

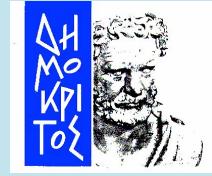
# Matter-Antimatter Asymmetry in the Universe and Kalb-Ramond Torsion background



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The background image shows the interior of a theater. The seating consists of red upholstered chairs arranged in rows, facing a stage area. The walls and ceiling are made of light-colored wood paneling. A large, dark red curtain hangs at the front of the stage. The ceiling is white with numerous small, glowing lights. The overall atmosphere is warm and dramatic.

# OUTLINE

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- **Motivation:** Observed matter/antimatter asymmetry in the Universe  
Origin and nature of neutrino masses

## Beyond the Standard Model Physics – role of Heavy right-handed neutrinos?

- Torsion in Space-time Geometry – Basic concepts
- Early Universe CPT & Lorentz symmetry Violation possibility induced by Torsion Backgrounds  
Evolution from Early Universe to current epoch
  - **compatibility with current phenomenology**
- Torsion **Quantum Fluctuations** in (**Quantum Gravity**) Path Integral & (right-handed) Neutrino Majorana mass generation through “chiral anomalies”
- Conclusions & Outlook

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    - Torsion **Quantum Fluctuations** in (**Quantum Gravity**) Path Integral & (right-handed) Neutrino Majorana mass generation through “chiral anomalies”
    - Conclusions & Outlook
- Non SUSY but allow for Right-Handed (Majorana) Neutrinos*
- Keep the Extension of SM minimal*
- Change the Geometry of the Early Universe*
- to provide extra sources of CP Violation*
- needed for Matter/Antimatter Asymmetry*

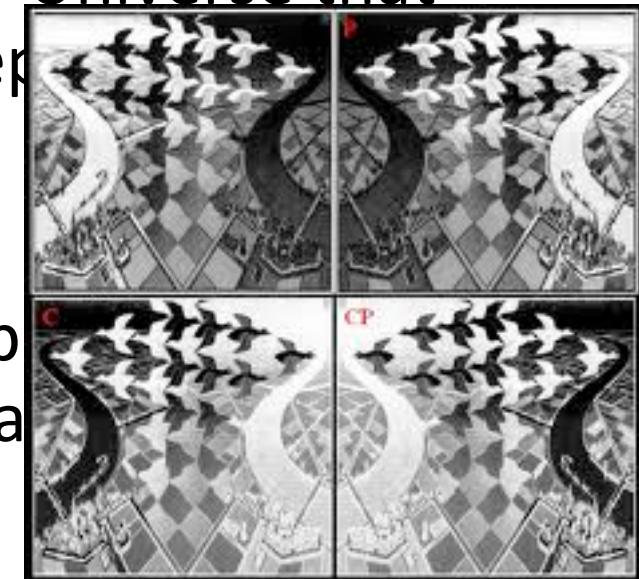
**NEUTRINOS,  
BARYOGENESIS  
&  
LEPTOGENESIS**

# Generic Concepts

- ***Leptogenesis***: physical *out of thermal equilibrium* processes in the (*expanding*) Early Universe that produce an asymmetry between leptons & antileptons
- ***Baryogenesis***: The corresponding processes that produce an asymmetry between baryons and antibaryons
- ***Ultimate question: why is the Universe made only of matter?***

# Generic Concepts

- **Leptogenesis:** physical *out of thermal equilibrium* processes in the (*expanding*) Early Universe that produce an asymmetry between leptons and antileptons



escher

- **Baryogenesis:** The corresponding processes in the Early Universe that produce an asymmetry between baryons and antibaryons
- **Ultimate question: why is the Universe made only of matter?**

# NEUTRINOS & LEPTOGENESIS

- 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

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

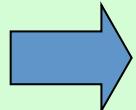
$T > 1 \text{ GeV}$

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



$$n_B - \bar{n}_B$$

but **not quantitatively in SM**, still a mystery



Assume CPT

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

C=charge conjugation

P = spatial reflexion  $\vec{x} \rightarrow -\vec{x}$

$$X \xrightarrow{\leftarrow} \ell + \dots$$

$\bar{A}$  = antiparticle

$$CP : \quad \overline{X} \xrightarrow{\leftarrow} \bar{\ell} + \overline{(\dots)}$$

Rates  $\Gamma \neq \bar{\Gamma}$

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

(ii) Directly generated out of equilibrium Baryogenesis

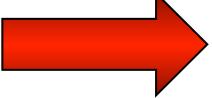
## ELECTROWEAK THEORY & FERMION # NON-CONSERVATION

Classical conservations of EW theory:  $B, L_e, L_\mu, L_\tau$

Quantum Anomalies:

$$\partial_\mu J_\mu^B = \partial_\mu J_\mu^L = \frac{n_f}{32\pi^2} \text{Tr} F_{\mu\nu} \tilde{F}_{\mu\nu} + U(1) \text{ part}$$

Allowed Processes (change of B by multiples of 3)

bosons  $\leftrightarrow$  bosons +  $9q + 3l$    $L_i - B/3$  Conserved  
(three quantities)

**BUT:**  
**OBSERVED NEUTRINO  
FLAVOUR OSCILLATIONS**



L-B conserved (one quantity)  
L=total Lepton #

If neutrinos Majorana



L violated, No conserved numbers

# OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

Kuzmin, Rubakov, Shaposhnikov

Rate of B violation in Early Universe

$$\Gamma \sim \begin{cases} (\alpha_W T)^4 \left(\frac{M_{\text{sph}}}{T}\right)^7 \exp\left(-\frac{M_{\text{sph}}}{T}\right), & T \lesssim M_{\text{sph}}, \\ \alpha_W (\alpha_W T)^4 \log(1/\alpha_W), & T \gtrsim M_{\text{sph}}, \end{cases}$$

$\alpha_W$  = SU(2) fine structure ‘‘constant’’

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Sphaleron Mass Scale  
 $(M_w/\alpha_w)$  = height of energy  
Barrier separating SU(2) vacua  
with different topologies

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Thermal Equilibrium (i.e.  $\Gamma > H$  (Hubble)) for B non conserv. occurs only for:

$$T_{\text{sph}}(m_H) < T < (\alpha_W)^5 M_{Pl} \sim 10^{12} \text{ GeV}$$

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

$$m_H \in [100, 300] \text{ GeV}$$

*BAU could be produced  
this way only when  
sphaleron interactions  
freeze out, i.e.*

