The Milky Way and its environment
Paris, 22th September 2016

Stellar population properties of disc galaxies in the local universe

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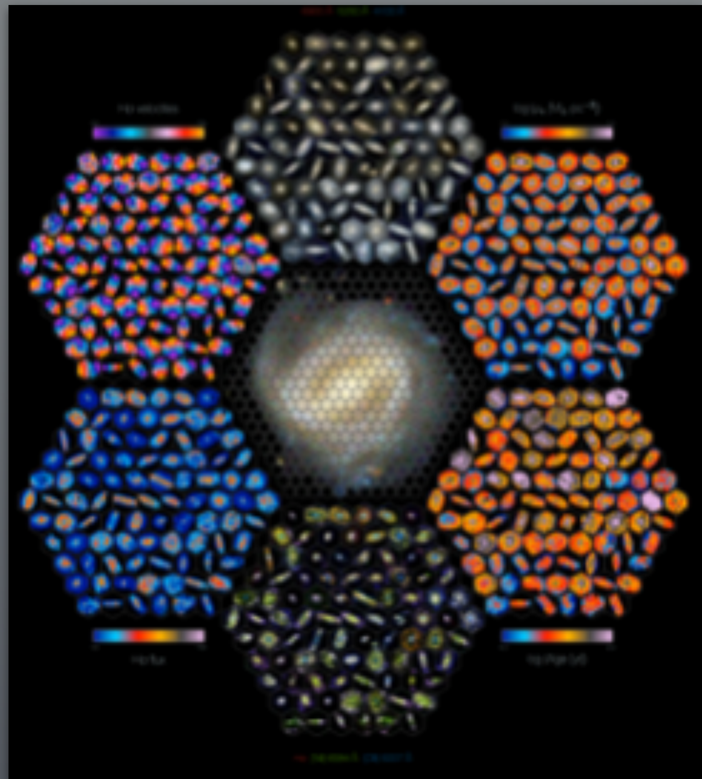
and Sebastian Sánchez (PI)
and the CALIFA collaboration

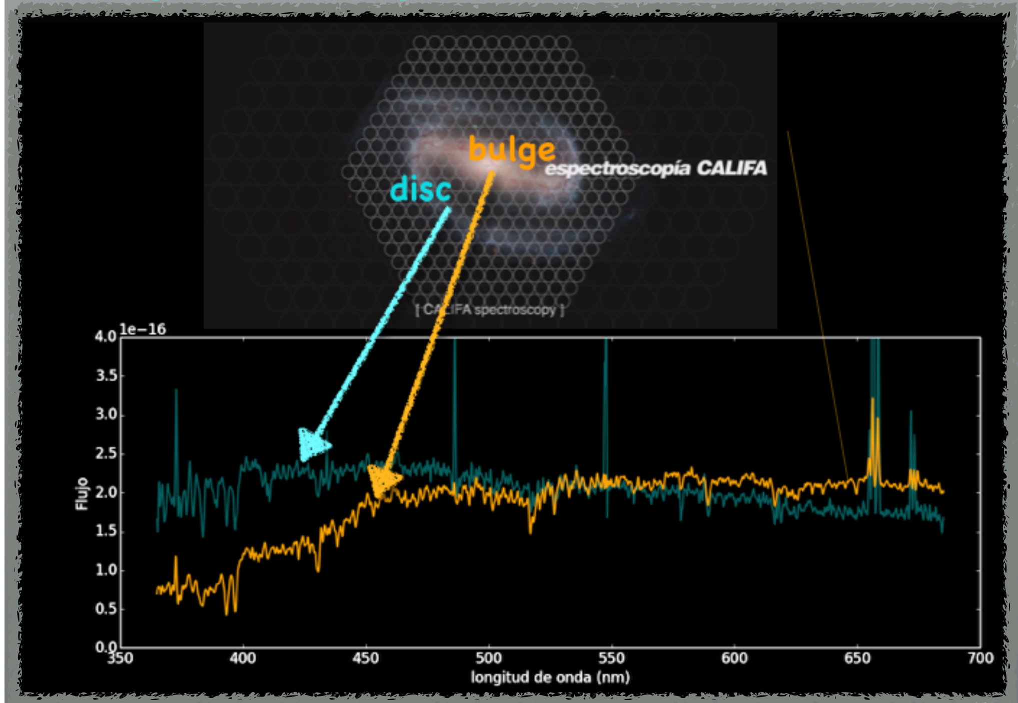
Spatial Resolve Stellar Population Properties

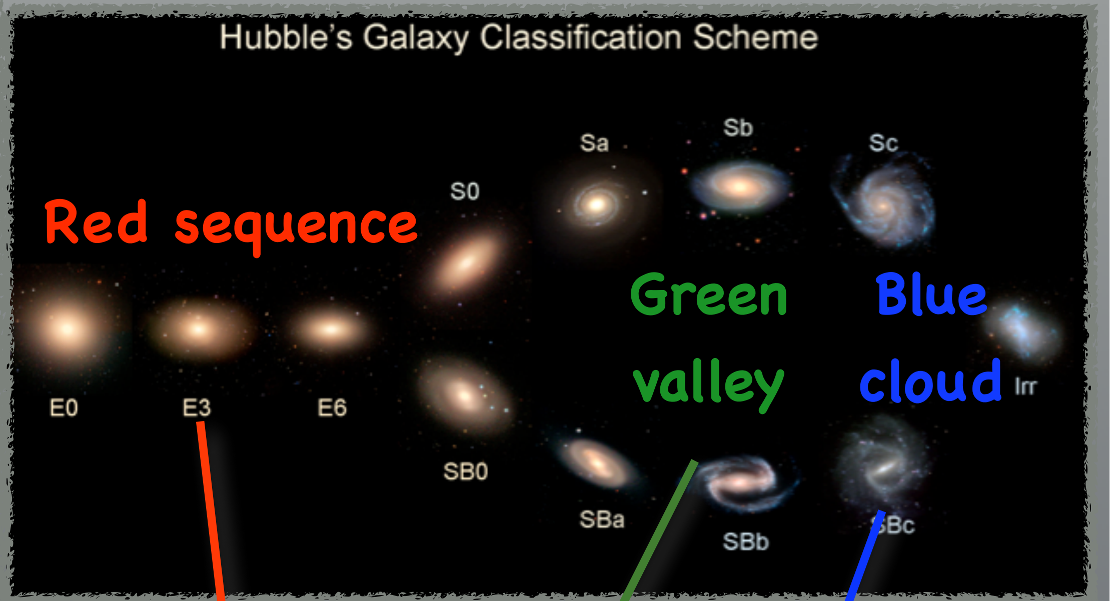


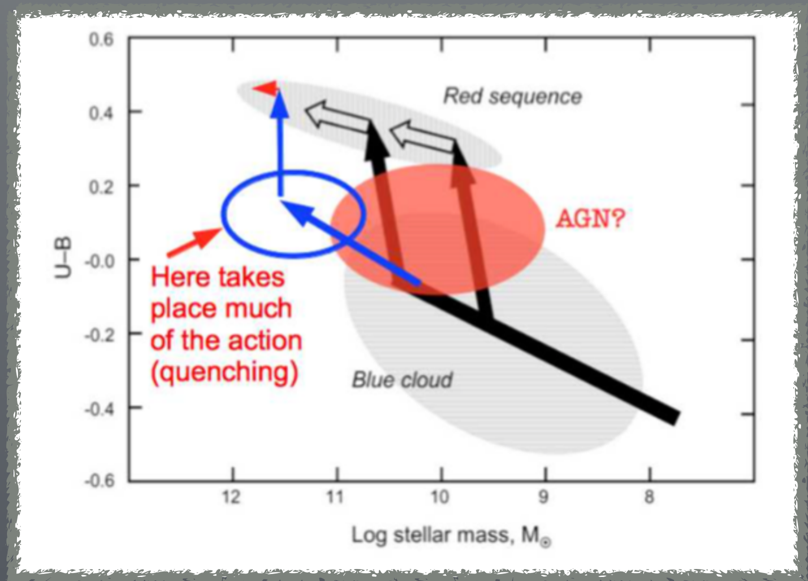
García-Benito et al. 2015, A&A, 576, 135

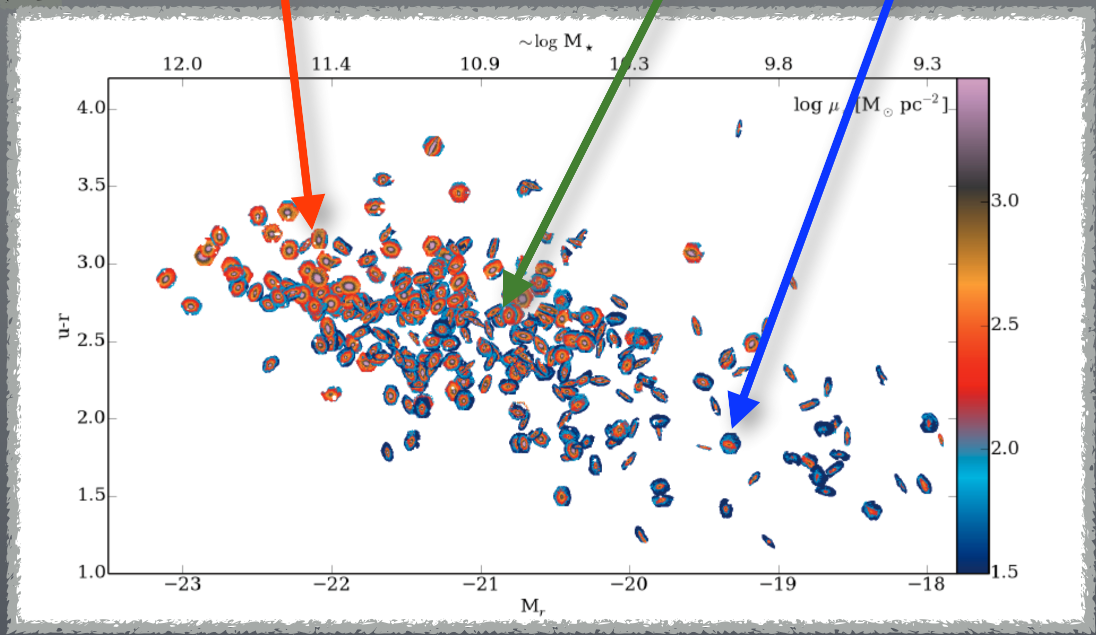
IFS to spatial resolve galaxies in their components:

to gain insights into the drivers of galaxy formation and evolution









Are global and/or local processes responsible of driving the evolution of galaxies?

Global relations

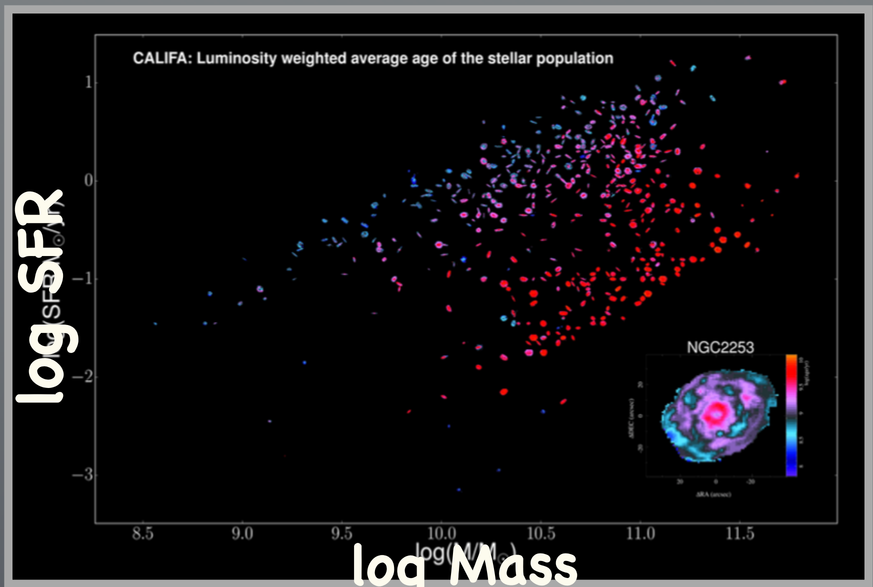
- * Mass-Metallicity
- * Mass-SFR
- * Mass-age

Local relations

- * $\mu\star$- local Z
- * $\mu\star$- Σ_{SFR}
- * $\mu\star$- local age

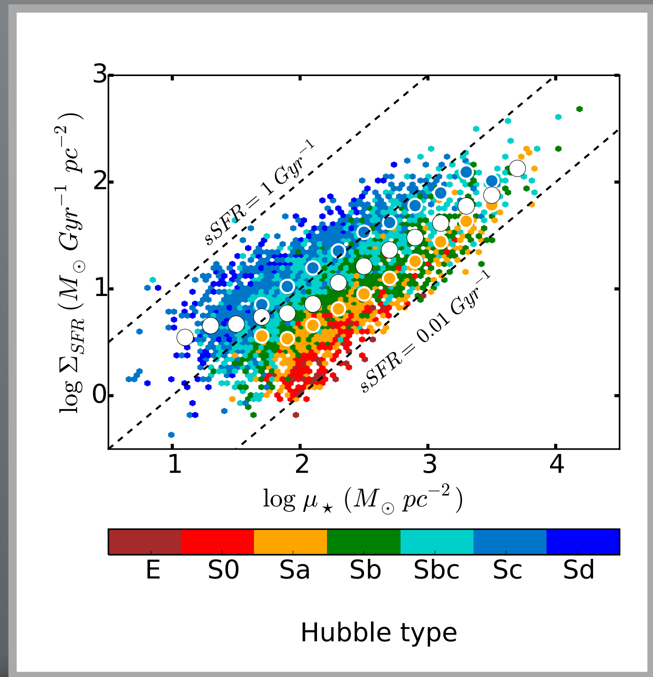
Main sequence of Star Formation (MSSF)

Global MSSF



Sánchez & CALIFA DR3, 2016

Local MSSF



González Delgado +, 2016

IFS surveys for nearby universe

Specification	MaNGA	SAMI	CALIFA	Atlas3D
Sample Size	10,000	3,400	600	260
Selection	$M > 10^9 M_\odot$	$M > 10^{8.2} M_\odot$	45" $< D_{25} <$ 80"	E/S0 $M > 10^{9.8} M_\odot$
Radial coverage	$1.5r_e$ (2/3), $2.5r_e$ (1/3)	1-$2r_e$	$>2.5r_e$	$<1r_e$
S/N at $1r_e$	15-30	10-30	~30	15
Wavelength range(Å)	3600-10300	3700-7350	3700-7500	4800-5380
Instrumental resolution	50-80 km/s	75/28 km/s	85/150 km/s	105 km/s
Input Spaxel Size	2.0″	1.6″	2.7″	1″
Input Spaxels per object	<3×127[1]	3×61	3×331	1,431
Spatial FWHM	2″	2″	2.5″	1.5″
Telescope size	2.5m	3.5m	3.5m	4.2m

