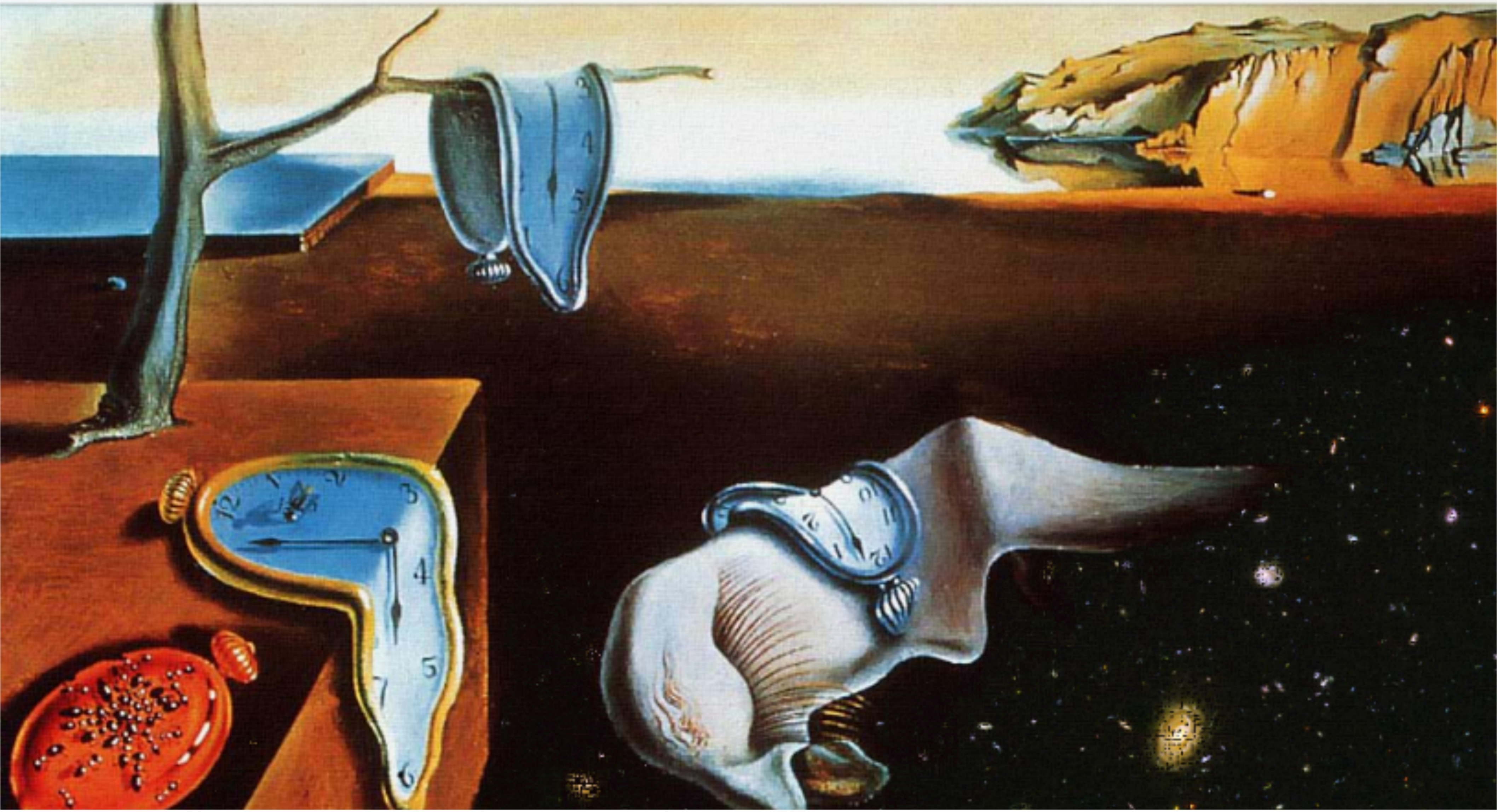
Exploring new paths to constrain the expansion history of the Universe with

Cosmic Chronometers



16^{th} Marcel Grossmann Meeting
5-10 July 2021

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

Systematics

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

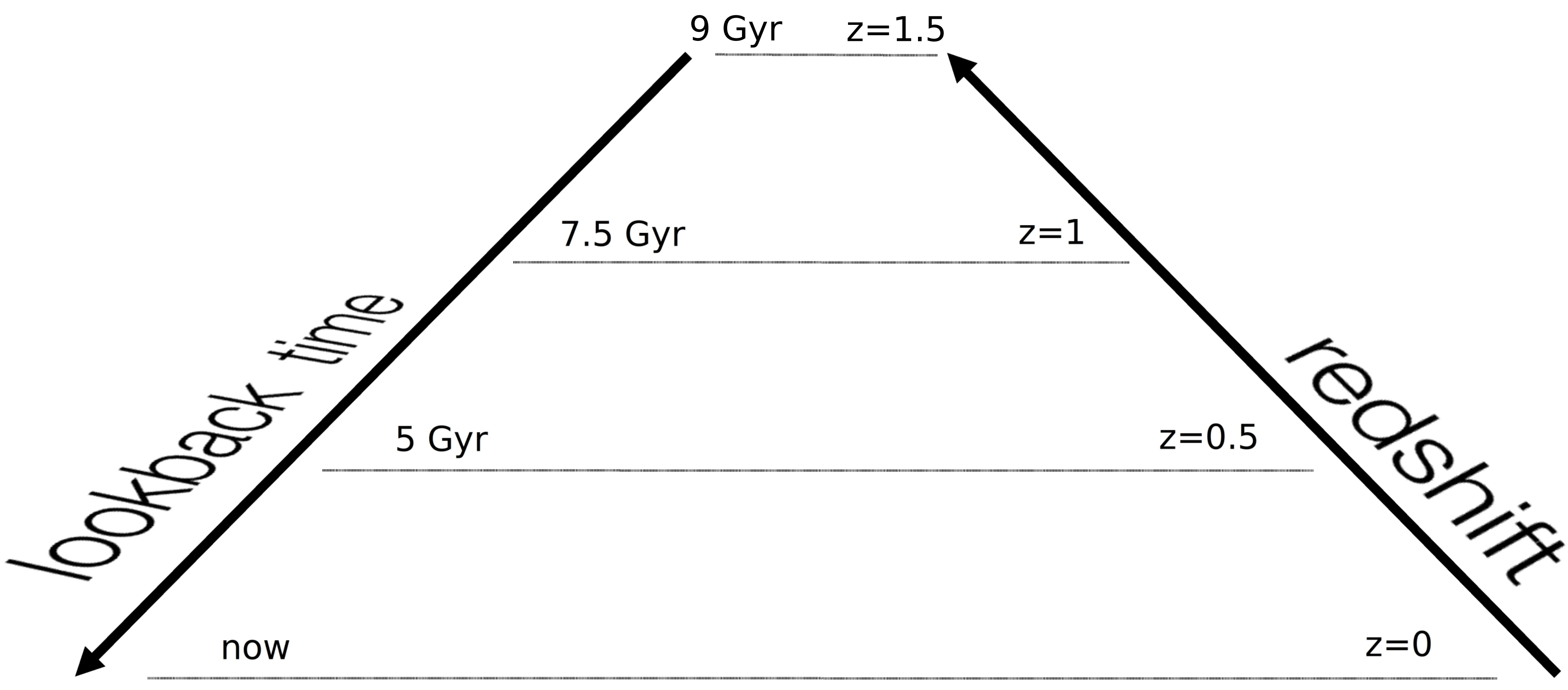
Measurements

Moresco et al. (2012a), JCAP, 08, 006
Moresco (2015), MNRAS Letter, 450, 16
Moresco et al. (2016a), JCAP, 05, 014
Borghi et al. (2021a), in prep

