Flavor-specific Neutrino Self-interaction in Cosmology

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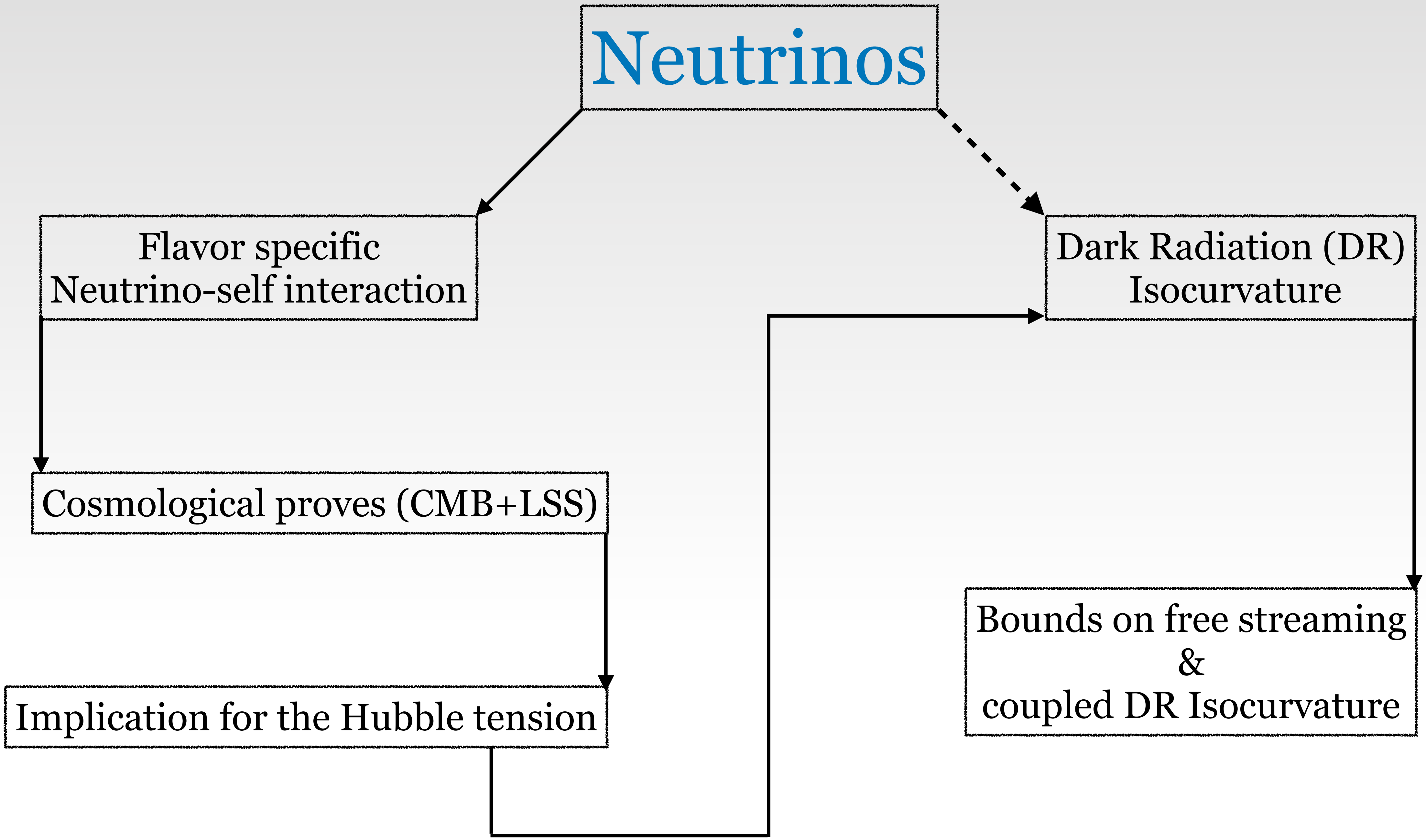
Overview



Part I

Part II

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

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

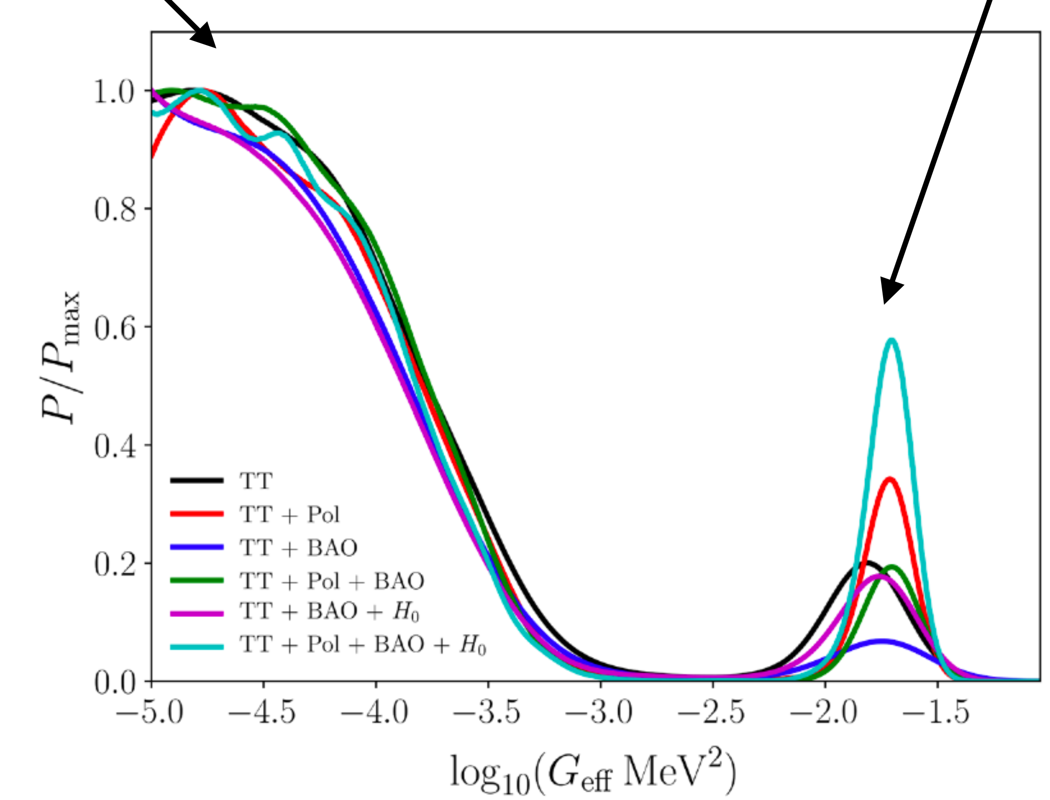
Flavor universal Self-interaction

(Mediator can be vector)

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

Moderately interacting (MI)

Strongly interacting (SI)



Lancaster et. al. (1704.06657)

(Using Planck 2015 data)

Cosmological signatures of Neutrino self interaction

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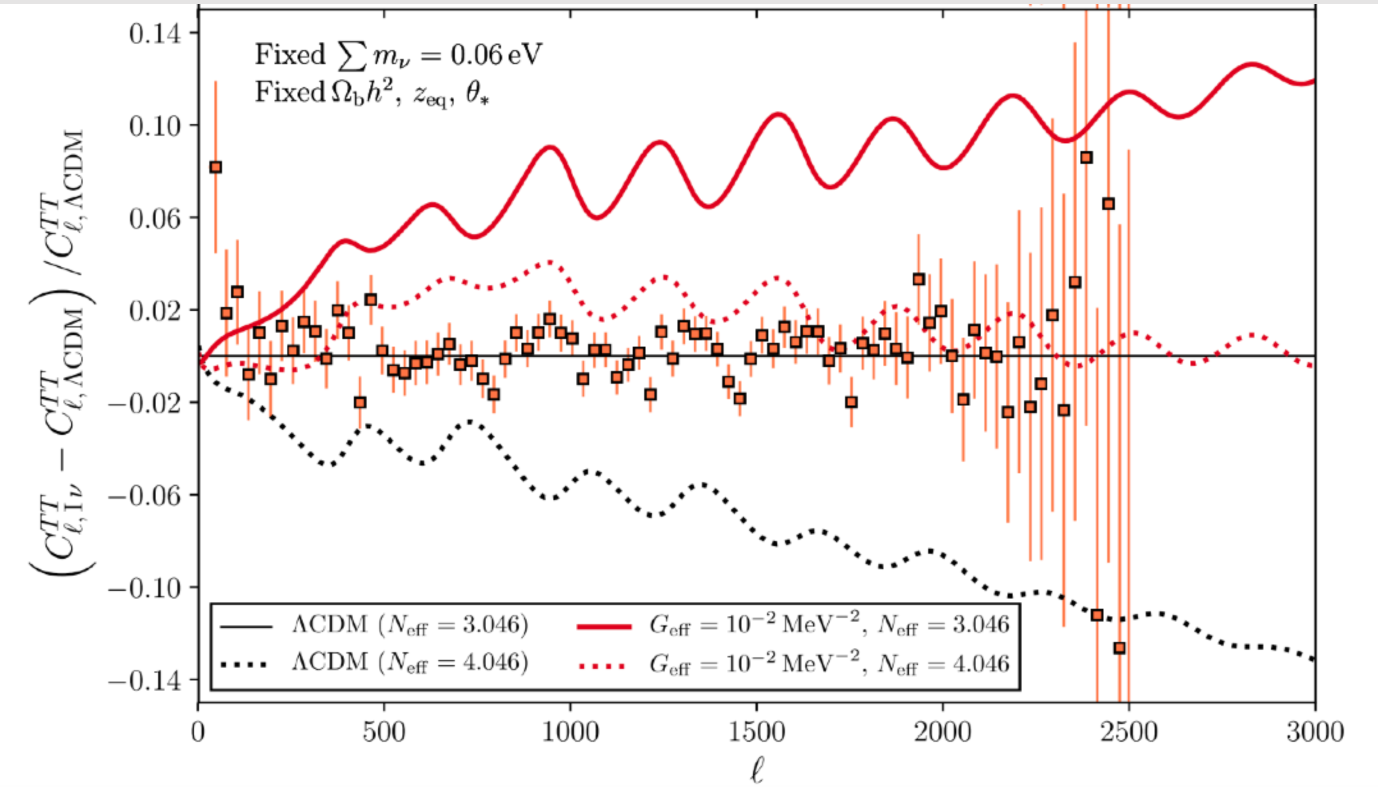

Kreisch et al (1902.00534)

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

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

$\sim 4.4\sigma$

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

Proposed as a solution (?) of Hubble tension

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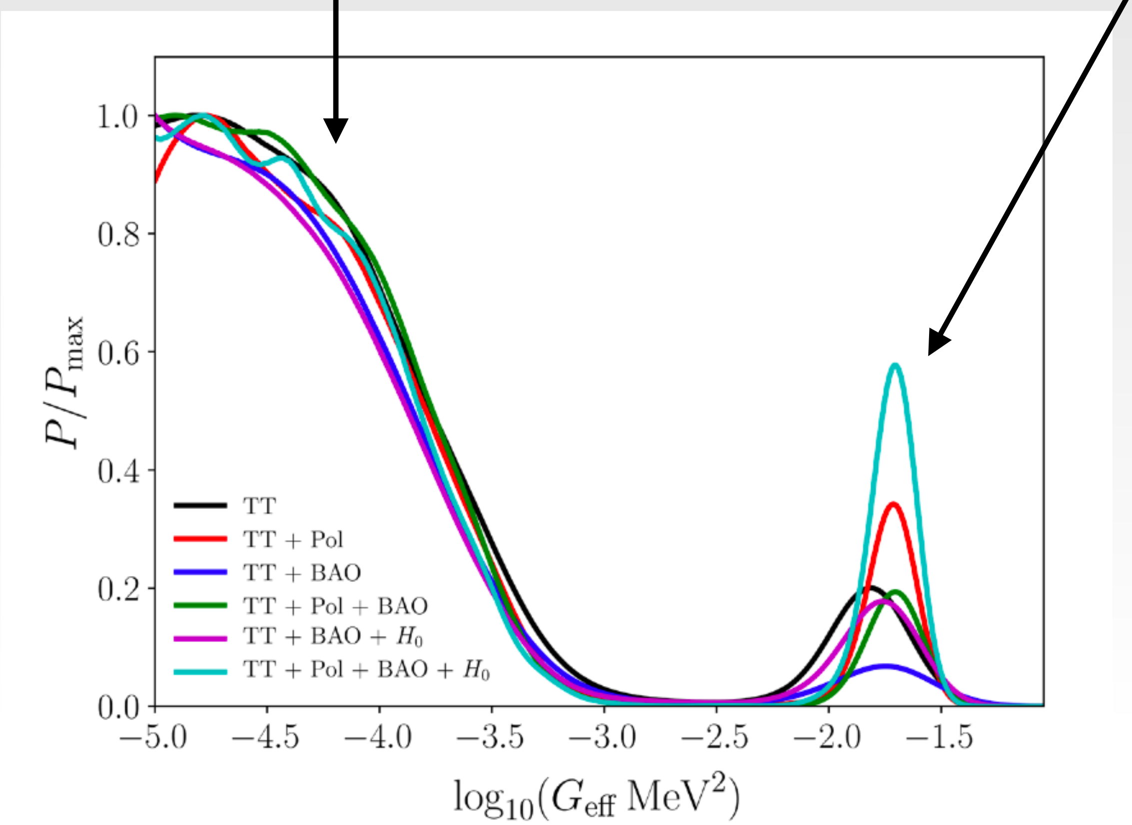

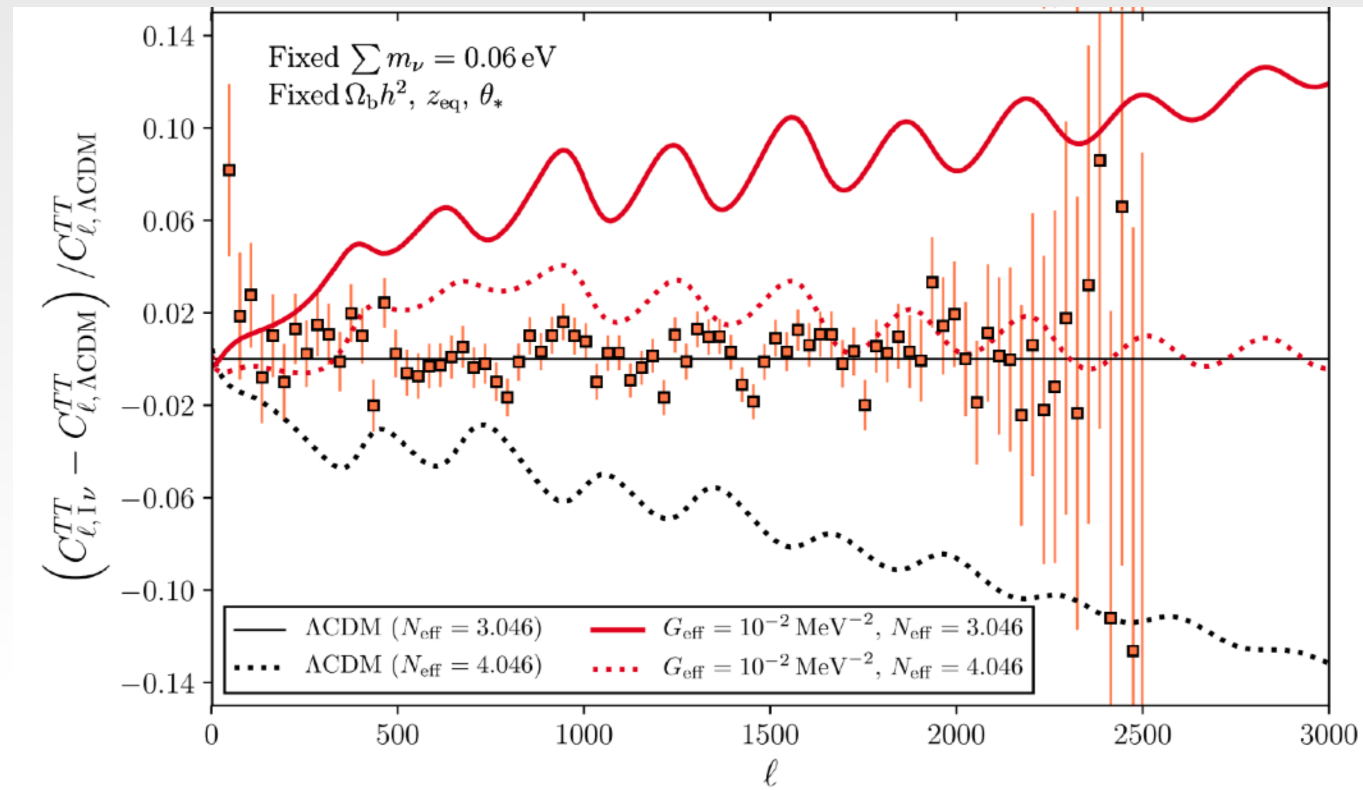

Kreisch et al (1902.00534)

