Rock ’n’ roll, jazzy, and classical solutions to the Hubble tension

Tensions between the Early and Late Universe
KITP
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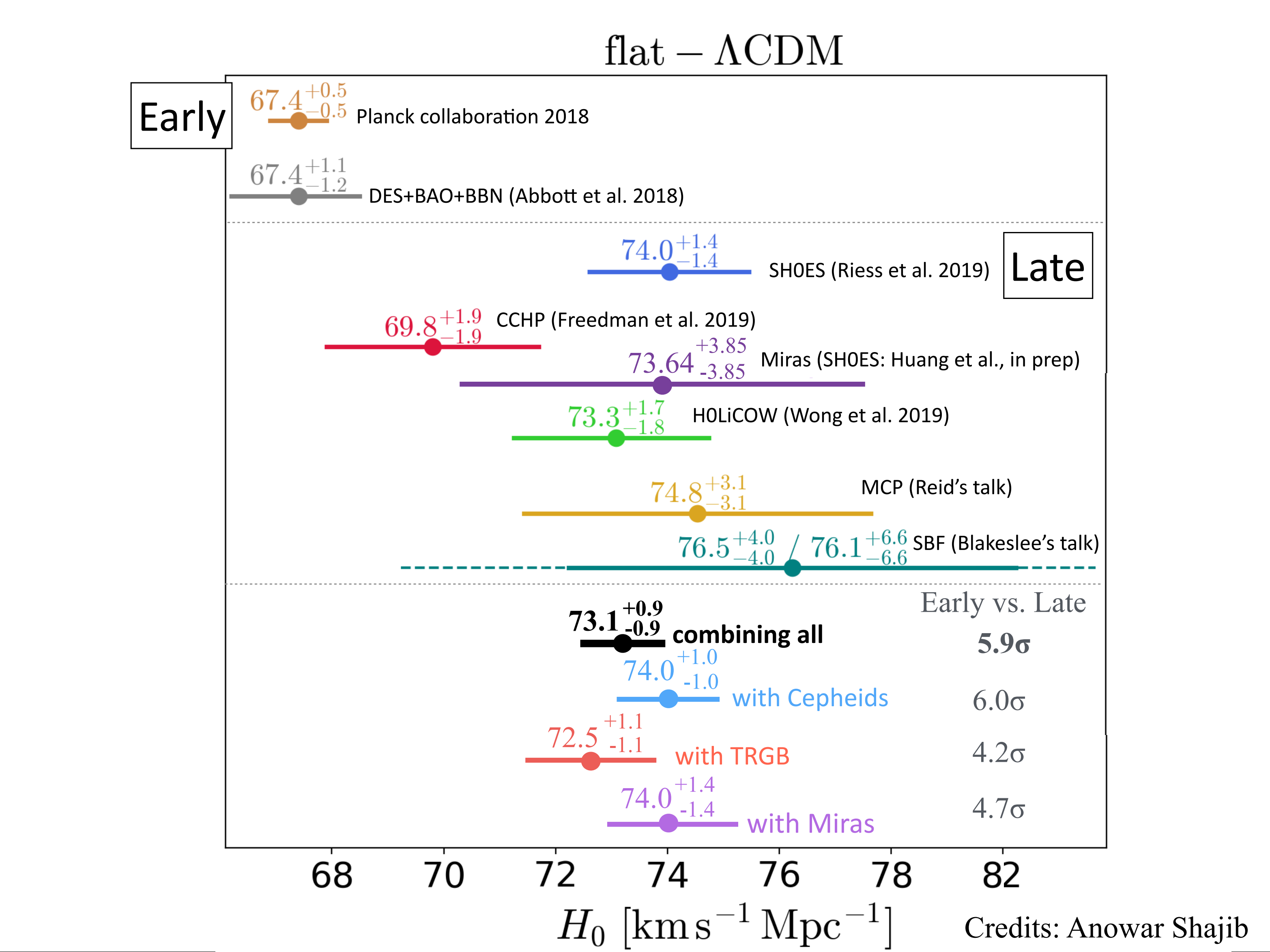
Let's summarize



Let's start with a poll

- How would you characterize the current situation?
  - $< 1\sigma$: Consistency
  - $> 2\sigma$: Curiosity
  - $> 3\sigma$: Tension/discrepancy
  - $> 4\sigma$: Problem
  - $> 5\sigma$: Crisis

Theorists to the rescue!

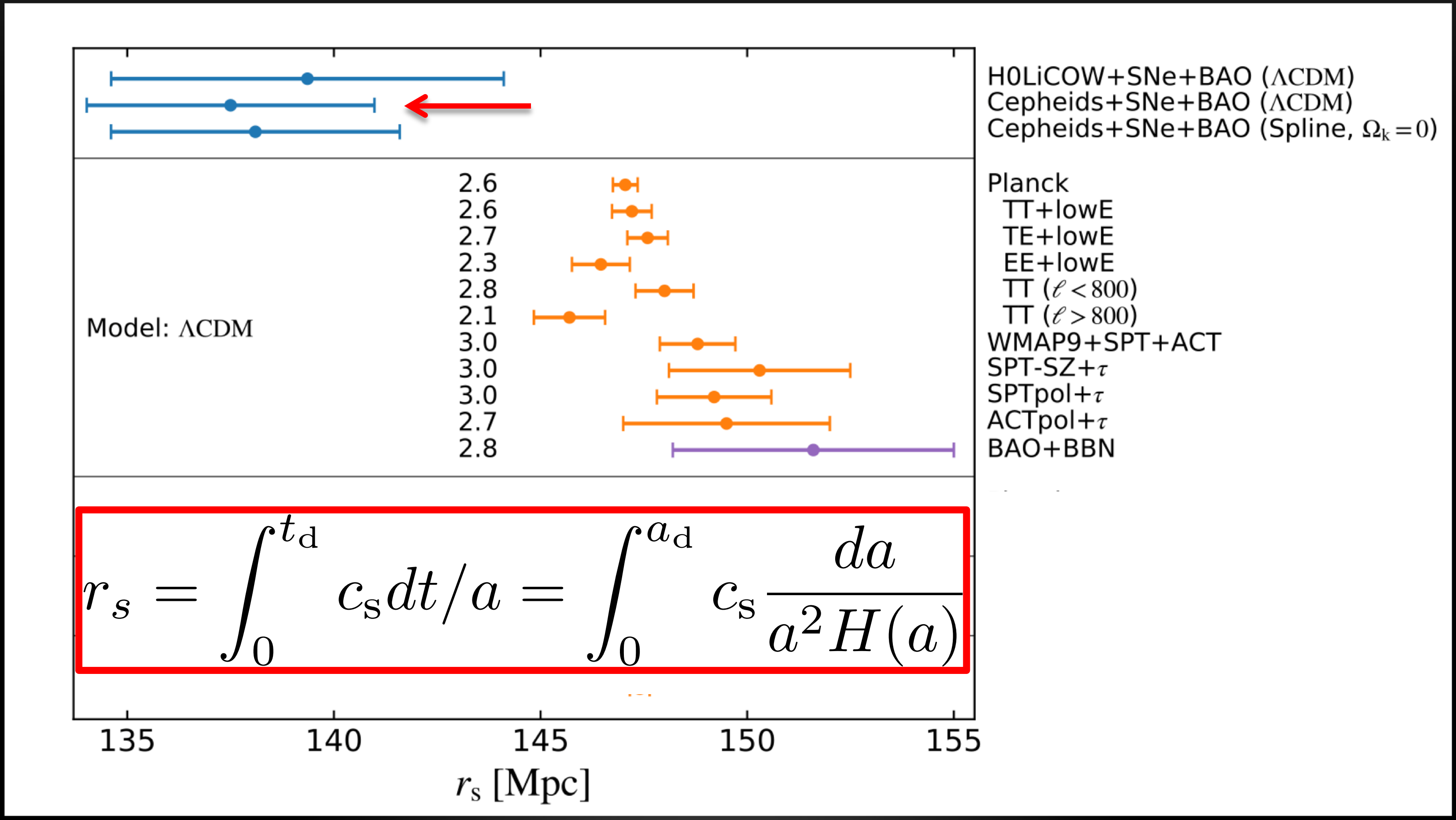
Whether we have a tension, a problem, or a crisis, our job as theorists is to identify what properties a successful solutions might have.

