Free-streaming and Coupled Dark Radiation Isocurvature Perturbations

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Overview

Dark Radiation (DR) Isocurvature

↓

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

↓

Bounds from Cosmological Datasets

↓

Implication for the Hubble tension

Motivation: 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**

Implication for the Hubble Tension

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

Additional variables to define the initial Isocurvature power spectrum

Isocurvature parameters

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

$n_{\rm iso}$

→ Or

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

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

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

Additional parameters

$N_{\rm dr}$ → Amount of Dark Radiation

$N_{\rm ur}$ → Amount of Neutrinos

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

Two Scale parametrization

$A_{\rm iso}(k_*)$ ⟶ Amplitude at the pivot scale k_*

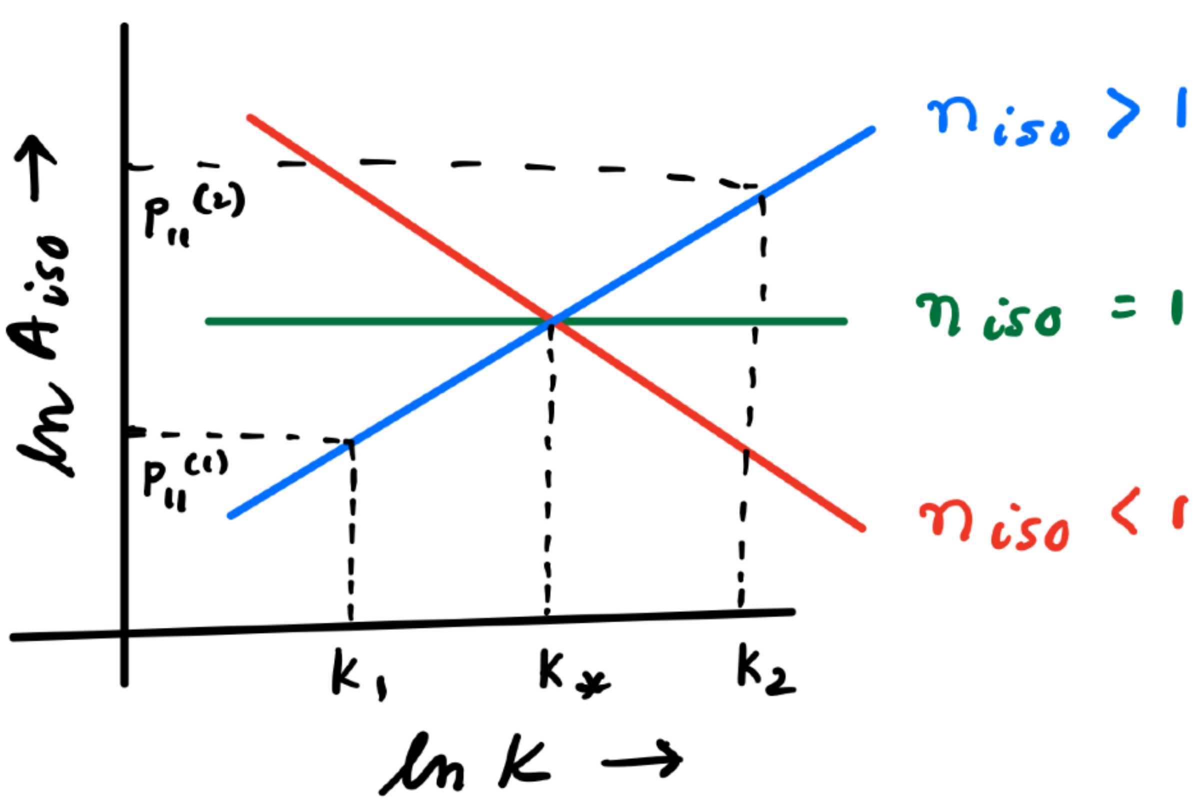
$n_{\rm iso}$ ⟶ Tilt

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

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

$$A_{\rm iso} = \mathcal{P}_{\mathcal{II}}^{(1)} \exp\left[(n_{\rm iso}-1)\ln\left(\frac{k_*}{k_1}\right)\right]$$

$$n_{\rm iso} = 1 + \frac{\ln \mathcal{P}_{\mathcal{II}}^{(1)} - \ln \mathcal{P}_{\mathcal{II}}^{(2)}}{\ln k_1 - \ln k_2}$$



Isocurvature Perturbation studies with CMB

Planck Collaboration

Baryon Isocurvature

CDM Isocurvature

Neutrino Isocurvature

Akrami et. al., arXiv:1807.06211

generalized

FDR Isocurvature

CDR Isocurvature

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

DR $\rightarrow$ Adiabatic + Isocurvature
Neutrinos $\rightarrow$ Adiabatic

Recipe

Derive DR Isocurvature initial conditions

↓

Calculate the effects on the CMB spectrum (Using CLASS)

