A Cosmic Conundrum

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Hubble tension

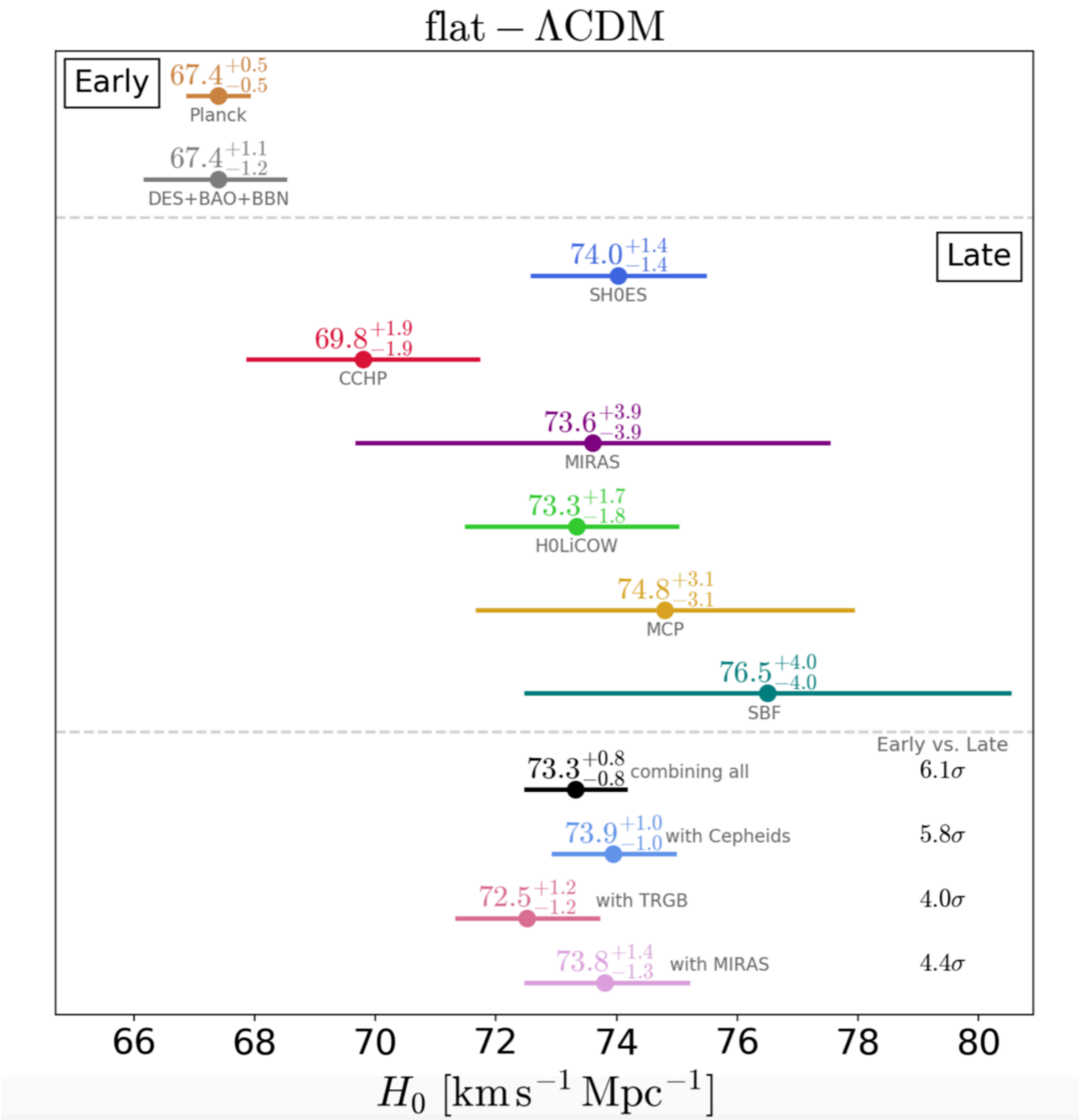
Cosmology is nowadays a data-driven science.

Difference in the Hubble constant between early & late universe determinations is causing excitement.

Hints of breakdown in ΛCDM, cf. string theory “Swampland”.

“The Hubble tension between the early and late universe may be the most exciting development in cosmology in decades.” - Adam Riess

“We wouldn’t call it a tension or a problem, but rather a crisis.” - David Gross

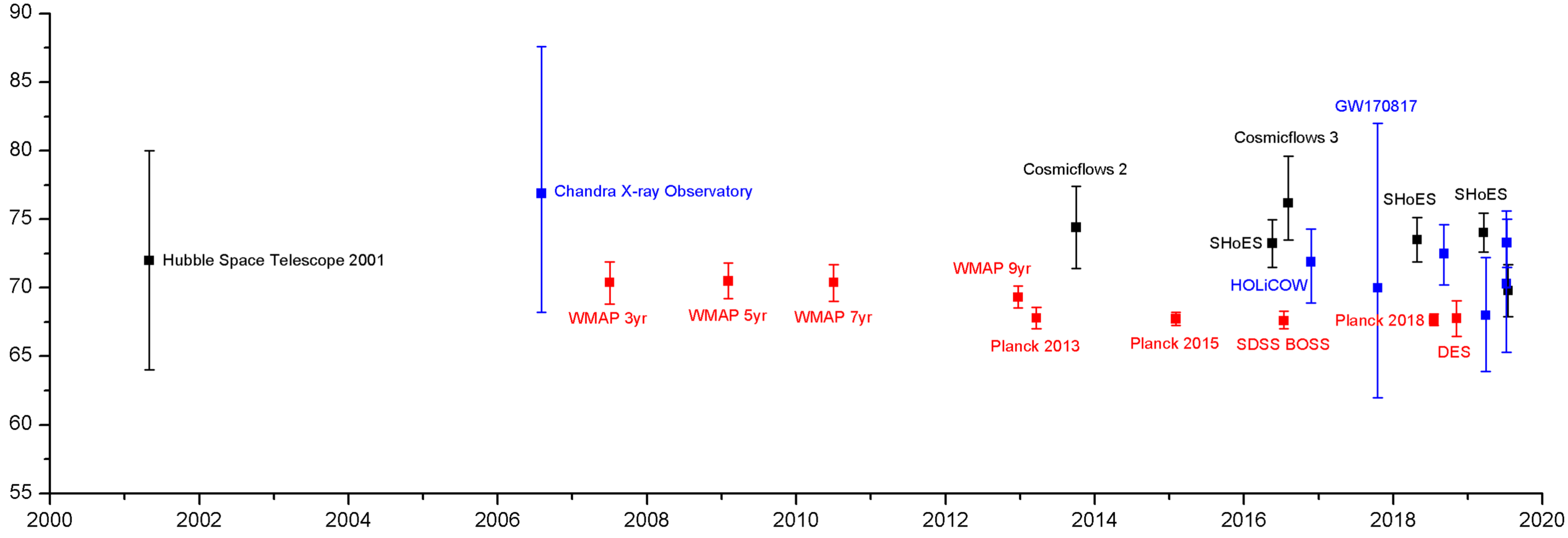


Outcome of July 2019 KITP meeting

Verde, Treu, Riess (1907.10625)

