Self-Interacting Neutrinos in Light of Large-Scale Structure Data

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Adam He, RA, Mikhail M. Ivanov, Vera Gluscevic, PRD 2024

Neutrino Self-Interactions (νSI)

Mediated by a massive scalar φ

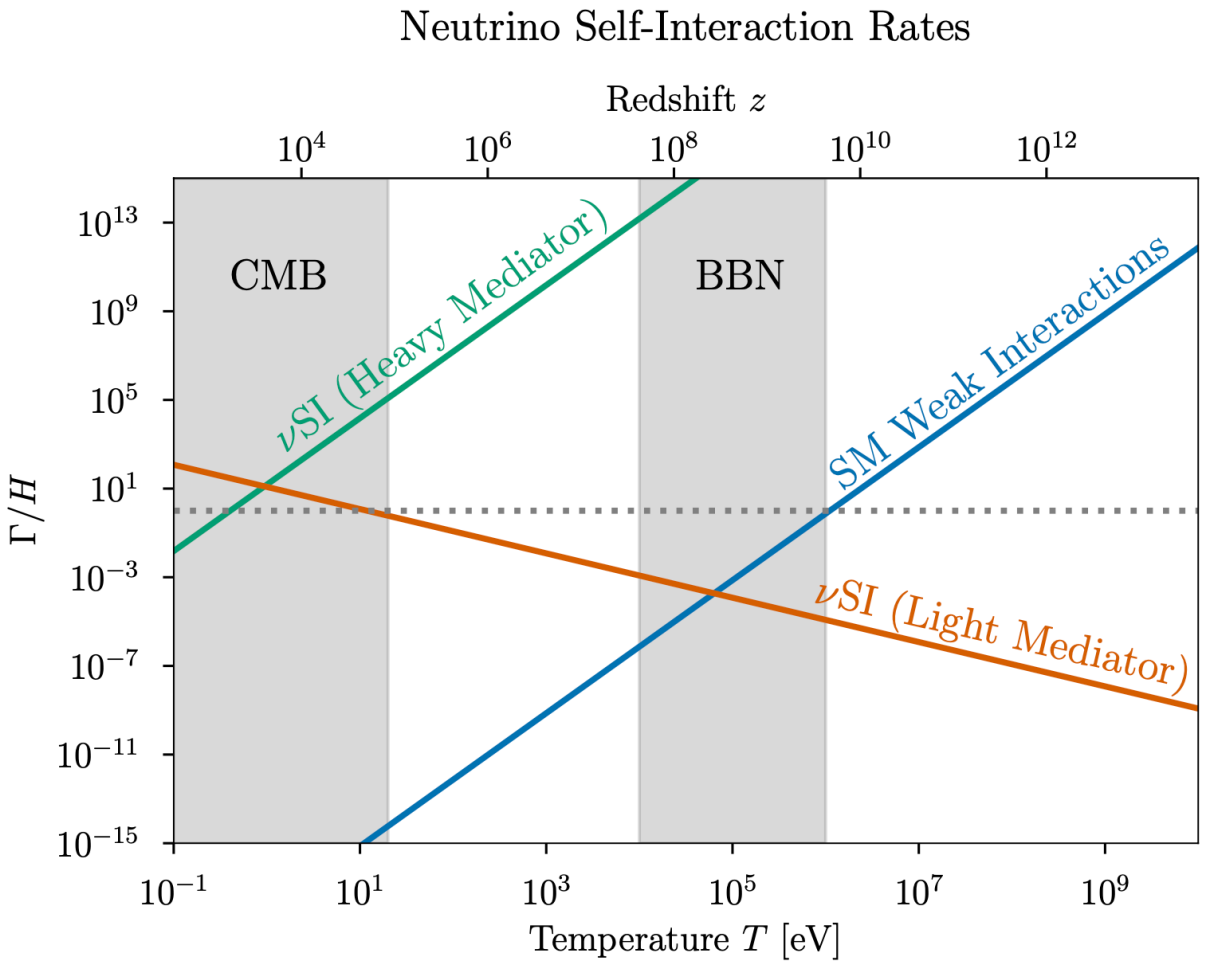
$$\mathcal{L}_{\rm int} = g_{ij}\bar{\nu}_i\nu_j\varphi$$

Flavor-universal scenario

$$g_{ij} \equiv g_\nu \delta_{ij}$$

Self-coupling constant

$$G_{\rm eff} \equiv |g_\nu|^2/m_\varphi^2$$



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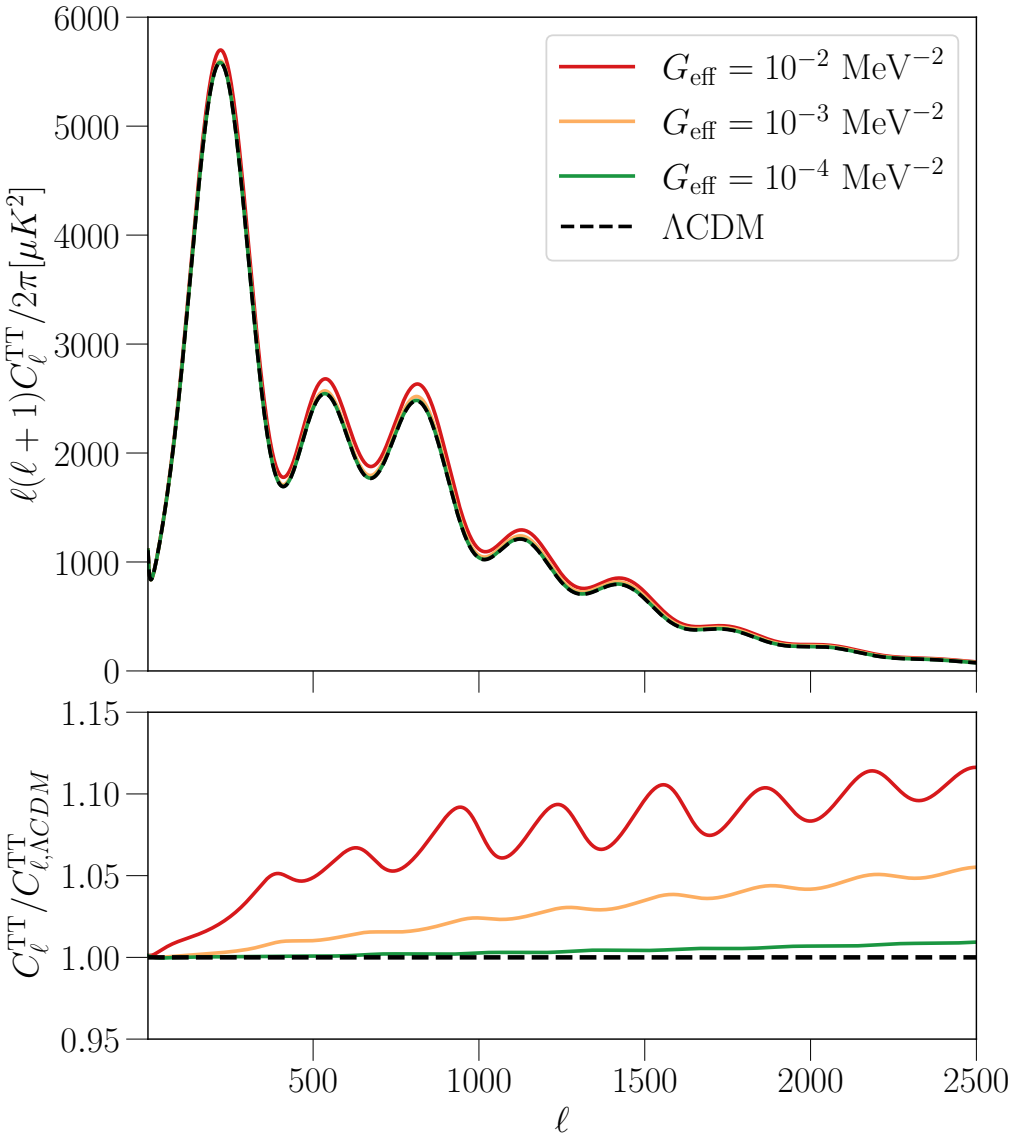
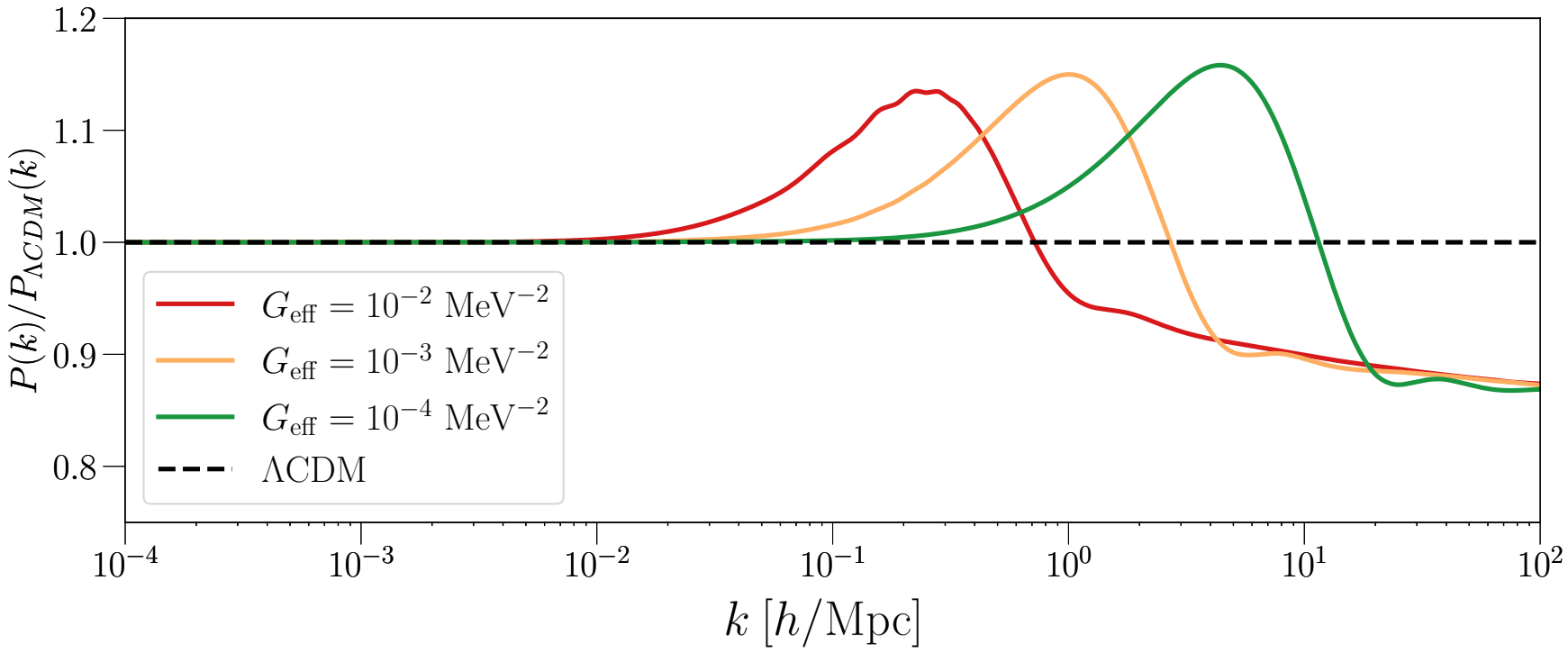
Cosmic Microwave Background (CMB)



