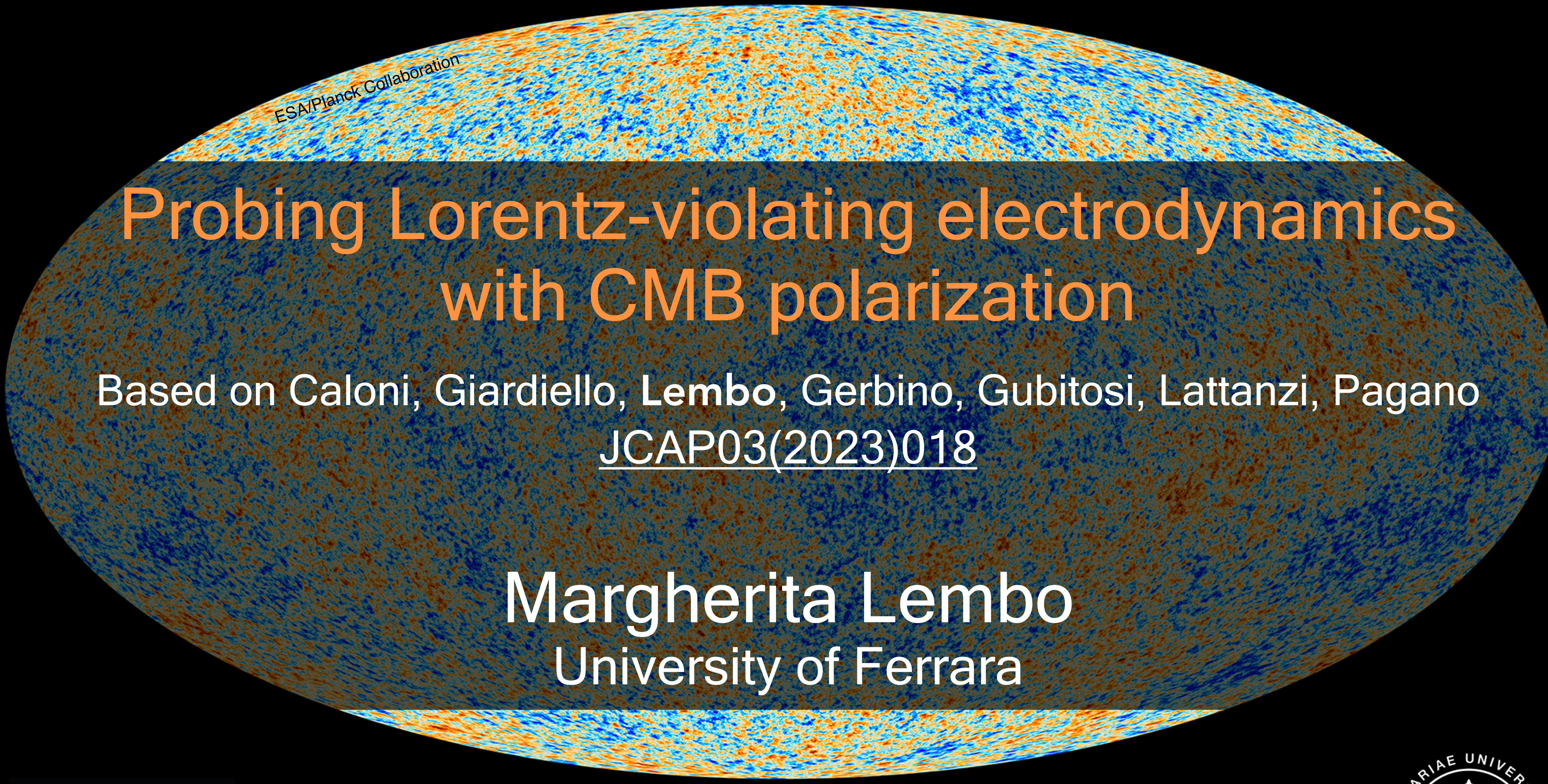
Cosmology in Miramare, Trieste

28 Aug - 02 Sep 2023



Probing Lorentz-violating electrodynamics with CMB polarization

