Delta Gravity: A possible explanation to *Dark Energy* from modified General Relativity

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Standard Cosmological Model: ΛCDM

- Based on General Relativity:

$$S = \int \left[\frac{1}{2\kappa} (R - 2\Lambda) + \mathcal{L}_{\mathrm{M}} \right] \sqrt{-g}\, \mathrm{d}^4 x$$

- Einstein Field Equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Standard Cosmological Model: ΛCDM

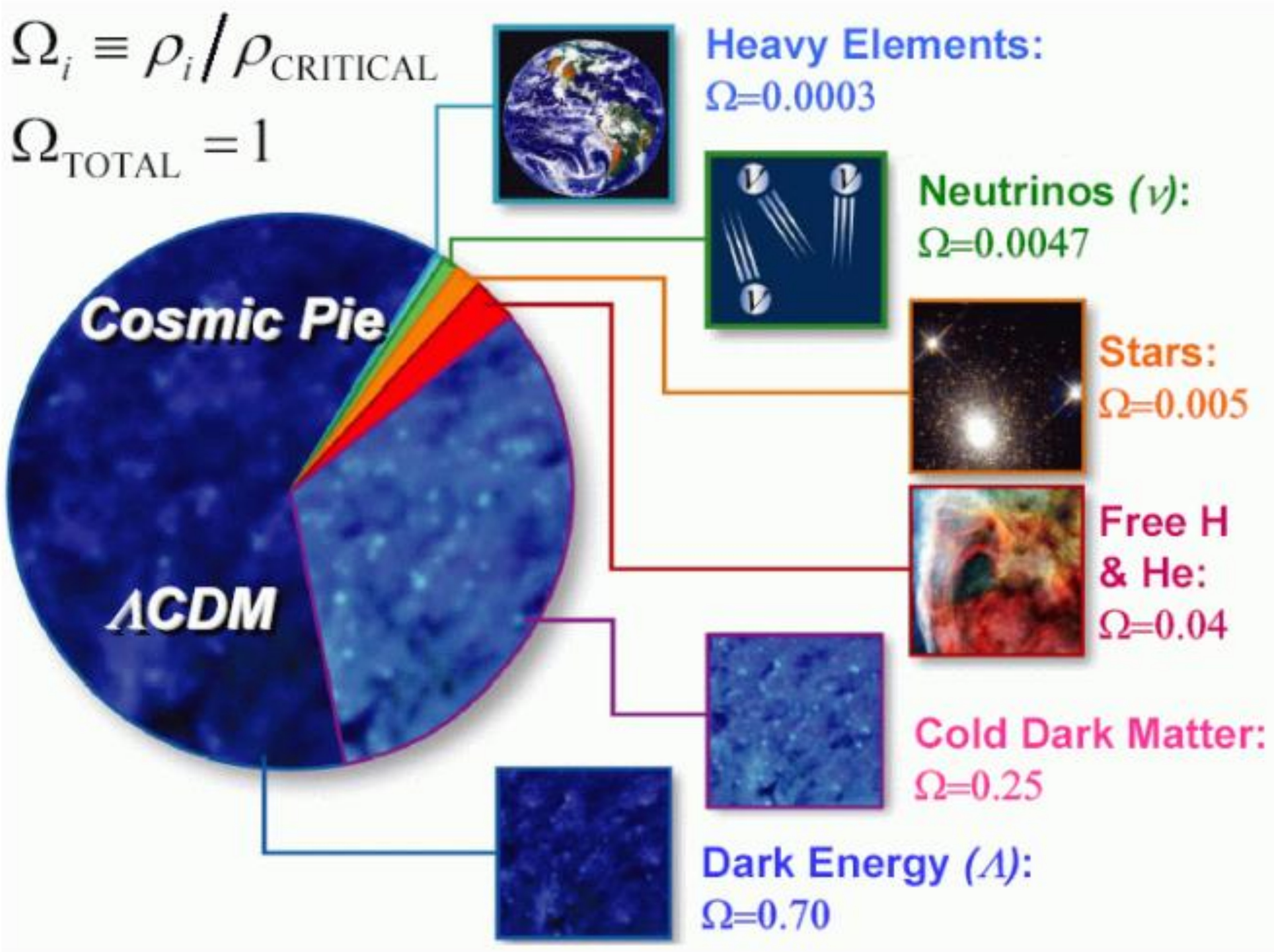
- Friedmann equations:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

Standard cosmological model: ΛCDM

- Λ + CDM
  - Dark Energy
  - Dark Matter
- Observational evidence?