- Free-streaming neutrinos travel through the photon-baryon plasma at early times
- Free-streaming neutrinos → Phase shift in the CMB power spectra towards larger scales and slight suppression of its amplitude
- Neutrino self-interactions delay the time at which neutrinos begin to free stream

Neutrino self-interactions shift the CMB power spectra peaks towards smaller scales and boost their fluctuation amplitude, as compared to the standard model

Matter Power Spectrum

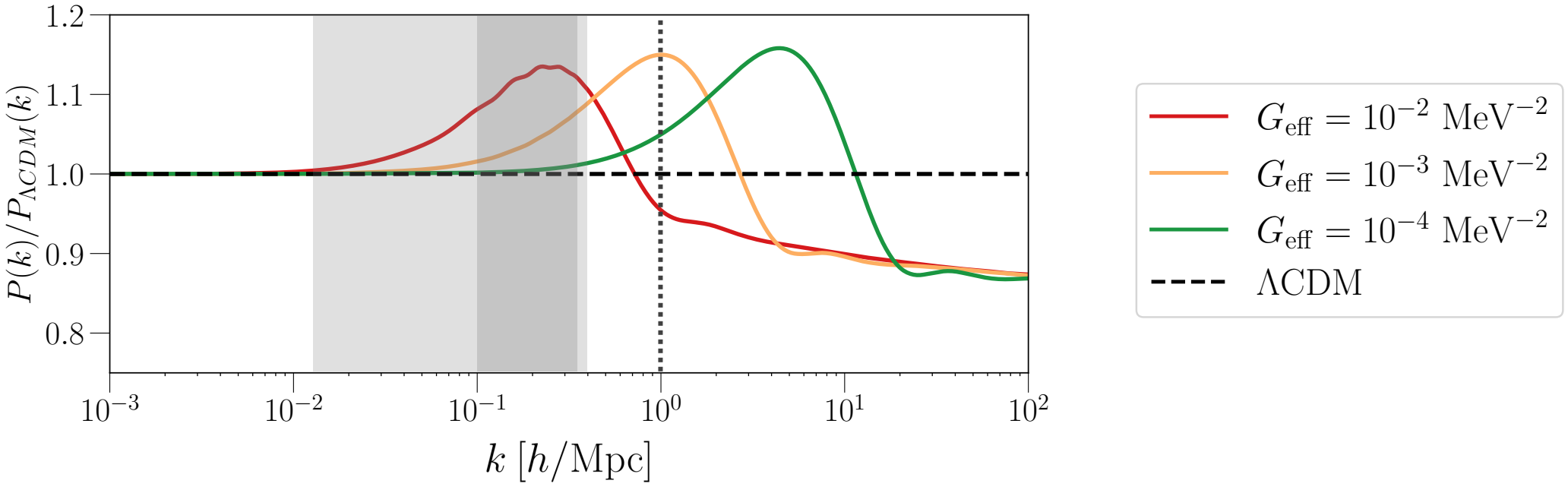


larger k: modes enter the horizon **before** neutrino decoupling $\Longrightarrow$ Suppression of $P(k)$

$k\sim0.2$ h/Mpc: modes enter the horizon **during** neutrino decoupling $\Longrightarrow$ Bump-like feature

smaller k: modes enter the horizon far **after** neutrino decoupling $\Longrightarrow$ Same to standard one

