VINCOLI COSMOLOGICI SU BIRIFRANGENZA

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(*in-vacuo*) BIREFRINGENCE

The two helicity states of electromagnetic waves have *different phase velocities :* $\omega_\pm = \omega_0 \pm \delta\omega$

$$\vec{E}_\pm = \Re\left((\hat{e}_1 \pm \imath\hat{e}_2)\, e^{\imath\left(\omega_\pm t - \vec{k}\cdot\vec{x}\right)}\right)$$

→ *linearly polarized radiation* rotates polarization direction during propagation

$$\alpha(t) = \delta\omega \cdot t$$

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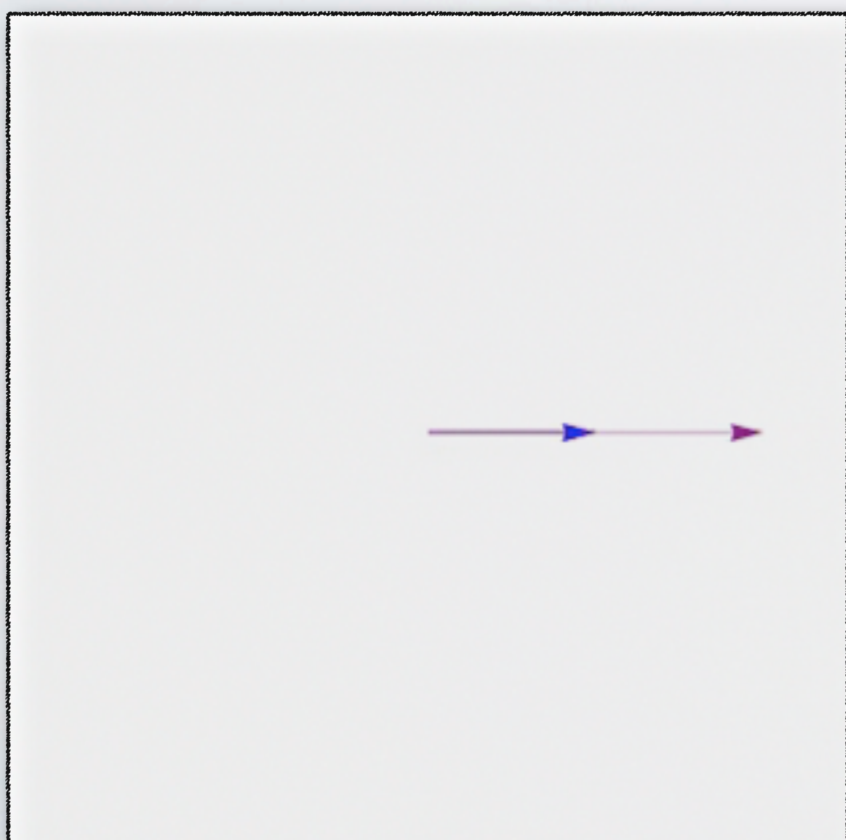

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MECHANISMS FOR BIREFRINGENCE

- Chern-Simons correction to Electrodynamics Lagrangian[1]

$$\mathcal{L}_{CS} \sim p_\mu A_\nu \tilde{F}^{\mu\nu}$$

- interaction of photons with axions[2]

$$\mathcal{L}_{int} \sim -\frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- *Quantum Gravity effects*

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[1]: S. M. Carroll, G. B. Field, R. Jackiw, Phys. Rev. D 41, 1231 (1990)

[2] : F. Finelli, M. Galaverni, Phys, Rev. D 79, 063002 (2009)

PLANCK-SCALE LORENTZ VIOLATIONS

- Planck-scale (QM and GR both non-negligible)

$$\longrightarrow \quad L_P \equiv \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35} m$$

- "quantum" properties of spacetime (symmetries)

→ *violation of Lorentz invariance*

- observable consequence:

→ *modified particle dispersion relations*

$$E \simeq p + \eta \frac{p^2}{E_P}$$

EFFECTIVE FIELD THEORY

- Effective field theory with mass-dimension 5 operators [1]

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2E_P}n^\alpha F_{\alpha\delta}n^\sigma\partial_\sigma\left(n_\beta\varepsilon^{\beta\delta\gamma\lambda}F_{\gamma\lambda}\right)$$

(n^α external four-vector)

- usually assume no space components for n^α:

$$n_\alpha = (n_0, 0, 0, 0)$$

$$\longrightarrow \quad \mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\xi}{2E_P}\varepsilon^{jkl}F_{0j}\partial_0 F_{kl} \qquad [\xi \equiv n_0^3]$$

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[1]: R.C. Myers, M. Pospelov, Phys, Rev. Lett. 90, 211601 (2003)

PLANCK-SCALE BIREFRINGENCE

- equation of motion from effective Lagrangian:

$$\left(-\omega^2 + p^2 \pm \frac{2\xi}{E_P}\omega^2 p\right) E_\pm = 0$$

(right- and left- circular polarizations)

