# Toward an independent reconstruction of the expansion history of the Universe

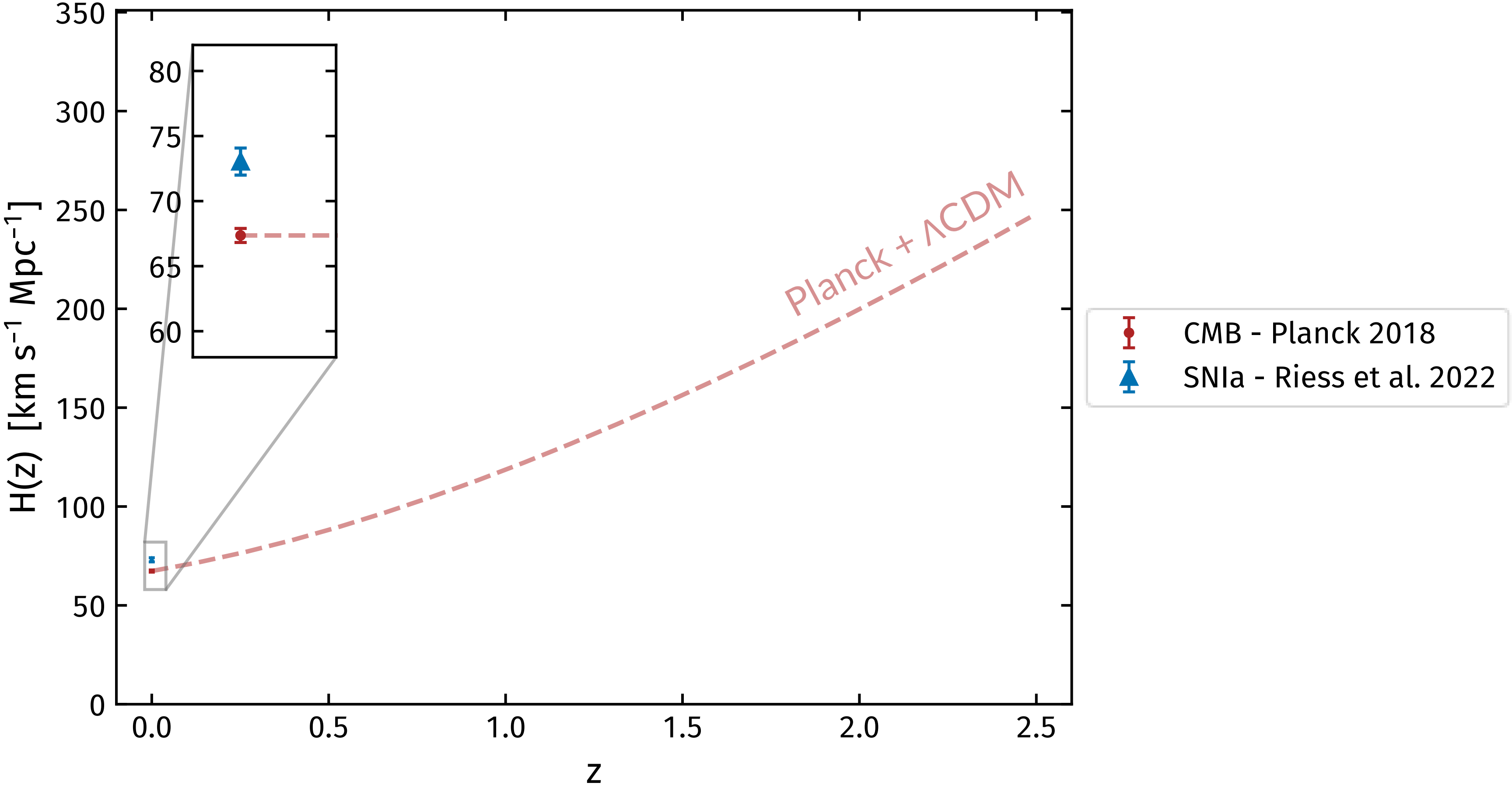

**Nicola Borghi**

University of Bologna

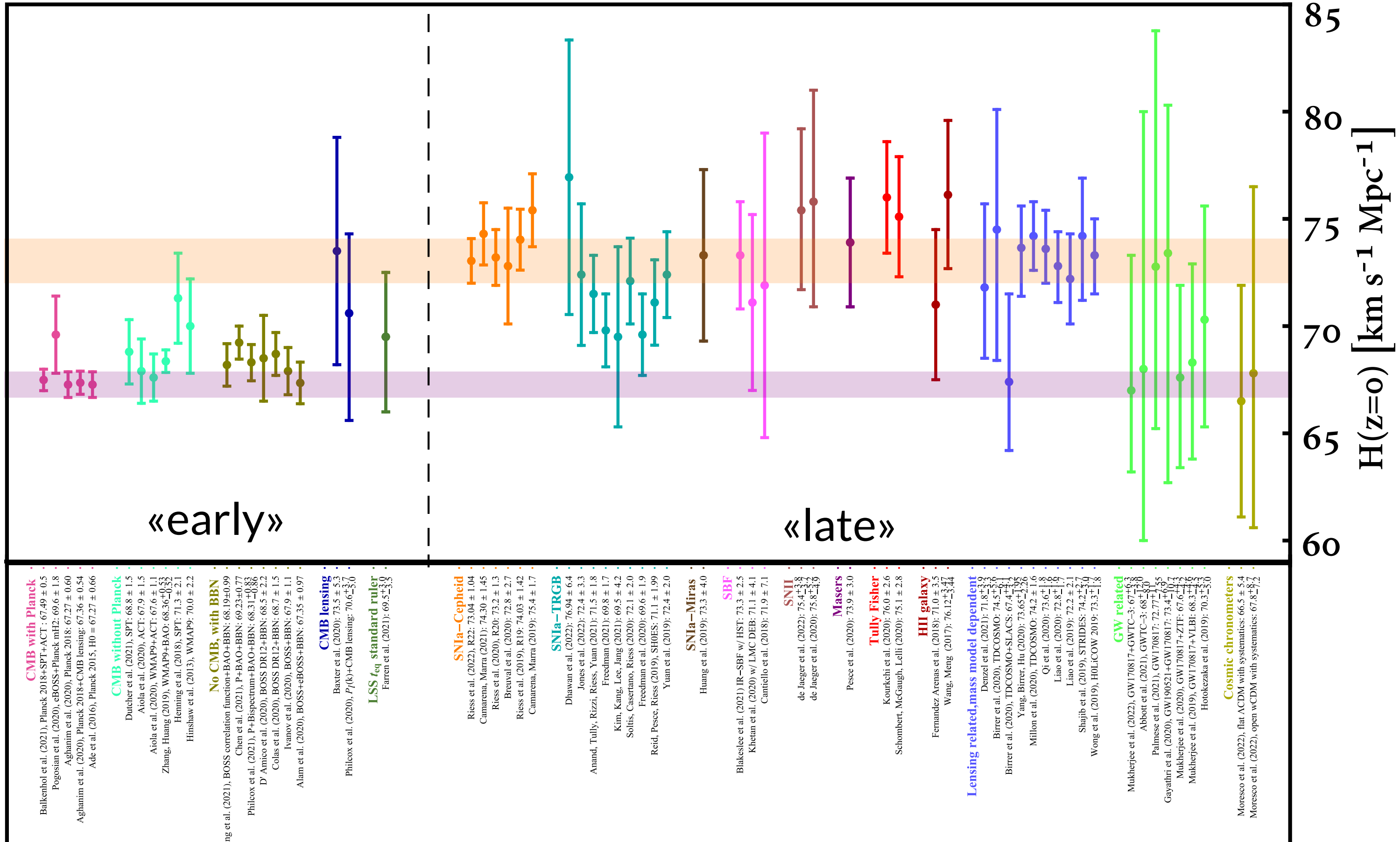
*with Michele Moresco, Andrea Cimatti, Lucia Pozzetti, Alexandre Huchet, Salvatore Quai, Kang Jiao*


- Borghi et al. 2022a (ApJ 927-164, arXiv:2106.14894)
- Borghi et al. 2022b (ApJL 928-L4, arXiv:2110.04304)
- Jiao et al. 2022 (*submitted*, arXiv:2205.05701)

# Expansion history – current constraints

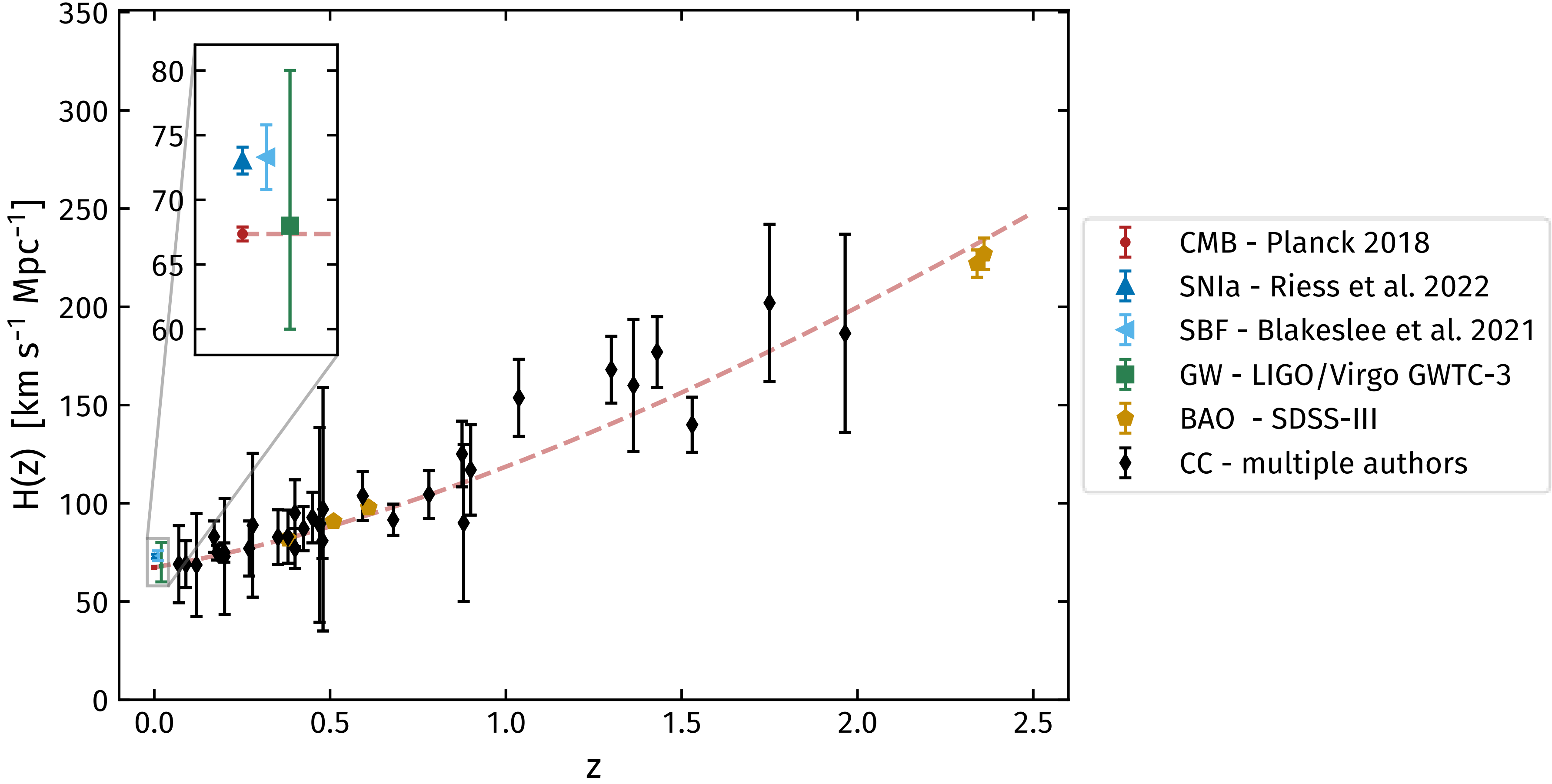


# Expansion history – current constraints

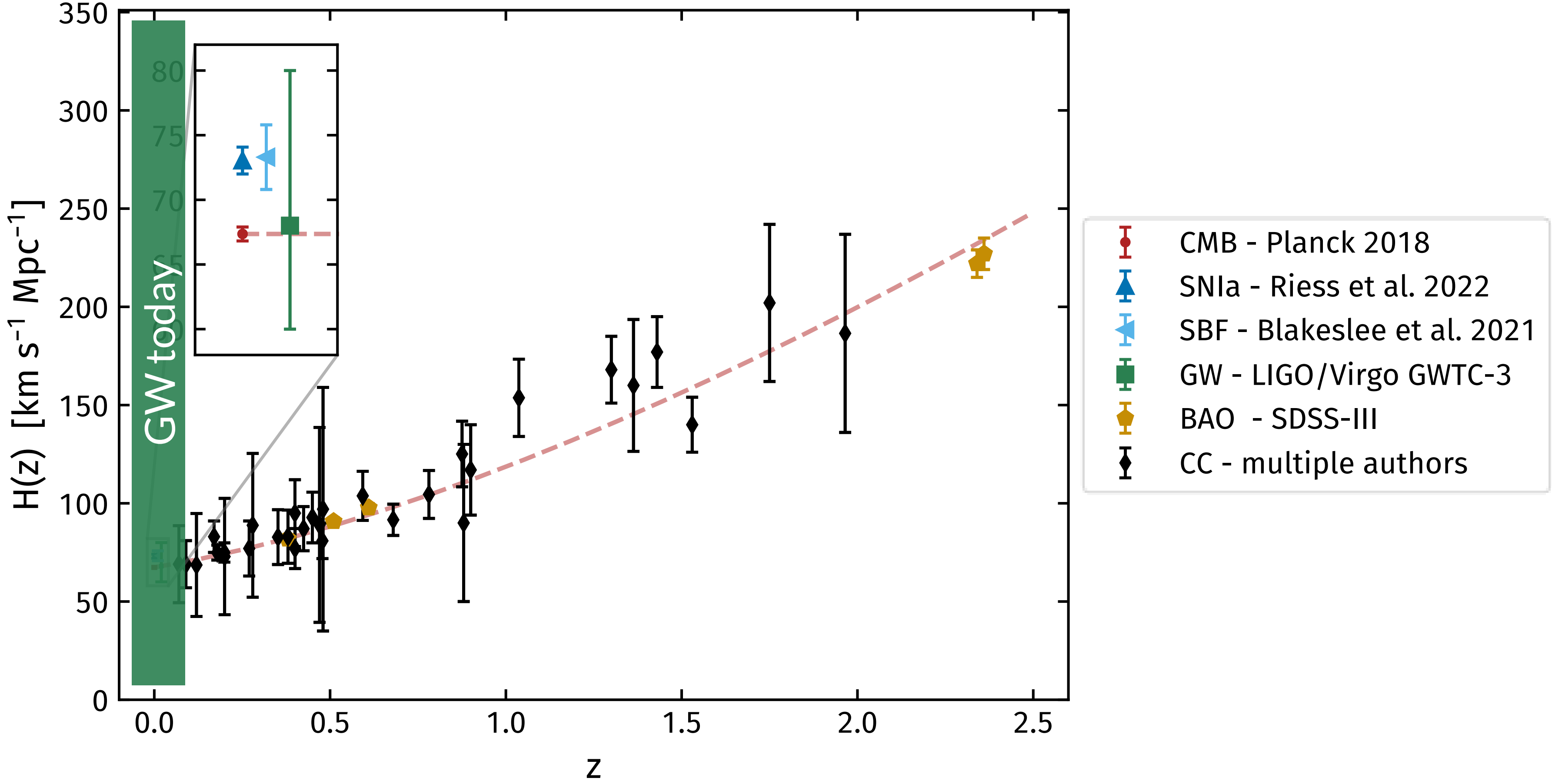



Abdalla et al. (2022, arXiv:2203.06142)