Large Scale Structure (LLS) Probes

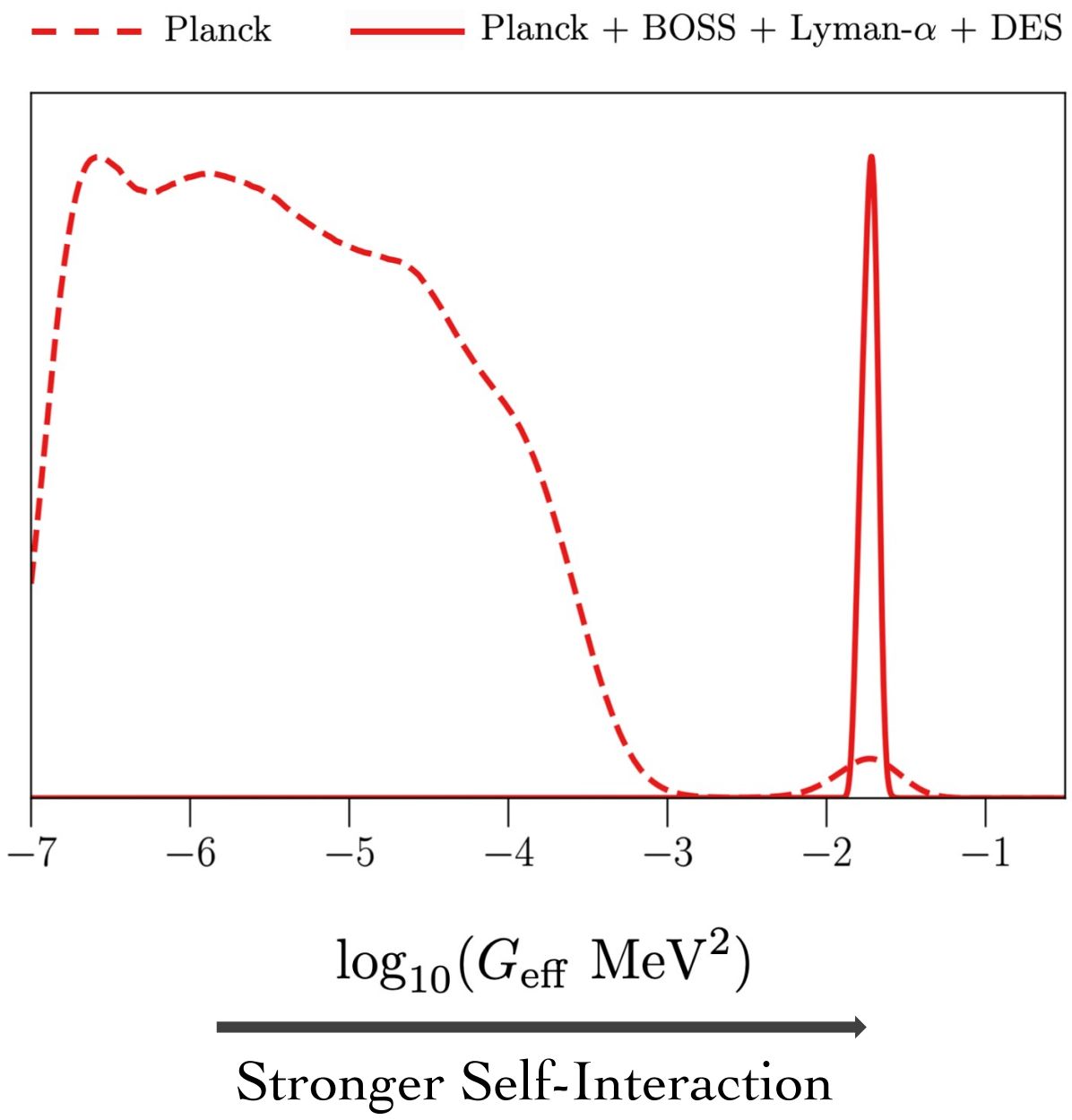


BOSS: anisotropic galaxy clustering data from BOSS DR12 at z = 0.38 and 0.61 (light grey)

Lyman-α: 1D Lyman-α flux power spectrum from SDSS DR14 BOSS and eBOSS quasars (dotted line)

DES: weak lensing data from DES-Y3 (dark grey)

Using effective field theory of LSS to model non-linear power spectrum [CLASS-PT, 2004.10607]



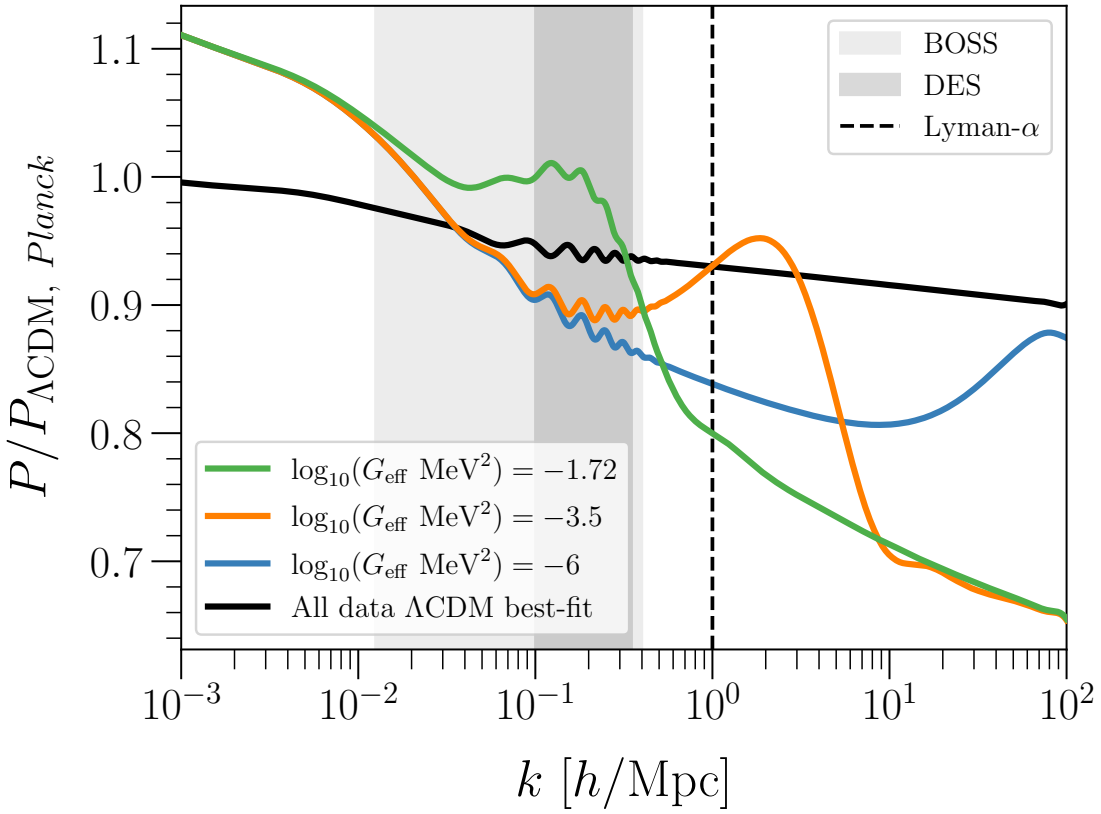
Baseline νSI Model

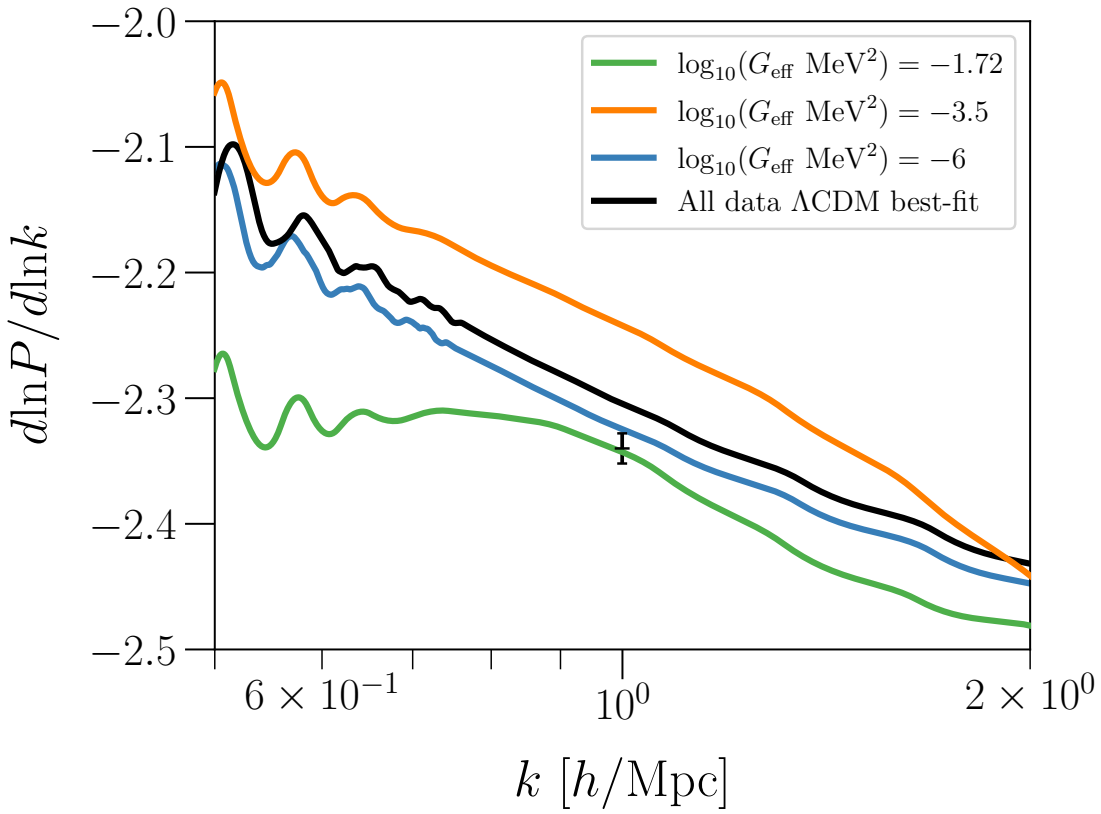
$G_{\rm eff} + \sum m_\nu$ + 6 standard parameters

with fixed $N_{\rm eff} = 3.046$

Data set	$\Delta\chi^2$ wrt ΛCDM+$\sum m_\nu$	$\Delta\chi^2$ wrt ΛCDM
Planck low–ℓ TT	−0.01	+0.09
Planck high–ℓ	−0.90	−1.52
Planck lensing	−0.08	−0.18
BOSS	+0.38	−1.53
Lyman–α	−24.91	−26.02
DES	−2.78	−1.03
τ prior	−0.14	+0.18
Total	−28.44	−30.01

