Free-streaming and Coupled Dark Radiation Isocurvature Perturbations

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PIKIMO - 2021 | 4 Dec, 2021

Overview

Dark Radiation (DR) Isocurvature

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Features of Free streaming DR Isocurvature (FDR)
&
coupled DR Isocurvature (CDR)

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Bounds from Cosmological Datasets

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Implication for the Hubble tension

Motivation: Isocurvature Perturbation in CMB

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

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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**

Implication for the Hubble Tension

Dark Radiation (DR)

Parametrized by ΔN_{eff}

Free-streaming DR (FDR)	Coupled/fluid DR (CDR)
Similar to (SM/free-streaming) neutrinos	Similar to (strongly) self-interacting neutrinos
Non zero anisotropic stress	Zero anisotropic stress

Additional variables to define the initial Isocurvature power spectrum

Isocurvature parameters

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

n_{iso}

→ Or

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

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

$k_1 = 0.002\ \text{Mpc}^{-1}$
$k_2 = 0.1\ \text{Mpc}^{-1}$

Additional parameters

N_{dr} → Amount of Dark Radiation

N_{ur} → Amount of Neutrinos

$$N_{\text{dr}} + N_{\text{ur}} \equiv N_{\text{tot}} = N_{\text{eff}}$$

Isocurvature Perturbation studies with CMB

Planck Collaboration

- Baryon Isocurvature
- CDM Isocurvature
- Neutrino Isocurvature

→ generalized →

- FDR Isocurvature
- CDR Isocurvature

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

DR → Adiabatic + Isocurvature
Neutrinos → Adiabatic

Recipe

Derive DR Isocurvature initial conditions

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Calculate the effects on the CMB spectrum (Using CLASS)

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Perform an MCMC analysis to find the constraints (Using Montepython)

Results for un-correlated DR Isocurvature

→ No correlation between isocurvature and adiabatic spectrum

Isocurvature Initial conditions

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

(In synchronous gauge)

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

$$\delta_i = \frac{\delta\rho_i}{\bar{\rho}_i}$$

$$\text{Isocurvature initial conditions:} \sum_i R_i \delta_i = 0$$

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

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	$-\frac{19R_{\rm DR}}{30(1-R_{\rm DR})(15+4R_{\rm DR}+4R_\nu)}$	
$\delta_{\rm DR}$	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	$-\frac{R_{\rm DR}R_b}{80(1-R_{\rm DR})}$

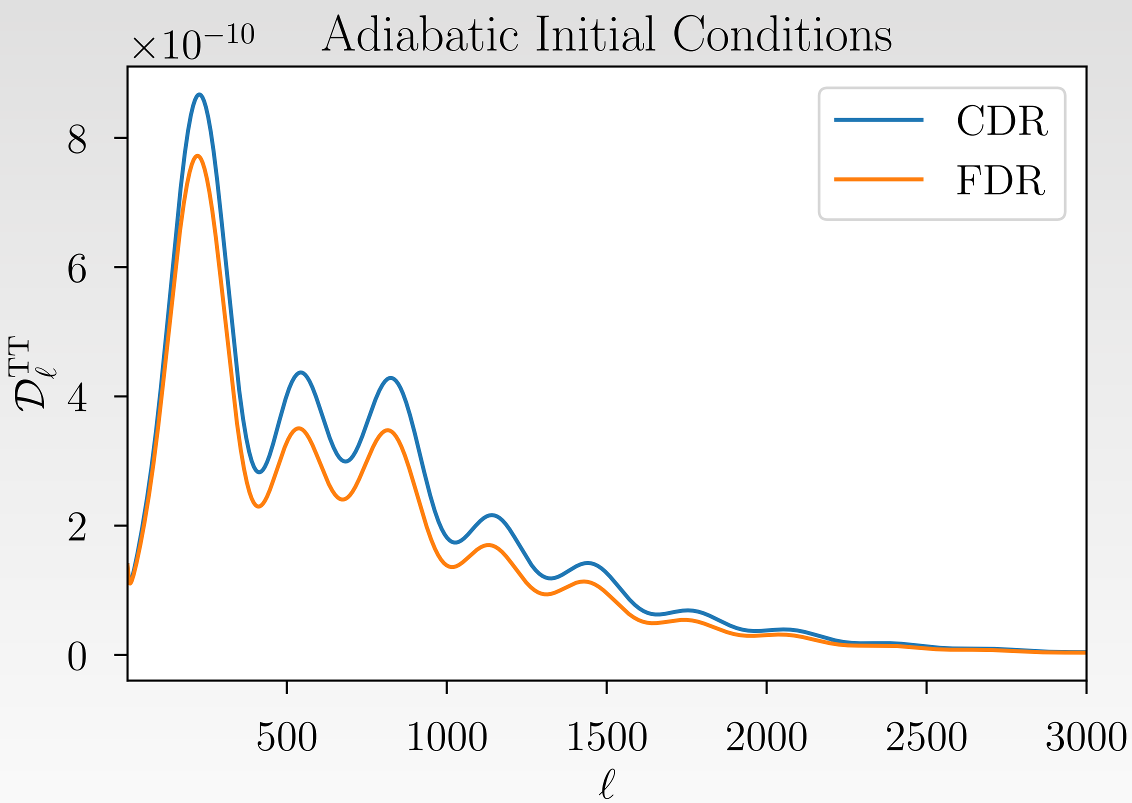
FDR - Isocurvature

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	$-\frac{R_{\rm DR}R_b}{80(1-R_{\rm DR})}$

