Searching for Hidden Signals in the Pantheon+ and SH0ES samples

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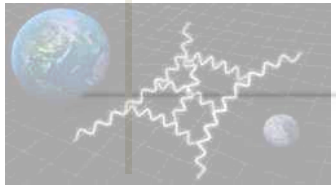
Main Questions



Q1: Is the absolute magnitude parameter M used for fitting with Pantheon+ homogeneous?

A1: No. The data favor a change of this parameter at about 20Mpc

Q2: Is the absolute luminosity of SnIa derived from the SH0ES data homogeneous across the sample?

A2: Maybe. There are hints at about 2σ for a change of this absolute luminosity at about 20-25Mpc.

Q3: Are the Pantheon+ and SH0ES data at various redshift bins consistent with isotropic Monte-Carlo simumations?

A3: Yes. In fact in many bins they are more isotropic than the Monte-Carlo simulations. This may be due to overestimated uncertainties of the Pantheon+ magnitudes.

Q4: Are there unexpected changes of the anisotropy level between consecutive distance/redshift bins?

A4: Yes. Based on Monte-Carlo expectations, there is an unexpected rise and drop of the anisotropy at about 20-40Mpc.

Measuring H(z) with the 2022 Pantheon+ dataset

from SnIa in Cepheid hosts at z<0.01

1701 SnIa datapoints (z_i, m_{Bi}, μ_{Cephj}), i=1,…,1701, j=1,…,77, 0.001<z_i,<2.26

Also provided $\mu_{SH0ESi}=m_{Bi}-M_{Cepheid}$

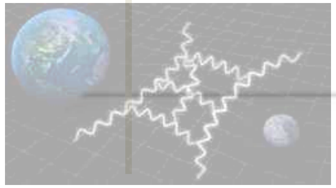
Standard maximum likelihood of previous Pantheon sample (no μ_{Cephj})

$$\chi^2 = \vec{Q}^T \cdot (C_{\rm stat+syst})^{-1} \cdot \vec{Q}, \qquad Q_i = m_{Bi} - M - \mu_{\rm model}(z_i), \quad \mu_{\rm model}(z_i) = 5\log(d_L(z_i)/Mpc) + 25,$$

$$d_L(z) = (1+z)c\int_0^z \frac{dz'}{H(z')}, \qquad H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}. \qquad \mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

Degeneracy between H_0 and M
(no way to fit H_0 without prior knowledge of M)

Measuring H(z) with the 2022 Pantheon+ dataset



The Pantheon+ Analysis: Cosmological Constraints

Dillon Brout (Harvard-Smithsonian Ctr. Astrophys.), Dan Scolnic (Duke U.), Brodie Popovic (Duke U.), Adam G. Riess (Baltimore, Space Telescope Sci. and Johns Hopkins U.), Joe Zuntz (Edinburgh U., Inst. Astron.) et al (Feb 8, 2022)

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On the homogeneity of SnIa absolute magnitude in the Pantheon+ sample Get access

Leandros Perivolaropoulos, Foteini Skara

Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 4, April 2023, Pages 5110–5125, https://doi.org/10.1093/mnras/stad451

Pantheon+ likelihood: Utilizing the 77 Cepheid distance moduli μ_{Cephj} of SnIa in Cepheid hosts:

$$Q_i' = \begin{cases} m_{Bi} - M - \mu_i^{\rm Ceph} & i \in \text{Cepheid hosts} \\ m_{Bi} - M - \mu_{\rm model}(z_i) & \text{otherwise,} \end{cases}$$

Best fit parameter values:

$$M = -19.25 \pm 0.03,$$
$$h = 0.734 \pm 0.01,$$
$$\Omega_{0m} = 0.333 \pm 0.018,$$

Broken degeneracy between H_0 and M due to the 77 SnIa distance moduli in Cepheid hosts

A way to fit H_0 along with other cosmological parameters without prior knowledge of M!

Agreement with Brout et.al. 2022

$$\Delta D_i' = \begin{cases} \mu_i - \mu_i^{\rm Cepheid} & i \in \text{Cepheid hosts} \\ \mu_i - \mu_{\rm model}(z_i) & \text{otherwise,} \end{cases}$$

Brout et al 2022: M not included in fit.

New degrees of freedom in the Pantheon+ likelihood

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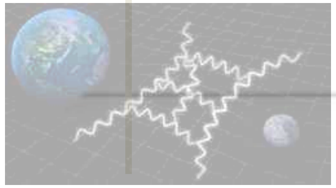


Allow for a transition of M at some distance d_c

$$M = \begin{cases} M_< & d < d_{crit} \\ M_> & d > d_{crit}, \end{cases}$$

$$\mu_{crit} = 5 log(d_{crit}/Mpc) + 25$$

New likelihood for Patheon+:

