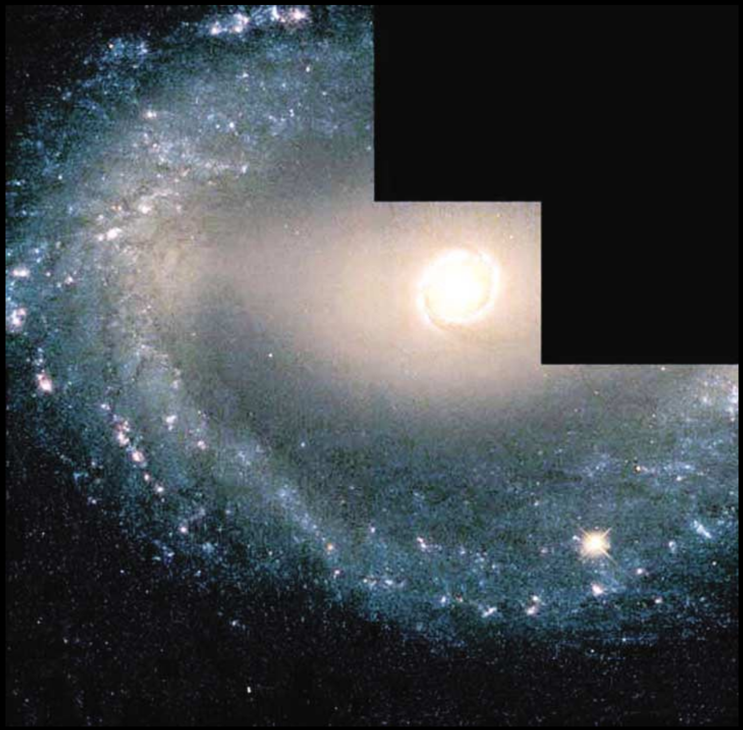

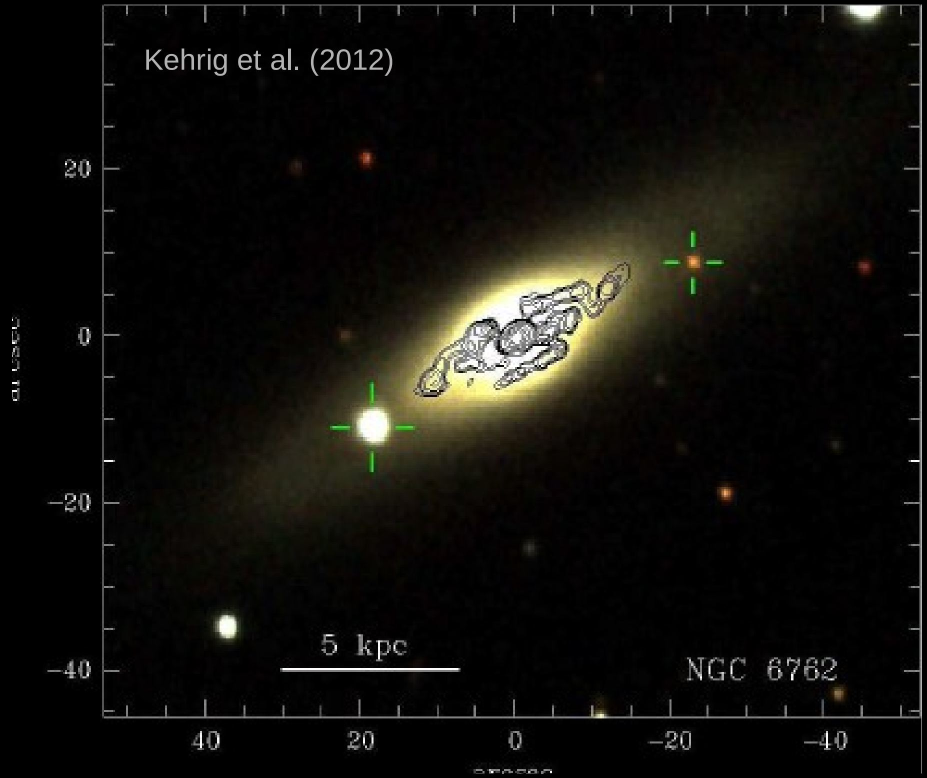

Inside-out star formation quenching and the need for a revision of bulge-disk decomposition concepts for spiral galaxies

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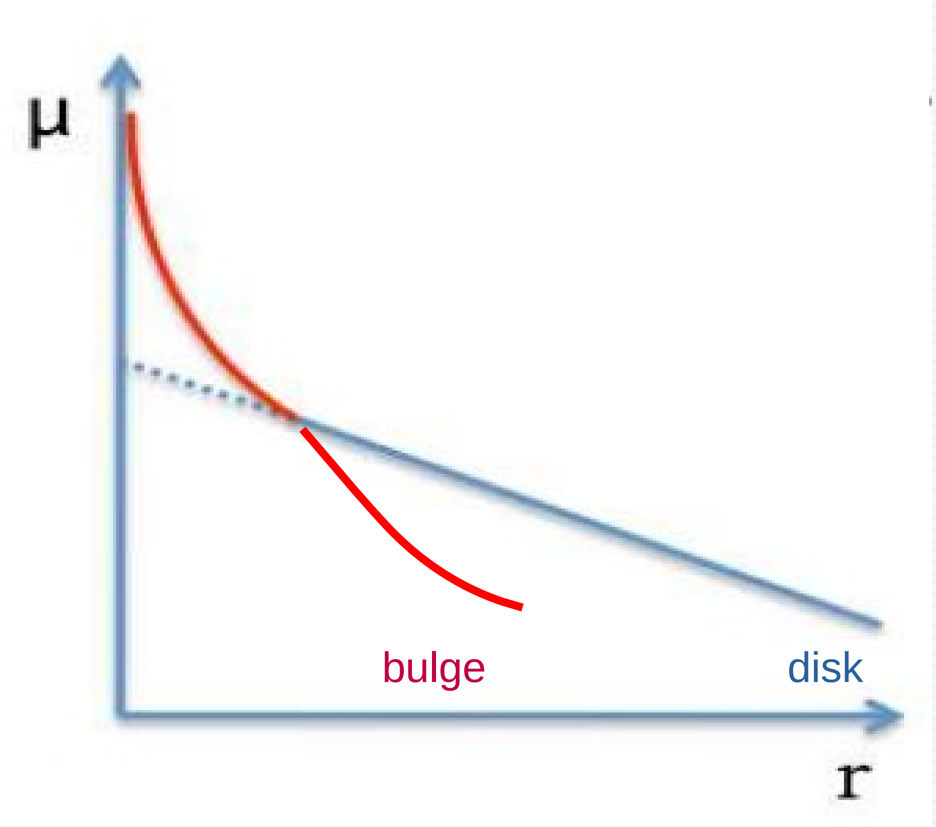
Bulge-disk decomposition of spiral galaxies

– bulge luminosity
(and $M_\star$ via a M/L ratio)

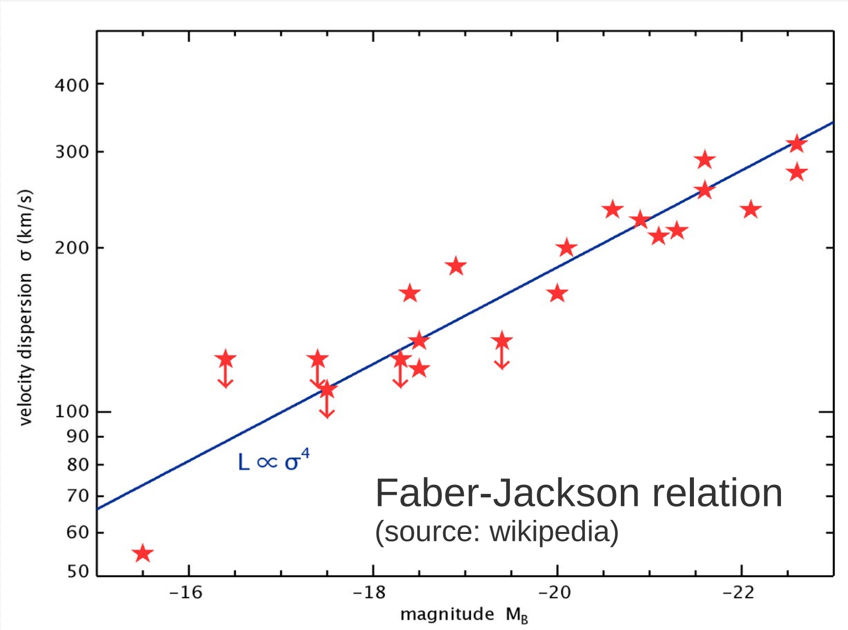
– Sérsic exponent η
(and empirical subdivision between classical bulges and pseudobulges)