Bottom line:

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.

w/ Christina Kreisch, Prateek Agrawal, David Pinner, Lisa Randall, Lloyd Knox

Approach: Discrepancy in the baryon sound horizon



$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Aylor et al. (2018)
See also 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.

$$c_s = \frac{1}{\sqrt{3\left(1 + \frac{3\rho_b}{4\rho_\gamma}\right)}}$$

$$r_s = \int_0^{a_d} da \frac{c_s(a)}{a^2 H(a)}$$

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

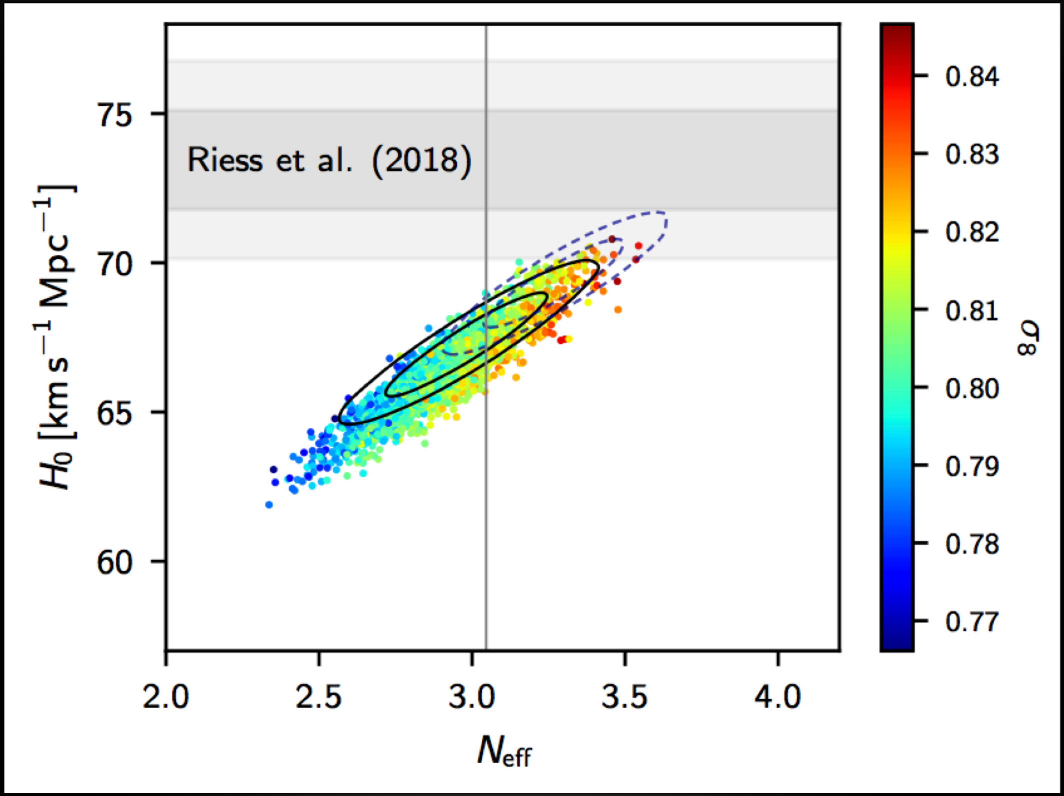
$$H^2(a) = \frac{8\pi G}{3} \sum_i \rho_i(a)$$

Classical solution: N_{eff}

- The presence of extra relativistic species is a hallmark of many extensions of the Standard Model (*N*-Naturalness, Twin Higgs, etc.)

N_{eff} alone doesn't work…

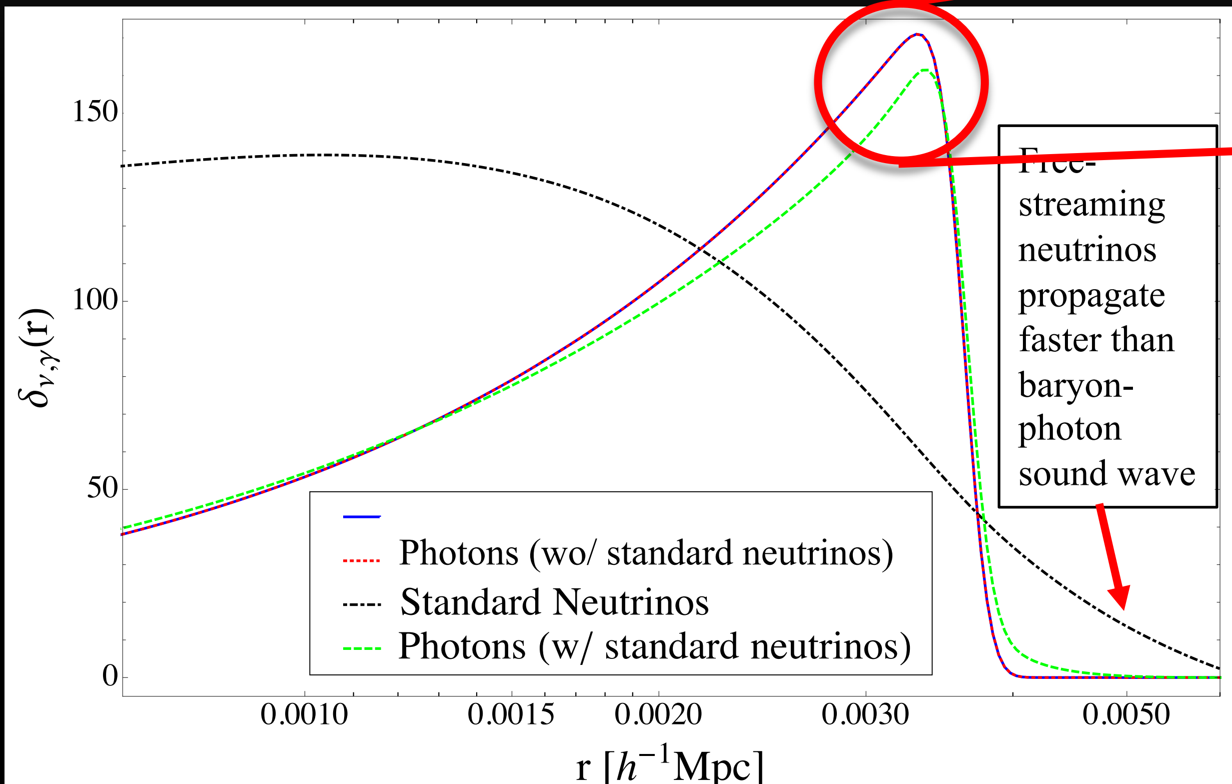
- It can get you partially there, but at the price of degrading high-l CMB

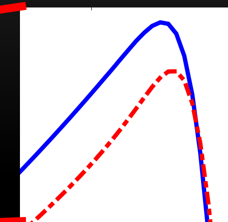


Planck Coll. (2018)

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)

Jazzy solution: Get rid of free-streaming

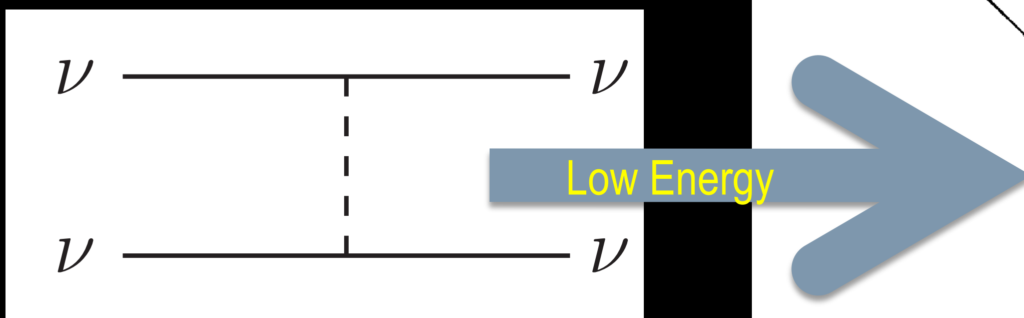
- Introduce neutrino self-interaction
- Require serious riffing on the Standard Model…

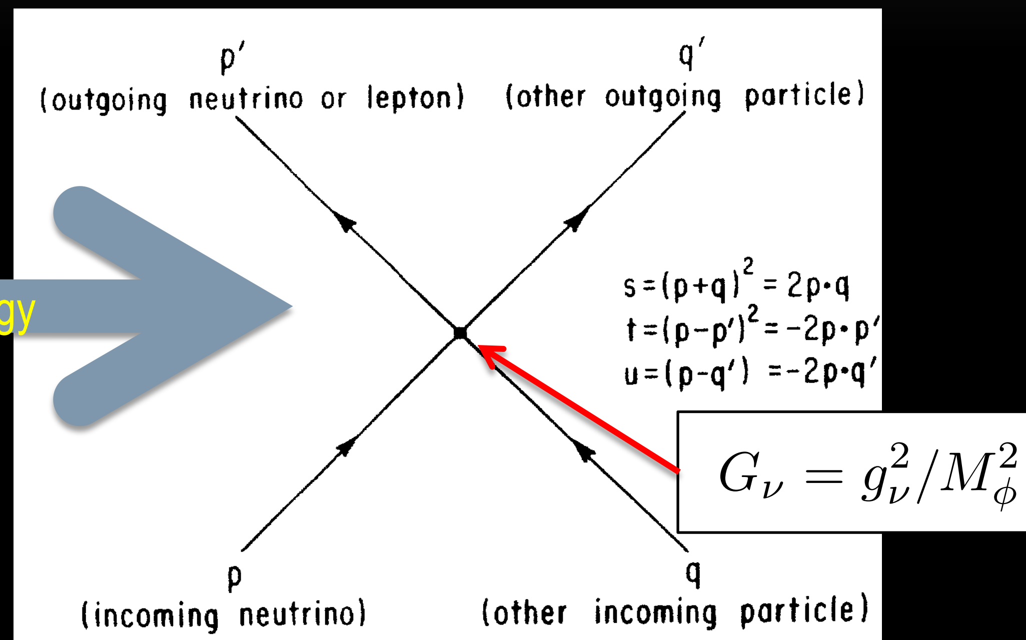
Cyr-Racine & Sigurdson (2014)
Oldengott et al. (2015)
Lancaster, Cyr-Racine, et al. (2017)
Oldengott et al. (2017)
Kreisch, Cyr-Racine, & Doré (2019)

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)