↓

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

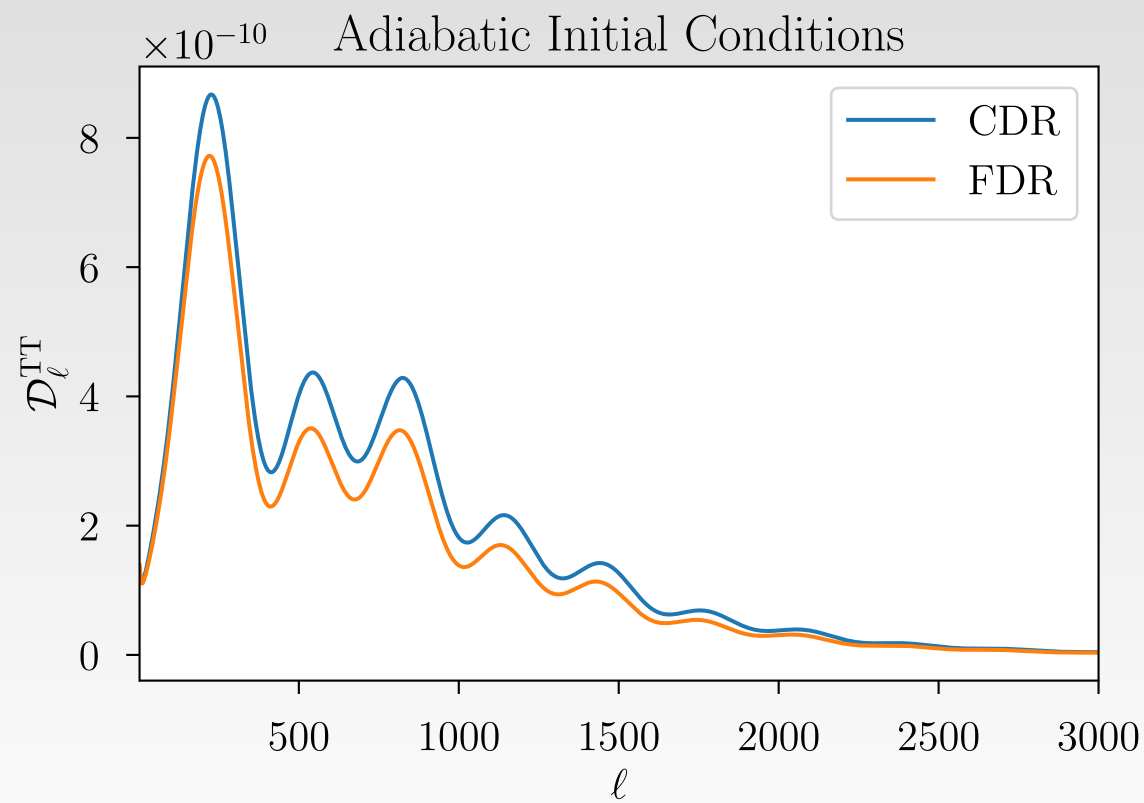
FDR - Isocurvature

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



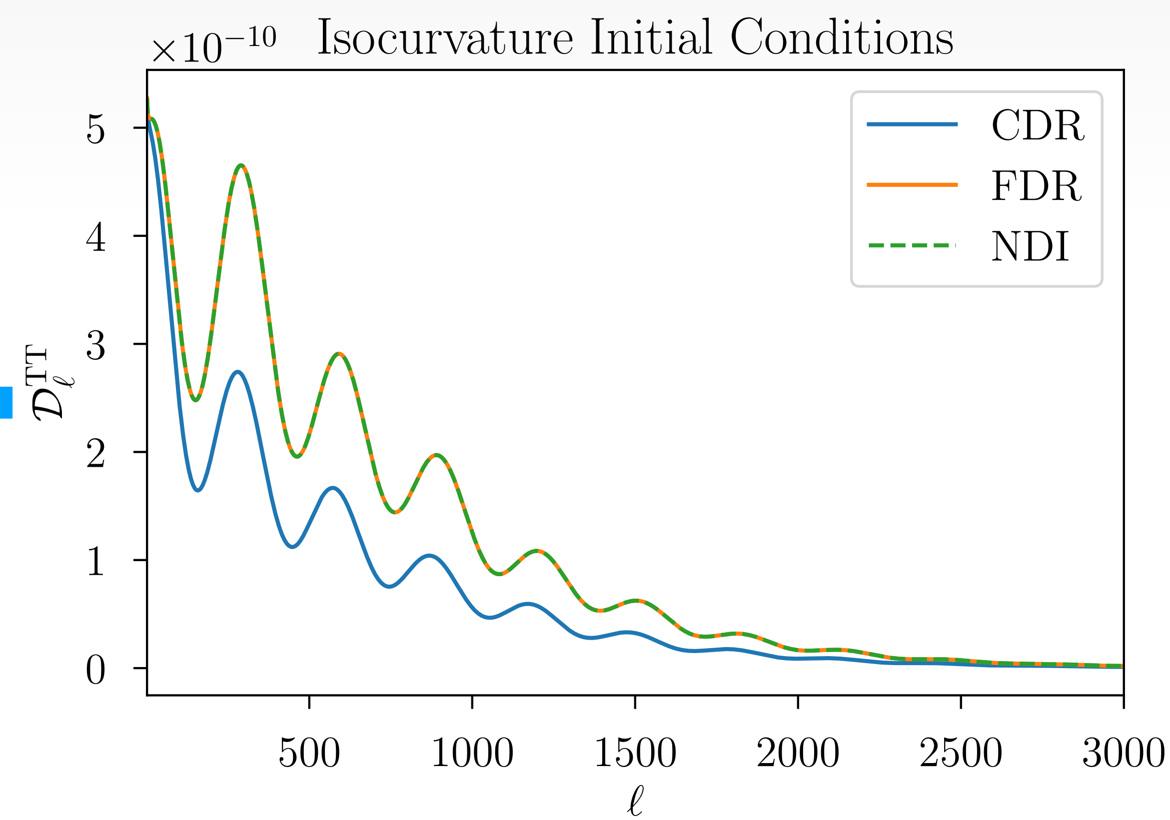
Adiabatic : $\delta_\gamma = \delta_\nu = \delta_{DR}$

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: $\phi + \psi = -\frac{2\sigma}{(k\tau)^2}$

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

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

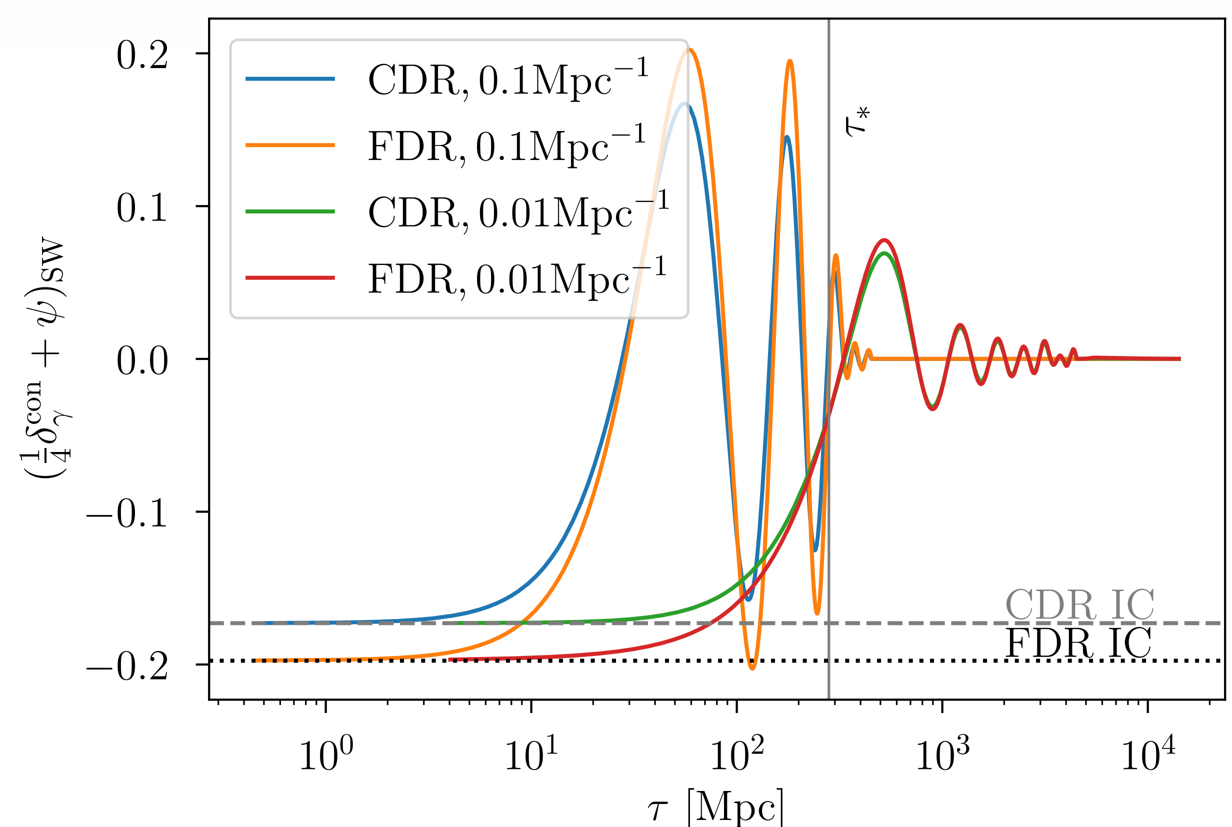
Metric potential affects CMB via Sachs - Wolfe redshifting: $\frac{1}{4}\delta_\gamma^{con} + \psi = \xi_\gamma + \phi + \psi$

