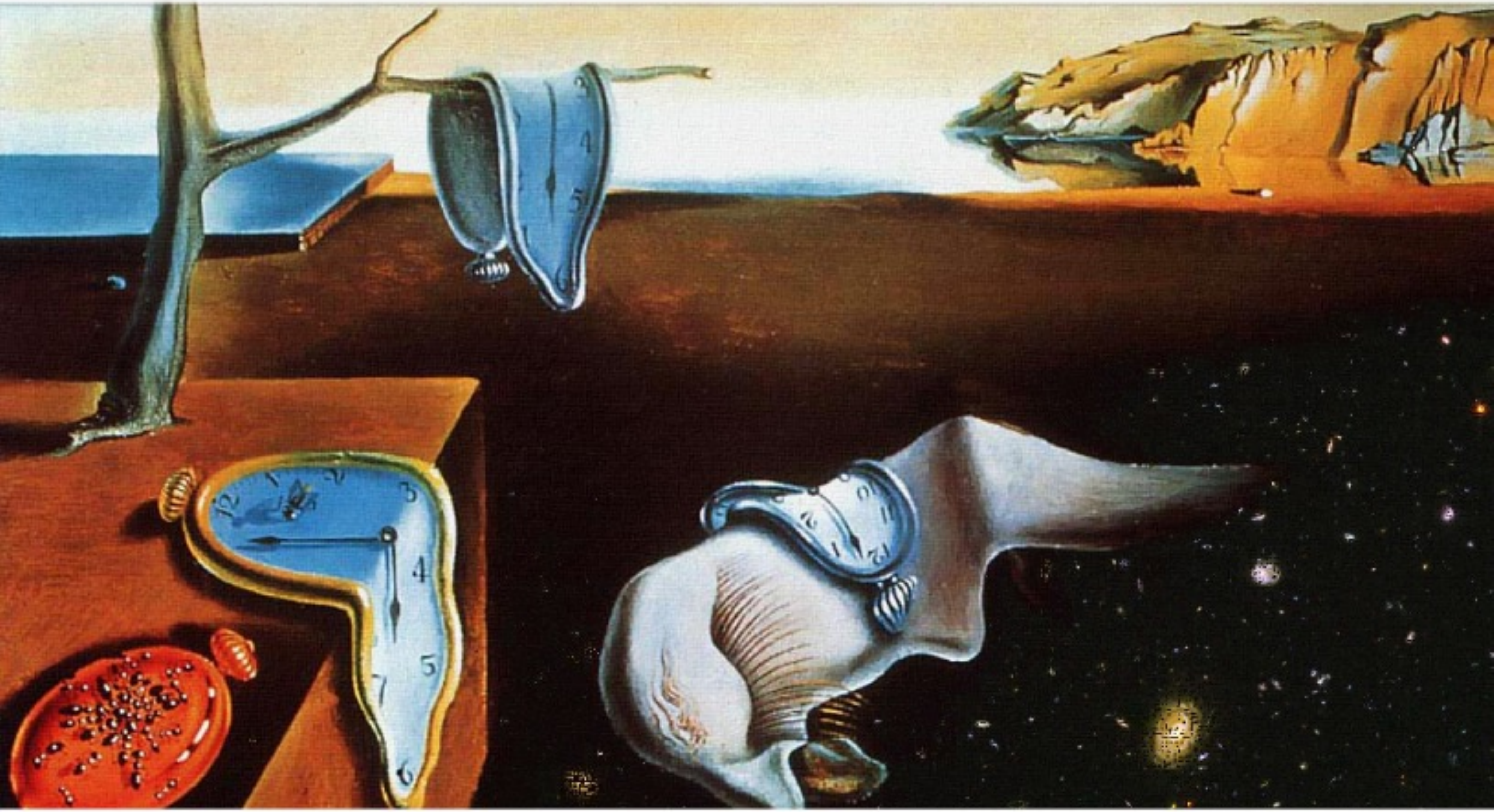
Addressing cosmological tensions with new emerging probes: a perspective from

Cosmic Chronometers



Tension in Cosmology
7-12 September 2022

Michele Moresco
Dipartimento di Fisica e Astronomia
Università di Bologna

Main collaborators: A. Cimatti (UniBo), L. Pozzetti (OAS-Bo), R. Jimenez, L. Verde (ICREA)

based on

Method

Moresco et al. (2012a), JCAP, 08, 006
Moresco et al. (2016a), JCAP, 05, 014

Selection

Moresco et al. (2013), A&A, 558, 61
Moresco et al. (2018), ApJ, 868, 84

Systematics

Moresco et al. (2018), ApJ, 868, 84
Moresco et al. (2020), ApJ, 898, 82

Measurements

Moresco et al. (2012a), JCAP, 08, 006
Moresco (2015), MNRAS Letter, 450, 16
Moresco et al. (2016a), JCAP, 05, 014
Borghi et al. (2021a), ApJ, 927, 164
Jiao et al. (2022), arXiv:2205.05701
Tomasetti et al. (in prep)

Cosmological constraints

Moresco et al. (2011), JCAP, 03, 045
Moresco et al. (2012b), JCAP, 07, 053
Moresco et al (2016b), JCAP, 12, 039
Moresco & Marulli (2017), MNRAS Letter, 471, 82
Borghi et al. (2021b), ApJL, 928, 4

Living Review on emerging cosmological probes **arXiv:2201.07241**:
‘Unveiling the Universe with Emerging Cosmological Probes’

Unveiling the Universe with Emerging Cosmological Probes

Michele Moresco[1,2], Lorenzo Amati[3], Luca Amendola[4], Simon Birrer[5,6], John P. Blakeslee[7], Michele Cantiello[8], Andrea Cimatti[1,9], Jeremy Darling[10], Massimo Della Valle[11], Maya Fishbach[12], Claudio Grillo[13,14], Nico Hamaus[15], Daniel Holz[16,17], Luca Izzo[18], Raul Jimenez[19,20], Elisabeta Lusso[21,9], Massimo Meneghetti[2,22], Ester Piedipalumbo[23,24], Alice Pisani[25,26,27], Alkistis Pourtsidou[28,29,30], Lucia Pozzetti[2], Miguel Quartin[31,32,4], Guido Risaliti[21,9], Piero Rosati[33,2], Licia Verde[19,20]

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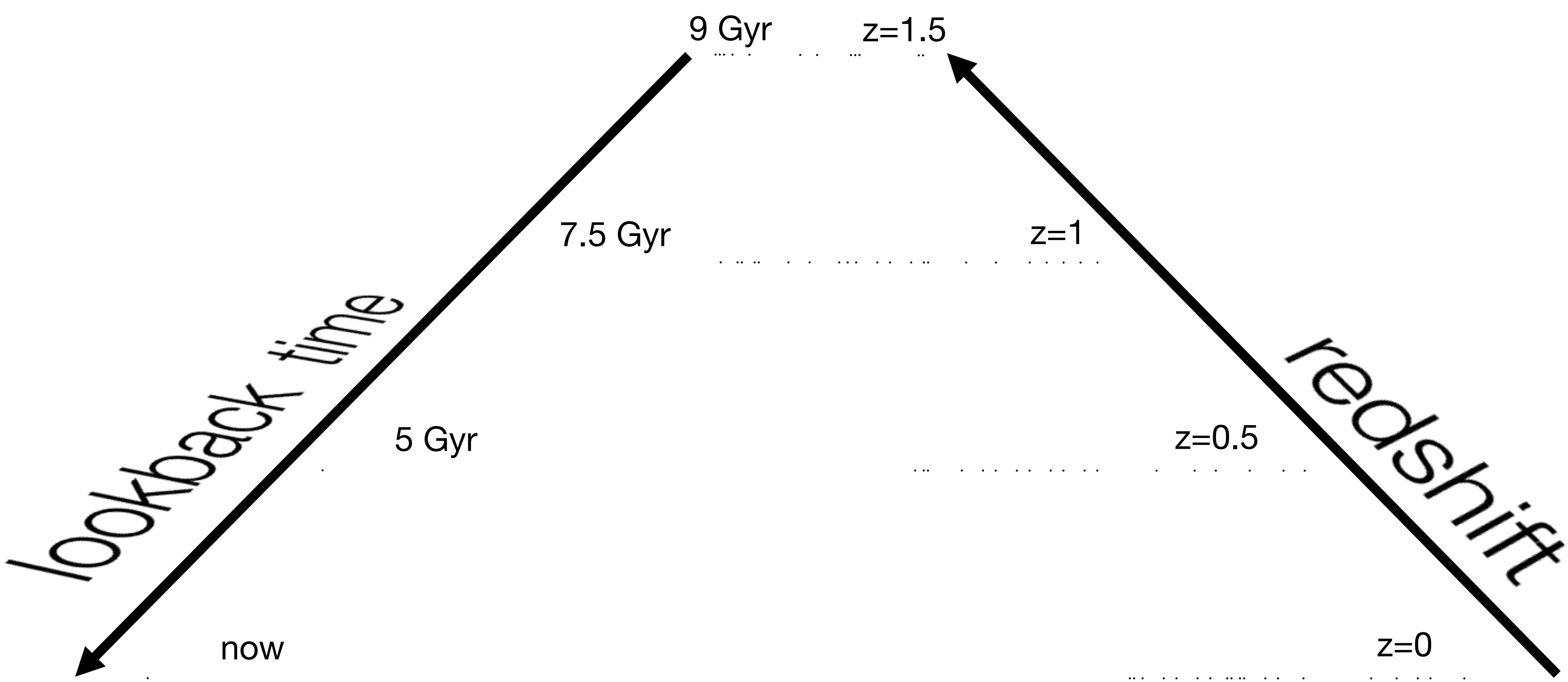
The basic idea



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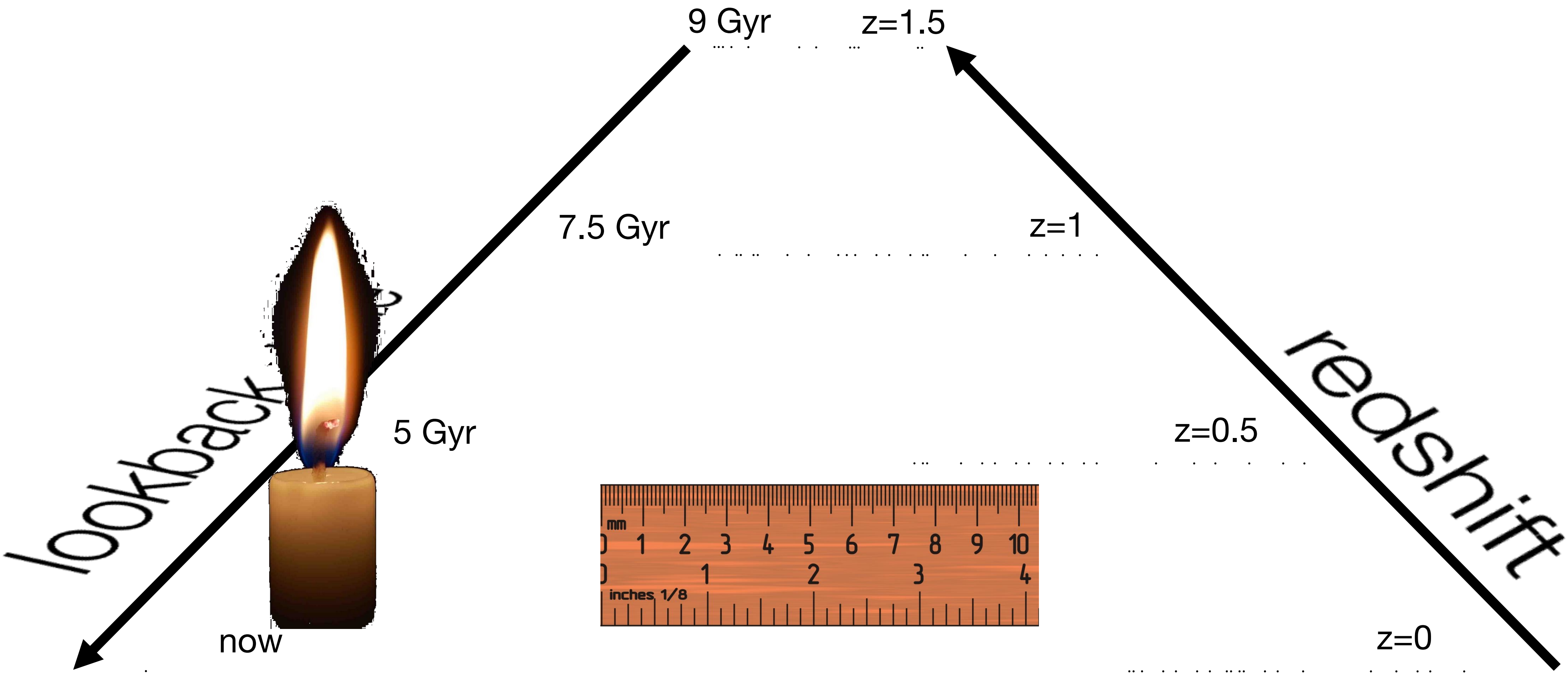

