The CALIFA survey across the Hubble sequence: How galaxies growth their bulges and disks

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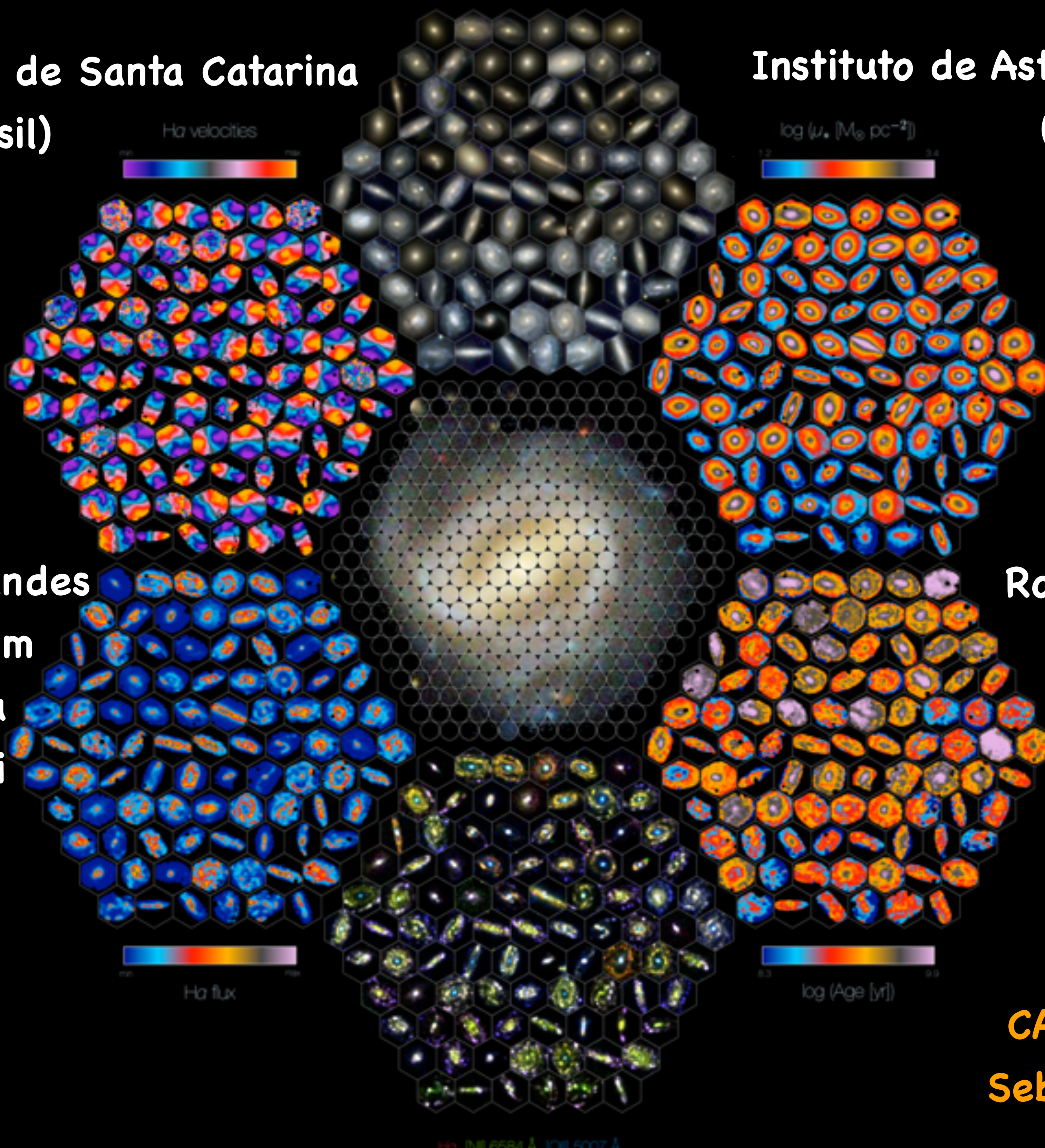

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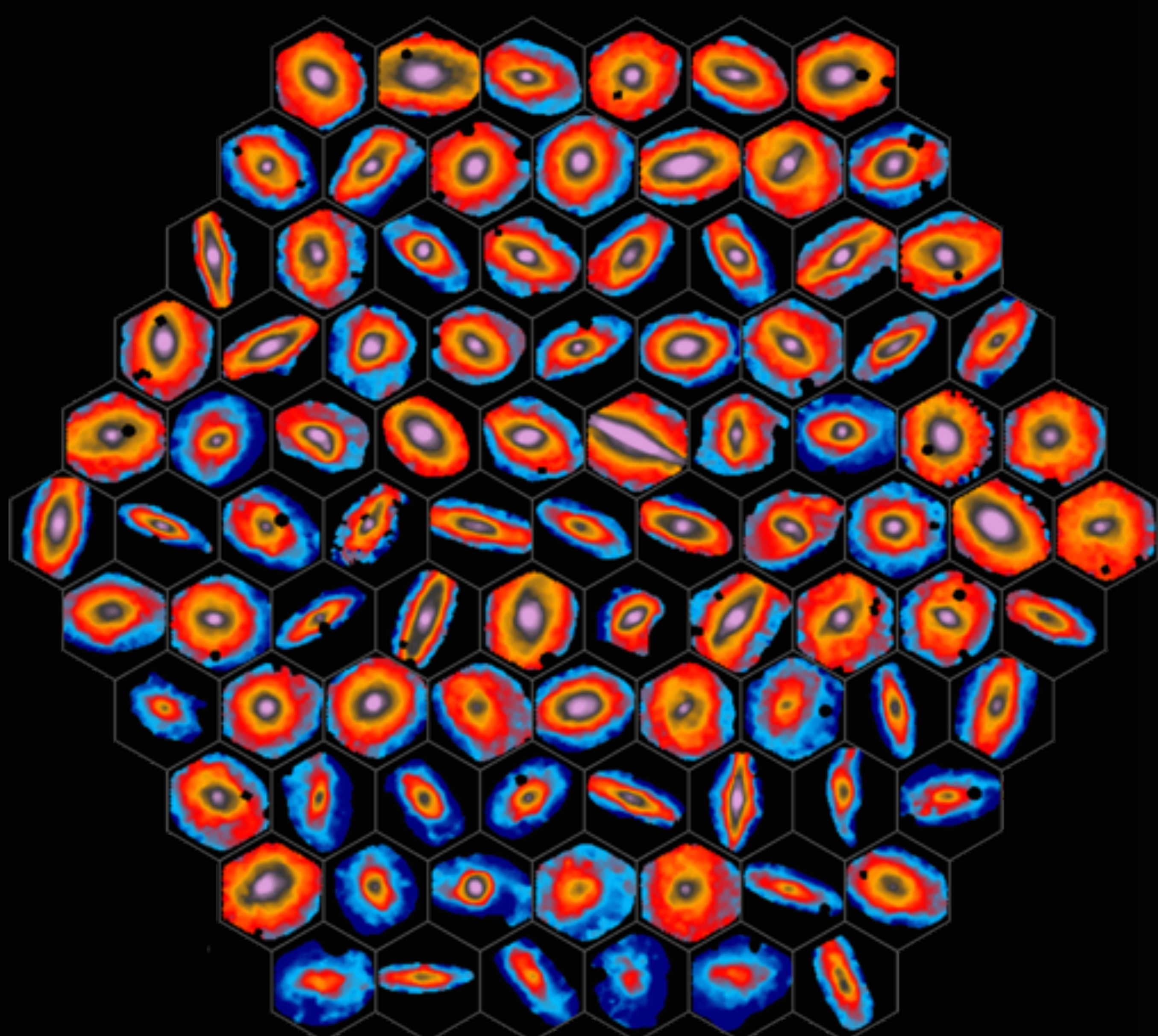
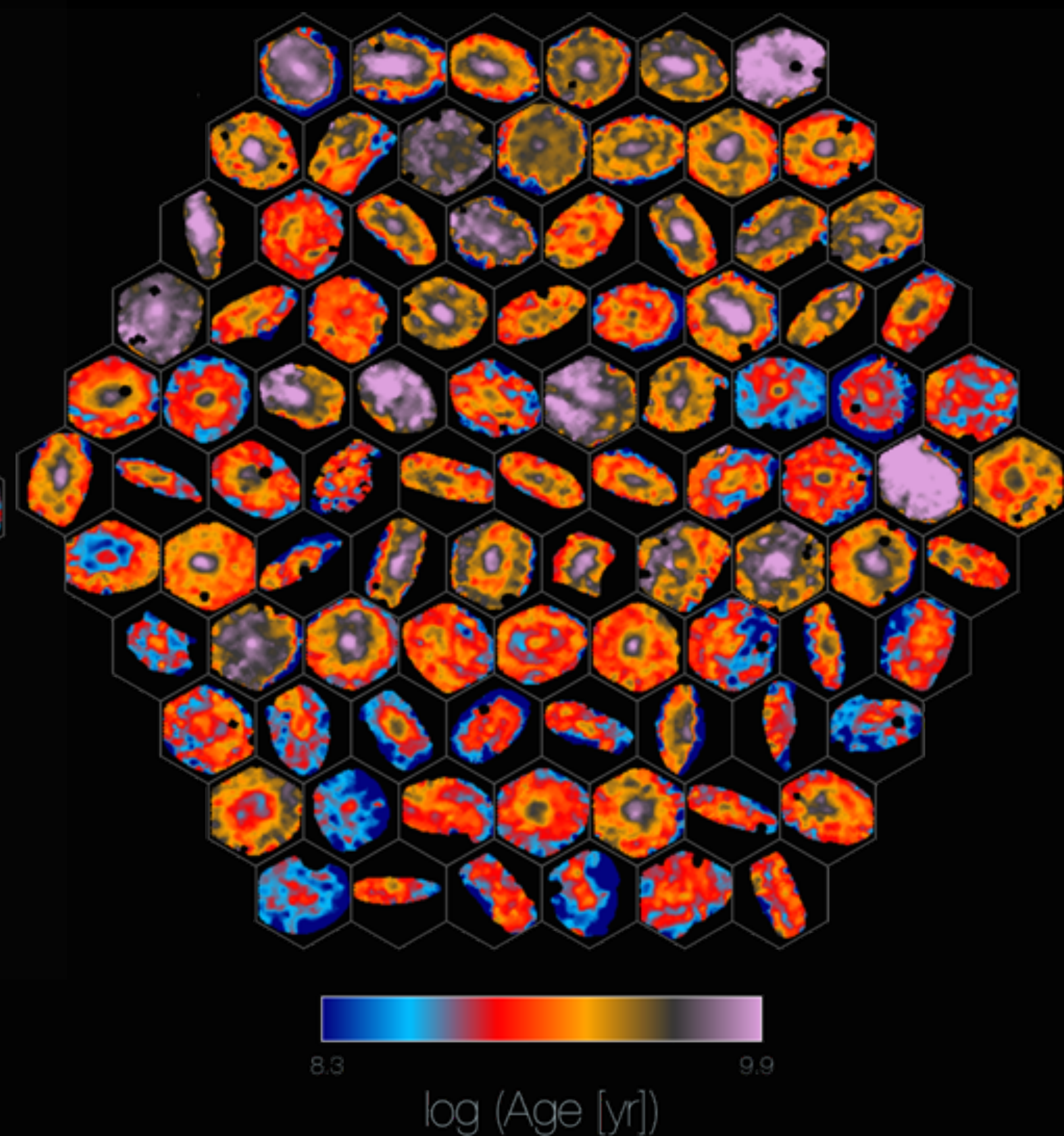
Stellar population properties of galaxies resolved in space and time provide:

spacial and time evolution information that allows to link
the local universe to the early one and provide
observational constraints for
galaxy formation models



