united nations educational, scientific and cultural organization
international atomic energy agency

the abdus salam international centre for theoretical physics
40th anniversary 1964 2004

SMR.1580 - 6

CONFERENCE ON FUNDAMENTAL SYMMETRIES AND FUNDAMENTAL CONSTANTS

15 - 18 September 2004

FUNDAMENTAL CONSTANTS AND LORENTZ VIOLATION

R. Lehnert
Algarve U. Portugal

strada costiera, 11 - 34014 trieste italy - tel. +39 040 2240111 fax +39 040 224163 - sci_info@ictp.trieste.it - www.ictp.trieste.it

Fundamental constants and Lorentz violation

Ralf Lehnert

Vanderbilt University

A. Motivation

B. Types of Lorentz Violation

C. Lorentz Violation through Varying Scalars

D. Specific Cosmological Model

E. Vacuum Cherenkov Radiation

F. Summary

A. Motivation

Why test Lorentz symmetry?

Lorentz/CPT symmetry is cornerstone of:

- present-day physics
- many candidate fundamental theories

$\longrightarrow$ **Lorentz/CPT symmetry must be tested**

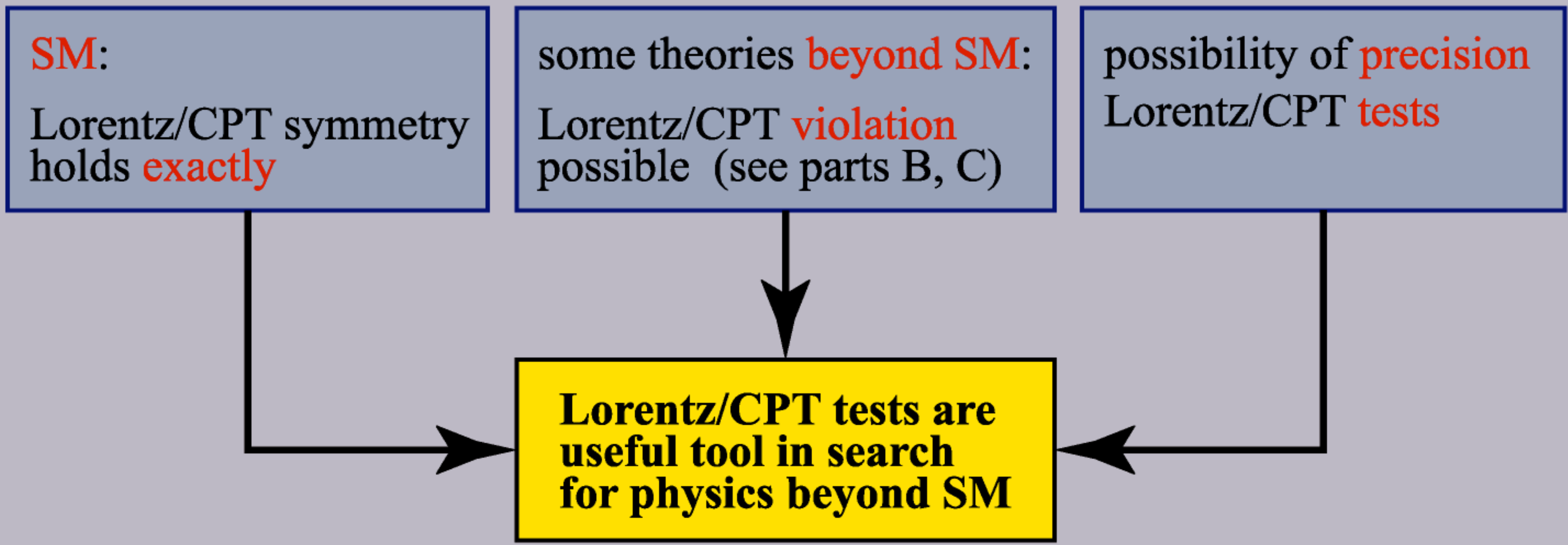
Why look at Lorentz violation (LV)?

