Lessons on solving the Hubble tension

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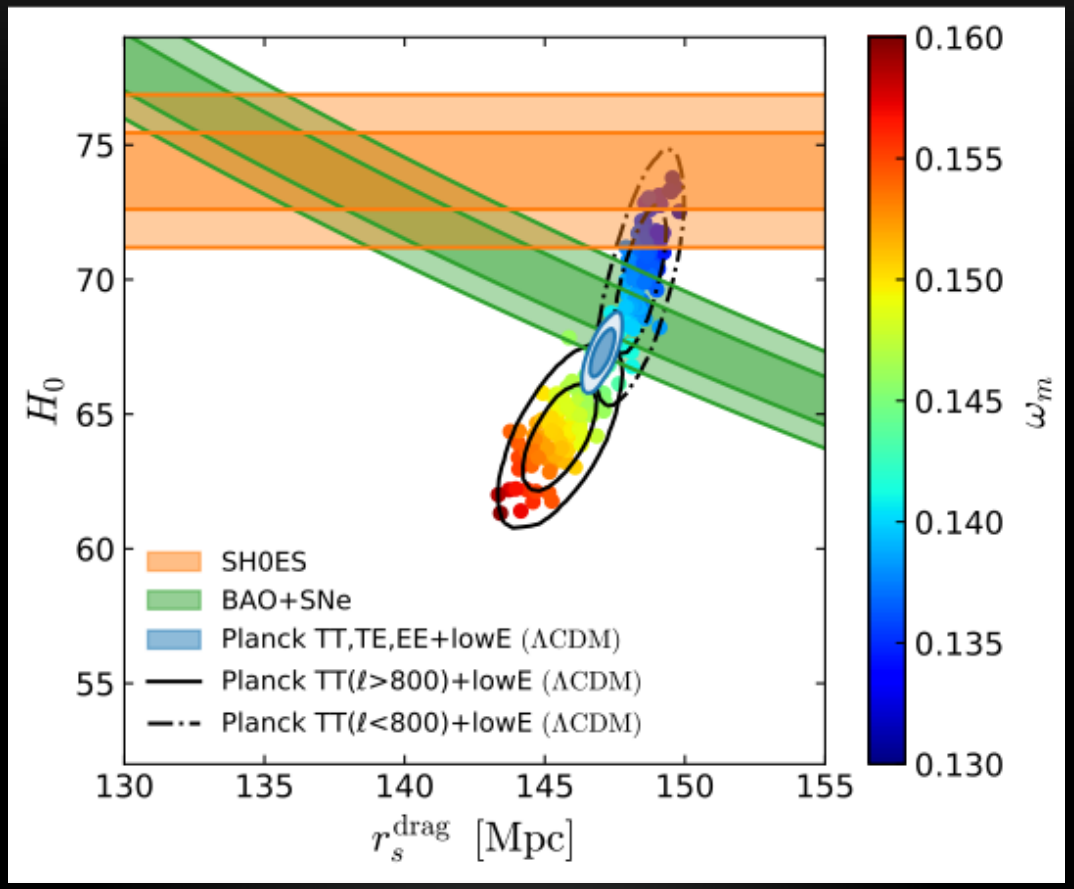
Approach: Discrepancy in the baryon sound horizon



Knox & Millea (2019)

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

How to modify the Baryon-Photon Sound Horizon

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

$$c_{\rm s} = \frac{1}{\sqrt{3(1+\frac{3\rho_{\rm b}}{4\rho_\gamma})}}$$

$$r_{\rm s} = \int_0^{a_{\rm d}} da \frac{c_{\rm s}(a)}{a^2 H(a)}$$

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

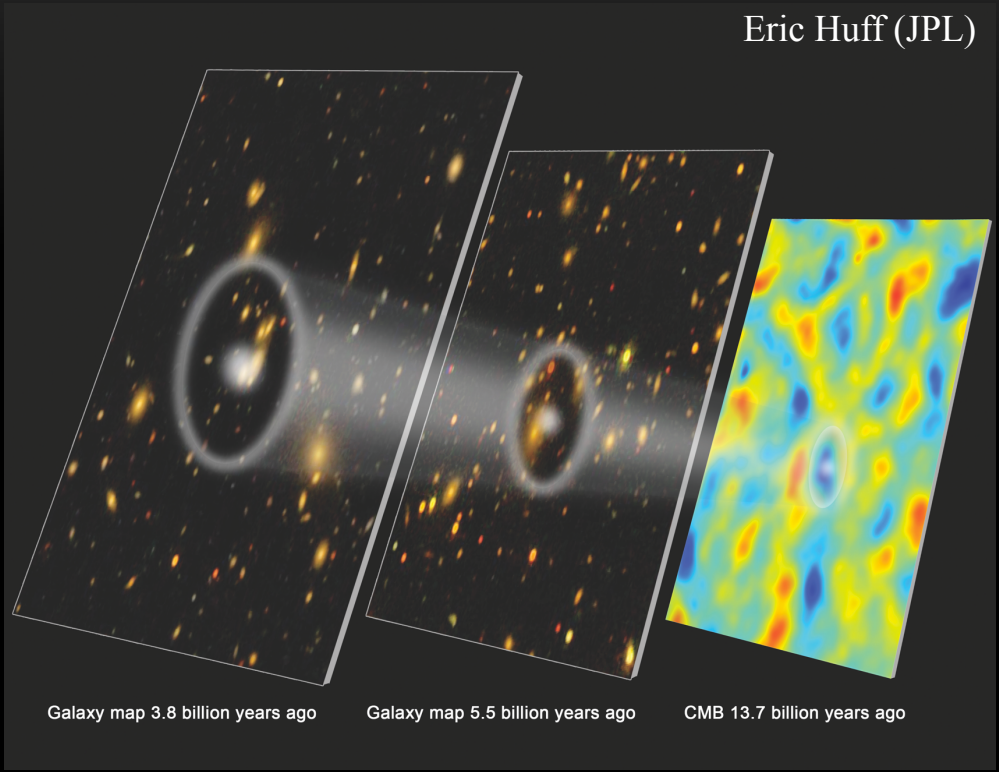
$$H^2(a) = \frac{8\pi G}{3} \sum_i \rho_i(a)$$

