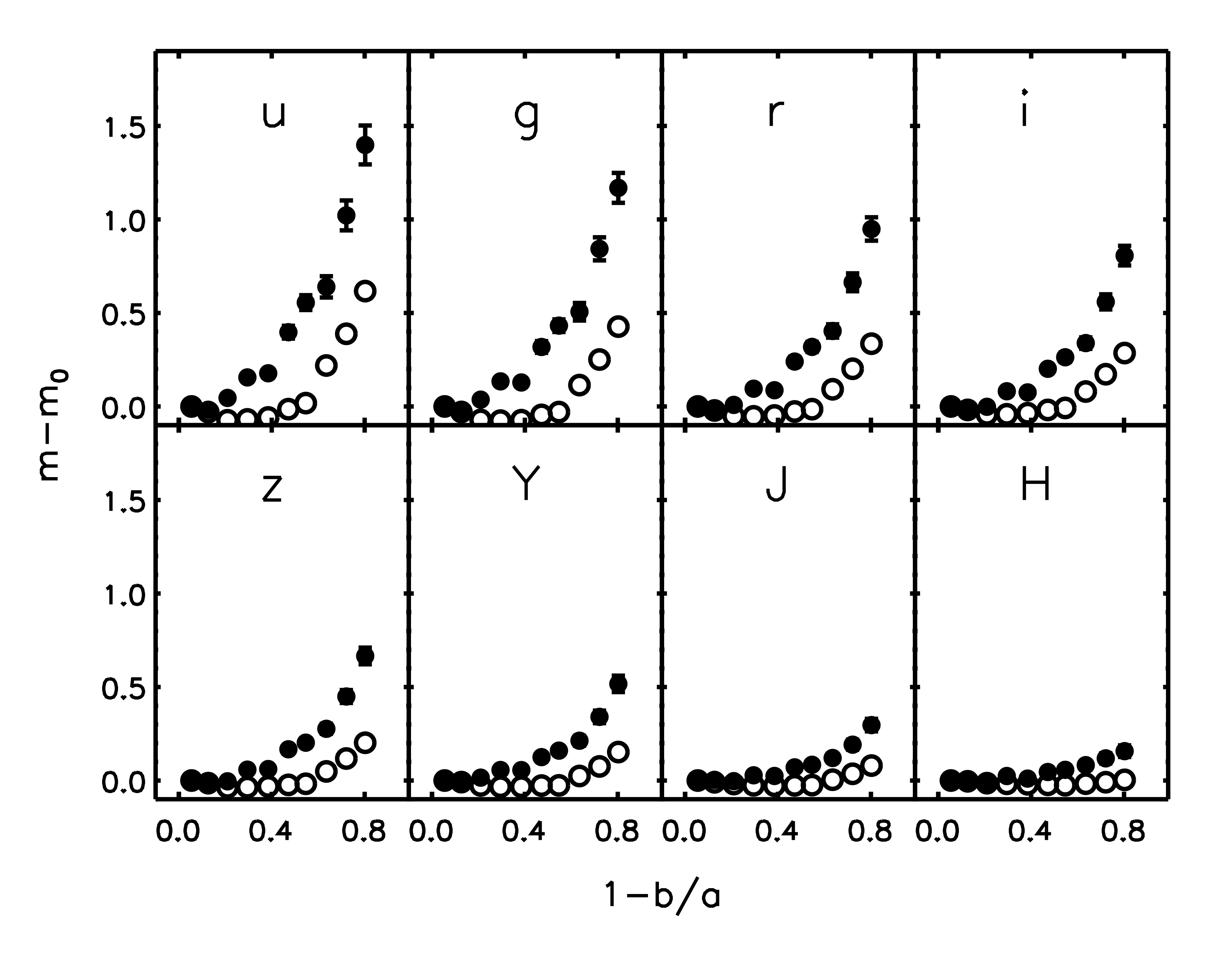

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Fitting the data

- Adopt the Tuffs et al. model to fit the data, since they are the most flexible (composed of 3 separate geometrical components: thick, thin disc and bulge)

- 5 parameters to describe attenuation by dust:
  - $\tau_{B,\perp}$: amount of dust in the ambient (i.e. diffuse) ISM
  - $\tau_{V,BC}$: optical depth of stellar birth clouds
  - $\mathrm{t_{thin}}$, $\mathrm{t_{thick}}$, $\mathrm{t_{bulge}}$: assign stars of different ages to the different geometrical components of the Tuffs et al. model
- Appeal to a Markov Chain Monte Carlo (MCMC) algorithm to efficiently explore the parameter space

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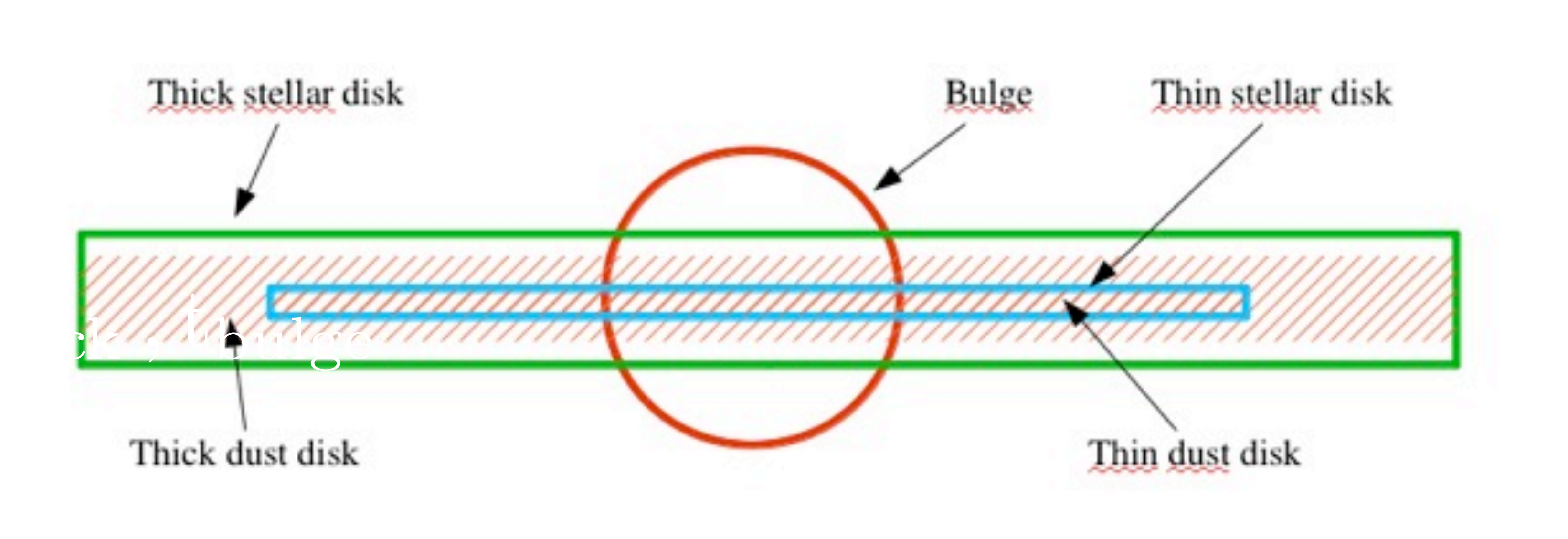

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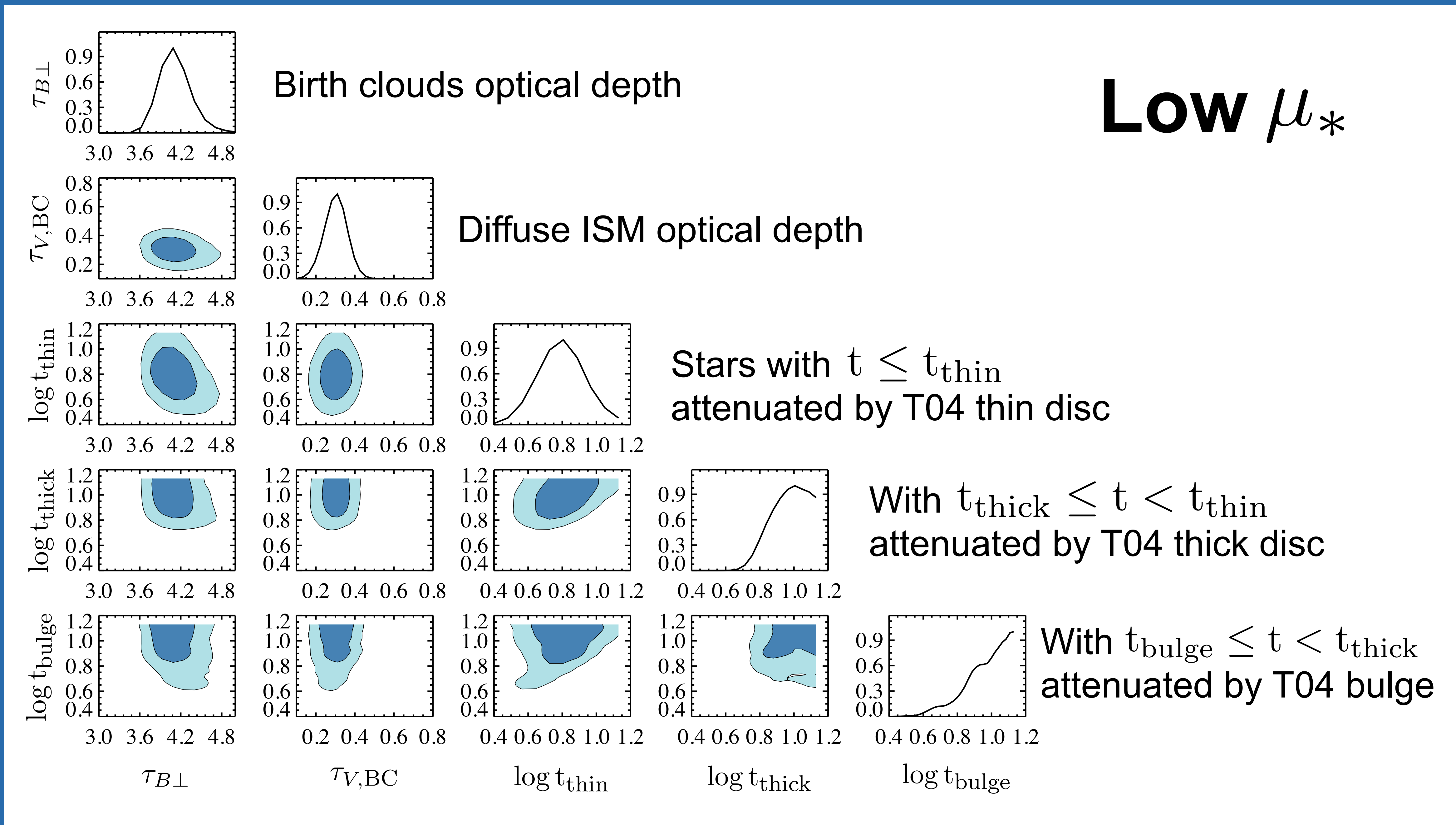
Results of the fit

• Result of MCMC is full posterior probability distributions for the parameters



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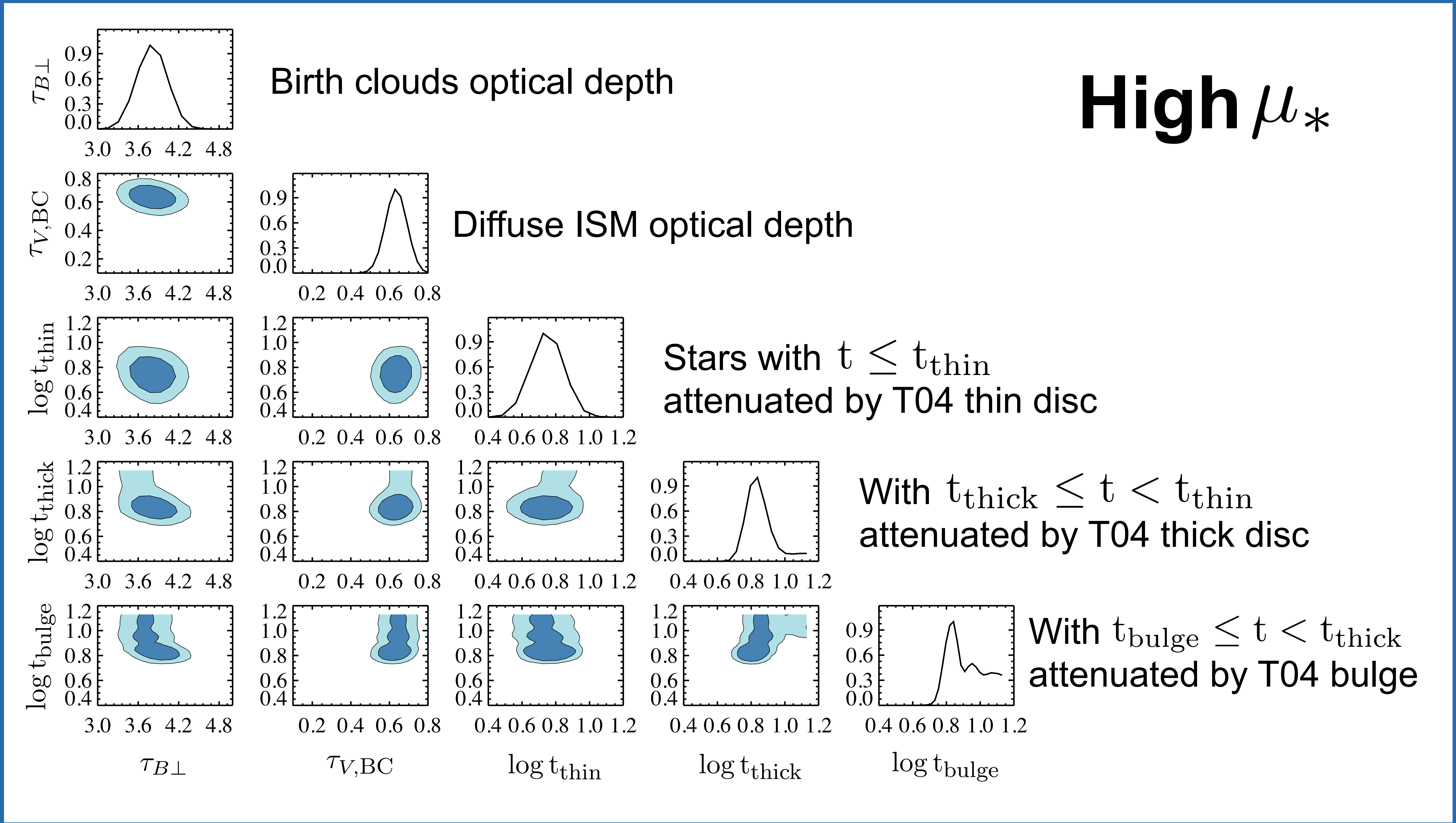

