Potential CPT Violation in the Early Universe and Matter-Antimatter Asymmetry in the Cosmos

Nick E. Mavromatos

King's College London,

Physics Dept., London UK

22 Δεκεμβριου, 2017 / ΕΚΠΑ

Ημεριδα προς τιμην του Φωκιωνα Χατζηιωαννου

Θεωρητικη Φυσικη στο ``Σπουδαστηριο” 1982-83

My personal experience:

Exposed to Discrete Symmetries C(harge sonjugation),
P(arity = spatial reflexion) and T(ime reversal)
and CPT theorem from relativistic quantum field theory books, like Bjorken and Drell and others

Influenced my future research, and I came back to this by looking at potential violations of the CPT theorem in microscopic models of (quantum) gravity and string theory
and related phenomenology

I learnt quantum mechanics in my third year from Prof. Hadjioannou, and I did get to know, through spoudasthrio and courses given there, my friends and collaborators G. Diamandis & V.G. Georgalas, from whom, like Prof. Hadjioannou I learned a lot.

Θεωρητικη Φυσικη στο ``Σπουδαστηριο” 1982-83

I would also like to mention that I did my BSc Thesis with the late Prof. Ktorides, from whom I also learnt a lot on quantum field theory but the strong influence of what Prof, Hadjioannou taught me has followed me in my subsequent years. I have always considered myself as one of his students, respected him a lot, and I expressed to him many times my gratitude; he knows, I hope, how much I like him and respect him as a scientist and person and I feel particularly honoured and happy today that I can express my gratitude publically on this pleasant occasion!

Thank you Prof. Hadjioannou for what you taught me and the ``ethos” you TRASNMITTED TO ME
I am truly grateful for this, and wish you the best !!

ERxposed

OUTLINE of TALK

I. Motivation – background information on matter-antimatter asymmetry in Standard Model → go beyond to reproduce observed baryon asymmetry....

II. why CPT Violation (CPTV) in early Universe?

III. A string-inspired model with spontaneous CPT Violation in the early universe due to Kalb-Ramond axions → matter-antimatter asymmetry: from early epochs to present day

IV. Conclusions-Outlook

Part I

Motivation:

Matter-Antimatter Asymmetry

in

the Standard Model

STANDARD MODEL INCOMPATIBLE WITH BARYOGENESIS

- Matter-Antimatter asymmetry in the Universe ⇨ Violation of Baryon # (B), C & CP

- Tiny CP violation (O(10^{-3})) in Labs: e.g. $K^0 \overline{K}^0$

- But Universe consists only of matter

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$ T > 1 GeV

Sakharov : Non-equilibrium physics of early Universe, **B, C, CP violation**

⇨ $n_B - \bar{n}_B$ but **not quantitatively in SM**, still a mystery

STANDARD MODEL INCOMPATIBLE WITH BARYOGENESIS

- Matter-Antimatter asymmetry in the Universe ⇨ Violation of Baryon # (B), C & CP
- Tiny CP violation ($O(10^{-3})$) in Labs: e.g. $K^0 \overline{K}^0$
- But Universe consists only of matter

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$ T > 1 GeV

Sakharov : Non-equilibrium physics of early Universe, **B, C, CP violation**

⇨ $n_B - \bar{n}_B$ but **not quantitatively in SM**, still a mystery

Sakharov's Conditions for Matter/Antimatter Asymmetry in the Universe

C=charge conjugation
P = spatial reflexion $\vec{x} \to -\vec{x}$

$$X \overset{\leftarrow}{\to} \ell + \ldots.$$

$\bar{A}$ = **antiparticle**

$$CP: \quad \overline{X} \overset{\leftarrow}{\to} \overline{\ell} + \overline{(\ldots)}$$

$$\text{Rates} \qquad \Gamma \neq \overline{\Gamma}$$

(i) Out of Equilibrium Lepton Asymmetry (Leptogenesis) → Baryon Asymmetry via B-L conserving (SM) processes

(ii) Directly generated out of equilibrium Baryogenesis

STANDARD MODEL INCOMPATIBLE WITH BARYOGENESIS

- Matter-Antimatter asymmetry in the Universe $\Rightarrow$ Violation of Baryon # (B), C & CP

- Tiny CP violation (O(10^{-3})) in Labs: e.g. $K^0 \overline{K}^0$

- But Universe consists only of matter

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$ T > 1 GeV

Sakharov : Non-equilibrium physics of early Universe, **B, C, CP violation**

$\Rightarrow$ $n_B - \bar{n}_B$ but **not quantitatively in SM**, still a mystery

Assume CPT invariance

Within the Standard Model, lowest CP Violating structures

$$d_{CP} = \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin\delta_{CP}$$
$$\cdot(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

Rubakov, Kuzmin, Shaposhnikov,
Gavela, Hernandez, Orloff,Pene

Kobayashi-Maskawa CP Violating phase

Shaposhnikov

$$D = \mathrm{Im}\,\mathrm{Tr}\left[\mathcal{M}_u^2\mathcal{M}_d^2\mathcal{M}_u\mathcal{M}_d\right]$$

$$\delta_{KM}^{CP} \sim \frac{D}{T^{12}} \sim 10^{-20}$$

<<

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$

$$T \simeq T_{\rm sph}$$

$$T_{\rm sph}(m_H) \in [130, 190]\mathrm{GeV}$$

This CP Violation Cannot be the Source of Baryon Asymmetry in The Universe

Beyond the Standard Model

- Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.) – to find EXTRA SOURCES OF CP VIOLATION within CPT invariant effective field theories

Beyond the Standard Model

- Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.) – to find EXTRA SOURCES OF CP VIOLATION within CPT invariant effective field theories

- THIS TALK: TRY EXOTIC SCENARIOS WITH (SIMPLIFIED) MODELS OF CPT VIOLATION IN EARLY UNIVERSE ?

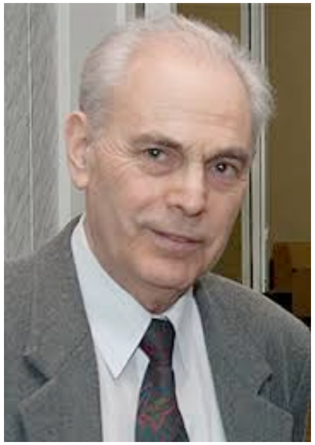
Consistency with stringent current constraints must be ensured

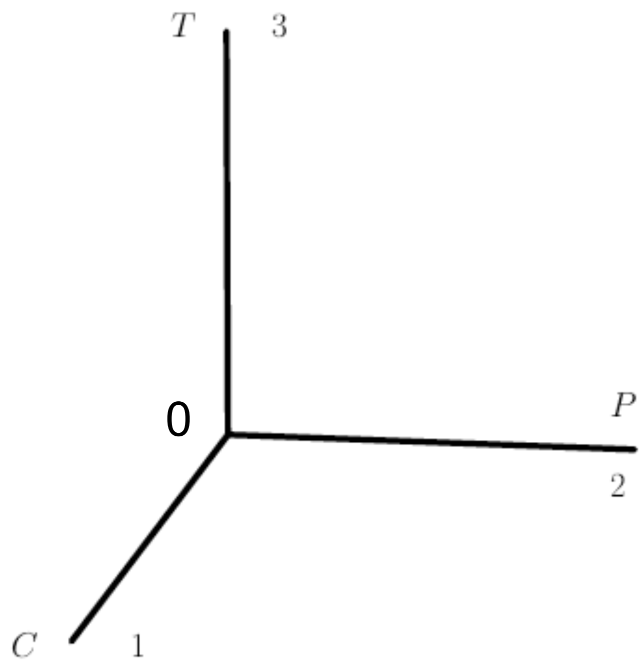
Part II

CPT Violation

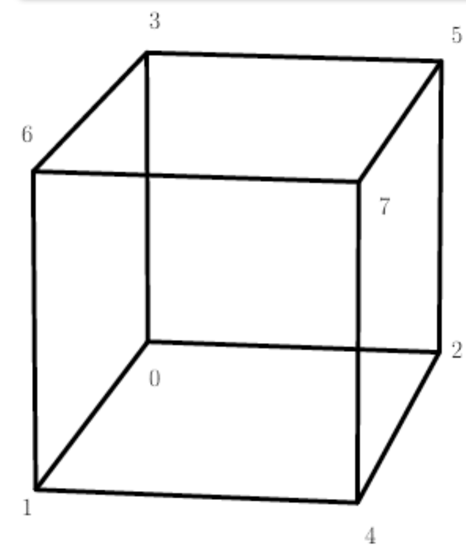
THEORY

C, P, T are Broken. Why Not CPT?





Lev Okun hep-ph/0210052v1



CPT mnemonic cube

Point 0: C even, P even, T even → CP, PT, TC, CPT even

1: C odd, P even, T even, → CP odd, PT even, CT odd, CPT odd

2: C even, P odd, T even → CP odd, PT odd, CT odd, CPT odd

3: C even, P even, T odd → CP even, PT odd, CT odd, CPT odd

4: C odd, P odd, T even → CP even, PT odd, CT odd, CPT even

etc

Mnemonic cube rule: (C, P, T) : + (-) even (odd)

$0(+,+,+),\ 1(-,+,+),\ 2(+,-,+),\ 3(+,+,-),\ 4(-,-,+),\ 5(+,-,-),\ 6(-,+,-),\ 7(-,-,-)$

CPT Theorem

Schwinger 1951

Lüders 1954

J S Bell 1954

Pauli 1955

Res Jost 1958

CPT Theorem

Conditions for the Validity of CPT Theorem

$$P: \vec{x} \to -\vec{x}, \quad T: t \to -t(T), \quad C\psi(q_i) = \psi(-q_i)$$

i → f , **T**: f → i

CPT Invariance Theorem :

A quantum field theory lagrangian is invariant under CPT if it satisfies

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell

CPT Theorem

Conditions for the Validity of CPT Theorem

$$P : \vec{x} \to -\vec{x}, \quad T : t \to -t(T), \quad C\psi(q_i) = \psi(-q_i)$$

i → f , **T**: f → i

CPT Invariance Theorem :
A quantum field theory lagrangian is invariant under CPT if it satisfies
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell

e.g. for (Dirac) fermions:

P: $\psi(t,\vec{x}) \to e^{i\delta}\gamma^0\psi(t,-\vec{x})$

T: $\psi_{\rm T}(t,\vec{x}) = i\gamma^1\gamma^3\psi^\star(-t,\vec{x})$

C: $\psi_C(t,\vec{x}) = i\gamma^2\gamma^0\overline{\psi}^T(t,\vec{x})$

CPT Theorem

Conditions for the Validity of CPT Theorem

$$P:\ \vec{x} \rightarrow -\vec{x}, \quad T:\ t \rightarrow -t(T), \quad C\psi(q_i) = \psi(-q_i)$$

CPT Invariance Theorem :
A quantum field theory lagrangian is invariant under CPT if it satisfies

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell
revisited by:
Greenberg, Chaichian, Dolgov, Novikov, Fujikawa, Tureanu ...

