Pantheon+ and friends:

an insight on peculiar velocities probes

Francesco Sorrenti

Département de physique théorique, Université de Genève

"Standard cosmology at the threshold of a change?"

Aristotle University of Thessaloniki

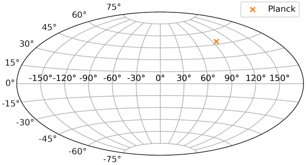
5^{th} June 2024

UNIVERSITÉ DE GENÈVE

Pantheon+ and friends

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

The dipole of Pantheon+SH0ES data (JCAP 11(2023)054)



For many far away sources, we expect same dipole as CMB

$\rightarrow$ In SN distances, Doppler term enhances the dipole due to our peculiar velocity at low redshift

$\Longrightarrow$ we need a rather *limited* number of sources

At $z \ll 1$, $\mathcal{H}(z)r(z) \simeq z$ and:

$$d_L(z,\mathbf{n}) \simeq \bar{d}_L(z)\left(1 + \frac{1}{\mathcal{H}(z)r(z)}\mathbf{v}_0 \cdot \mathbf{n}\right)$$

In a flat ΛCDM:

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

Actually, we neglected source term in $(\mathbf{v}_0 - \mathbf{v}(\mathbf{n}, r(z))) \cdot \mathbf{n}$

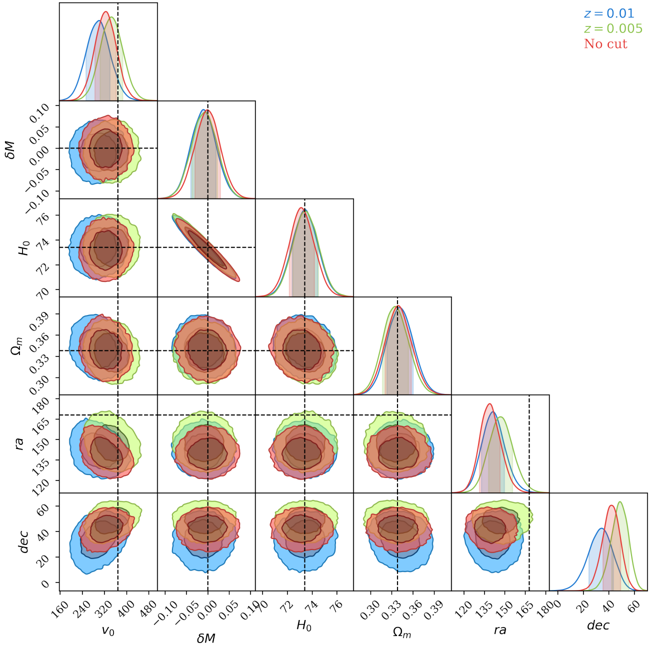
It is correct unless there is a large 'bulk velocity'

Results

Considering all the SNe with $z > z_{\rm cut}$:

$z_{\rm cut}$	v_0	H_0	Ω_m	ra	dec
Ref. value	369	73.6	0.334	167.942	-6.944
No cut	328^{+35}_{-42}	$73.11^{+1.07}_{-0.96}$	$0.339^{+0.018}_{-0.019}$	$139.4^{+7.2}_{-8.0}$	$42.0^{+7.2}_{-6.6}$
0.005	344^{+42}_{-40}	73.5 ± 1.0	$0.335^{+0.019}_{-0.018}$	$147.6^{+8.0}_{-9.5}$	$48.9^{+6.9}_{-6.7}$
0.01	302^{+38}_{-49}	$73.47^{+0.97}_{-1.09}$	$0.340^{+0.020}_{-0.017}$	$141.1^{+8.6}_{-8.2}$	$34.4^{+9.1}_{-10.1}$
0.0175	377^{+57}_{-62}	$73.46^{+1.10}_{-0.97}$	$0.342^{+0.016}_{-0.020}$	$132.4^{+10.3}_{-8.2}$	$45.2^{+8.3}_{-9.4}$
0.025	434^{+91}_{-77}	$73.38^{+1.10}_{-0.95}$	$0.341^{+0.020}_{-0.017}$	$137.1^{+11.9}_{-9.6}$	$42.1^{+9.9}_{-10.6}$
0.0375	490^{+110}_{-130}	$73.6^{+1.1}_{-1.0}$	$0.338^{+0.018}_{-0.021}$	141^{+18}_{-15}	33^{+17}_{-18}
0.05	370^{+150}_{-160}	$73.55^{+1.17}_{-0.99}$	$0.333^{+0.022}_{-0.019}$	167^{+37}_{-30}	21^{+34}_{-28}
0.1	620^{+250}_{-310}	$73.5^{+1.0}_{-1.2}$	$0.338^{+0.025}_{-0.026}$	211^{+29}_{-31}	-2^{+46}_{-24}

