Cosmic Polarization Rotation and Pseudoscalar-Photon Interaction

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Related talk and Poster: Gruppuso, Planck constraints on parity and birefringence

S. di Serego Alighieri and WTN, Searches for CPR (Poster)

Ref.: [1] W.-T. Ni, PLA 378 (2014) 1217-1223; RoPP 73 (2010) 056901

[2] W.-T. Ni, Dilaton field and cosmic wave propagation, PLA 378 (2014) 3413

*[3] S. di Serego Alighieri, W.-T. Ni and W.-P. Pan, Astrophys. J. **792**, 35 (2014).*

Outline

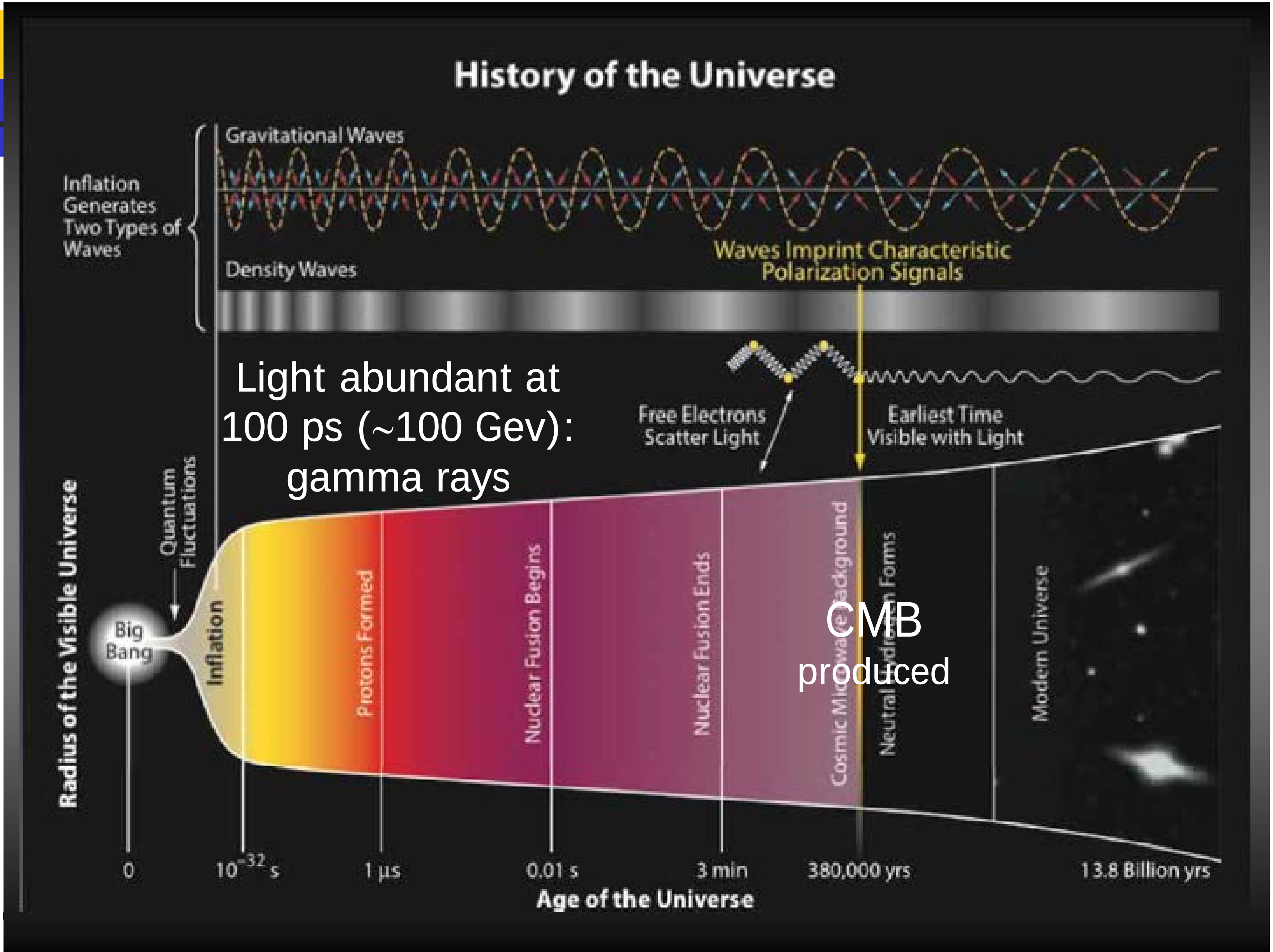
- Introduction – 3 processes to produce B-mode
- Equivalence Principles, Electromagnetism, & the Cosmic Connection – Axion, Dilaton and Skewon
- Photon sector

  Nonbirefingence

  axion, dilaton, skewon

  variation of fundamental constants?
- Observational constraints on CPR
- Summary

Let there be light!



B-mode production: 3 processes

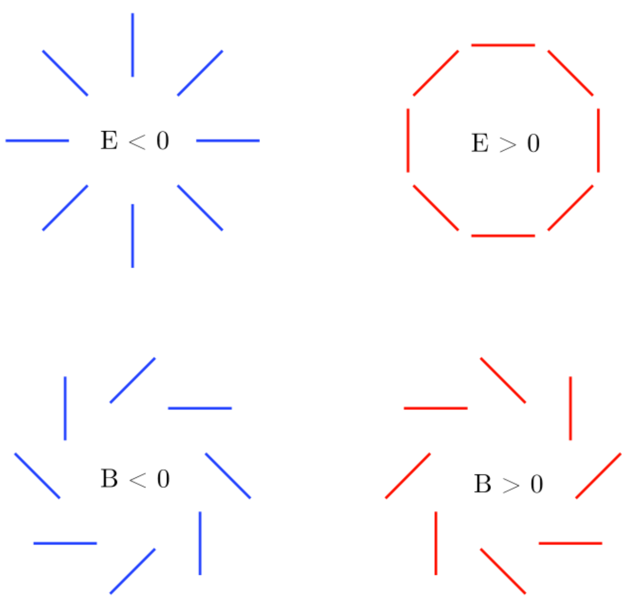
- (i) gravitational lensing from E-mode polarization (Zaldarriaga & Seljak 1997),
- (ii) local quadrupole anisotropies in the CMB within the last scattering region by large scale GWs (Polnarev 1985)
- (iii) cosmic polarization rotation (CPR) due to pseudoscalar-photon interaction (Ni 1973; for a review, see Ni 2010).

(iv) dust alignment

Propagation effect due to changing Pseudoscalar: the gradient gives a vector→ Chern-Simon theory

With an extra field as external field, the cosmos can have P, CPT and Lorentz asymmetrry

(The CPR has also been called Cosmological Birefringence)



Light, WEP I, WEP II & EEP

- Light is abundant since 100ps (Electroweak phase trans.) or earlier after Big Bang
- Galileo EP (WEP I) for photon: the light trajectory is dependent only on the initial direction – no splitting & no retardation/no advancement, independent of polarization and frequency
- WEP II, no polarization rotation
- EEP, no amplification/no attenuation, no spectral distortion

The ISSUE

(Why Minkowski Metric? from gravity point of view)

- How to derive spacetime structrure/the lightcone from classical, local and linear electrodynamics
- (i) the closure condition
- (ii) The Galileo weak equivalence principle
- (iii) The non-birefringence (vanishing double refraction) and "no amplification/dissipation" condition of astrophysical/cosmological electromagnetic wave propagation from observations

Premetric formulation of electromagnetism

- In the historical development, special relativity arose from the invariance of Maxwell equations under Lorentz transformation.
- In 1908, Minkowski [1] further put it into 4-dimensional geometric form with a metric invariant under Lorentz transformation.
- The use of metric as dynamical gravitational potential [2] and the employment of Einstein Equivalence Principle for coupling gravity to matter [3] are two important cornerstones to build general relativity
- In putting Maxwell equations into a form compatible with general relativity, Einstein noticed that the equations can be formulated in a form independent of the metric gravitational potential in 1916 [5,6].
- Weyl [7], Murnaghan [8], Kottler [9] and Cartan [10] & Schrödinger further developed and clarified this resourceful approach.

