The challenges for ΛCDM

and

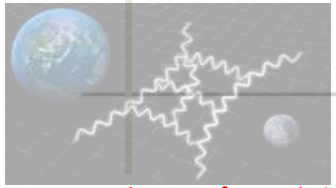
the physics transition approaches

Leandros Perivolaropoulos

Department of Physics, University of Ioannina, Greece

Corfu 2023 Workshop on Tensions in Cosmology

The large scale tensions of the standard model



ELSEVIER

New Astronomy Reviews

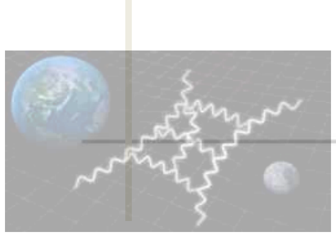
Volume 95, December 2022, 101659

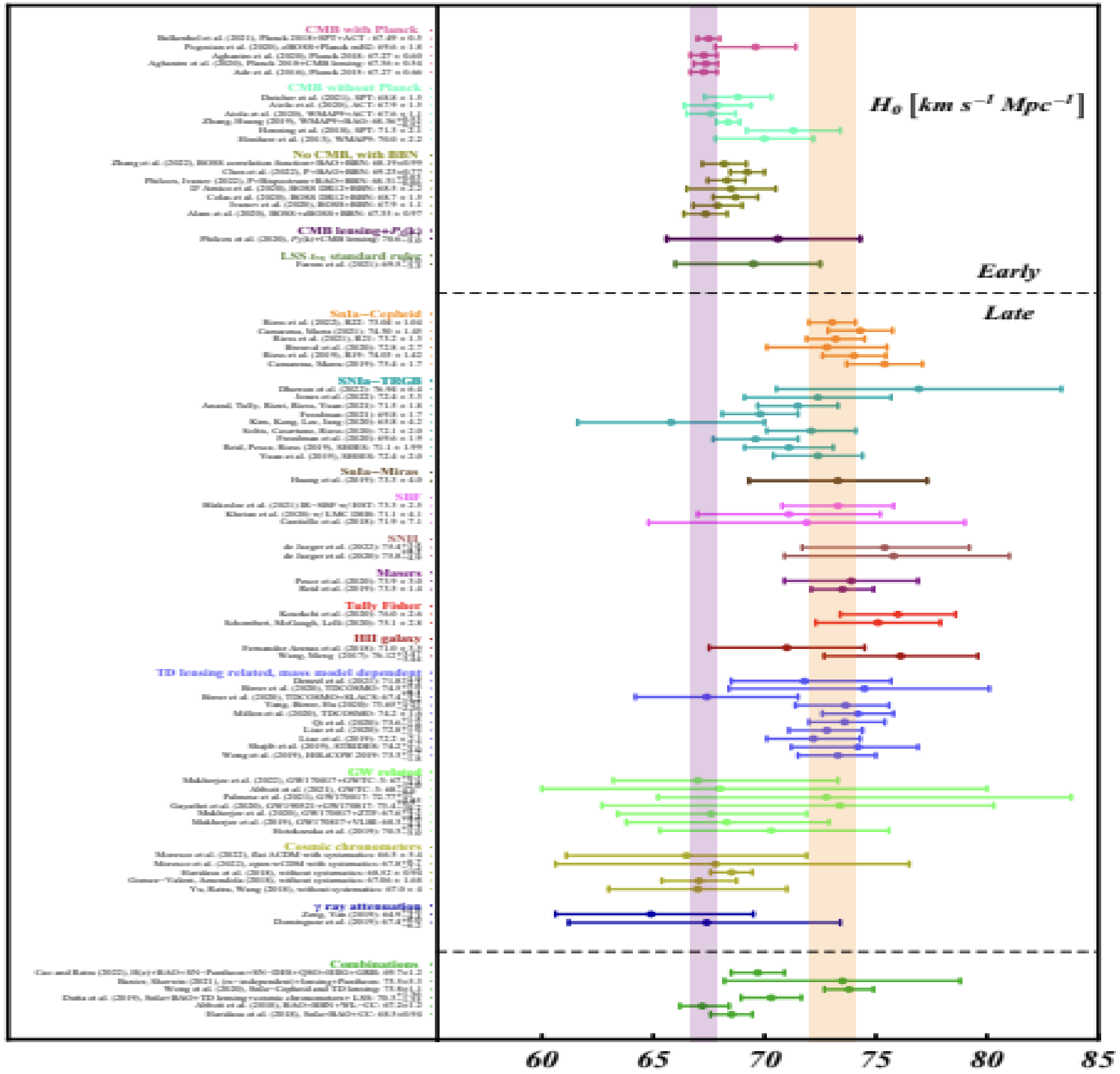
Challenges for ΛCDM: An update

L. Perivolaropoulos, F. Skara

1. **The Hubble crisis (2-5σ):** Local direct measurements of H_0 are in 5σ tension with CMB indirect measurements of H_0. (Sound horizon+CMB+BAO+BBN: H_0=67.4±0.5km/secMpc, SnIa+Cepheids: 73.04±1km/secMpc (5σ, 9%))
2. **The growth tension (2-3σ):** Direct measurements of the growth rate of cosmological perturbations (weak lensing, peculiar velocities, cluster counts) indicate a lower growth rate than that indicated by Planck-ΛCDM (lower matter density).
3. **Cosmic Dipoles (2-5σ)** Quasar+radio galaxies density dipole, large scale velocity bulk flow.
4. **CMB anisotropy anomalies (2-3σ):** Lack of power on large angular scales, small vs large scales tension (different best fit values of cosmological parameters), cold spot anomaly, hemispherical temperature variance asymmetry, preference for odd parity correlations etc.

The Hubble tension





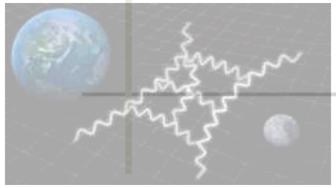
Q.: What is the feature that distinguishes the two groups of H_0 values?

Is it cosmic time of measurements?

or

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

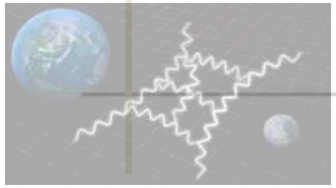
Local measurements



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

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??

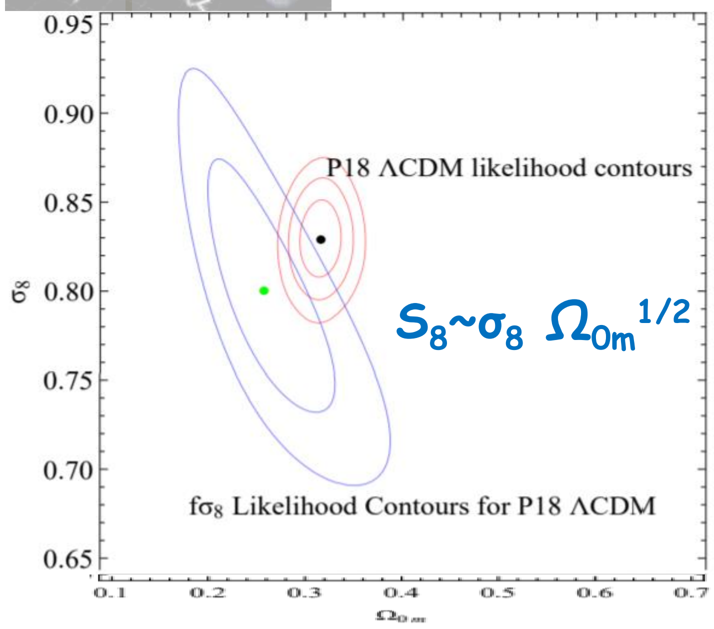
Could there be a physics change between local calibrator scales ($z<0.01$) and Hubble flow scales ($z>0.01$)?

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]

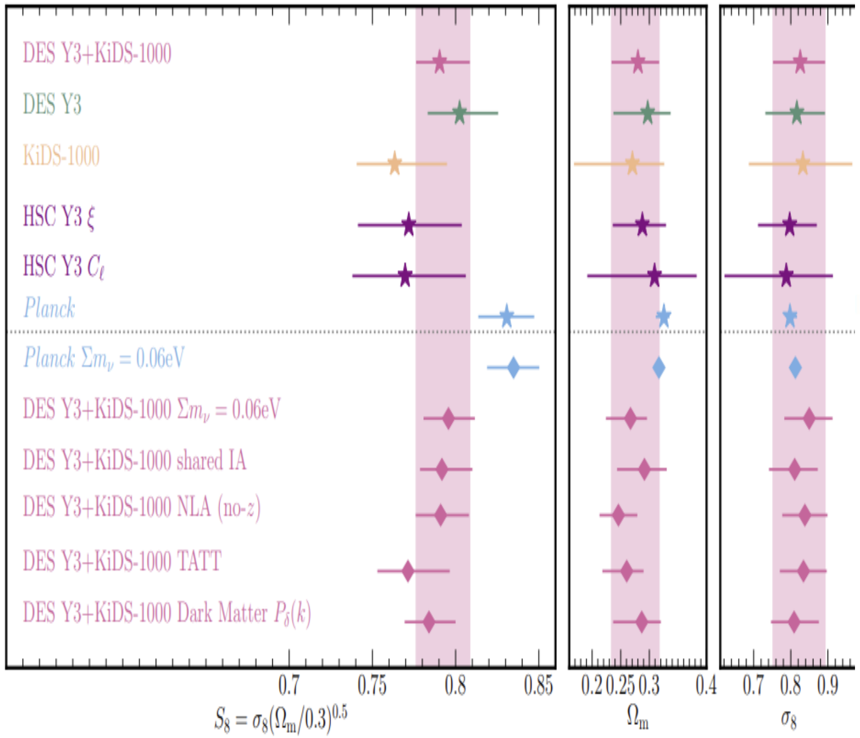


Redshift Space Distortions (galactic peculiar velocities)

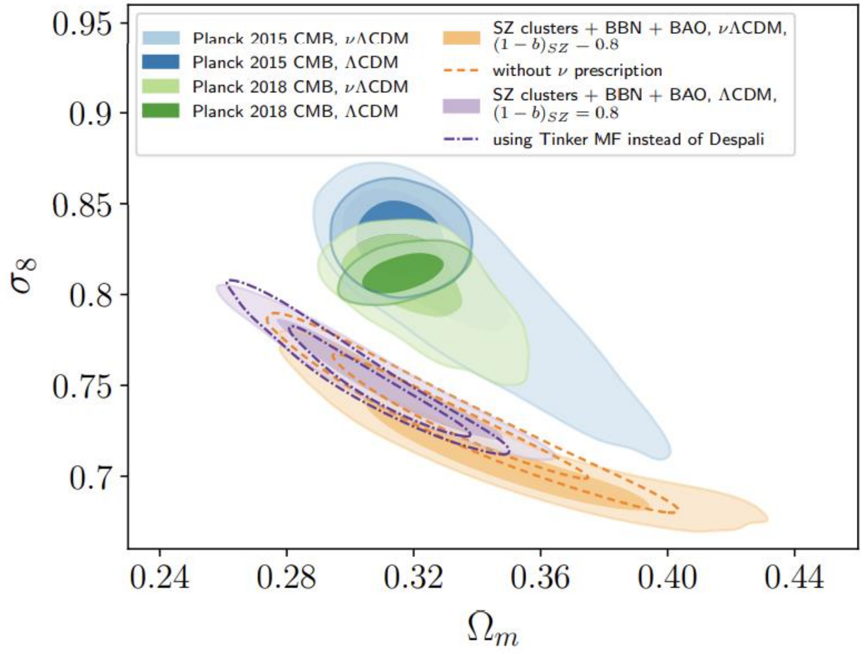
DES Y3 + KiDS-1000: Consistent cosmology combining cosmic shear surveys

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

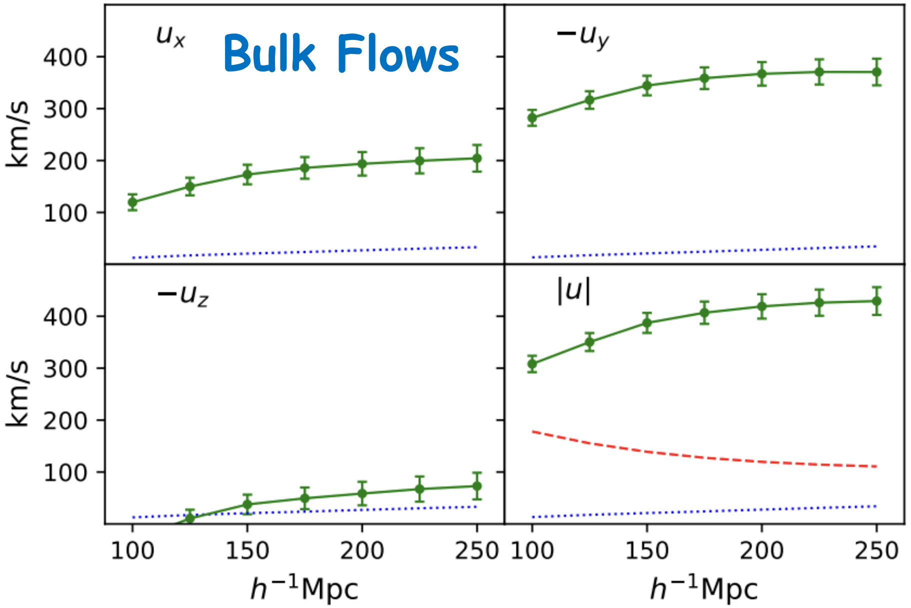
Cluster counts. II. Tensions, massive neutrinos, and modified gravity

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)?

