Hubble Tension Tomography

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CosmoVerse@Krakow (9 July - 11 July 2024)

History of Major Shifts of Cosmological Models

- **Geocentric (Ptolemy) to Heliocentric (Copernicus, 16th-17th c.):**
  - Retrograde motion (Copernicus)
  - Phases of Venus, Moons of Jupiter (Galileo, 1610)
- **Heliocentric to Infinite Universe (18th-19th c.):**
  - Improved telescopes, Uranus discovery (Herschel, 1781)
  - Stellar parallax (Bessel, 1838)
- **Infinite to Static Universe (Einstein, early 20th c.):**
  - Nebulae spectroscopy (Slipher)
  - Stellar distances (Leavitt, Hertzsprung)
- **Static to Expanding Universe (Lemaître, Hubble, 1920s-30s):**
  - Galactic redshift (Slipher, 1912-14)
  - Hubble's law (Hubble, 1929)
- **Expanding Universe to Inflationary Big Bang (1960s-80s):**
  - CMB (Penzias & Wilson, 1964)
  - Light element abundance (Alpher, Herman)
  - Inflation theory (Guth, Linde, 1980s)
- **Introduction of Dark Matter (1970s-80s):**
  - Galaxy rotation curves (Rubin, 1970s)
  - Gravitational lensing (Walsh et al., 1979)
  - Galaxy clusters (Zwicky, 1930s)
- **Lambda-CDM (late 1990s-present):**
  - Supernova observations (Perlmutter, Schmidt, Riess, 1998-99)
  - CMB (WMAP, Planck), BAO (SDSS, 2005)
- **Potential Future Shift (2020s-?):**
  - Hubble tension (Riess et al. vs Planck Collaboration)
  - S8 (growth rate) tension (KiDS, DES, Planck collaborations)
  - Cosmic dipoles tension (Various teams)
  - CMB anomalies (Planck Collaboration)
  - ISW (Integrated Sachs-Wolfe) tension
  - Lithium problem (Primordial Nucleosynthesis)

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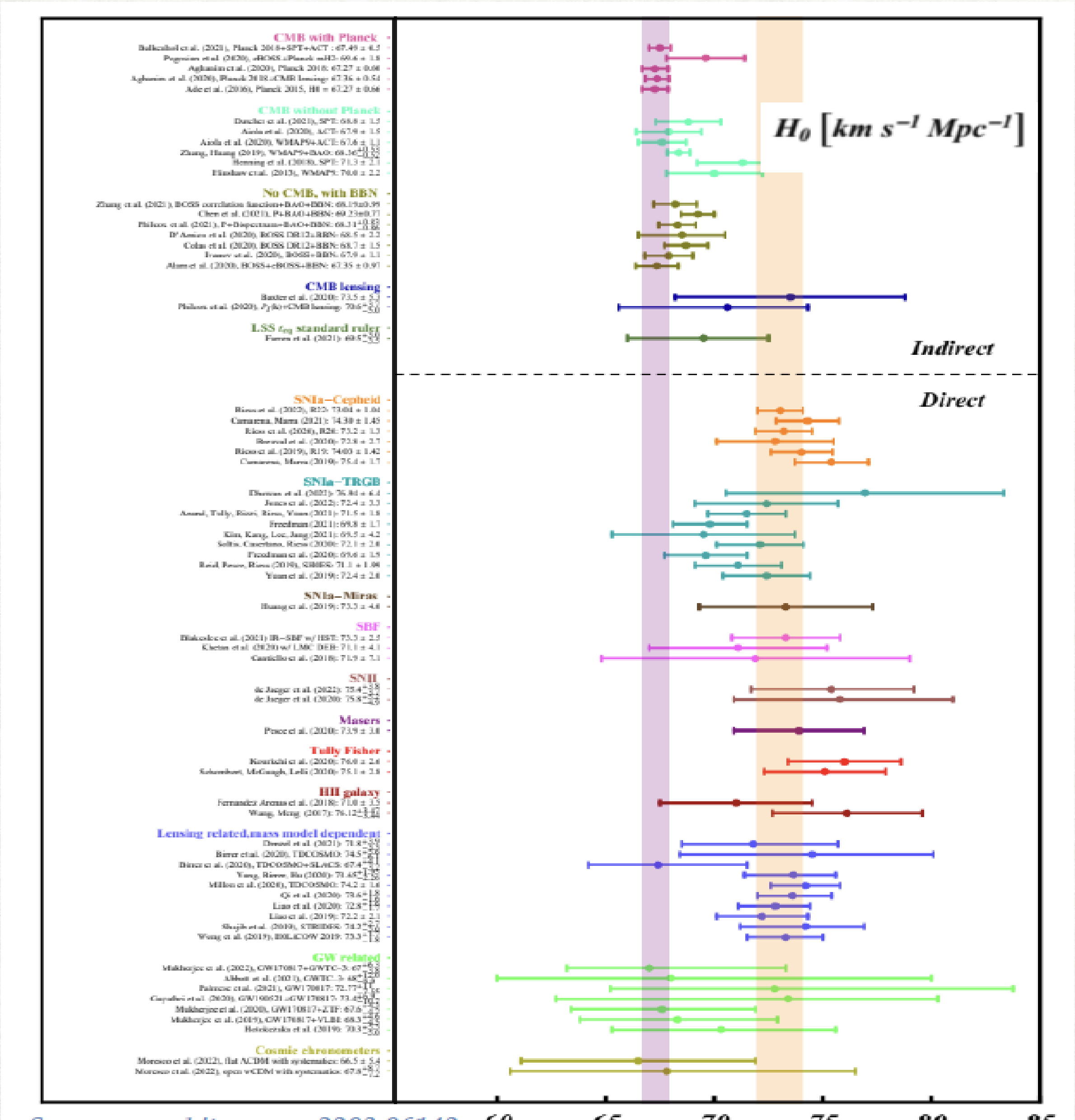
New Astronomy Reviews

Volume 95, December 2022, 101659

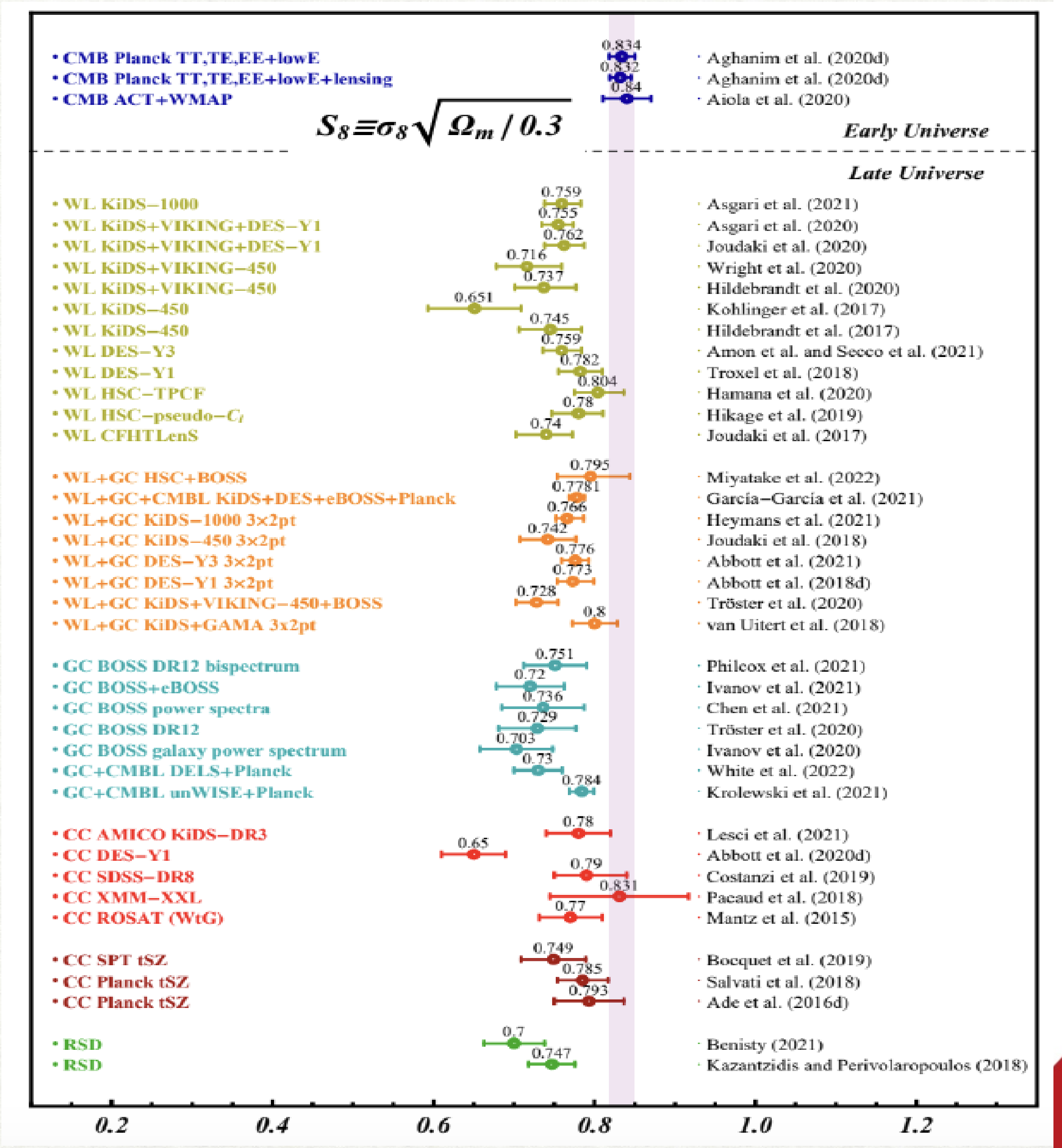
Challenges for ΛCDM: An update

L. Perivolaropoulos, F. Skara

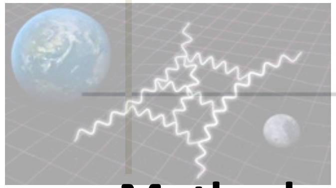
Hubble and Growth Tensions



Snowmass white paper 2203.06142



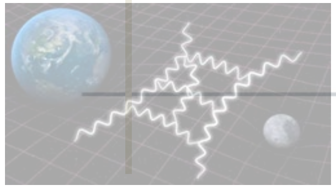
Local measurements



One step distance methods in Hubble flow
(z>0.01, local calibrator and sound horizon free)

Method	H_0(km/sec Mpc)	Arxiv-link	First author
Cosmic Chronometers	66.7±5.3	https://arxiv.org/pdf/2307.09501.pdf	Moresco
Cosmic Chronometers + HII gal.	65.9±3.0	https://arxiv.org/pdf/2208.03960.pdf	Jianchen Zhang eta
Gravitational Waves + Kilonovae	69.6±5.5	https://arxiv.org/pdf/2205.09145.pdf	Bulla etal
Gravitational Waves + Kilonovae	67.0 ± 3.6	https://arxiv.org/pdf/2306.12468.pdf	Sneppen etal
Lensing TD TDCOSMO	74.2±1.6	https://arxiv.org/pdf/1912.08027.pdf	Millon etal
Lensing TD TDCOSMO + SLACS	67.4±4	https://arxiv.org/pdf/2007.02941.pdf	Birrer etal
Lensing TD HFF	65.1 ±3.5	https://arxiv.org/pdf/2401.10980	Grillo etal
Lensing TD SN Refdfal	66.6 ±3.8	https://arxiv.org/pdf/2305.06367	Kelly etal
Megamasers (MCP)	66.0 ± 6.0	https://arxiv.org/pdf/1511.08311.pdf	Gao etal
Megamasers (MCP+SH0ES)	73.9±3.0	https://arxiv.org/pdf/2001.09213.pdf	Pesce etal
SZ effect	61±21	https://arxiv.org/pdf/astro-ph/0306073.pdf	Reese
Gamma ray attenuation	61.9±2.6	https://arxiv.org/pdf/2306.09878.pdf	Domínguez etal
T_{eq} standard ruler	64.8±2.4	https://arxiv.org/pdf/2204.02984.pdf	Philcox etal
BAO+ Ω_b/Ω_m (no Sound Horizon)	67.1±5.5	https://arxiv.org/pdf/2403.19227	Krokewski et al
BAO-DESI (no Sound Horizon)	69.88±0.93	https://arxiv.org/pdf/2405.20306	Pogosian et al

Local measurements



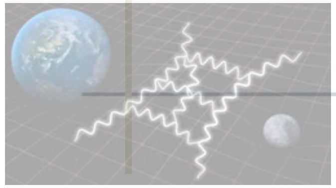
Distance ladder methods (local calibrators dependent)

Method	H_0(km/sec Mpc)	Arxiv-link	First author
Tully Fisher + Cepheid + TRGB	76.0 ± 3.4	https://arxiv.org/pdf/2004.14499.pdf	Kourkchi etal
SBF + Cepheids + TRGB	73.3 ± 3.1	https://arxiv.org/pdf/2101.02221.pdf	Blakeslee etal
SnII + Cepheids + TRGB	75.57±15	https://arxiv.org/pdf/2305.17243.pdf	Jaeger etal
Mira calibrators	73.3 ± 4.0	https://arxiv.org/pdf/1908.10883.pdf	Huang etal
Mira calibrators	72.37 ± 2.97	https://arxiv.org/pdf/2312.08423	Huang etal
TRGB calibrators (SH0ES)	73.22 ± 2.06	https://arxiv.org/pdf/2304.06693.pdf	Scolnic etal
Cepheid (SH0ES)	73.04 ± 1.04	https://arxiv.org/pdf/2112.04510.pdf	Riess etal
TRGB calibrators	76.94 ± 6.4	https://arxiv.org/pdf/2203.04241	Dhawan etal
TRGB calibrators	69.8 ± 0.6	https://arxiv.org/pdf/2106.15656	Freedman

Could we be missing something with ALL local calibrators??

Could there be a physics change between local calibrator scales ($z<0.01$) and Hubble flow scales ($z>0.01$)?

The Hubble Crisis Approaches



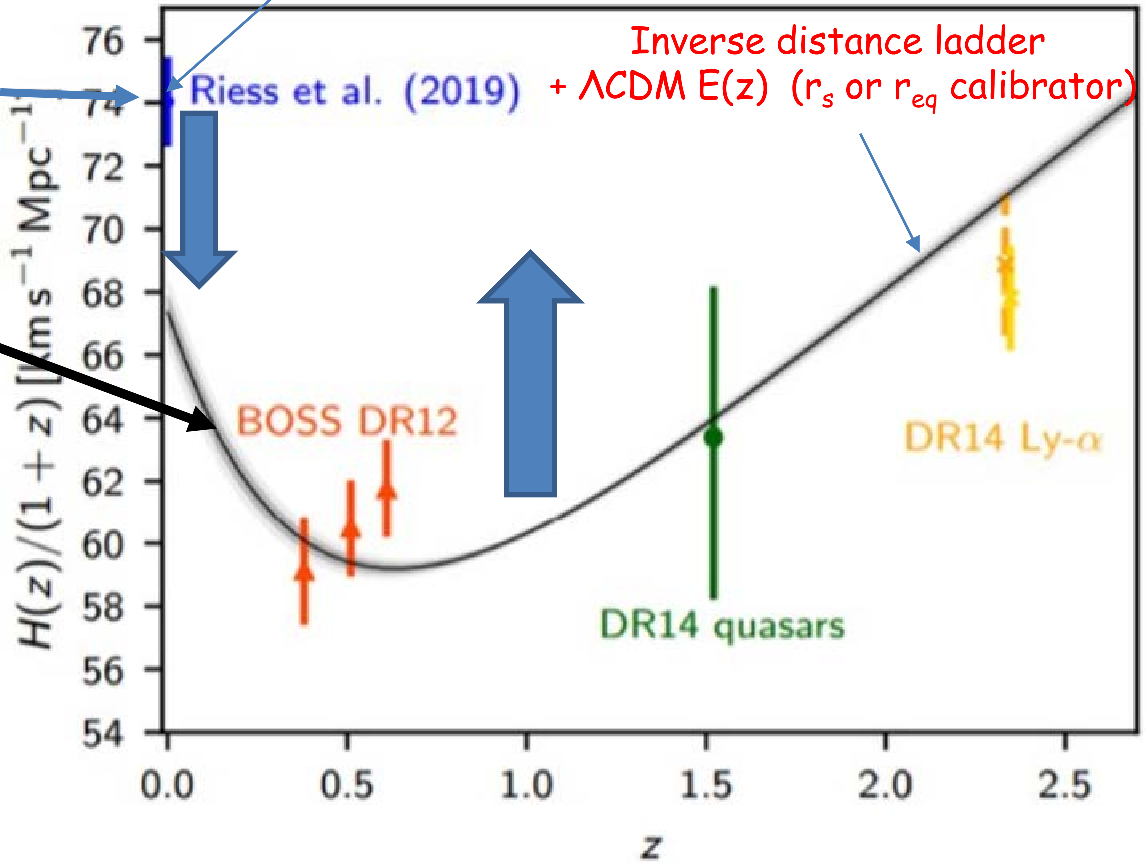
How can H(z) derived from late time calibrators (blue point and SnIa calibrated from it) become consistent with H(z) derived from early time calibrators (black line, CMB+BAO)?

Change SnIa Intrinsic Luminosity (systematics or physics change at $0<z<0.01$). (move blue point down)

Change sound horizon scale AND matter equality scale (Early DE transition at t_{rec} and more new physics at t_{eq}). (shift black line up)

Distance Ladder H(z) (M calibrator – Cepheids at z<0.01)

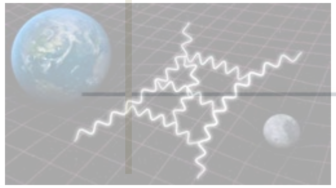
Inverse distance ladder + ΛCDM E(z) (r_s or r_{eq} calibrator)



Planck 2018 results. VI. Cosmological parameters

Planck Collaboration • N. Aghanim (Orsay, IAS) Show All(181)

The Hubble Crisis Approaches

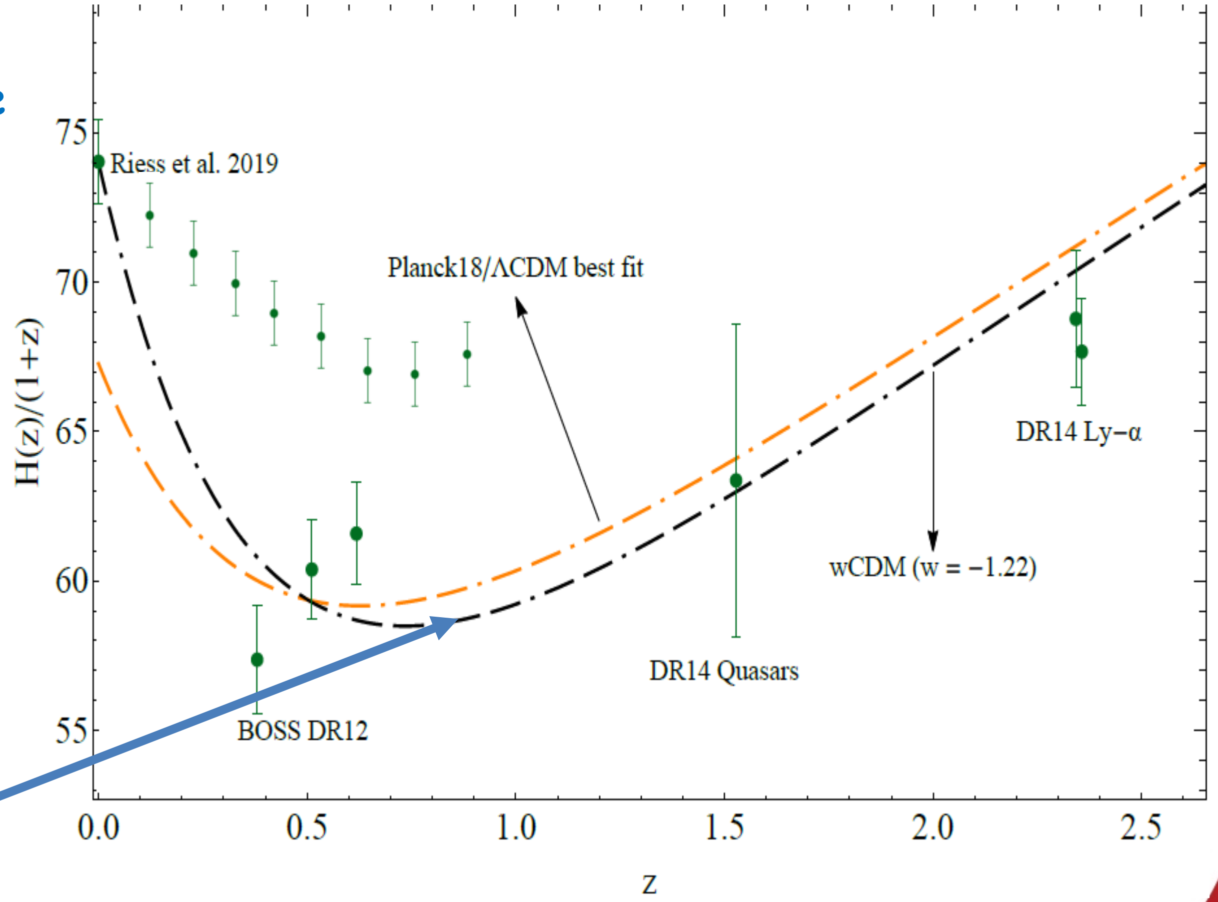


How can H(z) derived from late time calibrators (blue point and SnIa calibrated from it) become consistent with H(z) derived from early time calibrators (black line, CMB+BAO)?

Change SnIa Intrinsic Luminosity (systematics or physics change at $0<z<0.1$). (move blue point down)

Change sound horizon scale <u>AND matter equality scale</u> (Early DE transition at t_{rec} <u>and more new physics at t_{eq}</u>). (shift black line up)

Deform H(z) by eg dynamical dark energy (problems with BAO, growth, M). (distort black line)



Late-time approaches to the Hubble tension deforming H(z), worsen the growth tension

George Alestas (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.) (Mar 6, 2021)

Published in: *Mon.Not.Roy.Astron.Soc.* 504 (2021) 3, 3956-3962 • e-Print: 2103.04045 [astro-ph.CO]

H_0 tension, phantom dark energy, and cosmological parameter degeneracies

G. Alestas (Ioannina U.), L. Kazantzidis (Ioannina U.), L. Perivolaropoulos (Ioannina U.) (Apr 23, 2020)

Published in: *Phys.Rev.D* 101 (2020) 12, 123516 • e-Print: 2004.08363 [astro-ph.CO]

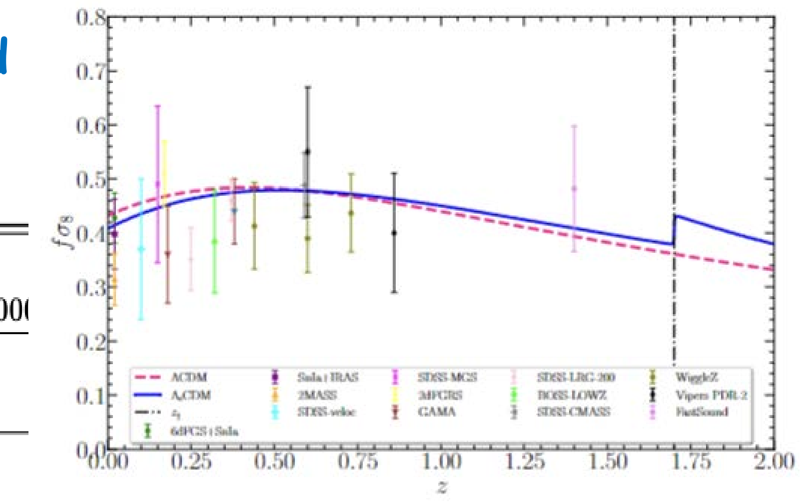
ΛsCDM a prime H(z) deformation model

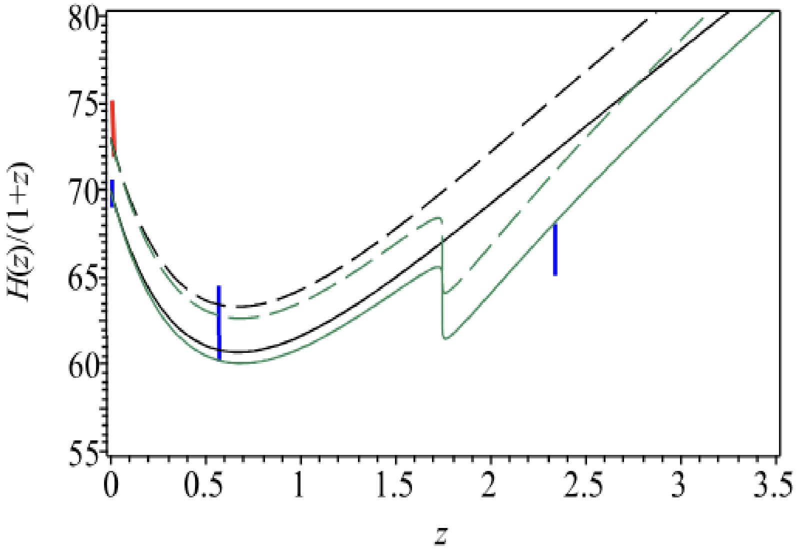
Growth, JWST tension improved

Akarsu, Cam, Paraskevas, LP in preparation.

