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Motivations

- Neutrino oscillations prove that there is a mass mixing matrix:

$$(\nu_e \;\; \nu_\mu \;\; \nu_\tau)\begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \Rightarrow \text{propagating mass eigenstates}$$

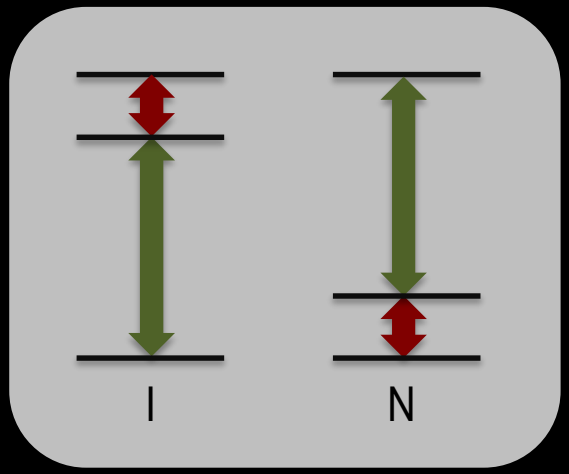
flavor eigenstates

$m_1, m_2, m_3, \theta_{12}, \theta_{23}, \theta_{13}, \delta$

Right-handed (Dirac) or self-conjugate (Majorana)

- Laboratory experiments measured:
  - 2 squared mass differences, 3 angles , bounds on phase
  - One missing mass! Knowing one new combination would fix everything (maybe up to ordering option) …

- Normal and inverted hierarchy:



$M_\nu > 0.11$ eV 0.06 eV

Motivations

… for measuring total neutrino mass M_ν with cosmology:

- For particle physicists
  - More sensitive than β- and double-β- decay (KATRIN, GERDA, …), works for Dirac and Majorana
  - Complementary to β-decay which contains independent information (on phases, angles, Dirac/Majorana…)
  - Can lead to full understanding of neutrino sector (or give hint of extensions to e.g. sterile neutrinos)
  - Hints on seesaw, leptogenesis, baryogenesis…

Motivations

… for measuring total neutrino mass M_ν with cosmology:

- For cosmologists
  - Safest output/reward of current observational efforts
  - Neglect neutrinos would bias results; e.g.:
    - neglecting >5% effect in small-scale power spectrum would point incorrectly to running, modified gravity etc…
    - At least 1% impact on H_0 value inferred from CMB (through angular diameter distance)
  - Excluding M_ν ~ 0.11eV would rule out IH
  - Excluding M_ν ~ 0.06 eV would point out at new physics or cosmology
    - Neutrinos decay or interact strangely
    - Standard neutrino decoupling does not apply (low-temperature reheating, entropy production, etc.)

Neutrino mass detection with CMB

A. Background effects :

1. for same equality redshift, peak scale, z_{reio}, change H_0, Ω_Λ: late Integrated Sachs-Wolfe, shifted τ_{reio} ,…

Constant peak angular scale: ΔH_0 / [1 km/s/Mpc] = - ΔM_ν / [0.1eV]

ΔH_0=0.6 km/s/Mpc coming from different choice of fiducial model (M_ν = 0 —> 0.06eV)

2. also small background effect on recombination history [Grohs et al. 1412.6875]

B. Perturbation effects :

3. early Integrated Sachs-Wolfe effect when neutrinos become non-relativistic at 500 < z < 1000

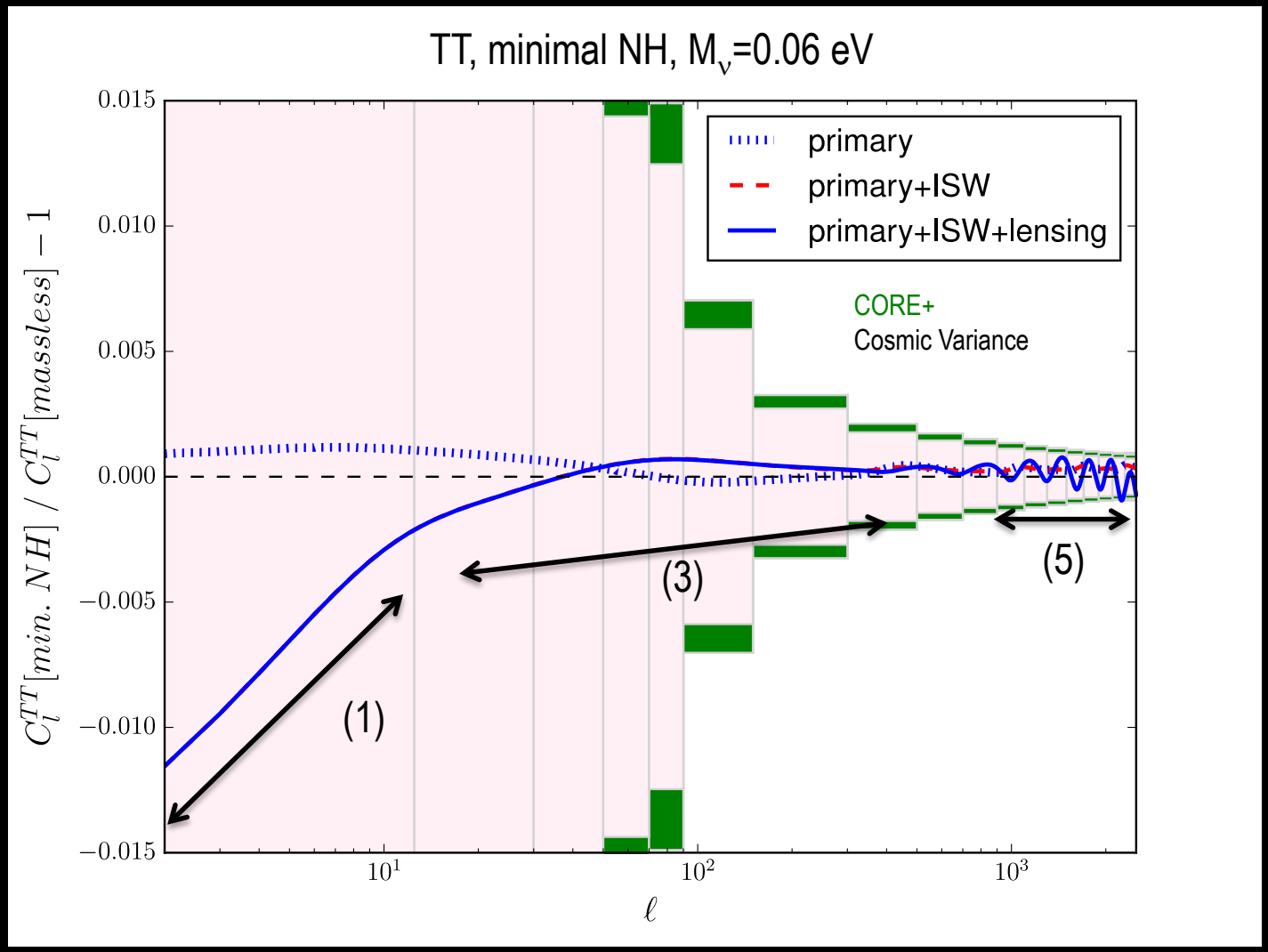
produces a feature in temperature spectrum for 10 < l < 200

4. fraction of neutrinos already non-relativistic at decoupling: slightly modified neutrino-photon gravitational interaction (very small)

