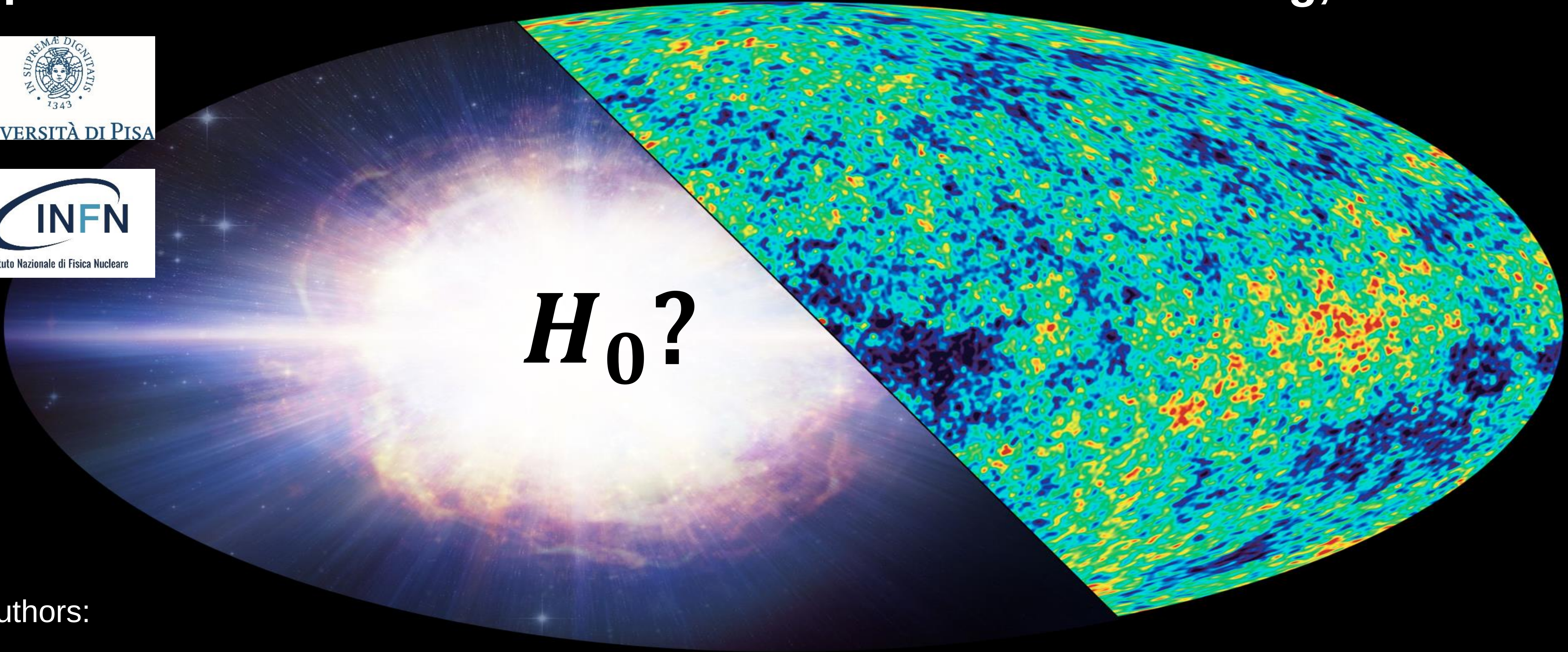
AN INCONSTANT HUBBLE CONSTANT ?

Speaker: Tiziano Schiavone

PLUS Meeting, 24/06/2021



Authors:

Maria Giovanna Dainotti, Biagio De Simone, Tiziano Schiavone, Giovanni Montani, Enrico Rinaldi, Gaetano Lambiase

This talk is based on the paper by Dainotti et al. (2021), ApJ 912, 150 (arXiv:2103.02117)

Authors: M. G. Dainotti, B. De Simone, T. Schiavone, G. Montani, E. Rinaldi, G. Lambiase

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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]

[1] National Astronomical Observatory of Japan, 2 Chome-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; maria.dainotti@nao.ac.jp
[2] The Graduate University for Advanced Studies, SOKENDAI, Shonankokusaimura, Hayama, Miura District, Kanagawa 240-0193, Japan
[3] Space Science Institute, Boulder, CO, USA
[4] Department of Physics "E.R. Caianiello," University of Salerno, Via Giovanni Paolo II, 132, I-84084 Fisciano (Salerno), Italy
[5] Department of Physics "E. Fermi," University of Pisa, Polo Fibonacci, Largo B. Pontecorvo 3, I-56127 Pisa, Italy
[6] INFN, Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Polo Fibonacci, Largo B. Pontecorvo 3, I-56127 Pisa, Italy
[7] ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Via E. Fermi 45, I-00044 Frascati (Rome), Italy
[8] Physics Department, "Sapienza" University of Rome, P.le Aldo Moro 5, I-00185 Rome, Italy
[9] Physics Department, University of Michigan, Ann Arbor, MI 48109, USA
[10] Interdisciplinary Theoretical & Mathematical Science Program, RIKEN (iTHEMS), 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
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Abstract

The Hubble constant (H_0) tension between Type Ia supernovae (SNe Ia) and Planck measurements ranges from 4 to 6σ. To investigate this tension, we estimate H_0 in the ΛCDM and $w_0 w_a$CDM (cold dark matter) models by dividing the Pantheon sample, the largest compilation of SNe Ia, into 3, 4, 20, and 40 bins. We fit the extracted H_0 values with a function mimicking the redshift evolution: $g(z) = H_0(z) = \tilde{H}_0/(1+z)^{\alpha}$, where α indicates an evolutionary parameter and $\tilde{H}_0 = H_0$ at $z = 0$. We set the absolute magnitude of SNe Ia so that $H_0 =$

STANDARD COSMOLOGICAL MODEL ΛCDM

COSMOLOGICAL CONSTANT Λ + COLD DARK MATTER

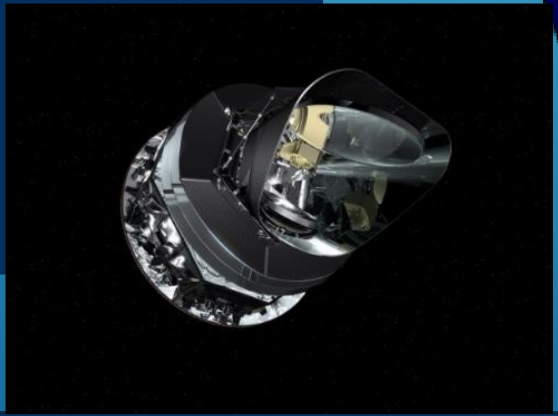
ΛCDM
«CONCORDANCE MODEL»

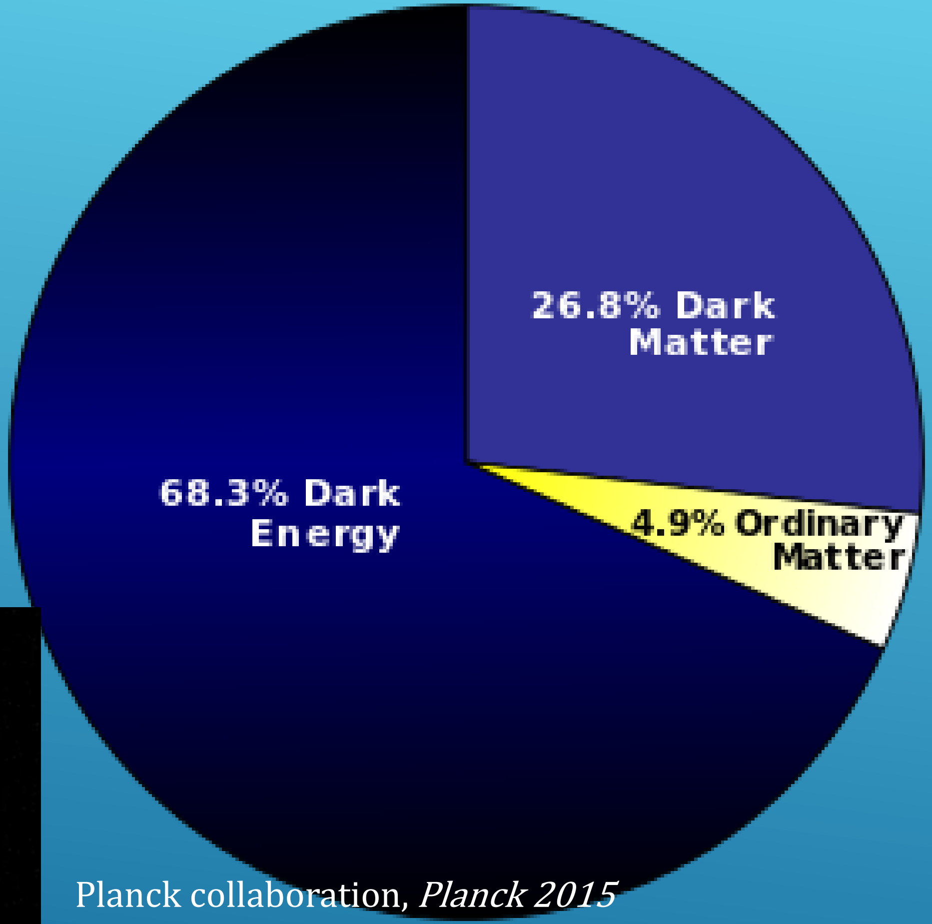
- **Ordinary Matter** (barionic matter and radiation)
- **Dark Matter**

WIMP? (*Weakly Interacting Massive Particles*)
Axions?

- **Dark Energy**

Cosmological constant Λ?





Planck collaboration, *Planck 2015 result, XIII. Cosmological parameters*, A&A 594, A13 (2016).