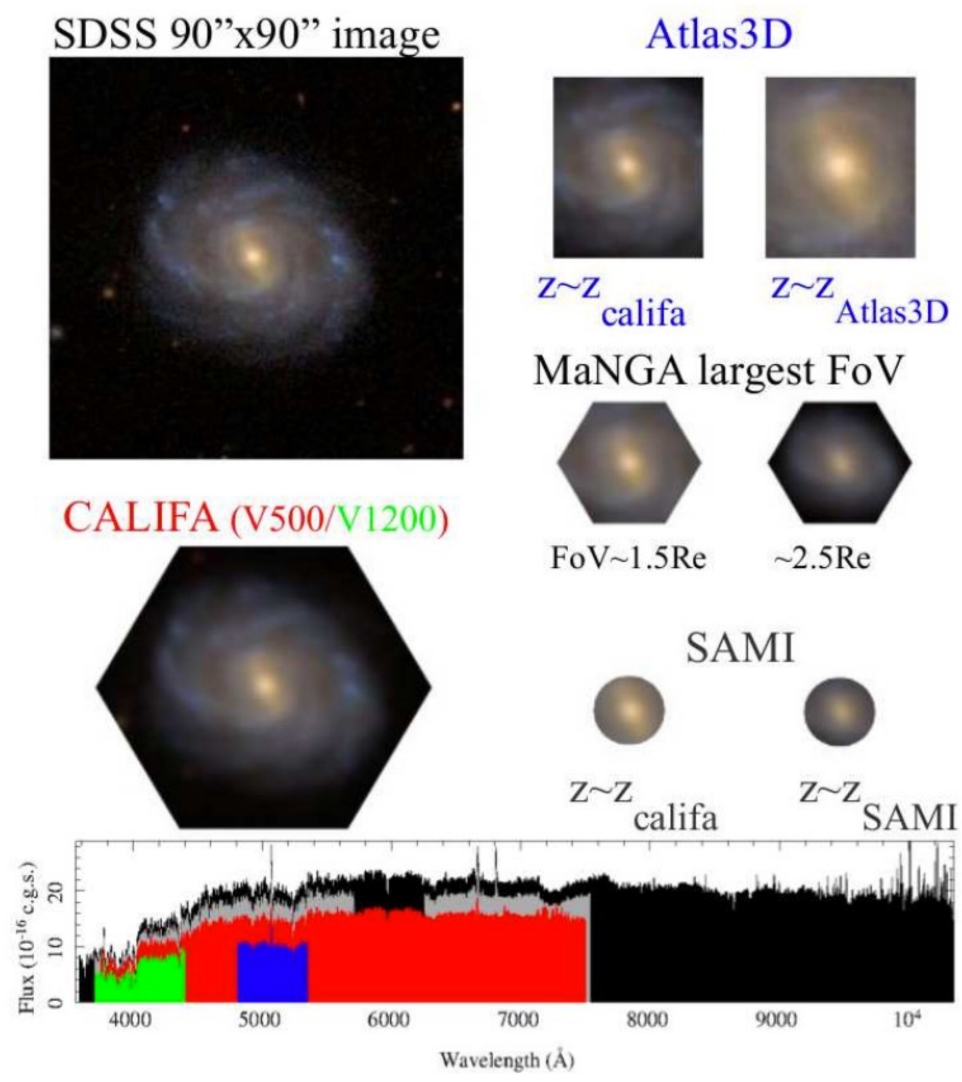
- ATLAS3D: Cappellari et al. 2011
- CALIFA: Sánchez et al. 2012
- SAMI: Croom et al. 2012
- MaNGA: Bundy et al. 2015

CALIFA
2x3x331 spaxels; 2.7"/spaxel
600 galaxies of any type
~1.200.000 spec.; 3700-7500 Å

Atlas3D
1577 spaxels; 0.94"/spaxel
260 ETGs
~400.000 spectra; 4810-5350 Å

MaNGA
3x(19-127) spaxels; 2"/spaxel
7000 gal. of any type (~1.5Re)
2000 gal. of any type (~2.5Re)
1000 gal. of any type (any Re)
~800.000 spec.; 3550-10000 Å

SAMI
9x61 spaxels; 1.6"/spaxel
3400 galaxies of any type
~1.900.000 spec.; 3700-9500 Å

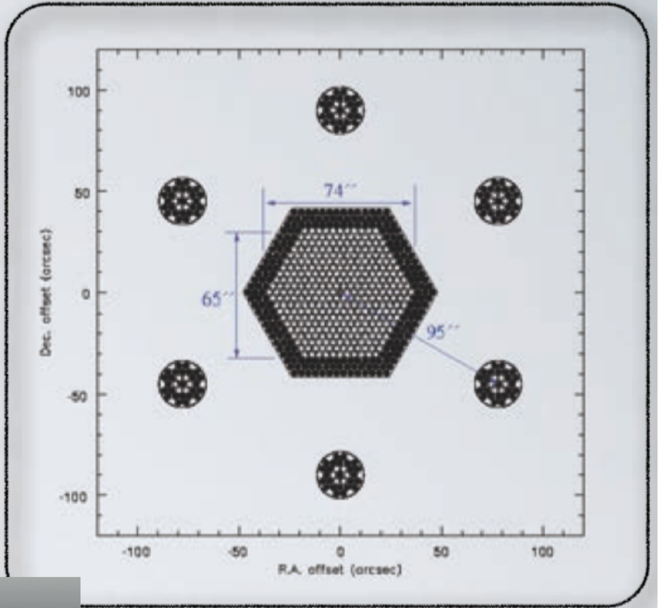


Sánchez et al. 2014

600 galaxies

0.005 < redshift < 0.03

Large homogeneous sample



E, S0, Sa to Sd

937 galaxies
Mother sample

Calar Alto Legacy Integral Field Area

Large FoV (1'x1')

FoV (>2.5 HLR)

λ range:
3700-7000 Å

Fibers 2.7 arsec
~ 0.5 - 1 kpc

Cover optical λ

PPAK at 3.5m CAHA

V1200@R = 1650
V500@R = 850

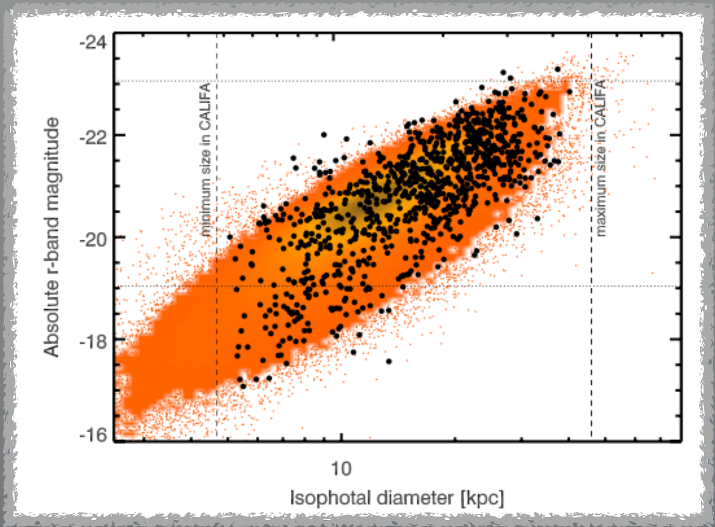
3 dithering:
final 1 arsec
sampling

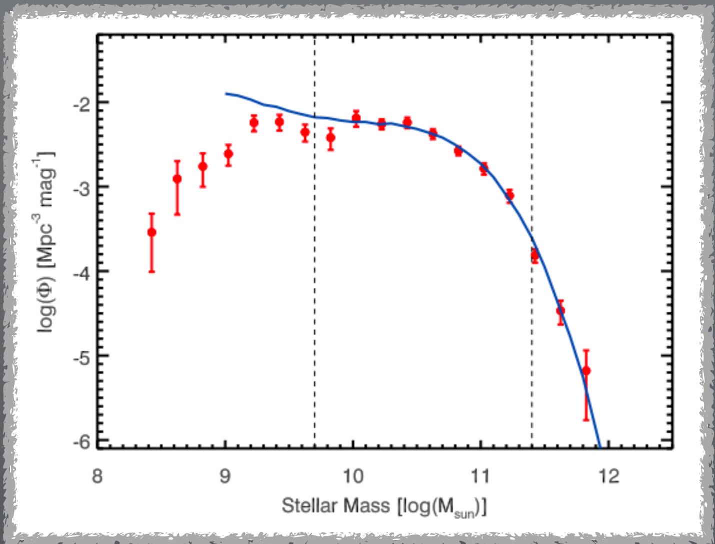
Properties of CALIFA sample

Walcher +, 2014, A&A, 569, A1

Mother sample

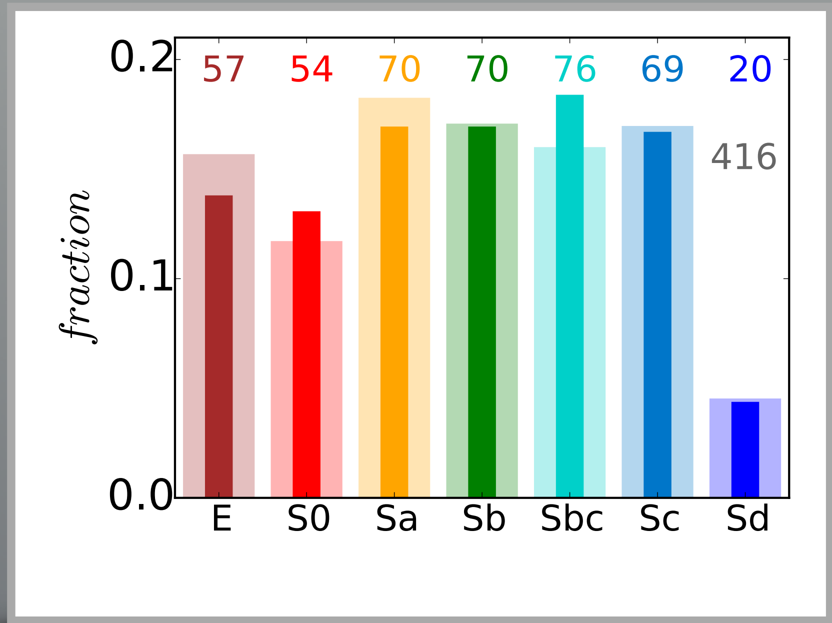
- 937 galx SDSS DR7
- 0.005 < z <0.03
- 45" < isoAr < 79.2"

