Anchors no more

Using peculiar velocities to constrain H_0 and the primordial Universe without calibrators[1]

arxiv: 2504.10453

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COSMOFondue

[1] with Davide Piras, Ruth Durrer, Martin Kunz

Distances in Cosmology

→ Measuring distances in an expanding Universe is particularly difficult!

$$d_L = \sqrt{\frac{L}{4\pi F}},$$

$$\mu = m - M = 5\log_{10}(d_L/1\mathrm{Mpc}) + 25$$

Distance ladder

- At each rung corresponds a distance measurements
- The calibrated combination of all the rungs let you measure up to the top of the ladder

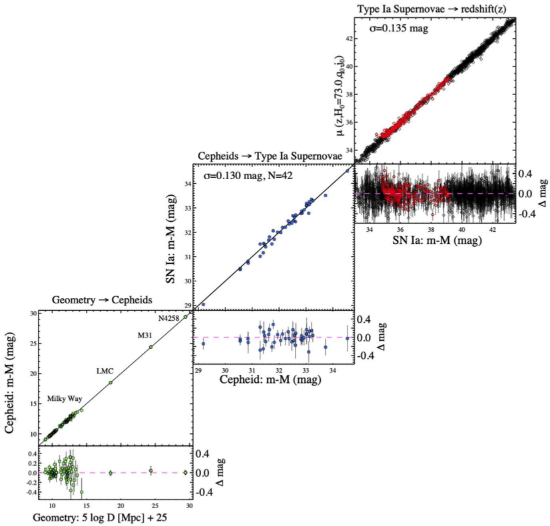


Figure: Credits: SH0ES team

Standard candle and distance anchors

→ Objects having the same intrinsic brightness

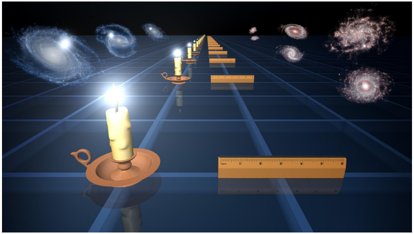


Figure: Credits: ESO

Leavitt's cepheids relation (1912)

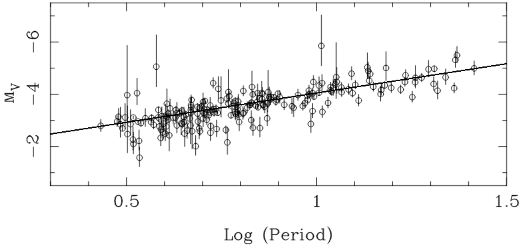


Figure: Leavitt's relation in the V band for a sample of 452 Galactic cepheids. Credits: M.A.T. Groenewegen, 2018.

⟶ We can use cepheids as distance anchors for Type Ia Supernovae (SNe Ia)

Hubble tension

Many possible cause

- The cosmological model?
- Unknown systematics affecting early-time observations?
- Unknown systematics affecting late-time observations?
- Unknown systematics affecting both?
- Problem with the distance anchors?

We need new independent methods!

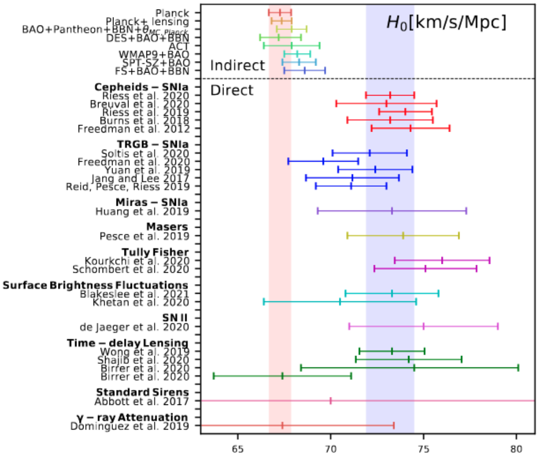


Figure: Credits: E. Di Valentino, 2020

Let's introduce the tools

$$\log(\mathcal{L}) = -\frac{1}{2}\left[\Delta\mu_n\, C^{-1}_{mn}\, \Delta\mu_m + \log(\det C_{mn}) + k\log(2\pi)\right]$$

$$\Delta\mu^i_L = \begin{cases} \mu^i + \delta M - \mu^i_{\rm ceph}, & i \in \text{Cepheid hosts} \\ \mu^i + \delta M - \mu^i_{\rm model}(z_i), & \text{otherwise} \end{cases}$$

