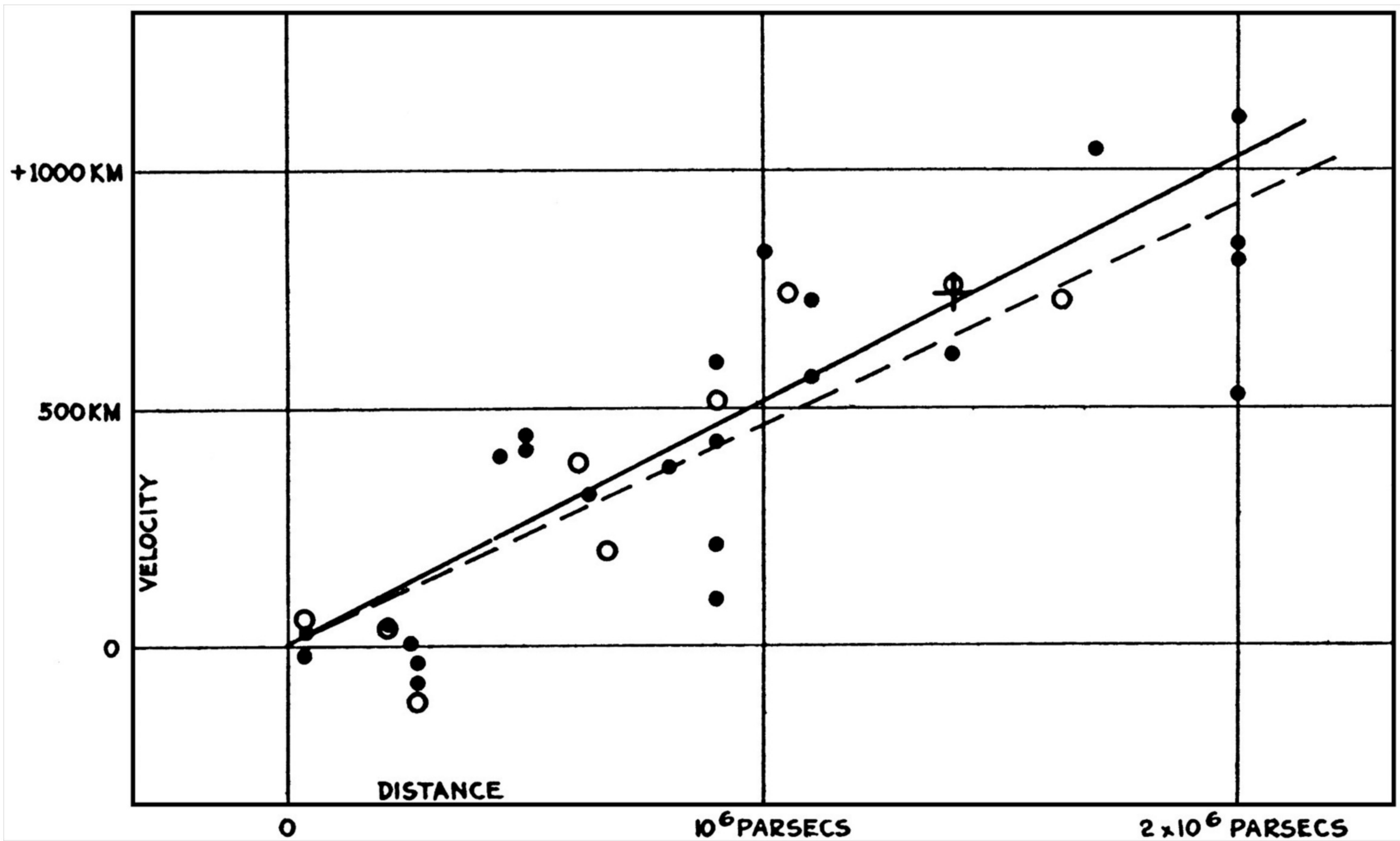
H(z) remastered

exploring new avenues to constrain the expansion history of the Universe



5th ASI/COSMOS Meeting on "LambdaCDM"
28th-29th May 2019

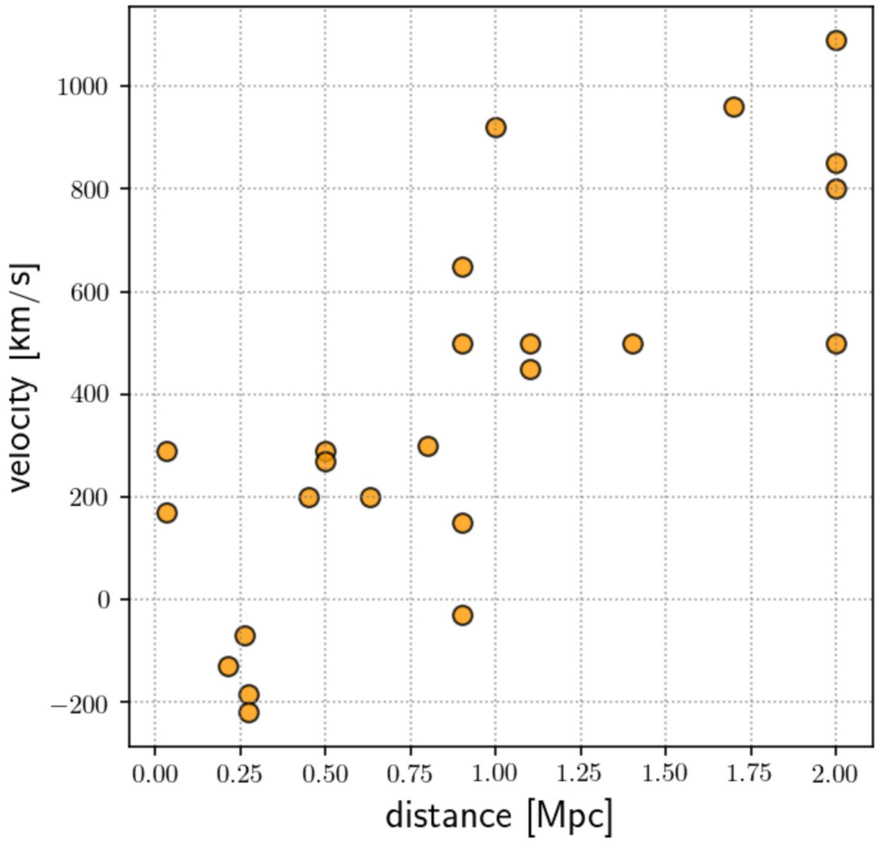
Michele Moresco
Dipartimento di Fisica e Astronomia
Università di Bologna

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

An instructive exercise

An instructive exercise

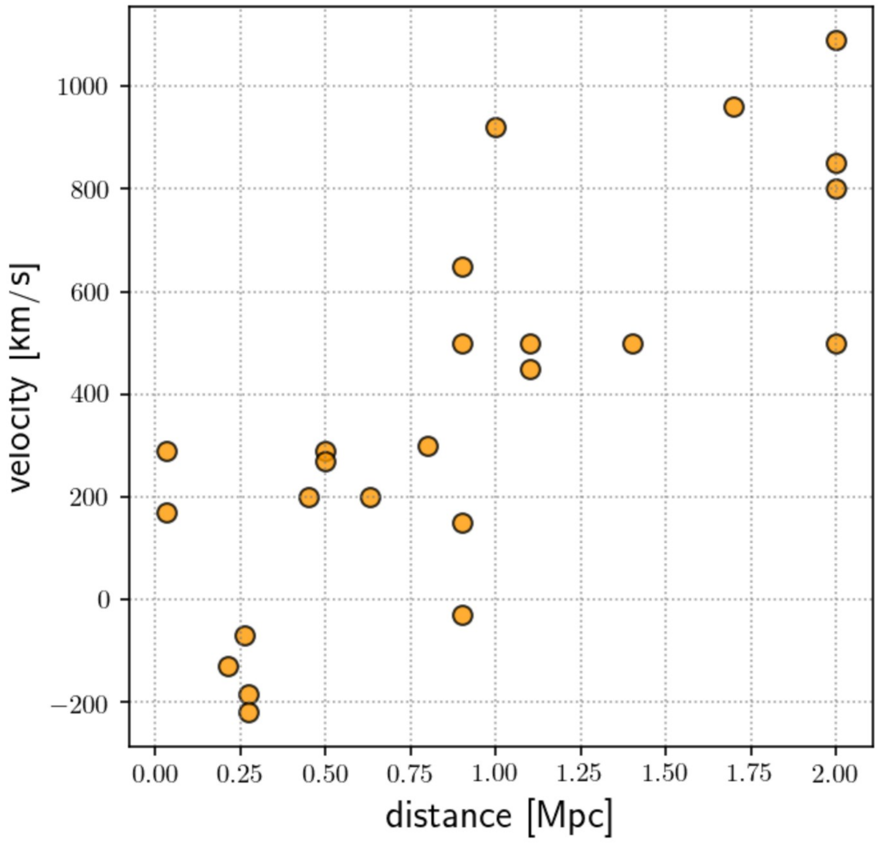
Data quality



An instructive exercise

Data quality

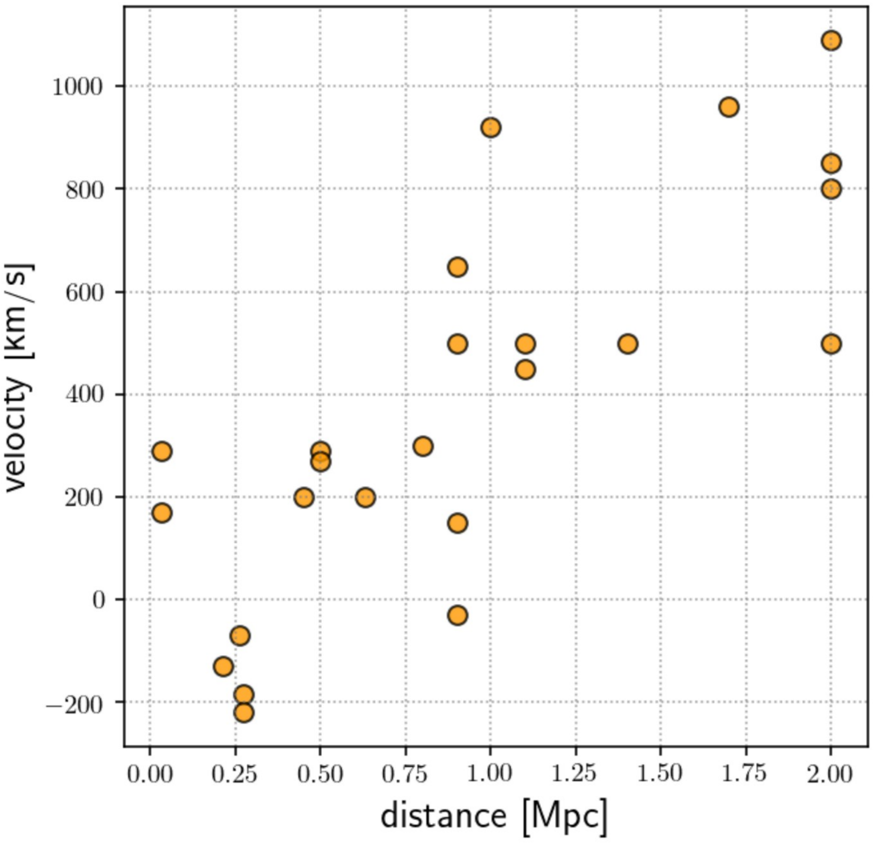
24 objects



An instructive exercise

Data quality

- 24 objects
- no associated errors



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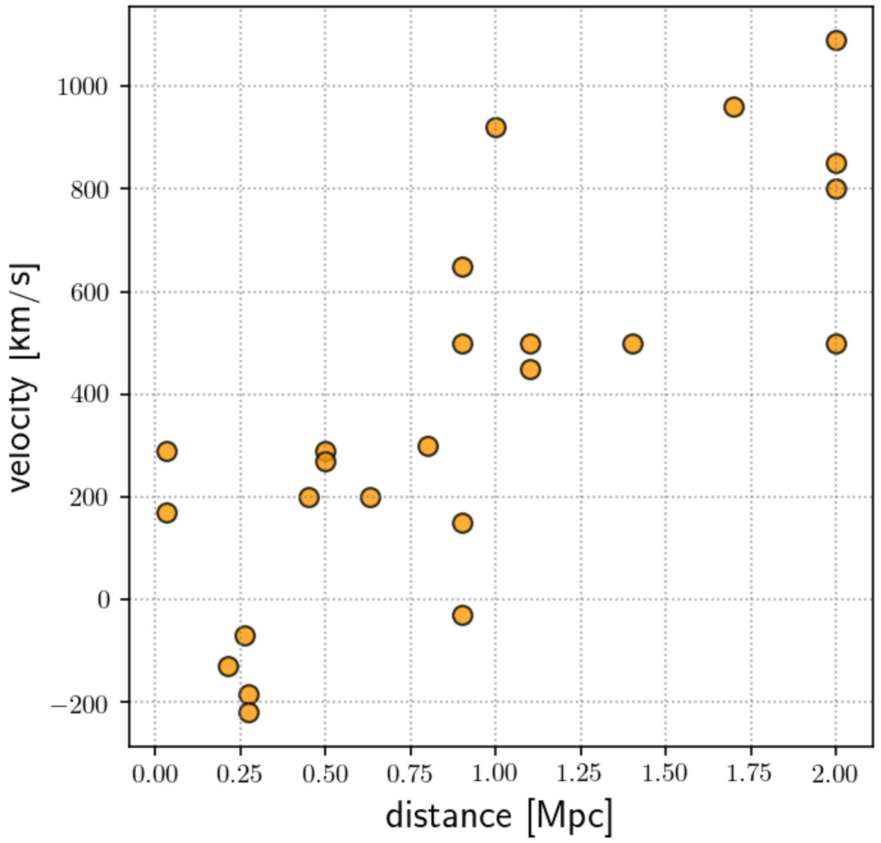
A real correlation?



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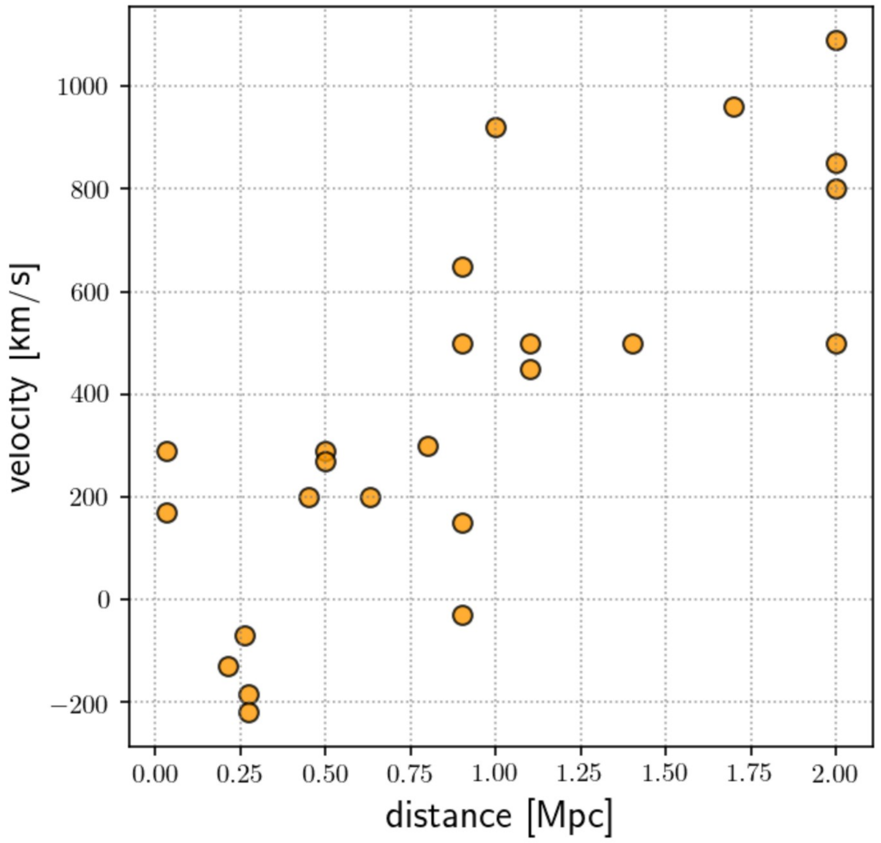
- rule of thumb: if removing <~10% of the data destroys the correlation (covering the data with one thumb), we should not trust it with confidence



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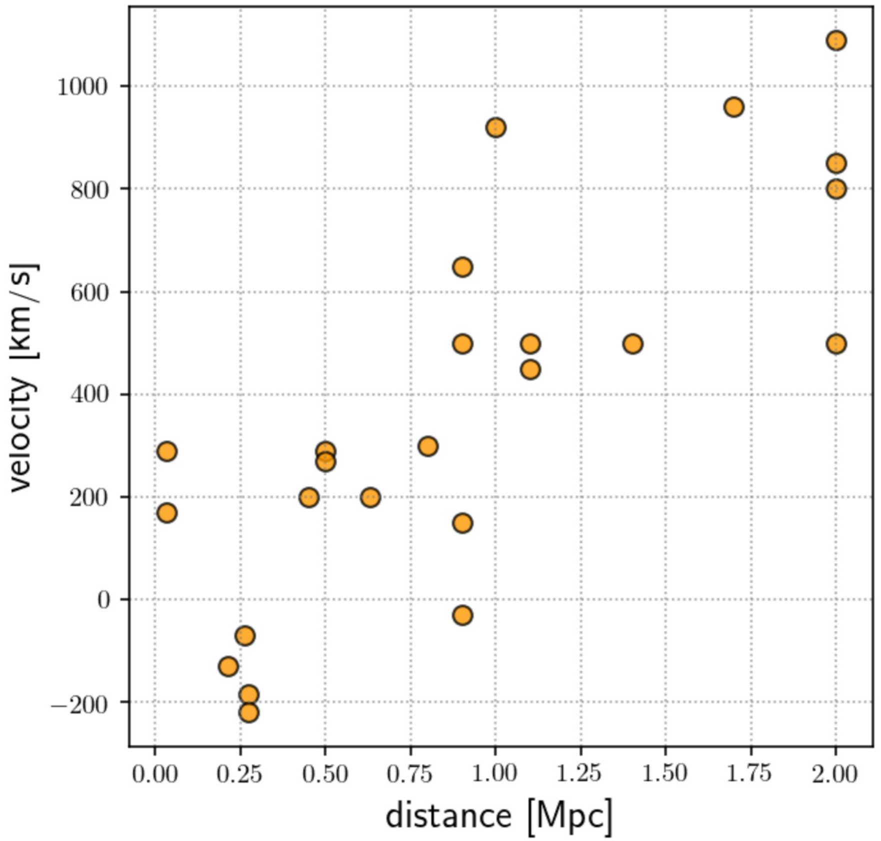

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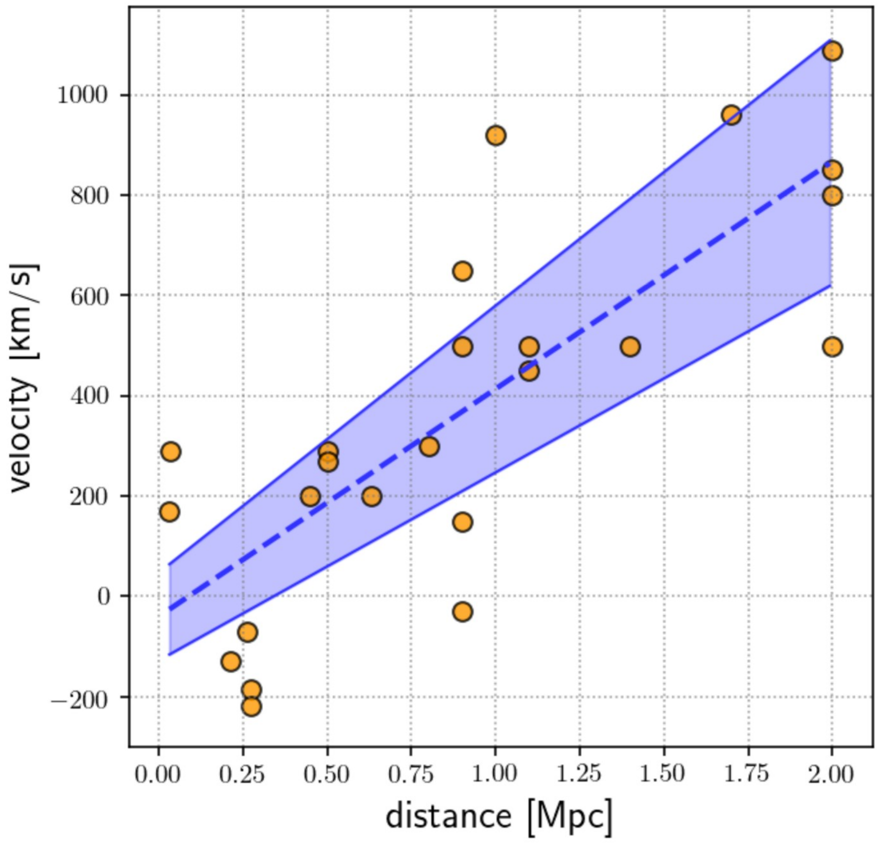
Large errorbars



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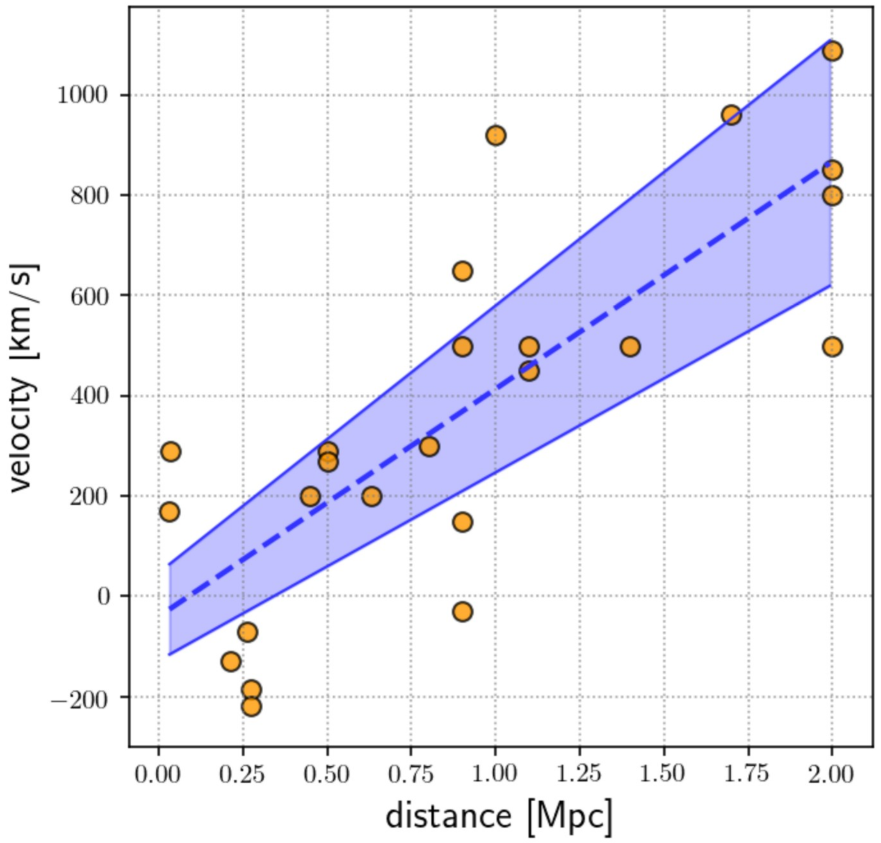
20%



