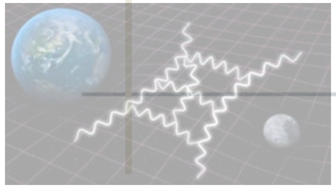
A reanalysis of the SH0ES data for H_0: Effects of new degrees of freedom on the Hubble tension

Leandros Perivolaropoulos
Department of Physics, University of Ioannina, Greece

Supported by:
H.F.R.I.
Hellenic Foundation for Research & Innovation

Slides of talk available at: https://cosmology.physics.uoi.gr/seminars/

Main Points



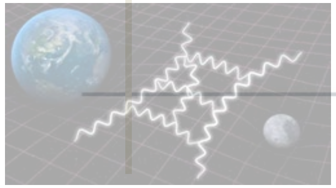
A reanalysis of the latest SH0ES data for H_0: Effects of new degrees of freedom on the Hubble tension

Leandros Perivolaropoulos (Ioannina U.), Foteini Skara (Ioannina U.) (Aug 23, 2022)

e-Print: 2208.11169 [astro-ph.CO]

1. New physics at ultra low redshifts ($z<0.02$) can lead to a resolution of the Hubble tension.
2. New degrees of freedom can be introduced in the baseline SH0ES analysis to detect such new physics signatures.
3. If a change of the SnIa absolute luminosity M_B is allowed at D_c~50Mpc (new degree of freedom) in the SH0ES analysis then the best fit value of H_0 drops from 73±1 km/(sec Mpc) to 67±4 km/(sec Mpc).
4. In the presence of the inverse distance ladder input on the SnIa absolute magnitude M_B, the transition model uncertainties drop dramatically and the extended model is strongly preferred over the SH0ES baseline model of universal value of M_B.

H_0 tension or M tension?



H_0 measurement using sound horizon standard ruler (inverse distance ladder):

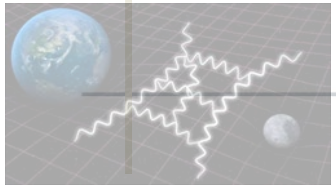
$$\theta_s = \frac{r_s}{D_A(z)} = \frac{H_0\, r_s}{\int_0^z \frac{dz}{E(z)}}$$

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

$$H_0^{\mathrm{P18}} = 67.36 \pm 0.54\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

Assumptions: P18ΛCDM E(z), Standard expansion before z_{rec}

H_0 tension or M tension?



H_0 measurement using sound horizon standard ruler (inverse distance ladder):

$$\theta_s = \frac{r_s}{D_A(z)} = \frac{H_0\, r_s}{\int_0^z \frac{dz}{E(z)}} \qquad r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Assumptions: P18ΛCDM E(z), Standard expansion before z_{rec}

$$H_0^{\mathrm{P18}} = 67.36 \pm 0.54 \ \mathrm{km\ s^{-1} Mpc^{-1}}$$

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25 \qquad \mathcal{M}_{z>0.01} = 23.80 \pm 0.01$$

M tension.

$$M_{z>0.01}^{P18} = -19.401 \pm 0.027 \quad < \quad M_B^{R21} = -19.25 \pm 0.03$$

On the use of the local prior on the absolute magnitude of Type Ia supernovae in cosmological inference

David Camarena (Espirito Santo U.), Valerio Marra (Espirito Santo U. and Trieste Observ. and Trieste U.) (Jan 21, 2021)

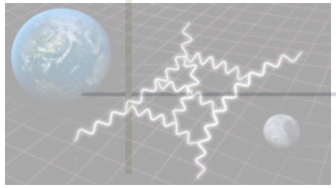
Published in: *Mon.Not.Roy.Astron.Soc.* 504 (2021) 5164-5171 • e-Print: 2101.08641 [astro-ph.CO]

Rapid transition of Geff at zt≃0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.) (Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

H_0 tension or M tension?



H_0 measurement using sound horizon standard ruler (inverse distance ladder):

$$\theta_s = \frac{r_s}{D_A(z)} = \frac{H_0\, r_s}{\int_0^z \frac{dz}{E(z)}}$$

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Assumptions: P18ΛCDM E(z), Standard expansion before z_{rec}

$$H_0^{\rm P18} = 67.36 \pm 0.54 \ {\rm km\ s^{-1} Mpc^{-1}}$$

On the use of the local prior on the absolute magnitude of Type Ia supernovae in cosmological inference

David Camarena (Espirito Santo U.), Valerio Marra (Espirito Santo U. and Trieste Observ. and Trieste U.) (Jan 21, 2021)

Published in: *Mon.Not.Roy.Astron.Soc.* 504 (2021) 5164-5171 • e-Print: 2101.08641 [astro-ph.CO]

Rapid transition of Geff at zt≃0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.) (Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

$$\mathcal{M} = M + 5 log\frac{c/H_0}{Mpc} + 25$$

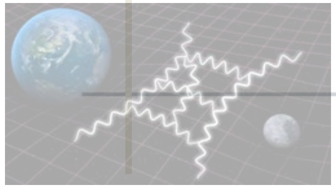
$$\mathcal{M}_{z>0.01} = 23.80 \pm 0.01$$

M tension.

$$M^{P18}_{z>0.01} = -19.401 \pm 0.027 \quad < \quad M_B^{R21} = -19.25 \pm 0.03$$

M depends on G_{eff}.

H_0 tension or M tension?



H_0 measurement using sound horizon standard ruler (inverse distance ladder):

$$\theta_s = \frac{r_s}{D_A(z)} = \frac{H_0\, r_s}{\int_0^z \frac{dz}{E(z)}}$$

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Assumptions: P18ΛCDM E(z), Standard expansion before z_{rec}

$$H_0^{\rm P18} = 67.36 \pm 0.54 \text{ km s}^{-1}\text{Mpc}^{-1}$$

On the use of the local prior on the absolute magnitude of Type Ia supernovae in cosmological inference

David Camarena (Espirito Santo U.), Valerio Marra (Espirito Santo U. and Trieste Observ. and Trieste U.) (Jan 21, 2021)

Published in: *Mon.Not.Roy.Astron.Soc.* 504 (2021) 5164-5171 • e-Print: 2101.08641 [astro-ph.CO]

Rapid transition of Geff at zt≃0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.) (Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

$$\mathcal{M}_{z>0.01} = 23.80 \pm 0.01$$

M tension.

$$M^{P18}_{z>0.01} = -19.401 \pm 0.027 \quad < \quad M_B^{R21} = -19.25 \pm 0.03$$

M depends on G_{eff}.

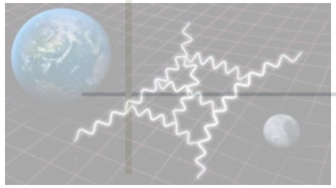
H_0 measurement using distance ladder:

$$\left.\begin{array}{l} \mathcal{M}_{z>0.01} = 23.80 \pm 0.01 \\ M_B^{R21} = -19.25 \pm 0.03 \end{array}\right\} \quad \begin{array}{l} \mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25 \\ M_{z>0.01} = M^{R20}_{z<0.01} \end{array} \Longrightarrow$$

H_0 Tension

$$H_0^{R21} = 73.04 \pm 1.04 \quad > \quad H_0^{\rm P18} = 67.36 \pm 0.54 \text{ km s}^{-1}\text{Mpc}^{-1}$$

H_0 tension or M tension?



H_0 measurement using sound horizon standard ruler (inverse distance ladder):

$$\theta_s = \frac{r_s}{D_A(z)} = \frac{H_0\, r_s}{\int_0^z \frac{dz}{E(z)}} \qquad r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Assumptions: P18ΛCDM E(z), Standard expansion before z_{rec}

$$H_0^{\rm P18} = 67.36 \pm 0.54 \ {\rm km\ s^{-1} Mpc^{-1}}$$

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25 \qquad \mathcal{M}_{z>0.01} = 23.80 \pm 0.01$$

M tension.

$$M^{P18}_{z>0.01} = -19.401 \pm 0.027 \quad < \quad M_B^{R21} = -19.25 \pm 0.03$$

On the use of the local prior on the absolute magnitude of Type Ia supernovae in cosmological inference

David Camarena (Espirito Santo U.), Valerio Marra (Espirito Santo U. and Trieste Observ. and Trieste U.) (Jan 21, 2021)

Published in: *Mon.Not.Roy.Astron.Soc.* 504 (2021) 5164-5171 • e-Print: 2101.08641 [astro-ph.CO]

Rapid transition of Geff at zt≃0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.) (Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

M depends on G_{eff}.

H_0 measurement using distance ladder:

$$\mathcal{M}_{z>0.01} = 23.80 \pm 0.01$$

$$M_B^{R21} = -19.25 \pm 0.03$$

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

$$M_{z>0.01} = M^{R20}_{z<0.01}$$

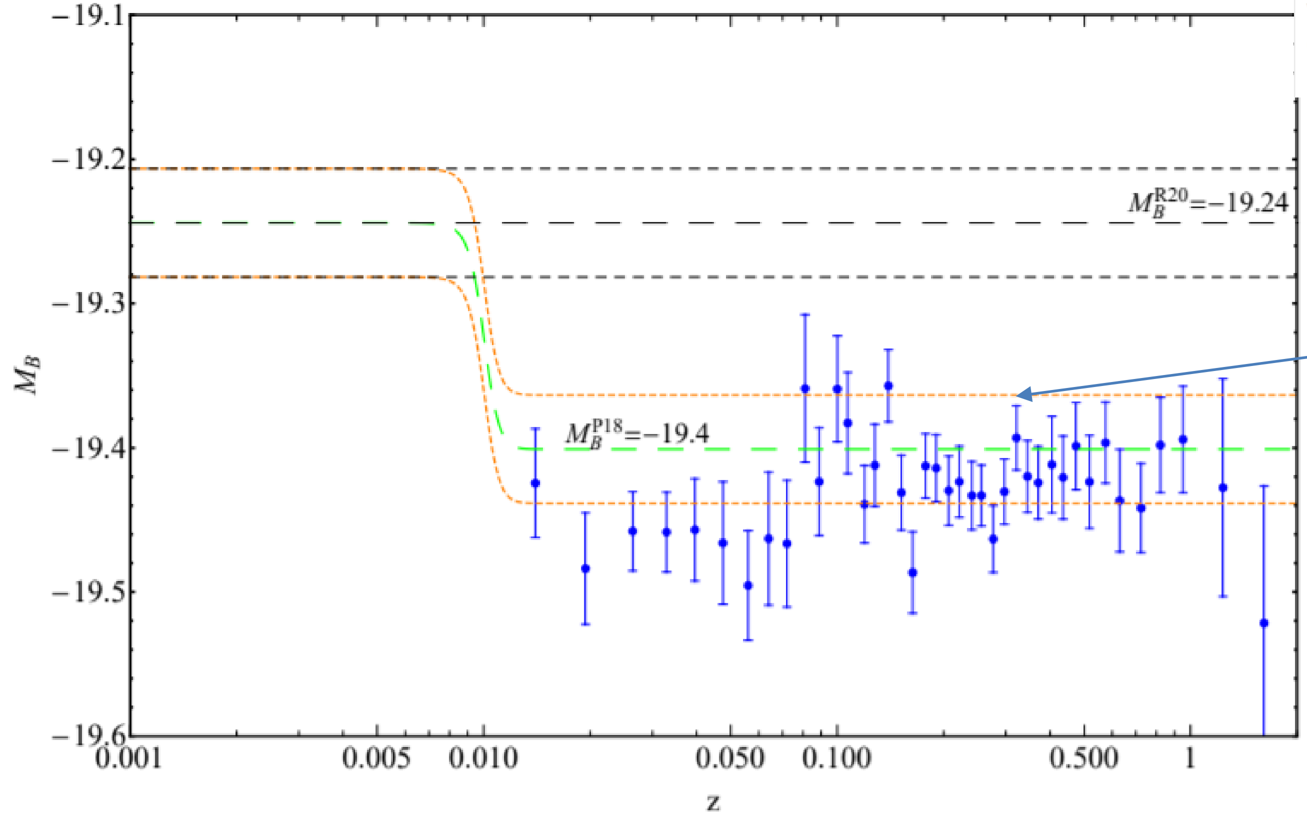
$$G_{\rm eff}(z<0.01) = G_{\rm eff}(z>0.01)$$

H_0 Tension

$$H_0^{R21} = 73.04 \pm 1.04 \quad > \quad H_0^{\rm P18} = 67.36 \pm 0.54 \ {\rm km\ s^{-1} Mpc^{-1}}$$

Assumption: G_{eff}(z<0.01)=G_{eff}(z>0.01)

The M transition hypothesis



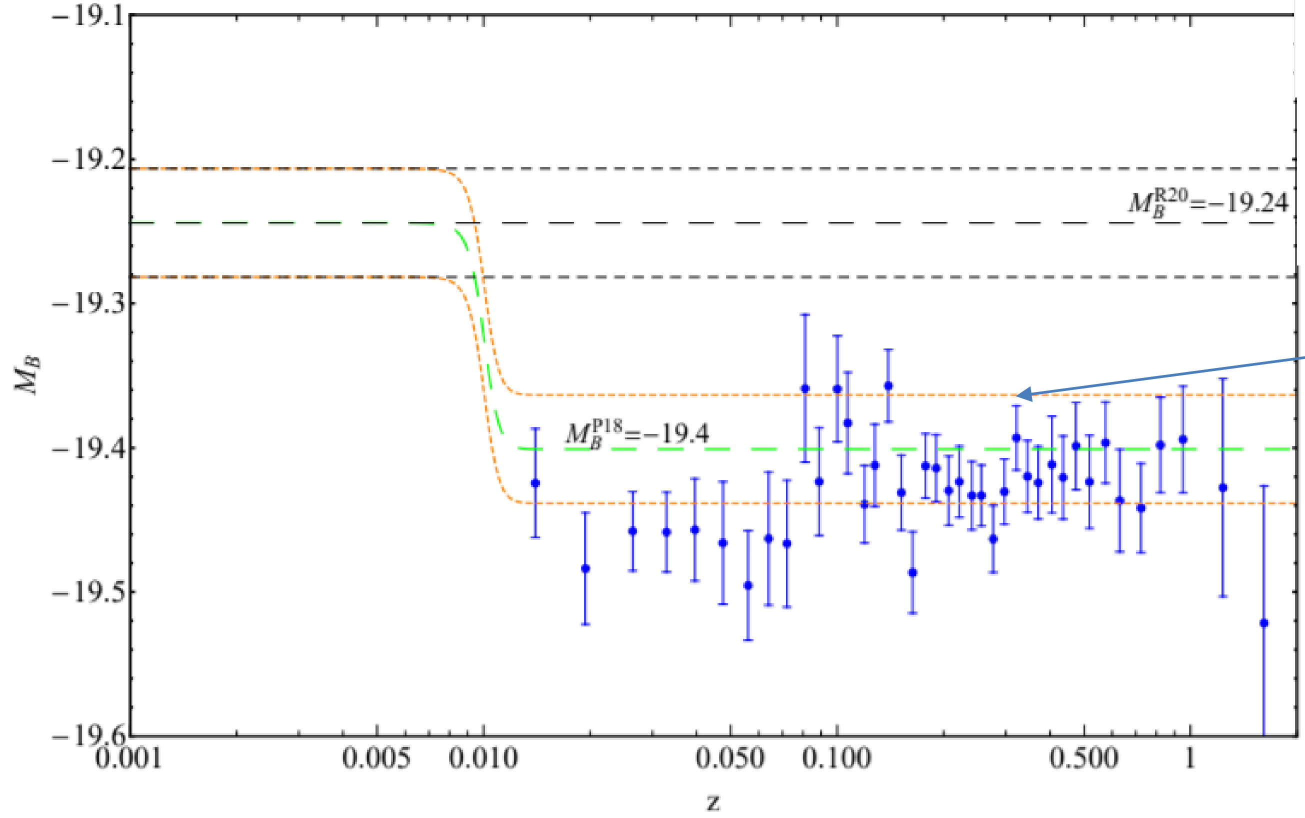
Rapid transition of Geff at zt≈0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.)
(Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

$$M_i = m(z_i) + 5\log_{10}\left[H_0^{P18}\cdot \mathrm{Mpc}/c\right] - 5\log_{10}(D_L(z_i)) - 25$$

The M transition hypothesis



Rapid transition of Geff at zt≈0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.) (Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

$w - M$ phantom transition at z_t <0.1 as a resolution of the Hubble tension

George Alestas (Ioannina U.), Lavrentios Kazantzidis (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.) (Dec 27, 2020)

Published in: *Phys.Rev.D* 103 (2021) 8, 083517 • e-Print: 2012.13932 [astro-ph.CO]

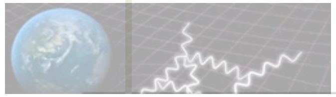
$$M_i = m(z_i) + 5\log_{10}\left[H_0^{P18}\cdot \mathrm{Mpc}/c\right] - 5\log_{10}(D_L(z_i)) - 25$$