Nongravitational physics is well described by Standard Model (SM),

but:
- phenomenological (many parameters)
- several distinct interactions
- excludes gravity

Solution:	look for more fundamental theory
Candidates:	string (M) theory, varying scalars (see part C), ...
Problem:	Planck-scale measurements (attainable energies $\ll$ Planck scale)
Idea:	experimentally check relations that - hold exactly in Standard Model - may be violated at fundamental level - can be measured with high precision

Lorentz/CPT symmetry satisfy these criteria:



B. Types of LV

Coordinate independence must be maintained regardless of LV:

Coordinate systems:

- arbitrary labeling of spacetime points $\rightarrow$ no physical reality

Coordinate independence:

- guaranteed with a spacetime-manifold description of physics
- allows two observers to relate their measurements (of the same quantity)

$\rightarrow$ coordinate independence = observer invariance

LV $\not\Rightarrow$ loss of coordinate independence

Example: point charge (m, q) in external e.m. field $F_{\alpha\beta}$

$$m \frac{dv^\alpha}{d\tau} = q F^\alpha{}_\beta v^\beta$$

v^α ... velocity
τ ... proper time

- tensor equation valid in all coordinate systems
- **but:** $F_{\alpha\beta}$ breaks, e.g., rotation symmetry

suggests two types of LV

(1) modification of transfs. between inertial frames

- relatively simple
- purely kinematical
- purely phenomenological

Examples:

- Robertson's framework
- its Mansouri-Sexl extension
- DSR theories

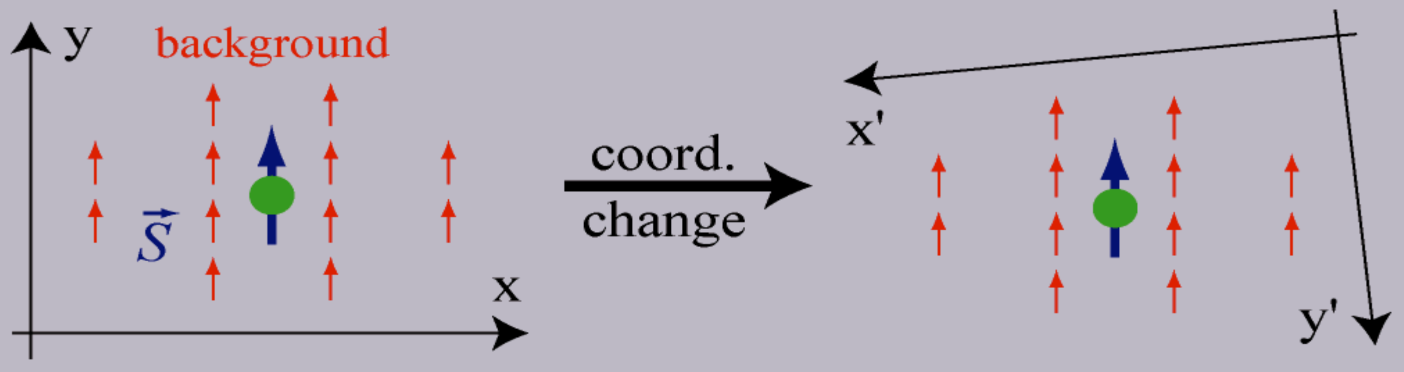
(2) nontrivial vacuum, LT are maintained

- motivated by candidate fundamental theories
- fully dynamical+microscopic description possible
- incorporates some of the kinematical approaches

→ it appears unnecessary to discuss type-1 LV separately in this talk

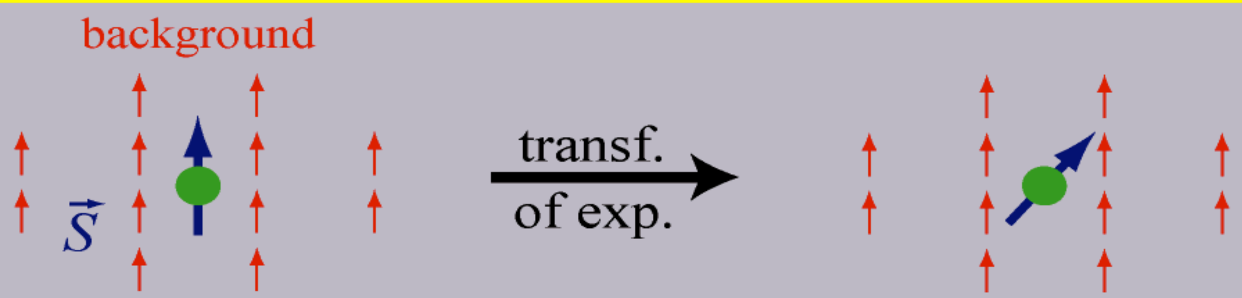
For type-2 LV (i.e., nontrivial vacua)
must distinguish between observer and particle Lorentz tranformations:

Coordinate independence (i.e., invariance under observer LT): **maintained**



different observers, same experiment

Lorentz violation (covariance **lost** under "particle Lorentz transformations"):



actual experimental situation

Some mechanisms for type-2 LV:

String field theory (Kostelecký *et al*. '90)
nontrivial vacuum through spontaneous LV

Spacetime foam (Ellis *et al*. '98)
nontrivial vacuum through virtual black holes

Nontrivial spacetime topology (Klinkhamer '00)
nontrivial vacuum through compact conventional dim.

