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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO
DI FISICA E ASTRONOMIA
"AUGUSTO RIGHI"

New frontiers in cosmology

in view of the Habitable World Observatory



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Shaping the Italian Contribution to HWO (Roma, 10-11 July 2025)

A long journey

Hubble (1928)

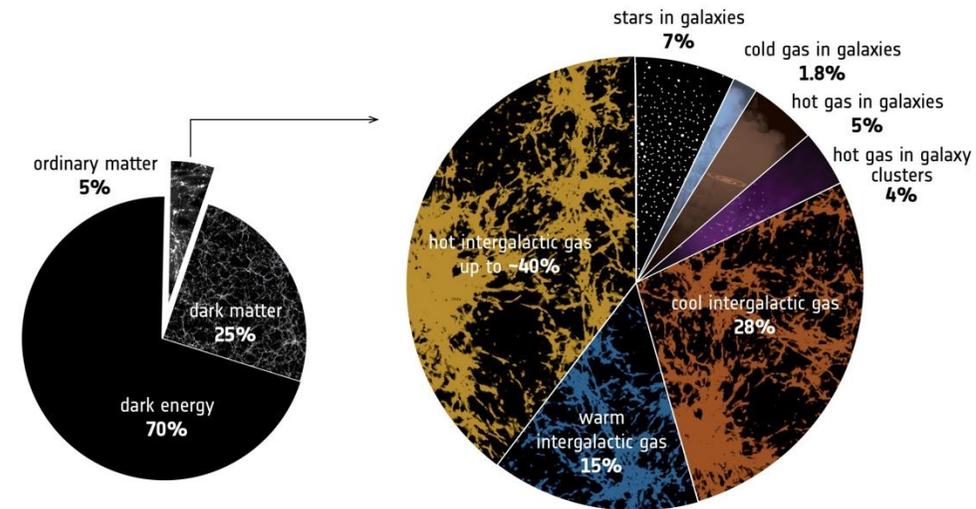
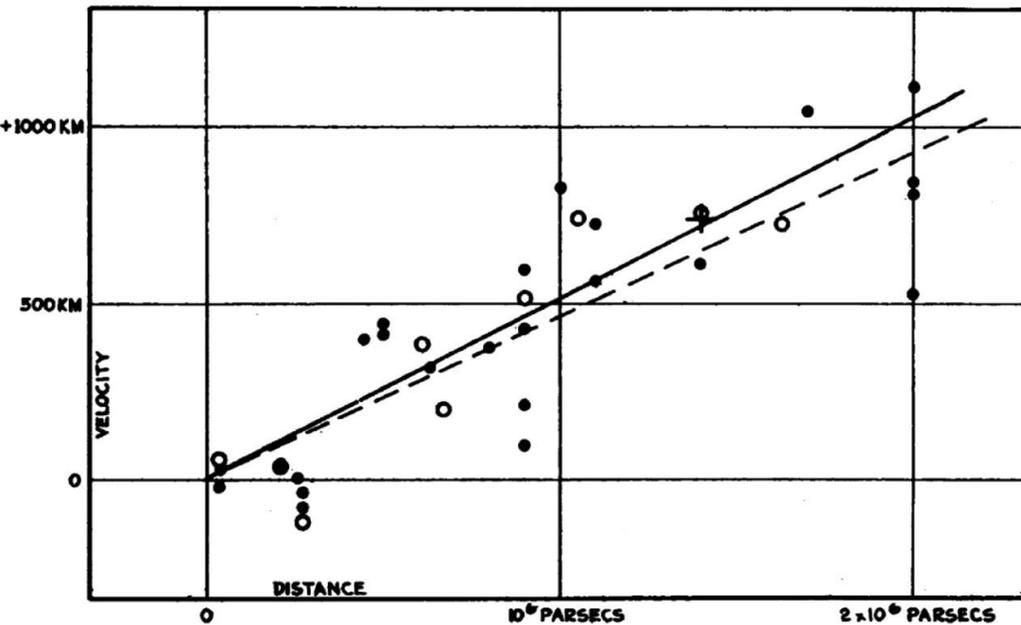
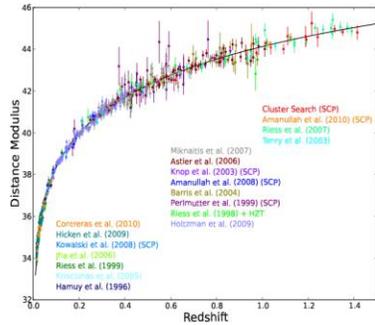
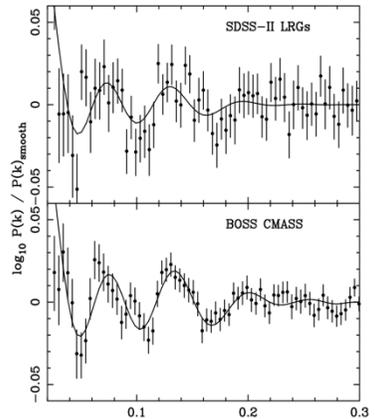
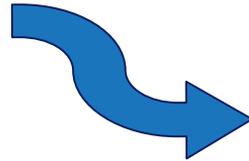


Image credit: ESA

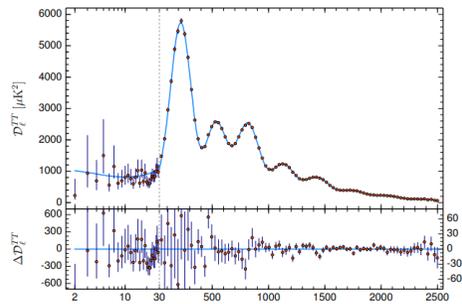
Complementarity is the key



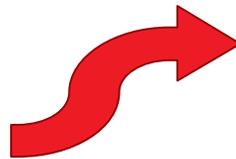
Amanullah et al. (2010)



Anderson et al. (2012)



