A new measurement of the expansion history of the Universe from cosmic chronometers in the LEGA-C survey

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Based on Borghi et al. 2021a (arXiv:2106.14894)
+ Borghi et al. 2021b (on arXiv soon)

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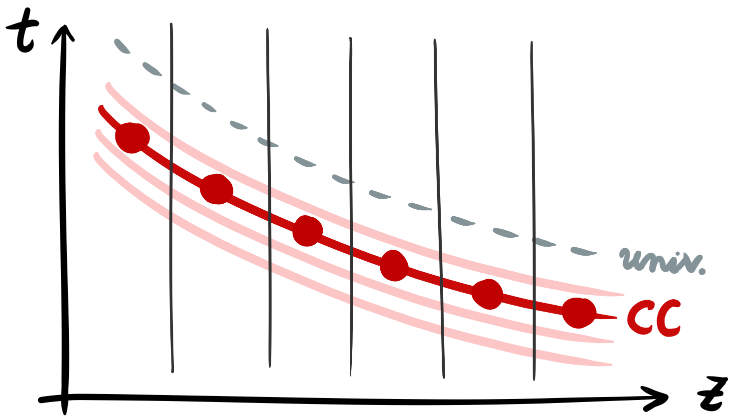
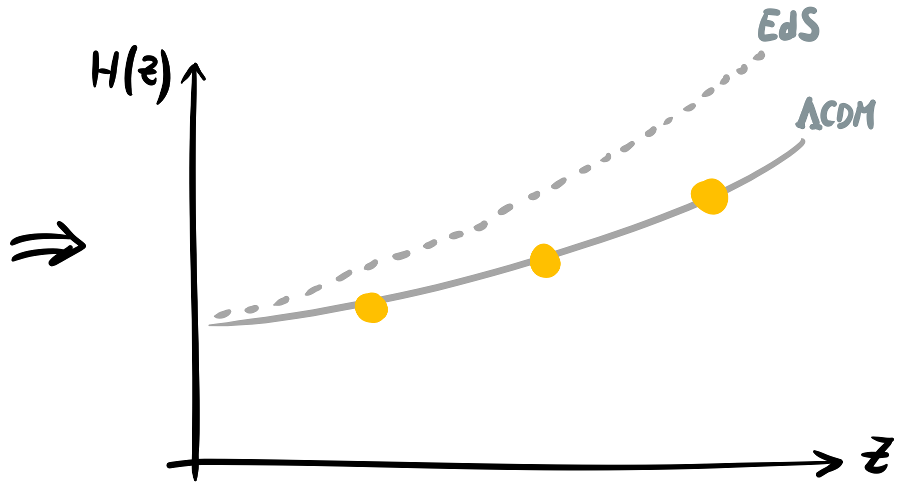
Cosmic chronometers - BASICS

Assuming a FLRW metric:
(Jimenez & Loeb, 2002)

$$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{\mathrm{d}z}{\mathrm{d}t}$$





- ✓ Direct measure of H(z)
- ✓ Differential approach
- ✓ Cosmological model-independent
  ideal to test cosmological models

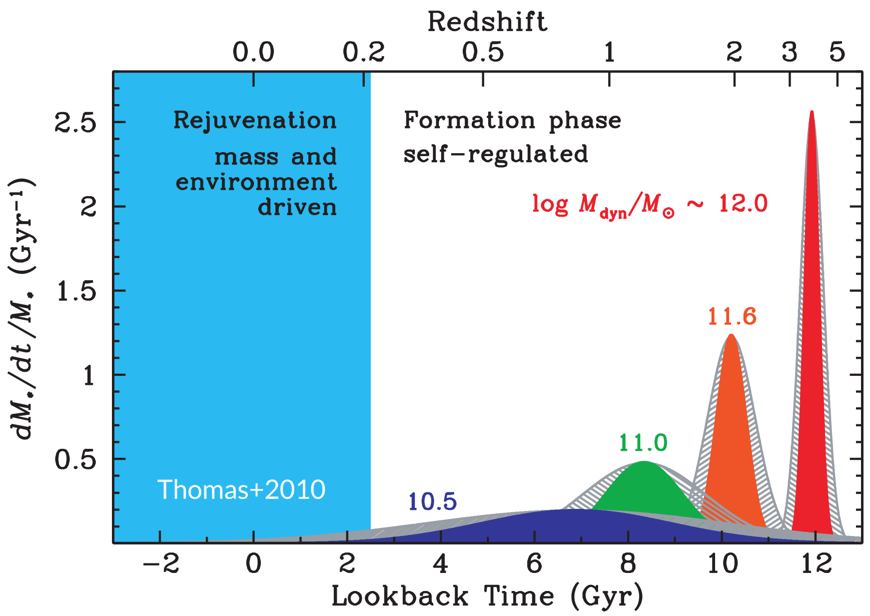
Key requirements:

1. Pure passive sample
2. Robust *dt* estimates **without cosmological priors**

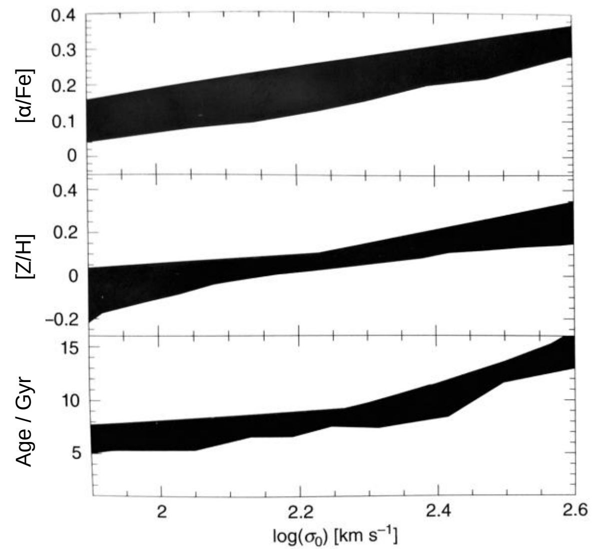
Cosmic chronometers - TRACERS

Best candidates: very massive and passive galaxies

- Homogeneous population in number density and stellar population
  (e.g. Gallazzi et al. 2005, Renzini 2006, Pozzetti et al. 2010)
- Oldest galaxies at each redshift
  (e.g. Cowie et al. 1996; Cimatti et al. 2004; Thomas et al. 2005, 2010)
- More synchronized SFHs