How well does it work?

- Hubble constant from SN-Ia vs Planck
- Is this correct?

The Last H_0 measurement, 2018

NEW PARALLAXES OF GALACTIC CEPHEIDS FROM SPATIALLY SCANNING THE HUBBLE SPACE TELESCOPE: IMPLICATIONS FOR THE HUBBLE CONSTANT

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	73.45±1.66 km/(Mpc s)	Parallax measurements of galactic cepheids; the value suggests a discrepancy with CMB measurements at the 3.7σ level. The uncertainty is expected to be reduced to below 1% with the final release of the Gaia catalog.

From CMB data, Planck 2015

Table 4. Parameter 68 % confidence limits for the base ΛCDM model from *Planck* CMB power spectra, in combination with lensing reconstruction ("lensing") and external data ("ext", BAO+JLA+H_0). While we see no evidence that systematic effects in polarization are biasing parameters in the base ΛCDM model, a conservative choice would be to use the parameter values listed in Column 3 (i.e., for TT+lowP+lensing). Nuisance parameters are not listed here for brevity, but can be found in the extensive tables on the Planck Legacy Archive, http://pla.esac.esa.int/pla; however, the last three parameters listed here give a summary measure of the total foreground amplitude (in μK^2) at $\ell = 2000$ for the three high-ℓ temperature power spectra used by the likelihood. In all cases the helium mass fraction used is predicted by BBN from the baryon abundance (posterior mean $Y_P \approx 0.2453$, with theoretical uncertainties in the BBN predictions dominating over the *Planck* error on $\Omega_b h^2$). The Hubble constant is given in units of km s^{-1} Mpc^{-1}, while r_* is in Mpc and wavenumbers are i

error: 3.7 σ

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP 68			+lensing+ext mits
			2227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
			1184 ± 0.00			
			4106 ± 0.000			
			.067 ± 0.01			
			.064 ± 0.02			
n_s	655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.004			
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086

Planck 2015
67.81±0.92 Mpc/(Km s)

SN-Ia 2018
73.45±1.66 Mpc/(Km s)

Delta Gravity

- We obtain the new action by extension of the **new symmetry** in EH action

$$S_0 = \int d^4x\sqrt{-g}\left(\frac{R}{2\kappa} + L_M\right) \Rightarrow S = \int d^4x\sqrt{-g}\left(\frac{R}{2\kappa} + L_M - \frac{\kappa_2}{2\kappa}\left(G^{\alpha\beta} - \kappa T^{\alpha\beta}\right)\tilde{g}_{\alpha\beta} + \kappa_2\tilde{L}_M\right)$$

- Delta Gauge Theories (extension by the new symmetry).
- $g_{uv} \rightarrow \tilde{g}_{uv}$
- We have two new kind of fields:
  - **Delta Matter**
  - **Delta Radiation**

¿?

$\tilde{\delta}$

new symmetry

https://arxiv.org/pdf/1210.6107.pdf

Equations of motion:

$$\tilde{\delta}\left[G_{\mu\nu}\right] \Rightarrow \begin{aligned} G^{\mu\nu} &= \kappa T^{\mu\nu} \\ F^{(\mu\nu)(\alpha\beta)\rho\lambda} D_\rho D_\lambda \tilde{g}_{\alpha\beta} + \frac{1}{2} g^{\mu\nu} R^{\alpha\beta} \tilde{g}_{\alpha\beta} - \frac{1}{2} \tilde{g}^{\mu\nu} R &= \kappa \tilde{T}^{\mu\nu}. \end{aligned}$$

Conservation rules:

$$\tilde{\delta}\left(D_\nu T^{\mu\nu}\right) = 0. \Rightarrow \begin{aligned} D_\nu T^{\mu\nu} &= 0 \\ D_\nu \tilde{T}^{\mu\nu} &= \frac{1}{2} T^{\alpha\beta} D^\mu \tilde{g}_{\alpha\beta} - \frac{1}{2} T^{\mu\beta} D_\beta \tilde{g}^\alpha_\alpha + D_\beta (\tilde{g}^\beta_\alpha T^{\alpha\mu}). \end{aligned}$$