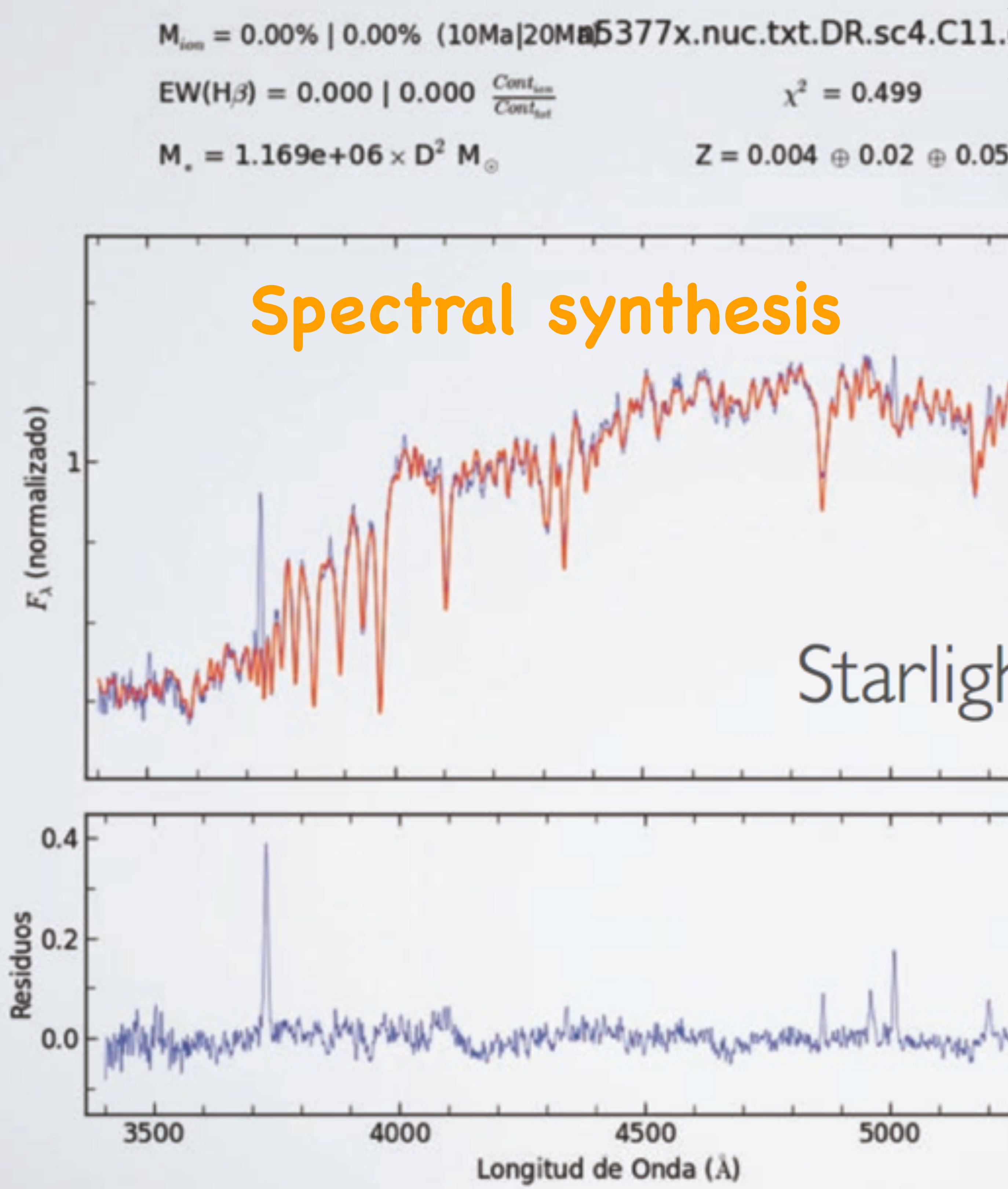


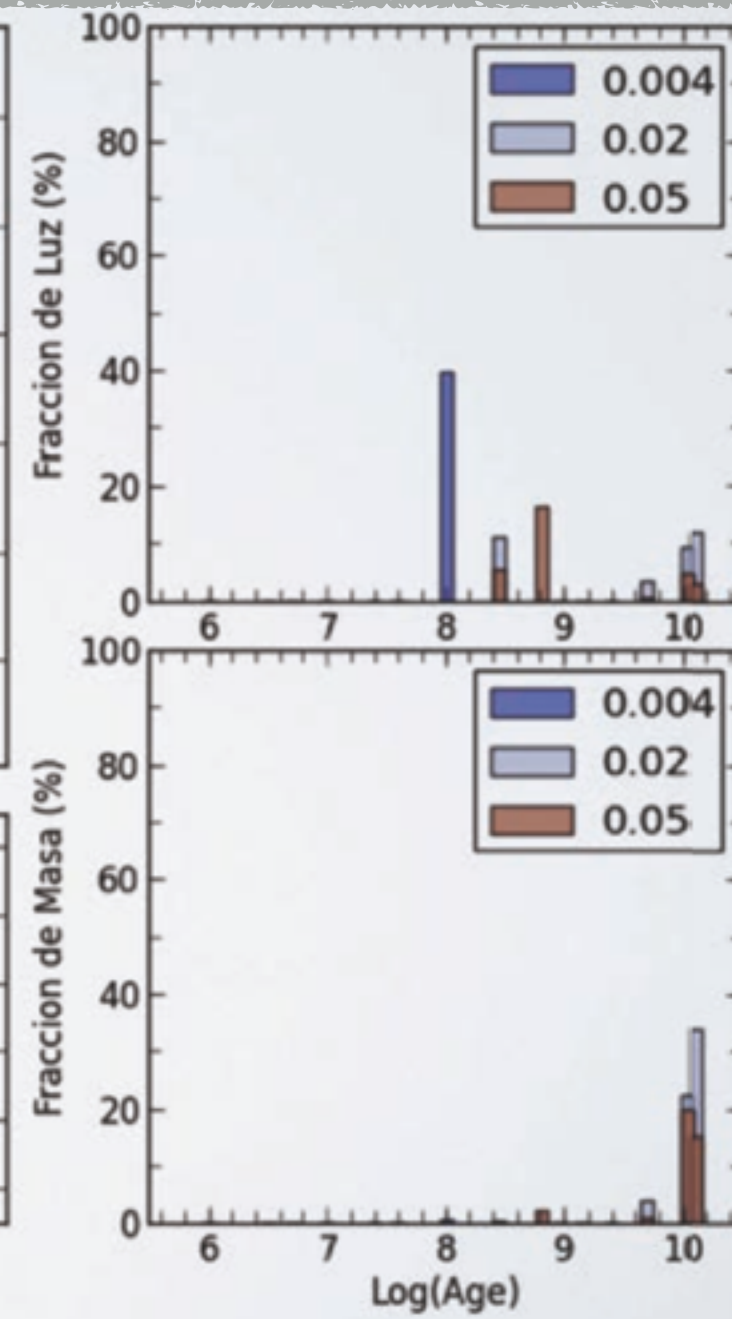
The method

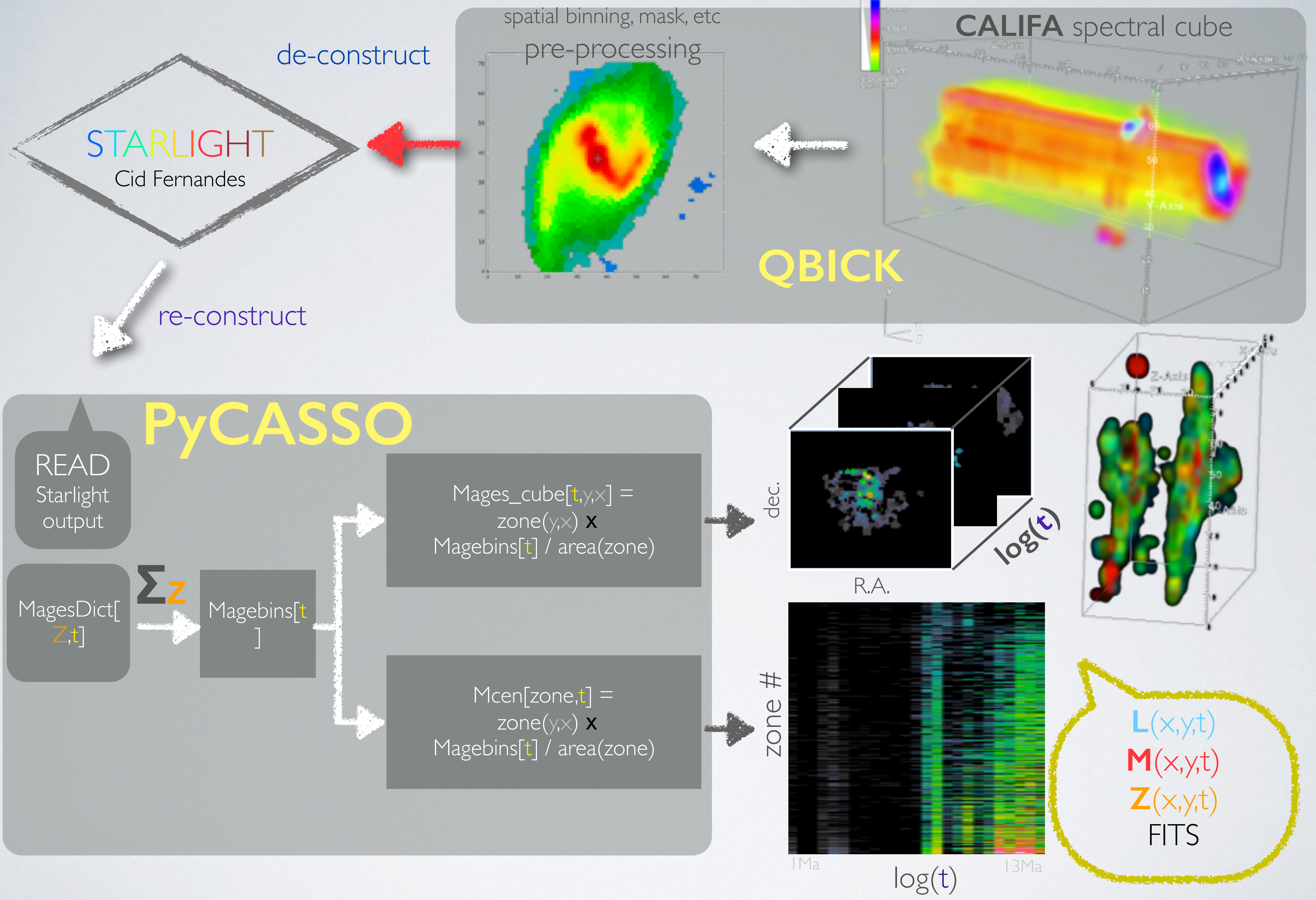
Decomposing galaxy spectra

$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \times SSP(\lambda;t,Z) \times e^{-\tau(\lambda)}$$

- Observables: *Full spectrum*
- SFH: *Mass or light fractions*
- Spectral Base
- Dust







Processing & Analysis pipelines

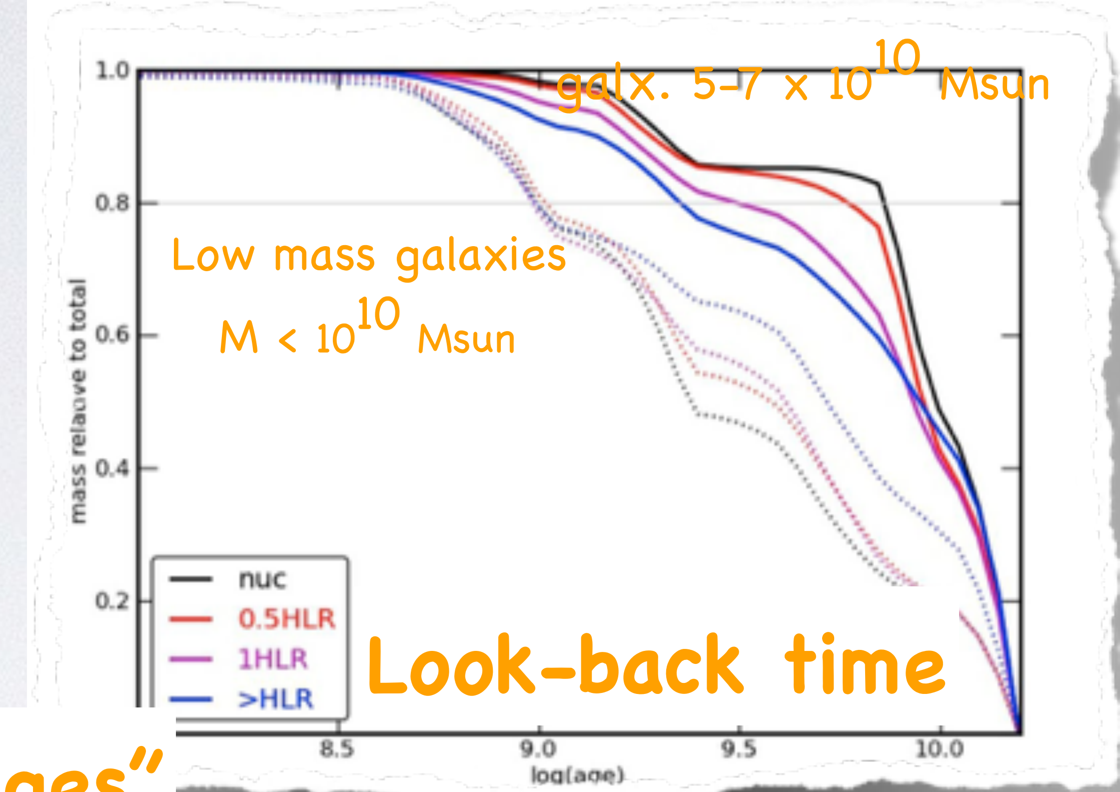
Look-back time studies with CALIFA galaxies

Mass galaxy assembly

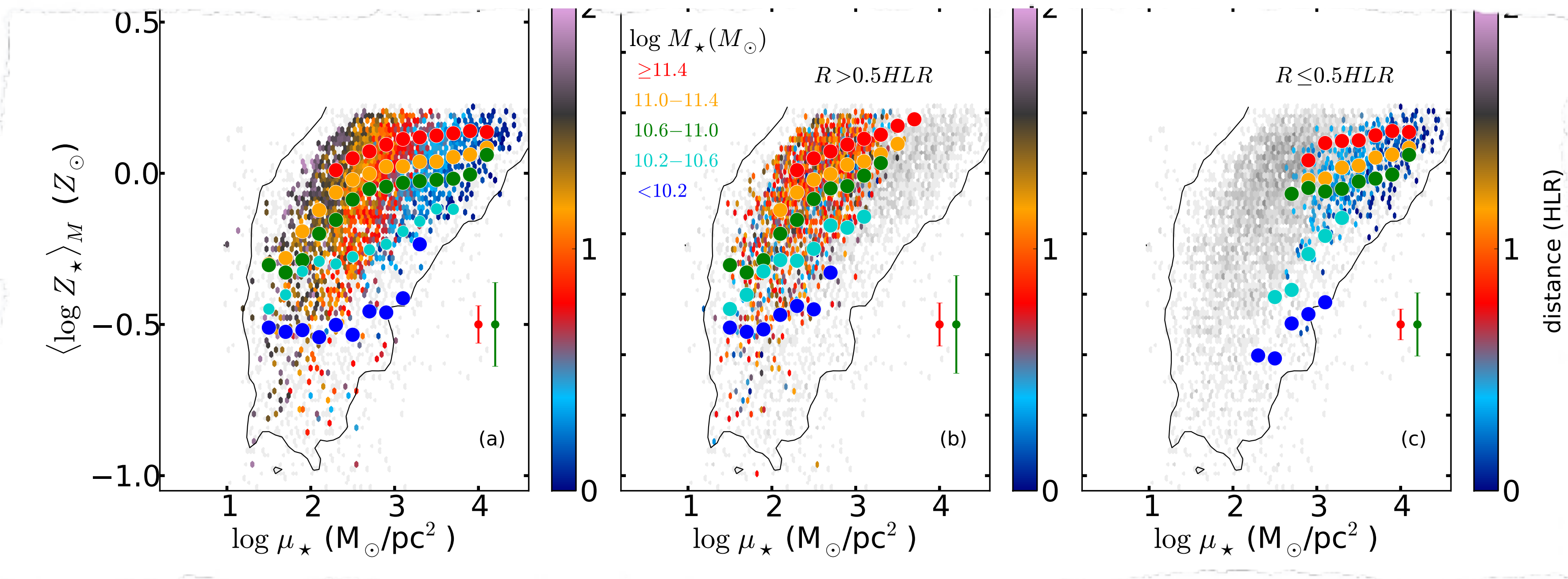
Pérez et al (ApJ, 764, L1, 2013)

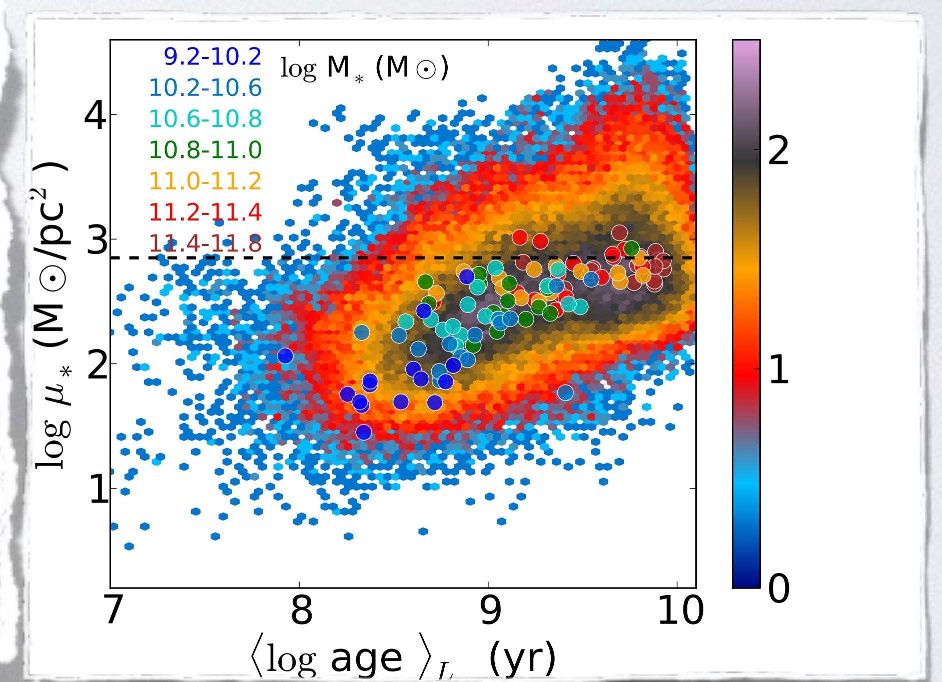
Galaxies grow their mass inside-out

Signal of downsizing is spatially preserved: inner part of massive galaxies grow their mass faster than outer parts

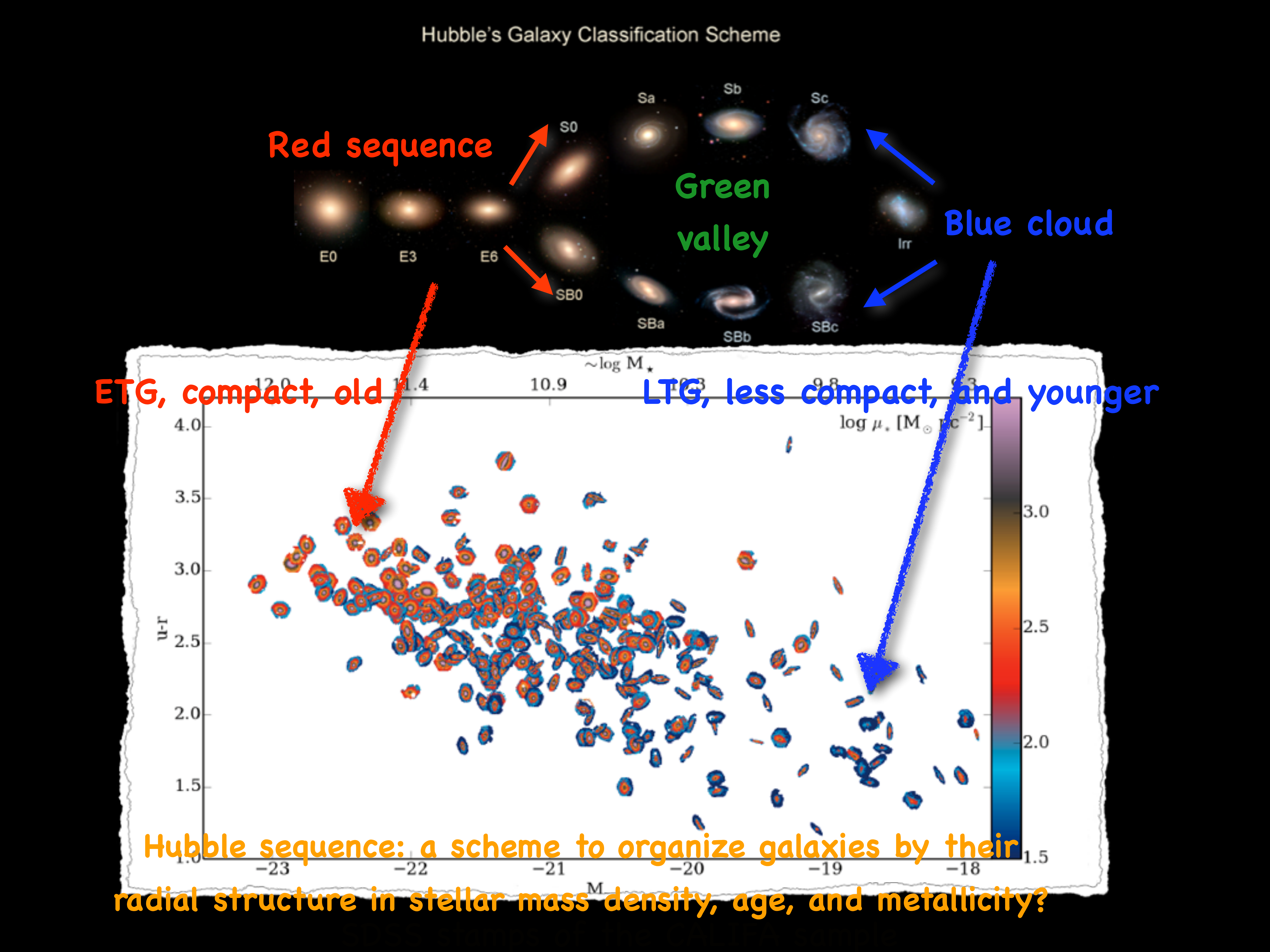


"local μZR" "galaxy disks" "galaxy bulges"