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

(ii)-(iii) CPT V well-defined as Operator Θ does not commute with Hamiltonian

$[\, \Theta, H \,] \neq 0$

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Barenboim, Borissov, Lykken
PHENOMENOLOGICAL models with non-local mass parameters

(ii)-(iv) Independent reasons for violation

$$\mathrm{S} = \int d^4x\, \bar{\psi}(x) i \partial\!\!\!/ \psi(x) + \frac{im}{\pi} \int d^3x \int dt dt'\, \bar{\psi}(t, \mathrm{x}) \frac{1}{t - t'} \psi(t', \mathrm{x}).$$

CPT VIOLATION

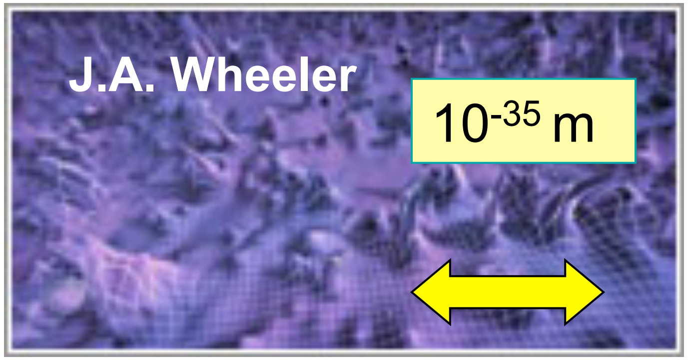
Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

(ii)-(iv) Independent reasons for violation

e.g. ***QUANTUM SPACE-TIME FOAM AT PLANCK SCALES***



CPT VIOLATION

Conditions for the Validity of CPT Theorem

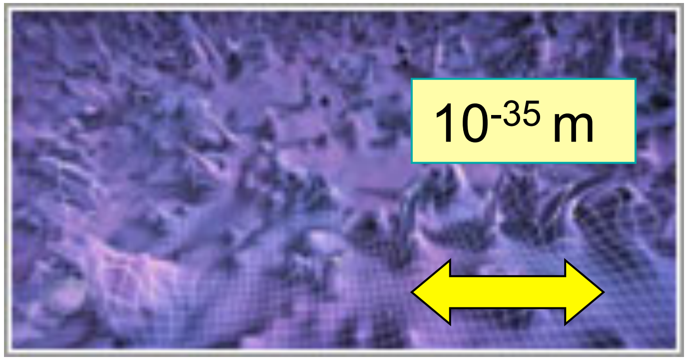
CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…

(ii)-(iv) Independent reasons for violation

QUANTUM GRAVITY INDUCED DECOHERENCE
EVOLUTION OF PURE QM STATES TO MIXED
AT LOW ENERGIES



CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

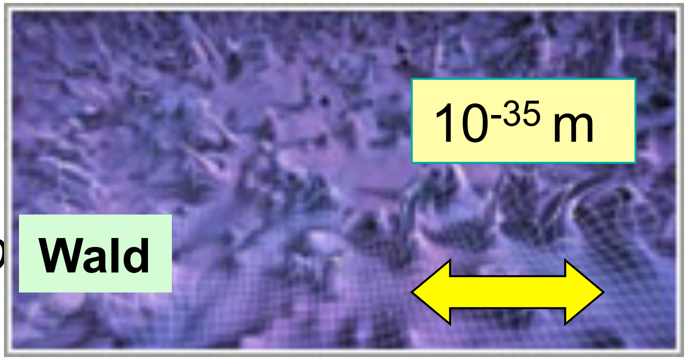
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

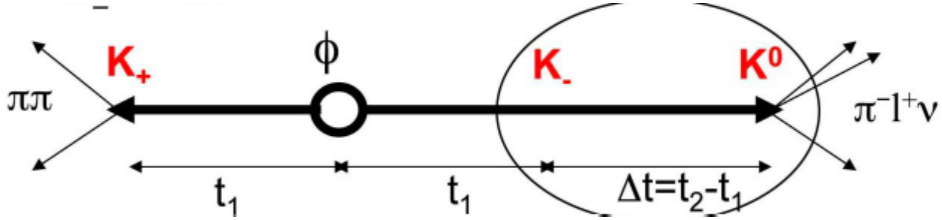
Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…

(ii)-(iv) Independent reasons for violation

QUANTUM GRAVITY INDUCED DECOHERENCE
EVOLUTION OF PURE QM STATES TO MIXED
AT LOW ENERGIES

*LOW ENERGY **CPT** OPERATOR **NOT** WELL DEFINED*





May contaminate initially antisymmetric neutral meson M state by symmetric parts (ω-effect)

CPT Invariance Theorem :

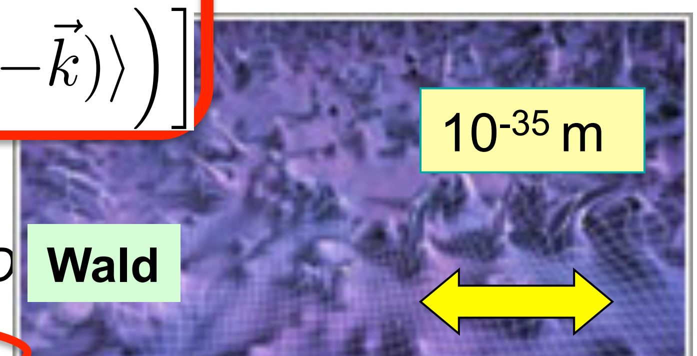
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) ~~Unitarity~~

Bernabeu, NEM, Papavassiliou (04),…

$$|i\rangle = \mathcal{N}\Big[|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle + \omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$$

$$\omega = |\omega| e^{i\vartheta}$$

*LOW ENERGY **CPT** OPERATOR **NOT** WELL DEFINED*



cf. ω-effect in EPR entanglement

CPT VIOLATION

Conditions for the Validity of CPT Theorem

This Talk

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Kostelecky, Bluhm, Colladay, Potting, Russell, Lehnert, Mewes, Diaz , Tasson….
Standard Model Extension (SME)

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

This Talk

CPT Invariance Theorem :
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Kostelecky, Bluhm, Colladay, Potting, Russell, Lehnert, Mewes, Diaz , Tasson….
Standard Model Extension (SME)

(ii)-(iv) Independent reasons for violation

$$\mathcal{L} \ni \dots + \overline{\psi}^f \left(i\gamma^\mu \nabla_\mu - m_f\right)\psi^f + a_\mu \overline{\psi}^f \gamma^\mu \psi^f + b_\mu \overline{\psi}^f \gamma^\mu \gamma^5 \psi^f + \dots$$

$[\,\Theta, H\,] \neq 0$

Lorentz & CPT Violation (from a_μ term)

Lorentz & CPT Violation (from b_μ term)

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
Lorentz invariance
) Locality
) Unitarity

Kostelecky, Bluhm, Colladay, Potting, Russell, Lehnert, Mewes, Diaz , Tasson….
Standard Model Extension (SME)

This Talk
Cosmological Implications CPTV & dominace or matter over antimatter in the Universe (Baryo-Lepto-genesis)

ndependent reasons for violation

$$i\gamma^\mu \nabla_\mu - m_f \Big) \psi^f + a_\mu \overline{\psi}^f \gamma^\mu \psi^f + b_\mu \overline{\psi}^f \gamma^\mu \gamma^5 \psi^f + \ldots$$

Lorentz & CPT Violation

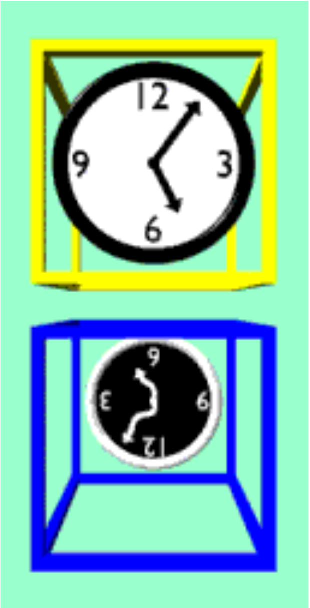
Lorentz & CPT Violation

Simplest ideas on CPT Violation (CPTV) do not work for Baryogenesis

CPT VIOLATION IN THE EARLY UNIVERSE

GENERATE Baryon and/or Lepton ASYMMETRY through CPT Violation

Assume CPT Violation was ***strong*** in the Early Universe



physics.indiana.edu

ONE POSSIBILITY:

particle-antiparticle mass differences

$[\,\Theta, H\,] \neq 0$ → $m \neq \overline{m}$

$$0 \neq H\Theta|m\rangle - \Theta H|m\rangle = H\Theta|m\rangle - m\Theta|m\rangle$$

($|m\rangle$ = mass eigenstate
$\Theta\,|m\rangle$ = antimatter state)

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

$$f(E,\mu) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

$$m \neq \overline{m}$$

$$\delta m = m - \overline{m}$$

$$\delta n \equiv n - \bar{n} = g_{df} \int \frac{d^3p}{(2\pi)^3} \left[f(E,\mu) - f(\bar{E},\bar{\mu})\right]$$

$$E = \sqrt{p^2 + m^2},\ \bar{E} = \sqrt{p^2 + \bar{m}^2}$$

Dolgov, Zeldovich
Dolgov (2009)

Assume dominant contributions to Baryon asymmetry from quarks-antiquarks

$$m(T) \sim gT$$ →

High-T quark mass >> Lepton mass

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

$$f(E,\mu) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

$$m \neq \overline{m}$$

$$\delta m = m - \overline{m}$$

$$\delta n \equiv n - \bar{n} = g_{df} \int \frac{d^3p}{(2\pi)^3} \left[f(E,\mu) - f(\bar{E},\bar{\mu})\right]$$

$$E = \sqrt{p^2 + m^2},\ \bar{E} = \sqrt{p^2 + \bar{m}^2}$$

Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

$$\beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left(18 m_u \delta m_u + 15 m_d \delta m_d\right)/T^2$$

Dolgov, Zeldovich
Dolgov (2009)

$n_\gamma = 0.24 T^3$ photon equilibrium density at temperature T

$$\beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left(18 m_u \delta m_u + 15 m_d \delta m_d\right) / T^2$$

$$n_\gamma = 0.24 T^3$$

Dolgov (2009)

Current bound for proton-anti proton mass diff.

$$\delta m_p < 8 \times 10^{-10}\, m_e$$

ASACUSA Coll. (2016)

$$\delta m_p < 7 \cdot 10^{-10}\ \mathrm{GeV}$$

ASACUSA Coll. (2011)

Reasonable to take: $\delta m_q \sim \delta m_p$ → ***Too small*** $\boldsymbol{\beta^{T=0}}$

NB: To reproduce the observed $\beta^{(T=0)} = 6 \cdot 10^{-10}$ need

$$\delta m_q (T = 100\ \mathrm{GeV}) \sim 10^{-5} - 10^{-6}\ \mathrm{GeV} >> \delta m_p$$

$$\beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left(18 m_u \delta m_u + 15 m_d \delta m_d\right) / T^2$$

$$n_\gamma = 0.24 T^3$$

Dolgov (2009)

Current bound for proton-anti proton mass diff.

$$\delta m_p < 8 \times 10^{-10}\, m_e$$

ASACUSA Coll. (2016)

$$\delta m_p < 7 \cdot 10^{-10}\ \mathrm{GeV}$$

ASACUSA Coll. (2011)

Reasonable to take: $\delta m_q \sim \delta m_p$

Too small

$\beta^{T=0}$

NB: To reproduce the observed $\beta^{(T=0)} = 6 \cdot 10^{-10}$ need

$$\delta m_q(T = 100\ \mathrm{GeV}) \sim 10^{-5} - 10^{-6}\ \mathrm{GeV} >> \delta m_p$$

CPT Violating quark-antiquark Mass difference alone CANNOT REPRODUCE observed BAU

But
CPT Violation (CPTV)
is associated
with many more
effects & parameters
to explore
in connection to
Baryogenesis…

STANDARD MODEL EXTENSION

Kostelecky *et al.*

$$\mathcal{L} = \frac{1}{2} i \bar{\psi} \Gamma^{\nu} \overset{\leftrightarrow}{\partial}_{\nu} \psi - \bar{\psi} M \psi, \qquad M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2} H^{\mu\nu}\sigma_{\mu\nu}$$

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + e^{\nu} + i f^{\nu}\gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