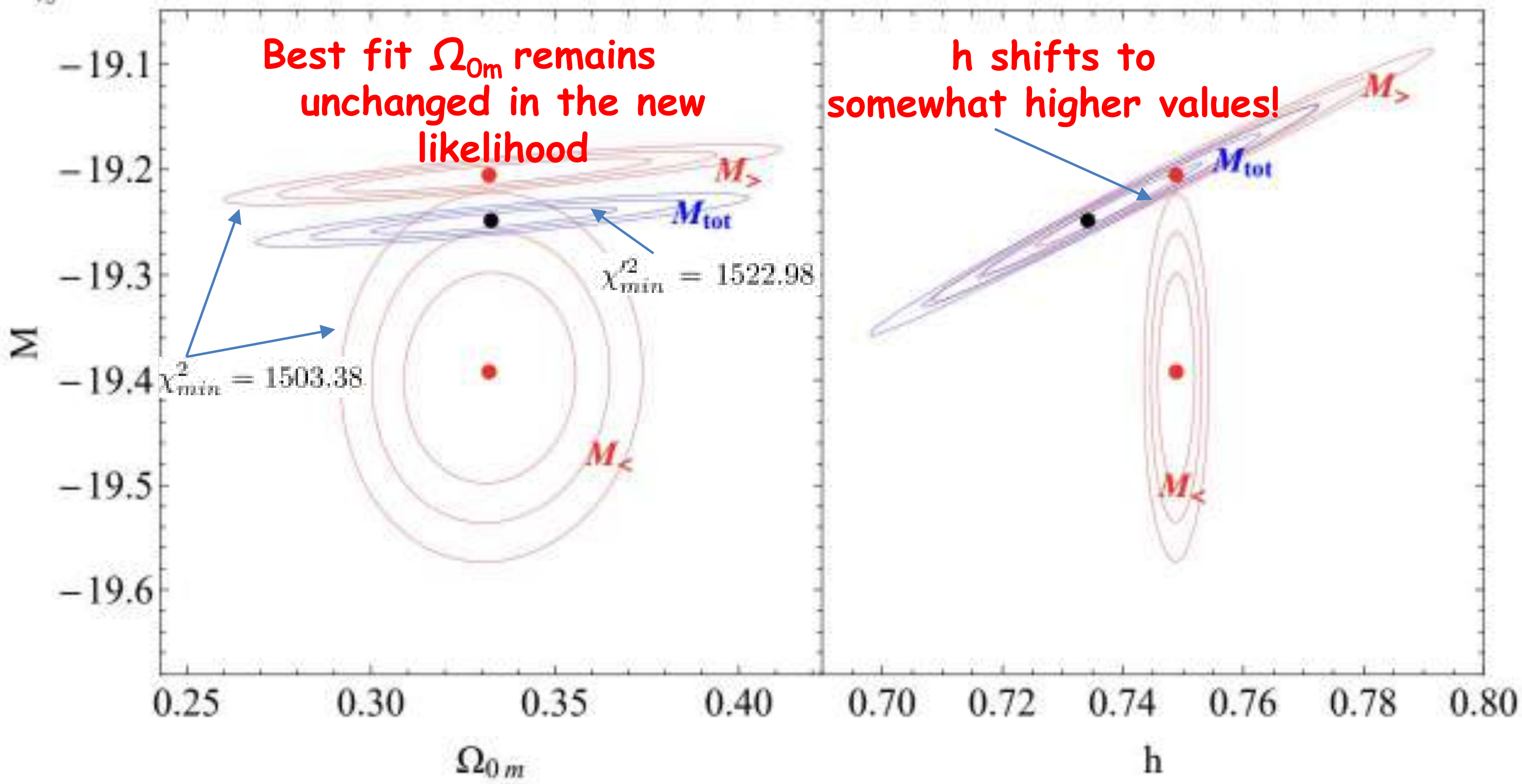
$$Q_i'' = \begin{cases} m_{Bi} - M_< - \mu_i^{\rm Cepheid} & \text{iff } \mu_{i,S} < \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_> - \mu_i^{\rm Cepheid} & \text{iff } \mu_{i,S} > \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_< - \mu_{\rm model}(z_i) & \text{iff } \mu_{i,S} < \mu_{crit}, \text{and } i \notin \text{Cepheid hosts} \\ m_{Bi} - M_> - \mu_{\rm model}(z_i) & \text{iff } \mu_{i,S} > \mu_{crit}, \text{and } i \notin \text{Cepheid hosts}, \end{cases}$$

Q:

1. What is the quality of fit of ΛCDM with the new likelihood?
2. Are the best fit $M_>$, $M_<$ consistent with each other and with the best fit M of the standard likelihood

New degrees of freedom in the Pantheon+ likelihood

Q: Does this modeling of $M_<$, $M_>$ affect the best fit values of other cosmological parameters?



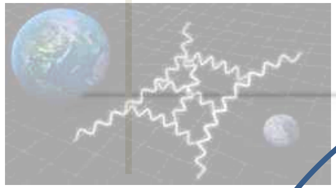
$$
\begin{aligned}
M_< &= -19.392 \pm 0.05, \\
M_> &= -19.205 \pm 0.03, \\
h &= 0.749 \pm 0.01, \\
\Omega_{0m} &= 0.332 \pm 0.02, \\
d_{crit} &= 19.95 \pm 0.1 Mpc,
\end{aligned}
$$

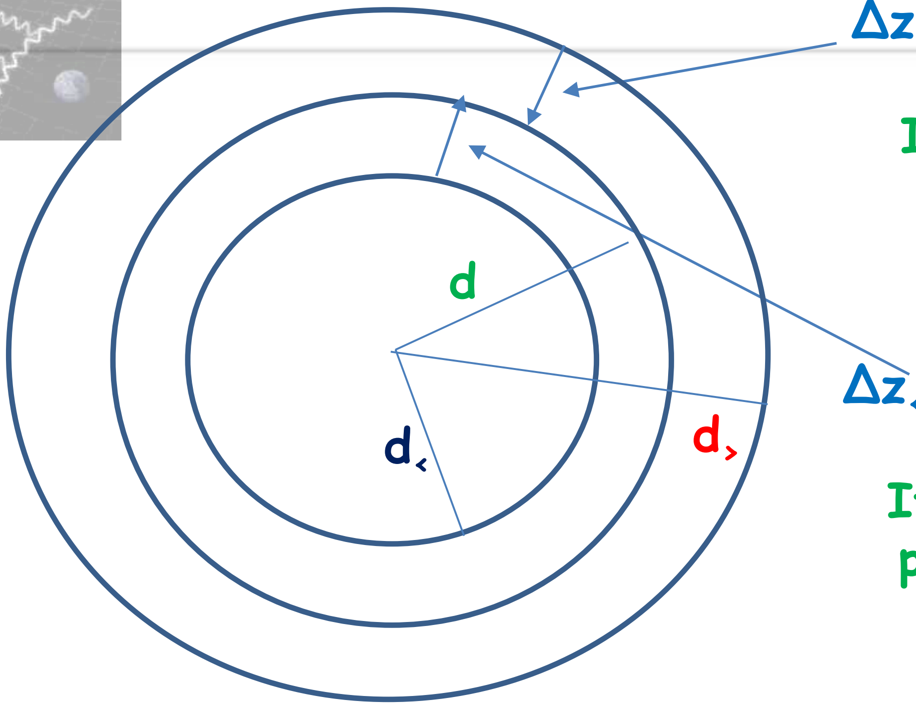
A_1: $\Delta\chi^2$=-19

A_2:No! Significant tension!

Q: What is the origin of this tension? Systematics? New Physics? Both?

The volumetric redshift bias: A known **but uncorrected** systematic in Pantheon+





$\Delta z_>$: Random peculiar velocities in outer shell compared to a given shell at redshift z.

If $\Delta z_> < 0$ then the outer shell galaxies are incorrectly projected on the z shell leading to smaller distance estimate than the true distance $d_>$.

$\Delta z_<$: Random peculiar velocities in inner shell compared to a given shell at redshift z.