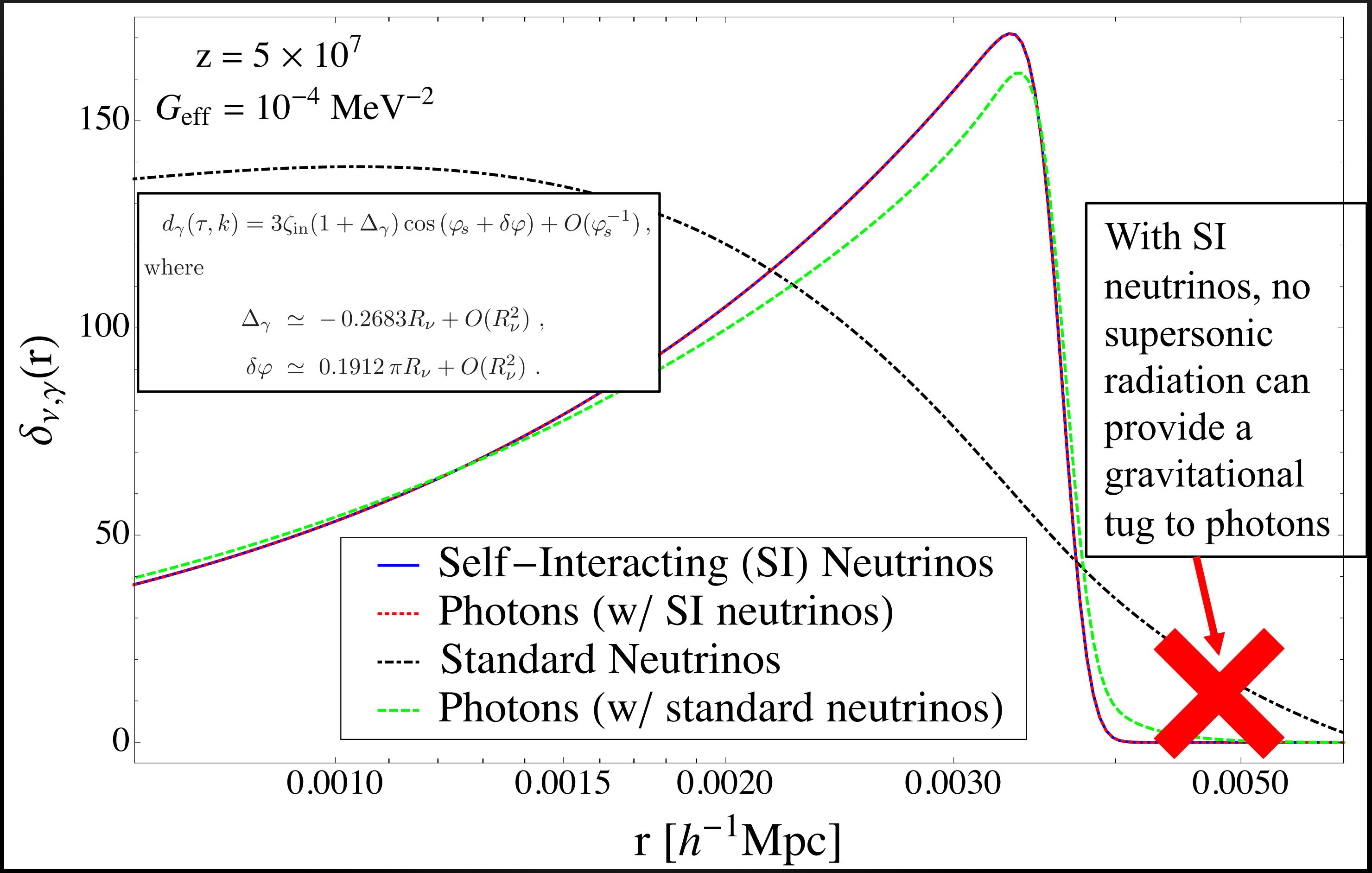




4-Fermion Interaction stronger than Fermi constant

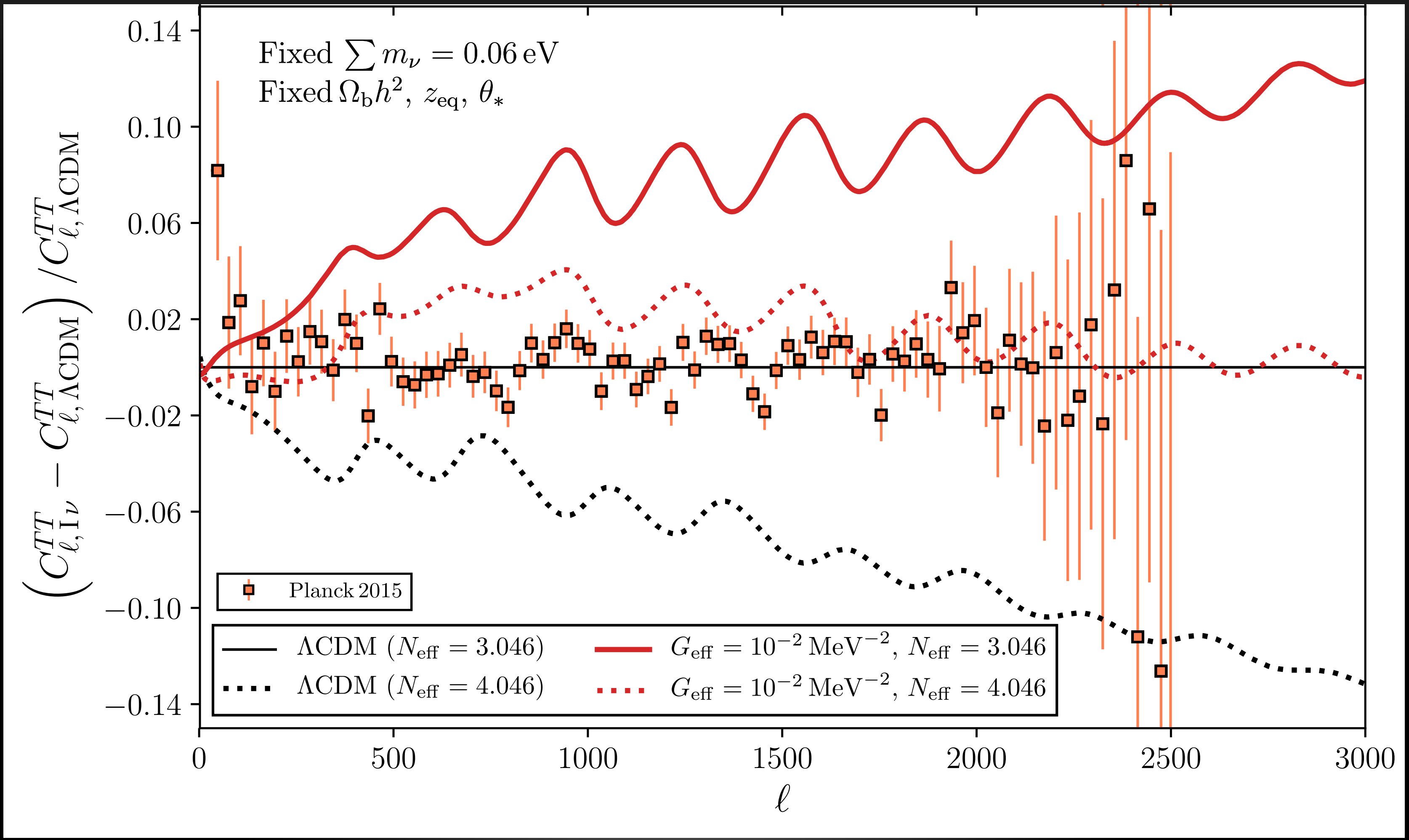
$$G_\nu > G_{\rm F}$$

Impact of self-interacting Neutrinos on CMB



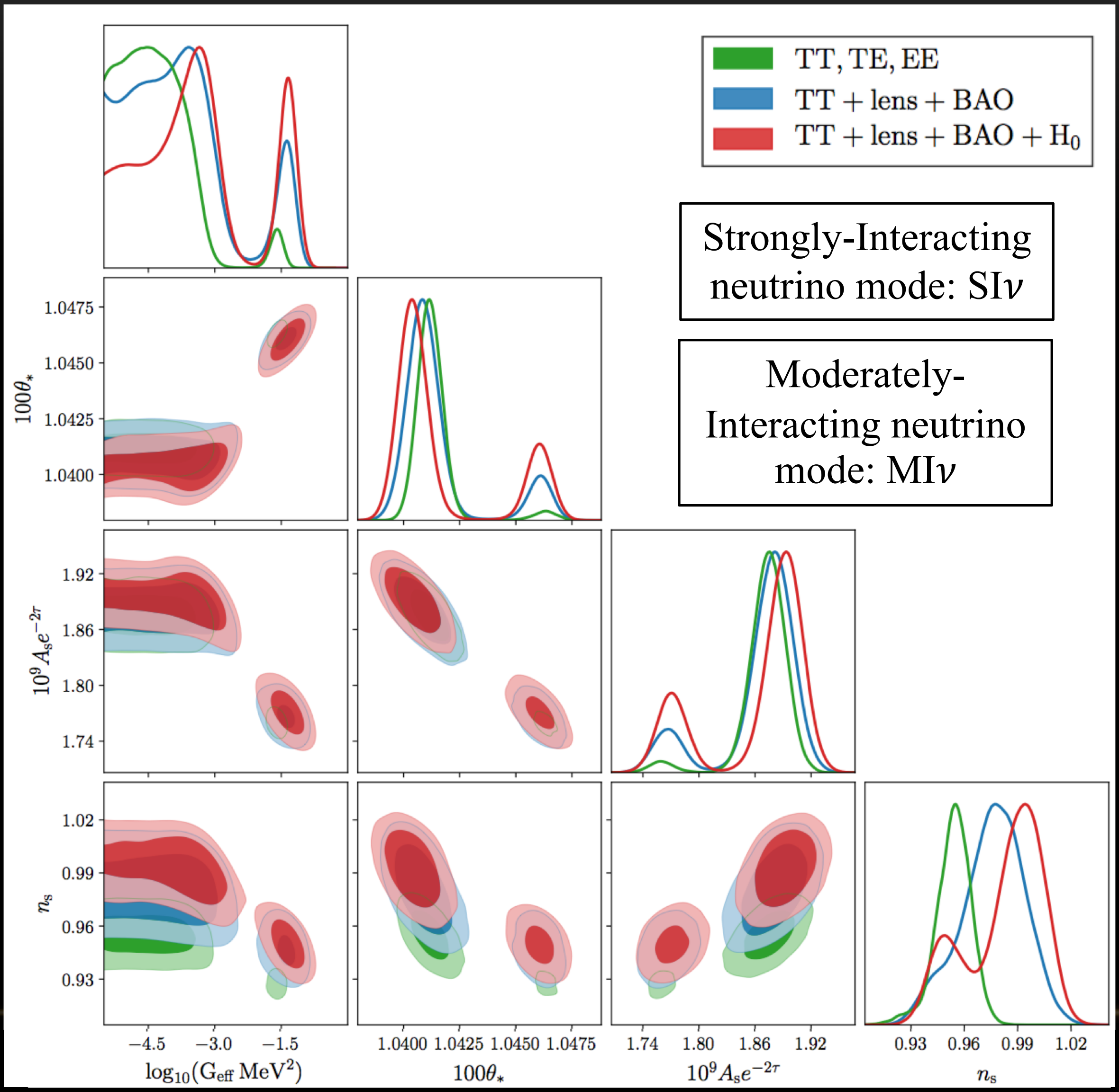
Cyr-Racine & Sigurdson (2014)

Impact of self-interacting Neutrinos on CMB



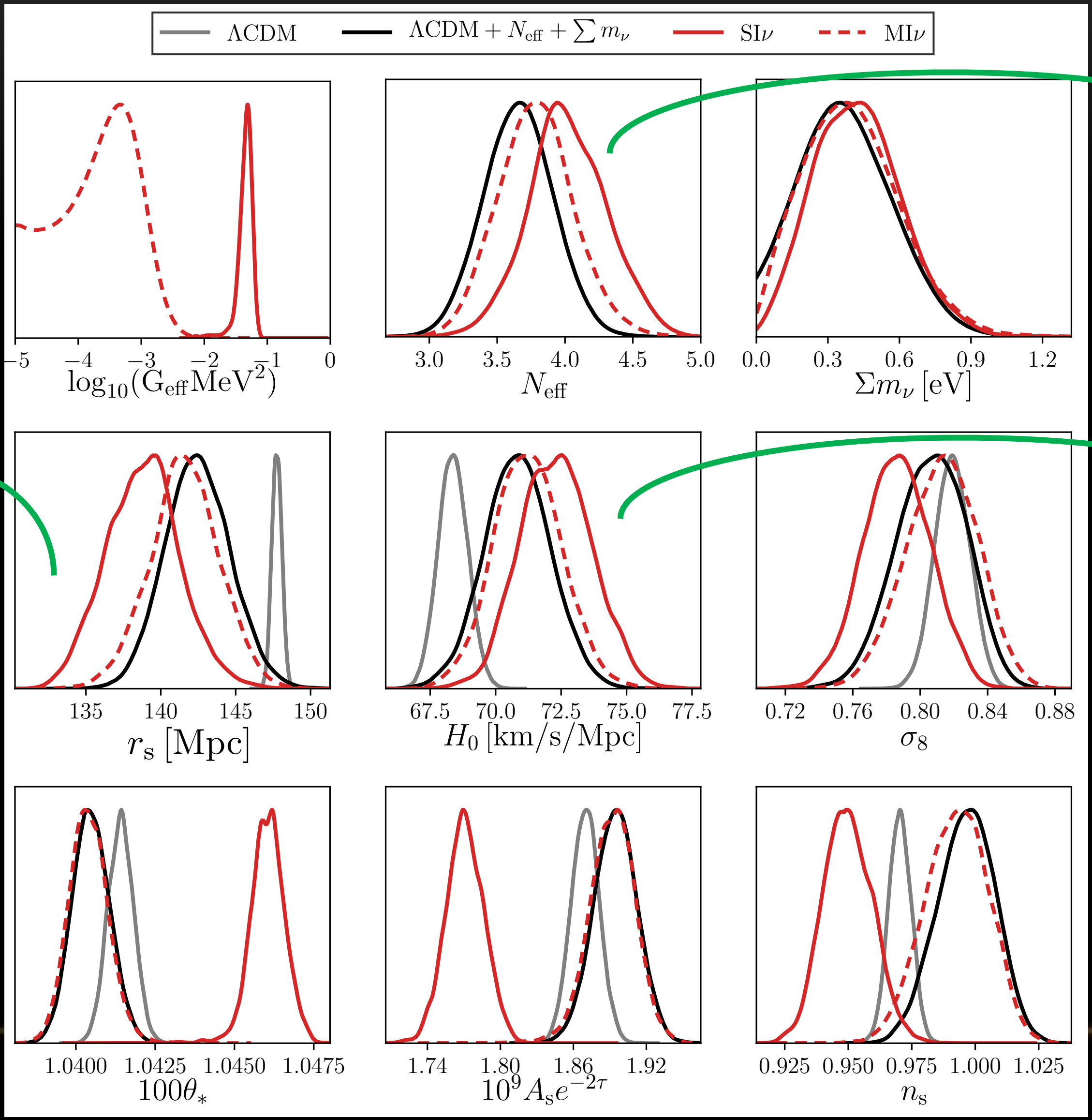
Kreisch, Cyr-Racine + (2019)

A tale of two statistical modes



Kreisch, Cyr-Racine + (2019)

Let's compare the two modes side-by-side



$N_{\rm eff} \sim 4$: extra energy density at early times