Some useful equations

- The effective metric is:

$$g_{\mu\nu}dx^\mu dx^\nu = -c^2dt^2 + R^2(t)\left(dx^2+dy^2+dz^2\right),$$
$$\tilde{g}_{\mu\nu}dx^\mu dx^\nu = -3F_a(t)c^2dt^2 + F_a(t)R^2(t)\left(dx^2+dy^2+dz^2\right).$$

$$\mathbf{g}_{\mu\nu} = g_{\mu\nu} + \tilde{g}_{\mu\nu} = -c^2(1+3\,F_a(t))dt^2 + (1+\ F_a(t))R^2(t)\left(dx^2+dy^2+dz^2\right)$$

- The normalized effective scale factor :

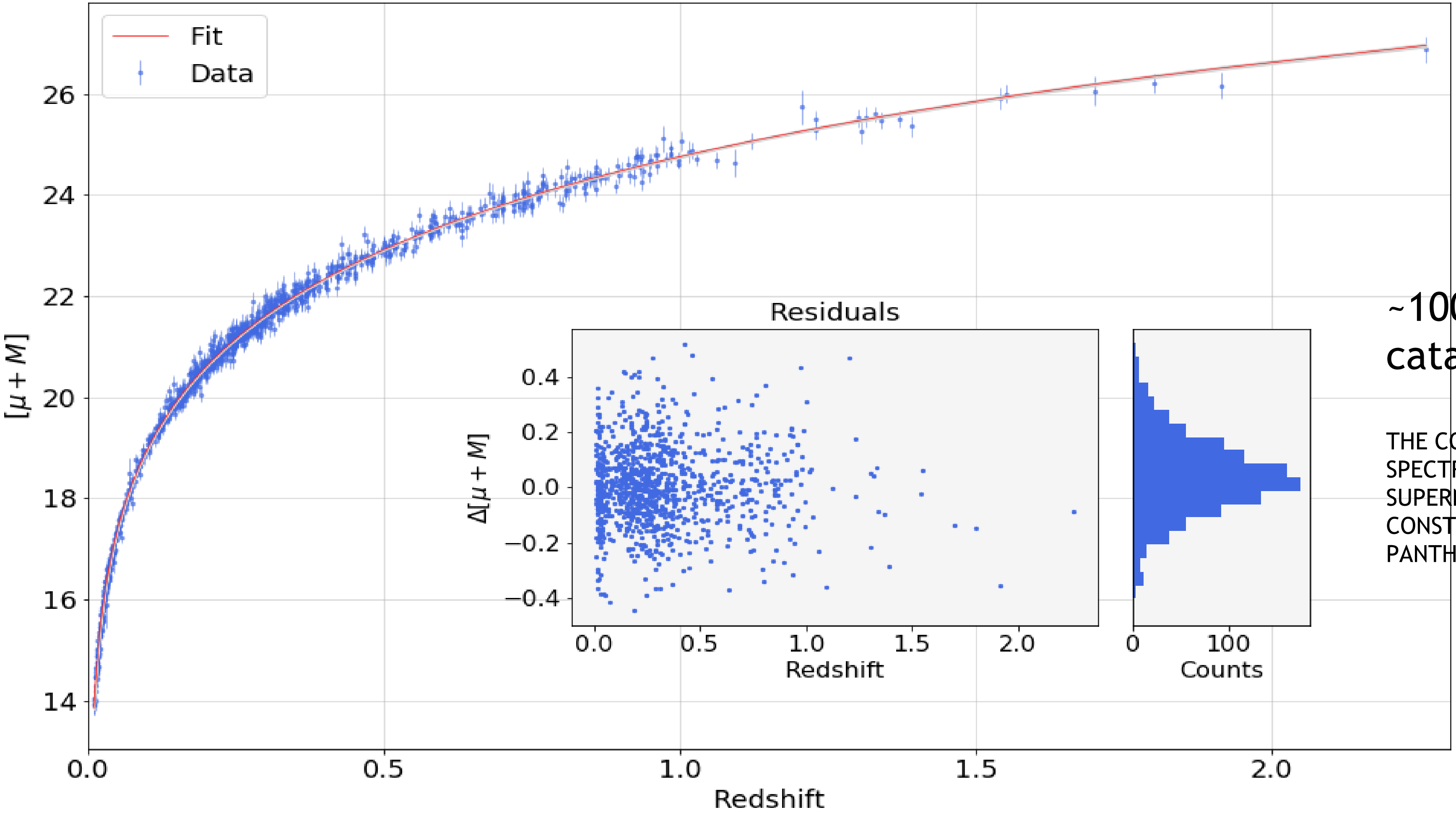
- To fit SN data:

$$Y_{DG}(L_2,C,Y) = \frac{Y}{R_{DG}(t_0)}\sqrt{\frac{1-L_2\frac{Y}{3}\sqrt{Y+C}}{1-L_2Y\sqrt{Y+C}}}$$

$$\mu = m - M = 5\log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right) \qquad d_L(z,L_2,C) = c\frac{(1+z)\sqrt{C}}{100\sqrt{h^2\Omega_{r0}}}\int_{Y(t_1)}^{1}\frac{Y}{\sqrt{Y+C}}\frac{dY}{Y_{DG}(t)}$$

¿Why Delta Gravity?