Gauge invariant photon perturbation

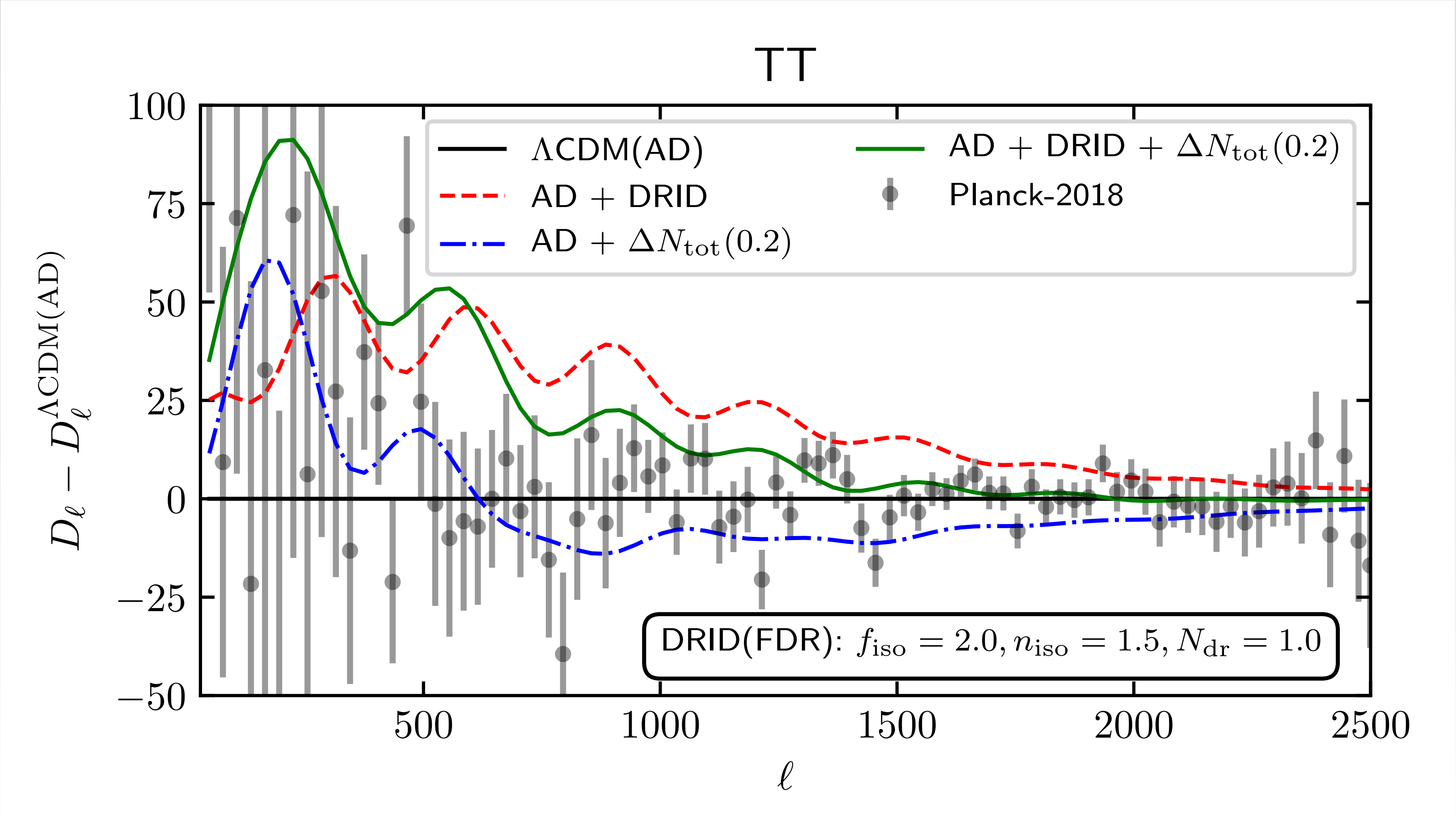
Isocurvature initial condition: $\xi_\gamma \approx \delta_\gamma < 0$

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

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

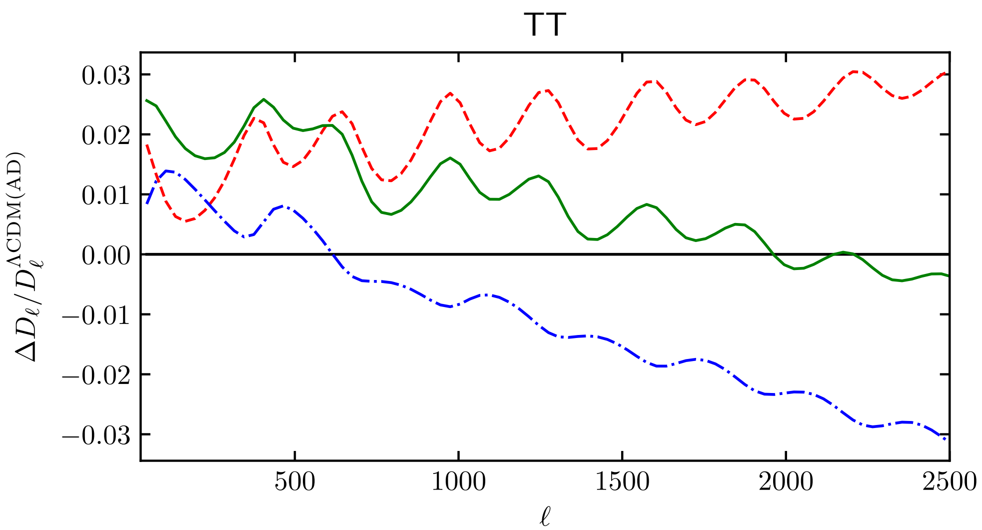


Isocurvature accommodate larger N_{eff} ($\equiv N_{\text{tot}}$)



SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

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



DRID ≡ Dark Radiation density Isocurvature

MCMC variables

New parameter w.r.t. ΛCDM

Fixed $N_{\rm ur}(=3.046)$ [FN] → $P_{II}^{(1)}, P_{II}^{(2)}, N_{\rm dr}$ → 3 new parameters

Varying $N_{\rm ur}$ [VN] → $P_{II}^{(1)}, P_{II}^{(2)}, N_{\rm dr}, N_{\rm ur}$ → 4 new parameters

Isocurvature initial conditions

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

↓

$$C_\ell \text{ (DRID)} \propto A_{\rm iso} N_{\rm dr}^2$$

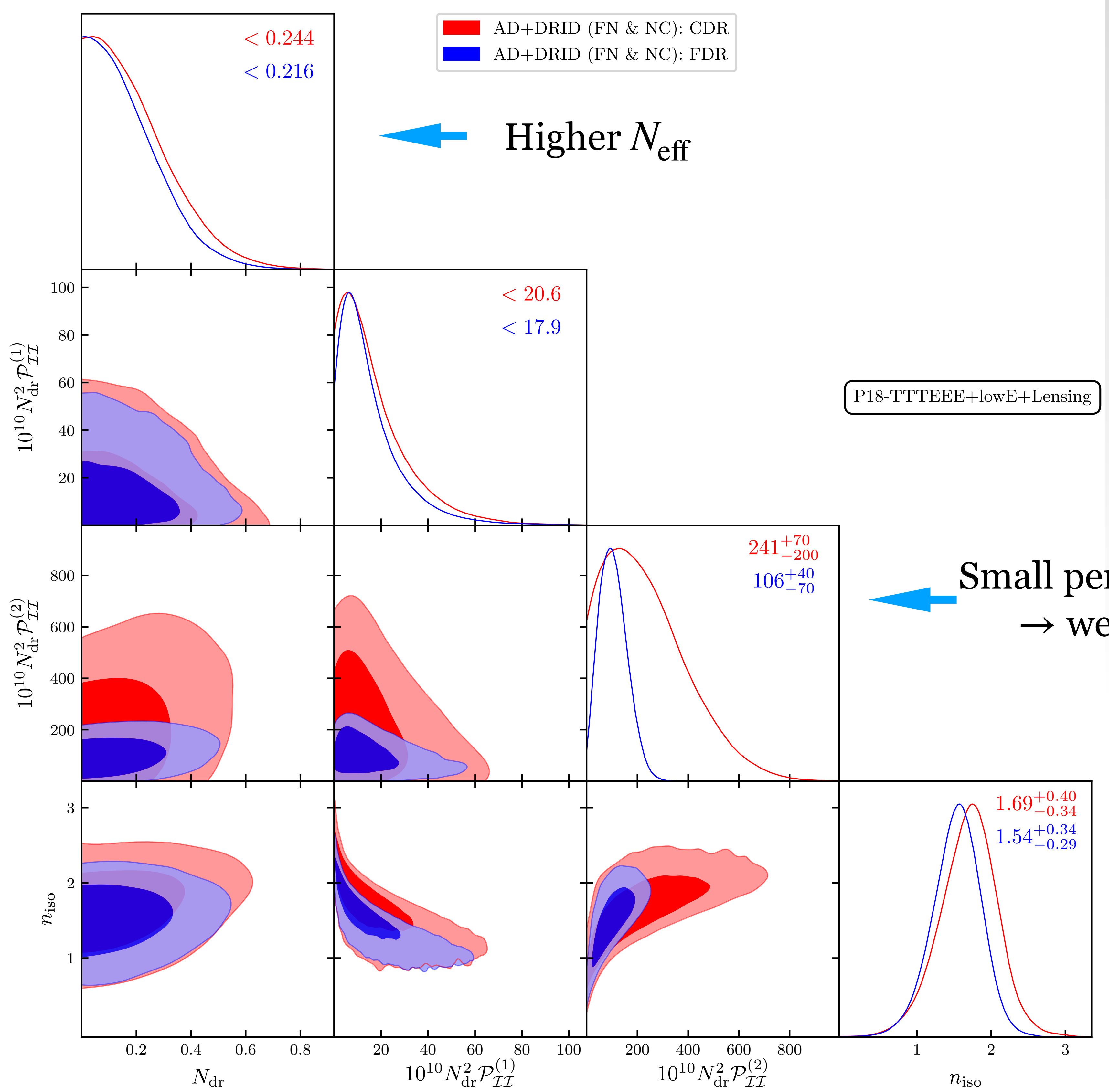
Physical isocurvature parameters: $N_{\rm dr}^2 P_{II}^{(1)}$ and $N_{\rm dr}^2 P_{II}^{(2)}$