Based on Caloni, Giardiello, **Lembo**, Gerbino, Gubitosi, Lattanzi, Pagano

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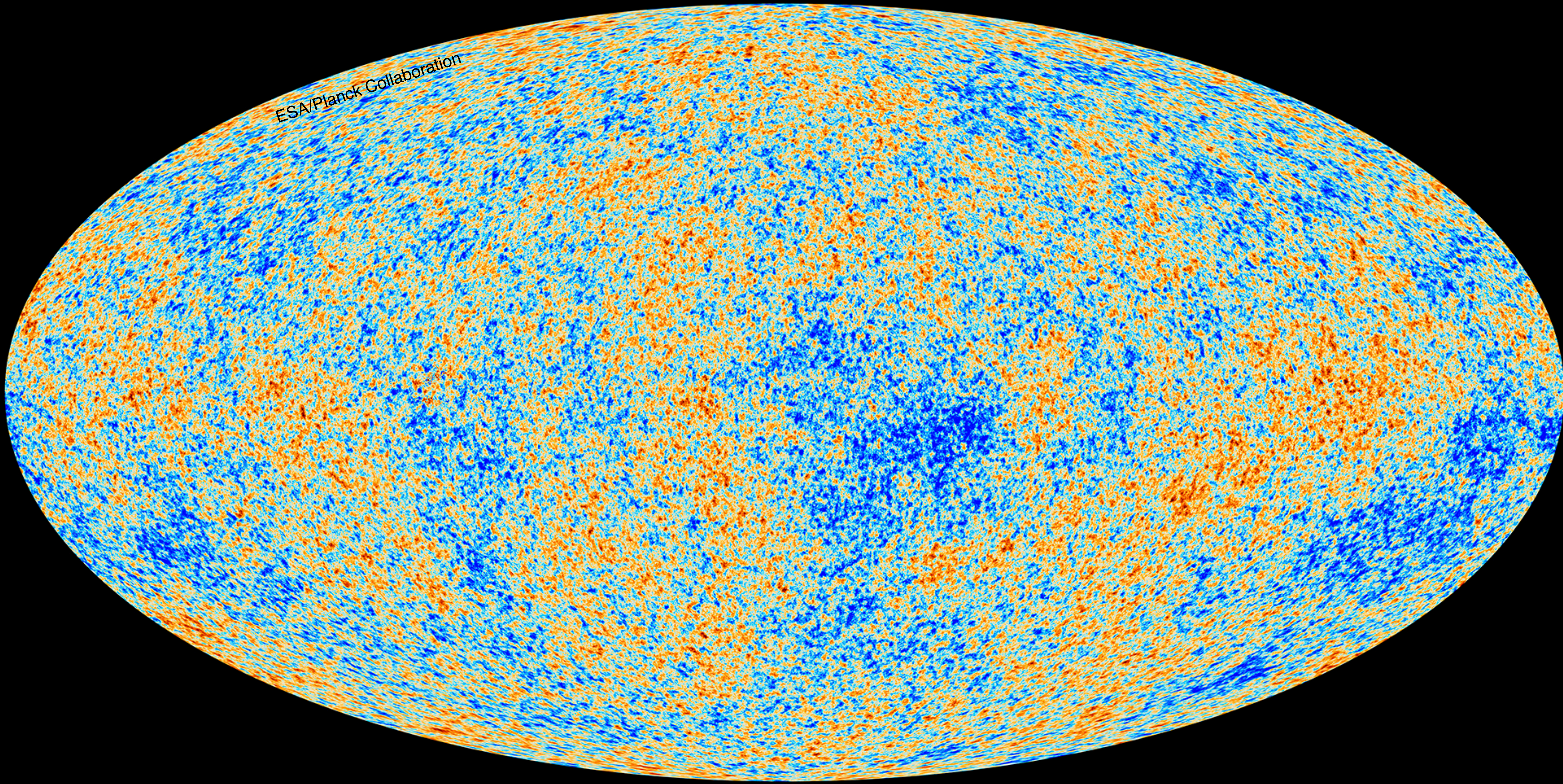
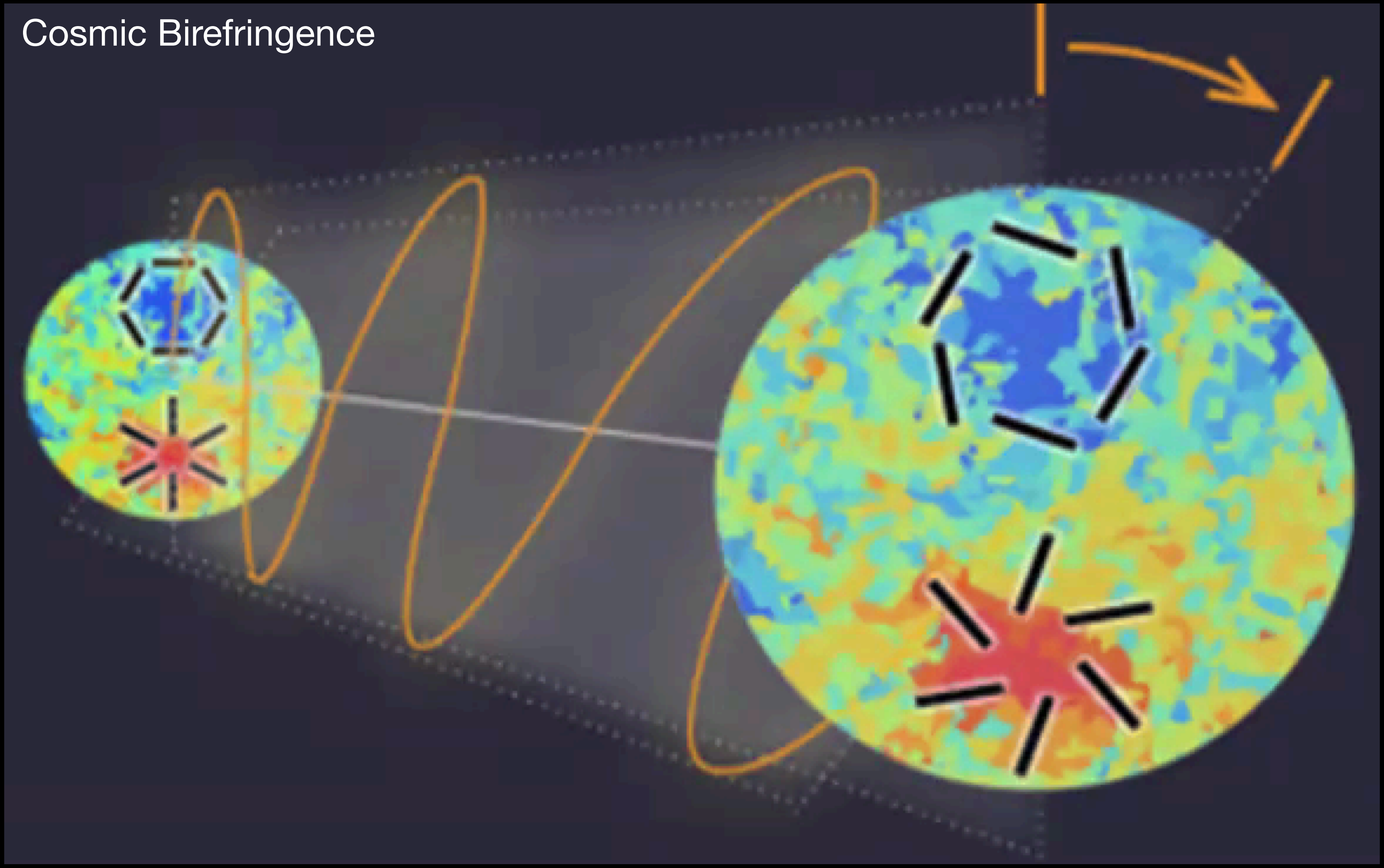