Degeneracy of G_{eff} with N_{eff} (H_0)

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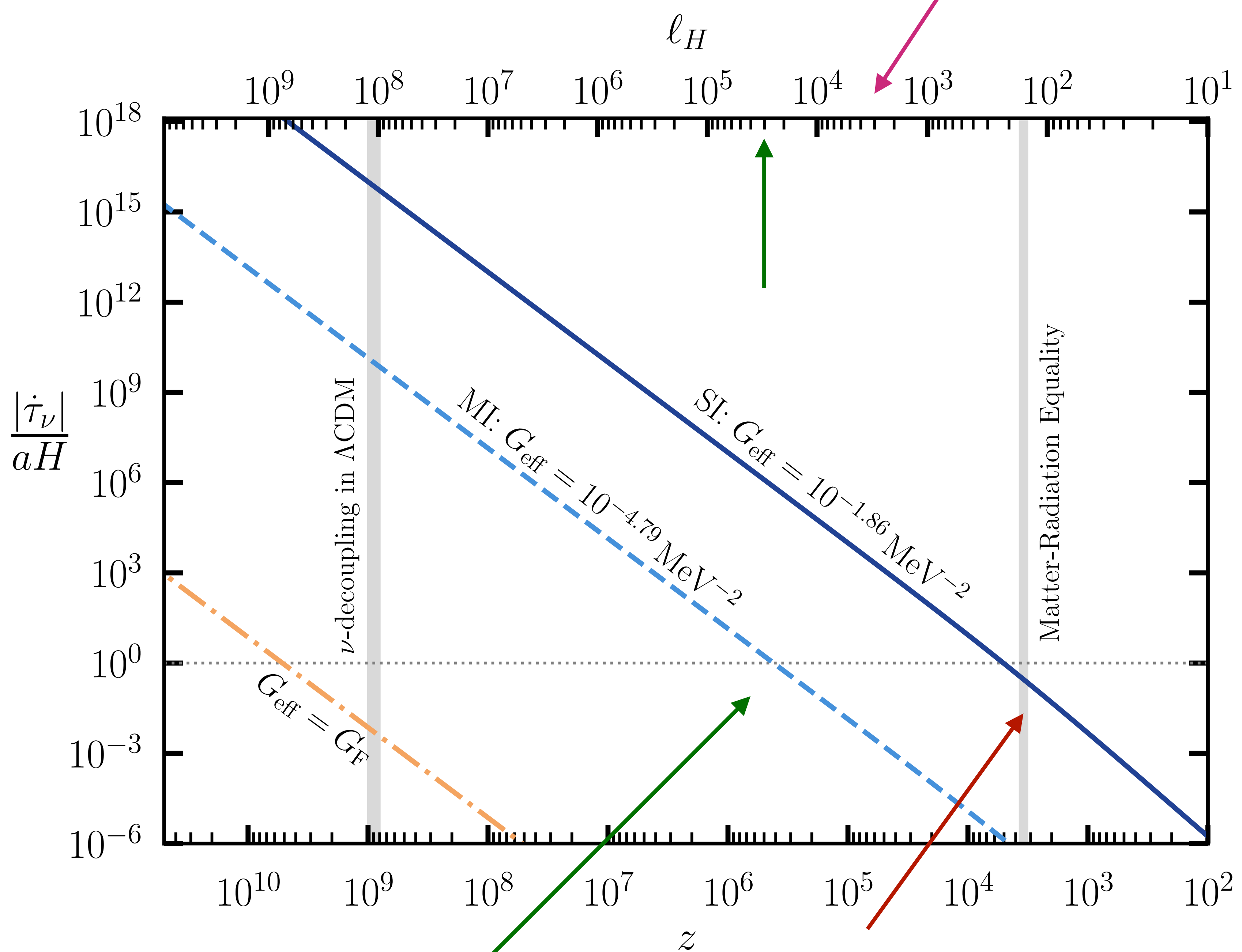
Proposed as a solution (?) of Hubble tension

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

Laboratory constraint

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

Sensitivity of Planck experiment



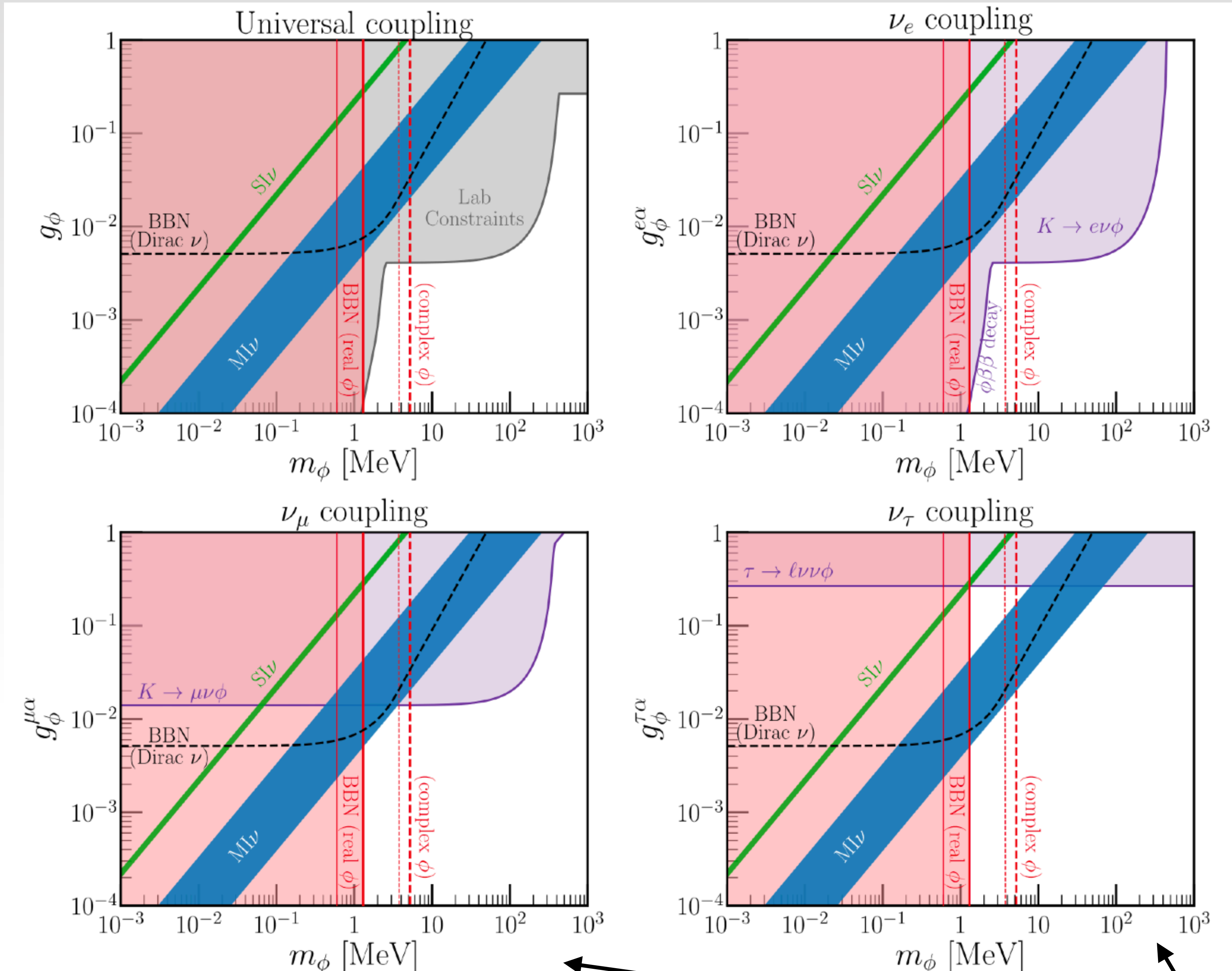
Anirban Das, SG : 2011.12315

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

(Also see, Lyu et. al., 2004.10868)

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 Self Interaction

Flavor specific neutrino self interaction in cosmology

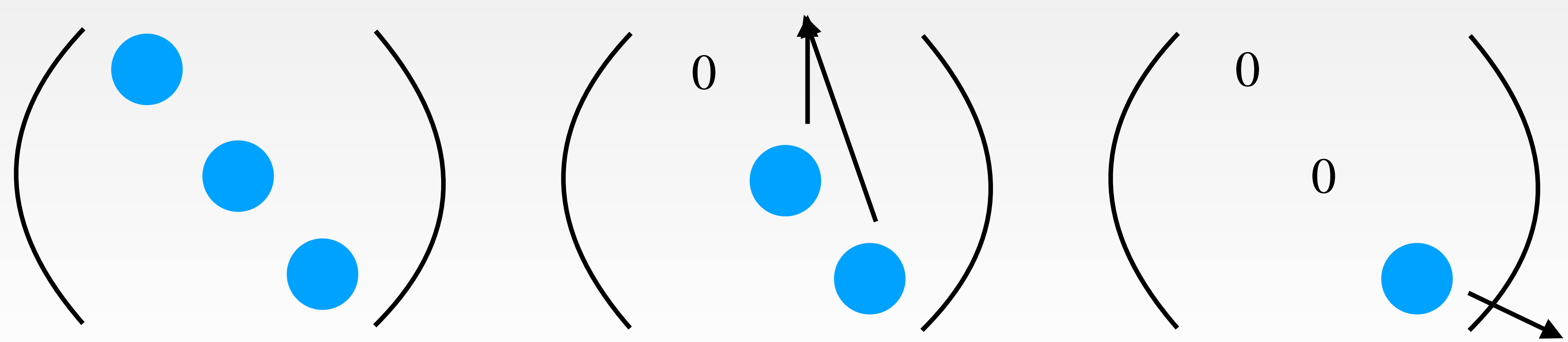
CMB is insensitive to specific flavor (ν_e, ν_μ, ν_τ) of Neutrino
(— Not sensitive to weak interaction)

<u>CMB is sensitive to flavor specific interaction 'collectively' though free-streaming properties</u>

Same coupling strength $G_{\rm eff}$

Coupling matrix

g_{ij} =



Can be $\nu_e/\nu_\mu/\nu_\tau$

$3c + 0f$
(Flavor universal)

$2c + 1f$

$1c + 2f$

c = coupled (interacting)
f = free-streaming (non-interacting)