Primary parameters used for MCMC runs

Fixed $N_{\rm ur}$ → $N_{\rm dr}^2 P_{II}^{(1)}, N_{\rm dr}^2 P_{II}^{(2)}, N_{\rm dr}$

Varying $N_{\rm ur}$ → $N_{\rm dr}^2 P_{II}^{(1)}, N_{\rm dr}^2 P_{II}^{(2)}, N_{\rm dr}, N_{\rm ur}$

MCMC results : FN - Planck



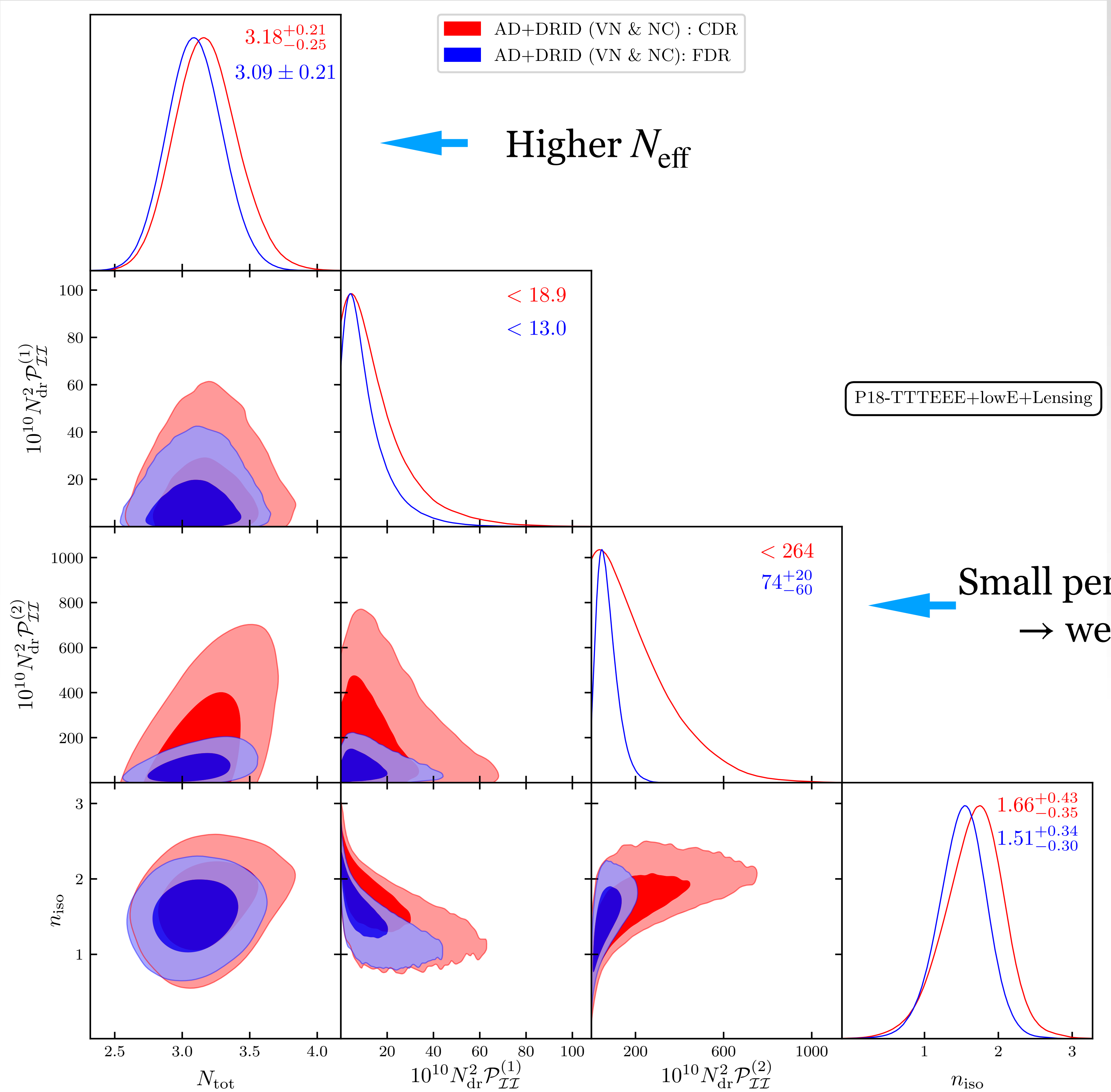
Higher $N_{\rm eff}$

Small perturbation in CDR
→ weak constraints

Blue tilt

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