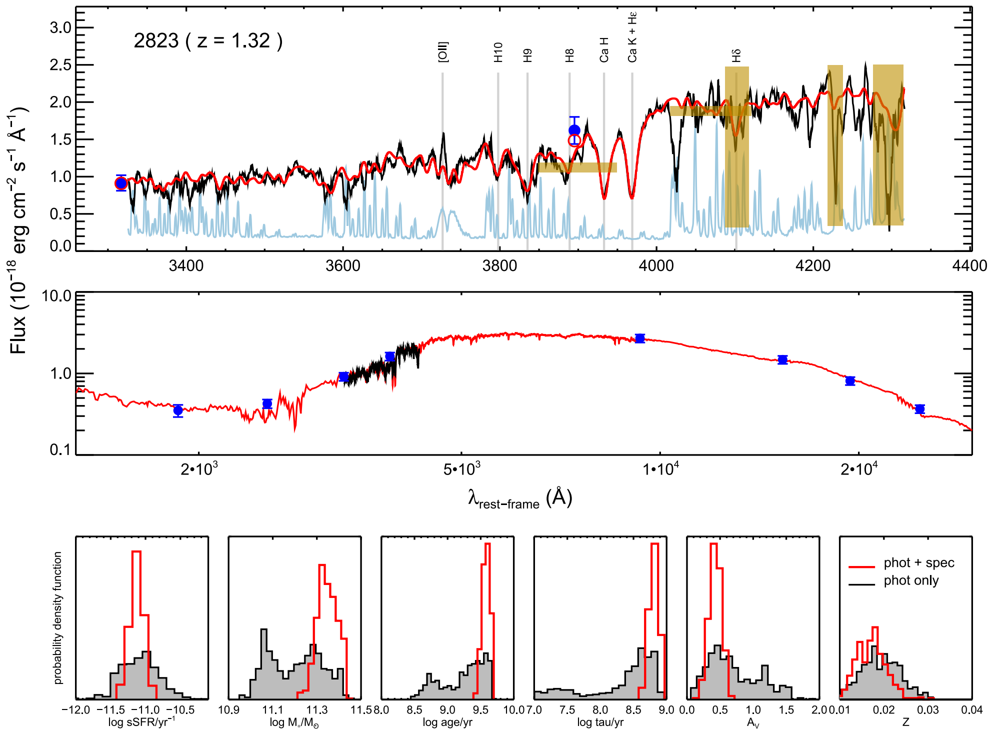


From the combination of various local early-type galaxies (Gallazzi et al. 2006, Thomas et al. 2010, Conroy et al. 2014, Johansson et al. 2012; Cimatti et al. 2019 book):



Cosmic chronometers - AGE

Different methods to derive galaxy's mean stellar ages: photometry, full-spectrum fitting, spectral indices

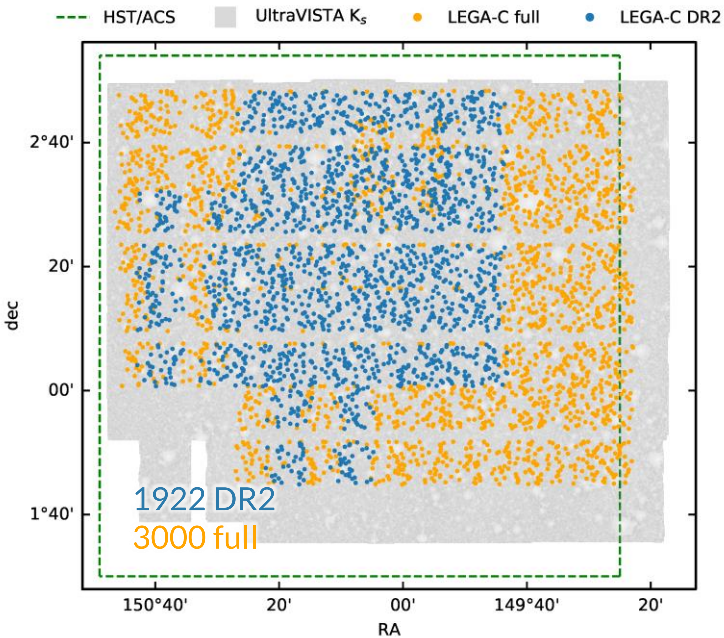


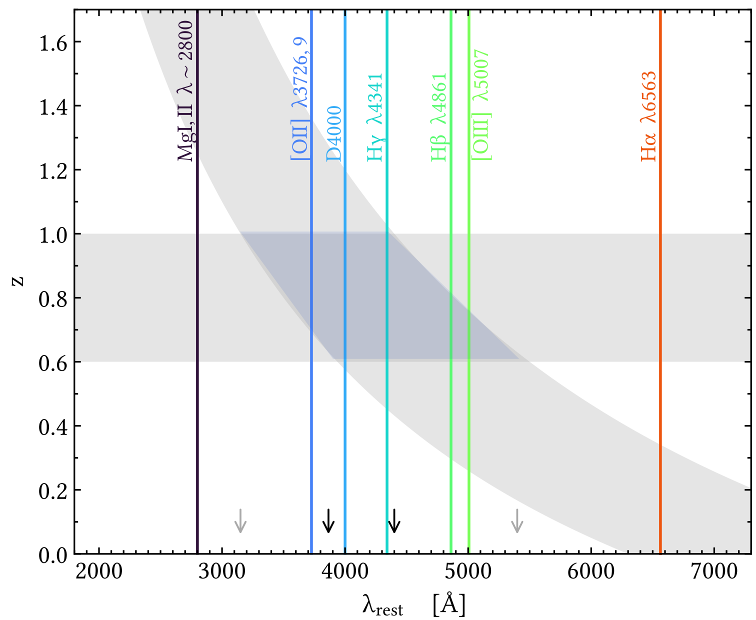
(Adapted from Belli et al., 2015)

- Photometry alone is not sufficient to obtain informative constraints on stellar population properties (e.g. age–metallicity degeneracy, Worthey et al. 1994)
- Spectral information is needed, e.g. full-spectrum fitting (e.g. Conroy 2018). But stringent requirements for flux calibration and high computational cost.
- The (old standard) analysis of Lick indices (e.g. Burstein et al. 1984; Faber et al. 1985; Worthey et al. 1994) is ideal for large galaxy surveys.

The LEGA-C survey (0.6 < z < 1)

(see Van der Wel et al. 2016 and Straatman et al. 2018)





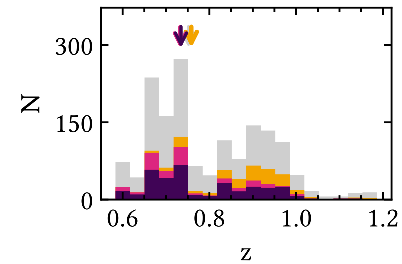
- 2 deg^2 in the COSMOS field; $K_{s,lim}$ = 20.7 -7.5 log((1+z)/1.8)
- VLT / VIMOS HR-Red; R ~ 3500, with S/N ≳ 20
- Narrow λ_{rest} interval uniformly sampled, Δλ ~ 500 Å