Data set	Planck	Planck+BAOtr	Planck+BAOtr +PP	Planck+BAOtr +PP&SH0ES	Planck+BAOtr +PP&SH0ES+KiDS-100[illegible]
Model	Λ_sCDM	Λ_sCDM	Λ_sCDM	Λ_sCDM	Λ_sCDM
	ΛCDM	ΛCDM	ΛCDM	ΛCDM	ΛCDM
$z_\dagger$	unconstrained	$1.70^{+0.09}_{-0.19}(1.65)$	$1.87^{+0.13}_{-0.21}(1.75)$	$1.70^{+0.10}_{-0.1[illegible]}(1.67)$	$1.72^{+0.09}_{[illegible]}(1.70)$
	$--$	$--$	$--$	[illegible]	
M_B[mag]	$--$	$--$	$-19.317^{+0.021}_{-0.025}(-19.311)$	$-19.290 \pm 0.017(-19.278)$	$-19.282 \pm 0.017(-19.2[illegible]$
	$--$	$--$	$-19.407 \pm 0.013(-19.411)$	$-19.379 \pm 0.012(-19.373)$	$-19.372 \pm 0.011(-19.3[illegible]$
H_0[km/s/Mpc]	$70.77^{+0.79}_{-2.70}(71.22)$	$73.30^{+1.20}_{-1.00}(73.59)$	$71.72^{+0.73}_{-0.92}(71.97)$	$72.82 \pm 0.65(73.20)$	$73.16 \pm 0.64(73.36)$
	$67.39 \pm 0.55(67.28)$	$68.84 \pm 0.48(68.61)$	$68.55 \pm 0.44(68.54)$	$69.57 \pm 0.42(69.73)$	$69.83 \pm 0.37(69.96)$
Ω_m	$0.2860^{+0.0230}_{-0.0099}(0.2796)$	$0.2643^{+0.0072}_{-0.0090}(0.2618)$	$0.2768^{+0.0072}_{-0.0063}(0.2759)$	$0.2683 \pm 0.0052(0.2646)$	$0.2646 \pm 0.0052(0.262[illegible]$
	$0.3151 \pm 0.0075(0.3163)$	$0.2958 \pm 0.0061(0.2984)$	$0.2995 \pm 0.0056(0.2992)$	$0.2869 \pm 0.0051(0.2849)$	$0.2837 \pm 0.0045(0.2816$
S_8	$0.801^{+0.026}_{-0.016}(0.791)$	$0.777 \pm 0.011(0.772)$	$0.791 \pm 0.011(0.794)$	$0.783 \pm 0.010(0.777)$	$0.774 \pm 0.009(0.773)$
	$0.832 \pm 0.013(0.835)$	$0.802 \pm 0.011(0.804)$	$0.808 \pm 0.010(0.804)$	$0.788 \pm 0.010(0.784)$	$0.781 \pm 0.008(0.782)$
$\chi^2_{\rm min}$	2778.06	2793.38	4219.68	4097.32	4185.34
	2780.52	2820.30	4235.18	4138.26	4226.50
$\ln \mathcal{B}_{ij}$	-1.28	-12.65	-7.52	-19.47	-19.77

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





Λ_sCDM model: A promising scenario for alleviation of cosmological tensions

Ozgur Akarsu, Eleonora Di Valentino, Suresh Kumar, Rafael C. Nunes, J. Alberto Vazquez et al. (Jul 20, 2023)

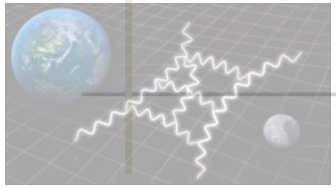
e-Print: 2307.10899 [astro-ph.CO]

Graduated dark energy: Observational hints of a spontaneous sign switch in the cosmological constant

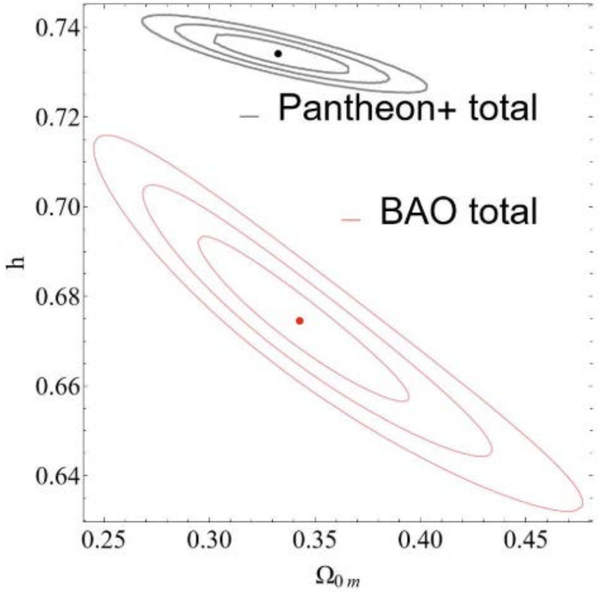
Özgür Akarsu (Istanbul, Tech. U.), John D. Barrow (Cambridge U., DAMTP), Luis A. Escamilla (UNAM, CCF), J. Alberto Vazquez (UNAM, CCF) (Dec 18, 2019)

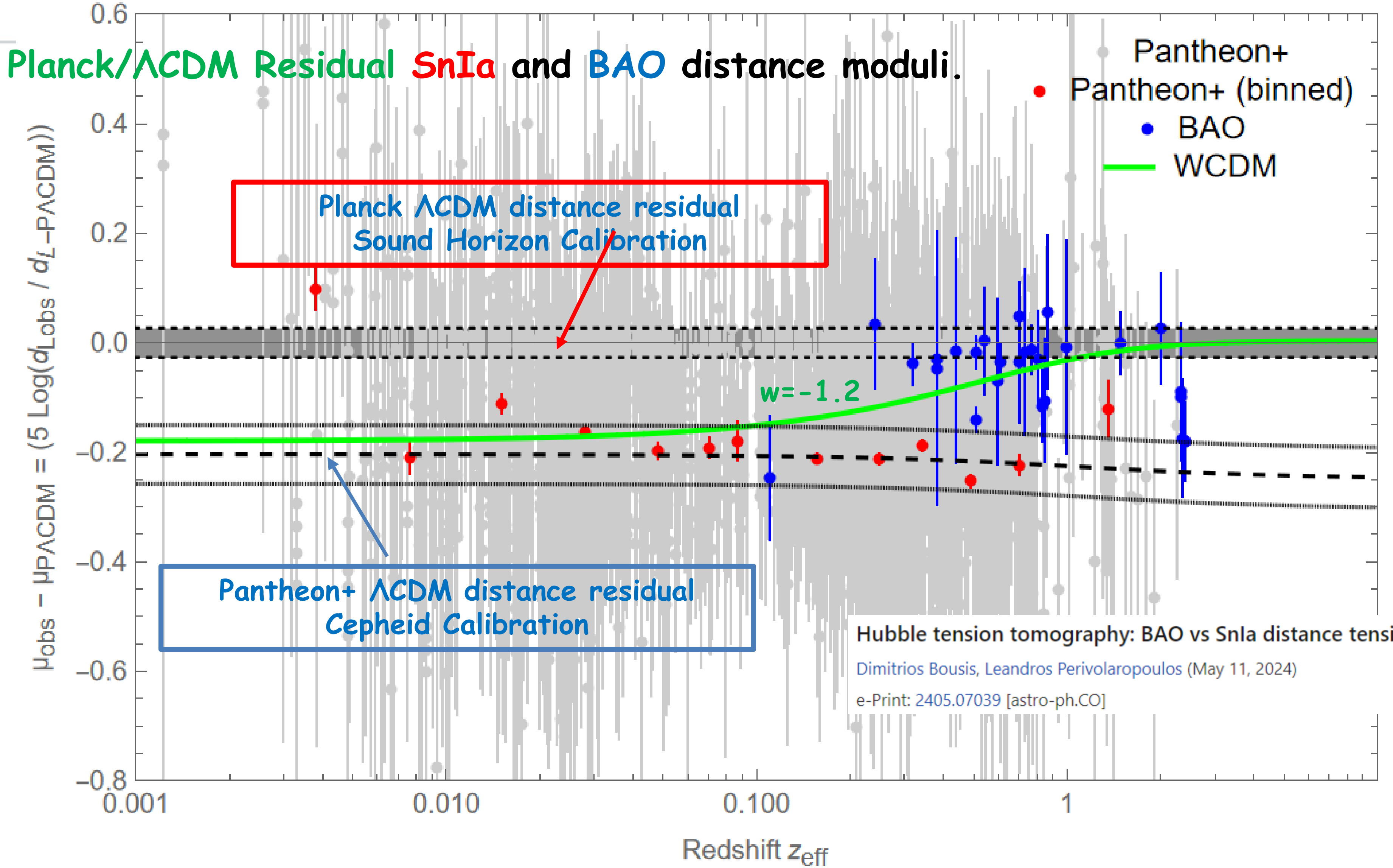
Published in: *Phys.Rev.D* 101 (2020) 6, 063528 • e-Print: 1912.08751 [astro-ph.CO]

Hubble Tension Tomography:
The problem with H(z) deformation models



The Hubble tension is a calibrator tension and can not be resolved by H(z) deformation.

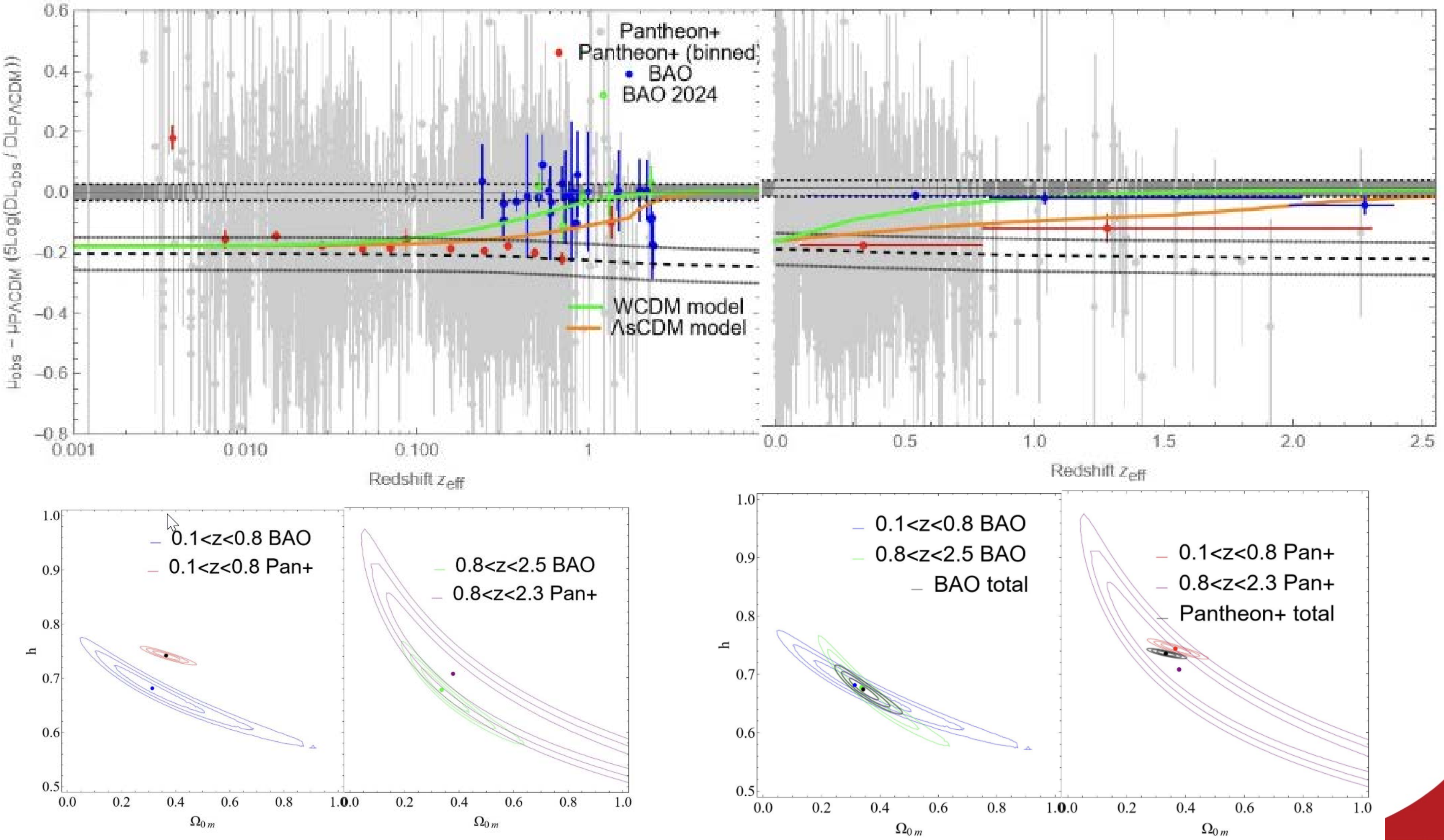




Hubble tension tomography: BAO vs SnIa distance tension

Dimitrios Bousis, Leandros Perivolaropoulos (May 11, 2024)

e-Print: 2405.07039 [astro-ph.CO]



Pantheon+
Pantheon+ (binned)
BAO
BAO 2024
WCDM model
ΛsCDM model
μobs − μPΛCDM (5Log(DLobs / DLPΛCDM))
Redshift zeff
Redshift zeff
0.1<z<0.8 BAO
0.1<z<0.8 Pan+
0.8<z<2.5 BAO
0.8<z<2.3 Pan+
h
Ω0m
Ω0m
0.1<z<0.8 BAO
0.8<z<2.5 BAO
BAO total
0.1<z<0.8 Pan+
0.8<z<2.3 Pan+
Pantheon+ total
h
Ω0m
Ω0m

Modified Gravity Approaches to the Tensions of ΛCDM

- Special Issue Editors
- Special Issue Information
- Keywords
- Published Papers

A special issue of *Universe* (ISSN 2218-1997). This special issue belongs to the section "Gravitation".

Deadline for manuscript submissions: **closed (29 February 2024)** | Viewed by 23873

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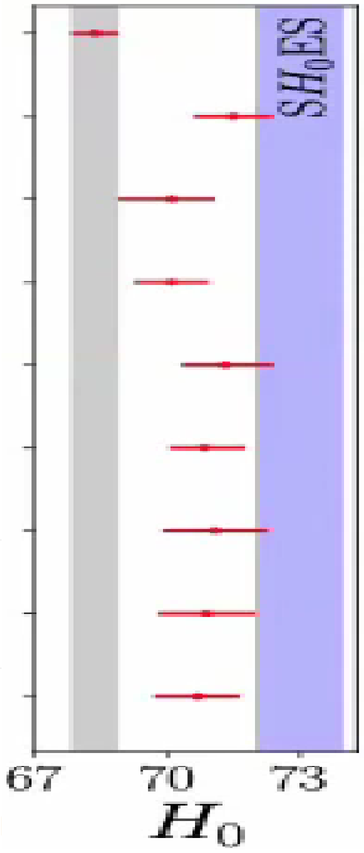
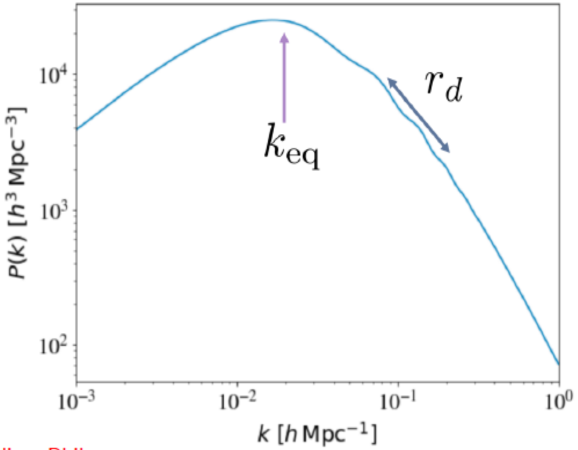
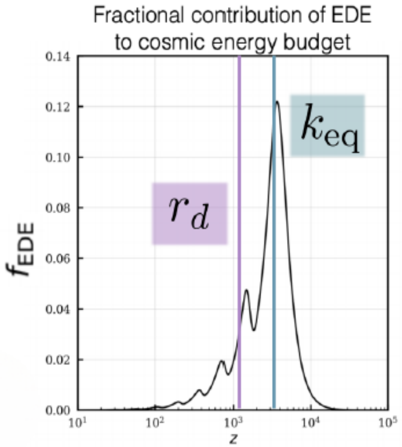


Two scales in $P(k)$, both standard rule





Credits: Oliver Philcox

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Opinion

Seven Hints that Early-Time New Physics Alone Is Not Sufficient to Solve the Hubble Tension

Sunny Vagnozzi [1,2]

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[2] Istituto Nazionale di Fisica Nucleare (INFN)—Trento Institute for Fundamental Physics and Applications (TIFPA), Via Sommarive 14, 38123 Povo, TN, Italy

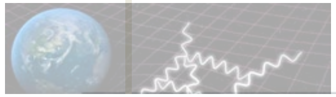
- **A**ges of the oldest astrophysical objects
- **B**aryon Acoustic Oscillations r_d-H_0 degeneracy slope
- **C**osmic chronometers
- **D**escending trends observed in a wide range of low-z datasets
- **E**arly integrated Sachs-Wolfe effect and its restrictions on early-time new physics
- **F**ractional matter density (Ω_m) constraints from uncalibrated cosmic standards
- **G**alaxy power spectrum r_d- and k_{eq}-based determinations of H_0

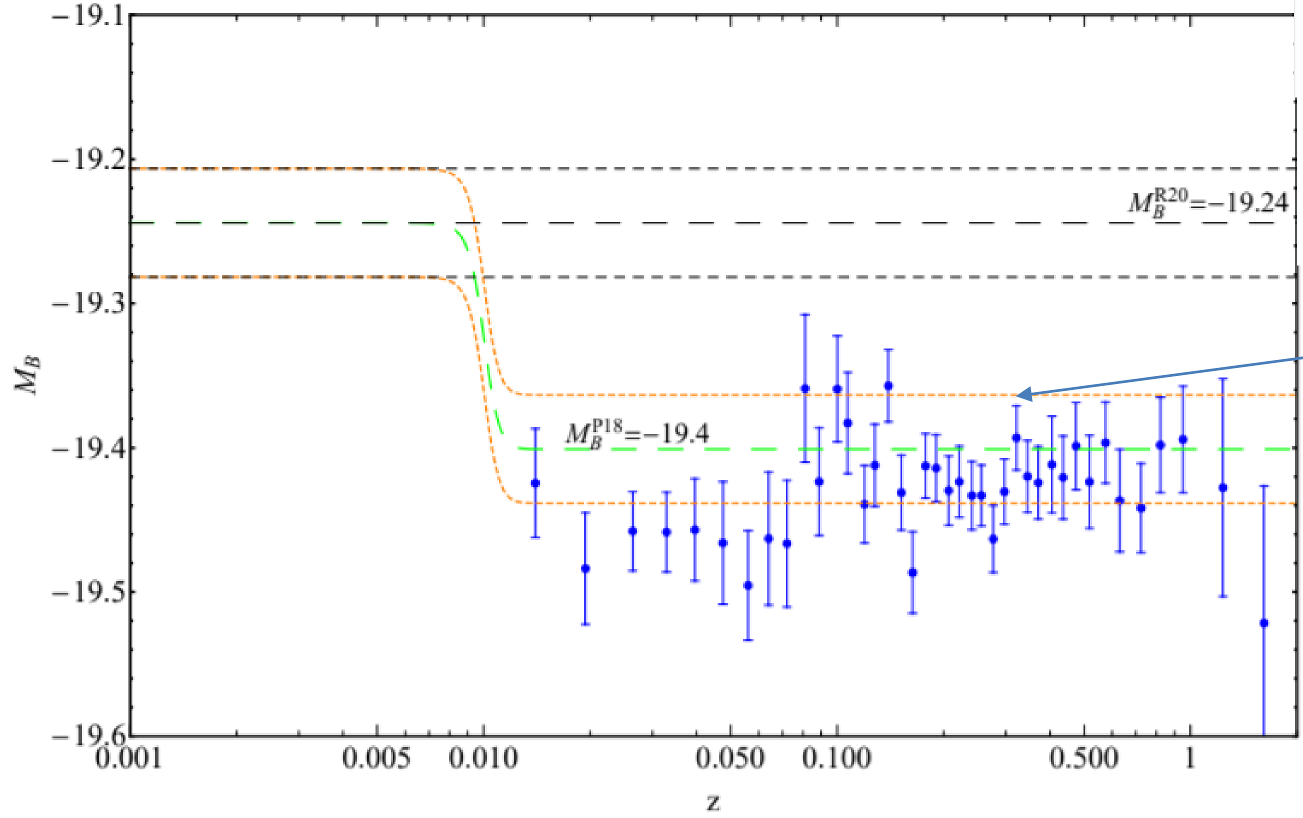
The Ups and Downs of Early Dark Energy solutions to the Hubble tension: A review of models, hints and constraints circa 2023

Vivian Poulin (U. Montpellier 2, LUPM), Tristan L. Smith (Swarthmore Coll. and New York U., CCPP), Tanvi Karwal (Pennsylvania U.) (Feb 17, 2023)

Published in: *Phys.Dark Univ.* 42 (2023) 101348 • e-Print: 2302.09032 [astro-ph.CO]

The Local Physics 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]

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

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]

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

Resolves M tension and Hubble tension.

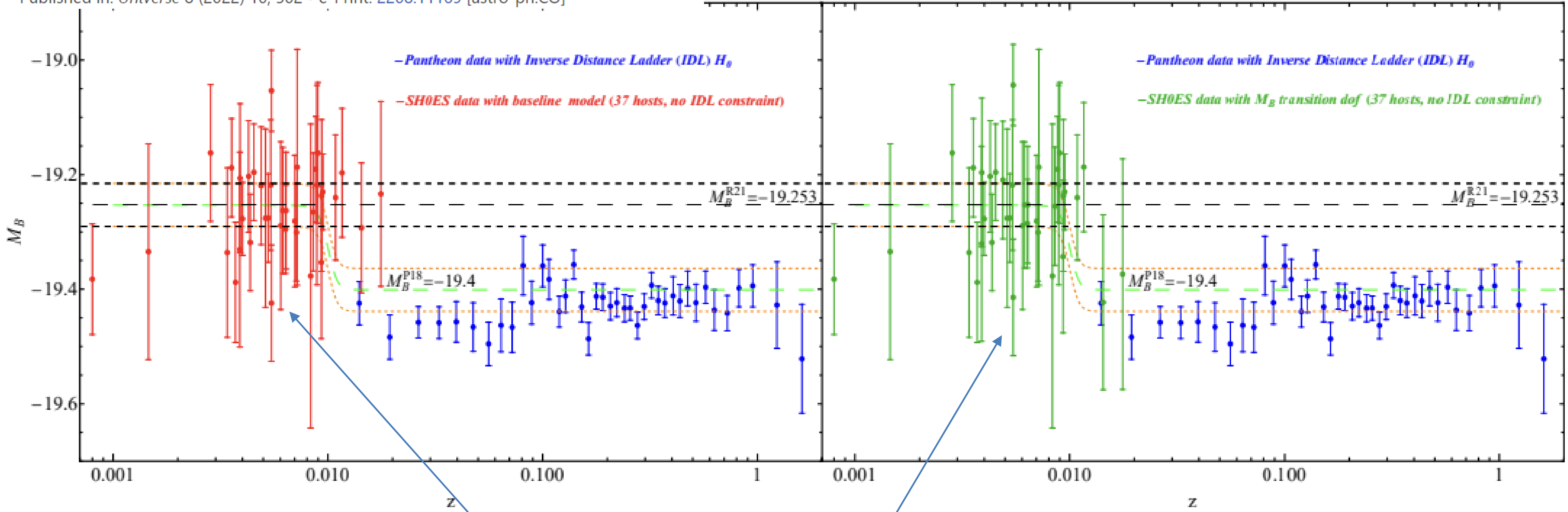
Can potentially also resolve growth tension if the transition is connected with weaker gravity at $z>z_t$

Hints for an M transition in SH0ES?

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)

Published in: *Universe* 8 (2022) 10, 502 • e-Print: 2208.11169 [astro-ph.CO]

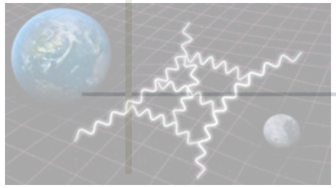


Derive μ_i and do not allow any transition
(the original SH0ES approach)

Allow (but do not enforce) an M transition at 50Mpc
(new degree of freedom approach)

$$M_{Bi} = m^0_{Bi} - \mu_i$$

Reanalyze the Local SH0ES Calibrator



Calibrate Cepheids in anchor galaxies and in SnIa hosts
3492 equations fit for 47 unknown parameters (including M of SnIa)

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

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

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

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

A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team

Adam G. Riess (Baltimore, Space Telescope Sci. and Johns Hopkins U.), Wenlong Yuan (Johns Hopkins U.), Lucas M. Macri (Texas A-M), Dan Scolnic (Duke U.), Dillon Brout (Harvard-Smithsonian Ctr. Astrophys.) et al (Dec 8, 2021)

Published in: *Astrophys.J.Lett.* 934 (2022) 1, L7 • e-Print: 2112.04510 [astro-ph.CO]

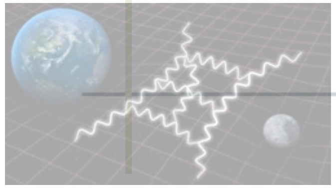
Express the system as linear vector transformation

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

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

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

Generalizing the baseline SH0ES modeling analysis: New degrees of freedom



Allow for a change (transition) of the SH0ES modeling parameters M_W, b_W, Z_W, M_B at a given distance D_c (cosmic time t_c).

