Enhanced recombination and the Hubble tension

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Outline

The main character: H_0

(Hubble, 1929)

$$Kr + X\cos\alpha\cos\delta + Y\sin\alpha\cos\delta + Z\sin\delta = v\ , \tag{1}$$

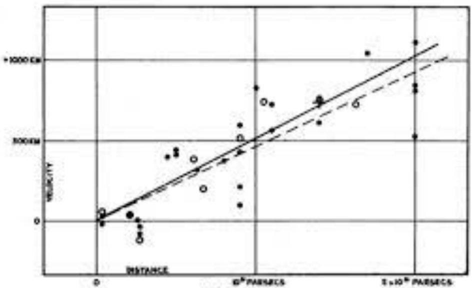


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

The main character: H_0

When $K \to H_0$ got the name "Hubble constant"? Probably (Sandage, 1958).
Hubble-Lemaître law (Lemaître, 1927):

$$v = H_0 r \; . \tag{2}$$

Hubble's original result:

$$H_0 = (465 \pm 50)\ \mathrm{km\ s^{-1}\ Mpc^{-1}} \; , \tag{3}$$

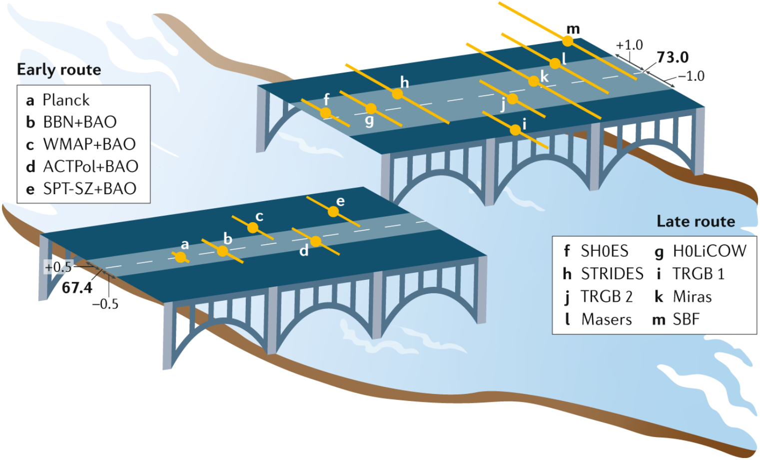
Previous investigation: (Lundmark, 1925)

$$X \cos\alpha \cos\delta + Y \sin\alpha \cos\delta + Z \sin\delta + k + lr + mr^2 - v = 0 \; . \tag{4}$$

Lundmark found $l \approx 10000\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$.
The Hubble parameter (and thus the Hubble constant) can be found implicitly already in (Friedmann, 1922).

What is the problem?

Discrepancy between inverse distance ladder measurements of H_0 and low redshifts ones.



Credits: Riess, Nat. Rev. Phys. 2 (2020) 10

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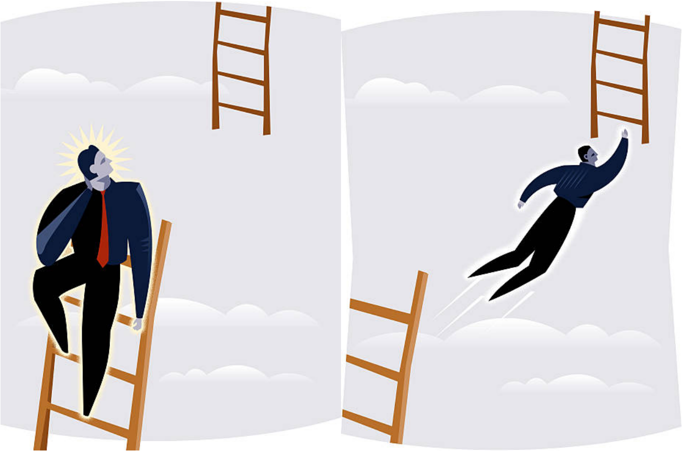


Credits: https://www.gettyimages.it

How is H_0 measured?

By measuring cosmological distances. These, in turn, are measured via fluxes and angles.

Benchwork: FLRW geometry $ds^2 = -dt^2 + a(t)^2\delta_{ij}dx^i dx^j$ (flat for simplicity here; taking into account spatial curvature does not solve the Hubble tension).