Sound horizon probe: BAO

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

Line of sight: $H(z)r_{\rm s}$

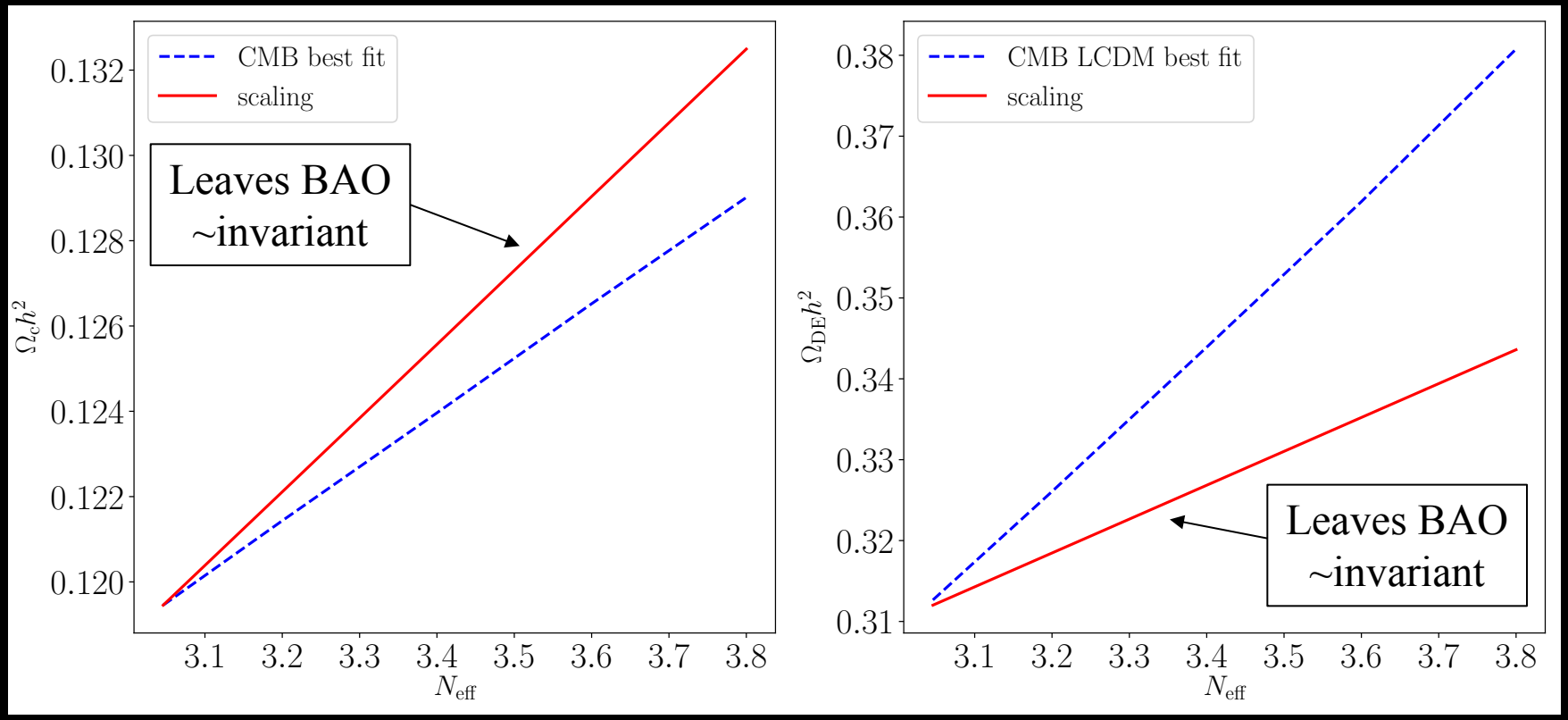
Transverse: $r_{\rm s}/D_A(z)$



BAO measurements are invariant under the change $H(z) \to f H(z)$

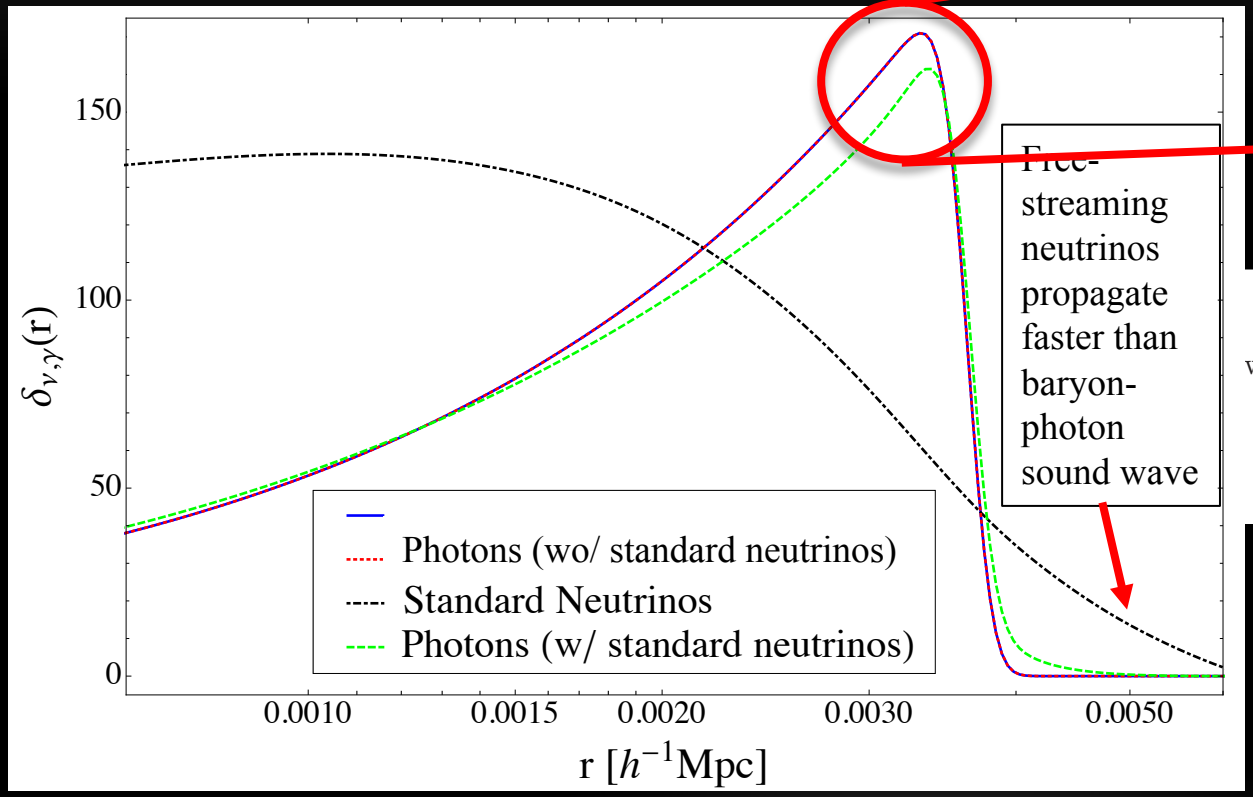
Canonical $N_{\rm eff}$ alone doesn't work…

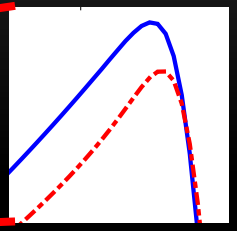
- BAO and CMB prefers different trajectories in energy density space.
- BAO likes scaling solution $H(z) \to f H(z)$, CMB doesn't.



Free-streaming neutrinos and the CMB

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