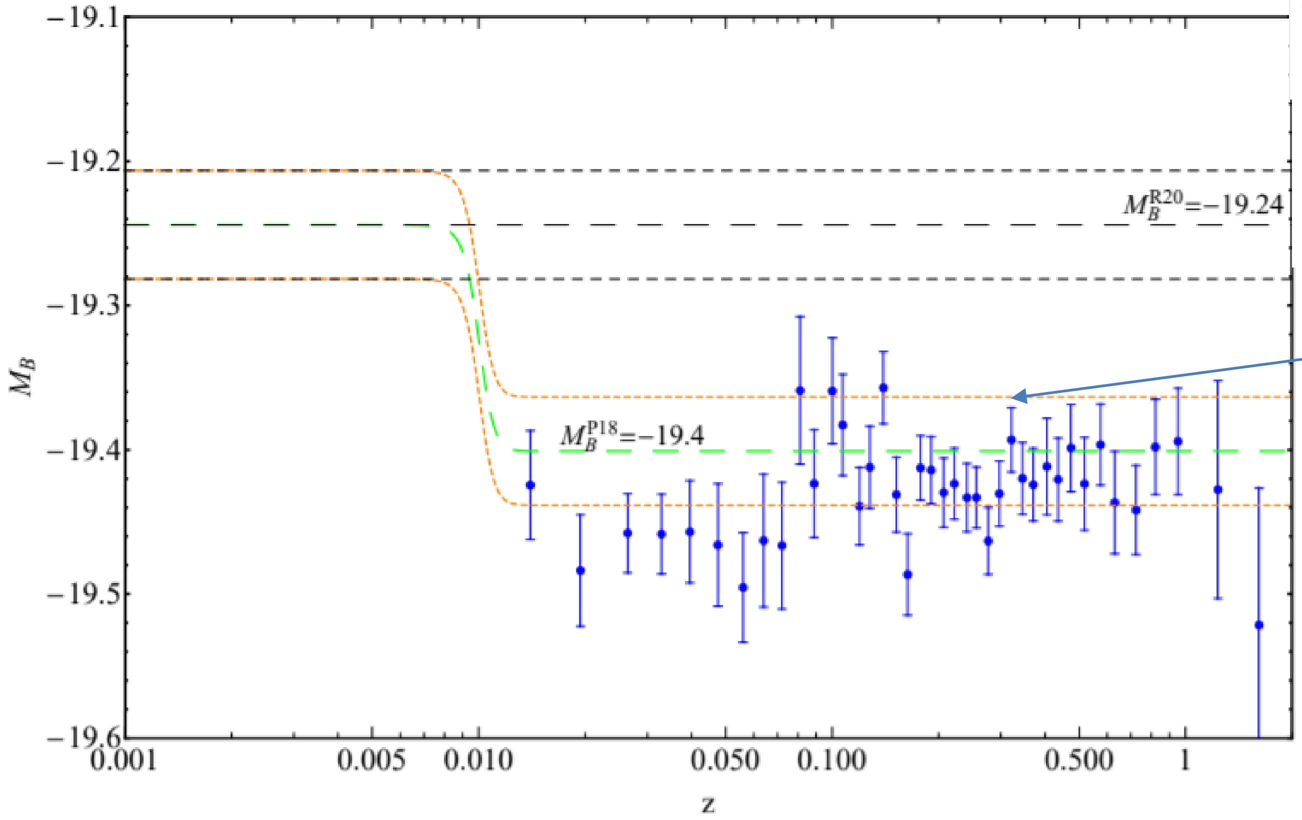
Late-transition versus smooth H(z)-deformation models for the resolution of the Hubble crisis

George Alestas (Ioannina U.), David Camarena, Eleonora Di Valentino (Sheffield U.), Lavrentios Kazantzidis (Ioannina U.), Valerio Marra (Trieste Observ. and IFPU, Trieste) et al. (Oct 8, 2021)

Published in: *Phys.Rev.D* 105 (2022) 6, 6 • e-Print: 2110.04336 [astro-ph.CO]

The M transition hypothesis





Rapid transition of Geff at zt≈0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.)
(Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

$w - M$ phantom transition at z_t <0.1 as a resolution of the Hubble tension

George Alestas (Ioannina U.), Lavrentios Kazantzidis (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.)
(Dec 27, 2020)

Published in: *Phys.Rev.D* 103 (2021) 8, 083517 • e-Print: 2012.13932 [astro-ph.CO]

$$M_i = m(z_i) + 5\log_{10}\left[H_0^{P18}\cdot {\rm Mpc}/c\right] - 5\log_{10}(D_L(z_i)) - 25$$

Late-transition versus smooth H(z)-deformation models for the resolution of the Hubble crisis

George Alestas (Ioannina U.), David Camarena, Eleonora Di Valentino (Sheffield U.), Lavrentios Kazantzidis (Ioannina U.), Valerio Marra (Trieste Observ. and IFPU, Trieste) et al. (Oct 8, 2021)

Published in: *Phys.Rev.D* 105 (2022) 6, 6 • e-Print: 2110.04336 [astro-ph.CO]

A fundamental physics transition induces a transition of M (absolute magnitude or luminosity) at $z<0.01$.

Resolves M tension and Hubble tension.

Can potentially also resolve growth tension if the transition is connected with weaker gravity at $z>z_t$

Hints for the transition in data

Intrinsic tension in the supernova sector of the local Hubble constant measurement and its implications

Radosław Wojtak, Jens Hjorth (Jun 16, 2022)

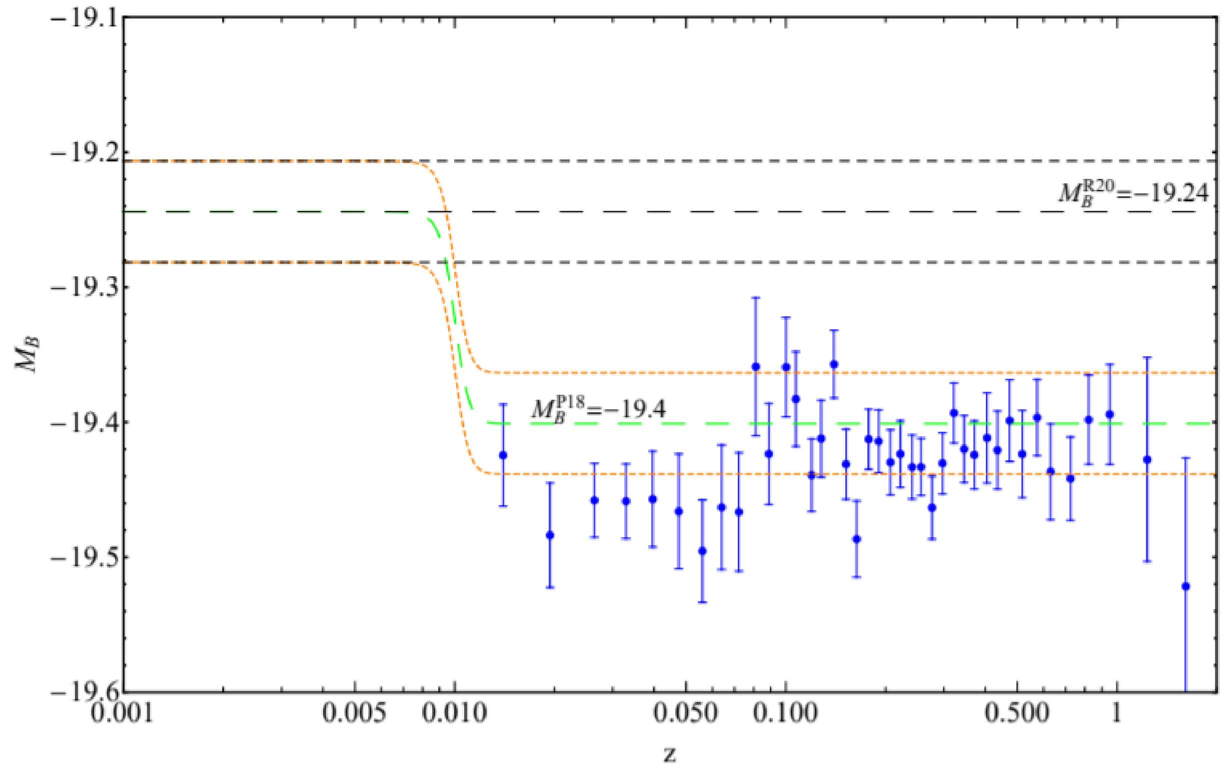
e-Print: 2206.08160 [astro-ph.CO]

A reanalysis of the latest SH0ES data for H_0: Effects of new degrees of freedom on the Hubble tension

Leandros Perivolaropoulos (Ioannina U.), Foteini Skara (Ioannina U.) (Aug 23, 2022)

e-Print: 2208.11169 [astro-ph.CO]

Gravitational Transition



Rapid transition of Geff at zt≃0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.)

(Feb 11, 2021)

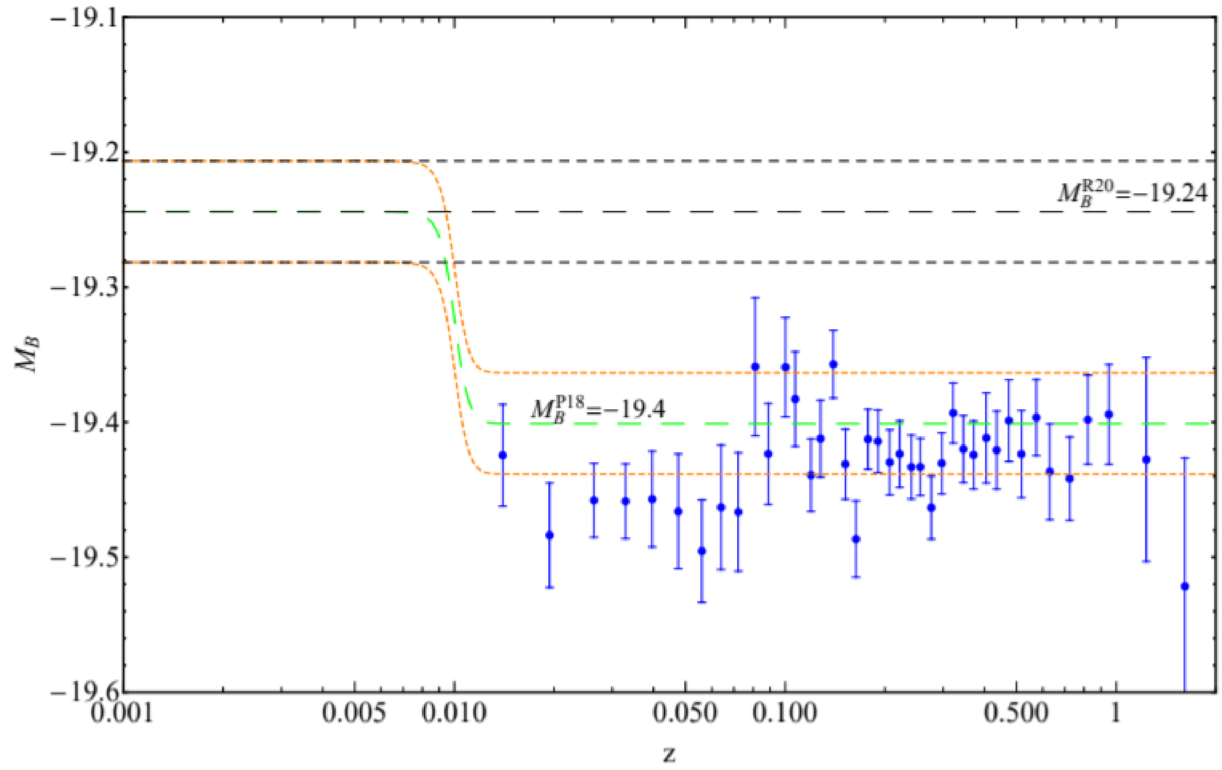
Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

SnIa luminosities in the context of a Planck/ΛCDM background

$$L \sim G_{\rm eff}^{b} \xrightarrow{\mu \equiv \frac{G_{\rm eff}}{G_{\rm N}}} \Delta M = \frac{15}{4} log_{10}\,(\mu)$$

$$L \sim M_{Chandr} \sim G^{-3/2}$$

Gravitational Transition



A 10% transition of G_{eff} is required for the reproduction of the required $\Delta M \sim 0.2$ for a pure Planck/ΛCDM background.

Rapid transition of Geff at zt≃0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.)

(Feb 11, 2021)

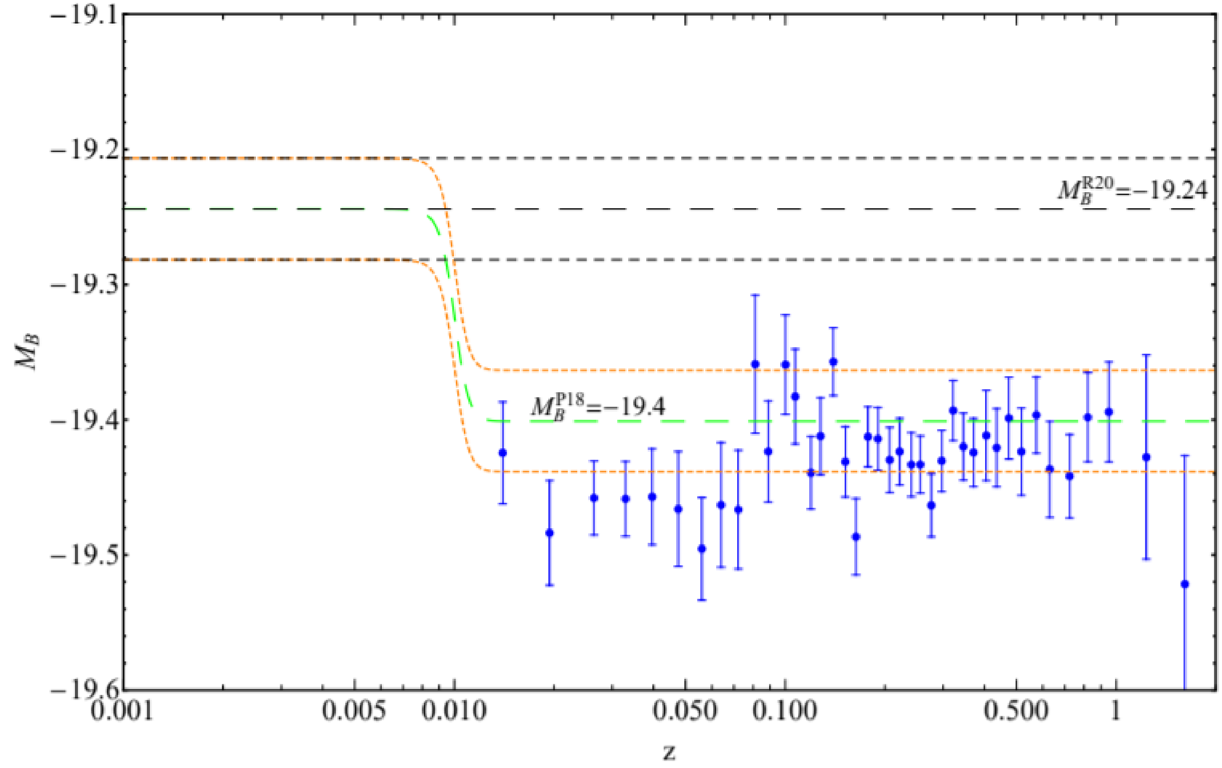
Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

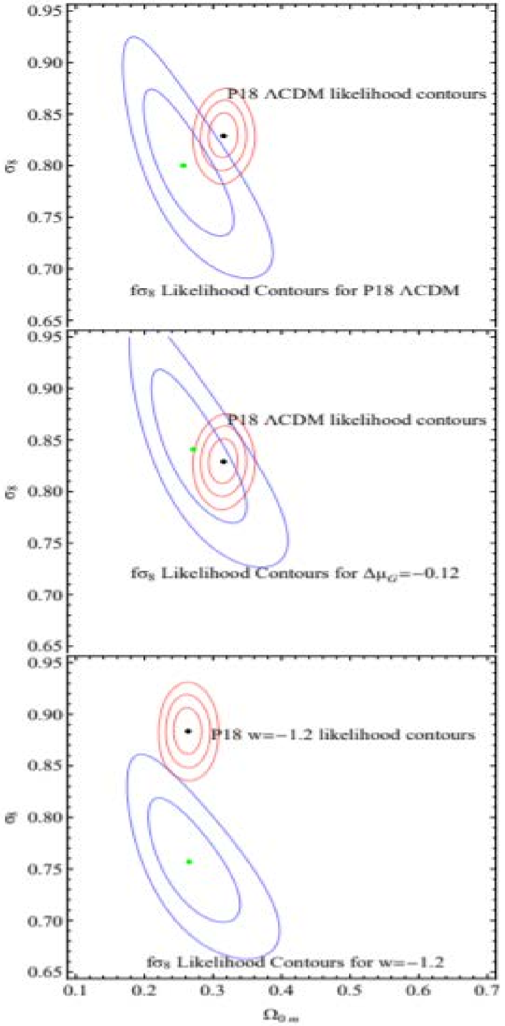
SnIa luminosities in the context of a Planck/ΛCDM background

$$L \sim G_{\rm eff}^{b} \xrightarrow{\mu \equiv \frac{G_{\rm eff}}{G_{\rm N}}} \Delta M = \frac{15}{4} log_{10}\left(\mu\right)$$

$$L \sim M_{Chandr} \sim G^{-3/2}$$

Gravitational Transition





The reduced value of G_{eff} leads to a higher σ_8 value thus resolving the growth tension

Better fit to BAO.
Growth tension resolved.
M problem resolved

A 10% transition of G_{eff} is required for the reproduction of the required ΔM~0.2 for a pure Planck/ΛCDM background.