STANDARD MODEL EXTENSION

Kostelecky *et al.*

$$\mathcal{L} = \tfrac{1}{2}\mathrm{i}\bar{\psi}\Gamma^{\nu}\overleftrightarrow{\partial}_{\nu}\psi - \bar{\psi}M\psi,$$

$$M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \tfrac{1}{2}H^{\mu\nu}\sigma_{\mu\nu}$$

LV & CPTV

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + \mathrm{e}^{\nu} + \mathrm{i}f^{\nu}\gamma_5 + \tfrac{1}{2}g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt
Phys.Rev.Lett. 93 (2004) 201301 hep-ph/0403019

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

LV & CPTV ← **SUPERGRAVITY induced effects in the Early Universe**

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt
Phys.Rev.Lett. 93 (2004) 201301 hep-ph/0403019

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

LV & CPTV ← **SUPERGRAVITY induced effects in the Early Universe**

Gravitational Baryogenesis

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt

Quantum Gravity (or something else (e.g. SUGRA)) may lead at low-energies (below Plnack scale or a scale M_*) to a term in the effective Lagrangian (in curved back space-time backgrounds):

$$J^\mu = \overline{\psi}_i \, \gamma^\mu \, \psi_i$$

$$\frac{1}{M_*^2} \int d^4x \sqrt{-g} (\partial_\mu \mathcal{R}) J^\mu$$

Standard Model extension type

Term Violates CP but is CPT conserving *in vacuo*
It ***Violates* CPT** in the background space-time of an ***expanding FRW Universe***

$$\dot{\mathcal{R}} = -(1-3w)\frac{\dot{\rho}}{M_P^2} = \sqrt{3}\,(1-3w)(1+w)\frac{\rho^{3/2}}{M_P^3}$$

Energy differences between particle vs antiparticles $\pm \dot{\mathcal{R}}/M_*^2$, ***Dynamical CPTV***

Baryon Asymmetry $\frac{n_B}{s} \approx \left. \frac{\dot{\mathcal{R}}}{M_*^2 T} \right|_{T_D}$

Calculate for various w in some scenarios

@ T < T_D ,
T_D = Decoupling T

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

Non-Commutative Geometries LV only

LV & CPTV ⟵ **Axisymmetric Background**
Geometries of the Early Universe
Torsionful Geometries (including strings…)

Early Universe T-dependent effects:
large @ high T, low values today
for coefficients of SME

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

LV & CPTV

Non-Commutative Geometries LV only

Axisymmetric Background

Geometries of the Early Universe

Torsionful Geometries (including strings…)

Early Universe T-dependent effects:
large @ high T, low values today
for coefficients of SME

STANDARD MODEL EXTENSION

Kostelecky *et al.*

$$\mathcal{L} = \frac{1}{2}\mathrm{i}\bar{\psi}\Gamma^{\nu}\overleftrightarrow{\partial}_{\nu}\psi - \bar{\psi}M\psi,$$

$$M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2}H^{\mu\nu}\sigma_{\mu\nu}$$

LV & CPTV

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + \mathrm{e}^{\nu} + \mathrm{i}f^{\nu}\gamma_5 + \frac{1}{2}g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

STANDARD MODEL EXTENSION

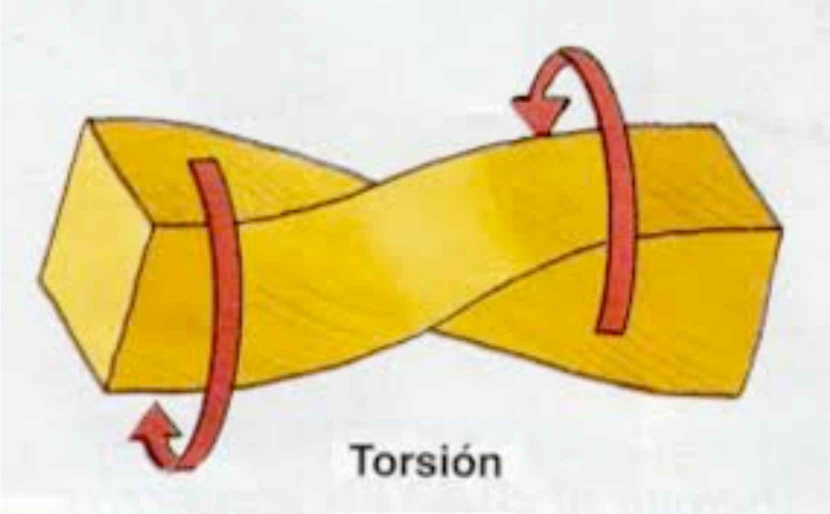
Kostelecky *et al.*

$$\mathcal{L} = \tfrac{1}{2}\mathrm{i}\bar{\psi}\Gamma^{\nu}\bar{\partial}_{\nu}\psi - \bar{\psi}M\psi, \qquad M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \tfrac{1}{2}H^{\mu\nu}\sigma_{\mu\nu}$$

LV & CPTV

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + e^{\nu} + \mathrm{i}f^{\nu}\gamma_5 + \tfrac{1}{2}g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

In particular,
Space-times with



CPTV Effects of different Space-Time-Curvature/ Spin couplings between fermions/antifermions

B. Mukhopadhyay, U. Debnath, N. Dadhich, M. Sinha
Lambiase, Mohanty, NEM, Ellis, Sarkar, deCesare, Bossingham

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a\psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu}e^\gamma_c e^\mu_a\right).$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \tfrac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd}e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu}e^\alpha_c e^\mu_a\right)$$

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$\gamma^a\gamma^b\gamma^c = \eta^{ab}\,\gamma^c + \eta^{bc}\,\gamma^a - \eta^{ac}\,\gamma^b - i\,\epsilon^{dabc}\,\gamma_d\,\gamma^5$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \tfrac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right).$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$\gamma^a\gamma^b\gamma^c = \eta^{ab}\,\gamma^c + \eta^{bc}\,\gamma^a - \eta^{ac}\,\gamma^b - i\,\epsilon^{dabc}\,\gamma_d\,\gamma^5$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right).$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \tfrac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

Standard Model Extension type Lorentz-violating coupling (Kostelecky *et al.*)

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right).$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \frac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\,\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

X

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

For homogeneous and isotropic **Friedman-Robertson-Walker** geometries the resulting B^μ ***vanish***

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right).$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \frac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

Can be constant in a given local frame in Early Universe **axisymmetric (Bianchi) cosmologies** or **near rotating Black holes**, Dirac Lagrangian (for concreteness, it

NEM & Sarben Sarkar, EPJ C73 (2013), 2359
John Ellis, NEM & Sarkar, PLB275 (2013), 407
De Cesare, NEM & Sarkar EPJ C75 (2015), 514
Bossingham, NEM, Sarkar arXiv:1712.03312

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar\psi\,\gamma^a D_a\psi - m\,\bar\psi\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu}e^\gamma_c e^\mu_a\right).$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \tfrac{i}{2}\left[\gamma^a,\gamma^b\right]$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar\psi\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd}e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu}e^\alpha_c e^\mu_a\right)$$

If **torsion** then $\Gamma_{\mu\nu} \neq \Gamma_{\nu\mu}$ ***antisymmetric*** part is the contorsion tensor, contributes

Dirac Lagrangian (for concreteness, it

NEM & Sarben Sarkar, EPJ C73 (2013), 2359
John Ellis, NEM & Sarkar, PLB275 (2013), 407
De Cesare, NEM & Sarkar EPJ C75 (2015), 514
Bossingham, NEM, Sarkar arXiv:1712.03312

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right).$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \frac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

in string theory models antisymmetric tensor field-strength (H-torsion) cosmological backgrounds lead to constant B^0 in FRW frame

Part III

CPT Violation in a String-Inspired Model of the Early Universe

A non-trivial example of Torsion: String Theories with Antisymmetric Tensor Backgrounds

NEM & Sarben Sarkar, EPJ C73 (2013), 2359
John Ellis, NEM & Sarkar, PLB275 (2013), 407
De Cesare, NEM & Sarkar EPJ C75 (2015), 514
Bossingham, NEM, Sarkar arXiv:1712.03312

Massless Gravitational multiplet of (closed) strings: **spin 0 scalar (dilaton)**
spin 2 traceless symemtric rank 2 tensor (graviton)
spin 1 asntisymmetric rank 2 tensor

A non-trivial example of Torsion: String Theories with Antisymmetric Tensor Backgrounds

NEM & Sarben Sarkar, EPJ C73 (2013), 2359
John Ellis, NEM & Sarkar, PLB275 (2013), 407
De Cesare, NEM & Sarkar EPJ C75 (2015), 514
Bossingham, NEM, Sarkar arXiv:1712.03312

Massless Gravitational multiplet of (closed) strings: **spin 0 scalar (dilaton)**
spin 2 traceless symemtric rank 2 tensor (graviton)
spin 1 asntisymmetric rank 2 tensor

KALB-RAMOND FIELD $B_{\mu\nu} = -B_{\nu\mu}$

Effective field theories (low energy scale E << M_s) `` **gauge**'' invariant

$$B_{\mu\nu} \to B_{\mu\nu} + \partial_{[\mu}\theta(x)_{\nu]}$$

Depend only on field strength : $H_{\mu\nu\rho} = \partial_{[\mu}B_{\nu\rho]}$

Bianchi identity : $$\partial_{[\sigma}H_{\mu\nu\rho]} = 0 \to d \star \mathbf{H} = 0$$

ROLE OF H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

4-DIM PART

$$S^{(4)} = \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big)$$
$$= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\ \Big)$$

$$\overline{\Gamma}^{\mu}_{\nu\rho} = \Gamma^{\mu}_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^{\mu}_{\nu\rho} \neq \overline{\Gamma}^{\mu}_{\rho\nu}$$

Contorsion

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

$$\sim \frac{1}{2}\partial^\mu b\, \partial_\mu b$$

4-DIM PART

$$S^{(4)} = \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big)$$

$$= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\ \Big)$$

$\kappa^2 = 8\pi\, G$

$$\overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

IN 4-DIM DEFINE DUAL OF H AS :

$$-3\sqrt{2}\partial_\sigma b = \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

b(x) **= Pseudoscalar (Kalb-Ramond (KR) axion)**

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu\overline{\mathcal{D}}_\mu\psi - (\overline{\mathcal{D}}_\mu\overline{\psi})\gamma^\mu\psi\Big)$$

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

$$\overline{\mathcal{D}}_a = \partial_a - \frac{i}{4}\overline{\omega}_{bca}\sigma^{bc}$$

$$\overline{\omega}_{ab\mu} = \omega_{ab\mu} + K_{ab\mu}$$

contorsion

$$K_{abc} = \frac{1}{2}\Big(T_{cab} - T_{abc} - T_{bca}\Big)$$

$$H_{cab}$$

Non-trivial contributions to B^μ

$$B^d = \epsilon^{abcd}e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\alpha\mu}e_c^\alpha e_a^\mu\right)$$

$$\overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu \overline{\mathcal{D}}_\mu\psi - (\overline{\mathcal{D}}_\mu\overline{\psi})\gamma^\mu\psi\Big)$$

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

$$S_\psi \ni \int d^4x\overline{\psi}\gamma^a\gamma^5 B_a\psi$$

$$\overline{\omega}_{ab\mu} = \omega_{ab\mu} + K_{ab\mu}$$

contorsion

$$K_{abc} = \frac{1}{2}\Big(T_{cab} - T_{abc} - T_{bca}\Big)$$

$$B^d \sim \epsilon^{abcd}H_{bca}$$

$$H_{cab}$$

Non-trivial contributions to ***B^μ***

$$B^d = \epsilon^{abcd}e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu}e^\alpha_c e^\mu_a\right)$$

$$\overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

When db/dt = constant → Torsion is constant

Covariant Torsion tensor

$$\overline{\Gamma}^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} + T^{\lambda}{}_{\mu\nu}$$

$$T_{ijk} \sim \epsilon_{ijk}\, \dot{b}$$

Constant

↓

$$S_{\psi} \ni \int d^4x \overline{\psi} \gamma^a \gamma^5 B_a \psi$$

constant ***B^0***

When db/dt = constant → Torsion is constant

In string theory a constant ***B^0*** background is guaranteed by **exact solutions** with linear in FRW time ***b = (const) t***