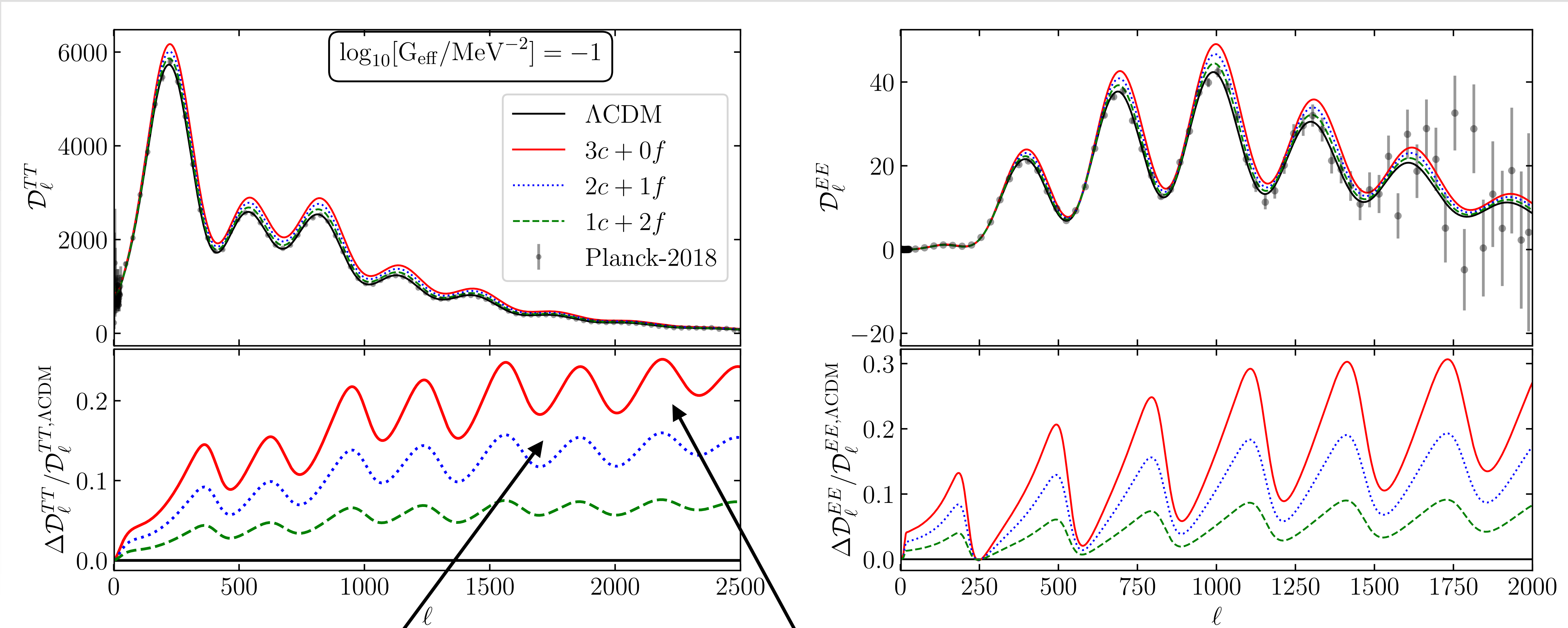
Assumptions

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

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

ΛCDM$\equiv 0c + 3f$

Effect on CMB spectrum



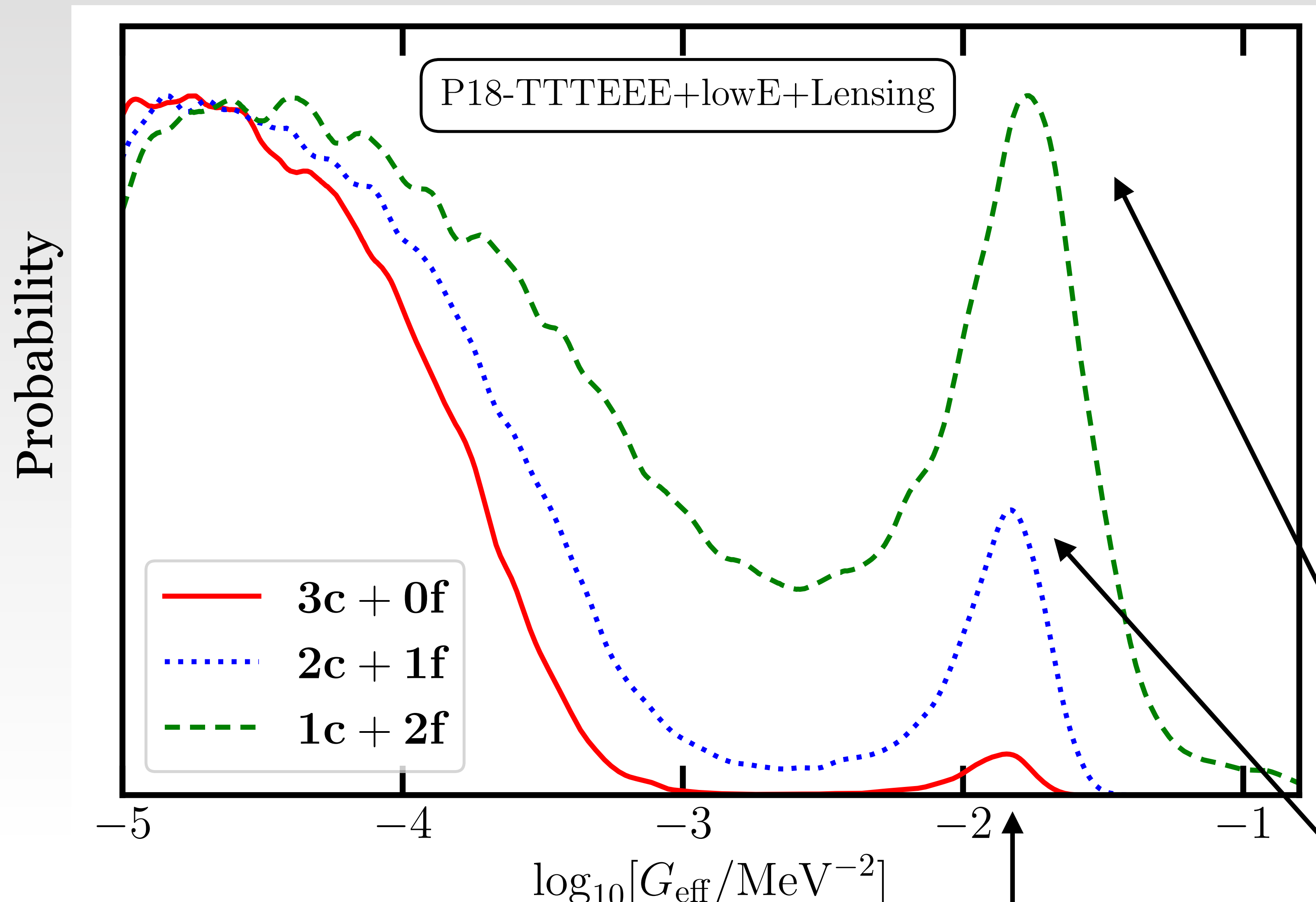
Phase shift (wiggle)

Enhancement at high ℓ

Changes are milder with less number of coupled neutrinos

ΛCDM$\equiv 0c + 3f$

Strong flavor specific interaction preferred by CMB



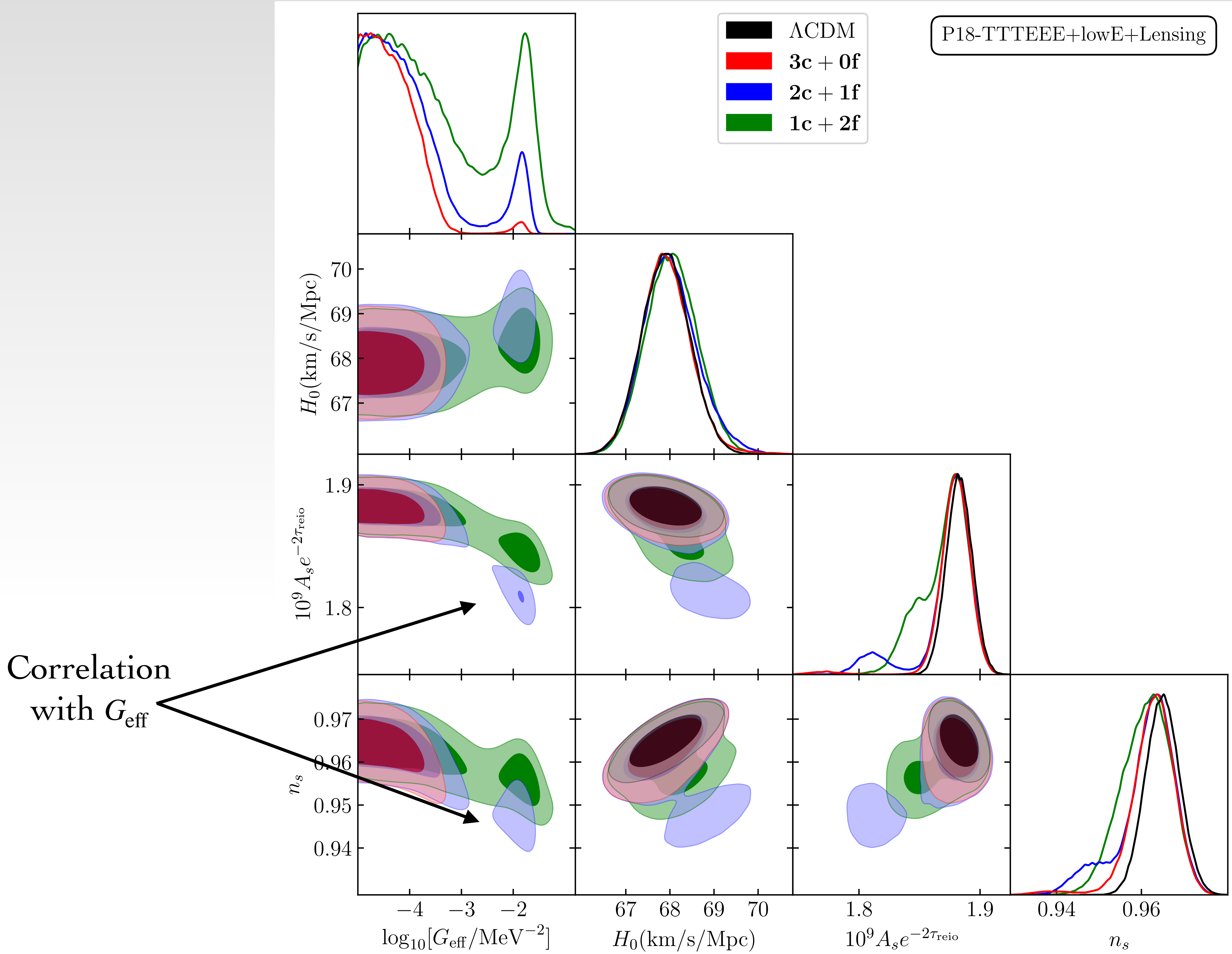
1-D Posterior

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



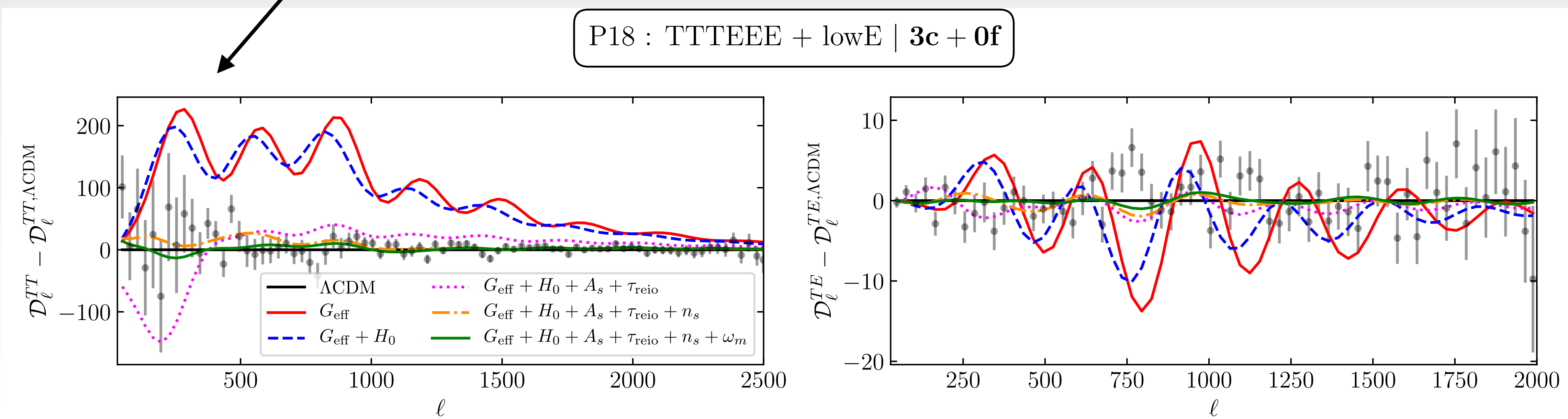
Anirban Das, SG : 2011.12315

Why SI mode is a good fit to CMB data?

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

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

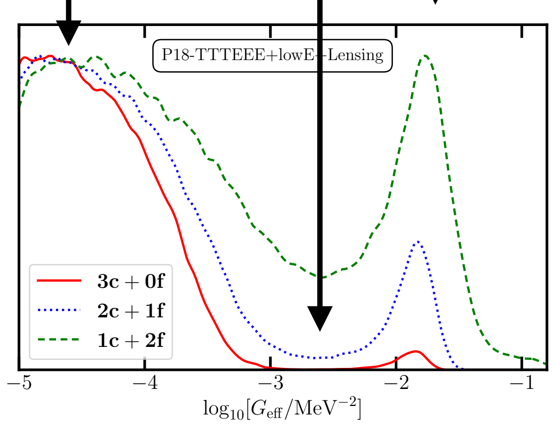
ΛCDM parameter ($A_s, n_s \ldots$) compensate for the changes

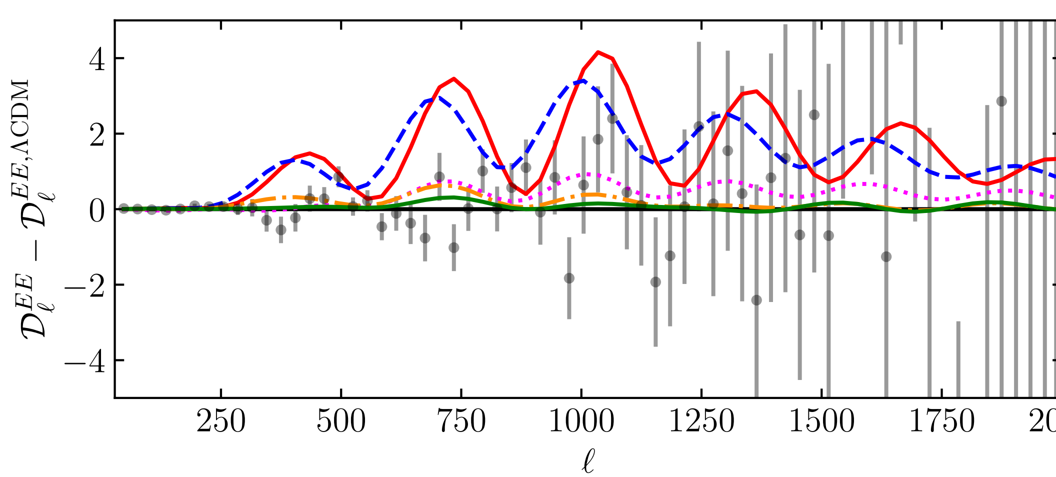


MI

Valley

SI





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_{eff}

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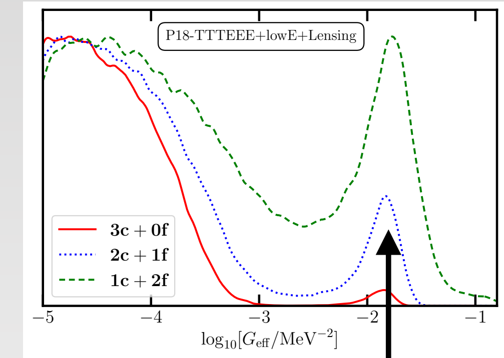
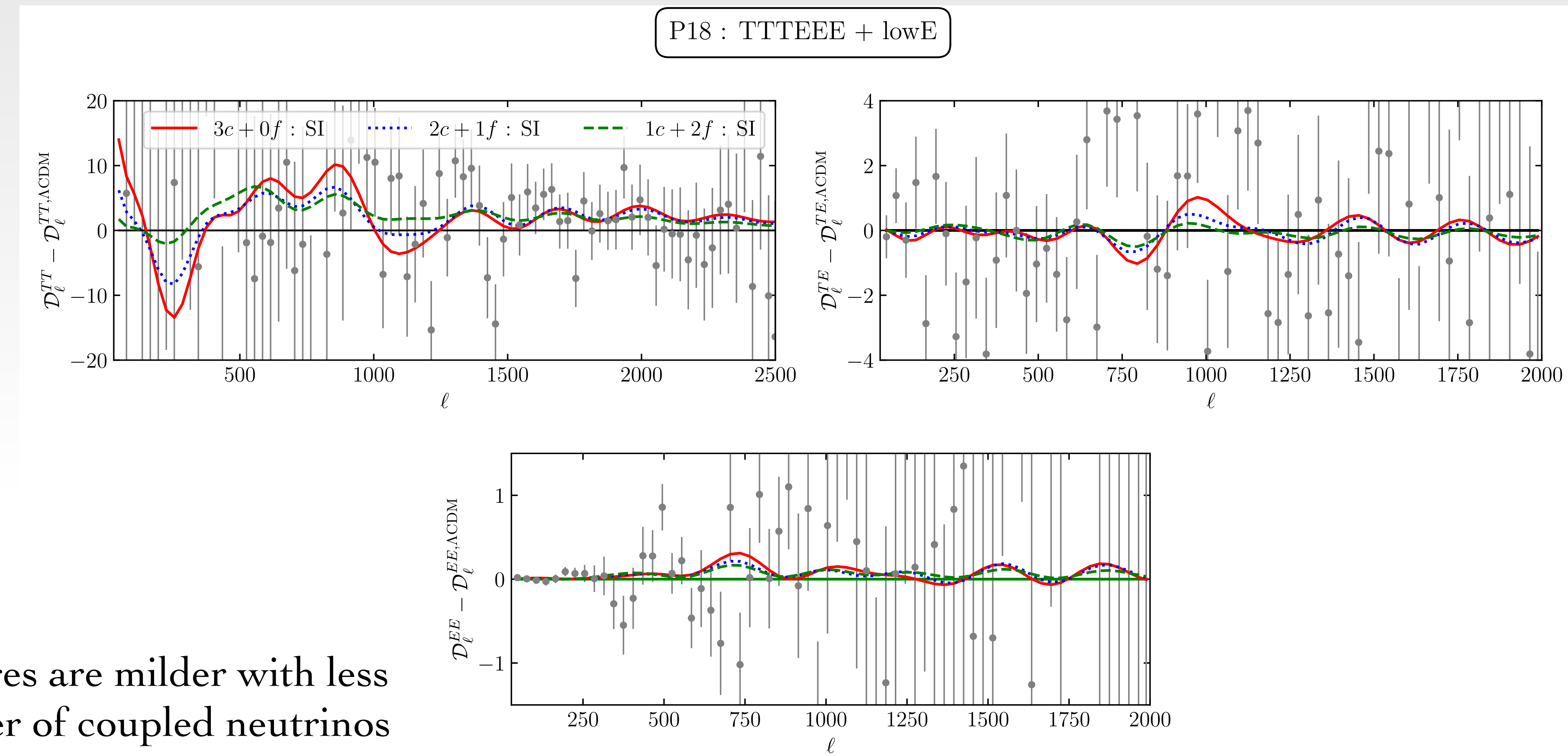
In flavor specific cases SI mode value of G_{eff} does not change