CDR - Isocurvature

$$\sigma_{DR} = 0$$

FDR vs CDR Isocurvature spectrum



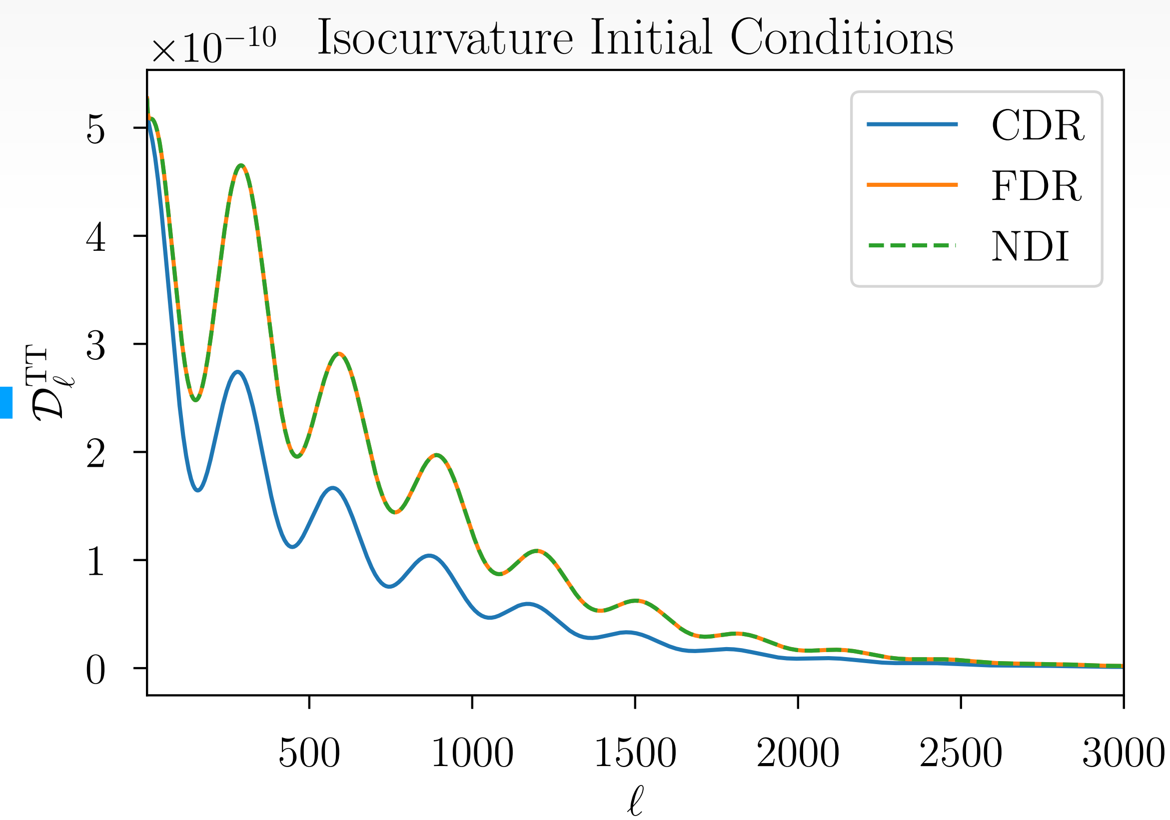
Adiabatic : $\delta_\gamma = \delta_\nu = \delta_{DR}$

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

FDR vs CDR Isocurvature spectrum

In Newtonian gauge: $\phi + \psi = -\dfrac{2\sigma}{(k\tau)^2}$

FDR: $\sigma_{\text{tot}} > 0 \rightarrow \sigma + \psi < 0$

CDR: $\sigma_{\text{tot}} < 0 \rightarrow \sigma + \psi > 0$

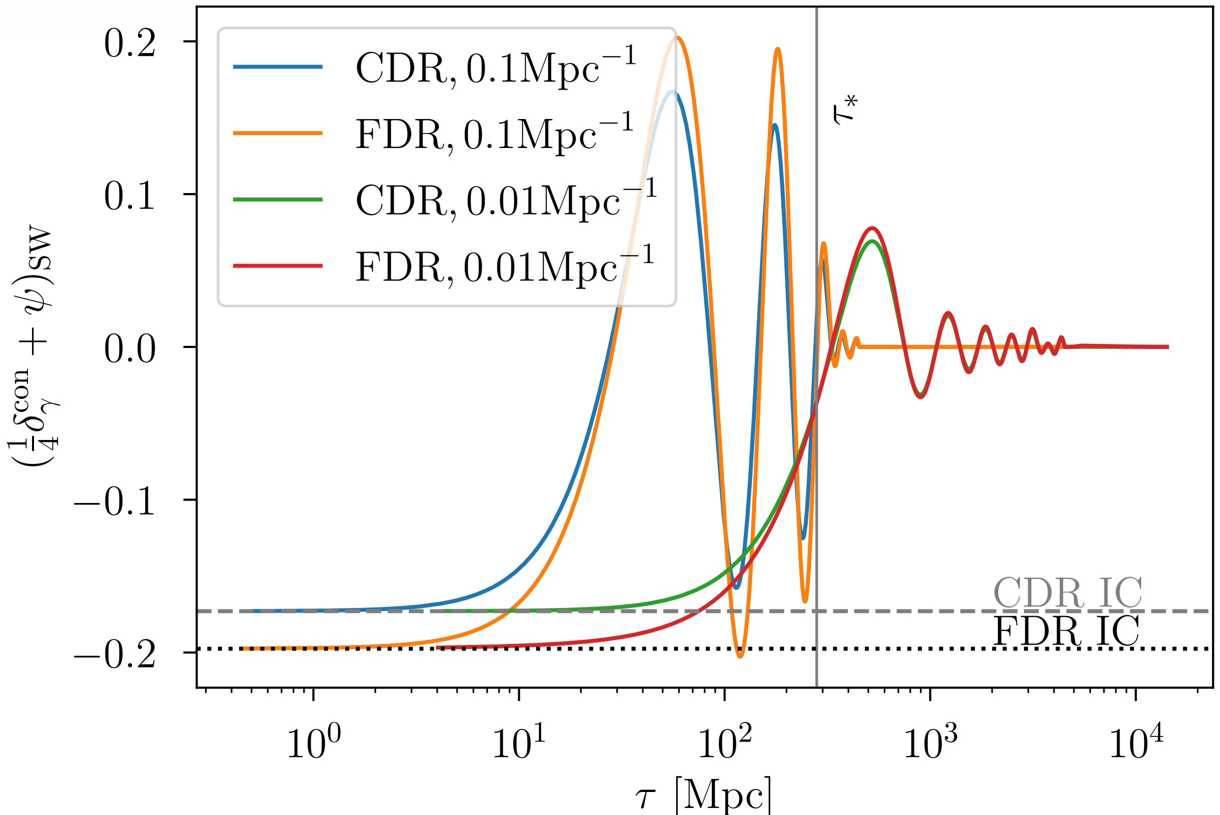
Metric potential affects CMB via Sachs - Wolfe redshifting: $\frac{1}{4}\delta_\gamma^{\text{con}} + \psi = \xi_\gamma + \phi + \psi$