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

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BAU COULD BE PRODUCED @

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

Compute CP  
Violation Effects

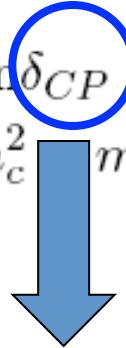
$$T_{\text{sph}}(m_H) \in [130, 190] \text{GeV}$$

$$m_H \in [100, 300] \text{GeV}$$

Use CKM  
Matrix for  
 $T > T_{\text{sph}}$

Within the Standard Model, lowest CP Violating structures

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



Kobayashi-Maskawa CP Violating phase

Shaposhnikov

$$D = \text{Im Tr} [\mathcal{M}_u^2 \mathcal{M}_d^2 \mathcal{M}_u \mathcal{M}_d]$$

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

<<

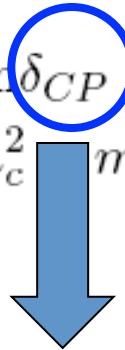
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This CP Violation  
Cannot be the  
Source of Baryon  
Asymmetry in  
The Universe

# Role of Neutrinos?

- Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.)
- Massive  $\nu$  are **simplest** extension of SM
- Right-handed massive  $\nu$  may provide extensions of SM with: **extra CP Violation**

## 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...  
Akhmedov, Rubakov, Smirnov,  
Davidson, Giudice, Notari, Raidal,  
Riotto, Strumia, **Pilaftsis**, Underwood,  
**Shaposhnikov** ... Hernandez, Giunti...

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Right-handed  
Massive **Majorana**  
neutrinos

Leptons

$$L_\alpha = \begin{pmatrix} \nu_\alpha \\ \alpha^- \end{pmatrix}, \quad \alpha = e, \mu, \tau$$

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Higgs scalar SU(2)

Dual:  $\tilde{\phi}_i = \epsilon_{ij} \phi_j^*$ .

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$\nu$ MSM

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

**Yukawa couplings**  
**Matrix (I= 1, ...N=2 or 3 )**

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

$\nu$ MSM

Boyarski, Ruchayskiy, Shaposhnikov

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



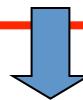
Yukawa couplings  
Matrix ( $I=1, \dots, N=3$ )

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**Yukawa couplings**

**Matrix ( $I=1,2,3$ )**

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

$$f_d = \text{diag}(f_1, f_2, f_3), \quad \tilde{K}_L = K_L P_\alpha, \quad \tilde{K}_R^\dagger = K_R^\dagger P_\beta$$

$$P_\alpha = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1), \quad P_\beta = \text{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$$

**Majorana phases**

Mixing

$$K_L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{L23} & s_{L23} \\ 0 & -s_{L23} & c_{L23} \end{pmatrix} \begin{pmatrix} c_{L13} & 0 & s_{L13} e^{-i\delta_L} \\ 0 & 1 & 0 \\ -s_{L13} e^{i\delta_L} & 0 & c_{L13} \end{pmatrix} \begin{pmatrix} c_{L12} & s_{L12} & 0 \\ -s_{L12} & c_{L12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{Lij} = \cos(\theta_{Lij}) \text{ and } s_{Lij} = \sin(\theta_{Lij}).$$

# SM Extension with N extra right-handed neutrinos

## $\nu$ MSM

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

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

**Yukawa couplings  
Matrix (N=2 or 3 )**

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

**NB:** Upon Symmetry Breaking  
 $\langle \Phi \rangle = v \neq 0 \rightarrow$  Dirac mass term



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Light Neutrino Masses through see saw

Minkowski,  
Yanagida,  
Mohapatra, Senjanovic

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

$$M_D = F_{\alpha I} v$$

$$v = \langle \phi \rangle \sim 175 \text{ GeV} \quad M_D \ll M_I$$





**This talk:** novel ways of  
**Mass generation** via  
**Torsion Quantum fluctuations**

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## *Thermal Properties*

*Two distinct physics cases:*

*(i)  $M_I > M_W = O(100)$  GeV*

&

*(ii)  $M_I < M_W$*

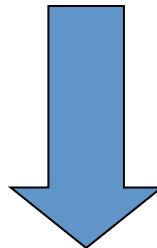
# Thermal Leptogenesis $M_I > M_W$

Independent of  
Initial Conditions  
 $\text{@ } T \gg T_{\text{eq}}$

Heavy Right-handed Majorana  $N_I$  enter **equilibrium at  $T = T_{\text{eq}} \approx 5M_I > T_{\text{decay}} \approx 3M_I$**

Lepton number Violation  
**@ 1-Loop**

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

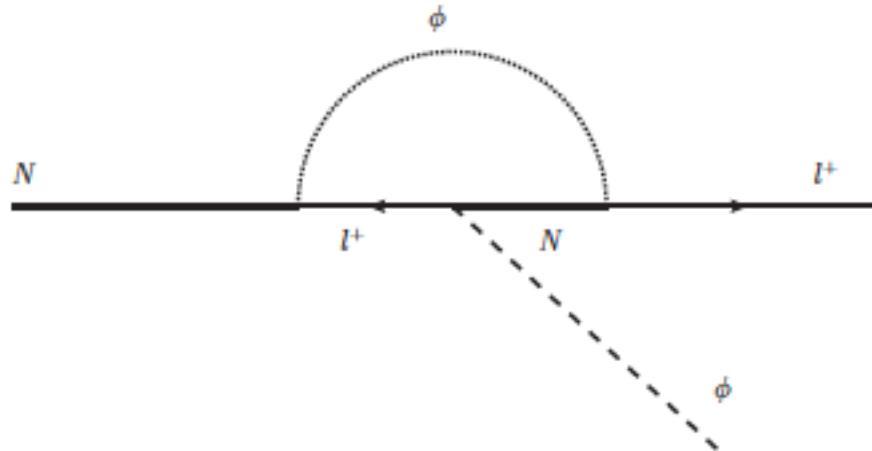


**Out of Equilibrium Decays**

$$T \simeq T_{\text{decay}} > T_{\text{sph}}$$



**Produce Lepton asymmetry**



Fukugita, Yanagida,

Kuzmin, Rubakov,  
Shaposhnikov

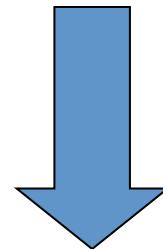
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**Produce Lepton asymmetry**

Equilibrated electroweak  
B+L violating sphaleron  
interactions



Fukugita, Yanagida,

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$N_I \rightarrow H$

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

*Out of Equilibrium Decays*



$T_{\text{sph}}$

Equilibrated  
B+L violating  
interactions

where

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

a, Yanagida,

n, Rubakov,  
shinkov

*Observed Baryon Asymmetry  
In the Universe (BAU)*

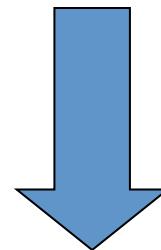
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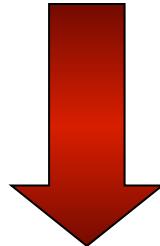
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**Produce Lepton asymmetry**

Equilibrated electroweak  
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**Independent of Initial  
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Fukugita, Yanagida,

Kuzmin, Rubakov,  
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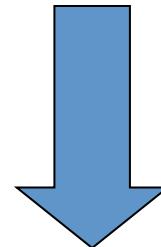
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**Produce Lepton asymmetry**

Equilibrated electroweak  
B+L violating sphaleron  
interactions

**Independent of Initial  
Conditions**

**B-L  
conserved**

Fukugita, Yanagida,

**Observed Baryon Asymmetry  
In the Universe (BAU)**



Kuzmin, Rubakov,  
Shaposhnikov

**Estimate BAU by solving Boltzmann equations  
for Heavy Neutrino Abundances**

Pilaftsis,  
Buchmuller, di Bari et al.