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

$$m^0_{B,i} = \mu_i + M_B$$

$$\Downarrow$$

$$m^0_{B,i} = \mu_i + M_B^{>}\Theta(D - D_c) + M_B^{<}\Theta(D_c - D)$$

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

$$\Downarrow$$

$$m_{B,i} - 5\log D_L(z_i) - 25 = M_B^{>}\Theta(D - D_c) + M_B^{<}\Theta(D_c - D) - 5\log H_0$$

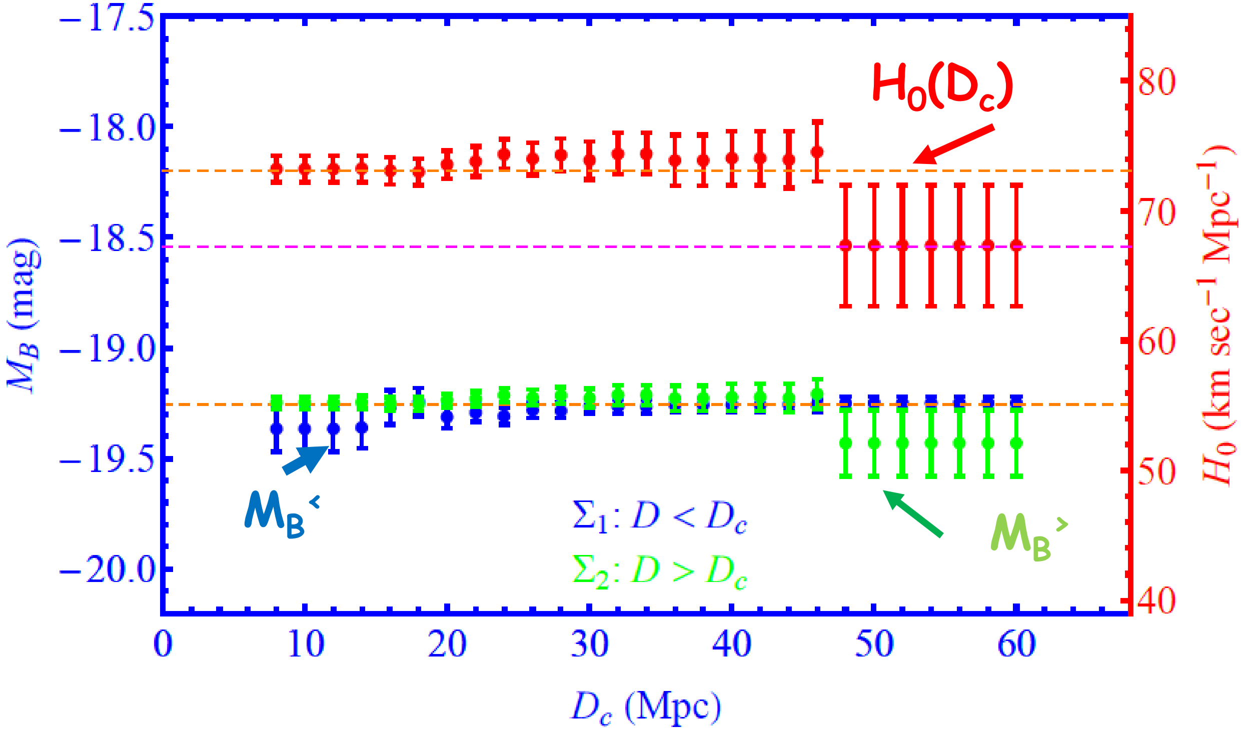
A Reanalysis of the Latest SH0ES Data for H_0: Effects of New Degrees of Freedom on the Hubble Tension

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

Published in: *Universe* 8 (2022) 10, 502 • e-Print: 2208.11169 [astro-ph.CO]

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 vector q.

Generalized Local Physics Analyses I



Spontaneous transition of the best fit value of H_0 when a transition at D_c~50Mpc is allowed. H_0=(67.3 ± 4.6) km/secMpc

A Reanalysis of the Latest SH0ES Data for H_0: Effects of New Degrees of Freedom on the Hubble Tension

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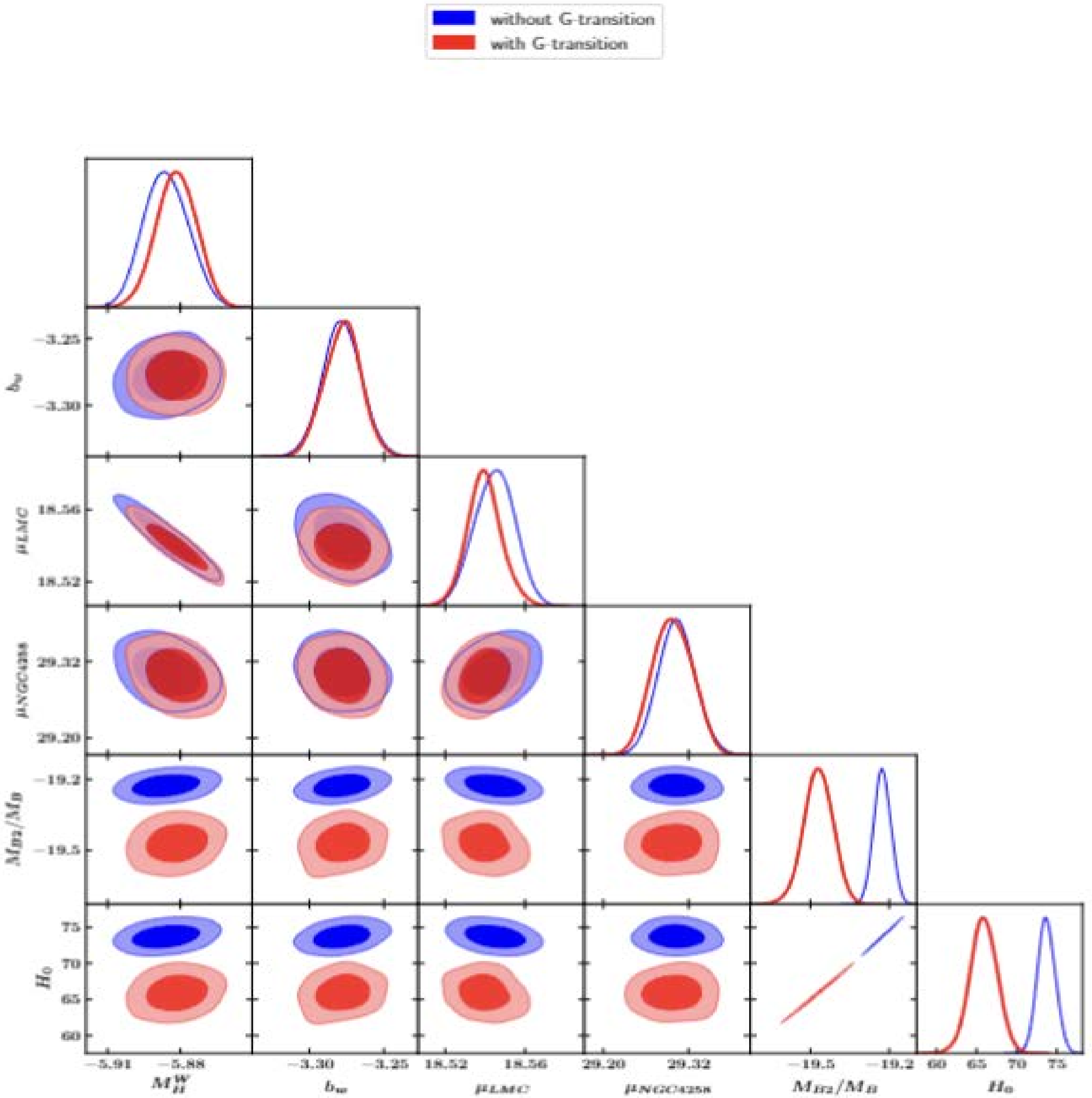
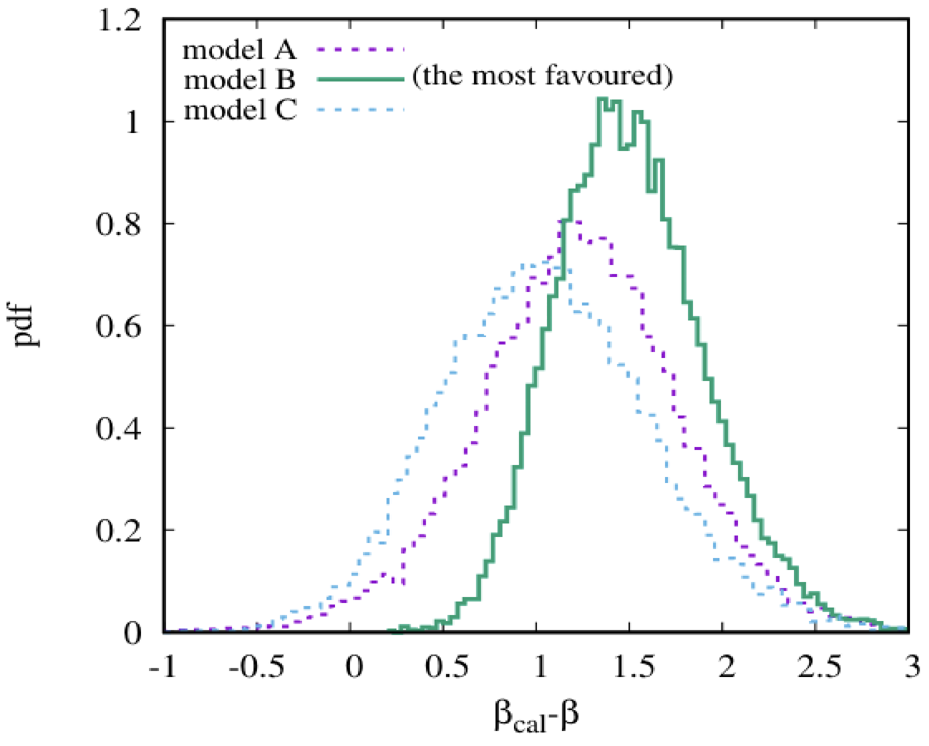


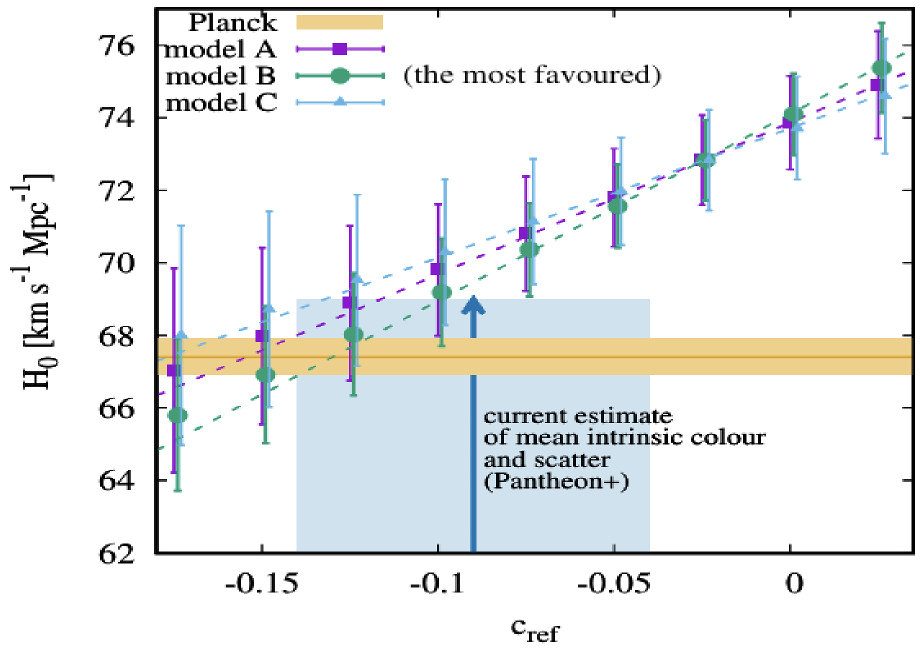
Ruchika, Melchiorri, LP 2024 (in preparation)
(Shift M_W^H, fit for M_B M_{B2})

Generalized Local Physics Analyses II



Allow for different color parameter between Cepheid hosted SnIa and Hubble flow SnIa

$$m_B = \mu + M_B + \alpha x_1 + \beta(c - c_{\rm ref}) \quad \text{for SN block,}$$
$$m_B = \mu + M_B + \alpha x_1 + \beta_{\rm cal}(c - c_{\rm ref}) \quad \text{for SN cal block.}$$



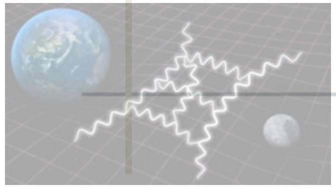
Intrinsic tension in the supernova sector of the local Hubble constant measurement and its implications #10

Radosław Wojtak, Jens Hjorth (Jun 16, 2022)

Published in: *Mon.Not.Roy.Astron.Soc.* 515 (2022) 2, 2790-2799 • e-Print: 2206.08160 [astro-ph.CO]

Discrepancy between the two values of the color parameter.

Main Points / Conclusion



The Hubble tension is a tension between early time and late time cosmic distance calibrators. New physics and a change of the standard model is likely to emerge from this tension.

New physics is likely in both the early time calibrators (sound horizon at t_{rec} and horizon at t_{eq}) or late time calibrators (local cosmic physics/astrophysics).

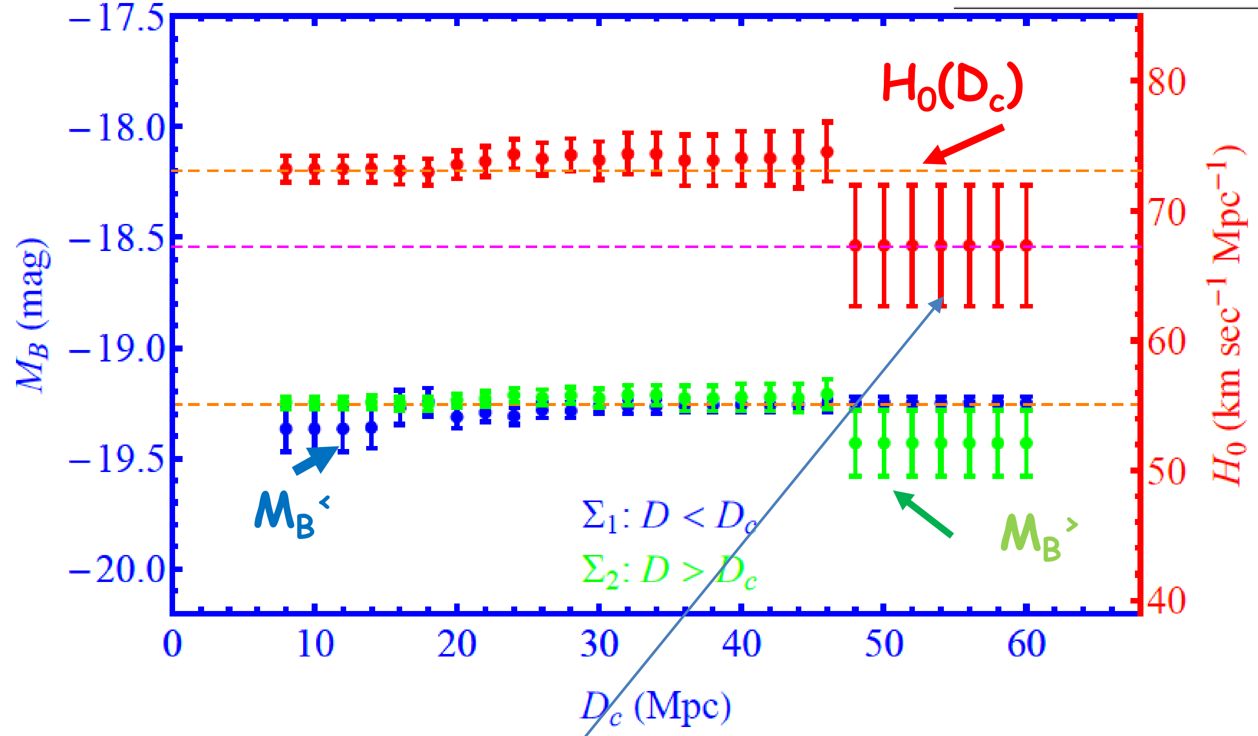
A late transition event involving a sudden change of the SnIa intrinsic luminosity occurring less than 150 million years ago ($z_t<0.01$) is a hypothesis that deserves further investigation by reanalyzing the SH0ES data with new degrees of freedom.

There are hints in the SH0ES data for such an ultralate physics transition.

Extra Slides

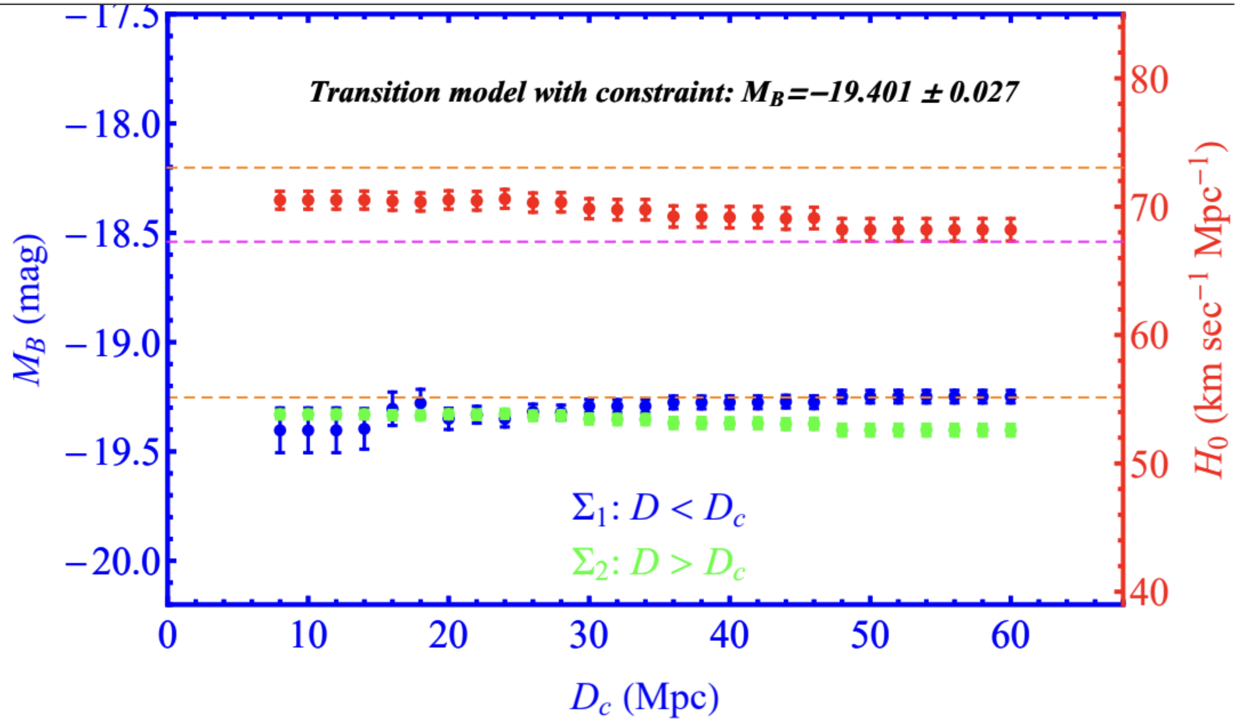
Results of the Generalized Analysis

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,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



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

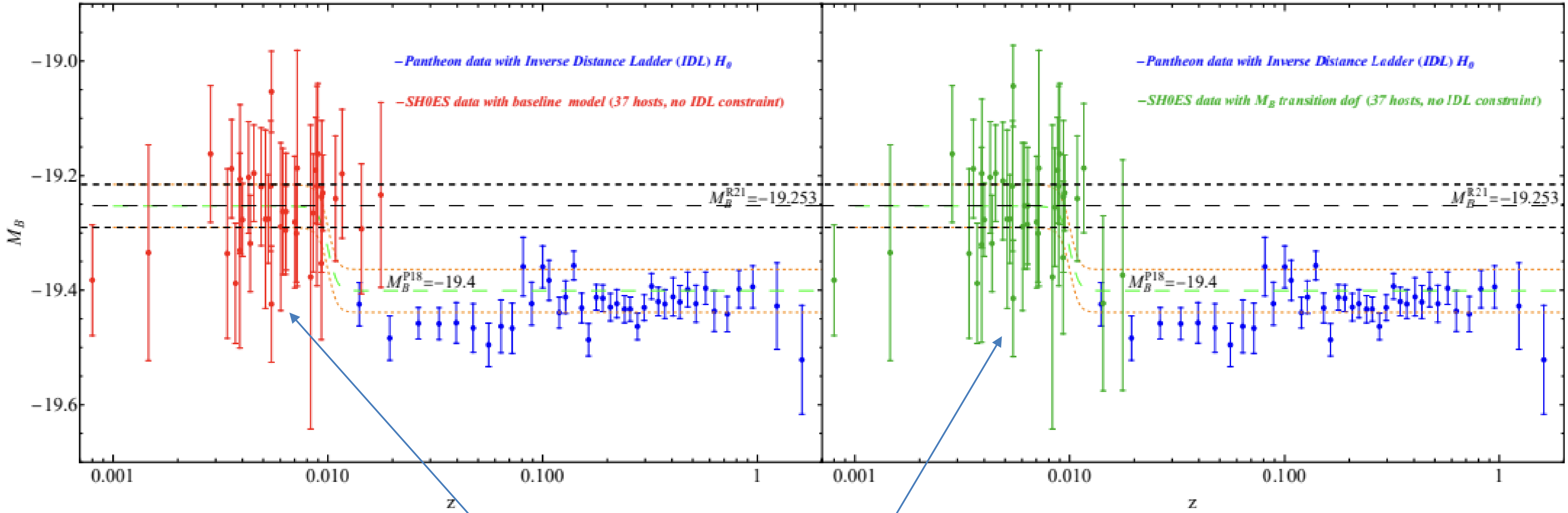
H_0=(67.3 ± 4.6) km/secMpc



Using Inverse distance ladder input

H_0=(68.2 ± 0.9) km/secMpc

Hints for an M transition in SH0ES?

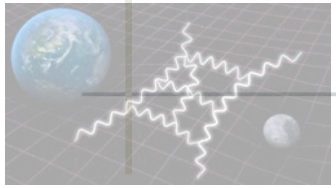


Derive μ_i and do not allow any transition
(the original SH0ES approach)

Allow (but do not enforce) an M transition
at 50Mpc
(new degree of freedom approach)

$$M_{Bi} = m^0_{Bi} - \mu_i$$

Measuring H_0–H(z) with standard candles: late time calibrators



Fit SnIa Standard Candles for H_0 , 0.02<z<0.1:

fit with kinematic expansion (0.01<z<0.1)

$$D_L(z,q_0) = cz\left[1+\frac{1}{2}(1-q_0)z\right]$$

$$m_{th}(z) = M + 5\,log_{10}\left[\frac{d_L(z)}{Mpc}\right] + 25$$

$$d_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$D_L(z) = \frac{H_0\, d_L(z)}{c}$$

$$m_{th}(z) = M + 5\,log_{10}\left(D_L(z)\right) + 5\,log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25$$

measure

measure locally (z<0.01, 40Mpc) using relative distance indicators (eg Cepheids)

Fit (assume M is the same in the Hubble flow (z>0.01))

Degeneracy between M (measured at z<0.01) and H_0 (fit at z> 0.01). No $E(z)=H(z)/H_0$ dependence.