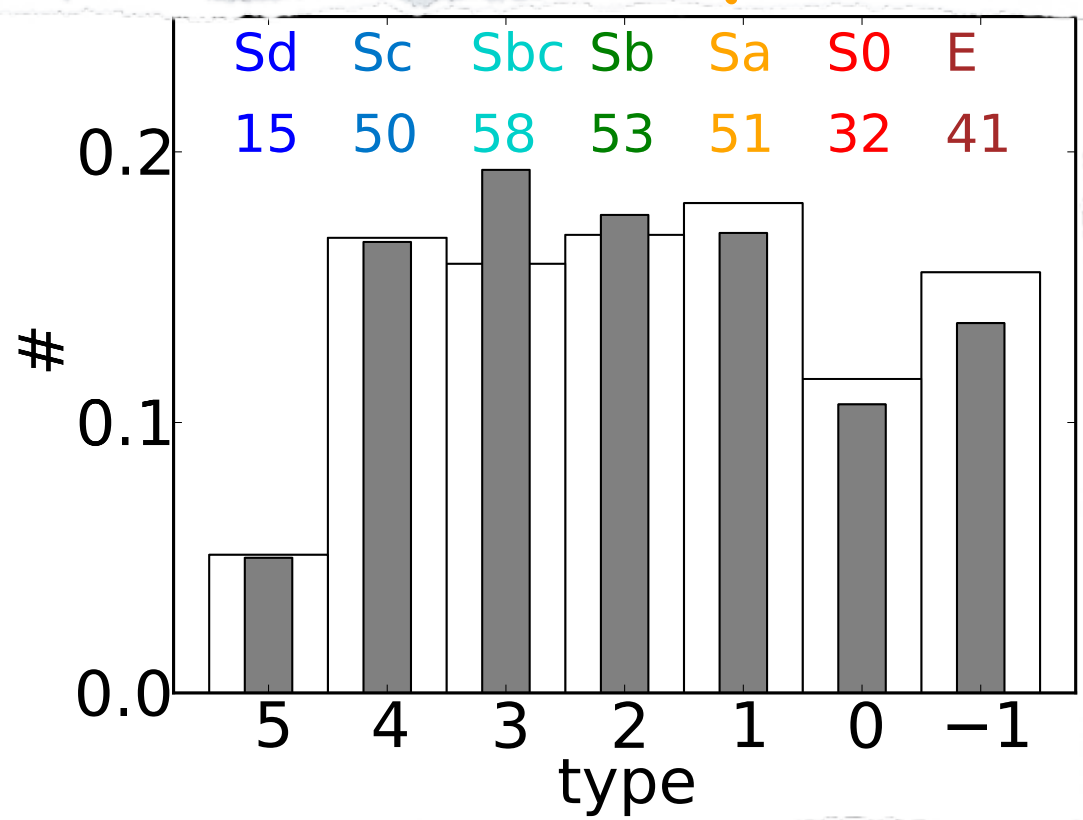


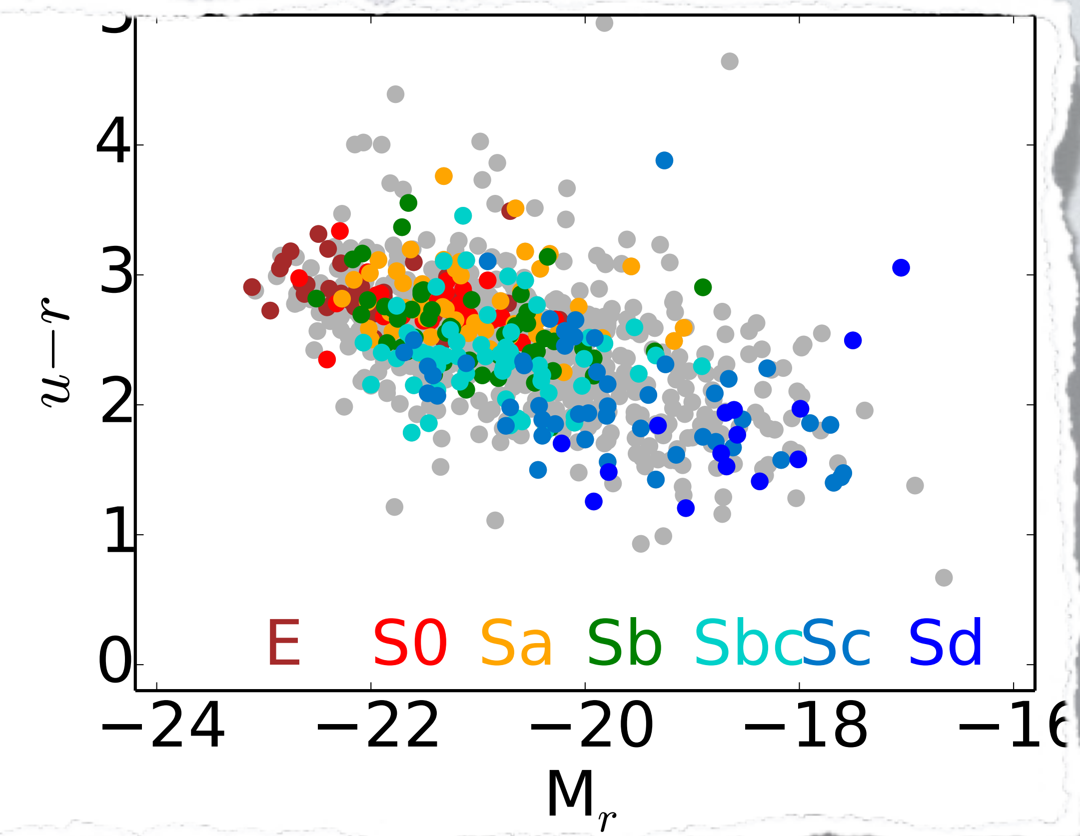


- **Disks: μ regulates the metallicity and SFH, galaxy Mass modulates the amplitude**
- **Spheroids: galaxy Mass dominates the physics of chemical enrichment (except for low mass galaxies) and the SFH**
- González Delgado et al (ApJ, 791, L16, 2014) & (A&A, 562, 47, 2014)


Hubble's Galaxy Classification Scheme
Red sequence
Green valley
Blue cloud
E0
E3
E6
S0
SB0
Sa
Sb
Sc
SBa
SBb
SBc
Irr
ETG, compact, old
LTG, less compact, and younger
~log M⋆
10.9
log μ⋆ [M⊙ pc⁻²]
u-r
4.0
3.5
3.0
2.5
2.0
1.5
−23
−22
−21
−20
−19
−18
3.0
2.5
2.0
1.5
Hubble sequence: a scheme to organize galaxies by their radial structure in stellar mass density, age, and metallicity?

CALIFA sample: 300 galaxies analyzed here





SSP GMe:

González Delgado + (2005) & Vazdekis + (2010)

IMF: Salpeter; Pádova 2000

log Z* = -2.3, -1.7, -1.3, -0.7, -0.4, 0, +0.22

39 ages: 0.001 to 14 Gyr

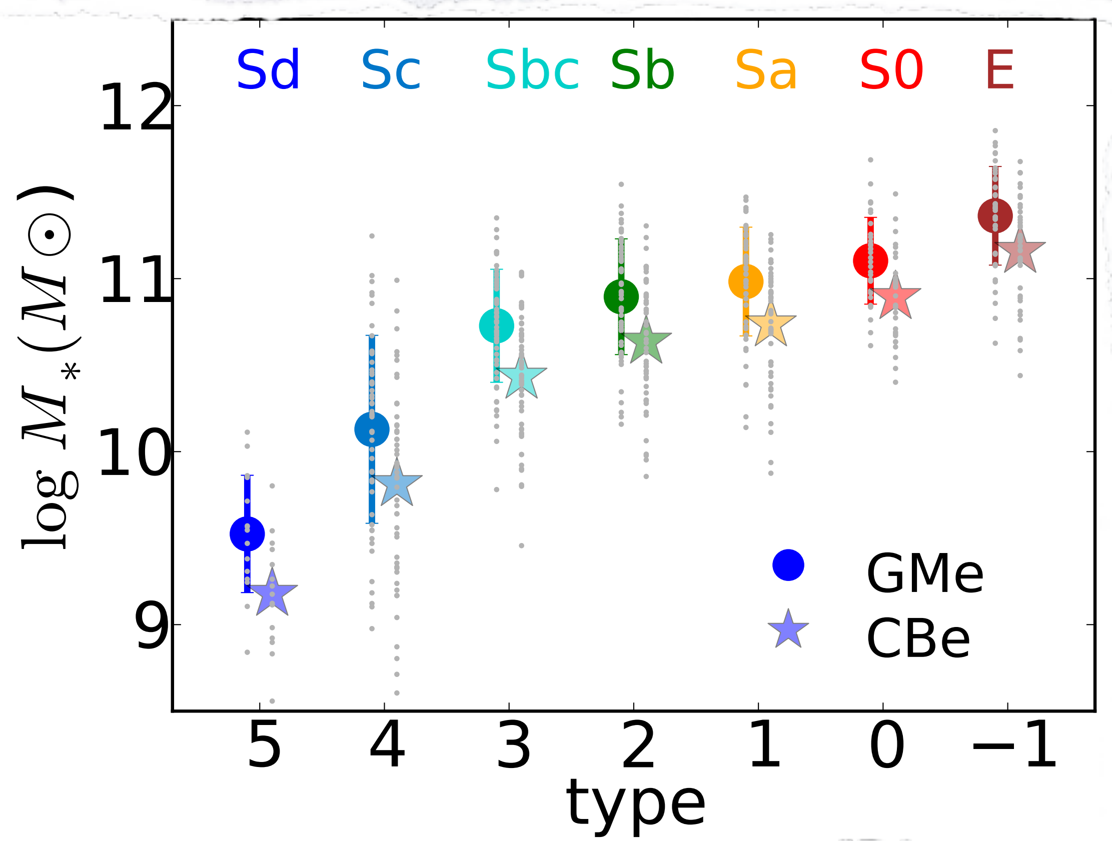
SSP CBe:

Charlot & Bruzual (2007)

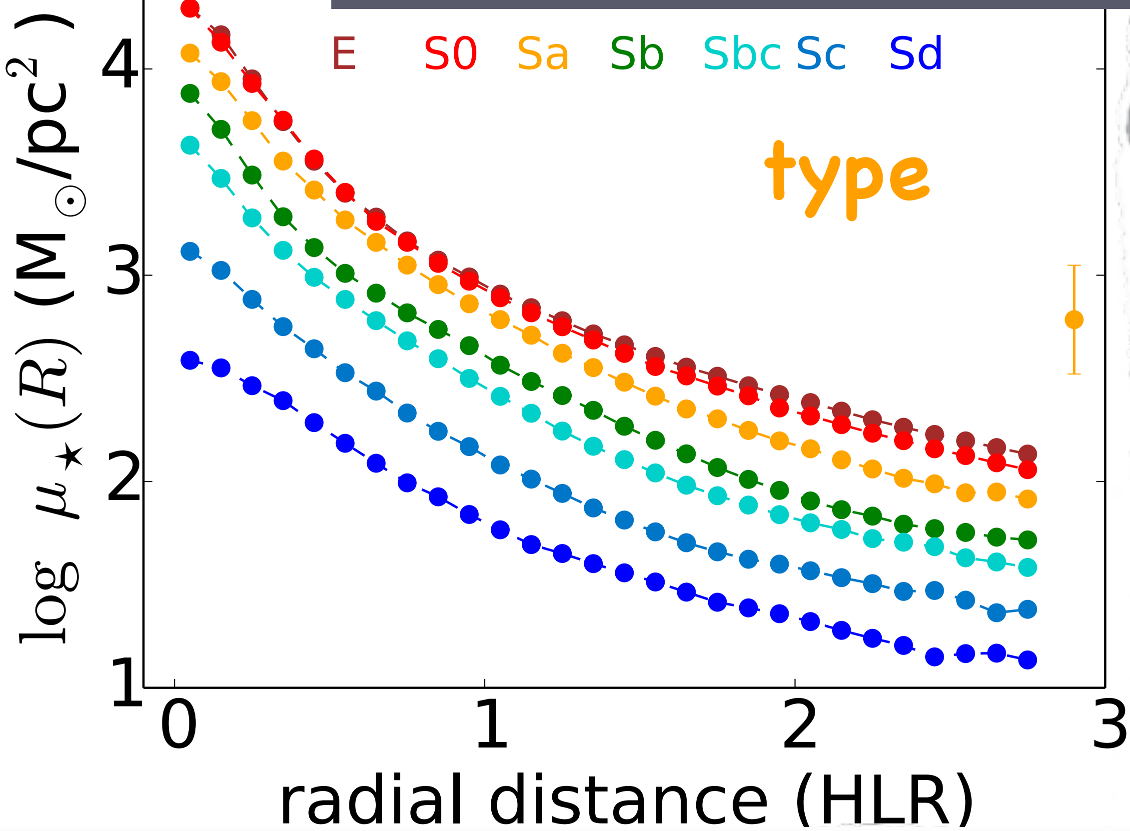
IMF: Chabrier; Pádova 1994

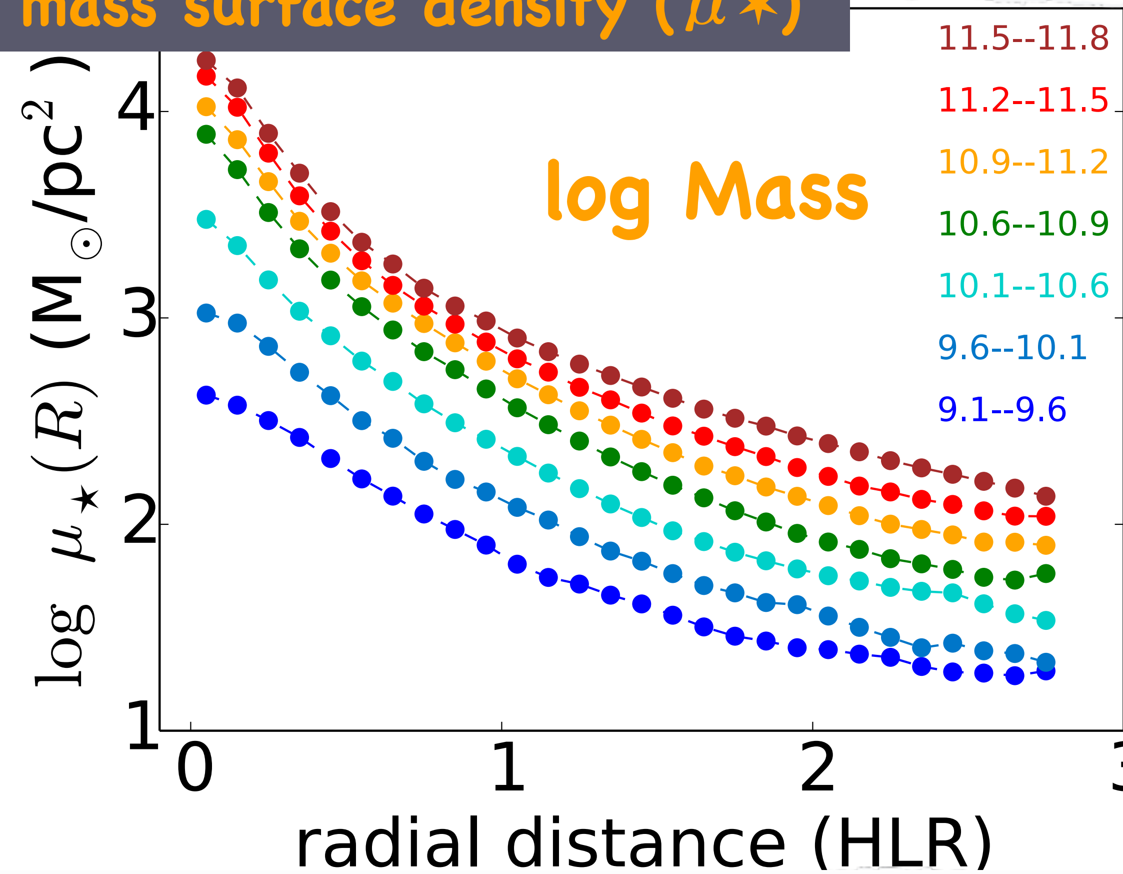
log Z* = -2.3, -1.7, -0.7, -0.4, 0, +0.4

41 ages: 0.001 to 14 Gyr

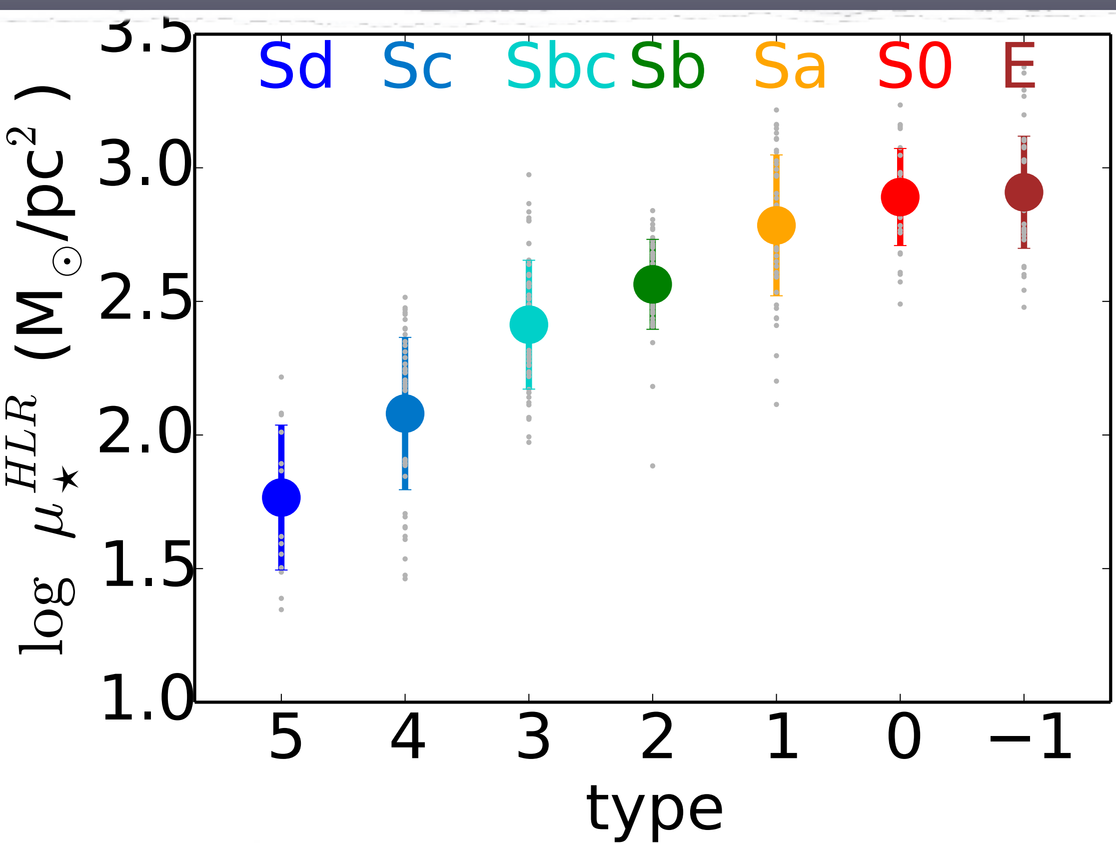


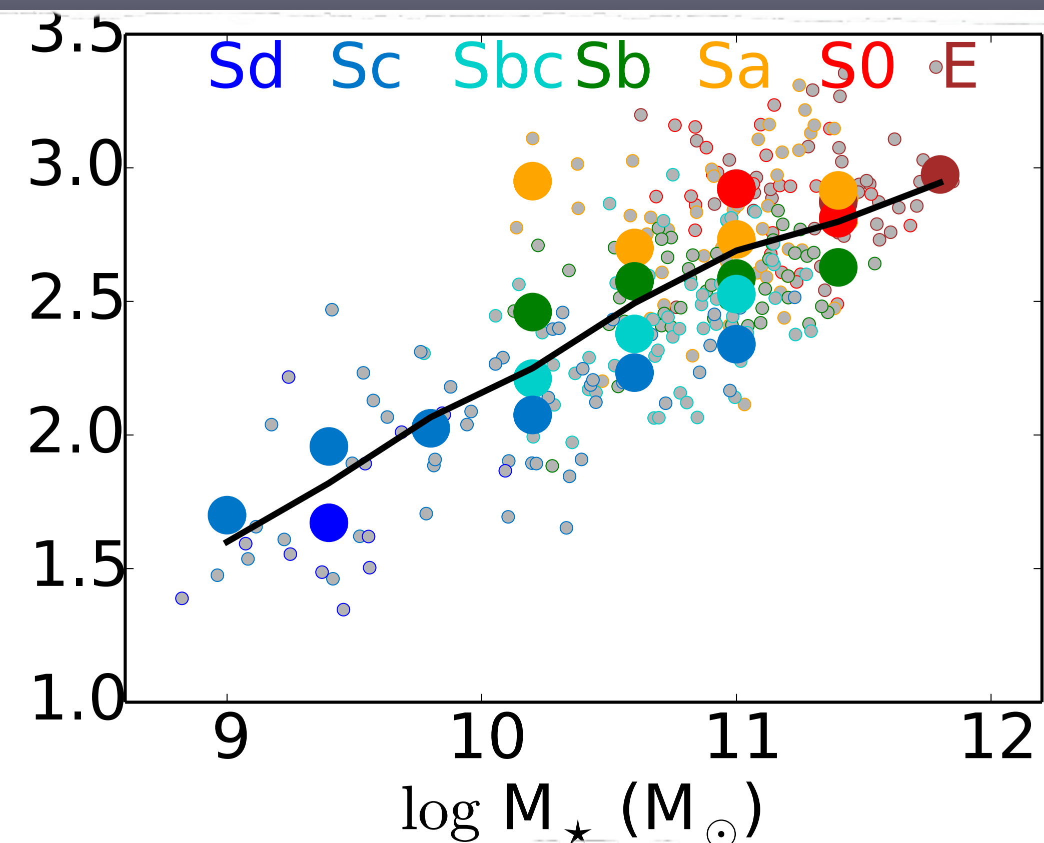
Radial structure of the stellar mass surface density ($\mu\star$)