MONDAY   LIGO (1908.06060) $H_0 = 68^{+14}_{-7}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

Evolution in Hubble



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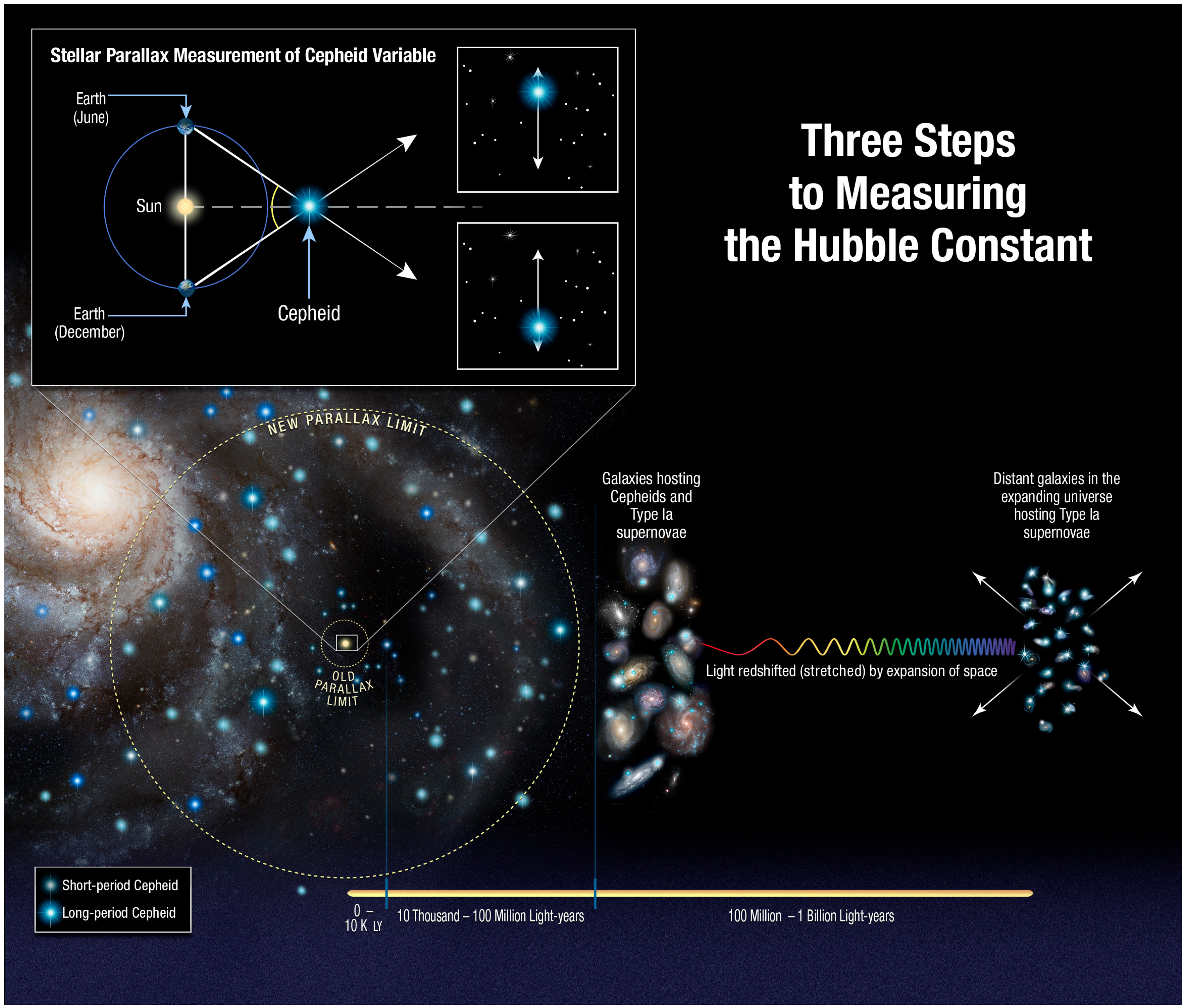
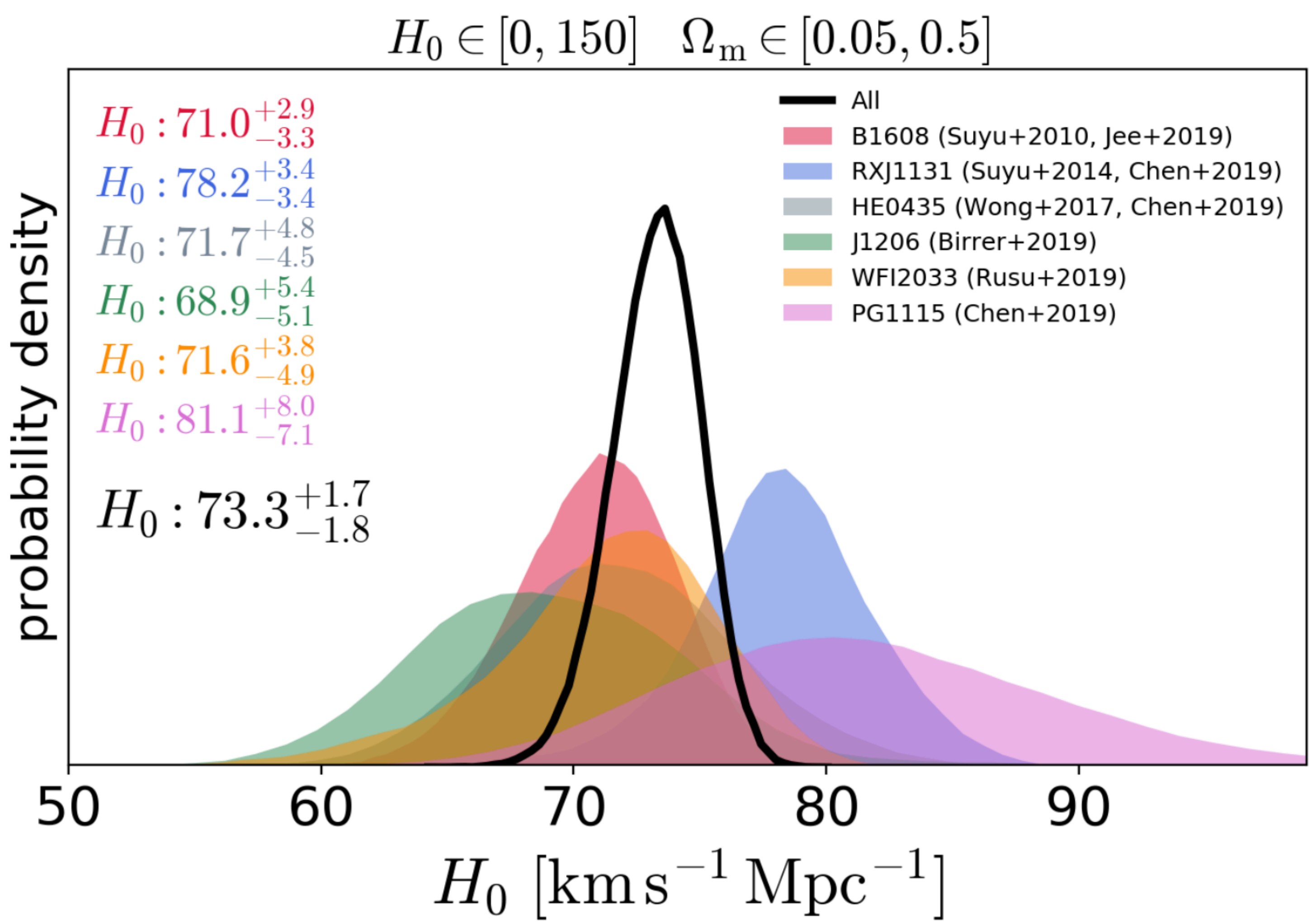