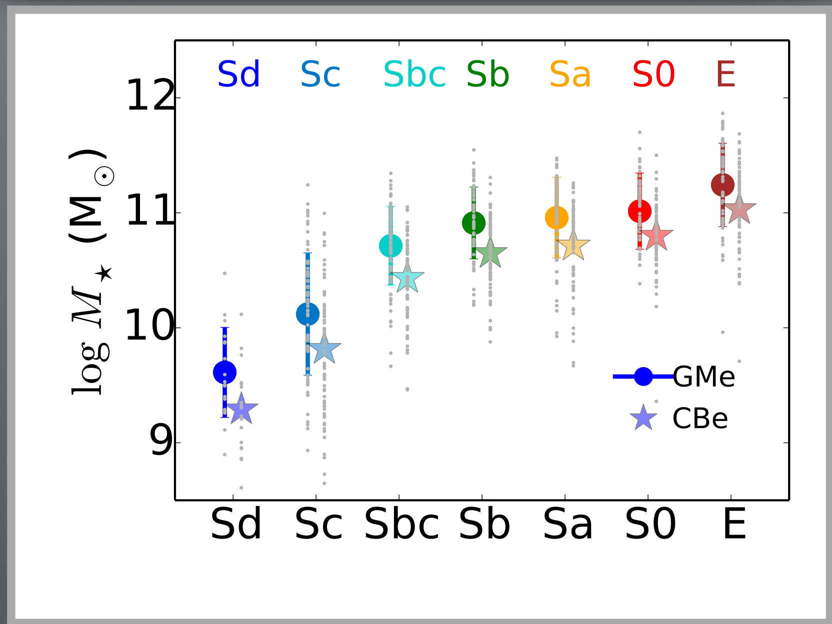




sub-sample in SP studies

- ~430 galx with V500+V1200

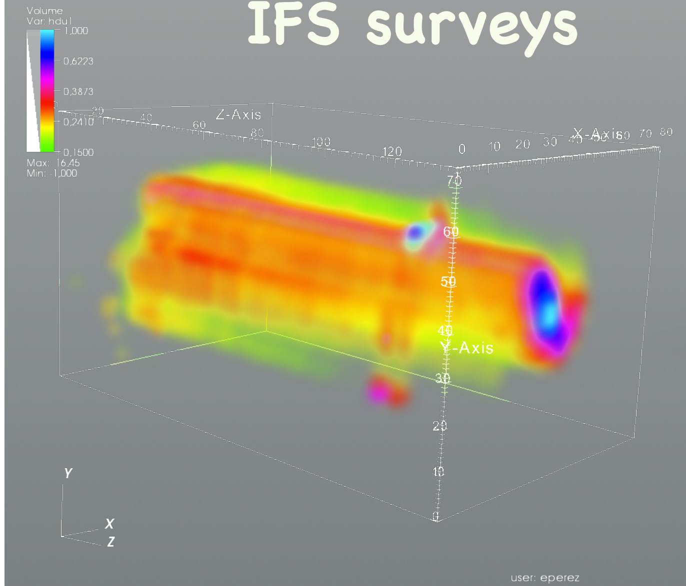




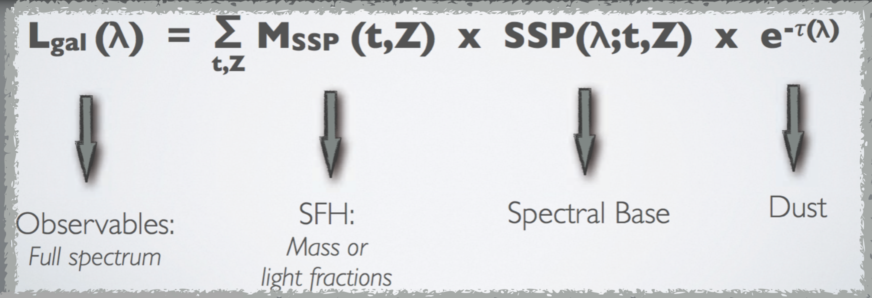
Galaxies in 3D

To dissect galaxies in space and time: 2D spatial and lookback time

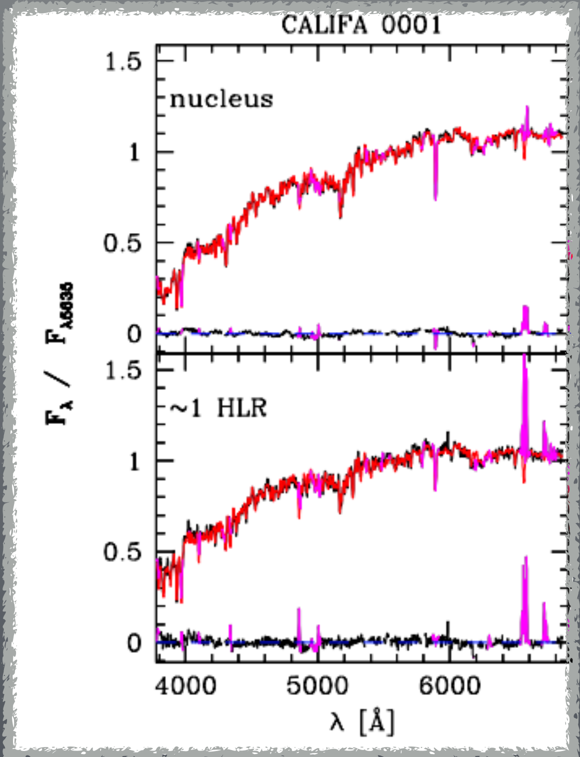
IFS surveys

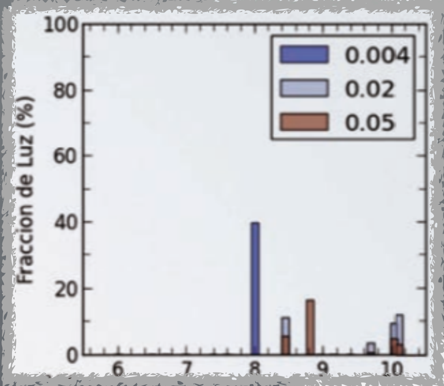


Fossil record method

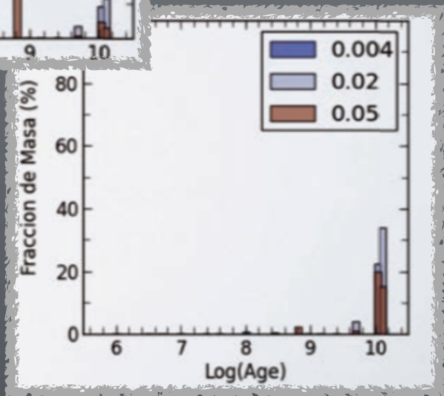


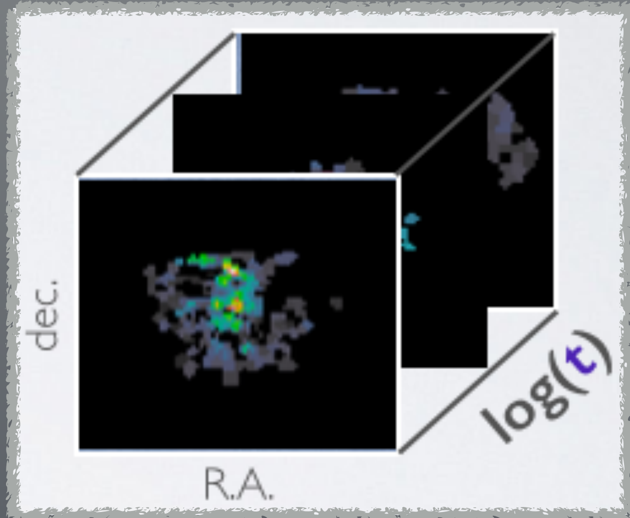
space-time cube



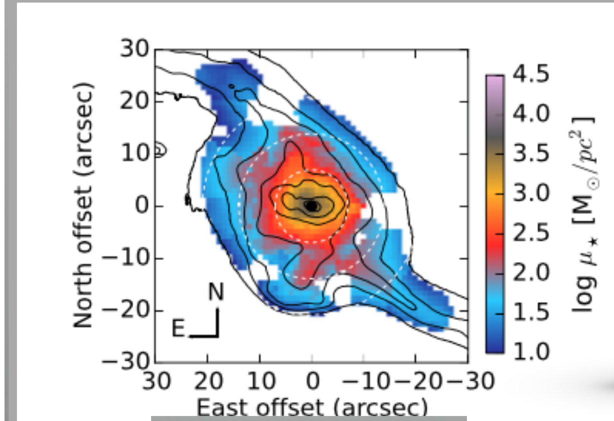


Light and Mass fraction

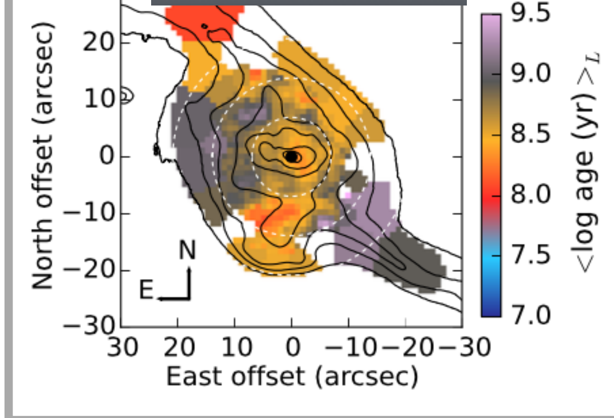


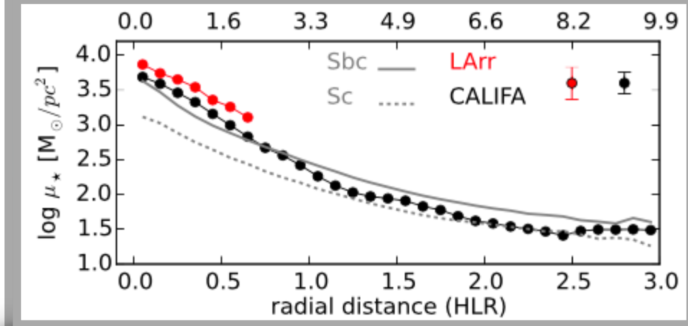


μ★, M★, ages, Z, Av, SFR

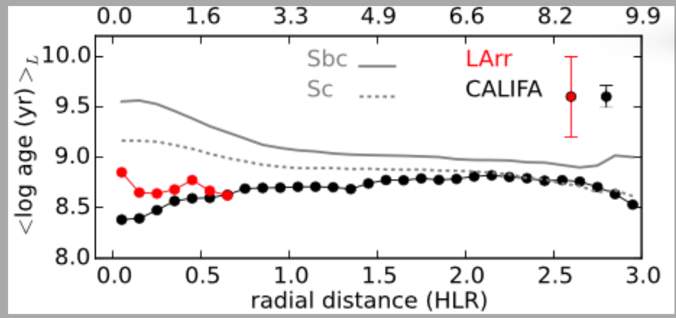


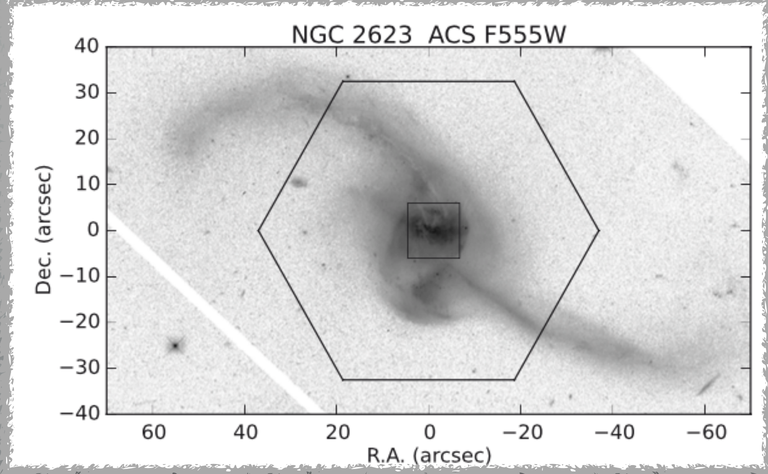
2D maps





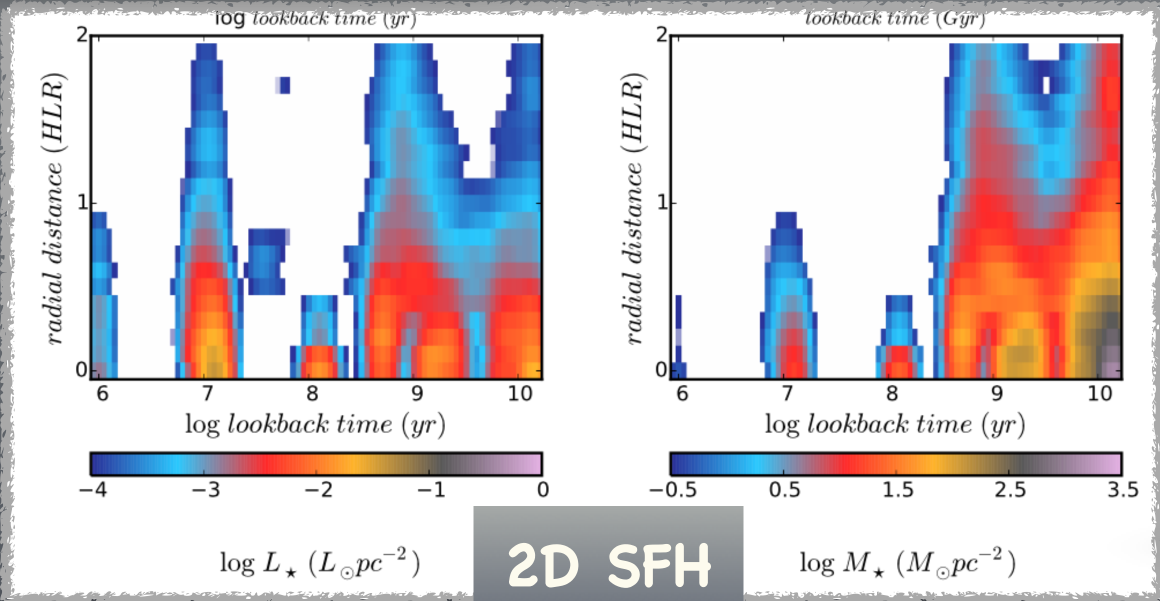
Radial Profiles





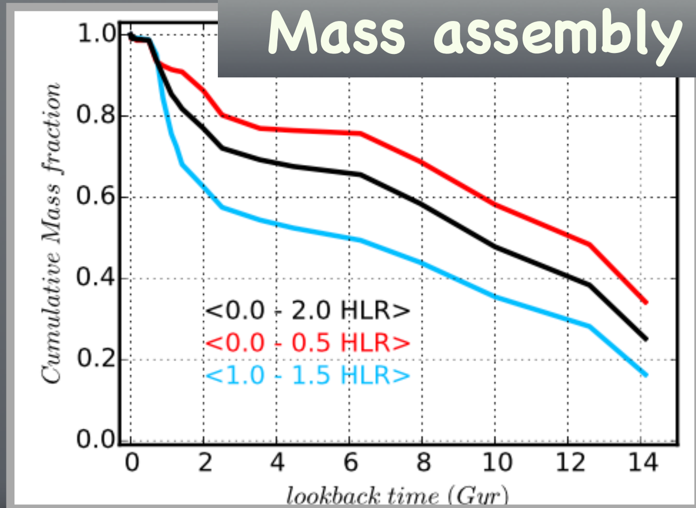
NGC2623

Radial x lookback time



2D SFH

Mass assembly



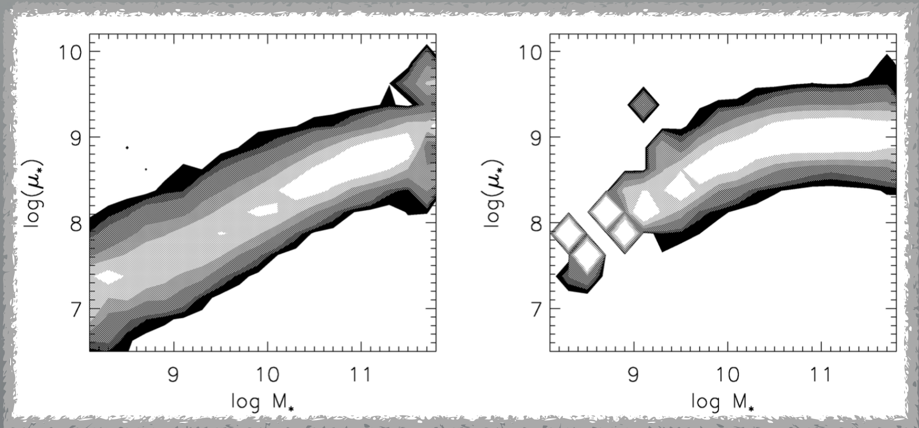
Cortijo Ferrero et al. 2016, MNRA

Stellar mass surface density (μ★)- age

Global relation

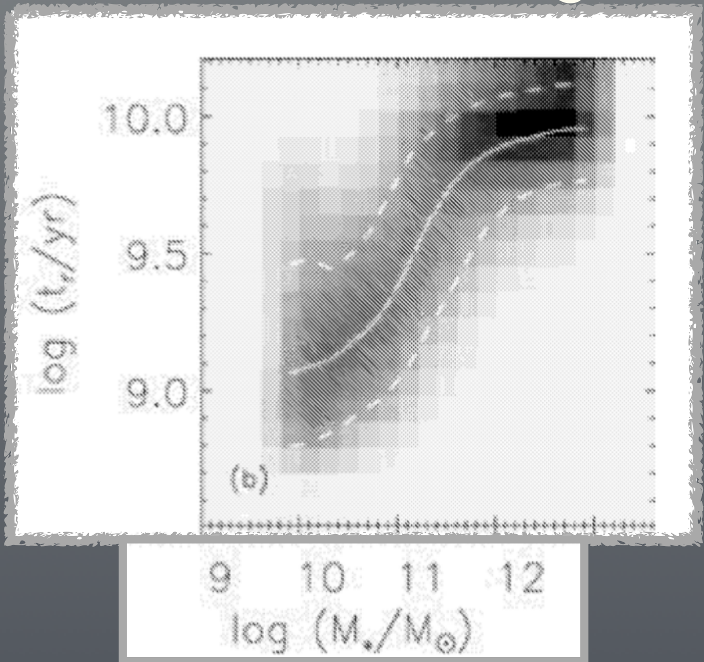
Kauffmann +, 2003

* SDSS: μ★ - M★



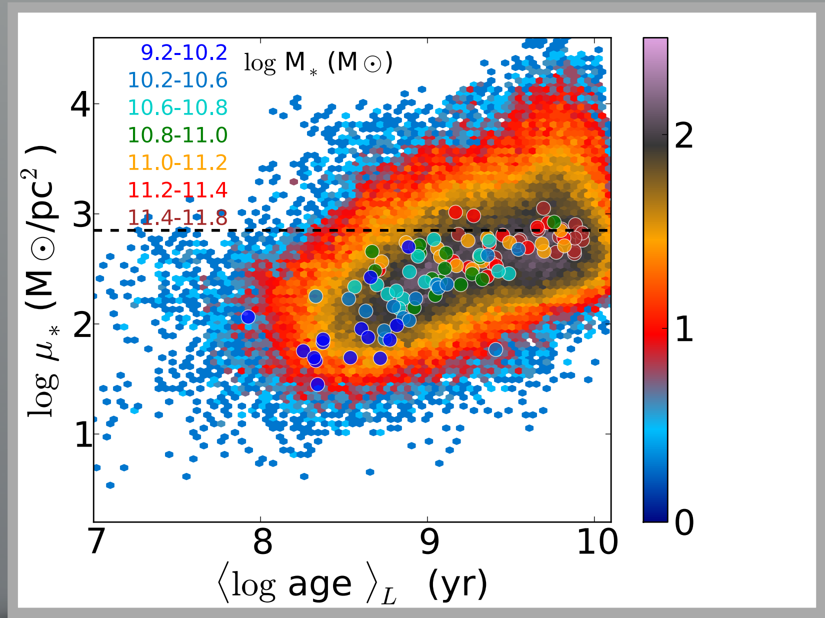
* SDSS: M★ - age

Gallazzi +, 2005



Local relation

* CALIFA: μ★ - age



González Delgado +, 2014, A&A, 562, 47

SFH in disks and spheroids

- Disks: μ★ drives the ages (SFH) of galaxies
- Spheroids: M★

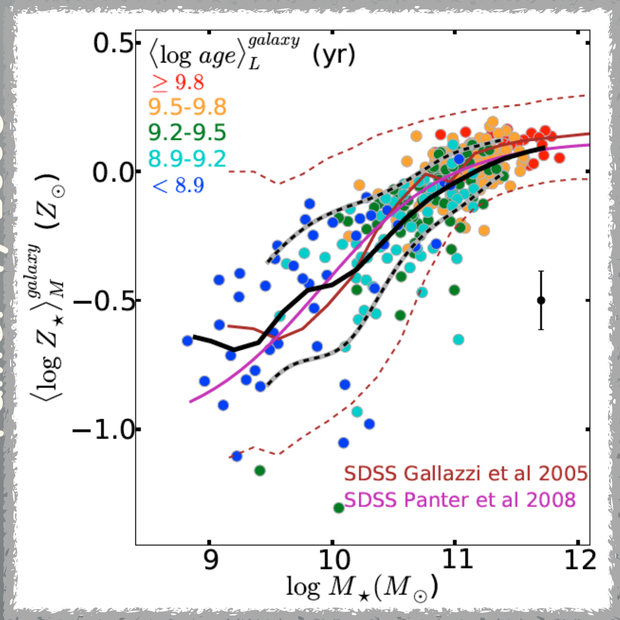
Stellar mass surface density ($\mu\star$)- Metallicity ($Z\star$)

Global relation (SDSS)