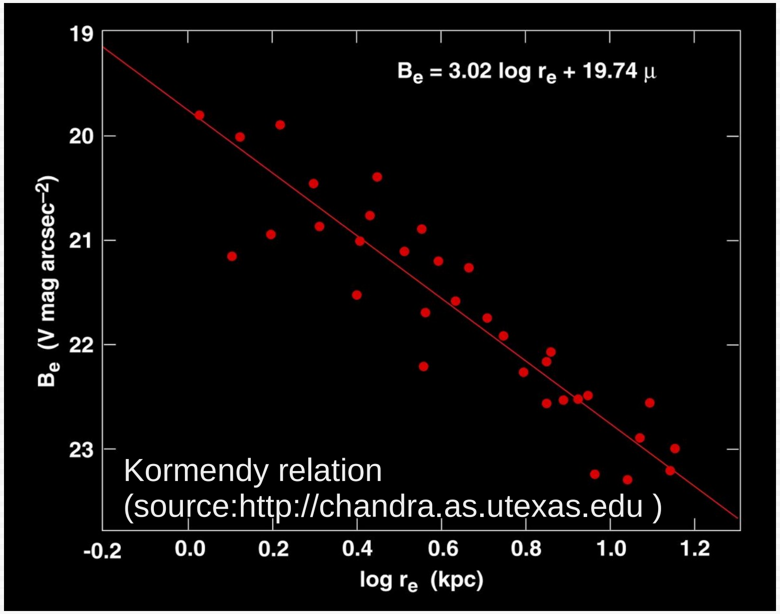
– effective radius R_{eff}
and mean surface brightness <μ>

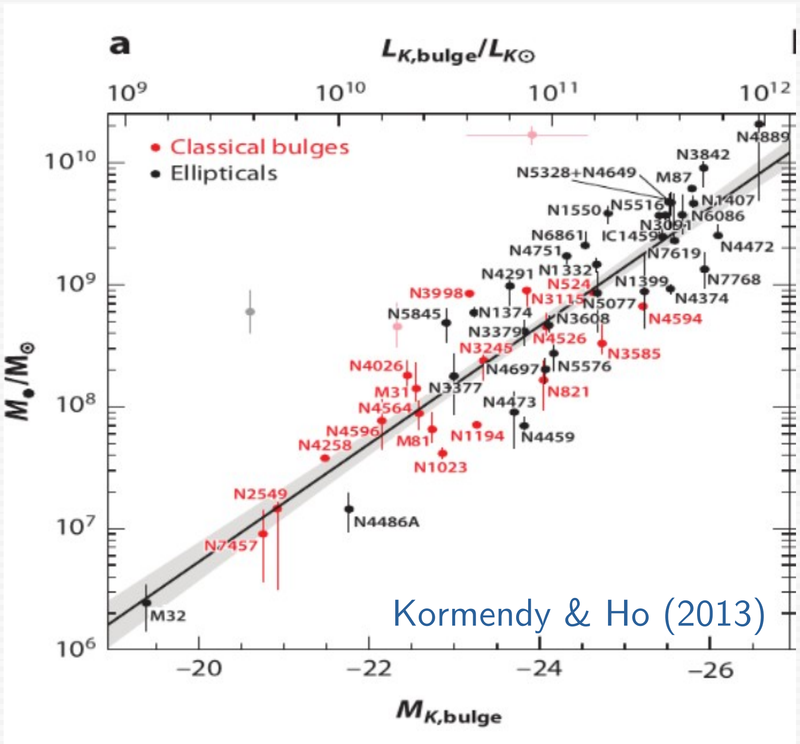


Gadotti (2012)

Galaxy scaling relations







– bulge vs super-massive BH relation

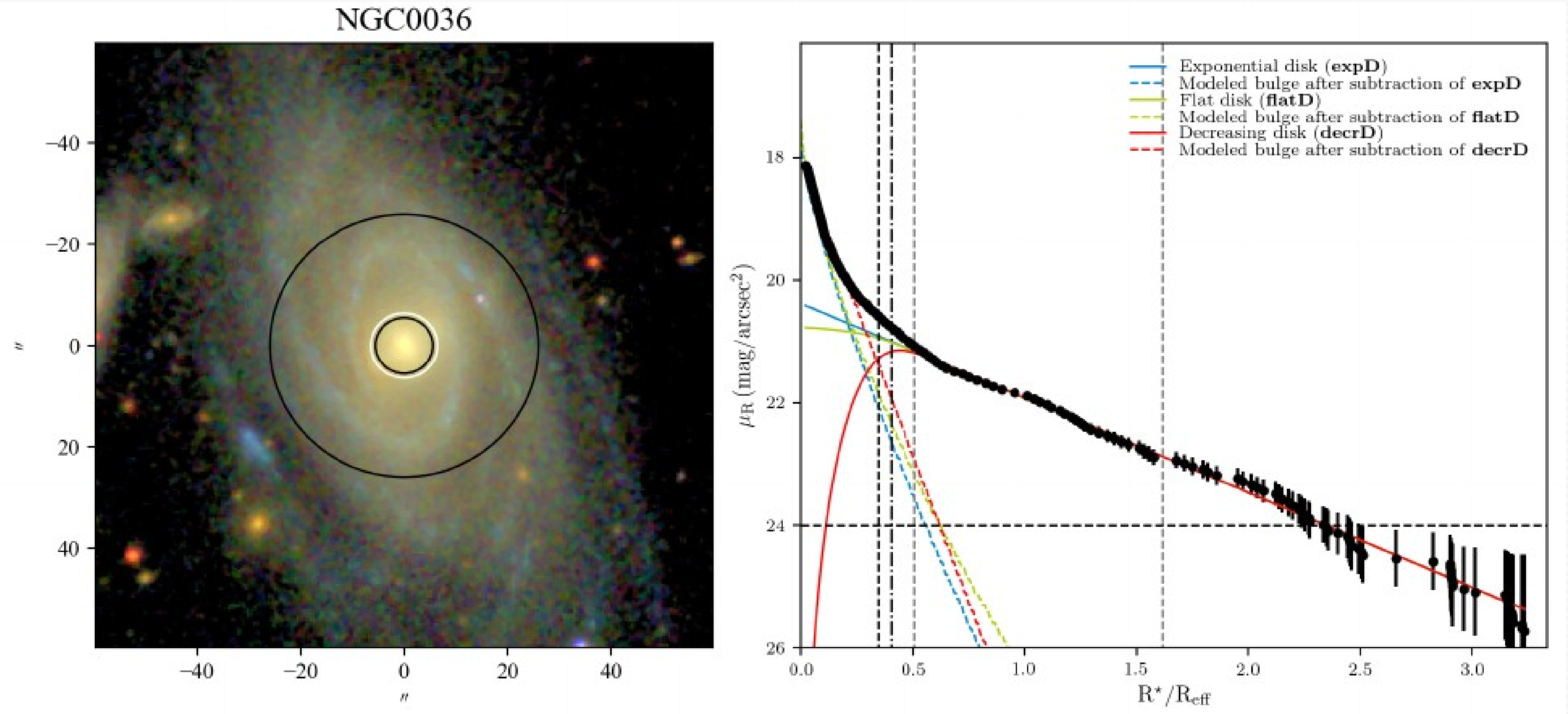
– “size” (R_{eff}) evolution of galaxies

– normalization of age and metallicity gradients to (R_{eff})

– Sérsic exponent η vs morphology, $\Sigma_\star$, galaxy mass $M_\star$

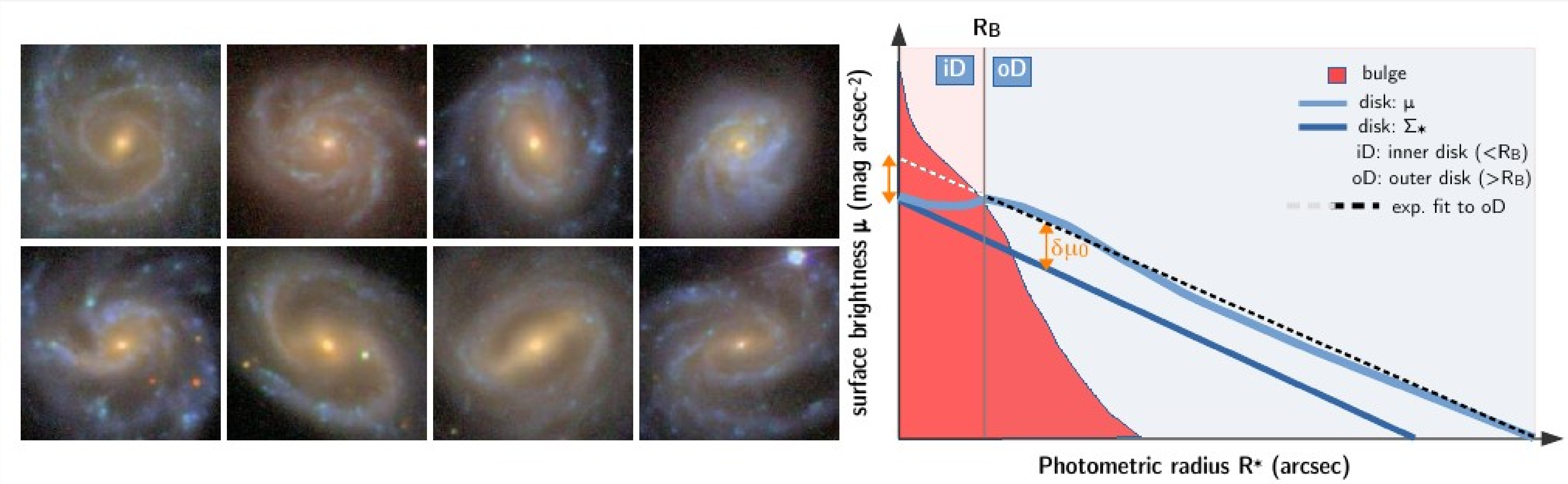
two questions related to the standard concept of bulge-disk decomposition

1) is there a disk beneath the bulge?