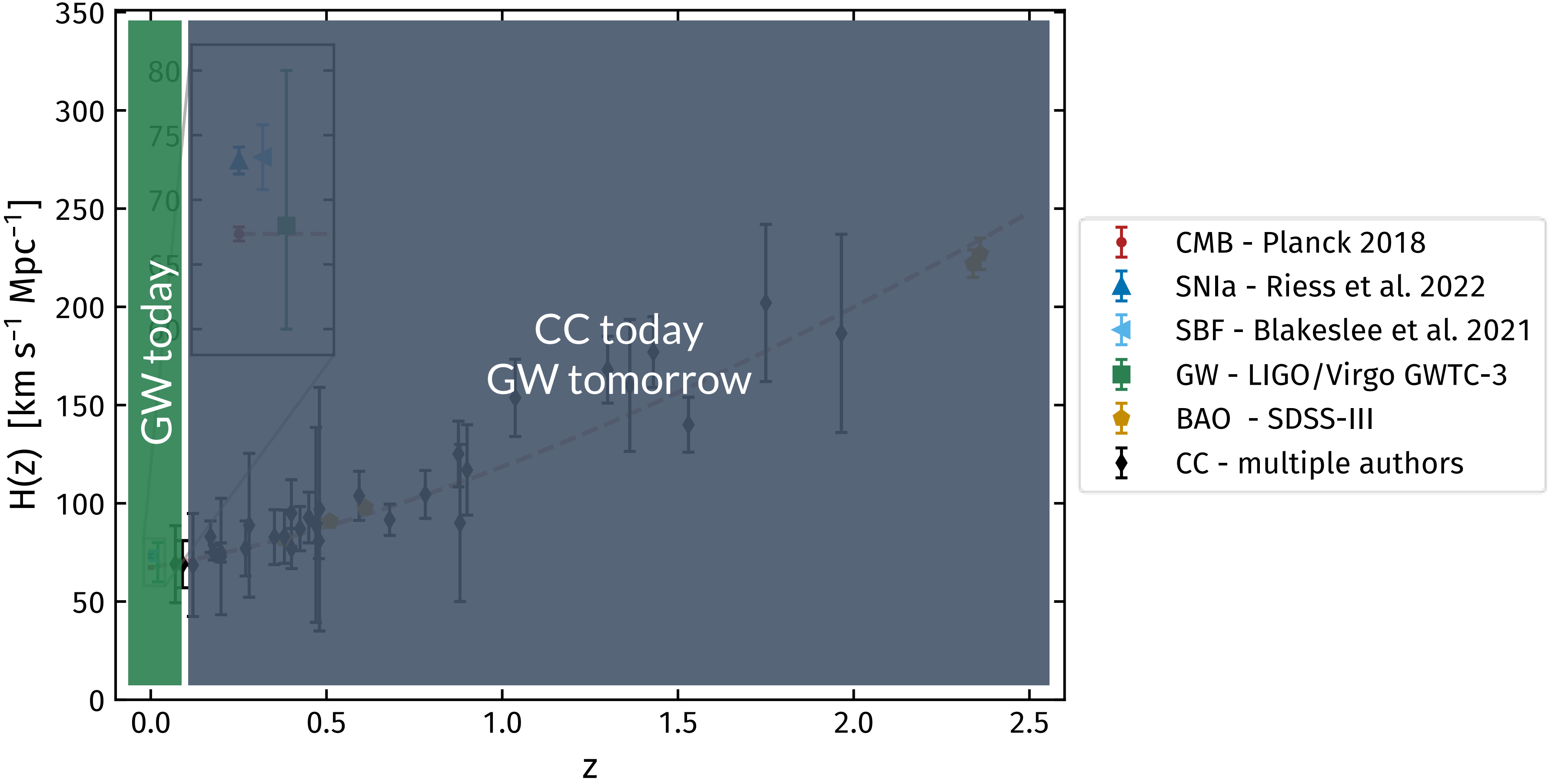
# Expansion history – current constraints



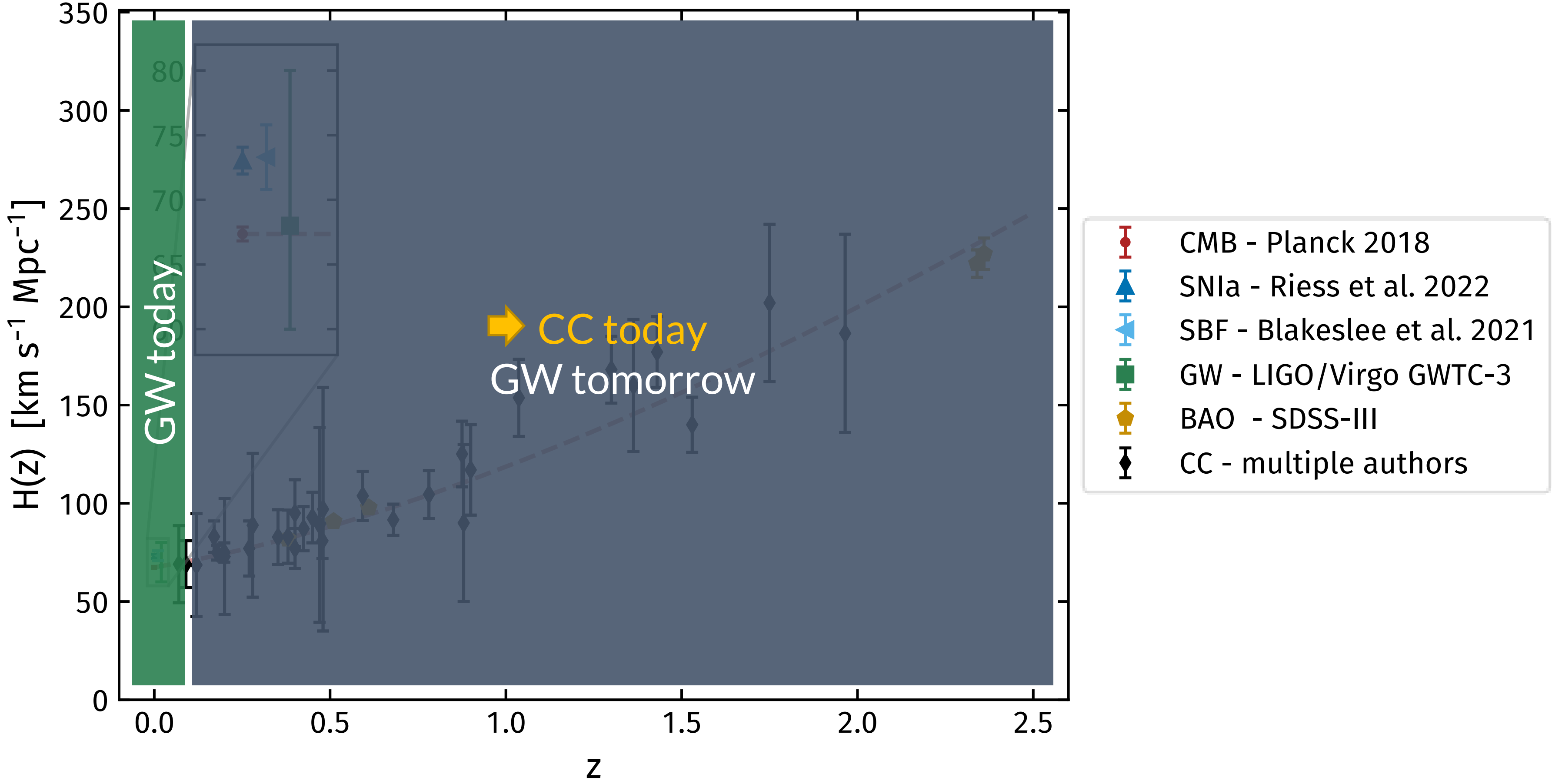
# Expansion history – current constraints



# Expansion history – current constraints



# Expansion history – current constraints



# Cosmic chronometers - BASICS

Assuming a FLRW metric:
Jimenez & Loeb (2002)

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

# Cosmic chronometers - BASICS

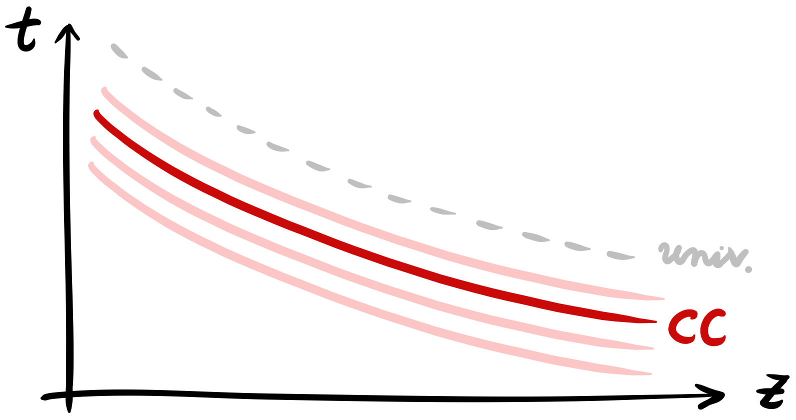
Assuming a FLRW metric:
Jimenez & Loeb (2002)

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

# Cosmic chronometers - BASICS

Assuming a FLRW metric:
Jimenez & Loeb (2002)

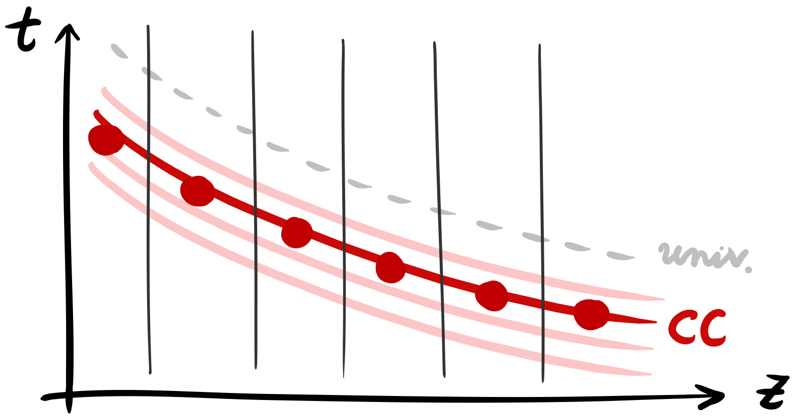
$$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{\mathrm{d}z}{\mathrm{d}t}$$



# Cosmic chronometers - BASICS

Assuming a FLRW metric:
Jimenez & Loeb (2002)

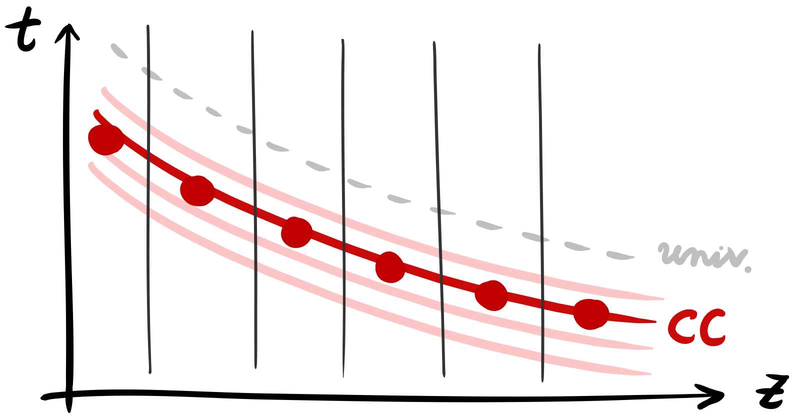
$$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{\mathrm{d}z}{\mathrm{d}t}$$



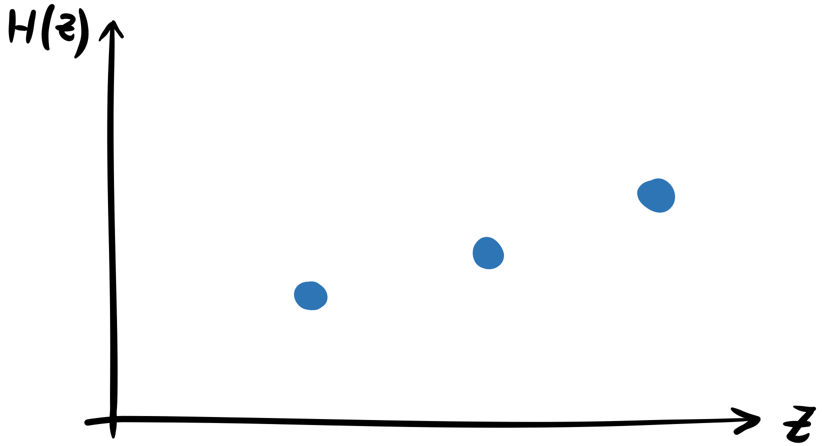
# Cosmic chronometers - BASICS

Assuming a FLRW metric:
Jimenez & Loeb (2002)

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



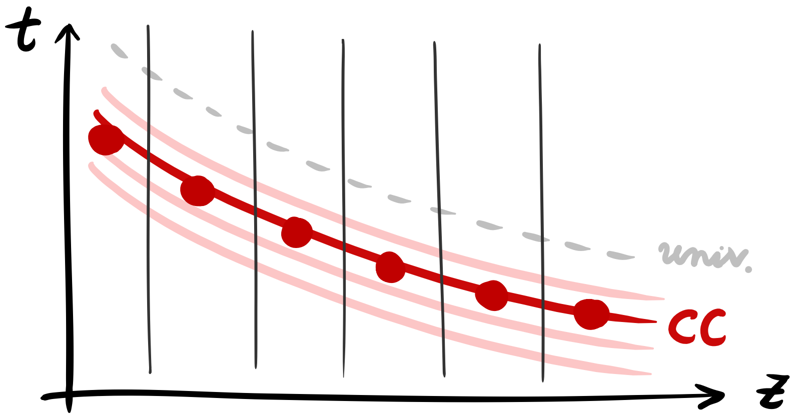

$\Rightarrow$



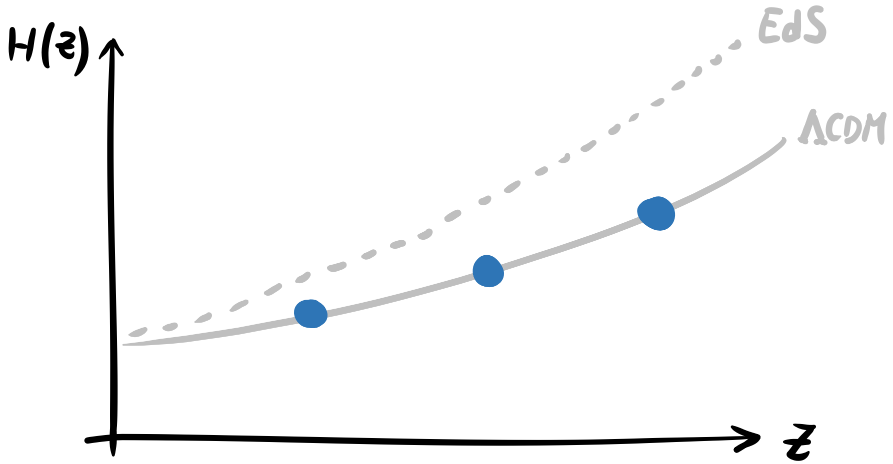
# Cosmic chronometers - BASICS

Assuming a FLRW metric: $$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{\mathrm{d}z}{\mathrm{d}t}$$

Jimenez & Loeb (2002)



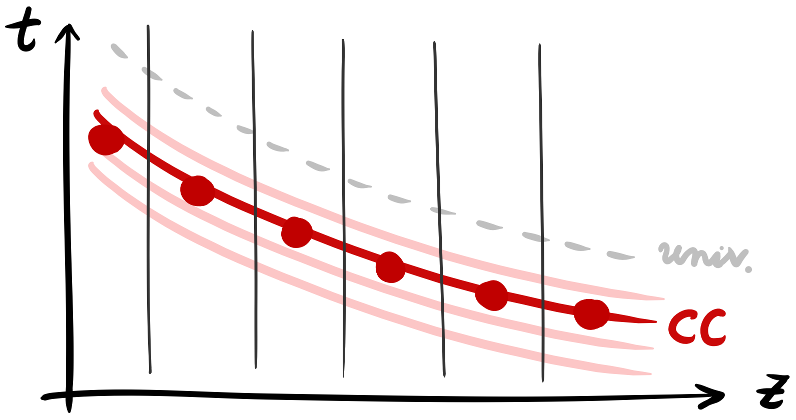

$\Rightarrow$



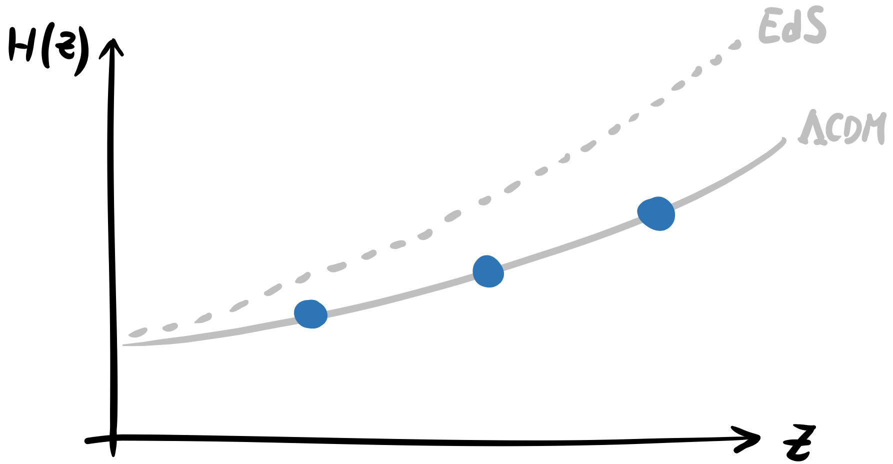
# Cosmic chronometers - BASICS

Assuming a FLRW metric: $H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{\mathrm{d}z}{\mathrm{d}t}$

Jimenez & Loeb (2002)