SDSS: global $M\star$ - $Z\star$

Gallazzi +, 2005

Panter +, 2008



Local relation

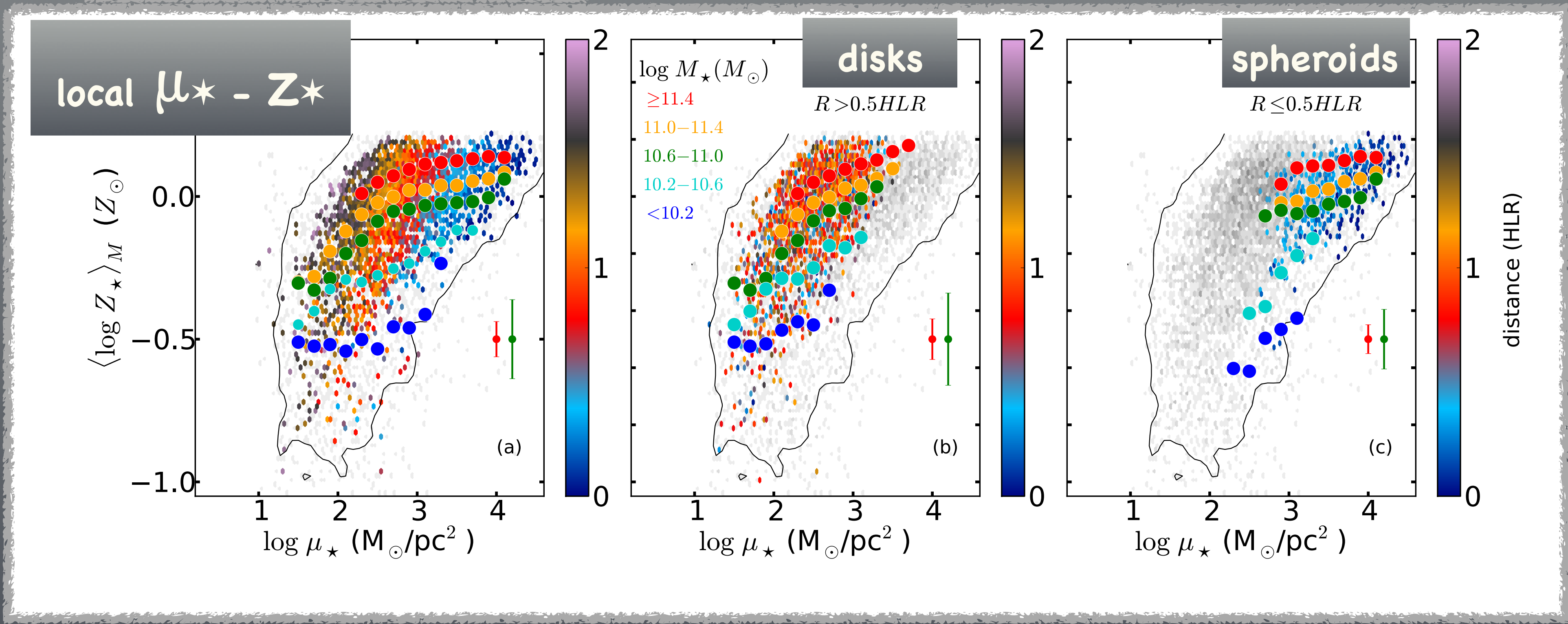
* CALIFA: $\mu\star$ -$Z\star$

Chemical enrichment

✳Disks: $\mu\star$ regulates the metallicity, galaxy Mass modulates the amplitude

✳ Spheroids: galaxy Mass dominates the physics of chemical enrichment (except for low mass galaxies)

González Delgado et al. 2014b, ApJ, 791, L16

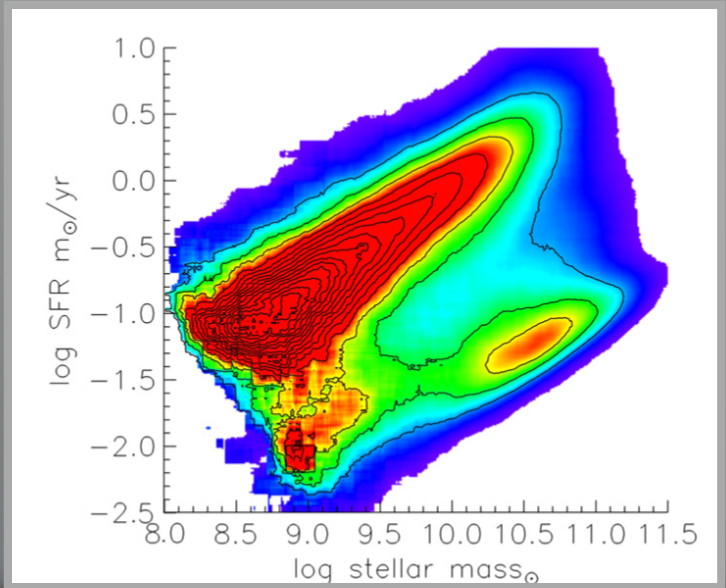


$\mu_\star$-intensity of the SFR: $\mu_\star$ - Σ_{SFR}

Global relation

* SDSS: $M_\star$ - SFR (MSSF)

Renzinni & Peng, 2015

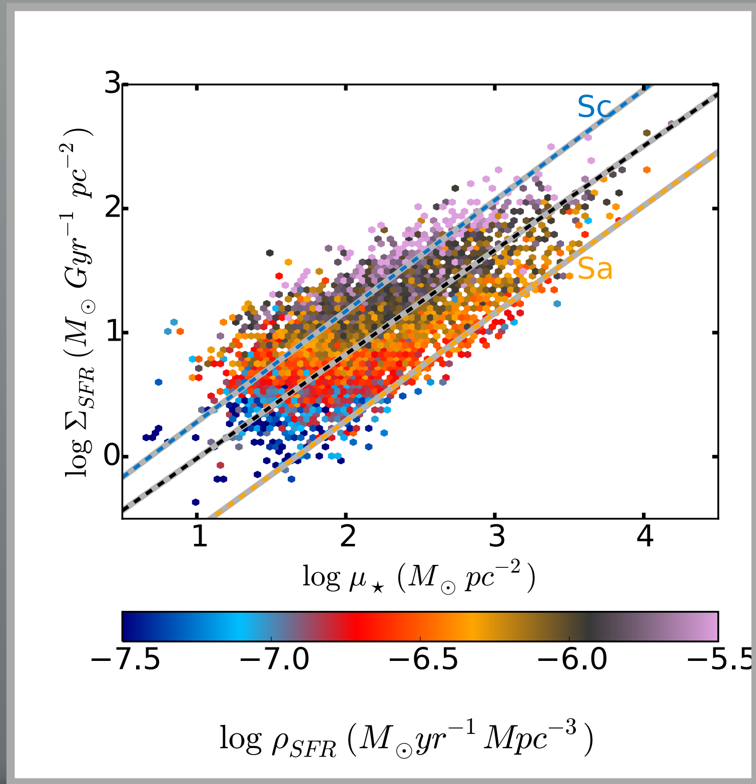


SFR = cte $M_\star^{\beta}$ with β < 1 (0.75 in RP2015)

* SFR = cte $\Sigma_{SFR}(HLR)/\mu_\star(HLR)\ M_\star$
* Σ_{SFR} = cte $\mu_\star^{\alpha}$
* $\mu_\star$ = cte $M_\star^{\gamma}$
* SFR = cte $M_\star^{1-\gamma(1-\alpha)}$
* with α = 0.8; γ = 0.5; β < 1

Local relation

* CALIFA: $\mu_\star$ - Σ_{SFR}



González Delgado +, 2016, A&A, 590, 44

Σ_{SFR} = cte $\mu_\star^{\alpha}$ with α = 0.8

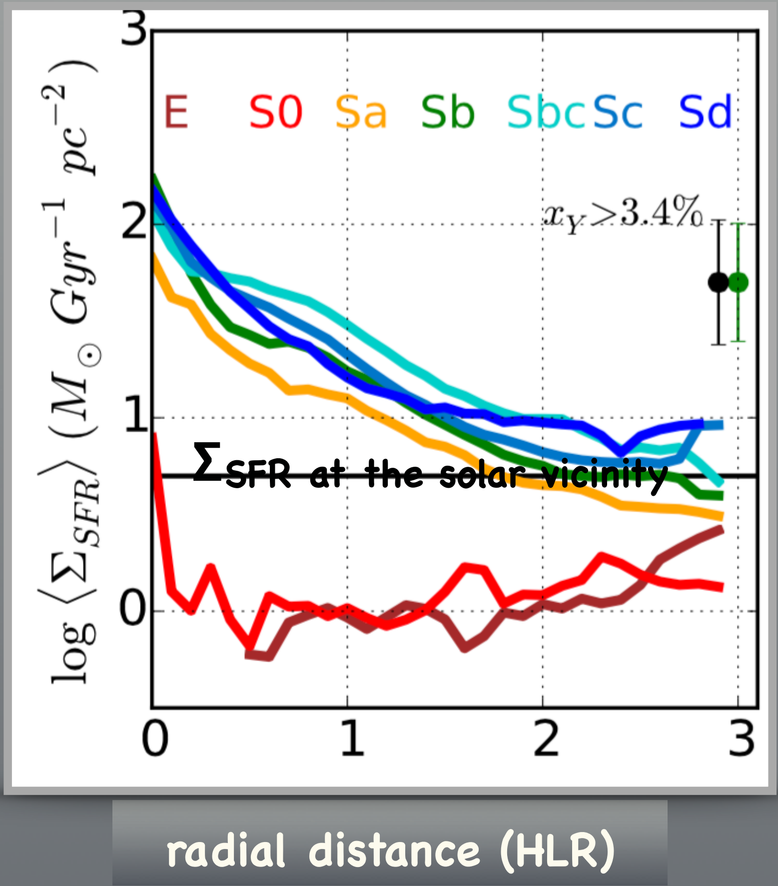
cte = local sSFR= $\Sigma_{SFR}/\mu_\star$

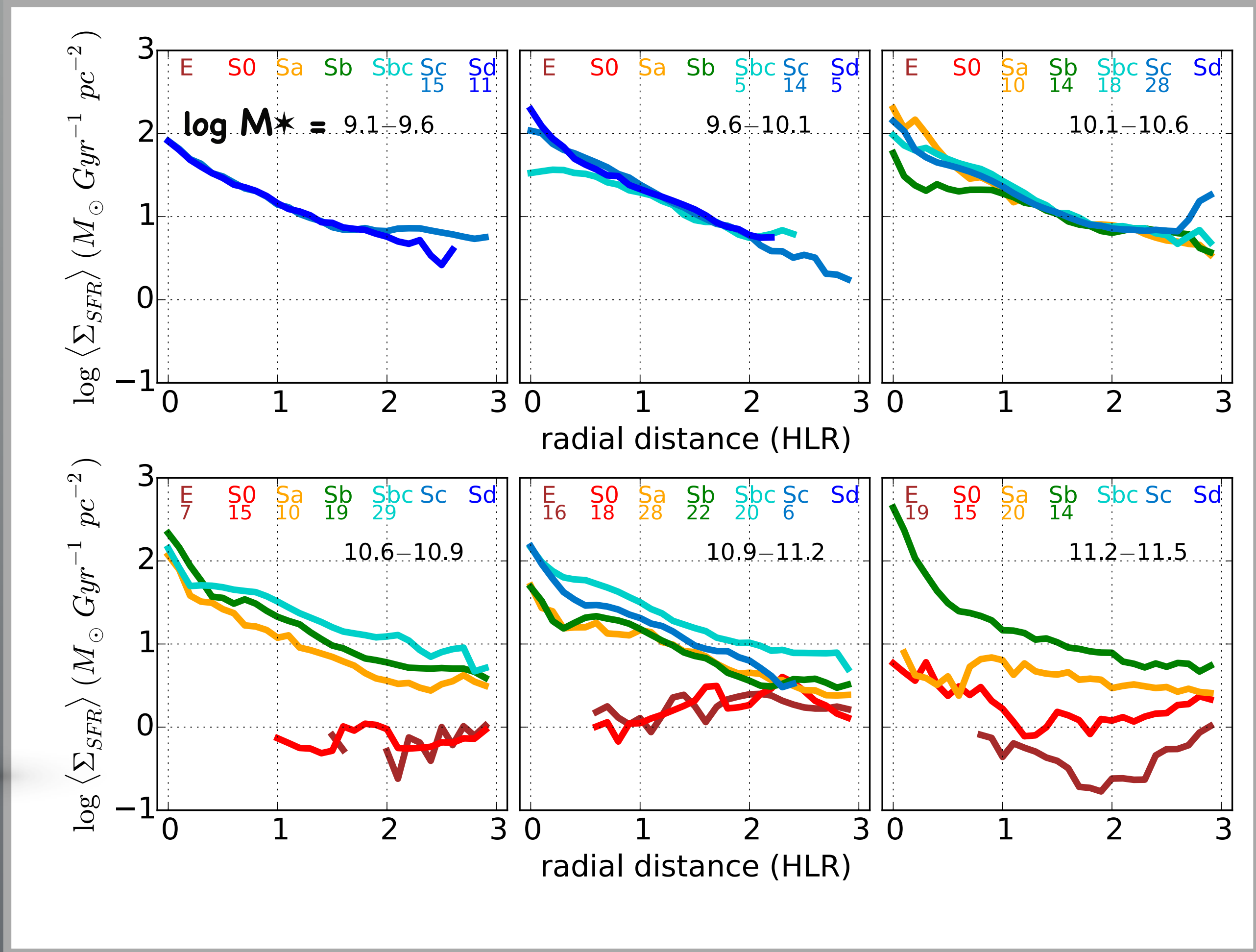
increases for early to late type spirals

Global relation is sub-linear (< 1)
because the sub-linearity of the local relation

Star formation along the Hubble sequence

Radial profiles: Σ_{SFR}



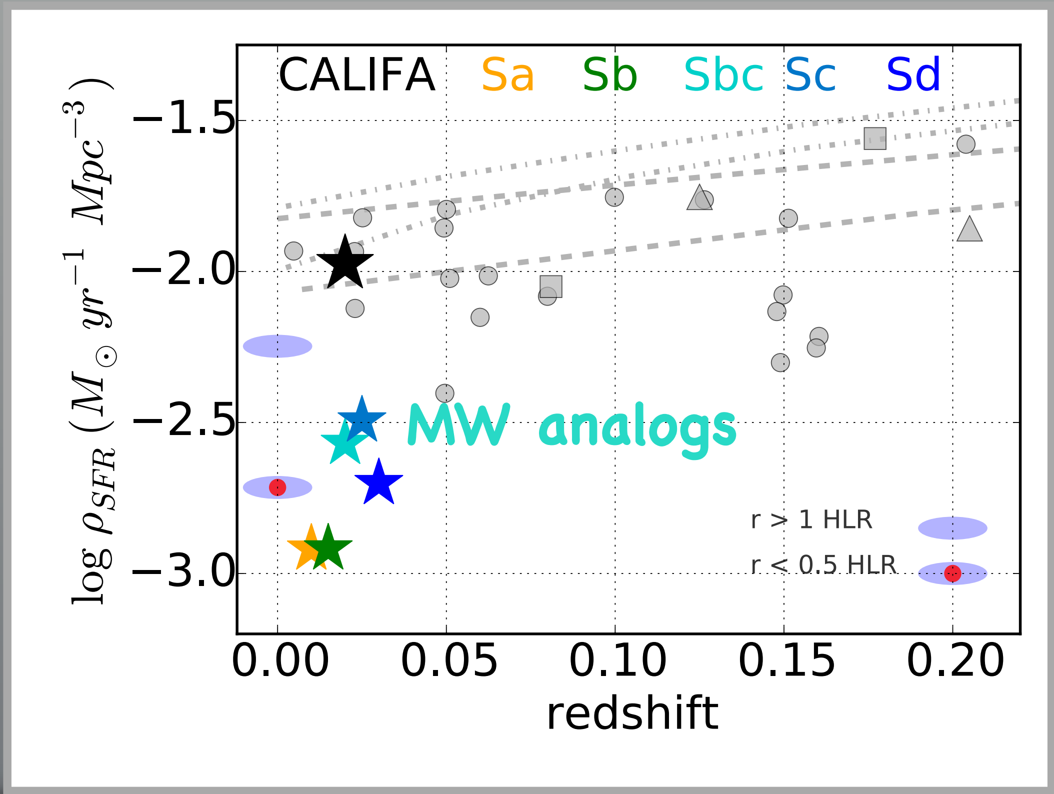


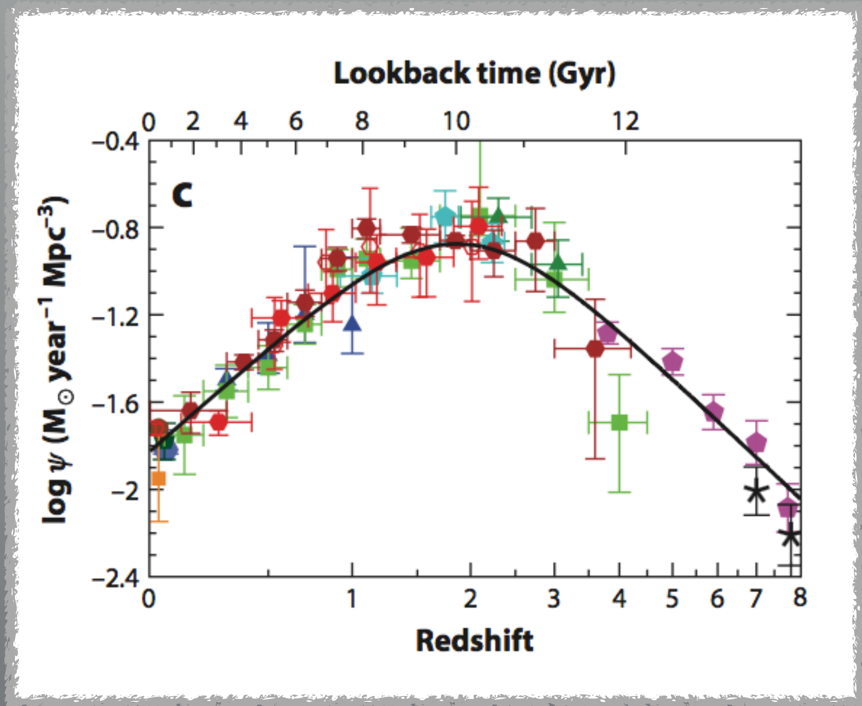
★ Spirals: Σ_{SFR}(1 HLR) ~20 Msun Gyr^{-1} pc^{-2}