# *Thermal Properties*

Ashaka, Shaposhnikov...

(ii)  $M_I < M_W$  (electroweak scale), e.g.  $M_I = O(1)$  GeV



Keep light neutrino masses in right order , Yukawa couplings must be:

$$F_{\alpha I} \sim \frac{\sqrt{m_{\text{atm}} M_I}}{v} \sim 4 \times 10^{-8}$$
 A red double-headed arrow symbol, indicating a comparison or equivalence between the two expressions.

*Baryogenesis through **coherent**  
oscillations right-handed singlet fermions*

Akhmedov, Rubakov, Smirnov

# *Thermal Properties*

Ashaka, Shaposhnikov...

(ii)  $M_I < M_W$  (electro-

**BUT...Assumption:** Interactions with plasma  
of SM particles do not destroy quantum mechanical  
coherence of oscillations ....

**MAY BE DIFFICULT TO ACHIEVE**



*Because they are **syn coherent***

*...this right-handed singlet fermions*

Akhmedov, Rubakov, Smirnov



**IDEA:**

**Instead of preserving  
CPT, can we have (in  $\nu$  MSM)  
CPT Violating backgrounds  
in Early universe →  
Efficient Leptogenesis →  
Baryogenesis through  
B-L preserving sphalerons?**

Change Geometry  
of Early Universe



**Can we maintain  $\nu$  MSM as a basis but use  
Geometrical origin of extra CP Violation →  
Lorentz Violating Torsionful Geometries**

**Also:**

**Geometrical Origin of Right-Handed Neutrino  
Masses used in  $\nu$  MSM (to give via Seesaw  
masses to the light (active) SM left-handed  
neutrinos)**

**Torsion Fluctuations in (Quantum Gravity)  
path integral**

# **CPT THEOREM IN RELATIVISTIC QFT**

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

Laws of Physics (field theory Lagrangian) invariant under the action of the antiunitary transformation CPT at any order if:

**CPT Invariance Theorem :**

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

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

**(ii)-(iv) Independent reasons for violation**

# **CONDITIONS FOR CPT VIOLATION**

## **CPT Invariance Theorem :**

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

**Kostelecky , Potting, Russell,  
Lehnert, Mewes, Diaz ....  
Standard Model Extension (SME)**

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

Lorentz  
Violation

Lorentz & CPT  
Violation

***(ii)-(iv) Independent reasons for violation***



**Torsion-background –  
induced SME with  
CPTV &  
Lorentz Violation**

# STANDARD MODEL EXTENSION

Kostelecky *et al.*

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

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

## + Gauge Sectors

$$O_{\mu\nu\dots}^{\text{SM}} C^{\mu\nu\dots} \rightarrow O_{\mu\nu\dots}^{\text{SM}} \langle C^{\mu\nu\dots} \rangle$$

Bolokhov, Pospelov 0703291.

Contributions to Matter & Gauge sectors → Complete classification  
Of dimension five Operators (gauge invariance requirement)

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Lorentz & CPT - Violating

CPT: well-defined quantum operator

$$[\widehat{CPT}, H] \neq 0$$

## + Gauge Sectors

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# Microscopic Origin of SME coefficients?

Several ``Geometry-induced'' examples:

Non-Commutative Geometries

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

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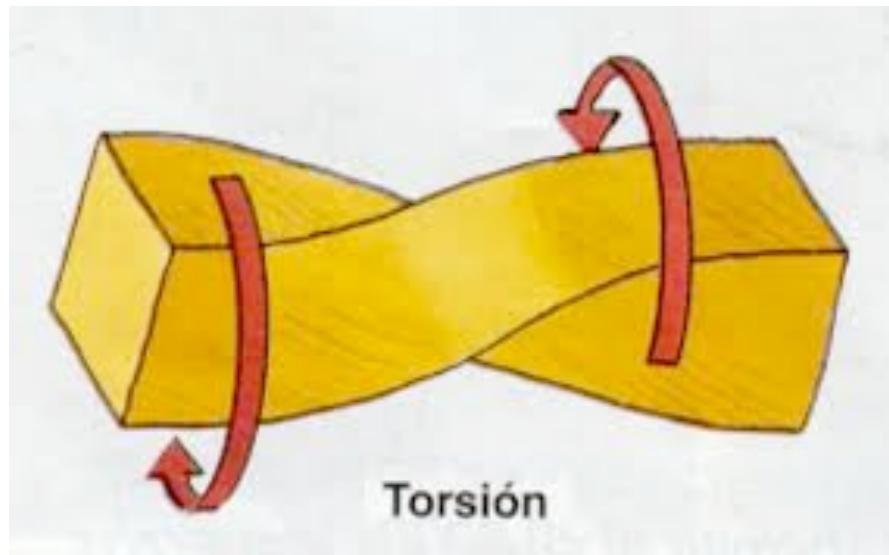
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# CPTV Effects of different Space-Time-Curvature/ Spin couplings between fermions/antifermions

Ellis, NEM, Sarkar, de Cesare

In Space-times with



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

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

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

Gravitational covariant derivative  
including spin connection

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

$$\omega_{bca} = e_{b\lambda} (\partial_a e_c^\lambda + \Gamma_{\gamma\mu}^\lambda e_c^\gamma e_a^\mu).$$

$$e_\mu^a e_\nu^b \eta_{ab} = g_{\mu\nu}$$

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

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

*B<sup>d</sup> may be constant in a given frame*  
*In some (torsionful) background*  
*Geometries → SME*



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### 3. Fermions in Gravity with TORSION

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

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

## Fermions and Torsion

Gravity with Torsion contains  
**Antisymmetric** parts in the spin connection:

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

$$\bar{\omega}_{\mu}^{ab} = e_{\nu}^a \partial_{\mu} e^{\nu b} + e_{\nu}^a e^{\sigma b} \Gamma_{\sigma\mu}^{\nu} = e_{\nu}^a e^{\nu b}_{;\mu}$$

$$K_{\mu}^{ab} = e_{\nu}^a e_{\rho}^b K_{\mu}^{\nu\rho}, \quad K_{\mu}^{\nu\rho} = -K_{\mu}^{\rho\nu} \quad \leftarrow \text{Contorsion tensor}$$

Torsion  $T_{\nu\rho}^{\mu}$

$$K_{\rho\mu}^{\nu} = \frac{1}{2} (T_{\rho\mu}^{\nu} - T_{\rho}^{\nu\mu} - T_{\mu}^{\nu\rho})$$

Torsion decomposes in vector,  $T_{\mu}$ , axial vector  $S_{\mu}$  and tensor  $q_{\mu\nu\rho}$  parts

Curvature tensor in first order torsionful formalism

$$R_{\mu\nu}^{ab} = 2\partial_{[\mu} \omega_{\nu]}^{ab} + 2\omega_{c[\mu}^a \omega_{\nu]}^{cb}$$

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

NEM & Sarben Sarkar, [arXiv:1211.0968](https://arxiv.org/abs/1211.0968)

John Ellis, NEM & Sarkar, [arXiv:1304.5433](https://arxiv.org/abs/1304.5433)

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Massless Gravitational multiplet of (closed) strings: spin 0 scalar (dilaton)  
spin 2 traceless symmetric rank 2 tensor (graviton)  
spin 1 antisymmetric rank 2 tensor

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

Effective field theories (low energy scale  $E \ll M_s$ ) ``gauge'' invariant

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

Depend only on field strength :

$$H_{\mu\nu\rho} = \partial_{[\mu} B_{\nu\rho]}$$

**Bianchi identity :**

$$\partial_{[\sigma} H_{\mu\nu\rho]} = 0 \rightarrow d \star H = 0$$

# ***ROLE OF H-FIELD AS TORSION***

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

4-DIM  
PART

$$\begin{aligned} S^{(4)} &= \int d^4x \sqrt{-g} \left( \frac{1}{2\kappa^2} R - \frac{1}{6} H_{\mu\nu\rho} H^{\mu\nu\rho} \right) \\ &= \int d^4x \sqrt{-g} \left( \frac{1}{2\kappa^2} \bar{R} \right) \end{aligned}$$

$$\bar{\Gamma}_{\nu\rho}^\mu = \Gamma_{\nu\rho}^\mu + \frac{\kappa}{\sqrt{3}} H_{\nu\rho}^\mu \neq \bar{\Gamma}_{\rho\nu}^\mu$$

**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

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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

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

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

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

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

contorsion

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

$$H_{cab}$$

Non-trivial contributions to  $B^\mu$

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

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In string theory a constant  $B^0$  background is guaranteed by exact conformal Field theory with linear in FRW time  $\mathbf{b} = (\text{const}) \mathbf{t}$

Antoniadis, Bachas, Ellis, Nanopoulos

## Strings in Cosmological backgrounds

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

$$a(t) = t$$

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

$$H_{\mu\nu\rho} = e^{2\Phi} \epsilon_{\mu\nu\rho\sigma} \partial^\sigma b(x)$$

$$b(x) = \sqrt{2} e^{-\phi_0} \sqrt{Q^2} \frac{M_s}{\sqrt{n}} t$$

Central charge of underlying world-sheet conformal field theory

$$n \in \mathbb{Z}^+$$

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

...

“internal” dims  
central charge

Kac-Moody  
algebra level

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

De Cesare, NEM & Sarkar [arXiv:1412.7077](https://arxiv.org/abs/1412.7077)

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

$$\dot{\bar{b}} = \tilde{c} \langle J_0^5 \rangle = \tilde{c} \langle \psi_i^\dagger \gamma^5 \psi_i \rangle = \text{constant} \neq 0$$

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

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



When  $db/dt = \text{constant} \rightarrow \text{Torsion is constant}$

Covariant Torsion tensor

$$\bar{\Gamma}^\lambda_{\mu\nu} = \Gamma^\lambda_{\mu\nu} + e^{-2\Phi} H^\lambda_{\mu\nu} \equiv \Gamma^\lambda_{\mu\nu} + T^\lambda_{\mu\nu}$$

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

Constant



constant  $B^0$

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



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

A photograph of a theater auditorium from an elevated perspective. The walls and ceiling are made of light-colored wood paneling, and the floor is filled with rows of red theater seats. The ceiling has several recessed lights. A large green rectangular overlay is positioned in the center of the image, containing yellow text.

**Torsion-background –  
induced  
Matter/Antimatter  
Asymmetry**

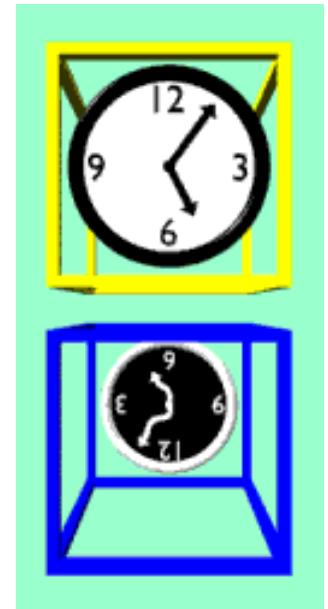
# **CPT VIOLATION IN THE EARLY UNIVERSE**

*GENERATE Baryon and/or Lepton ASYMMETRY  
in the Universe via CPT Violation*

Assume CPT Violation.  
e.g. due to **Quantum Gravity** with torsion  
fluctuations, **strong** in the Early Universe

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

**Through B-L conserving  
Sphaleron processes  
In the standard model**



[physics.indiana.edu](http://physics.indiana.edu)

# *CPTV Thermal Leptogenesis*

Early Universe  
 $T > 10^5$  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