Gauge invariant photon perturbation

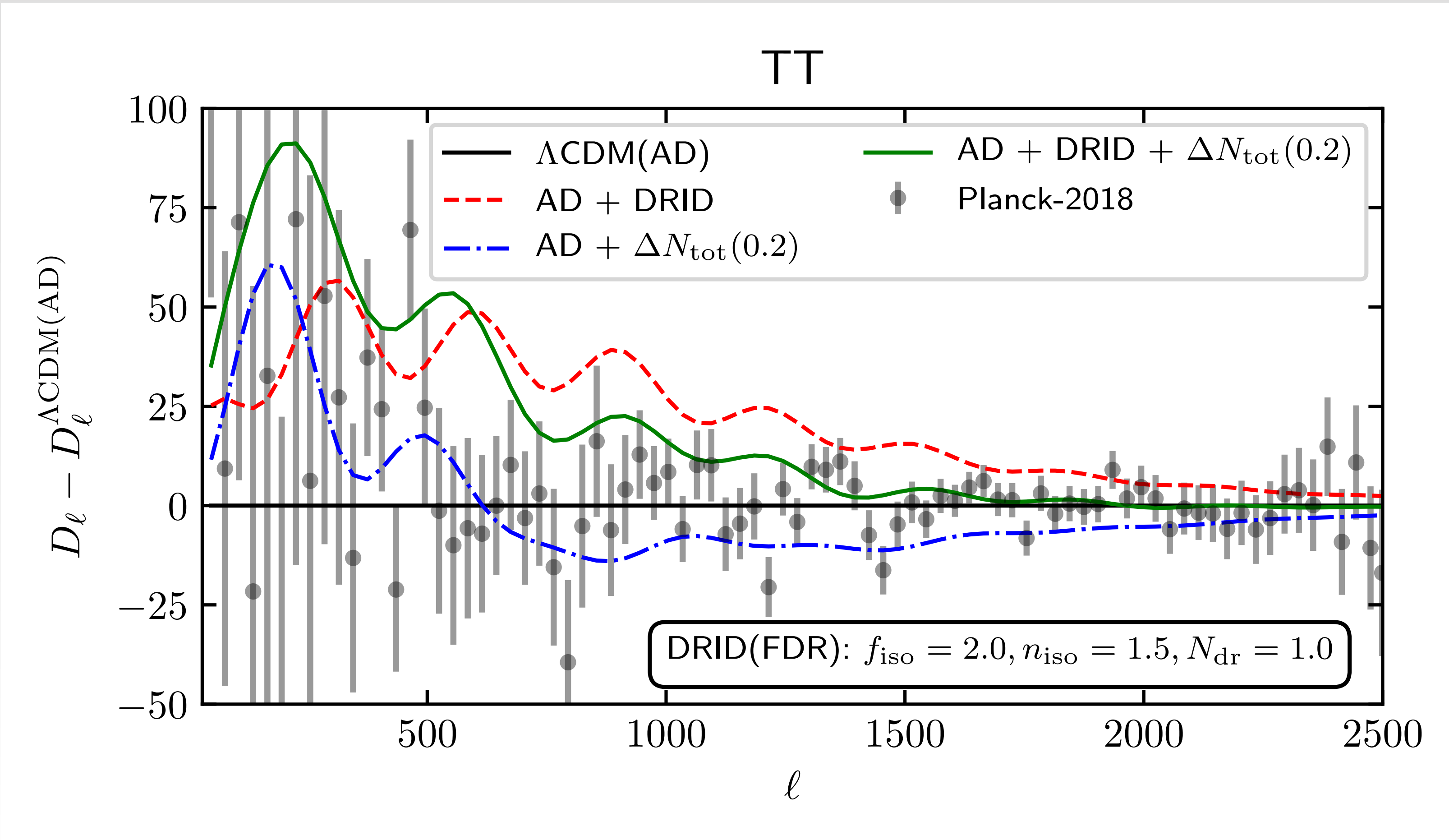
Isocurvature initial condition: $\xi_\gamma \approx \delta_\gamma < 0$

FDR: $\sigma_{\text{tot}} > 0 \rightarrow \sigma + \psi < 0 \rightarrow$ larger $|\xi_\gamma + \phi + \psi|$