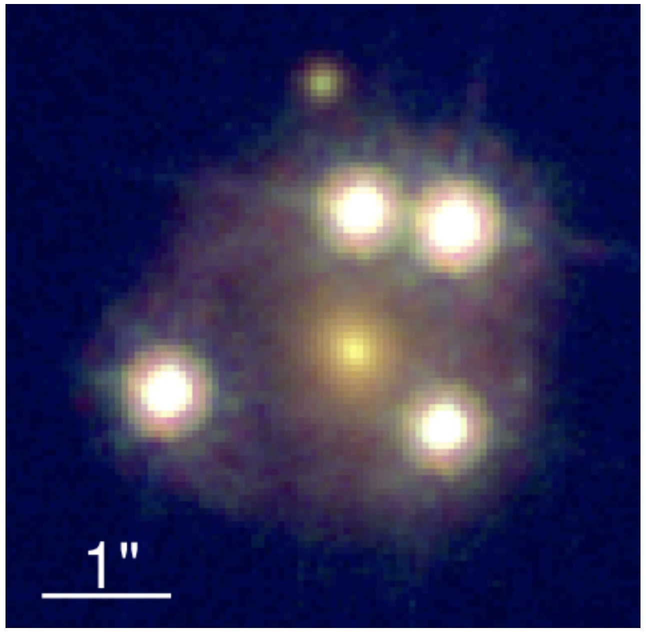
$$m_B - M = 25 + 5\log_{10}\left(\frac{d_L}{\mathrm{Mpc}}\right)$$

redshift range

$$0.0233 < z < 0.15$$

HOLiCOW





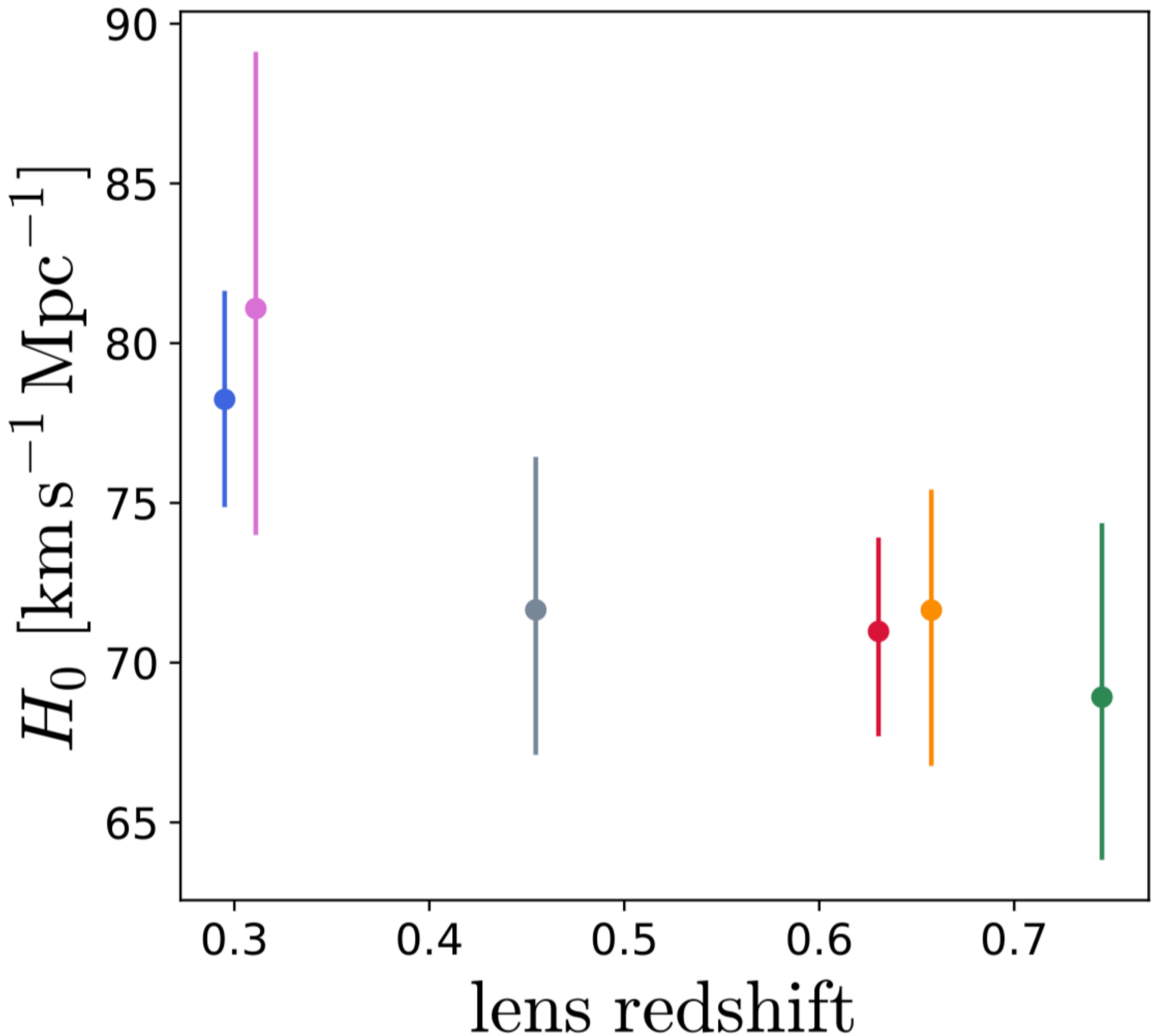
WFI2033-4723

$$(z_d, z_s) = (0.6575, 1.662)$$

Strong-lensing time delay

$$t(\theta, \beta) = \frac{(1 + z_d) D_d D_s}{c D_{ds}} \left[\frac{(\theta - \beta)^2}{2} - \psi(\theta) \right]$$