(Breda et al. 2020a, A&A 640, A20)

2) Inside-out star formation quenching (ioSFQ) in spiral galaxies



(Papaderos, Breda et al. 2022, A&A 658, A74; **P22**)

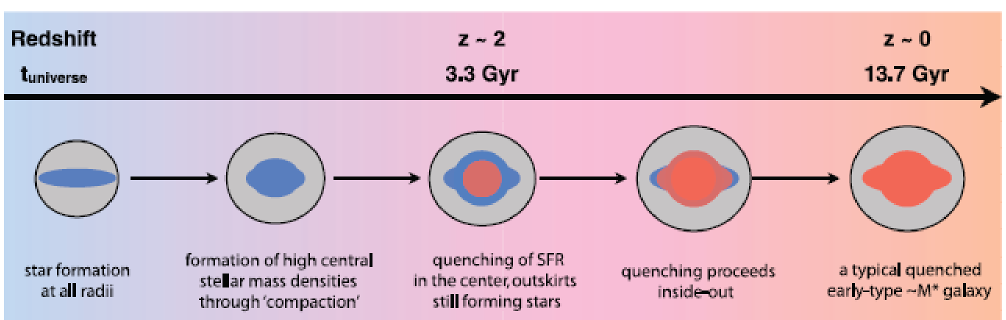


Fig. 4. Proposed sketch of the evolution of massive galaxies. Our results suggest a picture in which the total stellar mass and bulge mass grow synchronously in $z \sim 2$ main sequence galaxies, and quenching is concurrent with their total masses and central densities approaching the highest values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

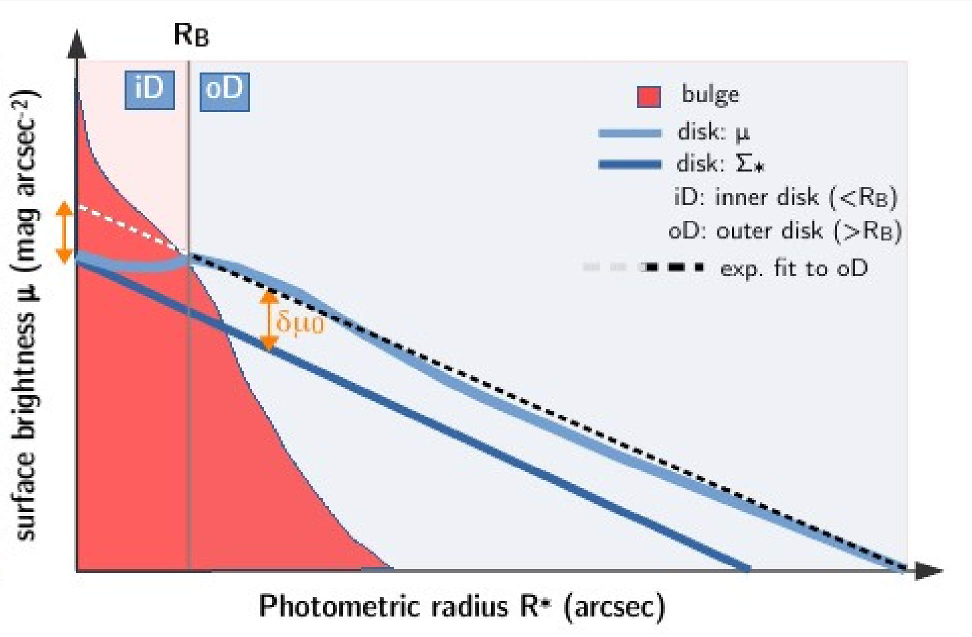
Tacchella et al. (2015)

Two effects:

– overestimation (and oversubtraction) of the disk beneath the bulge → underestimation of the luminosity of the bulge

– bias in colors and color gradients of bulges (subtraction of a blue SED from a red SED)

Inside-out star formation quenching (ioSFQ) in spiral galaxies



δ_{io} (mag): difference between the true magnitude of the disk inside the bulge radius **R_B** and the value obtained from inward extrapolation of the exponential fit to the disk

Problem: I(R*) cannot be directly inferred from observations

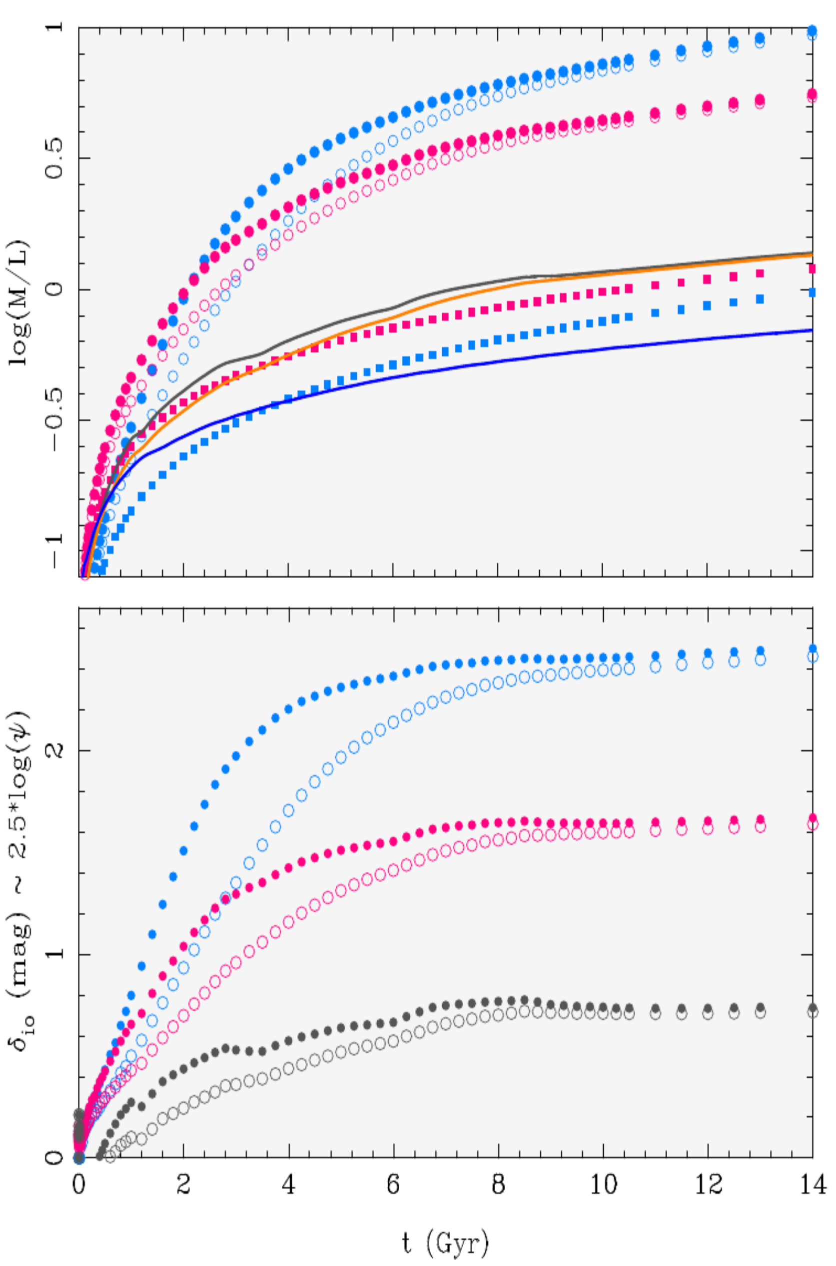
(**P22**)