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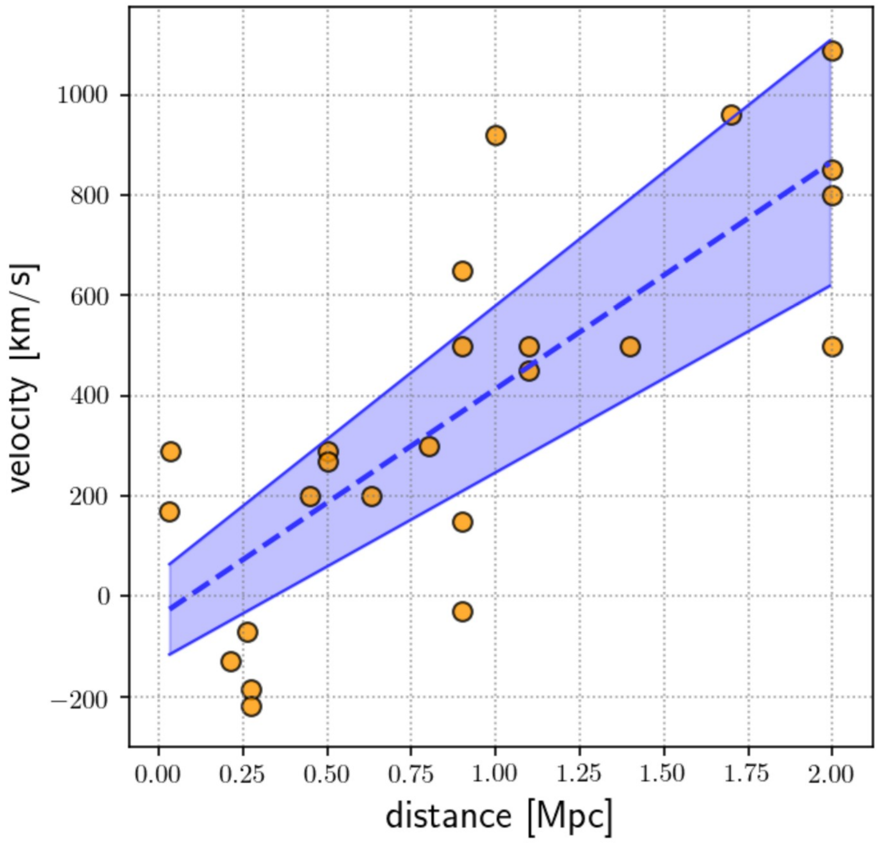
20%

$H_0 = 454 \pm 79$ km s^{-1} Mpc^{-1}



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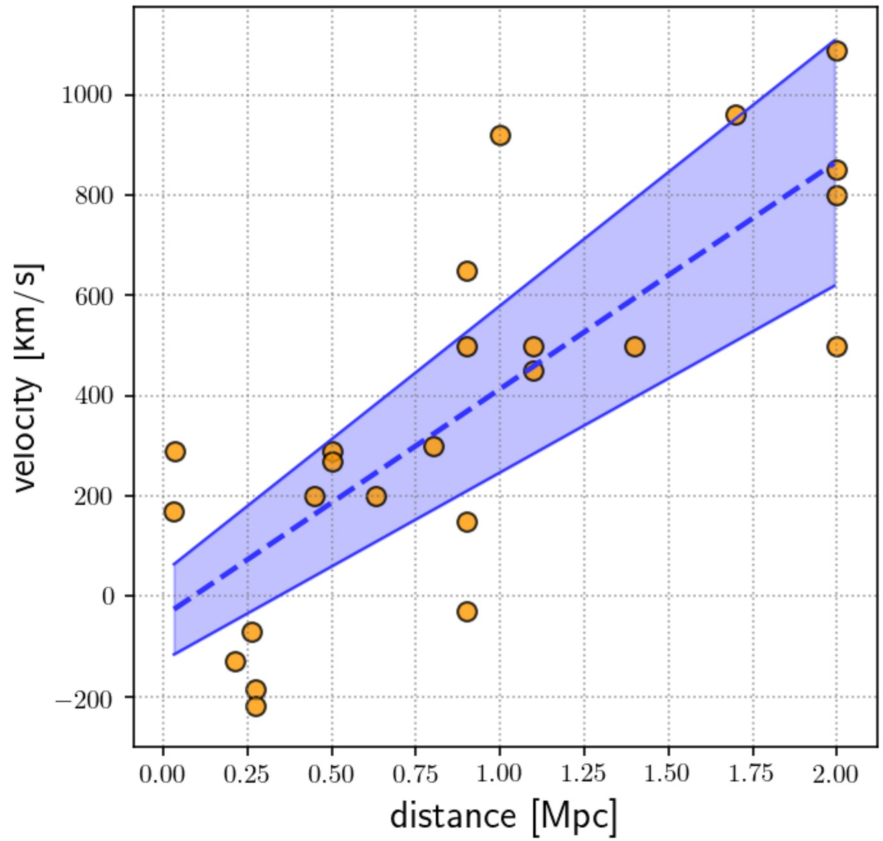


"For such scanty material, so poorly distributed, the results are fairly definite."

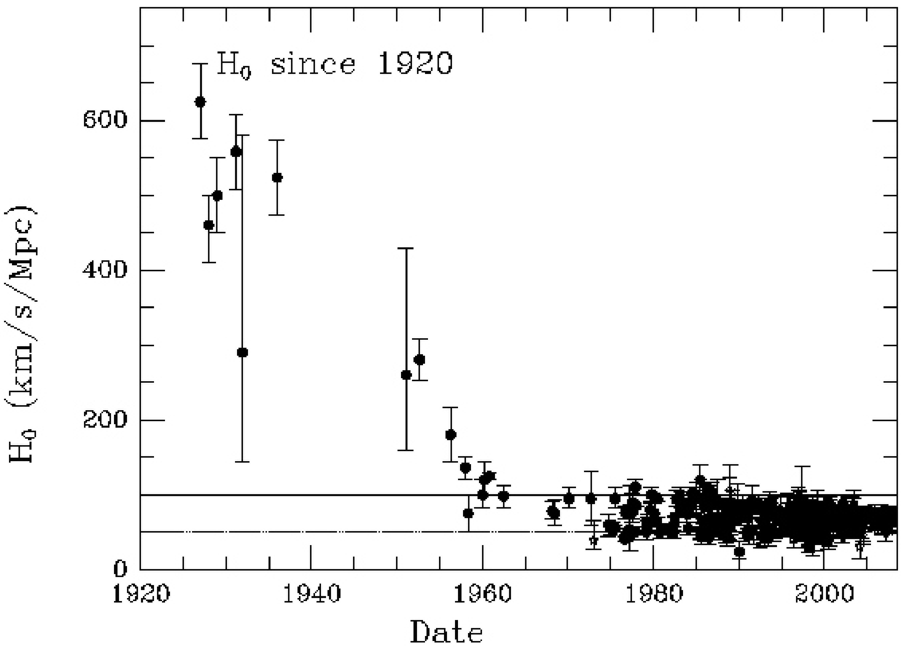
Hubble (1929)

Recurrent cycles of history

1920. The Great Debate

Recurrent cycles of history

1920. The Great Debate



from https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/

Recurrent cycles of history

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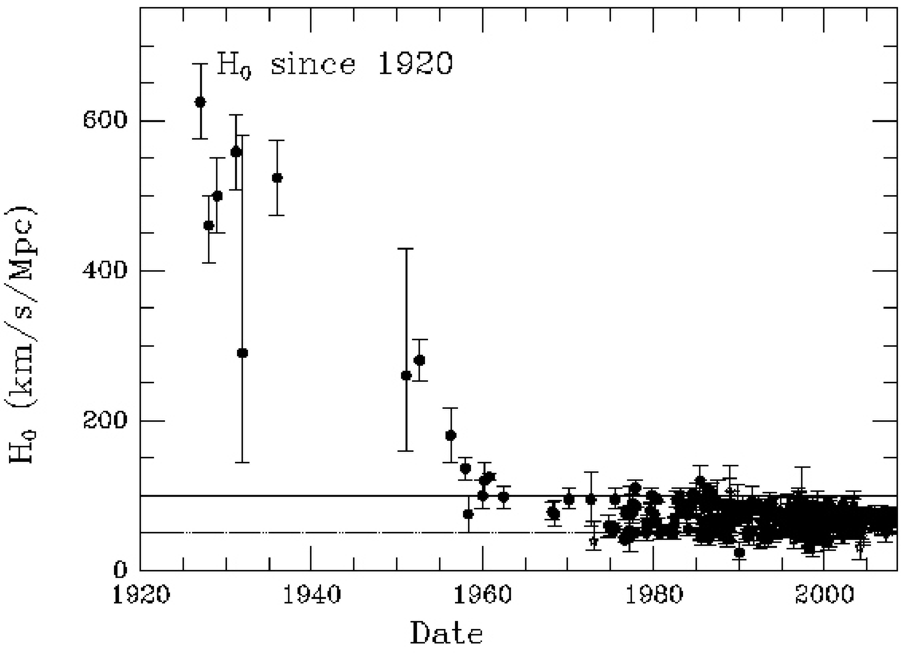

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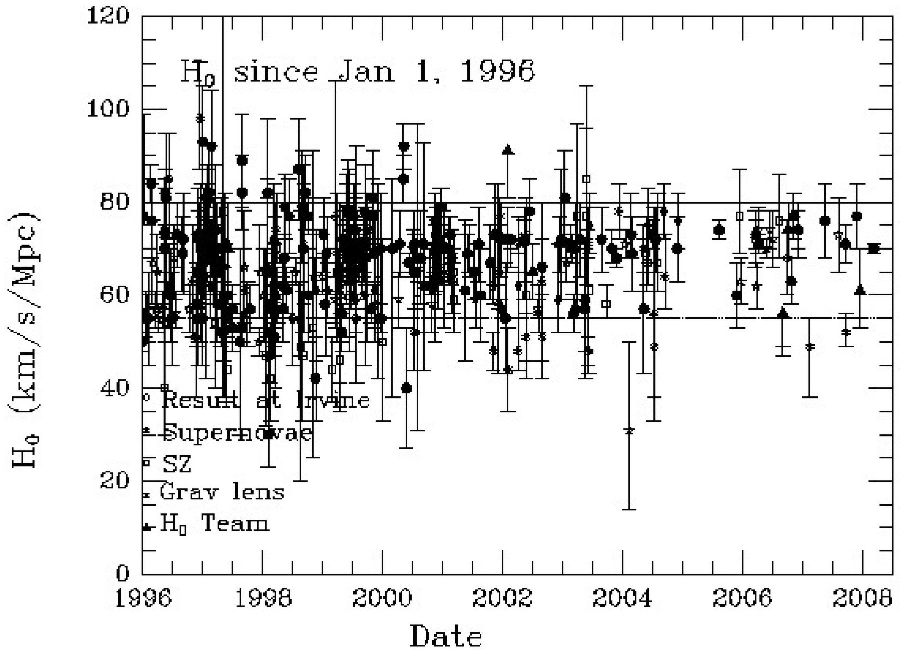

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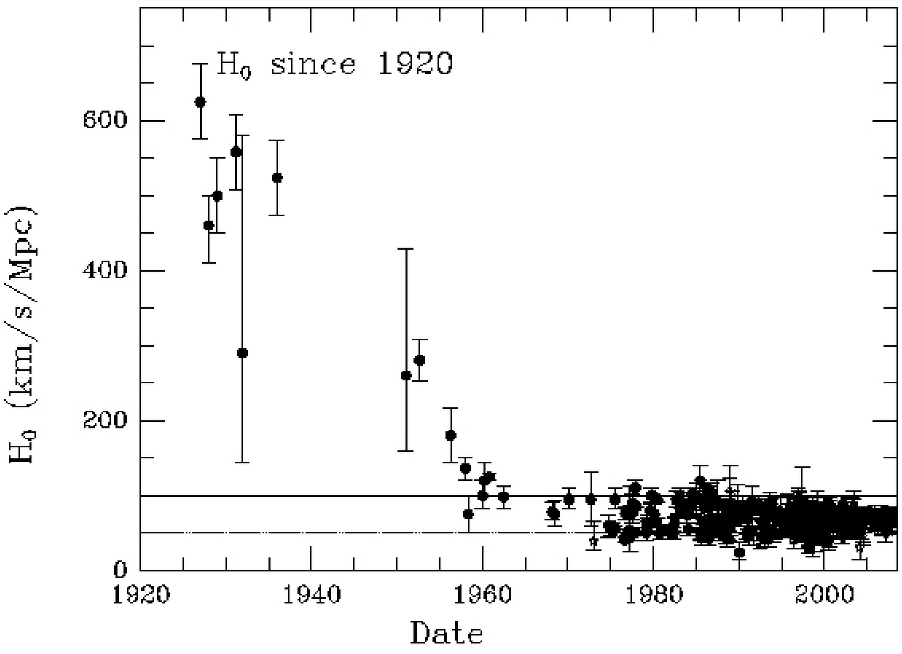

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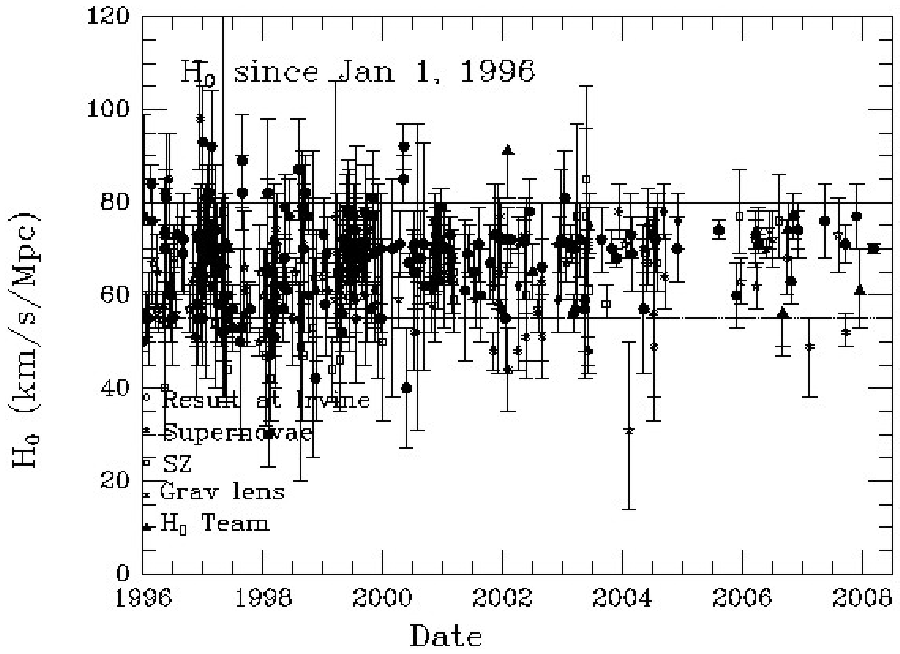
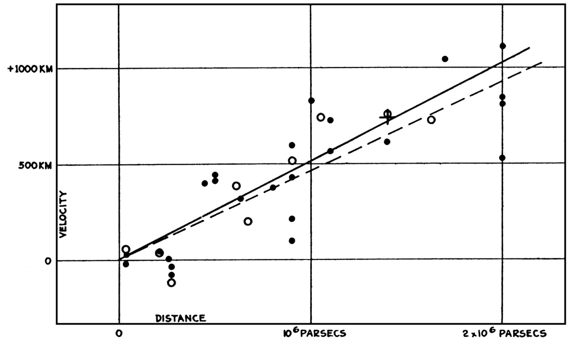


2019. The Great debate – season 2: 100 years after

$H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1} Planck collab. (2018)

$H_0 = 74.03 \pm 1.42$ km s^{-1} Mpc^{-1} Riess et al. (2019)

Extending to H(z)



Hubble (1929)

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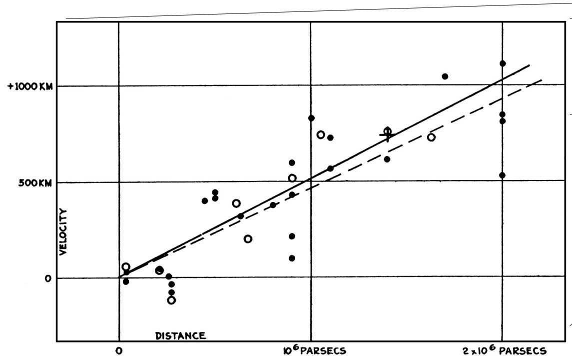
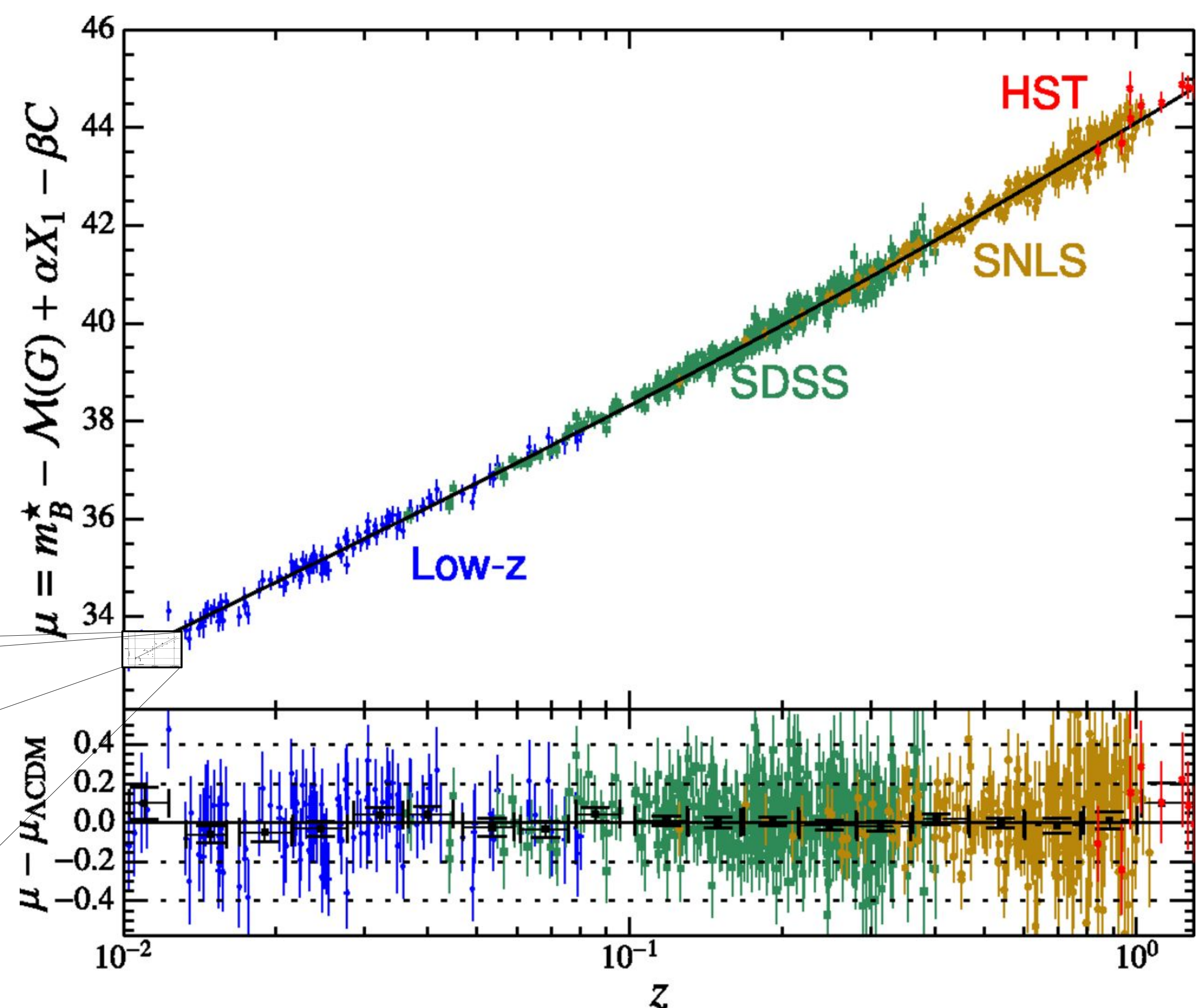


Hubble (1929)



Betoule et al. (2014)

Where to look at to get H(z) information...