SnIa luminosities in the context of a Planck/ΛCDM background

Rapid transition of Geff at zt≃0.01 as a possible solution of the Hubble and growth tensions

Valerio Marra (Espirito Santo U. and Trieste Observ. and SISSA, Trieste and INFN, Trieste), Leandros Perivolaropoulos (Ioannina U.)
(Feb 11, 2021)

Published in: *Phys.Rev.D* 104 (2021) 2, L021303 • e-Print: 2102.06012 [astro-ph.CO]

$$\mu \equiv \frac{G_{\rm eff}}{G_N}$$

$$L \sim G_{\rm eff}^b \quad \Longrightarrow \quad \Delta M = \frac{15}{4} log_{10}\left(\mu\right)$$

$$L \sim M_{Chandr} \sim G^{-3/2}$$

The new SH0ES measurement of H_0 : The distance ladder in practice

Use the following system of 3492 equations fit for 47 unknown parameters

jth Cepheid in ith galaxy

$$m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j}$$

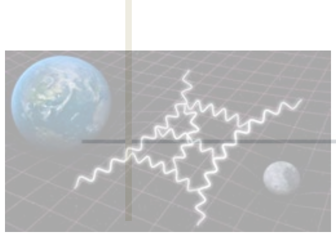
Cepheid calibration

$$m_{B,i} = \mu_i + M_B$$

SnIa calibration

$$m_{B,i} - 5\log D_L(z_i) - 25 = M_B - 5\log H_0$$

$m=\mu(H_0)+M_B$ ->Hubble flow SnIa



The new SH0ES measurement of H_0 : The distance ladder in practice

Use the following system of 3492 equations fit for 47 unknown parameters

jth Cepheid in ith galaxy

$$m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j}$$

Cepheid calibration

$$m_{B,i} = \mu_i + M_B$$

SnIa calibration

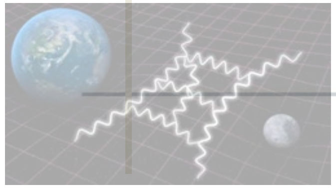
$$m_{B,i} - 5\log D_L(z_i) - 25 = M_B - 5\log H_0$$

$m=\mu(H_0)+M_B$ ->Hubble flow SnIa

$$\mathbf{q}=\left.\begin{pmatrix} \mu_1 \\ \cdots \\ \mu_{37} \\ \Delta\mu_{N4258} \\ M^W_H \\ \Delta\mu_{LMC} \\ \mu_{M31} \\ \Delta b_W \\ M_B \\ Z_W \\ X \\ \Delta zp \\ 5\log H_0 \end{pmatrix}\right\}\ 47\ \text{parameters}$$

$$b_W = b_W^0 + \Delta b_W \equiv -3.286 + \Delta b_W$$

The new SH0ES measurement of H_0 : The distance ladder in practice



Use the following system of 3492 equations fit for 47 unknown parameters

jth Cepheid in ith galaxy

$$m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j}$$

Cepheid calibration

$$m_{B,i} = \mu_i + M_B$$

SnIa calibration

$$m_{B,i} - 5\log D_L(z_i) - 25 = M_B - 5\log H_0$$

$m=\mu(H_0)+M_B$ ->Hubble flow SnIa

$$\mathbf{q} = \left.\begin{pmatrix} \mu_1 \\ \ldots \\ \mu_{37} \\ \Delta\mu_{N4258} \\ M^W_H \\ \Delta\mu_{LMC} \\ \mu_{M31} \\ \Delta b_W \\ M_B \\ Z_W \\ X \\ \Delta zp \\ 5\log H_0 \end{pmatrix}\right\} \text{47 parameters}$$

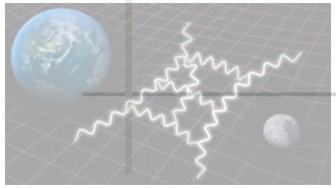
$$b_W = b^0_W + \Delta b_W \equiv -3.286 + \Delta b_W$$

Express the system as linear vector transformation

$$\mathbf{Y} = \mathbf{Lq}$$

Minimize χ^2: $\chi^2 = (\mathbf{Y} - \mathbf{Lq})^{\mathbf{T}}\mathbf{C}^{-1}(\mathbf{Y} - \mathbf{Lq})$

The new SH0ES measurement of H_0 : The distance ladder in practice



Use the following system of 3492 equations fit for 47 unknown parameters

jth Cepheid in ith galaxy

$$m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j}$$

Cepheid calibration

$$m_{B,i} = \mu_i + M_B \longleftarrow M_B^{R21} = -19.25 \pm 0.03$$

SnIa calibration

$$m_{B,i} - 5\log D_L(z_i) - 25 = M_B - 5\log H_0$$

$m=\mu(H_0)+M_B$ ->Hubble flow SnIa

$$H_0 = 73.04 \pm 1.04\, km\, s^{-1}\, Mpc^{-1}$$

$$\mathbf{q}= \left.\begin{pmatrix} \mu_1 \\ \dots \\ \mu_{37} \\ \Delta\mu_{N4258} \\ M_H^W \\ \Delta\mu_{LMC} \\ \mu_{M31} \\ \Delta b_W \\ M_B \\ Z_W \\ X \\ \Delta zp \\ 5\log H_0 \end{pmatrix}\right\} \text{47 parameters}$$

$$b_W = b_W^0 + \Delta b_W \equiv -3.286 + \Delta b_W$$

Express the system as linear vector transformation

$$\mathbf{Y} = \mathbf{Lq}$$

Minimize χ^2: $\chi^2 = (\mathbf{Y} - \mathbf{Lq})^{\mathbf{T}}\mathbf{C}^{-1}(\mathbf{Y} - \mathbf{Lq})$

The matrix equation

$$\mathbf{Y} = \mathbf{Lq}$$

Minimize χ^2: $\chi^2 = (\mathbf{Y} - \mathbf{Lq})^{\mathbf{T}} \mathbf{C}^{-1} (\mathbf{Y} - \mathbf{Lq})$

Anchor constraints:

$$\begin{aligned}
M_H^W &= -5.803 \pm 0.082 \\
M_H^W &= -5.903 \pm 0.025 \\
Z_W &= -0.21 \pm 0.12 \\
X &= 0 \pm 0.00003 \\
\Delta zp &= 0 \pm 0.1 \\
\Delta b_W &= 0 \pm 10 \\
\Delta \mu_{N4258} &= 0 \pm 0.03 \\
\Delta \mu_{LMC} &= 0 \pm 0.026
\end{aligned}$$

$$m_{H,i,j}^W = \mu_i + M_H^W + b_W [P]_{i,j} + Z_W [O/H]_{i,j} \qquad m_{B,i} = \mu_i + M_B \qquad m_{B,i} - 5\log D_L(z_i) - 25 = M_B - 5\log H_0$$

$$\mathbf{Y} = \begin{pmatrix}
\bar{m}_{H,1}^W \\ \dots \\ \bar{m}_{H,2150}^W \\ \hline
\bar{m}_{H,N4258,1}^W - \mu_{0,N4258} \\ \dots \\ \bar{m}_{H,N4258,443}^W - \mu_{0,N4258} \\ \bar{m}_{H,M31,1}^W \\ \dots \\ \bar{m}_{H,M31,55}^W \\ \bar{m}_{H,LMC,ground,1}^W - \mu_{0,LMC} \\ \dots \\ \bar{m}_{H,LMC,ground,270}^W - \mu_{0,LMC} \\ \bar{m}_{H,SMC,ground,1}^W - \mu_{0,SMC} \\ \dots \\ \bar{m}_{H,SMC,ground,143}^W - \mu_{0,SMC} \\ \bar{m}_{H,LMC,HST,1}^W - \mu_{0,LMC} \\ \dots \\ \bar{m}_{H,LMC,HST,69}^W - \mu_{0,LMC} \\ \hline
m_{B,1}^0 \\ \dots \\ m_{B,77}^0 \\ \hline
-5.803\ (M_{H,HST}^W) \\ -5.903\ (M_{H,Gaia}^W) \\ -0.21\ (Z_{W,Gaia}) \\ 0\ (X) \\ 0\ (\Delta zp) \\ 0\ (\Delta b_W) \\ 0\ (\Delta \mu_{N4258}) \\ 0\ (\Delta \mu_{LMC}) \\ \hline
m_{B,1}^0 - 5\log[cz_1(\dots)] - 25 \\ \dots \\ m_{B,277}^0 - 5\log[cz_{277}(\dots)] - 25
\end{pmatrix}$$

2150 Cepheids in 37 SnIa hosts
980 Cepheids in non SnIa hosts
77 SnIa in Cepheid hosts
8 External constraints
277 SnIa in Hubble flow

$$\mathbf{L} = \begin{pmatrix}
1 & \dots & 0 & 0 & 1 & 0 & 0 & [P]_1 & 0 & [O/H]_1 & 0 & 0 & 0 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 1 & 0 & 1 & 0 & 0 & [P]_{2150} & 0 & [O/H]_{2150} & 0 & 0 & 0 \\ \hline
0 & \dots & 0 & 1 & 1 & 0 & 0 & [P]_{N4258,1} & 0 & [O/H]_{N4258,1} & 0 & 0 & 0 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 0 & 1 & 1 & 0 & 0 & [P]_{N4258,443} & 0 & [O/H]_{N4258,443} & 0 & 0 & 0 \\
0 & \dots & 0 & 0 & 1 & 0 & 1 & [P]_{M31,1} & 0 & [O/H]_{M31,1} & 0 & 0 & 0 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 0 & 0 & 1 & 0 & 1 & [P]_{M31,55} & 0 & [O/H]_{M31,55} & 0 & 0 & 0 \\
0 & \dots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,ground,1} & 0 & [O/H]_{LMC,ground,1} & 0 & 1 & 0 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,ground,270} & 0 & [O/H]_{LMC,ground,270} & 0 & 1 & 0 \\
0 & \dots & 0 & 0 & 1 & 1 & 0 & [P]_{SMC,ground,1} & 0 & [O/H]_{SMC,ground,1} & 0 & 1 & 0 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 0 & 0 & 1 & 1 & 0 & [P]_{SMC,ground,143} & 0 & [O/H]_{SMC,ground,143} & 0 & 1 & 0 \\
0 & \dots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,HST,1} & 0 & [O/H]_{LMC,HST,1} & 0 & 0 & 0 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,HST,69} & 0 & [O/H]_{LMC,HST,69} & 0 & 0 & 0 \\ \hline
1 & \dots & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ \hline
0 & \dots & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \dots & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \dots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & \dots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & \dots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & \dots & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & \dots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \dots & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline
0 & \dots & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
0 & \dots & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1
\end{pmatrix}$$

2150 Cepheids in 37 SnIa hosts
980 Cepheids in non SnIa hosts
77 SnIa in Cepheid hosts
8 External constraints
277 SnIa in Hubble flow

$$\mathbf{q} = \begin{pmatrix} \mu_1 \\ \dots \\ \mu_{37} \\ \Delta\mu_{N4258} \\ M_H^W \\ \Delta\mu_{LMC} \\ \mu_{M31} \\ \Delta b_W \\ M_B \\ Z_W \\ X \\ \Delta zp \\ 5\log H_0 \end{pmatrix}$$

47 parameters

The matrix equation

$$\mathbf{Y} = \mathbf{Lq}$$

Minimize χ^2: $\chi^2 = (\mathbf{Y} - \mathbf{Lq})^{\mathbf{T}}\mathbf{C}^{-1}(\mathbf{Y} - \mathbf{Lq})$

$$m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j} \qquad m_{B,i} = \mu_i + M_B \qquad m_{B,i} - 5\log D_L(z_i) - 25 = M_B - 5\log H_0$$

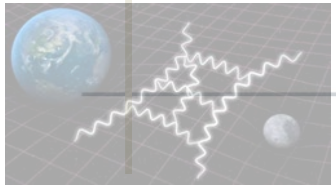
$$\mathbf{C}=\left(\begin{array}{cccccccccccccccccccc}
\sigma^2_{tot,1} & \ldots & Z_{cov} & Z_{cov} & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
Z_{cov} & \ldots & \sigma^2_{tot,37} & Z_{cov} & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
\hline
Z_{cov} & \ldots & Z_{cov} & \sigma^2_{tot,N4258} & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & \sigma^2_{tot,M31} & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & \sigma^2_{tot,LMC} & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
\hline
0 & \ldots & 0 & 0 & 0 & 0 & \sigma^2_{M_B,1} & \ldots & Sn_{cov} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Sn_{cov} & \ldots & Sn_{cov} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 0 & 0 & 0 & Sn_{cov} & \ldots & \sigma^2_{M_B,77} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Sn_{cov} & \ldots & Sn_{cov} \\
\hline
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & \sigma^2_{M^W_H,HST} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & \sigma^2_{M^W_H,Gaia} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & \sigma^2_{Z_W,Gaia} & 0 & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & \sigma^2_x & 0 & 0 & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & \sigma^2_{ground,zp} & 0 & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{b_W} & 0 & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{\mu,N4258} & 0 & 0 & \ldots & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{\mu,LMC} & 0 & \ldots & 0 \\
\hline
0 & \ldots & 0 & 0 & 0 & 0 & Sn_{cov} & \ldots & Sn_{cov} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{M_B,z,1} & \ldots & Sn_{cov} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 0 & 0 & 0 & Sn_{cov} & \ldots & Sn_{cov} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Sn_{cov} & \ldots & \sigma^2_{M_B,z,277}
\end{array}\right)$$

$$\mathbf{Y} = \left(\begin{array}{c}
\bar{m}^W_{H,1} \\ \ldots \\ \bar{m}^W_{H,2150} \\
\hline
\bar{m}^W_{H,N4258,1} - \mu_{0,N4258} \\ \ldots \\ \bar{m}^W_{H,N4258,443} - \mu_{0,N4258} \\ \bar{m}^W_{H,M31,1} \\ \ldots \\ \bar{m}^W_{H,M31,55} \\ \bar{m}^W_{H,LMC,ground,1} - \mu_{0,LMC} \\ \ldots \\ \bar{m}^W_{H,LMC,ground,270} - \mu_{0,LMC} \\ \bar{m}^W_{H,SMC,ground,1} - \mu_{0,SMC} \\ \ldots \\ \bar{m}^W_{H,SMC,ground,143} - \mu_{0,SMC} \\ \bar{m}^W_{H,LMC,HST,1} - \mu_{0,LMC} \\ \ldots \\ \bar{m}^W_{H,LMC,HST,69} - \mu_{0,LMC} \\
\hline
m^0_{B,1} \\ \ldots \\ m^0_{B,77} \\
\hline
-5.803\ (M^W_{H,HST}) \\ -5.903\ (M^W_{H,Gaia}) \\ -0.21\ (Z_{W,Gaia}) \\ 0\ (X) \\ 0\ (\Delta zp) \\ 0\ (\Delta b_W) \\ 0\ (\Delta\mu_{N4258}) \\ 0\ (\Delta\mu_{LMC}) \\
\hline
m^0_{B,1} - 5\log[cz_1(\ldots)] - 25 \\ \ldots \\ m^0_{B,277} - 5\log[cz_{277}(\ldots)] - 25
\end{array}\right)
\begin{array}{l}
\left.\vphantom{\begin{array}{c}a\\a\\a\end{array}}\right\} 2150\ \text{Cepheids in 37 SnIa hosts} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\end{array}}\right\} 980\ \text{Cepheids in non SnIa hosts} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\end{array}}\right\} 77\ \text{SnIa in Cepheid hosts} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\\a\\a\\a\\a\\a\end{array}}\right\} 8\ \text{External constraints} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\end{array}}\right\} 277\ \text{SnIa in Hubble flow}
\end{array}$$

$$\mathbf{L} = \left(\begin{array}{ccccccccccccc}
1 & \ldots & 0 & 0 & 1 & 0 & 0 & [P]_1 & 0 & [O/H]_1 & 0 & 0 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 1 & 0 & 1 & 0 & 0 & [P]_{2150} & 0 & [O/H]_{2150} & 0 & 0 & 0 \\
\hline
0 & \ldots & 0 & 1 & 1 & 0 & 0 & [P]_{N4258,1} & 0 & [O/H]_{N4258,1} & 0 & 0 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 1 & 1 & 0 & 0 & [P]_{N4258,443} & 0 & [O/H]_{N4258,443} & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 1 & 0 & 1 & [P]_{M31,1} & 0 & [O/H]_{M31,1} & 0 & 0 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 0 & 1 & 0 & 1 & [P]_{M31,55} & 0 & [O/H]_{M31,55} & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,ground,1} & 0 & [O/H]_{LMC,ground,1} & 0 & 1 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,ground,270} & 0 & [O/H]_{LMC,ground,270} & 0 & 1 & 0 \\
0 & \ldots & 0 & 0 & 1 & 1 & 0 & [P]_{SMC,ground,1} & 0 & [O/H]_{SMC,ground,1} & 0 & 1 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 0 & 1 & 1 & 0 & [P]_{SMC,ground,143} & 0 & [O/H]_{SMC,ground,143} & 0 & 1 & 0 \\
0 & \ldots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,HST,1} & 0 & [O/H]_{LMC,HST,1} & 0 & 0 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 0 & 1 & 1 & 0 & [P]_{LMC,HST,69} & 0 & [O/H]_{LMC,HST,69} & 0 & 0 & 0 \\
\hline
1 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
\hline
0 & \ldots & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hline
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1
\end{array}\right)
\begin{array}{l}
\left.\vphantom{\begin{array}{c}a\\a\\a\end{array}}\right\} 2150\ \text{Cepheids in 37 SnIa hosts} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\\a\end{array}}\right\} 980\ \text{Cepheids in non SnIa hosts} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\end{array}}\right\} 77\ \text{SnIa in Cepheid hosts} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\\a\\a\\a\\a\\a\end{array}}\right\} 8\ \text{External constraints} \\
\left.\vphantom{\begin{array}{c}a\\a\\a\end{array}}\right\} 277\ \text{SnIa in Hubble flow}
\end{array}$$

$$\mathbf{q}= \left.\begin{pmatrix} \mu_1 \\ \ldots \\ \mu_{37} \\ \Delta\mu_{N4258} \\ M^W_H \\ \Delta\mu_{LMC} \\ \mu_{M31} \\ \Delta b_W \\ M_B \\ Z_W \\ X \\ \Delta zp \\ 5\log H_0 \end{pmatrix}\right\} 47\ \text{parameters}$$

Analytic minimization of χ^2



$$\mathbf{Y} = \mathbf{L}\mathbf{q}$$

Minimize χ^2: $\chi^2 = (\mathbf{Y} - \mathbf{L}\mathbf{q})^T \mathbf{C}^{-1} (\mathbf{Y} - \mathbf{L}\mathbf{q})$

Best fit parameter values:

$$\chi^2 = (\mathbf{Y} - \mathbf{L}\mathbf{q})^T \mathbf{C}^{-1} (\mathbf{Y} - \mathbf{L}\mathbf{q}) = \mathbf{q}^T \mathbf{L}^T \mathbf{C}^{-1} \mathbf{L}\mathbf{q} - 2\mathbf{q}^T \mathbf{L}^T \mathbf{C}^{-1} \mathbf{Y} + \mathbf{Y}^T \mathbf{C}^{-1} \mathbf{Y}$$

$$\left.\frac{\partial \chi^2}{\partial \mathbf{q}}\right|_{\mathbf{q}_{best}} = 0 => 2\mathbf{L}^T \mathbf{C}^{-1} \mathbf{L}\mathbf{q}_{\mathbf{best}} - 2\mathbf{L}^T \mathbf{C}^{-1} \mathbf{Y} = 0$$

$$\Rightarrow \quad \mathbf{q}_{\mathbf{best}} = (\mathbf{L}^T \mathbf{C}^{-1} \mathbf{L})^{-1} \mathbf{L}^T \mathbf{C}^{-1} \mathbf{Y}$$

1σ errors of best fit parameters are diagonal elements of transformed covariance matrix:

$$\Sigma_{\mathbf{kl}} = \sum_{\mathbf{i}} \sum_{\mathbf{j}} \left[\frac{\partial \mathbf{q}_{\mathbf{best,k}}}{\partial \mathbf{Y}_{\mathbf{i}}}\right] \mathbf{C}_{\mathbf{ij}} \left[\frac{\partial \mathbf{q}_{\mathbf{best,l}}}{\partial \mathbf{Y}_{\mathbf{j}}}\right] \quad \Rightarrow \quad \Sigma = (\mathbf{L}^T \mathbf{C}^{-1} \mathbf{L})^{-1}$$

Best fit parameter values

Excellent agreement with published SH0ES result of baseline analysis for H_0.