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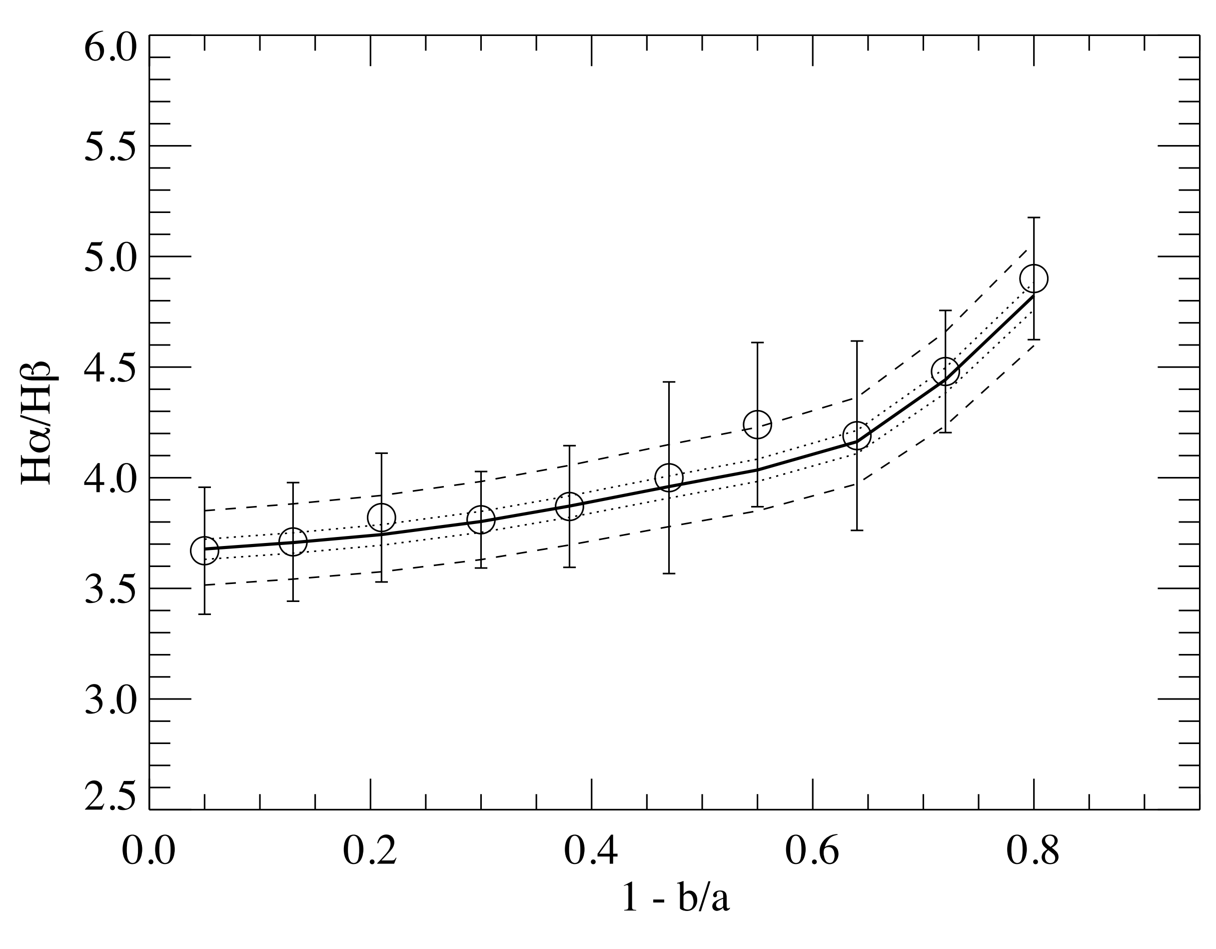
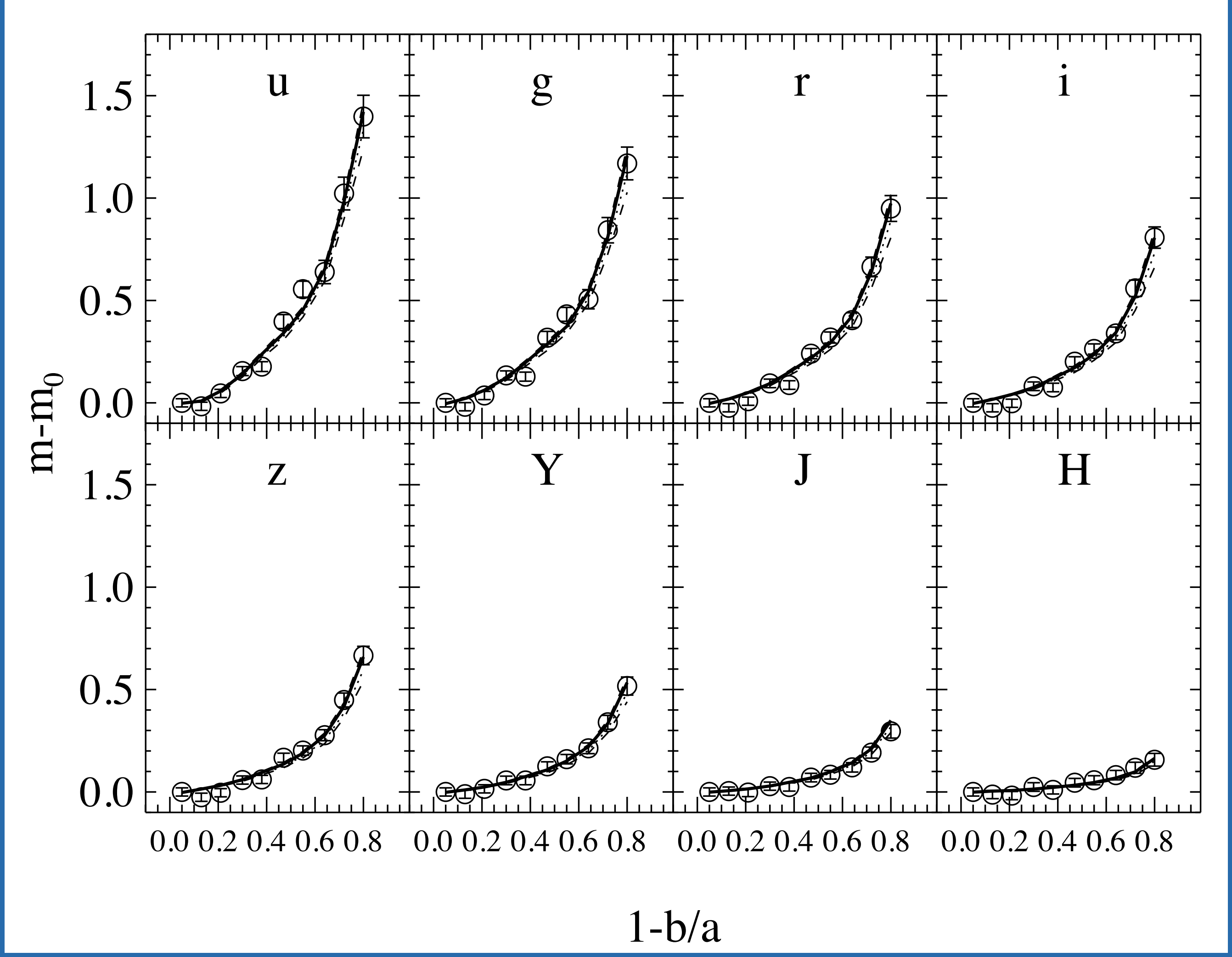
Results of the fit

Provides remarkable fit of the data!



Low μ_*



Both the variation of $H\alpha/H\beta$ ratio and $ugrizYJH$ attenuation curve with inclination is reproduced

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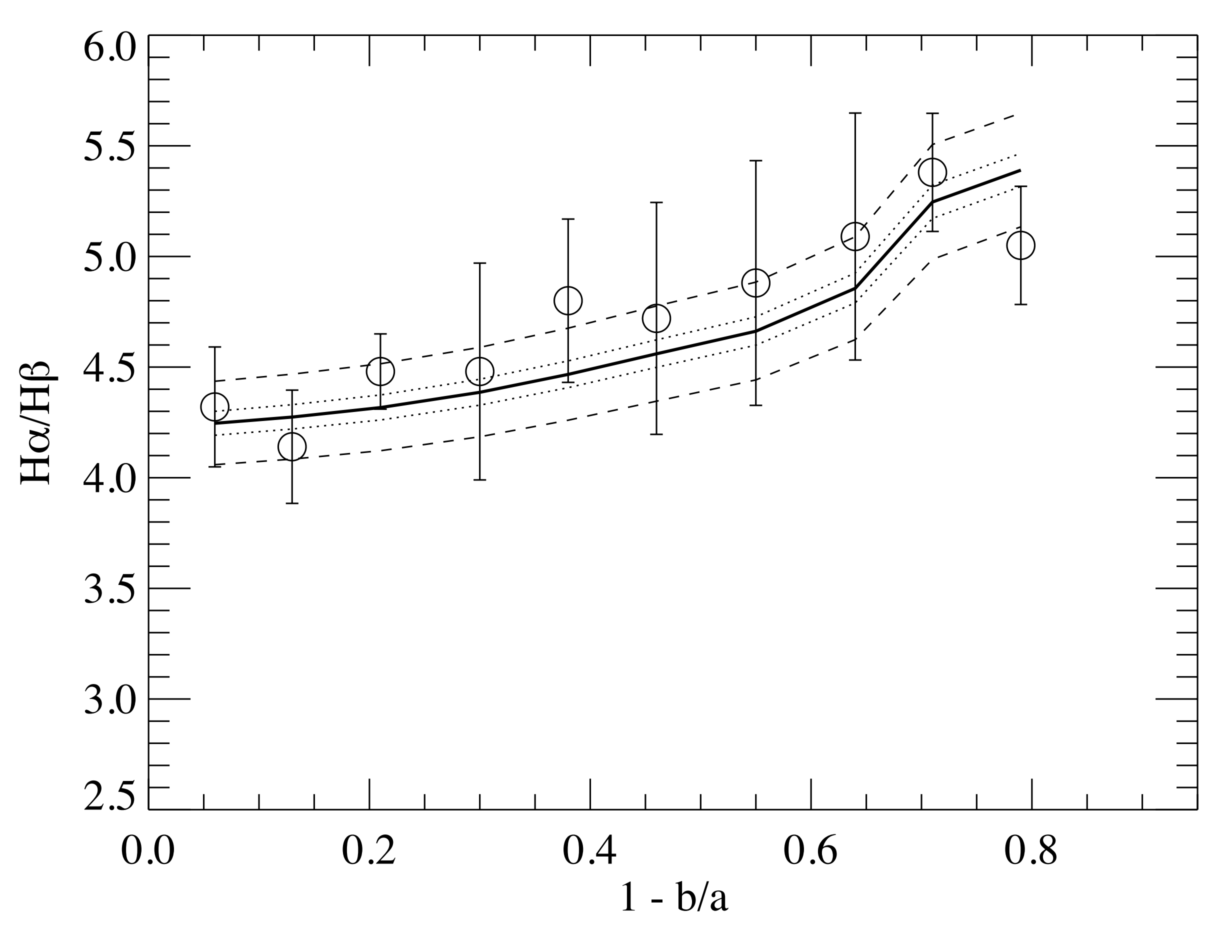