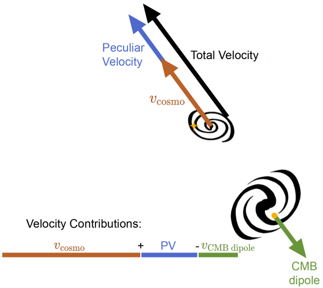


Figure: Credits: 2110.03487

$$\mu^i_{\rm model} = 5\log\left(\frac{d_L(z_i, \mathbf{n}_i)}{\rm Mpc}\right) + 25 \qquad (1)$$

where, at low z:

$$d_L(z, \mathbf{n}) \simeq \bar{d}_L(z)\left[1 + \frac{(1+z)^2}{H(z)\bar{d}_L(z)}\mathbf{n}(\mathbf{v}_\odot - \mathbf{v}(z, \mathbf{n}))\right],$$

with

$$\bar{d}_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz}{\sqrt{\Omega_m(1+z)^3 + 1 - \Omega_m}}$$

and

$$\mathbf{n}\cdot\mathbf{v}(z, \mathbf{n}) = \mathbf{n}\cdot\mathbf{v}^{(\rm bulk)} + n^i(\alpha_{ij} + \gamma\,\delta_{ij})n^j\,,$$

Covariances

$$C_{mn} = C_{mn}^{(\mathrm{e})} + C_{mn}^{(\mathrm{v}),\mathrm{disp}} + C_{mn}^{(\mathrm{v})} \,,$$

where:

- $C_{mn}^{(\mathrm{e})} \longrightarrow$ error covariance of the SNe where the peculiar velocity contribution is subtracted
- $C_{mn}^{(\mathrm{v}),\mathrm{disp}} = B_{mn}\sigma^2_{\mathrm{disp}}\delta_{mn} \quad ,$
- $C_{mn}^{(\mathrm{v})} = \frac{B_{mn}}{2\pi^2}\frac{D_1(z_m)\ D_1(z_n)}{D_1^2(0)}\left[\frac{H(z_m)f(z_m)}{(1+z_m)}\right]\left[\frac{H(z_n)f(z_n)}{(1+z_n)}\right]\int \mathrm{d}k W_{mn}(k)\mathcal{Z}(k,z_m,z_n)P_\delta(k,0)\, D_\mathrm{u}^2(k\sigma_\mathrm{u})\, E(\sigma_8) \,,$

with:

$$D_\mathrm{u}(k\sigma_u) = \mathrm{sinc}(k\sigma_u)$$

$$E(\sigma_8) = e^{-k(a_1(\sigma_8)+a_2(\sigma_8)k+a_3(\sigma_8)k^2)} \,.$$

$$\begin{cases} a_1(\sigma_8) = (-0.817 + 3.198\,\sigma_8)\ \mathrm{Mpc}/h \\ a_2(\sigma_8) = (0.877 - 4.191\,\sigma_8)\ \mathrm{Mpc}^2/h^2 \\ a_3(\sigma_8) = (-1.199 + 4.629\,\sigma_8)\ \mathrm{Mpc}^3/h^3 \,. \end{cases}$$

Bel et al. (2019)

veloce: the velocity power spectrum covariance emulator

VELOCE
THE VELOCITY COVARIANCE EMULATOR

Problem

Computationally expensive $\longrightarrow$ half million evaluations of the integral for Pantheon+ at each step of the MCMC

Solution

- Emulator based on `CosmoPower-JAX`
- Median performance at the sub-percent level
- Likelihood and sampling in `JAX`
- Sample the posterior in no more than 1 hour
- With standard approach ~ 25 years
  $\longrightarrow$ speed-up greater than 10^5