CDR: $\sigma_{\text{tot}} < 0 \rightarrow \sigma + \psi > 0 \rightarrow$ smaller $|\xi_\gamma + \phi + \psi|$

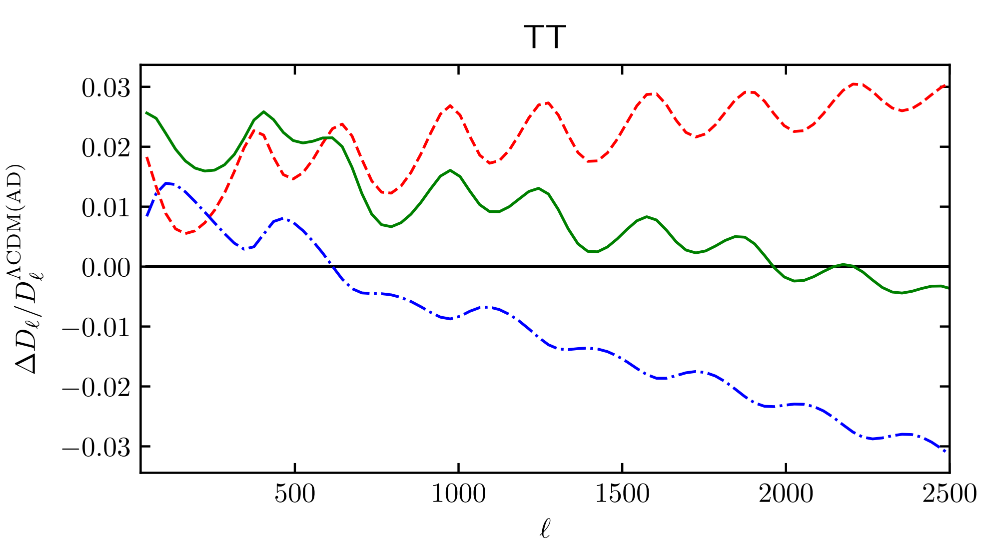


Isocurvature accommodate larger $N_{\rm eff}$ ($\equiv N_{\rm tot}$)



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 variables

New parameter w.r.t. ΛCDM: $P_{II}^{(1)}, P_{II}^{(2)}, N_{\rm dr}, N_{\rm ur}$

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Neutrino energy density

Isocurvature initial conditions

$$\delta_\gamma, \theta_\gamma, h, \eta \propto \frac{R_{\rm dr}}{1 - R_{\rm dr}} \approx R_{\rm dr} \propto N_{\rm dr}$$