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

$$m_{th}(\Omega_{0m},\mathcal{M}) = 5\,log_{10}D_L(z;\Omega_{0m}) + \mathcal{M}(M,H_0)$$

H_0 measurement using distance ladder:

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

$$M^{R21}_{z<0.01} = -19.25 \pm 0.03$$

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

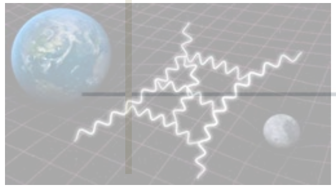
$$M_{z>0.01} = M^{R21}_{z<0.01}$$

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

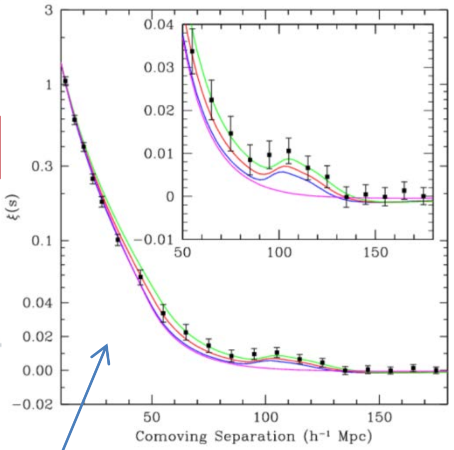
H_0 Tension

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

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



Measuring H_0-$H(z)$ with a stand early time calibrators



Sound Horizon at Recombination Standard Ruler (Early Universe):

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

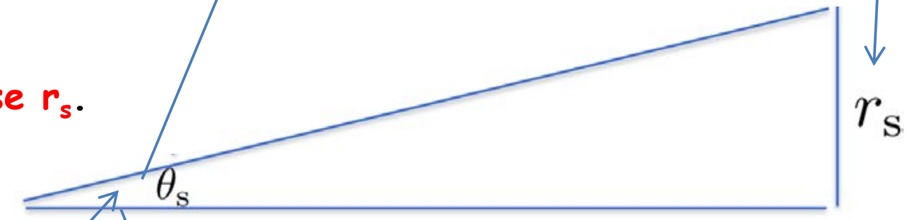
Depends on ρ_b, ρ_γ and ρ_{CDM}

1. EDE: Add new fluids to decrease r_s. But keep the same E(z).

r_s=147.6 Mpc from Planck and BBN values of ρ_b, ρ_γ and ρ_{CDM}

inferred

calculated



$$D_A(z = 1100)$$

2. E(z) deformation: New dark energy. But keep the same r_s.

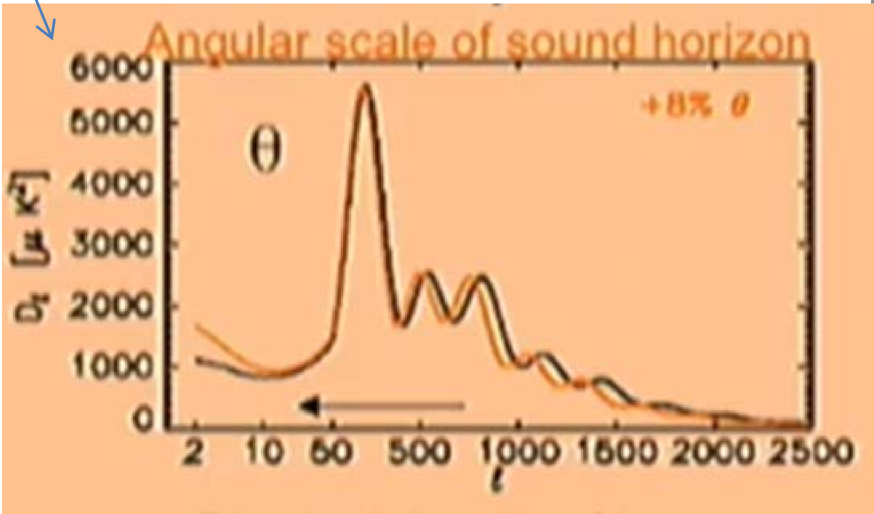
measured

Same with BAO (projected r_s on LSS) (z_s->z_{BAO}, θ_s->θ_{BAO} r_s->r_d)

$$\theta_s = \frac{r_s}{D_A(z)}$$

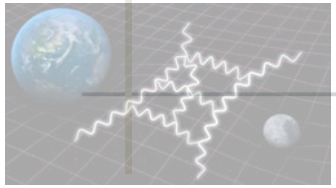
comoving

$$E(z) = \left[\Omega_{0m}(1+z)^3 + (1-\Omega_{0m})\right]^{\frac{1}{2}}$$



Degeneracy between r_s and H_0 and E(z).

Inverse Distance Ladder and the M tension



H_0 measurement using sound horizon standard ruler

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

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

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

Calibrate M from r_s (Inverse distance ladder)

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

$$\mathcal{M} = M + 5 log \frac{c/H_0}{Mpc} + 25 \qquad H_0 = H_0^{P18}$$

M tension. or M transition?

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

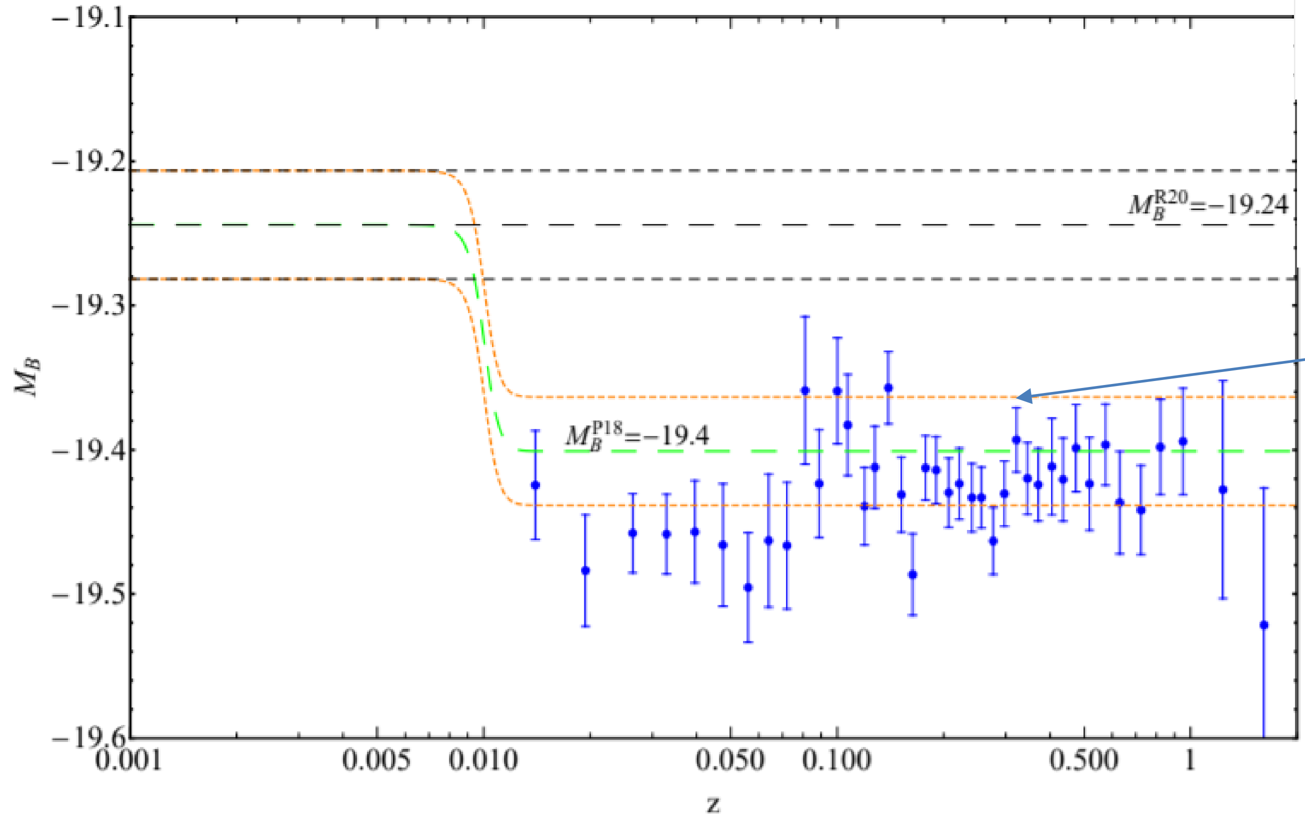
In Hubble flow. Local!

M depends on G_{eff}.

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]

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]

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

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]

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 $z>z_t$

The M transition Model: Fit to the data

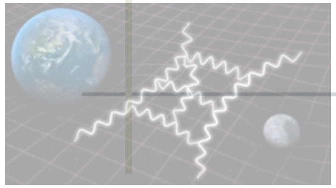


TABLE IV. Constraints at 68.3% CL of the cosmological parameters for the dark energy models explored in this work when the prior $M = -19.24 \pm 0.04$ mag of Eq. (3.1) from SH0ES is adopted. $\Delta\chi^2$ corresponds to the $\chi^2_{\rm min}$ difference of each model with the ΛCDM case. Only transitions models provide a competitive fit to data as compared to ΛCDM.

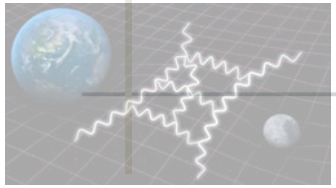
Parameters	ΛCDM	wCDM	CPL	$LwMT$ ($z_t \geq 0.01$)	PEDE	LMT ($z_t = 0.01$)
$\Omega_{\rm m,0}$	$0.3022^{+0.0051}_{-0.0052}$	0.2943 ± 0.0065	$0.2974^{+0.0067}_{-0.0068}$	$0.3073^{+0.0063}_{-0.0062}$	0.2789 ± 0.0049	0.3082 ± 0.0053
n_s	0.9704 ± 0.004	0.968 ± 0.004	0.967 ± 0.004	0.968 ± 0.004	0.963 ± 0.003	0.968 ± 0.004
H_0	68.36 ± 0.4	69.47 ± 0.72	69.25 ± 0.73	67.96 ± 0.55	71.85 ± 0.45	67.89 ± 0.40
$\sigma_{8,0}$	$0.8076^{+0.0058}_{-0.0062}$	$0.8215^{+0.0095}_{-0.0097}$	$0.8248^{+0.0096}_{-0.0097}$	$0.8084^{+0.0064}_{-0.0065}$	0.8531 ± 0.0059	0.8085 ± 0.0057
S_8	$0.8105^{+0.0097}_{-0.01}$	0.8135 ± 0.0098	$0.8210^{+0.0107}_{-0.0106}$	0.8181 ± 0.0100	0.8226 ± 0.0095	0.8194 ± 0.0099
M	-19.40 ± 0.01	-19.38 ± 0.02	-19.37 ± 0.02	-19.26 ± 0.04	-19.33 ± 0.01	-19.24 ± 0.04
ΔM	-	-	-	$-0.145^{+0.038}_{-0.035}$	-	-0.168 ± 0.039
$M_>$	-	-	-	-19.410 ± 0.011	-	-19.411 ± 0.011
Δw	-	-	-	unconstrained	-	-
a_t	-	-	-	> 0.986	-	-
w_0	-	-1.050 ± 0.027	-0.917 ± 0.078	-	-	-
w_a	-	-	$-0.53^{+0.33}_{-0.28}$	-	-	-
$\chi^2_{\rm min}$	3854	3851	3848	3833	3867	3835
$\Delta\chi^2$	-	-3	-6	-21	$+13$	-19

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]

Horizon at t_{eq}: An independent early time standard ruler hint at with CMB H_0



Parameter degeneracies:

Measured with Hubble free expansion rate $E(z)=H(z)/H_0$
1100>z>0.01 (CMB, BAO, SnIa): Accurate-no tension here

$$m_i(z_i) - 5\, log_{10} D_L(z_i; \Omega_{0m})$$

$$\theta_s \cdot \int_0^{z_d} \frac{1}{E(z;\Omega_{0m})} \qquad \theta_{eq} \cdot \int_0^{z_{eq}} \frac{1}{E(z;\Omega_{0m})}$$

Obtained from ΛCDM E(z) from t_{eq} using shape of LSS power spectrum.

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

$$\mathcal{R}_s = r_s H_0$$

$$\mathcal{R}_{eq} = r_{eq} H_0$$

A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team

Adam G. Riess (Baltimore, Space Telescope Sci. and Johns Hopkins U.), Wenlong Yuan (Johns Hopkins U.), Lucas M. Macri (Texas A-M), Dan Scolnic (Duke U.), Dillon Brout (Harvard-Smithsonian Ctr. Astrophys.) et al (Dec 8, 2021)

Published in: *Astrophys.J.Lett.* 934 (2022) 1, L7 • e-Print: 2112.04510 [astro-ph.CO]

Planck 2018 results. VI. Cosmological parameters

Planck Collaboration • N. Aghanim (Orsay, IAS) et al. (Jul 17, 2018)

Published in: *Astron.Astrophys.* 641 (2020) A6, *Astron.Astrophys.* 652 (2021) C4 (erratum) • e-Print: 1807.06209 [astro-ph.CO]

Determining the Hubble constant without the sound horizon: A 3.6% constraint on H_0 from galaxy surveys, CMB lensing, and supernovae

Oliver H.E. Philcox (Princeton U., Astrophys. Sci. Dept. and Princeton, Inst. Advanced Study), Gerrit S. Farren (Cambridge U., DAMTP), Blake D. Sherwin (Cambridge U., DAMTP and Cambridge U., KICC), Eric J. Baxter (Inst. Astron., Honolulu), Dillon J. Brout (Harvard-Smithsonian Ctr. Astrophys.) (Apr 6, 2022)

Published in: *Phys.Rev.D* 106 (2022) 6, 063530 • e-Print: 2204.02984 [astro-ph.CO]

Measured with ultralate time calibrators (Cepheids, TRGB etc) at z<0.01 (no Hubble flow)

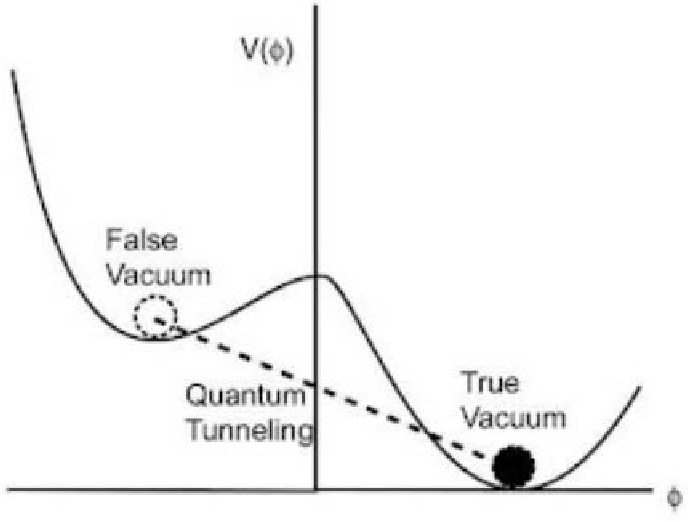
$$H_0^{R21} = 73.04 \pm 1.04$$

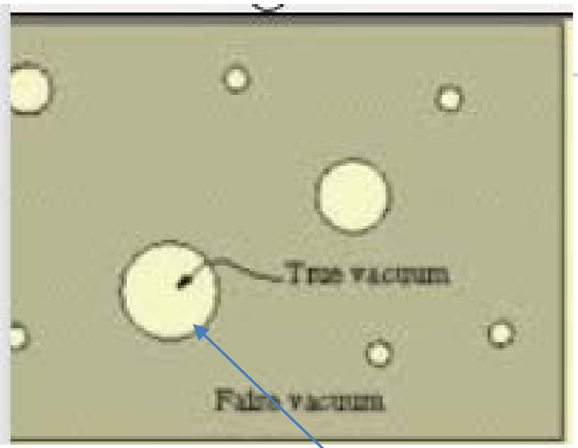
Measured from CMB, BBN assuming ΛCDM E(z) before recombination.

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

$$H_0 = 68.0^{+2.9}_{-3.2}\,\text{km}\,\text{s}^{-1}\text{Mpc}^{-1}$$

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

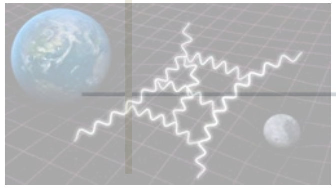
Predicted bubble scale is close to favored scale of transition

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]

Theoretical Model: Scalar Tensor Theory



Scalar Tensor Transition:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}F(\phi)R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

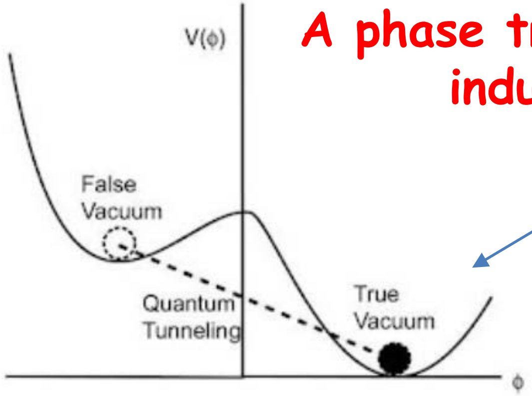
$8\pi G \sim 1/F(\Phi)$

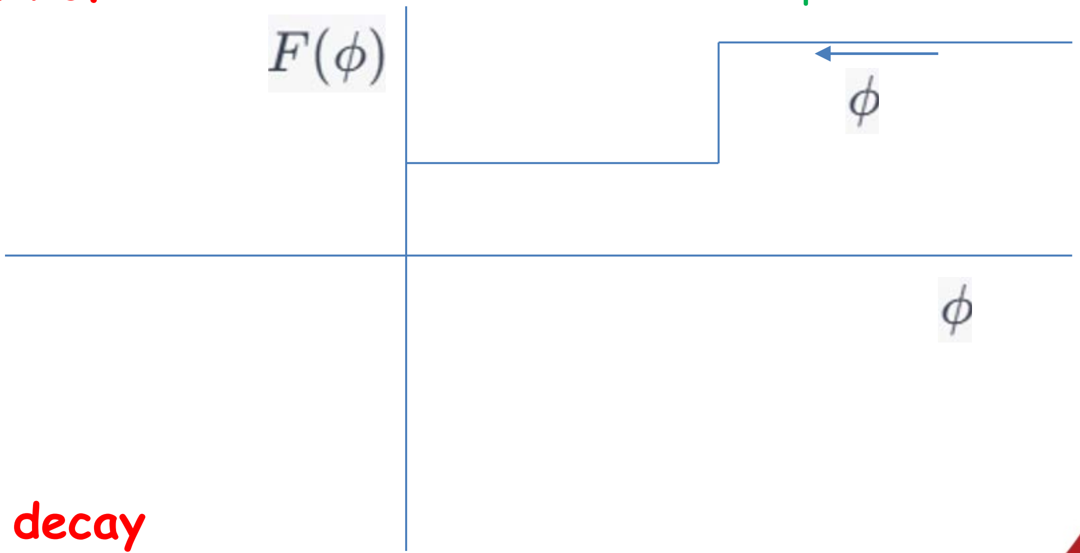
Temporal transition

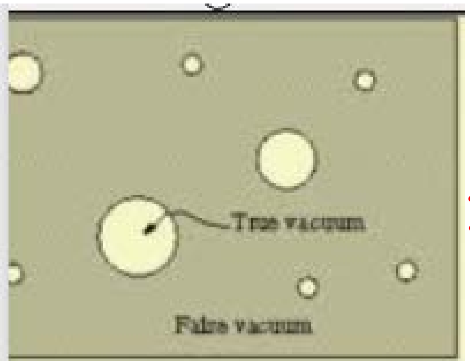
Field rolling in constant potential

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

Spatial transition

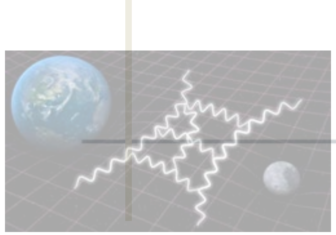


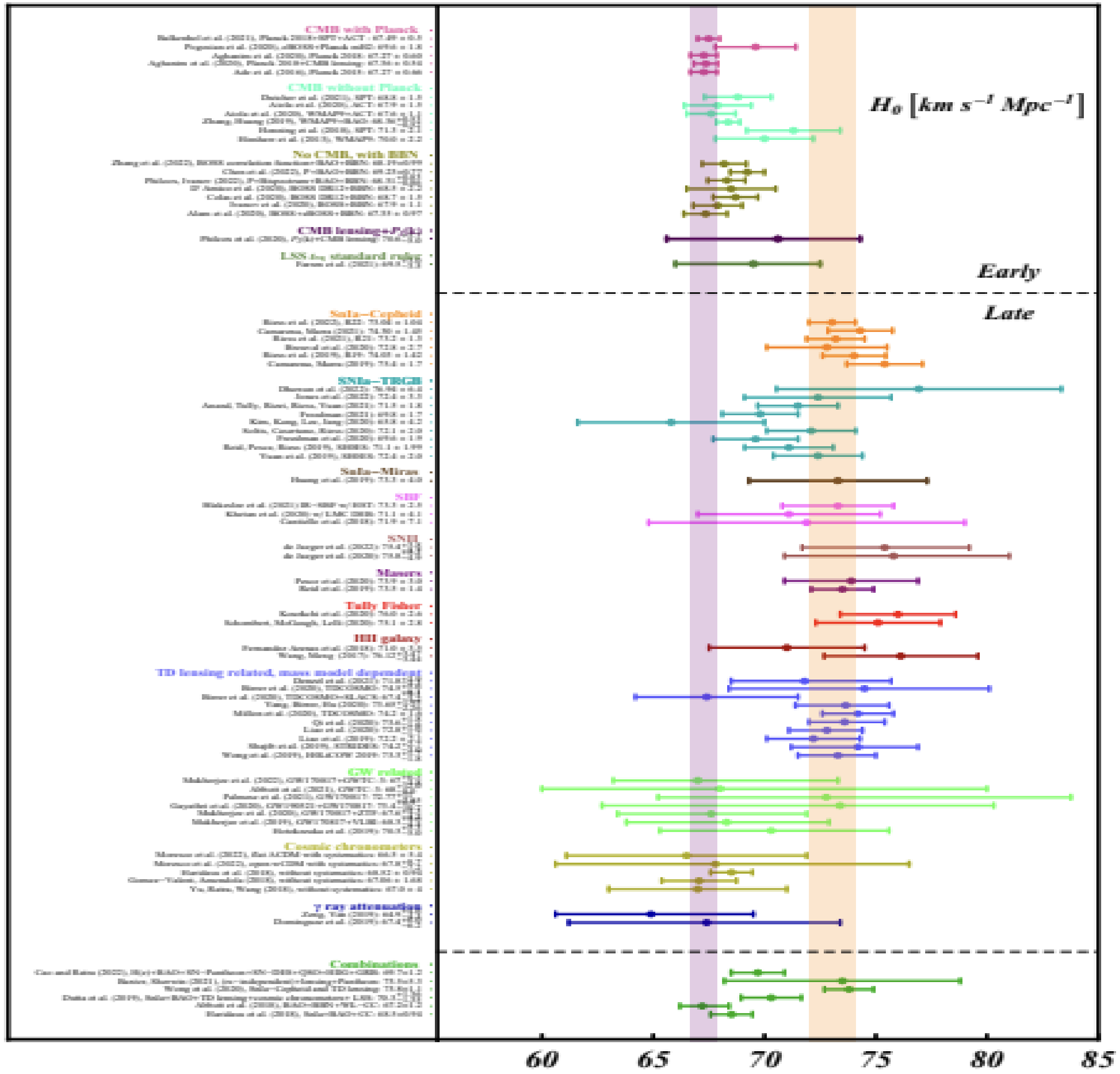




In the context of false vacuum decay bubbles of true vacuum form

The Hubble tension





Q.: What is the feature that distinguishes the two groups of H_0 values?

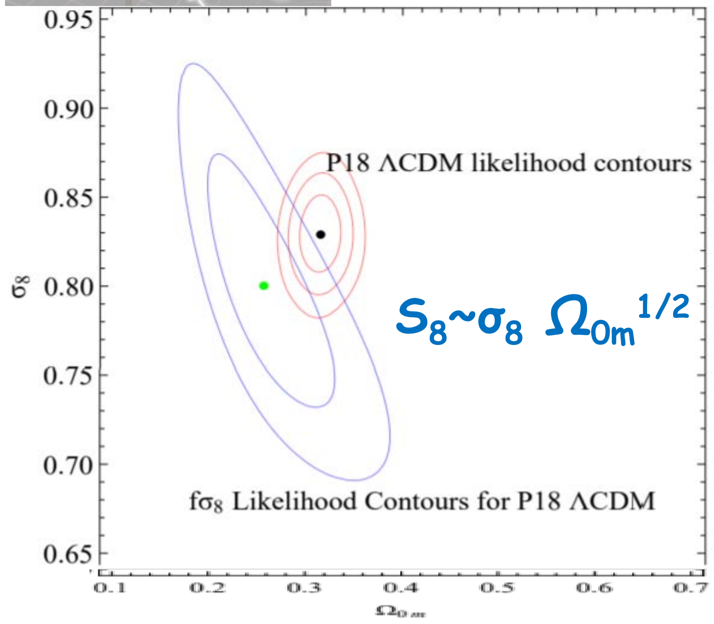
Is it cosmic time of measurements?

or

is it the use of local calibrators (distance ladder)?