MCMC results : VN - Planck



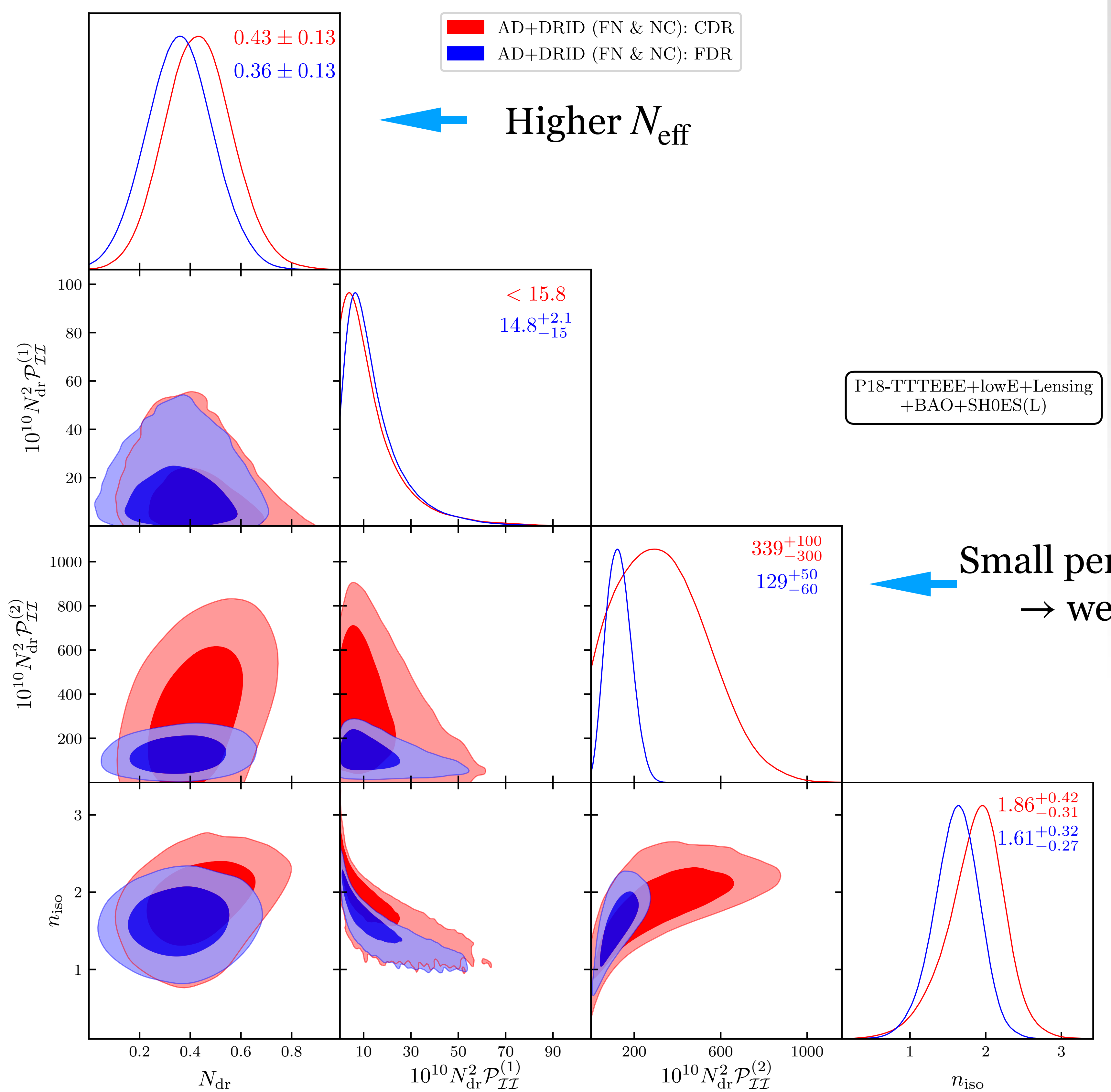
Higher $N_{\rm eff}$

Small perturbation in CDR
$\rightarrow$ weak constraints

Blue tilt

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

MCMC results : FN - Planck + BAO+ SH0ES(Latest)



Higher $N_{\rm eff}$

Small perturbation in CDR
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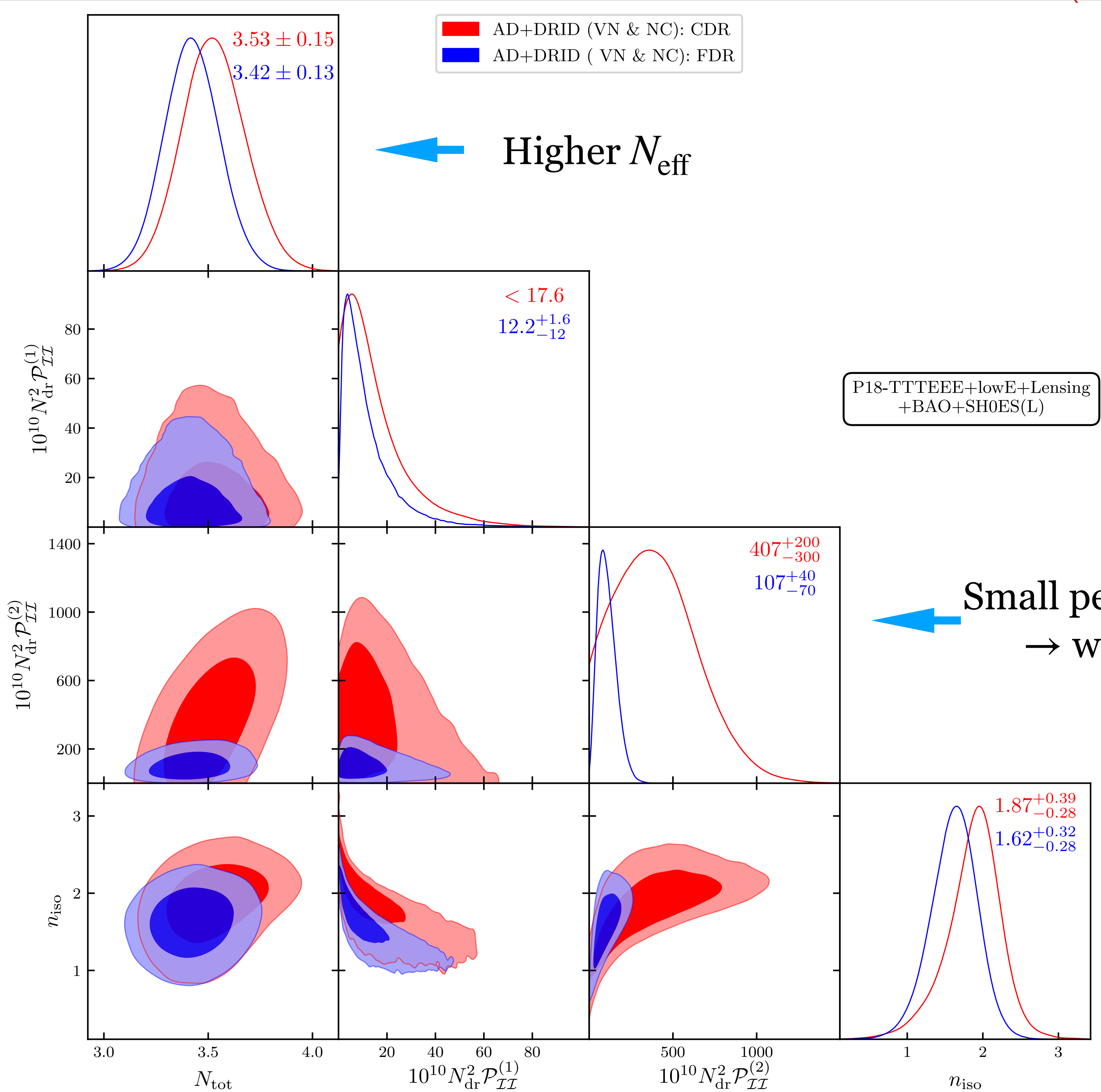
MCMC results : VN - Planck + BAO+ SH0ES(Latest)



