Cosmic Clocks

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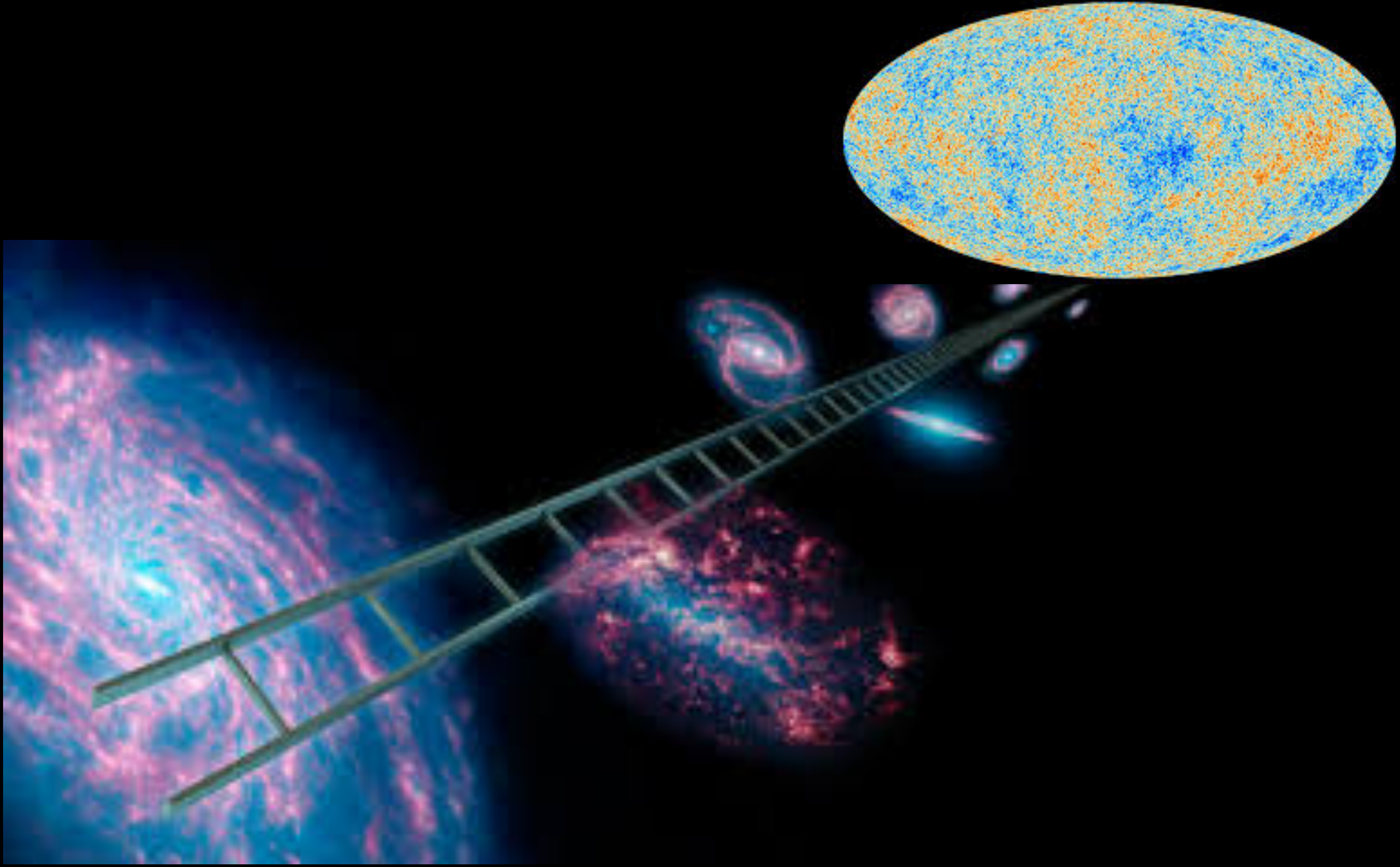
erc

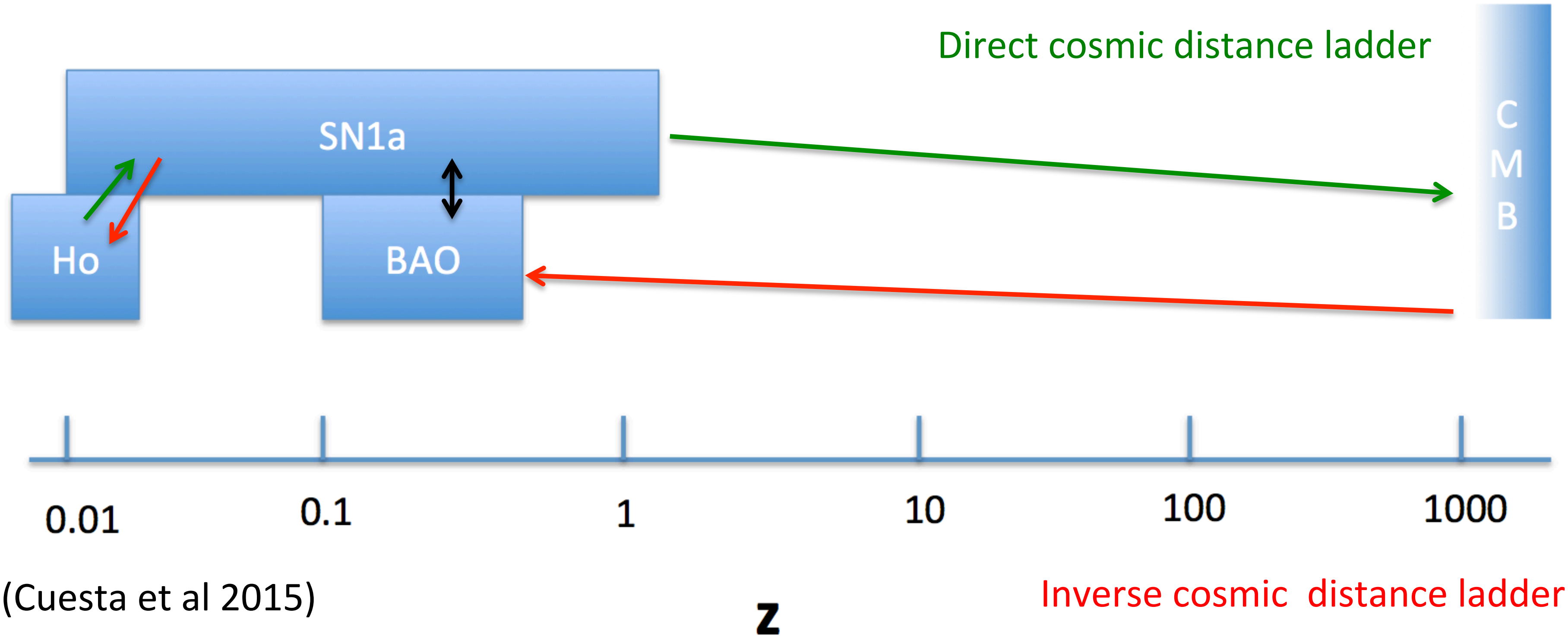
What is early and what is late?

Bernal, Verde, Riess 2016

The H0 game: E2E test



At glance: direct and inverse distance ladder



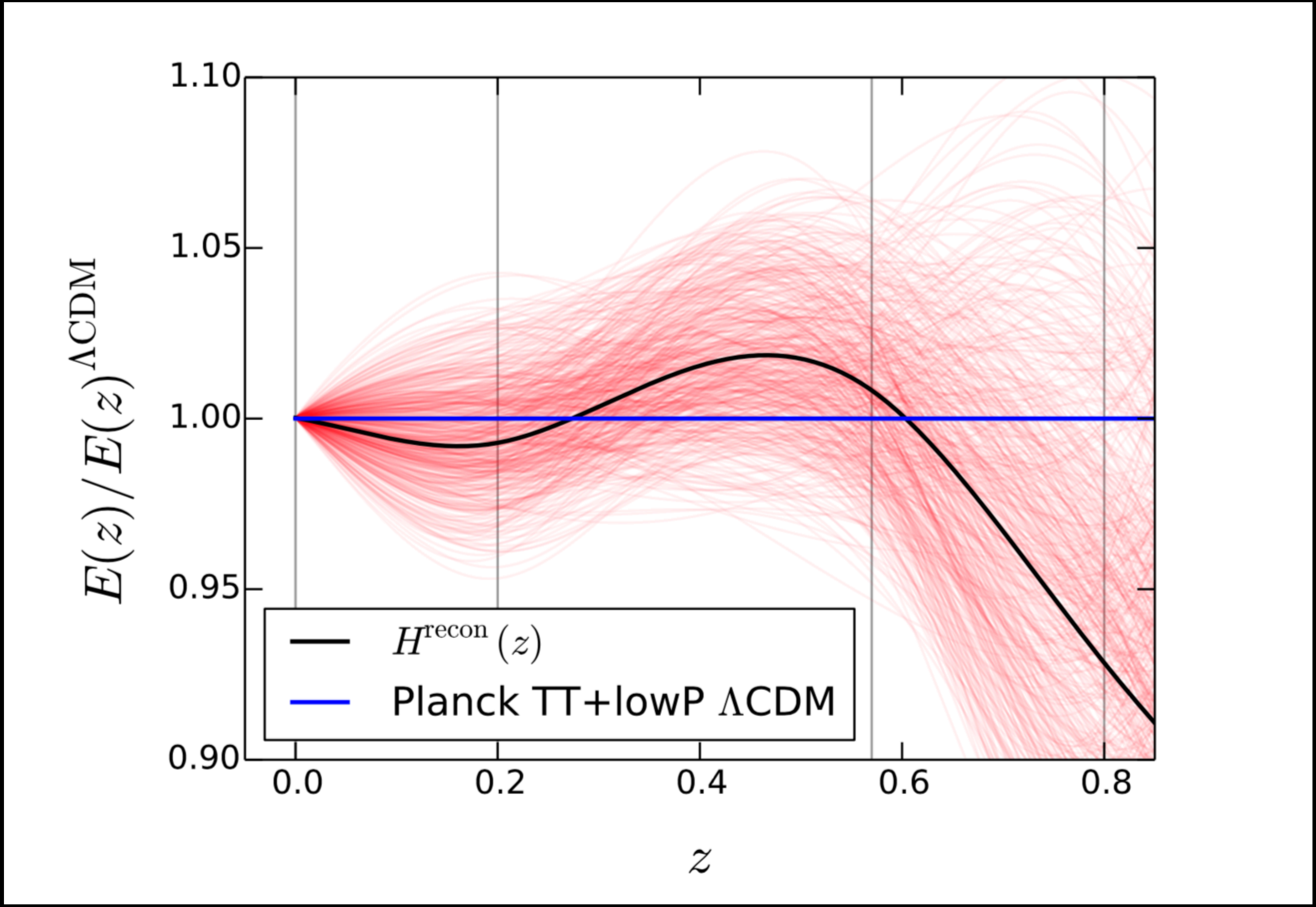
(Cuesta et al 2015)

H0: Direct measurement
Low z anchor

rd,
high z anchor

Auborg et al 2014,Cuesta et al 2014, Bernal et al 2016

The SHAPE of expansion history is well constrained



The issue is with the normalization

Bernal ,LV, Riess 2016

Good ladders need 2 good anchor points

What is early and what is late?

Early: CMB and pre-recombination physics

Late: z~0 but can use z<1 if you are careful
(e.g., BAO only relative distances, model-independent etc.)

And can use higher z if you spell out your assumtions

See philosophers of physics

What about other “things” that are not H0?