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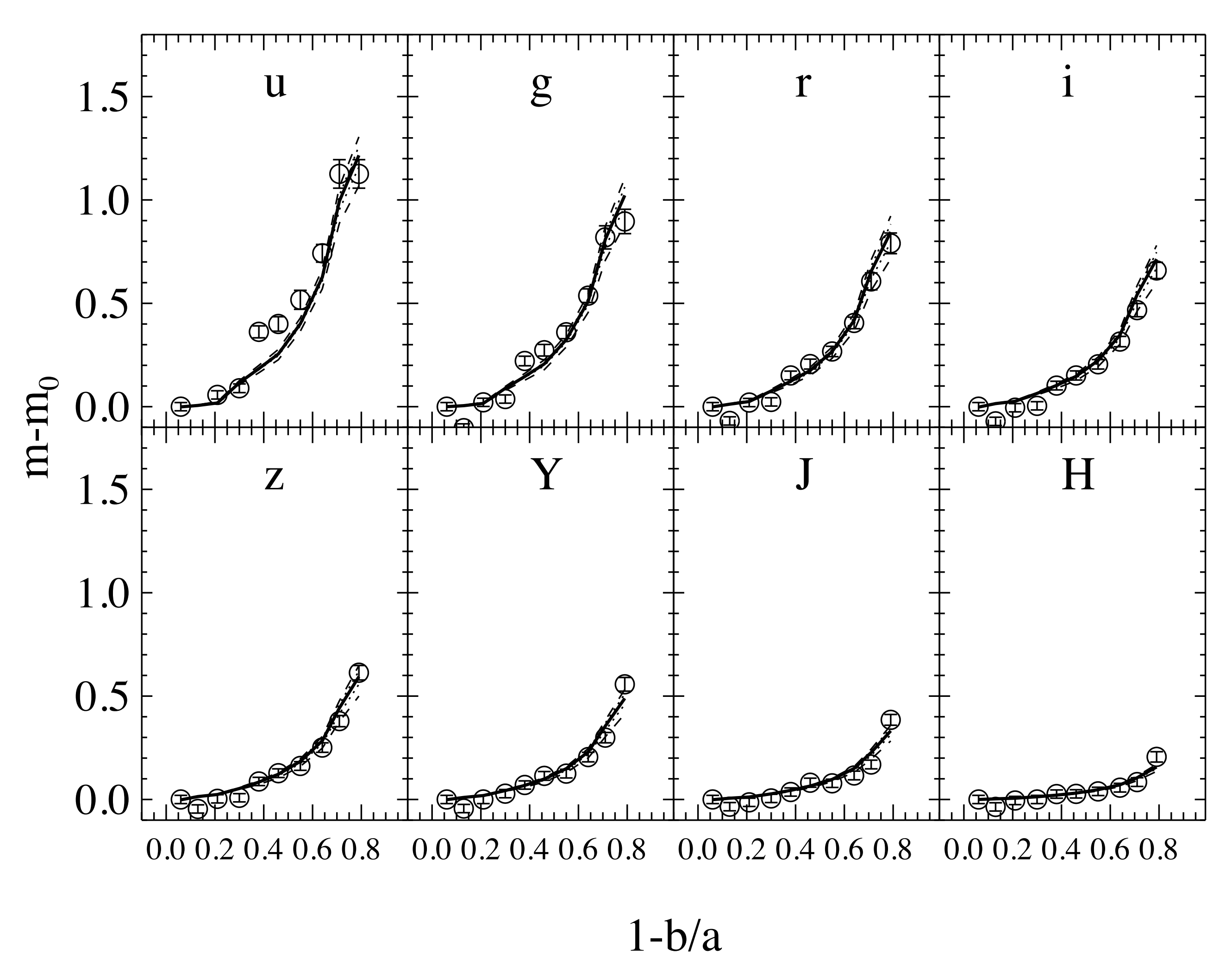

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Results of the fit

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• RT models predictions of the variation of dust attenuation with inclination agree with data from local galaxies

• Important to consider attenuation curves with different shapes to reproduce observations

• Fixed curves (Calzetti or Milky Way) unable to catch the variety of curves arising from the effect of inclination

• Posterior mean for the high and low μ_* samples similar, only significant difference in $\tau_{V,BC}$, linked to the different gas-phase metallicities of the two samples

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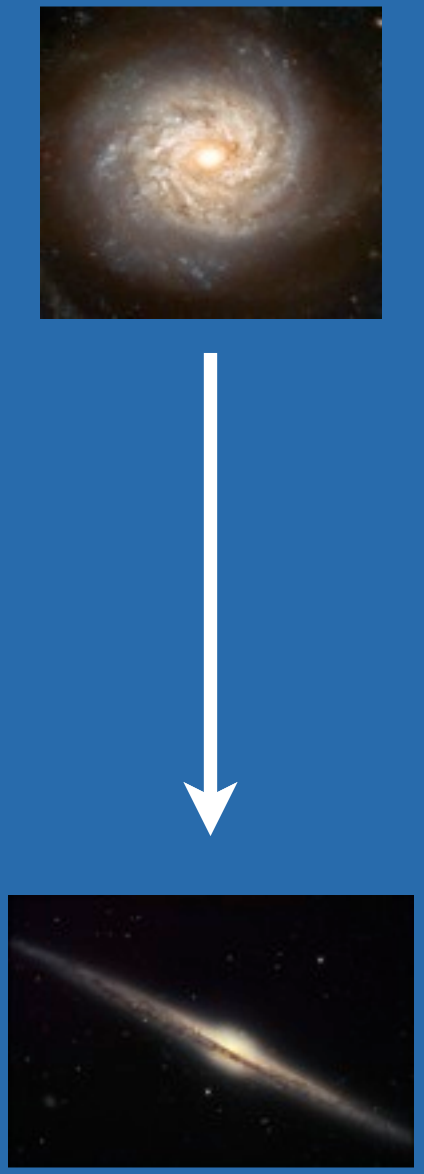
Dust attenuation: effect on galaxy colors

What is the effect of such dust prescriptions on galaxy colors?
Use the already built model library!



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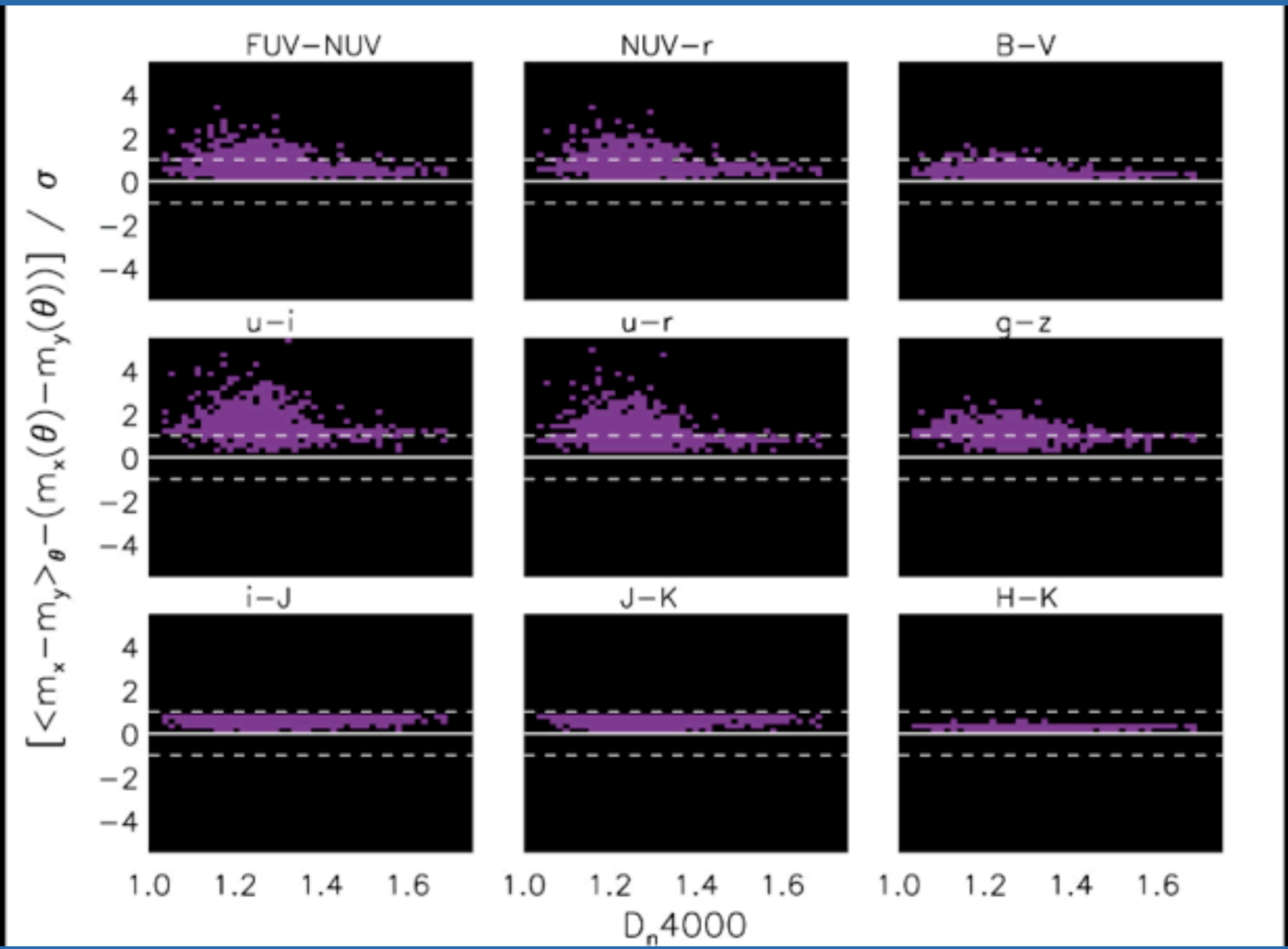
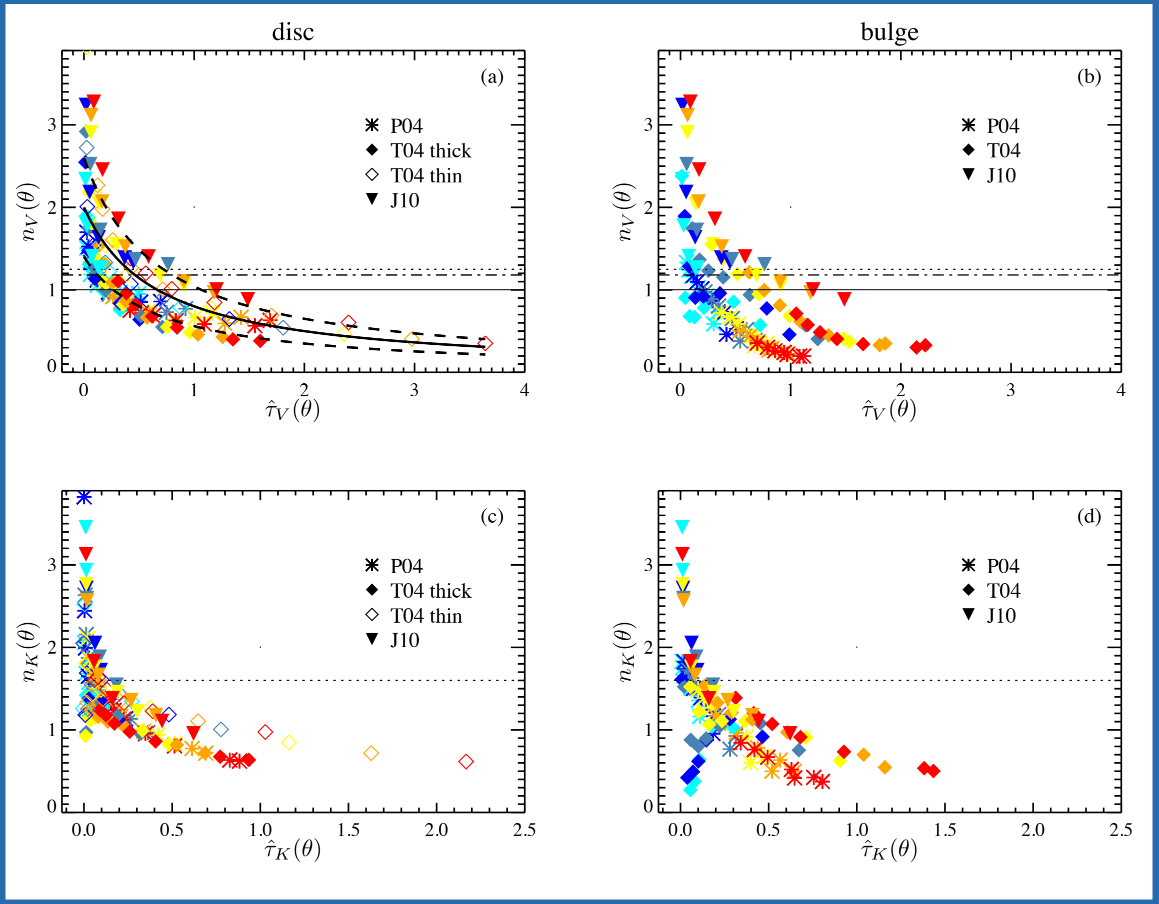


Summary

- Popular radiative transfer models predict a similar flattening of the optical attenuation curve with increasing effective optical depth



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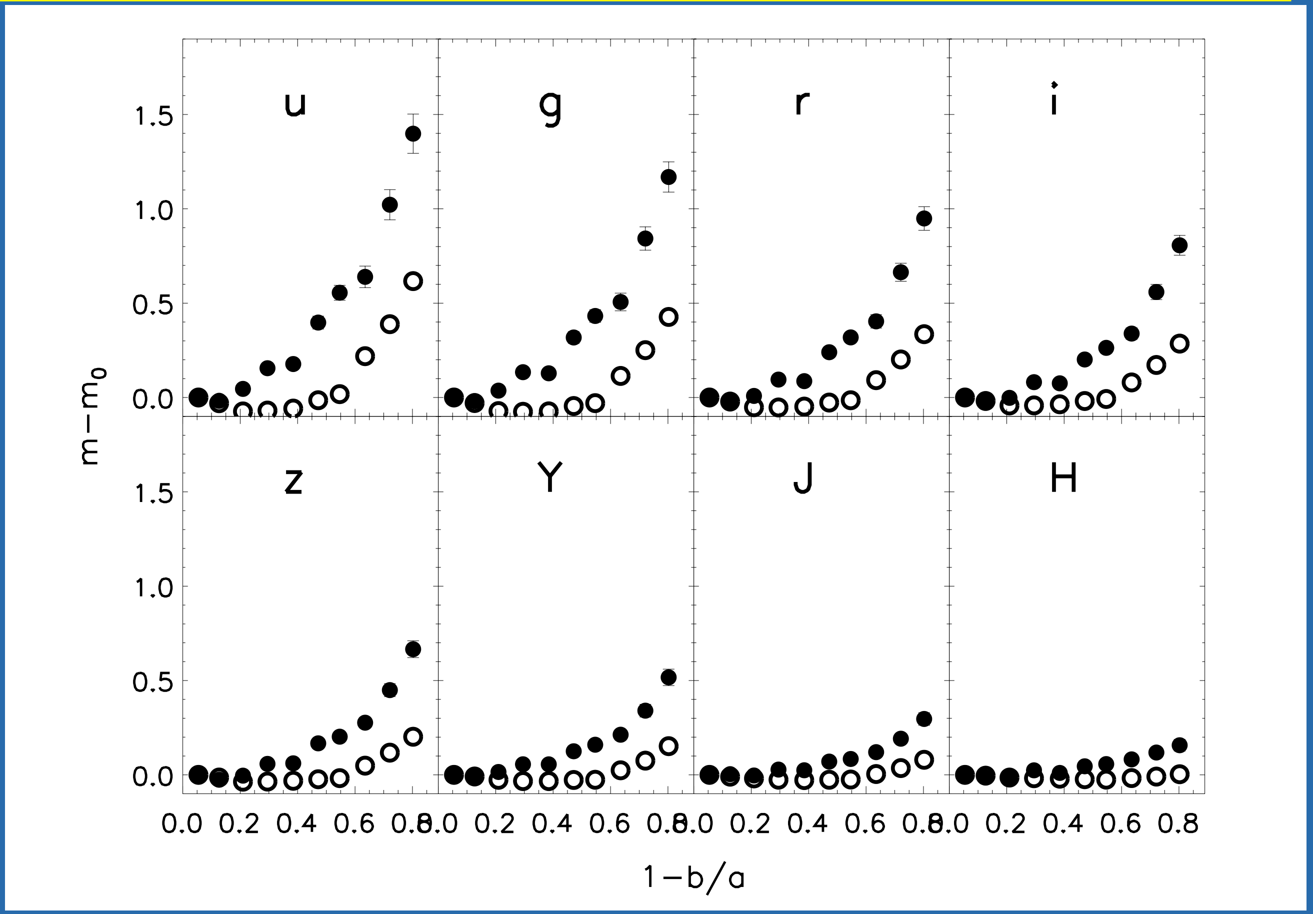
• SDSS + UKIDSS data allow us to compute attenuation curves of galaxies seen at different inclinations (but must account for biases)