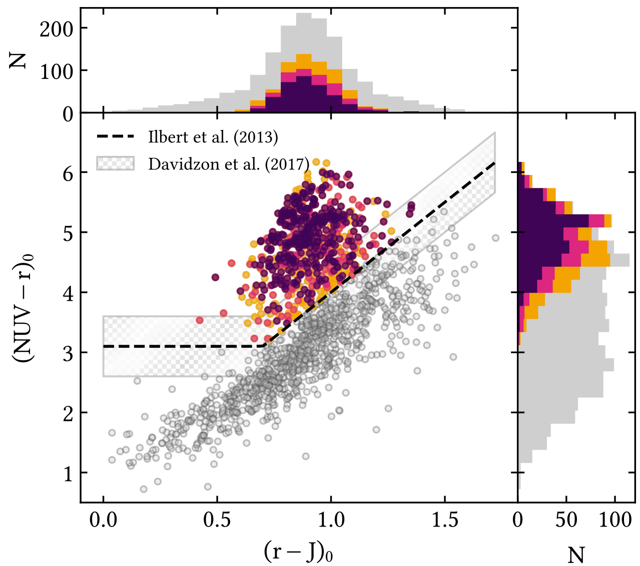
Selection of passive galaxies

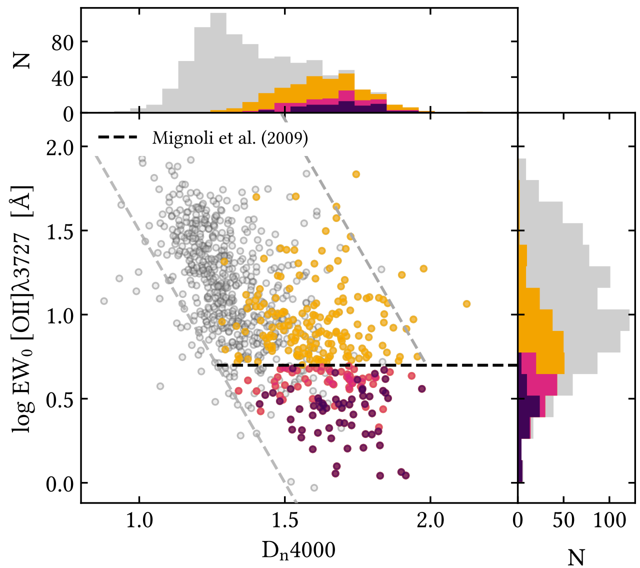
(see Renzini 2006, Franzetti et al. 2007, Moresco et al. 2013)

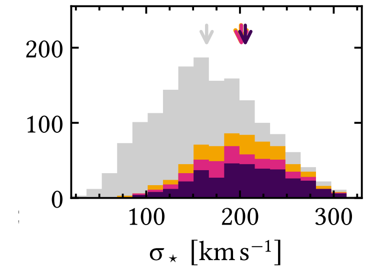
1. NUVrJ (Ilbert et al. 2013)
2. EW[OII]λ3727 < 5 Å cut (e.g. Mignoli et al. 2009)
3. Visual inspection of [OII]λ3727 and [OIII]λ5007 lines

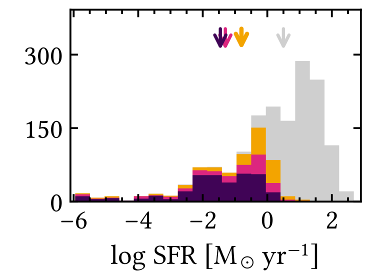
→ 350 (22%) massive and passive galaxies with $\langle \mathrm{sSFR/yr} \rangle = -12.1$