Metric-Free and Connection-Free

- Maxwell equations for macroscopic/spacetime electrodynamics in terms of independently measurable field strength F_{kl} (***E***, ***B***) and excitation (density with weight +1) H^{ij} (***D***, ***H***) do not need metric as primitive concept (See, e. g., Hehl and Obukhov [11]):
- $$H^{ij}{}_{,j} = -\,4\pi\, J^i, \qquad e^{ijkl}F_{jk,l} = 0, \qquad (1)$$
- with J^k the charge 4-current density and e^{ijkl} the completely anti-symmetric tensor density of weight +1 with $e^{0123} = 1$. We use units with the light velocity c equal to 1.To complete this set of equations, a constitutive relation is needed between the excitation and the field:
- $$H^{ij} = \chi^{ijkl}\, F_{kl}. \qquad (2)$$

Constitutive relation : $H^{ij} = \chi^{ijkl} F_{kl}$.

Since both H^{ij} and F_{kl} are antisymmetric, χ^{ijkl} must be antisymmetric in i and j, and k and l. Hence χ^{ijkl} has 36 independent components.

- Principal part: 20 degrees of freedom
- Axion part: 1 degree of freedom

  (Ni 1973,1974,1977; Hehl et al. 2008 Cr2O3)
- Skewon part: 15 degrees of freedom

  (Hehl-Ohbukhov-Rubilar skewon 2002)

$$\chi^{ijkl} = {}^{(\mathrm{P})}\chi^{ijkl} + {}^{(\mathrm{Sk})}\chi^{ijkl} + {}^{(\mathrm{A})}\chi^{ijkl}, \qquad (\chi^{ijkl} = -\,\chi^{jikl} = -\,\chi^{ijlk})$$

$$\begin{aligned}
{}^{(\mathrm{P})}\chi^{ijkl} &= (1/6)[2(\chi^{ijkl} + \chi^{klij}) - (\chi^{iklj} + \chi^{ljik}) - (\chi^{iljk} + \chi^{jkil})], \\
{}^{(\mathrm{A})}\chi^{ijkl} &= \chi^{[ijkl]} = \varphi\, e^{ijkl}, \\
{}^{(\mathrm{Sk})}\chi^{ijkl} &= (1/2)\,(\chi^{ijkl} - \chi^{klij}),
\end{aligned}$$

Related formulation in the photon sector: SME & SMS

- The photon sector of the SME Lagrangian is given by $\mathcal{L}_{\text{photon}}{}^{\text{total}} = -\,(1/4)\, F_{\mu\nu}\, F^{\mu\nu} - (1/4)\, (k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda}\, F^{\mu\nu} + (1/2)\, (k_{AF})^{\kappa} \varepsilon_{\kappa\lambda\mu\nu} A^{\lambda} F^{\mu\nu}$ (equation (31) of [7]). The CPT-even part ($-(1/4)\, (k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda}\, F^{\mu\nu}$) has constant components $(k_F)_{\kappa\lambda\mu\nu}$ which correspond one-to-one to our χ's when specialized to constant values minus the special relativistic χ with the constant axion piece dropped, i.e. $(k_F)^{\kappa\lambda\mu\nu} = \chi^{\kappa\lambda\mu\nu} - (1/2)\, (\eta^{\kappa\mu}\, \eta^{\lambda\nu} - \eta^{\kappa\nu}\, \eta^{\lambda\mu})$. The CPT-odd part $(k_{AF})^{\kappa}$ also has constant components which correspond to the derivatives of axion $\varphi,^{\kappa}$ when specilized to constant values.
- SMS in the photon sector due to Bo-Qiang Ma is different from both SME and $\chi^{\kappa\lambda\mu\nu}$-framework.

The ISSUE

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Skewonless case: EM wave propagation

Since our galactic Newtonian potential U is of the order of 10^{-6}, we use weak field approximation in the χ-g framework. The vacuum Maxwell equation, derived from the Lagrangian (9), is

$$(\chi^{ijk\ell}A_{k,\ell})_{,j} = 0. \quad (19)$$

Neglecting $\chi^{ijk\ell}{}_{,p}$ in slowly varying field, (19) becomes

$$\chi^{ijk\ell}A_{k,\ell j} = 0. \quad (20)$$

For weak field, we assume

$$\chi^{ijk\ell} = \chi^{(o)ijk\ell} + \chi^{(1)ijk\ell}, \quad (21)$$

where

$$\chi^{(o)ijk\ell} = \frac{1}{2}\eta^{ik}\eta^{j\ell} - \frac{1}{2}\eta^{i\ell}\eta^{kj} \quad (22)$$

with η^{ij} the Minkowski metric and $|\chi^{(1)}\text{'s}| \ll 1$.

Dispersion relation and Nonbirefringence condition

B. Conditions for gravitational nonbirefringence —— Photons propagate along a metric H_{ik}

Using eikonal approximation, we look for plane-wave solution propagating in the z-direction. Imposing radiation condition in the zeroth order and solving the dispersion relation for ω, we obtain

$$\omega_{\pm} = k \{1 + \tfrac{1}{4}[(K_1+K_2) \pm \sqrt{(K_1-K_2)^2+4K^2}]\} \tag{23}$$

where

$$\begin{aligned} K_1 &= \chi^{(1)1010} - 2\chi^{(1)1013} + \chi^{(1)1313}, \\ K_2 &= \chi^{(1)2020} - 2\chi^{(1)2023} + \chi^{(1)2323}, \\ K &= \chi^{(1)1020} - \chi^{(1)1023} - \chi^{(1)1320} + \chi^{(1)1323}. \end{aligned} \tag{24}$$

Photons with two different polarizations propagate with different speed $v_{\pm} = \frac{\omega_{\pm}}{k}$ and would split in 4-dimensional spacetime. The conditions for no splitting (no retardation) is $\omega_+ = \omega_-$, i.e.

$$K_1 = K_2 \;, \quad K = 0. \tag{25}$$

(25) gives two constraints on $\chi^{(1)}$'s.