★ Spirals: the dispersion in Σ_{SFR}(R) is small

★ MSSF is a sequence with Σ_{SFR} ~ constant

Star formation rate density





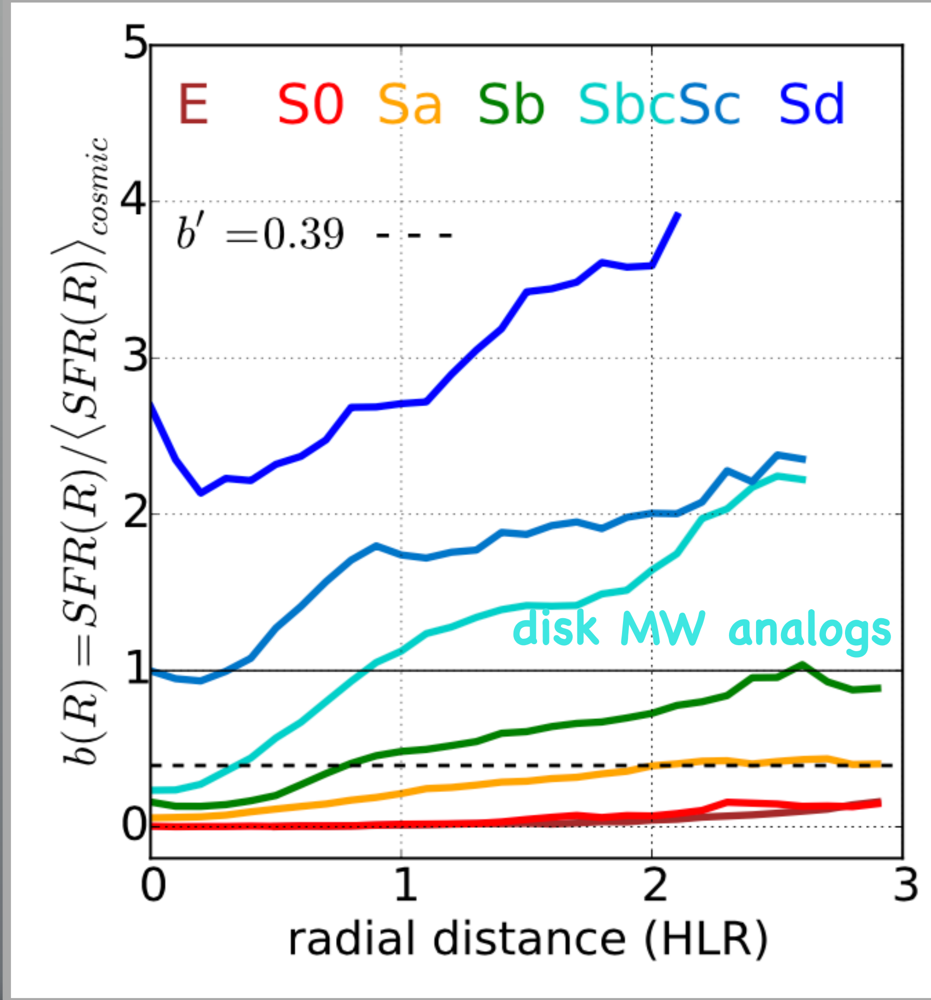
Madau & Dickinson, ARAA, 2014

- ρ_{SFR} = (0.0105 ± 0.0008) $M_\odot$ yr^{-1} Mpc^{-3}
- Most of the star formation is occurring in the disks of spirals (R> 1 HLR)
- E, S0, and the bulge of Sa and Sb contribute little to the recent SFR of the Universe, which is dominated by the disks of Sbc, Sc, and Sd spirals.

The Scalo b birthrate parameter

$$b = \mathrm{SFR} \,/\, \langle \mathrm{SFR} \rangle_{cosmic} = \mathrm{sSFR}\;\; t_\infty\, (1 - \mathcal{R})$$

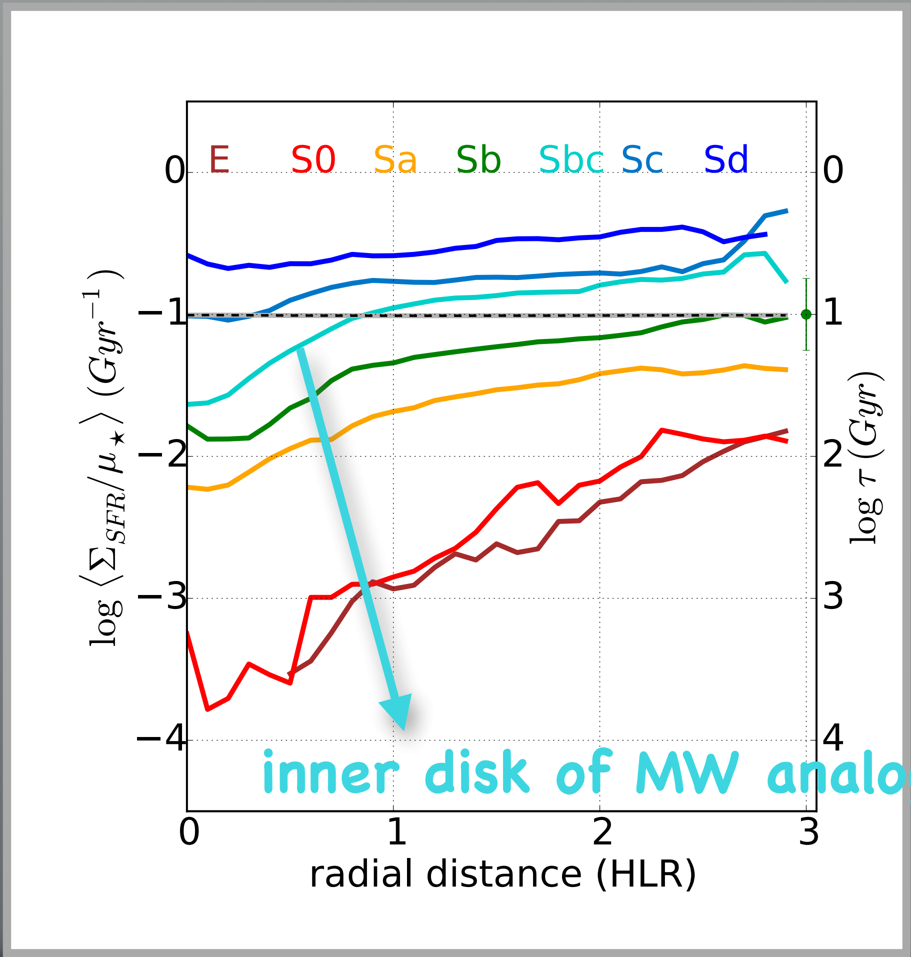
$$b' = \frac{\sum_i \mathrm{SFR}_i V_{max,i}^{-1}}{\sum_i \langle \mathrm{SFR} \rangle_{cosmic,i} V_{max,i}^{-1}}$$



- The volume averaged birthrate parameter, b' = 0.39 ± 0.03,
- Present day Universe is forming stars at ~ 1/3 of its past average rate.
- E, S0, and the bulge of Sa and Sb contribute little to the recent SFR of the Universe, which is dominated by the disks of Sbc, Sc, and Sd spirals.

Star formation along the Hubble sequence

Radial profiles: local sSFR = $\Sigma_{SFR}/\mu_\star = \tau^{-1}$



inner disk of MW analogs is quenched

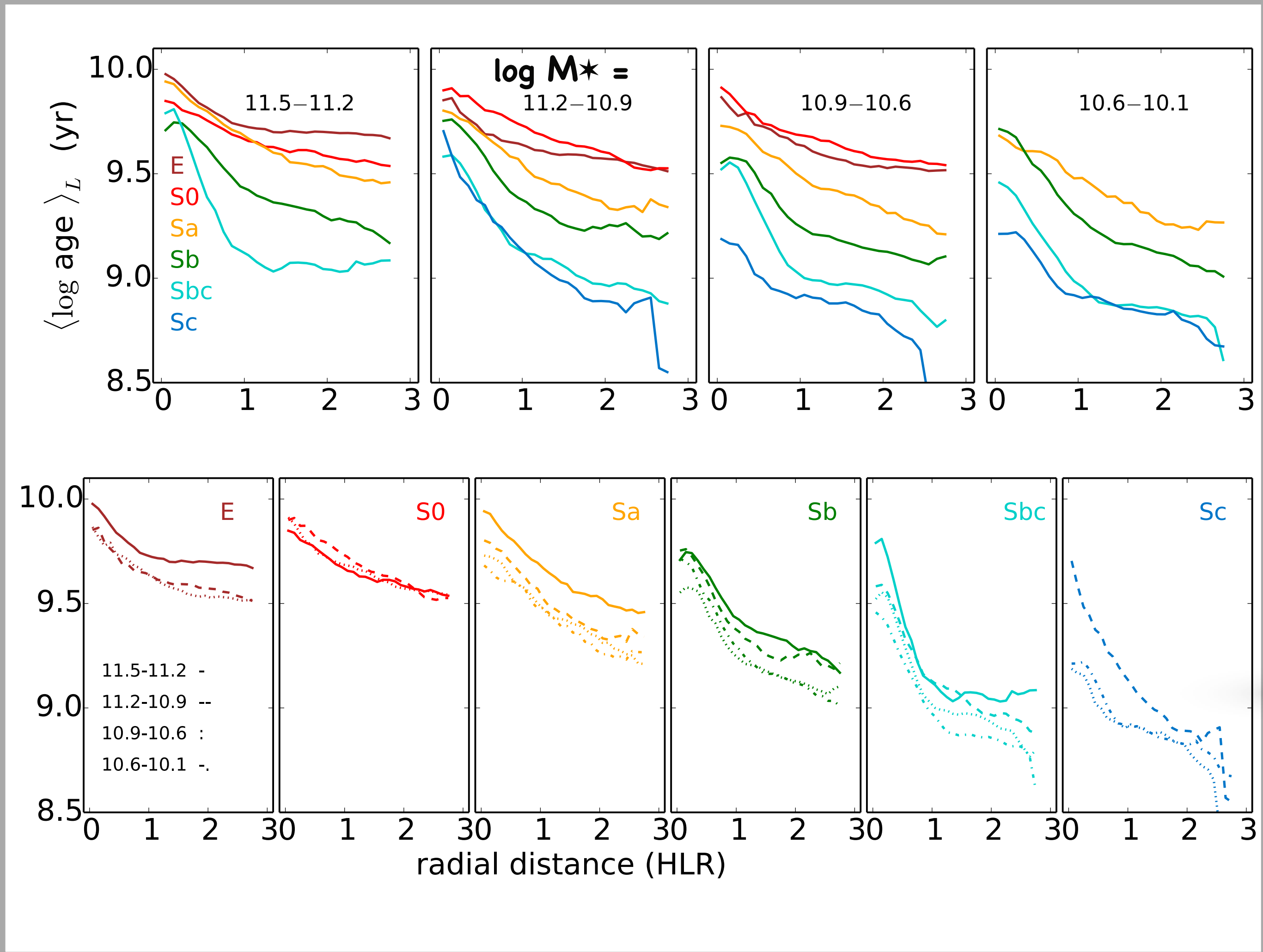
Galaxies are quenched inside-out

- ✳sSFR(R) values scale with Hubble type
- ✳sSFR(R) increases radially outwards, with a steeper slope in the inner 1 HLR.
- ✳galaxies are quenched inside-out, and this process is faster in the central, bulge-dominated part than in the disks.