Loop quantum gravity (Alfaro *et al*. '00)
nontrivial vacuum through choice of spin-network state

Noncommutative geometry (Carroll *et al*. '01)
nontrivial vacuum through fixed parameter $\theta^{\mu\nu} \sim [x^\mu, x^\nu]$

Varying scalars (Kostelecký, R.L., Perry '02)
this talk

⋮

C. LV through varying scalars

(1) intuitive argument:

Poincaré group

spacetime translations (broken) → Lorentz transformations (rotations + boosts)

angular-momentum tensor: $J^{\mu\nu} = \int d^3x \; (\theta^{0\mu} x^{\nu} - \theta^{0\nu} x^{\mu})$

here: energy-momentum tensor not conserved

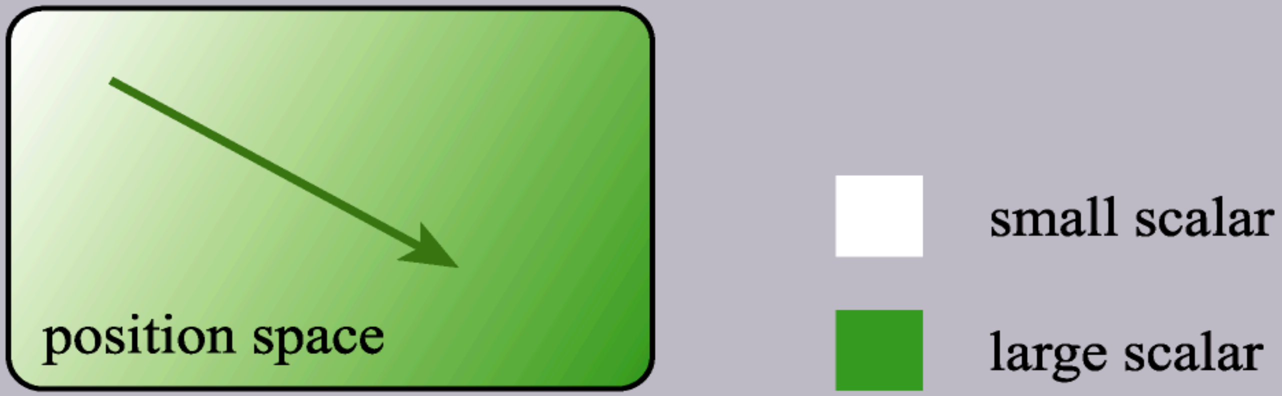
Lorentz-transformation generators do not exist

(Kostelecký, R.L., Perry '02;
Bertolami, R.L., Potting, Ribeiro '03)

(2) general example: rotations

in the presence of spacetime-varying scalars
effective vacuum can be viewed as nontrivial medium

⟶ different directions can be inequivalent



⟶ rotation symmetry can be broken

(3) explicit example: varying coupling

ξ ... spacetime-dependent coupling
ϕ, Φ ... scalar fields

$$\mathcal{L} \supset \xi \, \partial^\mu \phi \, \partial_\mu \Phi$$

integration by parts

$$\mathcal{L}' \supset -(\partial^\mu \xi) \, \phi \, \partial_\mu \Phi$$

slowly varying ξ:
$\partial^\mu \xi =: K^\mu \sim$ const.

$$\mathcal{L}' \supset -K^\mu \, \phi \, \partial_\mu \Phi$$

→ selects a direction in spacetime
→ Lorentz symmetry is broken

D. Specific cosmological model

N=4 supergravity in 4 dim. (Cremmer, Julia (1979))

- unrealistic in detail
- but: limit of N=1 supergravity in 11 dim., which is related to M-theory

