Flavor-specific Neutrino Self-interaction in Cosmology

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[Based on arXiv:2011.12315]

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Introduction

Neutrinos

The most illusive particle in the SM

Electroweak interaction

Secret Interaction ?

Self interaction, interaction with Dark sector etc.

- ✦ Anomalous signal in short- baseline experiments
- ✦ Supernova Neutrinos
- ✦ Cosmological signatures

Cosmological signatures of Neutrino self interaction

$$\mathscr{L}_{\rm int} \supset \frac{1}{2} g_{ij} \bar{\nu}_i \nu_j \phi, \quad g_{ij} = g\delta_{ij}$$

Flavor universal Self-interaction

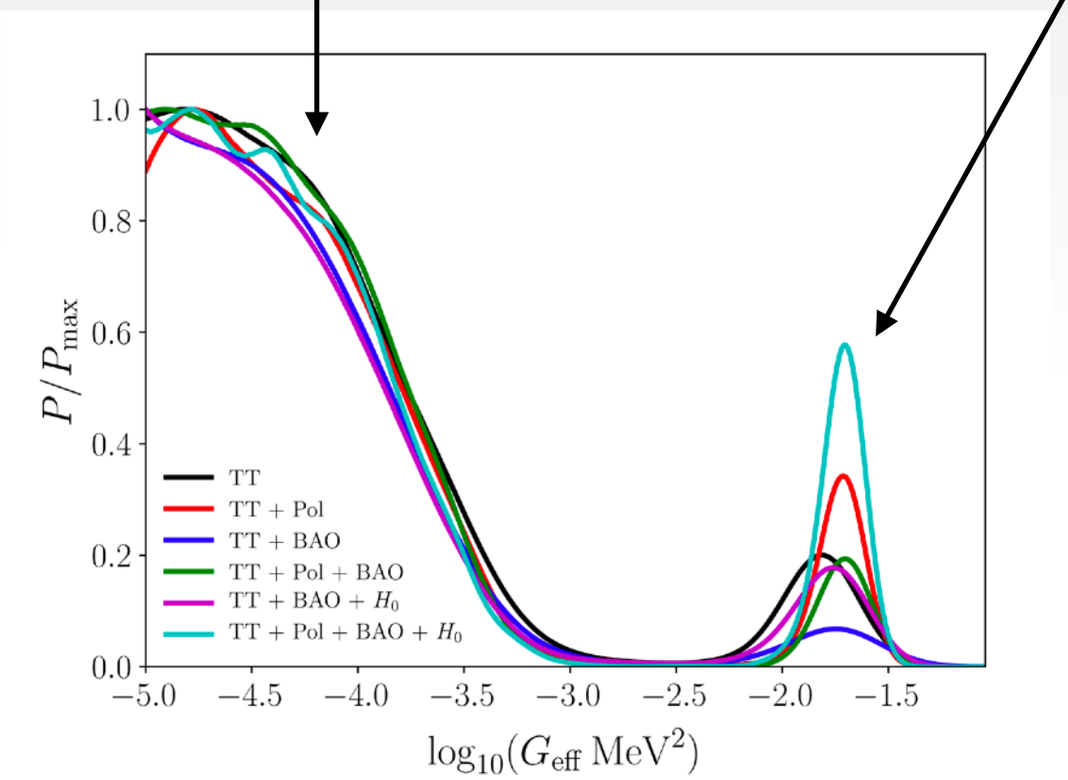
(Mediator can be vector)

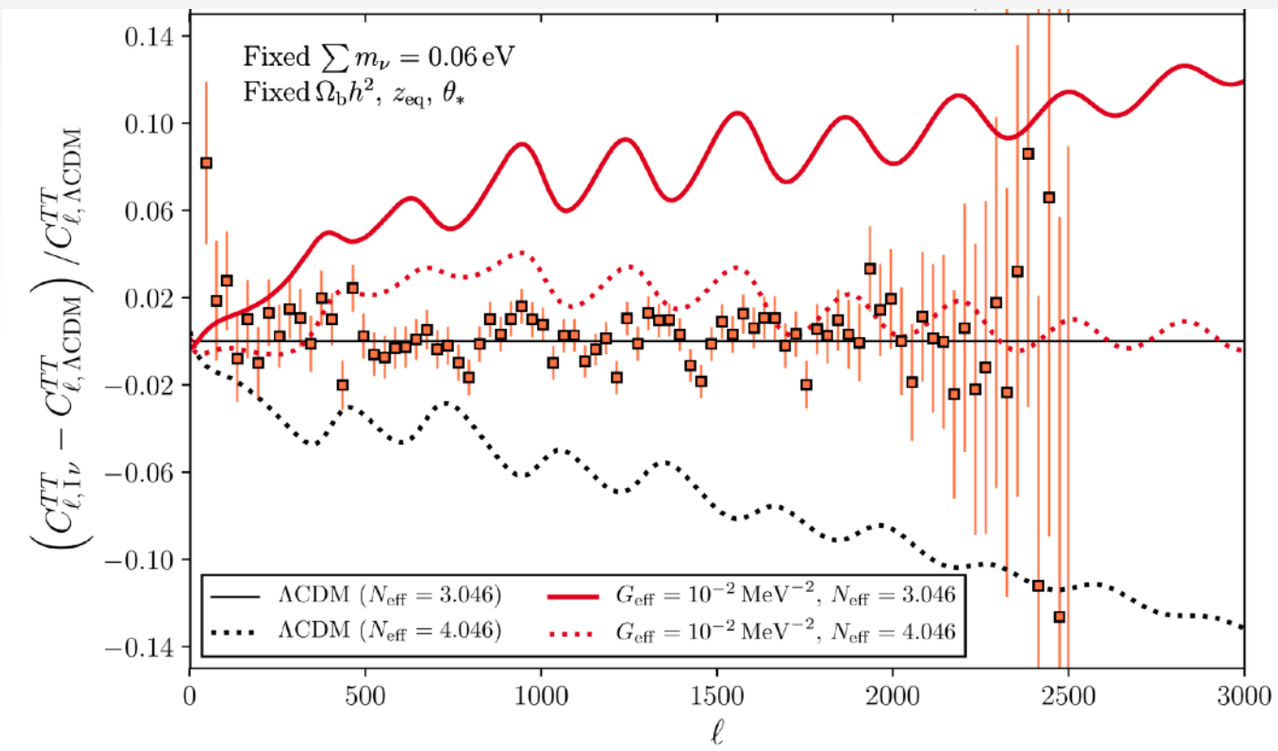
$$\mathscr{L}_{\rm eff} = G_{\rm eff}(\bar{\nu}\nu)(\bar{\nu}\nu), \quad G_{\rm eff} = \frac{g^2}{m_\phi^2}$$

Moderately interacting (MI)

Strongly interacting (SI)

Lancaster et. al. (1704.06657)





Kreisch et al (1902.00534)

