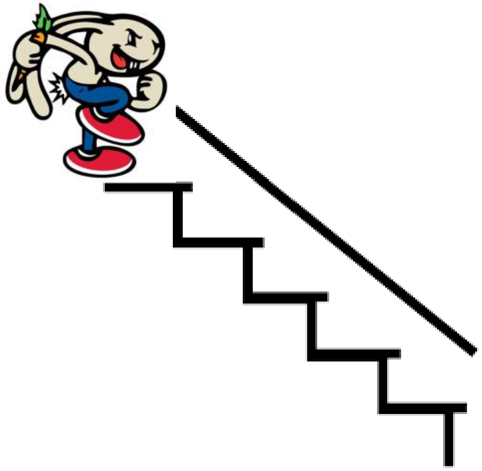
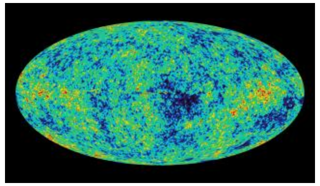
Going down the rabbit hole of the Hubble constant tension





Biagio De Simone, 4^{th} Summit on EDSU 2022, 9th November 2022

A world-wide collaboration for a universe-wide tension

On the Hubble Constant Tension in the SNe Ia Pantheon Sample

M. G. Dainotti[1,2,3], B. De Simone[4], T. Schiavone[5,6], G. Montani[7,8], E. Rinaldi[9,10], and G. Lambiase[4]

Published 2021 May 17 •

The Astrophysical Journal, Volume 912, Number 2

Citation M. G. Dainotti *et al* 2021 *ApJ* **912** 150

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On the Evolution of the Hubble Constant with the SNe Ia Pantheon Sample and Baryon Acoustic Oscillations: A Feasibility Study for GRB-Cosmology in 2030

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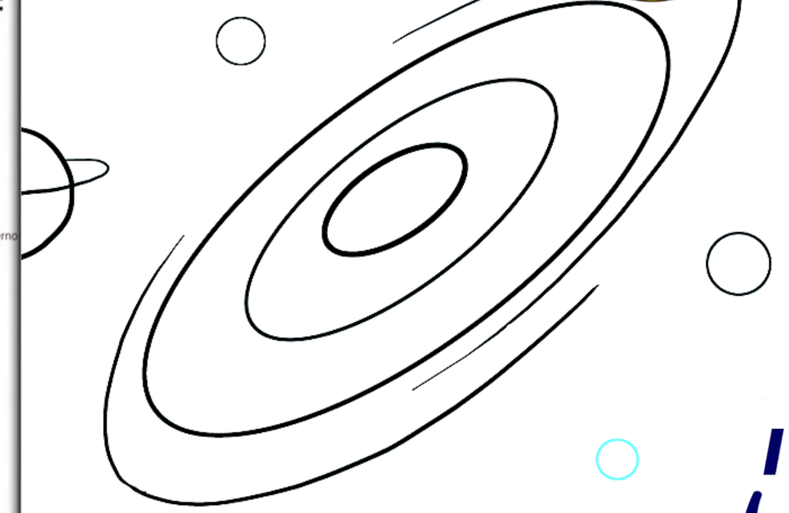
Academic Editors: Elena Moretti and Francesco Longo

Galaxies **2022**, *10*(1), 24; **https://doi.org/10.3390/galaxies10010024**

Received: 5 November 2021 / Revised: 21 January 2022 / Accepted: 25 January 2022 / Published: 29 January 2022

(This article belongs to the Special Issue Gamma-Ray Burst Science in 2030)



M.G. Dainotti, B. De Simone, T. Schiavone, G. Montani, E. Rinaldi, G. Lambiase, M. Bogdan, and S. Ugale

The H_0 tension (in a nutshell)

IMAGINE THE UNIVERSE LIKE A PIE, EXTENDED TO THE INFINITY…

…COSMOLOGY IS LIKE TASTING DIFFERENT SLICES OF THIS PIE AND, FROM THE TASTE, GUESS THE INGREDIENTS AND THE RECIPE

The H_0 tension (in a nutshell)

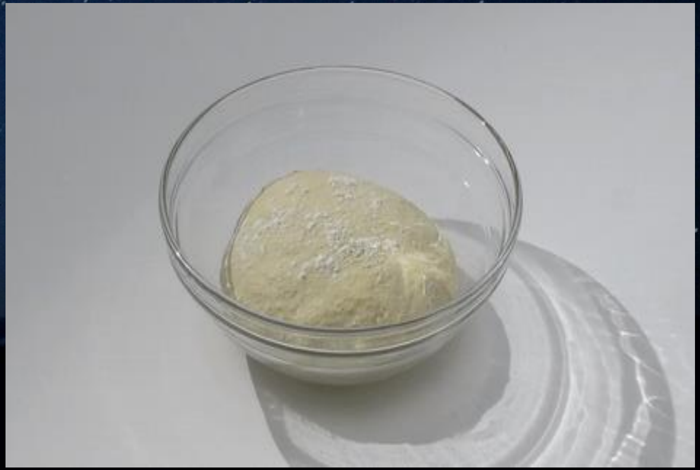
NOW IMAGINE THE FOLLOWING: YOU TASTE A SLICE OF PIE NEARBY AND A SLICE OF PIE TAKEN FROM THE FURTHEST POINT OBSERVABLE

