Tonale Winter School on Cosmology 2023
Working group questions – Cosmological Tensions

Sunny Vagnozzi

1 Basics of theoretical and observational cosmology

- Solve the first Friedmann equation for an empty ($\Omega_m = \Omega_\Lambda = \Omega_r = 0$), closed Universe ($k = +1$). Does your answer make sense? Why or why not?
- Consider an Universe filled with only radiation (or matter, as you prefer). Usually it is tacitly assumed that the first Friedmann equation applied to this case describes an *expanding* Universe. But is this the end of the story?
- Let's imagine the Universe expanded faster than expected during the radiation era (e.g. as parametrized by the effective number of neutrinos $N_{\text{eff}} > 3.046$). Would we end up with more or less Helium today?
- Why is there a 4 on the right-hand side of the Poisson equation ($4\rho_\gamma$ and $4\rho_\nu$)? Where does it come from physically speaking?
- Consider a spatially flat FLRW Universe, filled with only matter and dark energy. Let's say I raise H_0 (while keeping Ω_m fixed). Does the first CMB peak move to the left, to the right, or stays fixed?
- What about the turnaround in the matter power spectrum?
- What about the acoustic peak in the 2-point correlation function?
- Now let's start from a spatially flat model with matter density parameter $\Omega_m = 1$. Let's say I start trading matter Ω_m for dark energy with $\Omega_\Lambda = 1 - \Omega_m$, ending up with something like $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ (while keeping H_0 fixed). Does the turnaround in the matter power spectrum move to the left, to the right, or stays fixed?
- What about the acoustic peak in the 2-point correlation function?
- Do you think the CMB can constrain the dark energy equation of state w? Why or why not?
- Let's say Euclid or DESI tells us that dark energy is not a cosmological constant, i.e. $w(z) \neq -1$. Do you think this would eliminate the cosmological constant problem? Why or why not?
- Let's say we want to study the effect of raising or lowering Ω_Λ on cosmological observations. We can choose to work in a basis where our parameters are $\Omega_m h^2$ and Ω_Λ, or h and Ω_Λ – so in both cases, Ω_Λ is raised or lowered while keeping the other parameter fixed. I would argue that the latter choice of basis is not a good one if we are looking at the CMB. Why?
- Usually it is assumed that T_0, the CMB temperature today, is exquisitely measured and hence treated as fixed. What would be the effect on the CMB power spectrum if one changed T_0?
- If future experiments measure a non-zero tensor-to-scalar ratio r, would this confirm inflation?
- Do you know of any alternatives to inflation? Which ones?
- Do you know any models beyond ΛCDM? Which ones?

2 Measuring the Hubble constant – the Hubble tension

- The first estimate of the Hubble constant from Hubble himself was grossly wrong, of order 500. Use geological arguments to show that this number cannot be right, and to estimate an upper limit on H_0.
- What is the physical interpretation of the units km/s/Mpc?
- How do you think we could use black hole shadows to measure H_0?
- Let's say the photon equation of state is $w_\gamma \neq 1/3$. What implications do you think this would have for the acoustic angle θ_s?
- Do you know what is the neutrino-induced phase shift in the CMB acoustic peaks?
- Analyses in cosmology are typically done within a Bayesian framework. What do you think is the reason for this? And doesn't this introduce the problem of priors? Is there value in looking at different frameworks?
- How do you address unknown unknowns in systematics?

3 How (not) to solve the Hubble tension?

- BAO measurements are sometimes argued to potentially be model-dependent, because of fiducial cosmology assumptions (usually ΛCDM) in the data reduction process. Reflect on where, why, and how one has to assume a fiducial cosmology in obtaining BAO measurements.
- What about other late-time measurements, e.g. cosmographic SNeIa? Are they more or less (potentially) model-dependent?
- Have you ever heard about cosmic chronometers? Do you think they are model-dependent?
- Let's say we are concerned about the BAO model-dependence, and were to drop them. Do you think there would be room for late-time (new physics, i.e. not systematics) modifications to ΛCDM to completely solve the Hubble tension?
- Consider a super-late-time dark energy transition ("hockey-stick dark energy"), occurring below the redshift of the lowest SNeIa in the PantheonPlus sample. This would be consistent with BAO+SNeIa, and would naïvely solve the Hubble tension. Actually, it doesn't really work. Why? While you reflect on this,