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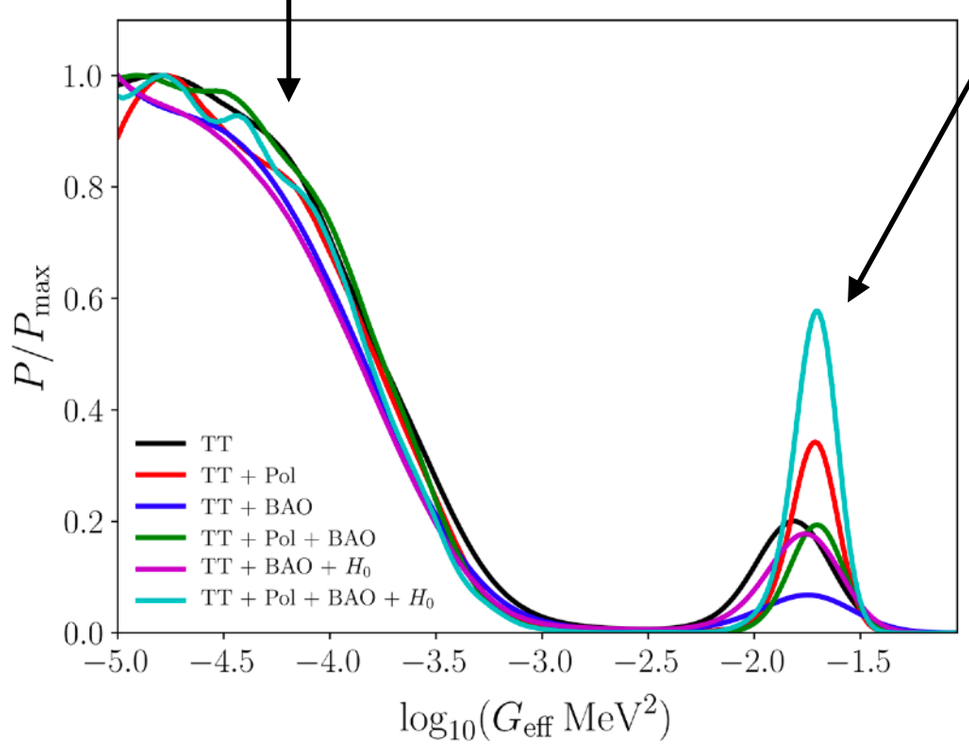
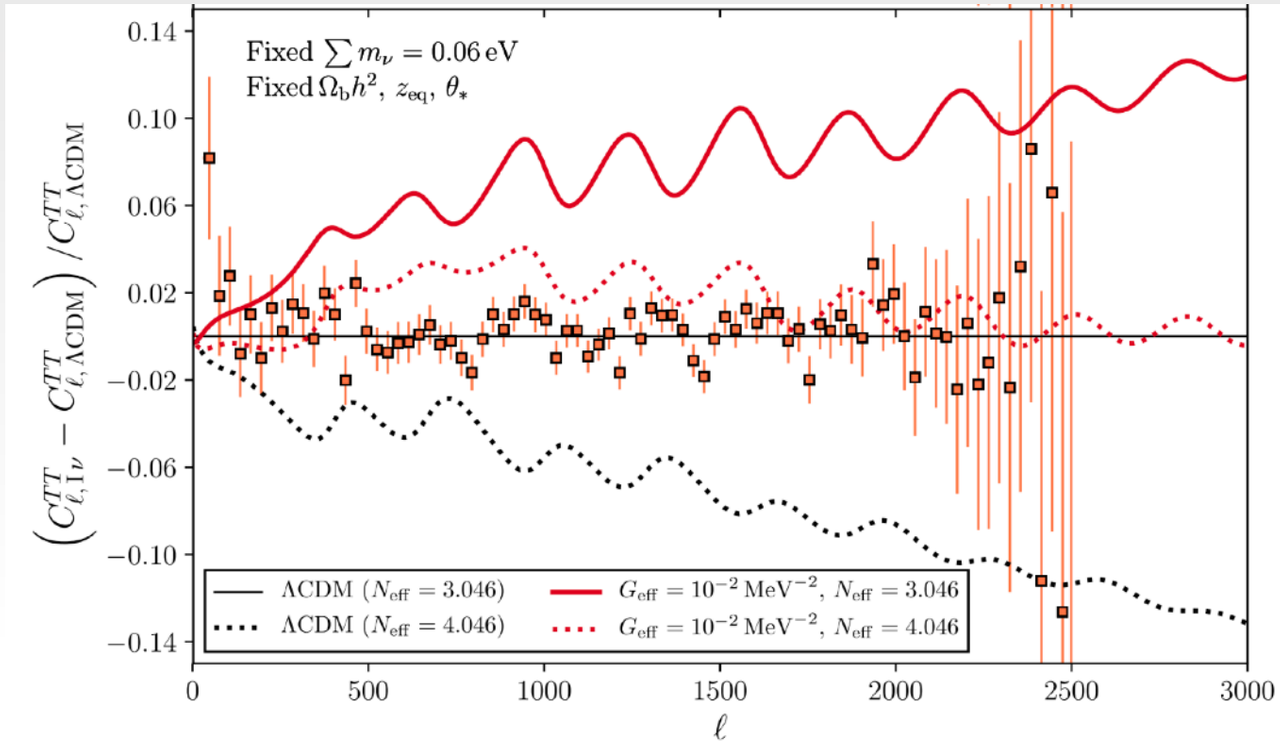




Kreisch et al (1902.00534)

Degeneracy of $G_{\rm eff}$ with $N_{\rm eff}$ (H_0)

CMB (Planck)
$H_0 = 67.36 \pm 0.54$

$\longleftrightarrow$ $\sim 4.4\sigma$

Local measurement (Reiss et. al.)
$H_0 = 74.03 \pm 1.42$

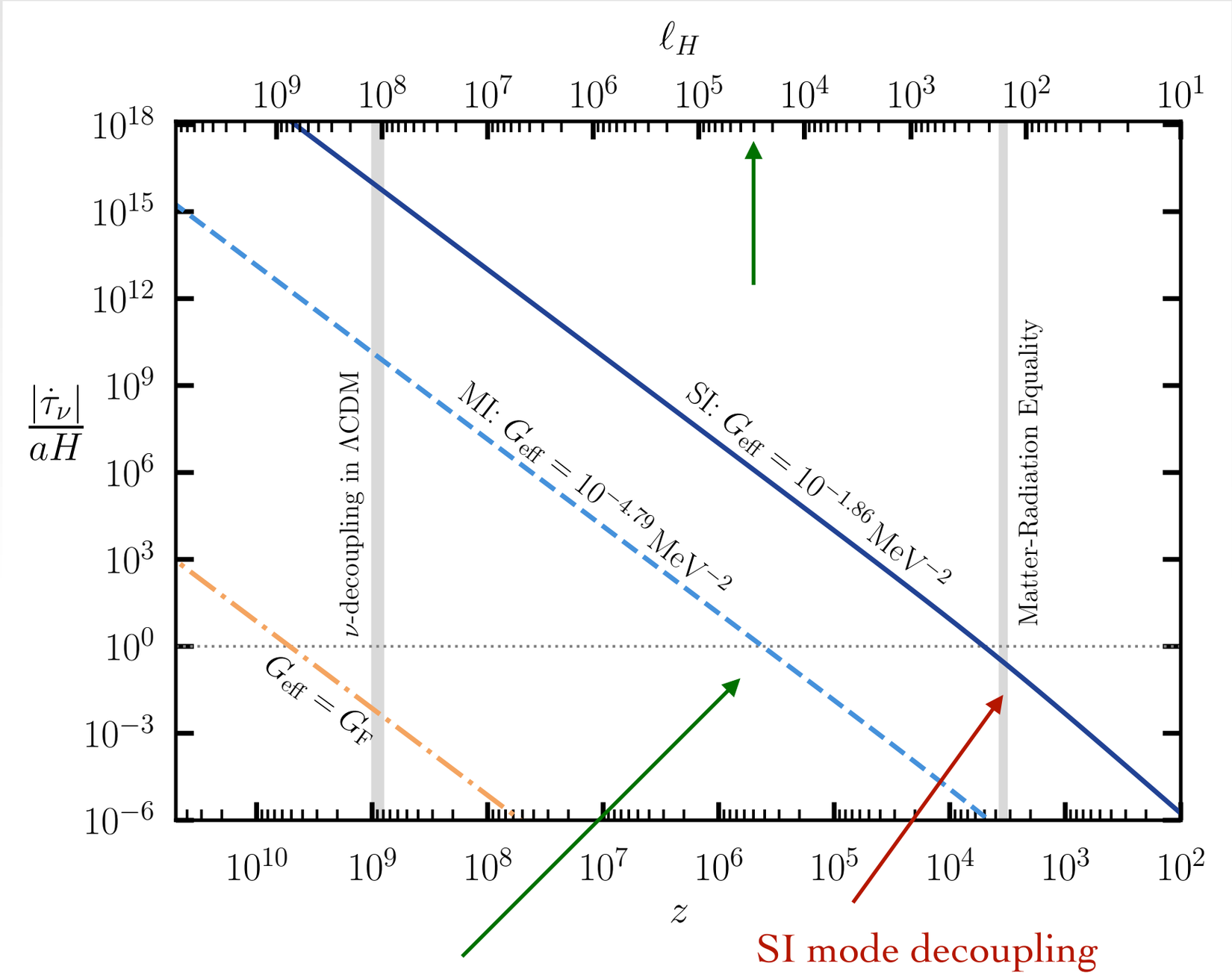
Proposed as a solution (?) of Hubble tension

(Doesn't work when CMB polarisation data is included)