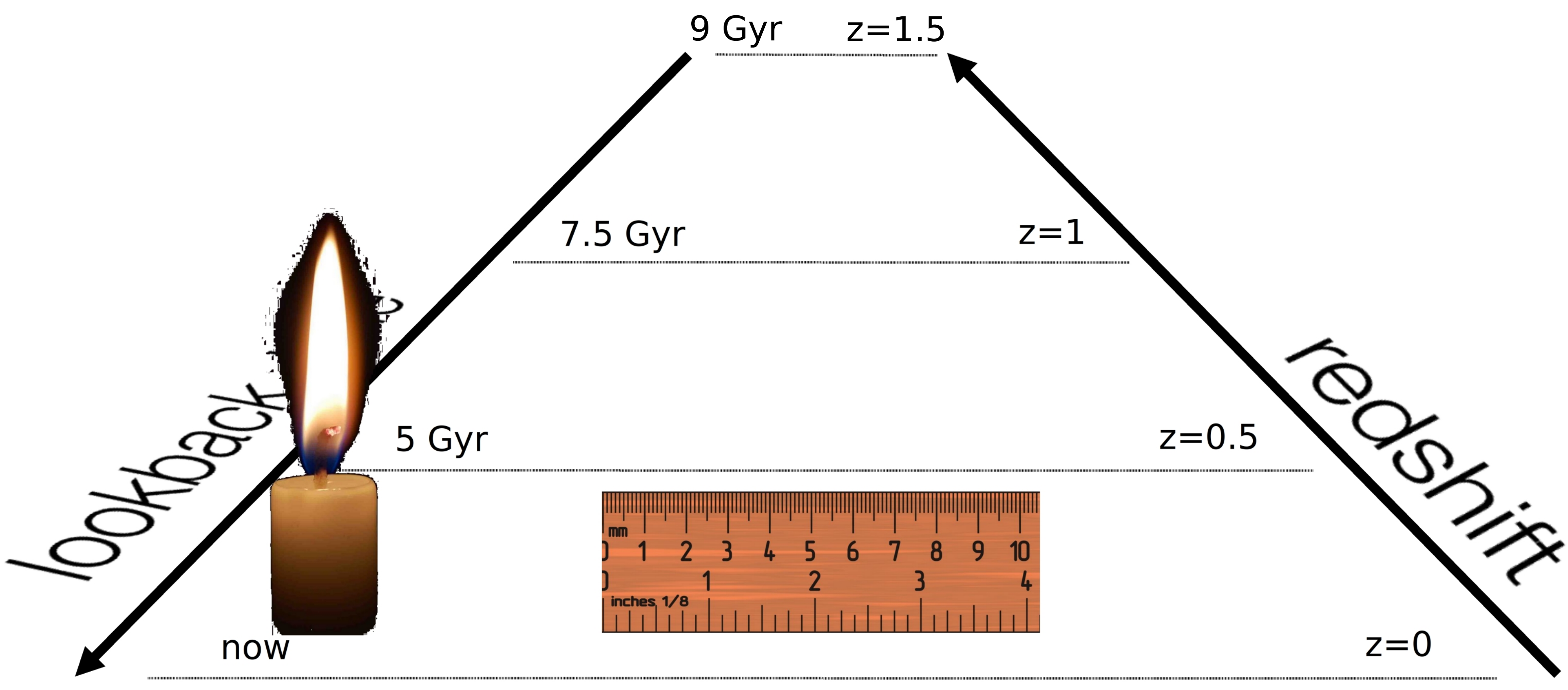
Cosmological constraints

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), in prep

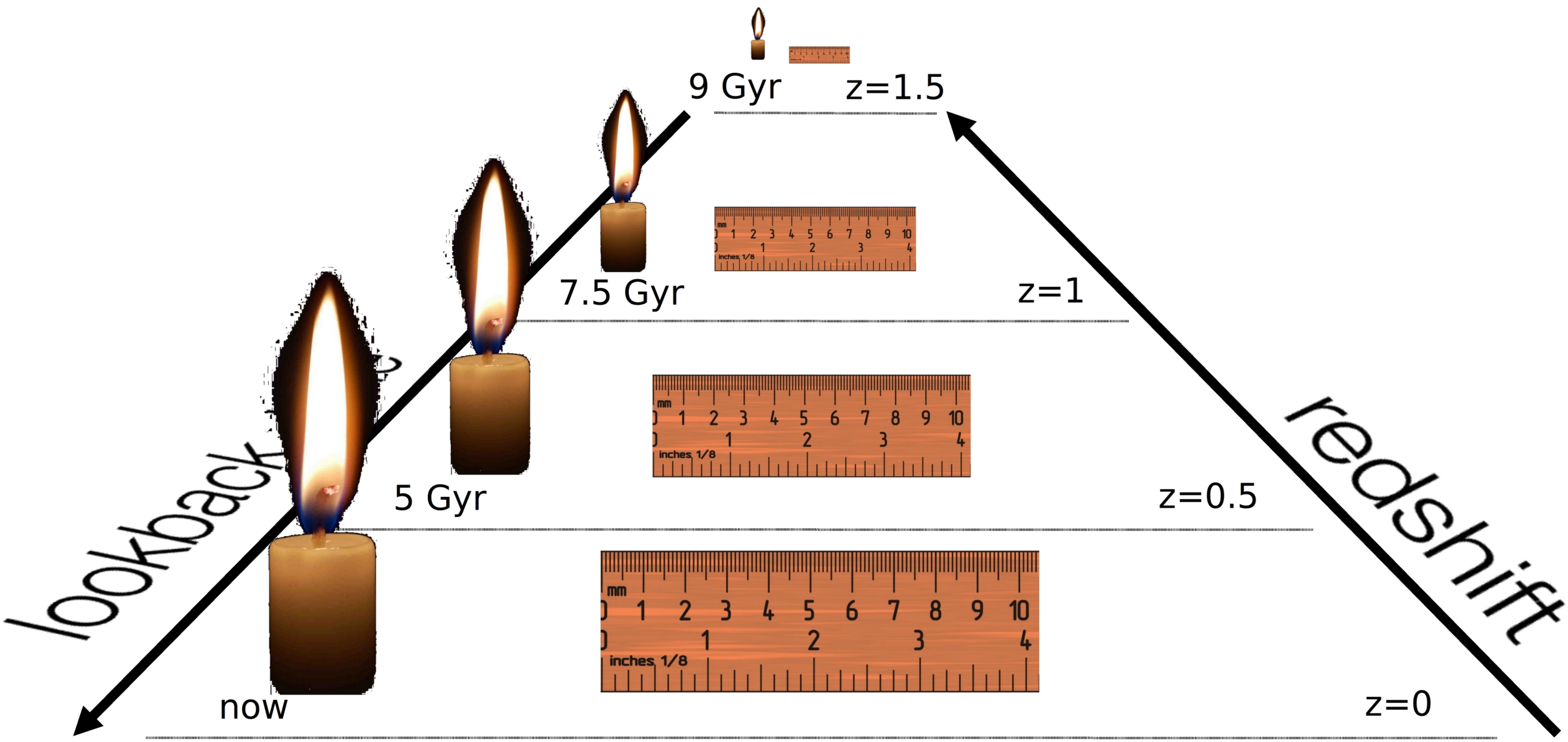
The basic idea



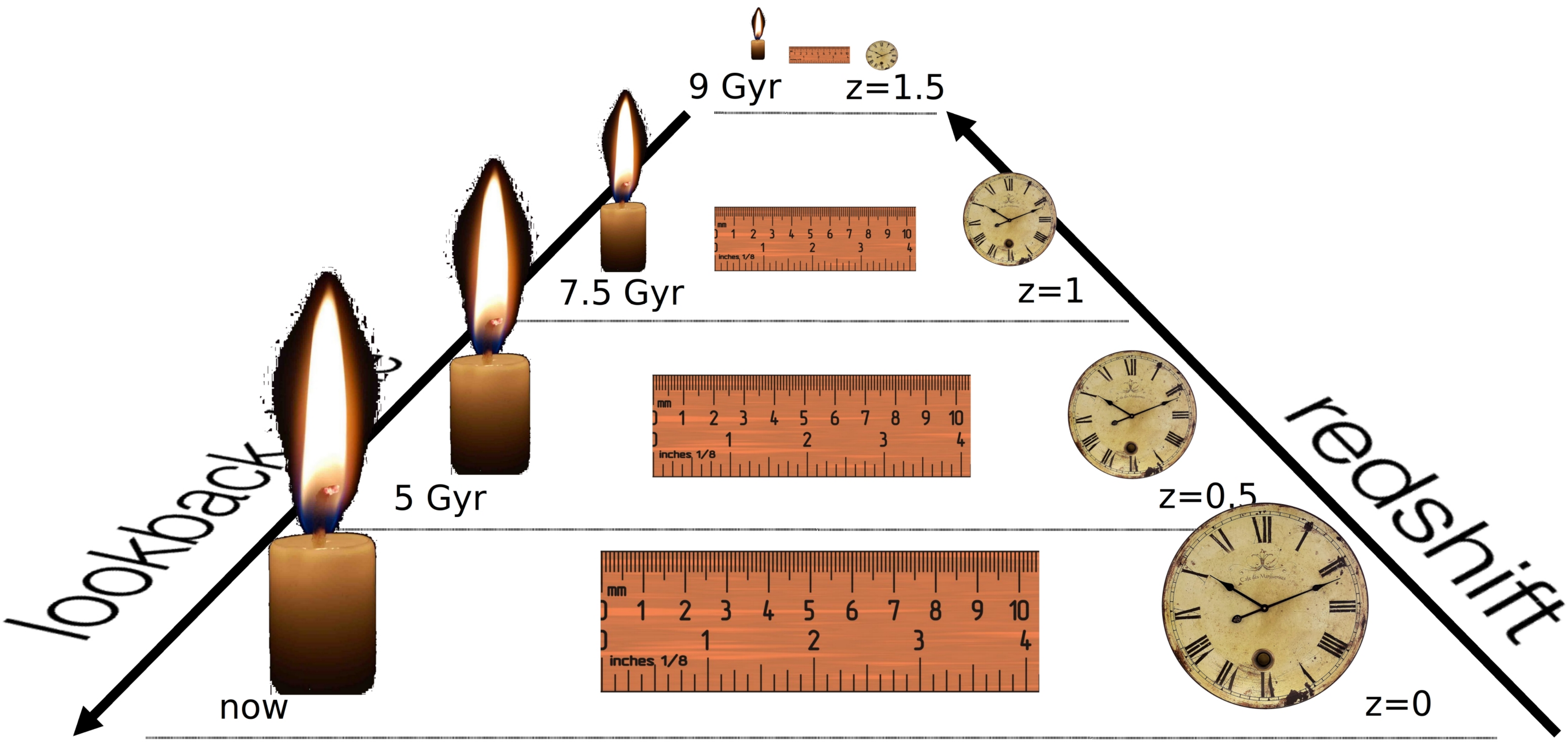
The basic idea



The basic idea



The basic idea



Cosmic chronometers in a nutshell

Chronometers, not clocks

Cosmic chronometers in a nutshell

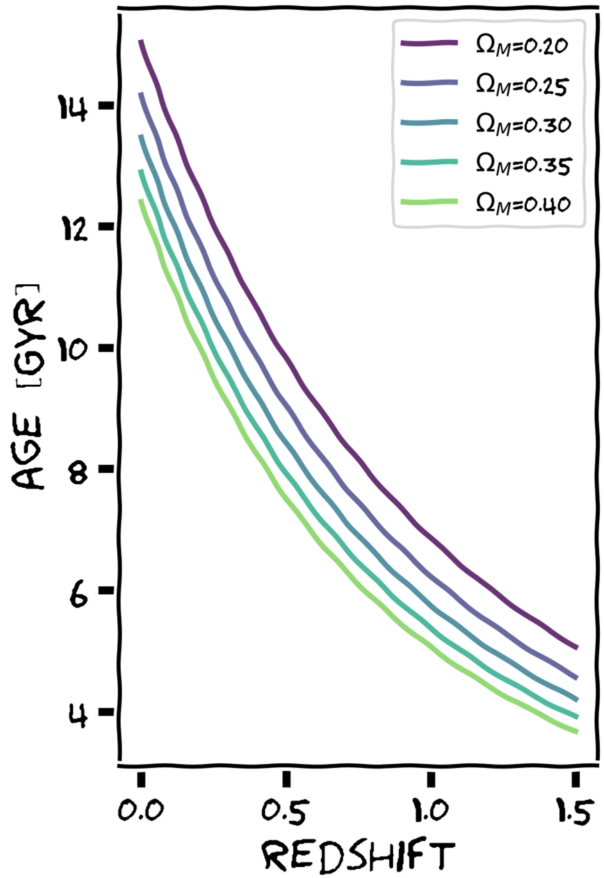
Chronometers, not clocks

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

Jimenez & Loeb (2002)

Cosmic chronometers in a nutshell

Chronometers, not clocks

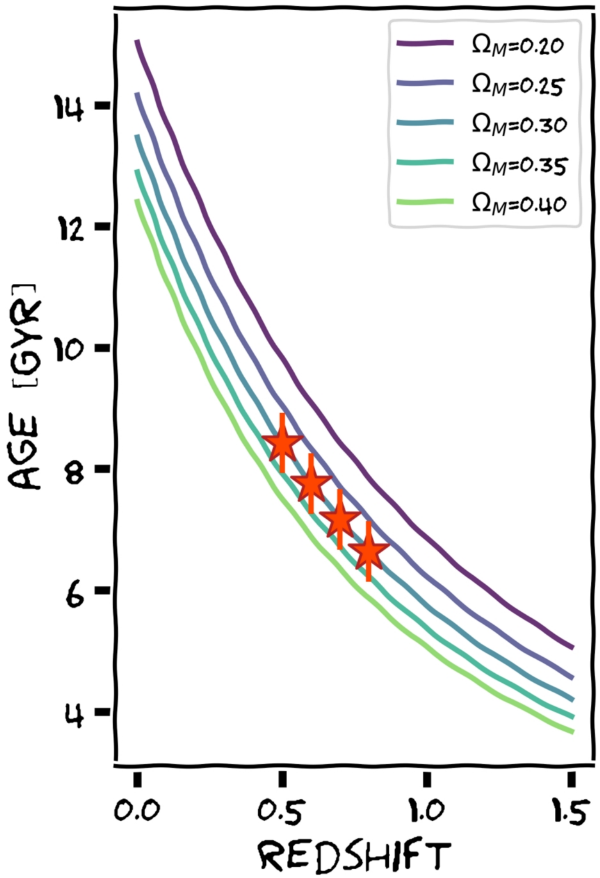


$$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{dz}{dt}$$

Jimenez & Loeb (2002)