The conditions for no splitting (no retardation) of electromagnetic waves propagating in every direction give the following ten constraints on $\chi^{(1)}$'s:

$$\chi^{(1)1220} = \chi^{(1)1330},$$
$$\chi^{(1)2330} = \chi^{(1)2110},$$
$$\chi^{(1)3110} = \chi^{(1)3220},$$
$$\chi^{(1)1020} = -\chi^{(1)1323},$$
$$\chi^{(1)2030} = -\chi^{(1)2131},$$
$$\chi^{(1)3010} = -\chi^{(1)3212},$$
$$\chi^{(1)1320} = -\chi^{(1)1230},$$
$$\chi^{(1)1320} = -\chi^{(1)2310},$$
$$\chi^{(1)1010} + \chi^{(1)1313} = \chi^{(1)2020} + \chi^{(1)2323},$$
$$\chi^{(1)1010} + \chi^{(1)1212} = \chi^{(1)3030} + \chi^{(1)3232}.$$

ne $H^{(1)ij}$, ψ and ϕ as

$$H^{(1)10} \equiv H^{(1)01} \equiv -2\chi^{(1)1220},$$
$$H^{(1)20} \equiv H^{(1)02} \equiv -2\chi^{(1)2330},$$
$$H^{(1)30} \equiv H^{(1)03} \equiv -2\chi^{(1)3110},$$
$$H^{(1)12} \equiv H^{(1)21} \equiv -2\chi^{(1)1020},$$
$$H^{(1)23} \equiv H^{(1)32} \equiv -2\chi^{(1)2030},$$
$$H^{(1)31} \equiv H^{(1)13} \equiv -2\chi^{(1)3010},$$
$$H^{(1)11} \equiv 2\chi^{(1)2020} + 2\chi^{(1)2121} - H^{(1)00},$$
$$H^{(1)22} \equiv 2\chi^{(1)3030} + 2\chi^{(1)3232} - H^{(1)00},$$
$$H^{(1)33} \equiv 2\chi^{(1)1010} + 2\chi^{(1)1313} - H^{(1)00},$$
$$\psi \equiv 1 + 2\chi^{(1)1212} + \tfrac{1}{2}\eta_{00}(H^{(1)00} - H^{(1)11} - H^{(1)22} - H^{(1)33}) - H^{(1)11} - H^{(1)22},$$
$$\phi \equiv \chi^{(1)0123}.$$

Note that in these definitions $H^{(1)00}$ is not defined and free. It is straightforward to show that if the ten constraints (26) are satisfied then χ can be written to first-order in $\chi^{(1)}$'s in the form

$$\chi^{ijk\ell} = (-H)^{\frac{1}{2}}\left(\frac{1}{2}H^{ik}H^{j\ell} - \frac{1}{2}H^{i\ell}H^{kj}\right)\psi + \phi e^{ijk\ell}, \tag{28}$$

where

$$H^{ij} = \eta^{ij} + H^{(1)ij},$$

$$H = \det(H_{ij}), \tag{29}$$

$$H_{ij}H^{jk} = \delta^k_i,$$

and

$$e^{ijk\ell} = \begin{cases} 1, \text{ if } (ijk\ell) \text{ is an even permutation of } (0123), \\ -1, \text{ if } (ijk\ell) \text{ is an odd permutation of } (0123), \\ 0, \text{ otherwise.} \end{cases} \tag{30}$$

Table I. Constraints on the spacetime constitutive tensor χ^{ijkl} and construction of the spacetime structure (metric + axion field φ + dilaton field ψ) from experiments/observations in the skewonless case

Experiment	Constraints	Accuracy
Pulsar Signal Propagation Radio Galaxy Observation Gamma Ray Burst (GRB)	$\chi^{ijkl} \to \frac{1}{2}(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}]\psi + \varphi e^{ijkl}$	10^{-16} 10^{-32} 10^{-38}
CMB Spectrum Measurement	$\psi \to 1$	8×10^{-4}
Cosmic Polarization Rotation Experiment	$\varphi - \varphi_0\ (\equiv \alpha) \to 0$	$\lvert\langle\alpha\rangle\rvert < 0.02$, $\langle(\alpha - \langle\alpha\rangle)^2\rangle^{1/2} < 0.03$
Eötvös-Dicke-Braginsky Experiments	$\psi \to 1$ $h_{00} \to g_{00}$	10^{-10} 10^{-6}
Vessot-Levine Redshift Experiment	$h_{00} \to g_{00}$	1.4×10^{-4}
Hughes-Drever-type Experiments	$h_{ij} \to g_{ij}$ $h_{0i} \to g_{0i}$ $h_{00} \to g_{00}$	$10^{-18}\ U$ 10^{-13} -10^{-14} 10^{-10}

2014.
PLAN

Three approaches to Axions/Pseudoscalar-photon interactions

- Top down approach – string theory
- Bottom up approach – QCD axion
- Phenomenological approach -- gravitation

Table 1. Various terms in the Lagrangian and their meaning.

Term	Dimension	Reference	Meaning
$e^{\alpha\beta\gamma} A_\alpha F_{\beta\gamma}$	3	Chern–Simons (1974)	Intergrand for topological invariant
$e^{ijkl}\varphi F_{ij} F_{kl}$	4	Ni (1973, 1974, 1977)	Pseudoscalar-photon coupling
$e^{ijkl}\varphi F_{ij}^{\mathrm{QCD}} F_{kl}^{\mathrm{QCD}}$	4	Peccei–Quinn (1977) Weinberg (1978) Wilczek (1978)	Pseudoscalar-gluon coupling
$e^{ijkl} V_i A_j F_{kl}$	4	Carroll–Field–Jackiw (1990)	External constant vector coupling

φ: Pseudoscalar field or pseudoscalar function of gravitational or relevant fields

$$\mathcal{L}_{\text{int}} \sim p_\mu A_\nu \tilde{F}^{\mu\nu},$$

$$\approx \xi \varphi_{,\mu} A_\nu \tilde{F}^{\mu\nu}$$

$$\approx \xi\,(1/2)\,\varphi\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

(Mod Divergence)

Galileo EP ➔Electromagnetism: Charged particles and photons

Special Relativity

$$L_I = -(\frac{1}{16\pi})\eta^{ikjl}\eta^{jl}F_{ij}F_{kl} - A_k j^k(-g)^{1/2} - \sum_I m_I \frac{ds_I}{dt}\delta(x-x_I)$$

$\chi - g$ framework

$$L_I = -(\frac{1}{16\pi})\chi^{ijkl}F_{ij}F_{kl} - A_k j^k(-g)^{1/2} - \sum_I m_I \frac{ds_I}{dt}\delta(x-x_I)$$

Galileo EP constrains χ:

$$\chi^{ijkl} = (-g)^{1/2}[\frac{1}{2}g^{ik}g^{jl} - \frac{1}{2}g^{il}g^{kj} + \eta\,\phi\,\varepsilon^{ijkl}]$$

(Pseudo)scalar-Photon Interaction

Table II. 1st-order and 2nd-order constraints on various constitutive tensors from various experiments/observations.

