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 $\Lambda$CDM, 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)

\[ H_0 = 68^{+14}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1} \]
Evolution in Hubble
\[
m_B - M = 25 + 5 \log_{10} \left( \frac{d_L}{\text{Mpc}} \right)
\]

redshift range

\[
0.0233 < z < 0.15
\]
Strong-lensing time delay

\[ t(\theta, \beta) = \frac{(1 + z_d)D_dD_s}{cD_{ds}} \left[ \frac{(\theta - \beta)^2}{2} - \psi(\theta) \right] \]
Interesting trend in Hubble with lens distance!!!
Other tensions exist around $2\sigma$. 

$$S_8 = \sigma_8 (\Omega_m/0.3)^\alpha$$
Intriguing puzzle: are we looking at new physics?

Standard model $\Lambda$CDM has only 6 parameters, cf. 19 in particle physics.

So as a theorist, one can expect a breakdown in $\Lambda$CDM.
New early physics

\[ H(z) = H_0 \sqrt{1 - \omega_m + \omega_m (1 + z)^3} \]

\[ H_0 = 67.73 \pm 3.04, \quad \omega_m = 0.31 \pm 0.07 \]

Cosmic chronometers, BAO data

Preference for Planck

\[ H_0 = 67.4 \pm 0.5, \quad \omega_m = 0.315 \pm 0.007 \]
New early physics

High Hubble appears to be in conflict with BAO.

BAO does not measure Hubble parameter directly.

\[ H(z) r_d, \quad r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} \, dz \]

Scalar field acting as early dark energy \( N_{\text{eff}} \sim 4 \) \( \text{Poulin et al. (2019)} \)

Increase # of relativistic d. o. f.

extra self-interacting neutrinos \( \text{Kreisch et al. (2019)} \)
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 $-30 \pm 15 \% (-20 \pm 10 \%) \quad 100(\sim 140)\text{Mpc}$

CosmicFlows (1905.08329)
$\Lambda$CDM Tension in Type Ia?

Hint of an underdensity in best cosmological probe.

Distance modulus 

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

“Hubble-Lemaître” law at low $z$

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

$$\mu = m_B - M = 25 + 5 \log_{10} \left( \frac{d_L}{\text{Mpc}} \right)$$
However, $\omega_m$ appears to show running with $z_{\text{max}}$.

\[
\chi^2 = \Delta \bar{\mu}^T \cdot C^{-1} \cdot \Delta \bar{\mu}, \quad \Delta \bar{\mu} = \bar{\mu} - \bar{\mu}_{\text{model}}(H_0, \omega_m)
\]

\[
C = D_{\text{stat}} + C_{\text{sys}}
\]

\[1903.11743\ (\text{JCAP})\]

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

Underdensity in Riess et al. range of redshift?
Statistical significance between $1 - 2\sigma$ in window.

Markov Chain Monte Carlo (100,000 iterations)

$z_{\text{max}} = 0.147$
“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 ≈ 5…”
Hubble ($\Lambda$CDM) 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.