CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

INSTITUTO de ASTROFÍSICA de ANDALUCÍA
I·A·A

Spatially resolved star formation history of CALIFA galaxies: Implications for galaxy formation

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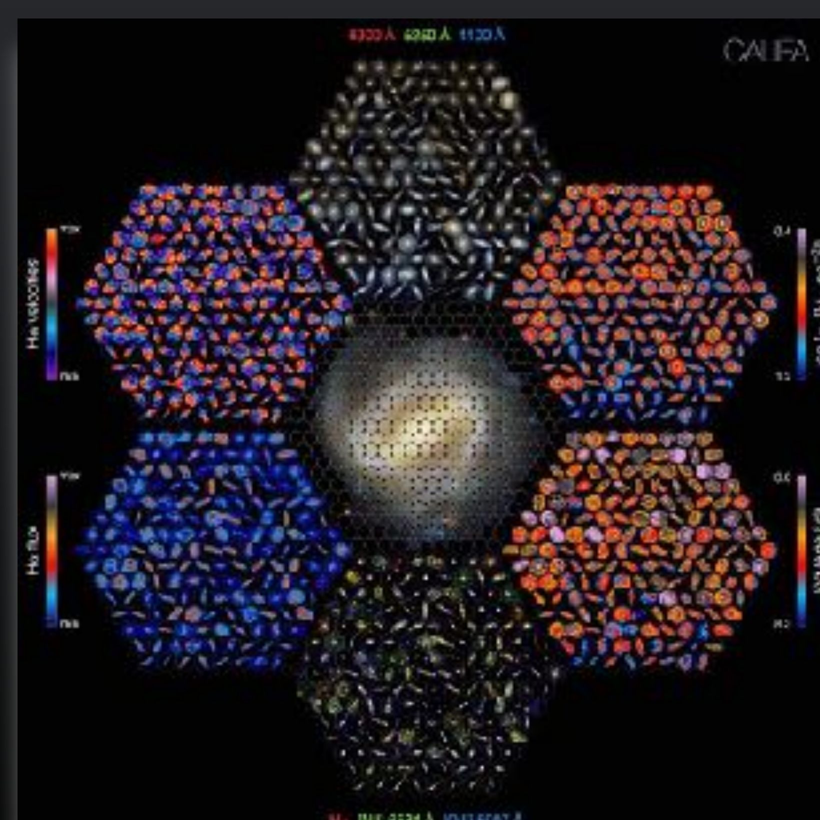
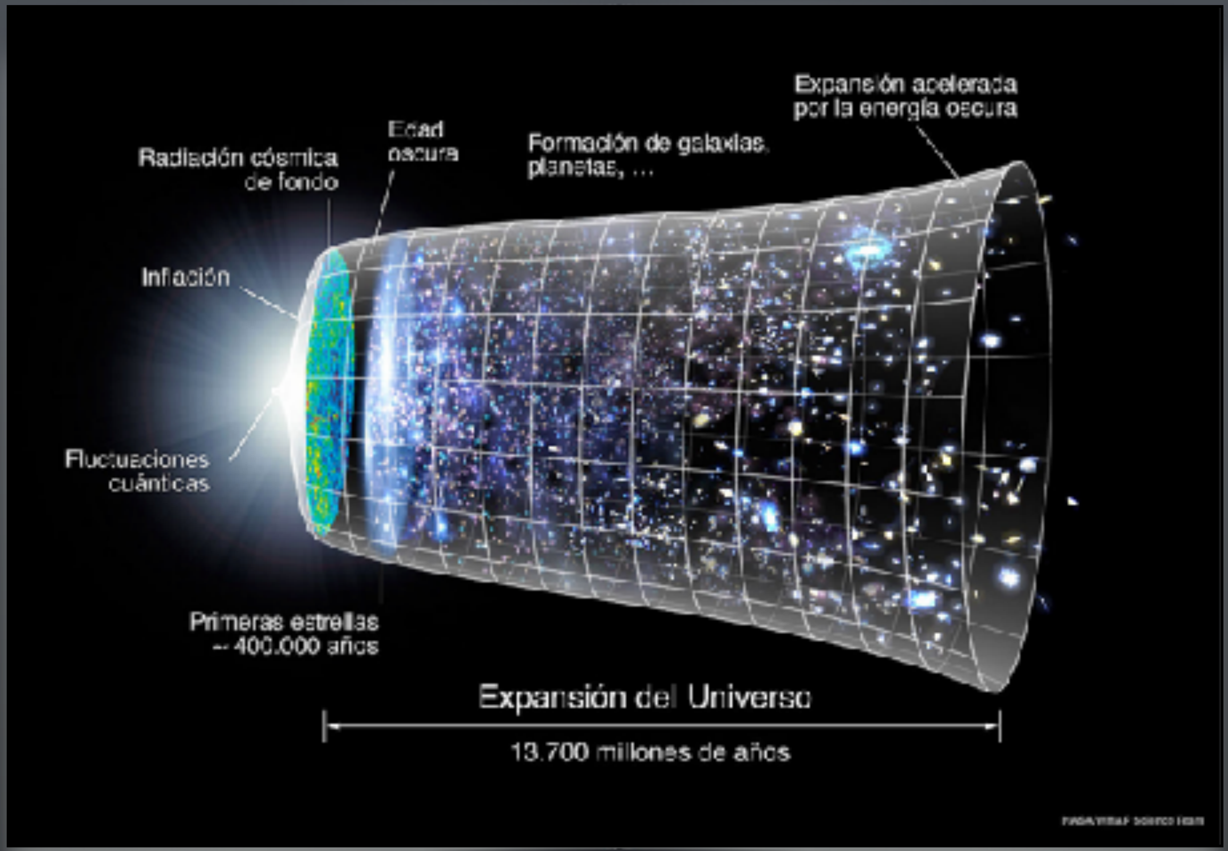
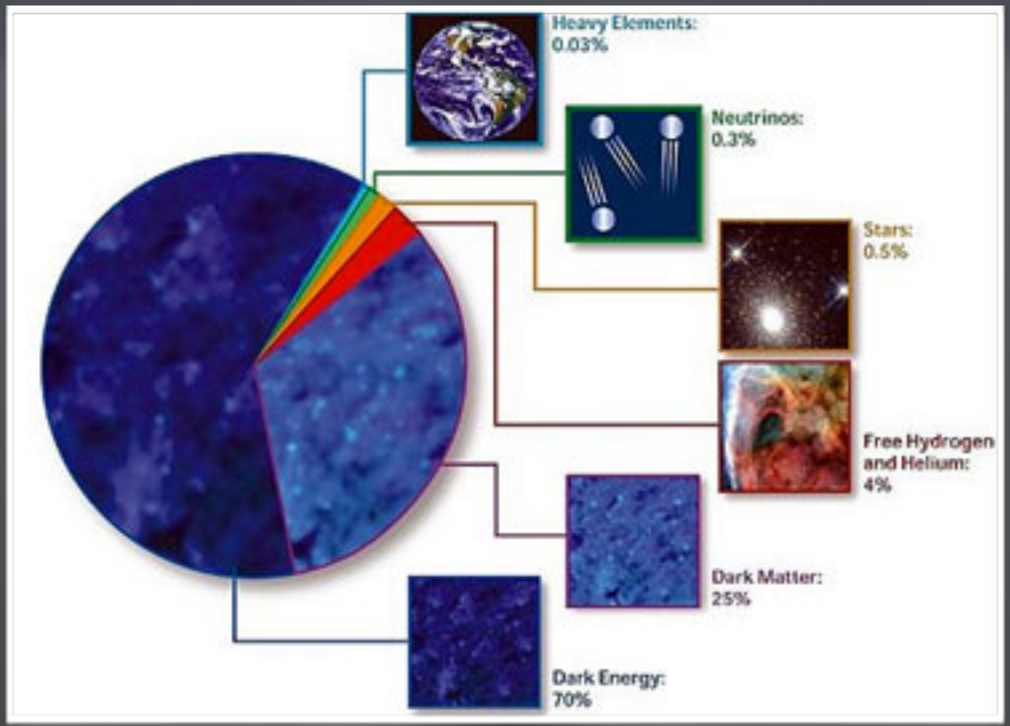


and CALIFA collaboration
IP: S.F. Sánchez (UNAM)

How galaxies form: Cosmological frame

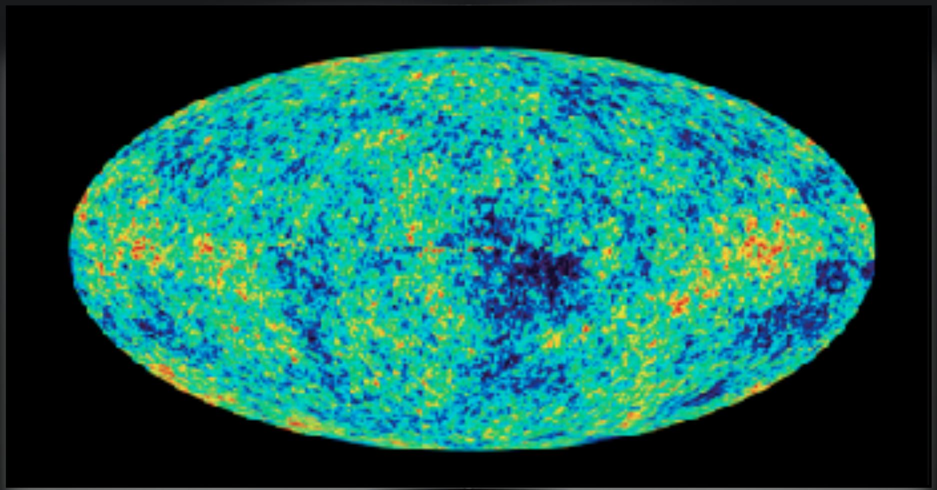


- The Universe is expanding
- It is accelerated

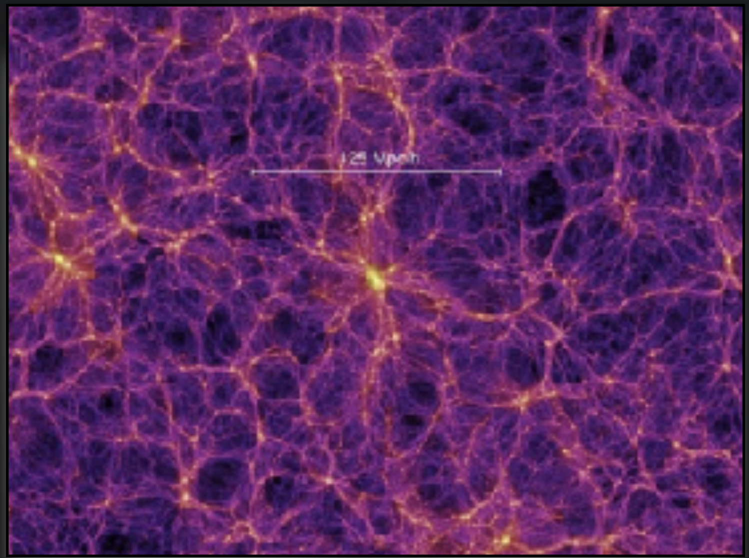


- 96% dark energy and dark matter
- 4% baryonic matter

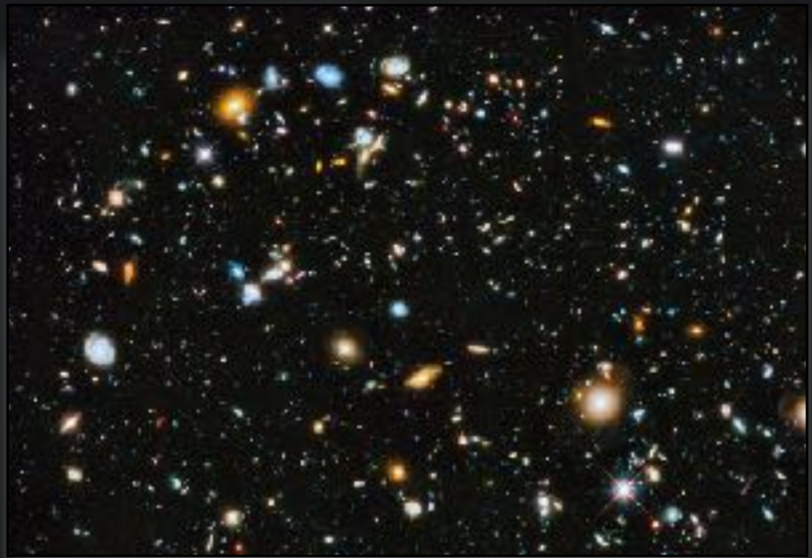
The growth from the primordial fluctuations



CMB: WMAP

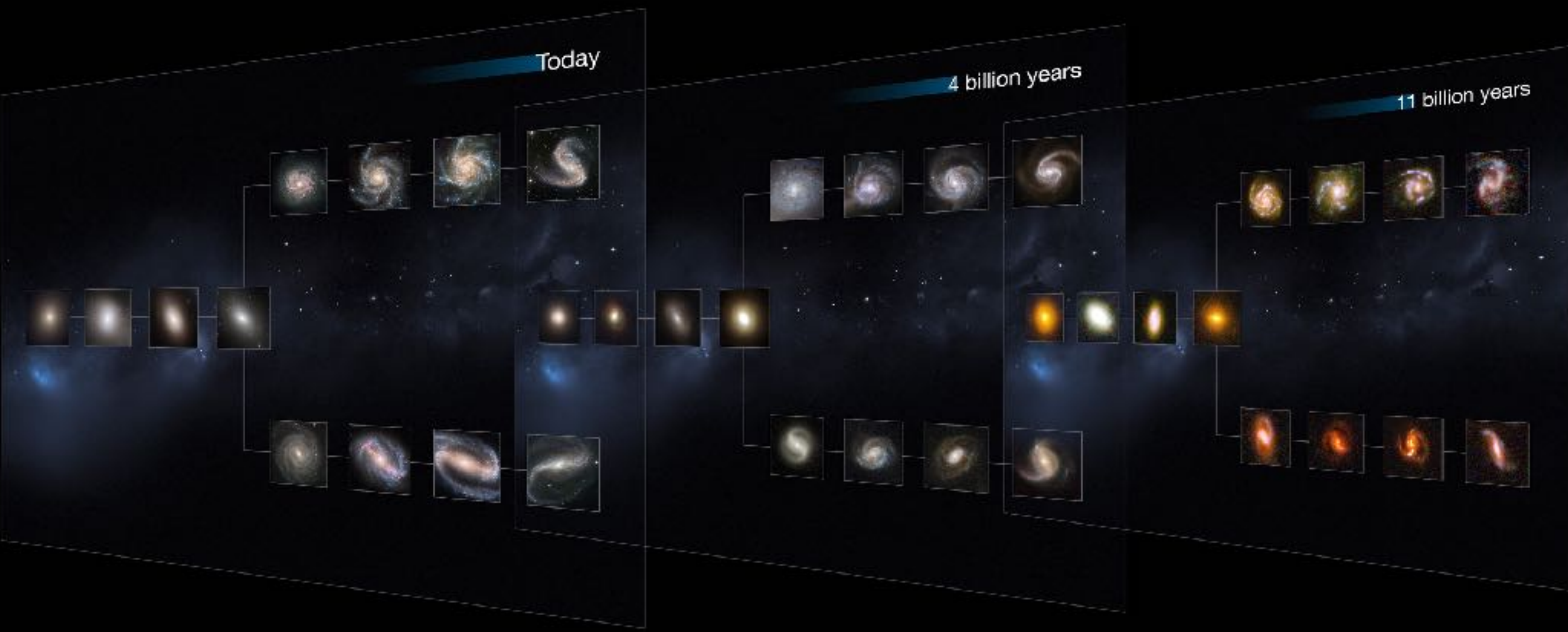


Millennium simmulations



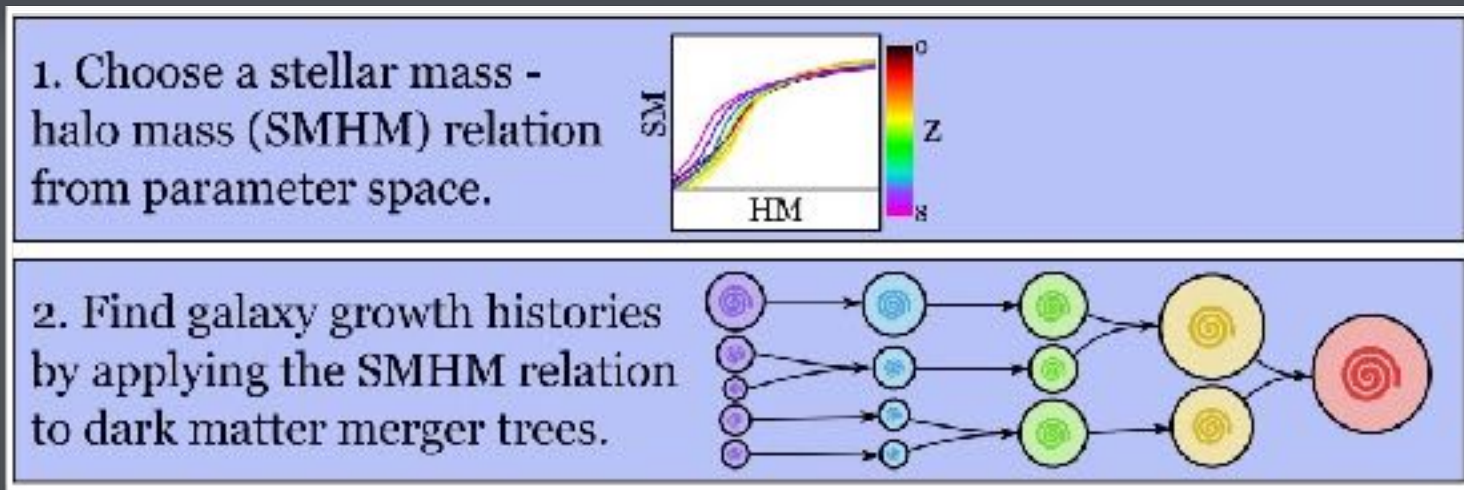
deep field of galaxies

How did the first structures formed and evolved
to explain the diversity of galaxies observed today?

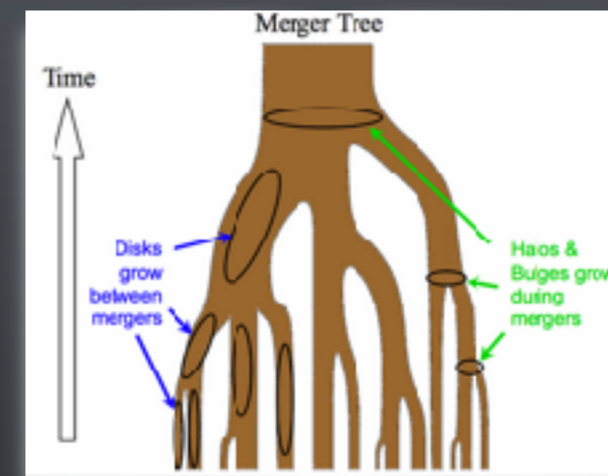


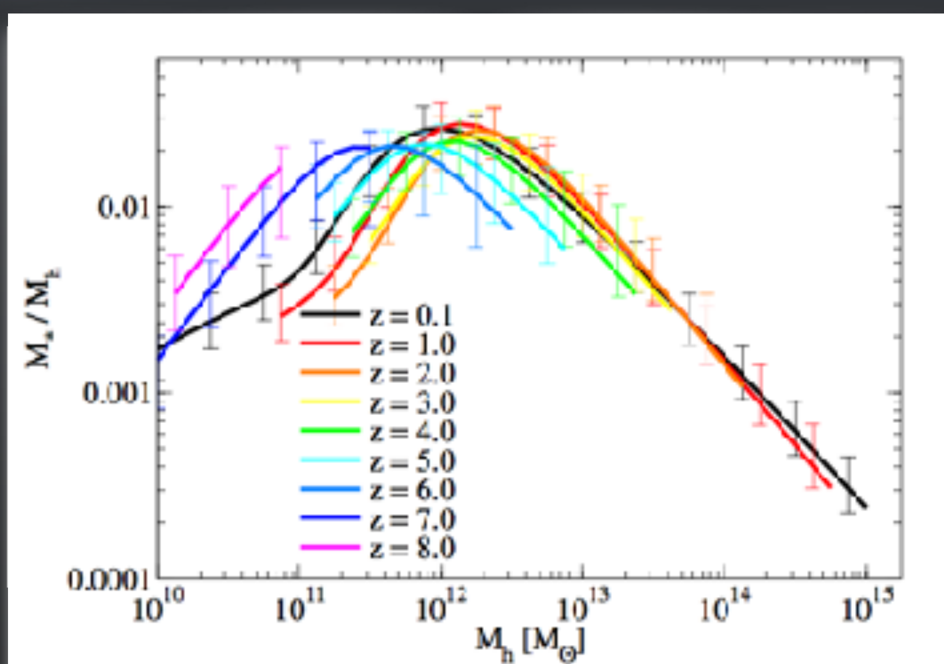
Hubble sequence evolution since z~2

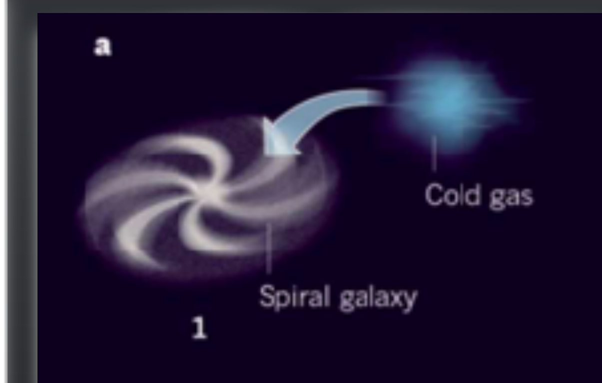
How galaxies form?

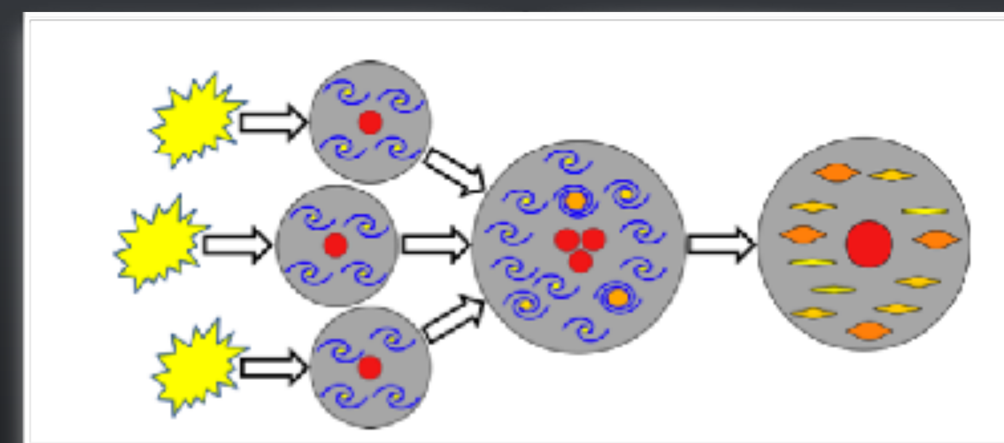


Merger tree of dark matter halos CDM









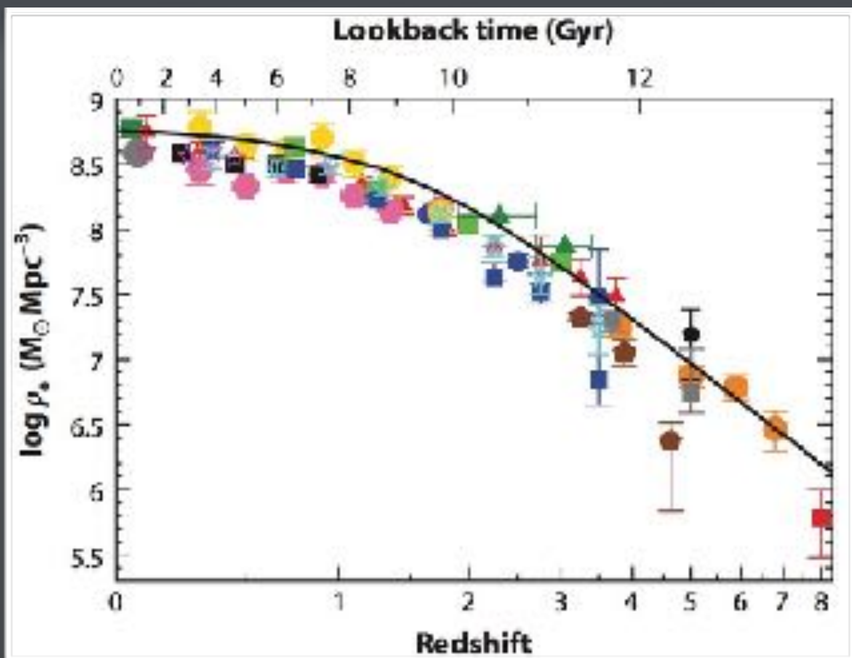
- Physical processes:
  - SF from gas in situ or/and accreted
  - Merger of galaxies with different SFH
  - Feedback: stellar, SNe, AGN
  - SF regulated through outflows

- Mergers account for 50% of the outer envelope of massive galaxies (Naab + 2009)
- Equal mass mergers are rare (Man +2012)
- Difficult to match the number of thin disk galaxies (Naab & Ostriker 2016)
- Galaxies like the MW assembled their mass through streams of cold gas from the cosmic web (Sánchez Almeida + 2014)
- Galaxy’s gas accretion and SFR depend on the cosmological dark matter specific accretion rate (Neistein + 2006)