Cosmic Dipoles



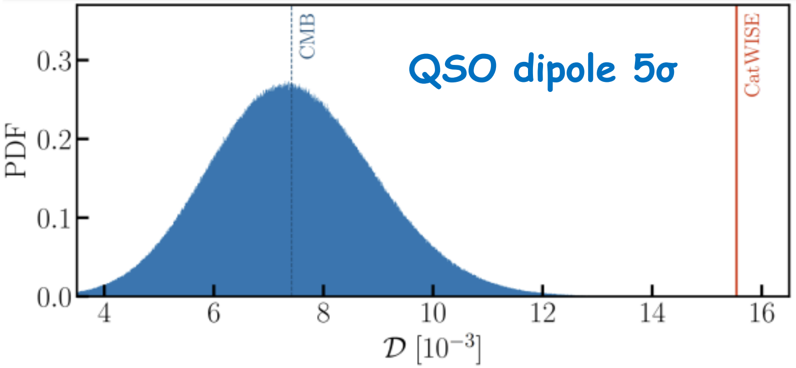
	$R = 150h^{-1}$Mpc	$R = 200h^{-1}$Mpc
Expectation (km/s)	139	120
Bulk Flow (km/s)	387 ± 28	419 ± 36
Direction	$l = 297° \pm 4°$	$l = 298° \pm 5°$
	$b = -6° \pm 3°$	$b = -8° \pm 4°$
χ^2 with 3 d.o.f.	19.34	29.13
Probability	0.023%	0.00021%

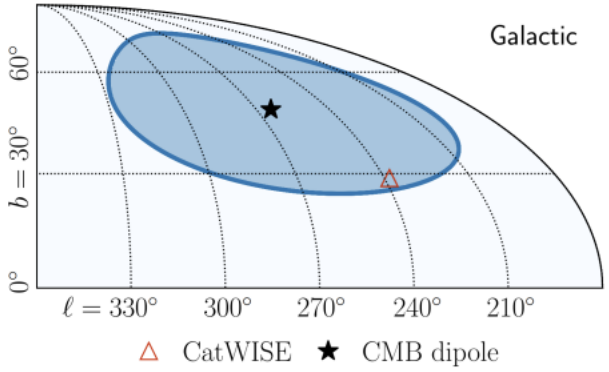
Analyzing the Large-Scale Bulk Flow using CosmicFlows4: Increasing Tension with the Standard Cosmological Model

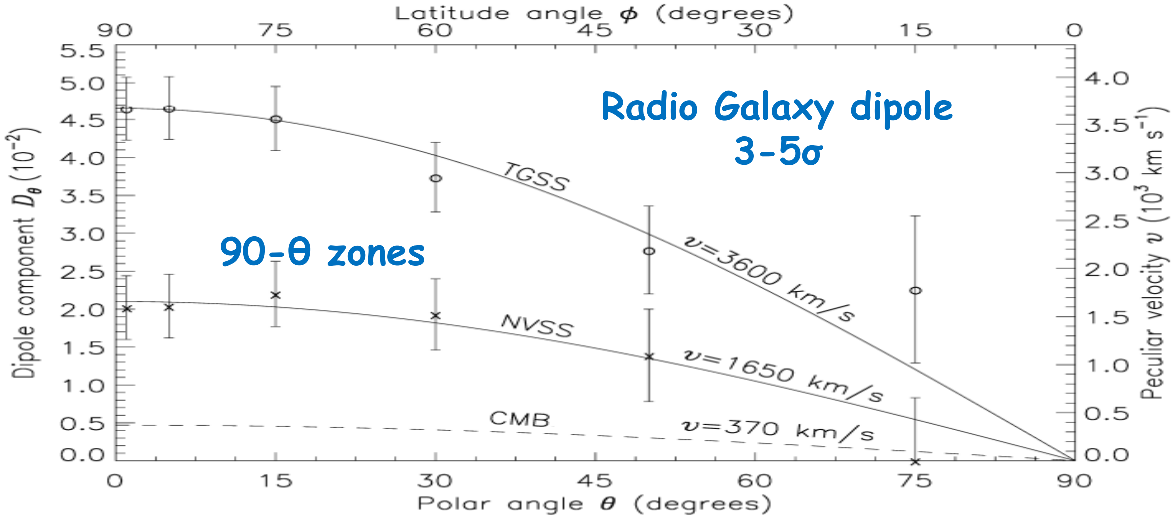
Richard Watkins, Trey Allen, Collin James Bradford, Albert Ramon, Alexandra Walker et al. (Feb 3, 2023)

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







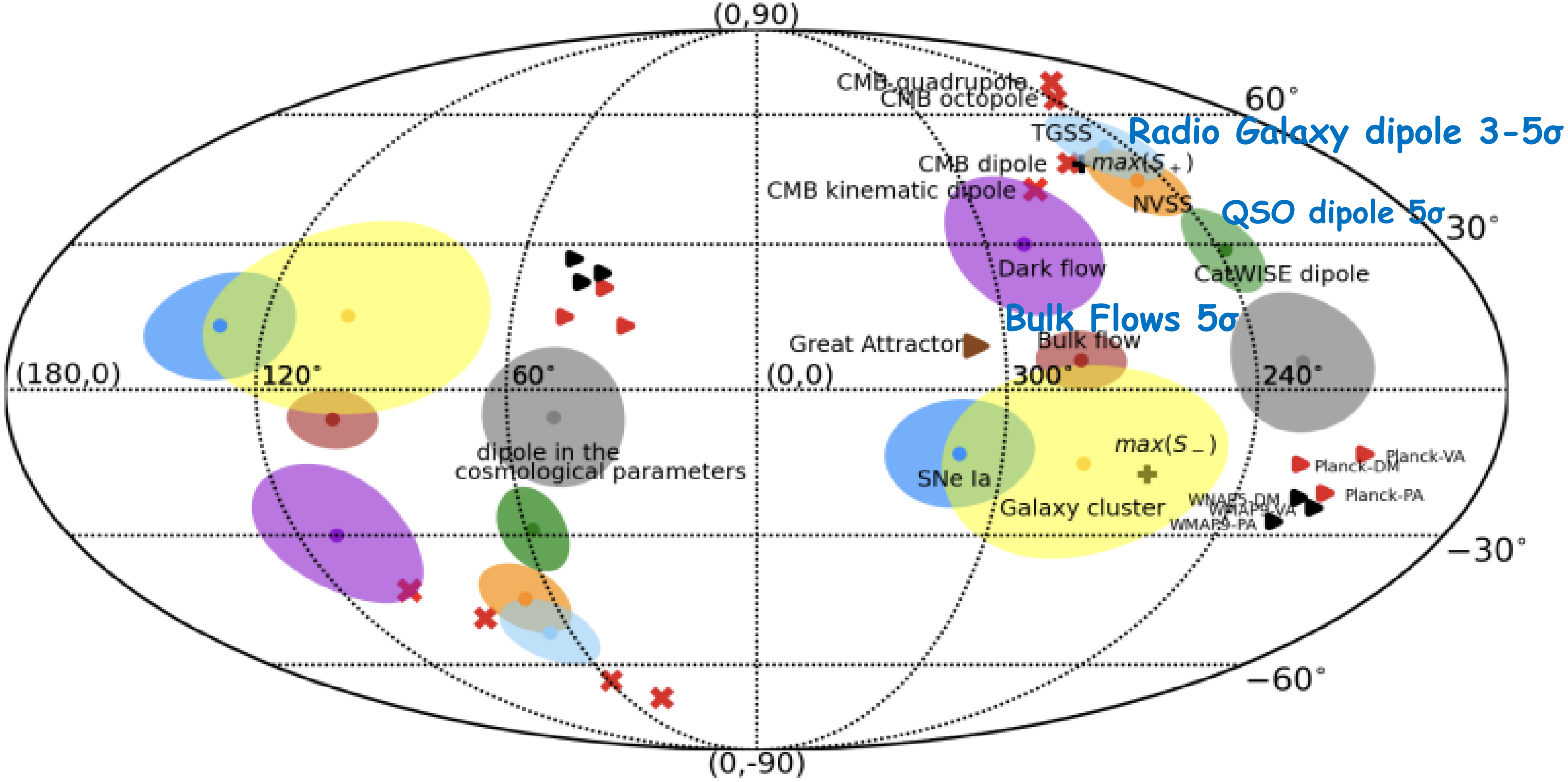
Singal, A. K. Large Peculiar Motion of the Solar System from the Dipole Anisotropy in Sky Brightness due to Distant Radio Sources. *The Astrophysical Journal Letters*, **742**(2):L23, 2011

Cosmic Dipoles

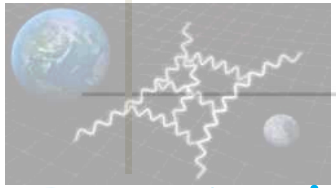
Is the Observable Universe Consistent with the Cosmological Principle?

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]



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)

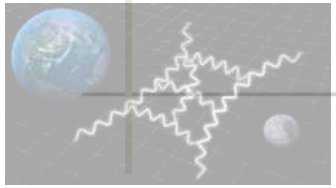
From sCDM to ΛCDM: Data and Simple Alternative (cosmological constant)

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.

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



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

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

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

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

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

fit with kinematic expansion (0.01<z<0.1)

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

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.

Fit for H(z) and cosmological parameters (Ω_{0m}) z_{max}~2.

Parametrize H(z): $H(z)^2 = H_0^2\left[\Omega_{0m}(1+z)^3 + (1-\Omega_{0m})\right]$

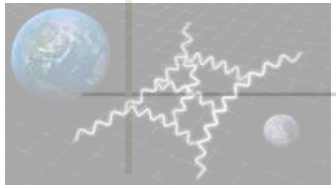
$$m_{th}(\Omega_{0m}, \mathcal{M}) = 5\,log_{10} D_L(z;\Omega_{0m}) + \mathcal{M}(M, H_0)$$

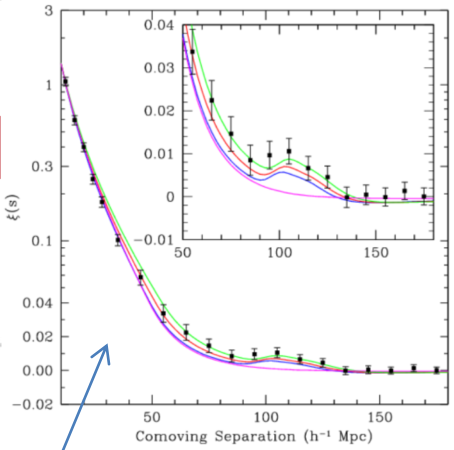
$$D_L(z, \Omega_{0m}) = c(1+z)\int_0^z \frac{dz'}{\left[\Omega_{0m}(1+z')^3 + (1-\Omega_{0m})\right]^{1/2}}$$

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

Minimize: $\chi^2(\mathcal{M}, \Omega_{0m}) = \sum_i \left[\frac{m_{obs,i} - m_{th}(z_i;\Omega_{0m}, \mathcal{M})}{\sigma_i^2}\right]$

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}

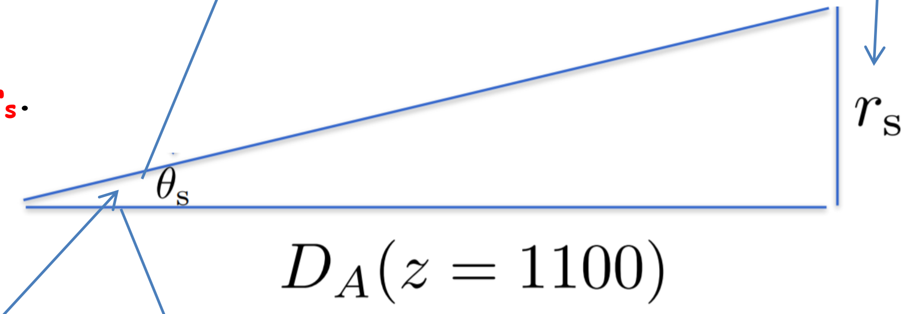
EDE: Add new fluids to decrease r_s.

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



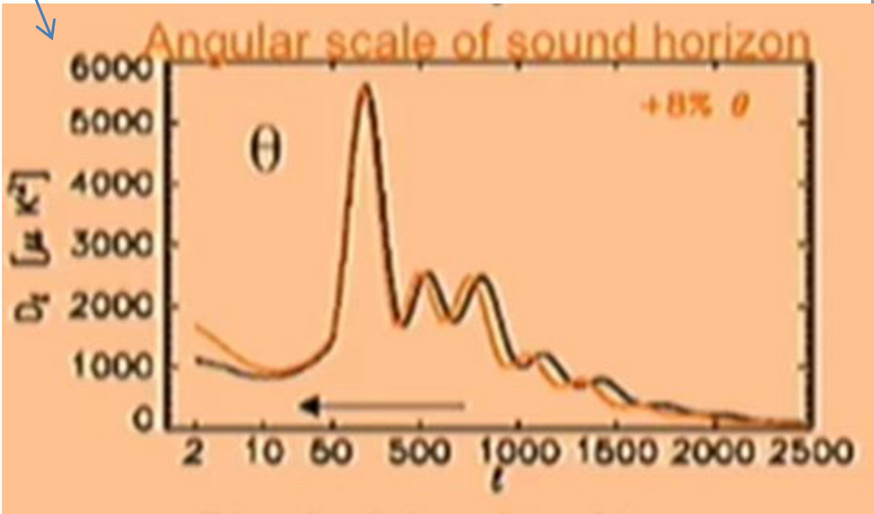
measured

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

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

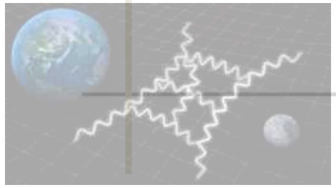
comoving

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



Degeneracy between r_s and H_0 and E(z).

H_0 tension: M tension, r_s tension or E(z) tension?



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.

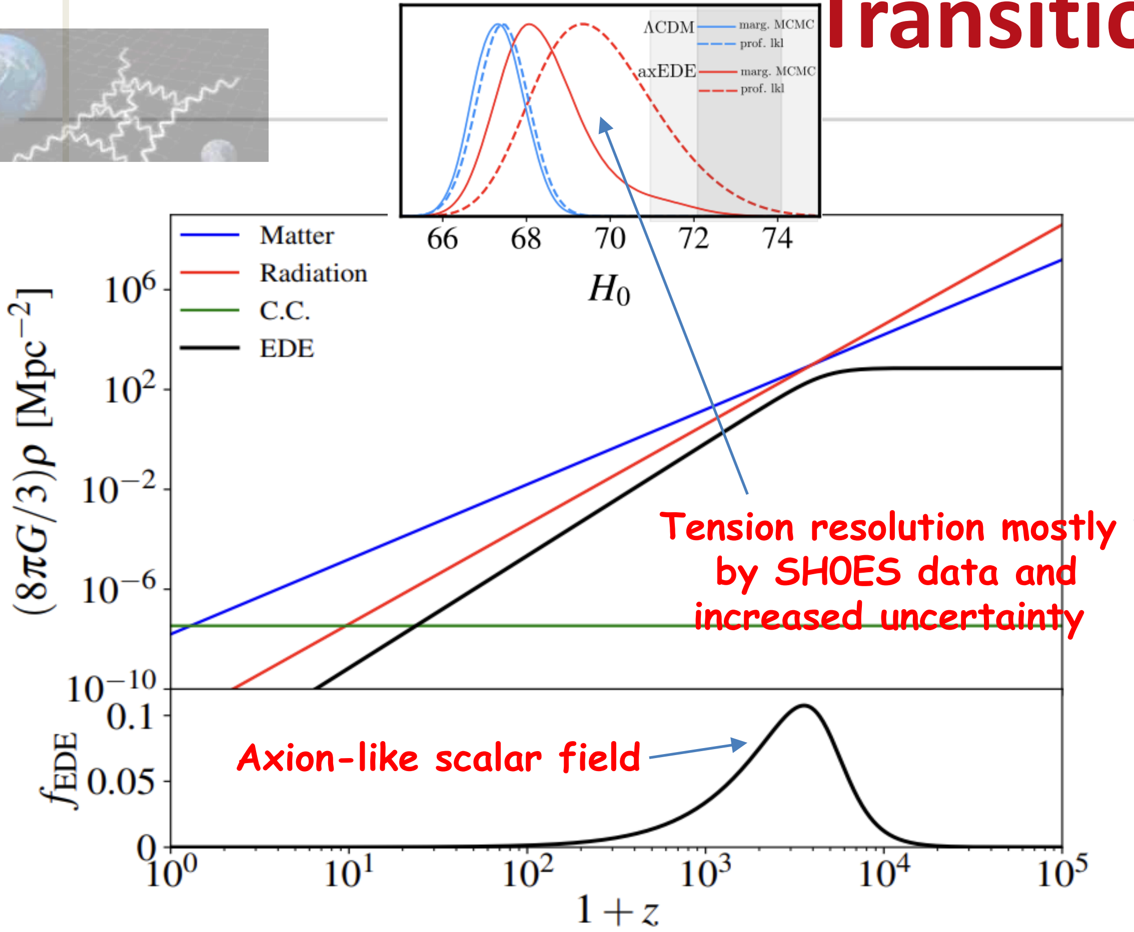
$$H_0^{P18} = 67.36 \pm 0.54 \text{ km s}^{-1}\text{Mpc}^{-1}$$

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

(New) Early Dark Energy Phase Transition

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

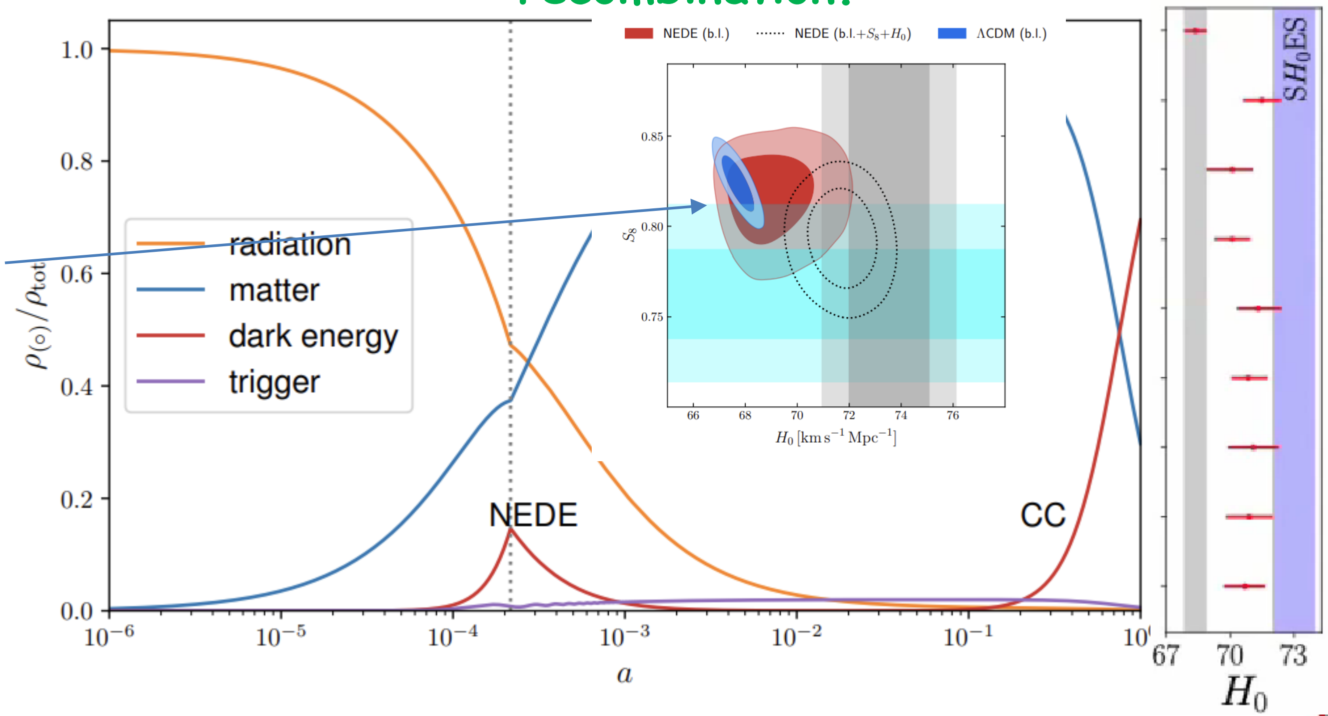
Thus, it does not interfere with E(z) after recombination.