Cosmic chronometers in a nutshell

Chronometers, not clocks

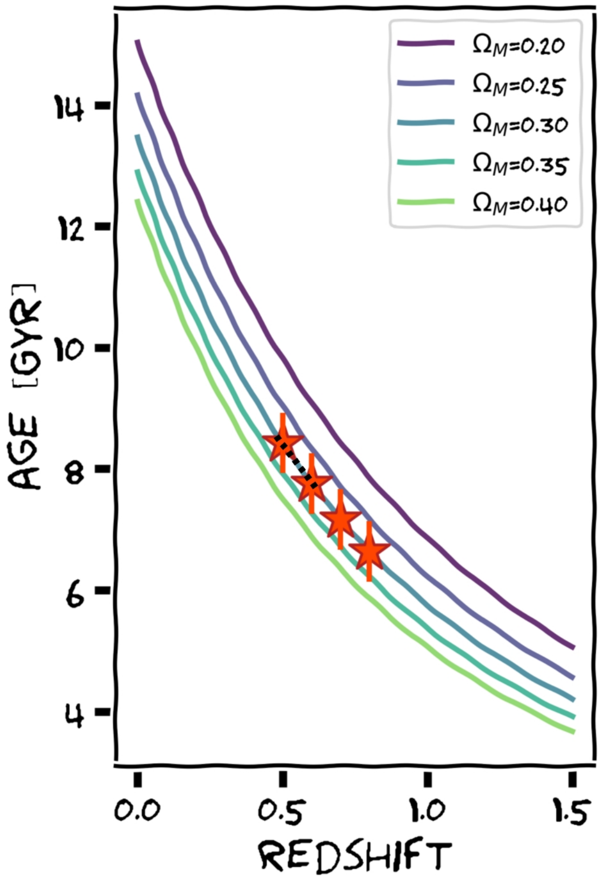


$$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{dz}{dt}$$

Jimenez & Loeb (2002)

Cosmic chronometers in a nutshell

Chronometers, not clocks



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

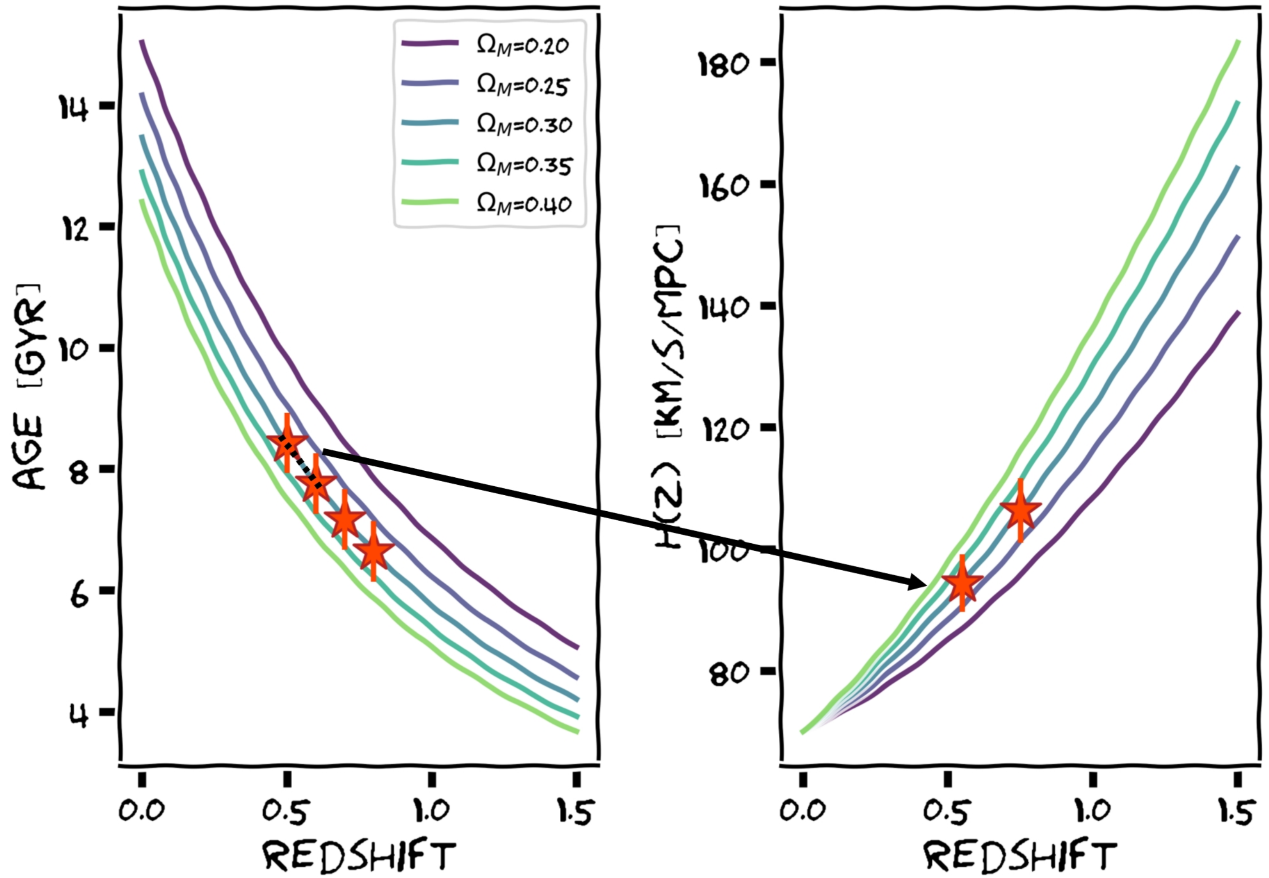
Jimenez & Loeb (2002)

Cosmic chronometers in a nutshell

Chronometers, not clocks

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

Jimenez & Loeb (2002)

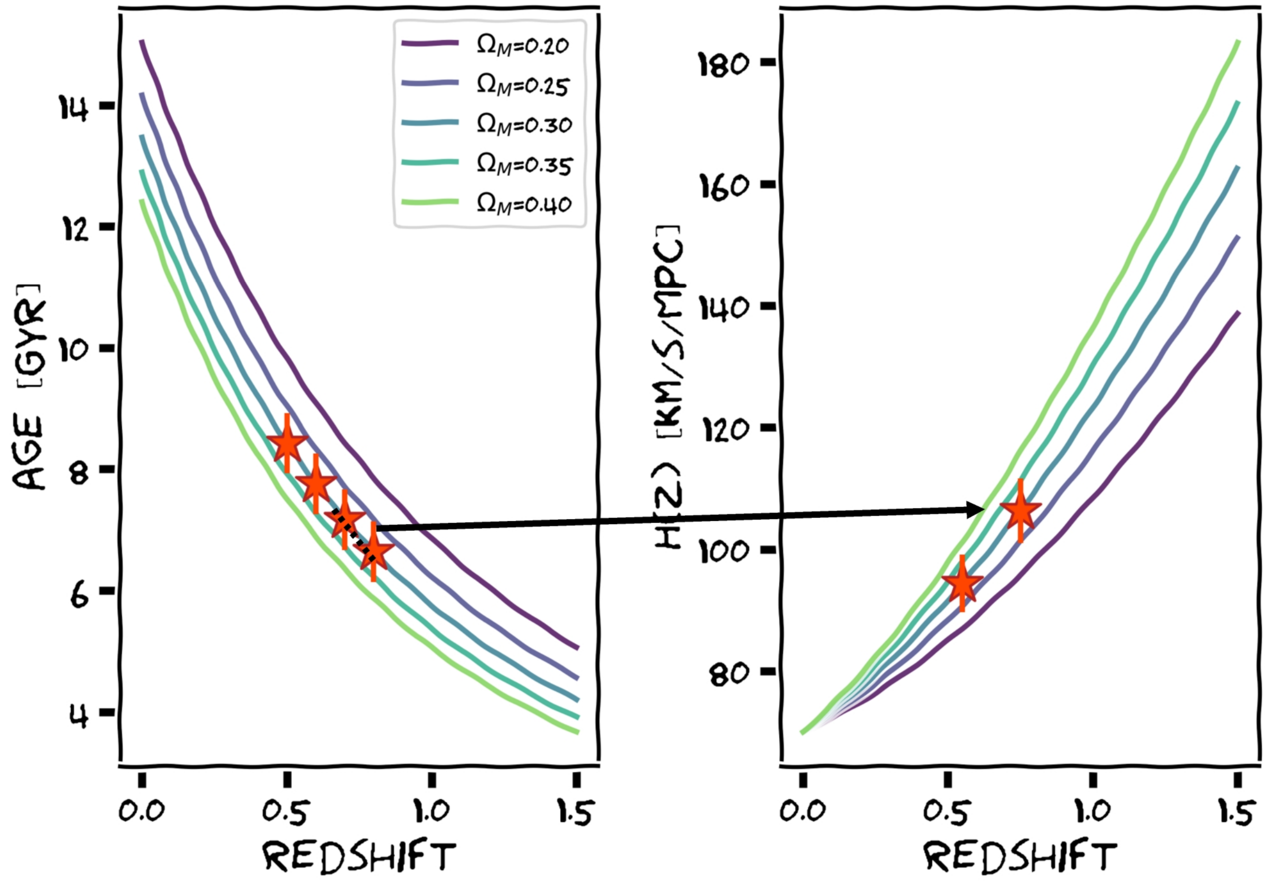


Cosmic chronometers in a nutshell

Chronometers, not clocks

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

Jimenez & Loeb (2002)