ESA/Planck Collaboration

CMB polarization - beyond the standard picture

Maxwell Lagrangian is expected to conserve parity → observing the parity-violating angular power spectra (e.g. TB and EB) allows us to constraint Lorentz and CPT violating theories



CMB polarization - beyond the standard picture

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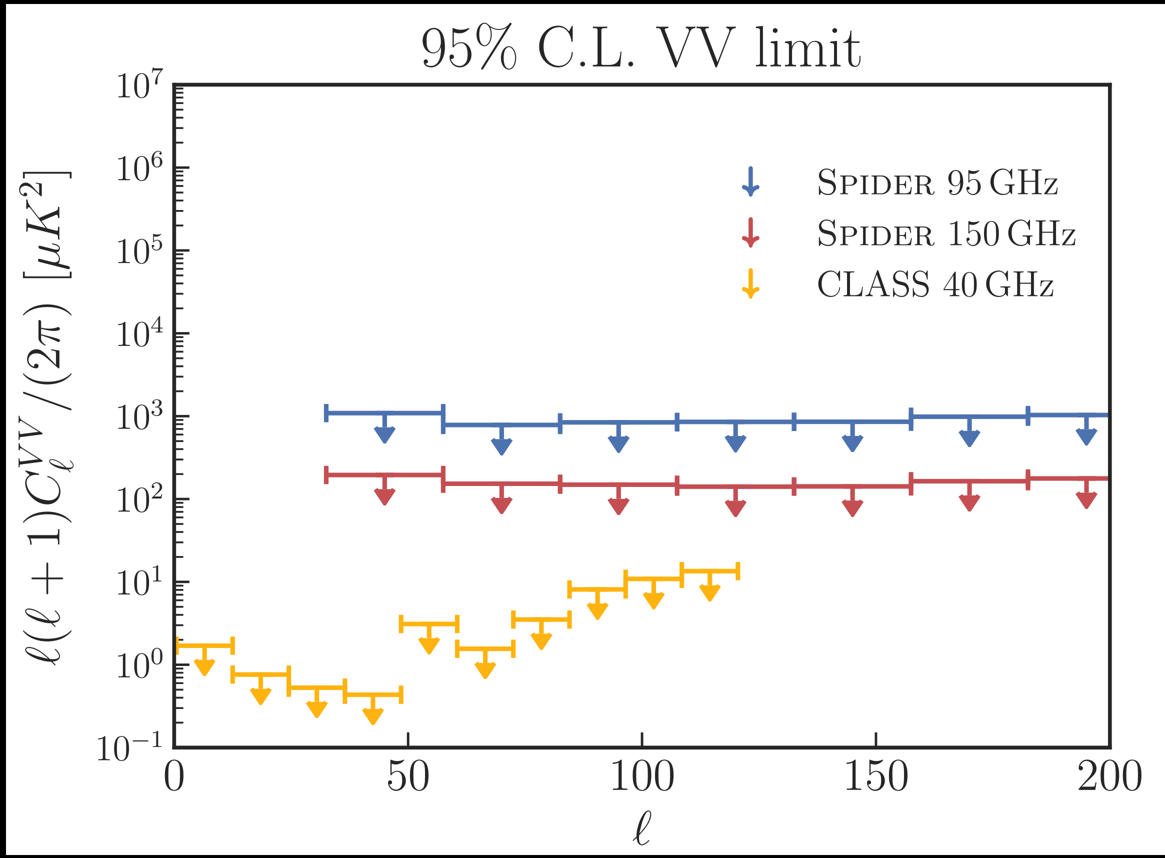
CMB photons are expected to be linearly polarized → observing circular polarization in the CMB could provide evidence for new physics

Why V modes?

- Photon-photon interactions
- Cosmic neutrino background
- **Lorentz invariance violations**
- Non-commutative spacetime
- Late-time astrophysical effects
- …



Imprints of Lorentz violation on the CMB spectra

Minimal SME, which only contains renormalizable operators with mass dimension ≤ 4

CPT-odd CPT-even

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \varepsilon^{\alpha\beta\mu\nu} A_\beta (k_{AF})_\alpha F_{\mu\nu} - \frac{1}{4} (k_F)^{\alpha\beta\mu\nu} F_{\alpha\beta} F_{\mu\nu} \right]$$

applying the *dark crystal formalism*
Lembo, Lattanzi, Pagano,
Gruppulo, Natoli and Forastieri (PRL21)

CMB spectra (including EB, TB, VV $\neq 0$) with LV effects as function of:

- CMB spectra without LV effects ;
- some effective parameters $\beta^2_{AF,T}$, $\beta^2_{AF,S}$, $\beta^2_{F,E}$ and $\beta^2_{F,B}$.

$\beta^2_{AF,T/S}$ are related to the time and space component of k_{AF}

$\beta^2_{F,E/B}$ depends of the components oh k_F in a non-trivial way

Dark crystal formalism

Link to the paper

Dark crystal in steps:

1. Writing down the general Lagrangian for a specific theory sourcing GFE
2. Recovering the modified Maxwell equations
3. Writing down the explicit expression for the susceptibility tensor
4. Expressing the components of the susceptibility tensor in terms of three quantities describing mixings between the U,Q and V Stokes parameters
5. Computing the CMB spectra as usual, taking care of expanding these coefficients with the correct spin-weighted spherical harmonics

Based on ML, Lattanzi, Pagano et al (PRL21)