AND

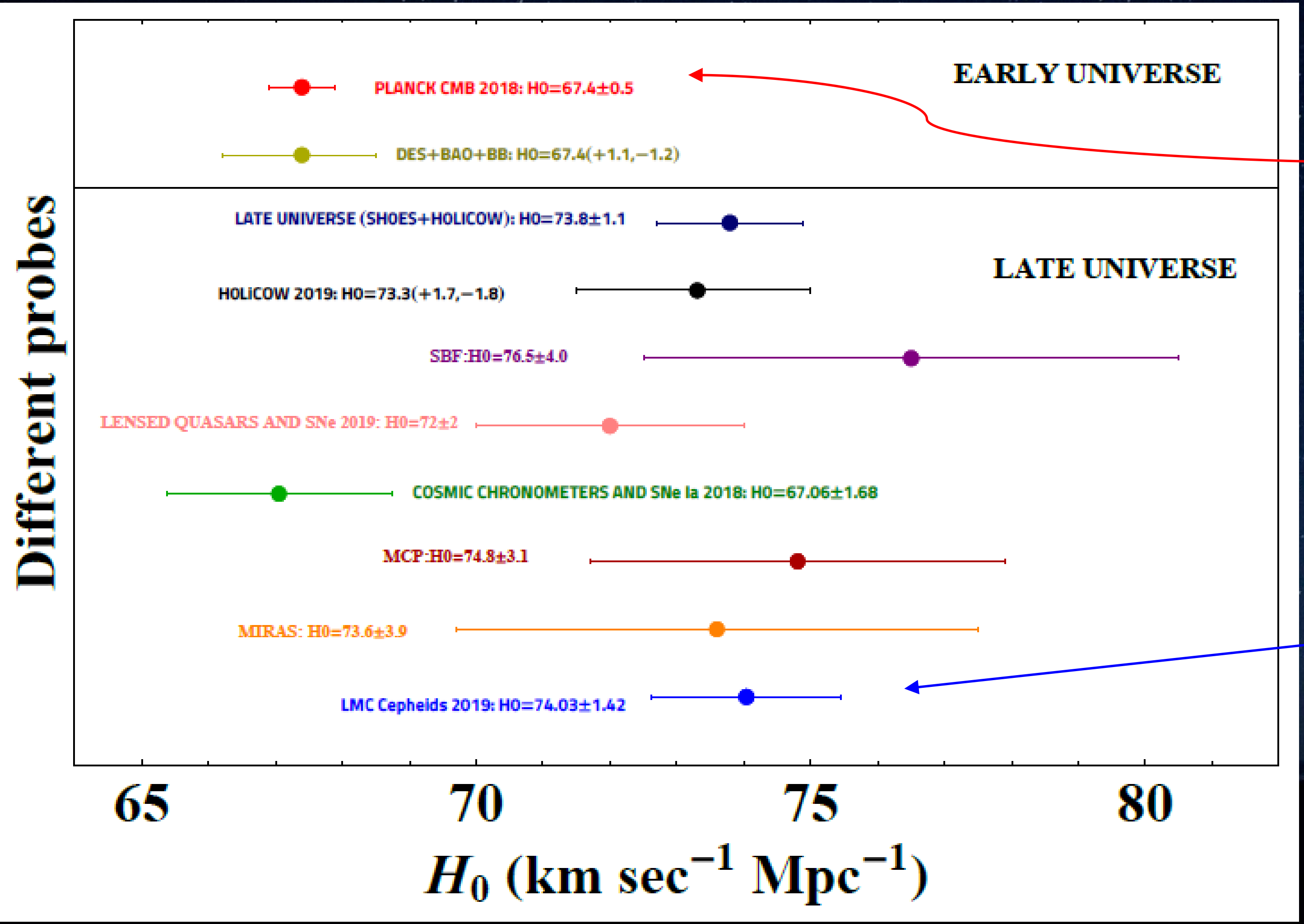
YOU DISCOVER THAT THE GROWTH TREND OF THE NEARBY DOUGH IS MUCH DIFFERENT FROM THE GROWTH TREND OF THE FURTHEST DOUGH

Nearby slice dough

Far away slice dough



Well, that's the H_0 tension!