Hubble constant is compatible with local measurement

Sound horizon is smaller than in LCDM

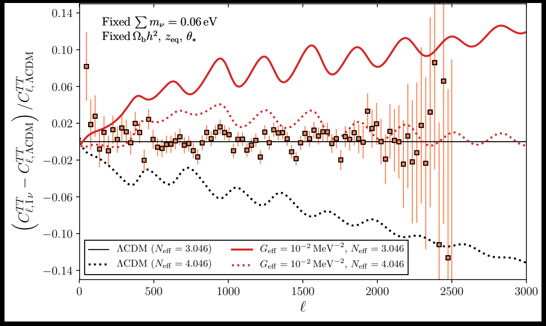
Kreisch, Cyr-Racine + (2019)

Why does the SIν work?

- $N_{\rm eff}$ increases Hubble at early times, hence reducing the sound horizon.

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

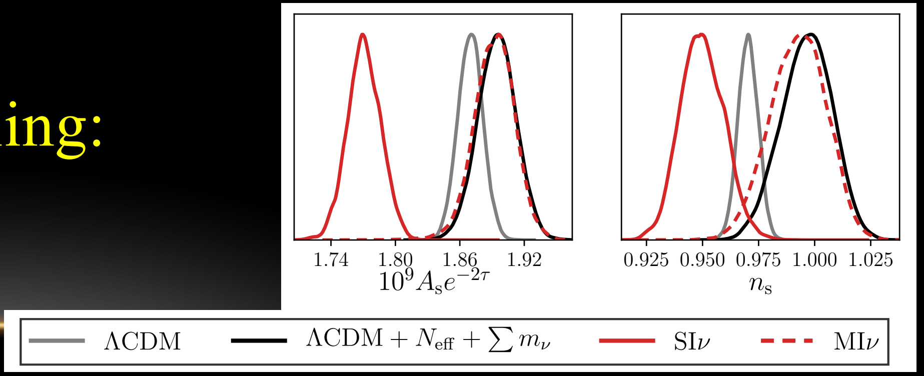
- The tightly-coupled neutrinos do not over damp or phase shift the photon-baryon fluctuations.



- Changes in the primordial spectrum of fluctuations (n_s, A_s) absorbs the remainder of the changes.