Mock dataset results

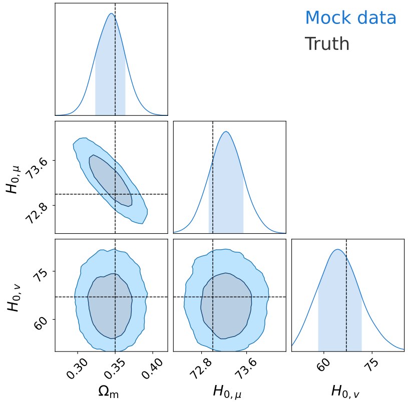


Figure: Fiducial: $H_{0,\mu} = 73$ km/s/Mpc, $H_{0,\mathrm{v}} = 67$ km/s/Mpc, $\Omega_\mathrm{m} = 0.35$

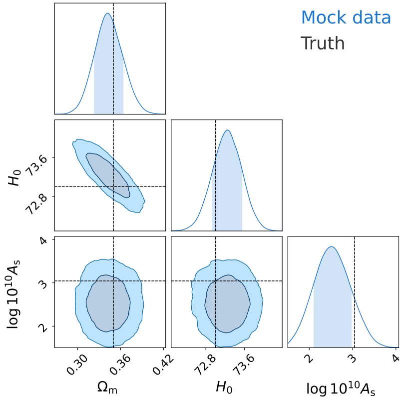


Figure: Impose $H_{0,\mu} = H_{0,v}$, but vary $\log 10^{10} A_\mathrm{s}$

N-body simulation results

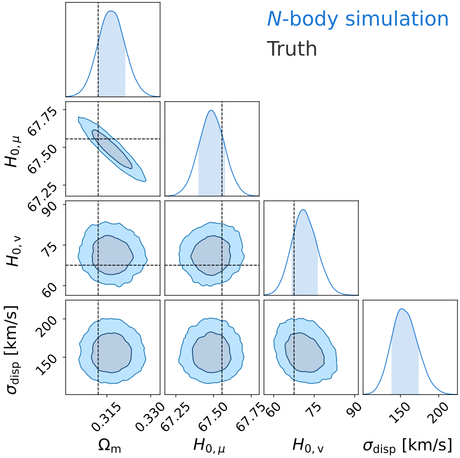


Figure: Fiducial: $H_{0,\mu} = H_{0,\mathrm{v}} = 67.556$ km/s/Mpc, $\Omega_{\mathrm{m}} = 0.312046$, $\log 10^{10} A_{\mathrm{s}} = 3.098$

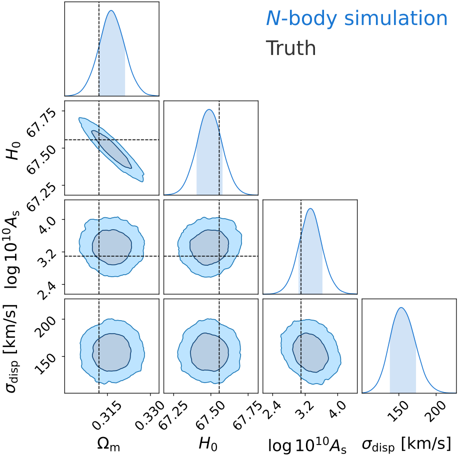


Figure: Sampling over $\log 10^{10} A_{\mathrm{s}}$

N-body simulation results: no anchors!