«H_0 TENSION»: the discrepancy in 4.4σ between the local value of the Hubble constant H_0 based on Supernovae Ia and Cepheids and the value of H_0 referred to the Cosmic Microwave Background (CMB)

The Hubble constant

THE HUBBLE CONSTANT H_0 IS A PARAMETER THAT DESCRIBES THE RATE OF EXPANSION OF THE UNIVERSE

$$H_0 \stackrel{\text{def}}{=} \frac{R'(t_0)}{R(t_0)}$$

→ $R(t_0)$ SCALE FACTOR OBTAINED FROM THE METRIC AND COMPUTED IN THE PRESENT t_0

FOR SMALL REDSHIFT VALUES (FOR SMALL COSMOLOGICAL DISTANCES) H_0 CAN BE USED IN THE HUBBLE'S LAW

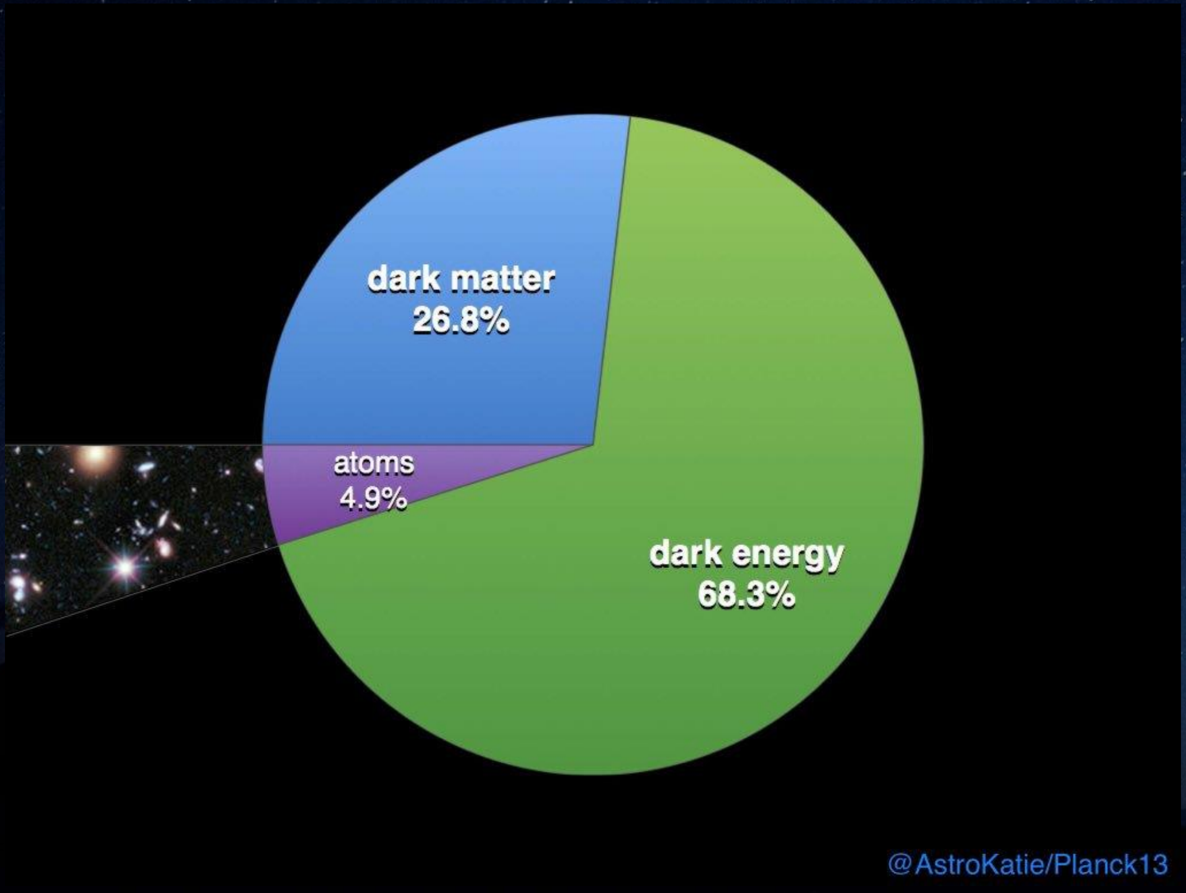
$$v = H_0 * D$$

VELOCITY OF THE ESCAPING GALAXY ← v

D → DISTANCE OF THE ESCAPING GALAXY

Why is that a “problem”?

THE MOST ACCREDITED MODEL TO DESCRIBE THE STRUCTURE OF THE UNIVERSE IS THE **ΛCDM MODEL**



ΛCDM MODEL IS BASED ON THE PRESENCE OF THE «**COLD DARK MATTER**» (CDM) AND THE «COSMOLOGICAL CONSTANT» **Λ**

THIS MODEL IS ABLE TO DESCRIBE THE OBSERVATION OF THE *UNIVERSE WITH ACCELERATED EXPANSION*… BUT IN THIS MODEL H_0 IS CONSIDERED AS A CONSTANT.

The ingredients “to taste” (1)

IN THIS ANALYSIS WE FOCUSED ON A PARTICULAR CLASS OF INGREDIENTS, NAMELY THE SUPERNOVAE TYPE Ia

EXPLOSION OF A WHITE DWARF IN A BINARY SYSTEM WHERE IT INTERACTS WITH THE COMPANION STAR

IF THE COMPANION STAR EXPANDS ENOUGH THEN ITS MATERIALS STARTS TO FALL ON THE WHITE DWARF, THUS INCREASING ITS MASS AND WHEN THE CHANDRASEKHAR LIMIT IS REACHED, $[M \sim 1{,}4\ M_{\odot}$ (SOLAR MASSES)] THEN THE COMBUSTION OF CARBON AND OXYGEN IS IGNITED, CAUSING A BRIGHT EXPLOSION