- H_0 and Ω_m agree well with Pantheon+ and insensitive to z_{cut}
- v_0 remains within about 2σ of the Planck value
- Direction is very different!



Planck direction is excluded at more than 3σ !

χ^2 analysis

z_{cut}	$\chi^2_{\text{No-dip}}$ - $\chi^2_{\text{best-fit}}$	χ^2_{Planck} - $\chi^2_{\text{best-fit}}$	$\chi^2_{z_{HD}}$ - $\chi^2_{\text{best-fit}}$
No cut	88.2	66.4	9.1
0.005	88.5	68.5	19.1
0.01	62.1	41.4	15.0
0.0175	53.6	42.6	14.4
0.025	41.7	19.2	-2.1
0.0375	22.3	5.3	1.3
0.05	8.7	0.9	-1.0
0.1	7.4	3.4	2.9

where z_{HD} is the cmb corrected redshift with v_{pec} correction

For $z_{\text{cut}} \leq 0.02$:

- Best fit dipole very strongly favored over no dipole or the Planck dipole
- Also wrt Pantheon+ p-value ≥ 97.5 %

For $z_{\text{cut}} \geq 0.05$:

- Dipole no longer clearly detected $\Longrightarrow$ dipole correction is of the same order of noise

'Bulk velocity'

$\mathbf{v}_{\text{bulk}} = \mathbf{v}_0 - \mathbf{v}_{\text{Planck}}$ is the bulk velocity of a sphere around us with radius $R \lesssim z/H_0$

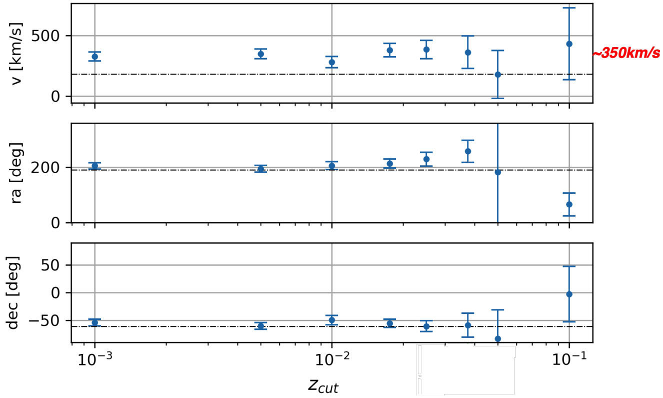
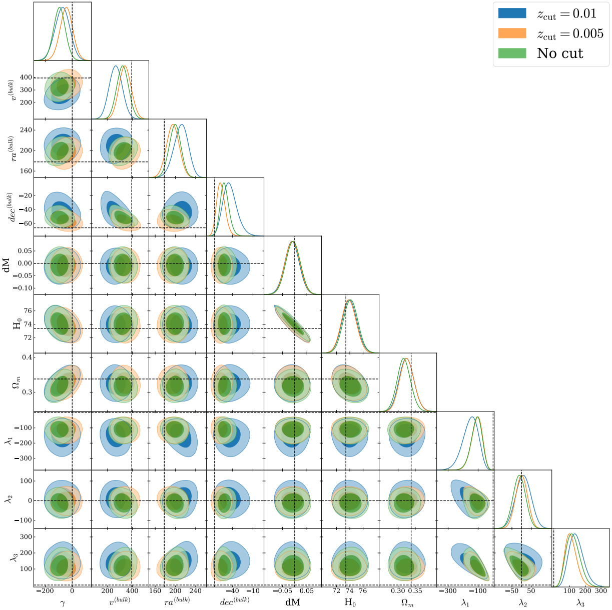


Figure: Ref.: $|\mathbf{v}_{\text{bulk}}| = 182$km/sec (ra, dec) = (191°,-61°) used by Pantheon+

Larger amplitude, but directions in agreement!