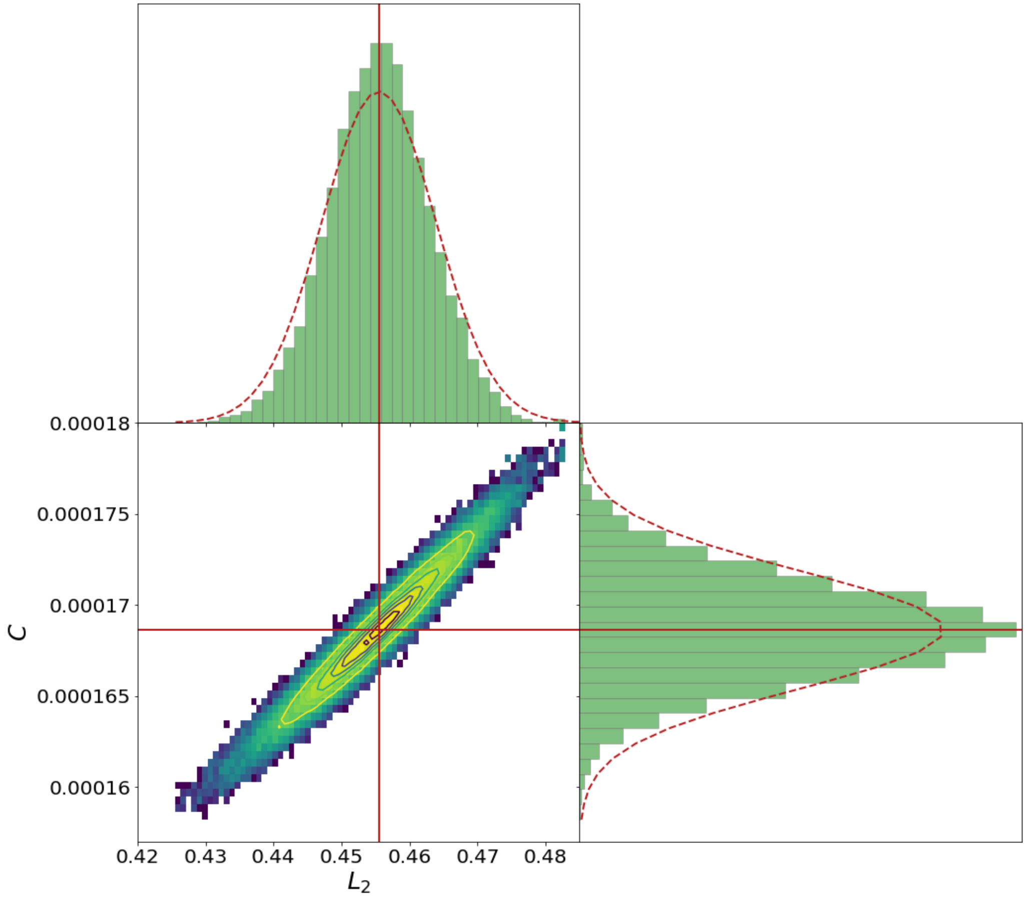
- **DG PREDICTS ACCELERATING UNIVERSE WITHOUT DARK ENERGY!!!!!!**



~1000 SN data. Most updated catalog, 2018 (Scolnic & Jones)

THE COMPLETE LIGHT-CURVE SAMPLE OF SPECTROSCOPICALLY CONFIRMED TYPE IA SUPERNOVAE FROM PAN-STARRS1 AND COSMOLOGICAL CONSTRAINTS FROM THE COMBINED PANTHEON SAMPLE

Results from MCMC (Markov Chain Monte Carlo):