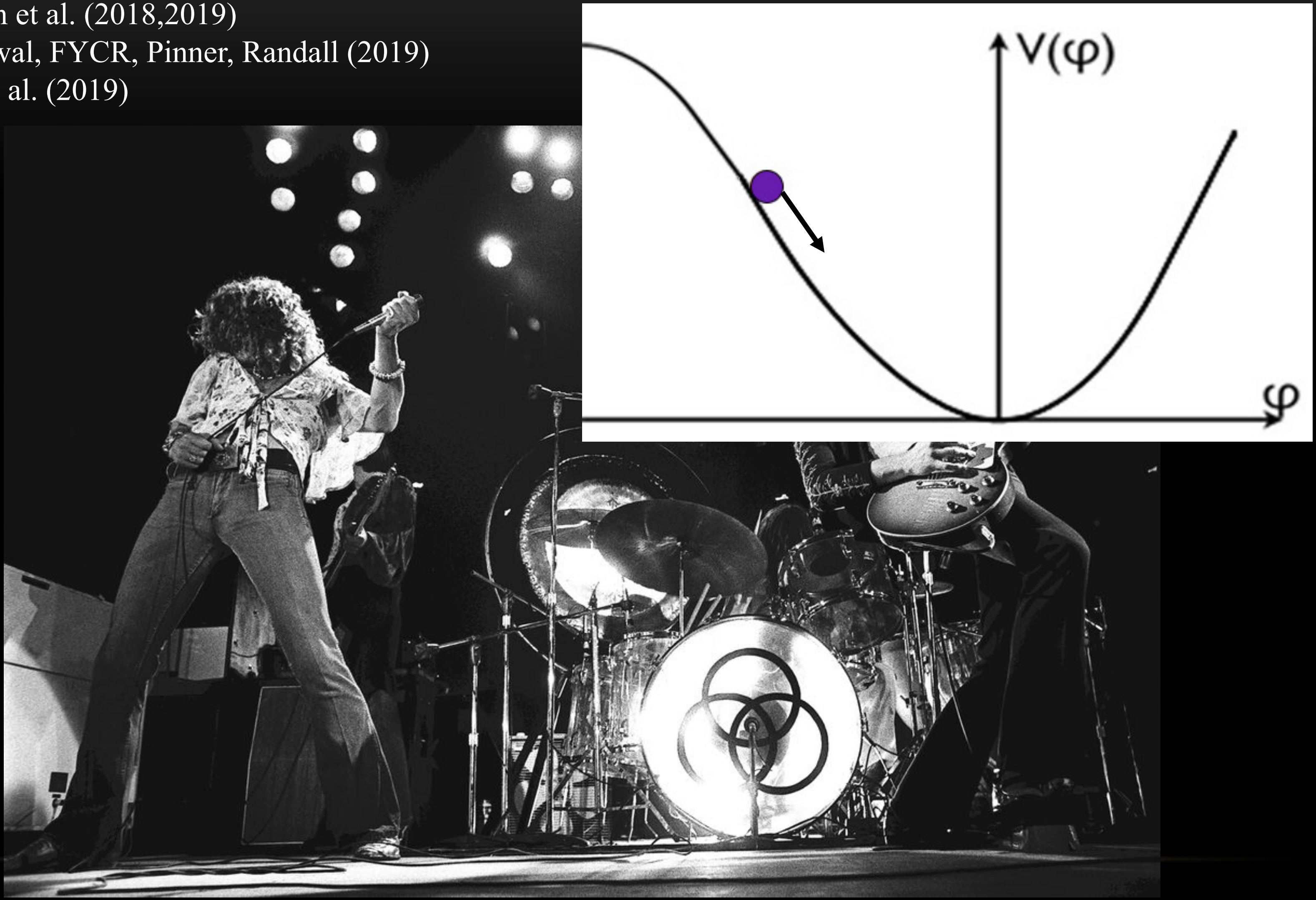
- Tooth fairy: need large coupling:

$$G_{\rm eff} \sim 10^{10} G_{\rm F}$$



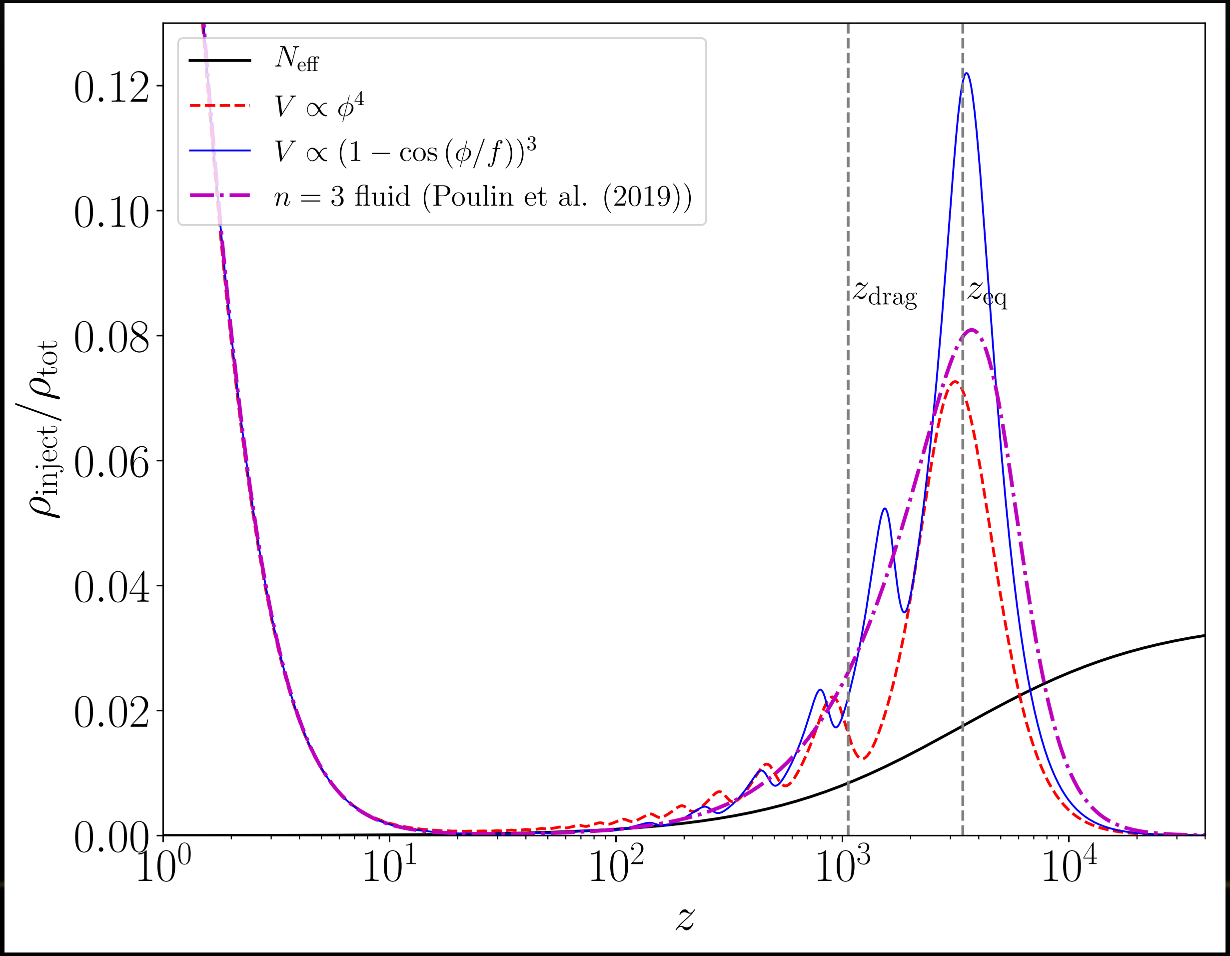
Rock'n'roll solution: Localized injection

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



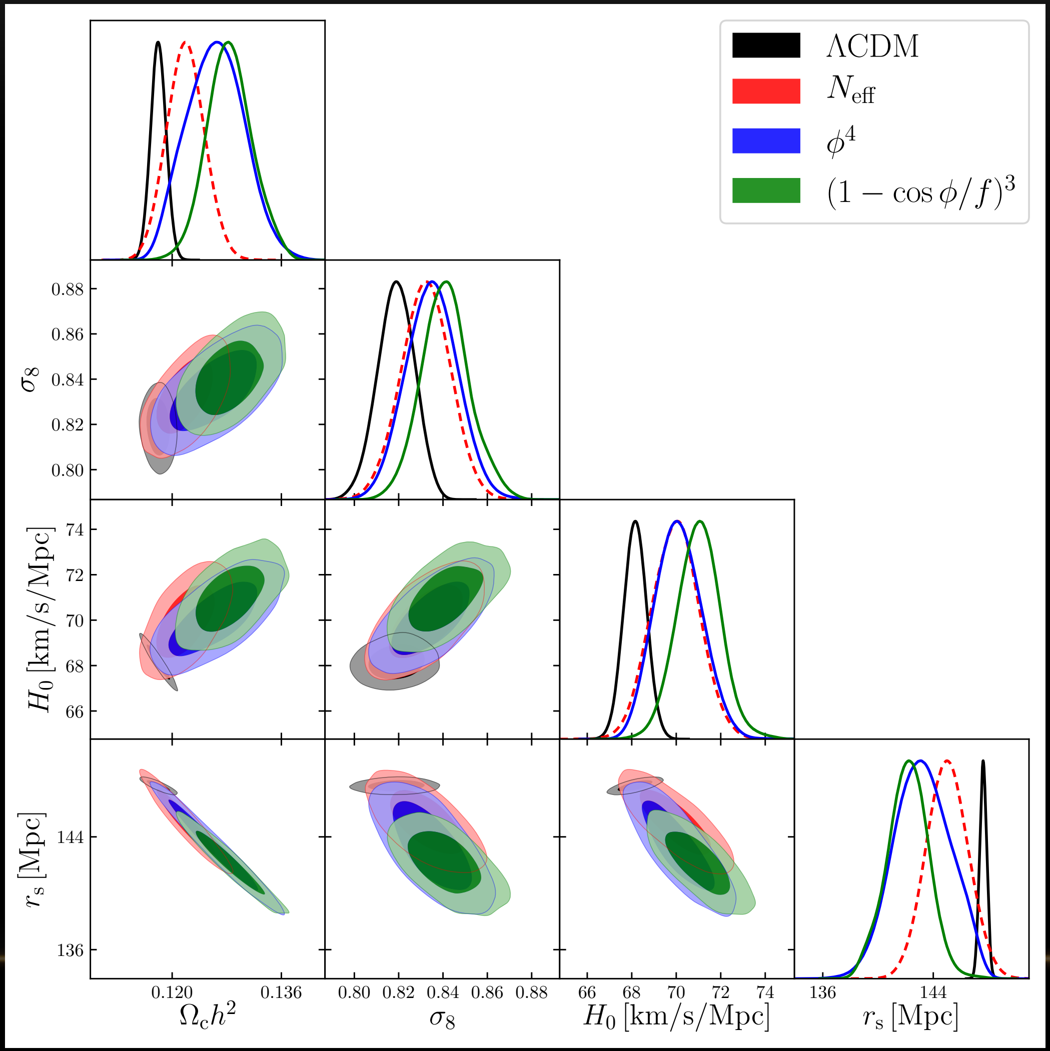
Rock'n'roll solution: Localized injection

- Need energy injection around matter-radiation equality.