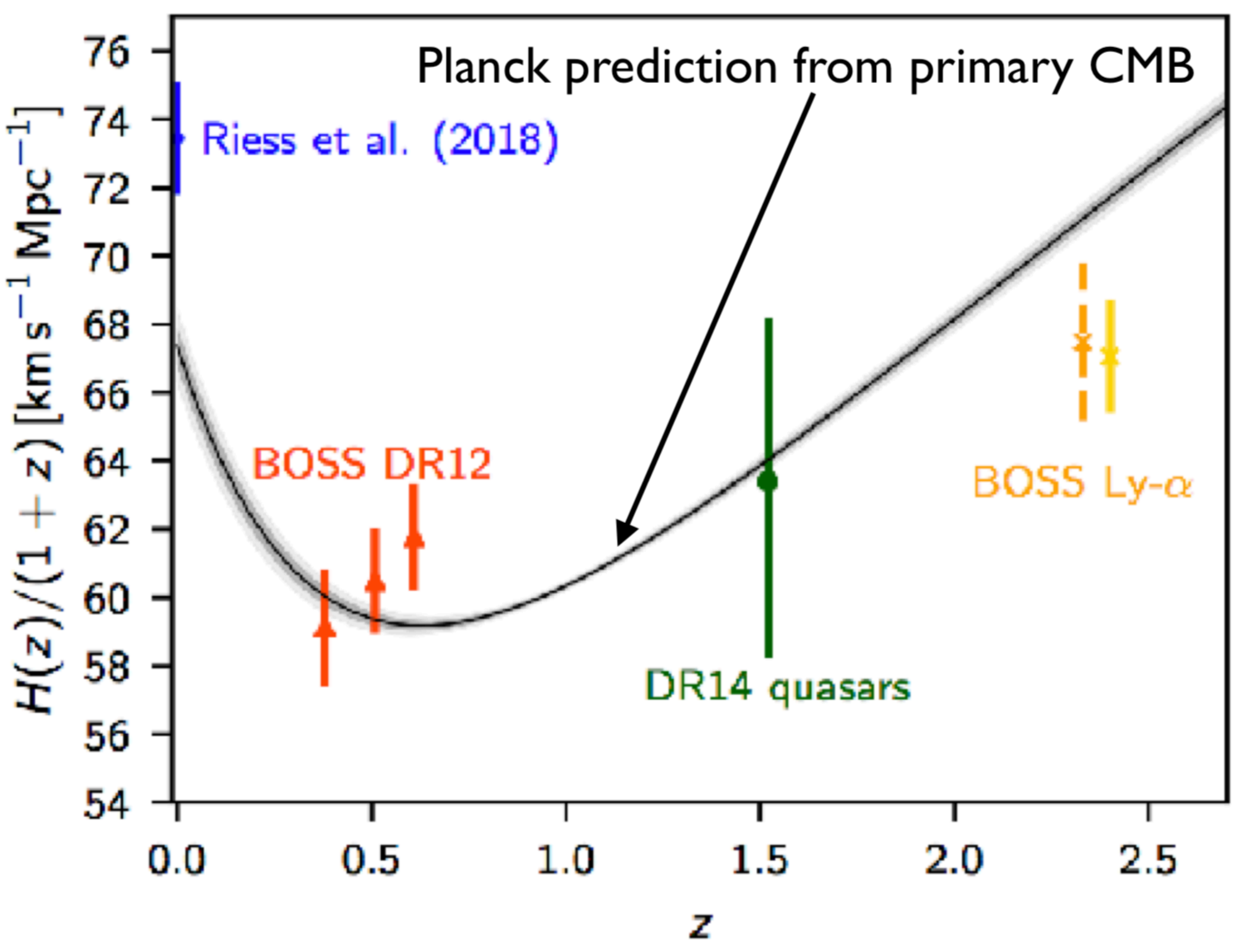
HOLiCOW

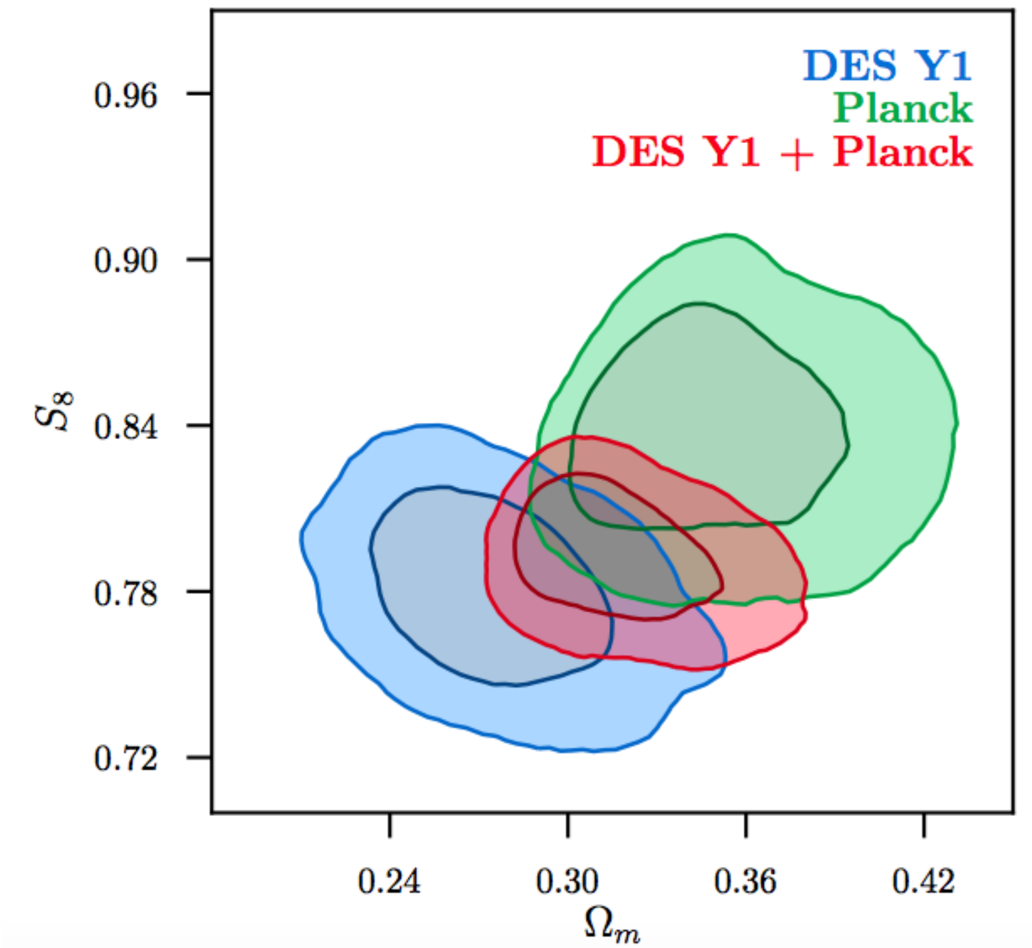


Interesting trend in Hubble with lens distance!!!

ΛCDM Tension

Other tensions exist around 2 **σ**.





$$S_8 = \sigma_8(\Omega_m/0.3)^\alpha$$

Intriguing puzzle: are we looking at new physics?

arXiv.org > astro-ph > arXiv:1903.07603

Search...