The growth tension

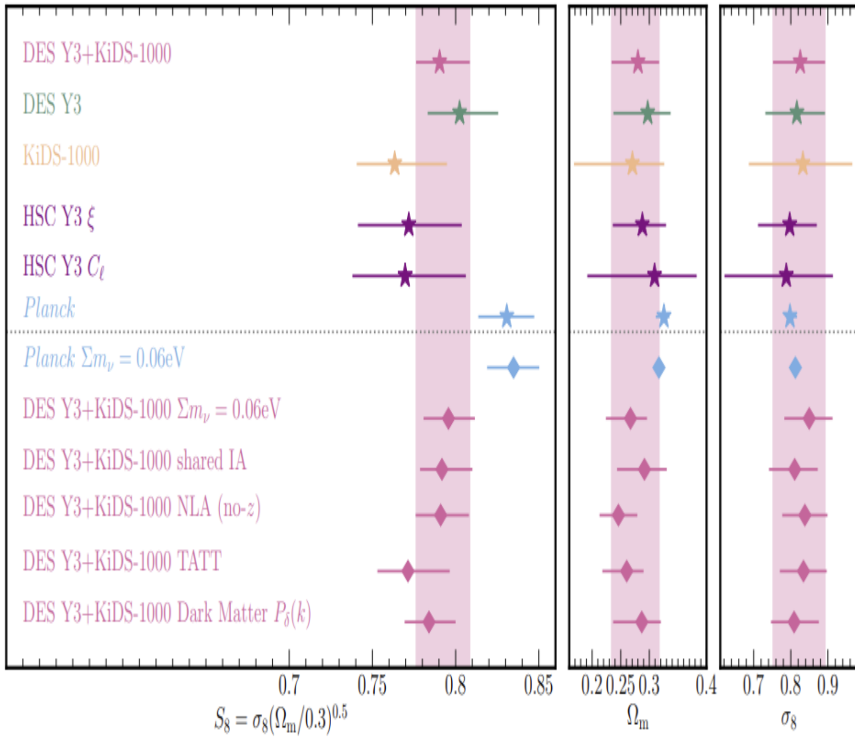
A rapid transition of $G_{\rm eff}$ at $z_t \simeq 0.01$ as a solution of the Hubble and growth tensions
Valerio Marra, Leandros Perivolaropoulos (Feb 11, 2021)
e-Print: 2102.06012 [astro-ph.CO]



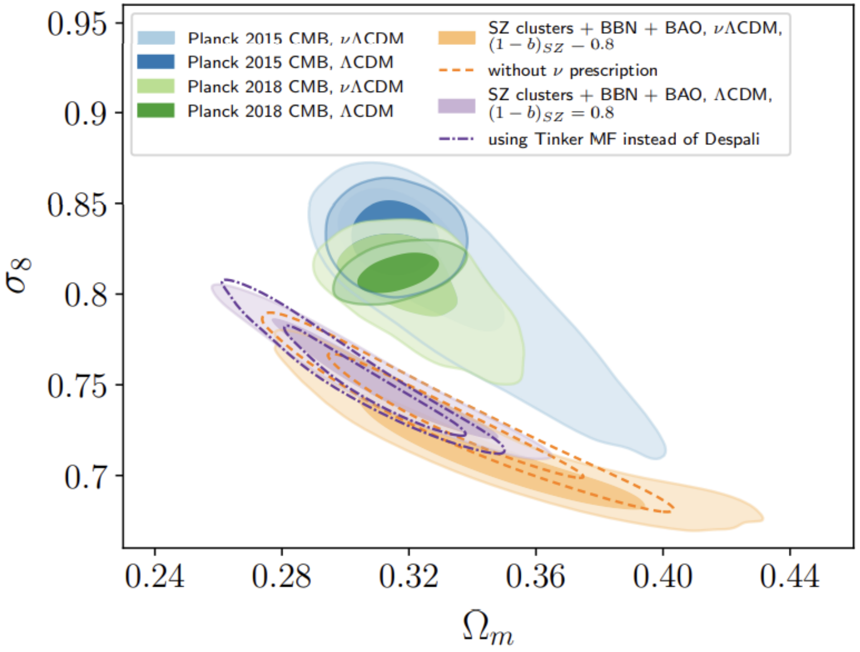
$S_8 \sim \sigma_8\ \Omega_{0m}^{1/2}$

Redshift Space Distortions (galactic peculiar velocities)

DES Y3 + KiDS-1000: Consistent cosmology combining cosmic shear surveys
Kilo-Degree Survey and DES Collaborations • T.M.C. Abbott (Cerro-Tololo InterAmerican Obs.) et al. (May 26, 2023)
e-Print: 2305.17173 [astro-ph.CO]



Weak Lensing

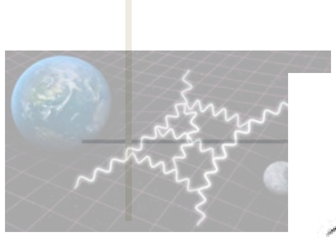


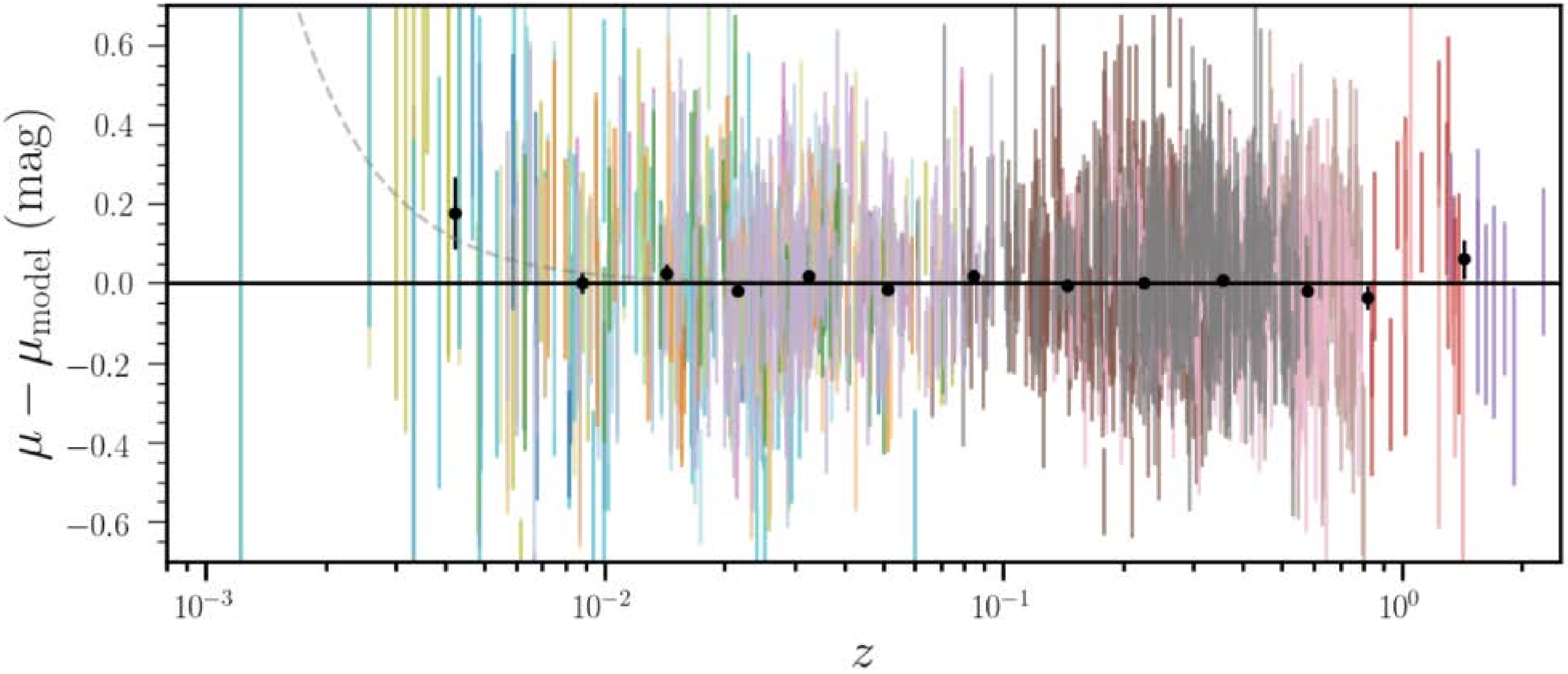
Cluster counts

Cluster counts. II. Tensions, massive neutrinos, and modified gravity
Stéphane Ilić (Prague, Inst. Phys. and IRAP, Toulouse), Ziad Sakr (IRAP, Toulouse and USJ, Beirut), Alain Blanchard (IRAP, Toulouse) (Aug 1, 2019)
Published in: *Astron.Astrophys.* 631 (2019) A96 • e-Print: 1908.00163 [astro-ph.CO]

Could gravity be weaker on cosmological scales compared to local scales (recent times)?

Distance residuals



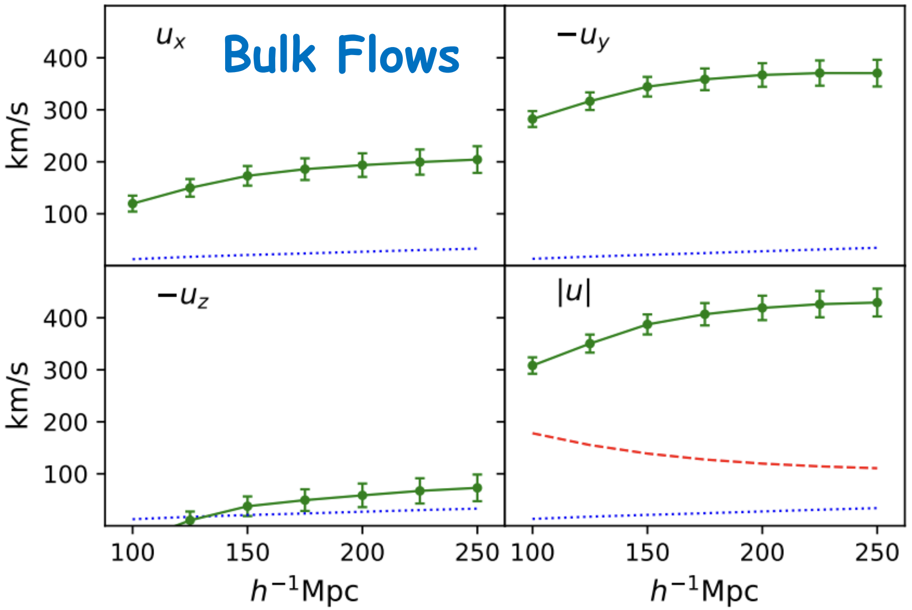


The Pantheon+ Analysis: Cosmological Constraints

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)

Published in: *Astrophys.J.* 938 (2022) 2, 110 • e-Print: 2202.04077 [astro-ph.CO]

Cosmic Dipoles



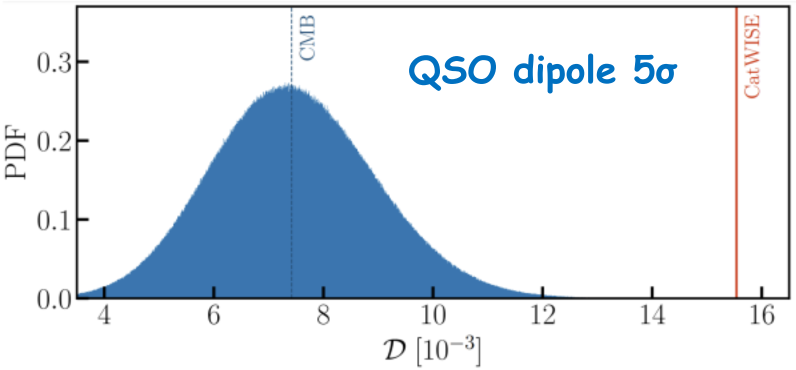
	$R = 150h^{-1}$Mpc	$R = 200h^{-1}$Mpc
Expectation (km/s)	139	120
Bulk Flow (km/s)	387 ± 28	419 ± 36
Direction	$l = 297° \pm 4°$	$l = 298° \pm 5°$
	$b = -6° \pm 3°$	$b = -8° \pm 4°$
χ^2 with 3 d.o.f.	19.34	29.13
Probability	0.023%	0.00021%

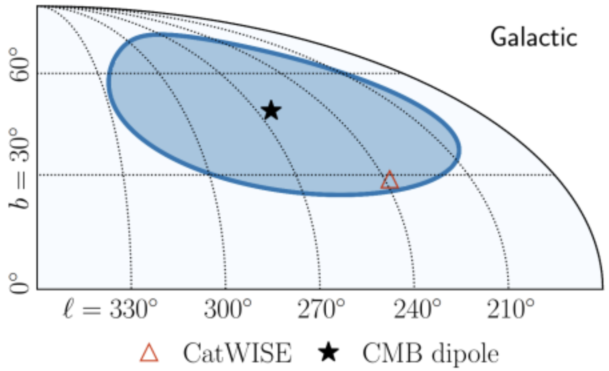
Analyzing the Large-Scale Bulk Flow using CosmicFlows4: Increasing Tension with the Standard Cosmological Model

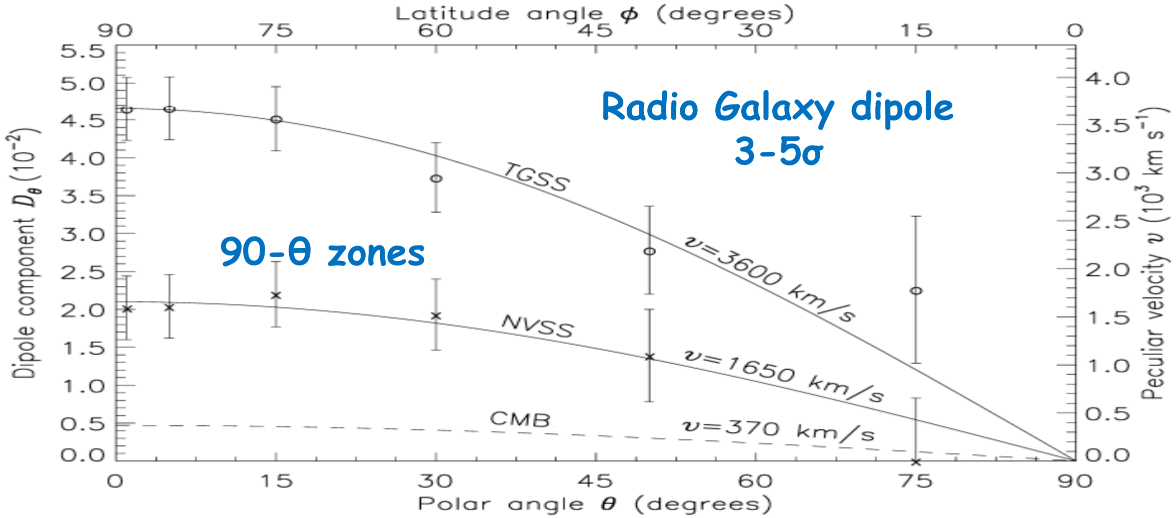
Richard Watkins, Trey Allen, Collin James Bradford, Albert Ramon, Alexandra Walker et al. (Feb 3, 2023)

e-Print: 2302.02028 [astro-ph.CO]

Secrest, N. J. et al. A Test of the Cosmological Principle with Quasars. *The Astrophysical Journal Letters*, **908**(2):L51, 2021







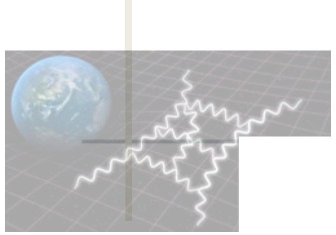
Singal, A. K. Large Peculiar Motion of the Solar System from the Dipole Anisotropy in Sky Brightness due to Distant Radio Sources. *The Astrophysical Journal Letters*, **742**(2):L23, 2011

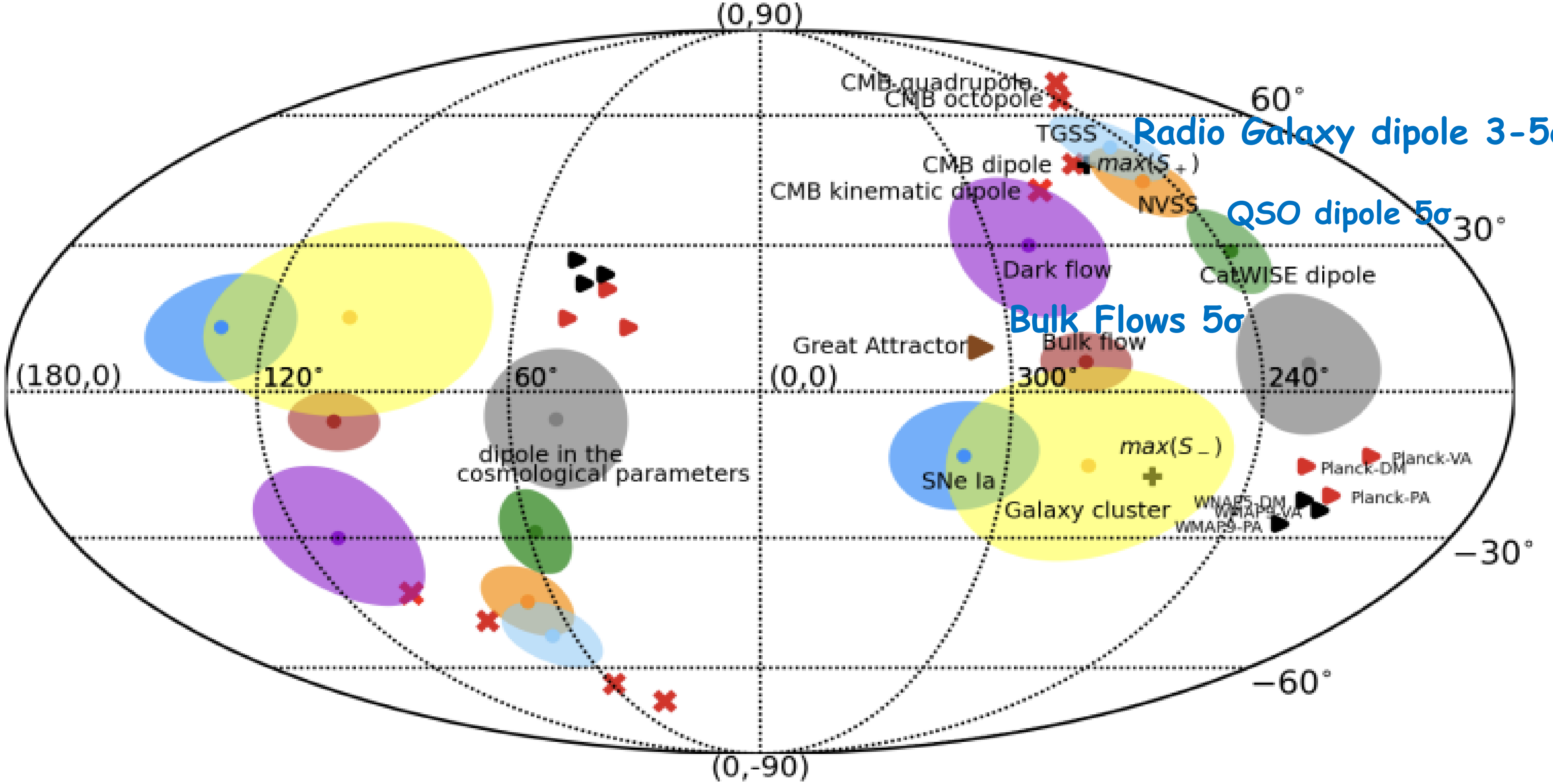
Cosmic Dipoles

Is the Observable Universe Consistent with the Cosmological Principle?

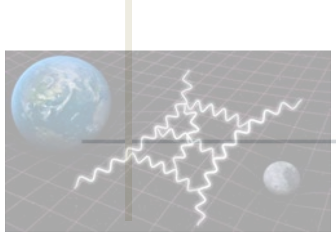
Pavan Kumar Aluri (Indian Inst. Tech. (BHU), Varanasi), Paolo Cea (INFN, Bari), Pravabati Chingangbam (Bangalore, Indian Inst. Astrophys.), Ming-Chung Chu (Hong Kong U.), Roger G. Clowes (Central Lancashire U.) et al. (Jul 12, 2022)

e-Print: 2207.05765 [astro-ph.CO]





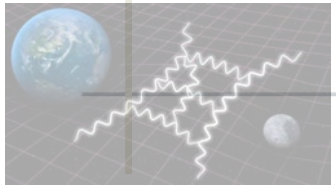
Local measurements



One step distance methods in Hubble flow
(z>0.01, local calibrator and sound horizon free)

Method	H_0(km/sec Mpc)	Arxiv-link	First author
Cosmic Chronometers	66.7±5.3	https://arxiv.org/pdf/2307.09501.pdf	Moresco
Cosmic Chronometers + HII gal.	65.9±3.0	https://arxiv.org/pdf/2208.03960.pdf	Jianchen Zhang etal
Gravitational Waves + Kilonovae	69.6±5.5	https://arxiv.org/pdf/2205.09145.pdf	Bulla etal
Gravitational Waves + Kilonovae	67.0 ± 3.6	https://arxiv.org/pdf/2306.12468.pdf	Sneppen etal
Lensing Time Delays TDCOSMO I	74.2±1.6	https://arxiv.org/pdf/1912.08027.pdf	Millon etal
Lensing Time Delays TDCOSMO IV	67.4±4	https://arxiv.org/pdf/2007.02941.pdf	Birrer etal
Megamasers	66.0 ± 6.0	https://arxiv.org/pdf/1511.08311.pdf	Gao etal
Megamasers (SH0ES)	73.9±3.0	https://arxiv.org/pdf/2001.09213.pdf	Pesce etal
SZ effect	61±21	https://arxiv.org/pdf/astro-ph/0306073.pdf	Reese
Gamma ray attenuation	61.9±2.6	https://arxiv.org/pdf/2306.09878.pdf	Domínguez etal
T_{eq} standard ruler	64.8±2.4	https://arxiv.org/pdf/2204.02984.pdf	Philcox etal

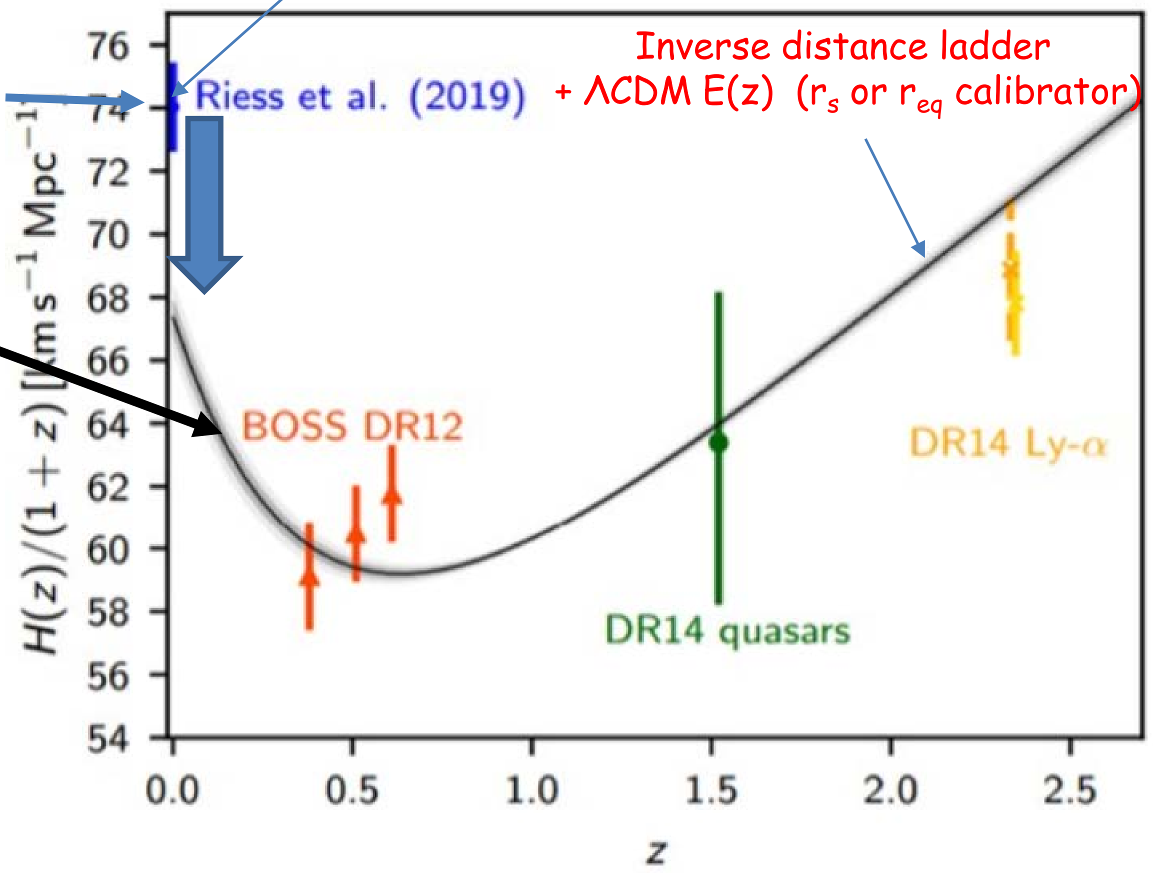
The Hubble Crisis Approaches



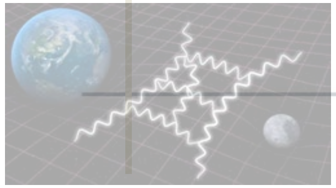
How can H(z) derived from late time calibrators (blue point and SnIa calibrated from it) become consistent with H(z) derived from early time calibrators (black line, CMB+BAO)?

Change SnIa Intrinsic Luminosity (systematics or physics change at 0<z<0.01). (move blue point down)

Distance Ladder H(z) (M calibrator – Cepheids at z<0.01)



Local measurements



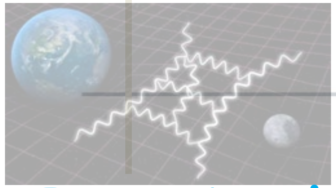
Distance ladder methods (local calibrators dependent)

Method	H_0(km/sec Mpc)	Arxiv-link	First author
Tully Fisher + Cepheid + TRGB	76.0 ± 3.4	https://arxiv.org/pdf/2004.14499.pdf	Kourkchi etal
SBF + Cepheids + TRGB	73.3 ± 3.1	https://arxiv.org/pdf/2101.02221.pdf	Blakeslee etal
SnII + Cepheids + TRGB	75.57±15	https://arxiv.org/pdf/2305.17243.pdf	Jaeger etal
Mira calibrators	73.3 ± 4.0	https://arxiv.org/pdf/1908.10883.pdf	Huang etal
TRGB (SH0ES)	73.22 ± 2.06	https://arxiv.org/pdf/2304.06693.pdf	Scolnic etal
Cepheid (SH0ES)	73.04 ± 1.04	https://arxiv.org/pdf/2112.04510.pdf	Riess etal

Could we be missing something with ALL local calibrators??