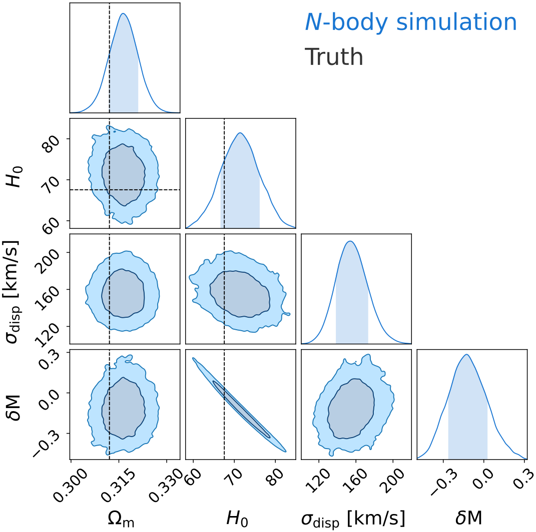


Figure: Simulation ‘without cepheids‘

Pantheon+ results

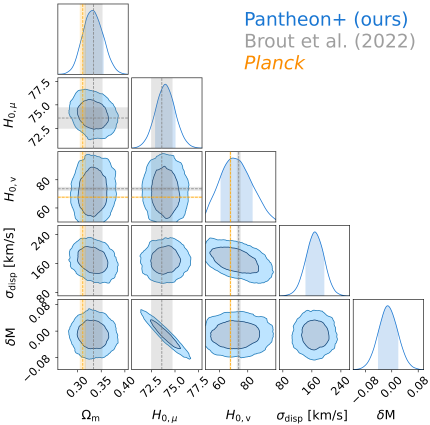


Figure: $H_{0,\mu} = 74.0 \pm 1.0$,

$H_{0,v} = 72.0^{+12.0}_{-11.0}$, $\Omega_m = 0.33 \pm 0.02$,

$\sigma_{disp} = 169 \pm 25$

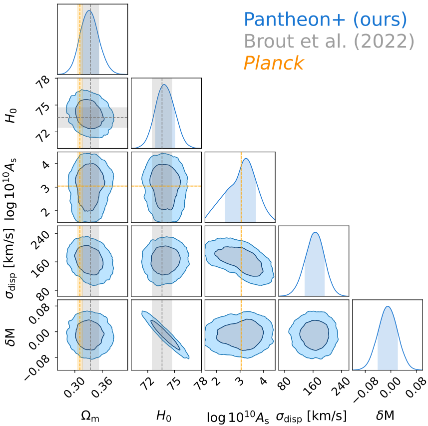


Figure: $H_{0,\mu} = H_{0,v} = 73.9 \pm 1.0$,

$A_s = 3.1^{+0.5}_{-0.8}$, $\Omega_m = 0.33 \pm 0.02$,

$\sigma_{disp} = 165^{+26}_{-28}$

Pantheon+ results: no anchors!

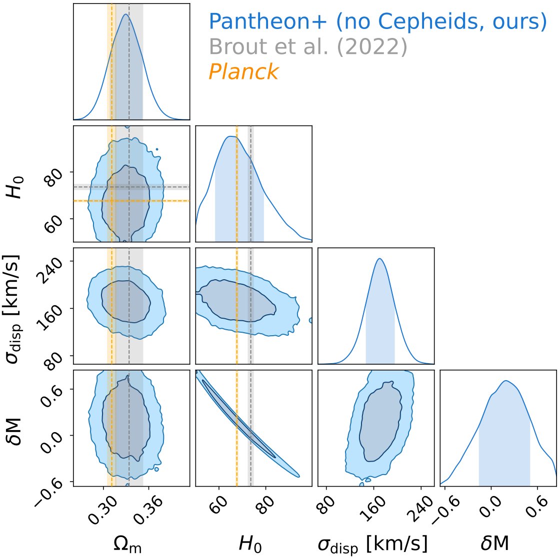


Figure: $67.7^{+11.3}_{-9.2}$ km/s/Mpc

Conclusions

Bright future for peculiar velocity surveys

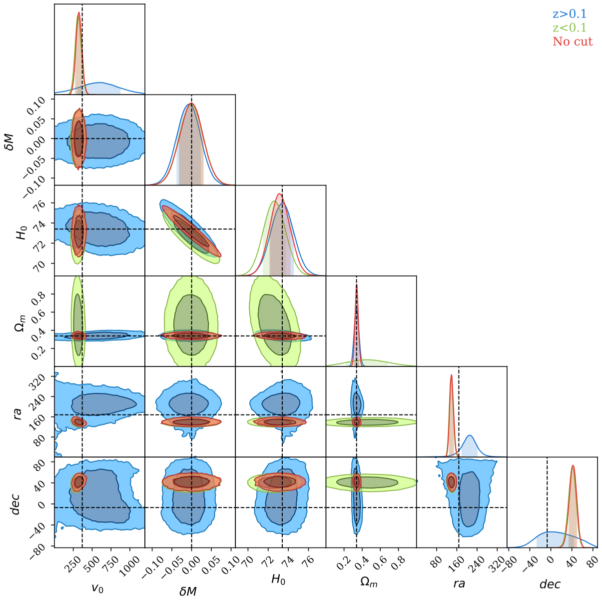
- It is possible to constrain cosmological parameters
- We created an efficient and differentiable routine $\longrightarrow$ `veloce` package
- We validated our results with mock, N-body simulations and applied to Pantheon+
- We showed it is possible to constrain H_0 without anchors

