Planck-scale induced birefringence and the CMB

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JCAP **0908** (2009) 021 [arXiv: 0904.3201]

Modified dispersion relations

quantum spacetime $\rightsquigarrow$ "quantum" spacetime symmetries

[Amelino-Camelia + Majid, IJMP **A15** (2000), Gambini + Pullin, PRD **59** (1999)]

$\rightsquigarrow$ Dispersion relation modifications governed by the Planck scale $[E_p \simeq 10^{28} eV]$

$$E^2 = p^2 + m^2 + \Delta_{QG}(p, m, E_p)$$

(with $\Delta_{QG} \xrightarrow{E_p \to \infty} 0$ and $\Delta_{QG} \xrightarrow{p \to 0} 0$)

First-order correction to *massless* particles dispersion relation

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

(η can be either positive or negative)

(in-vacuo) Birefringence

Orthogonal polarization states of photons can behave differently:

$$E_{\pm} \simeq p + \eta_{\pm} \frac{p^2}{E_P}$$

If the polarization states are left/right circular and $\eta_+ = -\eta_-$
$\rightarrow$ The two helicity states of electromagnetic waves have
different phase velocities

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

$\rightarrow$ linearly polarized radiation rotates its polarization vector during propagation
$\Rightarrow$ *in-vacuo* birefringence

(as for light propagation through materials with chiral molecules, as sugar and quartz)

- R. Gambini and J. Pullin, Phys. Rev. D 59 (1999) 124021
- G. Amelino-Camelia, New J. Phys. 6 (2004) 188
- R.C. Myers, M.Pospelov, PRL 90 (2003) 211601

Effective field theory for in-vacuo birefringence

Modifications of photons dispersion relation of the form $\frac{p^2}{E_{Pl}}$ can be generated by an effective field thoery with mass-dimension five corrections to the Lagrangian of electrodynamics

Myers-Pospelov model: [R.C. Myers, M.Pospelov, PRL 90 (2003) 211601]

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

where n^{α} is an external four-vector (Lorentz invariance violated)
This is the only admissible correction term under a few simple assumptions

(quadratic, gauge invariant, one more derivative than kinetic term, Lorentz invariant (except for n^{α}), not reducible to lower-dimension operators, nor to a total derivative)

Myers-Pospelov model

MP assumed pure-time vector $n_\alpha = (n_0, 0, 0, 0)$:

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

→ violated invariance under boost transformation
preserved space isotropy

Quantum gravity intuition: ξ roughly of order one

Several astrophysical analyses on observable features of this model

· T. Jacobson, S. Liberati and D. Mattingly, Nature 424 (2003) 1019 [arXiv:astro-ph/0212190v2].
· G. Amelino-Camelia, New J. Phys. 6 (2004) 188 [arXiv:gr-qc/0212002].
· R. J. Gleiser and C. N. Kozameh, Phys. Rev. D 64 (2001) 083007 [arXiv:gr-qc/0102093].
· D. Mattingly, Living Rev. Rel. 8 (2005) 5 [arXiv:gr-qc/0502097].
· L. Maccione and S. Liberati, JCAP 0808 (2008) 027 [arXiv:0805.2548 [astro-ph]].

→ are CMBP data sensitive to the Planck scale?

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Birefringence emerging from MP Lagrangian

Modified Maxwell equations

$$\vec{\nabla}\cdot\vec{B}=0 \qquad \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t} \qquad \vec{\nabla}\times\vec{B}=\frac{\partial\vec{E}}{\partial t}+\frac{2\xi}{E_p}\frac{\partial^2\vec{B}}{\partial t^2} \qquad \vec{\nabla}\cdot\vec{E}=0$$

Dispersion law:

$$\omega_\pm = p\left(1\pm\frac{\xi}{E_p}p\right)$$

$\rightarrow$ Polarization rotation angle (if radiation initially linearly polarized):

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

Planck-scale Birefringence and CMB

CMB photons are known to be $\sim$ 10% linearly polarized

- free streaming toward us since when the universe was $\sim 350000\ yr$ old
  $\rightarrow$ large accumulation of the polarization rotation effect
- α depends on energy $\rightarrow$ must consider energy redshift
  $\omega(z) = (1+z)\omega(0)$

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

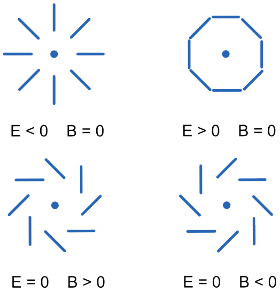
[assuming standard Λ-CDM cosmological model]

Measuring rotation

Polarization can be decomposed
into “Electric” and “Magnetic” modes:

$$E(\hat{n}) = \sum_{lm} E_{lm} Y_{lm}(\hat{n}) \quad \text{even under parity}$$

$$B(\hat{n}) = \sum_{lm} B_{lm} Y_{lm}(\hat{n}) \quad \text{odd under parity}$$



Density perturbations are scalars
→ can produce only E-modes of polarization

Rotation of original polarization generates B-modes

Cross-Correlation Power Spectra

→ tool of analysis:
cross-correlation power spectra

$$C_l^{XY} = \frac{1}{2l+1} \sum_m < X_{lm}^* Y_{lm} >, \quad X, Y = T, E, B$$

if a rotation occurs:

$$\begin{aligned}
C_\ell^{EE} &= \tilde{C}_\ell^{EE} \cos^2(2\alpha) + \tilde{C}_\ell^{BB} \sin^2(2\alpha) \\
C_\ell^{BB} &= \tilde{C}_\ell^{EE} \sin^2(2\alpha) + \tilde{C}_\ell^{BB} \cos^2(2\alpha) \\
C_\ell^{EB} &= \frac{1}{2}\left(\tilde{C}_\ell^{EE} - \tilde{C}_\ell^{BB}\right) \sin(4\alpha) \\
C_\ell^{TE} &= \tilde{C}_\ell^{TE} \cos(2\alpha) \\
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Effects of rotation on power spectra