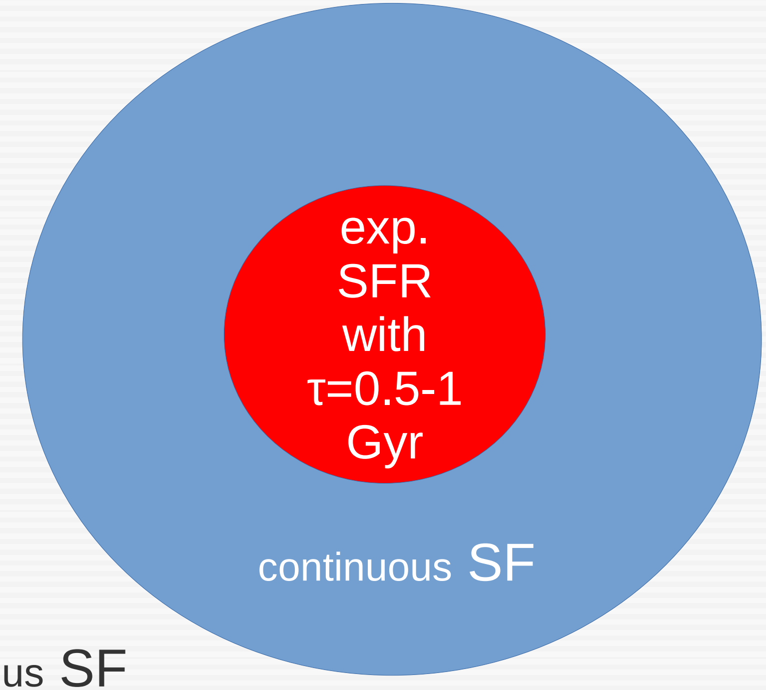
$$-2.5\log_{10}\left(2\pi\int_0^{R_B} R^\star\, I(R^\star)\,\mathrm{d}R^\star\right) + \text{constant}$$

However, an estimate can be obtained based on the mean M/L ratio within the bulge radius (bulge+inner disk) and in the outer (visible) disk

$$\delta_{io}\ (\text{mag}) \simeq 2.5\cdot\log(\psi) = 2.5\cdot\log\left(\frac{\mathcal{M}/\mathcal{L}_{iD}}{\mathcal{M}/\mathcal{L}_{oD}}\right)$$

1st estimate of δ_{io} (from evolutionary synthesis and a simple two-zone galaxy model)





■ continuous SF
○ exp. τ=1 Gyr
● exp. τ=0.5 Gyr

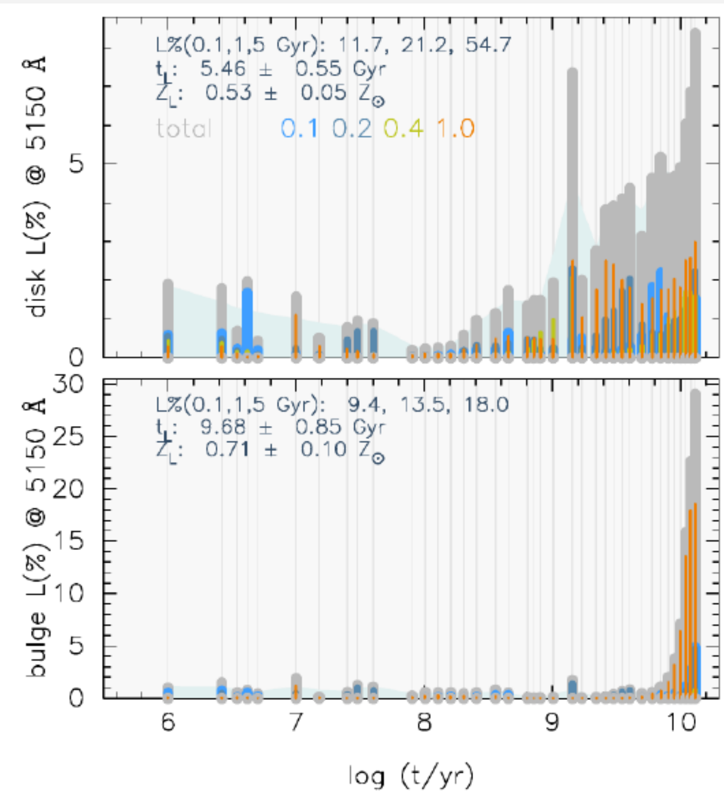
$$\delta_{io}\ (\mathrm{mag}) \simeq 2.5 \cdot \log(\psi) = 2.5 \cdot \log\left(\frac{\mathcal{M}/\mathcal{L}_{iD}}{\mathcal{M}/\mathcal{L}_{oD}}\right)$$

Conclusion: $\boldsymbol{\delta_{io}}$ can be significant
(>0.6 mag in the K band)

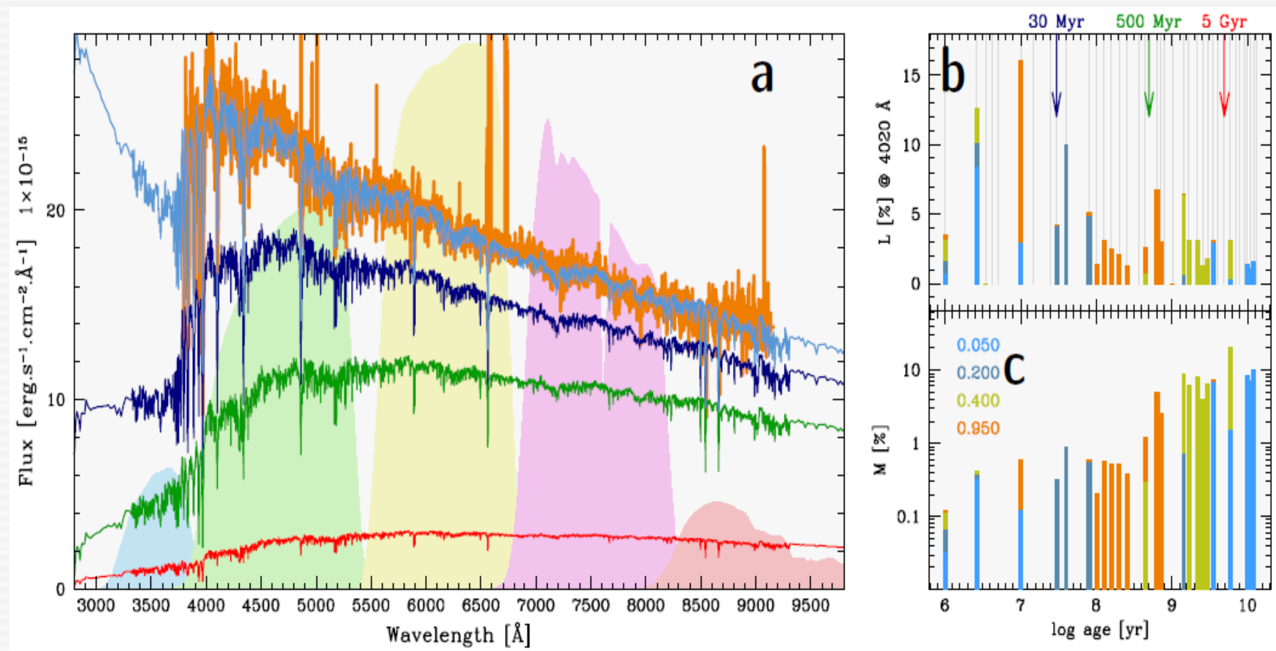
B, R , K

2nd estimate of δ_{io} (from population spectral synthesis)

goal: determination of the surface brightness enhancement in the outer disk due to young stars