Next steps

- Applying our routine to other datasets (ZTF, LSST)
- Considering vorticity power spectrum

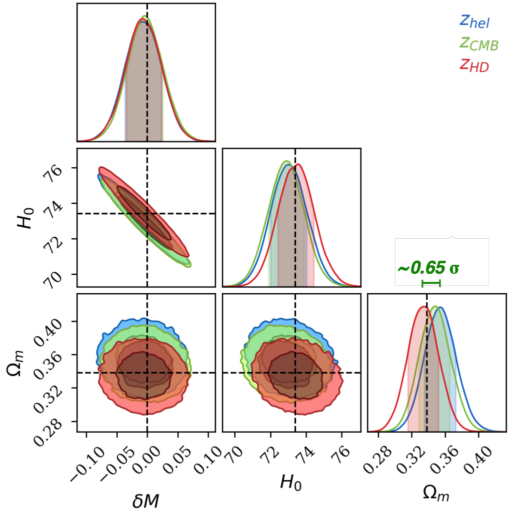
Thanks for your attention!

Low-z vs high-z supernovae



- High-z Snae constrain cosmological parameters
- Low-z Snae determine dipole

Peculiar velocities in Pantheon+



- Vorticity is neglected
- 'Ad hoc" $\mathbf{v}_{\text{bulk}}$ within $R = 200h^{-1}$Mpc

Pantheon+SH0ES

https://github.com/PantheonPlusSH0ES/DataRelease

- 1701 SNe lightcurves → 77 Cepheid hosts

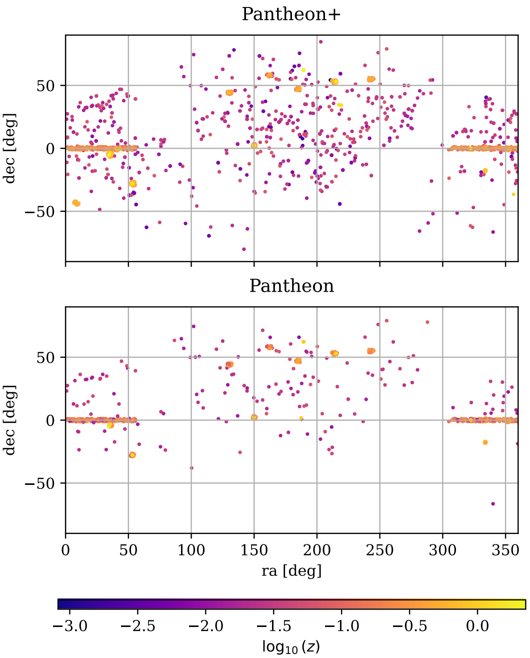
$$\mu = 5\log_{10}(D_L/1\text{Mpc}) + 25 = 5\log_{10} D_L + M$$

- Covariances (statistical + systematics)
- z_{hel}: Heliocentric Redshift
- z_{CMB}: CMB Corrected Redshift
- z_{HD}: Hubble Diagram Redshift (with CMB and v_{pec} corrections)

About redshift

- At very low z, SNe have correlated velocities which will reduce the dipole amplitude
- Higher z_{cut}, the less SNe in the sample and the smaller their contribution to the dipole

$z_{\rm cut}$	Pantheon+ without Cepheids	Cepheid hosts	Pantheon
No cut	1624	77	1048
0.005	1615	50	1048
0.01	1576	7	1046
0.0175	1468	2	1010
0.025	1312	0	976
0.0375	1126	0	915
0.05	1054	0	890
0.1	960	0	837


Pantheon+
Pantheon
dec [deg]
50
0
−50
ra [deg]
0
50
100
150
200
250
300
350
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
log10 (z)