→ *Planck-scale birefringent* dispersion law:

$$\omega_\pm = p \pm \frac{\xi}{E_P} p^2$$

- linear polarization rotation angle:

$$\alpha(T) = 2\frac{\xi}{E_p} p^2 T$$

→ suppressed by Planck scale <u>but:</u>

- linear in *propagation time T*
- quadratic in *photons energy p*

BIREFRINGENCE AND CMB

- CMB radiation ~10% linearly polarized
  (Thomson scattering of quadrupolar anisotropic radiation)

⟶ Stokes parameters: $Q \equiv E_x^2 - E_y^2$

$$U \equiv 2\Re\{E_x E_y^*\}$$

- effect of polarization rotation: $Q' = Q\cos(2\alpha) + U\sin(2\alpha)$

$$U' = U\cos(2\alpha) - Q\sin(2\alpha)$$

problems:
- Stokes parameters are frame dependent
- don't know original polarization direction

CMB POWER SPECTRA

- spin-two combinations: $(Q \pm iU)' = e^{\mp 2i\alpha}(Q \pm iU)$

$\longrightarrow$ spin-weighted spherical harmonics expansion

$$(Q \pm iU) = \sum_{\ell m} {}_{\pm 2}a_{\ell m} \; {}_{\pm 2}Y_{\ell m}$$

- parity-eigenstates construction:

$$E_{\ell m} \equiv \frac{1}{2}\left({}_{+2}a_{\ell m} + {}_{-2}a_{\ell m}\right)$$

$$B_{\ell m} \equiv \frac{1}{2i}\left({}_{+2}a_{\ell m} - {}_{-2}a_{\ell m}\right)$$

$\longrightarrow$

$$E = \sum_{\ell m} E_{\ell m} Y_{\ell m} \qquad \text{(odd)}$$

$$B = \sum_{\ell m} B_{\ell m} Y_{\ell m} \qquad \text{(even)}$$

- cross-correlation power spectra:

$$\mathcal{C}_\ell^{XY} \equiv \frac{1}{2\ell + 1} \sum_m < X^*_{\ell m} Y_{\ell m} > \qquad (X, Y = T, E, B)$$

