The Dipole of the Pantheon+SH0ES Data

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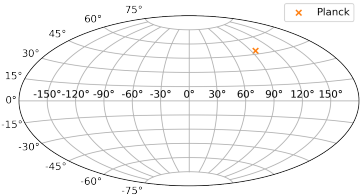
CMB dipole



- $v_0 = (369 \pm 0.9)\mathrm{km/s}$
- $(l, b) = (263.99 \pm 0.14, 48.26 \pm 0.03)$
- $(\mathrm{ra}, \mathrm{dec}) = (167.942 \pm 0.007, -6.944 \pm 0.007)$

$\rightarrow$ 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:

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

In a flat ΛCDM:

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

Pantheon+SH0ES: analysis

1701 SNe lightcurves → 77 Cepheid hosts

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

MCMC routine

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

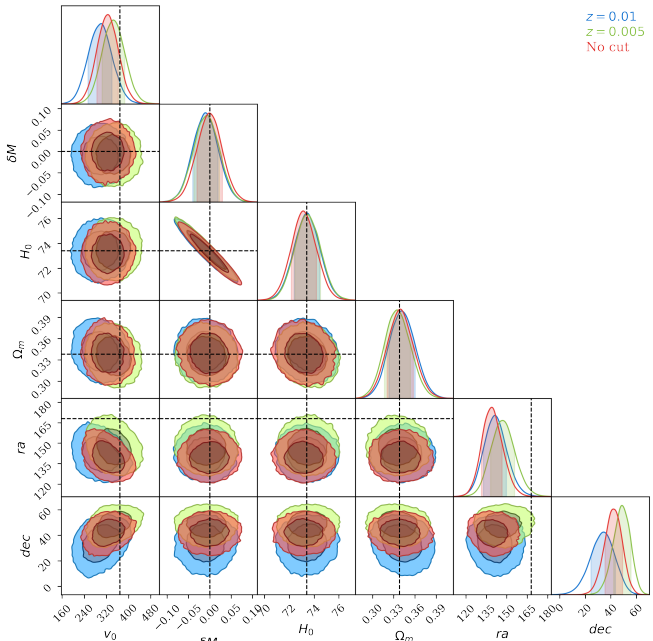
$$\Delta\mu_L^i = \begin{cases} \mu^i + \delta M - \mu^i_{\mathrm{ceph}}, & i \in \text{Cepheid hosts} \\ \mu^i + \delta M - \mu^i_{\mathrm{model}}, & \text{otherwise} \end{cases} \qquad \mu^i_{\mathrm{model}} = 5\log\left(\frac{D_L(z_i, \mathbf{n}_i)}{\mathrm{Mpc}}\right) + 25 \tag{3}$$

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°]

Results

$z_{\rm cut}$	v_0	H_0	Ω_m	ra	dec
Ref. value	369	73.4	0.338	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 !

'Bulk velocity'

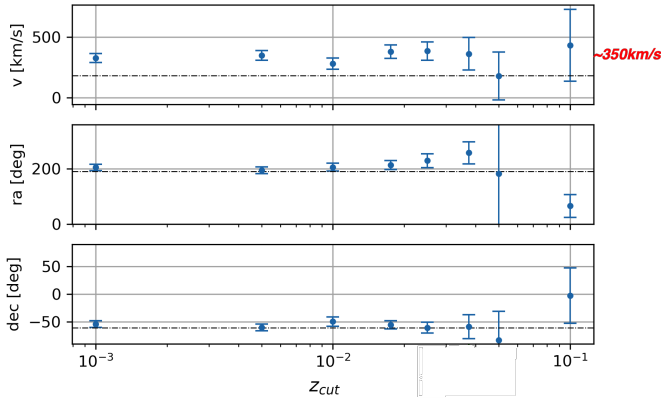
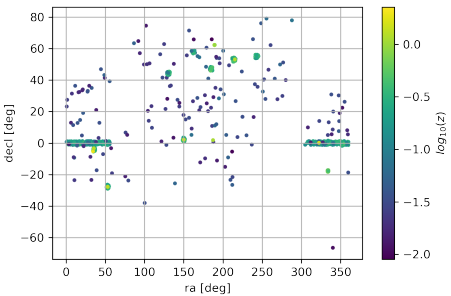