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



Allowing for a dipole, a monopole and a quadrupole for the source:

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

with α_{ij} symmetric traceless tensor.

- Monopole, dipole, quadrupole are detected
- Dipole consistent with Watkins et al., 2023

	$\Delta\chi^2$	
$z_{\rm cut}$	*Bulk + quadrupole*	*Bulk + quadrupole + monopole*
No cut	5.92	10.08
0.005	3.15	3.45
0.01	6.40	7.33
0.0175	5.36	7.07
0.025	7.95	8.06
0.0375	8.04	8.64
0.05	9.37	9.21
0.1	9.52	9.80

Table: $\Delta\chi^2$ differences wrt our previous analysis

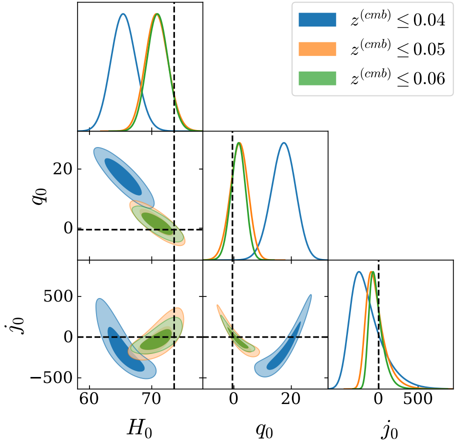
- At low z, all the multipoles are of the same order
- At high z, quadrupole is more relevant and the only one clearly detected

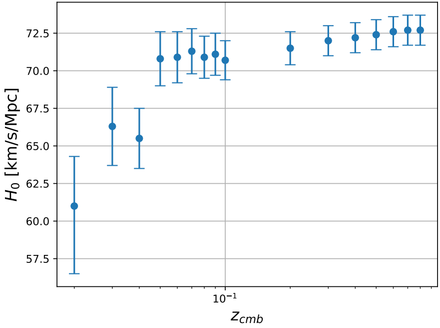
An agnostic approach *(in preparation)*

Taylor expanding:

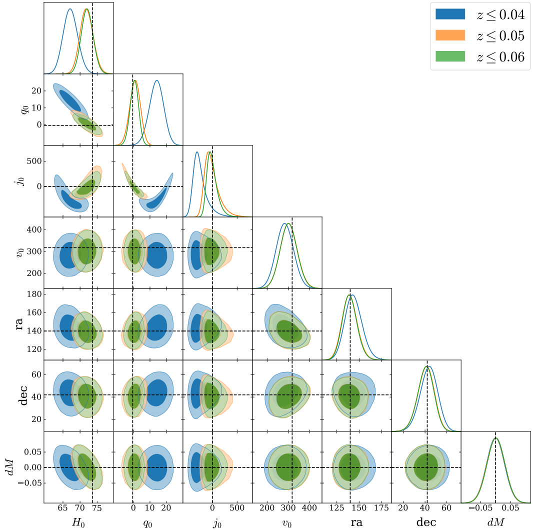
$$d_L(z) = z\, d^{(1)} + \frac{1}{2} z^2\, d^{(2)} + \frac{1}{6} z^3\, d^{(3)} \tag{4}$$