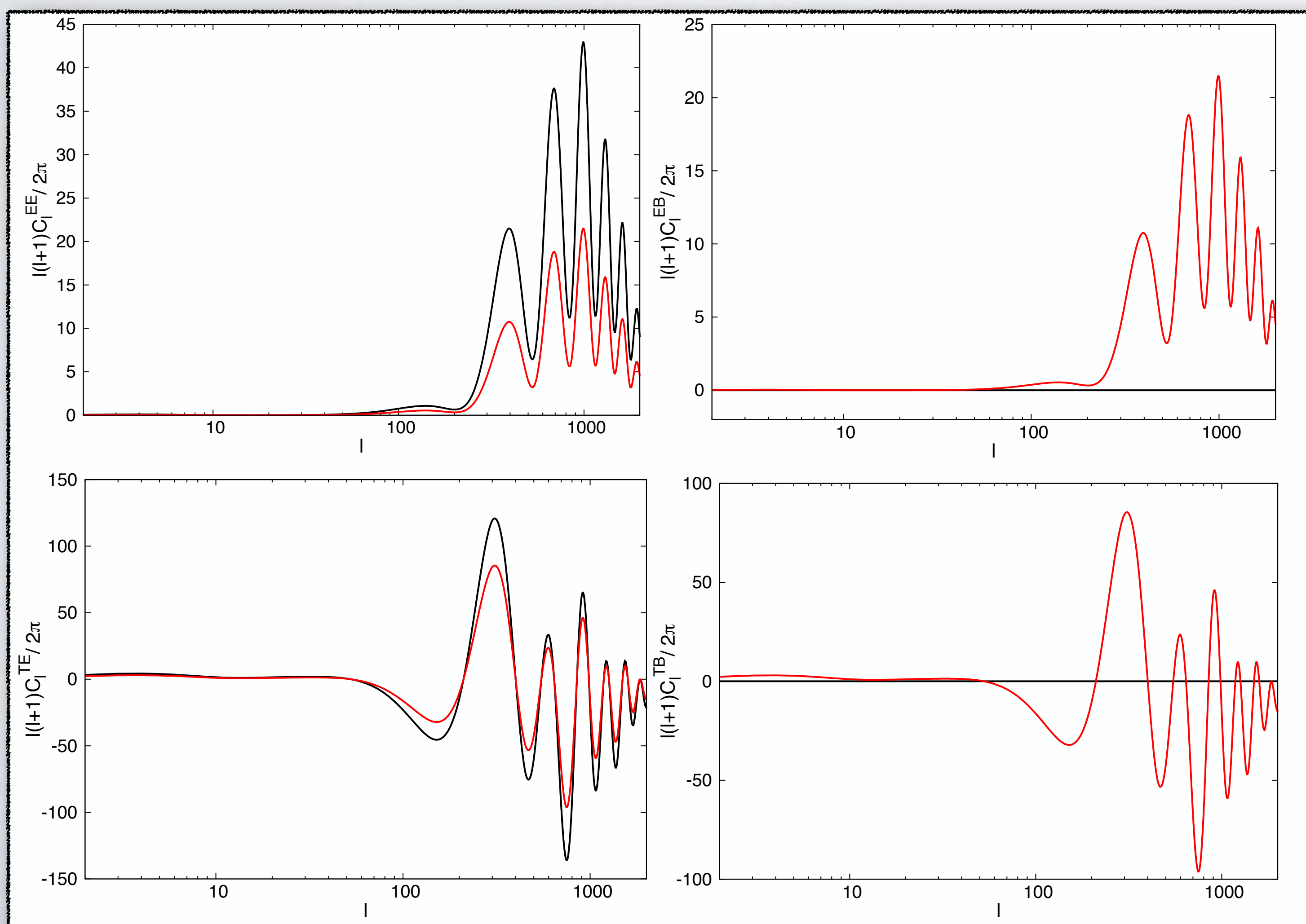
ROTATION OF POWER SPECTRA

- B modes are parity-even

  ⟶ standard physics can produce only E modes

- under rotation mixing of E and B modes

  ⟶ rotation of power spectra (TB and EB spectra become nonzero)



$$\mathcal{C}_\ell^{EE\,\prime} = \mathcal{C}_\ell^{EE}\cos^2(2\alpha) + \mathcal{C}_\ell^{BB}\sin^2(2\alpha)$$
$$\mathcal{C}_\ell^{BB\,\prime} = \mathcal{C}_\ell^{EE}\sin^2(2\alpha) + \mathcal{C}_\ell^{BB}\cos^2(2\alpha)$$
$$\mathcal{C}_\ell^{EB\,\prime} = \frac{1}{2}\left(\mathcal{C}_\ell^{EE} - C_\ell^{BB}\right)\sin(4\alpha)$$
$$\mathcal{C}_\ell^{TE\,\prime} = \mathcal{C}_\ell^{TE}\cos(2\alpha)$$
$$\mathcal{C}_\ell^{TB\,\prime} = \mathcal{C}_\ell^{TE}\sin(2\alpha)$$

DATA ANALYSIS

Rotation angle depends (quadratically) on energy:

- consider energy redshift $\omega(z) = (1+z)\,\omega(0)$

$$\longrightarrow \quad \alpha(z) = 2\frac{\xi}{E_P}\frac{p_0^2}{H_0}\int_0^z \frac{1+z'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz'$$

- exploit different energy channels to improve constraints (*cannot average* α *on different energies !*)

Method:

- data from WMAP5 (94 GHz) and BOOMERanG03 (145 GHz)
- best-fit analysis on power spectra (including TB and EB) adding α to standard set of parameters

RESULTS

Experiment	$\alpha \pm \sigma(\alpha)$	$\xi \pm \sigma(\xi)$
WMAP (94 GHz)	-1.6 ± 2.1	-0.09 ± 0.12
BOOMERanG (145 GHz)	-5.2 ± 4.0	-0.123 ± 0.096
WMAP +BOOMERanG	--	-0.110 ± 0.075

- CMB data do have Planck-scale sensitivity
- first limit on ξ from cosmological data

G. Gubitosi L. Pagano, G. Amelino-Camelia, A. Melchiorri, A. Cooray, JCAP (2009)

FORECASTS

Significant improvement of limits on ξ, thanks also to multifrequency data availability

Experiment	Channel (GHz)	$\sigma(\alpha)$	$\sigma(\xi)$
PLANCK	70	0.64	$6.0 \cdot 10^{-2}$
	100	0.14	$6.5 \cdot 10^{-3}$
	143	0.073	$1.7 \cdot 10^{-3}$
	217	0.10	$1.0 \cdot 10^{-3}$
	all	--	$8.5 \cdot 10^{-4}$
EPIC	70	$2.1 \cdot 10^{-3}$	$1.9 \cdot 10^{-4}$
	100	$1.8 \cdot 10^{-3}$	$7.8 \cdot 10^{-5}$
	150	$1.5 \cdot 10^{-3}$	$2.9 \cdot 10^{-5}$
	220	$1.2 \cdot 10^{-3}$	$1.1 \cdot 10^{-5}$
	all	--	$1.0 \cdot 10^{-5}$
CVL	150	$6.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$
	217	$6.1 \cdot 10^{-4}$	$6.1 \cdot 10^{-6}$

SYSTEMATIC EFFECTS

- misleading rotation from bad orientation of polarimeters

⟶ check how much a miscalibration could affect the results

- consider realistic miscalibration of BOOMERanG polarimeters (*0.9* ± *0.7*)°

⟶ new estimate on α [1]

$$\alpha = (-4.3 \pm 4.1)^\circ$$

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[1] L. Pagano, *et al.*, Phys. Rev. D80 (2009) 043522