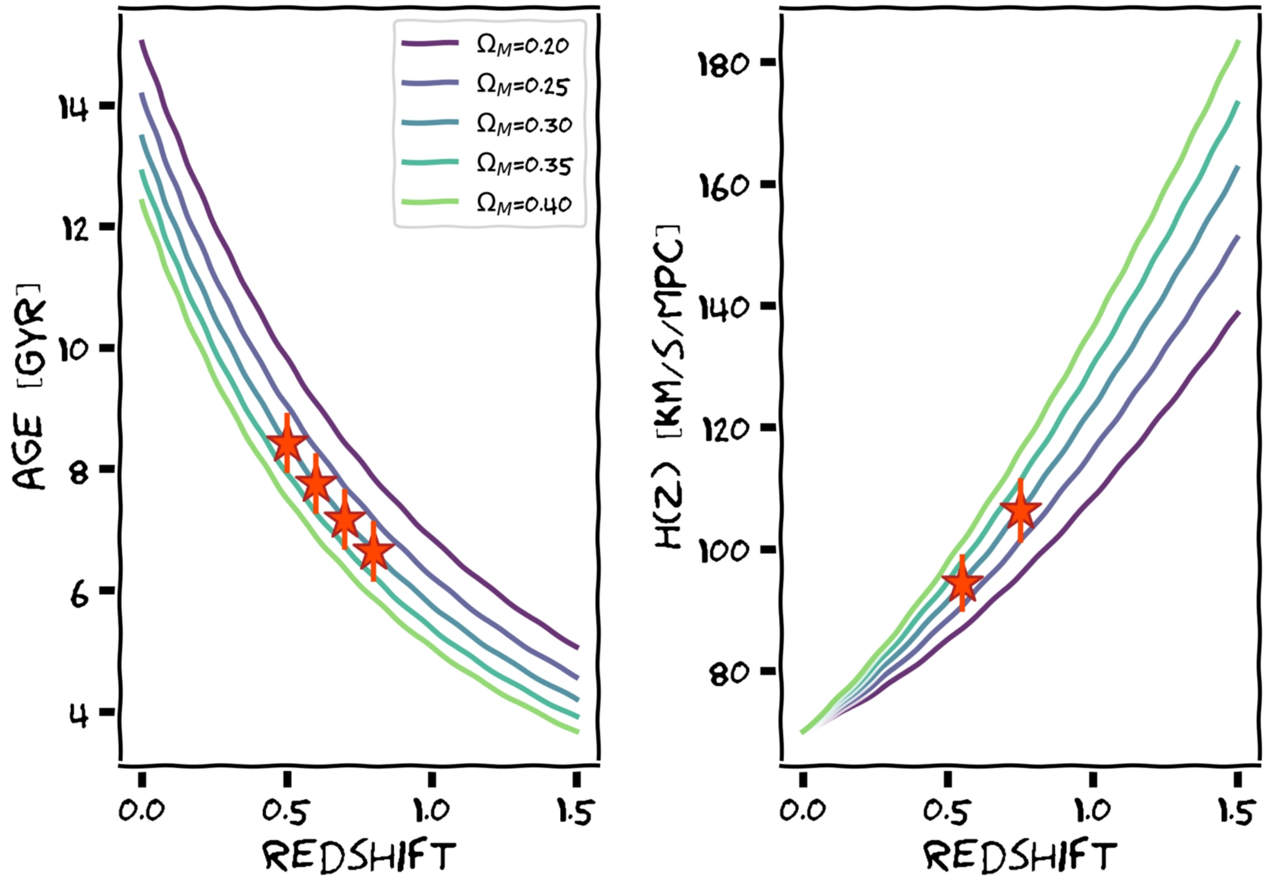


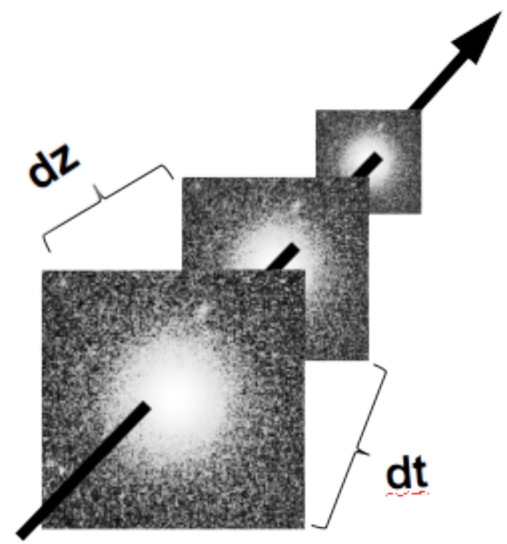
Cosmic chronometers in a nutshell

Chronometers, not clocks

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

Jimenez & Loeb (2002)





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

Cosmic chronometers handbook

What about the tracers?

What about the age?

What about the systematics?

Pros and cons

Cosmic chronometers handbook

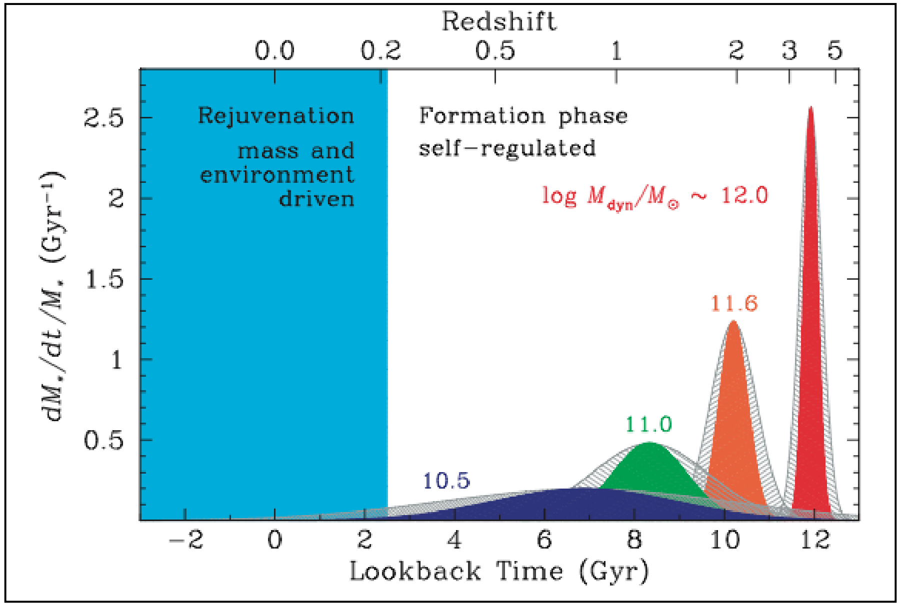
What about the tracers? (Moresco et al. 2013, 2018, Borghi et al. 2021)

- best tracers: very massive and passively evolving galaxies

Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies



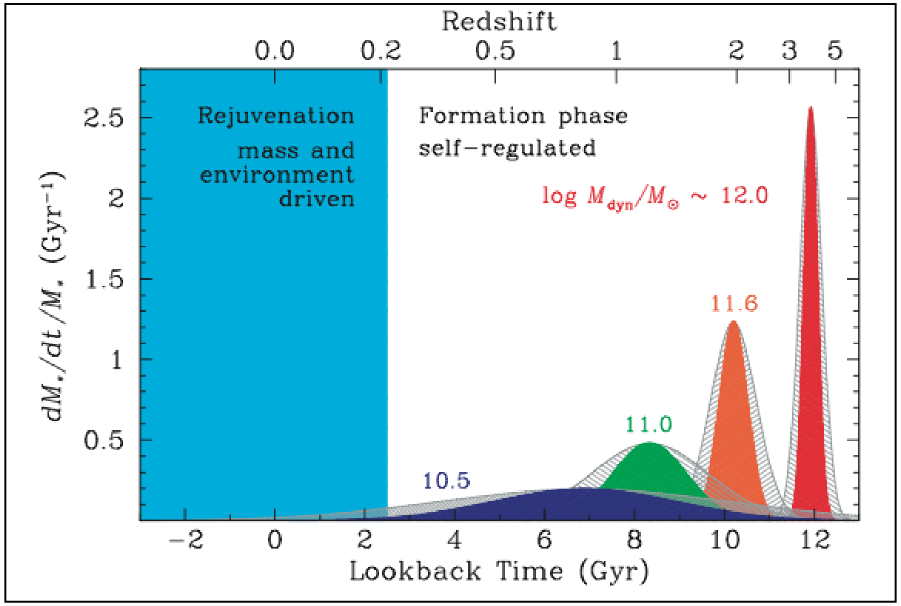
Thomas et al. (2010)

Cosmic chronometers handbook

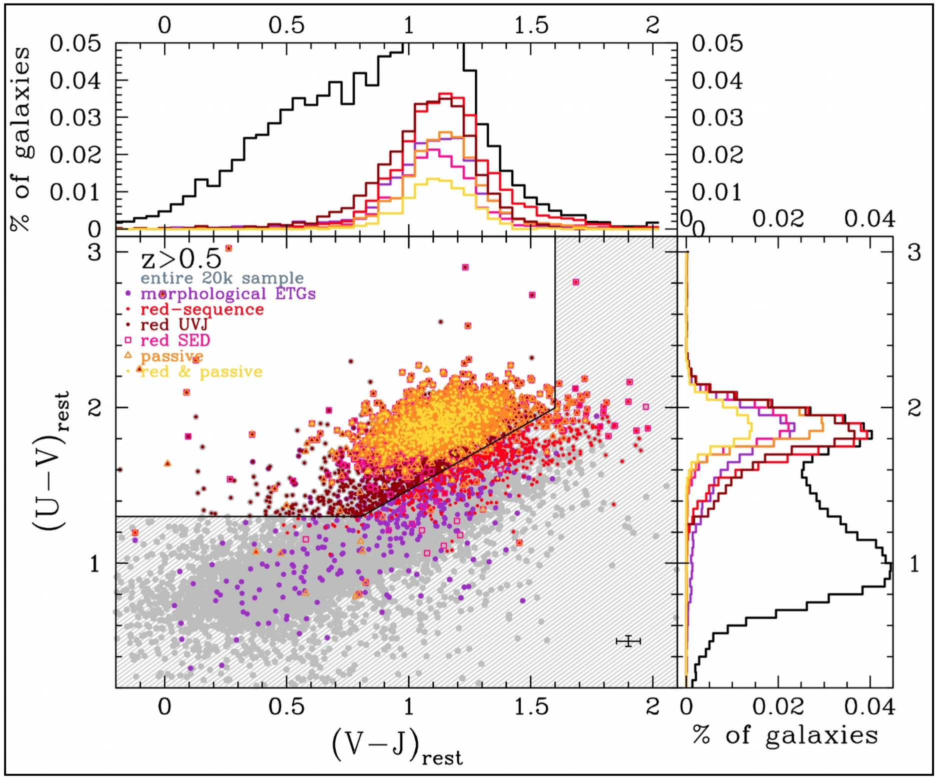
What about the tracers?