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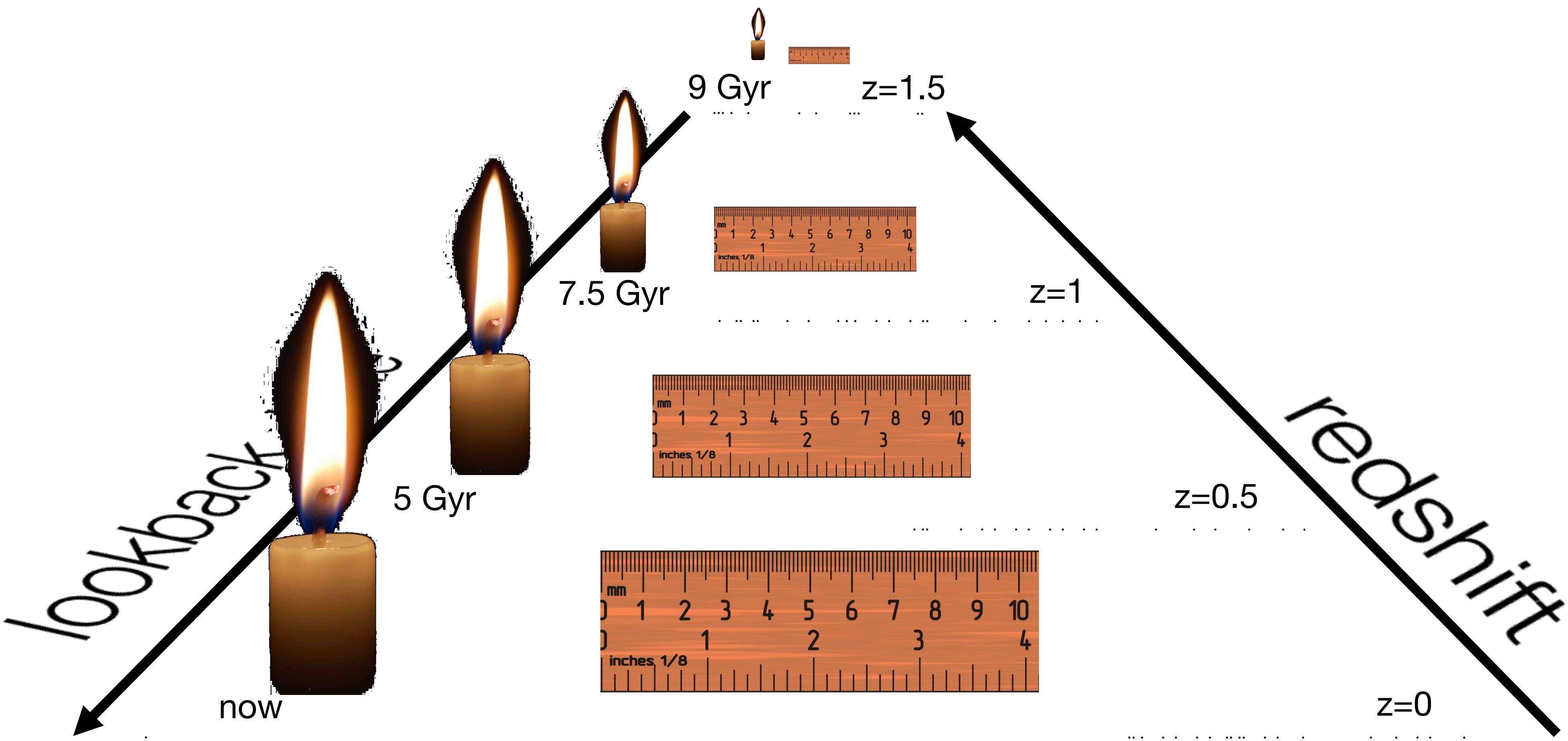

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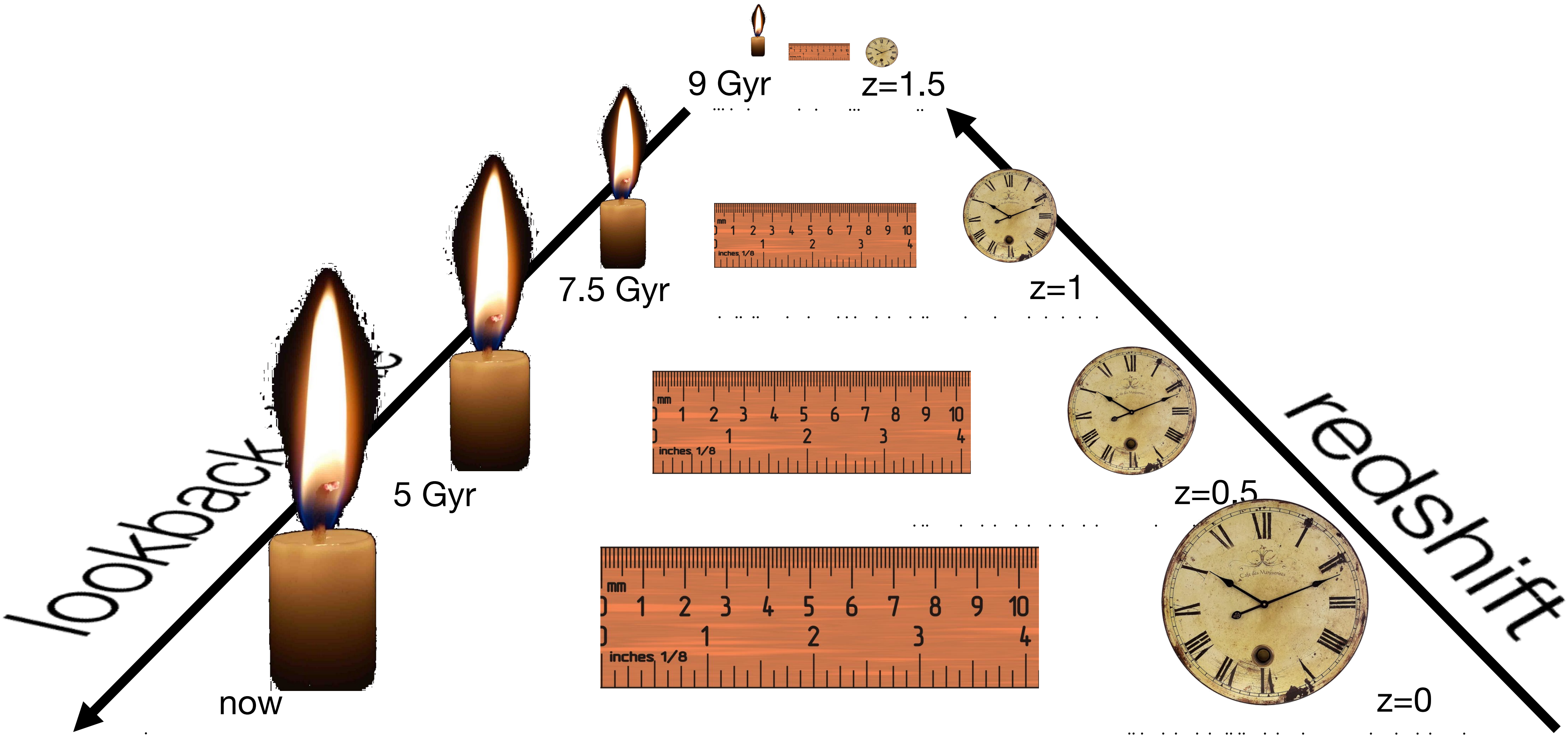

Cosmic chronometers in a nutshell

Chronometers, not clocks

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$$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{dz}{dt}$$

Jimenez & Loeb (2002)

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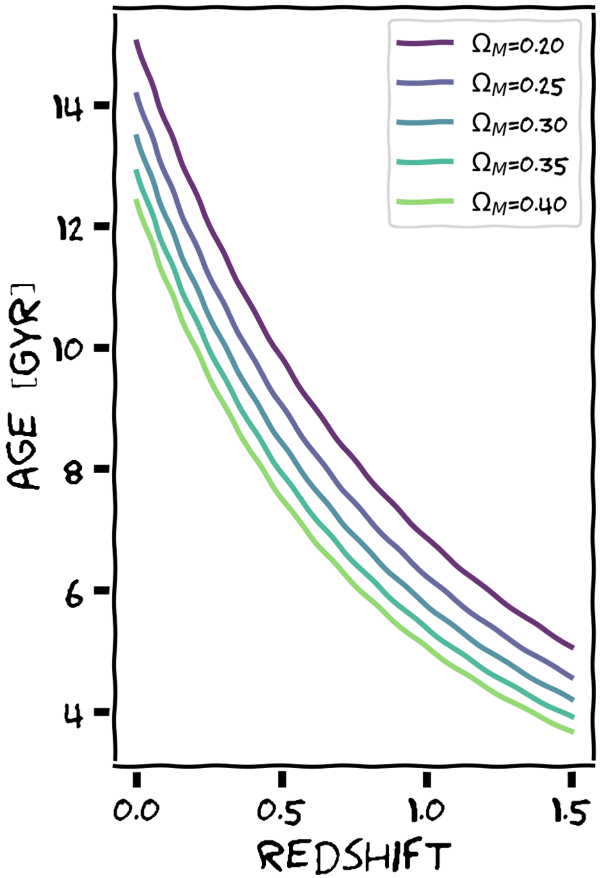

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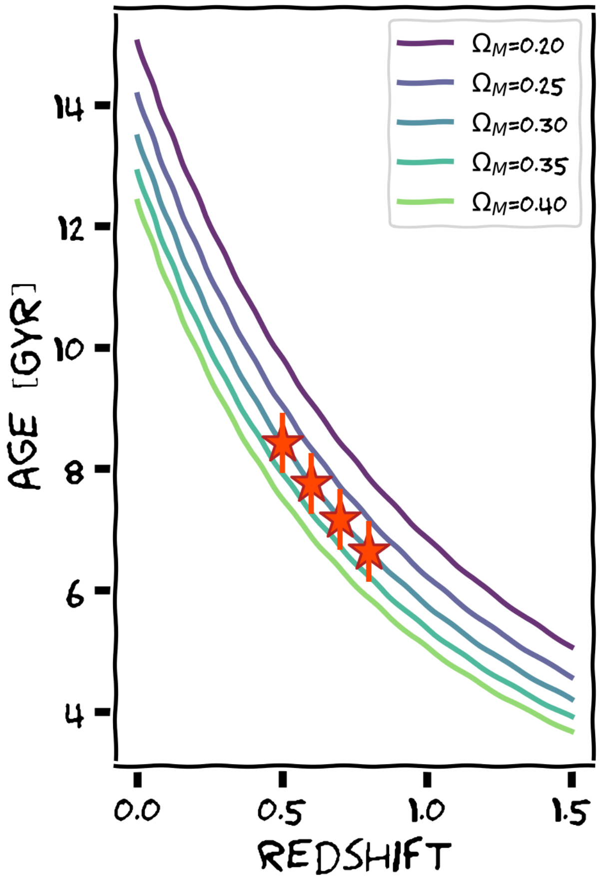

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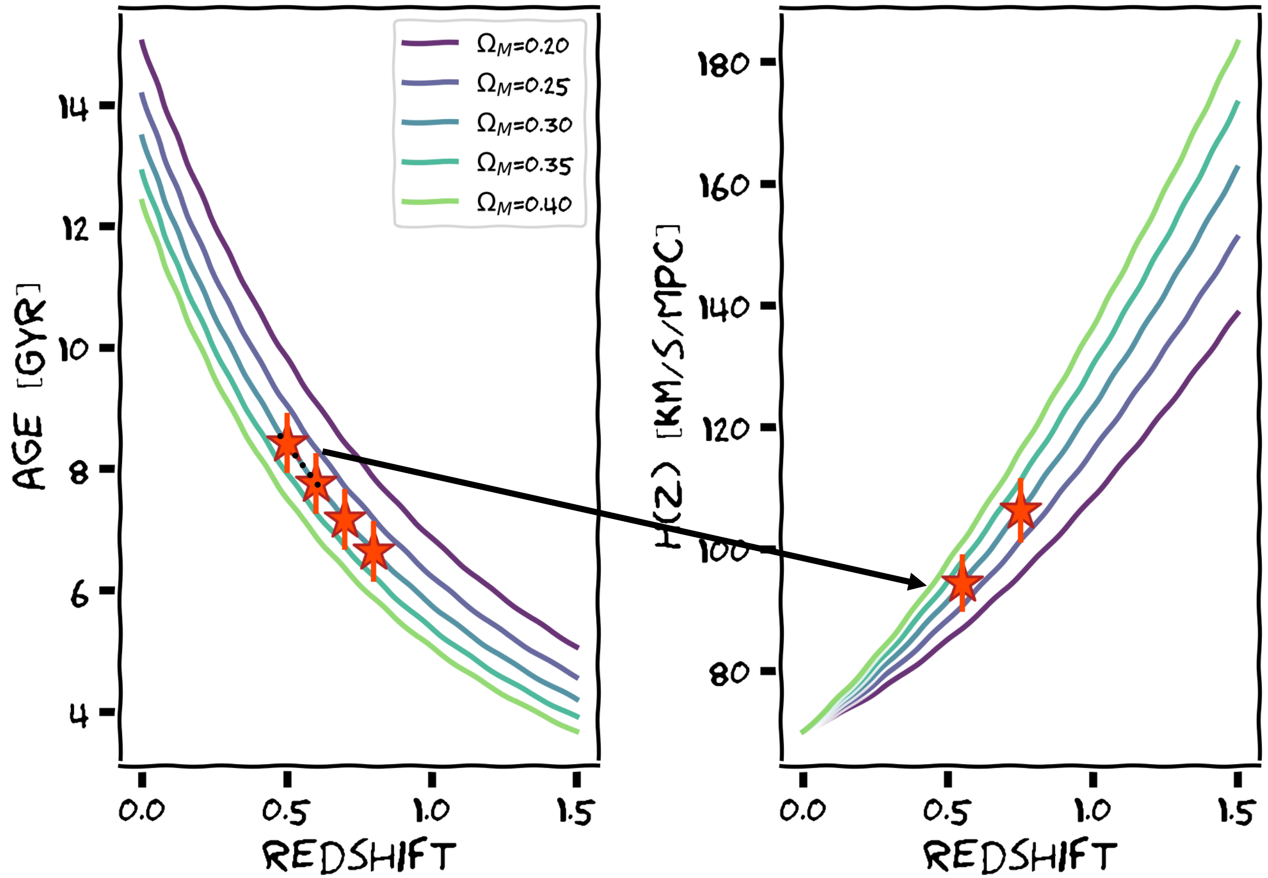

