Lessons on solving the Hubble tension

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Approach: Discrepancy in the baryon sound horizon

See also Arendse et al. (2019), Aylor et al. (2018), Bernal et al. (2016), Verde et al. (2017)

Knox & Millea (2019)
How to modify the Baryon-Photon Sound Horizon

• Can either change the sound speed, or the Hubble rate at early times.

\[ r_s = \int_0^a \frac{\rho}{a^2 H(a)} \, da \]

Can we change the Hubble rate before recombination without ruining everything else?

\[ c_s = \frac{1}{\sqrt{3(1 + \frac{3\rho_b}{4\rho_\gamma})}} \]

\[ H^2(a) = \frac{8\pi G}{3} \sum_i \rho_i(a) \]
Sound horizon probe: BAO

BAO primarily measures 2 “processed” versions of the baryon-photon sound horizon.

Line of sight: \( H(\bar{z}) r_s \)

Transverse: \( r_s / D_A(\bar{z}) \)

BAO measurements are invariant under the change \( H(\bar{z}) \rightarrow fH(\bar{z}) \)
Canonical $N_{\text{eff}}$ alone doesn’t work...

- BAO and CMB prefers different trajectories in energy density space.
- BAO likes scaling solution $H(z) \rightarrow fH(z)$, CMB doesn’t.

Leaves BAO $\sim$invariant

Leaves BAO $\sim$invariant
Free-streaming neutrinos and the CMB

Baryon-photon perturbations interact with all relativistic species through their gravitational coupling

\[ d_\gamma(\tau, k) = 3\zeta_{in}(1 + \Delta_\gamma) \cos (\varphi_s + \delta \varphi) + O(\varphi_s^{-1}) , \]

where

\[ \Delta_\gamma \approx -0.2683 R_\nu + O(R_\nu^2) , \]

\[ \delta \varphi \approx 0.1912 \pi R_\nu + O(R_\nu^2) . \]

\[ R_\nu = \frac{\rho_\nu}{\rho_\gamma + \rho_\nu} \approx 0.403 \]

for \( N_{eff} \approx 3.046 \)

Cyr-Racine & Sigurdson (2014)

Bashinsky & Seljak (2004)
Follin et al. (2015)
Baumann, Green, Meyers & Wallisch (2016)
Choi, Chiang & Loverde (2018)
Beyond Free-streaming Neutrinos

New Unknown Interaction:

\[ \mathcal{L}_{\text{phen}} \supset -\frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} (g^{\alpha\beta}_\phi \nu_\alpha \nu_\beta \phi + \text{h.c.}) \]

See e.g. Cherry, Friedland & Shoemaker (2014), Ng & Beacom (2014), Blinov et al. (2019)

Cyr-Racine & Sigurdson (2014)
Oldengott et al. (2015)
Lancaster, Cyr-Racine, et al. (2017)
Oldengott et al. (2017)
Kreisch, Cyr-Racine, & Doré (2019)

4-Fermion Interaction stronger than Fermi constant

\[ G_\nu > G_F \]
interacting neutrinos can partially compensate for these physical baryon abundance, it was found that the most horizon, the epoch of matter-radiation equality, and the (see e.g. Ref. [117]) for the case of free-streaming neutrinos, increasing and in photons, respectively. The effects on the CMB of neutrinos is more visible in this case due to the sharp, well-defined peaks of the polarization spectrum [113]. This allows to directly see in which direction the spectrum is shifted compared to standard CDM since the oscillations in the residuals lean in the direction of the phase shift, that is, self-terms of $\sum m_\nu = 0.06\,\text{eV}$, $\Omega_b h^2$, $z_{eq}$, $\theta_*$.
Another possibility: Localized energy injection

- Need energy injection around matter-radiation equality.

Karwal & Kamionkowski, 2016
Poulin et al. (2018, 2019)
Agrawal, FYCR, Pinner, Randall (2019)
Lin et al. (2019)
Smith, Poulin & Amin (2019)
Planck 2018 model comparison

Planck 2018 +
BAO + Panth +
SH0ES

Interacting Neutrinos
Energy Injection
LCDM
General lesson #1

- The epoch between \( z = 10^3 \) and \( 10^4 \) seems to be key in addressing the current tensions. Is matter-radiation more involved than we think? Is this related to the \( \ell < 800 \) vs \( \ell > 800 \) discrepancy?
General lesson #2

- Adding energy before recombination always require a larger dark matter density and a larger scalar spectral index.
General lesson #3: Finding a satisfactory particle model is challenging

See also Ng & Beacom (2014) and Arcadi et al. (2018)

Blinov et al. (2019)
General lesson #3: Finding a satisfactory particle model is challenging

- It appears highly nontrivial to obtain the right potential shape (fine-tuning, breaking of perturbation theory, sensitivity to UV corrections)
Take Home Messages

• As precision increases, cracks might be appearing in the standard cosmological model.
• We have yet to identify a complete solution that is palatable to both cosmologists and particle physicists, but have found important clues about what a successful model would look like.

Thank you!