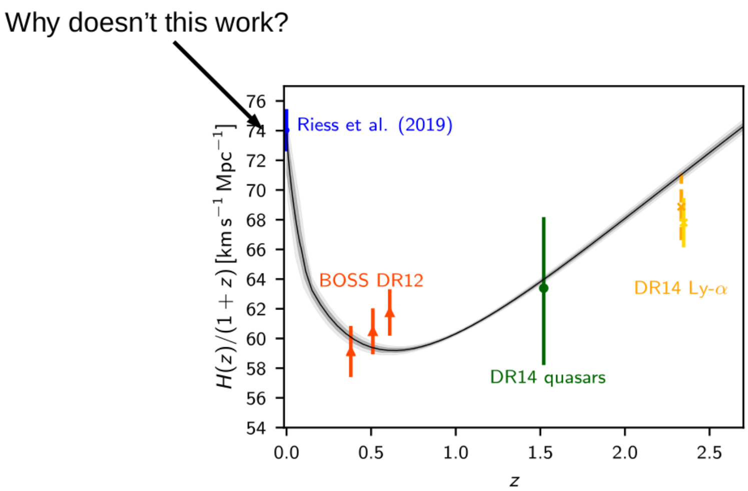

Figure 1: Credits for this Figure go to Marius Millea.

come up with a reason why this model is called hockey-stick dark energy.

- We saw that the Hubble tension is best rephrased as a tension between calibrators – r_s for BAO and M_B for SNeIa. Look at the above figure. Could you imagine some crazy oscillations going in between the BAO and SNeIa datapoints and solving the tension while remaining consistent with both the ΛCDM calibration for r_s, and the SH0ES calibration for M_B? What would be the problems for such an "ugly" solution? I can think of at least three problems, can you come up with more?

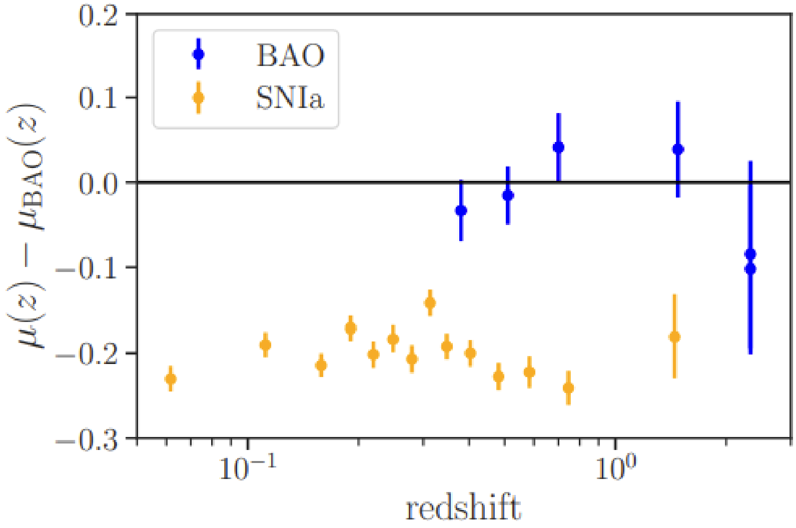

Figure 2: Figure from Tutusaus, Kunz & Favre, `arXiv:2311.16862`.

- If there is a sufficiently huge modification to $H(z)$ at extremely early times (say, way before BBN), this would affect r_s while being completely consistent with (the complete lack of pre-BBN) data. Why then are we just looking for modifications around recombination to reduce r_s? What would be the main problem with a super-early-time modification?
- Why does EDE require a higher value of ω_c (think about the early ISW effect)?
- The ratio of the matter power spectrum $P(k)$ in EDE (with a high value of ω_c) versus ΛCDM is given below. In principle, you could think that some new physics might "absorb" this excess clustering and help

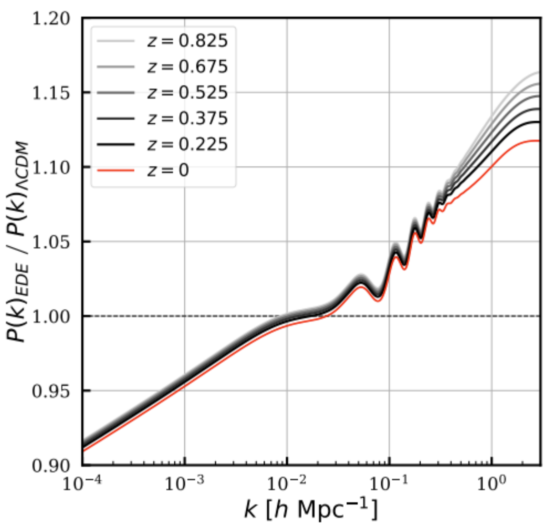

Figure 3: Figure from Hill, McDonough, Toomey & Alexander, Phys. Rev. D **102** (2020) 043507 [`arXiv:2003.07355`].