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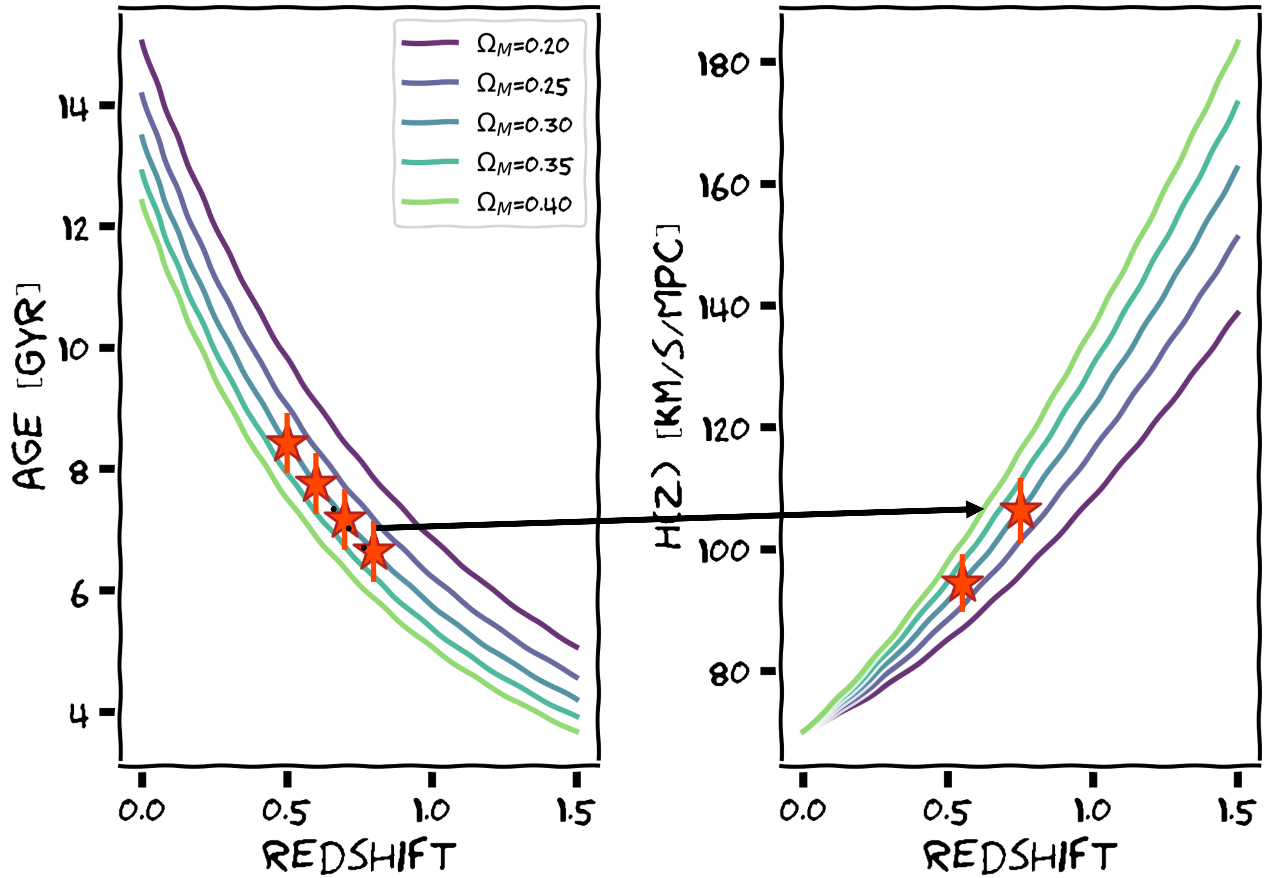

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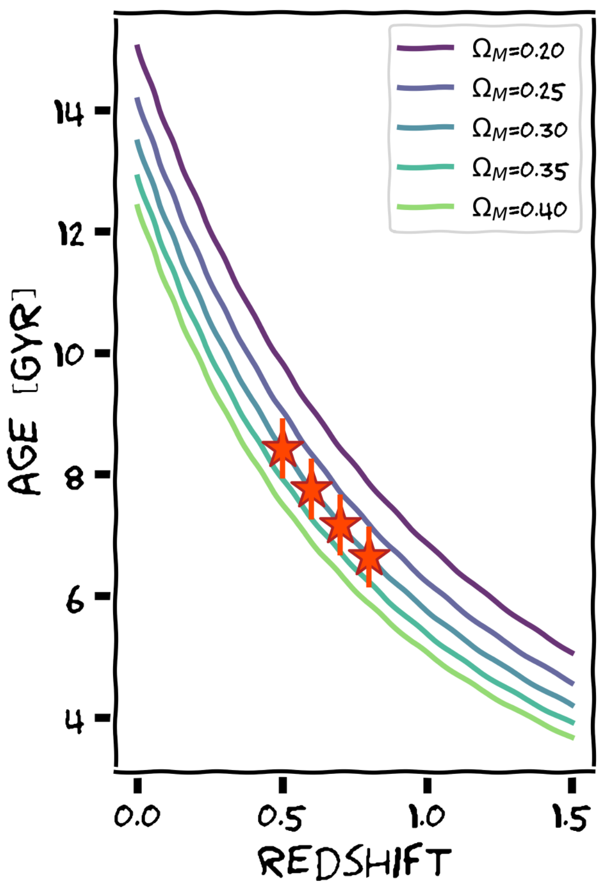

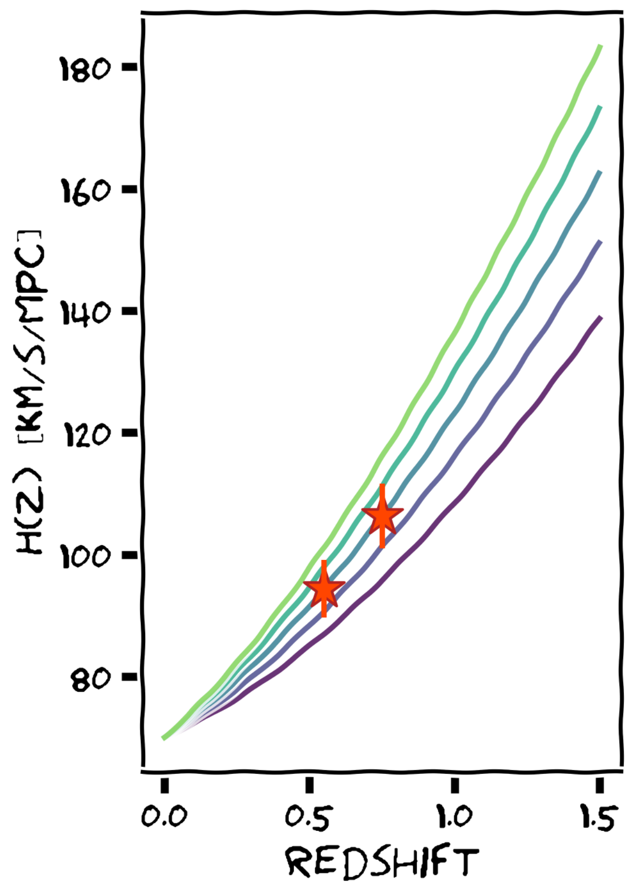

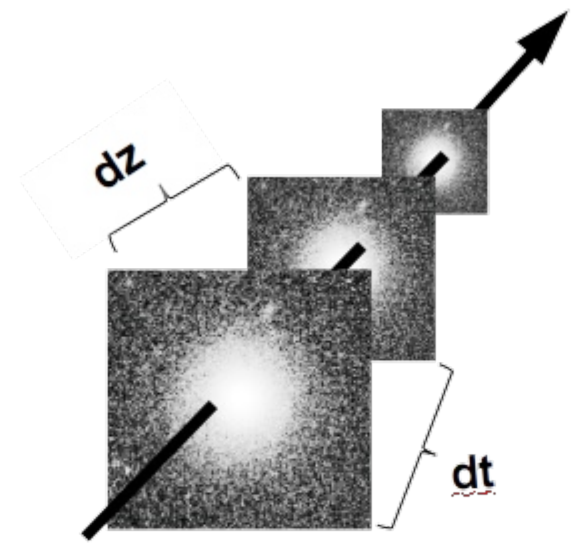

Eldest crust of galaxies at each redshift to map the **differential age evolution** of the Universe

What about the tracers?

What about the age?

What about the systematics?

Pros and cons

Cosmic chronometers handbook

What about the tracers? (Moresco et al. 2013, 2018, Borghi et al. 2021)

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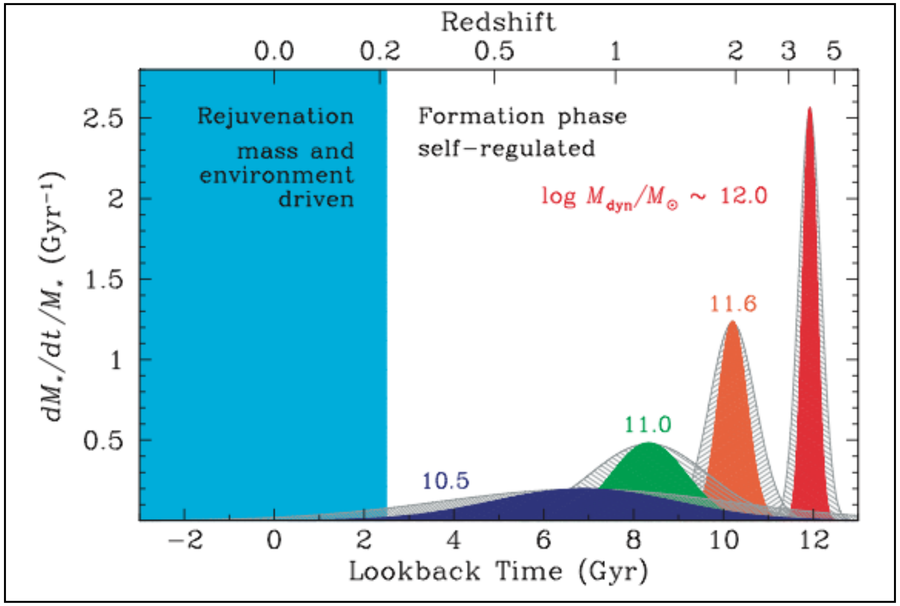

Thomas et al. (2010)

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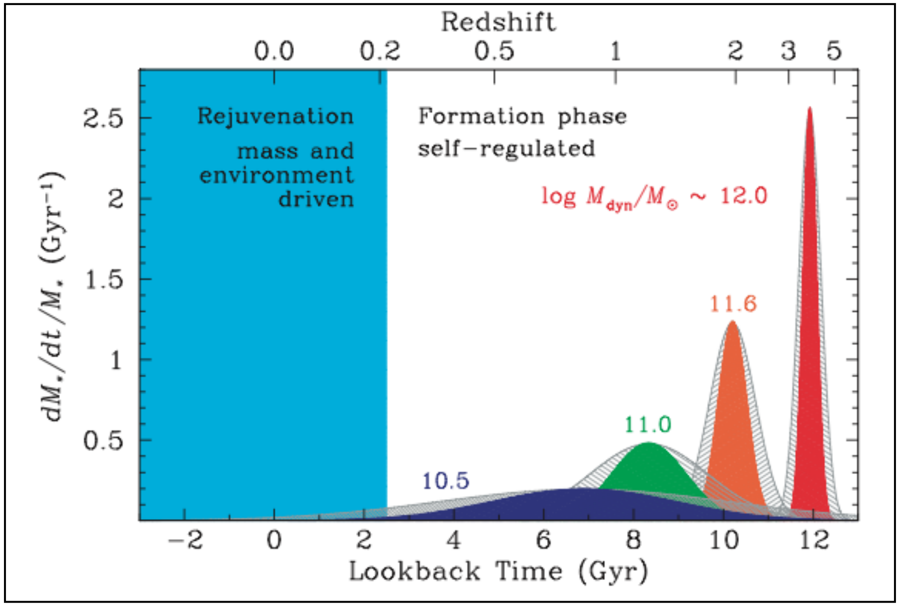

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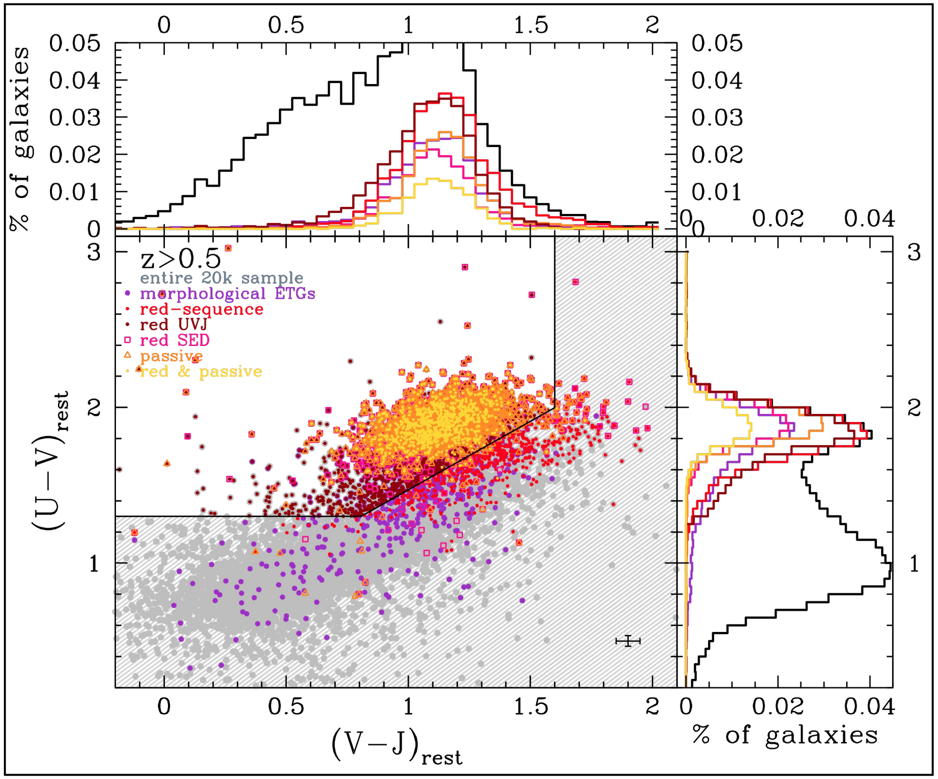