Rock‘n’roll solution: Localized injection

- With the right potential, this can work very well:

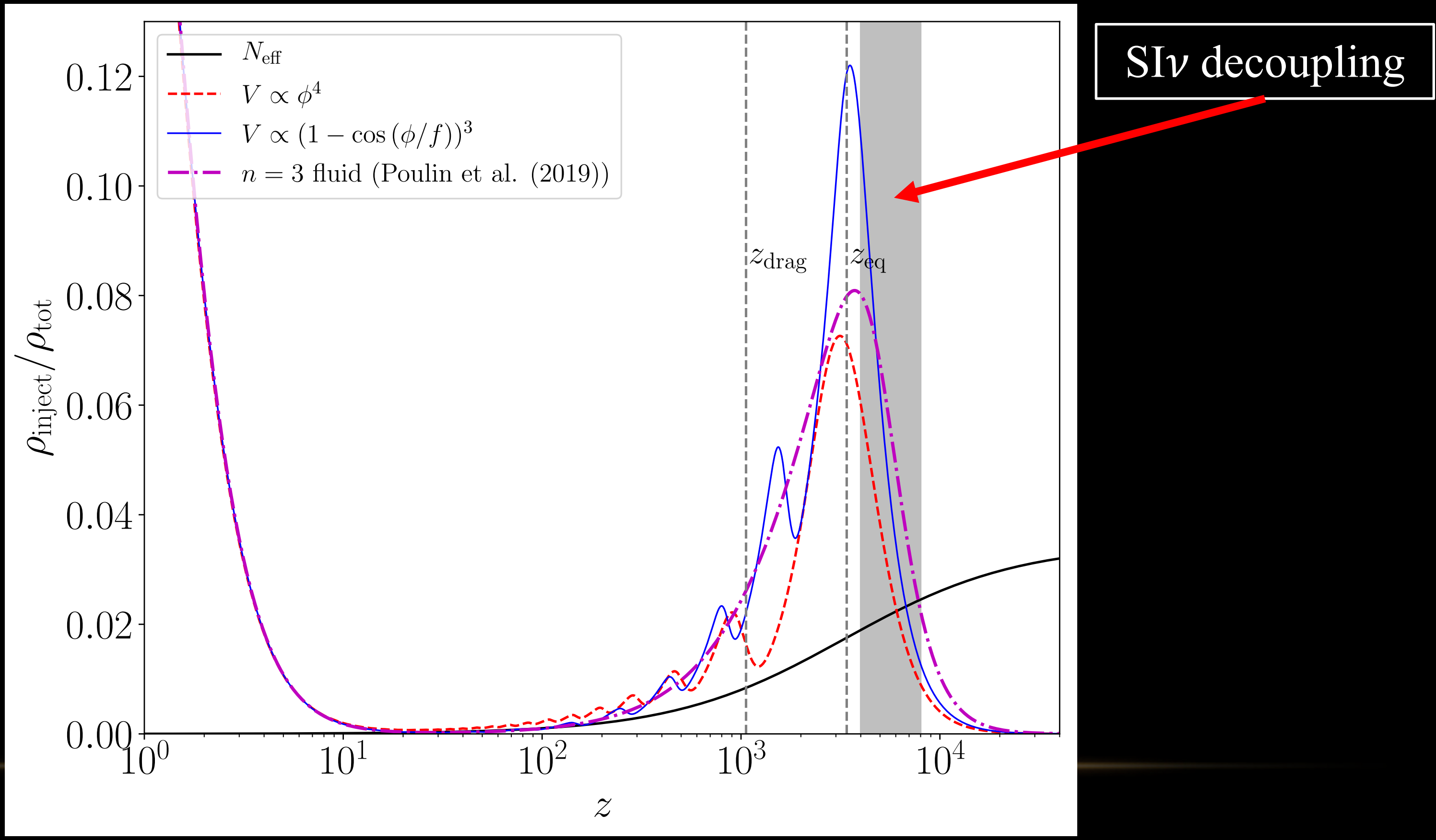


Reality check

Solutions	Solve H_0	S_8 tension	Tooth fairies	Model building
N_{eff}	No	Worse	None (?)	Easy
Localized energy injection	Yes	Worse	Coincidence Problem at eV scale, need complex potential	Hard
Interacting neutrinos	Yes (?)	Better	Need extremely strong interaction	Hard

General lesson #1

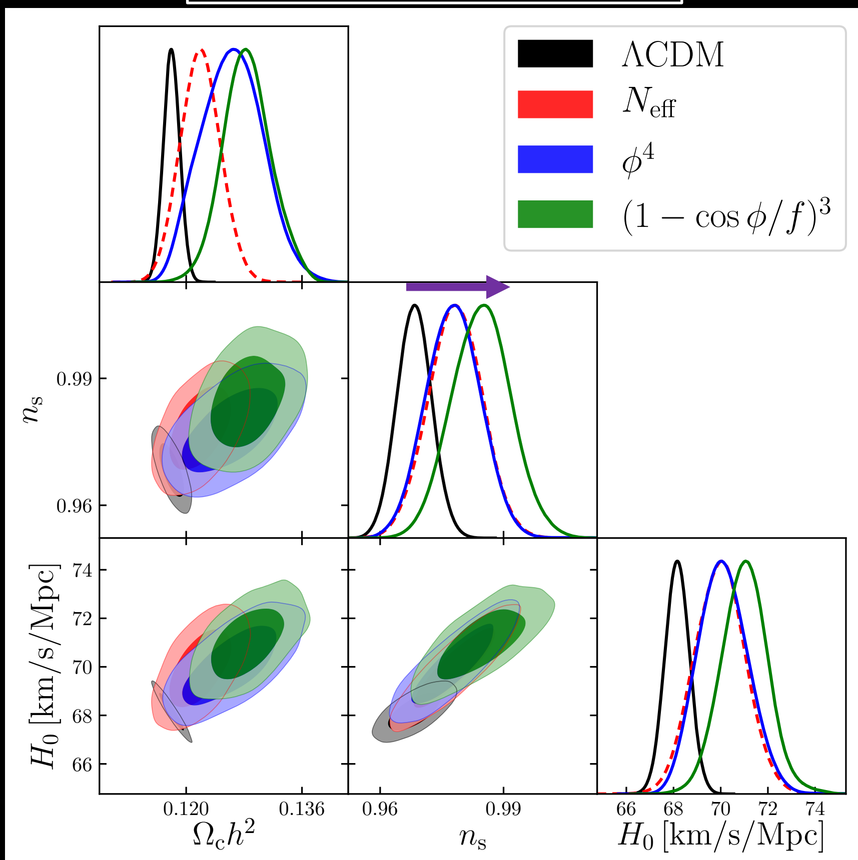
- The epoch between $z = 10^3$ and 10^4 seems to be key in addressing the current tensions. Is matter-radiation more involved than we think? Is this related to the $\ell < 800$ vs $\ell > 800$ discrepancy?