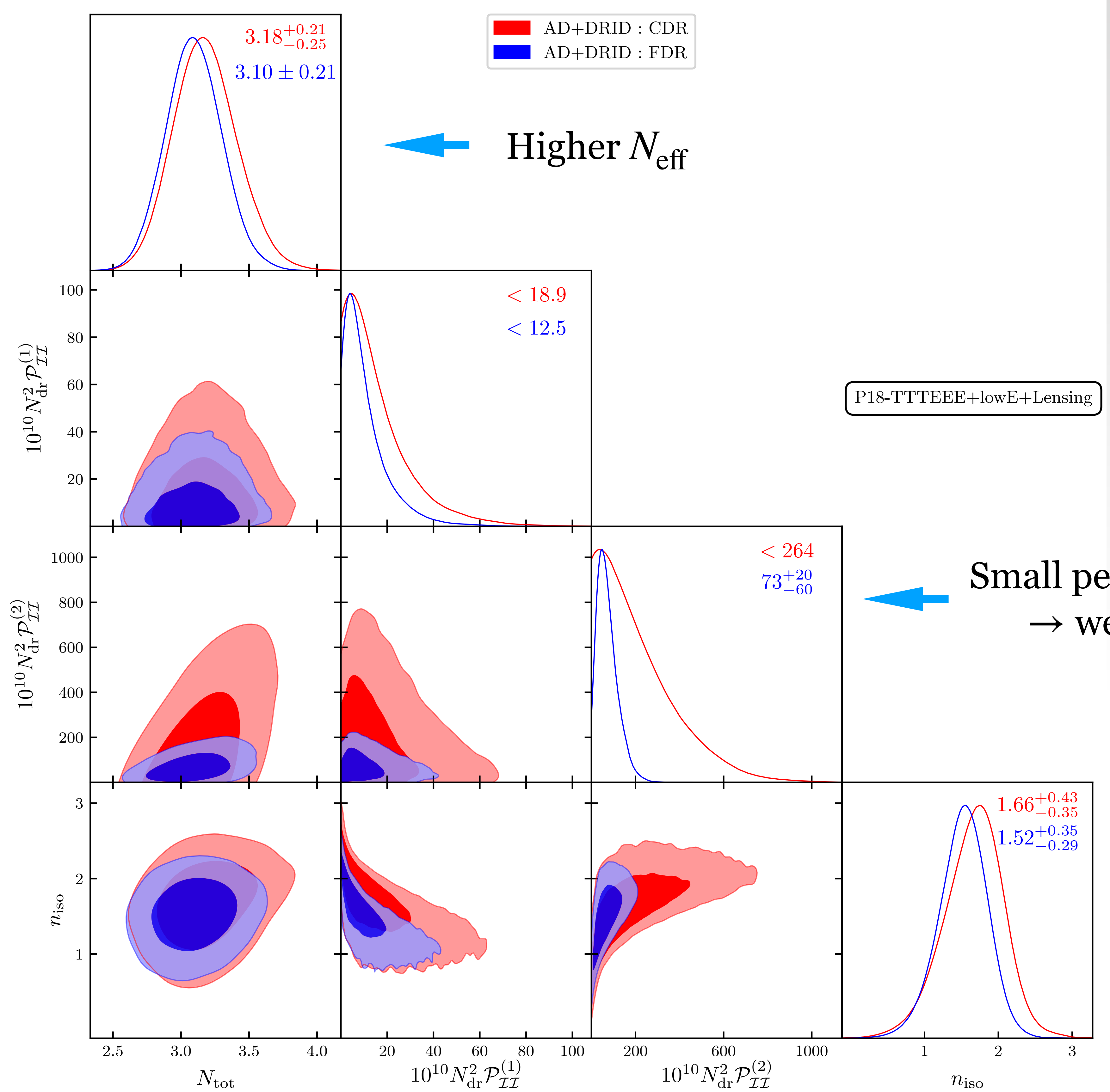
↓

C_ℓ (DRID) $\propto A_{\rm iso} N_{\rm dr}^2$

Physical isocurvature parameters: $N_{\rm dr}^2 P_{II}^{(1)}$ and $N_{\rm dr}^2 P_{II}^{(2)}$

Parameters used for MCMC runs: $N_{\rm dr}^2 P_{II}^{(1)}, N_{\rm dr}^2 P_{II}^{(2)}, N_{\rm dr}, N_{\rm ur}$