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

where

$$\Delta_\gamma \simeq -0.2683 R_\nu + O(R_\nu^2),$$

$$\delta\varphi \simeq 0.1912\,\pi R_\nu + O(R_\nu^2).$$

$$R_\nu = \frac{\rho_\nu}{\rho_\gamma+\rho_\nu} \simeq 0.403$$

for $N_{\rm eff} \simeq 3.046$

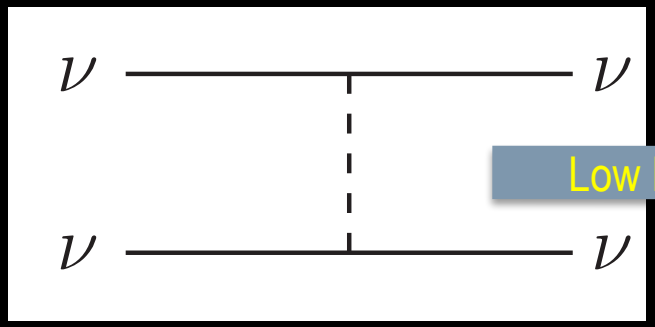
Cyr-Racine & Sigurdson (2014)

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

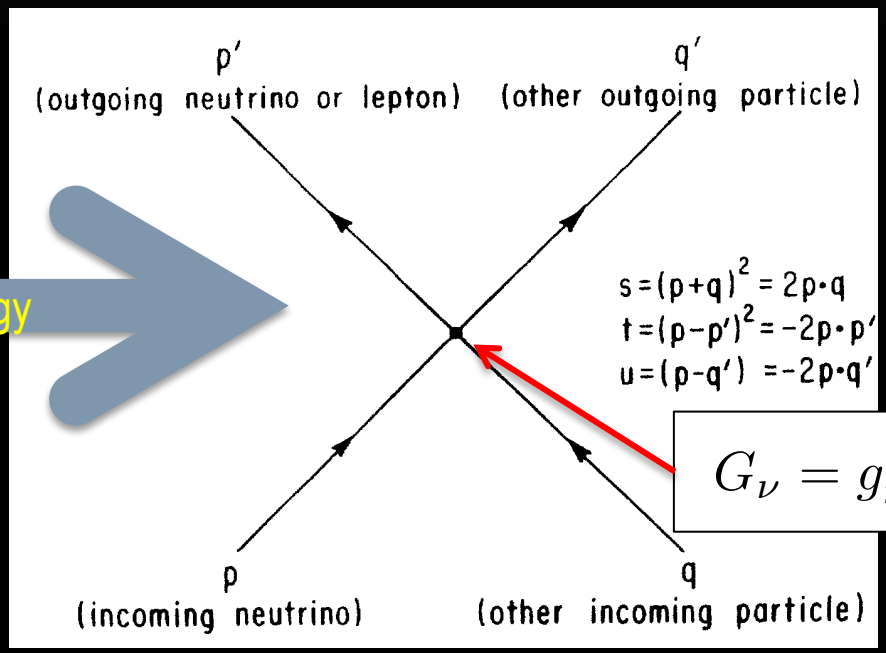
Beyond Free-streaming Neutrinos

New Unknown Interaction: $\mathcal{L}_{\rm phen} \supset -\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}(g_\phi^{\alpha\beta}\nu_\alpha\nu_\beta\phi + \text{h.c.})$