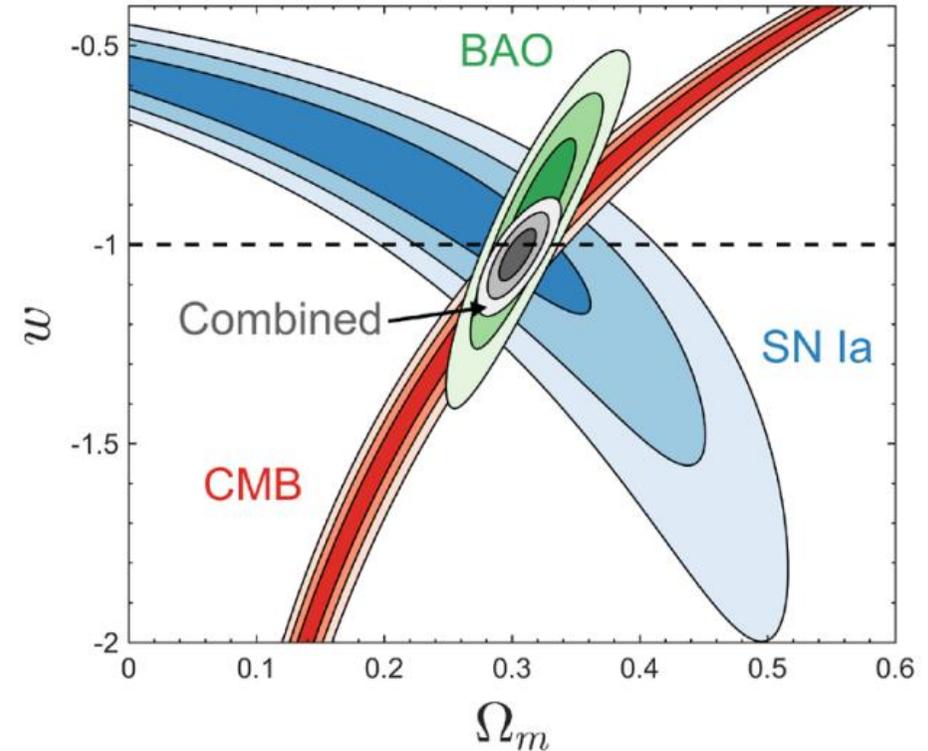
Planck collaboration (2018)



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

Synergy between differences

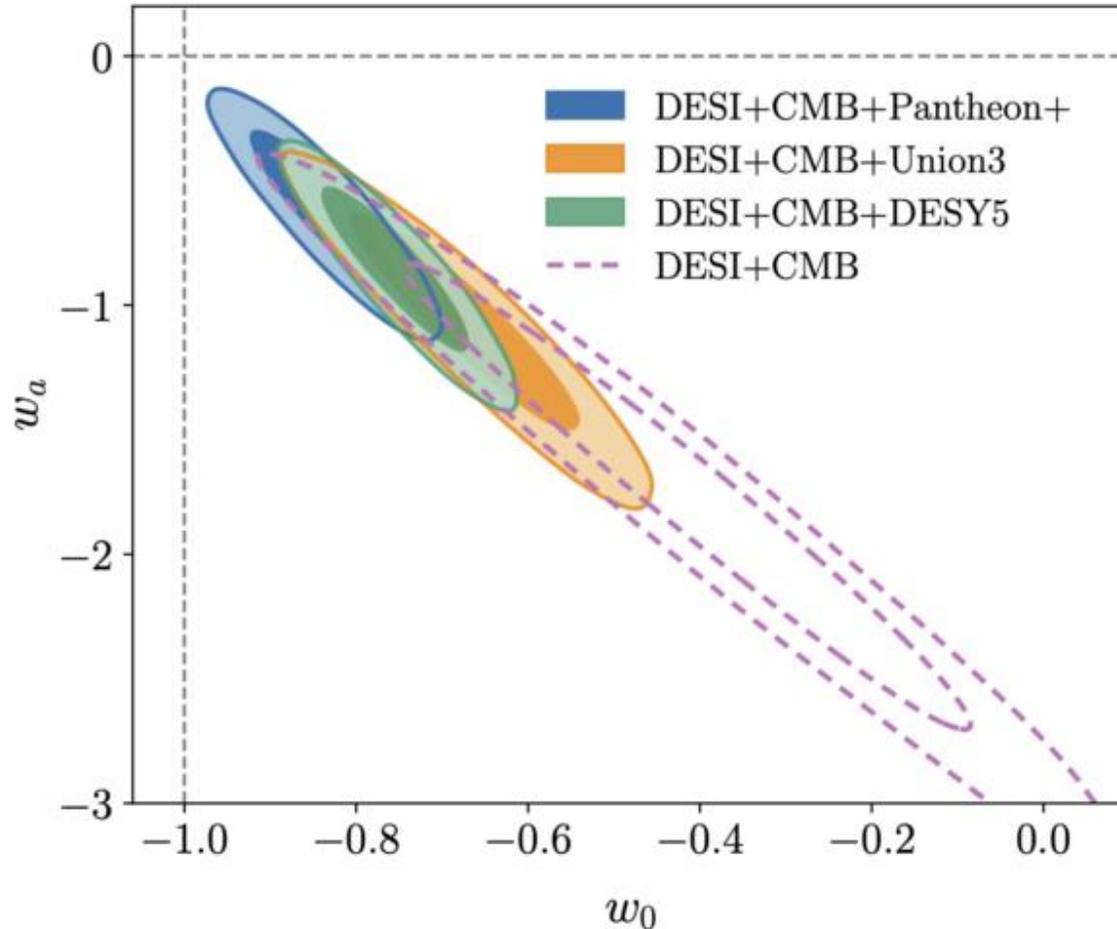
Huterer & Shafer (2018)



as done in the past, moving beyond in crucial

New tensions and frontiers in cosmology

DESI DR2 Results II (2025)