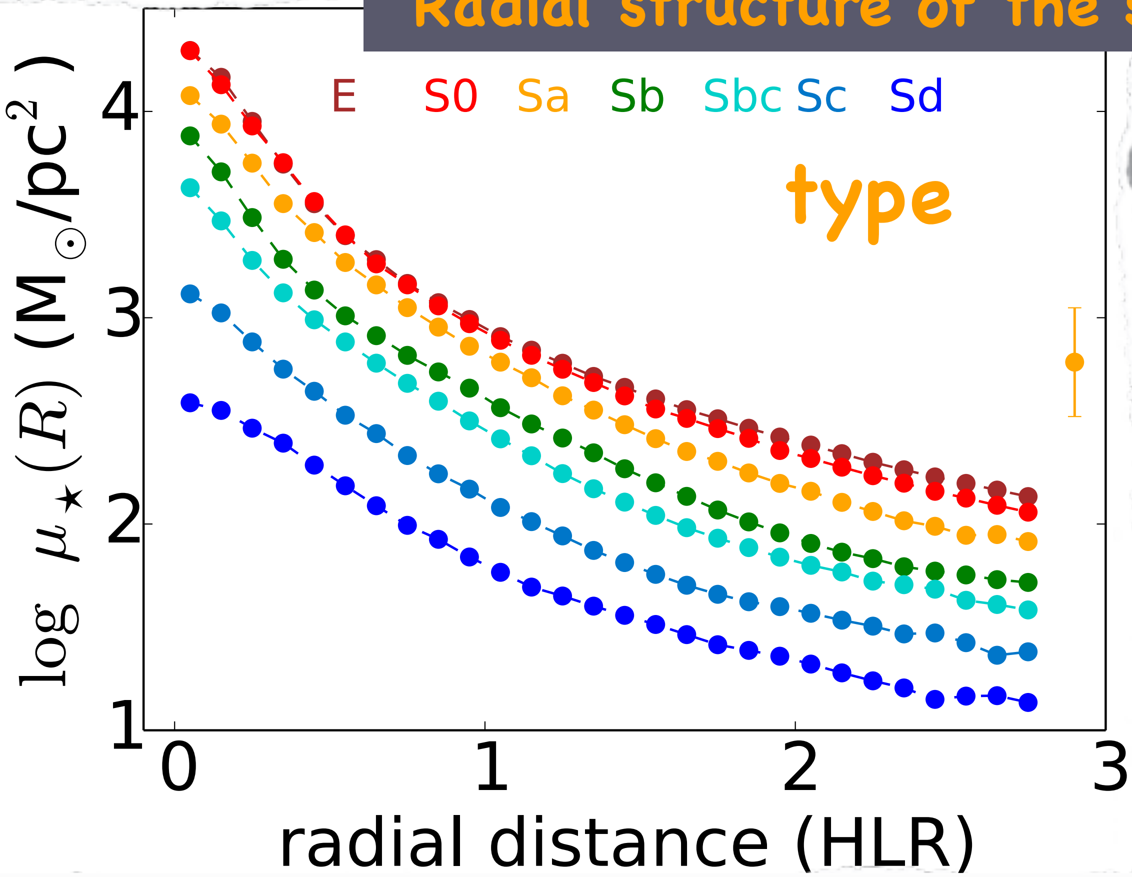


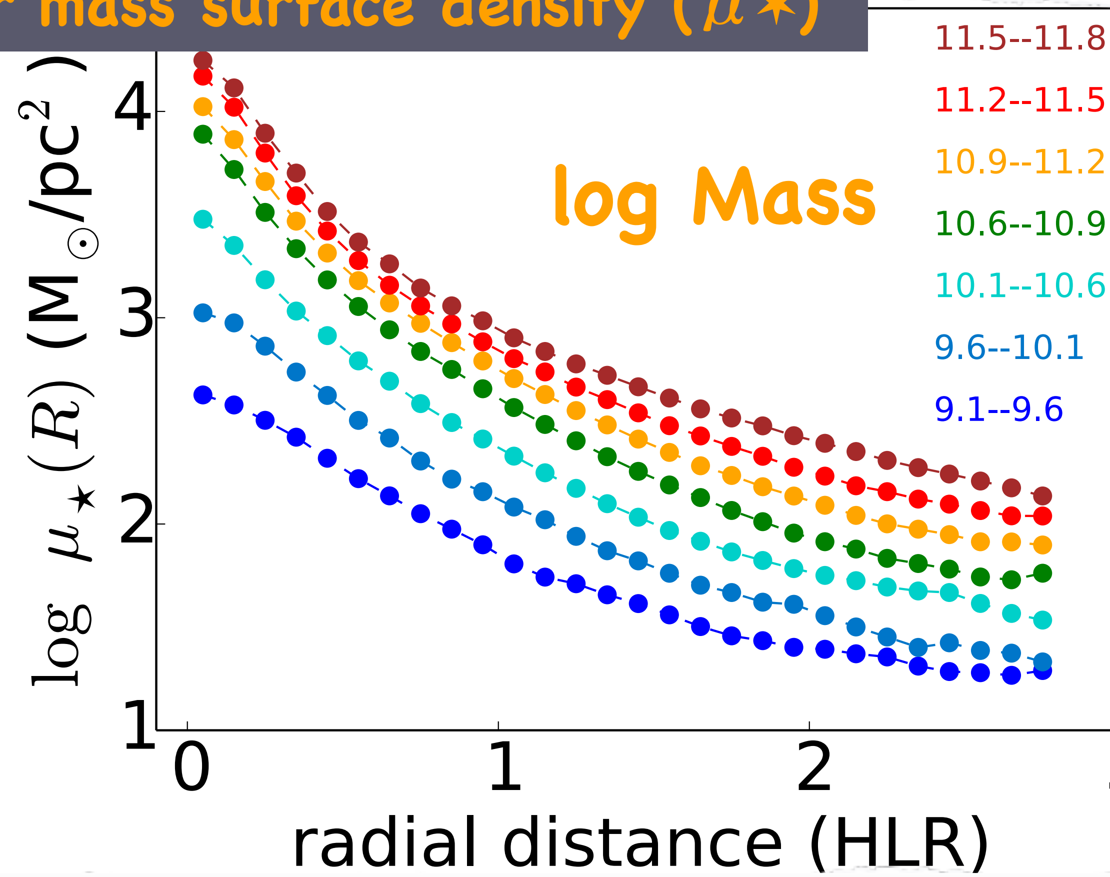
declining profile that scale with Hubble type and M✶
at constant M✶: early type are more compact that late type galaxies
this trend is preserved with radial distance
E and SO are equally compact: a similar formation process



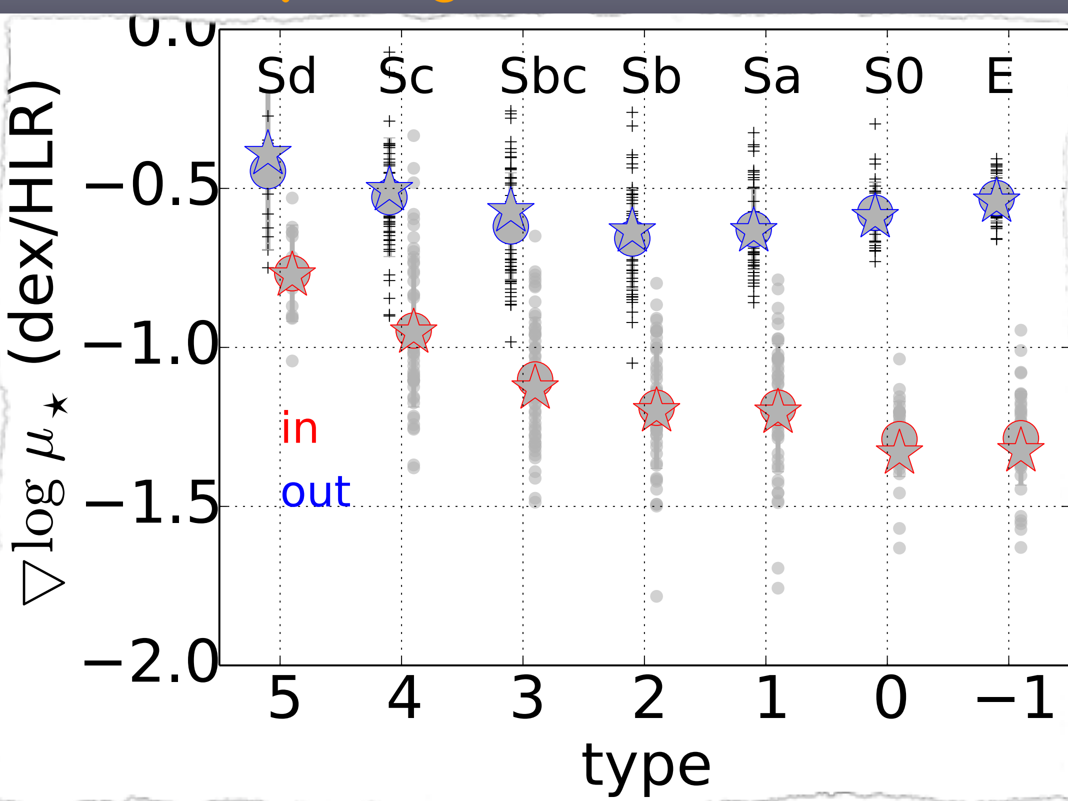


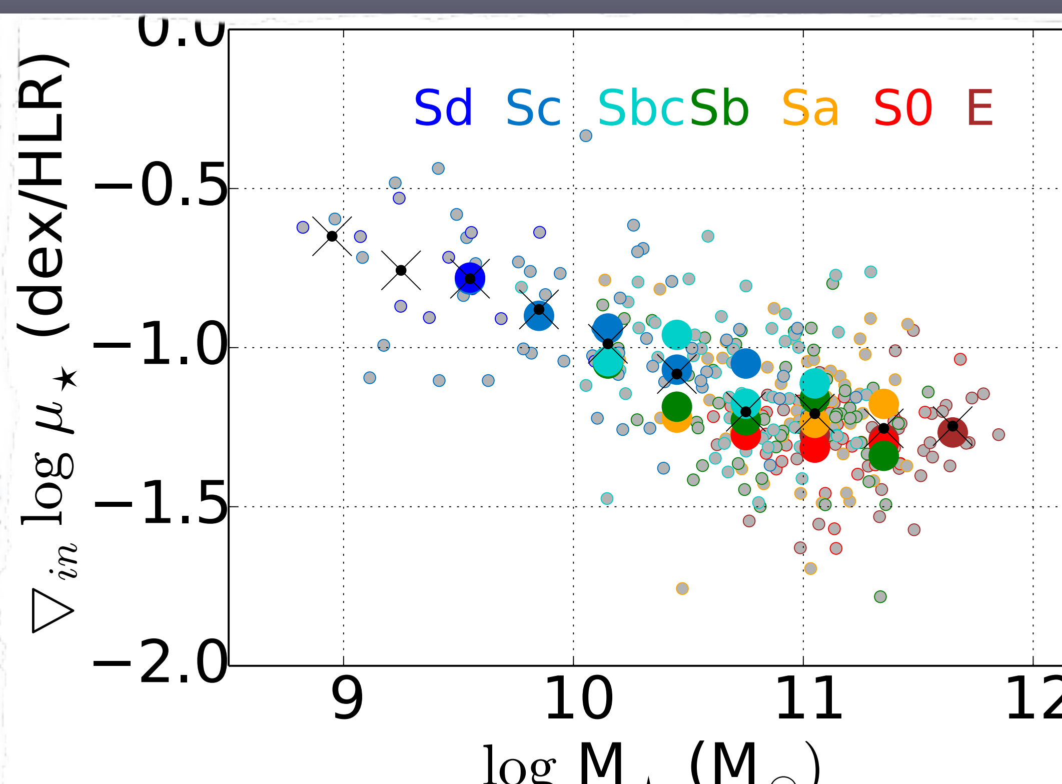
Radial structure of the stellar mass surface density ($\mu\star$)



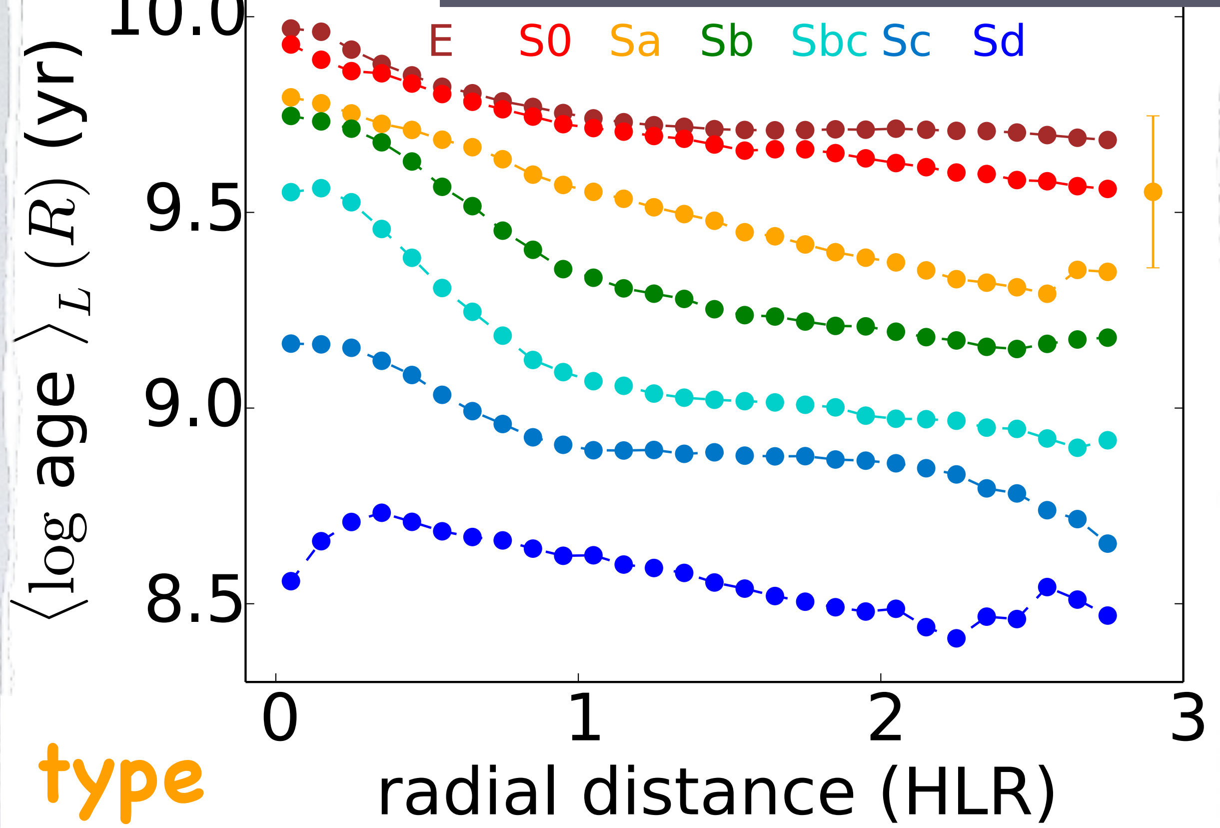


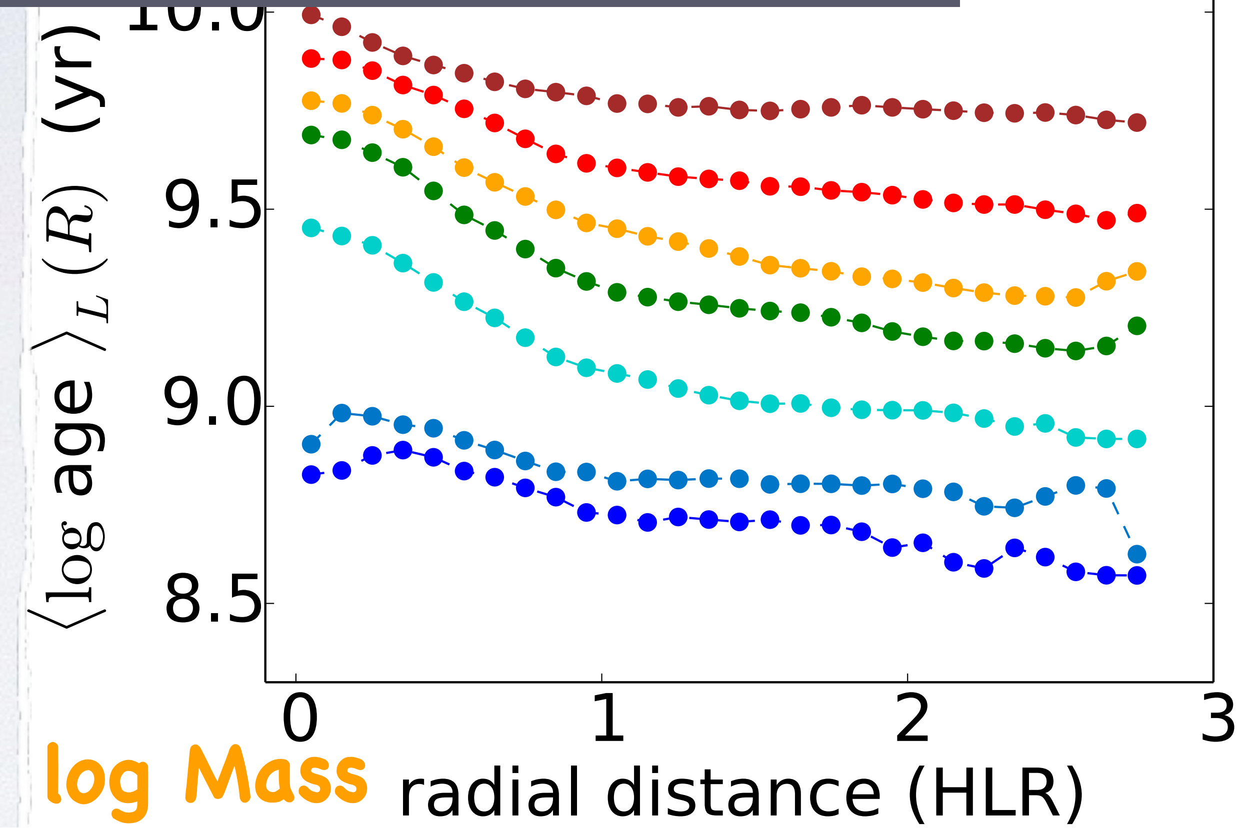
Inner gradient correlates with the Hubble type
steepen from late to early type, and M✶
at M* = cte, the inner gradient steepen with morphology
Morphology and not only M* determine the radial structure of $\mu\star$