Laboratory constraint

Universal coupling is strongly ruled out by laboratory constraints

$$\dot{\tau}_\nu = -\, a(G_{\rm eff})^2 T_\nu^5$$

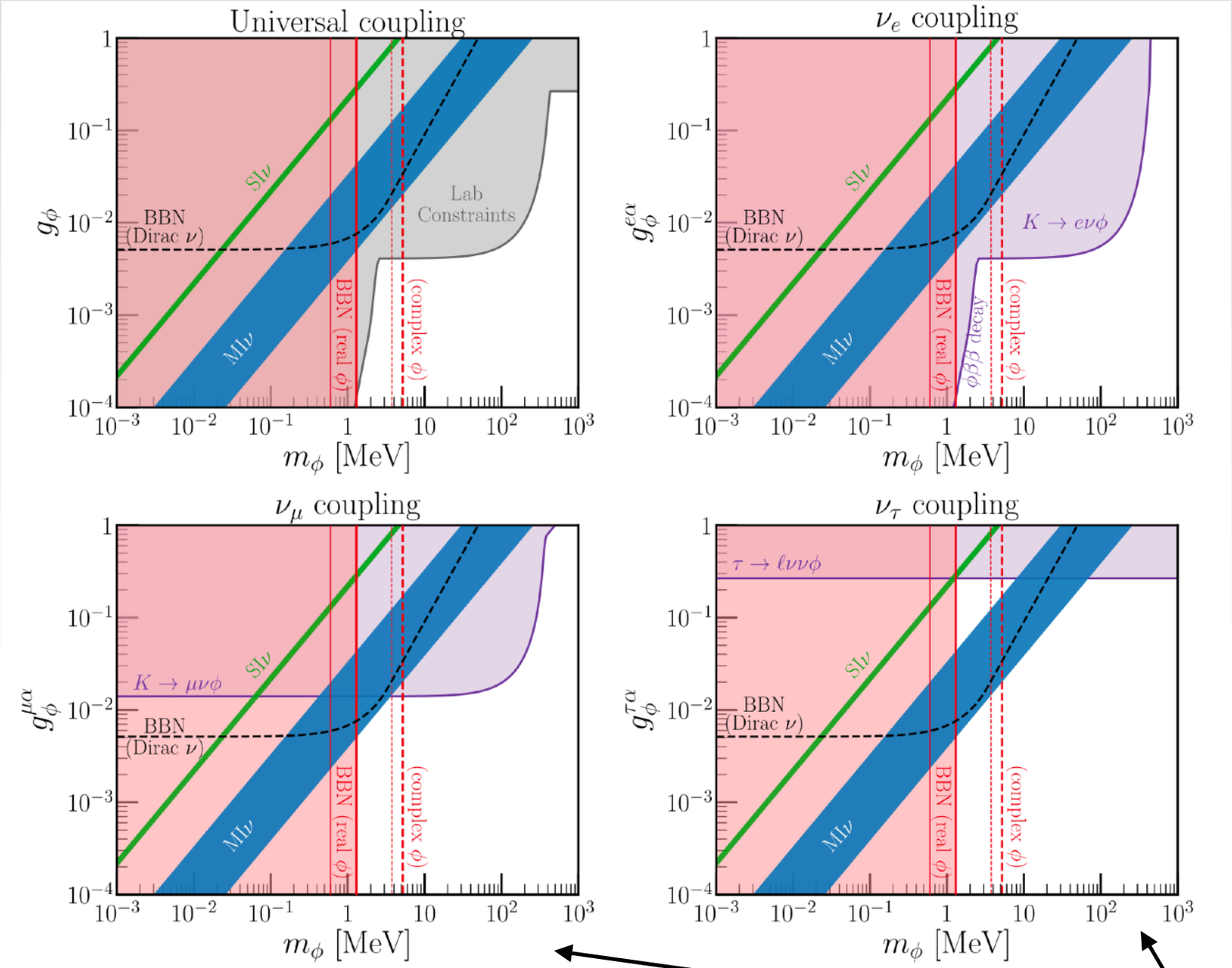


MI mode is virtually the ΛCDM mode

SI mode decoupling happens roughly at matter-radiation equality

Laboratory constraint

Universal coupling is strongly ruled out by laboratory constraints



Blinov et. al., 1905.02727

Constraints are comparatively weaker for coupling with ν_μ and ν_τ

$(g_\phi \equiv g)$

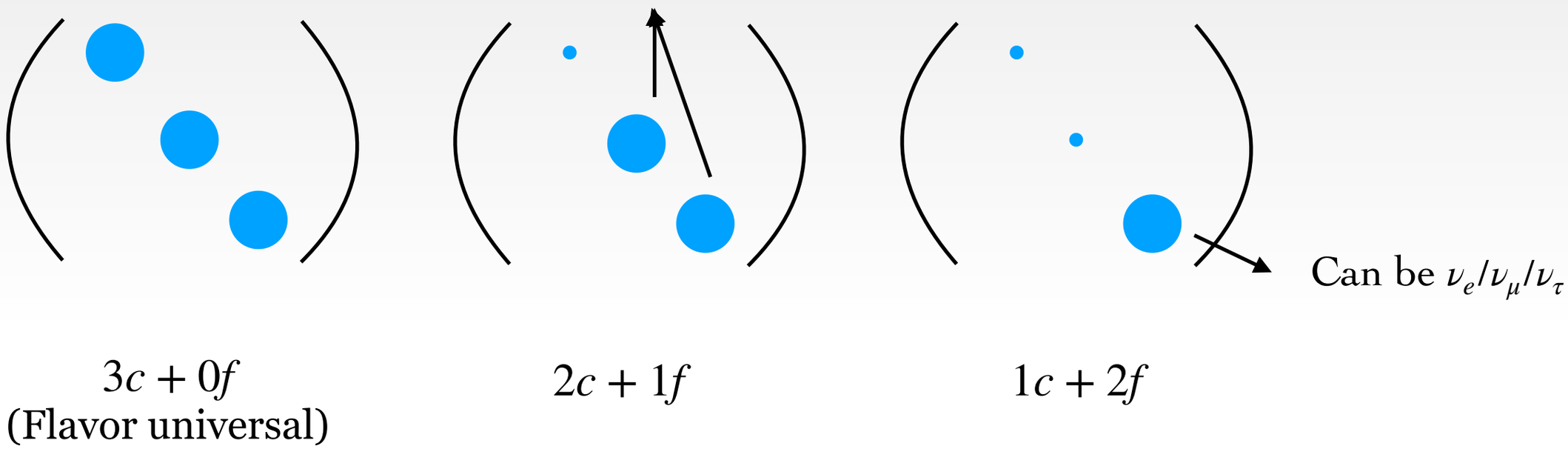
Need for cosmological analysis of Flavor specific neutrino self interaction

Flavor specific neutrino self interaction in cosmology

CMB is insensitive to specific flavor (ν_e, ν_μ, ν_τ) of Neutrino
(Not sensitive to weak interaction)

<u>CMB is sensitive to flavor specific interaction 'collectively'</u>

Same coupling strength $G_{\rm eff}$



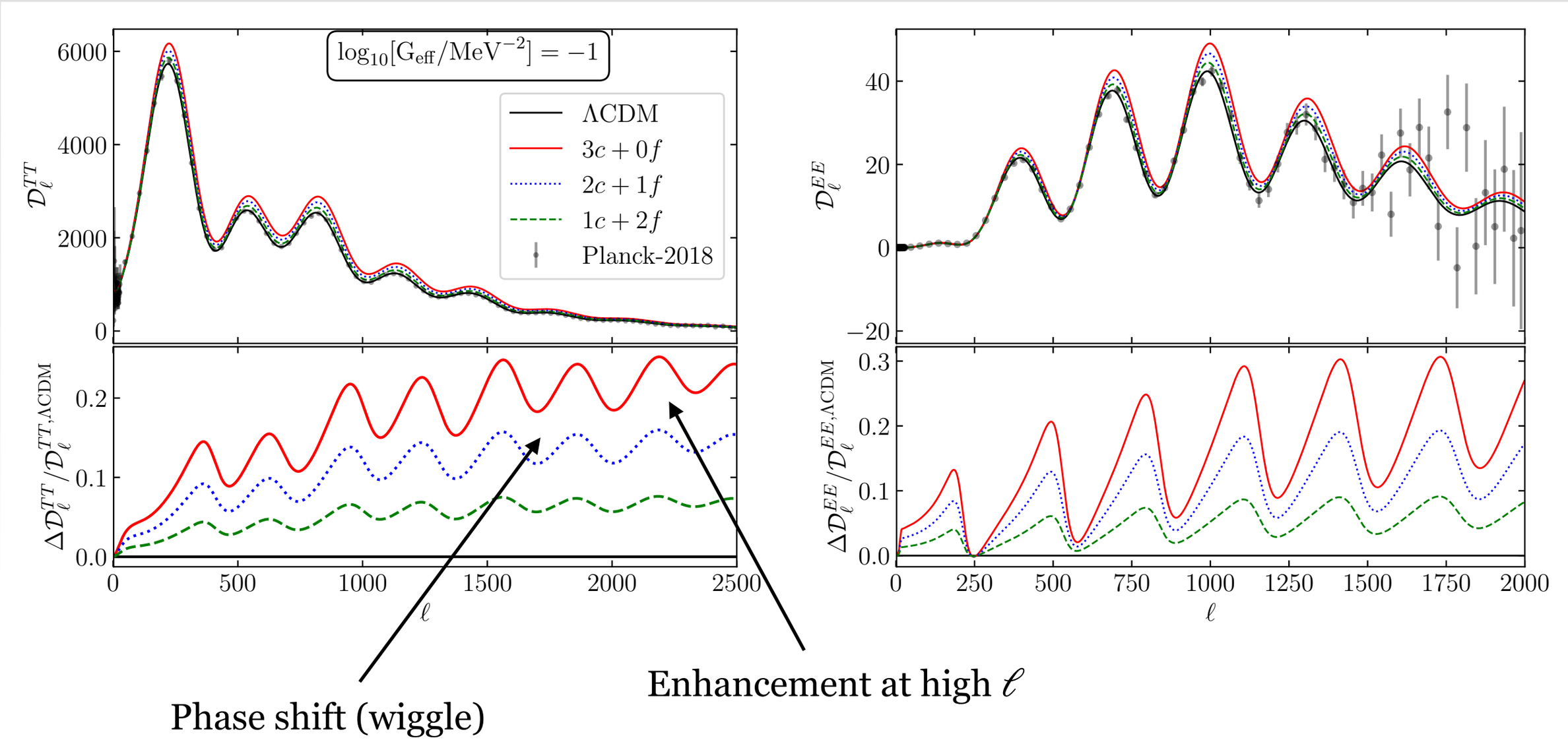
Common coupling strength $G_{\rm eff}$ for coupled flavors (CMB insensitive to specific flavor)