Parameter	Best fit value	σ
μ_{N1309}	32.51	0.05
μ_{N1365}	31.33	0.05
μ_{N1448}	31.3	0.04
μ_{N1559}	31.46	0.05
μ_{N2442}	31.47	0.05
μ_{N2525}	32.01	0.06
	...	
μ_{U9391}	32.82	0.05
$\Delta\mu_{N4258}$	-0.01	0.02
M_H^W	-5.89	0.02
$\Delta\mu_{LMC}$	0.01	0.02
μ_{M31}	24.37	0.07
Δb_W	-0.013	0.015
M_B	-19.25	0.03
Z_W	-0.22	0.05
X	0.	0.
Δzp	-0.07	0.01
$5 \log H_0$	9.32	0.03
H_0	73.04	1.04

M tension

H_0 tension

Best fit parameter values

Parameter	Best fit value	σ
μ_{N1309}	32.51	0.05
μ_{N1365}	31.33	0.05
μ_{N1448}	31.3	0.04
μ_{N1559}	31.46	0.05
μ_{N2442}	31.47	0.05
μ_{N2525}	32.01	0.06
...		
μ_{U9391}	32.82	0.05
$\Delta\mu_{N4258}$	-0.01	0.02
$\boxed{M_H^W}$	-5.89	0.02
$\Delta\mu_{LMC}$	0.01	0.02
μ_{M31}	24.37	0.07
$\boxed{\Delta b_W}$	-0.013	0.015
$\boxed{M_B}$	-19.25	0.03
$\boxed{Z_W}$	-0.22	0.05
X	0.	0.
Δzp	-0.07	0.01
$\boxed{5 \log H_0}$	9.32	0.03
$\boxed{H_0}$	73.04	1.04

Excellent agreement with published SH0ES result of baseline analysis for H_0.

Main questions:

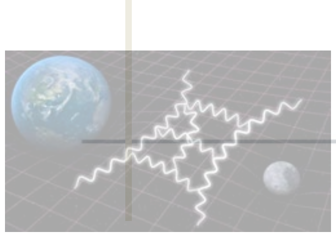
1. Self-consistency test: Are the values of the Cepheid modeling parameters b_{Wi} and Z_{Wi} obtained from each host i consistent with a universal value for each parameter?

2. Extension of baseline analysis with new degrees of freedom: How can new degrees of freedom and/or constraints be included in a generalized analysis?

M tension

H_0 tension

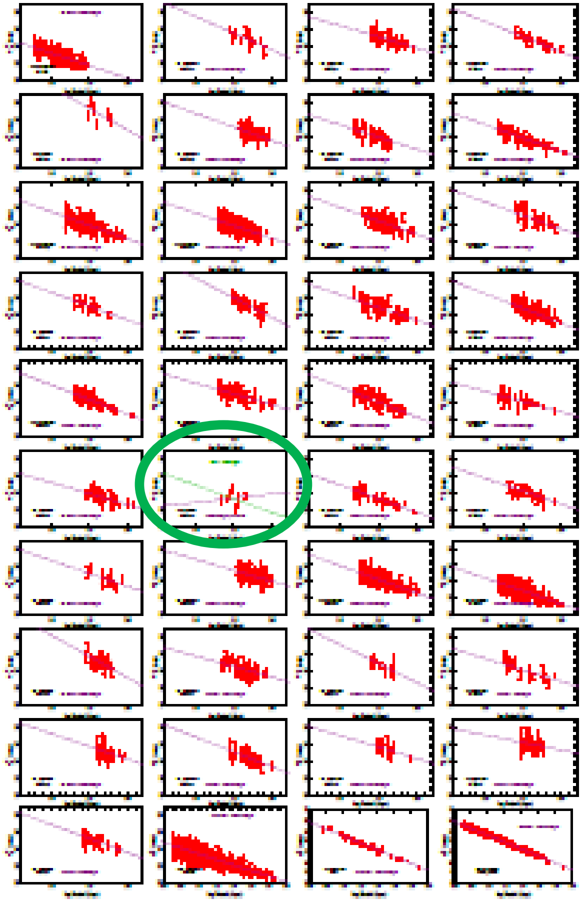
Self consistency test I
Modeling parameter b_{Wi} in each host

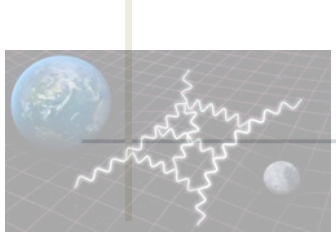


Find best fit b_{Wi} slope and intercept s_i in each Cepheid host i
(37 SnIa+Cepheid + 3 pure Cepheid hosts)

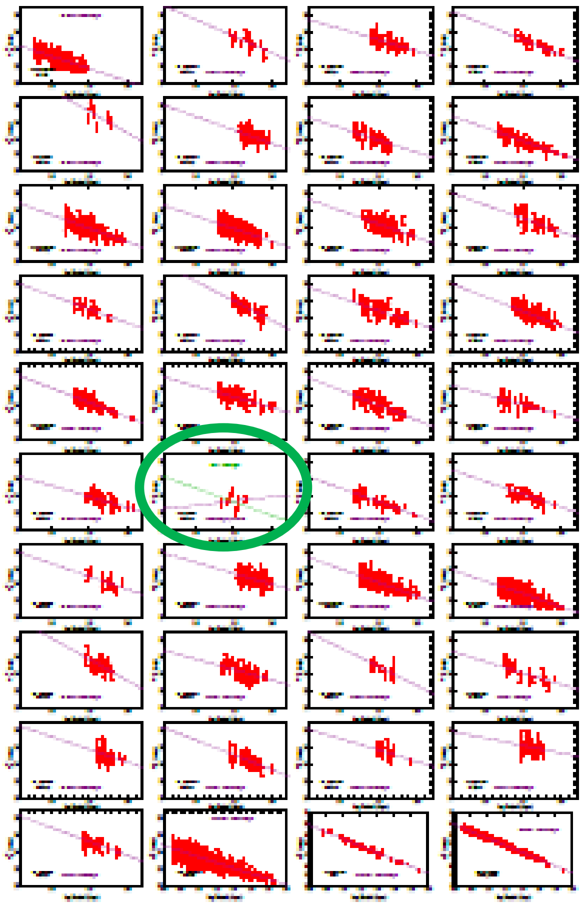
$$m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j} \Rightarrow m^W_{H,i,j} = s_i + b_{W,i}\log P_i$$

Best fit m_H^W-logP slopes:





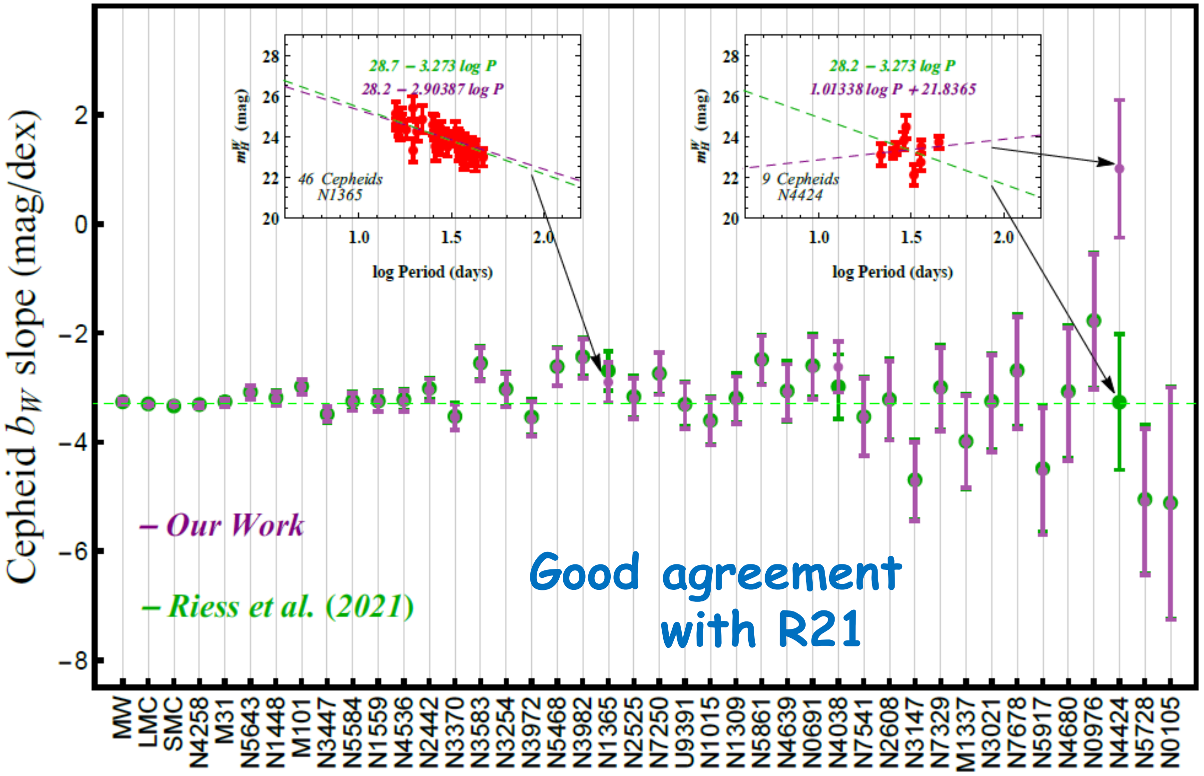
Best fit m_H^W-logP slopes:



Self consistency test I
Modeling parameter b_{Wi} in each host

Find best fit b_{Wi} slope and intercept s_i in each Cepheid host i
(37 SnIa+Cepheid + 3 pure Cepheid hosts)

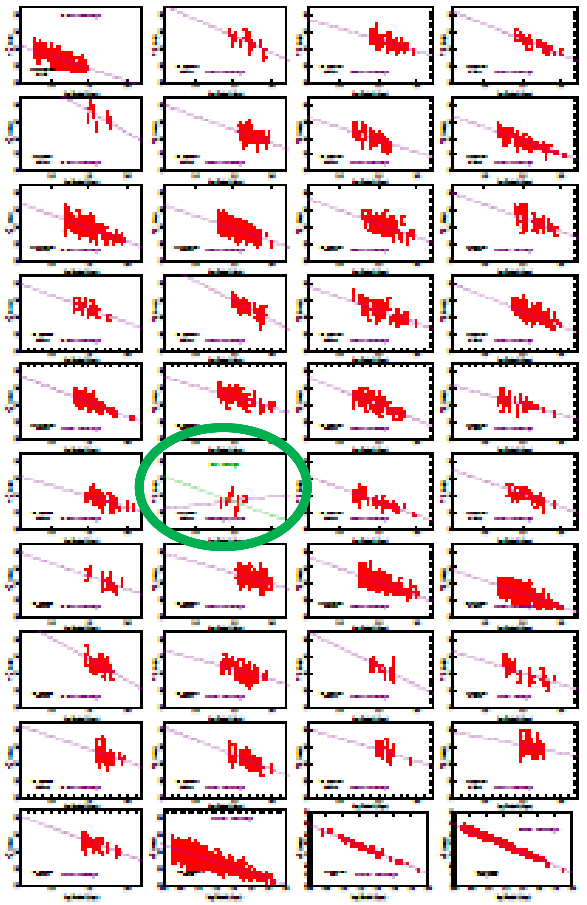
$$m_{H,i,j}^{W} = \mu_i + M_H^W + b_W[P]_{i,j} + Z_W[O/H]_{i,j} \;\Rightarrow\; m_{H,i,j}^{W} = s_i + b_{W,i}\log P_i$$



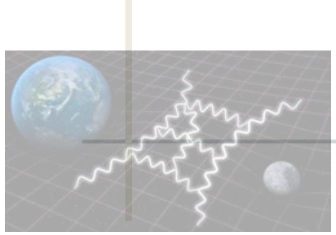
Consistency with universal slope b_W:

$$\chi^2(b_W) = \sum_{i=1}^{N} \frac{(b_{W,i} - b_W)^2}{\sigma_{b_{W,i}}^2} \;\Rightarrow\; \frac{\chi^2_{bW,min}}{dof} = 1.55 \quad >1$$

Best fit m_H^W-logP slopes:

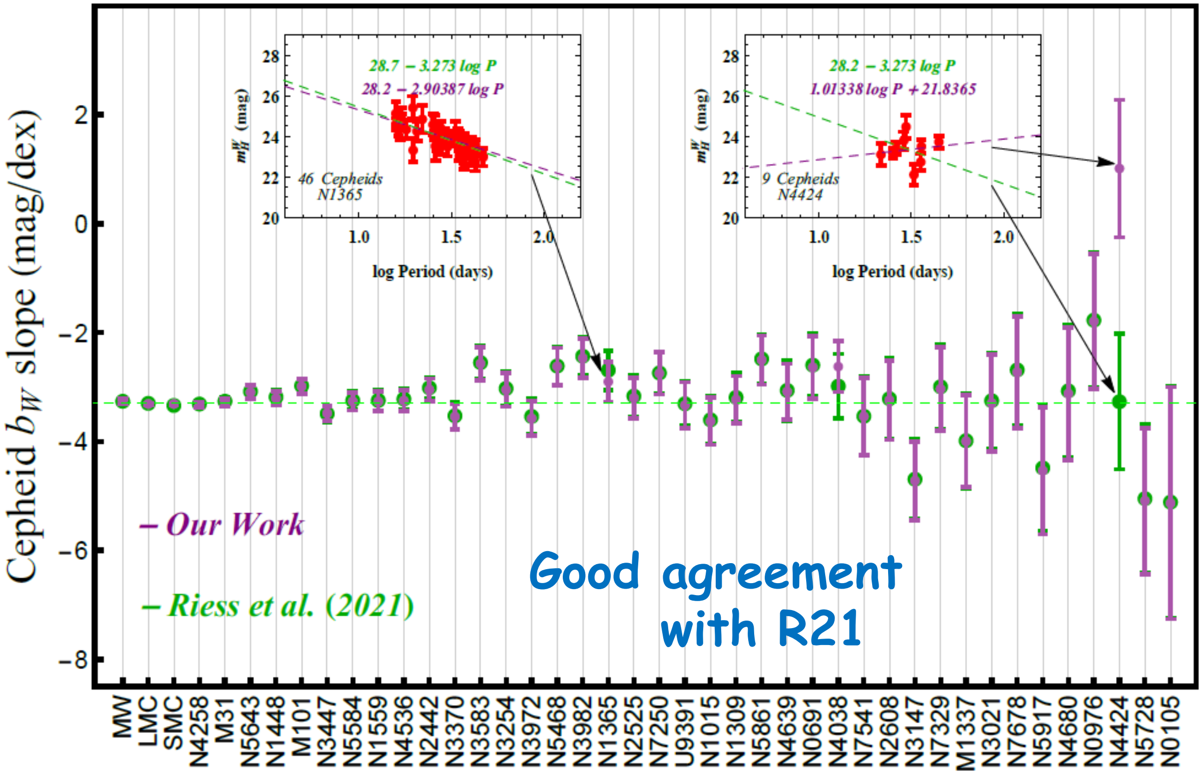


Self consistency test I
Modeling parameter b_{Wi} in each host



Find best fit b_{Wi} slope and intercept s_i in each Cepheid host i
(37 SnIa+Cepheid + 3 pure Cepheid hosts)

$$m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j} \quad \Longrightarrow \quad m^W_{H,i,j} = s_i + b_{W,i}\log P_i$$



Good agreement with R21

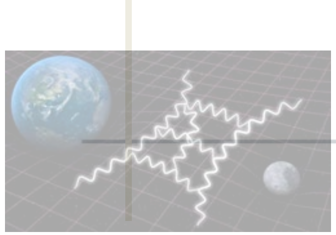
Consistency with universal slope b_W:

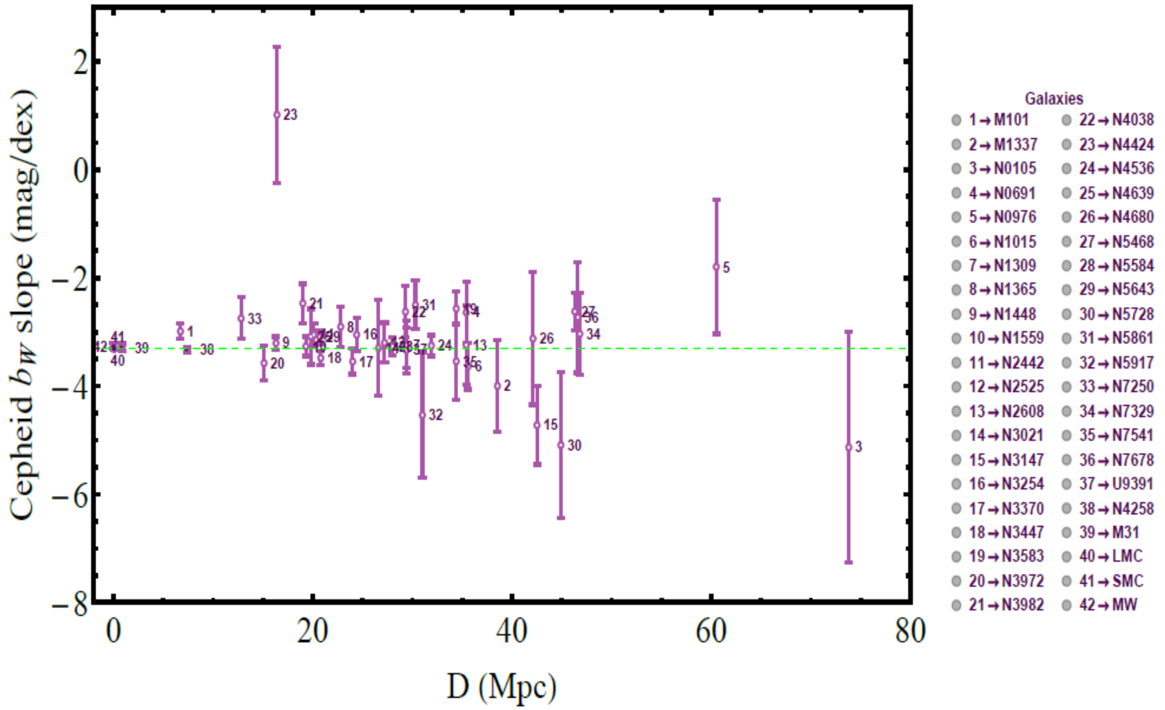
$$\chi^2(b_W) = \sum_{i=1}^{N} \frac{(b_{W,i} - b_W)^2}{\sigma^2_{b_{W,i}}} \quad \Longrightarrow \quad \frac{\chi^2_{bW,min}}{dof} = 1.55 \quad >1$$

$$\frac{\chi^2_{bW,min}}{dof} \simeq 1 \quad \Longrightarrow \quad \sigma_{b,scat} \simeq 0.18$$