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



Low Energy



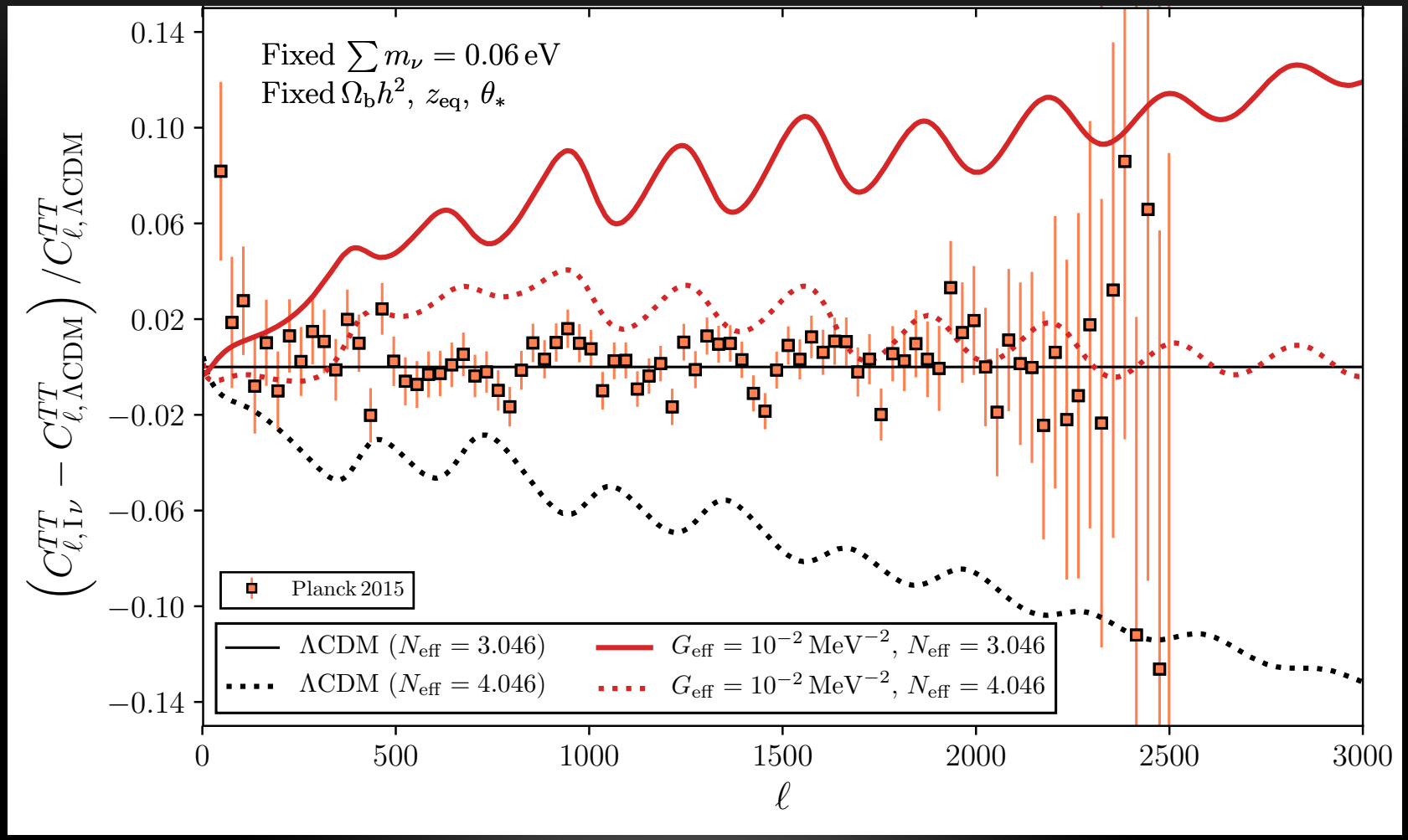
$$G_\nu = g_\nu^2/M_\phi^2$$

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

$$G_\nu > G_{\rm F}$$

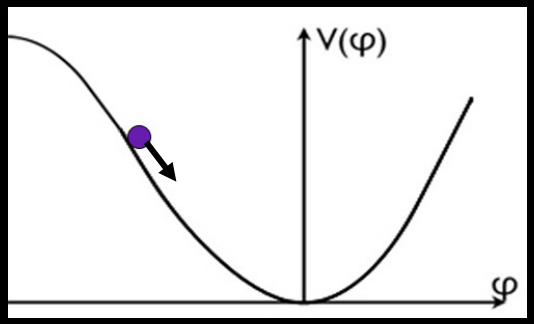
Impact of self-interacting Neutrinos on CMB