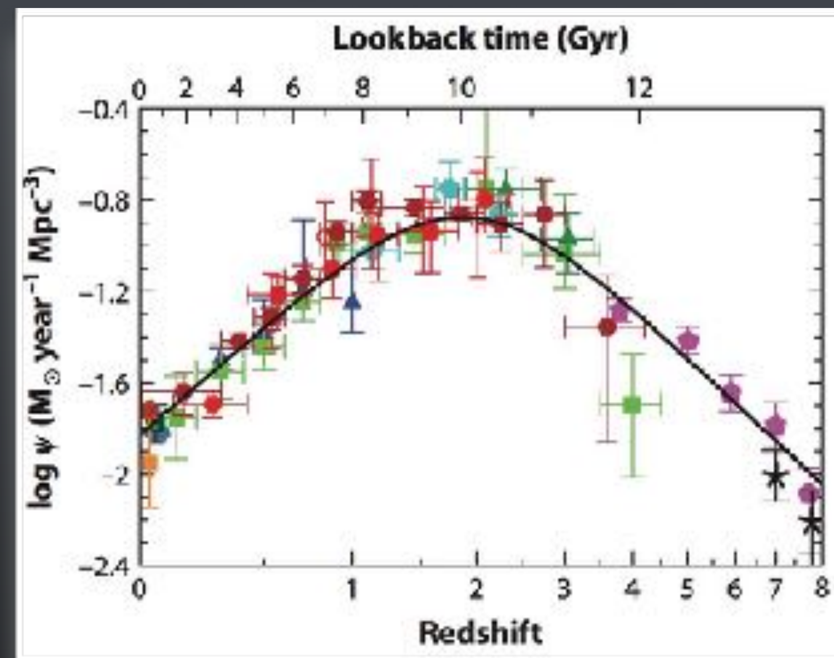
Fundamental observational results

- Stellar mass density

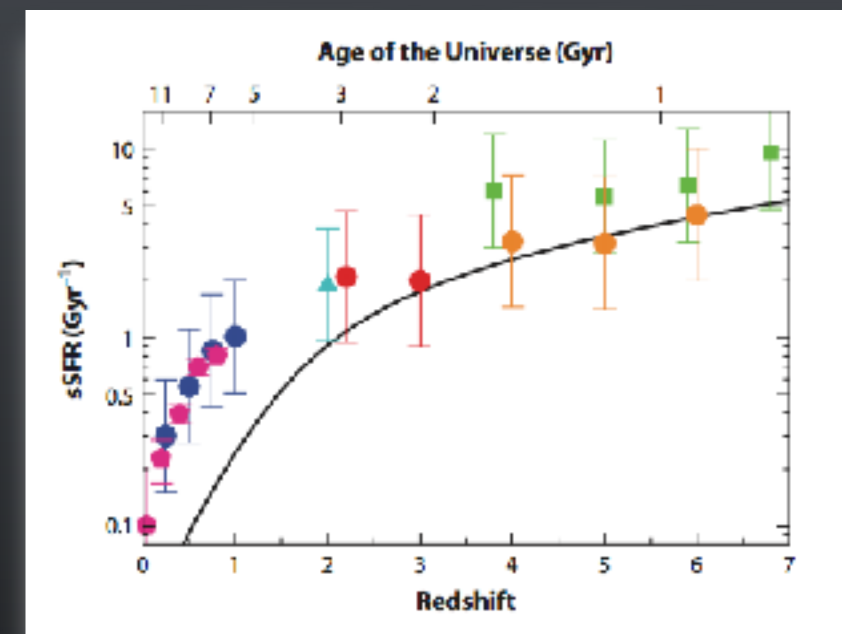
Madau & Dickinson 2014, ARAA



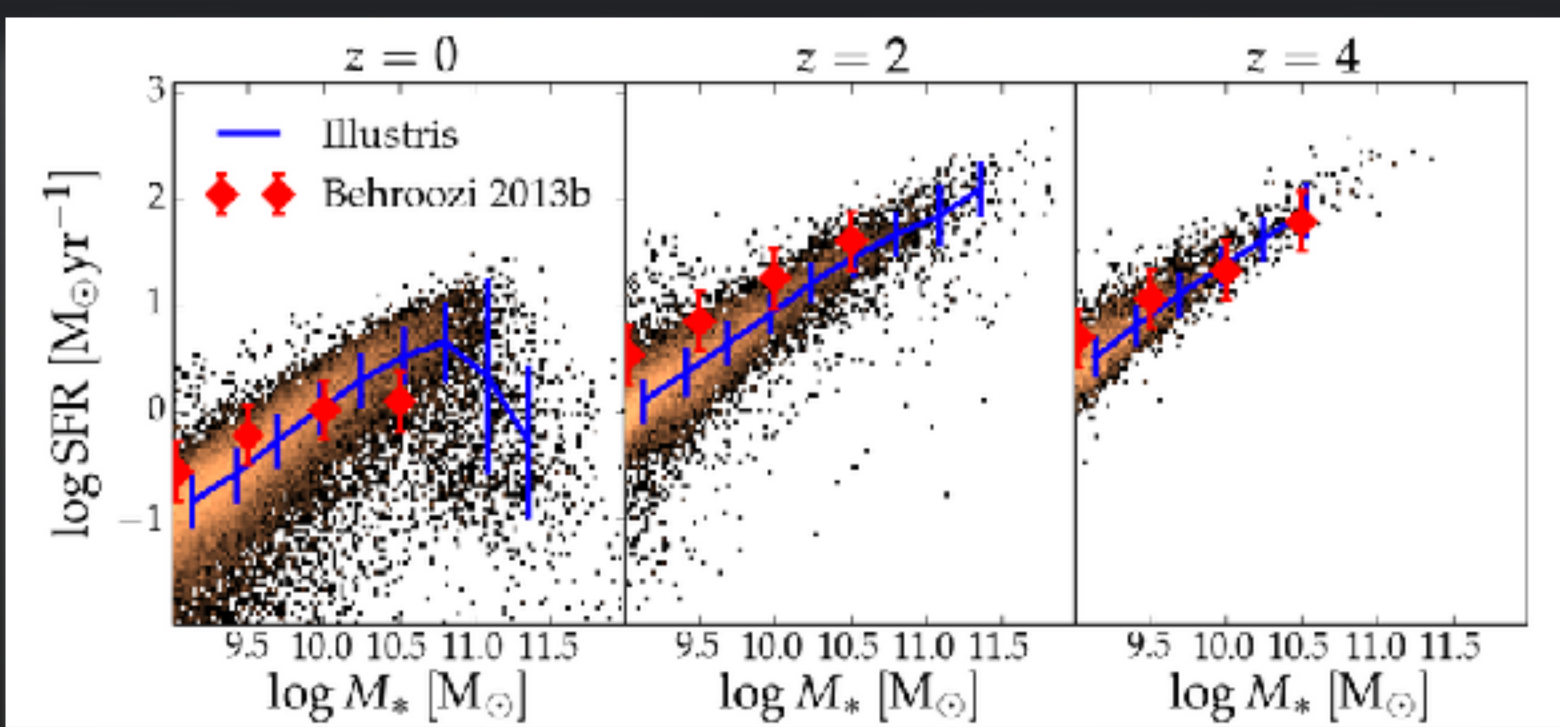
- Star formation rate density



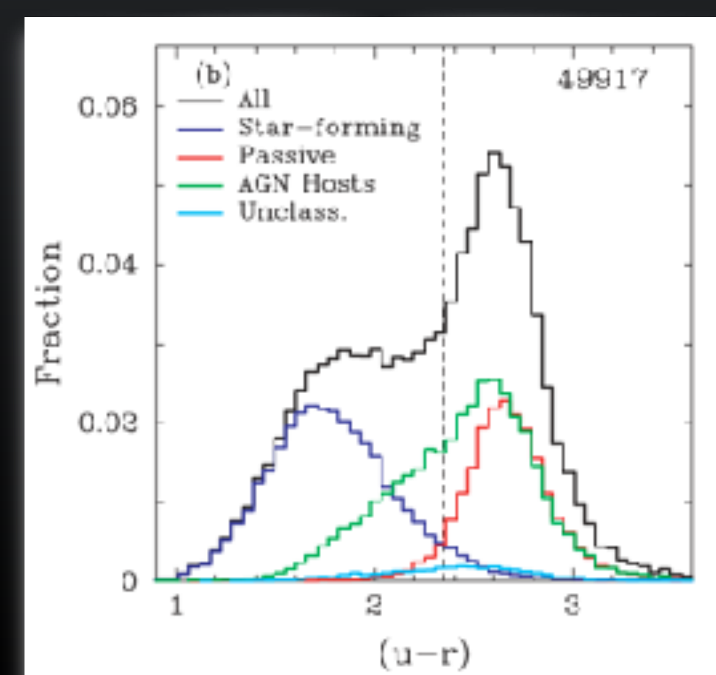
- Specific SFR (sSFR)



- Main Sequence of Star formation

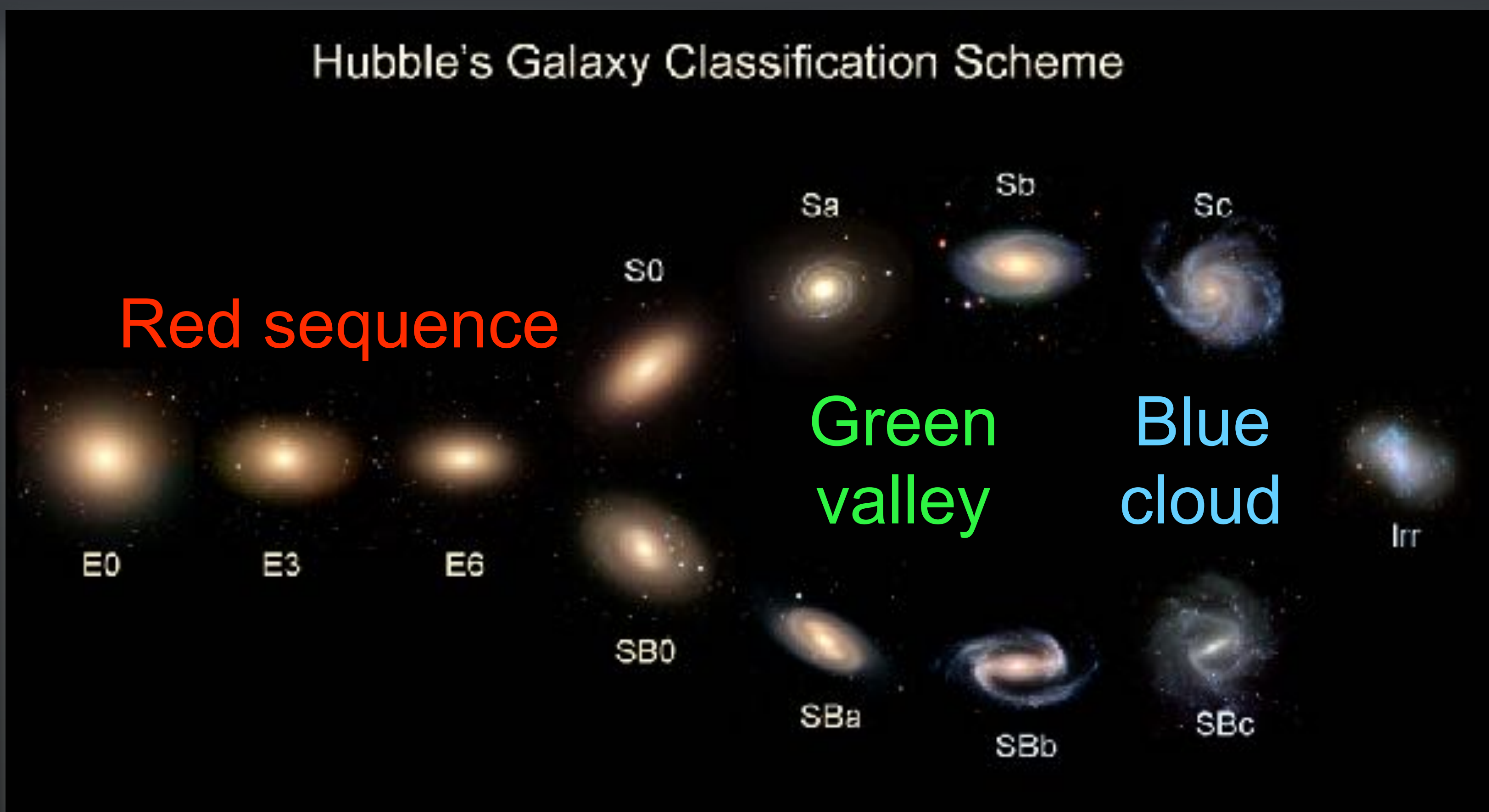


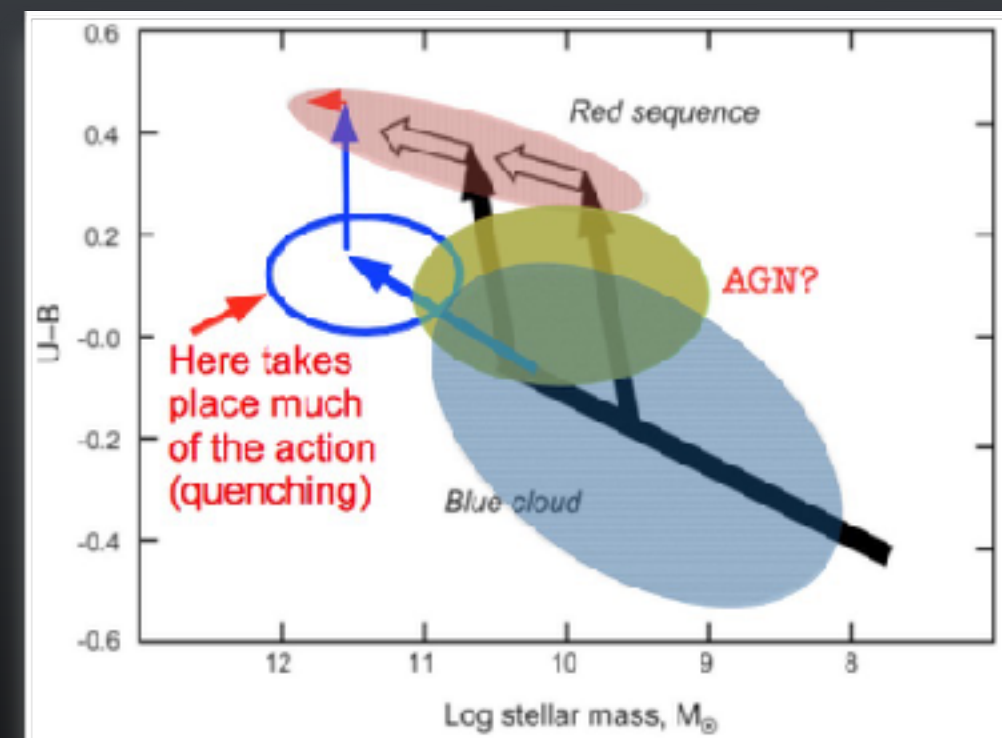
- Bimodal distribution of galaxy population



How did galaxies form? Star formation history of the Universe

- When and how the galaxies grow in mass?
- Which are the physical processes?
- Origin of the Hubble sequence?
- When did the bulge and disk form?

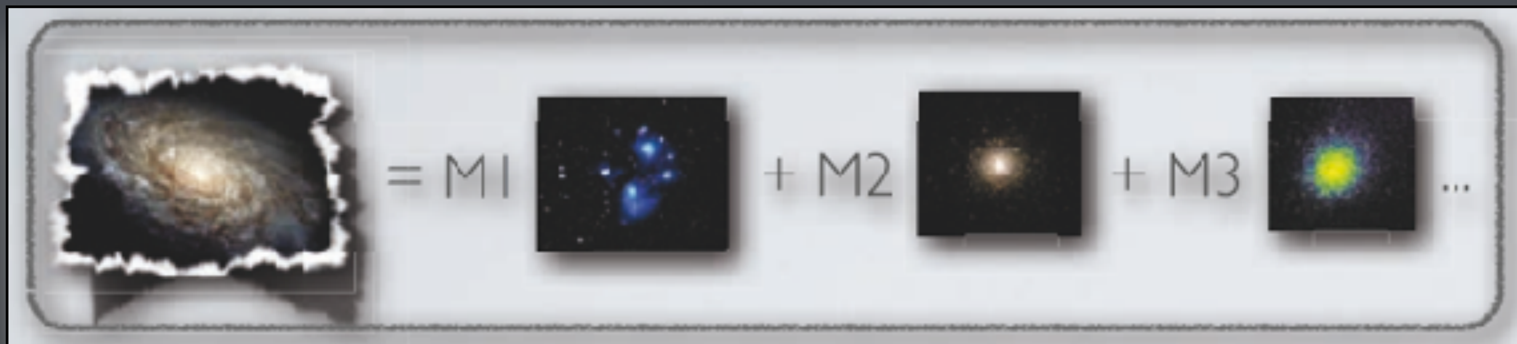


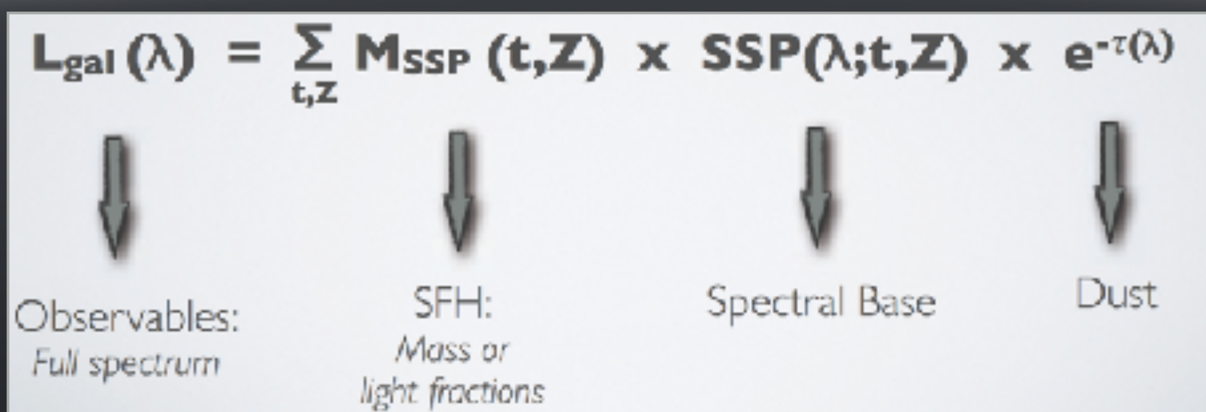


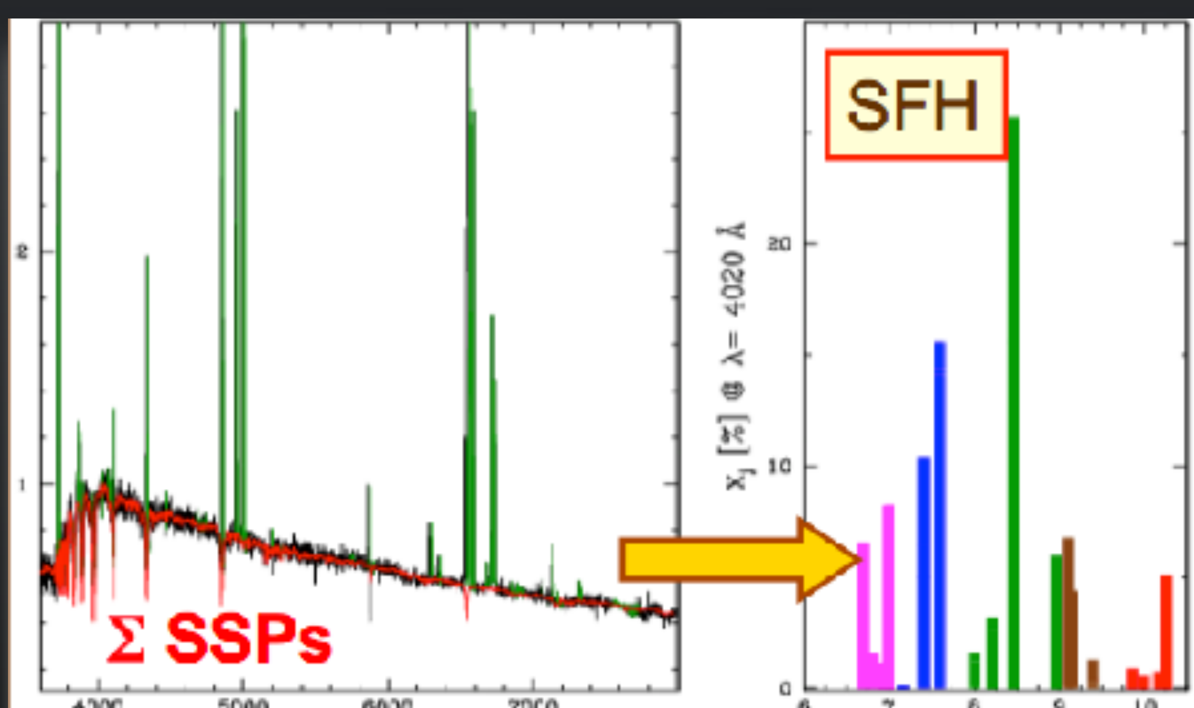
Two observational ways

- Cosmological surveys (different redshifts)
- Nearby galaxies (SFH: lookback time studies)

Fossil record: Full spectral synthesis

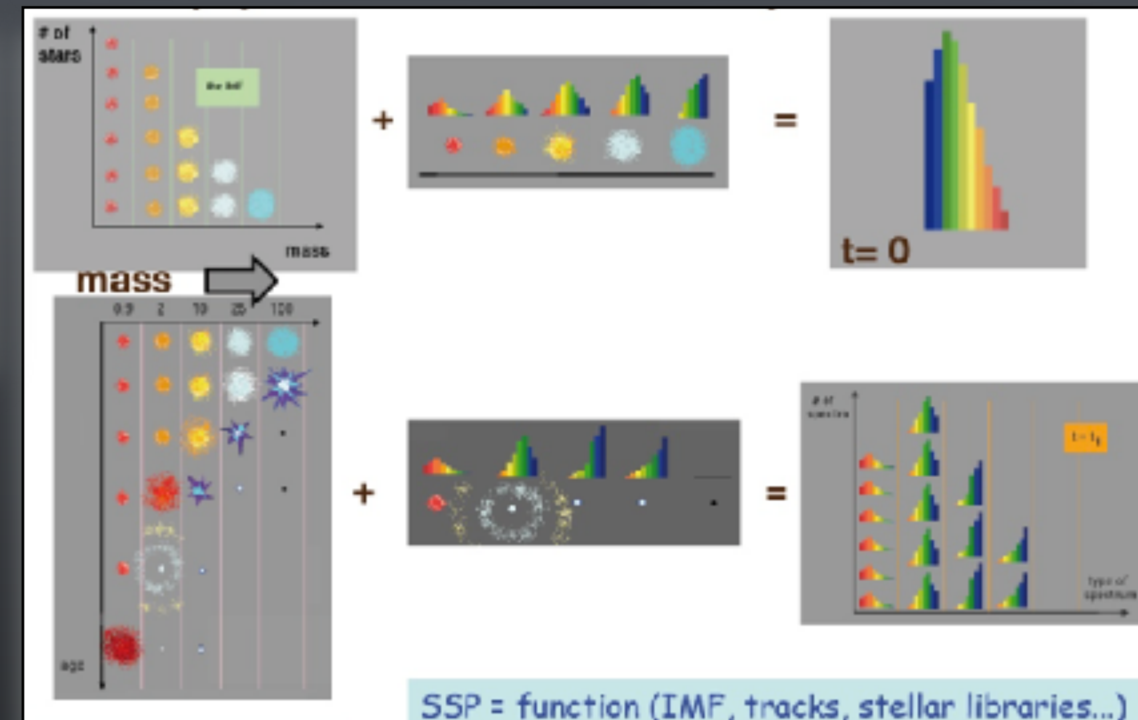






wavelength log lookback time

Models: Ingredients

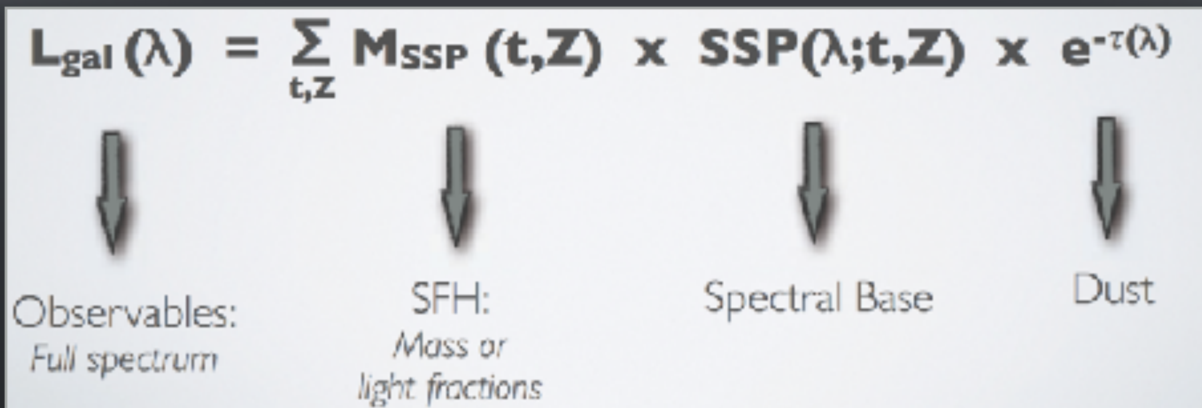


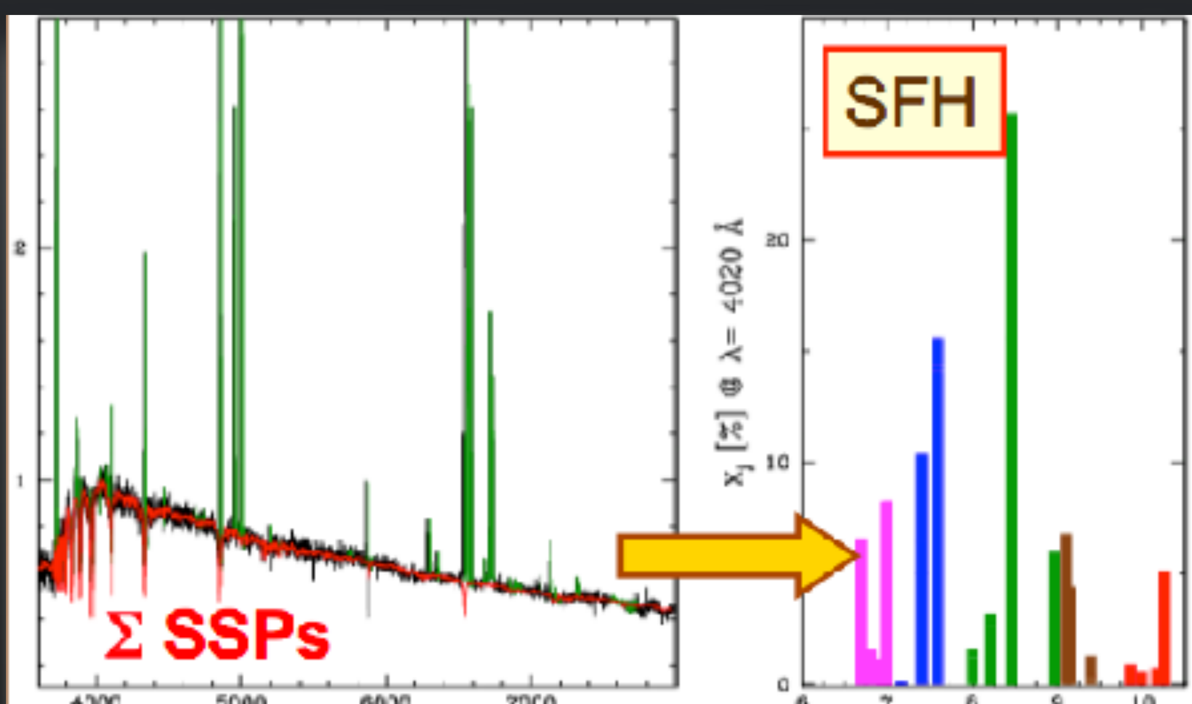
SFH, Mass, age, metallicity, Av, SFR, sSFR, surface mass density

- Evolutionary synthesis models
  - ⋆ Tracks
  - ⋆ IMF
  - ⋆ Stellar libraries
- Full spectral fitting code