Covariant Torsion tensor

$$\overline{\Gamma}^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} +$$

Antoniadis, Bachas, Ellis, Nanopoulos

$$T_{ijk} \sim \epsilon_{ijk}\, \dot{b}$$

Constant

$$S_\psi \ni \int d^4x \overline{\psi} \gamma^a \gamma^5 B_a \psi$$

constant ***B^0***

In string theory a constant ***B⁰*** background is guaranteed by exact conformal Field theory with linear in FRW time ***b = (const) t***

Antoniadis, Bachas, Ellis, Nanopoulos

Strings in Cosmological backgrounds

$$ds^2 = g^E_{\mu\nu}(x)dx^\mu dx^\nu = dt^2 - a(t)^2\delta_{ij}dx^i dx^j$$

$$a(t) = t$$

$$\Phi = -\ln a(t) + \phi_0$$

$$H_{\mu\nu\rho} = e^{2\Phi}\epsilon_{\mu\nu\rho\sigma}\partial^\sigma b(x) \qquad b(x) = \sqrt{2}e^{-\phi_0}\sqrt{Q^2}\frac{M_s}{\sqrt{n}}t$$

Central charge of uderlying world-sheet conformal field theory $n \in Z^+$

$$c = 4 - 12Q^2 - \frac{6}{n+2} + c_I$$

``internal" dims central charge

Kac-Moody algebra level

De Cesare, NEM, Sarkar, Eur.Phys.J. C75 (2015) 10, 514

NB:

Perturbatively we may also have such a constant B^0 background in the presence of **Lorentz-violating condensates** of fermion axial current temporal component

<0 | J^{05} |0> ≠ 0

at the high-density, high-temperature Early Universe epochs

Lagrangian :

$$\mathcal{L} = \sqrt{-g}\Big[\frac{1}{2\kappa^2}R - \frac{1}{2}(\partial_\mu b)^2 - \Omega +$$

$$\sum_i [\overline{\psi}_i(i\gamma^\mu\partial_\mu - m_i)\psi_i + \frac{\kappa}{3\sqrt{6}}\partial_\mu b\,\overline{\psi}_i\gamma^\mu\gamma^5\psi_i] + \dots\Big]$$

vacuum energy

i = Standard Model fermionic species

$\mathcal{O}((\partial b)^4)$

higher derivative terms in strings

De Cesare, NEM, Sarkar, Eur.Phys.J. C75 (2015) 10, 514

NB:

Perturbatively we may also have such a constant B^0 background in the presence of **Lorentz-violating condensates** of fermion axial current temporal component

$$\langle 0 \,|\, J^{05} \,|0\rangle \neq 0$$

at the high-density, high-temperature Early Universe epochs

Eqs of motion for pseudoscalar:

$$\partial^\mu\Big(\sqrt{-g}\big[\epsilon_{\mu\nu\rho\sigma}(\partial^\sigma\overline{b} - \tilde{c}\,J^{5\,\sigma}) + \mathcal{O}\Big((\partial\overline{b})^3\Big)\,\big]\Big) = 0$$

$$\dot{\overline{b}} = \tilde{c}\,\langle J^5_0\rangle = \tilde{c}\,\langle\psi_i^\dagger\gamma^5\psi_i\rangle = \text{constant} \neq 0$$

$i \neq$ Majorana neutrinos

Condensate may be **subsequently destroyed** at a temperature Tc $\langle 0 \,|\, J^{05} \,|0\rangle \to 0$ by relevant operators so eventually in an expanding FRW Universe **for $T < T_c$**

$$B^0 \sim \dot{\overline{b}} \sim 1/a^3(t) \sim T^3$$

weak torsion today, compatible with stringent experimental limits

When db/dt = constant → Torsion is constant

Covariant Torsion tensor

$$\overline{\Gamma}^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} + T^{\lambda}{}_{\mu\nu}$$

$$T_{ijk} \sim \epsilon_{ijk} \dot{b}$$

Constant

$$S_{\psi} \ni \int d^4x \overline{\psi} \gamma^a \gamma^5 B_a \psi$$

constant ***B^0***

When db/dt = constant → Torsion is constant

Covariant Torsion tensor

$$\overline{\Gamma}^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} + T^{\lambda}{}_{\mu\nu}$$

$$T_{ijk} \sim \epsilon_{ijk}\, \dot{b}$$

Constant

$$S_{\psi} \ni \int d^4x \overline{\psi} \gamma^a \gamma^5 B_a \psi$$

constant ***B***^{0}

LV & CPTV

$$\mathcal{L} = \tfrac{1}{2} i \bar{\psi}\, \gamma^{\nu}\, \bar{\partial}_{\nu} \psi - \bar{\psi} M \psi,$$

$$M \equiv m + b_{\mu}\, \gamma^5\, \gamma^{\mu}$$

Standard Model Extension type with CPT and Lorentz Violating background $b^0 = B^0$

If Fermions are **DIRAC** (e.g. quarks, electrons)

DISPERSION RELATIONS OF FERMIONS ARE *DIFFERENT* FROM THOSE OF ANTI-FERMIONS IN *SUCH* GEOMETRIES

CPTV Dispersion relations ($B_0 = b_0$)

$$E = \sqrt{\vec{p}^2 + m^2 + B_0^2 + 2|\vec{p}|\, B_0}$$

$$\overline{E} = \sqrt{\vec{p}^2 + m^2 + B_0^2 - 2|\vec{p}|\, B_0}$$

but (bare) **masses** are equal between **particle/anti-particle** sectors

Abundances of fermions in Early Universe, then, ***different*** from those of antifermions, if B_0 is ***non-trivial***, **ALREADY IN THERMAL EQUILIBRIUM**

If Fermions are **DIRAC** (e.g. quarks, electrons)

DISPERSION RELATIONS OF FERMIONS ARE *DIFFERENT* FROM THOSE OF ANTI-FERMIONS IN *SUCH* GEOMETRIES

CPTV Dispersion relations (B_0 = b_0)

$$E = \sqrt{\vec{p}^2 + m^2 + B_0^2 + 2|\vec{p}|\, B_0}$$

$$\overline{E} = \sqrt{\vec{p}^2 + m^2 + B_0^2 - 2|\vec{p}|\, B_0}$$

but (bare) **masses** are equ

$$n - \overline{n} = \frac{g}{(2\pi)^3} \int d^3p \Big(\frac{1}{1 + e^{E/T}} - \frac{1}{1 + e^{\overline{E}/T}} \Big) \neq 0$$

$$E \neq \overline{E}$$

Abundances of fermions in Early Universe, then, ***different*** from those of antifermions, if B_0 is ***non-trivial***, **ALREADY IN THERMAL EQUILIBRIUM**

If Fermions are **DIRAC** (e.g. quarks, electrons)

DISPERSION RELATIONS OF FERMIONS ARE *DIFFERENT* FROM THOSE OF ANTI-FERMIONS IN *SUCH* GEOMETRIES

CPTV Dispersion relations ($B_0 = b_0$)

$$E = \sqrt{\vec{p}^2 + m^2 + B_0^2 + 2|\vec{p}|\, B_0}$$

$$\overline{E} = \sqrt{\vec{p}^2 + m^2 + B_0^2 - 2|\vec{p}|\, B_0}$$

but (bare) **masses** are equ

$$n - \overline{n} = \frac{g}{(2\pi)^3} \int d^3p \Big(\frac{1}{1 + e^{E/T}} - \frac{1}{1 + e^{\overline{E}/T}} \Big) \neq 0$$

$$E \neq \overline{E}$$

Abundances of fermions in Early Universe, then, ***different*** from those of antifermions, if B_0 is ***non-trivial***, **ALREADY IN THERMAL EQUILIBRIUM**

But for Majorana fermions (their own antiparticles) situation is different...

cf below...

COSMOLOGICAL CONSEQUENCES of SME-type CPTV

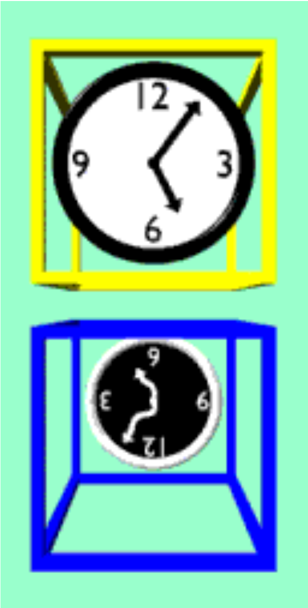
Matter-antimatter asymmetry in Universe

-Lepto(Baryo)genesis

CPT VIOLATION IN THE EARLY UNIVERSE

De Cesare, NEM & Sarkar arXiv:1412.7077
(Eur.Phys.J. C75 (2015) 10, 514)

Right-Handed Heavy Majorana Neutrinos



physics.indiana.edu

Mechanism
For Torsion-Background-Induced tree-level
Leptogenesis → Baryogenesis

Through B-L conserving
Sphaleron processes
In the standard model

SM Extension with N extra right-handed neutrinos

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\,\bar{N}_I^c N_I + \text{h.c.}$$

Paschos, Hill, Luty , Minkowski,
Yanagida, Mohapatra, Senjanovic,
de Gouvea…, Liao, Nelson,
Buchmuller, Anisimov, di Bari…
Nanopoulos, Ellis, Dimopoulos,
March-Russell...
Akhmedov, Rubakov, Smirnov,
Davidson, Giudice, Notari, Raidal,
Riotto, Strumia, Pilaftsis, Underwood,
Shaposhnikov … Hernandez, Giunti...
Antoniadis, Kiritsis, Rizos, Tomaras,
Tamvakis...Leontaris, Vlachos...