Could there be a physics change between local calibrator scales ($z<0.01$) and Hubble flow scales ($z>0.01$)?

Why is ΛCDM still our standard model?



Inertia due to the several standard model successes (human factor).

Lack of SIMPLE alternative model. Too many tensions (tension noise).

Comparison with previous standard model changes

From Steady State to Big Bang: Data and Simple alternative supported by simple theory (Friedman equations)

From sCDM to ΛCDM: Data and Simple Alternative (cosmological constant)

Peebles 1984, Efstathiou 1990 and Krauss-Turner 1995 (Universe age, matter power spectrum and peculiar velocities)

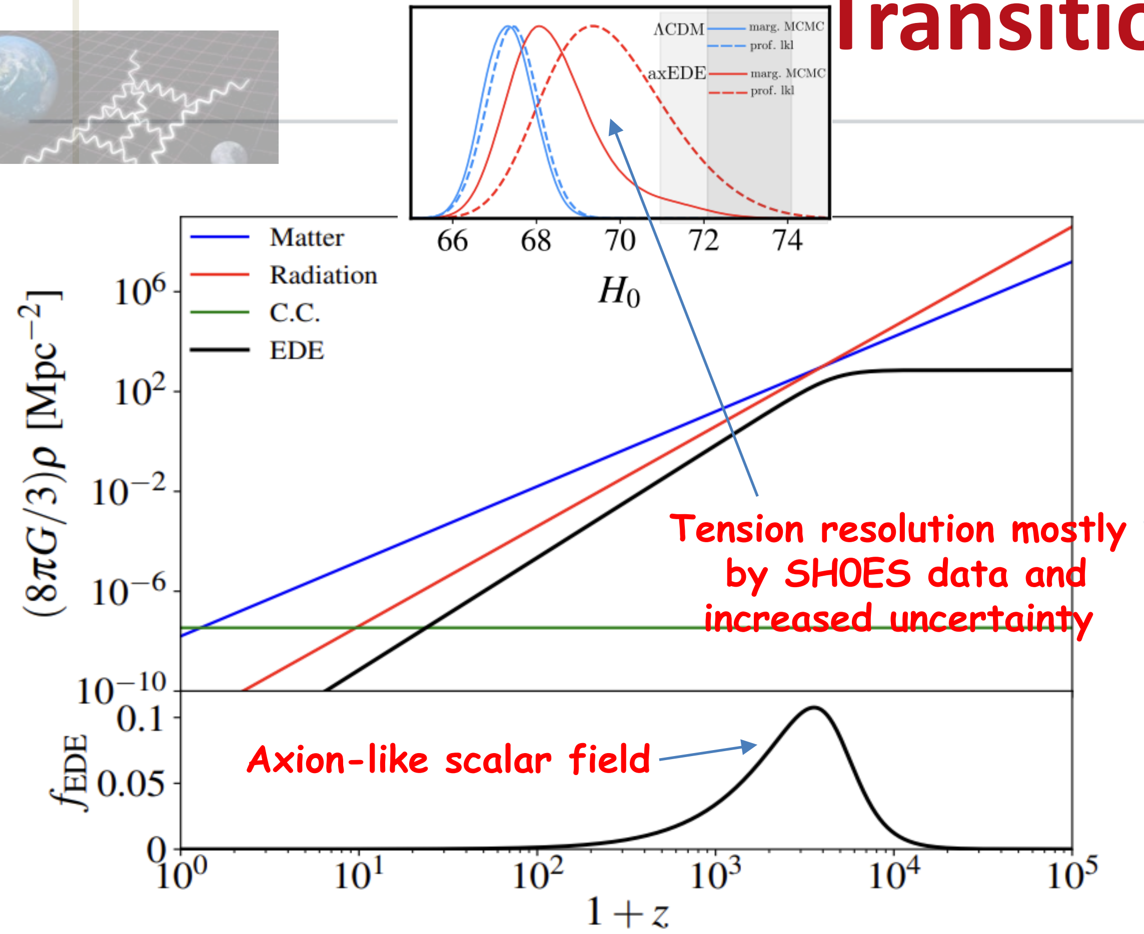
Q: What is the new simple and generic replacement of ΛCDM that will release most tensions with just 1-2 parameters?

For model building we need to understand deeply the data and the origins of the assumptions hidden in the tensions.

(New) Early Dark Energy Phase Transition

NEDE involves a more abrupt event (transition) and the DE disappears more efficiently after recombination.

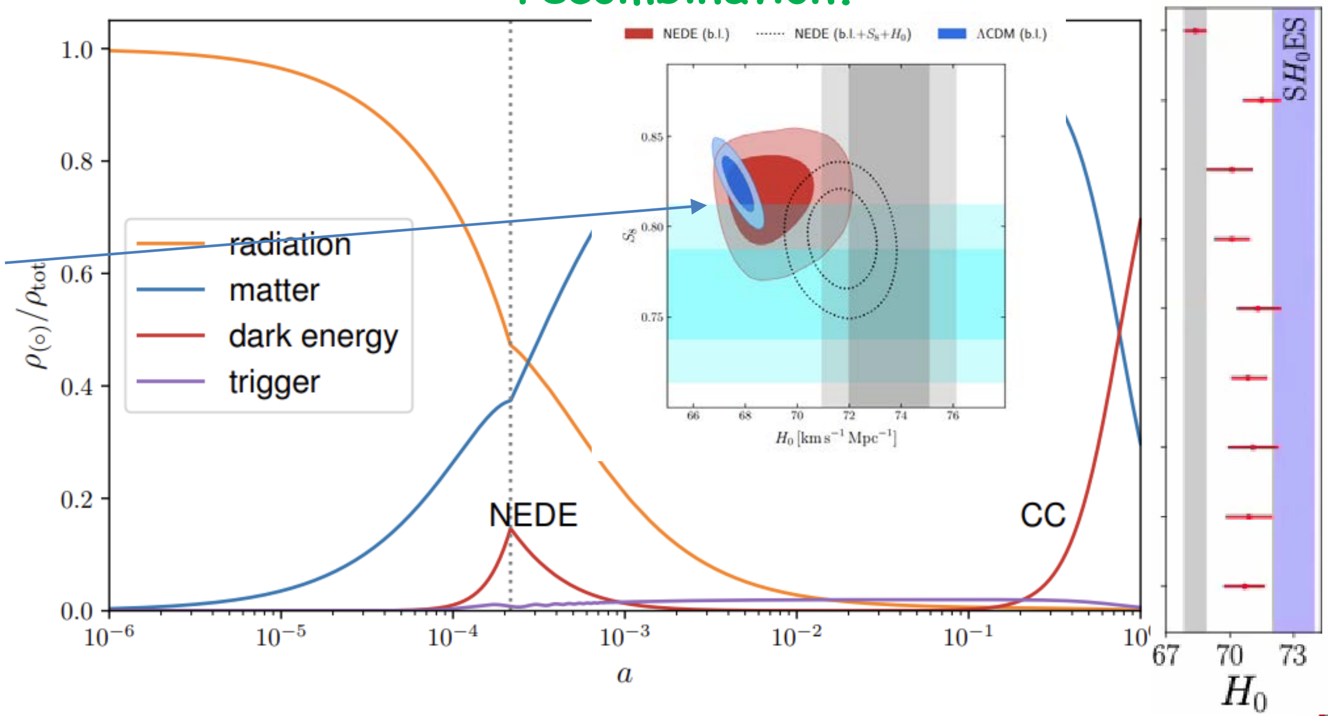
Thus, it does not interfere with E(z) after recombination.



The Ups and Downs of Early Dark Energy solutions to the Hubble tension: a review of models, hints and constraints circa 2023

Vivian Poulin (U. Montpellier 2, LUPM), Tristan L. Smith (Swarthmore Coll. and New York U., CCPP), Tanvi Karwal (Pennsylvania U.) (Feb 17, 2023)

e-Print: 2302.09032 [astro-ph.CO]

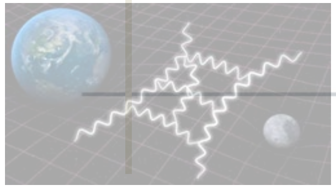


New Early Dark Energy as a solution to the H_0 and S_8 tensions

Florian Niedermann, Martin S. Sloth (Jul 7, 2023)

e-Print: 2307.03481 [hep-ph]

The ΛsCDM Model

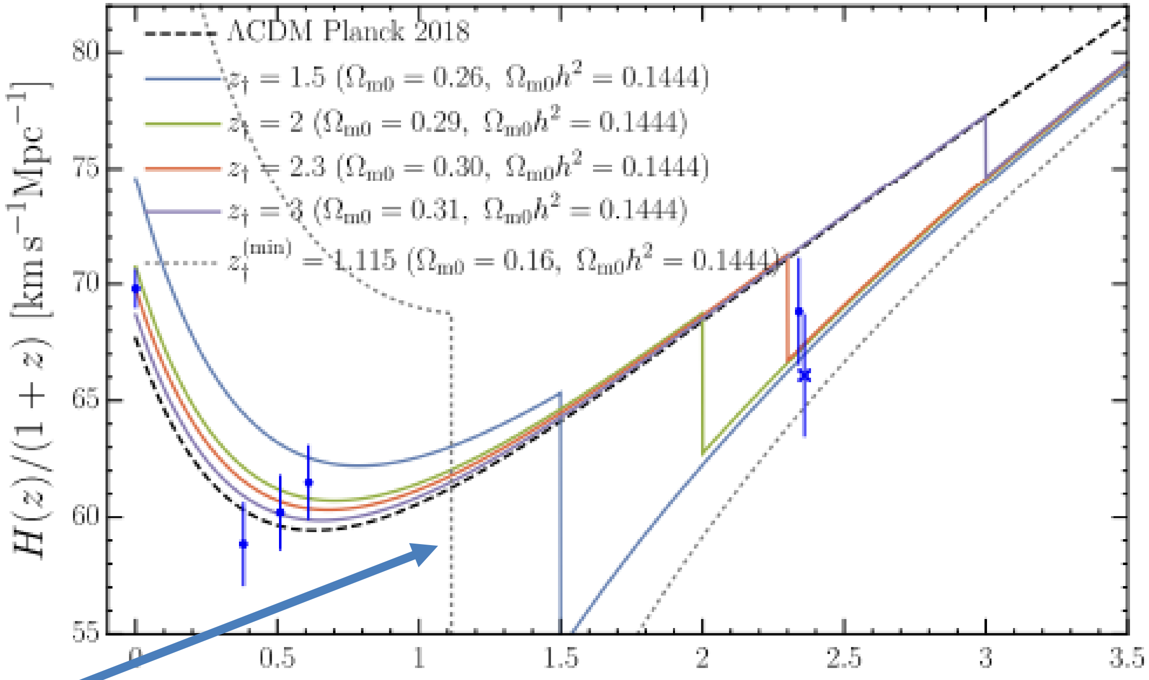


Relaxing cosmological tensions with a sign switching cosmological constant

Özgür Akarsu (Istanbul, Tech. U.), Suresh Kumar (Indira Gandhi U., Meerpur), Emre Özülker (Istanbul, Tech U.), J. Alberto Vazquez (UNAM, CCF) (Aug 20, 2021)

Published in: *Phys.Rev.D* 104 (2021) 12, 123512 • e-Print: 2108.09239 [astro-ph.CO]

How can H(z) derived from late time calibrators (blue point) become consistent with H(z) derived from early time calibrator (black line)?



Change SnIa Intrinsic Luminosity (systematics or physics change at $0<z<0.1$). (move blue point down)

Change sound horizon scale (Early DE transition at t_{rec}). (shift black line up)

Deform H(z) by eg dynamical dark energy (problems with BAO, growth, M). (distort black line)

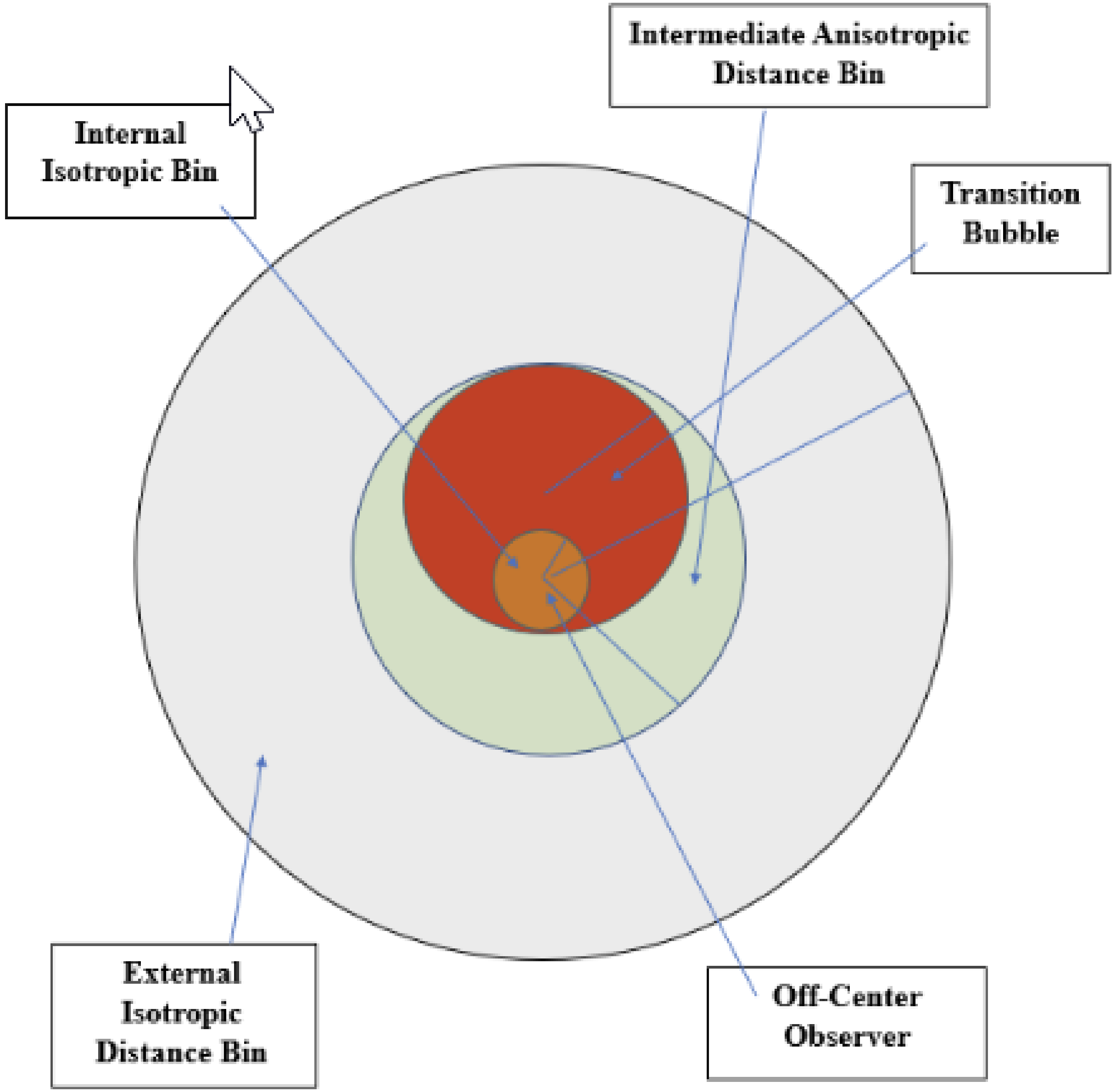
An abrupt transition event may be needed to resolve the tension.

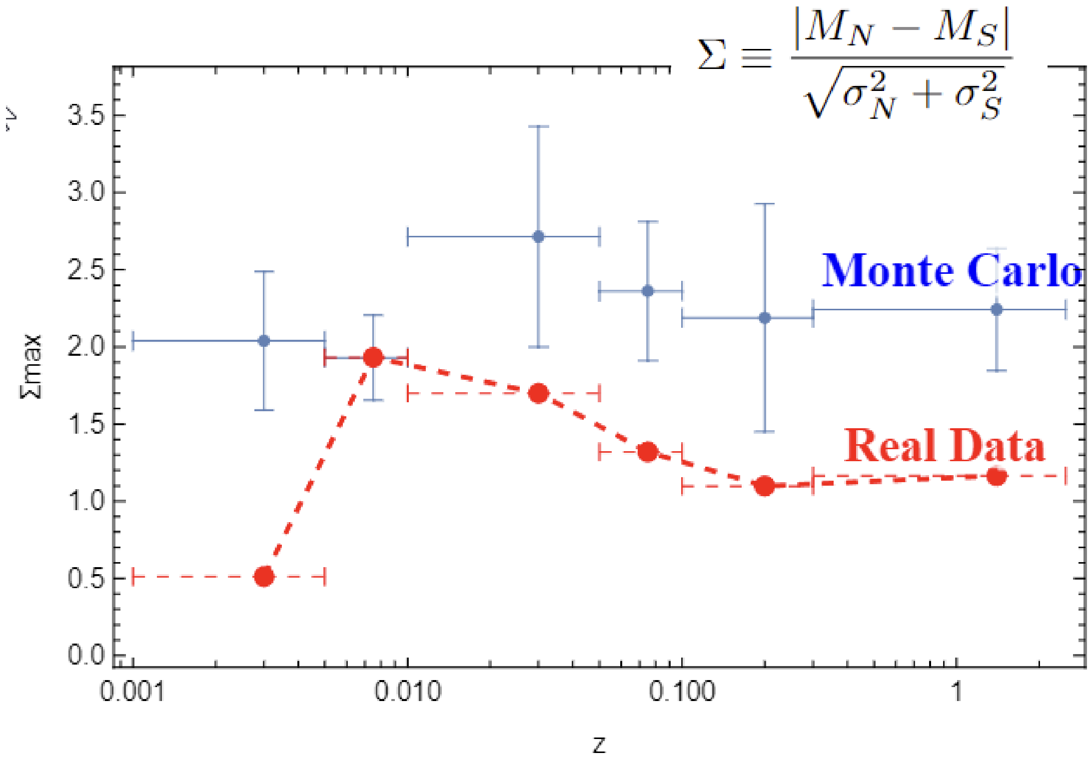
Late-time approaches to the Hubble tension deforming H(z), worsen the growth tension

George Alestas (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.) (Mar 6, 2021)

Published in: *Mon.Not.Roy.Astron.Soc.* 504 (2021) 3, 3956-3962 • e-Print: 2103.04045 [astro-ph.CO]

Predicted Anisotropy in the context of Spatial Transition





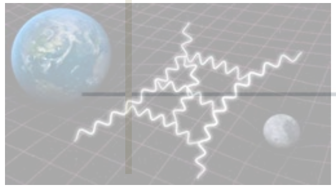
Off-center observer in a bubble of distinct transition physics
or
systematics

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]

Issues on the SH0ES Analysis for H_0



Q1: What are the SnIa calibration parameters?

A: The SnIa (bolometric) absolute magnitude M (or M_B).

Also, the SnIa color and stretch parameters c and s, and the Cepheid calibration parameters b_W (period-luminosity), Z_W (metallicity-luminosity), M_W (Cepheid zero-point amplitude), R_W (Cepheid color-luminosity)

Q2: Are the best fit values of these parameters consistent among different subgroups of the SnIa+Cepheid data

A2: There are hints for inhomogeneities which affect the best fit value of H_0.

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)
Published in: *Universe* 8 (2022) 10, 502 • e-Print: 2208.11169 [astro-ph.CO]

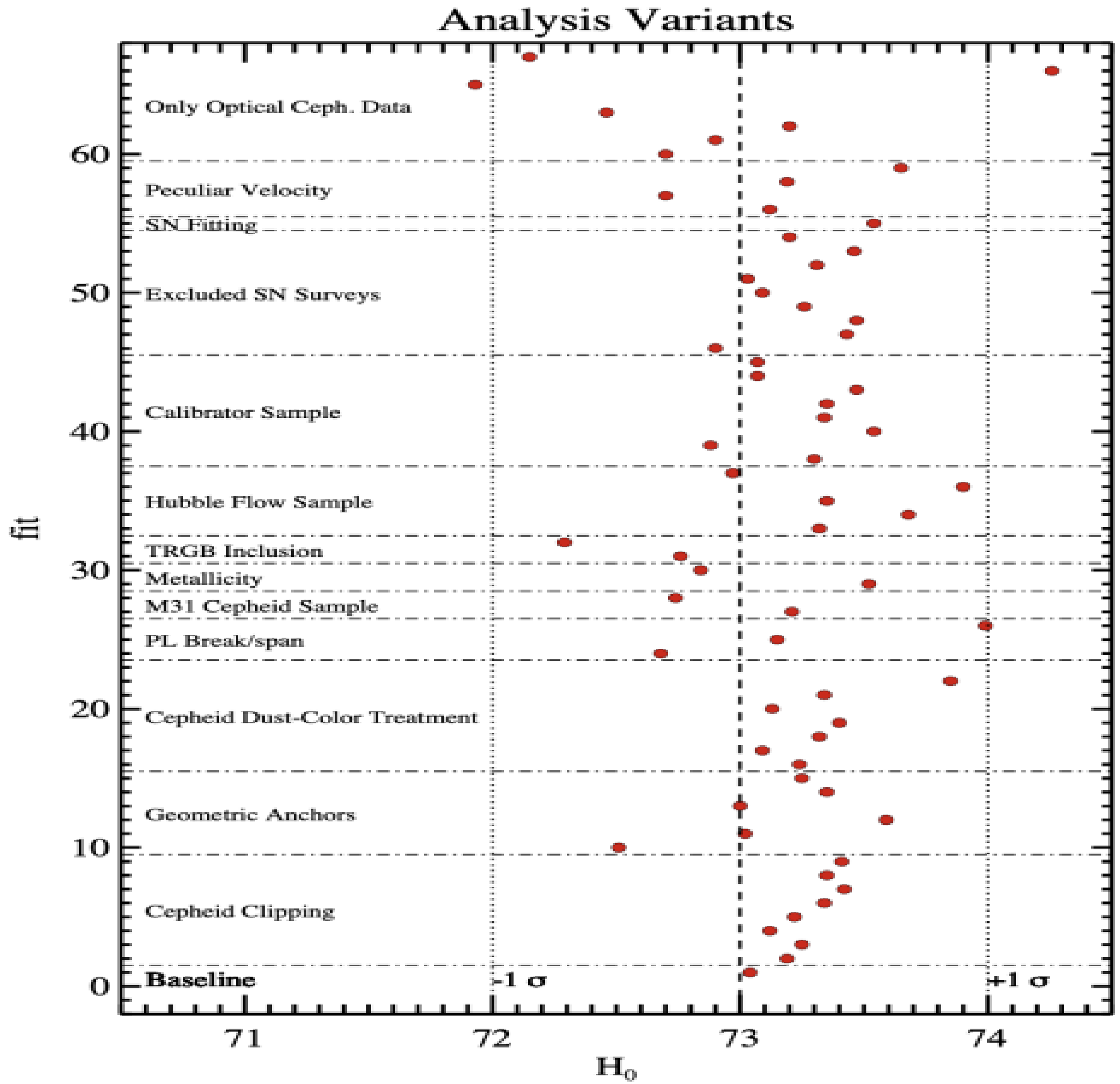
Intrinsic tension in the supernova sector of the local Hubble constant measurement and its implications
Radosław Wojtak, Jens Hjorth (Jun 16, 2022)
Published in: *Mon.Not.Roy.Astron.Soc.* 515 (2022) 2, 2790-2799 • e-Print: 2206.08160 [astro-ph.CO]

Sensitivity of the Hubble Constant Determination to Cepheid Calibration
Edvard Mortsell, Ariel Goobar, Joel Johansson, Suhail Dhawan (May 24, 2021)
Published in: *Astrophys.J.* 933 (2022) 2, 212 • e-Print: 2105.11461 [astro-ph.CO]

Q3: What could be the origin of these inhomogeneities?

A3: Statistics, Systematics or New Physics.

Variants of the SH0ES Analysis for H_0 considered by SH0ES team



No variant allows for a break in the calibrator parameter values at some distance or with other criteria

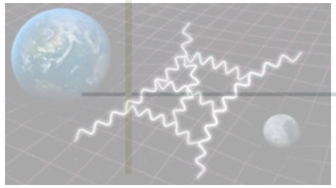
(except period luminosity with break at 10 days).

A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team

Adam G. Riess (Baltimore, Space Telescope Sci. and Johns Hopkins U.), Wenlong Yuan (Johns Hopkins U.), Lucas M. Macri (Texas A-M), Dan Scolnic (Duke U.), Dillon Brout (Harvard-Smithsonian Ctr. Astrophys.) et al. (Dec 8, 2021)

Published in: *Astrophys.J.Lett.* 934 (2022) 1, L7 • e-Print: 2112.04510 [astro-ph.CO]

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)
Published in: *Astrophys.J.* 938 (2022) 2, 110 • e-Print: 2202.04077 [astro-ph.CO]

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 (no transition allowed):

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

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

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

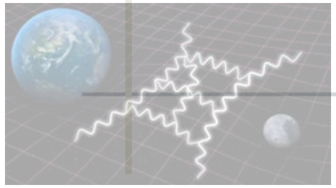
Brout et al 2022: M not included in fit.