The full data set strongly favors presence of a strong neutrino self-interaction, at ~5σ level





Green: best-fit νSI model from Planck+LSS analysis, while orange and blue correspond to smaller couplings

Black: best-fit ΛCDM+ $\sum m_\nu$ model from Planck+LSS analysis

All curves are divided by the best-fit power spectrum from a Planck–only analysis of ΛCDM

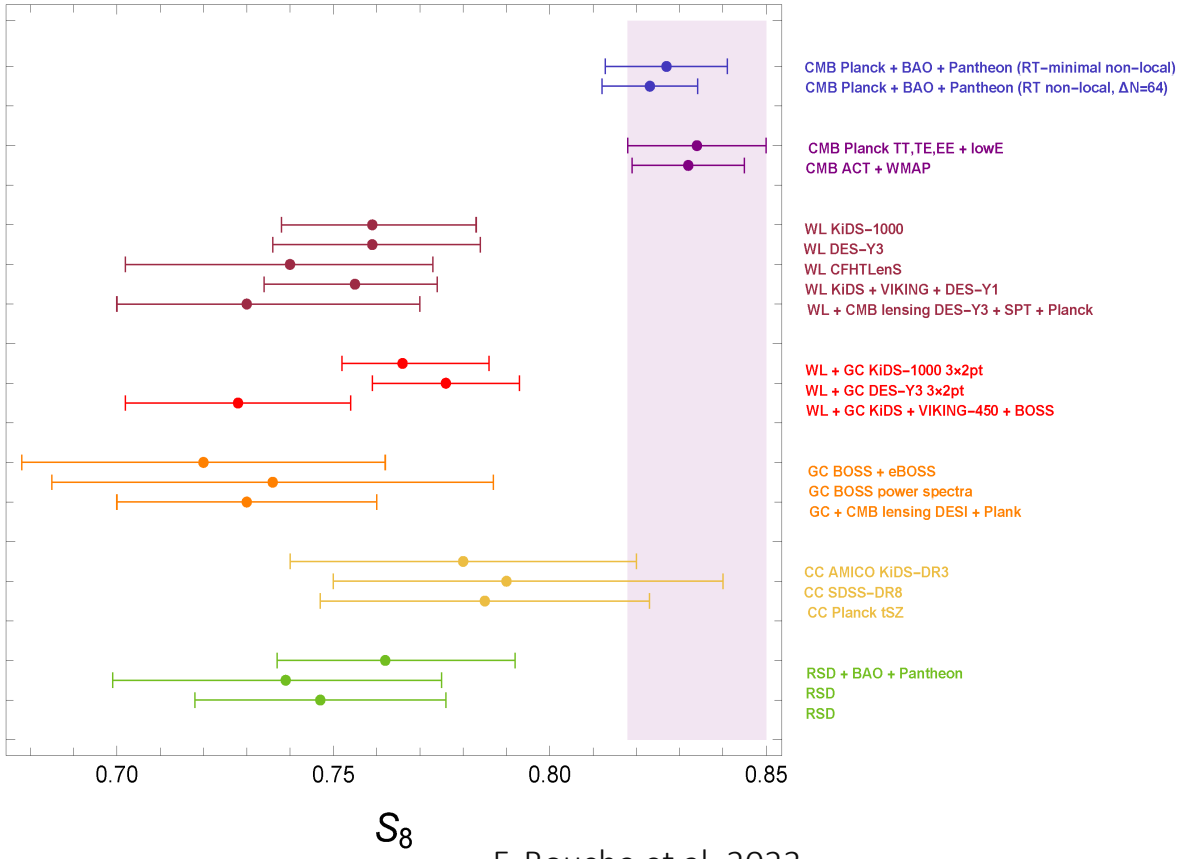
Data Point: the slope measurement derived from Lyman-α forest, with a 2σ uncertainty

Observational Tensions

within standard cosmological model

S_8 Tension

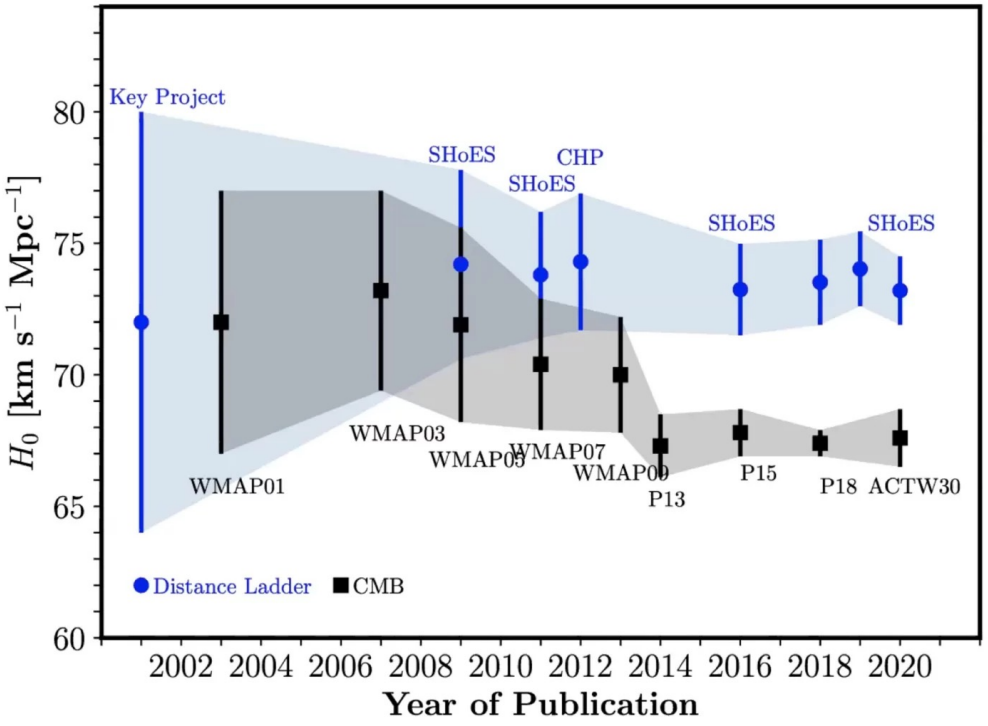
Between **CMB** and **LSS** measurements