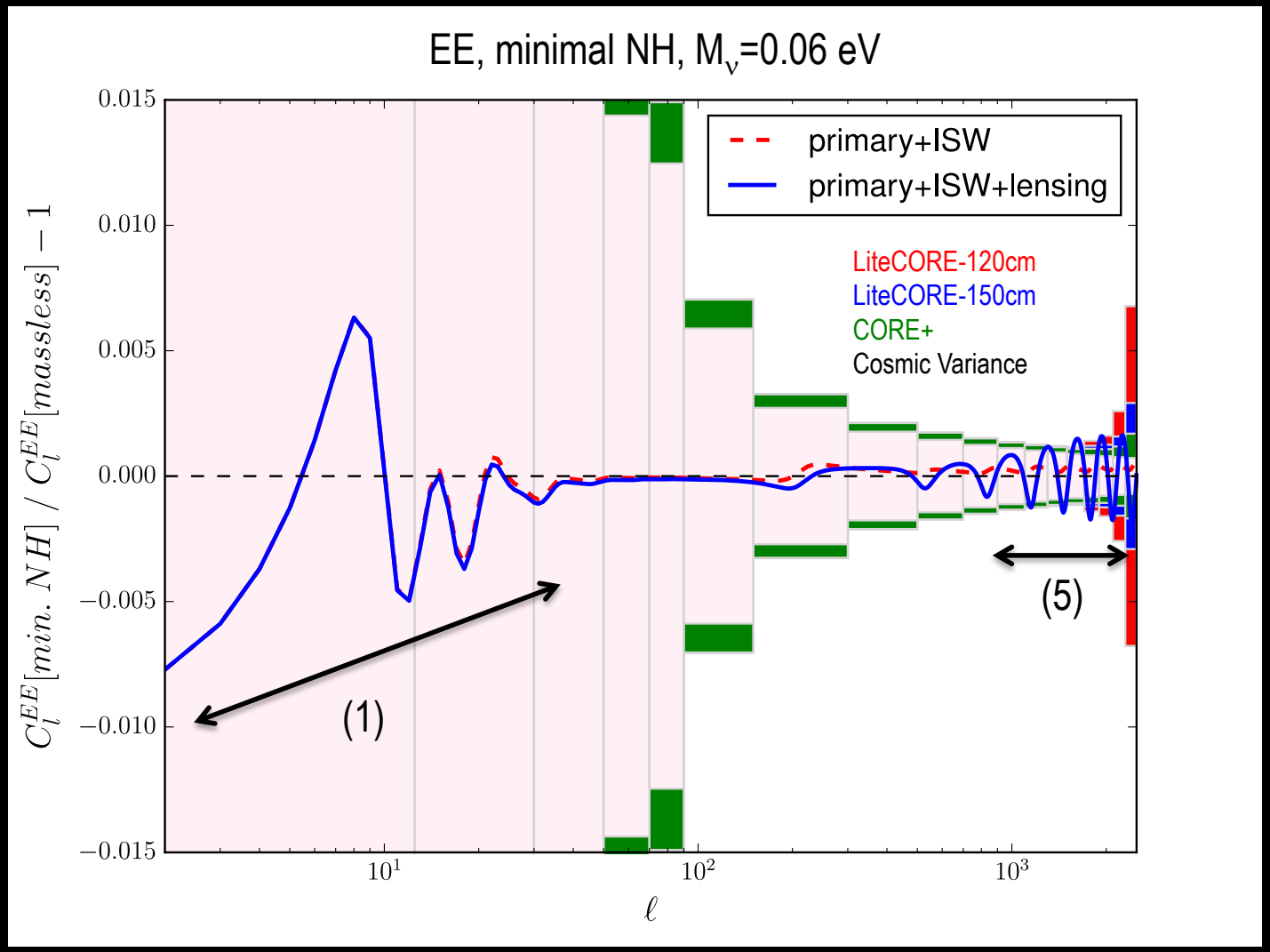
5. reduced CMB lensing (spectrum of temperature, polarisation, extracted lensing potential):