New degrees of freedom in the Pantheon+ likelihood

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

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



Allow for a transition of M at some distance d_c

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

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

New likelihood for Patheon+:

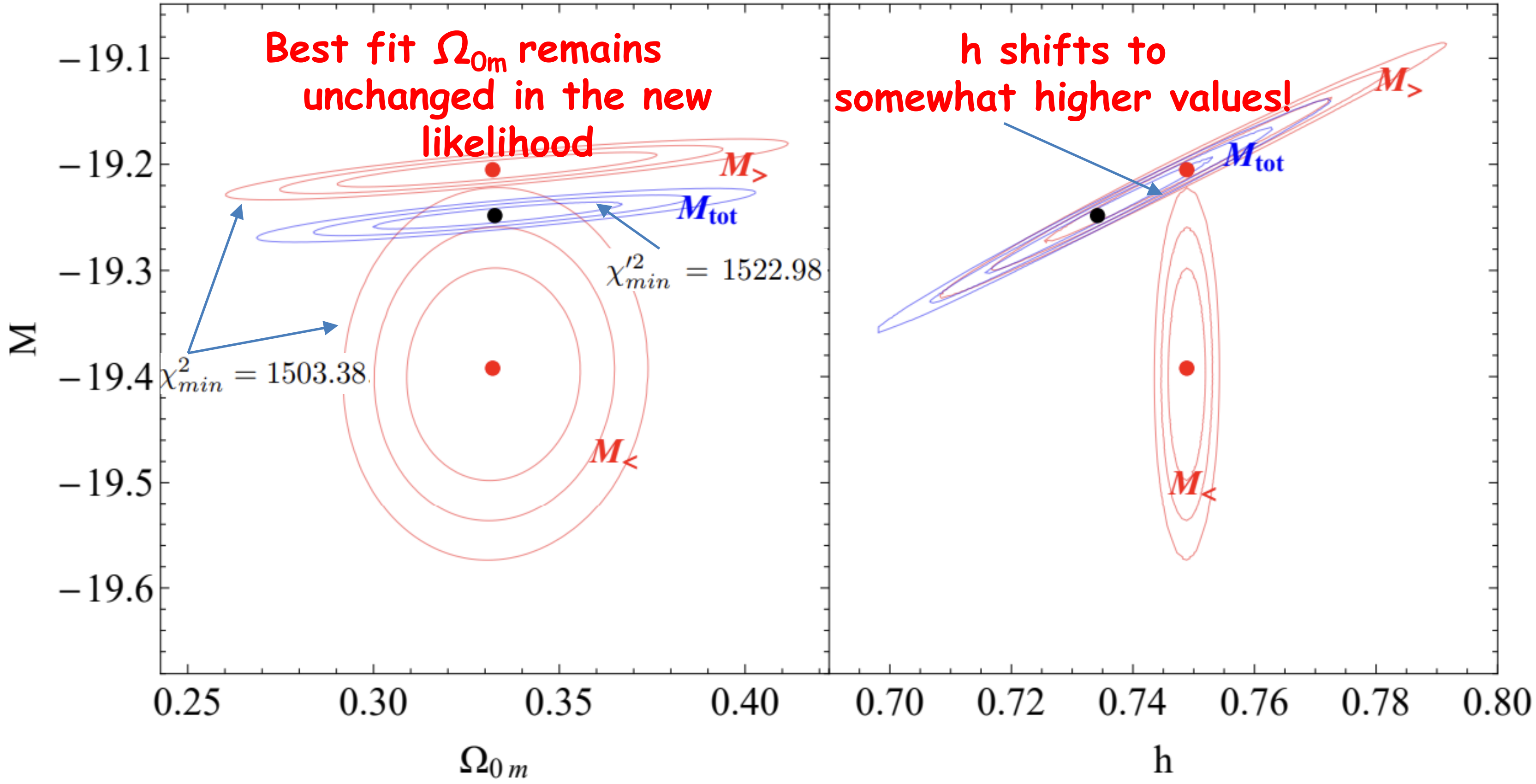
$$Q_i'' = \begin{cases} m_{Bi} - M_< - \mu_i^{\rm Cepheid} & \text{iff } \mu_{i,S} < \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_> - \mu_i^{\rm Cepheid} & \text{iff } \mu_{i,S} > \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_< - \mu_{\rm model}(z_i) & \text{iff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

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?



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

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

A_2: No! Significant tension!

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

Hemisphere Comparison Method: Isotropy of SnIa Absolute Magnitudes

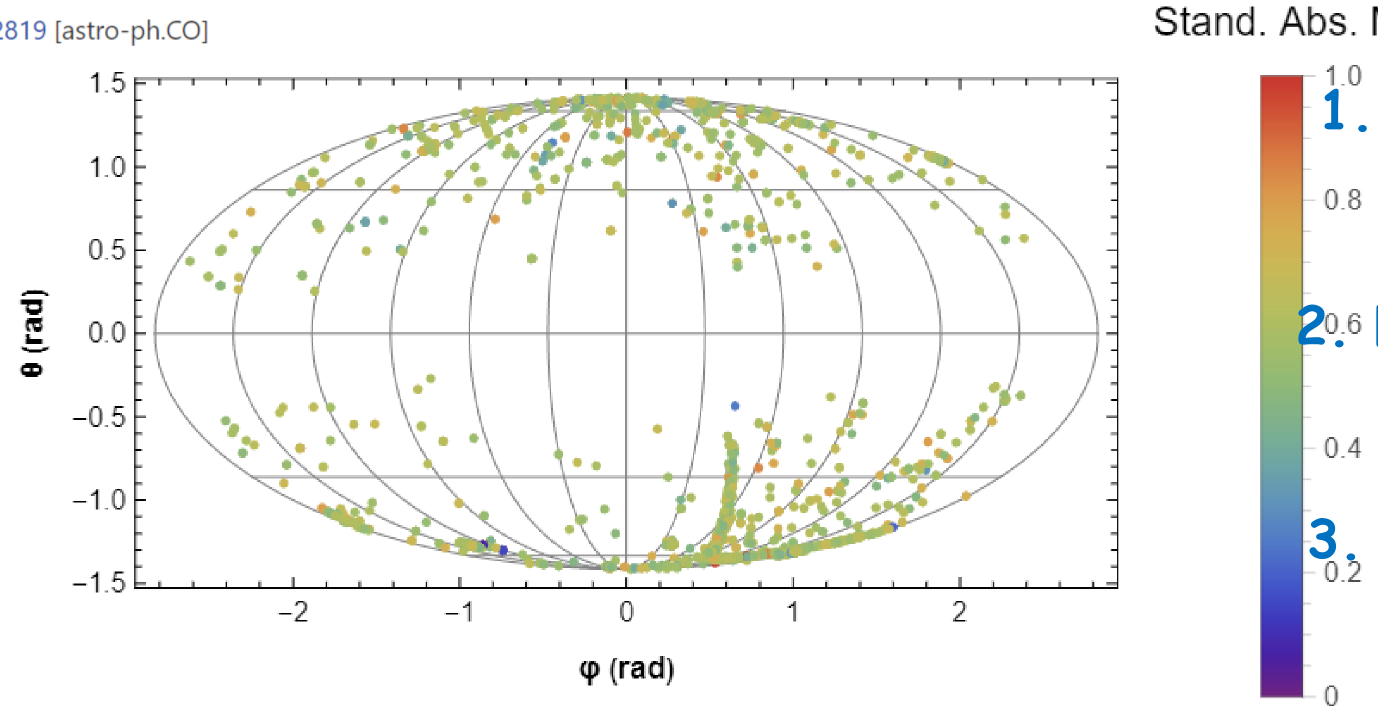
On the isotropy of SnIa absolute magnitudes in the Pantheon+ and SH0ES samples

Leandros Perivolaropoulos (May 22, 2023)

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

$$M_{Bi} = m^0_{Bi} - \mu_i$$

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



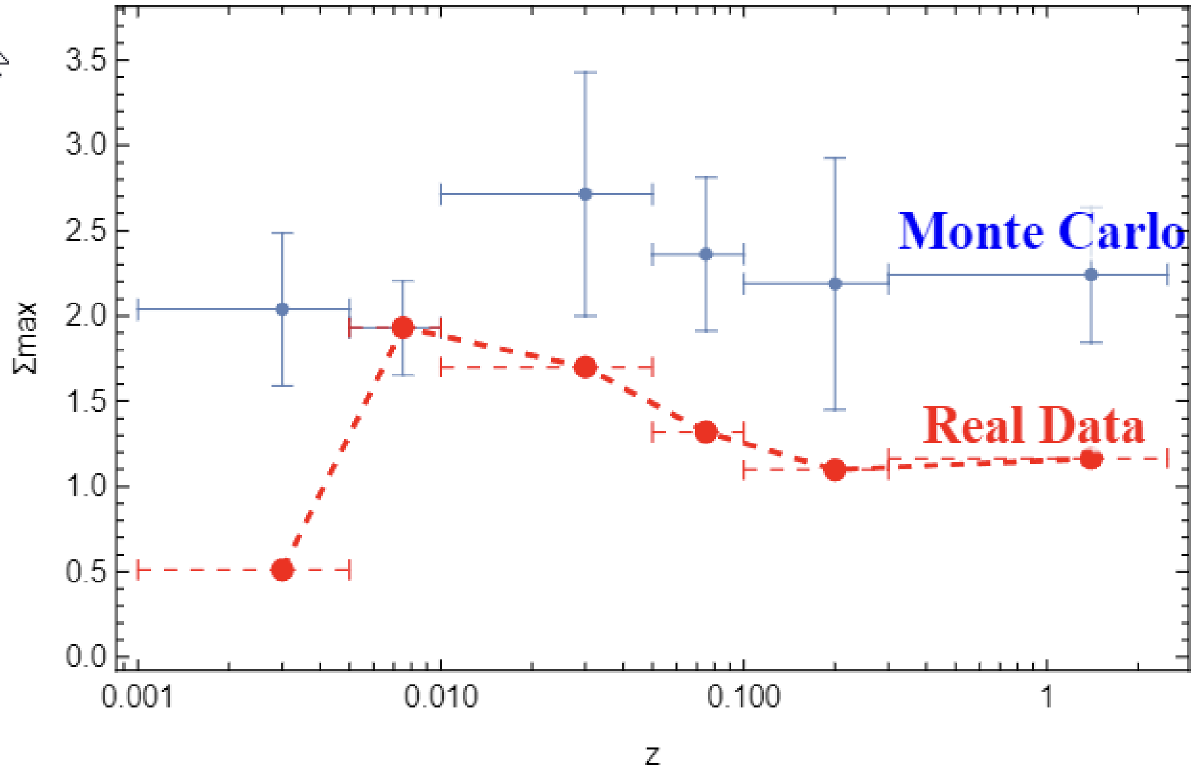
Standardized SnIa absolute magnitudes of Pantheon+.

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:

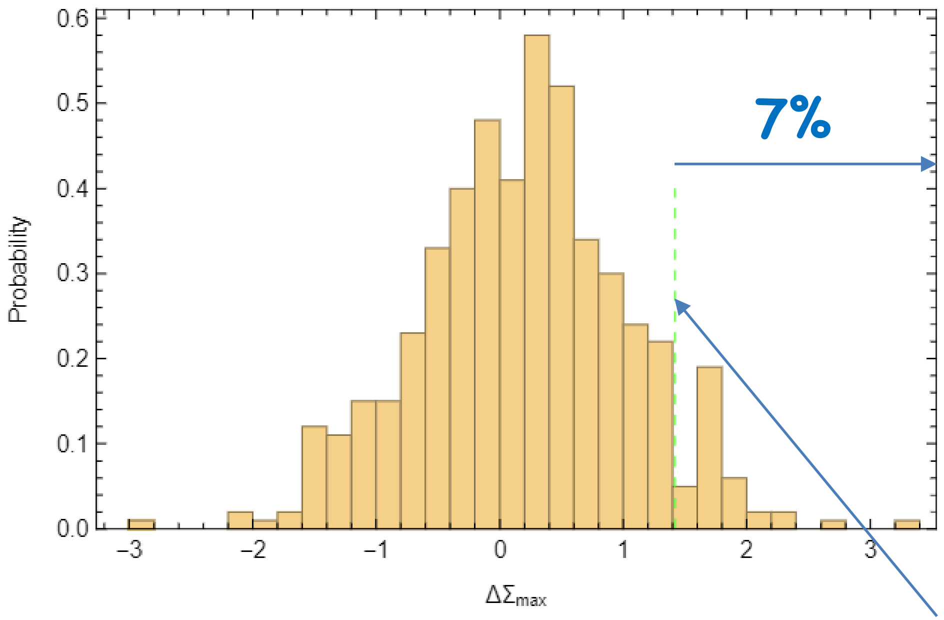
$$\Sigma \equiv \frac{|M_N - M_S|}{\sqrt{\sigma_N^2 + \sigma_S^2}}$$

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?

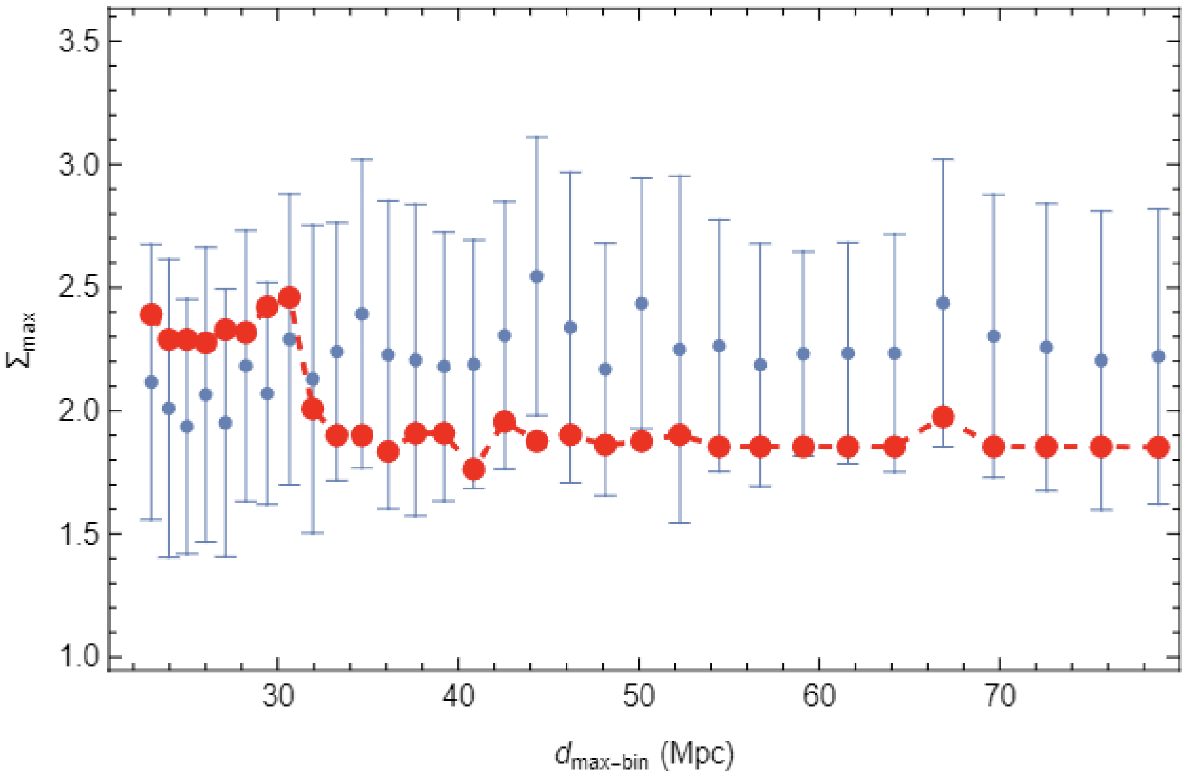


Real data 1->2 bin

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

Sudden changes appear of anisotropy level appear at low redshift bins

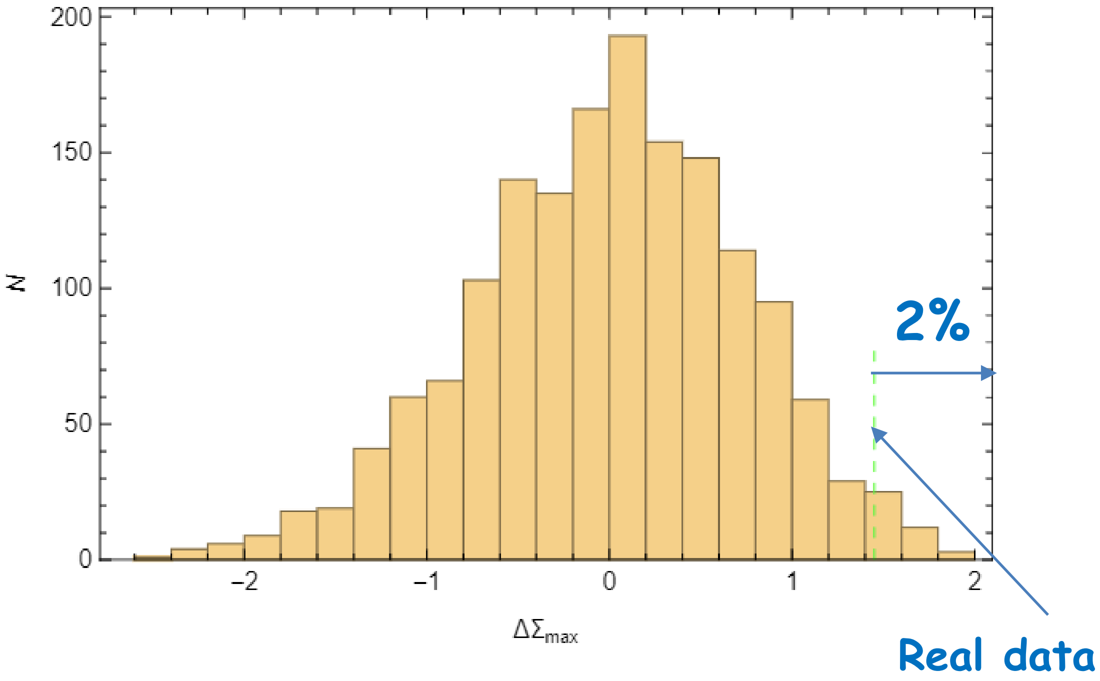
Comparison of SH0ES M-anisotropy with isotropic Monte-Carlo samples.



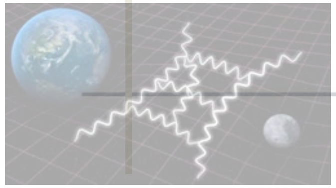
Cumulative low distance bin

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

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



Measuring H(z) with the 2022 Pantheon+ dataset



from SnIa in Cepheid hosts at z<0.01

1701 SnIa datapoints $(z_i, m_{Bi}, \mu_{Cephj})$, $i=1,\ldots,1701$, $j=1,\ldots,77$, $0.001<z_i<2.26$

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

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

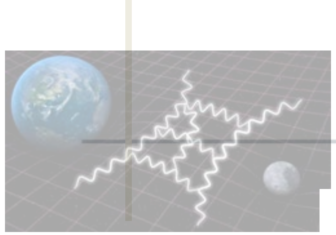
$$\chi^2 = \vec{Q}^T \cdot (C_{\text{stat+syst}})^{-1} \cdot \vec{Q}, \qquad Q_i = m_{Bi} - M - \mu_{\text{model}}(z_i), \quad \mu_{\text{model}}(z_i) = 5\log(d_L(z_i)/Mpc) + 25,$$

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

Degeneracy between H_0 and M

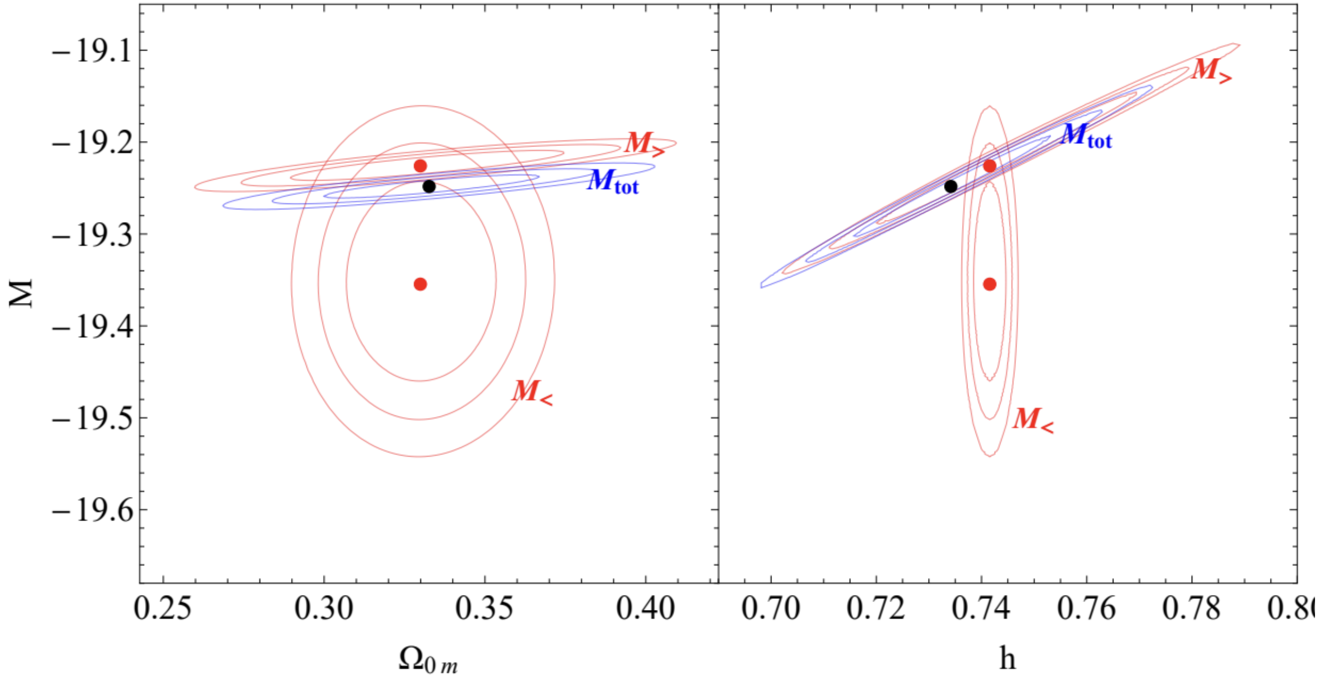
(no way to fit H_0 without prior knowledge of M)

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.