⇒

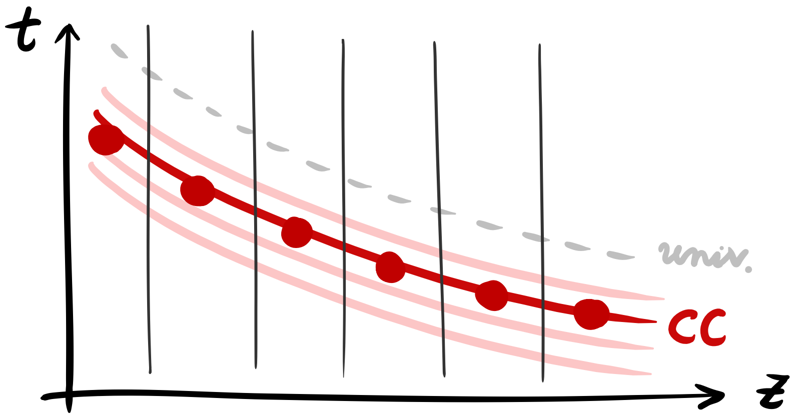



- ✓ Direct measure of H(z)
- ✓ Differential approach
- ✓ Cosmological model-independent
  *ideal to test cosmological models*

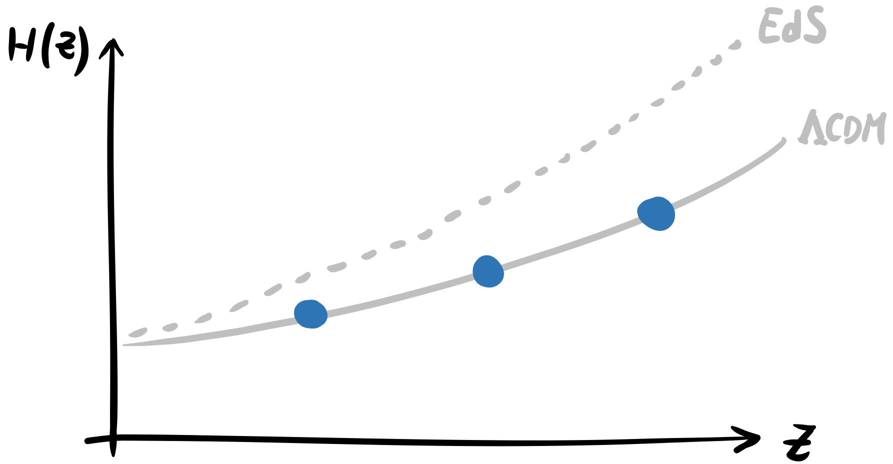
# Cosmic chronometers - BASICS

Assuming a FLRW metric: $$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z}\frac{\mathrm{d}z}{\mathrm{d}t}$$

Jimenez & Loeb (2002)




⇒




- ✓ Direct measure of H(z)
- ✓ Differential approach
- ✓ Cosmological model-independent
  *ideal to test cosmological models*

Key requirements:

1. Pure sample of tracers
2. Robust *dts* **w/o cosmological priors**

# Cosmic chronometers - TRACERS

# Cosmic chronometers - TRACERS

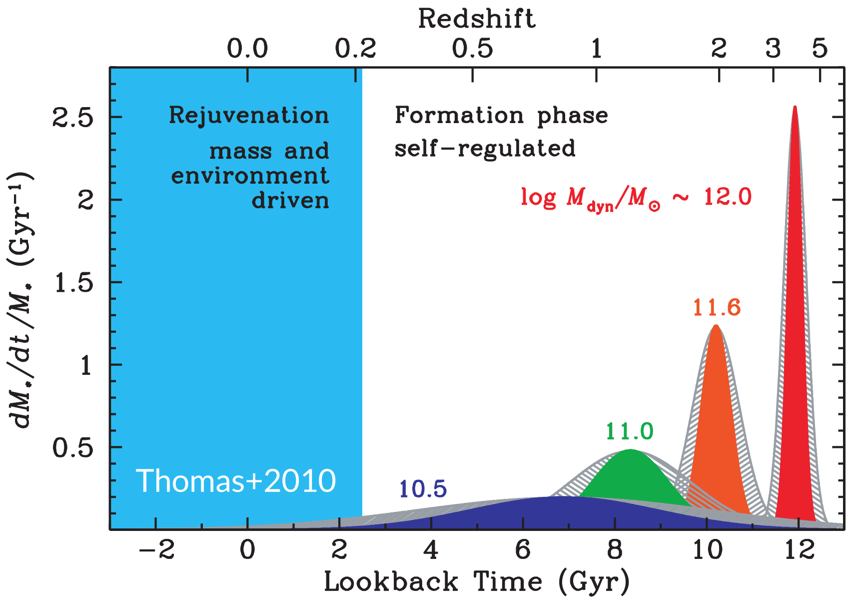
**Most massive and passive galaxies**

- Oldest galaxies at each redshift
  (e.g., Cowie et al. 1996; Cimatti et al. 2004; Thomas et al. 2005, 2010)
- More synchronized SFHs

# Cosmic chronometers - TRACERS

**Most massive and passive galaxies**

- Oldest galaxies at each redshift
  (e.g., Cowie et al. 1996; Cimatti et al. 2004; Thomas et al. 2005, 2010)
- More synchronized SFHs

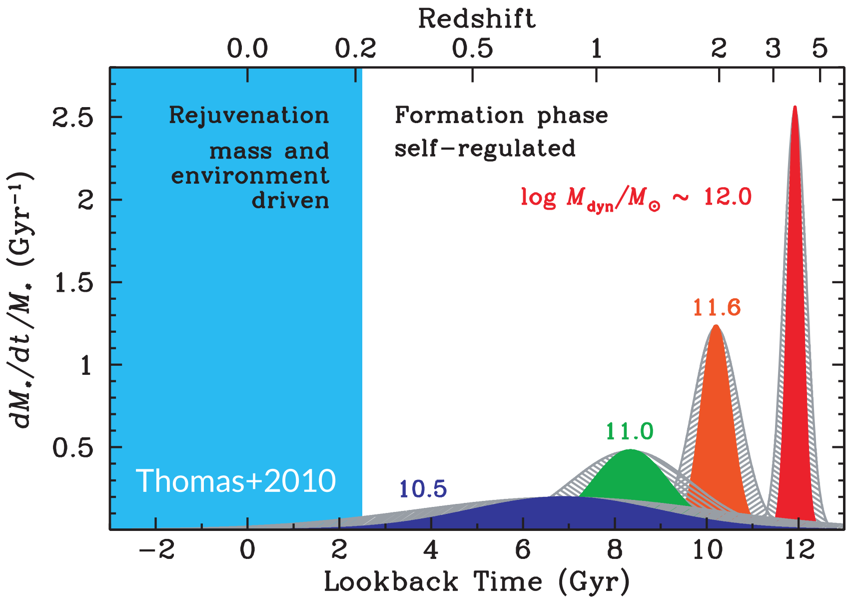


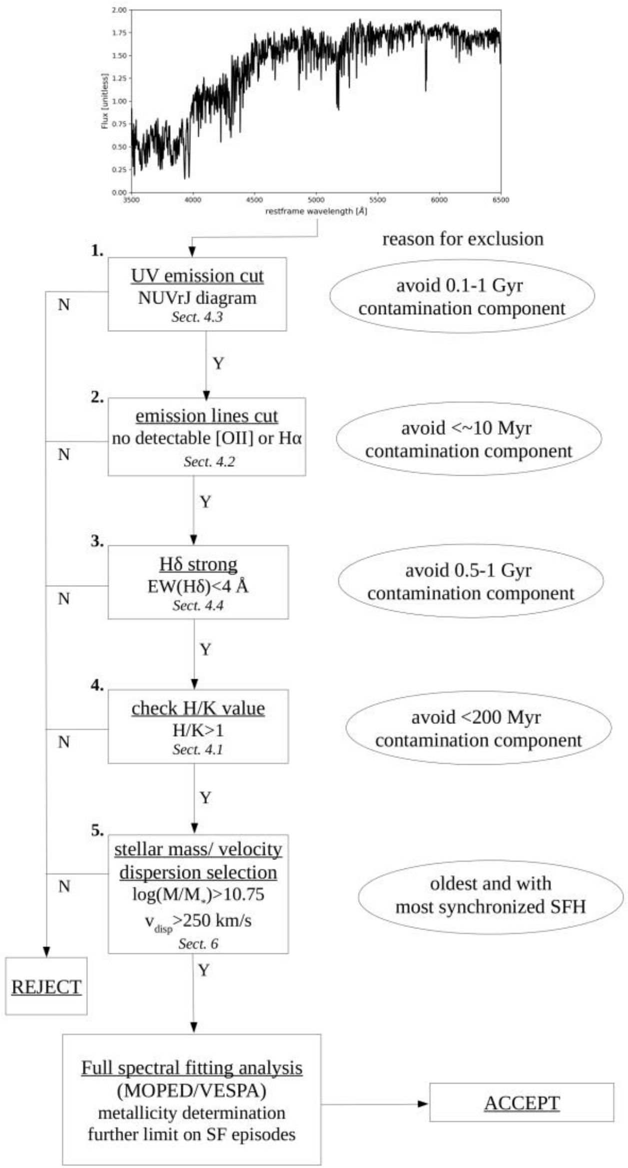
# Cosmic chronometers - TRACERS

**Most massive and passive galaxies**

- Oldest galaxies at each redshift
  (e.g., Cowie et al. 1996; Cimatti et al. 2004; Thomas et al. 2005, 2010)
- More synchronized SFHs

… but minimizing the contamination is fundamental!



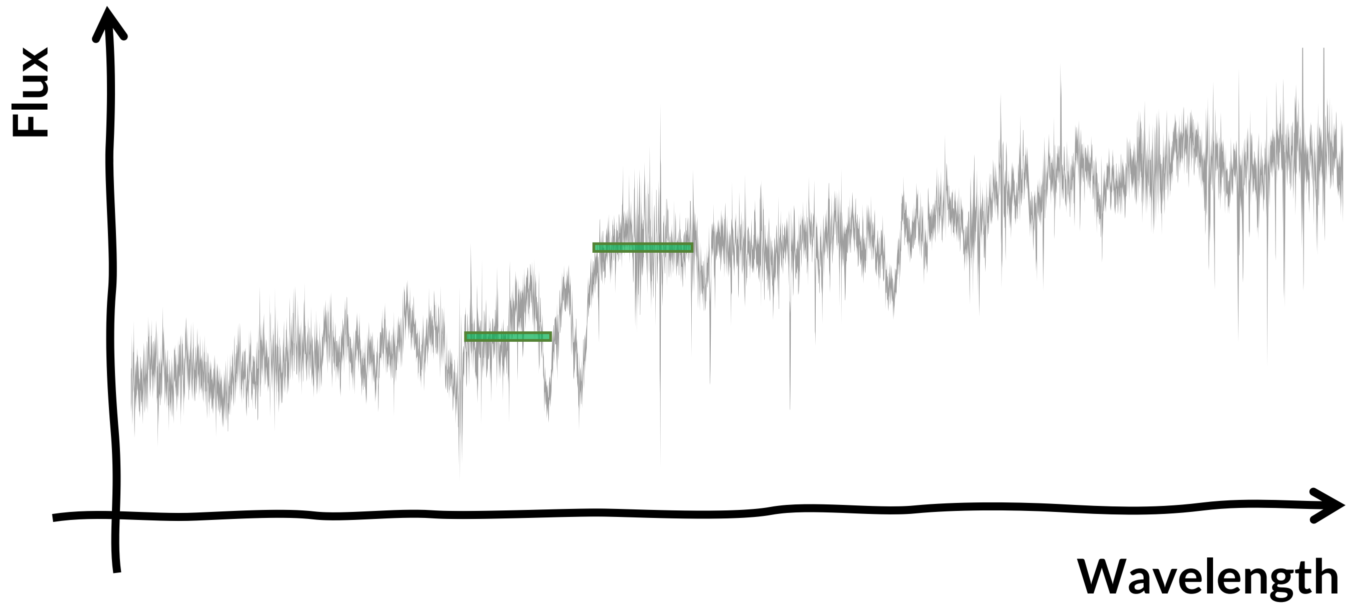




see Moresco et al. 2018

# Cosmic chronometers – dt

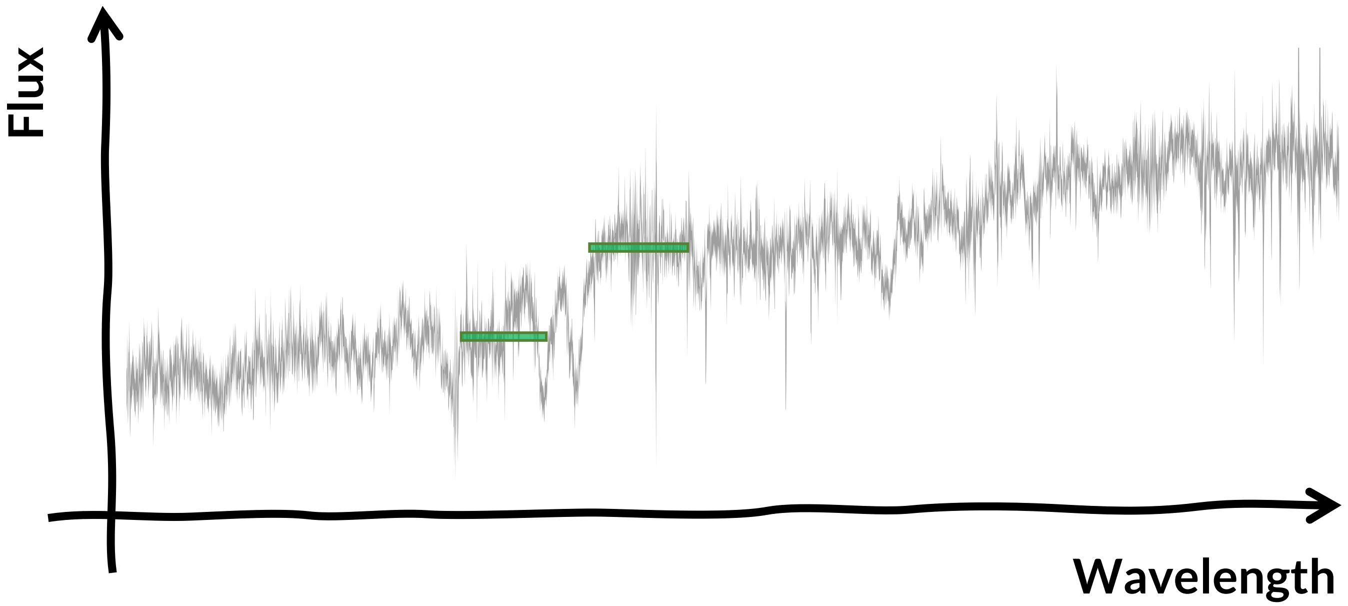
# Cosmic chronometers – dt

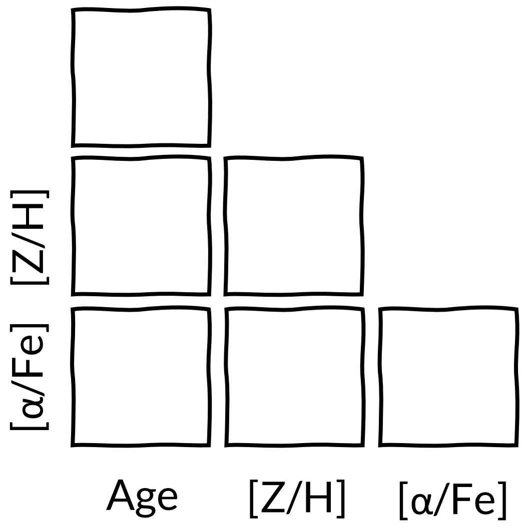
> Measure the D4000 index $\rightarrow$ d$t$ = $A$(…)*dD4000 where $A$(…) calibrated from SPS models



# Cosmic chronometers – dt

- Measure the D4000 index $\rightarrow$ $dt = A(\ldots) * dD4000$ where $A(\ldots)$ calibrated from SPS models
- Measure galaxies' ages, then derive age(z): ~~photometry~~, full-spectrum fitting, Lick indices