Assumptions

Massless neutrinos
3 flavor ($N_{\rm eff} = 3.046$)
Flavor diagonal interaction

c = coupled (interacting)
f = free-streaming (non-interacting)
• $\equiv 0$

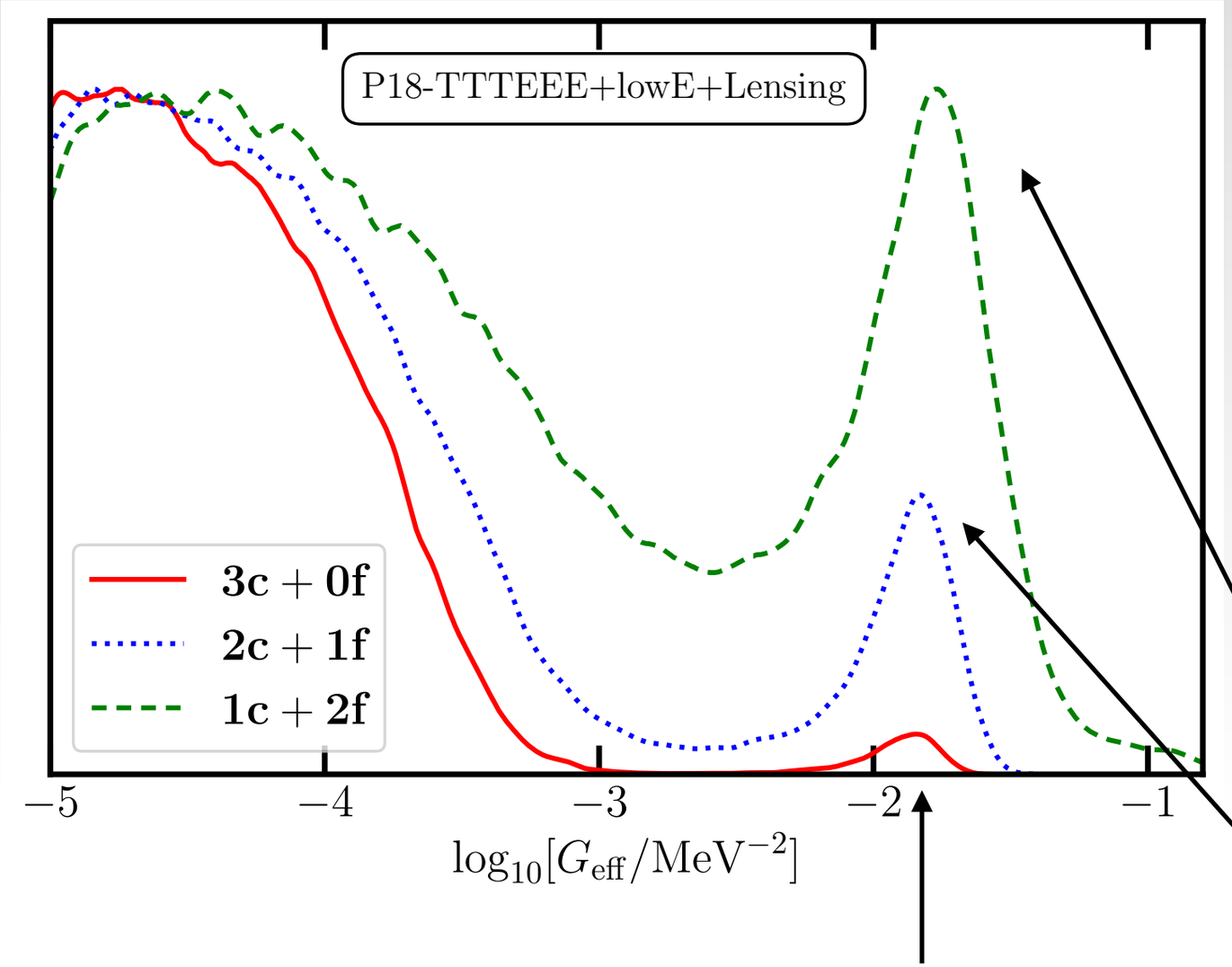
Effect on CMB spectrum



Changes are milder with less number of coupled neutrinos

ΛCDM$\equiv 0c + 3f$

Strong flavor specific interaction preferred by CMB

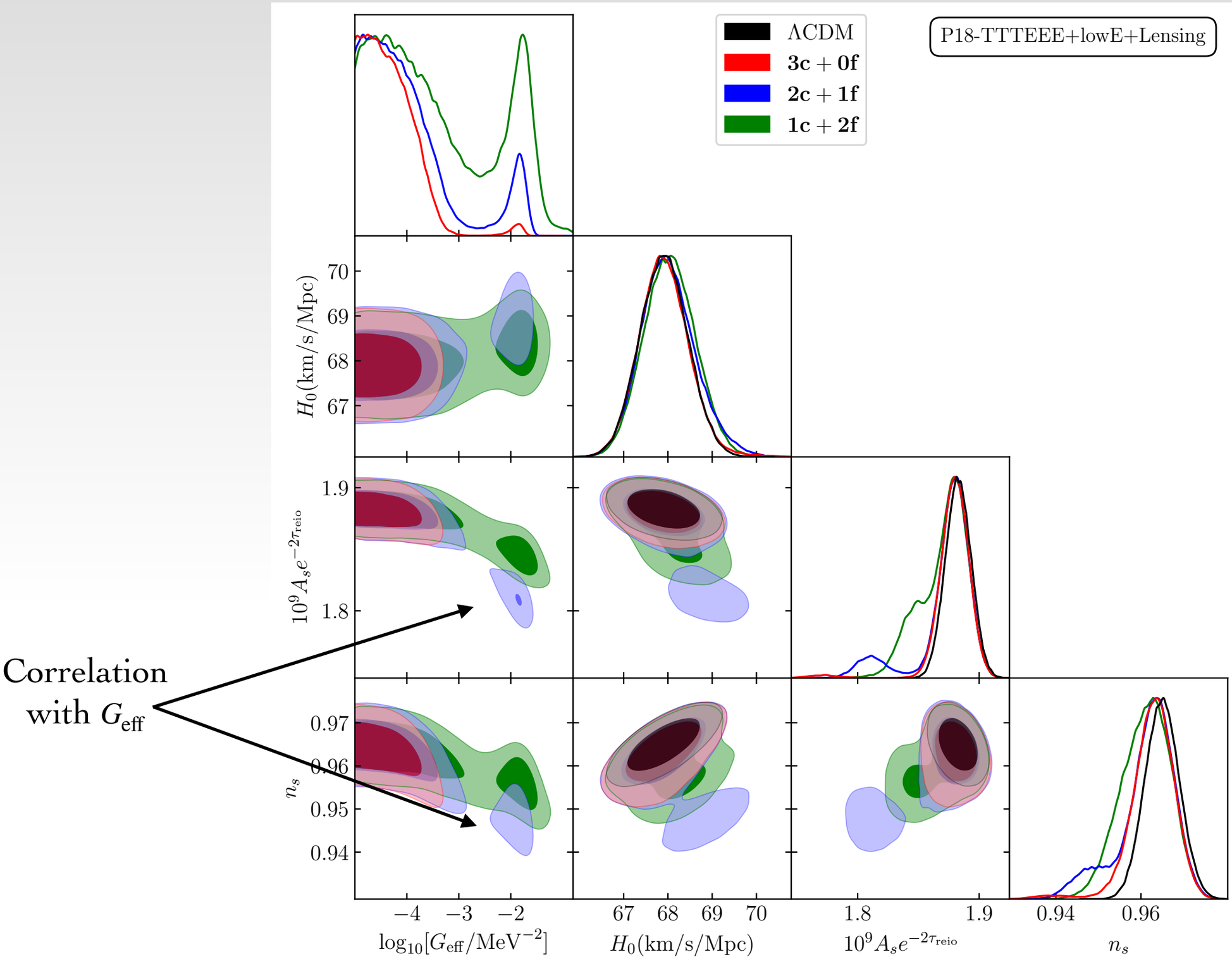


The position of the SI peak remains approximately the same

Significance of the SI mode increases dramatically in flavor specific scenario

Anirban Das, SG : 2011.12315

Strong flavor specific interaction preferred by CMB



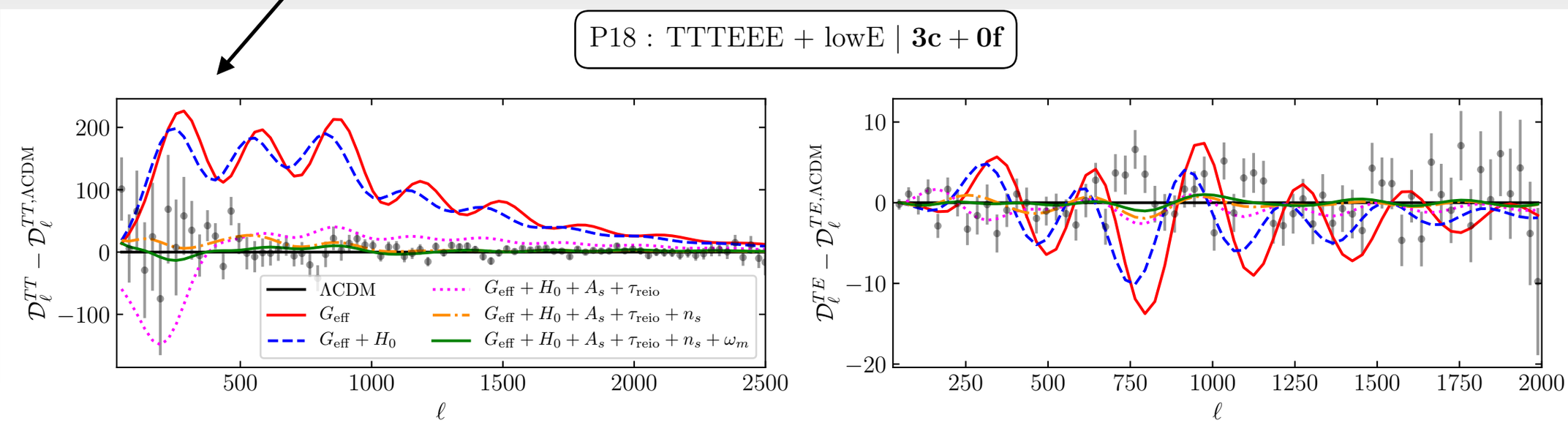