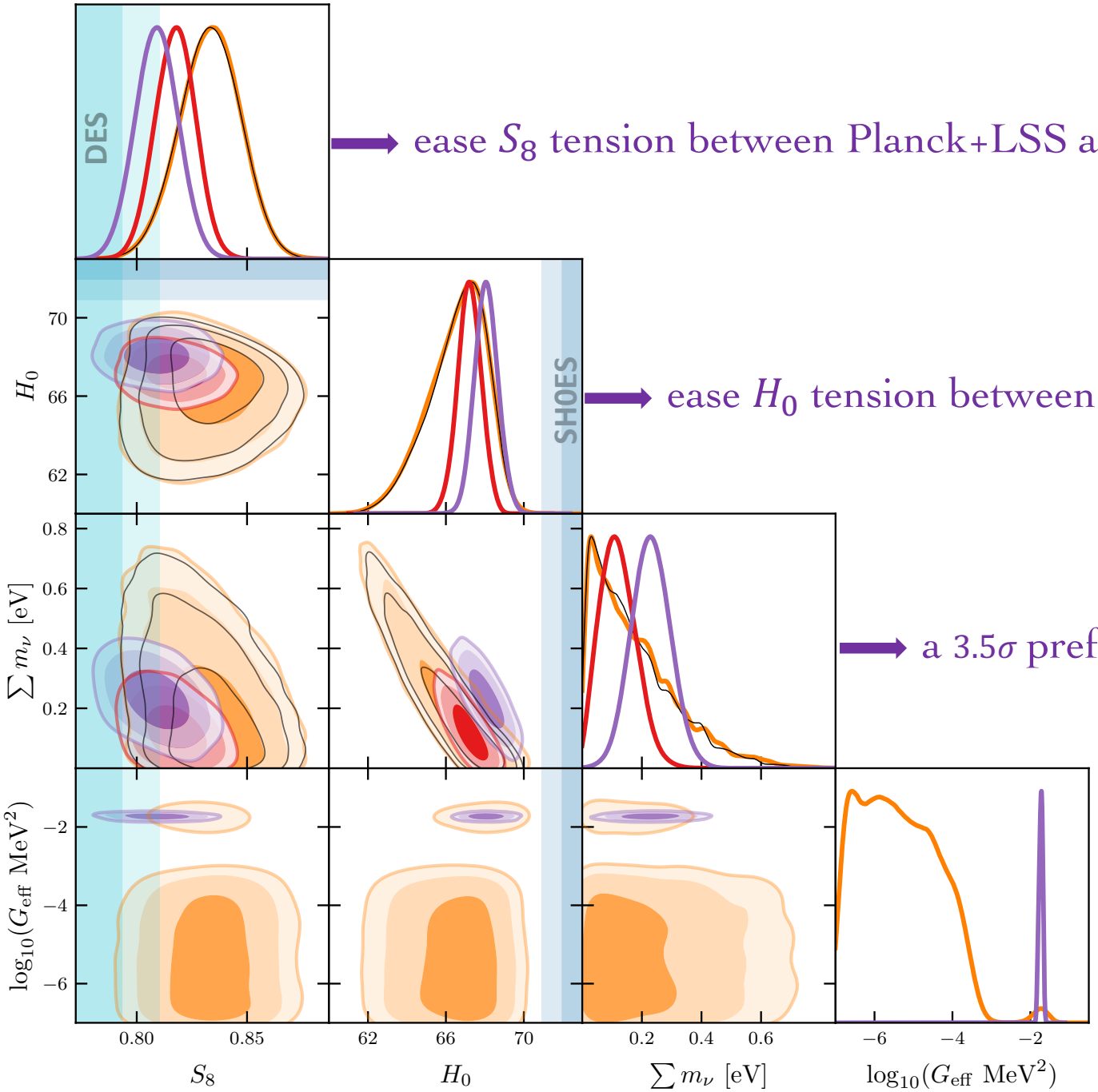
F. Bouche et al. 2023

H_0 Tension

Between **CMB** and **local** measurements



Credit : W. Freedman



→ ease S_8 tension between Planck+LSS and DES measurements

→ ease H_0 tension between Planck+LSS and SH0ES measurements

→ a 3.5σ preference for non-zero sum of neutrino masses

Planck: self-interacting neutrinos

All data: self-interacting neutrinos

Planck: ΛCDM+$\sum m_\nu$

All data: ΛCDM+$\sum m_\nu$

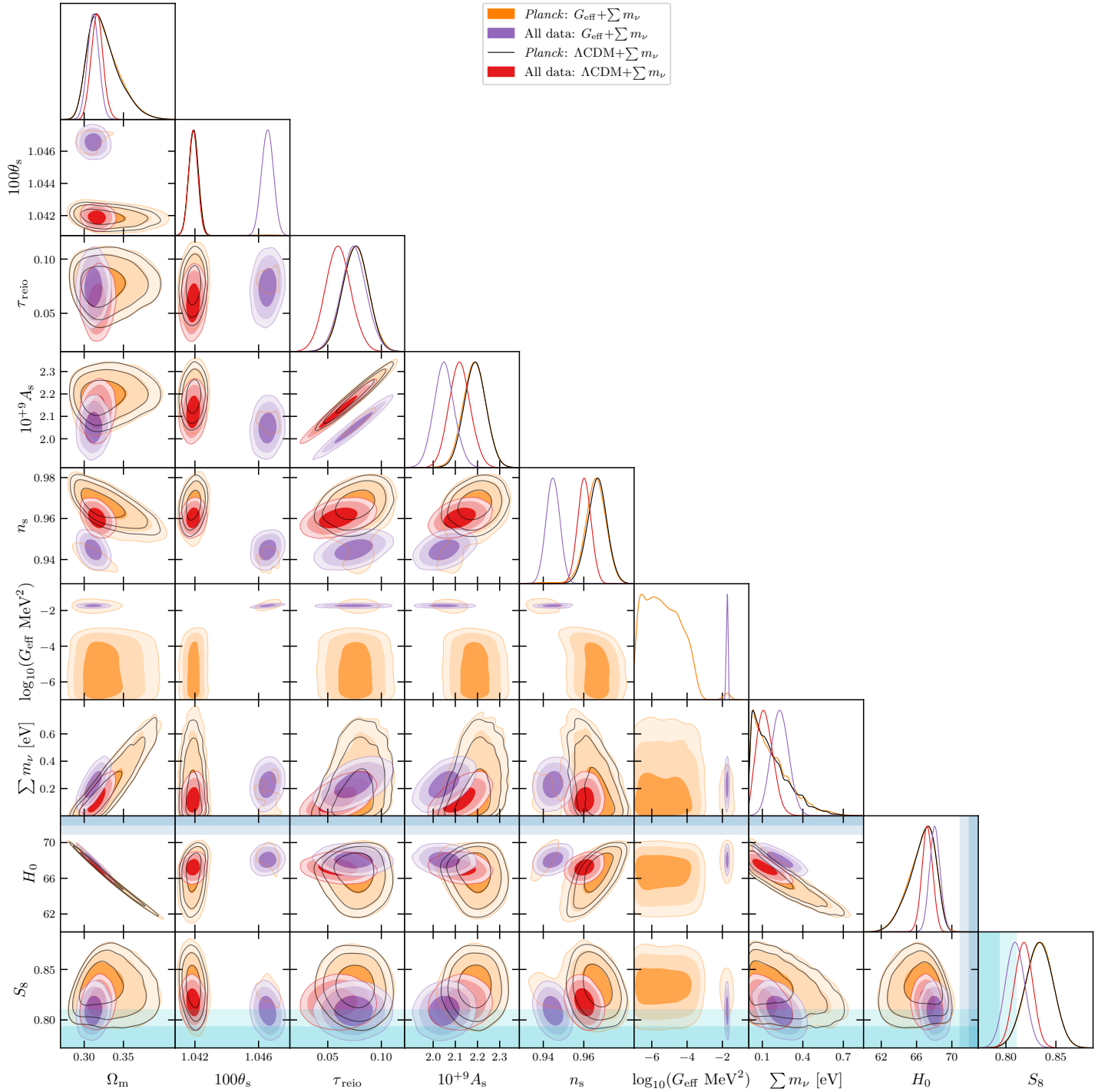
Summary

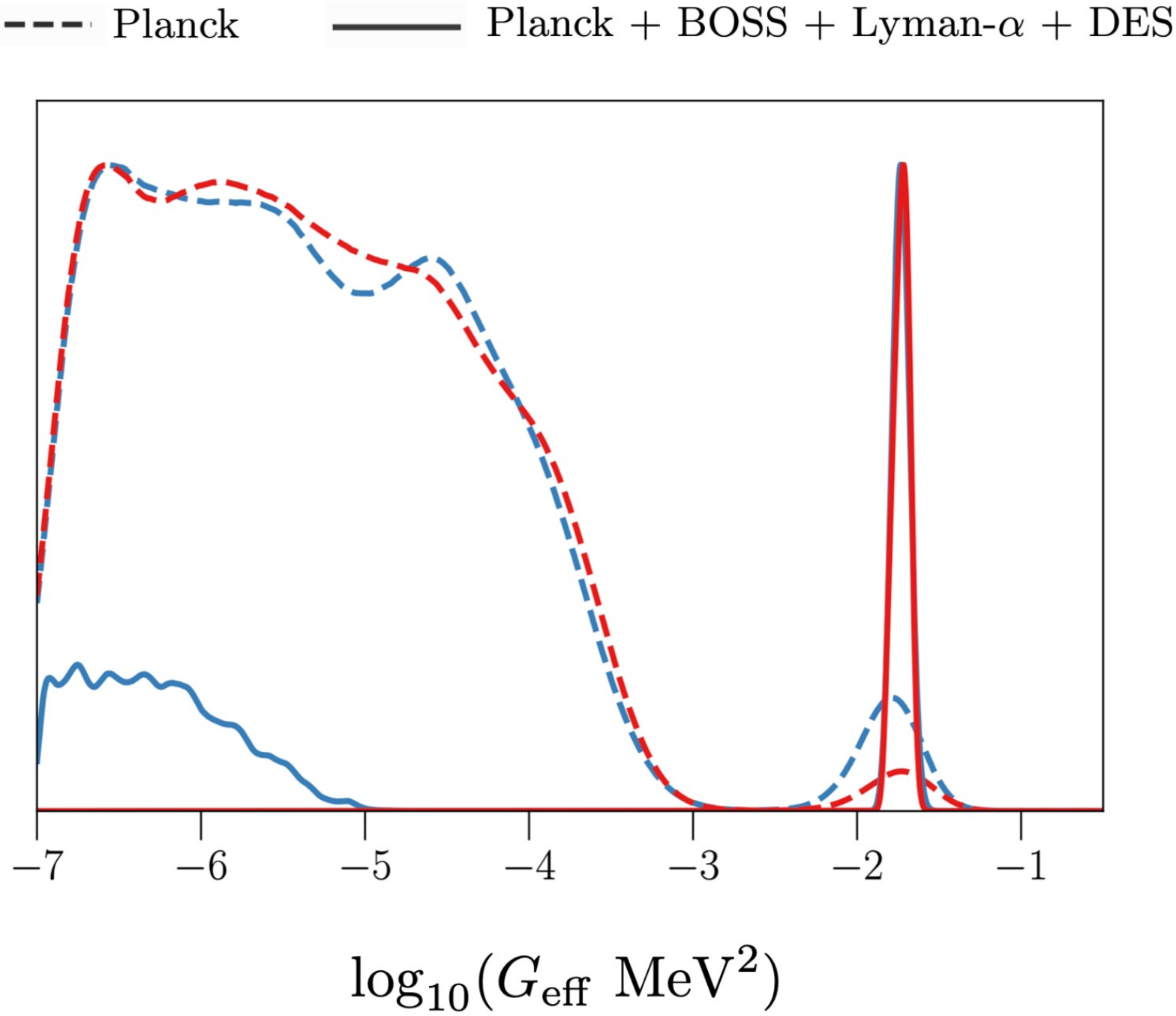