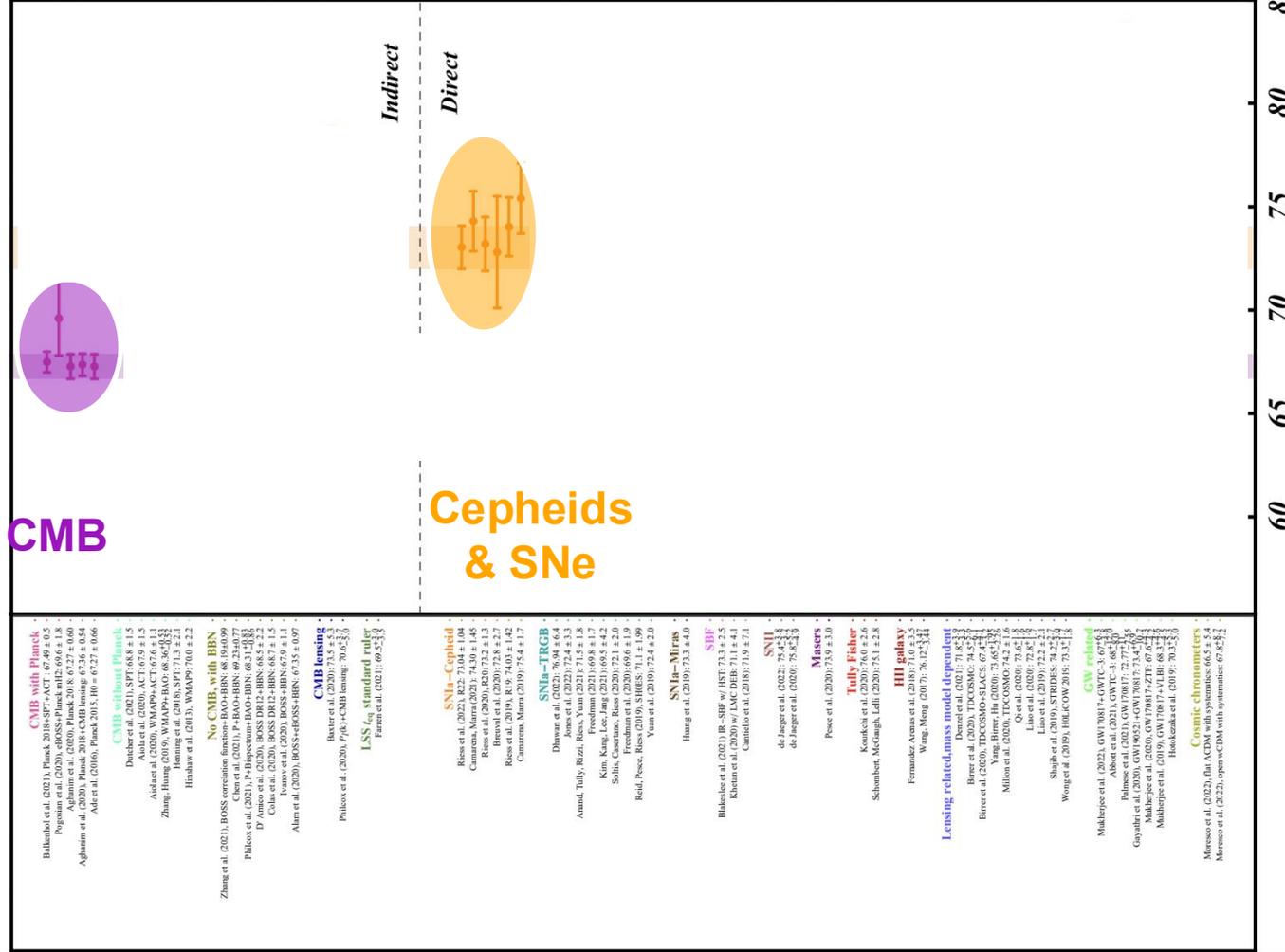
What is the **nature of dark energy**?
Is it a cosmological constant or is it
(and if, how) evolving with redshift?

What is the **nature of dark matter**?

What **physics** drives the **cosmic expansion** and the large-scale evolution of the universe?

New tensions and frontiers in cosmology

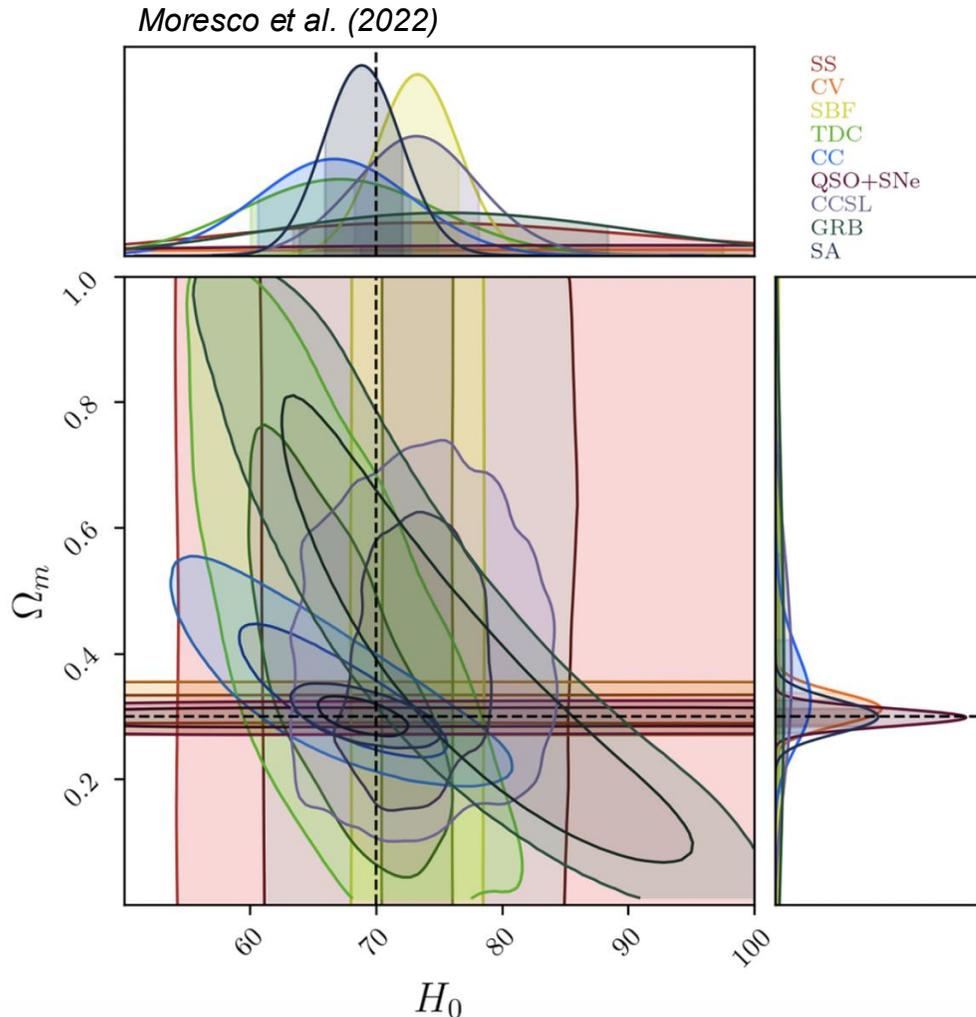
Abdalla et al. (2022)



Is the observed H_0 tension due to **systematics** in one (or both) measurements?

Does it point toward **new physics**?