Generalized Faraday effect (GFE): conversion between polarization states of propagating radiation in a cosmological setting

$$\frac{\mathrm{d}}{\mathrm{d}s}\mathbf{S} = \boldsymbol{\rho} \times \mathbf{S}$$

$$\mathbf{S} = (Q, U, V)$$

$$\boldsymbol{\rho} = \left(\rho_Q, \rho_U, \rho_V\right)$$

We can recast the GFE parameters in terms of the components of an effective “cosmic susceptibility tensor”

$$\chi = \begin{pmatrix} \chi_{xx} & i\chi_{xy} & -i\chi_{xz} \\ -i\chi_{xy} & \chi_{yy} & i\chi_{yz} \\ i\chi_{xz} & -i\chi_{yz} & \chi_{zz} \end{pmatrix}$$

The diagonal (off-diagonal) elements are responsible for different linear (circular) polarization states propagating with different velocities, and as such they violate isotropy (parity)

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$$C_\ell^{EE} = (1-Z)\,\widetilde{C}_\ell^{EE} + \sum_{\ell_1} K^{11}_{\ell_1\ell}\,\widetilde{C}^{EE}_{\ell_1} + \sum_{\ell_1} K^{22}_{\ell_1\ell}\,\widetilde{C}^{BB}_{\ell_1}$$

$$C_\ell^{BB} = (1-Z)\,\widetilde{C}_\ell^{BB} + \sum_{\ell_1} K^{11}_{\ell_1\ell}\,\widetilde{C}^{BB}_{\ell_1} + \sum_{\ell_1} K^{22}_{\ell_1\ell}\,\widetilde{C}^{EE}_{\ell_1}$$

$$C_\ell^{VV} = \sum_{\ell_1} K^{33}_{\ell_1\ell}\,\widetilde{C}^{EE}_{\ell_1} + \sum_{\ell_1} K^{44}_{\ell_1\ell}\,\widetilde{C}^{BB}_{\ell_1}$$

$$C_\ell^{TE} = \left(1 - 0.5\,Z\right)\widetilde{C}_\ell^{TE}$$

$$C_\ell^{EB} = \sqrt{\beta^2_{AF,T}}\left(\widetilde{C}_\ell^{EE} - \widetilde{C}_\ell^{BB}\right)$$

$$C_\ell^{TB} = \sqrt{\beta^2_{AF,T}}\,\widetilde{C}_\ell^{TE}$$

$$C_\ell^{EV} = C_\ell^{BV} = C_\ell^{TV} = 0$$

$\widetilde{C}^{XX}$ if no LV effects are in place

$$Z = \beta^2_{AF,T} + \beta^2_{AF,S} + \frac{\left(\beta^2_{F,E} + \beta^2_{F,B}\right)}{4}$$

$$K^{11} = K^{11}\left(\beta^2_{AF,S}\right)$$

$$K^{22} = K^{22}\left(\beta^2_{AF,T}, \beta^2_{AF,S}\right)$$

$$K^{33(44)}_{\ell_1\ell} = K^{33(44)}_{\ell_1\ell}\left(\beta^2_{F,B(E)}, \beta^2_{F,E(B)}\right)$$

$\beta^2_{AF,\,T/S}$ are related to the time and space component of k_{AF}

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$$Z = \beta^2_{AF,T} + \beta^2_{AF,S} + \beta^2_F$$

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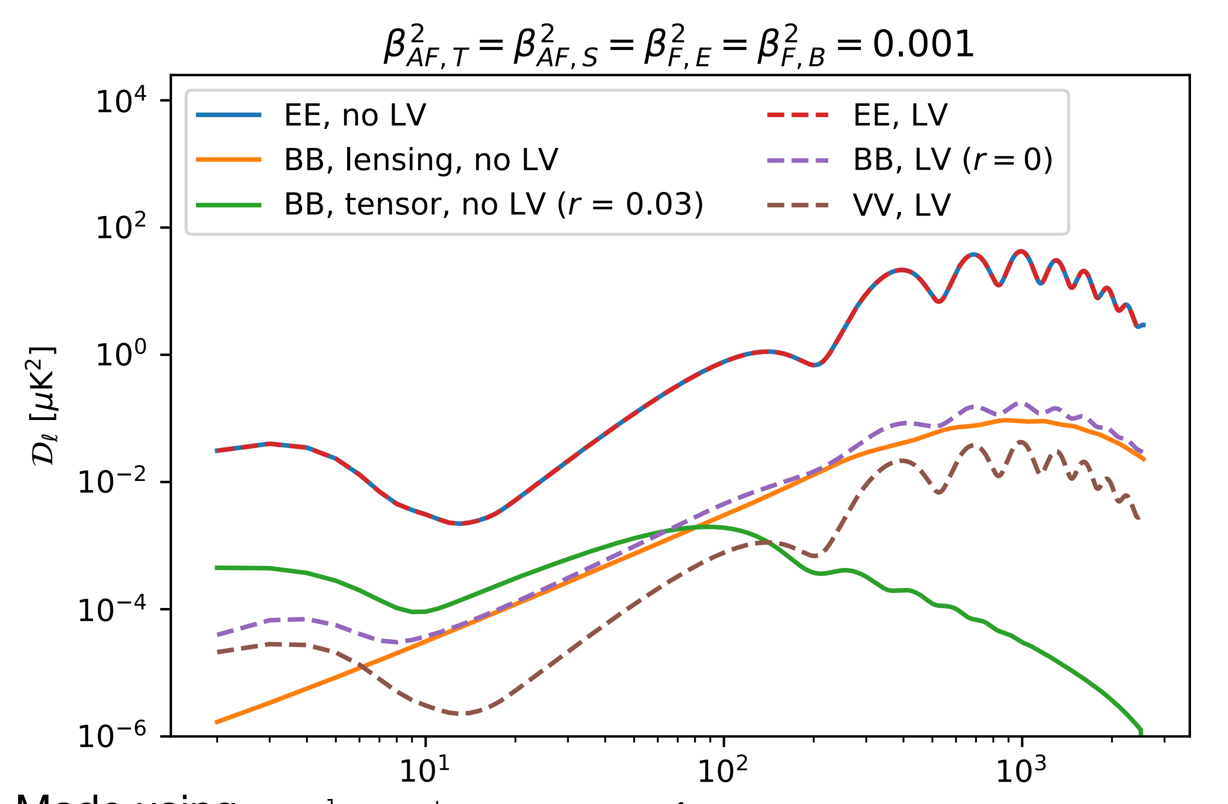
Standard CMB power spectra (no LV) in solid lines, with LV effects in dashed lines.
The VV spectrum is non-vanishing only in the LV case.