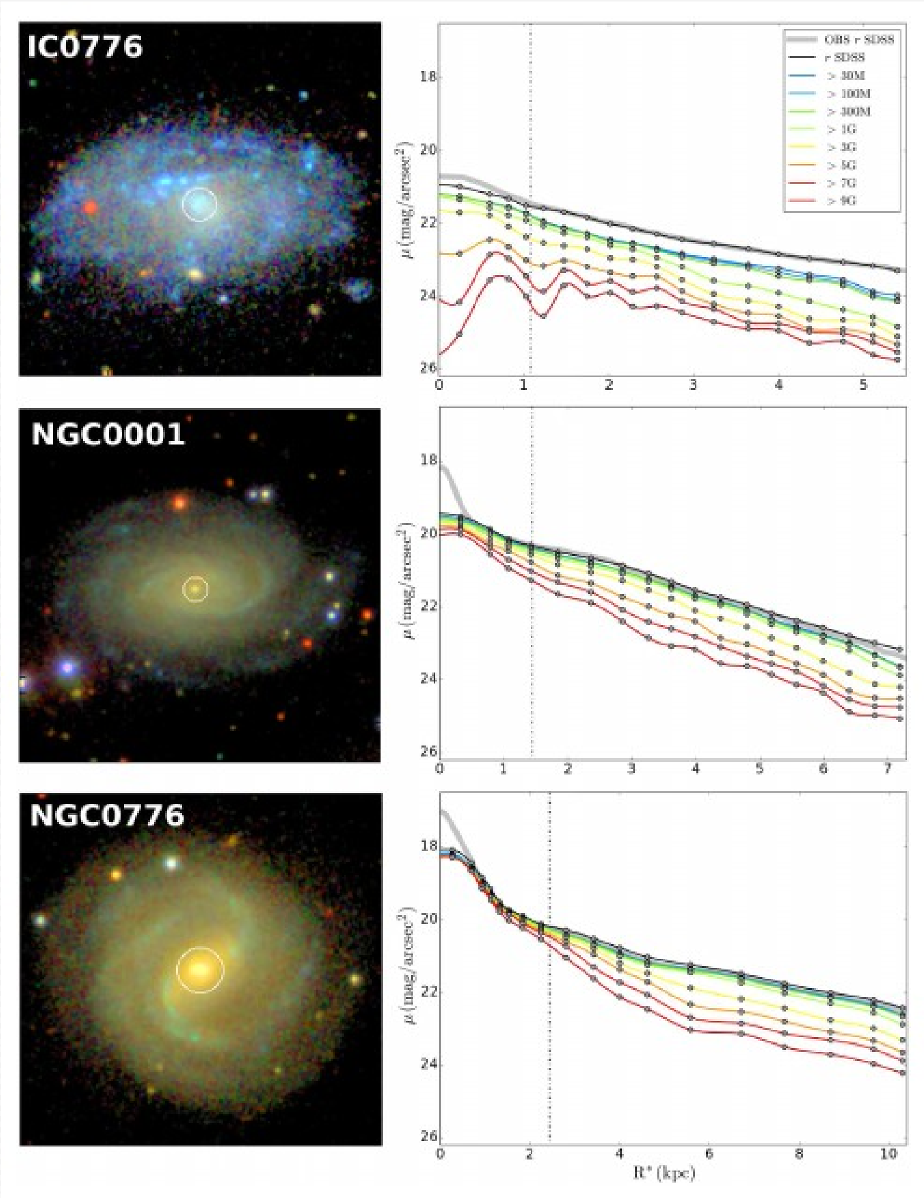


P22



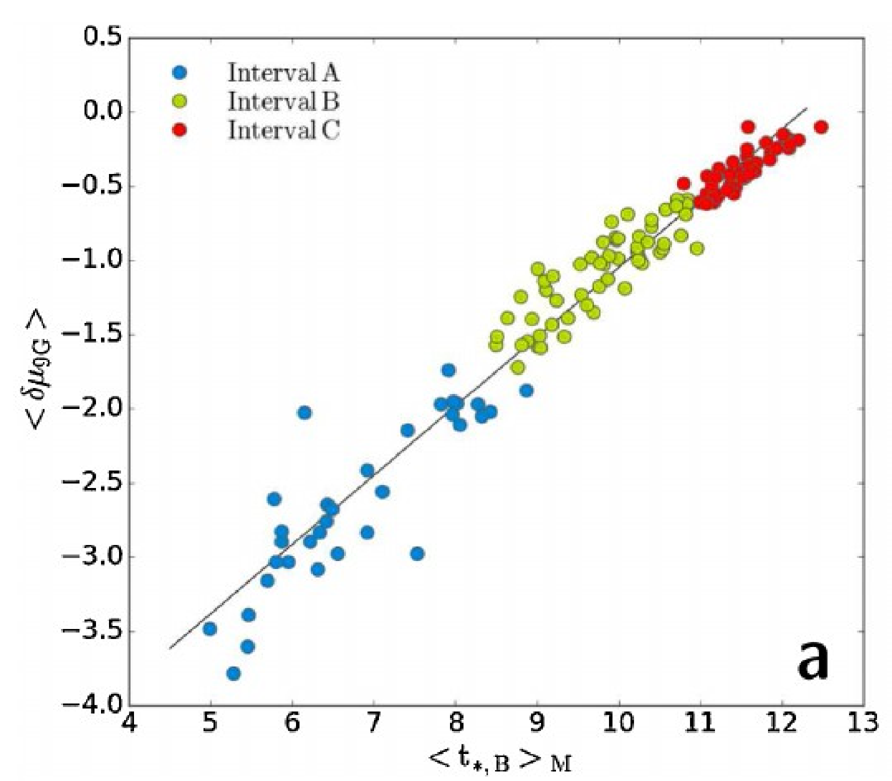
RemoveYoung (**RY**; Gomes & Papaderos 2016)

previous applications of RY to spiral galaxies and a proposed physically motivated classification for bulges



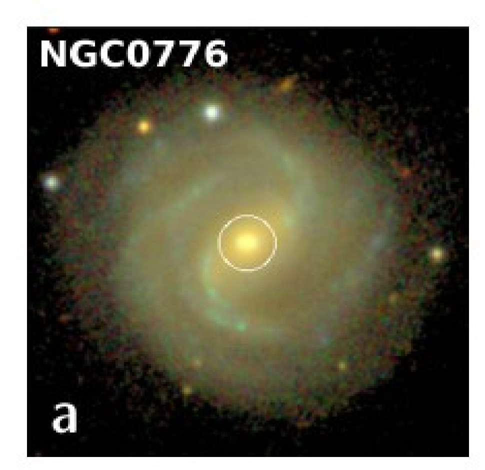
application of RY to 135 spiral galaxies from CALIFA
(Breda & Papaderos 2018)

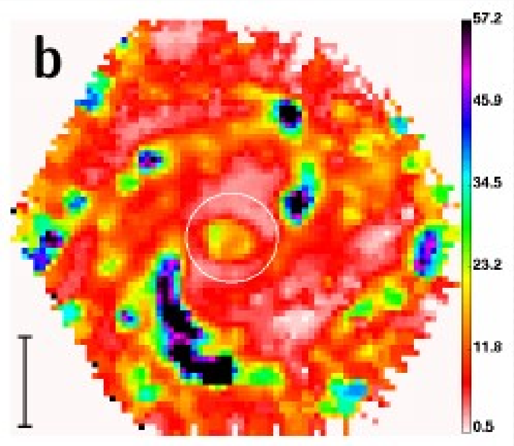
<10.5 log(M⋆) >10.7



$<\delta\mu_{9G}>$ a measure of the luminosity fraction of stars older than 9 Gyr to the r-band luminosity of the bulge

2nd estimate of δ_{io} (from population spectral synthesis): suppression of stellar populations younger than an adjustable age cutoff t_{cut} from spiral galaxies