IMPORTANT FEATURE: THE PEAK LUMINOSITY OF SUPERNOVAE Ia IS FIXED

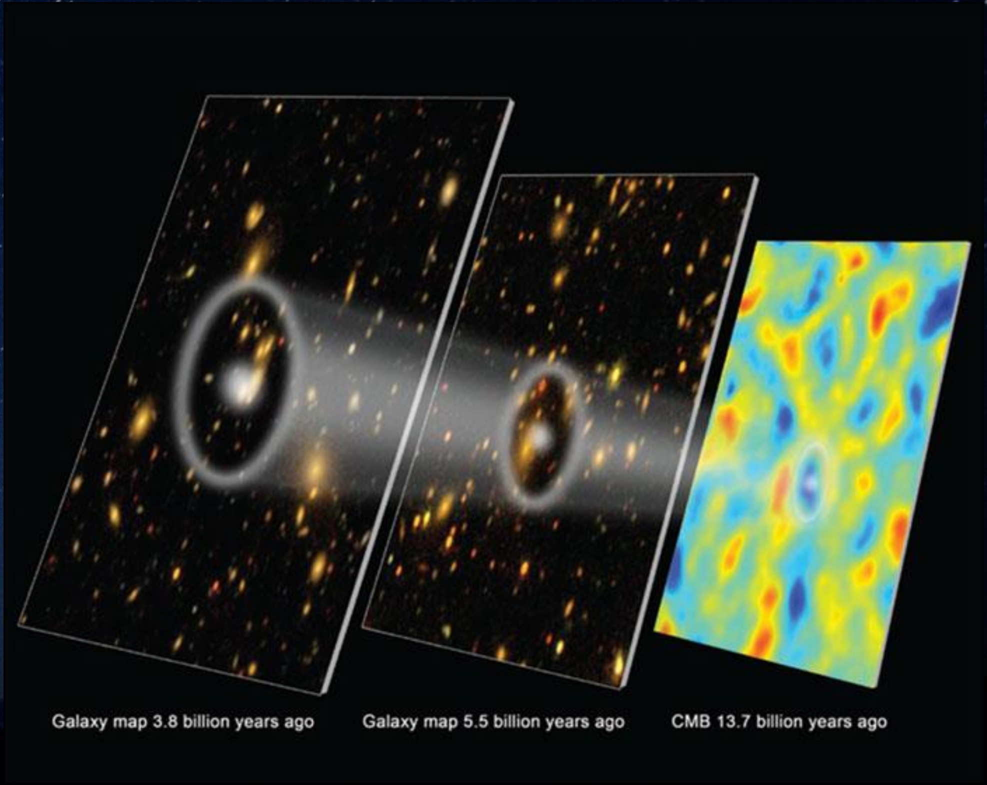
The ingredients “to taste” (2)

A FURTHER GEOMETRICAL PROBE WAS USED TO TEST THE COSMOLOGICAL MODELS AND THE HUBBLE TENSION

- BARYON ACOUSTIC OSCILLATIONS (BAOs) ARE A TRACK OF THE DISTRIBUTION OF MATTER AT THE EPOCH OF RECOMBINATION (380’000 YEARS AFTER THE BIG BANG)

- WHEN MATTER STARTED TO COOL DOWN DURING THE RECOMBINATION, THE GRAVITY PUSH FOUND NO OBSTACLE SINCE NO PRESSURE GIVEN BY THE HEATING OF MATTER WAS PRESENT. THUS, A MARK IN THE MATTER DISTRIBUTION IN THE UNIVERSE WAS SET AND A SERIES OF «BUBBLES» WAS CREATED