SM Extension with N extra right-handed neutrinos

$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \, \bar{N}_I^c N_I + \text{h.c.}$$

Majorana masses to (2 or 3) active (light) neutrinos via ***seesaw***

Yukawa couplings Matrix (N=2 or 3)

SM Extension with N extra right-handed neutrinos

$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\,\bar{N}_I^c N_I + \text{h.c.}$$

Majorana masses to (2 or 3) active (light) neutrinos via ***seesaw***

Yukawa couplings Matrix (N=2 or 3)

$v = \langle \phi \rangle \sim 175$ GeV

NB: Upon Symmetry Breaking
<Φ> = v ≠ 0 → Dirac mass term

$$m_\nu = -M^D \frac{1}{M_I} [M^D]^T$$

Minkowski, Yanagida, Mohapatra, Senjanovic Sechter, Valle …

$$M_D = F_{\alpha I} v \qquad M_D \ll M_I$$

CPTV Thermal Leptogenesis

Early Universe
T >> 10^2 GeV

CPT Violation

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

$$N_I \rightarrow H\nu,\ \bar{H}\bar{\nu}$$

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
$T >> 10^2$ GeV

CPT Violation

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
$T >> 10^2$ GeV

CPT Violation

One generation of *massive neutrinos N suffices for generating CPTV Leptogenesis;*

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \rightarrow H\nu,\ \bar{H}\bar{\nu}$$

CPTV Thermal

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
T >> 10^2 GeV

CPT Violation

One generation* of *massive neutrinos N suffices for generating CPTV Leptogenesis; mass m free to be fixed

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \rightarrow H\nu,\ \bar{H}\bar{\nu}$$

various mechanisms for generation of *m* not discussed here

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Constant H-torsion (antisymmetric tensor field strength in string models)

Early Universe
$T >> 10^2$ GeV

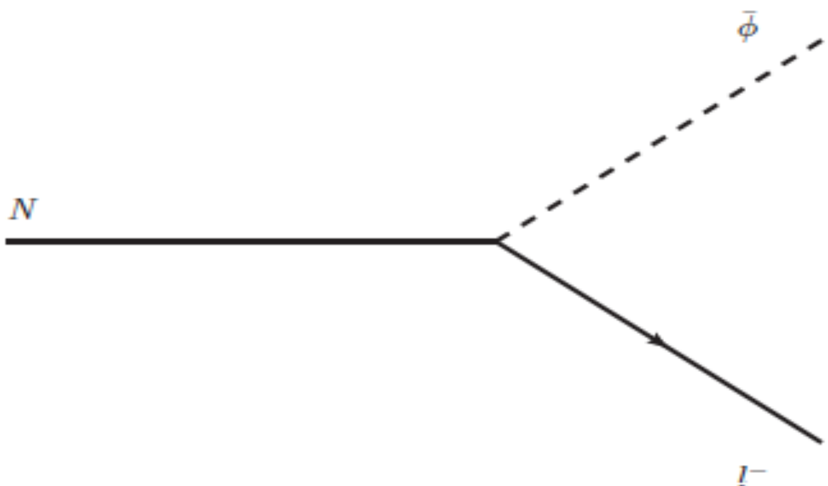
CPT Violation

Lepton number & CP Violations **@ tree-level**
due to Lorentz/CPTV Background

$$B_\mu = B_0\,\delta^0_\mu$$

$$N_I \rightarrow H\nu,\ \bar{H}\bar{\nu}$$

Produce Lepton asymmetry



CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Constant H-torsion

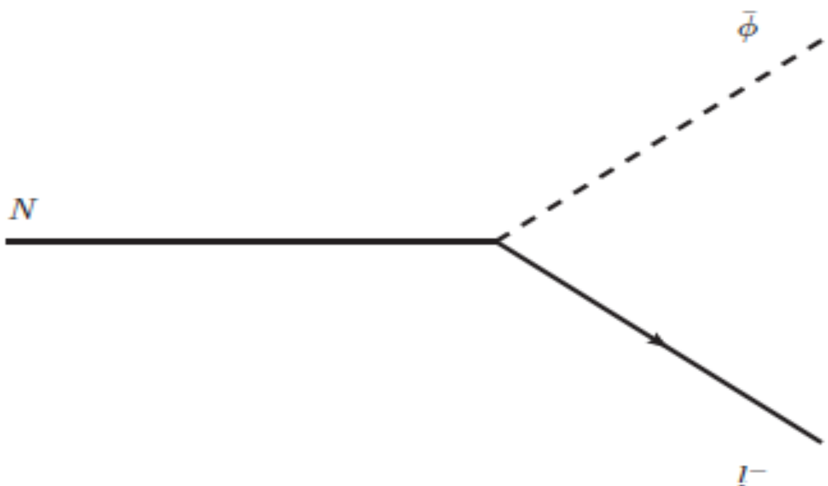
CPT Violation

Early Universe
T >> 10^2 GeV

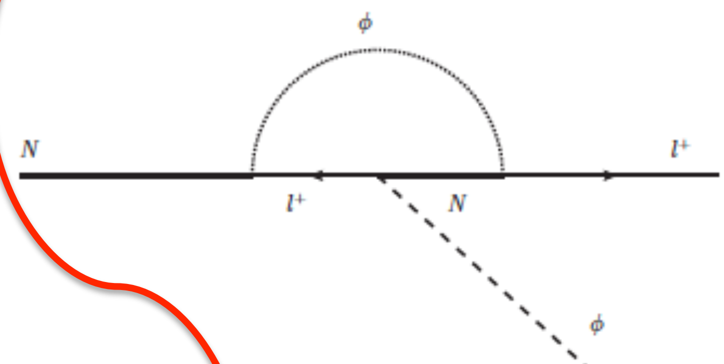
Lepton number & CP Violations @ **tree-level**
due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

Produce Lepton asymmetry



Contrast with one-loop conventional Leptogenesis in absence of H-torsion



Fukugita, Yanagida,

CPTV Thermal

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Constant H-torsion

Early Universe
$T >> 10^2$ GeV

CPT Violation

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

Produce Lepton asymmetry

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not\partial N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
$T \gg 10^2$ GeV

CPT Violation

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

Produce Lepton asymmetry

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
T >> 10^2 GeV

CPT Violation

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$ *

Produce Lepton asymmetry

*

Decoupling Temperature T_D : **decay process out of equilibrium**
@ which Lepton asymmetry is evaluated

$$\Gamma \simeq H = 1,66\, T_D^2 \mathcal{N}^{1/2} m_P^{-1}$$

assume standard cosmology

$$T_D \simeq 6.2 \cdot 10^{-2} \frac{|Y|}{\mathcal{N}^{1/4}} \sqrt{\frac{m_P(\Omega^2 + B_0^2)}{\Omega}}$$

for one generation of RH heavy neutrino

$$\Omega^2 = m_N^2 + B_0^2$$

$\mathcal{N}$ = d.o.f. = O(100)

Estimate: Total Lepton number asymmetry ΔL : $(N \to l^- \overline{\phi}.) - (N \to l^+ \phi)$

Solve appropriate system of Boltzmann Equations for heavy Right-handed neutrino abundance and Lepton asymmetry

Bossingham, NEM, Sarkar
arXiv:1712.03312

*

$$\frac{\Delta L^{TOT}}{s} \simeq (0.008 - 0.014)\frac{B_0}{m_N},$$

@ $T = T_D : \quad m_N/T_D \simeq (1.44 - 1.62).$

For Higgs portal Yukawa |*Y*| = O(10^{-5})

$T_D \approx 10^5$ GeV

$$\frac{B_0}{m_N} \sim 10^{-9} - 10^{-8},$$

NB: Uncertainties due to approximate methods (e.g. Pade) used in solution

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Early Universe
$T > 10^5$ GeV

CPT Violation

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

Produce Lepton asymmetry

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \to$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

CPTV Thermal

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Early Universe
T > 10^5 GeV

CPT Violation

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

?

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \to$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

CPT Violation

Early Universe
$T > 10^5$ GeV

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

$$N_I \rightarrow H\nu,\ \bar{H}\bar{\nu}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental
Conditions Dependent

$$L = \frac{2}{M} l_L l_L \phi\phi + \mathrm{H.c.}$$

where

$$l_L = \begin{pmatrix}\nu_e \\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L$$

Observed Baryon Asymmetry
In the Universe (BAU)

Fukugita, Yanagida,

CPTV Thermal

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

CPT Violation

Early Universe
T > 10^5 GeV

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \to$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

Equilibrated electroweak B+L violating sphaleron interactions

B-L conserved

Environmental Conditions Dependent

Observed Baryon Asymmetry In the Universe (BAU)

Estimate BAU by fixing CPTV background parameters
In some models this means fine tuning ….

B^0 : (string) theory underwent a **phase transition** @ $T \approx T_d = 10^5$ GeV, from B^0 = const = 1 MeV **to** :

(i) **either $B^0 = 0$**

(ii) **or B^0 small today but non zero**

$$B^0 \sim \dot{\bar{b}} \sim 1/a^3(t) \sim T^3$$

$$B_0 = c_0 T^3 \qquad c_0 = 10^{-42}\,\mathrm{meV}^{-2}$$

$$B_{0\,\mathrm{today}} = \mathcal{O}\left(10^{-44}\right)\,\mathrm{meV}$$

Quite safe from stringent Experimental Bounds

$$|B^0| < 10^{-2}\,\mathrm{eV}$$

$$B_i \equiv b_i < 10^{-31}\,\mathrm{GeV}$$

B^0 : (string) theory underwent a **phase transition** @ $T \approx T_d = 10^5$ GeV, from B^0 = const = 1 MeV **to** :

(i) **either $B^0 = 0$**

(ii) **or B^0 small today but non zero**

$$B^0 \sim \dot{\bar{b}} \sim 1/a^3(t) \sim T^3$$

$$B_0 = c_0 T^3 \qquad c_0 = 10^{-42}\,\mathrm{meV}^{-2}$$

$$B_{0\,\mathrm{today}} = \mathcal{O}\left(10^{-44}\right)\ \mathrm{meV}$$

Quite safe from stringent Experimental Bounds

$$|B^0| < 10^{-2}\,\mathrm{eV}$$
$$B_i \equiv b_i < 10^{-31}\,\mathrm{GeV}$$

De Cesare, NEM, Sarkar, Eur.Phys.J. C75 (2015) 10, 514

NB:

Perturbatively we may also have such a constant ***B^0*** background in the presence of **Lorentz-violating condensates** of fermion axial current temporal component

$\langle 0 | J^{05} | 0 \rangle \neq 0$

at the high-density, high-temperature Early Universe epochs

Eqs of motion for pseudoscalar:

$$\partial^\mu \Big(\sqrt{-g} \big[\epsilon_{\mu\nu\rho\sigma} (\partial^\sigma \overline{b} - \tilde{c}\, J^{5\,\sigma}) + \mathcal{O}\Big((\partial \overline{b})^3 \Big) \big] \Big) = 0$$

$$\dot{\overline{b}} = \tilde{c}\, \langle J^5_0 \rangle = \tilde{c}\, \langle \psi_i^\dagger \gamma^5 \psi_i \rangle = \text{constant} \neq 0$$

$i \neq$ Majorana neutrinos

Condensate may be **subsequently destroyed** at a temperature Tc **$\langle 0 | J^{05} | 0 \rangle \rightarrow 0$** by relevant operators so eventually in an expanding FRW Universe **for $T < T_c$**

$$B^0 \sim \dot{\overline{b}} \sim 1/a^3(t) \sim T^3$$

weak torsion today, compatible with stringent experimental limits

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not\partial N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not B\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

CPT Violation

Early Universe
$T > 10^5$ GeV

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

$$N_I \rightarrow H\nu,\ \bar{H}\bar{\nu}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \rightarrow$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental
Conditions Dependent

Observed Baryon Asymmetry
In the Universe (BAU)

Estimate BAU by fixing CPTV background parameters
In some models this means fine tuning ….

e.g. May Require
Fine tuning of
Vacuum energy

CPTV Thermal

$$\mathcal{L} = i\overline{N}\not\partial N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not B\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
$T > 10^5$ GeV

CPT Violation

Constant H-torsion
$B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

$$N_I \to H\nu,\ \bar{H}\bar{\nu}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \to$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental
Conditions Dependent

Observed Baryon Asymmetry
In the Universe (BAU)

Estimate BAU by fixing CPTV background parameters
In some models this means fine tuning ….

e.g. May Require
Fine tuning of
Vacuum energy

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

$$\sim \frac{1}{2}\partial^\mu b\, \partial_\mu b$$

4-DIM PART

$$S^{(4)} = \int d^4x \sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\, H^{\mu\nu\rho}\Big)$$

$$= \int d^4x \sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\ \Big)$$

$\kappa^2 = 8\pi\, G$

IN 4-DIM DEFINE DUAL OF H AS :

$$-3\sqrt{2}\partial_\sigma b \;=\; \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

***b(x)* = Pseudoscalar (Kalb-Ramond (KR) axion)**

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

$$\sim \frac{1}{2}\partial^\mu b\, \partial_\mu b$$

4-DIM PART

$$S^{(4)} = \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\, H^{\mu\nu\rho}\Big)$$

$$= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\ \Big)$$

constant if

$$\dot{b} = \text{const}$$

$\kappa^2 = 8\pi G$

need to be cancelled by bulk contrib.