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- break degeneracies to measure *dt*: **different methods**

SED-fitting
full spectral-fitting
absorption features (Lick indices)

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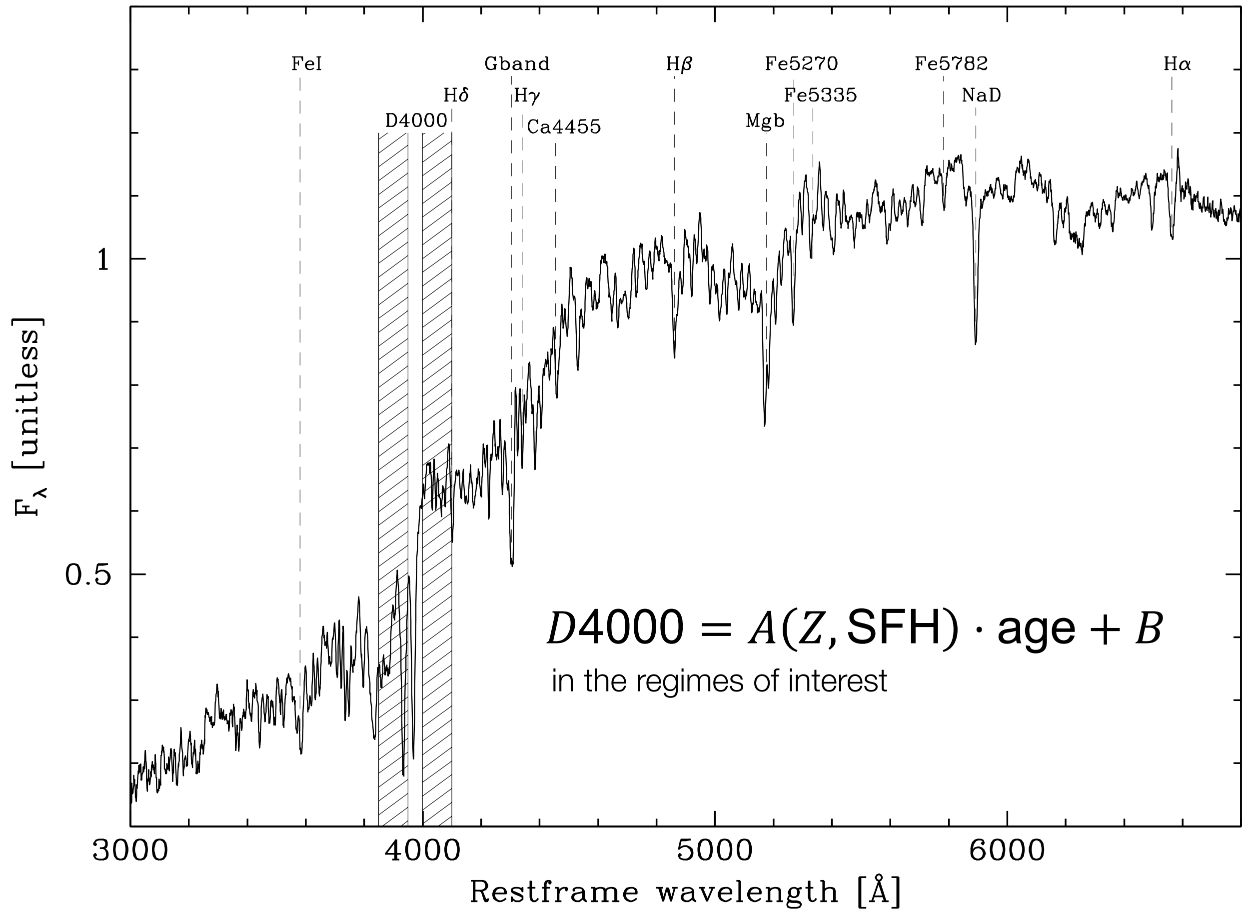

$$D4000 = A(Z, \mathrm{SFH}) \cdot \mathrm{age} + B$$

in the regimes of interest

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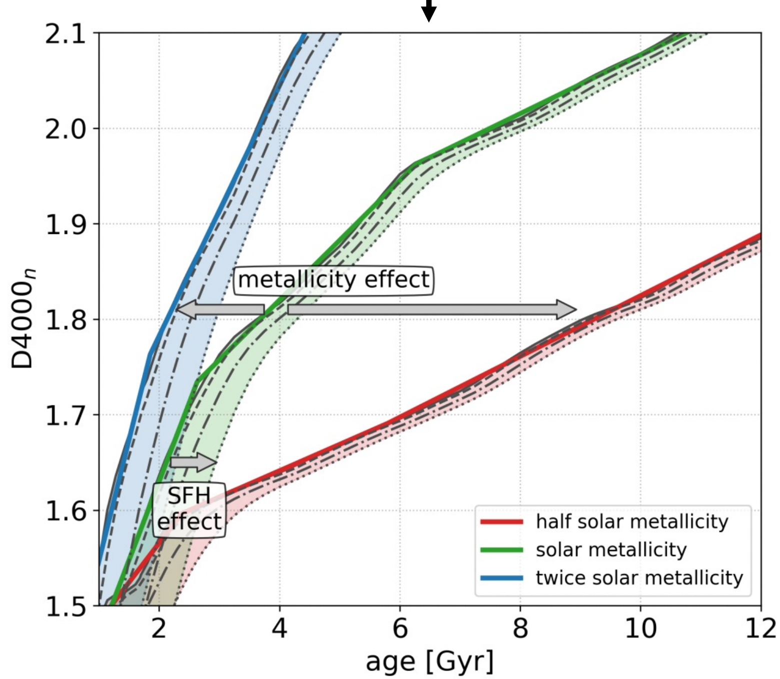
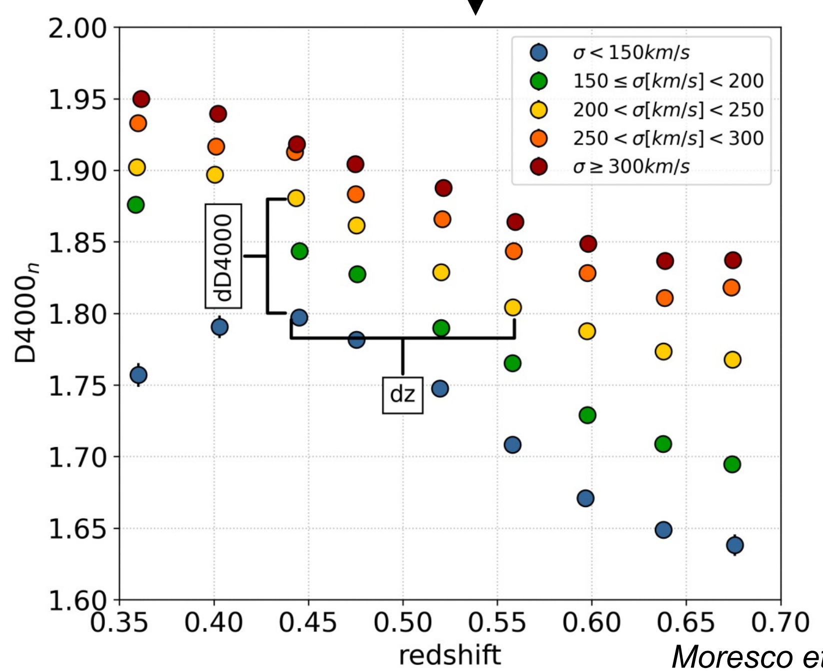
$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

calibrated on different SPS models

estimated from data





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- young population component/frosting
- progenitor bias

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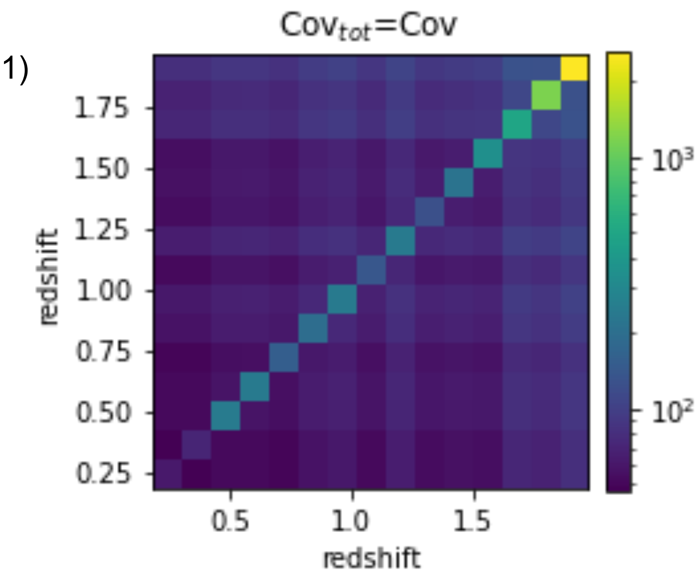

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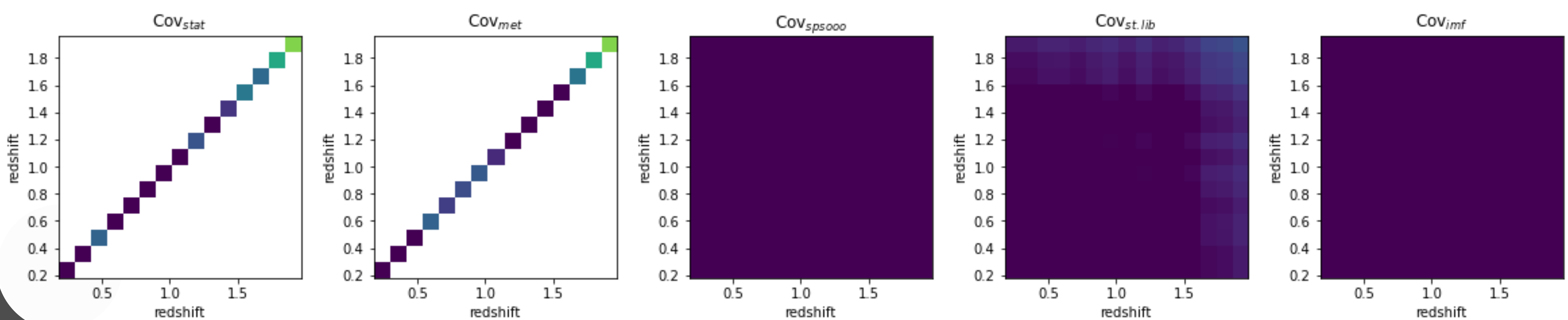
$$Cov_{tot} = Cov_{stat} + Cov_{met} + Cov_{SFH} + Cov_{young} + Cov_{model}$$



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Pros and cons

Pros

differential approach
better accuracy in estimating relative ages
systematics minimized
evolution estimated in narrow z-bins

direct measure of H(z)

cosmology-independent
ideal to test cosmological model

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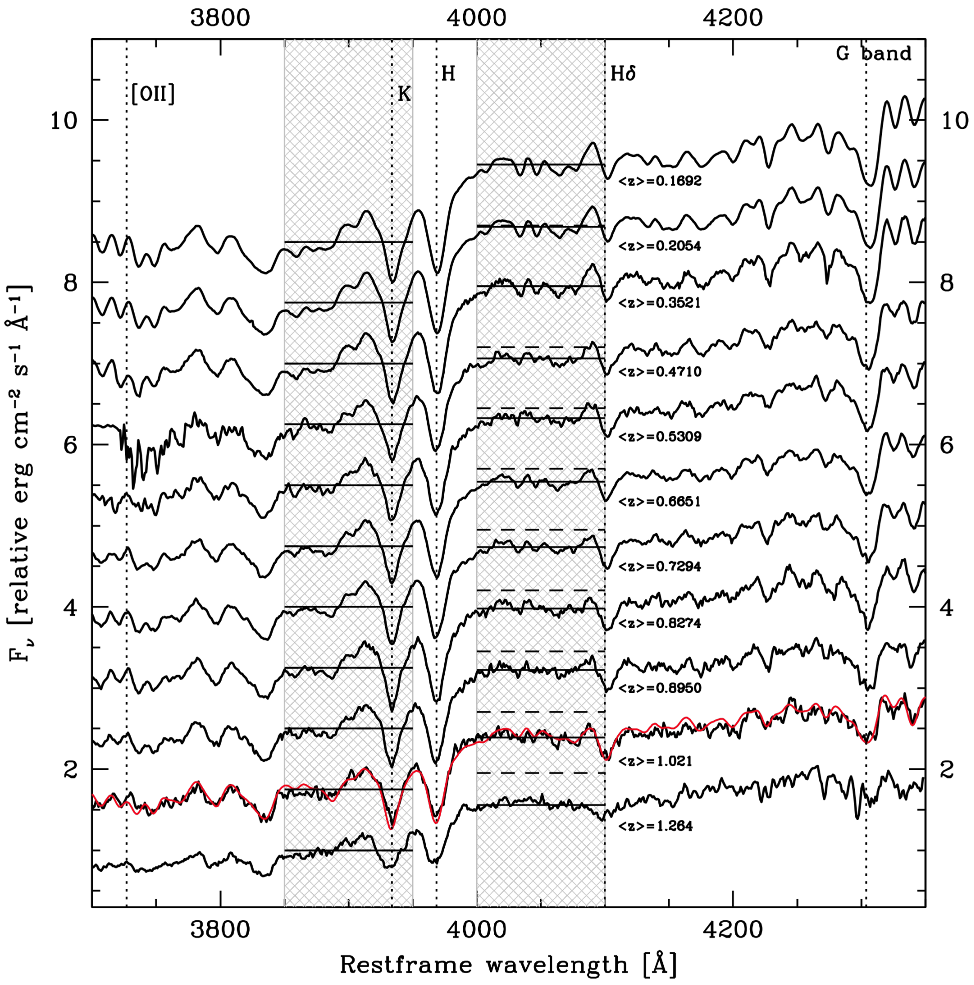
Pros and cons