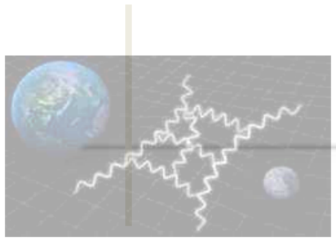
If $\Delta z_> > 0$ then the outer shell galaxies are incorrectly projected on the z shell leading to larger distance estimate than the true distance $d_>$.

Problem: There are more galaxies in the outer shell than in the inner shell due to larger volume of the outer shell!

More galaxies at higher distances are incorrectly projected to lower distance in the Hubble diagram due to peculiar velocities!

Thus: $d-d_{\Lambda CDM}(z)>0$ for $z<0.01$ where the effect is important.

The volumetric redshift bias



The volumetric redshift bias is dominant at low redshifts where the volume difference is more prominent.

For $z<0.01$ $\mu_{<}-\mu_{model}(z)>0$

$$m_{B<}-M_{<}-\mu_{model}^{vrb}(z) > m_{B<}-M-\mu_{model}^{true}(z) = 0$$

$$\Downarrow \quad \mu_{model}^{vrb}(z)=\mu_{model}^{true}(z)$$

$$M_{<}<M=M_{>}$$

If volumetric redshift bias is not corrected it leads to a lower SnIa absolute magnitude at $z<0.01$

$m_{B<}-M_{>}-\mu_{model}^{vrb}(z;p) = 0 \Longrightarrow$ Incorrect value for p.

For $z>0.01$ (no vrb): $m_{B>}-\mu_{model}(z)=M_{>}$

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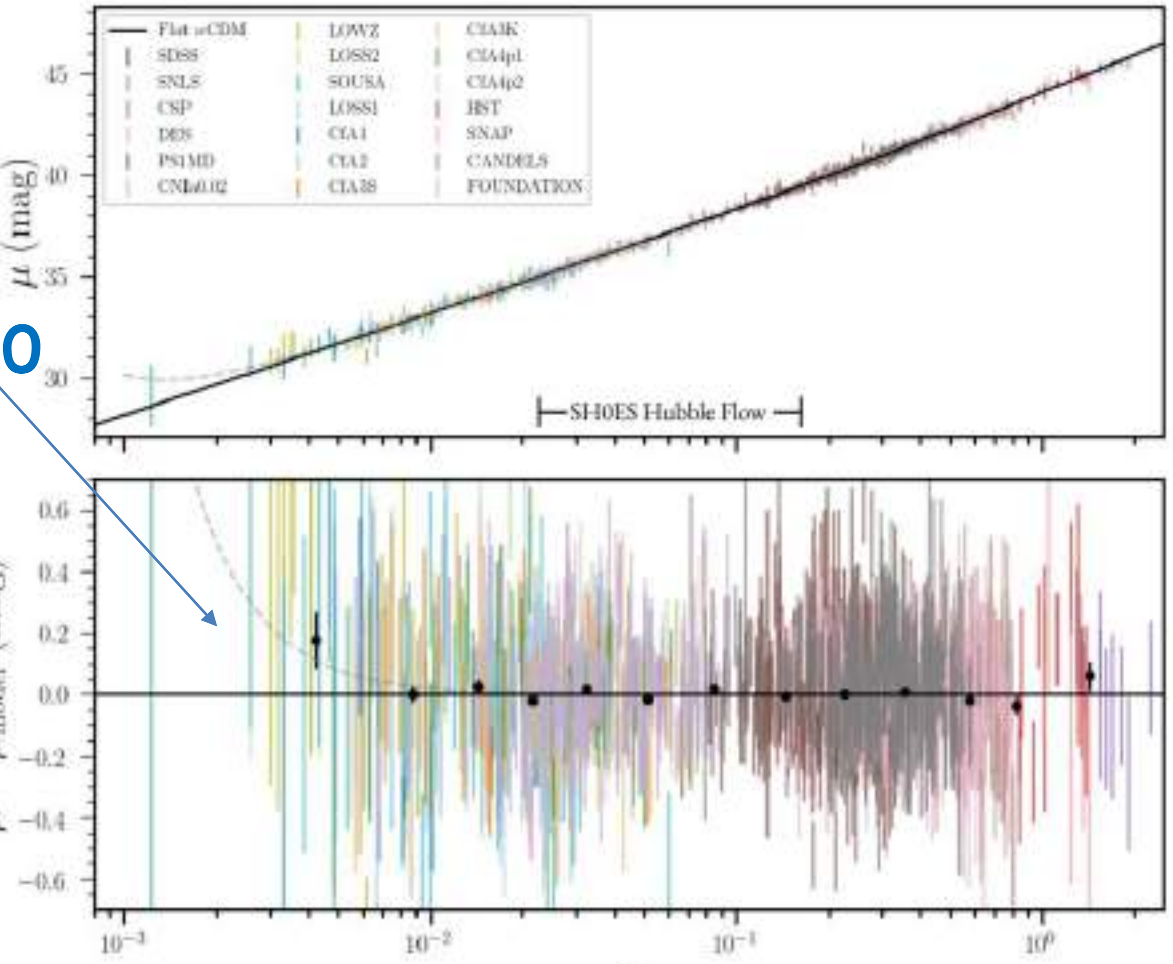