STANDARD COSMOLOGICAL MODEL ΛCDM

COSMOLOGICAL CONSTANT Λ + COLD DARK MATTER

FLRW metric (Friedmann-Lemaître-Robertson-Walker)

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-k\,r^2} + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\right]$$

$a(t)$: scale factor

k: curvature parameter

$H(t)$: Hubble function

FLRW dynamics
Homogeneous and isotropic Universe

GR + cosmological constant Λ

- I Friedmann equation

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\chi\,\rho + \Lambda}{3} - \frac{k}{a^2}$$

- II Friedmann equation (acceleration equation)

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{\chi}{6}\,(\rho + 3\,p) + \frac{\Lambda}{3}$$

$$\left(\frac{\ddot{a}}{a}\right) > 0$$

$$p_{DE}(\rho_{DE}) = w\,\rho_{DE}$$

$$w < -1/3 \quad \text{Dark Energy}$$

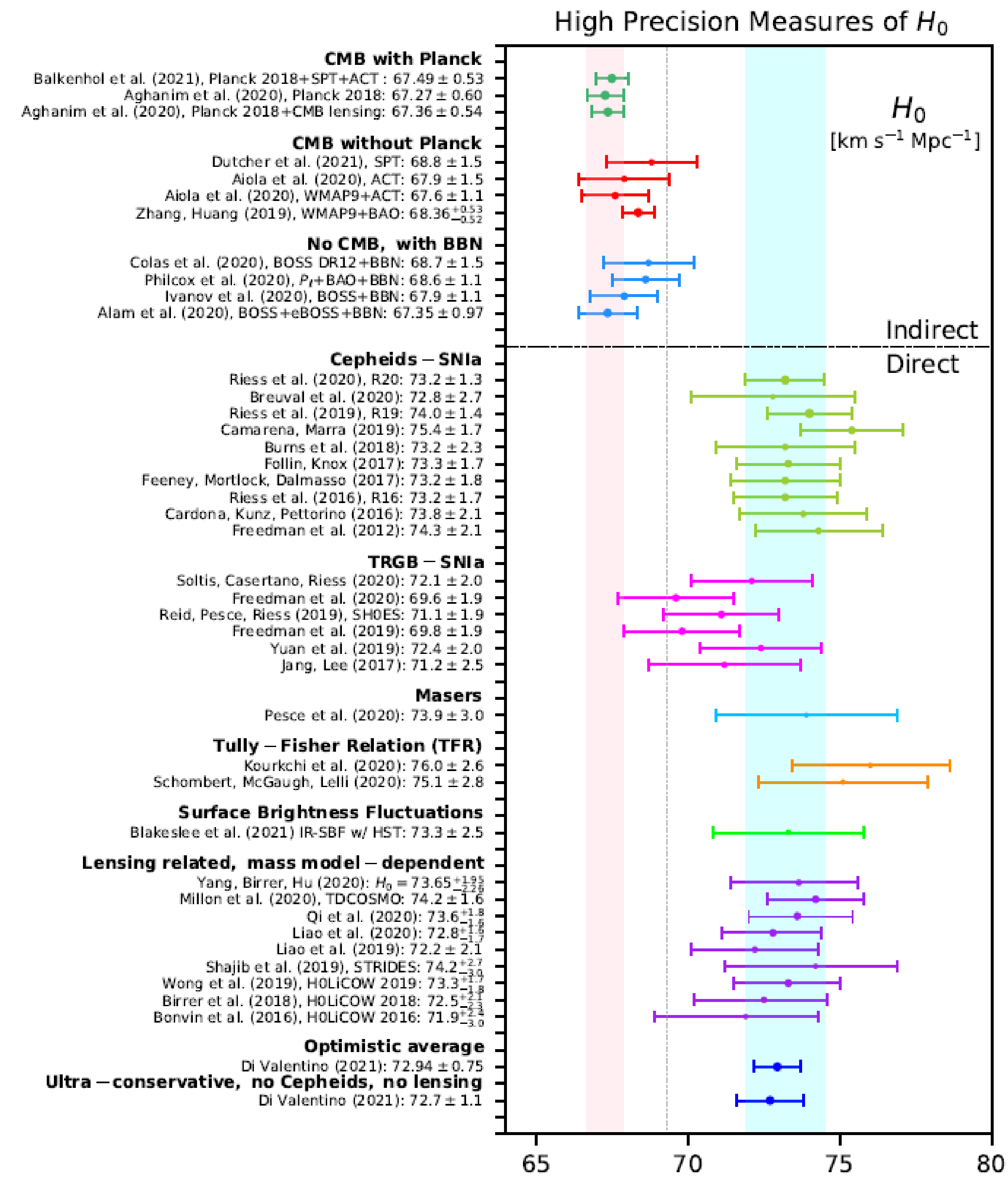
$$w = -1 \quad \rightarrow \quad \Lambda$$

Stress-energy tensor of cosmological fluid

$$T^{\mu}_{\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & -p & 0 & 0 \\ 0 & 0 & -p & 0 \\ 0 & 0 & 0 & -p \end{pmatrix}$$

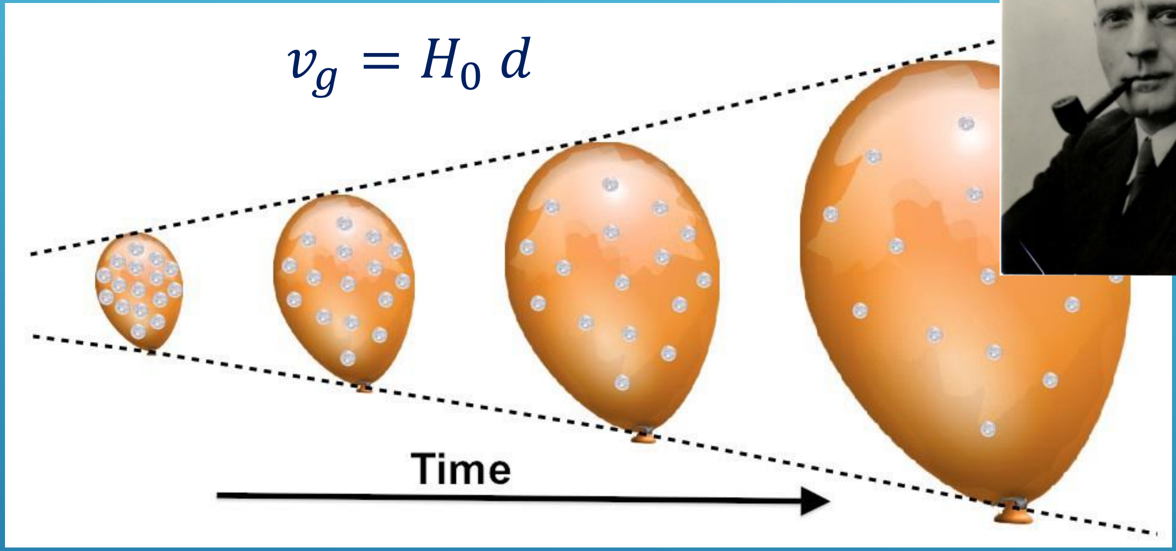
$\rho = \rho(t)$ energy density

$p = p(t)$ pressure



HUBBLE CONSTANT TENSION

Cosmic expansion and Hubble law



Di Valentino et al. (2021), Invited Review, arXiv:2103.01183

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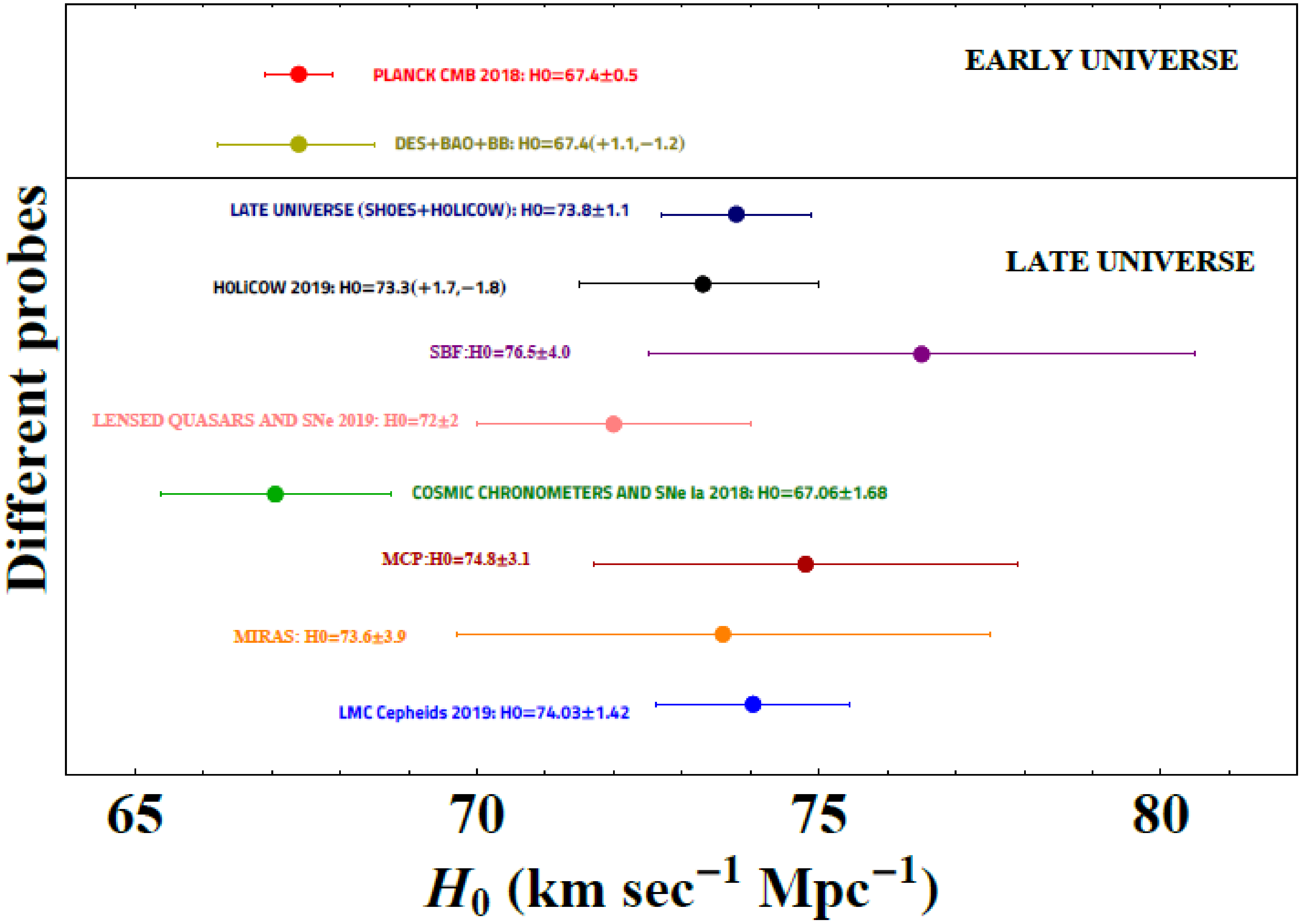

HUBBLE CONSTANT TENSION

$$H(t = t_0) = H(z = 0) \equiv H_0$$

Hubble constant

Dainotti et al. (2021), ApJ 912, 150 (arXiv:2103.02117)