From $d^{(i)}$ we can obtain H_0, q_0, j_0



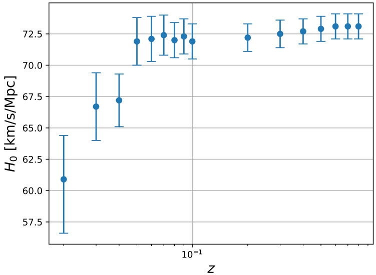


An agnostic approach *(in preparation)*

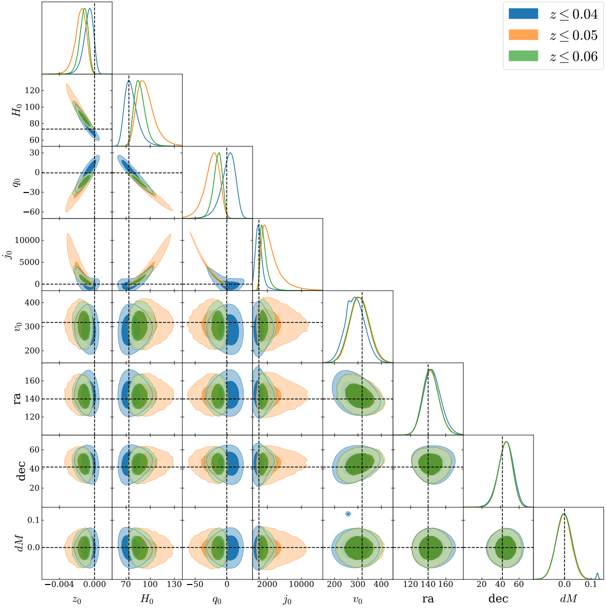


Allowing a dipole for the redshift z:

$$z^{(1)} \simeq z - \mathbf{v} \cdot \mathbf{n} \tag{5}$$

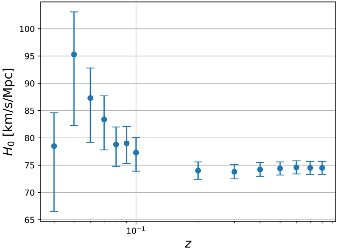


An agnostic approach: redshift monopole and dipole *(in preparation)*



Allowing also a monopole z_0, i.e. a possible local overdensity:

$$z^{(2)} \simeq z + z_0 - \mathbf{v} \cdot \mathbf{n} \tag{6}$$



$z <$	$\Delta\chi^2$
0.04	7.81
0.05	4.63

Table: $\Delta\chi^2$ differences wrt our cosmological analysis

Conclusions

Bright future for peculiar velocity surveys

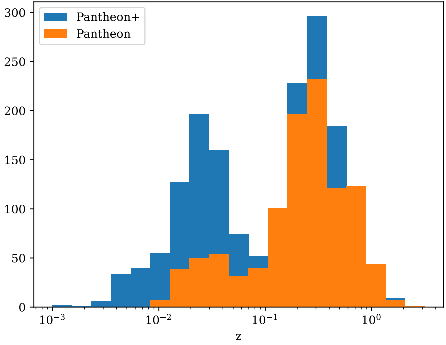
- v_{pec} appear to be relevant in many of the key cosmology topics
- Further detailed analysis seems necessary

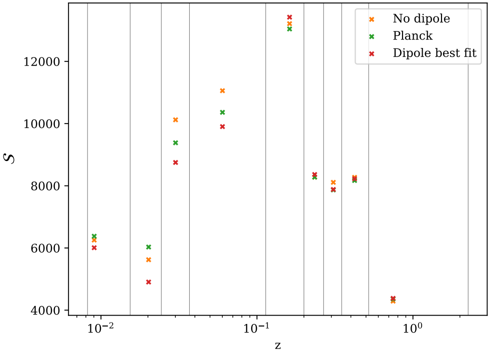
Next steps

- Finalising agnostic approach study
- Applying our routine to other datasets

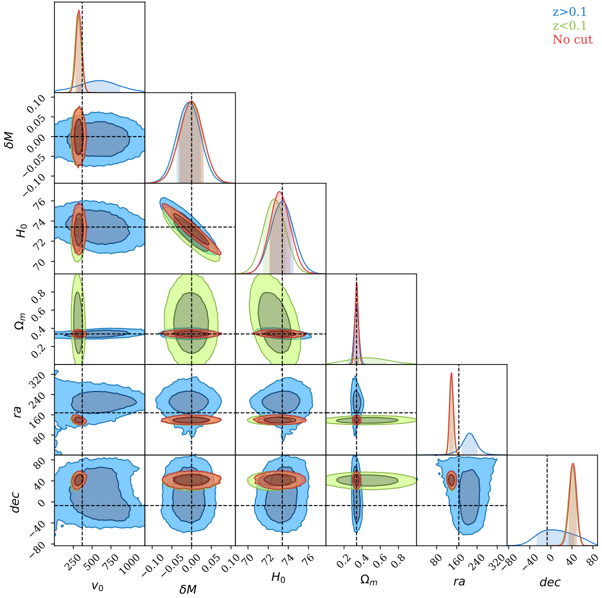
Thanks for your attention!