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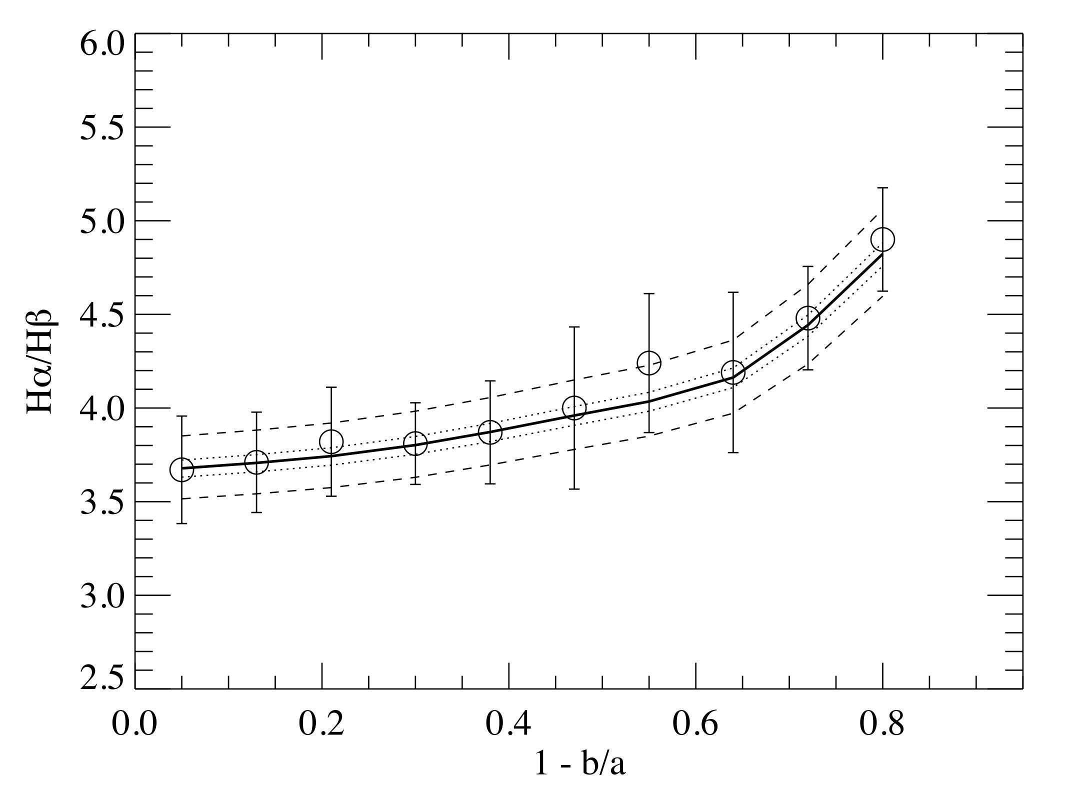
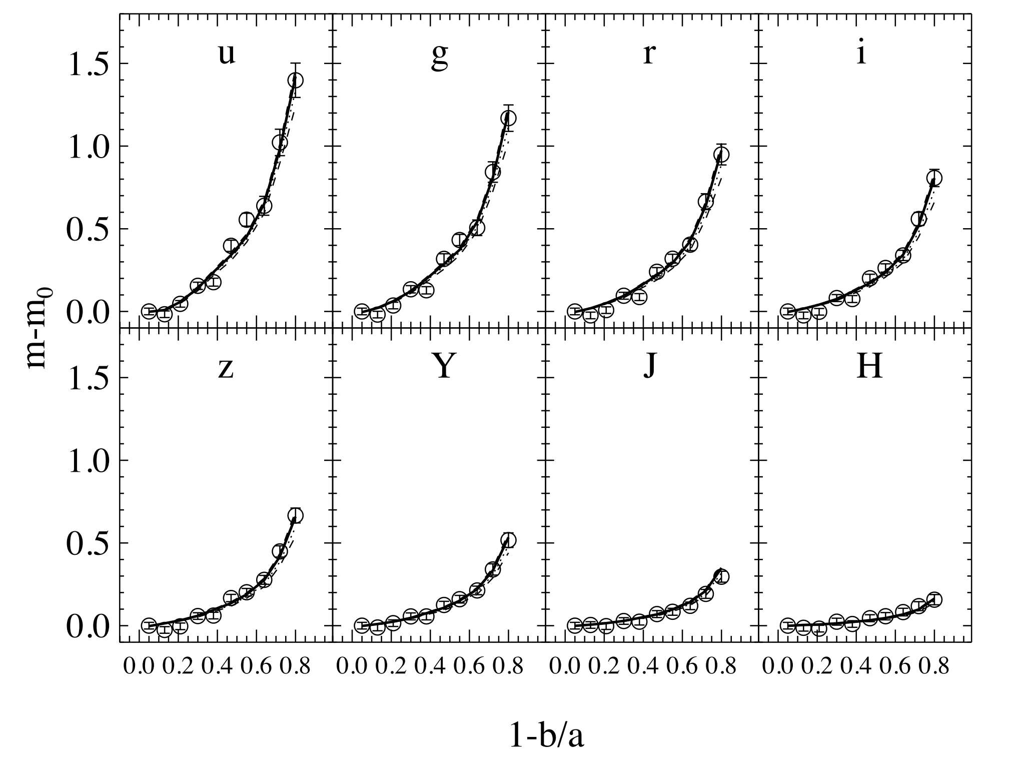
- SDSS + UKIDSS data allow us to compute attenuation curves of galaxies seen at different inclinations (but must account for biases)

- Can reproduce observed dependance of $H\alpha/H\beta$ ratio and attenuation curves with inclination by combining Tuffs et. al, 2004 models with Charlot & Bruzual spectral evolution models





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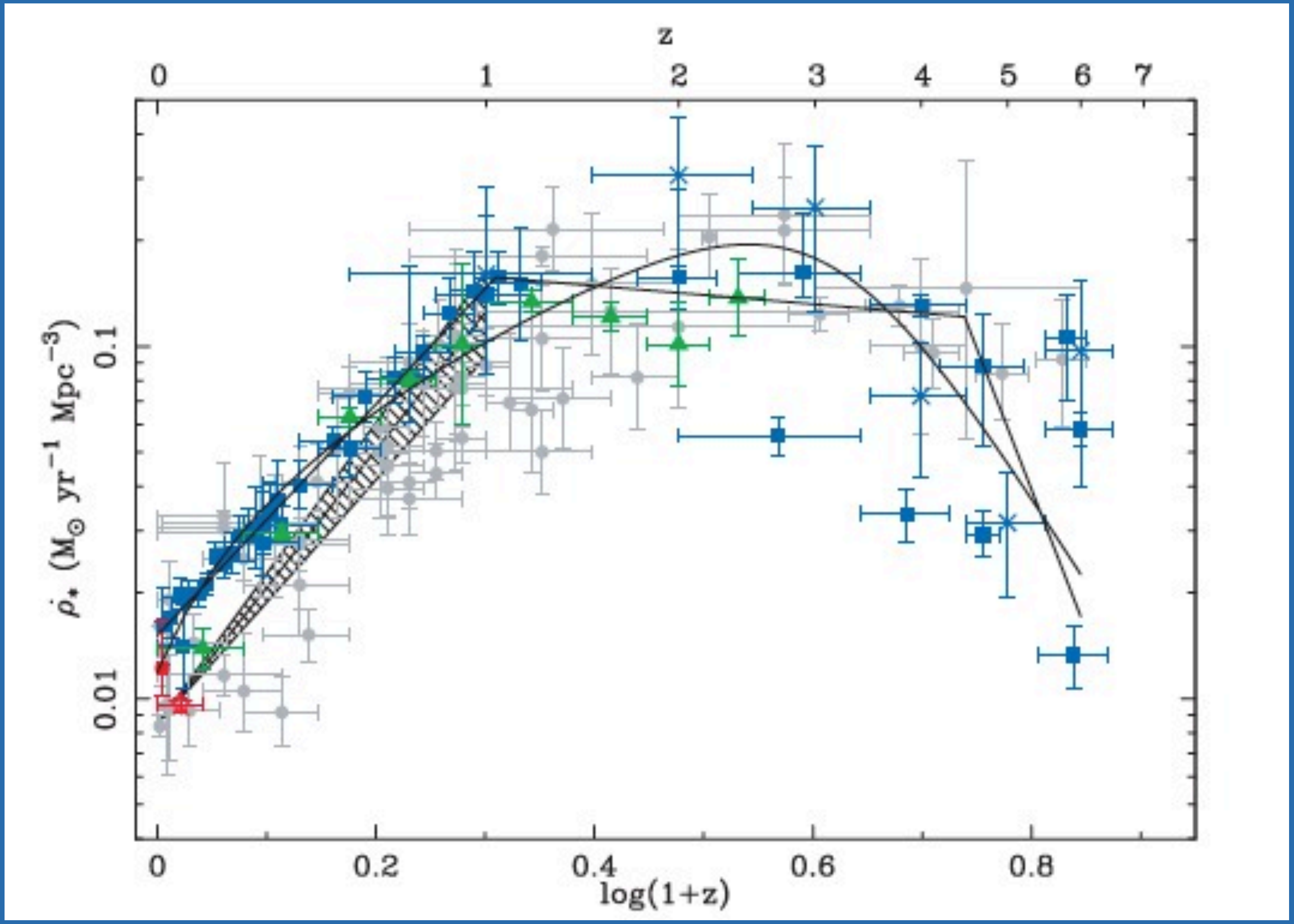
SFR and dust attenuation

- SFR density, tells us the rate of galaxies mass assembly
- Linked to merging history of galaxies, gas inflows and outflows, AGN and SNe feedback



Hopkins & Beacom (2006)

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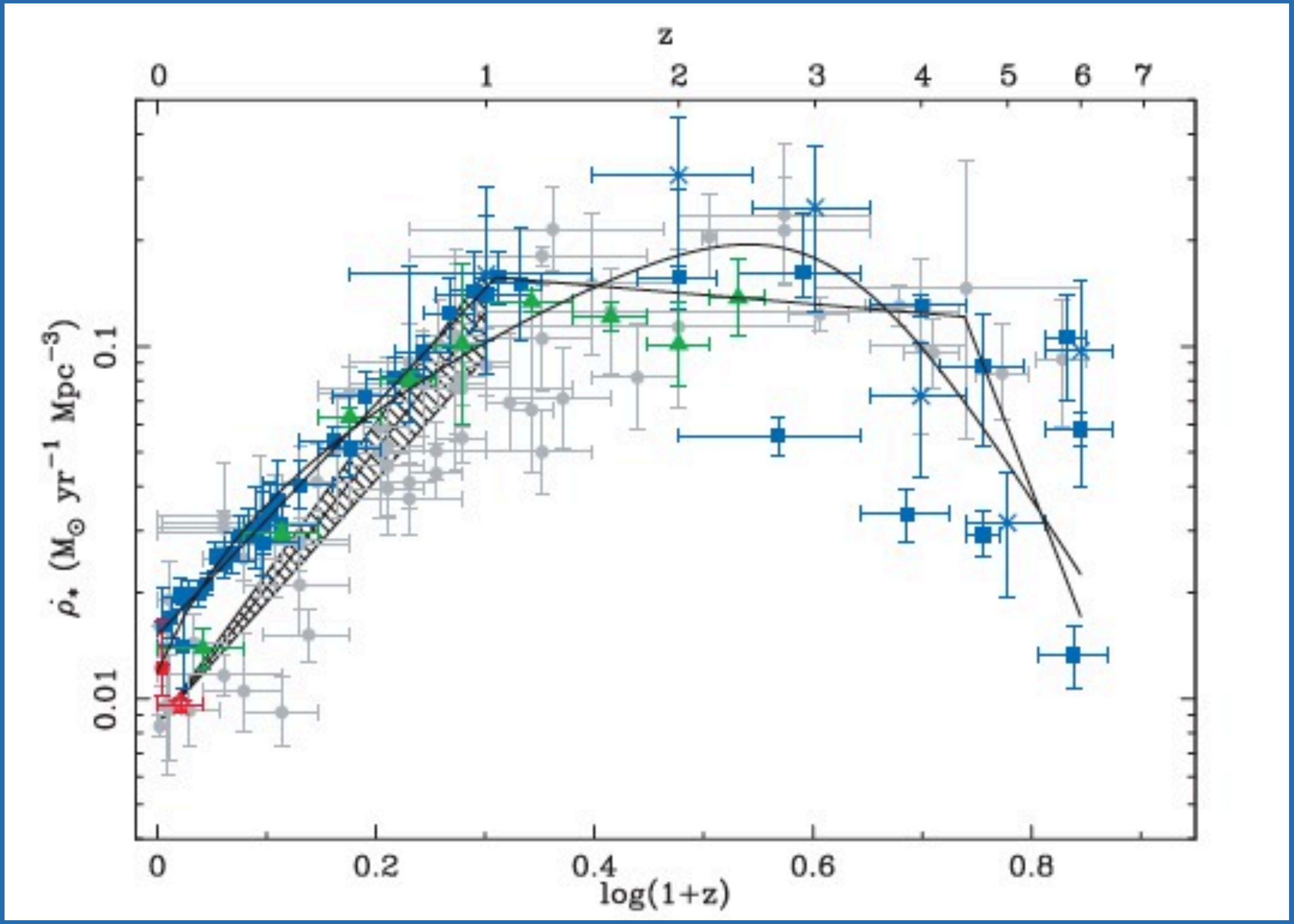

Hopkins & Beacom (2006)

• But...challenging to get SFR estimate at intermediate-to-high z

• Difficult to use emission lines

• FIR also difficult to observe (at least right now...)