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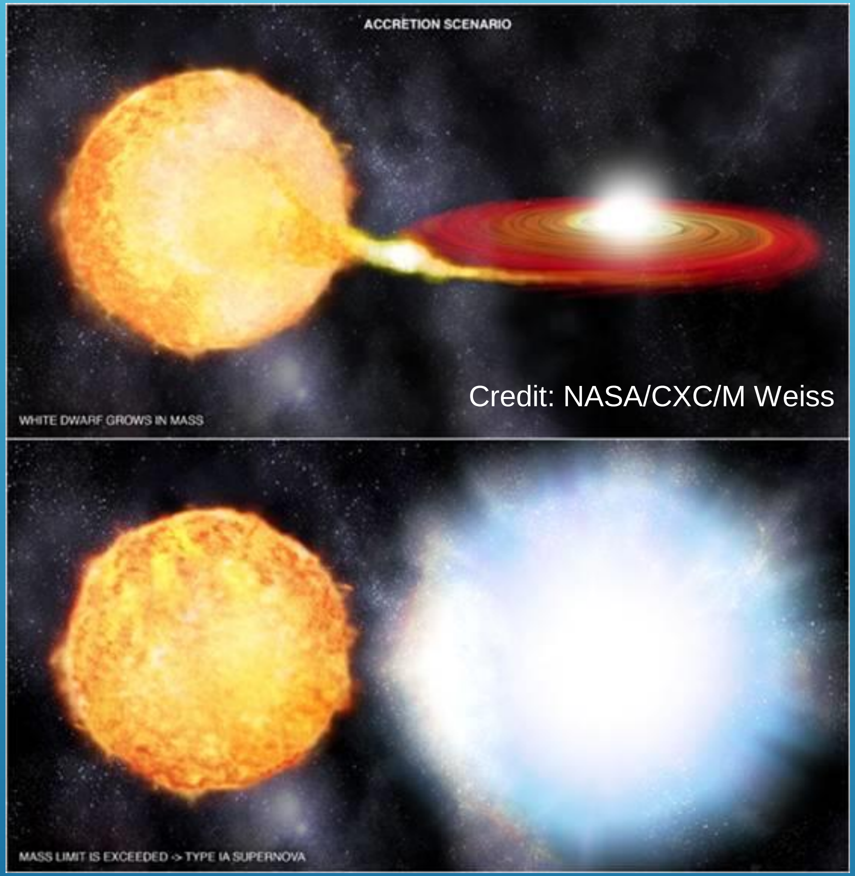
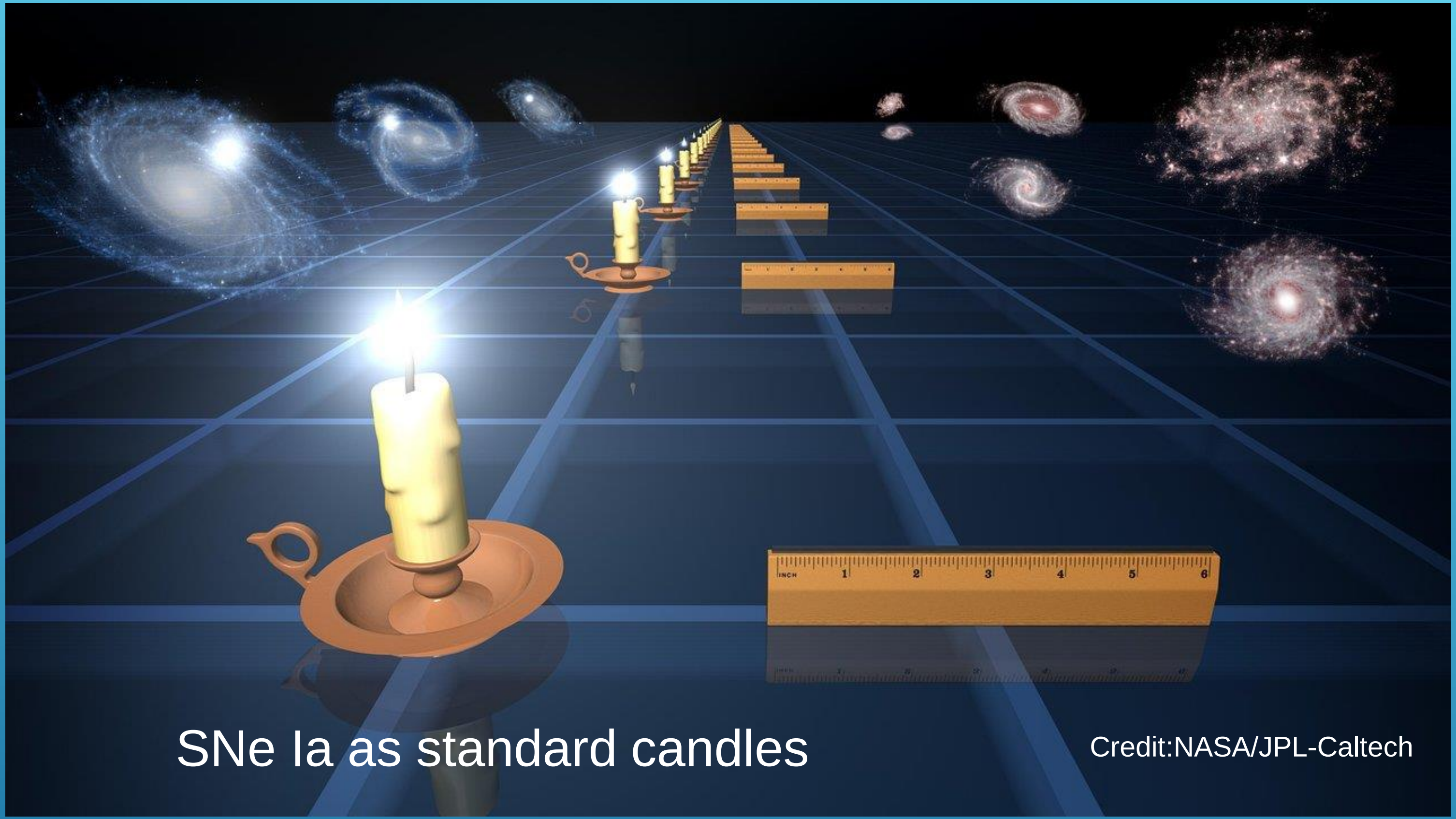
TYPE IA SUPERNOVAE (SNe Ia)



Credit: NASA/CXC/M Weiss



SNe Ia as standard candles

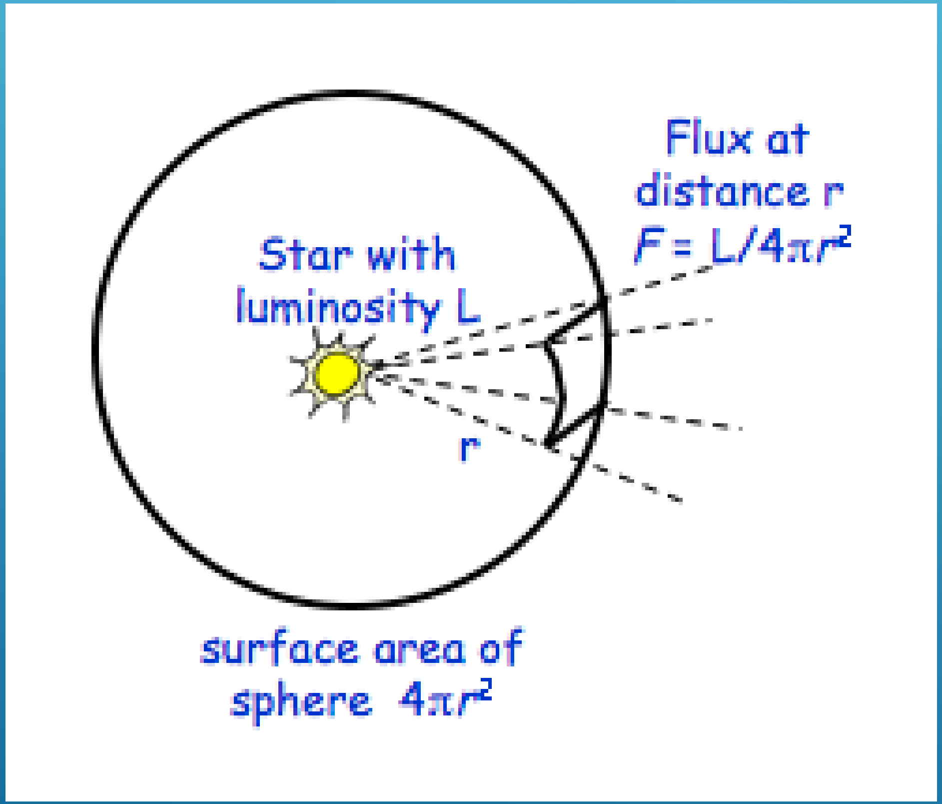
Credit:NASA/JPL-Caltech

Chandrasekhar mass limit $\sim 1.44\ M_{\odot}$

Fixed absolute magnitude

LUMINOSITY DISTANCE d_L

Euclidean space, static Universe



Expanding Universe

$$F = \frac{L}{4\pi d_L^2}$$ Observed flux

$$d_L(z) = a_0\, r\,(1+z)$$ Luminosity distance

Flat geometry (k=0)

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

LUMINOSITY DISTANCE d_L

Luminosity distance depends on the cosmological model

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

$$H(z) = H_0\, E(z)$$

Ω_{i0}: cosmological density parameters

m: matter

r: radiation

LUMINOSITY DISTANCE d_L

Luminosity distance depends on the cosmological model

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$$H(z) = H_0\, E(z)$$

Ω_{i0}: cosmological density parameters

m: matter

r: radiation

- ► ΛCDM model

$$E(z) = \sqrt{\Omega_{m0}\,(1+z)^3 + \Omega_{r0}\,(1+z)^4 + \Omega_\Lambda}$$

LUMINOSITY DISTANCE d_L

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► ΛCDM model

$$E(z) = \sqrt{\Omega_{m0}\,(1+z)^3 + \Omega_{r0}\,(1+z)^4 + \Omega_\Lambda}$$

► wCDM model

$$w = w(z)$$

$$E(z) = \sqrt{\Omega_{m0}\,(1+z)^3 + \Omega_{r0}\,(1+z)^4 + \Omega_{\mathrm{DE}0}\exp\left[3\int_0^z \frac{dz'}{1+z'}\,(1+w(z'))\right]}$$

LUMINOSITY DISTANCE d_L

Luminosity distance depends on the cosmological model

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

$$H(z) = H_0\, E(z)$$

Ω_{i0}: cosmological density parameters

m: matter

r: radiation

- ΛCDM model

$$E(z) = \sqrt{\Omega_{m0}\,(1+z)^3 + \Omega_{r0}\,(1+z)^4 + \Omega_\Lambda}$$

- wCDM model

$$w = w(z)$$

$$E(z) = \sqrt{\Omega_{m0}\,(1+z)^3 + \Omega_{r0}\,(1+z)^4 + \Omega_{\mathrm{DE}0}\exp\left[3\int_0^z \frac{dz'}{1+z'}\,(1+w(z'))\right]}$$

- $w_0 w_a$CDM model

$$w(z) = w_0 + \frac{w_a\, z}{1+z}$$

CPL parameterization (Chevallier-Polarski-Linder)

DISTANCE MODULUS μ

From the underlying theoretical cosmological model:

$$\mu_{th} = 5 \log_{10} d_L + 25$$

It depends on the luminosity distance expressed in Mpc

From SNe Ia observations:

$$\mu_{obs} = m_B - M + \alpha\, x_1 - \beta\, c + \Delta M + \Delta B$$

Modified Tripp formula

B-band apparent magnitude

Absolute magnitude for x1=0=c

Stretch parameter

Color parameter

Host-galaxy mass correction

Bias correction

Tripp (1998), A&A 331, 815

Betoule et al. (2014), A&A 568, A22

Scolnic et al. (2018), ApJ 859, 101

PANTHEON SAMPLE ANALYSIS

1048 spectroscopically confirmed SNe Ia from different surveys (PS1, SDSS, ESSENCE, SNLS, SCP, GOODS, CANDELS/CLASH)

$$0.01 < z < 2.26$$

Statistical analysis:

$$\chi^2 = \Delta\mu^T C^{-1} \Delta\mu$$

where

$$\Delta\mu = \mu_{obs} - \mu_{th}$$

$$C = D_{stat} + C_{sys}$$

Uncertainty matrix C (1048x1048)

Cobaya package* in Python to minimize χ^2

Statistical matrix (diagonal matrix, 1048x1048)

Systematic covariance matrix (symmetric, 1048x1048)

Scolnic et al. (2018), ApJ 859, 101

Repository: https://github.com/dscolnic/Pantheon

* Torrado & Lewis, arXiv:2005.05290

PANTHEON SAMPLE BINNED ANALYSIS

Hubble constant tension also inside the SNe Ia data?