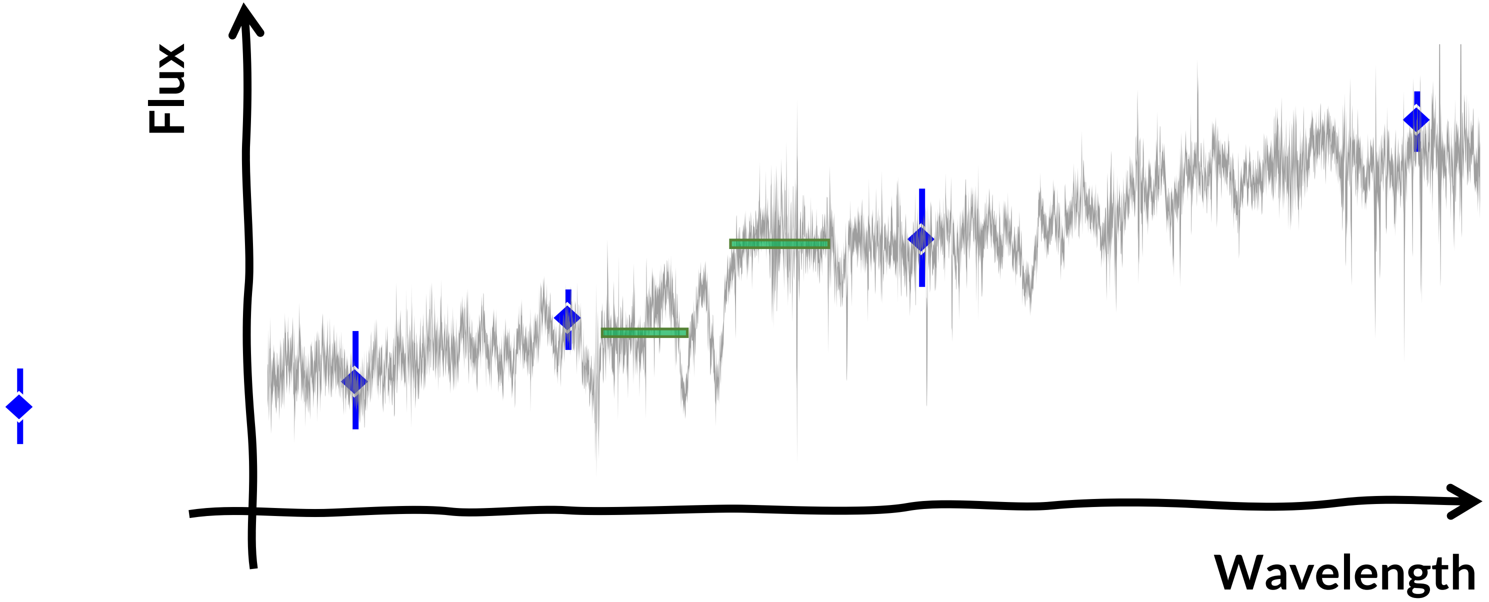


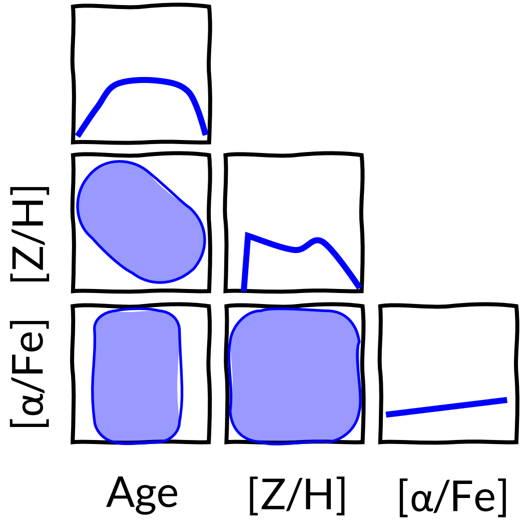



# Cosmic chronometers – dt

> Measure the D4000 index → $dt = A(\ldots)*dD4000$ where $A(\ldots)$ calibrated from SPS models

> Measure galaxies' ages, then derive age(z): ~~photometry~~, full-spectrum fitting, Lick indices

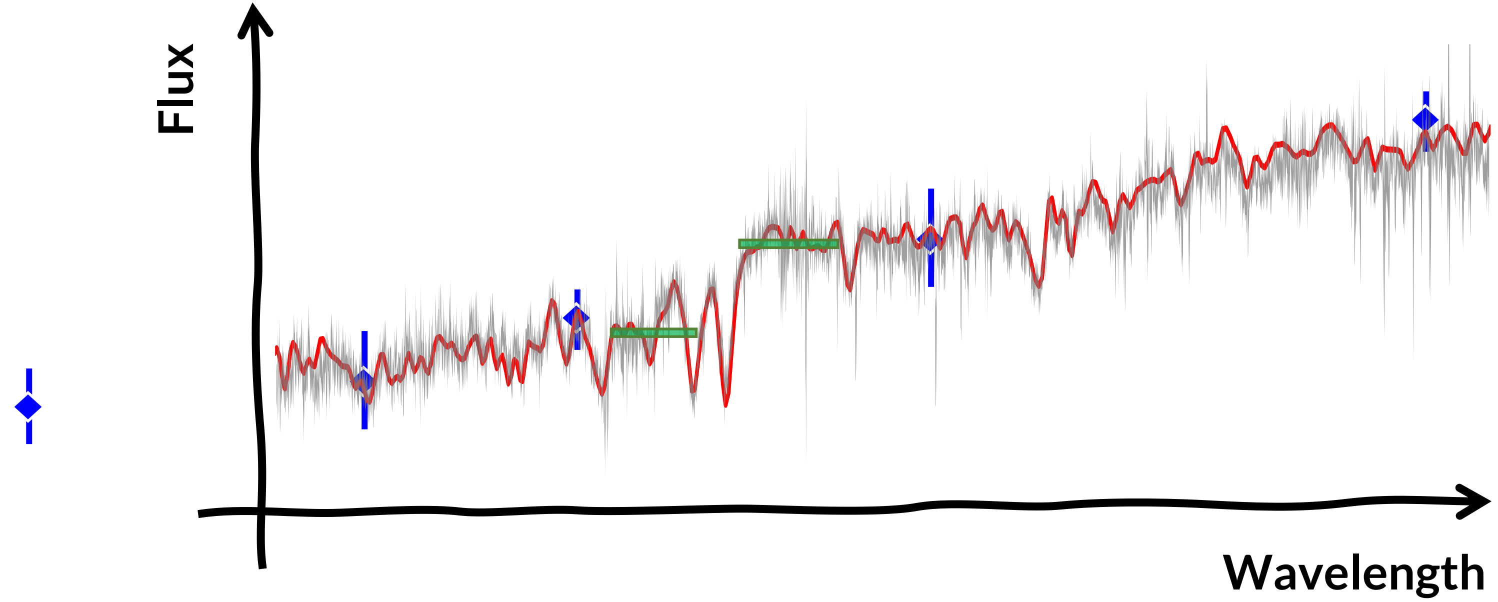


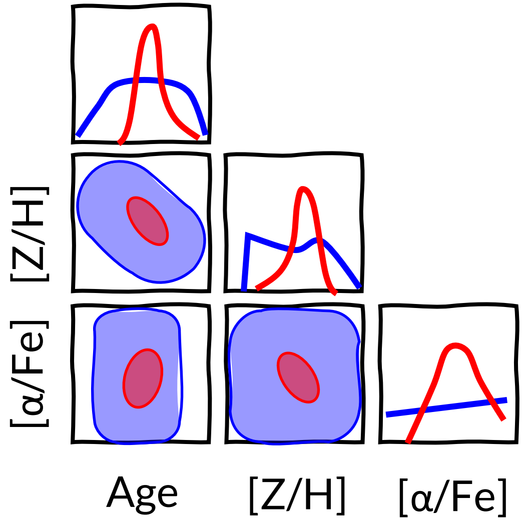



# Cosmic chronometers – dt

> Measure the D4000 index → $dt = A(\ldots)*dD4000$ where $A(\ldots)$ calibrated from SPS models

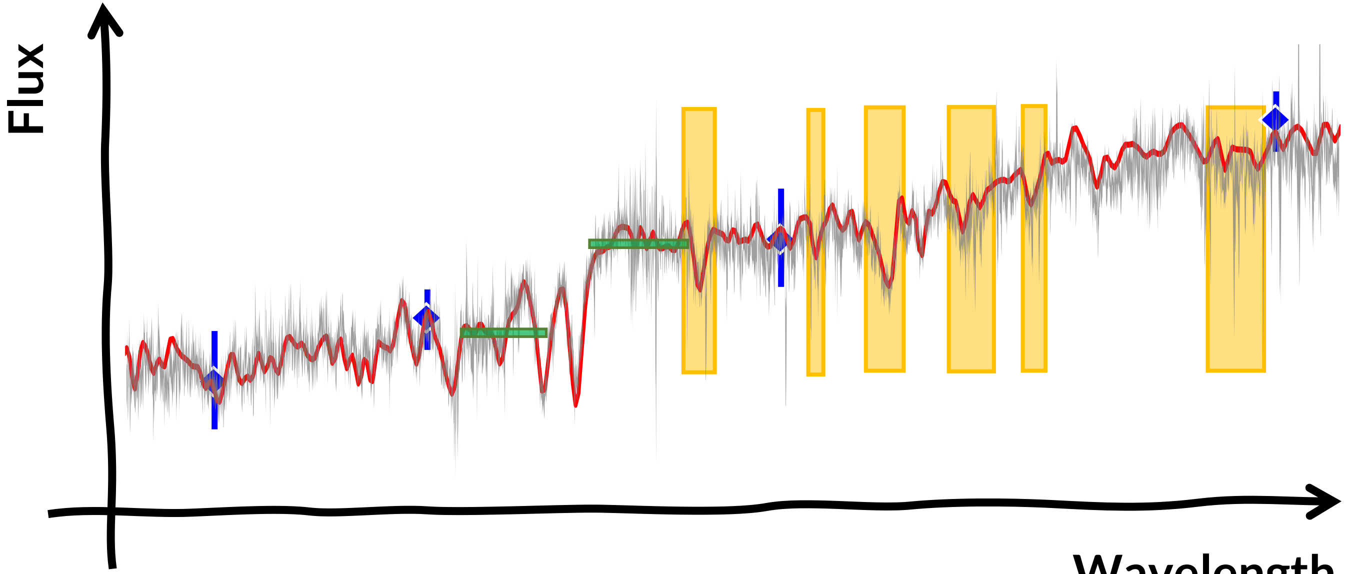
> Measure galaxies' ages, then derive age(z): ~~photometry~~, full-spectrum fitting, Lick indices

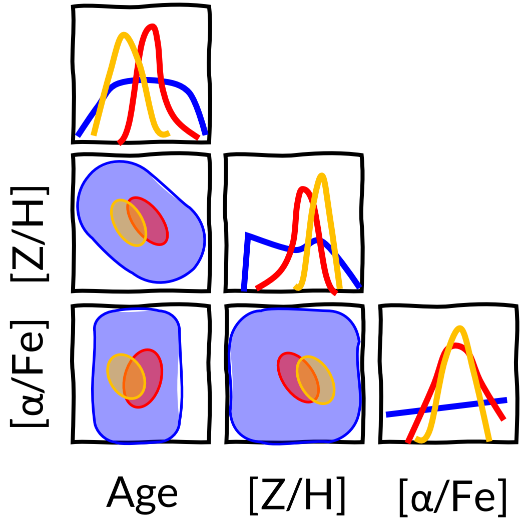


# Cosmic chronometers – dt

- Measure the D4000 index → dt = $A(\ldots)$*dD4000 where $A(\ldots)$ calibrated from SPS models
- Measure galaxies' ages, then derive age(z): ~~photometry~~, full-spectrum fitting, Lick indices

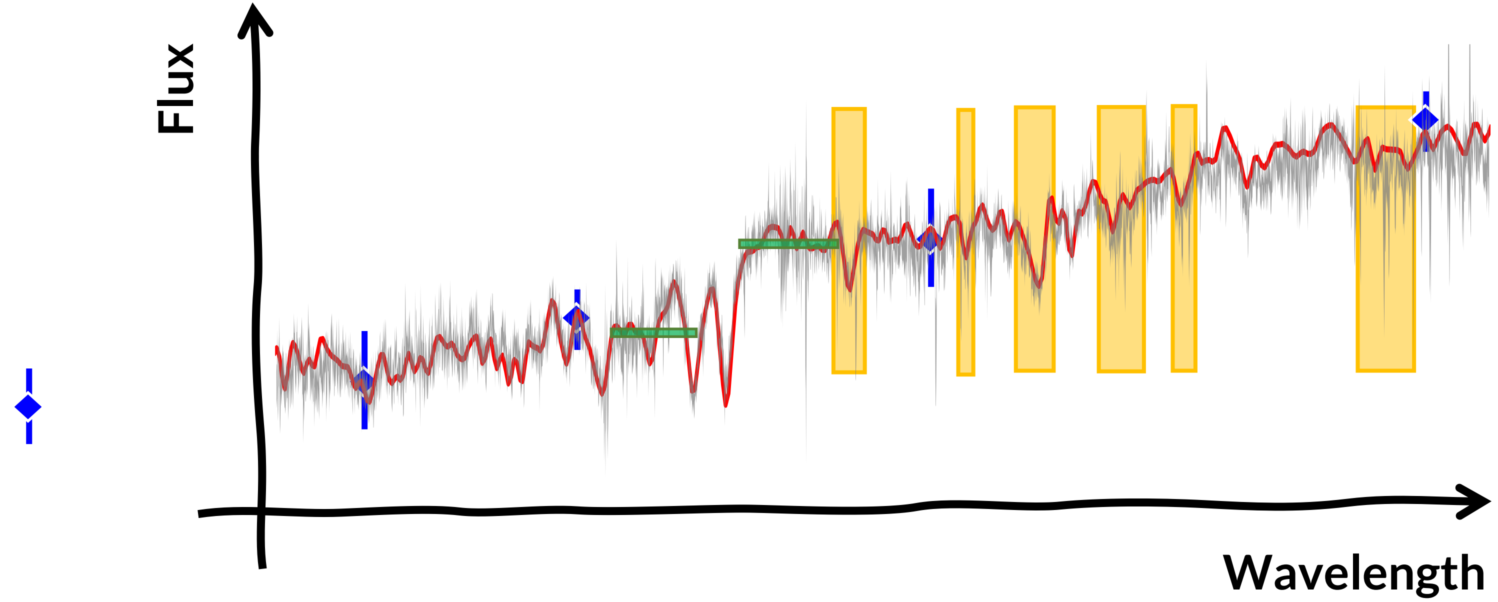


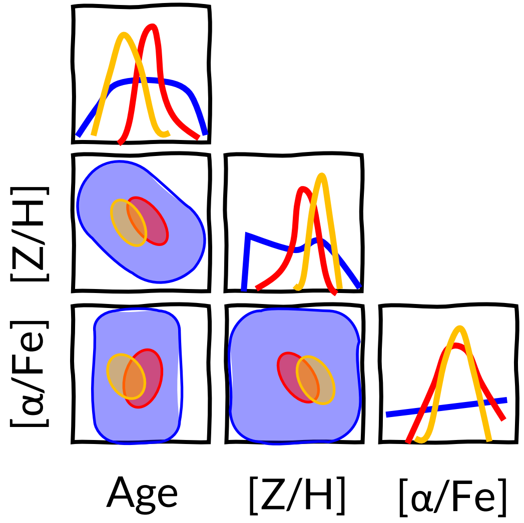



# Cosmic chronometers – dt

- > Measure the D4000 index $\rightarrow$ $dt = A(\ldots)$*dD4000 where $A(\ldots)$ calibrated from SPS models
- > Measure galaxies' ages, then derive age(z): ~~photometry~~, full-spectrum fitting, Lick indices

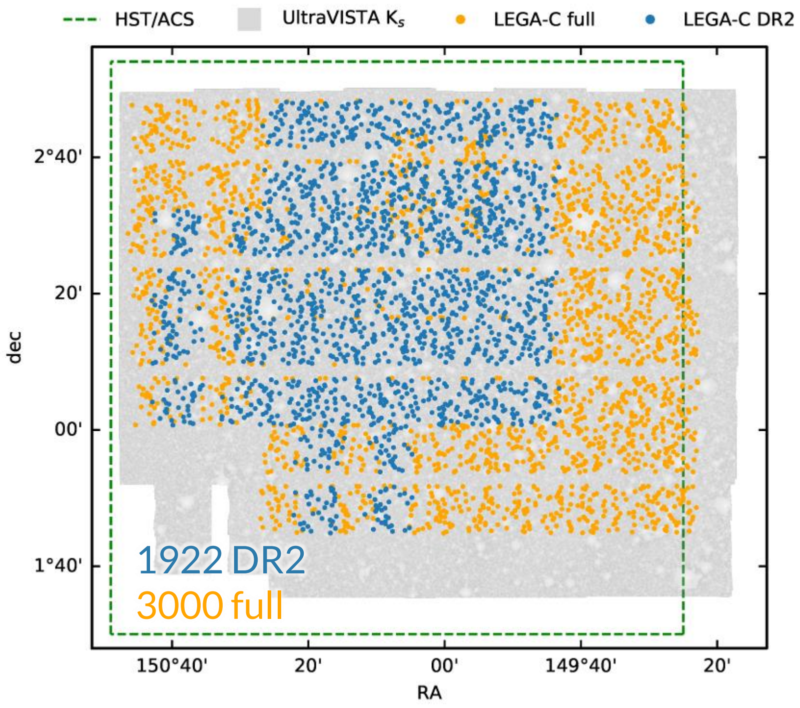
⟳ **repeat by varying SPS models & ingredients to account for systematics!**