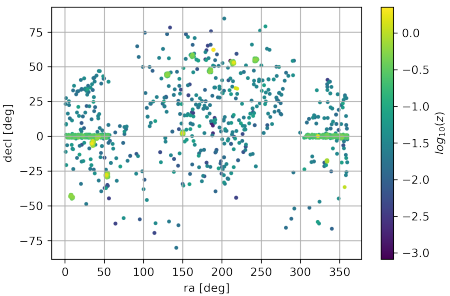
Figure: Ref.: $|\mathbf{v}_{\rm bulk}| = 182$km/sec (ra, dec) = (191°,-61°)

$\mathbf{v}_{\rm bulk} = \mathbf{v}_0 - \mathbf{v}_{\rm Planck}$ Larger amplitude, but directions in agreement!

Thanks for your attention!

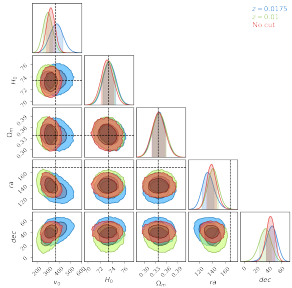


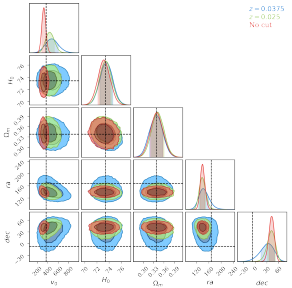
(a) Pantheon

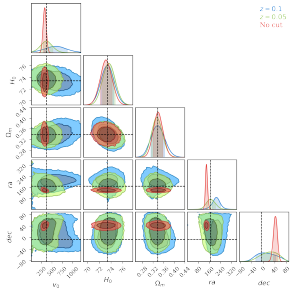


(b) Pantheon+

Pantheon+ z dependence







Luminosity distance

For a spatially flat universe:

$$D_L(z,\mathbf{n}) = \bar{D}_L(z)\left\{1+\frac{1}{\mathcal{H}(z)r(z)}(\mathbf{v}_0\cdot\mathbf{n})+\left(\frac{1}{\mathcal{H}(z)r(z)}-1\right)\left((\mathbf{v}\cdot\mathbf{n})+\Psi+\int_0^{r(z)}dr(\dot{\Psi}+\dot{\Phi})\right)-\Phi+\int_0^{r(z)}\frac{dr}{r}\left[1-\frac{r(z)-r}{2r(z)}\Delta_{\mathbf{n}}\right](\Phi+\Psi)\right\} \quad (4)$$

In a flat ΛCDM:

$$\bar{D}_L(z)=\frac{1+z}{H_0}\int_0^z\frac{dz}{\sqrt{\Omega_m(1+z)^3+1-\Omega_m}} \quad (5)$$

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

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

Pantheon+SH0ES

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

- 1701 SNe lightcurves → 77 Cepheid hosts
- Covariances (statistical + systematics)
- z_{hel}: Heliocentric Redshift
- z_{CMB}: CMB Corrected Redshift
- z_{HD}: Hubble Diagram Redshift (with CMB and v_{pec} corrections)

z_{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

χ^2 analysis

$z_{\rm cut}$	$\chi^2_{\rm No-dip}$ - $\chi^2_{\rm best-fit}$	$\chi^2_{\rm Planck}$ - $\chi^2_{\rm best-fit}$	$\chi^2_{z_{HD}}$ - $\chi^2_{\rm best-fit}$
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