Pros	Cons
differential approach better accuracy in estimating relative ages systematics minimized evolution estimated in narrow z-bins	homogeneity of the sample should be handled accurately
direct measure of H(z)	relies on metallicity prior/estimate
cosmology-independent ideal to test cosmological model	SPS model dependence should be assessed carefully

A worked example



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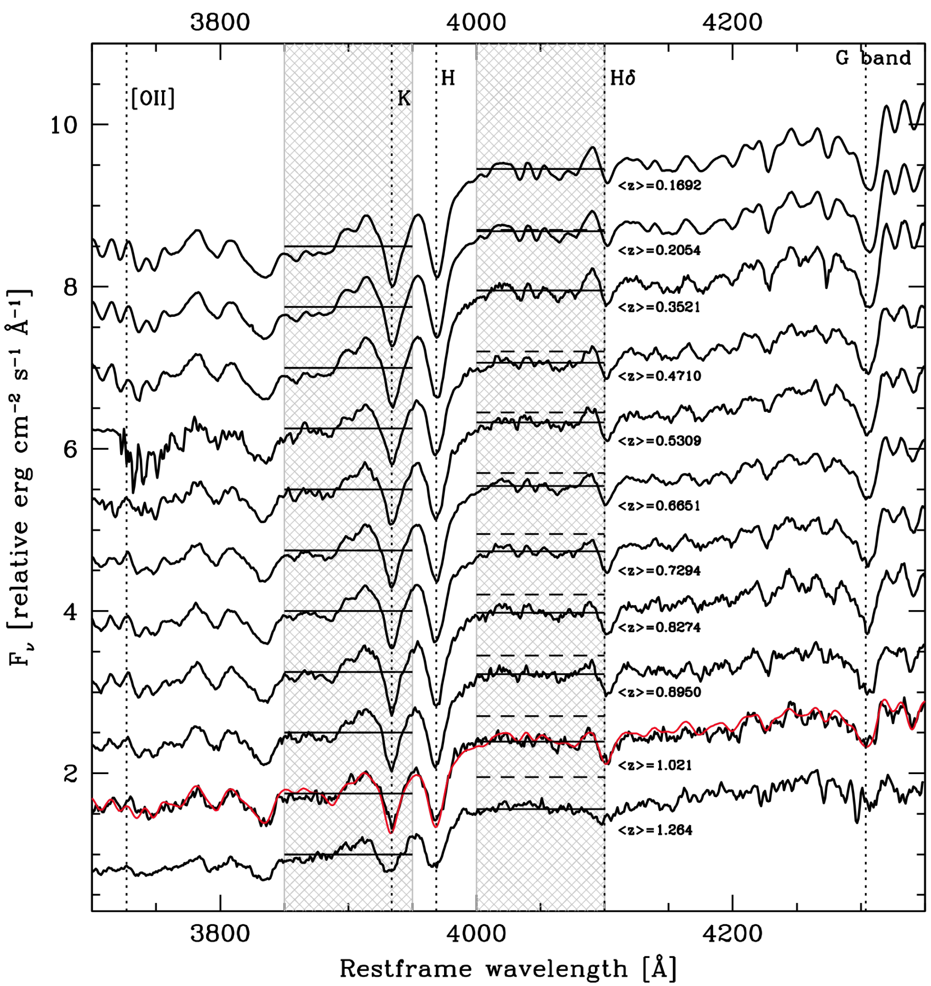
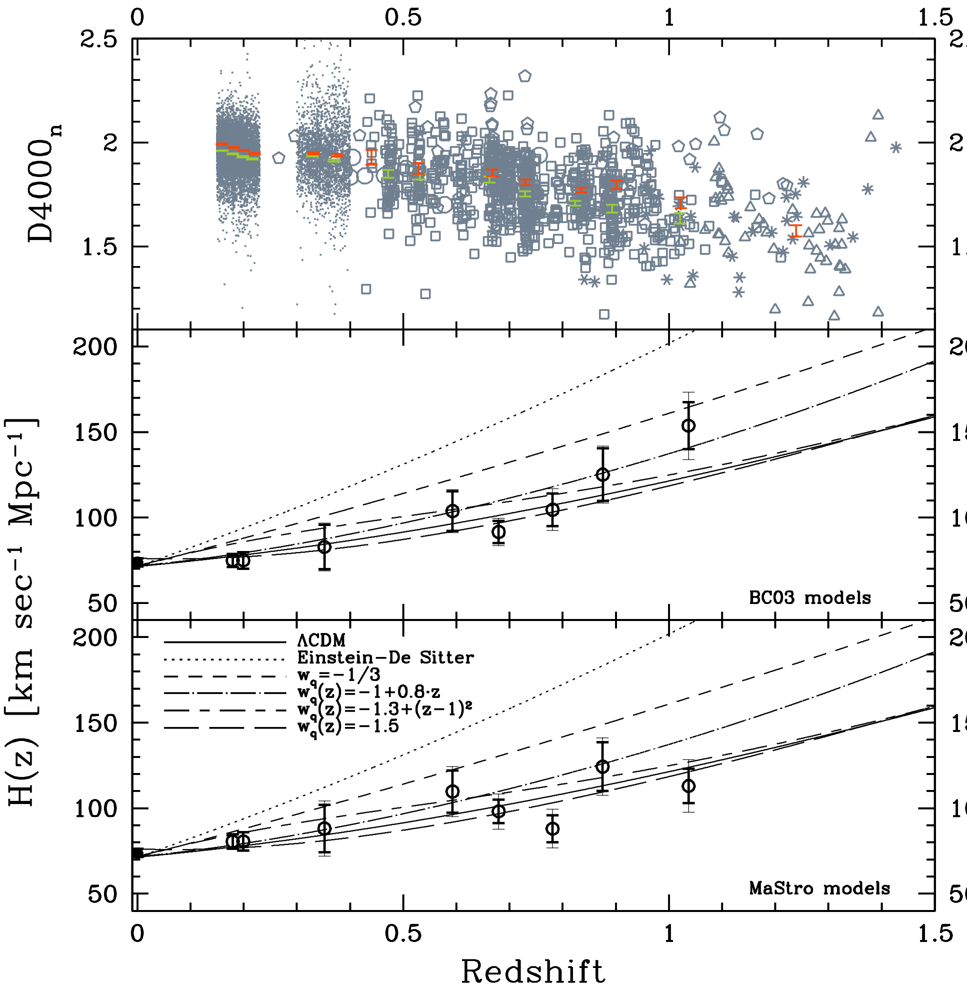
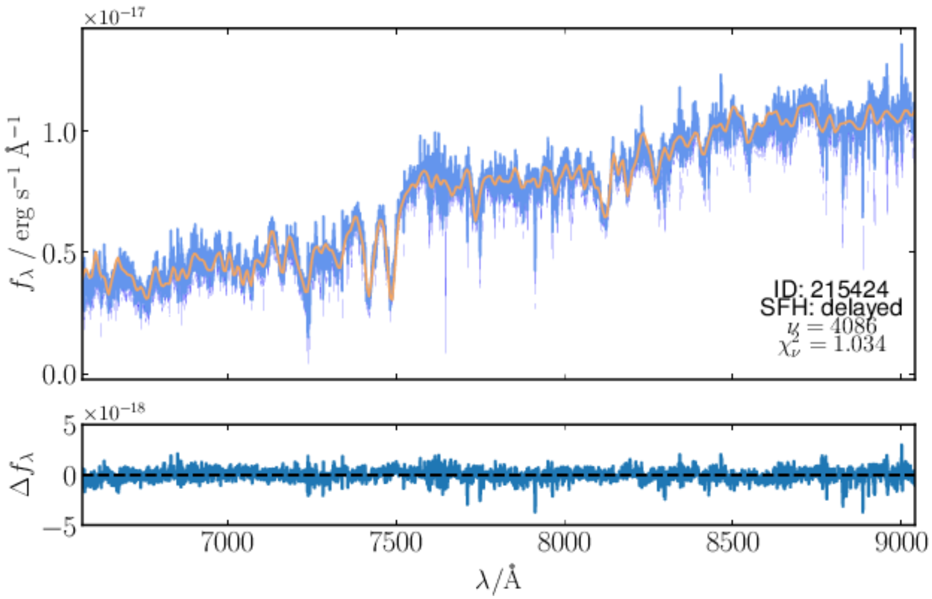


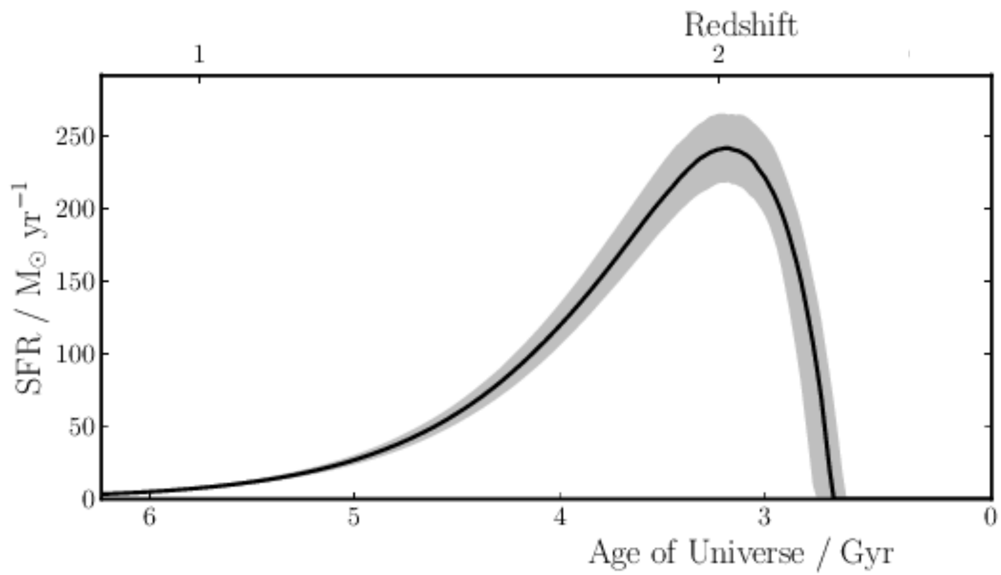


Moresco et al. (2012a)

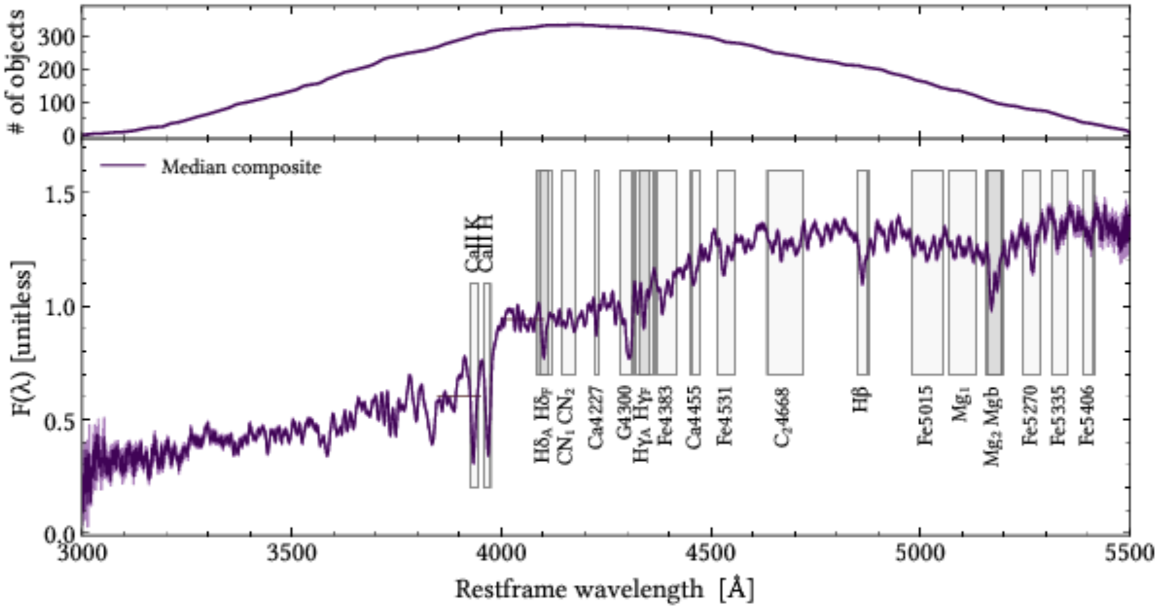
Robustness of the differential ages

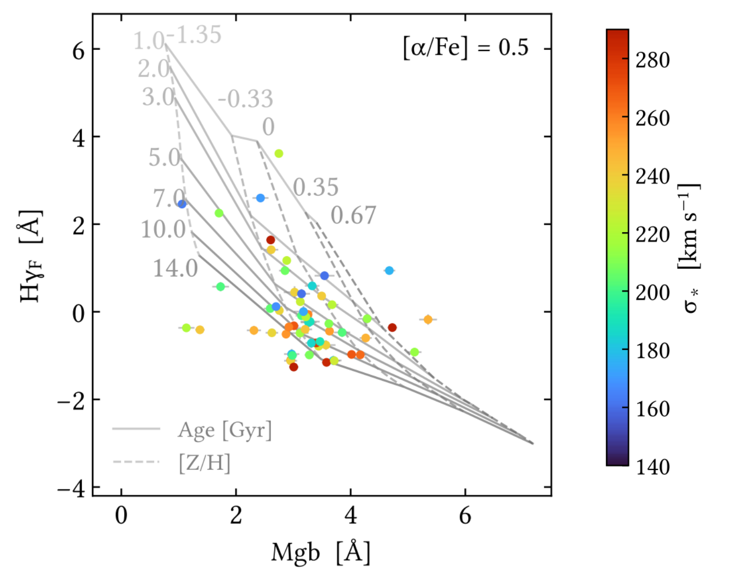
Full spectral fitting (Kang et al. 2022)