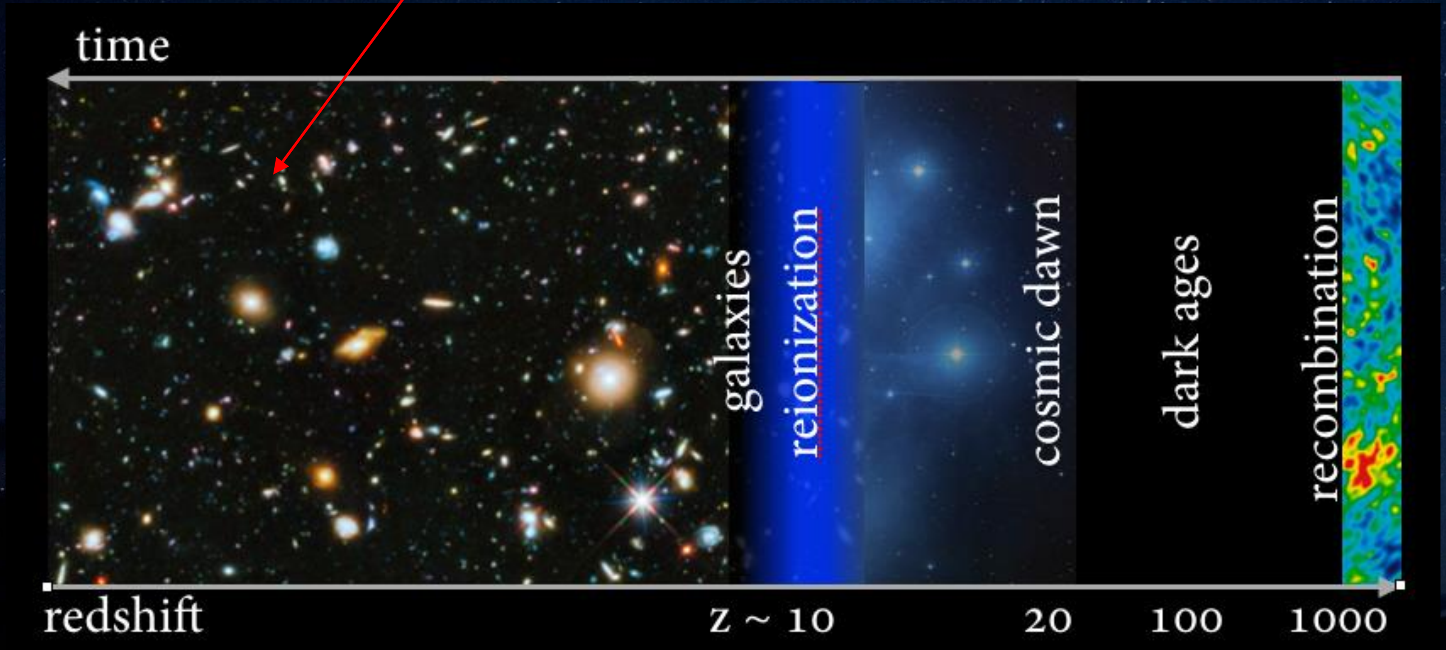
- ON THE BOUNDARIES OF THESE BUBBLES, WE CAN OBSERVE THE CLUSTERING OF GALAXIES (GEOMETRICAL PROBE FOR COSMOLOGICAL MODELS)



Slicing our local pie

FOR OUR PURPOSES WE BASE OUR ANALYSIS ON THE **PANTHEON SAMPLE** (SCOLNIC ET AL. 2018), A COLLECTION OF 1048 SPECTROSCOPICALLY CONFIRMED SUPERNOVAE Ia WITH A REDSHIFT RANGE OF $0 < z < 2.26$

WE DIVIDE THE PANTHEON SAMPLE IN 3 BINS ORDERED IN REDSHIFT + 1 BAO PER BIN



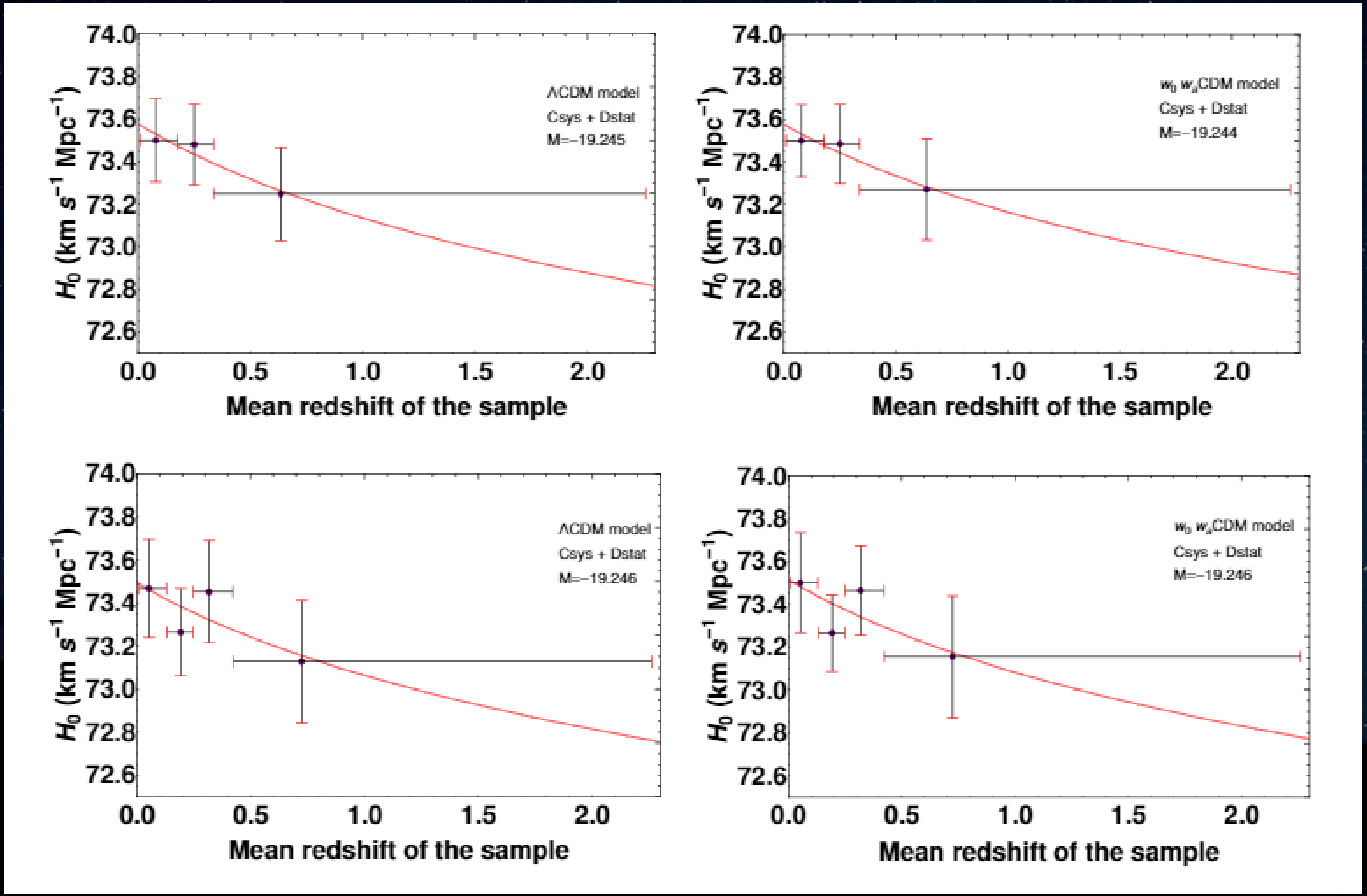
TO INVESTIGATE THE «H_0 TENSION» PROBLEM THE IDEA IS TO FIT THE GIVEN VALUES OF H_0 AND THOSE VALUES SHOULD COME EACH ONE FROM ONE BIN OF SNe Ia ORDERED IN REDSHIFT