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]

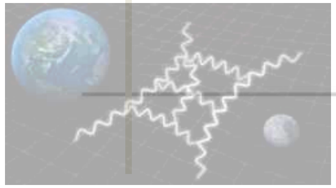


New Early Dark Energy as a solution to the H_0 and S_8 tensions

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

e-Print: 2307.03481 [hep-ph]

Inverse Distance Ladder and the 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}

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

Calibrate M from r_s (Inverse distance ladder)

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

$$H_0 = H_0^{P18}$$

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

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 tension. or M transition?

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

M depends on G_{eff}.

H_0 measurement using distance ladder:

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

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

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

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

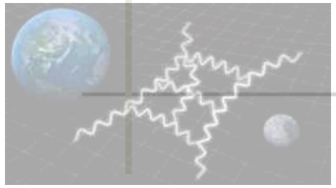
$$G_{\rm eff}(z<0.01) = G_{\rm eff}(z>0.01)$$

H_0 Tension

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

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

The Hubble Crisis Approaches

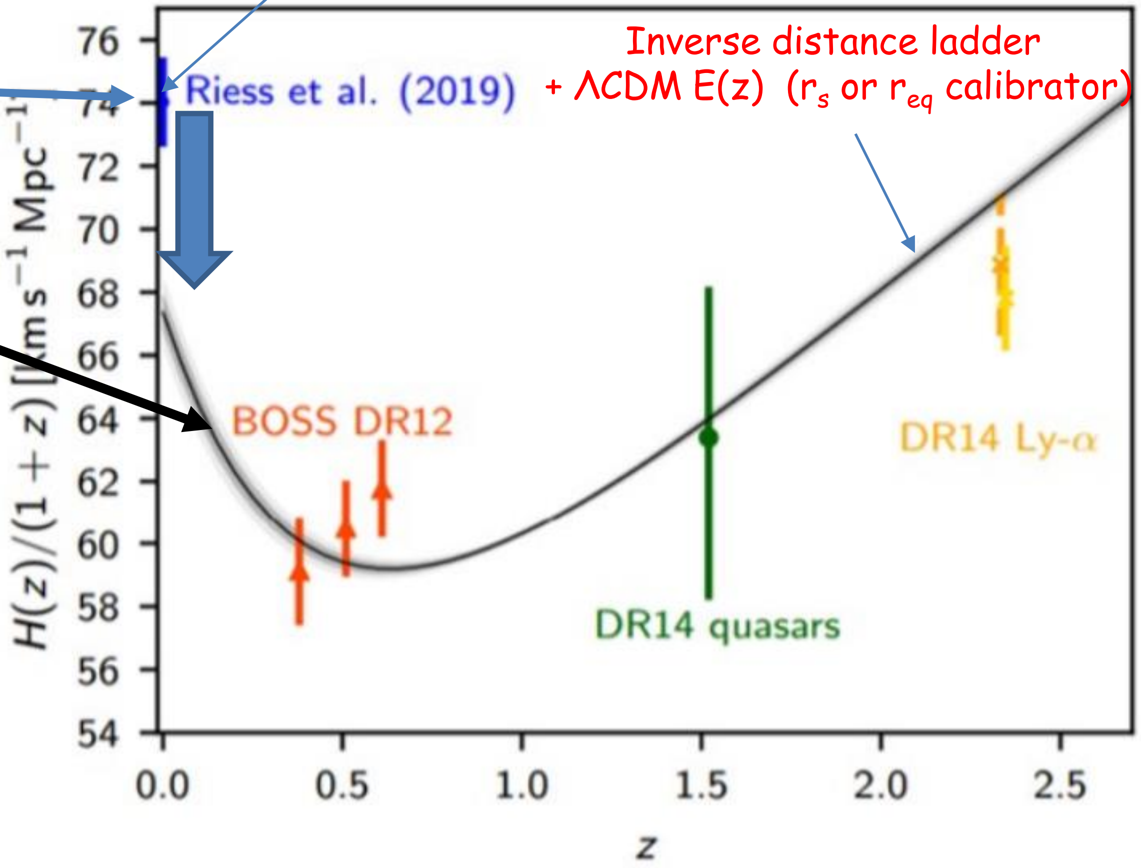


How can H(z) derived from late time calibrators (blue point) become consistent with H(z) derived from early time calibrators (black line)?

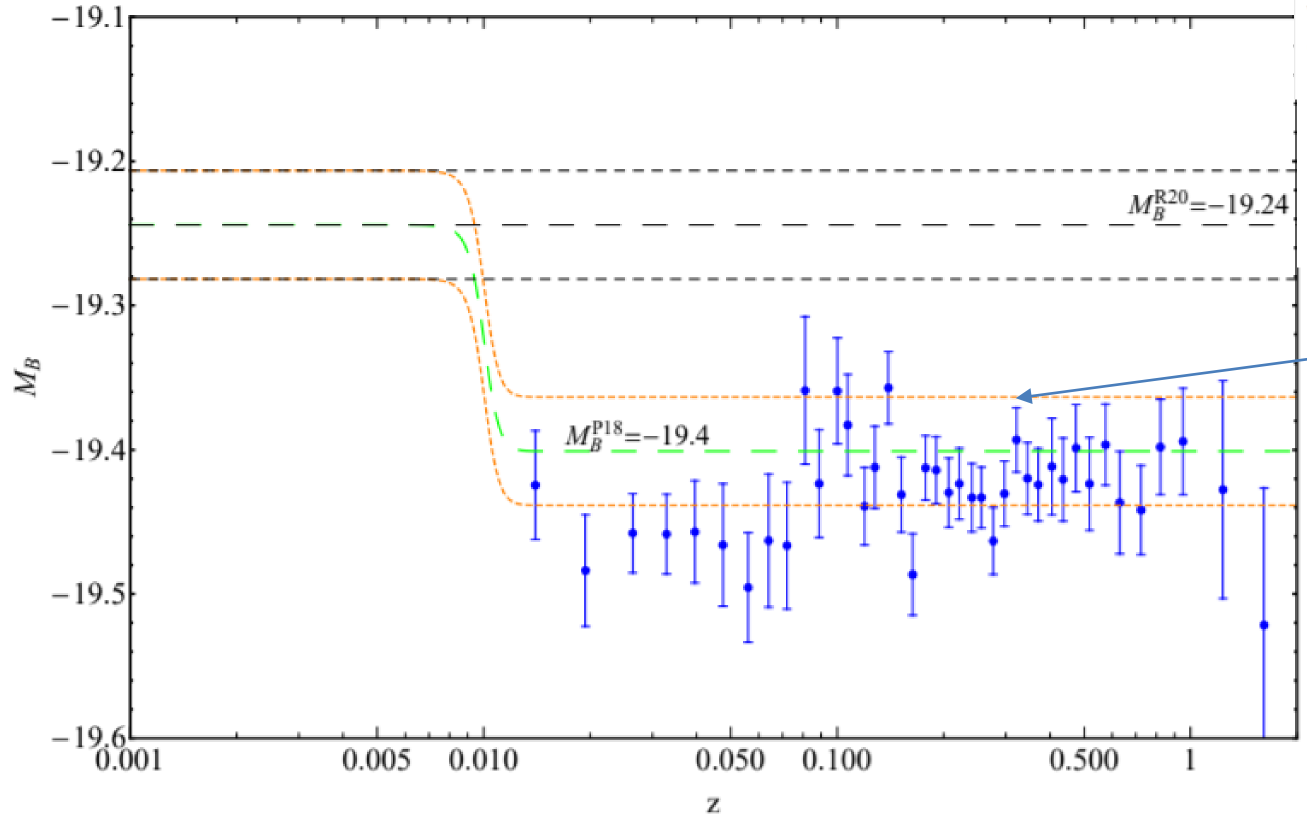
Change SnIa Intrinsic Luminosity (systematics or physics change at 0<z<0.01). (move blue point down)

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

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



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)

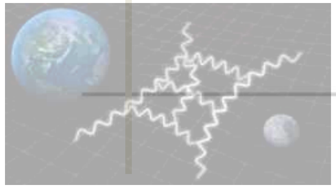
Published in: *Phys.Rev.D* 105 (2022) 6, 6 • e-Print: 2110.04336 [astro-ph.CO]

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 $z>z_t$

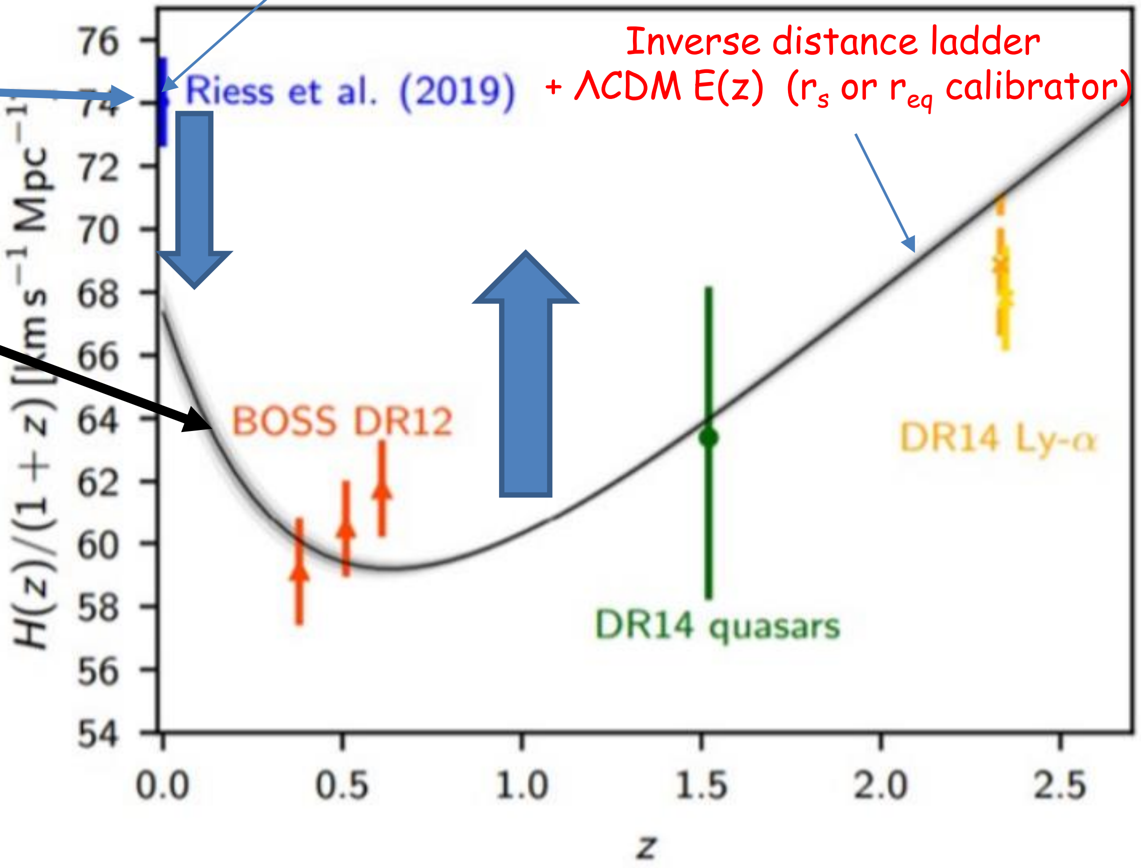
The Hubble Crisis Approaches



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

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

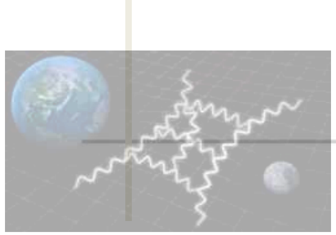
How can H(z) derived from late time calibrators (blue point) become consistent with H(z) derived from early time calibrators (black line)?



Change SnIa Intrinsic Luminosity
(systematics or physics change at 0<z<0.1).
(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)

The Hubble Crisis Approaches

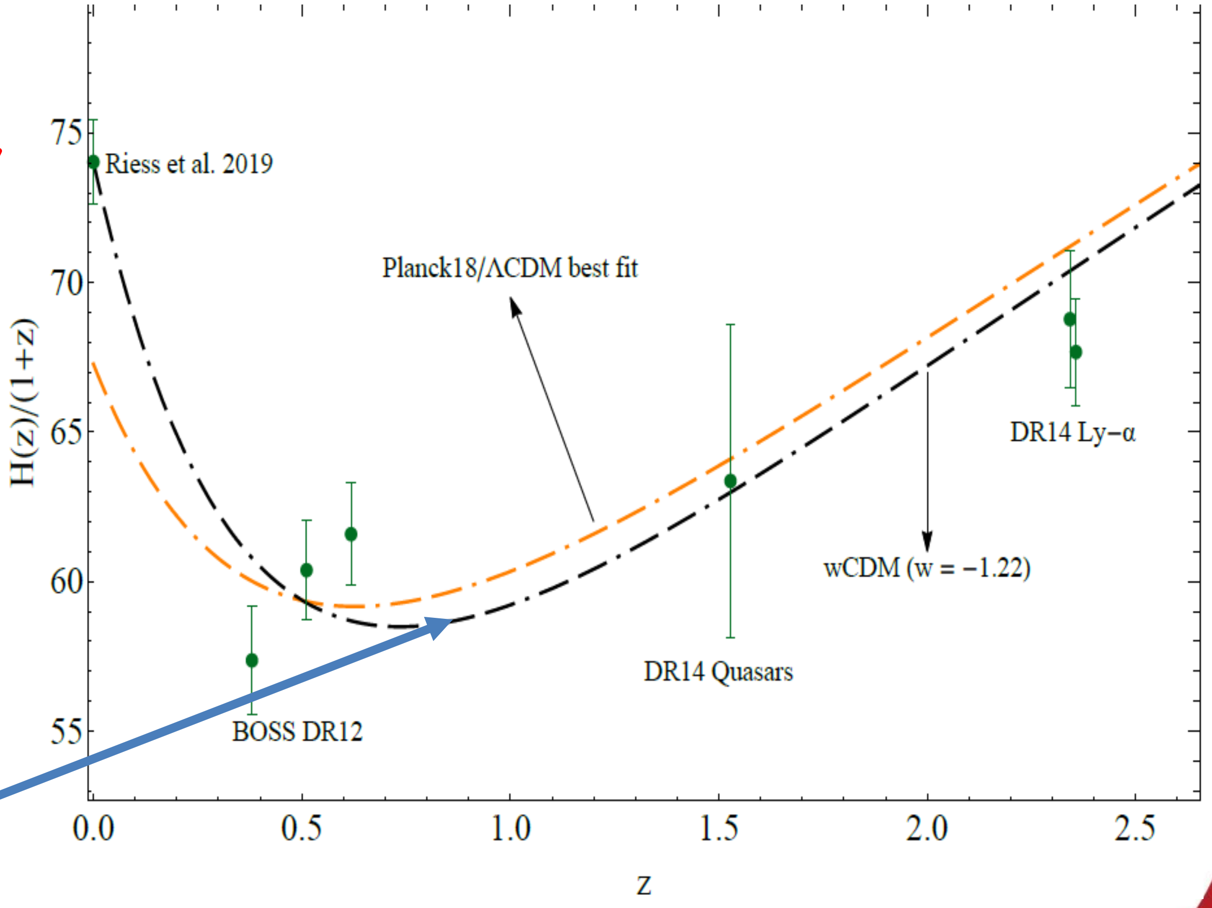


How can H(z) derived from late time calibrators (blue point) become consistent with H(z) derived from early time calibrator (black line)?