Constitutive tensor	Birefringence (in the geometric optics approximation)	Dissipation/ amplification	Spectroscopic distortion	Cosmic polarization rotation
Metric: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}]$	No	No	No	No
Metric + dilaton: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}]\psi$	No (to all orders in the field)	Yes (dilaton gradient)	No	No
Metric + axion: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}] + \varphi e^{ijkl}$	No (to all orders in the field)	No	No	Yes (axion gradient)
Metric + dilaton + axion: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}]\psi + \varphi e^{ijkl}$	No (to all orders in the field)	Yes (dilaton gradient)	No	Yes (axion gradient)
Metric + type I skewon	No to first order	Yes	Yes	No
Metric + type II skewon	No to first order; yes to 2nd order	No to first order; no to 2nd order	No	No
Metric + ${}^{(P)}\chi^{(e)}$+ type II skewon	No to first order; no to 2nd order	No to first order; no to 2nd order	No	No
Asymmetric metric induced: ½ $(-g)^{1/2}(g^{ik}g^{jl} - g^{il}g^{jk})$	No (to all orders in the field)	No	No	Yes (axion gradient

The birefringence condition in Table I – historical background

netic wave propagation [29–32]. We constructed the relation (8) in the weak-violation/weak-field approximation of the Einstein Equivalence Principle (EEP) and applied to pulsar observations in 1981 [29–31]; Haugan and Kauffmann [32] reconstructed the relation (8) and applied to radio galaxy observations in 1995. After the cornerstone work of Lämmerzahl and Hehl [33], Favaro and Bergamin [34] finally proved the relation (8) without assuming weak-field approximation (see also Dahl [35]). Polarization measurements of

[24]). Recent polarization observations on gamma-ray bursts gives even better constraints on nonbirefringence in cosmic propagation [27,28]. The observation on the polarized gamma-ray burst GRB 061122 (z = 1.33) gives a lower limit on its polarization fraction of 60% at 68% confidence level (c.l.) and 33% at 90% c.l. on the 250-800 keV energy range [27]. The observation on the polarized gamma-ray burst GRB 140206A constrains the linear polarization level of the second peak of this GRB of 28 % at 90% c.l. on the 200-400 keV energy range [28]; the redshift of the source is measured from the GRB afterglow optical spectroscopy to be z = 2.739. Since birefringence is proportional to the wave vector k in our case, as gamma-ray of a particular frequency (energy) travels in the cosmic spacetime, the two linear polarization eigen modes would pick up small phase differences. A linear polarization mode from distant source resolved into these two modes will become elliptical during travel and lose part of the linear coherence. The way of gamma ray losing linear coherence depends on the frequency. For a band of frequency, the extent of losing frequency depends on the distance of travel. The depolarization distance is proportional to span Δf of the frequency band × the integral $I = \int(1 + z(t))dt$ of the redshift factor $(1 + z(t))$ with respect to the time of travel. For GRB 140206A, this is about

$$\Delta f\, I = \Delta f \int (1 + z(t))dt \approx 2 \times 10^{20}\ \mathrm{Hz} \times 10^{18}\ \mathrm{s} \approx 2 \times 10^{38}. \tag{21}$$

Empirical Nonbirefringence Constraint

Since we do observe linear polarization in the 202-400 kHz frequency band of GRB 140206A with lower bound of 28 %, this gives a fractional constraint of about 10^{-38} or better on a combination of χ's. A more detailed modeling would give better limit.

The distribution of GRBs is basically isotropic. When this procedure is applied to an ensemble of polarized GRBs from various directions, the relation (20) would be verified to 10^{-38} or better. For a more detailed discussion, please see [29].

$$\chi^{ijkl} = (-h)^{1/2}[(1/2)h^{ik}h^{jl} - (1/2)h^{il}h^{kj}]\psi + \varphi e^{ijkl}$$

- to 10^{-38}, i.e., less than $10^{-34} = O(M_w/M_{planck})^2$ a significant constraint on quantum gravity

Empirical foundations of the closure relation for the skewonless case

In terms of $\kappa_{ij}{}^{kl}$ (defined in (6)) and re-indexed $\kappa_I{}^J$, the constitutive tensor (20) is represented in the following forms:

$$\kappa_{ij}{}^{kl} = (1/2)\, \underline{e}_{ijmn}\, \chi^{mnkl} = (1/2)\, \underline{e}_{ijmn}\, (-h)^{1/2}\, h^{mk}\, h^{nl}\, \psi + \varphi\, \delta_{ij}{}^{kl}, \tag{22}$$

$$\kappa_I{}^J = (1/2)\, \underline{e}_{ijmn}\, (-h)^{1/2}\, h^{mk}\, h^{nl}\, \psi + \varphi\, \delta_I{}^J, \tag{23}$$

where $\delta_{ij}{}^{kl}$ is a generalized Kronecker delta defined as

$$\delta_{ij}{}^{kl} = \delta_i{}^k\, \delta_j{}^l - \delta_i{}^l\, \delta_j{}^k. \tag{24}$$

Less than 100 operations

The (generalized) closure relation is satisfied

$$\kappa_I{}^J\, \kappa_J{}^K = \delta_I{}^J\, [(1/2)\psi^2 + \varphi^2)] + {}^{(\mathrm{P})}\kappa_I{}^K\, \varphi = (1/2)\, \delta_I{}^J\, \psi^2 + 2\, \kappa_I{}^K\, \varphi.$$

From table I, this is verified to 10×10^{-38}

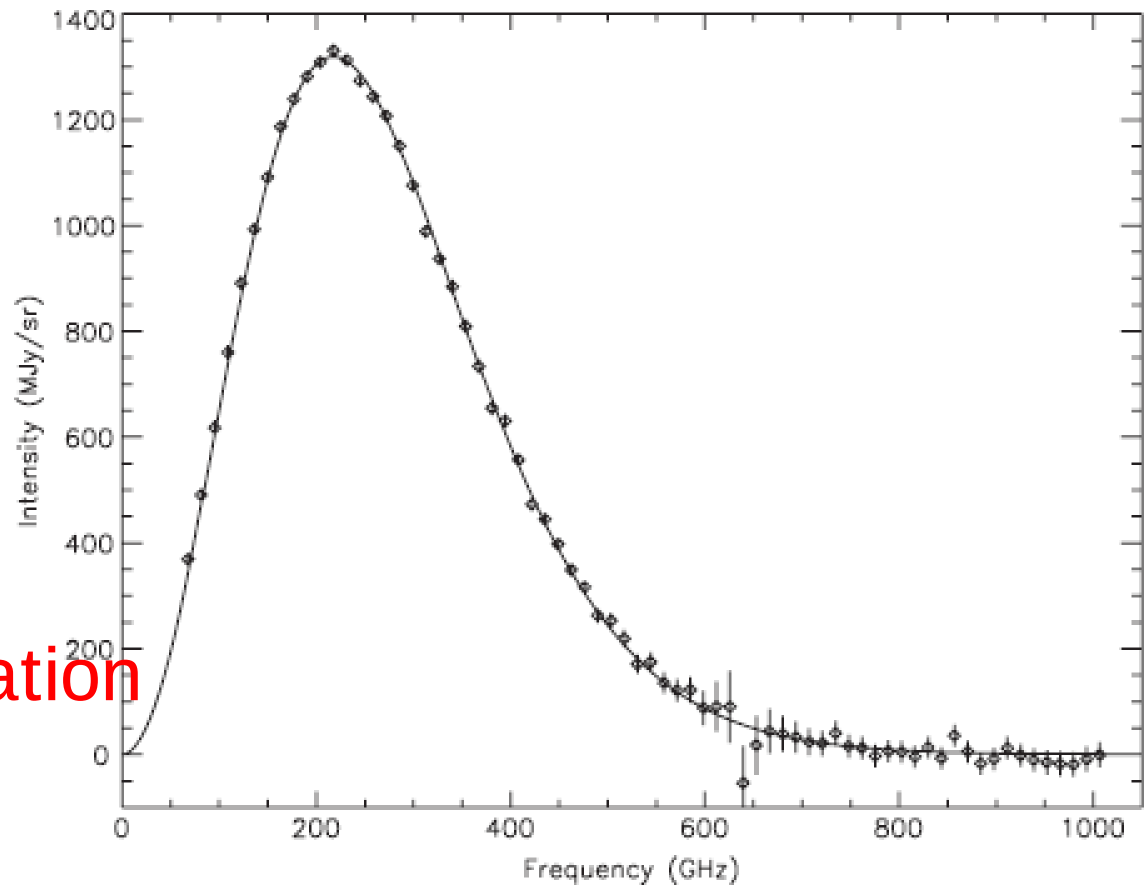
The Cosmic MW Background Spectrum: 2.7255 ± 0.0006 K