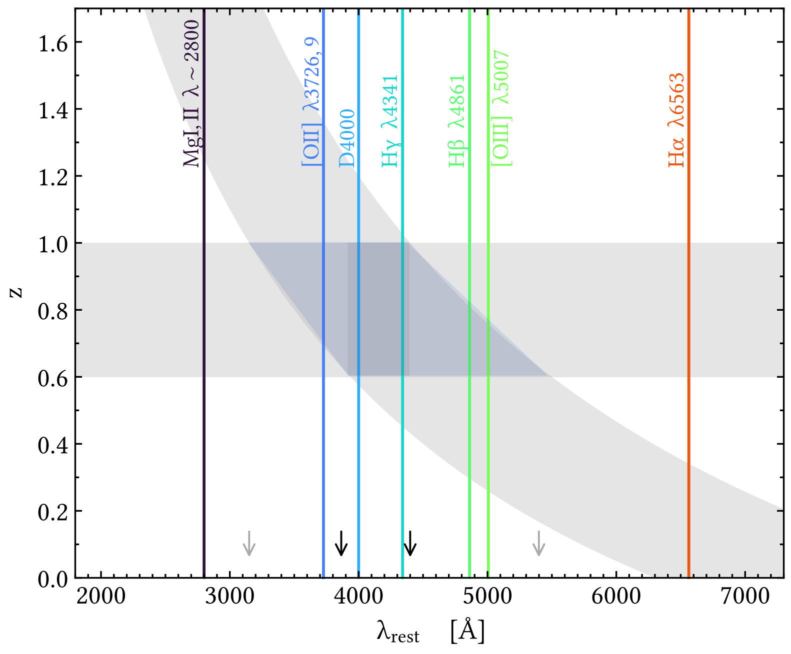


# The LEGA-C ESO survey ($0.6 < z < 1$)

(van der Wel et al. 2016 and 2021 and Straatman et al. 2018)



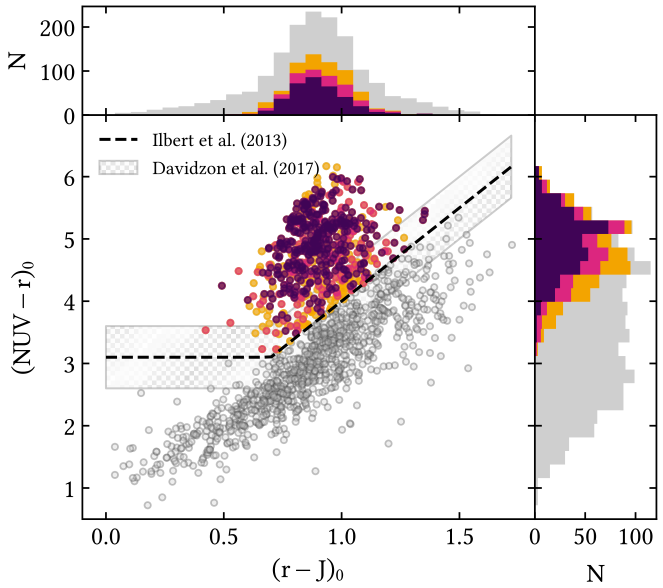

- 2 deg$^2$ - COSMOS field;
  $K_{s,lim}$ = 20.7 -7.5 log((1+z)/1.8)

- VLT / VIMOS HR-Red;
  R ~ 3500; S/N ≳ 20; Δλ ~ 500 Å

# Selection of passive galaxies

(see also Renzini 2006, Franzetti et al. 2007, Moresco et al. 2013)

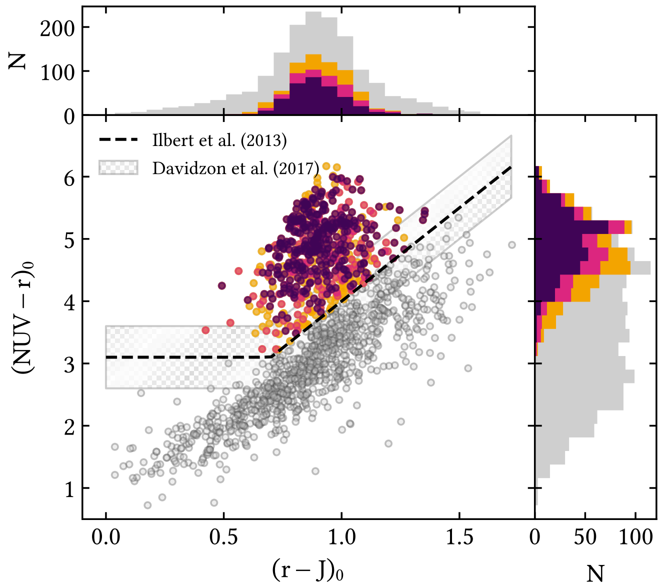
1. NUVrJ (Ilbert et al. 2013)

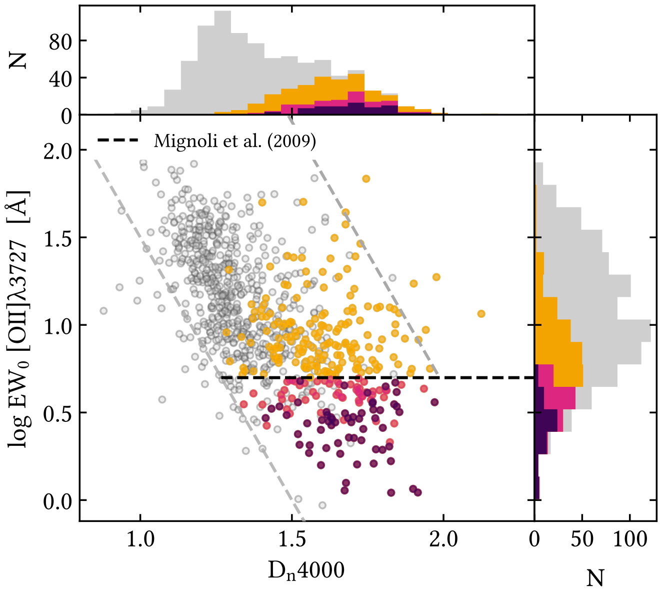


# Selection of passive galaxies

(see also Renzini 2006, Franzetti et al. 2007, Moresco et al. 2013)

1. NUVrJ (Ilbert et al. 2013)
2. EW[OII]λ3727 < 5 Å cut (e.g., Mignoli et al. 2009)



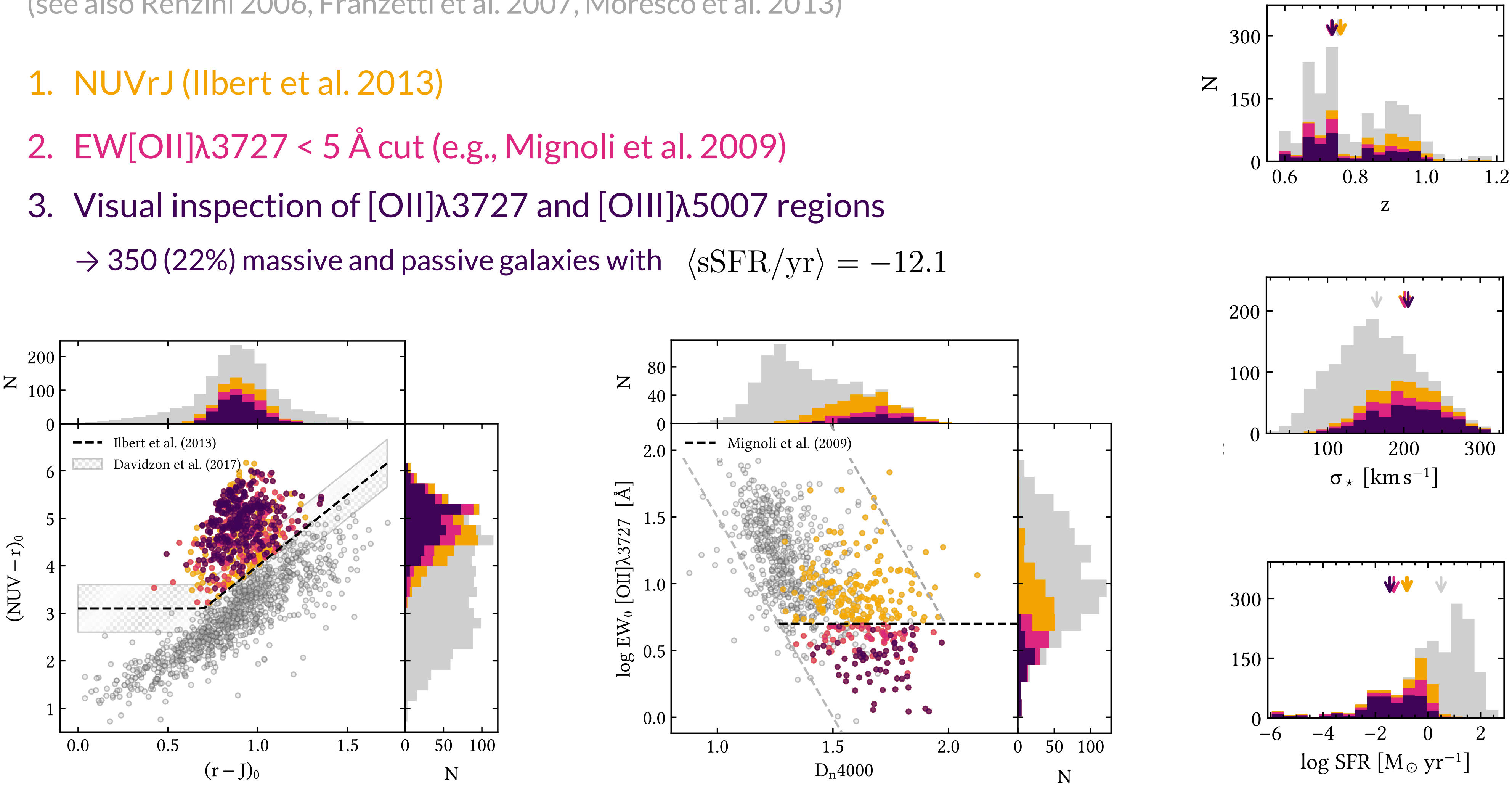



# Selection of passive galaxies

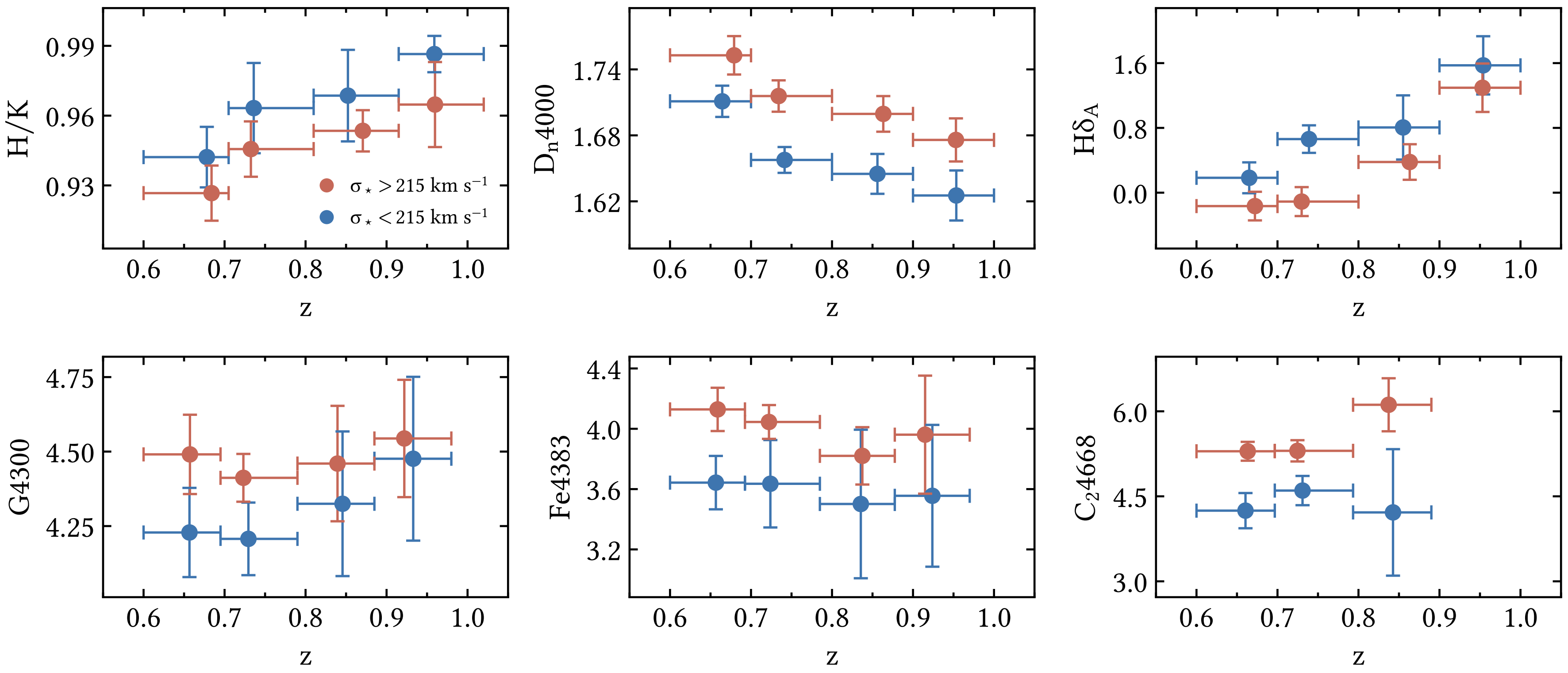
(see also Renzini 2006, Franzetti et al. 2007, Moresco et al. 2013)

1. NUVrJ (Ilbert et al. 2013)
2. EW[OII]λ3727 < 5 Å cut (e.g., Mignoli et al. 2009)
3. Visual inspection of [OII]λ3727 and [OIII]λ5007 regions

→ 350 (22%) massive and passive galaxies with $\langle \mathrm{sSFR/yr} \rangle = -12.1$



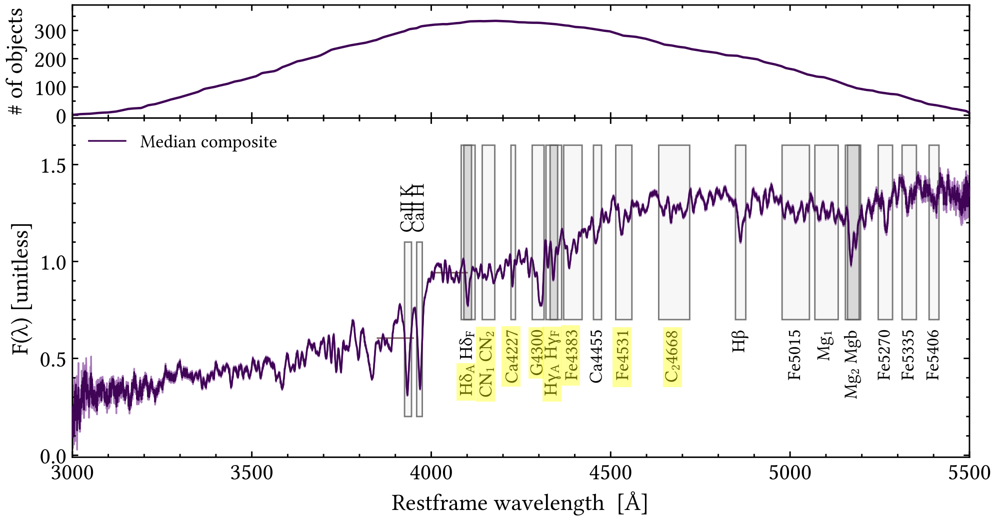
# Stellar population properties – Observed trends (mean)



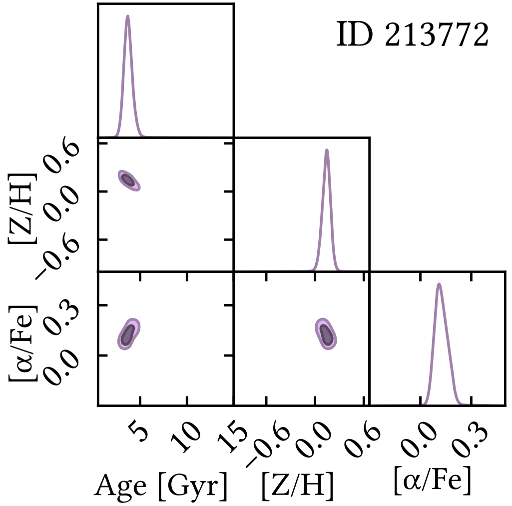
# Stellar population properties - ANALYSIS