dominant effects

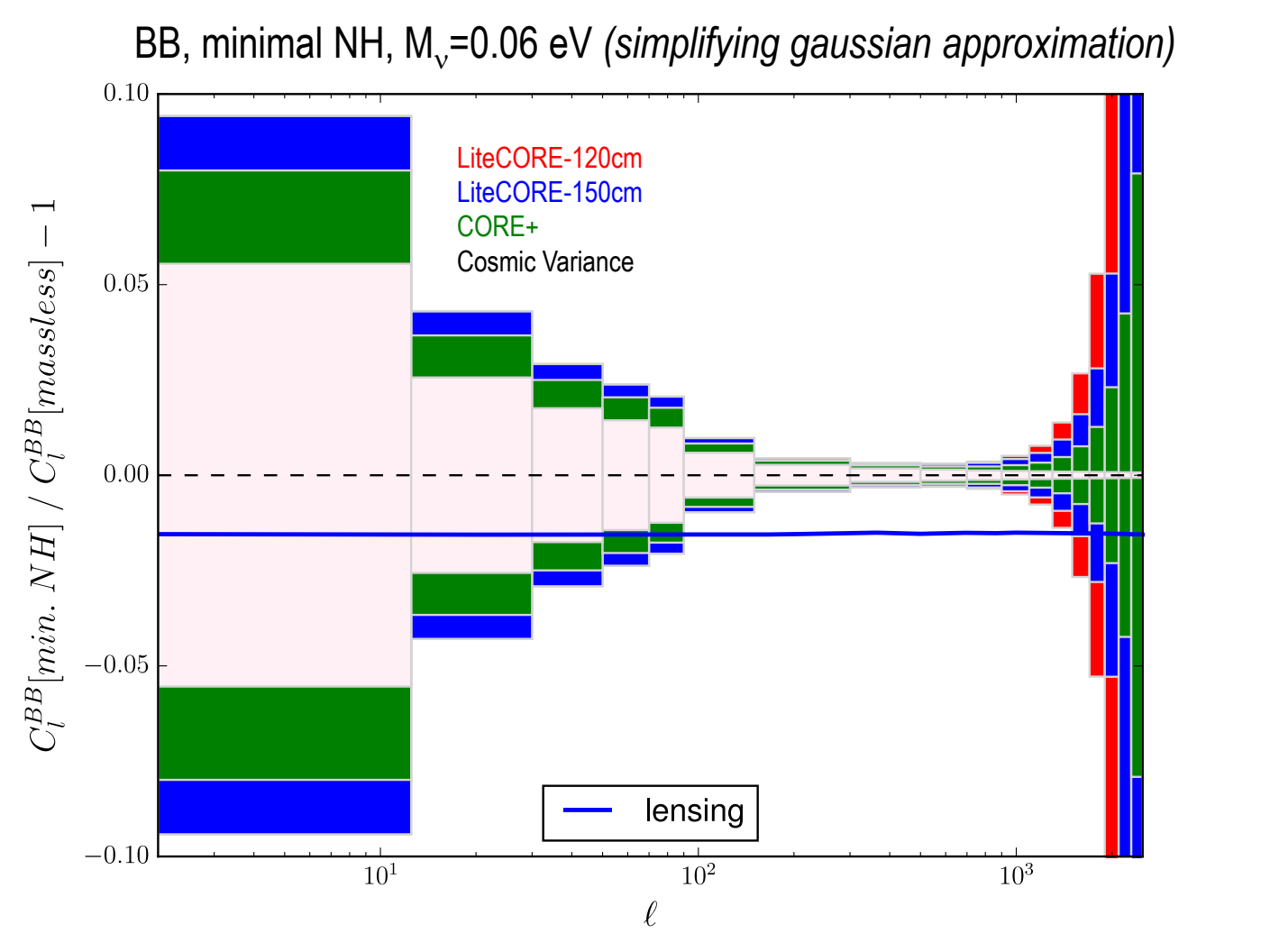
Neutrino mass detection with CMB



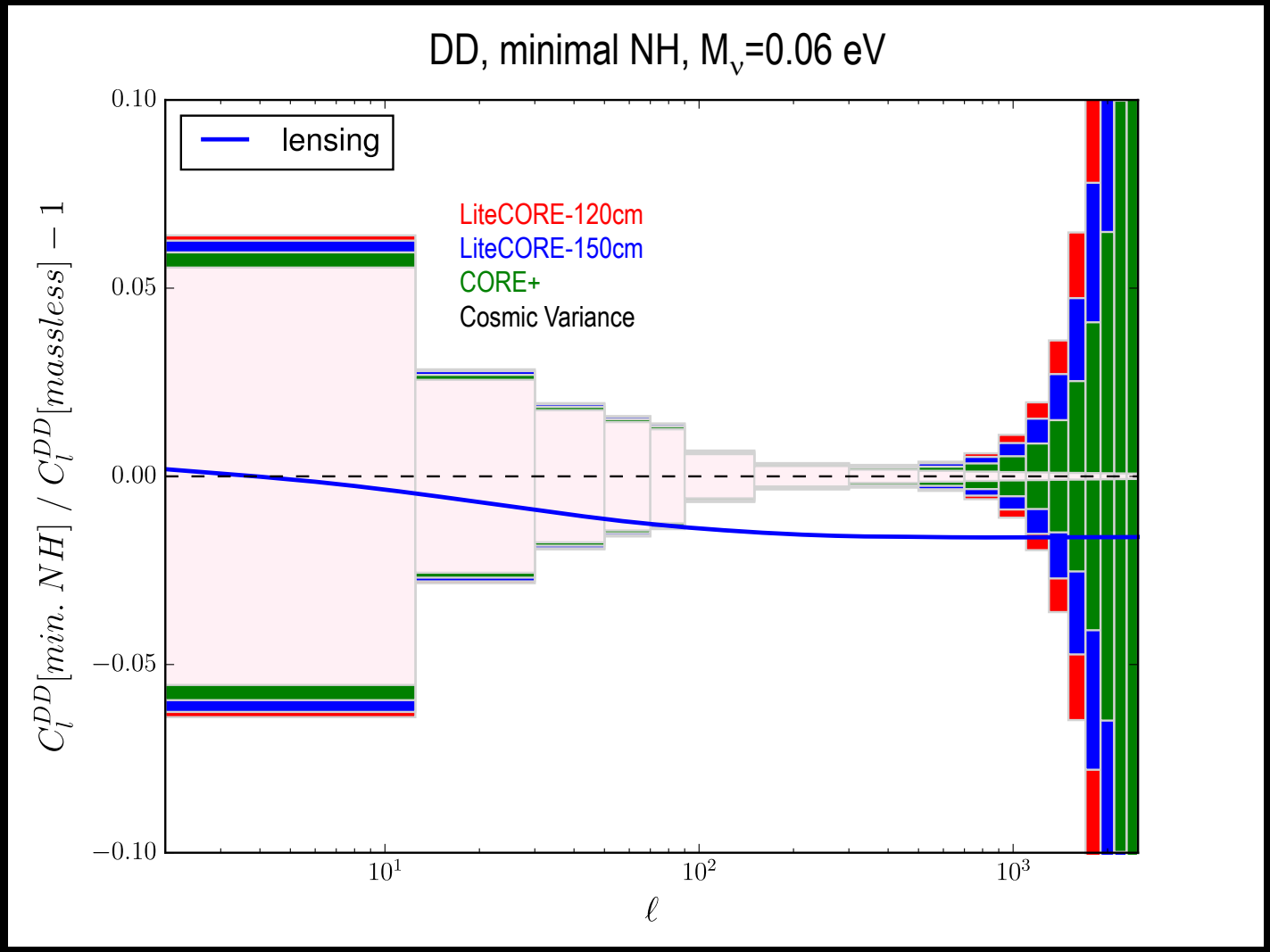
Neutrino mass detection with CMB



Neutrino mass detection with CMB



Neutrino mass detection with CMB



Suite of 81 MCMC MontePython forecasts

at TTK (RWTH Aachen),

with Thejs Brinckmann and Sébastien Clesse.

Suite of 81 MCMC MontePython forecasts

A. Instruments: Core+ / LiteCore 150cm / LiteCore 120cm

Channel [GHz]	FWMH [arcmin]	ΔT [μK arcmin]	ΔP [μK arcmin]
LiteCORE-120, $l_{\max} = 3000$, $f_{\rm sky} = 0.7$			
80	13.5	8.8	12.5
90	11.9	7.1	10.0
100	10.5	8.5	12.0
120	8.8	6.7	9.5
140	7.4	5.3	7.5
166	6.3	5.0	7.0
195	5.4	3.6	5.0
LiteCORE-150, $l_{\max} = 3000$, $f_{\rm sky} = 0.7$			
80	10.8	8.8	12.5
90	9.5	7.1	10.0
100	8.4	8.5	12.0
120	7.0	6.7	9.5
140	5.9	5.3	7.5
166	5.0	5.0	7.0
195	4.3	3.6	5.0
CORE+, $l_{\max} = 3000$, $f_{\rm sky} = 0.7$			
100	8.4	6.0	8.5
115	7.3	5.0	7.0
130	6.5	4.2	5.9
145	5.8	3.6	5.0
160	5.3	3.8	5.4
175	4.8	3.8	5.3
195	4.3	3.8	5.3
220	3.8	5.8	8.1
255	3.3	8.9	12.6

Suite of 81 MCMC MontePython forecasts

A. Instruments: Core+ / LiteCore 150cm / LiteCore 120cm

B. Likelihoods:

- Unlensed TT, TE, EE
- Lensed TT, TE, EE, BB *(neglecting intrinsic non-gaussianity; delensing irrelevant)*
- Lensed TT, TE, EE + extracted deflection field DD

Suite of 81 MCMC MontePython forecasts

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C. Fiducial models: minimal NH, minimal IH

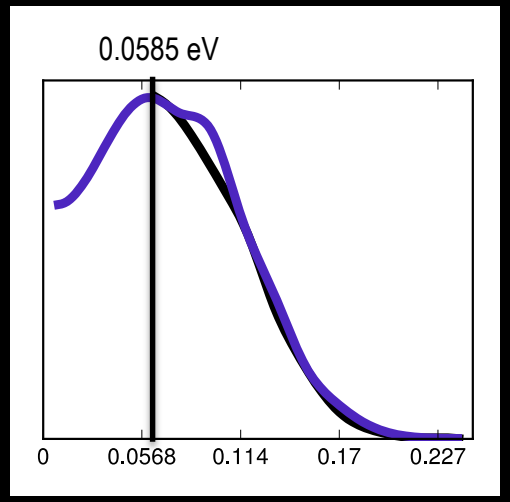
D. Fitted models: ΛCDM extensions:

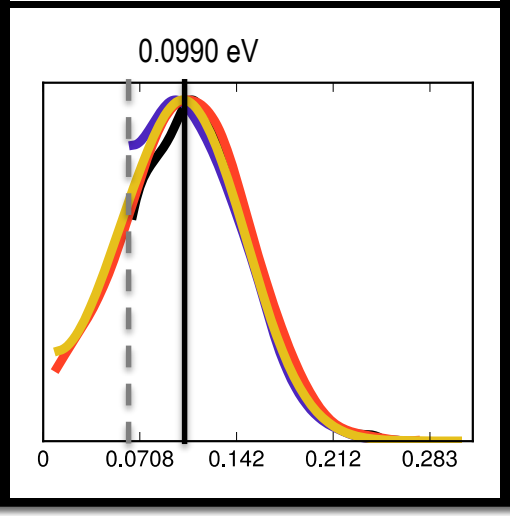
- 7 params (M_ν),
- 8 params (Y_{He}, r, w, N_{eff}, running, Ω_k)