Expansion rate: $H(z) = H_0 E(z)$, with $E(z)$ depending on the matter content.
Comoving distance to a source at a redshift z:

$$\chi = \int_0^z \frac{dz'}{H(z')} = \frac{1}{H_0}\int_0^z \frac{dz'}{E(z')} \,. \tag{5}$$

Luminosity distance: $D_L(z) = (1+z)\chi$, angular-diameter distance $D_A(z) = \chi/(1+z)$.

Standard candles and standard rulers

Source of known luminosity L (standard candle) $\to$ luminosity distance via measurement of the flux f:

$$D_L = \sqrt{\frac{L}{4\pi f}} \,. \tag{6}$$

Source of known proper dimension s (standard ruler) $\to$ angular-diameter distance via measurement of the angular size θ:

$$D_A = \frac{s}{\theta} \,. \tag{7}$$

Given a cosmological model (FLRW geometry plus the matter content) we are able to determine H_0.

H_0 from the CMB

In the early universe there is a standard ruler: the speed of sound horizon:

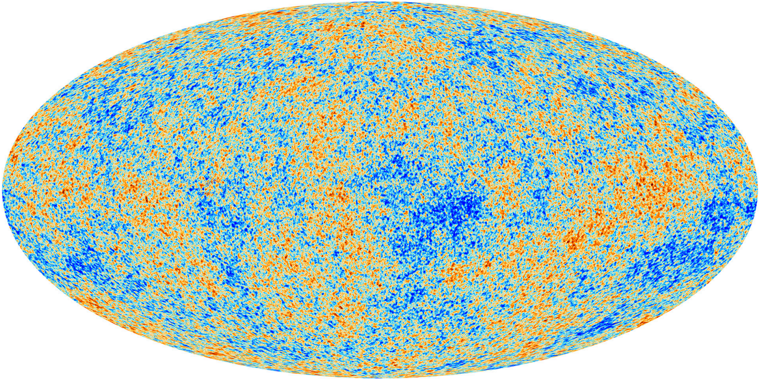
$$r_\star = \int_{z_\star}^{\infty} \frac{dz' c_s(z')}{H(z')} \; . \tag{8}$$

The speed of sound is that of the coupled baryon-photon fluid (coupled by Thomson scattering):

$$c_s^2 = \frac{1}{3[1+R(z)]} \; , \qquad R(z) \equiv \frac{3\Omega_b}{4\Omega_\gamma} \frac{1}{1+z} \; . \tag{9}$$

Write $H(z)^2 = \Omega_m H_0^2 (1+z)^3 + \Omega_r H_0^2 (1+z)^4$. The combinations $\Omega_i H_0^2$ are directly determined from CMB observation (they are 2 out of the 6 free parameters fitted to the CMB data), so $r_\star$ can be derived ($r_\star \approx 144$ Mpc). (Planck collaboration, 2018)

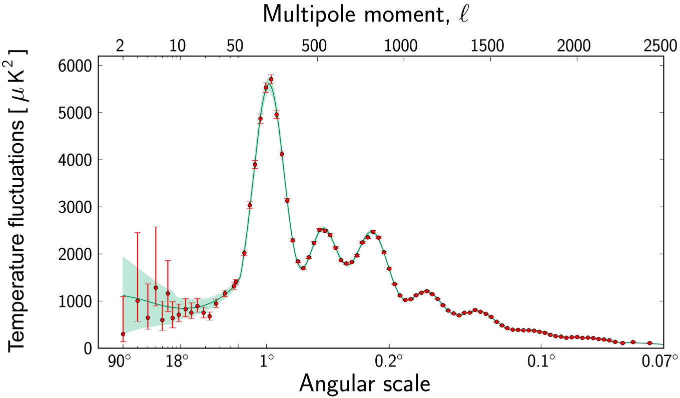
CMB sky



https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

H_0 from the CMB

We can actually (statistically) measure the angular size of $r_\star$ in the CMB sky (it is the first peak position). It is $\theta_\star$ (or θ_s), another one of the 6 free parameters fitted to the CMB data.