IN 4-DIM DEFINE DUAL OF H AS :

$$-3\sqrt{2}\partial_\sigma b = \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

***b(x)* = Pseudoscalar (Kalb-Ramond (KR) axion)**

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

CPT Violation

Construct Microscopic (Quantum) Gravity models with strong CPT Violation in Early Universe, but maybe weak today… Fit with all available data… Estimate in this way matter-antimatter asymmetry in Universe.

CONCLUSIONS so far

- CPT Violation (CPTV) due to (strong) quantum fluctuations in space-time at early eras or LV early Universe Geometries is a possibility and may explain the observed matter-antimatter asymmetry in the cosmos, consistently with current-era bounds of CPTV
- One framework for early universe CPTV: Standard Model Extension (SME)
- A string-inspired model of the Early Universe entailing CPT and Lorentz Violation due to Kalb-Ramond-axion- modified background geometries – Consistent phenomenology in current era

…to explore further, in connection with Early Universe Cosmology – CMB polarization etc

Ενα μεγαλο ευχαριστω στον Καθηγητη μου Φ. Χατζηιωαννου για οτι με διδαξε

Του ευχομαι να ειναι παντα καλα και να εμπνεει με την παρουσια του τους νεους Επιστημονες

Επισης τις καλυτερες ευχες μου για
Καλες Γιορτες και ευτυχισμενη
την νεα χρονια 2018 στον ιδιο
και την οικογενεια του

SPARES

*

Proper Treatment through solving Boltzmann Eqs.

T. Bossingham, N.E.M., Sarkar

Boltzmann equation in presence of CPTV & LV Background B_0

RHN Helicity specific λ_r :

$$\mathrm{d}n_r/\mathrm{d}t + 3Hn_r - \frac{g}{2\pi^2}\, 2\lambda_r\, \frac{B_0}{T}\, T^3 \int \mathrm{d}u\, u\, f(E(B_0 = 0), u)$$

$$= \frac{g}{8\pi^3} \int \frac{d^3p}{E(B_0 \neq 0)} C[f] + \mathcal{O}(B_0^2)$$

Summing over RHN Helicities $\Sigma_r \lambda_r = 0$ (**for small *$B_0/T \ll 1$***) :

$$\frac{\mathrm{d}n_N}{\mathrm{d}t} + 3Hn_N = \frac{g}{8\pi^3} \int \frac{\mathrm{d}^3p}{E} \tilde{C}[f] + \mathcal{O}(B_0^2)$$

But **still modified** due to *B_0–Dependence of Energy-Momentum dispersion $E(p, B_0)$*

NB:

If Fermions are **DIRAC** (e.g. quarks, electrons)

DISPERSION RELATIONS OF FERMIONS ARE *DIFFERENT* FROM THOSE OF ANTI-FERMIONS IN *SUCH* GEOMETRIES

CPTV Dispersion relations ($B_0 = b_0$)

$$E = \sqrt{\vec{p}^2 + m^2 + B_0^2 + 2|\vec{p}|\, B_0}$$

$$\overline{E} = \sqrt{\vec{p}^2 + m^2 + B_0^2 - 2|\vec{p}|\, B_0}$$

but (bare) **masses** are equal between **particle/anti-particle** sectors

Abundances of fermions in Early Universe, then, ***different*** from those of antifermions, if **B_0** is ***non-trivial***, **ALREADY IN THERMAL EQUILIBRIUM**

* **Boltzmann Eqs.**

T. Bossingham, N.E.M., Sarkar

$$Y_x = n_x/s \qquad x = N,\ l^{\pm}$$

Standard Cosmology at early eras (radiation era)

$$z = m_N/T$$

$$a \sim t^{1/2}$$

$$T \sim a^{-1} \Rightarrow s \sim T^3.$$

$$H \sim T^2/2 = m_N^2/2z^2.$$

H = Hubble parameter

Helicities

$$\mathcal{L} \equiv Y_{l^-}^{(-)} - Y_{l^+}^{(+)}$$

Lepton asymmetry

$$\bar{Y}_N \equiv \frac{Y_N^{(-)} + Y_N^{(+)}}{2}$$

Heavy RHN abundance averaged over helicities

NB: RHN-Higgs portal Yukawa coupling $|Y| \to |y|$

$m_N \to m$ RHN mass

*

Boltzmann Eqs.

T. Bossingham, N.E.M., Sarkar

RHN helicities Summed up system of Boltzmann for **small $B_0/(T\ \text{or}\ m_N) << 1$**

$$168\frac{m_N^5}{M_{pl}\,z^4}\frac{d\bar{Y}_N}{dz} = -\Big\{\gamma^{eq,(-)}(N\to l^-h^+)\frac{Y_N^{(-)}}{Y_N^{(-),eq}} - \gamma^{eq,(-)}(l^-h^+\to N) + \gamma^{eq,(+)}(N\to l^+h^-)\frac{Y_N^{(+)}}{Y_N^{(+),eq}} - \gamma^{eq,(+)}(l^+h^-\to N)\Big\},$$

$$84\frac{m_N^5}{M_{pl}\,z^4}\frac{d\mathcal{L}}{dz} + 2I_l = \gamma^{eq,(-)}(N\to l^-h^+)\frac{Y_N^{(-)}}{Y_N^{(-),eq}} - \gamma^{eq,(+)}(N\to l^+h^-)\frac{Y_N^{(+)}}{Y_N^{(+),eq}} - \left(\gamma^{eq,(-)}(l^-h^+\to N)\frac{Y_{l^-}^{(-)}}{Y_{l^-}^{(-),eq}} - \gamma^{eq,(+)}(l^+h^-\to N)\frac{Y_{l^+}^{(+)}}{Y_{l^+}^{(+),eq}}\right)$$

$$\bar{Y}_N \equiv \frac{Y_N^{(-)}+Y_N^{(+)}}{2}, \qquad \mathcal{L} \equiv Y_{l^-}^{(-)} - Y_{l^+}^{(+)}, \qquad I_l \equiv 10.7052\frac{g_l m_N^4 B_0}{\pi^2 e M_{pl} z^4}$$

* Thermally averaged equilibrium interaction rates

$$\gamma^{eq,(-)}(N \to l^- h^+) = \gamma^{eq,(-)}(l^- h^+ \to N) = \Lambda f_1(z)[1 + \varepsilon_1(z)]$$

$$\gamma^{eq,(+)}(N \to l^+ h^-) = \gamma^{eq,(+)}(l^+ h^- \to N) = \Lambda f_1(z)[1 - \varepsilon_1(z)]$$

$$z = m_N/T$$

$$\Lambda = \frac{3|y|^2 m_N^4}{16(2\pi)^3}$$

$$z < 1$$

High temperature regime

$$f_1(z) = z^{-2/3}(0.2553 - 0.1447z^2 + 0.0957z^4)$$

$$\varepsilon_1(z) = z\frac{B_0}{m_N}\frac{0.6062 - 0.3063z^2}{0.2553 - 0.1447z^2 + 0.0957z^4}$$

* **Boltzmann Eqs.**

T. Bossingham, N.E.M., Sarkar

RHN helicities Summed up system of Boltzmann for **small $B_0/(T \text{ or } m_N) << 1$**

$$\frac{d\bar{Y}_N}{dz} + P(z)\bar{Y}_N = Q(z) , \quad z < 1$$

$$\frac{d\mathcal{L}}{dz} + J(z)\mathcal{L} = H(z) , \quad z < 1$$

$$P(z) = a^2 z^{10/3}\left(1 - 0.3909z^2 + 0.2758z^4\right);$$

$$Q(z) = b^2 z^{10/3}\left(1 - 0.5668z^2 + 0.3749z^4\right),$$

$$J(z) = \mu^2 z^{10/3}\left(1 - 0.5668z^2 + 0.3749z^4\right)$$

$$H(z) = \nu^2 z^{13/3}\left(1 - 0.2385z^2 - 0.3538z^4\right)\bar{Y}_N(z) - \sigma^2 z^{13/3}\left(1 - 0.1277z^2 - 1.4067z^4\right) - \delta^2$$

$$a^2 \equiv \frac{0.0724|y|^2 e M_{pl}}{168 g_N \pi m_N} \simeq 0.167$$

$$b^2 \equiv \frac{0.0957|y|^2 M_{pl}}{168(2\pi)^3 m_N} \simeq 0.0056$$

$$|y| \sim 10^{-5}$$

$$m_N \sim 100\,\mathrm{TeV}$$

$$\mu^2 \equiv \frac{0.0362|y|^2 e M_{pl}}{84 g_l \pi m_N} \simeq 0.227;$$

$$\nu^2 \equiv \frac{0.1041|y|^2 e M_{pl} B_0}{84 g_N \pi m_N^2} \simeq 1.3055\frac{B_0}{m_N}$$

$$\sigma^2 \equiv \frac{0.0479|y|^2 M_{pl} B_0}{84(2\pi)^3 m_N^2} \simeq 0.0056\frac{B_0}{m_N}$$

$$\delta^2 \equiv \frac{21.4104}{84}\frac{g_l B_0}{\pi^2 e m_N} \simeq 0.038\frac{B_0}{m_N}$$

*

Boltzmann Eqs.

T. Bossingham, N.E.M., Sarkar

RHN helicities Summed up system of Boltzmann for **small** ***B_0 / (T or m_N) << 1***

$$\frac{d\bar{Y}_N}{dz} + P(z)\bar{Y}_N = Q(z)\,, \quad z < 1$$

$$\frac{d\mathcal{L}}{dz} + J(z)\mathcal{L} = H(z)\,, \quad z < 1$$

$$P(z) = a^2 z^{10/3}\left(1 - 0.3909z^2 + 0.2758z^4\right);$$

$$Q(z) = b^2 z^{10/3}\left(1 - 0.5668z^2 + 0.3749z^4\right)$$

$J(z)$ ... $5668z^2 + 0.3749z^4)$

... $0.3538z^4)\bar{Y}_N(z)$

... $1.4067z^4) - \delta^2$

$a^2 \equiv \frac{0.0724|y|^2 e \ldots}{16 \ldots}$

$b^2 \equiv \frac{0.095 \ldots}{168(2 \ldots}$

... $\equiv \frac{\ldots 0362|y|^2 e M_{pl}}{84 g_l \pi m_N} \simeq 0.227;$

$$\nu^2 \equiv \frac{0.1041|y|^2 e M_{pl} B_0}{84 g_N \pi m_N^2} \simeq 1.3055\frac{B_0}{m_N}$$

$$\sigma^2 \equiv \frac{0.0479|y|^2 M_{pl} B_0}{84(2\pi)^3 m_N^2} \simeq 0.0056\frac{B_0}{m_N}$$

$$\delta^2 \equiv \frac{21.4104}{84}\frac{g_l B_0}{\pi^2 e m_N} \simeq 0.038\frac{B_0}{m_N}$$

$|y| \sim 10^{\ldots}$

$m_N \sim 100\ \mathrm{TeV}$

Solve **analytically in region z < 1**
→extrapolate to z = O(1) freezeout region
by using **Pade approximant** methods
and others

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$\rho_{\rm out} = \$\rho_{\rm in}$$

$$\$ \neq S\,S^\dagger$$

$$S = e^{i\int H dt}$$

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\Theta\rho_{\rm in} = \overline{\rho}_{\rm out}$$

If Θ well-defined can show that $\$^{-1} = \Theta^{-1}\$\Theta^{-1}$ exists !

INCOMPATIBLE WITH DECOHERENCE !