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)

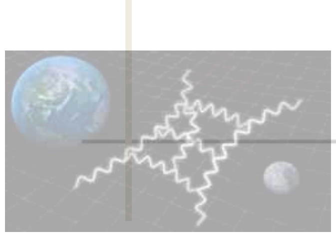


Late-time approaches to the Hubble tension deforming H(z), worsen the growth tension

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]

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)

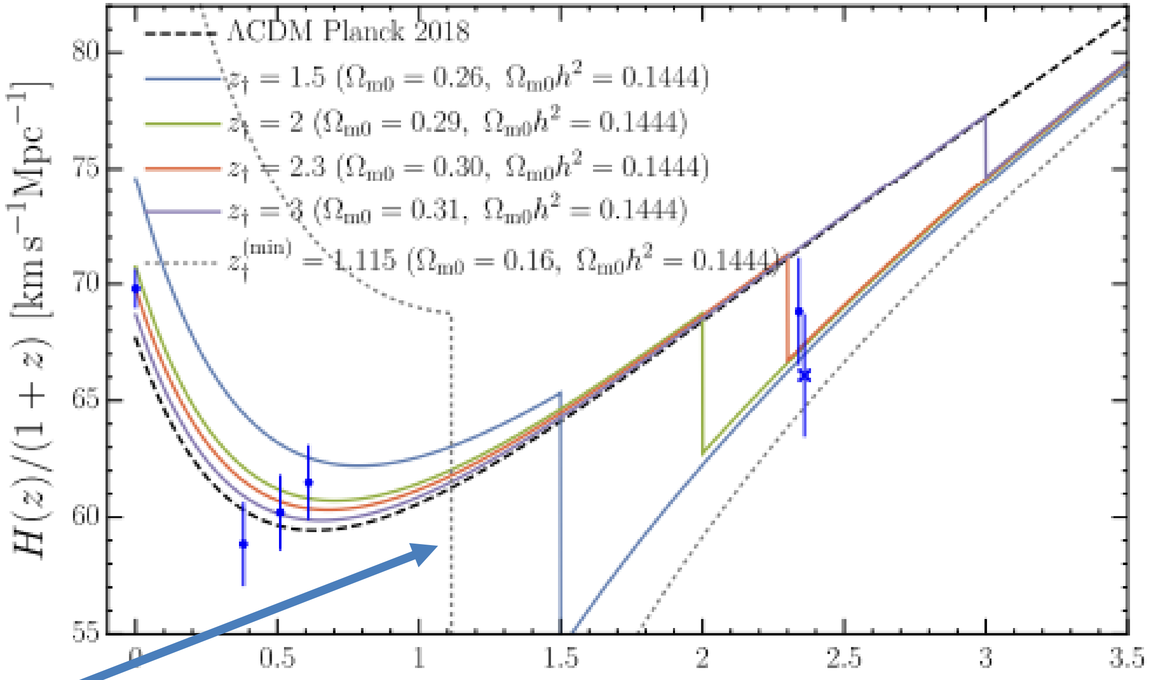
Published in: *Phys.Rev.D* 104 (2021) 12, 123512 • e-Print: 2108.09239 [astro-ph.CO]

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)



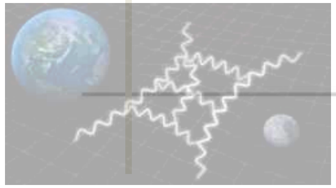
An abrupt transition event may be needed to resolve the tension.

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]

Theoretical Model: Scalar Tensor Theory



Scalar Tensor Transition:

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

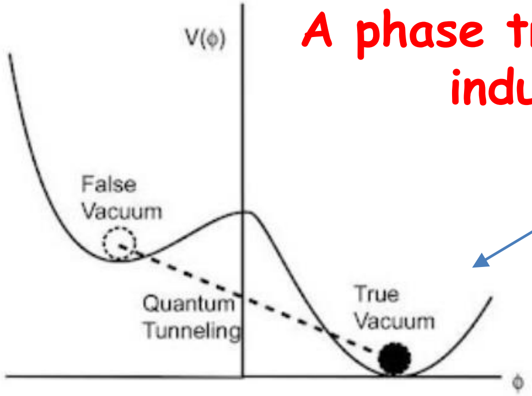
$8\pi G \sim 1/F(\Phi)$

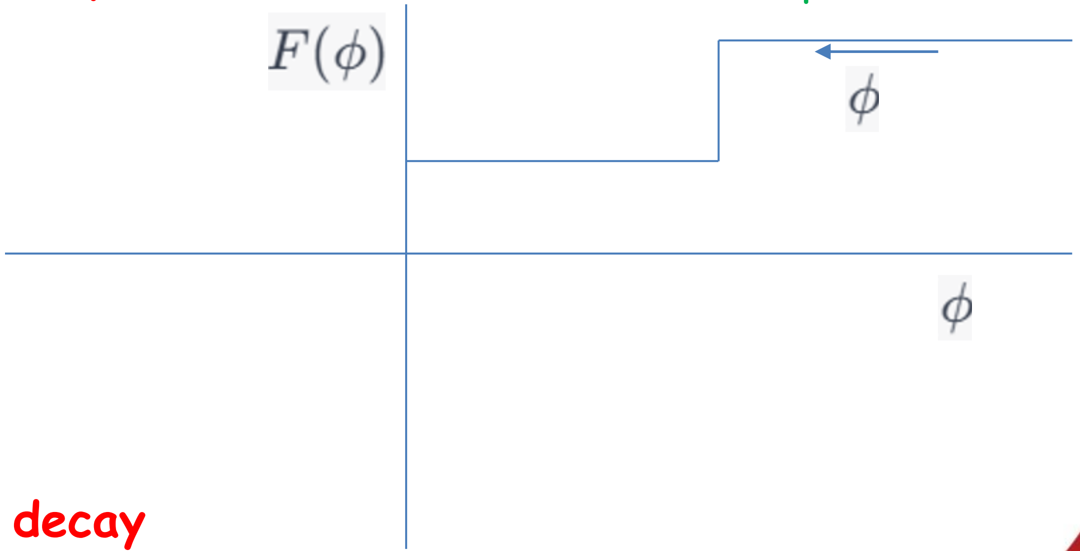
Temporal transition

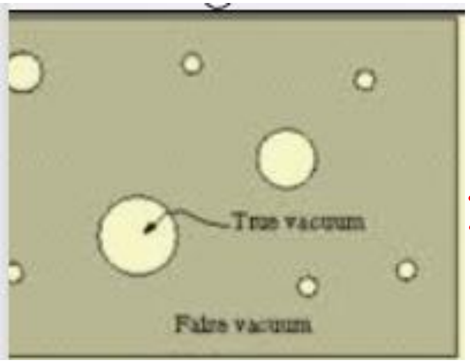
Field rolling in constant potential

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

Spatial transition

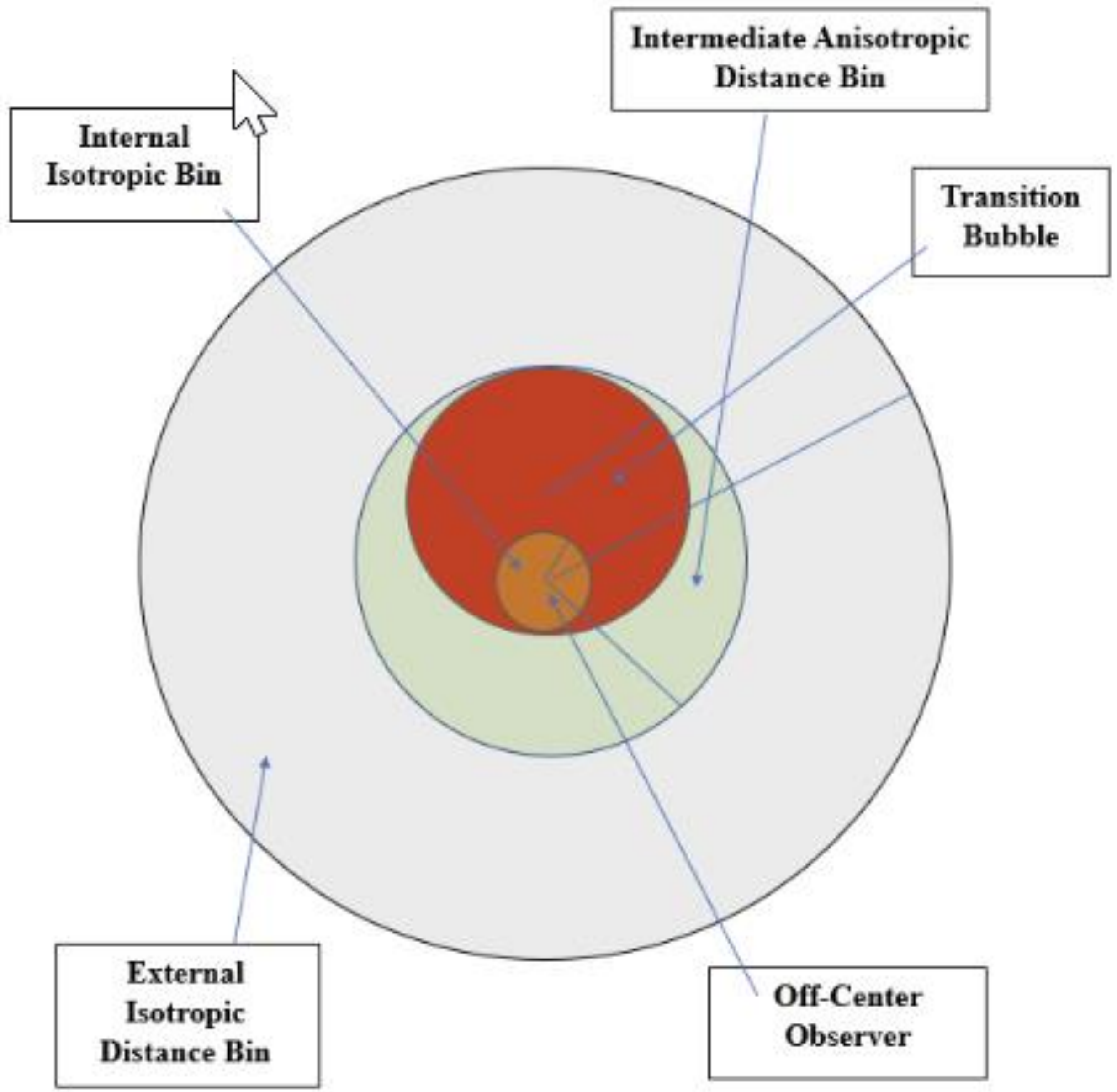




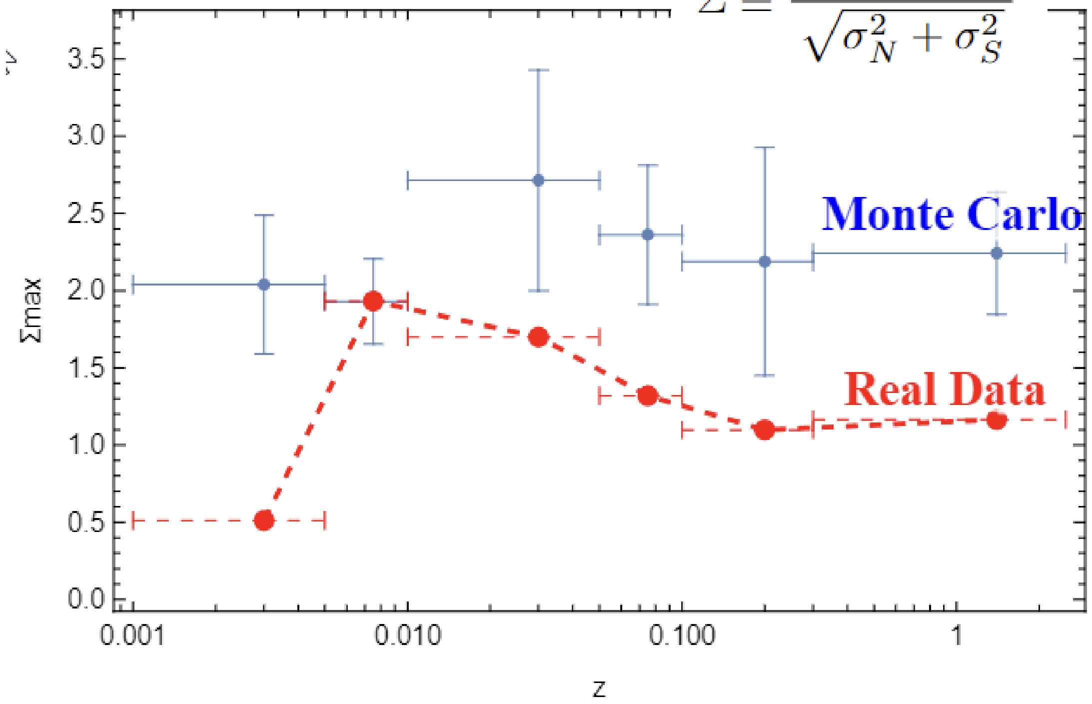


In the context of false vacuum decay bubbles of true vacuum form

Predicted Anisotropy in the context of Spatial Transition



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



Off-center observer in a bubble of distinct transition physics

or

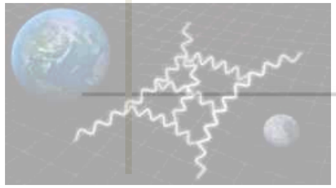
systematics

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]