• UV is the most accessible SFR proxy, but suffers severe dust attenuation

SFR and dust attenuation: data

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- COSMOS + Spitzer/MIPS @ 24 μm
- 31 passbands
- Spectroscopic redshift (zCOSMOS) where available, otherwise photo-z
- Maximum redshift $z_{max} = 1.3$
- AGN excluded through MID-IR diagnostics
- Total of 18 000 galaxies (16 500 star forming and 1000 passive)
- Low z sample of 700 galaxies from SWIRE (GALEX+SDSS+2MASS+MIPS)

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- Physical parameters from LePhare + BC03 templates
- Rest-frame luminosities from nearest rest-frame filter (consistent to 10 % with BC03 rest-frame luminosities and with Ilbert (2009))
- SFR from Bell (2005)

$$SFR^{tot}[M_{\odot}/yr] = 8.6\ 10^{-11}(L_{IR} + 1.9\ \mathcal{L}_{NUV})$$

$$\mathcal{L}_{NUV} = \nu L_{\nu}(2300\text{Å})(L_{\odot})$$

L_{IR} obtained extrapolating the 24 flux with Dale & Helou (2002) templates

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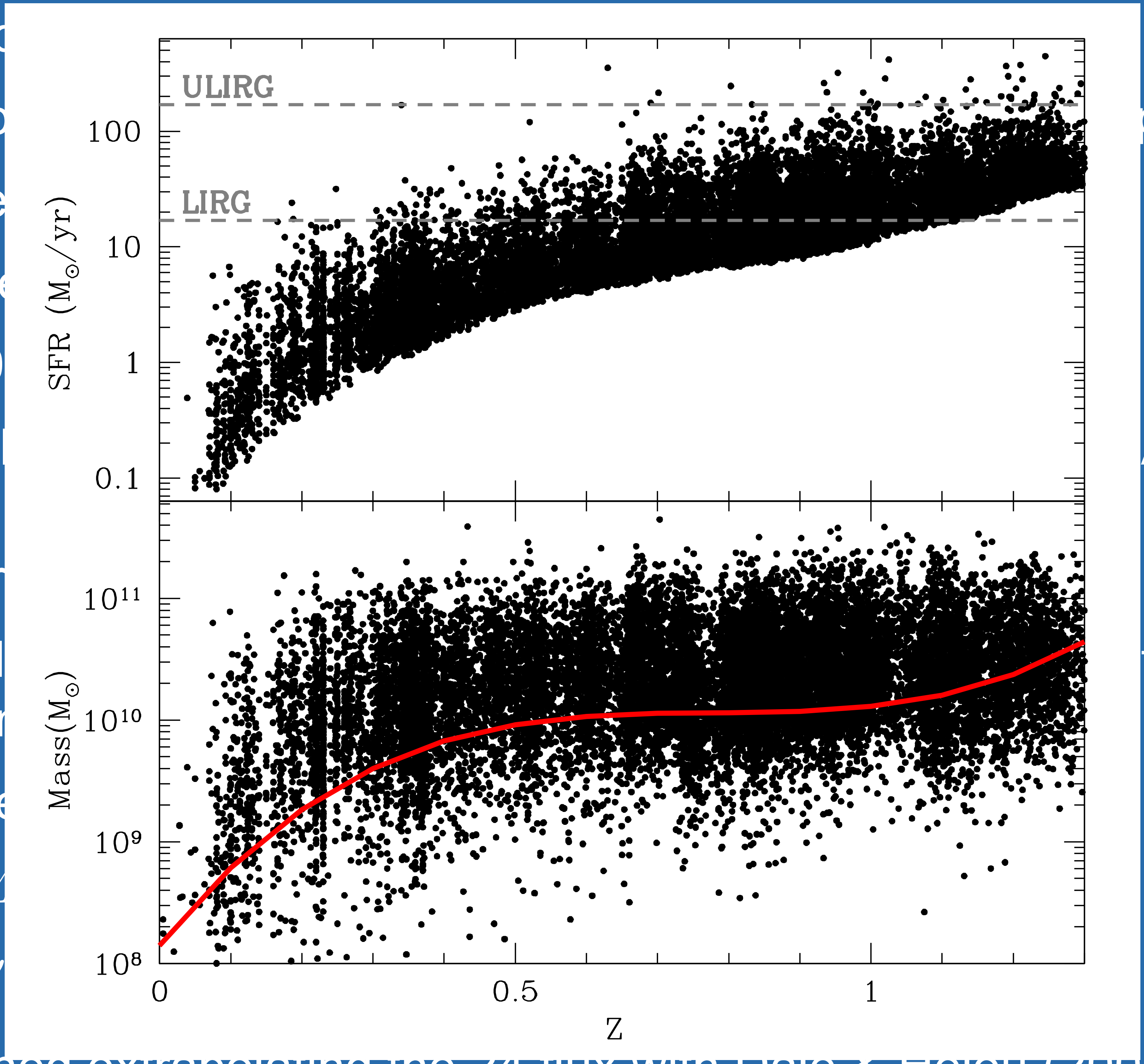

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- 31 passbands
- Spectroscopic redshift (zCOSMOS) where available, otherwise photo-z
- Maximum redshift $z_{max} = 1.3$
- AGN excluded through MID-IR diagnostics
- Total of 18 000 galaxies (16 500 star forming and 1000 passive)
- Low z sample of 700 galaxies from SWIRE (GALEX+SDSS+2MASS+MIPS)

- Physical parameters from LePhare + BC03 templates
- Rest-frame luminosities from nearest rest-frame filter (consistent to 10 % with BC03 rest-frame luminosities and with Ilbert (2009))
- SFR from Bell (2005)

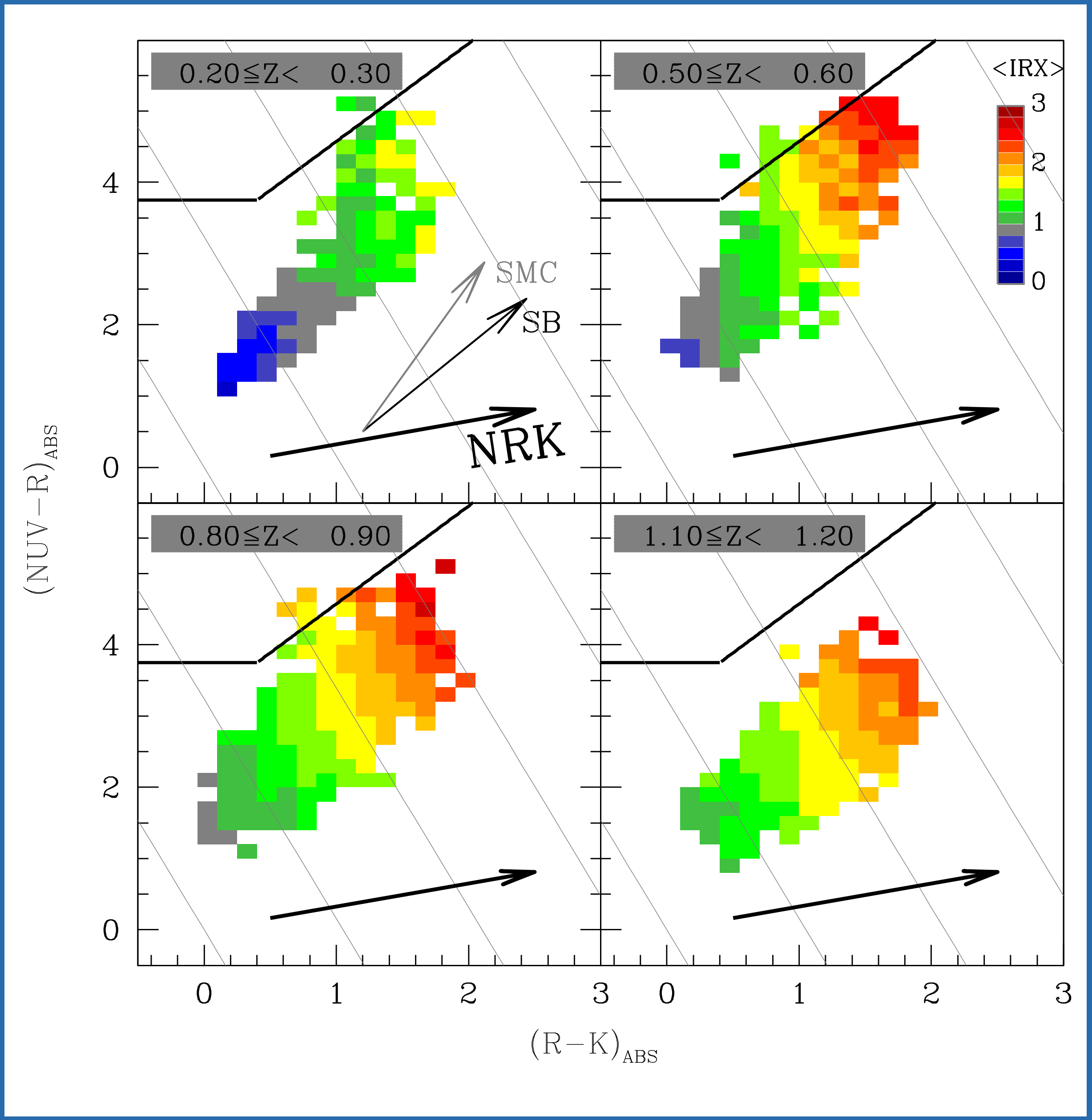
$$SFR^{tot}[M_{\odot}/yr] = 8.6\ 10^{-11}(L_{IR} + 1.9\ \mathcal{L}_{NUV})$$

$$\mathcal{L}_{NUV} = \nu L_{\nu}(2300\text{Å})(L_{\odot})$$

L_{IR} obtained extrapolating the 24 flux with Dale & Helou (2002) templates

The infrared excess IRX

- Infrared excess $IRX = \frac{L_{IR}}{\mathcal{L}_{NUV}}$, measures the global energy budget between energetic photons and dust



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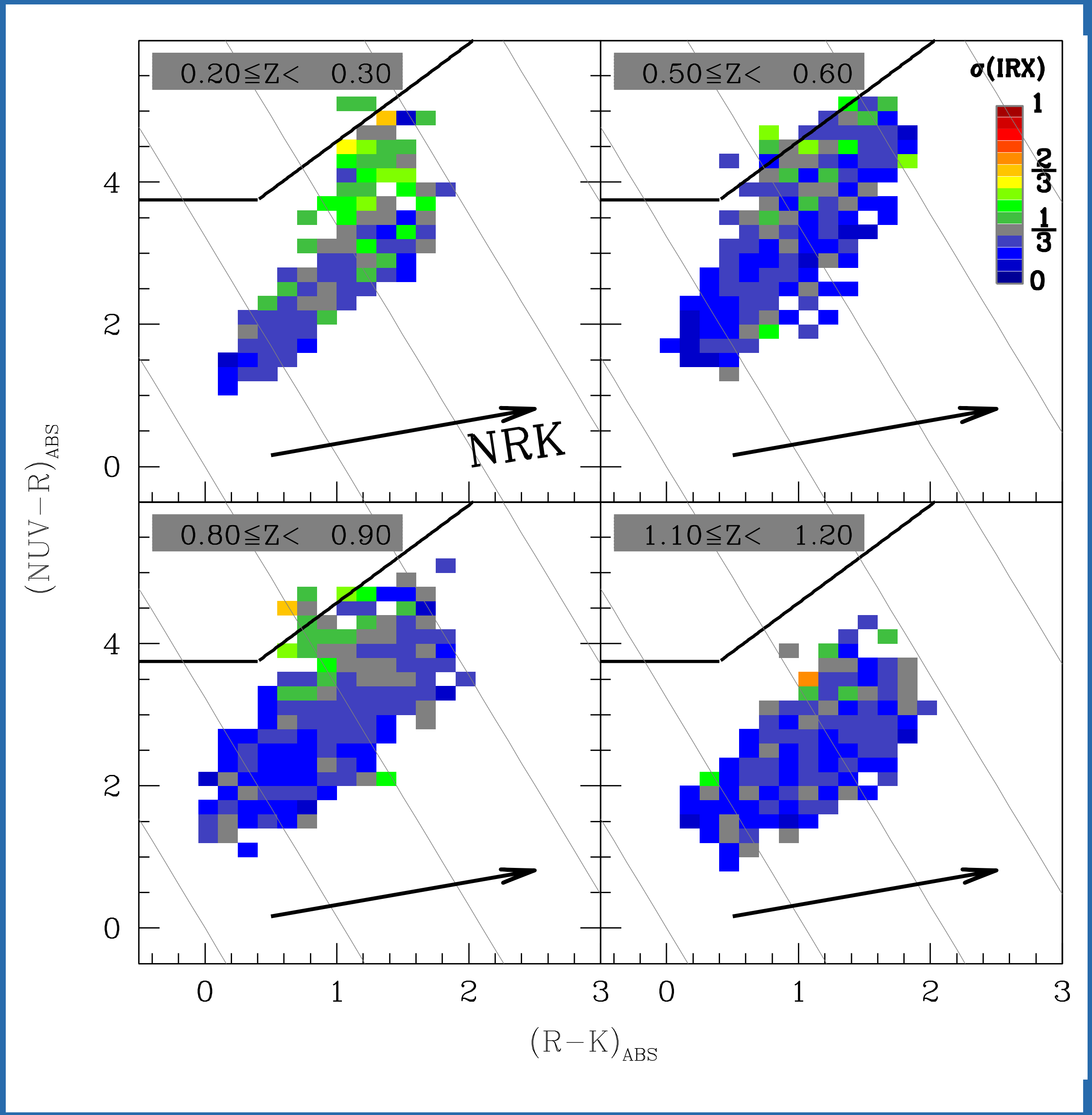