⟶ could illuminate some generic features of a promising candidate fundamental theory

consider case in which one graviphoton is excited:

bosonic action:

$$\mathcal{L}_b = g^{1/2} \left(-R/4 - M(\alpha,\beta) F^{\mu\nu} F_{\mu\nu} - N(\alpha,\beta) \tilde{F}^{\mu\nu} F_{\mu\nu} + \frac{\partial^\mu \alpha\, \partial_\mu \alpha + \partial^\mu \beta\, \partial_\mu \beta}{8\beta^2} \right)$$

where M and N are known functions of α and β

Toy cosmology

eq. of motion can be integrated analytically
under the following assumptions:

- flat (k=0) Friedmann-Robertson-Walker model
- classical fields
- scalars α and β + dust (fermions) as source for Einstein eq.
- $F^{\mu\nu} = 0$

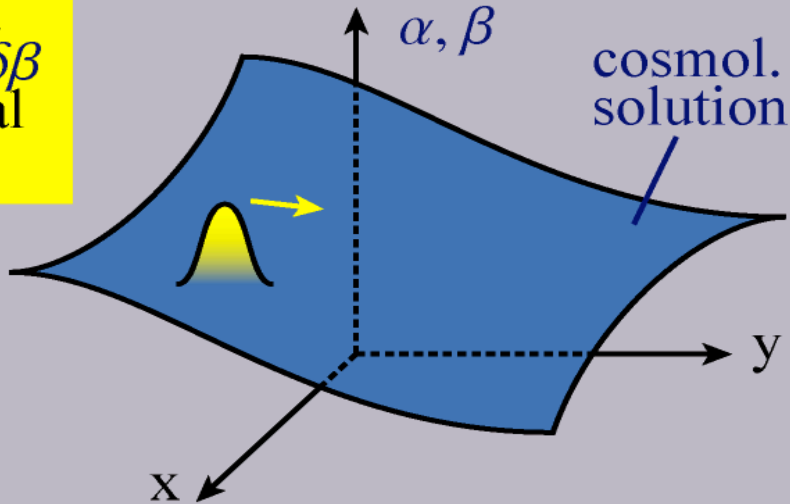
solution:

- cosmological scale factor $\sim t^{2/3}$ at late times , as expected for matter-dominated universe (t ... comoving time)
- α and β depend non-trivially on t

$M(\alpha,\beta)$ and $N(\alpha,\beta)$ acquire time dependence
on cosmological scales

Effects in scalar-field sector

small localized excitation $\delta\alpha$, $\delta\beta$ of cosmological solution



Result: the propagation of $\delta\alpha$, $\delta\beta$ (i.e., the effective scalar particles) is governed by a Lorentz-violating dispersion relation

Bertolami, R.L., Potting, Ribeiro (Oct. '03)
Arkani-Hamed *et al.* (Dec. '03)

Effects in scalar-coupled sector

small local excitations of $F^{\mu\nu}$ in cosmological background $\alpha(t)$, $\beta(t)$:

$$\mathcal{L}_F = -M(t) F^{\mu\nu} F_{\mu\nu} - N(t) \tilde{F}^{\mu\nu} F_{\mu\nu}$$

the conventional electrodynamics lagrangian is:

$$\mathcal{L}_{em} = -\frac{1}{4e^2} F^{\mu\nu} F_{\mu\nu} - \frac{\theta}{16\pi^2} \tilde{F}^{\mu\nu} F_{\mu\nu}$$

comparison: fine-structure parameter and θ angle are time dependent

$$e^2(t) = \frac{1}{4M(t)} \qquad \theta(t) = 16\,\pi^2 N(t)$$

Result: varying couplings and the associated Lorentz violation in the sector coupled to the scalars (here: electrodynamics)

Kostelecký, R.L., Perry '02
Arkani-Hamed *et al.* '03

Look in particular at θ-angle term

integration by parts at the level of action yields:

$$\mathcal{L}_{\rm em} \supset -(k_{AF})^{\mu} A^{\nu} \widetilde{F}_{\mu\nu} ,$$