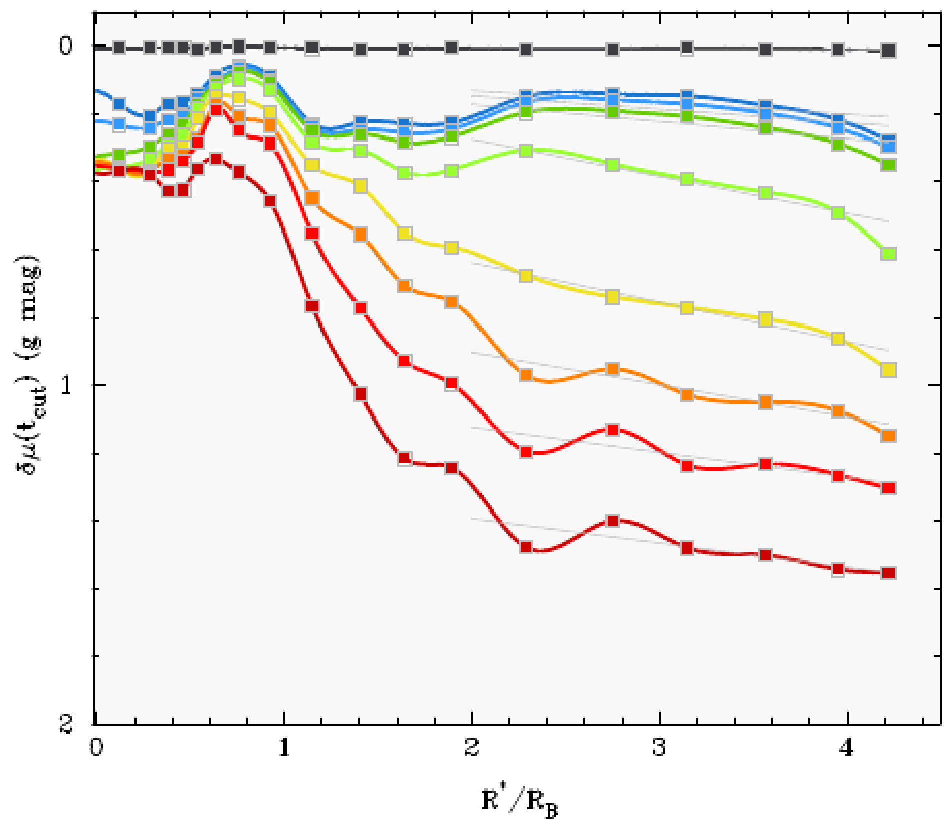
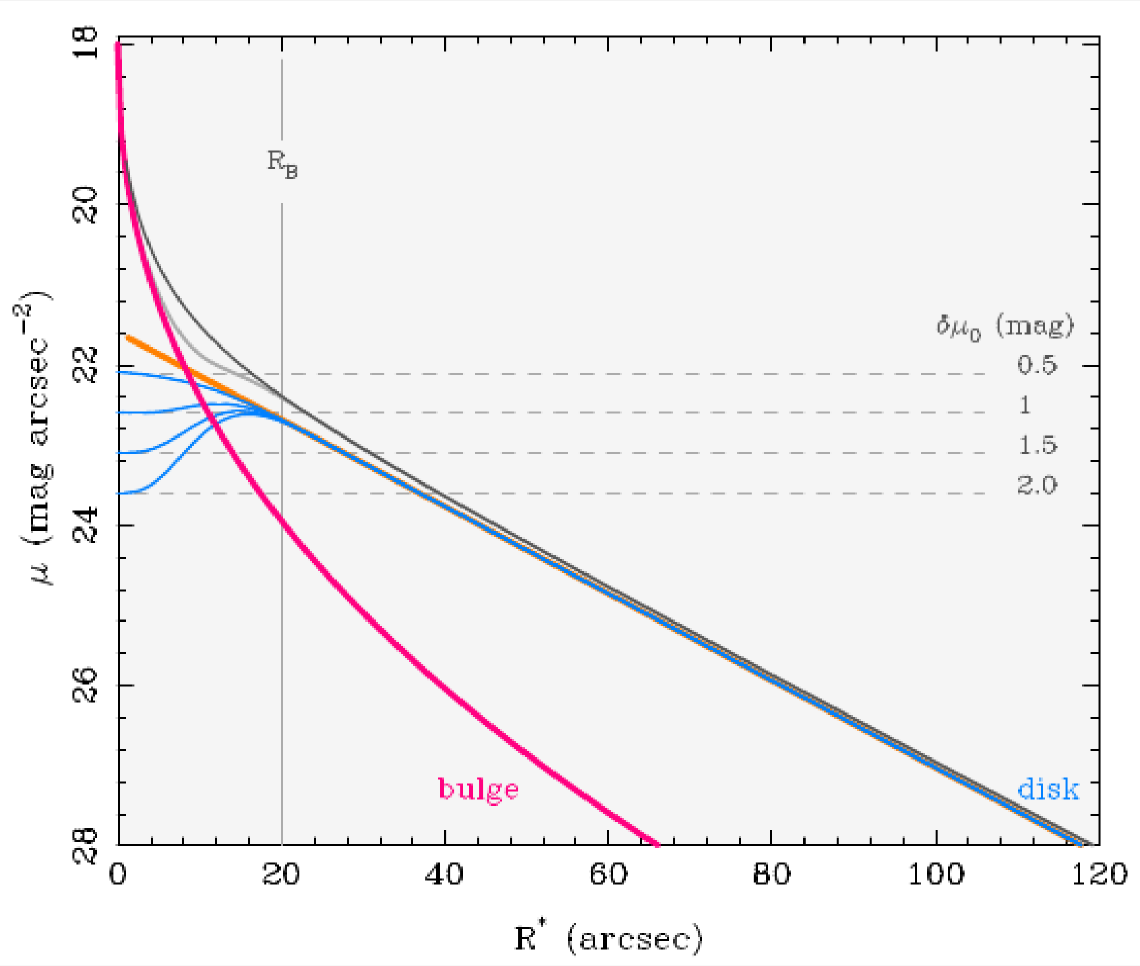


Fig. 4. Dimming $\delta\mu$ (mag) relative to the observed, emission-line corrected g-band SBP of NGC 0776 (black) as a function of normalized radius $R^{\star}/R_{\mathrm{B}}$ after suppression of stellar populations younger than a t_{cut} between 0.03 and 9 Gyr. The color-coding is same as in Fig. 3d. Gray lines show linear fits for $R^{\star}/R_{\mathrm{B}} \geq 2$, i.e., in a radius interval in which the contribution of the bulge and bar become negligible.

B/D decomposition after removal of stars younger than 9 Gyr increases the (bulge+bar)/disk ratio by a factor of 3. But, which t_{cut} to use?

A modified exponential profile for the disk



$$I(R^\star) = I_{\rm exp} \cdot [1 - \epsilon_1 \ \exp(-P_3(R^*))],$$

where $P_3(R^\star)$ is defined as

$$P_3(R^*) = \left(\frac{R^\star}{\epsilon_2\,\alpha}\right)^3 + \left(\frac{R^\star}{\alpha}\ \frac{1-\epsilon_1}{\epsilon_1}\right).$$

(Papaderos et al. 1996)

or other fitting functions, e.g.,
a core-Sérsic profile
(Graham et al. 2003, Trujillo et al. 2004)

ioSFQ and statistics of bulgeless galaxies

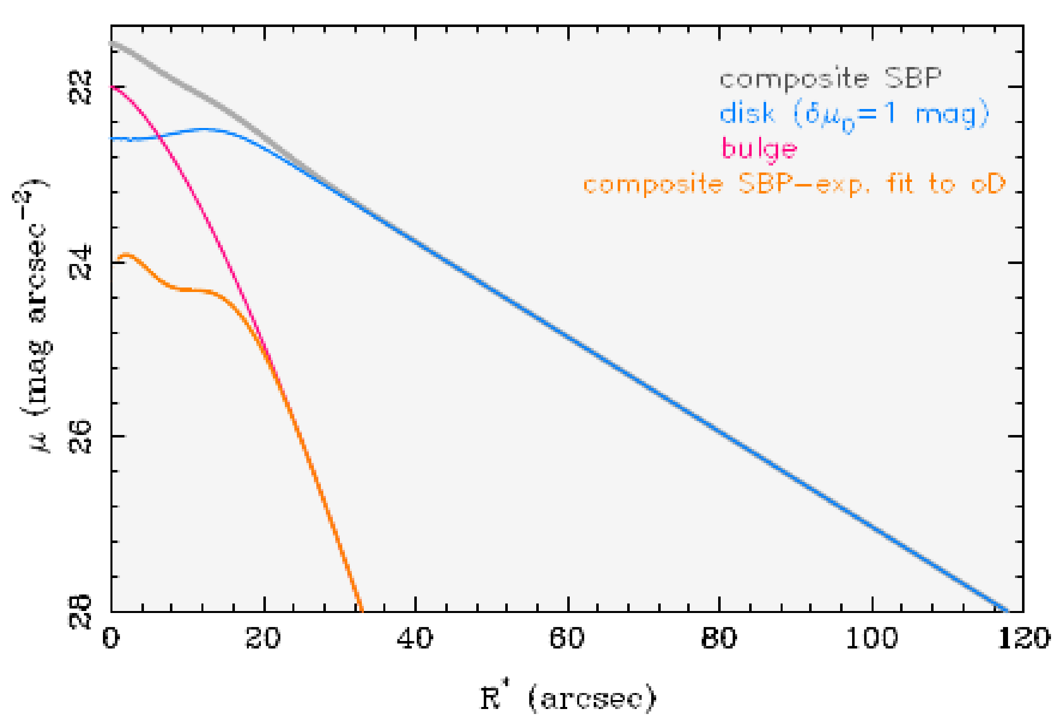
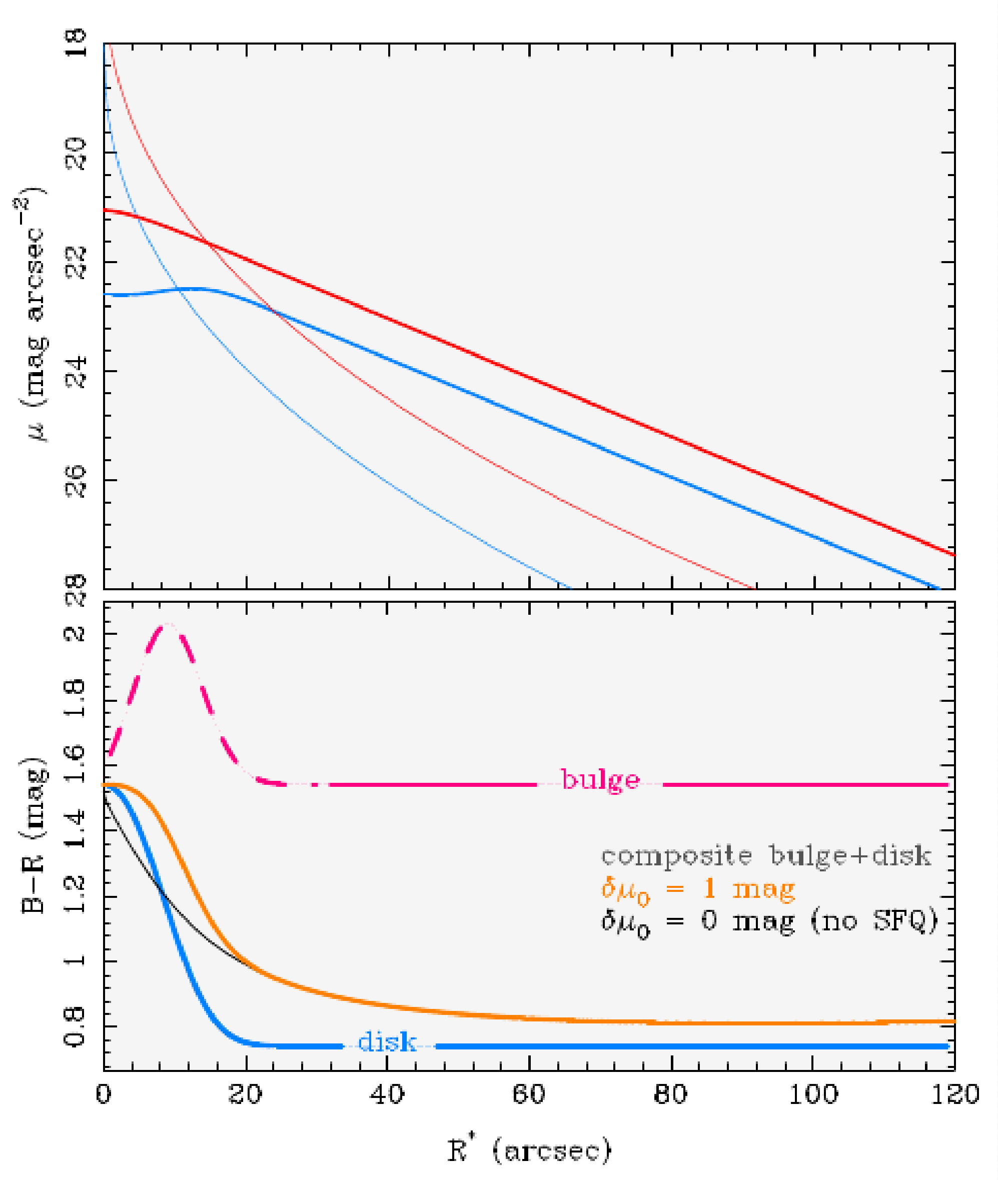