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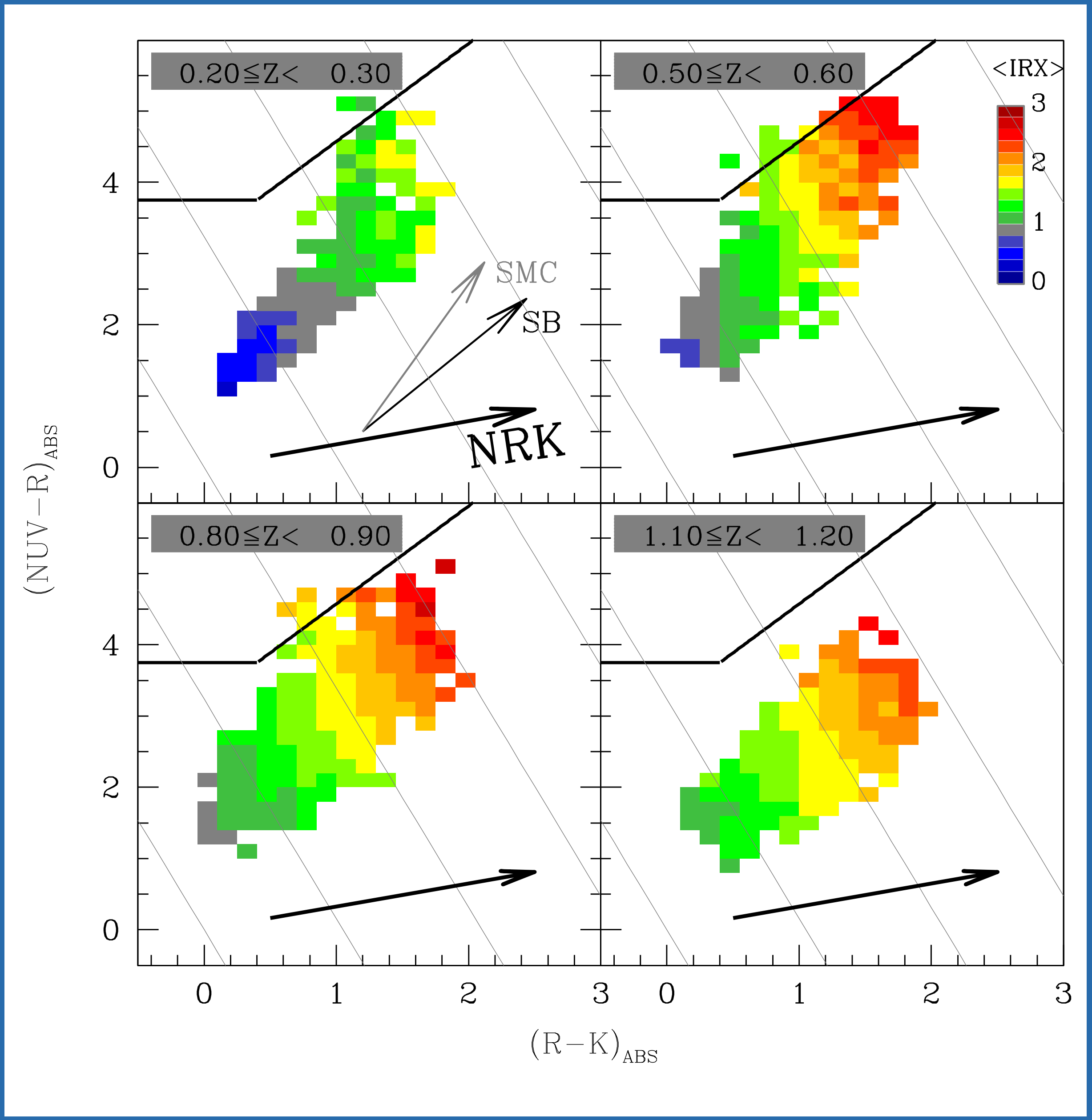

- Volume-weighted IRX increases by 1.5-2 dex from blue- to red-side
- Stripes of constant IRX
- Can combine (NUV-r) and (r-K) in a single vector perpendicular to IRX stripes

$$NRK(\theta) = \sin\theta(NUV - r) + \cos\theta(r - K)$$

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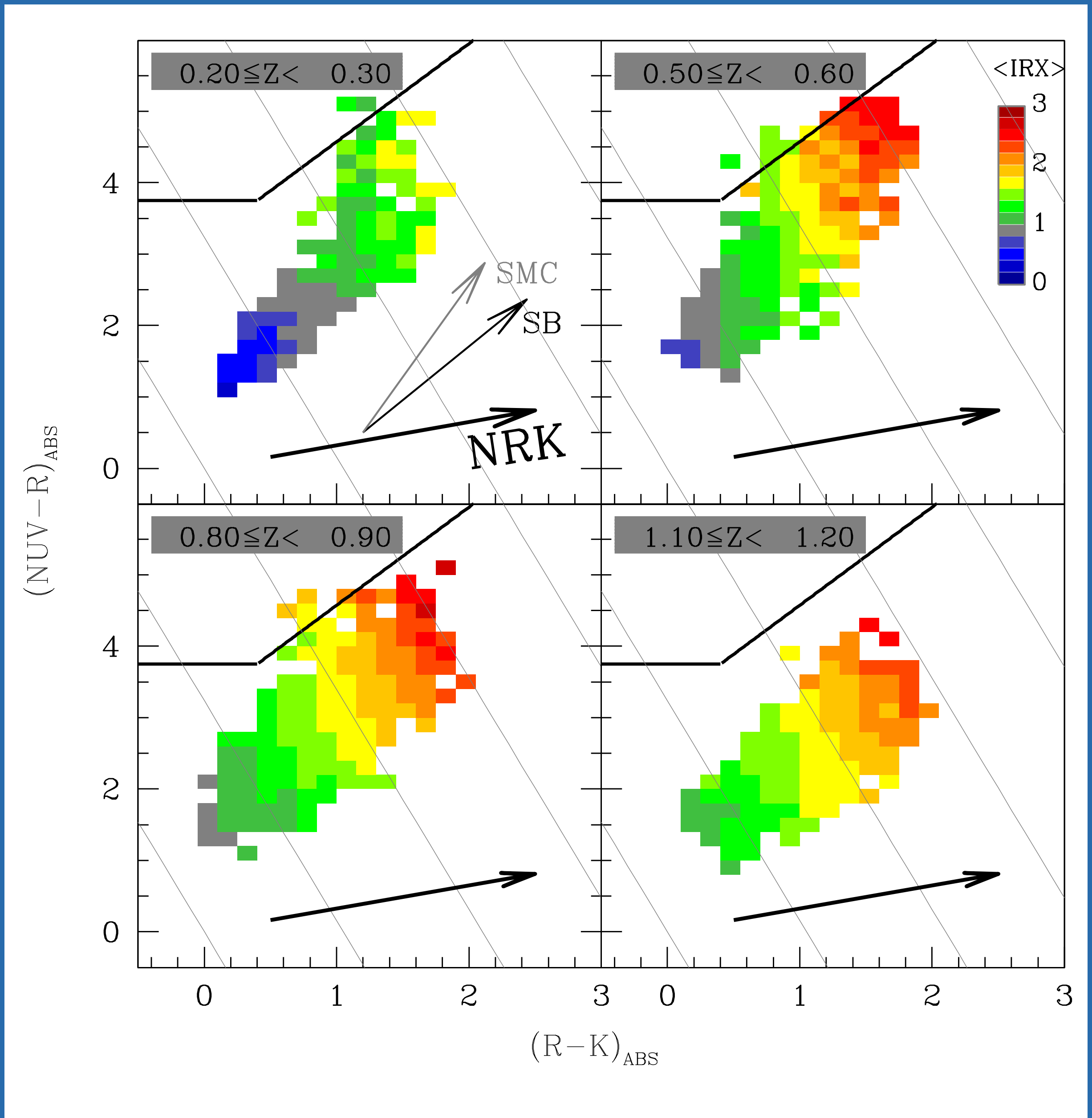

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- We can then relate IRX and its redshift evolution, to the vector NRK

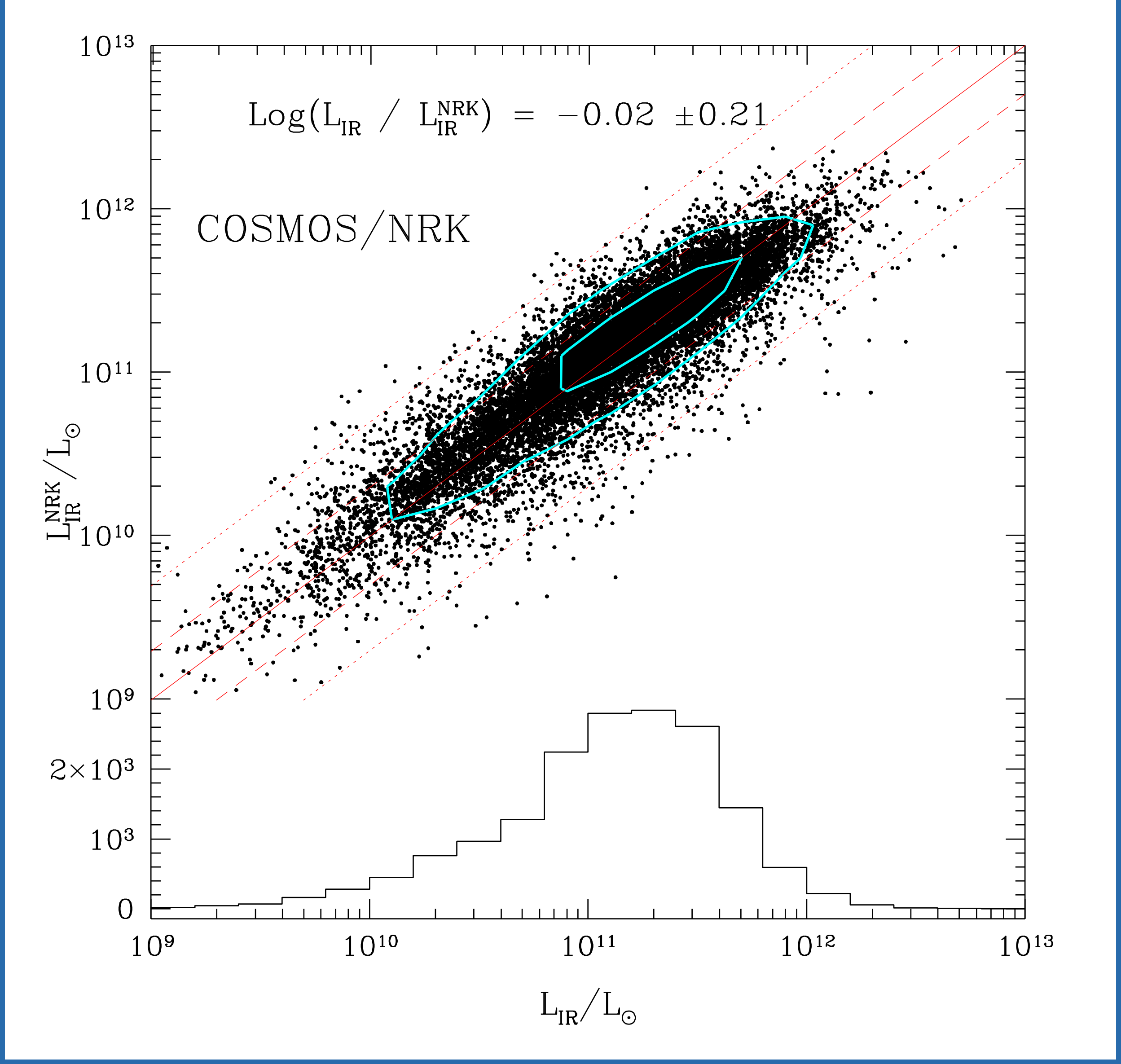
$$IRX(z, NRK) = f(z) + a \cdot NRK$$

- The slope of the relation is constant with redshift (a independent on z)
- The normalization changes

The infrared excess IRX

- Previous relations can be used to estimate the total IR luminosity from UV + NIR

$$L_{IR}^{NRK} = \mathcal{L}_{NUV} \cdot IRX(z, NRK)$$



- Allows a better estimate of the total IR luminosity than UV-to-near infrared SED fitting
- Almost no bias, and small rms (0.2 dex)
- Shows that the IRX, hence the total IR luminosity, is encoded in NUV-to-NIR