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

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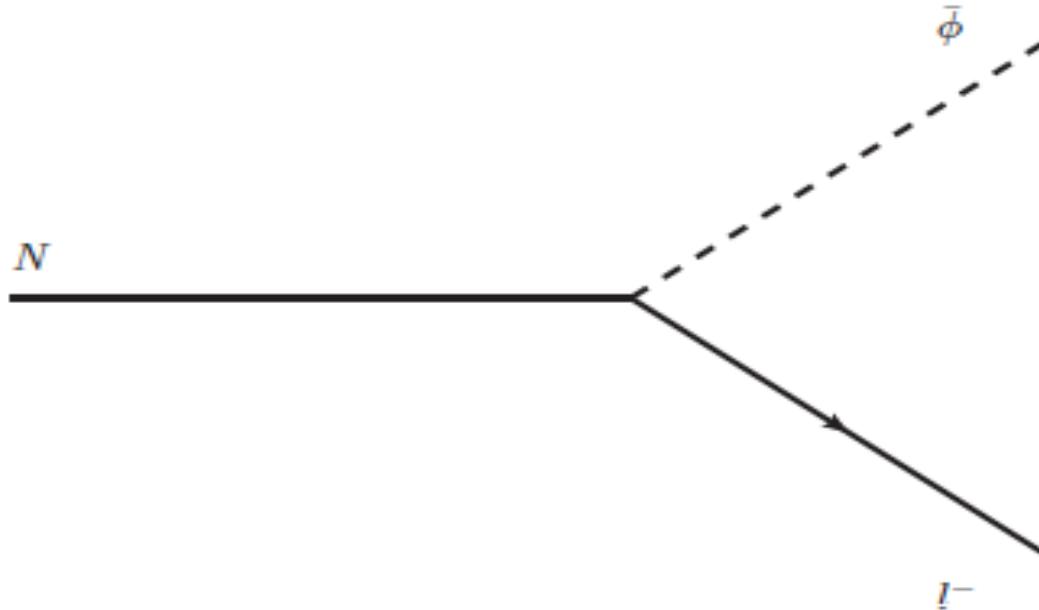
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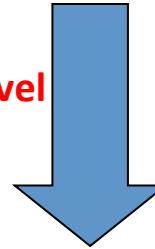
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Constant H-torsion



Produce Lepton asymmetry

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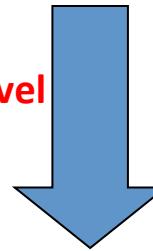
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## CPT Violation



Constant H-torsion

$$\Omega = \sqrt{B_0^2 + m^2}$$

$$n_N = e^{-\beta m} \left( \frac{m}{2\pi\beta} \right)^{\frac{3}{2}}$$

$$B^0 \ll T, m$$

$$T_D \simeq m$$

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

$$H = 1/t \sim \Gamma|_D$$

$$1/t_D \sim T_D^2$$

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

$$\mathcal{N} \approx 10^2$$

$$\Delta L^{TOT} = \frac{2\Omega B_0}{\Omega^2 + B_0^2} n_N$$

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

$$m_\nu \sim \frac{Y_k^2 v^2}{m} \leq 10^{-2} \text{ eV}$$

# CPTV Thermal

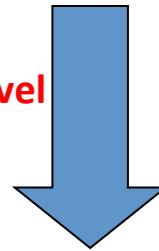
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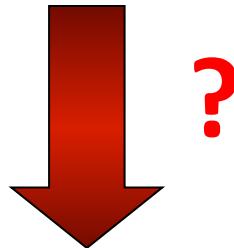
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## CPT Violation



*Produce Lepton asymmetry*



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$$B^0 \ll T, m$$

$$T_D \simeq m$$

Equilibrated electroweak  
 B+L violating sphaleron interactions

Produce Lepton asymmetry

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

*Environmental  
 Conditions Dependent*

B-L conserved

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

where

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

Observed Baryon Asymmetry  
 In the Universe (BAU)

# CPTV Thermal

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

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## CPT Violation



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

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

Produce Lepton asymmetry

Equilibrated electroweak  
 B+L violating sphaleron interactions

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

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

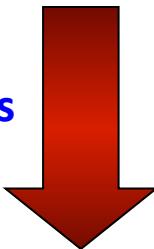
$$B^0 \sim 1 \text{MeV}$$

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



*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

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

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

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

If a small  $B^a$  is present today

Standard Model Extension type coupling  $b_\mu$

Kostelecky, Mewes, Russell, Lehnert ...

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

If due to H-torsion, it should couple universally (gravity) to all particle species of the standard model (electrons etc)

Very Stringent constraints from astrophysics on spatial ONLY components (e.g. Masers)

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

Can it be connected smoothly with some form of temperature T dependence to the  $B^0$  of  $O(1 \text{ MeV})$  in our case, required for Leptogenesis at  $T=10^5 \text{ GeV}$  ?

## 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

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

$$\dot{\bar{b}} = \tilde{c} \langle J_0^5 \rangle = \tilde{c} \langle \psi_i^\dagger \gamma^5 \psi_i \rangle = \text{constant} \neq 0$$

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

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



**B<sup>0</sup>** : (string) theory underwent a **phase transition**  
 @ T ≈ T<sub>d</sub> = 10<sup>5</sup> GeV, from B<sup>0</sup> = const = 1 MeV **to** :  
**B<sup>0</sup> small today but non zero, scales with scale factor**  
**as a<sup>-3</sup> ≈ const x T<sup>3</sup>**

$$B_0 = c_0 T^3$$

$$c_0 = 10^{-42} \text{ meV}^{-2}$$

$$B_{0 \text{ today}} = \mathcal{O}(10^{-44}) \text{ meV}$$

Quite safe from stringent  
Experimental Bounds

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

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



A LV & CPTV background of Kalb-Ramond H-Torsion generates Matter-Antimatter Asymmetry (Leptogenesis) via (Right-handed) neutrino CP Violating (tree-level) decays in the Early Universe

IN THE EARLY UNIVERSE  
 (KALB-RAMOND) NEUTRINO CP VIOLATING (TREE-LEVEL) DECAYS  
 INFLATIONARY (REHEATING) PHASE

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

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



# **Torsion-Quantum Fluctuations & Neutrino Mass Generation**

What About the Quantum Fluctuations of the H-torsion ?  
Even in the absence of a non-trivial H-background

Physical Effect in Generating Majorana masses for neutrinos  
via coupling to ordinary axion fields