D. J. Fixsen, Astrophys. J. 707 (2009) 916

No amplification/
No attenuation
(No dilaton)

No distortion
(No Type I Skewon

Redshifted(Acceleration
Equivalent)



The cosmic microwave background radiation temperature at a redshift of 2.34

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Present & Past

$$\bar{T}(z) = \bar{T}(z=0)(1+z)$$

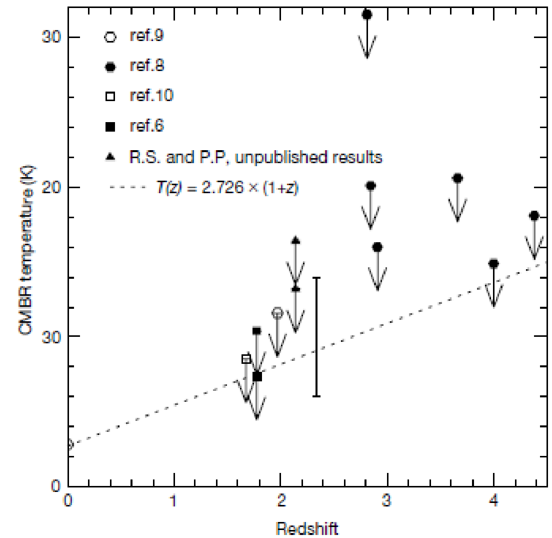
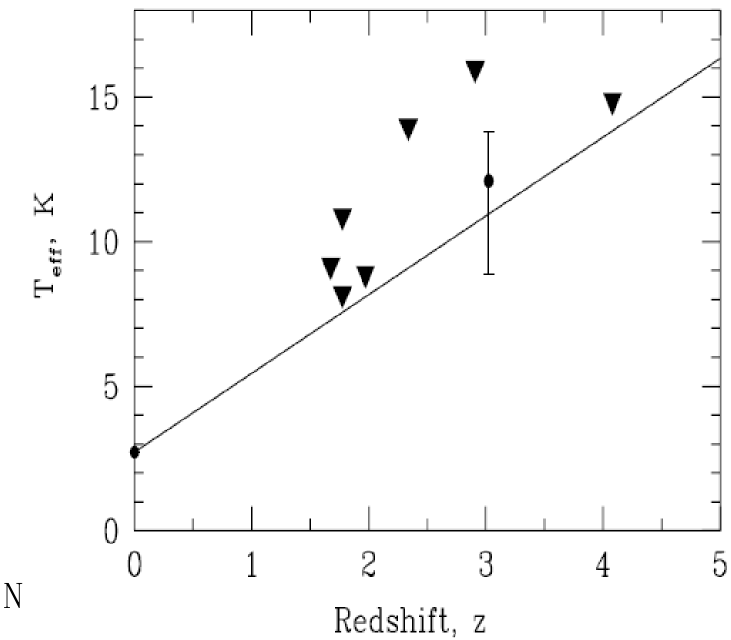


Figure 5 Measurements of the cosmic microwave background radiation temperature at various redshifts. The point at $z = 0$ shows the result of the Cosmic Background Explorer (COBE) determination[3], $T_{CMBR}(0) = 2.726 \pm 0.010$ K. Upper limits are previous measurements[3,8–10] using the same techniques as we did. We also include our two new unpublished upper limits at $z = 2.1394$ along the line of sight toward Tololo 1037−270. The measurement from this work, $6.0 < T_{CMBR} < 14.0$ K at $z = 2.33771$, is indicated by a vertical bar. The dashed line is the prediction from the hot Big Bang.

- 6.0K < T(2.33771) < 14K Prediction: 9.1 K(2000)
- The measurement is based on the excitation of the two first hyperfine levels of carbon (C and C+ induced by collisions and by the tail of the CMB photon distributions. Nature 2000

  (inconsistency : H2 and HD abundance measurement) (2001)
- **The cosmic microwave background radiation temperature at z = 3.025 toward QSO0347-3819, P Molaro et al Astronomy & Astrophysics 2002**
- Measurement of effective temperature at different redshift