Stellar ages: a tool to measure the expansion rate

- Absolute stellar ages (clocks) at z=0 provide an estimate of the current expansion rate.

$$H_0 = \frac{A}{t}\int_0^{z_t} \frac{1}{1+z}\left[\Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0})(1+z)^{3(1+w)}\right]^{-1/2} dz$$

Relies on knowing other background cosmological parameters
(or the expansion history “shape”)

“The local and distant Universe, stellar ages and H0”
JCAP 2019 ,Jimenez, Cimatti, Verde, Moresco, Wandelt

Stellar ages: a tool to measure the expansion rate

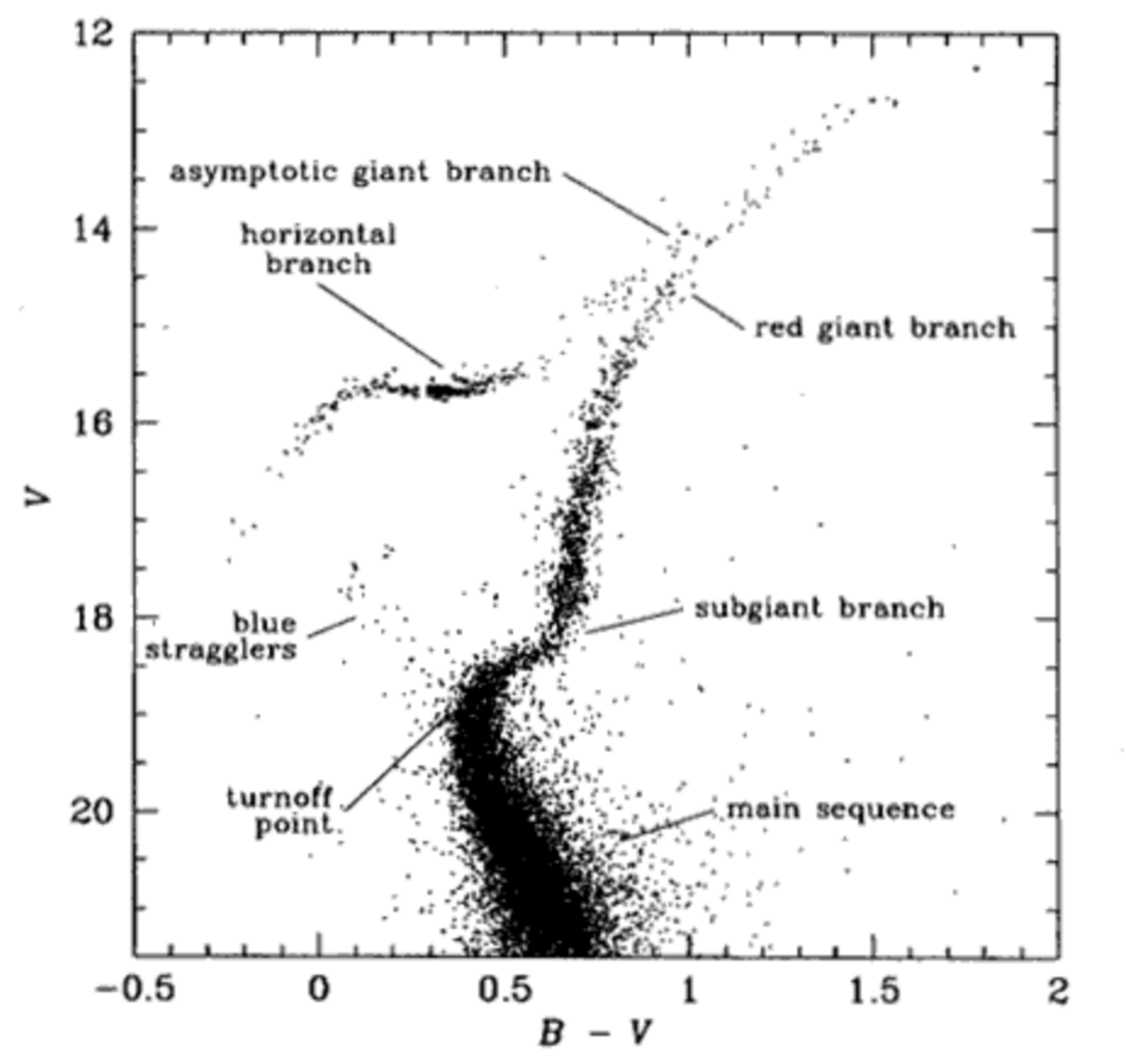
- relative stellar ages (Chronometers) at z provide an estimate of the expansion rate at z

$$\delta t(z) \simeq \frac{\delta z}{H(z)(1+z)}$$

Relies on being able to estimate dt

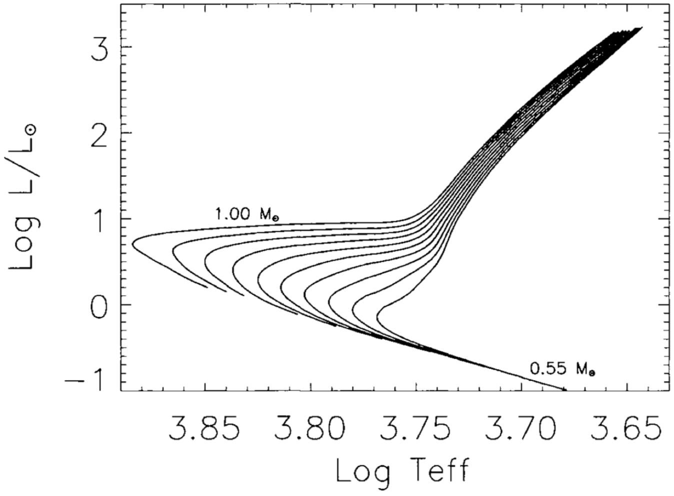
suite of papers on "Chronometers" since 2003
Jimenez, Moresco,, Cimatti, Verde

Globular Clusters have been for decades obvious places to estimate the age of the oldest stars



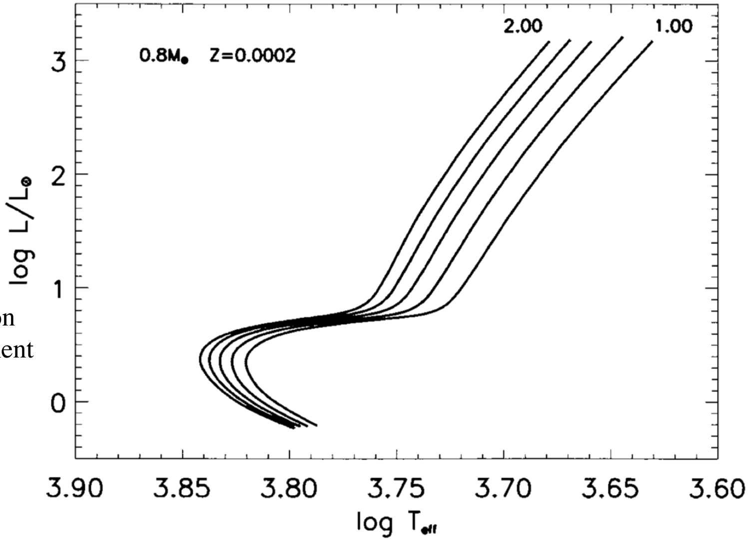
GC were very old (13.5 Gyr),
even when common wisdom was
H0~55 and CDM Universe
(no Lambda)

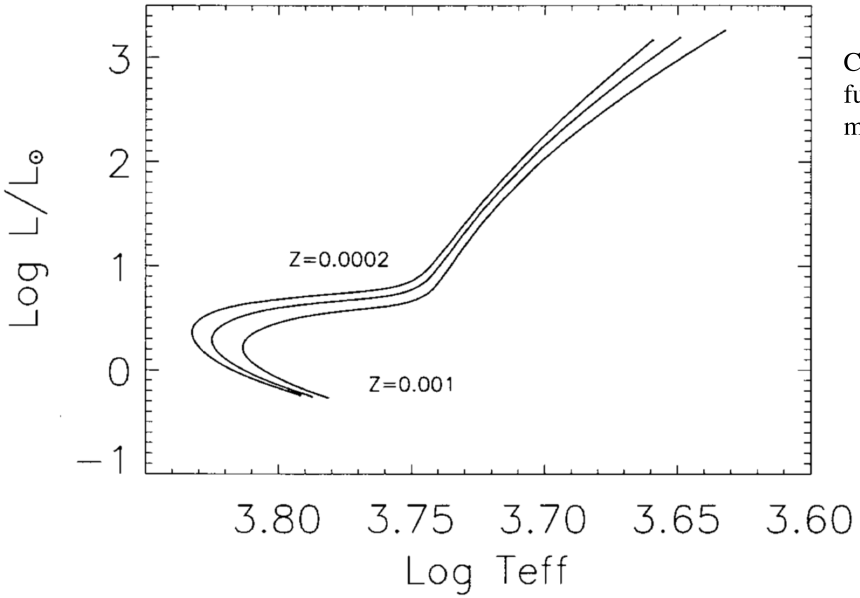
However, the morphology of the HR diagram depends on a few physical parameters besides age: metallicity, Helium content, convection, alpha-enhancement elements and DISTANCE



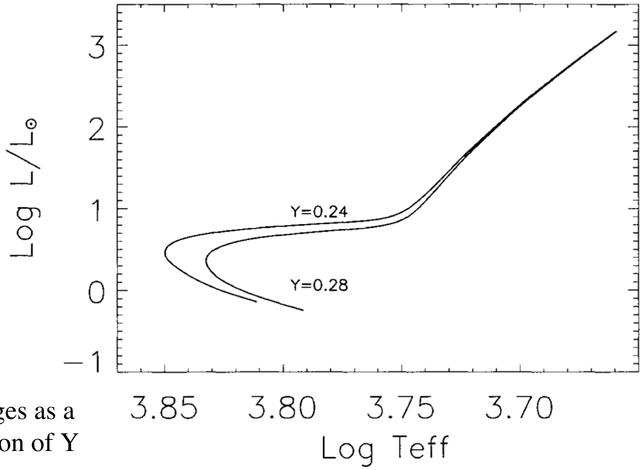
Changes as a function of Mass (age)

Changes as a function of convection treatment (mixing-length)





Changes as a function of metallicity



Changes as a function of Y (He)

Include model uncertainties and vary all parameters at the same time
Bayesian approach: standard MCMC (pioneered by Chaboyer and collab.)