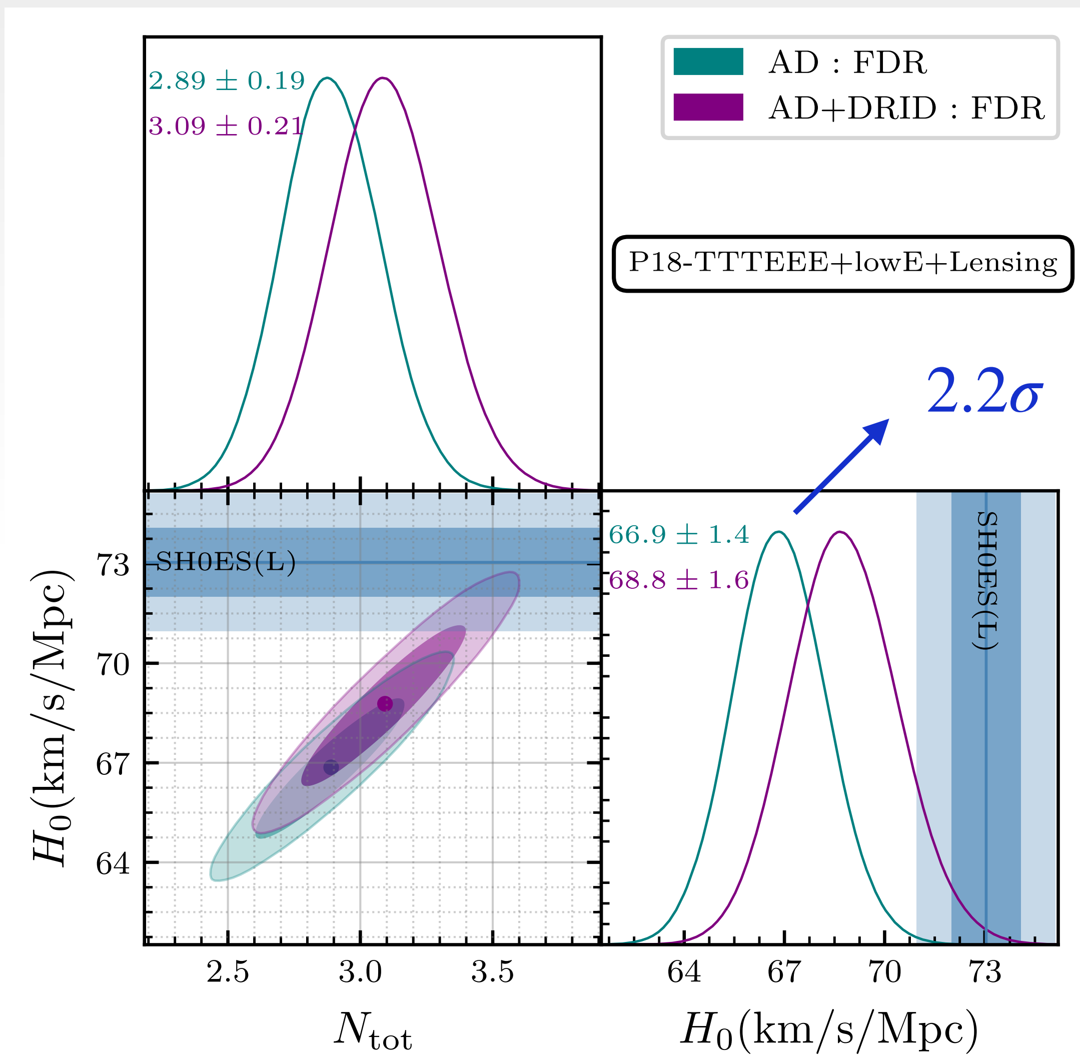
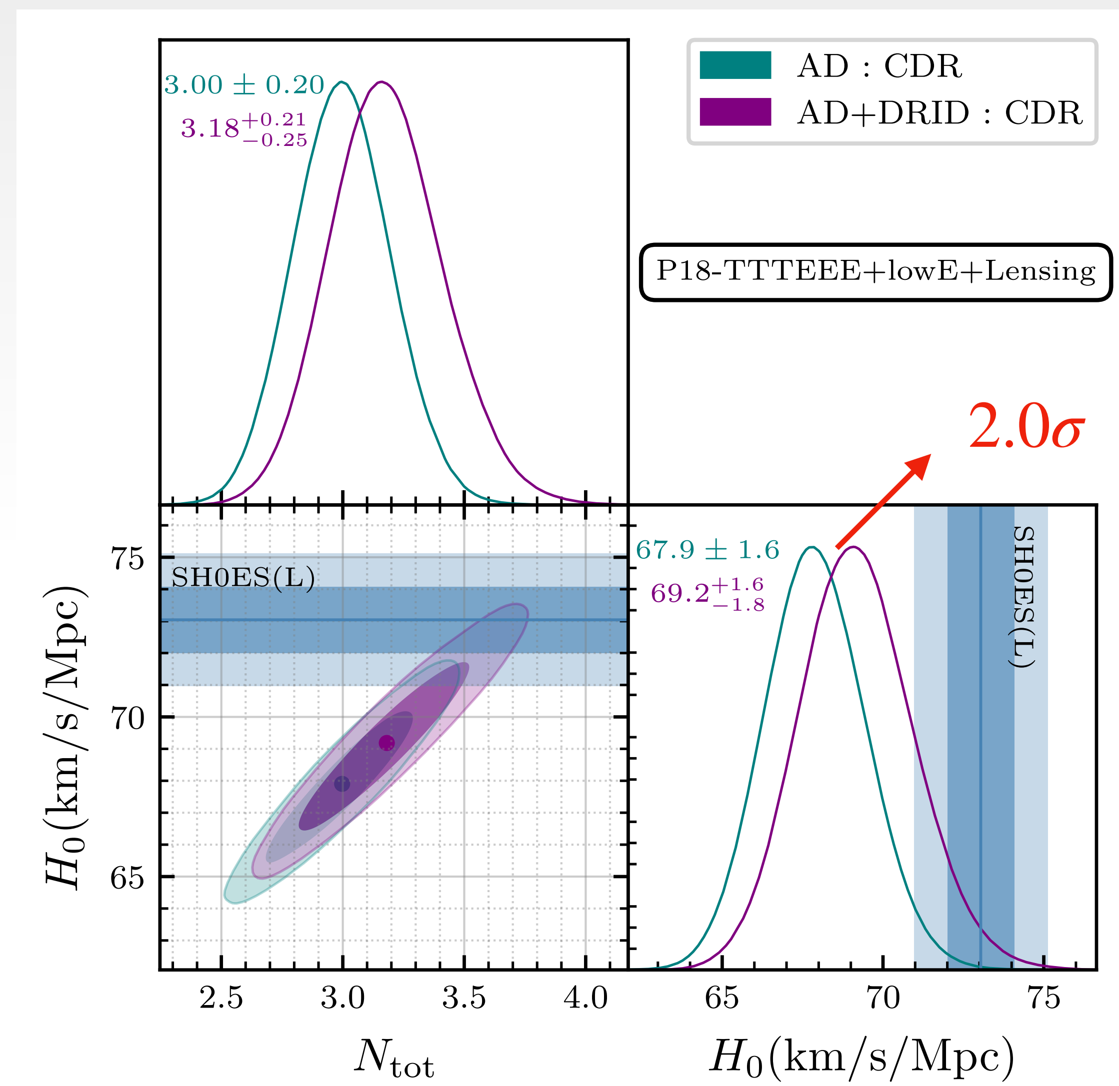
Higher $N_{\rm eff}$

Small perturbation in CDR
→ weak constraints

Blue tilt

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

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

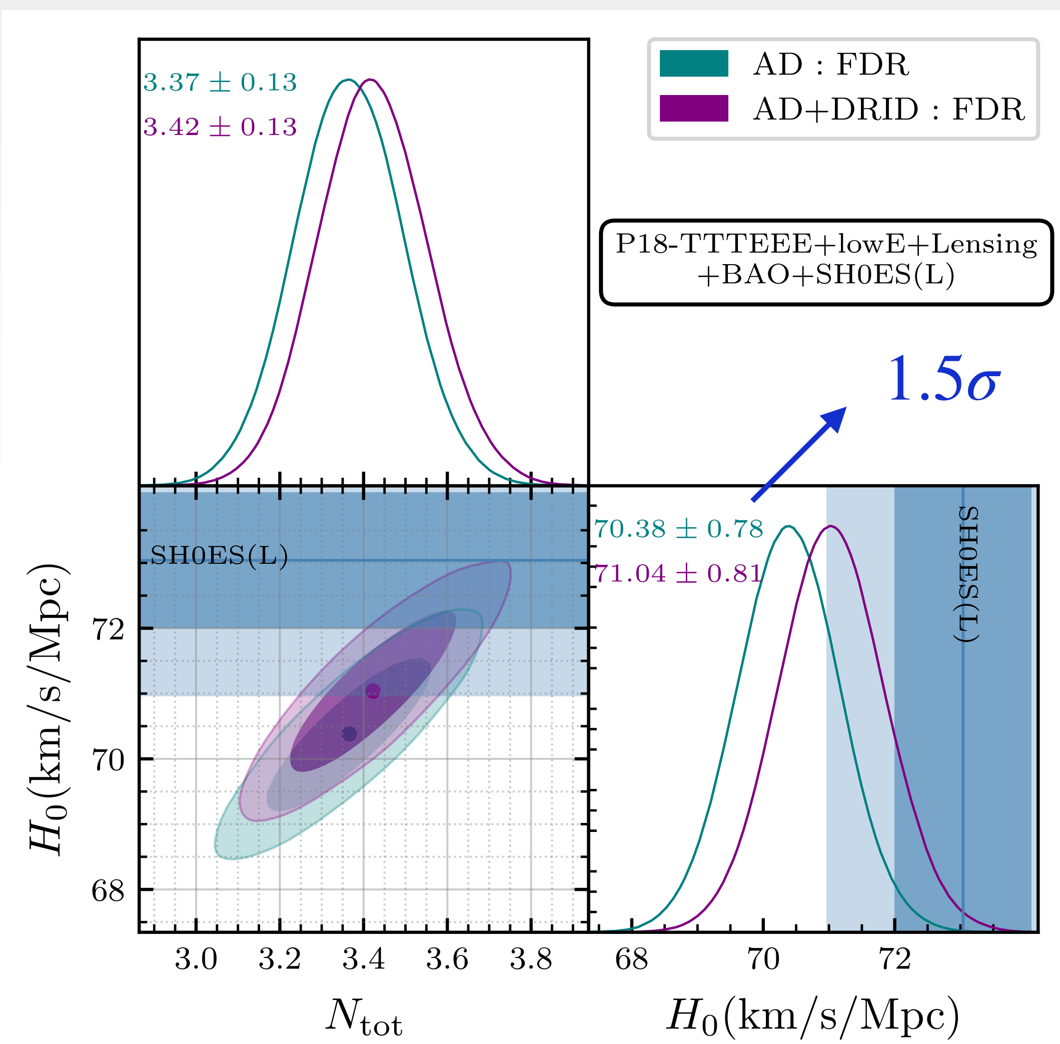
	FDR	CDR
FN	$H_0 = 69.69^{+0.82}_{-1.3}$ km/s/Mpc 2.5σ	$H_0 = 69.57^{+0.88}_{-1.5}$ km/s/Mpc 2.5σ
VN	 2.2σ	 2.0σ