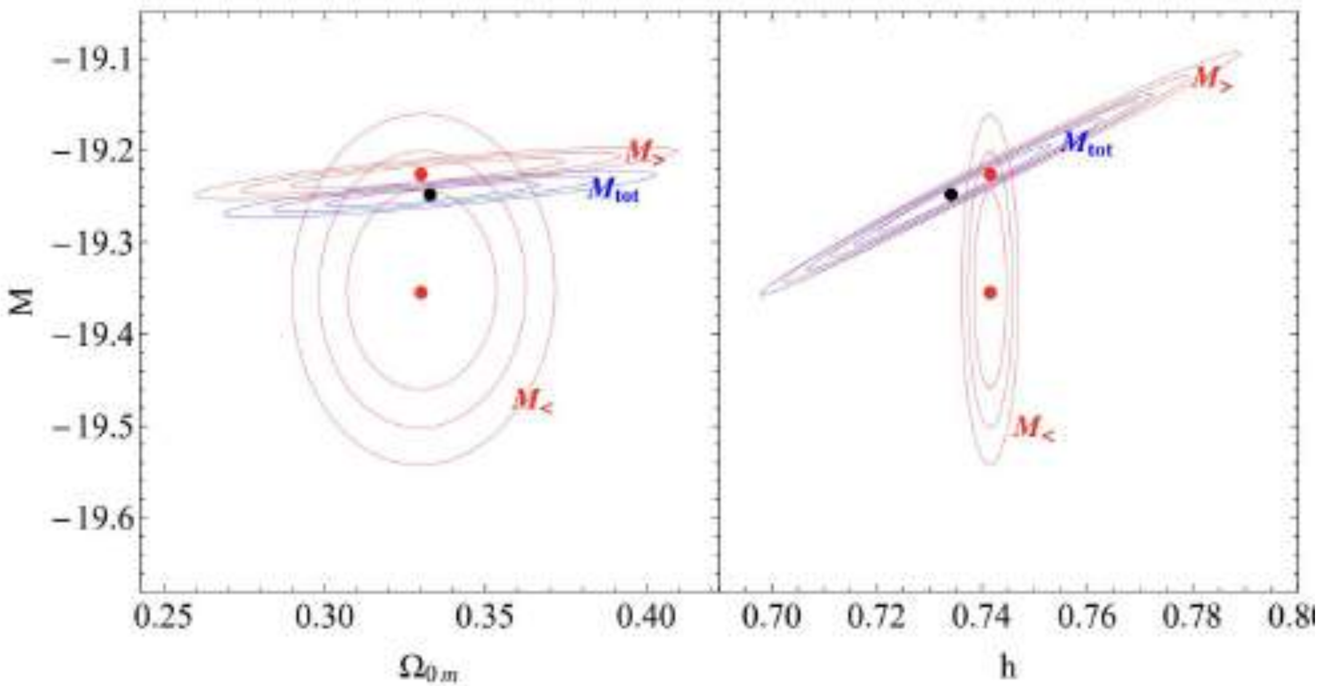
Thus, we expect: $M_{>}>M_{<}$

Q: Is this the only reason for the $M_{>}-M_{<}$ inconsistency or there is also a physical transition of SnIa luminosity?

Another new likelihood for Pantheon+

Remove Hubble diagram distance moduli data with z<0.01 but keep distance moduli data of SnIa in Cepheid hosts.

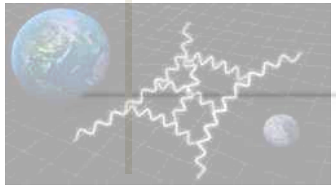
$$
Q_i''' = \begin{cases}
m_{Bi} - M_< - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} < \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\
m_{Bi} - M_> - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} > \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\
0 & \text{iff } z_i < 0.01 \\
m_{Bi} - M_< - \mu_{\text{model}}(z_i) & \text{iff } z_i > 0.01 \text{ and } \mu_{i,S} < \mu_{crit}, \text{and } i \notin \text{Cepheid hosts} \\
m_{Bi} - M_> - \mu_{\text{model}}(z_i) & \text{iff} z_i > 0.01 \text{ and } \ \mu_{i,S} > \mu_{crit}, \text{and } i \notin \text{Cepheid hosts},
\end{cases}
$$



$$
\begin{aligned}
M_< &= -19.355 \pm 0.05, \\
M_> &= -19.226 \pm 0.03, \\
h &= \quad 0.74 \pm 0.01, \\
\Omega_{0m} &= \quad 0.33 \pm 0.02, \\
d_{crit} &= 19.95 \pm 0.1 Mpc,
\end{aligned}
$$

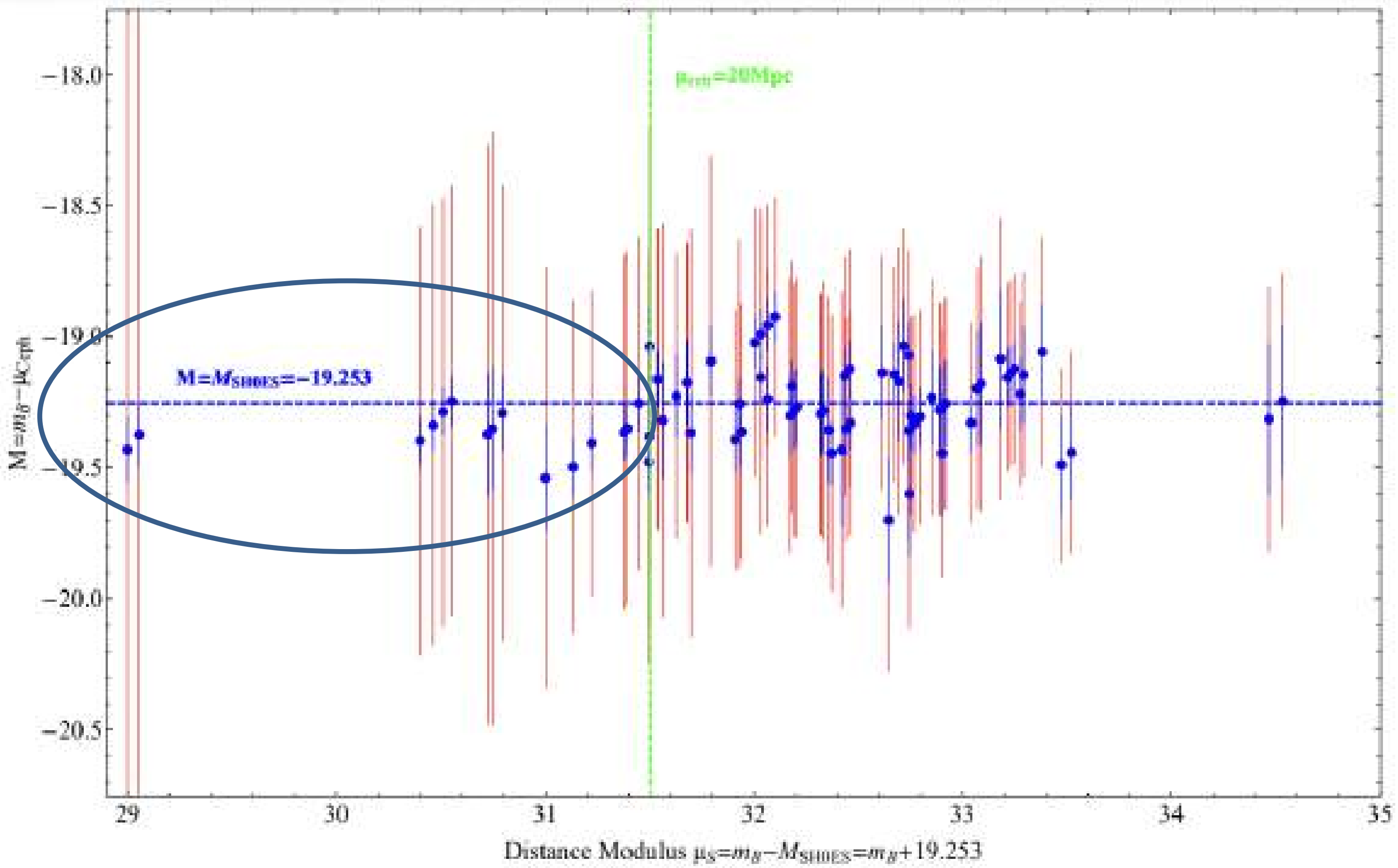
The tension between $M_<$ and $M_>$ is smaller but a significant part of it remains

SnIa luminosities in Pantheon+



Closeby SnIa ($d<d_c$=20Mpc) in Cepheid hosts are systematically brighter more distant SnIa ($M<M_{SH0ES}=M_{best-fit}$)

Q: How often could this happen by chance?