1. Thomas, Maraston & Johannson 2011 (TMJ) SSP models → (*age*, [Z/H], [α/Fe])

2. Optimized set of spectral indices:




3. Bayesian approach **with uninformative priors** (no cosmological priors!)

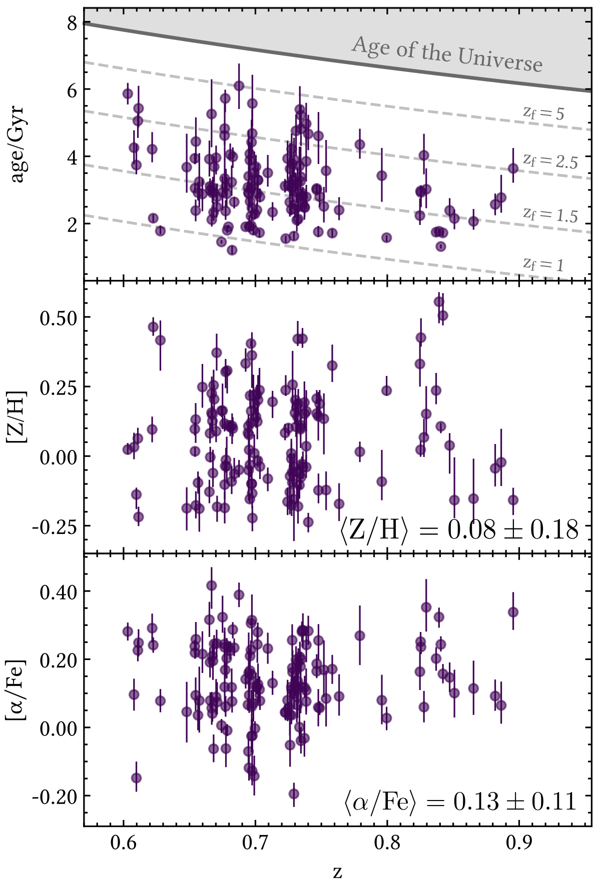



➢ Constraints for **140 individual** passive galaxies

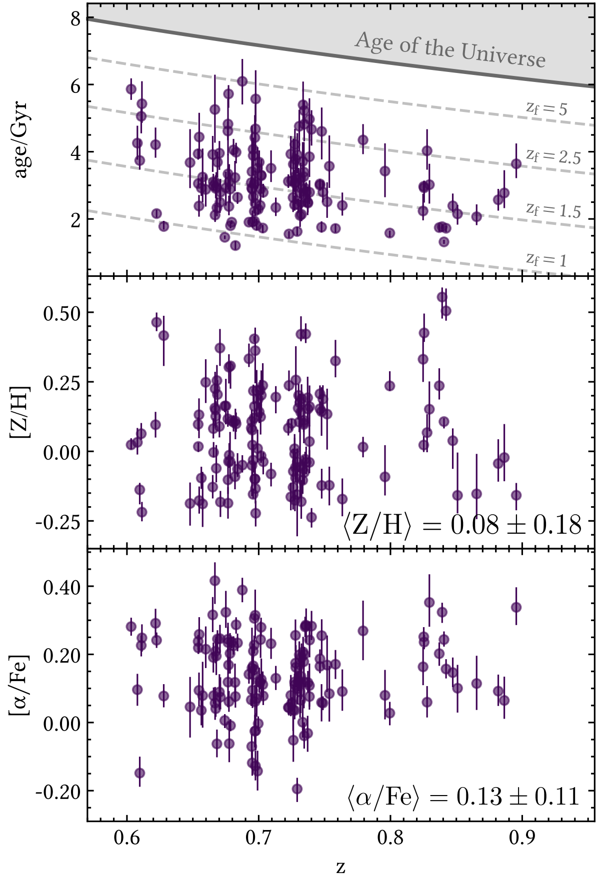
$$\langle \mathrm{S/N} \rangle \simeq 26 \,\mathrm{per\ resol.\ element}$$

$$\sigma_{age} \simeq 0.4 \text{ Gyr}, \quad \sigma_{[\mathrm{Z/H}],[\alpha/\mathrm{Fe}]} \simeq 0.05 \text{ dex}$$

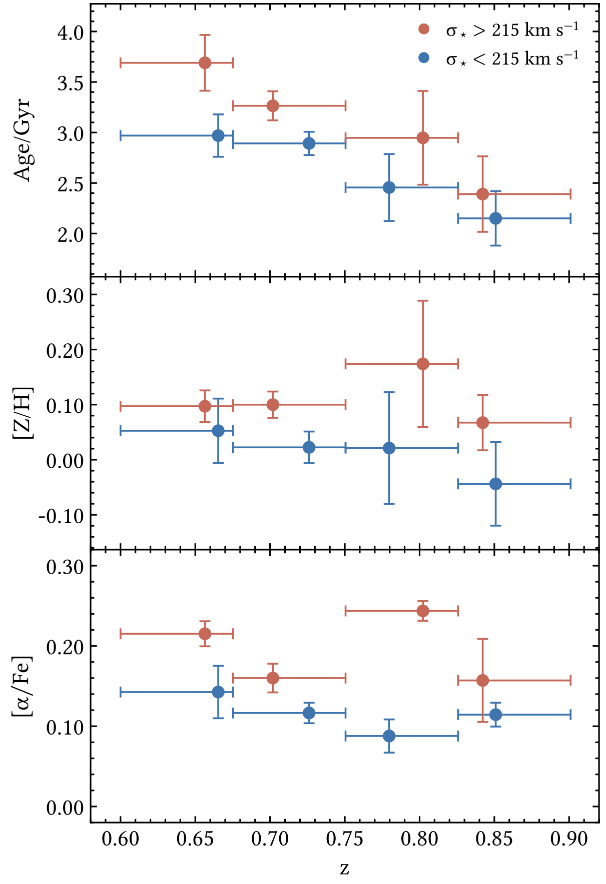
# Stellar population properties - RESULTS



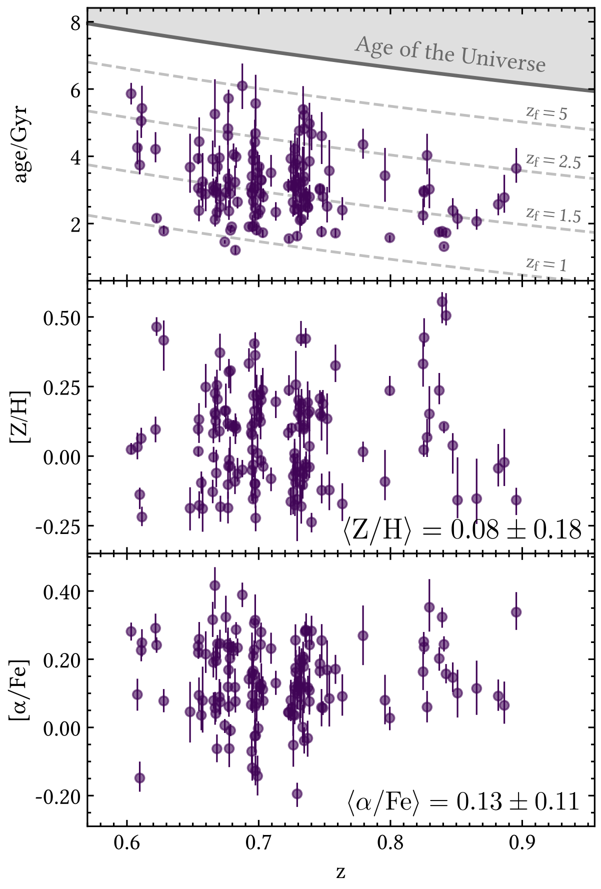
# Stellar population properties - RESULTS



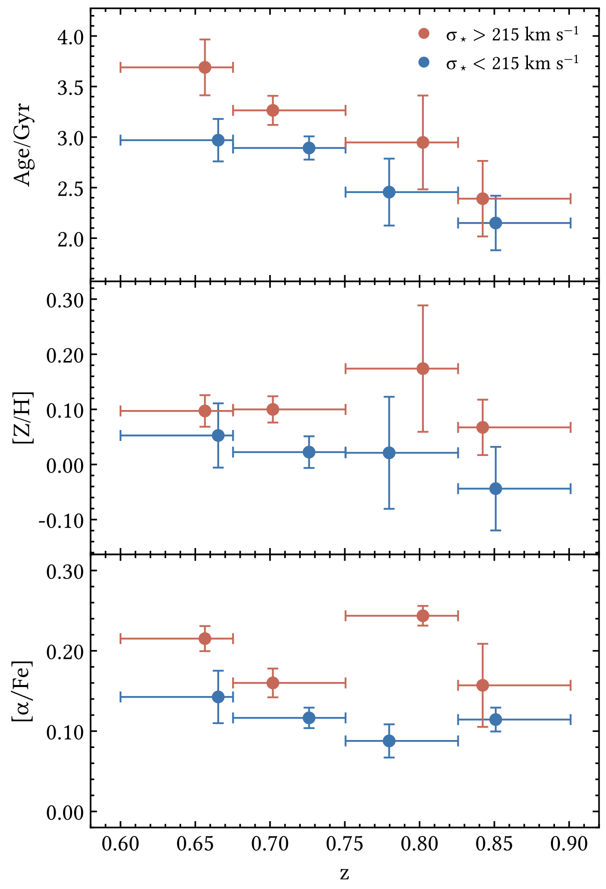

2 mass regimes ($M_t$~$10^{11}\,M_\odot$) & 4 $z$ bins



# Stellar population properties - RESULTS

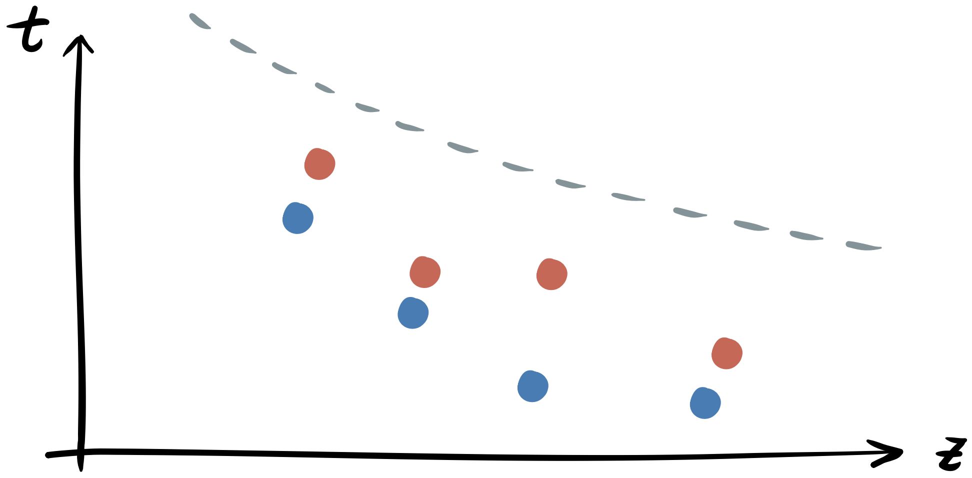



2 mass regimes ($M_t$~$10^{11}\,M_\odot$) &
4 $z$ bins

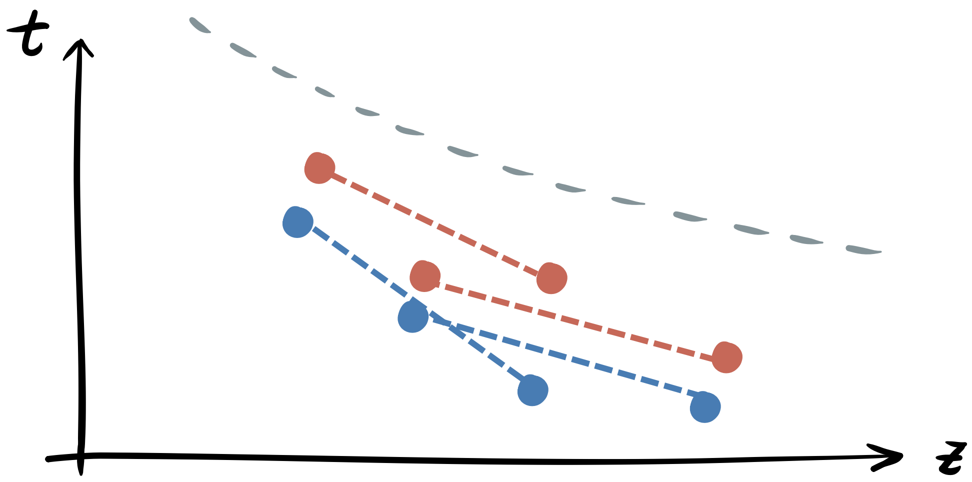



➢ *mass downsizing*, two **nearly parallel age-z relations**, no clear evolution in [Z/H]-z and [α/Fe]-z

# A new measurement of H(z)

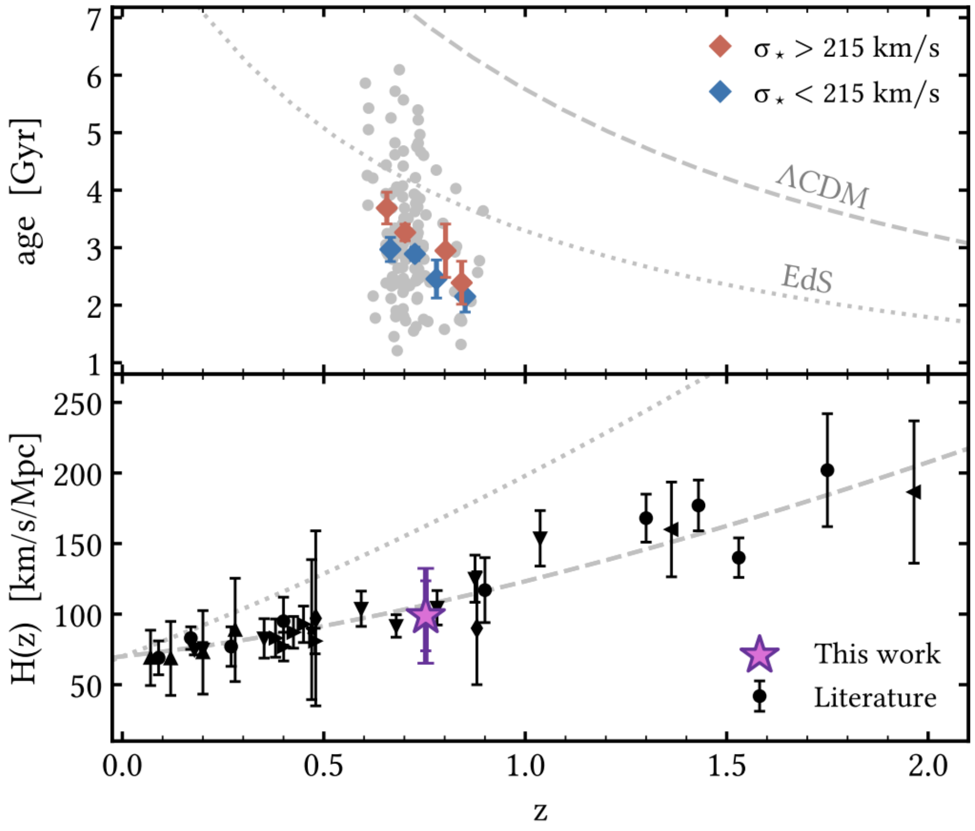


# A new measurement of H(z)



# A new measurement of H(z)

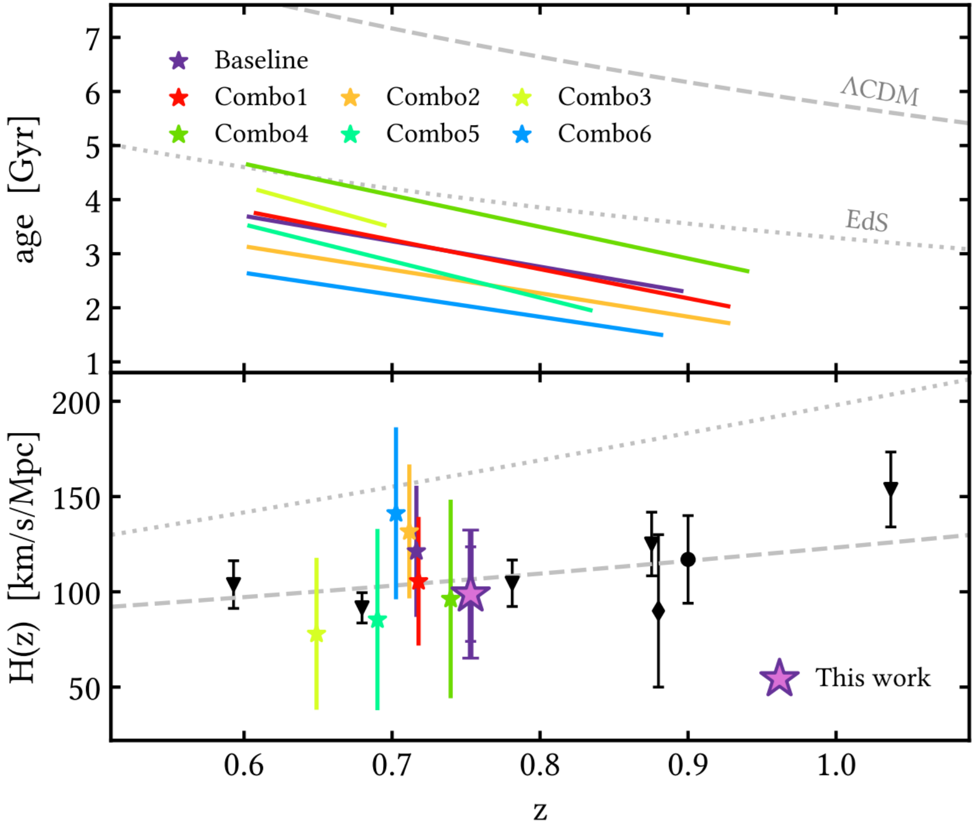
$$H(z = 0.75) = 98.8 \pm 24.8(stat) \pm 22.7(syst)$$