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Astrophysics > Cosmology and Nongalactic Astrophysics

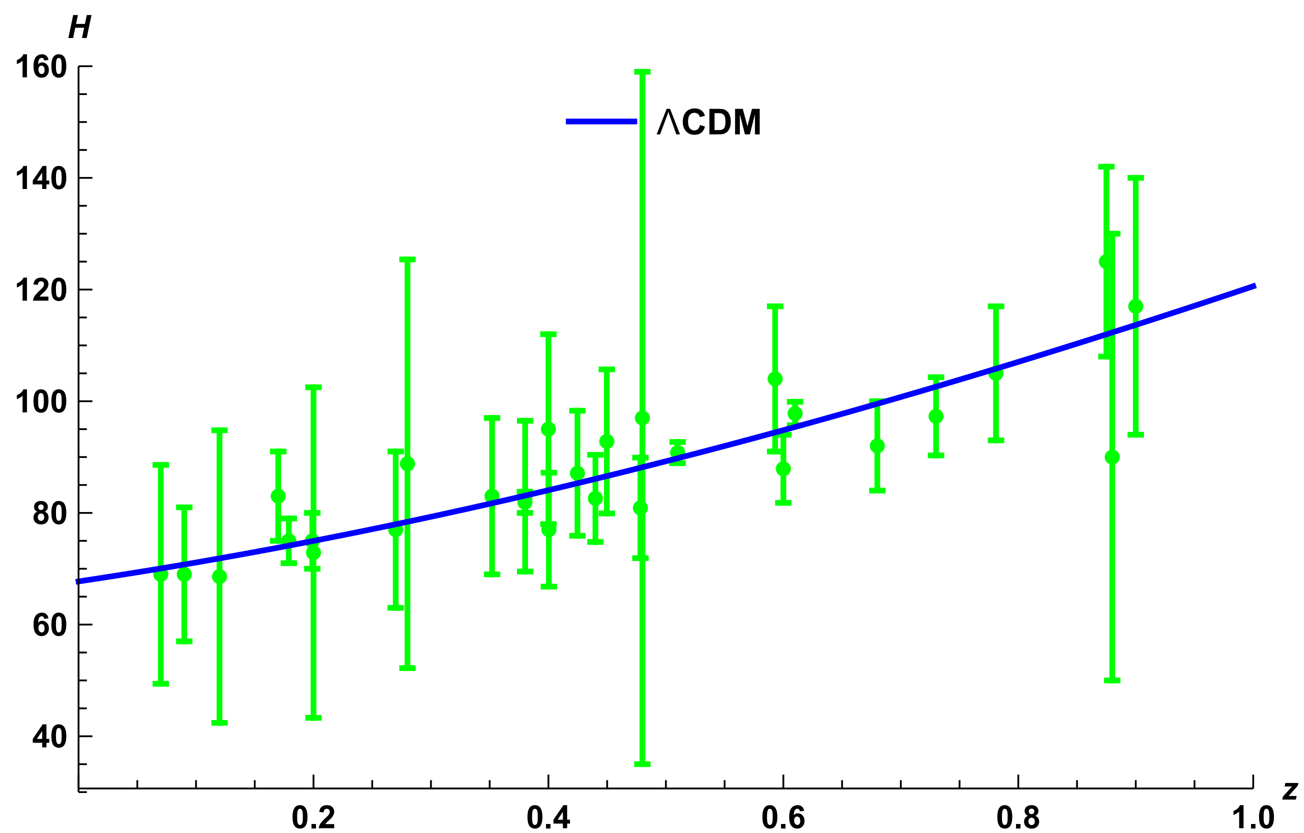
Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics Beyond LambdaCDM

Adam G. Riess, Stefano Casertano, Wenlong Yuan, Lucas M. Macri, Dan Scolnic

Standard model ΛCDM has only 6 parameters, cf. 19 in particle physics.

So as a theorist, one can expect a breakdown in ΛCDM.

New early physics



Cosmic chronometers, BAO data

$$H(z) = H_0\sqrt{1-\omega_m+\omega_m(1+z)^3} \qquad H_0 = 67.73 \pm 3.04, \quad \omega_m = 0.31 \pm 0.07$$

Preference for Planck $\qquad H_0 = 67.4 \pm 0.5, \quad \omega_m = 0.315 \pm 0.007$

New early physics

High Hubble appears to be in conflict with BAO.

BAO does not measure Hubble parameter directly.

$$H(z)r_d, \quad r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} \mathrm{d}z$$

Scalar field acting as early dark energy   Poulin et al. (2019)

Increase # of relativistic d. o. f. $N_{eff} \sim 4$

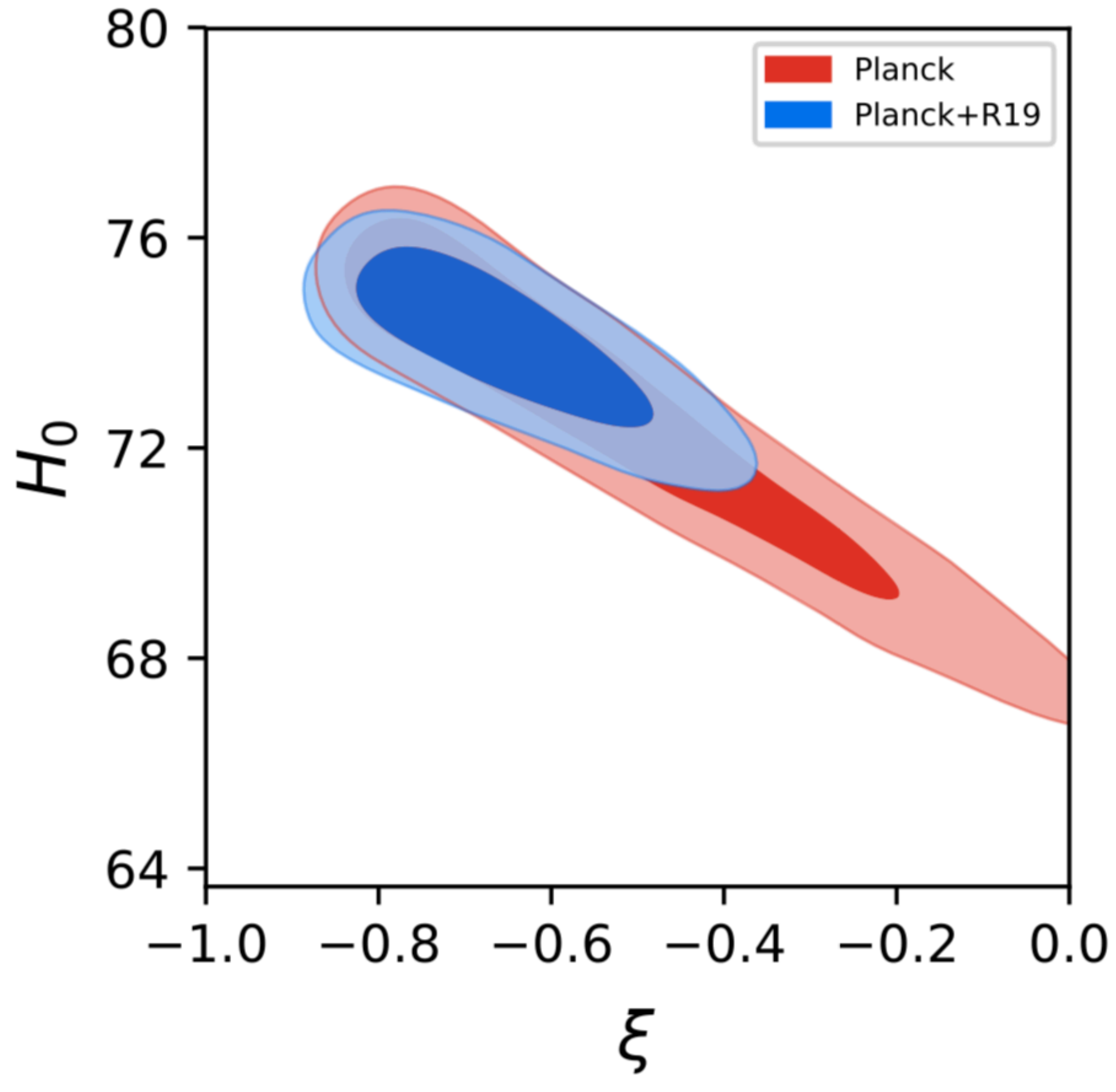
extra self-interacting neutrinos   Kreisch et al. (2019)

New late physics

Separate strategy: take all data at face value.