$$g(z) = \frac{\widetilde{H}_0}{(1+z)^{\alpha}}$$

α = evolution parameter

$$\widetilde{H}_0 = H_0(z=0)$$

Previous results for ΛCDM model (3, 4 bins)



Dainotti, M.G., De Simone, B., et al., 2021, *On the Hubble constant tension in the SNe Ia Pantheon sample*

Published in «The Astrophysical Journal»

In the previous paper, we left only H_0 as a free parameter to vary. But what about allowing both the parameters H_0 and Ω_{0m} (total density of matter) in the ΛCDM?

We here omit the $w_0 w_a$CDM model results for brevity (compatible with the ΛCDM ones)

Previous results for ΛCDM model (3, 4 bins)

Flat ΛCDM Model, Fixed Ω_{0m}, with Full Covariance Submatrices $\mathcal{C}$							
Bins	$\tilde{H}_0$ (km s^{-1} Mpc^{-1})	α	$\frac{\alpha}{\sigma_\alpha}$	M	H_0 ($z = 11.09$) (km s^{-1} Mpc^{-1})	H_0 ($z = 1100$) (km s^{-1} Mpc^{-1})	% Tension Reduction
3	73.577 ± 0.106	0.009 ± 0.004	2.0	-19.245 ± 0.006	72.000 ± 0.805	69.219 ± 2.159	54%
4	73.493 ± 0.144	0.008 ± 0.006	1.5	-19.246 ± 0.008	71.962 ± 1.049	69.271 ± 2.815	66%
20	73.222 ± 0.262	0.014 ± 0.010	1.3	-19.262 ± 0.014	70.712 ± 1.851	66.386 ± 4.843	68%
40	73.669 ± 0.223	0.016 ± 0.009	1.8	-19.250 ± 0.021	70.778 ± 1.609	65.830 ± 4.170	57%

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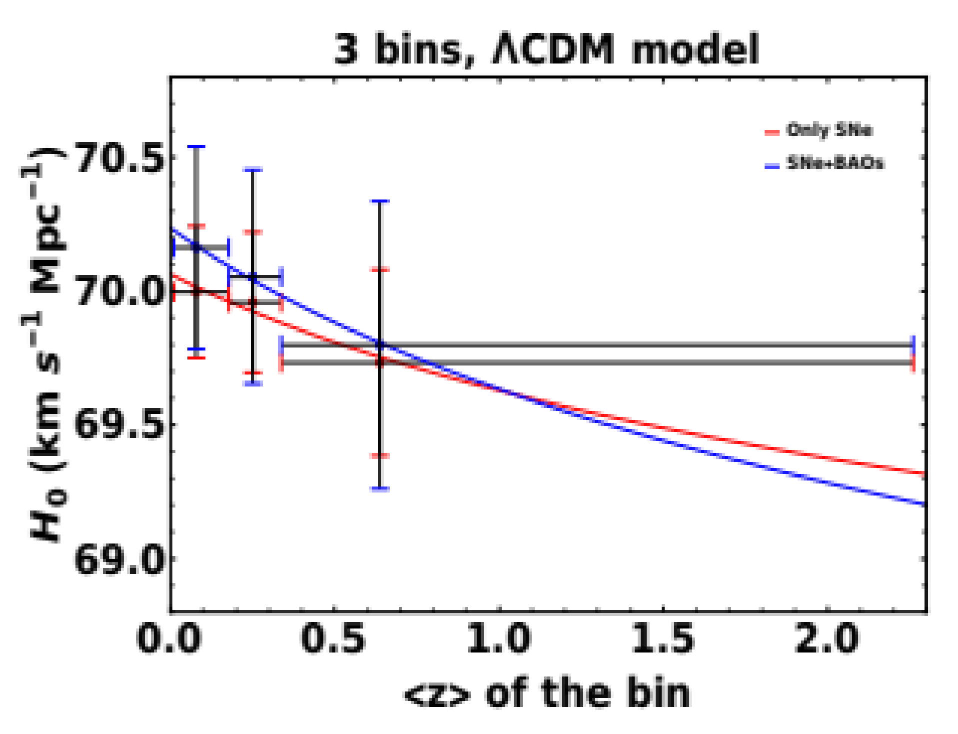
In the previous paper, we left only H_0 as a free parameter to vary. But what about allowing both the parameters H_0 and Ω_{0m} (total density of matter) in the ΛCDM?

