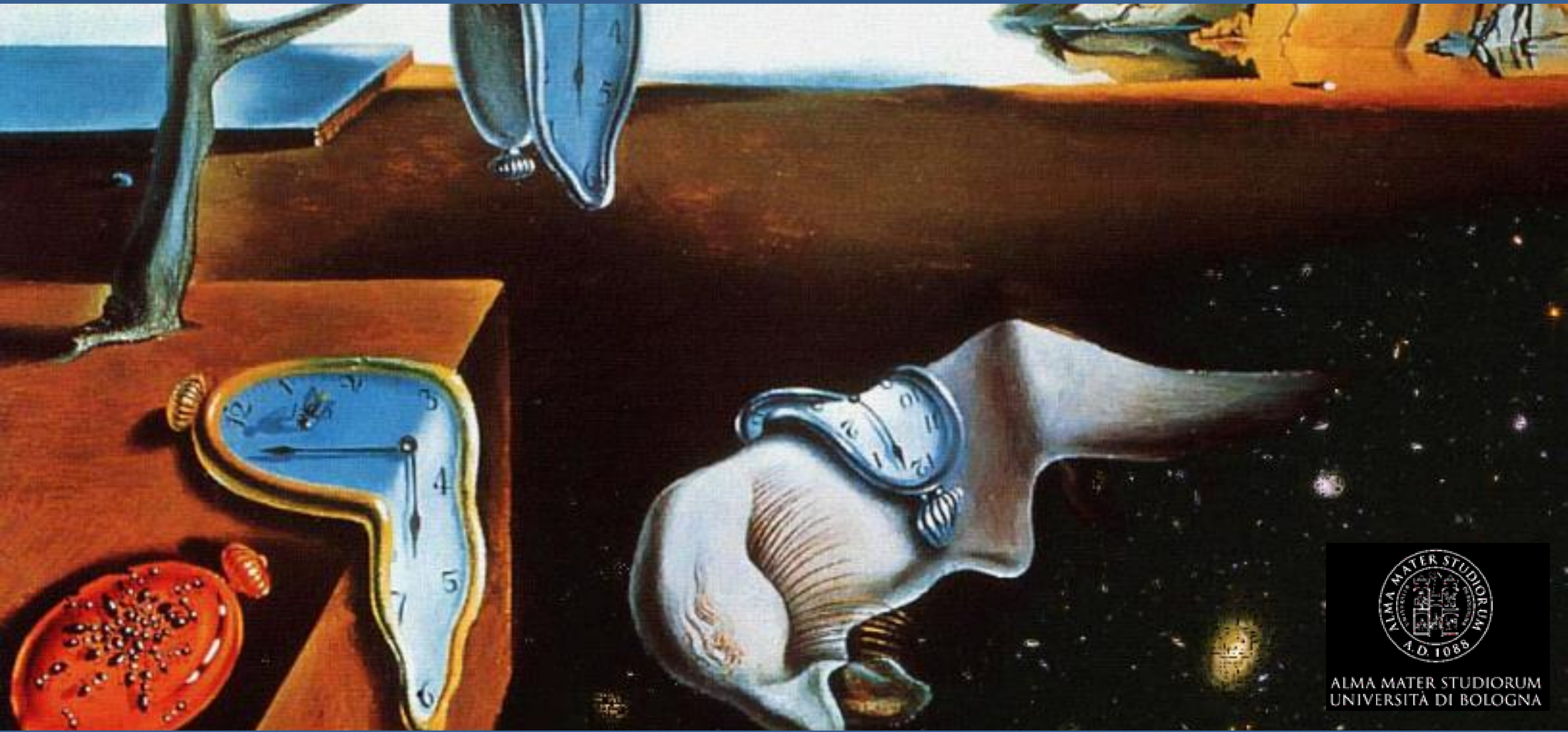
Shedding light on the Hubble tension with novel cosmological probes

Cosmic Chronometers and Cosmic Clocks



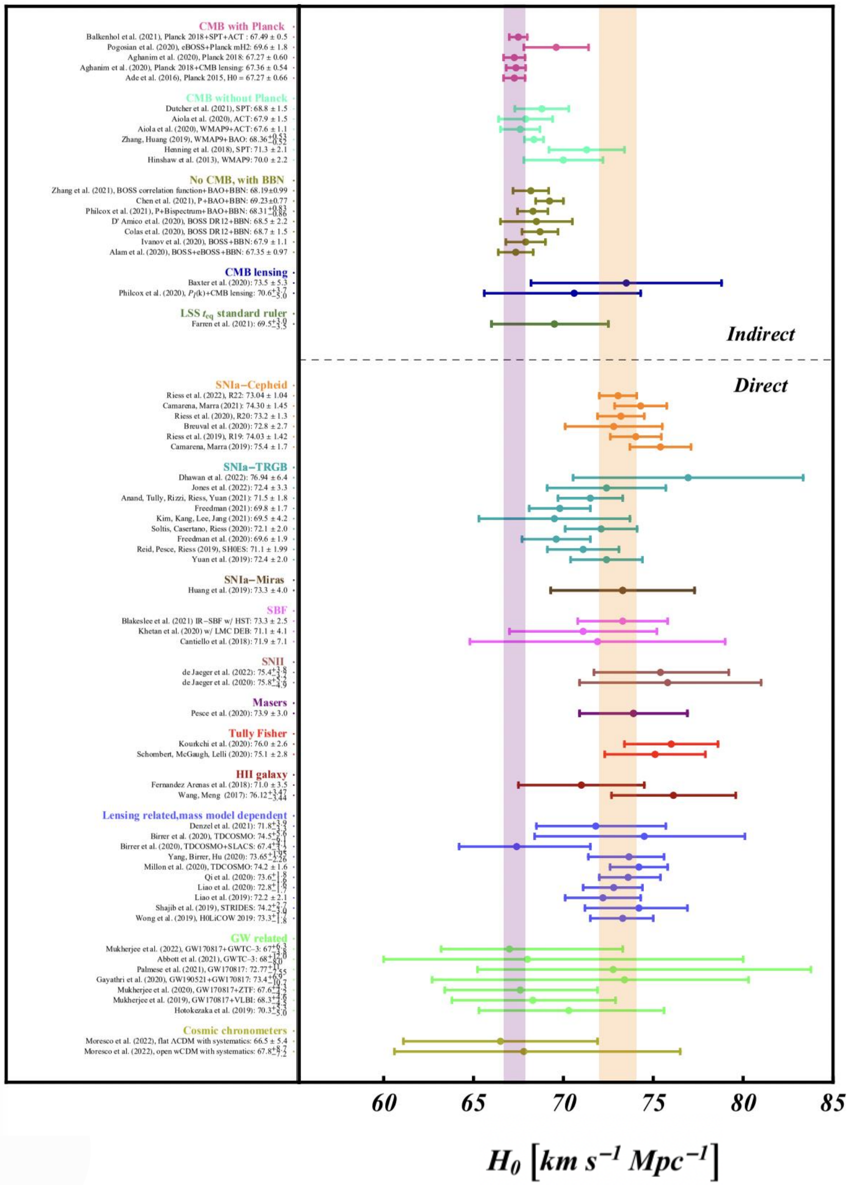
GGI workshop
Exploring New Frontiers
in Cosmology
23 July 2026

Michele Moresco
Dipartimento di Fisica e Astronomia “Augusto Righi”
Università di Bologna

<u>Main collaborators</u>: A. Cimatti, N. Borghi, E. Tomasetti (UniBo), L. Pozzetti (INAF-OAS), R. Jimenez, L. Verde (ICREA)

Crisis and solutions

Abdalla et al. (2022)



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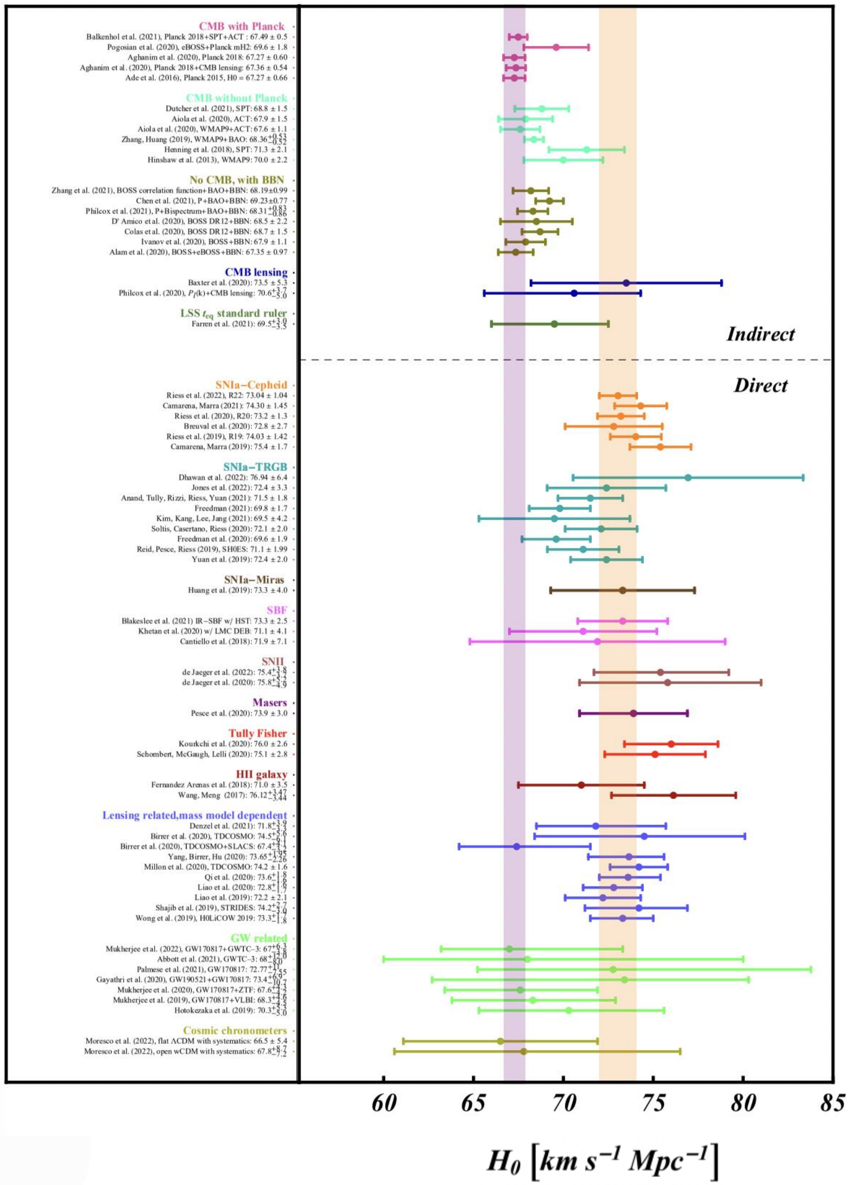
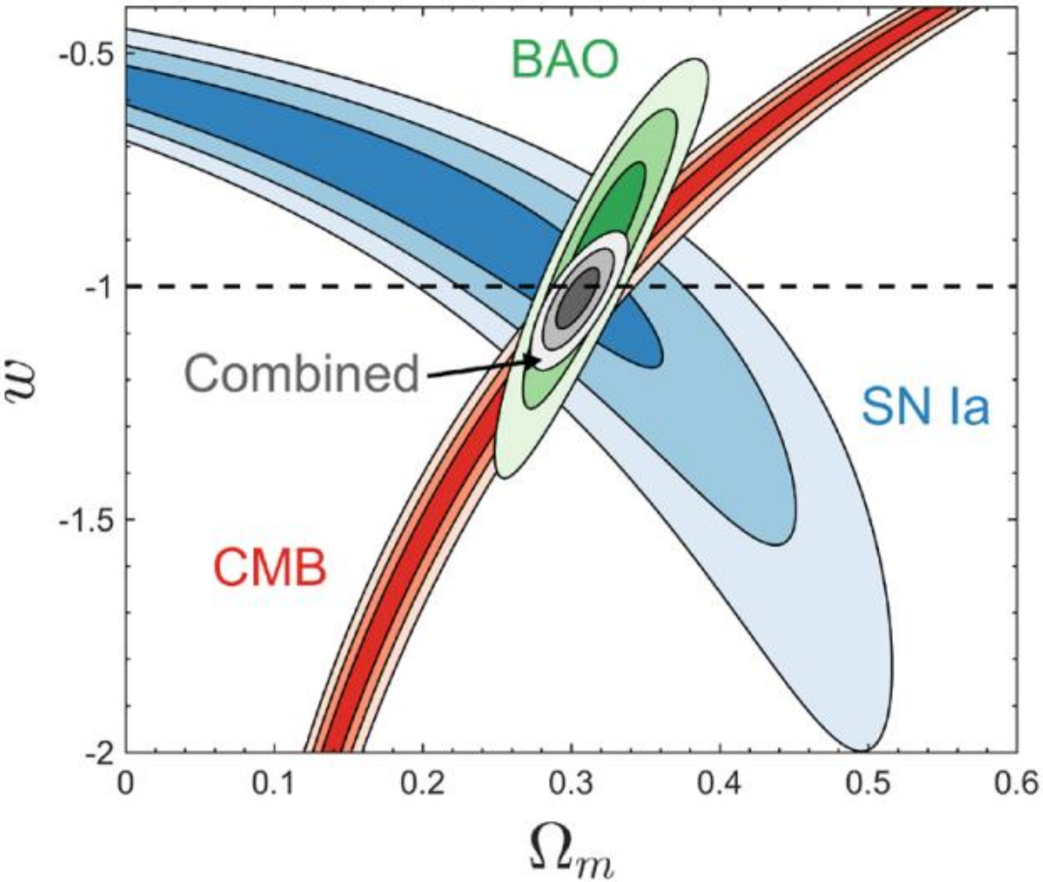


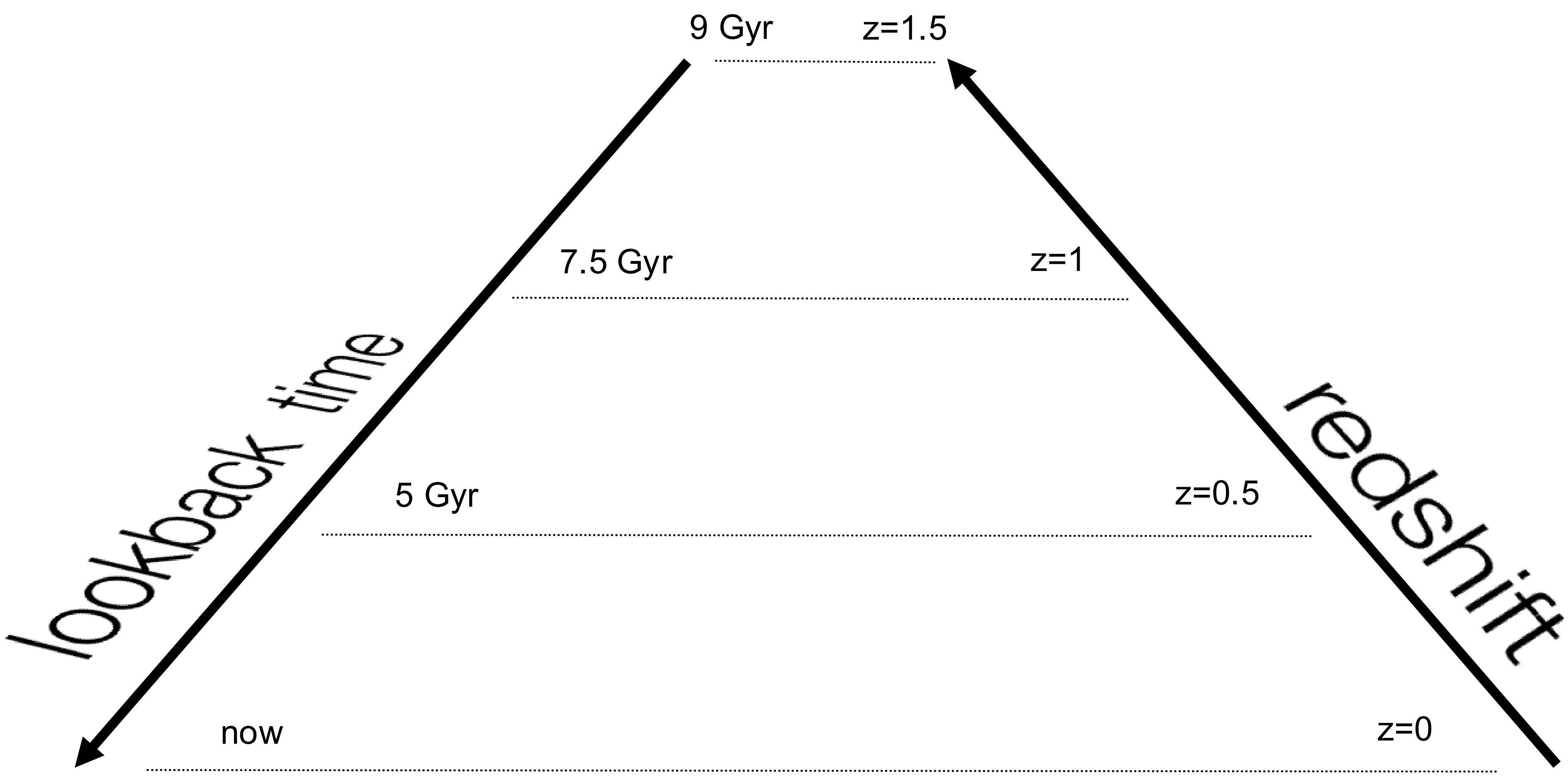
Different probes, different cosmic times, different sensitivity to parameters, different systematics

Synergy within differences

Huterer & Shafer (2018)



Looking for new routes



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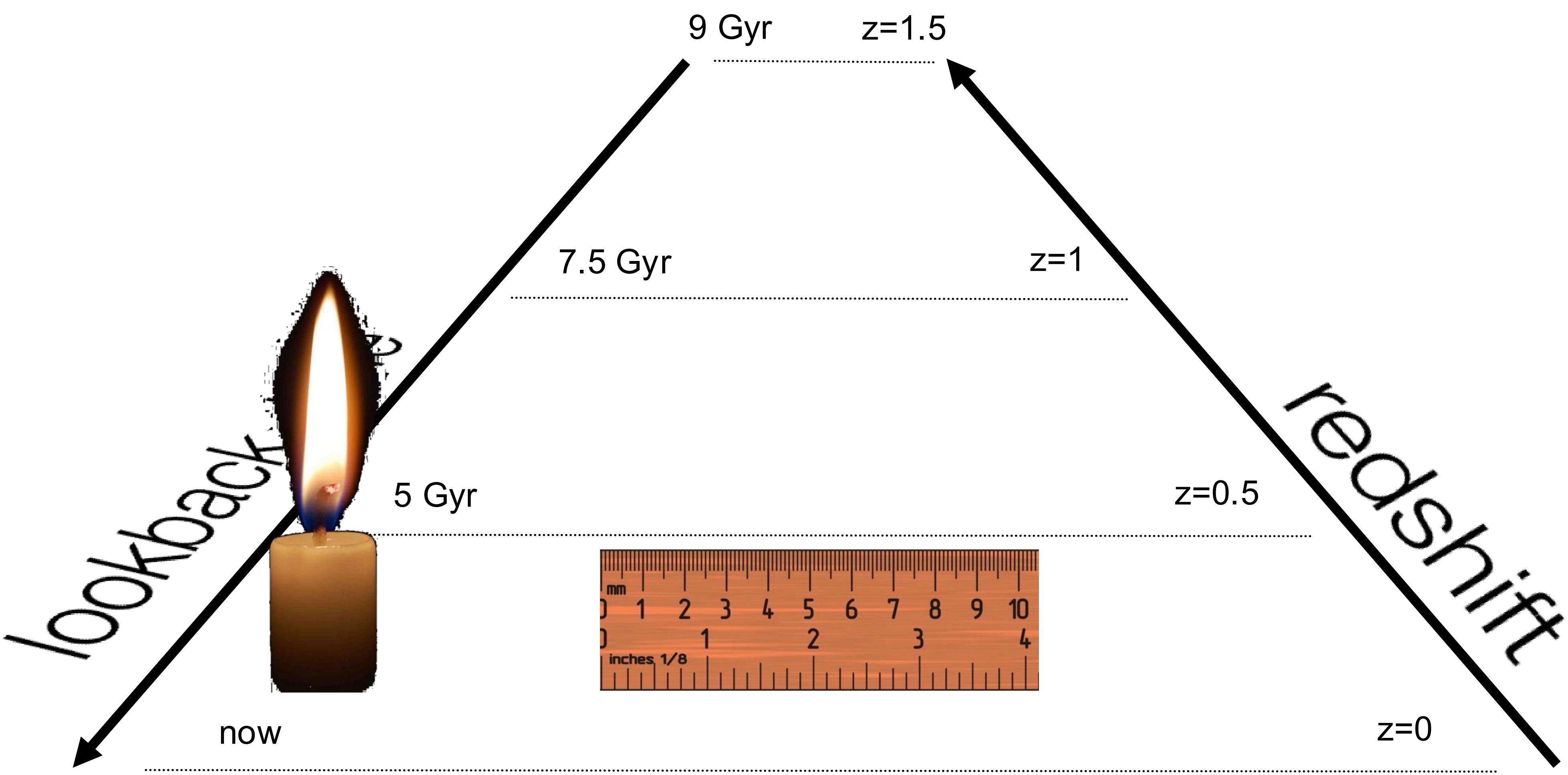

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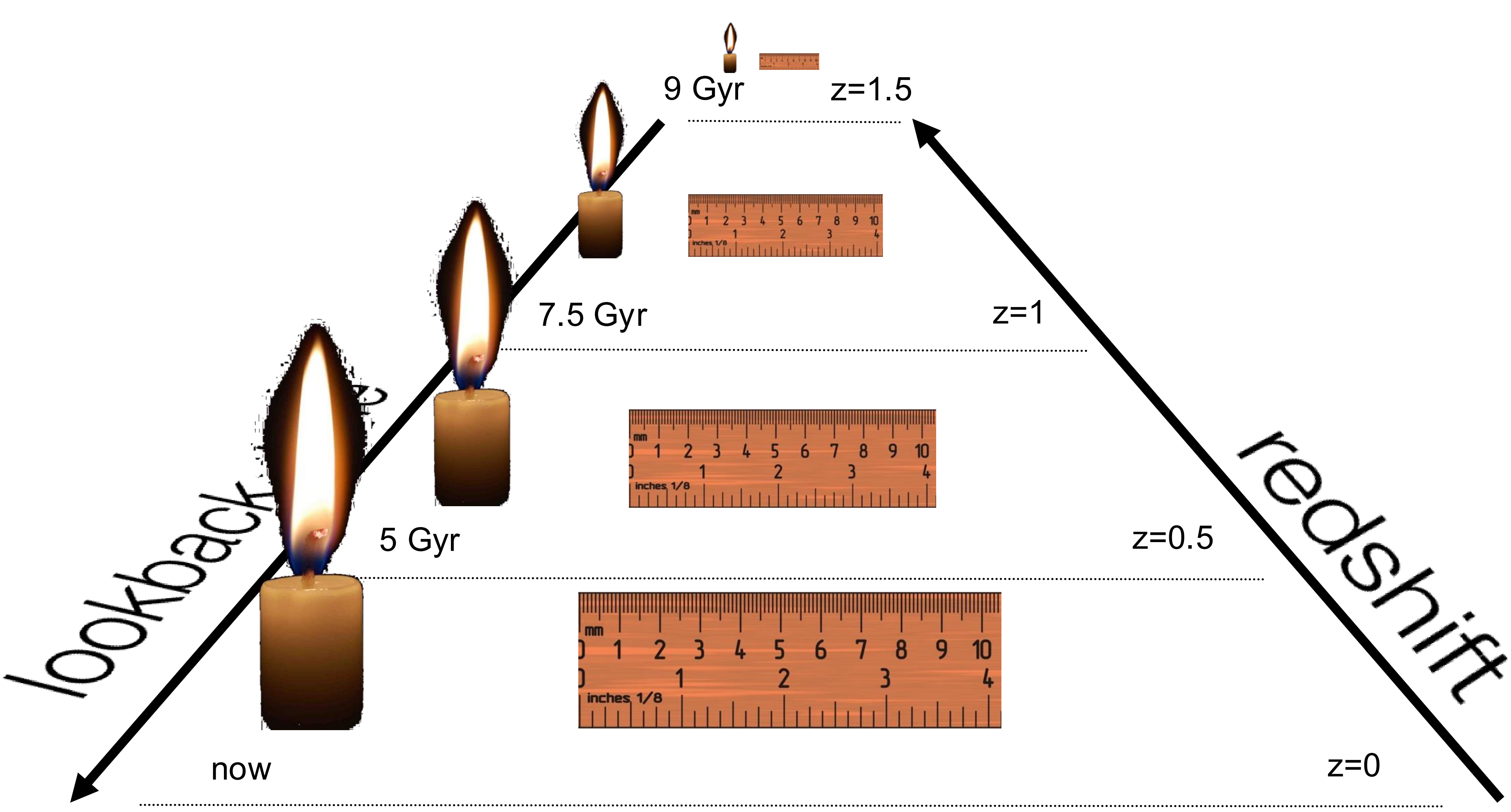

Bridging galaxy evolution and cosmology

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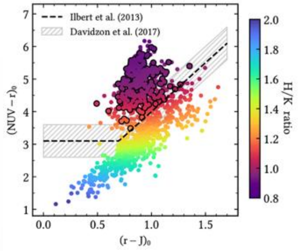

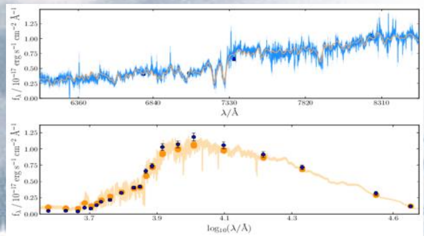

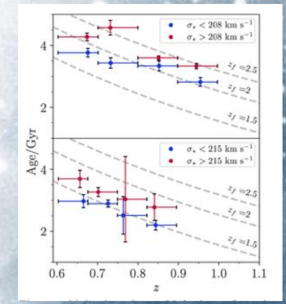

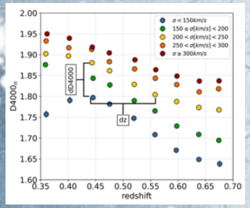

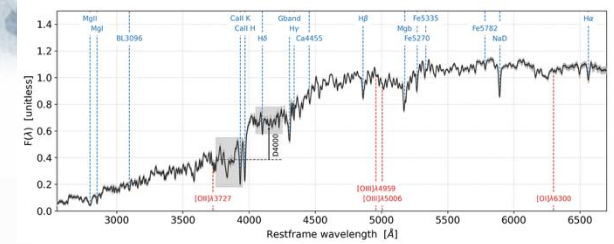

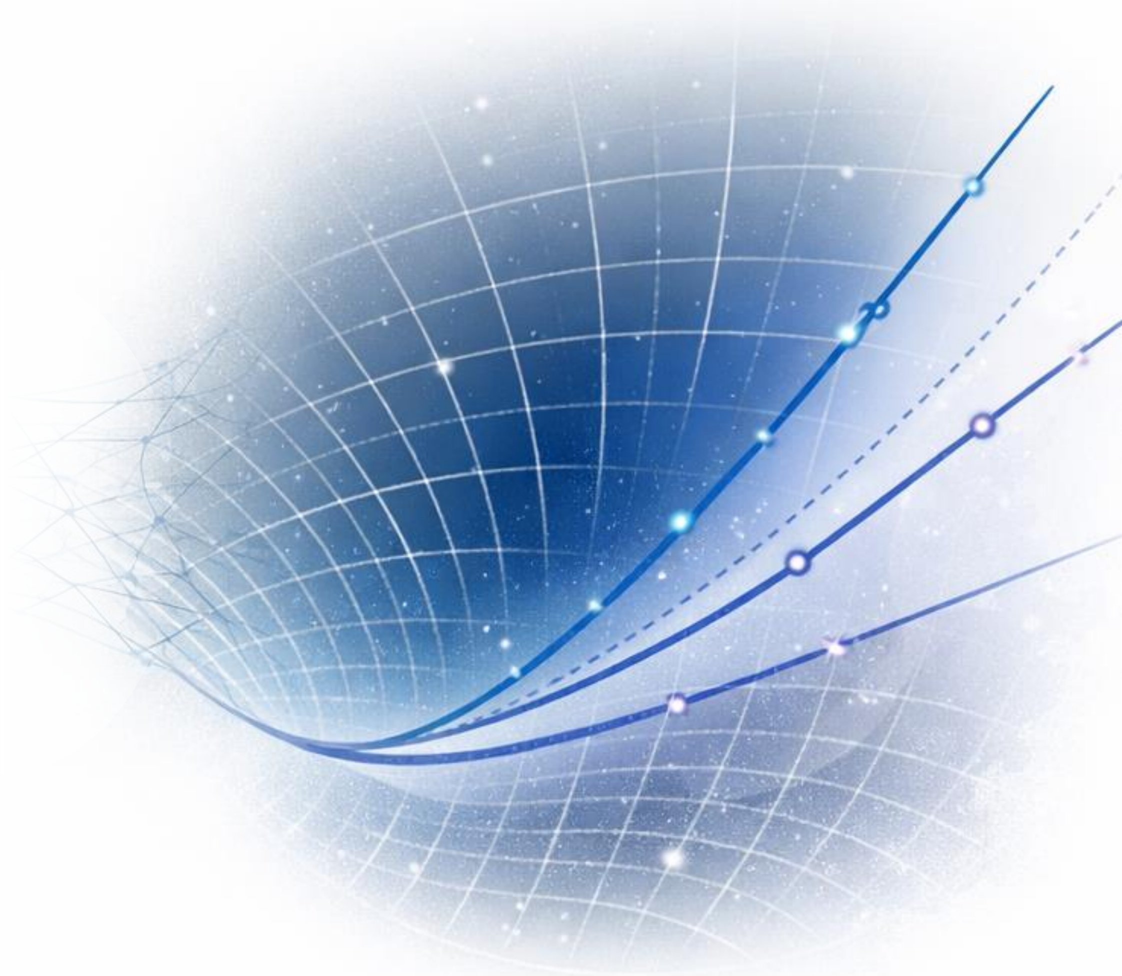

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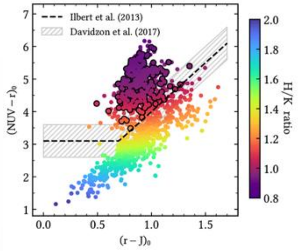

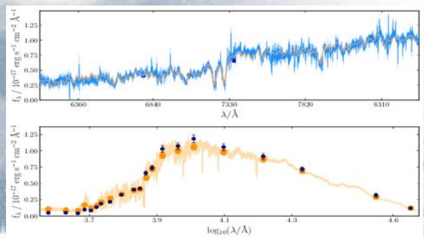

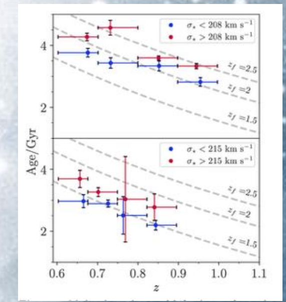

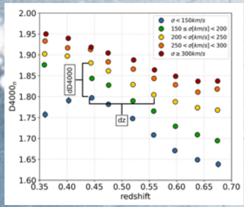

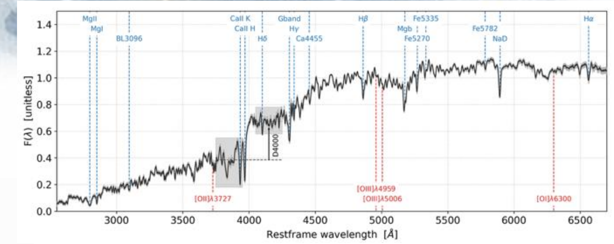

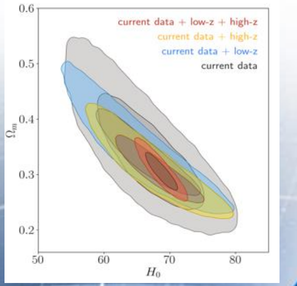

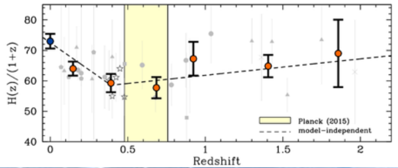

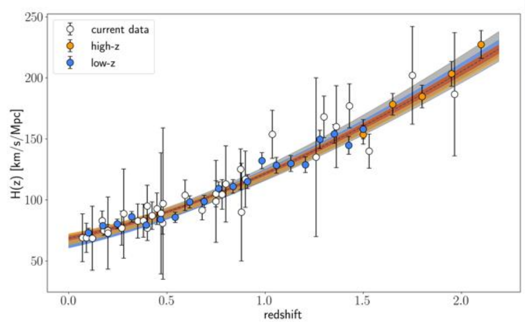

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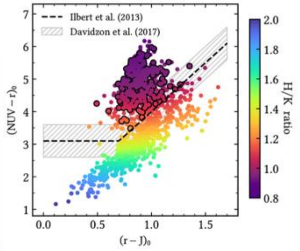

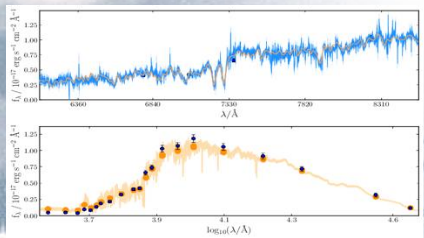

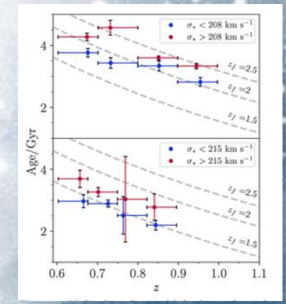

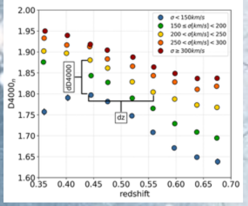

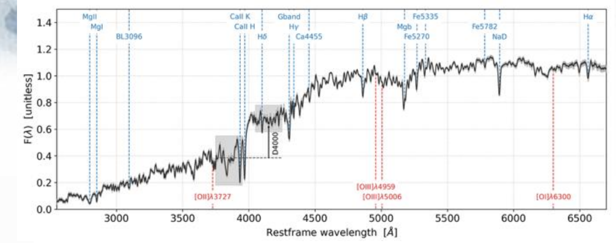

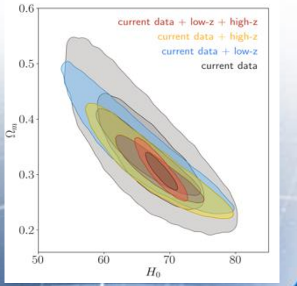

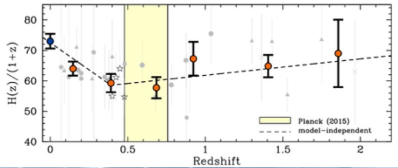

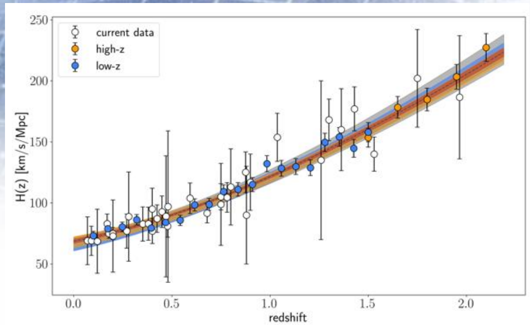

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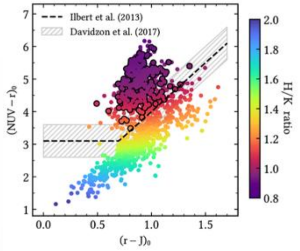
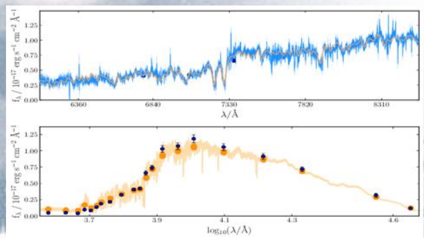
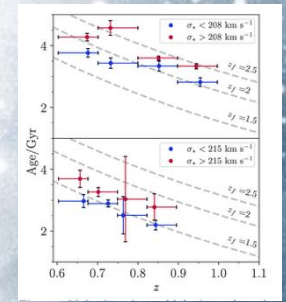
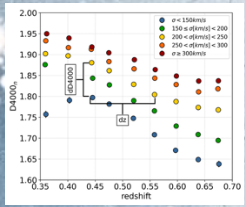
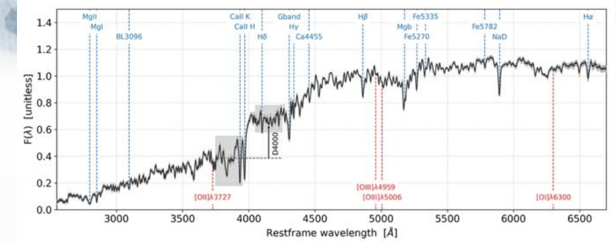


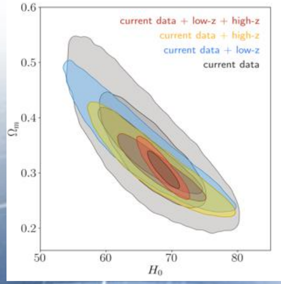


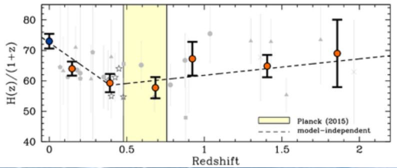


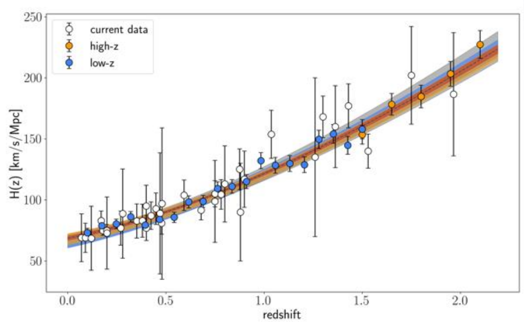




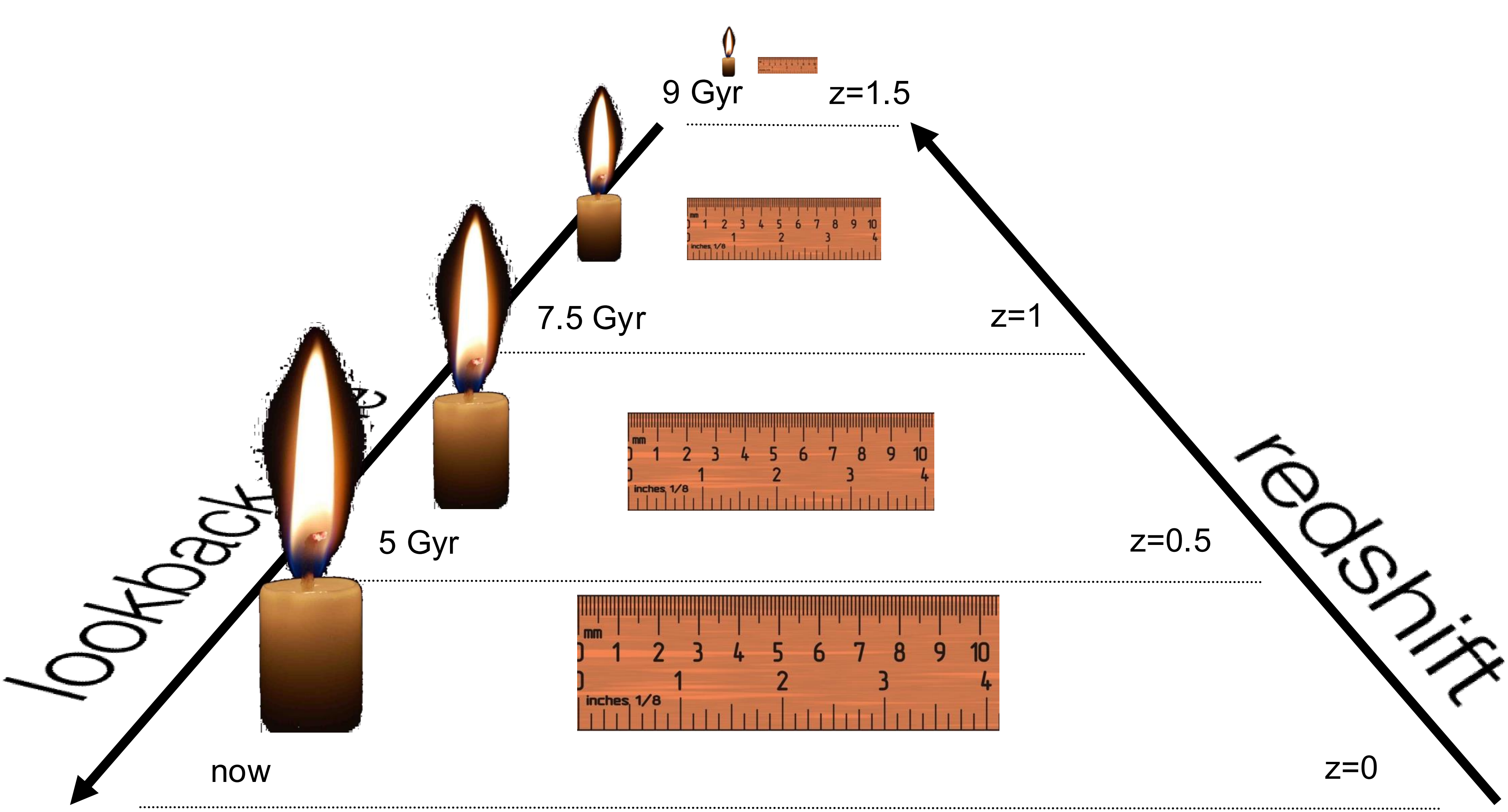
TIME
as a tracer







Looking for new routes



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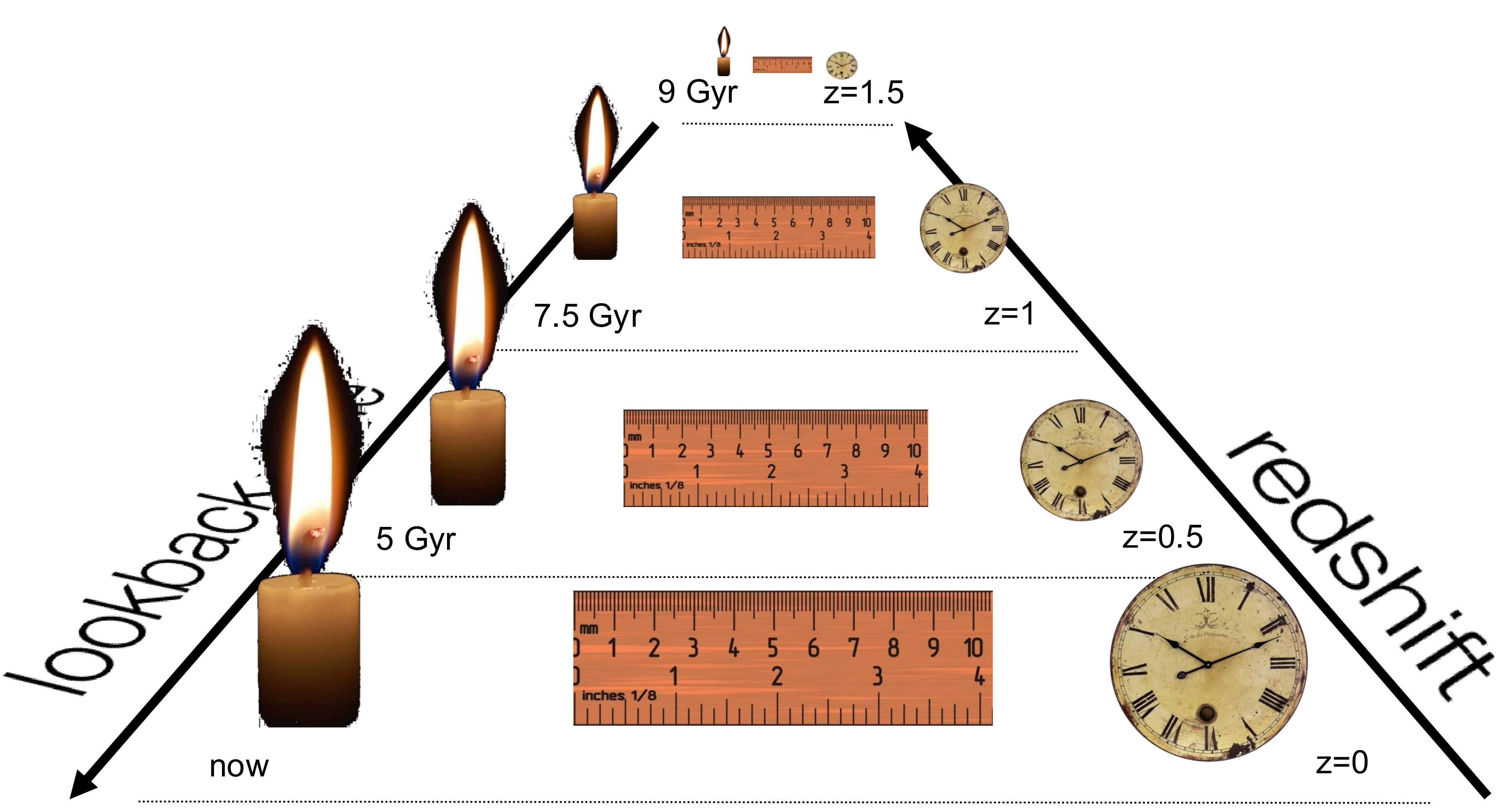
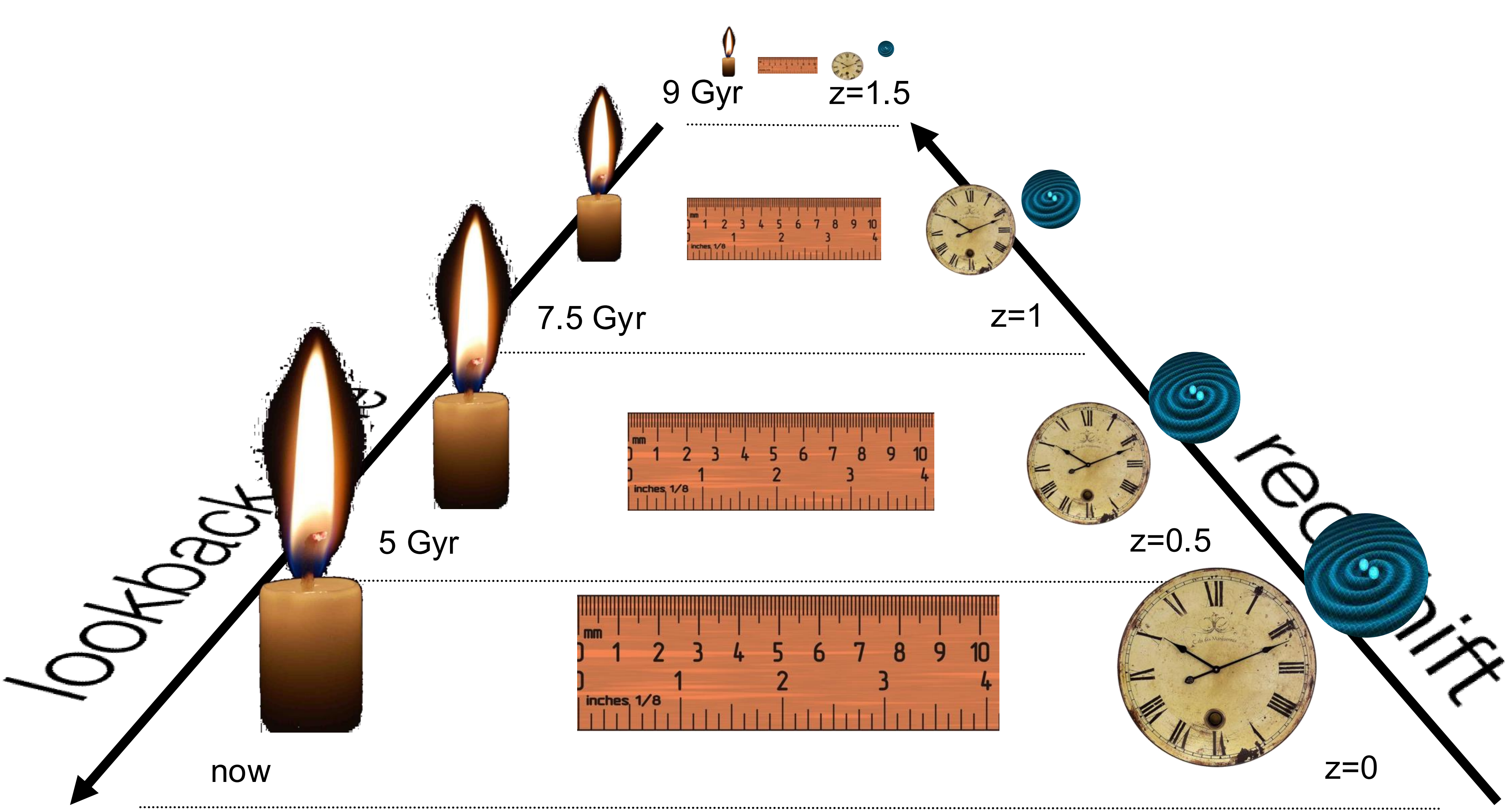