(Moresco et al. 2013, 2018, Borghi et al. 2021)

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample



Thomas et al. (2010)



Moresco et al. (2013)

Cosmic chronometers handbook

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

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

Cosmic chronometers handbook

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

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*

Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

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

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*: **different methods**
  - SED-fitting
  - full spectral-fitting
  - absorption features (Lick indices) → see Borghi's talk

Cosmic chronometers handbook

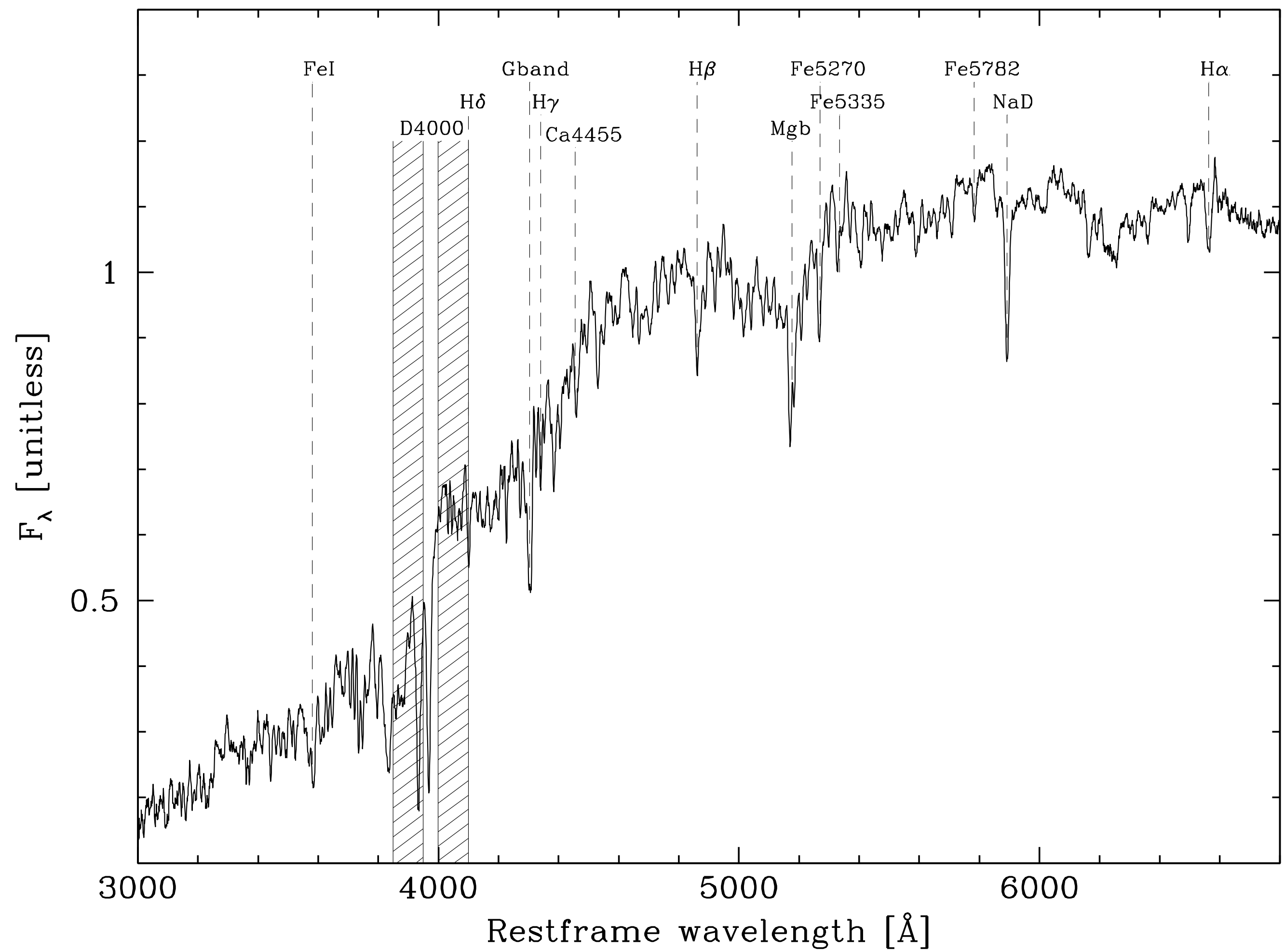
What about the tracers? (Moresco et al. 2013, 2018, Borghi et al. 2021)

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

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

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach



$$D4000=A(Z,\mathrm{SFH})\cdot \mathrm{age}+B$$
in the regimes of interest

Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

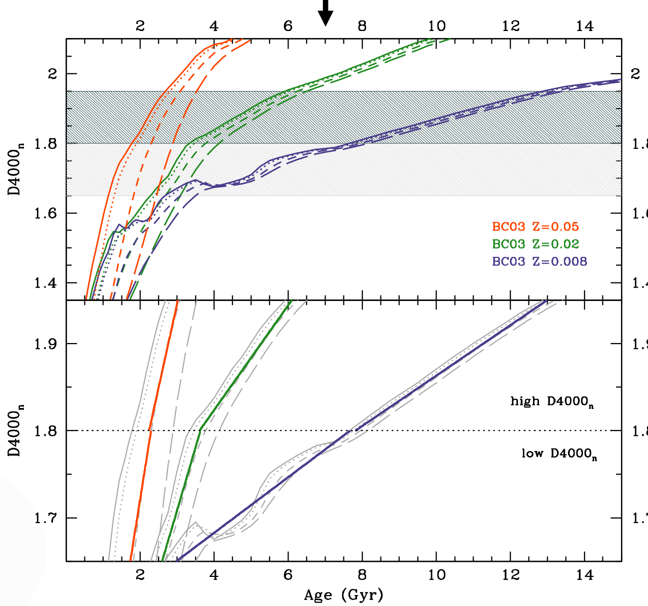
What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

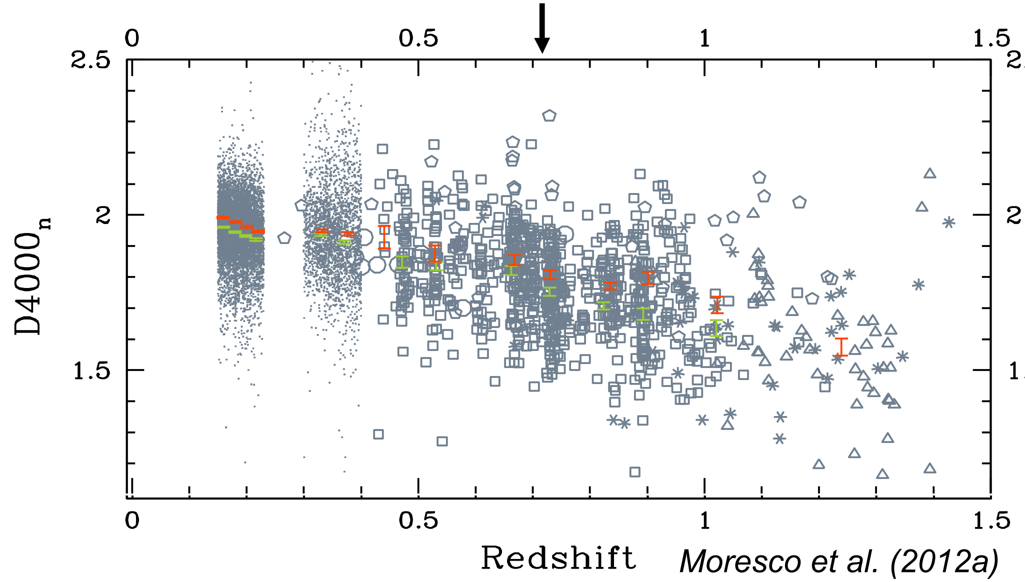
- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach

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

calibrated on different SPS models

estimated from data





Moresco et al. (2012a)

Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach

What about the systematics? (Moresco et al. 2012a, 2018, 2020)

Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age?
(Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach

What about the systematics?
(Moresco et al. 2012a, 2018, 2020)

- dependence on stellar population synthesis models
- young population component/frosting
- progenitor bias

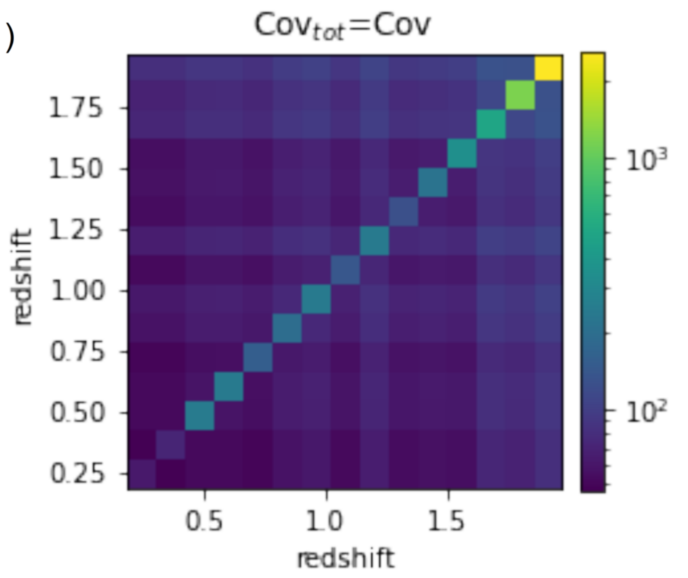
Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

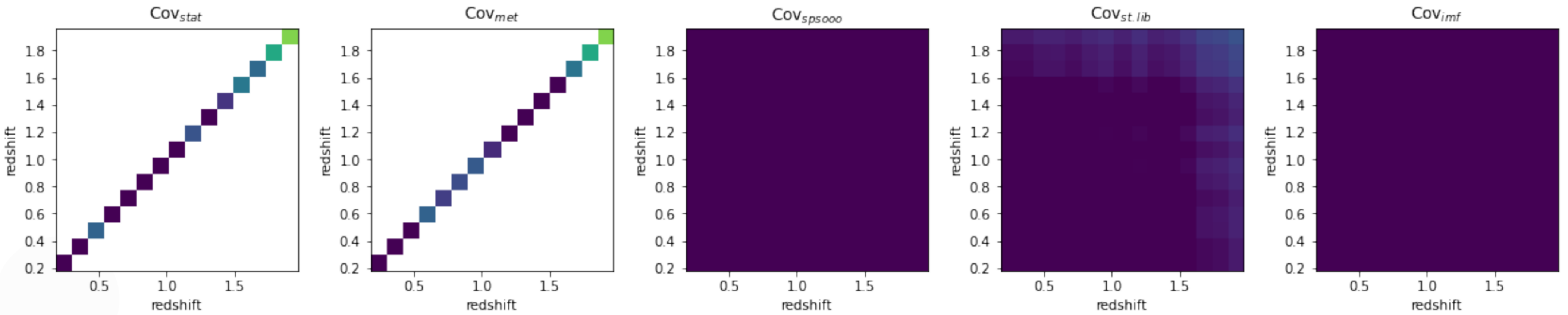
- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach



What about the systematics? (Moresco et al. 2012a, 2018, 2020)

- dependence on stellar population synthesis models
- young population component/frosting
- progenitor bias

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



Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach

What about the systematics? (Moresco et al. 2012a, 2018, 2020)

- dependence on stellar population synthesis models
- young population component/frosting
- progenitor bias

Pros and cons

Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach

What about the systematics? (Moresco et al. 2012a, 2018, 2020)

- dependence on stellar population synthesis models
- young population component/frosting
- progenitor bias