Allow for additional uncertainty σ_{scat}: $\chi^2(b_W) = \sum_{i=1}^{N} \frac{(b_{W,i} - b_W)^2}{\sigma^2_{b_{W,i}} + \sigma^2_{b,scat}}$

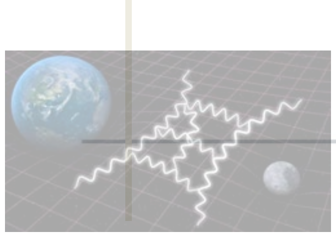
Modeling parameter b_{Wi} in each host i: Consistency of distance bins

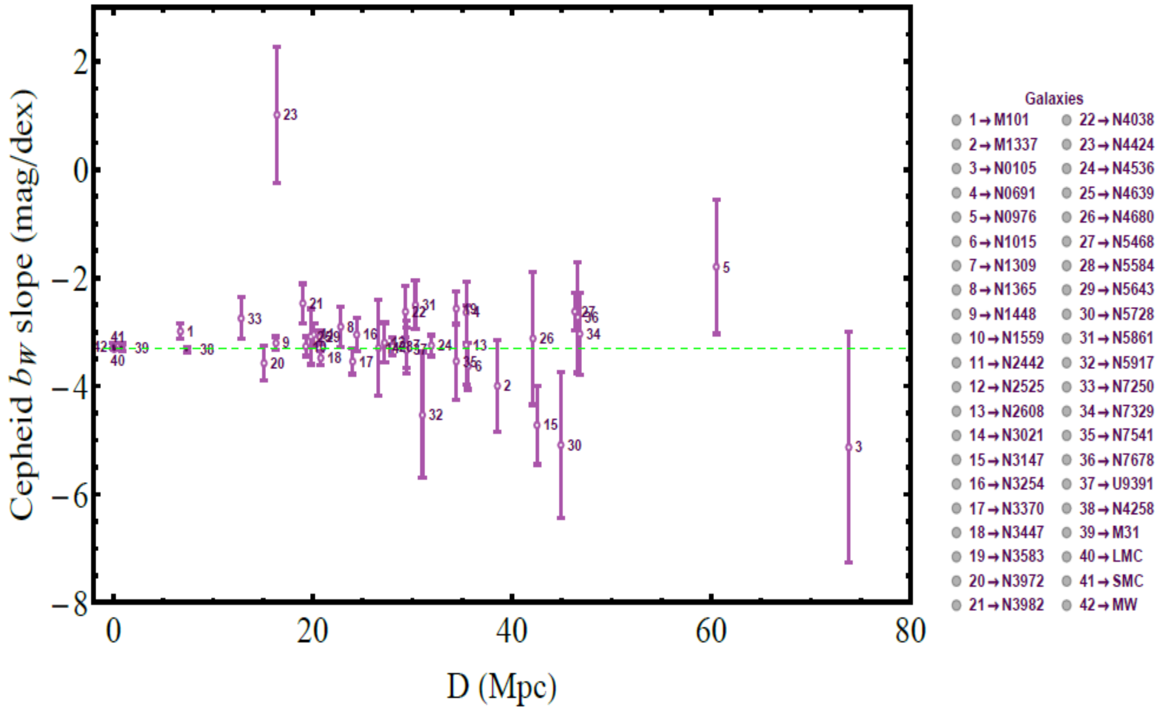




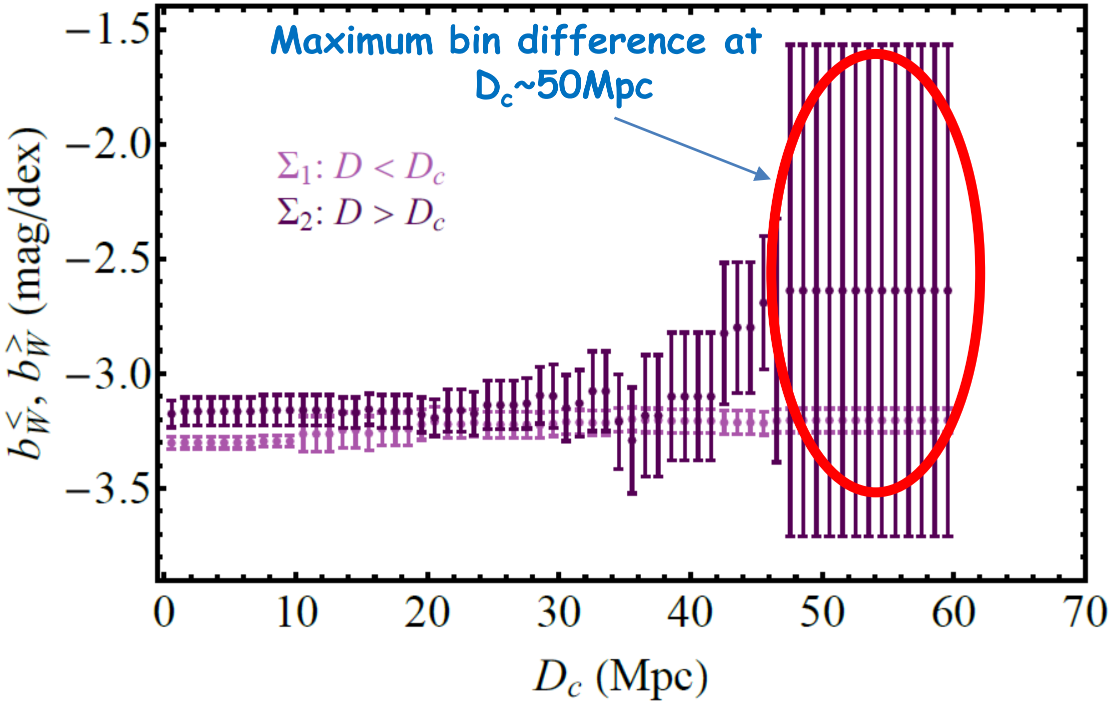
Best fit m_H^W-logP, slopes (b_{Wi}) in terms of the host distance

Modeling parameter b_{Wi} in each host i: Consistency of distance bins





Best fit m_H^W-logP, slopes (b_{Wi}) in terms of the host distance

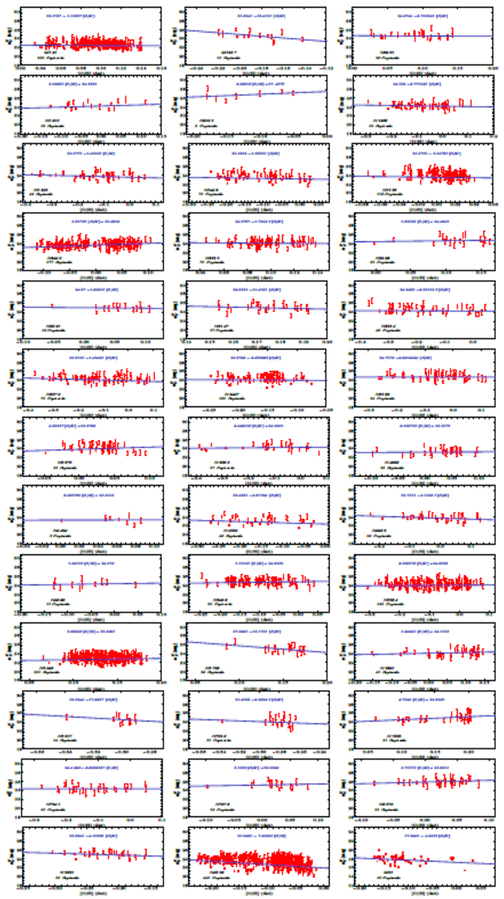


Consistency between high and low distance bins split at distance D_c

Self consistency test II
Modeling parameter Z_{Wi} in each host i

Find best fit Z_{Wi} slope and intercept s_i in each Cepheid host i
(37 SnIa+Cepheid + 2 pure Cepheid hosts)

$$m_{H,i,j}^{W} = \mu_i + M_H^W + b_W[P]_{i,j} + Z_W[O/H]_{i,j} \quad \Longrightarrow \quad m_{H,i,j}^{W} = s_i + Z_{W,i}[O/H]_{i,j}$$



Best fit m_H^W-[O/H] slopes

Consistency with universal metallicity slope Z_W:

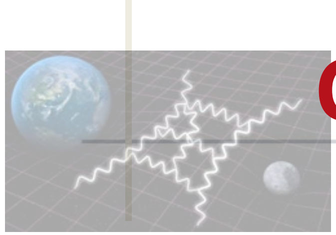
$$\chi^2(Z_W) = \sum_{i=1}^{N} \frac{(Z_{W,i} - Z_W)^2}{\sigma_{Z_{W,i}}^2} \quad \Longrightarrow \quad \frac{\chi^2_{ZW,min}}{dof} = 22$$

Demand:

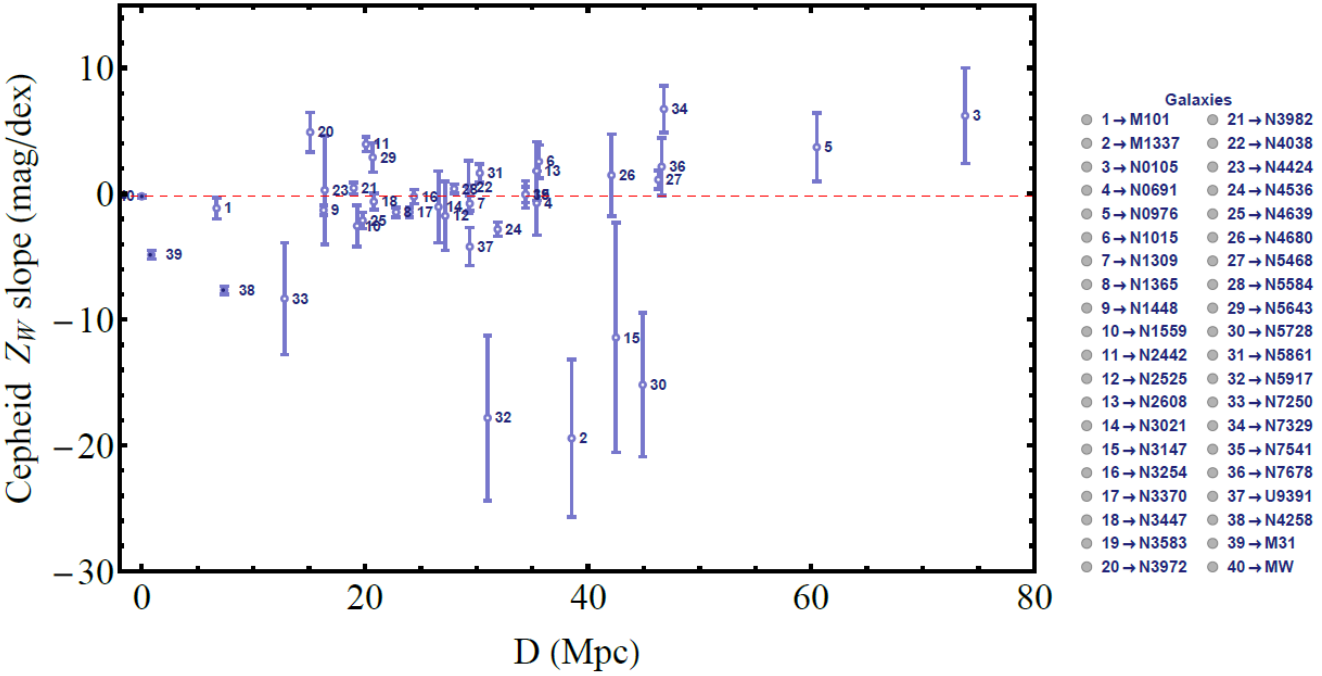
$$\frac{\chi^2_{ZW,min}}{dof} \simeq 1 \quad \Longrightarrow \quad \sigma_{Z,scat} \simeq 3.2$$

$$\chi^2(Z_W) = \sum_{i=1}^{N} \frac{(Z_{W,i} - Z_W)^2}{\sigma_{Z_{W,i}}^2 + \sigma_{Z,scat}^2}$$

Modeling parameter Z_{Wi} in each host i:



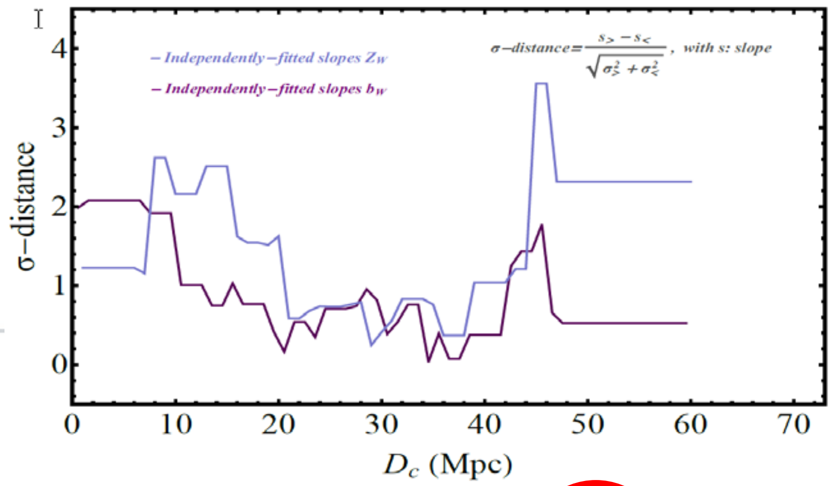
Consistency of distance bins

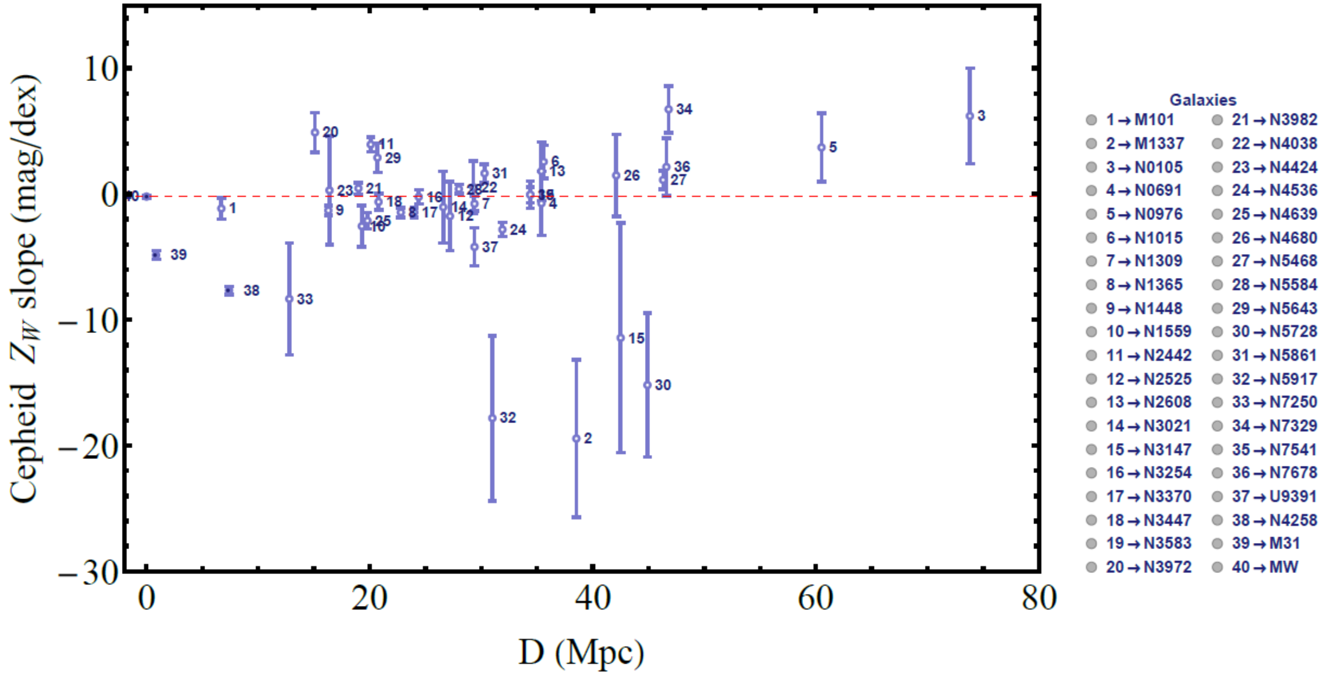


Z_{wi} slope in terms of the host distance

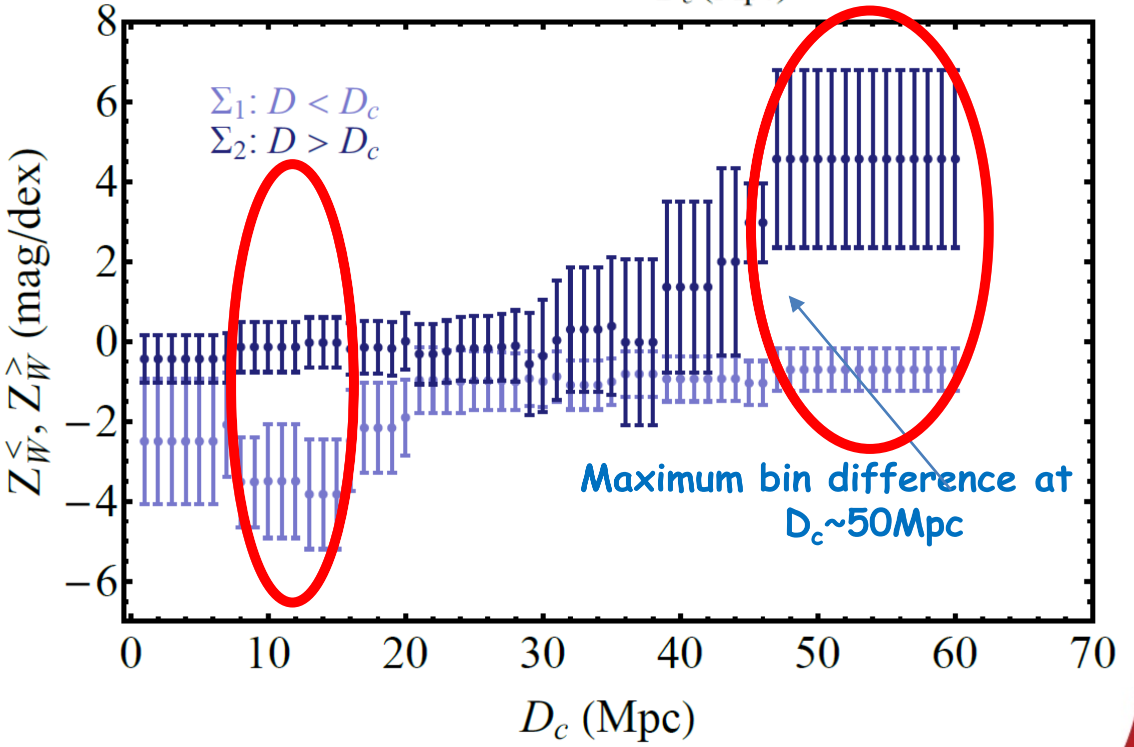
Modeling parameter Z_{Wi} in each host i:

Consistency of distance bins



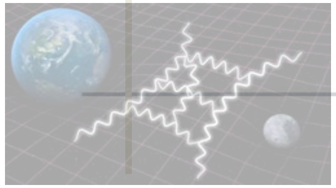


Z_{wi} slope in terms of the host distance



Consistency between high and low distance bins split at distance D_c

Generalizing the baseline SH0ES modeling analysis: New degrees of freedom

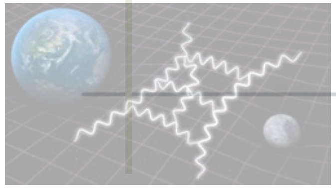


Allow for a change (transition) of the modeling parameters M_W, b_W, Z_W, M_B at a given distance D_c (cosmic time t_c).