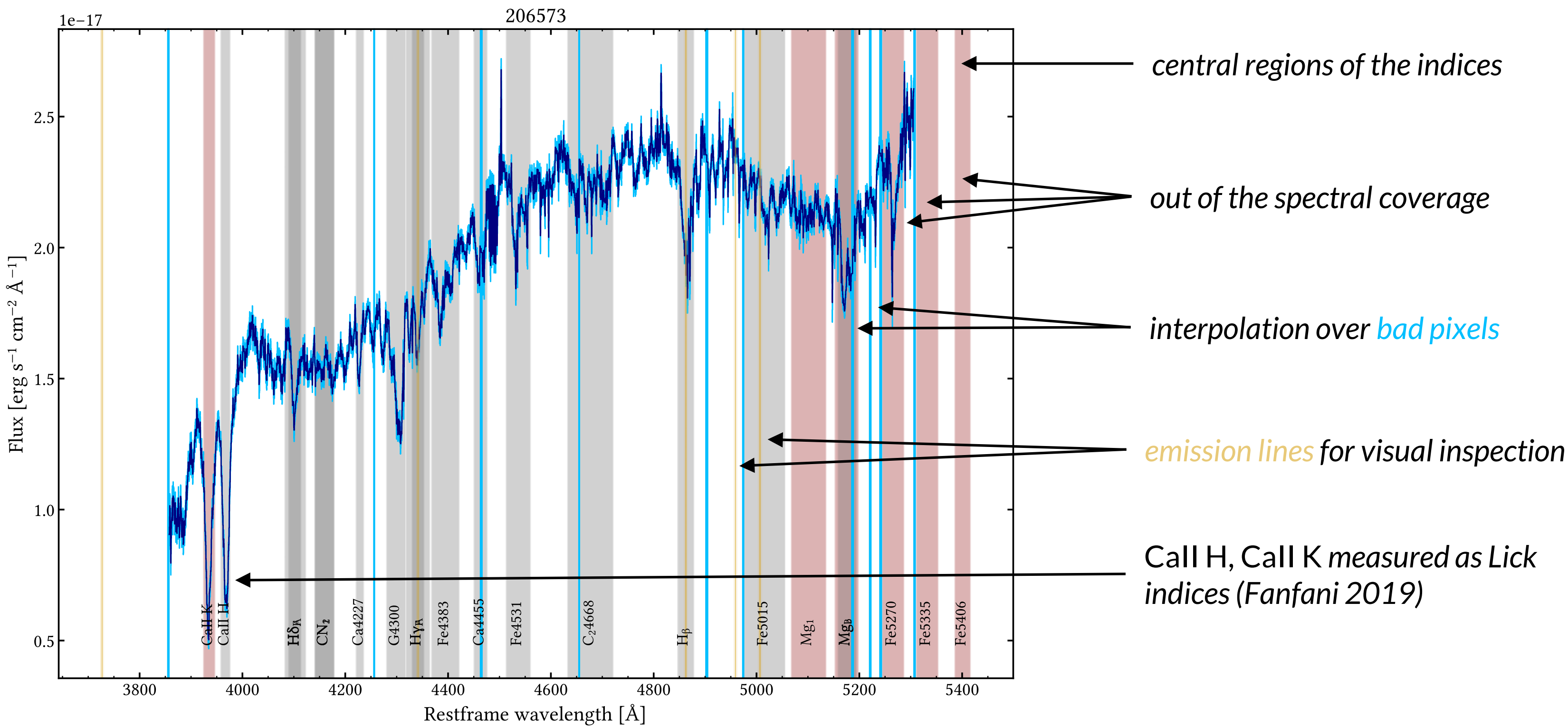




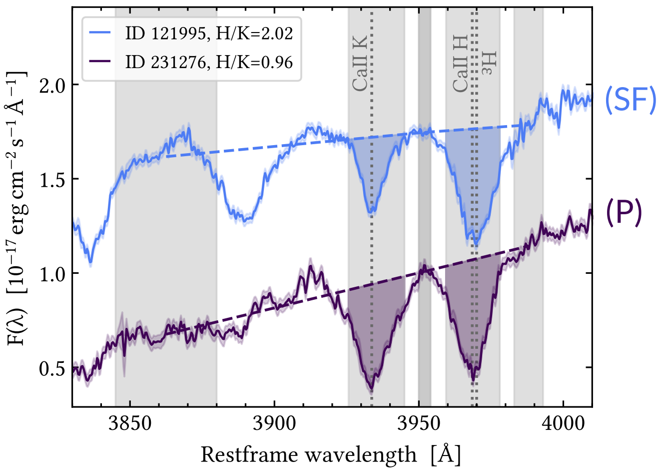
Pylick

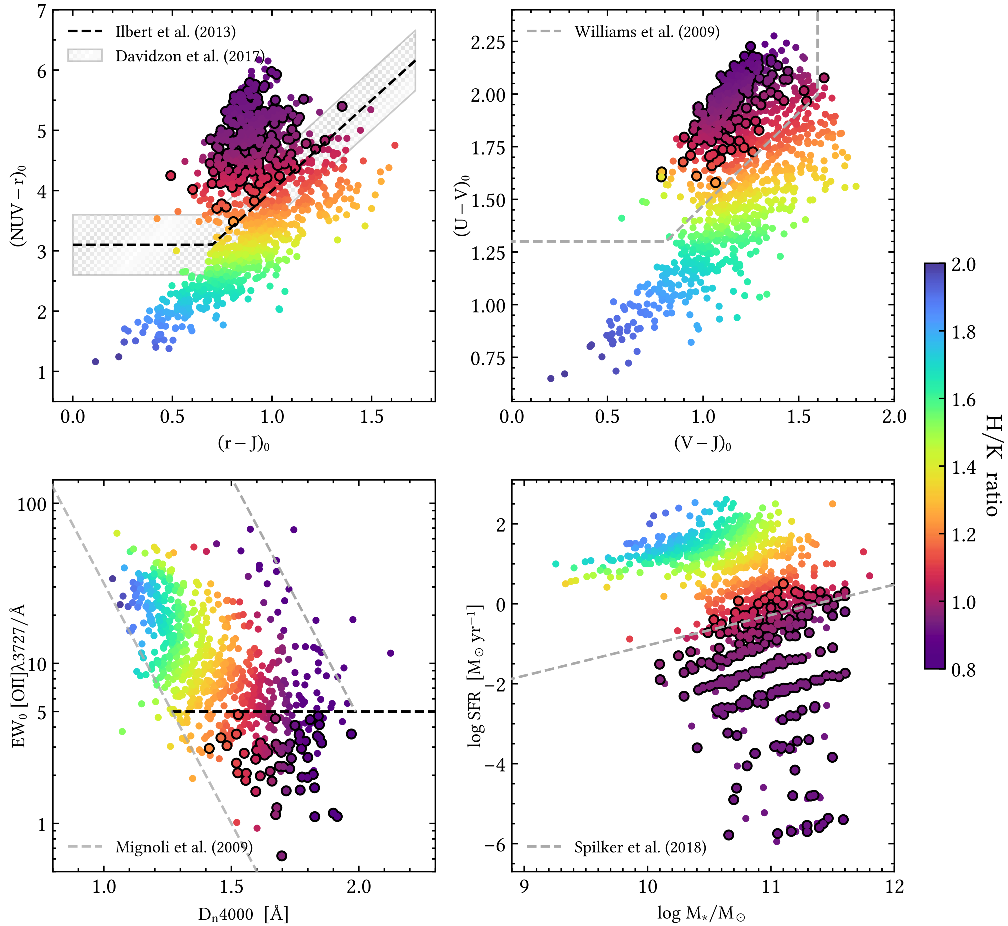
[Available on GitLab]

Flexible Python tool to measure spectral line indices on galaxy spectra. Currently, 54 index definitions are implemented. New indices can be easily defined by the user (e.g. CaII H and CaII K).



Are these galaxies really passive? - The H/K ratio





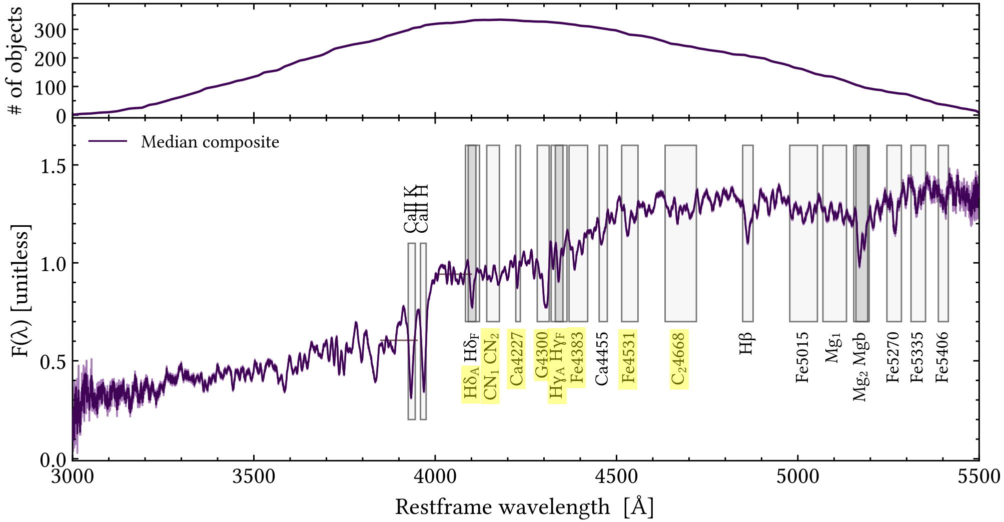
- CaII K bimodality, passive threshold **~5.5 Å**
- H/K = (CaII H + Hε) / CaII K
  strong Hε absorption from A & B-type stars, <1 Gyr episodes of star formation
- H/K<1.1 ↔ sSFR/yr < -11

(see also e.g. Rose 1984, Longhetti et al. 1999, Moresco et al. 2018)