The **timing** of the Universe as a new cosmological probe

Looking for new routes



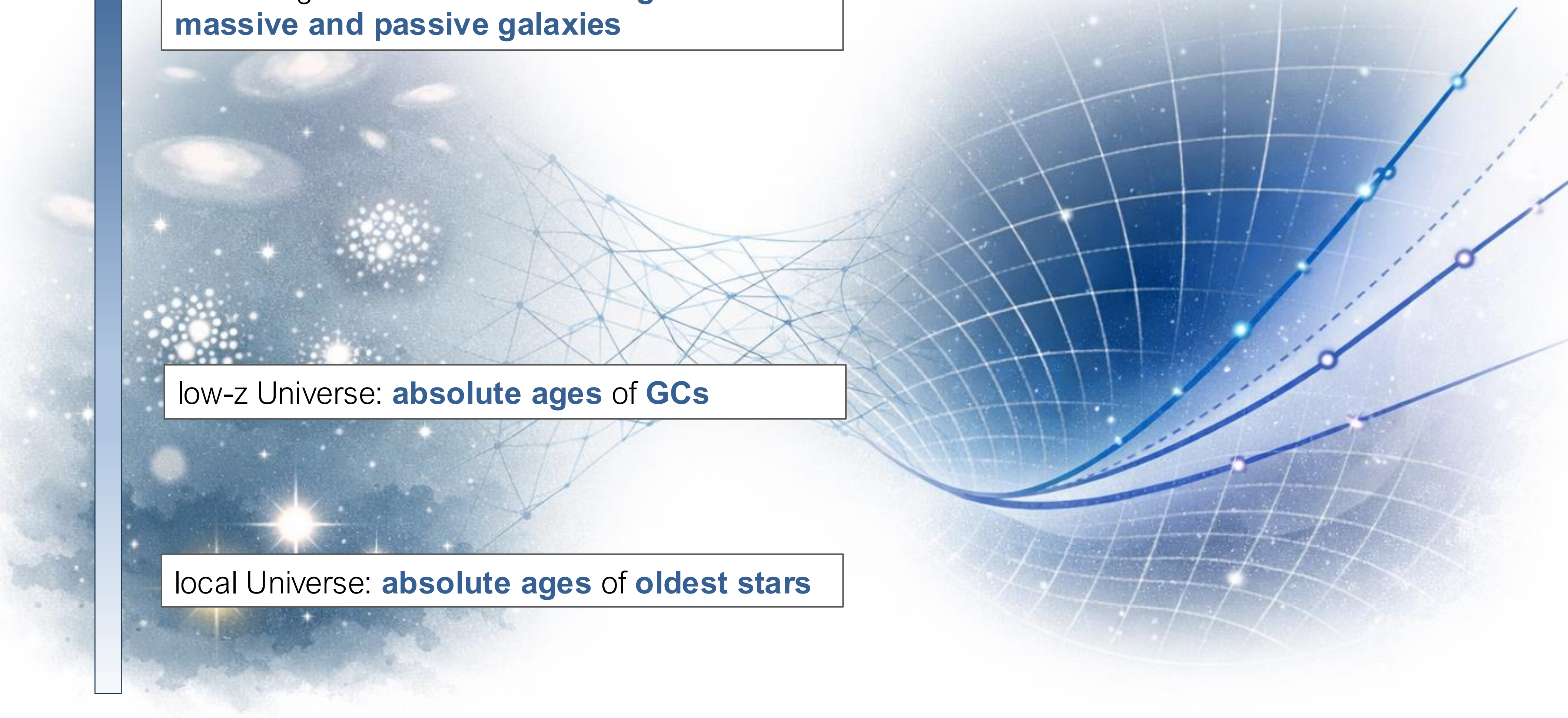
in parallel, also GW as sirens can be used to probe the expansion history of the Universe

Exploring new cosmological probes

low- to high-z Universe: **relative ages** of **massive and passive galaxies**

low-z Universe: **absolute ages** of **GCs**

local Universe: **absolute ages** of **oldest stars**



Exploring new cosmological probes

low- to high-z Universe: **relative ages** of **massive and passive galaxies**

Moresco et al. (2011), Moresco et al. (2012a), Moresco et al. (2012b), Moresco et al. (2013), Moresco (2015), Moresco et al. (2016a), Moresco et al (2016b), Moresco & Marulli (2017), Moresco et al. (2018), Moresco et al. (2022), Moresco (2024), Moresco (2026), Moresco et al. (2020), Borghi et al. (2022a), Borghi et al. (2022b), Jiao et al. (2023), Tomasetti et al. (2023), Jimenez et al. (2023), Tomasetti et al. (2025)

low-z Universe: **absolute ages** of **GCs**

Tomasetti et al. (2025a, 2025b, 2026)

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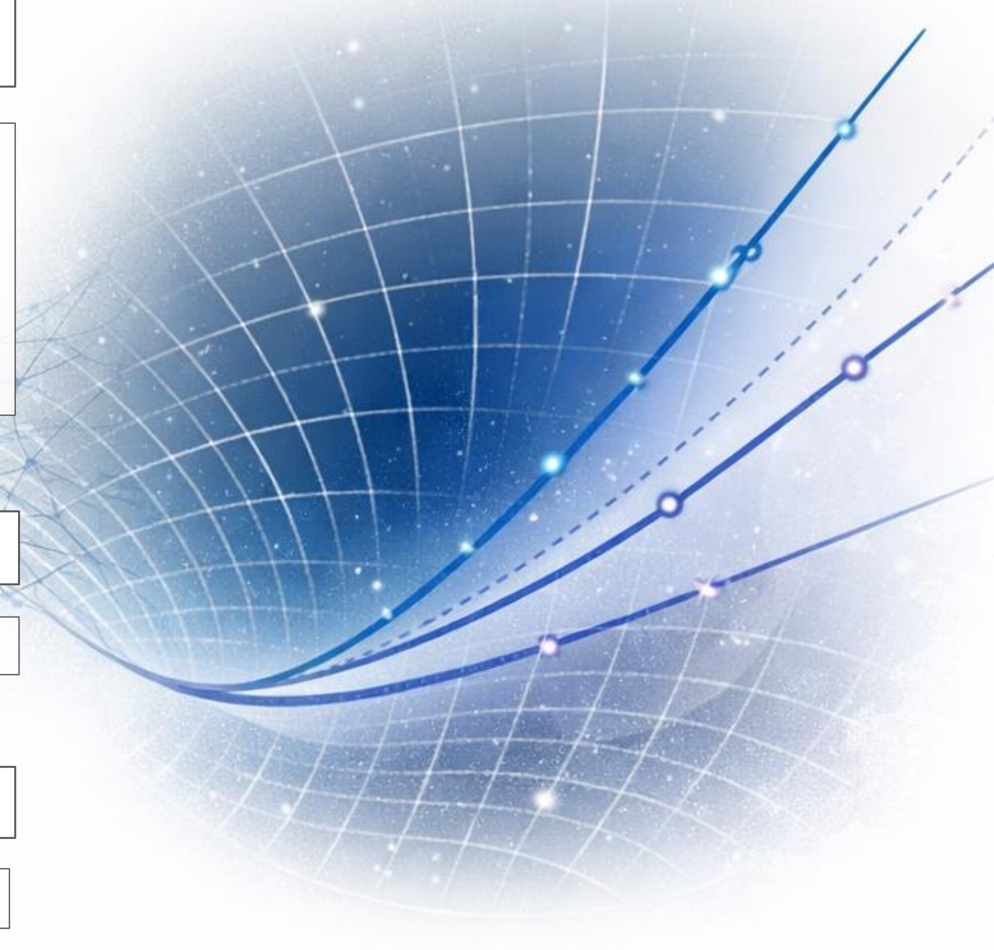
Cimatti and Moresco (2023), Tomasetti et al. (2026)



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Cimatti and Moresco (2023), Tomasetti et al. (2026)

low- and high-z Universe: **GWs as standard sirens**

Moresco et al. (2022), Borghi et al. (2024, 2026), Tagliazucchi et al. (2025, 2026a, 2026b, 2026 in prep)

CHIMERA

Public code: **CHIMERA**
(*https://chimera-gw.readthedocs.io/*)

Cosmic chronometers

based on

Method

Moresco et al. (2012a), JCAP, 08, 006
Moresco et al. (2016a), JCAP, 05, 014
Moresco et al. (2022), Living Reviews in Relativity, 25,1
Moresco (2024), chapter in book Hubble Constant Tension
Moresco (2026), chapter in book Encyclopedia of Astrophysics

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. (2022a), ApJ, 927, 164
Jiao et al. (2023), ApJS, 265, 48
Tomasetti et al. (2023), A&A, 679, 96
Jimenez et al. (2023), JCAP, 11, 047
Tomasetti et al. (2025), arXiv:2512.22964

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. (2022b), ApJL, 928, 4

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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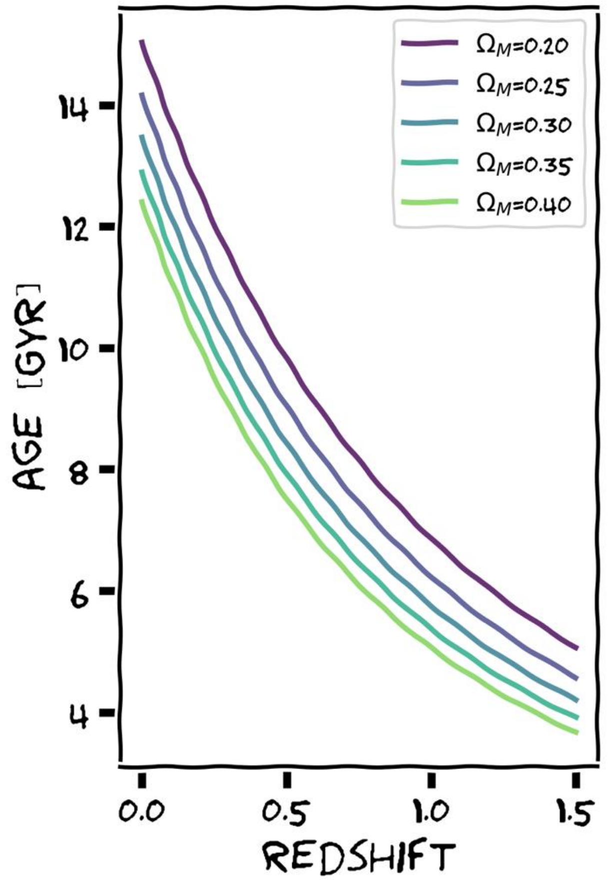

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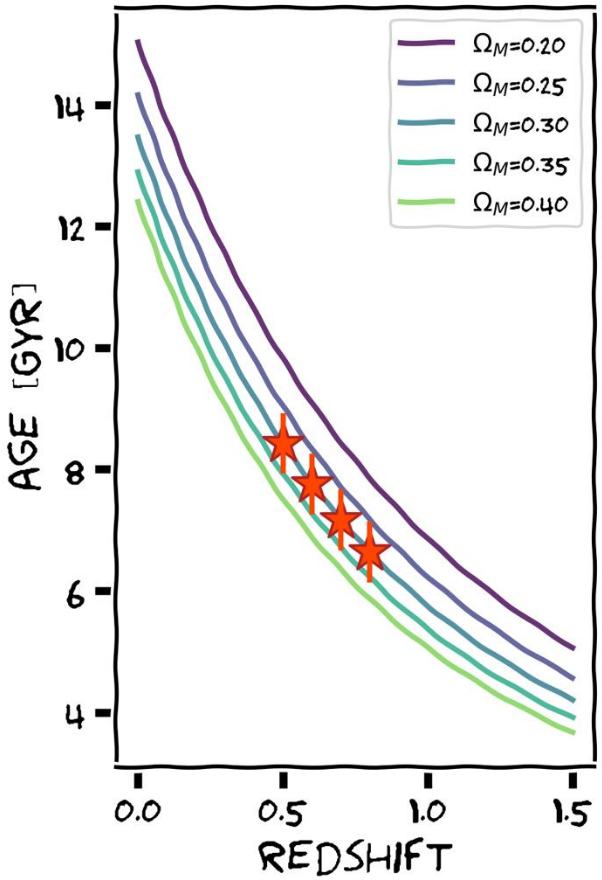

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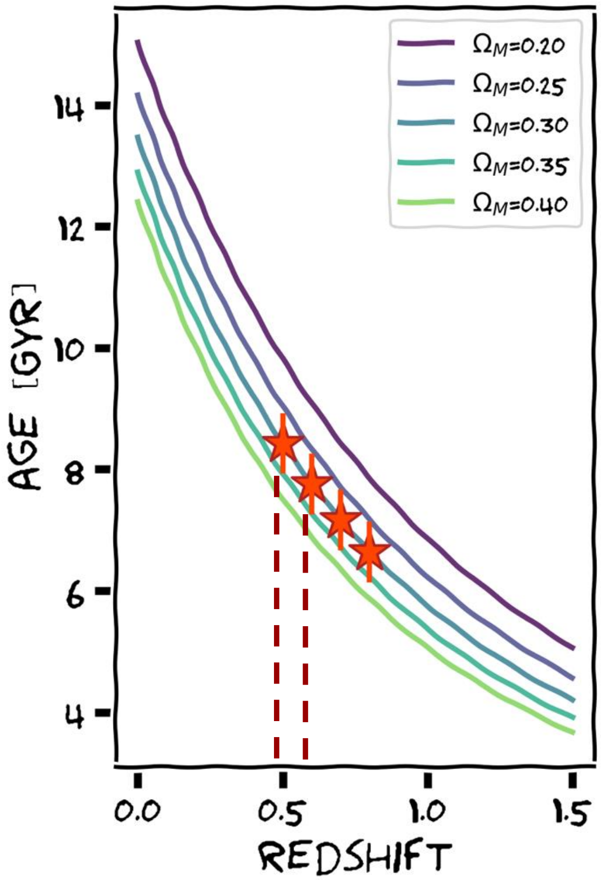

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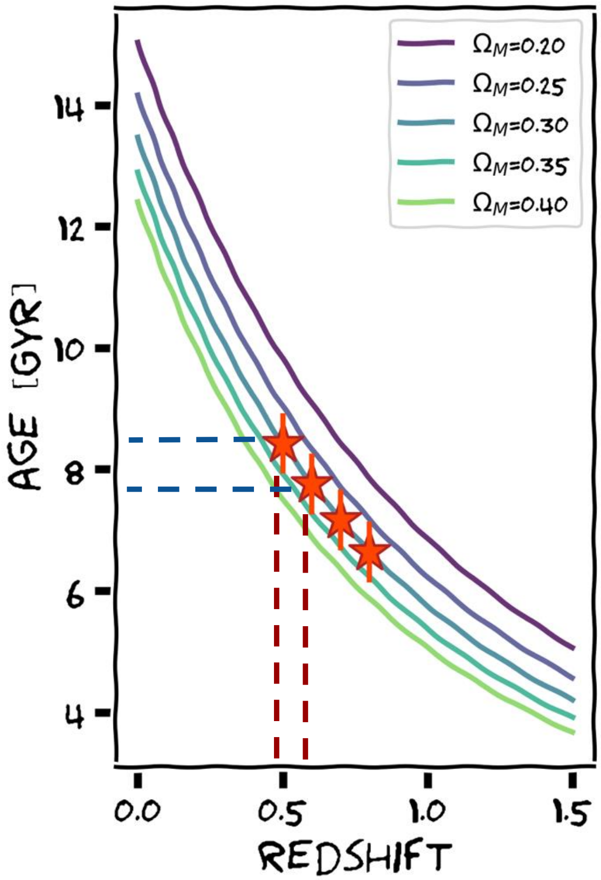

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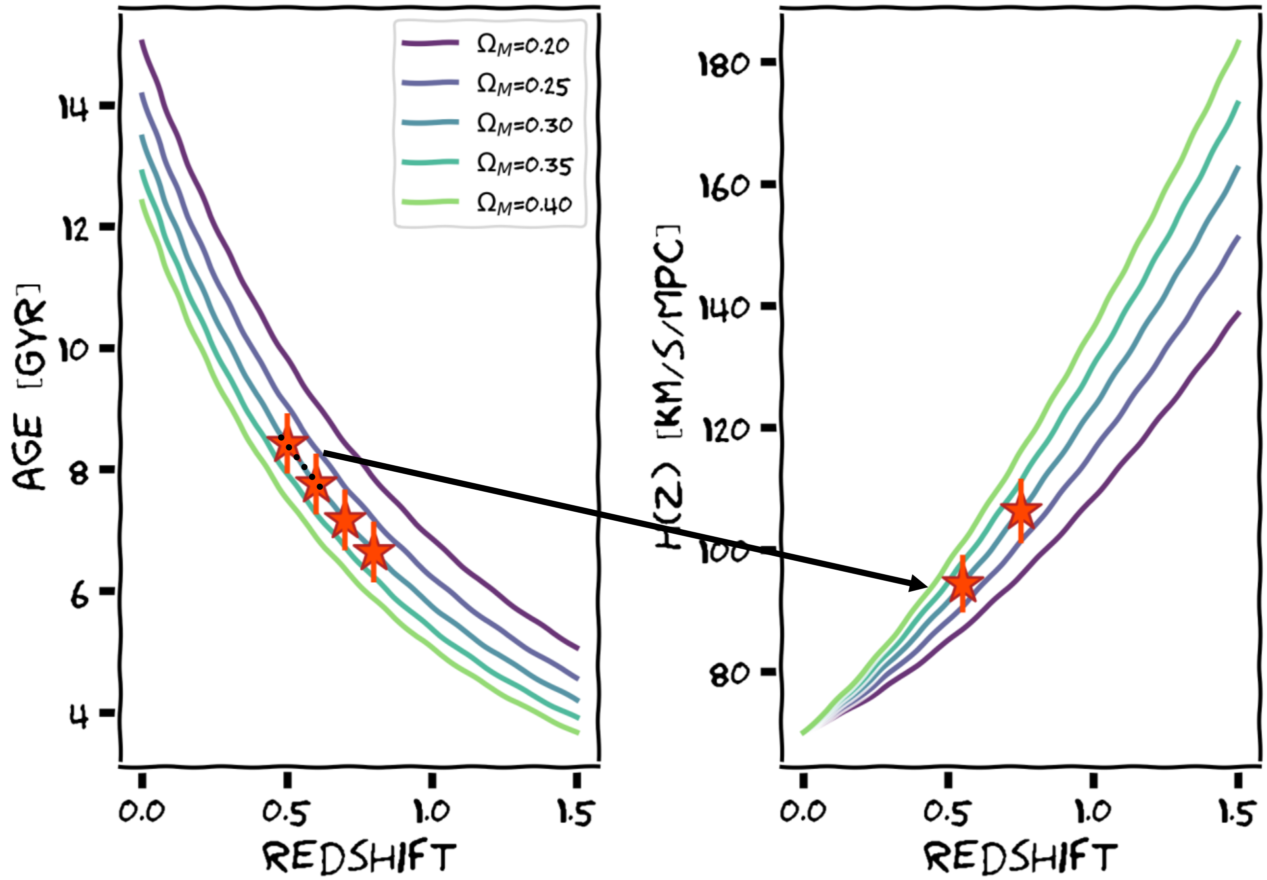

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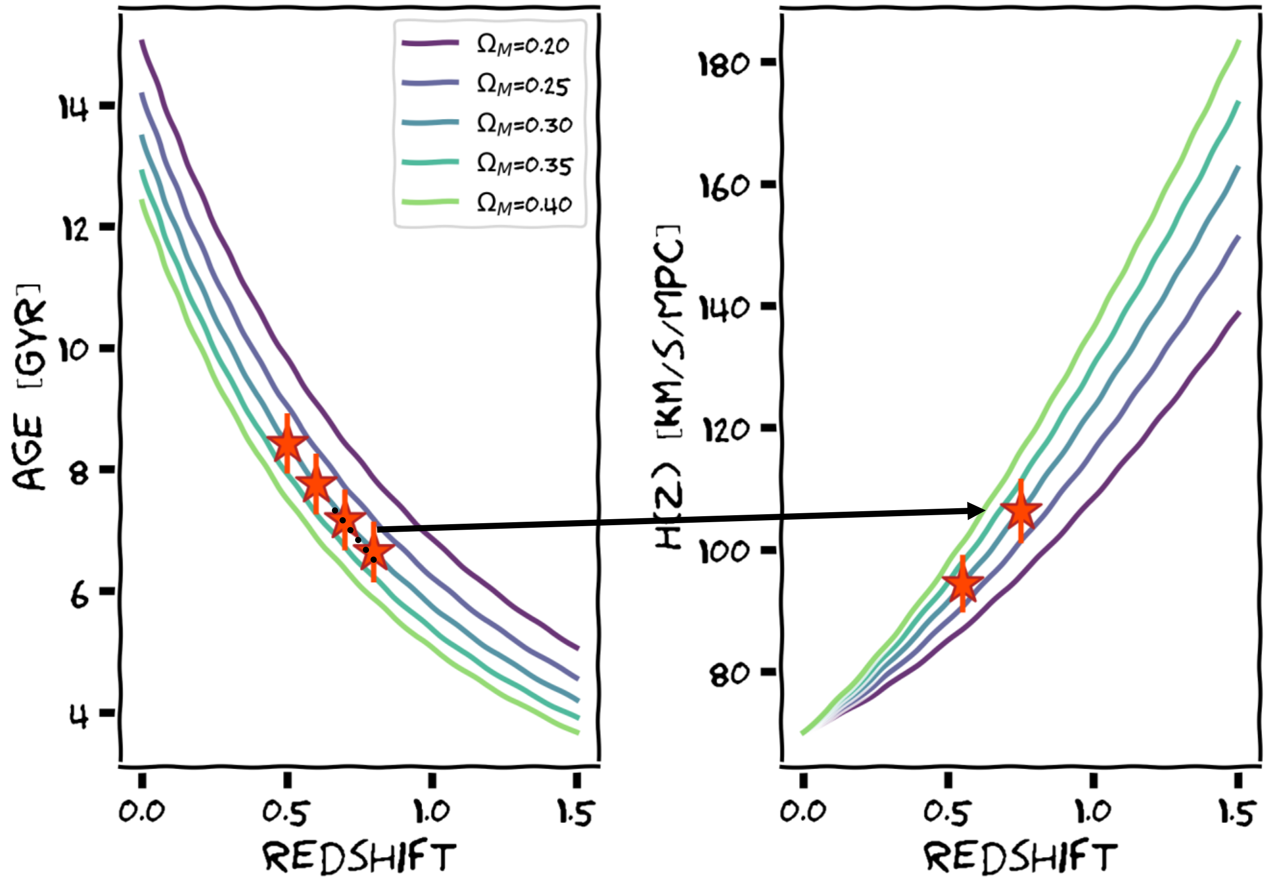

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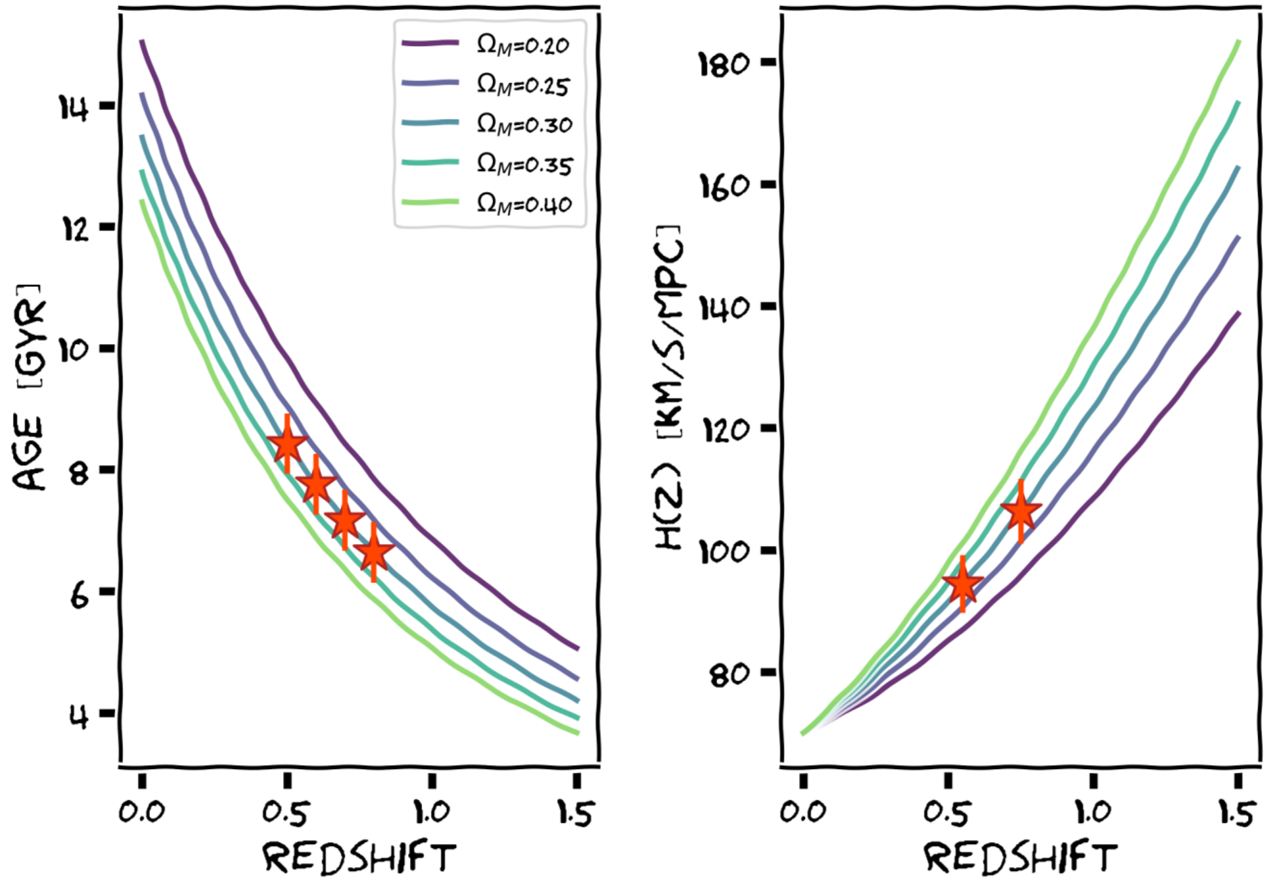
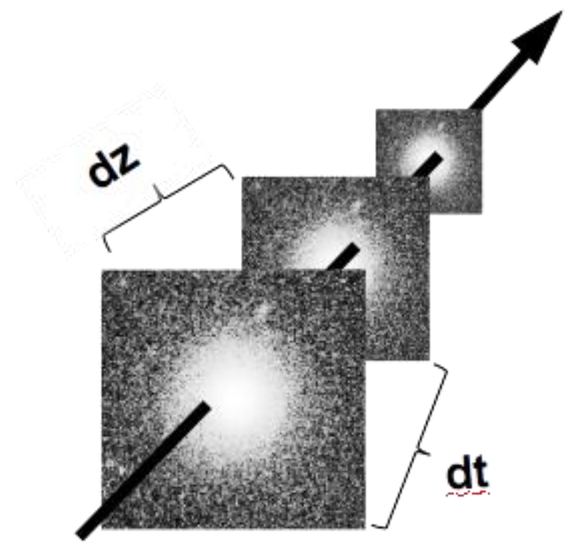




Eldest crust of galaxies at each redshift to map the **differential age evolution** of the Universe

Cosmic chronometers handbook

What about the tracers?

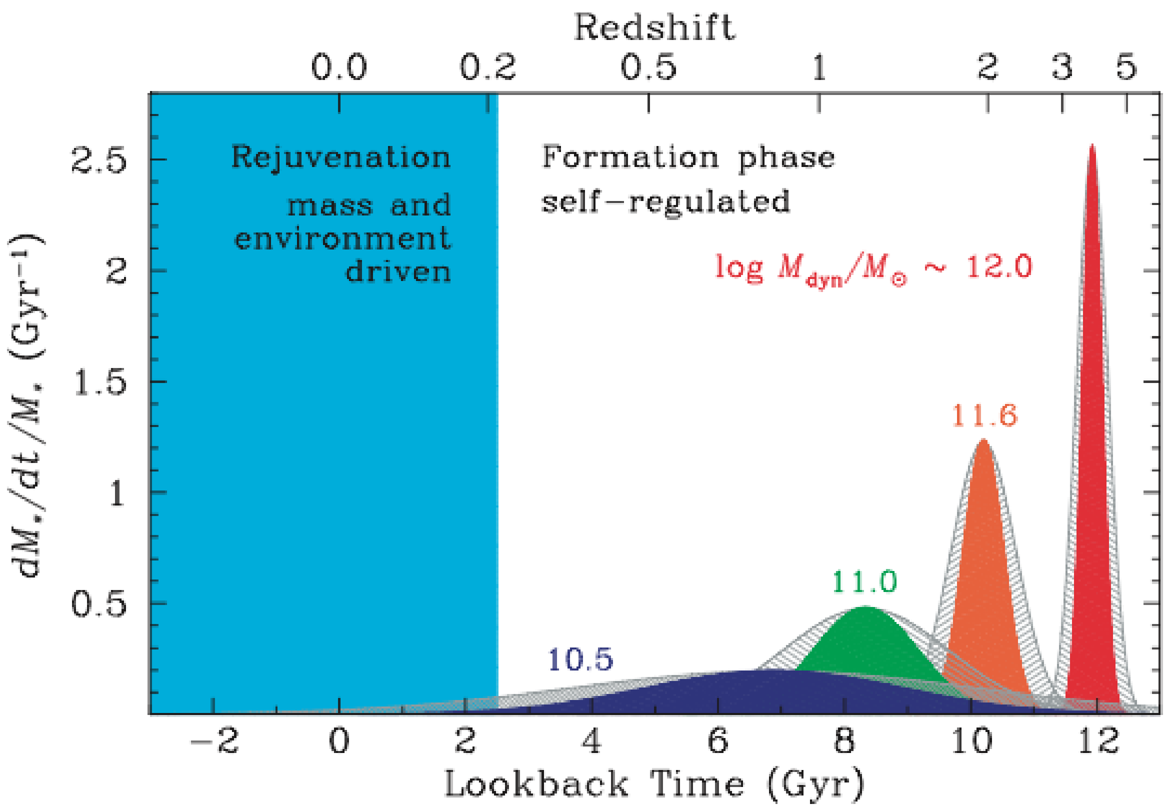
What about the age?

What about the systematics?

Pros and cons

What about the tracers? (Moresco et al. 2013, 2018, Borghi et al. 2022a, Tomasetti et al. 2023)

- best tracers: very massive and passively evolving galaxies



Thomas et al. (2010)

Cosmic chronometers handbook

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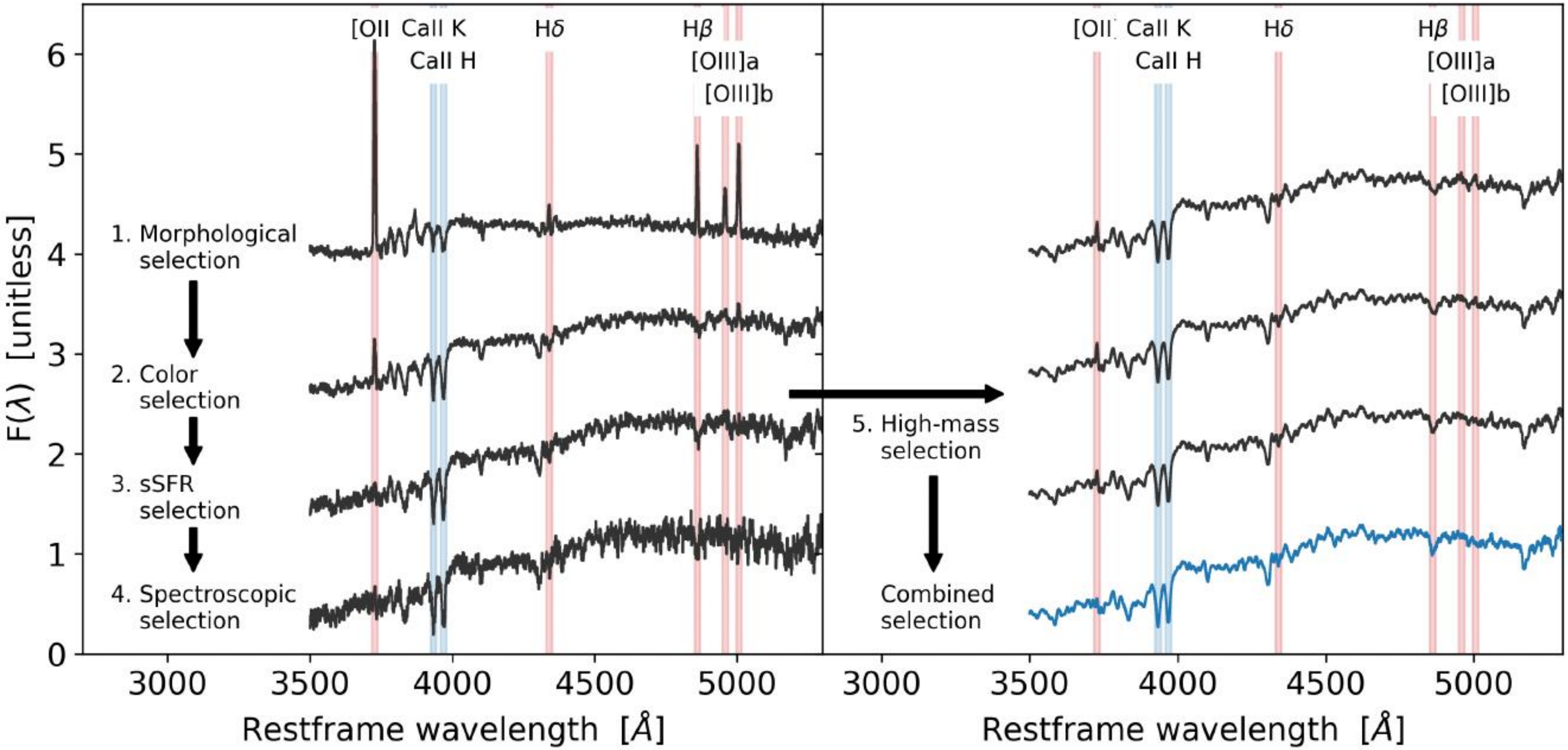
- multiple selection criteria and indicators to maximize the purity of the sample



Moresco et al. (2024)

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- measure *dt*, not *t*
- **no cosmological assumptions on the age** $\longrightarrow$ revised version of codes

Cosmic chronometers handbook

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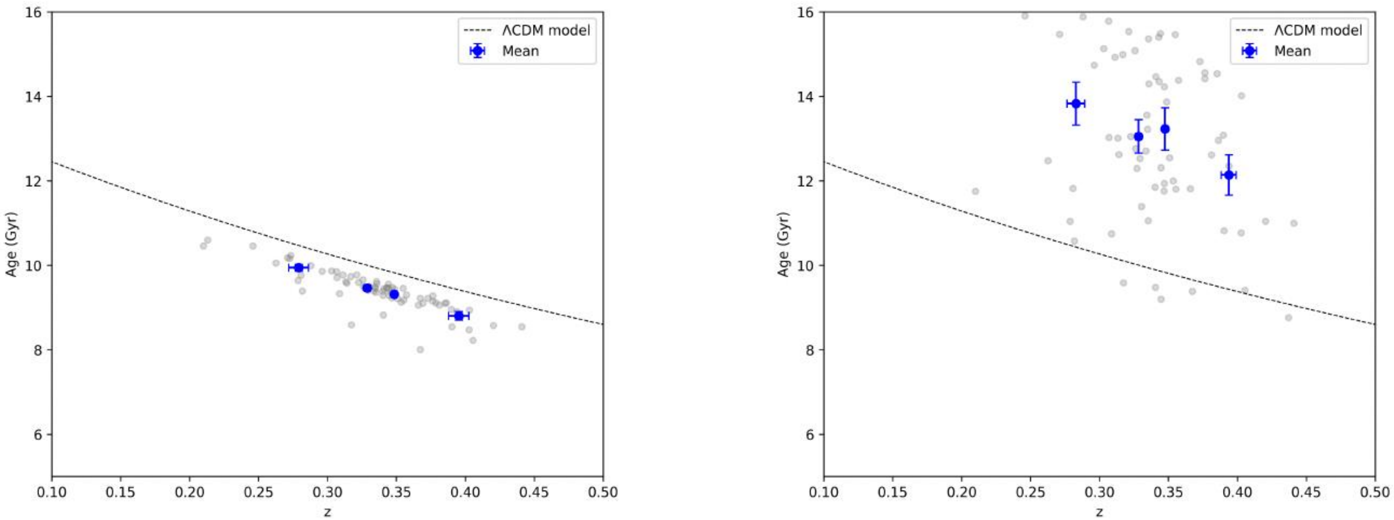
What about the age? (Moresco et al. 2011, 2012a, 2015, 2016a, Borghi et al. 2022a Kang et al. 2023, Tomasetti et al. 2023, Jimenez et al. 2023)

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

- measure *dt*, not *t*
- **no cosmological assumptions on the age** ⟶ revised version of codes



(a) Fixed cosmology (b) Free cosmology

Cosmic chronometers handbook

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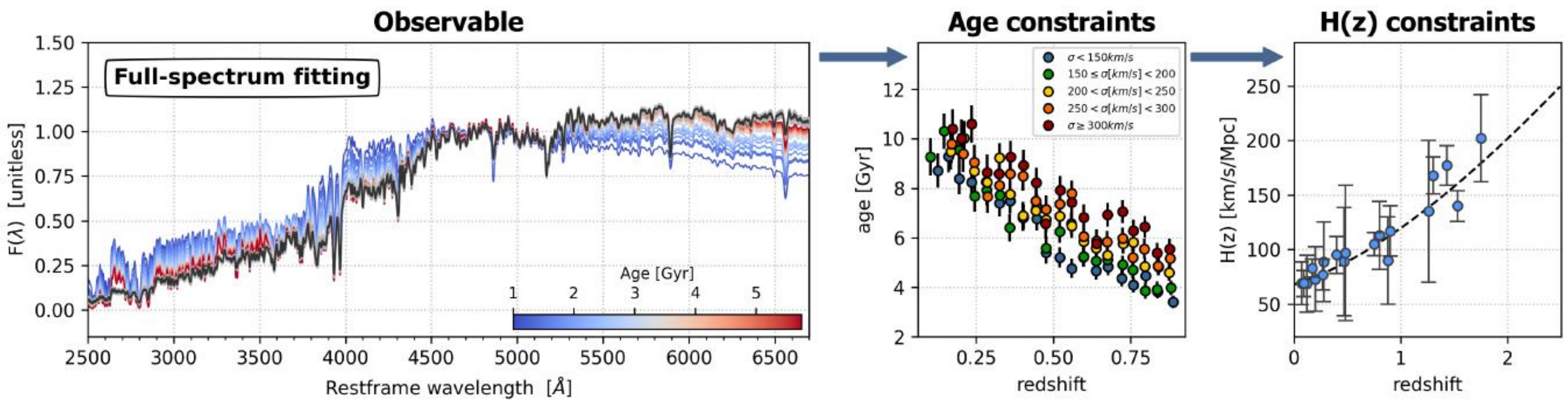
- measure *dt*, not *t*
- no cosmological assumptions on the age
- break degeneracies to measure *dt*: **different methods**

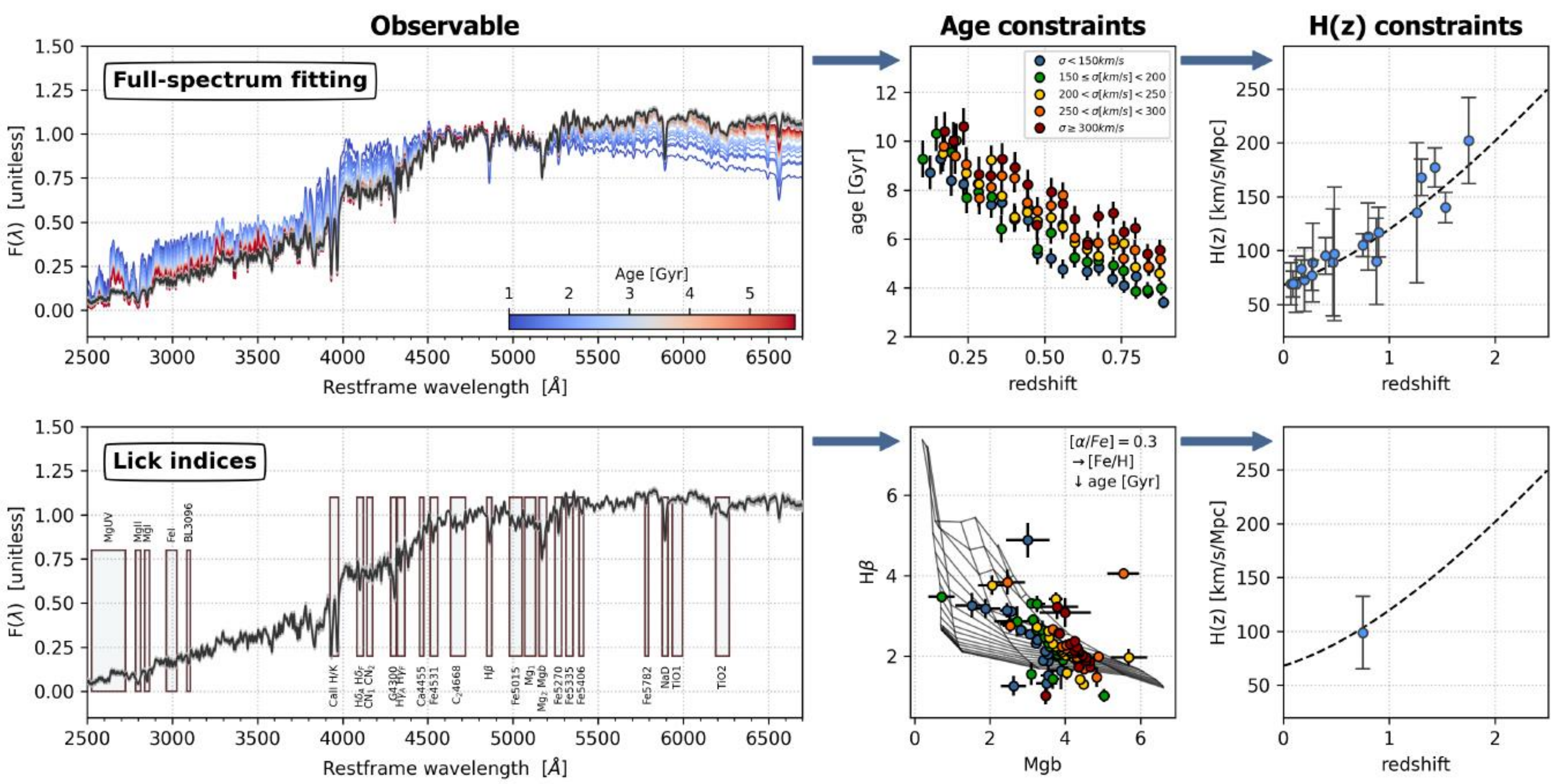
SED-fitting
full-spectral-fitting
absorption features (Lick indices)
ML

Different approaches



Moresco et al. (2024)

Different approaches



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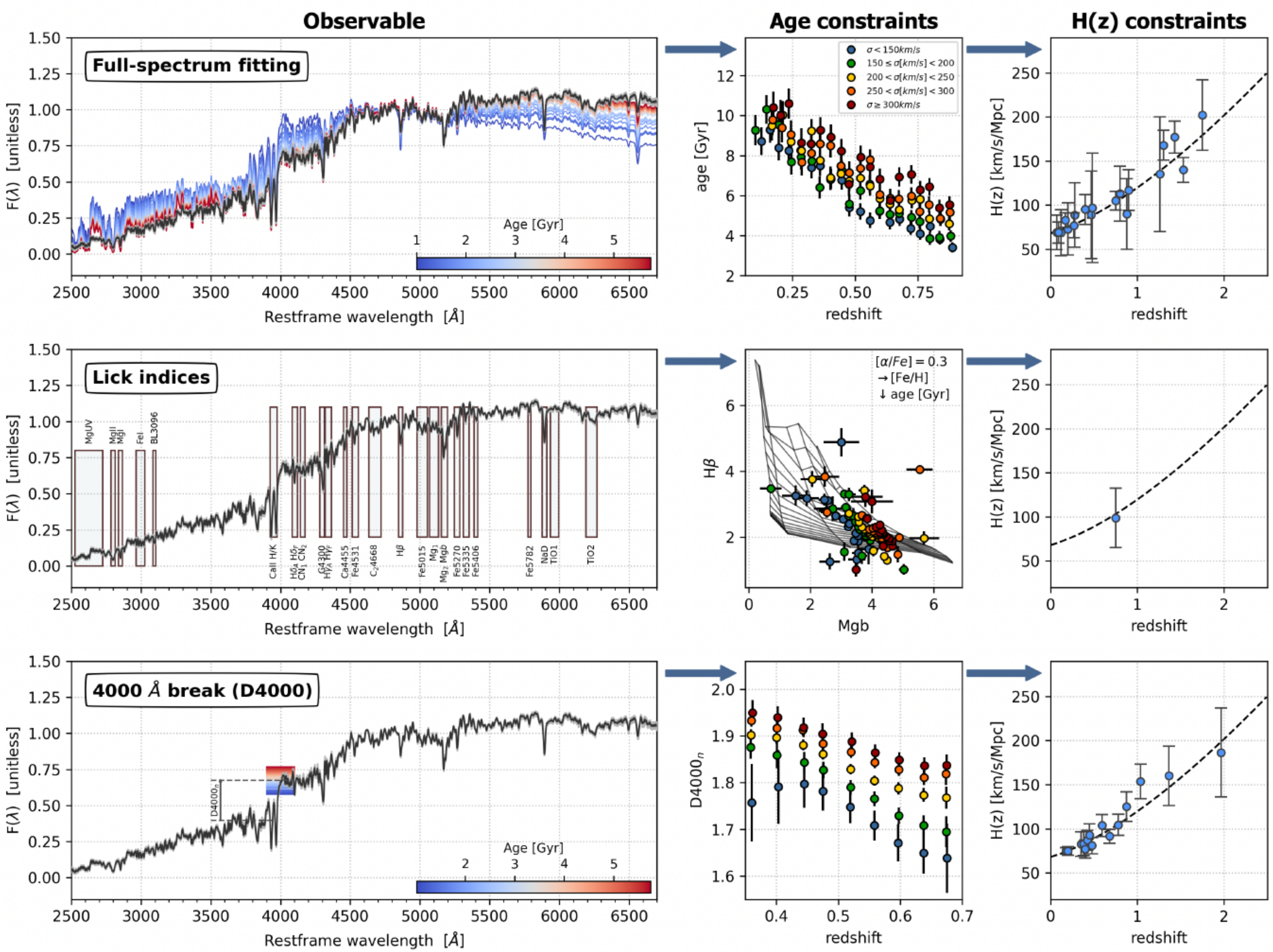

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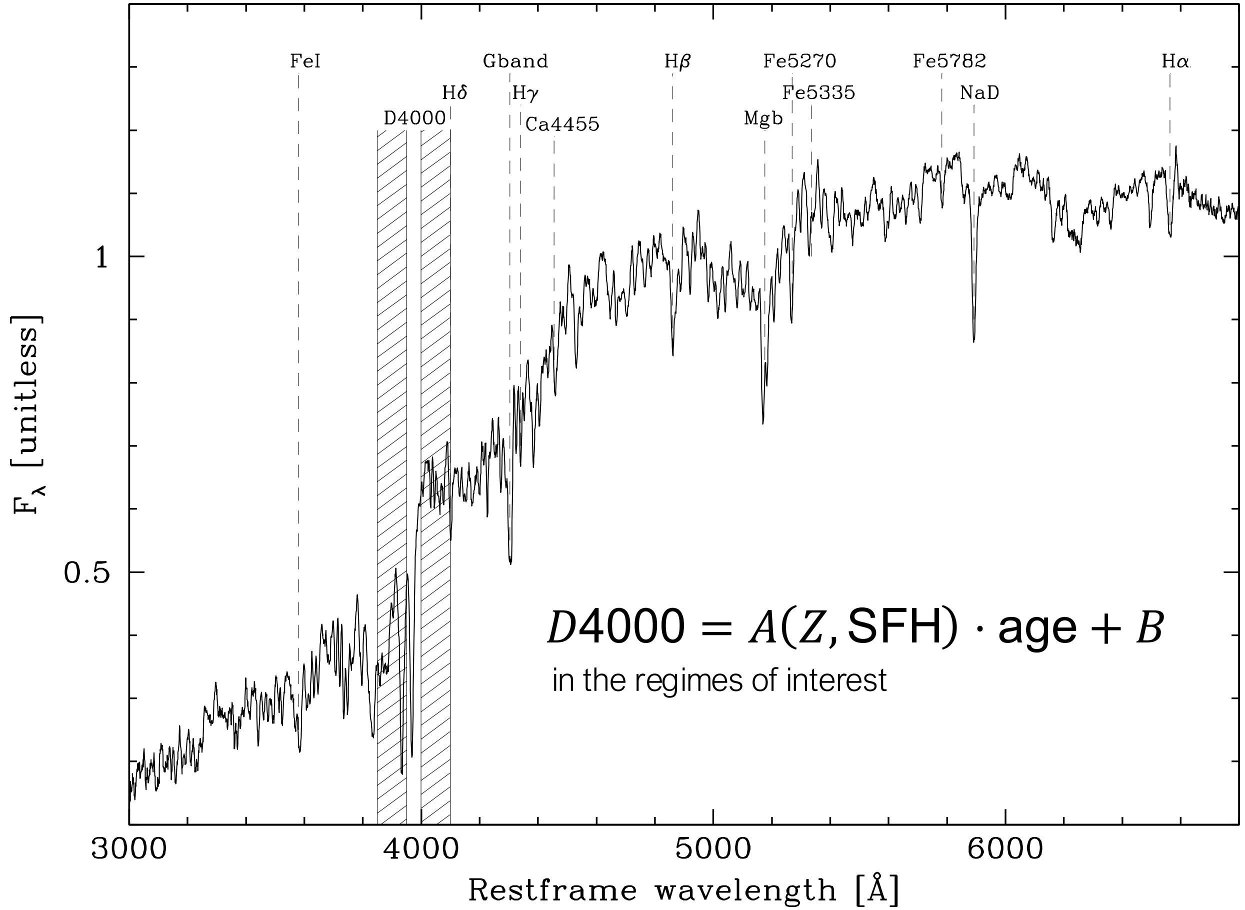
- the D4000 approach