Monte Carlo Simulation

Steps:

1. Group SnIa that are in the same host and find the weighted mean absolute magnitude corresponding to each j host:

$$M_j = \frac{\sum_{i=1}^{N_j} M_i/\sigma_i^2}{\sum_{i=1}^{N_j} 1/\sigma_i^2}$$

$$\sigma^2(M_j) = \frac{1}{\sum_{i=1}^{N_j} 1/\sigma_i^2}$$

2. For a critical distance d_c split the host absolute magnitudes in low distance and high distance bins e.g.

$$M_< = \frac{\sum_{i=1}^{N_k} M_i/\sigma_i^2}{\sum_{i=1}^{N_k} 1/\sigma_i^2}$$

$$\sigma^2(M_<) = \frac{1}{\sum_{i=1}^{N_k} 1/\sigma_i^2}$$

3. For each critical distance d_{crit}, define the M transition statistic:

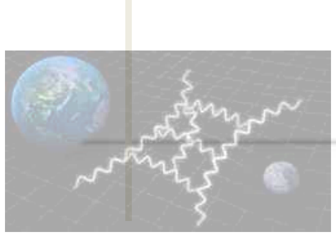
$$\Sigma(\mu_{crit}) \equiv \frac{|M_> - M_<|}{\sqrt{\sigma_{M_>}^2 + \sigma_{M_<}^2}}$$

$$\mu_{crit} = 5log(d_{crit}/Mpc) + 25$$

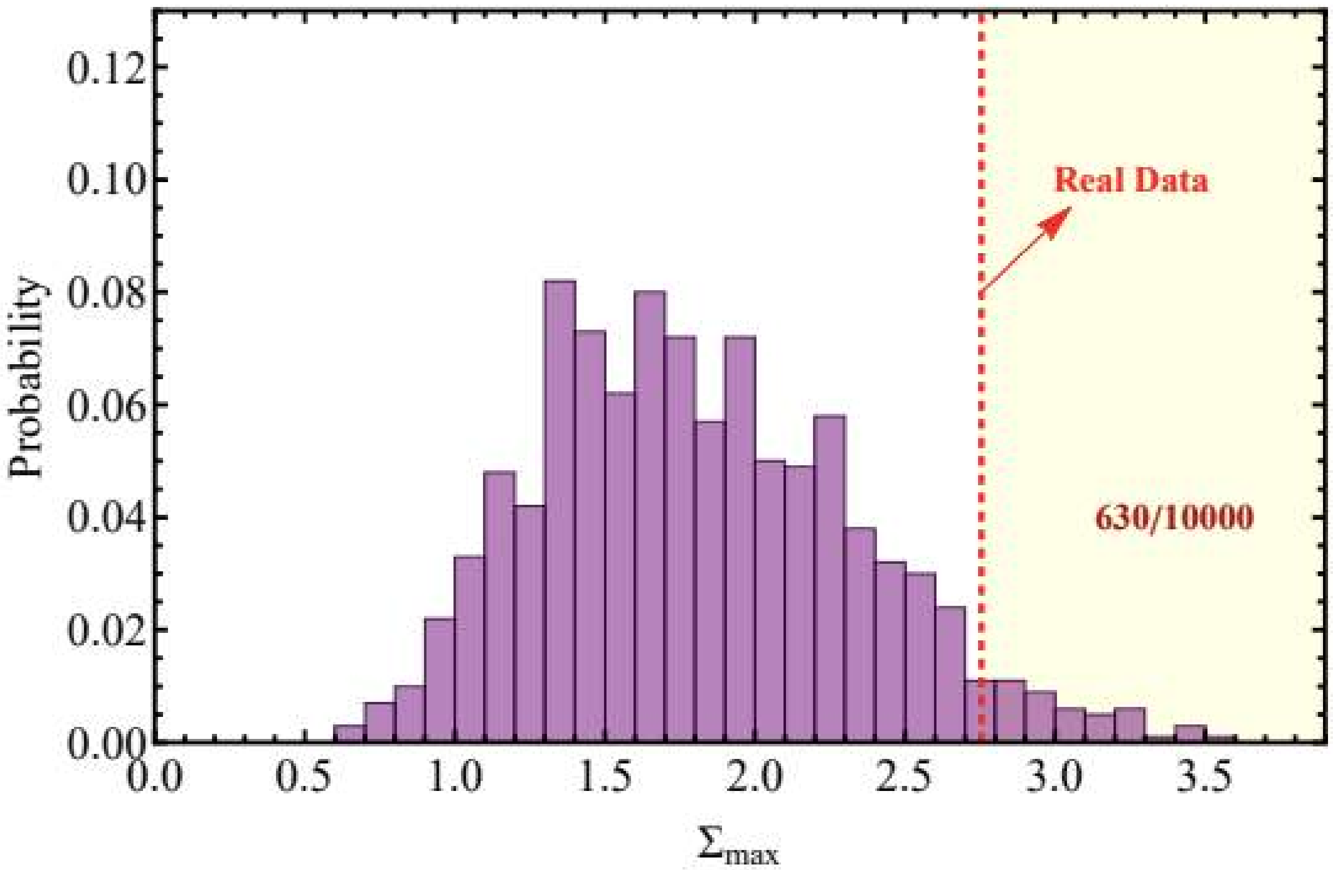
4. In the real data we have Σ_{max} = 2.75, at d_{crit}=22.4Mpc.

Q: How often would a larger Σ_{max} occur in Monte Carlo simulated SH0ES/Pantheon+ SnIa in Cepheid host data?

Monte Carlo Simulation



A: 94% of the simulated datasets have Σ_{max} smaller than the Σ_{max} of the real data and only about 6% have Σ_{max} larger than the real data.