Measurement of the T_{CMB} evolution from the Sunyaev-Zel'dovich effect

A & A 2014

G. Hurier[1], N. Aghanim[1], M. Douspis[1], and E. Pointecouteau[2,3]

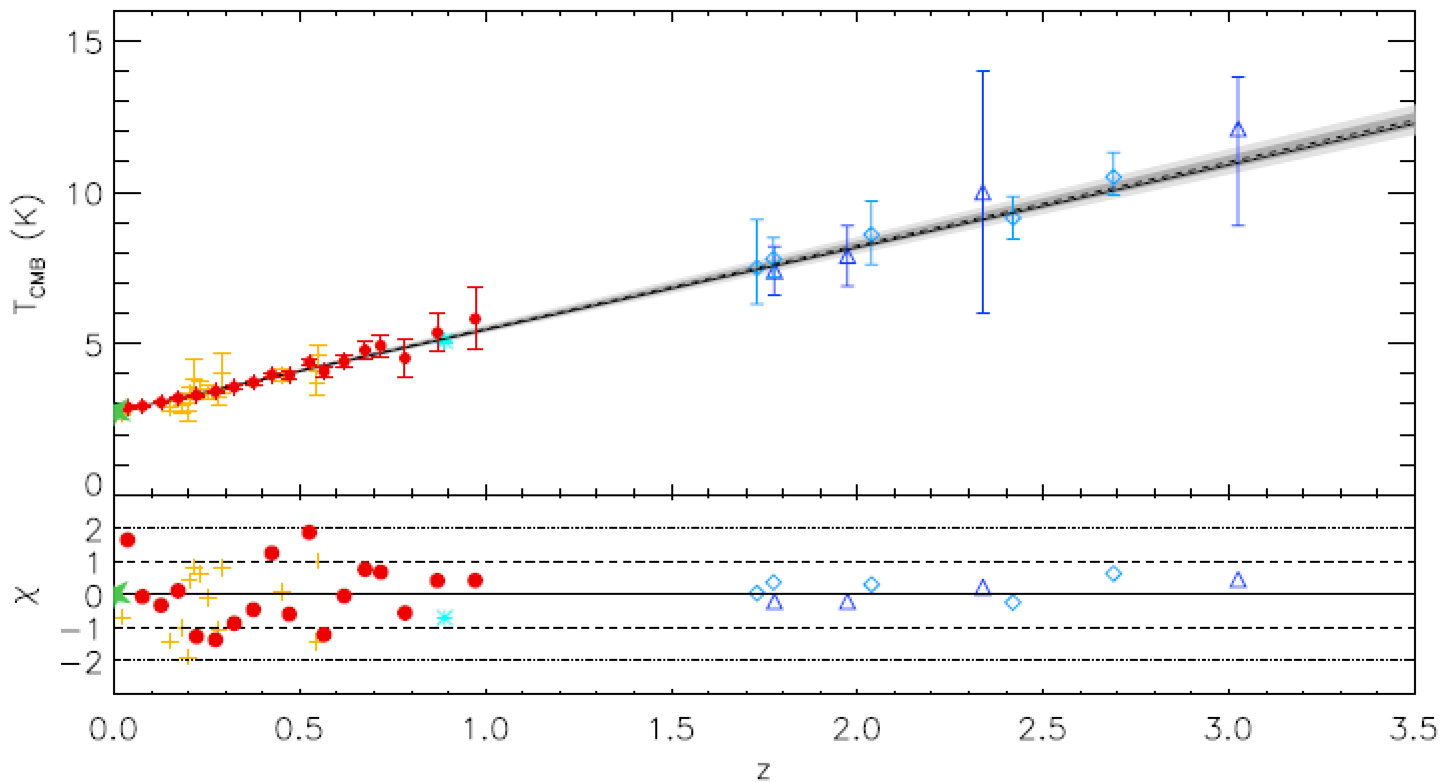


Fig. 8. *Top panel*: T_{CMB} as a function of redshift. The red filled circles represent T_{CMB} measured from the tSZ emission law in redshift bins of *Planck* clusters. The green star shows COBE-FIRAS measurement at $z = 0$ (Fixsen 2009). The orange crosses show T_{CMB} measurements using individual clusters (Battistelli et al. 2002; Luzzi et al. 2009). Dark-blue triangles represent measurements from C_I and C_{II} absorption (Cui et al. 2005; Ge et al. 1997; Srianand et al. 2000; Molaro et al. 2002) at $z = (1.8, 2.0, 2.3, 3.0)$. Blue diamonds show the measurements from CO absorption lines (Srianand et al. 2008; Noterdaeme et al. 2011), and finally the light-blue asterisk is the constraint from various molecular species analyses by Muller et al. (2013). The solid black line presents the standard evolution for T_{CMB} and the dashed black line represents our best-fitting model combining all the measurements. The 1 and 2σ envelopes are displayed as shaded dark and light-gray regions. *Bottom panel*: deviation from the standard evolution in units of standard deviation. The dashed and dotted black lines correspond to the 1 and 2σ levels.

In this section, we derive the electromagnetic wave propagation and the dispersion relation in dilaton and axion field. Let us begin with the general problem of wave propagation in electrodynamics (1a, 1b) with constitutive relation (2) for explaining and fixing the scheme. The sourceless Maxwell equation (1b) is equivalent to the local existence of a 4-potential A_i such that

$$F_{ij} = A_{j,i} - A_{i,j}, \tag{10}$$

with a gauge transformation freedom of adding an arbitrary gradient of a scalar function to A_i. The Maxwell equation (1a) in vacuum with (3) is then

$$(\chi^{ijkl} A_{k,l})_{,j} = 0. \tag{11}$$

Using the derivation rule, we have

$$\chi^{ijkl} A_{k,l,j} + \chi^{ijkl}{}_{,j} A_{k,l} = 0. \tag{12}$$

(i) For slowly varying, nearly homogeneous field/medium, and/or (ii) in the eikonal approximation with typical wavelength much smaller than the gradient scale and time-variation scale of the field/medium, the second term in (12) can be neglected compared to the first term, and we have

$$\chi^{ijkl} A_{k,lj} = 0. \tag{13}$$

This approximation is usually called the eikonal approximation. In this approximation, the dispersion relation is given by the generalized covariant quartic Fresnel equation (see, e.g. [9]). It is well-known that axion does not contribute to this dispersion relation [9,25,26,29–33]. Dilaton does not contribute to this dispersion relation either. The generalized Fresnel equation is algebraic and homogeneous in the wave covector. Since the dilaton only gives a multiplicative scalar factor in the equation, it does not change the dispersion relation.

To derive the influence of the dilaton field and the axion field on the dispersion relation, one needs to keep the second term in Eq. (12). This has been done for the axion field in Refs. [21,25,26, 37–39]. Here we develop it for the joint dilaton field and axion field. Near the origin in a local inertial frame, the constitutive tensor density in dilaton field ψ and axion field φ [Eq. (9)] becomes

$$\chi^{ijkl}(x^m) = [(1/2)\eta^{ik}\eta^{jl} - (1/2)\eta^{il}\eta^{kj}]\psi(x^m) + \varphi(x^m)e^{ijkl} + O(\delta_{ij}x^i x^j), \quad (14)$$

where η^{ij} is the Minkowski metric with signature -2 and δ_{ij} the Kronecker delta. In the local inertial frame, we use the Minkowski metric and its inverse to raise and lower indices. Substituting (14) into Eq. (12) and multiplying by 2, we have

$$\psi A^{i}{}_{,}{}^{j}{}_{j} + \psi A^{j}{}_{,}{}^{i}{}_{j} + \psi_{,j}A^{i}{}_{,}{}^{j} - \psi_{,j}A^{j}{}_{,}{}^{i} + 2\varphi_{,j}e^{ijkl}A_{k,l} = 0. \quad (15)$$

We notice that (15) is both Lorentz covariant and gauge invariant.

Results

derived that the amplitude and phase factor of propagation in the cosmic dilaton and cosmic axion field is changed by

$$(\psi(P_1)/\psi(P_2))^{1/2}\exp[ikz - ikt \pm (-i)(\varphi(P_1) - \varphi(P_2))t].$$

Constraint from CMB spectrum

$$|\Delta\psi|/\psi \leq 4(0.0006/2.7255) \approx 8 \times 10^{-4}. \qquad (33)$$

Direct fitting to the CMB data with the addition of the scale factor $\psi(P_1)/\psi(P_2)$ would give a more accurate value.

Dilaton and variation of constants

(v) In the very early universe, dilaton is sometimes postulated to explain the inflation. The implication of these inflation models to the subsequent evolution of dilaton field to the last scattering surface and thereafter should be thoroughly investigated as it could be assessable to experimental tests

- Fritzsch et al, variation of the fine structure constant (some astophysical observations)
- Shu Zhang & Bo-Qiang Ma, (Possible) Lorentz violation from gamma-ray bursts (~10 Gev)

$$E^2 = p^2c^2\left[1 - s_n\left(\frac{pc}{E_{LV,n}}\right)^n\right],$$

which corresponds to a modified light speed

$$v(E) = c\left[1 - s_n\frac{n+1}{2}\left(\frac{E}{E_{LV,n}}\right)^n\right],$$

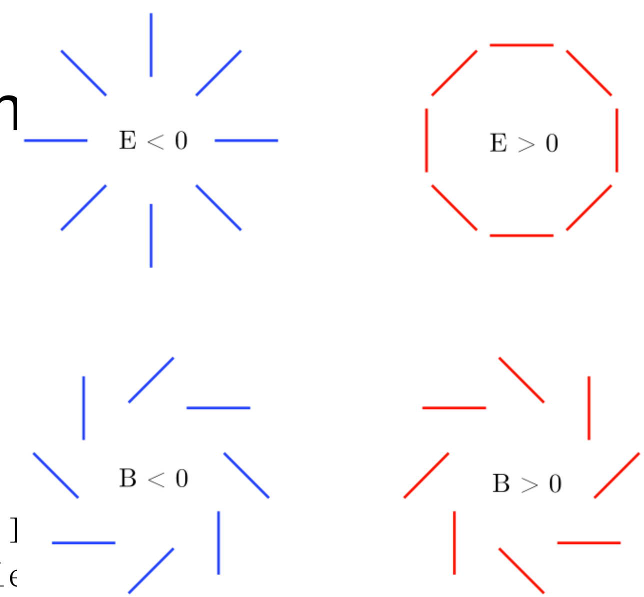
CMB observations

7 orders or more improvement in amplitude, 15 orders improvement in power since 1965