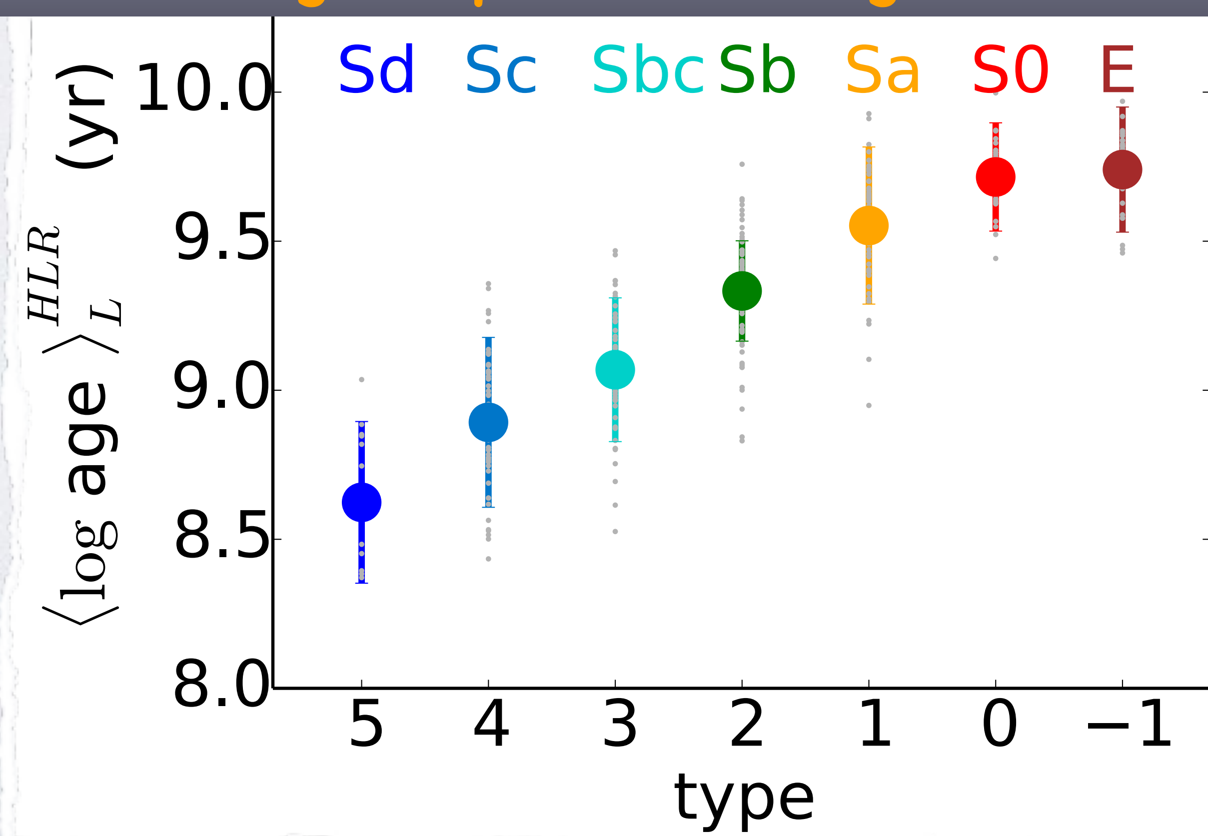


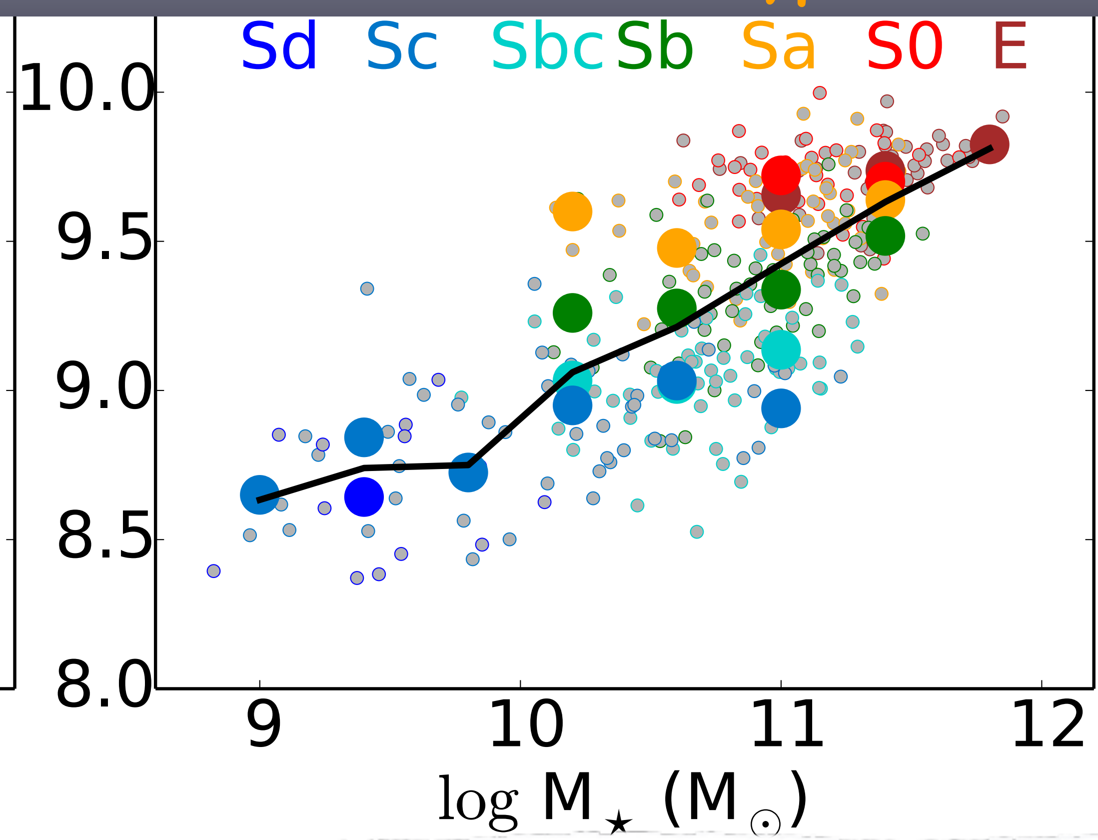
Radial structure of the stellar ages



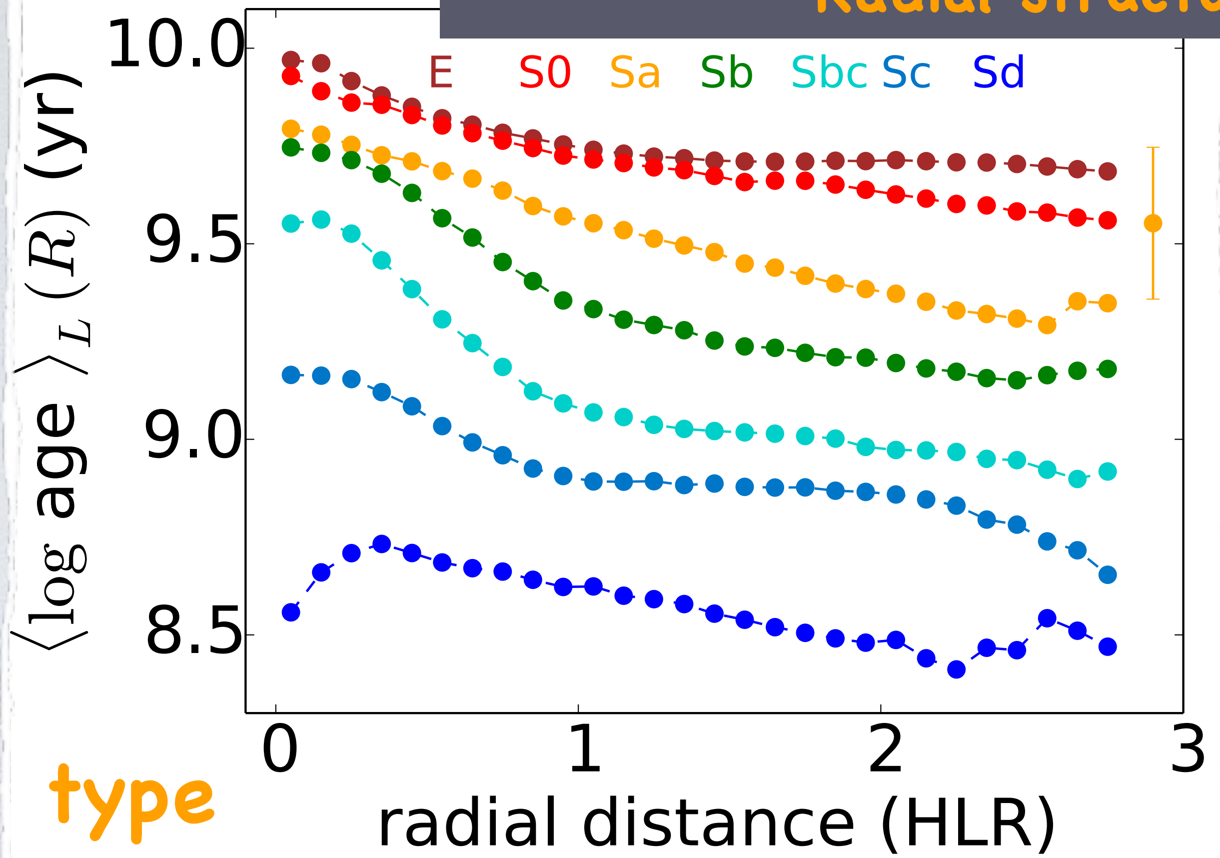


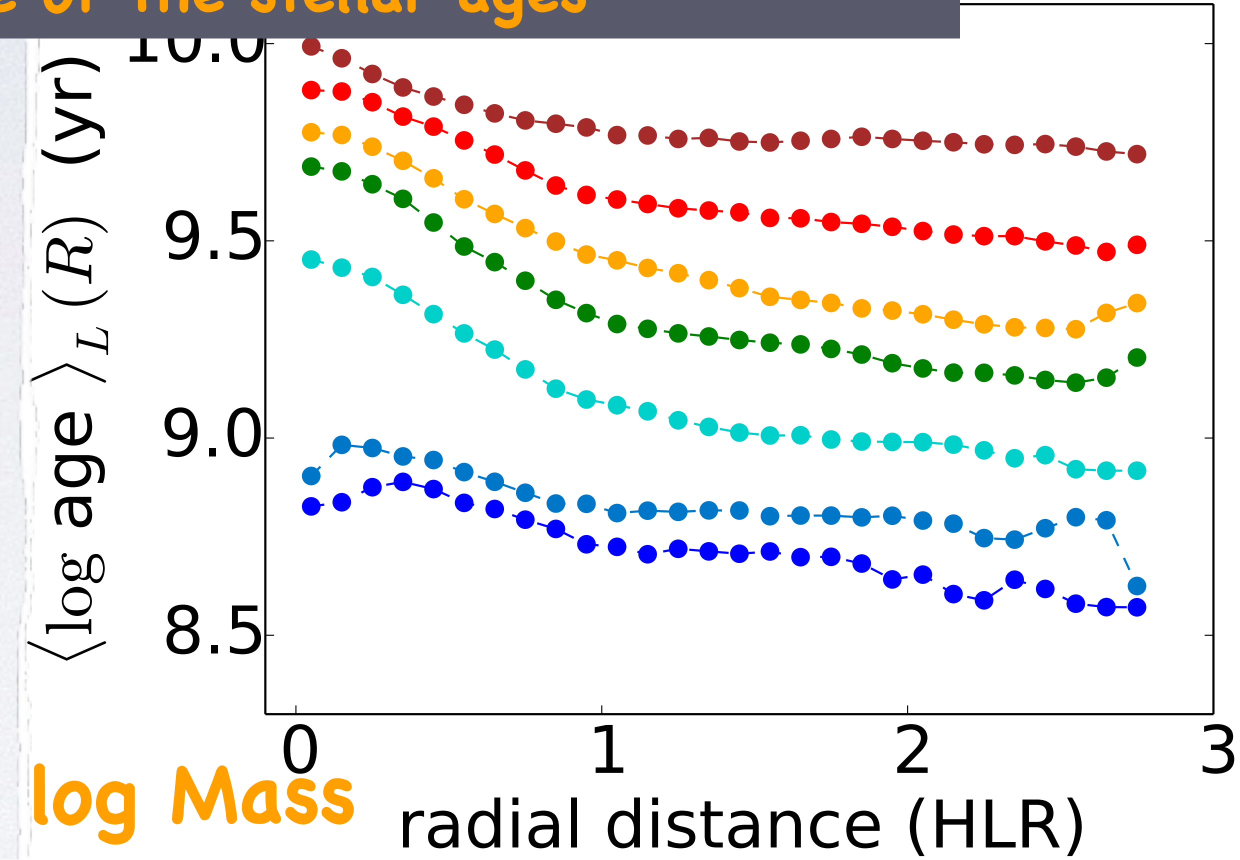
declining profile that scale with Hubble type and M✶
at constant M✶: early type are older that late type galaxies
"downsizing" behavior is preserved with radial distance
high dispersion M✶-age relation: SFH is linked to Hubble type