Many (most of the) cosmological functions depend on the Hubble parameter H(z)

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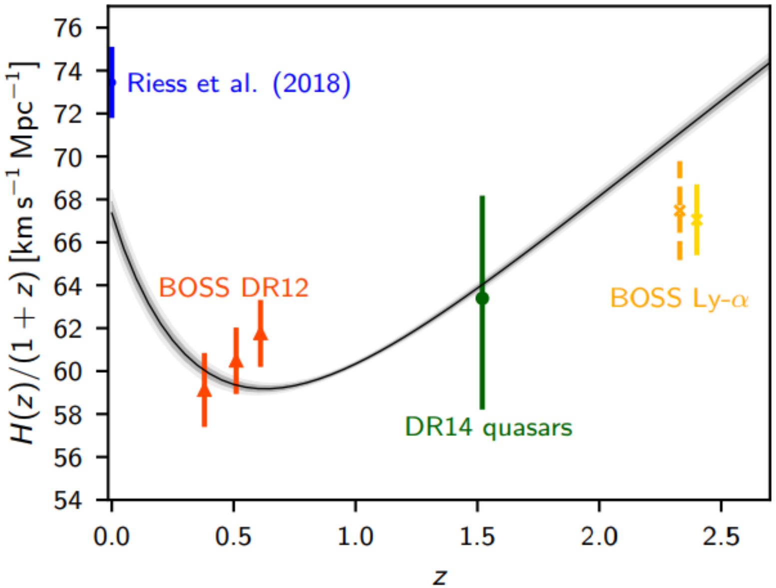
BAO: acoustic-scale distance ratio $D_V(z)/r_{drag}$, where $D_V = \left[(1+z)^2 d_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$



Planck collab. VI (2018)

$$d_A(z)=(1+z)^{-1}d_M(z)=(1+z)^{-1}\begin{cases}\dfrac{c}{H_0\sqrt{\Omega_k}}\sinh\left(\sqrt{\Omega_k}\,d_C(z)H_0/c\right)\\ d_C(z)\\ \dfrac{c}{H_0\sqrt{|\Omega_k|}}\sin\left(\sqrt{|\Omega_k|}\,d_C(z)H_0/c\right)\end{cases}$$

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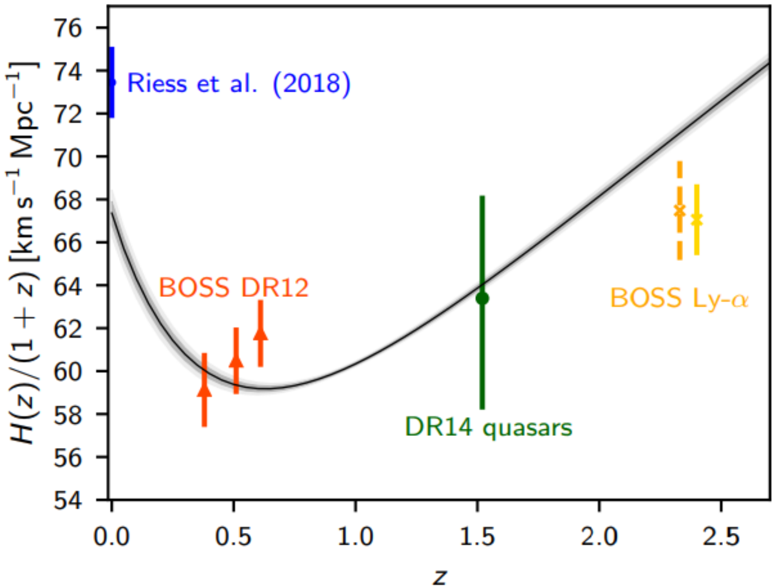

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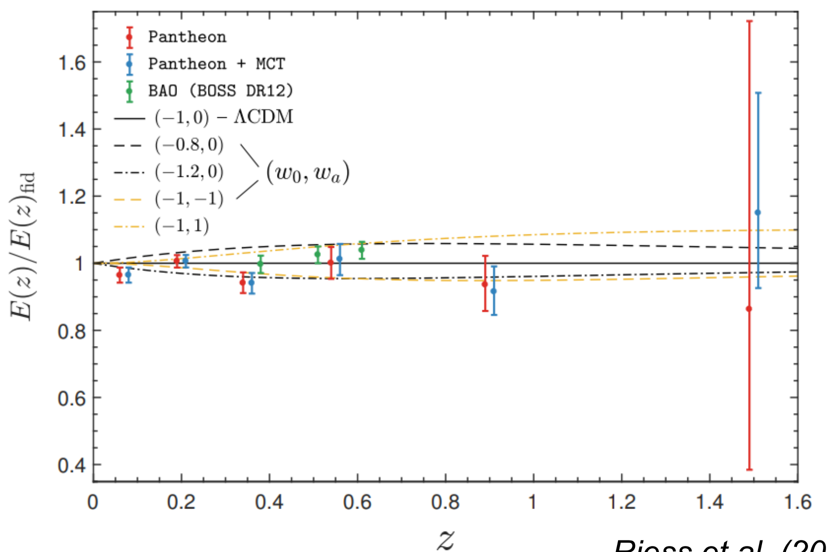
$$d_A(z) = (1+z)^{-1} d_M(z) = (1+z)^{-1} \begin{cases} \frac{c}{H_0\sqrt{\Omega_k}} \sinh\left(\sqrt{\Omega_k}\, d_C(z) H_0/c\right) \\ d_C(z) \\ \frac{c}{H_0\sqrt{|\Omega_k|}} \sin\left(\sqrt{|\Omega_k|}\, d_C(z) H_0/c\right) \end{cases}$$

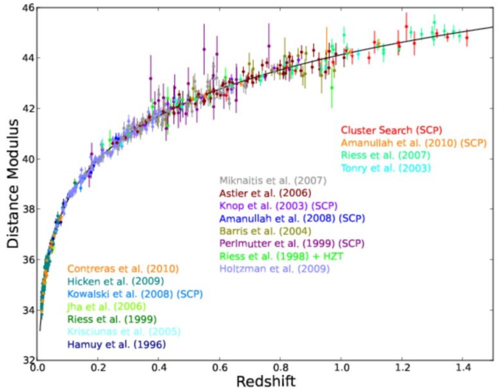
SNe: distance modulus (luminosity distance $d_L(z)$)



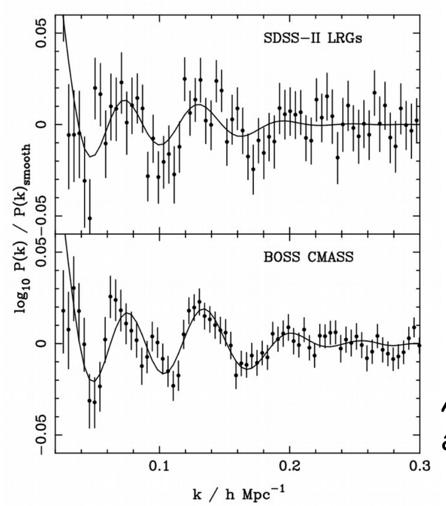
$$d_L(z) = (1+z) d_M(z) = (1+z) \begin{cases} \frac{c}{H_0\sqrt{\Omega_k}} \sinh\left(\sqrt{\Omega_k}\, d_C(z) H_0/c\right) \\ d_C(z) \\ \frac{c}{H_0\sqrt{|\Omega_k|}} \sin\left(\sqrt{|\Omega_k|}\, d_C(z) H_0/c\right) \end{cases}$$

Riess et al. (2017)

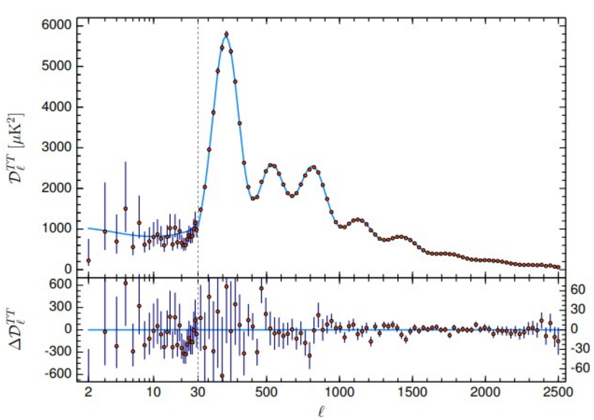
… and why



Amanullah et al. (2010)



Anderson et al. (2012)



Planck collaboration (2018)

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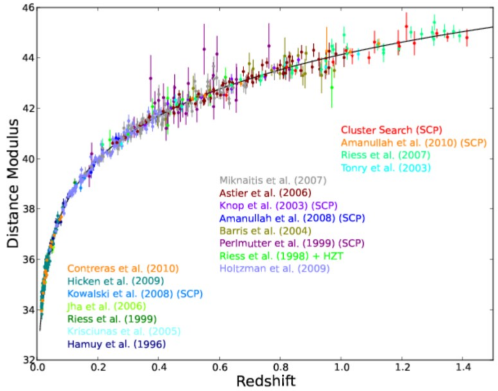

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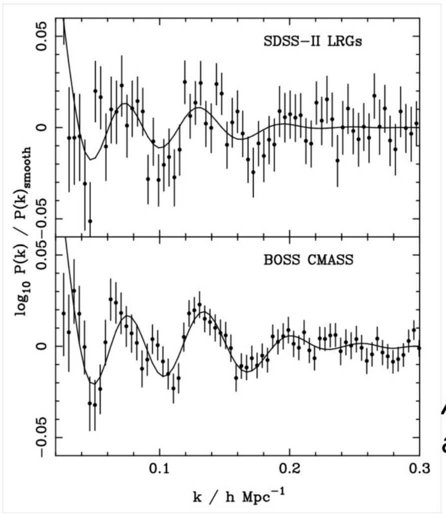

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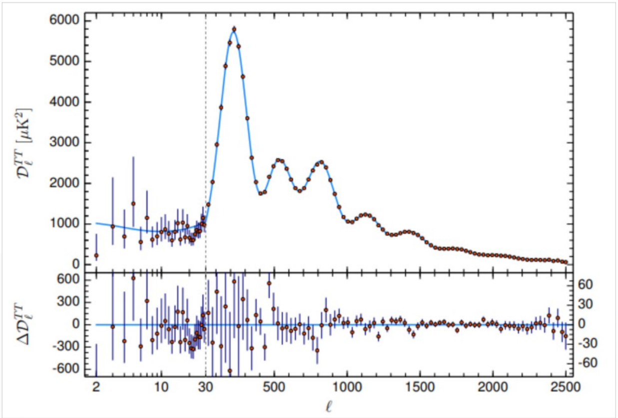
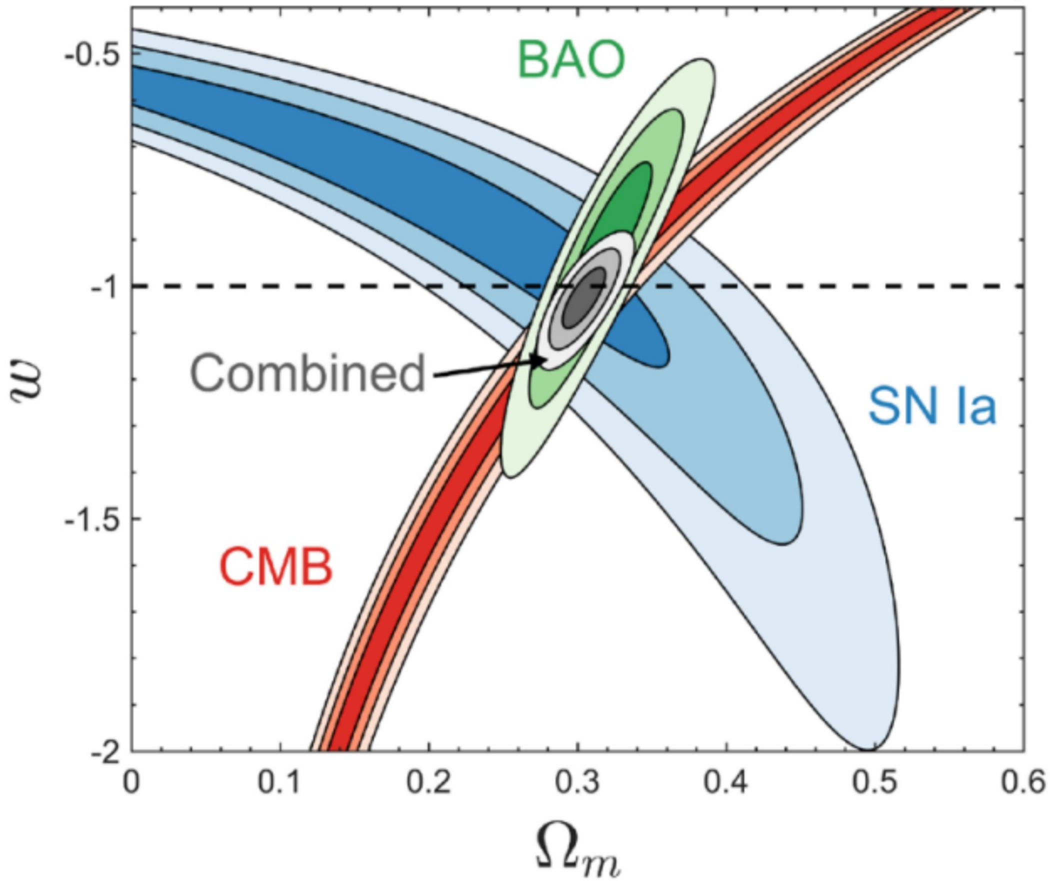


Planck collaboration (2018)

Huterer & Shafer (2018)



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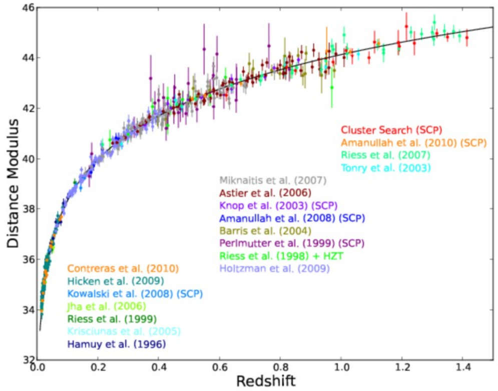

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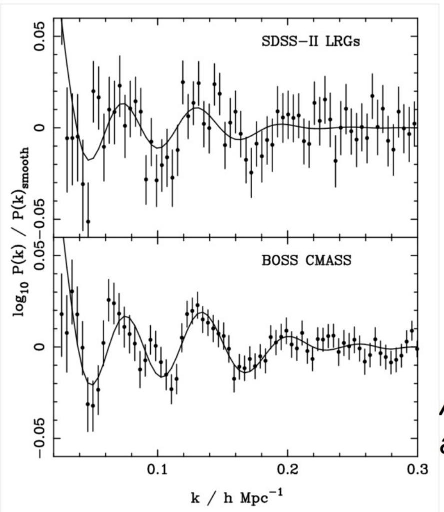

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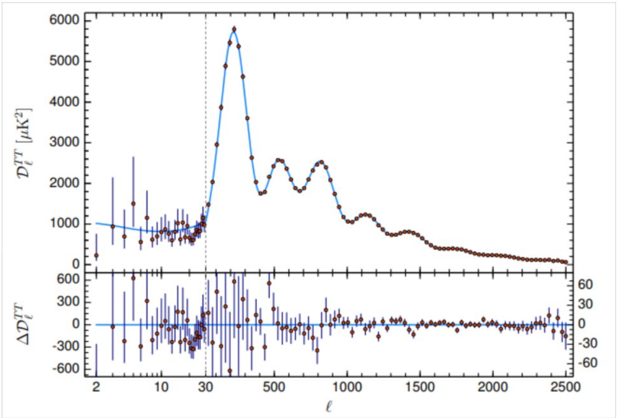
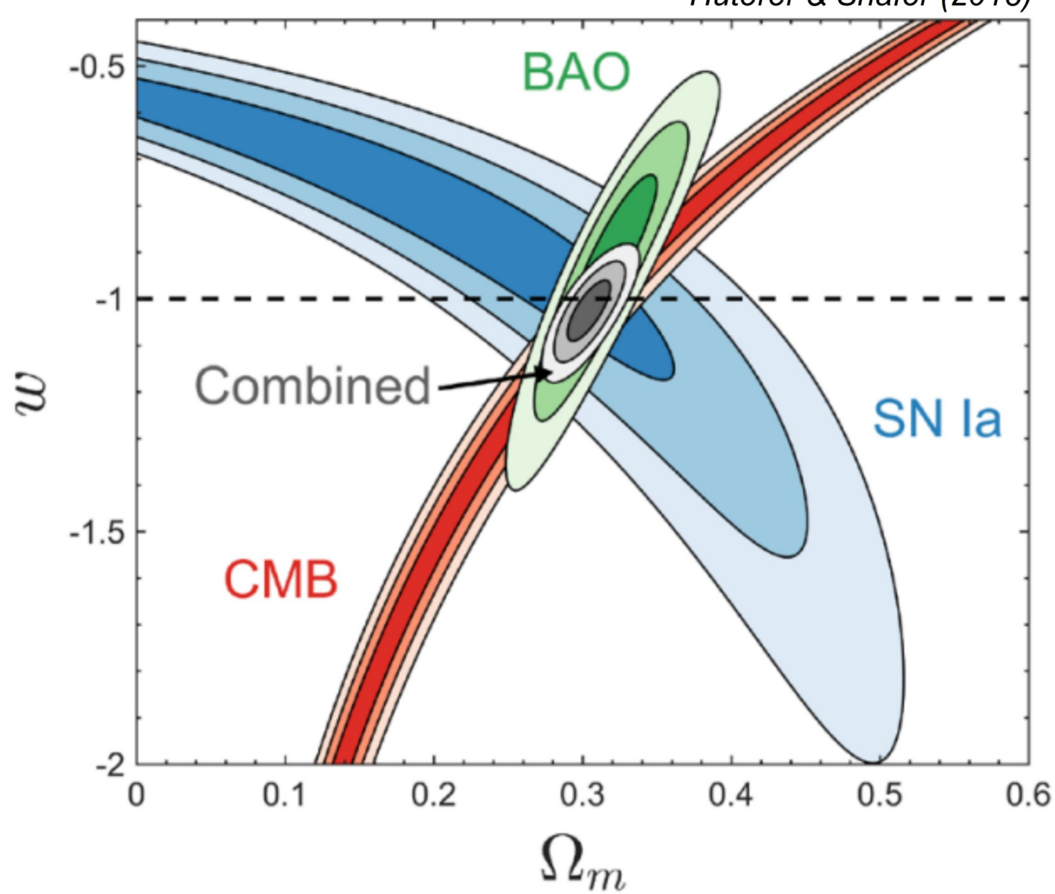


Planck collaboration (2018)

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

Synergy within differences

Huterer & Shafer (2018)



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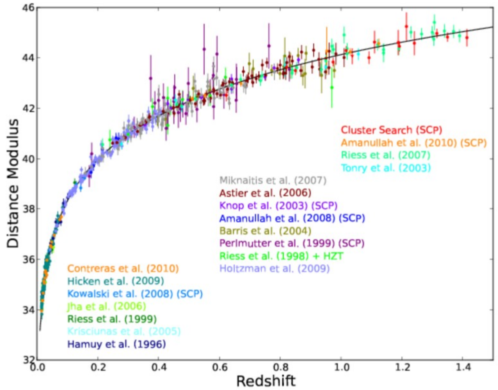

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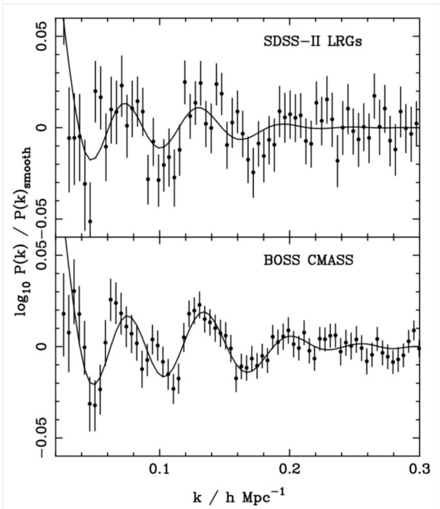

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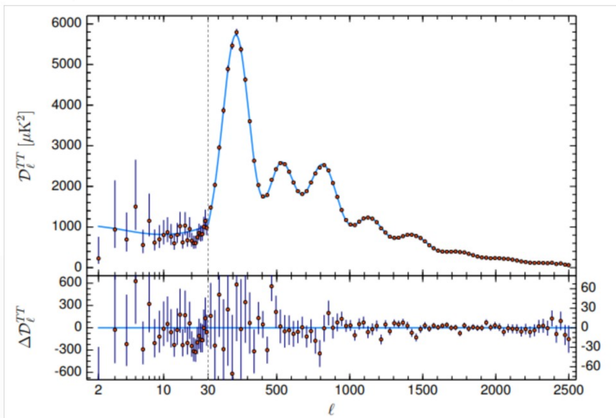