For example if b_W was allowed to change, the Cepheid modeling would have to change as:

$$\boxed{m^W_{H,i,j} = \mu_i + M^W_H + b_W[P]_{i,j} + Z_W[O/H]_{i,j}}$$

Generalizing the baseline SH0ES modeling analysis:
New degrees of freedom



Allow for a change (transition) of the modeling parameters M_W, b_W, Z_W, M_B at a given distance D_c (cosmic time t_c).

For example if b_W was allowed to change, the Cepheid modeling would have to change as:

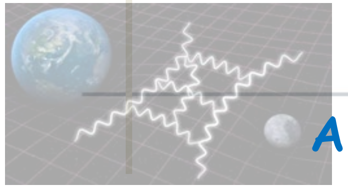
$$\boxed{m_{H,i,j}^{W} = \mu_i + M_H^W + b_W[P]_{i,j} + Z_W[O/H]_{i,j}}$$

$$\Downarrow$$

$$\boxed{m_{H,i,j}^{W}(D) = \mu_i + M_H^W + b_W^{>}\Theta(D-D_c)[P]_{i,j} + b_W^{<}\Theta(D_c-D)[P]_{i,j} + Z_W[O/H]_{i,j}}$$

The new matrix equation Y=L q would have the same data/constraints Y (labeled with their distance) the same covariance matrix C but different model matrix L and parameter matrix q.

The new matrix equation



Allow for a change (transition) of the modeling parameter q_j at a given distance D_c (cosmic time t_c).

1. Assign a distance D_i to each entry $1<i<3492$ of the data/constraint vector Y.

The new matrix equation

Allow for a change (transition) of the modeling parameter q_j at a given distance D_c (cosmic time t_c).

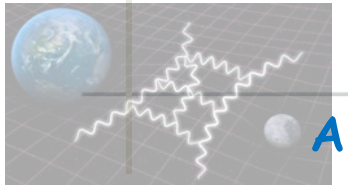
1. Assign a distance D_i to each entry $1<i<3492$ of the data/constraint vector Y.

2. In the parameter vector q split the parameter q_j to two new parameters $q_j^{<}=q_j$ $(D<D_c)$ and $q_j^{>}=q_j+1$ $(D>D_c)$.

$$\mathbf{q}_{(47\times1)} = \begin{pmatrix} \cdots \\ \cdots \\ q_j \\ \cdots \\ \cdots \end{pmatrix} \to \mathbf{q}_{(48\times1)} = \begin{array}{l} \begin{pmatrix} \cdots \\ \cdots \\ q_j \\ q_{j+1} \\ \cdots \\ \cdots \end{pmatrix} \end{array} \begin{array}{l} \\ \\ \to q_j^{<} \\ \to q_j^{>} \\ \\ \\ \end{array}$$

$q_j^{<}$ $q_j^{>}$

The new matrix equation



Allow for a change (transition) of the modeling parameter q_j at a given distance D_c (cosmic time t_c).

1. Assign a distance D_i to each entry 1<i<3492 of the data/constraint vector Y.

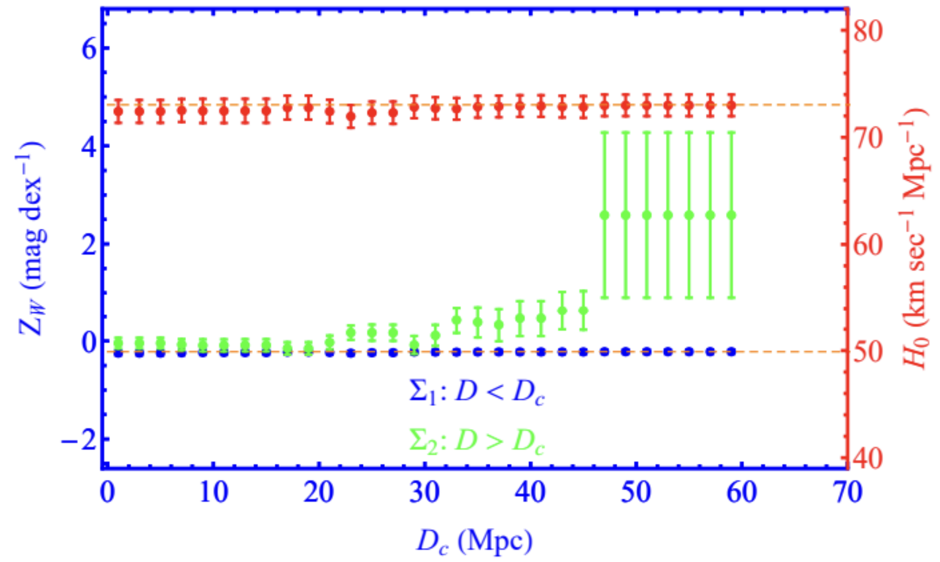
2. In the parameter vector q split the parameter q_j to two new parameters $q_j^{<}=q_j$ $(D<D_c)$ and $q_j^{>}=q_j+1$ $(D>D_c)$.

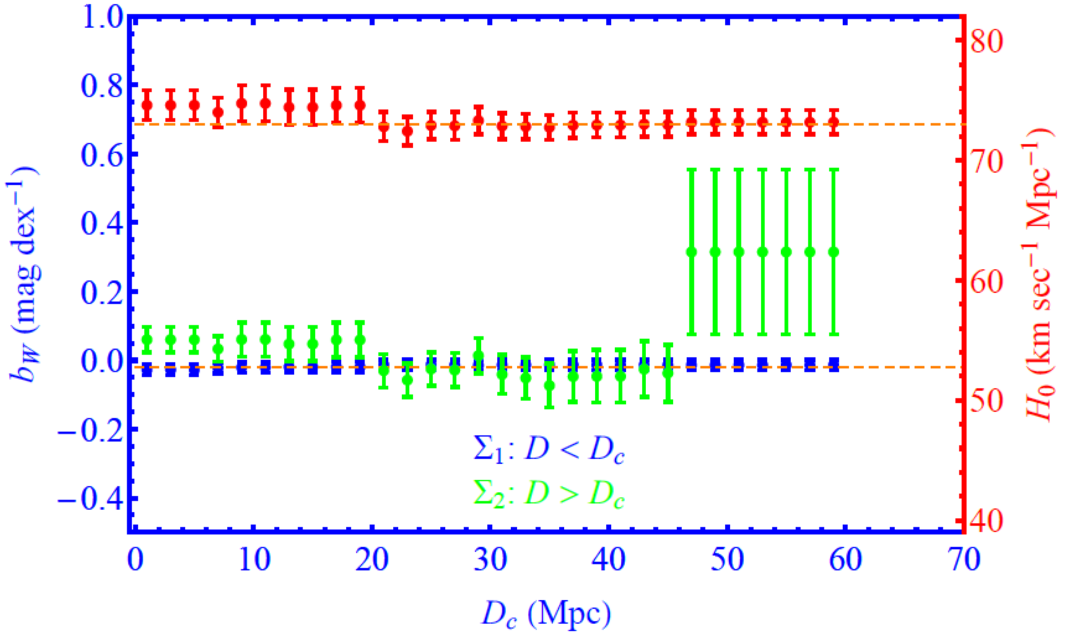
$$\mathbf{q}_{(47\times 1)} = \begin{pmatrix} \cdots \\ \cdots \\ q_j \\ \cdots \\ \cdots \end{pmatrix} \rightarrow \mathbf{q}_{(48\times 1)} = \begin{array}{cl} \begin{pmatrix} \cdots \\ \cdots \\ q_j \\ q_{j+1} \\ \cdots \end{pmatrix} & \begin{array}{l} \\ \\ \rightarrow q_j^{<} \\ \rightarrow q_j^{>} \\ \\ \end{array} \end{array}$$

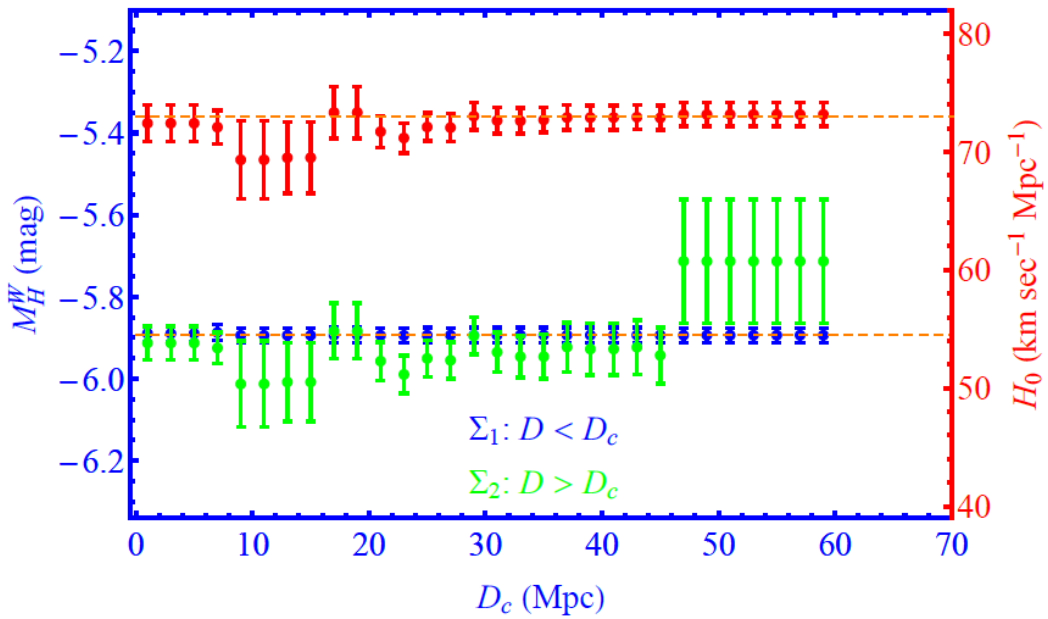
3. In the modeling matrix L split column j to two new columns corresponding to $D<D_c$ (zero entries for rows with $D>D_c$ in Y) and $D>D_c$ (zero entries for rows with $D<D_c$ in Y) .

$$\mathbf{L}_{(3492\times 47)} = \begin{pmatrix} \cdots & L_{1,j} & \cdots \\ \cdots & L_{2,j} & \cdots \\ \cdots & L_{3,j} & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & L_{3491,j} & \cdots \\ \cdots & L_{3492,j} & \cdots \end{pmatrix} \left\} \begin{array}{c} D_{Y_1} < D_c \\ D_{Y_2} > D_c \\ D_{Y_3} > D_c \\ \cdots \\ \cdots \\ D_{Y_{3491}} < D_c \\ D_{Y_{3492}} > D_c \end{array} \right. \Longrightarrow \mathbf{L}_{(3492\times 48)} = \begin{array}{c} \begin{array}{cccc} & q_j^{<} & q_j^{>} & \end{array} \\ \begin{pmatrix} \cdots & L_{1,j} & 0 & \cdots \\ \cdots & 0 & L_{2,j+1} & \cdots \\ \cdots & 0 & L_{3,j+1} & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & L_{3491,j} & 0 & \cdots \\ \cdots & 0 & L_{3492,j+1} & \cdots \end{pmatrix} \end{array}$$