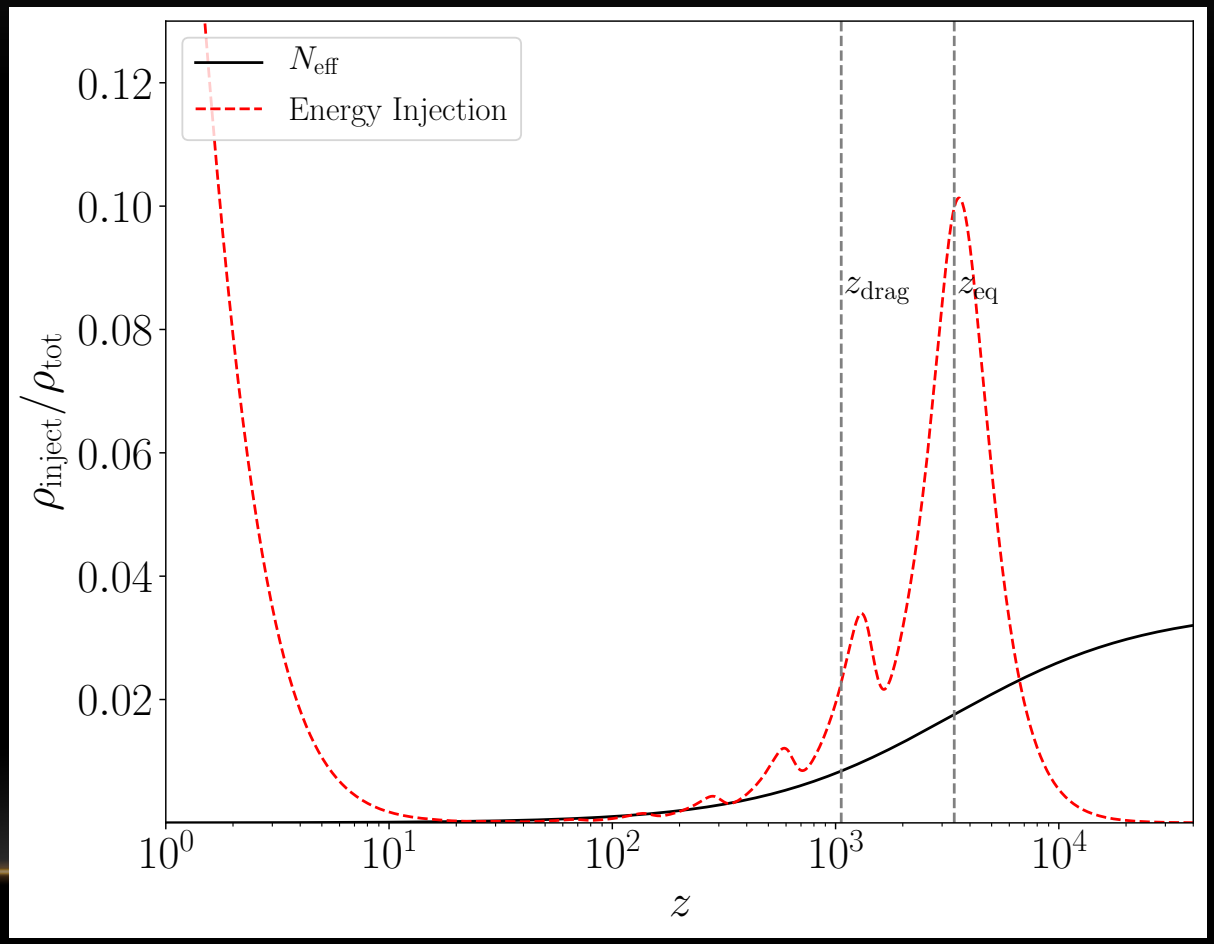
Kreisch, Cyr-Racine + (2019)

Another possibility: Localized energy injection

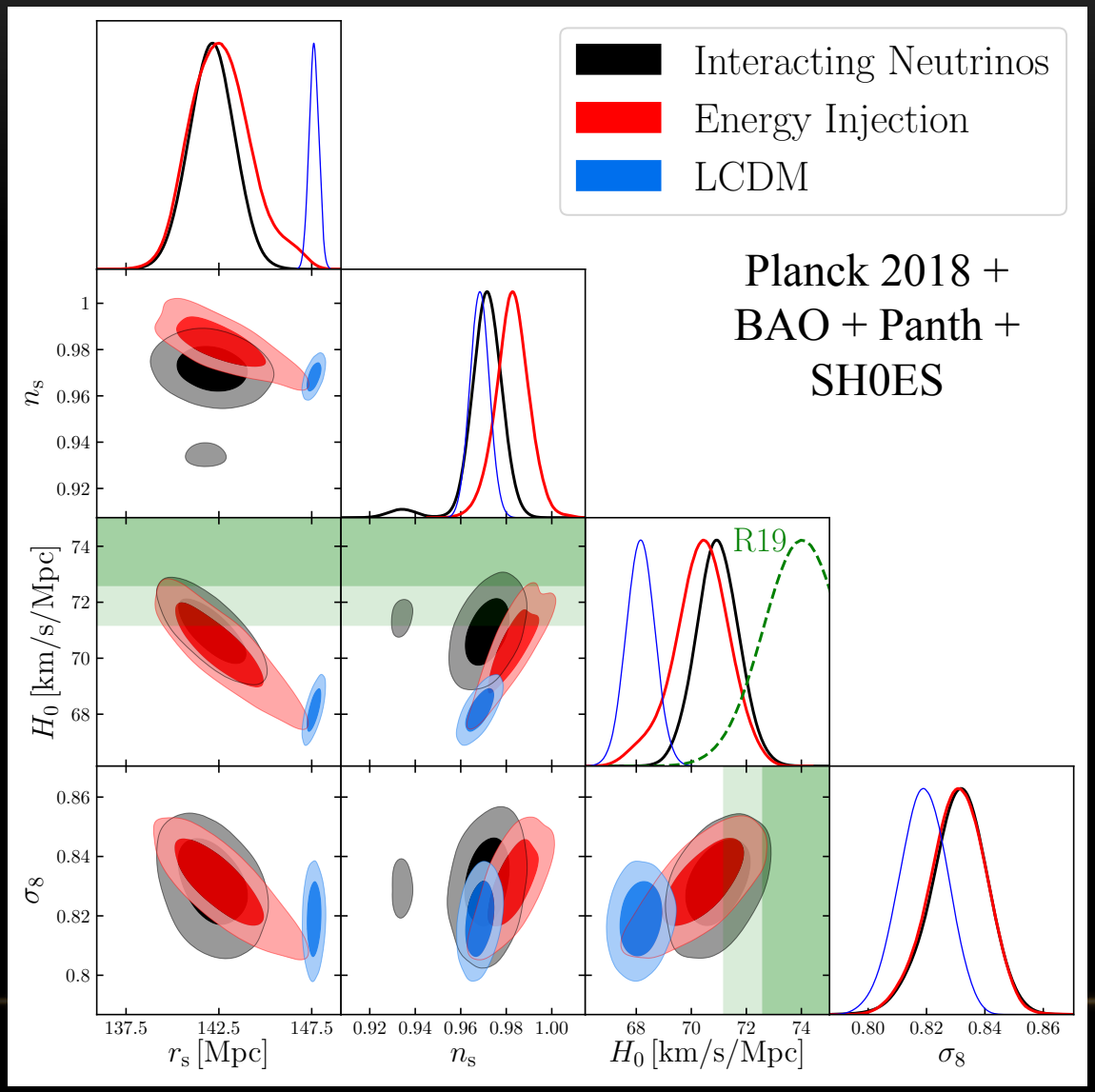
- Need energy injection around matter-radiation equality.