Lick indices (Borghi et al. 2022)





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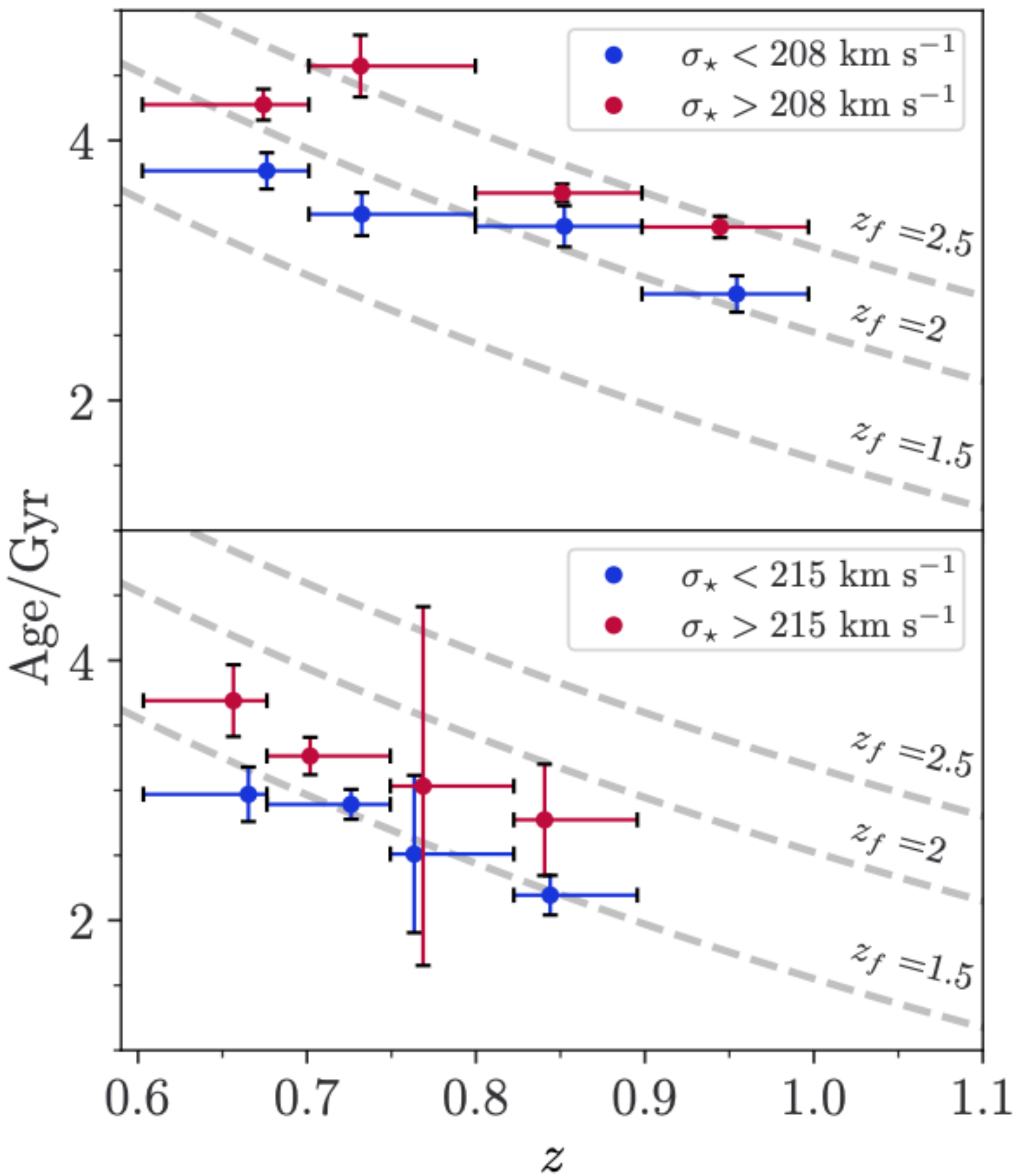
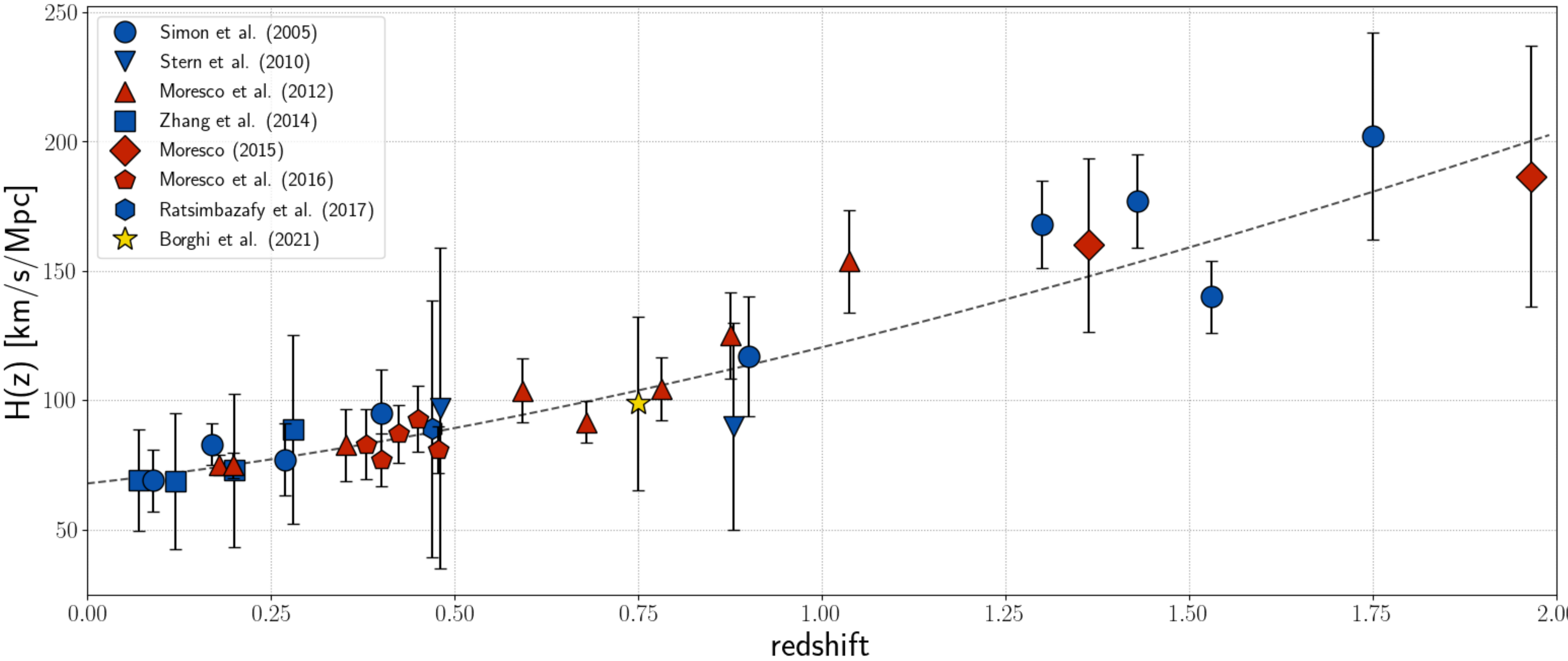


H(z): state of art



Moresco et al. (2022)

Cosmological applications

Estimating the Hubble constant

- direct fit to data
- extrapolation to z=0

Explore cosmological models

- analyze/reject cosmological models using a cosmology independent estimate
- study models without relying on analytical expression (comparison on the data, not on the parameters)

Probe combination

- combination with “standard” cosmological probes to:
    - compare performances
    - improve accuracy on parameters from synergy between probes
    - compare early- vs late-Universe probe results
- constrain the dark energy EoS, and its evolution
- break degeneracies between parameters (neutrino masses)
- check systematics

Model-independent estimate of cosmological parameters

- constraint on the transition redshift

...and many more...

Addressing the tension

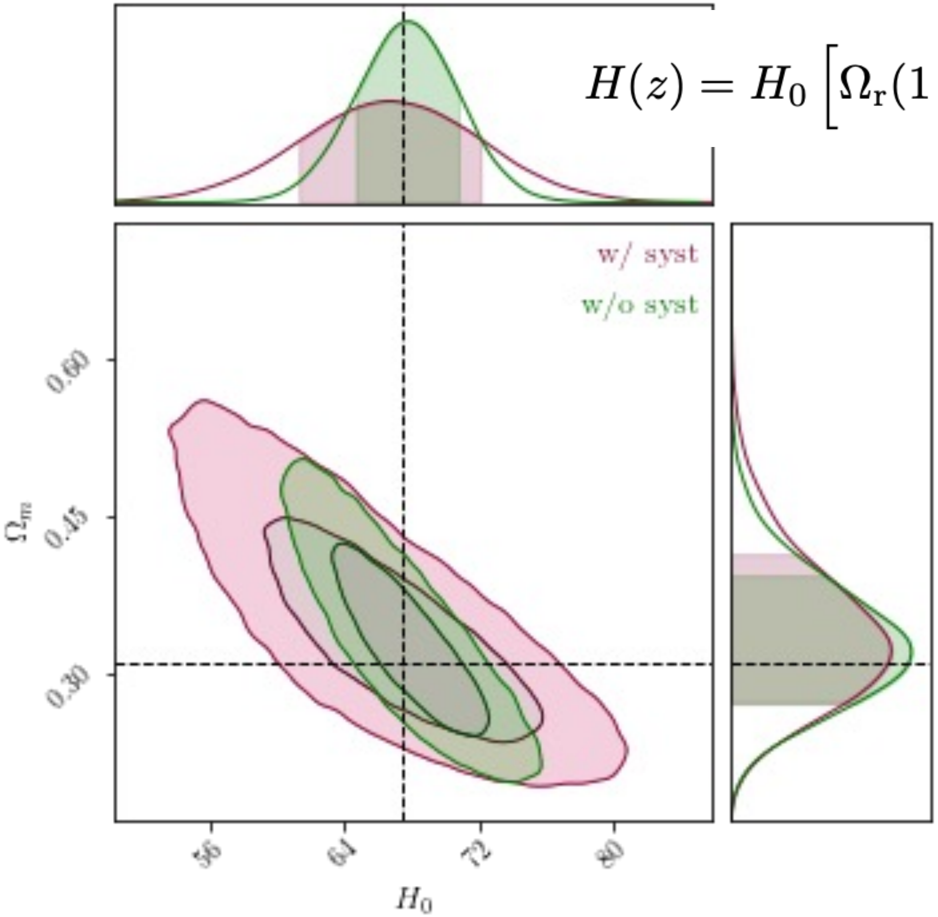
Assuming a cosmological model

$$H(z) = H_0 \left[\Omega_{\rm r}(1+z)^4 + \Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{\rm de}(1+z)^{3(1+w)}\right]^{1/2}$$

Addressing the tension

Assuming a cosmological model

The importance of the covariance



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$H_0 = 66.5 \pm 5.4$ km s^{-1} Mpc^{-1}

flat LCDM model, current data
Moresco et al. (2020, 2022)

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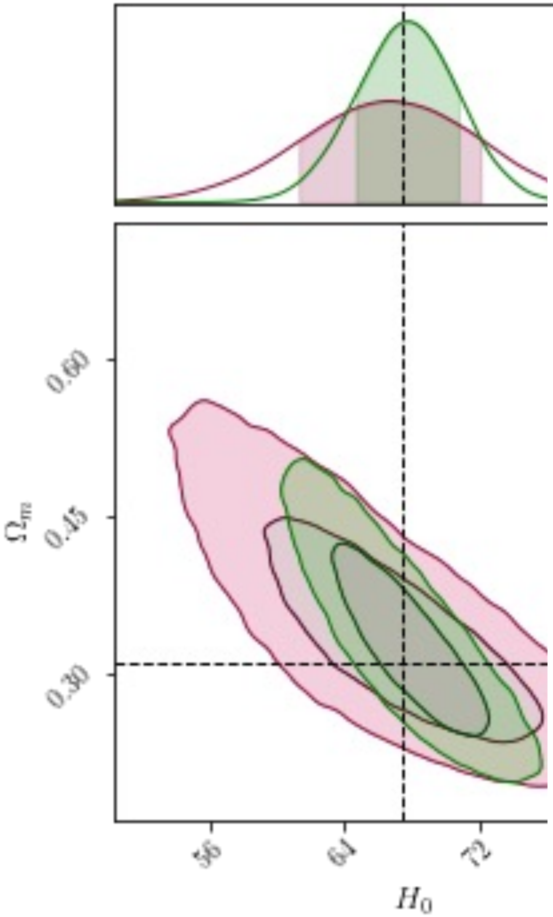