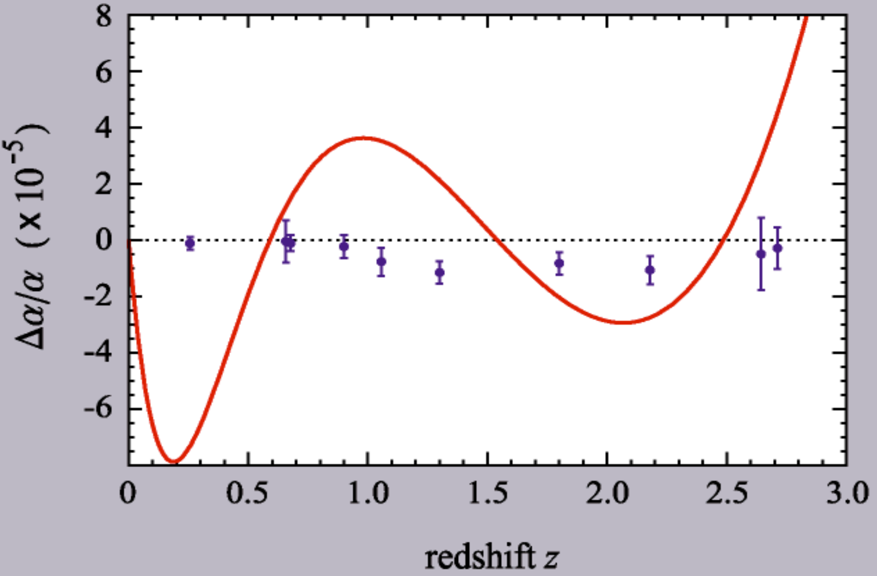
where $(k_{AF})^{\mu} \sim \partial^{\mu}\theta$ is approximate const. on small scales

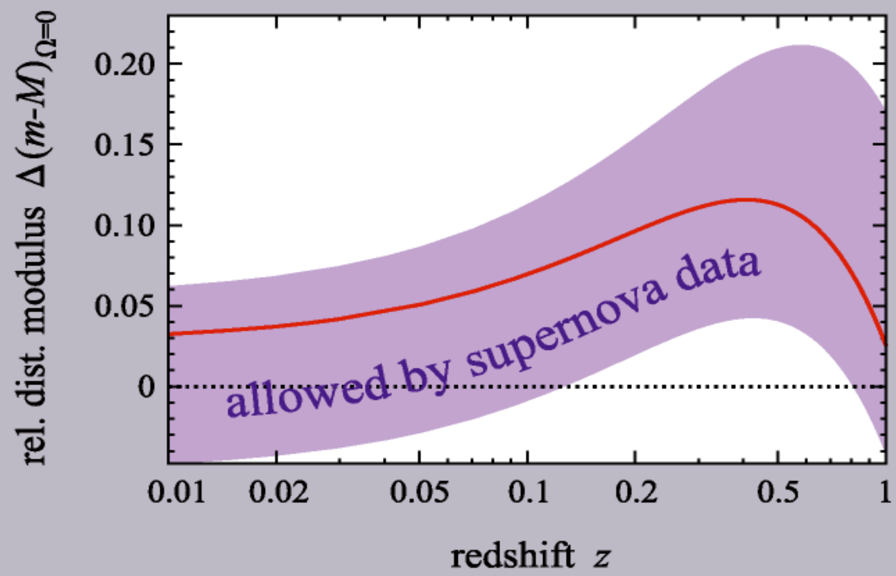
→ a Lorentz-violating Chern-Simons-type term is generated

Remarks: - discussed extensively in lit.: Carroll, Field, Jackiw '90; Colladay, Kostelecký '98; Coleman, Glashow '99; Jackiw, Kostelecký '99; Klinkhamer '00; Belich *et al.* '03; . . .

- in the present model, $(k_{AF})^{\mu}$ must be timelike
- $(k_{AF})^{\mu}$ leads to Cherenkov radiation (see next part)

aside: sample solution for massive scalars





variation of fine-structure parameter is within one order of magnitude of the Webb *et al*. dataset

cosmological expansion history is consistent with observations

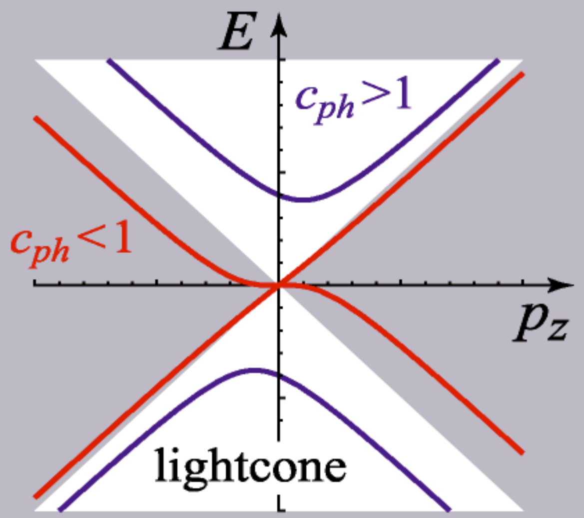
(Bertolami, R.L., Potting, Ribeiro '03)