MCMC results



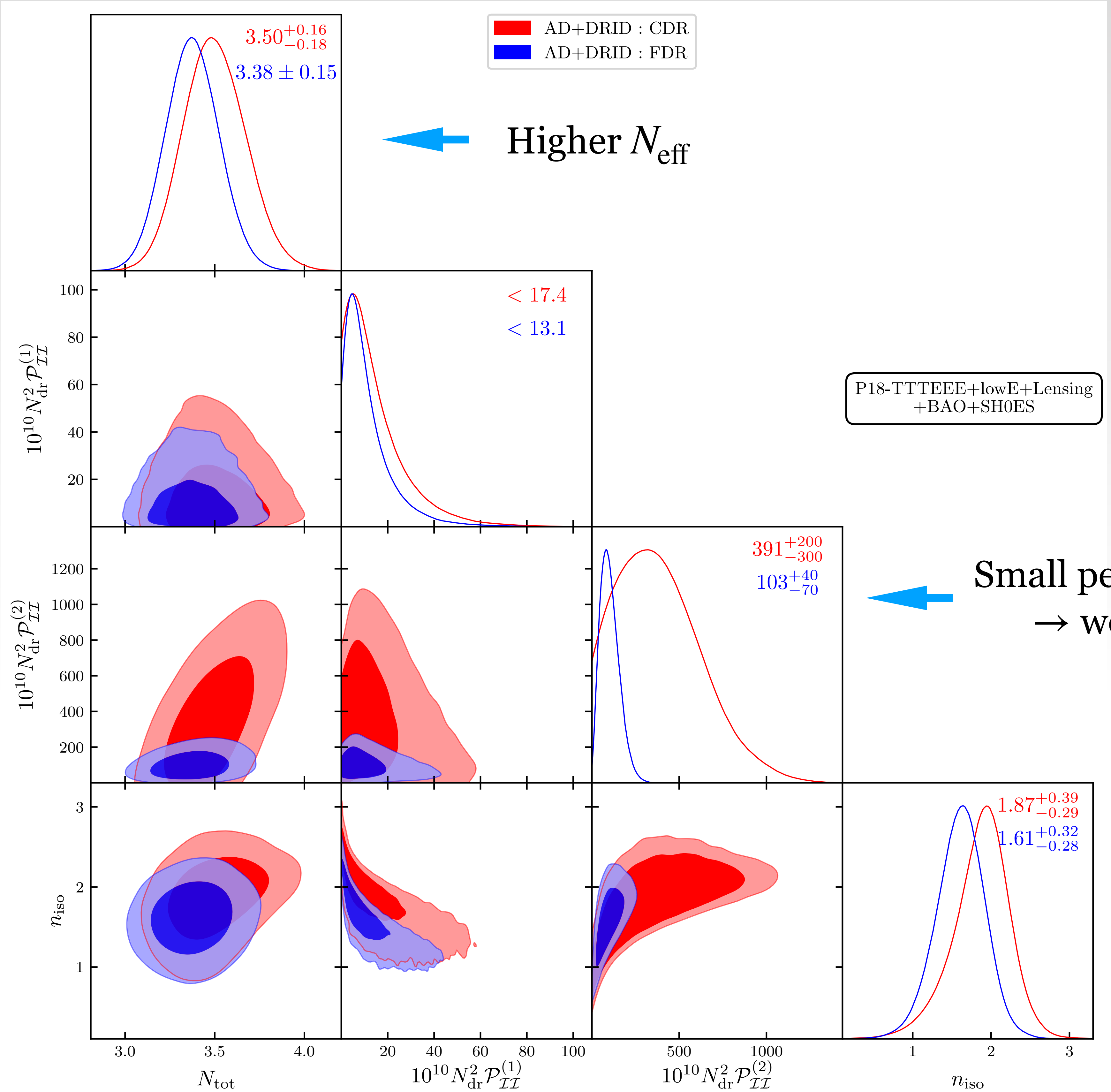
Higher $N_{\rm eff}$

Small perturbation in CDR
→ weak constraints

Blue tilt

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

MCMC results

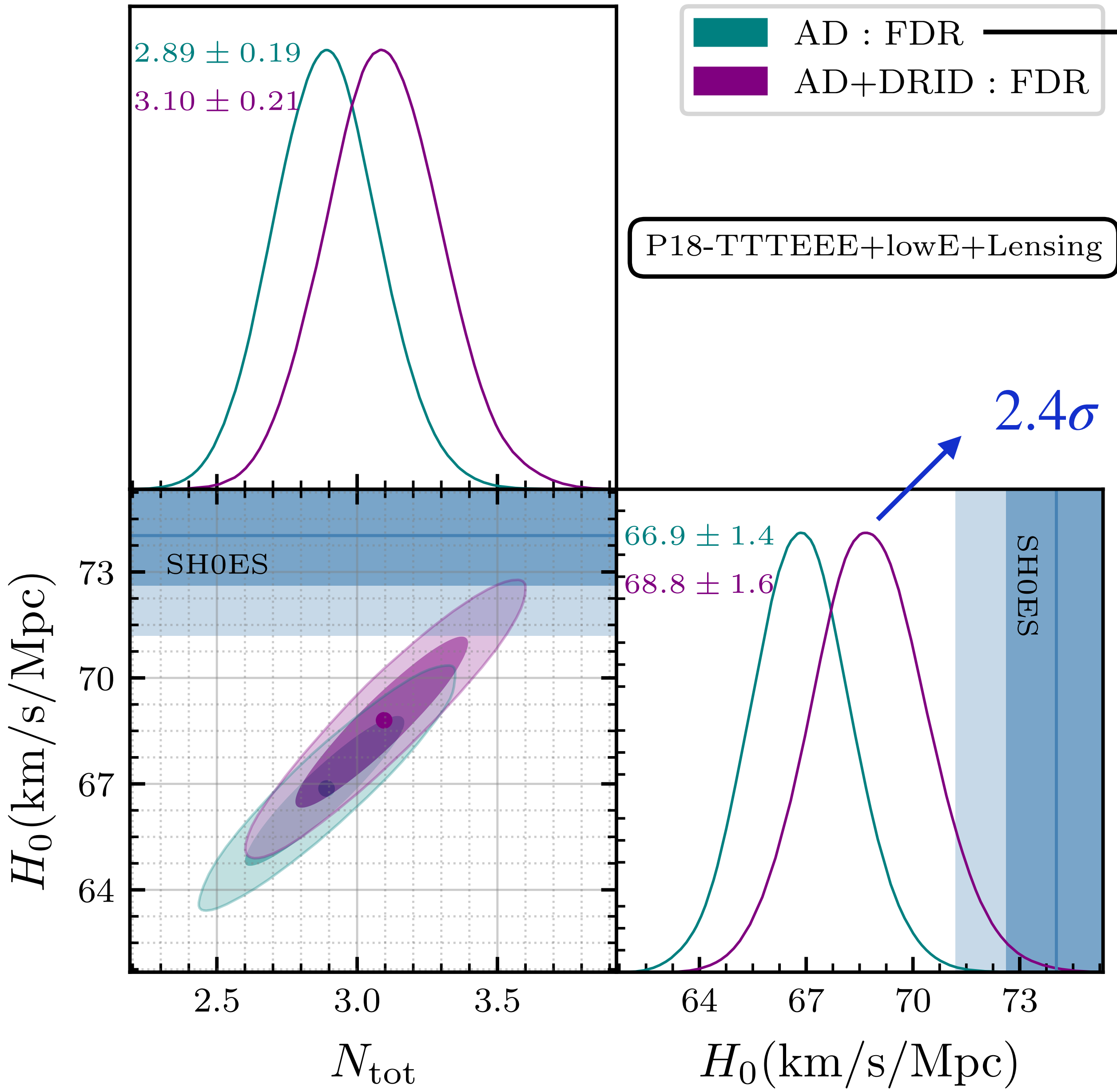


Higher $N_{\rm eff}$

Small perturbation in CDR $\rightarrow$ weak constraints

Blue tilt

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

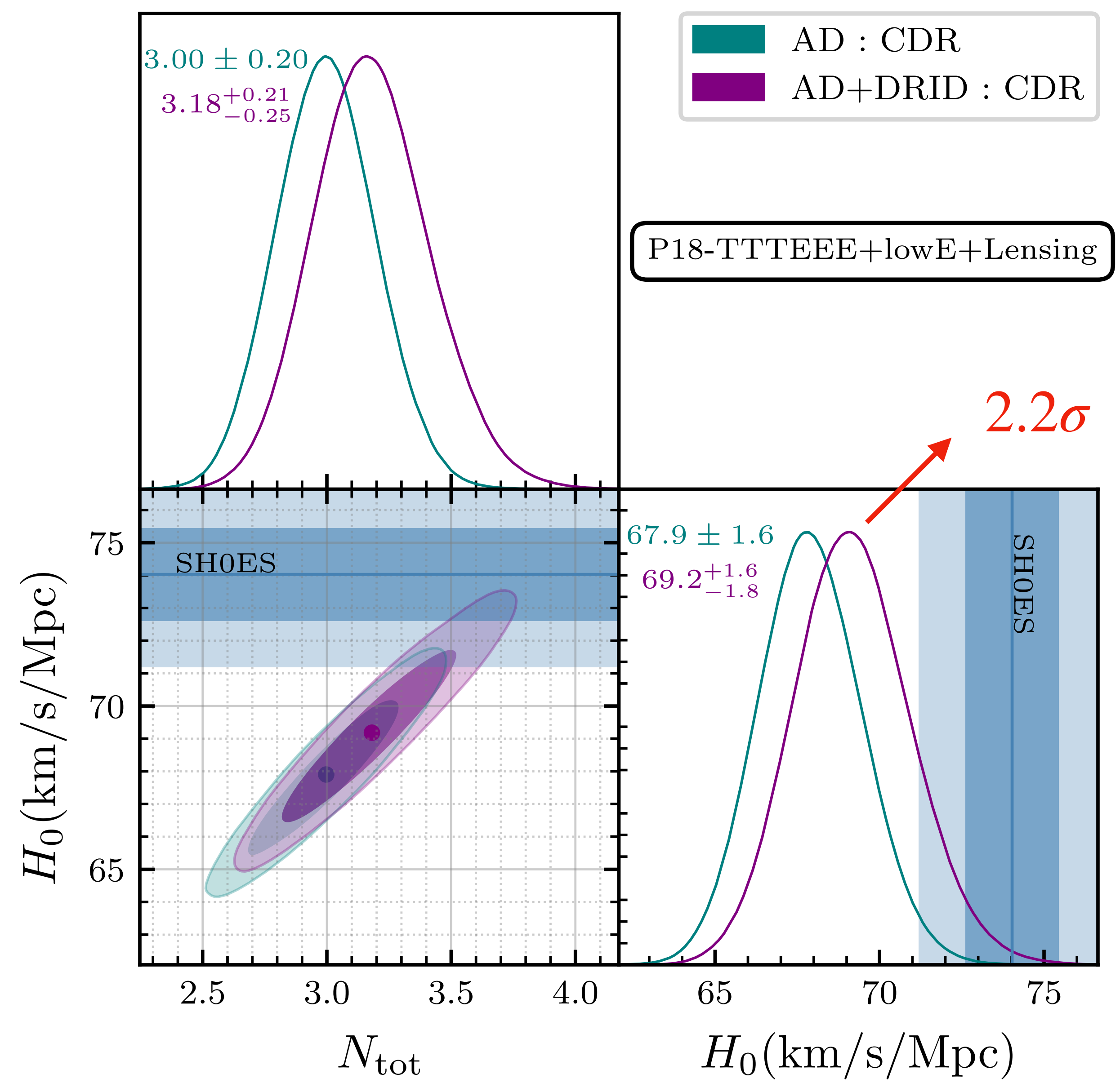


→ ΛCDM with varying $N_{\rm eff}$

Hubble Tension : Discrepancy between CMB and local determination of H_0

2.4σ