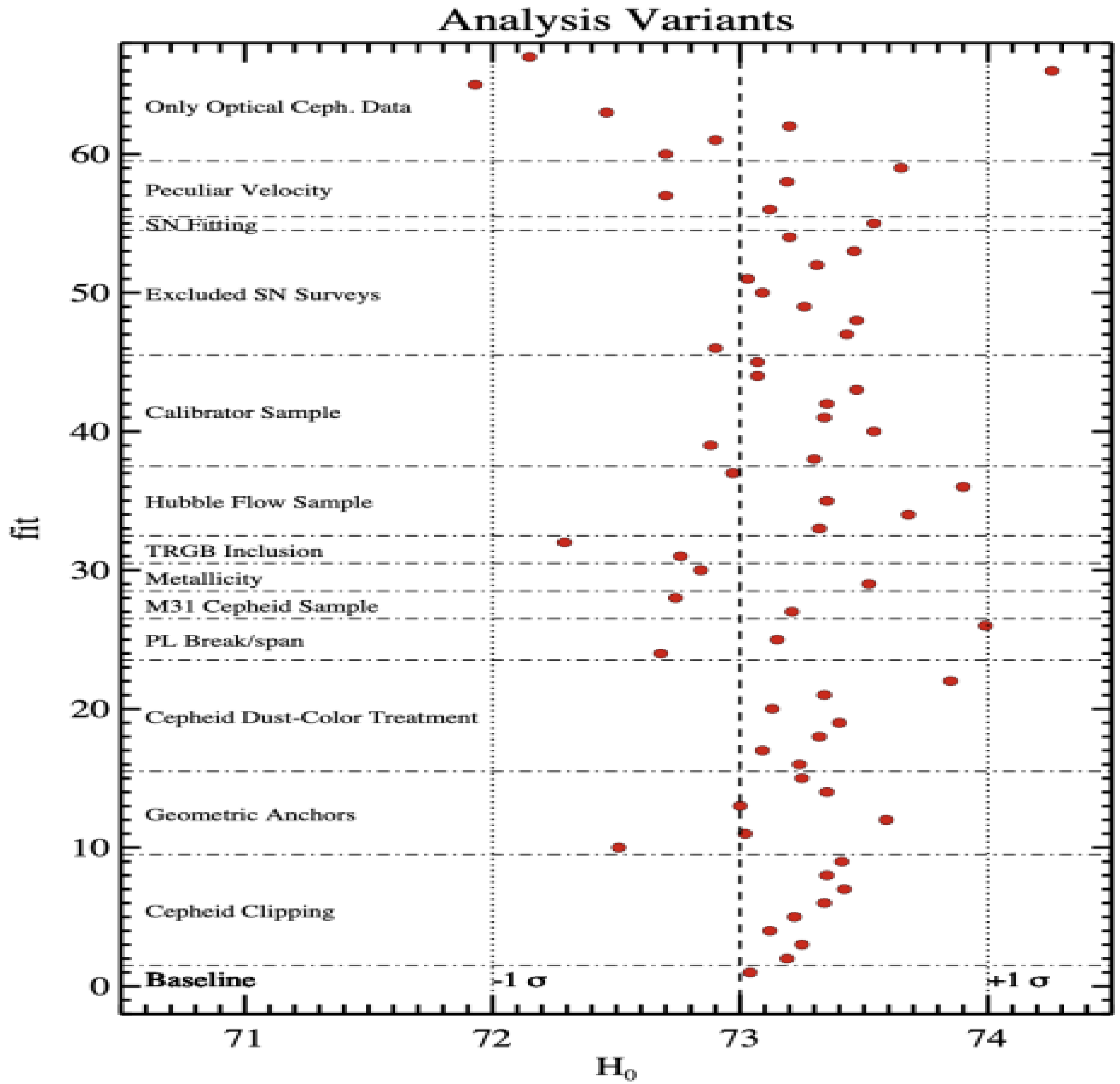
Intrinsic tension in the supernova sector of the local Hubble constant measurement and its implications
Radosław Wojtak, Jens Hjorth (Jun 16, 2022)
Published in: *Mon.Not.Roy.Astron.Soc.* 515 (2022) 2, 2790-2799 • e-Print: 2206.08160 [astro-ph.CO]

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).

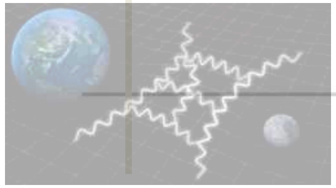
A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s^{-1} Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team #

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]

The latest 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

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

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

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]

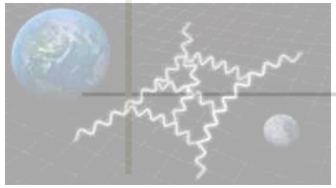
$$H_0 = 73.04 \pm 1.04\, km\, s^{-1}\, Mpc^{-1}$$

Express the system as linear vector transformation

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

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

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:

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

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

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

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

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

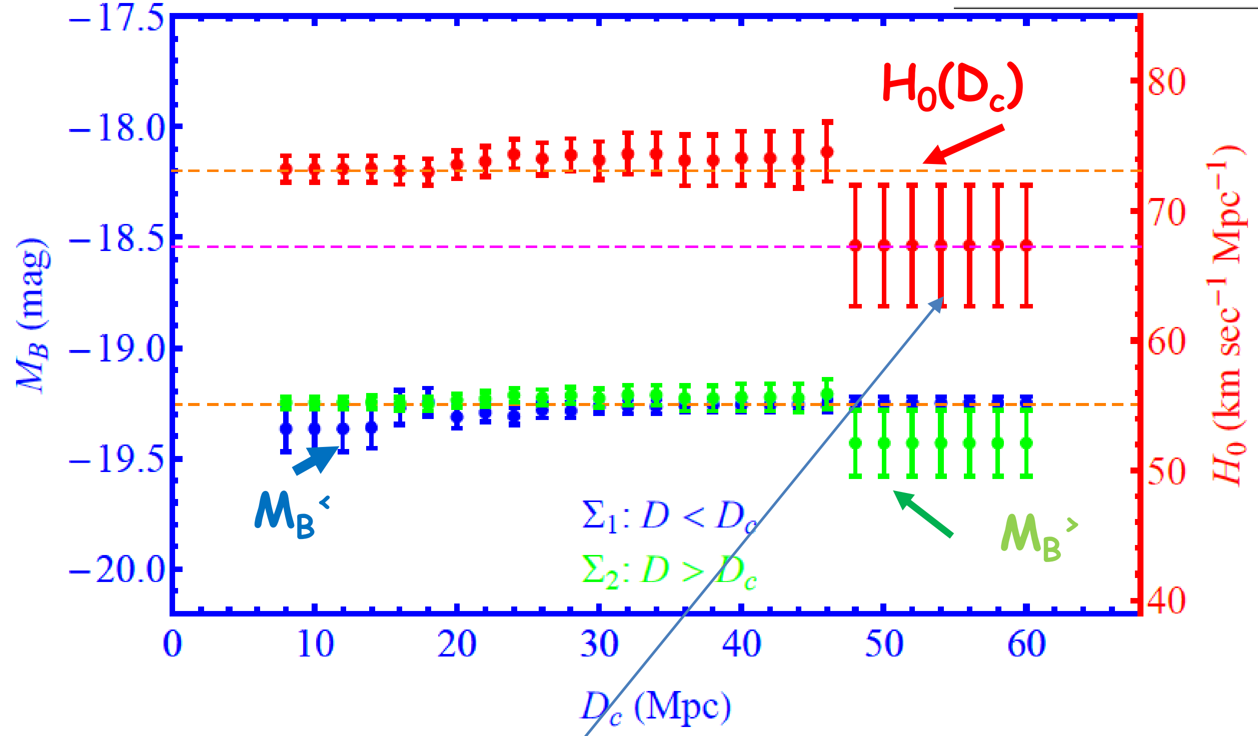
Leandros Perivolaropoulos (Ioannina U.), Foteini Skara (Ioannina U.) (Aug 23, 2022)

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

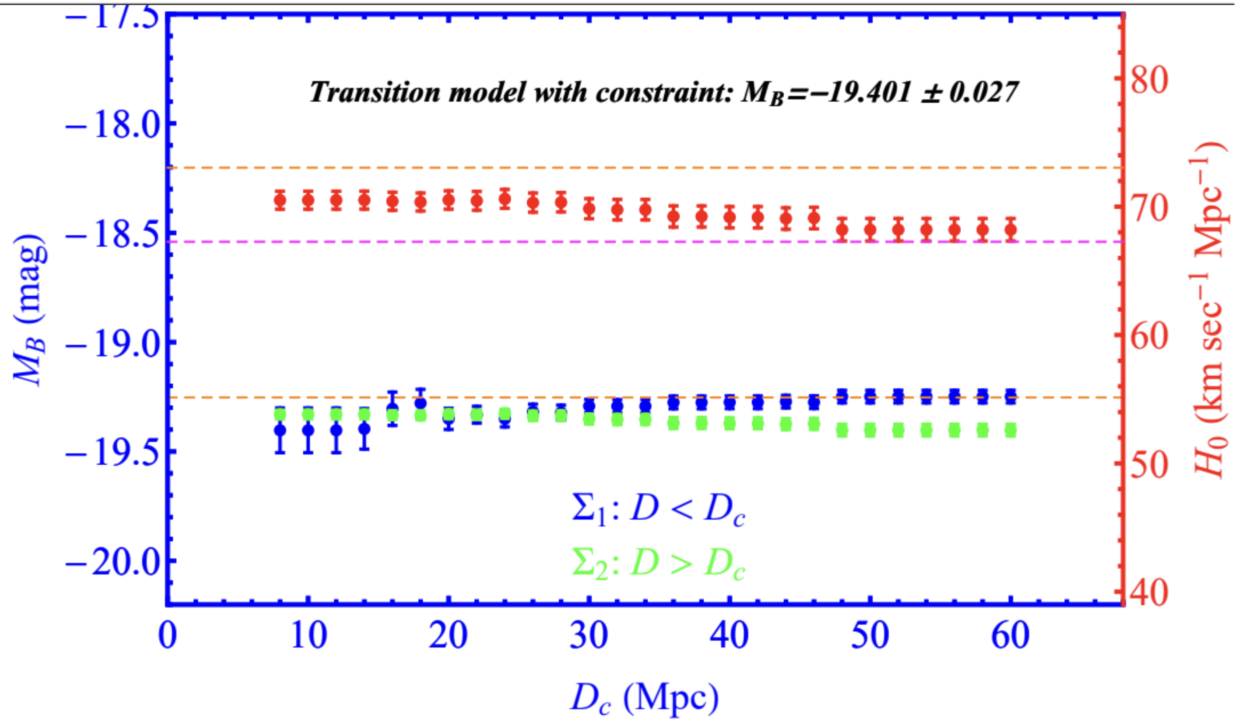
The new matrix equation Y=L q would have the same data/constraints Y (labeled with their distance) the same covariance matrix C but different model matrix L and parameter matrix q.

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

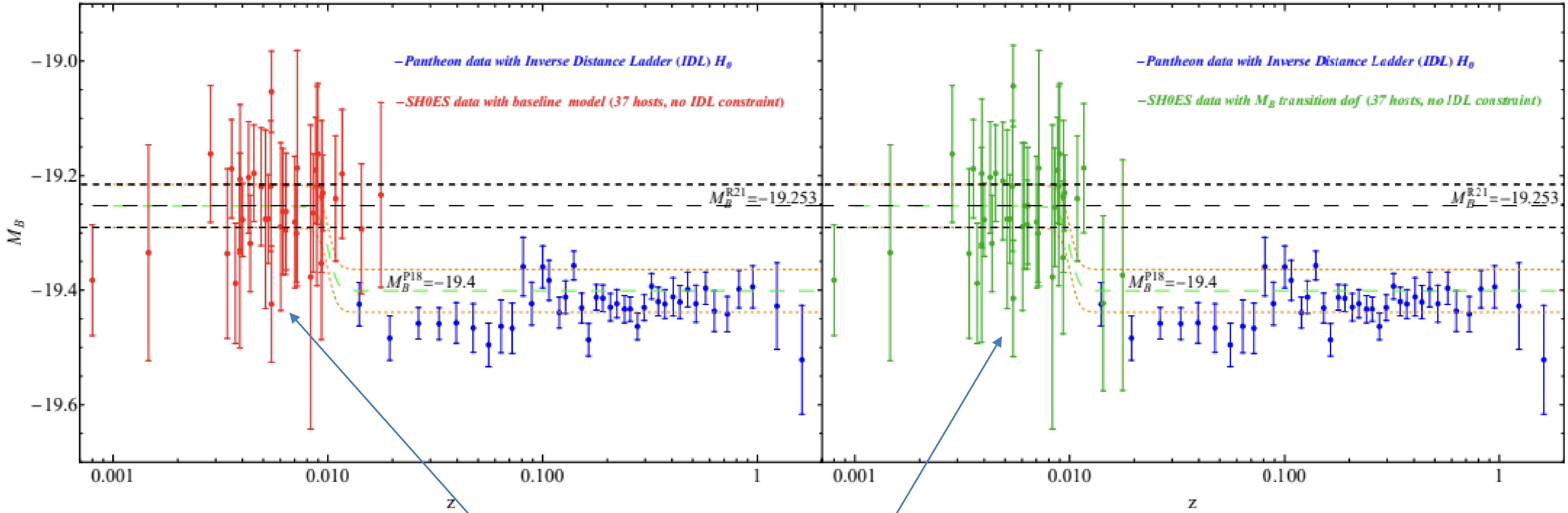


Spontaneous transition of the best fit value of H_0 when a transition at D_c~50Mpc is allowed.
H_0=(67.3 ± 4.6) km/secMpc



Using Inverse distance ladder input
H_0=(68.2 ± 0.9) km/secMpc

Hints for an M transition in SH0ES?

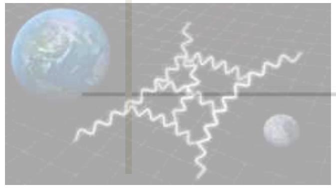


Derive μ_i and do not allow any transition
(the original SH0ES approach)

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

$$M_{Bi} = m_{Bi}^0 - \mu_i$$

Measuring H(z) with the 2022 Pantheon+ datase



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

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

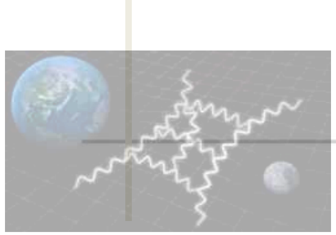
Brout et al 2022: M not included in fit.