H_0 FROM THE CMB

Use the definition of the (comoving) angular-diameter distance:

$$\int_0^{z_\star} \frac{dz'}{H(z')} = D_A(z_\star) = r_\star/\theta_\star \,. \tag{10}$$

Here, $H(z)$ contains the contribution of dark energy (to which the CMB spectrum is practically insensitive). For the ΛCDM:

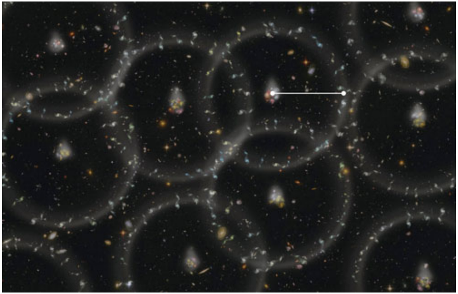
$$H(z)^2 = H_0^2[\Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda] \,. \tag{11}$$

So, adjust $\Omega_\Lambda H_0^2$ in order to match $D_A(z_\star) = r_\star/\theta_\star$. Then H_0 is determined.

Using Planck 2018 data, in particular $100\theta_\star = 1.04110 \pm 0.00031$ and $z_\star = 1089.92 \pm 0.25$, one gets $r_\star = 144.43 \pm 0.26$ Mpc and $H_0 = 67.36 \pm 0.54$ km s^{-1} Mpc^{-1} (all at 68% CL).

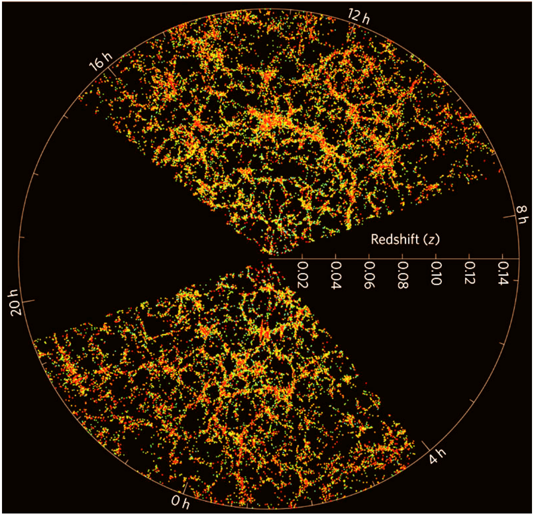
Late-times model-independent constraints
BAO and uncalibrated SNIa

A lot happens from z_* (roughly 0.4 Myr after the Big Bang) to $z = 0$ (today, roughly 14 Gyr after the Big Bang). We need extra constraints. Baryon acoustic oscillations (BAO) help us because their physics depends on $r_\star^{\rm drag} \approx r_\star$ (since photons and baryons were tightly coupled, but photons were many more).



https://astro.ucla.edu/~wright/BAO-cosmology.html

Galaxy distribution

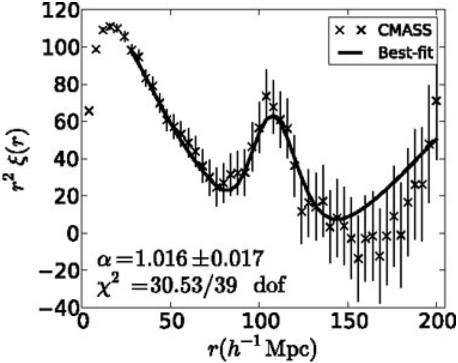


Credits: SDSS collaboration

BAO

The BAO angular and radial features also depend on $r_\star$ (they also are statistically determined):

$$r_\star^{\rm drag} = \theta_{BAO} D_A(z_{BAO}) \,, \qquad H(z_{BAO}) r_\star^{\rm drag} = \Delta z_{BAO} \,. \qquad (12)$$



https://ned.ipac.caltech.edu/level5/March14/Percival/Percival4.html

BAO and uncalibrated SNeIa constraints

BAO and uncalibrated SNeIa ("Hubble flow" SNeIa, very far, high z) allow to constrain $H_0 r_\star^{\rm drag}$ at different redshifts ($\ll z_\star$) $\rightarrow$ $H_0 = 67.66 \pm 0.42$ (using Planck 2018, for determining $r_\star^{\rm drag}$).