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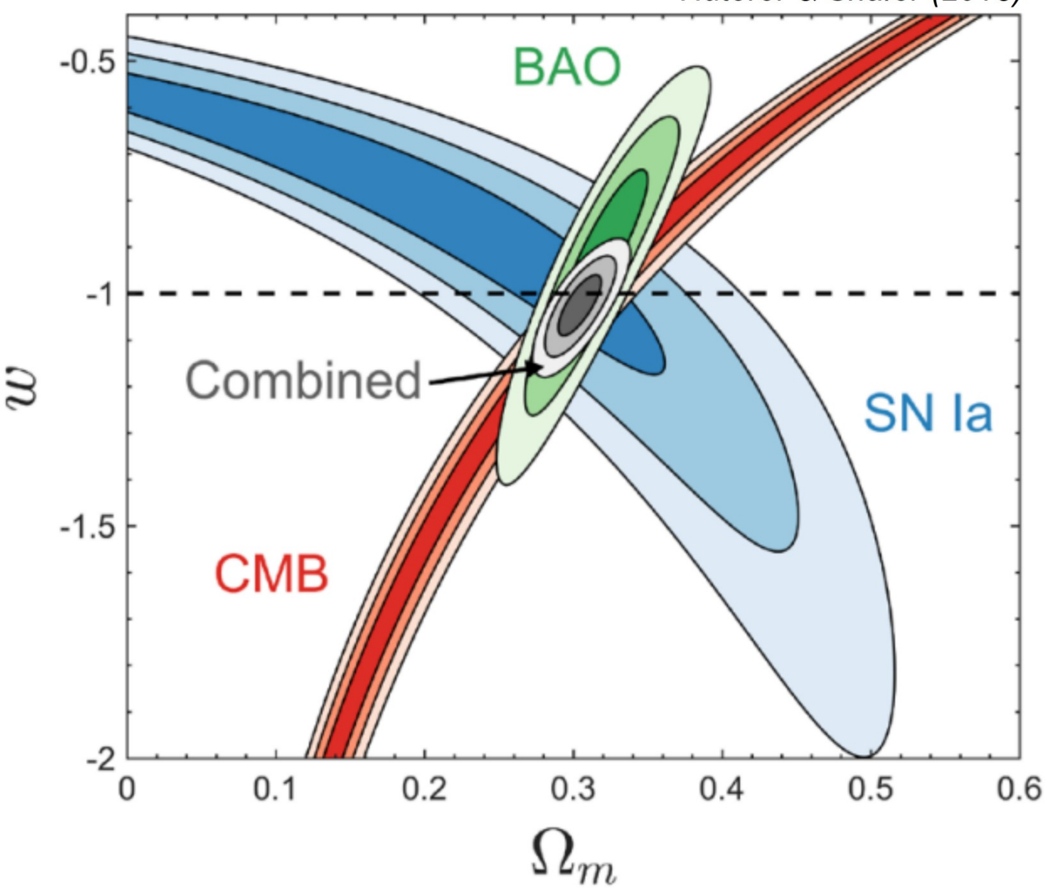


as done in the past, moving <u>beyond</u> in crucial

Hubble parameter measurements

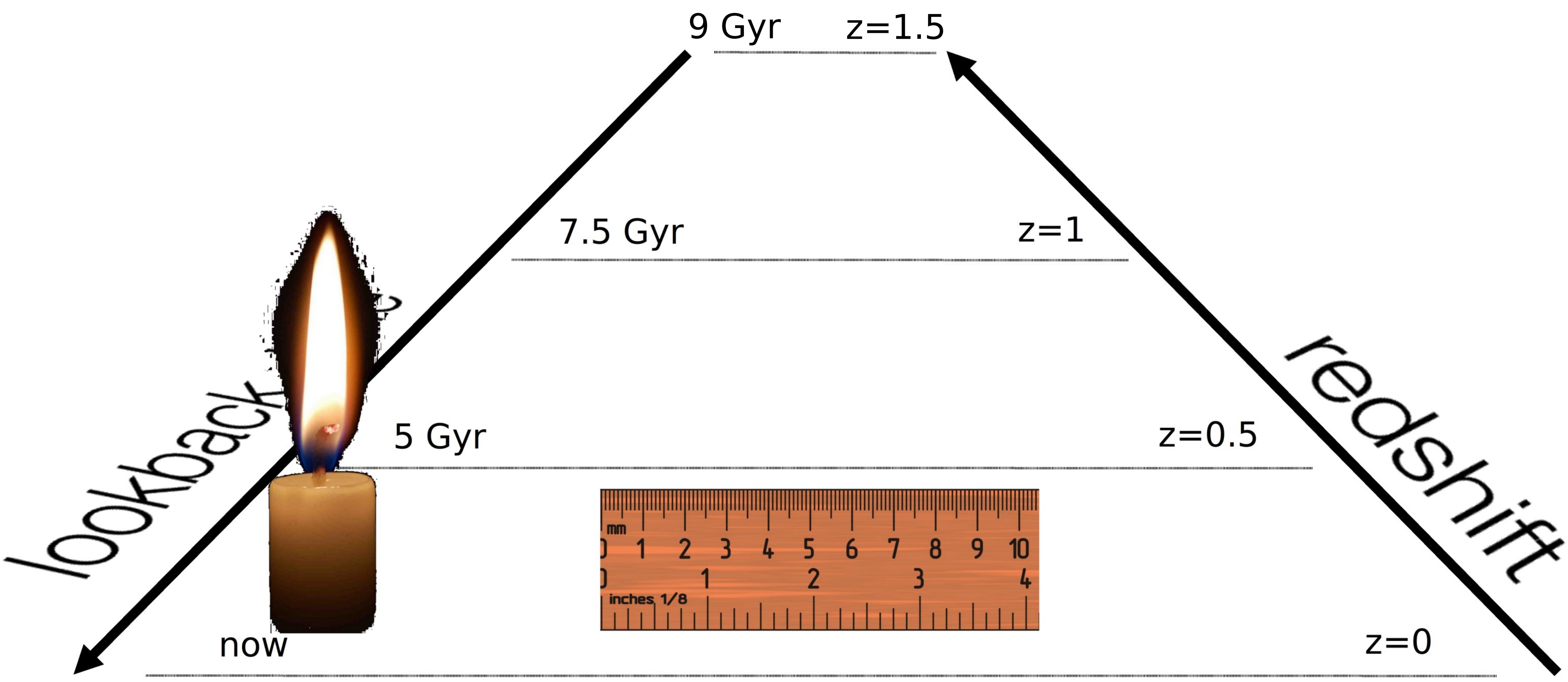
Cosmic chronometers

Cosmic chronometers

- basic idea
- how to apply the method & systematics involved
- results
- cosmological applications

The basic idea

Need for standards



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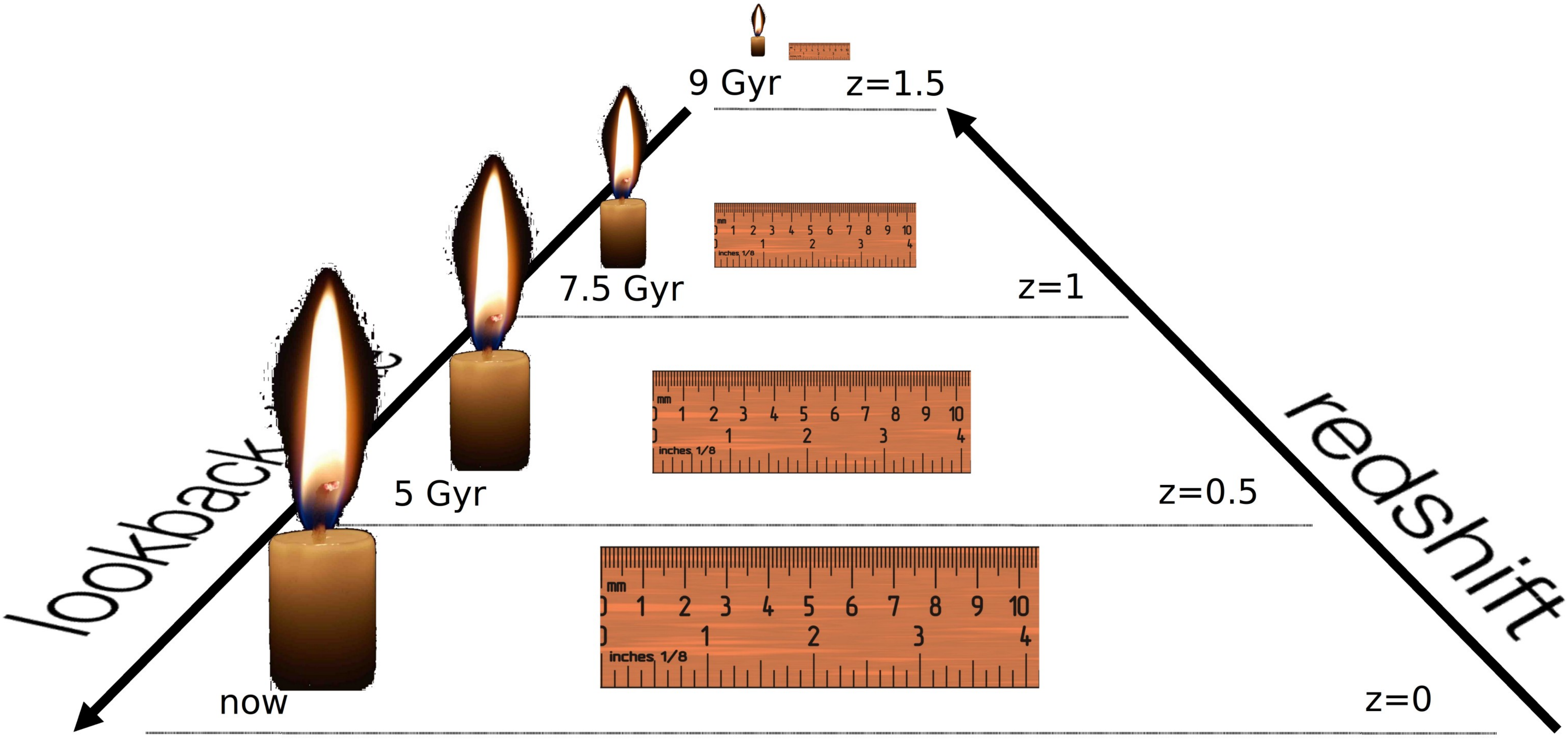

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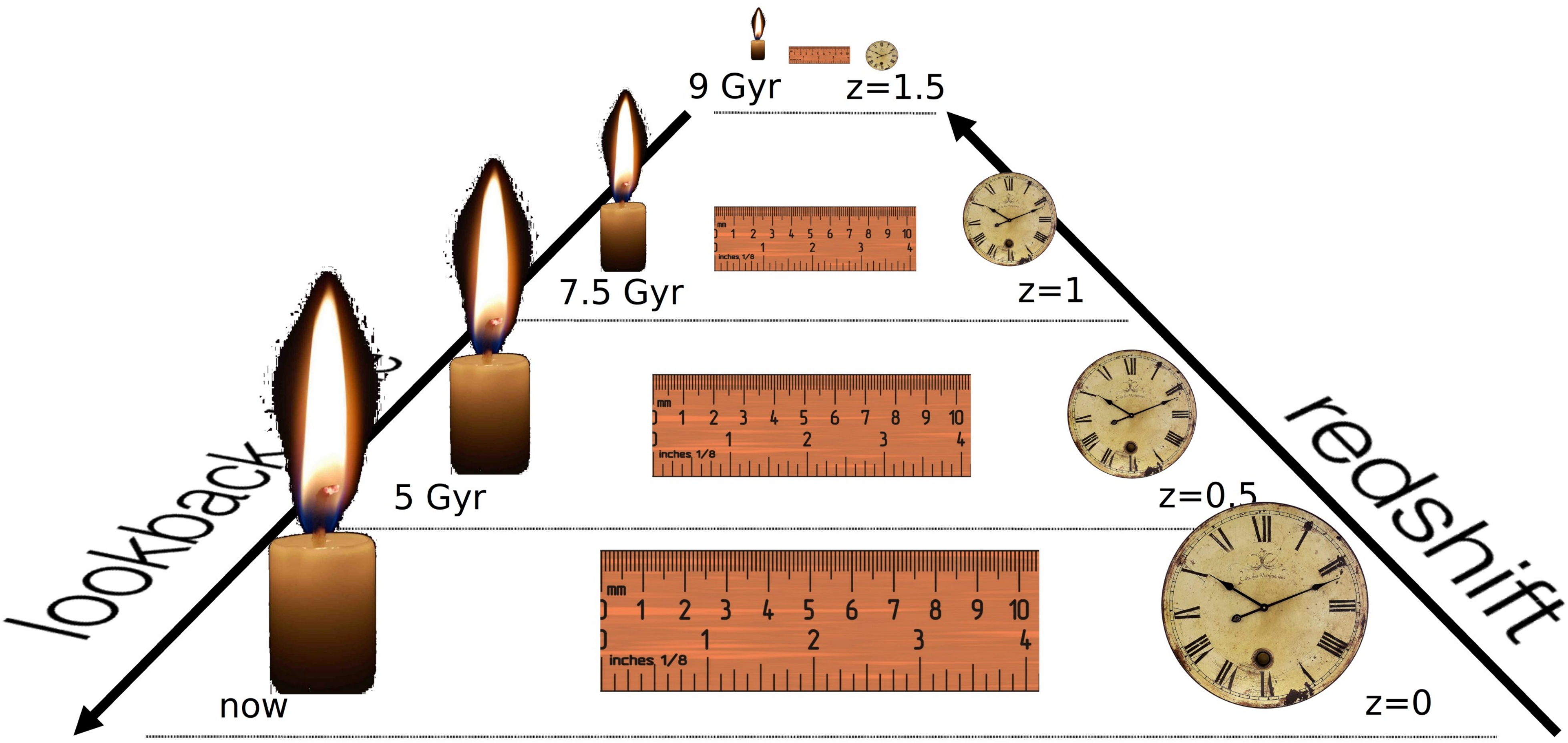

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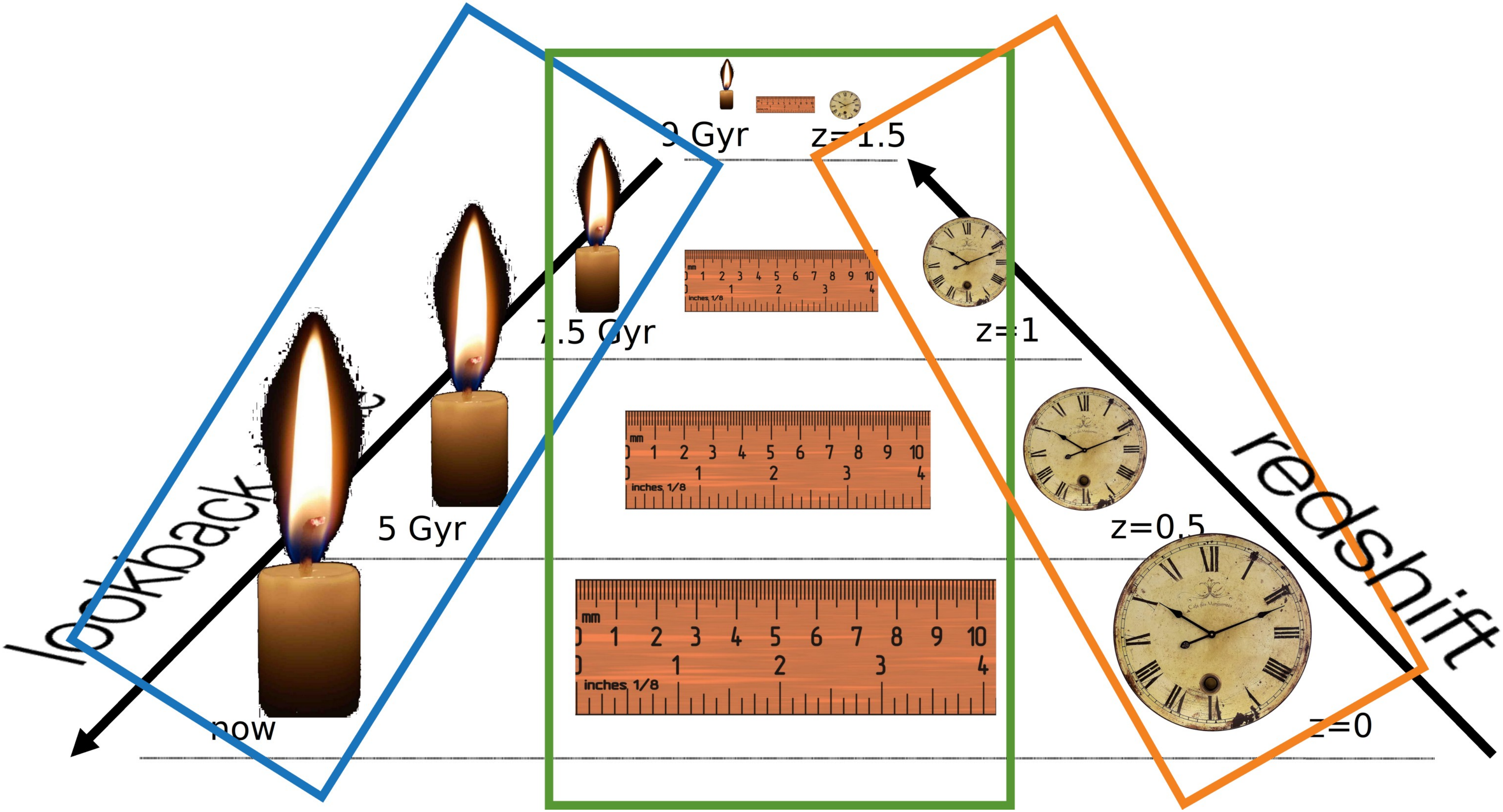

SNe
Supernovae Type Ia

BAO
Baryonic Acoustic Oscillations

CC
Cosmic Chronometers

Cosmic chronometers in a nutshell

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

Jimenez & Loeb (2002)

Cosmic chronometers in a nutshell

What about
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model dependence,
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rejuvenation, ...
What about **systematics**?

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What about **systematics**?

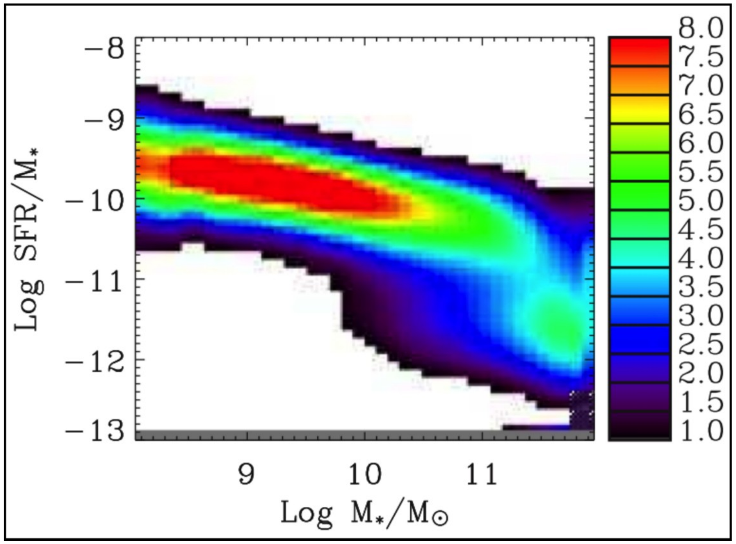
What are the real
pros and cons?

How to apply the method

What about the tracers?

Very massive and passively evolving early-type galaxies:

- they dominate the luminous/massive end of the LF/MF, and are **passively evolving** systems



Brinchmann et al. (2004)

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- most massive --> oldest
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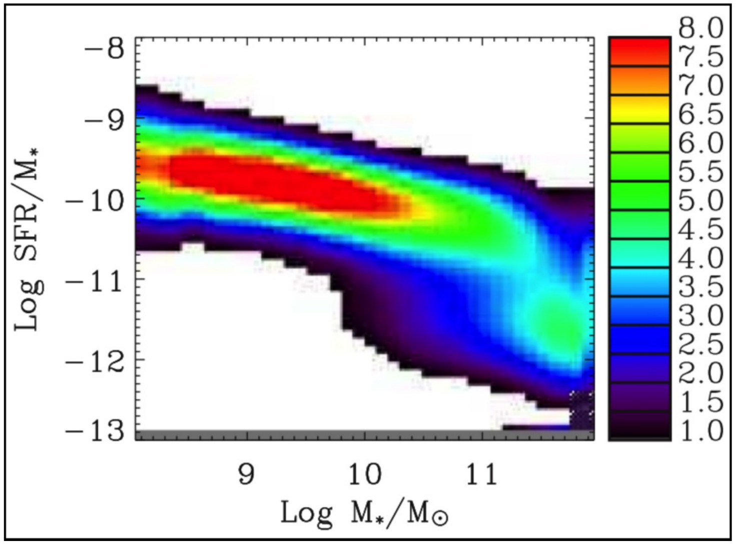
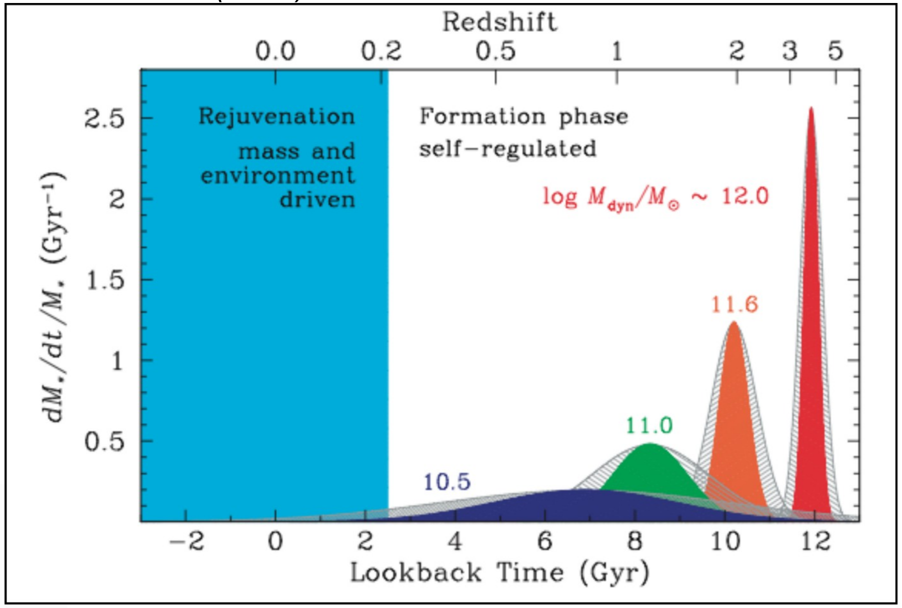


Brinchmann et al. (2004)

Thomas et al. (2010)



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Very massive and passively evolving early-type galaxies:

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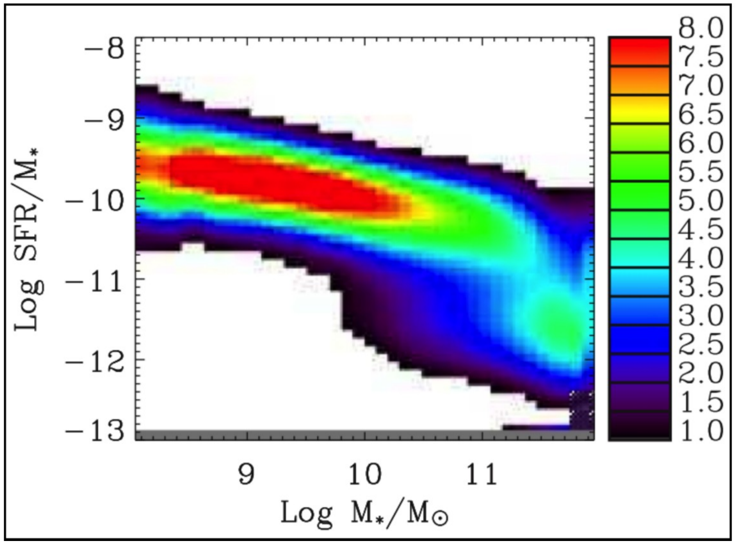
- **homogeneous** population (metallicity and number density) also in redshift



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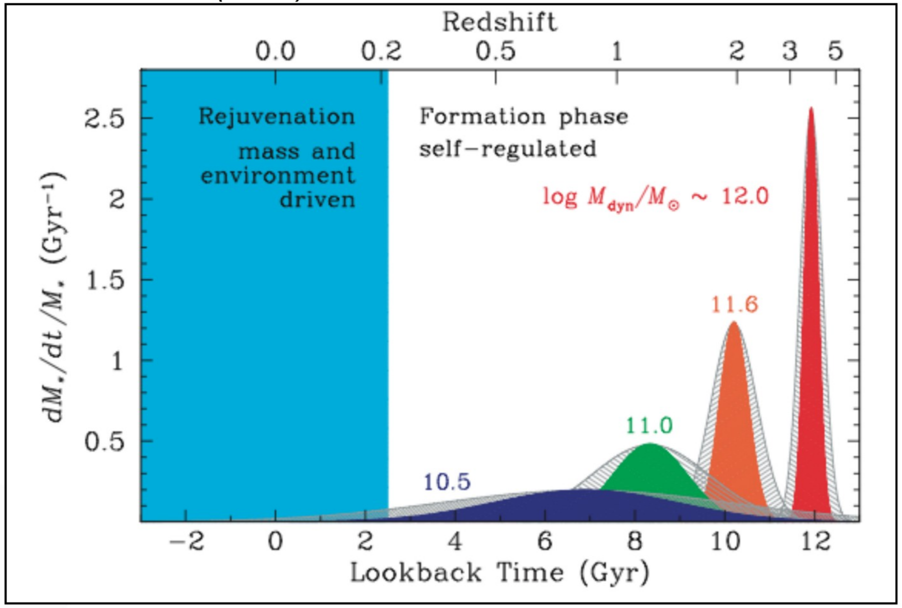
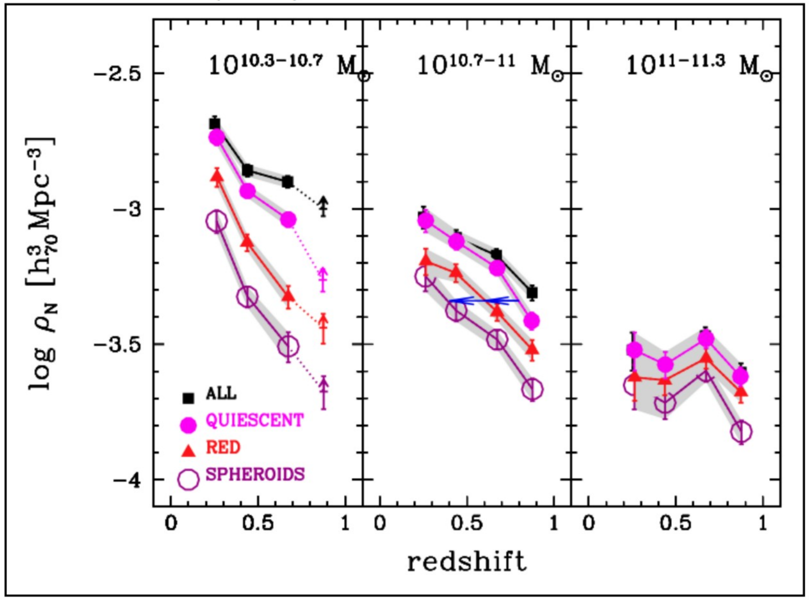


Pozzetti et al. (2010)



Are all passive galaxies ok?