New tensions and frontiers in cosmology



Several **new cosmological probes** are quickly improving, and will play a significant roles in the future:

- new distance indicators (Surface Brightness Fluctuations, Tip of the Red Giant Branch, ...)
- gravitational waves as standard sirens
- ages of the oldest objects as cosmological probes
- strong and weak lensing

...and many more...

The more independent cosmological probes, the more we can improve our constraints and keep systematics under control

Cosmology with HWO

HWO will operate in a landscape where it will compete with potential future surveys specifically focused on cosmology.

Nevertheless, it could also work in synergy with them, and also provide valuable insights for cosmology. A quick check in the SCDD shows that cosmology exploitation with HWO is currently under development, and many more science cases could be proposed.

Evolution of Elements Working Group:

- *Stars and Stellar Population* Sub-Working Group:
 - **Distance Ladder 3.0**

Galaxy Growth Working Group

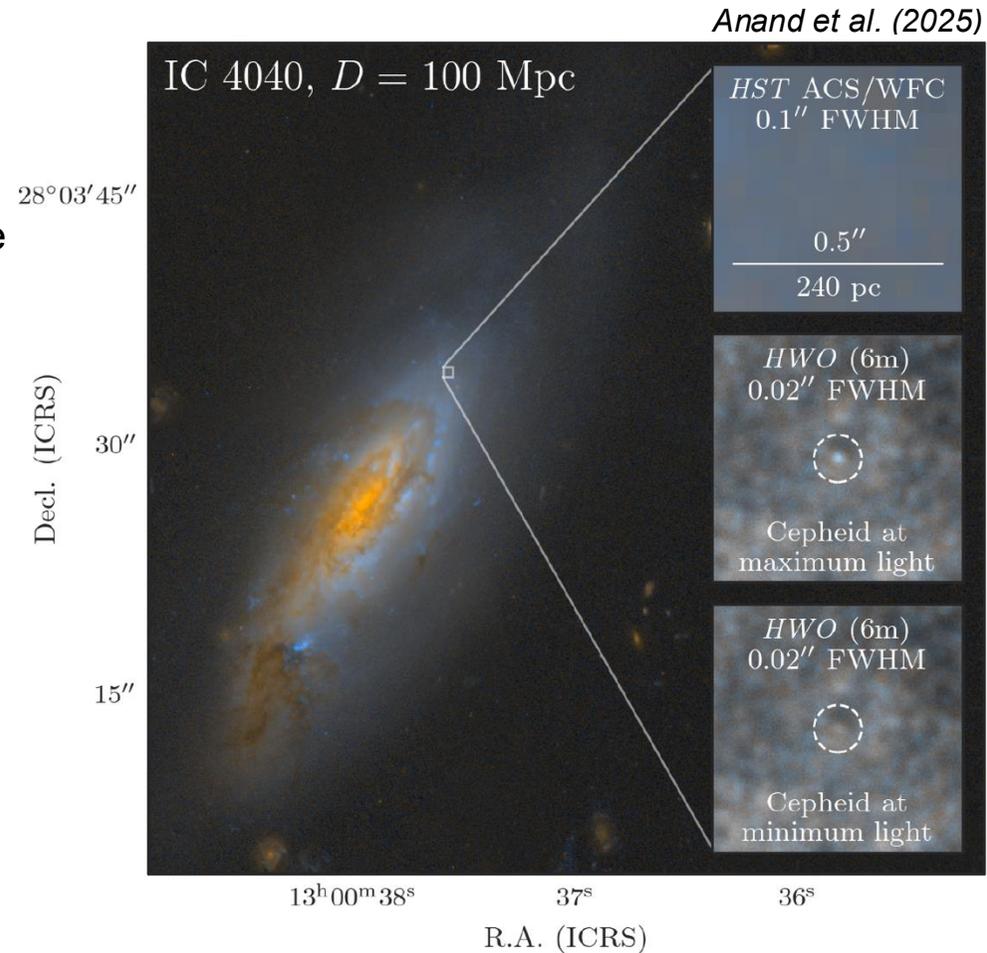
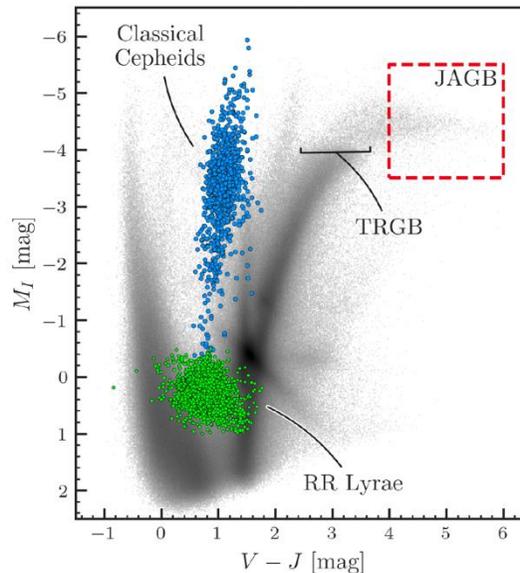
- *Dark Sector* Sub-Working Group:
 - **Constraining Dark Matter Halo Mass Function down to $10^7 M_{\text{Sun}}$ through Strong Gravitational Lensing**
 - **Dark Matter through Dwarf Satellite Galaxies in Milky-Way Analogue Galaxies in the Local Volume**

A new ladder in the sky

Typically the distance ladder is based on 3 rungs:
parallaxes → Cepheids → SNe Ia

HWO will have the sensitivity and resolution to measure Cepheid distances out to 100 Mpc, and it would be possible to do it with just 2 rungs (no SNe Ia), bypassing several systematics and reaching a 1% accuracy on H_0 (Anand et al. 2025).

HWO will help advance also several other distance indicators, like TRGB, J-AGB stars, RR-Lyrae and SBF, measuring them up to several hundred Mpc.