Lookback time studies: SFH of nearby galaxies

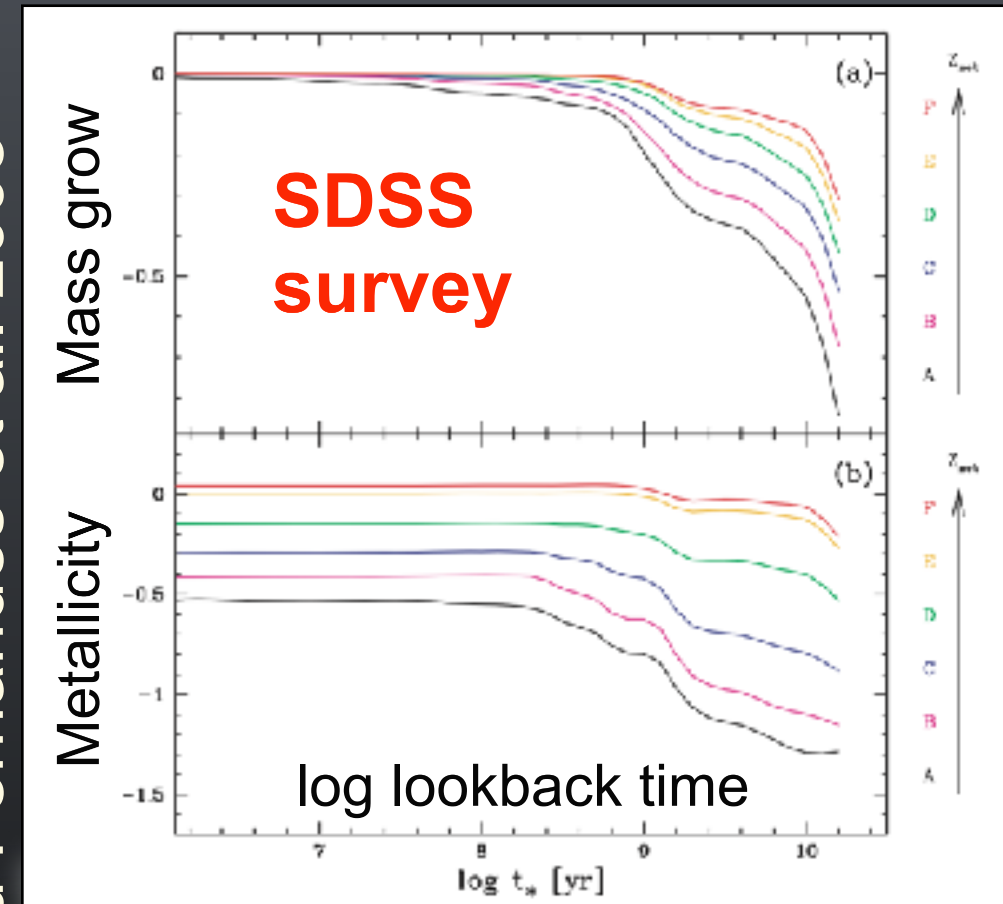
Fossil record: Full spectral synthesis





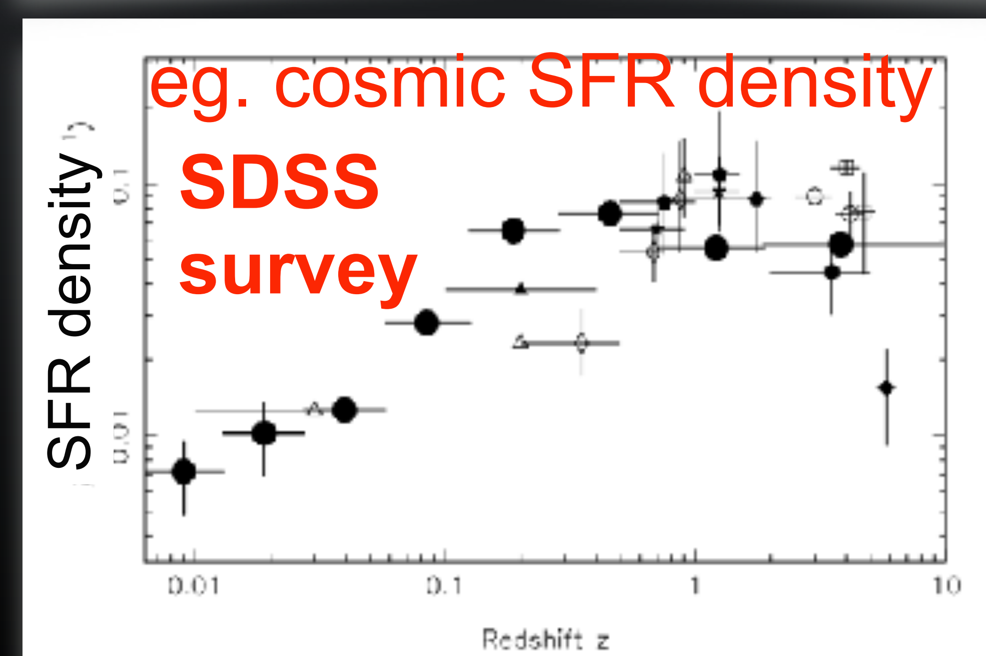
eg. Mass and Metallicity assembly

Cid Fernandes et al. 2008

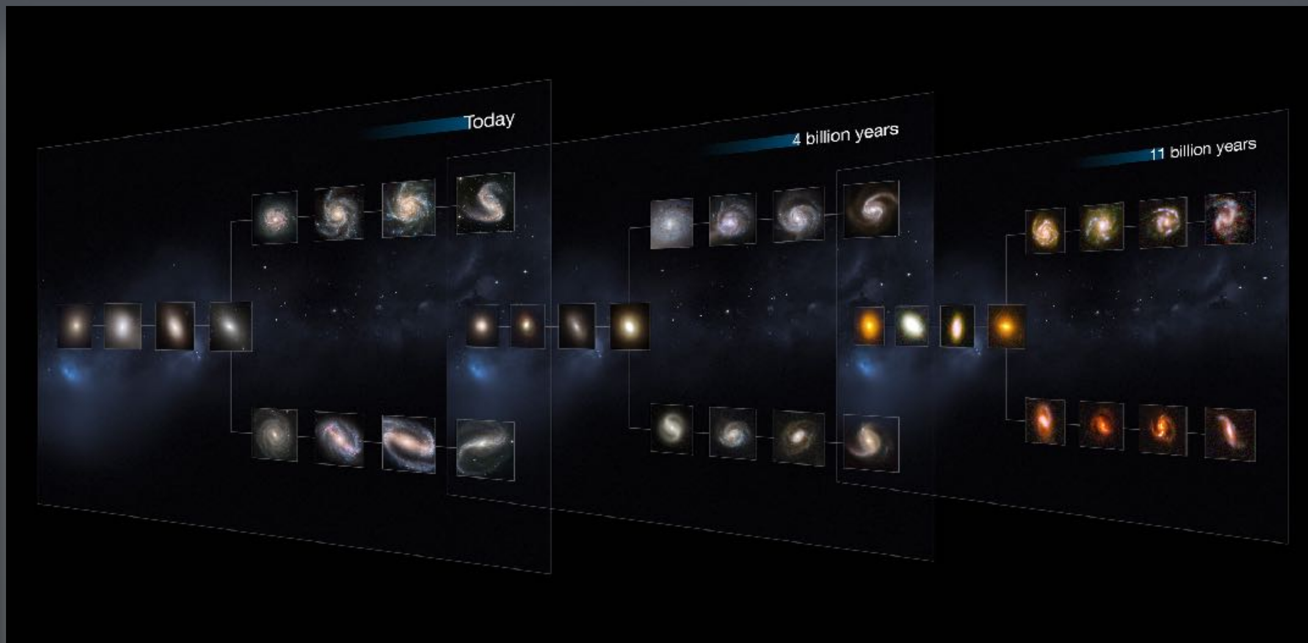


R. Cid Fernandes,[1*] N. V. Asari,[1] L. Sodré Jr.,[2] G. Stasińska,[3] A. Mateus,[2] J. P. Torres-Papaqui[1] and W. Schoenell[1]

Heavens et al. 2007

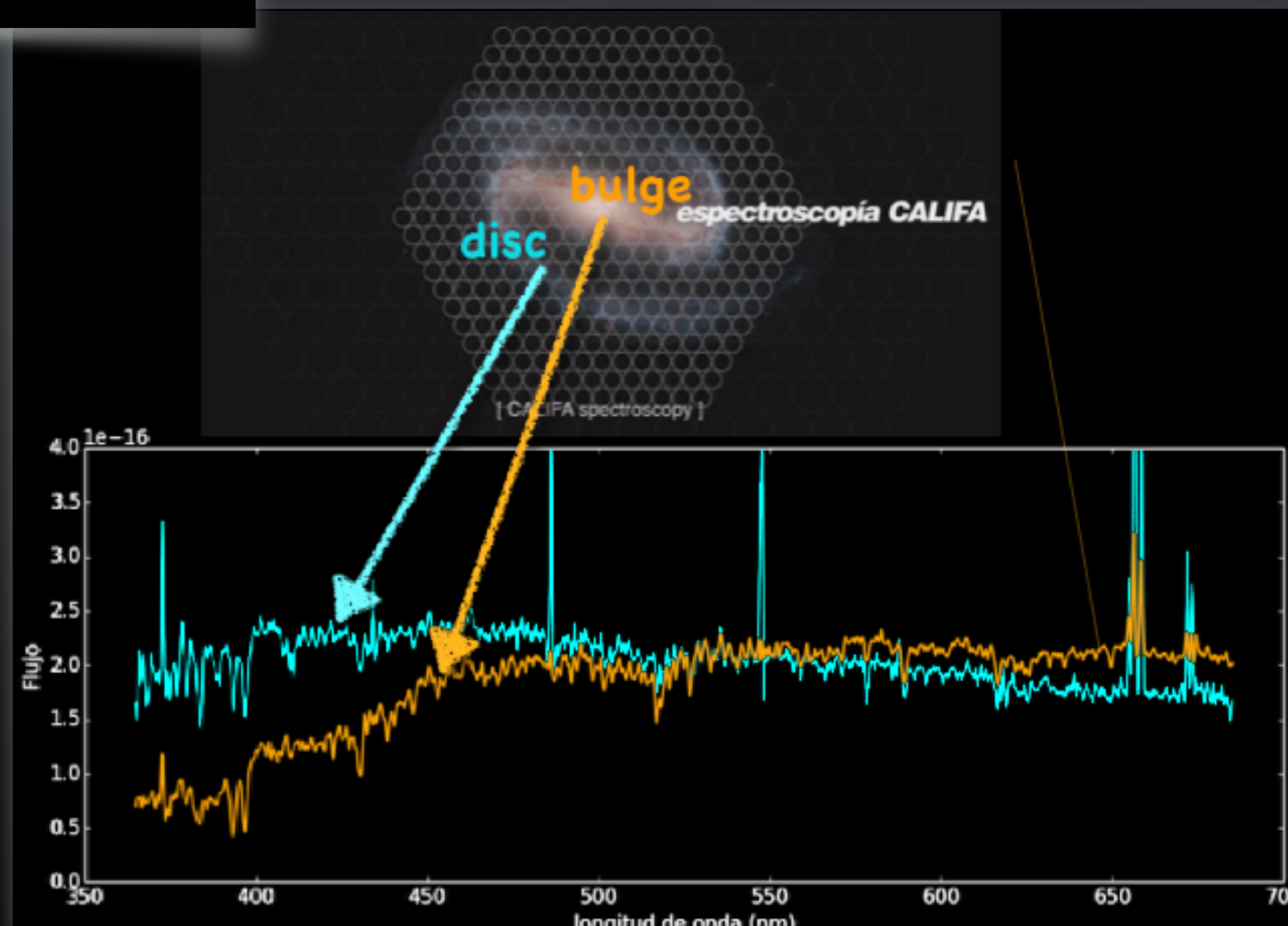


Spatially resolved SFH of galaxies



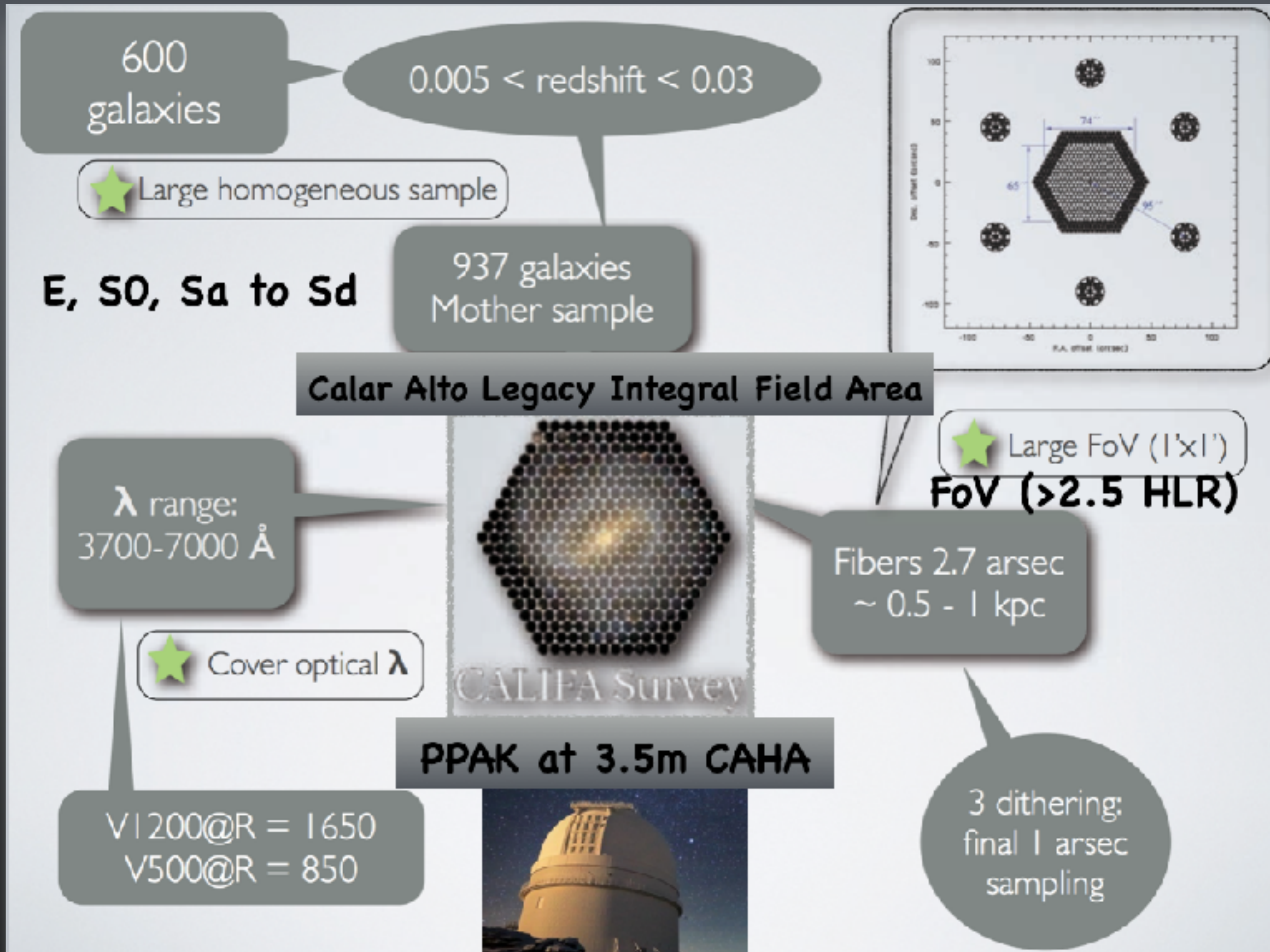
- Why to study the spatial resolved properties of galaxies?
- How did the first structures formed and evolved to explain the diversity of galaxies observed today?
- How did the bulges and disks formed?

IFS:
Spatially resolved the properties of galaxies



IFS: PPaK@3.5m CAHA

CALIFA: Spatially resolved properties of galaxies



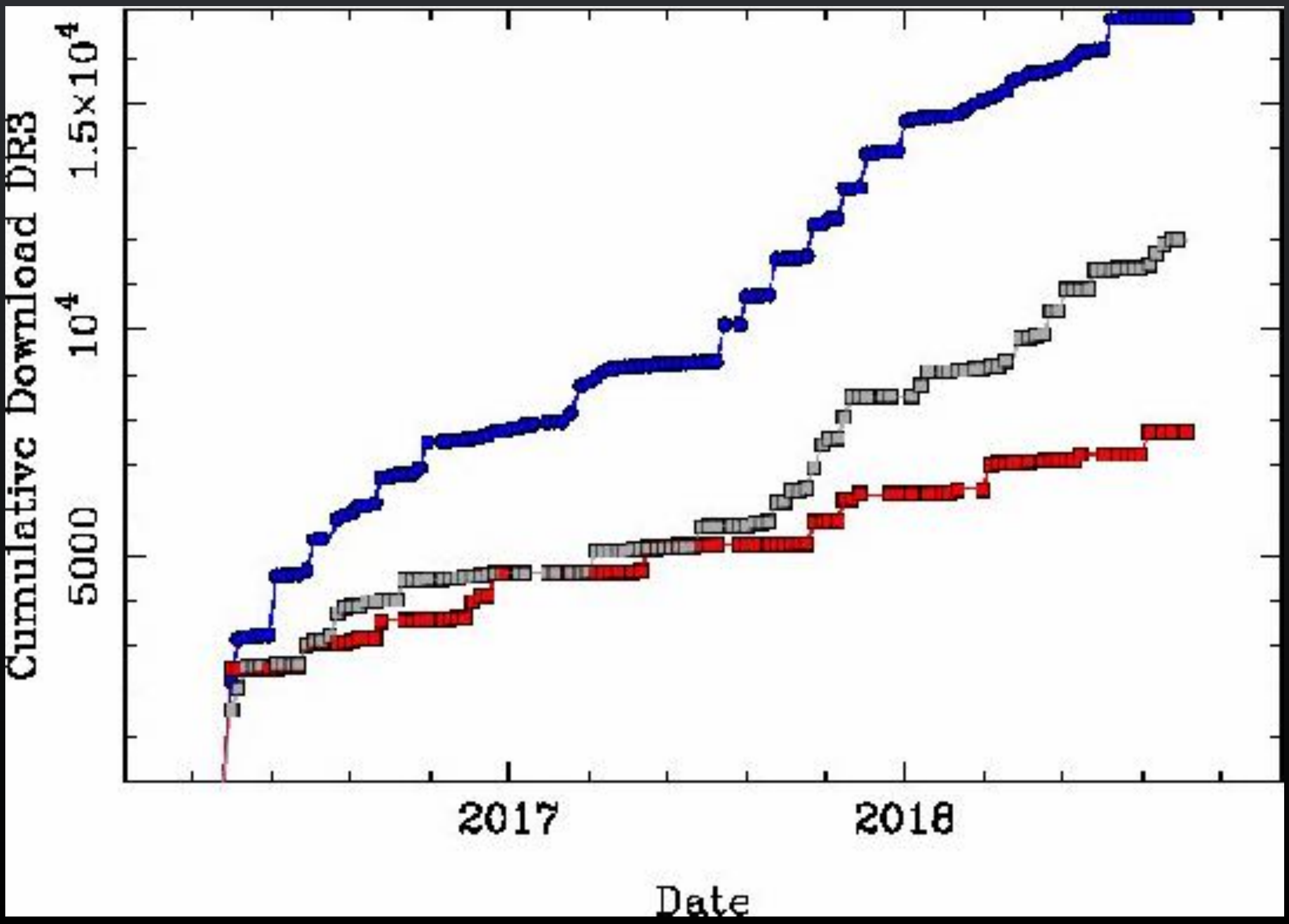
- Sánchez, et al, 2012, A&A 538, 8.
- Husemann et al, 2013, A&A 549, 87. DR1
- García-Benito et al, 2014, A&A 549, 87. DR2
- Sánchez, et al, 2016, A&A 594, 36. DR3
- Walcher, et al, 2014, A&A 569, 1.

- Stellar populations
- Ionized gas
- Kinematics: gas and stars

CALIFA: Spatially resolved properties of galaxies

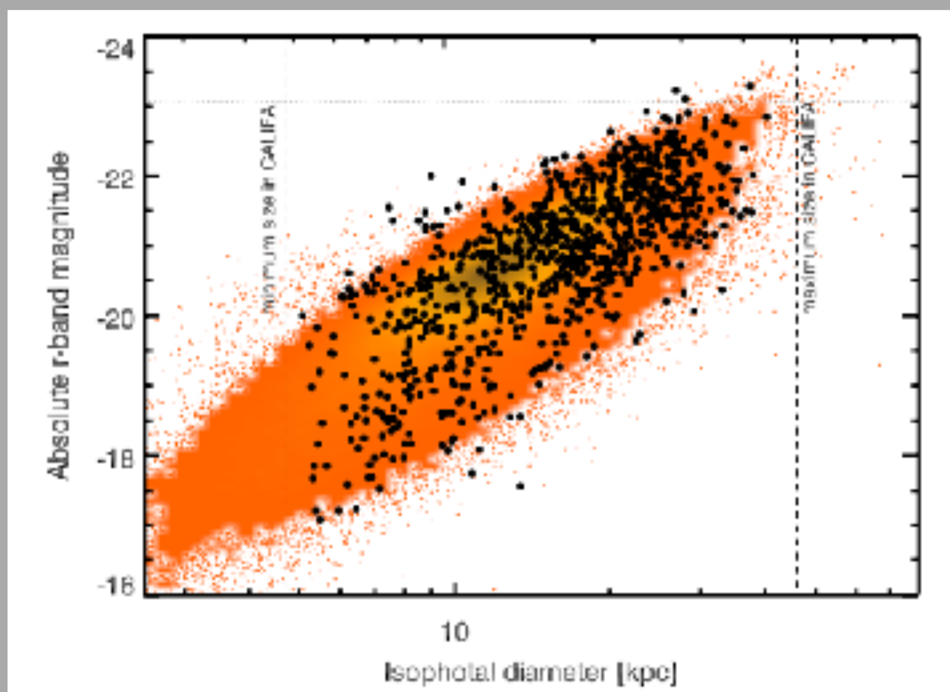
Publications with the string "CALIFA" in the title	177
Publications with the string "CALIFA" in the abstract	264
Citations to the survey presentation article [1)]	470
Citations to the DR1 article [2)]	121
Citations to the DR2 article [3)]	100
Citations to the DR3 article [4)]	58

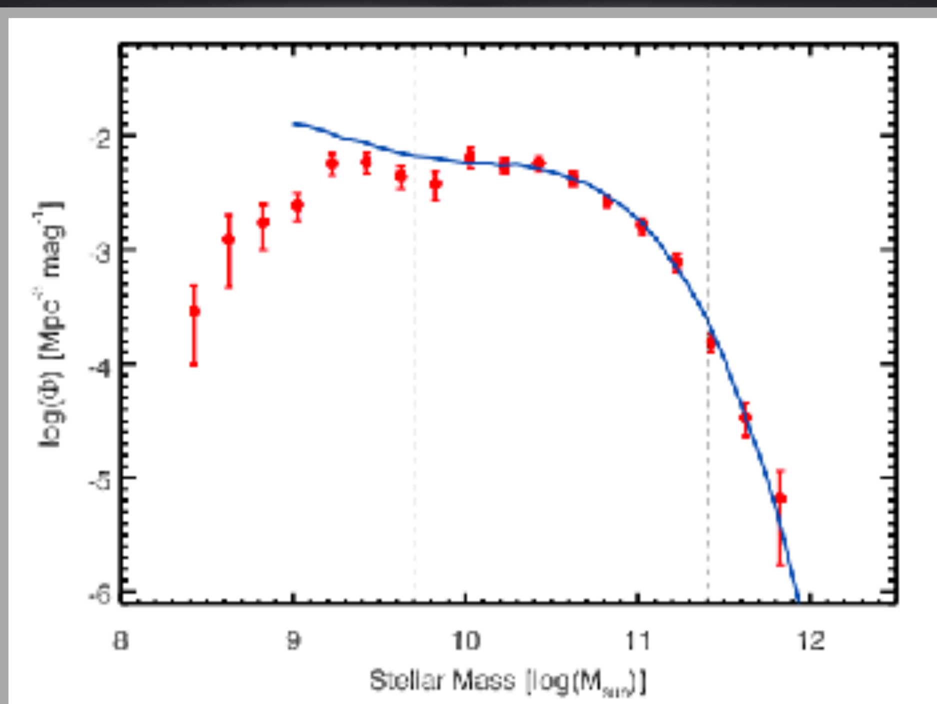
- 20+ PhDs
- 20000 data cubes downloads



CALIFA mother sample

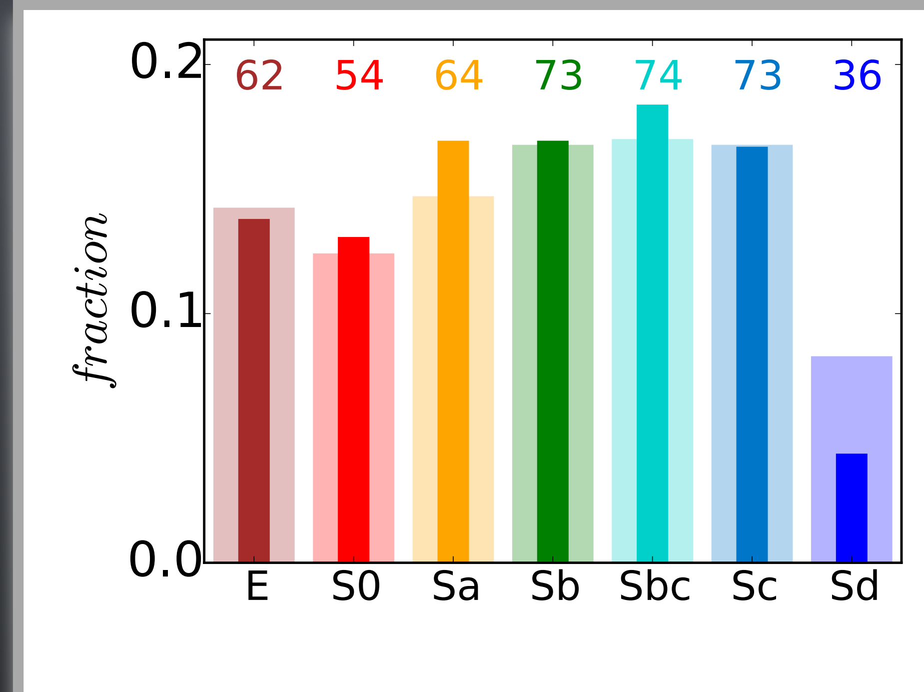
- 937 galaxies
- 0.005 < z < 0.03
- 45" < isoA_r < 79.2"

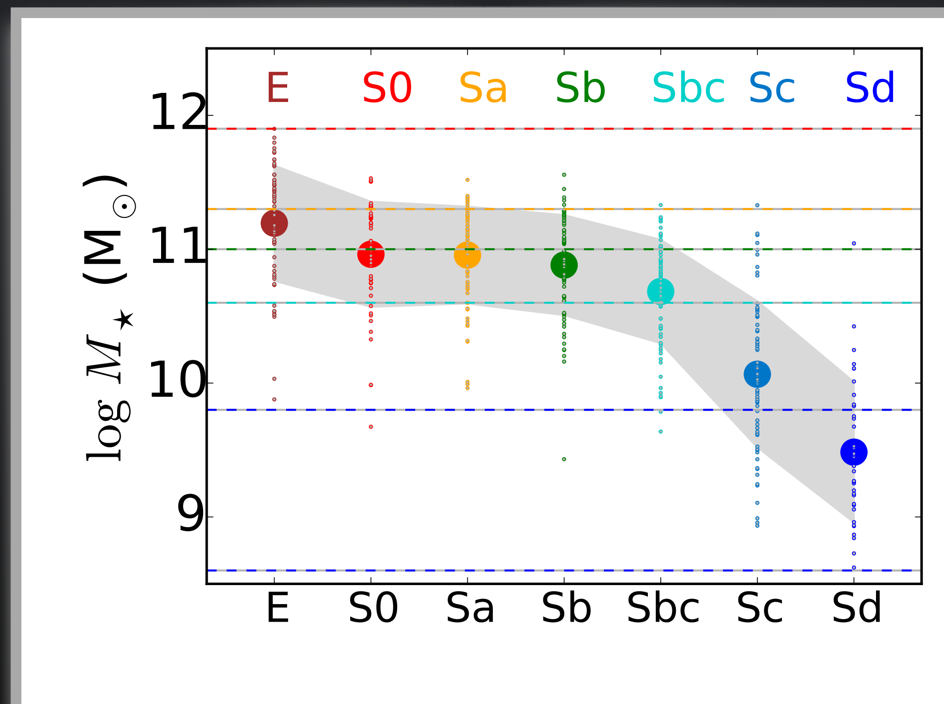




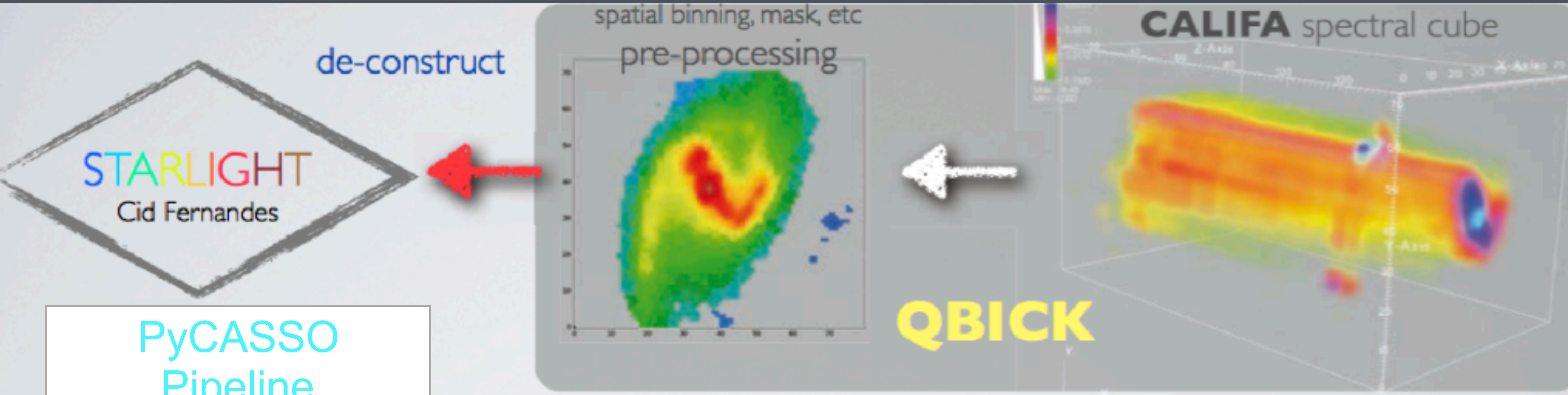
Sub-sample in SFH studies

- 436 galaxies (mergers excluded)
- V500 + V1200 COMBO

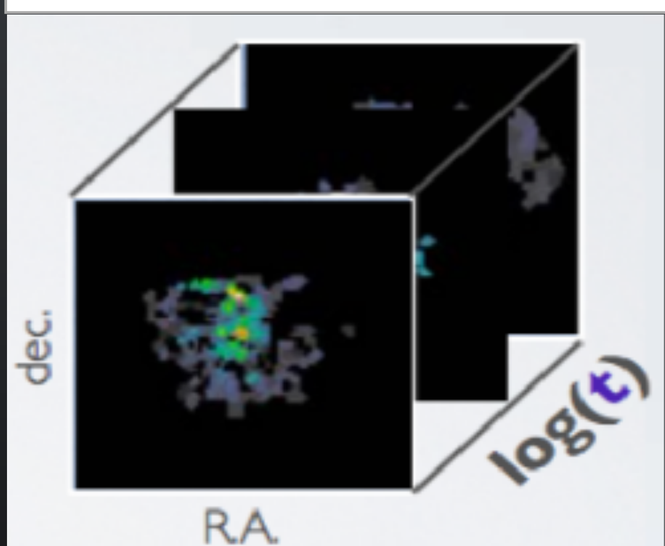




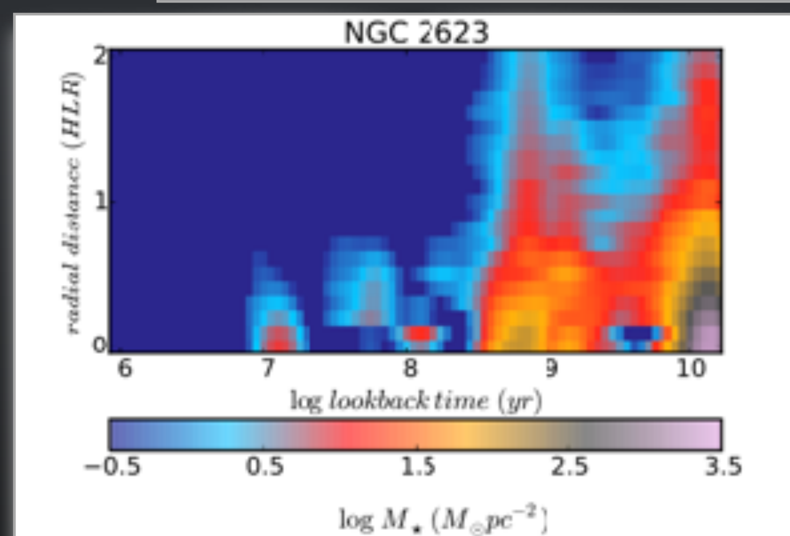
Spatially resolved SFH of galaxies: PyCASSO Pipeline