Anirban Das, SG : 2011.12315

Origin of the SI mode

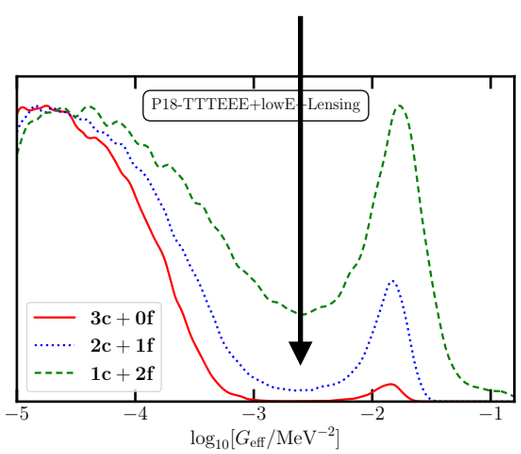
SI mode interaction strength keep neutrino coupled till matter-radiation equality

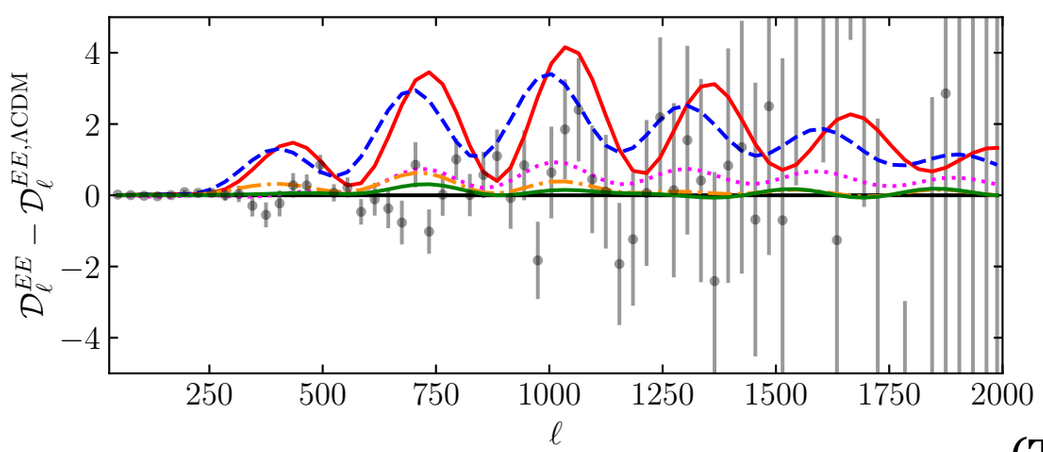
Affects all the CMB peaks ($\ell \gtrsim 100$)

ΛCDM parameter ($A_s, n_s \ldots$) compensate for the changes



Valley





Spectral changes due to modes between MI & SI cannot be compensated by changes in ΛCDM parameters

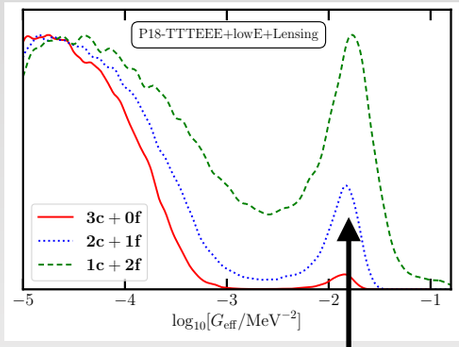
Existence of the 'Valley'
(The dip in between MI and SI mode)

SI mode enhancement in flavor specific scenario

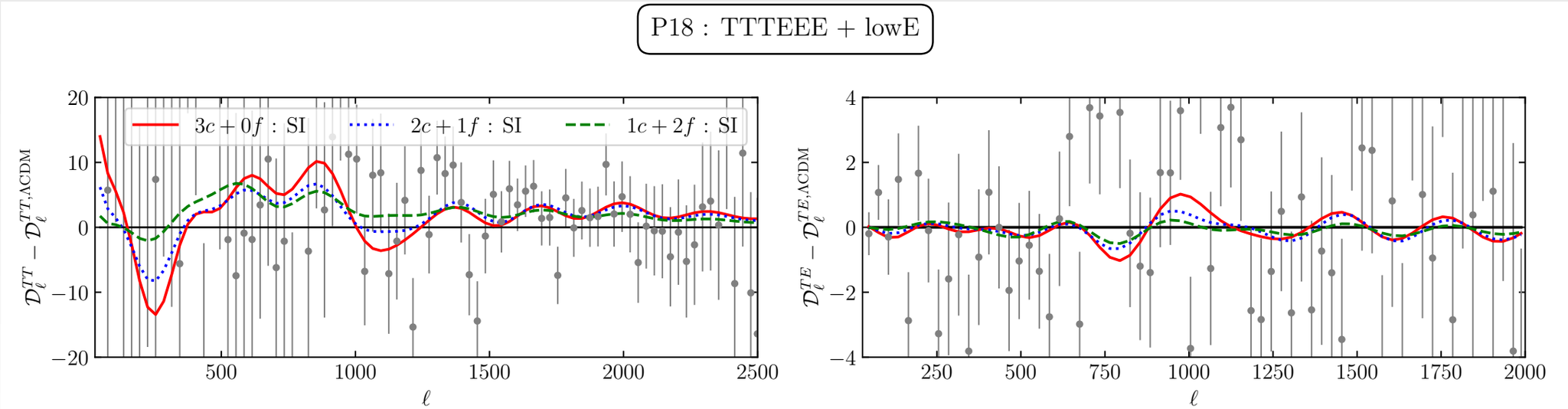
The existence of SI mode is connect with the value of $G_{\rm eff}$