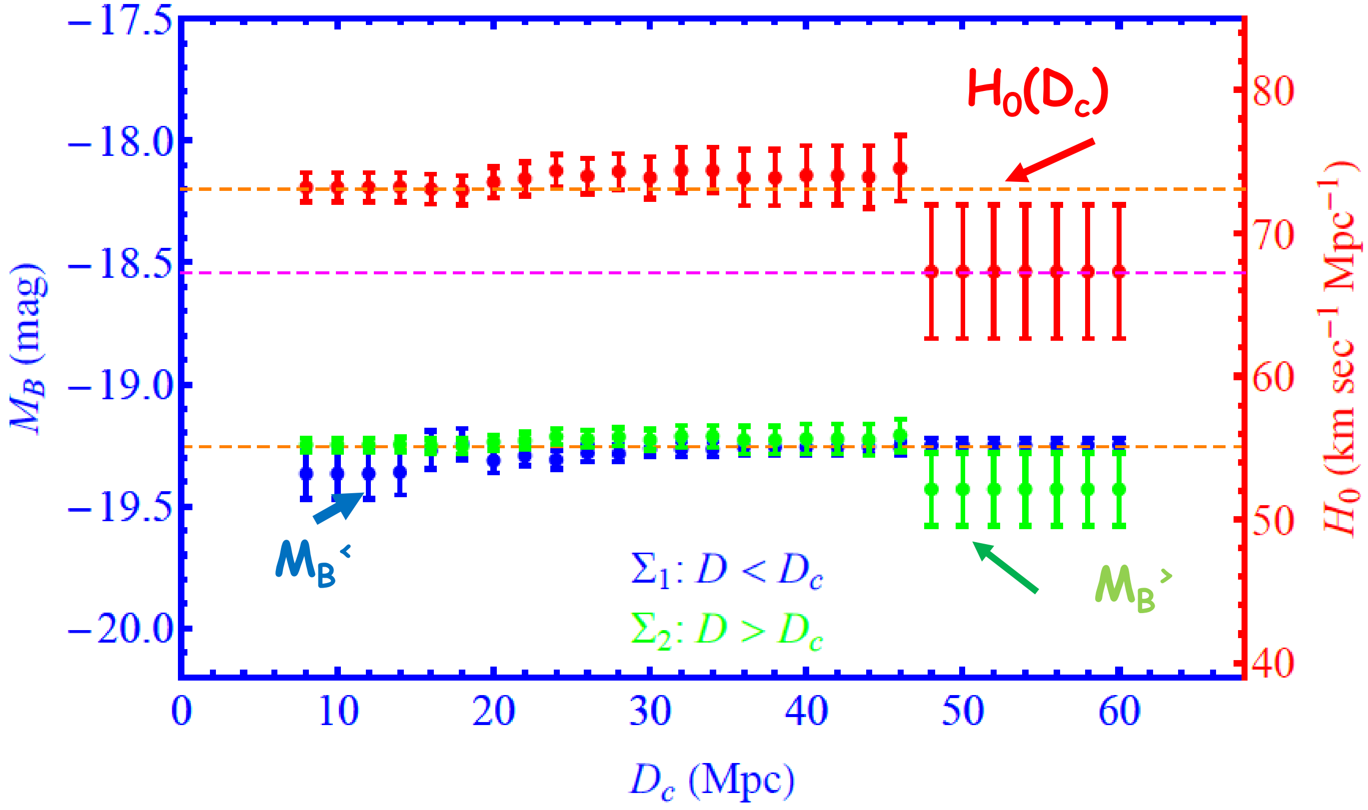
Results of the Generalized Analysis

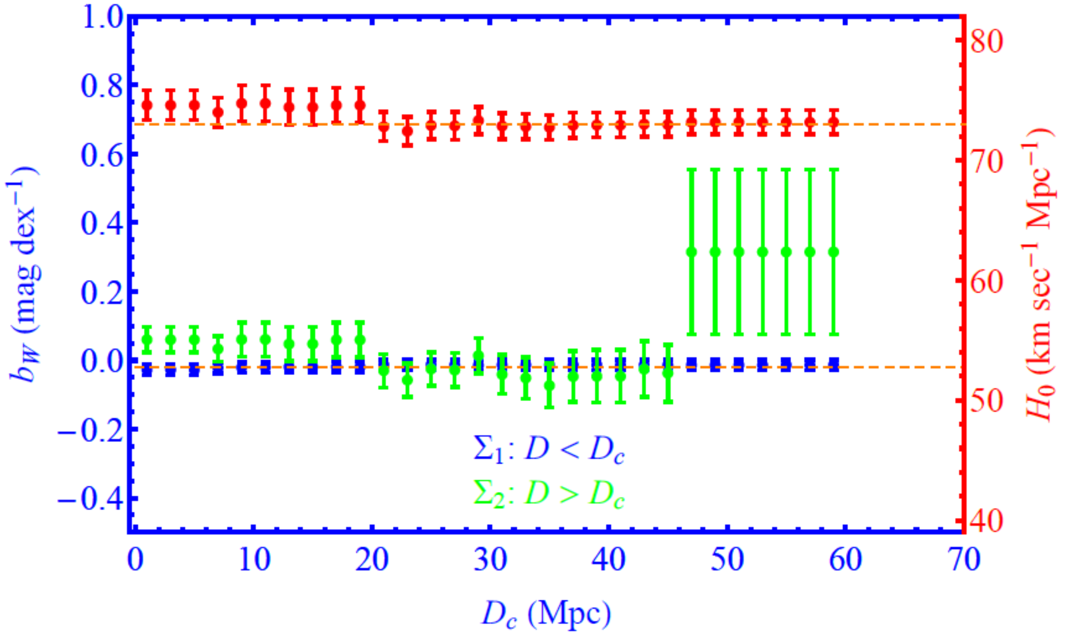


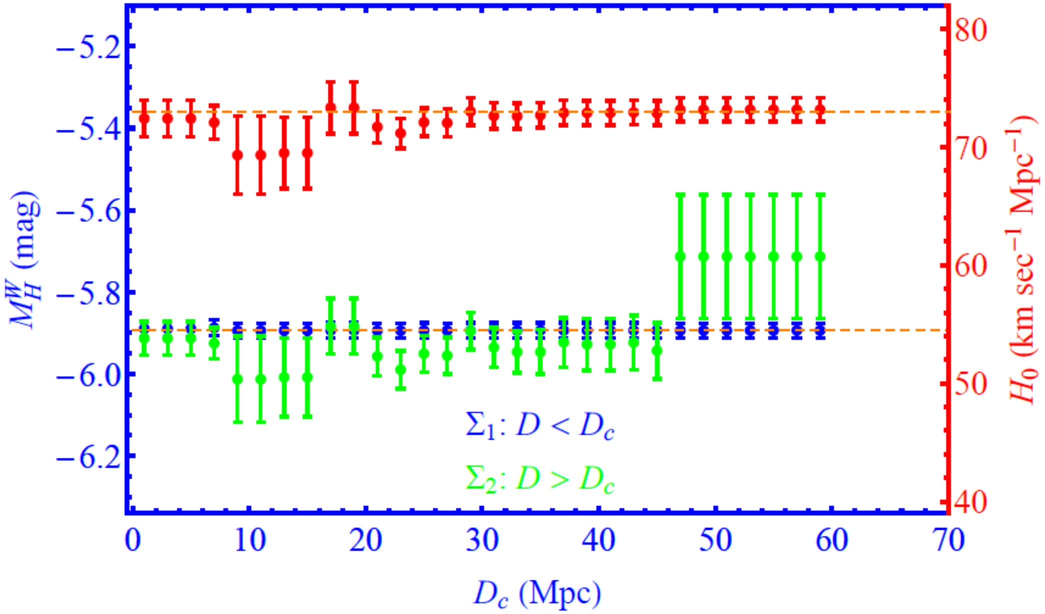




Results of the Generalized Analysis







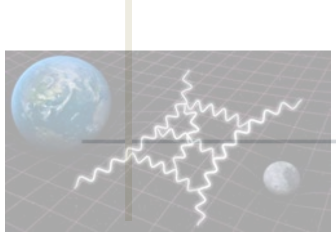
Spontaneous transition of the best fit value of H_0 when a transition at D_c~50Mpc is allowed.

Including the inverse distance ladder constraint

Inverse distance ladder constraint: $M_B^{P18} = -19.401 \pm 0.027$

Modify data/constraint vector Y -> 3493 entries,
modeling matrix L -> 3493 x 48 and covariance matrix
C -> 3493 x 3493

Including the inverse distance ladder constraint



Inverse distance ladder constraint: $M_B^{P18} = -19.401 \pm 0.027$

Modify data/constraint vector Y -> 3493 entries, modeling matrix L -> 3493 x 48 and covariance matrix C -> 3493 x 3493

$$
\mathbf{C}=\left(\begin{array}{ccccccccccccccccccccc}
\sigma^2_{tot,1} & \cdots & Z_{cov} & Z_{cov} & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
Z_{cov} & \cdots & \sigma^2_{tot,37} & Z_{cov} & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
\hline
Z_{cov} & \cdots & Z_{cov} & \sigma^2_{tot,N4258} & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & \sigma^2_{tot,M31} & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & \sigma^2_{tot,LMC} & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & \sigma^2_{M_B,1} & \cdots & Sn_{cov} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Sn_{cov} & \cdots & Sn_{cov} & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
0 & \cdots & 0 & 0 & 0 & 0 & Sn_{cov} & \cdots & \sigma^2_{M_B,77} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Sn_{cov} & \cdots & Sn_{cov} & \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \sigma^2_{M^W_H,HST} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \sigma^2_{M^W_H,Gaia} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \sigma^2_{Z_W,Gaia} & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & \sigma^2_x & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & \sigma^2_{ground,zp} & 0 & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{b_W} & 0 & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{\mu,N4258} & 0 & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{\mu,LMC} & 0 & \cdots & 0 & \\
0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \boxed{\sigma^2_{M_B}} & 0 & \cdots & 0 \\
\hline
0 & \cdots & 0 & 0 & 0 & 0 & Sn_{cov} & \cdots & Sn_{cov} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_{M_B,z,1} & \cdots & Sn_{cov} & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
0 & \cdots & 0 & 0 & 0 & 0 & Sn_{cov} & \cdots & Sn_{cov} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Sn_{cov} & \cdots & \sigma^2_{M_B,z,277} &
\end{array}\right)
$$

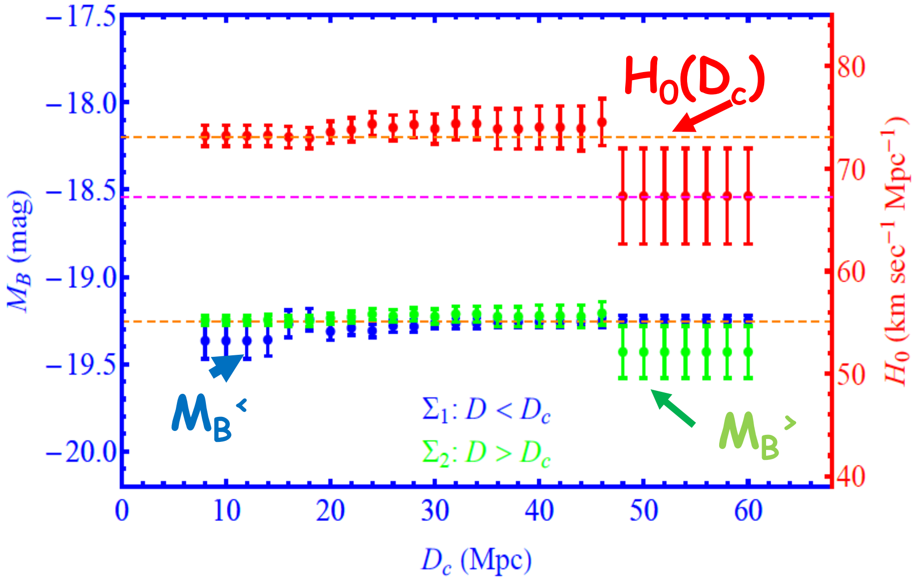
9

$$
\mathbf{Y}=\left(\begin{array}{c}
\left.\begin{array}{c} m^W_{H,1} \\ \cdots \\ m^W_{H,2150} \end{array}\right\} \text{2150 Cepheids in 37 SnIa hosts} \\
\hline
\left.\begin{array}{c} m^W_{H,N4258,1} - \mu_{0,N4258} \\ \cdots \\ m^W_{H,N4258,443} - \mu_{0,N4258} \\ m^W_{H,M31,1} \\ \cdots \\ m^W_{H,M31,55} \\ m^W_{H,LMC,ground,1} - \mu_{0,LMC} \\ \cdots \\ m^W_{H,LMC,ground,270} - \mu_{0,LMC} \\ m^W_{H,SMC,ground,1} - \mu_{0,SMC} \\ \cdots \\ m^W_{H,SMC,ground,143} - \mu_{0,SMC} \\ m^W_{H,LMC,HST,1} - \mu_{0,LMC} \\ \cdots \\ m^W_{H,LMC,HST,69} - \mu_{0,LMC} \end{array}\right\} \text{980 Cepheids in non SnIa hosts} \\
\hline
\left.\begin{array}{c} m^0_{B,1} \\ \cdots \\ m^0_{B,77} \end{array}\right\} \text{77 SnIa in Cepheid hosts} \\
\hline
\left.\begin{array}{c} -5.803\ (M^W_{H,HST}) \\ -5.903\ (M^W_{H,Gaia}) \\ -0.21\ (Z_{W,Gaia}) \\ 0\ (X) \\ 0\ (\Delta zp) \\ 0\ (\Delta b_W) \\ 0\ (\Delta\mu_{N4258}) \\ 0\ (\Delta\mu_{LMC}) \\ \boxed{-19.401\ (M_B)} \end{array}\right\} \text{8 External constraints} \\
\hline
\left.\begin{array}{c} m^0_{B,1} - 5\log[cz_1(\ldots)] - 25 \\ \cdots \\ m^0_{B,277} - 5\log[cz_{277}(\ldots)] - 25 \end{array}\right\} \text{277 SnIa in Hubble flow}
\end{array}\right)
$$

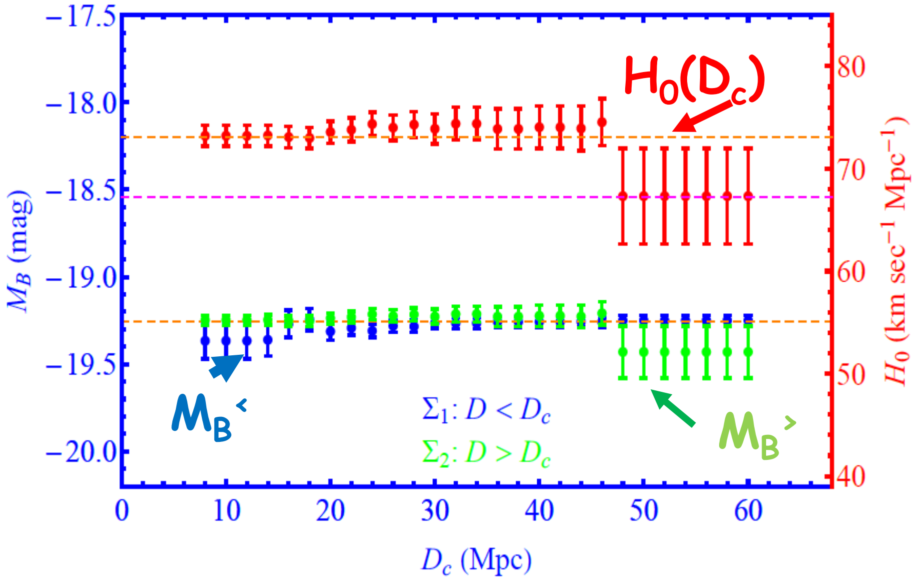
9

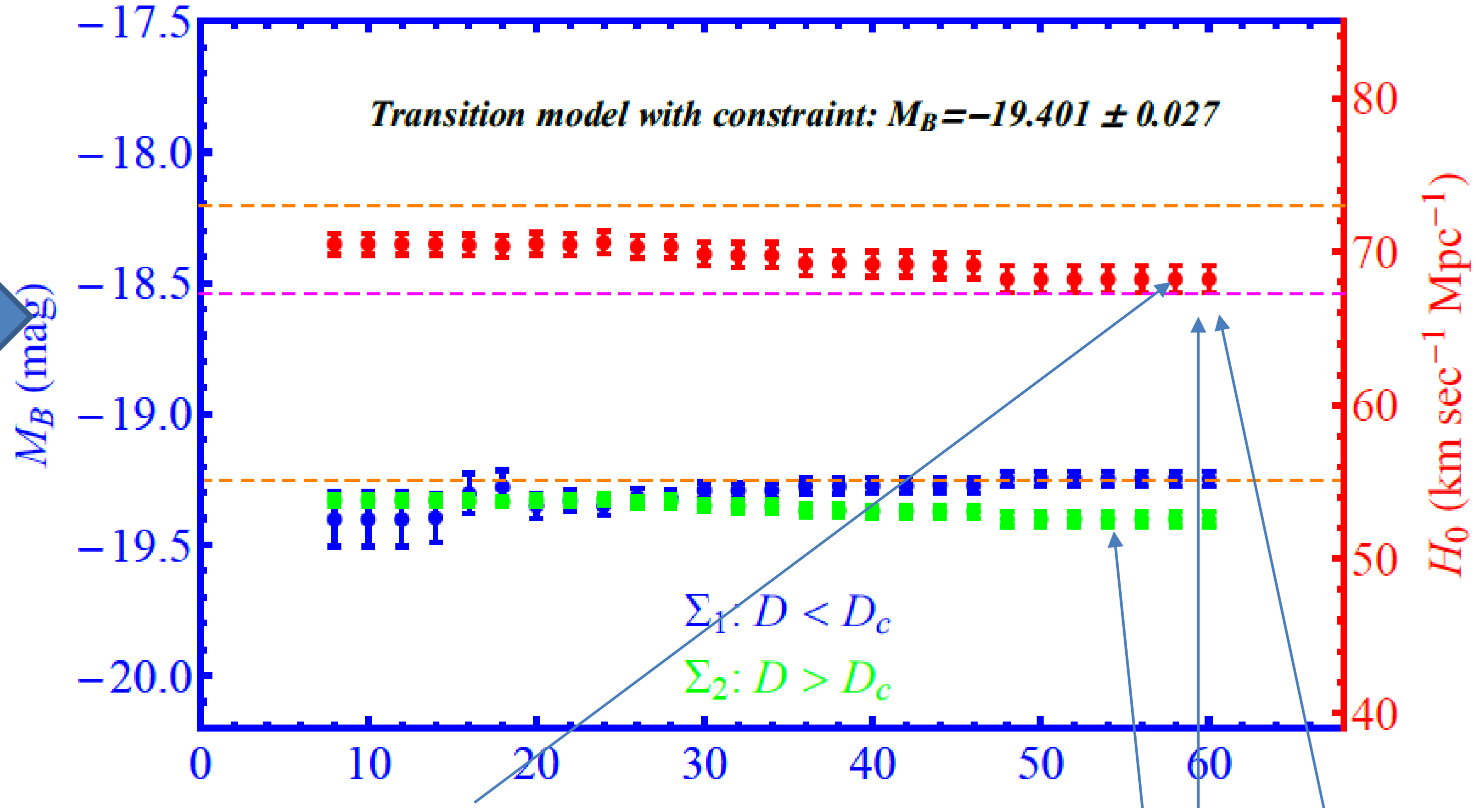
M_B› in the transition model

Results of the Generalized Analysis with M_B constraint



Results of the Generalized Analysis with M_B constraint



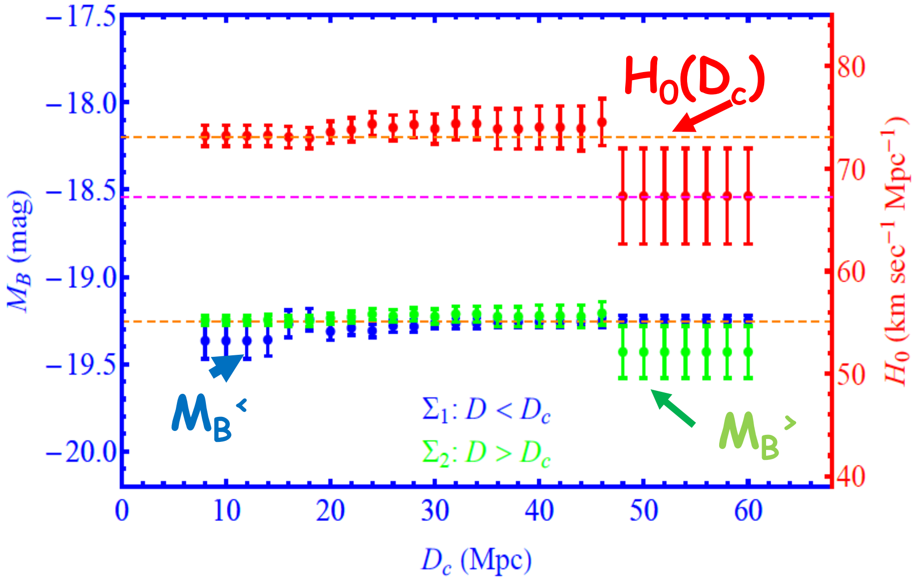


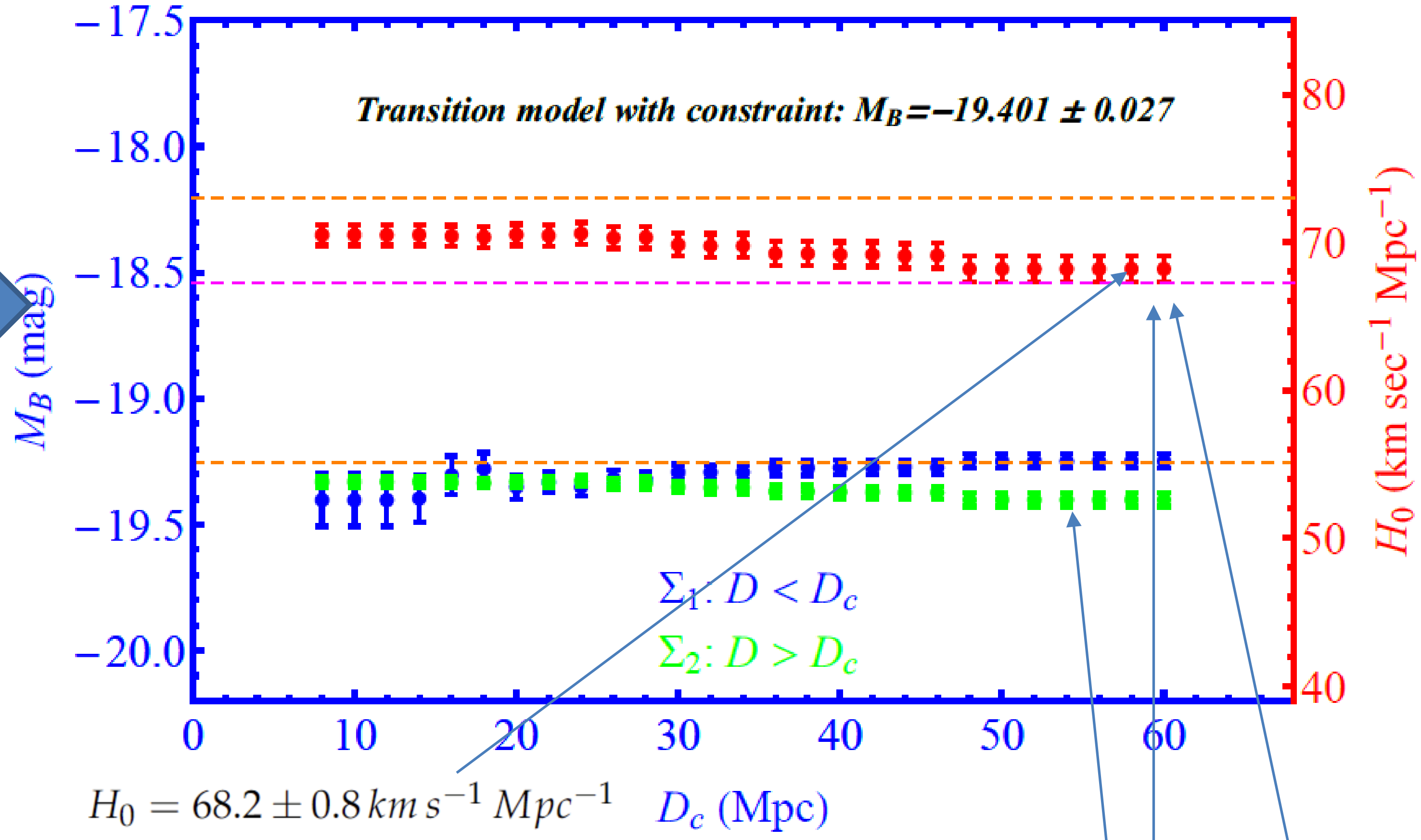
$H_0 = 68.2 \pm 0.8\, km\, s^{-1}\, Mpc^{-1}$