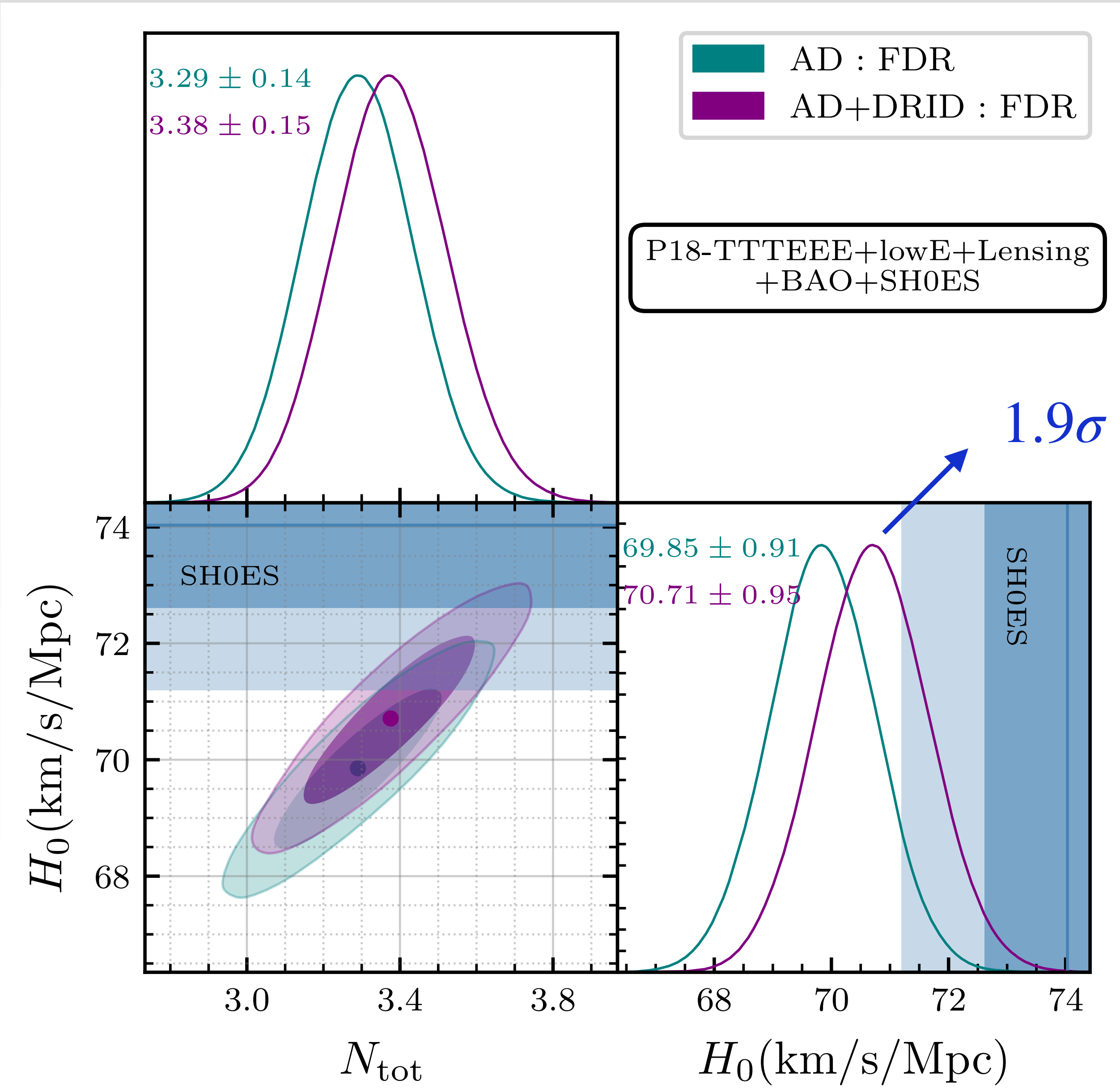
2.2σ

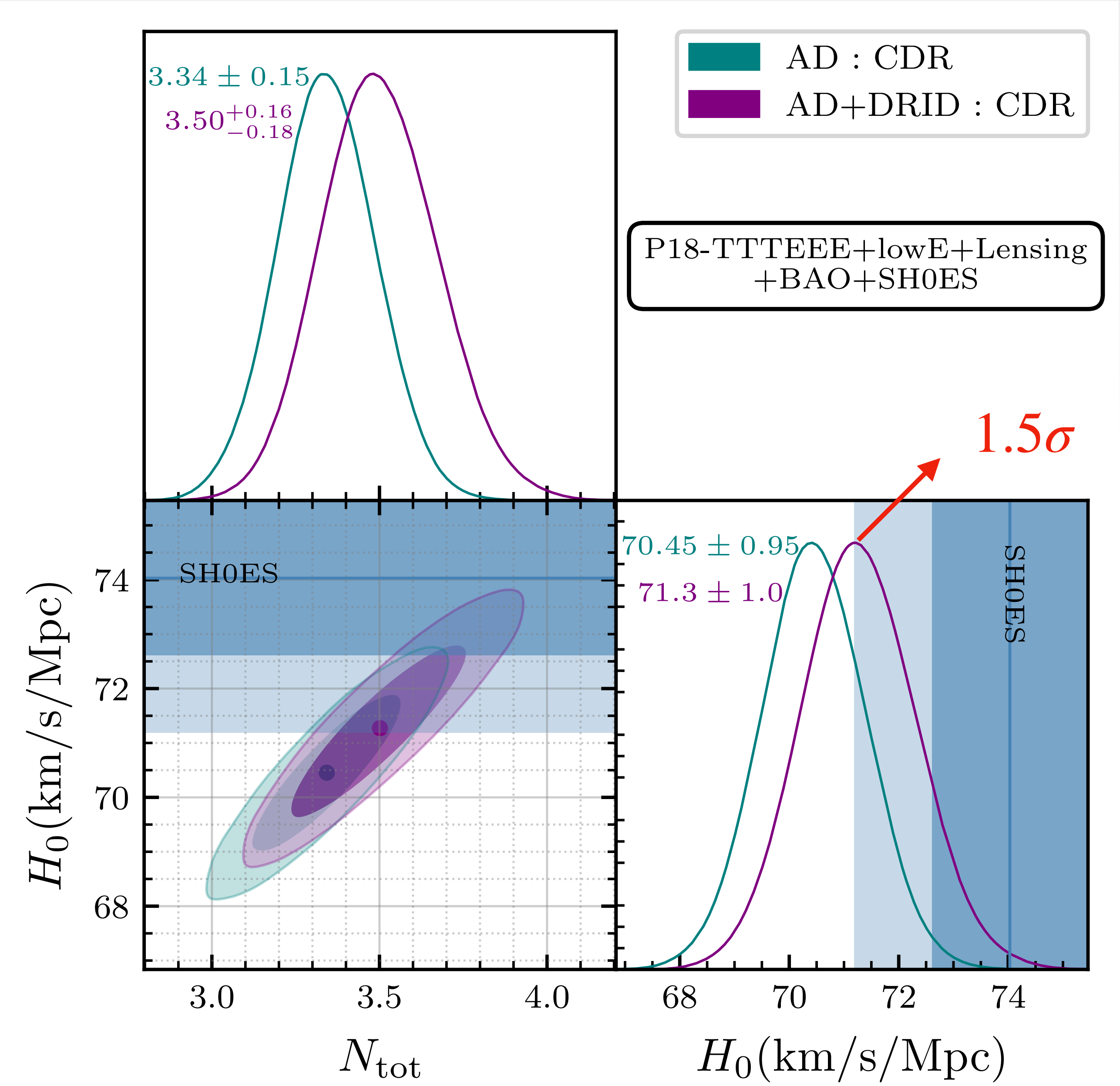


H_0 (SH0ES) = 74.03 ± 1.42 km/s/Mpc

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: $N^2_{\rm dr}P^{(1)}_{II}, N^2_{\rm dr}P^{(2)}_{II}, N_{\rm dr}, N_{\rm ur}$

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

AIC -ve : Model preferred

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: $N^2_{\rm dr} P^{(1)}_{II}, N^2_{\rm dr} P^{(2)}_{II}, N_{\rm dr}, N_{\rm ur}$

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

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Constraint on isocurvature parameters

$$\frac{\delta\sigma}{\sigma} \lesssim 2\times10^{-4}$$

Isocurvature constraints at 95 % C.L.

	Planck	Planck +BAO+ SHoES
FDR	$\leq 2\times10^{-8}$	$\leq 2.2\times10^{-8}$
CDR	$\leq 6\times10^{-8}$	$\leq 10\times10^{-8}$

$$\frac{\delta\sigma}{\sigma} \lesssim 5\times10^{-4}$$

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
- First bound on CDR Isocurvature
- Blue tilted isocurvature accommodates a larger Hubble constant
- For CDR isocurvature - the Hubble tension is reduced to 1.5σ

THANK YOU