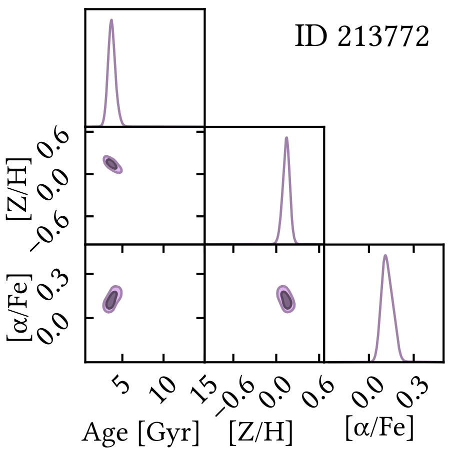
Stellar population properties

1. Thomas, Maraston & Johannson 2011 (TMJ) SSP models $\rightarrow$ (age, [Z/H], [α/Fe])

2. Optimized set of spectral indices:



3. Bayesian approach **with uninformative priors** (e.g. no cosmological priors!)

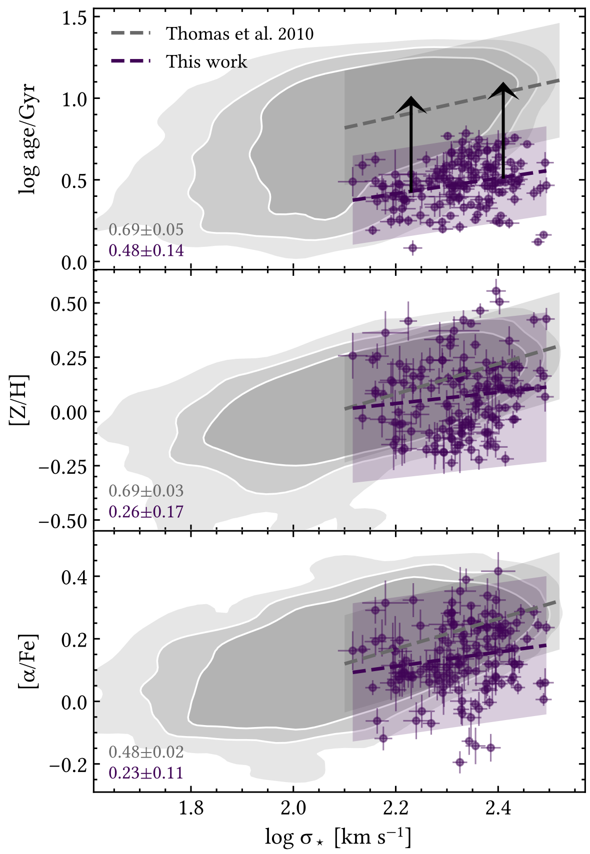


➢ Constraints for **140 individual** passive galaxies

$\langle \mathrm{S/N} \rangle \simeq 26$ per resol. element

$\sigma_{age} \simeq 0.4$ Gyr, $\quad \sigma_{[Z/H],[\alpha/Fe]} \simeq 0.05$ dex

Stellar population properties – RESULTS



➢ Vertical offset of ~5.5 Gyr → very good agreement with the ageing of the Universe!

➢ Scaling relations similar to the ones observed at z=0 and consistent with *mass-downsizing*

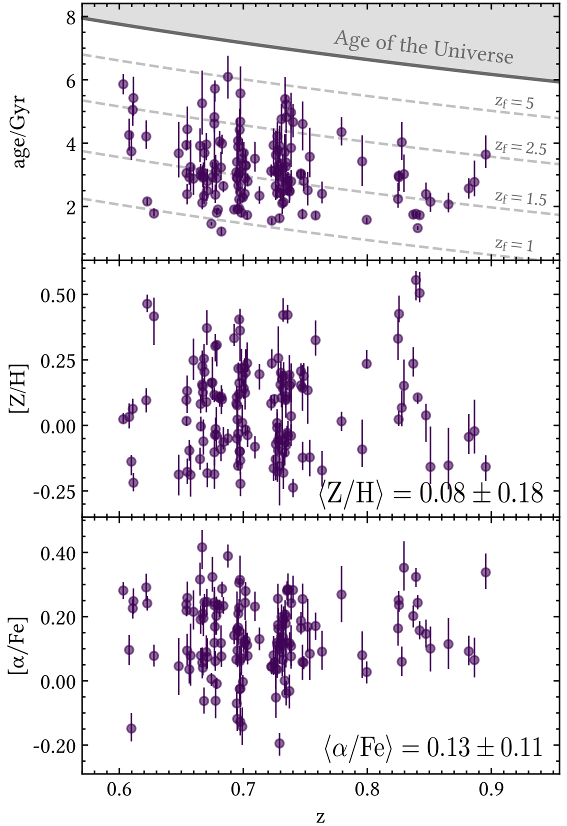
(more massive galaxies are older, have higher [Z/H] and build up their mass over shorter Δt, e.g. Cowie et al. 1996, Cimatti et al. 2006)

y	$a \pm \mathrm{err}(a)$	$b \pm \mathrm{err}(b)$	rms
log *age*/Gyr	0.48 ± 0.14	-0.63 ± 0.33	0.14
[Z/H]	0.26 ± 0.17	-0.53 ± 0.40	0.17
[α/Fe]	0.23 ± 0.11	-0.39 ± 0.26	0.11

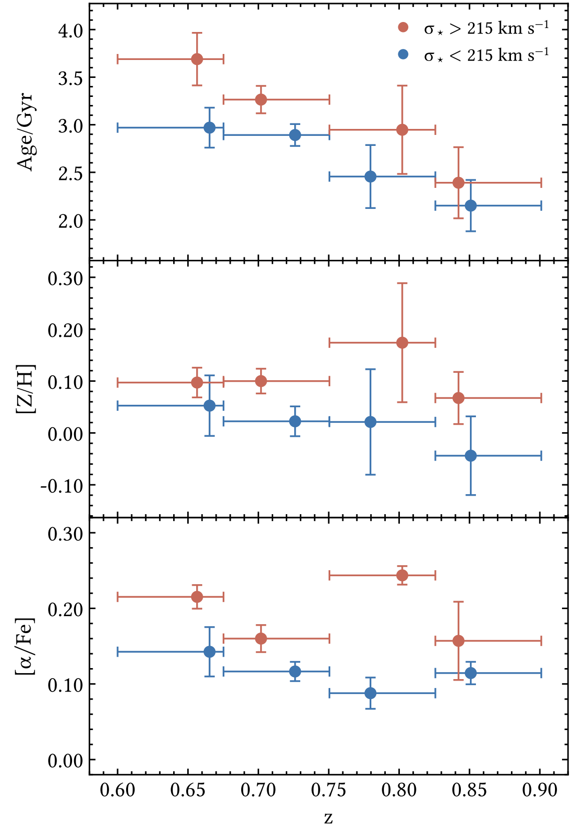
NOTE—Fits are of the form: $y = a \cdot \log\sigma_\star + b$.

(see also, e.g. Thomas+05, 10; Gallazzi+05, 14; Onodera+12, 15; Jørgensen+13; Choi+14; McDermid+15; Lonoce+15, 20; Scott+17, Siudek+17; Wu+18; Belli+19; Carnall+19; Estrada-Carpenter+19; Morishita+19; Tacchella+21; Beverage+21)

Stellar population properties – age-z

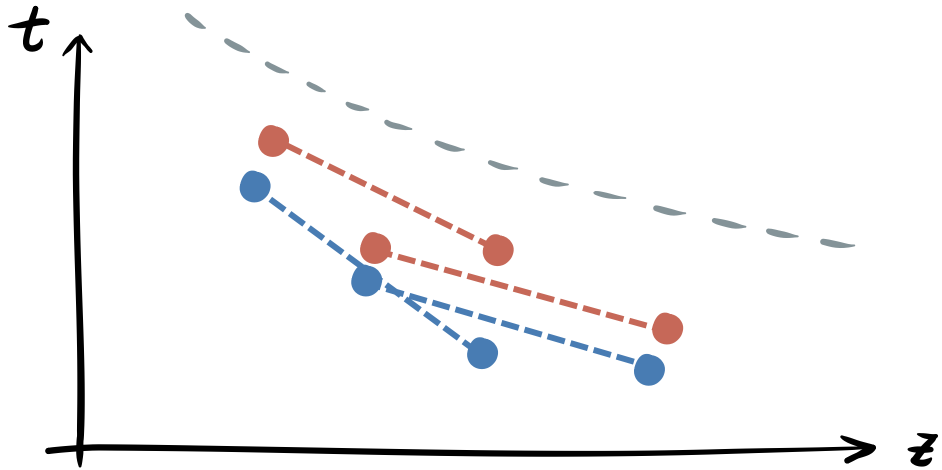


2 mass regimes (M_t~$10^{11}\,M_\odot$) & 4 z bins



- Confirms the downsizing scenario and the passive nature of this population
- Two **nearly parallel age-z relations** for both the higher σ ~ 230 km/s and the lower σ ~ 200 km/s mass regime.