- **1948** Gamow – hot big bang theory; Alpher & Hermann – about 5 K CMB
- Dicke -- oscillating (recycling) universe: entropy → CMB
- **1965** Penzias-Wilson excess antenna temperature at 4.08 GHz 3.5±1 K 2.5 →4.5 (CMB temperature measurement)
- Precision to $10^{-(3\text{-}4)}$ → dipolar (earth) velocity measurement
- to $10^{-(5\text{-}6)}$ **1992** COBE anisotropy meas. → acoustic osc.
- **2002** Polarization measurement (DASI)
- **2013** Lensing B-mode polarization (SPTpol)
- **2014** POLARBEAR, BICEP2 and PLANCK (lensing & dust B-mode)

Three processes can produce CMB B-mode polarization observed

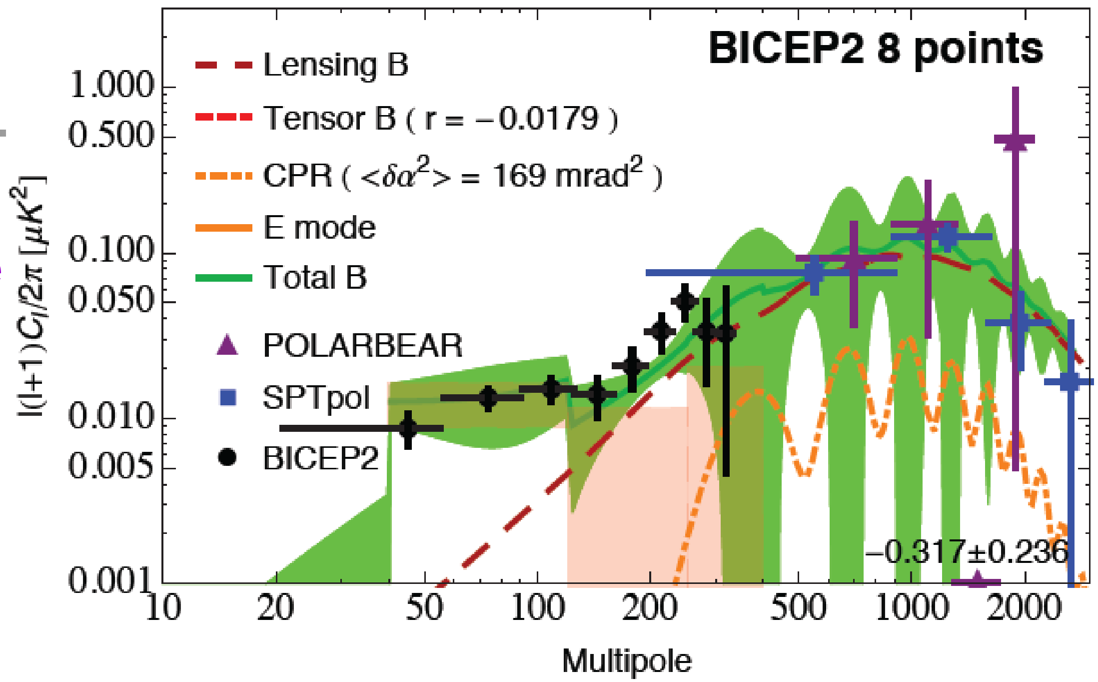
- (i) gravitational lensing from E-mode polarization (Zaldarriaga & Seljak 1997),
- (ii) local quadrupole anisotropies in the CMB within the last scattering region by large scale GWs (Polnarev 1985)
- (iii) cosmic polarization rotation (CPR) due to pseudoscalar-photon interaction (Ni 1973; for a review, see Ni 2010). (The CPR has also been called Cosmological Birefringence)
- (iv) Dust alignment



CPR and PS-P I
Serego Alighie

See poster & ref's

The CMB B-Mode power spectrum comparing the data points and the models, including the lensing, the CPR & the dust contributions **(Preliminary)**



The current combined evidence so far is consistent with a null CPR and upper limits are of the order of 1 degree with fluctuations constrained to about 2 degrees.

Table 1: A summary of CPR searches

Experiment	CPR angle ±stat (±syst)	Frequency or λ	Distance	Direction	Reference
Resolved RG radio pol.	α=-0.6°±1.5°	3.6 cm	<z>=0.78	All-sky (uniformity ass.)	Leahy 1997
RG UV pol.	α=-0.8°±2.2°	~1300Å	<z>=2.80	All-sky (uniformity ass.)	di Serego A. et al. 2010
Resolved RG UV pol.	α=-1.4°±1.1°	~3000Å	z=0.811	RA=176.4°, Dec = 31.6°	Wardle et al. 1997
RG UV pol.	<α²> ≤ (3.7°)²	~1300Å	<z>=2.80	All-sky (stoch. var.)	Kamionkowski 2010
CMB pol. BOOMERanG	α=4.3°±4.1°	145 GHz	z~1100	RA~82°, Dec~-45°	Pagano et al. 2009
CMB pol. QUAD	α=-0.64°±0.50°(±0.50°)	100-150 GHz	z~1100	RA~82°, Dec~-50°	Brown et al. 2009
CMB pol. BICEP1	α=2.77°±0.86°(±1.3°)	100-150 GHz	z~1100	-50°<RA<50°,-70°<Dec<-45	Kaufman et al. 2014
CMB pol. WMAP9	α=0.36°±1.24°(±1.5°)	23-94 GHz	z~1100	All-sky (uniformity ass.)	Hinshaw et al. 2013
CMB pol. B-mode	<δα²> ≤ (1.56°)²	95-150 GHz	z~1100	Various regions	di Serego A. et al. 2014

NEW CONSTRAINTS ON COSMIC POLAR-IZATION ROTATION FROM DETECTIONS OF B-MODE POLARIZATION IN CMB

di Serego Alighieri, Ni and Pan

- consistent with no CPR detection
- The constraint on CPR fluctuation is about 1. 5°.