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

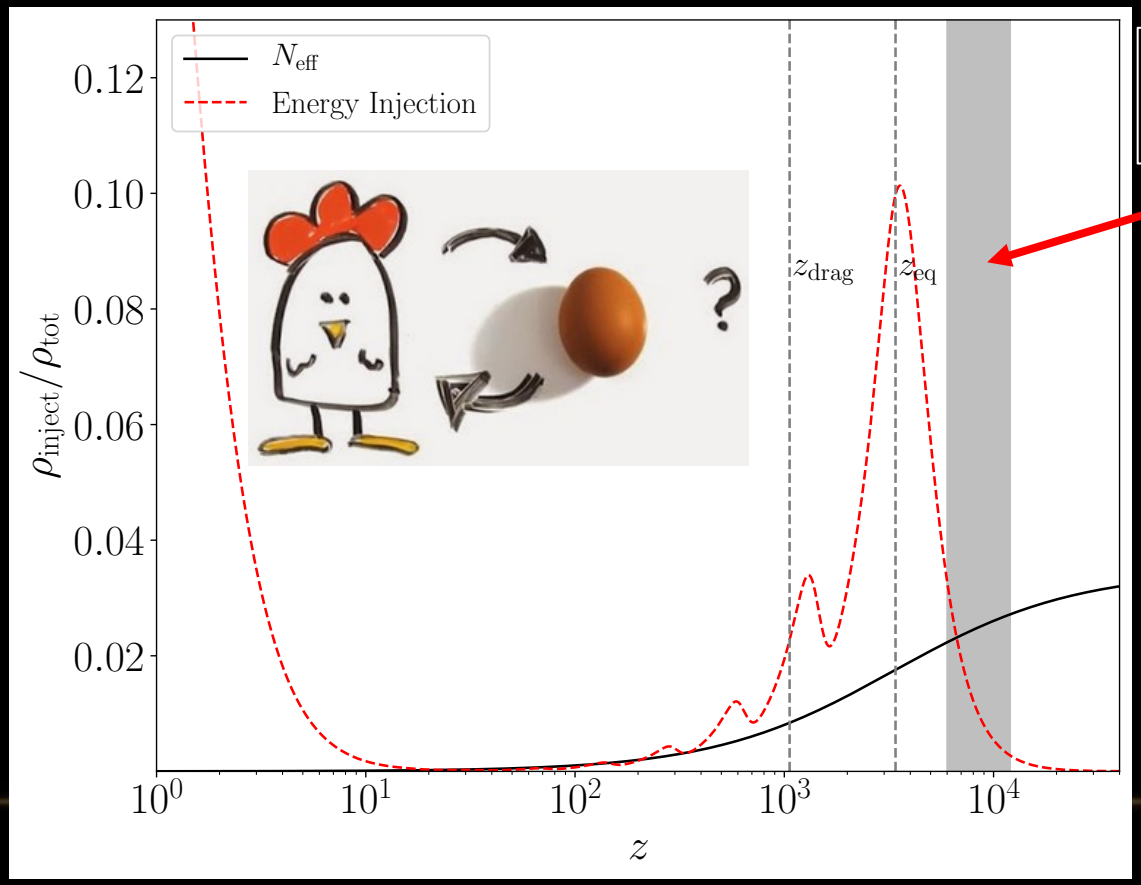


Planck 2018 model comparison



General lesson #1

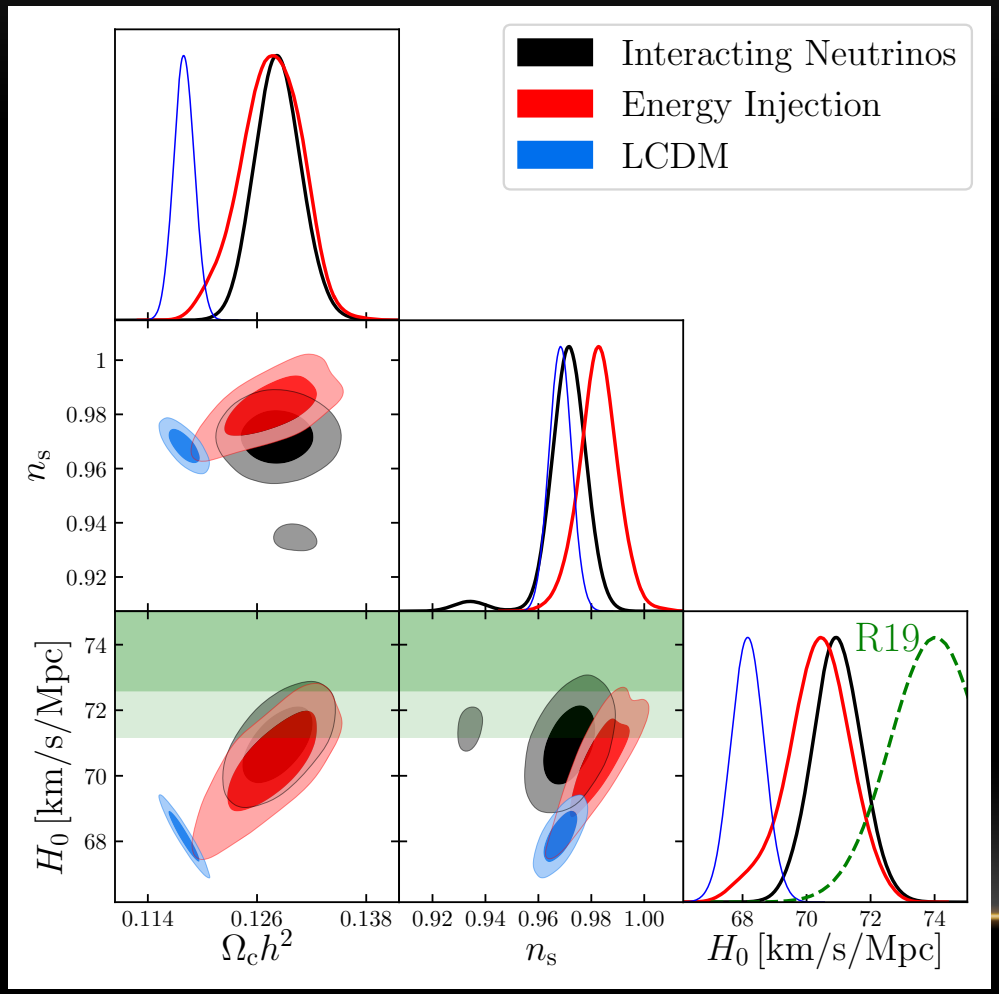
- The epoch between $z = 10^3$ and 10^4 seems to be key in addressing the current tensions. Is matter-radiation more involved than we think? Is this related to the $\ell < 800$ vs $\ell > 800$ discrepancy?