- Redshift bin divisions: 3, 4, 20 and 40
- Equally populated subsamples of SNe Ia
- Building submatrices C and subvector $\Delta\mu$, considering the redshift order of SNe
- Statistical analysis for each redshift bin, χ^2 minimization, MCMC, posterior distribution and D'Agostini method

$0.01 < z < 2.26$

Pantheon sample – redshift range

$0.01 < z < 0.18$

1st bin of 3

$0.18 < z < 0.34$

2nd bin of 3

$0.34 < z < 2.26$

3rd bin of 3

PANTHEON SAMPLE BINNED ANALYSIS

Hubble constant tension also inside the SNe Ia data?

- Focus on the H_0 values in different bins priors: $60 < H_0 < 80\ km\ s^{-1}\ Mpc^{-1}$
- Fixed M with a preliminary analysis for the 1st bin, imposing the local value $H_0 = 73.5\ km\ s^{-1}\ Mpc^{-1}$
- Fixed $\Omega_{m0} = 0.298$ for the ΛCDM model
- Fixed $\Omega_{m0} = 0.308, \quad \mathrm{w_0} = -1.009,$ $\mathrm{w_a} = -0.129$ for the $w_0 w_a$CDM model

Extracting H_0 value for each bin

Test: nonlinear fit

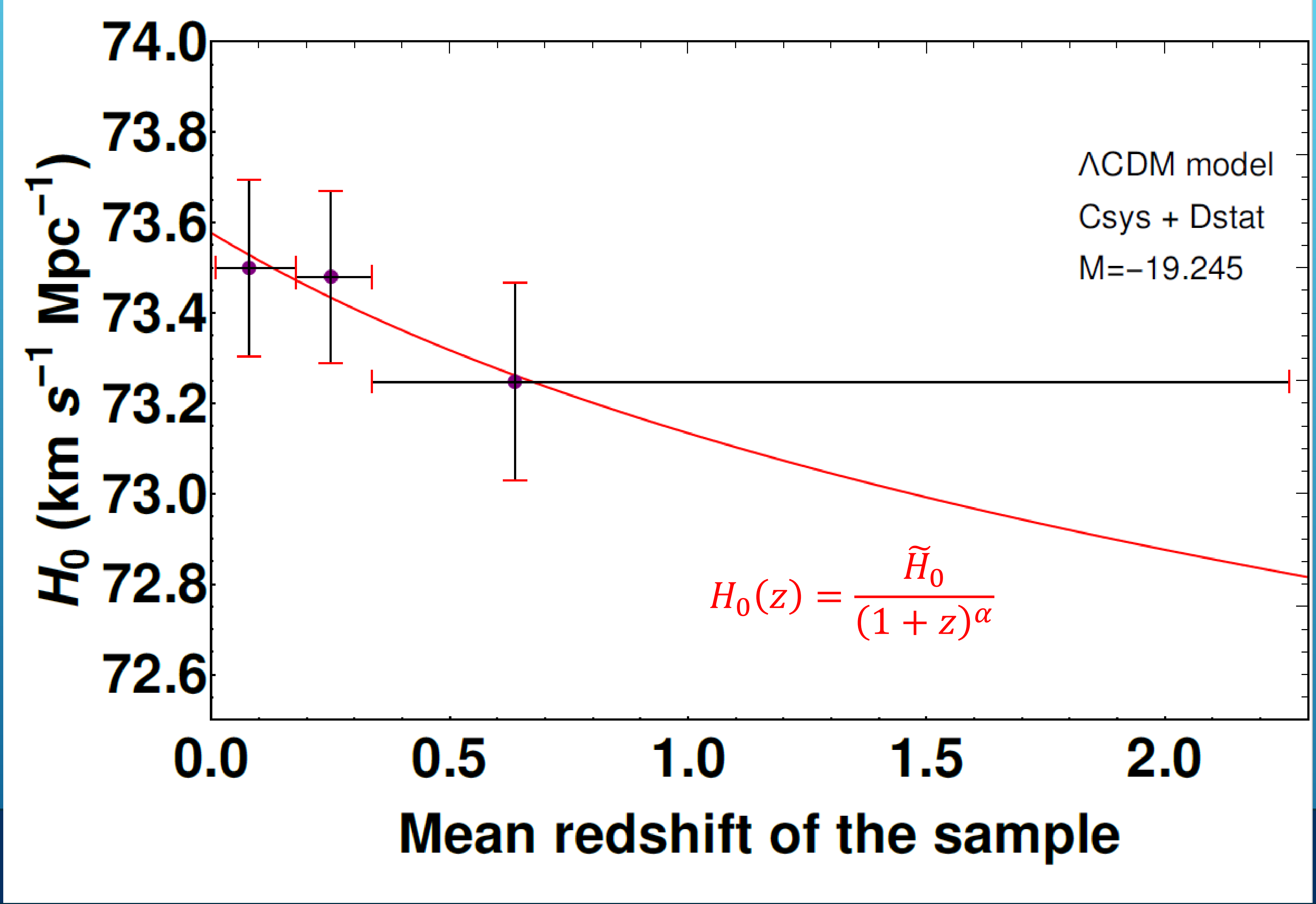
$$H_0(z) = \frac{\widetilde{H}_0}{(1+z)^{\alpha}}$$

α: evolutionary parameter

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

IS HUBBLE CONSTANT ACTUALLY CONSTANT?

3 bins



Dainotti et al. (2021), ApJ 912, 150 (arXiv:2103.02117)

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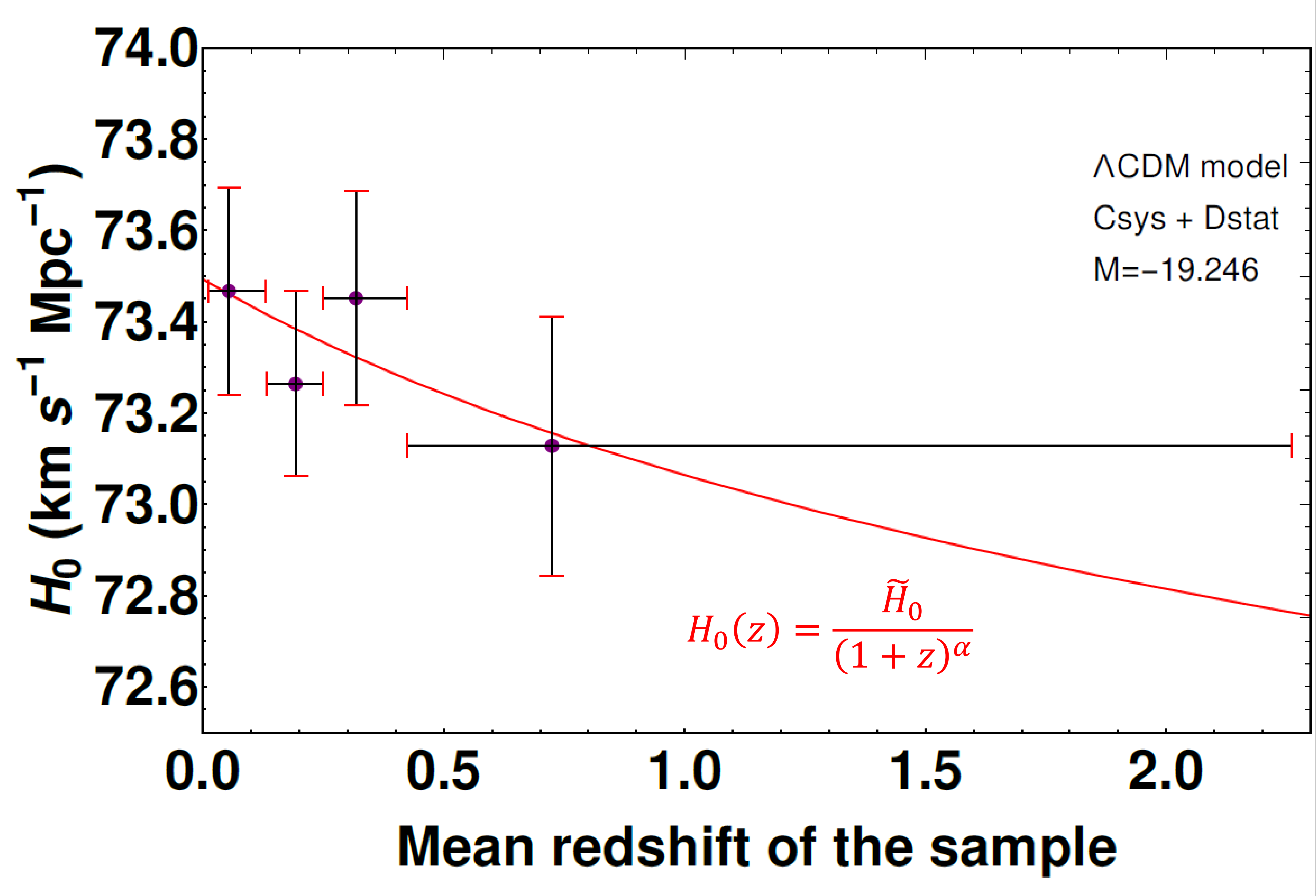
IS HUBBLE CONSTANT ACTUALLY CONSTANT?