EDE. What is one of the simplest examples of such new physics that comes to your mind? A figure with an answer is given in the last page of these questions, but don't peek yet! Do spend some time thinking about it. Consider then the model I have shown in the Figure. It turns out that such a model doesn't work when combined with EDE. Why do you think is the case?

- Besides r_s there is another scale imprinted in the clustering of matter, $k_{\rm eq}$. Do you think this can play an important role in the Hubble tension discussion?
- What do you think can be done about prior volume effects?

4 Other tensions and challenges for ΛCDM

- Do you know of any other tensions and challenges for ΛCDM beyond the Hubble tension? (note: we'll discuss these tomorrow anyway, but the timing of the workshops are a bit unfortunate in this sense)
- Even if you haven't heard about all the tensions I will discuss in the next lecture, I'm sure you will have heard about the S_8 tension. Have you ever heard of "dark scattering"-type modifications to ΛCDM? Why do you think they are potentially interesting in the context of the S_8 tension?
- There is a fundamental difference between the H_0 and S_8 tensions, and therefore in the way we should assess the viability of models which can solve the S_8 tension. Can you think of what this important difference is?
- Why is the age of the Universe (today or at high redshift) a potentially important actor in the Hubble tension discussion?
- Do you think ΛCDM is: alive and kicking; dying; already dead?

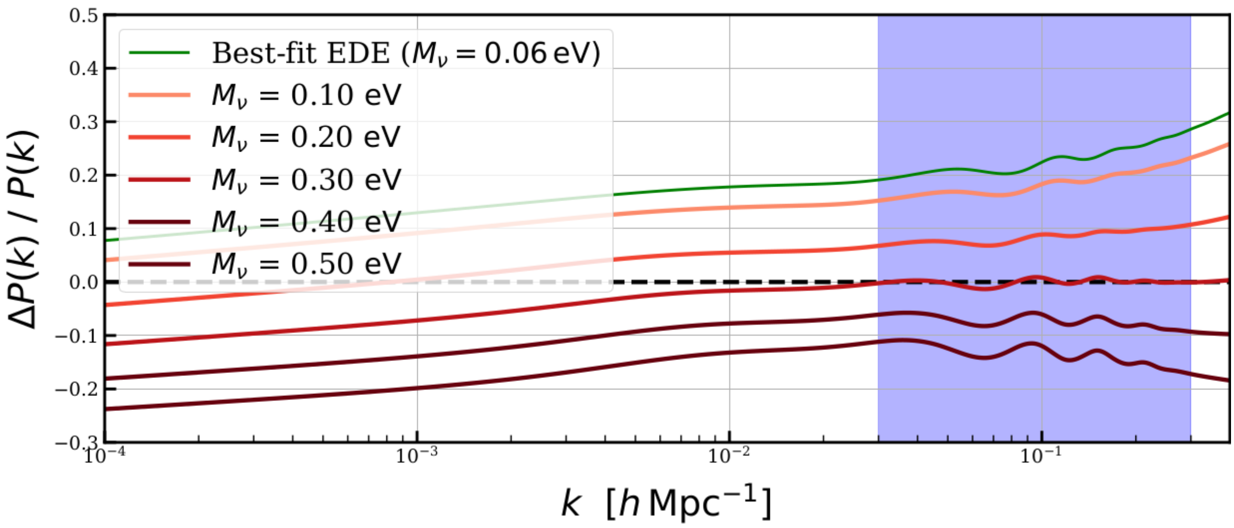

Figure 4: Credits for this figure go to my former student Alex Reeves (who did his Master's with me, George Efstathiou, and Blake Sherwin in Cambridge). You can read the paper that came out of his work, which also answers the question I asked, here: Reeves, Herold, Vagnozzi, Sherwin & Ferreira, Mon. Not. Roy. Astron. Soc. **520** (2023) 3688 [`arXiv:2207.01501`].