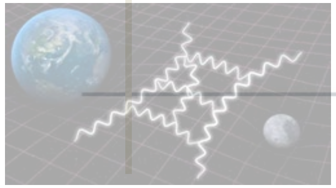
$$Q_i''' = \begin{cases} m_{Bi} - M_< - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} < \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_> - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} > \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ 0 & \text{iff } z_i < 0.01 \\ m_{Bi} - M_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



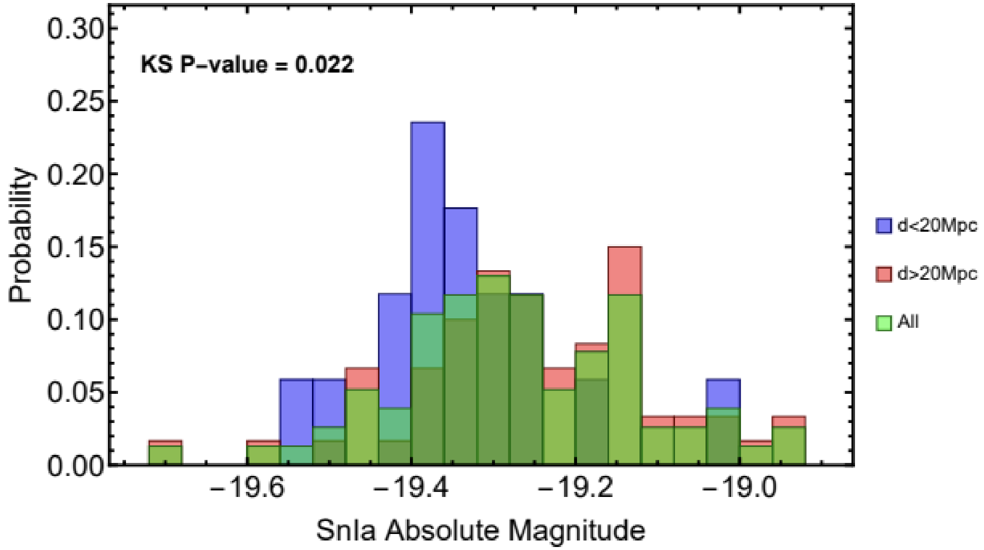
$$\begin{aligned} M_< &= -19.355 \pm 0.05, \\ M_> &= -19.226 \pm 0.03, \\ h &= 0.74 \pm 0.01, \\ \Omega_{0m} &= 0.33 \pm 0.02, \\ d_{crit} &= 19.95 \pm 0.1 Mpc, \end{aligned}$$

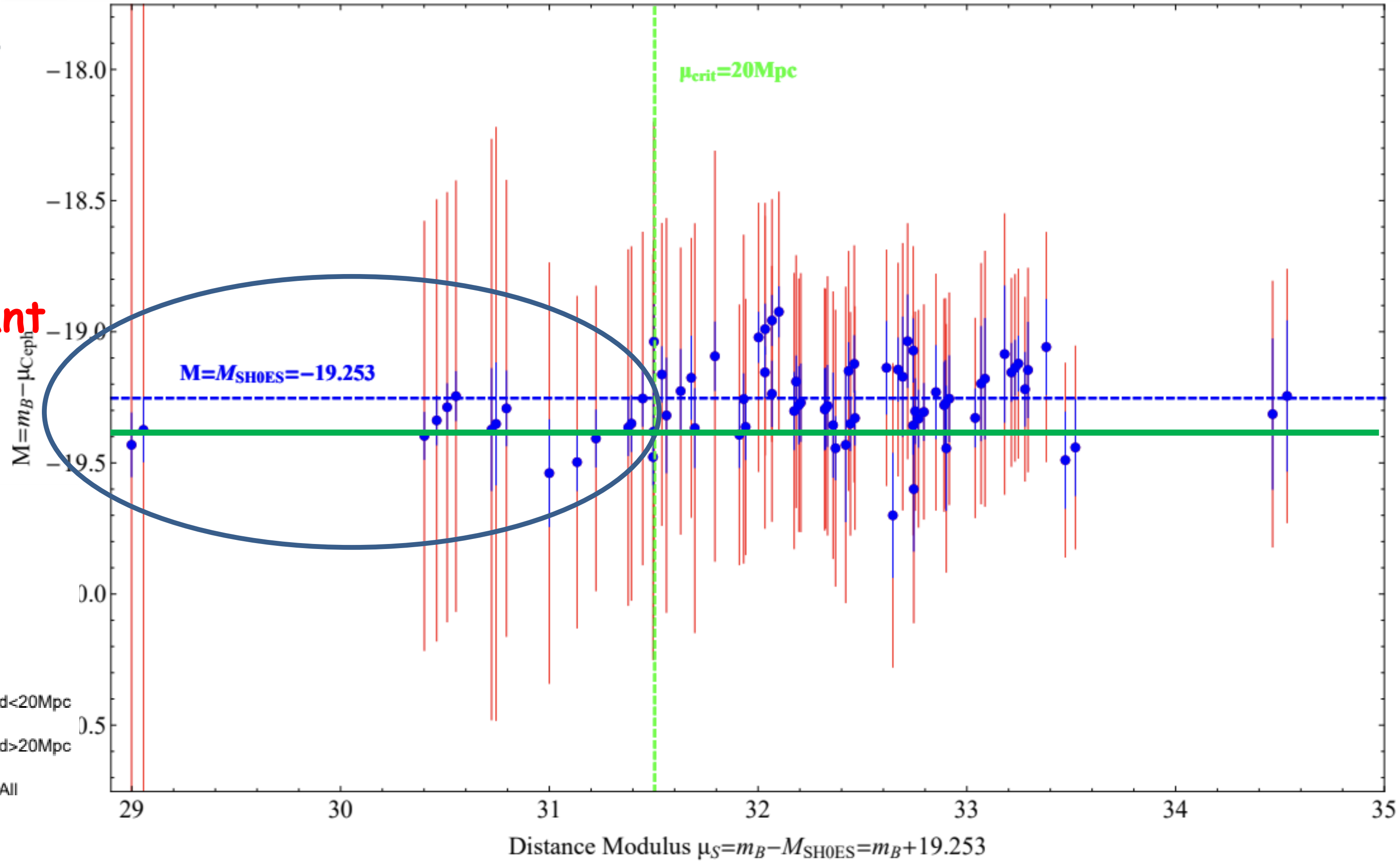
The tension between $M_<$ and $M_>$ is smaller but a significant part of it remains

SnIa luminosities in Pantheon+



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

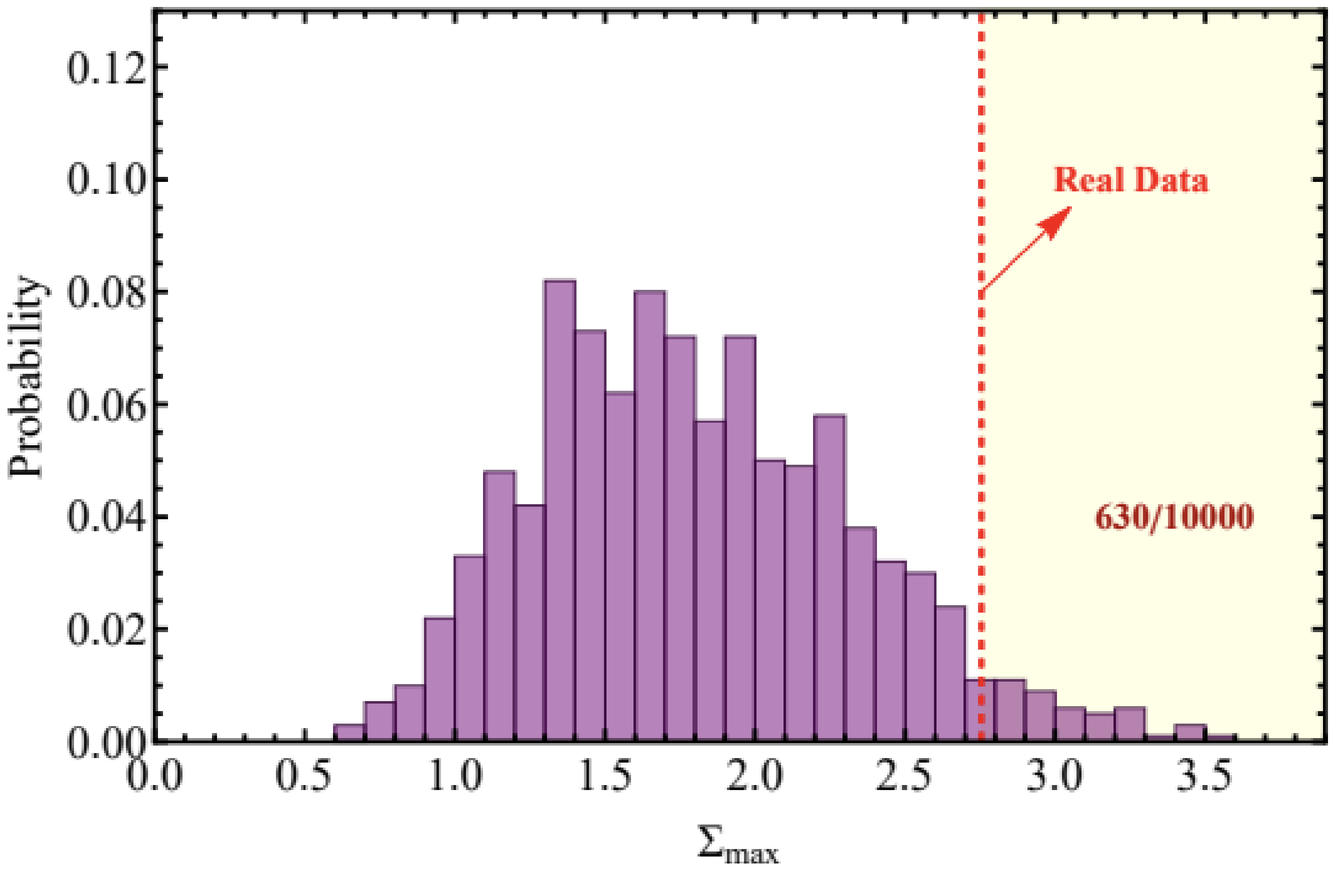




Q: How often could this happen by chance?

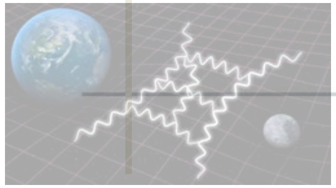
Monte Carlo Simulation

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.

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:

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

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

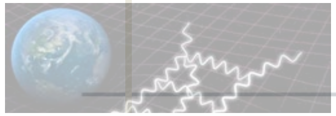
A Reanalysis of the Latest SH0ES Data for H_0: Effects of New Degrees of Freedom on the Hubble Tension

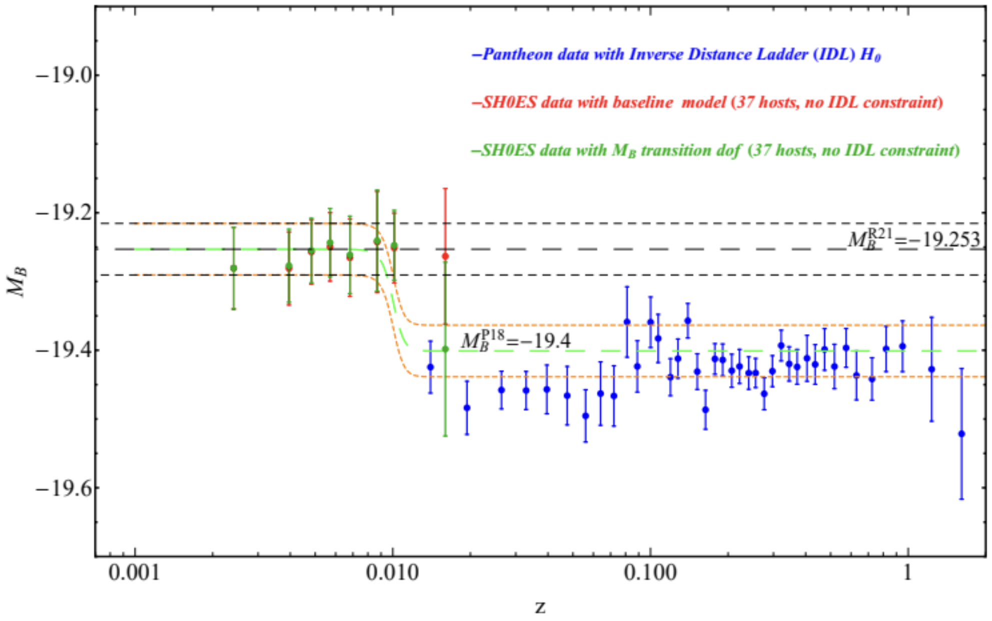
Leandros Perivolaropoulos (Ioannina U.), Foteini Skara (Ioannina U.) (Aug 23, 2022)

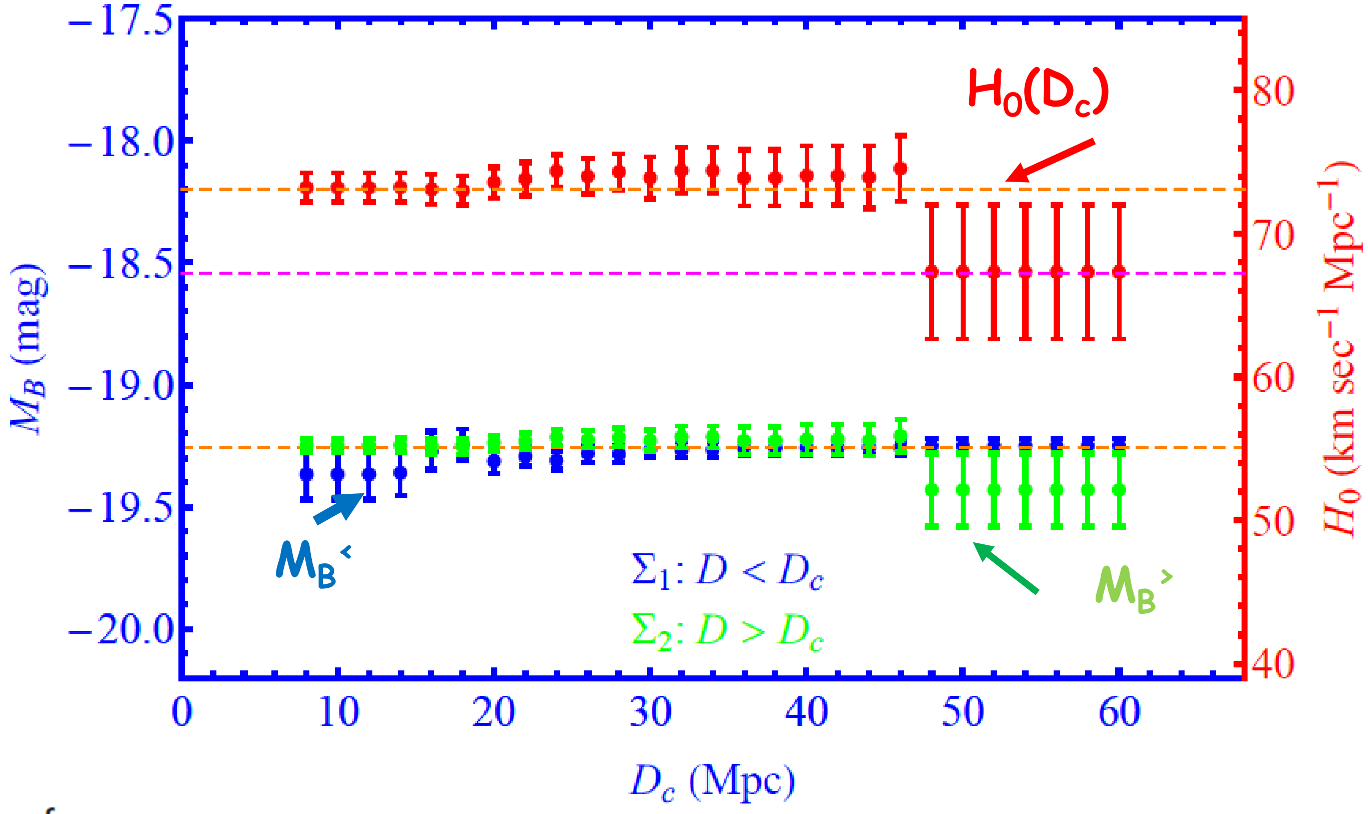
Published in: *Universe* 8 (2022) 10, 502 • e-Print: 2208.11169 [astro-ph.CO]

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.

Results of the Generalized SH0ES Analysis







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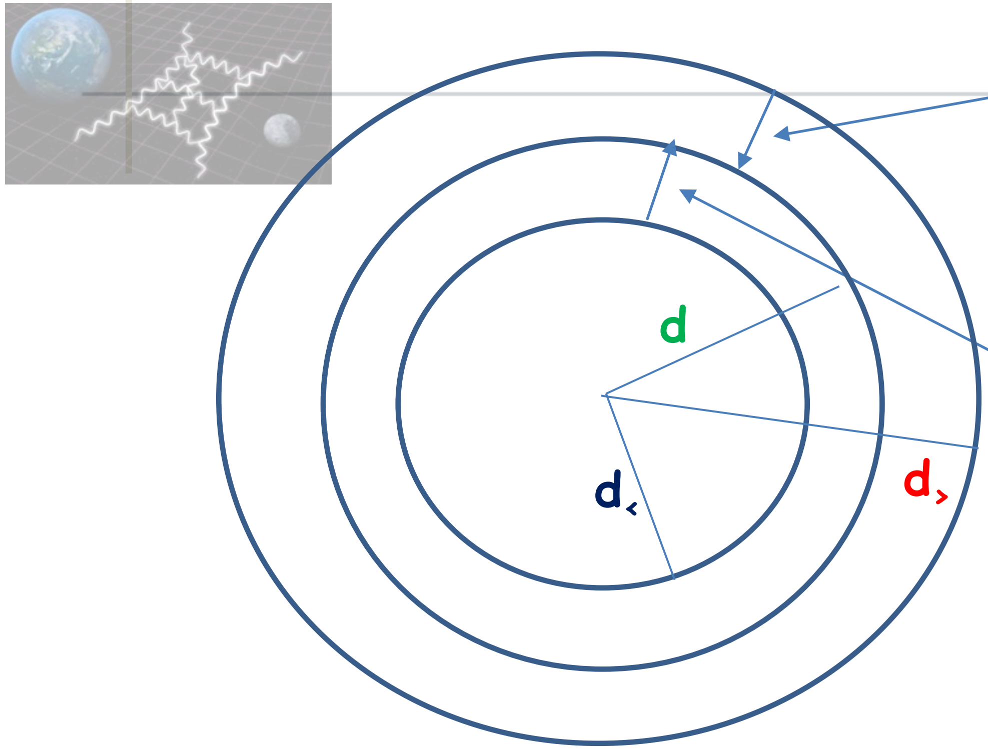
Spontaneous transition of the best fit value of H_0 when a transition at D_c~50Mpc is allowed.

The volumetric redshift bias:
A known <u>but uncorrected</u> 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.

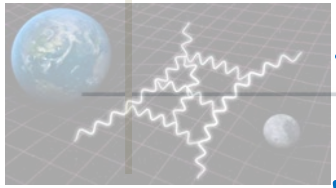
If $\Delta z_{>} > 0$ then the outer shell galaxies are incorrectly projected on the z shell leading to larger distance estimate than the true distance $d_{>}$.

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

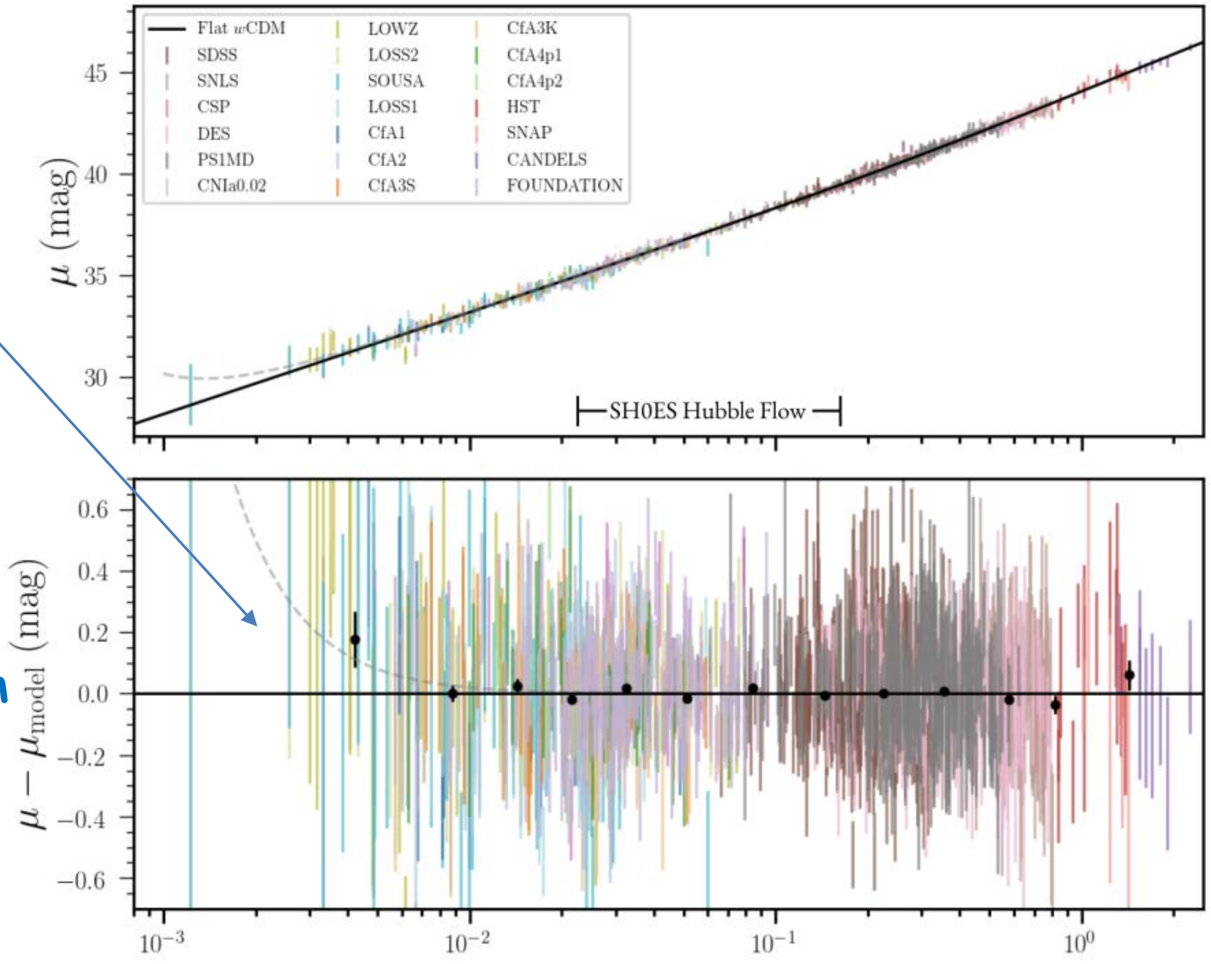


The volumetric redshift bias is dominant at low redshifts where the volume difference is more prominent.

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)

Published in: *Astrophys.J.* 938 (2022) 2, 110 • e-Print: 2202.04077 [astro-ph.CO]



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

$m_{B<} - \mu_{model}(z) > M_<$

This is the observed M from the Hubble diagram assuming ΛCDM for $z<0.01$.

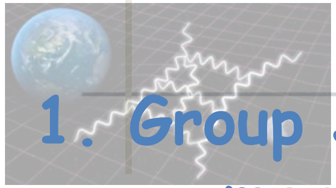
For $z>0.01$: $m_{B>} - \mu_{model}(z) = M_>$

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?

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:

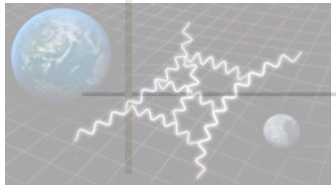
$$\Sigma(\mu_{crit}) \equiv \frac{|M_> - M_<|}{\sqrt{\sigma_{M_>}^2 + \sigma_{M_<}^2}}$$

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

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?

Theoretical Model: Scalar Tensor Theory



Gravitational transitions via the explicitly broken symmetron screening mechanism

Leandros Perivolaropoulos (Ioannina U.), Foteini Skara (Ioannina U.) (Mar 19, 2022)

Published in: *Phys.Rev.D* 106 (2022) 4, 043528 • e-Print: 2203.10374 [astro-ph.CO]

Scalar Tensor Transition:

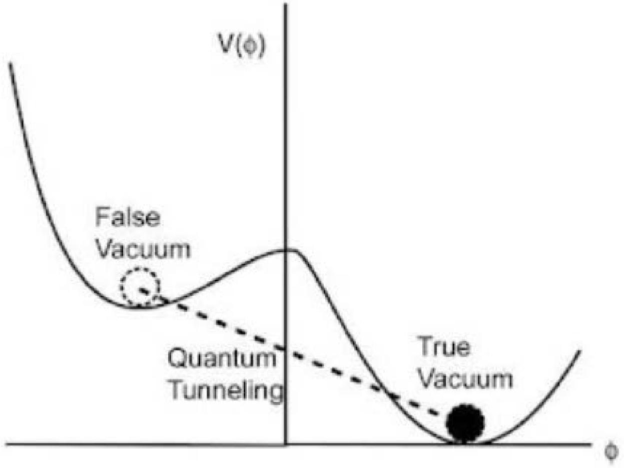
$$S = \int d^4x\sqrt{|g|}\left[\frac{1}{2}\xi\varphi^2 R - \frac{1}{2}(\partial\varphi)^2 - V(\varphi) + \mathcal{L}_m\right],$$

$$8\pi G_N = \xi^{-1}v^{-2}$$

v: potential minimum

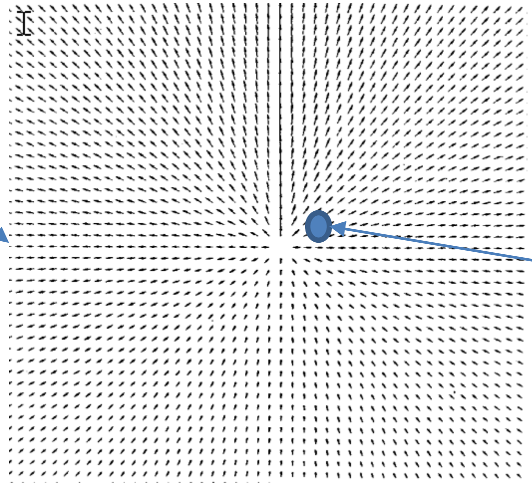
$$\frac{1}{\sqrt{8\pi G_N}} = M_{\rm Pl} \sim 10^{19}{\rm GeV},$$

Cosmological Constant: Λ=V(v)



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

Hubble scale



Global monopole field dark energy (natural dipoles)

Observer

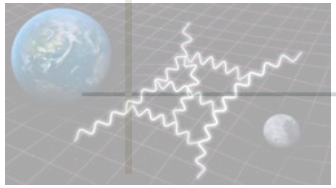
Alternative: Topological Quintessence

Topological Quintessence

Juan C. Bueno Sanchez (Madrid U.), Leandros Perivolaropoulos (Ioannina U.) (Oct, 2011)

Published in: *Phys.Rev.D* 84 (2011) 123516 • e-Print: 1110.2587 [astro-ph.CO]

Main Questions



Q1: Is a G_{eff} late gravity transition consistent with current constraints of G_{eff}?

A1: Yes. Only the current/local time derivative of G_{eff} is heavily constrained.

Q2: Are there hints for a gravitational fundamental physics transition in astrophysical data on scales less than 70Mpc (z_t<0.02)?

A2: Yes, there are some 2σ level hints in the Cepheid, Patheon+ and Tully-Fisher data. (LP recent work)

Q3: Are there theoretical models that naturally and generically predict this type of transition?

A3: Yes, a false vacuum decay of a non-minimally coupled scalar field (eg chameleon or symmetron field) can generically induce it (first order phase transition)

Topological Quintessence

Juan C. Bueno Sanchez (Madrid U.), Leandros Perivolaropoulos (Ioannina U.) (Oct, 2011)

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