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

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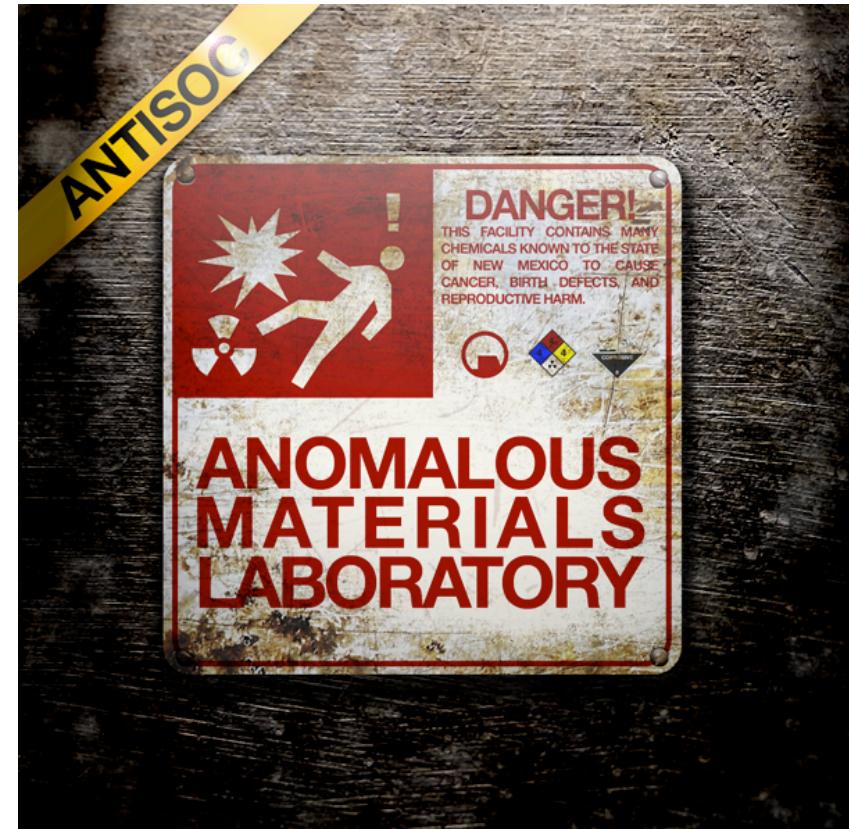
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Geometric origin  
due to Torsion flcts

# **ANOMALOUS GENERATION OF RIGHT-HANDED MAJORANA NEUTRINO MASSES THROUGH TORSIONFUL QUANTUM GRAVITY UV complete string models ?**

NEM & Pilaftsis 2012  
PRD 86, 124038  
arXiv:1209.6387



# Fermionic Field Theories with H-Torsion

## EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

**Fermions:**

$$S_\psi \ni -\frac{3}{4} \int d^4 \sqrt{-g} S_\mu \bar{\psi} \gamma^\mu \gamma^5 \psi = -\frac{3}{4} \int S \wedge {}^*J^5$$

+ standard Dirac terms without torsion

$$\mathbf{S} = {}^*\mathbf{T}$$

$$S_d = \frac{1}{3!} \epsilon^{abc} {}_d T_{abc} \quad T_{abc} \rightarrow H_{cab} = \epsilon_{cabd} \partial^d b$$

Bianchi identity

$$d {}^*S = 0$$

classical

conserved  
“torsion” charge

$$Q = \int {}^*S$$

Postulate conservation at quantum level by adding counterterms

Implement  $d {}^*S = 0$  via  $\delta(d {}^*S)$  constraint  
 → Lagrange multiplier in Path integral → b-field

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$$\begin{aligned} & \int D\mathbf{S} D\mathbf{b} \exp \left[ i \int \frac{3}{4\kappa^2} \mathbf{S} \wedge {}^*\mathbf{S} - \frac{3}{4} \mathbf{S} \wedge {}^*\mathbf{J}^5 + \left( \frac{3}{2\kappa^2} \right)^{1/2} \mathbf{b} d{}^*\mathbf{S} \right] \\ &= \int D\mathbf{b} \exp \left[ -i \int \frac{1}{2} \mathbf{d}\mathbf{b} \wedge {}^*\mathbf{d}\mathbf{b} + \frac{1}{f_b} \mathbf{d}\mathbf{b} \wedge {}^*\mathbf{J}^5 + \frac{1}{2f_b^2} \mathbf{J}^5 \wedge {}^*\mathbf{J}^5 \right], \end{aligned}$$

multiplier field  $\Phi(x) \equiv (3/\kappa^2)^{1/2} b(x)$ .

$$f_b = (3\kappa^2/8)^{-1/2} = \frac{M_P}{\sqrt{3\pi}}$$

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partial integrate

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Hence, effective action of torsion-full QED

$$\int Db \exp \left[ -i \int \frac{1}{2} db \wedge {}^* db - \frac{1}{f_b} b G(\mathbf{A}, \omega) + \frac{1}{2f_b^2} \mathbf{J}^5 \wedge {}^* \mathbf{J}^5 \right] .$$

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$$bR\tilde{R} - bF\tilde{F}$$

coupling

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EFFECTIVE ACTION AFTER INTEGRATING OUT  
QUANTUM TORSION FLUCTUATIONS**

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+ Standard Model terms for fermions

**SHIFT SYMMETRY**  $b(x) \rightarrow b(x) + c$

$c R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma}$  and  $c F^{\mu\nu} \tilde{F}_{\mu\nu}$  total derivatives

# ANOMALOUS MAJORANA NEUTRINO MASS TERMS from QUANTUM TORSION

**OUR SCENARIO** *Break* such *shift symmetry* by coupling first  $b(x)$  to another pseudoscalar field such as QCD axion  $a(x)$  (or e.g. other string axions)

$$\begin{aligned} \mathcal{S} = & \int d^4x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \right. \\ & + \frac{1}{2f_b^2} J_\mu^5 J^{5\mu} + \gamma(\partial_\mu b) (\partial^\mu a) + \frac{1}{2} (\partial_\mu a)^2 \\ & \left. - y_a i a \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right) \right], \quad (1) \end{aligned}$$

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 & \left. - \textcircled{- y_a i a \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right)} \right], \quad (1)
 \end{aligned}$$

Yukawa

neutrino fields

## Field redefinition

$$b(x) \rightarrow b'(x) \equiv b(x) + \gamma a(x)$$

so, effective action becomes

$$\begin{aligned} \mathcal{S} = & \int d^4x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu b')^2 + \frac{1}{2} (1 - \gamma^2) (\partial_\mu a)^2 \right. \\ & + \frac{1}{2f_b^2} J_\mu^5 J^{5\mu} + \frac{b'(x) - \gamma a(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \\ & \left. - y_a i a \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right) \right]. \end{aligned} \quad (1)$$