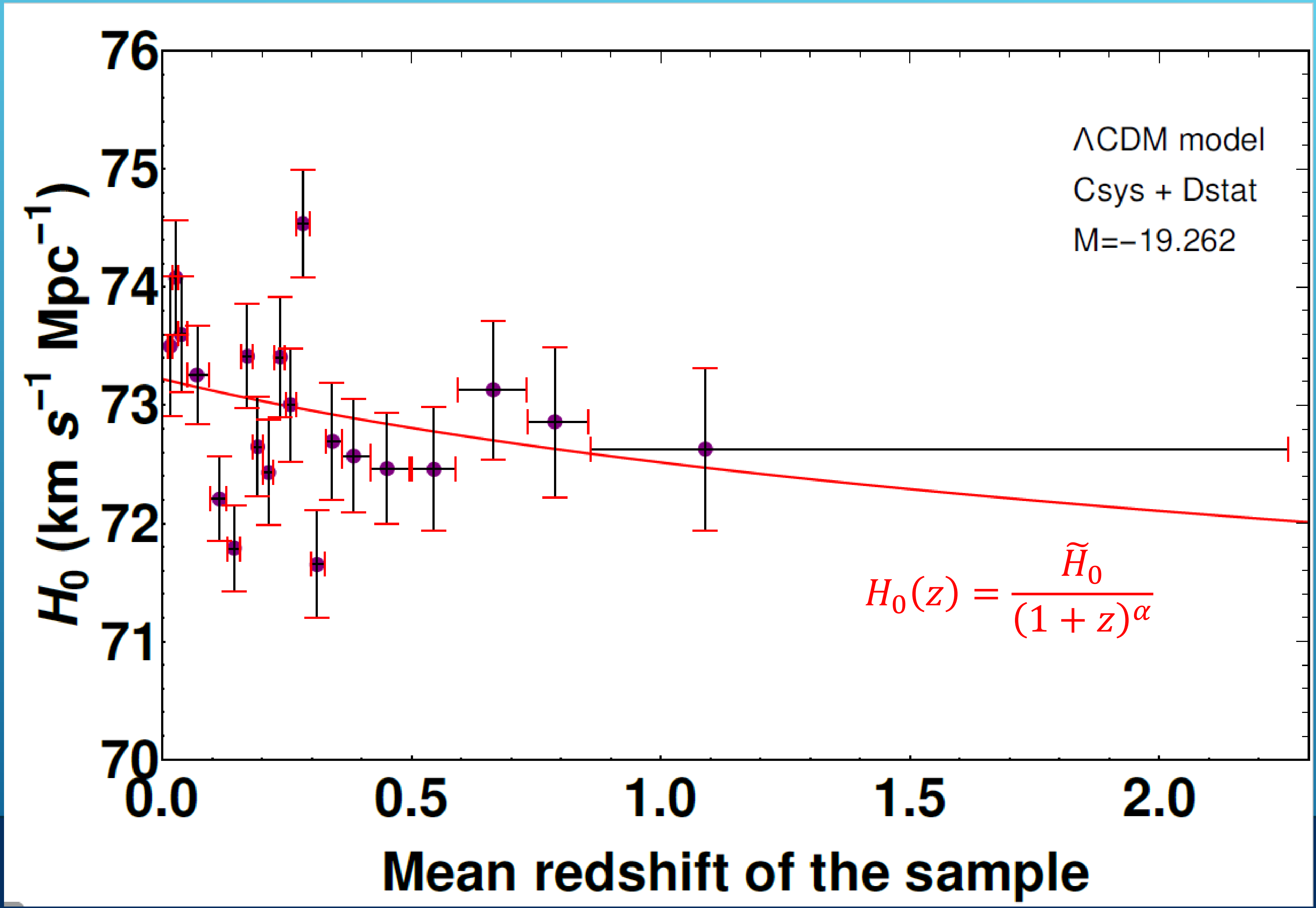
4 bins



Dainotti et al. (2021), ApJ 912, 150 (arXiv:2103.02117)

IS HUBBLE CONSTANT ACTUALLY CONSTANT?

20 bins



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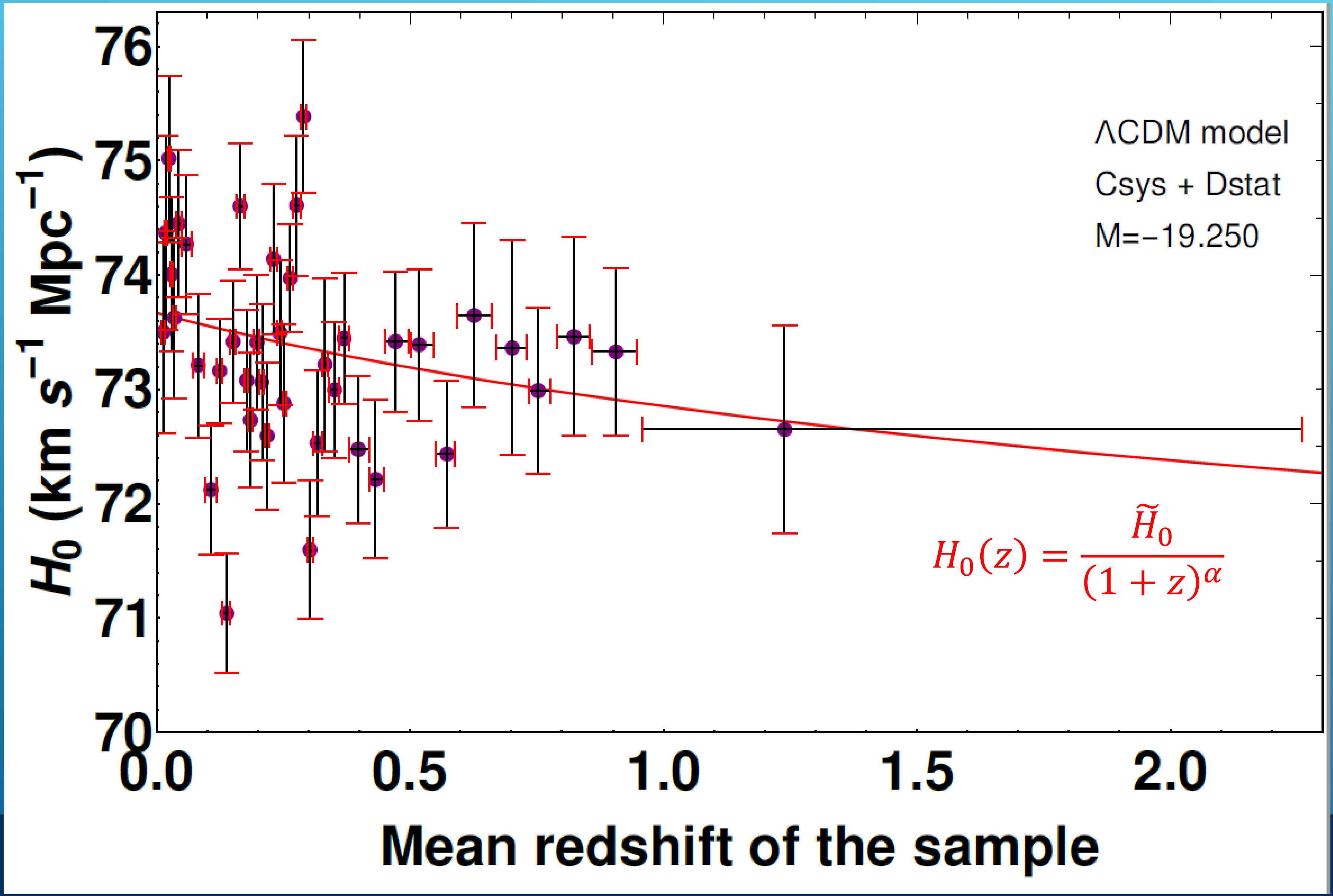
IS HUBBLE CONSTANT ACTUALLY CONSTANT?

40 bins



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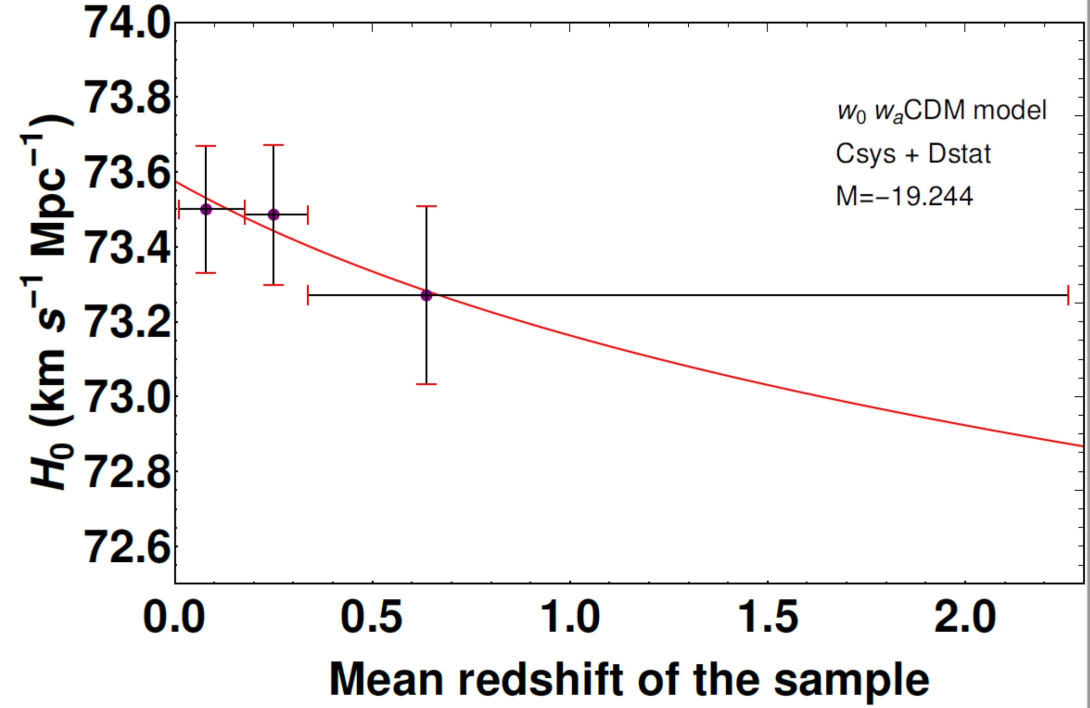
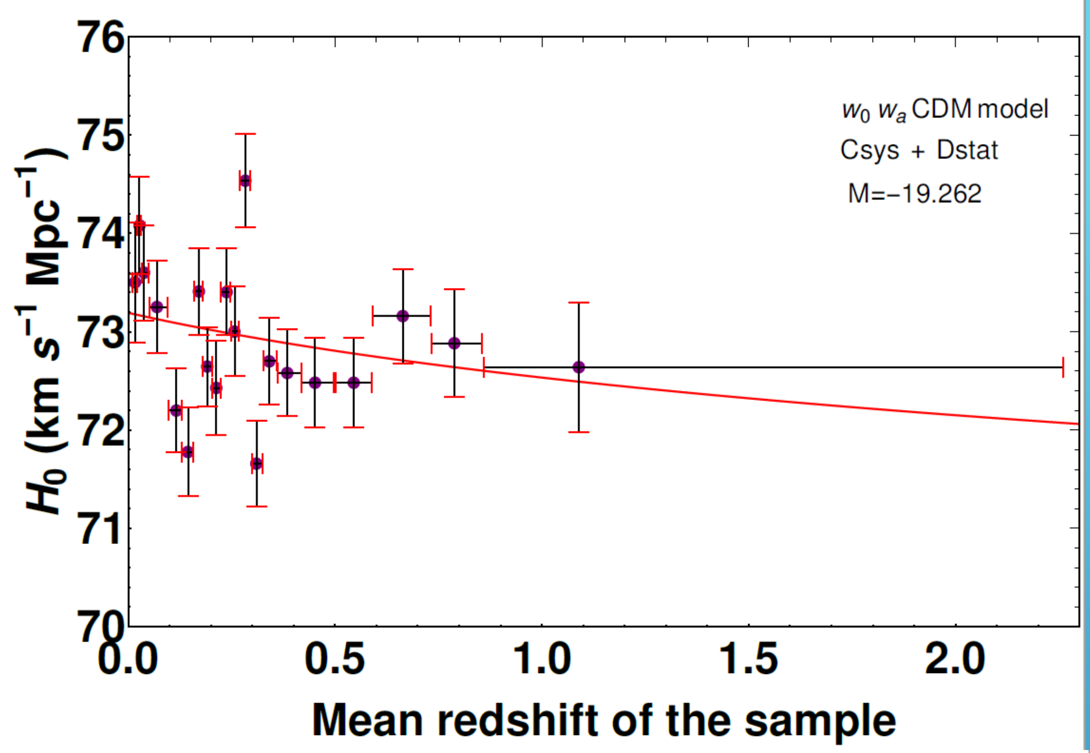
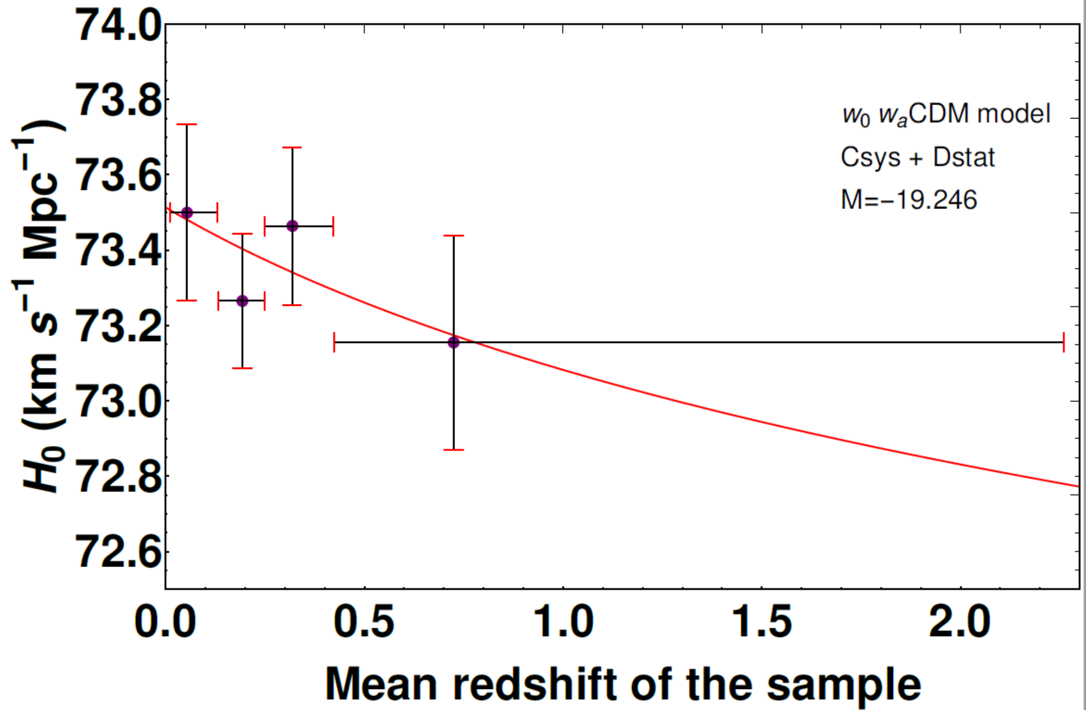