Fig. 10. Simulation of a seemingly bulgeless galaxy that consists of a faint bulge (red; B/T ratio ~0.1) and an SF-quenched disk (blue) with $\delta\mu_0 = 1$ mag. The residual bulge emission after subtraction of an exponential model to the outer disk ($R^\star > 20''$) is shown in orange.

ioSFQ and colors of bulges



The neglect of ioSFQ in bulge-disk decomposition studies leads to an overestimation of the colors of bulges (and, additionally, strongly impacts color gradients within the bulge radius)

… further problems (and possible sources of biases) in decomposition studies of spiral galaxies

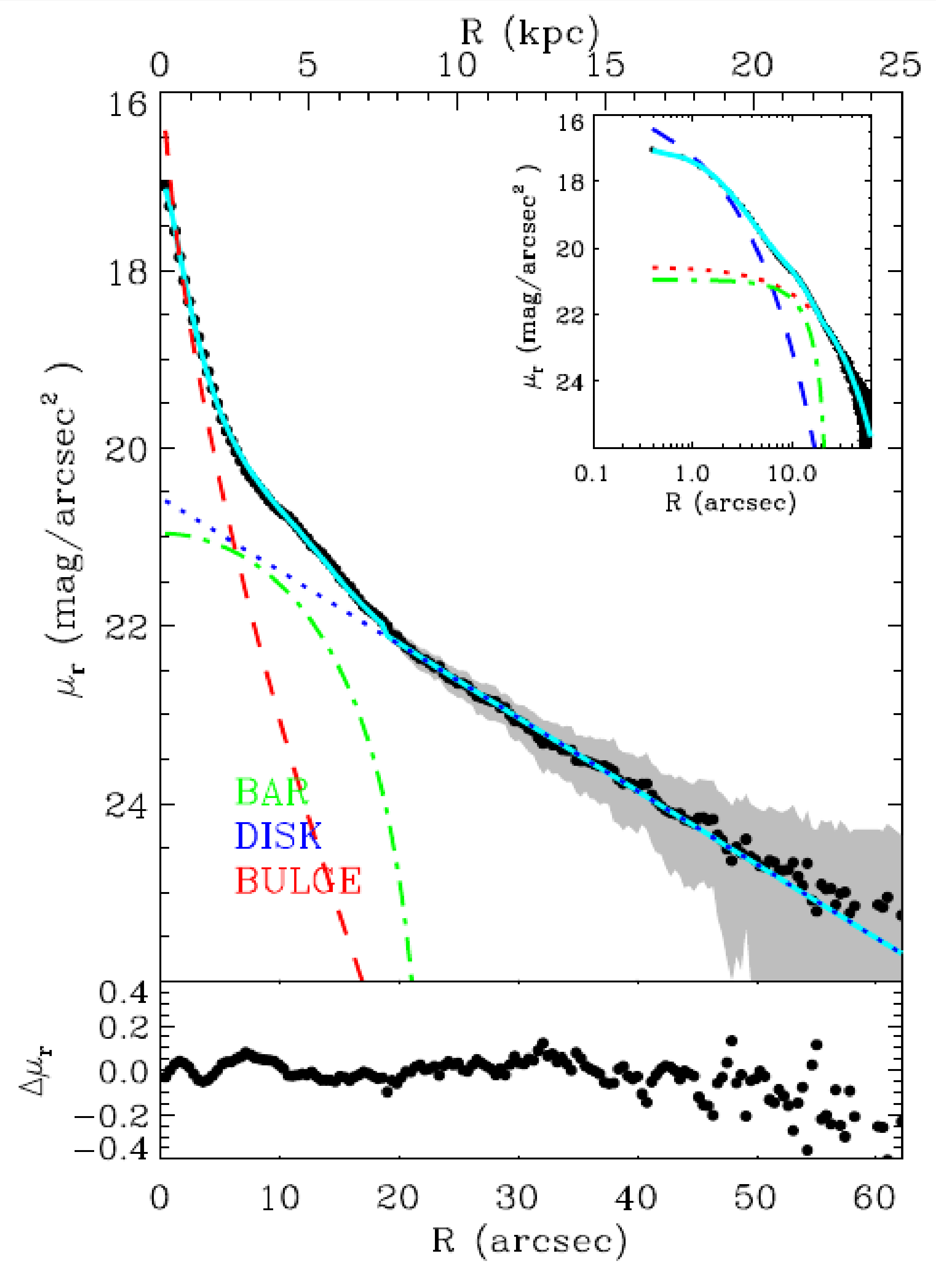
- neglect of the bar
(Méndez-Abreu et al. 2008, BP18)

- fitting a Sérsic model to an imperfect Sérsic profile (Noeske+2003, Breda+2019)