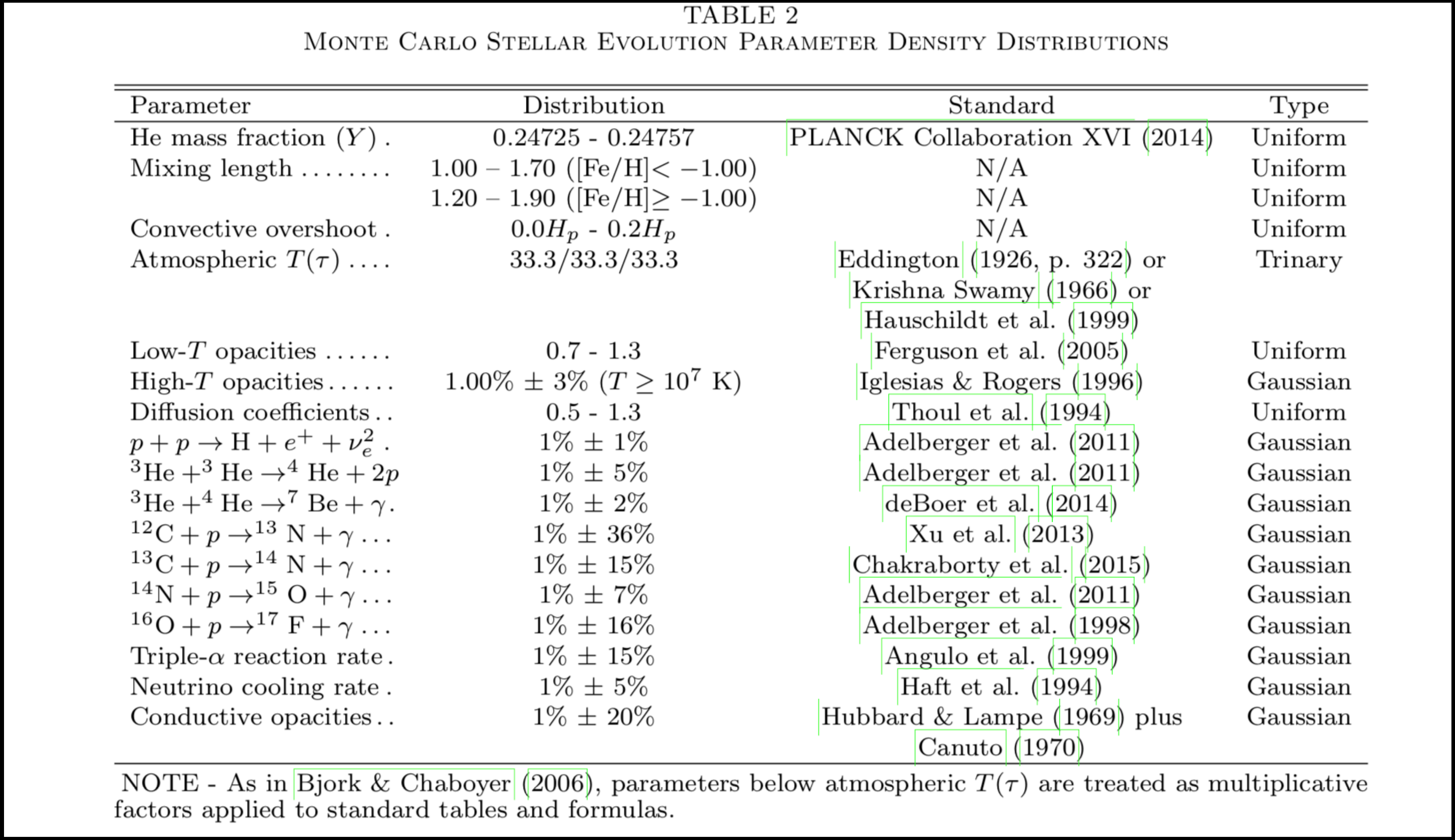


TABLE 2
MONTE CARLO STELLAR EVOLUTION PARAMETER DENSITY DISTRIBUTIONS

Parameter	Distribution	Standard	Type
He mass fraction (Y)	0.24725 - 0.24757	PLANCK Collaboration XVI (2014)	Uniform
Mixing length	1.00 – 1.70 ([Fe/H]<-1.00)	N/A	Uniform
	1.20 – 1.90 ([Fe/H]≥ -1.00)	N/A	Uniform
Convective overshoot	$0.0H_p$ - $0.2H_p$	N/A	Uniform
Atmospheric $T(\tau)$	33.3/33.3/33.3	Eddington (1926, p. 322) or Krishna Swamy (1966) or Hauschildt et al. (1999)	Trinary
Low-T opacities	0.7 - 1.3	Ferguson et al. (2005)	Uniform
High-T opacities	1.00% ± 3% ($T \geq 10^7$ K)	Iglesias & Rogers (1996)	Gaussian
Diffusion coefficients	0.5 - 1.3	Thoul et al. (1994)	Uniform
$p + p \rightarrow \mathrm{H} + e^+ + \nu_e^2$	1% ± 1%	Adelberger et al. (2011)	Gaussian
$^3\mathrm{He} +^3 \mathrm{He} \rightarrow^4 \mathrm{He} + 2p$	1% ± 5%	Adelberger et al. (2011)	Gaussian
$^3\mathrm{He} +^4 \mathrm{He} \rightarrow^7 \mathrm{Be} + \gamma$	1% ± 2%	deBoer et al. (2014)	Gaussian
$^{12}\mathrm{C} + p \rightarrow^{13} \mathrm{N} + \gamma$	1% ± 36%	Xu et al. (2013)	Gaussian
$^{13}\mathrm{C} + p \rightarrow^{14} \mathrm{N} + \gamma$	1% ± 15%	Chakraborty et al. (2015)	Gaussian
$^{14}\mathrm{N} + p \rightarrow^{15} \mathrm{O} + \gamma$	1% ± 7%	Adelberger et al. (2011)	Gaussian
$^{16}\mathrm{O} + p \rightarrow^{17} \mathrm{F} + \gamma$	1% ± 16%	Adelberger et al. (1998)	Gaussian
Triple-α reaction rate	1% ± 15%	Angulo et al. (1999)	Gaussian
Neutrino cooling rate	1% ± 5%	Haft et al. (1994)	Gaussian
Conductive opacities	1% ± 20%	Hubbard & Lampe (1969) plus Canuto (1970)	Gaussian

NOTE - As in Bjork & Chaboyer (2006), parameters below atmospheric $T(\tau)$ are treated as multiplicative factors applied to standard tables and formulas.

0' Malley 2018

Sanity check: relative ages (w/o distance uncertainties)

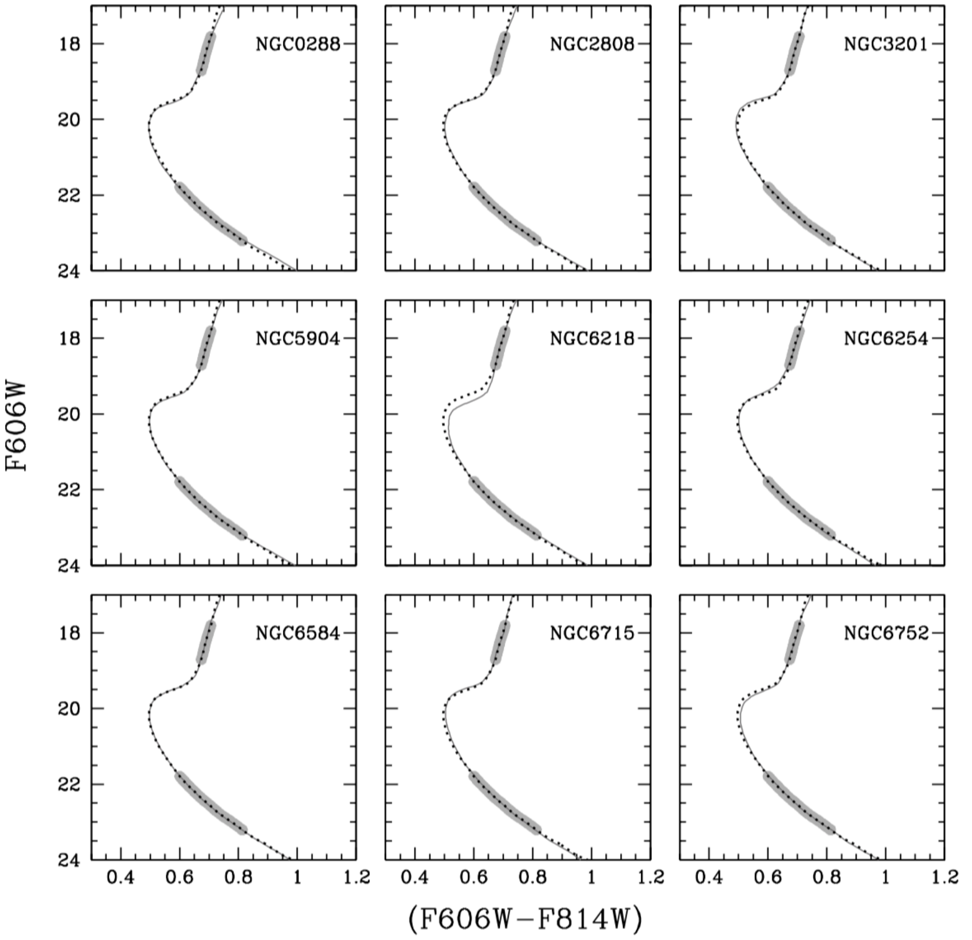


Fig. 3.— Examples of MS−fitting for the $-1.3 \leq [Fe/H]_{\rm CG} < -1.1$ metallicity group. The reference cluster is NGC 6981 (dashed line). Each cluster MRL (solid line) has been fitted to the reference cluster in the magnitude intervals $[(M^{\rm TO}_{\rm F606W} - 2.5) < M_{\rm F606W} < (M^{\rm TO}_{\rm F606W} - 1.5)]$ and $[(M^{\rm TO}_{\rm F606W} + 1.5) < M_{\rm F606W} < (M^{\rm TO}_{\rm F606W} + 3.0)]$ (shaded regions).

This method provides relative ages to a formal precision of 2-7%.
We demonstrate that the calculated relative ages are independent of the choice of theoretical model.

Marin Franch et al 2008

Absolute stellar ages at z=0 provide an estimate of the current expansion rate.

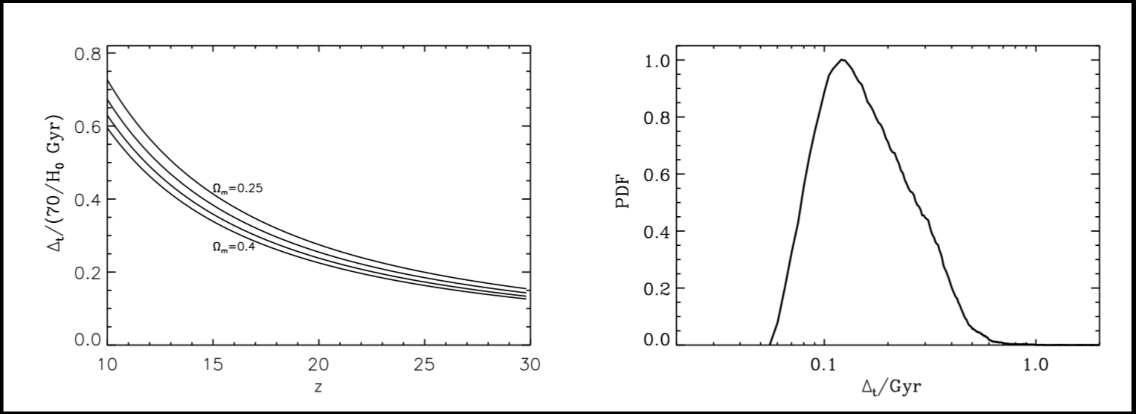
$$H_0 = \frac{A}{t}\int_0^{z_t} \frac{1}{1+z}\left[\Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0})(1+z)^{3(1+w)}\right]^{-1/2} dz$$

Relies on knowing other background cosmological parameters
(or the expansion history “shape”)

Use zf=11 but using zf=8 does not change the results

Need also a way to connect t to tU

(the second step is not needed
for H0 but for comparing
with tU from CMB)

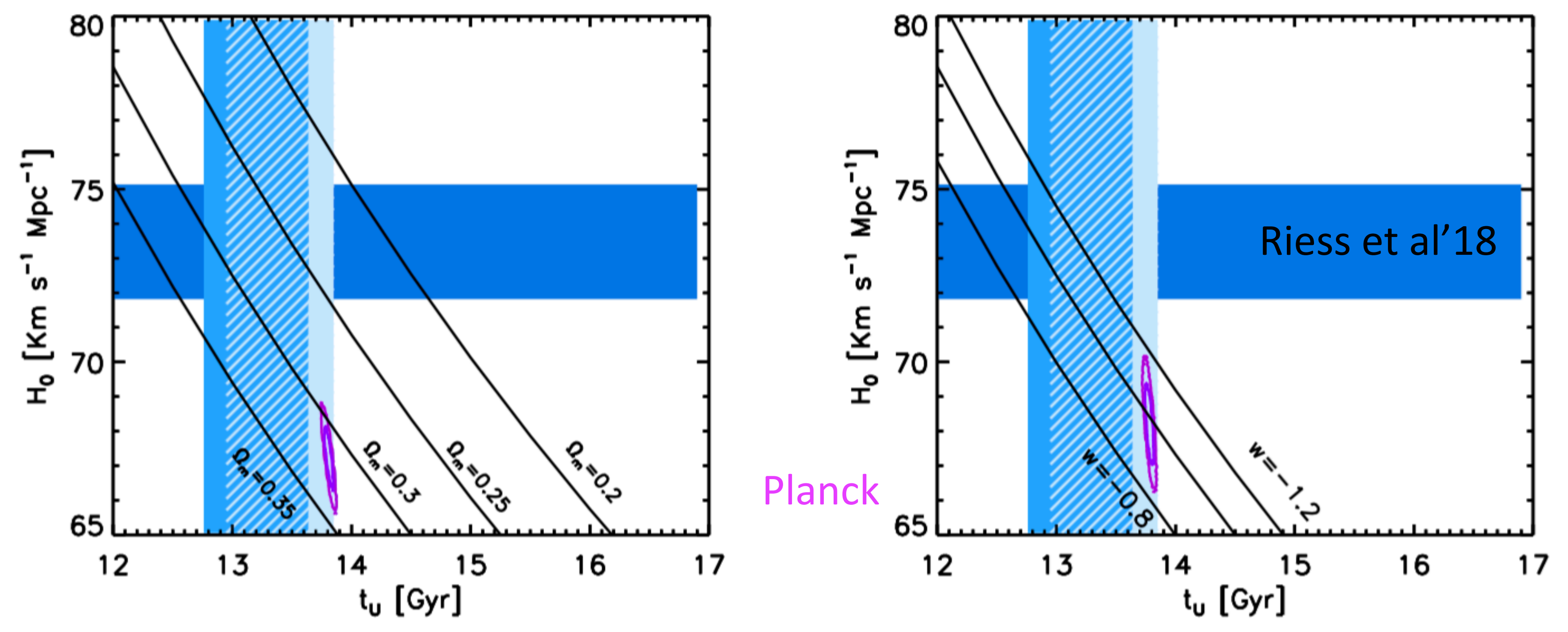


“The local and distant Universe, stellar ages and H0”
JCAP 2019 ,Jimenez, Cimatti, Verde, Moresco, Wandelt