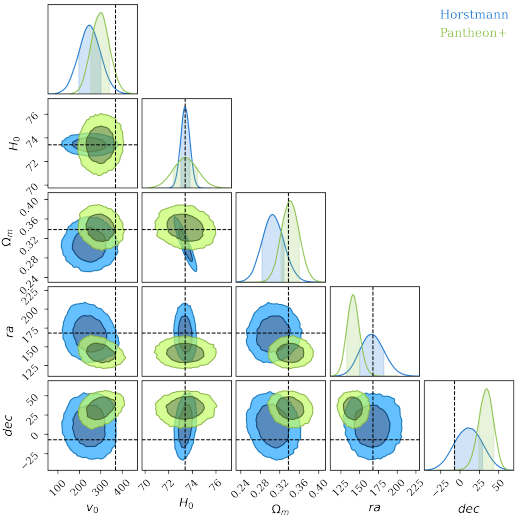
For $z_{\rm cut} \leq 0.02$:

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

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

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

Comparison with Pantheon

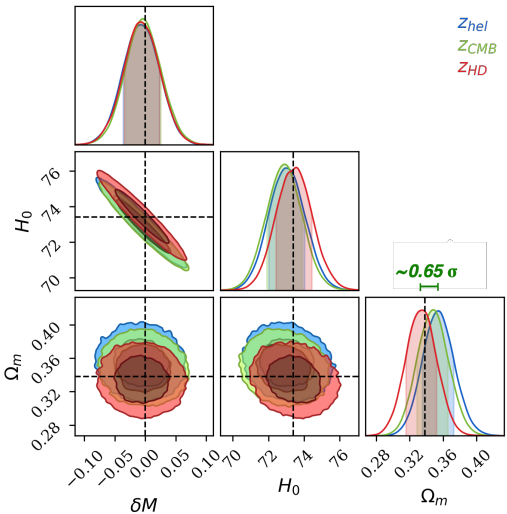


- Validity check
- For Pantheon v_0 is 2.4σ smaller
- Pantheon roughly agrees with Planck dipole and 'our' dipole

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

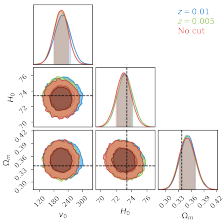
Figure: Thanks to N. Horstmann arXiv:2111.03055

Peculiar velocities in Pantheon+

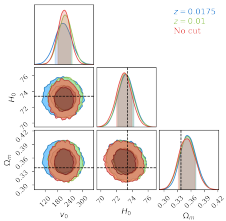


- Vorticity is neglected
- 'Ad hoc" $\mathbf{v}_{\rm bulk}$ within $R = 200h^{-1}$Mpc