Dramatic drop of uncertainties

Consistency with Planck18 H_0

Results of the Generalized Analysis with M_B constraint

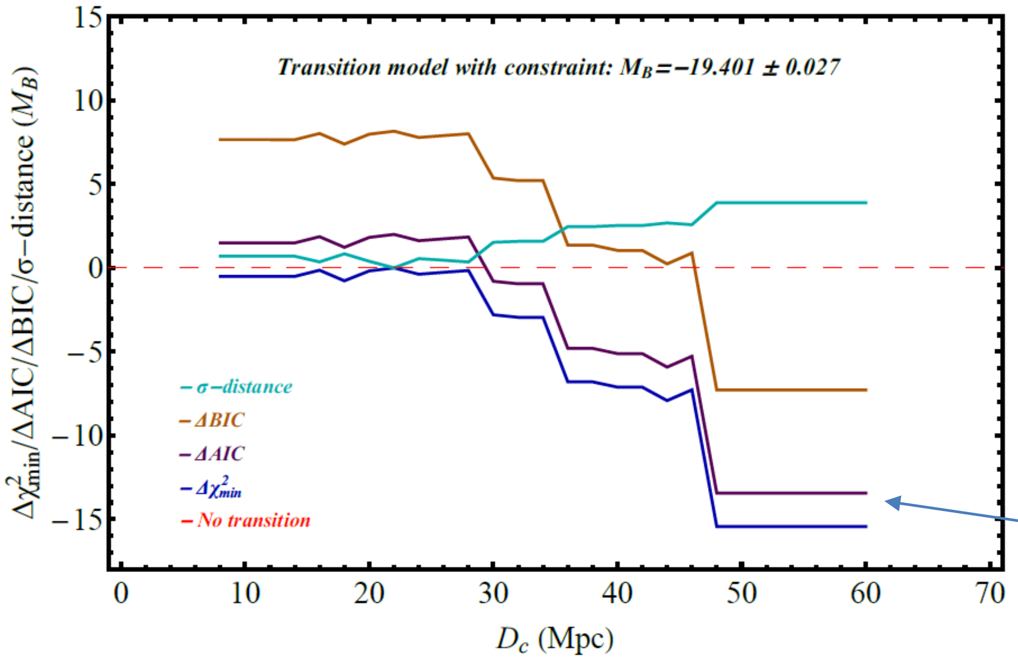




$H_0 = 68.2 \pm 0.8\, km\, s^{-1}\, Mpc^{-1}$

Dramatic drop of uncertainties

Consistency with Planck18 H_0



Strong preference of transition model over baseline model in the presence of the inverse distance ladder constraint (DAIC=-13).

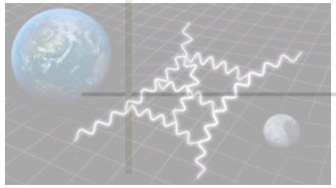
Results of the Generalized Analysis

Model	χ^2_{min}	χ^2_{red} [a]	ΔAIC	ΔBIC	H_0 $[Km\, s^{-1}\, Mpc^{-1}]$	M_B $[mag]$	M_H^W $[mag]$	Δb_W $[mag/dex]$	Z_W $[mag/dex]$
Baseline	3552.76	1.031	0	0	73.043 ± 1.007	-19.253 ± 0.029	-5.894 ± 0.018	-0.013 ± 0.015	-0.217 ± 0.045
Transition[b] M_B	3551.31	1.031	0.55	6.71	67.326 ± 4.647	-19.250 ± 0.029 -19.430 ± 0.150 1.2σ	-5.894 ± 0.018	-0.013 ± 0.015	-0.217 ± 0.045
Transition[b] M_H^W	3551.31	1.031	0.55	6.71	73.162 ± 1.014	-19.250 ± 0.029	-5.894 ± 0.018 -5.713 ± 0.151 1.2σ	-0.013 ± 0.015	-0.217 ± 0.045
Transition[b] Z_W	3549.99	1.030	-0.77	5.39	72.981 ± 1.007	-19.255 ± 0.029	-5.894 ± 0.018	-0.014 ± 0.015	-0.217 ± 0.045 2.588 ± 1.686 1.7σ
Transition[b] b_W	3550.86	1.030	0.10	6.26	73.173 ± 1.013	-19.249 ± 0.029	-5.894 ± 0.018	-0.013 ± 0.015 0.315 ± 0.239 1.4σ	-0.217 ± 0.045
Baseline+Constraint[c]	3566.78	1.035	0	0	70.457 ± 0.696	-19.332 ± 0.020	-5.920 ± 0.017	-0.026 ± 0.015	-0.220 ± 0.045
Transition[b,c] M_B**+Constraint**	3551.34	1.031	-13.44	-7.27	68.202 ± 0.879	-19.249 ± 0.029 -19.402 ± 0.027 3.9σ	-5.893 ± 0.018	-0.013 ± 0.015	-0.217 ± 0.045

Results of the Generalized Analysis

Model	χ^2_{min}	χ^2_{red} [a]	ΔAIC	ΔBIC	H_0 $[Km\, s^{-1}\, Mpc^{-1}]$	M_B $[mag]$	M_H^W $[mag]$	Δb_W $[mag/dex]$	Z_W $[mag/dex]$
Baseline	3552.76	1.031	0	0	73.043 ± 1.007	-19.253 ± 0.029	-5.894 ± 0.018	-0.013 ± 0.015	-0.217 ± 0.045
Transition[b] M_B	3551.31	1.031	0.55	6.71	67.326 ± 4.647	-19.250 ± 0.029 -19.430 ± 0.150 1.2σ	-5.894 ± 0.018	-0.013 ± 0.015	-0.217 ± 0.045
Transition[b] M_H^W	3551.31	1.031	0.55	6.71	73.162 ± 1.014	-19.250 ± 0.029	-5.894 ± 0.018 -5.713 ± 0.151 1.2σ	-0.013 ± 0.015	-0.217 ± 0.045
Transition[b] Z_W	3549.99	1.030	-0.77	5.39	72.981 ± 1.007	-19.255 ± 0.029	-5.894 ± 0.018	-0.014 ± 0.015	-0.217 ± 0.045 2.588 ± 1.686 1.7σ
Transition[b] b_W	3550.86	1.030	0.10	6.26	73.173 ± 1.013	-19.249 ± 0.029	-5.894 ± 0.018	-0.013 ± 0.015 0.315 ± 0.239 1.4σ	-0.217 ± 0.045
Baseline+Constraint[c]	3566.78	1.035	0	0	70.457 ± 0.696	-19.332 ± 0.020	-5.920 ± 0.017	-0.026 ± 0.015	-0.220 ± 0.045
Transition[b,c] M_B+Constraint	3551.34	1.031	-13.44	-7.27	68.202 ± 0.879	-19.249 ± 0.029 -19.402 ± 0.027 3.9σ	-5.893 ± 0.018	-0.013 ± 0.015	-0.217 ± 0.045

Main Points



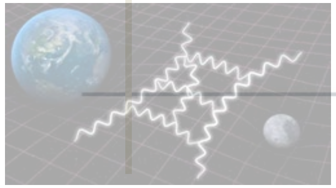
1. New physics at ultra low redshifts ($z<0.02$) can lead to a resolution of the Hubble tension.

2. New degrees of freedom can be introduced in the baseline SH0ES analysis to detect such new physics signatures.

3. If a change of the SnIa absolute luminosity M_B is allowed at D_c~50Mpc (new degree of freedom) in the SH0ES analysis then the best fit value of H_0 drops from 73±1 km/(sec Mpc) to 67±4 km/(sec Mpc).

4. In the presence of the inverse distance ladder input on M_B the transition model uncertainties drop dramatically and the extended model is strongly preferred over the SH0ES baseline model of universal value of M_B.

Theoretical Model: Scalar Tensor Theory

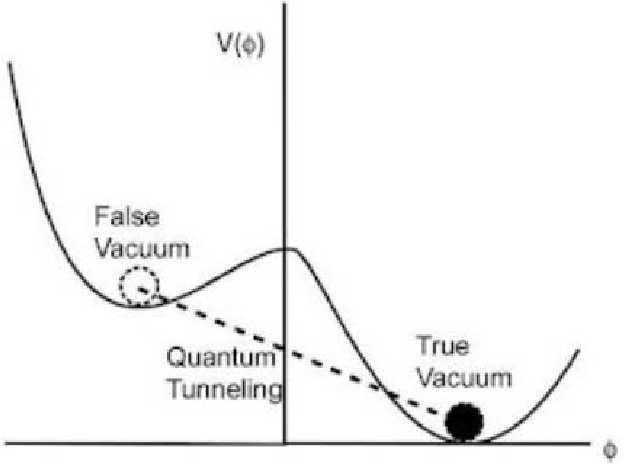


Scalar Tensor Transition:
$$S=\int d^4x\sqrt{|g|}\left[\frac{1}{2}\xi\varphi^2R-\frac{1}{2}(\partial\varphi)^2-V(\varphi)+\mathcal{L}_m\right],\qquad 8\pi G_N=\xi^{-1}v^{-2}$$

v: potential minimum

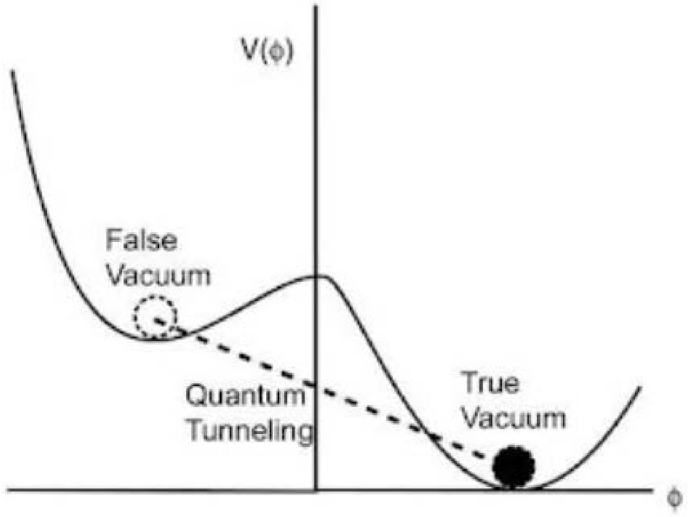
$$v=\frac{1}{\sqrt{8\pi G_N}}=M_{\mathrm{Pl}}\sim 10^{19}\mathrm{GeV},$$

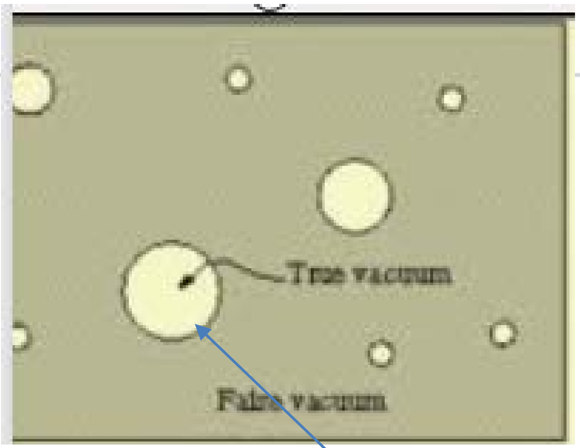
Cosmological Constant: Λ=V(v)



A phase transition (false vacuum decay) would induce a transition in the strength of gravity as well

Generic Distance Scale





In the context of false vacuum decay bubbles of true vacuum form

Scale of True Vacuum Bubbles:

$$R_b = \delta / H_0$$

$$\delta \simeq [4B_1 \ln (M_P/T_c)]^{-1}$$

O(1) Planck mass

$$H_0 = 70\, km\, s^{-1}\, Mpc^{-1}$$

$$T_c = 2.7^{\circ} K \simeq 2 \times 10^{-4} eV$$

R_b~15Mpc

Predicted bubble scale is close to favored scale of transition

Late-time vacuum phase transitions: Connecting sub-eV scale physics with cosmological structure formation

Amol V. Patwardhan, George M. Fuller (Jan 9, 2014)

Published in: *Phys.Rev.D* 90 (2014) 6, 063009 • e-Print: 1401.1923 [astro-ph.CO]

Constraints

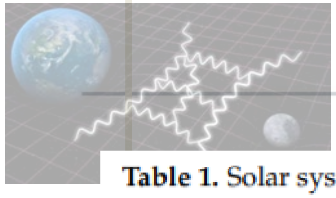


Table 1. Solar system, astrophysical and cosmological constraints on the evolution of the gravitational constant. Methods with star (*) constrain G_N, while the rest constrain $G_{\rm eff}$. The latest and strongest constraints are shown for each method.

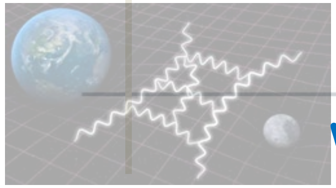
Method	$\left.\frac{\Delta G_{\rm eff}}{G_{\rm eff}}\right\vert_{max}$	$\left.\frac{\dot{G}_{\rm eff}}{G_{\rm eff}}\right\vert_{max}$ (yr^{-1})	Time Scale (Yr)	References
Lunar ranging		1.47×10^{-13}	24	[34]
Solar system		4.6×10^{-14}	50	[35,36]
Pulsar timing		3.1×10^{-12}	1.5	[37]
Strong Lensing		10^{-2}	0.6	[38]
Orbits of binary pulsar		1.0×10^{-12}	22	[39]
Ephemeris of Mercury		4×10^{-14}	7	[40]
Exoplanetary motion		10^{-6}	4	[41]
Hubble diagram SnIa	0.1	1×10^{-11}	$\sim 10^8$	[42]
Pulsating white-dwarfs		1.8×10^{-10}	0	[43]
Viking lander ranging		4×10^{-12}	6	[44]
Helioseismology		1.6×10^{-12}	4×10^9	[45]
Gravitational waves	8	5×10^{-8}	1.3×10^8	[46]
Paleontology	0.1	2×10^{-11}	4×10^9	[47]
Globular clusters		35×10^{-12}	$\sim 10^{10}$	[48]
Binary pulsar masses		4.8×10^{-12}	$\sim 10^{10}$	[49]
Gravitochemical heating		4×10^{-12}	$\sim 10^8$	[50]
Strong lensing		3×10^{-1}	$\sim 10^{10}$	[38]
Big Bang Nucleosynthesis *	0.05	4.5×10^{-12}	1.4×10^{10}	[30]
Anisotropies in CMB *	0.095	1.75×10^{-12}	1.4×10^{10}	[51]

Hints for a Gravitational Transition in Tully–Fisher Data

George Alestas (Ioannina U.), Ioannis Antoniou (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.) (Apr 29, 2021)

Published in: *Universe* 7 (2021) 10, 366 • e-Print: 2104.14481 [astro-ph.CO]

Main Points / Conclusion



Viable early and late approaches to the Hubble tension appear to require the existence of an abrupt transition event either at t_{rec} or at present t_0.

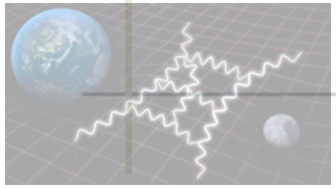
The late transition event may involve a sudden diming of the SnIa intrinsic luminosity occurring less than 150 million years ago (z_t<0.01).

Such a diming may be due to a sudden increase of the strength G_{eff} of gravitational interactions by about 10% at z_t<0.01. This is a viable and testable conjecture.

There are hints for such a transition in the recent Cepheid+SnIa SH0ES data for the measurement of H0 with distance ladder methods.

Theoretical models supporting such an event may involve a false vacuum decay models where the true vacuum has a similar energy scale as the observed cosmological constant scale (0.002eV) and a decay rate $\Gamma \sim H_0$.

The distance ladder and the new SH0ES data



Calibrating Cepheids+SnIa with geometric distance measurements:
The distance ladder (distance <-> absolute luminosity ladder $m=\mu+M(p)$)

1. Measure geometrically (parallax etc) the distance to nearby Cepheid variable stars and their properties (period, metallicity). Thus find Cepheid absolute luminosity in anchor galaxies (d<8Mpc).
2. Calibrate Cepheids: Connect absolute luminosity to their properties (period, metallicity).
3. Use calibrated Cepheids to measure distances to Cepheid+SnIa hosts (larger distances). Thus find SnIa absolute luminosities
4. Calbrate SnIa: Connect absolute luminosity to their properties (light curve stretch, color).
5. Use calibrated SnIa (known absolute luminosity) to measure distances in the Hubble flow. Thus, measure H_0.

New SH0ES data release: Significant increase of number of Cepheid calibrators (from 2416 to 3130) of SnIa calibrators in SnIa hosts (from 19 to 42) and of SnIa in Hubble flow (from 217 to 277).