Thus, the part of the $M_{<}$-$M_{>}$ inconsistency that is due to actual SnIa luminosity mismatch is at about 2σ level.

Hemisphere Comparison Method: Isotropy of SnIa Absolute Magnitudes

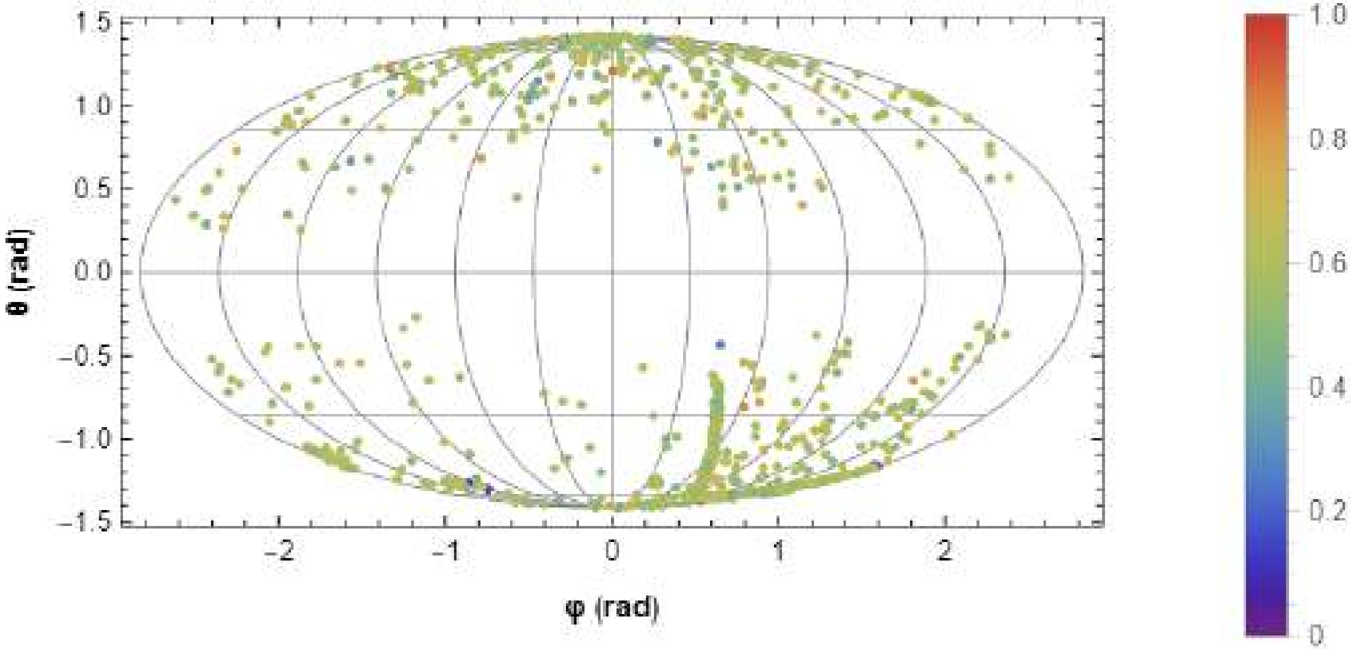
On the isotropy of SnIa absolute magnitudes in the Pantheon+ and SH0ES samples

Leandros Perivolaropoulos (May 22, 2023)

e-Print: 2305.12819 [astro-ph.CO]

$$M_{res} \equiv M_i - M_{SH0ES}$$

$$\bar{M} \equiv \frac{M - M_{min}}{M_{max} - M_{min}}$$



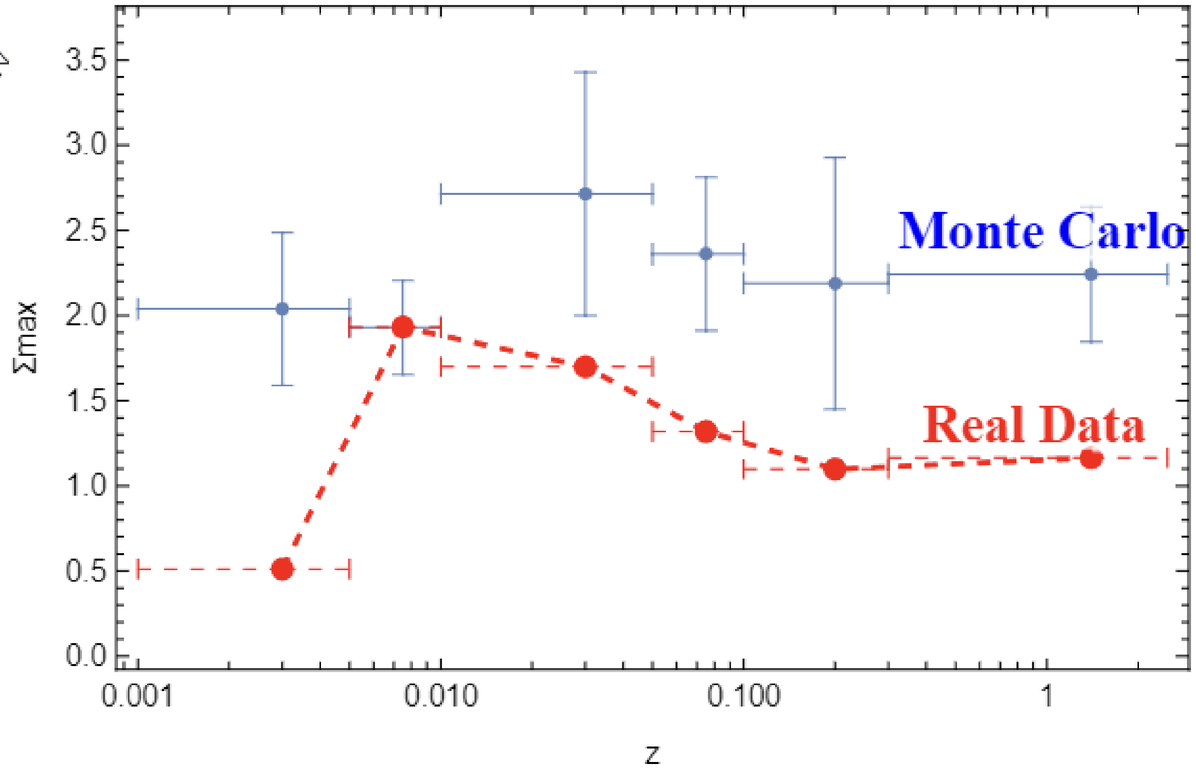
Standardized SnIa absolute magnitudes of Pantheon+.