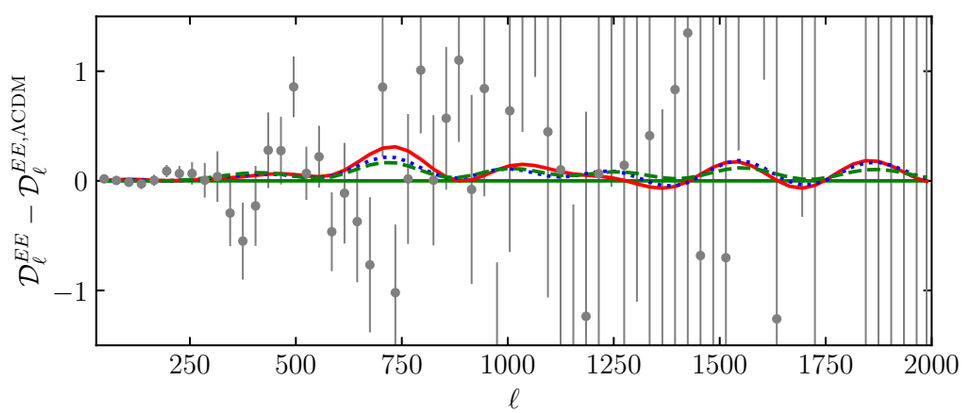
↓

In flavor specific cases SI mode value of $G_{\rm eff}$ does not change



SI





Changes are milder with less number of coupled neutrinos

↓

More freedom to fit The residual (smaller χ^2)

SI mode fits some features of the residual

*MI mode residual is virtually equivalent to ΛCDM
*Planck 2018 data with error bar are shown

Effect on H_0 : Phase shift

Neutrino self interaction can enhance H_0 even when $N_{\rm eff}$ is kept fixed

Photon transfer function — $\cos(kr_s^* + \phi_\nu)$

Phase shift due to free-streaming neutrinos

$$\ell \approx kD_A^* = (m\pi - \phi_\nu)\frac{D_A^*}{r_s^*}$$

$$\phi_\nu \simeq 0.19\pi R_\nu$$

$$D_A^* = \int_0^{z^*} \frac{1}{H(z)} dz$$

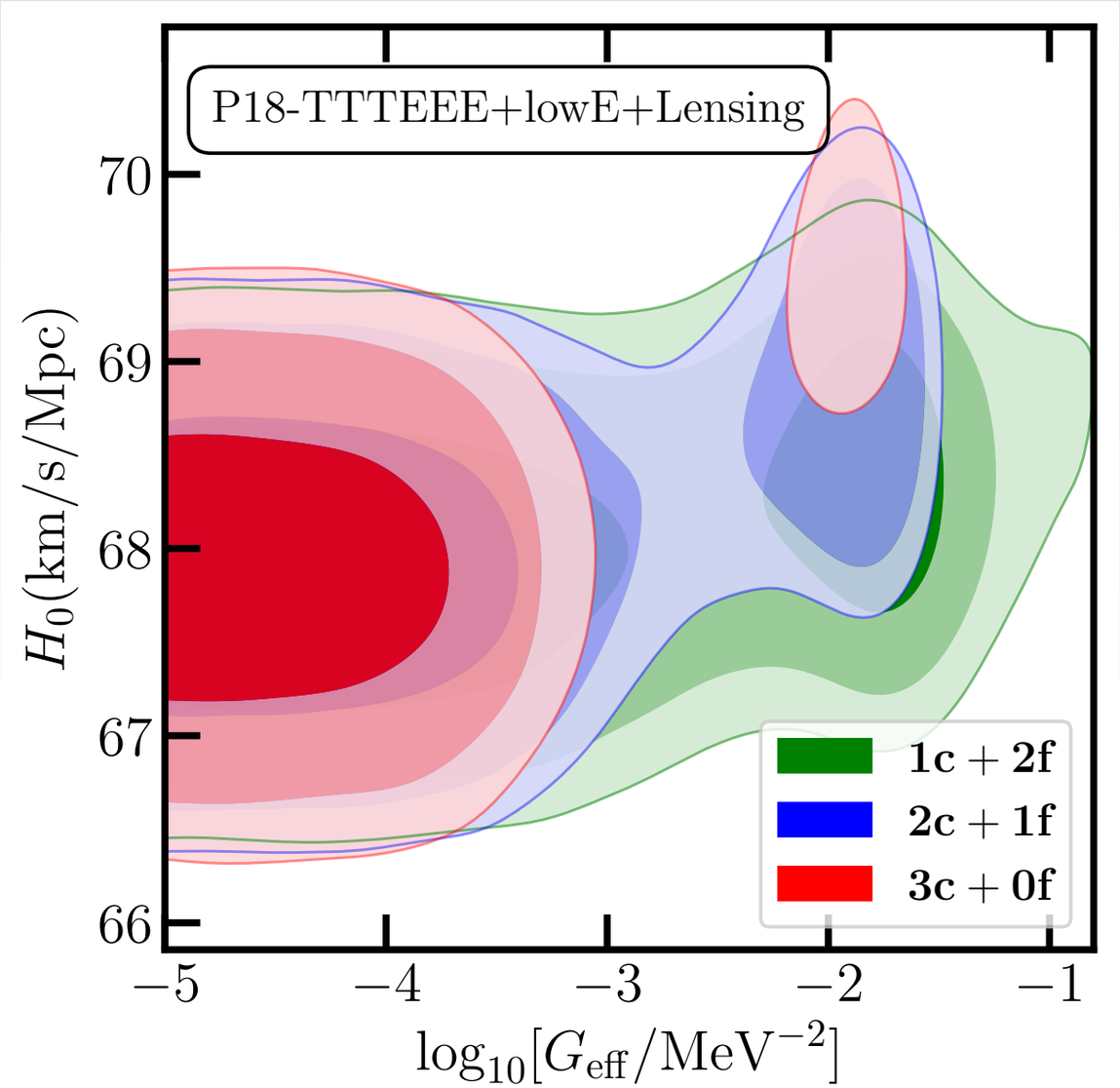
$$R_\nu = \frac{\rho_\nu}{\rho_\gamma + \rho_\nu}$$

$$r_s^* = \int_{z^*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

$$R_\nu = R_\nu^{\Lambda\rm CDM} \times \begin{cases} 0, & \text{for } 3c + 0f \\ \frac{1}{3}, & \text{for } 2c + 1f \\ \frac{2}{3}, & \text{for } 1c + 2f \end{cases}$$

Change in ϕ_ν is compensated (mostly) by change D_A^* — through change in Ω_Λ and H_0