- First H(z) from the analysis of the **stellar population** (*age*, [Z/H], and [α/Fe]) of **individual galaxies**
  - poorly mapped redshift range
  - near to the transition z (~0.7)
  - *syst*: set of indices, binning, SP model (Vazdekis+15), and SFH

# A new measurement of H(z)

$$H(z = 0.75) = 98.8 \pm 24.8(stat) \pm 22.7(syst)$$




- First H(z) from the analysis of the **stellar population** (*age*, [Z/H], and [α/Fe]) of **individual galaxies**
  - poorly mapped redshift range
  - near to the transition z (~0.7)
  - *syst*: set of indices, binning, SP model (Vazdekis+15), and SFH
- With different sets of spectral features: ±1Gyr absolute ages

**…but final H(z) is robust (<0.2σ)**

# A new measurement of H(z) – Recent update

$$H(z = 0.75) = 98.8 \pm 24.8(stat) \pm 22.7(syst)$$

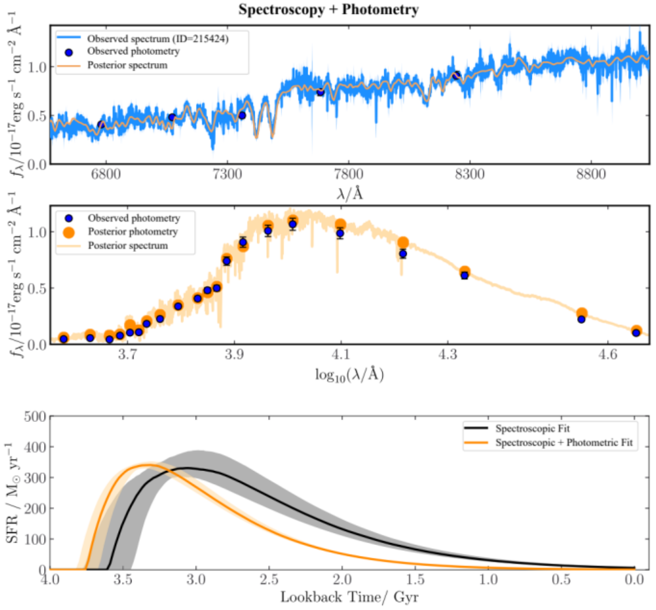
➢ Spectral features

$\Updownarrow$

$$H(z = 0.80) = 113.1 \pm 15.2(stat)^{+24.2}_{-4.0}(syst)$$

➢ Full-spectrum fitting

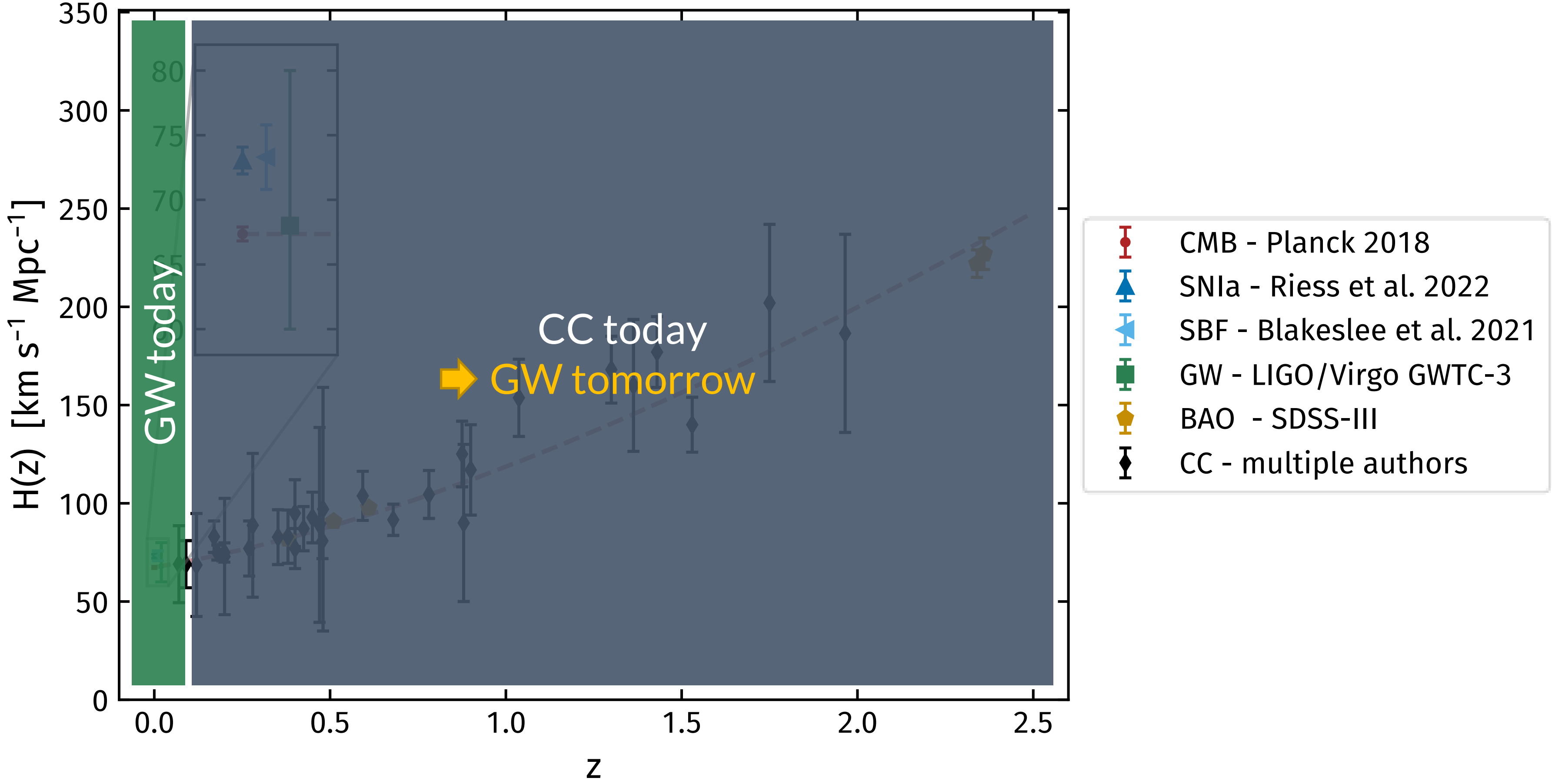
Jiao et al. (*submitted*, arXiv:2205.05701)




- ➢ Completely different methods, SPS models, & assumptions
  - ➢ Full-spectrum fitting (all the 350 CC in LEGA-C)
  - ➢ Added photometric data & calibration
  - ➢ Extended SFH: **τ~0.4 Gyr**

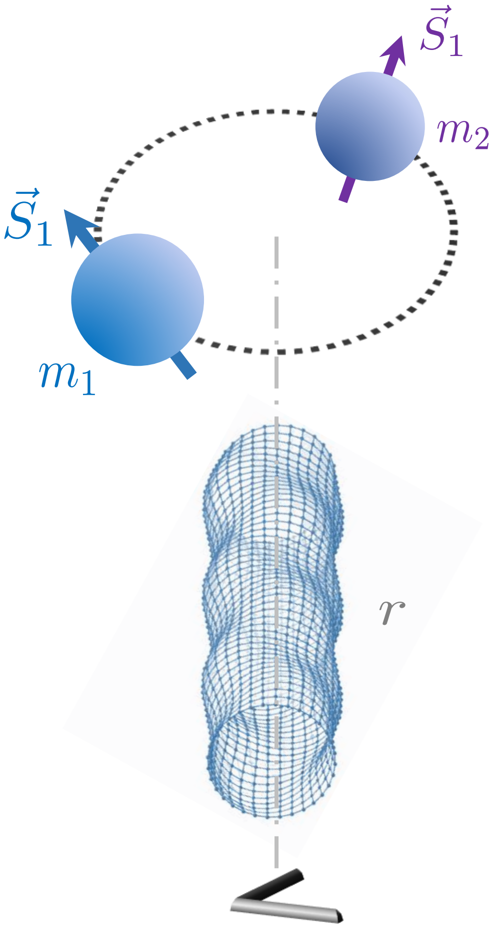
- ➢ Understood offsets in the absolute ages (~0.5 Gyr older w.r.t. Borghi et al. 2022a), but final H(z)s values are consistent

# Expansion history – current constraints



# Gravitational wave cosmology – STANDARD SIRENS

$$d_{\rm L} \approx \frac{c\,z}{H_0} + \mathcal{O}^2(z)$$




Two compact objects in (adiabatically) quasi-circular orbits (15 parameters, 8 intr. and 7 extr.):

- Component masses: $m_1$, $m_2$
- Component spins: $\vec{S}_1$, $\vec{S}_2$ ($2 \times 3$ params)
- Source distance: $r$
- Sky location (RA, DEC): $\alpha$, $\delta$
- Orbital plane orientation: inclination $\iota$, polarization angle $\psi$
- At coalescence: phase $\phi_c$, time $t_c$

... in the context of an expanding Universe (amplitude is diluted, phase is redshifted):

- Distance $\rightarrow$ luminosity distance $d_L = a_0 r(1+z)$
- Degeneracy: $\{m, S\}$ at $z \leftrightarrow \{(1+z)m, (1+z)^2 S\}$ at $z = 0$

$$h(t) \propto \frac{\mathcal{M}_z^{5/3} f(t)^{2/3}}{d_L} F_{+,\times}(angles)\cos(\phi(t))$$

(Schutz 1986; Holz & Hughes, 2005)

# Gravitational wave cosmology – STANDARD SIRENS

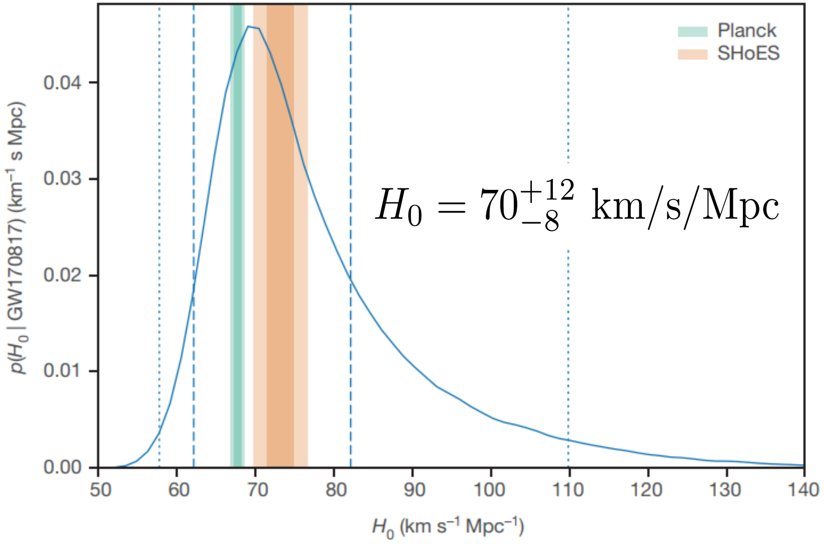
$$d_{\mathrm{L}} \approx \frac{c\,z}{H_0} + \mathcal{O}^2(z)$$

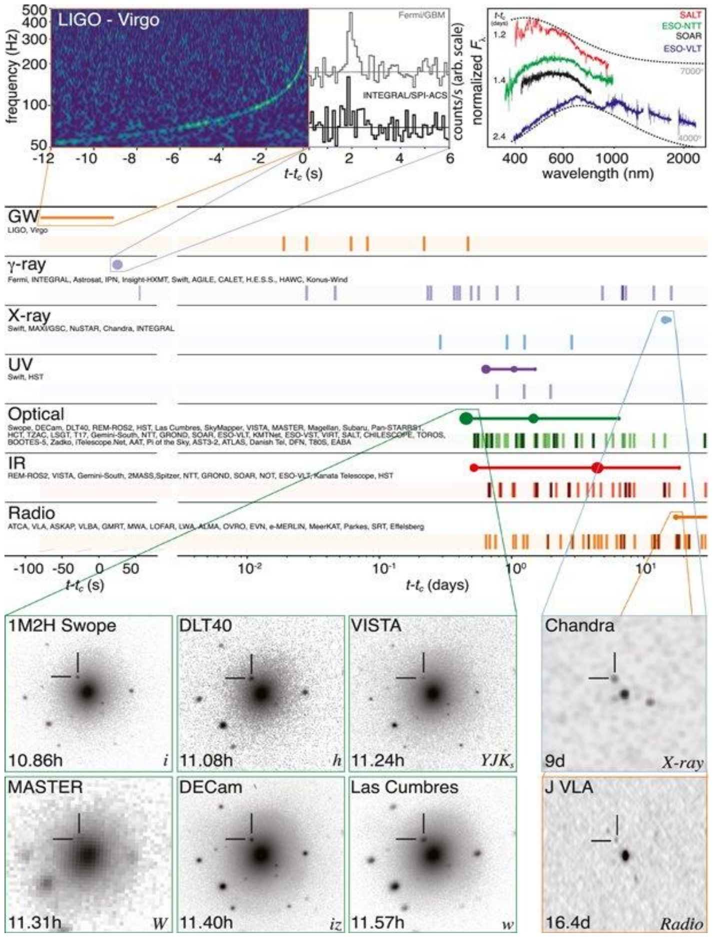
## THE COUNTERPART METHOD (BRIGHT SIRENS)

### GW170817 (BNS)

- $\mathbf{d_L}$ from GWs
- **z** from the host galaxy (NGC 4993)

Abbott et al. *Nature* 551, 85-77 (2017)



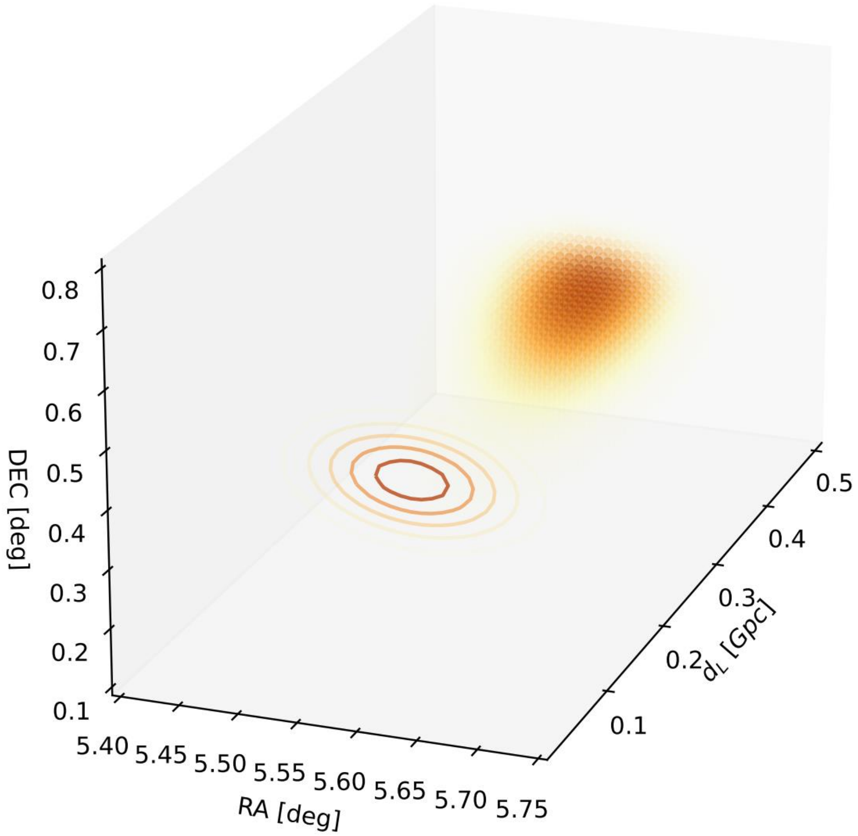




LIGO/VIRGO COLLABORATION & ESO

# Gravitational wave cosmology – STANDARD SIRENS

$$d_{\mathrm{L}} \approx \frac{c\,z}{H_0} + \mathcal{O}^2(z)$$

## THE STATISTICAL METHOD (DARK SIRENS)

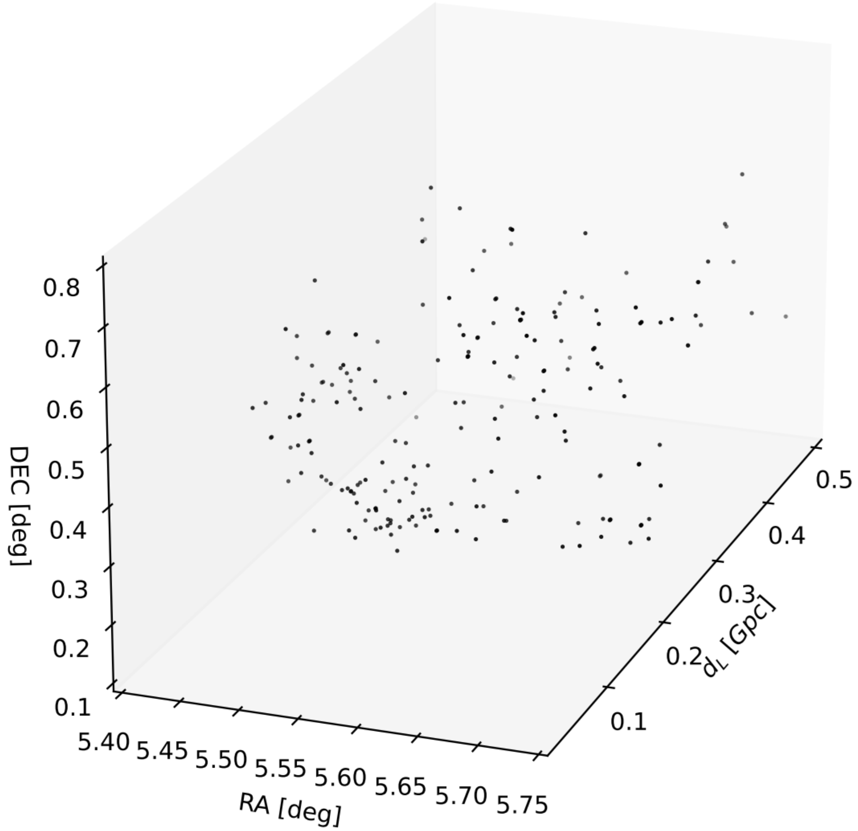


# Gravitational wave cosmology – STANDARD SIRENS

$$d_{\rm L} \approx \frac{c\, z}{H_0} + \mathcal{O}^2(z)$$

<u>THE STATISTICAL METHOD (DARK SIRENS)</u> ⟶

- **Astrophysical properties of the binary population** (e.g. source-frame mass distribution, merger rate in z, ...)
- **Galaxy gatalogs** as z prior,
- Compare GW and galaxies spatial clustering
- ...