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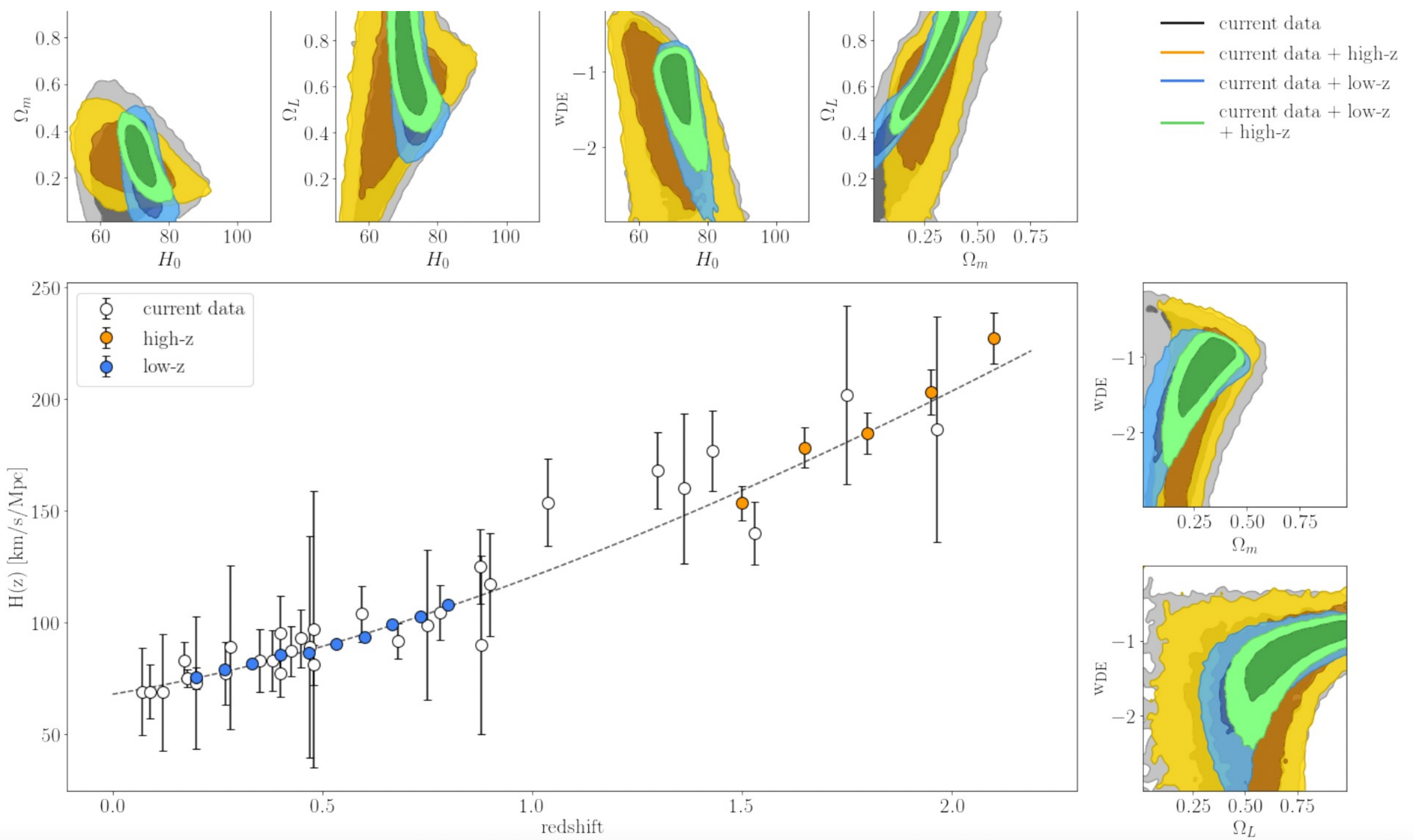


H_0 = 66.5 ± 5.4 km s^{-1} Mpc^{-1}

flat LCDM model, current data
Moresco et al. (2020, 2022)

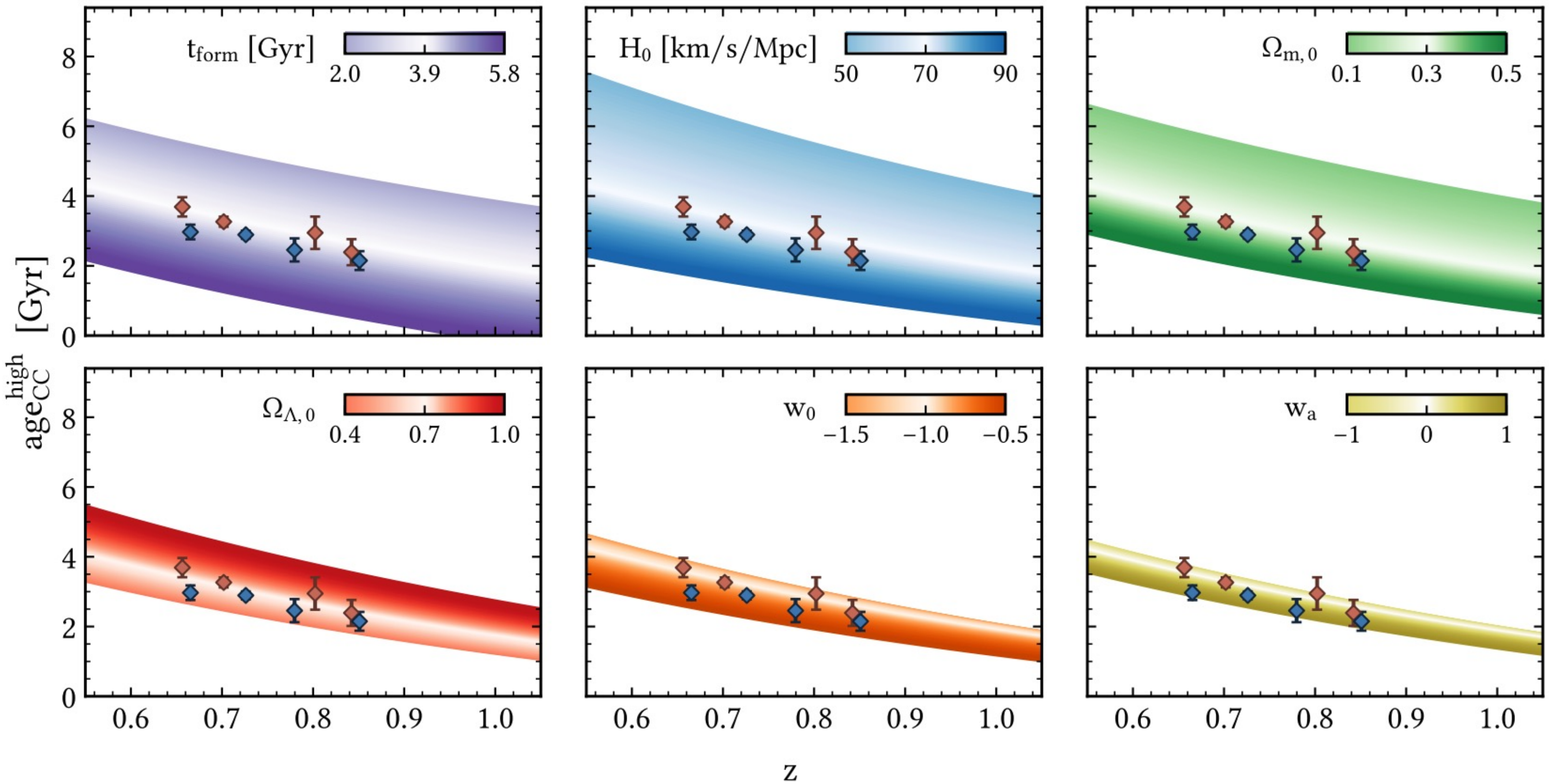
H_0 = 71.6 +3.1 −2.7 km s^{-1} Mpc^{-1}

open wCDM model, current data + forecasts
Moresco et al. (2022)

Addressing the tension

Changing the “observable”

Assuming a cosmological model, it is also possible to directly fit age(z) (**but attention to the homogeneity of the data!**)



Borghi et al. (2022b), Tomasetti et al. (in prep)

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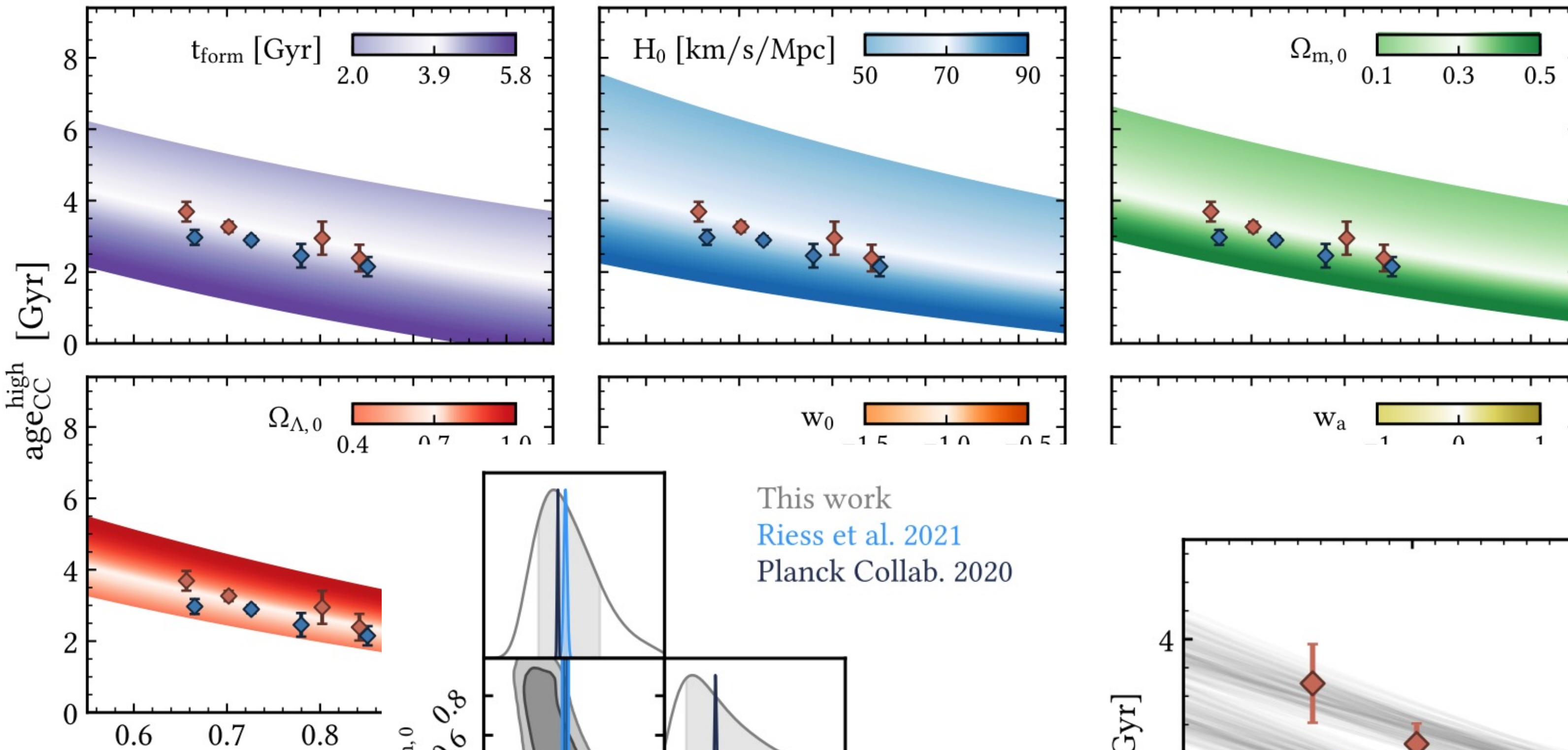
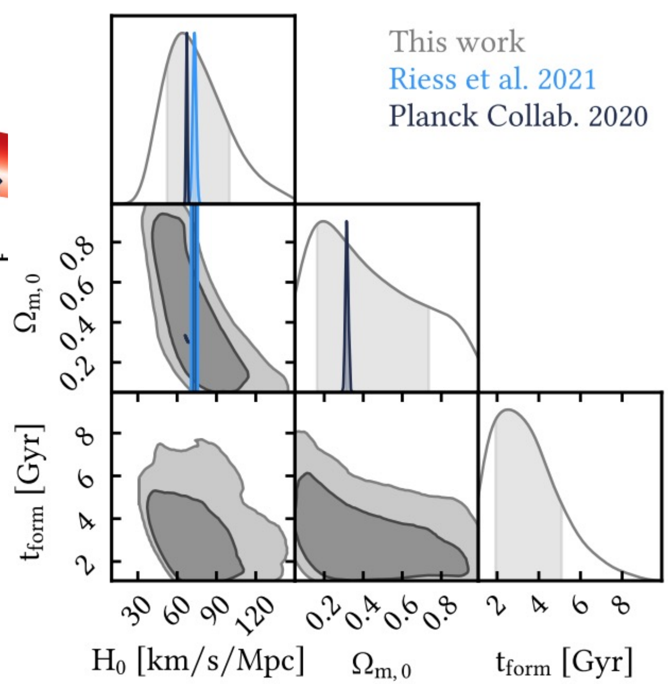
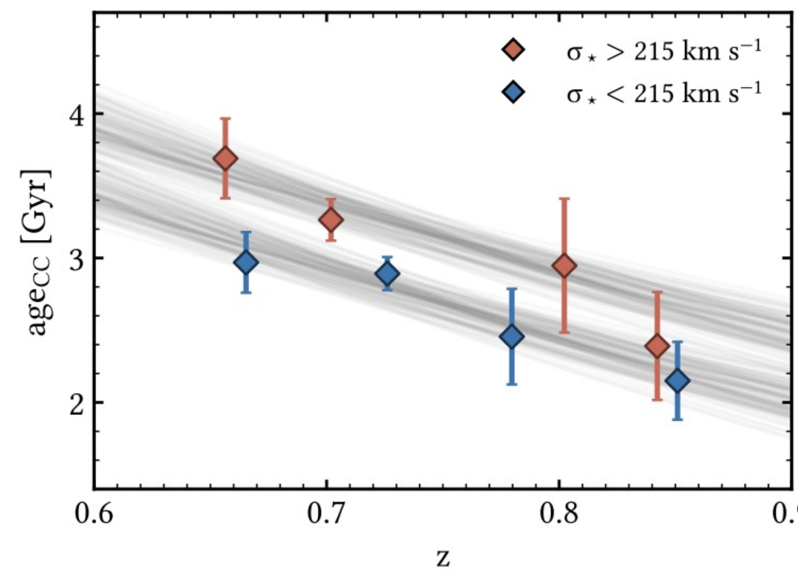