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

in the regimes of interest

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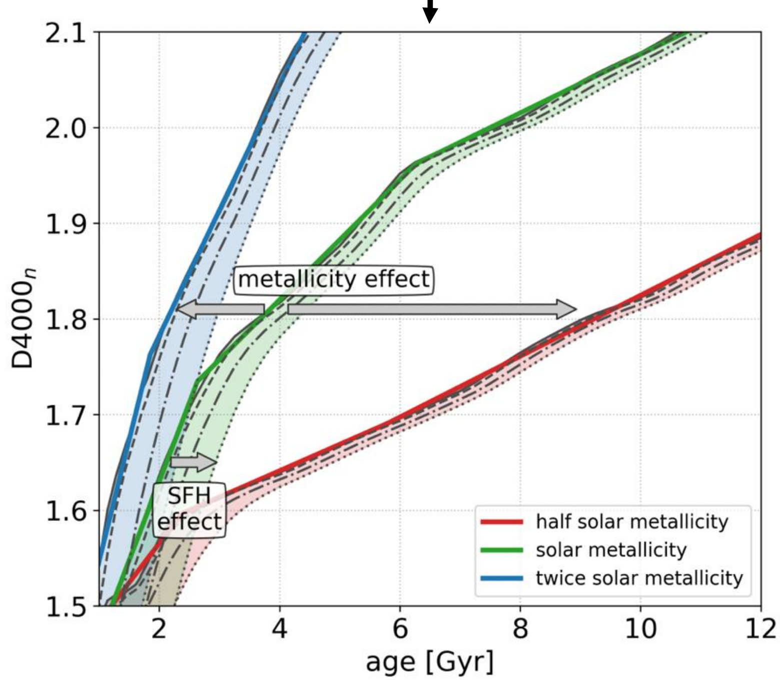
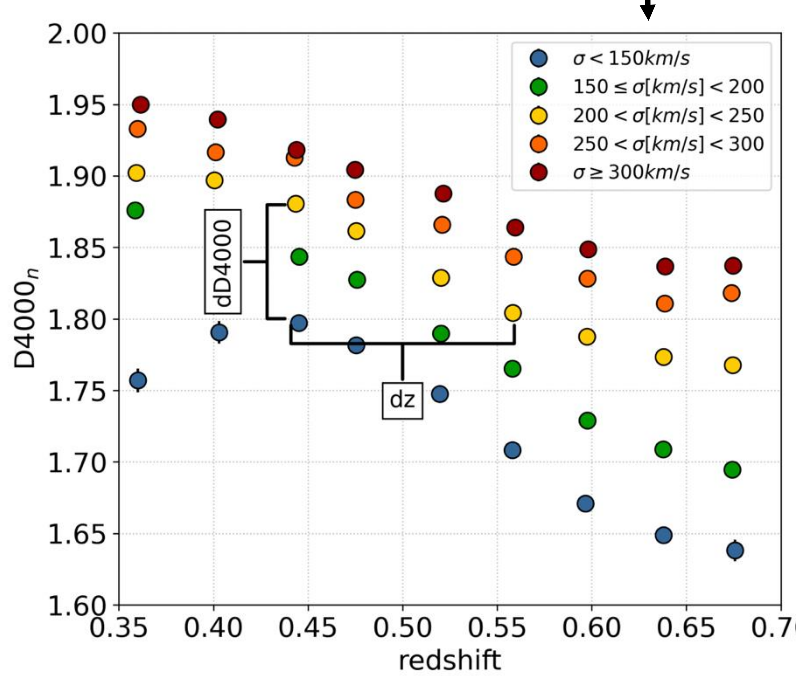
$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

calibrated on different SPS models

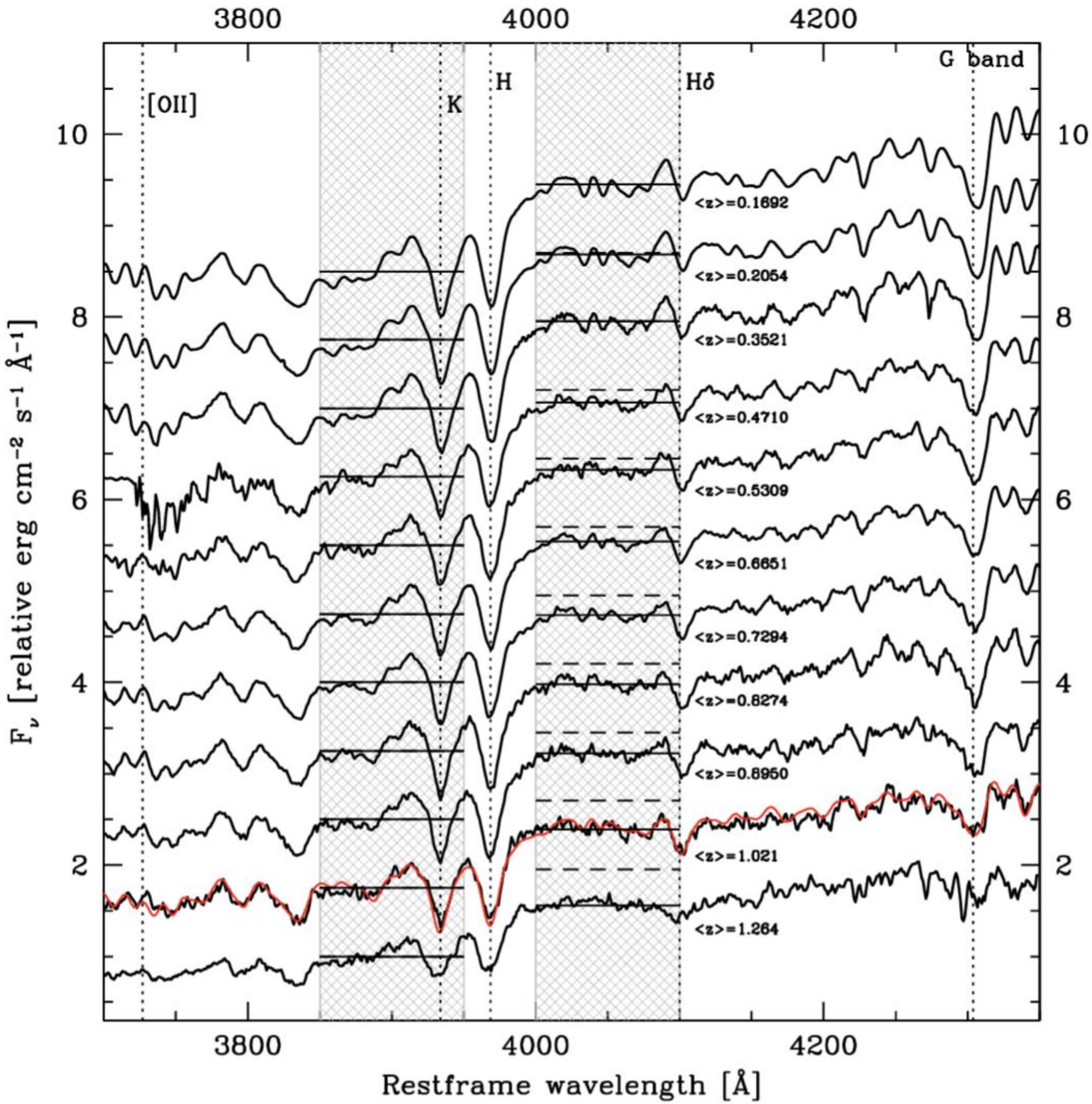
estimated from data





Moresco et al. (2022)

Direct detection of the evolution of the Universe



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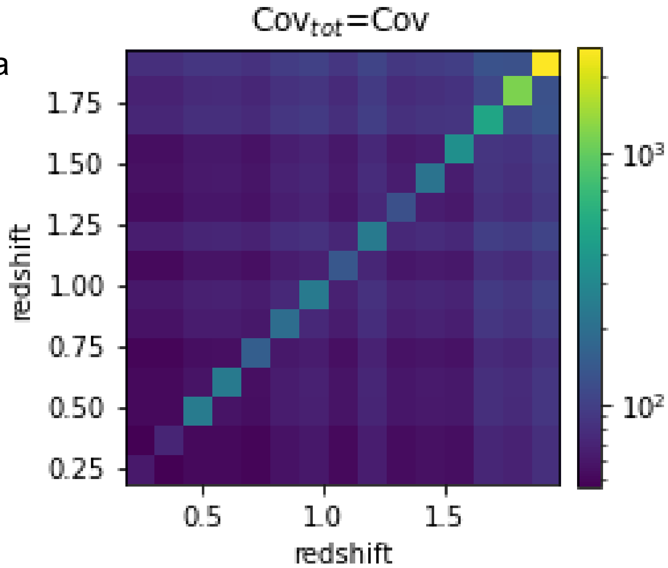

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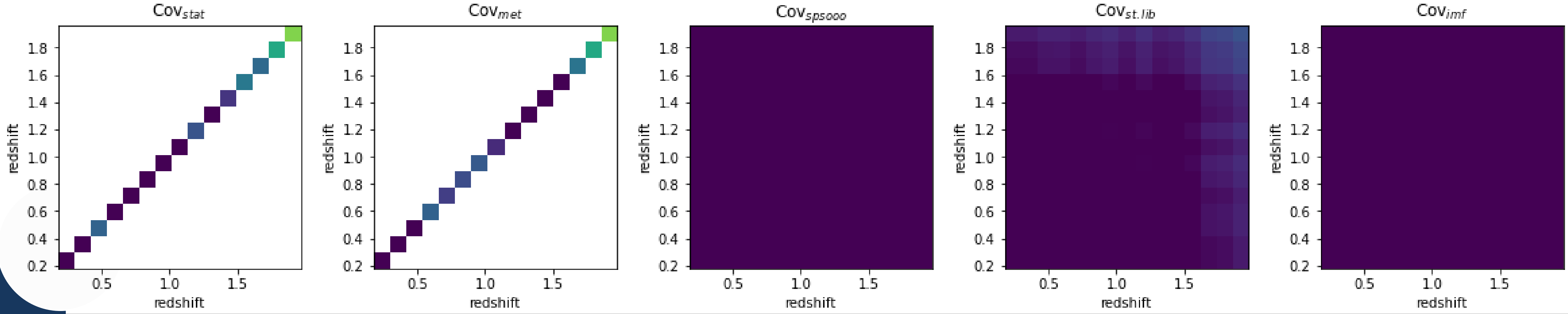
$$Cov_{tot} = Cov_{stat} + Cov_{met} + Cov_{SFH} + Cov_{young} + Cov_{model}$$



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Pros and cons

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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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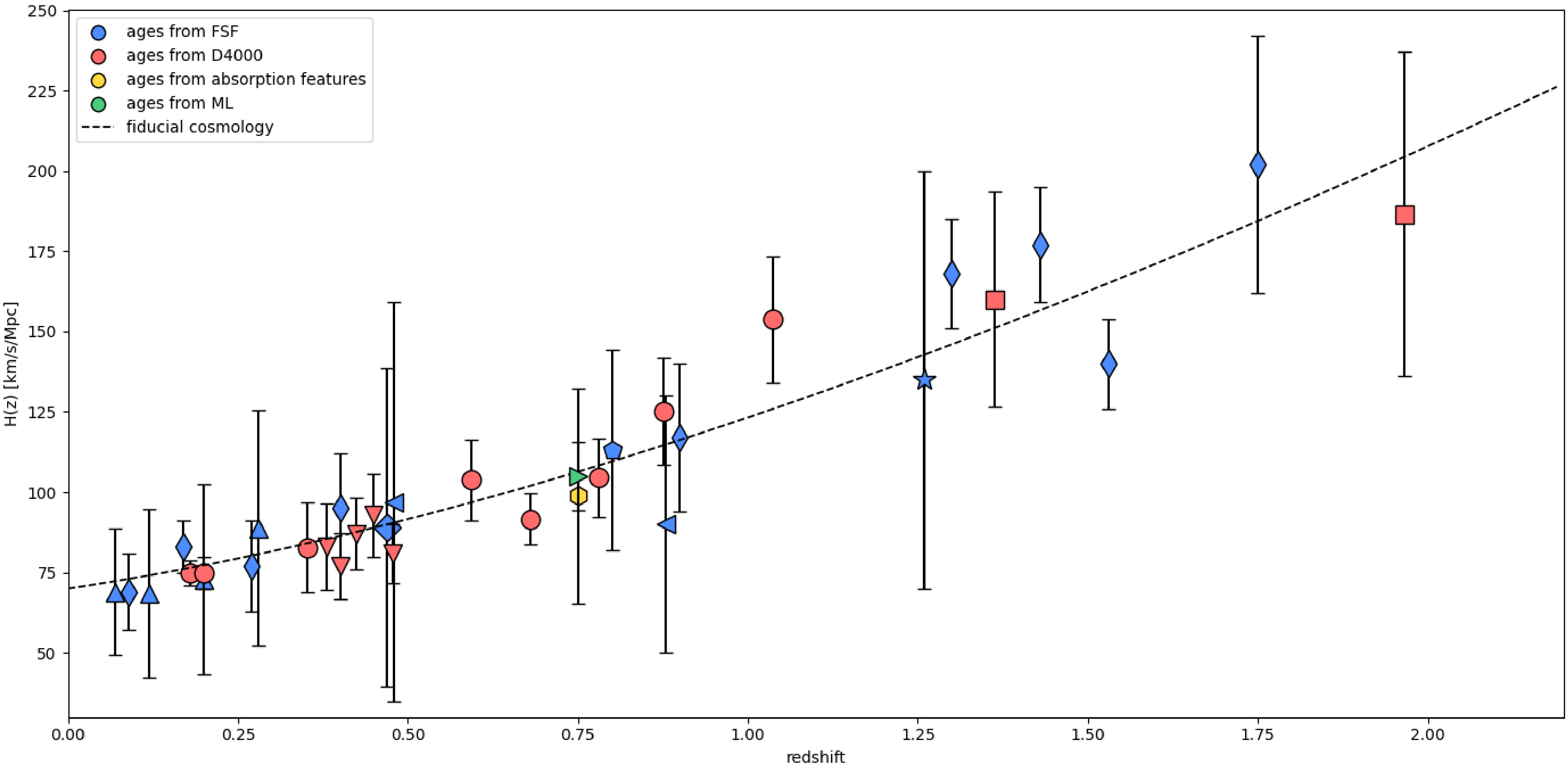
Pros and cons

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

State of the art

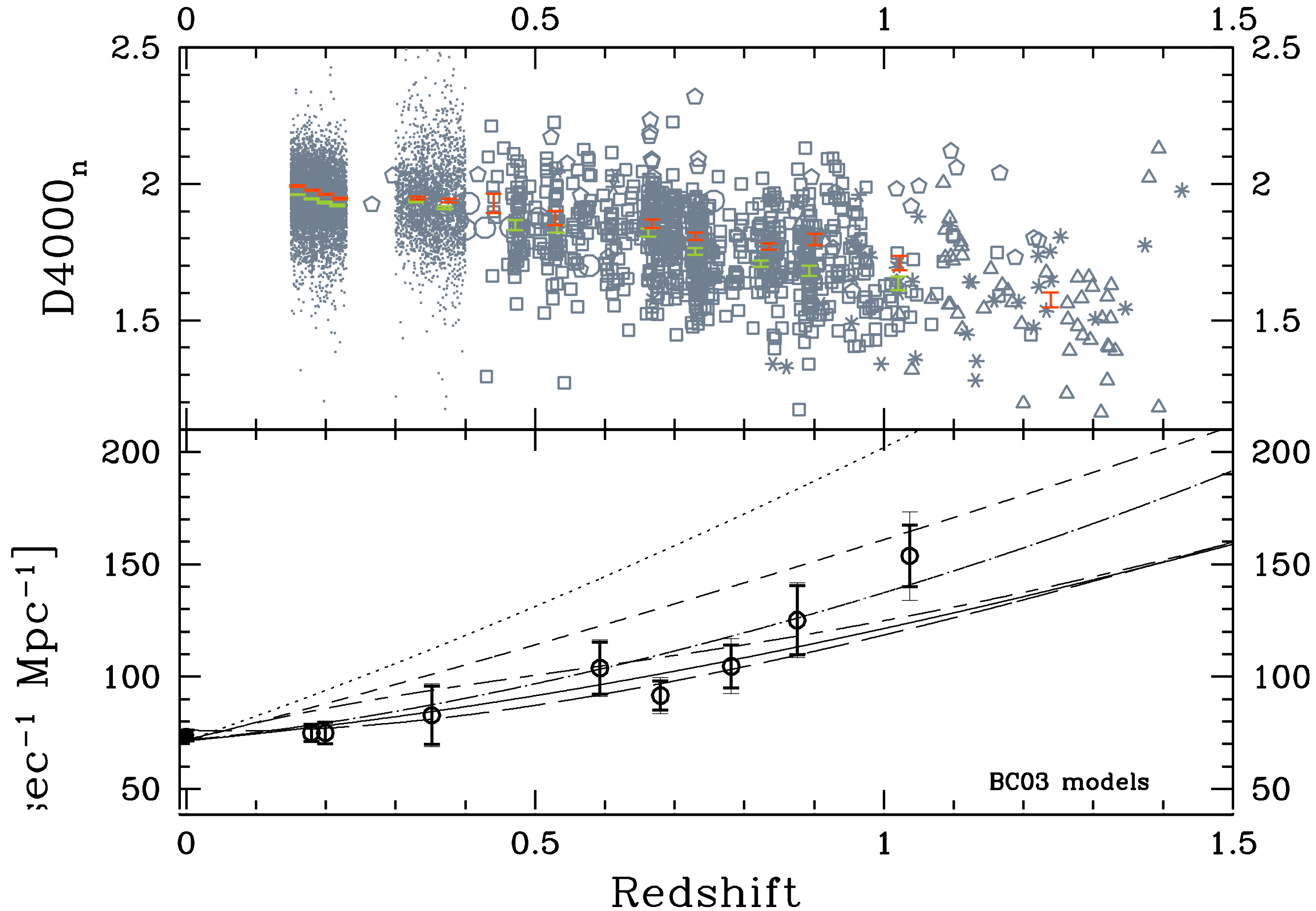


Cosmological inferences

Explore cosmological models

- cosmology-independent estimate of the expansion rate of the Universe
- ideal testbed for model comparison

Moresco et al. (2012a)



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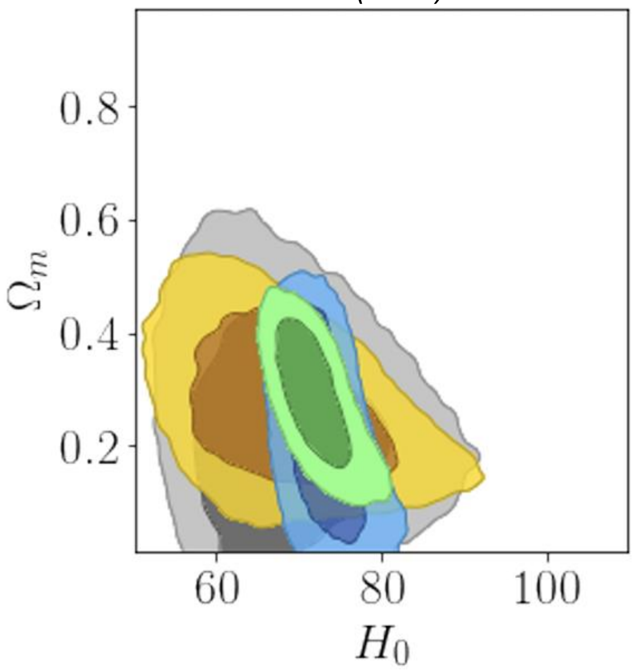
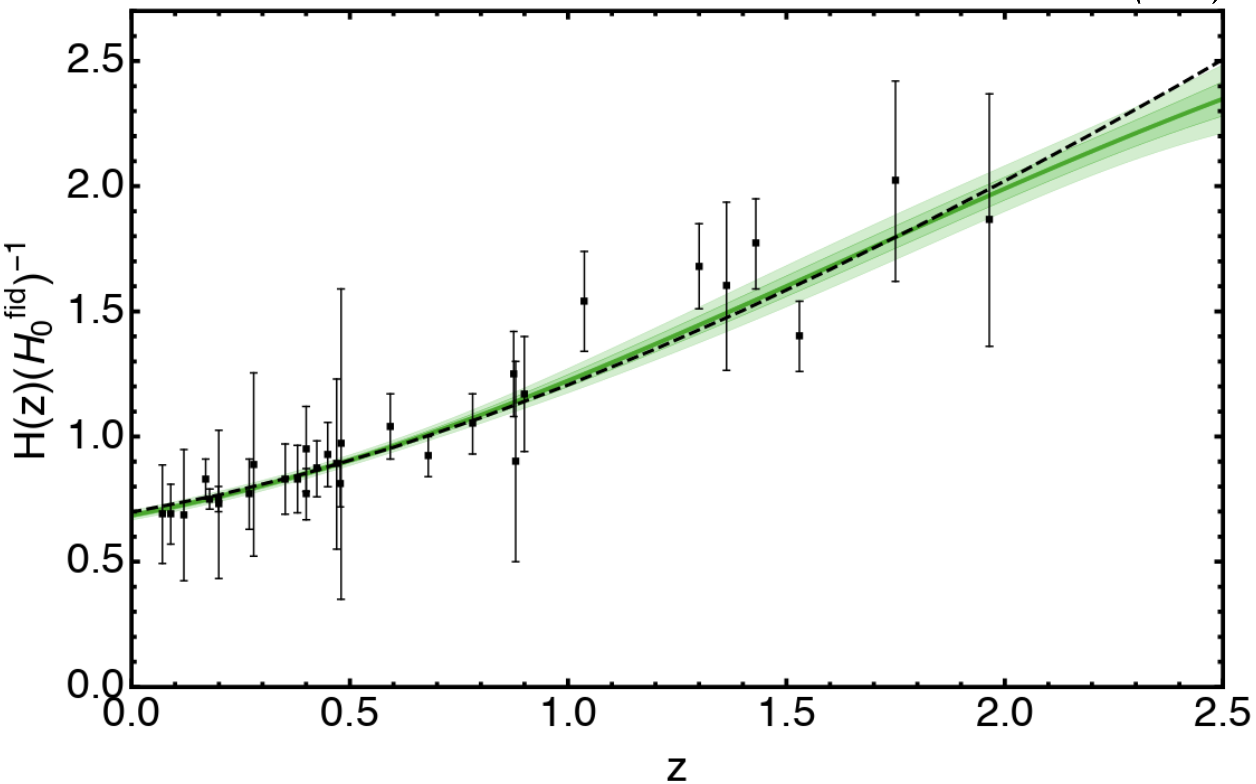
Shed light into the Hubble tension

- direct fit to data
- extrapolation to z=0

Moresco et al. (2022)



Haridasu et al. (2018)



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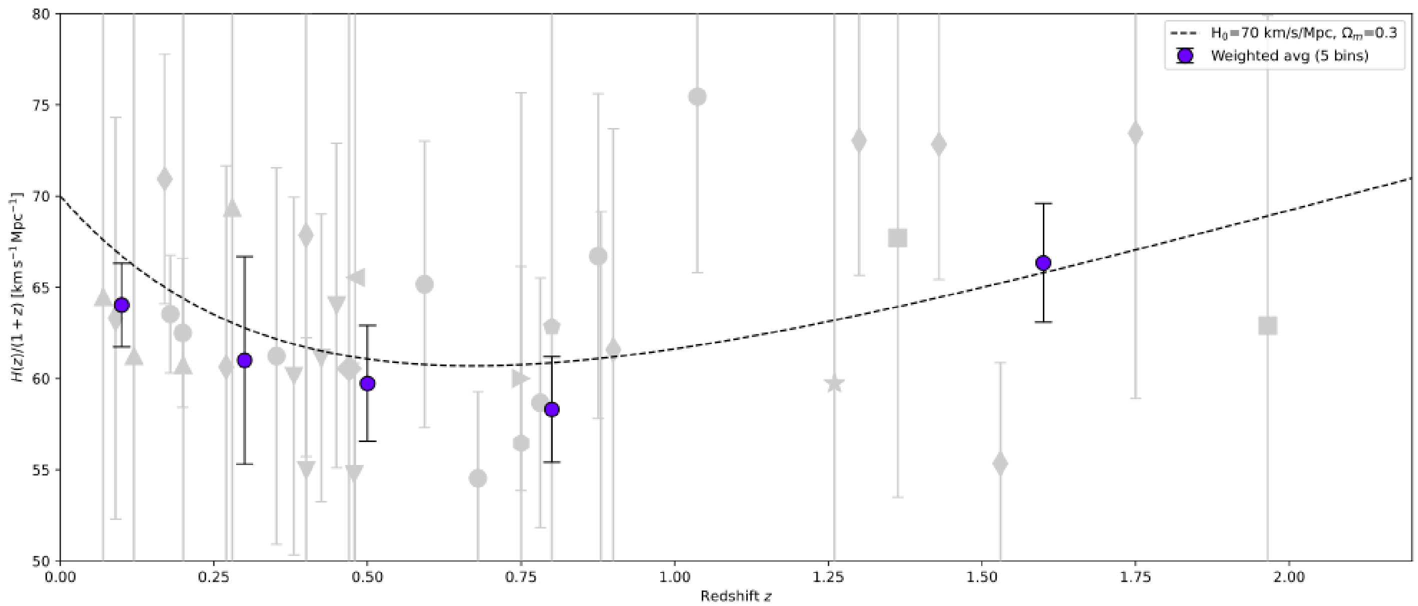
Direct observation of cosmic reacceleration

- constraint on the transition redshift



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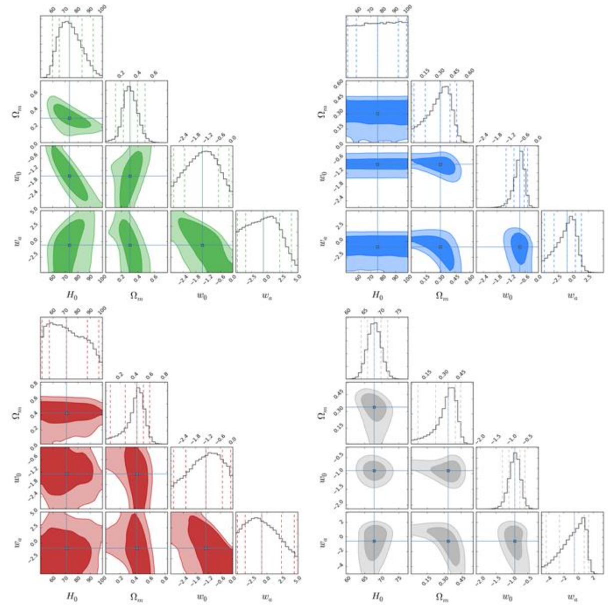
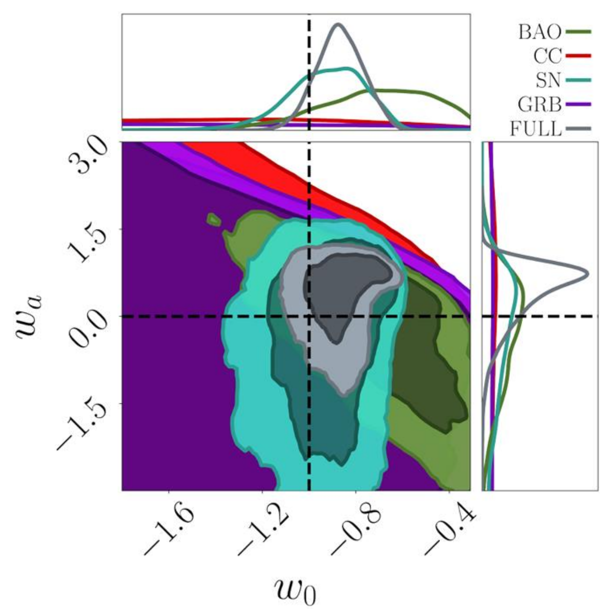
Probe combination

- 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



Moresco et al. (2016)



Cogato et al. (2024)

Cosmological inferences

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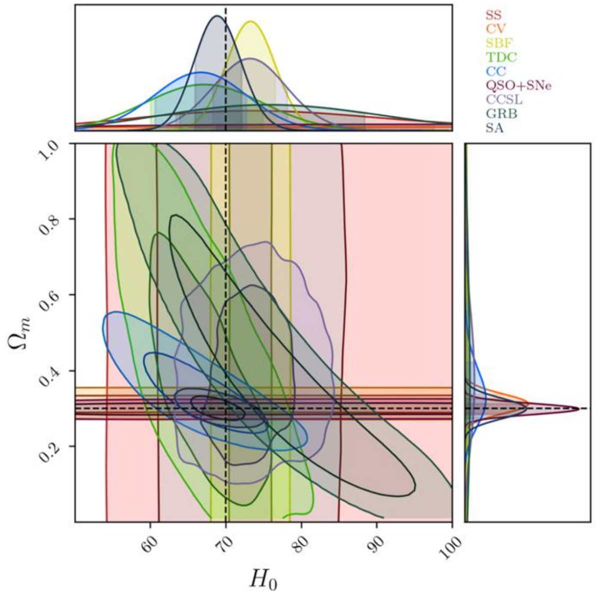
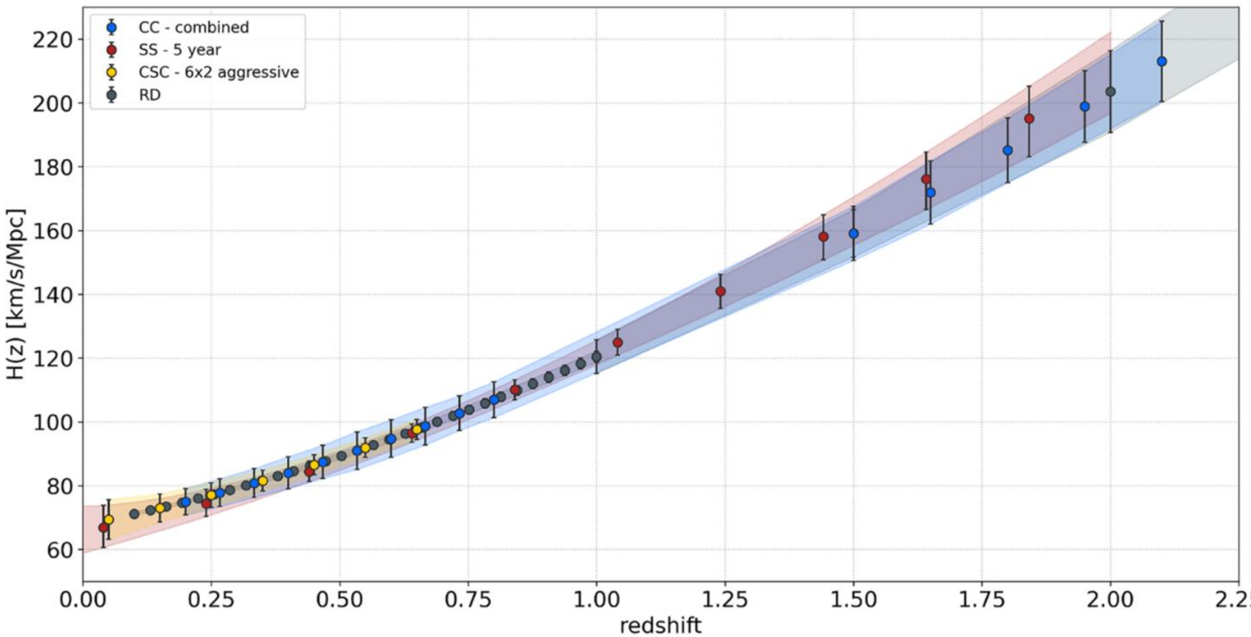
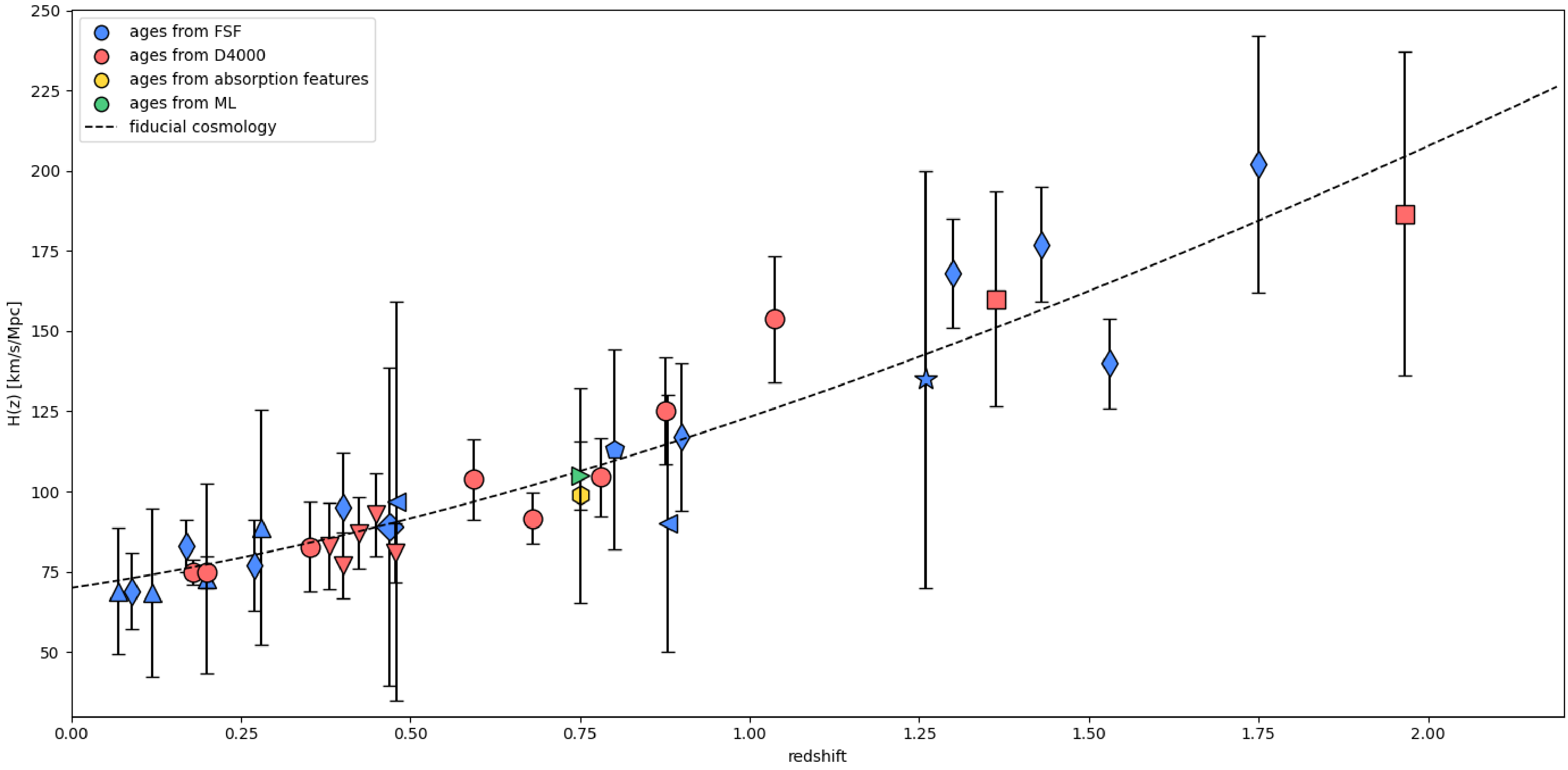




Moresco et al. (2022)

State of the art



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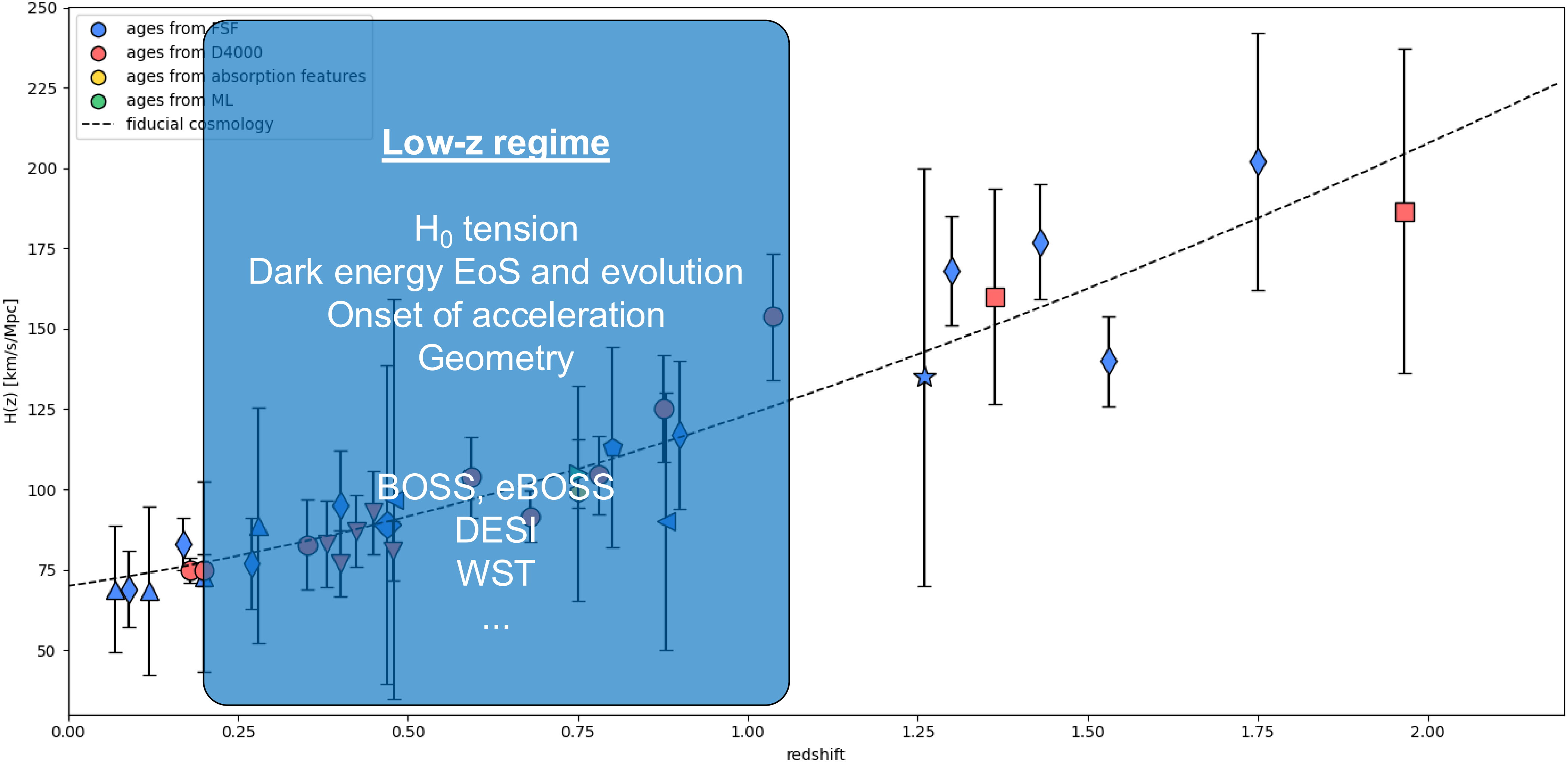

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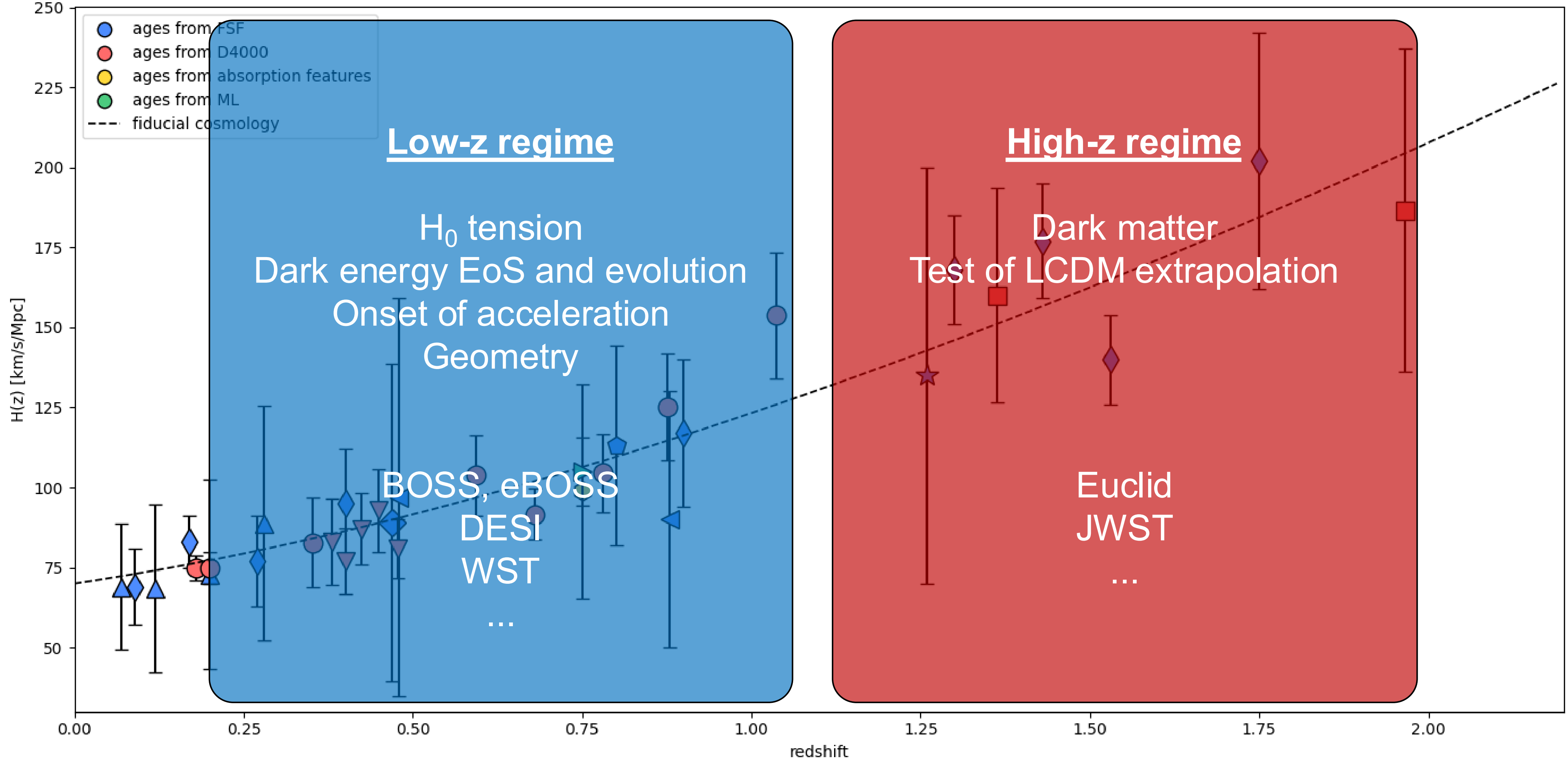
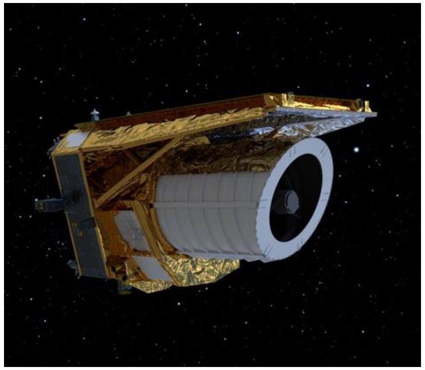


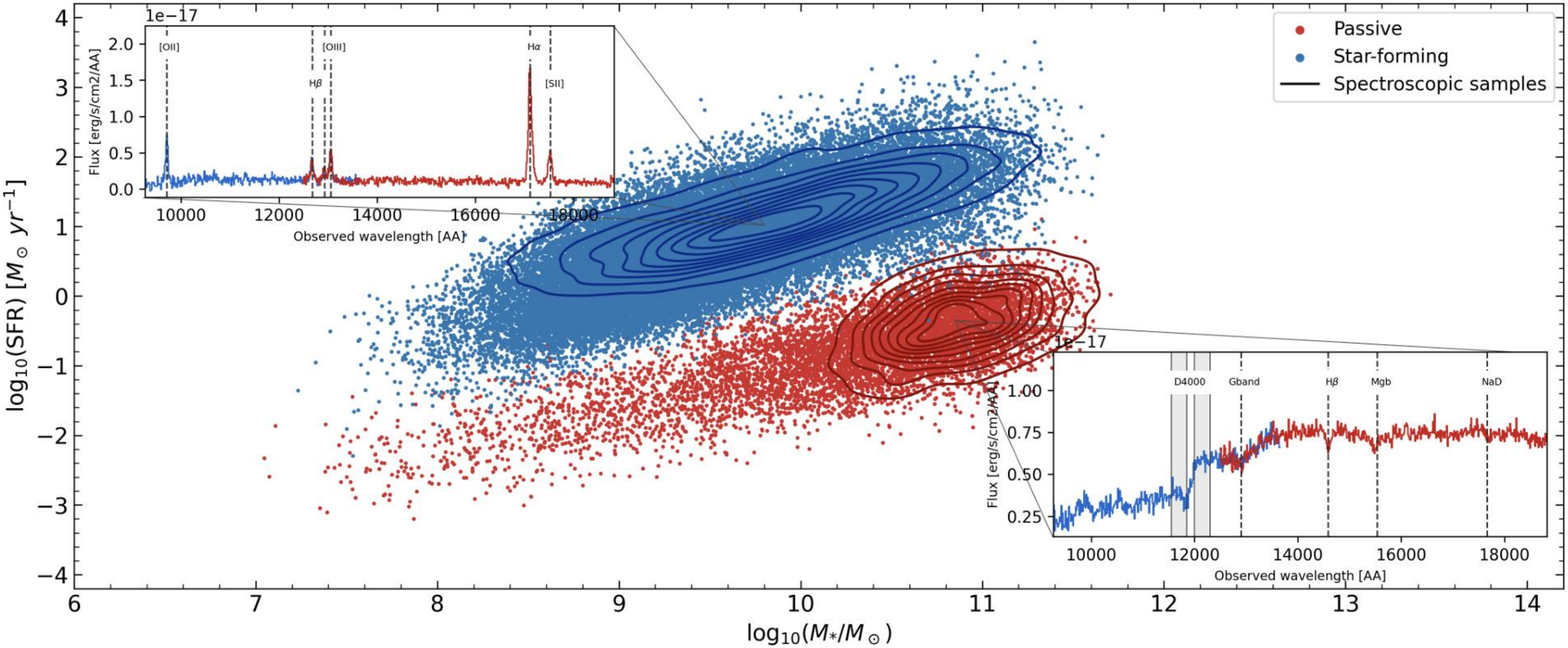
Present and future

ESA Euclid mission

Expected few thousands very massive and passive galaxies at 1.5 < z < 2.1 in the Euclid Deep Fields, with blue and red grism coverage



Euclid Collaboration: Mellier et al. (2025)



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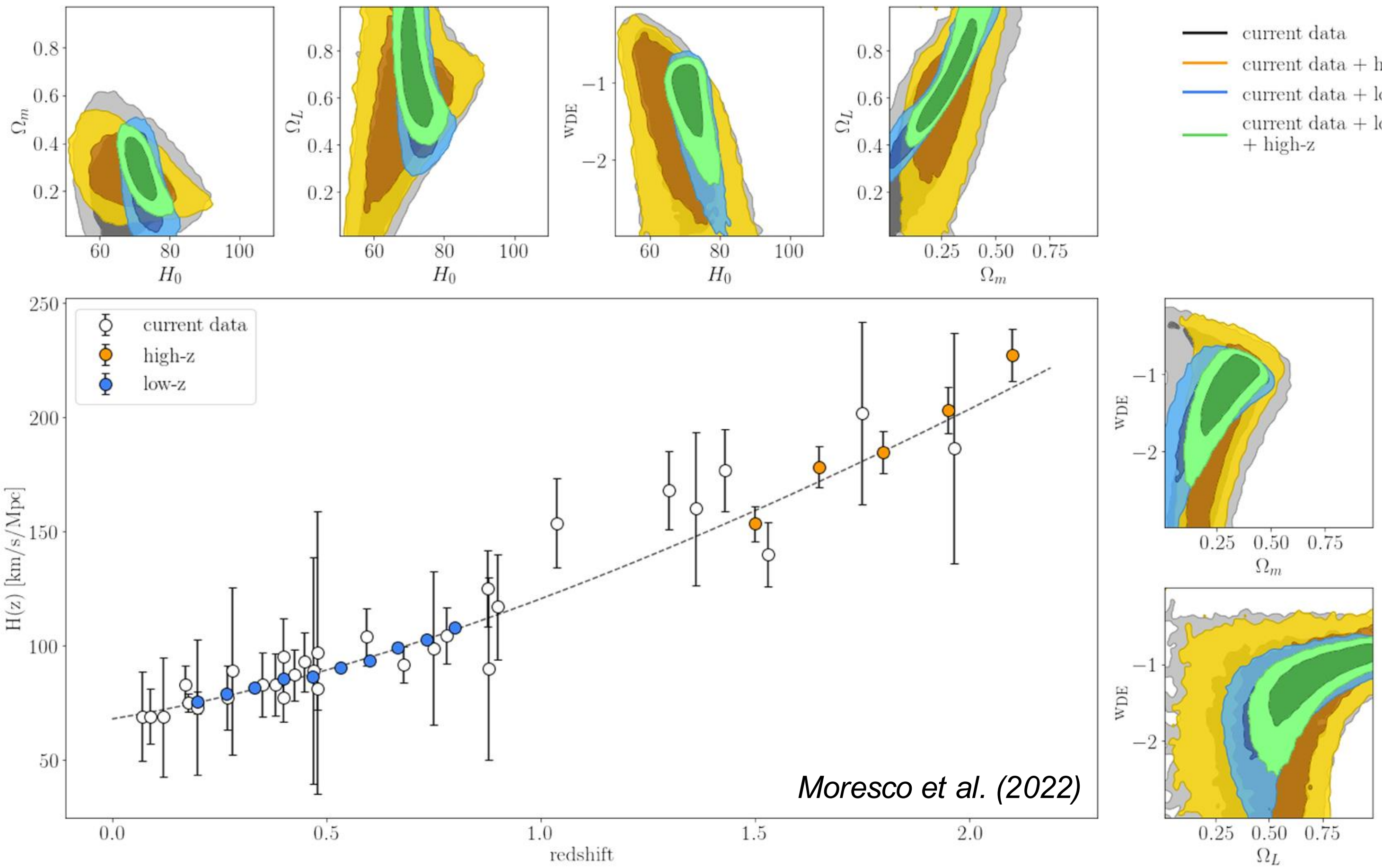
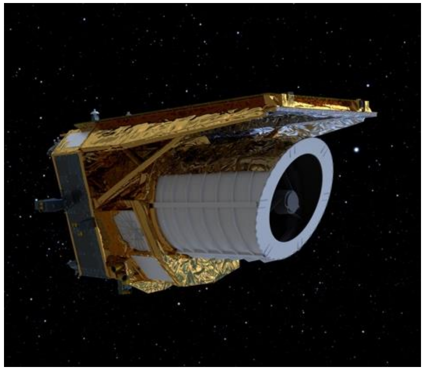
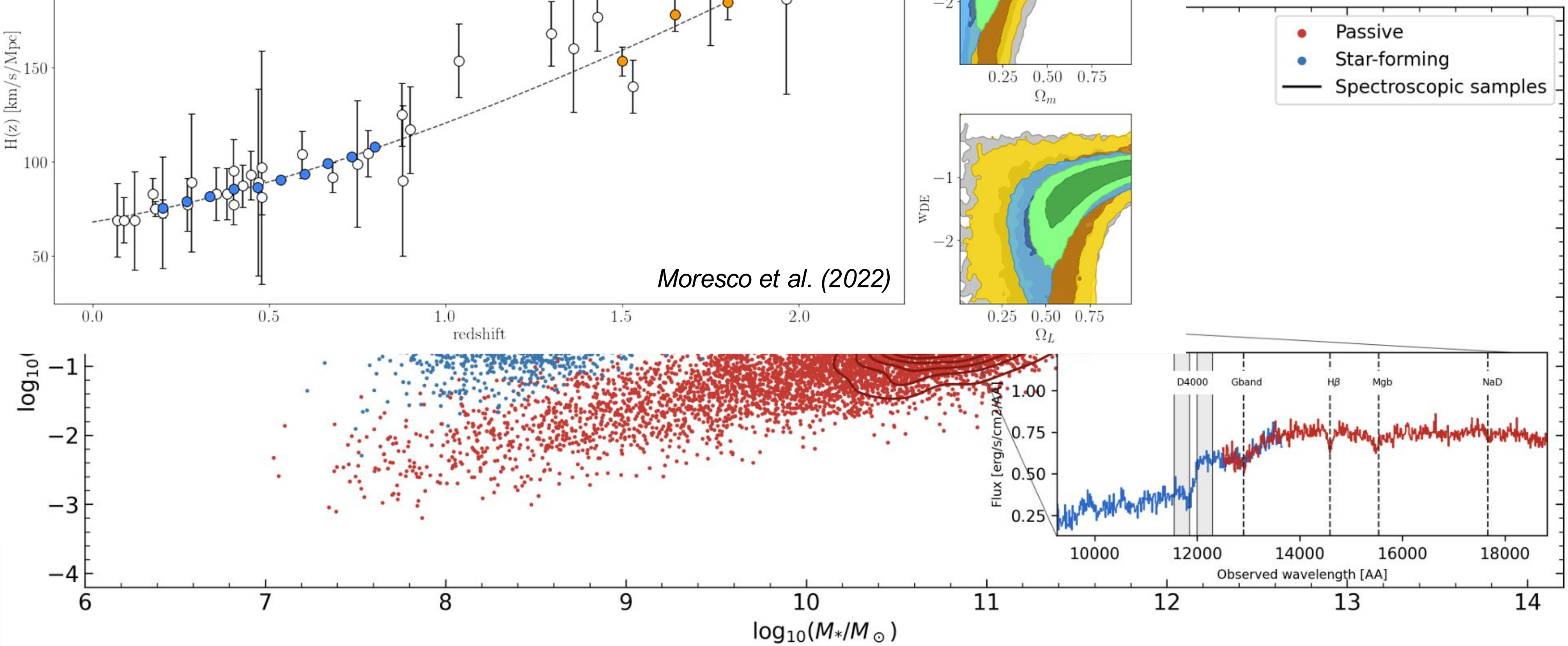