A new ladder in the sky

Anand et al. (2025)

Observation Requirement	State of the Art	Incremental Progress (Enhancing)	Substantial Progress (Enabling)	Major Progress (Breakthrough)
Imaging of resolved stars in distant galaxies	Highest available imaging resolution = JWST IR	JWST-resolution imaging in optical (0.031'' pixels vs. 0.04'' for HST)	0.02—0.025'' pixels in optical (severely undersampled)	Well-sampled, diffraction-limited optical+IR imaging
Wavelength range	NIR	VI	VI	VI+NIR
Pixel scale	0.031'' in NIR	0.031'' in optical	0.02-0.025'' in optical	0.01'' in optical/NIR (Nyquist sampled in V)
Spatial resolution (PSF FWHM)	~0.035'' at 1 μm	~0.035'' in optical	~0.025'' in V	Diffraction limited at 500nm, ~0.02'' (6m aperture)
FOV	11 arcmin ² (HST ACS), 10 arcmin ² (JWST NIRCам)	11 arcmin ² across optical + NIR	25 arcmin ² across optical + NIR	36 arcmin ² across optical + NIR
Faint limiting magnitude in given band	F814W < 29 (HST), F090W < 31 (JWST)	V < 31, I < 30	V < 32, I < 31	V < 33, I < 32
Bright limiting magnitude in given band	F090W > 16 (JWST, stare mode), F555W ~7 (HST, scan mode)	—	I > 12 (Magellanic Cepheids)	I > 7 (MW Cepheids)
Absolute flux calibration uncertainty	1% (HST + CALSPEC)	—	—	0.5% (Landolt mission)

Constraining dark matter

It is possible to constrain DM by counting the low-mass satellites of MW-like galaxies

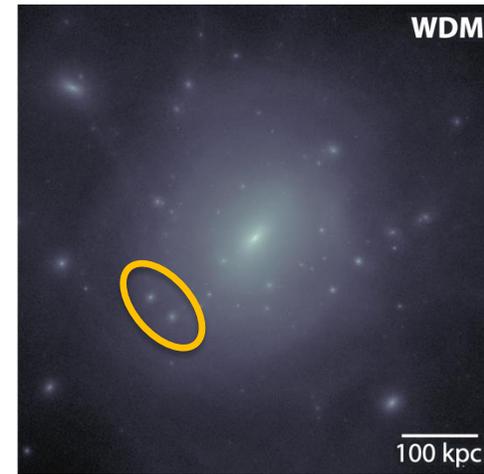
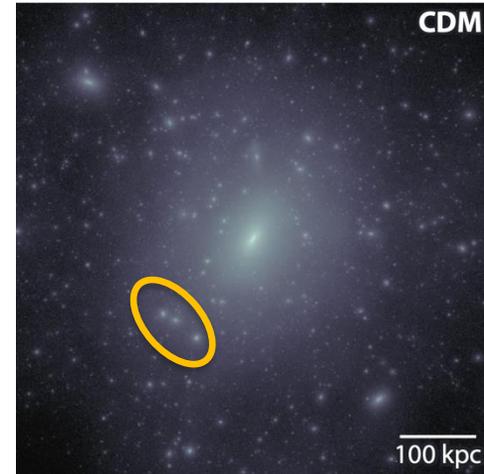
→ different DM models predict a different numbers of satellites

With HWO it is possible to detect the smallest galactic satellites of nearby large galaxies by counting individual stars.

→ cosmological constraints on DM particle mass can be obtained from a sample of 500-1000 of these “ultra-faint” satellites

Not possible with:

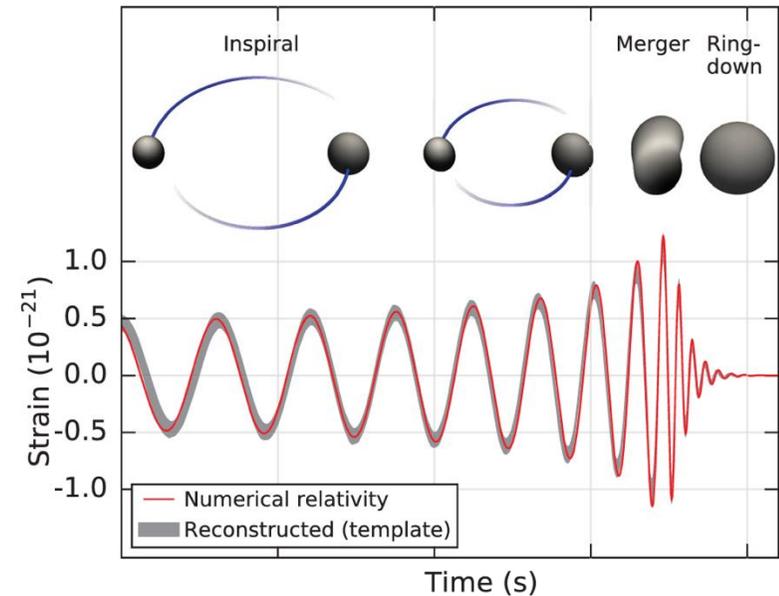
- Hubble due to low sensitivity
- JWST since it does not have the optical-band resolution for such observations.



Synergy with GW observatories

Merging compact binaries can provide direct measurement of the luminosity distance (**standard sirens**):

$$h(t) = \frac{\mathcal{M}_c(z)^{5/3} f(t)^{2/3}}{d_L} F(\text{angles}) \cos[\Phi(t)]$$



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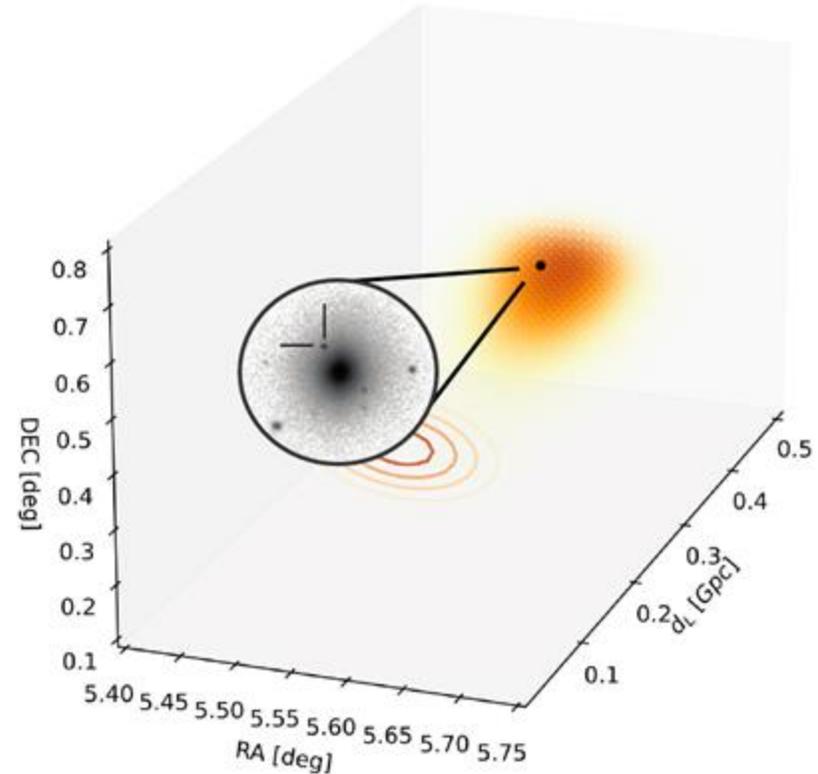
Synergy with GW observatories

Merging compact binaries can provide direct measurement of the luminosity distance (**standard sirens**):

$$h(t) = \frac{\mathcal{M}_c(z)^{5/3} f(t)^{2/3}}{d_L} F(\text{angles}) \cos[\Phi(t)]$$

However, to derive cosmological constraints, it is needed to break the degeneracy with redshift.