Supernovae redshift contribution





Low-z vs high-z supernovae



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

Pantheon+SH0ES: analysis

1701 SNe lightcurves → 77 Cepheid hosts

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

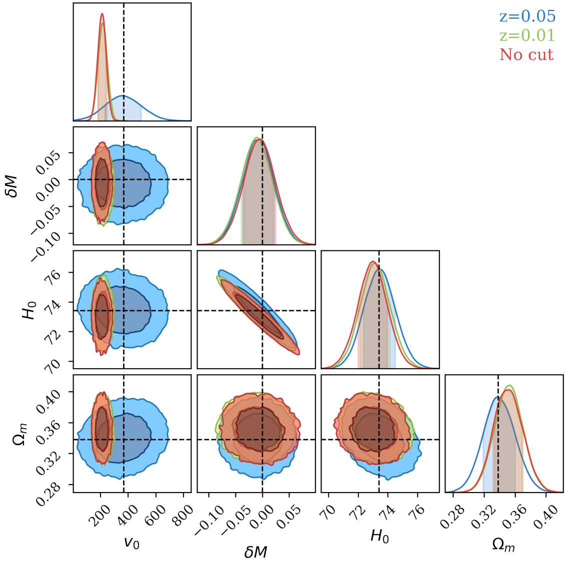
MCMC routine

$$\log(\mathcal{L}) = -\frac{1}{2}\Delta\boldsymbol{\mu}^T C^{-1}\Delta\boldsymbol{\mu} \tag{7}$$

$$\Delta\mu_L^i = \begin{cases} \mu^i + \delta M - \mu^i_{\text{ceph}}, & i \in \text{Cepheid hosts} \\ \mu^i + \delta M - \mu^i_{\text{model}}, & \text{otherwise} \end{cases} \qquad \mu^i_{\text{model}} = 5\log\left(\frac{D_L(z_i, \mathbf{n}_i)}{\text{Mpc}}\right) + 25 \tag{8}$$

Parameter	Prior range
v_0	[0, 1200] km/s
δM	[-100, 100]
H_0	[30, 100] km/s/Mpc
Ω_m	[0, 1]
ra	[0°, 360°]
dec	[-90°, 90°]

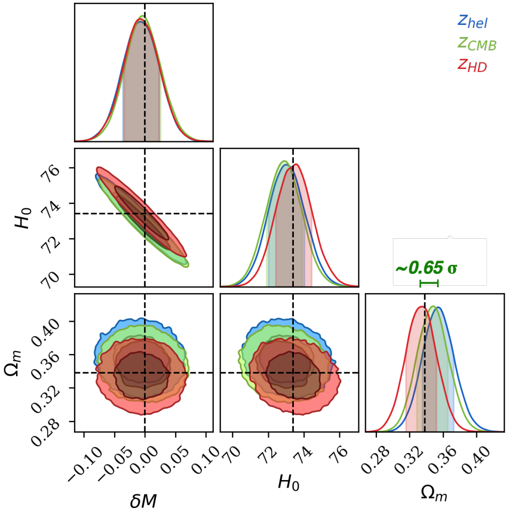
Fixing the velocity direction



Fixing direction according to Planck

$\longrightarrow |v_0|$ smaller than Planck value

Peculiar velocities in Pantheon+



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

Luminosity distance

For a spatially flat universe:

$$D_L(z,\mathbf{n}) = \bar{D}_L(z)\left\{1+\frac{1}{\mathcal{H}(z)r(z)}(\mathbf{v}_0\cdot\mathbf{n}) - \left(\frac{1}{\mathcal{H}(z)r(z)}-1\right)\left[(\mathbf{v}\cdot\mathbf{n}) - \Psi - \int_0^{r(z)} dr(\dot{\Psi}+\dot{\Phi})\right] - \Phi + \int_0^{r(z)}\frac{dr}{r}\left[1-\frac{r(z)-r}{2r(z)}\Delta_{\mathbf{n}}\right](\Phi+\Psi)\right\} \tag{9}$$

In a flat ΛCDM:

$$\bar{D}_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz}{\sqrt{\Omega_m(1+z)^3+1-\Omega_m}} \tag{10}$$