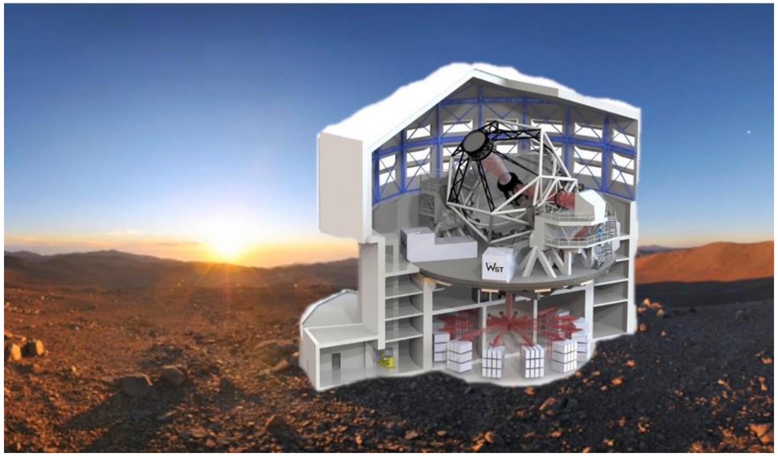


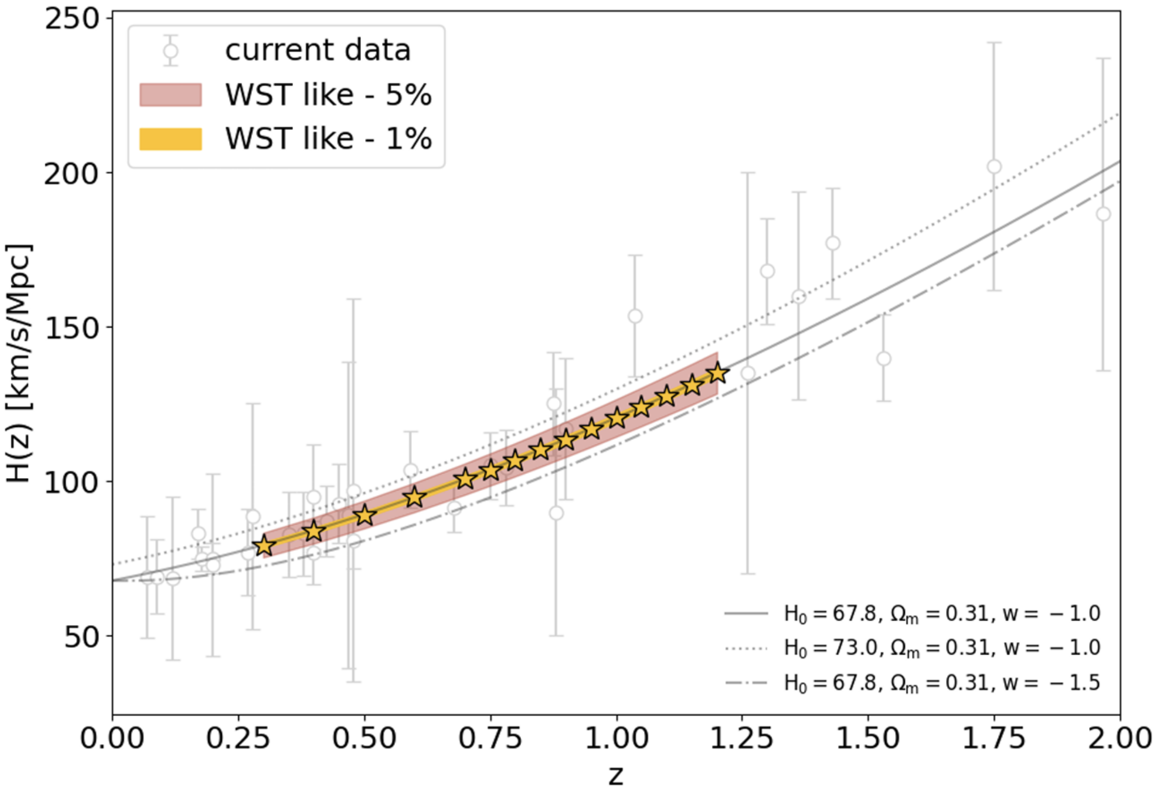
Present and future

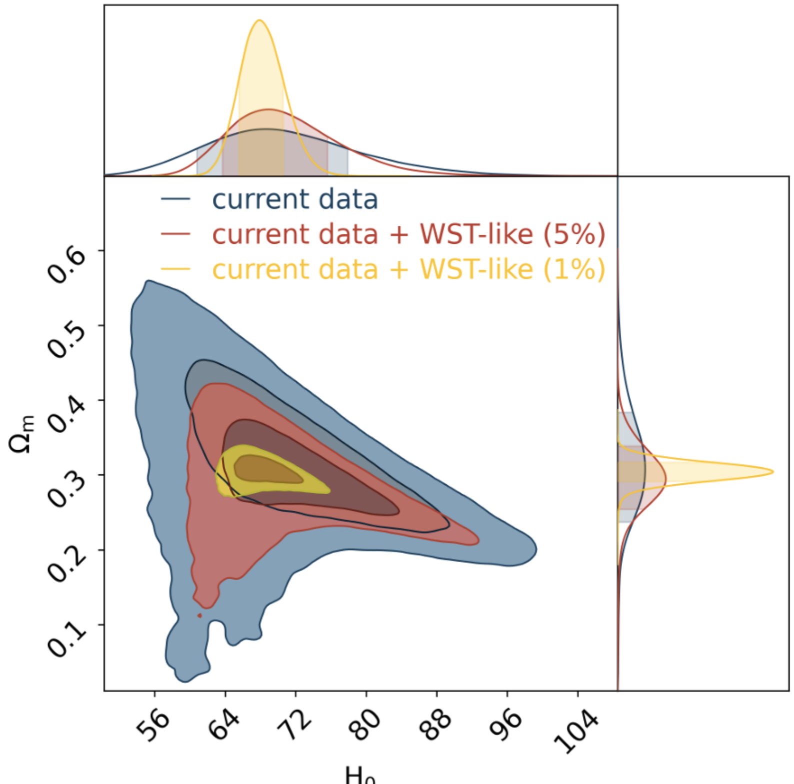
Wide-field Spectroscopic Telescope

Project of a 12 meter wide-field spectroscopic survey telescope; simultaneous operation of
- a 3 deg^2, 30000-multiplex MOS in low and high-res
- a 3×3 arcmin^2 IFS

Expected ~2 million CCs at 0.3 < z < 1.2







Tomasetti et al. (2026)

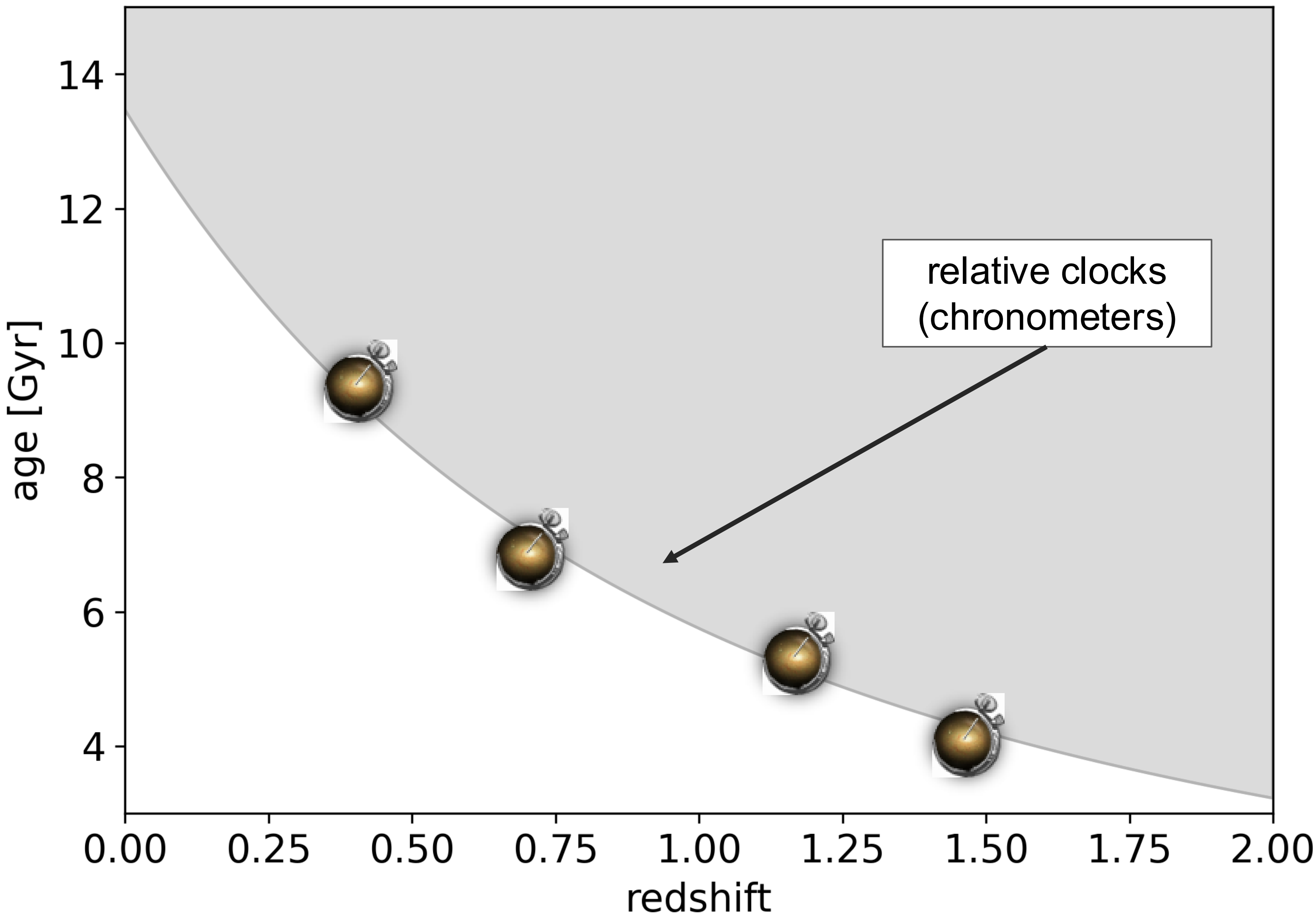
Ages of the oldest stellar objects

based on

Cimatti and Moresco (2023), ApJ, 953, 149
Tomasetti et al. (2025), A&A, 696, 98
Tomasetti et al., (2025), A&A, 699, 240
Tomasetti et al. (2026), A&A, 707, 111
Tomasetti et al. (2026), arXiv:2607.19472

New paper today! on lensed GC as cosmological probes **arXiv:2607.19472**

Expansion history of the Universe



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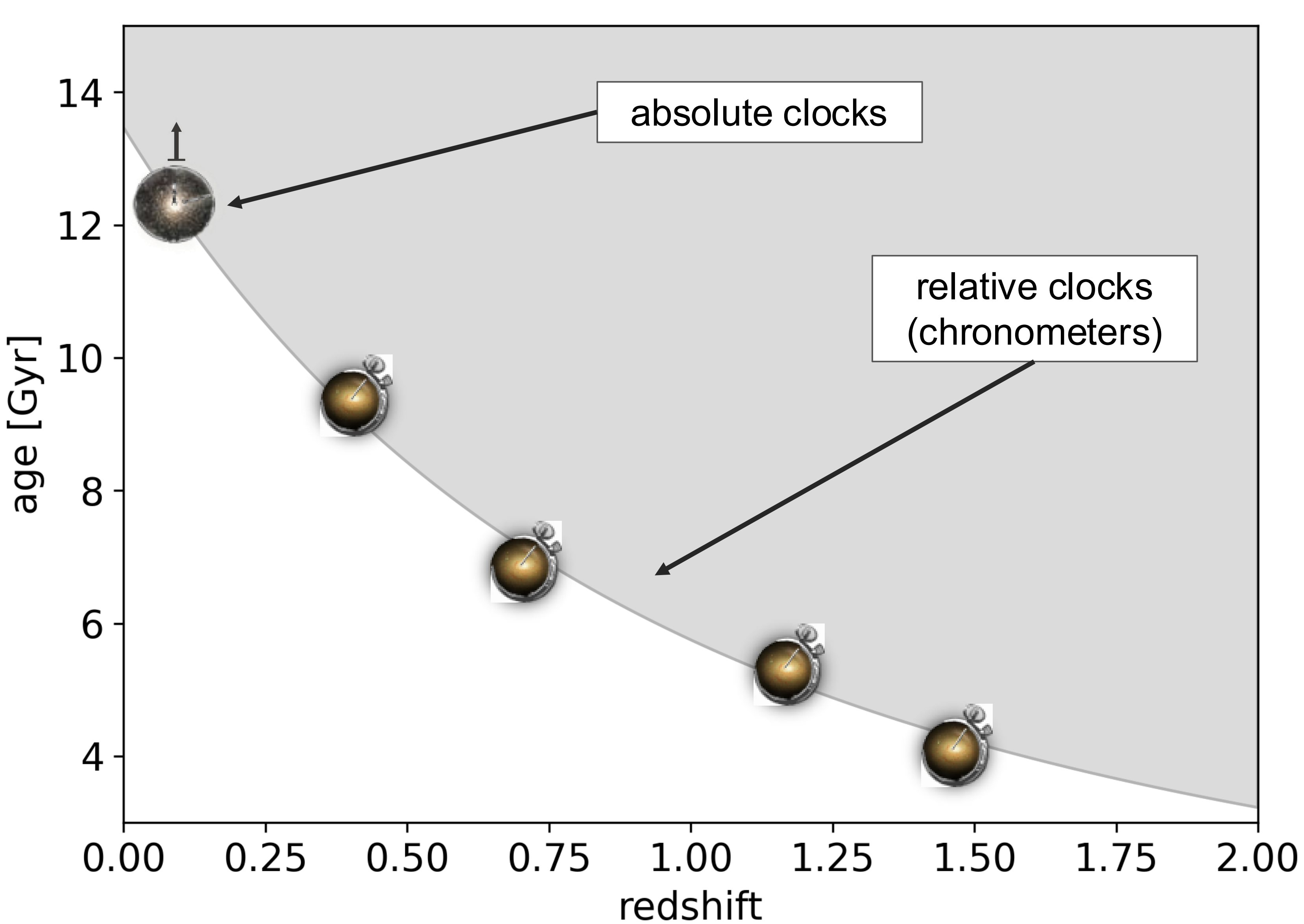

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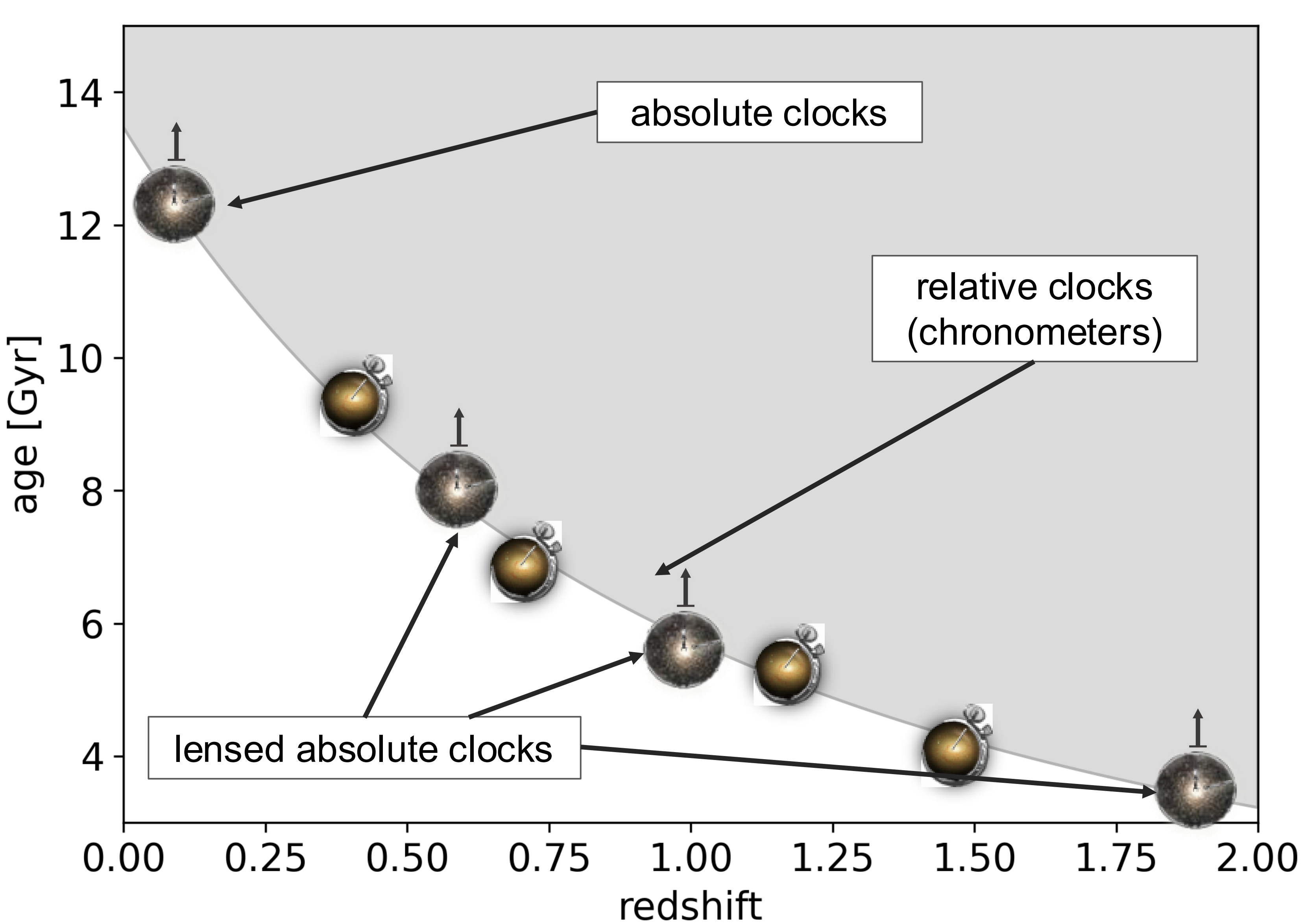
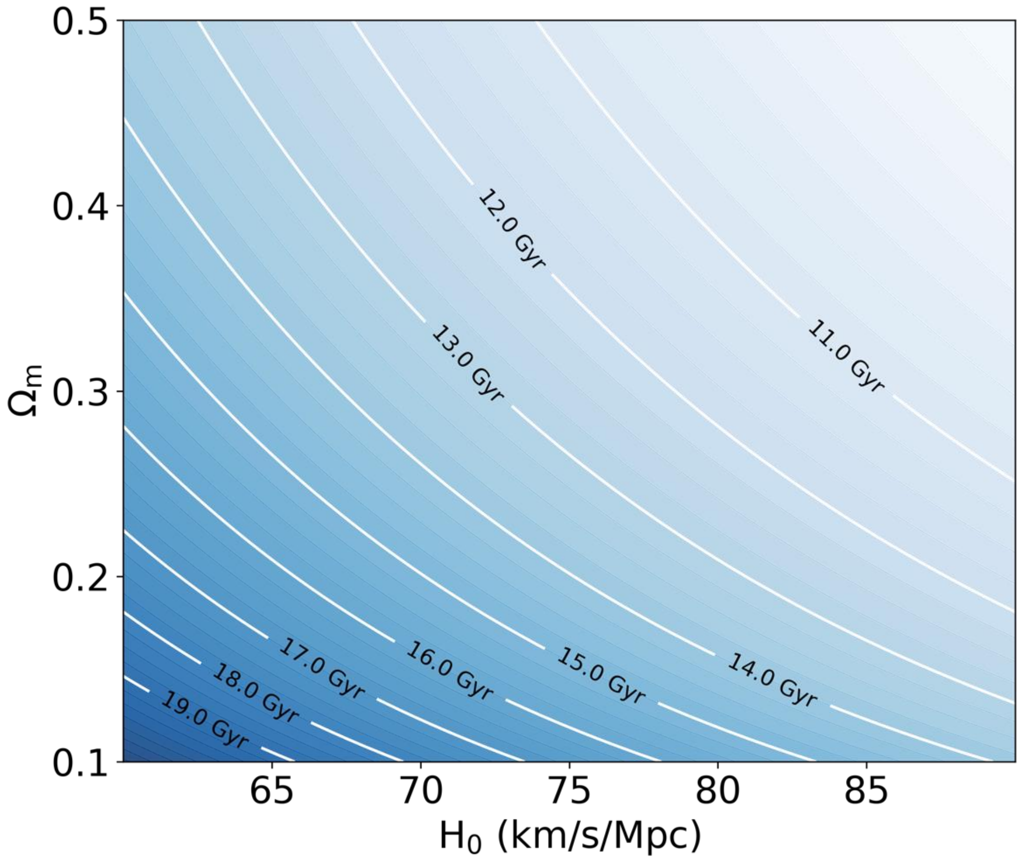


Cosmology from the oldest stars in the Universe

$$H_0 = \frac{A}{t}\int_0^{zf} \frac{1}{1+z}\left[\Omega_M(1+z)^3 + (1-\Omega_M)\right]^{1/2} dz$$

flat ΛCDM cosmology



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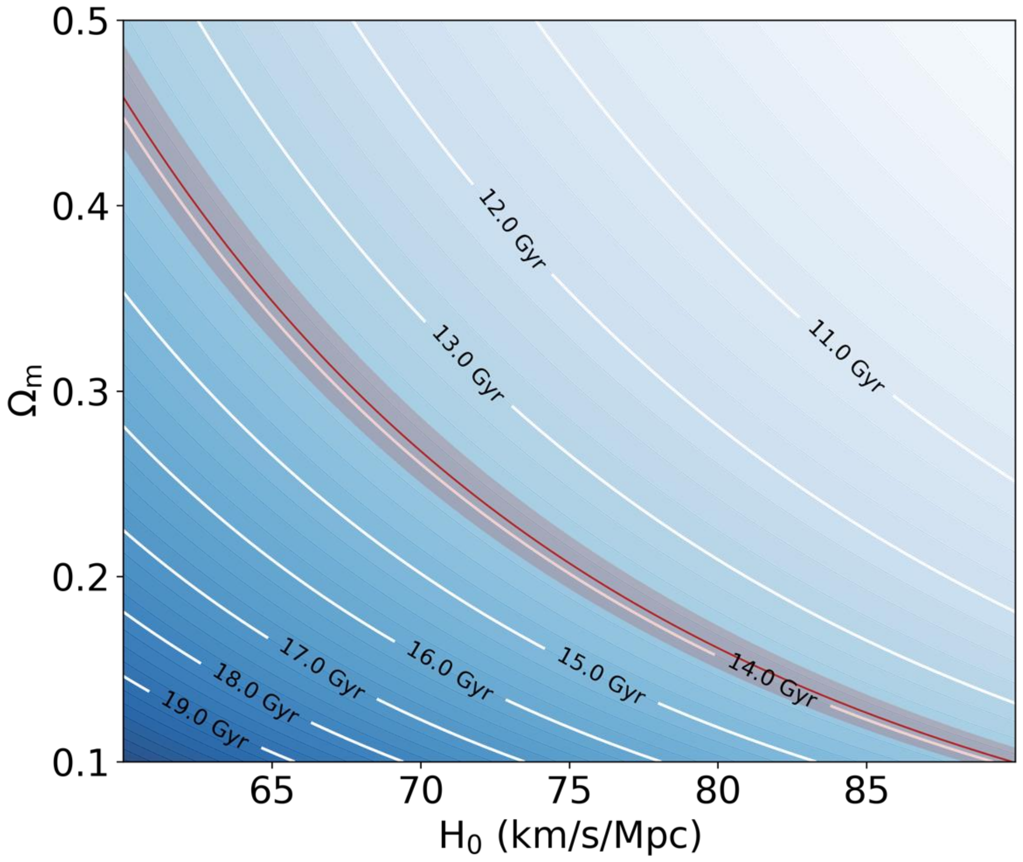

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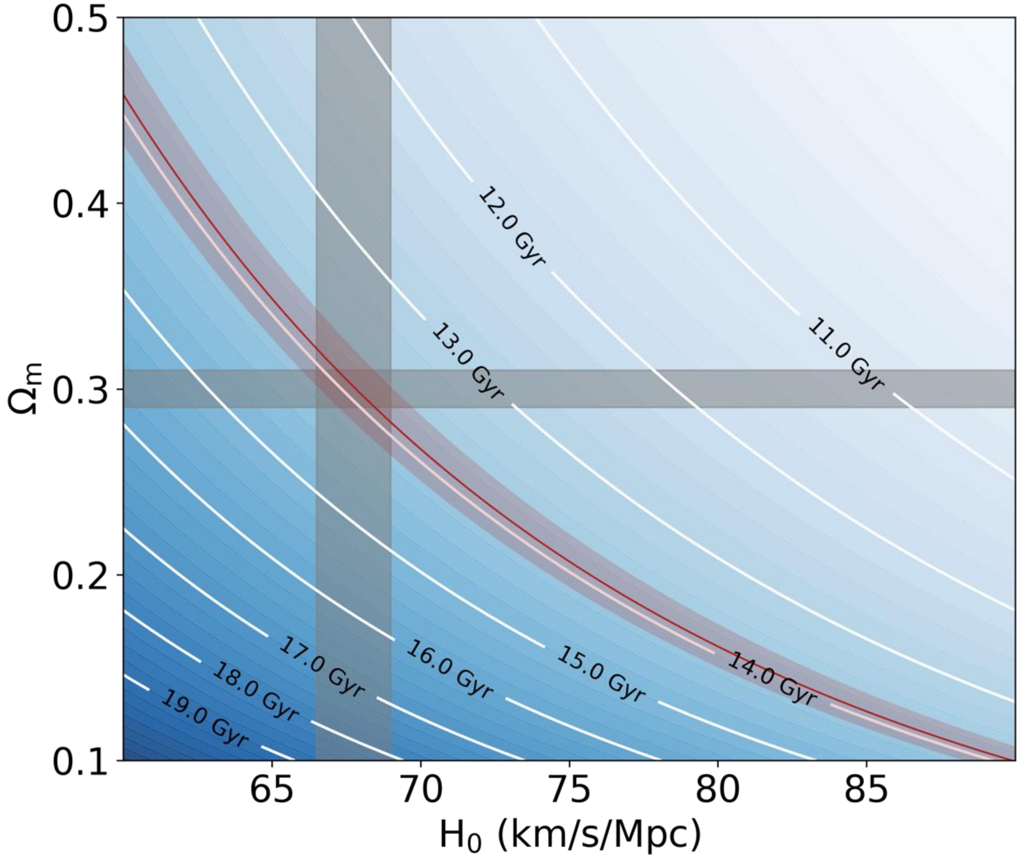

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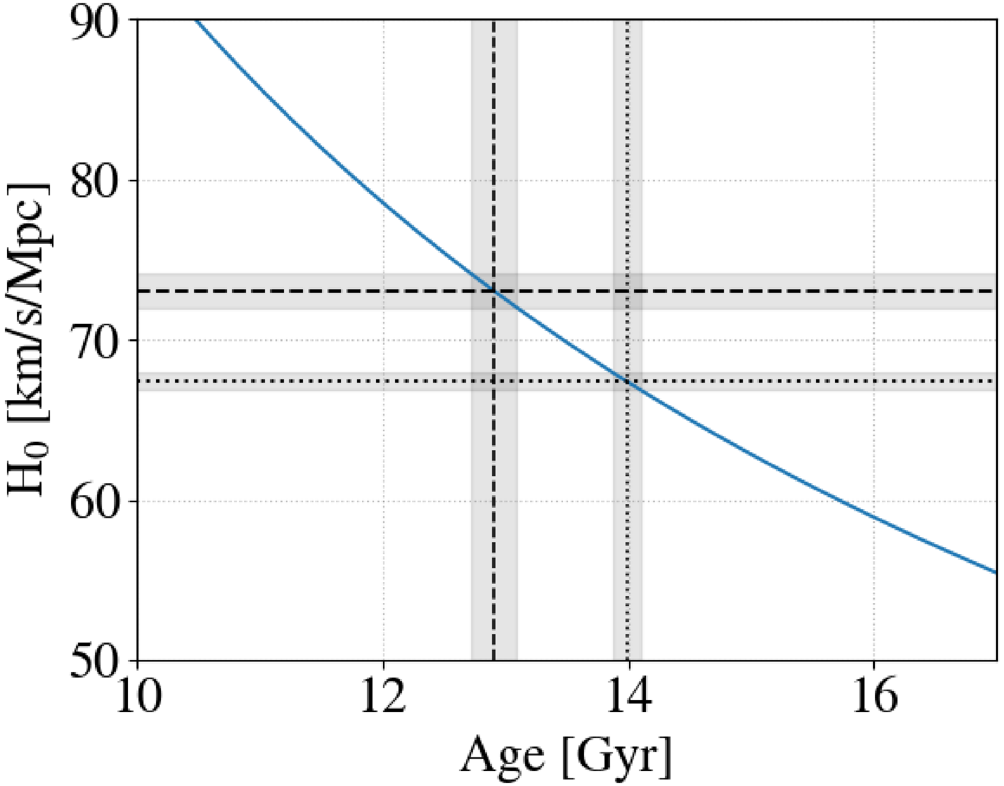

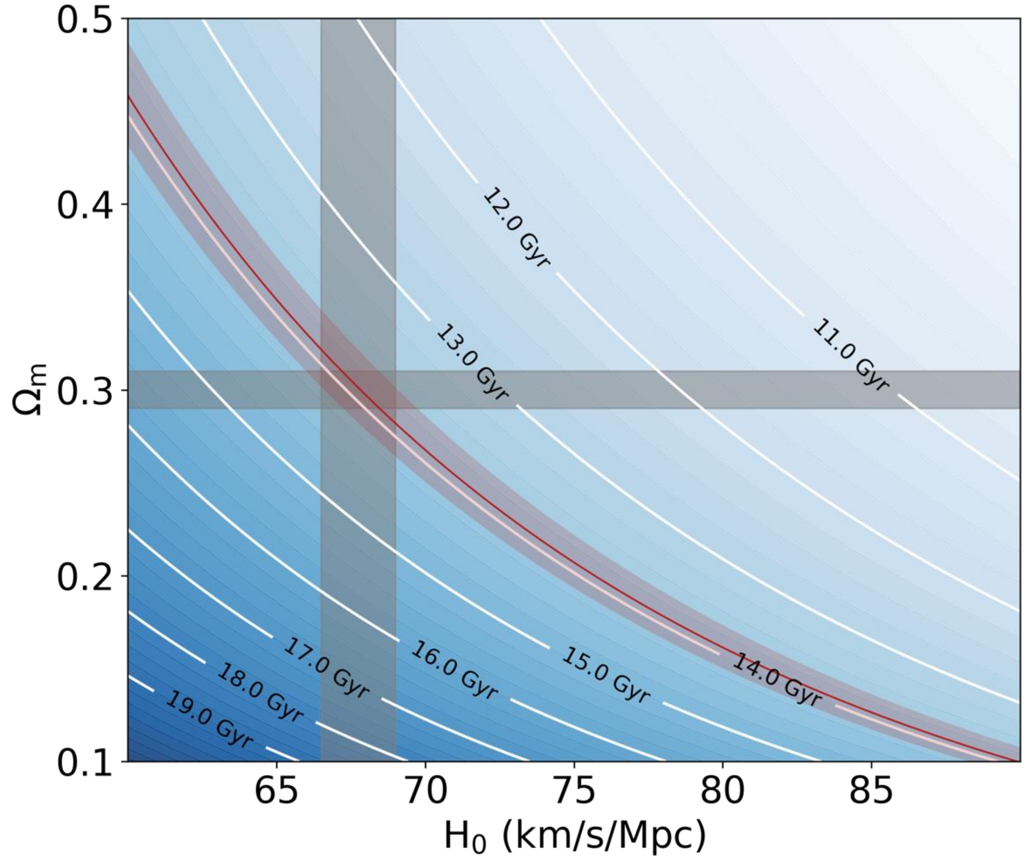

5.67 km/s/Mpc → 1.09 Gyr

Cosmology from the oldest stars in the Universe

Cimatti & Moresco (2023)

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flat ΛCDM cosmology

Galactic globular clusters (GC). Key role due to their nearly coeval and old stellar populations and the possibility to apply isochrone fitting to a large number of stars with high statistics.
O'Malley et al. (2017), Brown et al. (2018), Oliveira et al. (2020), Valcin et al. (2020)

Galactic individual stars. Old individual stars reported in the literature.
Schlaufman et al. (2018), Bond et al. (2013), Plotnikova et al. (2022).

White dwarfs (WD). If the distance, magnitude, color, and atmospheric type for a WD are known, its age can be derived based on the well-understood WD cooling curves and initial–final mass relations calibrated using star clusters.
Fouesneau et al. (2019)

Nucleochronometry. The relative abundances of nuclides with half-lifes of several Gyr (e.g. U, Th, Eu) can be exploited as chronometers.
Christlieb 2016

Ultra faint and dwarf spheroidal galaxies (UFD). UFDs in the Local Group have old stellar populations and may be the fossil remnants of systems formed in the reionization era.
Brown et al. (2014)

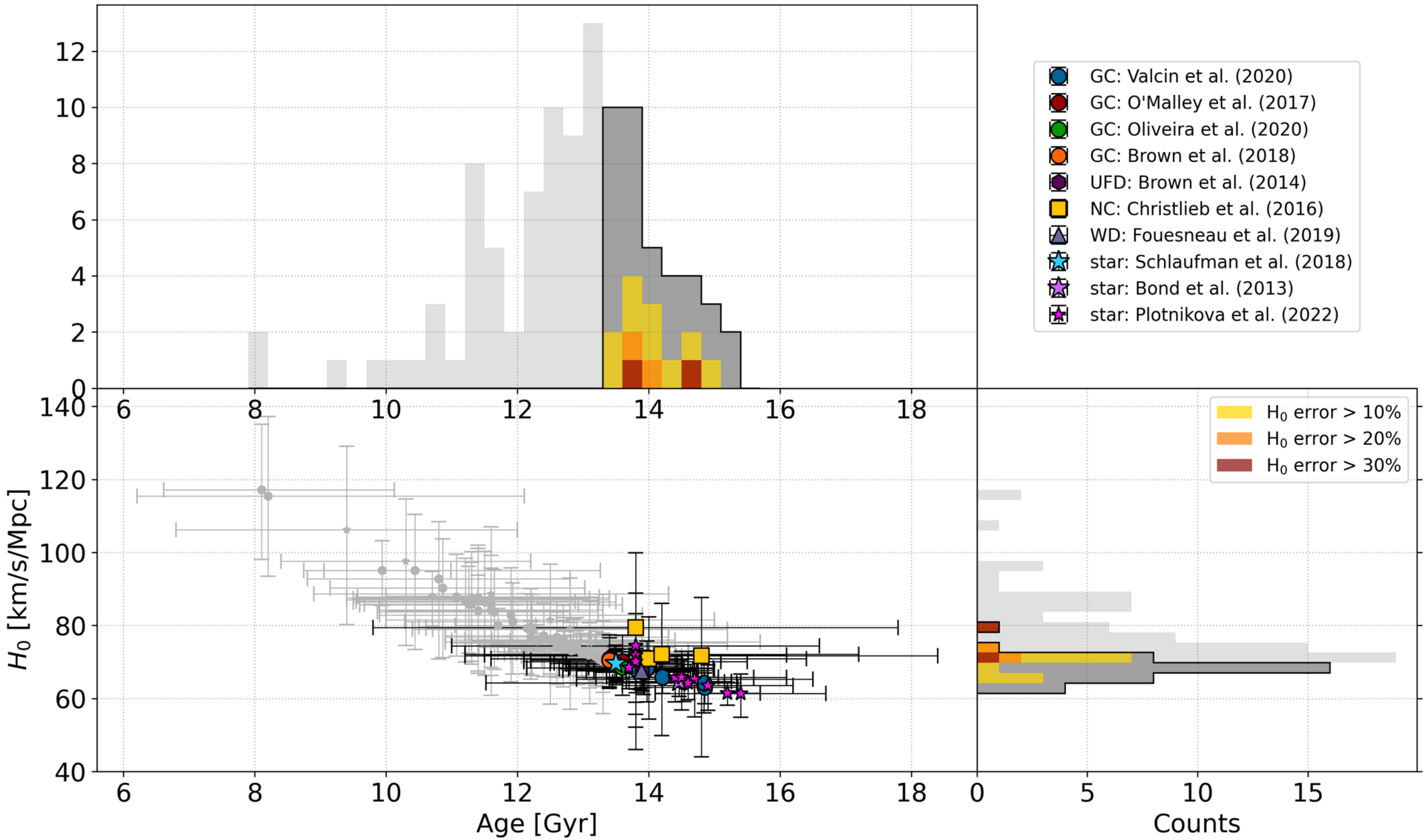
Diverse tracers, diverse method, diverse systematics.

Cosmology from the oldest stars in the Universe

Cimatti & Moresco (2023)

$$H_0 = \frac{A}{t}\int_0^{zf} \frac{1}{1+z}\left[\Omega_M(1+z)^3 + (1-\Omega_M)\right]^{1/2} dz$$

flat ΛCDM cosmology



Cosmology from the oldest stars in the Universe

Cimatti & Moresco (2023)

$$H_0 = \frac{A}{t}\int_0^{zf} \frac{1}{1+z}\left[\Omega_M(1+z)^3 + (1-\Omega_M)\right]^{1/2} dz$$

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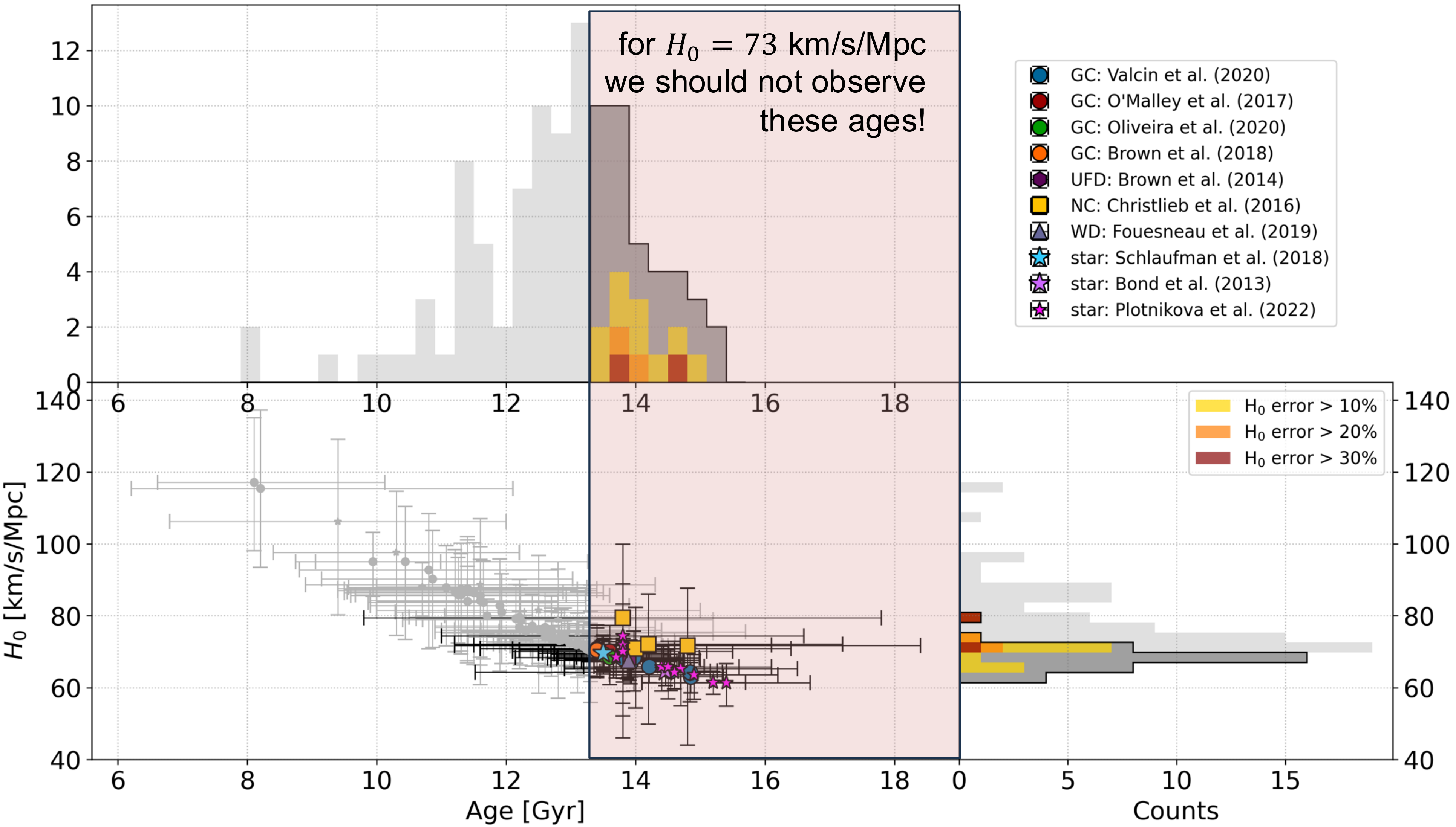
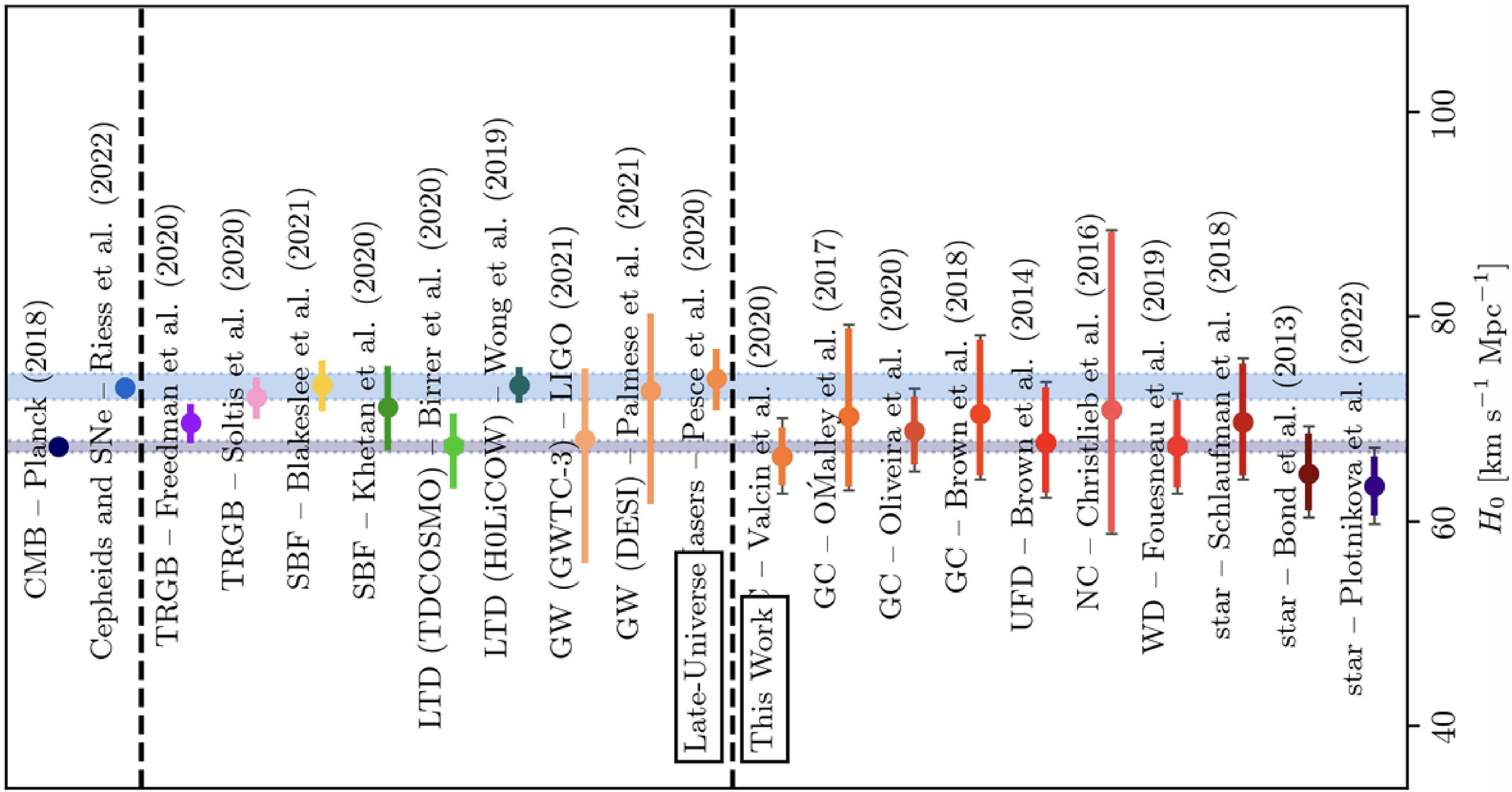


The oldest stellar ages in the context of the H_0 tension

Cimatti & Moresco (2023)



The oldest stellar ages in the context of the H_0 tension

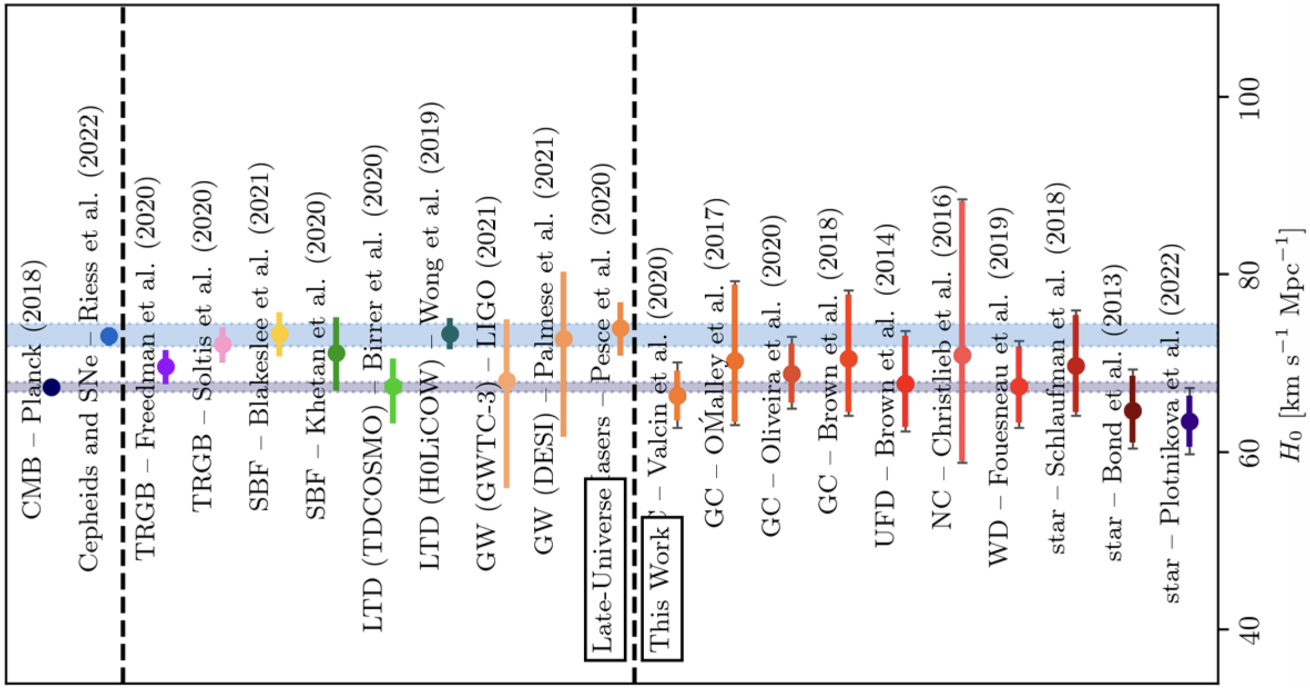
Method	# of objects	Mean Age [Gyr]	H_0 [km/s/Mpc]	$P(H_0 \geq H_{0,\mathrm{Planck}})$	$P(H_0 \leq H_{0,\mathrm{SH0ES}})$
GC (Valcin et al. 2020)	14	14.08±0.53	$66.32^{+2.91}_{-2.75}$	0.35	0.99
GC (O'Malley et al. 2017)	2	13.49±1.4	$70.28^{+8.64}_{-6.85}$	0.65	0.64
GC (Oliveira et al. 2020)	2	13.57±0.85	$68.82^{+3.43}_{-3.20}$	0.67	0.90
GC (Brown et al. 2018)	1	13.4±1.2	$70.52^{+7.25}_{-5.99}$	0.68	0.65
UFD (Brown et al. 2014)	1	13.9±1	$67.69^{+5.46}_{-4.83}$	0.52	0.85
NC (Christlieb 2016)	4	14.17±2.5	$70.89^{+17.37}_{-11.86}$	0.59	0.56
WD (Fouesneau et al. 2019)	1	13.89±0.84	$67.37^{+4.56}_{-4.02}$	0.50	0.91
Individual star (Schlaufman et al. 2018)	1	13.5±1	$69.66^{+5.81}_{-5.08}$	0.66	0.73
Individual star (Bond et al. 2013)	1	14.46±0.8	$64.67^{+3.99}_{-3.54}$	0.23	0.99
Very Metal Poor Stars (Plotnikova et al. 2022)	11	14.73±0.59	$63.45^{+2.93}_{-2.80}$	0.08	0.999