A new measurement of H(z)



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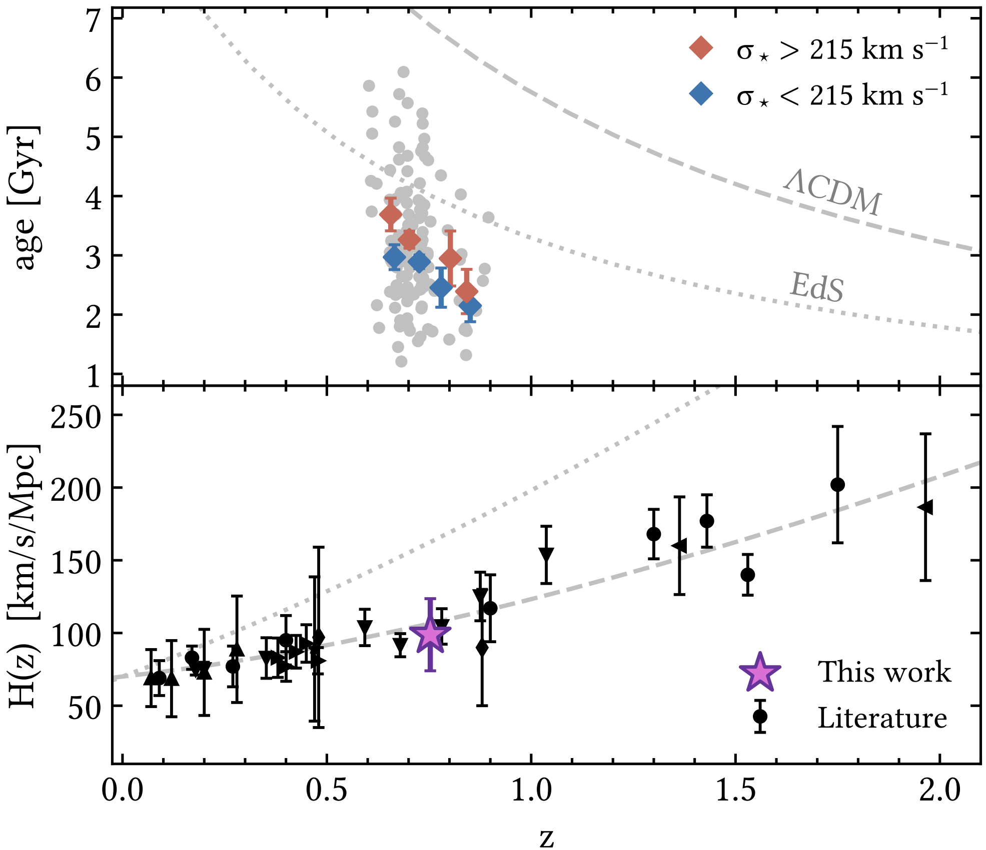

- Four independent H(z) measurements, wmean in z and in σ_* to maximize S/N

- First H(z) estimate derived analysing single galaxies with Lick indices
  - poorly mapped redshift range
  - near to the transition phase
  - robust against SPS model choice (test with Vazdekis et al. 2015)

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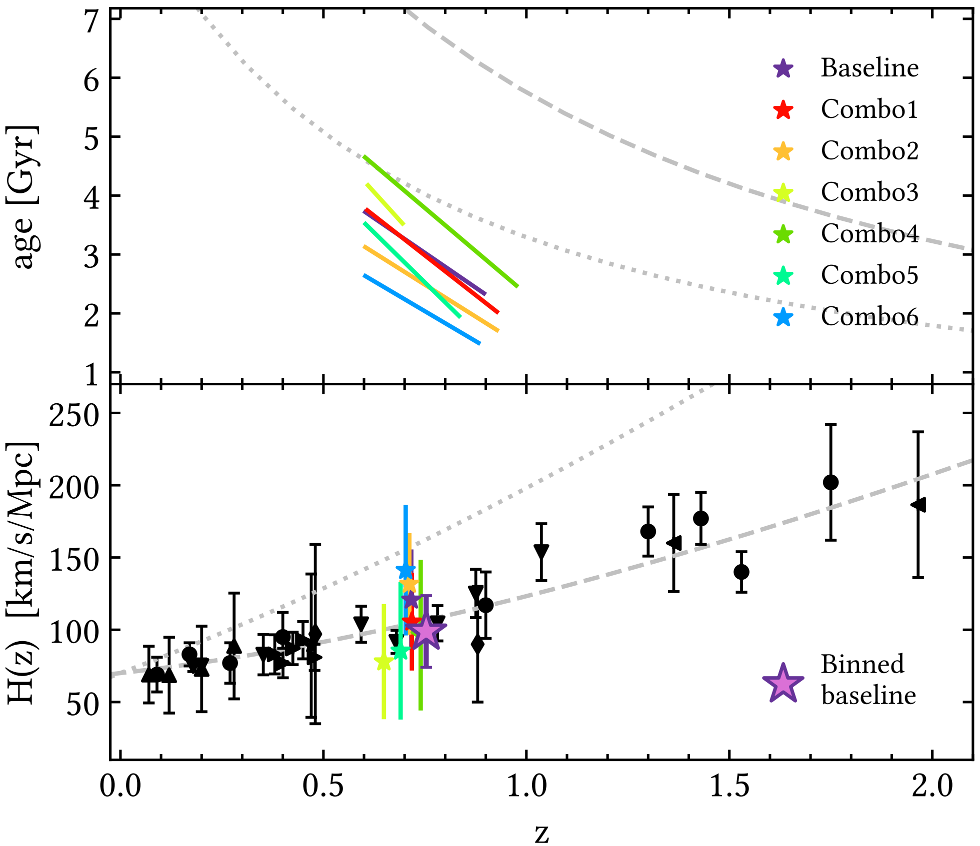