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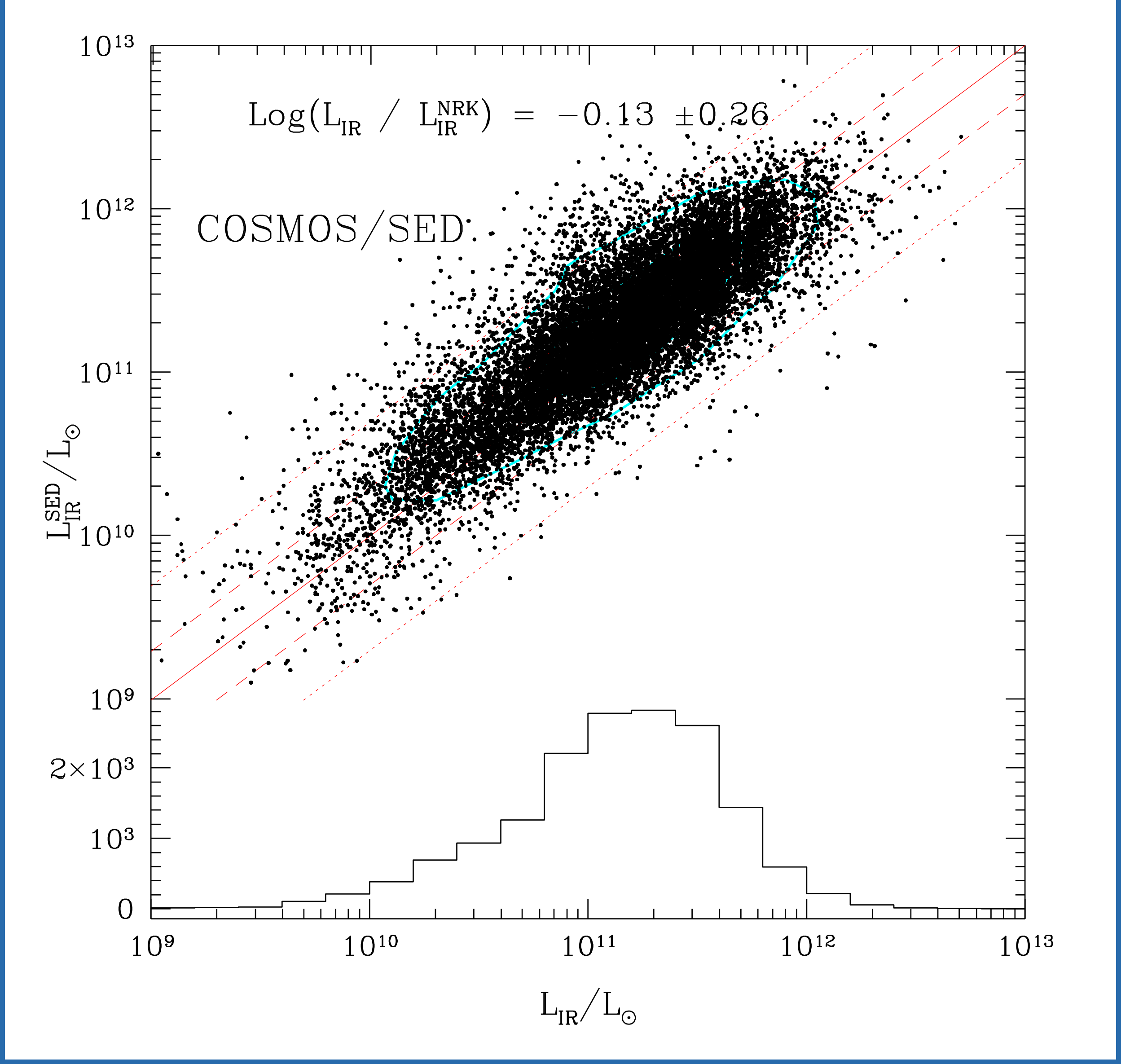

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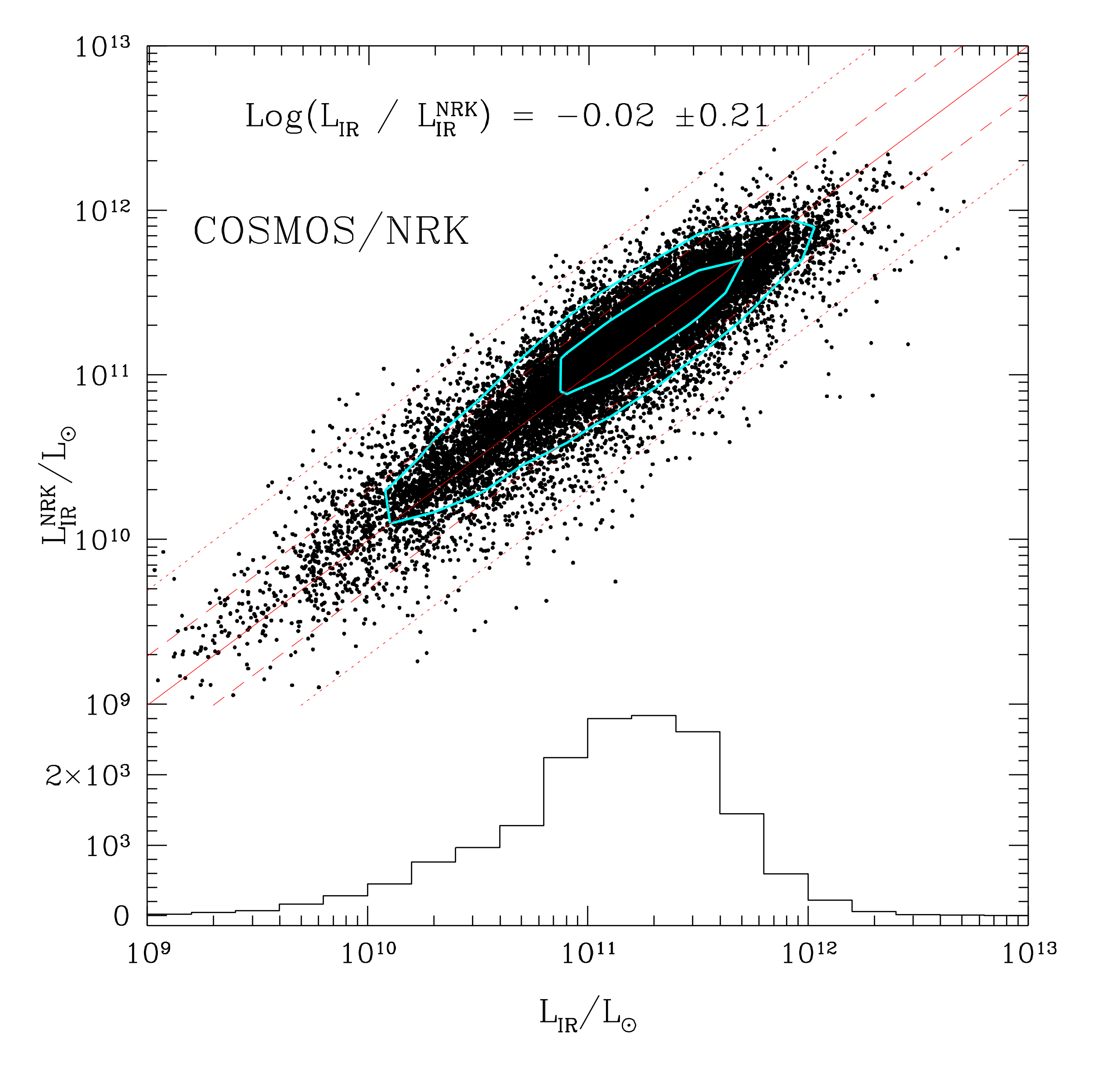

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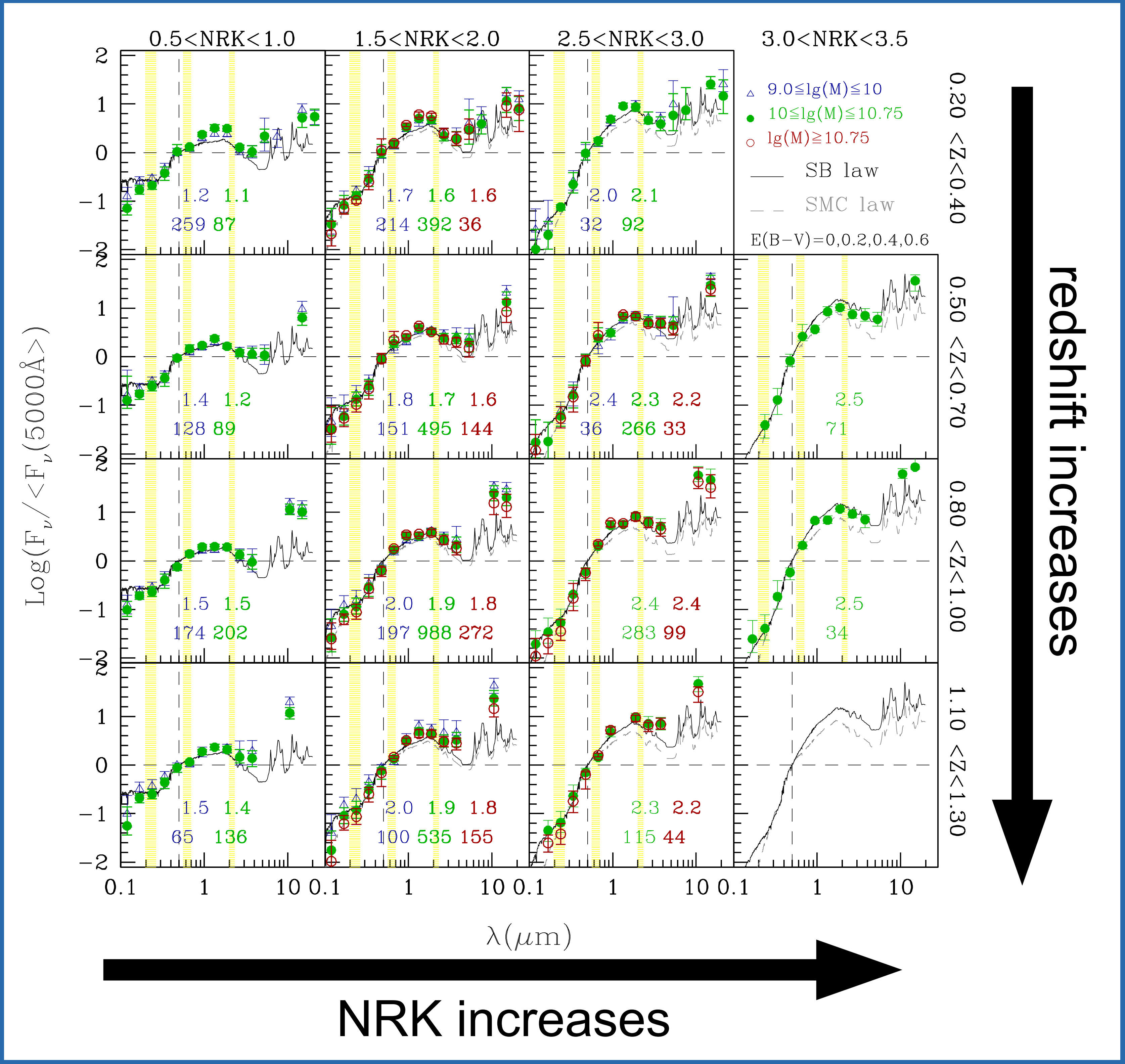
The infrared excess IRX

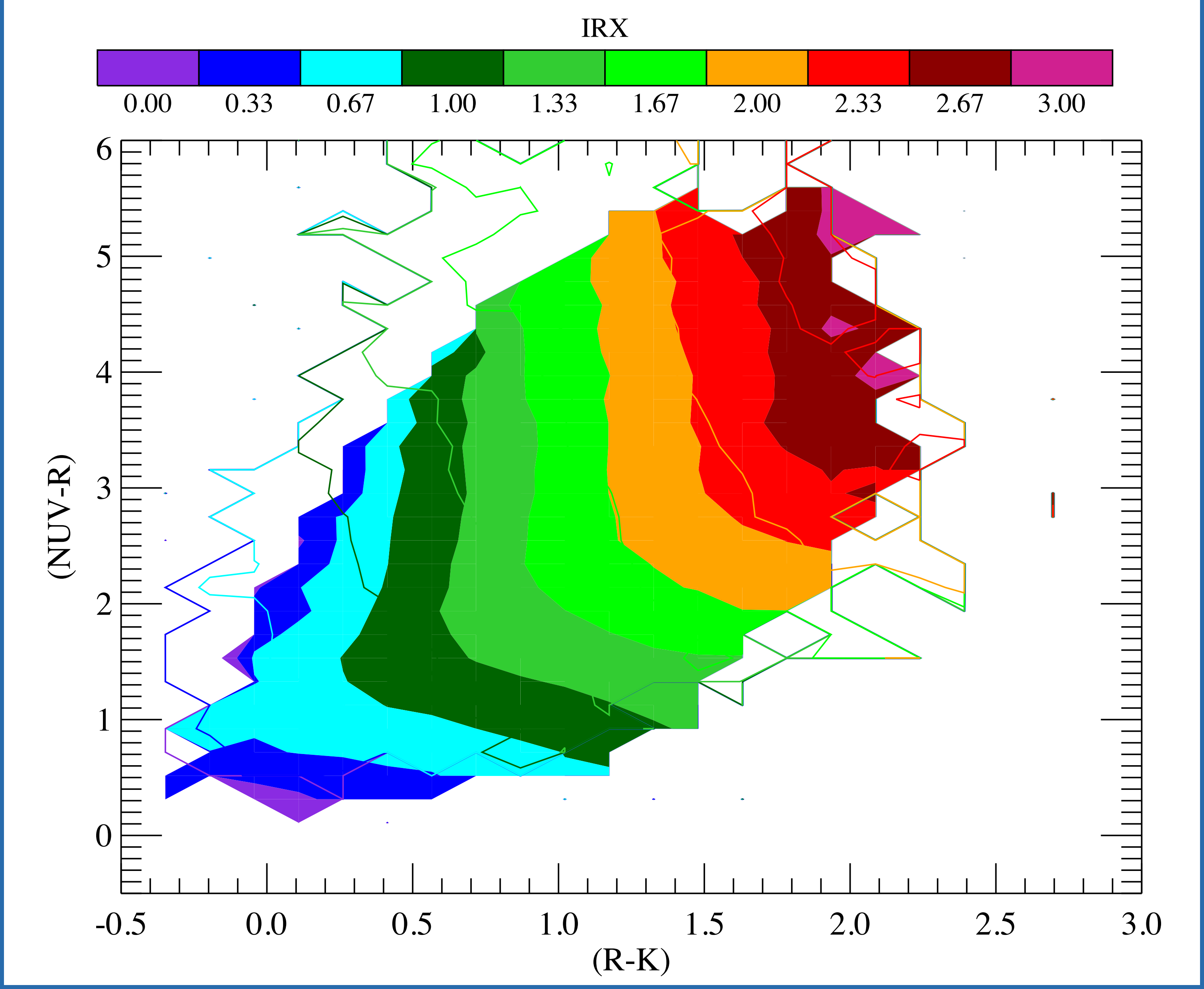
How well the NRK vector traces the SED evolution?