Made using camb-cpt

Constraining LV electrodynamics with current CMB data

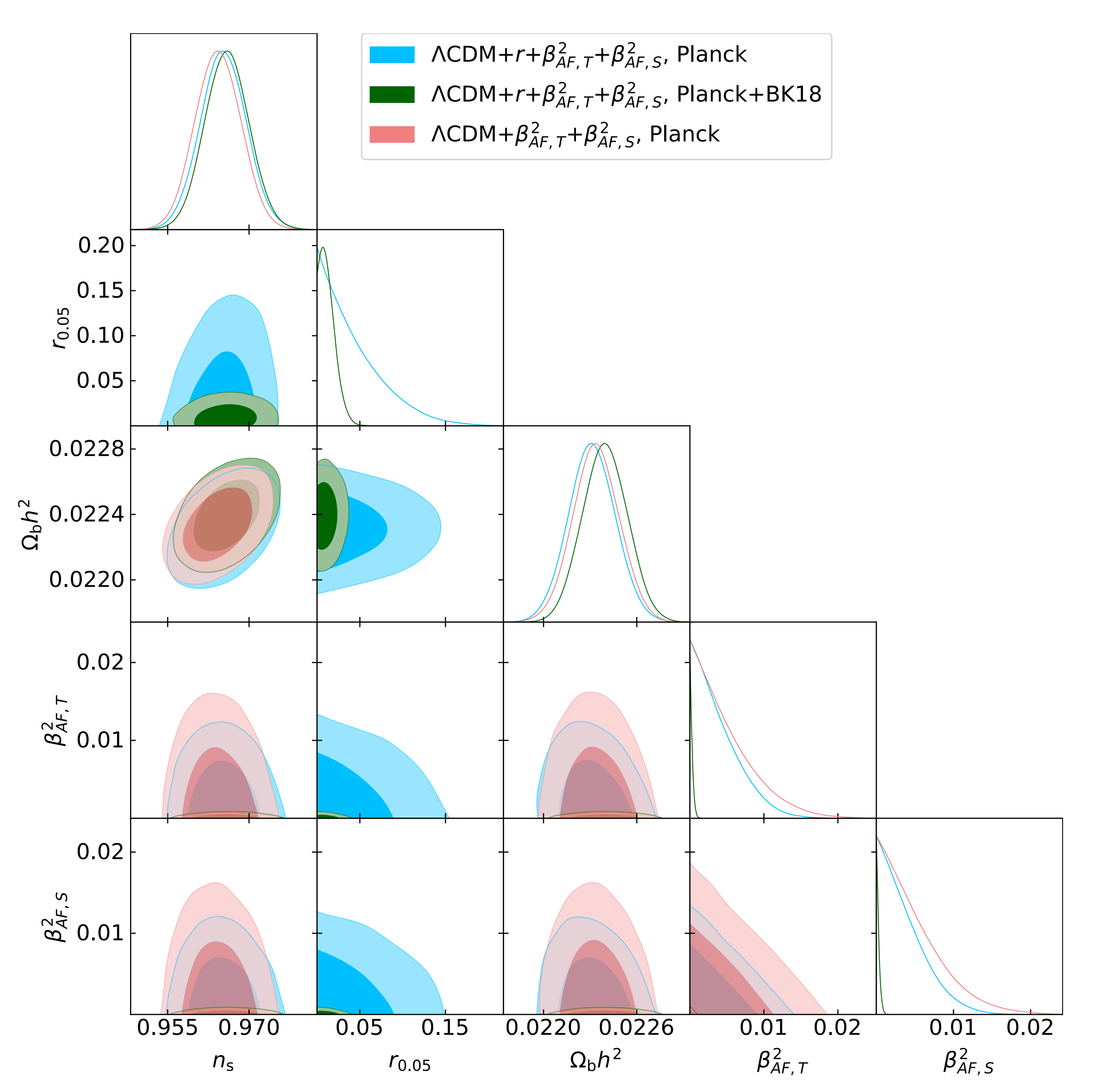
- We perform a MCMC analysis to obtain constraints on the LV parameters $\beta^2_{AF,T}$, $\beta^2_{AF,S}$, $\beta^2_{F,E}$ and $\beta^2_{F,B}$, jointly with other cosmological, foreground and nuisance parameters.
- Our modified version of `camb` (`camb-cpt`) has been interfaced with the MCMC sampler `Cobaya`.
- We have considered the following data combinations:

  (i) Planck 2018;
  (ii) Planck 2018 + BK18;
  (iii) Planck 2018 + BK18 + CLASS + SPIDER;
  (iv) Planck 2018 + BK18 + ACT.

  For the V-modes data, a simple custom-made likelihood has been added to the framework and since both CLASS and SPIDER are completely noise dominated, we can safely add together their respective χ^2.
- Our baseline scenario is $\Lambda CDM + r$.
- For the foreground and nuisance parameters, we followed the prescriptions provided by Planck, BICEP and ACT collaborations.