DM becomes DE at late times.

$$\dot{\rho}_c + 3H\rho_c = \xi H \rho_x,$$
$$\dot{\rho}_x + 3H(1+\omega)\rho_x = -\xi H \rho_x$$



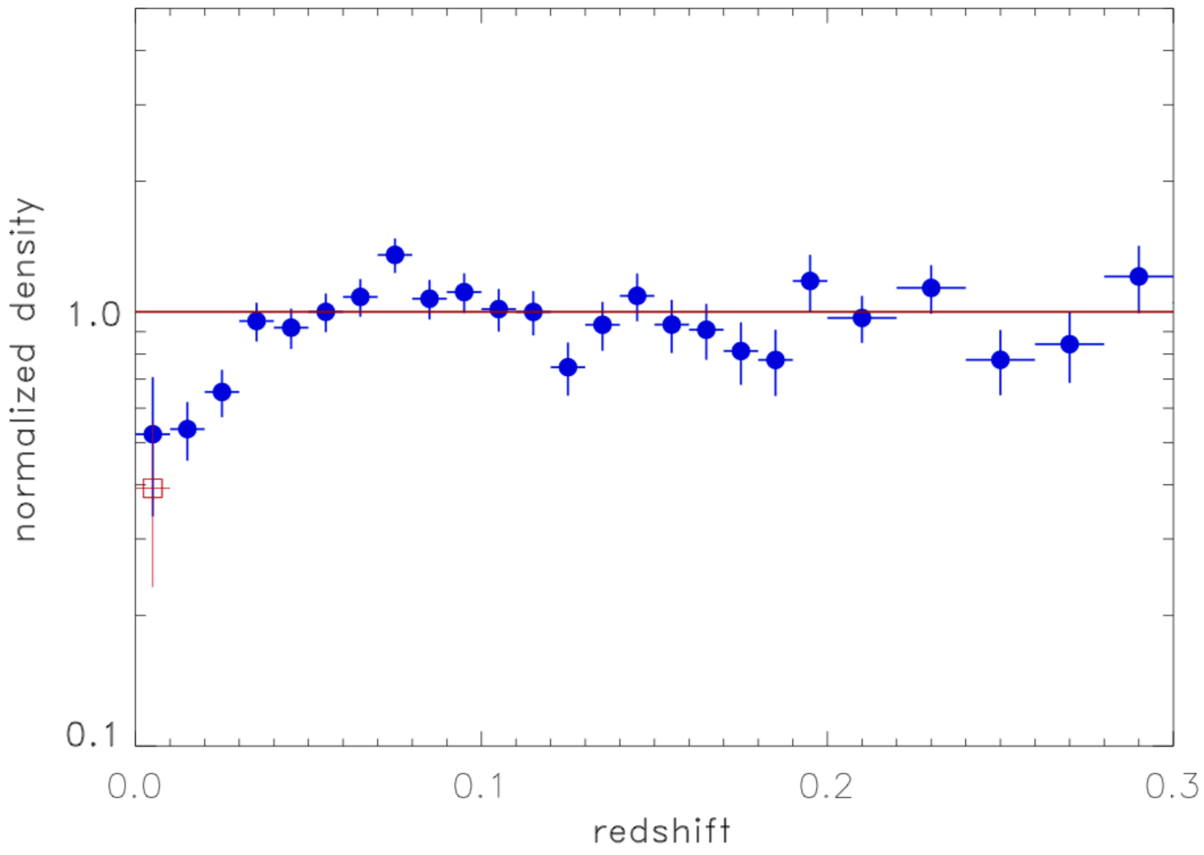
Di Valentino et al. (1908.04281)

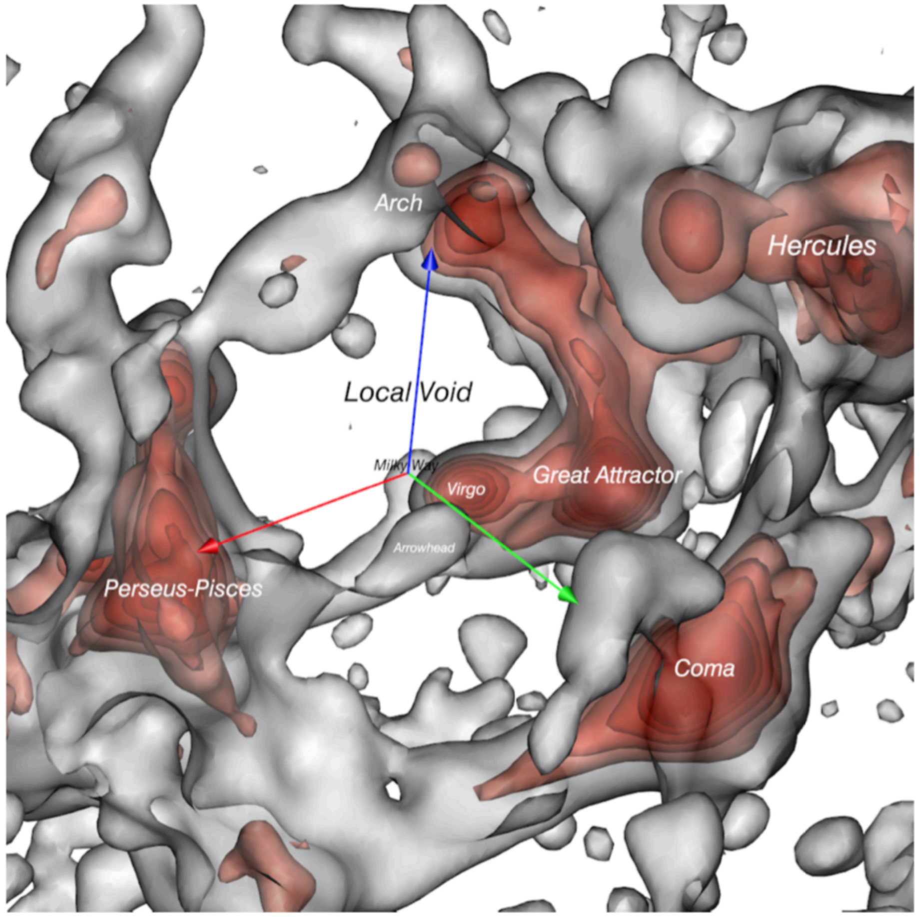
Something else?