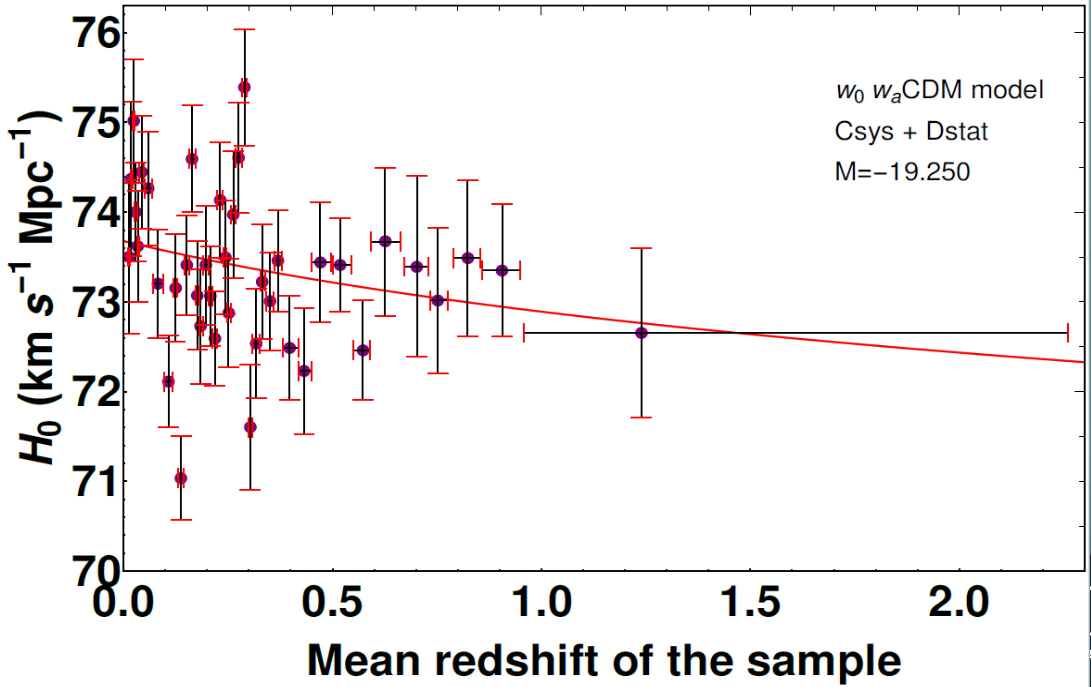
$w_0\ w_a$CDM model
Csys + Dstat
M=−19.244
H_0 (km s^{-1} Mpc^{-1})
Mean redshift of the sample
74.0
73.8
73.6
73.4
73.2
73.0
72.8
72.6
0.0
0.5
1.0
1.5
2.0



$w_0\ w_a$CDM model
Csys + Dstat
M=−19.262
H_0 (km s^{-1} Mpc^{-1})
Mean redshift of the sample
76
75
74
73
72
71
70
0.0
0.5
1.0
1.5
2.0

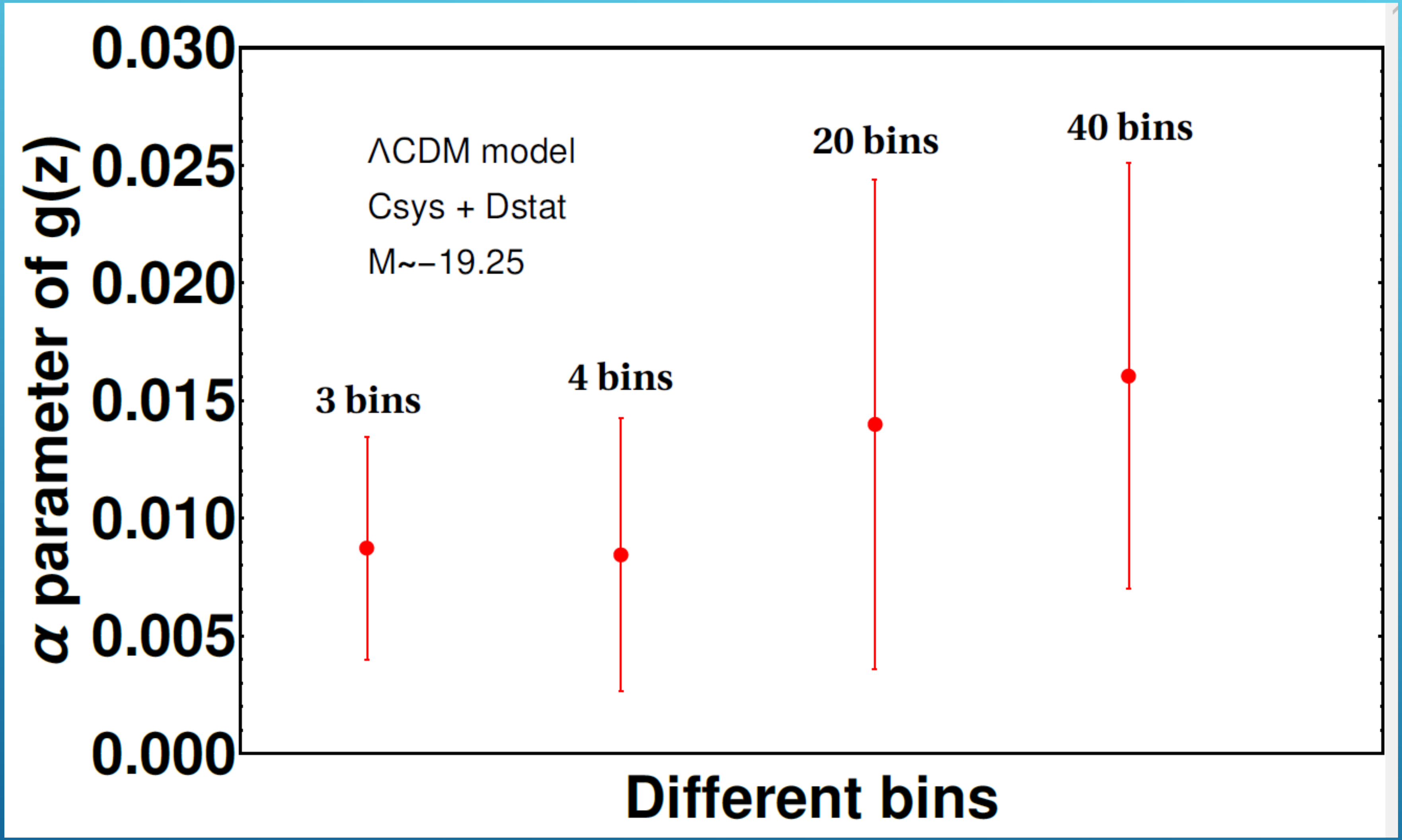


$w_0\ w_a$CDM model
Csys + Dstat
M=−19.246
H_0 (km s^{-1} Mpc^{-1})
Mean redshift of the sample
74.0
73.8
73.6
73.4
73.2
73.0
72.8
72.6
0.0
0.5
1.0
1.5
2.0



$w_0\ w_a$CDM model
Csys + Dstat
M=−19.250
H_0 (km s^{-1} Mpc^{-1})
Mean redshift of the sample
76
75
74
73
72
71
70
0.0
0.5
1.0
1.5
2.0

IS HUBBLE CONSTANT ACTUALLY CONSTANT?