Clear preference to lower H0 values

$P(H_0<H_{0,\mathrm{SH0ES}})$ = 90.3%

(~2sigma)

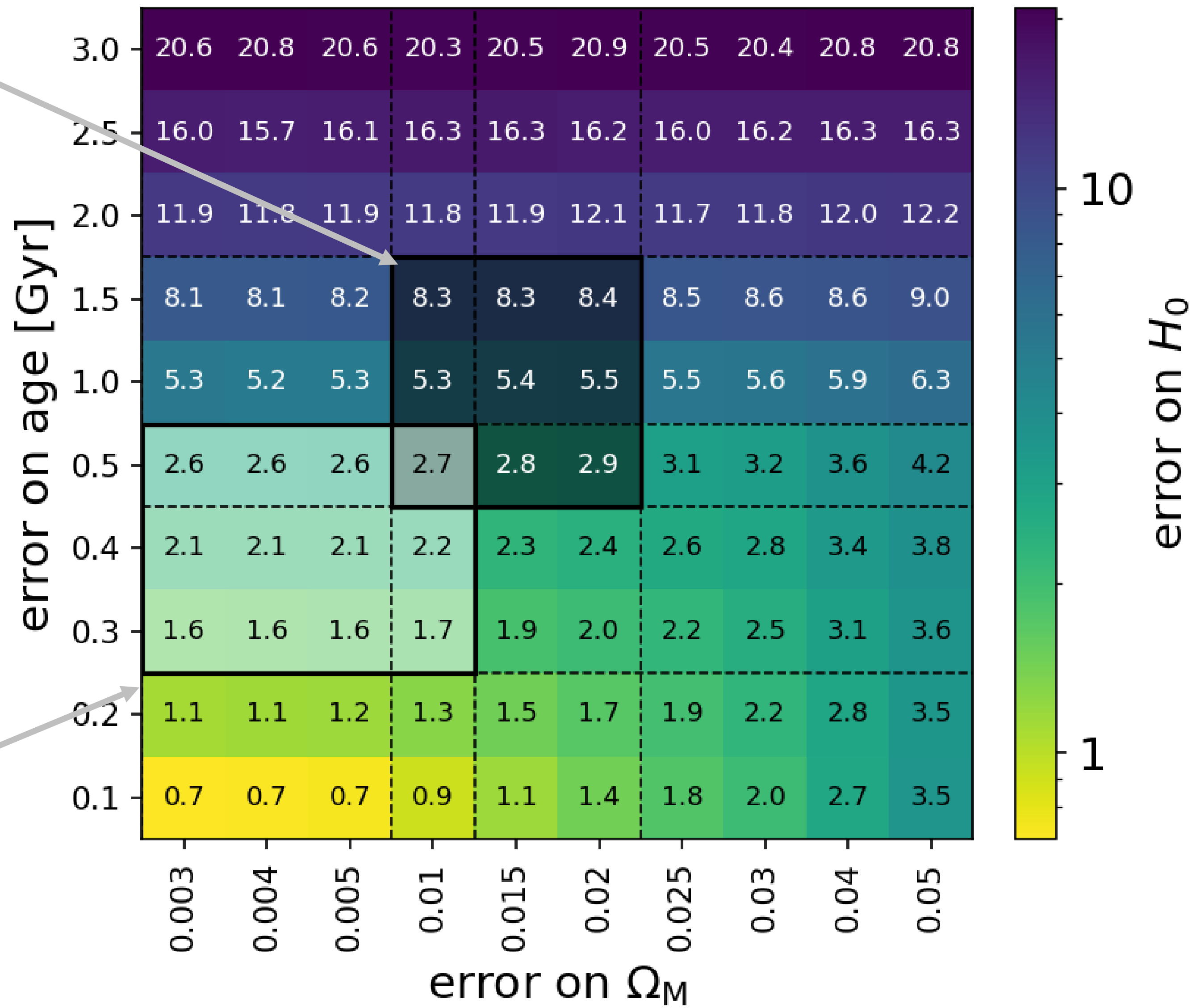
N.B. No significant difference when also including the additional conservative systematic error



An eye to the future

current constraints

future forecasts

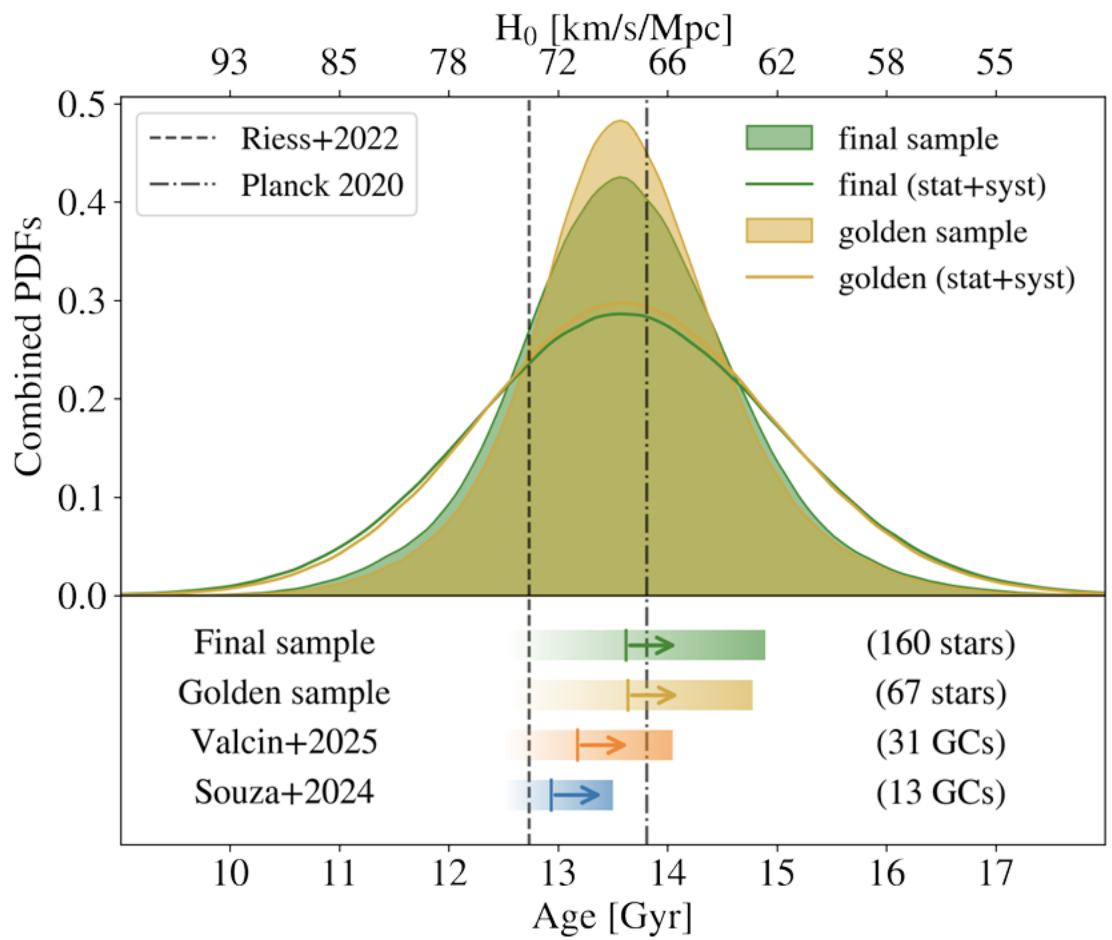


Cimatti & Moresco (2023)

Oldest MW stellar ages as cosmological probe

Tomasetti et al. (2026a)

- MW «age sample» of ~200’000 MSTO and SGB stars (relative distance uncertainty <1% and extinction uncertainty <0.2 mag, Nepal et al. 2024b)
- Ages estimated with StarHorse **without the cosmological prior** (age_{max}=20 Gyr)
- Selected the oldest and best ages (error on age < 1Gyr, age > 12.5 Gyr)



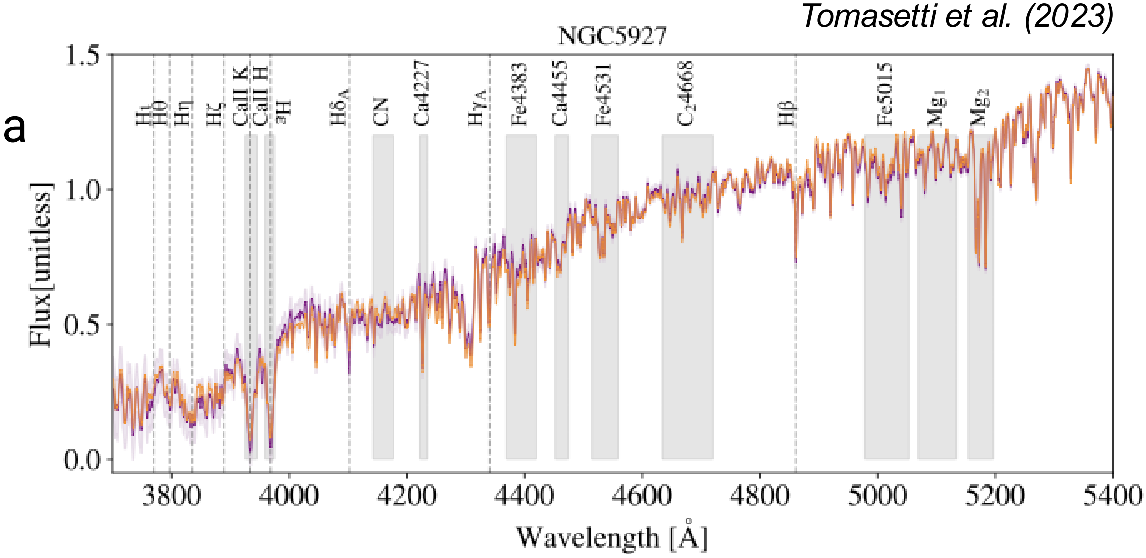
42 stars >13 Gyr at 90% CL (stat+syst)

Considering statistical and systematic uncertainties:

age = 13.6 ± 1.4 Gyr

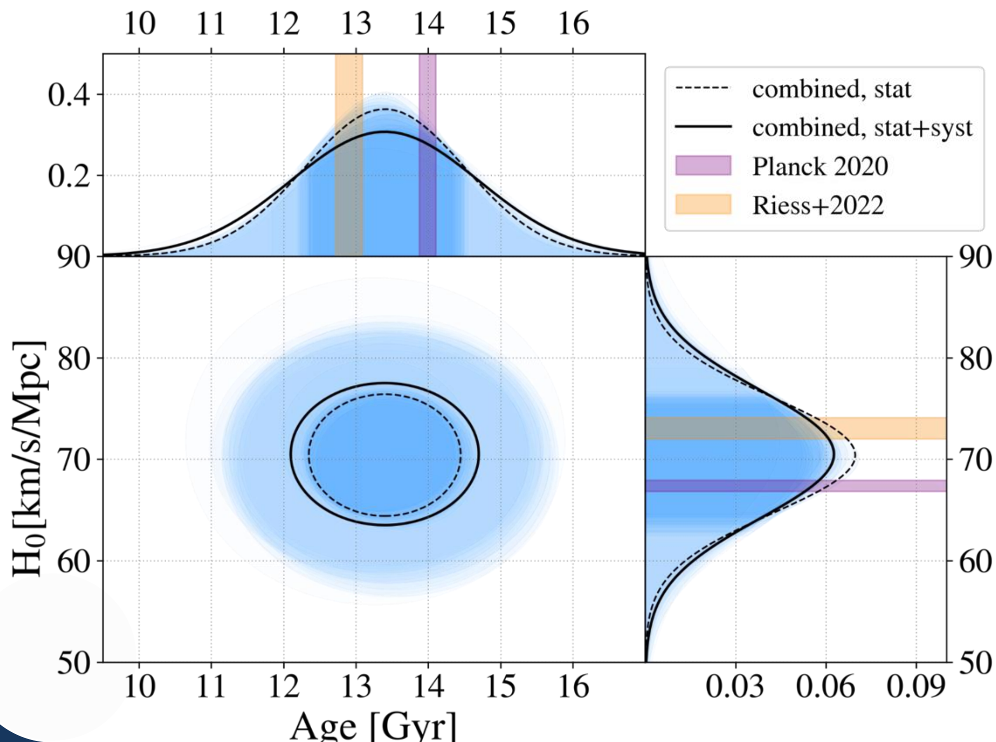
Globular clusters as cosmic clocks

Tomasetti et al. (2023)



Analysis of the integrated spectra of 77 local GCs from the WAGGS survey with a multi-component model with Bagpipes.

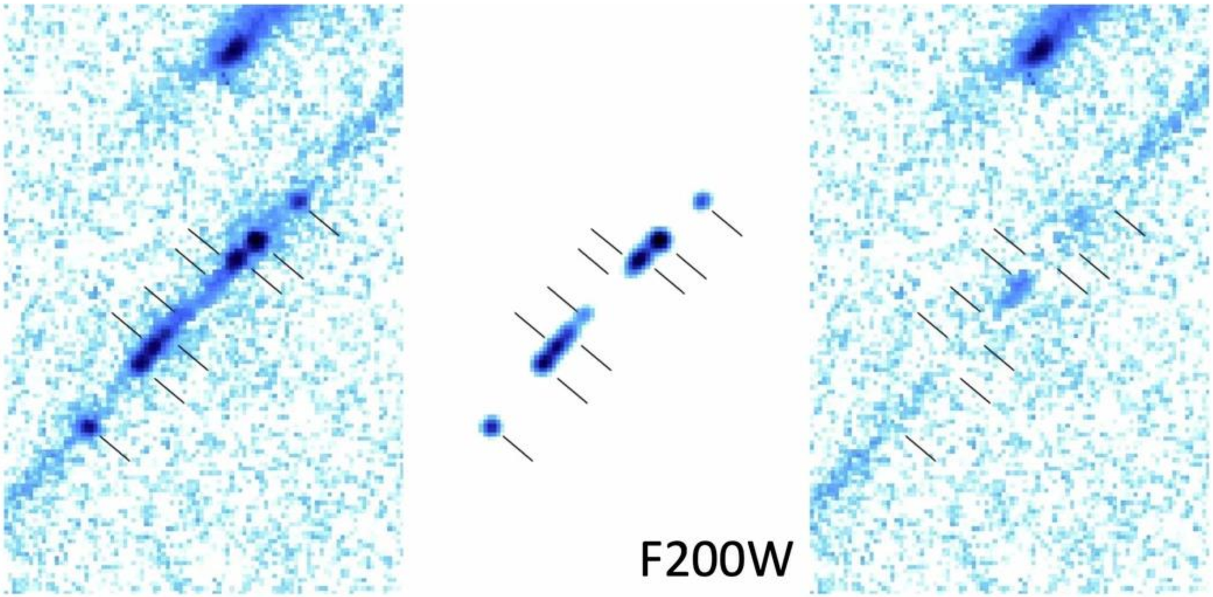
No cosmological prior in the parameter estimation process
(Jiao+2023, Tomasetti+2023)



We obtain a sample of **24 old** GCs with mean age=13.4 ± 1.1 Gyr

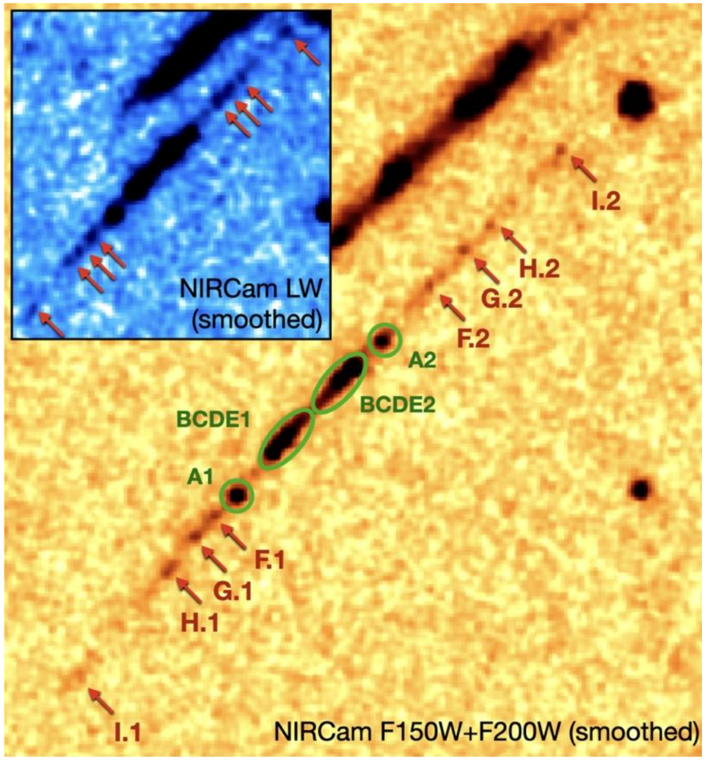
$$\mathbf{H_0 = 70.5_{-6.3}^{+7.7}\ km/s/Mpc}$$
(stat+syst)

Moving to higher redshifts: lensed GC



Adamo+2024

Messa+2025



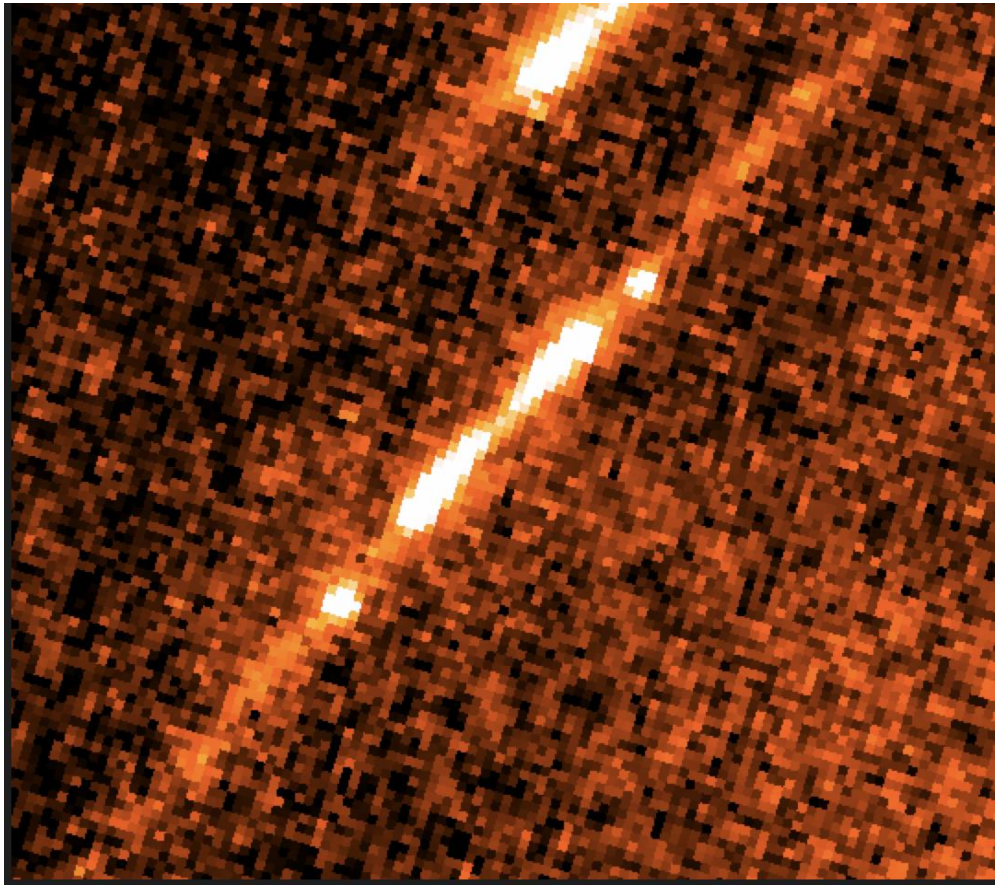
The **Cosmic Gems** at z=9.625
(Adamo+2024, Messa+2025, Vanzella+2026)

- 5 mirrored point sources
- Very-high magnifications (μ~40-300)
- Mass-weighted ages <50 Myr
- 4 additional sources in the tail

Moving to higher redshifts: lensed GC

Tomasetti et al. (2026c), arXiv:2607.19472

- Deconvolution to isolate the oldest emission
- Fit without cosmological prior
- Measure absolute ages (where SFH begins)



Deconvolution photometry with STARRED (STARlet REgularized Deconvolution)
Michalewicz+2023, Millon+2024

- 2-channel deconvolution (point source + extended emission)
- Deconvolution to a Gaussian PSF with 2 pixel FWHM
- Wavelet (starlet) regularization to separate the signal from the noise

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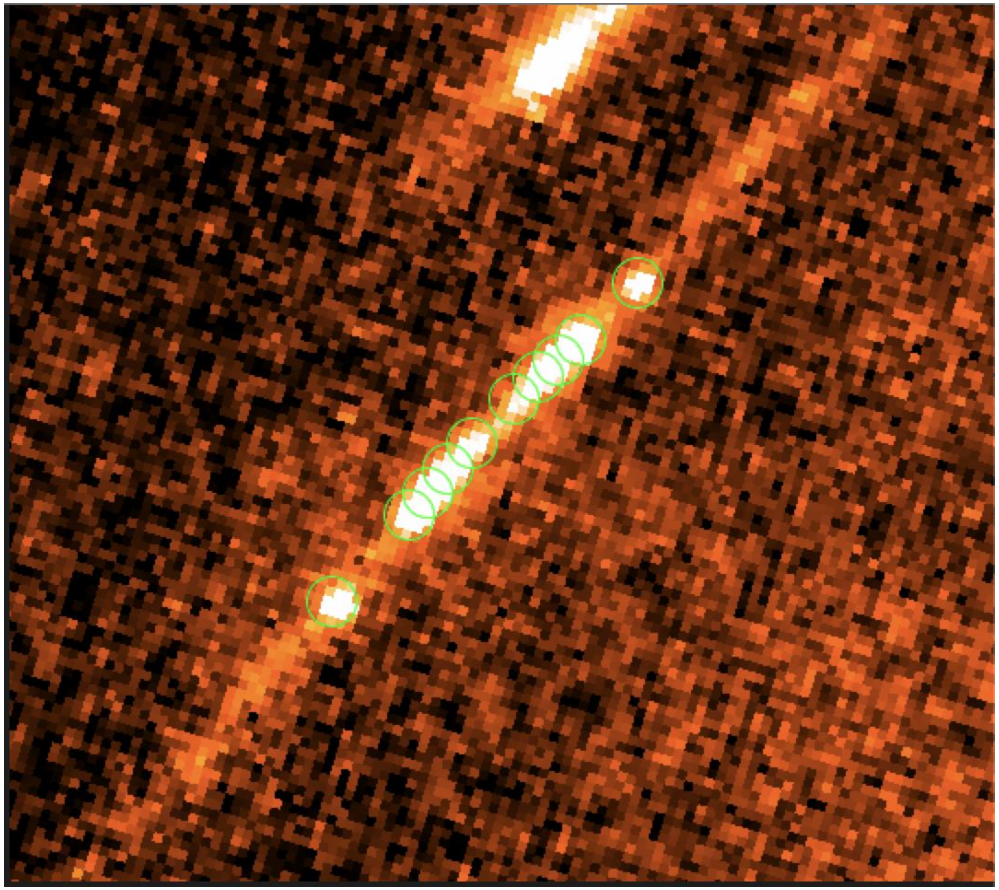

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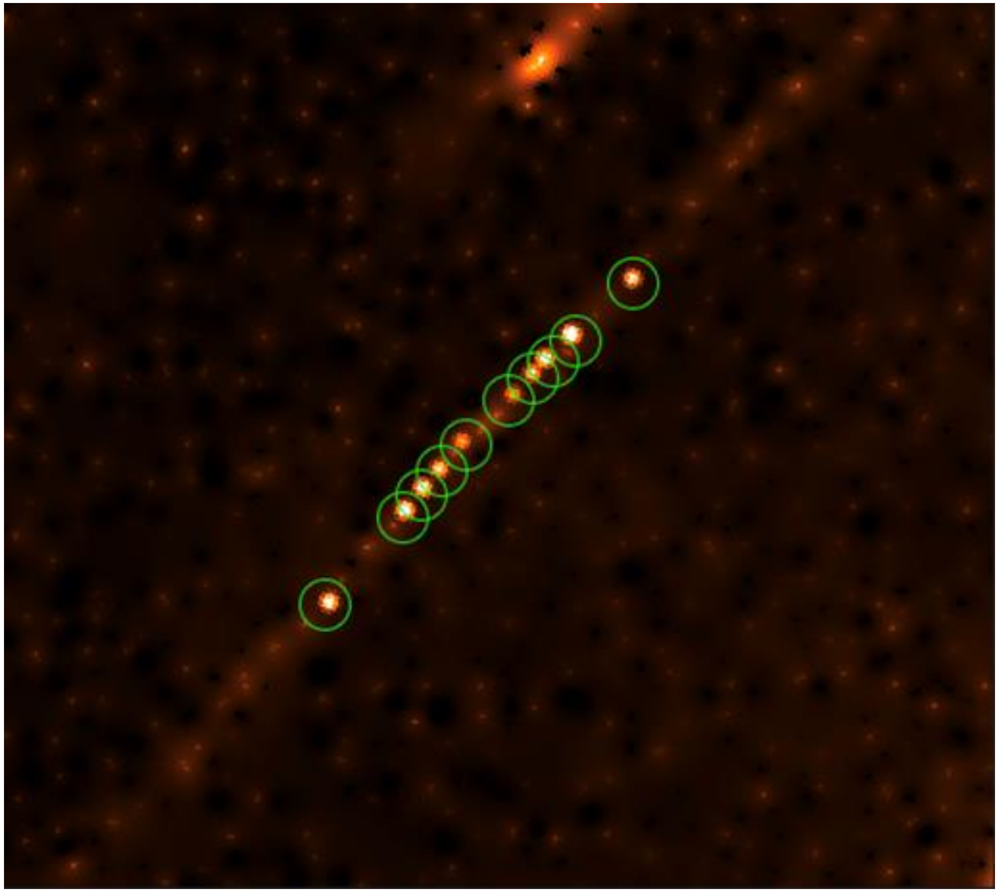

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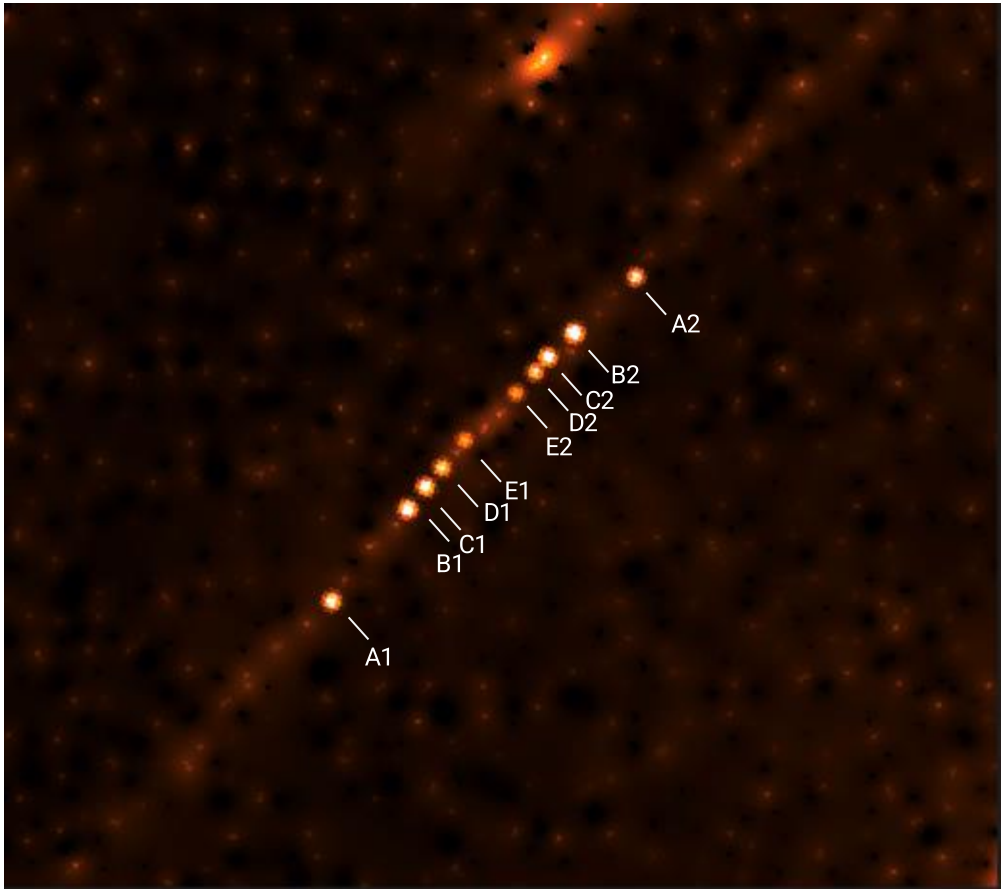

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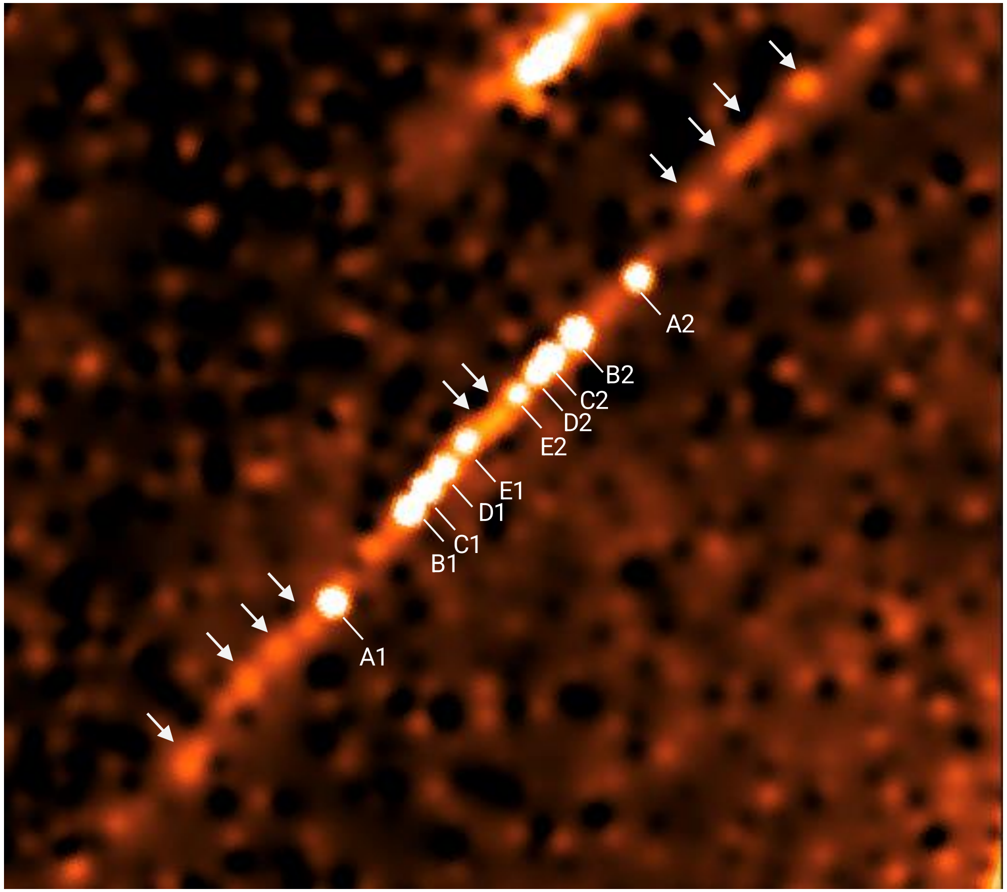

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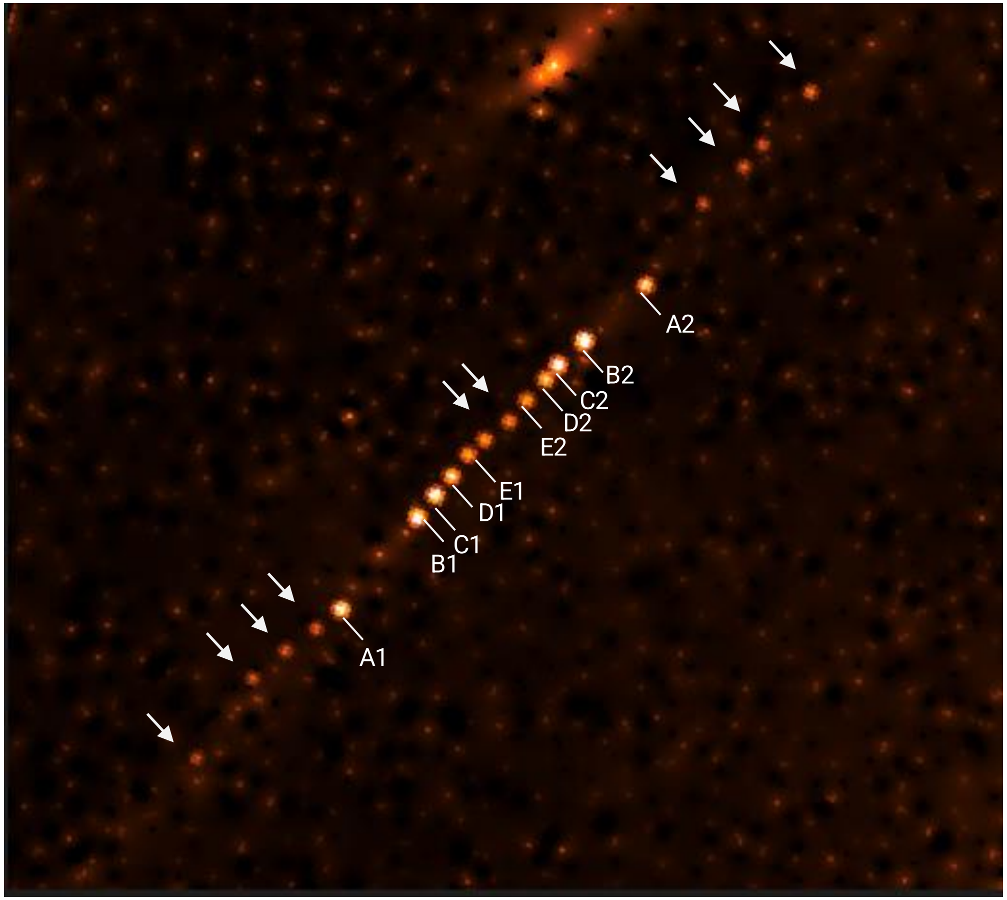

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- 2-channel deconvolution (point source + extended emission)
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- Wavelet (starlet) regularization to separate the signal from the noise

STARRED allows us to deblend and extract the SEDs for both central and tail sources, and resolve a sixth pair of sources (F1–F2) within the innermost region

Moving to higher redshifts: lensed GC

Tomasetti et al. (2026c), arXiv:2607.19472

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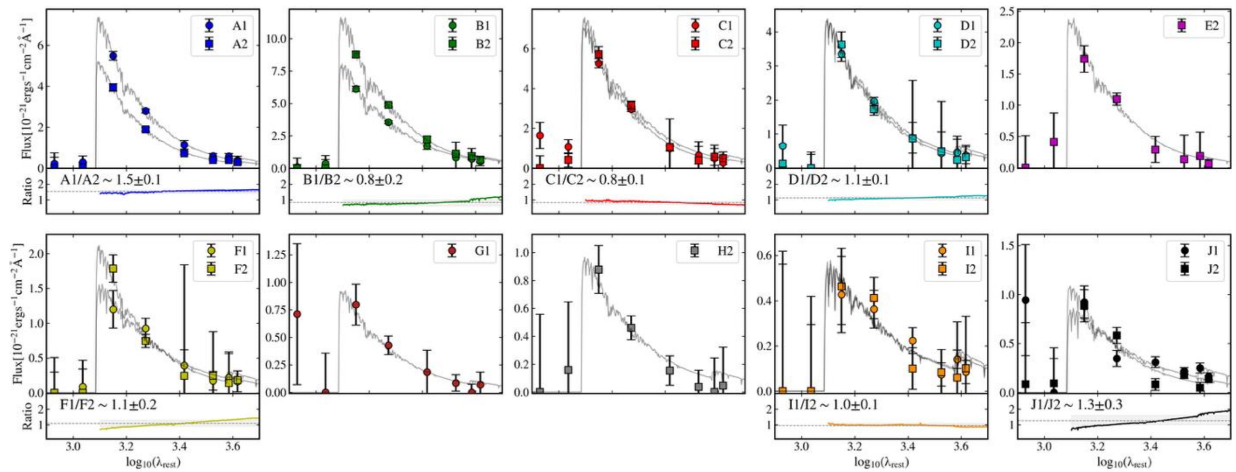
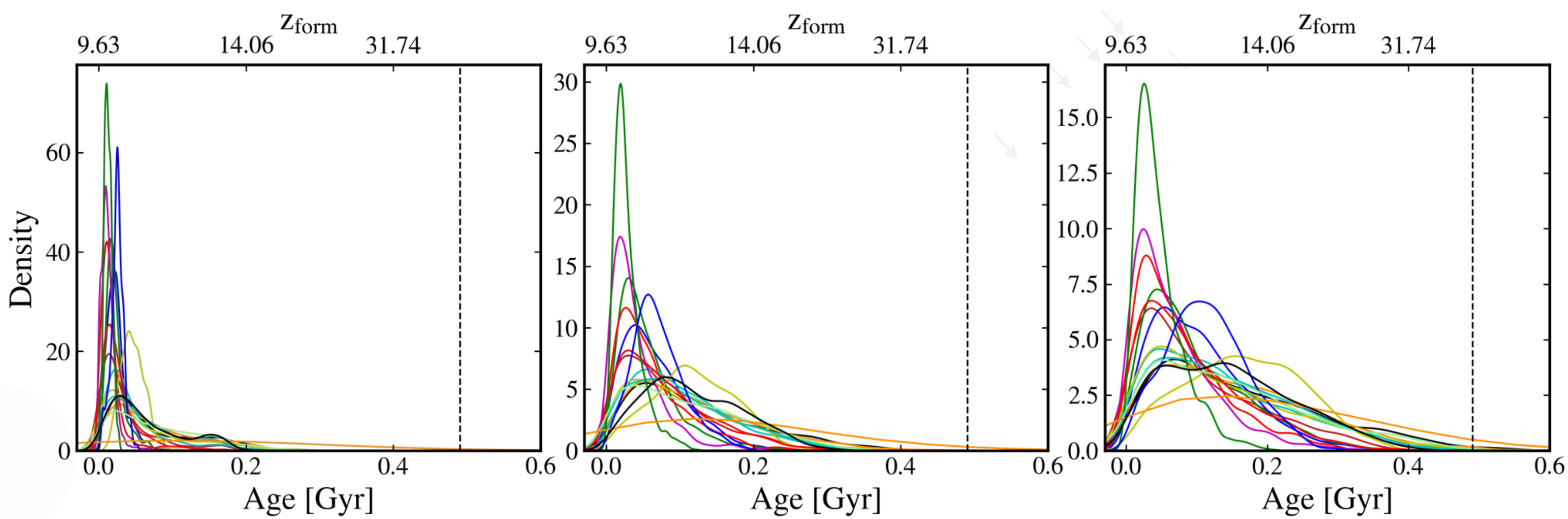




Moving to higher redshifts: lensed GC

Tomasetti et al. (2026c), arXiv:2607.19472

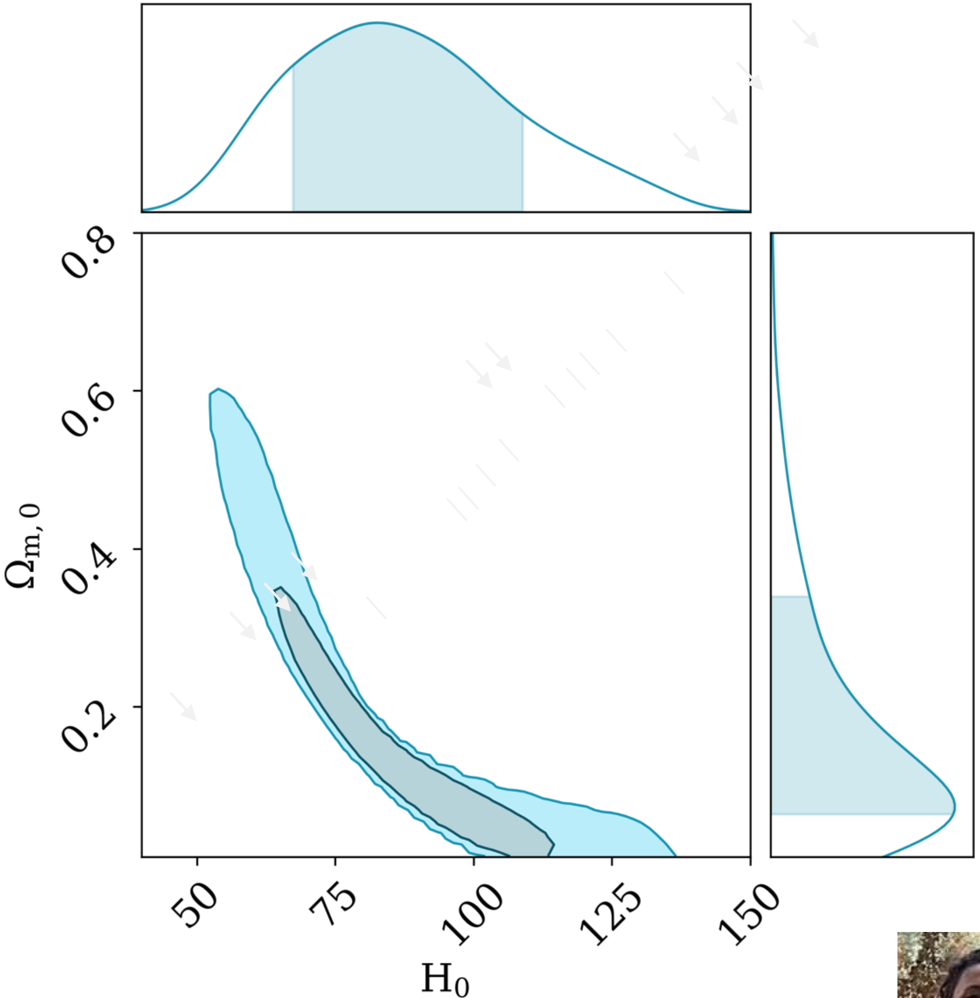
Oldest local GCs

13.61 ± 0.25 (stat) ± 0.23 (syst) Gyr

Valcin+2026

Cosmic Gems

102 ± 62 (stat) Myr



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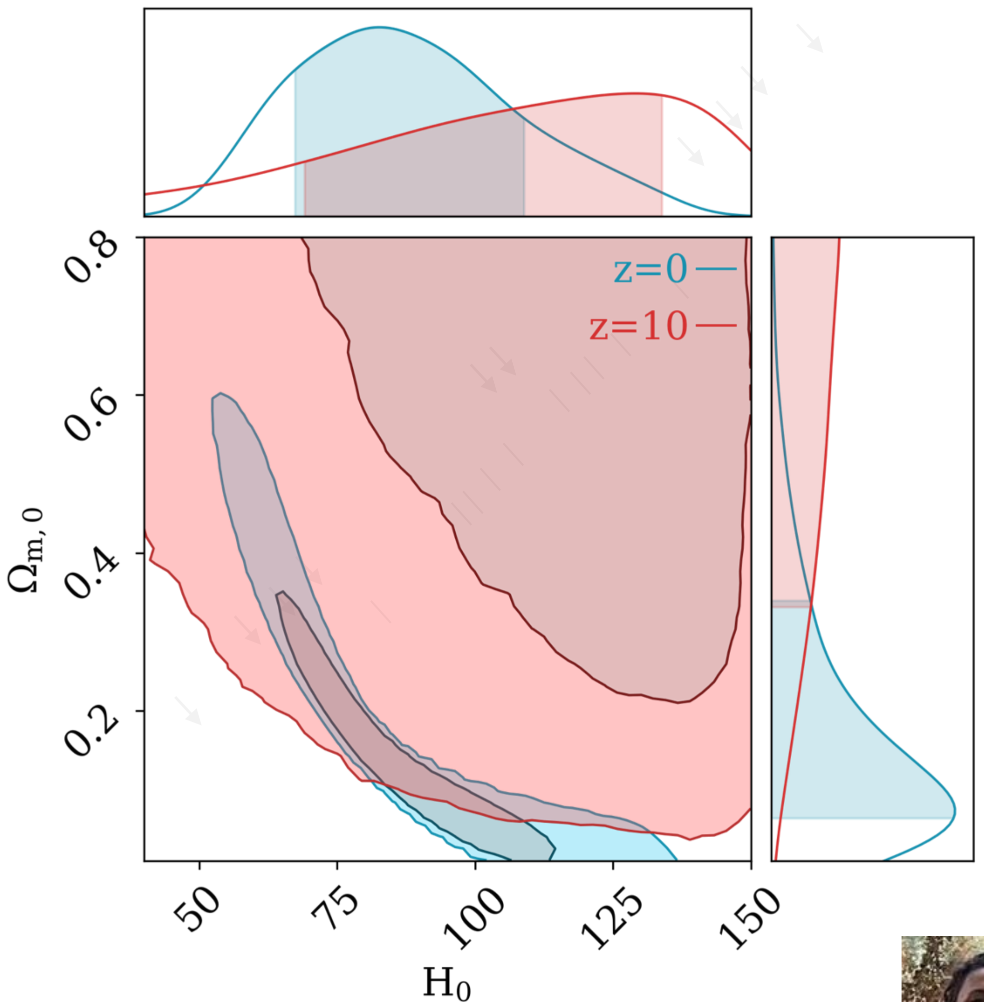

Moving to higher redshifts: lensed GC

Tomasetti et al. (2026c), arXiv:2607.19472

⇨ **Oldest local GCs**

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⇨ **Cosmic Gems**

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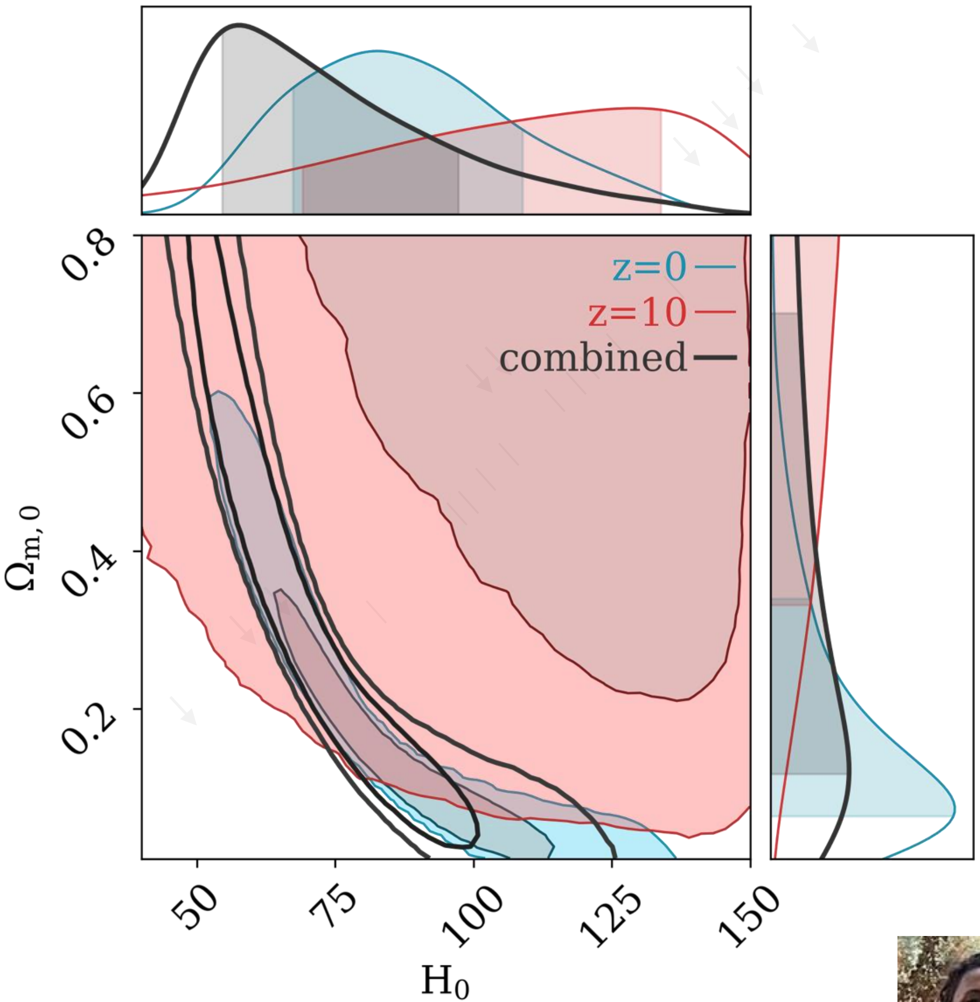