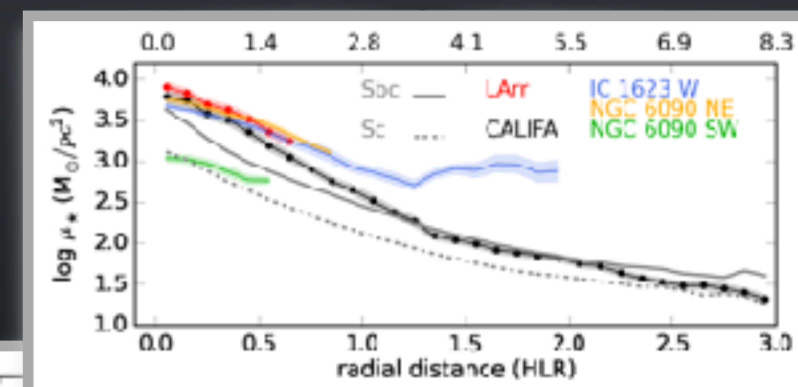


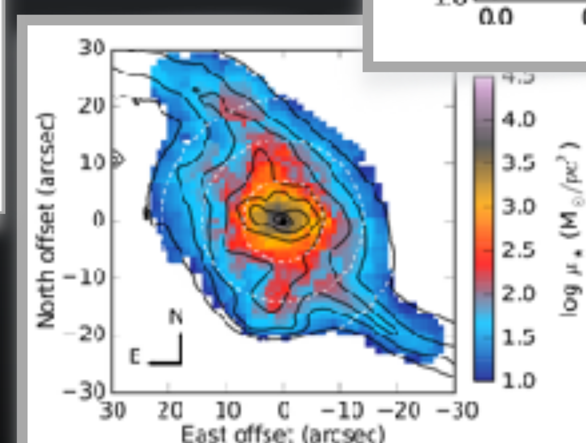
PyCASSO Pipeline



Data Products







http://pycasso.iaa.es/

http://pycasso.ufsc.br/

- Cid Fernandes González Delgado, et al. 2014 A&A, 561, 30
- Cid Fernandes, Pérez, García-Benito, González Delgado, et al. 2013 A&A, 557, 86
- de Amorim, PhD 2014; de Amorim, et al. 2017 MNRAS, 471, 3727

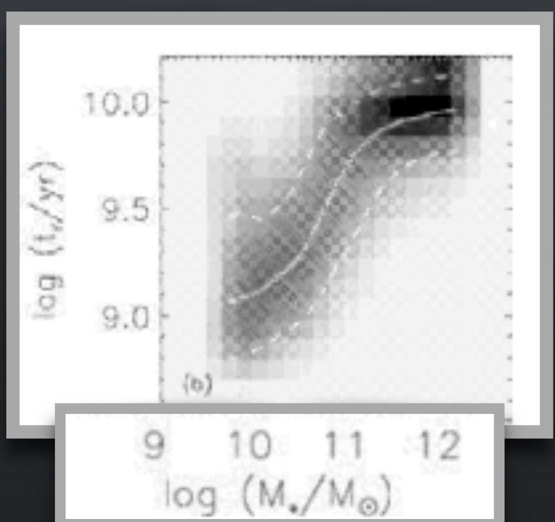
Are global and/or local processes responsible of driving the evolution of galaxies?

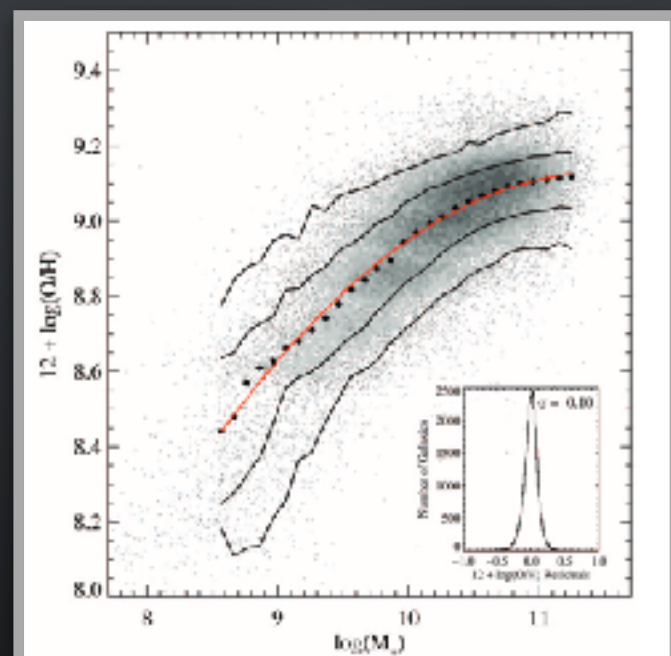
Global relations

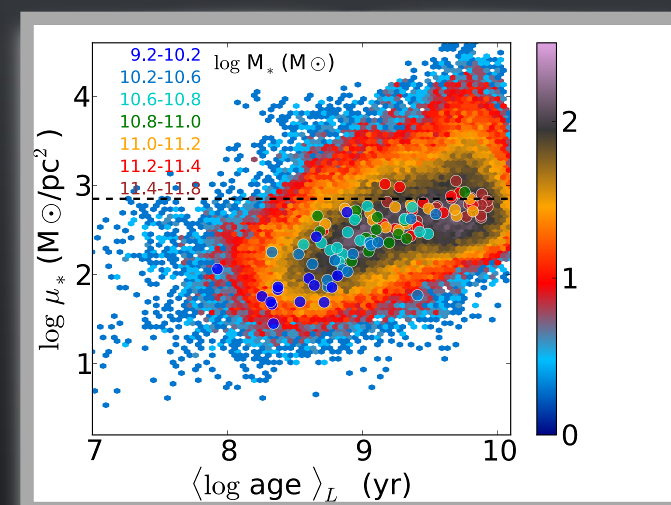
- Mass - Metallicity
- Mass - SFR (MSSF)
- Mass - age

Local relations

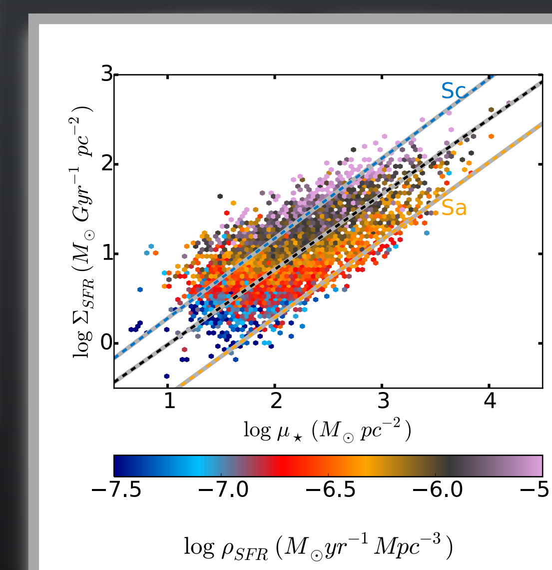
- μ⋆ - local Z
- μ⋆ - Σ_{SFR}
- μ⋆ - local age

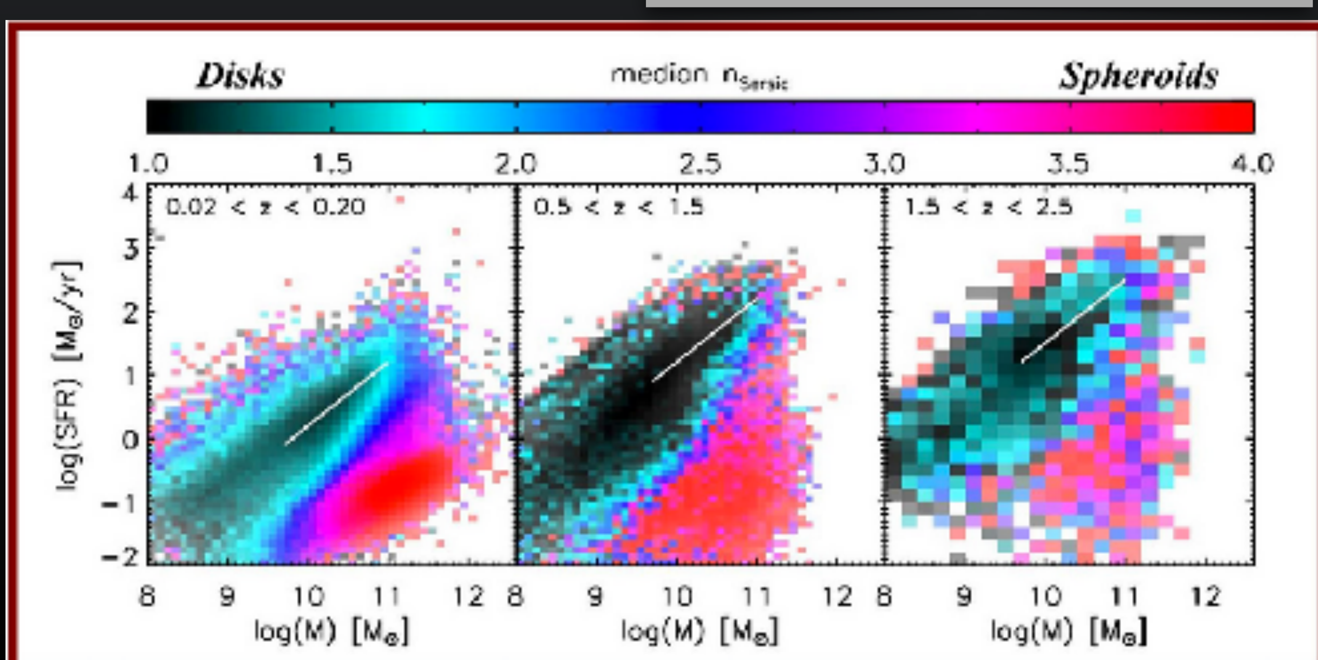


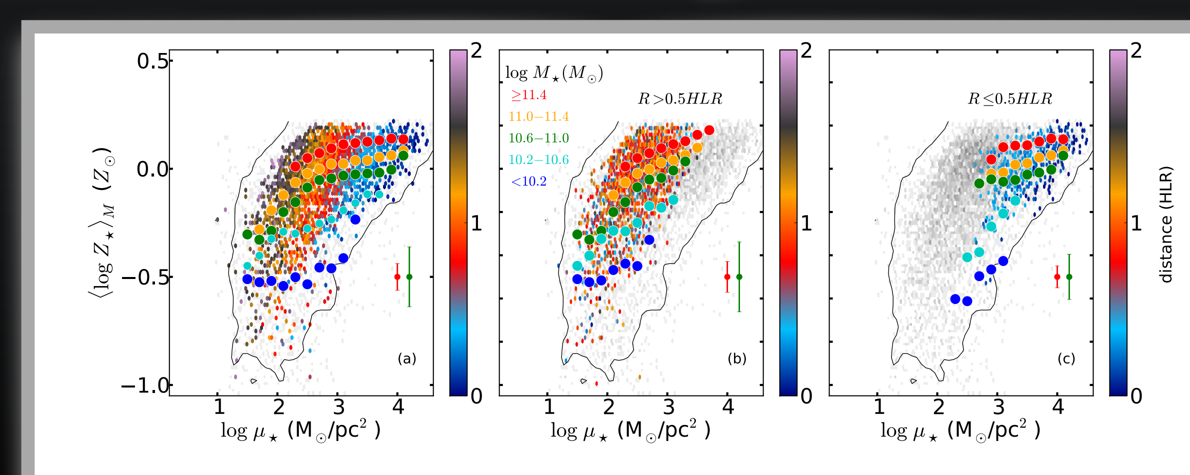




MSSF





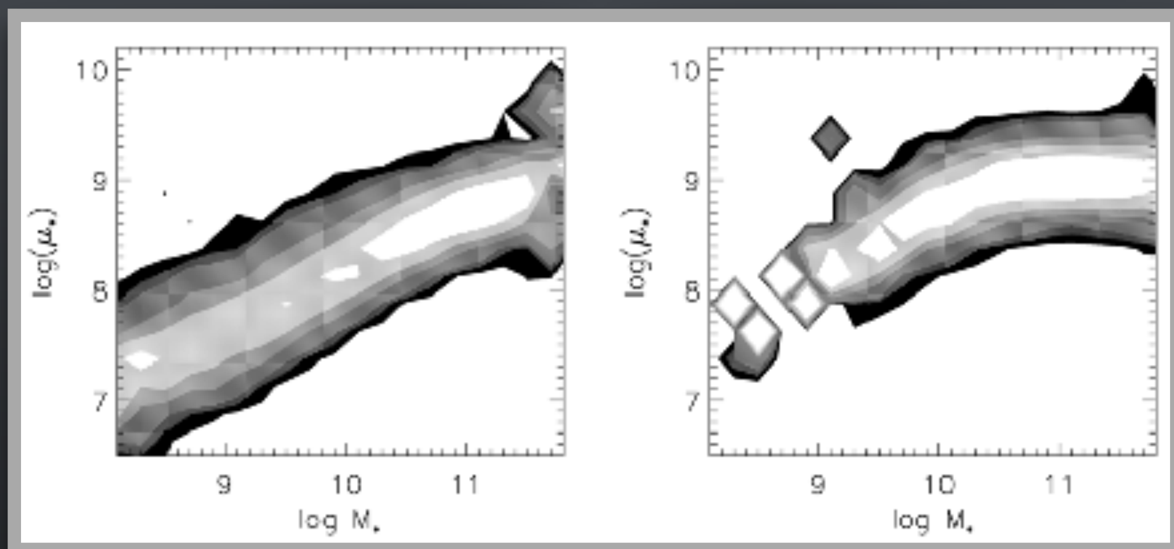


Stellar mass surface density (μ✶)- age

Global relation

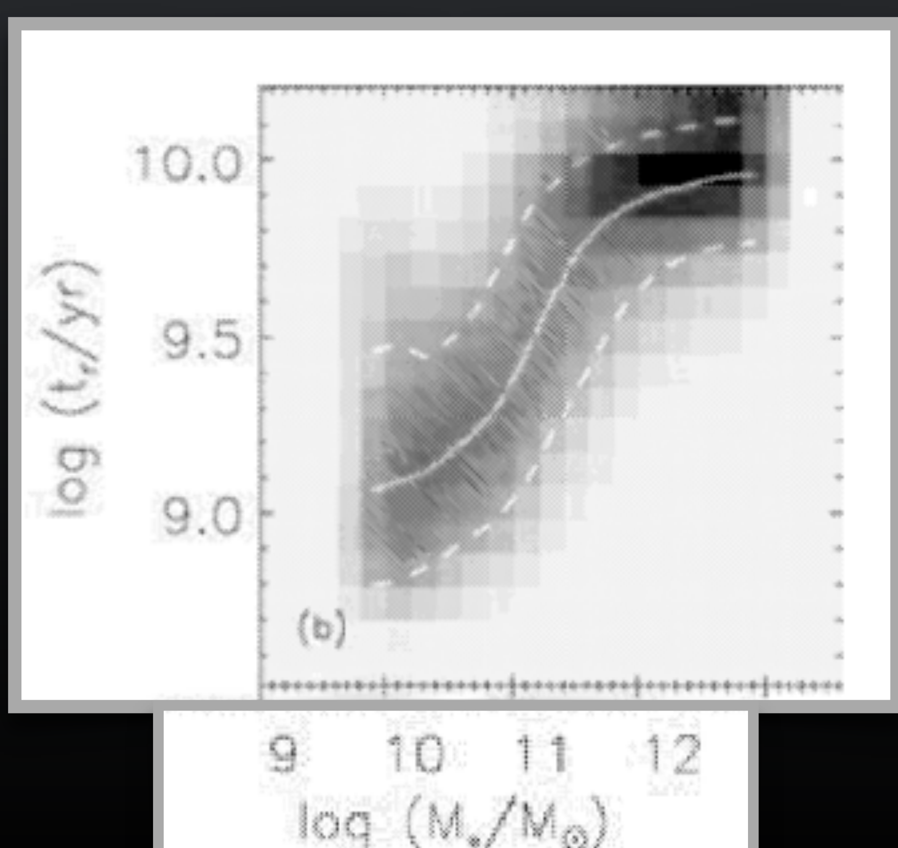
* SDSS: μ✶ - M✶

Kauffmann +, 2003



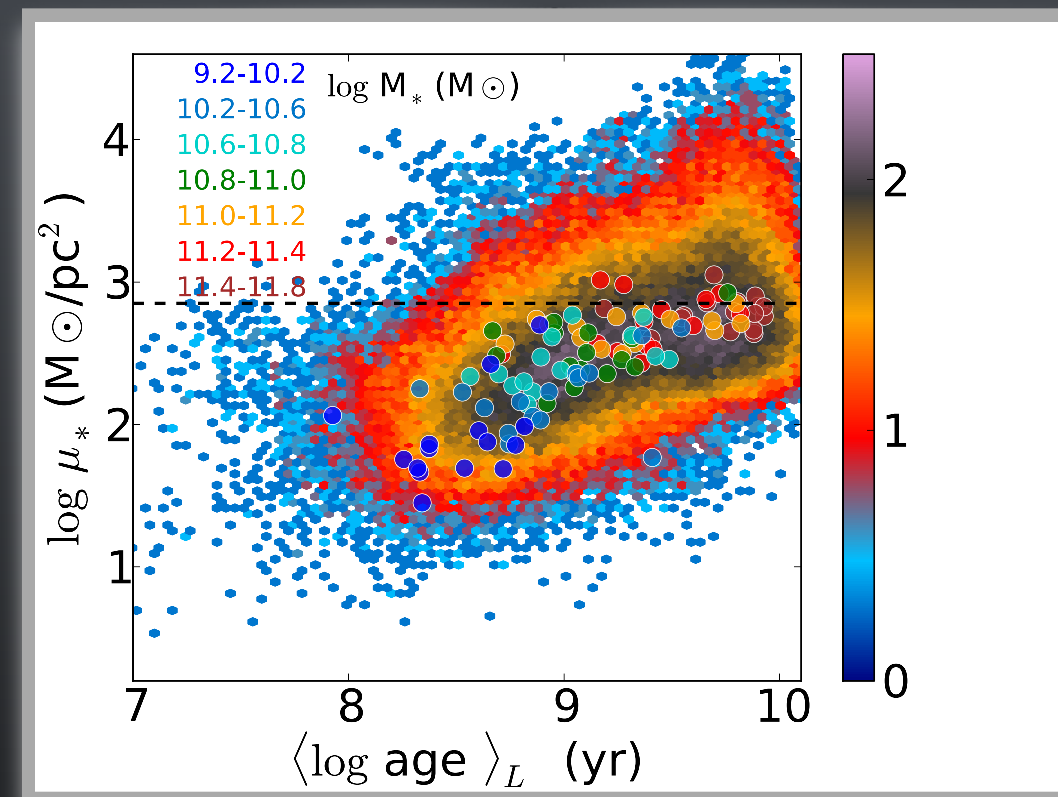
* SDSS: M✶ - age

Gallazzi +, 2005



Local relation

* CALIFA: μ✶ - age



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

SFH in disks and spheroids

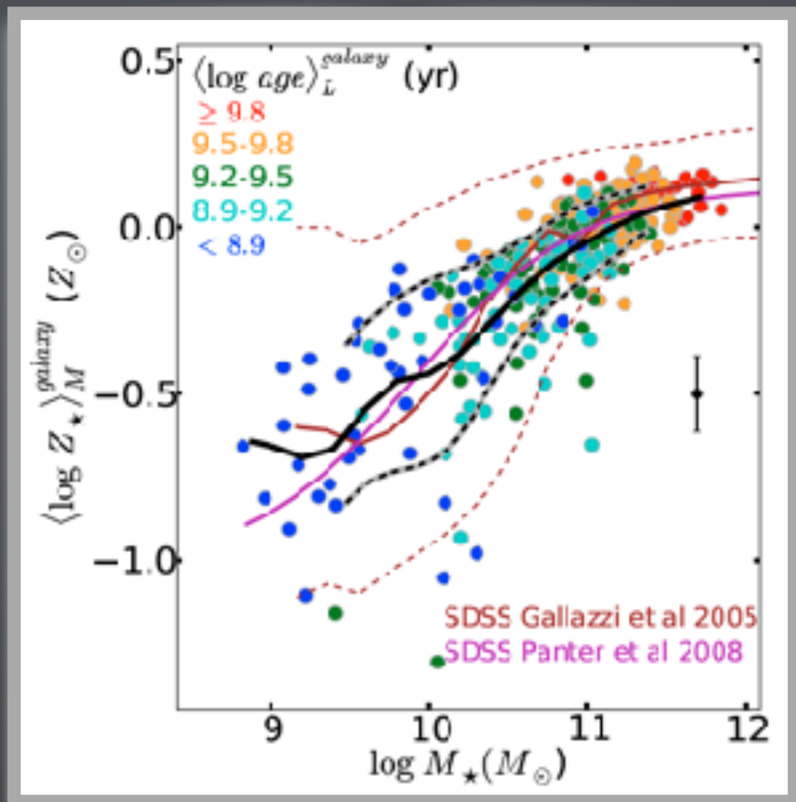
- ✳ Disks: μ✶ drives the ages (SFH) of galaxies
- ✳ Spheroids: M✶

Stellar mass surface density (μ★)- Metallicity (Z★)

SDSS: global M★ - Z★

Gallazzi +, 2005
Panter +, 2008

Global relation (SDSS)



Local relation

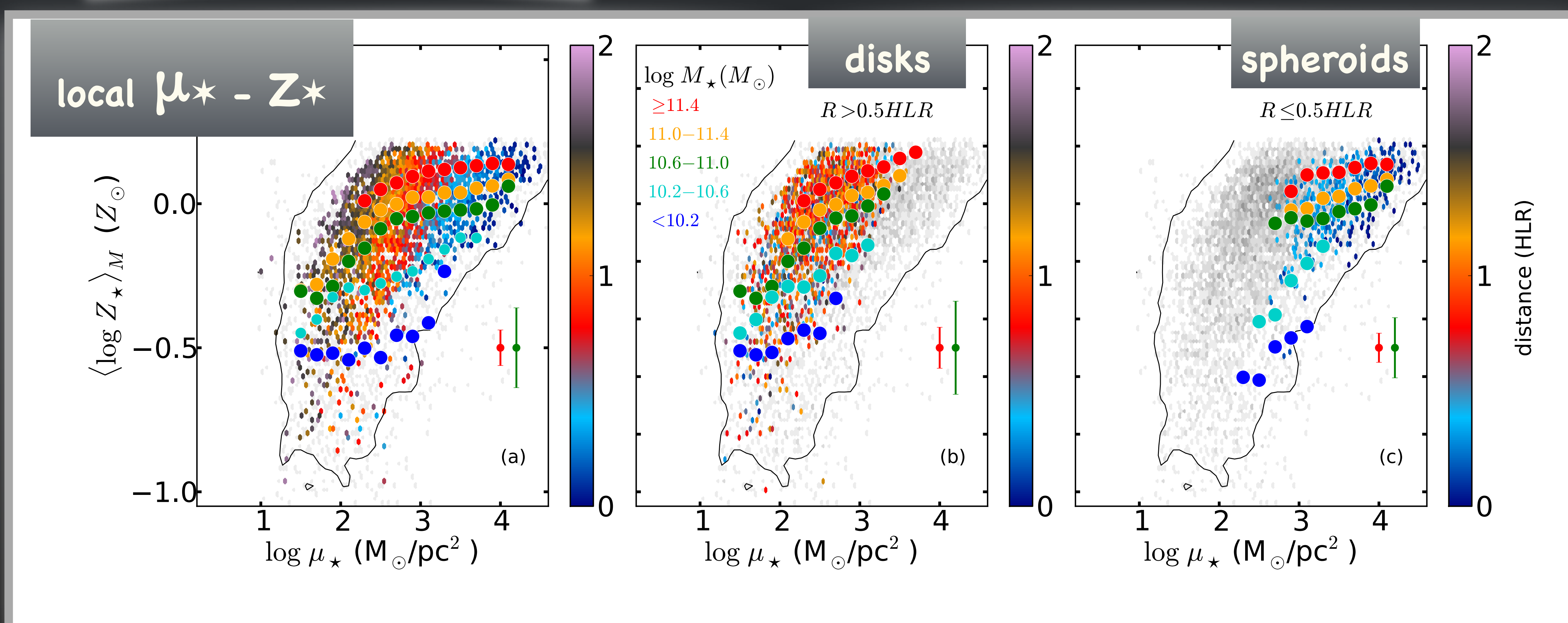
* CALIFA: μ★ -Z★

Chemical enrichment

✳Disks: μ✶ 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

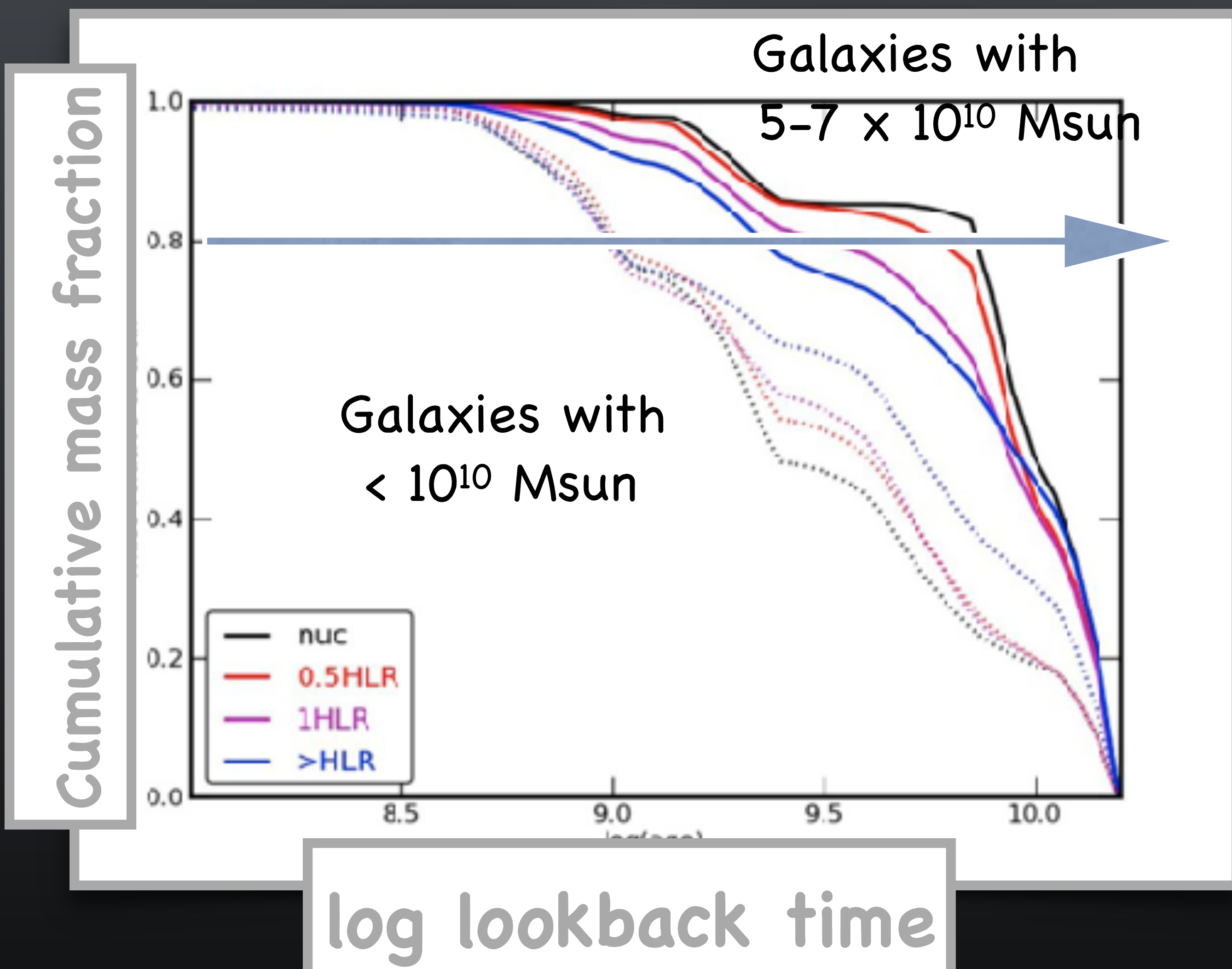


THE ASTROPHYSICAL JOURNAL LETTERS, 764:L1 (6pp), 2013 February 10
doi:10.1088/2041-8205/764/1/L1