Comparison with Pantheon

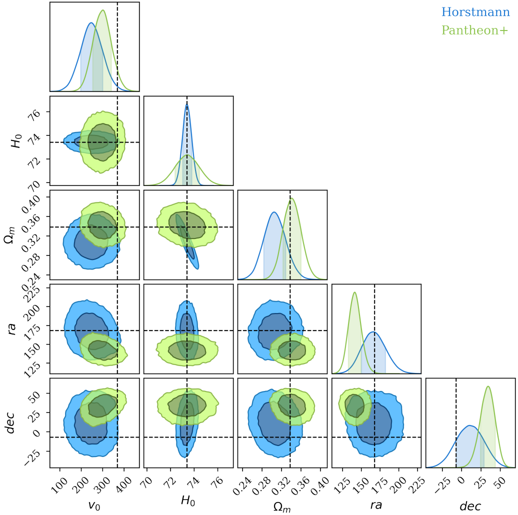


Figure: Thanks to N. Horstmann arXiv:2111.03055

- Validity check
- For Pantheon v_0 is 2.4σ smaller
- Pantheon roughly agrees with Planck dipole and 'our' dipole

$z_{\rm cut}$	Pantheon+	Pantheon
0.01	1576	1046

Pantheon+ and friends

- Pantheon+ 1701 SNe Ia (77 cepheid hosted)
- DES Y5 1635 SNe Ia *at higher z*
- ZTF DR2.5 with ∼3000 SNe Ia *coming soon*
- CF4 55877 galaxies gathered into 38065 groups
- *Euclid* test of homogeneity and isotropy

How to define $\mathbf{v}_{pec}$

In term of redshift:

$$cz = H_0 r + \hat{\mathbf{r}} \cdot \mathbf{v}_{pec},$$

where $\mathbf{v}_{pec} = \mathbf{v_G} + \mathbf{v_R}$,

with: $\mathbf{v_G} = -\nabla v, \qquad \nabla \cdot \mathbf{v_R} = 0$

We define divergence θ and vorticity $\boldsymbol{\omega}$:

$$\theta = \nabla \cdot \mathbf{v}_G \tag{2}$$

$$\boldsymbol{\omega} = \nabla \times \mathbf{v_R} \tag{3}$$

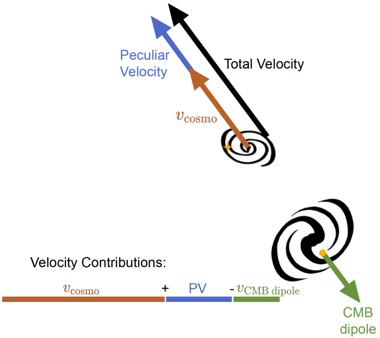
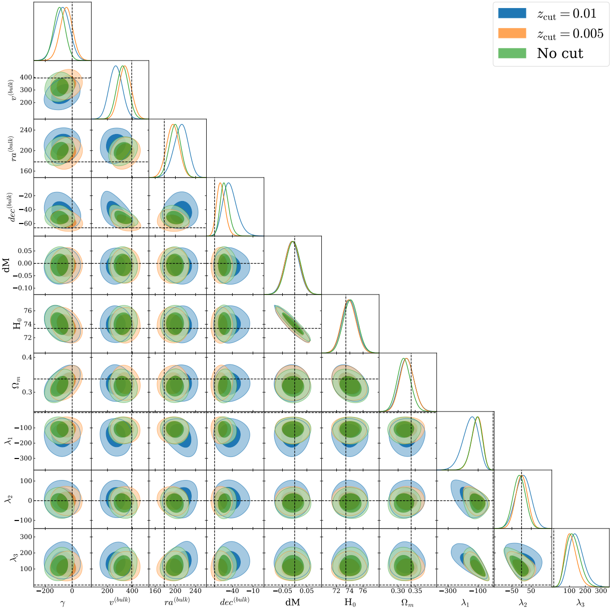


Figure: Credits: 2110.03487

The low multipoles in the Pantheon+SH0ES data (2403.17741)



Modeling source velocity as:

$$\mathbf{n} \cdot \mathbf{v}(\mathbf{n}(t_0 - t(z)), t_0) = \mathbf{n} \cdot \mathbf{v}^{(\rm bulk)} + n^i(\alpha_{ij} + \gamma\, \delta_{ij})n^j \,,$$

with α_{ij} symmetric traceless tensor.

- Monopole, dipole, quadrupole are detected and of similar amplitude
- Dipole consistent with CF4 (Watkins et al., 2023)

  and aligned with Shapley Supercluster (ra,dec)=(200^o,-30^o)