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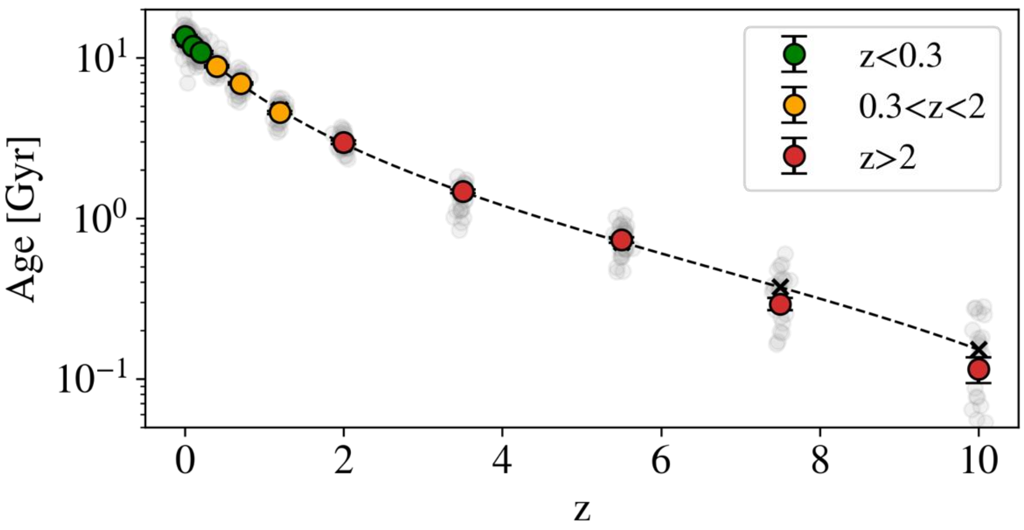
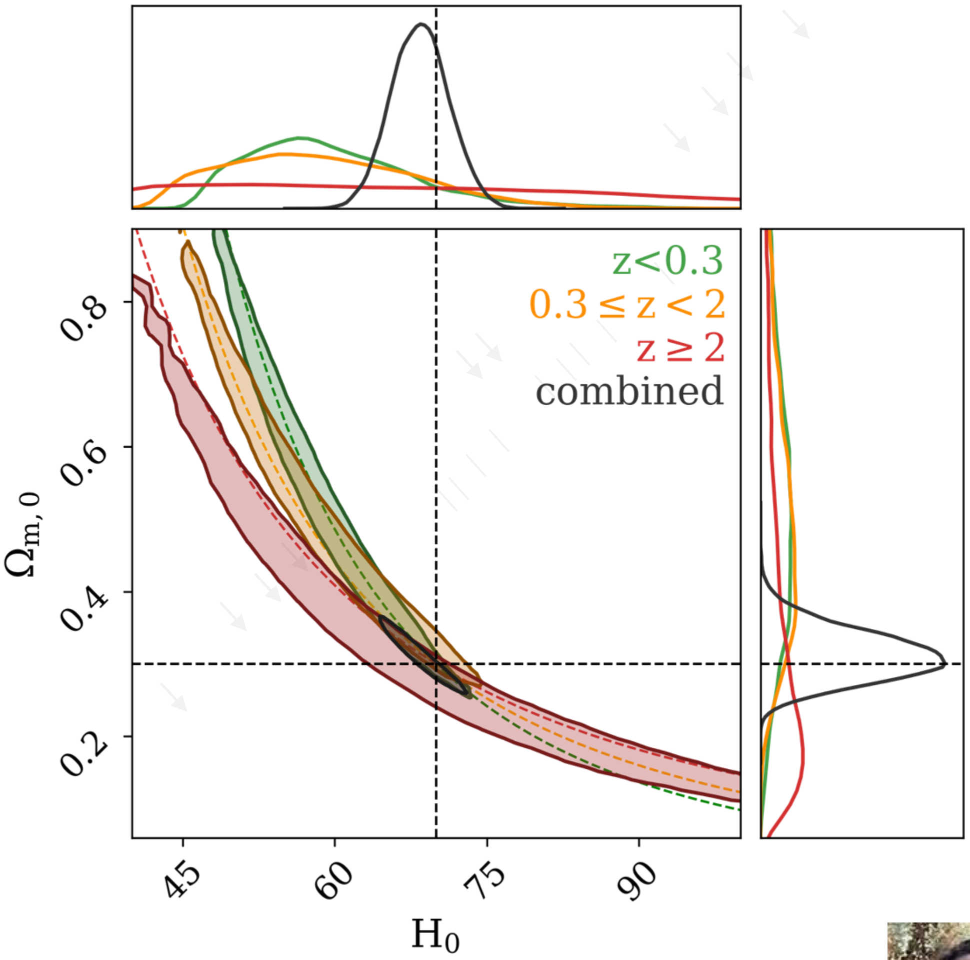


Forecasts:
- Local GCs + 10 high-z bins
- At each redshift N~30 old systems
- Formed at $z_f \in [10,30]$
- Statistical error: $\sigma = 10\% + 100$ Myr floor

$$H_0 = 68.4 \pm 2.8 \text{ km/s/Mpc} \qquad (4\%)$$
$$\Omega_m = 0.31^{+0.04}_{-0.03} \qquad (11\%)$$



Conclusions

Cosmic chronometers

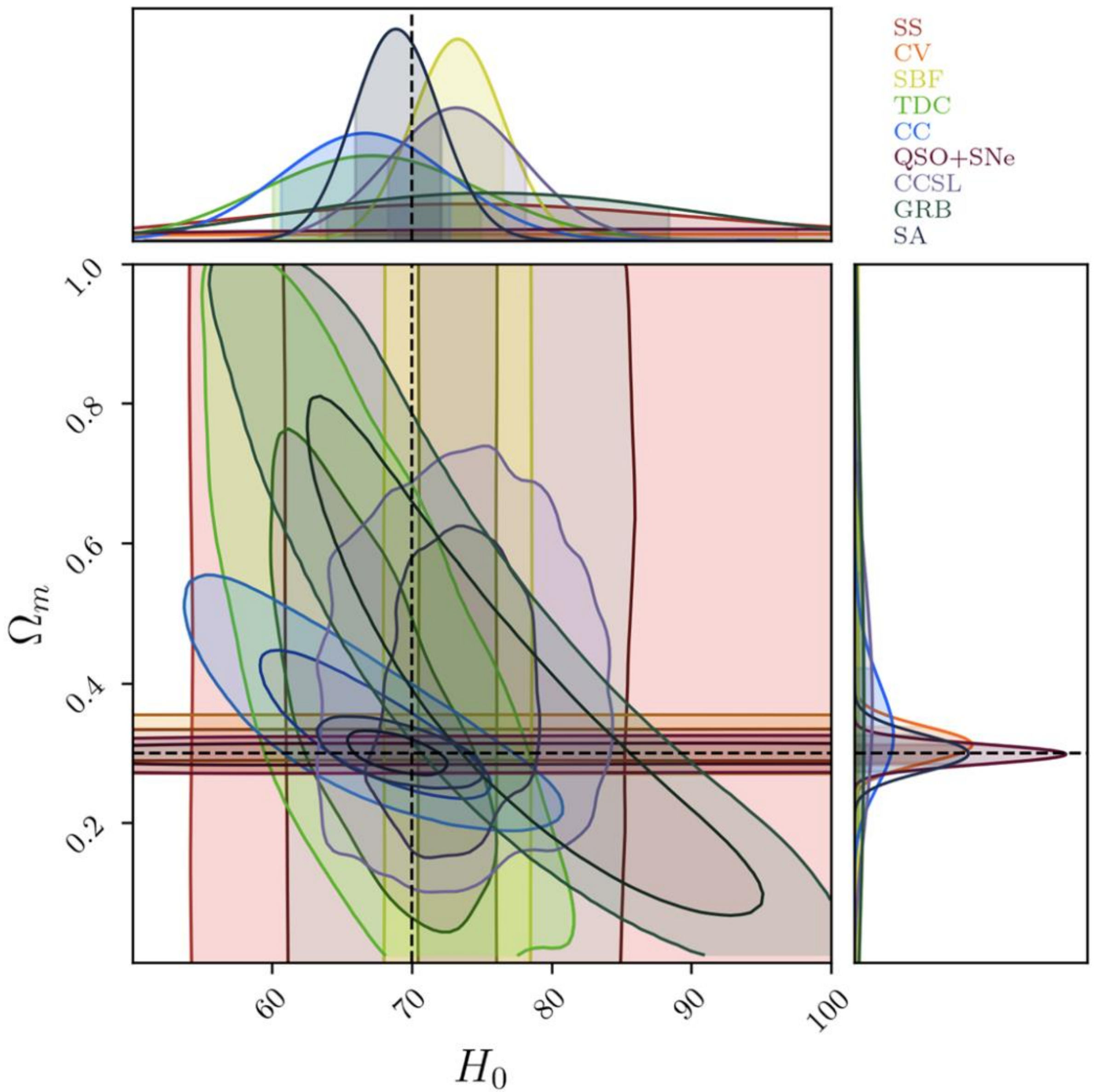
- Basics of "cosmic chronometer" approach, as complementary technique to constrain the expansion history of the Universe
- Main strength: **direct and cosmology independent estimate of H(z)** → ideal framework to test cosmological models
- Importance of cosmic chronometers (in combination with other 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, and 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

Oldest stars

- **High potential for the oldest stars** as cosmological probes: bridge between two worlds and communities with (on average) few interactions and overlaps, but with very fruitful interaction
- **GC can act as cosmic clocks** to provide a lower limit to the age of the Universe

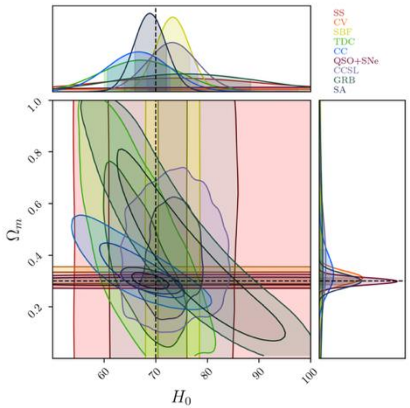
Ongoing ERC synergy grant (lead by University of Barcelona, Licia Verde)

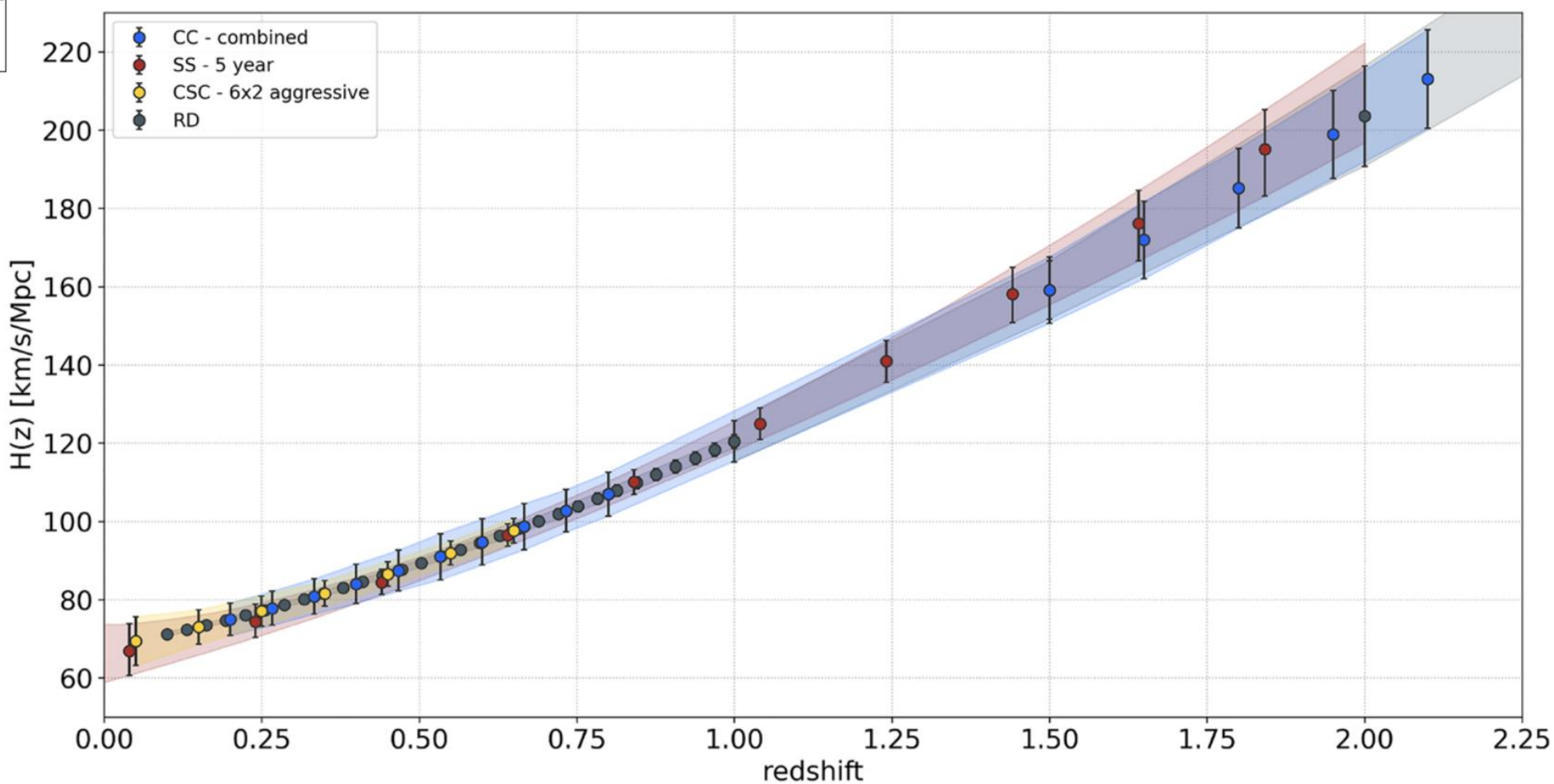
Conclusions



Moresco et al. (2022)

Conclusions

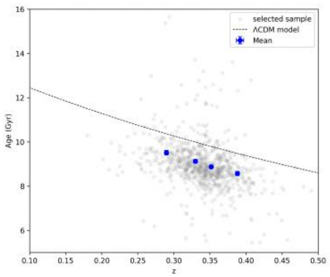




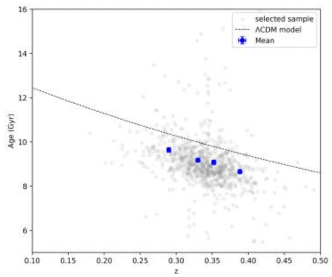
Moresco et al. (2022)

Backup slides

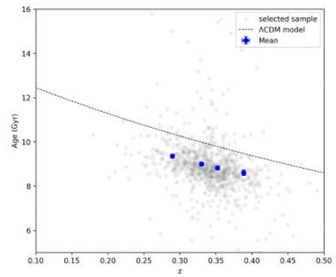
What about the IMF?



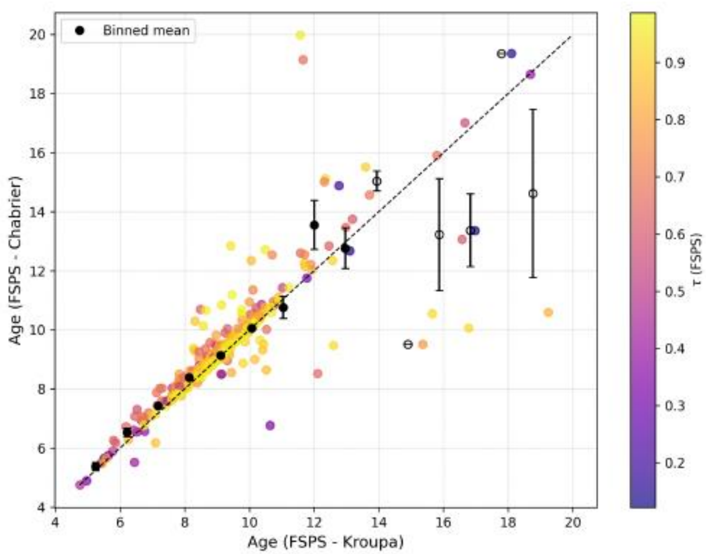
(a) Kroupa



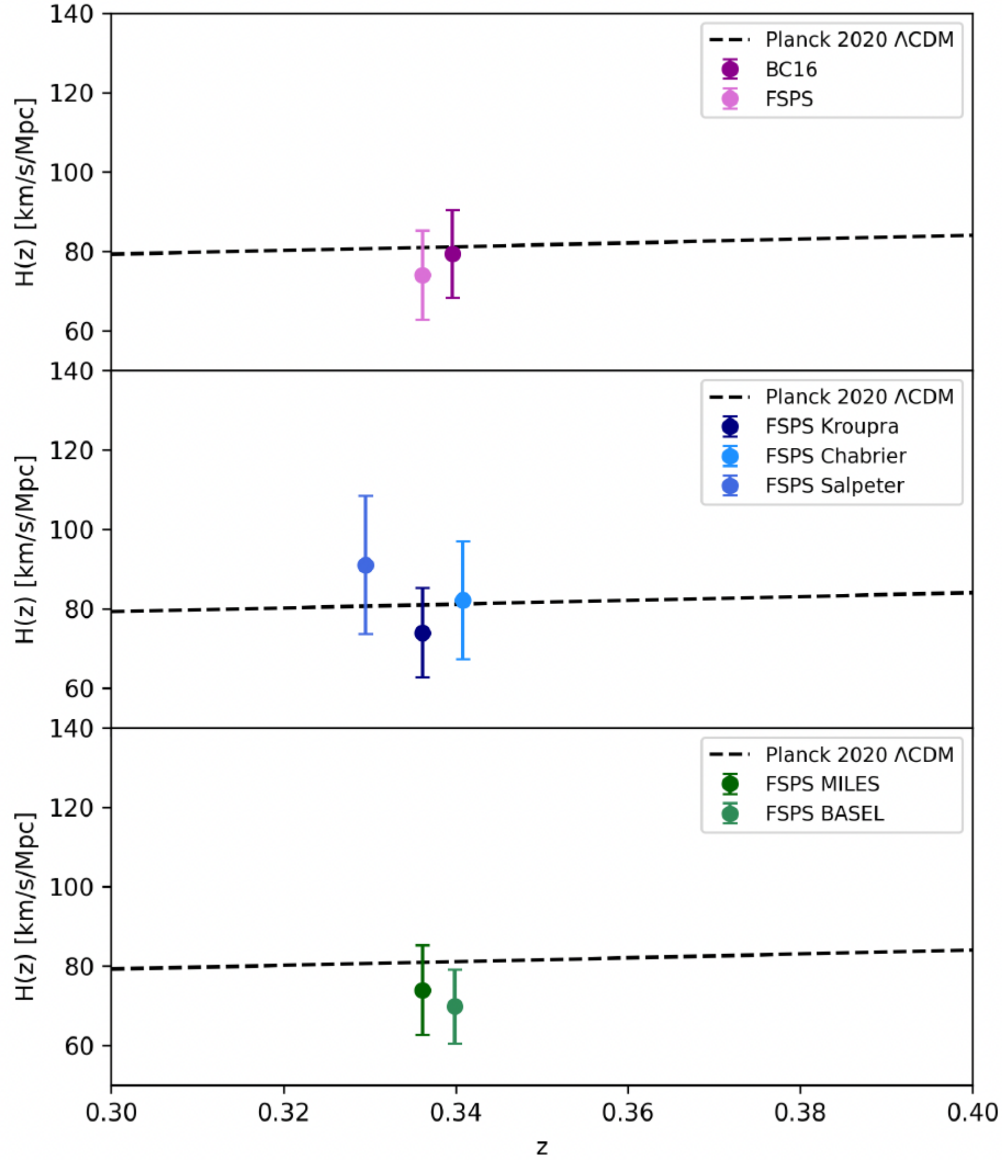
(b) Chabrier



(c) Salpeter

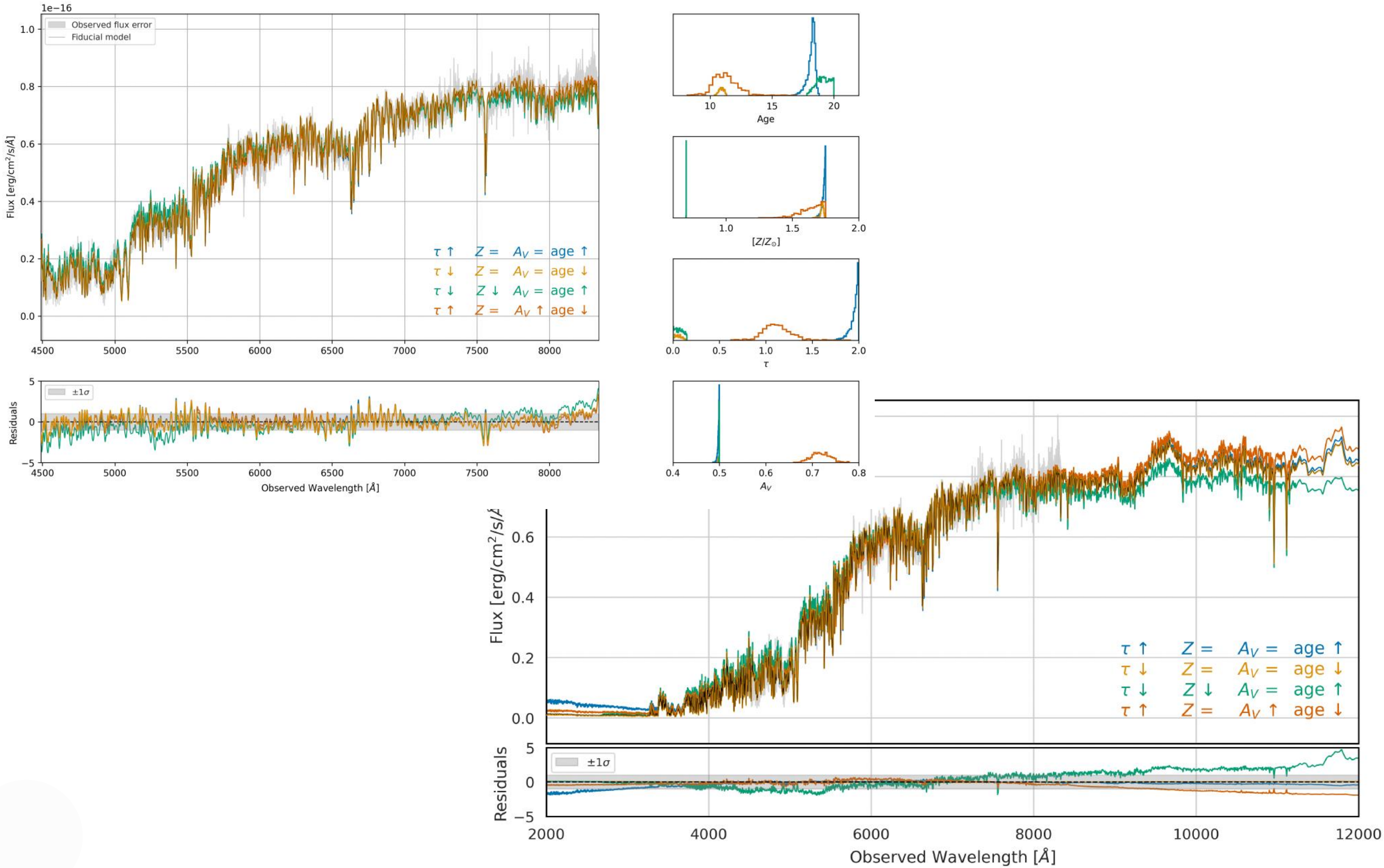


(c) Chabrier vs. Kroupa



Master Thesis of G. Ruggeri

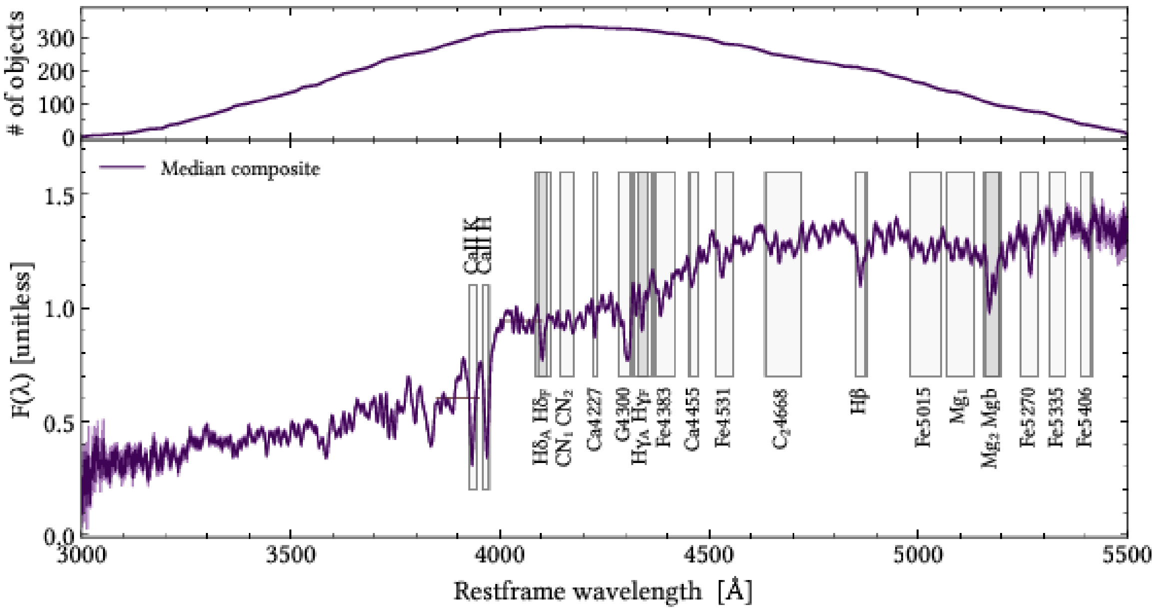
Parameters degeneracies

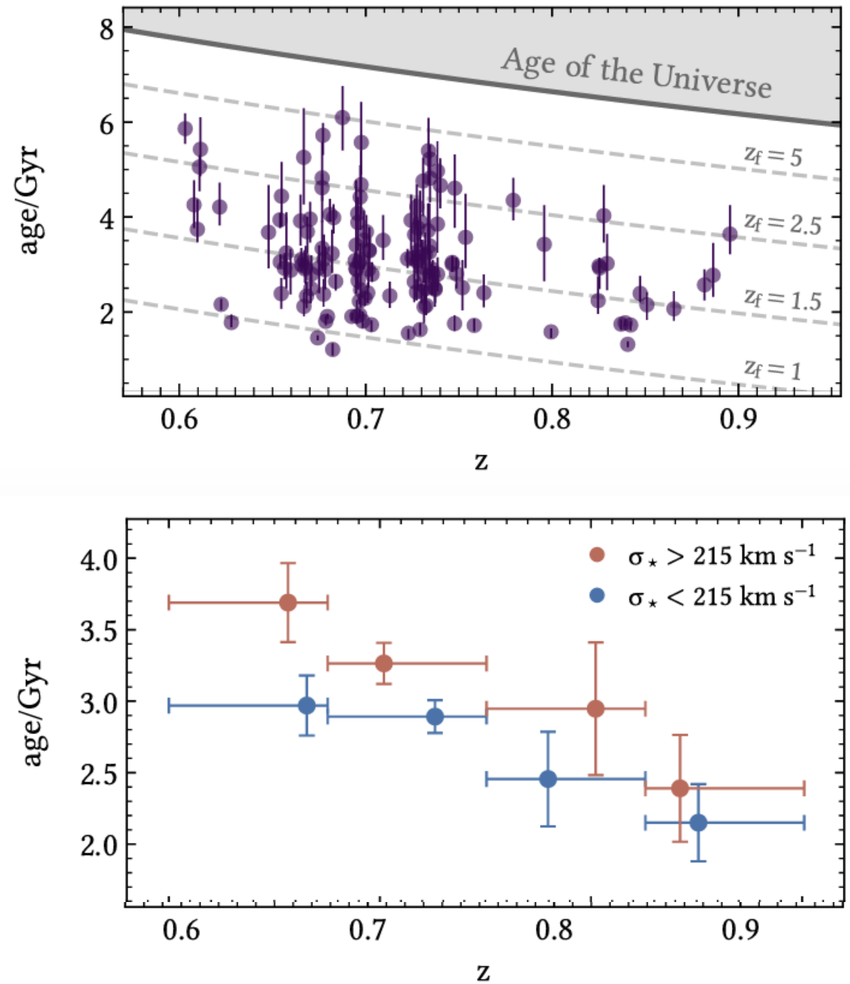


Master Thesis of G. Ruggeri

Cosmic chronometers with absorption features

Borghi et al. (2022a, 2022b)





Data LEGA-C DR2

Sample combination of photometric and innovative spectroscopic criteria to maximize purity

Method Lick indices (absorption features tracers of age, metallicity and α/Fe)

Cosmic chronometers with full-spectral-fitting

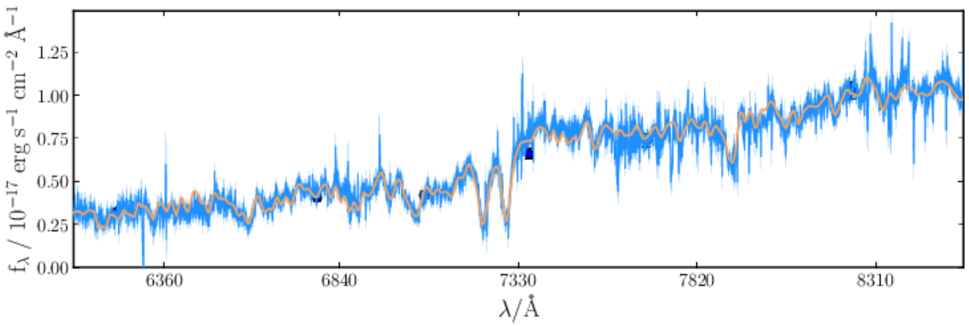
Jiao et al. (2023)

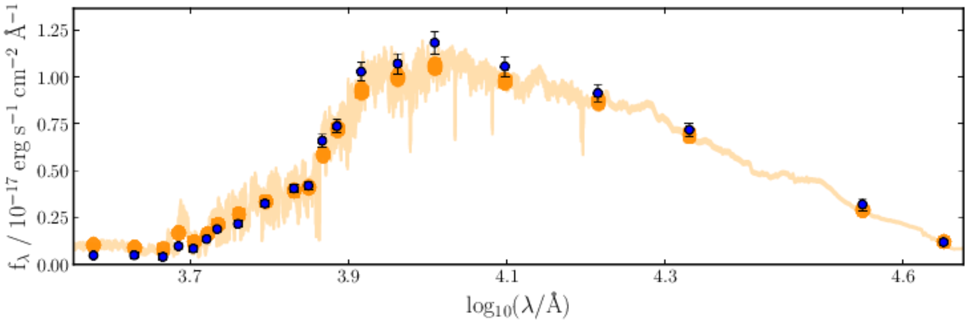
Data LEGA-C DR2

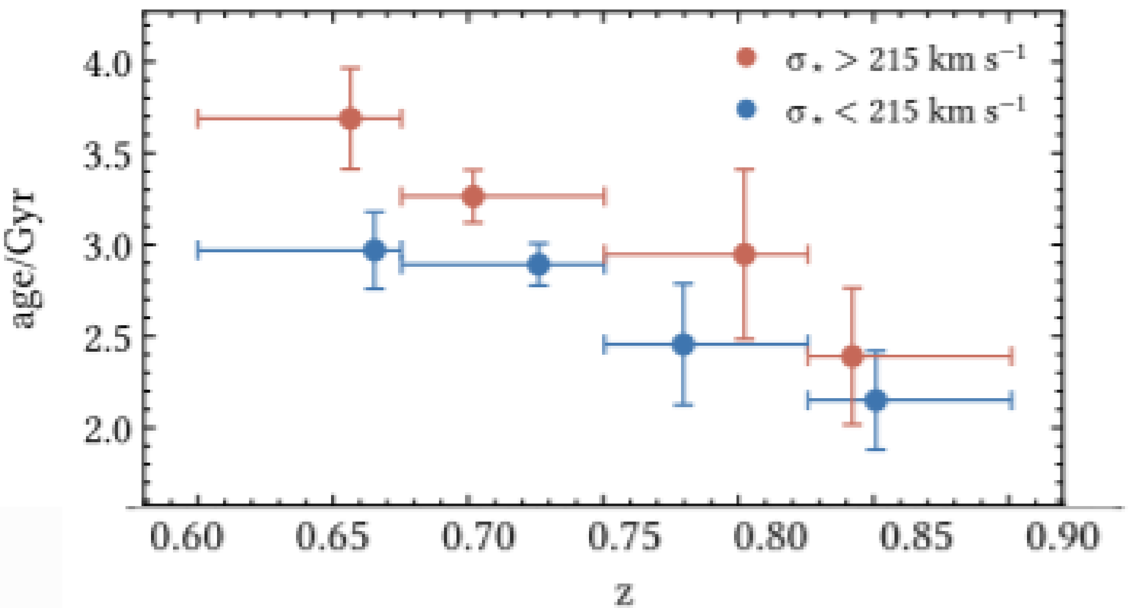
Sample same as Borghi et al. (2022a)

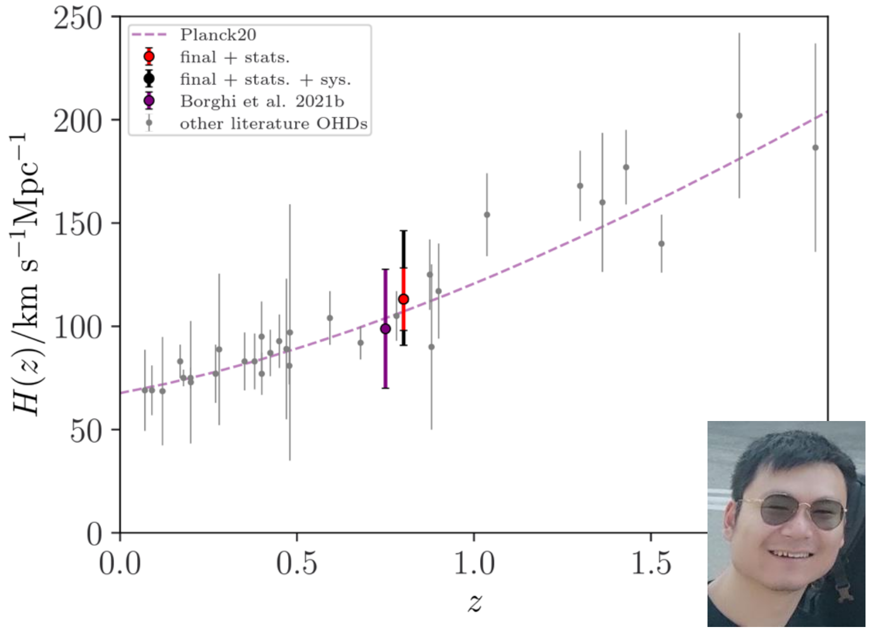
Method Full-spectral-fitting w. BAGPIPES (spectrum+photometry)
→ <u>no cosmological prior on the age</u>

- Ages compatible with the age of the Universe, and evidence of mass-downsizing



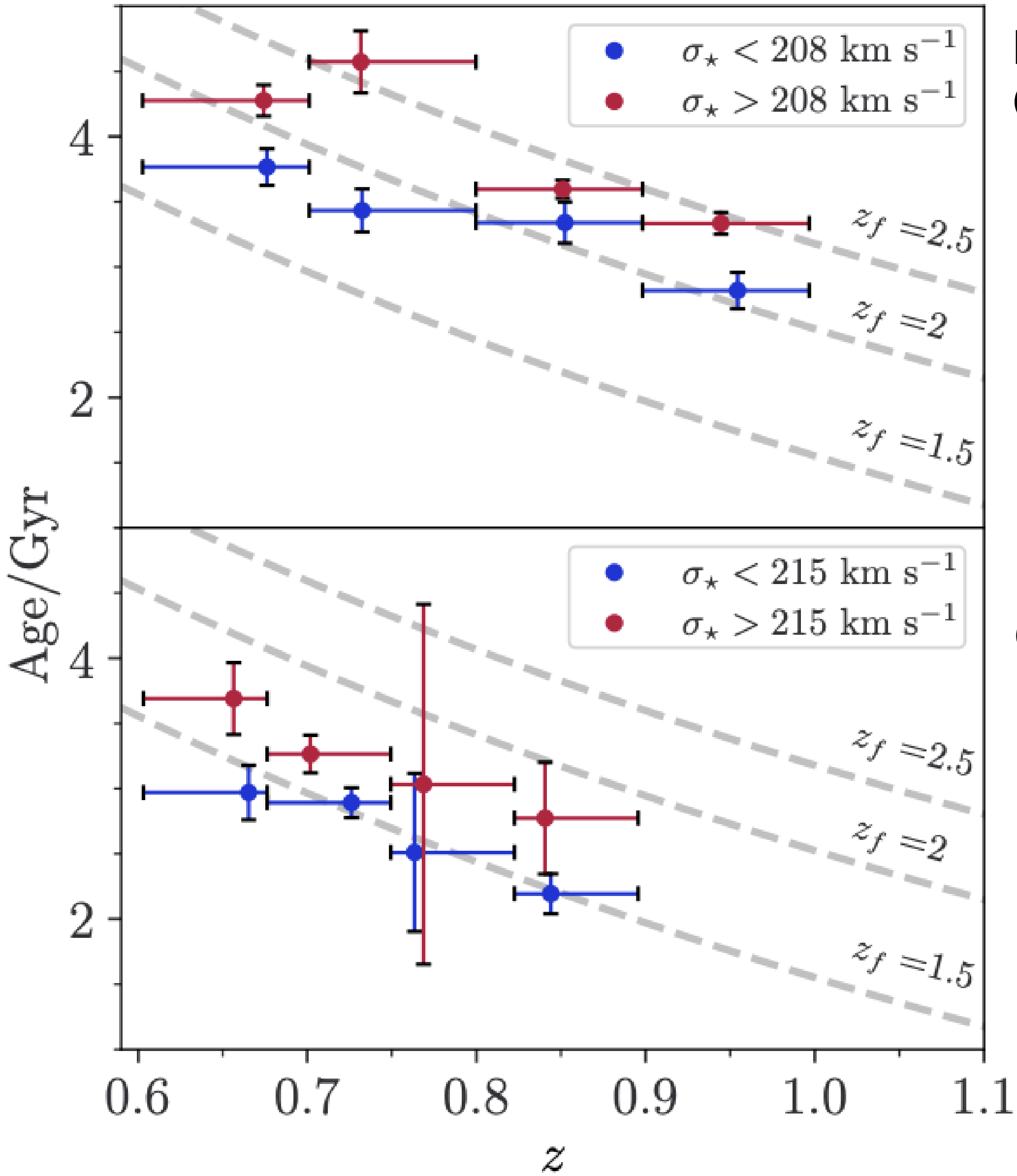






Main results

Same sample, different methods



Full spectral fitting
(Kang et al. 2022)

Lick indices
(Borghi et al. 2022)

Different absolute ages, but **extremely stable** and **consistent differentual ages**

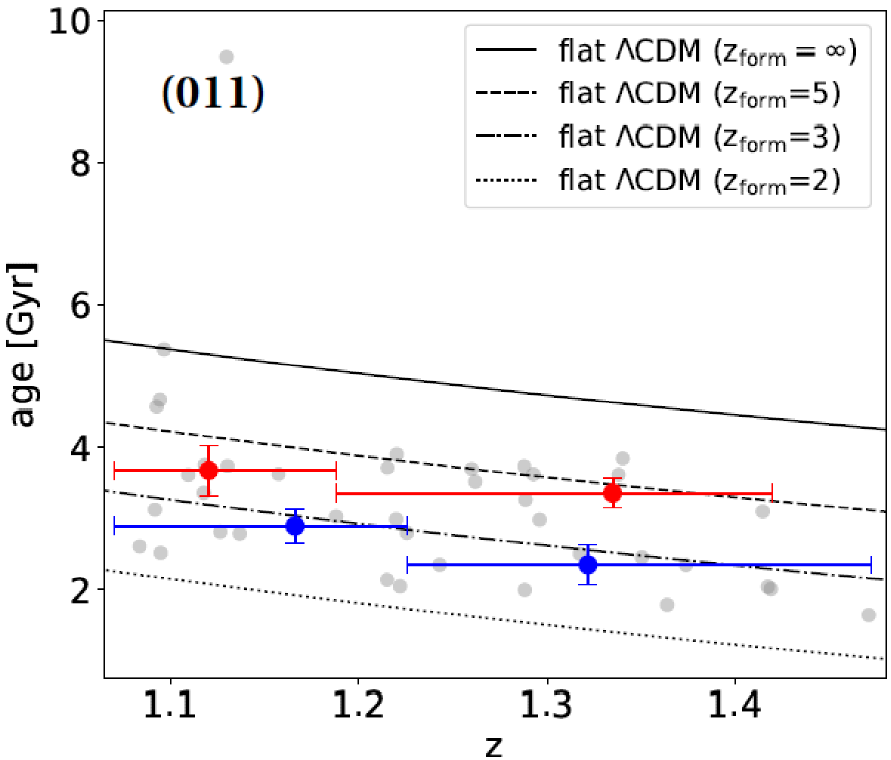
Cosmic chronometers with full-spectral-fitting 2

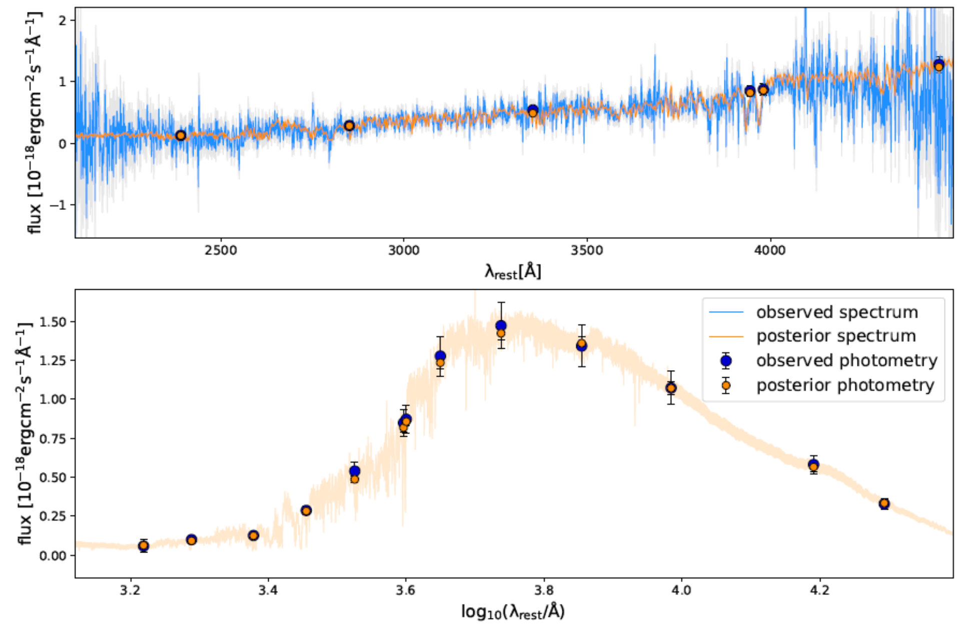
Tomasetti et al. (2023)

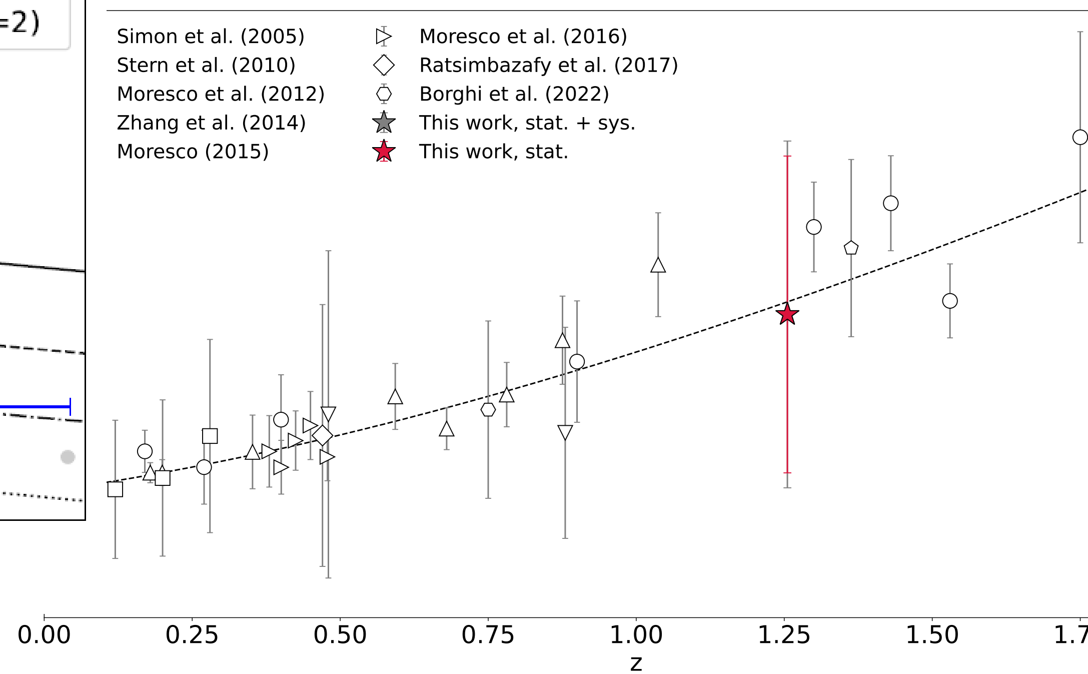
Data VANDELS DR4

Sample combined photometric+spectroscopic selection (49 CC)

Method Full-spectral-fitting w. BAGPIPES (spectrum+photometry)