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	

Cosmic chronometers handbook

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

- best tracers: very massive and passively evolving galaxies
- passive means passive: minimize the contamination for cosmological purposes
- multiple selection criteria and indicators to maximize the purity of the sample

What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2021)

- measure *dt*, not *t*
- no cosmological assumptions
- break degeneracies to measure *dt*
- the D4000 approach

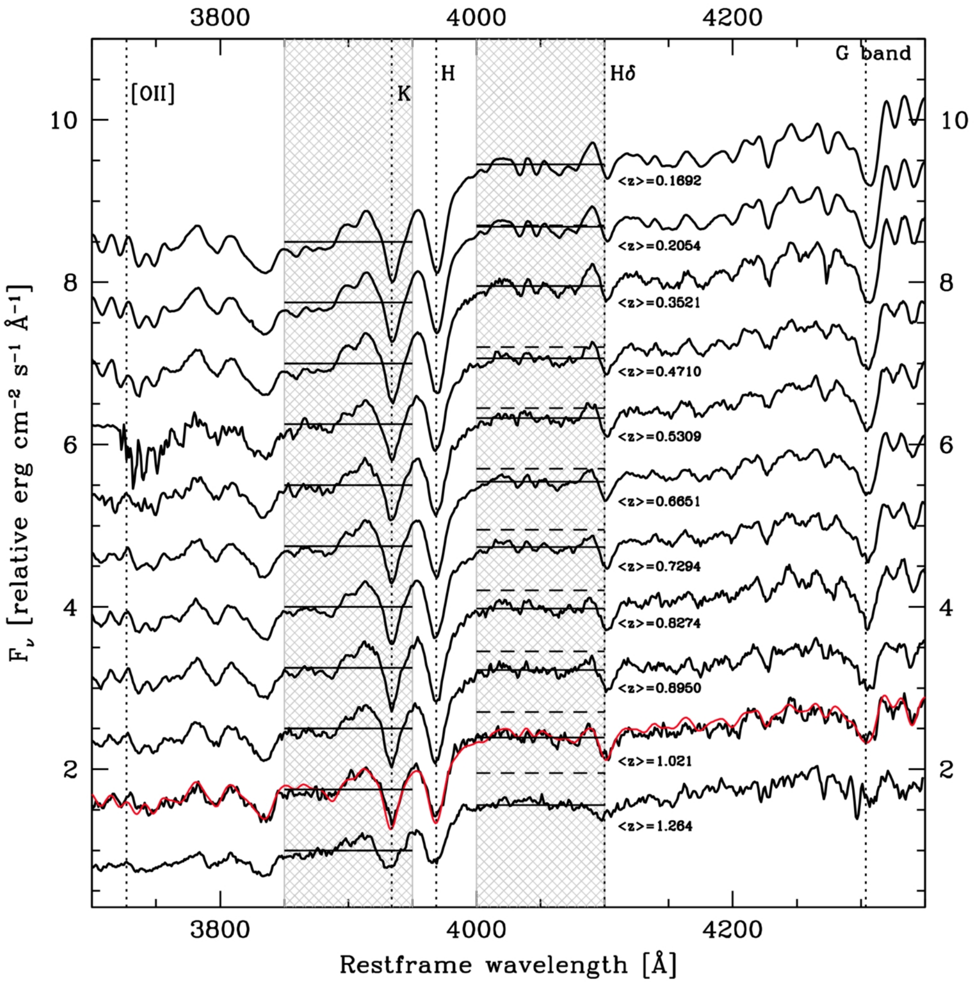
What about the systematics? (Moresco et al. 2012a, 2018, 2020)

- dependence on stellar population synthesis models
- young population component/frosting
- progenitor bias

Pros and cons

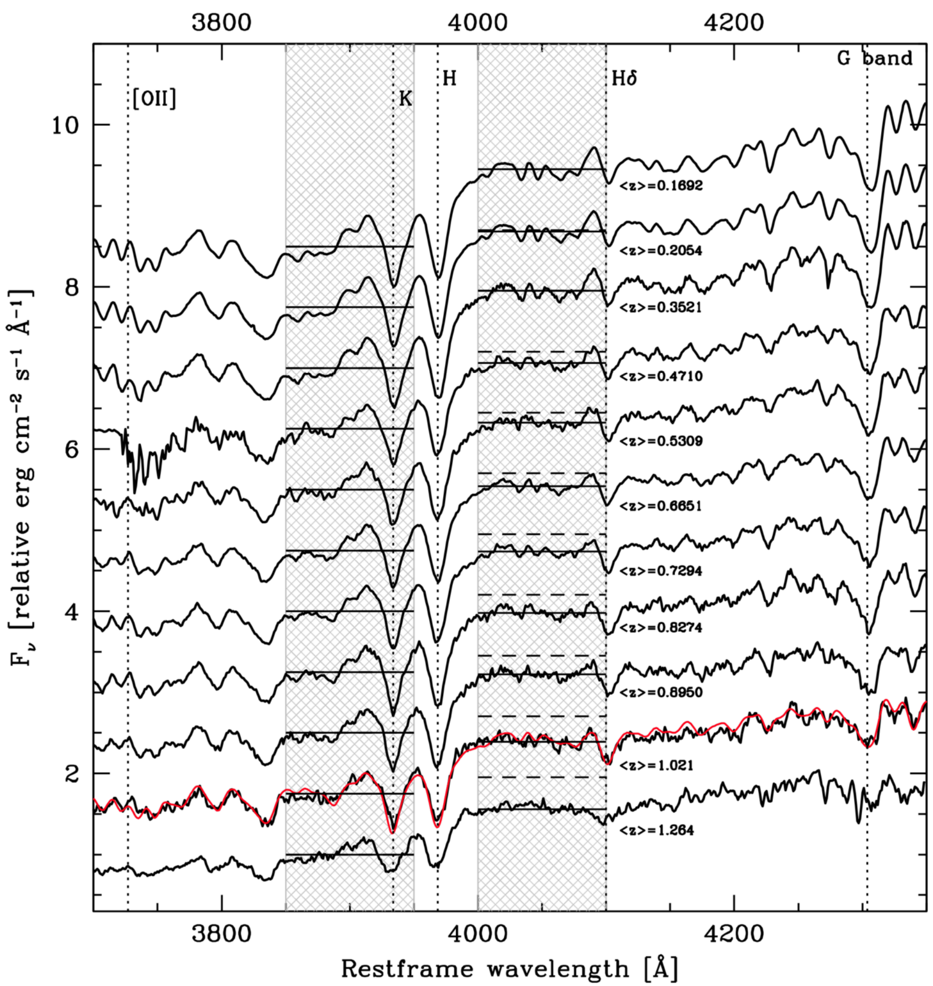
Pros	Cons
differential approach better accuracy in estimating relative ages systematics minimized evolution estimated in narrow z-bins	homogeneity of the sample should be handled accurately
direct measure of H(z)	relies on metallicity prior/estimate
cosmology-independent ideal to test cosmological model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

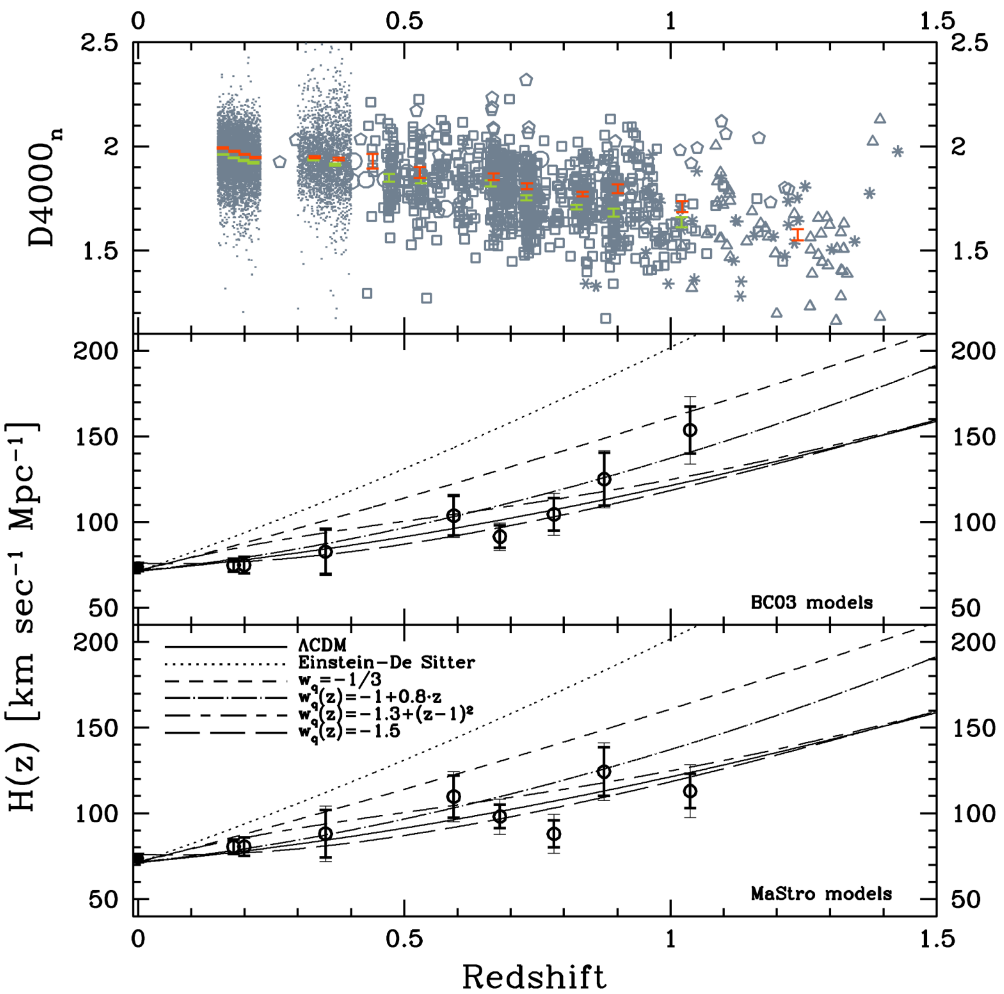
A worked example



Moresco et al. (2012a)

A worked example





Moresco et al. (2012a)

Main results

SDSS+

- 8 measurements at 0.15<z<1.4
- **precision ~5% at z~0.2** including systematic errors
- precision ~12% across the entire redshift range
- direct and robust (6σ) evidence of the accelerated expansion
- new path to discriminate alternative cosmologies