One can use this "inverse" cosmic ladder approach (from CMB down in redshift to SNIa) to calibrate SNeIa M_B (blue absolute magnitude). This is then found incompatible with the same M_B determined from the usual "direct" distance ladder (parallax-cepheids-SNeIa) (Camarena and Marra, 2021).

MODEL-INDEPENDENT CONSTRAINTS AND CMB

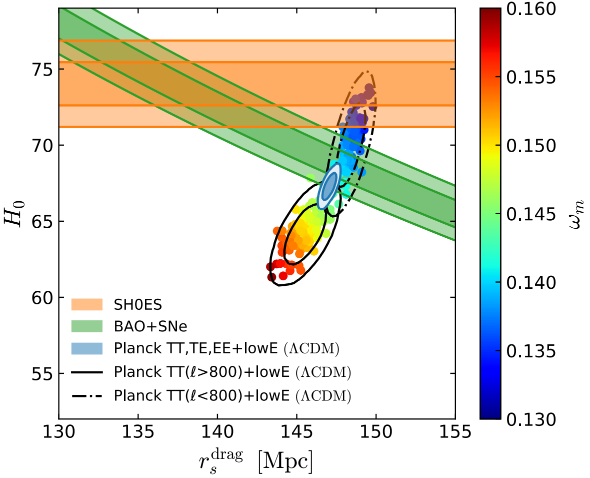


Fig. 1 of (Knox and Millea, 2020)

Example of concordance

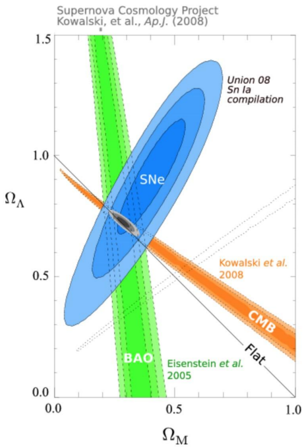
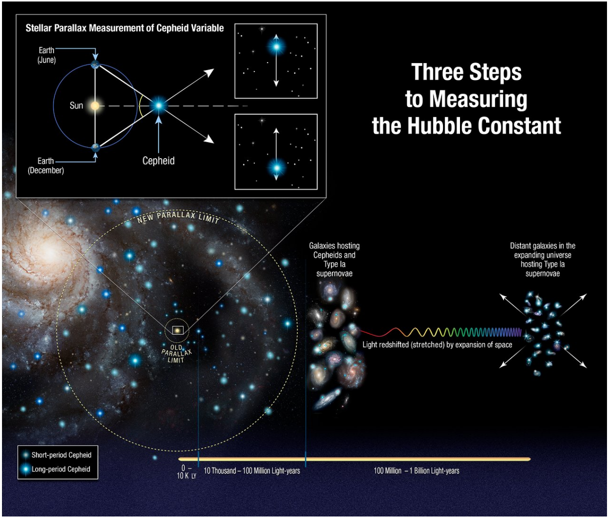


Figure 1: Empirical constraints on Ω_Λ and Ω_M cosmological parameters. Contours at 68.3%, 95.4%, and 99.7% confidence level (1, 2 and 3-σ) obtained from CMB, BAO, and the Union SN set (coloured regions), as well as their combination (grayscale region, assuming $w = -1$)

Local distance ladder



Credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

Local determination of H_0

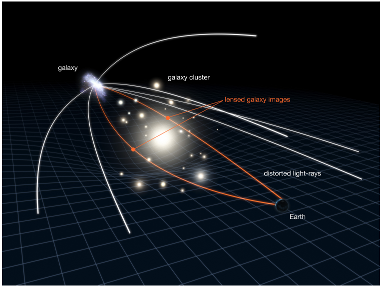
- 3 rungs parallax-cepheids-SNeIa: $H_0 = 73.2 \pm 1.3$ km s^{-1} Mpc^{-1} (SH0ES collaboration, Riess et al., 2021);
- Tip of the red giant branch (TRGB) instead of cepheids: $H_0 = 69.8 \pm 1.9$ (Freedman et al., 2019);
- H_0 from the time delay among lensed images: $H_0 = 73.3 \pm 1.8$ (H0LiCOW collaboration, 2018);
- Several other local (meaning low-z) determinations of H_0 compatible with the SH0ES one.