SI



Changes are milder with less number of coupled neutrinos

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

SI mode fits some features of the residual

$\Lambda\text{CDM} \equiv 0c + 3f$

*MI mode residual is virtually equivalent to ΛCDM

*Planck 2018 data with error bar are shown

Parameter Values

Planck 2018: TTTTEEE+lowE

Parameters	$3c+0f$		$2c+1f$		$1c+2f$	
	SI	MI	SI	MI	SI	MI
$\Omega_b h^2$	0.022 ± 0.00016	0.022 ± 0.00015	0.022 ± 0.00016	0.022 ± 0.00015	0.022 ± 0.00015	0.022 ± 0.00015
$\Omega_c h^2$	0.1205 ± 0.0015	0.1201 ± 0.0014	0.1205 ± 0.0014	0.1201 ± 0.0013	0.1203 ± 0.0014	0.1201 ± 0.0013
$100\theta_s$	1.0464 ± 0.00087	1.0419 ± 0.0003	1.045 ± 0.00076	1.0419 ± 0.00031	1.043 ± 0.00058	1.0419 ± 0.0003
$\ln(10^{10} A_s)$	2.984 ± 0.017	3.042 ± 0.0161	3 ± 0.0167	3.042 ± 0.0161	3.024 ± 0.0166	3.042 ± 0.016
n_s	0.9386 ± 0.004	0.9626 ± 0.005	0.9473 ± 0.0046	0.9628 ± 0.005	0.9553 ± 0.0049	0.963 ± 0.005
$\tau_{\rm reio}$	0.0543 ± 0.0077	0.0537 ± 0.0077	0.0538 ± 0.0077	0.0538 ± 0.0077	0.0539 ± 0.0076	0.0539 ± 0.0077
$\log_{10}(G_{\rm eff}/{\rm MeV}^{-2})$	-1.92 ± 0.18	-4.35 ± 0.42	-1.93 ± 0.24	-4.24 ± 0.5	-1.9 ± 0.37	-4.06 ± 0.6
$H_0(\,{\rm km\,s^{-1}Mpc^{-1}})$	69.44 ± 0.64	67.82 ± 0.61	68.81 ± 0.63	67.83 ± 0.6	68.3 ± 0.62	67.83 ± 0.61
$r_s^*(\rm Mpc)$	144.54 ± 0.35	144.84 ± 0.32	144.64 ± 0.34	144.85 ± 0.32	144.76 ± 0.32	144.84 ± 0.31
σ_8	0.834 ± 0.008	0.824 ± 0.0075	0.829 ± 0.0079	0.824 ± 0.0075	0.825 ± 0.0083	0.824 ± 0.0075
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	5.14	0.18	1.8	0.28	0	0.1

Significance of the SI mode is increasing →

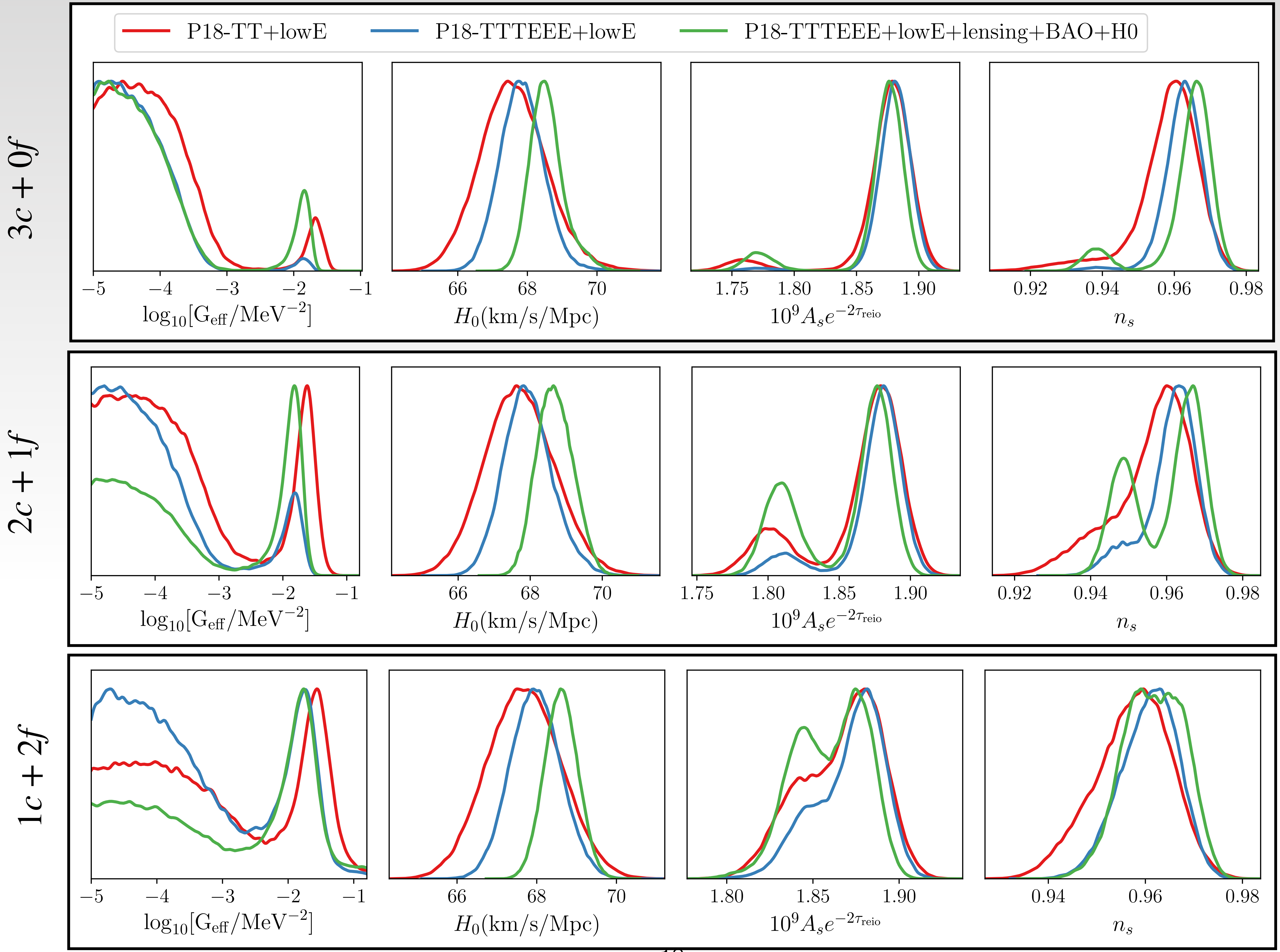
Parameter Values

Planck 2018: TTTTEEE+lowE+lensing+BAO+ShoES

Parameters	$3c+0f$		$2c+1f$		$1c+2f$	
	SI	MI	SI	MI	SI	MI
$\Omega_b h^2$	0.023 ± 0.00014	0.022 ± 0.00013	0.022 ± 0.0001	0.022 ± 0.00013	0.022 ± 0.0001	0.022 ± 0.00013
$\Omega_c h^2$	0.1206 ± 0.001	0.1188 ± 0.0009	0.12 ± 0.001	0.1188 ± 0.0009	0.12 ± 0.0009	0.1188 ± 0.0009
$100\theta_s$	1.0465 ± 0.00079	1.042 ± 0.00029	1.045 ± 0.00068	1.042 ± 0.00029	1.043 ± 0.00056	1.042 ± 0.00029
$\ln(10^{10} A_s)$	2.98 ± 0.0153	3.044 ± 0.0144	3.0 ± 0.0151	3.044 ± 0.0145	3.0 ± 0.0151	3.045 ± 0.0142
n_s	0.9383 ± 0.004	0.966 ± 0.0045	0.9483 ± 0.004	0.966 ± 0.0046	0.9572 ± 0.004	0.966 ± 0.0042
$\tau_{\rm reio}$	0.0532 ± 0.007	0.0563 ± 0.0071	0.0544 ± 0.007	0.0565 ± 0.0071	0.0554 ± 0.007	0.0566 ± 0.0071
$\log_{10}(G_{\rm eff}/{\rm MeV}^{-2})$	-1.91 ± 0.16	-4.34 ± 0.43	-1.91 ± 0.22	-4.22 ± 0.52	-1.86 ± 0.36	-4.03 ± 0.61
$H_0({\rm km\,s^{-1}Mpc^{-1}})$	69.45 ± 0.42	68.46 ± 0.41	69.08 ± 0.42	68.47 ± 0.4	68.75 ± 0.41	68.48 ± 0.41
$r_s^*({\rm Mpc})$	144.5 ± 0.26	145.12 ± 0.24	144.73 ± 0.26	145.12 ± 0.23	144.93 ± 0.24	145.12 ± 0.24
σ_8	0.833 ± 0.0065	0.821 ± 0.006	0.827 ± 0.0065	0.821 ± 0.0059	0.822 ± 0.0071	0.821 ± 0.006
$\chi^2 - \chi^2_{\Lambda{\rm CDM}}$	1.99	0.17	-1.35	0.25	-1.67	0.33

Better fit than ΛCDM

Constraints with other dataset



Anirban Das, SG : 2011.12315

Effect on H_0 : Phase shift

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

Bashinsky et. al. , astro-ph/0310198
Baumann et. al. , 1508.06342
Ghosh et. al. , 1908.09843

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

Phase shift due to free-streaming neutrinos

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

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

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

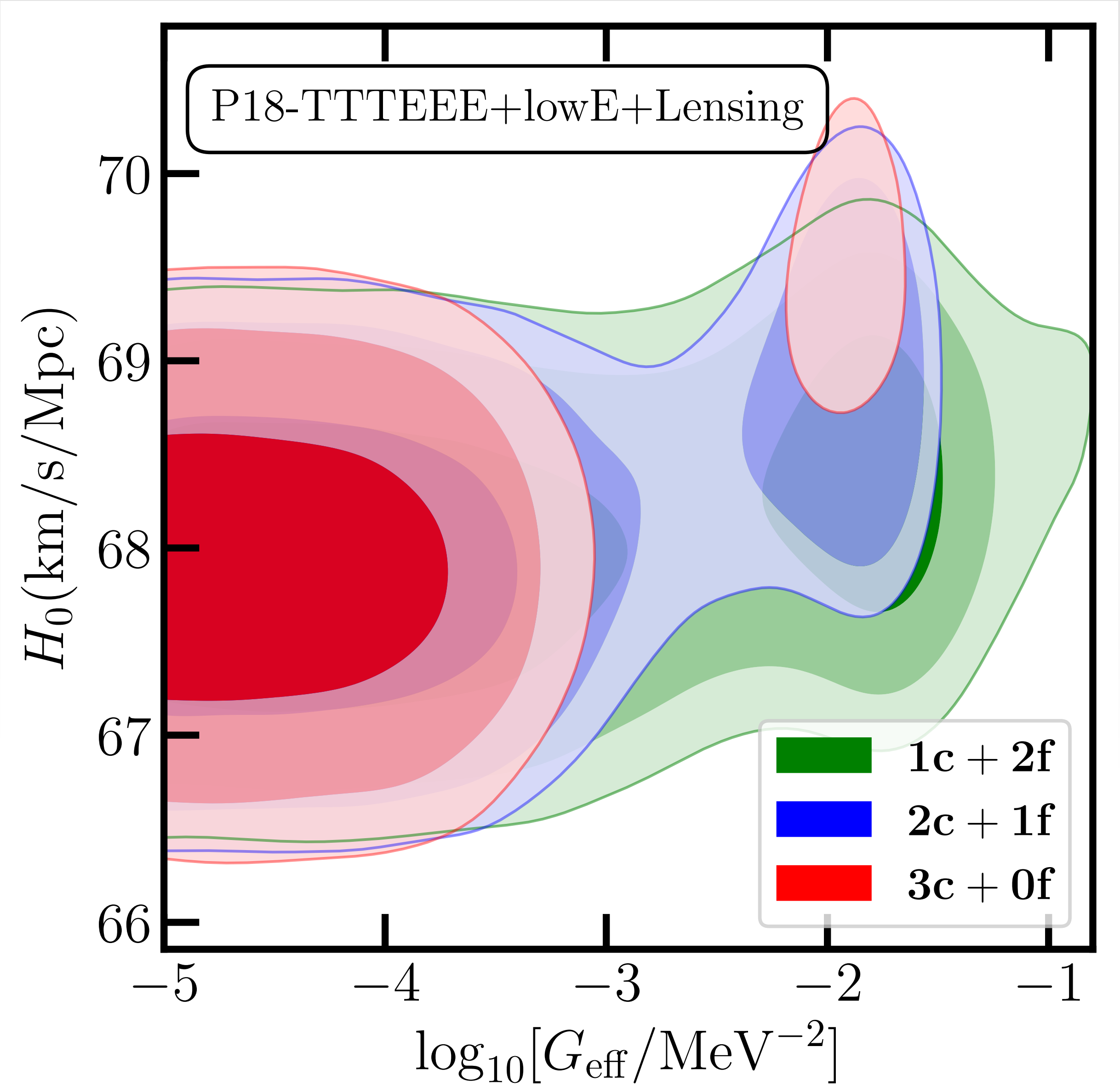
$$D_A^* = \int_0^{z^*} \frac{1}{H(z)} dz$$

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

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

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



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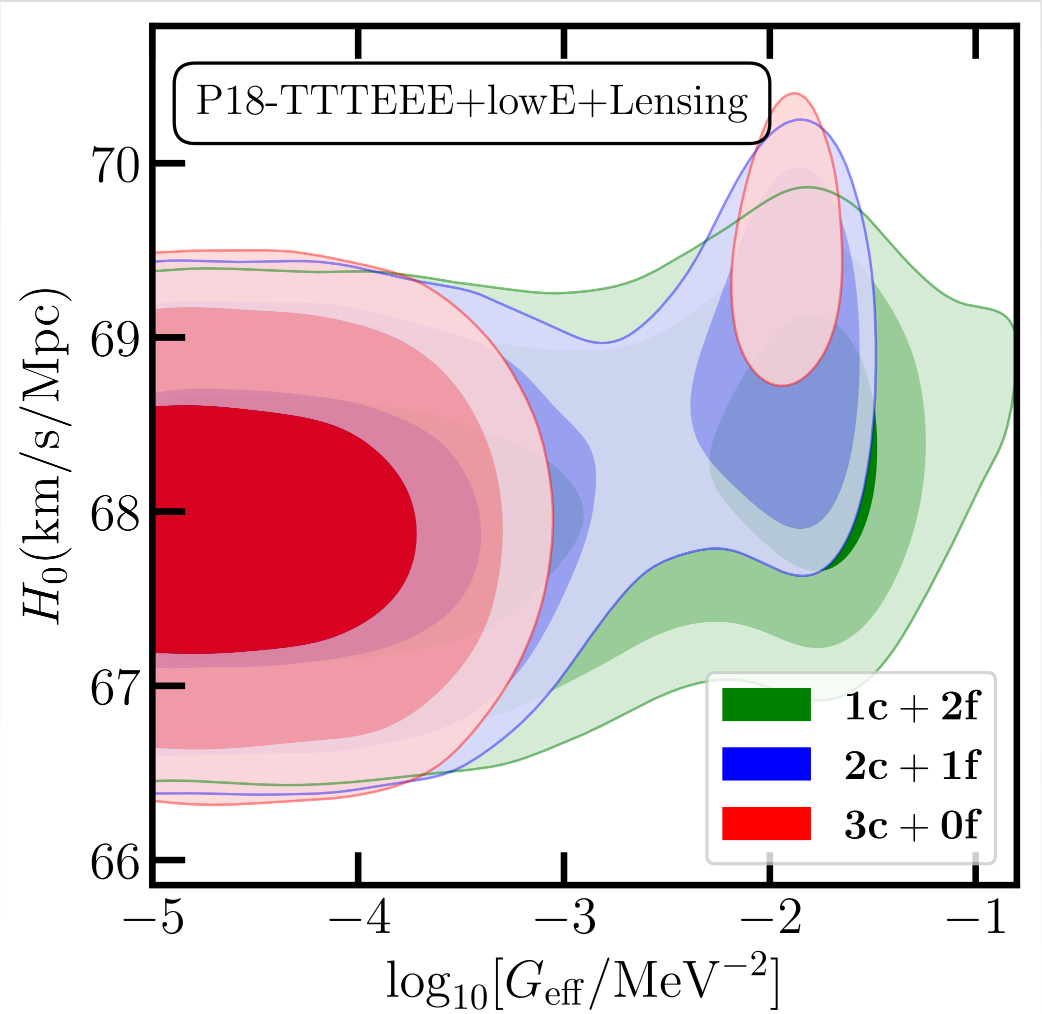
Effect on H_0 : Phase shift