Two different things

- H0 (do not need tU, but need t_*)
- $t_* \rightarrow$ tU (then argument independent on H0)

Age of Oldest stars observed locally --> age of the Universe



very-low-metallicity stars

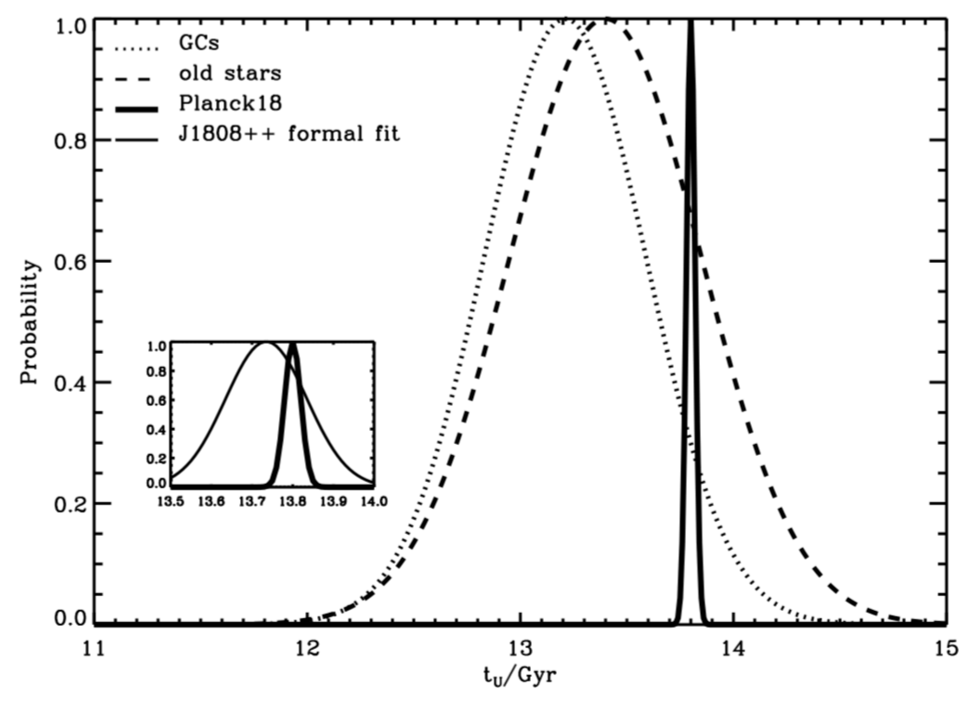
HD140283 (Bond et al 2013)

J18082002-5104378 A (Schlaufman et al 2018)

O'Malley et al '18 22 GC

Jimenez et al 2019

Age of Oldest stars observed locally --> age of the Universe



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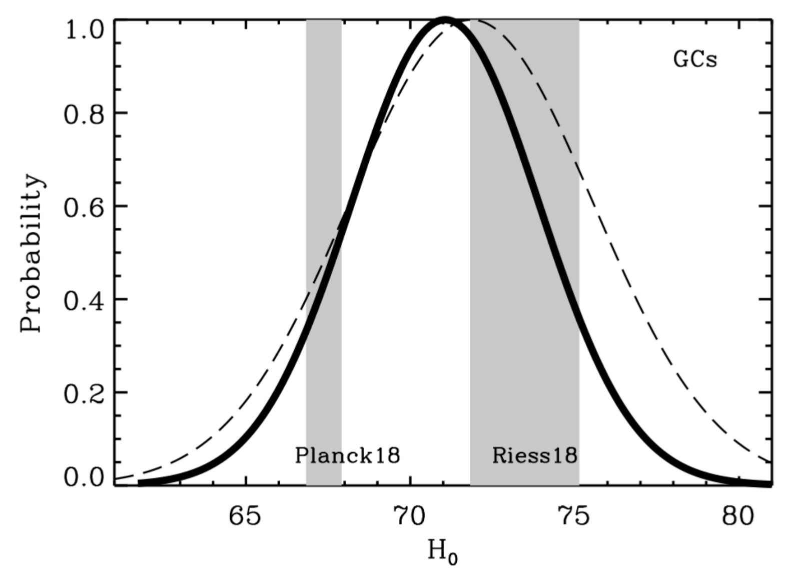
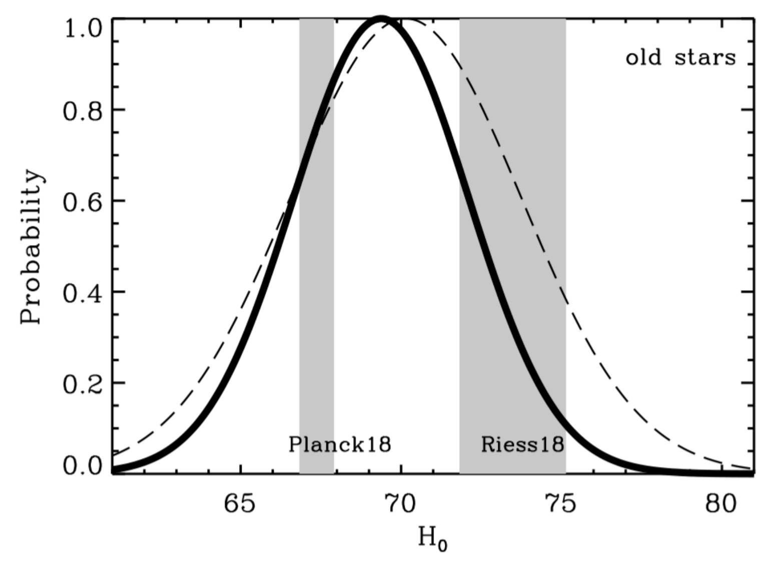
PROOF OF PRINCIPLE

With a late-time estimate of matter density…





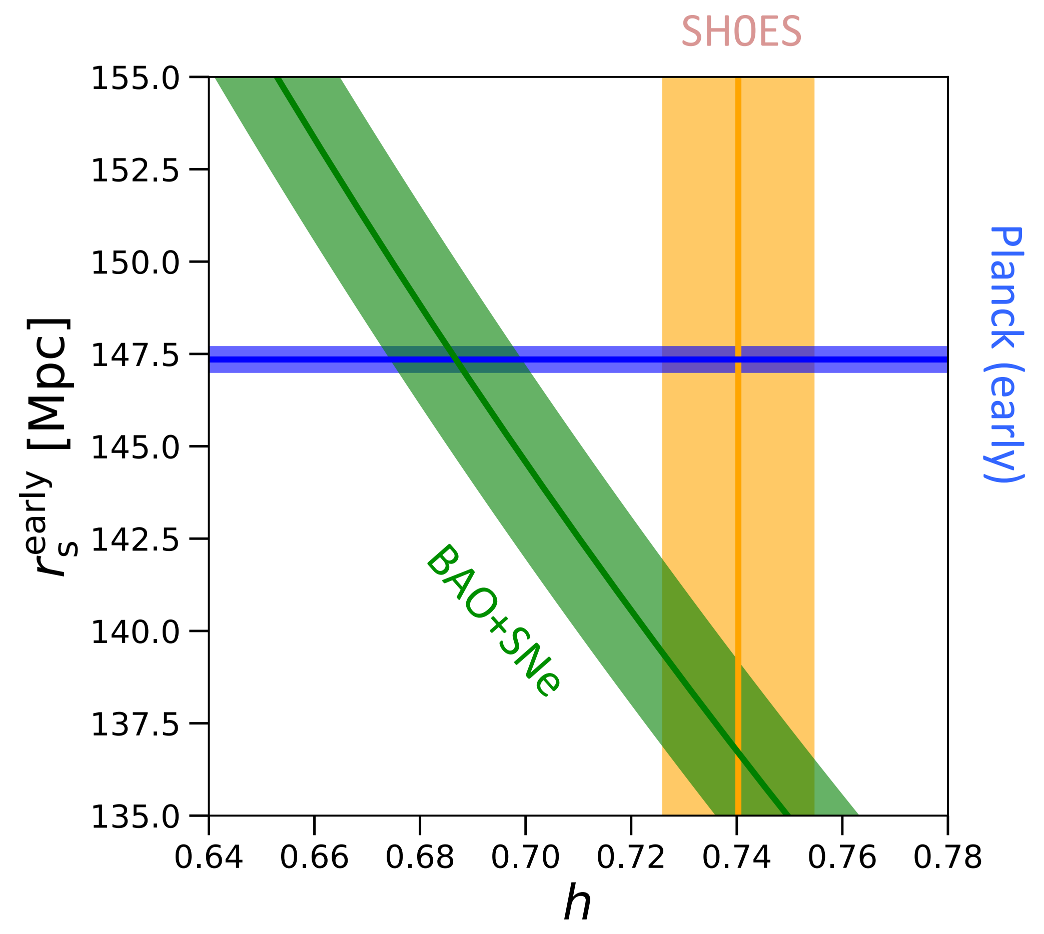
Standard analysis must be improved

“The local and distant Universe, stellar ages and H0”
JCAP 2019 ,Jimenez, Cimatti, Verde, Moresco, Wandelt

D. Valcin thesis

In a ΛCDM model

Work in progress



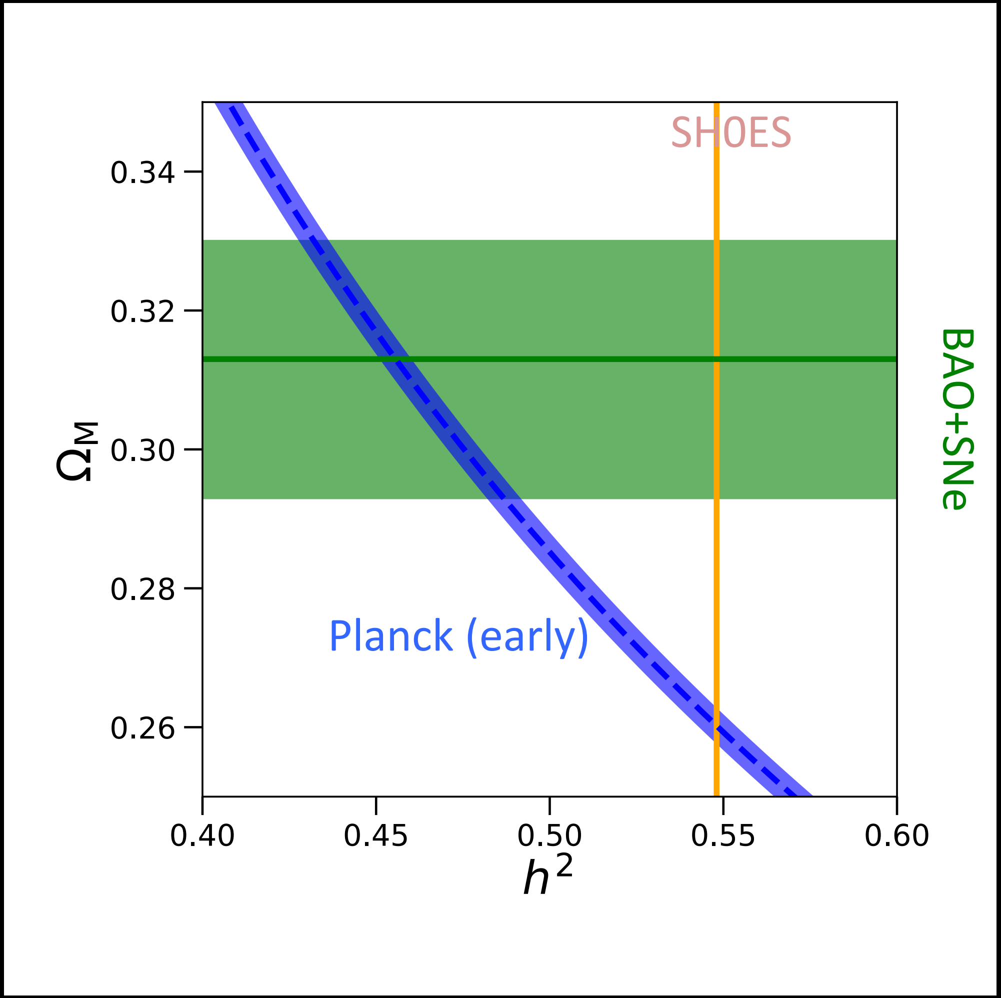
Verde Bellini et al 2017

AND with the latest data

Moreover in a LCDM model….