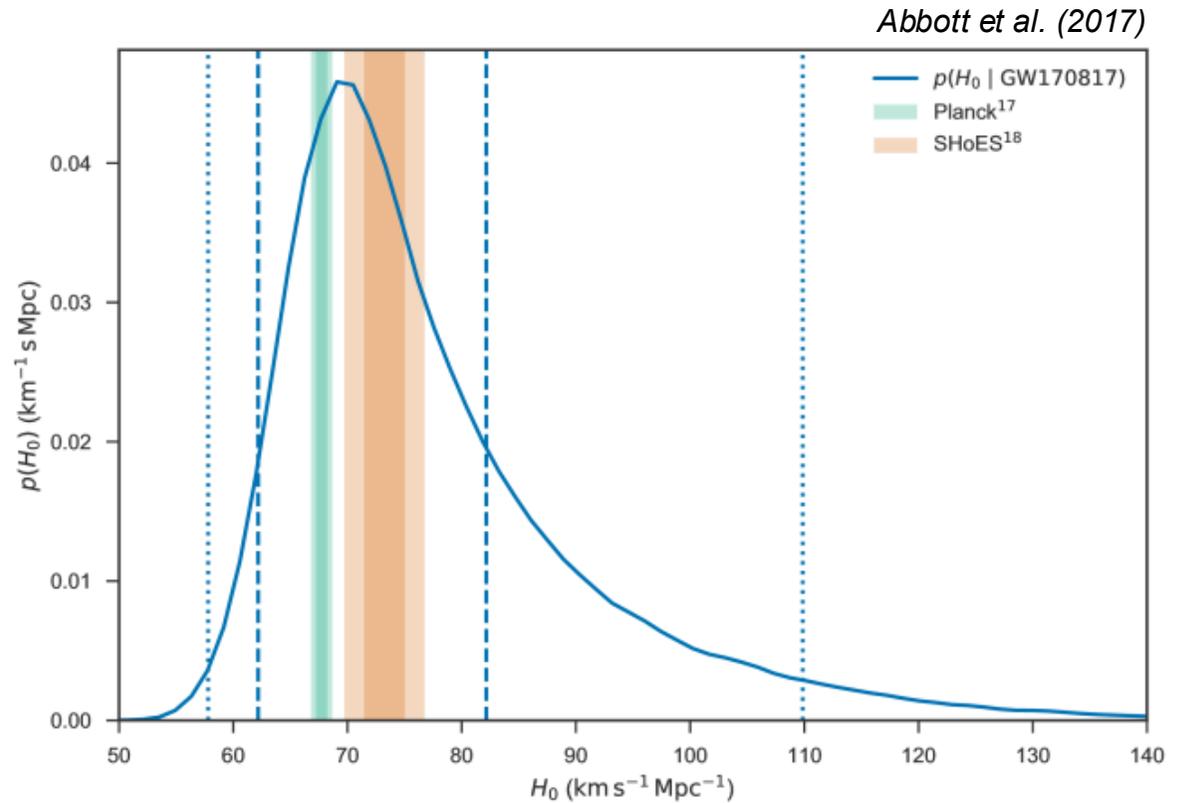
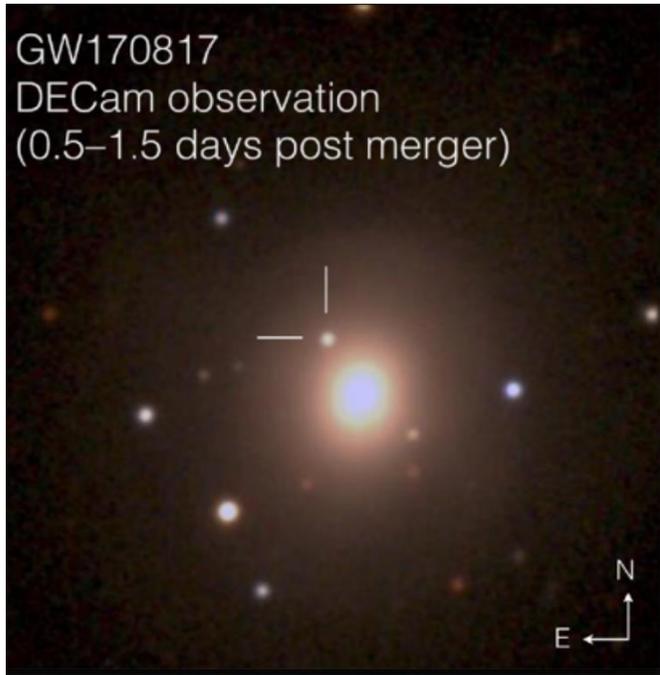
In case of bright sirens (e.g. Binary Neutron Stars), this can be done by identifying in the GW localization volume the host of the GW event.