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

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

Anirban Das, SG : 2011.12315

	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^*(Mpc)	144.58 ± 0.32	144.69 ± 0.31	144.87 ± 0.29
D_A^*(Mpc)	12.69 ± 0.036	12.72 ± 0.034	12.773 ± 0.028

$$\theta_s \approx \theta_* \equiv \frac{r_s^*}{D_A^*}$$

Flavor specific SINU - with varying $N_{\rm eff}$: $1c + 2f + \Delta N_{\rm eff}$

SINU can accommodates larger $N_{\rm eff}$
$\leftarrow$ Enhancement of CMB spectra due to self-interaction compensates additional silk damping

In addition to enhancement of H_0 due to phase shift , larger $N_{\rm eff}$ can also boost the H_0 value

$1c + 2f + \Delta N_{\rm eff}$

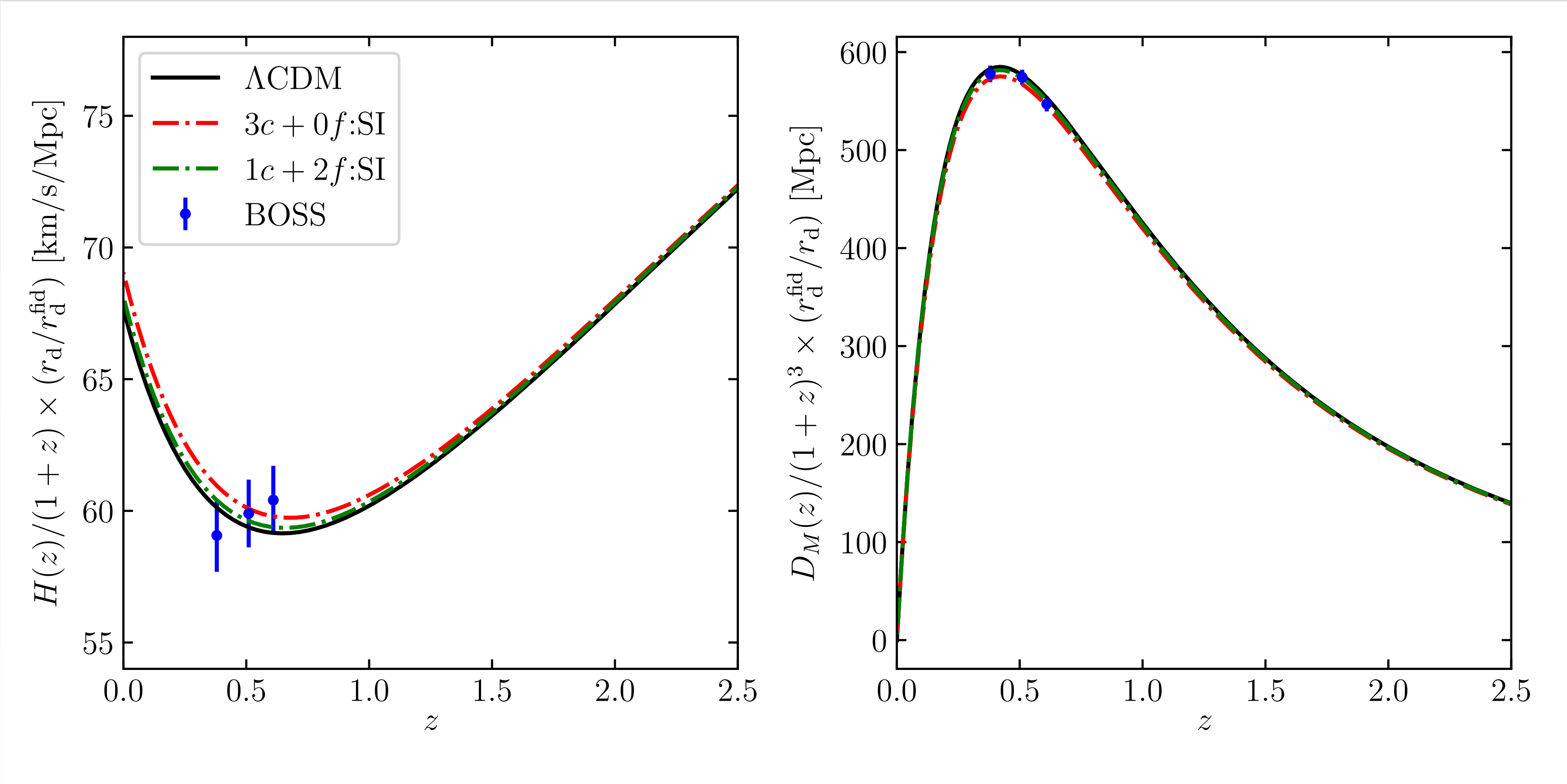
- $1c$: 1 coupled flavor
- $2f$: 2 free streaming flavor
- $\Delta N_{\rm eff}$: Additional free streaming ν (e.g. sterile ν)

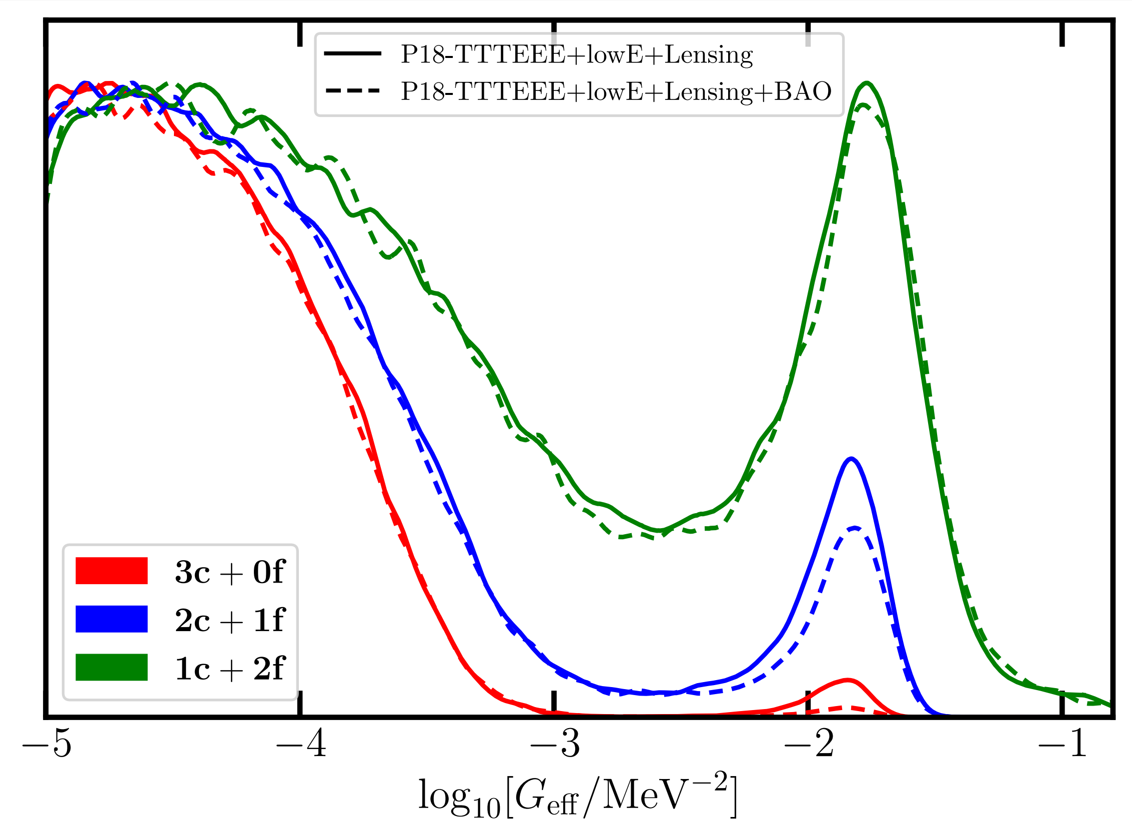
$1c + 2f + \Delta N_{\rm eff}$

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
H_0 $(1c + 2f)$	67.9 ± 1.00	68.3 ± 0.62	68.75 ± 0.41

Effect of BAO data

Anirban Das, SG : 2011.12315





Strong self interaction is disfavored by BAO data

Part I : Summary : CMB favors Flavor specific self-interaction

- 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

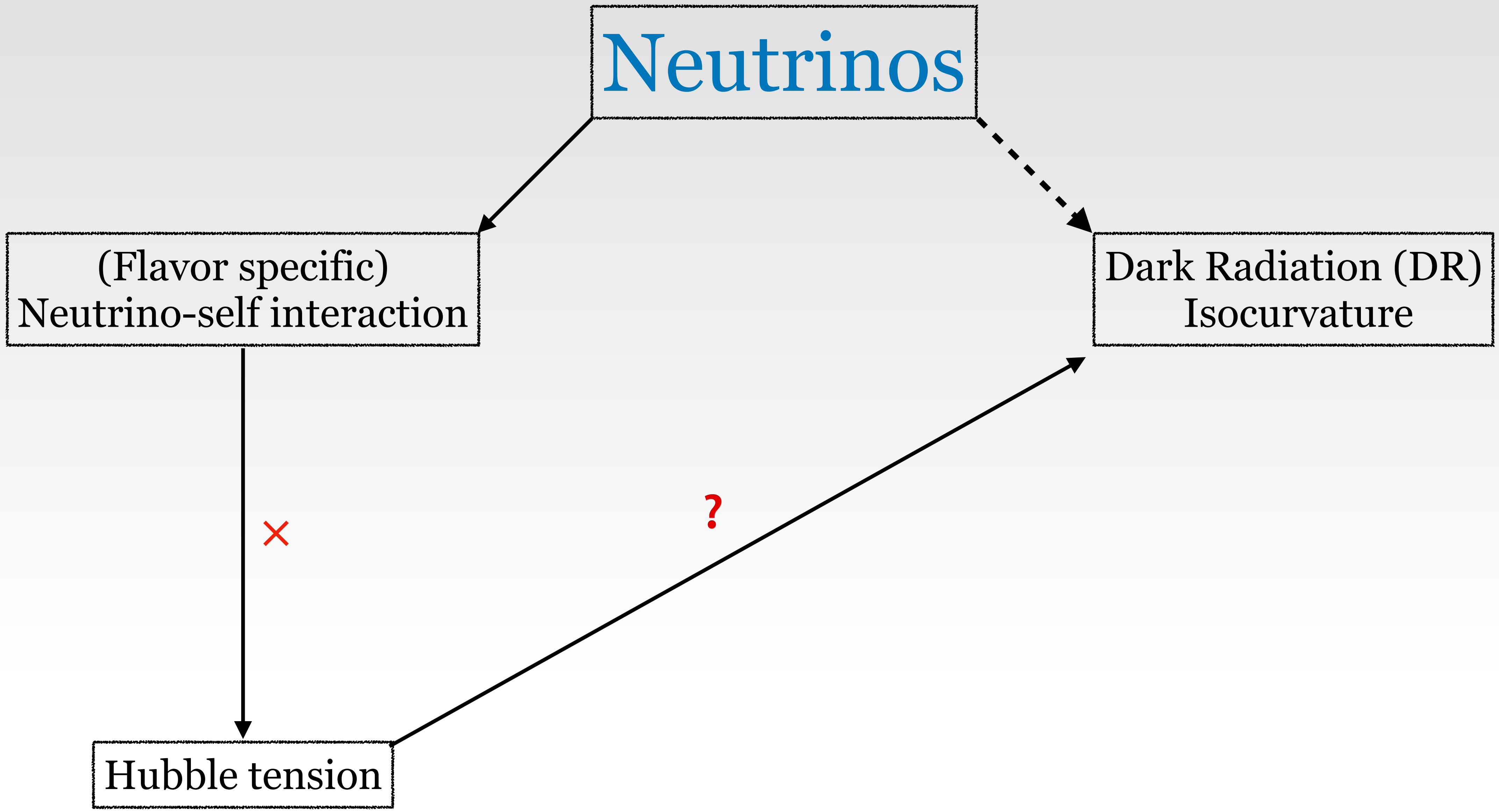
Future direction

- Effect of non-diagonal interaction

  — aries naturally when considering massive Neutrinos
- Phenomenological model for flavor specific interaction

Cosmology favors Flavor specific neutrino self interaction

Part II : Dark Radiation Isocurvature



Isocurvature Perturbation in CMB

Primordial perturbation → (Observation from Planck) → Adiabatic / (almost) scale invariant / Gaussian

↓

Single field slow roll inflation

Other fields during inflation (Multi field inflation) → **Isocurvature** Non Gaussianity

Probe using CMB and LSS data

DR from decay of separate field during inflation (e.g. - curvaton) → Isocurvature perturbation in DR

Dark Radiation (DR)

Parametrized by $\Delta N_{\rm eff}$

Free-streaming DR (FDR)

Similar to (SM/free-streaming) neutrinos

Non zero anisotropic stress

Coupled/fluid DR (CDR)

Similar to (strongly) self-interacting neutrinos

Zero anisotropic stress

Isocurvature parameters

$A_{\rm iso}(k_*)$ $\left[\text{or } f_{\rm iso} \equiv A_{\rm iso}/A_{\rm adia}\right]$

$n_{\rm iso}$

→ Or

$P_{II}^{(1)}\ (\equiv A_{\rm iso}(k_1))$

$P_{II}^{(2)}\ (\equiv A_{\rm iso}(k_2))$

$k_1 = 0.002\ {\rm Mpc}^{-1}$

$k_2 = 0.1\ {\rm Mpc}^{-1}$

Isocurvature Initial conditions

(In synchronous gauge)

variable	$\mathcal{O}(0)$	$\mathcal{O}(k\tau)$	$\mathcal{O}((k\tau)^2)$	$\mathcal{O}(\omega k^2\tau^3)$
δ_γ	$-\frac{R_{\rm DR}}{1-R_{\rm DR}}$	0	$\frac{R_{\rm DR}}{6(1-R_{\rm DR})}$	
θ_γ/k	0	$-\frac{R_{\rm DR}}{4(1-R_{\rm DR})}$	0	
δ_ν	$-\frac{R_{\rm DR}}{1-R_{\rm DR}}$	0	$\frac{R_{\rm DR}}{6(1-R_{\rm DR})}$	
θ_ν/k	0	$-\frac{R_{\rm DR}}{4(1-R_{\rm DR})}$	0	
σ_ν	0	0	$-\frac{19R_{\rm DR}}{30(1-R_{\rm DR})(15+4R_{\rm DR}+4R_\nu)}$	
$\delta_{\rm DR}$	1	0	$-\frac{1}{6}$	
$\theta_{\rm DR}/k$	0	$\frac{1}{4}$	0	
$\sigma_{\rm DR}$	0	0	$\frac{15-15R_{\rm DR}+4R_\nu}{30(1-R_{\rm DR})(15+4R_{\rm DR}+4R_\nu)}$	
η	0	0	$\frac{-R_{\rm DR}+R_{\rm DR}^2+R_{\rm DR}R_\nu}{6(1-R_{\rm DR})(15+4R_{\rm DR}+4R_\nu)}$	
h	0	0	0	$\frac{R_{\rm DR}R_b}{40(1-R_{\rm DR})}$
δ_b	0	0	$\frac{R_{\rm DR}}{8(1-R_{\rm DR})}$	
δ_c	0	0	0	$-\frac{R_{\rm DR}R_b}{80(1-R_{\rm DR})}$