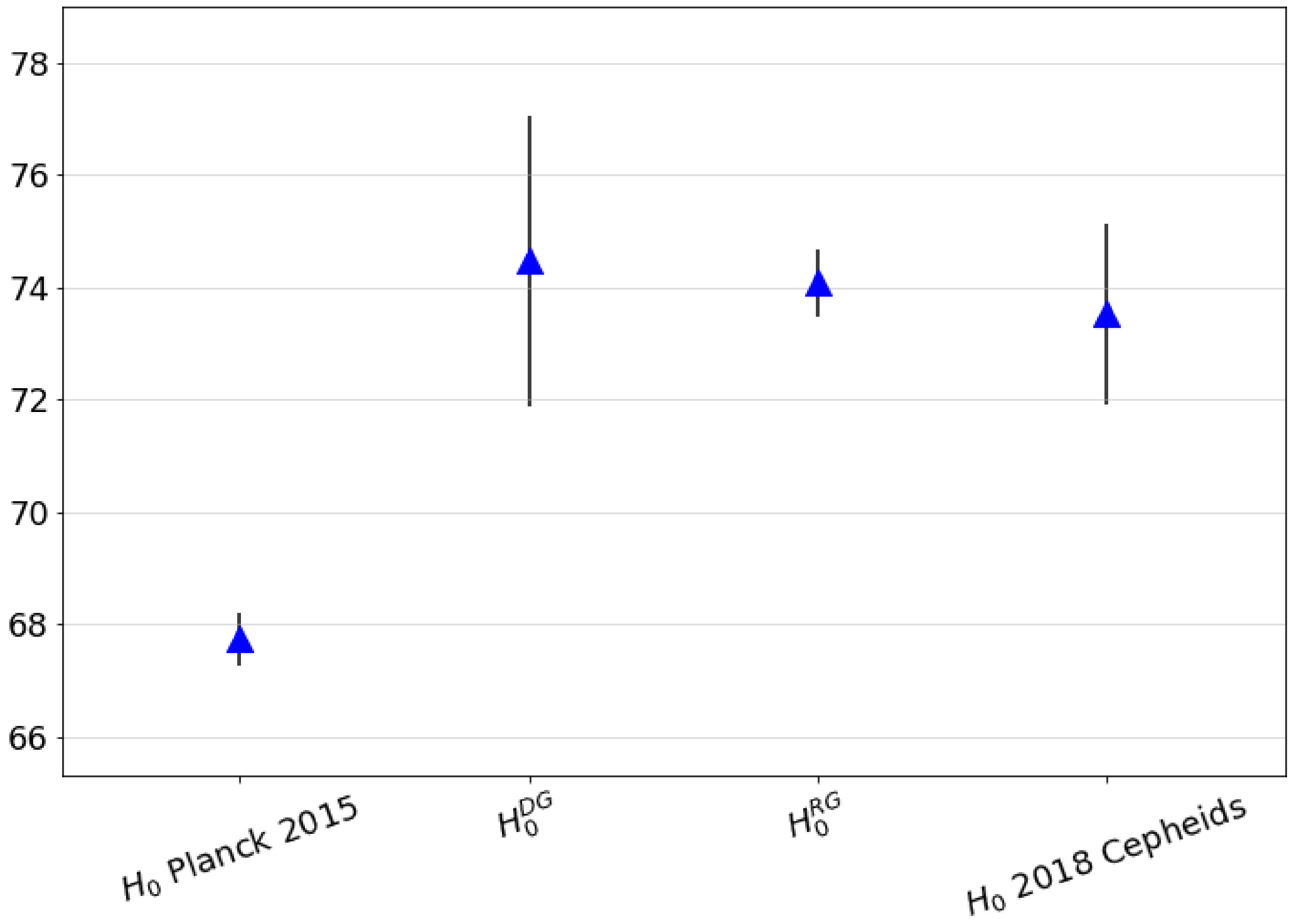
WITH THE TWO FREE PARAMETERS FITTED:

L_2 and C

WE CAN PREDICT COSMOLICAL INTERESTING VALUES, LIKE H_0

Good H_0 Value in Delta Gravity

- H_0 is higher than LCDM with Planck data
- **It is in concordance with the last independent-model measurement**
- The **acceleration is naturally produced from the geometry of the Model**, and it is not imposed using a constant, like Λ



This is not the end...

- We are working on obtain the CMB Power Spectrum
- We want to fit the CMB and compare with SN-Ia data

Thanks!

https://arxiv.org/abs/1704.02888

$\tilde{\delta}$ Gravity, $\tilde{\delta}$ matter and the accelerated expansion of the Universe

Jorge Alfaro, Pablo González

https://arxiv.org/abs/1811.05828

An accelerating Universe without Λ in concordance with the last H_0 measured value

Jorge Alfaro, Marco San Martin, Joaquin Sureda