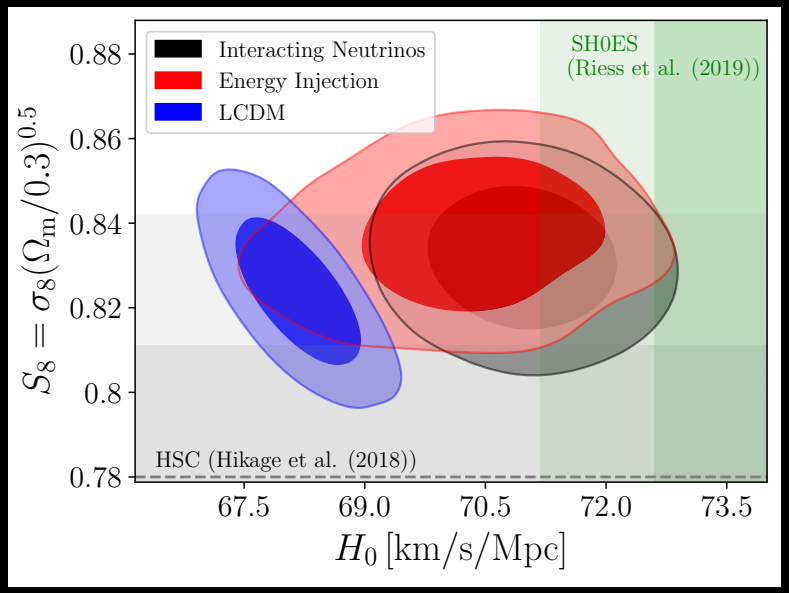


Neutrino decoupling

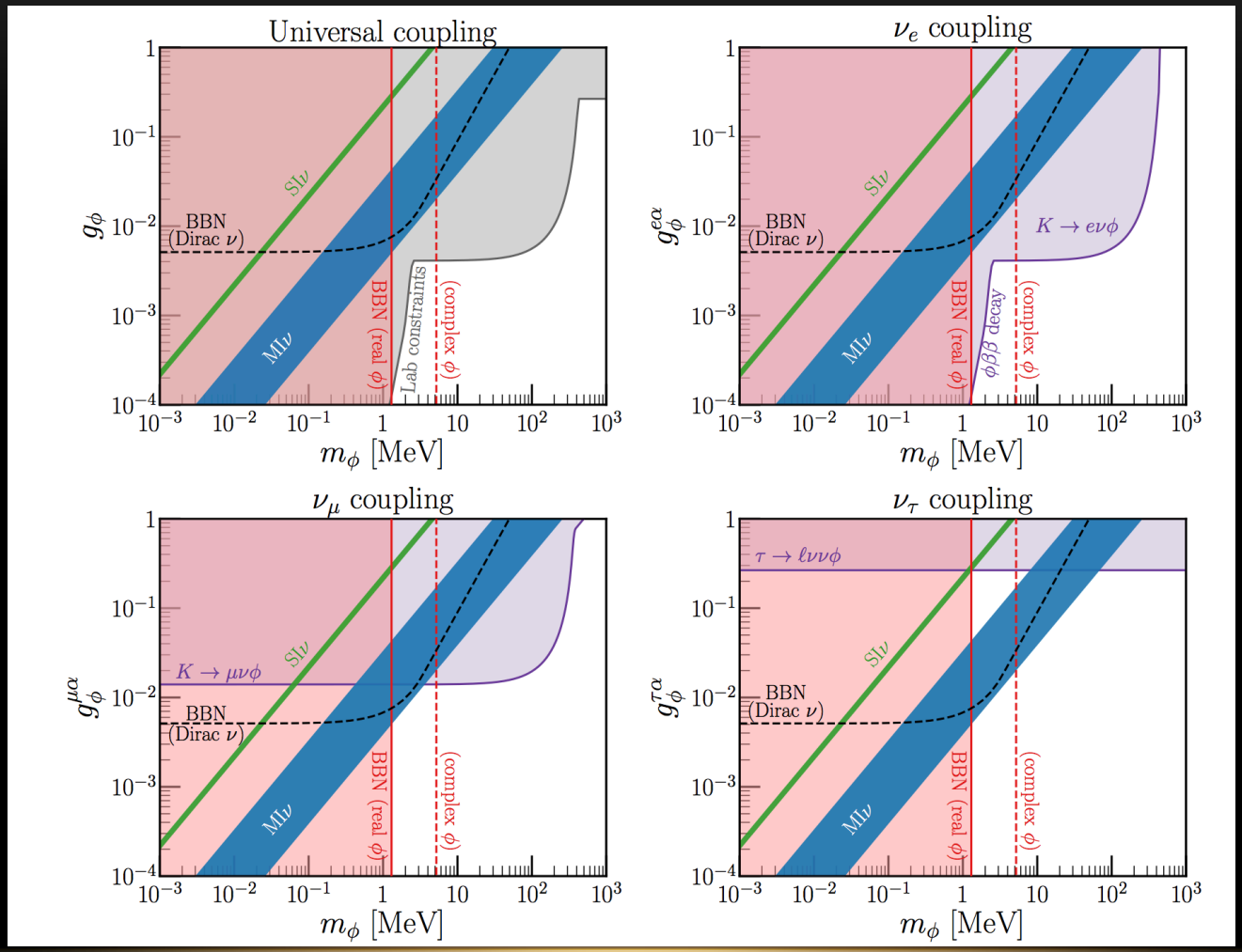
General lesson #2

- 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