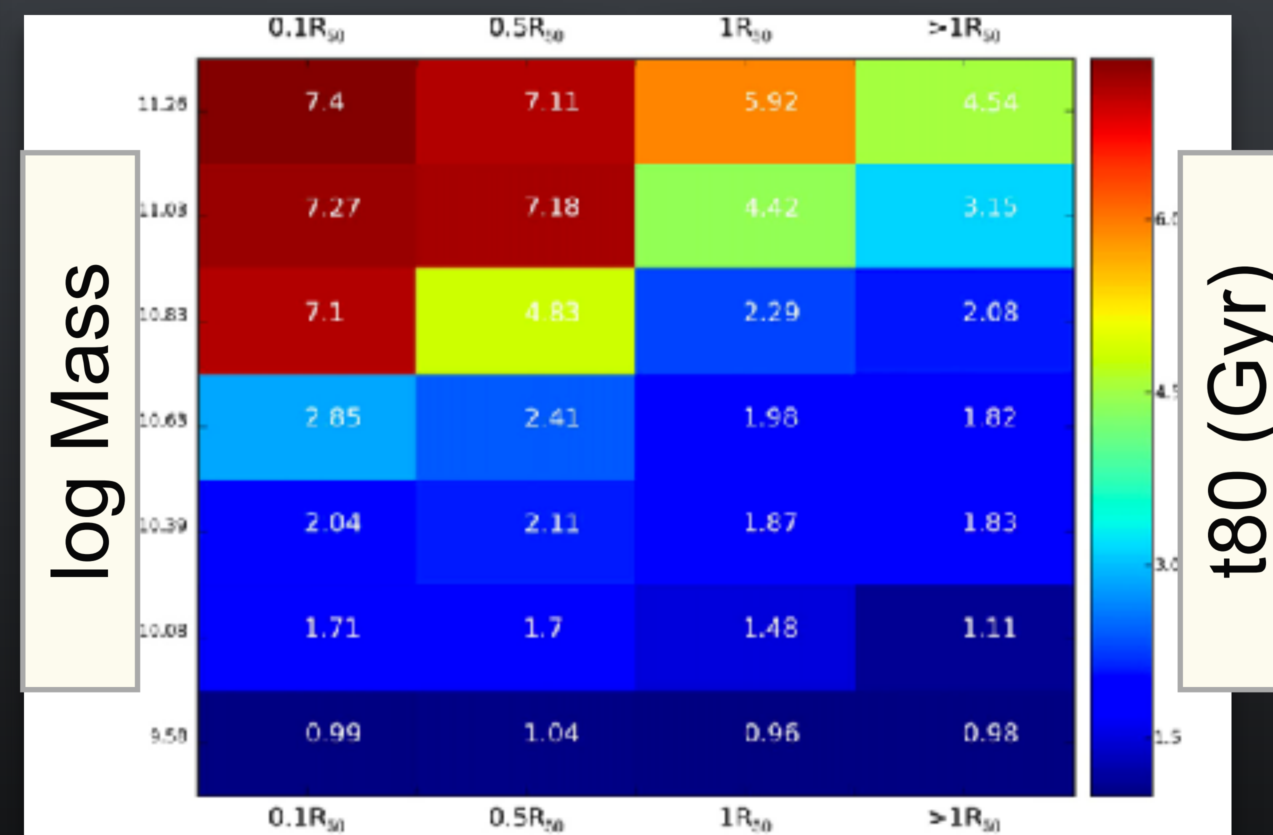
2013, ApJL, 764, L1

THE EVOLUTION OF GALAXIES RESOLVED IN SPACE AND TIME: A VIEW OF INSIDE-OUT GROWTH FROM THE CALIFA SURVEY

E. Pérez[1], R. Cid Fernandes[1,2], R. M. González Delgado[1], R. García-Benito[1], S. F. Sánchez[1,3], B. Husemann[4], D. Mast[1,3], J. R. Rodón[1], D. Kupko[4], N. Backsmann[4], A. L. de Amorim[2], G. van de Ven[5], J. Walcher[4], L. Wisotzki[4], C. Cortijo-Ferrero[1], and CALIFA collaboration[6]



100 CALIFA galaxies

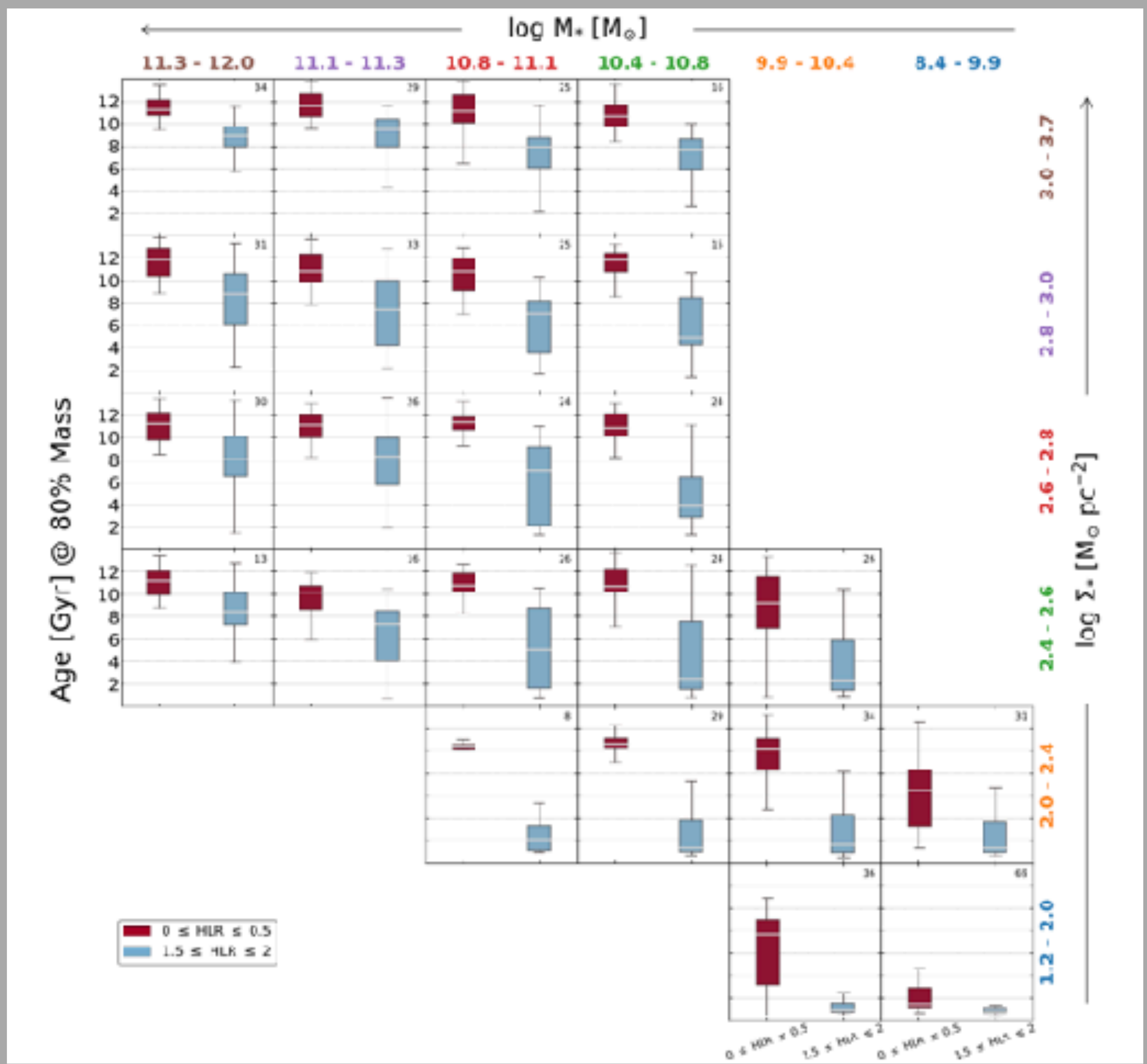


t80 = age at which galaxy gets 80% of mass

Mass assembly:
Galaxies grow inside-out

- In the inner regions t80 > t80 in outer regions
- Galaxies (including low mass) grow inside-out
- The downsizing is preserved with the distance

Mass assembly: Galaxies grow inside-out



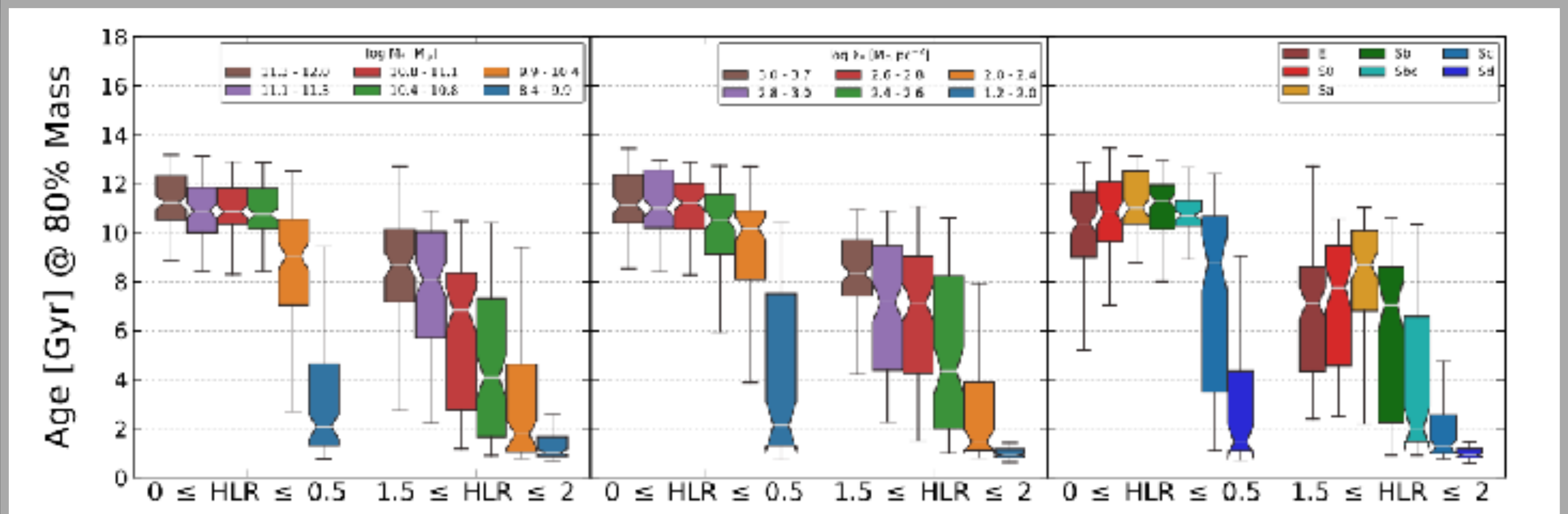
García-Benito et al., 2017, A&A, arXiv:1709.00413

The whole CALIFA sample > 600 galaxias
t80_in > t80_out

Independently :

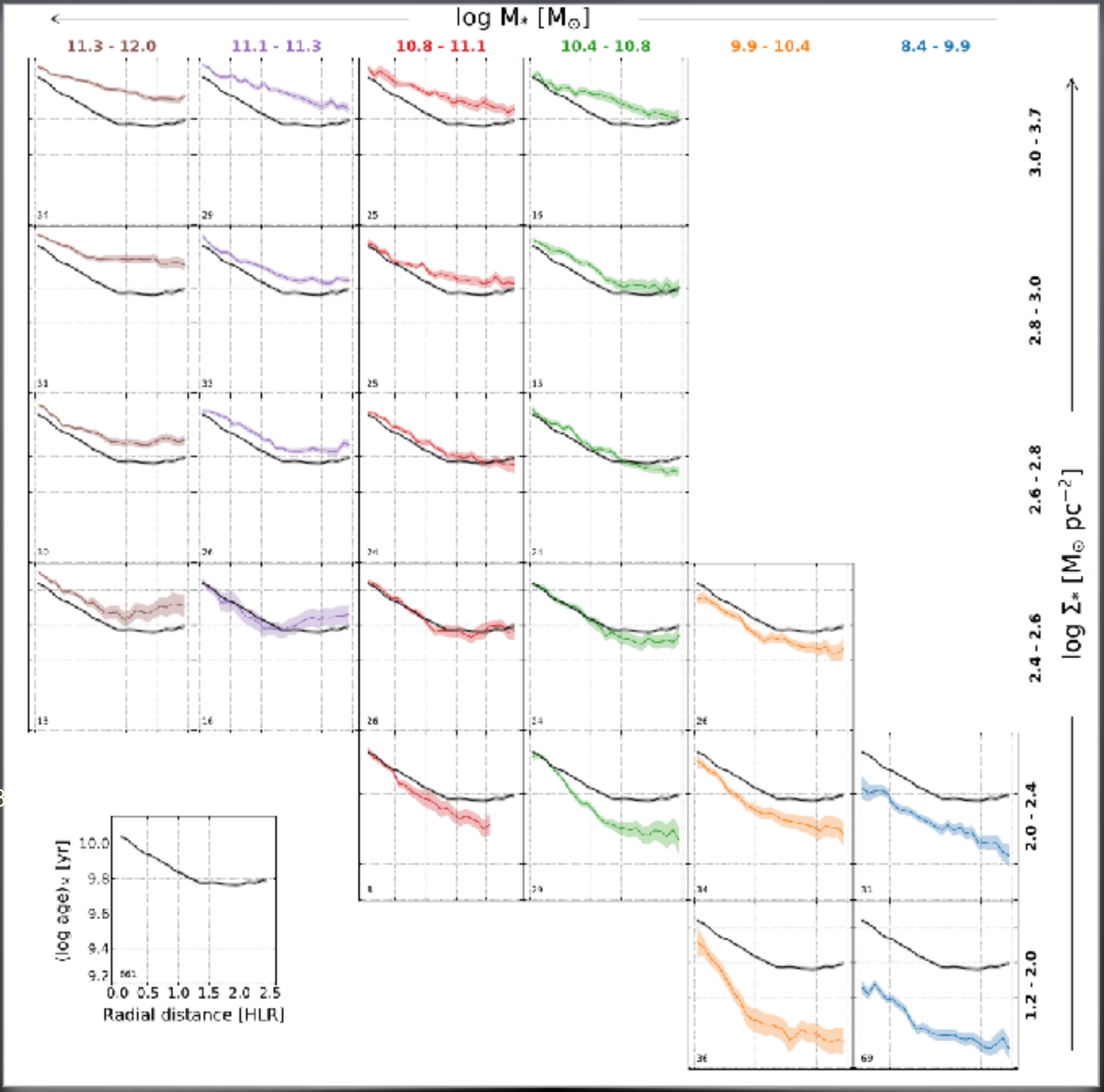
- Galaxy Mass
- Stellar Mass surface density
- Hubble type

In agreement with MaNGA by Ibarra-Medel, 2016, MNRAS, 463, 2799



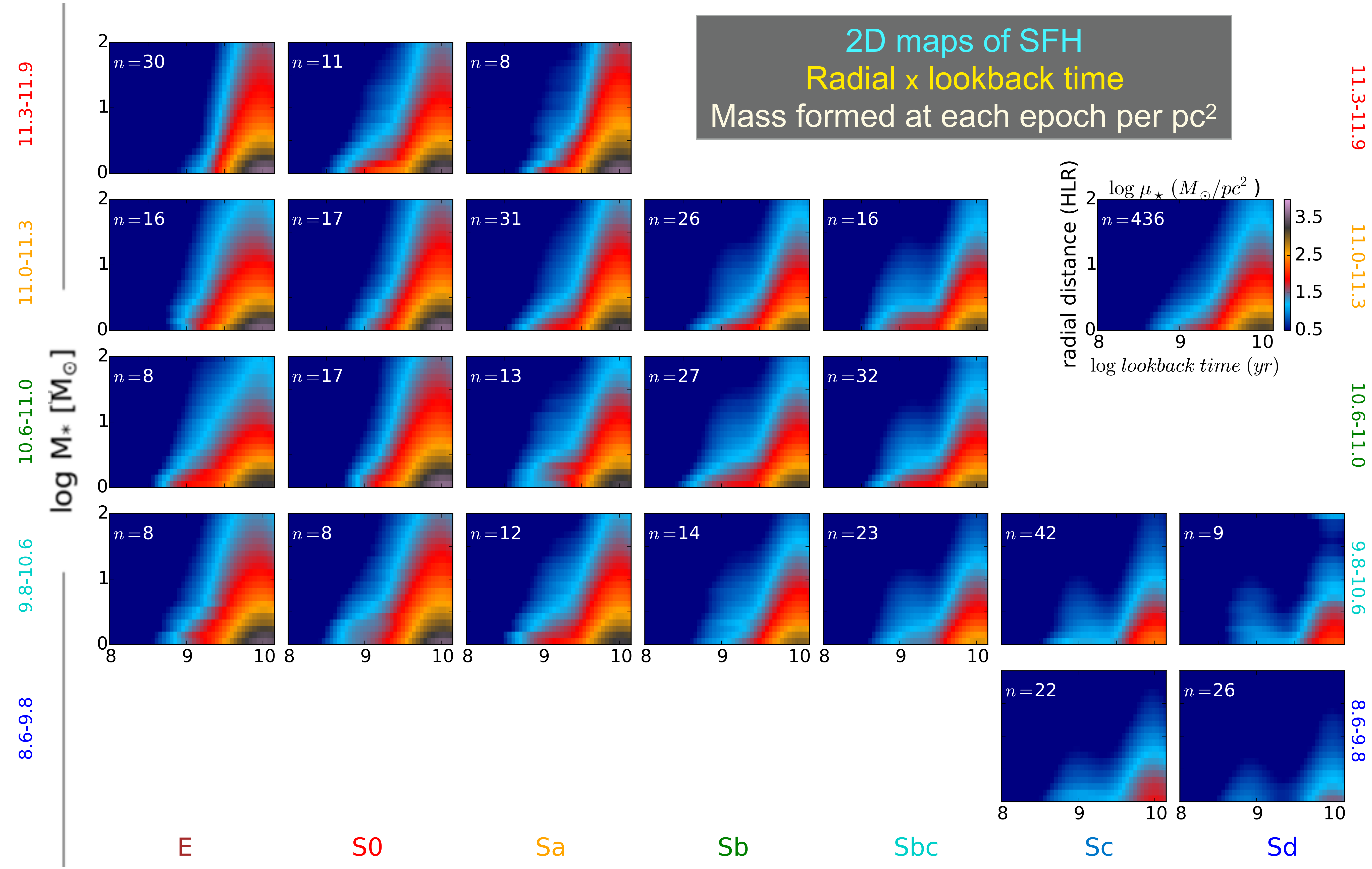
Mass assembly: Galaxies grow inside-out

Radial negative age gradients: for all types of galaxies, independent of galaxy Mass, and Hubble type

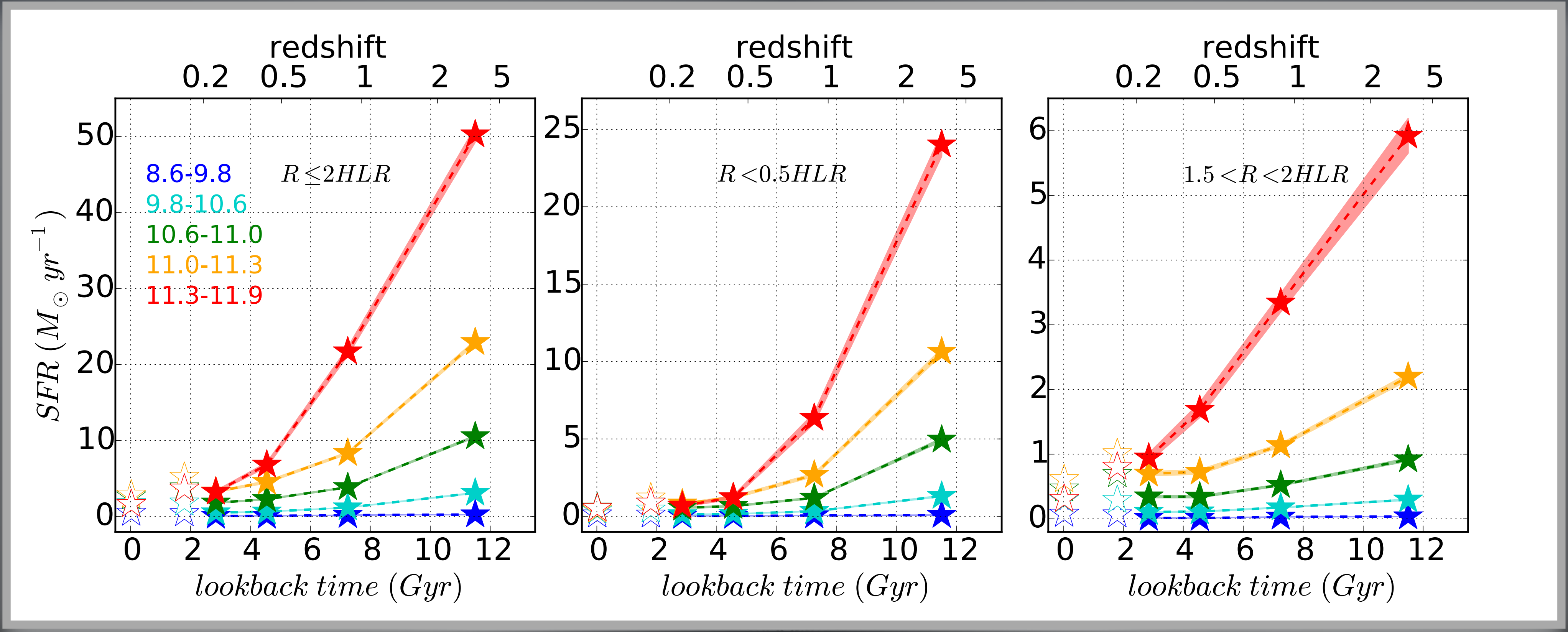


- García-Benito et al., 2017, A&A, arXiv:1709.00413
- González Delgado et al., 2015, A&A, 581, 103
- González Delgado et al., 2014, A&A, 562, 47

Spatially resolved SFH (morpholgy vs galaxy Mass)



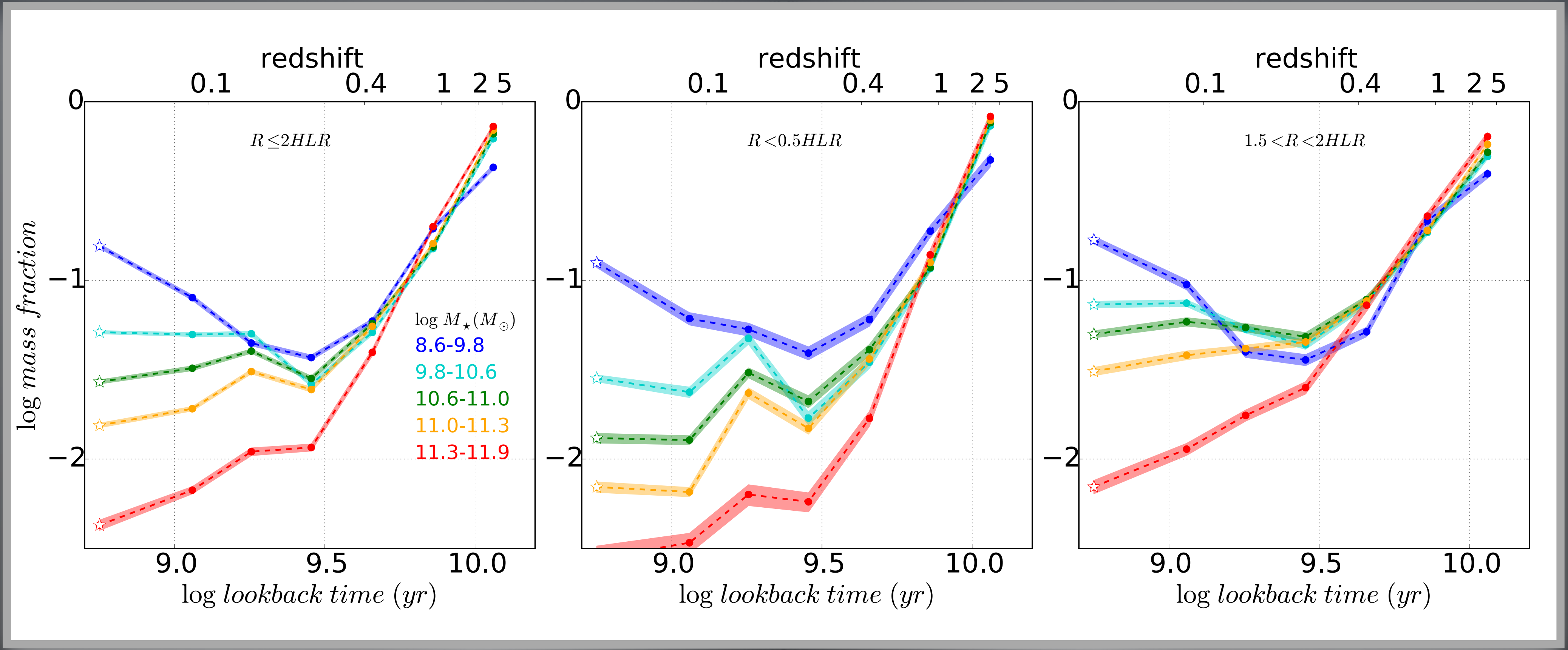
Spatially resolved SFH: SFR(t)



- SFR(t) declines rapidly as the Universe evolves.
- At any epoch, SFR is proportional to $M_\star$
- In the past, SFR was higher in the inner than in the outer regions

González Delgado +, 2017, A&A, arXiv:1706.06119

Spatially resolved SFH: Mass fraction

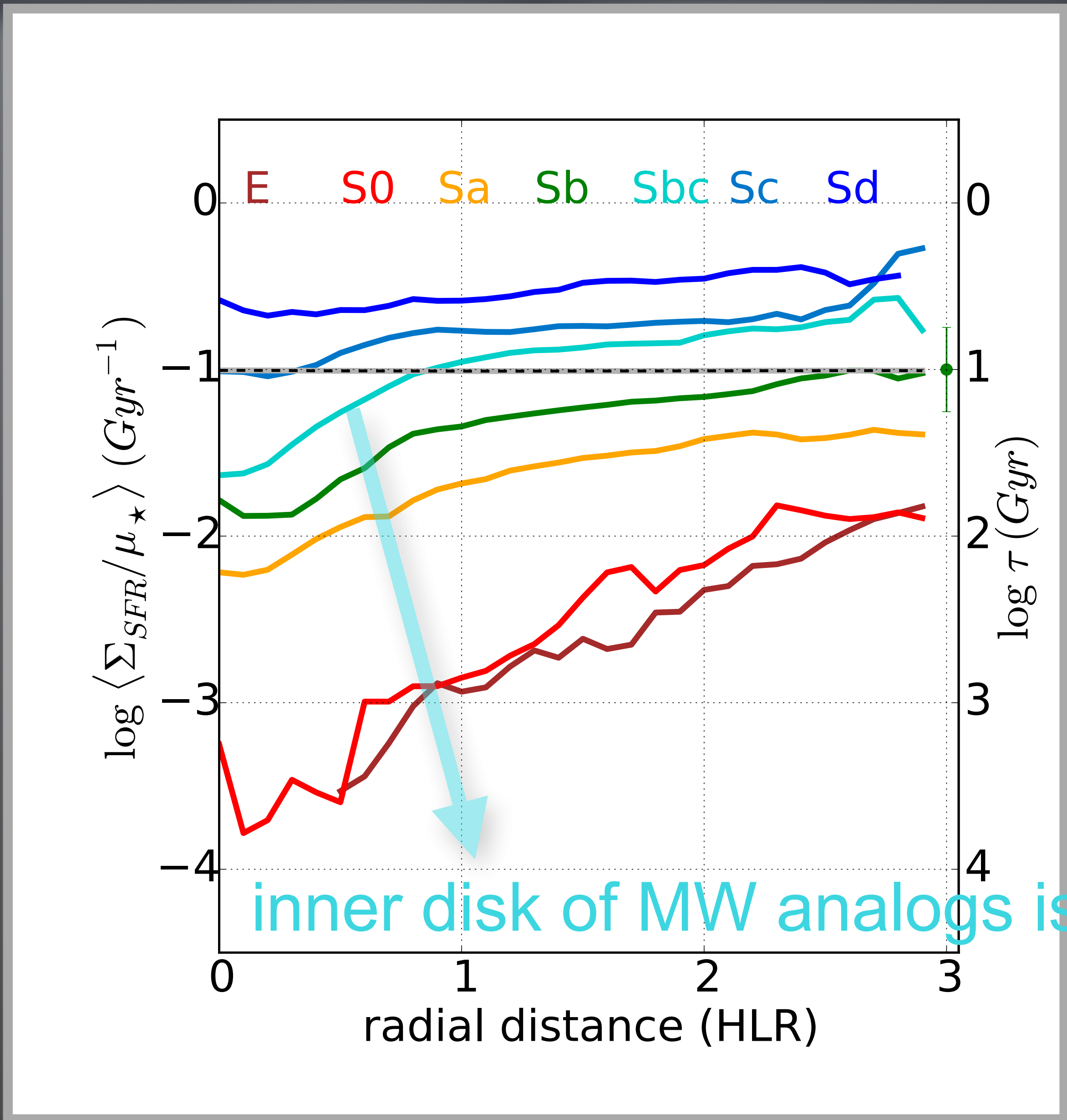


- Galaxies formed very fast.
- Peak happens at z >=2
- It is independent of $M_\star$
- Subsequent SFH depends on $M_\star$ (“downsizing” effect)