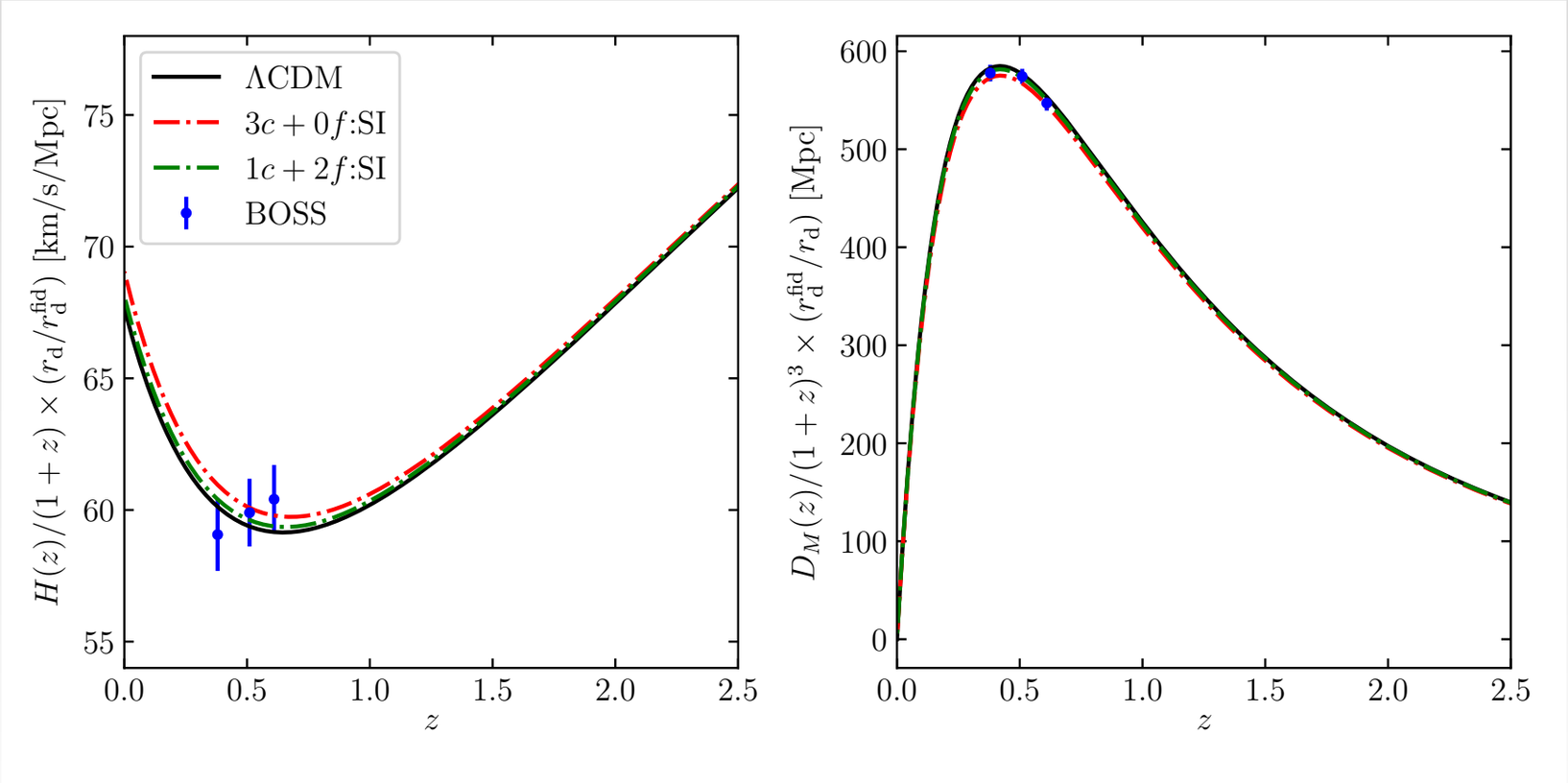
Effect on H_0 : Phase shift

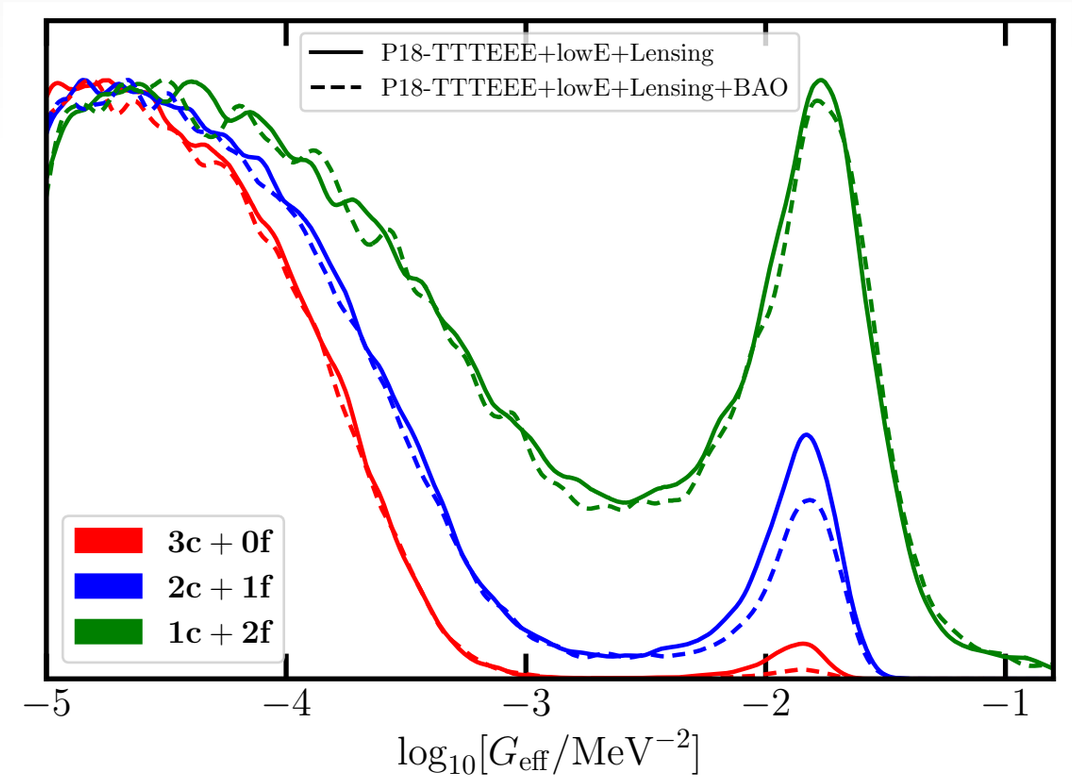


Anirban Das, SG : 2011.12315

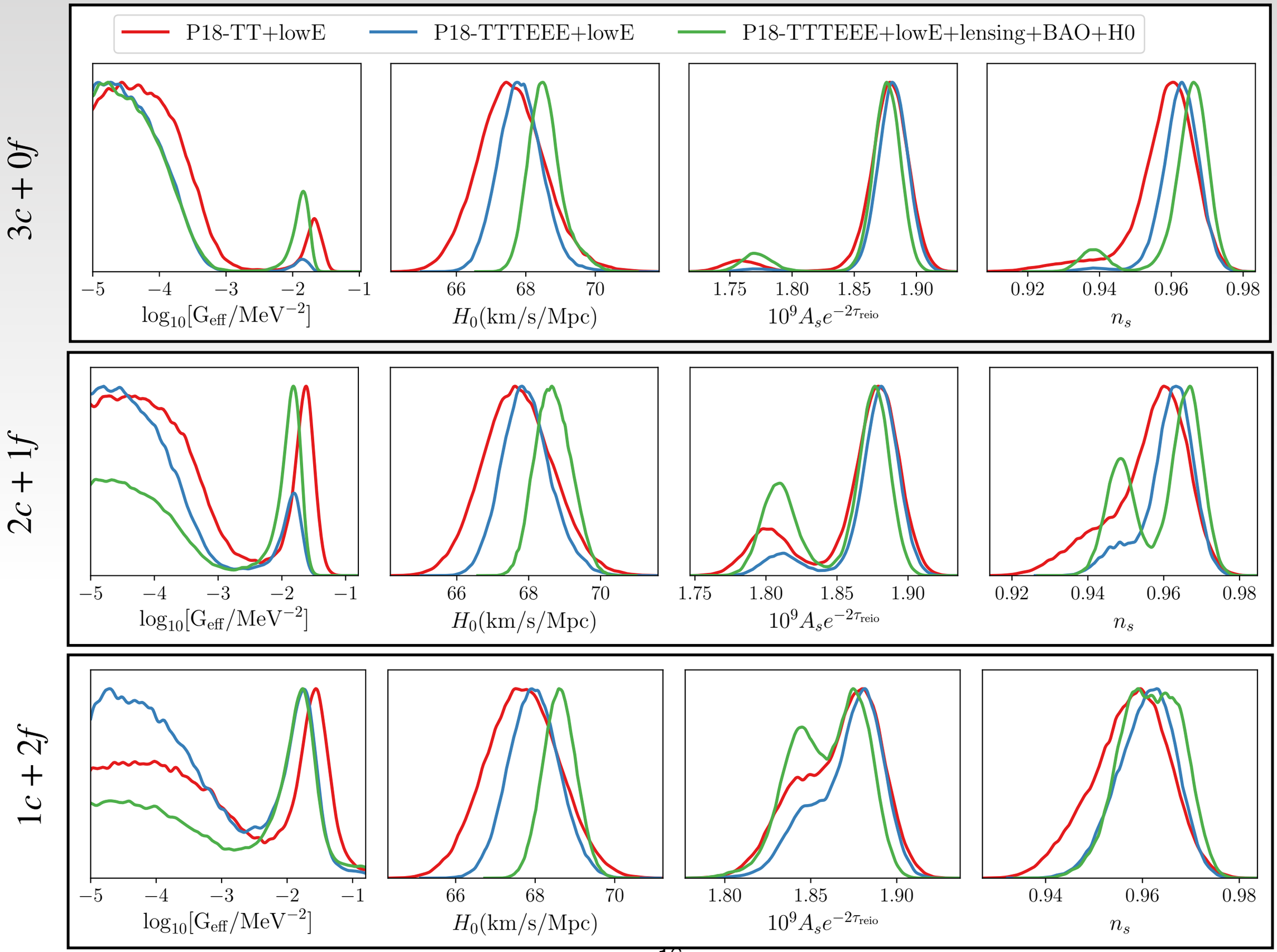
*Even when $N_{\rm eff}$ is varied in $1c + 2f$ scenario H_0 does not increase substantially