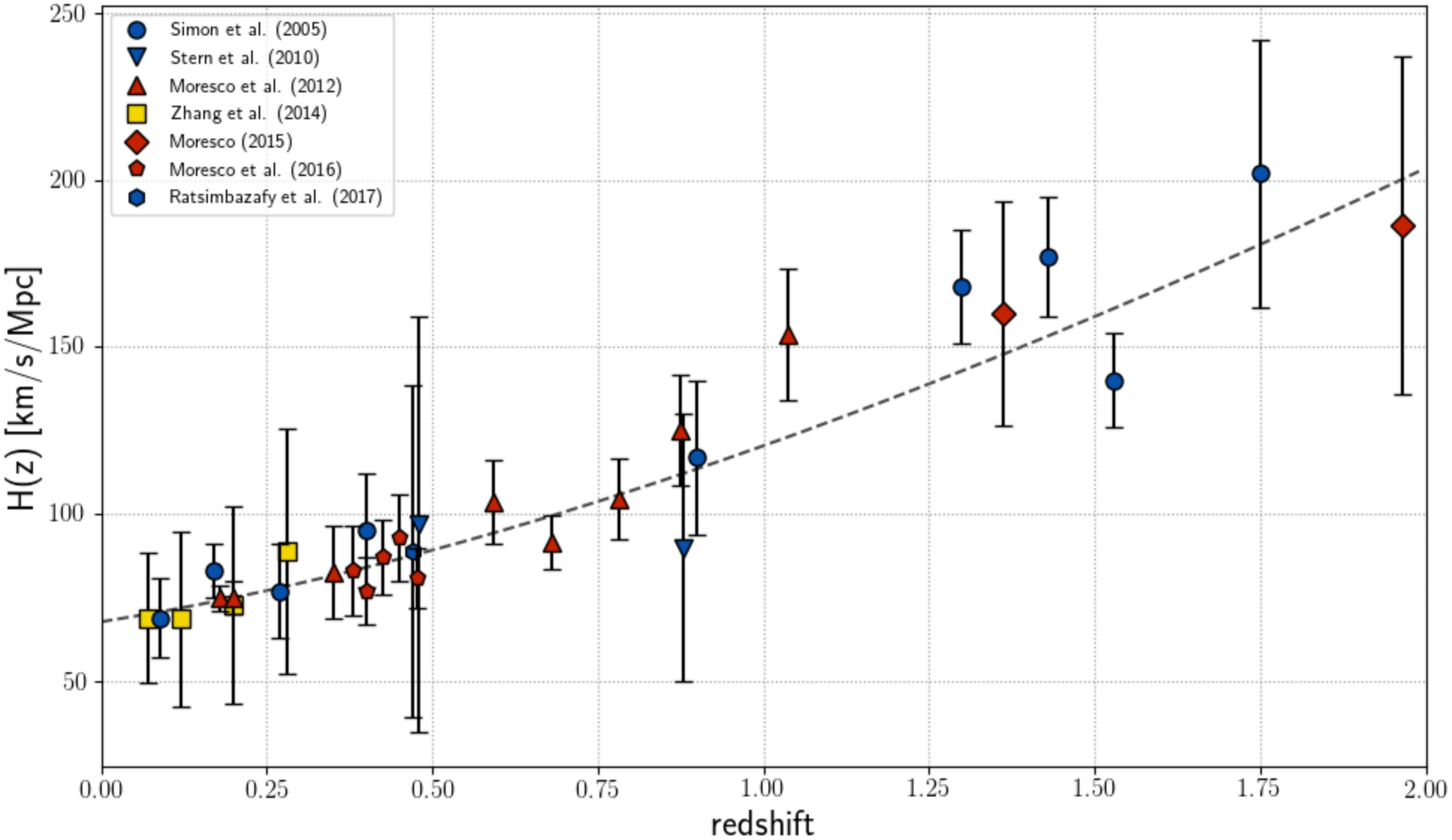
BOSS

- 5 H(z) measurements at 0.3<z<0.5
- **precision of ~6% at z~0.4**, once averaged
- mapping a **crucial redshift range** to probe the transition between accelerated and decelerated expansion

high-z

- test case (<30 galaxies) to show the potential of this approach at high z (e.g. Euclid)
- improved cosmological constraints (~5% for Ω_m and w_0)

H(z): state of art



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

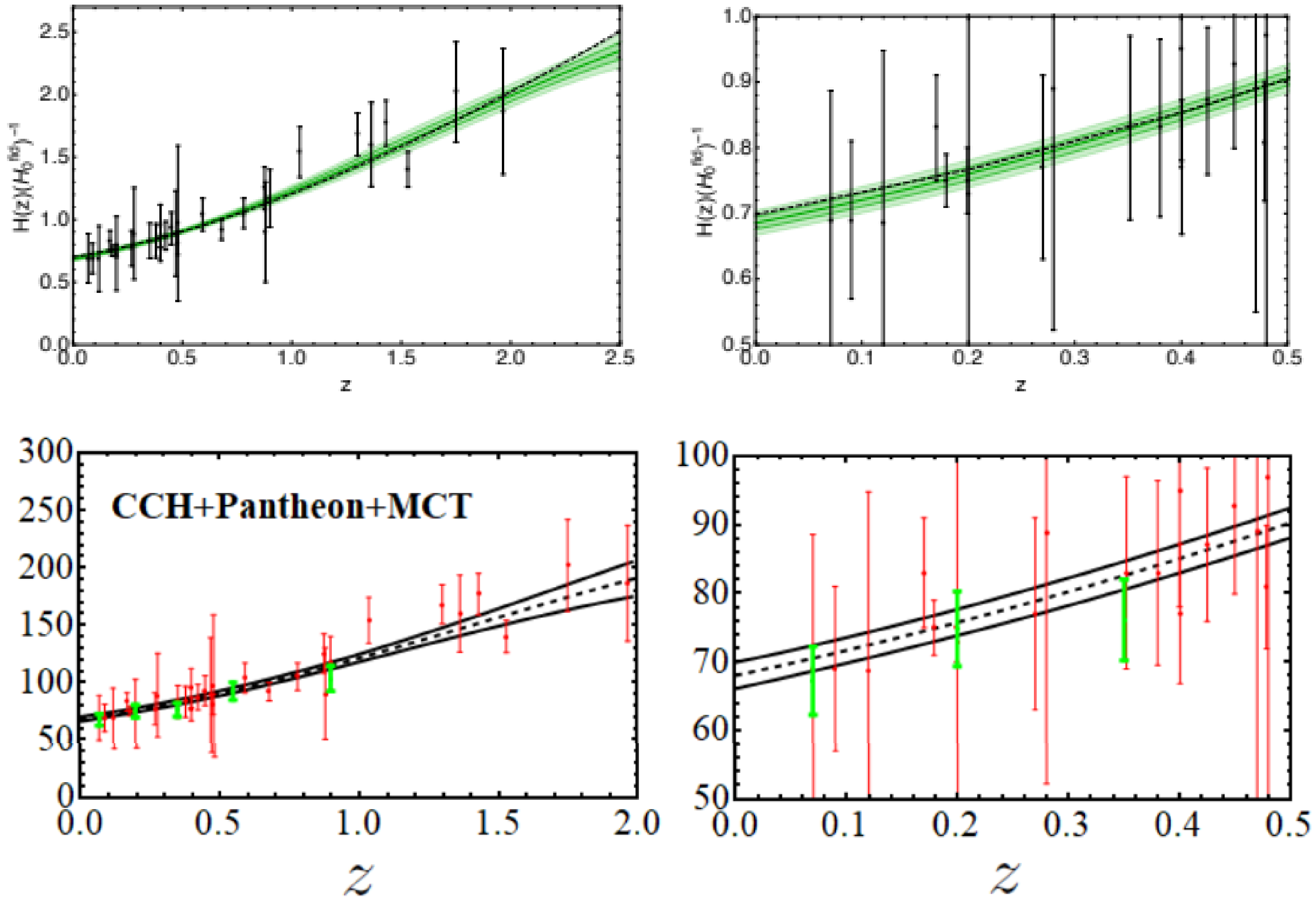
...and many more...

Estimating the Hubble constant

- 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



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

Haridasu et al. (2018)

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

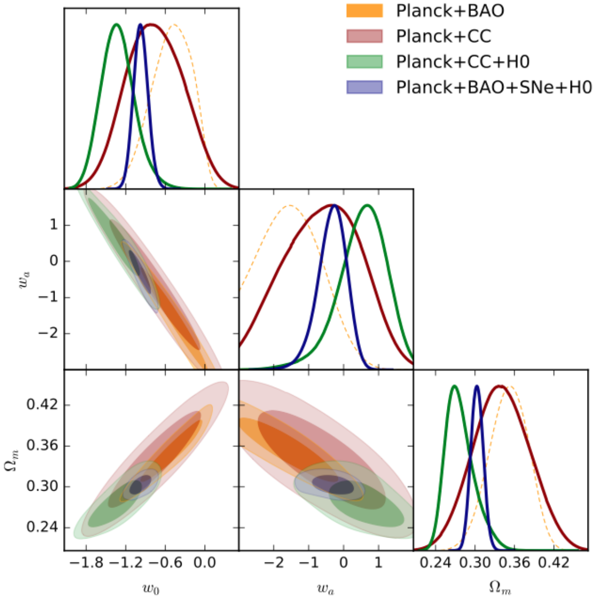
Gomez-Valent & Amendola (2018,2019)

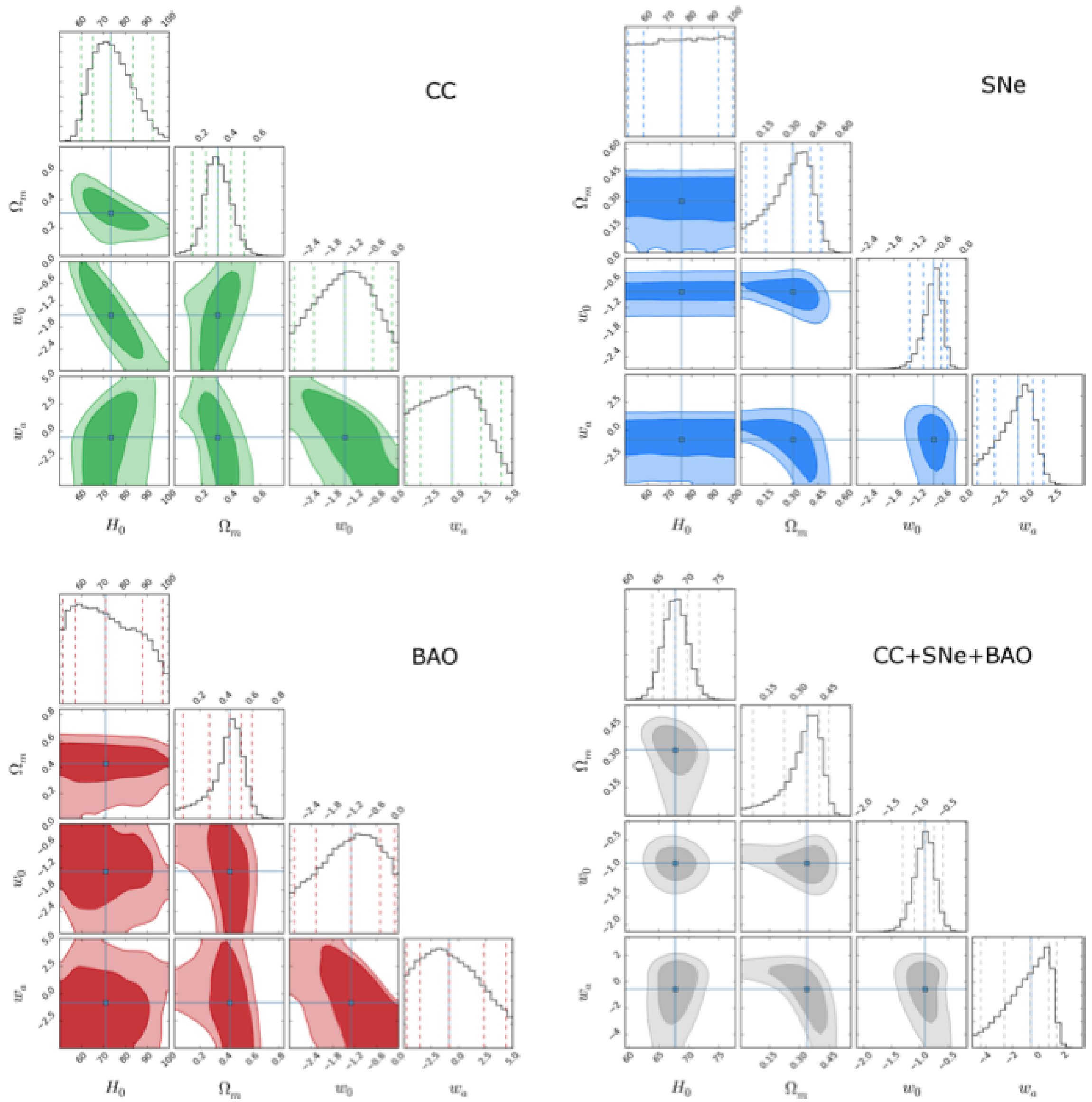
Combining with (and challenging) standard probes