Radial structure of the stellar ages

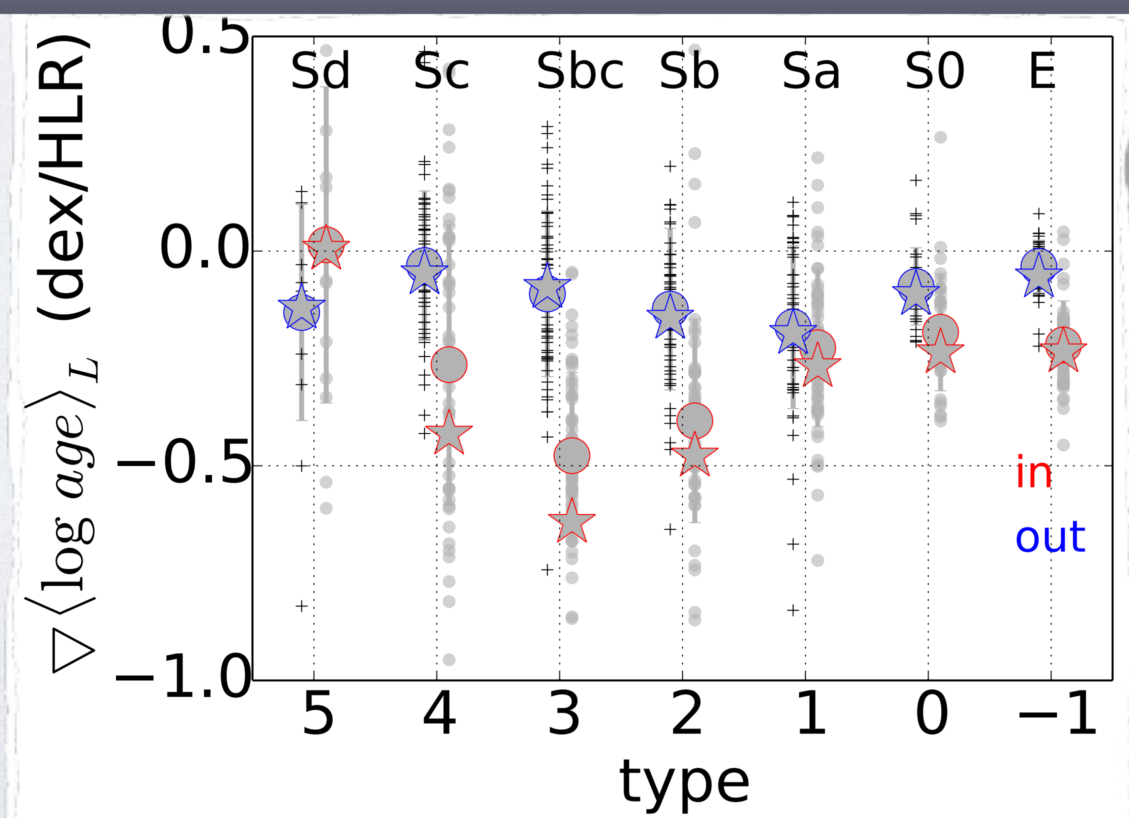


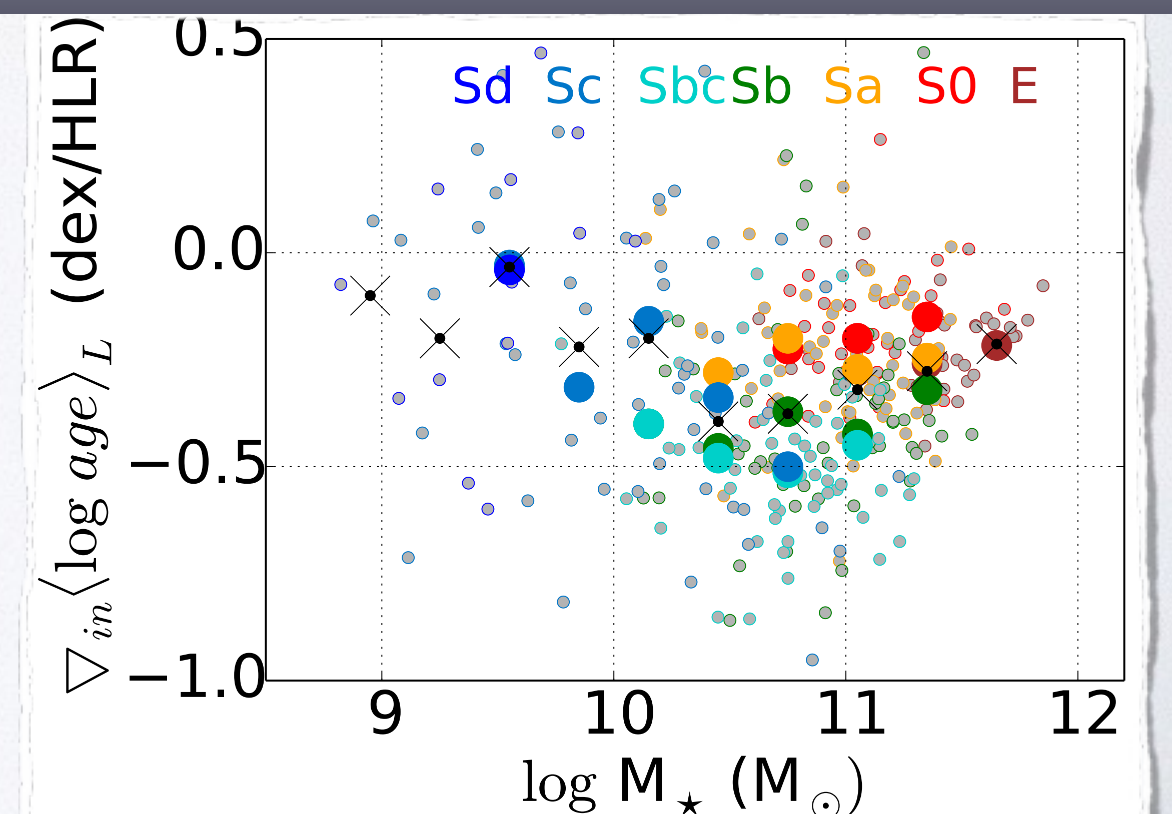


negative gradients (quenching outwards): largest in MW type galaxies (Sbc)

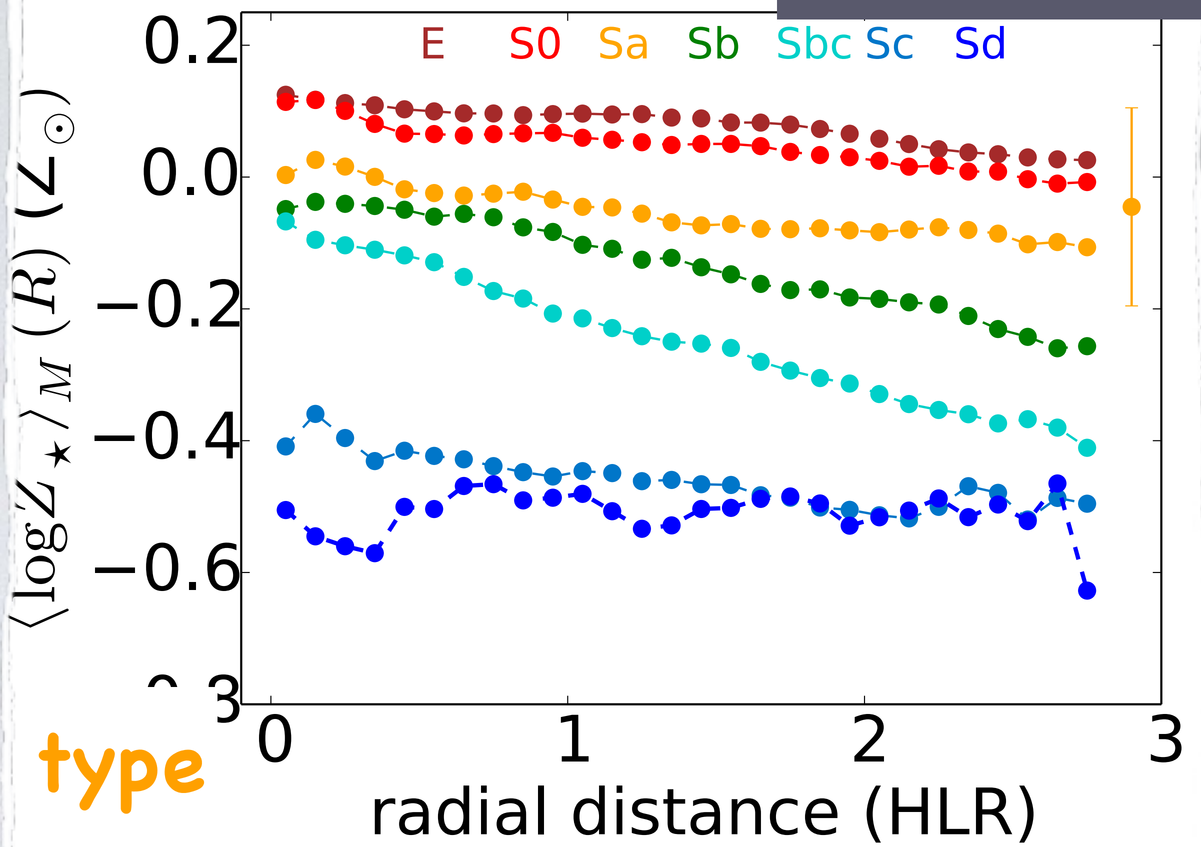
at constant galaxy Mass: late types steeper age gradient

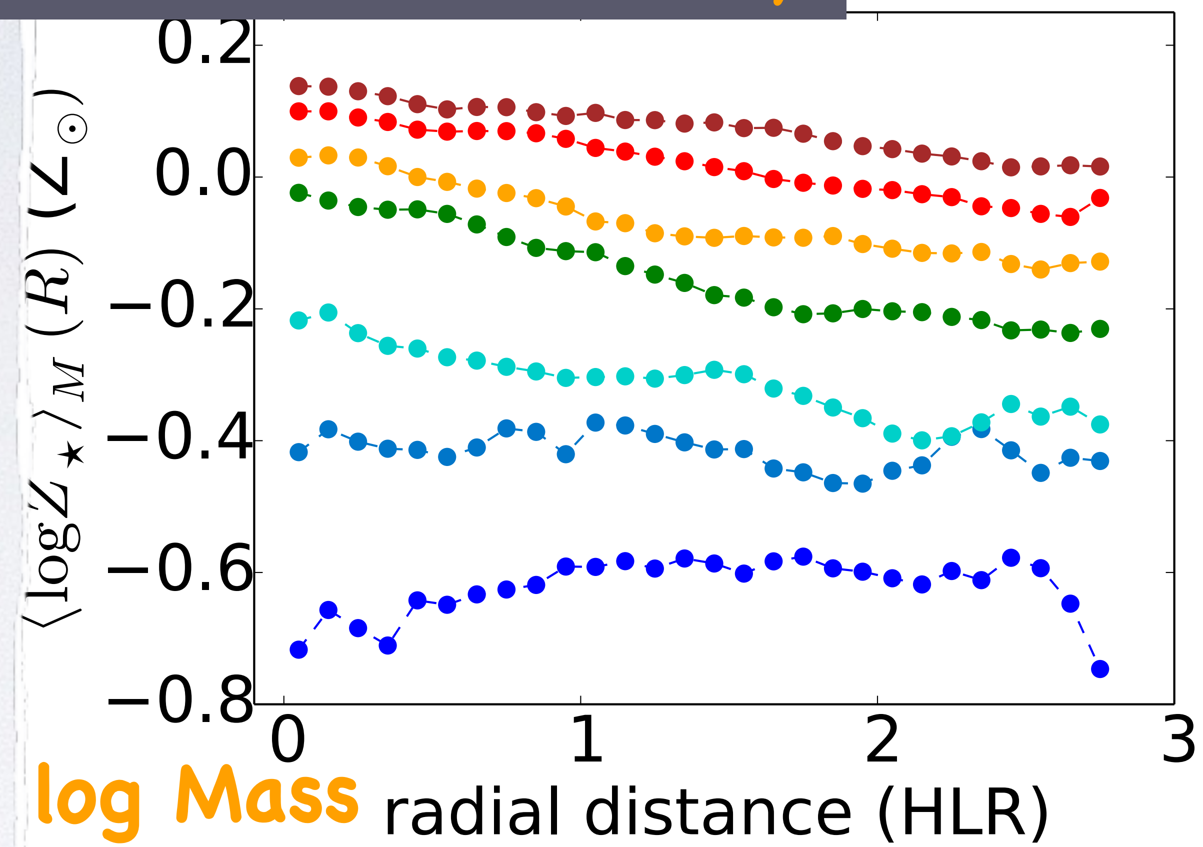
dispersion on $\nabla_{in}\langle \log age \rangle_L$–$M_\star$ relation is strongly related with the Hubble type





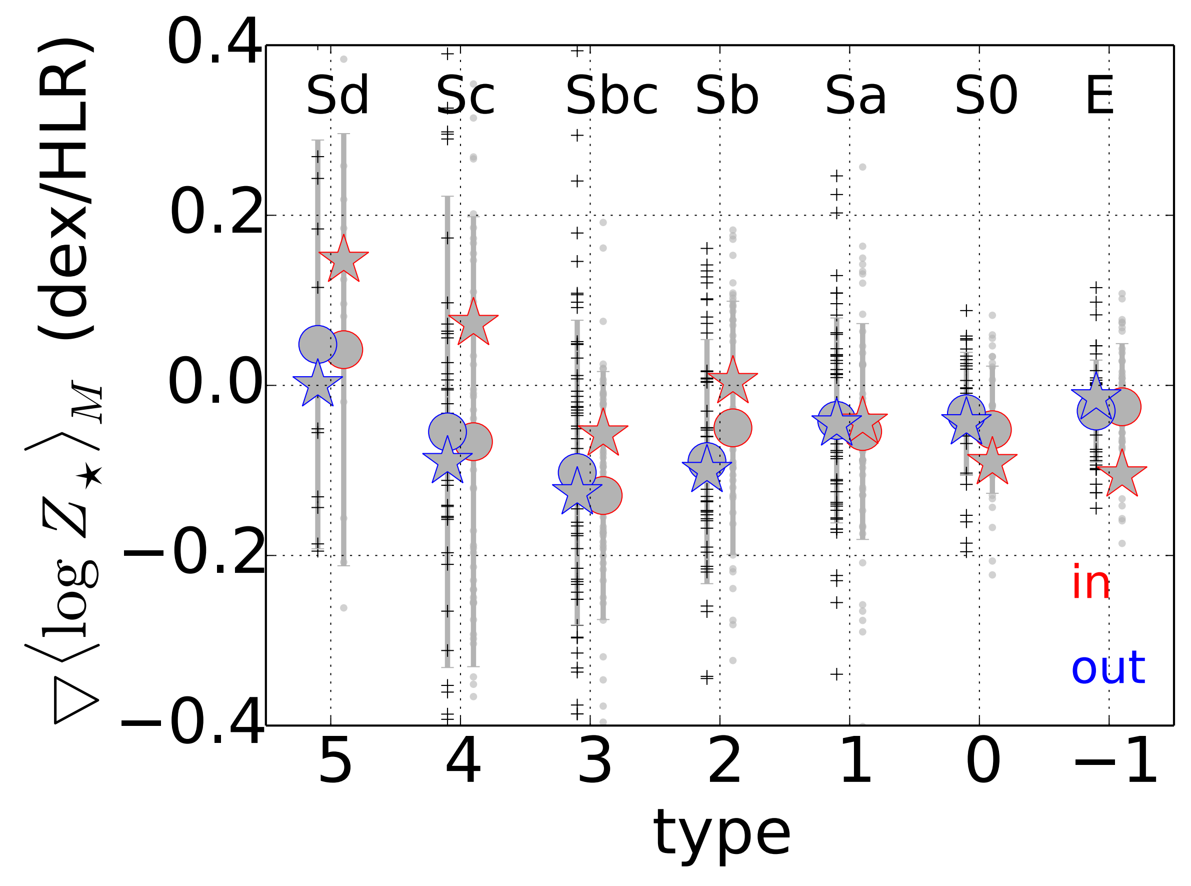
Radial structure of the stellar metallicity

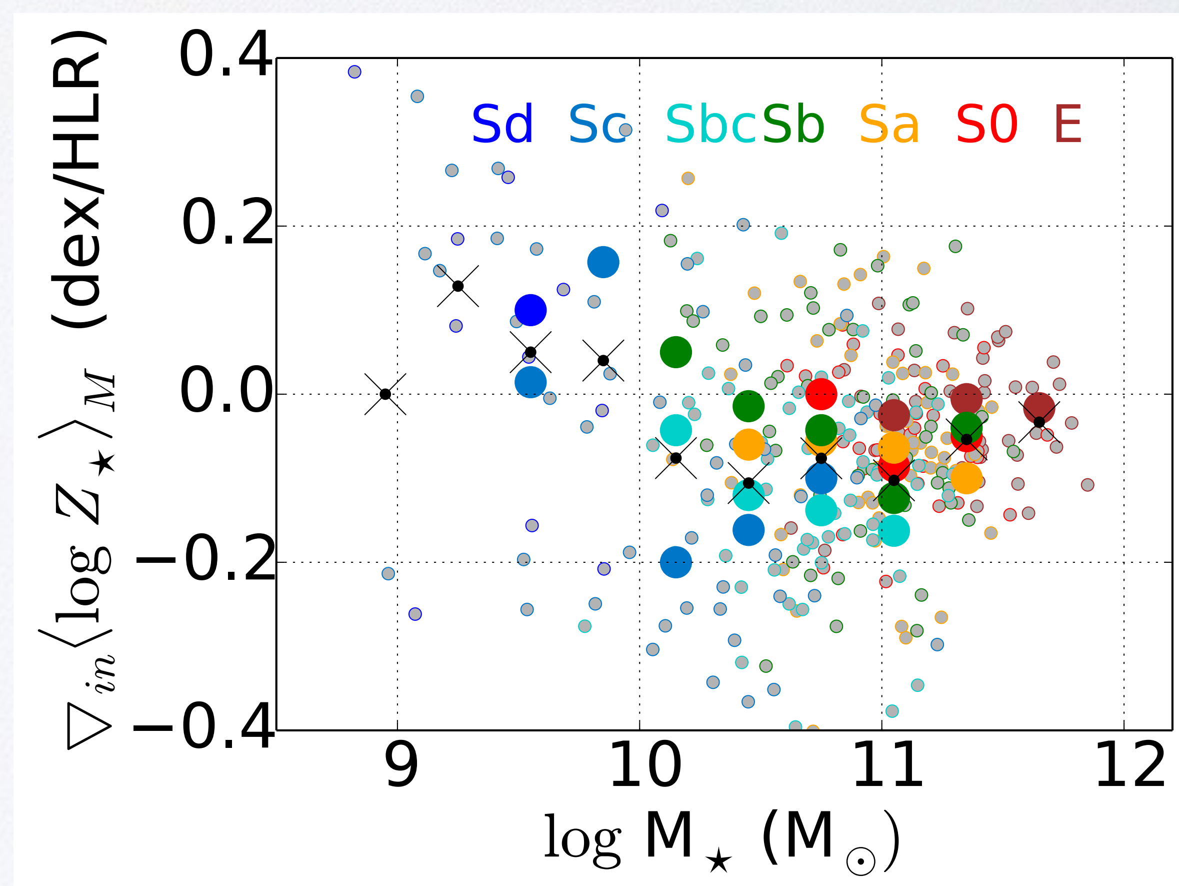




declining profiles (except in late spirals): largest gradient in MW type galaxies (Sbc)

dispersion in the $\nabla_{in}\langle \log Z \rangle_M$–$M\star$ relation is related with morphology