E. Vacuum Cherenkov Radiation

Conventional Cherenkov effect:
phase speed of light in medium < speed of charge

$$c_{ph} = \frac{E}{|\vec{p}\,|}$$

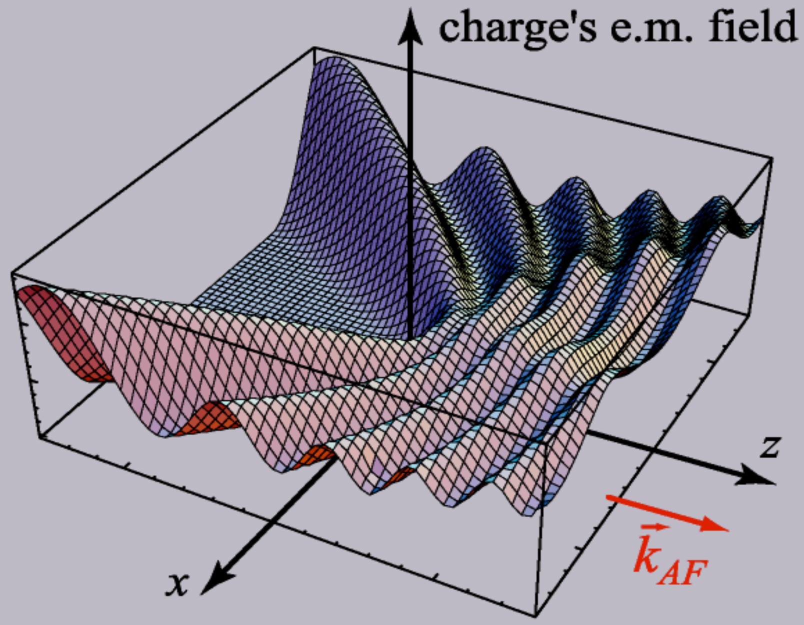
Electrodynamics with nonzero Chern-Simons-type coefficient $(k)_{AF}$:



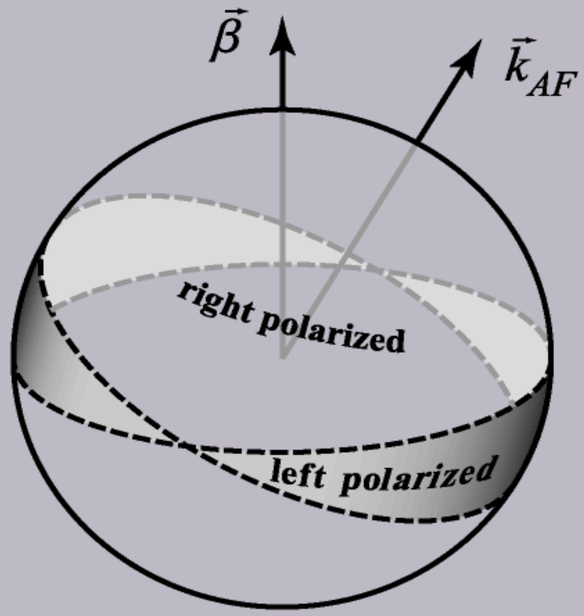
- $(k)_{AF}$ leads to effects similar to those in dispersive macroscopic medium
- plane-wave dispersion relation is modified
- phase speeds < 1 are possible

Question: Does this lead to Cherenkov-type radiation?

Answer: Yes. Analytical solution for charged point dipole possible



no shock-wave singularity,
as expected for dispersion



polarization of vacuum
Cherenkov radiation

- Cherenkov effect requires long-range fields for E transport to infinity
- radiation rate $\sim (k_{AF})^2$ $\rightarrow$ strongly suppressed

R.L., Potting (Jun. '04)
Arkani-Hamed *et al*. (Jul. '04)

F. Summary

varying scalars are generically associated with Lorentz violation regardless of the mechanism driving the variation:

(a) the scalar itself obeys an effective dispersion relation that breaks Lorentz symmetry

(b) couplings to other fields induce Lorentz violations in these fields (e.g., varying fine-structure parameter)

interesting because:

(i) many candidate fundamental theories contain scalars, which can acquire expectation values in a cosmological context

(ii) many phenomenological models in cosmology involve varying scalars (e.g., quintessence, k-essence, inflation, ghost condensate, ...)