- SED evolution primary driven by NRK
- Redshift and mass plays a secondary role at fixed NRK

Modeling

Can we reproduce the observed IRX stripes with spectral evolution models?



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- Star formation and chemical enrichment histories from Millennium semi-analytic post-treatment
- IRX stripes clearly present in models
- Different orientation of stripes...work in progress

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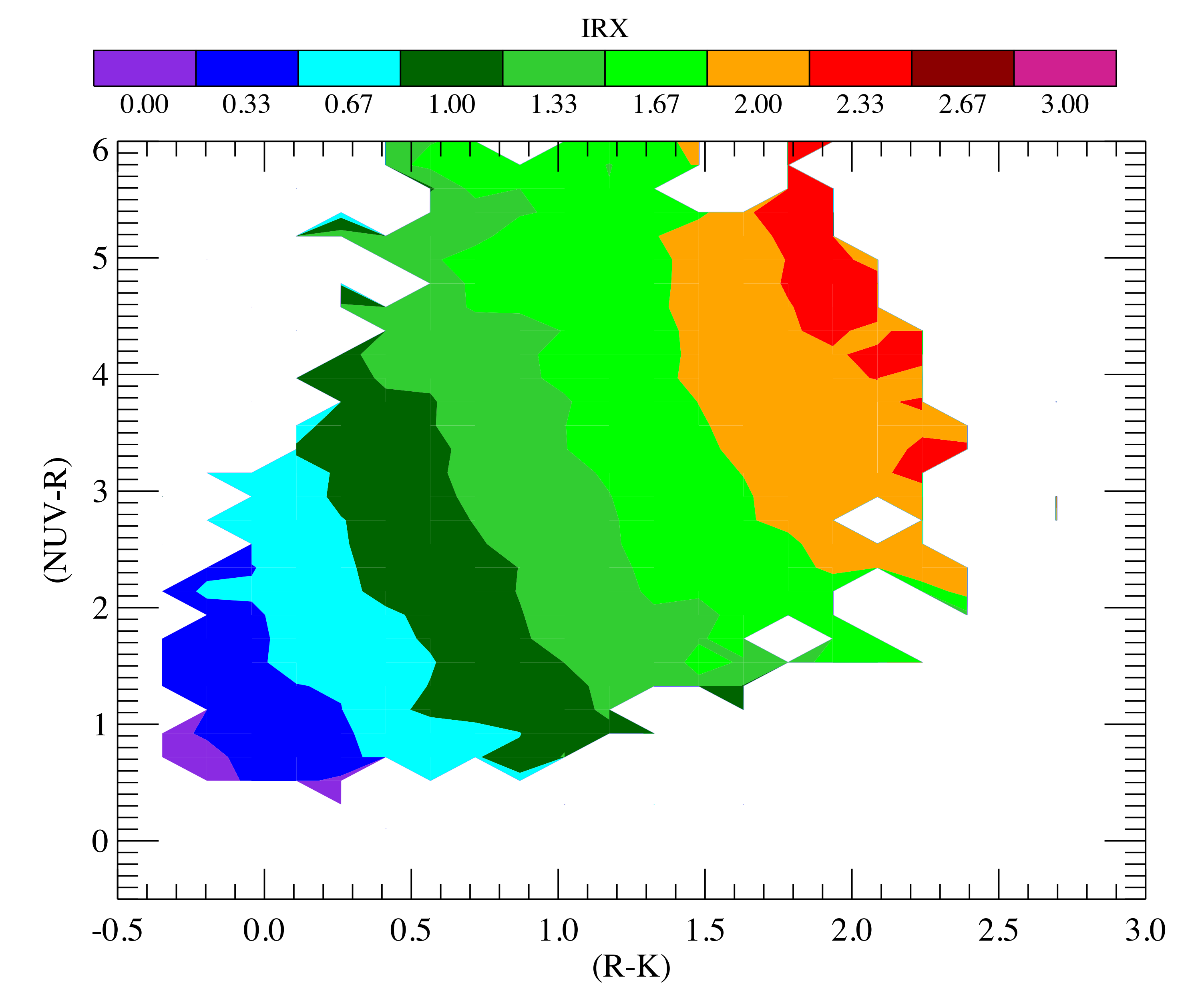

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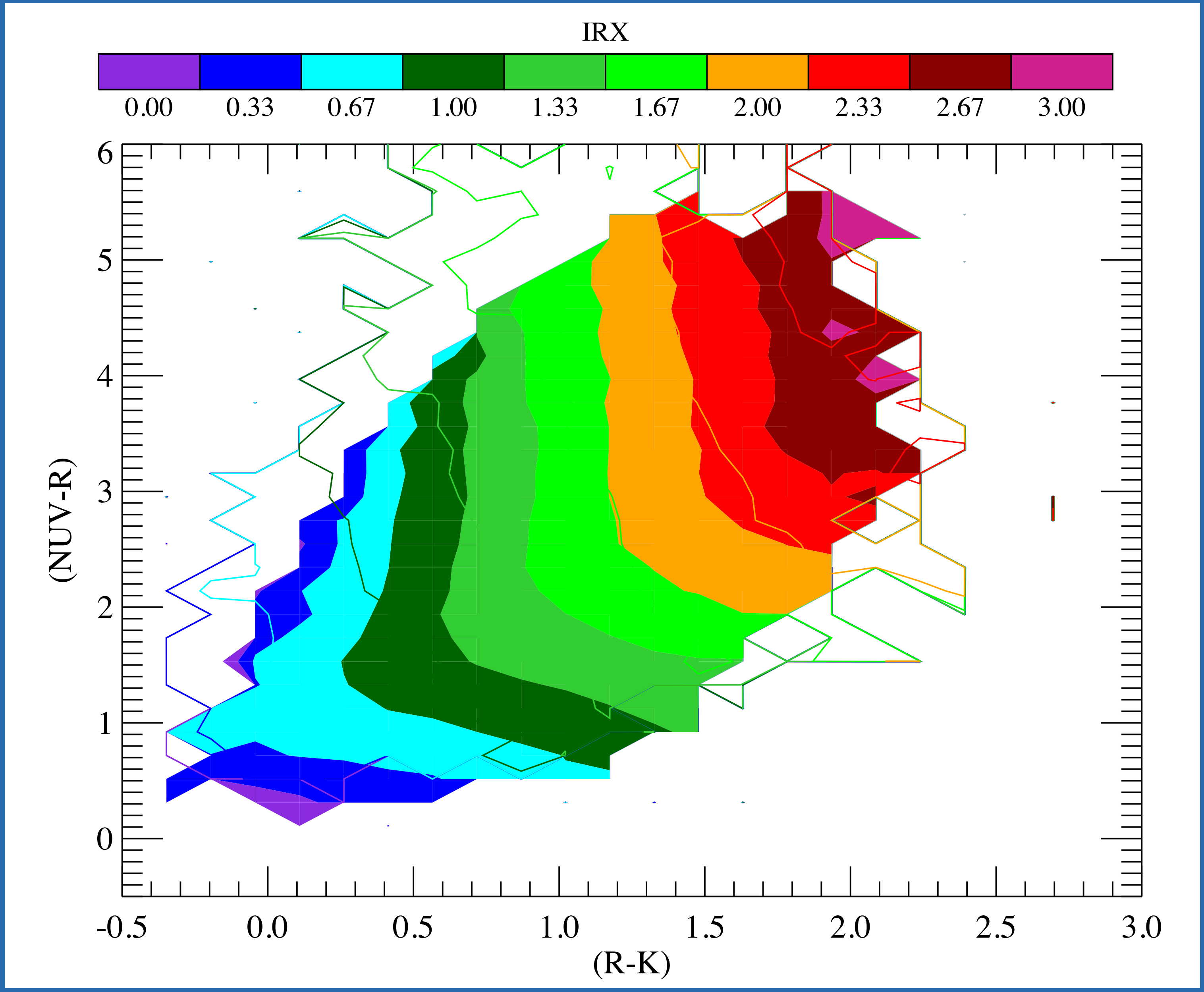

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Conclusion

• NUV + optical + NIR photometry (NRK vector) encodes the infrared excess IRX

• IRX + UV can be used to estimate the total IR luminosity, hence improving SFR measures

• Calibrated over a wide redshift range $0 < z < 1.2$

• Allows the access of SFR at intermediate z, where FIR observations are difficult

Outline (2)

5) Fitting the data:

a) Results of the fit

6) Discussion of the results

7) Examples / applications

8) **SFR and dust attenuation:** how to reliably infer the SFR from UV-to-near infrared colors, in absence of MIR/FIR observations?

a) The data

b) Encoding the infrared excess IRX into the (NUV-R) vs (R-K) diagram

c) Modeling

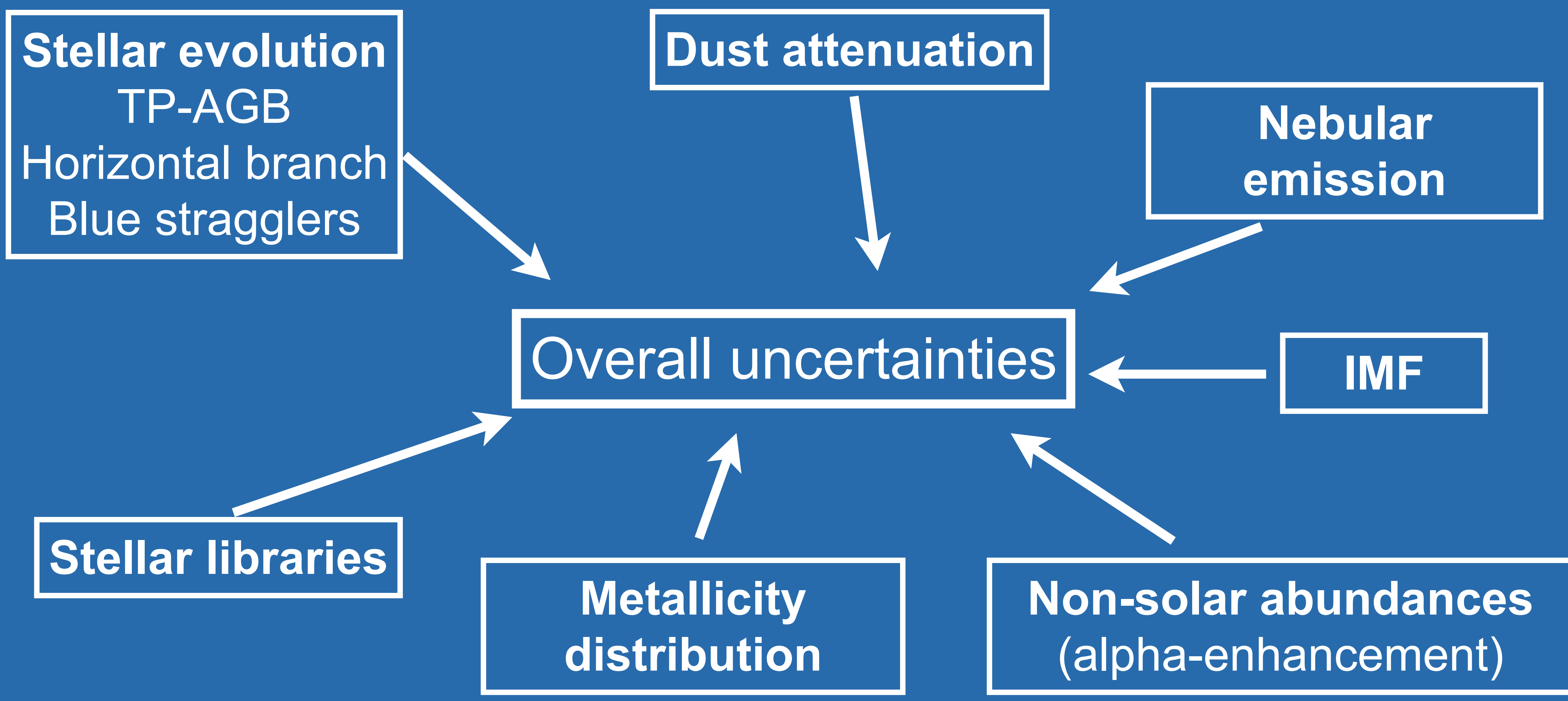
d) Discussion

9) Future developments

Future developments (1)

General topic of my PhD thesis:

Uncertainties in the spectral modeling of galaxies



Future developments (2)

- Work motivated by the recognition that nowadays the **systematics uncertainties in spectral evolution models are the major limitation in the interpretation of galaxies SEDs**

- This limitation will become even more crucial with new generation of instrument, like **LSST and EUCLID**

- We are approaching the Terabyte data regime, billions of objects, possibility of doing **precision extragalactic astrophysics**, but need to control model systematics

- Need to adopt different statistical approach, incorporating the tools already used by cosmo-statisticians (i.e. Bayesian approach, MCMC and others), and developing new tools (i.e. Gaussian Random Process based interpolation)

Future developments (3)

- Currently working on several projects, involving the following sources of uncertainty:
  - Spectral libraries interpolation / extrapolation
  - IMF, constraints from integrated colors and spectra
  - Non-solar abundances, alpha-elements and CN
- Finally, in collaboration with Stephane Charlot and Ben Wandelt we are searching for the best Bayesian tool (Fisher matrix? Monte Carlo?) to incorporate all the above-cited uncertainties into the new generation of Charlot & Bruzual spectral models


Thanks!!