And what about the $w_0 w_a$CDM model?

NEW! $H_0(z)$ fitting (3 bins ΛCDM)



Flat ΛCDM model, without BAOs, varying H_0 and Ω_{0m}		
$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
70.093 ± 0.102	0.009 ± 0.004	2.0
Flat ΛCDM model, including BAOs, varying H_0 and Ω_{0m}		
$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
70.084 ± 0.148	0.008 ± 0.006	1.2

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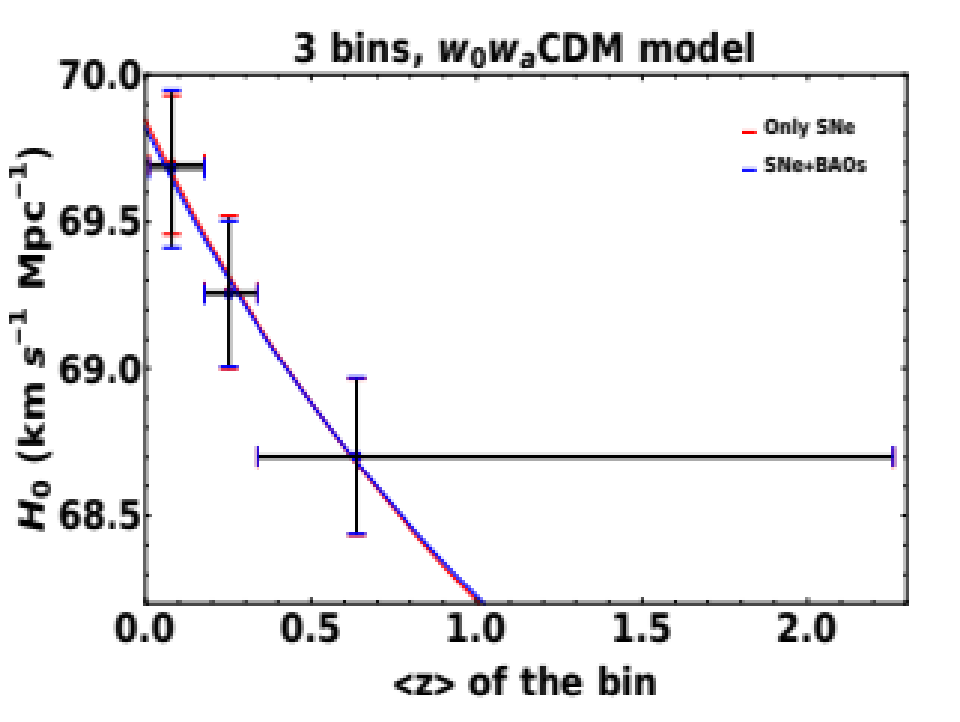
NEW! $H_0(z)$ fitting (3 bins $\mathrm{w_0 w_a}CDM$)



Flat w_0w_aCDM model, without BAOs, varying H_0 and w_a		
$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
69.847 ± 0.119	0.034 ± 0.006	5.7
Flat w_0w_aCDM model, including BAOs, varying H_0 and w_a		
$\mathcal{H}_0$	η	$\frac{\eta}{\sigma_\eta}$
69.821 ± 0.126	0.033 ± 0.005	5.8

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Published in «Galaxies»

Discussion of the results and conclusions

SNe Ia ANALYSIS: POSSIBLE ASTROPHYSICAL EFFECTS

POSSIBLE EXISTENCE OF EVOLUTIONARY EFFECTS ON THE OBSERVABLES LIKE COLOR, STRETCH AND MASS CORRECTION OR STATISTICAL FLUCTUATIONS OR EVEN HIDDEN BIASES (WE ARE NOT GOOD TASTER YET...)

- IN ANOTHER PAPER, NICOLAS ET AL. 2021, IT IS SHOWN THAT THE STRETCH FACTOR SHOWS AN EVOLUTIONARY TREND WITH REDSHIFT AND THIS MAY EXPLAIN OUR OBSERVED TREND.

- NEW DATA ARE NEEDED TO FURTHER EXPLORE OUR RESULTS (EX. PANTHEON+)

Discussion of the results and conclusions

SNe Ia ANALYSIS: POSSIBLE THEORETICAL MODELING

THIS RESULTS CAN BE EXPLAINED THANKS TO DIFFERENT THEORETICAL FRAMEWORKS (THE RECIPE FOR MAKING THE UNIVERSE IS MUCH MORE DIFFERENT THAN WE THOUGHT...)