Borghi et al. (2022b), Tomasetti et al. (in prep)

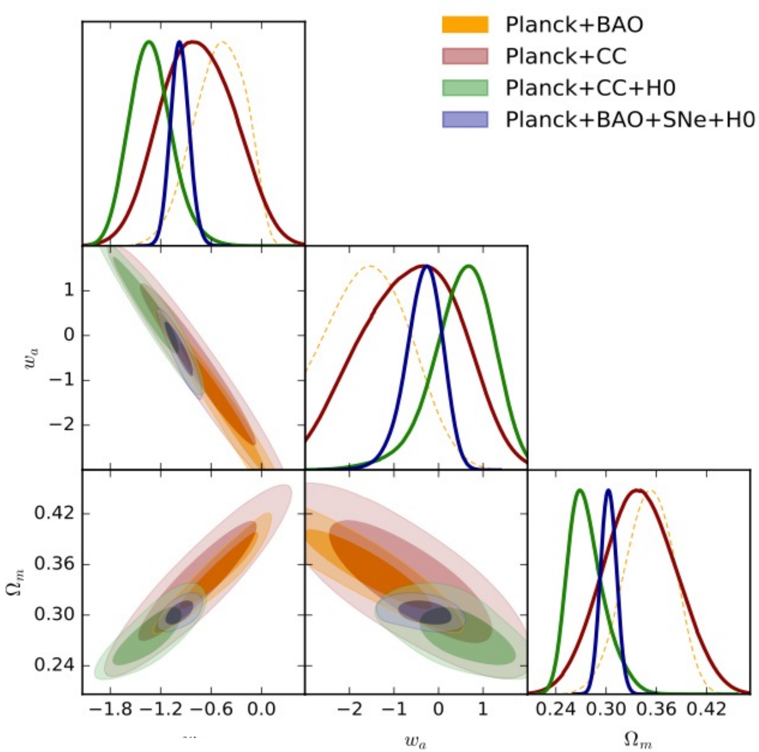
Addressing the tension

Combining (and challenging with) independent probes

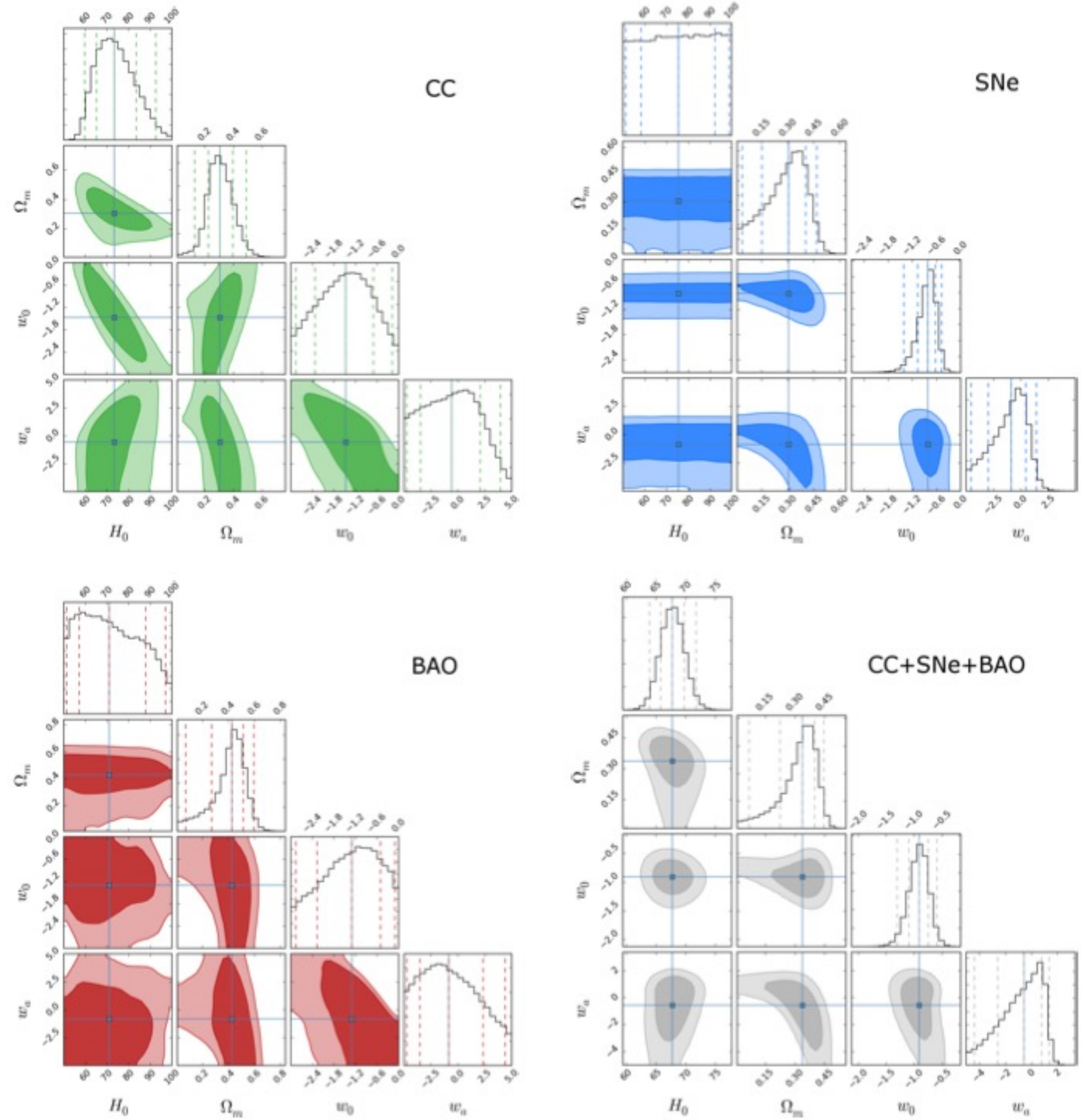
Each probe is more sensible to some parameters, and less to others

Constraining power comparable to the one of BAO (CC+SNe ~ CC+SNe+BAO)

Combining probes maximizes accuracy



Moresco et al. (2012b)



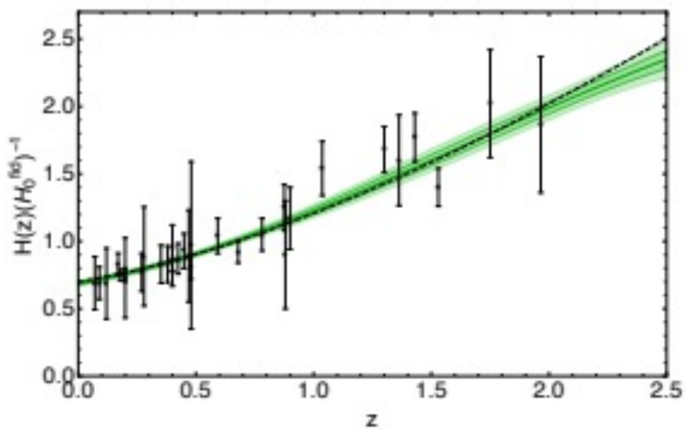
Moresco et al. (2016b)

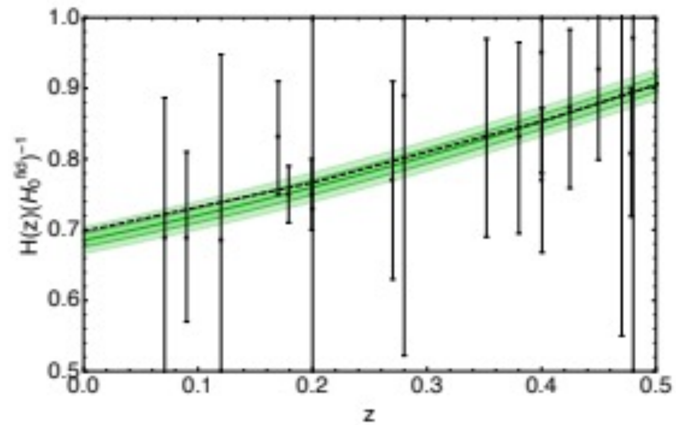
Addressing the tension

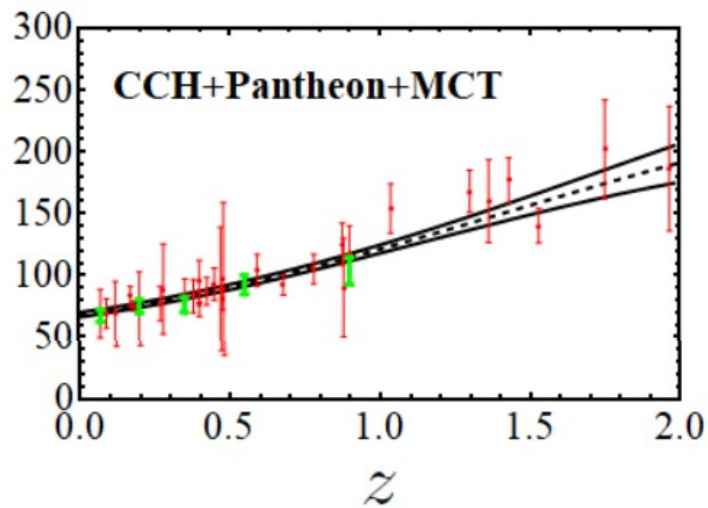
Going model-independent

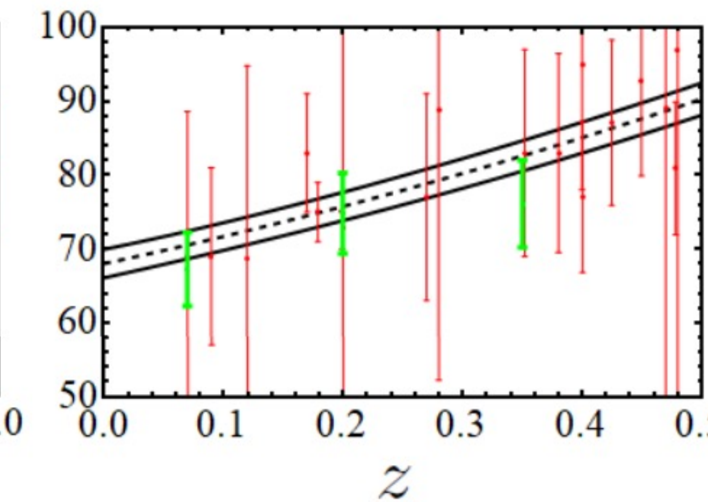
- H_0 as extrapolation of H(z=0)
- Gaussian process, multi-task Gaussian process or Weighted Polynomial Regression can be exploited to combine probes
- cosmology-independent estimate

For these efforts, it is fundamental to:
- use the systematic covariance
- clearly specify which probes are combined
- explore the relative contribution of each probe, and their compatibility









$H_0 = 68.52^{+0.94\ +2.51(syst)}_{-0.94}$ km s^{-1} Mpc^{-1}

Haridasu et al. (2018)

$H_0 = 68.90 \pm 1.96$ km s^{-1} Mpc^{-1}

Gomez-Valent & Amendola (2018,2019)

Conclusions

- Basics of “cosmic chronometer” approach, as complementary technique to constrain the expansion history of the Universe
- Fundamental steps of the CC approach: selection criterion, age estimate, differential approach, analysis of systematics
- Main strength: **direct and cosmology independent estimate of H(z)** → ideal framework to test cosmological models
- Importance of cosmic chronometers (in combination with other probes) to obtain **competitive constraints on cosmological parameters w.r.t standard probes**
- CC can be used to set constraints on H_0, by extrapolating it to z=0 or assuming a cosmological model
- Current constraints give an error of the order of 5 km/s/Mpc and a value between early- and late-Universe probes
- Future analysis and improvement in systematics can improve the accuracy by ~ a factor 2

To fetch CC data for your own analysis, contact me (michele.moresco@unibo.it) or visit https://mmoresco.gitlab.io/home/ (also for information on how to include the systematic covariance in the analysis)