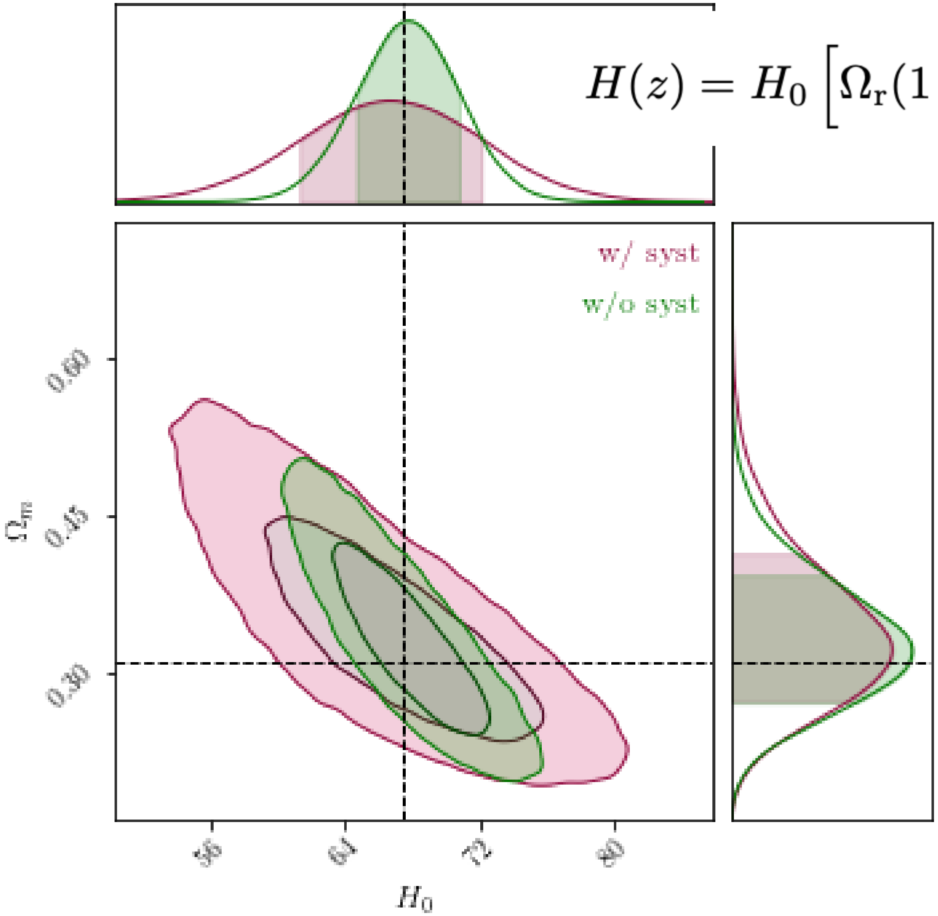




Addressing the tension

Assuming a cosmological model

The importance of the covariance



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

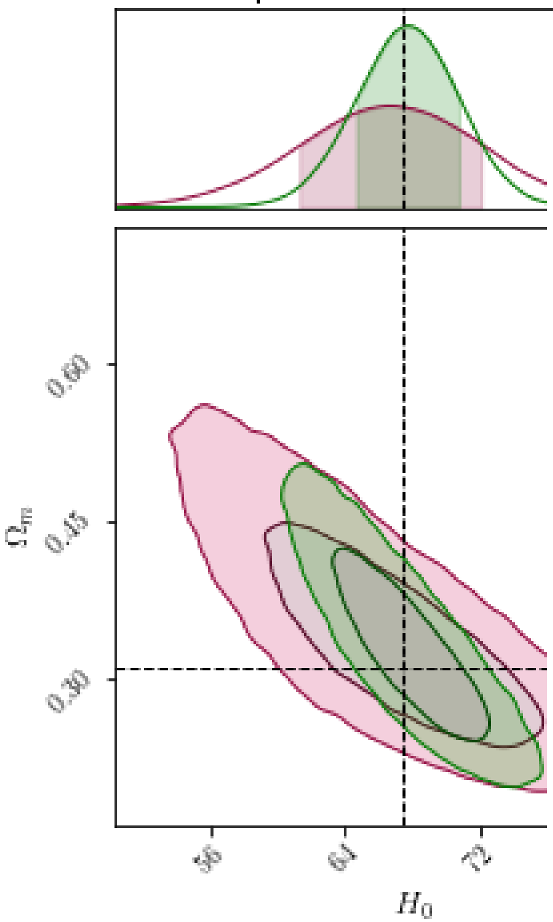
$H_0 = 66.5 \pm 5.4$ km s^{-1} Mpc^{-1}

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

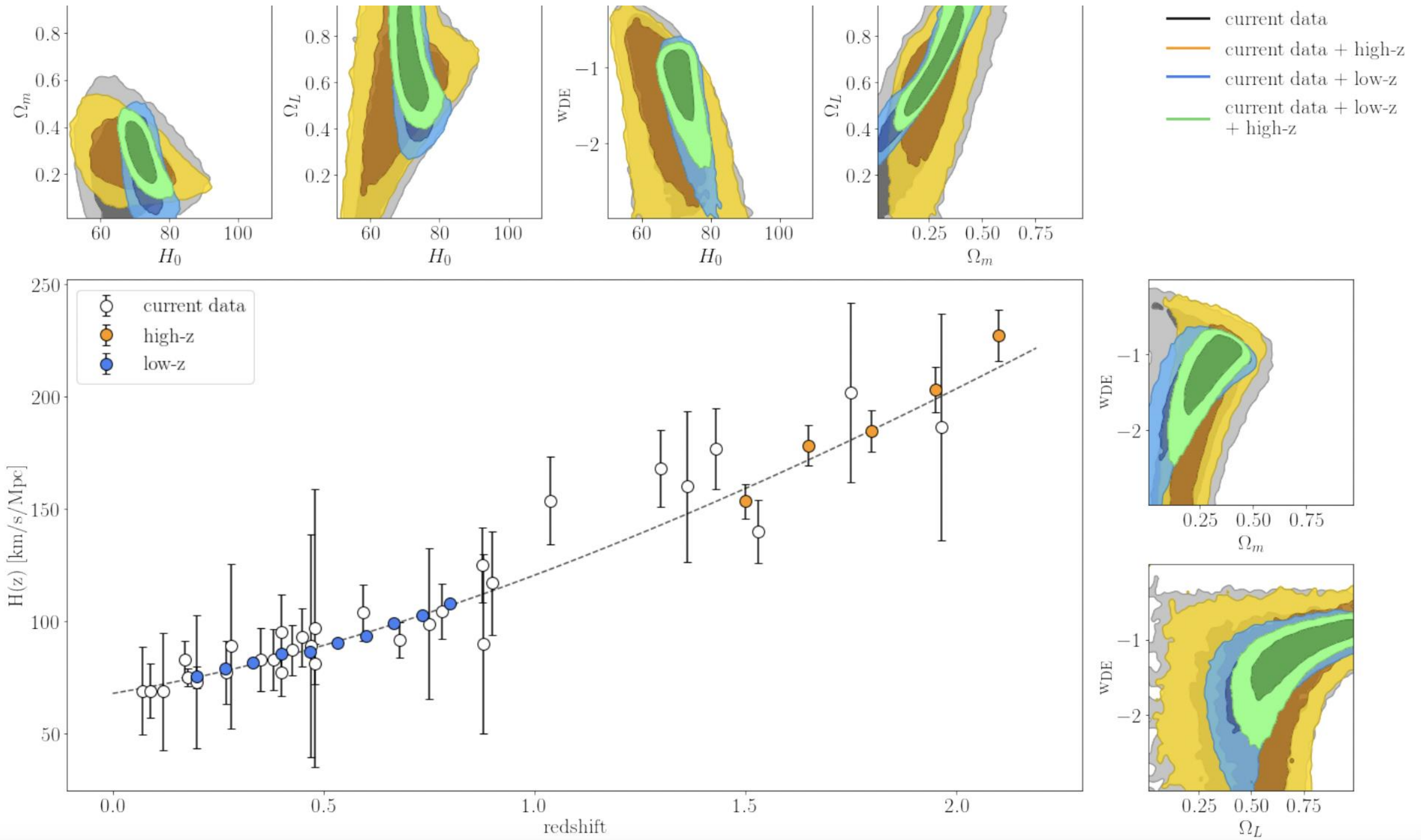
Addressing the tension

Assuming a cosmological model

The importance of the covariance



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



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

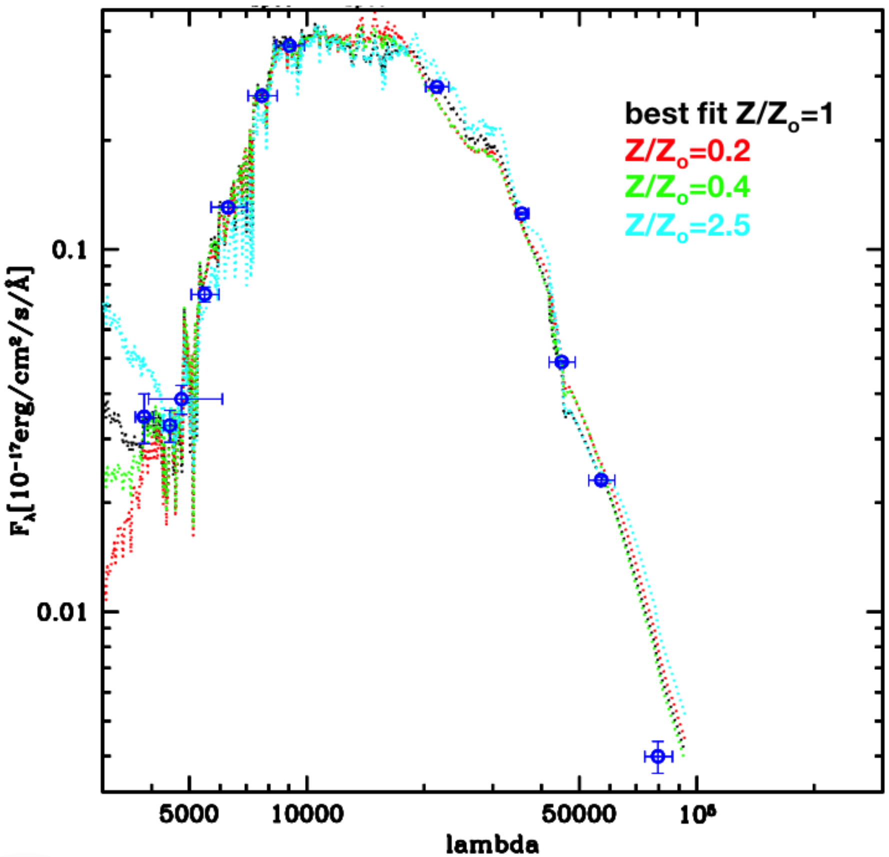
flat LCDM model, current data
Moresco et al. (2020, 2022)

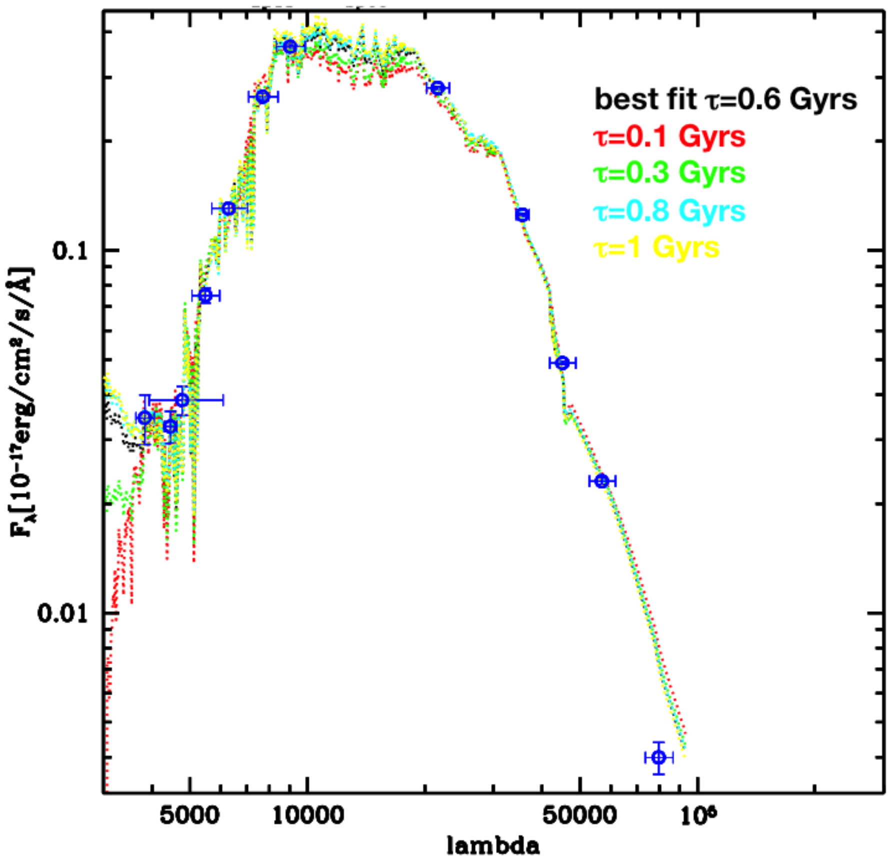
$H_0 = 71.6 +3.1 -2.7$ km s^{-1} Mpc^{-1}

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

Difficulty in age estimate

Different combination of parameters may yield to the same spectral energy distribution shape → **age-metallicity degeneracy**



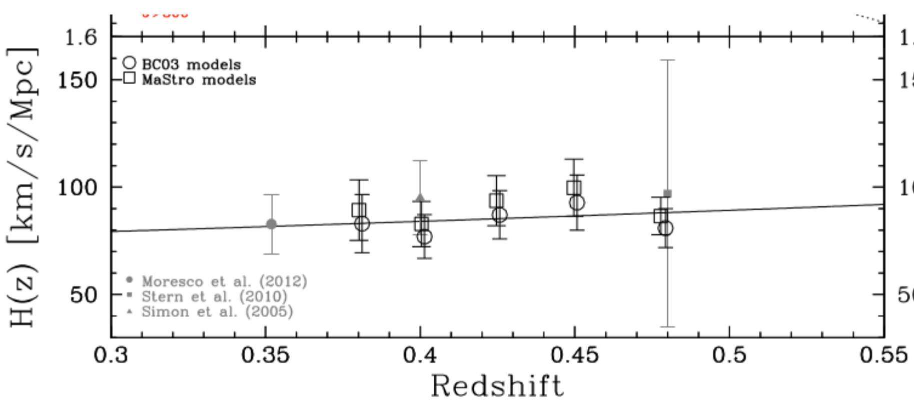


Addressing systematics 1: SPS models

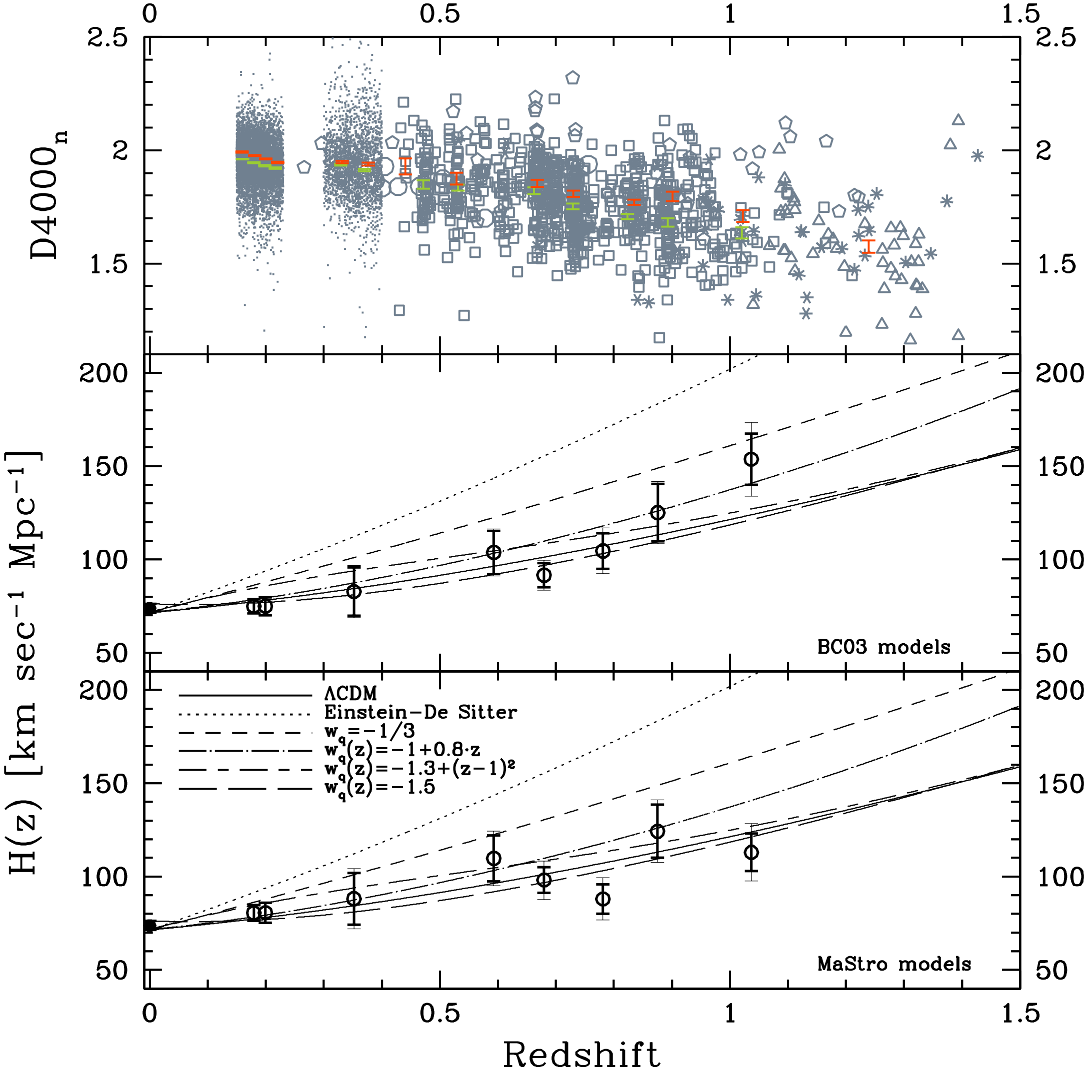
To assess the robustness of the results w.r.t the assumed SPS model, different ones have been explored

In all analyses, the results are fully compatible within errorbars

dD4000 more stable than dage



Moresco et al. (2016a)

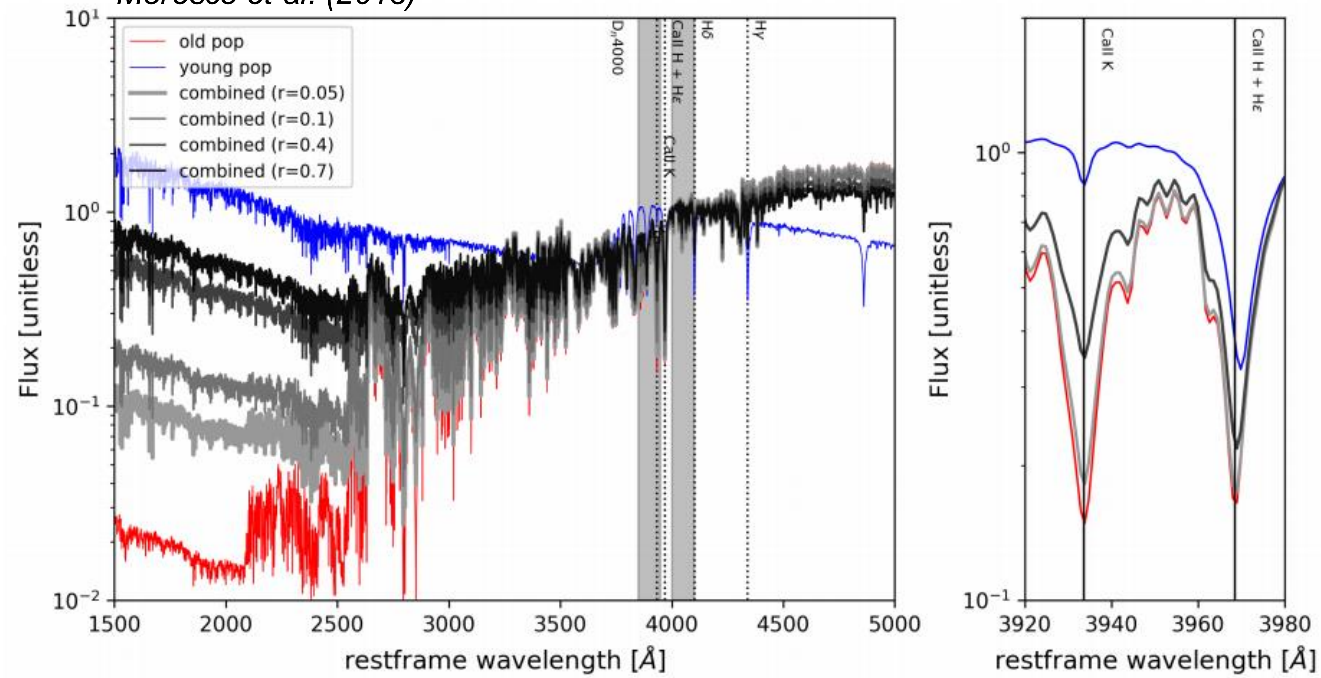


Moresco et al. (2012a)

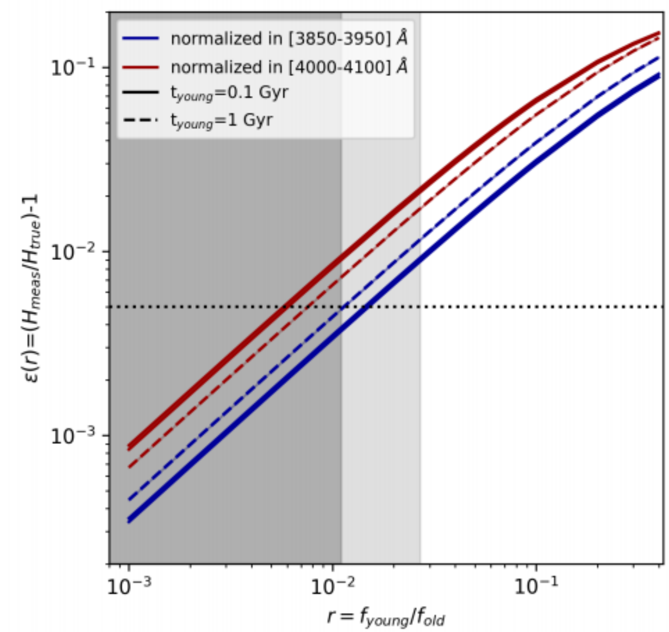
Addressing systematics 2: rejuvenation

The presence of a young, underlying component can bias the measurement: several indicators can be used to trace it

Moresco et al. (2018)



- UV flux
- emission lines
- colors (e.g. NUVrJ)
- H/K ratio



H/K ratio

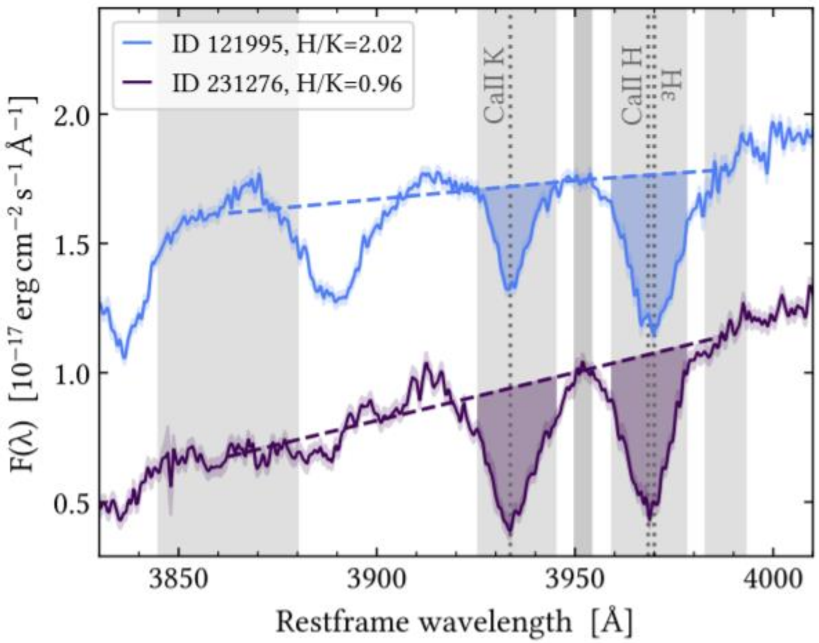
contamination

cov. matrix

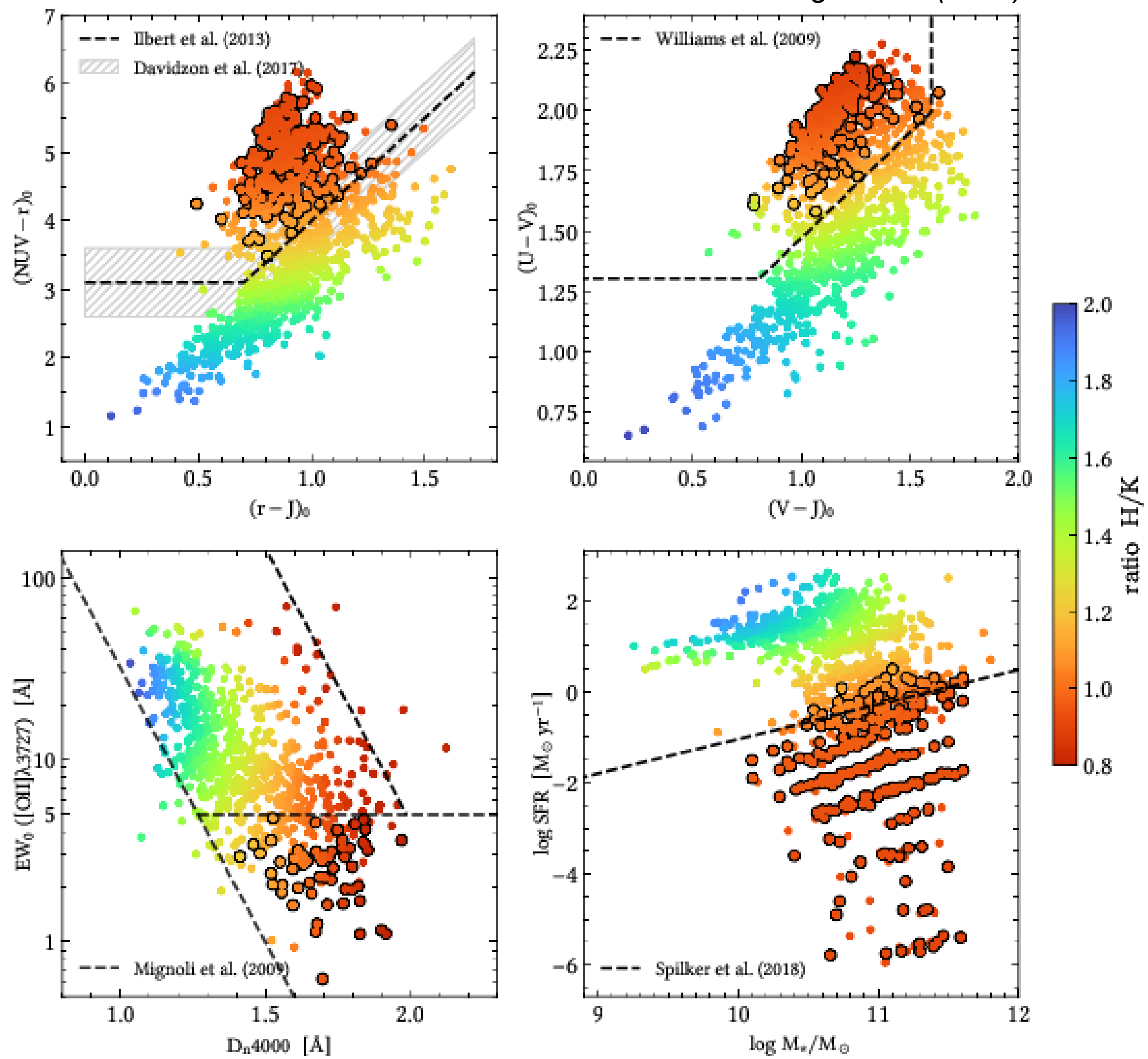
$$Cov_{young} = H(z_1)H(z_2)\varepsilon(r_1)\varepsilon(r_2)$$

Revising the H\K diagnostic

Powerful indicator introduced by Rose (1984), then mostly disappeared; definition revised

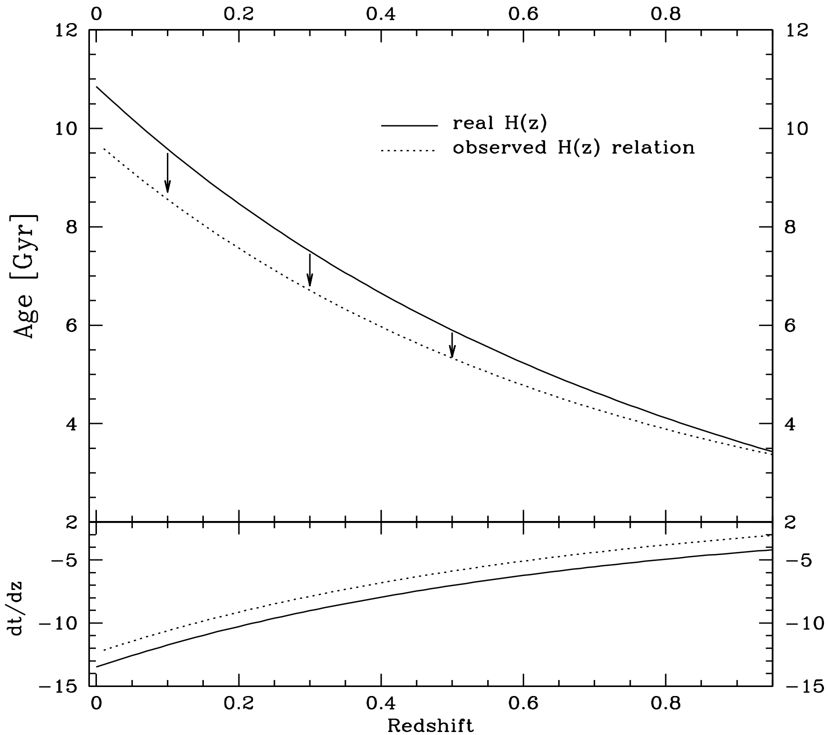


Borghi et al. (2021)



Strong and significant correlation with all the main SF indicators

Addressing systematics 3: progenitor bias



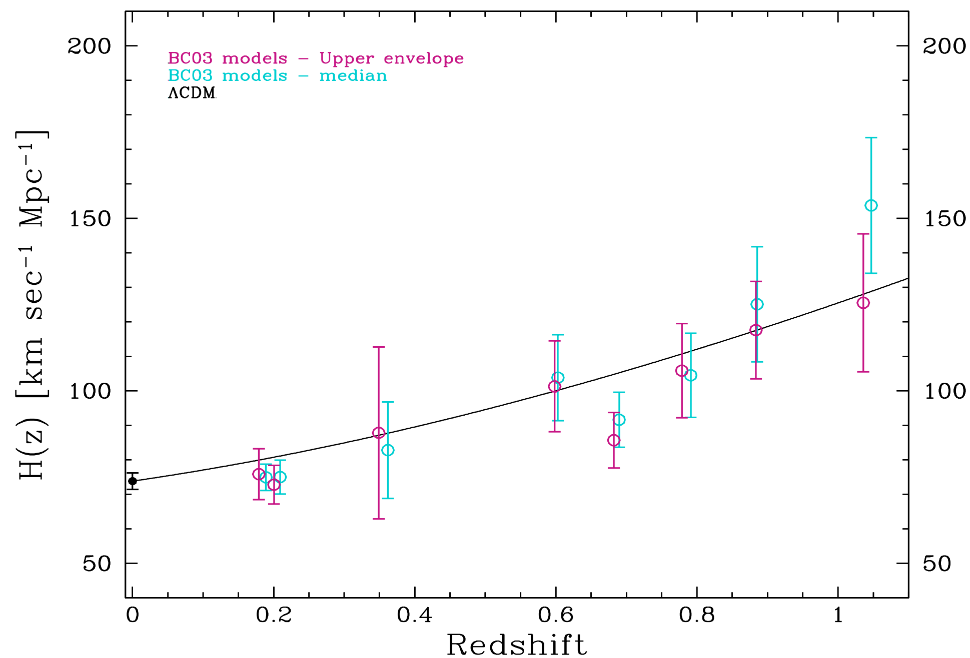
ETGs at high redshift might be biased towards the oldest progenitors of present-day ETGs, therefore not sampling the same population considered at intermediate redshifts

$$H(z)_{observed} = H(z)_{true}(1+\Delta_{progbias})$$

$$\Delta_{progbias} = \frac{1}{1-\delta/dt} - 1$$

$$\delta/dt \approx \frac{\Delta z_{form}}{\Delta z}\frac{1+z}{1+z_{form}}\frac{H(z)}{H(z_{form})}$$

Upper envelope test



Moresco et al. (2012a)

Addressing systematics 4: final ingredients

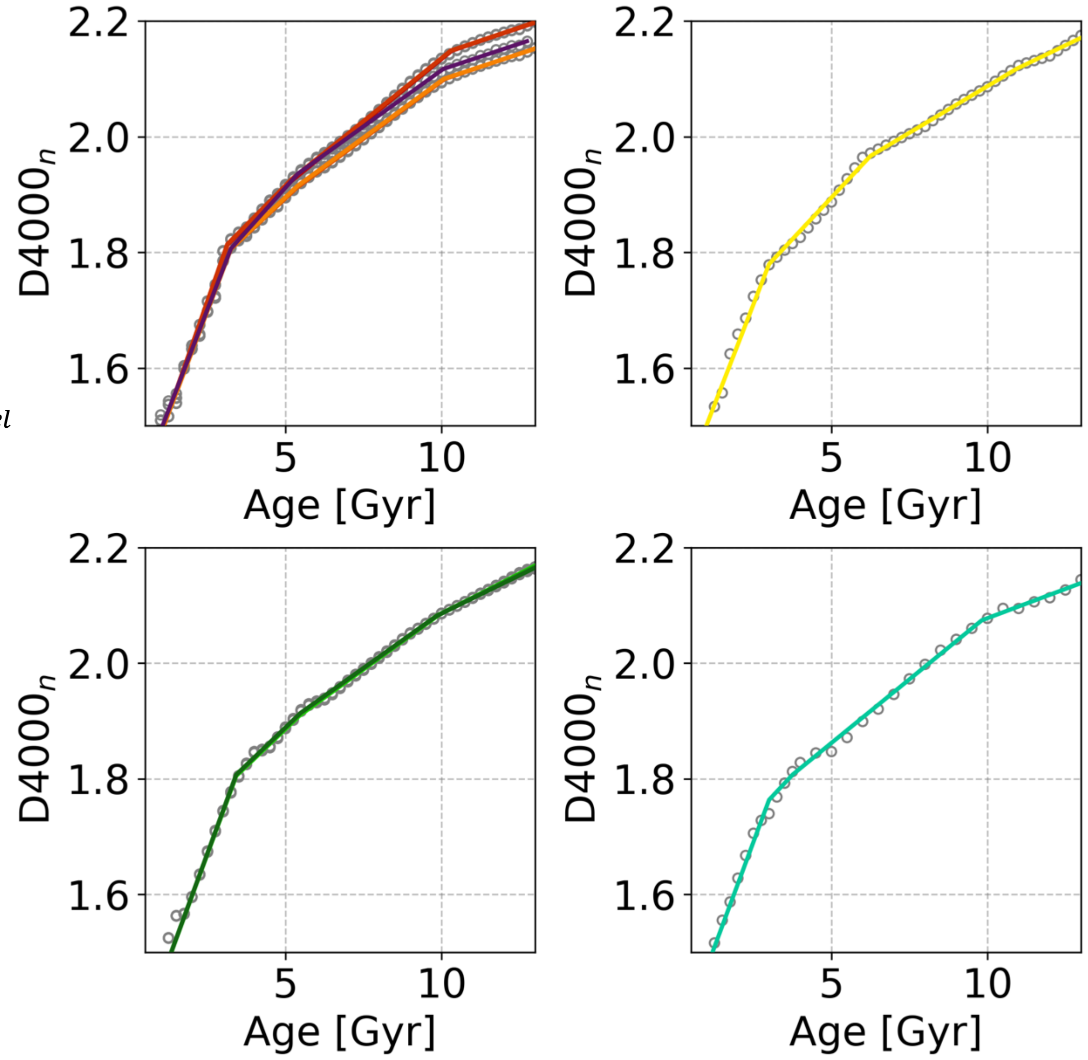
Wide range of SPS model explored (BC03, BC16, M11, FSPS, E-MILES), considering various ingredients (IMFs, stellar libraries) to assess the full impact of SPS model in the covariange matrix of the method

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

Impact estimated as a function of redshift by calculating for various possible combinations

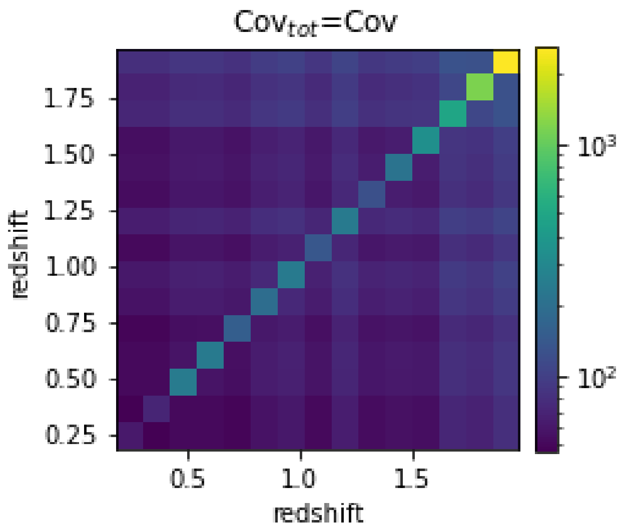
$$H(z)_{i,j} = -\frac{A_j}{1+z}\frac{dz}{dD4000_i}$$

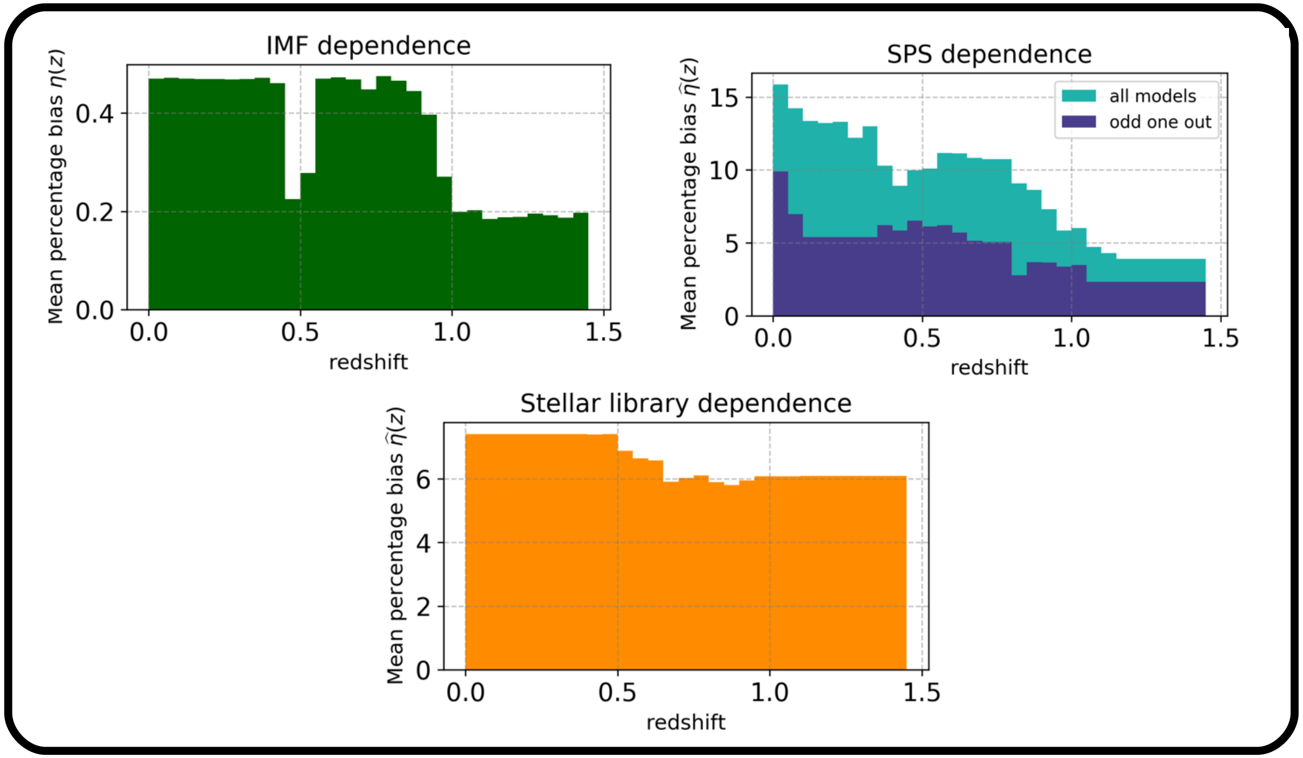
Total impact due to SPS modeling of the order Of ~5-10%, but can improved with a better model comparison

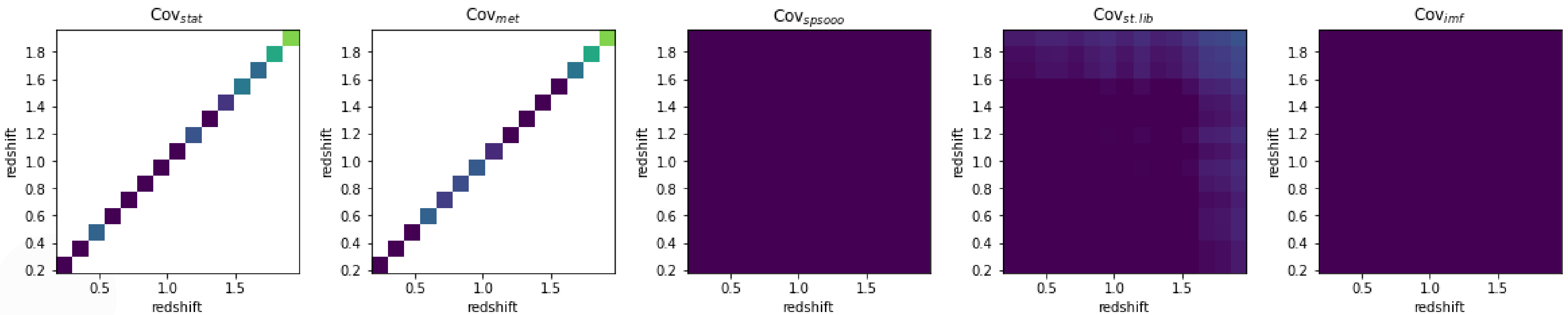


Moresco et al. (2020)

Wrapping up: CC total covariance matrix







Data exploited

- **SDSS MGS+LRGs, zCOSMOS-20k, UDS, GDDS, GOODS-S, K20, and more**: more than 11000 massive and passive galaxies in the range 0.15<z<1.4
(Moresco et al. 2012a)

- **SDSS BOSS DR9**: more than 130000 massive and passive galaxies in the range 0.2<z<0.8
Moresco et al. (2016a)

- **high-z ETGs**: most massive and passive ETGs (30 galaxies) from literature in the range 1.4<z<2.2
Moresco (2015)

Metallicity estimate from literature (when available) or estimated directly on high-SNR stacked spectra

Accurate selection combining photometric, spectroscopic (and eventually morphological) criteria, selecting the purest sample of cosmic chronometers

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

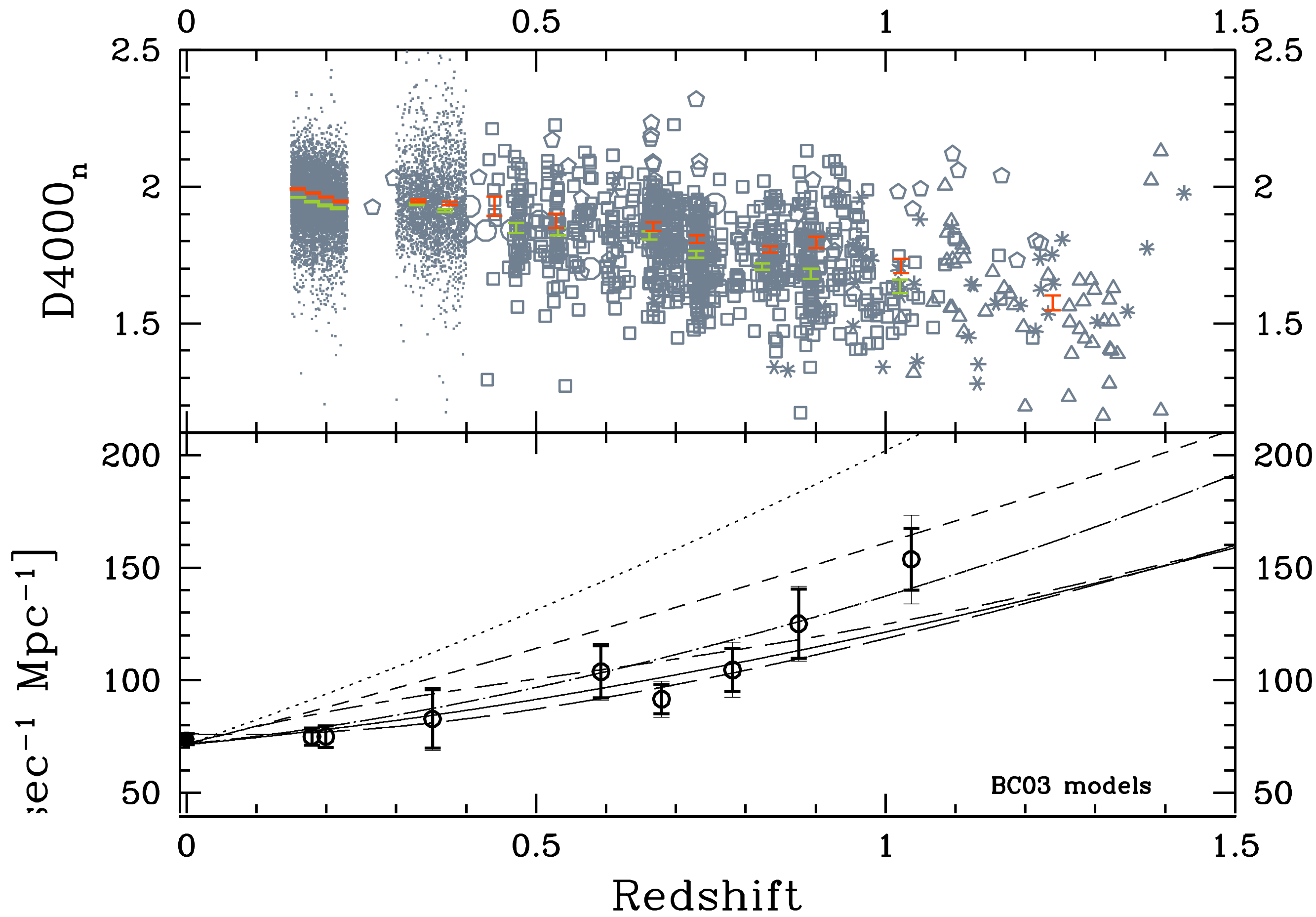
- 5 H(z) measurements at 0.3<z<0.5
- **precision of ~6% at z~0.4**, once averaged
- mapping a **crucial redshift range** to probe the transition between accelerated and decelerated expansion

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)

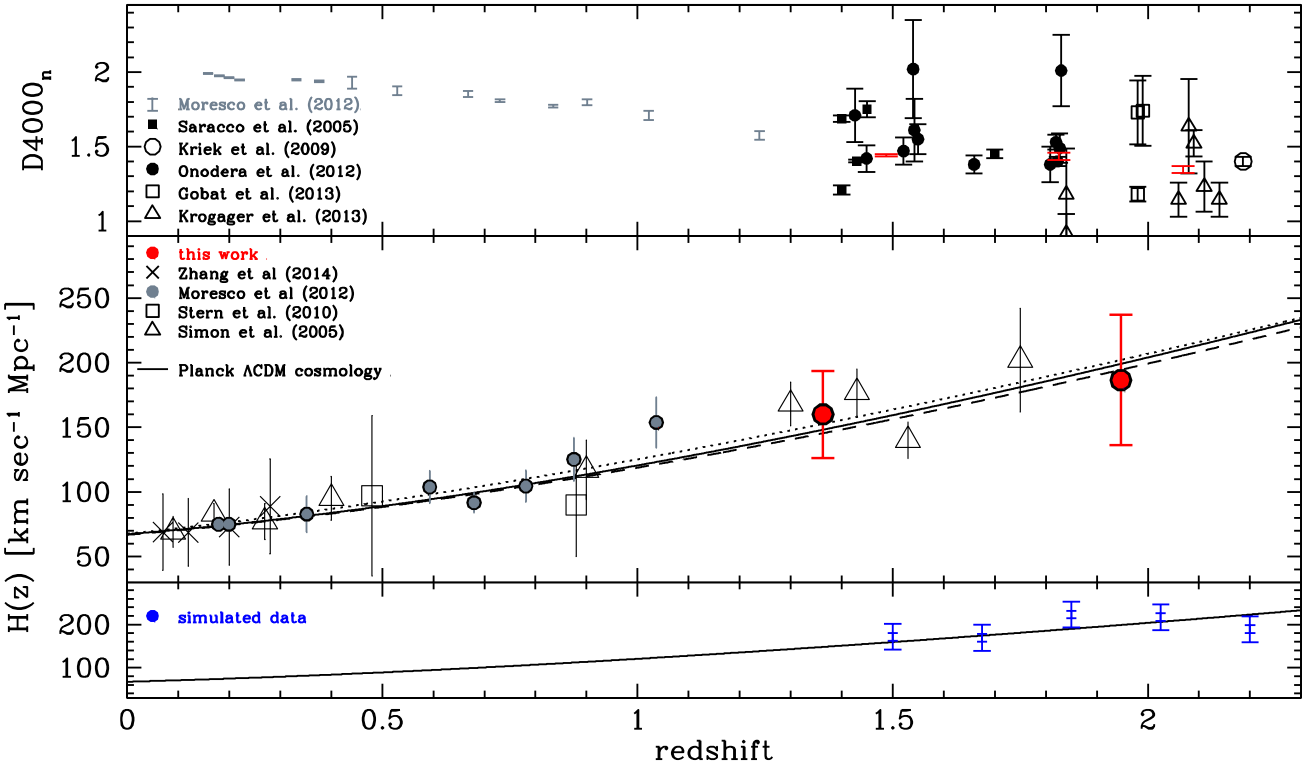
Results on the SDSS-extended catalog

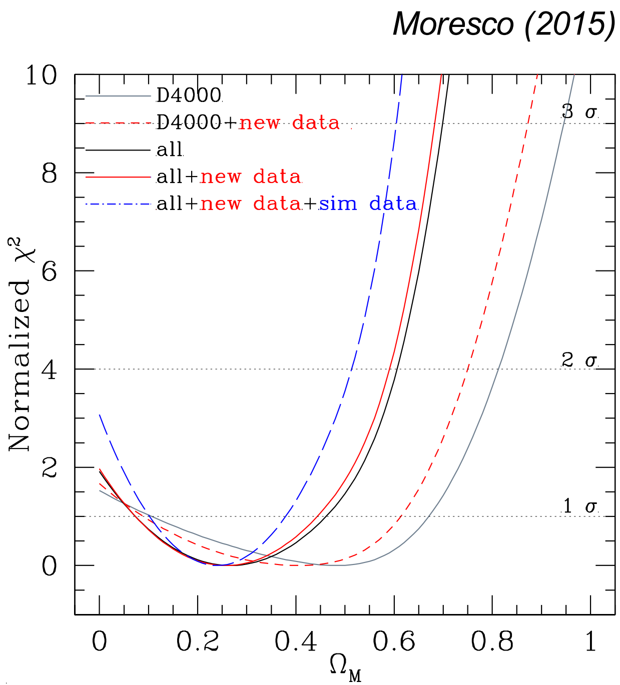
- **precision ~5% at z~0.2**
  including systematic errors
- precision ~12% across the entire redshift range
- **consistent results with different SPS models**
- EdS model discarded at 7σ
- direct and robust (6σ) evidence of the accelerated expansion
- new path to discriminate alternative cosmologies



Moresco et al. (2012a)

Moving to higher redshifts



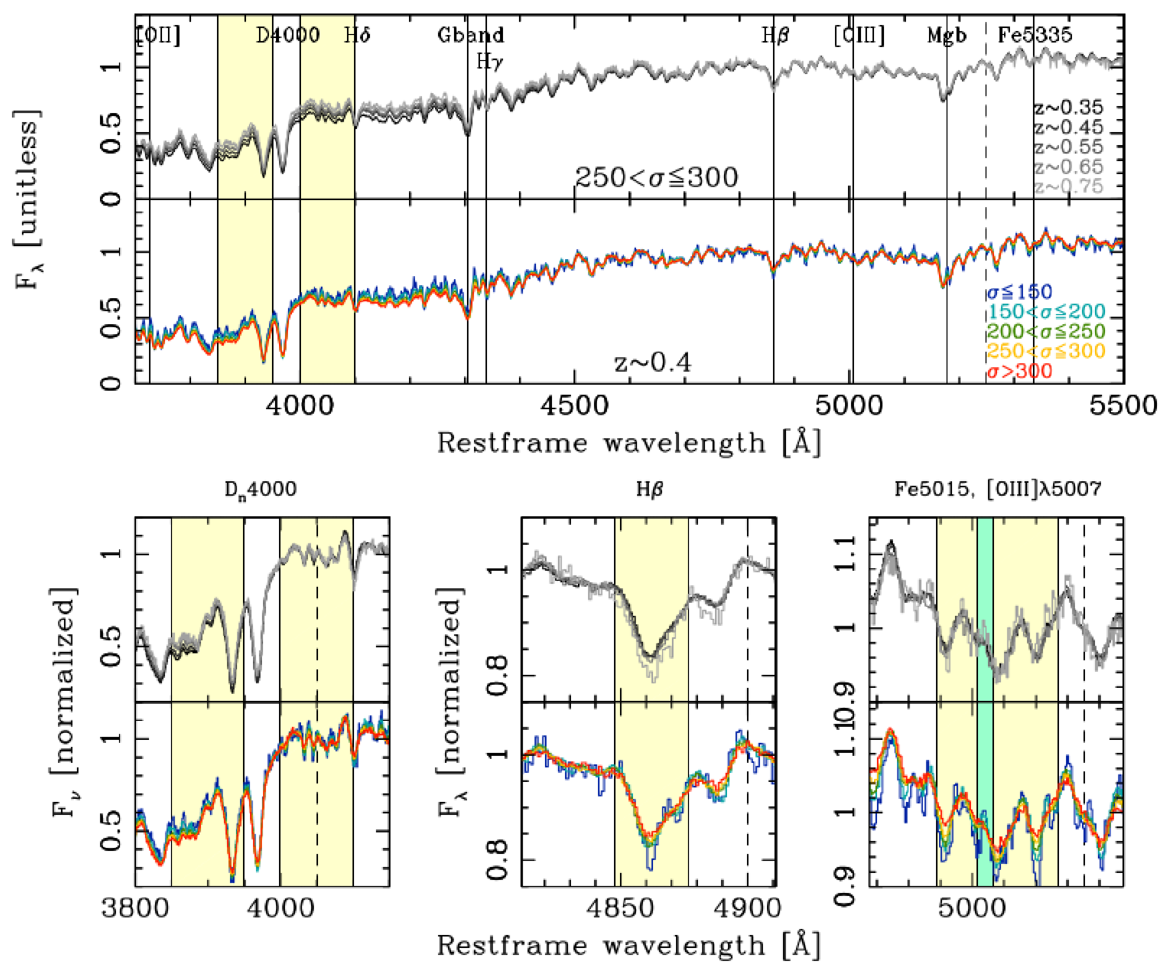


- **2 new H(z) points, for the first time at z~2**
- test case (<30 galaxies) to show the potential of this approach at high z (e.g. Euclid)
- improved cosmological constraints (~5% for Ω_m and w_0)