Suite of 81 MCMC MontePython forecasts

First conclusion: even with Core+, mass splitting is irrelevant

Fiducial model	Fitted model
NH (minimal M_ν ~ 0.06eV)	Degenerate (M_ν>0)
NH (minimal M_ν ~ 0.06eV)	NH (M_ν>0.06eV)
IH (minimal M_ν ~ 0.1eV)	Degenerate (M_ν>0)
IH (minimal M_ν ~ 0.1eV)	NH (M_ν>0.06eV)
IH (minimal M_ν ~ 0.1eV)	IH (M_ν>0.1eV)
NH (same M_ν ~ 0.1eV)	Degenerate (M_ν>0)
NH (same M_ν ~ 0.1eV)	NH (M_ν>0.06eV)
NH (same M_ν ~ 0.1eV)	IH (M_ν>0.1eV)

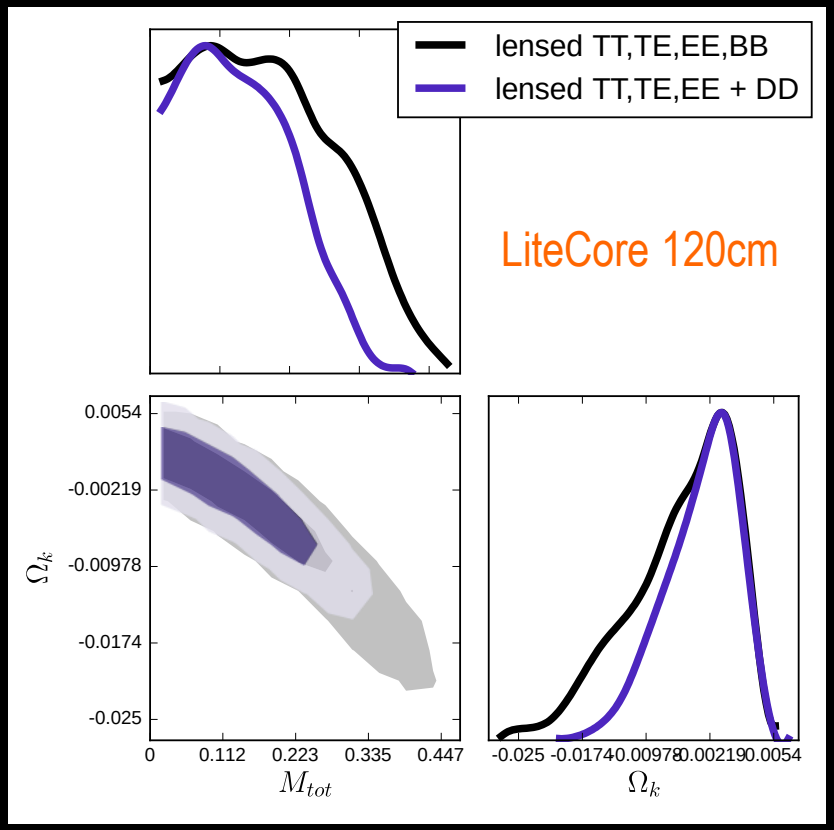


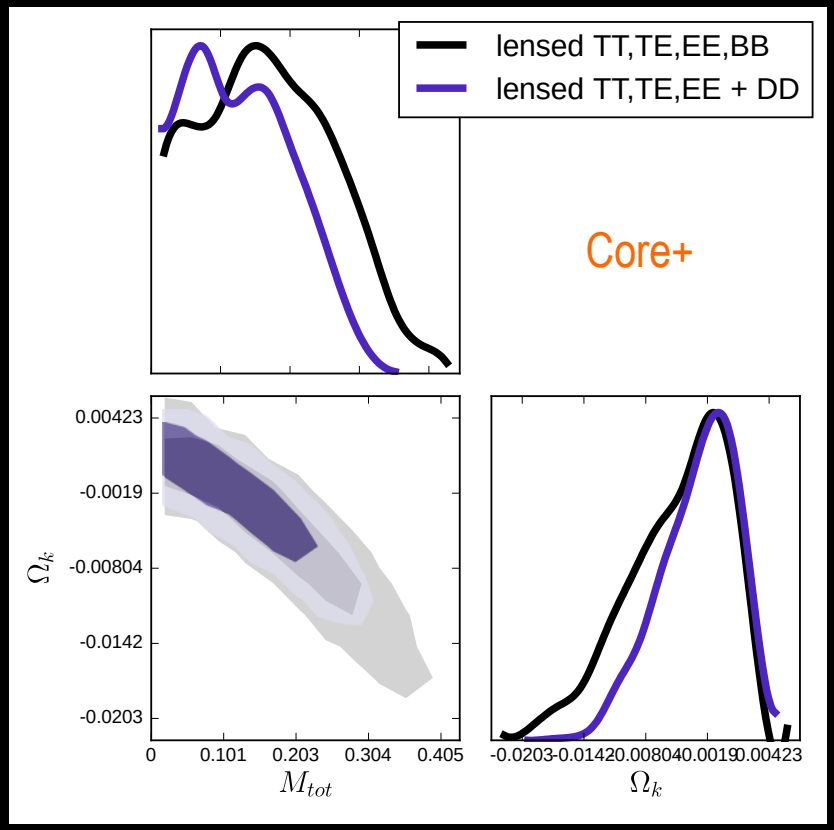


Suite of 81 MCMC MontePython forecasts

Second conclusion: <u>same results with lensed BB or lensing extraction</u>,

excepted for ΛCDM + M_ν + Ω_k *(while without lensing at all: 4 times worse)*





Suite of 81 MCMC MontePython forecasts

Third conclusion: minor impact of resolution / sensitivity, in most cases $\sigma(M_\nu) \sim 44$ meV

Results based on runs with lensing extraction:

Symmetrised $\sigma(M_\nu)$ in meV	LiteCore120	LiteCore150	Core+
ΛCDM + M_ν	45	44	43
ΛCDM + M_ν + ΔN_{eff}	45	44	44
ΛCDM + M_ν + w	36	36	35
ΛCDM + M_ν + Y_{He}	45	44	44
ΛCDM + M_ν + running	45	44	44
ΛCDM + M_ν + r	43	41	41
ΛCDM + M_ν + Ω_k	92	88	84