1. Select random direction and split sky in North-South hemispheres in given redshift bin.
2. Find weighted average of absolute magnitudes in each hemisphere (M_N, M_S) and their uncertainties.
3. Define anisotropy level statistic:

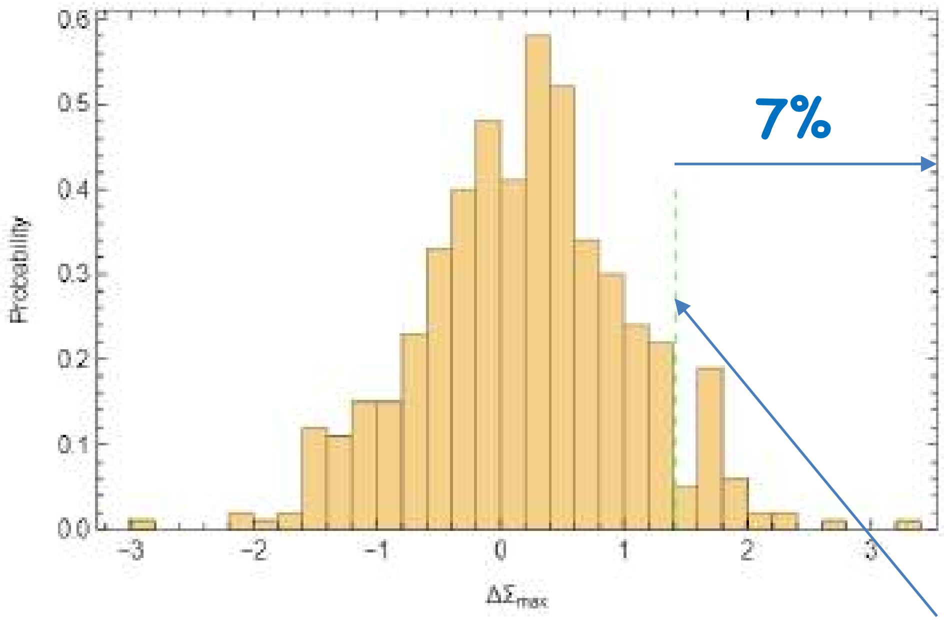
$$\Sigma \equiv \frac{|M_N - M_S|}{\sqrt{\sigma_N^2 + \sigma_S^2}}$$

4. Find direction of maximum anisotropy level Σ_{max} .
5. Repeat for N isotropic Monte-Carlo samples to find anticipated range of Σ_{max}.

Comparison of Pantheon+ M-anisotropy with isotropic Monte-Carlo samples.



How frequent are these changes in Monte-Carlo isotropc data?

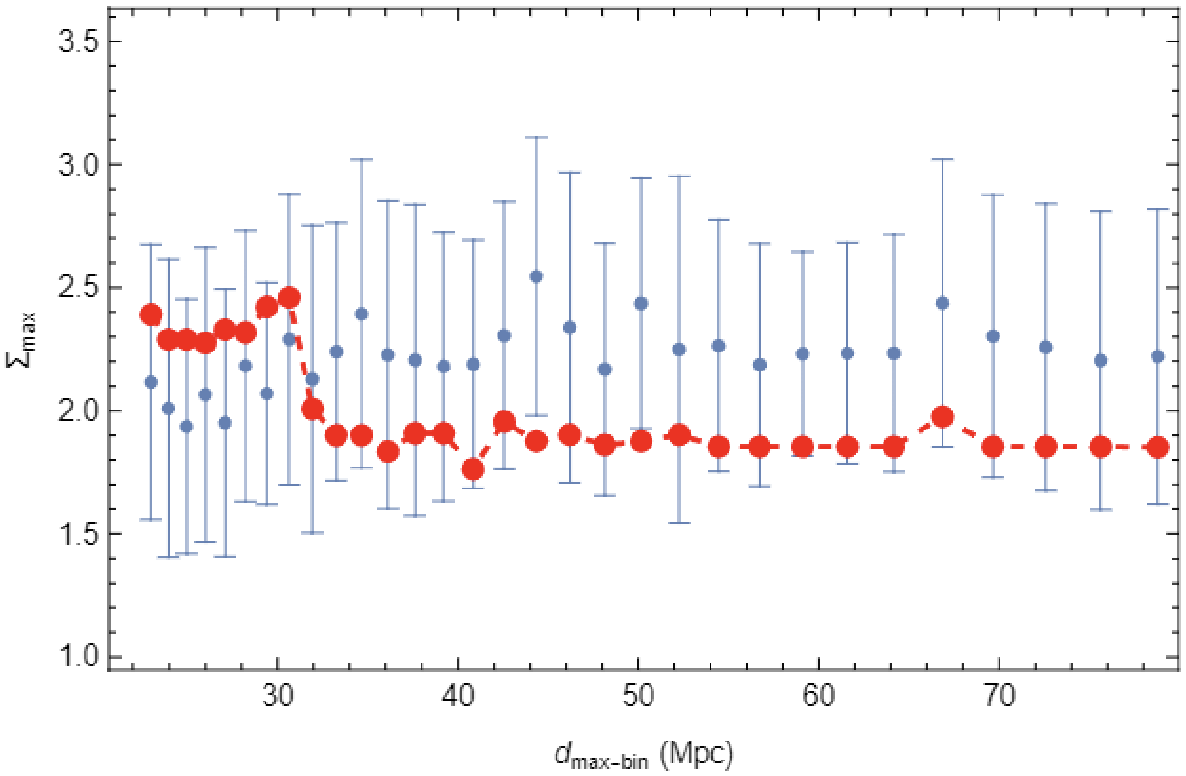


Real data 1->2 bin

Monte-Carlo simulated data are more anisotropic than real data (overestimated uncertainties?)