Comparing the above SH0ES result with the $H_0 = 67.36 \pm 0.54$ km s^{-1} Mpc^{-1} Planck result one estimates a 5σ tension.

The tension is to be intended as inverse distance ladder *vs.* low-z H_0 measurements. The latter might involve a "direct" distance ladder (SH0ES) or not (H0LiCOW).

Determination of H_0 via strong lensing time delays

Arrival time of each of the multiple images of quasars depends on different distances travelled, and hence on H_0. Refsdal's idea (Refsdal, 1964).



Credits: NASA and ESA

EASE THE TENSION
PROPOSED SOLUTIONS

100 pages of proposals: (Di Valentino et al., 2021). Spoiler: no one works.

General approach. Work on:

$$H_0 = \frac{\theta_\star}{r_\star} \int_0^{z_\star} \frac{dz}{E(z)} \,. \tag{13}$$

Only $\theta_\star$ is here directly measured (one out of the 6 parameters fitting CMB data). So, work on the rest:

- Reduce $r_\star \rightarrow$ modify the early-times history of the universe (e.g. increase N_{eff});
- Modify $E(z)$, i.e. the late-times history of the universe (e.g. $w < -1$).

Late-times solutions

New cosmological physics

- Phantom dark energy (Di Valentino et al., 2020);
- Interacting dark energy (Di Valentino et al., 2020);
- Decaying dark matter (Pandey et al., 2020);
- Running vacuum (Solá et al., 2017);
- Bulk viscosity (Yang et al., 2019)
- ...

Typically don't work because of constraints from BAO, SNIa and Cosmic chronometers. Essentially, deviations from the ΛCDM are not allowed.

Late-times solutions
New local physics

New Physics affecting the local calibration:

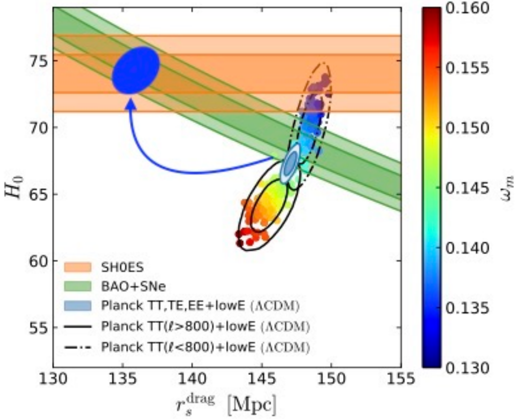
- Screened fifth forces (Desmond and Sakstein, 2020);
- Late-times transition in G_{eff} (Marra and Perivolaropoulos, 2021);
- Chameleon dark energy (Cai et al., 2021)

Still, the tension with H0LiCOW remains.

Another intriguing possibility is that the usual FLRW framework might need to be changed (Camarena et al. 2022). Drop the Copernican principle, use ΛLTB instead of FLRW.

Early-times solutions

The main idea is to reduce $r_\star$ (somehow).



Adapted from (Knox and Millea, 2020)

Early-times solutions

Work on:

$$r_\star = \int_{z_\star}^{\infty} \frac{c_\mathrm{s}(z)dz}{H(z)} \,. \tag{14}$$

Don't touch anything. Personal thoughts:

- In order to alleviate the Hubble tension, $r_\star \approx 138$ Mpc is sufficient, i.e. a value smaller than the *Planck* best fit of about 4%;
- The value $r_\star \approx 144$ Mpc is obtained already integrating up to $z \simeq 4 \times 10^5$. This suggests that there is no need of modifying the cosmological physics for larger redshifts.

The only relevant physical cosmological phenomenon that happens between $z \simeq 4 \times 10^5$ and $z_\star$ is recombination.

Early dark energy

E.g. some primordial scalar field (many references). Issues:

- Too *ad-hoc*, i.e. choose the "right" potential, the "right" initial conditions;
- It must eventually disappear (then, also *ad hoc*);
- Increases the S_8 tension (tension between how much matter we have and how much it clusters, basically);

In general (Ivanov et al. 2020) any new physics before recombination (meaning, a new matter component doing the job of easing the Hubble tension) unbalances the dark matter content worsening the S_8 tension.