BLACK: standard spectra
RED: spectra resulting from a total rotation of 30°

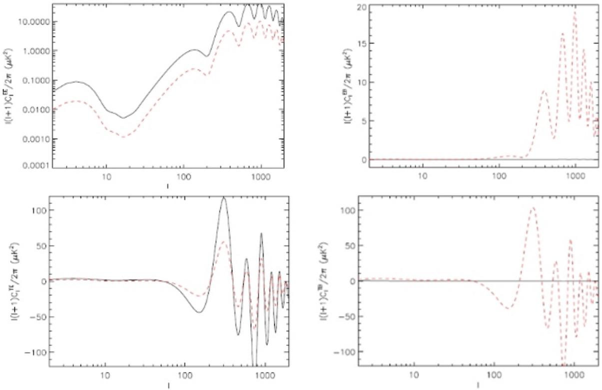

Figure: EE, TE, EB and TB spectra (from top to bottom and left to right)

Analysis on recent experiments data

Data from WMAP5 (94GHz) and Boomerang (145GHz)

· E. Komatsu et al. [WMAP Collaboration], arXiv:astro-ph/0803.0547

· C. J. MacTavish et al., arXiv:astro-ph/0507503

- α is energy-dependent, we cannot give a WMAP+BOOMERANG joint estimation on it, but a joint estimation is useful for ξ, wich does not depend on energy.

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

$[\alpha \propto \frac{\xi}{E_p} p_0^2]$

GG, L. Pagano, G. Amelino-Camelia, A. Melchiorri, A. Cooray, JCAP (2009) [arXiv: 0904.3201]

At 95% confidence level:

$$-0.260 < \xi < 0.040$$

First limit on ξ in CMB reference frame

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Check on systematic effects

- Misleading detection of rotation can be due to a miscalibration of polarimeters (bad orientation)
  $\Rightarrow$ check how much a miscalibration could have influenced our result
- we considered a realistic miscalibration of BOOMERANG polarimeters of $(0.9 \pm 0.7)^\circ$

$\Rightarrow$ new estimate on α from BOOMERANG:

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

L. Pagano *et al.* Phys.Rev.**D80** (2009) 043522 [arXiv:0905.1651]

$\Rightarrow$ new estimate on ξ (including WMAP)

$$\xi = 0.097 \pm 0.075$$

Forecasts on future experiments

Future experiments will be able to significantly improve limits on ξ, thanks also to multi-frequency data availability (disentanglement from other effects)

Experiment	Channel	$\sigma(\alpha)$	$\sigma(\xi)$
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	$1.0 \cdot 10^{-3}$
	100+143+217	-	$8.5 \cdot 10^{-4}$
Spider	145	0.27	$6.1 \cdot 10^{-3}$
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	$1.2 \cdot 10^{-3}$	$1.1 \cdot 10^{-5}$
	70+100+150+220	-	$1.0 \cdot 10^{-5}$
CVL	150	$6.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$
	217	$6.1 \cdot 10^{-4}$	$6.1 \cdot 10^{-6}$

Table: Expected 1σ error for PLANCK $70, 100, 143, 217$ GHz, Spider 145 GHz, EPIC $70, 100, 150, 220$ GHz and two ideal CVL experiment at 150 GHz and 217 GHz on α (in degrees) and ξ.

GG, L.Pagano, G.Amelino-Camelia, A.Melchiorri, A.Cooray, JCAP (2009) [arXiv: 0904.3201]

Reference frame issue

- very strong limits on ξ coming from astrophysical analyses (GRBs: $|\xi| \lesssim 2 \times 10^{-7}$, Crab Nebula observations:$|\xi| \lesssim 10^{-9}$) .
  L.Maccione,S.Liberati,A.Celotti,J.G.Kirk,P.Ubertini Phys.Rev.**D78** (2008) 103003 [arXiv:astro-ph/0809.0220]
- but $\xi = n_0^3 \rightarrow$ related to the time-component of a 4-vector
  $\rightarrow$ can't give an absolute limit on the parameter
  (one may have $n_\alpha \sim (0, 1, 1, 1)$ in one reference frame and $n_\alpha \sim (10^{-3}, 1, 1, 1)$ in another moving with velocity $\beta = 10^{-3}$)

$\rightarrow$ need informations on the other components of the vector to compare results

(see GG, G. Genovese, G.Amelino-Camelia, A.Melchiorri [arXiv: :1003.0878])

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Conclusions and Outlook

- CMB data do gain sensitivity to Planck scale
- peculir energy dependence of Planck-scale birefringence
- CMB covers entire sky $\rightsquigarrow$ test anisotropic LIV effects (work in progress)