The short answer is **NO.**

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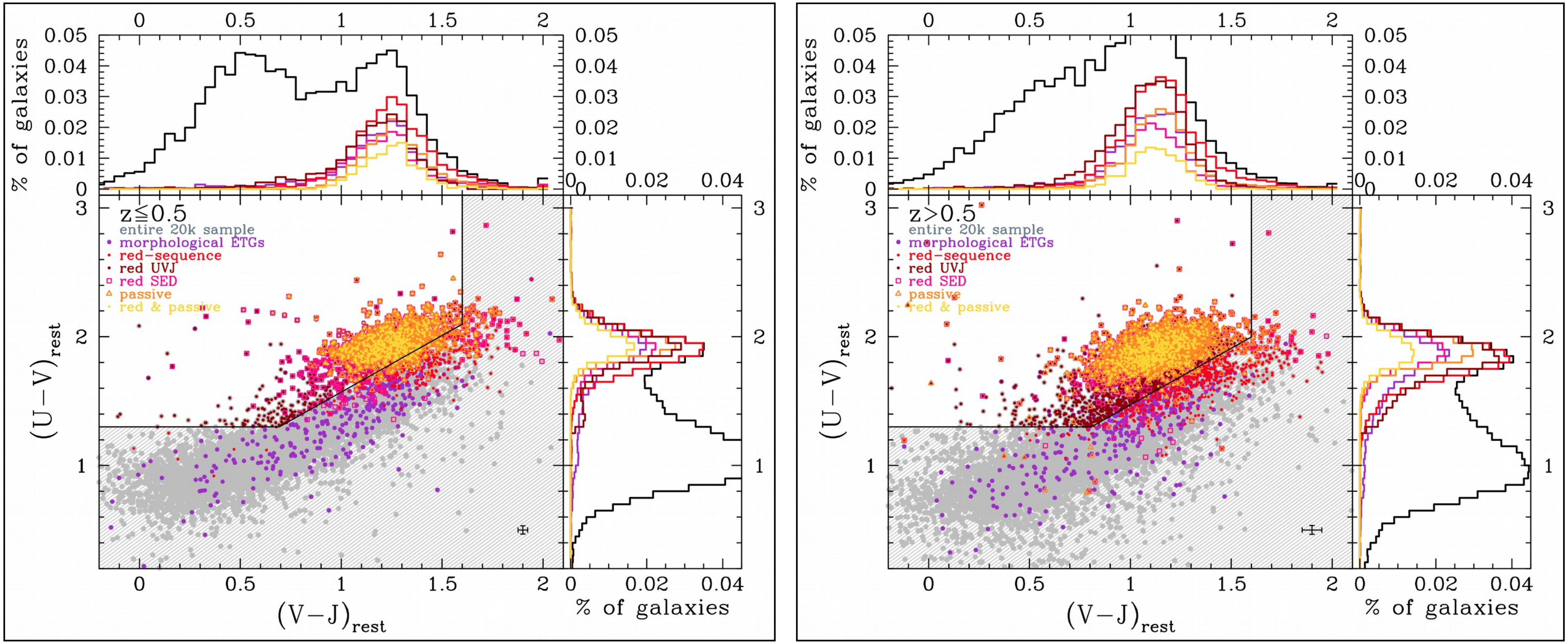

Moresco et al. (2013)

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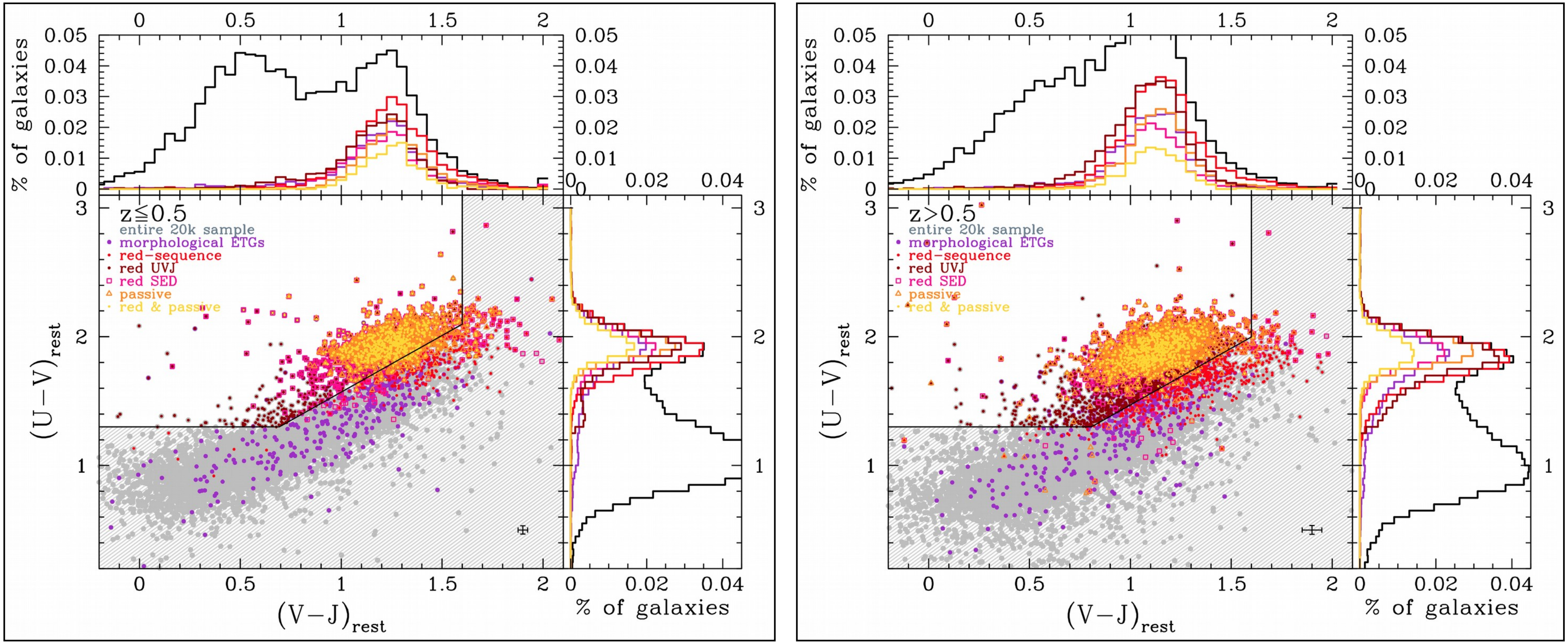

Moresco et al. (2013)

The selection criterion is **crucial** to ensure the purity of the sample:
- most massive galaxies
- no sign of on-going star formation

What about age?

Constraining the age of a population is a difficult task

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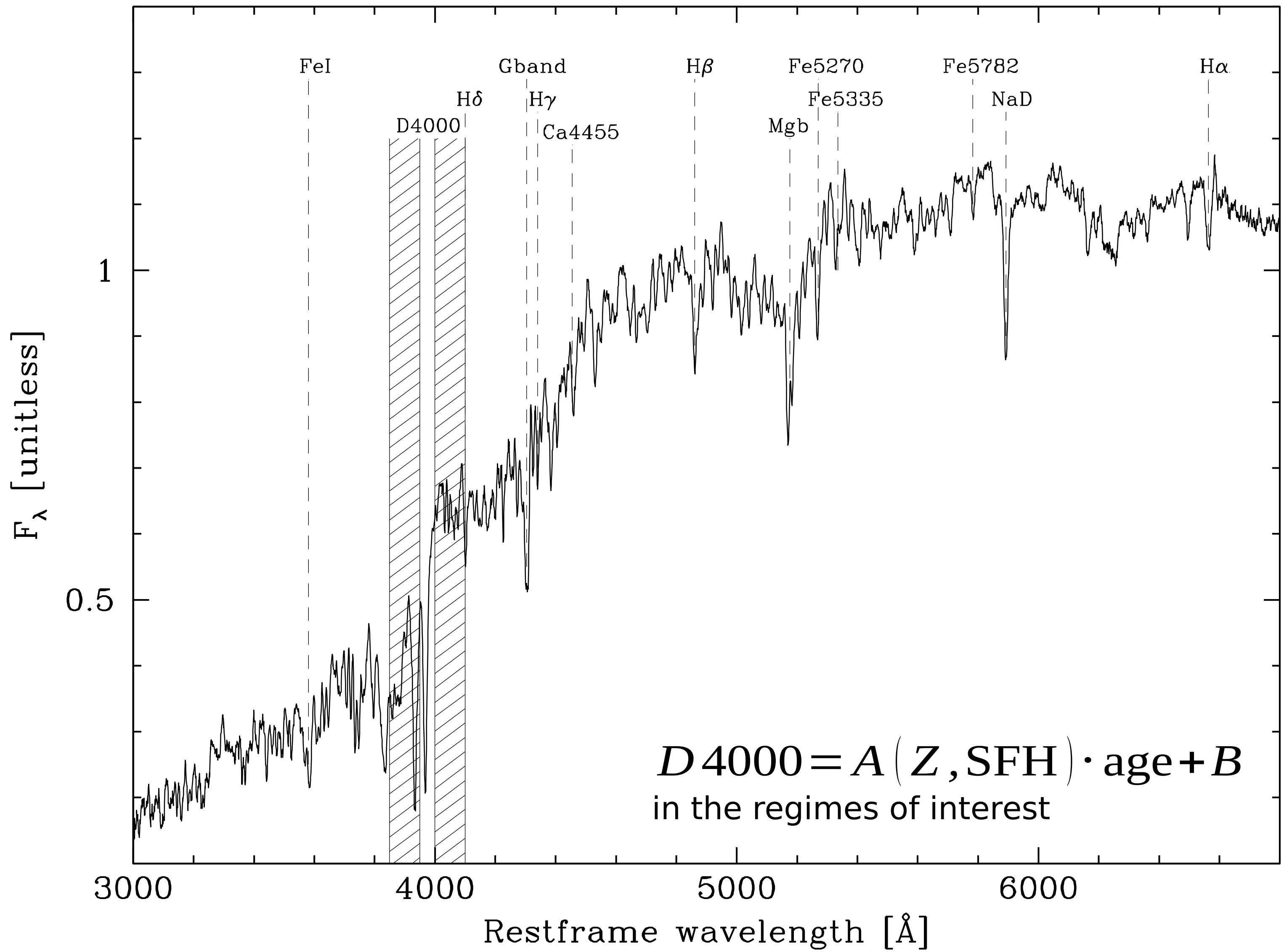
Constraining the age of a population is a difficult task



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

in the regimes of interest

A step further in the method

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

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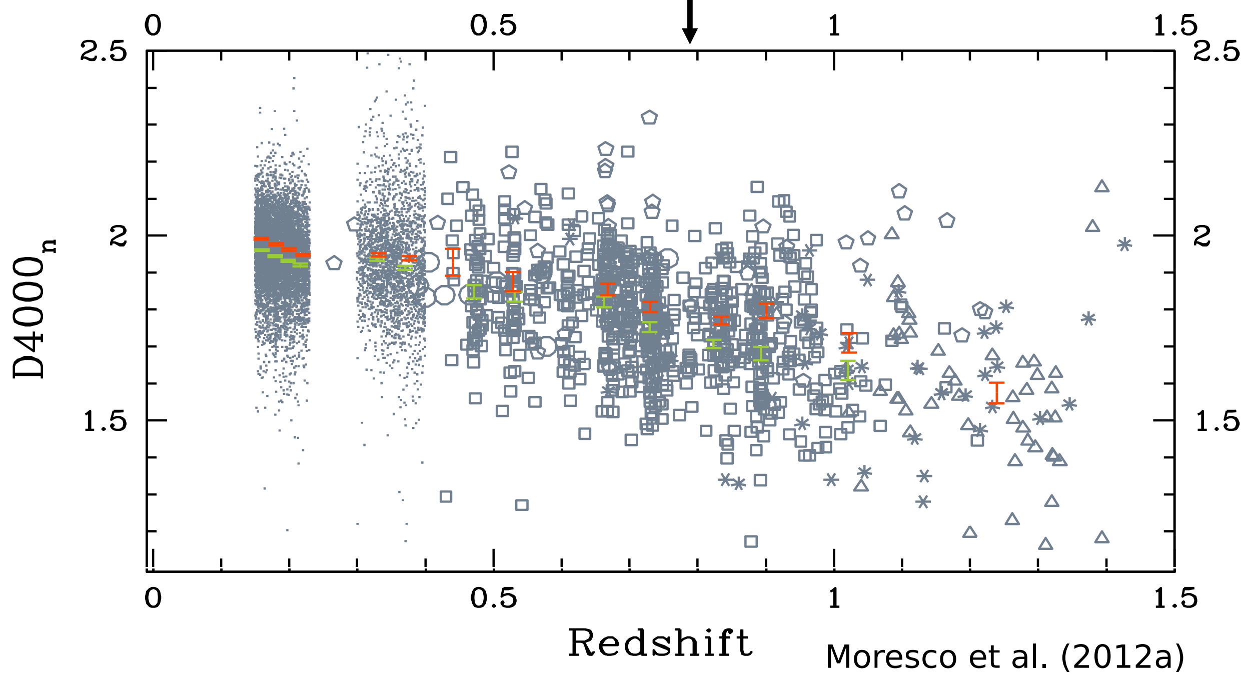
$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

estimated from data



Moresco et al. (2012a)

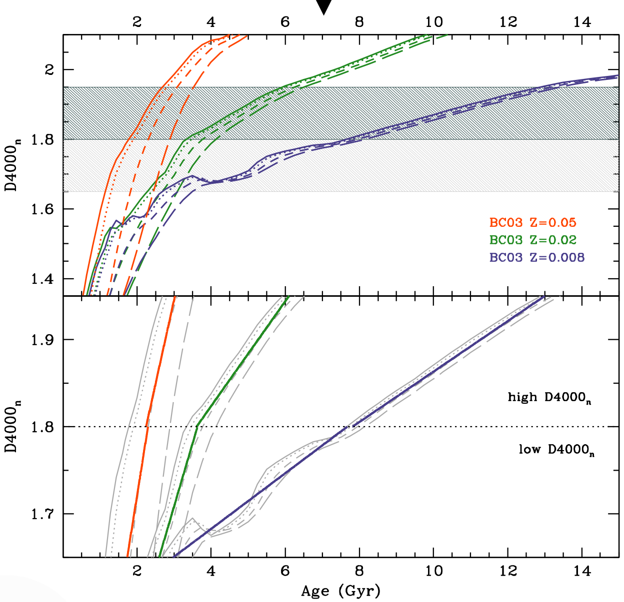
A step further in the method

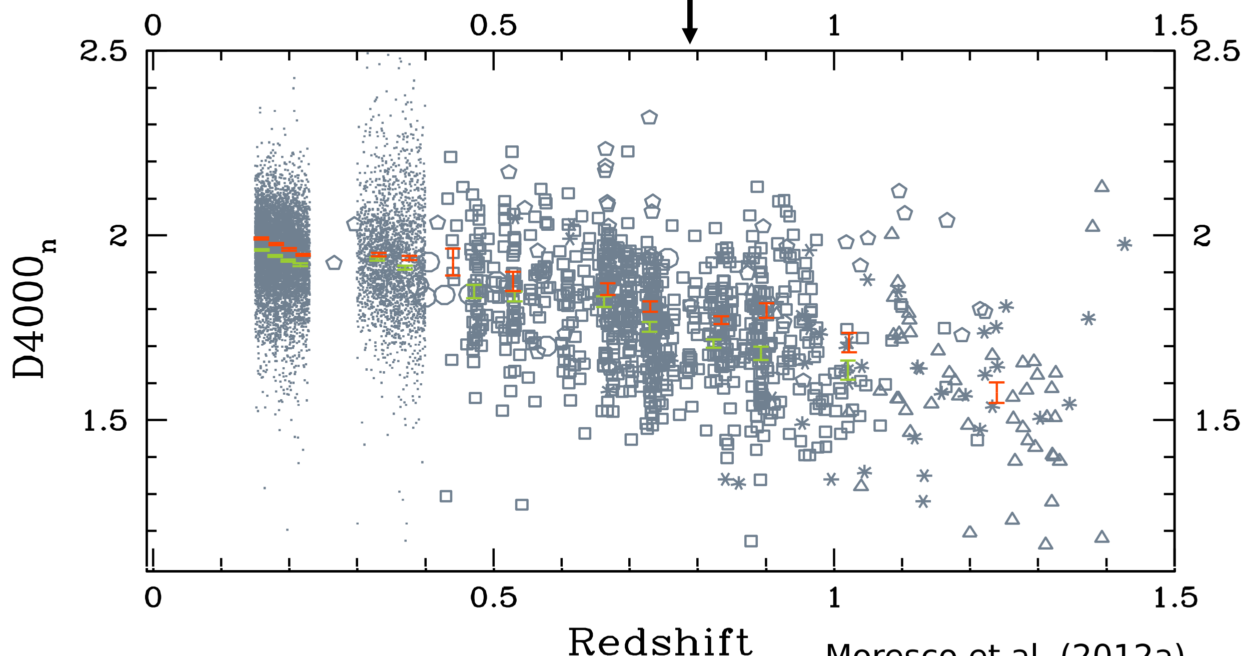
$$H(z) = -\frac{1}{1+z} A(Z,SFH) \frac{dz}{dD4000_n}$$

calibrated on different SPS models

estimated from data

$$A(Z,SFH) = \langle A(Z) \rangle \pm \sigma_A(SFH)$$





Moresco et al. (2012a)

Addressing systematics 1: SPS models

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

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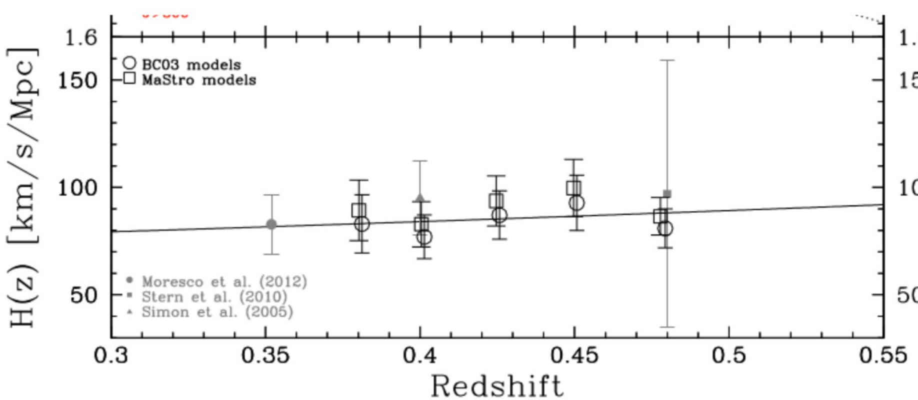
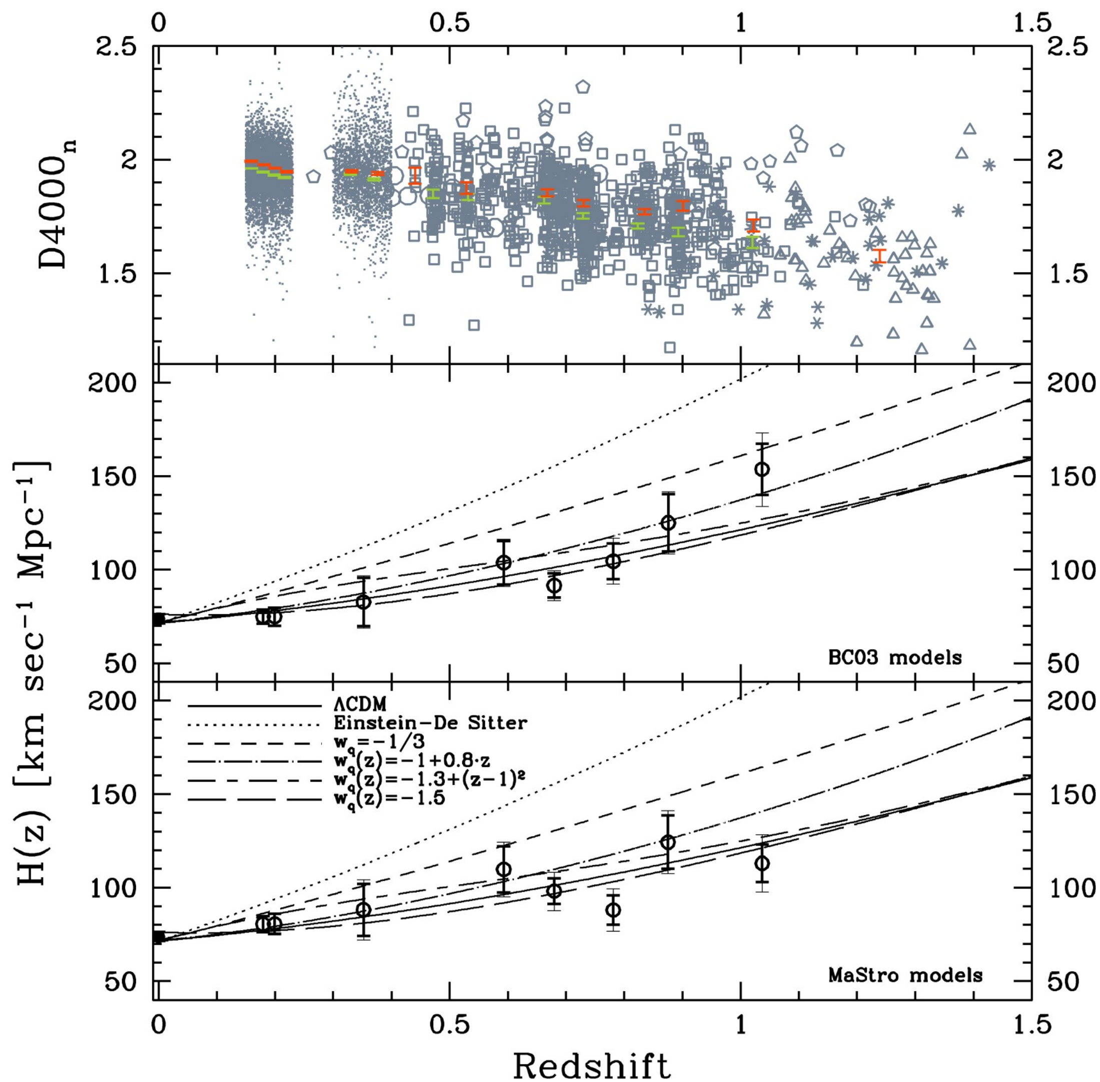
In all analyses, the results are fully compatible within errorbars