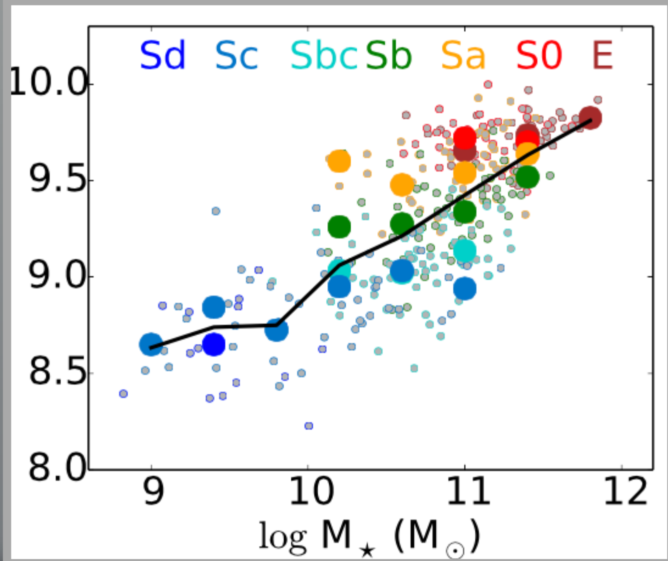
González Delgado +, 2016, A&A, 590, 44

Quenching related with the morphology

Radial profiles of age



Mass-age relation

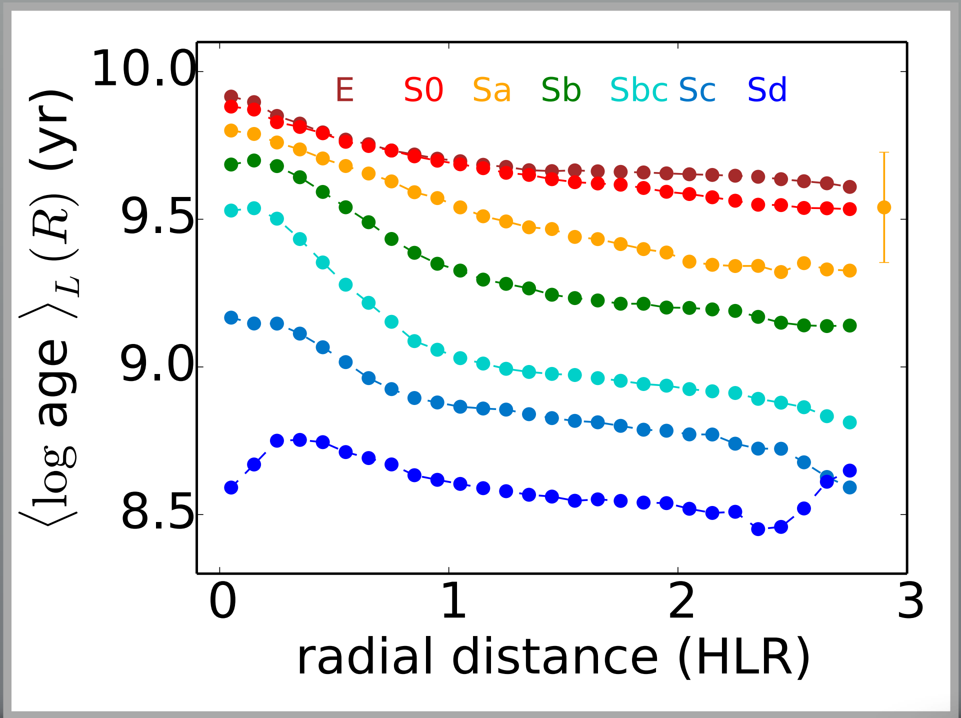


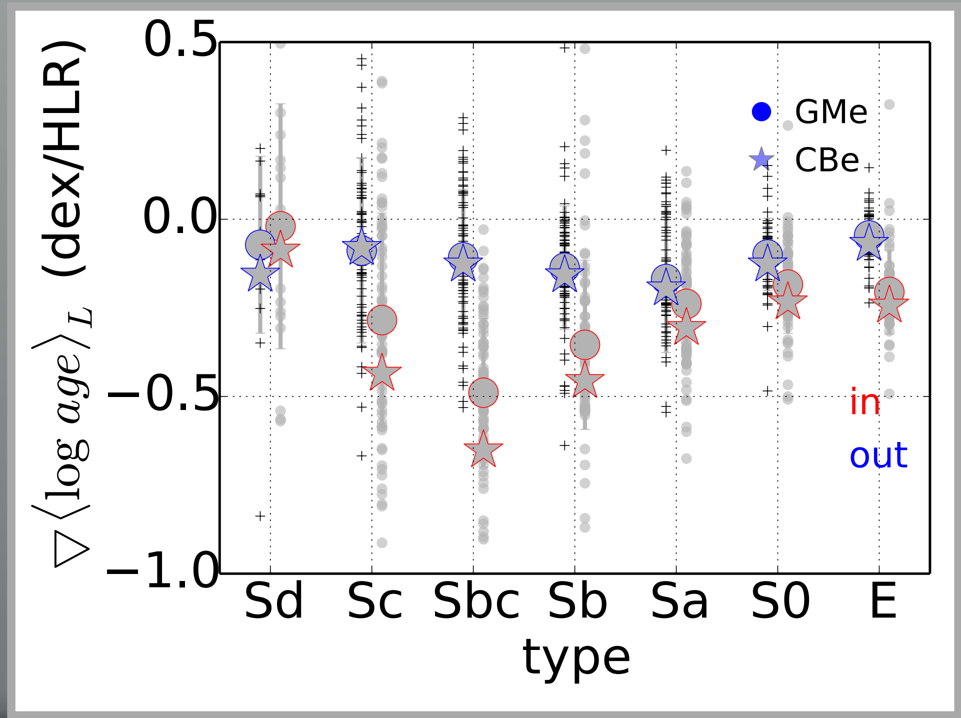
M∗ - age:
dispersion links to the morphology

- 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 the shutdown of star formation occurs outwards and earlier in galaxies with a large spheroid than in galaxies of later Hubble type.

Stellar Population properties along the Hubble sequence

Radial profiles: ages



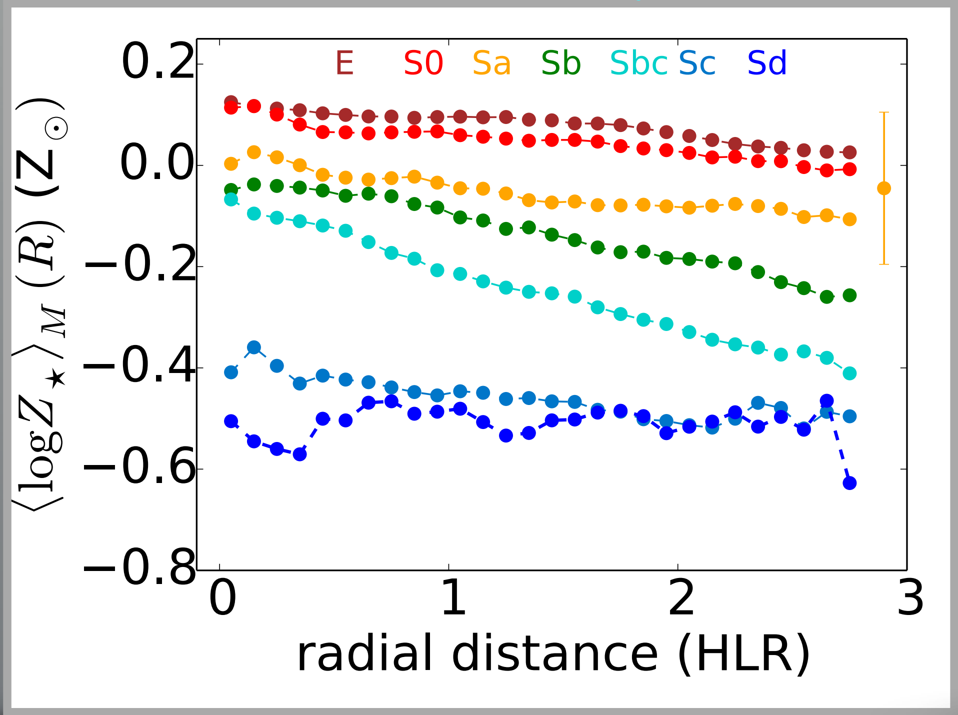


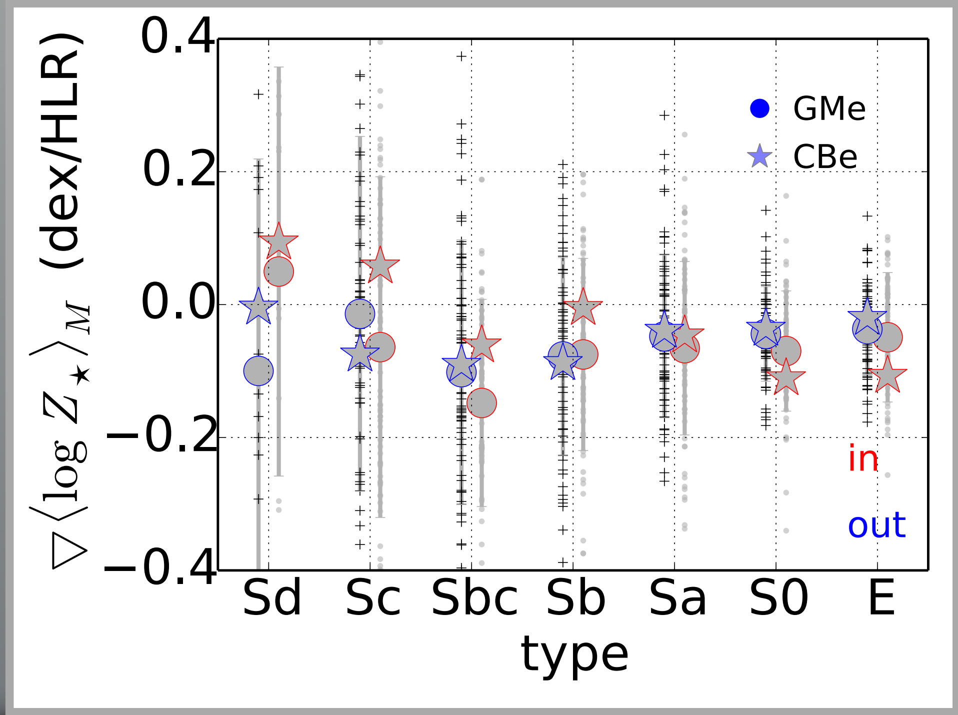
- declining profiles: galaxies are growing inside-out
- largest age gradient in MW like galaxies (Sbc)
- downsizing behavior is preserved with radial distance
- E and S0: no evidence of growing through minor dry mergers, no inversion of the ⟨log age⟩ toward older ages beyond 1–2 HLR

González Delgado et al. 2015, A&A, 581, 103

Stellar Population properties along the Hubble sequence

Radial profiles: stellar metallicity





- declining profiles, evidence of disks growing inside-out
- largest gradient in MW type galaxies (Sbc), as predicted by chemical evolution models (e.g. Molla & Díaz 2005)
- Sbc galaxies have a ▽⟨logZ⋆⟩~ −0.1 [dex/HLR] similar to the predictions by RaDES simulations (Few et al. 2012; Pilkington et al. 2012a).
- later type: very flat, small ▽in⟨log Z⟩M L
- dispersion in the ▽in⟨log Z⟩M−M⋆⋆ relation is related with morphology
- E and S0: no evidence of a steepening of ⟨log Z⟩M L beyond 1-2 HLR if they were growing through minor dry mergers

Mass assembly

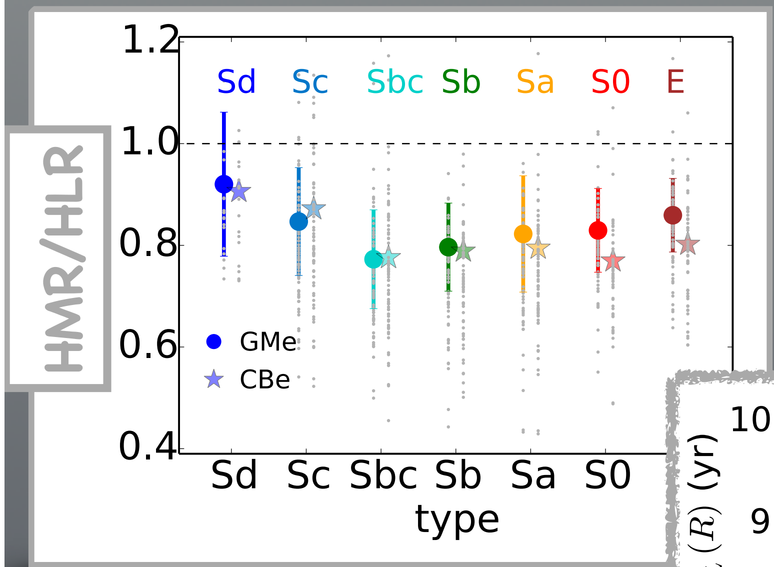
Galaxies grow inside-out

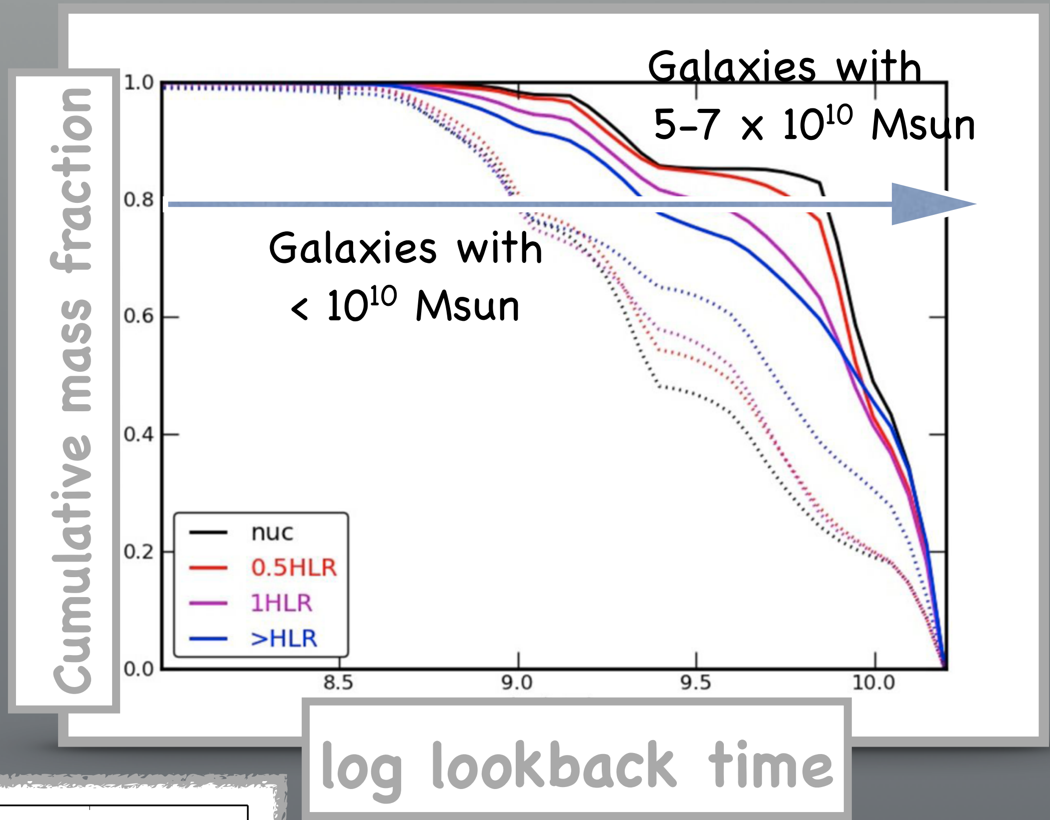
Pérez et al. 2013, ApJL, 764, L1

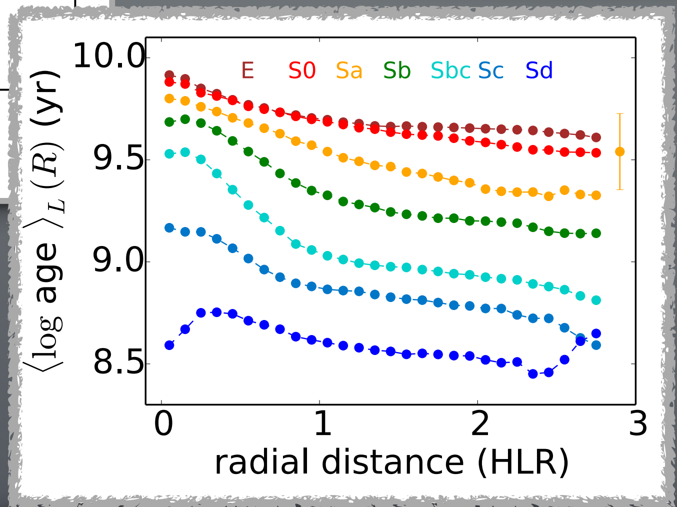
Other evidence:

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

HMR/HLR = Half Mass Radius / Half Light Radius







Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 449, 1177–1214 (2015) doi:10.1093/mnras/stv151

Evolutionary stellar population synthesis with MILES – II. Scaled-solar and α-enhanced models

A. Vazdekis,[1,2★] P. Coelho,[3] S. Cassisi,[4] E. Ricciardelli,[5] J. Falcón-Barroso,[1,2] P. Sánchez-Blázquez,[6] F. La Barbera,[7] M. A. Beasley[1,2] and A. Pietrinferni[4]

BaSTI, IMF Salpeter, MILES

and alpha-enhanced SSP (a/Fe = 0, 0.4)

Preliminaries results from the spectral fit using CSP

CSP with SFR= 1 Msun/yr and width 0.2 dex in time

ages (18 CSP) = 11.5, 7.25, 4.55, 2.85, 1.8, 1.14, 0.72, 0.45, 0.285, 0.18, 0.11, 0.072, 0.045, 0.028, 0.018, 0.011, 0.006, 0.002 Gyr