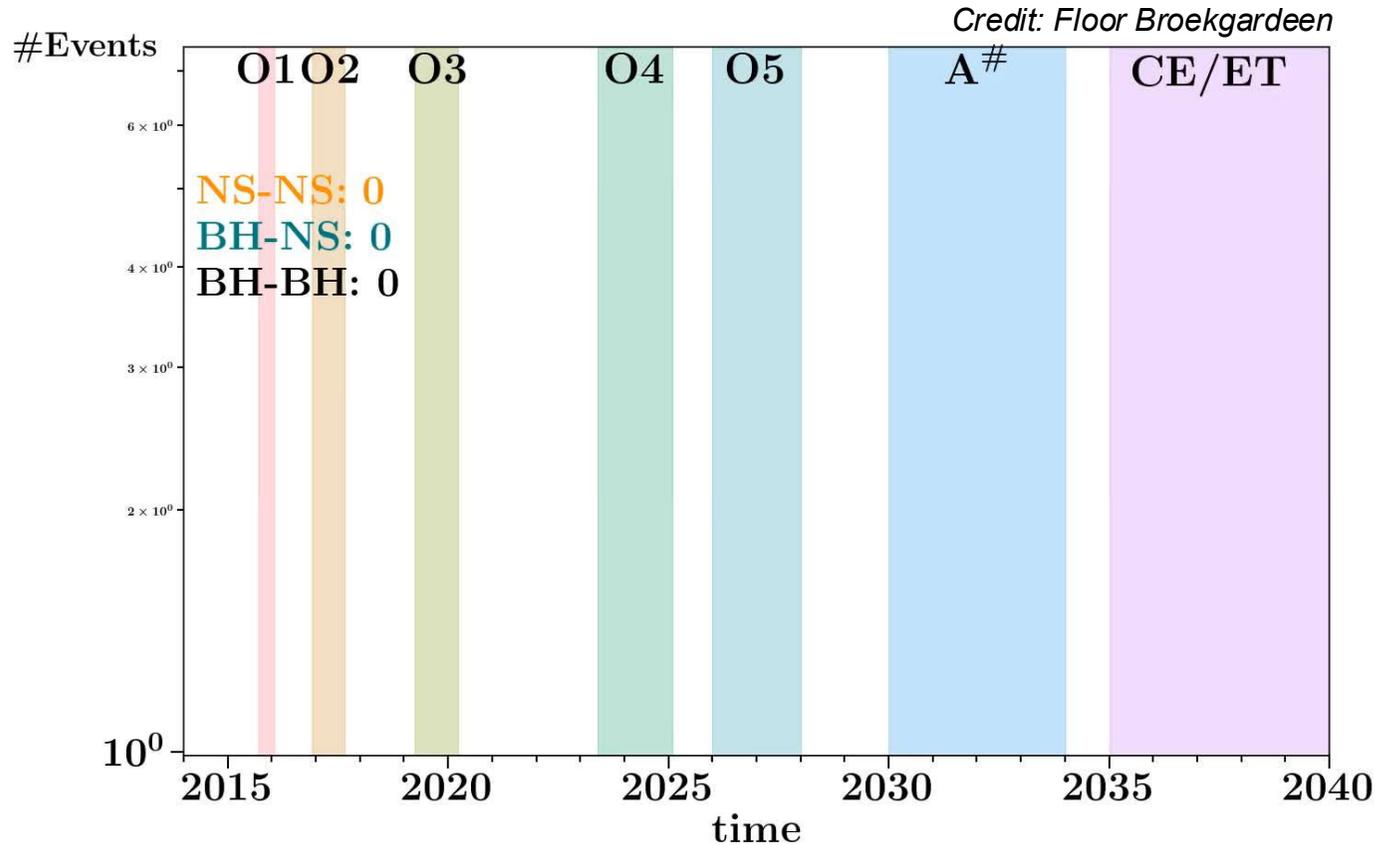
$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_R(1+z')^4 + \Omega_M(1+z')^3 + \Omega_\Lambda}} \times \left[\mathbb{E}_0 + \frac{1 - \mathbb{E}_0}{(1+z)^n} \right]$$

Synergy with GW observatories

Results on H_0 with just 1 BNS with EM counterpart!