FDR - Isocurvature

$$\text{Adiabatic intial condition}: \delta_\gamma = \delta_\nu = \delta_{\rm DR}$$

For both CDR & FDR isocurvature: $\sum_i R_i \delta_i = 0$

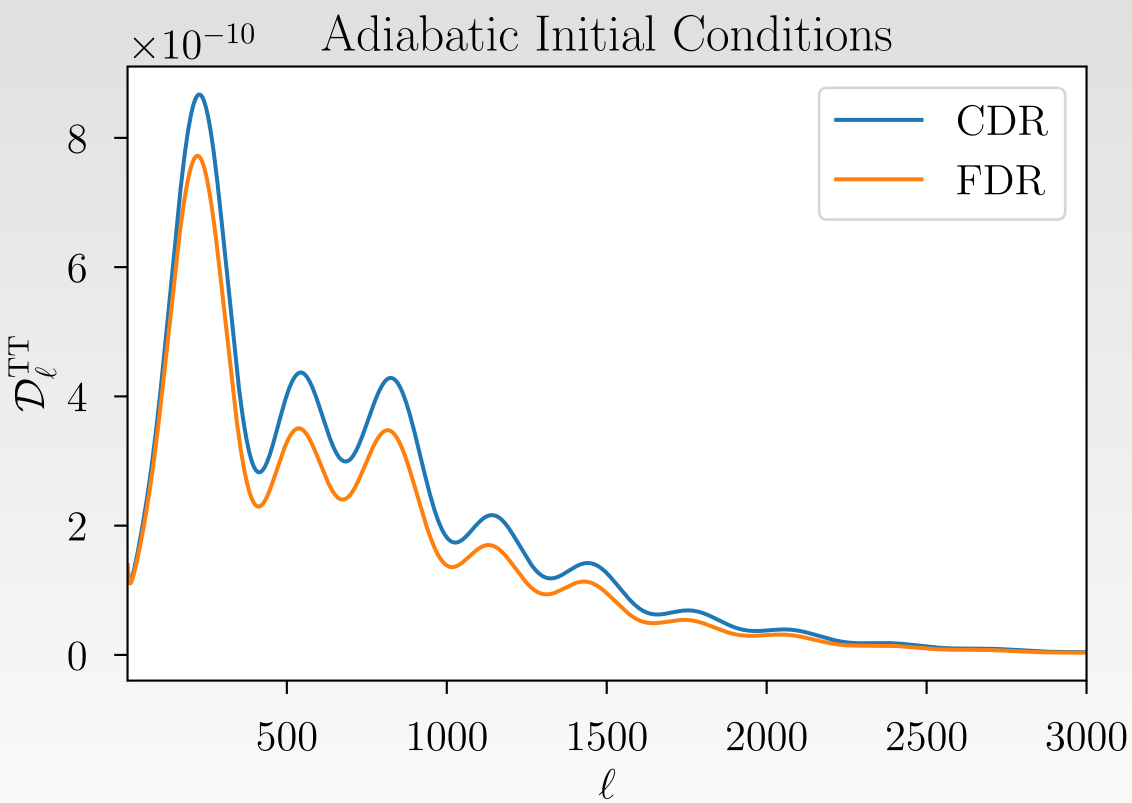
$$R_i = \bar{\rho}_i/(\bar{\rho}_\gamma + \bar{\rho}_\nu + \bar{\rho}_{\rm DR})$$

variable	$\mathcal{O}(0)$	$\mathcal{O}(k\tau)$	$\mathcal{O}((k\tau)^2)$	$\mathcal{O}(\omega k^2\tau^3)$
δ_γ	$-\frac{R_{\rm DR}}{1-R_{\rm DR}}$	0	$\frac{R_{\rm DR}}{6(1-R_{\rm DR})}$	
θ_γ/k	0	$-\frac{R_{\rm DR}}{4(1-R_{\rm DR})}$	0	
δ_ν	$-\frac{R_{\rm DR}}{1-R_{\rm DR}}$	0	$\frac{R_{\rm DR}}{6(1-R_{\rm DR})}$	
θ_ν/k	0	$-\frac{R_{\rm DR}}{4(1-R_{\rm DR})}$	0	
σ_ν	0	0	$-\frac{R_{\rm DR}}{2(1-R_{\rm DR})(15+4R_\nu)}$	
$\delta_{\rm DR}$	1	0	$-\frac{1}{6}$	
$\theta_{\rm DR}/k$	0	$\frac{1}{4}$	0	
η	0	0	$\frac{R_{\rm DR}R_\nu}{6(1-R_{\rm DR})(15+4R_\nu)}$	
h	0	0	0	$\frac{R_{\rm DR}R_b}{40(1-R_{\rm DR})}$
δ_b	0	0	$\frac{R_{\rm DR}}{8(1-R_{\rm DR})}$	
δ_c	0	0	0	$-\frac{R_{\rm DR}R_b}{80(1-R_{\rm DR})}$

$\sigma_{DR} = 0$ CDR - Isocurvature

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

FDR vs CDR Isocurvature spectrum



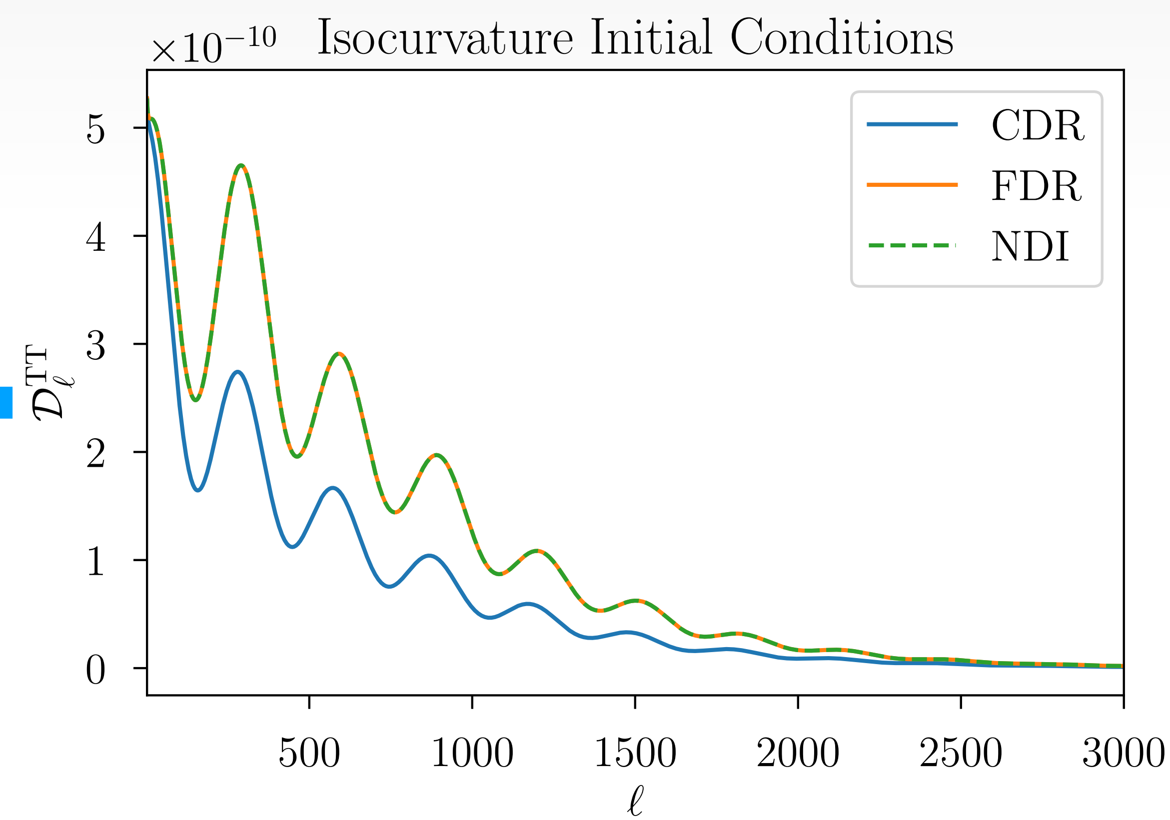
Adiabatic : $\delta_\gamma = \delta_\nu = \delta_{DR}$

FDR free-streams out of potential well
→ Smaller potential → Smaller CMB anisotropy

CDR does not free-stream
→ larger CMB anisotropy

$$\sum_i R_i \delta_i = 0$$

For isocurvature metric fluctuation is sourced by anisotropic stress (σ) at leading order

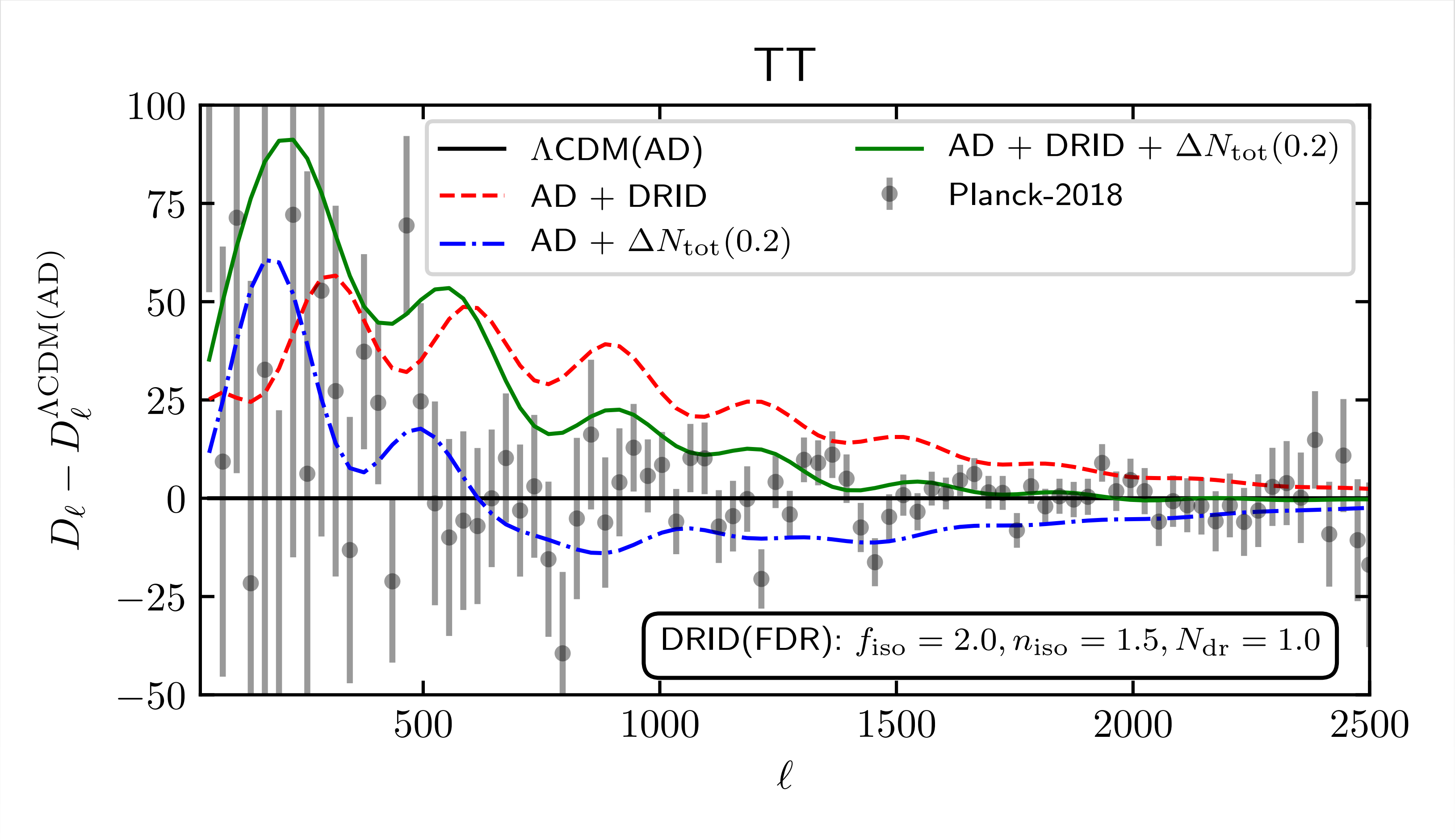


FDR: $\sigma_{tot} > 0$ → More anisotropy

CDR: $\sigma_{tot} < 0$ → Less anisotropy

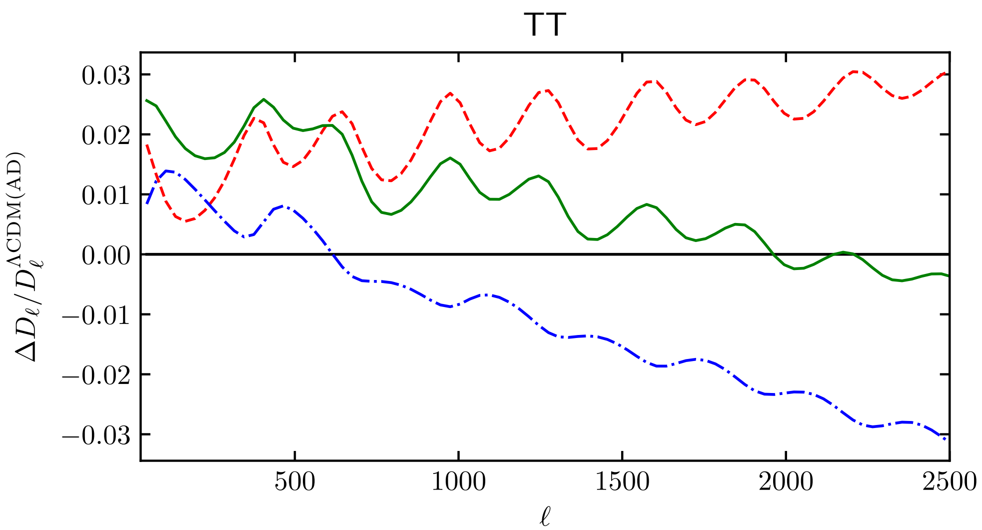
SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Isocurvature accommodate larger $N_{\rm eff}$ ($\equiv N_{\rm tot}$)