$$H_0(z) = \frac{\widetilde{H}_0}{(1+z)^{\alpha}}$$

$\alpha = 0 \;\rightarrow\;$ no evolution

Error bars, 1 σ

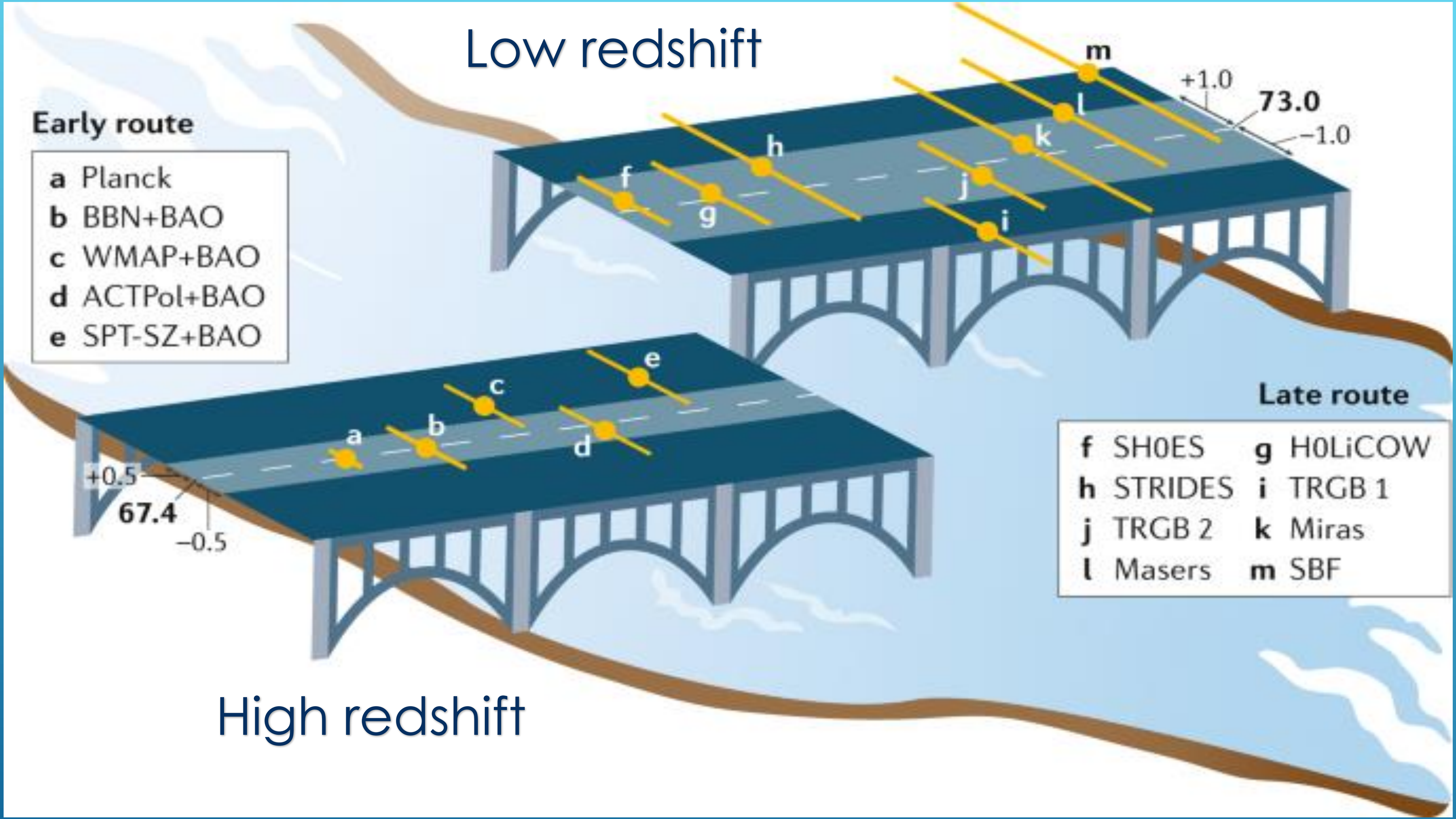
Slight and unexpected evolution of $H_0(z)$

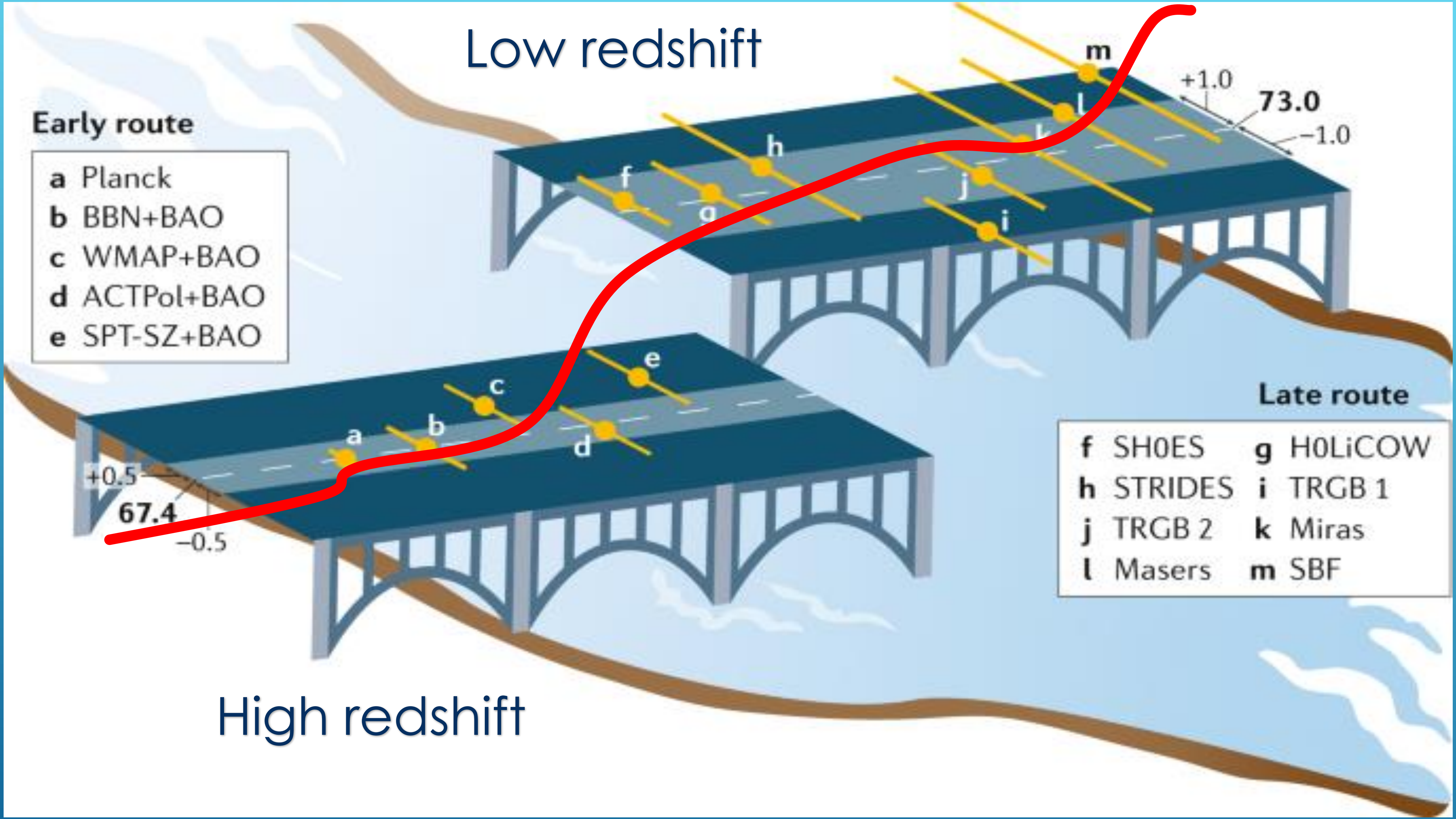
Fit results ΛCDM model

Bins	$\tilde{H}_0$ (km s^{-1} Mpc^{-1})	α	$\frac{\alpha}{\sigma_\alpha}$	M
3	73.577 ± 0.106	0.009 ± 0.004	2.0	-19.245 ± 0.006
4	73.493 ± 0.144	0.008 ± 0.006	1.5	-19.246 ± 0.008
20	73.222 ± 0.262	0.014 ± 0.010	1.3	-19.262 ± 0.014
40	73.669 ± 0.223	0.016 ± 0.009	1.8	-19.250 ± 0.021

Fit results $w_0 w_a$CDM model

Bins	$\tilde{H}_0$ (km s^{-1} Mpc^{-1})	α	$\frac{\alpha}{\sigma_\alpha}$	M
3	73.576 ± 0.105	0.008 ± 0.004	1.9	-19.244 ± 0.005
4	73.513 ± 0.142	0.008 ± 0.006	1.2	-19.246 ± 0.004
20	73.192 ± 0.265	0.013 ± 0.011	1.9	-19.262 ± 0.018
40	73.678 ± 0.223	0.015 ± 0.009	1.7	-19.250 ± 0.022


Low redshift
Early route
a Planck
b BBN+BAO
c WMAP+BAO
d ACTPol+BAO
e SPT-SZ+BAO
+1.0
73.0
−1.0
+0.5
67.4
−0.5
Late route
f SH0ES
g H0LiCOW
h STRIDES
i TRGB 1
j TRGB 2
k Miras
l Masers
m SBF
High redshift


Low redshift
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j TRGB 2
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l Masers
m SBF
High redshift

EXTRAPOLATED VALUES AT HIGH REDSHIFTS

$$H_0(z) = \frac{\widetilde{H}_0}{(1+z)^{\alpha}}$$

	ΛCDM model		$w_0 w_a$CDM model	
Bins	$H_0(z=11.09)$ (km s^{-1} Mpc^{-1})	$H_0(z=1100)$ (km s^{-1} Mpc^{-1})	$H_0(z=11.09)$ (km s^{-1} Mpc^{-1})	$H_0(z=1100)$ (km s^{-1} Mpc^{-1})
3	72.000 ± 0.805	69.219 ± 2.159	72.104 ± 0.766	69.516 ± 2.060
4	71.962 ± 1.049	69.271 ± 2.815	71.975 ± 1.020	69.272 ± 2.737
20	70.712 ± 1.851	66.386 ± 4.843	70.852 ± 1.937	66.804 ± 5.093
40	70.778 ± 1.609	65.830 ± 4.170	70.887 ± 1.595	66.103 ± 4.148

Consistent in 1 σ with the Planck measurement from the CMB, at the redshift of the last scattering surface z=1100

$$H_0^{[PLANCK]} = (67.4 \pm 0.5) km\ s^{-1}\ Mpc^{-1}$$

POSSIBLE EXPLANATIONS OF $H_0(z)$

$$H_0(z) = \frac{\widetilde{H}_0}{(1+z)^{\alpha}}$$

Astrophysical reasons or trouble with the Pantheon Sample

- Hidden evolution of an astrophysical parameter of SNe Ia (stretch, metallicity, …)
- Astrophysical properties (host galaxies, selection effects)
- Biases not considered in the Pantheon Sample
- Systematics uncertainties of the sample

New Physics

- Local inhomogeneities
- Late-time modification of gravity

GENERAL RELATIVITY

$$G_{\mu\nu} = \chi\, T_{\mu\nu}$$

Dark energy → modified source

$f(R)$ MODIFIED GRAVITY

$$G_{\mu\nu} = \chi\, T_{\mu\nu}$$

Geometrical modification of gravity theory

General Relativity		$f(R)$ modified gravity
$\mathcal{L}_{EH} = R$ Einstein-Hilbert	Gravitational Lagrangian density	$\mathcal{L}_g = f(R)$ Extra degree of freedom
$S_{EH} = -\frac{1}{2\chi}\int_\Omega d^4x\,\sqrt{-g}\,R$	Gravitational action	$S_g = -\frac{1}{2\chi}\int_\Omega d^4x\,\sqrt{-g}\,f(R)$
$G_{\mu\nu} = \chi\, T_{\mu\nu}$	Gravitational field equations	$f'(R)\,R_{\mu\nu} - \frac{1}{2}\,f(R)\,g_{\mu\nu} + g_{\mu\nu}\,g^{\rho\sigma}\,\nabla_\rho\nabla_\sigma f'(R) - \nabla_\mu\nabla_\nu f'(R) = \chi\,T_{\mu\nu}$

T.P. SOTIRIOU, V. FARAONI, $f(R)$ *theories of gravity*, Rev. Mod. Phys. 82, 451-497 (2010).