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

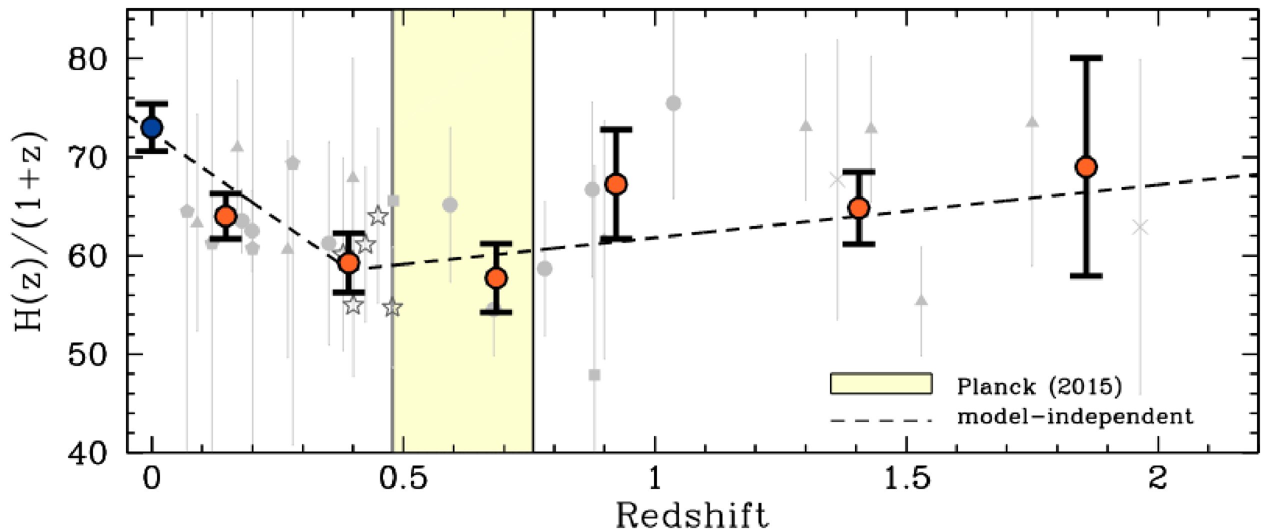




Moresco et al. (2016b)

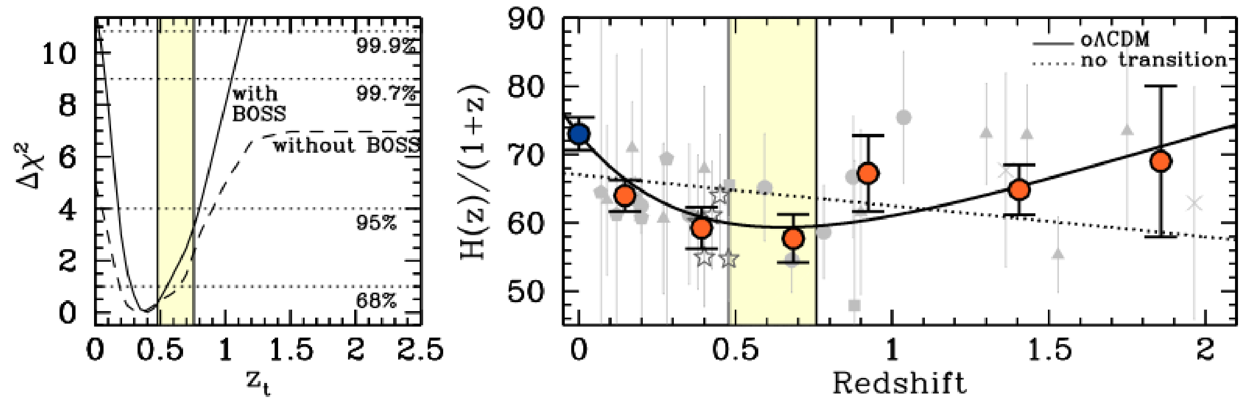
Mapping the transition redshift

Analysis of the full datasets provides the **first cosmology-independent evidence of transition redshift** with high confidence



$z_t = 0.4 \pm 0.1$

($z_t = 0.64^{+0.1}_{-0.06}$ for oΛCDM)



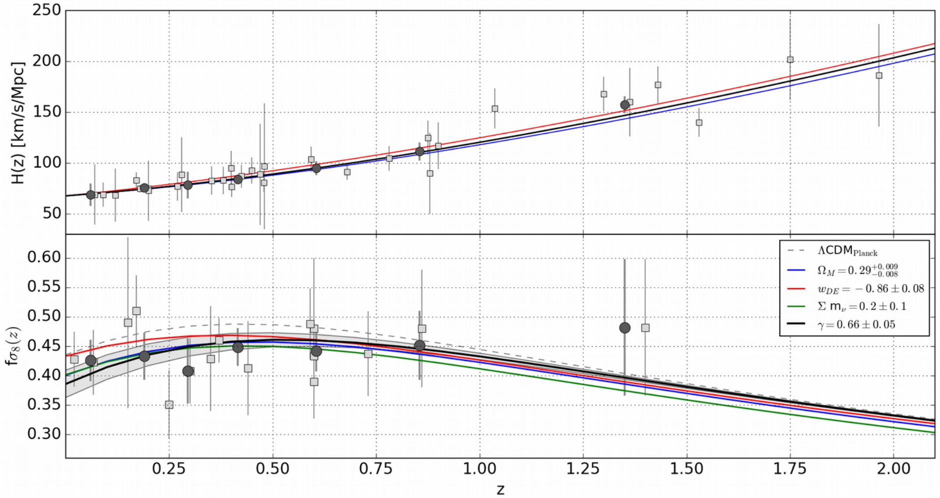
Moresco et al. (2016a)

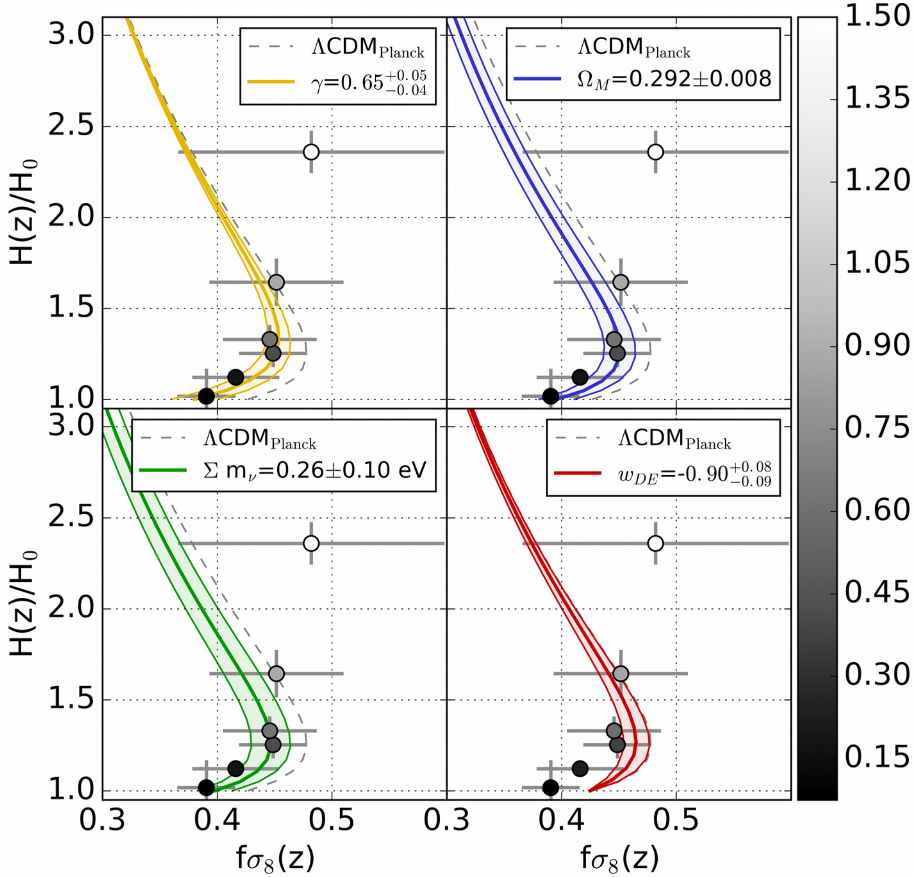
Combining expansion and growth

Idea firstly proposed by Linder (2017): joint constraints on expansion and growth to disentangle models

First observational approach

Small tension of present data with Planck (2015), which may be solved by relaxing some parameters of the flat ΛCDM model





Moresco & Marulli (2017)

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
- Analysis:
    - ~11000 ETGs at $0.15<z<1.4$, **8 new H(z) measurements** at a **precision of 5-12% across the entire range**
    - ~30 ETGs at $z>1.4$, **2 new H(z) measurements** pushing the limit **to z~2**
    - ~130000 ETGs at $0.2<z<0.8$, **5 new H(z) measurements** mapping the transition redshift between accelerated and decelerated expansion
- 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 $z=0$