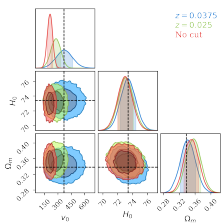
Position fixed



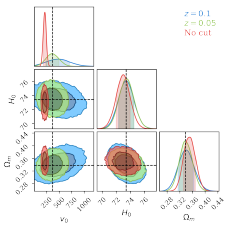
(a) Lowest redshifts



(b) Low redshift

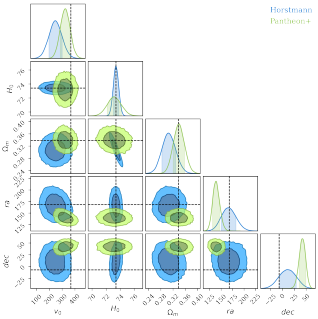


(c) Medium redshift

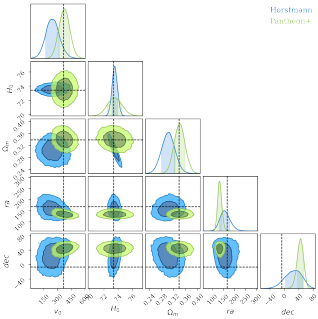


(d) High redshift

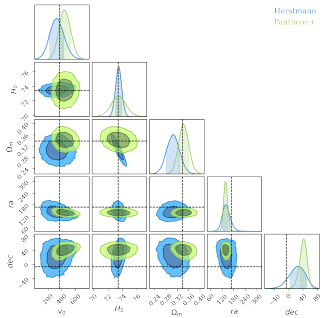
Comparison with Pantheon



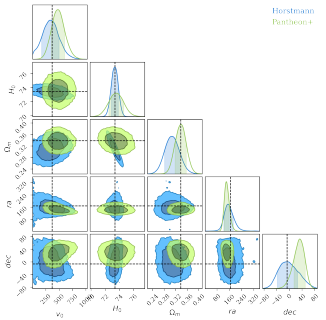
(a) No cut



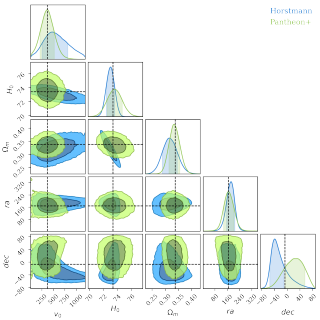
(b) z=0.0175



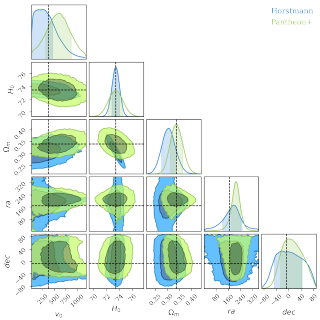
(a) z=0.025



(b) z=0.0375


Herstmann
Pantheon+
v_0
H_0
Ω_m
ra
dec

(a) z=0.05


Herstmann
Pantheon+
v_0
H_0
Ω_m
ra
dec

(b) z=0.1

Conclusions

We have determined the dipole of the Pantheon+ data

- It is significantly different from the CMB dipole (more than 3σ at $z_{\rm cut} \leq 0.02$)
- Pantheon still marginal consistent with CMB

Next steps

- Test the hypothesis of significant bulk flow
- Studying higher multipoles

Quadrupole (in preparation)

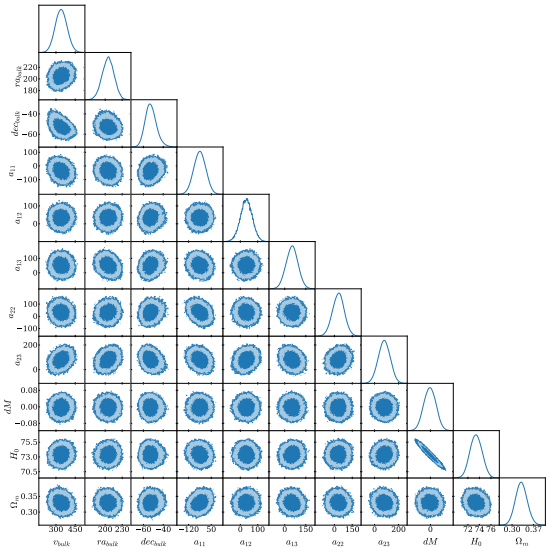


Figure: Fixing $\mathbf{v_0}$

Quadrupole eigevalues (in preparation)

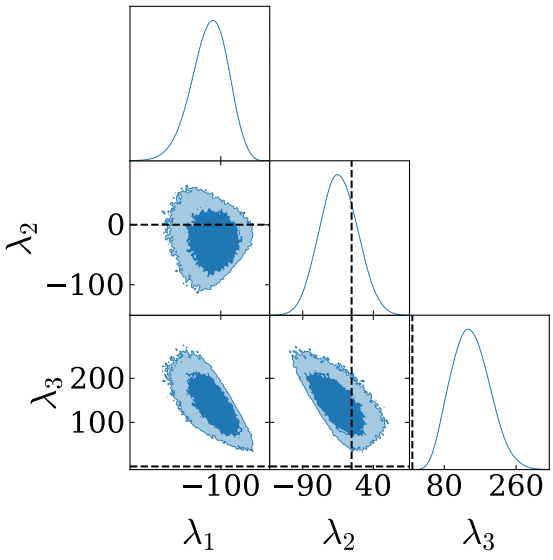


Figure: Fixing $\mathbf{v_0}$