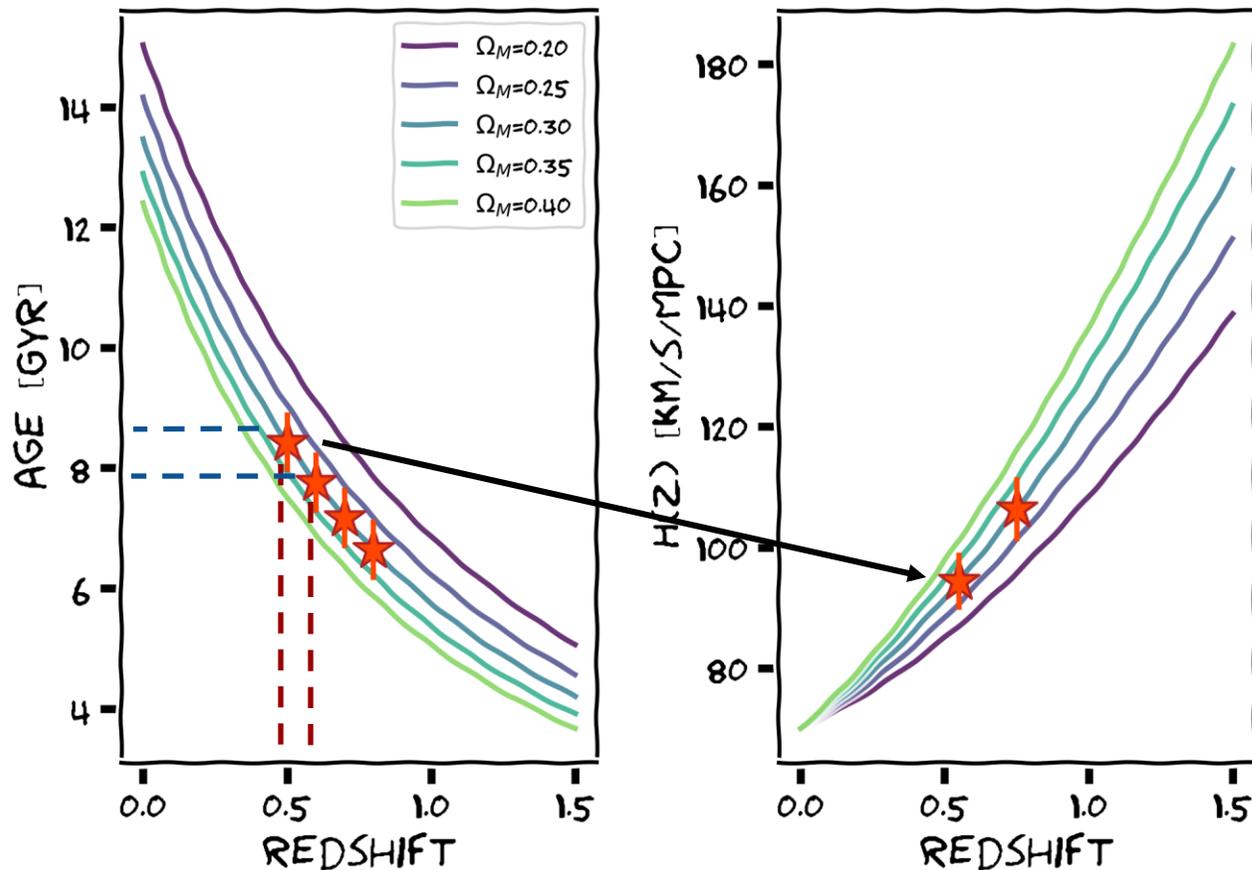


Synergy with GW observatories

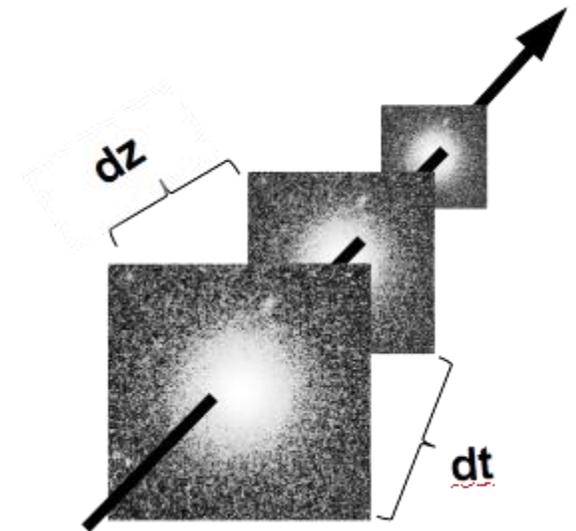


In $< \sim 15$ years, we will have the next generation GW observatories operating, like Einstein Telescope and Cosmic Explorer.

Clocks and chronometers in the sky

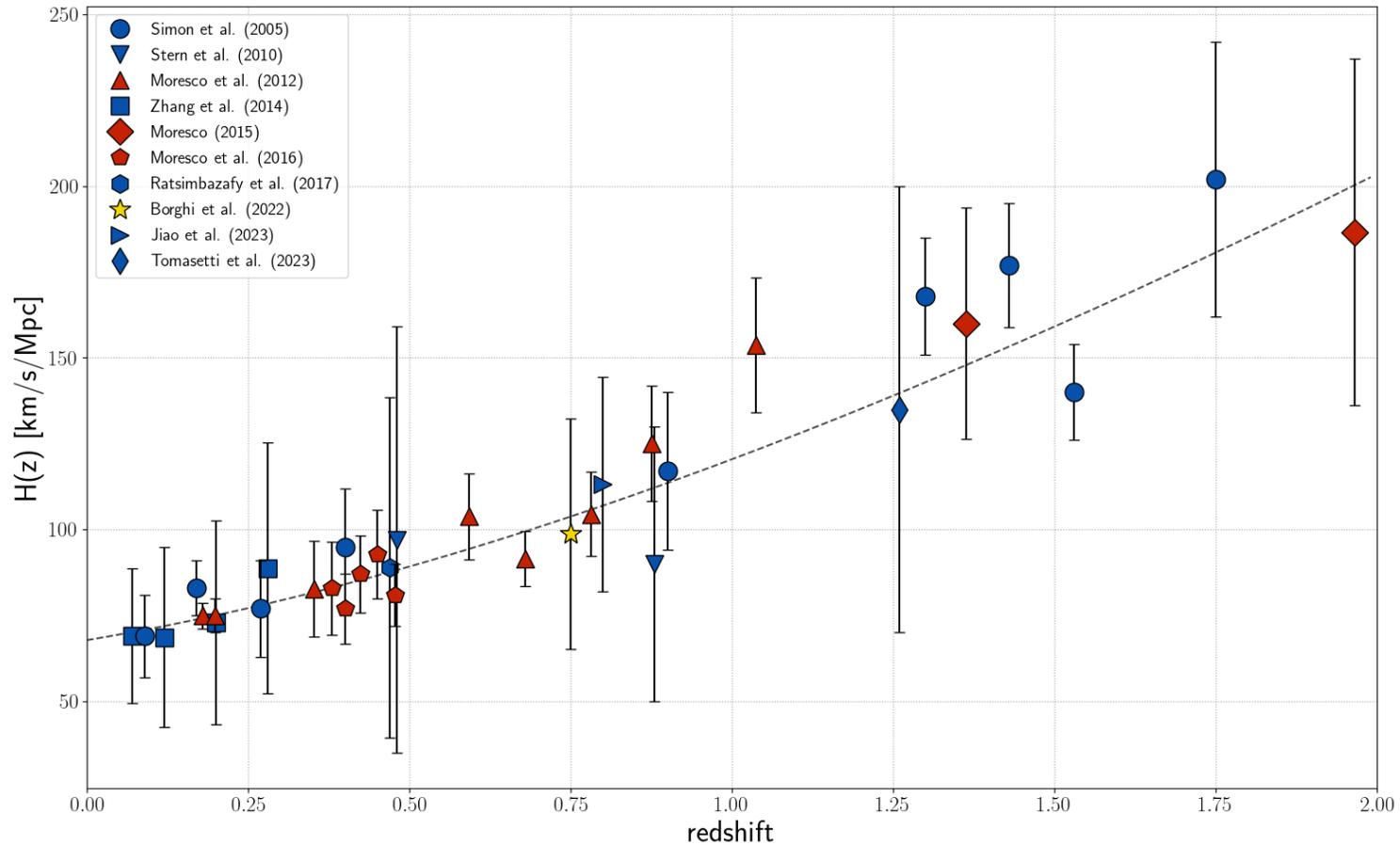


$$H(z) = \frac{\dot{a}}{a} = -\frac{1}{1+z} \frac{dz}{dt}$$



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

Ages as cosmological probes



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

Wish list

- Large diameter ($>6\text{m}$) could allow to have the angular resolution, sensitivity, and PSF stability to obtain precise photometry of individual stars in galaxies at 100 Mpc
 - Distance ladder with just 2 rungs
 - Several independent distance indicators (TRGB, SBF, J-AGB, ...)
- Transient detectability could provide synergy with future GW observatories (e.g. Einstein Telescope and Cosmic Explorer)
 - Cosmological parameters and modified gravity constraints
- Extended UV-O-NIR spectroscopy could enable:
 - Detection and characterization of galaxies, and decrease the systematics involved in determining the ages of stellar populations → improved determination of the expansion history of the Universe
 - Host characterization for GW transients



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