must have

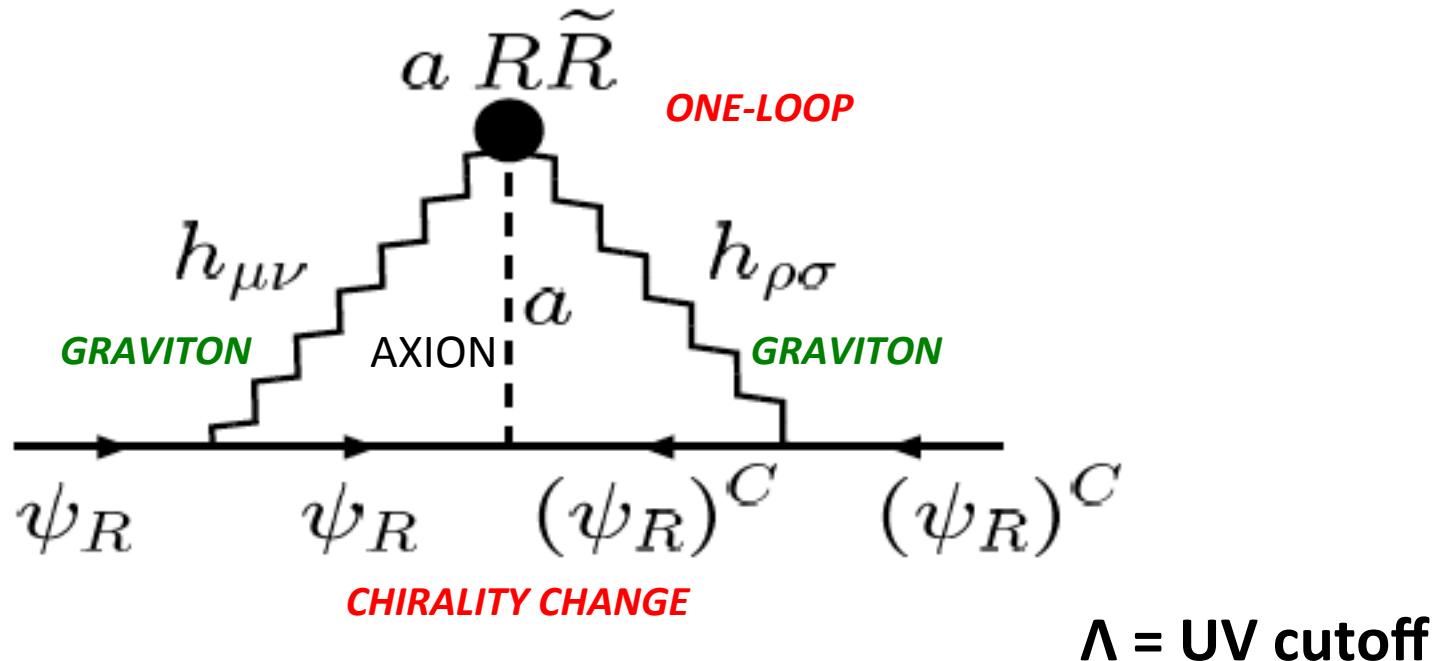
$$|\gamma| < 1$$

otherwise axion field  $a(x)$  appears as a ghost  $\rightarrow$  canonically normalised kinetic terms

$$\begin{aligned} \mathcal{S}_a = & \int d^4x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu a)^2 - \frac{\gamma a(x)}{192\pi^2 f_b \sqrt{1 - \gamma^2}} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \right. \\ & \left. - \frac{i y_a}{\sqrt{1 - \gamma^2}} a \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right) + \frac{1}{2f_b^2} J_\mu^5 J^{5\mu} \right]. \end{aligned}$$

**CHIRALITY CHANGE**

# THREE-LOOP ANOMALOUS FERMION MASS TERMS



$$M_R \sim \frac{1}{(16\pi^2)^2} \frac{y_a \gamma \kappa^4 \Lambda^6}{192\pi^2 f_b (1 - \gamma^2)} = \frac{\sqrt{3} y_a \gamma \kappa^5 \Lambda^6}{49152 \sqrt{8} \pi^4 (1 - \gamma^2)}$$

## SOME NUMBERS

$$\Lambda = 10^{17} \text{ GeV}$$

$$\gamma = 0.1$$

$M_R$  is at the TeV  
for  $y_a = 10^{-3}$

$$\Lambda = 10^{16} \text{ GeV}$$

$M_R \sim 16 \text{ keV},$   
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**INTERESTING  
WARM DARK MATTER  
REGIME**

Appropriate Hierarchy for the other two massive  
Right-handed neutrinos for Leptogenesis-Baryogenesis  
& Dark matter constraints can be arranged  
by choosing Yukawa couplings

## Finiteness of the mass

Arvanitaki, Dimopoulos *et al.*

### MULTI-AXION SCENARIOS (e.g. string axiverse)

$$\mathcal{S}_a^{\text{kin}} = \int d^4x \sqrt{-g} \left[ \frac{1}{2} \sum_{i=1}^n \left( (\partial_\mu a_i)^2 - M_i^2 \right) + \gamma(\partial_\mu b)(\partial^\mu a_1) \right. \\ \left. - \frac{1}{2} \sum_{i=1}^{n-1} \delta M_{i,i+1}^2 a_i a_{i+1} \right] ;$$

$$\delta M_{i,i+1}^2 < M_i M_{i+1}$$

positive mass spectrum  
for all axions

simplifying all mixing equals

$$M_R \sim \frac{\sqrt{3} y_a \gamma \kappa^5 \Lambda^{6-2n} (\delta M_a^2)^n}{49152 \sqrt{8} \pi^4 (1 - \gamma^2)} \quad n \leq 3$$

$$M_R \sim \frac{\sqrt{3} y_a \gamma \kappa^5 (\delta M_a^2)^3}{49152 \sqrt{8} \pi^4 (1 - \gamma^2)} \frac{(\delta M_a^2)^{n-3}}{(M_a^2)^{n-3}} \quad n > 3$$

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**$M_R$ : UV finite for  $n=3$  @ 2-loop independent of axion mass**



# Conclusions & Outlook

# CONCLUSIONS-OUTLOOK

- Reviewed theoretical models for ***TORSION-induced*** Lorentz and CPT Violation in the Early Universe that may play a role in generating matter-antimatter asymmetry in the early Universe
- Stringent Bounds today, no observed effects of torsion
- Use models to link present bounds on CPTV parameters to early Universe
- Hopefully higher sensitivities in the future
- **May be we observe something entirely unexpected...**
- ***Quantum Fluctuations of Torsion*** (Quantum Gravity) → generate anomalous (right-handed) Majorana neutrino masses beyond seesaw mechanism – truly **geometrical origin of neutrino masses**





Thank you  
for  
your  
attention !

# **SPARES**

# Microscopic Origin of SME coefficients?

Several "Geometry-induced" examples:

Non-Commutative Geometries

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

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) → Tachyonic instabilities, coupling with tensorial fields (gauge etc),  $\rightarrow \langle A_\mu \rangle \neq 0, \langle T_{\mu_1 \dots \mu_n} \rangle \neq 0$ ,

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor  $\psi$  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  $D_\mu = \partial_\mu - A_\mu^a T^a - q A_\mu$ .