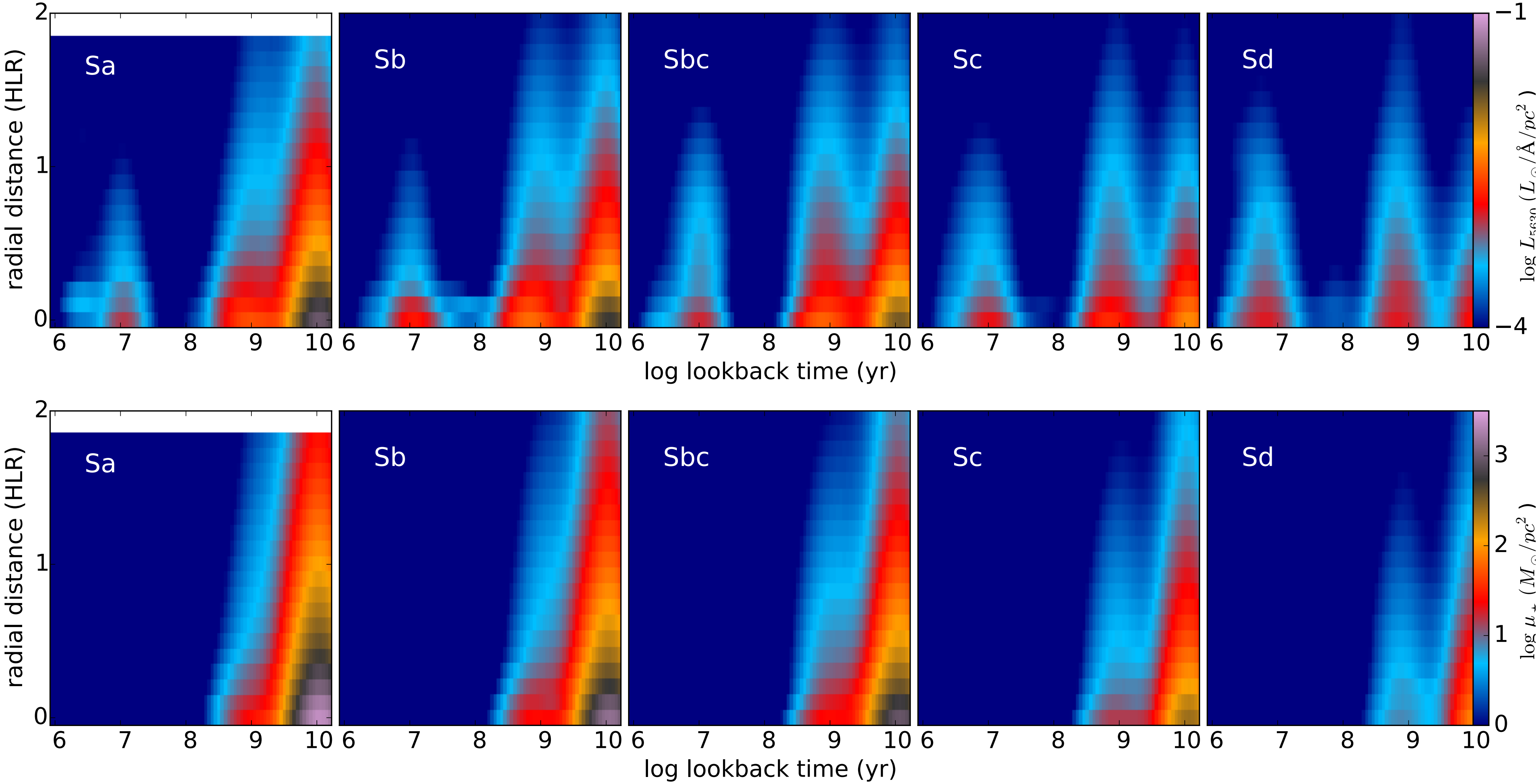
metal (8) = 0.4, 0.25, 0.06, -0.35, -0.66, -1.26, -1.79, -2.28

alpha/Fe = 0 (solar scale), 0.4

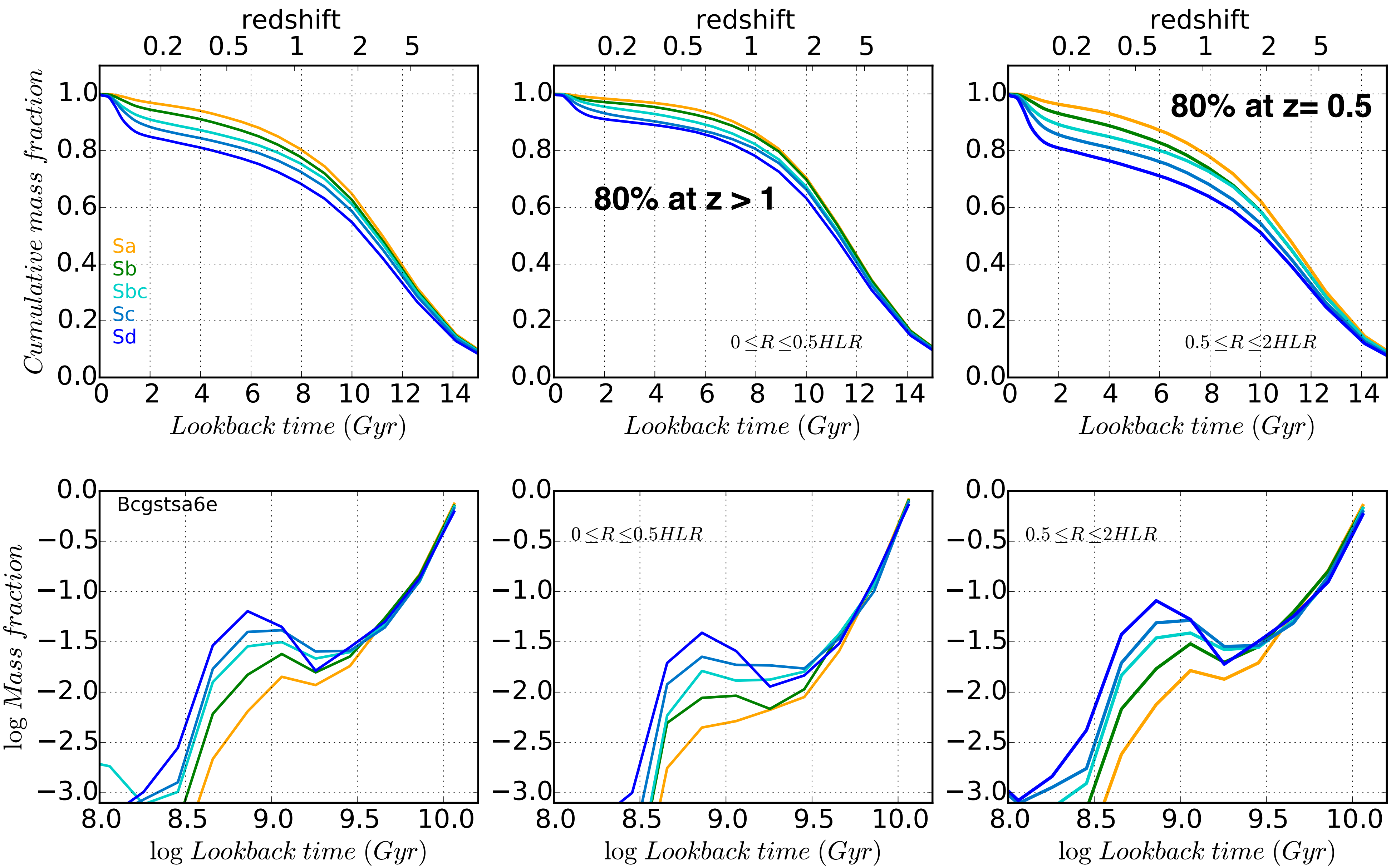
2D maps of SFH of spirals: Radial x lookback time

Mass formed at each epoch per pc²

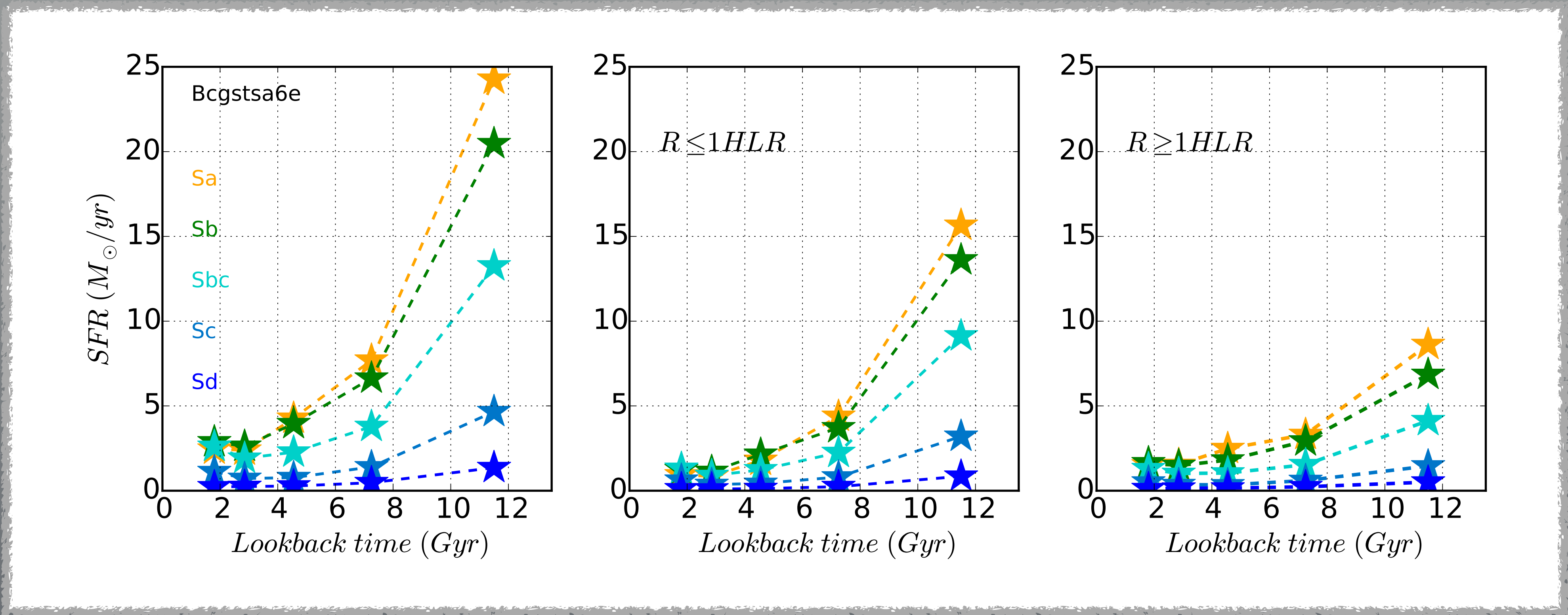
and Luminosity per pc²



Spirals: Mass fraction and mass growth



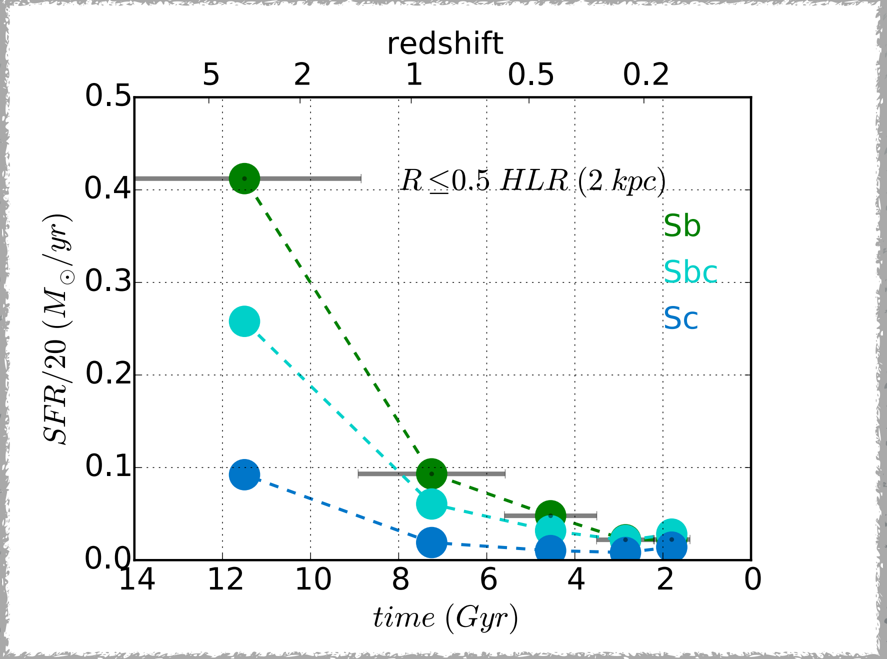
Spirals: SFR vs lookback

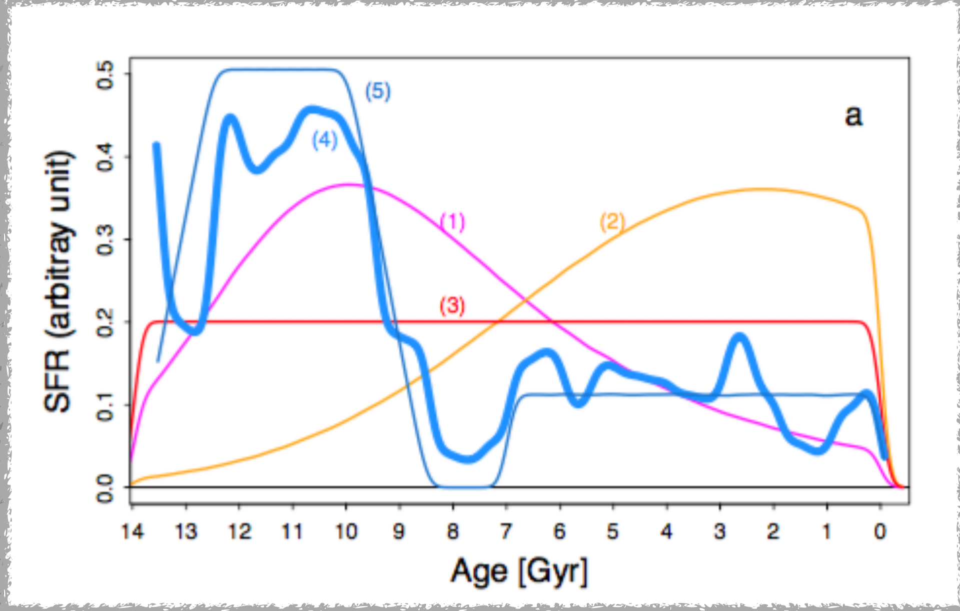


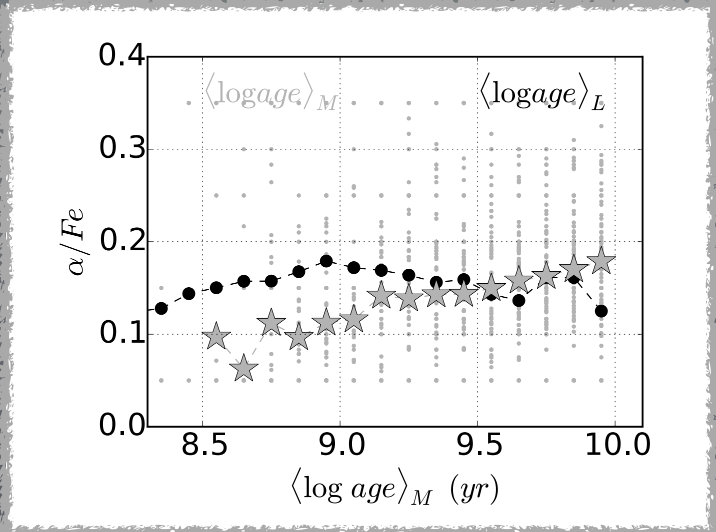
- In the past, SFR was higher in more massive spirals
- SFR declines faster in the inner part of the galaxy than in the disk
- Sbc (Mass ~8x10^10 Msun, Salpeter IMF), SFR= 14/1 (HLR < 1) and 7/1 (HLR > 1)
- Sc (Mass ~5x10^10 Msun, Salpeter IMF), SFR= 9/1 (HLR < 1) and 4/1 (HLR > 1)