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  - poorly mapped redshift range
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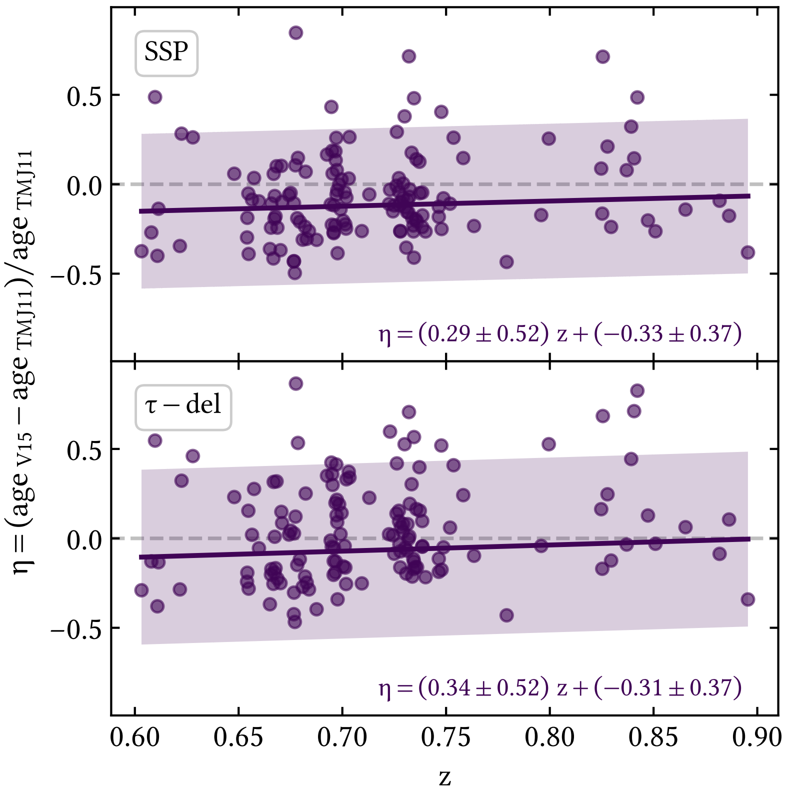
- Systematic under/over-estimates of galaxy ages (±1Gyr) using different index sets

- Final H(z) measurement robust against (even very) different index sets (<0.2σ)!

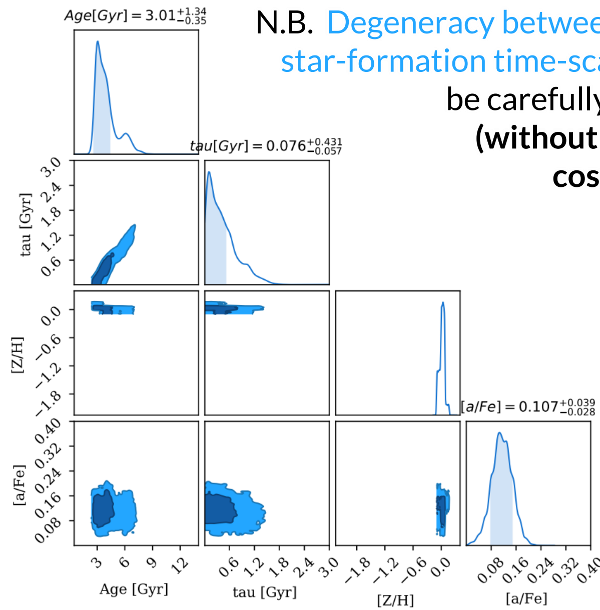
A new measurement of H(z)

Dependence on the SPS model and a more extended SFR(t) tested with Vazdekis et al. (2015) models

$$\mathrm{SFR}(t) \propto \frac{t_0 - t}{t_0} e^{-(t_0 - t)/\tau}$$

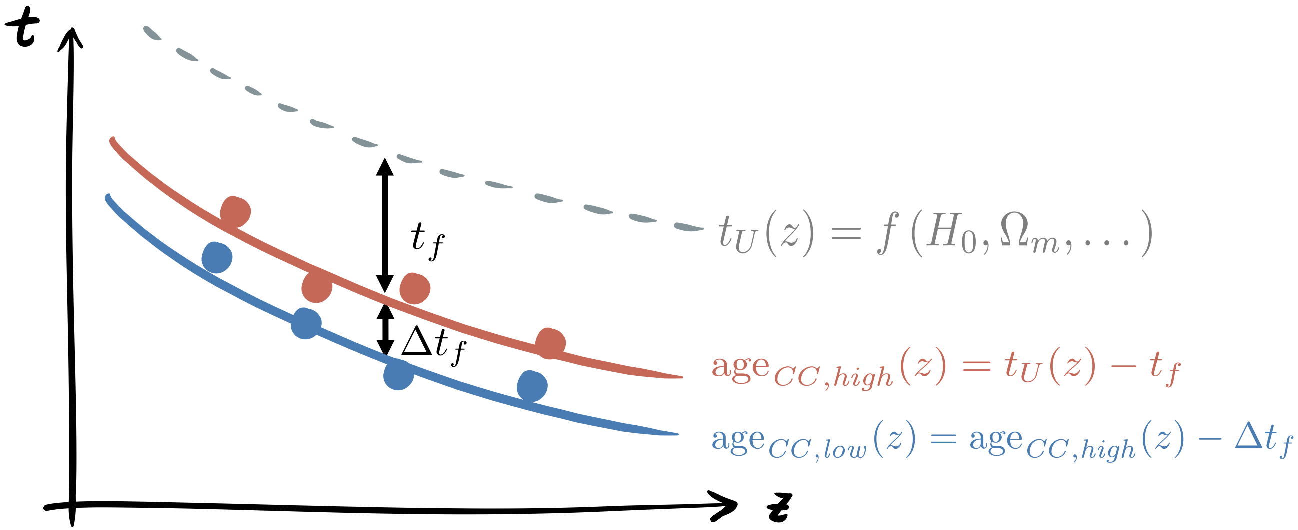


- Final H(z) measurements ≲1σ with the baseline result based on TMJ models

- 

N.B. Degeneracy between age and star-formation time-scale should be carefully assessed **(without assuming cosmological priors!)**