Early: high
Late: low

Ω_m

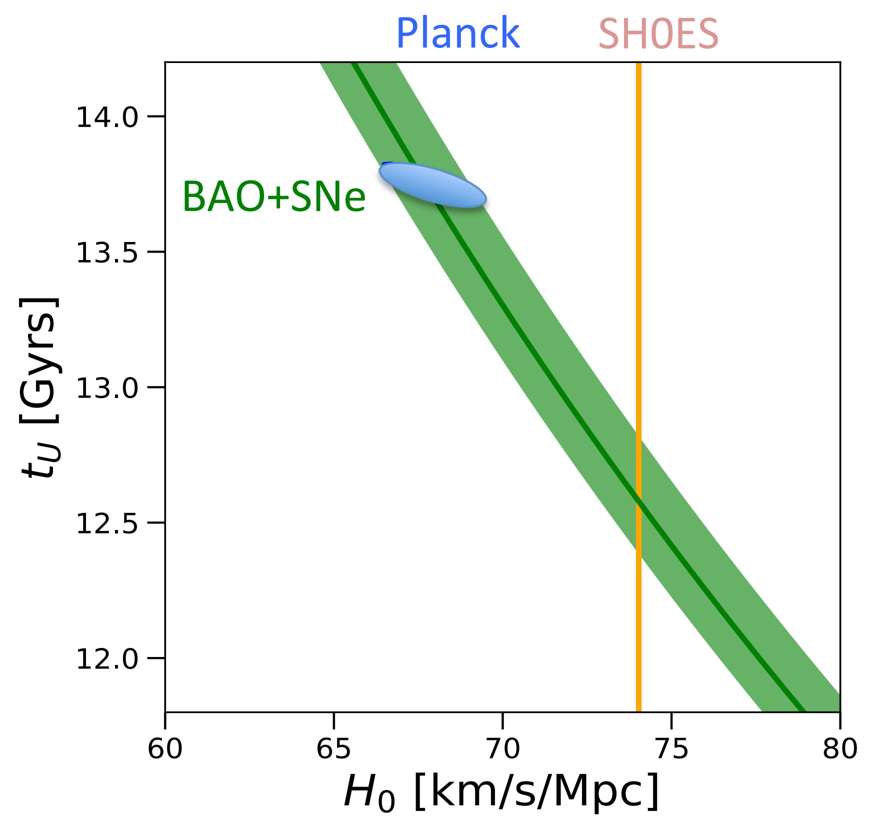


PRELIMINARY

Age of the Universe from re-analysis of Globular clusters ages. Marginalize over: metalicity, absorption, He fraction distance, AND models (MIST, Dartmouth , Padova)

Early : high t_0
Late: low t_0

?



D. Valcin

PRELIMINARY

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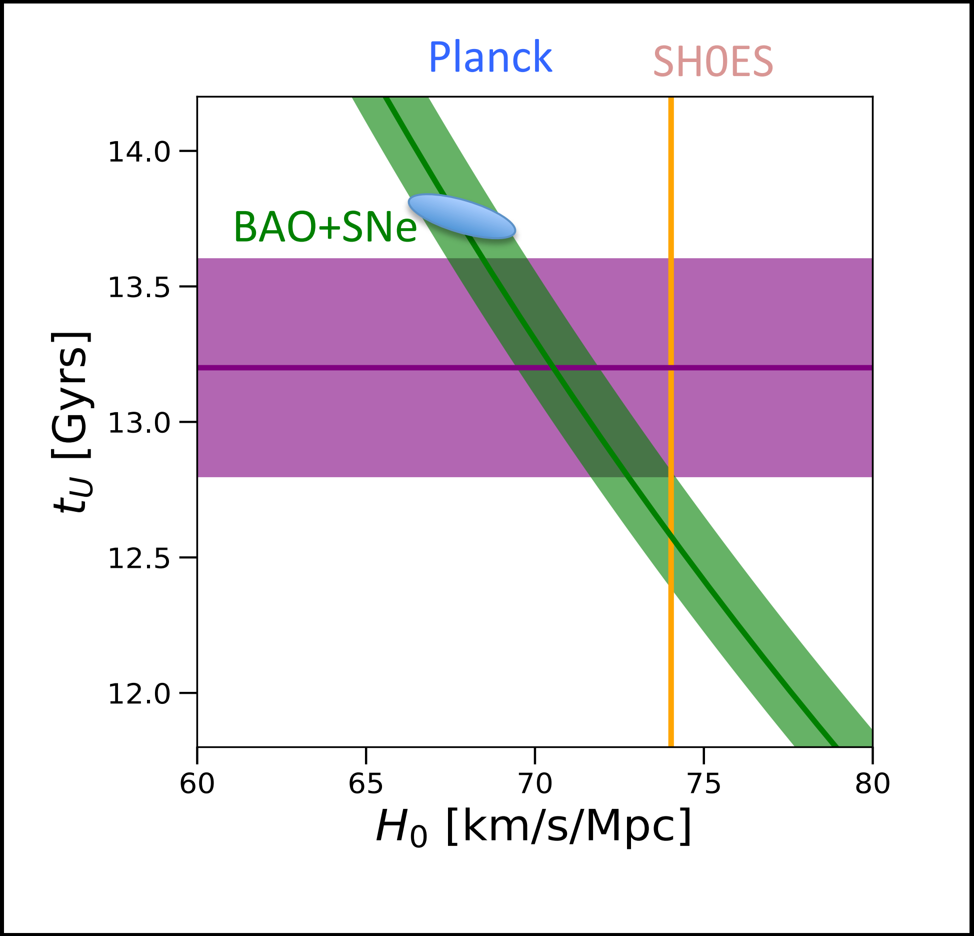


GC ("blinded")

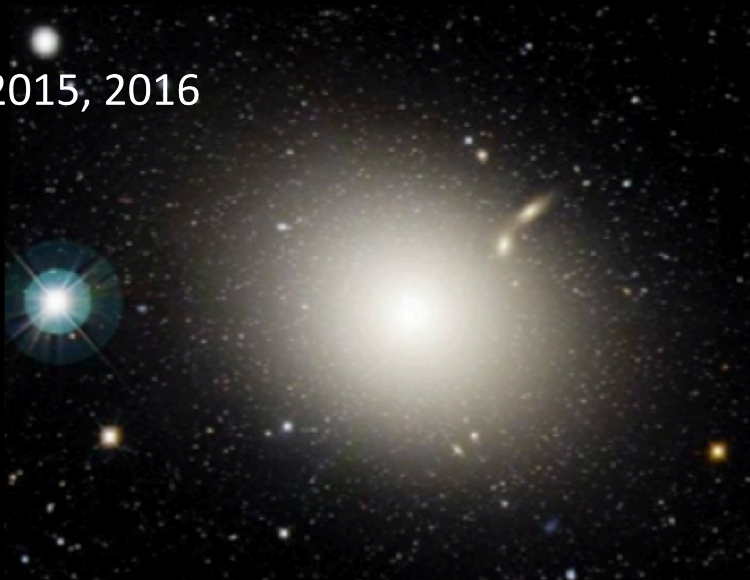
D. Valcin

Probes of the expansion history

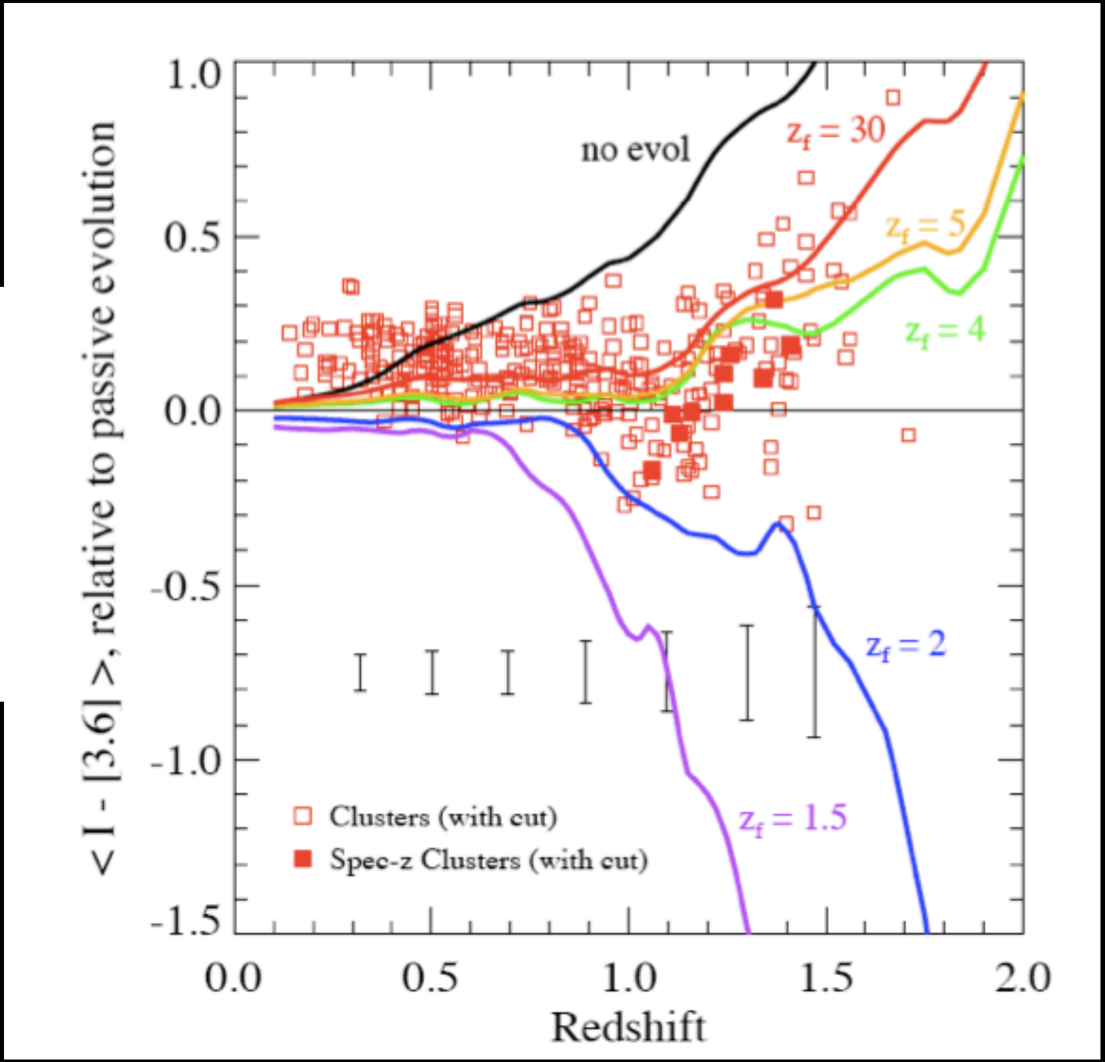
Some old elliptical galaxies have stellar populations well described by a single age

$$\delta t(z) \simeq \frac{\delta z}{H(z)(1+z)}$$

Simon et al. 2005, Stern et al. 2010, Moresco et al. 2012, 2015, 2016



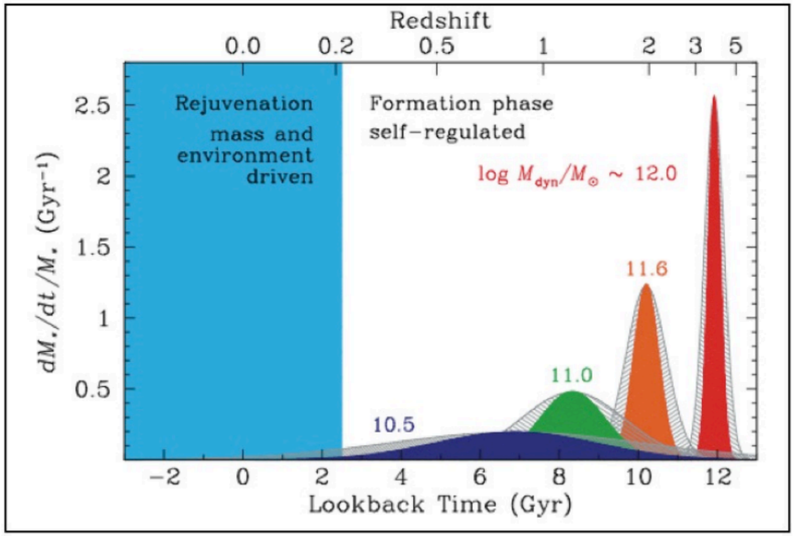
Passively evolving old systems



- 15% of local, bright ellipticals show "frosting" of recent (< 1 Gyr) star formation
- only 1-2% by mass
- "downsizing": less frosting in most massive galaxies