Could there be a more mundane explanation?

Boehringer, Chon, Collins (1907.12402)

Underdensity $-30 \pm 15\,\%(-20 \pm 10\,\%) \quad 100(\sim 140)\mathrm{Mpc}$





CosmicFlows (1905.08329)

ΛCDM Tension in Type Ia?

Hint of an underdensity in best cosmological probe.

Distance modulus

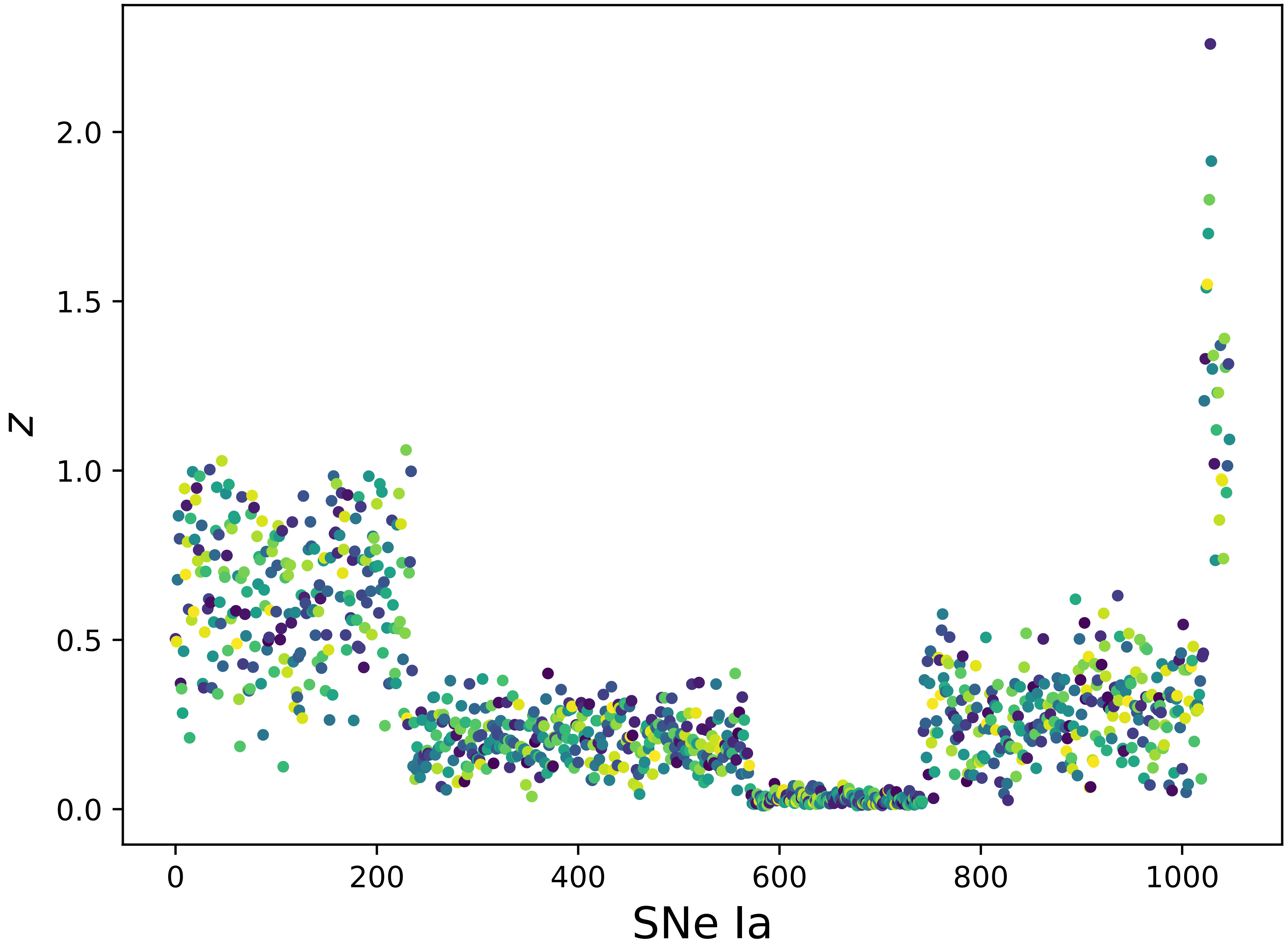
$$d_L(z) = c(1+z)\int_0^z \frac{\mathrm{d}z'}{H(z')}$$

"Hubble-Lemaître" law at low z

$$d_L \approx \frac{c}{H_0} z$$

$$\mu = m_B - M = 25 + 5\log_{10}\left(\frac{d_L}{\mathrm{Mpc}}\right)$$

Pantheon Dataset

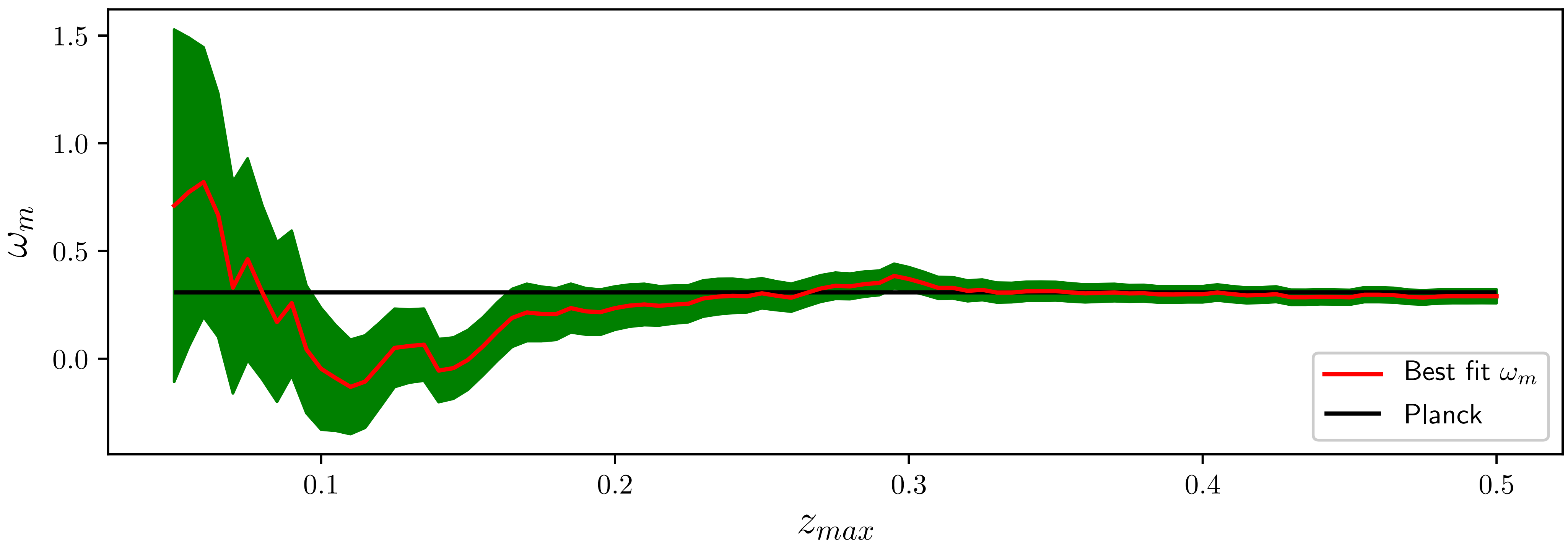


Scolnic et al. (2017)