Constraining LV electrodynamics with current CMB data

$\beta^2_{AF,T/S}$ related to time/space components of k_{AF} (CPT odd)



Datasets:

Planck and BK18

Models:

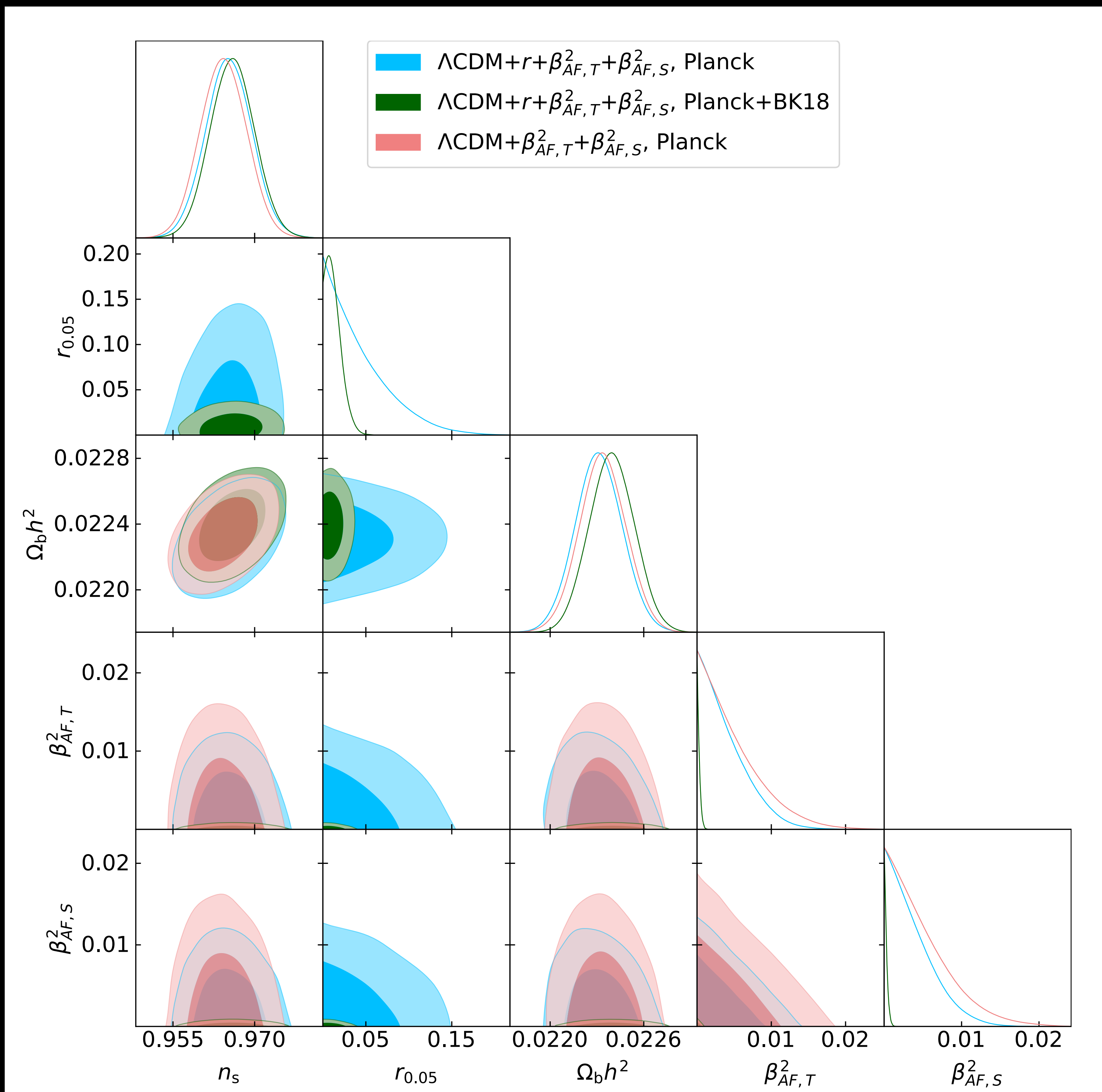
$$\Lambda CDM + \beta^2_{AF,T} + \beta^2_{AF,S}$$
$$\Lambda CDM + r + \beta^2_{AF,T} + \beta^2_{AF,S}$$
($\beta^2_F = 0$ in both cases)

As expected, the bounds on $\beta^2_{AF,T/S}$ are tightened when r is varied jointly with the CPT-odd parameters, even if using Planck data only.

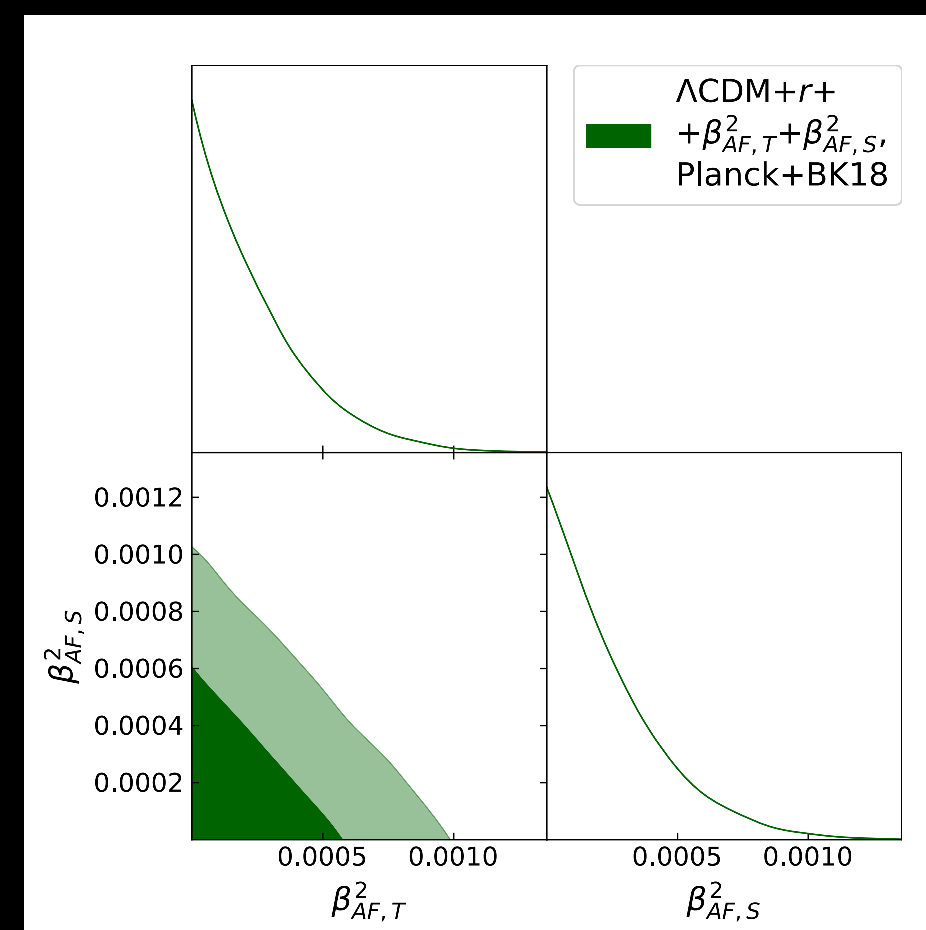
The improvement is dramatic when BK18 data are added to the analysis.