Constraints from age-redshift relations

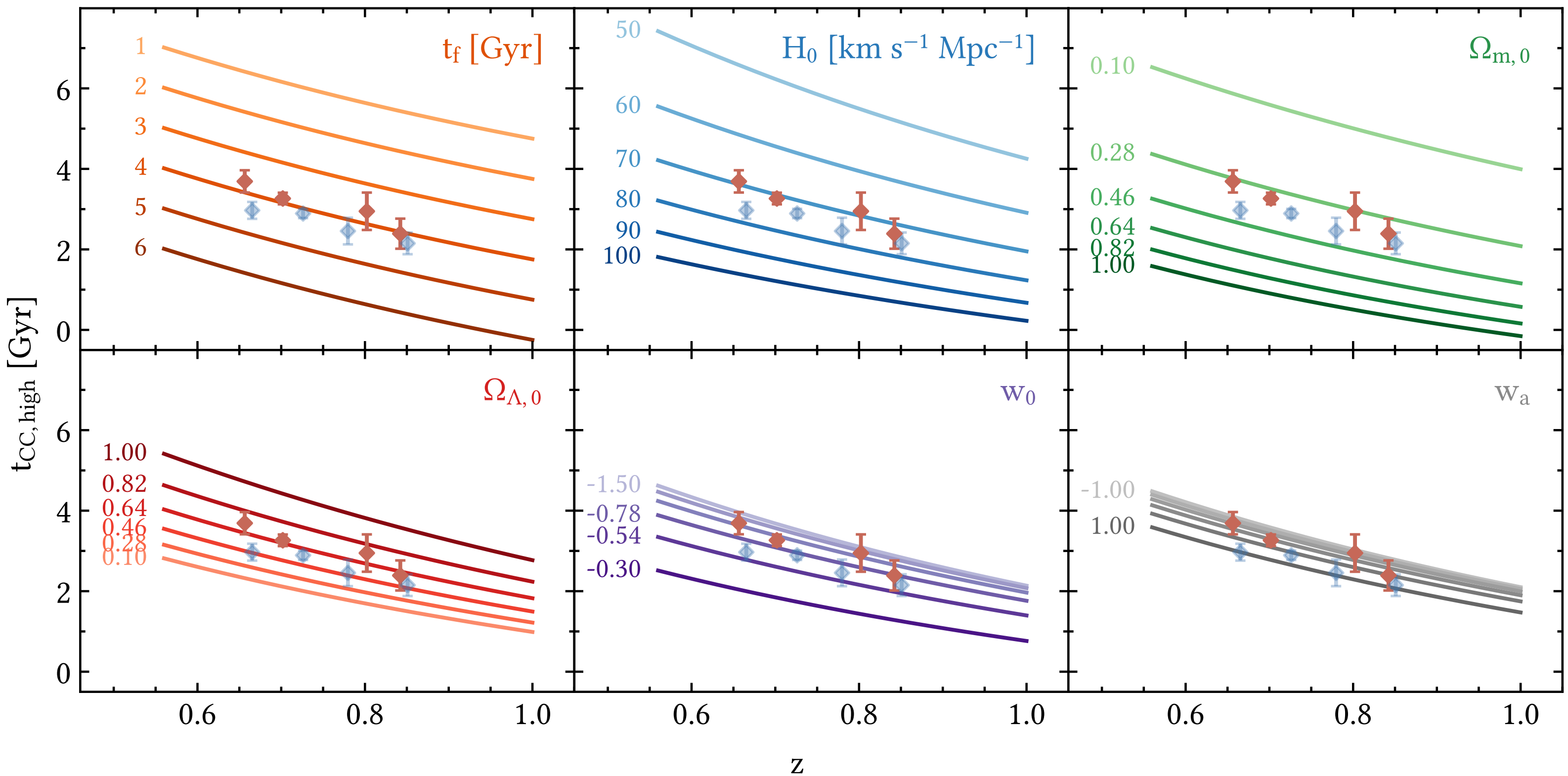


- $t_U(z)$ relation from cosmological models
- High mass population age ($t_{CC,\,high}$) traces the age of the universe with a constant offset of t_f (CC)
- Constant age difference between low and high mass regimes $\Delta t_f = 0.5$ Gyr

Constraints from age-redshift relations

When not varied, the parameters are set to the following fiducial values:

t_f = 3.8 Gyr H_0 = 70 km/s/Mpc $\Omega_{m,0}$ = 0.3 $\Omega_{\Lambda,0}$ = 0.7 w_0 = −1 w_a = 0



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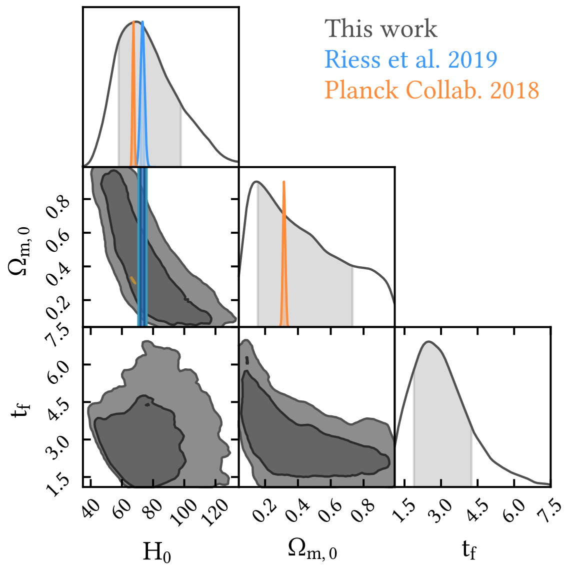

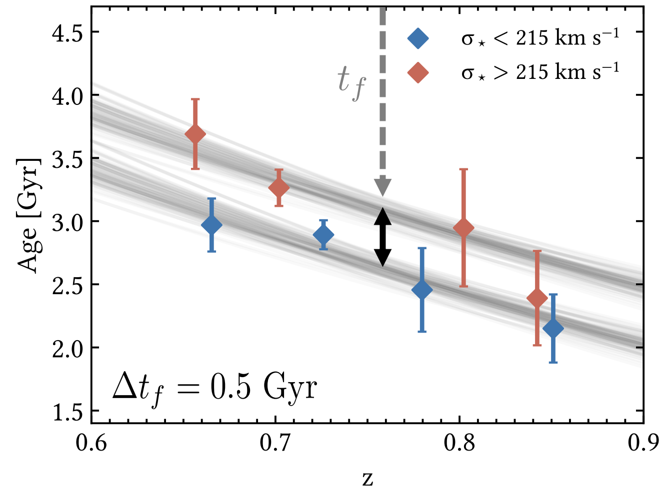

Table 1. Contraints for a fΛCDM model

Priors	H_0 [km s^{-1} Mpc^{-1}]	Ω_m	t_f [Gyr]
Flat	74^{+23}_{-16}	$0.38^{+0.36}_{-0.23}$	$2.9^{+1.4}_{-1.0}$
$\Omega_m \sim \mathcal{N}(\mathit{Planck18})$	79^{+14}_{-11}	$0.31^{+0.01}_{-0.01}$	$2.8^{+0.9}_{-0.9}$

- Promising, but high degeneracies due to small z leverage.
- Not straightforward to combine different datasets (e.g. different selections, methods to compute ages, index sets, …).

Summary

1. **Selected 350 massive and passive galaxies from LEGA-C DR2 at $0.6 < z < 1$**
   - High R~3500, and ⟨S/N⟩ ≃ 18 and minimal contamination (confirmed from SED-derived properties, composite spectrum, observed indices e.g. H/K).
2. **The H/K ratio is as promising diagnostic to detect star-forming contaminants.**
3. **Derived SSP (age, [Z/H], [α/Fe]) for 140 passive galaxies without assuming cosmological priors.**
   - Extensive study of several index combinations to select the optimal one. Results consistent with a passively evolving population.
4. **Measured positive (age, [Z/H], [α/Fe]) scaling relations as a function of stellar velocity dispersion.**
   - Slopes in agreement with local results and intermediate redshift results based on composite spectra analysis.

➢ **Cosmological studies** (Borghi et al, 2021b):
   - **A new direct H(z=0.7) measurement**
   - Hubble constant constraint assuming a fΛCDM model

Additional refs. for the CC method:
- Jimenez, R. & Loeb, A.(2002) – CCs method definition
- Moresco, M., et al. (2012a&b, 2016a&b, 2018, 2020) – H(z) measurements and cosmology constraints
- Haridasu, B. S., et al. (2018); Gómez-Valent, A. & Amendola, L. H (2018) – H0 from CCs
- Vagnozzi, S., et al. (2020) – cosmo geometry