- We use the effective field theory of large-scale structure to model matter distribution on non-linear scales within the self-interacting neutrino cosmology for the first time
- CMB+LSS data set strongly favors the presence of a strong neutrino self-interaction
- The self-interacting neutrino model eases both H_0 and S_8 tensions
- There is a preference for a non-zero sum of neutrino masses at the level of ~0.3 eV under this self-interacting neutrino model

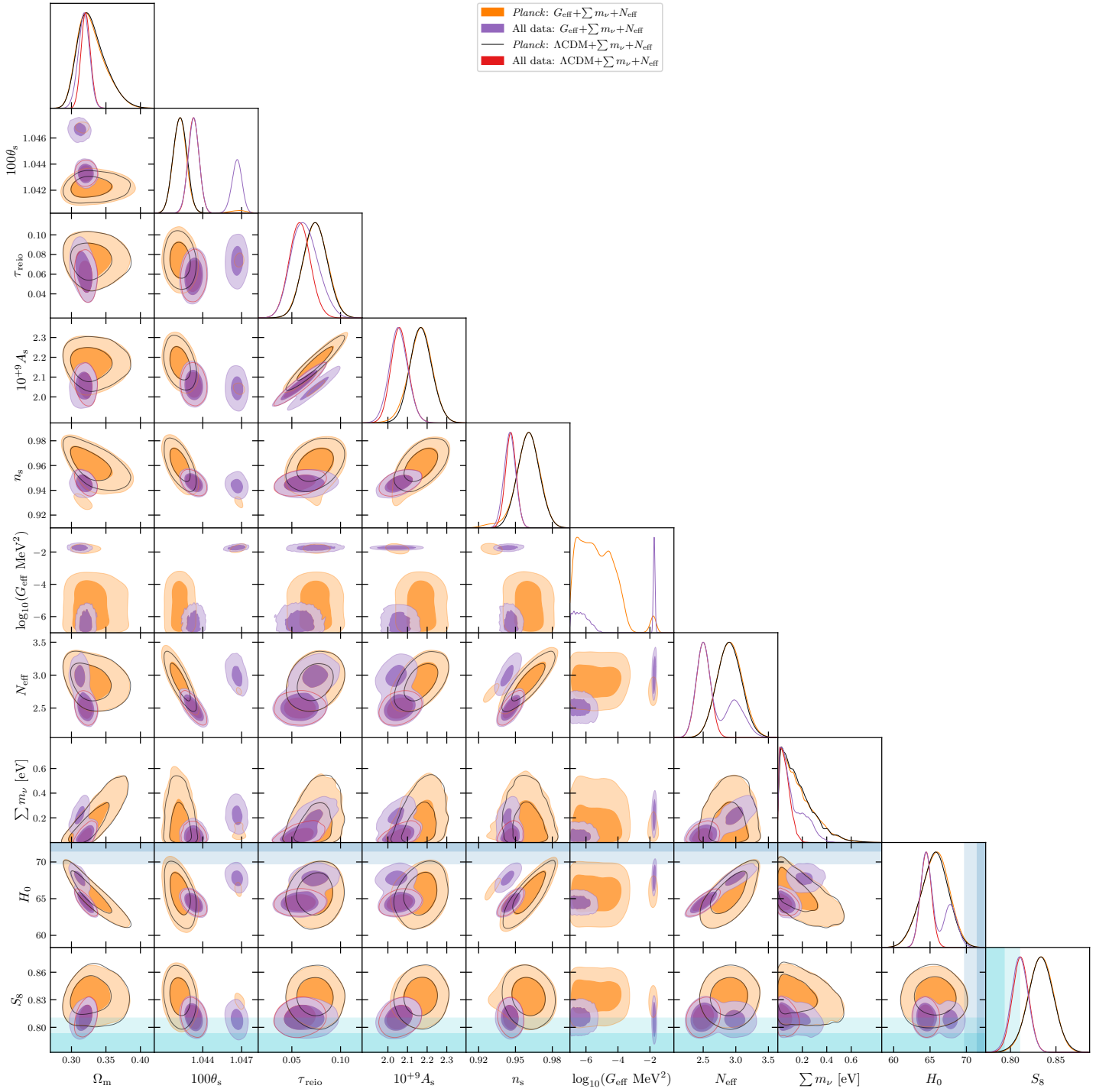
To be further explored with the next generation of spectroscopic surveys!