Constraining LV electrodynamics with current CMB data

$\beta^2_{AF,T/S}$ related to time/space components of k_{AF} (CPT odd)

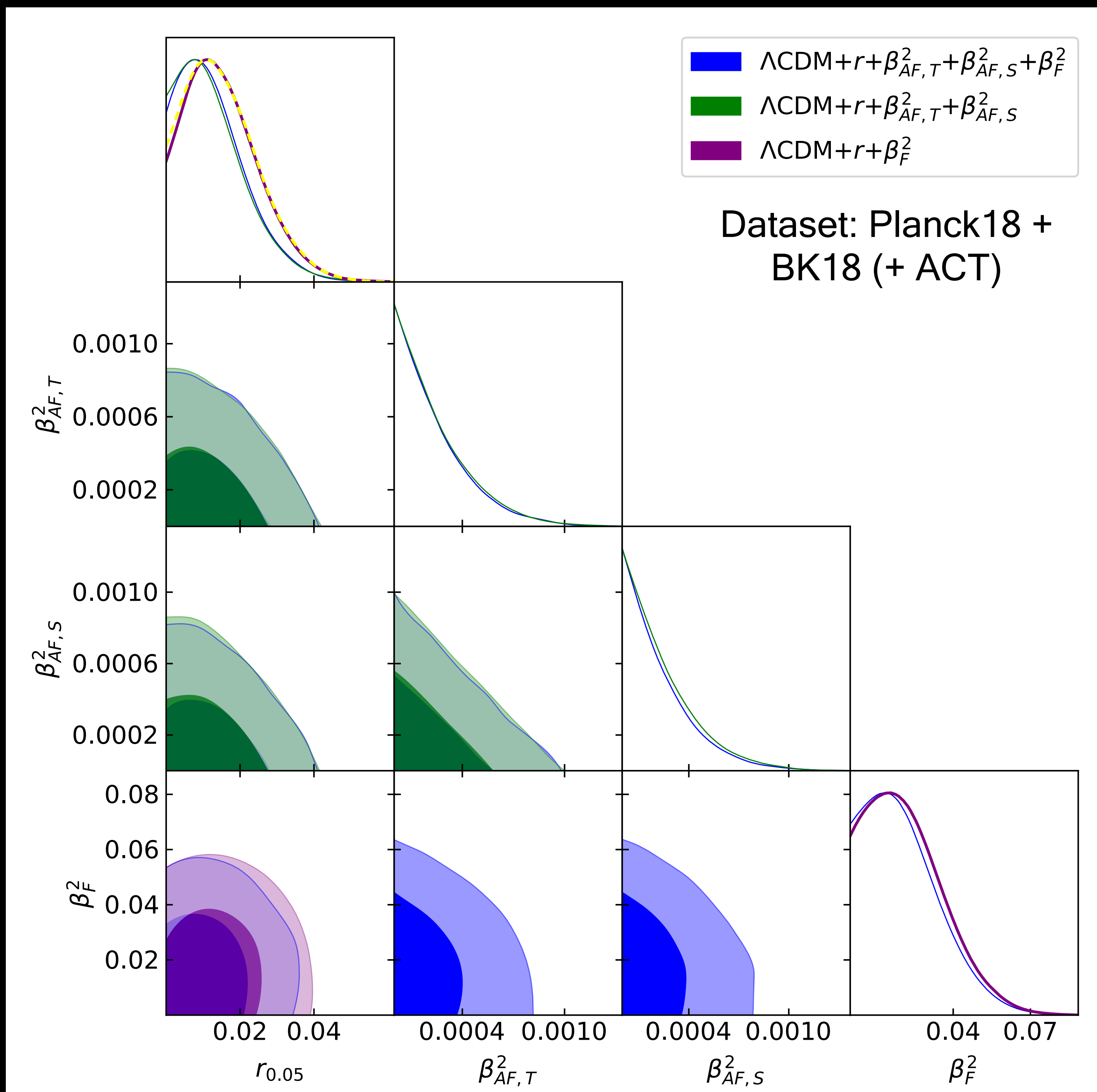


A zoom-in of the lower right triangle to better appreciate the impact of BK18 data on the constraints on the $\beta^2_{AF,T/S}$.



Constraining LV electrodynamics with current CMB data

$\beta^2_{AF,T/S}$ are related to the time and space component of k_{AF} (CPT odd)
β^2_F depends of the components of k_F in a non-trivial way (CPT even)



<u>Datasets:</u>
Planck, BK18 and ACT

<u>Models:</u>

$$\Lambda CDM + r + \beta^2_{AF} \;\; (\beta^2_F = 0)$$
$$\Lambda CDM + r + \beta^2_F \;\; (\beta^2_{AF} = 0)$$
$$\Lambda CDM + r + \beta^2_{AF,T} + \beta^2_{AF,S} + \beta^2_F$$

The bounds on β^2_F improve when all the β^2 are allowed to vary.