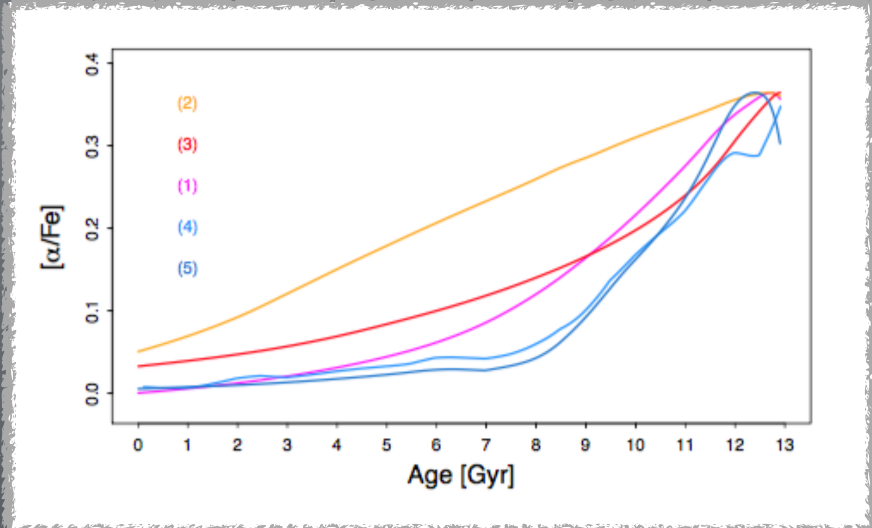
CALIFA SFH: Sb-Sbc-Sc

Simulations of MW thick disk from Haywood et al. 2016



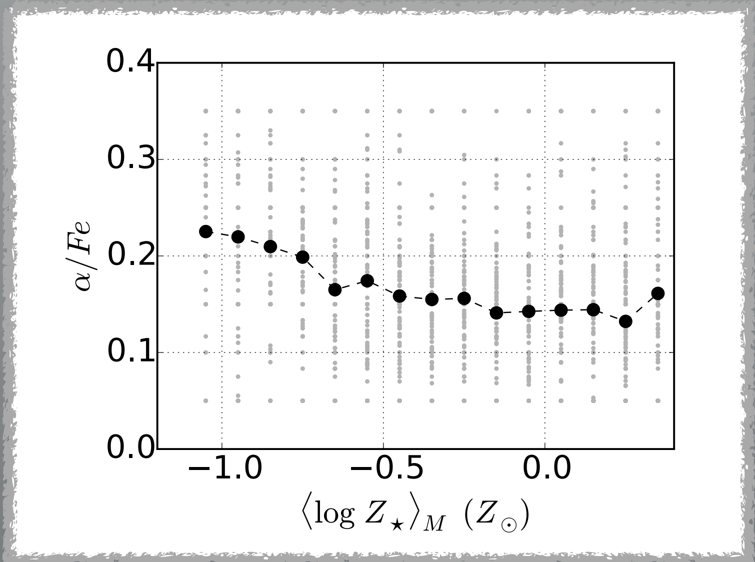


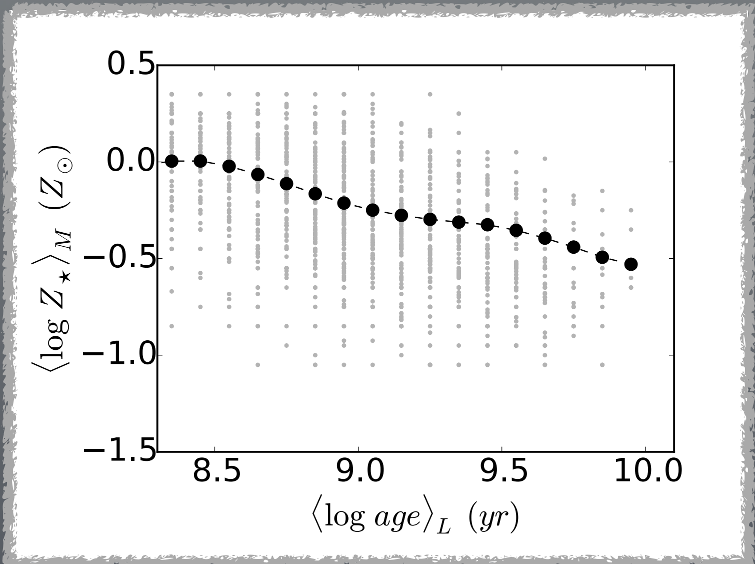




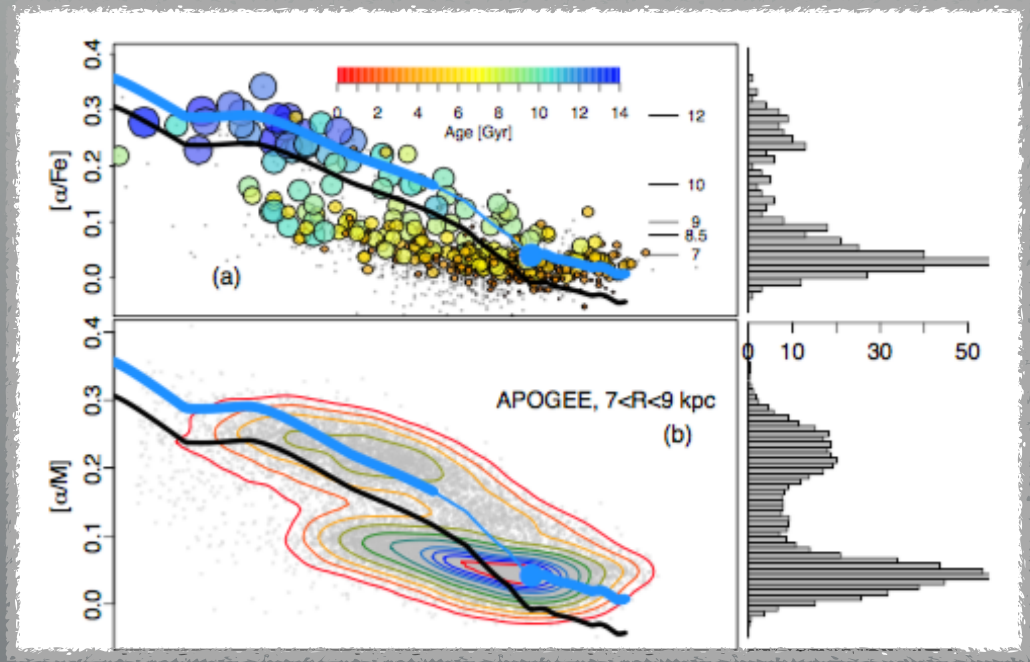
Haywood et al. 2016

Solar vicinity: 1.5-2 HLR of Sbc-Sc in CALIFA



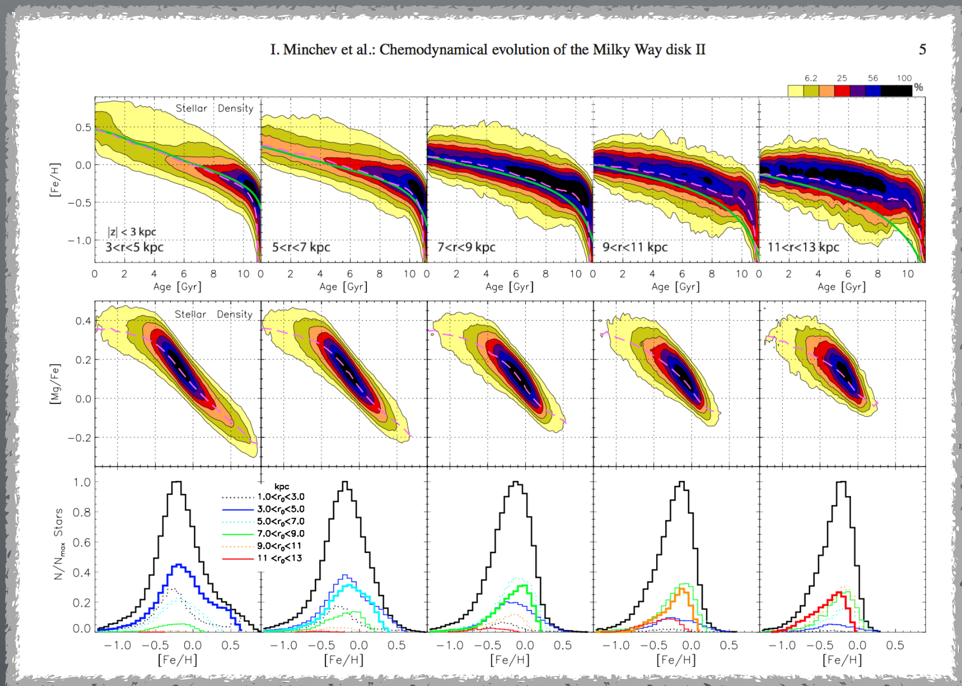


MW APOGGE



Haywood et al. 2016

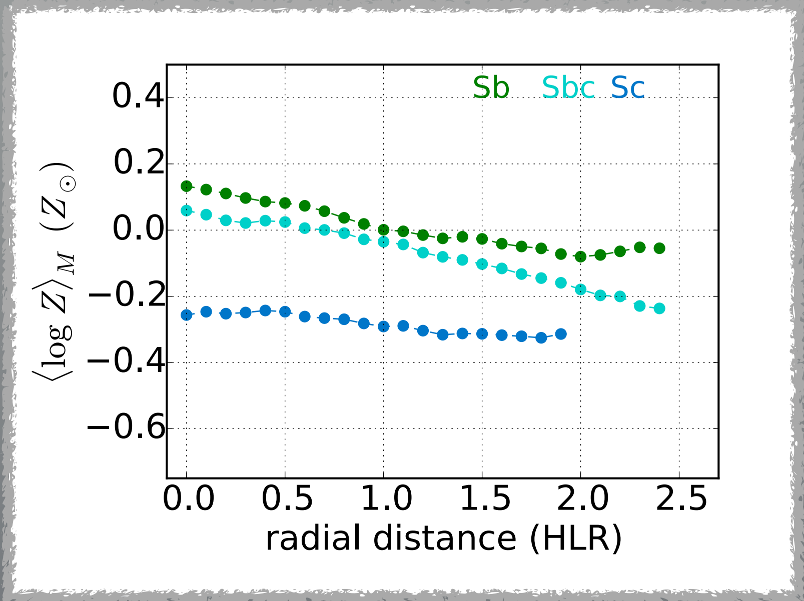
Simulations of MW thin disks

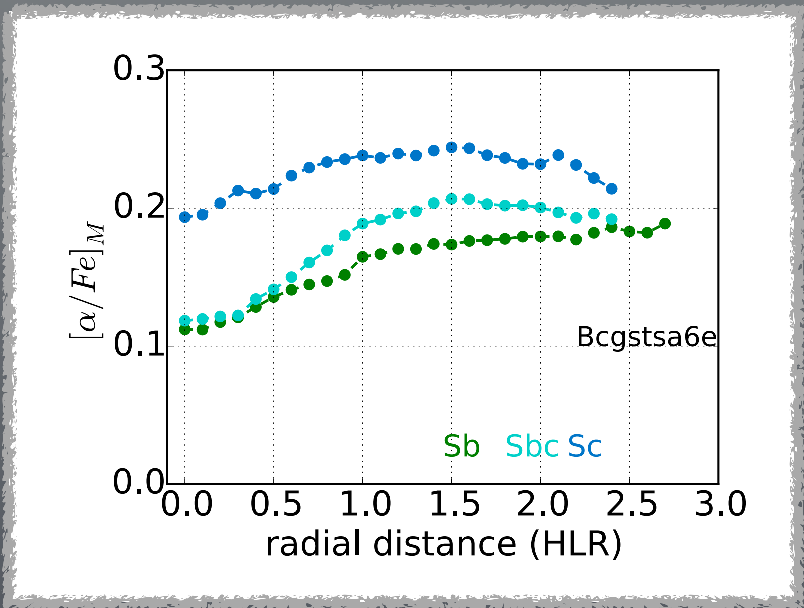


Minchev et al. 2014

CALIFA: Sb-Sbc-Sc

$\nabla\langle \log Z_\star \rangle \sim -0.1$ [dex/HLR] (-0.02 dex/kpc)

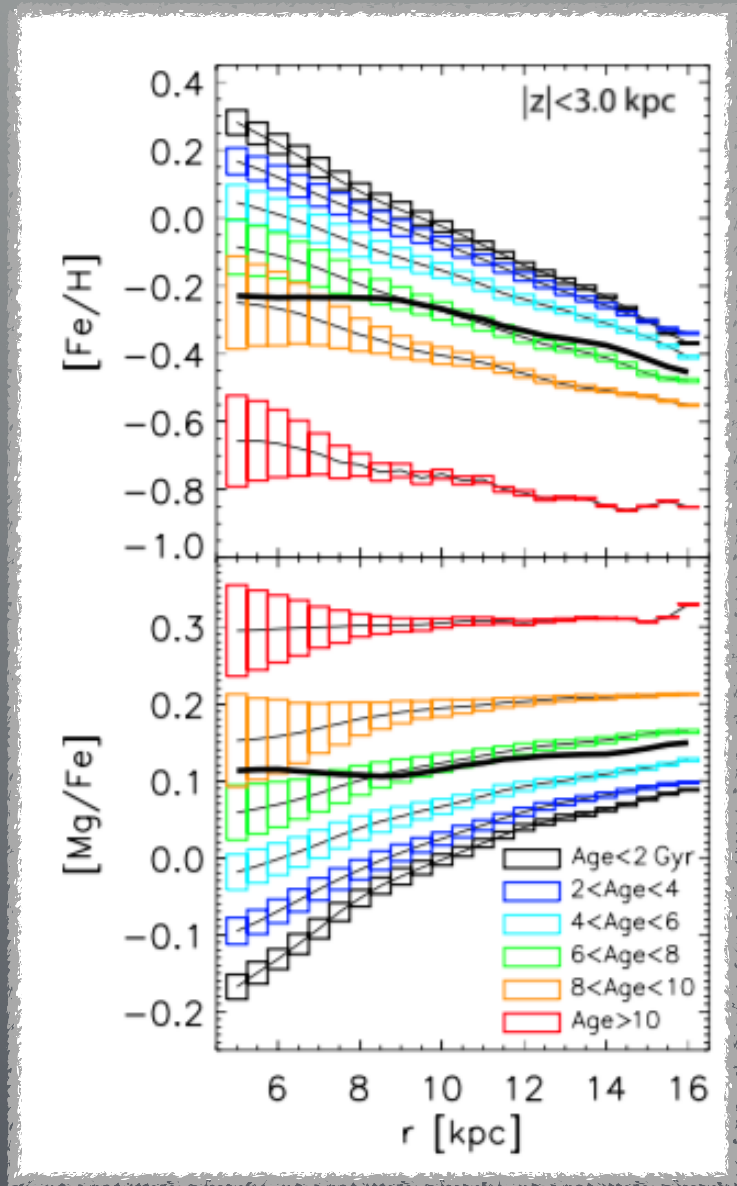




Simulations of MW disks

$\nabla\langle \log Z_\star \rangle \sim -0.016$ [dex/kpc] (all stars and z < 3 kpc)

$\nabla\langle \log Z_\star \rangle \sim -0.027$ [dex/kpc] (all stars and z < 0.25 kpc)



Minchev et al. 2014

Conclusions

✳ Hubble sequence is a useful scheme to organize galaxies by their spatially resolved stellar density, age, and metallicity.

✳ Spirals form a galaxy sequence with constant intensity of the SFR.

✳ Local processes are relevant in setting the SF in the disks of galaxies probably through a density dependence SFR law.

✳ Stellar mass sets the average properties of the stellar population in galaxies, but have little impact on quenching.

✳ Morphology plays the main role in the shut down of the star formation activity in galaxies.

✳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
✳García-Benito et al., 2015, A&A, 576, 135
✳González Delgado et al. 2015, A&A, 581, 103.
✳López Fernández et al. 2016, MNRAS, 458, 184
✳González Delgado et al. 2016, A&A, 590, 44
✳Cortijo-Ferrero et al. 2016, MNRAS, submitted