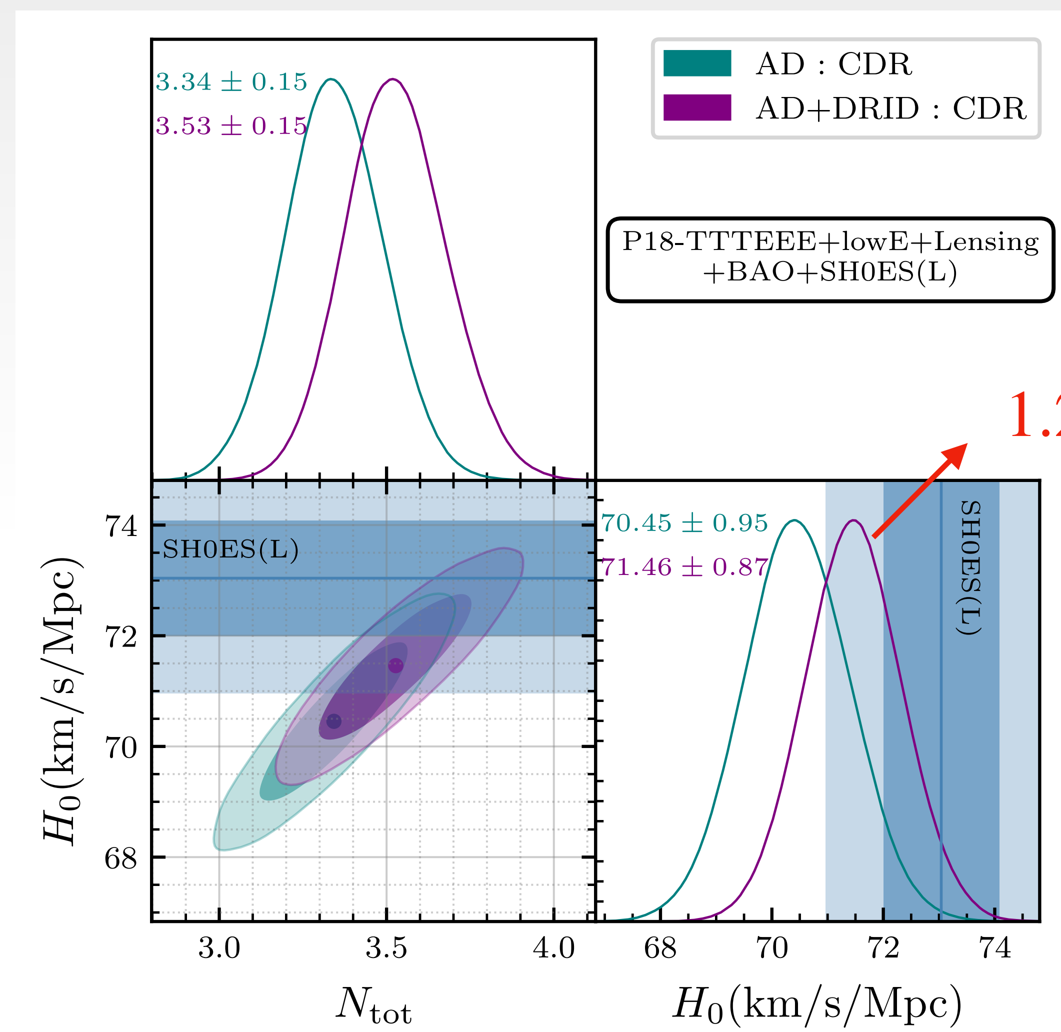
H_0 [SH0ES(L)] = 73.04 ± 1.04 km/s/Mpc

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Isocurvature accommodates larger $N_{\rm eff}$ → larger H_0 : Planck +BAO+SH0ES(L) Data

	FDR	CDR
FN	$H_0 = 70.94 \pm 0.80$ km/s/Mpc 1.6σ	$H_0 = 71.28 \pm 0.85$ km/s/Mpc 1.3σ
VN		





H_0 [SH0ES(L)] = 73.04 ± 1.04 km/s/Mpc

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Model Comparison

Planck

Planck+BAO+SHoEs

Scenario	H_0(km/s/Mpc)	GT	$\sqrt{\Delta\chi^2}$	ΔAIC
FN, FDR	$69.69^{+0.82}_{-1.3}$	2.5σ	4.0	-9.4
FN, CDR	$69.57^{+0.88}_{-1.5}$	2.5σ	4.1	-5.1
VN, FDR	$68.8^{+1.6}_{-1.6}$	2.2σ	4.4	-6.1
VN, CDR	$69.2^{+1.6}_{-1.8}$	2.0σ	4.1	-3.7

$$\mathrm{GT} \equiv \frac{\mathrm{H}_{0,\mathcal{D}} - \mathrm{H}_{0,\mathrm{SH0ES}}}{\sqrt{\sigma^2_{\mathcal{D}} + \sigma^2_{\mathrm{SH0ES}}}}$$

$$\Delta\chi^2 \equiv \chi^2_{\mathrm{min},\mathcal{D}+\mathrm{BAO}+\mathrm{SH0ES}} - \chi^2_{\mathrm{min},\mathcal{D}},$$

$$\Delta\mathrm{AIC} = \chi^2_{\mathrm{min,M}} - \chi^2_{\mathrm{min},\Lambda\mathrm{CDM}} + 2(\mathrm{N_M} - \mathrm{N}_{\Lambda\mathrm{CDM}}).$$