New degrees of freedom in the Pantheon+ likelihood

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



Allow for a transition of M at some distance d_c

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

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

New likelihood for Patheon+:

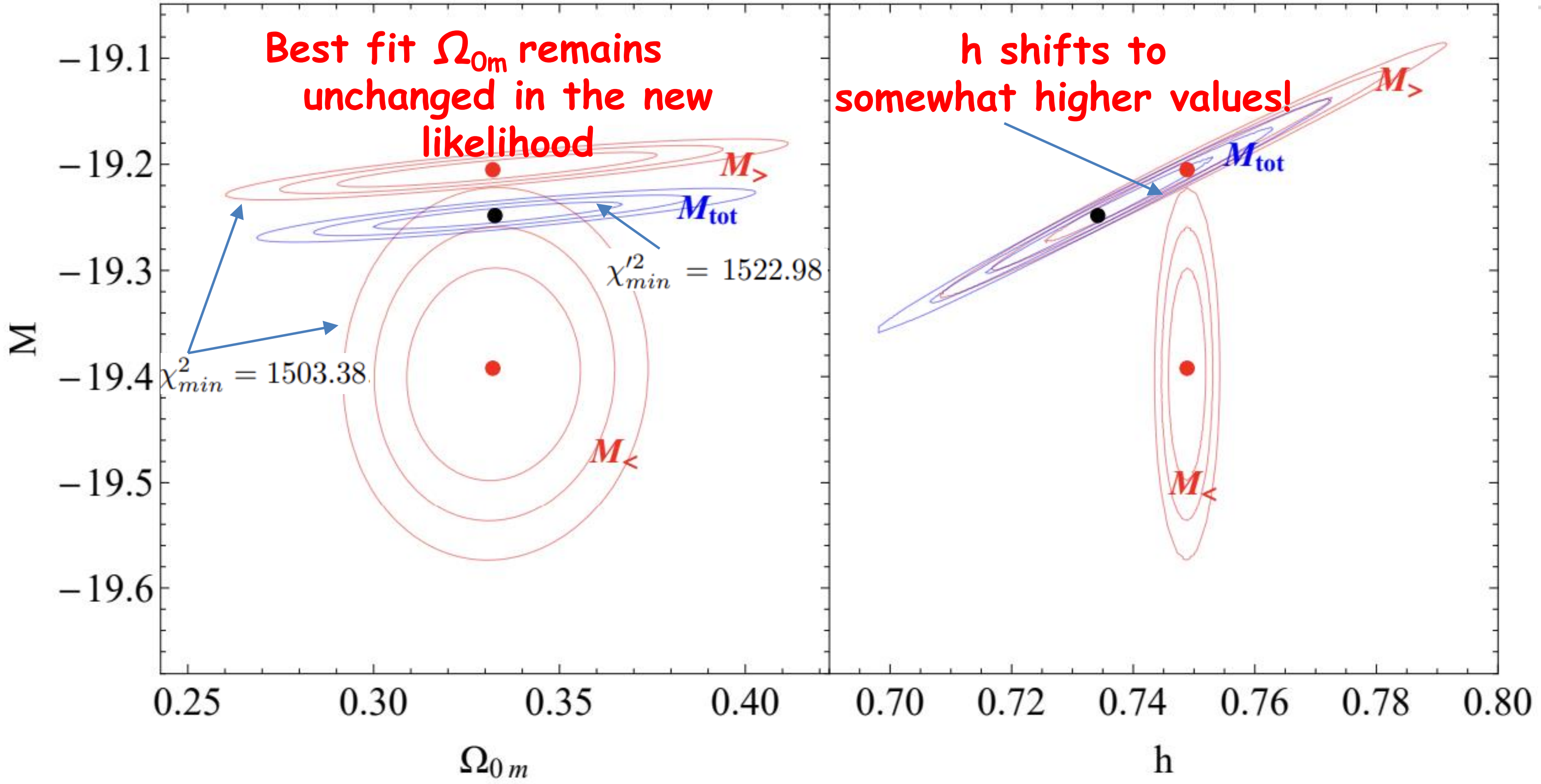
$$Q_i'' = \begin{cases} m_{Bi} - M_< - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} < \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_> - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} > \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_< - \mu_{\text{model}}(z_i) &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

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

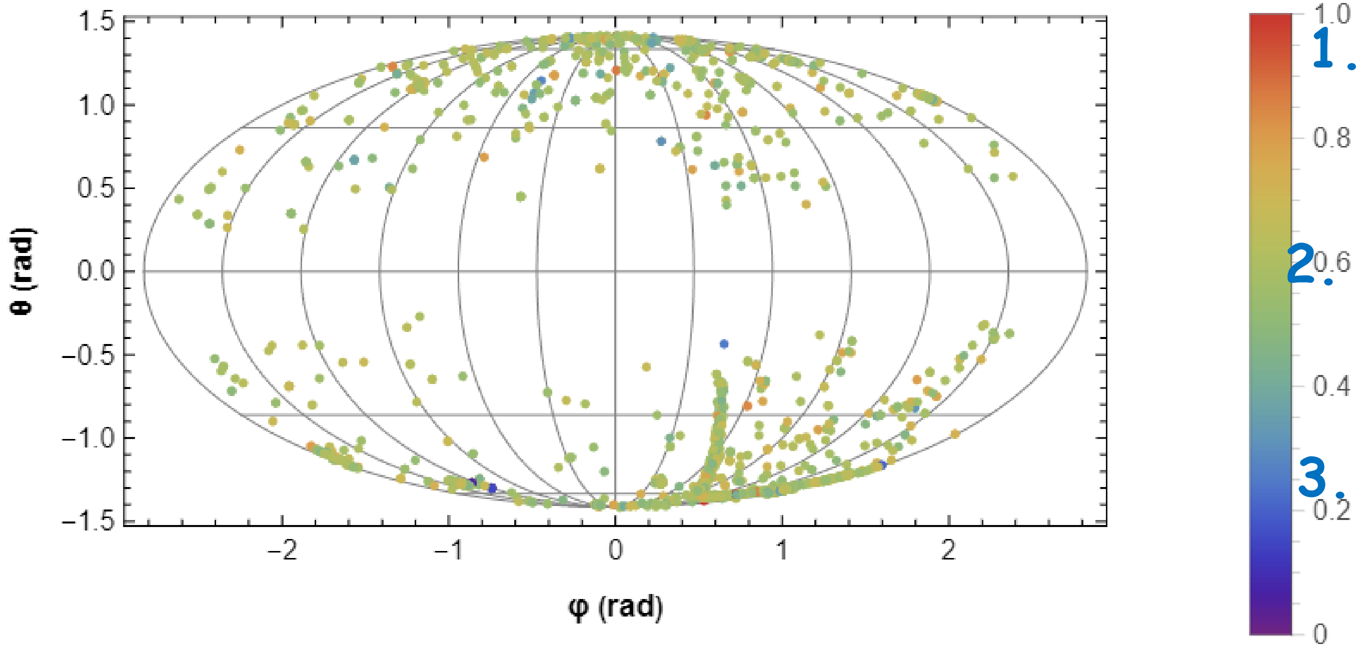
Leandros Perivolaropoulos (May 22, 2023)

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

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

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

Stand. Abs. Mag.



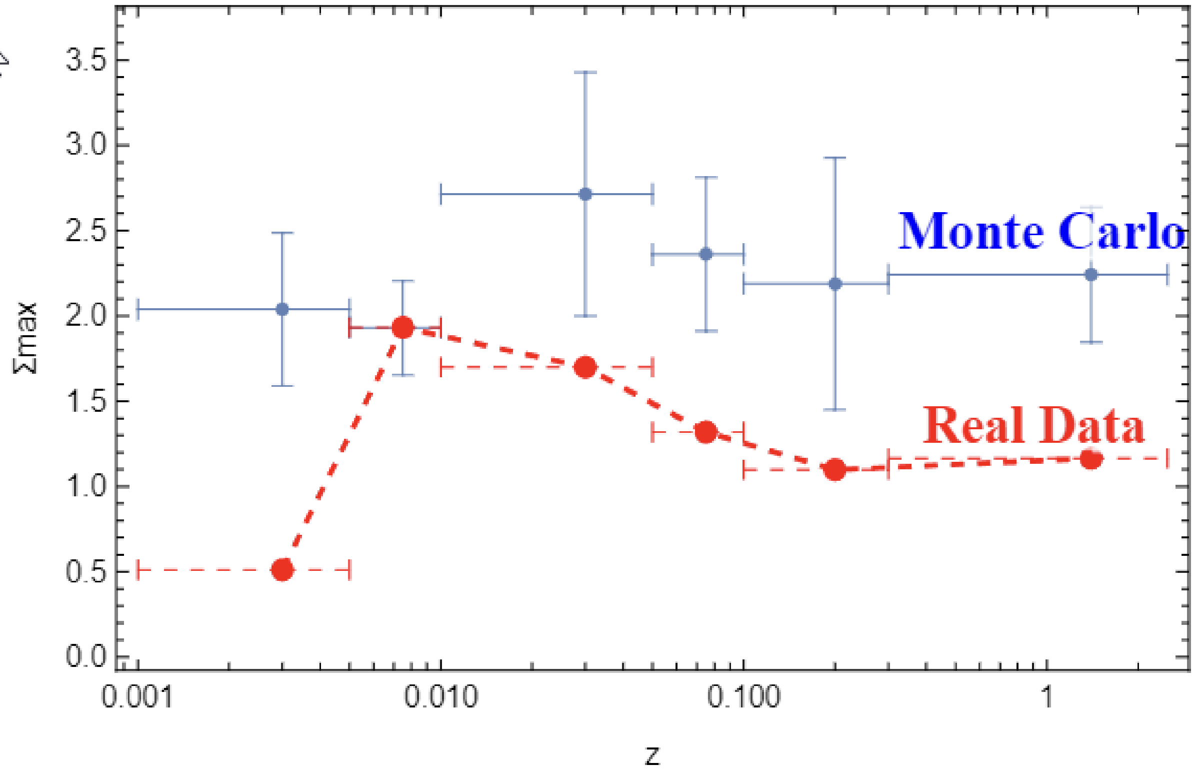
Standardized SnIa absolute magnitudes of Pantheon+.

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:

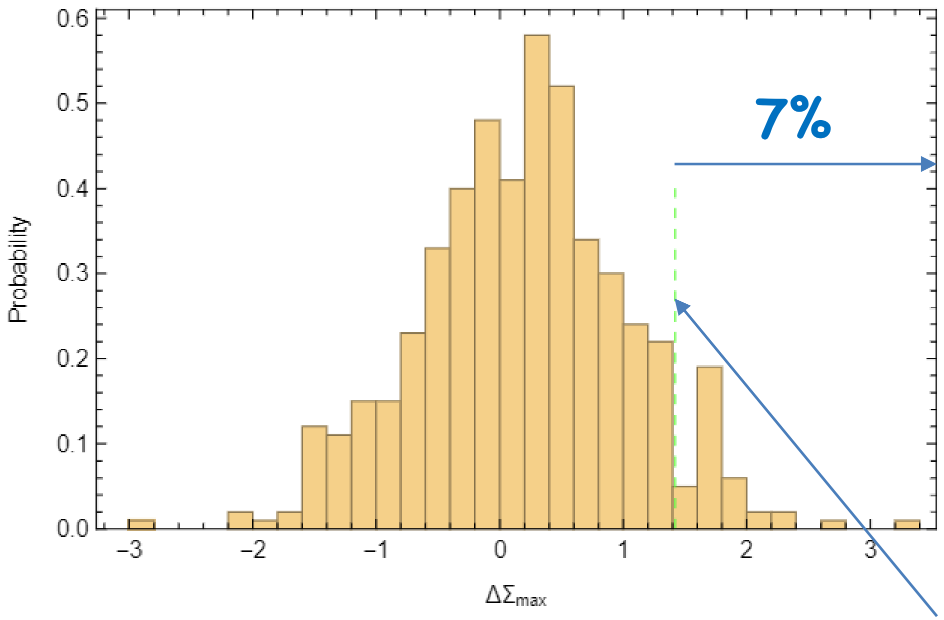
$$\Sigma \equiv \frac{|M_N - M_S|}{\sqrt{\sigma_N^2 + \sigma_S^2}}$$

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?

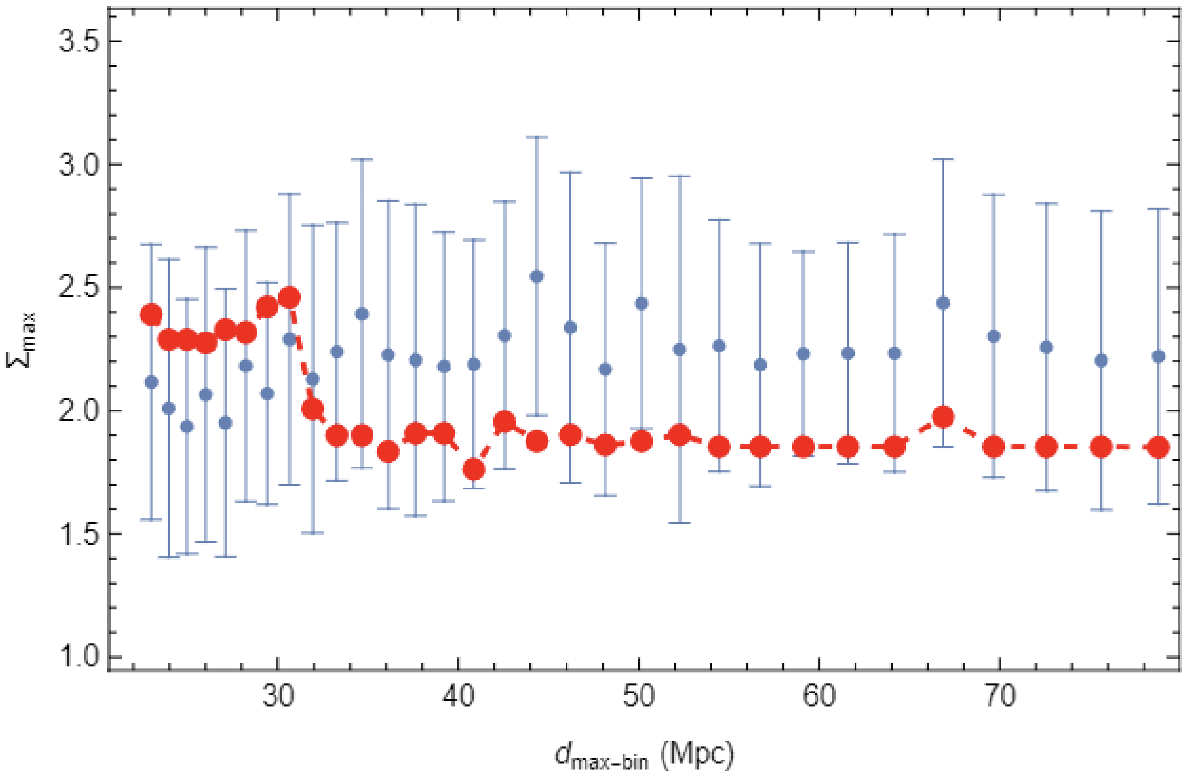


Real data 1->2 bin

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

Sudden changes appear of anisotropy level appear at low redshift bins

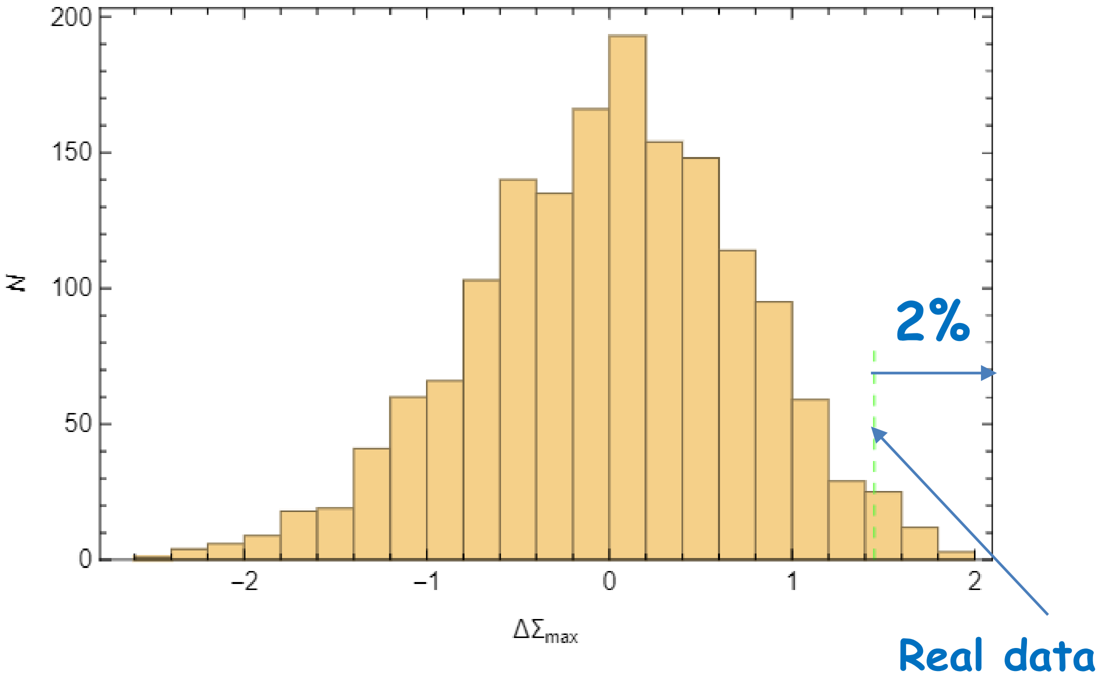
Comparison of SH0ES M-anisotropy with isotropic Monte-Carlo samples.



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?



Main Points / Conclusion

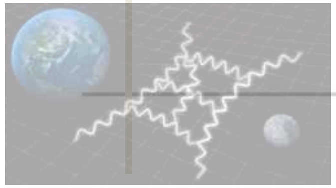
There are three main classes of observational problems (tensions) of the standard cosmological model (ΛCDM): The Hubble tension, the perturbation growth tension and the presence of horizon scale cosmic dipoles.