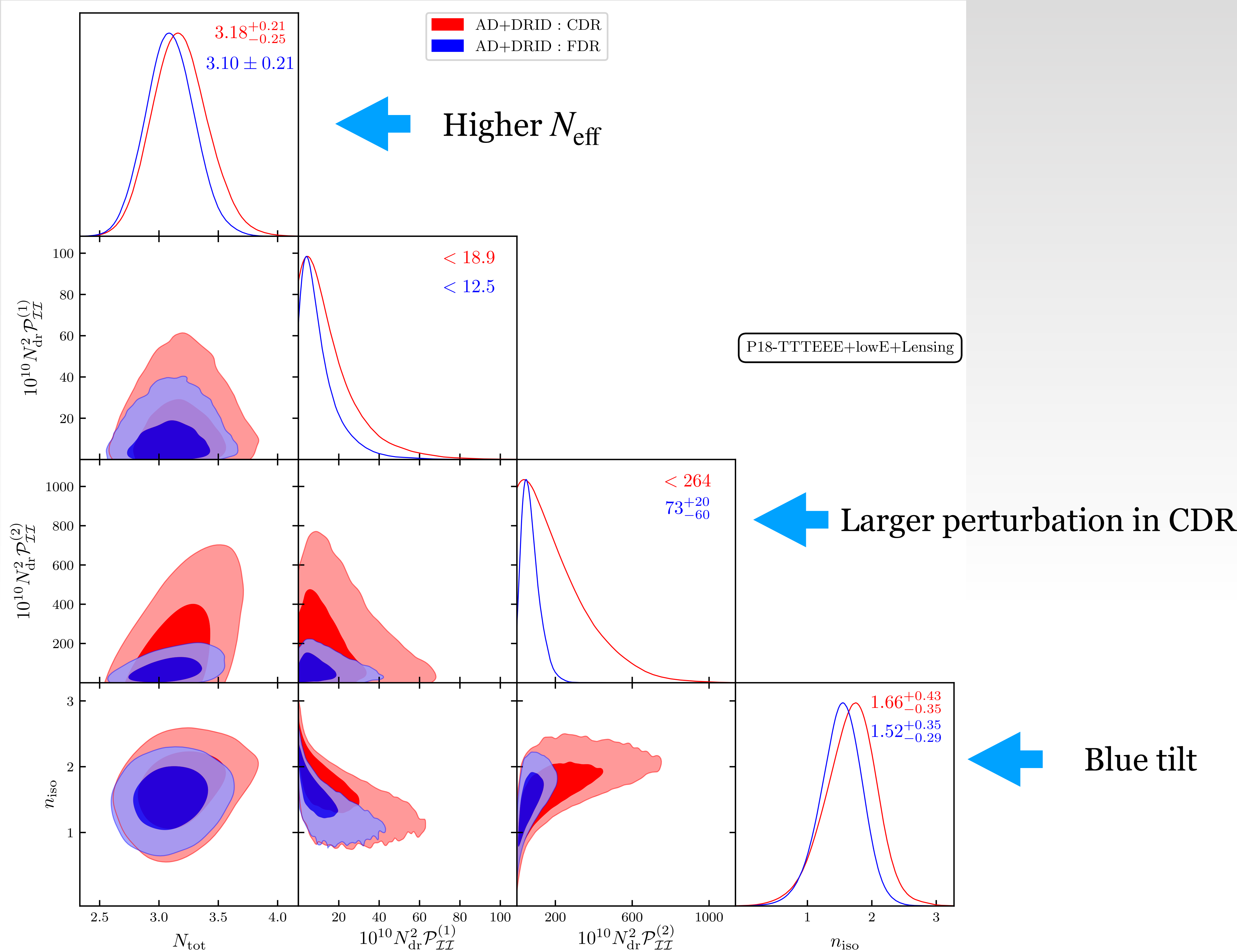
SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Blue tilted ($n_{\rm iso} > 1$) isocurvature compensates for the larger silk damping due to higher $N_{\rm eff}$



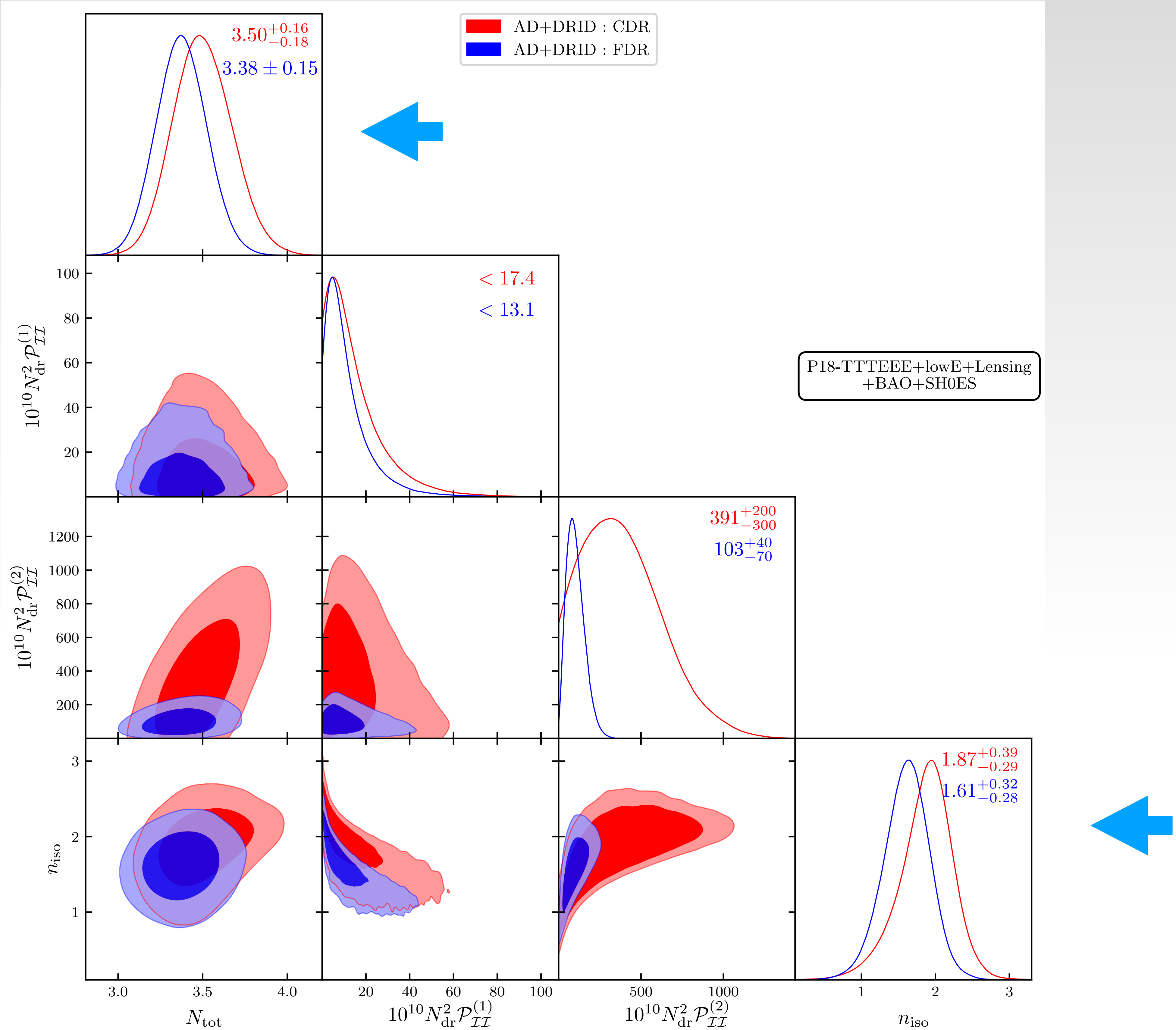
DRID ≡ Dark Radiation density Isocurvature

MCMC results



SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

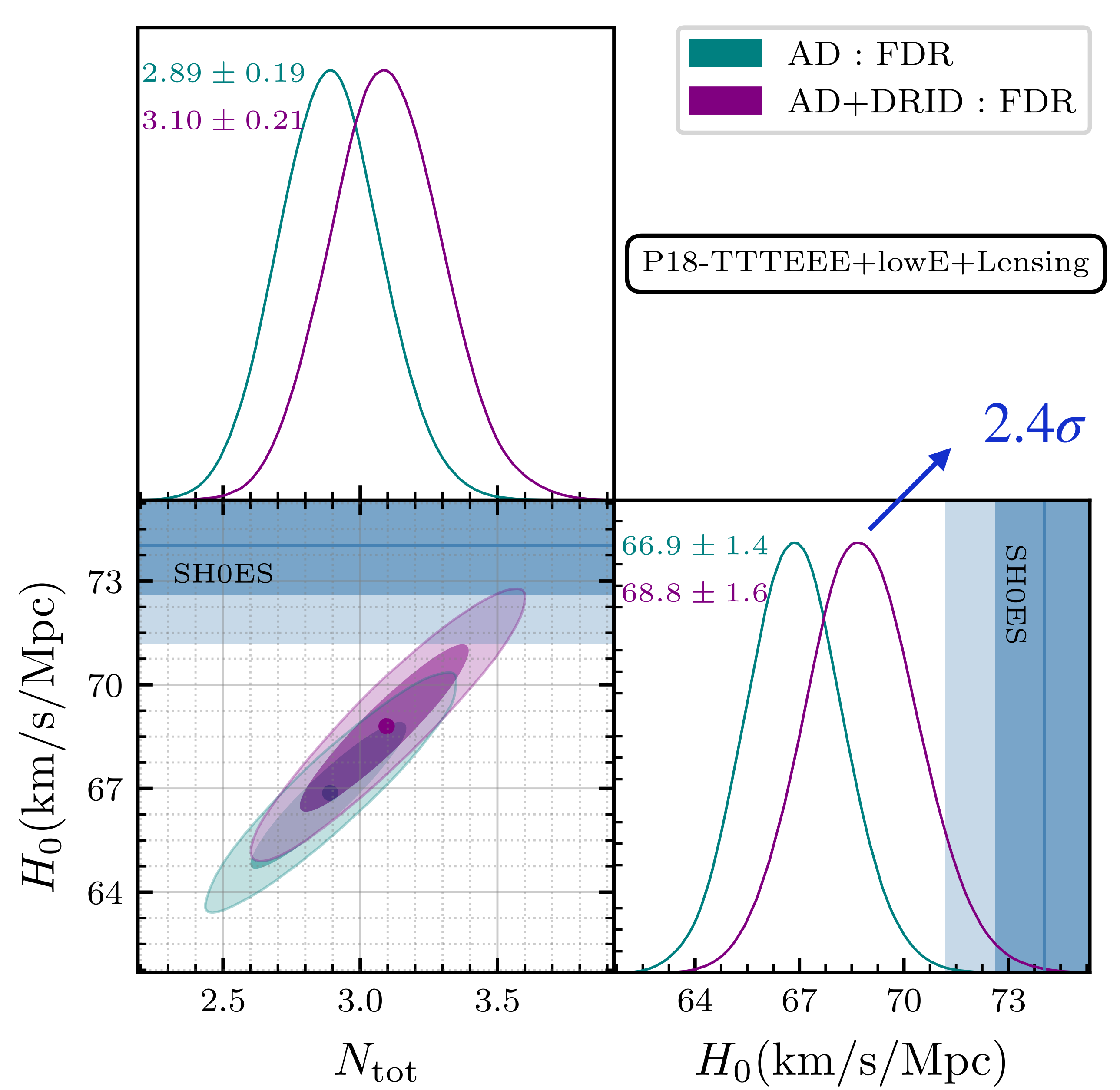
MCMC results

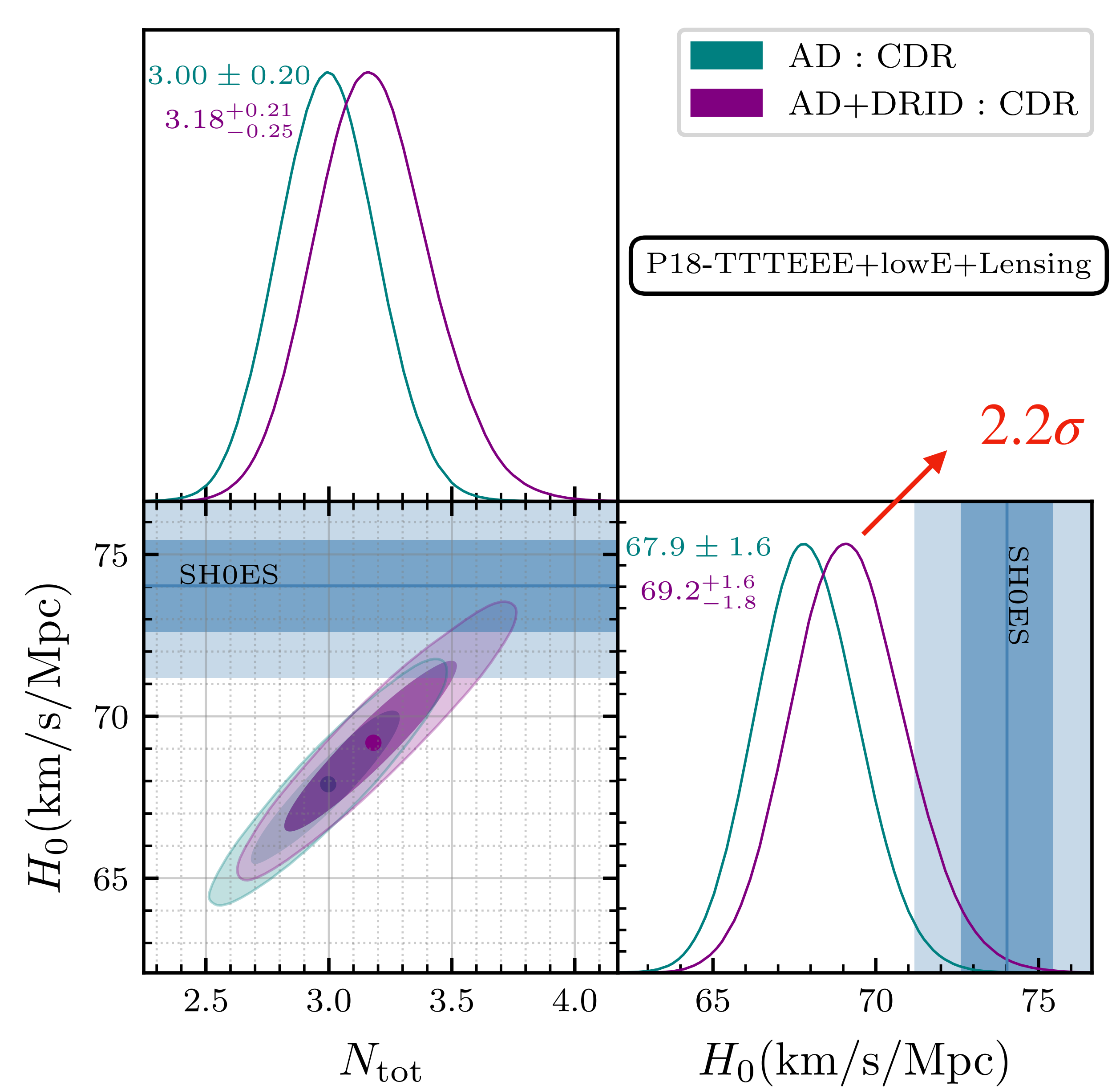


SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Isocurvature accommodates larger $N_{\rm eff}$ → larger H_0