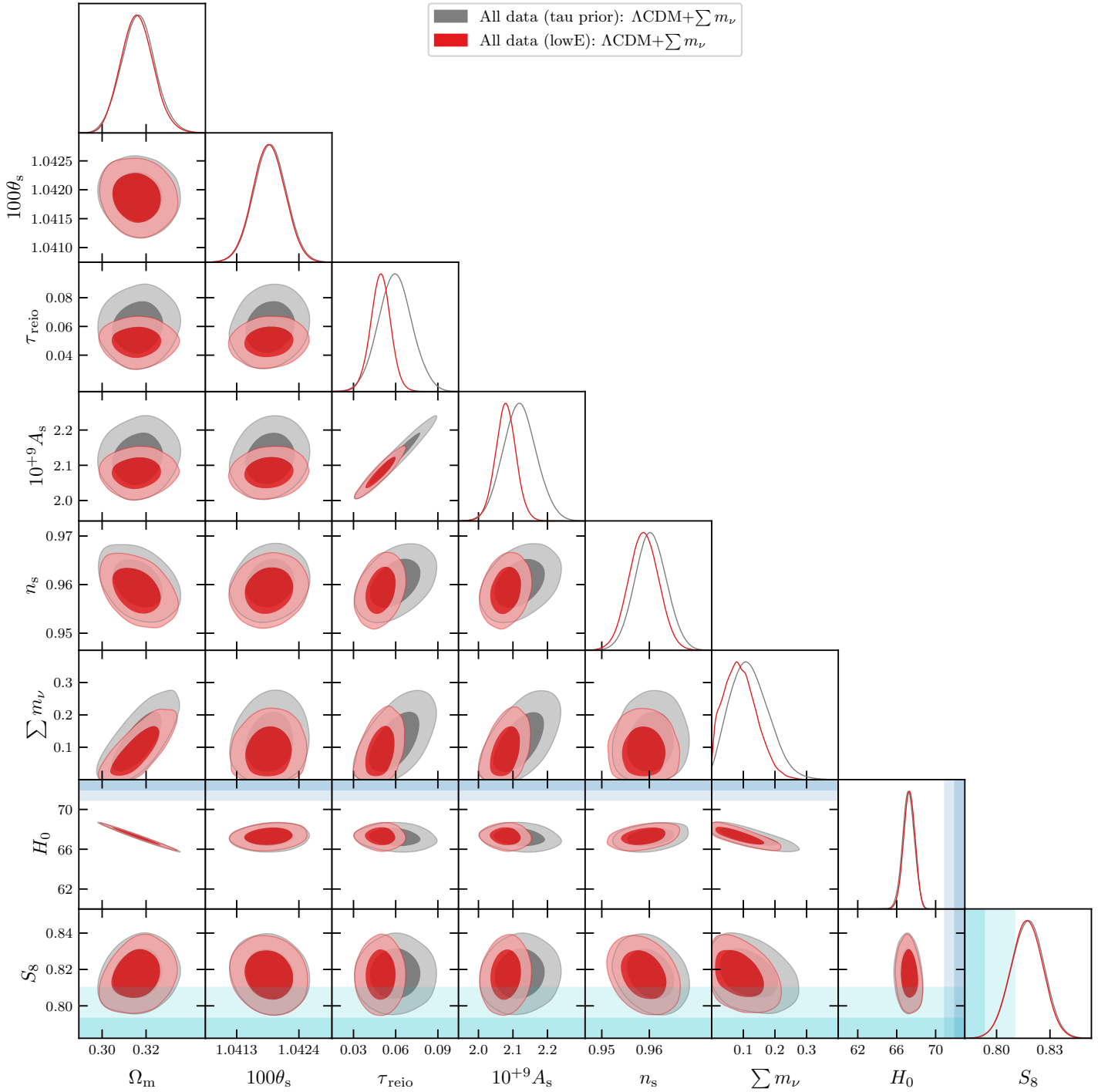
Thanks

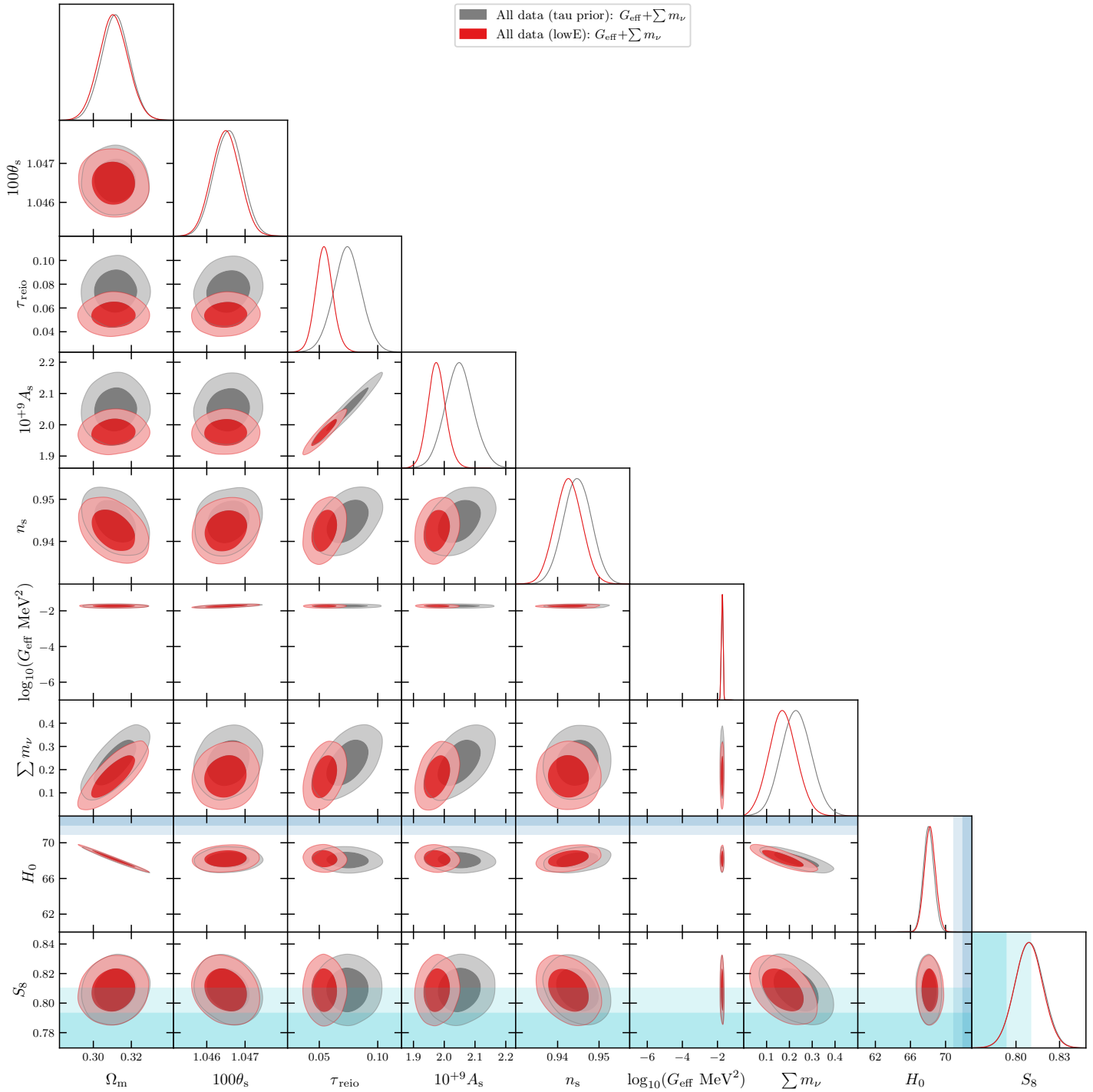
Back up


Planck: $G_{\rm eff}+\sum m_\nu$
All data: $G_{\rm eff}+\sum m_\nu$
Planck: ΛCDM+$\sum m_\nu$
All data: ΛCDM+$\sum m_\nu$
$\Omega_{\rm m}$
$100\theta_{\rm s}$
$\tau_{\rm reio}$
$10^{+9}A_{\rm s}$
$n_{\rm s}$
$\log_{10}(G_{\rm eff}\ {\rm MeV}^2)$
$\sum m_\nu$ [eV]
H_0
S_8


Planck
Planck + BOSS + Lyman-α + DES
−7
−6
−5
−4
−3
−2
−1
log10(Geff MeV2)


Planck: $G_{\rm eff}+\sum m_\nu+N_{\rm eff}$
All data: $G_{\rm eff}+\sum m_\nu+N_{\rm eff}$
Planck: ΛCDM+$\sum m_\nu+N_{\rm eff}$
All data: ΛCDM+$\sum m_\nu+N_{\rm eff}$
$\Omega_{\rm m}$
$100\theta_{\rm s}$
$\tau_{\rm reio}$
$10^{+9}A_{\rm s}$
$n_{\rm s}$
$\log_{10}(G_{\rm eff}\ {\rm MeV}^2)$
$N_{\rm eff}$
$\sum m_\nu$ [eV]
H_0
S_8


All data (tau prior): ΛCDM+∑m_ν
All data (lowE): ΛCDM+∑m_ν
Ω_m
$100\theta_s$
τ_{reio}
$10^{+9}A_s$
n_s
$\sum m_\nu$
H_0
S_8


All data (tau prior): $G_{\rm eff}+\sum m_\nu$
All data (lowE): $G_{\rm eff}+\sum m_\nu$
$\Omega_{\rm m}$
$100\theta_{\rm s}$
$\tau_{\rm reio}$
$10^{+9}A_{\rm s}$
$n_{\rm s}$
$\log_{10}(G_{\rm eff}\ {\rm MeV}^2)$
$\sum m_\nu$
H_0
S_8