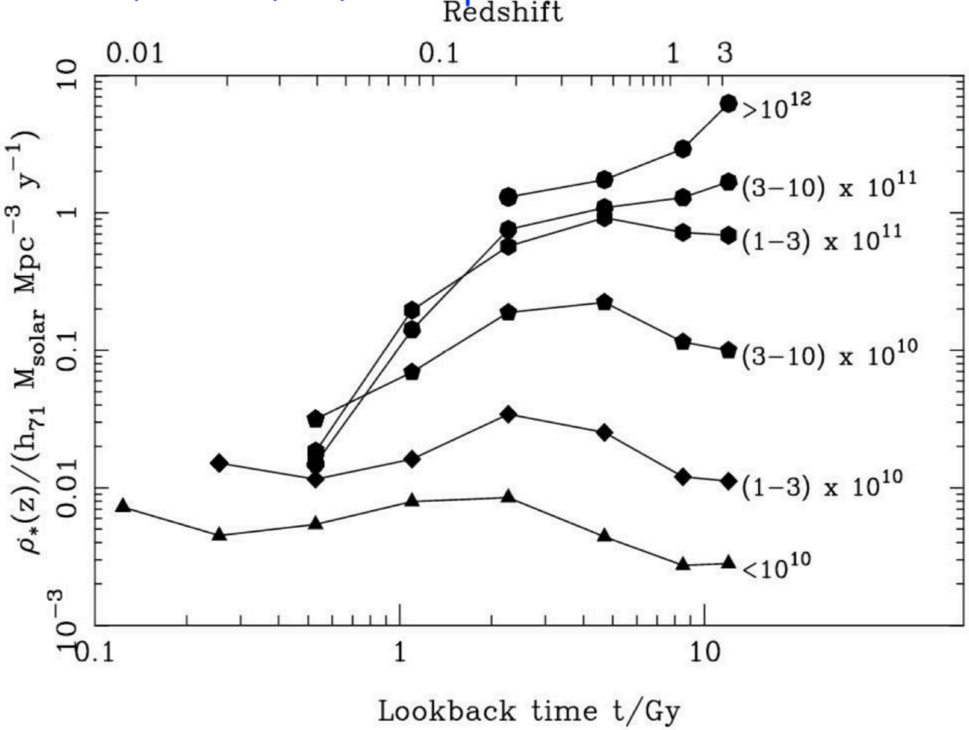
Eisenhardt et al 08

These old, massive, red and dead galaxies do not have extended star formation histories. Downsizing.



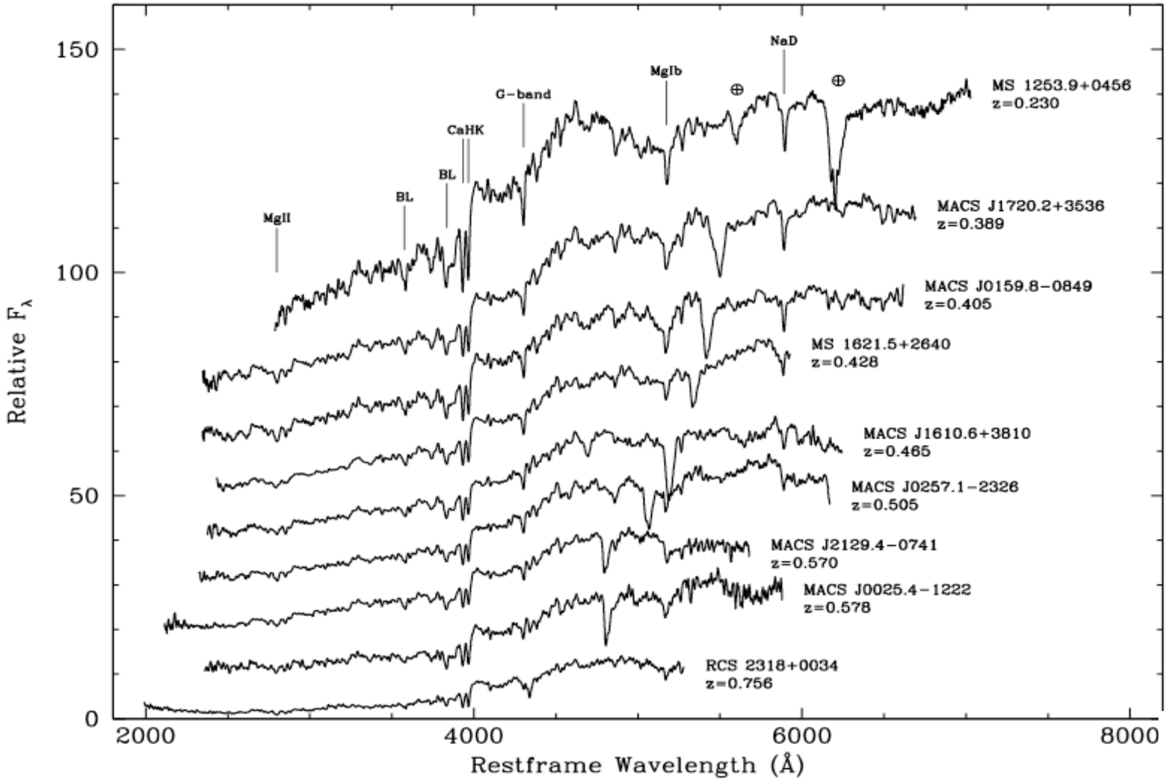
Thomas et al. (2010)

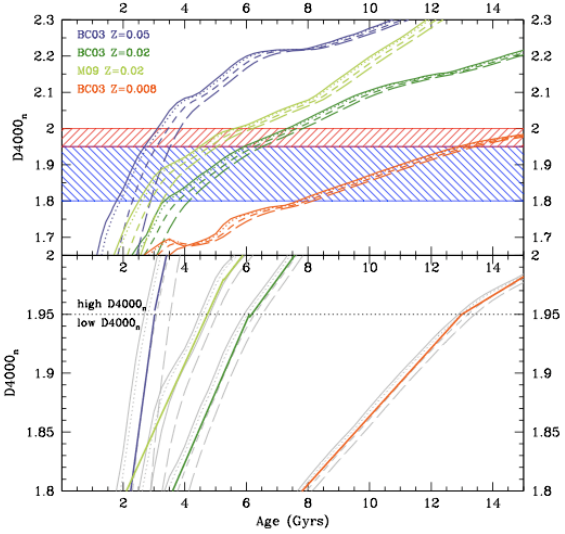
Heavens, Panter, RJ, Dunlop Nature 2004



Curves offset vertically for clarity

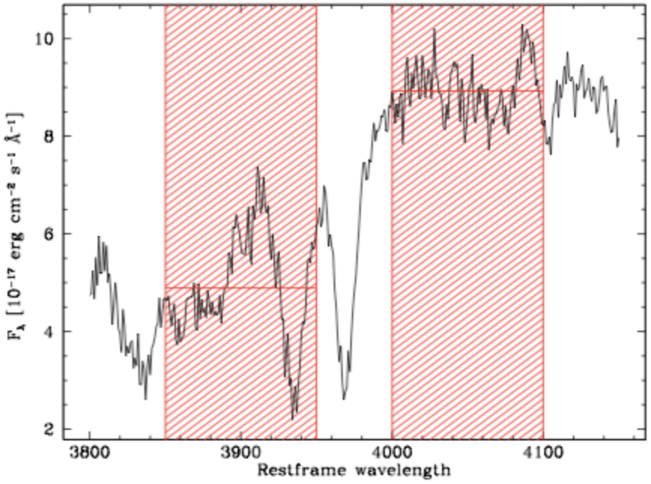
Relative aging of galaxies using D4000 break





MODELS

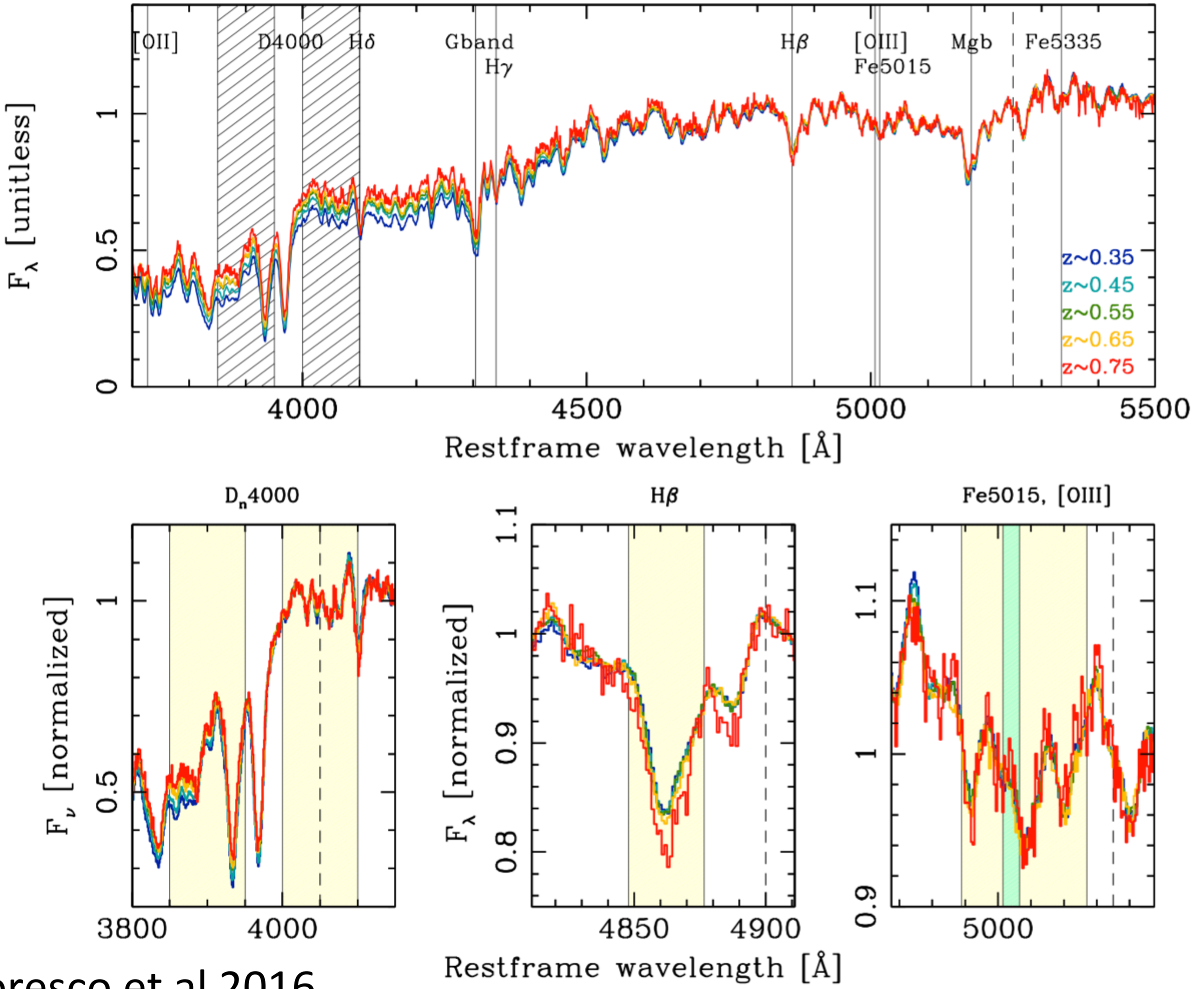
$$H(z) = -\frac{A}{1+z}\frac{dz}{dD4000_n}$$



Moresco, Jimenez, Cimatti, Pozzetti JCAP (2010)