Exploring the SDSS-BOSS survey

- Selection of the **most massive and passive ETGs** sample from the BOSS parent catalog: more than 130000 galaxies at 0.2<z<0.8
- **Separated analysis in velocity dispersion and redshift bins**, D4000 measurement, and median stacked spectra
- **Full spectral analysis** with 3 independent codes, and measurement of metallicity
- Average metallicity around Z/Z_{sun}=1.35±0.3

Moresco et al. (2016a)



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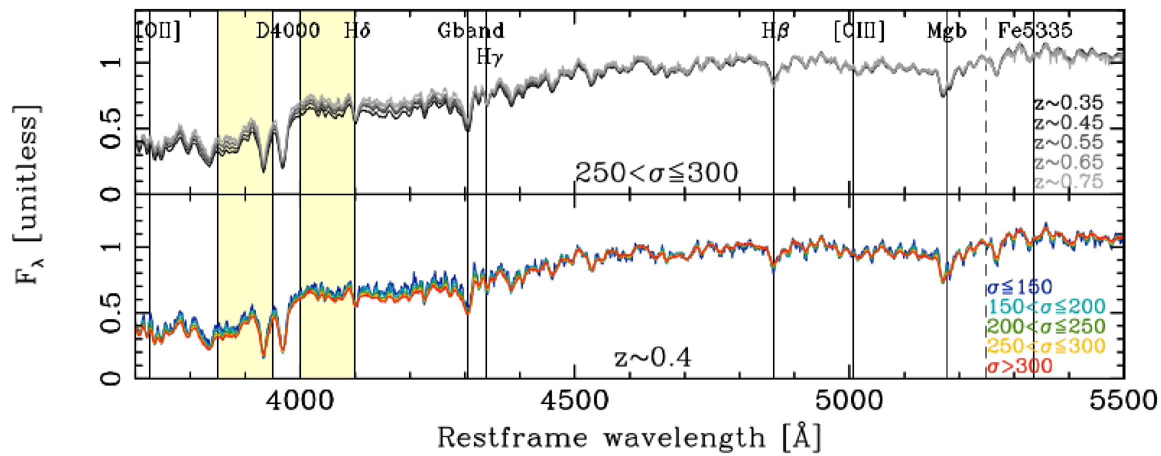
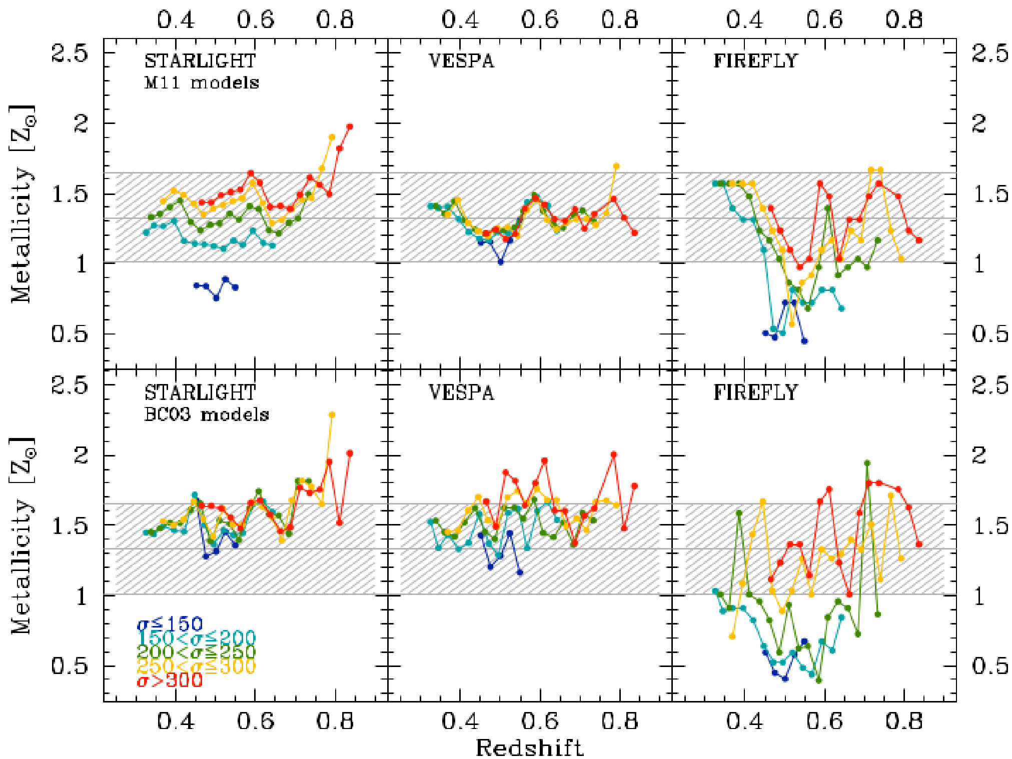
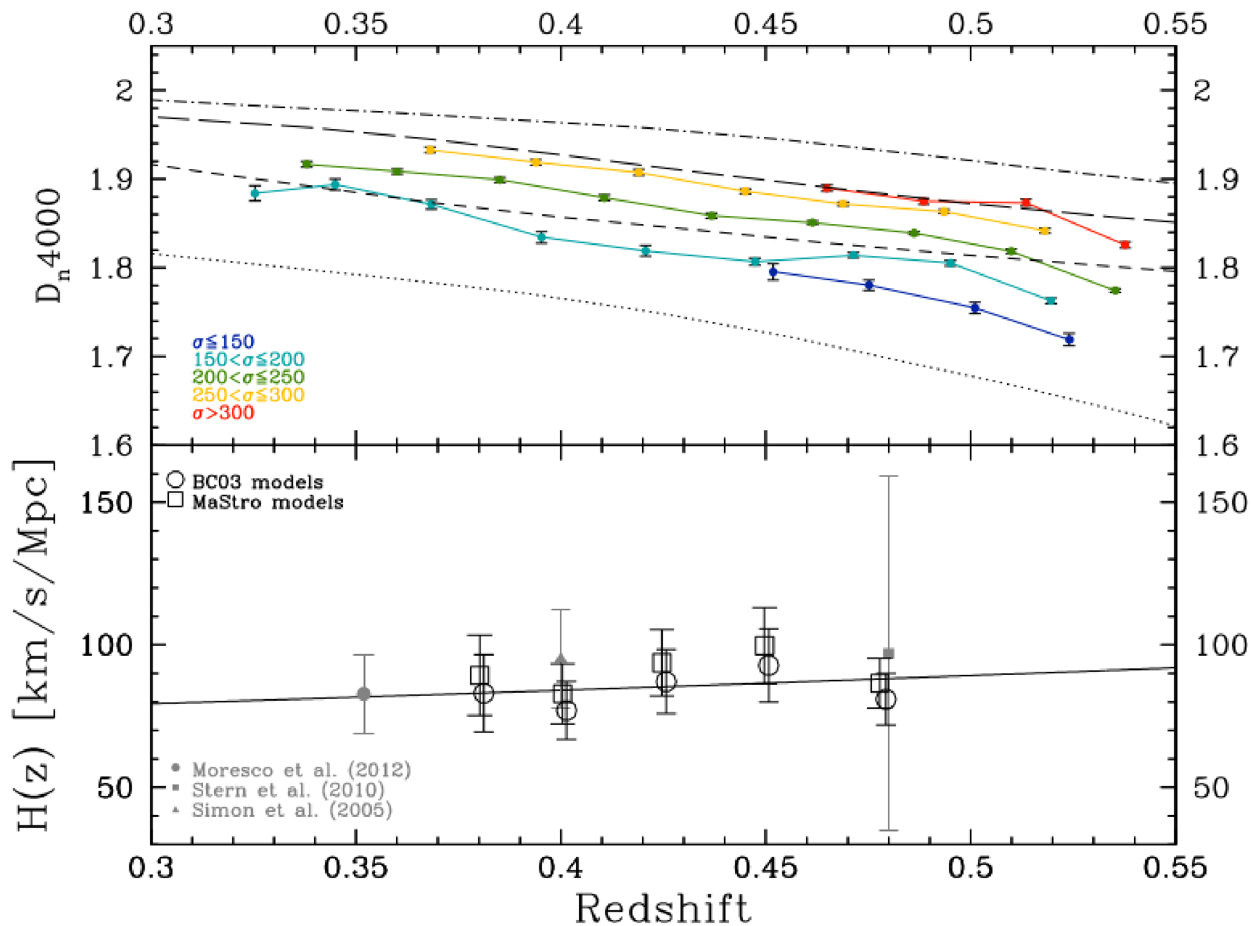




Exploring the SDSS-BOSS survey

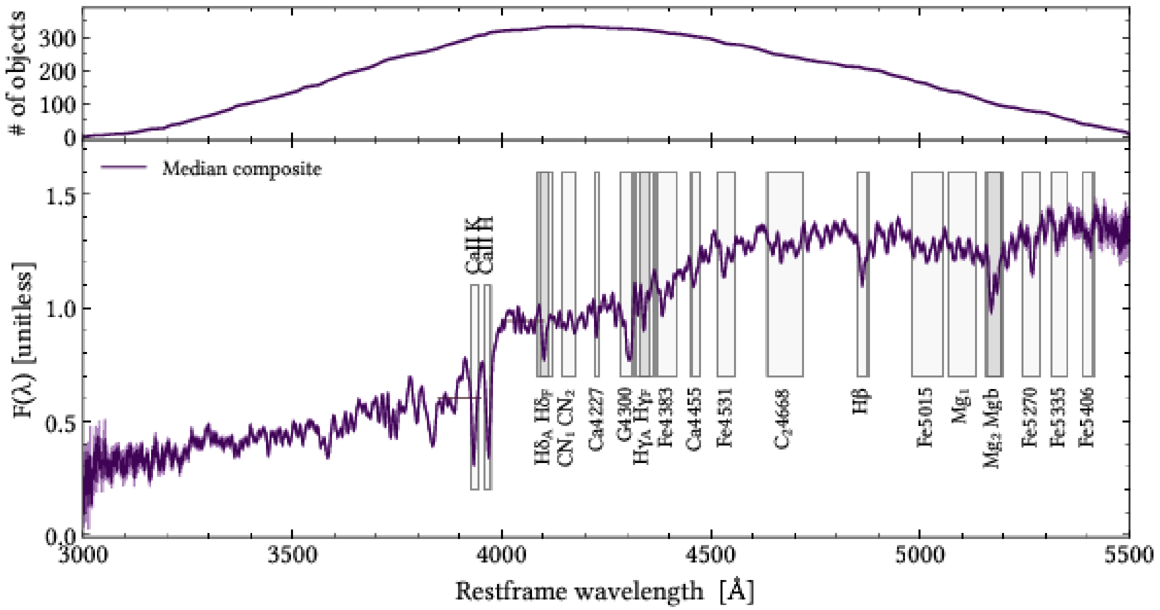
- Obtained **5 new H(z) values at 0.3<z<0.5**
- **Accuracy of ~6%**, once averaged
- mapping a **crucial redshift range** to probe the transition between accelerated and decelerated expansion



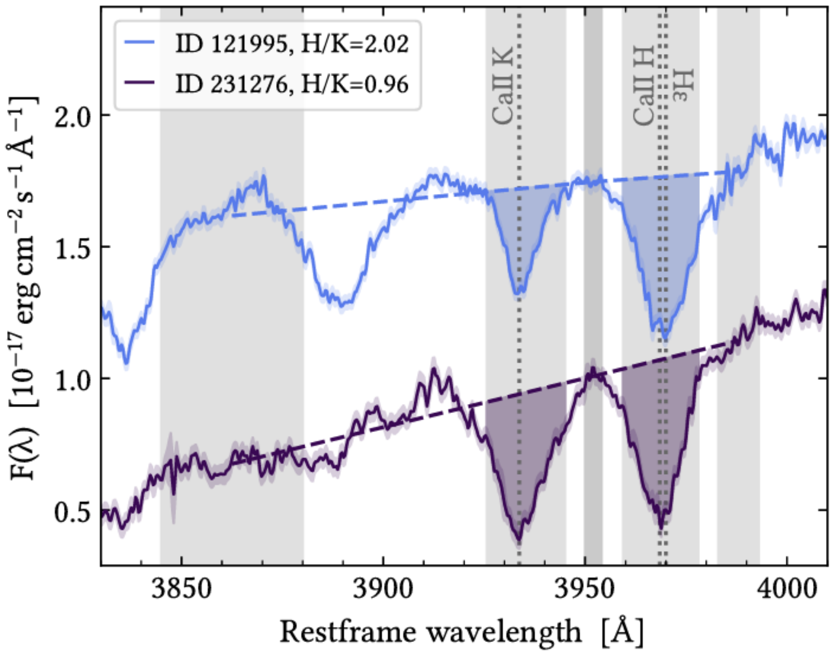
Moresco et al. (2016a)

Cosmic chronometers with absorption features

Borghi et al. (2022a, 2022b)



contamination by young population
⟹ rejected



old population

Data LEGA-C DR2

Sample combination of photometric and innovative spectroscopic criteria to maximize purity

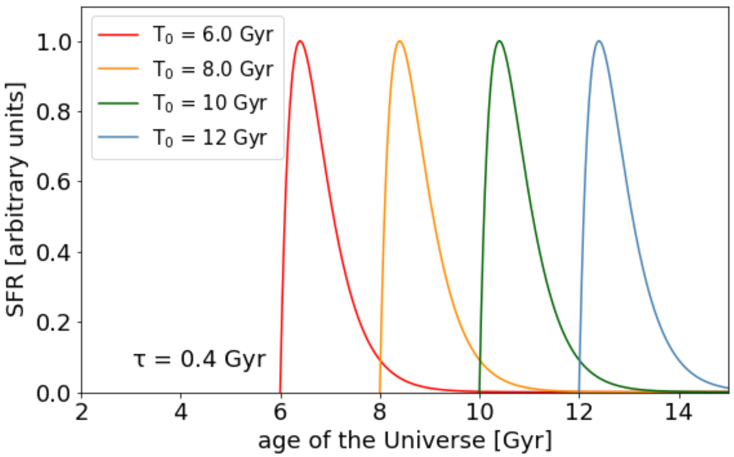
Method Lick indices (absorption features tracers of age, metallicity and α/Fe)

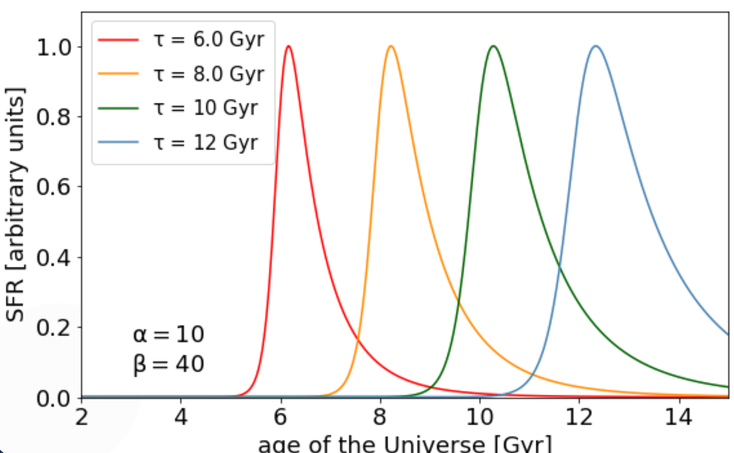
Changing SFH

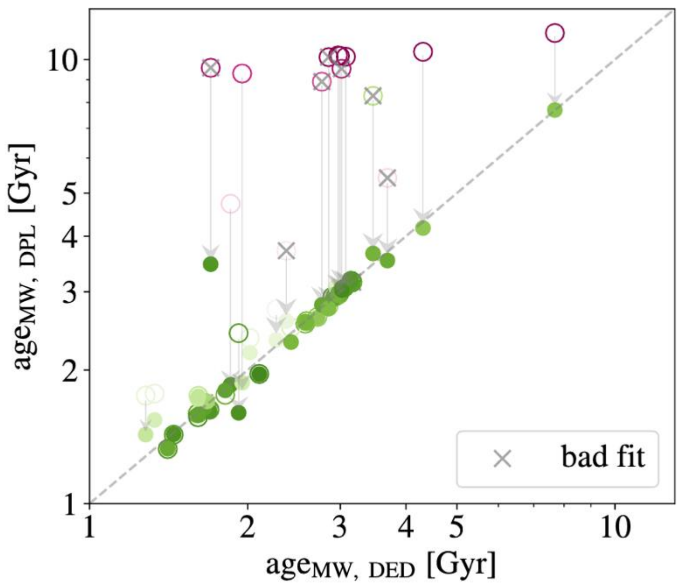
Tomasetti et al. (2023)

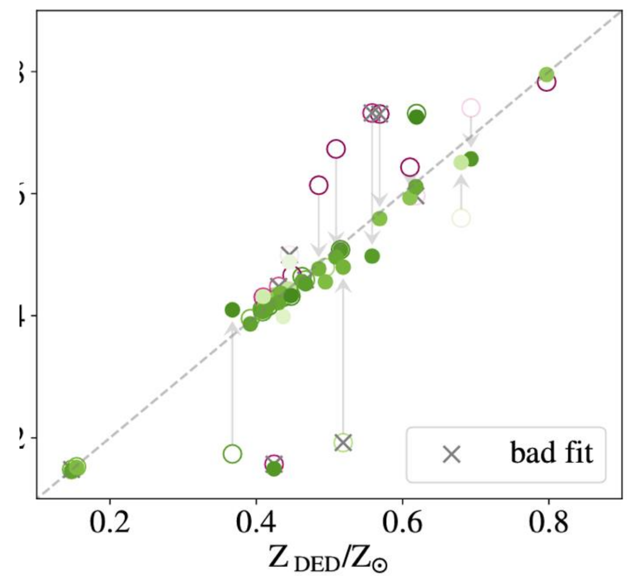
Analysis with different SFHs (delayed exponentially declining and double power law)

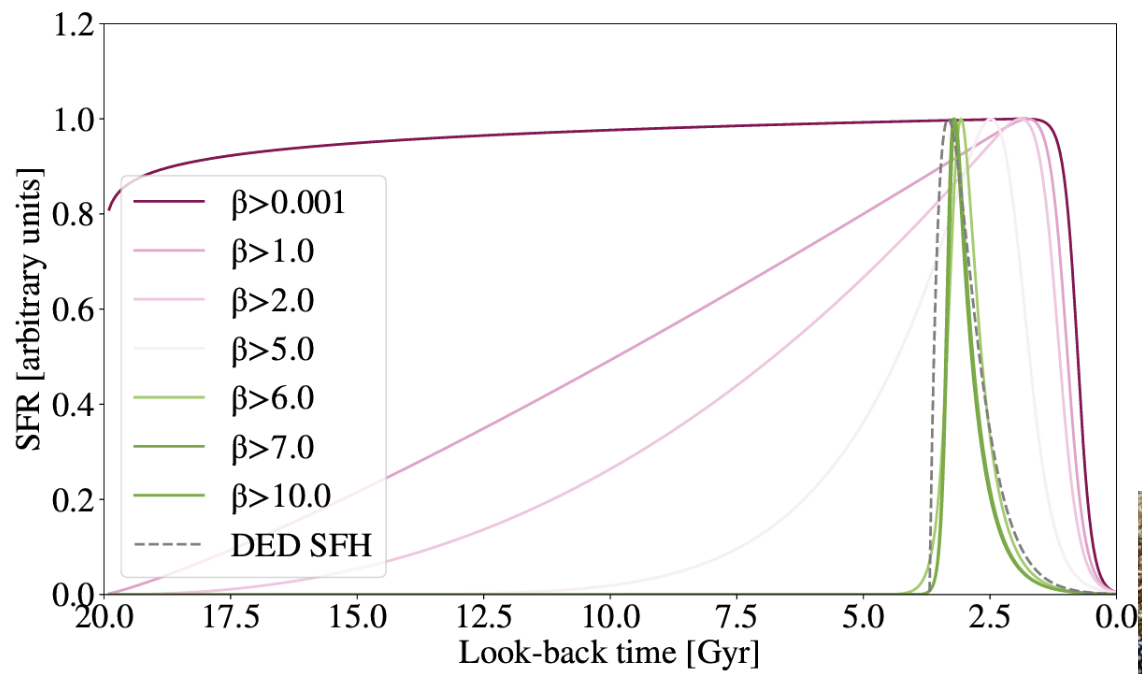
only 2% fluctuation in median age mass and metallicity



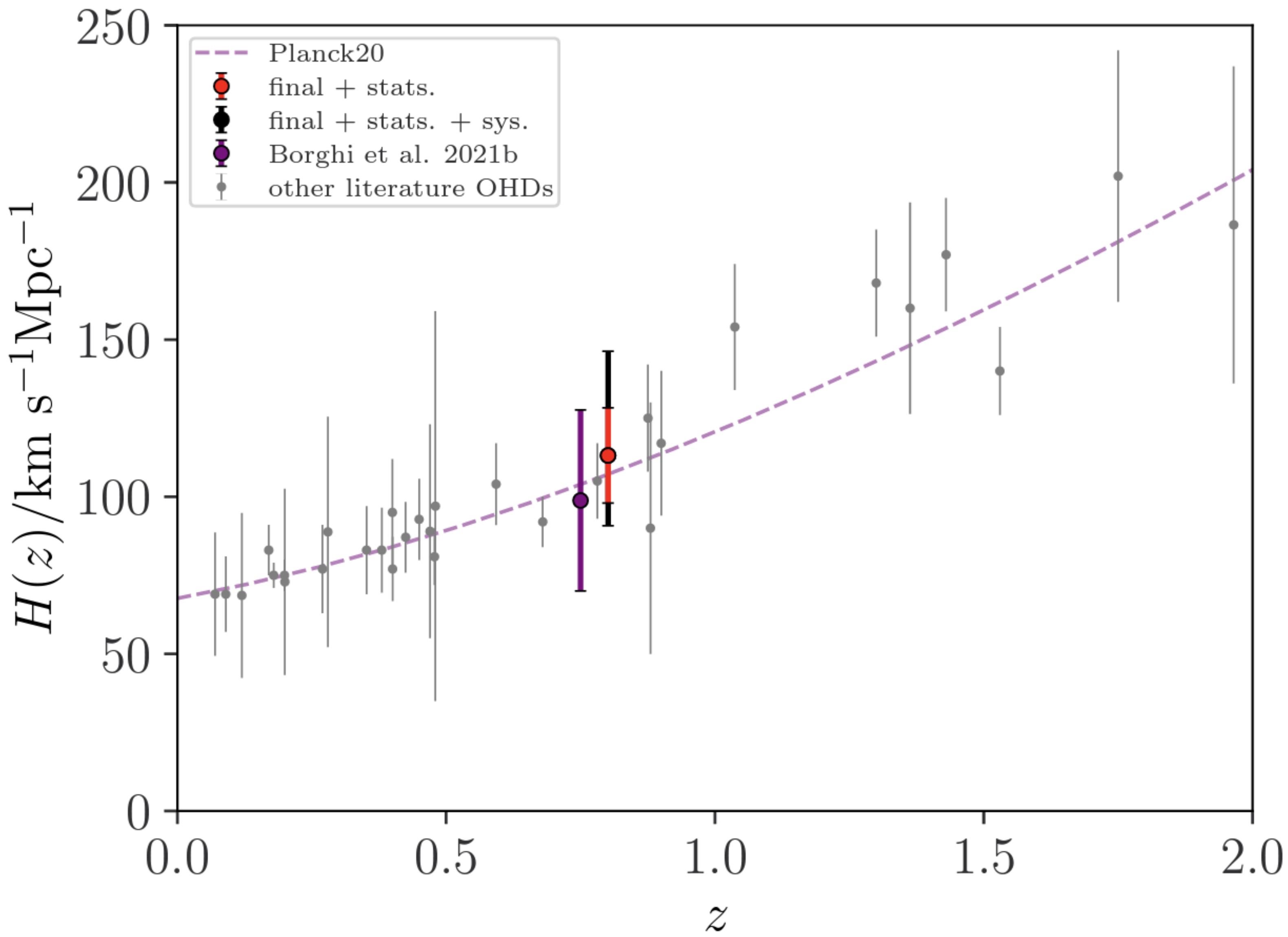








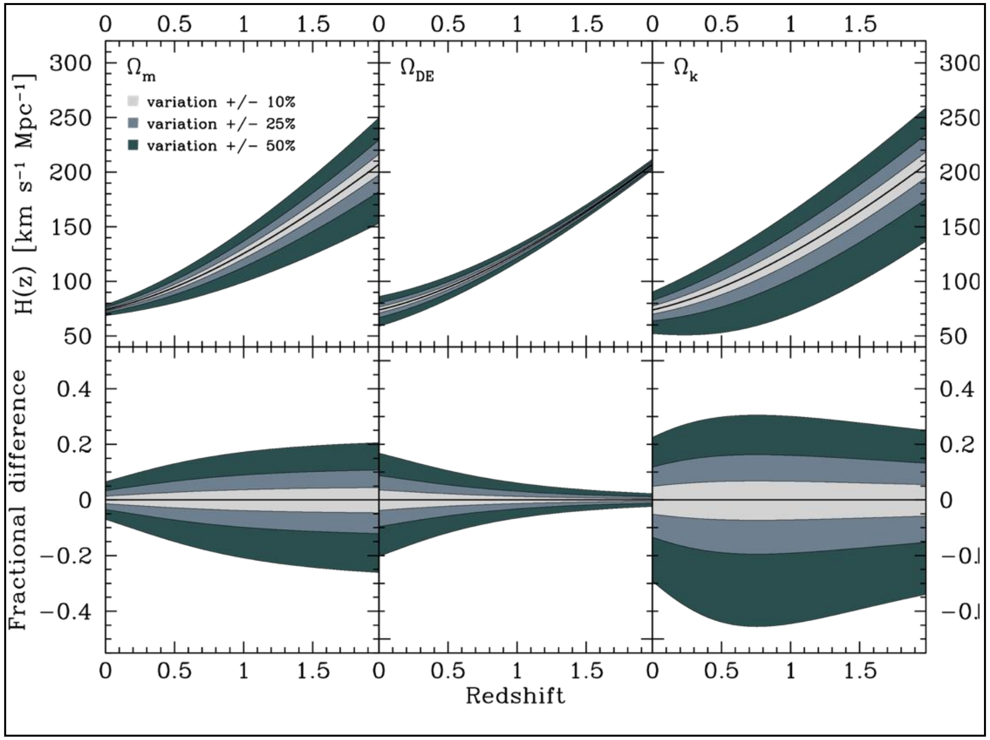
Robustness of the differential ages

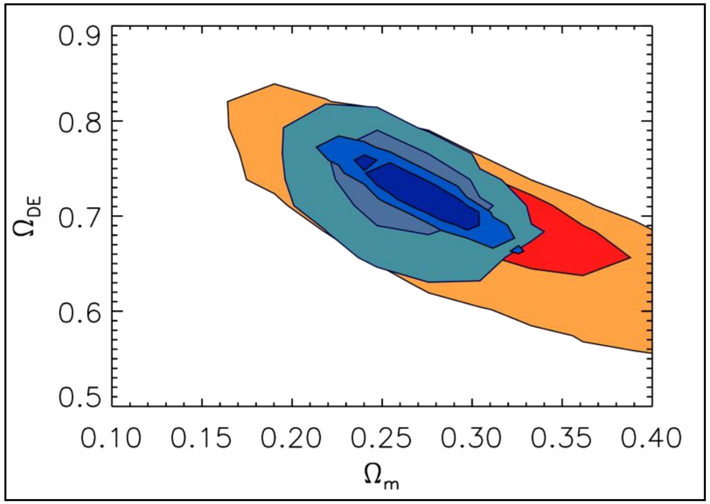


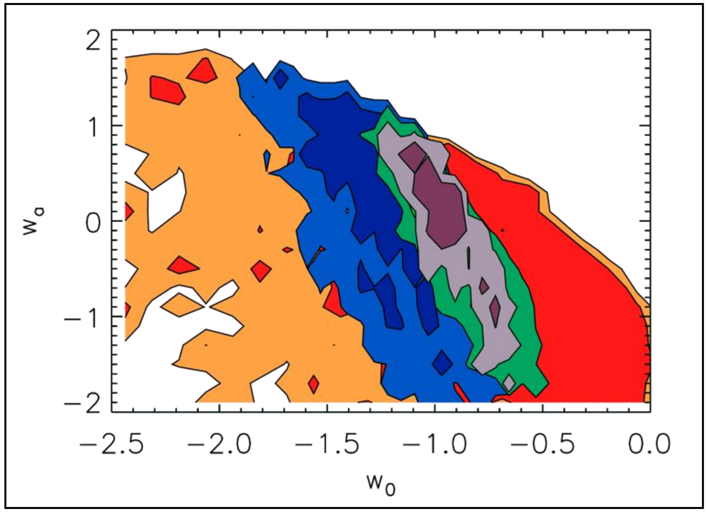
Cosmological constraints

$$H(z) = H_0\left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE}(1+z)^{3(1+w_0+w_a)}e^{-3w_a\frac{a}{1+z}}\right]^{1/2}$$

Moresco et al. (2012b)





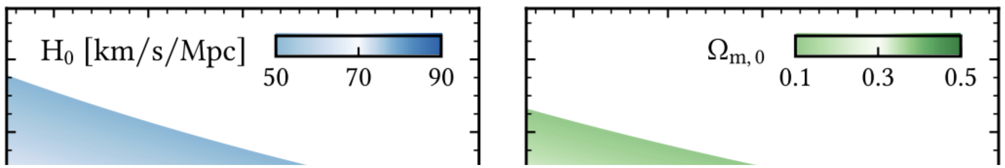


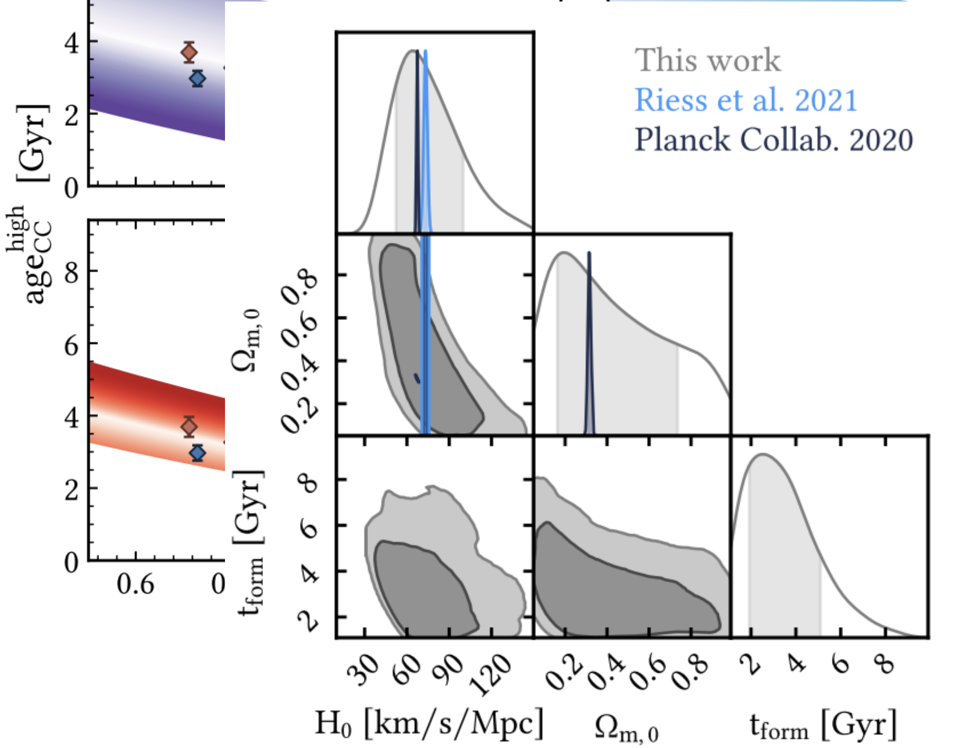
WMAP5+H_0(Freedman2001)
WMAP5+H_0(Riess2011)
WMAP5+H_0(Riess2011)+CC
WMAP5+H_0(Riess2011)+CC simulated 5% error
WMAP5+H_0(Riess2011)+CC simulated 2.5% error

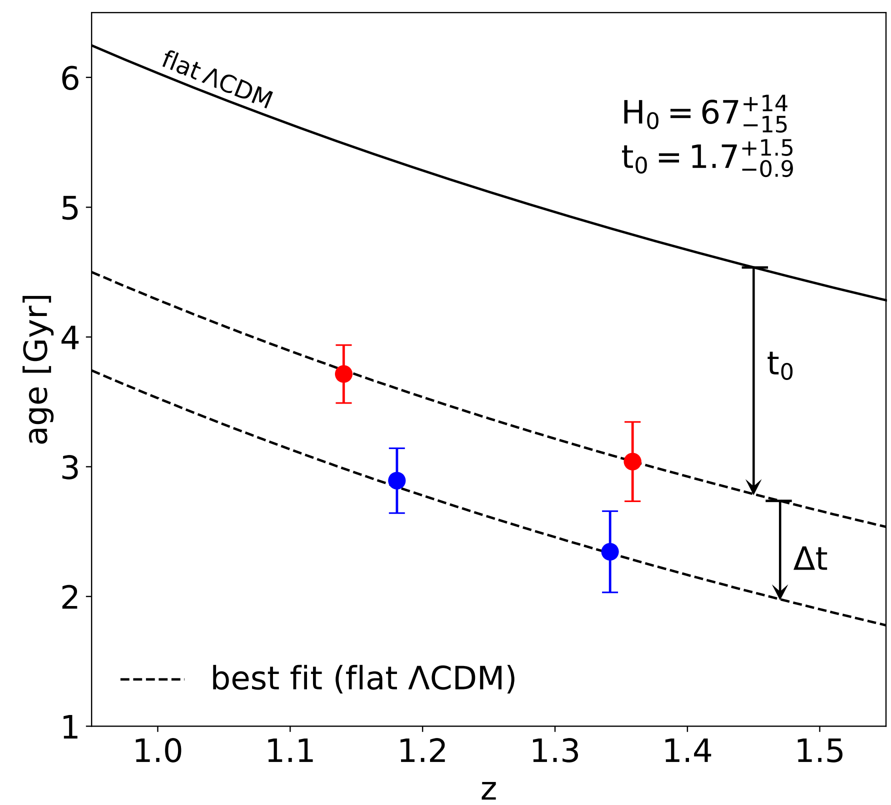
Addressing the tension

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. (2023)

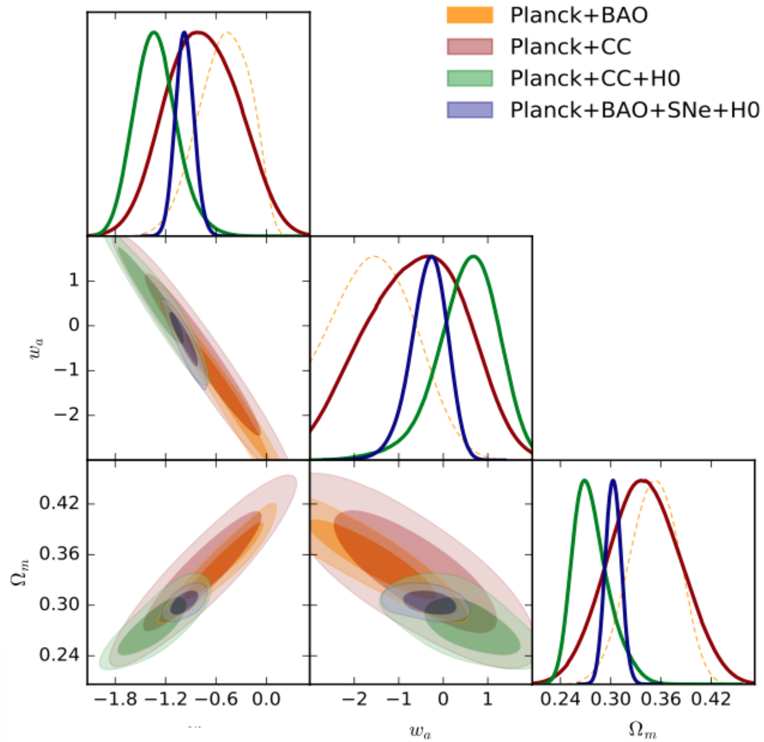
Addressing the tension

Combining (and challenging with) independent probes

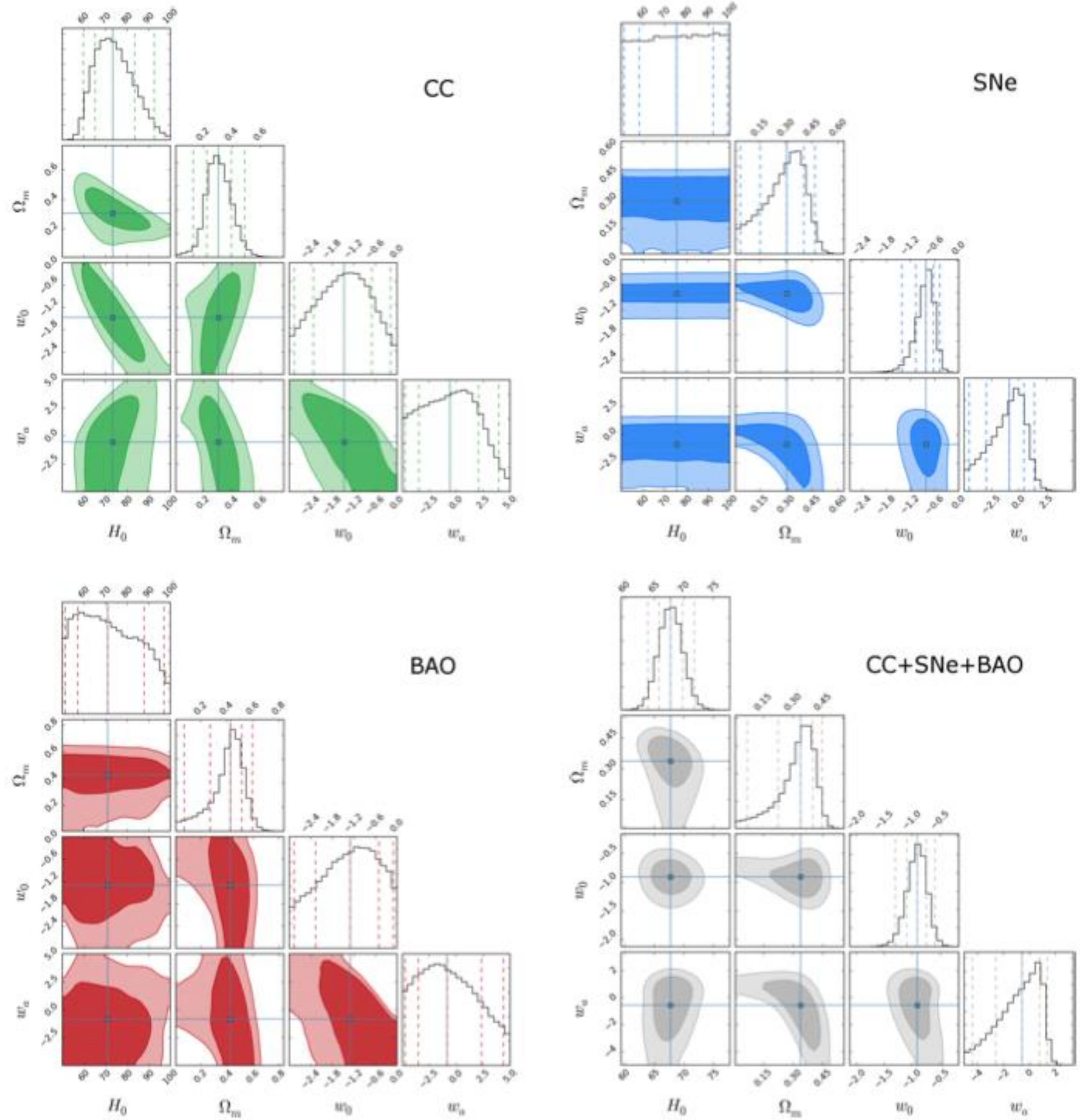
Each probe is more sensible to some parameters, and less to others

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

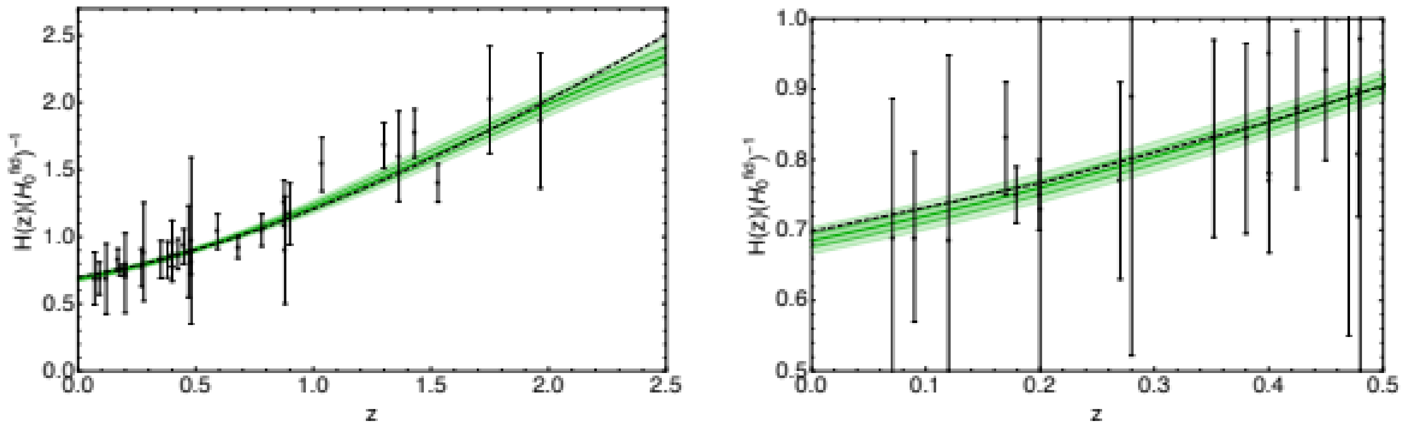
Going model-independent

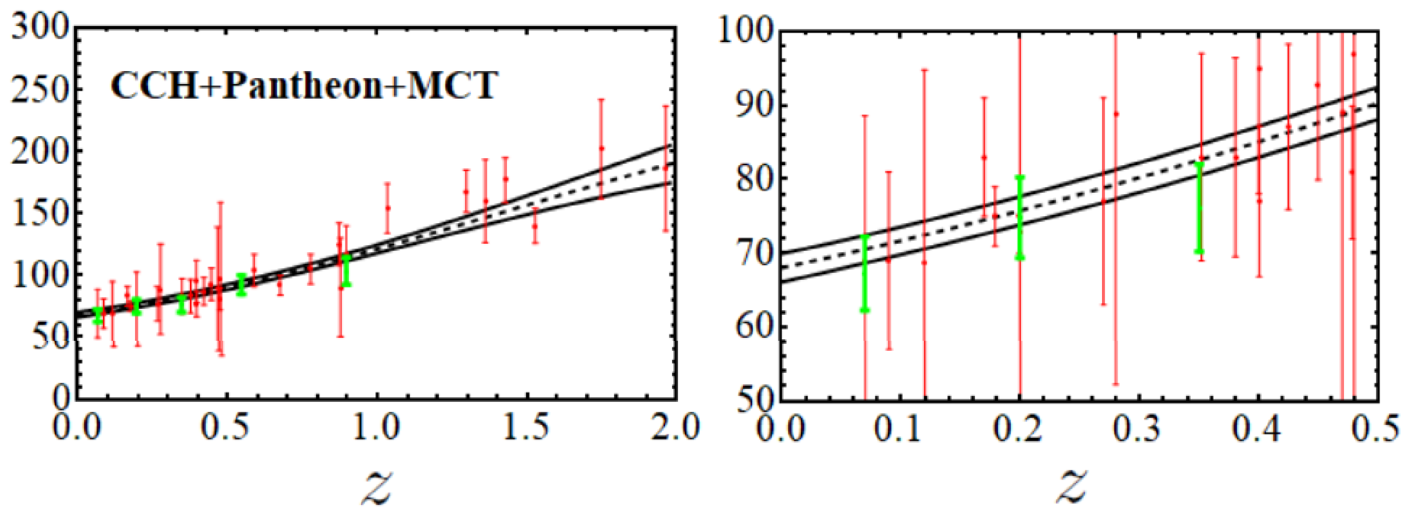
- H_0 as extrapolation of H(z=0)

- 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}

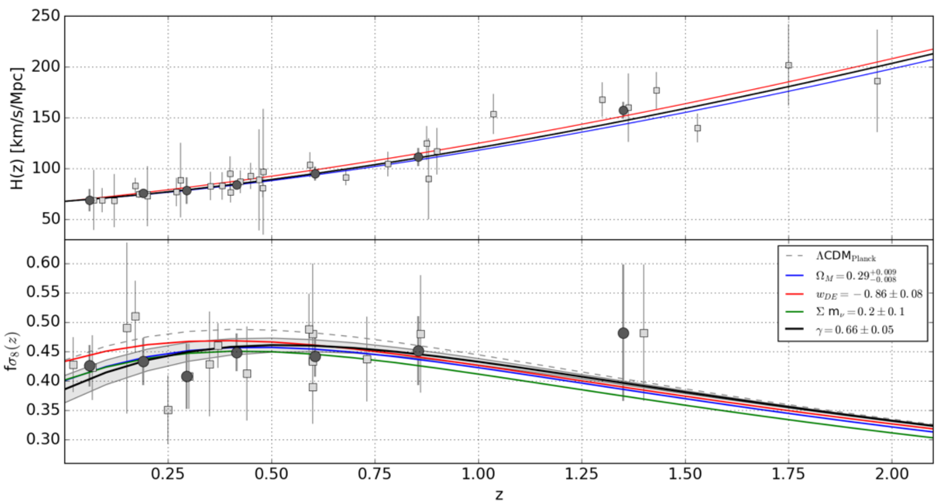
Gomez-Valent & Amendola (2018,2019)

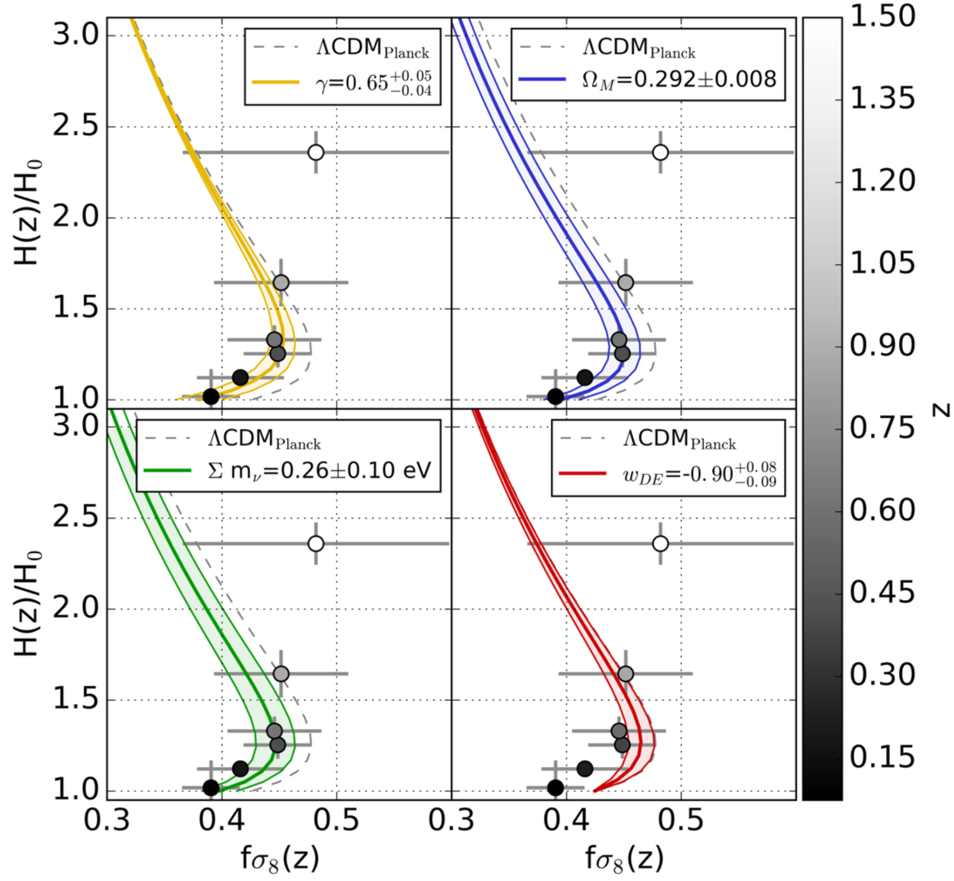
Combining expansion and growth

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)