González Delgado +, 2017, A&A, arXiv:1706.06119

Star formation along the Hubble sequence

Local specific SFR: $\text{sSFR} = \Sigma_{SFR}/\mu_\star = \tau^{-1}$



inner disk of MW analogs is quenched

Galaxies are quenched inside-out

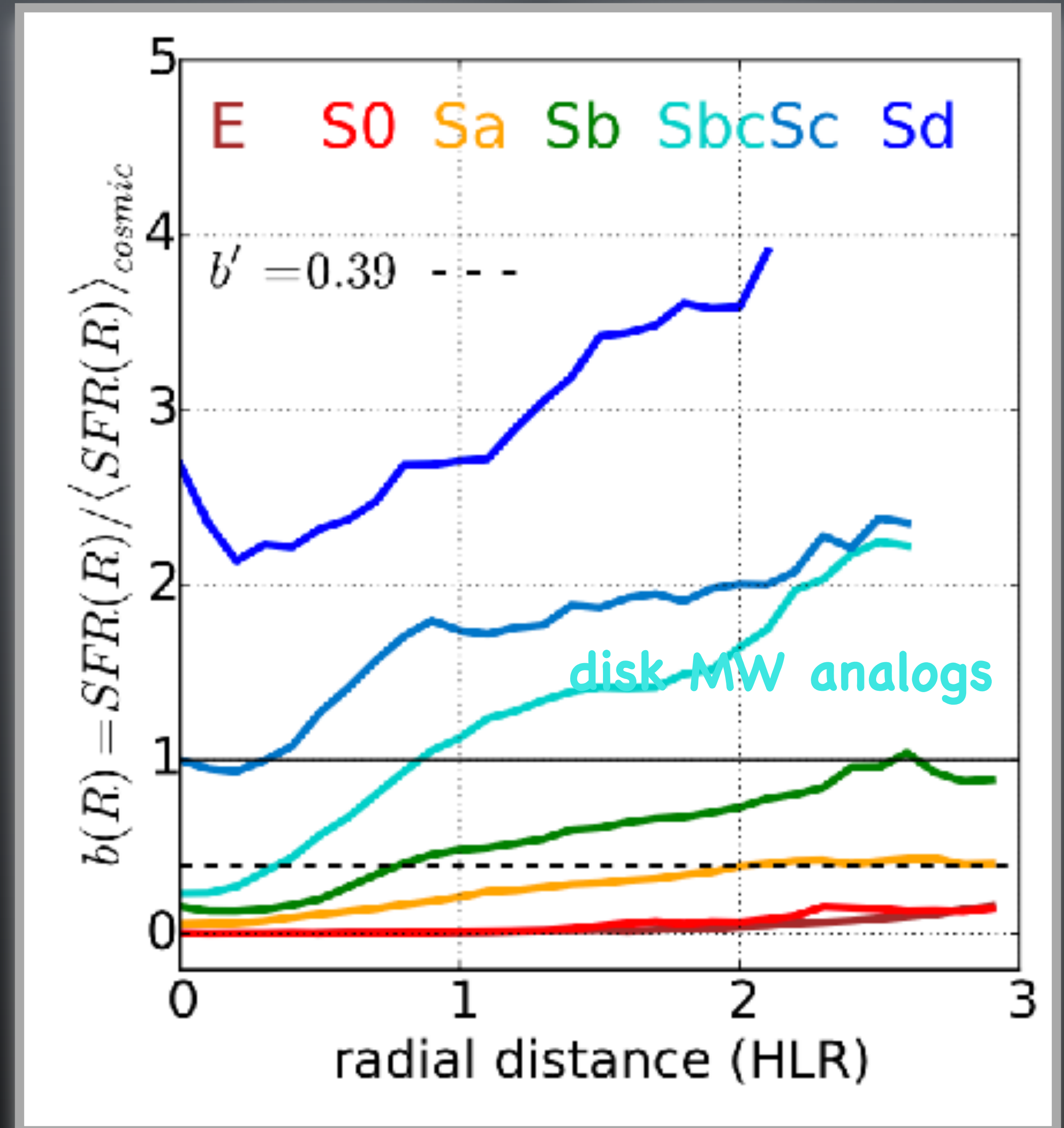
- sSFR(R) values scale with Hubble type
- sSFR(R) increases radially outwards, with a steeper slope in the inner 1 HLR.
- Galaxies are quenched inside-out, and this process is faster in the central bulge-dominated part (or the thick disk) than in the disk (thin).

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

The Scalo *b* birthrate parameter

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

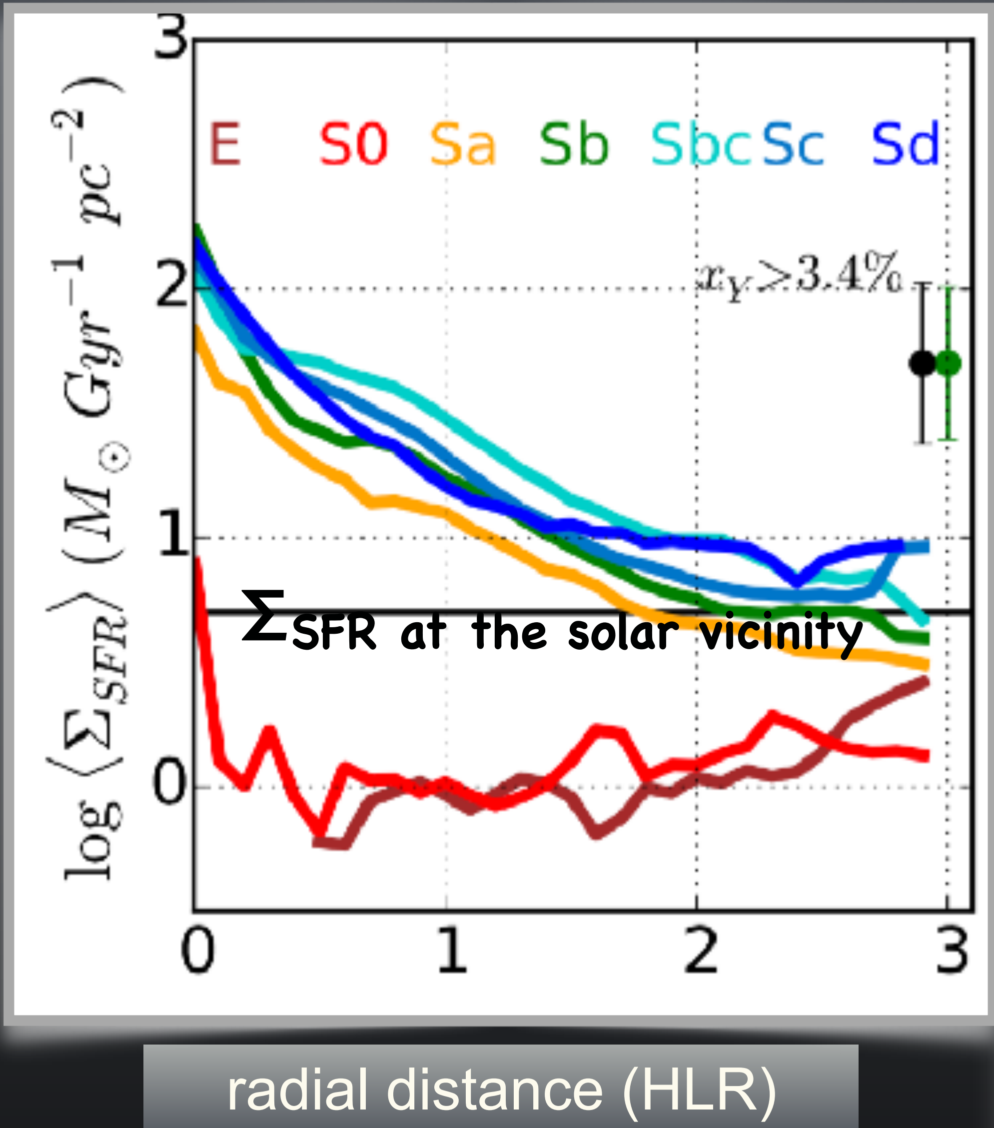
$$b' = \frac{\sum_i \mathrm{SFR}_i V^{-1}_{max,i}}{\sum_i \langle \mathrm{SFR} \rangle_{cosmic,i} V^{-1}_{max,i}}$$

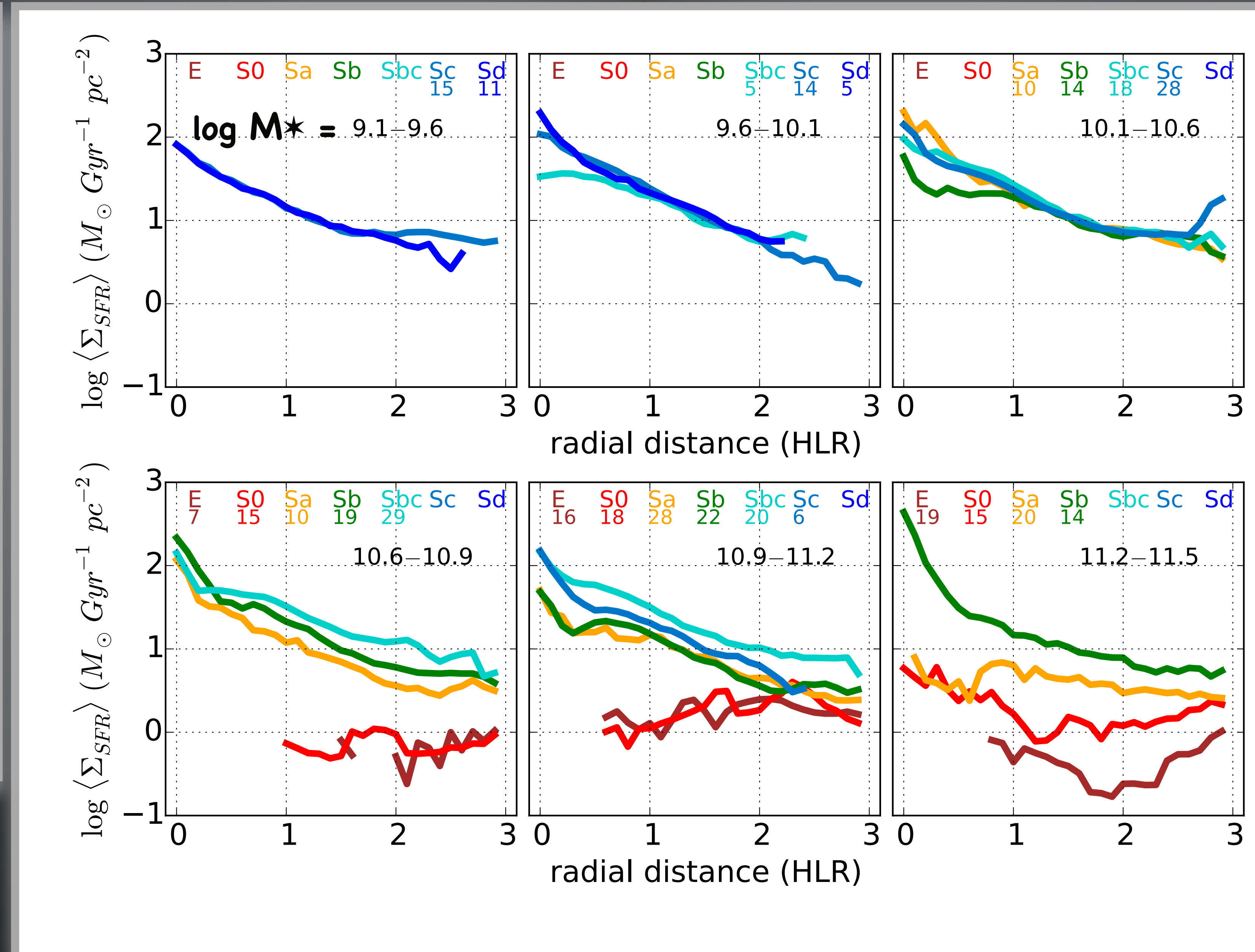


- The volume averaged birthrate parameter, $b' = 0.39 \pm 0.03$,
- Present day Universe is forming stars at ~1/3 of its past average rate.
- E, S0, and the bulge of Sa and Sb contribute little to the recent SFR of the Universe, which is dominated by the disks of Sbc, Sc, and Sd spirals.

Recent Star formation along the Hubble sequence

Recent Star formation rate intensity: Radial profiles of Σ_{SFR}





- Spirals: Σ_{SFR}(1 HLR) ~20 M⊙ Gyr^{-1} pc^{-2}
- Spirals: the dispersion in Σ_{SFR}(R) is small
- MSSF is a sequence with Σ_{SFR} ~ constant

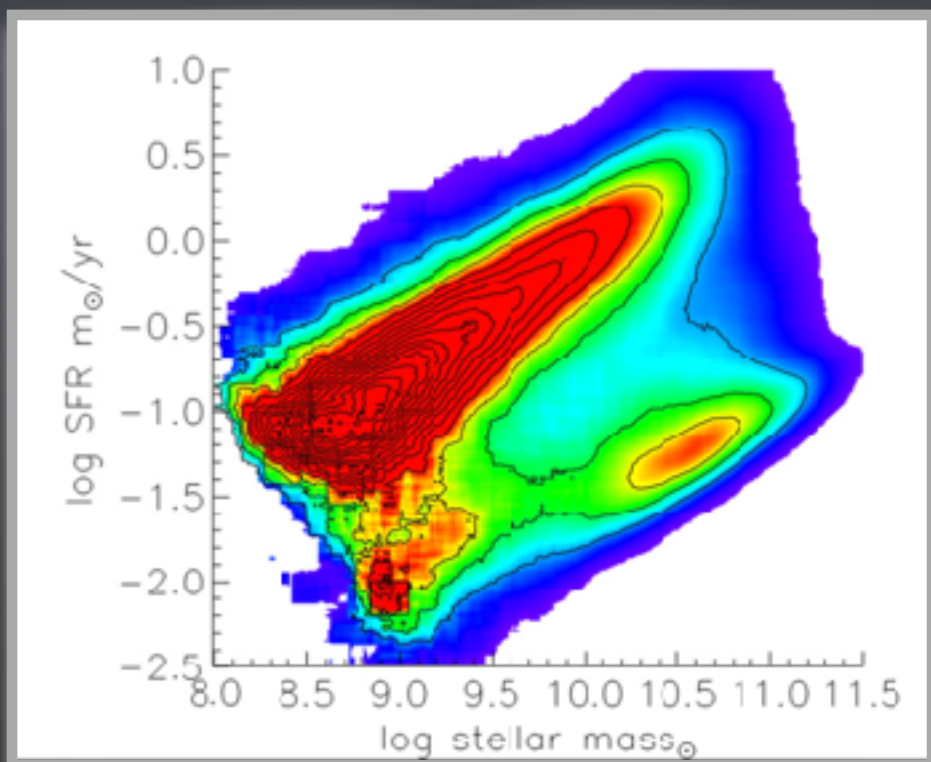
González Delgado +, 2016, A&A, 590, 44

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

Global relation

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

Renzini & Peng, 2015



confirmed by Cano-Díaz +, 2016, ApJL, with Ha

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

* $SFR = cte\ \Sigma_{SFR}(HLR) / \mu_\star(HLR)\ M_\star$

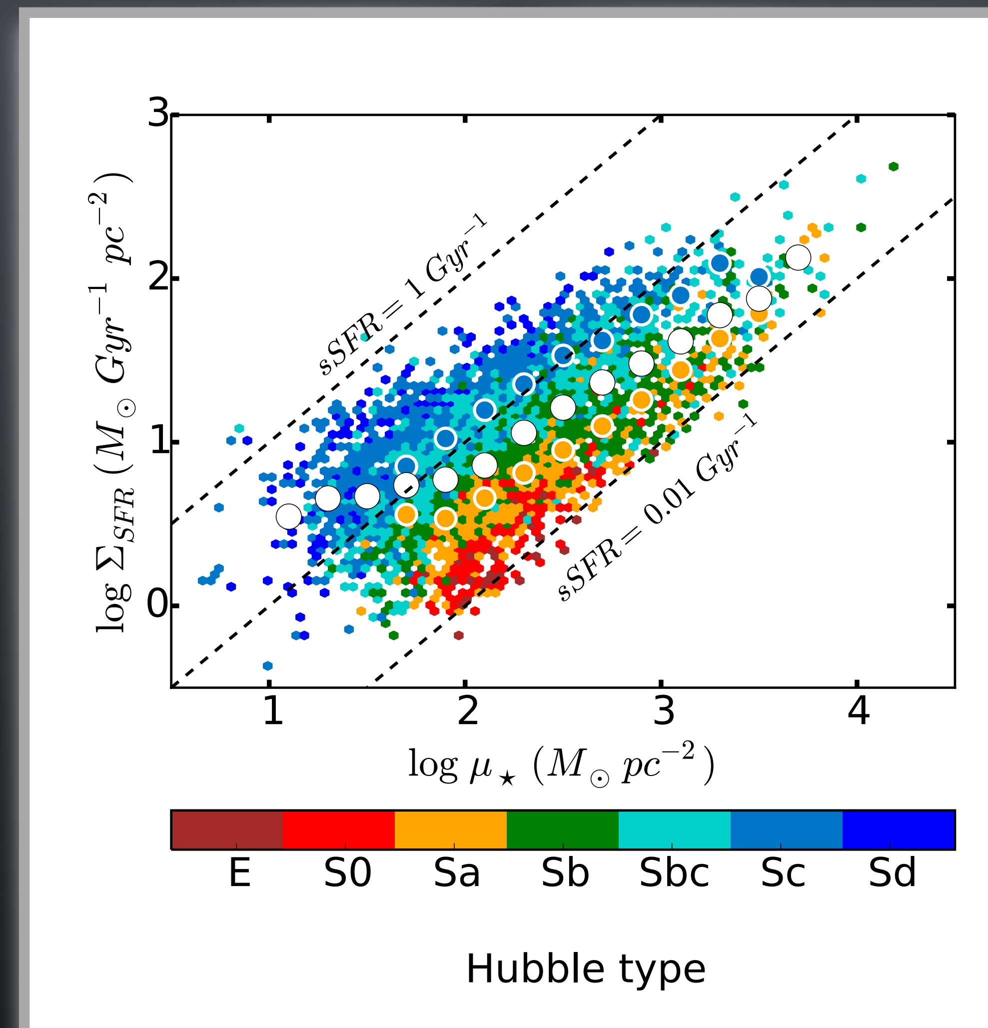
* $\Sigma_{SFR} = cte\ \mu_\star\ \alpha$

* $\mu_\star = cte\ M_\star^{\gamma}$
* $SFR = cte\ M_\star^{1-\gamma(1-\alpha)}$

* with $\alpha = 0.8$; $\gamma = 0.5$; $\beta < 1$

Local relation

CALIFA: $\mu_\star$ - Σ_{SFR}



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

$\Sigma_{SFR} = cte\ \mu_\star^{\alpha}$, $\alpha = 0.8$

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

increases from early to late type spirals

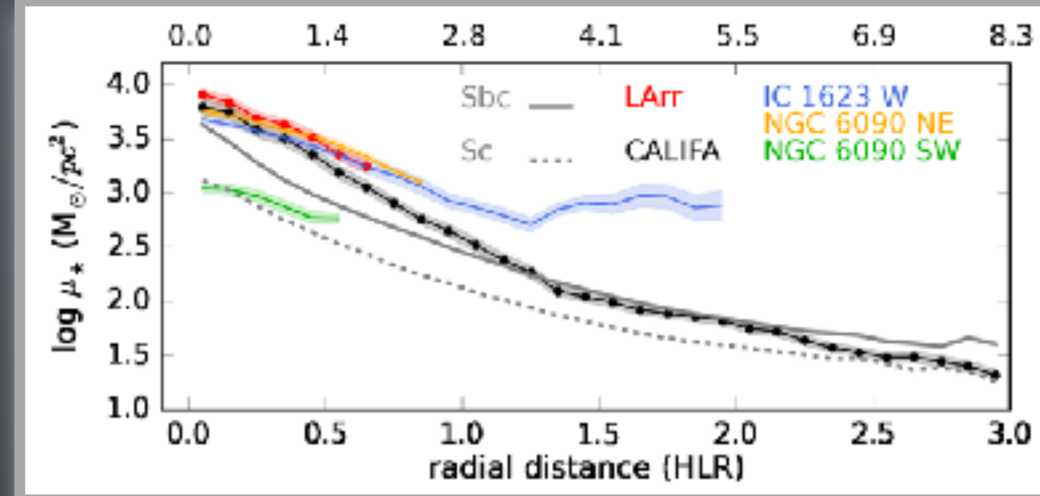
Global relation is sub-linear (< 1)
because the sub-linearity of the local relation

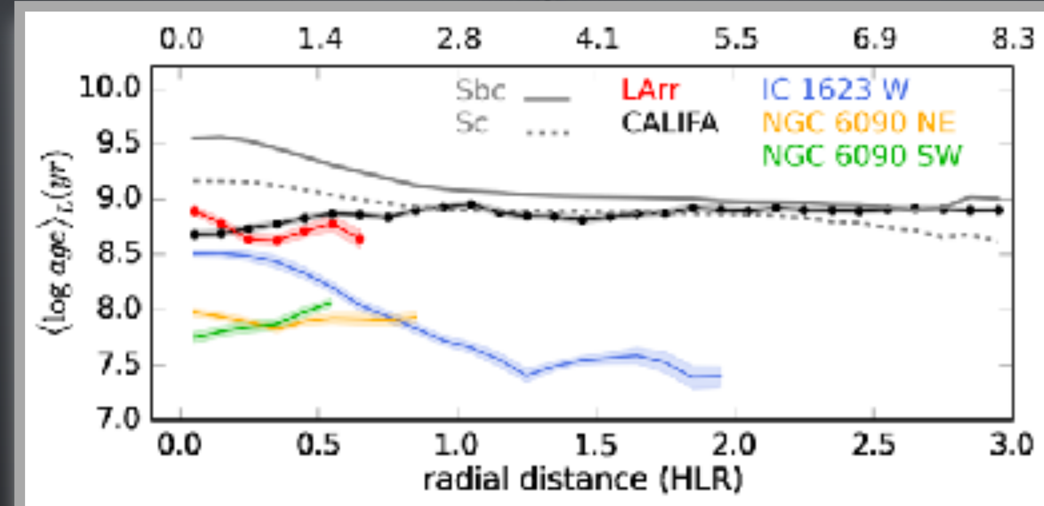
Mergers in the CALIFA sample

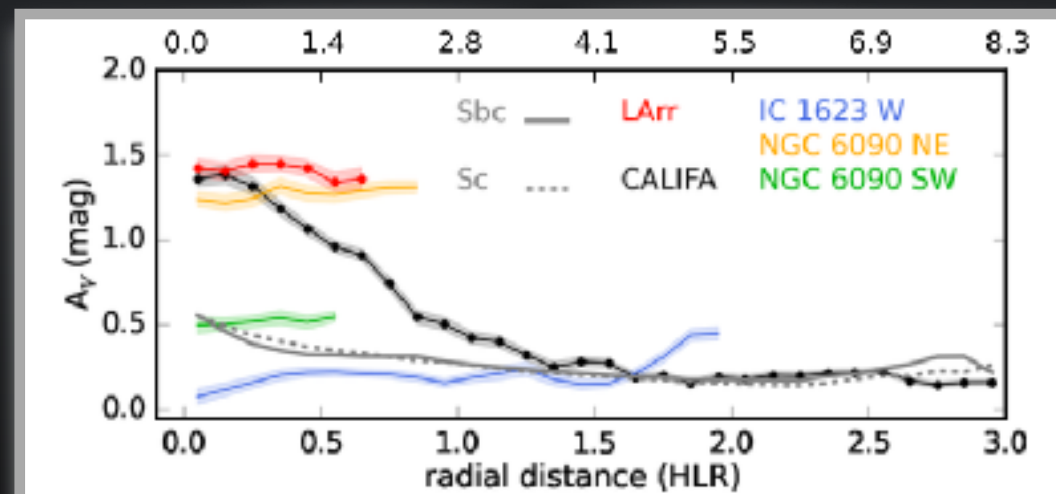
Pre-mergers: Mice, IC1623, NGC6090
Mergers: NGC2623

LIRG (IC1623, NGC6090, NGC2323)
MICE: No LIRG

Property	Mice	IC 1623	NGC 6090	NGC 2623
CALIFA ID	577 (A); 939(B)	–	2945	213
RA	12 46 10.7	01 07 46.3	16 11 40.8	08 38 23.8
Dec	+30 43 38	−17 30 32	+52 27 27	+25 45 17
Interaction stage	IIIa	IIIb	IIIb	IV
z	0.022049	0.020067	0.029304	0.018509
Scale (kpc/″)	0.47	0.42	0.61	0.39
HLR (kpc)	4.6 (A); 3.8 (B)	2.8	4.2	3.3
Stellar mass ($M_\odot$)	1.2×10^{11}(A), 1.5×10^{11}(B)	3.9×10^{10}	6.8×10^{10}	5.4×10^{10}
$\log(L_{IR}[L_\odot])$	10.62	11.65	11.51	11.54
$SFR_{30\ Myr}$ ($M_\odot$/yr)	3(A), 2(B)	20	51	8