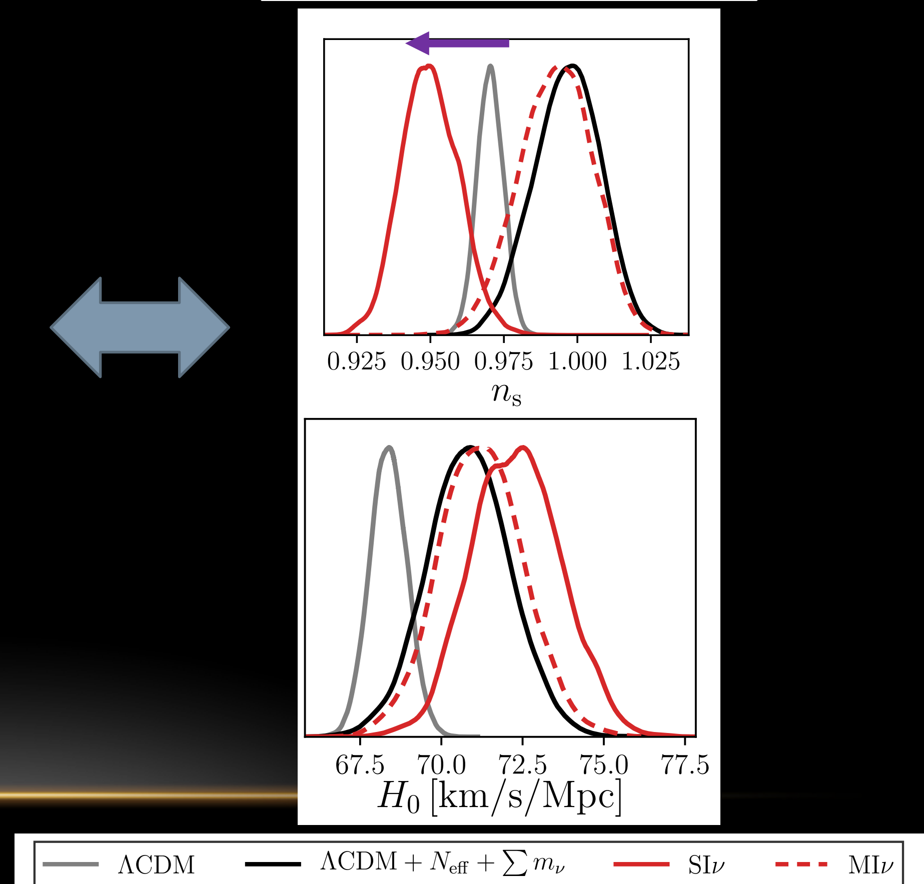
General lesson #2

- Energy injection models always require a larger dark matter density and a larger scalar spectral index.

Energy Injection



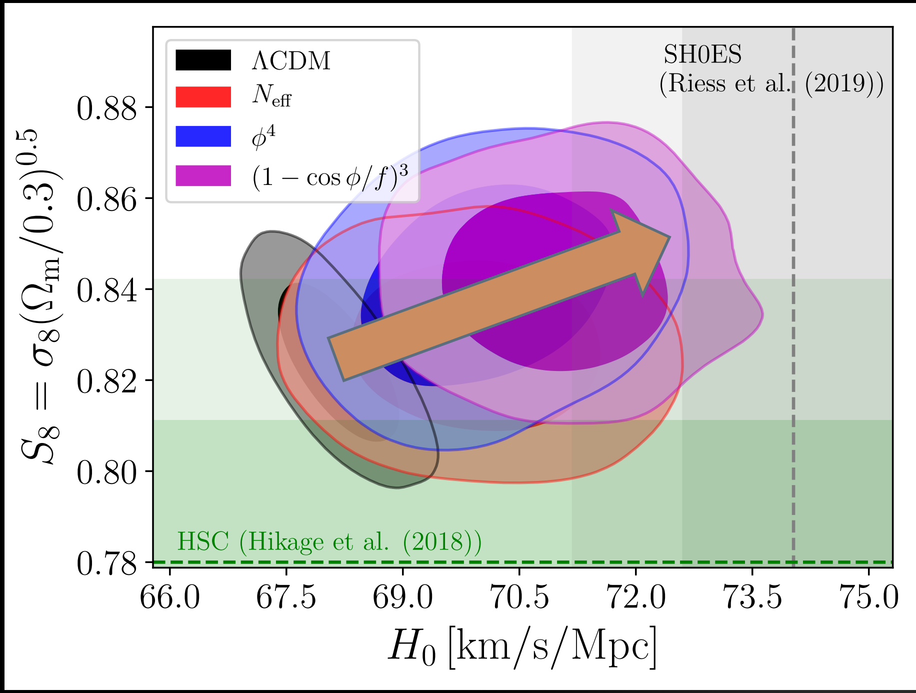
Interacting Neutrinos



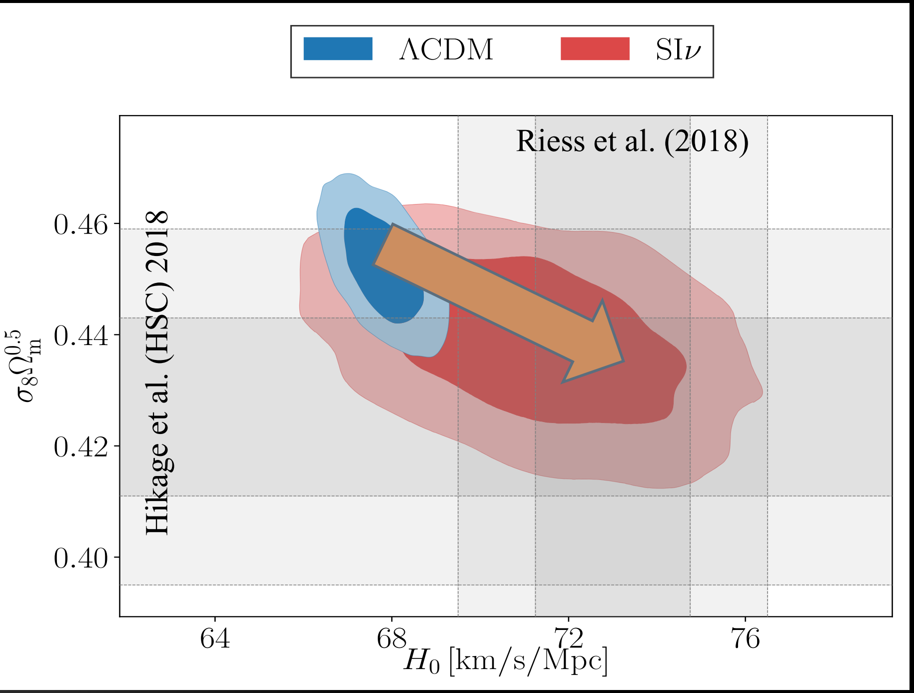
General lesson #2

- This highlights the importance of S_8 in distinguishing solutions.

Energy Injection



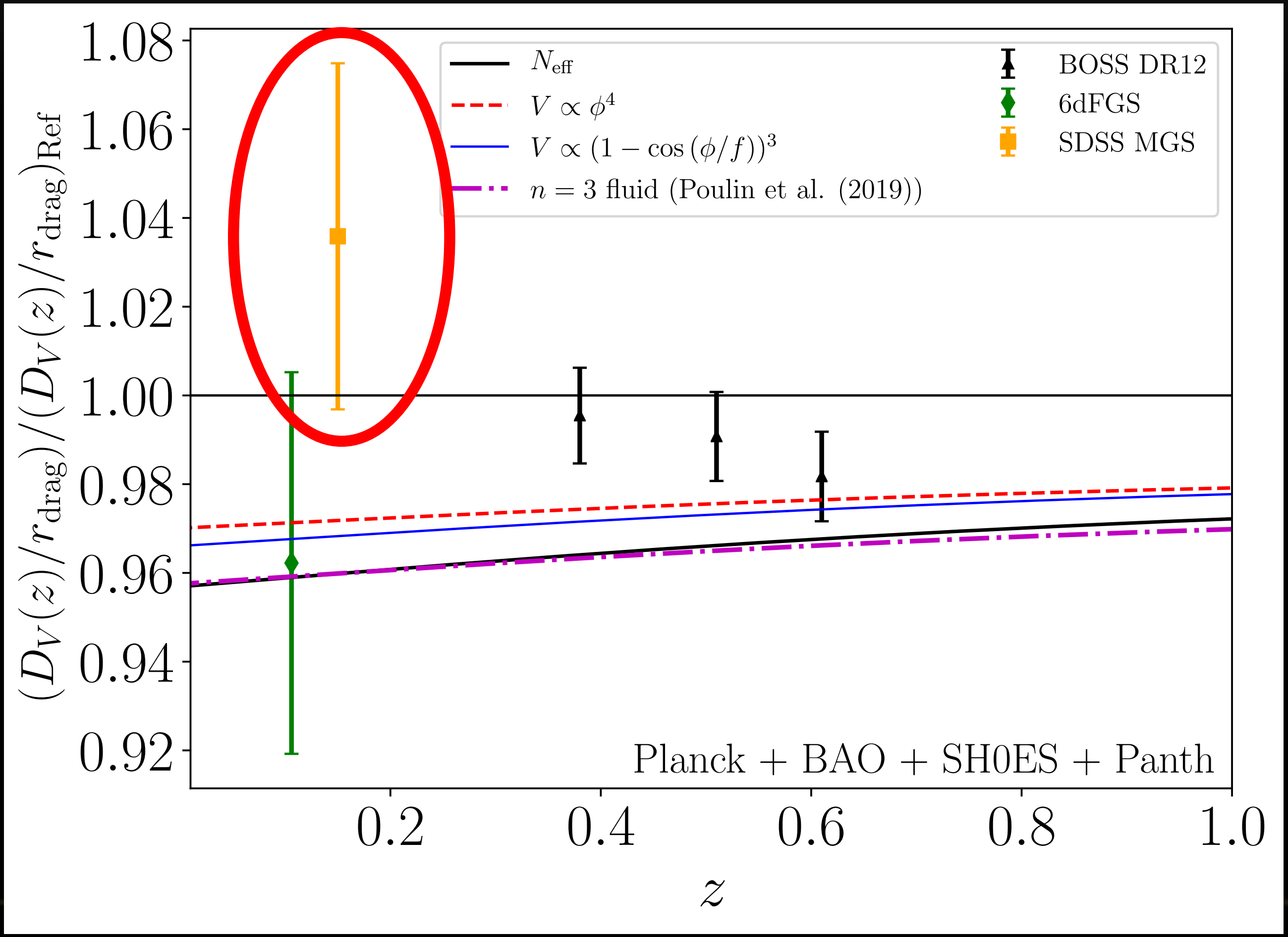
Interacting Neutrinos



Kreisch, Cyr-Racine + (2019)