volume effect in Bayesian parameter inference: w>-1 or r>0 requires smaller M_ν

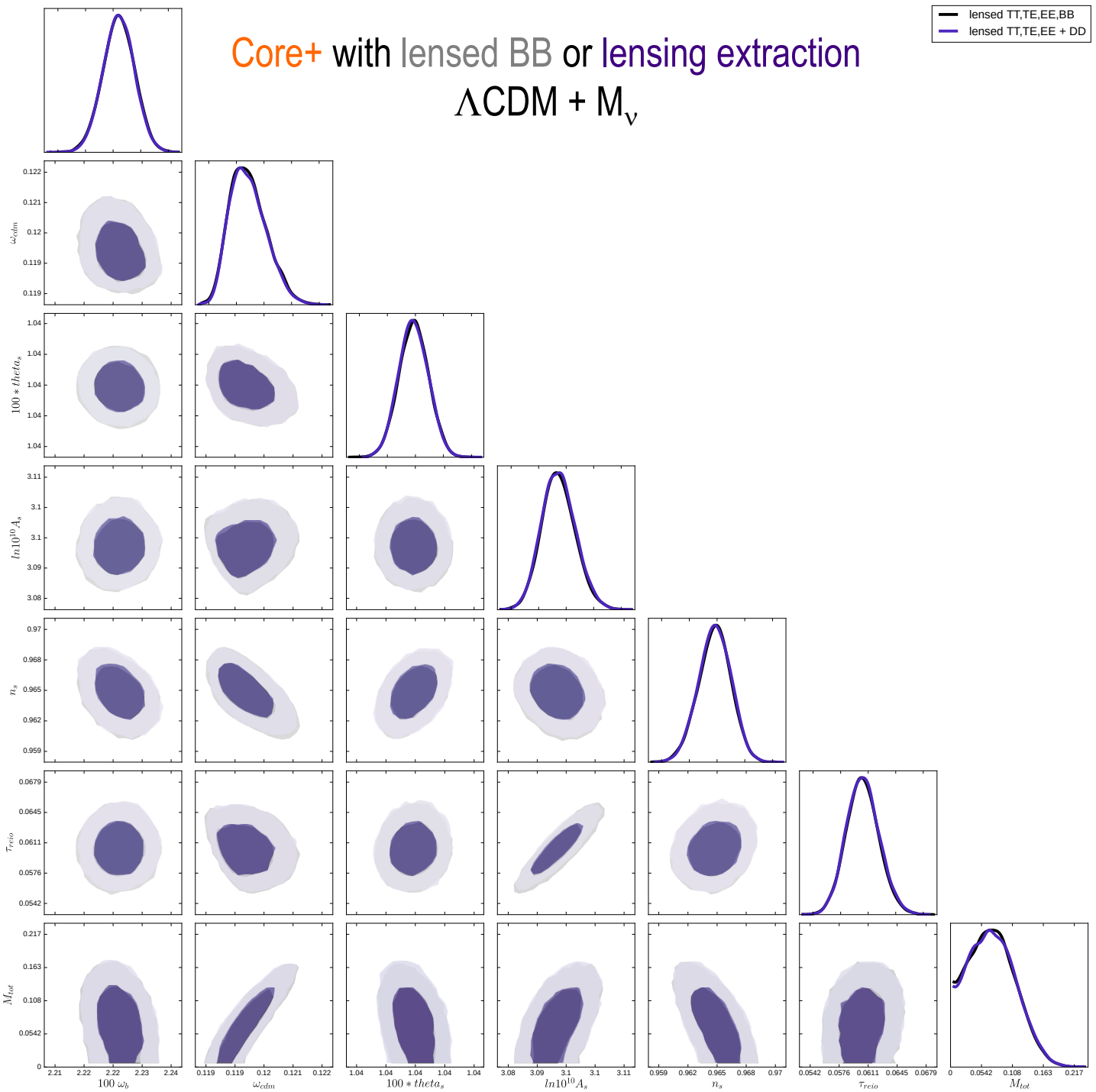
Conclusions

- LiteCore / Core+ alone :
  - robust errorbar $\sigma(M_\nu) \sim 44$ meV
  - (excepted with free Ω_k *:* twice worse sensitivity)

- Very useful probe in combination with LSS experiments
  - Planck + Euclid : $\sigma(Mv) = 25\text{-}30$ meV : at least 2 sigma detection
  - Core+ / LiteCore + Euclid : $\sigma(Mv) = 15\text{-}20$ meV: at least 3-4 sigma detection
  - Even better with SKA?

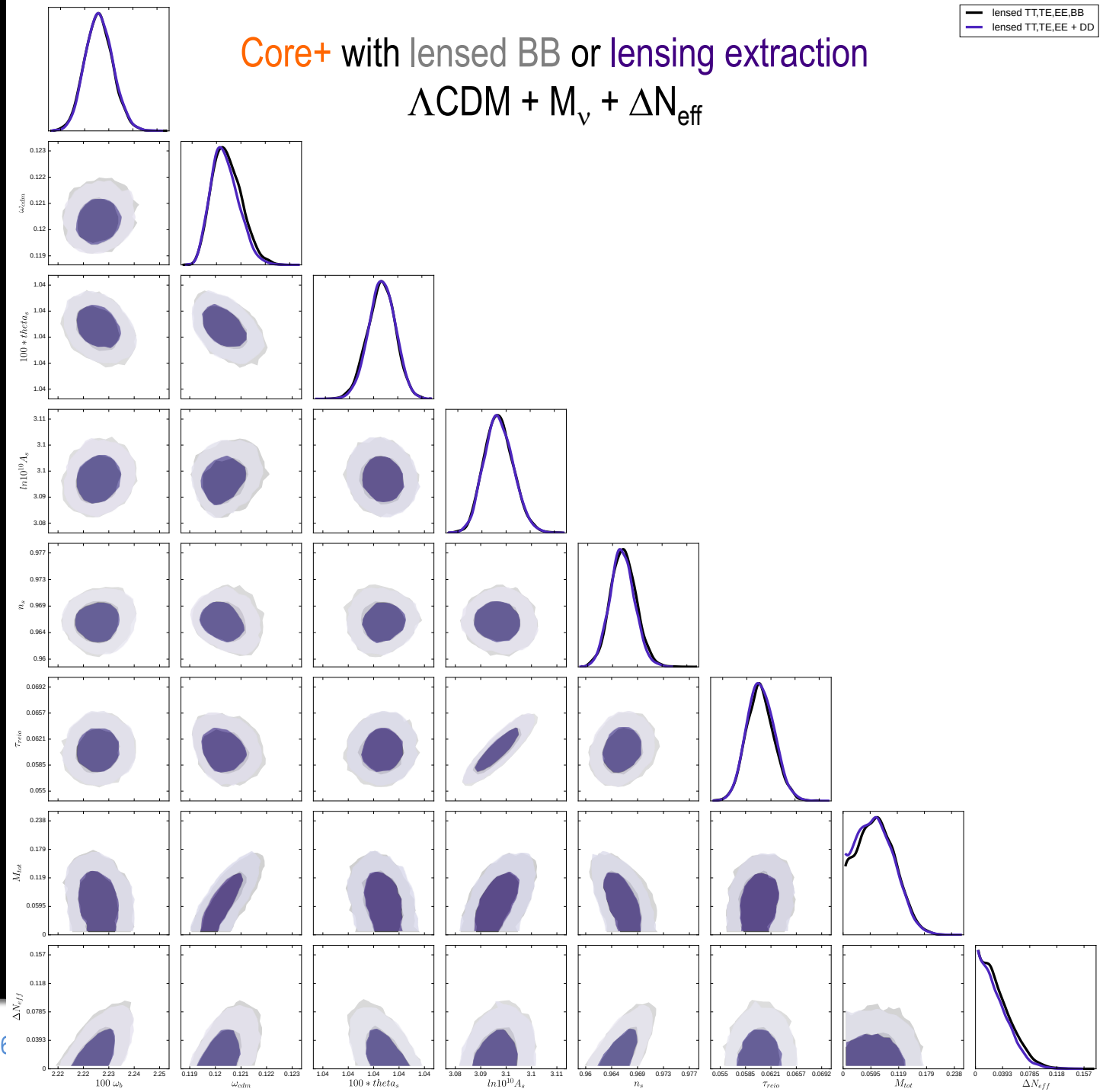
Core+ with lensed BB or lensing extraction