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

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

Addressing systematics 2: rejuvenation

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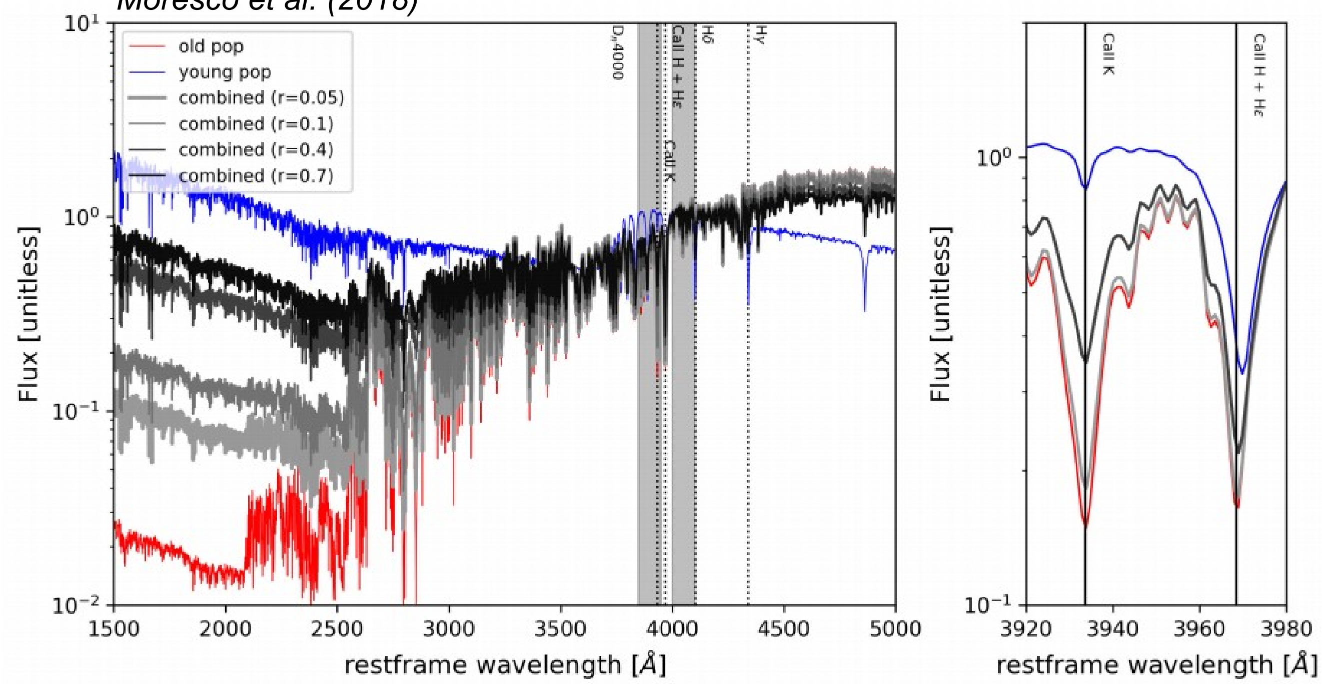
Moresco et al. (2018)



- UV flux
- emission lines
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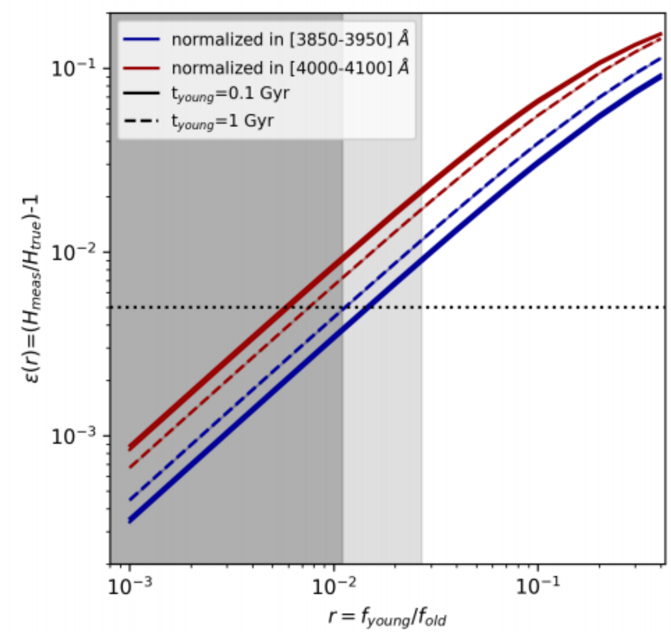
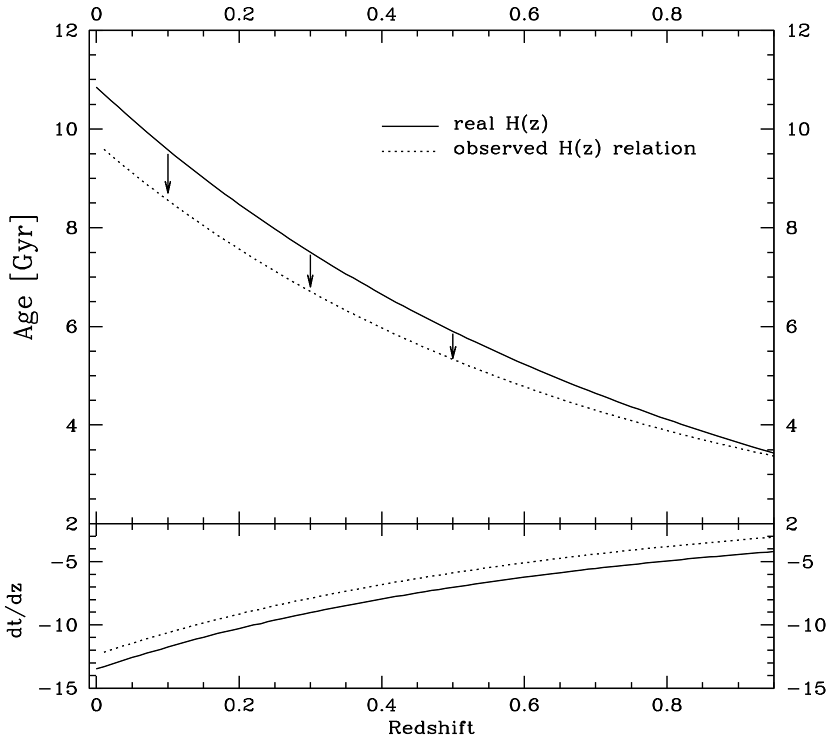


H/K ratio → contamination → cov. matrix

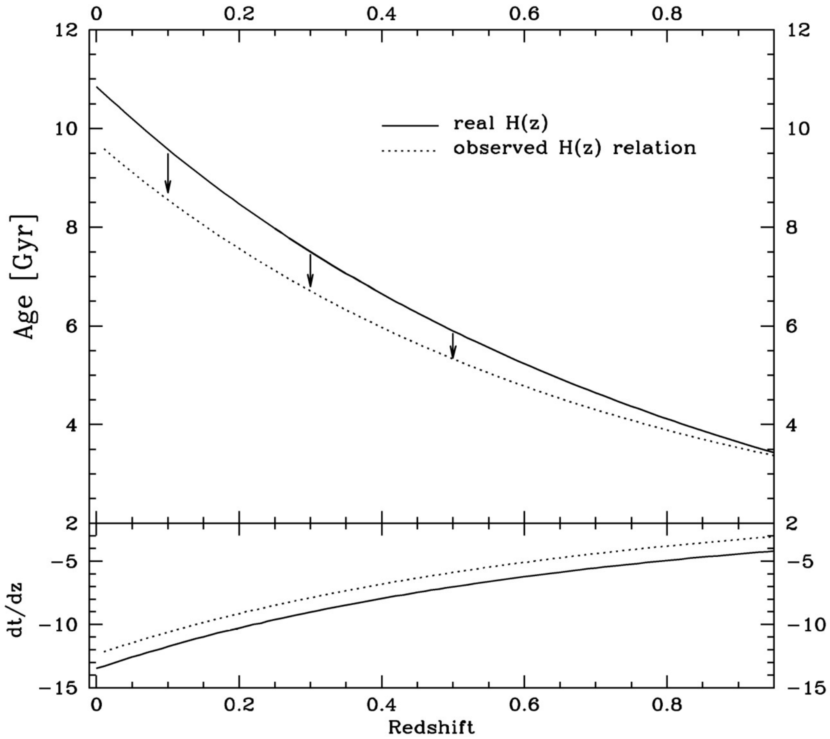
$$Cov_{young} = H(z_1)\,H(z_2)\,\varepsilon(r_1)\,\varepsilon(r_2)$$

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

Addressing systematics 3: progenitor bias



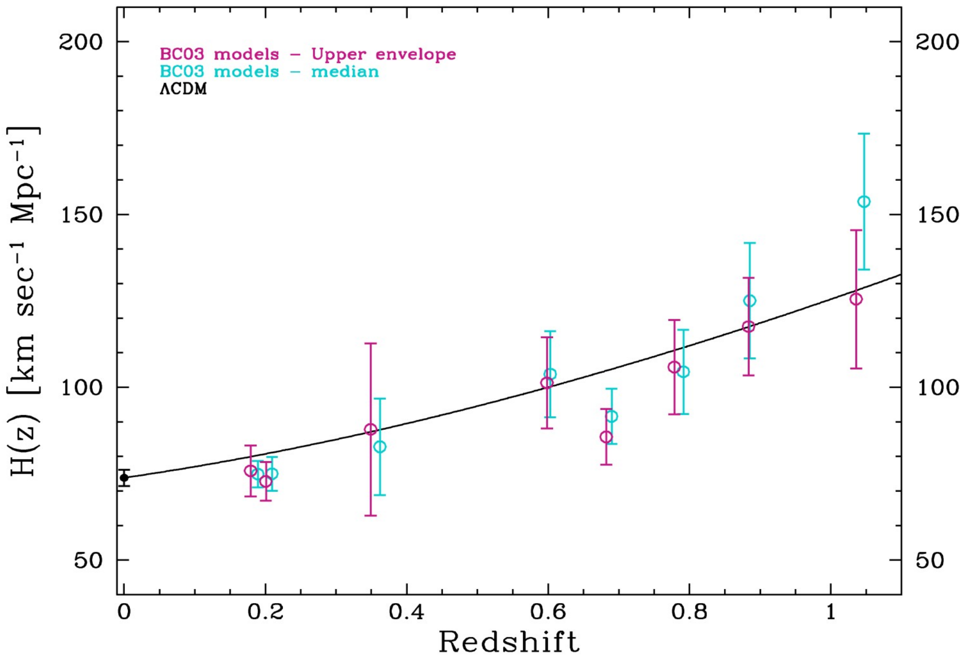
ETGs at high redshift might be biased towards the oldest progenitors of present-day ETGs, therefore not sampling the same population considered at intermediate redshifts

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

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

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

Upper envelope test



Moresco et al. (2012a)

Pros & cons

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

PROs	**CONs**

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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 models	

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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 models

CONs

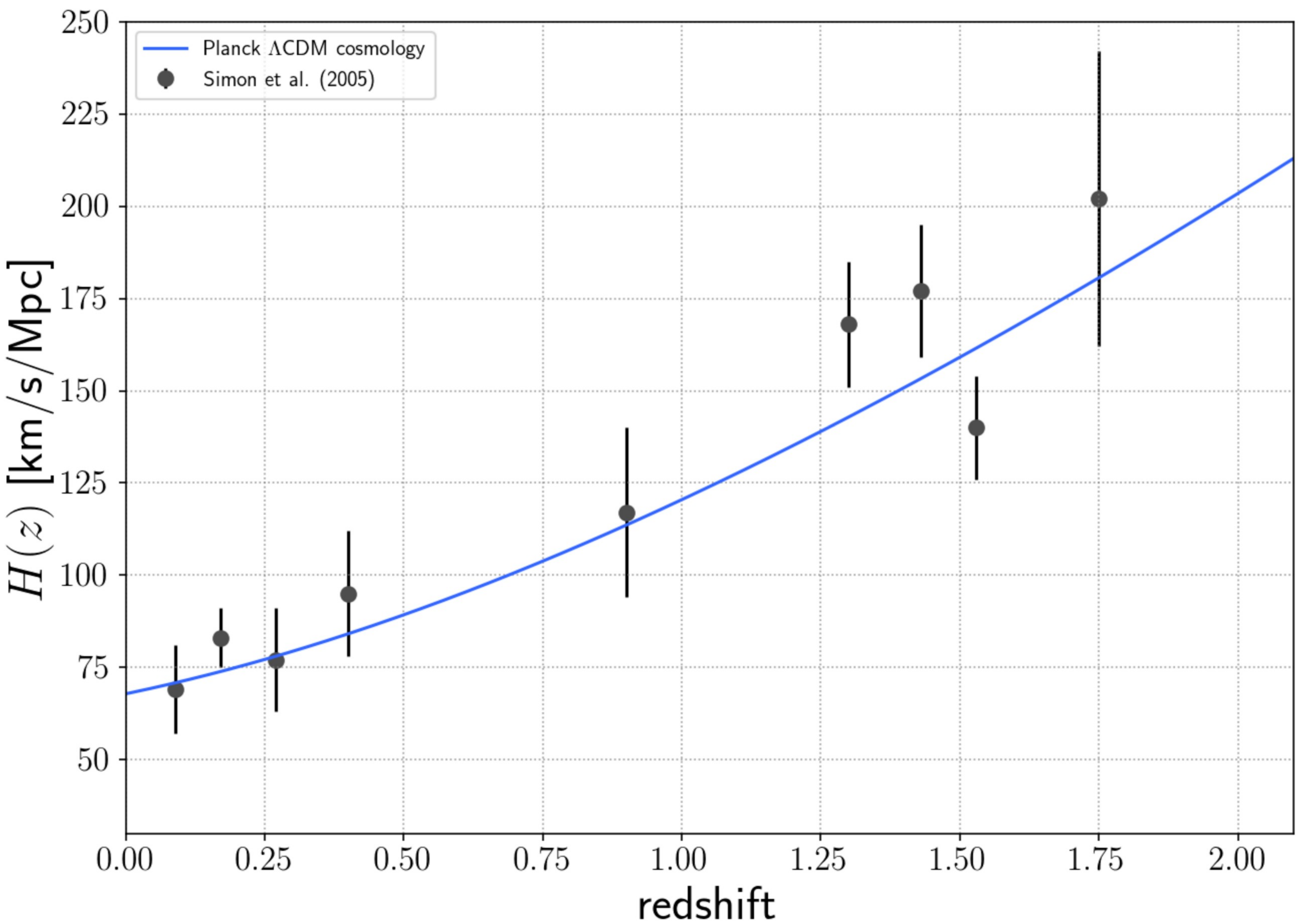
homogeneity of the sample should be handled accurately

relies on metallicity prior/estimate

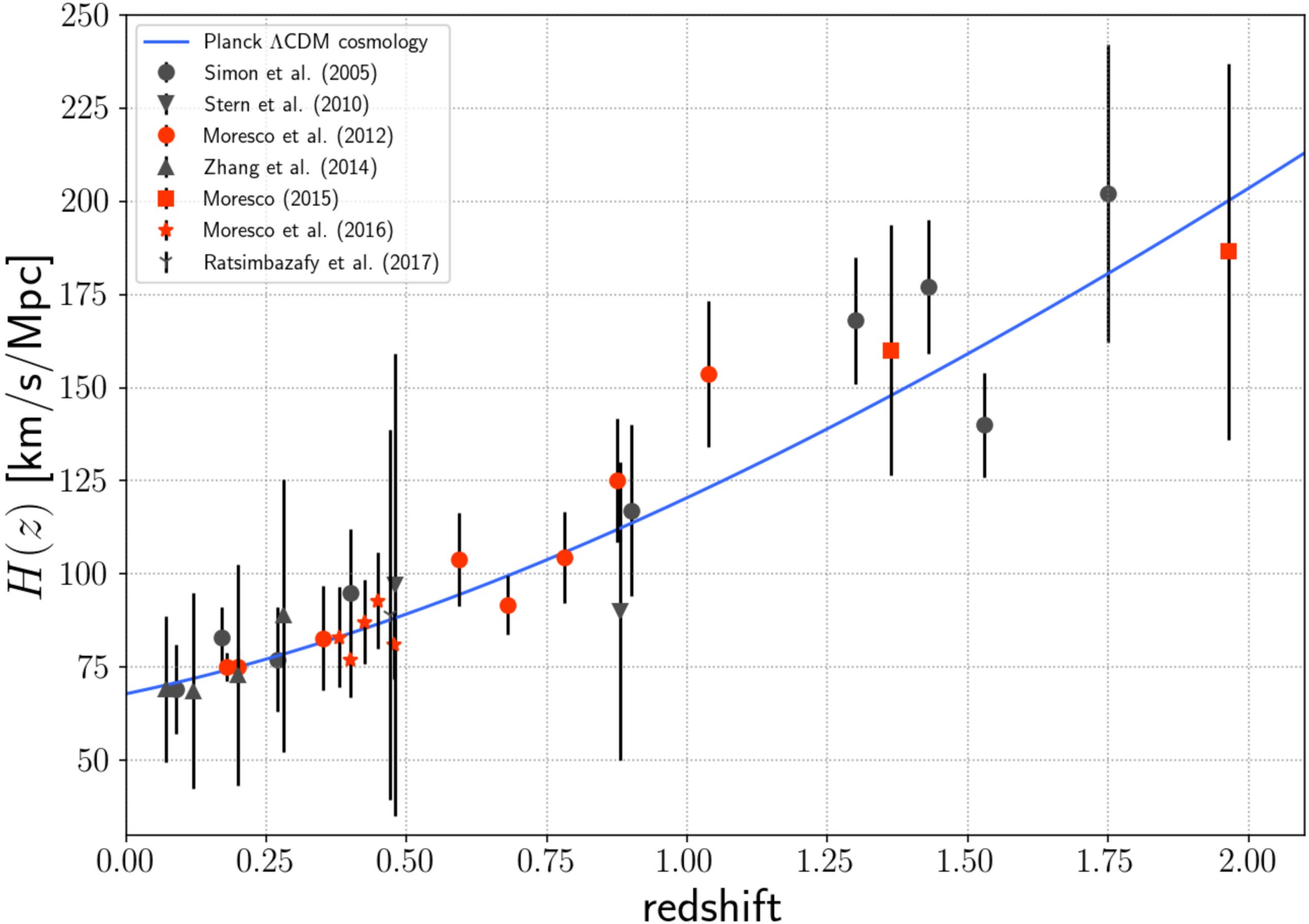
SPS model dependency should be assessed carefully

The results

H(z) – status pre-2009



H(z) – state of art



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)