Viable early and late approaches to the Hubble tension appear to require the existence of an abrupt transition event either before t_{rec} or at z~2 orduring the last 150Myrs.

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

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

Measuring H(z) with the 2022 Pantheon+ dataset



from SnIa in Cepheid hosts at z<0.01

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

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

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

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

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

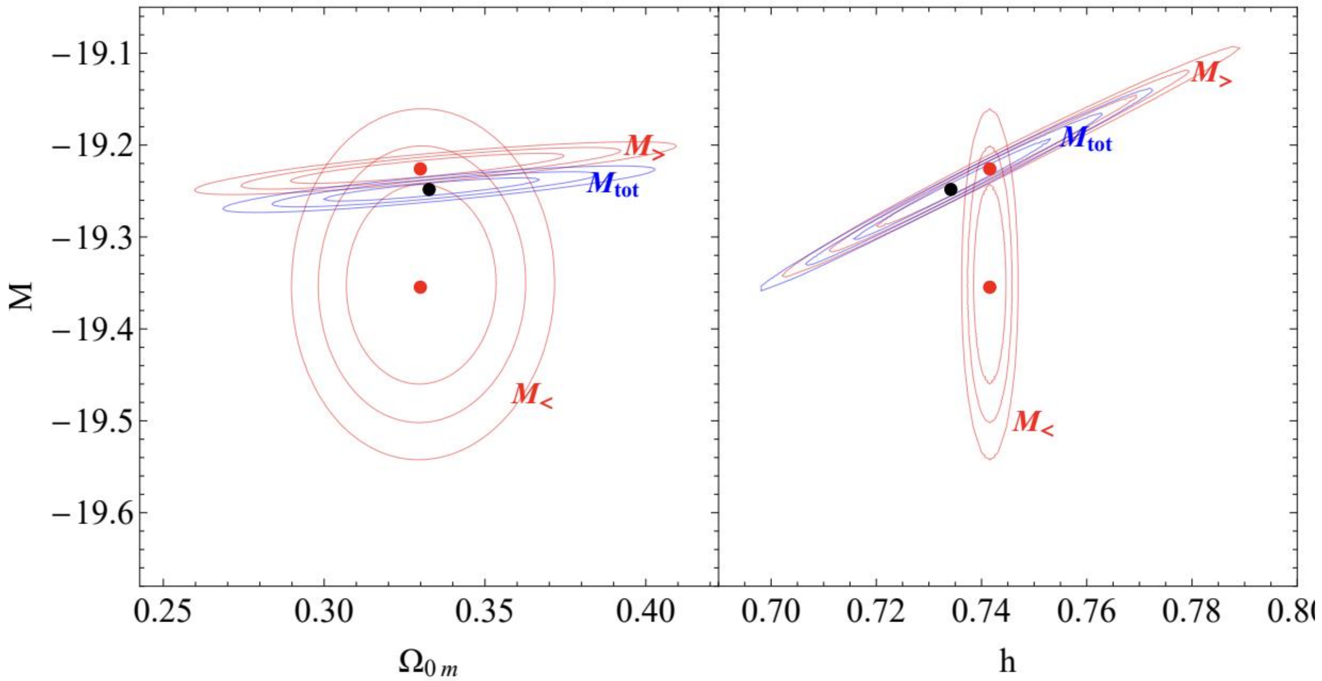
Degeneracy between H_0 and M

(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.

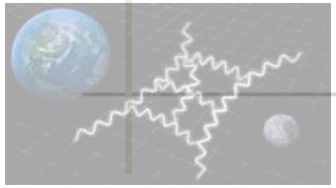
$$Q_i''' = \begin{cases} m_{Bi} - M_< - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} < \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ m_{Bi} - M_> - \mu_i^{\text{Cepheid}} & \text{iff } \mu_{i,S} > \mu_{crit}, \text{and } i \in \text{Cepheid hosts} \\ 0 & \text{iff } z_i < 0.01 \\ m_{Bi} - M_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



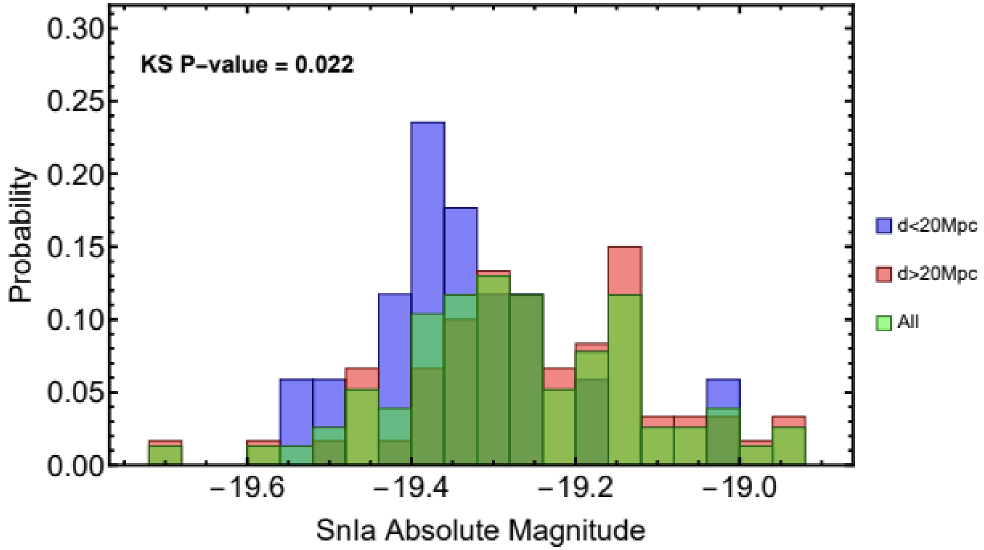
$$\begin{aligned} M_< &= -19.355 \pm 0.05, \\ M_> &= -19.226 \pm 0.03, \\ h &= 0.74 \pm 0.01, \\ \Omega_{0m} &= 0.33 \pm 0.02, \\ d_{crit} &= 19.95 \pm 0.1 Mpc, \end{aligned}$$

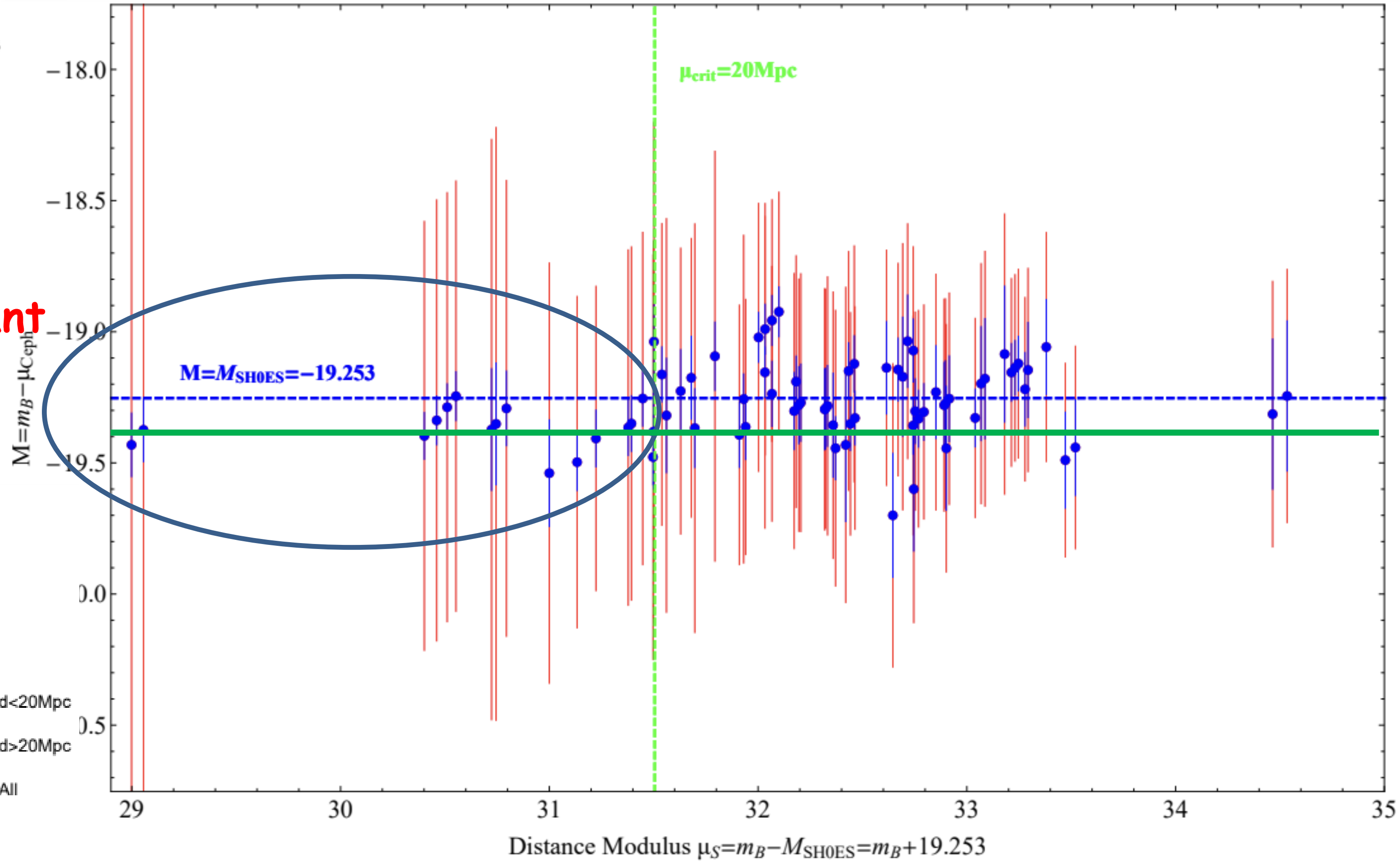
The tension between $M_<$ and $M_>$ is smaller but a significant part of it remains

SnIa luminosities in Pantheon+



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

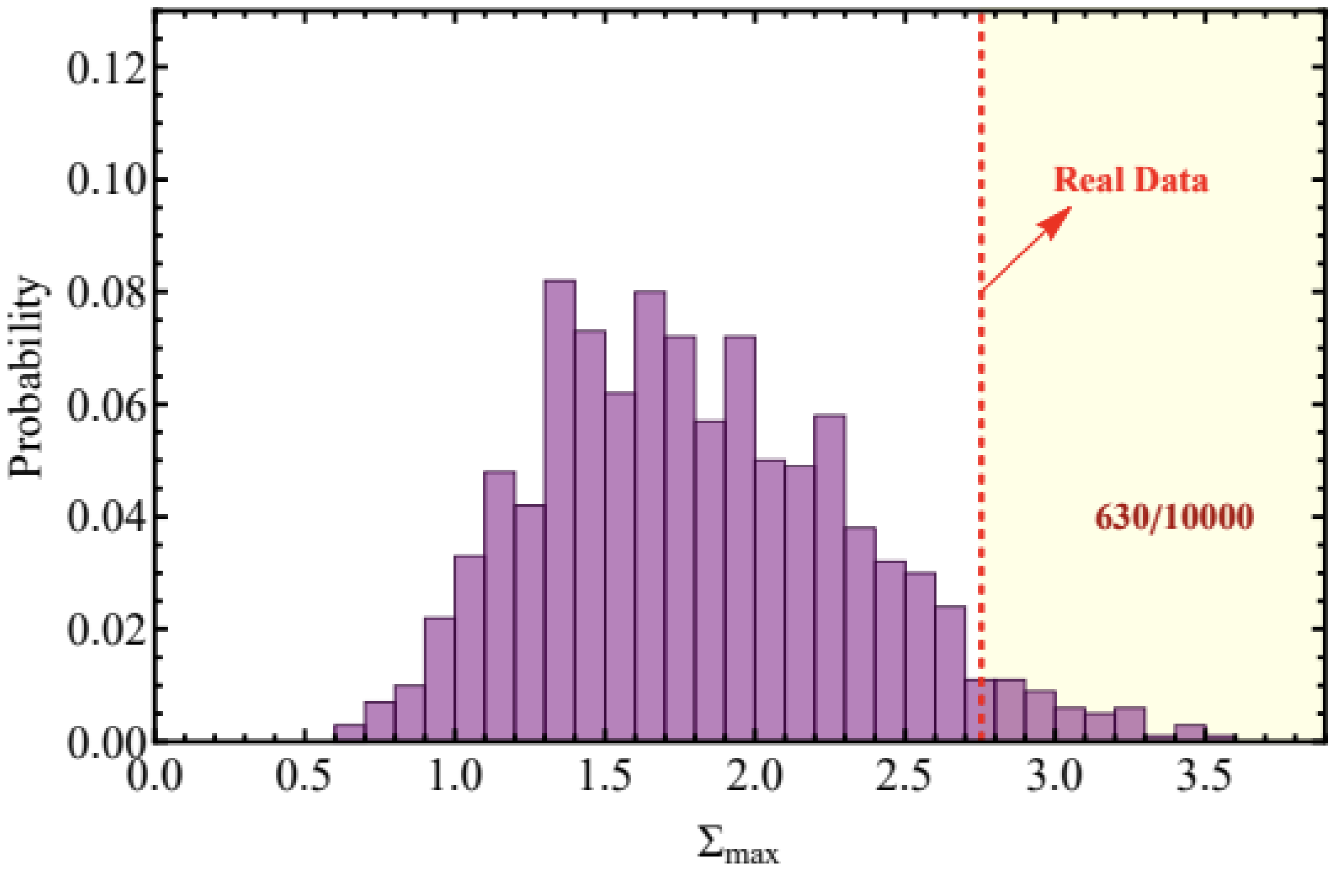




Q: How often could this happen by chance?