Conclusions: Galaxies are growing inside-out in agreement with

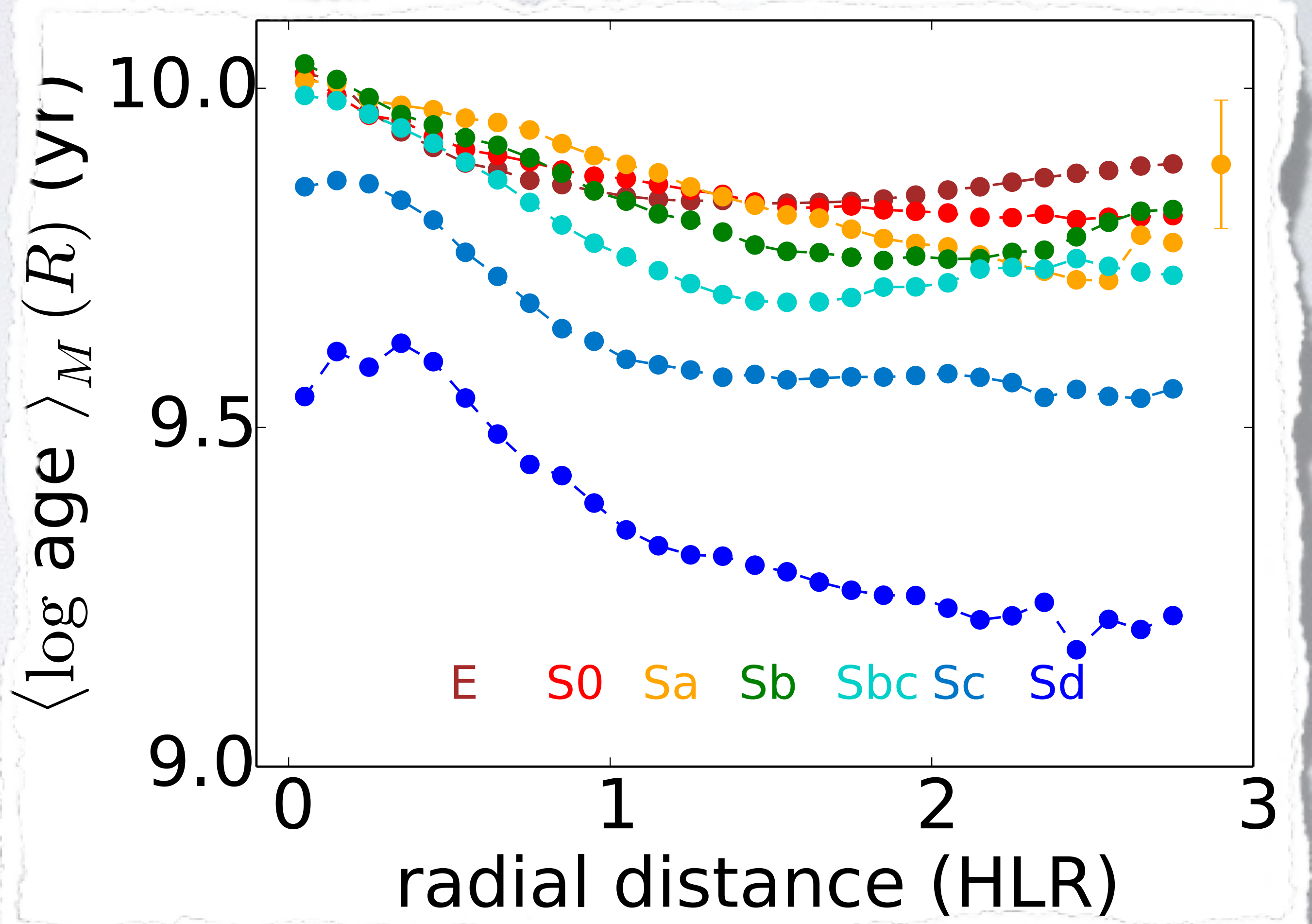
Pérez et al. 2013 (APJL, 764, L1)

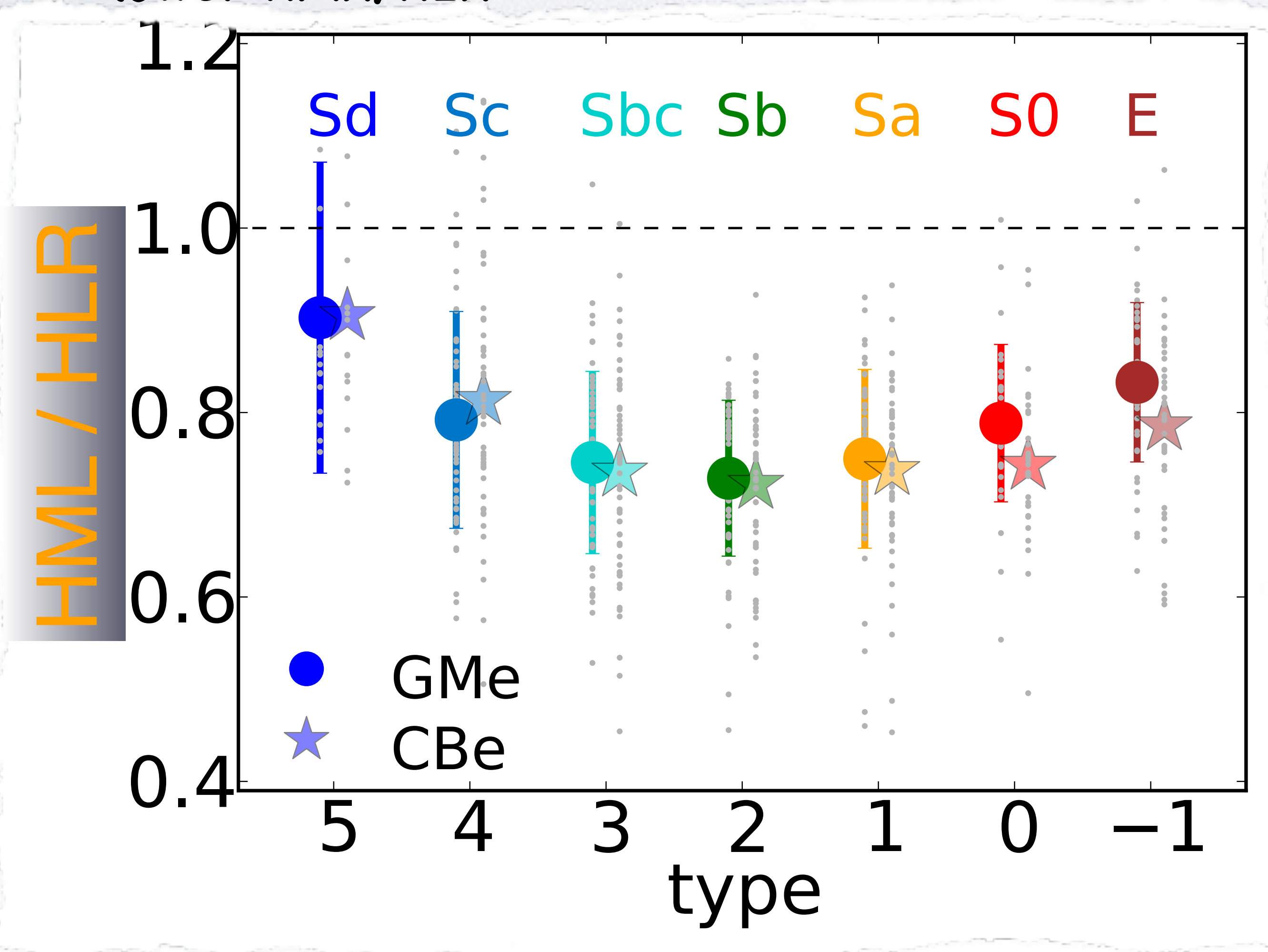
Evidence:

- The negative radial stellar age gradients.
- The negative metallicity gradients
- Galaxies are more compact in mass than in light.

HMR/HLR: ratio of the radius that contains half of mass and half of the light.

Milky Way-like galaxies are the galaxies with lower HMR/HLR



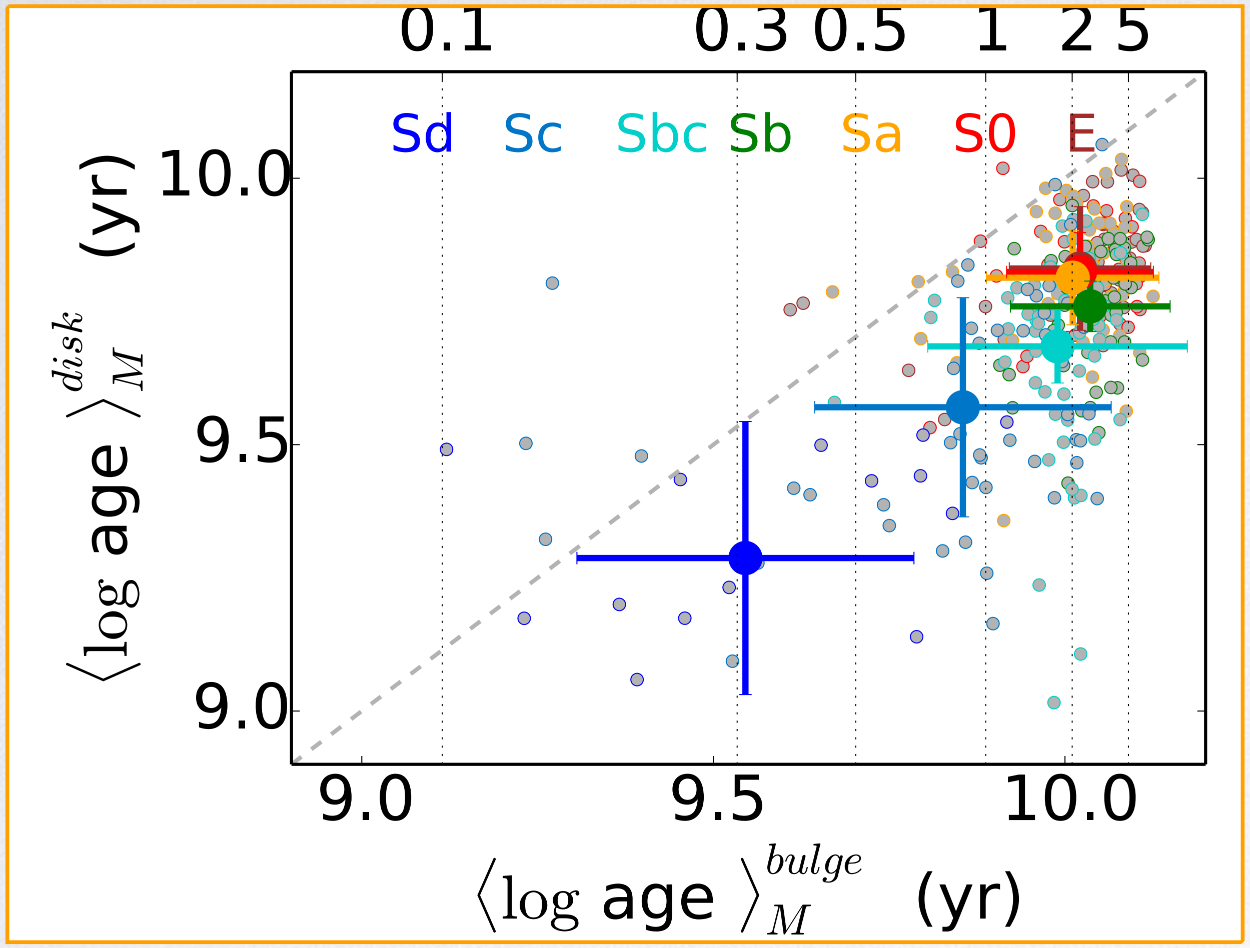


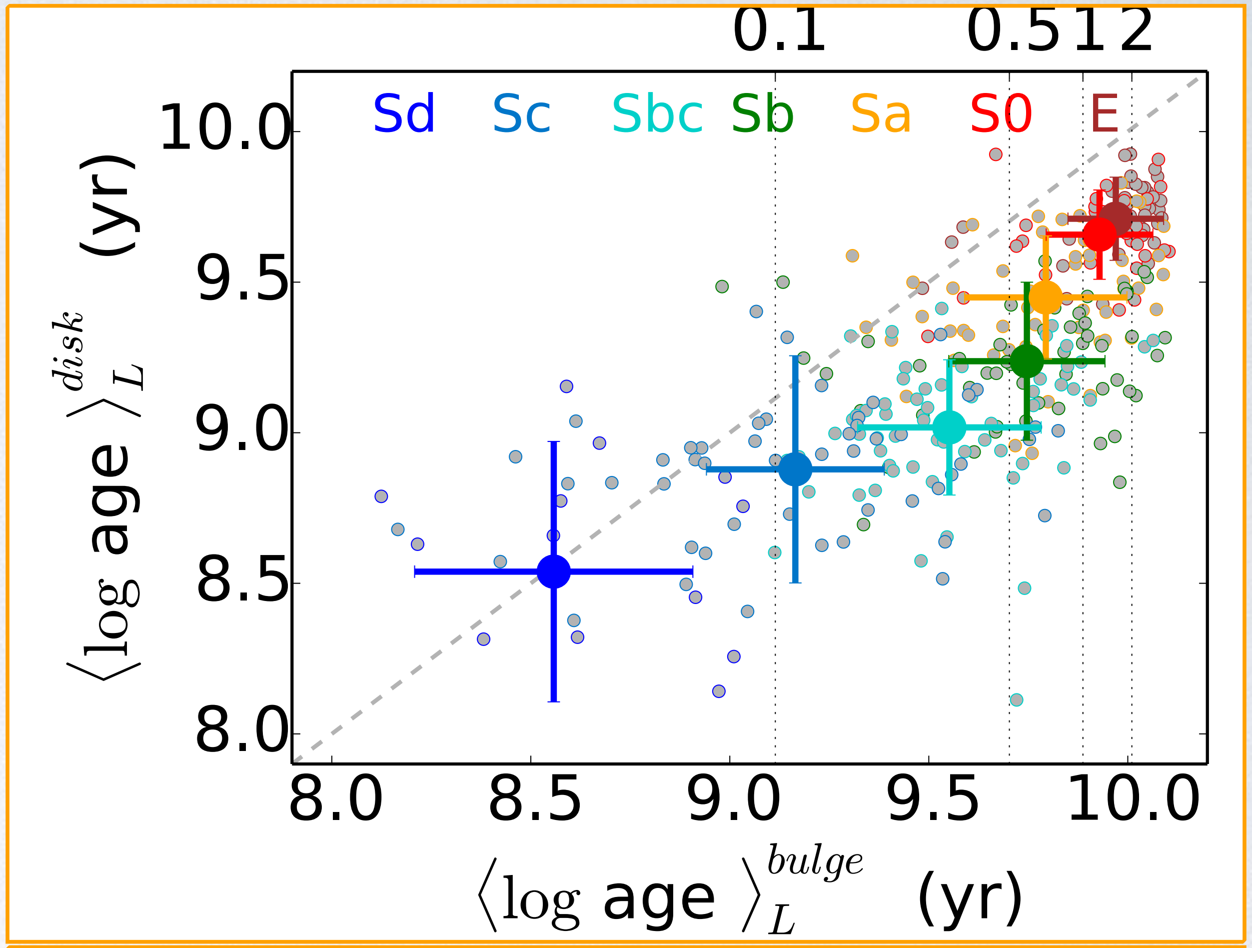
But the flattening beyond 2 HLR

Spirals: The mass was formed in a more uniformly distributed in disks beyond 2HLR

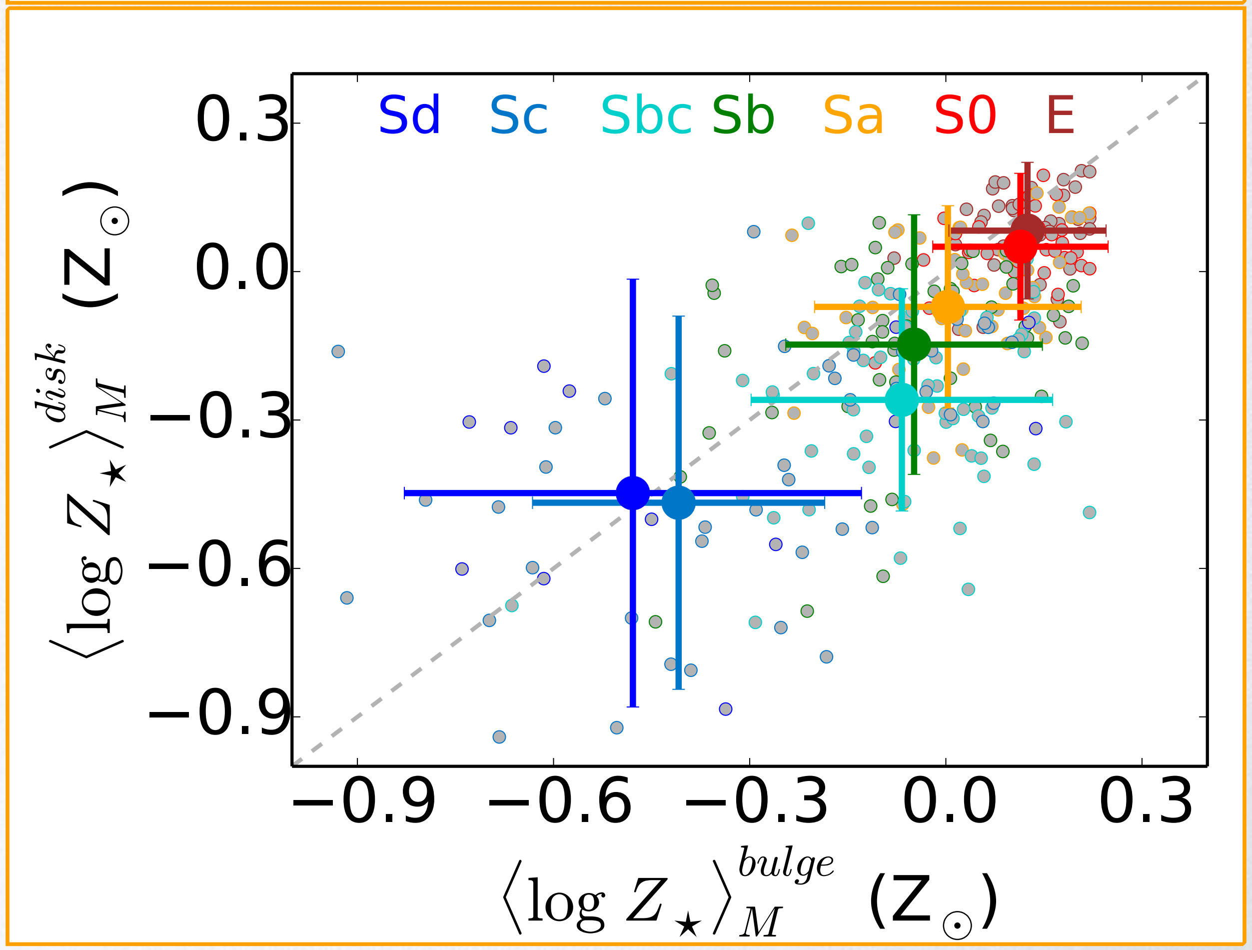
E's and S0's : the stellar mass was accreted at z≤ 1 outer of 2 HLR