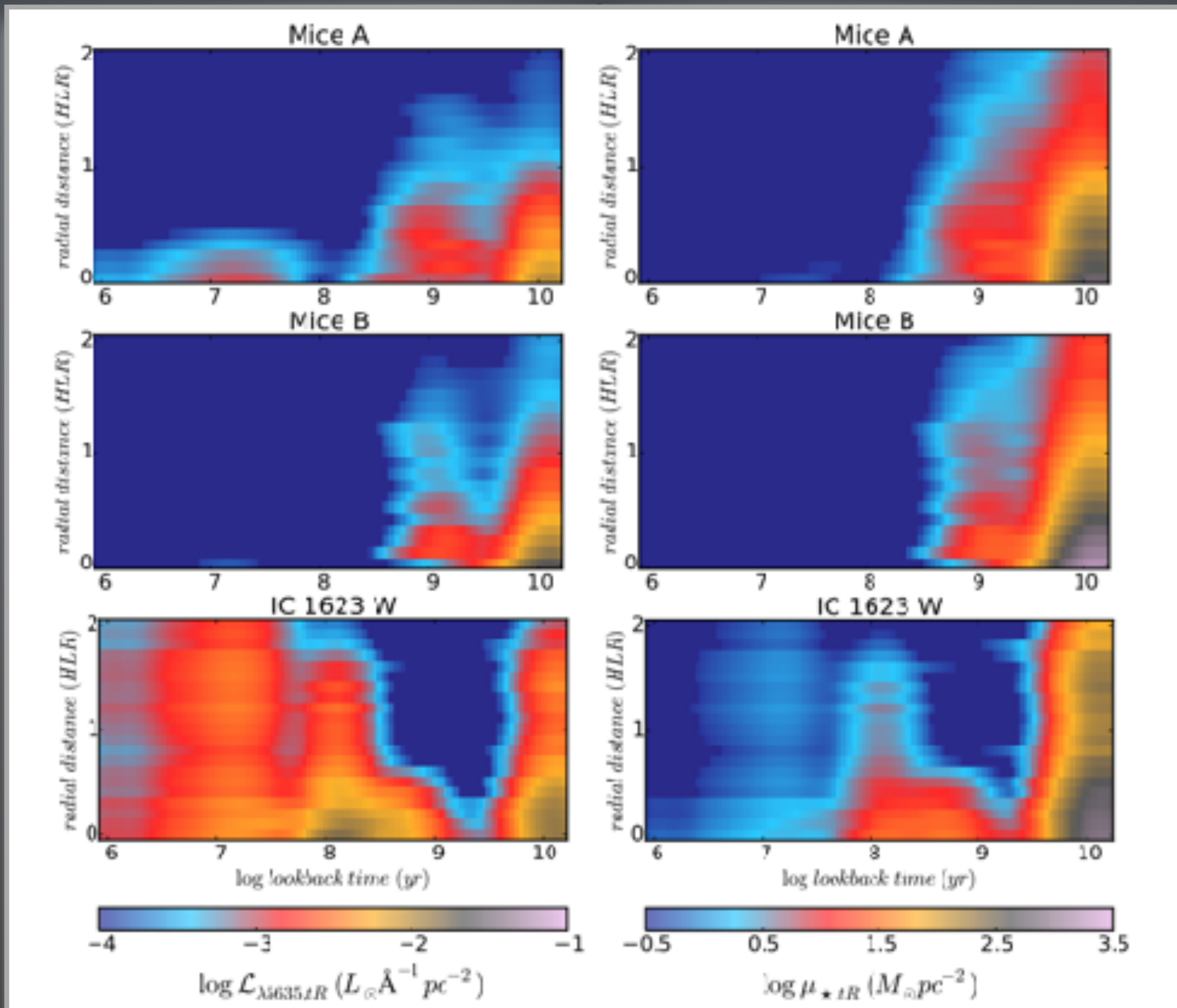


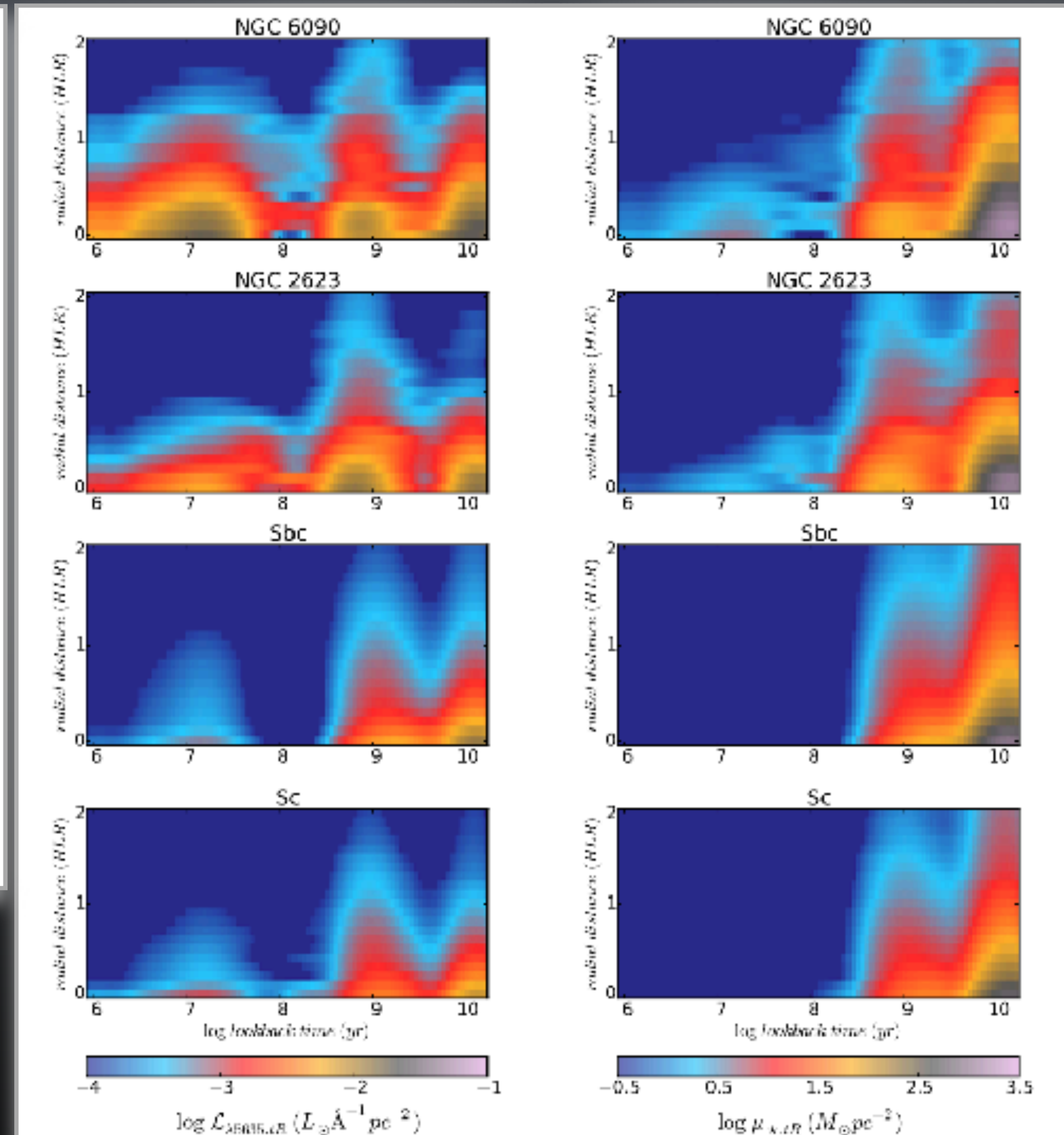




- Cortijo-Ferrero et al. 2017, MNRAS, 467,3898
- Cortijo-Ferrero et al. 2017, A&A, arXiv:1706.01896
- Cortijo-Ferrero et al. 2017, A&A, arXiv:1707.05324

Mergers in the CALIFA sample

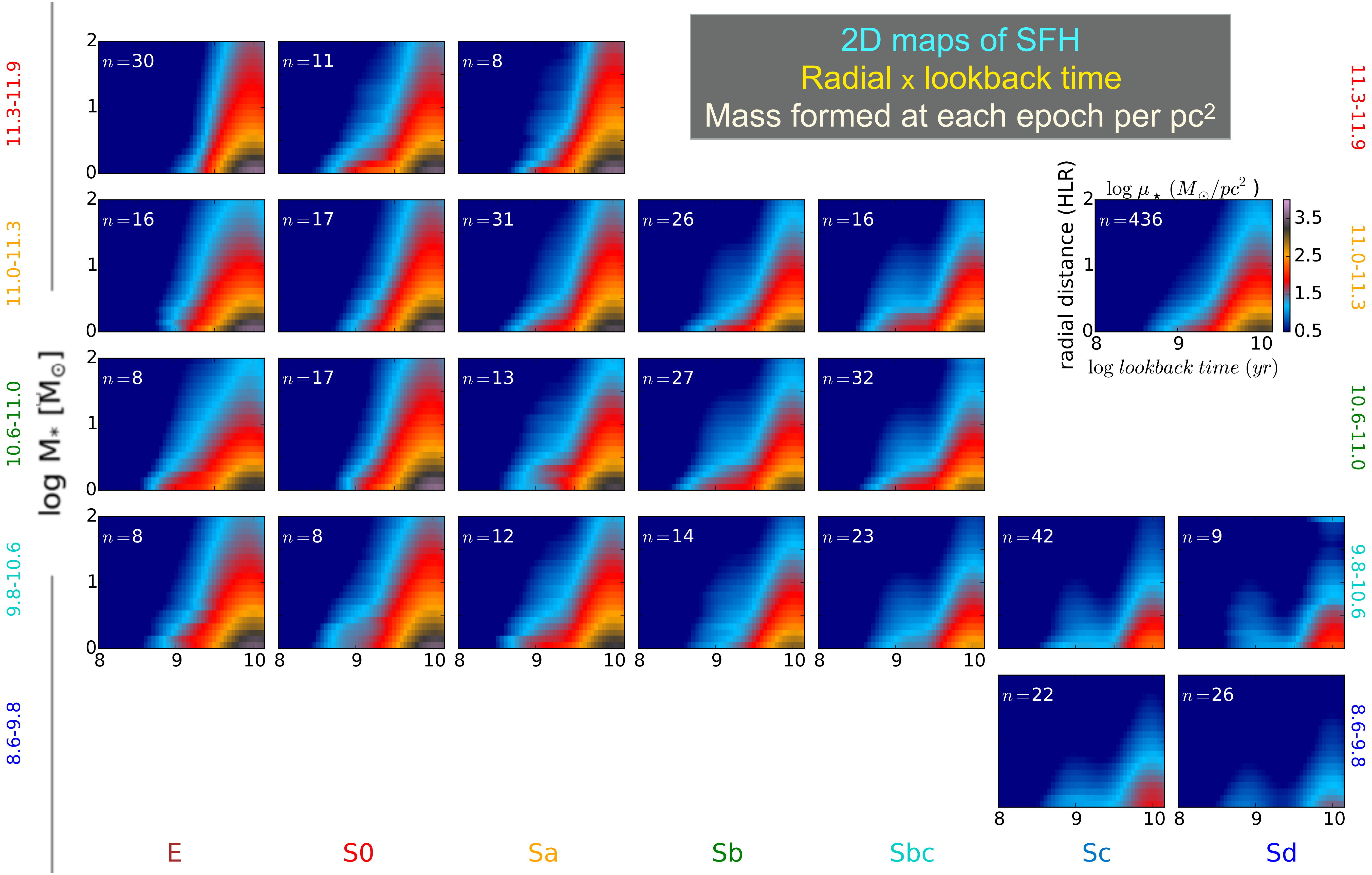




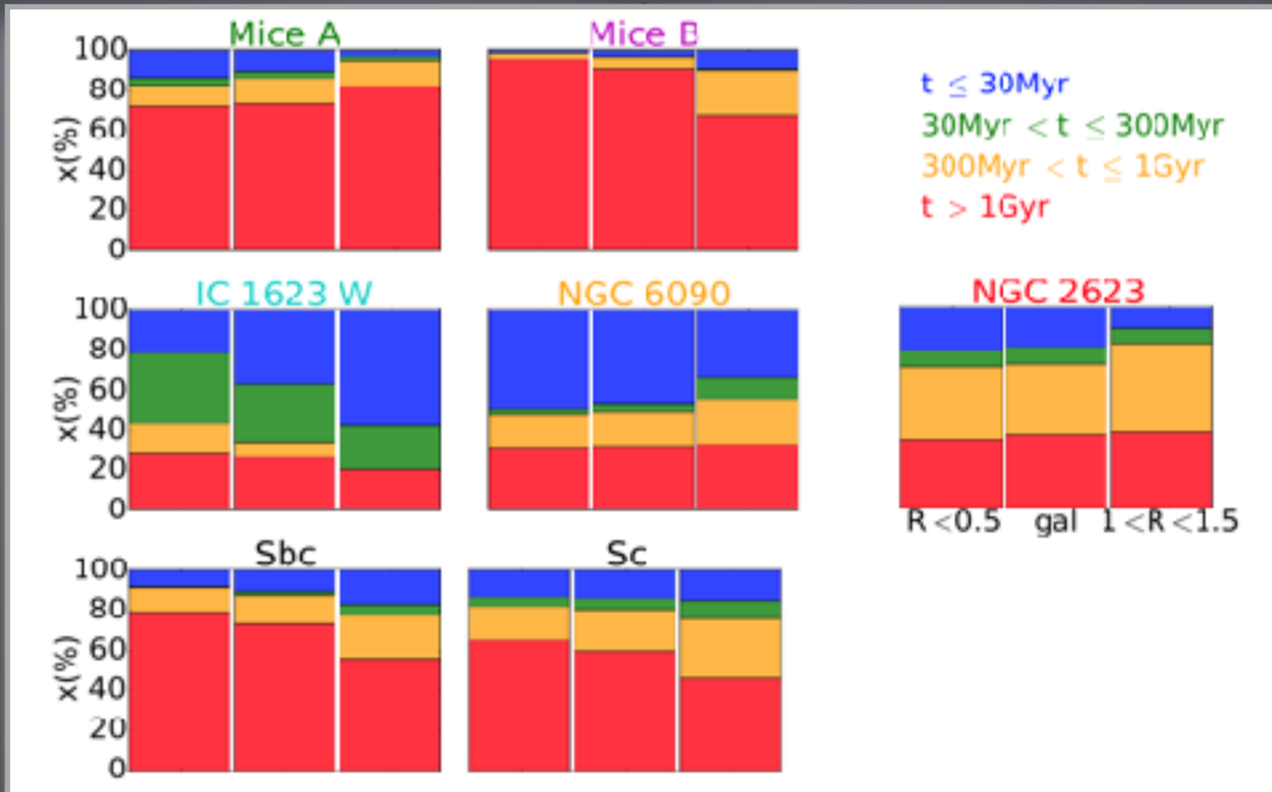
2D SFH pre-mergers and mergers compared with Sbc and Sc of similar mass

- Cortijo-Ferrero et al. 2017, A&A, arXiv:1707.05324

Spatially resolved SFH (morpholgy vs galaxy Mass)



Mergers in the CALIFA sample: Global enhancement ?



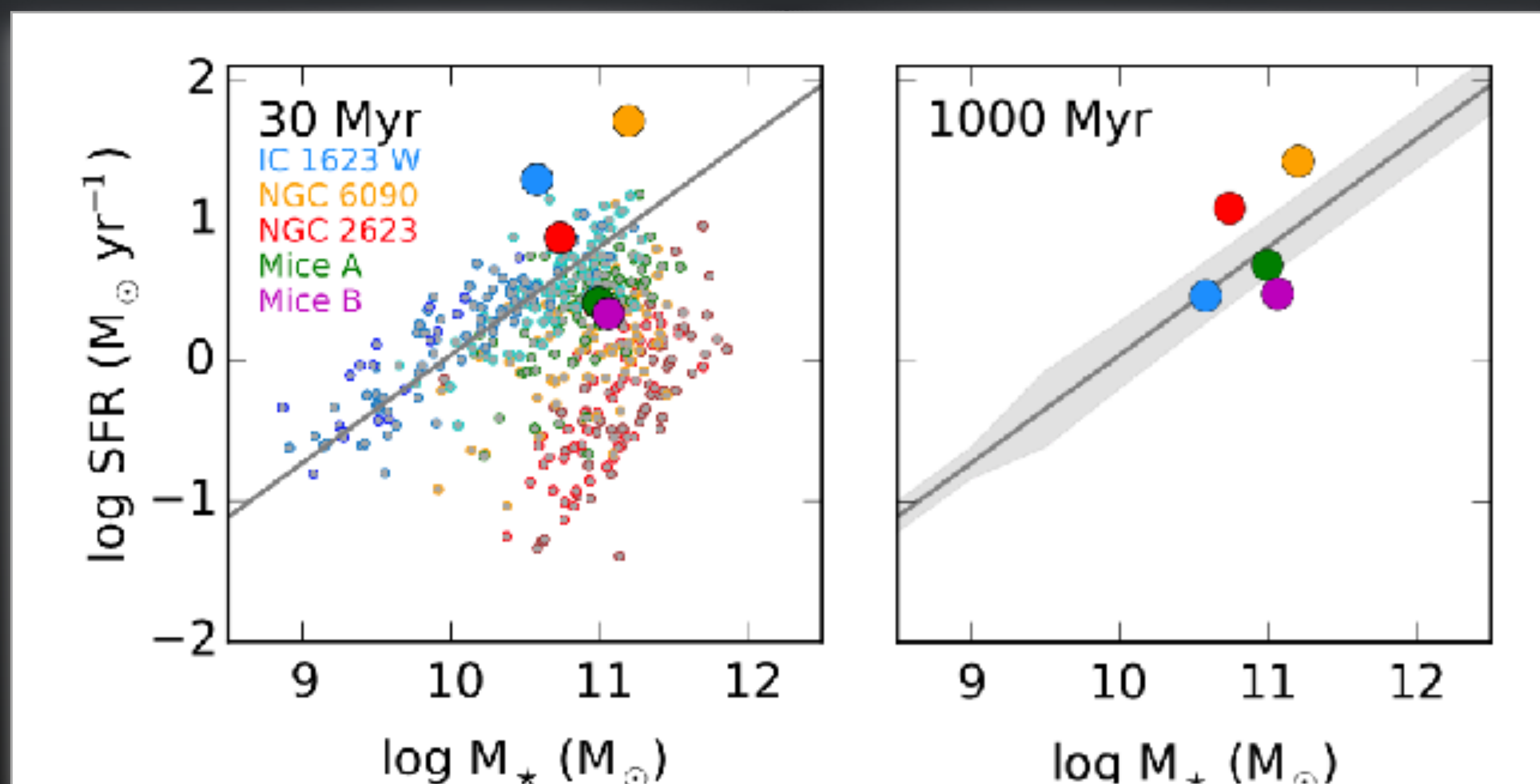
- Except for the Mice, mergers show larger fraction of light (and mass) at intermediate (< 1 Gyr) and young (< 30 Myr) ages

- Are mergers out of the main sequence of SF?
- merger state?
- time scale?

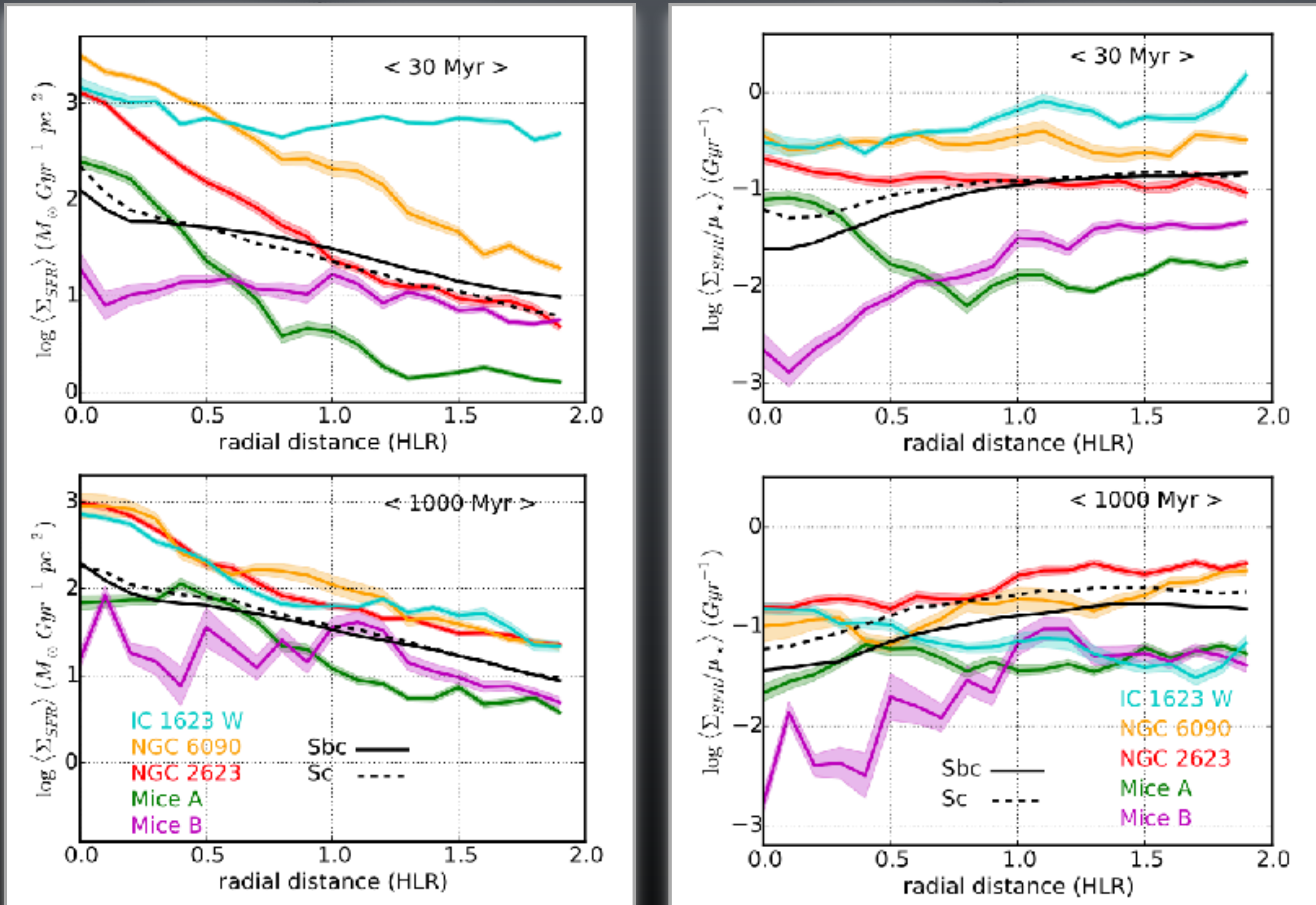
Pre-mergers (Mice):
close to prograde orbit

Pre-mergers (IC1623, NGC6090):
first pericentre passage and coalescence

mergers (NGC2323):
advance merger



Mergers in the CALIFA sample: SFI, and sSFR in different time scales



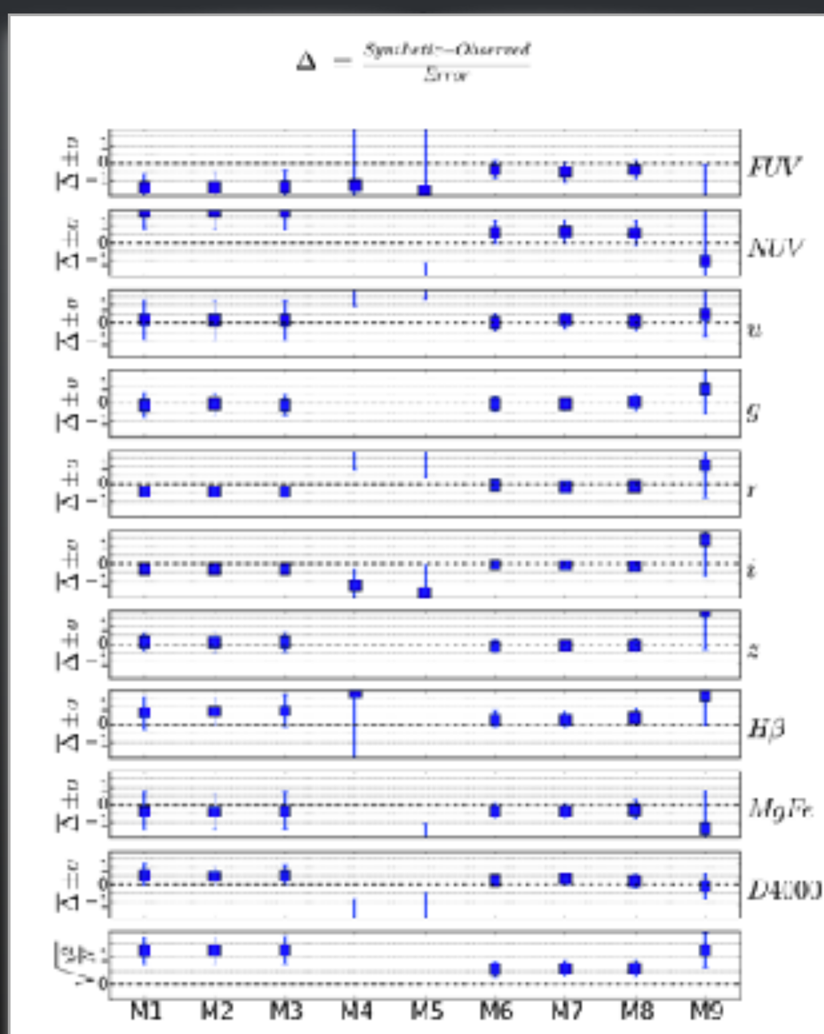
- Major phases of SF occurs in time scales 30 Myr to few 100Myr
- Pre-mergers (IC1623, NGC6090): enhancement of SF spatially extended (center and disk) in scale of 30 Myr
- Pre-mergers Mice: No enhancement of SF
- Mergers (NGC2623): enhancement of SF spatially extended occurs in more extended phase,~1 Gyr, and more concentrated (inner 1 HLR) in the last 30 Myr

Parametric SFR: Tau model

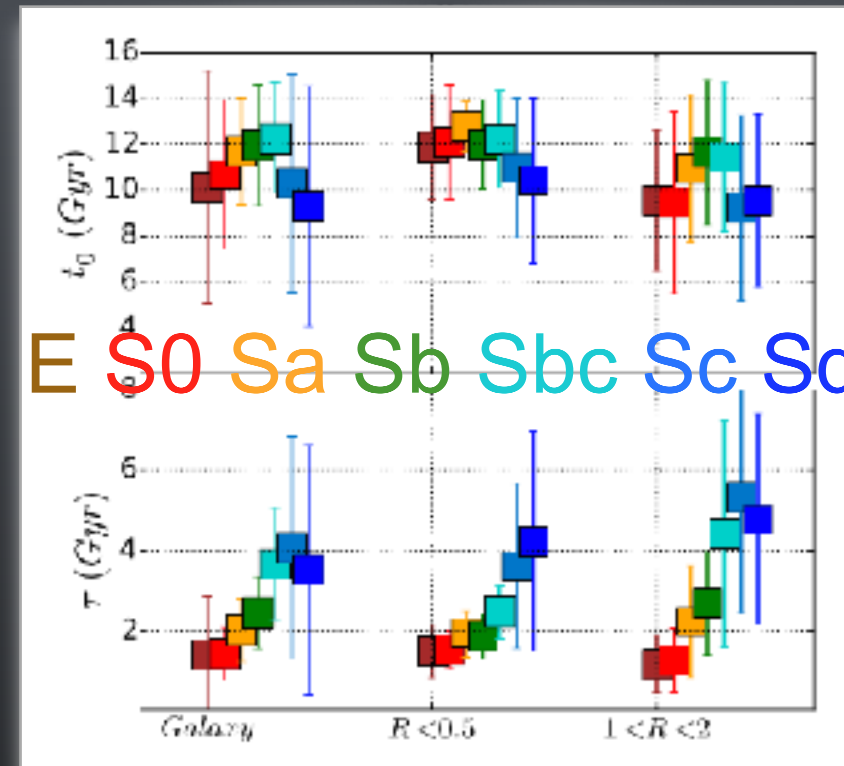
$$\psi(t) = \frac{A}{\tau^2}(t_0 - t)e^{-(t_0-t)/\tau}$$

Observational constrains:

- FUV, NUV,
- SDSS-bands,
- indexes (Hβ, FeMg, and D4000)



López Fernández +, 2018, A&A, sube

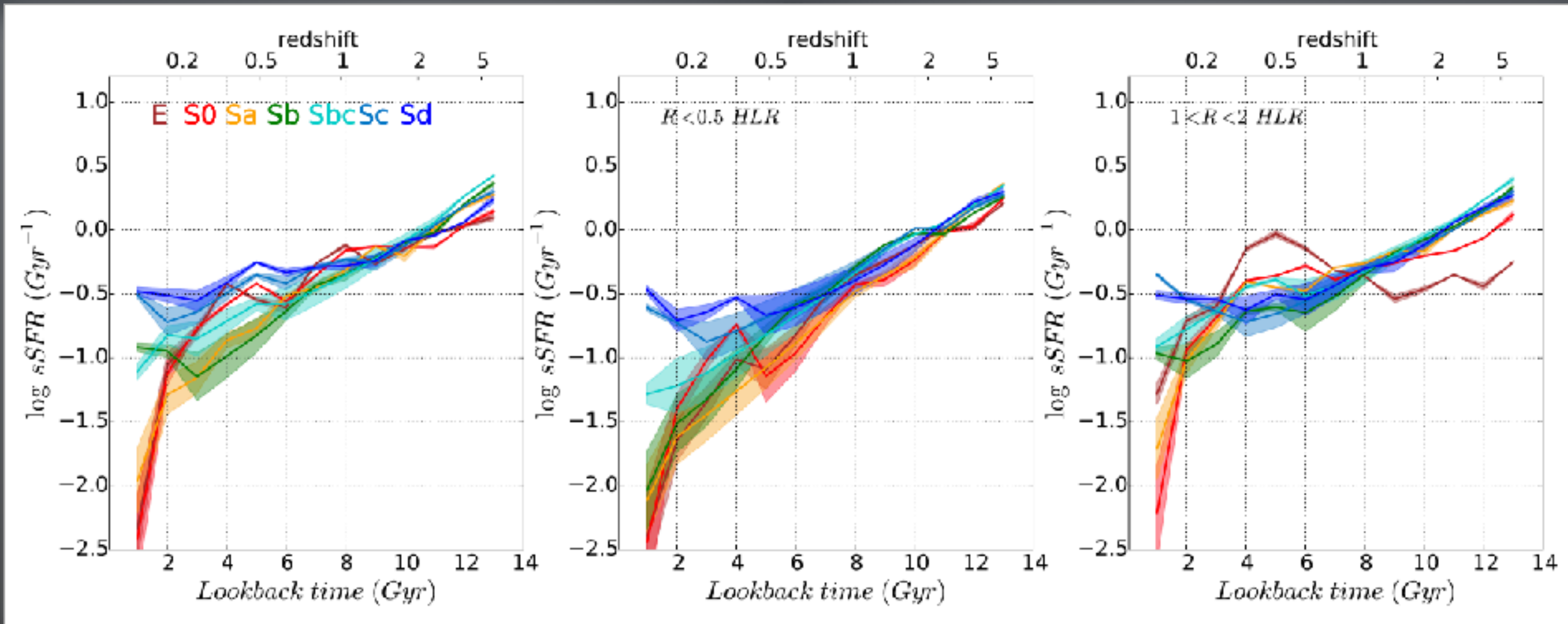


- The mass is assembled at earlier epochs in the inner (≤ 0.5 HLR) than in the outer (1-2 HLR) regions.
- The time since the onset of the star formation, t_0, is higher in the inner (t_0 ~ 13–10 Gyr, for Sa to Sd) than the outer regions (t_0 ~ 11–9 Gyr, for Sa to Sd)
- The e-folding time, τ, is similar or smaller in the inner than the outer regions.