The constraints on $\beta^2_{AF,T/S}$ do not improve significantly when the two parameters are varied jointly with β^2_F.

Note again the improved bounds on r when $\beta^2_{AF,T}$ and $\beta^2_{AF,S}$ are varied.

Bounds on the LV operators using CMB data

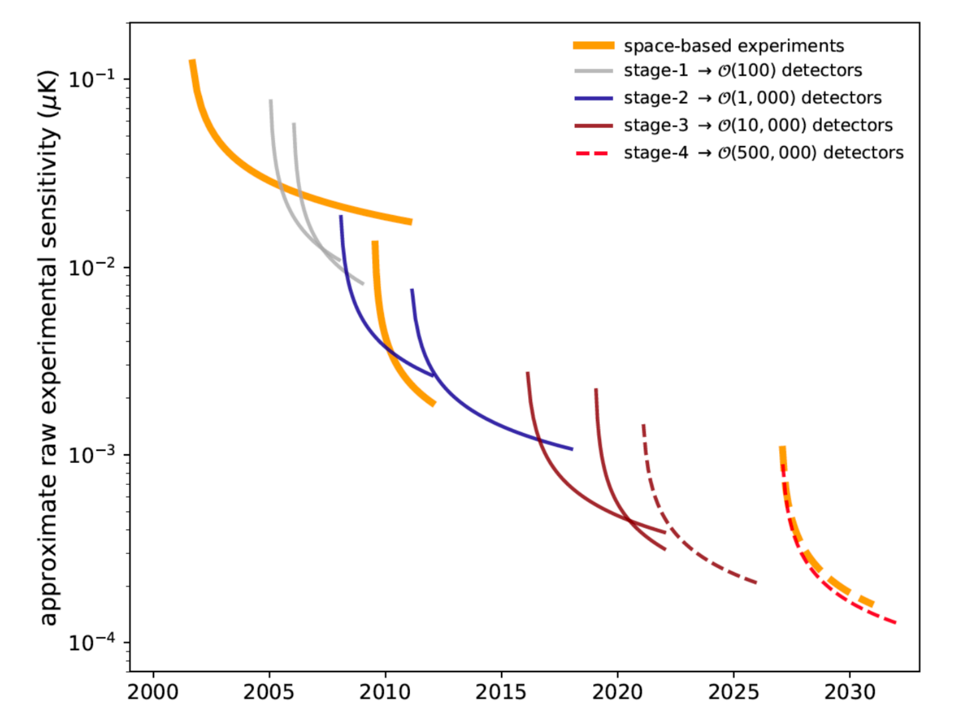
We translated the bounds on the phenomenological parameters $\beta^2_{AF,T}$, $\beta^2_{AF,S}$ and β^2_F into constraints on the LV couplings k_{AF} and $k_F$appearing in the action.

Dataset	Model (ΛCDM+)	$\lvert k^{(3)}_{(V)00}\rvert \times 10^{44}$ (GeV)	$\lvert \mathbf{k_{AF}}\rvert \times 10^{44}$ (GeV)	$k_{F,E+B} \times 10^{31}$
Planck	$\beta^2_{AF,T}+\beta^2_{AF,S}$	< 6.81	< 3.31	-
Planck	$r+\beta^2_{AF,T}+\beta^2_{AF,S}$	< 5.96	< 2.86	-
Planck+BK18	$r+\beta^2_{AF,T}$	< 1.71	-	-
Planck+BK18	$r+\beta^2_{AF,S}$	-	< 0.83	-
Planck+BK18	$r+\beta^2_{AF,T}+\beta^2_{AF,S}$	< 1.56	< 0.77	-
Planck+BK18	$r+\beta^2_F$	-	-	< 2.31
Planck+BK18	$r+\beta^2_{AF,T}+\beta^2_{AF,S}+\beta^2_F$	< 1.56	< 0.77	< 2.27
Planck+BK18+ACT	$r+\beta^2_{AF,T}$	< 1.66	-	-
Planck+BK18+ACT	$r+\beta^2_{AF,S}$	-	< 0.81	-
Planck+BK18+ACT	$r+\beta^2_{AF,T}+\beta^2_{AF,S}$	< 1.55	< 0.76	-
Planck+BK18+ACT	$r+\beta^2_F$	-	-	< 2.35
Planck+BK18+ACT	$r+\beta^2_{AF,T}+\beta^2_{AF,S}+\beta^2_F$	< 1.54	< 0.74	< 2.31

Margherita Lembo - margherita.lembo@unife.it

Summary and future prospects

- We perform a comprehensive study of the signatures of Lorentz violation in electrodynamics on the CMB anisotropies. In the framework of the minimal SME, we consider effects generated by renormalizable operators, both CPT-odd and CPT-even, responsible for sourcing, respectively, cosmic birefringence and circular polarization.
- Our constraints on the LV parameters are roughly one and two order-of-magnitude tighter than the previous ones. For the previous constraints, see Tables D15 and D16 of Kostelecky&Russell (arXiv:0801.0287)
- Enhancing the sensitivity on V-modes will likely yield to stronger constraints. This will allow to disentangle the effects of the phenomenological $\beta^2_{F,E}$ and $\beta^2_{F,B}$ parameters. It is also possible to exploiting the coupling between total intensity and circular polarisation introduced by a non-ideal HWP (PhD student in Ferrara, Nicolò Rafuzzi is working on this).
- Forthcoming CMB experiments will largely improve our sensitivity on such extensions of the standard electrodynamics, thanks to unprecedented sensitivity to linear CMB polarization. A rough estimate gives a factor of 5 improvement on the physical coefficients in the LV action (assuming that the constraints on the β^2s are dominated by B-mode measurements).



Credits: SO collaboration