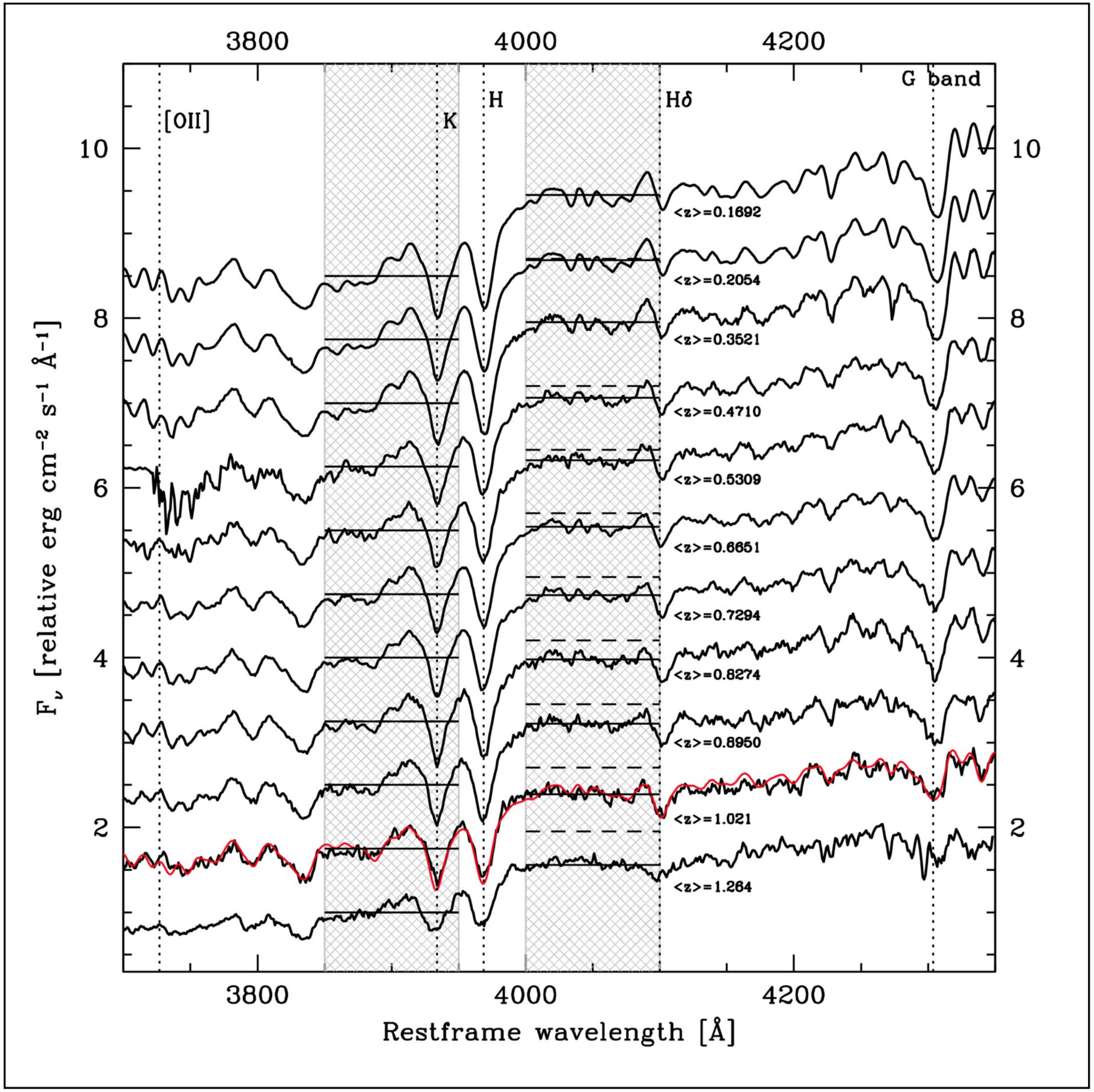
- **SDSS BOSS DR9**: more than 130000 massive and passive galaxies in the range 0.2<z<0.8
Moresco et al. (2016a)

- **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

Stacked spectra: an 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

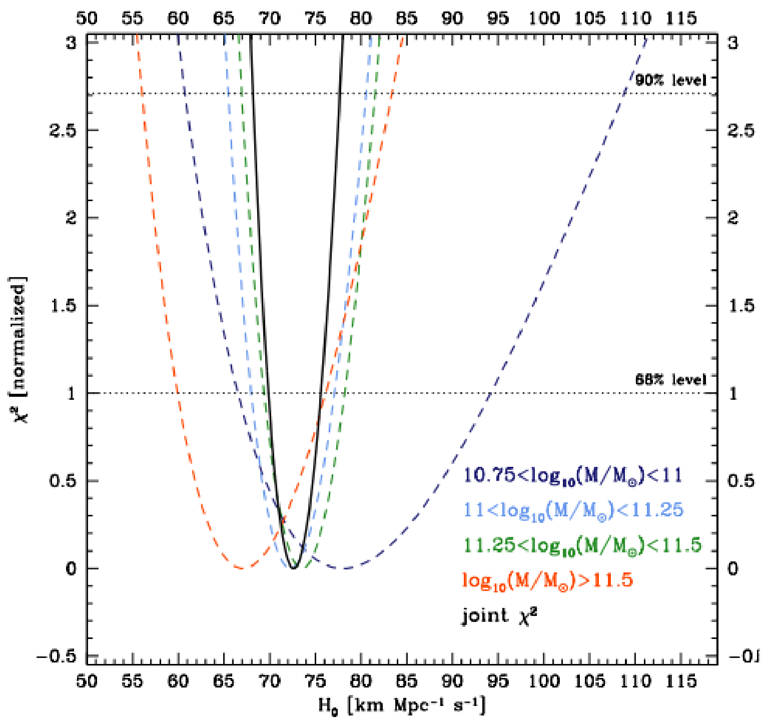
high-z

- 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)

Cosmological applications

Estimating the Hubble parameter

- fitting D4000(z) relation of SDSS ETGs
- cosmology-dependent estimate (ΛCDM)



$H_0 = 72.6 \pm 2.9(\mathrm{stat}) -2.3(\mathrm{syst})$ km s^{-1} Mpc^{-1}

Moresco et al. (2011)

Estimating the Hubble parameter

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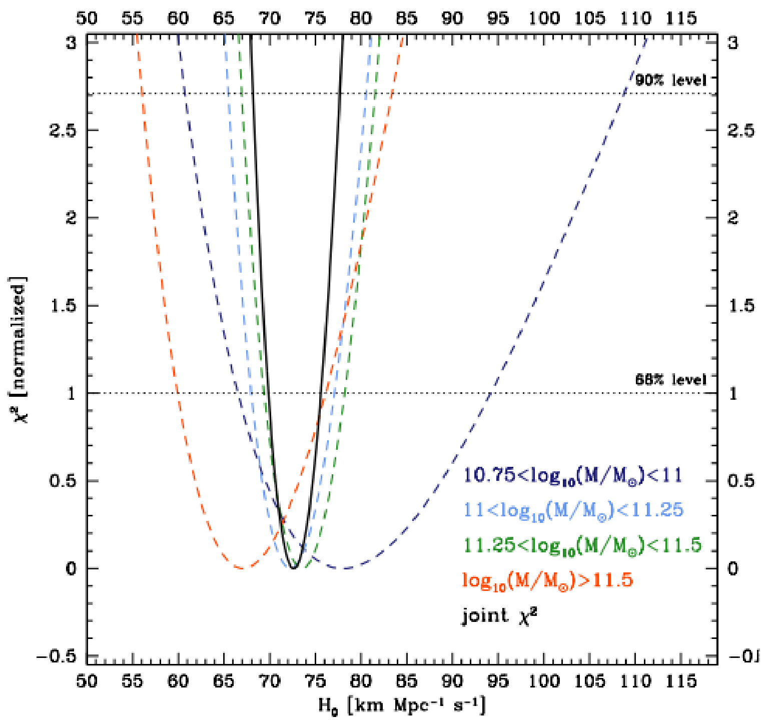
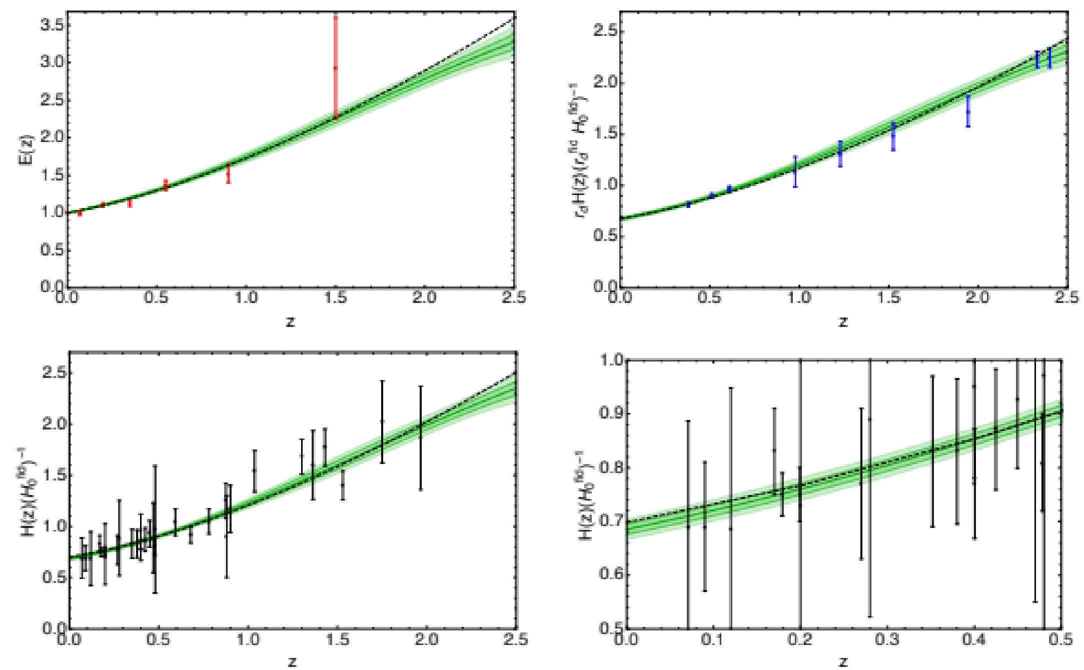


H_0 = 72.6 ±2.9(stat) -2.3(syst) km s^{-1} Mpc^{-1}

- H_0 as extrapolation of H(z=0)
- multi-task Gaussian process to combine probes
- cosmology-independent estimate



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

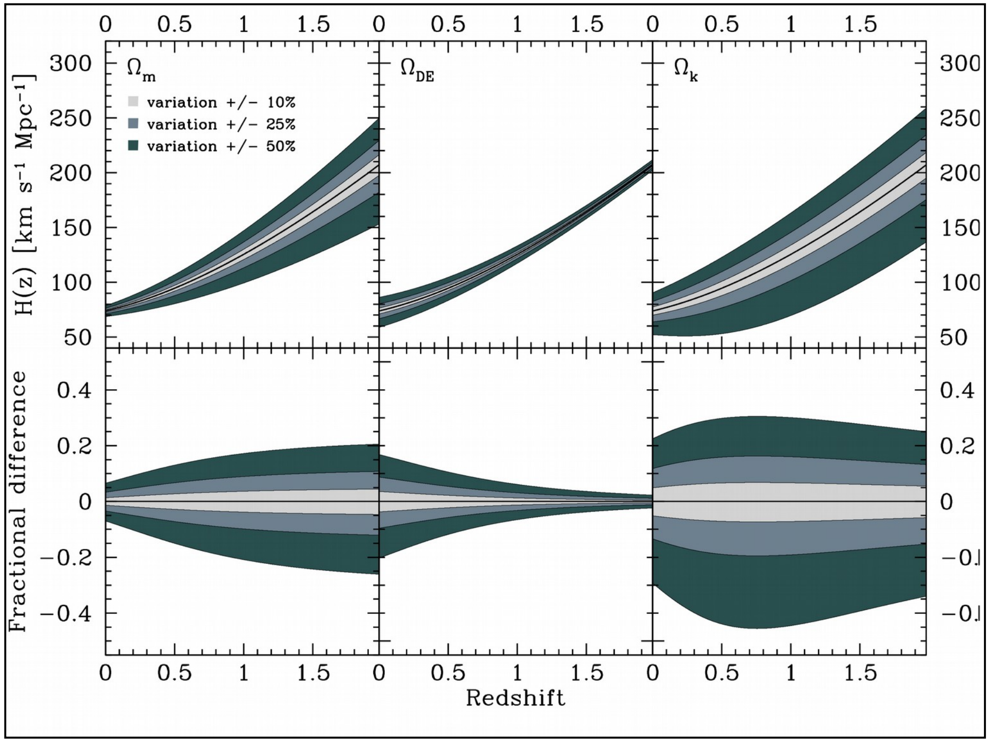
Moresco et al. (2011)

Haridasu et al. (2018)

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)



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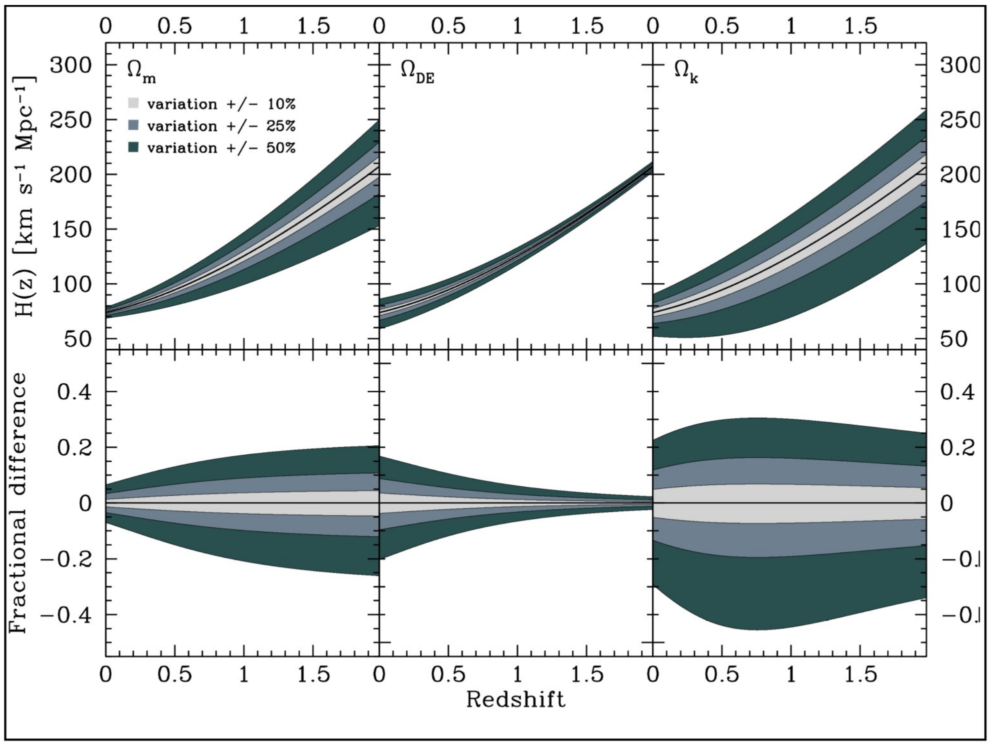
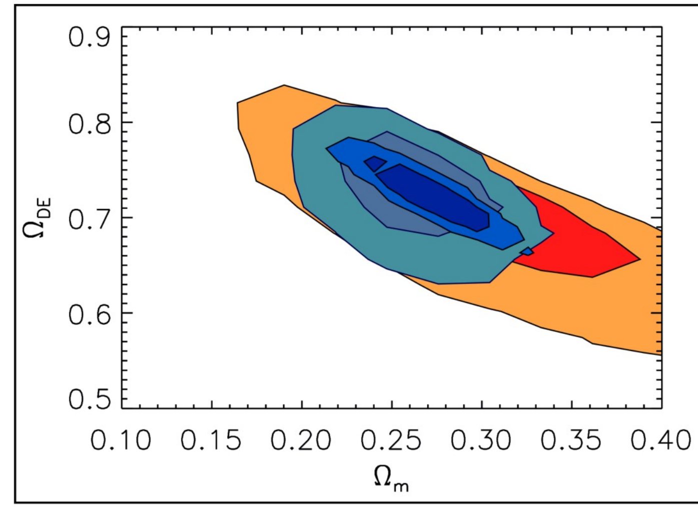
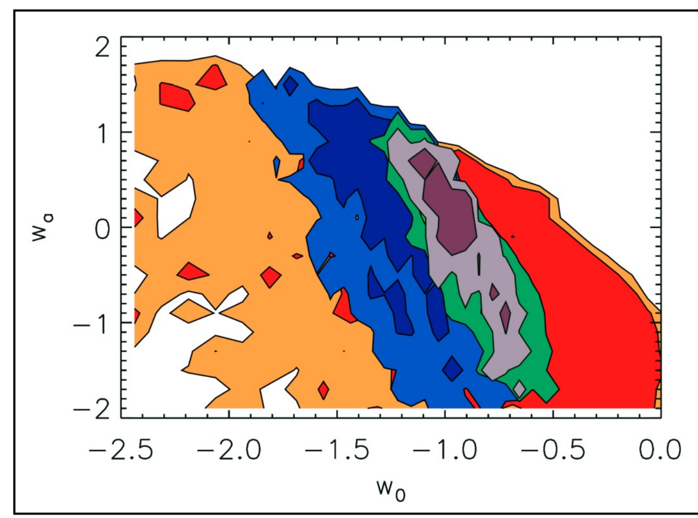






WMAP5+H_0(Freedman2001)

WMAP5+H_0(Riess2011)

WMAP5+H_0(Riess2011)+CC

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

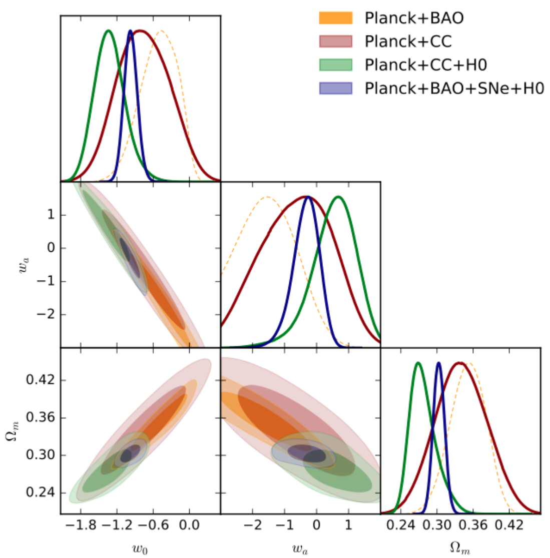
WMAP5+H_0(Riess2011)+CC simulated 2.5% error

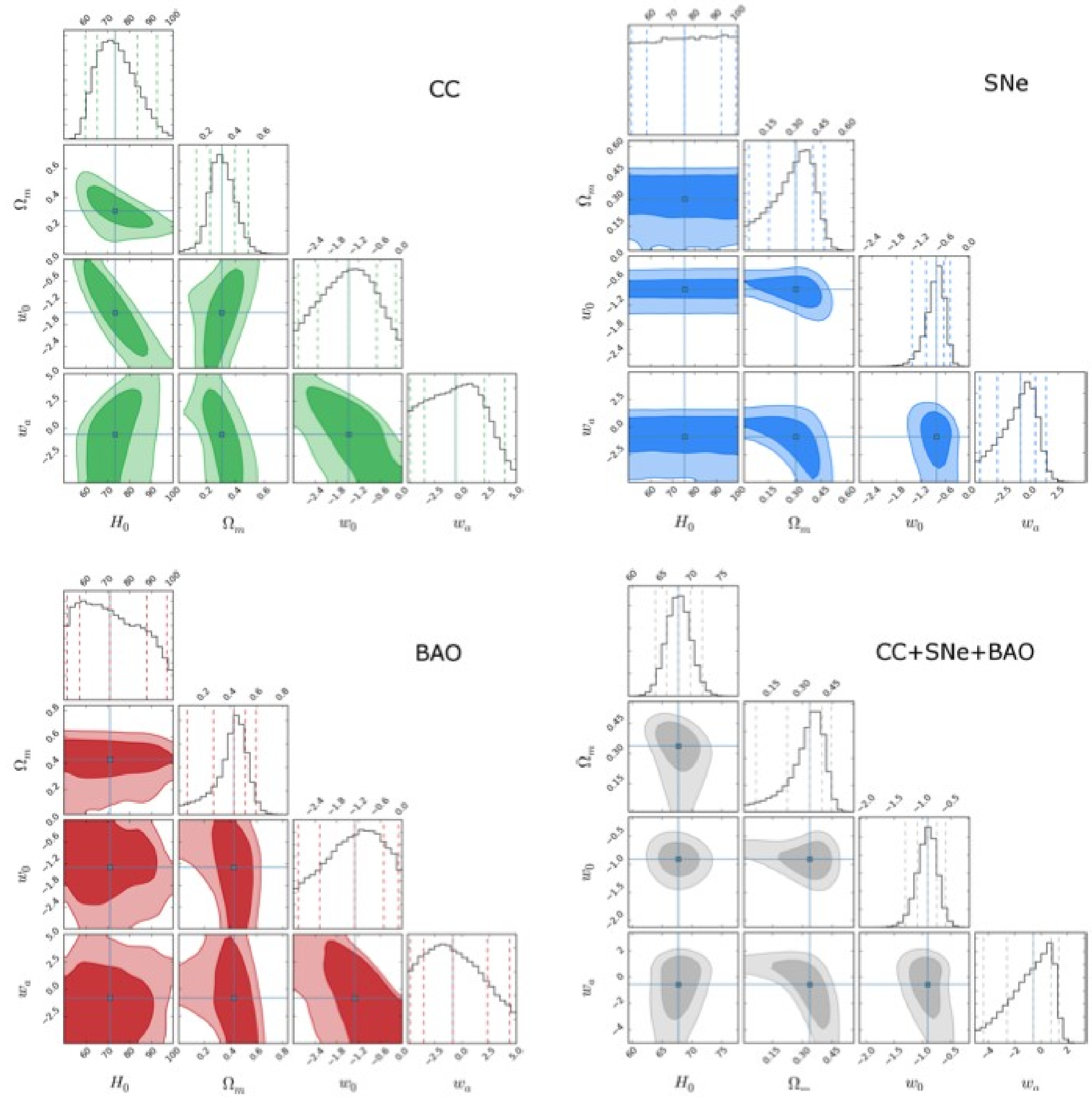
Combining with (and challenging) standard probes