ΛCDM + M_ν



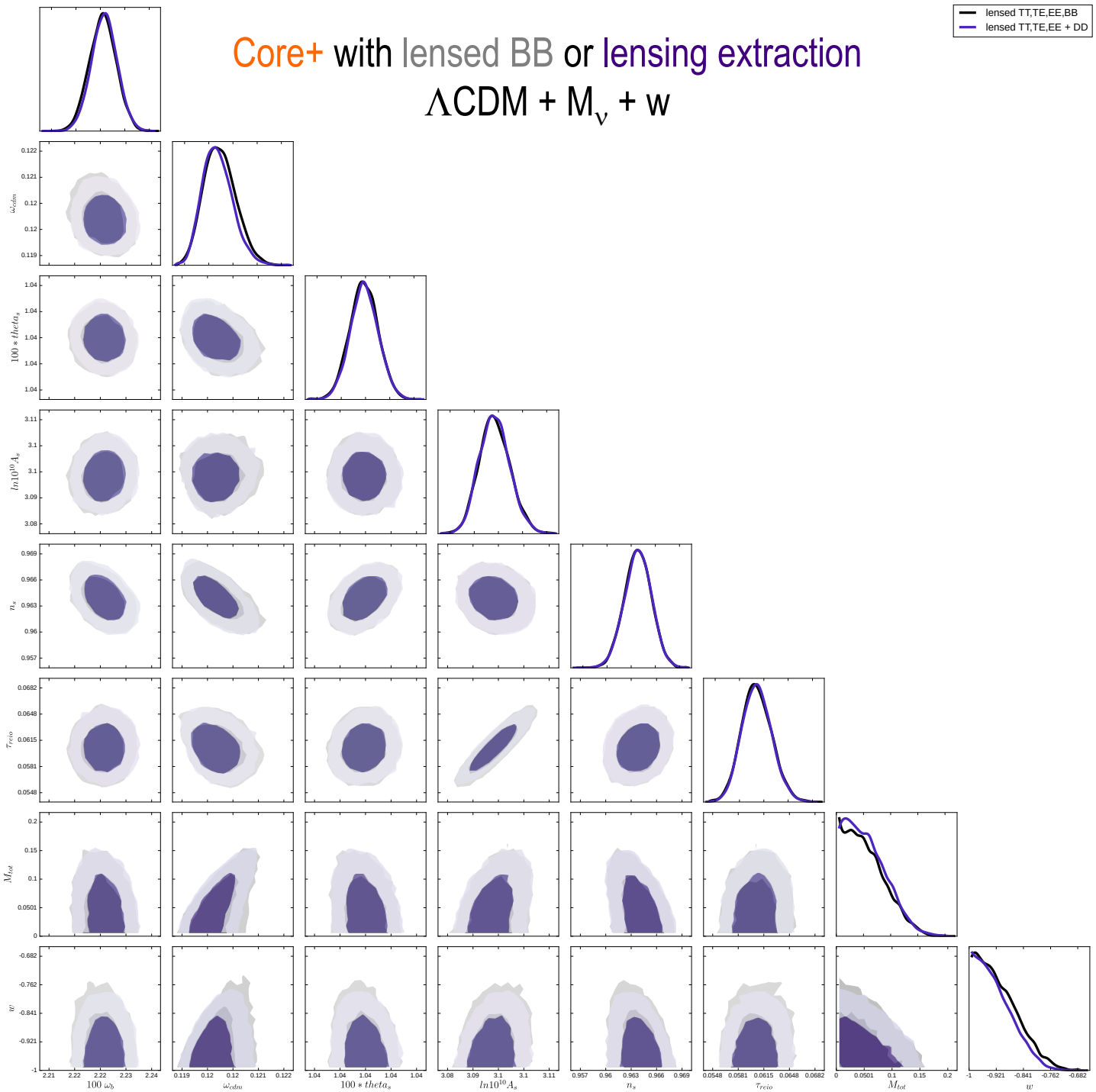
Core+ with lensed BB or lensing extraction

ΛCDM + M_ν + ΔN_{eff}



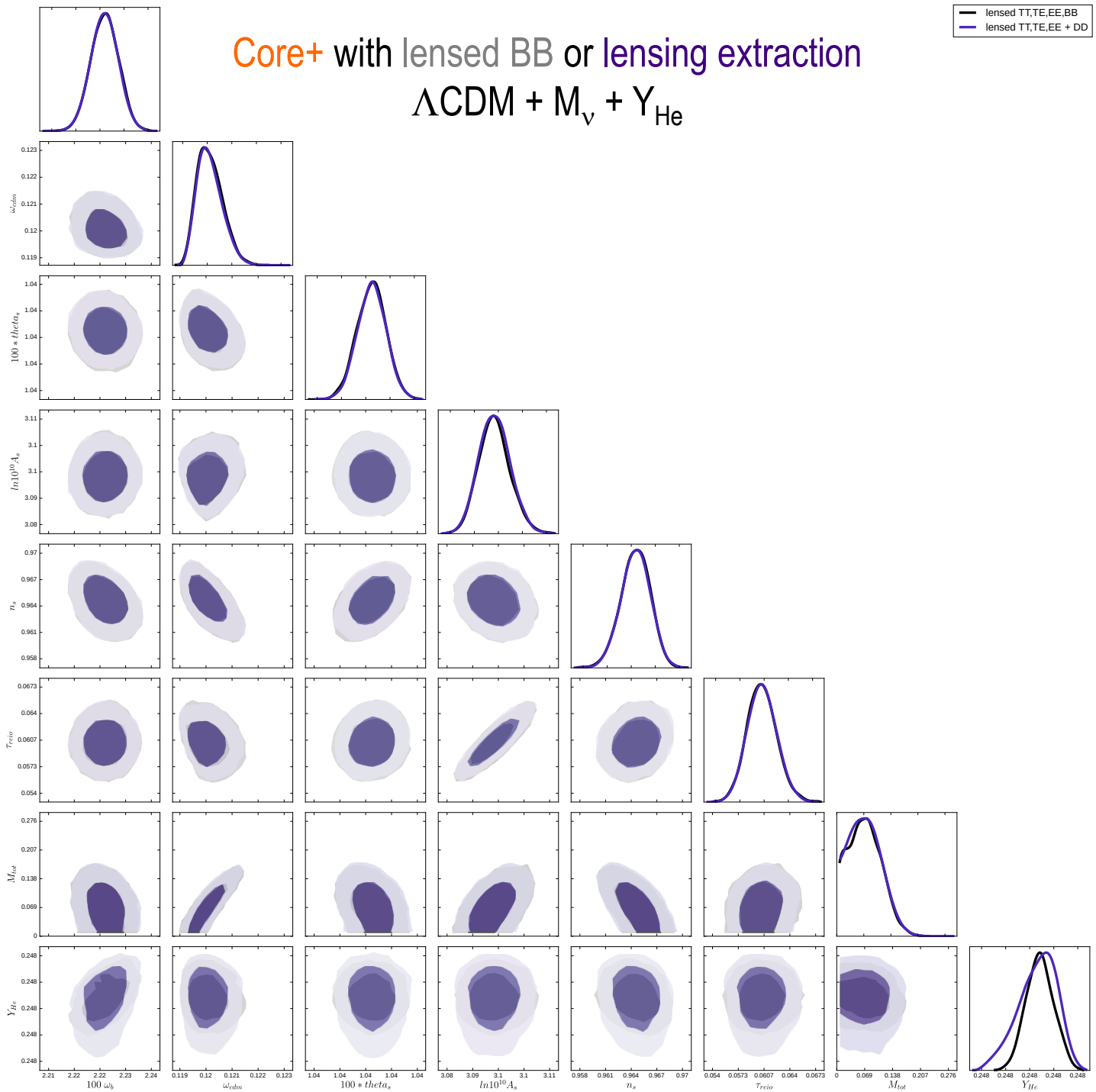
Core+ with lensed BB or lensing extraction