C. Kreisch et al. 2019

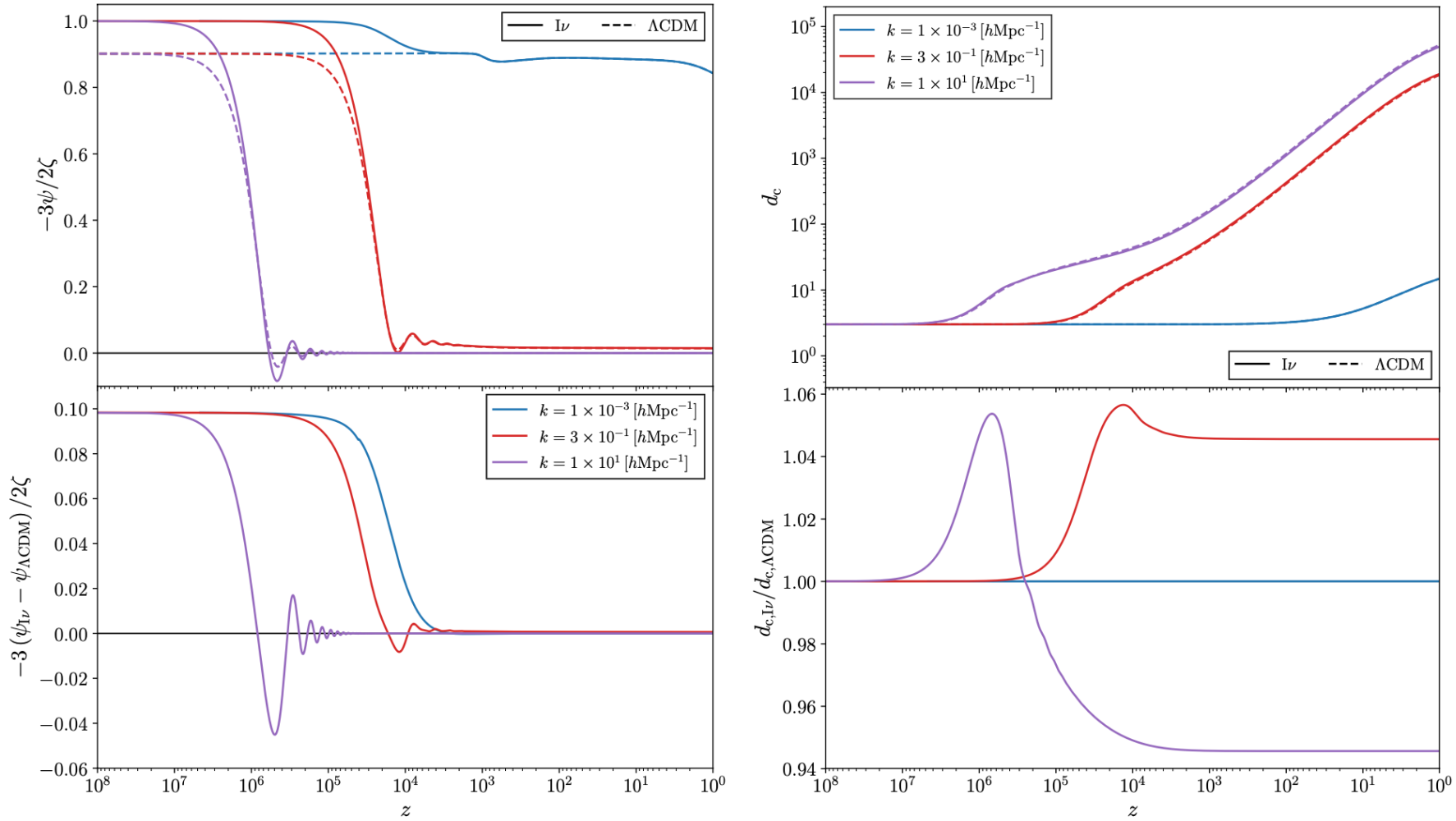
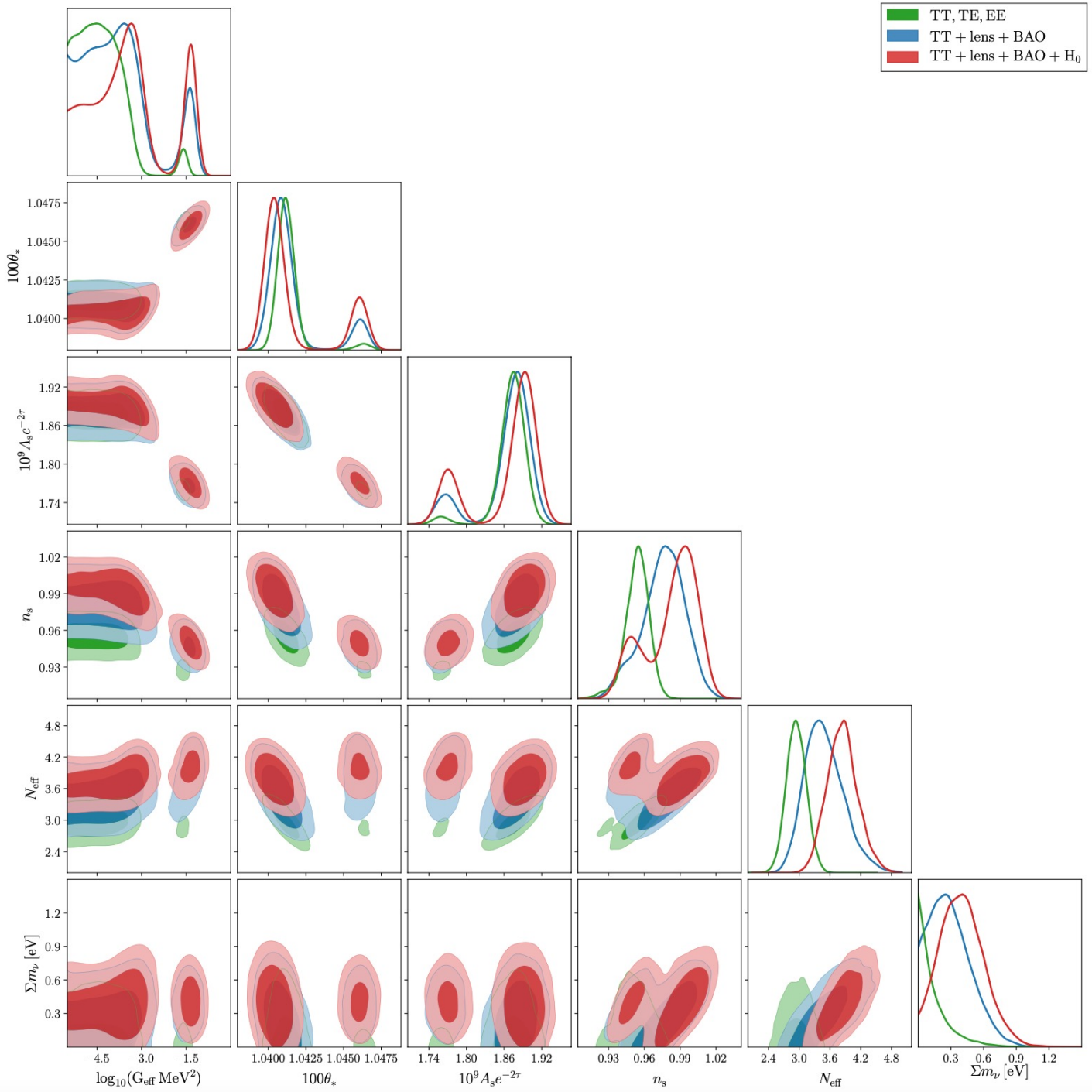


FIG. 2: The evolution of the ψ gravitational potential (left) and of the gauge invariant dark matter density contrast d_c (right) for different k-modes as a function of redshift. Solid lines correspond to the interacting neutrino case with $G_{\rm eff} = 10^{-2}$ MeV^{-2}, $N_{\rm eff} = 3.046$, and $\sum m_\nu = 0.06$ eV, whereas dashed lines correspond to the ΛCDM case. On the left, we plot $-3\psi/(2\zeta)$, where ζ is the gauge-invariant curvature perturbation. The lower left panel shows the normalized difference between the interacting neutrino and ΛCDM ψ potential, while the lower right panel shows the ratio of the dark matter fluctuations in the two models. The onset of neutrino free-streaming for the interacting neutrino model shown here occurs at $z_{{\rm dec},\nu} \simeq 10^4$. Dark matter fluctuations entering the horizon while neutrinos are still tightly coupled decay and appear damped at present relative to ΛCDM, while those entering the horizon during neutrino decoupling receive a net boost that persists until the present epoch.



C. Kreisch et al. 2019