At $z \ll 1$, $\mathcal{H}(z)r(z) \simeq z$ and:

$$D_L(z,\mathbf{n}) \simeq \bar{D}_L(z)\left(1+\frac{1}{\mathcal{H}(z)r(z)}\mathbf{v}_0\cdot\mathbf{n}\right)$$

A little caveat

- We neglect source term $\mathbf{v}(\mathbf{n}, r(z))$ in:

$$(\mathbf{v}_0 - \mathbf{v}(\mathbf{n}, r(z))) \cdot \mathbf{n} \tag{11}$$

- It is correct unless there is a large 'bulk velocity'

- Since it cannot be modelled independently from the data, we see $\mathbf{v}_0$ as difference between observer velocity and a common bulk

Pantheon+SH0ES

https://github.com/PantheonPlusSH0ES/DataRelease

- 1701 SNe lightcurves → 77 Cepheid hosts

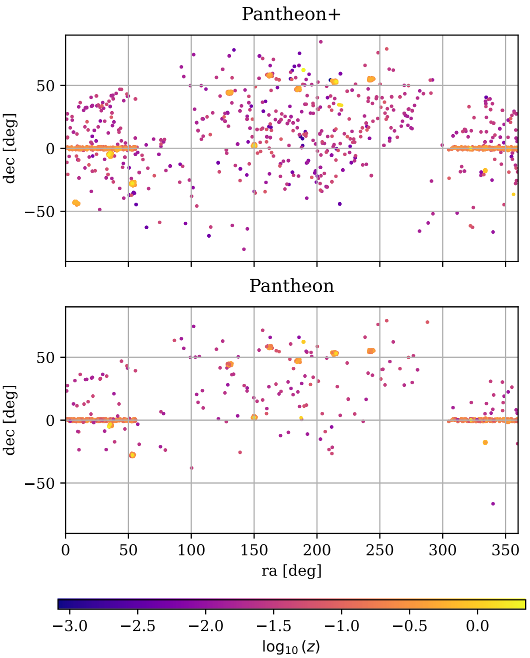
$$\mu = 5\log_{10}(D_L/1\mathrm{Mpc}) + 25 = 5\log_{10} D_L + M$$

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

MCMC routine

$$\log(\mathcal{L}) = -\frac{1}{2}\Delta\boldsymbol{\mu}^T C^{-1}\Delta\boldsymbol{\mu}$$

$$\Delta\mu_L^i = \begin{cases} \mu^i + \delta M - \mu^i_{\mathrm{ceph}}, & i \in \text{Cepheid hosts} \\ \mu^i + \delta M - \mu^i_{\mathrm{model}}, & \text{otherwise} \end{cases} \qquad \mu^i_{\mathrm{model}} = 5\log\left(\frac{D_L(z_i, \mathbf{n}_i)}{\mathrm{Mpc}}\right) + 25 \tag{12}$$

Parameter	Prior range
v_0	[0, 1200] km/s
δM	[-100, 100]
H_0	[30, 100] km/s/Mpc
Ω_m	[0, 1]
ra	[0°, 360°]
$\sin$(dec)	[-1,1]

Comparison with Pantheon

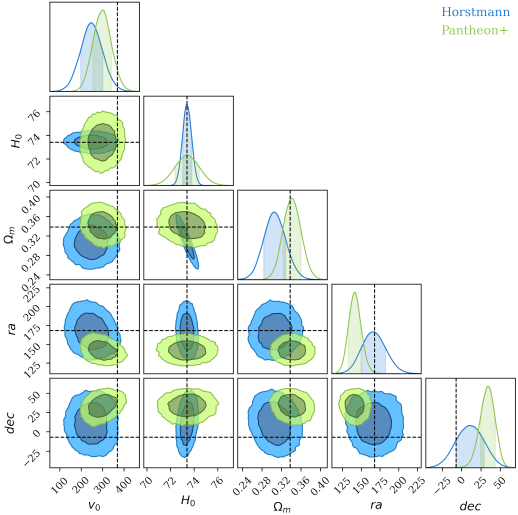
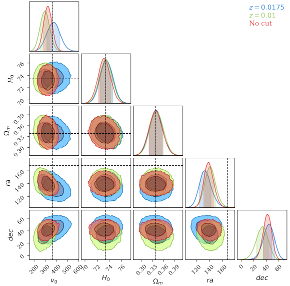