ΛCDM + M_ν + w



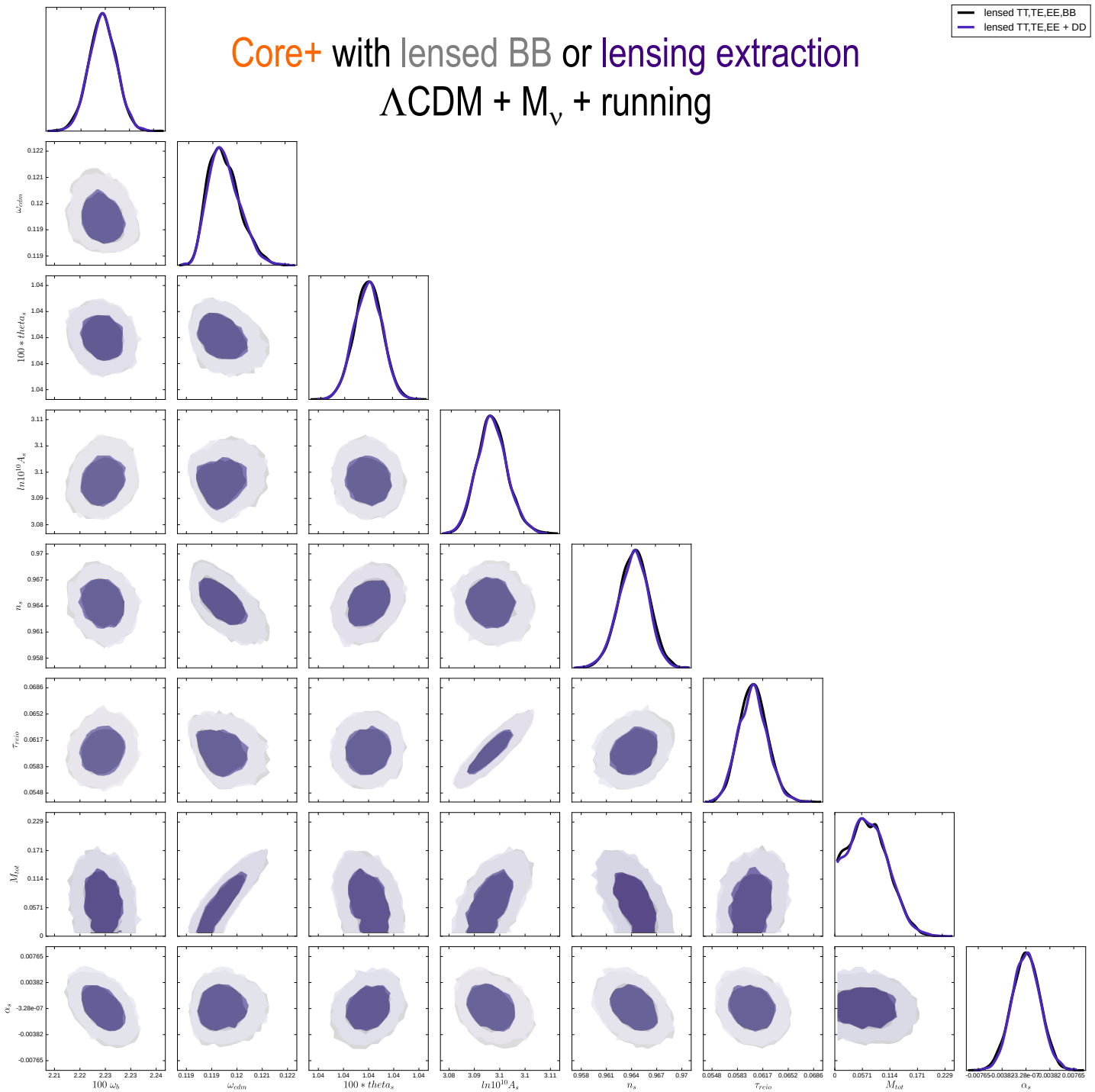
Core+ with lensed BB or lensing extraction

ΛCDM + M_ν + Y_{He}



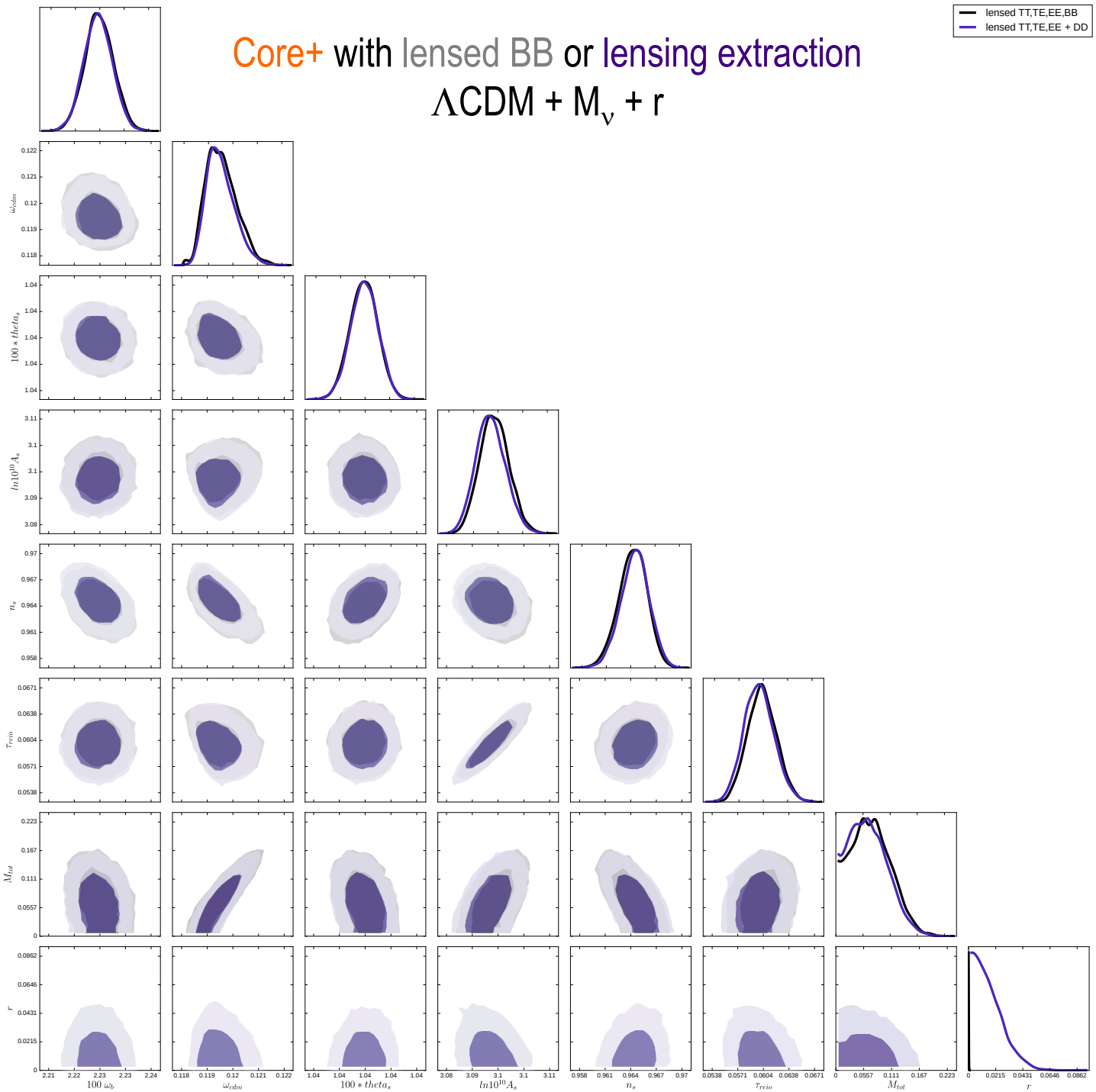
Core+ with lensed BB or lensing extraction