IF NOT DUE TO RESIDUAL EVOLUTIONARY EFFECTS ON THE OBSERVABLES LIKE COLOR, STRETCH AND MASS CORRECTION OR STATISTICAL FLUCTUATIONS OR EVEN HIDDEN BIASES

- MODIFIED GRAVITY SCENARIO, $G = G(z)$ -> IN MODIFIED THEORIES THERE IS A VARIATION OF THE G CONSTANT (ex. $\mathrm{f}(R)$ THEORIES)

> THE HU-SAWICKI MODEL WITH VARYING Ω_{0m} HAS BEEN ANALYZED BUT THE HUBBLE CONSTANT TENSION WAS PROVEN TO HOLD ANYWAY

THIS «G» MAY NOT BE A CONSTANT, AFTER ALL...

$$F = \frac{Gm_1m_2}{d^2}$$

Thank you for your attention!

IF THERE ARE ANY QUESTIONS, PLEASE FEEL FREE TO ASK

If you want to join us:

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Have a look at our papers:
Dainotti et al. 2021
https://arxiv.org/abs/2103.02117

Have a look at our papers:
Dainotti et al. 2022
https://arxiv.org/pdf/2201.09848.pdf

BACKUP 1 – theory vs. data

FOR EACH BIN OF SUPERNOVAE Ia, A χ^2 TEST IS PERFORMED IN ORDER TO FIND THE BEST VALUE FOR H_0

$$\mu_{obs}^{(SN)} = m_B - M + \alpha x_1 - \beta c + \Delta M + \Delta B$$

$$\mu_{th}^{(SN)}(z, H_0, \dots) = 5 * \log_{10}\left(\frac{d_L(z. H_0, \dots)}{10pc}\right) + 25$$

$$\chi^2 = \sum_i \frac{(\mu_{obs}^i - \mu_{th}^i)^2}{\varepsilon_{\mu obs}^{i\;\;2}}$$

THIS IS THE GENERALIZATION WITH THE COVARIANCE MATRIX C, WHICH INCLUDES STATISTICAL UNCERTAINTIES (DIAGONAL PART) AND SYSTEMATIC CONTRIBUTIONS (OFF-DIAGONAL)

$$\chi_{SNe}^2 = \Delta\mu^T C^{-1} \Delta\mu \qquad \Delta\mu = \mu_{obs}^{(SN)} - \mu_{th}^{(SN)}$$

THE BAOs CONTRIBUTION:

$$\chi^2_{BAO} = \Delta d^T \cdot \mathcal{M}^{-1} \cdot \Delta d \qquad \Delta d = d_z^{obs}(z_i) - d_z^{theo}(z_i) \qquad D_V(z) = \left[\frac{czd_L^2(z)}{(1+z)^2 H(z)}\right]^{1/3}, \qquad d_z(z) = \frac{r_s(z_d)}{D_V(z)}.$$

TOTAL CHI-SQUARE TEST: $\chi^2 = \chi_{SNe}^2 + \chi_{BAOs}^2$

BACKUP 2 – 2D PARAMETERS SPACE

In the previous paper, we left only H_0 as a free parameter to vary.

But what about allowing both the parameters H_0 and Ω_{0m} (total density of matter) in the ΛCDM?

And what happens in the $w_0 w_a$CDM model when we allow both H_0 and w_a to vary?

$$d_L(z.H_0,\dots) = c(1+z)\int_0^{z'} \frac{dz'}{H(z')}$$

(ΛCDM)

$$H(z) = H_0\sqrt{\Omega_{0m}\,(1+z)^3 + \cancel{\Omega_{0r}\,(1+z)^4} + \Omega_{0\Lambda} + \cancel{\Omega_{0k}\,(1+z)^2}}$$

neglected neglected

Ω_{0DE}= dark energy density in the $w_0 w_a CDM$

$(w_0 w_a CDM))$

$$H(z) = H_0\sqrt{\Omega_{0m}\,(1+z)^3 + \Omega_{0DE}\,(1+z)^{3\,(1+w_0+w_a)}\,e^{-3\,w_a\,\frac{z}{1+z}}}$$

BACKUP 3 – SOME CONSIDERATIONS

In this case, the parameter space has been enlarged up to 2-dimensions.

1) In order to have a reliable statistical representation of the Pantheon sample, we focus our analysis on the case of 3 bins, ignoring the subsequent divisions of the Pantheon sample.

2) In the current analysis, it is important to consider the following constraint in the $w_0 w_a CDM$ case,

$$w(z) > -1 \quad \text{where} \quad w(z) = w_0 + w_a * \frac{z}{1+z}$$

is the CPL parametrization

otherwise the analysis would describe a universe which is not expanding (contradicting the main cosmological observations).

BACKUP 4 – Hu-Sawicki model

Testing the Hu & Sawicki (2007) model with $n = 1$

$$S_g = -\frac{1}{2\chi}\int d^4x\sqrt{-g}f(R)$$

$$f(R) = R + F(R) = R - m^2 \frac{c_1 \left(R/m^2\right)^n}{c_2 \left(R/m^2\right)^n + 1}$$

In the case of $F_{R0} = -10^{-7}$ (value of the field at the present time)