- (in)consistency of Sérsic exponents in different photometric bands

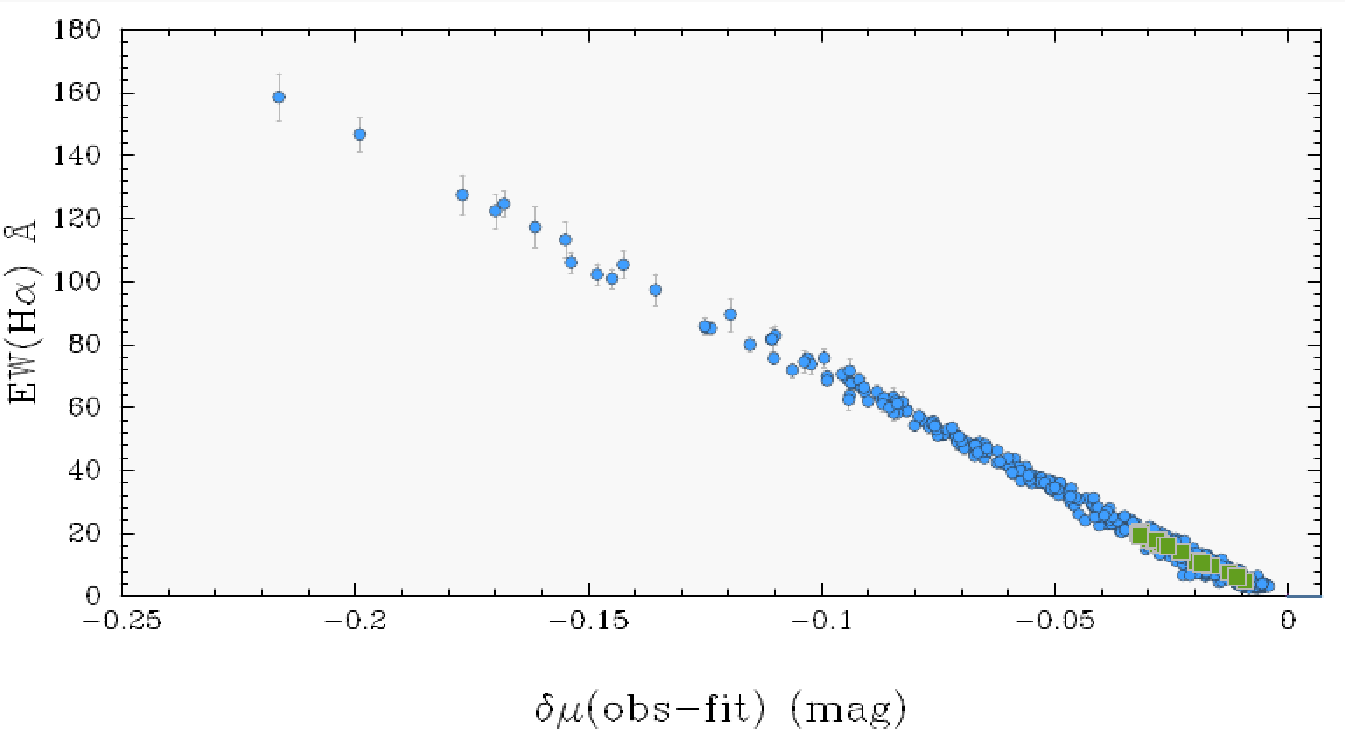
- plausibility of solutions, e.g., are colors and color gradients determined from B/D decomposition physically meaningful?
(cf., e.g., dos Reis, Buitrago et al. 2020)

- impact of nebular emission on B/D decomposition studies of higher-z spirals



Méndez-Abreu et al. (2017)

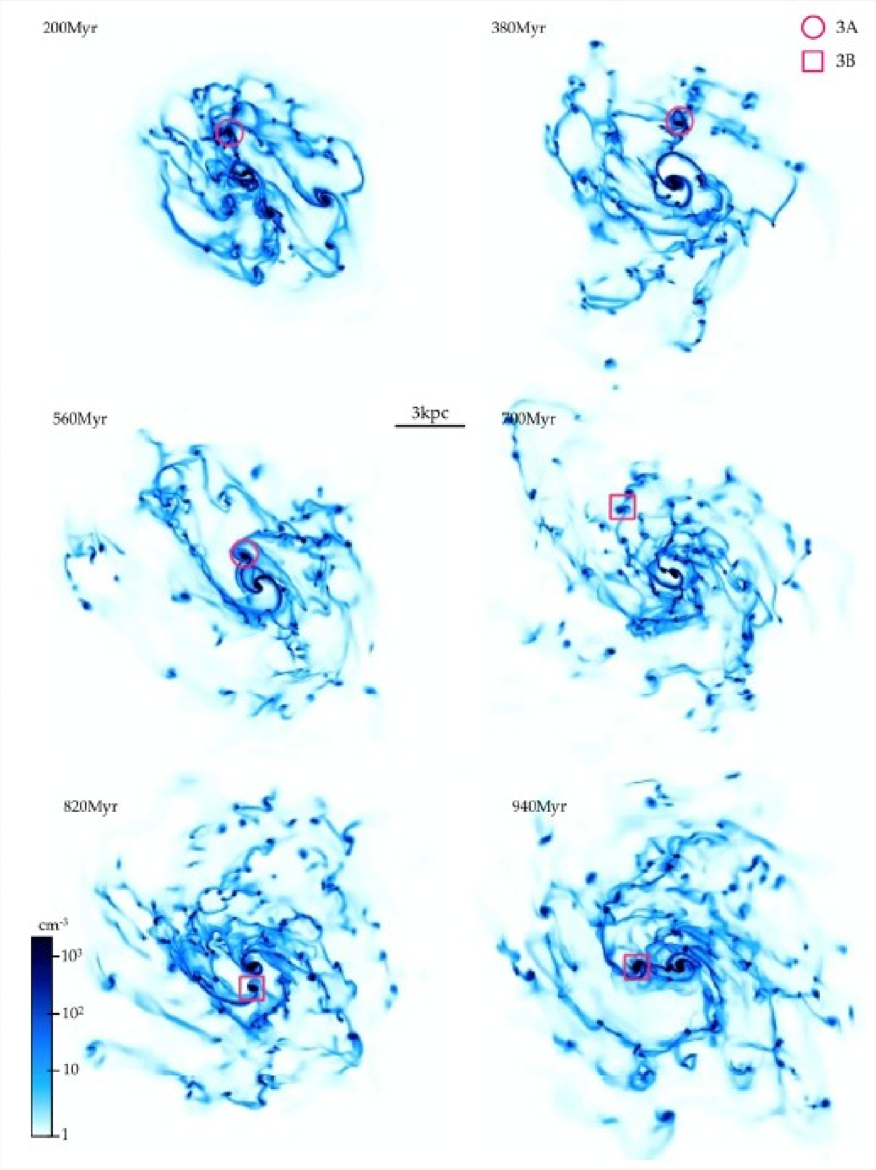
Surface brightness enhancement of the disk by nebular emission in local galaxies



Relation between EW(Hα) and SDSS r-band surface brightness enhancement: 0.74 r mag/kÅ

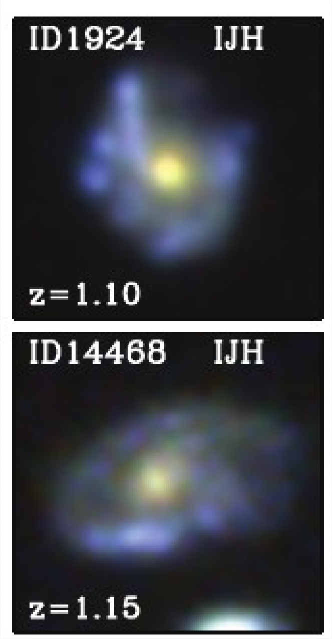
→ nebular emission has a nearly negligible effect in the outer disk of local spiral galaxies

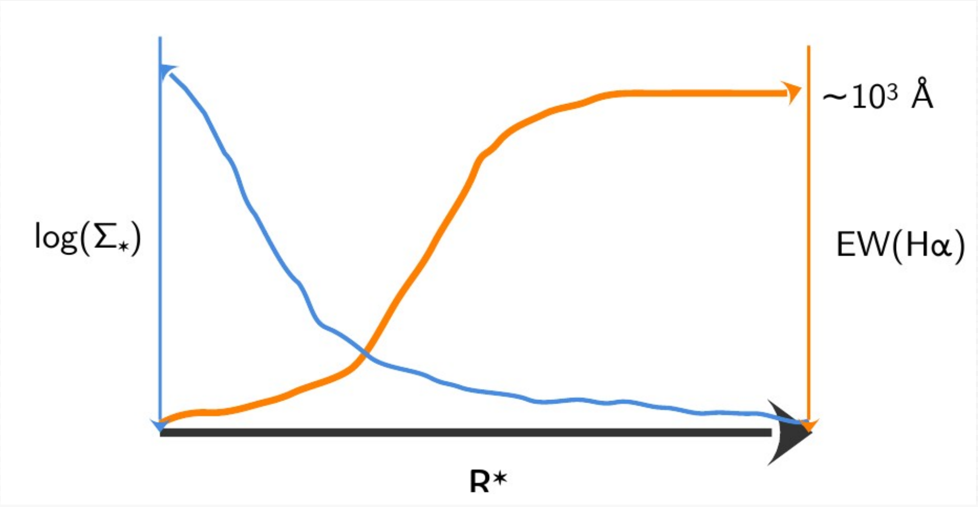
... however, nebular emission is important in high-z proto-spirals; it could elevate their surface brightness by more than 1 mag



Violent disk instabilities in high-z proto-disks
(Bournaud et al. 2009,2014)

Wuyts+2012





Summary

– **local spirals:** The usual practice of inwardly extrapolating the exponential model for the outer disk encompasses the implicit assumption that the specific SFR is spatially constant all over the disk.
It is important to study the effect of inside-out SF quenching (ioSFQ) on the radial intensity profiles of disks, especially in their central part (is there a disk beneath the bulge?) and to explore alternative fitting functions for the disk.

– **spiral galaxies at higher z** (out to z∼1-3): SF clumps forming out of violent disk instabilities probably show very large (∼10^3 Å) restframe emission-line EWs
→
nebular emission enhances the surface brightness of the disk in various z intervals, possibly leading to grave biases in bulge-disk decomposition studies of high-z spirals in early phases of their assembly