Relative aging of galaxies

These are DATA



Moresco et al 2016

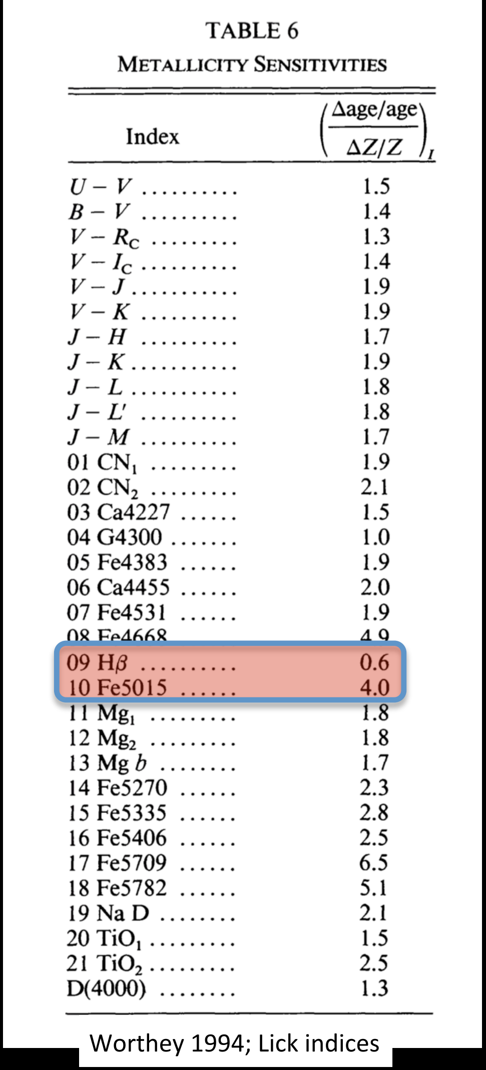


TABLE 6

METALLICITY SENSITIVITIES

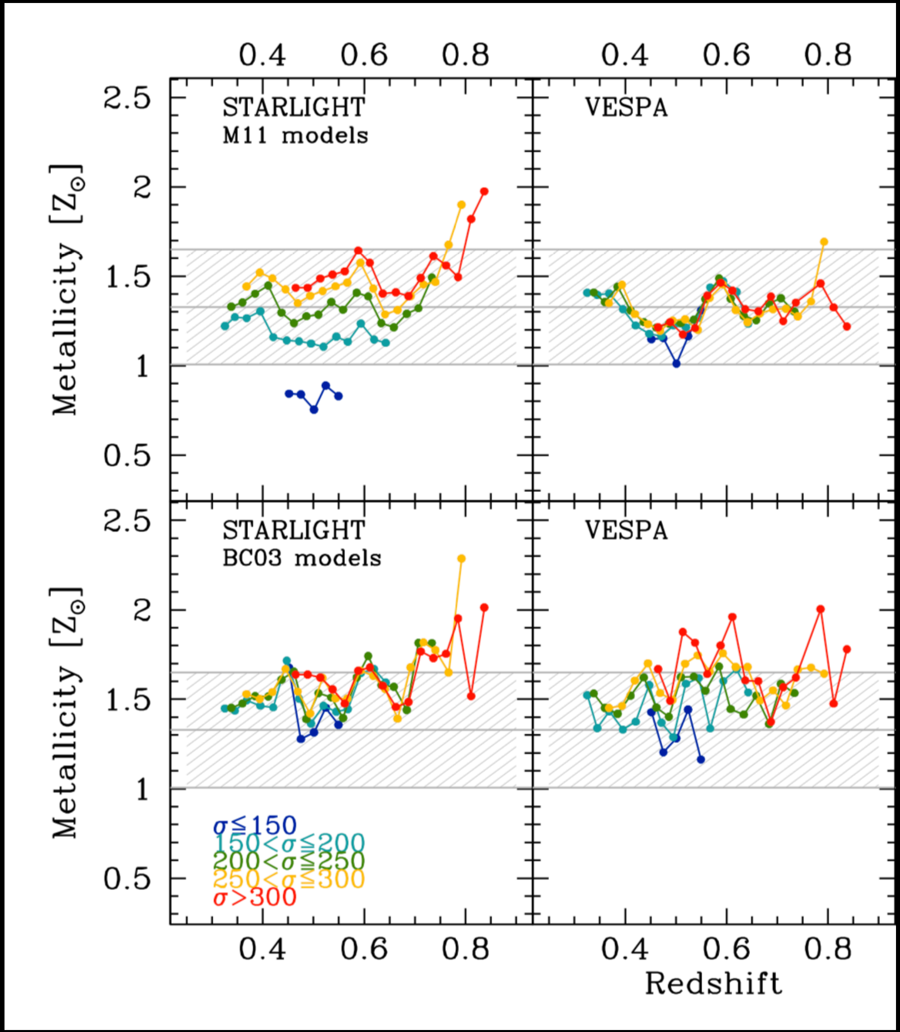
Index	$\left(\frac{\Delta age/age}{\Delta Z/Z}\right)_I$
$U-V$	1.5
$B-V$	1.4
$V-R_C$	1.3
$V-I_C$	1.4
$V-J$	1.9
$V-K$	1.9
$J-H$	1.7
$J-K$	1.9
$J-L$	1.8
$J-L'$	1.8
$J-M$	1.7
01 CN_1	1.9
02 CN_2	2.1
03 Ca4227	1.5
04 G4300	1.0
05 Fe4383	1.9
06 Ca4455	2.0
07 Fe4531	1.9
08 Fe4668	4.9
09 Hβ	0.6
10 Fe5015	4.0
11 Mg_1	1.8
12 Mg_2	1.8
13 Mg *b*	1.7
14 Fe5270	2.3
15 Fe5335	2.8
16 Fe5406	2.5
17 Fe5709	6.5
18 Fe5782	5.1
19 Na D	2.1
20 TiO_1	1.5
21 TiO_2	2.5
D(4000)	1.3

Worthey 1994; Lick indices

Hβ is the Lick index least sensitive to metallicity: tracks age. While Fe5015 tracks metallicity.
High-z galaxies are younger, while all galaxies have same metallicity.

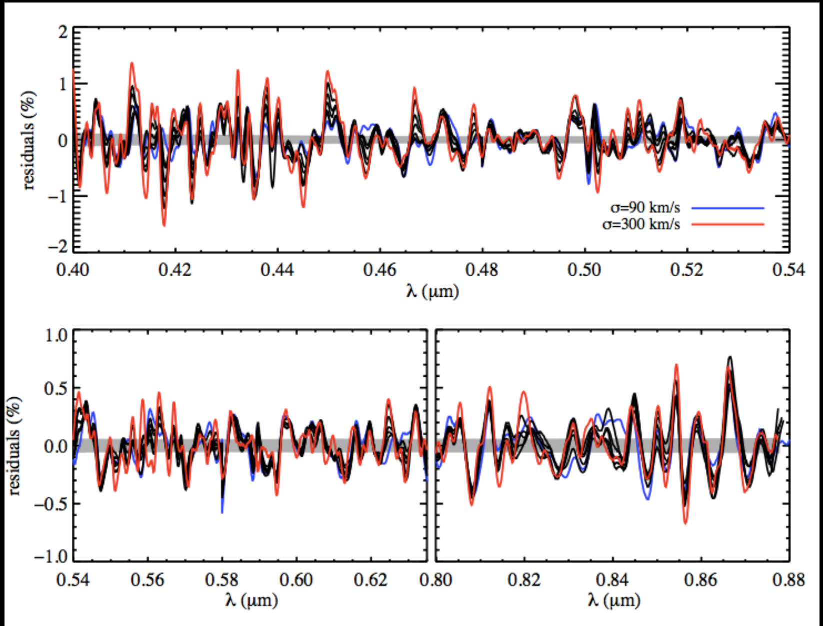
Full Spectral fitting gives an excellent estimate of the metallicity for the selected passively evolving galaxies. Also, formal fits are excellent with current stellar models.

From Moresco et al. 2016



Current models DO provide formal fits to data

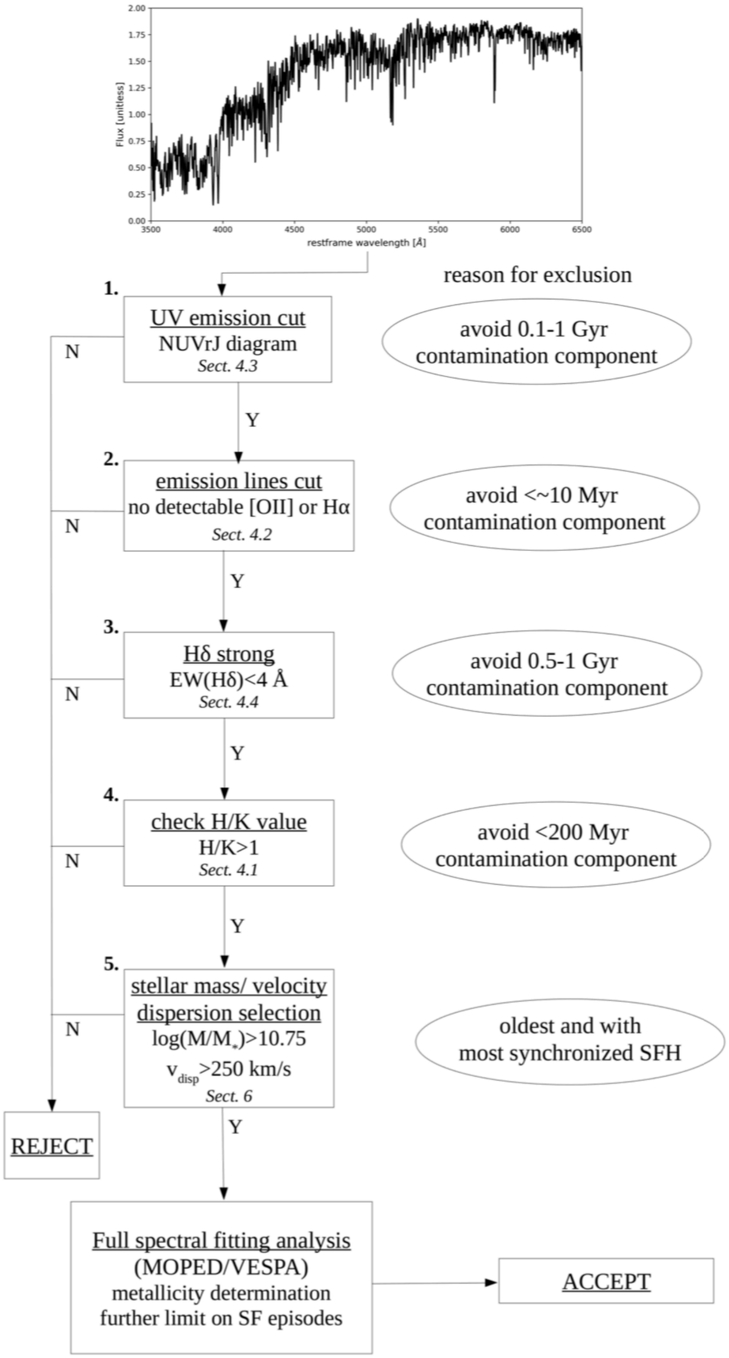
From Conroy et al. 2013



They not only fit for age and metallicity BUT ALSO FOR ALL SINGLE ELEMENT ABUNDANCES!
(for stacked SDSS spectra)