Schöneberg et. al., arXiv: 2107.10291

Parameter values: FDR DRID

FDR (FN & NC)	P18-TTTEEE +lowE+lensing	P18-TTTEEE+lowE+ lensing+BAO+SH0ES(L)
$10^2\omega_b$	$2.264^{+0.018}_{-0.021}$	2.281 ± 0.015
ω_{cdm}	$0.1217^{+0.0017}_{-0.0025}$	0.1245 ± 0.0025
$100\theta_s$	1.04219 ± 0.00045	1.04193 ± 0.00047
τ_{reio}	$0.0563^{+0.0070}_{-0.0079}$	0.0561 ± 0.0072
$10^{10}\mathcal{P}^{(1)}_{\mathcal{RR}}$	23.11 ± 0.49	22.83 ± 0.47
$10^{10}\mathcal{P}^{(2)}_{\mathcal{RR}}$	$20.55^{+0.35}_{-0.41}$	20.72 ± 0.36
$10^{10}N^2_{\rm dr}\mathcal{P}^{(1)}_{\mathcal{II}}$	< 17.9	$14.8^{+2.1}_{-15}$
$10^{10}N^2_{\rm dr}\mathcal{P}^{(2)}_{\mathcal{II}}$	106^{+40}_{-70}	129^{+50}_{-60}
$N_{\rm dr}$	< 0.216	0.36 ± 0.13
H_0(km/s/Mpc)	$69.69^{+0.82}_{-1.3}$	70.94 ± 0.80
σ_8	$0.8249^{+0.0075}_{-0.0087}$	0.8313 ± 0.0085
$10^9 A_s$	$2.098^{+0.031}_{-0.035}$	2.107 ± 0.032
n_s	$0.9700^{+0.0062}_{-0.0074}$	0.9752 ± 0.0062
$n_{\rm iso}$	$1.54^{+0.34}_{-0.29}$	$1.61^{+0.32}_{-0.27}$
$f_{\rm iso}$	< 18.7	< 6.52
$N_{\rm tot}$	< 3.26	3.41 ± 0.13
$f_{\rm dr}$	$0.052^{+0.022}_{-0.047}$	$0.104^{+0.036}_{-0.032}$
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	-1.94	-15.4

FDR (VN & NC)	P18-TTTEEE +lowE+lensing	P18-TTTEEE+lowE+ lensing+BAO+SH0ES(L)
$10^2\omega_b$	2.252 ± 0.025	2.282 ± 0.015
ω_{cdm}	0.1200 ± 0.0031	0.1248 ± 0.0025
$100\theta_s$	1.04241 ± 0.00052	1.04189 ± 0.00047
τ_{reio}	0.0554 ± 0.0077	0.0560 ± 0.0072
$10^{10}\mathcal{P}^{(1)}_{\mathcal{RR}}$	23.32 ± 0.55	22.80 ± 0.46
$10^{10}\mathcal{P}^{(2)}_{\mathcal{RR}}$	20.37 ± 0.44	20.73 ± 0.36
$10^{10}N^2_{\rm dr}\mathcal{P}^{(1)}_{\mathcal{II}}$	< 13.0	< 13.3
$10^{10}N^2_{\rm dr}\mathcal{P}^{(2)}_{\mathcal{II}}$	74^{+20}_{-60}	107^{+40}_{-70}
N_{ur}	$2.06^{+1.0}_{-0.50}$	$2.29^{+1.1}_{-0.49}$
$N_{\rm dr}$	< 1.32	< 1.44
H_0(km/s/Mpc)	68.8 ± 1.6	71.04 ± 0.81
σ_8	0.820 ± 0.010	0.8318 ± 0.0086
$10^9 A_s$	2.086 ± 0.037	2.108 ± 0.032
n_s	0.9655 ± 0.0090	0.9756 ± 0.0062
$n_{\rm iso}$	$1.51^{+0.34}_{-0.30}$	$1.62^{+0.32}_{-0.28}$
$f_{\rm iso}$	$14.8^{+7.8}_{-14}$	$15.0^{+7.1}_{-14}$
$N_{\rm tot}$	3.09 ± 0.21	3.42 ± 0.13
$f_{\rm dr}$	$0.33^{+0.14}_{-0.32}$	$0.33^{+0.14}_{-0.32}$
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	-3.92	-14.08

SG, Soubhik Kumar, Yuhsin Tsai: arXiv:2107.09076

Parameter values: CDR DRID

CDR (FN & NC)	P18-TTTEEE +lowE+lensing	P18-TTTEEE+lowE+ lensing+BAO+SH0ES(L)
$10^2\omega_b$	$2.262^{+0.019}_{-0.024}$	2.286 ± 0.016
ω_{cdm}	$0.1228^{+0.0018}_{-0.0030}$	0.1268 ± 0.0028
$100\theta_s$	$1.04230^{+0.00034}_{-0.00038}$	1.04260 ± 0.00034
τ_{reio}	$0.0562^{+0.0070}_{-0.0080}$	$0.0568^{+0.0066}_{-0.0075}$
$10^{10}\mathcal{P}^{(1)}_{\mathcal{RR}}$	23.32 ± 0.47	23.19 ± 0.47
$10^{10}\mathcal{P}^{(2)}_{\mathcal{RR}}$	20.33 ± 0.35	20.22 ± 0.36
$10^{10}N^2_{\rm dr}\mathcal{P}^{(1)}_{\mathcal{II}}$	< 20.6	< 15.8
$10^{10}N^2_{\rm dr}\mathcal{P}^{(2)}_{\mathcal{II}}$	241^{+70}_{-200}	339^{+100}_{-300}
$N_{\rm dr}$	< 0.244	0.43 ± 0.13
H_0(km/s/Mpc)	$69.57^{+0.88}_{-1.5}$	71.28 ± 0.85
σ_8	0.8237 ± 0.0069	0.8270 ± 0.0069
$10^9 A_s$	2.083 ± 0.032	2.072 ± 0.032
n_s	$0.9649^{+0.0062}_{-0.0056}$	$0.9650^{+0.0071}_{-0.0055}$
$n_{\rm tot}$	$1.69^{+0.40}_{-0.34}$	$1.86^{+0.42}_{-0.31}$
$f_{\rm tot}$	< 22.4	$7.1^{+1.7}_{-3.2}$
$N_{\rm tot}$	< 3.29	3.48 ± 0.13
$f_{\rm dr}$	$0.059^{+0.024}_{-0.052}$	0.123 ± 0.034
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	1.34	−11.06

CDR (VN & NC)	P18-TTTEEE +lowE+lensing	P18-TTTEEE+lowE+ lensing+BAO+SH0ES(L)
$10^2\omega_b$	2.257 ± 0.026	2.287 ± 0.016
ω_{cdm}	$0.1220^{+0.0033}_{-0.0038}$	$0.1276^{+0.0028}_{-0.0032}$
$100\theta_s$	$1.04258^{+0.00061}_{-0.00073}$	$1.04226^{+0.00063}_{-0.00081}$
τ_{reio}	$0.0561^{+0.0071}_{-0.0081}$	0.0565 ± 0.0072
$10^{10}\mathcal{P}^{(1)}_{\mathcal{RR}}$	23.45 ± 0.55	23.11 ± 0.50
$10^{10}\mathcal{P}^{(2)}_{\mathcal{RR}}$	20.19 ± 0.46	20.35 ± 0.45
$10^{10}N^2_{\rm dr}\mathcal{P}^{(1)}_{\mathcal{II}}$	< 18.9	< 17.6
$10^{10}N^2_{\rm dr}\mathcal{P}^{(2)}_{\mathcal{II}}$	< 264	407^{+200}_{-300}
N_{ur}	2.94 ± 0.25	$3.18^{+0.27}_{-0.22}$
$N_{\rm dr}$	< 0.304	$0.35^{+0.15}_{-0.27}$
H_0(km/s/Mpc)	$69.2^{+1.6}_{-1.8}$	71.46 ± 0.87
σ_8	0.820 ± 0.011	0.8304 ± 0.0092
$10^9 A_s$	2.073 ± 0.039	2.081 ± 0.038
n_s	0.9617 ± 0.0090	$0.9675^{+0.0086}_{-0.0075}$
$n_{\rm iso}$	$1.66^{+0.43}_{-0.35}$	$1.87^{+0.39}_{-0.28}$
$f_{\rm iso}$	58^{+22}_{-53}	$31.7^{+6.7}_{-27}$
$N_{\rm tot}$	$3.18^{+0.21}_{-0.25}$	3.53 ± 0.15
$f_{\rm dr}$	$0.076^{+0.031}_{-0.068}$	$0.098^{+0.041}_{-0.074}$
$\chi^2 - \chi^2_{\Lambda\rm CDM}$	0.8	−11.68

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

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

Conclusion

- 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 2.0σ

THANK YOU