General lesson #3

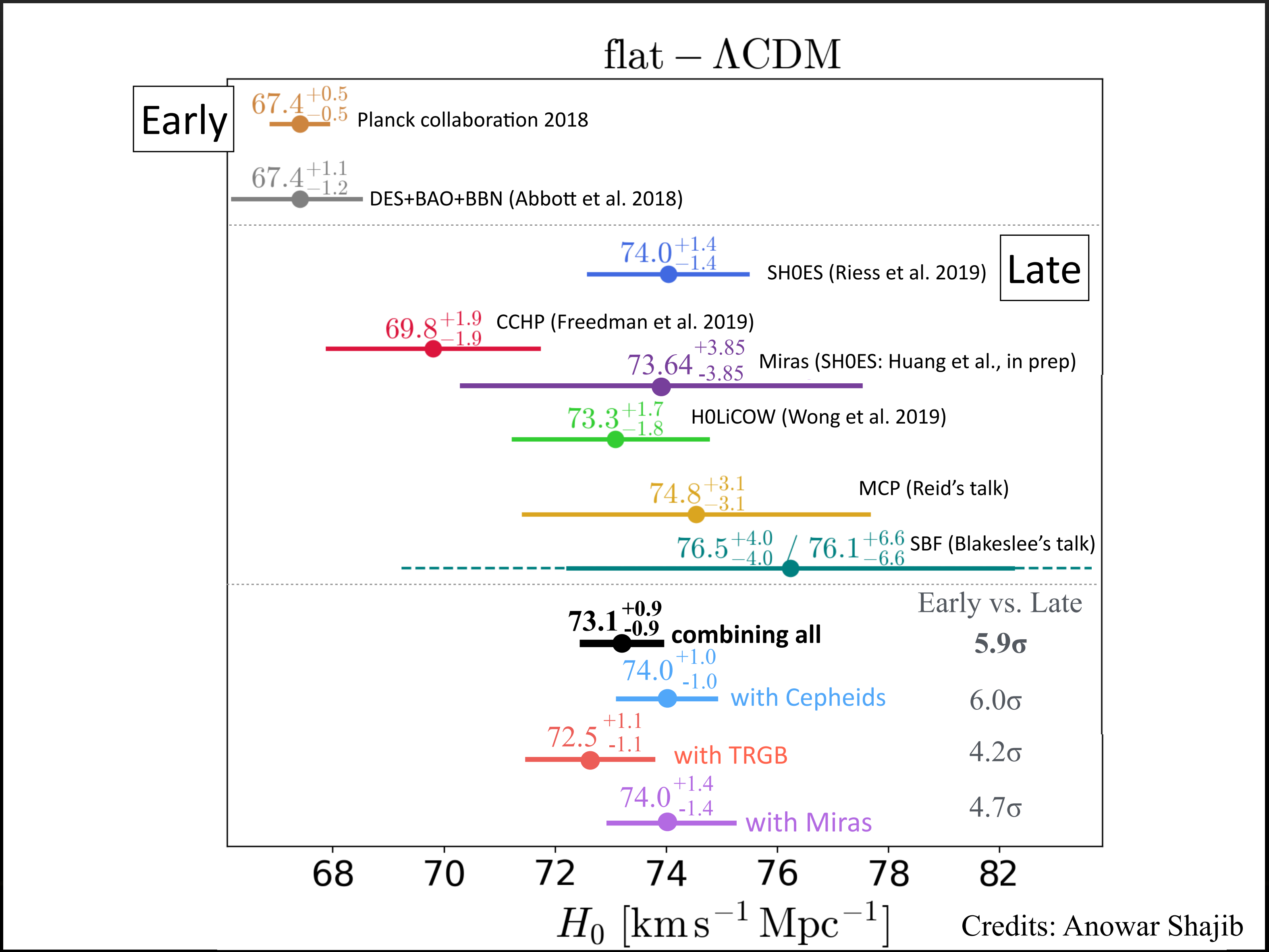
- BAO plays an important role in the tension



Important 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.
- Main message: It is possible to find radically different cosmological model that nonetheless can provide excellent fit to the data.

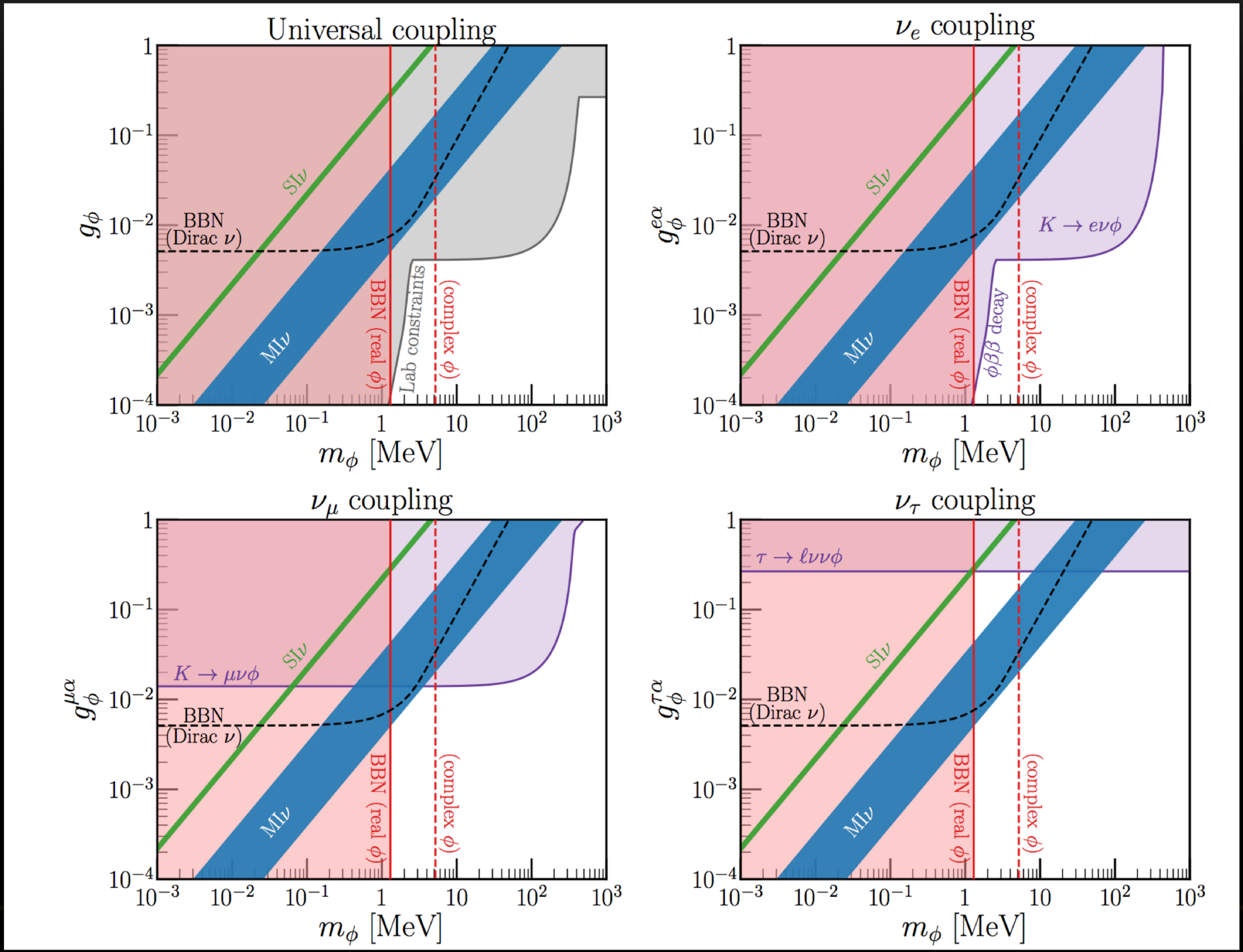
The end



flat − ΛCDM
Early
$67.4^{+0.5}_{-0.5}$ Planck collaboration 2018
$67.4^{+1.1}_{-1.2}$ DES+BAO+BBN (Abbott et al. 2018)
Late
$74.0^{+1.4}_{-1.4}$ SH0ES (Riess et al. 2019)
$69.8^{+1.9}_{-1.9}$ CCHP (Freedman et al. 2019)
$73.64^{+3.85}_{-3.85}$ Miras (SH0ES: Huang et al., in prep)
$73.3^{+1.7}_{-1.8}$ H0LiCOW (Wong et al. 2019)
$74.8^{+3.1}_{-3.1}$ MCP (Reid's talk)
$76.5^{+4.0}_{-4.0}$ / $76.1^{+6.6}_{-6.6}$ SBF (Blakeslee's talk)
Early vs. Late
$73.1^{+0.9}_{-0.9}$ combining all 5.9σ
$74.0^{+1.0}_{-1.0}$ with Cepheids 6.0σ
$72.5^{+1.1}_{-1.1}$ with TRGB 4.2σ
$74.0^{+1.4}_{-1.4}$ with Miras 4.7σ
68 70 72 74 76 78 82
H_0 $[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$
Credits: Anowar Shajib

Finding a concrete model is hard…

Blinov et al. (2019)



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

CMB Polarization data