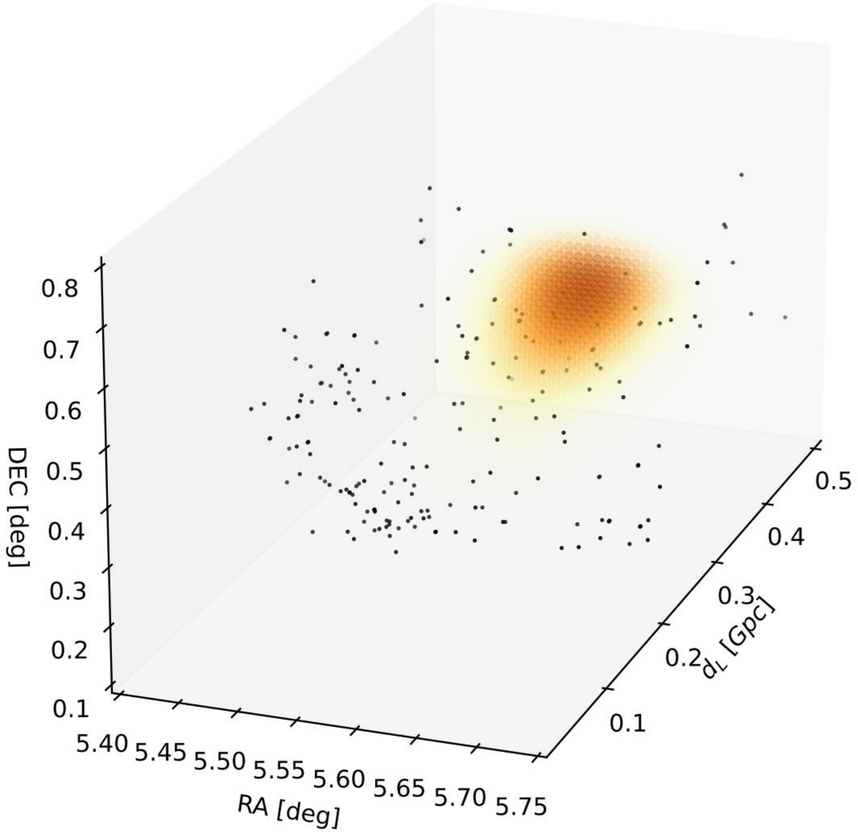


# Gravitational wave cosmology – STANDARD SIRENS

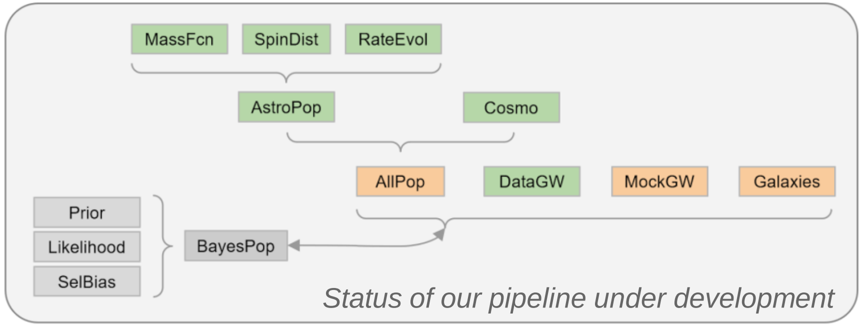
$$d_\mathrm{L} \approx \frac{c\,z}{H_0} + \mathcal{O}^2(z)$$

<u>THE STATISTICAL METHOD (DARK SIRENS)</u> ⟶

- **Astrophysical properties of the binary population** (e.g. source-frame mass distribution, merger rate in z, ...)
- **Galaxy gatalogs** as z prior,
- Compare GW and galaxies spatial clustering
- ...




*Current activity:* Joint inference of cosmo & astroph params. using galaxies (with M. Mancarella, M. Maggiore, M. Moresco)



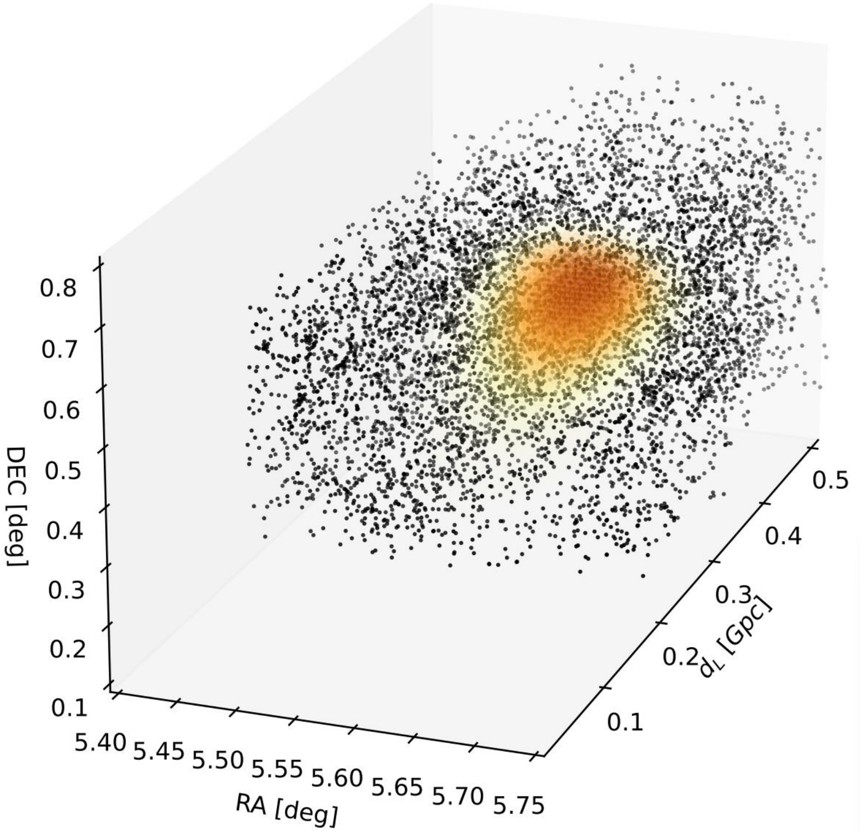

*Future:* Synergies between 3rd gen GW detectors (e.g., **ET**) and future galaxy surveys (e.g., **Euclid**; NB, M. Moresco, A. Cimatti)

# Gravitational wave cosmology – STANDARD SIRENS

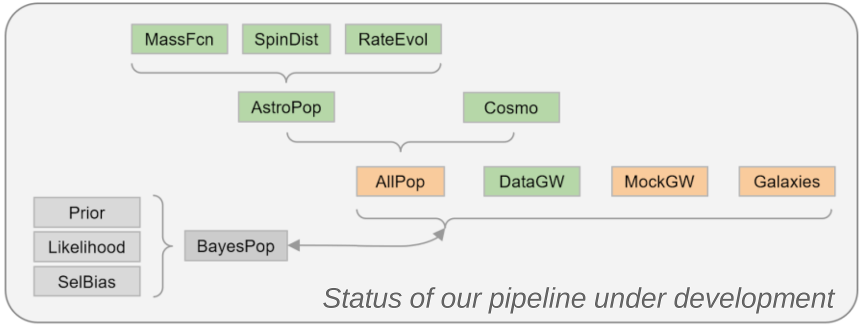
$$d_{\rm L} \approx \frac{c\,z}{H_0} + \mathcal{O}^2(z)$$

**THE STATISTICAL METHOD (DARK SIRENS)** ⟶

- **Astrophysical properties of the binary population** (e.g. source-frame mass distribution, merger rate in z, ...)
- **Galaxy gatalogs** as z prior,
- Compare GW and galaxies spatial clustering
- ...

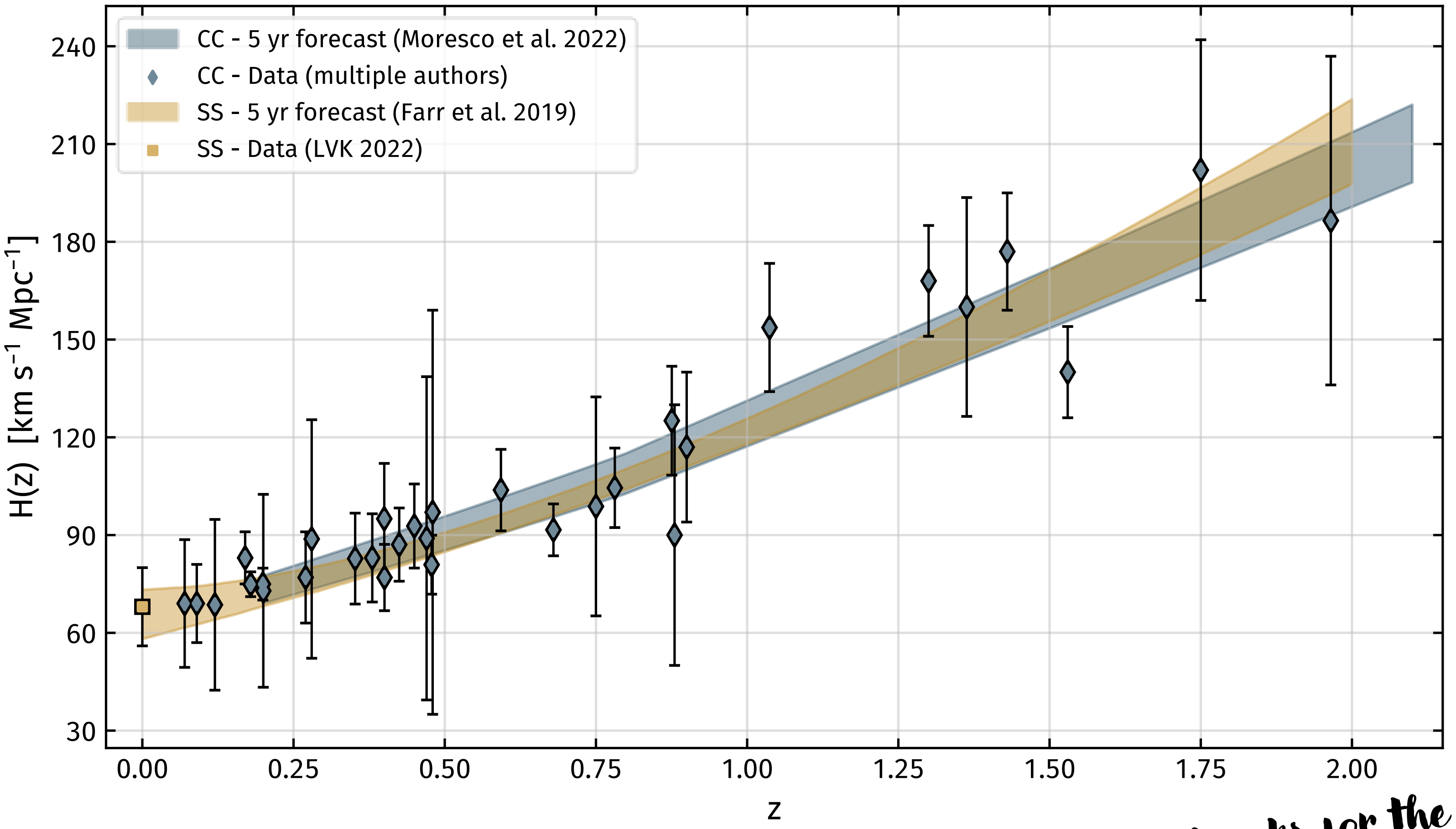



*Current activity:* Joint inference of cosmo & astroph params. using galaxies (with M. Mancarella, M. Maggiore, M. Moresco)




*Future:* Synergies between 3rd gen GW detectors (e.g., **ET**) and future galaxy surveys (e.g., **Euclid**; NB, M. Moresco, A. Cimatti)

# Expansion history – Synergies with different probes




Thanks for the attention!

# The current CC's H(z) dataset & systematics

| $z$ | $H(z)$ | $\sigma_{H(z)}$ | M | reference |
|---|---|---|---|---|
| 0.07 | 69.0 | 19.6 | F | Zhang et al. (2014) |
| 0.09 | 69 | 12 | F | Simon et al. (2005) |
| 0.12 | 68.6 | 26.2 | F | Zhang et al. (2014) |
| 0.17 | 83 | 8 | F | Simon et al. (2005) |
| 0.179 | 75 | 4 | D | Moresco et al. (2012a) |
| 0.199 | 75 | 5 | D | Moresco et al. (2012a) |
| 0.20 | 72.9 | 29.6 | F | Zhang et al. (2014) |
| 0.27 | 77 | 14 | F | Simon et al. (2005) |
| 0.28 | 88.8 | 36.6 | F | Zhang et al. (2014) |
| 0.352 | 83 | 14 | D | Moresco et al. (2012a) |
| 0.38 | 83 | 13.5 | D | Moresco et al. (2016b) |
| 0.4 | 95 | 17 | F | Simon et al. (2005) |
| 0.4004 | 77 | 10.2 | D | Moresco et al. (2016b) |
| 0.425 | 87.1 | 11.2 | D | Moresco et al. (2016b) |
| 0.445 | 92.8 | 12.9 | D | Moresco et al. (2016b) |
| 0.47 | 89.0 | 49.6 | F | Ratsimbazafy et al. (2017) |

| $z$ | $H(z)$ | $\sigma_{H(z)}$ | M | reference |
|---|---|---|---|---|
| 0.4783 | 80.9 | 9 | D | Moresco et al. (2016b) |
| 0.48 | 97 | 62 | F | Stern et al. (2010) |
| 0.593 | 104 | 13 | D | Moresco et al. (2012a) |
| 0.68 | 92 | 8 | D | Moresco et al. (2012a) |
| 0.75 | 98.8 | 33.6 | L | Borghi et al. (2021a) |
| 0.781 | 105 | 12 | D | Moresco et al. (2012a) |
| 0.875 | 125 | 17 | D | Moresco et al. (2012a) |
| 0.88 | 90 | 40 | F | Stern et al. (2010) |
| 0.9 | 117 | 23 | F | Simon et al. (2005) |
| 1.037 | 154 | 20 | D | Moresco et al. (2012a) |
| 1.3 | 168 | 17 | F | Simon et al. (2005) |
| 1.363 | 160 | 33.6 | D | Moresco (2015) |
| 1.43 | 177 | 18 | F | Simon et al. (2005) |
| 1.53 | 140 | 14 | F | Simon et al. (2005) |
| 1.75 | 202 | 40 | F | Simon et al. (2005) |
| 1.965 | 186.5 | 50.4 | D | Moresco (2015) |

**32 measurements**

D: D4000

F: full-spectrum fitting

L: Lick indices

Full covariance matrix provided in Moresco et al. (2020), arXiv:2003.07362,

https://gitlab.com/mmoresco/CCcovariance

$$\mathrm{Cov}^{\mathrm{tot}} = \mathrm{Cov}^{\mathrm{stat}} + \mathrm{Cov}^{\mathrm{met}} + \mathrm{Cov}^{\mathrm{SFH}} + \mathrm{Cov}^{\mathrm{young}} + \mathrm{Cov}^{\mathrm{IMF}} + \mathrm{Cov}^{\mathrm{st.spec.}} + \mathrm{Cov}^{\mathrm{SPS}}$$