Sudden changes appear of anisotropy level appear at low redshift bins

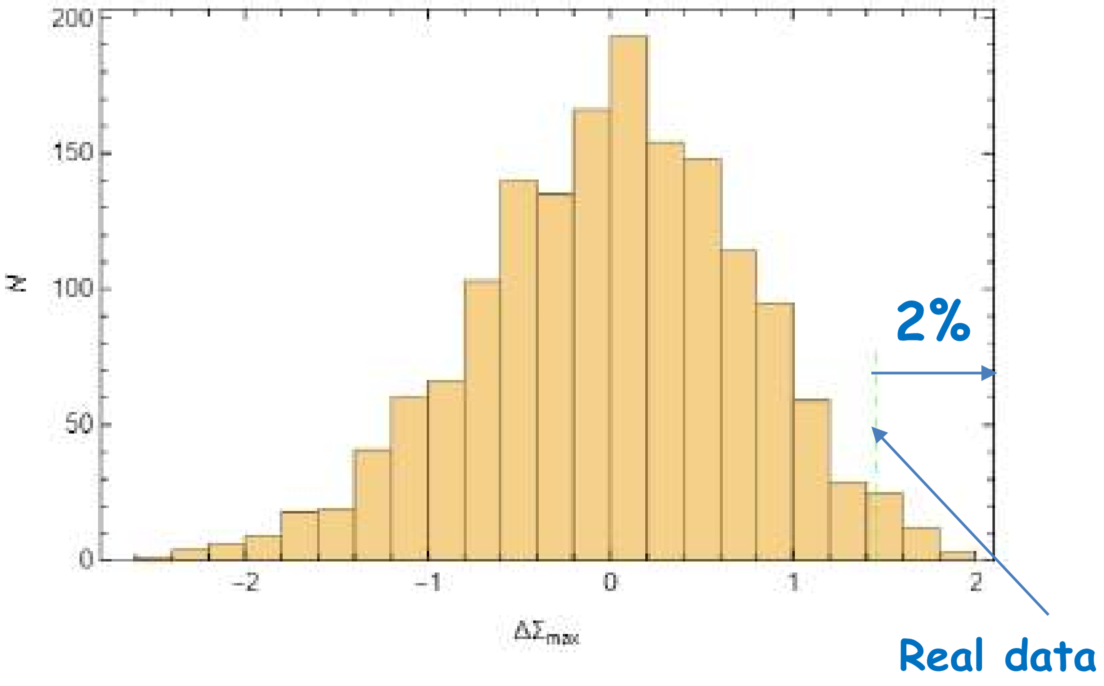
Comparison of SH0ES M-anisotropy with isotropic Monte-Carlo samples.



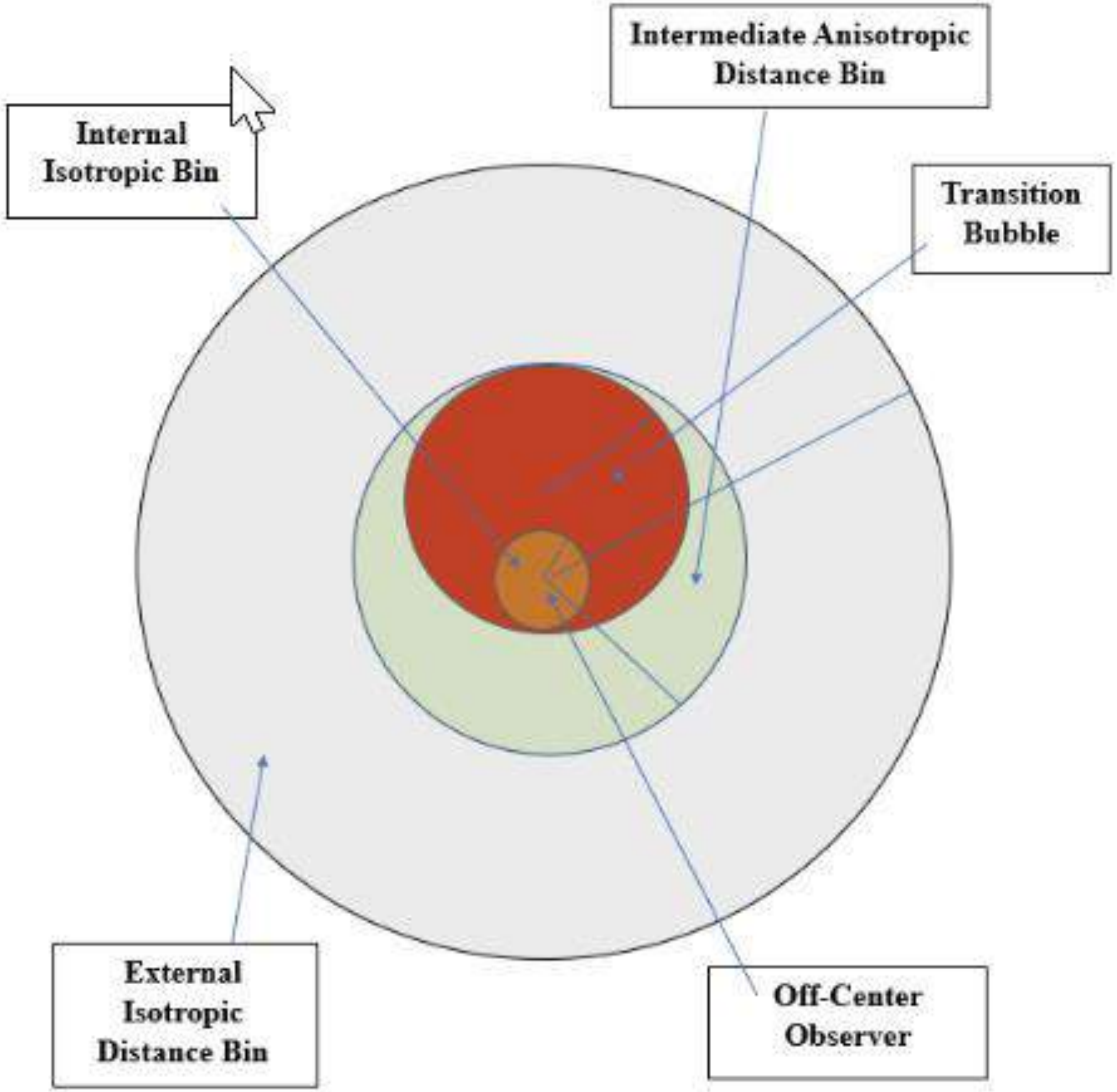
Cumulative low distance bin

Sudden change appear in anisotropy level of cumulative bin appear at about 30Mpc

How frequent are these changes in Monte-Carlo isotropc data?

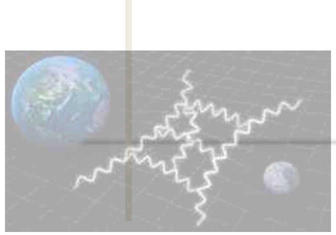


Possible Physical Realization



Off-center observer in a bubble of distinct transition physics
or
systematics

Main Questions



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