Hence Θ ill-defined at low-energies in QG foam models

Wald (79)

Proof

A THEOREM BY R. WALD (1979): **If $\$ \neq S\ S^\dagger$, then CPT is violated, at least in its strong form.**

PROOF: Suppose CPT is conserved, then there exists unitary, invertible operator Θ : $\Theta\overline{\rho}_{in} = \rho_{out}$ acting on density matrices ρ = Tr |ψ><ψ|

$\rho_{out} = \$\ \rho_{in} \rightarrow \Theta\overline{\rho}_{in} = \$\ \Theta^{-1}\overline{\rho}_{out} \rightarrow \overline{\rho}_{in} = \Theta^{-1}\$\ \Theta^{-1}\overline{\rho}_{out}$.

But $\overline{\rho}_{out} = \$\overline{\rho}_{in}$, hence : $\overline{\rho}_{in} = \Theta^{-1}\$\Theta^{-1}\ \$\ \overline{\rho}_{in}$

BUT THIS IMPLIES THAT \$ HAS AN INVERSE- $\Theta^{-1}\$\Theta^{-1}$, IMPOSSIBLE (information loss), hence CPT MUST BE VIOLATED (at least in its strong form).

NB1: IT ALSO IMPLIES: $\Theta = \$\ \Theta^{-1}\ \$$ (fundamental relation for a full CPT invariance).

NB2: My preferred way of CPTV by Quantum Gravity Introduces fundamental arrow of time/microscopic time irreversibility...

NB3: Effective theories decoherence, i.e. (low-energy) experimenters do not have access to all d.o.f. of quantum gravity (e.g. back-reaction effects...)

Proof

A THEOREM BY R. WALD (1979): **If $\$ \neq S\, S^\dagger$, then CPT is violated, at least in its strong form.**

PROOF: Suppose CPT is conserved, then there exists unitary, invertible operator Θ : $\Theta \overline{\rho}_{in} = \rho_{out}$ acting on density matrices ρ = Tr |ψ><ψ|

$\rho_{out} = \$\, \rho_{in} \rightarrow \Theta \overline{\rho}_{in} = \$\, \Theta^{-1} \overline{\rho}_{out} \rightarrow \overline{\rho}_{in} = \Theta^{-1} \$\, \Theta^{-1} \overline{\rho}_{out}$.

But $\overline{\rho}_{out} = \$ \overline{\rho}_{in}$, hence : $\overline{\rho}_{in} = \Theta^{-1} \$ \Theta^{-1}\, \$\, \overline{\rho}_{in}$

CPT is **antiunitary** (due to T) when acting on |ψ>

BUT THIS IMPLIES THAT $\$$ HAS AN INVERSE- $\Theta^{-1} \$ \Theta^{-1}$, IMPOSSIBLE (information loss), hence CPT MUST BE VIOLATED (at least in its strong form.

NB1: IT ALSO IMPLIES: $\Theta = \$\, \Theta^{-1}\, \$$ (fundamental relation for a full CPT invariance).

NB2: My preferred way of CPTV by Quantum Gravity Introduces fundamental arrow of time/microscopic time irreversibility...

NB3: Effective theories decoherence, i.e. (low-energy) experimenters do not have access to all d.o.f. of quantum gravity (e.g. back-reaction effects...)

Proof

A THEOREM BY R. WALD (1979): **If $\$ \neq S\ S^\dagger$, then CPT is violated, at least in its strong form.**

PROOF: Suppose CPT is conserved, then there exists unitary, invertible operator Θ : $\Theta\overline{\rho}_{in} = \rho_{out}$ acting on density matrices ρ = Tr |ψ><ψ|

$\rho_{out} = \$\ \rho_{in} \to \Theta\overline{\rho}_{in} = \$\ \Theta^{-1}\overline{\rho}_{out} \to \overline{\rho}_{in} = \Theta^{-1}\$\ \Theta^{-1}\overline{\rho}_{out}.$

But $\overline{\rho}_{out} = \$\overline{\rho}_{in}$, hence : $\overline{\rho}_{in} = \Theta^{-1}\$\Theta^{-1}\ \$\ \overline{\rho}_{in}$

BUT THIS IMPLIES THAT \$ HAS AN INVERSE- $\Theta^{-1}\$\Theta^{-1}$, IMPOSSIBLE (information loss), hence CPT MUST BE VIOLATED (at least in its strong form).

NB1: IT ALSO IMPLIES: $\Theta = \$\ \Theta^{-1}\ \$$ (fundamental relation for a full CPT invariance).

NB2: My preferred way of CPTV by Quantum Gravity Introduces fundamental arrow of time/microscopic time irreversibility...

NB3: Effective theories decoherence, i.e. (low-energy) experimenters do not have access to all d.o.f. of quantum gravity (e.g. back-reaction effects...)

Proof

A THEOREM BY R. WALD (1979): **If $\$ \neq S\, S^{\dagger}$, then CPT is violated, at least in its strong form.**

PROOF: Suppose CPT is conserved, then there exists unitary, invertible operator Θ : $\Theta\overline{\rho}_{in} = \rho_{out}$ acting on density matrices ρ = Tr |ψ><ψ|

$\rho_{out} = \$\ \rho_{in} \rightarrow \Theta\overline{\rho}_{in} = \$\ \Theta^{-1}\overline{\rho}_{out} \rightarrow \overline{\rho}_{in} = \Theta^{-1}\$\ \Theta^{-1}\overline{\rho}_{out}$.

But $\overline{\rho}_{out} = \$\overline{\rho}_{in}$, hence : $\overline{\rho}_{in} = \Theta^{-1}\$\Theta^{-1}\ \$\ \overline{\rho}_{in}$

BUT THIS IMPLIES THAT \$ HAS AN INVERSE- $\Theta^{-1}\$\Theta^{-1}$, IMPOSSIBLE (information loss), hence CPT MUST BE VIOLATED (at least in its strong form).

NB1: IT ALSO IMPLIES: $\Theta = \$\ \Theta^{-1}\ \$$ (fundamental relation for a full CPT invariance).

NB2: My preferred way of CPTV by Quantum Gravity Introduces fundamental arrow of time/microscopic time irreversibility...

NB3: Effective theories decoherence, i.e. (low-energy) experimenters do not have access to all d.o.f. of quantum gravity (e.g. back-reaction effects...)

CPT symmetry without CPT invariance ?

But....nature may be tricky: WEAK FORM OF CPT INVARIANCE might exist, such that the fundamental "arrow of time" does not show up in any experimental measurements (scattering experiments).

Probabilities for transition from ψ =initial pure state to ϕ =final state

$$P(\psi \to \phi) = P(\theta^{-1}\phi \to \theta\psi)$$

where θ: $\mathcal{H}_{\rm in} \to \mathcal{H}_{\rm out}$, $\mathcal{H}$= Hilbert state space,
$\Theta\rho = \theta\rho\theta^\dagger$, $\theta^\dagger = -\theta^{-1}$ (anti − unitary).

In terms of superscattering matrix $:

$$\$^\dagger = \Theta^{-1}\$\Theta^{-1}$$

Here, Θ is well defined on pure states, but \$ has no inverse, hence $\$^\dagger \ne \$^{-1}$ (full CPT invariance: $\$= SS^\dagger$, $\$^\dagger = \$^{-1}$).

CPT symmetry without CPT invariance ?

But....nature may be tricky: WEAK FORM OF CPT

INVAR

of time

measu

Probab

ϕ =fin

where

$\Theta\rho =$

In term

Supporting evidence for Weak CPT from Black-hole thermodynamics: *Although white holes do not exist (strong CPT violation), nevertheless the CPT reverse of the most probable way of forming a black hole is the most probable way a black hole will evaporate:* **the states resulting from black hole evaporation are precisely the CPT reverse of the initial states which collapse to form a black hole.**

$$\$^\dagger = \Theta^{-1}\$\Theta^{-1}$$

Here, Θ is well defined on pure states, but \$ has no inverse, hence $\$^{\dagger} \ne \$^{-1}$ (full CPT invariance: $\$ = SS^\dagger$, $\$^\dagger = \$^{-1}$).

In principle this question can be settled experimentally

CPT symmetry without CPT invariance ?

But....nature may be tricky: WEAK FORM OF CPT

INVAR

of tim

measu

Probal

ϕ =fin

where

$\Theta\rho =$

In tern

Supporting evidence for Weak CPT from Black-hole thermodynamics: *Although white holes do not exist (strong CPT violation), nevertheless the CPT reverse of the most probable way of forming a black hole is the most probable way a black hole will evaporate:* **the states resulting from black hole evaporation are precisely the CPT reverse of the initial states which collapse to form a black hole.**

$$\$^{\dagger} = \Theta^{-1}\$\Theta^{-1}$$

Here, Θ is well defined on pure states, but \$ has no inverse, hence $\$^{\dagger} \neq \$^{-1}$ (full CPT invariance: $\$ = SS^{\dagger}$, $\$^{\dagger} = \$^{-1}$).

In principle this question can be settled experimentally

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$\rho_{\rm out} = \$\rho_{\rm in}$$

$$\$ \neq S\, S^{\dagger}$$

$$S = e^{i\int H dt}$$

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\Theta\rho_{\rm in} = \overline{\rho}_{\rm out}$$

If Θ well-defined can show that $\$^{-1} = \Theta^{-1}\$\Theta^{-1}$ exists !

INCOMPATIBLE WITH DECOHERENCE !

Hence Θ ill-defined at low-energies in QG foam models

Wald (79)

If CPT ill-defined →
tiny effect (if due to Quantum Gravity decoherence) → concept of antiparticle still well-defined,
but...

↓

(i) observable effects in entangled (neutral) meson-states

(ii) spin-statistics theorem violation? → e.g. **VIP2 Expt**

Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$|i\rangle = \mathcal{N}\Big[|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle + \omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$$

$$\omega = |\omega|e^{i\vartheta}$$

May contaminate initially antisymmetric neutral meson *M* state by symmetric parts (ω-effect)

Wald (79)

Bernabeu, NEM, Papavassiliou (04),…

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Including conventional CPTV (θ) in the Hamiltonian

Bernabeu, Botella, NEM, Nebot EPJC 77 (2017) 865

$$\mathbf{H}|B_H\rangle = \mu_H|B_H\rangle, \quad |B_H\rangle = p_H|B_d^0\rangle + q_H|\bar{B}_d^0\rangle,$$
$$\mathbf{H}|B_L\rangle = \mu_L|B_L\rangle, \quad |B_L\rangle = p_L|B_d^0\rangle - q_L|\bar{B}_d^0\rangle.$$

H (L) = (High (Low) mass states

$$|\Psi_0\rangle \propto |B_L\rangle|B_H\rangle - |B_H\rangle|B_L\rangle + \omega\left\{\theta\left[|B_H\rangle|B_L\rangle + |B_L\rangle|B_H\rangle\right] + (1-\theta)\frac{p_L}{p_H}|B_H\rangle|B_H\rangle - (1+\theta)\frac{p_H}{p_L}|B_L\rangle|B_L\rangle\right\}$$

ω-effect

CPTV in Hamiltonian

$$\theta = \frac{\mathrm{H}_{22} - \mathrm{H}_{11}}{\mu_H - \mu_L}$$

Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$|i\rangle = \mathcal{N}\Big[|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle + \omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$$

$$\omega = |\omega|e^{i\vartheta}$$

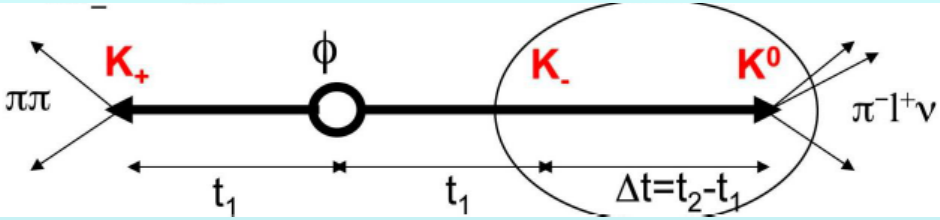
May contaminate initially antisymmetric neutral meson M state by symmetric parts (ω-effect)