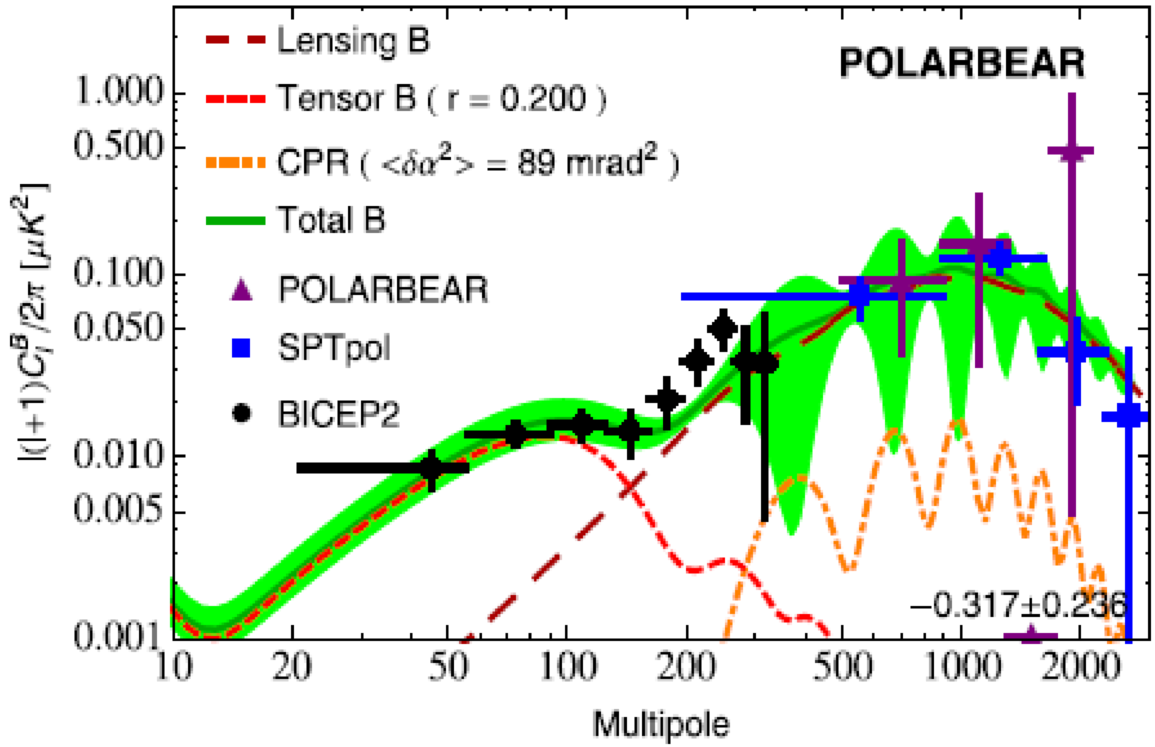


Figure 3. Same as Figure 2, but for the POLARBEAR data points (purple filled triangle). *r* is set to 0.2 to conform to BICEP2 data; the effect of setting *r* to 0.2 or to 0 for the fitting of the CPR fluctuation is small since the power contributed by a non-vanishing *r* to the total power is small for the multipoles measured in the POLARBEAR experiment.

References

for EP experiments with polarized bodies & Spin-Spin Experiments, see following

- W.-T. Ni, Equivalence principles, spacetime structure and the cosmic connection, to be published as Chapter 5 in the book: One Hundred Years of General Relativity: from Genesis and Empirical Foundations to Gravitational Waves, Cosmology and Quantum Gravity, edited by Wei-Tou Ni (World Scientific, Singapore, 2015).
- W-T Ni, Rep. Prog. Phys. 73 (2010) 056901.
- W.-T. Ni, Spacetime structure and asymmetric metric from the premetric formulation of electromagnetism, to be submitted to arXiv.
- And References therein together with references in the 3 articles of the title page

Summary

- Pseudoscalar-photon (axion) interactions arisen from the study of EP, QCD, string theory and pre-metric EM
- CPR is a way to probe pseudoscalar-photon interaction and a possible way to probe inflation dynamics,
- New CPR constraints from B-mode are summarized
- Good calibration is a must for measuring CPR
- CPR is a means to test EEP or to find new physics
- From the empirical route to construct spacetime structure, axion, dilaton and type II skewon are possibilities which could be explored further

Workshop on:

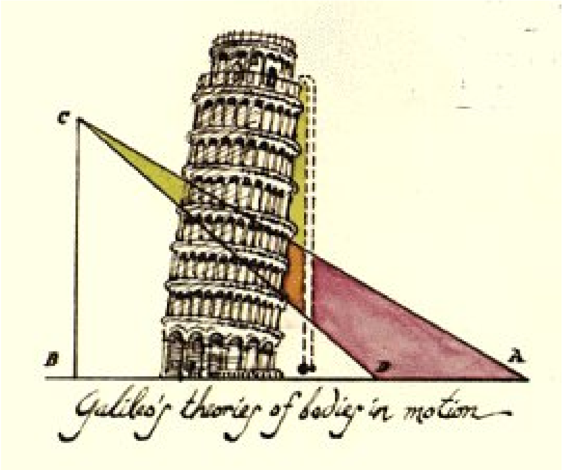
Cosmic Polarization Rotation:
from Galilean Principles to Cosmology

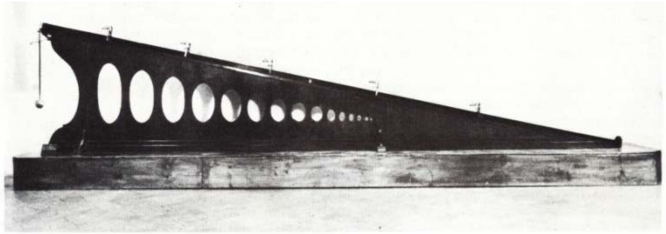
Thank you

Villa Il Gioiello, Arcetri, Firenze, Italy
7-8 September 2015
Organizing Committee: Jon Kaufman, Brian Keating, Wei-Tou Ni, Sperello di Serego Alighieri
Please write to: sperello@arcetri.astro.it

Galileo's experiment on inclined planes (1592)

- **Galileo's Equivalence Principle**
  The trajectories of test bodies under gravity are the same, independent of their compositions.
- The motion with constant force has constant acceleration. 。





CPR Discussions (1404.1701)

Ap. J. September 1, 2014

- We have investigated, both theoretically and experimentally, the possibility to detect CPR, or set new constraints to it, using its coupling with the B-mode power spectra of the CMB.
- Three experiments have detected B-mode polarization in the CMB:
- SPTpol (Hanson et al. 2013) for $500 < l < 2700$,
- POLARBEAR (Ade et al. 2014a) for $500 < l < 2100$,
- BICEP2 (Ade et al. 2014b) for $20 < l < 340$.

Discussion

Looking for empirical evidence for going from generalized to original closure relation also

- Skewonless case is summarized in Table I
- Skewonful case is summarized in Table II
- With the empirical constraints, axion, dilaton and Type II skewon would warrant to be studied further in vacuum and in cosmos. There are eight degrees of freedom. Among this asymmetric metric would be to be explored for torsion, dark matter, dark energy. Eddington, Einstein, Straus, Schrödinger ... have considered this. It might be considered again in a different way. Especially when skewon could be source for torsion (Hehl's talk in this workshop)

Table II. 1st-order and 2nd-order constraints on various constitutive tensors from various experiments/observations.

Constitutive tensor	Birefringence (in the geometric optics approximation)	Dissipation/ amplification	Spectroscopic distortion	Cosmic polarization rotation
Metric: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}]$	No	No	No	No
Metric + dilaton: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}]\psi$	No (to all orders in the field)	Yes (dilaton gradient)	No	No
Metric + axion: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}] + \varphi e^{ijkl}$	No (to all orders in the field)	No	No	Yes (axion gradient)
Metric + dilaton + axion: ½ $(-h)^{1/2}[h^{ik} h^{jl} - h^{il} h^{kj}]\psi + \varphi e^{ijkl}$	No (to all orders in the field)	Yes (dilaton gradient)	No	Yes (axion gradient)
Metric + type I skewon	No to first order	Yes	Yes	No
Metric + type II skewon	No to first order; yes to 2nd order	No to first order; no to 2nd order	No	No
Metric + ${}^{(P)}\chi^{(c)}$+ type II skewon	No to first order; no to 2nd order	No to first order; no to 2nd order	No	No
Asymmetric metric induced: ½ $(-g)^{1/2}(g^{ik}g^{jl} - g^{il}g^{jk})$	No (to all orders in the field)	No	No	Yes (axion gradient