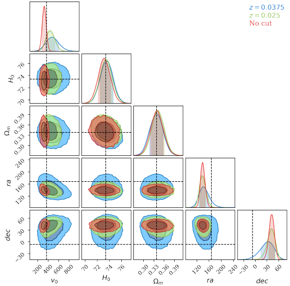
Figure: Thanks to N. Horstmann arXiv:2111.03055

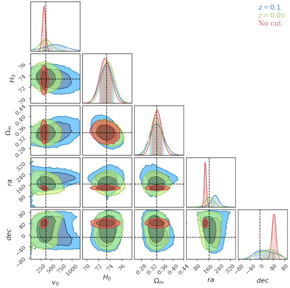
- Validity check
- For Pantheon v_0 is 2.4σ smaller
- Pantheon roughly agrees with Planck dipole and 'our' dipole

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

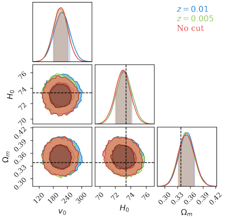
Pantheon+ z dependence



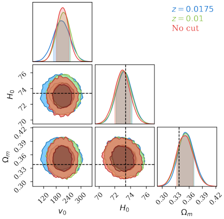




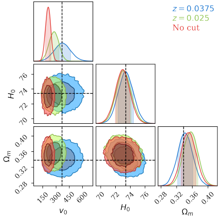
Position fixed



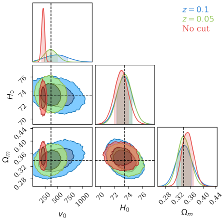
(a) Lowest redshifts



(b) Low redshift

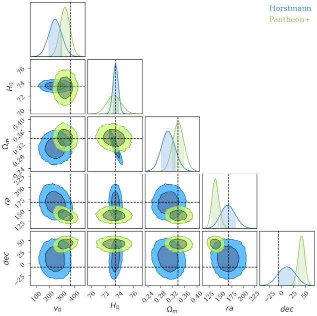


(c) Medium redshift

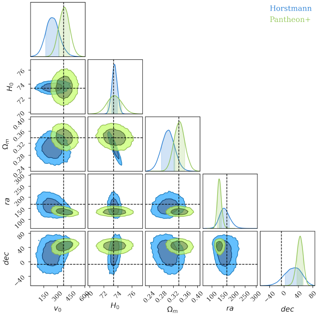


(d) High redshift

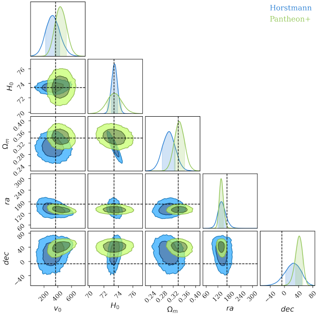
Comparison with Pantheon



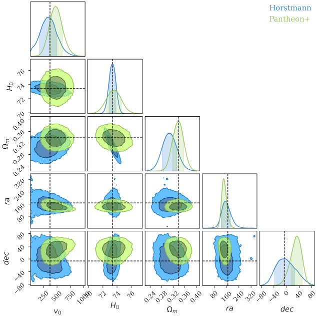
(a) No cut



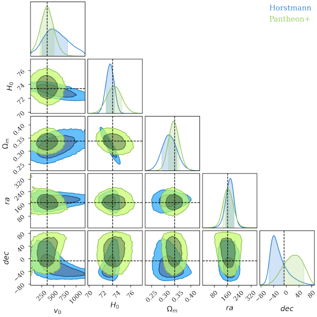
(b) z=0.0175



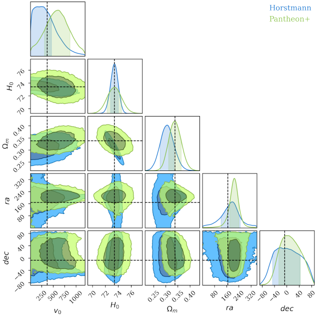
(a) z=0.025



(b) z=0.0375


Horstmann
Pantheon+
H_0
Ω_m
ra
dec
v_0

(a) z=0.05


Horstmann
Pantheon+
H_0
Ω_m
ra
dec
v_0

(b) z=0.1