However, ω_{m} appears to show running with z_{max}.

$$\chi^2 = \Delta\vec{\mu}^T \cdot \mathbf{C}^{-1} \cdot \Delta\vec{\mu}, \quad \Delta\vec{\mu} = \vec{\mu} - \vec{\mu}_{\mathrm{model}}(H_0, \omega_m)$$
$$\mathbf{C} = \mathbf{D}_{\mathrm{stat}} + \mathbf{C}_{\mathrm{sys}}$$

1903.11743 (JCAP)

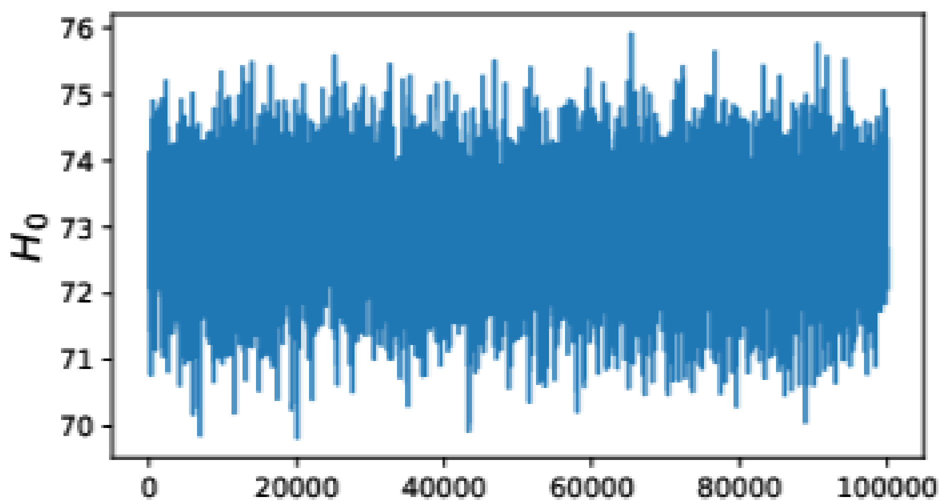


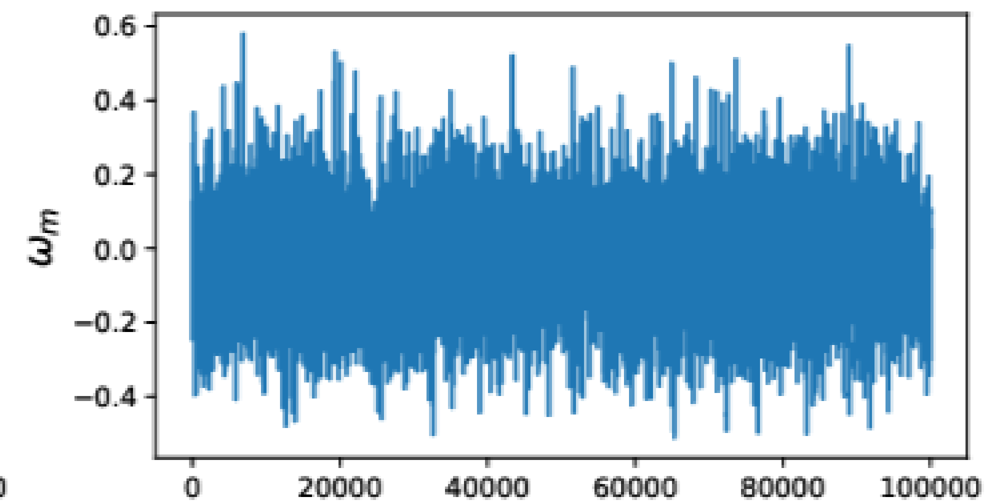
(Independently observed by M. van Putten, confirmed by D. Scolnic)

Underdensity in Riess et al. range of redshift?

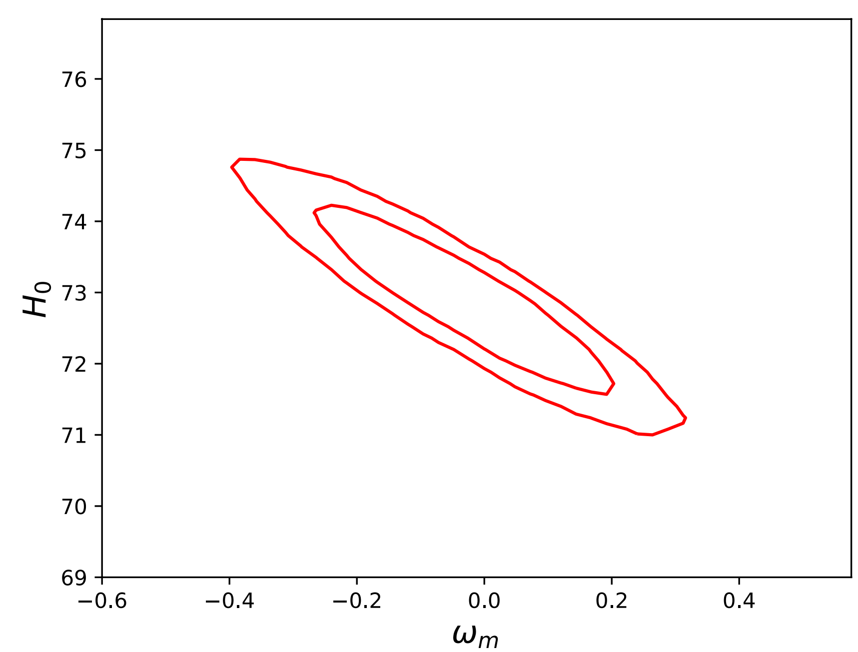
Statistical significance between 1- 2 **σ** in window.

Markov Chain Monte Carlo (100,000 iterations)





$$z_{\max} = 0.147$$



Astro2020 Science White Paper

The Next Generation of Cosmological Measurements with Type Ia Supernovae

Thematic Areas: Cosmology and Fundamental Physics

Scolnic & usual suspects (2019)

"In the 2020s, surveys will discover hundreds of thousands of SNe Ia across a large redshift range ($0 < z < 2$)..."

"The boost in statistics from ongoing/recent surveys will be on the order of 5× at low-z (owing to ZTF, Foundation, ATLAS, ASAS-SN and 2× at mid-z (owing to DES). The boost in statistics from future surveys will be on the order of 300× at mid-z (owing to LSST) and 1000× at high-z (owing to WFIRST). JWST will be able to extend to even higher redshifts, perhaps $z \approx 5$..."

Summary

Hubble (ΛCDM) tension is an exciting, fast developing field.

It is multidisciplinary (astronomy, data science, theory).

People are quick to make claims of new physics.

Likely resolution will be interdisciplinary.

Underdensity (personally) is quite compelling + needs study.

Universe may be “lumpier” than we imagine.