Conclusions: Ages and metallicity in bulges and disks

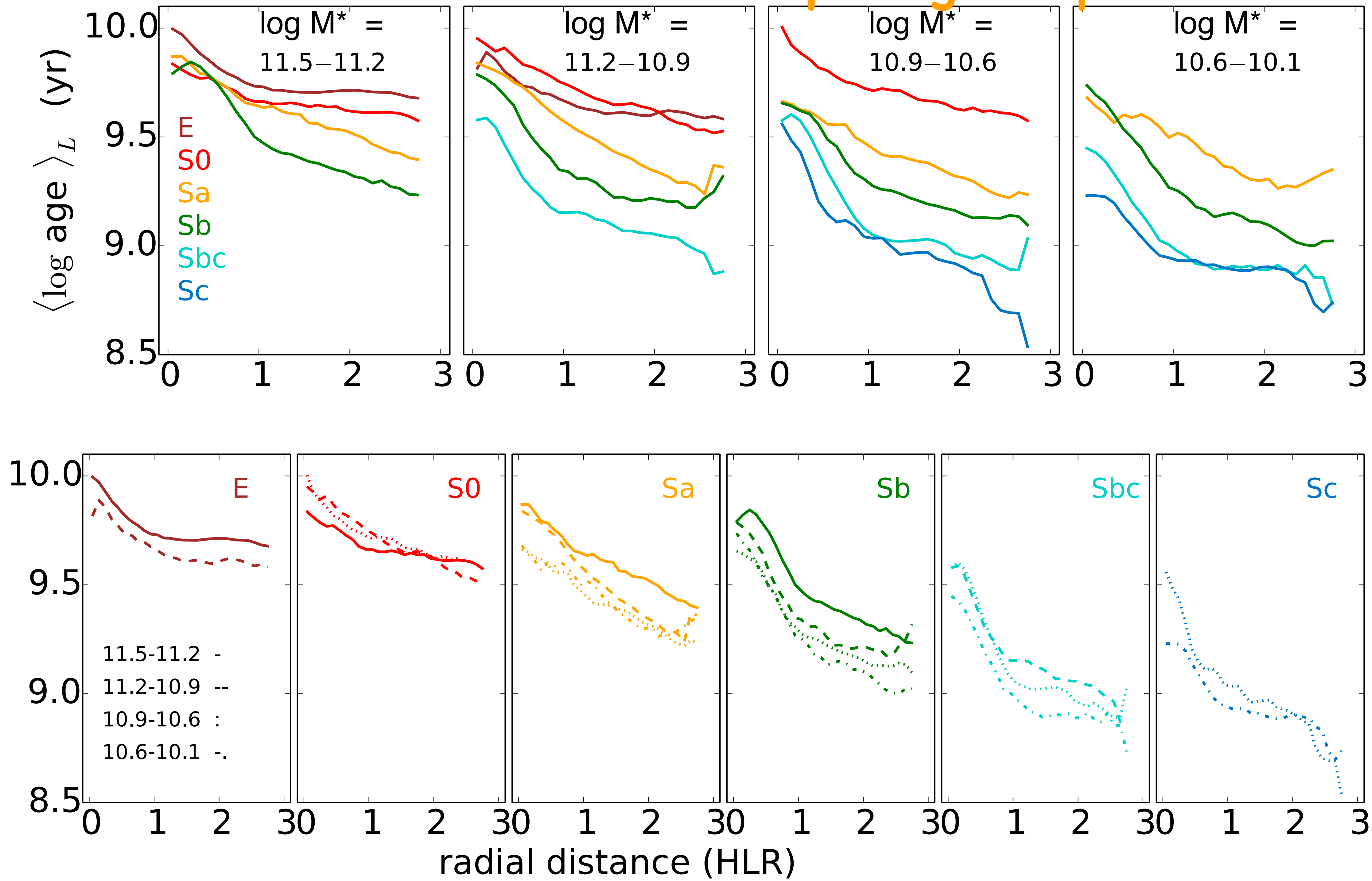




- The mean stellar ages of disks and bulge are correlated, late type spirals hosting the younger disks.
- Bulges of S0 and early type spirals are old and metal rich as the core of E's. They formed by similar processes, throughout mergers
- Late type spirals have younger bulges, and have larger contribution from secular evolution
- Disks are younger and more metal poor than bulges, as indicative of the inside-out formation scenario

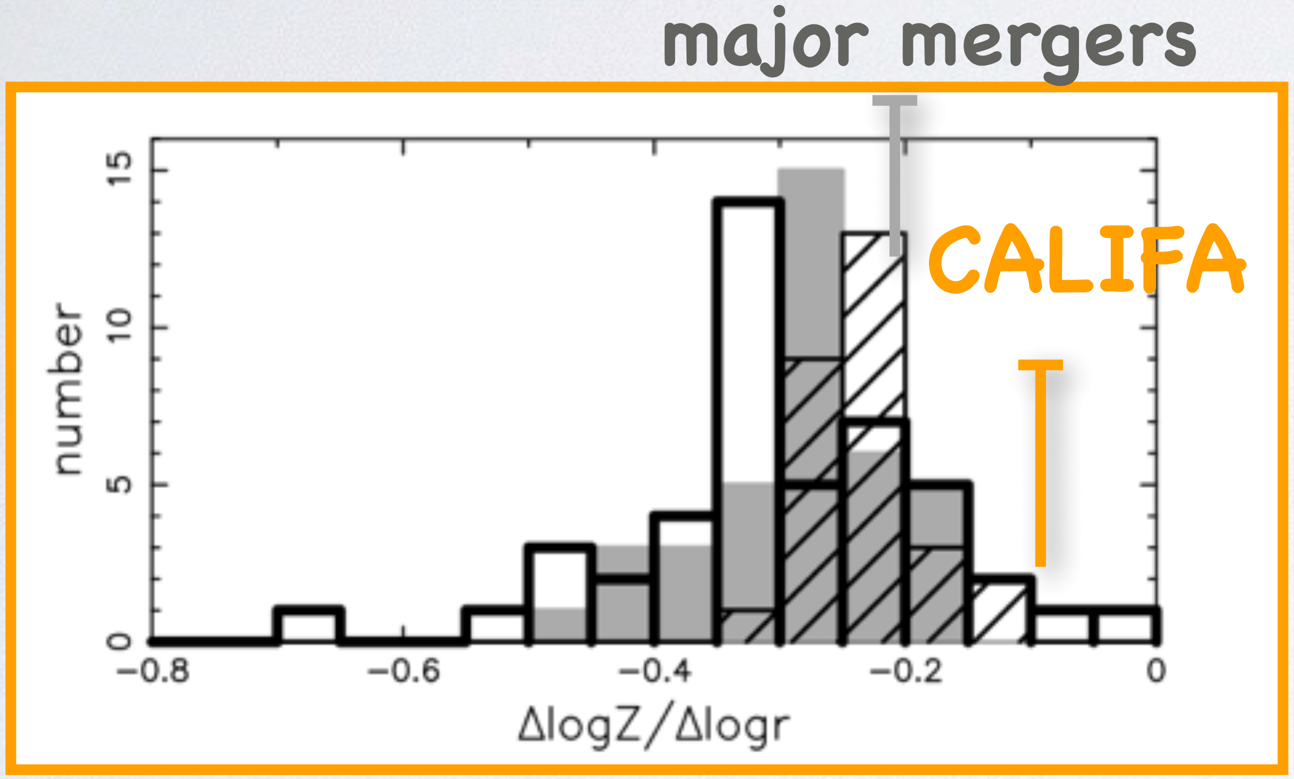


Conclusions: Galaxies are morphological quenched



- Galaxies of equal M⋆: have different galaxy averaged age, and radial age gradients.
- SFH and their radial variations are modulated primarily by galaxy morphology, and only secondarily M*.
- Galaxies are morphologically quenched, and that the shutdown of star formation occurs outwards and earlier in galaxies with a large spheroid than in galaxies of later Hubble type.

Cosmological simulations:
Comparing with CALIFA massive galaxies



e.g. GRAPE-SPH:
Chemodynamical simulations for elliptical galaxies
Kobayashi, 2004, MNRAS, 347, 740

Conclusions

- The radial profiles of the metallicity in E-S0 galaxies of our sample are relatively flat; $\nabla\langle \log Z_\star \rangle \sim -0.1$ [dex/dex]
- This points to major merger as relevant in the formation of central 2 HLR of E-S0 galaxies.
- In our results there is no evidence either of a inversion of ⟨log age⟩ toward older ages beyond 1−2 HLR, or of a steepening of the metallicity if these galaxies were growing in size through minor dry mergers in the central 2 HLR.
- Massive galaxies probably accreted massive satellites that were able to retain their metal rich gas against winds, producing flatter metal-licity gradients (Hirschmann et al. 2014).
- Alternatively, the flattening of the metallicity radial profile can result from the quenching of star formation. When this happens, the metal cycle stops and only stars of that last star formation event remain.

Cosmological hydrodynamical simulations for disk formation and classical chemical evolution models: Comparing with CALIFA spiral galaxies

Conclusions:

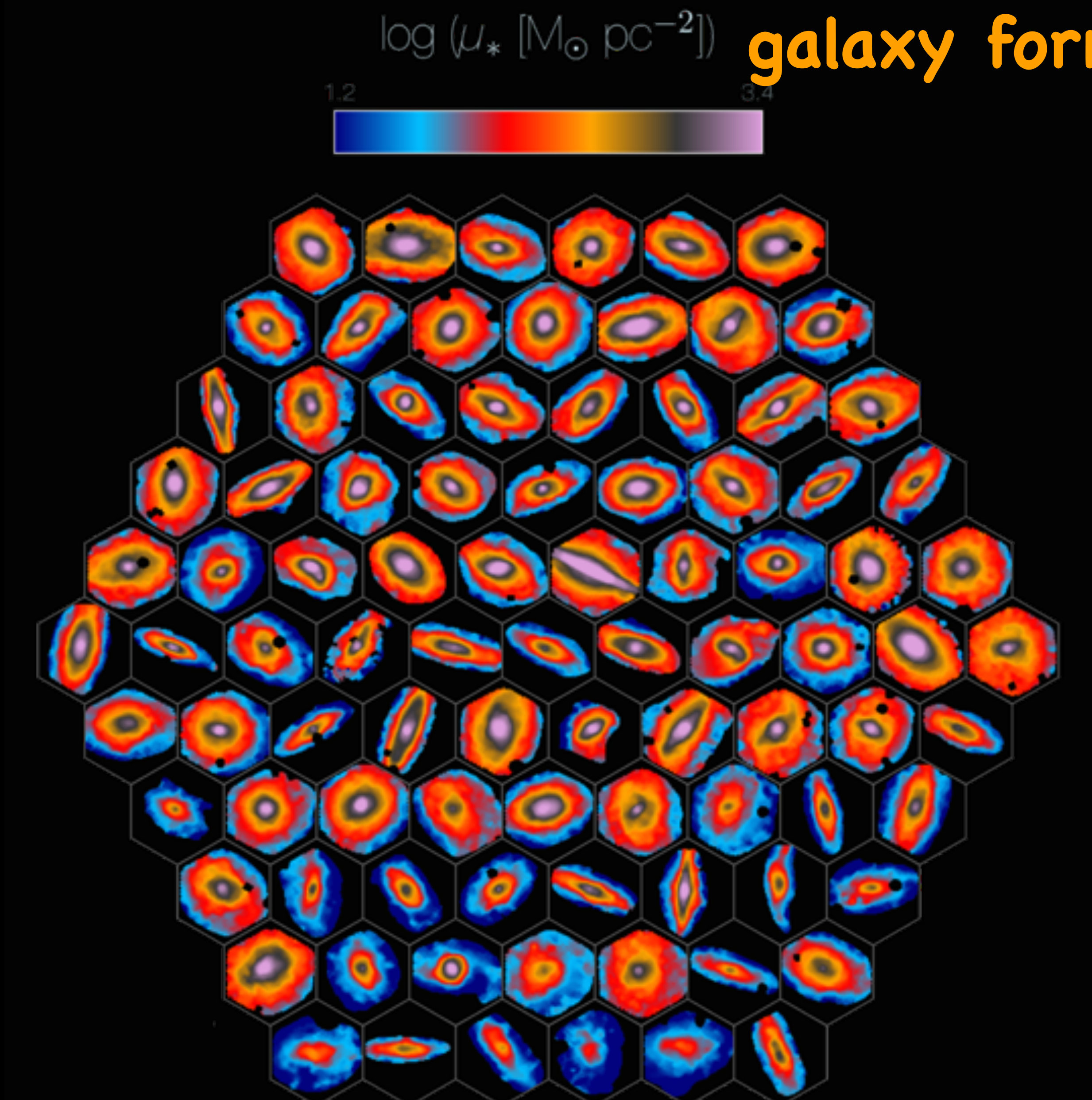
- The averaged metallicity gradient in the disk of spirals are flatter than the predictions by the classical chemical evolution models (Chiappini et al. 2001; Mollá & Díaz 2005, e.g), but are similar to those measured above the Galactic disk ($\nabla\langle \log Z_\star \rangle \sim -0.025$ [dex/kpc]).

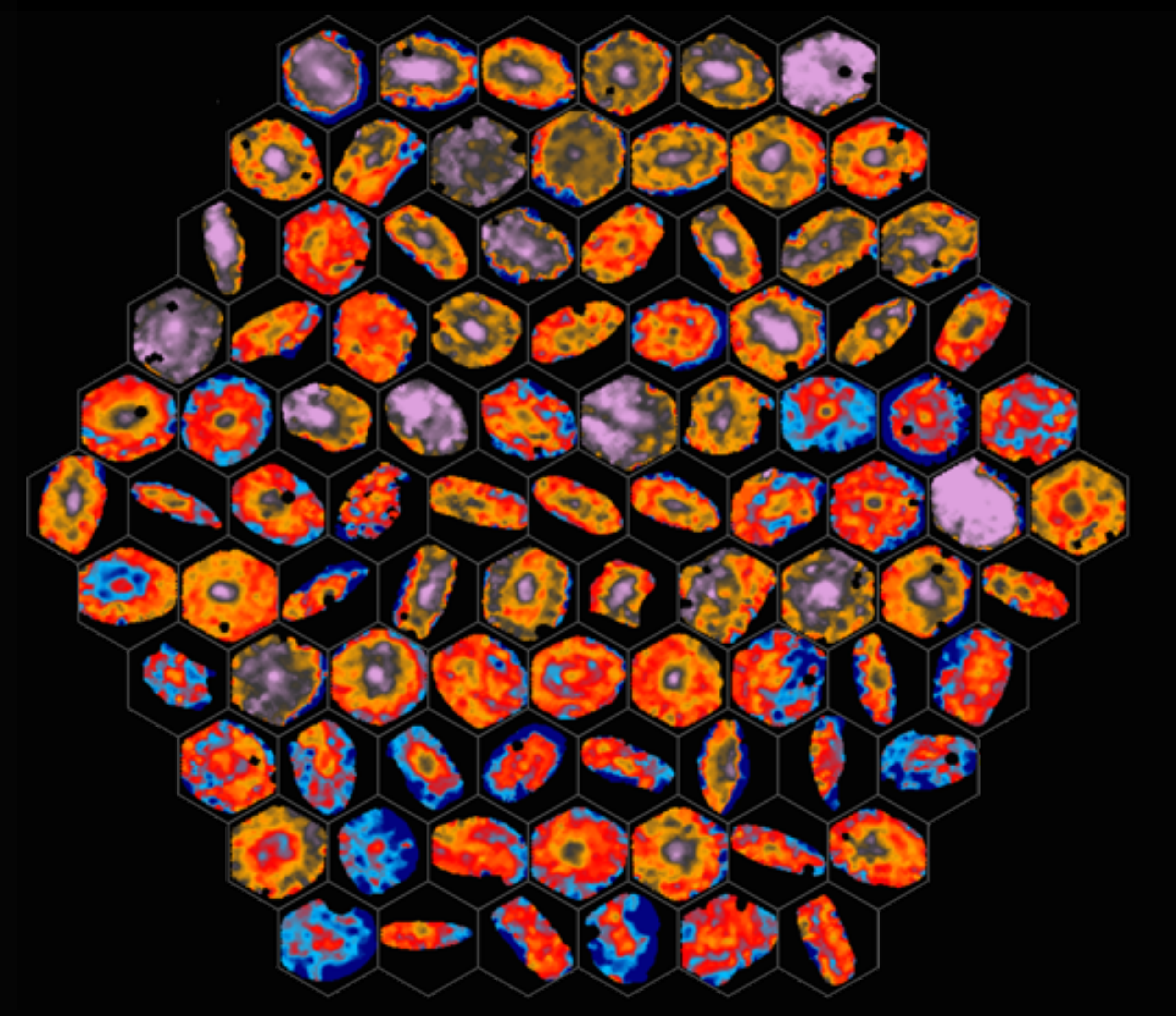
- The largest gradient happens in intermediate types and intermediate galaxy mass, as predicted by the Mollá & Díaz (2005) models.

- Sbc galaxies have a $\nabla\langle \log Z_\star \rangle \sim -0.1$ [dex/HLR] similar to the predictions by RaDES simulations (Few et al. 2012; Pilkington et al. 2012a).

- This indicates that the feedback recipes used in these simulations are able to recover realistic galaxies with small bulges.

The radial structure of the stellar density, ages and metallicity are linked to the Hubble type, and they provide useful constrains for galaxy formation models





✳WEAVE , IFU mode (fov = 2 sq. arcmin, with 1-2.5 arcsec/sparxel) to trace the stellar population of galaxies beyond 3 HLR in a large sample of galaxies covering all the Hubble type and range of stellar mass from 10^9 to 10^12 Msu give relevant clues for galaxy formation models

✳MaNGA and SAMI can not get which are limited by their fov and spatial resolution

CALIFA

Calar Alto Legacy Integral Field Area survey

- Pérez et al. 2013, ApJL, 764, L1
- Cid Fernandes et al. 2013, A&A, 557, 86
- Cid Fernandes et al. 2014, A&A, 561, 130
- González Delgado et al. 2014, A&A, 562, 47
- González Delgado et al. 2014, ApJL, 791, L16
- González Delgado et al. 2015, A&A, submitted.

- Data release (DR2) paper: García Benito et al. 2014, A&A, arXiv1409.8302