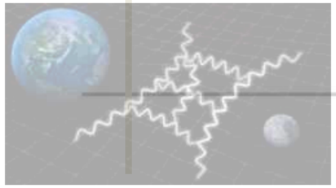
Monte Carlo Simulation

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:

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

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

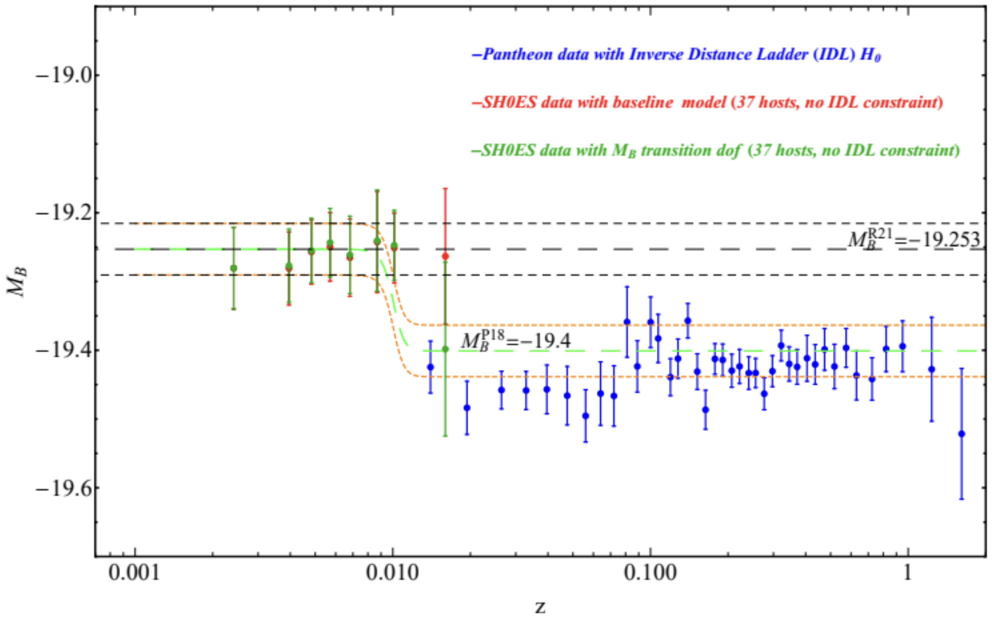
A Reanalysis of the Latest SH0ES Data for H_0: Effects of New Degrees of Freedom on the Hubble Tension

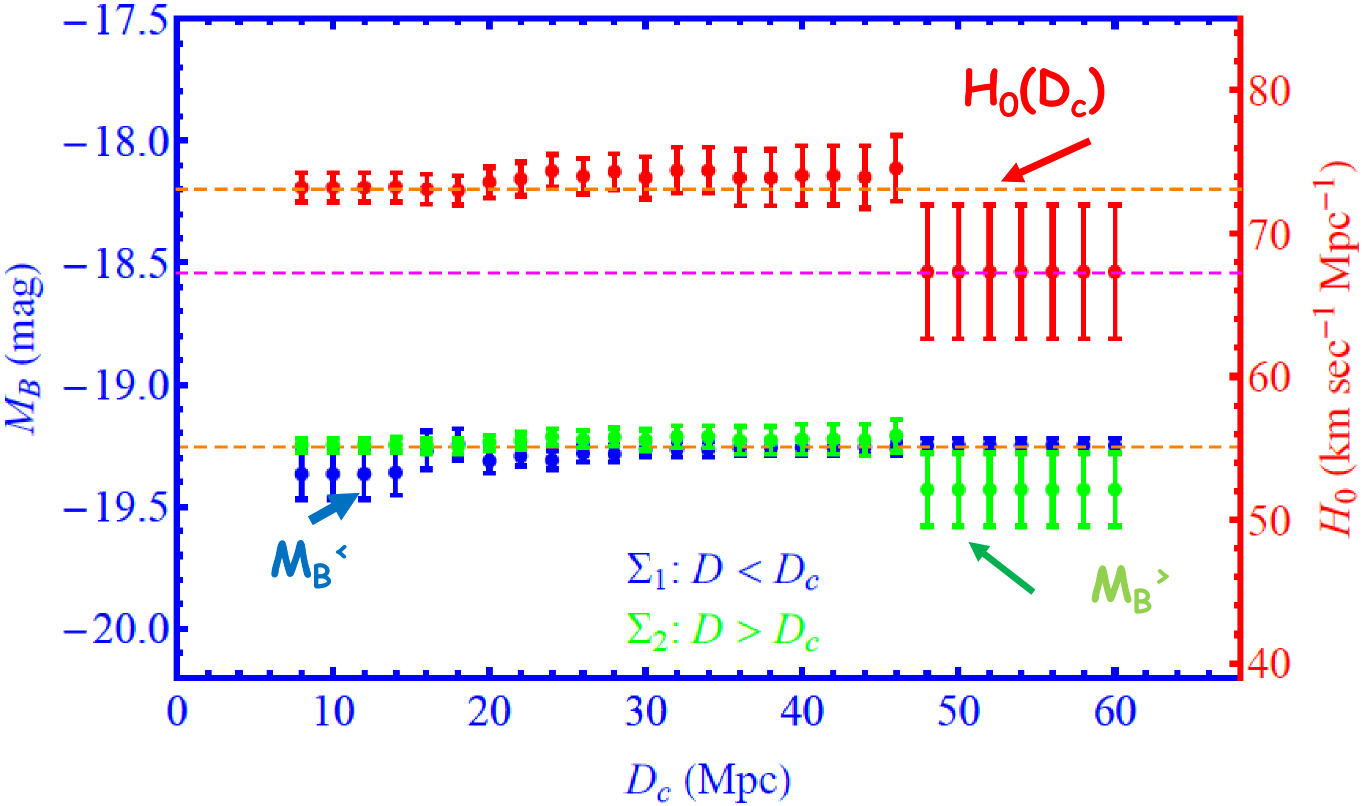
Leandros Perivolaropoulos (Ioannina U.), Foteini Skara (Ioannina U.) (Aug 23, 2022)

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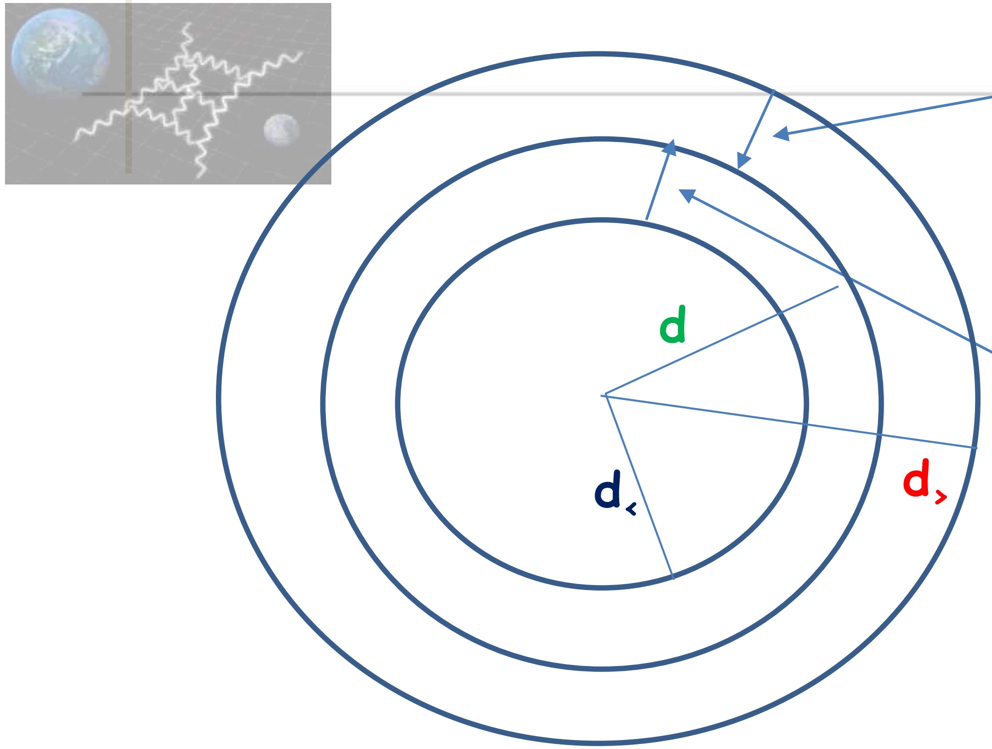
Spontaneous transition of the best fit value of H_0 when a transition at D_c~50Mpc is allowed.

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



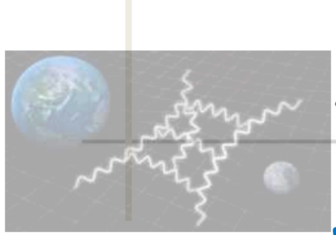
$\Delta z_>$: Random peculiar velocities in outer shell compared to a given shell at redshift z.
If $\Delta z_> < 0$ then the outer shell galaxies are incorrectly projected on the z shell leading to smaller distance estimate than the true distance $d_>$.

$\Delta z_<$: Random peculiar velocities in inner shell compared to a given shell at redshift z.
If $\Delta z_> > 0$ then the outer shell galaxies are incorrectly projected on the z shell leading to larger distance estimate than the true distance $d_>$.

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

More galaxies at higher distances are incorrectly projected to lower distance in the Hubble diagram due to peculiar velocities!
Thus: $d-d_{\Lambda CDM}(z)>0$ for $z<0.01$ where the effect is important.

The volumetric redshift bias



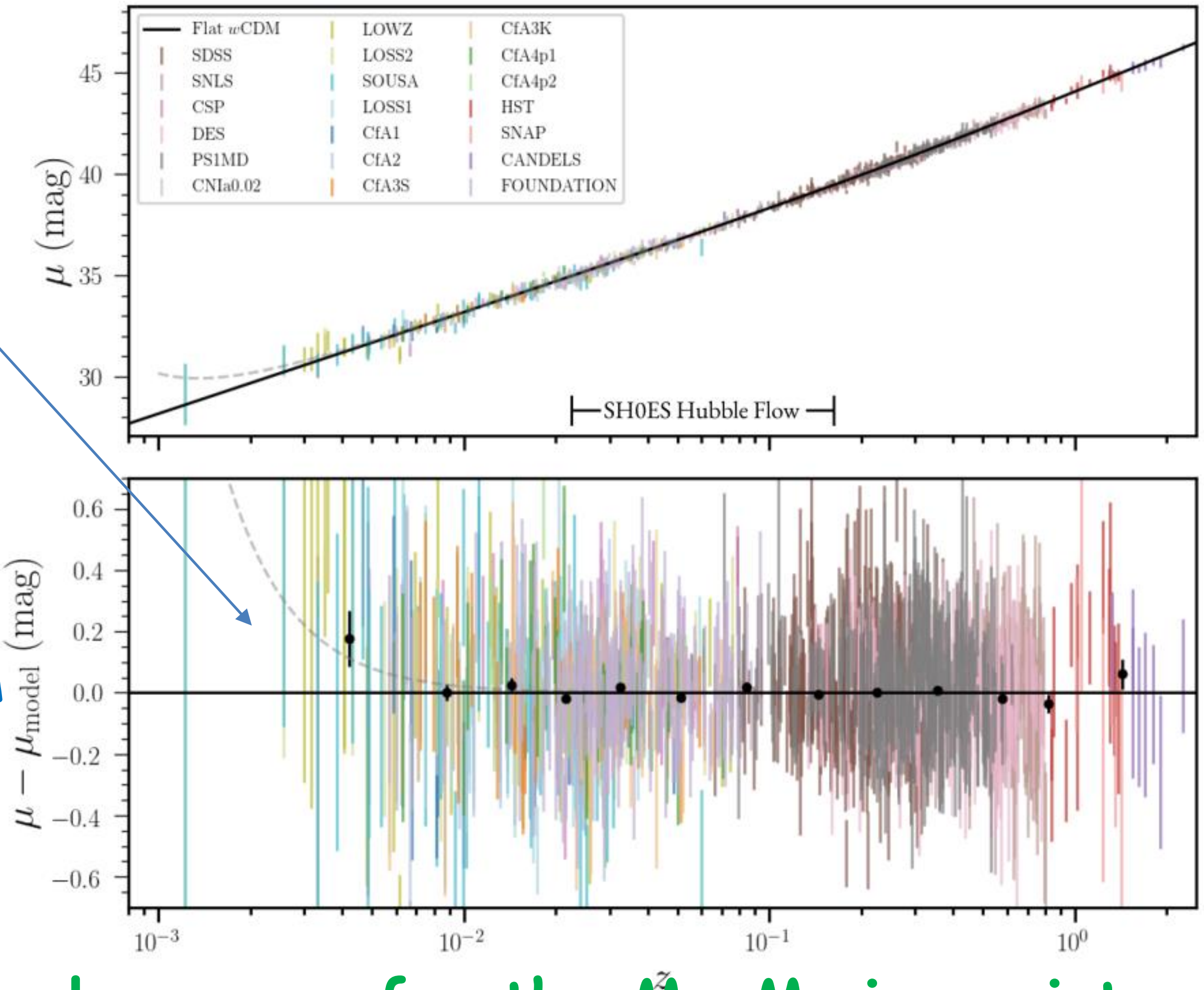
The volumetric redshift bias is dominant at low redshifts where the volume difference is more prominent.

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:

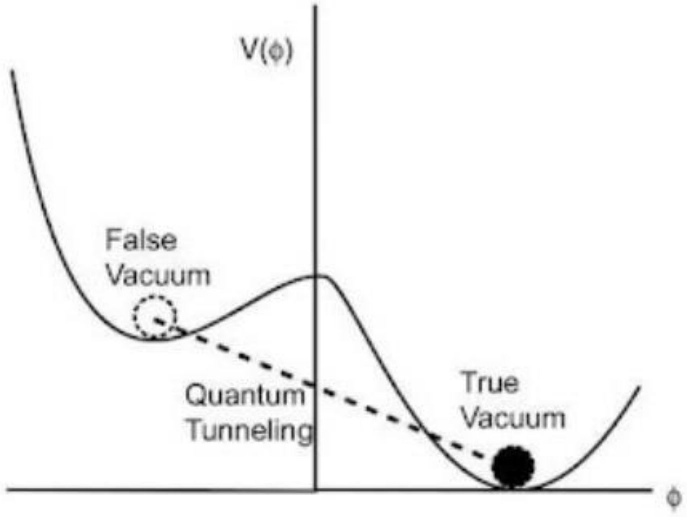
$$\Sigma(\mu_{crit}) \equiv \frac{|M_> - M_<|}{\sqrt{\sigma_{M_>}^2 + \sigma_{M_<}^2}}$$

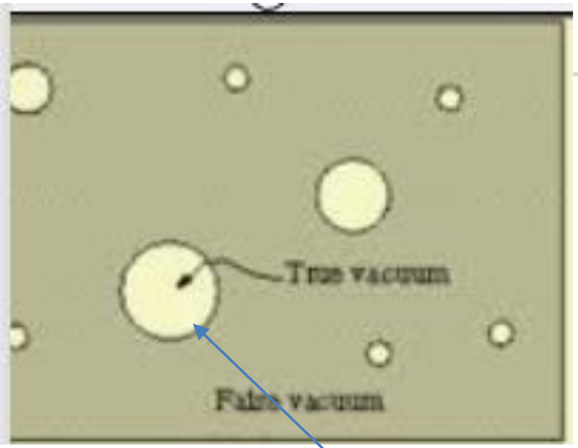
$$\mu_{crit} = 5log(d_{crit}/Mpc) + 25.$$

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?

Generic Distance Scale





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

Predicted bubble scale is close to favored scale of transition

Scale of True Vacuum Bubbles:

$$R_b = \delta / H_0$$

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

O(1) Planck mass

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

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

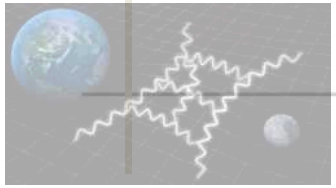
R_b~15Mpc

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



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]

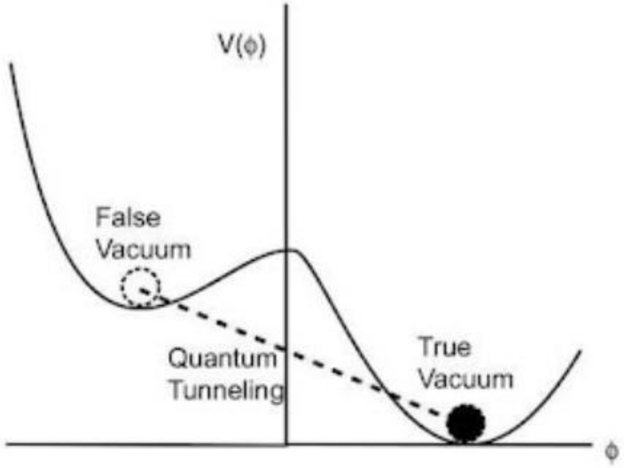
Scalar Tensor Transition:

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

v: potential minimum

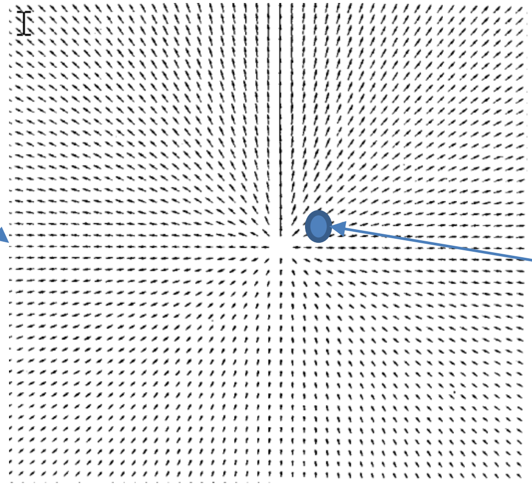
$$\frac{1}{\sqrt{8\pi G_N}}=M_{\rm Pl}\sim10^{19}{\rm GeV},$$

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

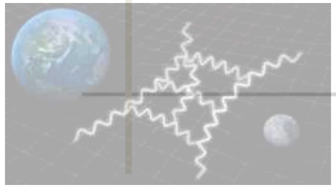
Alternative: Topological Quintessence

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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