R: Ricci scalar

$f'(R) \equiv \frac{df}{dR}$

∇_μ: covariant derivative

$f(R)$ MODIFIED THEORIES OF GRAVITY

Geometrical modification of gravity theory

$$\mathcal{L}_g = f(R) = \mathrm{R} + \mathrm{F}(R)$$

Deviation from Einstein-Hilbert theory

Modified gravitational field equations

$$f'(R)\, R_{\mu\nu} - \frac{1}{2}\, f(R)\, g_{\mu\nu} + g_{\mu\nu}\, g^{\rho\sigma}\, \nabla_\rho \nabla_\sigma f'(R) - \nabla_\mu \nabla_\nu f'(R) = \chi\, T_{\mu\nu}$$

$$G_{\mu\nu} = \chi\, \left(T_{\mu\nu} + T_{\mu\nu}^{[F]}\right)$$

Explicit modification of Einstein-Hilbert equations

No-Einsteinian geometrical contribution

can be recast as an effective source

$$T_{\mu\nu}^{[F]} = -\frac{1}{\chi}\left[F'(R)\, R_{\mu\nu} - \frac{1}{2}\, F(R)\, g_{\mu\nu} + g_{\mu\nu}\, g^{\rho\sigma}\, \nabla_\rho \nabla_\sigma F'(R) - \nabla_\mu \nabla_\nu F'(R)\right]$$

JORDAN FRAME $f(R)$ GRAVITY

Dynamically equivalent action to $f(R)$ theories

Jordan frame

$$S_g = -\frac{1}{2\chi}\int_\Omega d^4y\,\sqrt{-g}\,\left[\phi\, R - V(\phi)\right]$$

Scalar field $\phi = f'(A)$

Potential

$$V(\phi) = A(\phi)\phi - f(A(\phi))$$

- The extra degree of freedom of $f(R)$ is replaced by a scalar field
- Non-minimal coupling between scalar field and metric
- Corresponding field equations:

$$G_{\mu\nu} = \frac{\chi}{\phi}\,T_{\mu\nu} - \frac{1}{2\,\phi}\,g_{\mu\nu}\,V(\phi) + \frac{1}{\phi}\left[\nabla_\mu\nabla_\nu\phi - g_{\mu\nu}\,\Box\phi\right]$$

$$3\,\Box\phi + 2\,V(\phi) - \phi\,V'(\phi) = \chi\,T$$

II order diff. eqs. in $g_{\mu\nu}$

RUNNING HUBBLE CONSTANT & $f(R)$ GRAVITY

Jordan frame $\chi \rightarrow \chi_{eff} = \frac{\chi}{\phi}$ $\chi = \frac{8\pi G}{c^4}$

Impact of a non-minimal coupled scalar field: effective Einstein constant χ_{eff} or effective Newton constant G_{eff}

If the scalar field evolves like: $\phi \sim (1+z)^{2\alpha}$ then $\chi_{eff} \sim (1+z)^{-2\alpha}$

Critical density $\rho_{c0} = \frac{3\,H_0^2}{\chi} \rightarrow \frac{3\,H_0^2(z)}{\chi_{eff}}$

$H_0(z) \sim \frac{1}{(1+z)^{\alpha}}$

CONCLUSIONS

$H_0?$
$H_0(z)?$

- Binned analysis of the SNe Ia Pantheon Sample (low redshifts)
- Unexpected evolution and decreasing trend of $H_0(z)$, results valid in 2 σ
- Our results hold in different bins and for the ΛCDM and $w_0 w_a$CDM models
- A Running Hubble constant allows a new interpretation of the tension: it is no longer a discrepancy between local probes and Planck data, but an intrinsic evolutionary behavior of $H_0(z)$
- New measurements to obtain better constraints on the evolutionary parameter α
- Possible hints of a new Physics (modified gravity?)

THANK YOU FOR LISTENING

CONTACT

tiziano.schiavone@phd.unipi.it

tiziano.schiavone@pi.infn.it

University of Pisa & INFN, Sezione di Pisa

Room 174, Building C INFN,

Largo B. Pontecorvo 3, 56127, Pisa

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Costante o non costante, questo è il problema

Un team di scienziati guidato da Maria Giovanna Dainotti ha analizzato un database di oltre 1000 esplosioni di supernova e ha scoperto che i modelli che descrivono l'espansione dell'universo rappresentano meglio i dati quando viene introdotta una variazione temporale della costante di Hubble. Se questo verrà confermato da futuri dati osservativi, potrebbe indicare l'evidenza di una nuova fisica che opera su scala cosmica. Tutti dettagli su ApJ

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Cosmologia: la "costante di Hubble" non sarebbe costante

La scoperta di un team di ricercatori della Sapienza, dell'Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (Enea) e dell'Università di Pisa. Lo studio è stato pubblicato sulla rivista The Astrophysical Journal

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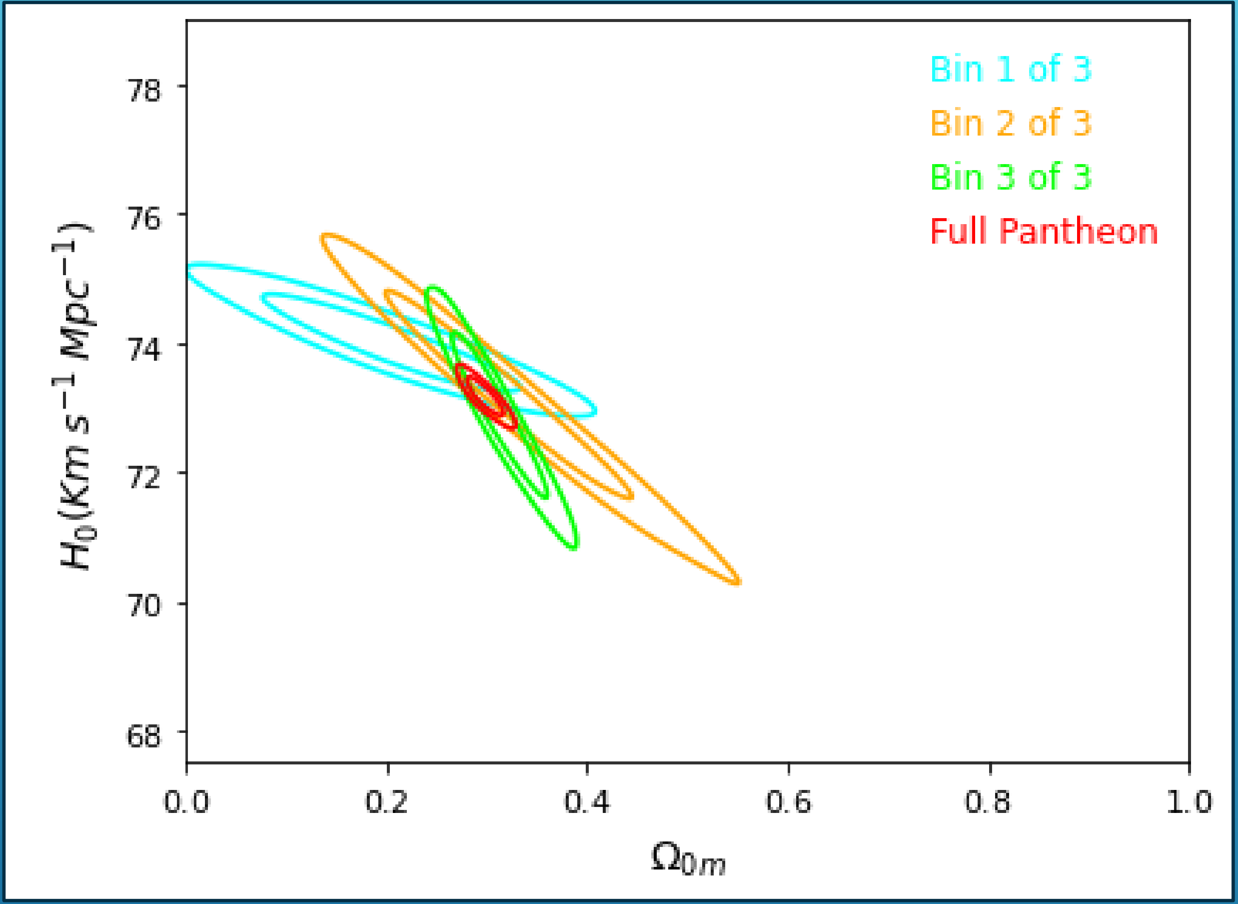
PANTHEON SAMPLE BINNED ANALYSIS

Hubble constant tension also inside the SNe Ia data?

- Redshift bin divisions: 3, 4, 20 and 40
- Equally populated subsamples of SNe Ia
- Building submatrices C and subvector $\Delta\mu$, considering the redshift order of SNe
- Statistical analysis for each redshift bin, χ^2 minimization, MCMC, posterior distribution and D'Agostini method



PANTHEON SAMPLE ANALYSIS

$$C = D_{stat} + C_{sys}$$

D_{stat} Statistical matrix
(diagonal matrix, 1048x1048)
Includes distance errors σ^2
for each SNe

C_{sys} Systematic covariance matrix
(matrix, 1048x1048)
Includes N systematic (S_k)
sources of errors

$$\sigma^2 = \sigma_N^2 + \sigma_{mass}^2 + \sigma_{\mu-z}^2 + \sigma_{lens}^2 + \sigma_{int}^2 + \sigma_{bias}^2$$

- σ_N^2: Photometric error
- σ_{mass}^2: Mass-step correction
- $\sigma_{\mu-z}^2$: Peculiar velocity and redshift
- σ_{lens}^2: Lensing
- σ_{int}^2: Intrinsic scatter
- σ_{bias}^2: Bias correction

$$C_{ij,sys} = \sum_{k=1}^{N} \frac{\partial \mu_i}{\partial S_k} \frac{\partial \mu_j}{\partial S_k} \sigma_{S_k}^2$$

S_k: systematics → $(m_B, x_1, c, m_B c, x_1 m_B, x_1 c)$

σ_{S_k}: systematic error