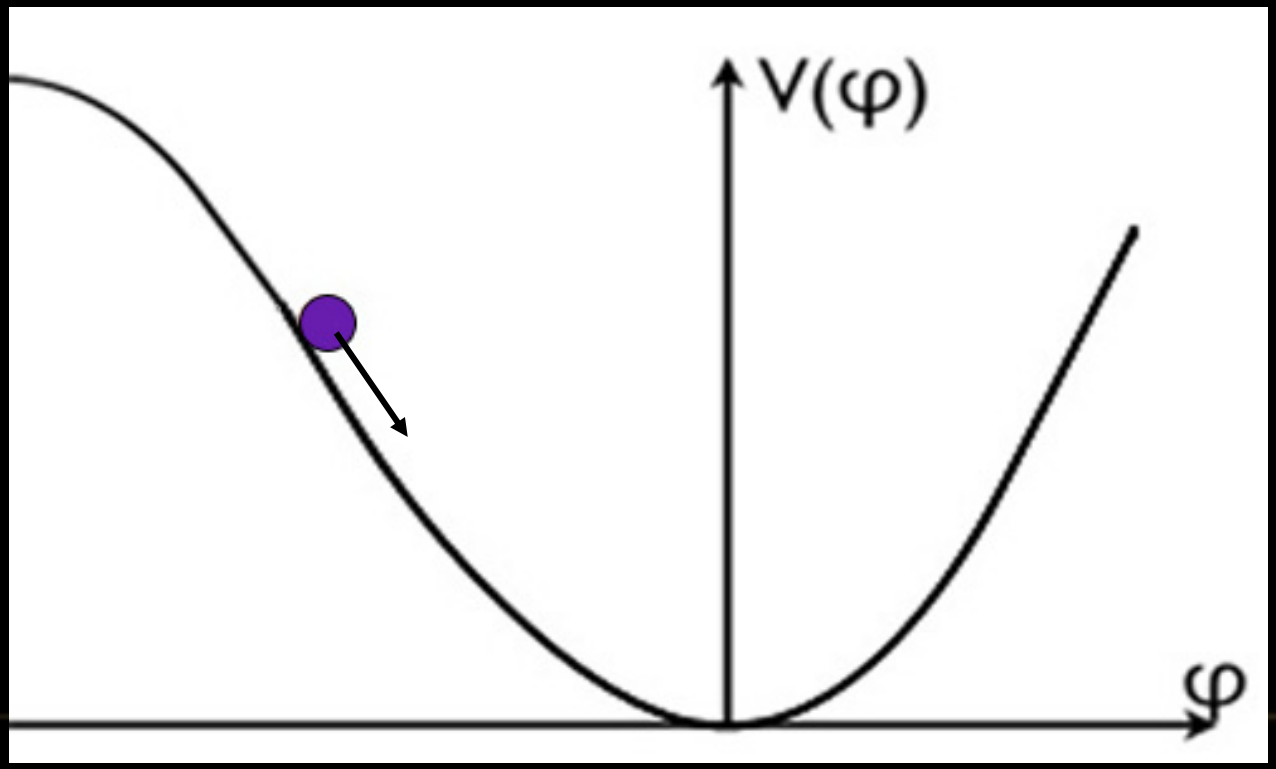


Blinov et al. (2019)

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

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!