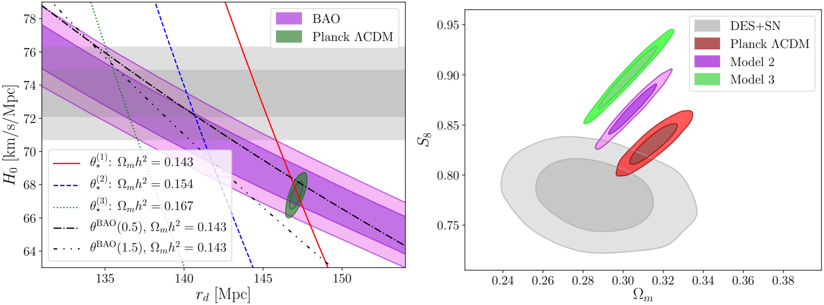
Early dark energy
Example

(Poulin et al., 2019)

$$\Omega_\varphi = \frac{2\Omega_\varphi(a_c)}{(a/a_c)^{3(w_n+1)} + 1} \, . \tag{15}$$

Seen as a scalar field, this is initially frozen, then it dilutes faster than matter.

General problem for early-times solutions



From (Jedamzik et al., 2021)

Enhanced recombination

Start again from:

$$H_0 = \frac{\theta_\star}{r_\star}\int_0^{z_\star}\frac{dz}{E(z)}\,, \quad r_\star = \int_{z_\star}^{\infty}\frac{dz'\,c_s(z')}{H(z')}\,. \tag{16}$$

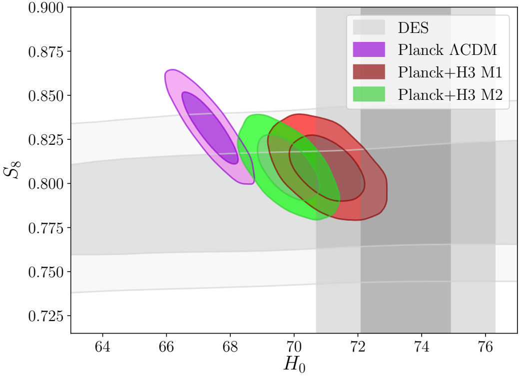
Don't touch anything. Just $z_\star$.
If you put $z_\star = 1166$ instead of $z_\star = 1090$ (an increase of 7%), you get $H_0 \approx 70$, so that would remove the tension.

However, recombination physics is very well established (Seager et al. 1999). How can one make it happen earlier?

Recombination codes: Recfast, CosmoRec, +++ (see `http://www.jb.man.ac.uk/~jchluba/Science/CosmoRec/Welcome.html`)

Enhanced recombination

Primordial magnetic fields (Jedamzik and Pogosian, 2020) might favour baryon clumping on very small scales, making recombination occur earlier.



From (Jedamzik and Pogosian, 2020)

Enhanced recombination

Baryon clumping model

This can be seen in general (i.e. phenomenologically, with no magnetic fields) and it also relieves the S_8 tension (Rashkovetskyi et al., 2021).

Main idea:

$$\frac{d(n_e a^3)}{dt} = -\alpha n_e^2 a^3 + \beta n_{2s} a^3 \ . \tag{17}$$

(Effective three-level recombination process).

Introduce inhomogeneities and perform a spatial average:

$$\langle n_e^2 \rangle \geq \langle n_e \rangle \ , \tag{18}$$

hence recombination is enhanced (in terms of $\langle n_e \rangle$).

Problem: conflict with the damping tail of the CMB spectrum (since the small-scale physics, photon diffusion, is modified).

New ideas?

Can using more complete (correct) kinetic equations help?
Example: $N_{\rm eff} = 2.92$ (Planck, 2018) $\rightarrow$ 3.044 (Froustey et al., 2020). Using the BBGKY hierarchy (truncated).
Usually, (Uehling and Uhlenbeck, 1933):

$$\frac{d(n_e a^3)}{dt} = \int d\Pi (2\pi)^4 \delta^{(4)}(P_f - P_i) |\mathcal{M}|^2_{\mathrm{H}+\gamma\rightarrow e^-+p^+} f_H f_\gamma (1-f_e)(1-f_p) - \int d\Pi (2\pi)^4 \delta^{(4)}(P_f - P_i) |\mathcal{M}|^2_{e^-+p^+\rightarrow \mathrm{H}+\gamma} f_e f_p (1+f_{\mathrm{H}})(1+f_\gamma) \,, \quad (19)$$

where

$$d\Pi \equiv \frac{d^3 p_e}{(2\pi)^3 2E_e} \frac{d^3 p_p}{(2\pi)^3 2E_p} \frac{d^3 p_{\mathrm{H}}}{(2\pi)^3 2E_{\mathrm{H}}} \frac{d^3 p_\gamma}{(2\pi)^3 2E_\gamma} \,. \quad (20)$$