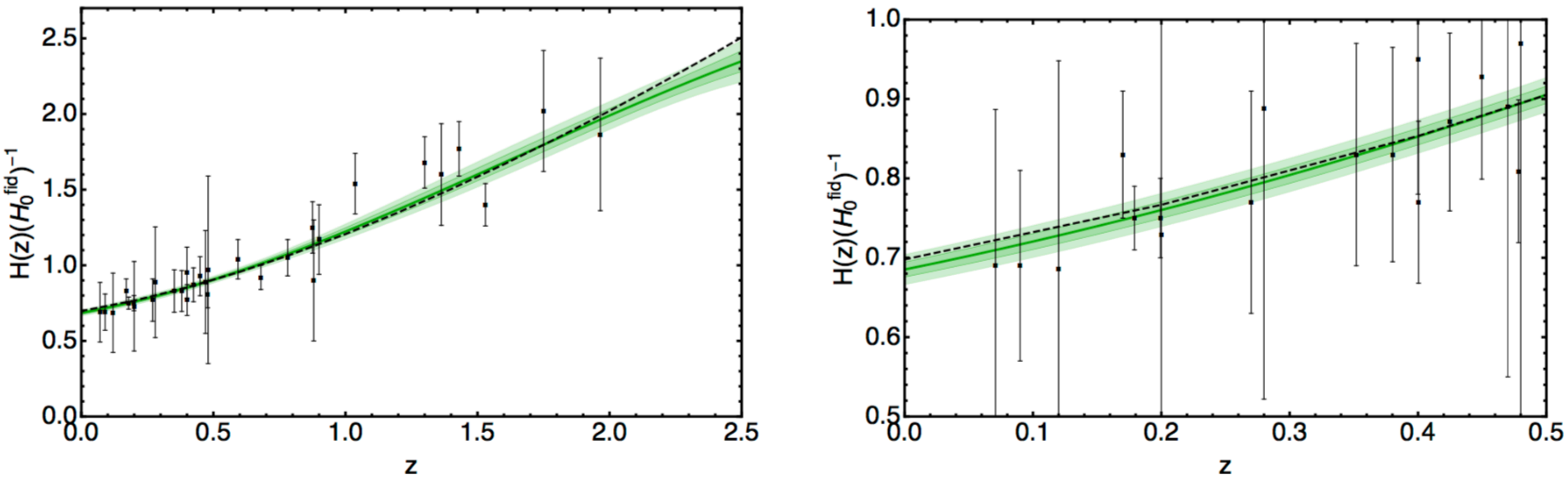
Selection is key

Workflow to select cosmic chronometers

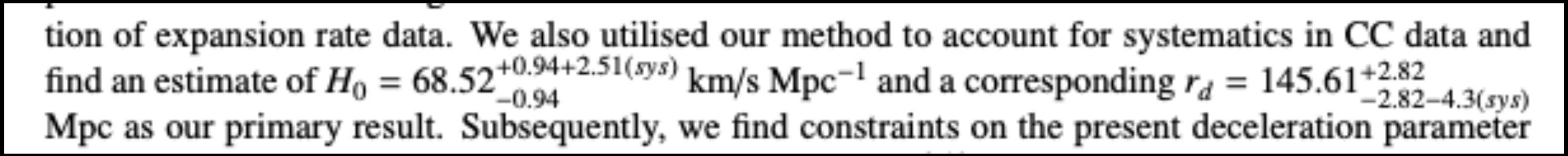


Moresco et al 2018

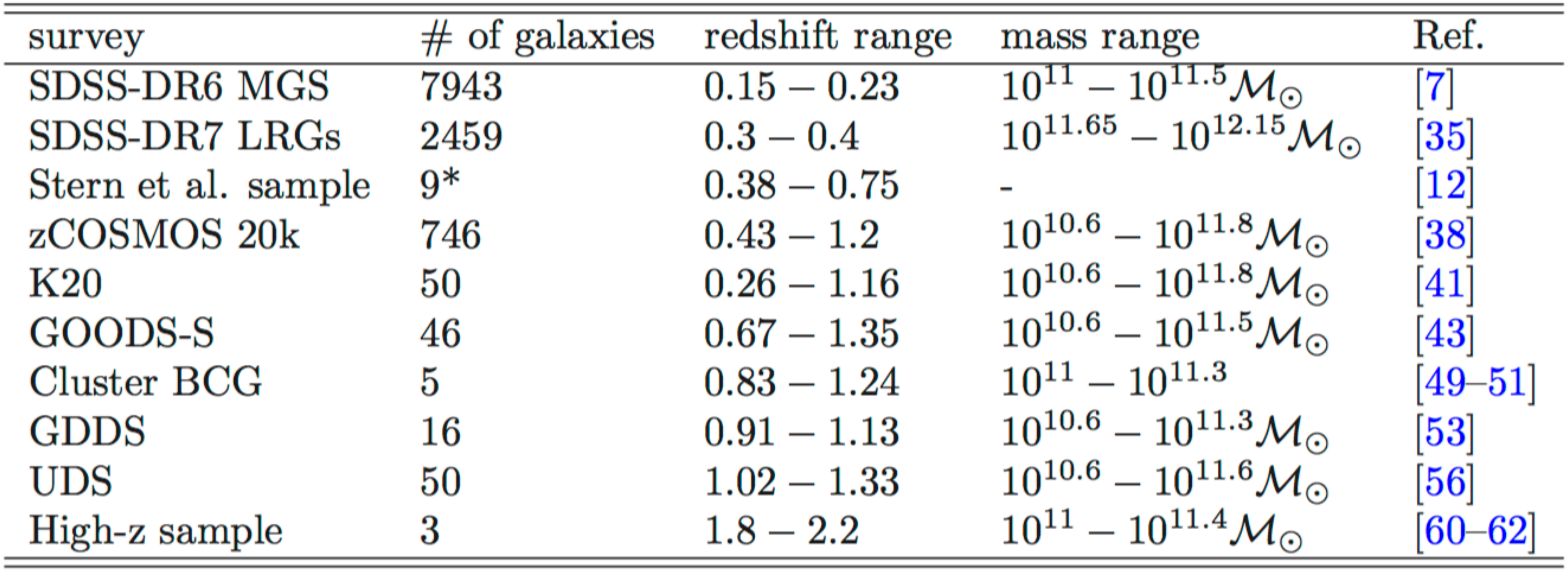
Reconstructed expansion history with chronometers



Haridasu et al. 2018



tion of expansion rate data. We also utilised our method to account for systematics in CC data and find an estimate of $H_0 = 68.52^{+0.94+2.51(sys)}_{-0.94}$ km/s Mpc^{-1} and a corresponding $r_d = 145.61^{+2.82}_{-2.82-4.3(sys)}$ Mpc as our primary result. Subsequently, we find constraints on the present deceleration parameter

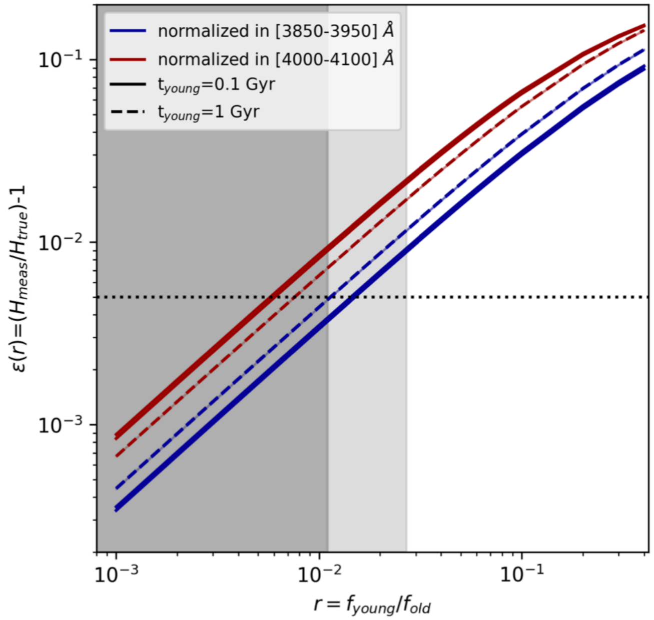


survey	# of galaxies	redshift range	mass range	Ref.
SDSS-DR6 MGS	7943	$0.15 - 0.23$	$10^{11} - 10^{11.5}\mathcal{M}_\odot$	[7]
SDSS-DR7 LRGs	2459	$0.3 - 0.4$	$10^{11.65} - 10^{12.15}\mathcal{M}_\odot$	[35]
Stern et al. sample	9*	$0.38 - 0.75$	-	[12]
zCOSMOS 20k	746	$0.43 - 1.2$	$10^{10.6} - 10^{11.8}\mathcal{M}_\odot$	[38]
K20	50	$0.26 - 1.16$	$10^{10.6} - 10^{11.8}\mathcal{M}_\odot$	[41]
GOODS-S	46	$0.67 - 1.35$	$10^{10.6} - 10^{11.5}\mathcal{M}_\odot$	[43]
Cluster BCG	5	$0.83 - 1.24$	$10^{11} - 10^{11.3}$	[49–51]
GDDS	16	$0.91 - 1.13$	$10^{10.6} - 10^{11.3}\mathcal{M}_\odot$	[53]
UDS	50	$1.02 - 1.33$	$10^{10.6} - 10^{11.6}\mathcal{M}_\odot$	[56]
High-z sample	3	$1.8 - 2.2$	$10^{11} - 10^{11.4}\mathcal{M}_\odot$	[60–62]

Moresco et al.(++) 2013

Next steps

Significant effort devoted to constrain and quantify systematic uncertainties for chronometers



Computing the Full Cov Matrix

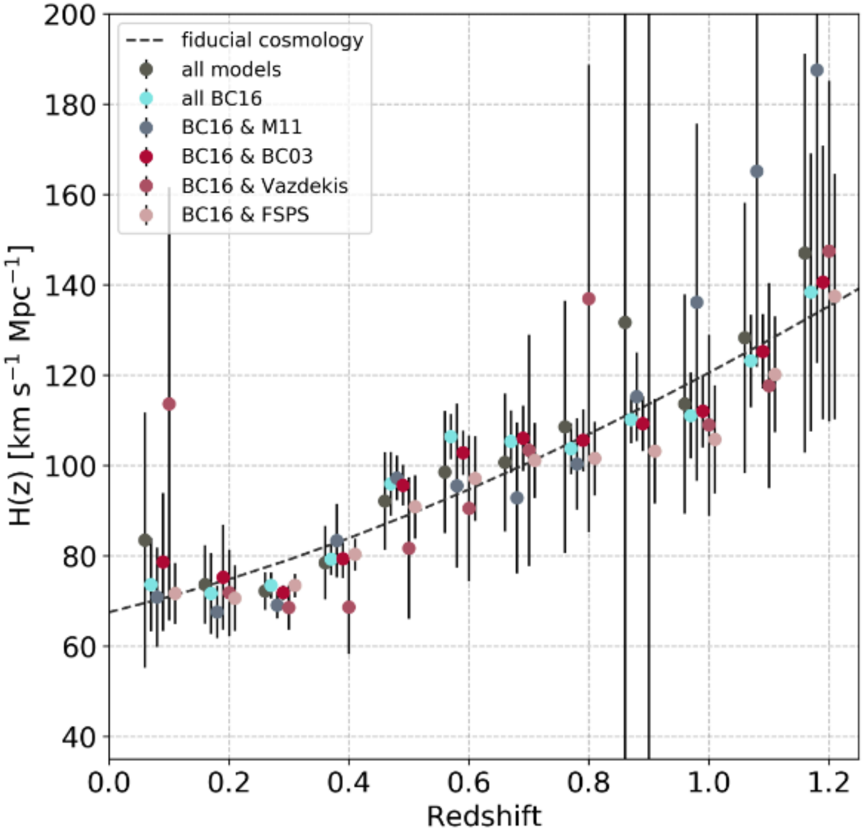
$$\mathrm{Cov}_{\mathrm{ij}}^{\mathrm{tot}} = \mathrm{Cov}_{\mathrm{ij}}^{\mathrm{stat}} + \mathrm{Cov}_{\mathrm{ij}}^{\mathrm{young}} + \mathrm{Cov}_{\mathrm{ij}}^{\mathrm{model}} + \mathrm{Cov}_{\mathrm{ij}}^{\mathrm{met}}$$

$$\mathrm{Cov}_{ij}^{\mathrm{young}} = H_{true}(z_1)H_{true}(z_2)\epsilon(r(z_1))\epsilon(r(z_2))$$

where ε(r) is the percentage variation of dDn4000 as a function of the young component fraction r, namely (1 − α)−1 where α is the slope of the relations in Fig. 6. We note that formally r = r(z), since the contamination due to a young component could be different depending on the couple of points used to estimate H(z); the only assumption we make here is that r is constant between the two redshifts considered to provide one H(z) measurement

$$\frac{H(z)_{meas}}{H(z)_{true}} = \frac{dD_n4000_{true}}{dD_n4000_{meas}} = 1 + \epsilon(r)$$

Significant effort devoted to constraint systematic uncertainties for chronometers: estimate of the covariance given by systematics of the model.



SUMMARY

In the early vs late approach we should look at quantities beyond H0

I mentioned tU

Ωm

t* → H0 via Ωm

Chronometers-→ H(z)