Each probe is more sensible to some parameter

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

Combining probes maximizes accuracy





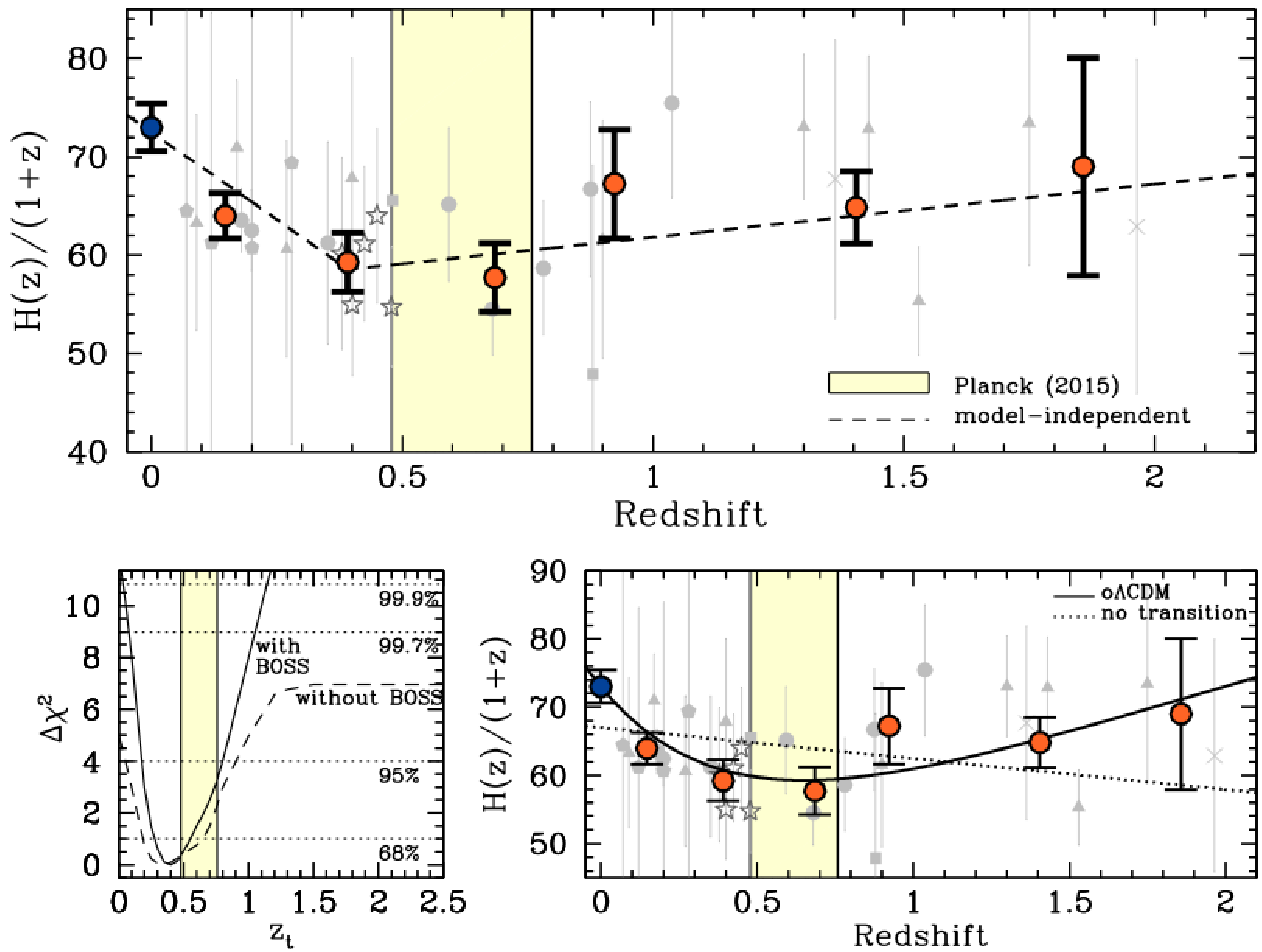
Moresco et al. (2016b)

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)



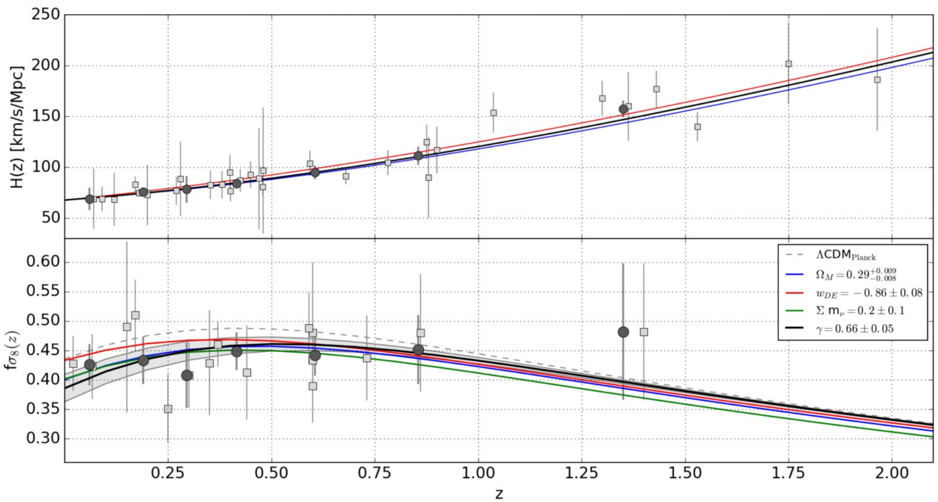
Moresco et al. (2016a)

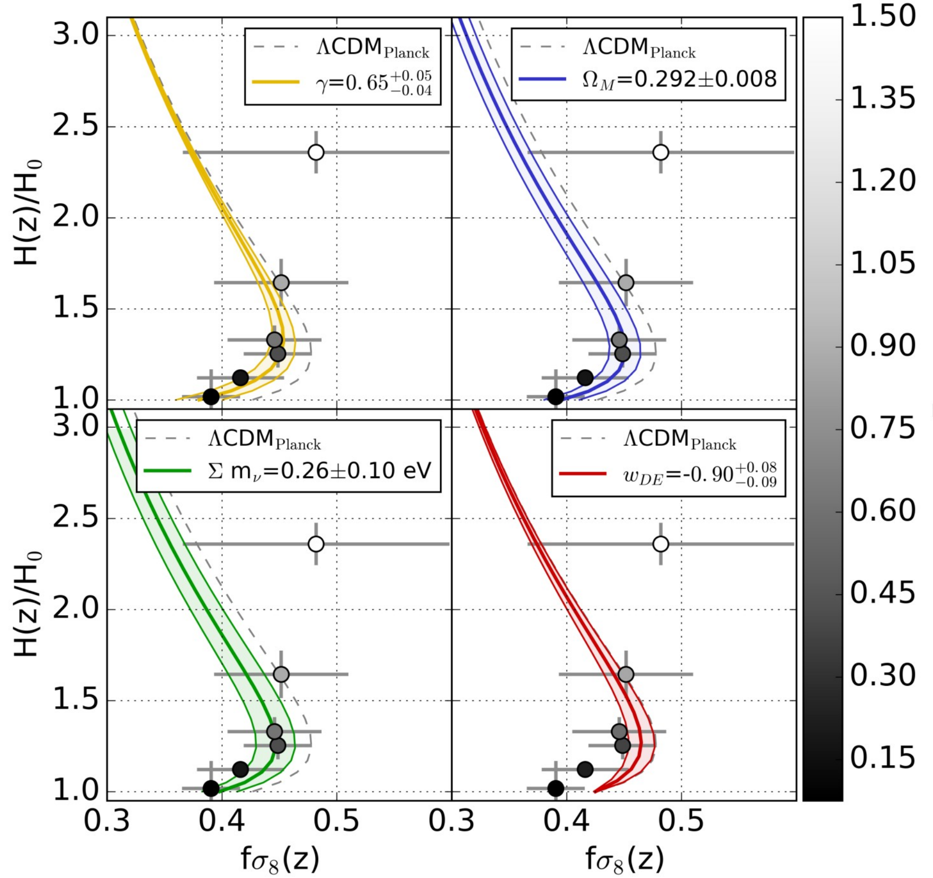
Combining expansion and growth

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)

Independent constraint on H_0

It is also possible to use the ages of the oldest objects in the Universe to constrain t_U, and hence H_0, in an independent way

$$\mathrm{age}_{GC} \xrightarrow{\text{upper limit on}} \mathrm{age}_{Univ} \xrightarrow[\text{cosmological model}]{\text{for a given}} H_0$$

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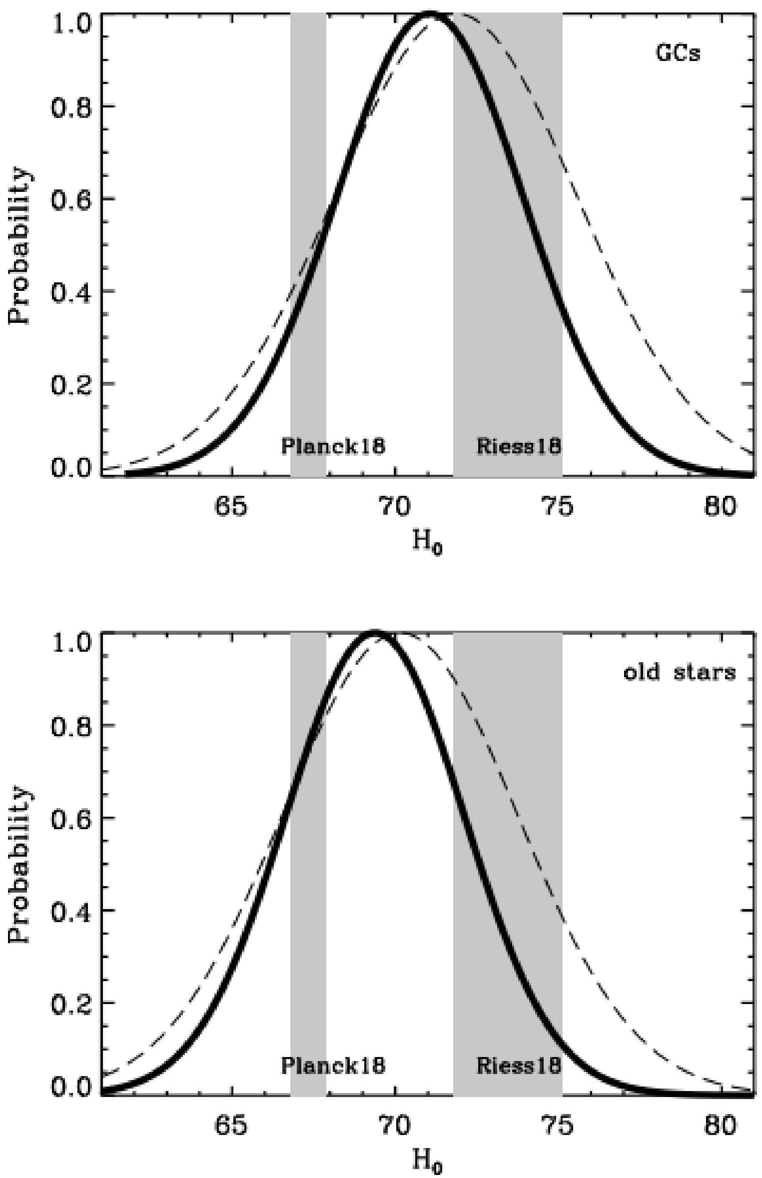
$$\text{age}_{GC} \xrightarrow{\text{upper limit on}} \text{age}_{Univ} \xrightarrow[\text{cosmological model}]{\text{for a given}} H_0$$

No data assumed from CMB, just Ω_M from local probes



Jimenez et al. (2019)

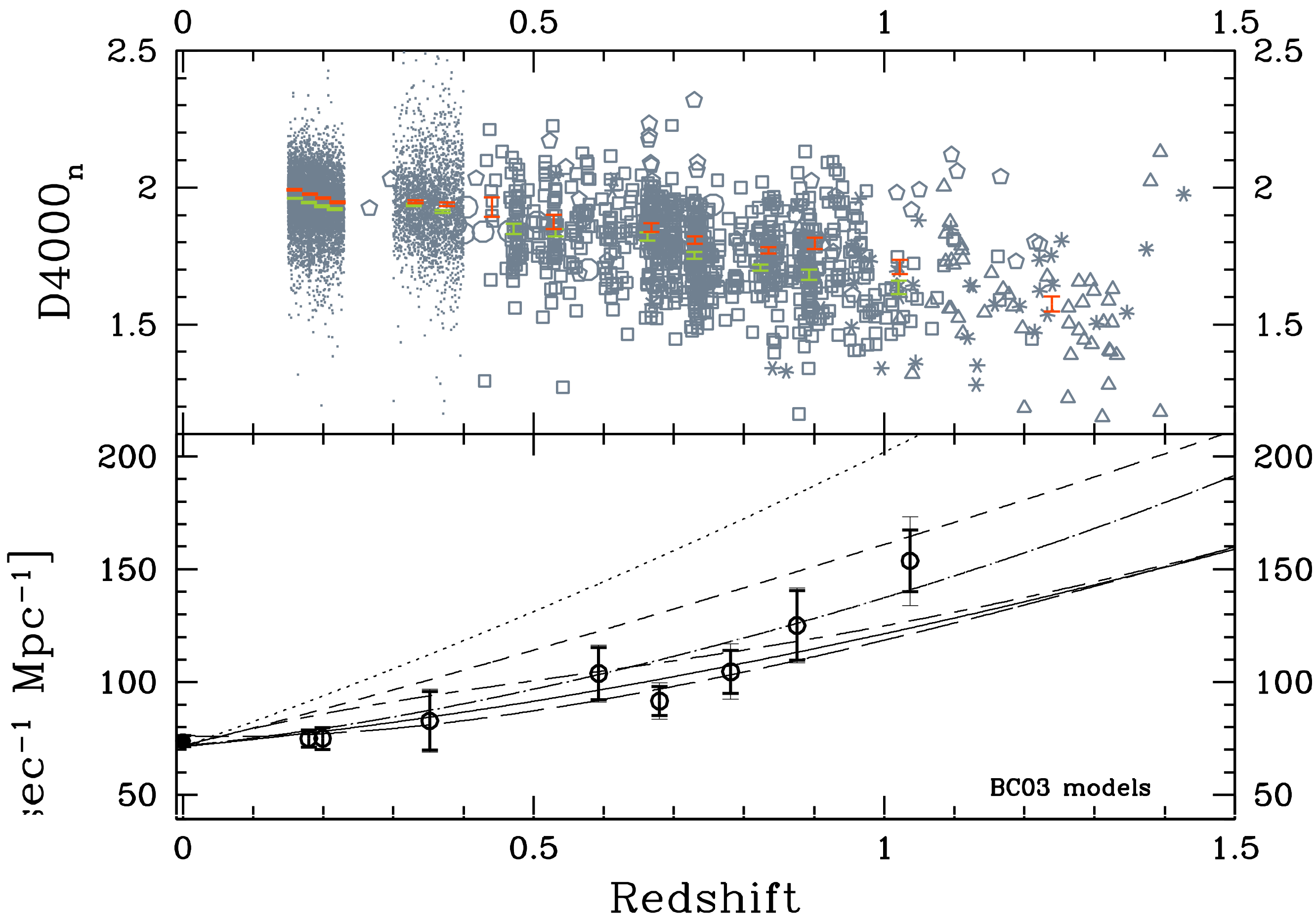
Conclusions

- Basics of “cosmic chronometer” approach, as complementary technique to constrain cosmological parameters
- 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 $z=0$

Backup slides

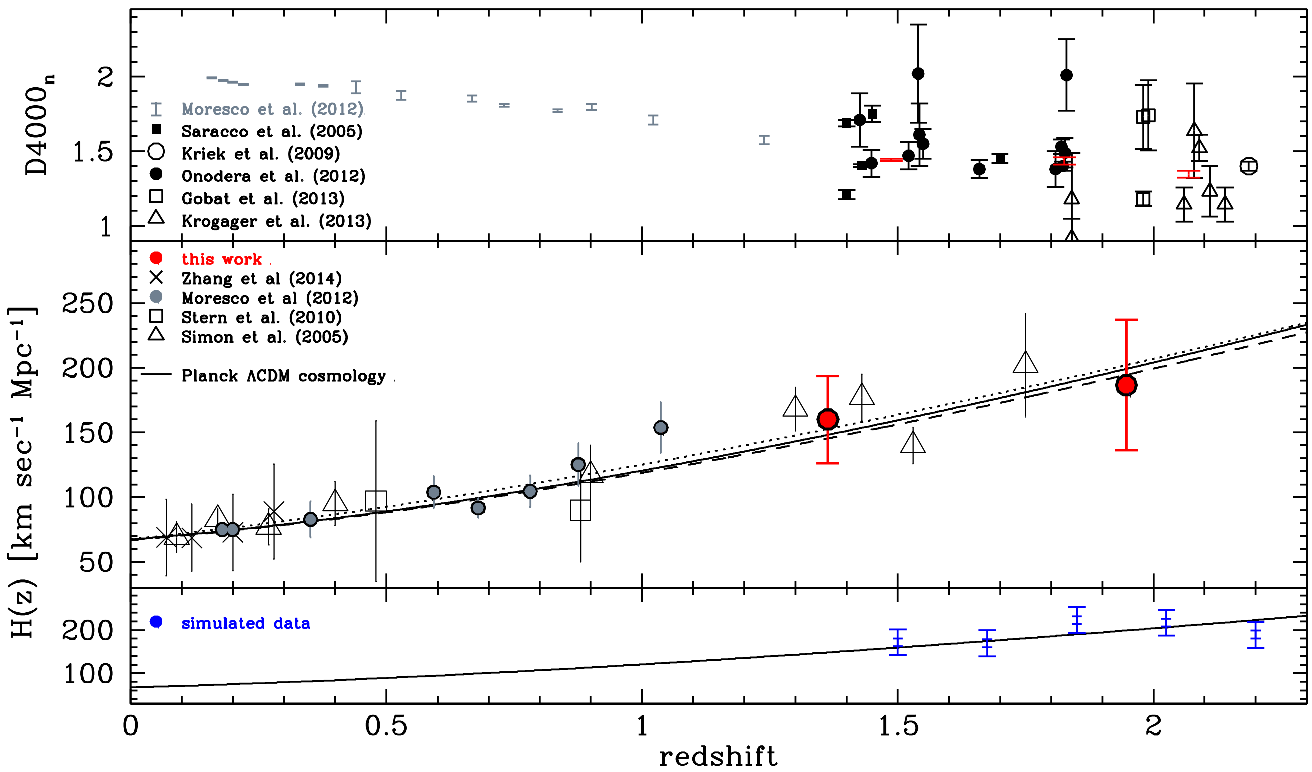
Results on the SDSS-extended catalog

- **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

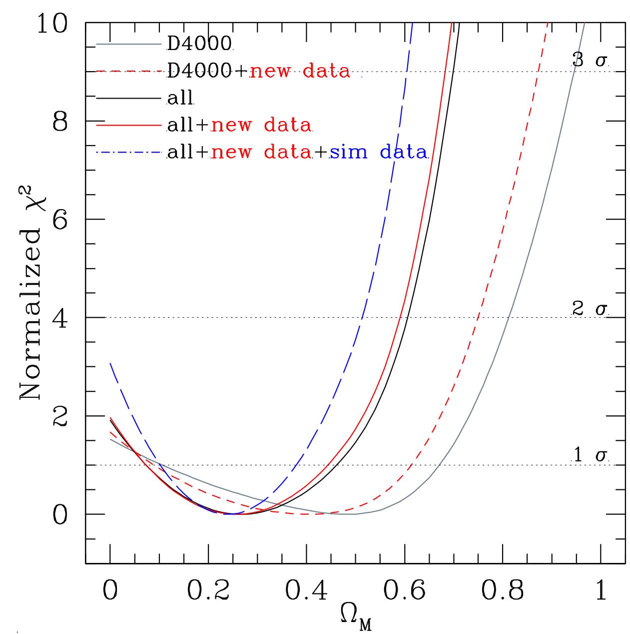


Moresco et al. (2012a)

Moving to higher redshifts



Moresco (2015)

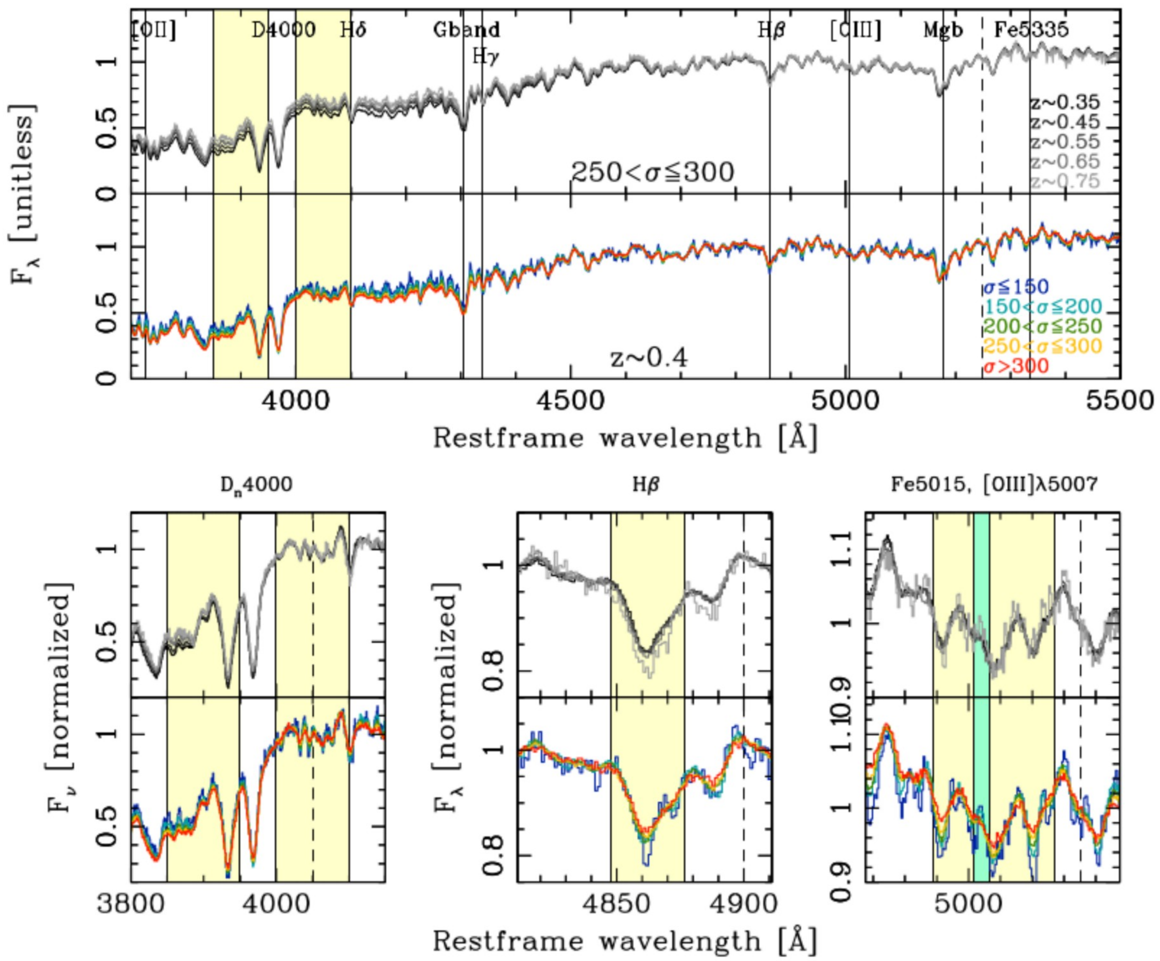


- **2 new H(z) points, for the first time at z~2**
- test case (<30 galaxies) to show the potential of this approach at high z (e.g. Euclid)
- improved cosmological constraints (~5% for Ω_m and w_0)

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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