These results confirm that galaxies, of any morphological type, grow inside-out.

Parametric SFR: Tau model

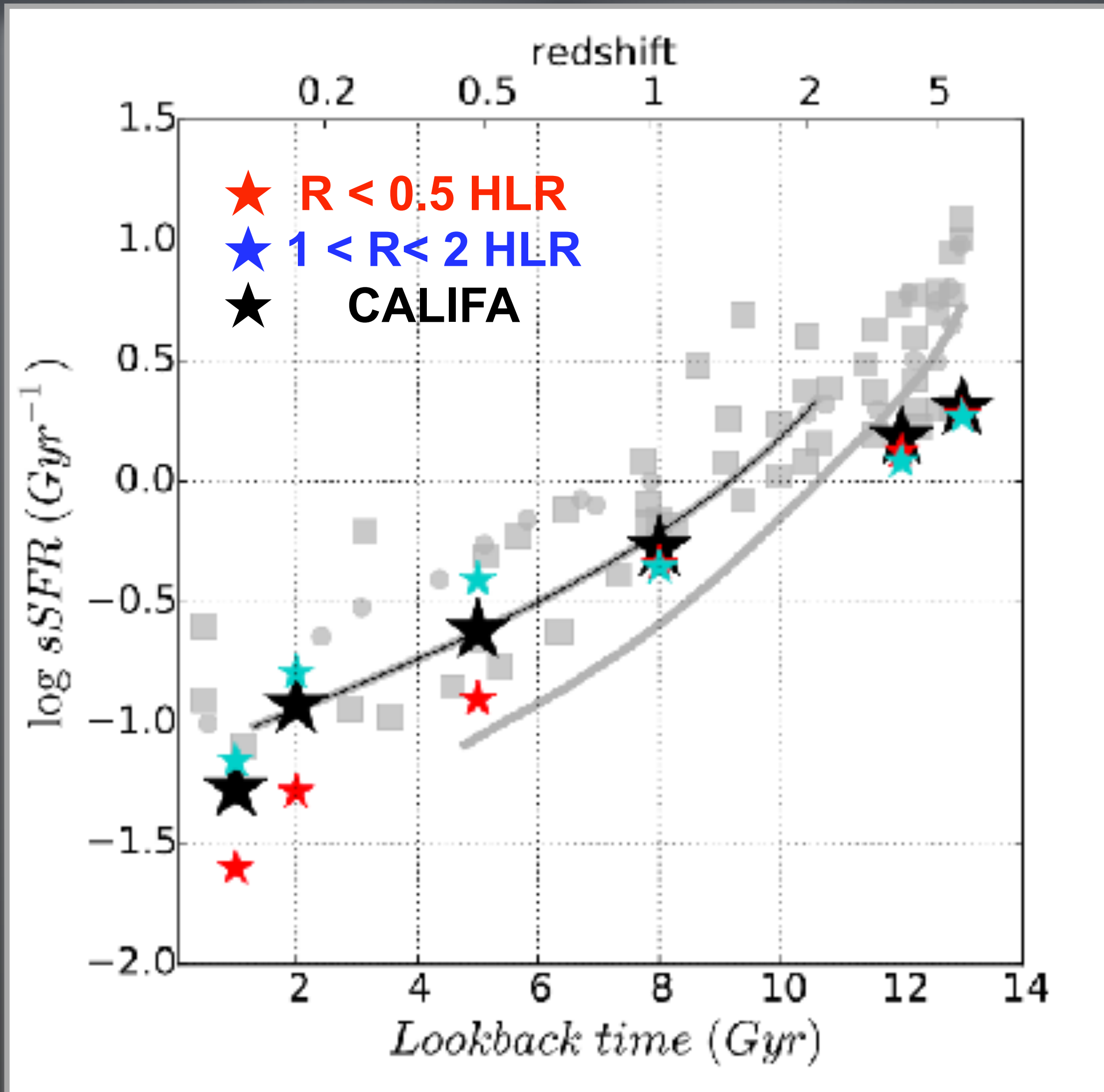
López Fernández +, 2017, A&A, in prep



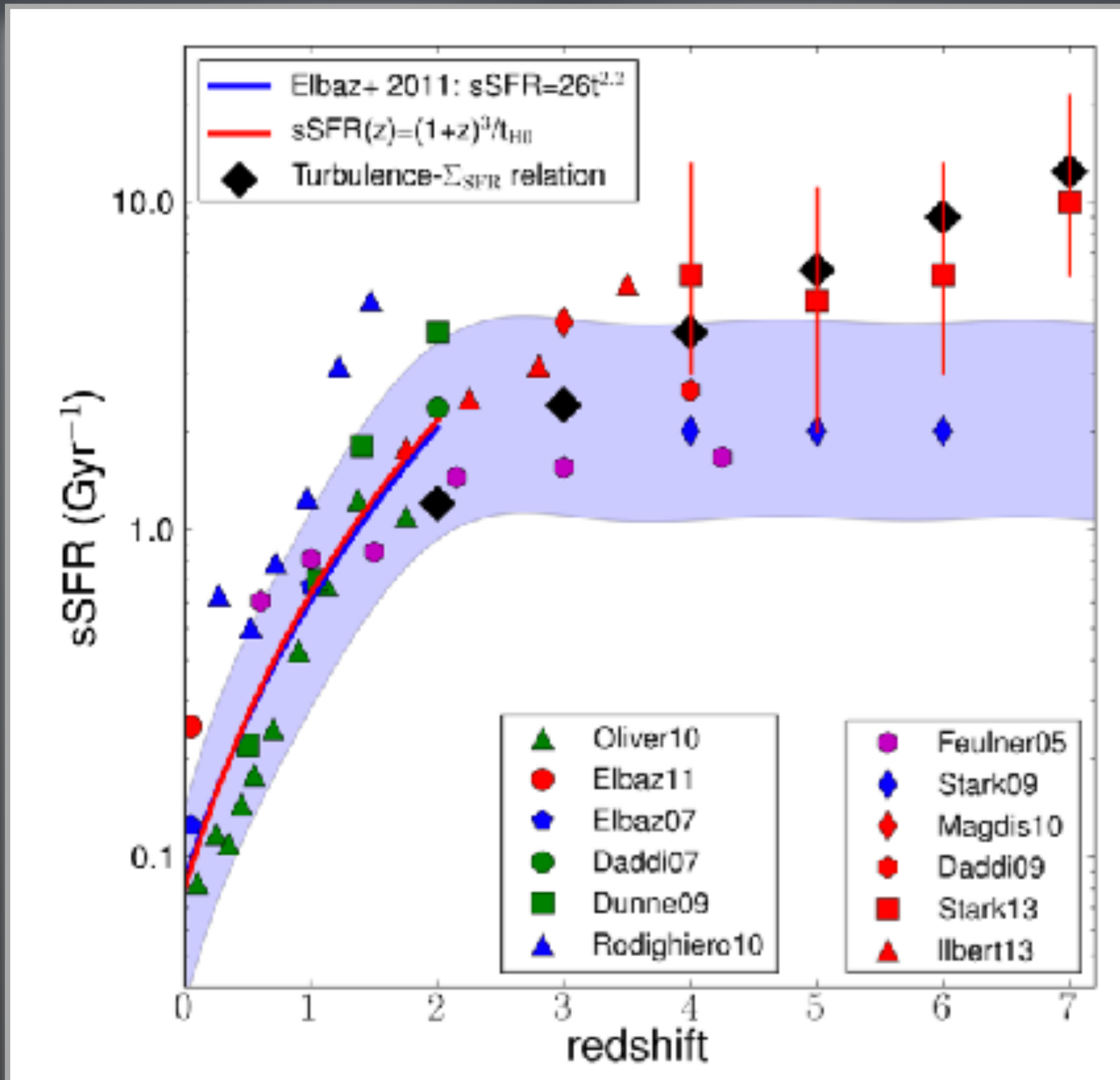
- ✳ sSFR declines rapidly as the Universe evolves, but more rapidly for early than late type galaxies, and for the inner than the outer regions of galaxies.

Cosmic evolution of the ρSFR and sSFR

López Fernández +, 2017, A&A, in prep



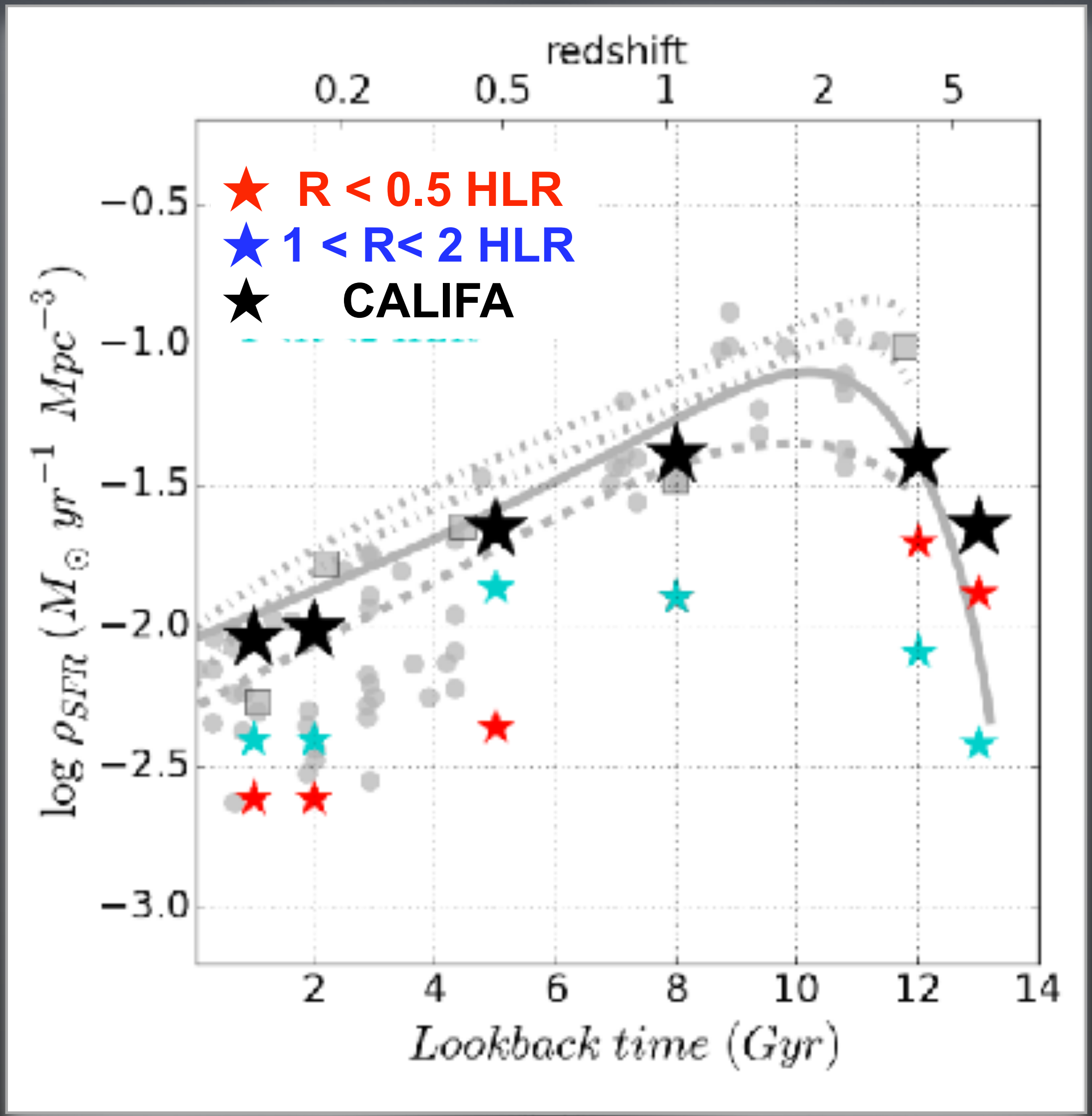
Lehnert +, 2015, A&A,577, 112



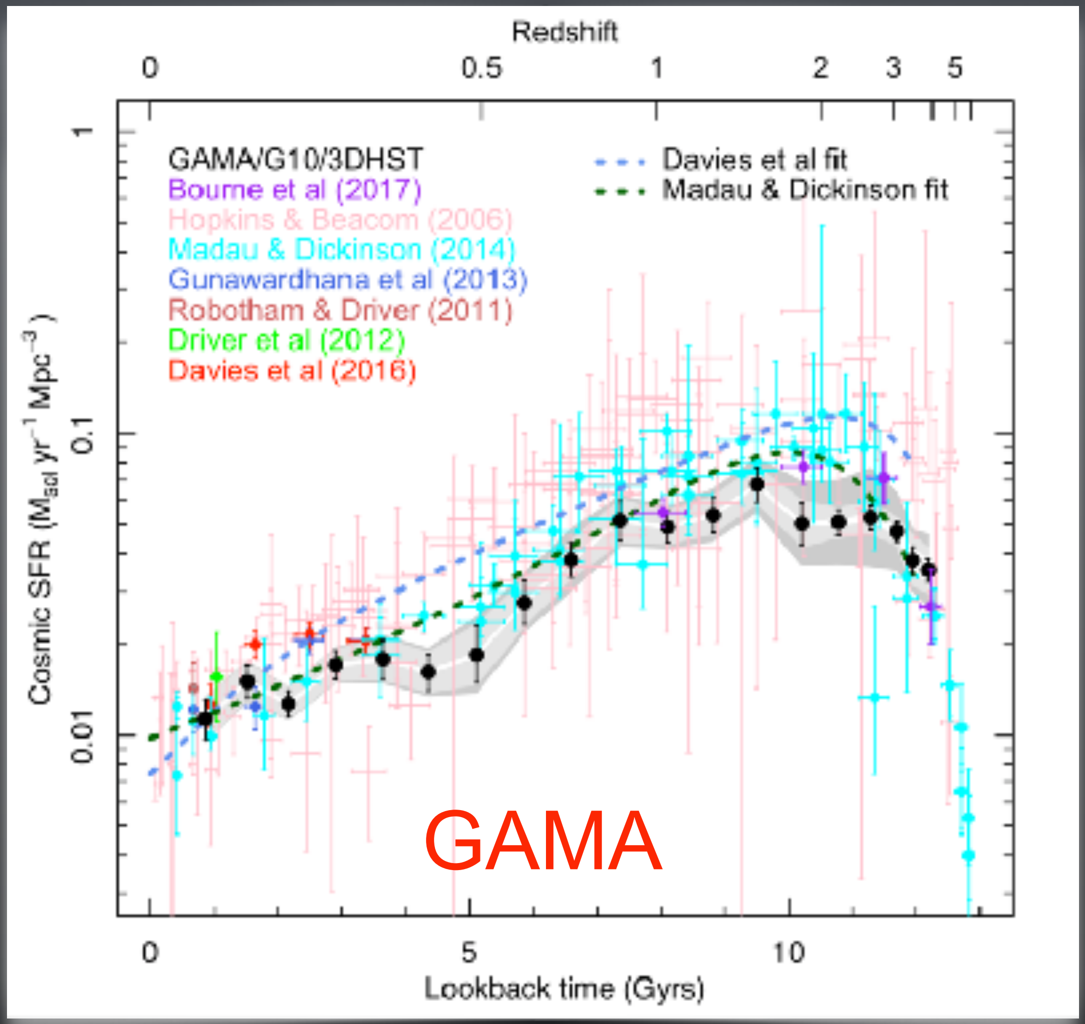
- At z=0, inner regions have larger sSFR than outer regions
- At z >1, inner and outer regions have similar sSFR
- sSFR declines with time in similar way as the redshift survey galaxies
- at z>2, that our estimations are in the lower envelope of the high redshift galaxies

Cosmic evolution of the ρ_{SFR} and sSFR

López Fernández +, 2017, A&A, in prep



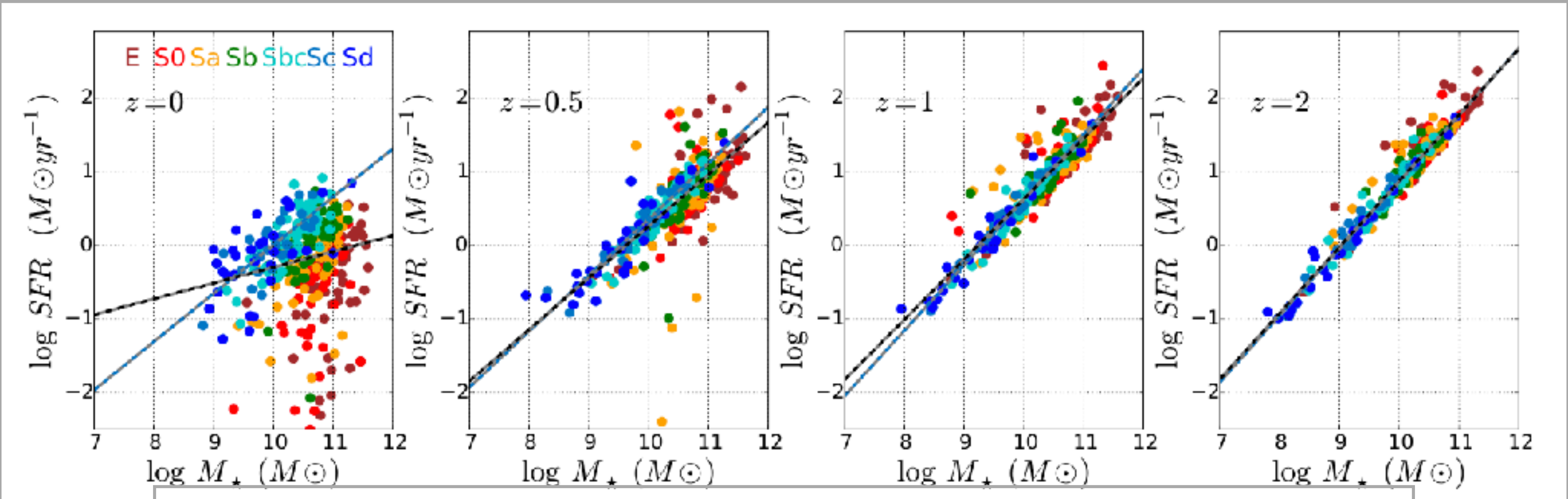
Driver +, 2017, MNRAS, arXiv:1710.06628



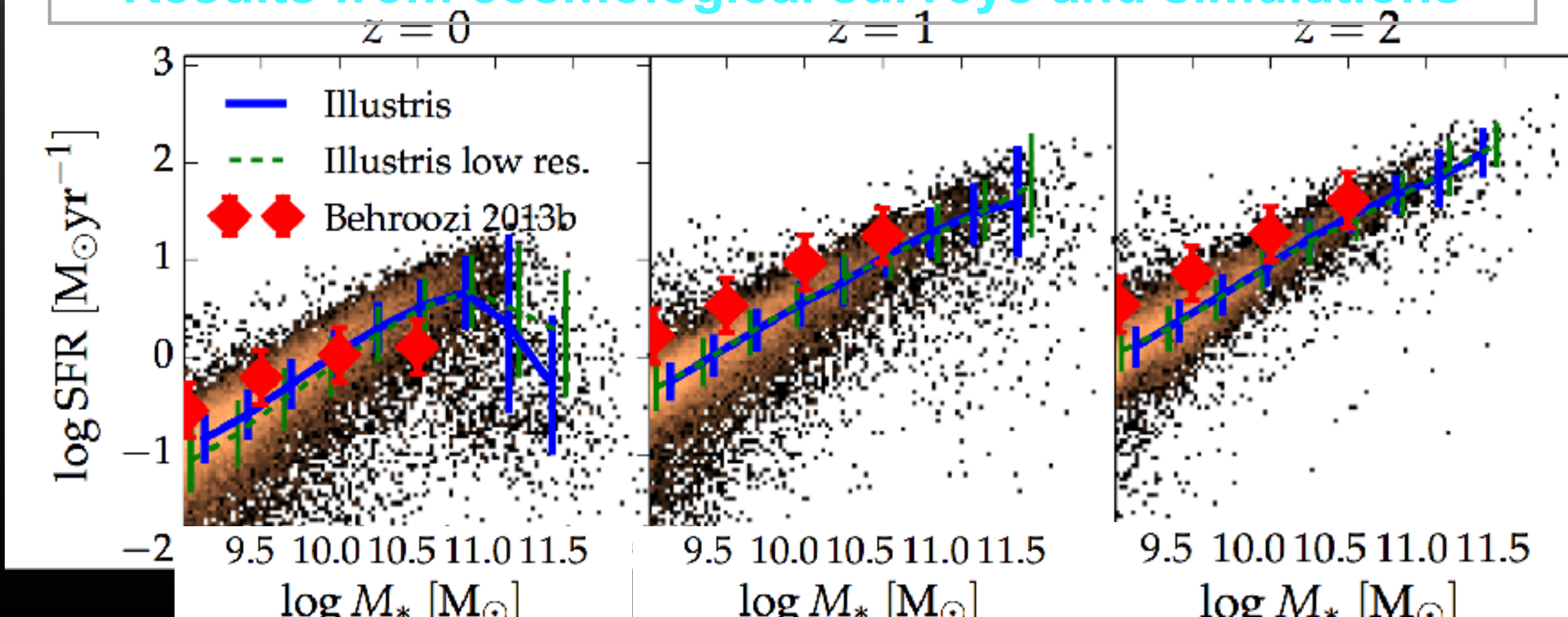
- Now: Most of the star formation is occurring in the disks of spirals (R > 1 HLR)
- Now: E, S0, and the bulge of Sa and Sb contribute little to the recent SFR of the Universe, which is dominated by the disks of Sbc, Sc, and Sd spirals.
- In the past (z > 1): The progenitors of ETG are the main contributors to ρ_{SFR}.
- In the past (z > 1): Inner and outer regions contribute in a similar way to ρ_{SFR}

CALIFA sample is very suited for obtaining the SFR density of the Universe

Cosmic evolution of Main Sequence of Star Formation



Results from cosmological surveys and simulations



SFH: fossil record cosmology *vs.* redshift galaxy surveys

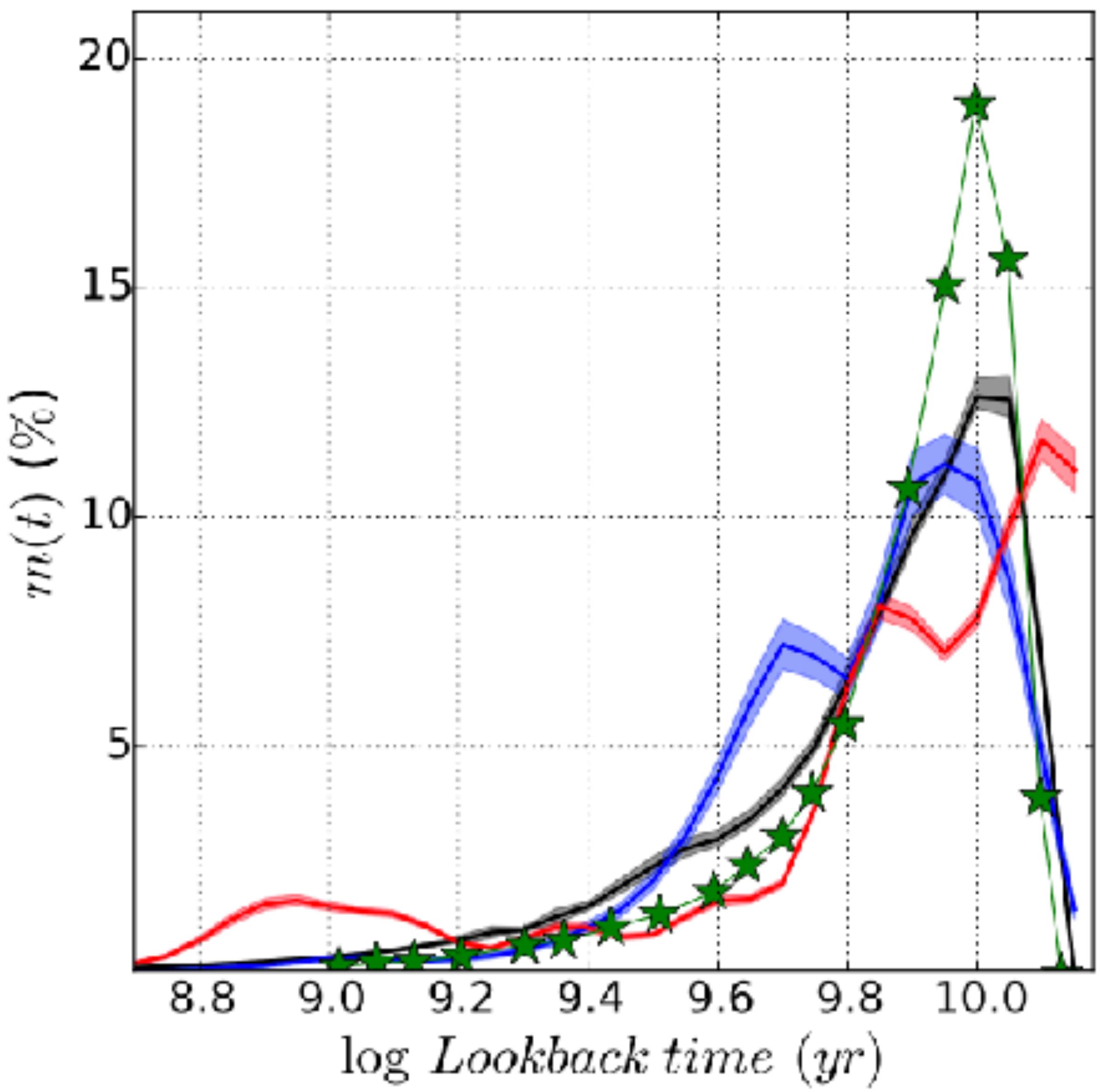


Fig. 9. The mass fractions, $m(t)$ obtained with parametric SFHs: τ-delayed (black), a combination of two exponential SFR (blue), and non-parametric SFH derived with the STARLIGHT code (red), are compared with $m(t)$ from (Madau & Dickinson 2014) (green stars). The shaded bands around the mean curves represent ± the error in the mean.

- The average SFH of CALIFA galaxies confirms that galaxies grow their mass mainly in a mode that is well represented by a τ-delayed or exponential mode.
- The peak is at high redshift (z~2), and the e-folding time ~ 3.9 Gyr.
- An additional secondary mode scale free mass growth, as detected in the SFH of galaxies by using non-parametric models, cannot be successfully modeled by using a combination of two-exponential SFR laws.

Conclusions: Impact of CALIFA survey

- DR3 released 11 April 2016 (the collaboration is closed today).
- CALIFA was a pioneer project in the field of 3D IFS surveys.
- It has been the most successful project done in CAHA.
- Legacy projects like CALIFA seem to be the most useful way for a successful continuation of CAHA.

web sites where to retrieve our data products from STARLIGHT

http://pycasso.iaa.es/

2D maps (ages, μ✶, Z✶, Av, Σ_{SFR}, Xy, sigma✶, V✶)

M✶ and SP integrated properties

Papers lead by our group related to this talk

✳4 PhD theses
✳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. 2017, MNRAS, 467, 3898
✳de Amorim et al., 2017, MNRAS, 471, 3727
✳Cortijo-Ferrero et al. 2017, A&A, 607, 70
✳González Delgado et al. 2017, A&A, 607, 128
✳García-Benito et al., 2017, A&A, 608, 27
✳Cortijo-Ferrero et al., 2017, A&A, 467, 3898
✳Lacerda, et al., 2017, MNRAS, 474, 3727
✳López-Fernández et al., 2018, A&A, 615, 27