Effect of BAO data





Constraints with other dataset



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Conclusion

- Flavor specific neutrino self interaction is phenomenologically motivated

  → takes into account laboratory constraints
- The significance of the SI mode is increased dramatically

  → similar in χ^2 to ΛCDM fit
- The position of the SI mode peak in Flavor specific interaction remains almost the same in Flavor universal case
- However, does not predict a larger H_0 than flavor universal case

Flavor specific neutrino self interaction can provide similar (in some case better) fit to the CMB (& LSS) data

Cosmology favors Flavor specific neutrino self interaction

Extra

Parameter Values

Table 4: Parameter values and 68% confidence limits in **3c + 0f**.

Parameters	TT+lowE		TTTEEE+lowE	
	SI	MI	SI	MI
$\Omega_b h^2$	0.022 ± 0.0003	0.022 ± 0.00022	0.022 ± 0.00016	0.022 ± 0.00015
$\Omega_c h^2$	0.1212 ± 0.0025	0.1203 ± 0.0021	0.1205 ± 0.0015	0.1201 ± 0.0014
$100\theta_s$	1.0469 ± 0.00068	1.0419 ± 0.00048	1.0464 ± 0.00087	1.0419 ± 0.0003
$\ln(10^{10} A_s)$	2.968 ± 0.0186	3.036 ± 0.017	2.984 ± 0.017	3.042 ± 0.0161
n_s	0.9317 ± 0.0085	0.9593 ± 0.0071	0.9386 ± 0.004	0.9626 ± 0.005
$\tau_{\rm reio}$	0.0501 ± 0.0082	0.0516 ± 0.0079	0.0543 ± 0.0077	0.0537 ± 0.0077
$\log_{10}(G_{\rm eff}/{\rm MeV}^{-2})$	-1.72 ± 0.17	-4.17 ± 0.51	-1.92 ± 0.18	-4.35 ± 0.42
$H_0(\,{\rm km\,s^{-1}Mpc^{-1}})$	68.97 ± 1.05	67.52 ± 0.93	69.44 ± 0.64	67.82 ± 0.61
$r_s^*({\rm Mpc})$	144.70 ± 0.53	144.97 ± 0.49	144.54 ± 0.35	144.84 ± 0.32
σ_8	0.826 ± 0.01	0.824 ± 0.009	0.834 ± 0.008	0.824 ± 0.0075
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	2.33	-0.01	5.14	0.18

Anirban Das, SG : 2011.12315

Parameter Values

Table 5: Parameter values and 68% confidence limits in **2c + 1f**.

Parameters	TT+lowE		TTTEEE+lowE	
	SI	MI	SI	MI
$\Omega_{\rm b}h^2$	0.022 ± 0.00027	0.022 ± 0.00021	0.022 ± 0.00016	0.022 ± 0.00015
$\Omega_{\rm c}h^2$	0.1211 ± 0.0023	0.1203 ± 0.002	0.1205 ± 0.0014	0.1201 ± 0.0013
$100\theta_s$	1.0452 ± 0.00059	1.0419 ± 0.0005	1.045 ± 0.00076	1.0419 ± 0.00031
$\ln(10^{10}A_s)$	2.99 ± 0.0179	3.036 ± 0.01714	3 ± 0.0167	3.042 ± 0.0161
n_s	0.9407 ± 0.0079	0.9596 ± 0.0068	0.9473 ± 0.0046	0.9628 ± 0.005
$\tau_{\rm reio}$	0.0501 ± 0.008	0.0516 ± 0.0079	0.0538 ± 0.0077	0.0538 ± 0.0077
$\log_{10}(G_{\rm eff}/{\rm MeV}^{-2})$	-1.69 ± 0.2	-4.03 ± 0.6	-1.93 ± 0.24	-4.24 ± 0.5
$H_0(\,{\rm km\,s^{-1}Mpc^{-1}})$	68.34 ± 1.00	67.57 ± 0.92	68.81 ± 0.63	67.83 ± 0.6
$r_s^*({\rm Mpc})$	144.75 ± 0.51	144.98 ± 0.49	144.64 ± 0.34	144.85 ± 0.32
σ_8	0.823 ± 0.01	0.824 ± 0.009	0.829 ± 0.0079	0.824 ± 0.0075
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	-0.17	-0.05	1.8	0.28

Anirban Das, SG : 2011.12315

Parameter Values

Table 6: Parameter values and 68% confidence limits in **1c** + **2f**.

Parameters	TT+lowE		TTTEEE+lowE	
	SI	MI	SI	MI
$\Omega_b h^2$	0.022 ± 0.00023	0.022 ± 0.00021	0.022 ± 0.00015	0.022 ± 0.00015
$\Omega_c h^2$	0.1207 ± 0.0021	0.1203 ± 0.002	0.1203 ± 0.0014	0.1201 ± 0.0013
$100\theta_s$	1.0434 ± 0.00062	1.0419 ± 0.0004	1.043 ± 0.00058	1.0419 ± 0.0003
$\ln(10^{10} A_s)$	3.01 ± 0.0179	3.037 ± 0.01664	3.024 ± 0.0166	3.042 ± 0.016
n_s	0.9513 ± 0.0069	0.9609 ± 0.0059	0.9553 ± 0.0049	0.963 ± 0.005
$\tau_{\rm reio}$	0.051 ± 0.008	0.0519 ± 0.008	0.0539 ± 0.0076	0.0539 ± 0.0077
$\log_{10}(G_{\rm eff}/{\rm MeV}^{-2})$	-1.75 ± 0.4	-3.94 ± 0.6	-1.9 ± 0.37	-4.06 ± 0.6
$H_0(\,{\rm km\,s^{-1}Mpc^{-1}})$	67.9 ± 1.00	67.56 ± 0.93	68.3 ± 0.62	67.83 ± 0.61
$r_s^*({\rm Mpc})$	144.88 ± 0.5	144.96 ± 0.5	144.76 ± 0.32	144.84 ± 0.31
σ_8	0.821 ± 0.01	0.823 ± 0.009	0.825 ± 0.0083	0.824 ± 0.0075
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	-0.91	-0.03	0	0.1

Anirban Das, SG : 2011.12315

H_0 values

Table 7: Parameter values and 68% confidence limits for SI mode in **3c + 0f** and **2c + 1f**, and ΛCDM in TTTEEE+lowE+lensing data.

	SI: **3c + 0f**	SI: **2c + 1f**	ΛCDM
$H_0(\,\mathrm{km\,s^{-1}Mpc^{-1}})$	69.47 ± 0.59	68.87 ± 0.58	67.90 ± 0.54
Ω_Λ	0.7035 ± 0.0071	0.6989 ± 0.0072	0.6912 ± 0.0073
$100\theta_s$	1.0463 ± 0.00094	1.0447 ± 0.00079	1.04186 ± 0.00029
$r_s^*(\mathrm{Mpc})$	144.58 ± 0.32	144.69 ± 0.31	144.87 ± 0.29
$D_A^*(\mathrm{Mpc})$	12.69 ± 0.036	12.72 ± 0.034	12.773 ± 0.028

Table 13: values of H_0 (1σ errorbar) and upper limit of $N_{\rm eff}$ (95% C.L) for **1c + 2f** + $\Delta N_{\rm eff}$ for all dataset.

Parameters	TT+lowE	TTTEEE+lowE+lensing	TTTEEE+lowE+lensing+BAO+H0
H_0	$69.7^{+1.3}_{-2.1}$	$68.77^{+0.66}_{-0.95}$	$70.04^{+0.84}_{-0.84}$
$N_{\rm eff}$	< 3.76	< 3.38	< 3.58