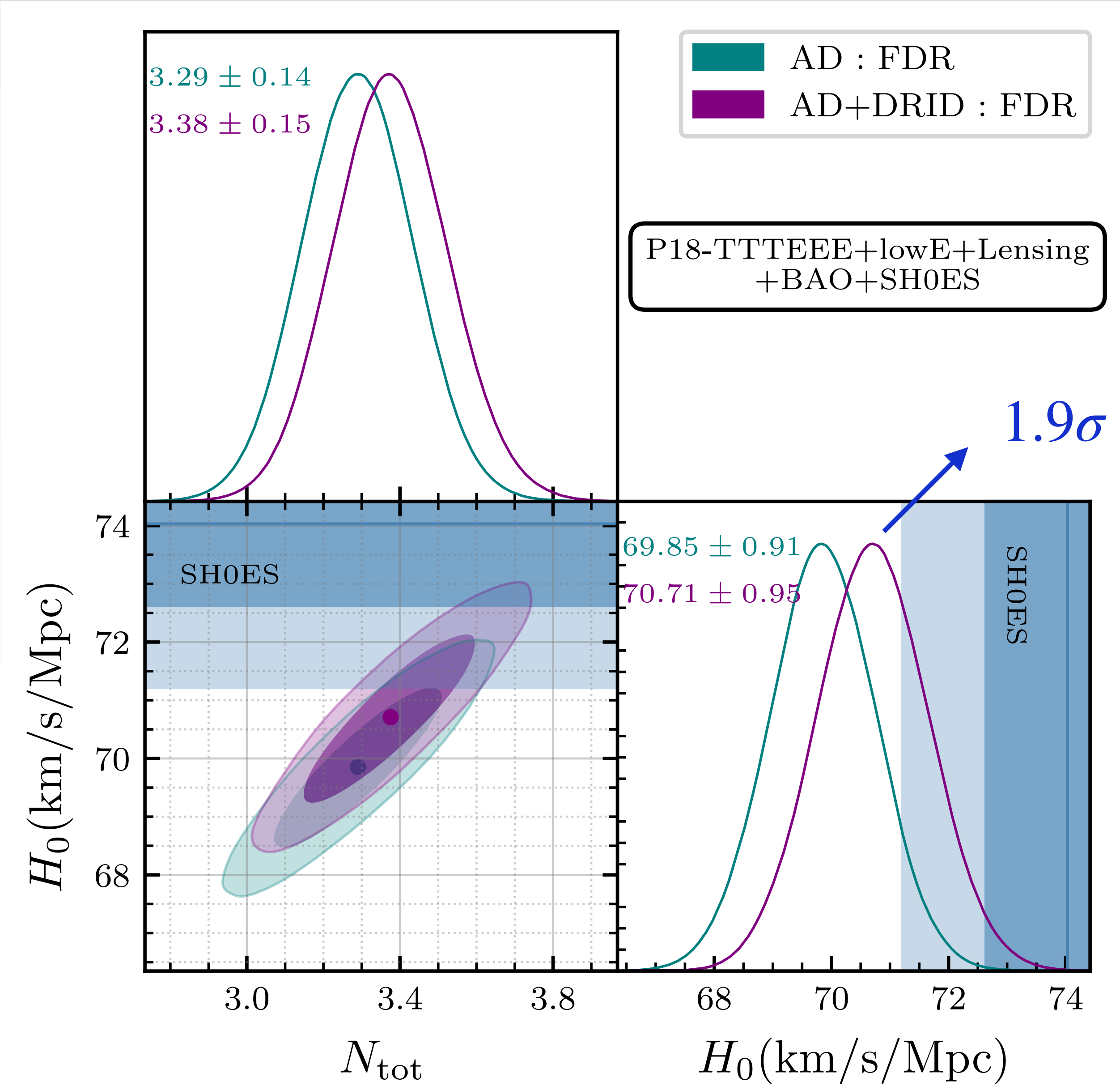
H_0 (SH0ES) = 74.03 ± 1.42 km/s/Mpc

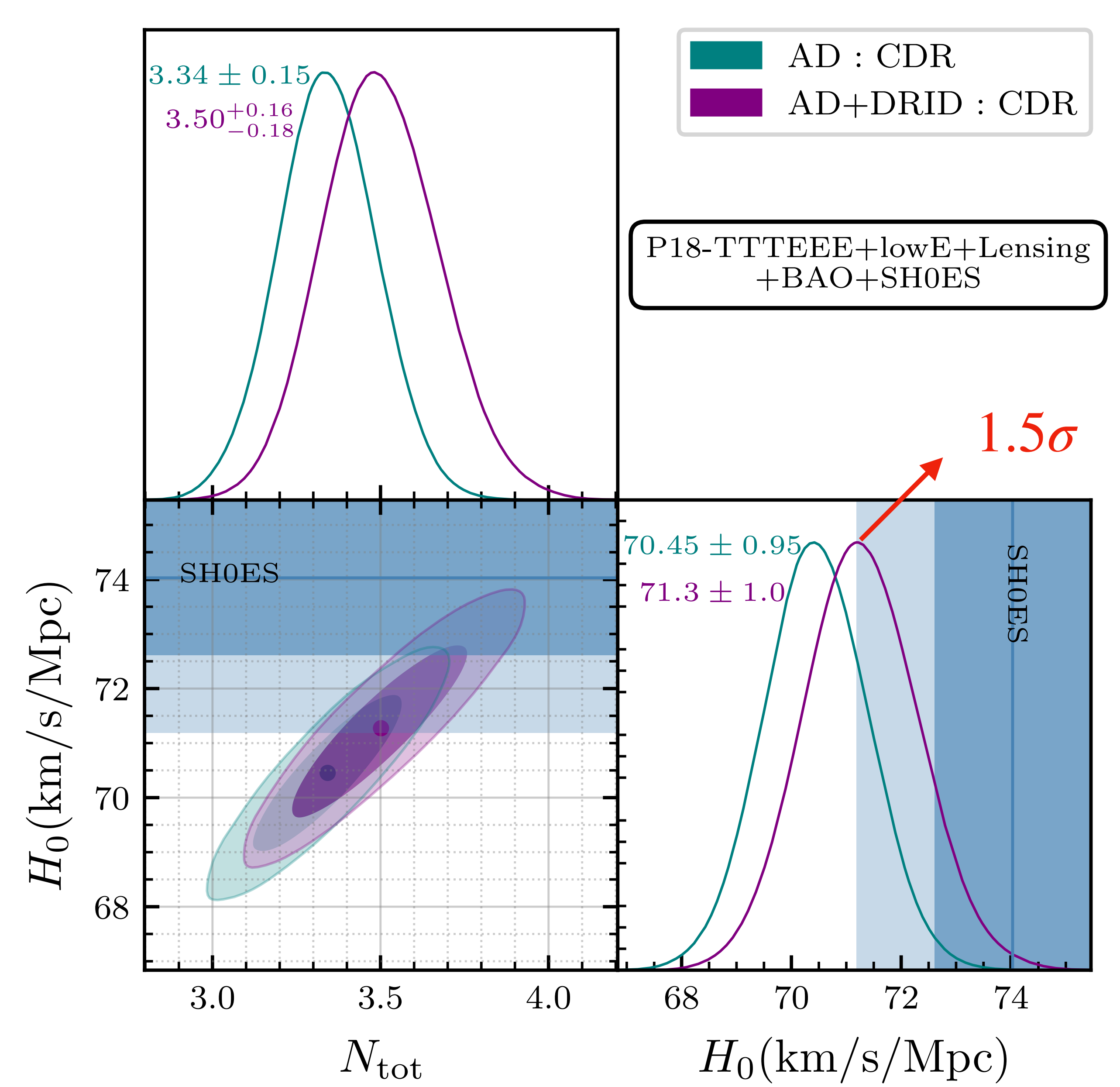




SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Isocurvature accommodates larger N_{eff} → larger H_0





SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Parameter values: FDR DRID

FDR	P18-TT+lowE	P18-TTTEEE +lowE+lensing	P18-TTTEEE+lowE+ lensing+BAO+SH0ES
$100\ \omega_b$	$2.3^{+0.052}_{-0.064}$	$2.253^{+0.025}_{-0.026}$	$2.278^{+0.017}_{-0.017}$
ω_{cdm}	$0.1252^{+0.0046}_{-0.0058}$	$0.12^{+0.0031}_{-0.0031}$	$0.1241^{+0.0027}_{-0.0028}$
$100 * \theta_s$	$1.042^{+0.00073}_{-0.00077}$	$1.042^{+0.00052}_{-0.00053}$	$1.042^{+0.0005}_{-0.0005}$
$\tau_{\rm reio}$	$0.05416^{+0.0085}_{-0.0091}$	$0.05534^{+0.0075}_{-0.008}$	$0.05594^{+0.007}_{-0.0075}$
$10^{10} P^{(1)}_{\mathcal{RR}}$	$22^{+1.1}_{-1.1}$	$23.32^{+0.57}_{-0.57}$	$22.88^{+0.49}_{-0.49}$
$10^{10} P^{(2)}_{\mathcal{RR}}$	$20.55^{+0.57}_{-0.63}$	$20.37^{+0.43}_{-0.46}$	$20.68^{+0.37}_{-0.39}$
$10^{10} N^2_{\rm dr} P^{(1)}_{\mathcal{II}}$	$17.48^{+2.1}_{-17}$	$11.22^{+1.7}_{-11}$	$11.84^{+1.7}_{-12}$
$10^{10} N^2_{\rm dr} P^{(2)}_{\mathcal{II}}$	$228.9^{+61}_{-2.2e+02}$	73.91^{+26}_{-60}	102.1^{+37}_{-67}
$N_{\rm ur}$	$2.469^{+1.3}_{-0.79}$	$2.031^{+1.1}_{-0.49}$	$2.265^{+1.1}_{-0.47}$
$N_{\rm dr}$	$1.19^{+0.34}_{-1.2}$	$1.066^{+0.32}_{-1.1}$	$1.111^{+0.33}_{-1.1}$
H_0	$74.03^{+3.9}_{-5.1}$	$68.8^{+1.6}_{-1.7}$	$70.71^{+0.97}_{-0.98}$
σ_8	$0.8231^{+0.015}_{-0.015}$	$0.82^{+0.01}_{-0.01}$	$0.8302^{+0.009}_{-0.0092}$
$10^{+9} A_s$	$2.079^{+0.045}_{-0.049}$	$2.087^{+0.036}_{-0.038}$	$2.105^{+0.033}_{-0.034}$
n_s	$0.9828^{+0.017}_{-0.017}$	$0.9654^{+0.0091}_{-0.0092}$	$0.9741^{+0.0068}_{-0.0068}$
$n_{\rm iso}$	$1.72^{+0.36}_{-0.32}$	$1.52^{+0.35}_{-0.29}$	$1.61^{+0.32}_{-0.28}$
$f_{\rm iso}$	$17.4^{+7.0}_{-17}$	$11.9^{+5.2}_{-11}$	$13.0^{+5.3}_{-12}$
$N_{\rm tot}$	$3.66^{+0.4}_{-0.54}$	$3.097^{+0.21}_{-0.21}$	$3.376^{+0.15}_{-0.16}$
$f_{\rm dr}$	$0.3285^{+0.097}_{-0.33}$	$0.3444^{+0.1}_{-0.34}$	$0.3293^{+0.095}_{-0.33}$
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	-0.36	-3.54	-9.24
AIC	+7.64	+4.46	-1.24

4 extra parameter compared to ΛCDM: $N^2_{\rm dr} P^{(1)}_{II}$, $N^2_{\rm dr} P^{(2)}_{II}$, $N_{\rm dr}$, $N_{\rm ur}$

$$\text{AIC} = \Delta\chi^2 + 2n$$

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Parameter values: CDR DRID

CDR	P18-TT+lowE	P18-TTTEEE +lowE+lensing	P18-TTTEEE+lowE+ lensing+BAO+SH0ES
$100\ \omega_b$	$2.267^{+0.039}_{-0.05}$	$2.257^{+0.026}_{-0.028}$	$2.285^{+0.018}_{-0.018}$
ω_{cdm}	$0.1301^{+0.0053}_{-0.011}$	$0.122^{+0.0034}_{-0.004}$	$0.1272^{+0.0031}_{-0.0035}$
$100 * \theta_s$	$1.042^{+0.0011}_{-0.0012}$	$1.043^{+0.00064}_{-0.00075}$	$1.042^{+0.00065}_{-0.00081}$
$\tau_{\rm reio}$	$0.05327^{+0.0079}_{-0.0087}$	$0.0561^{+0.0075}_{-0.0084}$	$0.05643^{+0.007}_{-0.0077}$
$10^{10} P^{(1)}_{\mathcal{RR}}$	$23.06^{+0.93}_{-0.95}$	$23.46^{+0.55}_{-0.57}$	$23.14^{+0.52}_{-0.54}$
$10^{10} P^{(2)}_{\mathcal{RR}}$	$20.32^{+0.69}_{-0.67}$	$20.19^{+0.45}_{-0.48}$	$20.34^{+0.45}_{-0.44}$
$10^{10} N^2_{\rm dr} P^{(1)}_{\mathcal{II}}$	25.54^{+4}_{-26}	$16.43^{+2.9}_{-16}$	$15.39^{+2.6}_{-15}$
$10^{10} N^2_{\rm dr} P^{(2)}_{\mathcal{II}}$	$662.7^{+91}_{-6.6e+02}$	$218.7^{+50}_{-2.2e+02}$	$390.6^{+1.6e+02}_{-3.2e+02}$
$N_{\rm ur}$	$3.408^{+0.46}_{-0.72}$	$2.938^{+0.24}_{-0.26}$	$3.164^{+0.27}_{-0.24}$
$N_{\rm dr}$	$0.2589^{+0.051}_{-0.26}$	$0.2444^{+0.064}_{-0.24}$	$0.3372^{+0.14}_{-0.27}$
H_0	$71.79^{+3}_{-4.7}$	$69.19^{+1.7}_{-1.9}$	$71.27^{+1}_{-1.1}$
σ_8	$0.8341^{+0.017}_{-0.023}$	$0.8205^{+0.01}_{-0.011}$	$0.8298^{+0.0096}_{-0.0096}$
$10^{+9} A_s$	$2.077^{+0.054}_{-0.051}$	$2.073^{+0.038}_{-0.04}$	$2.081^{+0.038}_{-0.038}$
n_s	$0.9677^{+0.016}_{-0.016}$	$0.9617^{+0.0092}_{-0.0094}$	$0.9671^{+0.0086}_{-0.0079}$
$n_{\rm iso}$	$1.83^{+0.45}_{-0.41}$	$1.66^{+0.43}_{-0.35}$	$1.87^{+0.39}_{-0.29}$
$f_{\rm iso}$	< 31.7	58^{+22}_{-53}	49^{+23}_{-44}
$N_{\rm tot}$	$3.666^{+0.37}_{-0.71}$	$3.182^{+0.22}_{-0.26}$	$3.501^{+0.17}_{-0.19}$
$f_{\rm dr}$	$0.07186^{+0.014}_{-0.072}$	$0.07591^{+0.021}_{-0.076}$	$0.09615^{+0.04}_{-0.077}$
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	2.72	0.46	−5.8
AIC	+10.72	+8.46	+2.2

4 extra parameter compared to ΛCDM: $N^2_{\rm dr} P^{(1)}_{II}, N^2_{\rm dr} P^{(2)}_{II}, N_{\rm dr}, N_{\rm ur}$

$$\text{AIC} = \Delta\chi^2 + 2n$$

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Constraint on isocurvature parameters

$$\frac{\delta\sigma}{\sigma} \lesssim 2\times 10^{-4}$$

Isocurvature constraints at 95 % C.L.

	Planck	Planck +BAO+ SHoES
FDR	$\leq 2\times 10^{-8}$	$\leq 2.2\times 10^{-8}$
CDR	$\leq 6\times 10^{-8}$	$\leq 10\times 10^{-8}$

$$\frac{\delta\sigma}{\sigma} \lesssim 5\times 10^{-4}$$

95 % C.L. limits of $N_{\rm dr}^2 P_{II}^{(2)}$ for $N_{\rm dr} = 0.4$

Planck ≡ TTTEEE+lowE+lensing

$$P_{II}^{(2)} = A_{\rm iso}\ (k = \ 0.1{\rm Mpc}^{-1})$$

Part II : Conclusion: DR isocurvature alleviates Hubble tension

- DR isocurvature is a very generic in multi field inflation models
- In presence of isocurvature perturbation :

  FDR gives more anisotropy than CDR
- Blue tilted isocurvature accommodates a larger Hubble constant
- For CDR isocurvature - the Hubble tension is reduced to 1.5σ

THANK YOU