Note the Bose enhancement and Pauli blocking contributions. The latter are typically negligible ($n_b \ll n_\gamma$). The former is taken into account in the rate α (it corresponds to the stimulated emission Einstein coefficient).

Enhanced recombination

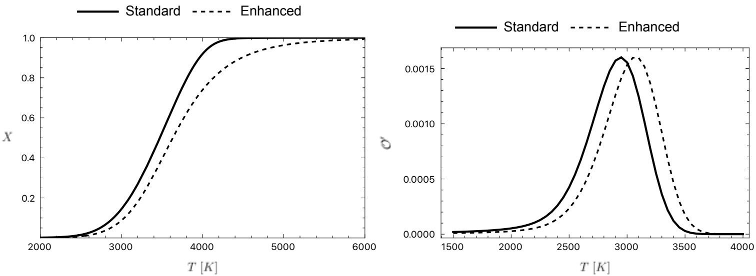
Naively, taking into account the quantum statistical contributions one might expect the standard recombination equation:

$$\frac{dX}{dT} = \frac{\alpha n}{HT} C_{\mathrm{rec}}[X^2 - (1 - X)/S] \,, \tag{21}$$

to be corrected as:

$$\frac{dX}{dT} = \frac{\alpha n}{HT} C_{\mathrm{rec}}[X^2(2 - X) - (1 - X)^3/S] \,. \tag{22}$$

Enhanced recombination



The new peak occur at $z_\star \approx 1120$.
Using this, one finds $r_\star \approx 141$ Mpc. This provides $H_0 \approx 69$ km/s/Mpc, a slightly larger value which alleviates the Hubble tension (from 4.2σ to about 2σ).

But

Actually the correction:

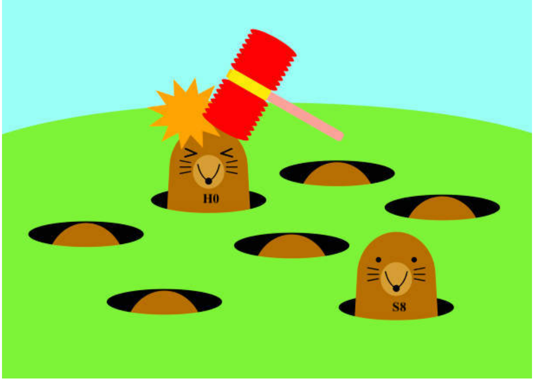
$$\frac{dX}{dT} = \frac{\alpha n}{HT} C_{\rm rec}[X^2(2-X) - (1-X)^3/S] \,, \tag{23}$$

though helps, cannot be motivated by the Bose enhancement and Pauli blocking contributions. The former is already taken into account in the standard calculation, whereas the latter is negligible for electrons and protons at the temperatures relevant to recombination.

So, work in progress. Keep trying.

Advantage: not modifying the small-scale physics does not tamper with the CMB spectrum damping til.

Conclusions



Credits: Analogy taken from a talk by Sunny Vagnozzi

Conclusions

- The Hubble tension is quite a conundrum;
- A possible solution should take into account and be compatible with all datasets;
- A possible solution should not worsen the S_8 tension, but preferably solve it as well;
- A possible solution should be well-motivated and not *ad hoc*;

Perspectives

- Early-times solutions of the Hubble tension must fix into the very well understood pre-recombination physics, without spoiling it. This is very difficult.
- Perhaps tiny changes in the collisional term of the Boltzmann equation taking into account correlations might help?
- Perhaps there is more room for late-times solutions;
- Perhaps there is no **the** solution, but a combination of small corrections (both at early- and late-times) will solve the tension.