Wald (79)

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Bernabeu, NEM, Papavassiliou (04),…

Current Measurement Status of ω-effect



KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

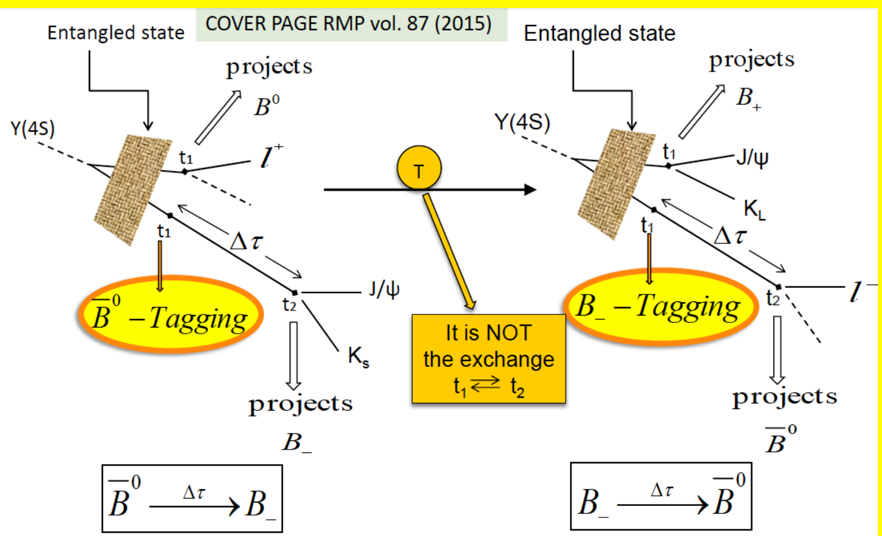
$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

$$|\omega| < 1.0\times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$

Neutral Kaons

Prospects KLOE-2 Re(ω), Im(ω) → 2 x 10^{-5}



Nautral B-mesons

Equal Sign Dilepton Asymmetry
(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 087)

$$-0.0084 \le Re(\omega) \le 0.0100 \qquad 95\%\text{C.L}$$

Novel signal from (f,g) ←→ (g,f)
(Bernabeu, Botella, NEM, Nebot EPJC 77 (2017) 865)

Im (θ)	$(0.99 \pm 1.98)10^{-2}$
Im (ω)	$\pm(6.40 \pm 2.80)10^{-2}$

STANDARD MODEL EXTENSION

V.A. Kostelecký, R. Bluhm, D. Colladay, R. Lehnert, R. Potting, N. Russell

In this case Lorentz symmetry is violated and hence CPT, but no quantum decoherence or unitarity loss. CPT well-defined operator, does not commute with Hamiltonian of the system.

String theory (non supersymmetric) $\rightarrow$ Tachyonic instabilities, coupling with tensorial fields (gauge etc), $\rightarrow < A_\mu > \neq 0$, $< T_{\mu_1 \dots \mu_n} > \neq 0$,

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor ψ reps. electrons, quarks etc. with charge q

$$(i\gamma^\mu D^\mu - M - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu - -\frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

where $D_\mu = \partial_\mu - A^a_\mu T^a - qA_\mu$.

CPT & Lorentz violation: a_μ , b_μ. Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$.

NB1: : mass differences between particle/antiparticle not necessarily.

NB2: In general $a_\mu, b_\mu \dots$ might be energy dependent and NOT constants (c.f. Lorentz-Violation due to quantum space time foam, back reaction effects); ALSO in stochastic models of QG

$\langle a_\mu , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects

STANDARD MODEL EXTENSION

V.A. Kostelecký, R. Bluhm, D. Colladay, R. Lehnert, R. Potting, N. Russell

In this case Lorentz symmetry is violated and hence CPT, but no quantum decoherence or unitarity loss. CPT well-defined operator, does not commute with Hamiltonian of the system.

String theory (non supersymmetric) $\rightarrow$ Tachyonic instabilities, coupling with tensorial fields (gauge etc), $\rightarrow < A_\mu > \neq 0$, $< T_{\mu_1 \dots \mu_n} > \neq 0$,

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor ψ reps. electrons, quarks etc. with charge q

$$(i\gamma^\mu D^\mu - M - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu - -\frac{1}{2} H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

where $D_\mu = \partial_\mu - A^a_\mu T^a - qA_\mu$.

CPT & Lorentz violation: a_μ , b_μ. Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$.

NB1: : mass differences between particle/antiparticle not necessarily.

NB2: In general $a_\mu, b_\mu \dots$ might be energy dependent and NOT constants (c.f. Lorentz-Violation due to quantum space time foam, back reaction effects); ALSO in stochastic models of QG

$\langle a_\mu , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects

STANDARD MODEL EXTENSION

Kostelecky *et al.*

$$\mathcal{L} = \frac{1}{2} i \bar{\psi} \Gamma^{\nu} \bar{\partial}_{\nu} \psi - \bar{\psi} M \psi,$$

$$M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2} H^{\mu\nu}\sigma_{\mu\nu}$$

$$+\mathcal{L}_I$$

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + e^{\nu} + i f^{\nu}\gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

$$\mathcal{L}_I \supset \frac{\lambda\langle T\rangle}{M^k}\overline{\psi}(\gamma^0)^{k+1}(i\partial_0)^k\psi + h.c.$$

Bertolami, Colladay, Kostelecky, Potting
Phys.Lett. B395 (1997) 178-183
hep-ph/9612437 & hep-ph/9706216

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

LV & CPTV ← **SME structures in string theory with spontaneous LV induce matter asymmetry in the Early Universe**

$$\mathcal{L}_I \supset \frac{\lambda\langle T\rangle}{M^k}\overline{\psi}(\gamma^0)^{k+1}(i\partial_0)^k\psi + h.c.$$

Bertolami, Colladay, Kostelecky, Potting
Phys.Lett. B395 (1997) 178-183
hep-ph/9612437 & hep-ph/9706216

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

LV & CPTV ⇐ **SME structures in string theory with spontaneous LV induce matter asymmetry in the Early Universe**

tensors v.e.v.≠0

$$\mathcal{L}_I \supset \frac{\lambda\langle T\rangle}{M^k}\overline{\psi}(\gamma^0)^{k+1}(i\partial_0)^k\psi + h.c.$$

string scale

$$\langle T\rangle \sim (m_l/M)^l M$$

Bertolami, Colladay, Kostelecky, Potting
Phys.Lett. B395 (1997) 178-183
hep-ph/9612437 & hep-ph/9706216

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

LV & CPTV ← **SME structures in string theory with spontaneous LV induce matter asymmetry in the Early Universe**

$$\mathcal{L}_I \supset \frac{\lambda\langle T\rangle}{M^k}\overline{\psi}(\gamma^0)^{k+1}(i\partial_0)^k\psi + h.c.$$

→ **chemical potential μ & energy splitting particle-antiprticle (e.g. quark-antiquark)**

$$\langle T\rangle \sim (m_l/M)^l M$$

Bertolami, Colladay, Kostelecky, Potting
Phys.Lett. B395 (1997) 178-183
hep-ph/9612437 & hep-ph/9706216

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

LV & CPTV ← **SME structures in string theory with spontaneous LV induce matter asymmetry in the Early Universe**

$$\mathcal{L}_I \supset \frac{\lambda \langle T \rangle}{M^k} \overline{\psi} (\gamma^0)^{k+1} (i\partial_0)^k \psi + h.c.$$

→ **chemical potential μ & energy splitting particle-antiprticle (e.g. quark-antiquark)**

$$\langle T \rangle \sim (m_l/M)^l M$$

$$n_q - n_{\bar{q}} = \frac{g}{(2\pi)^3} \int d^3p \, [f_q(\vec{p}) - f_{\bar{q}}(\vec{p})]$$

$$= \frac{g}{2\pi^2} \int_{m_q}^{\infty} dE \, E \sqrt{E^2 - m_q^2} \left[\frac{1}{1 + e^{(E-\mu)/T}} - \frac{1}{1 + e^{(E+\mu)/T}} \right]$$

$\mu \sim m_l^2/M$ for $k = 0 \quad l = 2$

baryon asymmetry strong in the past **diluted today** by sphaleron effects

Bertolami, Colladay, Kostelecky, Potting
Phys.Lett. B395 (1997) 178-183
hep-ph/9612437 & hep-ph/9706216

Microscopic Origin of SME coefficients?

But…No concrete Microscopic Models
Only Phenomenological

Several ``Geometry-induced''

LV & CPTV ← **SME … theory with spontaneous LV … metry in the Early Universe**

$$\mathcal{L}_I \supset \frac{\lambda\langle T \ldots}{\ldots} \ldots)^k \psi + h.c.$$

→ **chemical potential μ & energy splitting particle-antiprticle (e.g. quark-antiquark)**

$$\langle T \rangle \sim (m_l/M)^l M \ldots$$

$$n \ldots = \frac{g}{(2\pi)^3} \int d^3p \, [f_q(\vec{p}) - f_{\bar{q}}(\vec{p})]$$

$$= \frac{g}{2\pi^2} \int_{m_q}^{\infty} dE \, E \sqrt{E^2 - m_q^2} \left[\frac{1}{1 + e^{(E-\mu)/T}} - \frac{1}{1 + e^{(E+\mu)/T}} \right]$$

$\mu \sim m_l^2/M$ for $k = 0 \;\; l = 2$

baryon asymmetry strong in the past **diluted today** by sphaleron effects

STANDARD MODEL EXTENSION

V.A. Kostelecký, R. Bluhm, D. Colladay, R. Lehnert, R. Potting, N. Russell

In this case Lorentz symmetry is violated and hence CPT, but no quantum decoherence or unitarity loss. CPT well-defined operator, does not commute with Hamiltonian of the system.

String theory (non supersymmetric) $\rightarrow$ Tachyonic instabilities, coupling with tensorial fields (gauge etc), $\rightarrow < A_\mu > \neq 0$, $< T_{\mu_1 \ldots \mu_n} > \neq 0$,

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor ψ reps. electrons, quarks etc. with charge q

$$(i\gamma^\mu D^\mu - M - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu - -\frac{1}{2} H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

where $D_\mu = \partial_\mu - A^a_\mu T^a - qA_\mu$.

CPT & Lorentz violation: a_μ , b_μ. Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$.

NB1: : mass differences between particle/antiparticle not necessarily.

NB2: In general $a_\mu, b_\mu \ldots$ might be energy dependent and NOT constants (c.f. Lorentz-Violation due to quantum space time foam, back reaction effects); ALSO in stochastic models of QG

$\langle a_\mu , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects

SM Extension with N extra right-handed neutrinos

νMSM

$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \, \bar{N}_I^c N_I + \text{h.c.}$$

From Constraints (compiled ν oscillation data) on (light) sterile neutrinos:
Giunti, Hernandez ...
N=1 *excluded by data*

Yukawa couplings Matrix (N=2 or 3)

$$F = \widetilde{K}_L \, f_d \, \widetilde{K}_R{}^\dagger$$

Model with 2 or 3 singlet fermions works well in reproducing Baryon Asymmetry and is consistent with Experimental Data on neutrino oscillations

Model with N=3 also works fine, and in fact it allows ***one*** of the Majorana fermions to almost ***decouple*** from the rest of the SM fields, thus providing candidates for ***light*** (keV region of mass) sterile neutrino ***Dark Matter.***

SM Extension with N extra right-handed neutrinos

Non SUSY $\nu\mathrm{MSM}$

Boyarski, Ruchayskiy, Shaposhnikov

$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \, \bar{N}_I^c N_I + \mathrm{h.c.}$$