ΛCDM + M_ν + running



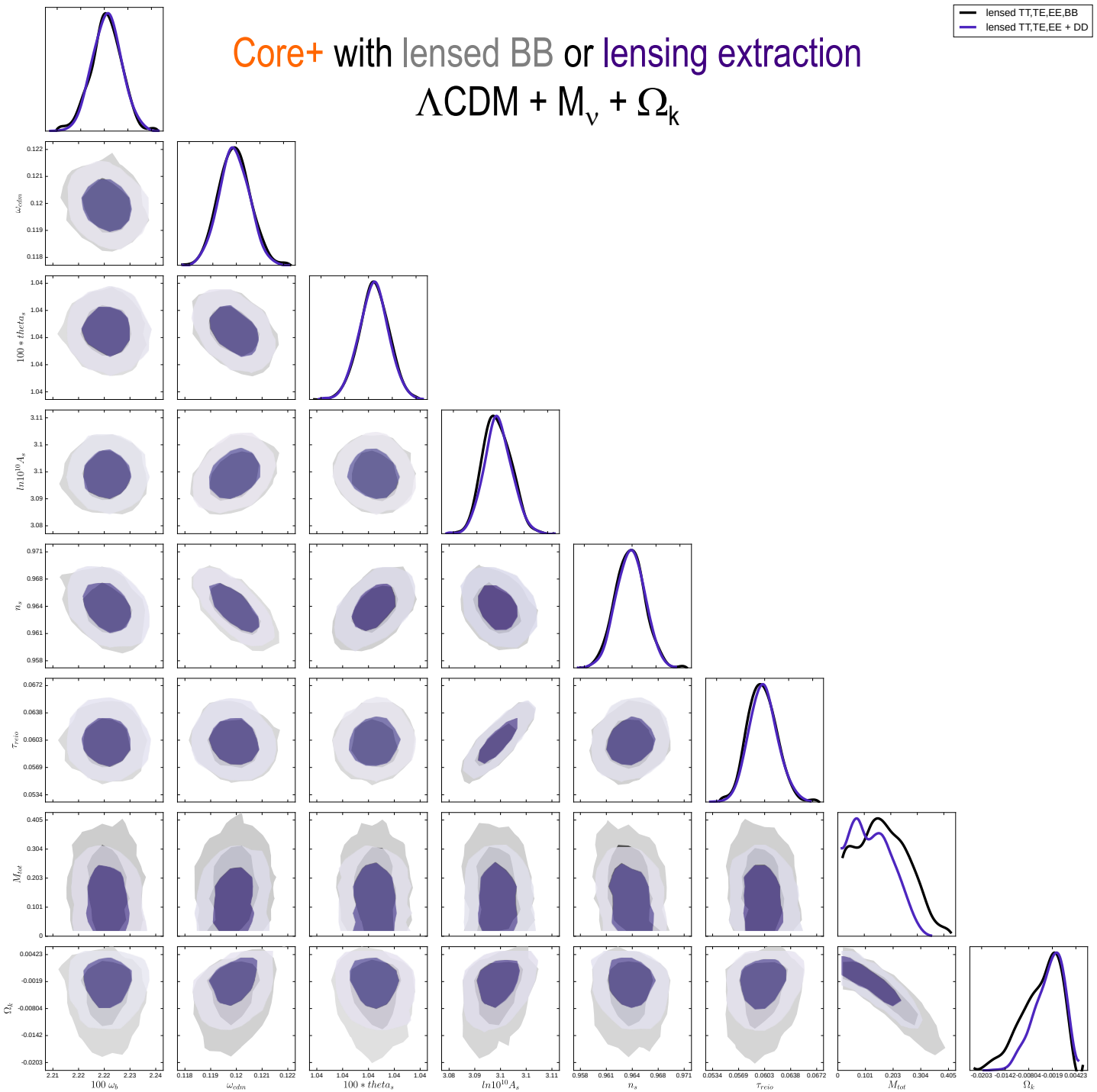
Core+ with lensed BB or lensing extraction

ΛCDM + M_ν + r



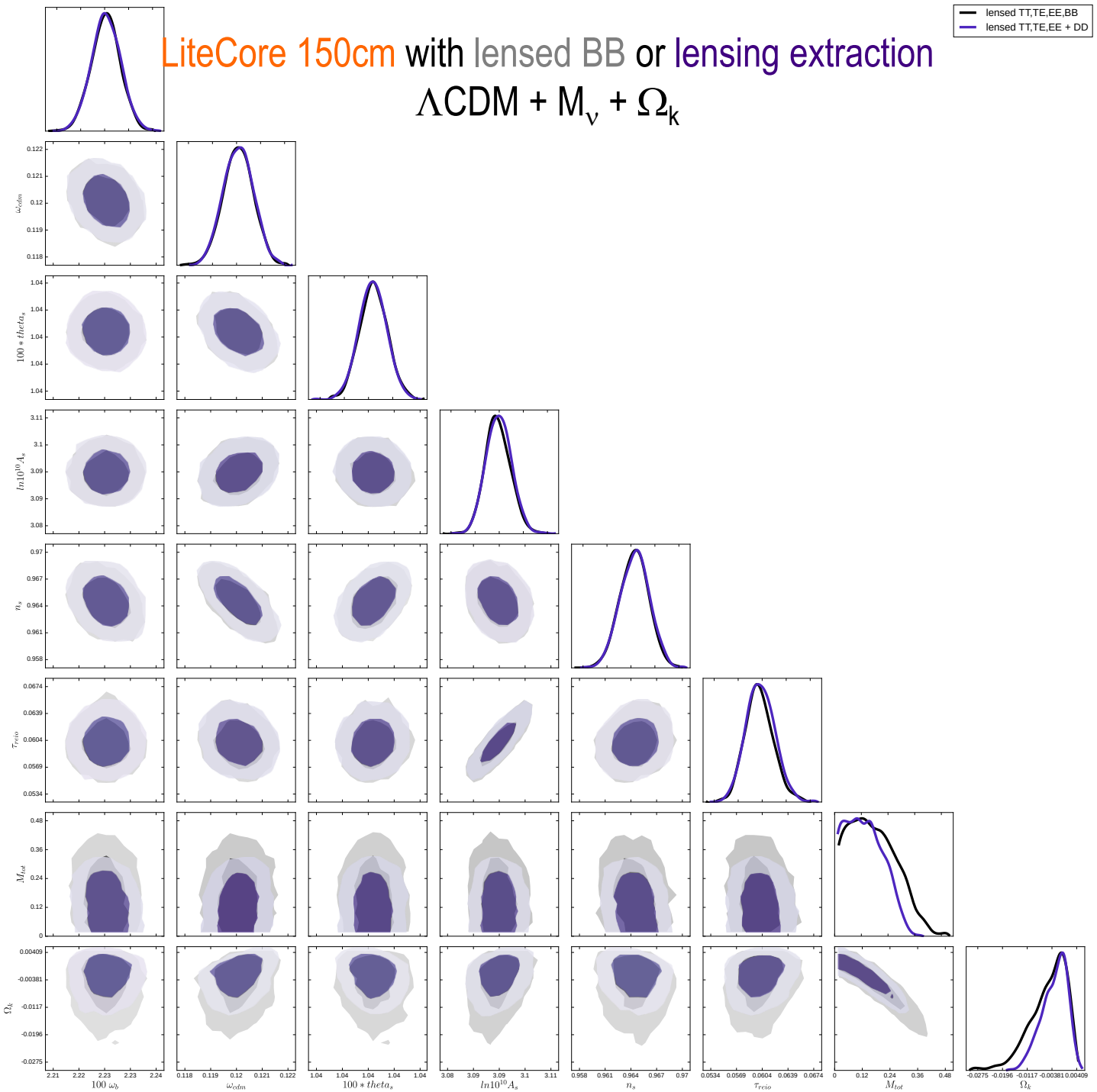
Core+ with lensed BB or lensing extraction

ΛCDM + M_ν + Ω_k



LiteCore 150cm with lensed BB or lensing extraction

ΛCDM + M_ν + Ω_k



LiteCore 120cm with lensed BB or lensing extraction

ΛCDM + M_ν + Ω_k