CPT & Lorentz violation:  $a_\mu, b_\mu$ . 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

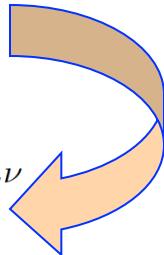
# Non-commutative effective field theories

$$[x^\mu, x^\nu] = i\theta^{\mu\nu}$$



Moyal  $\star$  products

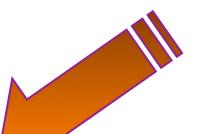
$$f \star g(x) \equiv \exp(\frac{1}{2}i\theta^{\mu\nu}\partial_{x^\mu}\partial_{y^\nu})f(x)g(y)|_{x=y}$$



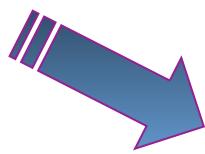
$$\theta_{\mu\nu}\theta^{\mu\nu} > 0$$

$$\begin{aligned}\hat{A}_\mu &= A_\mu - \frac{1}{2}\theta^{\alpha\beta}A_\alpha(\partial_\beta A_\mu + F_{\beta\mu}), \\ \hat{\psi} &= \psi - \frac{1}{2}\theta^{\alpha\beta}A_\alpha\partial_\beta\psi.\end{aligned}$$

$$D_\mu\psi = \partial_\mu\psi - iqA_\mu\psi$$



$$\mathcal{L} = \frac{1}{2}i\bar{\psi} \star \gamma^\mu \overset{\leftrightarrow}{D}_\mu \hat{\psi} - m\bar{\psi} \star \hat{\psi} - \frac{1}{4q^2}\hat{F}_{\mu\nu} \star \hat{F}^{\mu\nu}$$



$$\begin{aligned}\hat{D}_\mu\hat{\psi} &= \partial_\mu\hat{\psi} - i\hat{A}_\mu \star \hat{\psi} \quad \hat{f} \star \overset{\leftrightarrow}{D}_\mu \hat{g} \equiv \hat{f} \star \hat{D}_\mu \hat{g} - \hat{D}_\mu \hat{f} \star \hat{g} \\ \mathcal{L} &= \frac{1}{2}i\bar{\psi} \gamma^\mu \overset{\leftrightarrow}{D}_\mu \psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &\quad - \frac{1}{8}iq\theta^{\alpha\beta}F_{\alpha\beta}\bar{\psi}\gamma^\mu \overset{\leftrightarrow}{D}_\mu \psi + \frac{1}{4}iq\theta^{\alpha\beta}F_{\alpha\mu}\bar{\psi}\gamma^\mu \overset{\leftrightarrow}{D}_\beta \psi \\ &\quad + \frac{1}{4}mq\theta^{\alpha\beta}F_{\alpha\beta}\bar{\psi}\psi \\ &\quad - \frac{1}{2}q\theta^{\alpha\beta}F_{\alpha\mu}F_{\beta\nu}F^{\mu\nu} + \frac{1}{8}q\theta^{\alpha\beta}F_{\alpha\beta}F_{\mu\nu}F^{\mu\nu}.\end{aligned}$$

CPT invariant SME type field theory (Q.E.D.) - only even number of indices appear in effective non-renormalisable terms. (**Carroll et al. hep-th/0105082**)

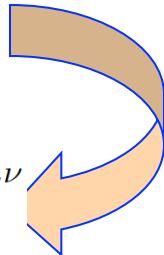
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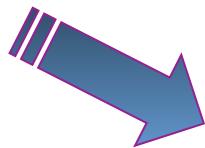
$$f \star g(x) \equiv \exp(\frac{1}{2}i\theta^{\mu\nu}\partial_{x^\mu}\partial_{y^\nu})f(x)g(y)|_{x=y}$$



$$\theta_{\mu\nu}\theta^{\mu\nu} > 0$$

$$\begin{aligned}\hat{A}_\mu &= A_\mu - \frac{1}{2}\theta^{\alpha\beta}A_\alpha(\partial_\beta A_\mu + F_{\beta\mu}), \\ \hat{\psi} &= \psi - \frac{1}{2}\theta^{\alpha\beta}A_\alpha\partial_\beta\psi.\end{aligned}$$

$$D_\mu\psi = \partial_\mu\psi - iqA_\mu\psi$$



$$\mathcal{L} = \frac{1}{2}i\bar{\psi} \star \gamma^\mu \overset{\leftrightarrow}{D}_\mu \hat{\psi} - m\bar{\psi} \star \hat{\psi} - \frac{1}{4q^2}\hat{F}_{\mu\nu} \star \hat{F}^{\mu\nu}$$

$$\hat{D}_\mu \hat{\psi} = \partial_\mu \hat{\psi} - i\hat{A}_\mu \star \hat{\psi} \quad \hat{f} \star \overset{\leftrightarrow}{D}_\mu \hat{g} \equiv \hat{f} \star \hat{D}_\mu \hat{g} - \hat{D}_\mu \hat{f} \star \hat{g}$$

$$\begin{aligned}\mathcal{L} = & \frac{1}{2}i\bar{\psi} \gamma^\mu \overset{\leftrightarrow}{D}_\mu \psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & - \frac{1}{8}iq\theta^{\alpha\beta}F_{\alpha\beta}\bar{\psi}\gamma^\mu \overset{\leftrightarrow}{D}_\mu \psi + \frac{1}{4}iq\theta^{\alpha\beta}F_{\alpha\mu}\bar{\psi}\gamma^\mu \overset{\leftrightarrow}{D}_\beta \psi \\ & + \frac{1}{4}mq\theta^{\alpha\beta}F_{\alpha\beta}\bar{\psi}\psi \\ & - \frac{1}{2}q\theta^{\alpha\beta}F_{\alpha\mu}F_{\beta\nu}F^{\mu\nu} + \frac{1}{8}q\theta^{\alpha\beta}F_{\alpha\beta}F_{\mu\nu}F^{\mu\nu}.\end{aligned}$$

CPT invariant SME type field theory (Q.E.D.) - only even number of indices appear in effective non-renormalisable terms. (**Carroll et al. hep-th/0105082**)

# STANDARD MODEL EXTENSION

Lorentz Violating

Kostelecky *et al.*

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

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

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

## + Gauge Sectors

$$O_{\mu\nu\dots}^{\text{SM}} C^{\mu\nu\dots} \rightarrow O_{\mu\nu\dots}^{\text{SM}} \langle C^{\mu\nu\dots} \rangle$$

Bolokhov, Pospelov 0703291.

Contributions to Matter & Gauge sectors → Complete classification  
Of dimension five Operators (gauge invariance requirement)

# Gravitational Baryogenesis

Davoudiasl, Kitano, Kribs,  
Murayama, Steinhardt

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

$$J^\mu = \bar{\psi}_i \gamma^\mu \psi_i \quad \frac{1}{M_*^2} \int d^4x \sqrt{-g} (\partial_\mu \mathcal{R}) J^\mu$$

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**

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LIKE A CHEMICAL  
POTENTIAL FOR FERMIONS

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Baryon Asymmetry

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

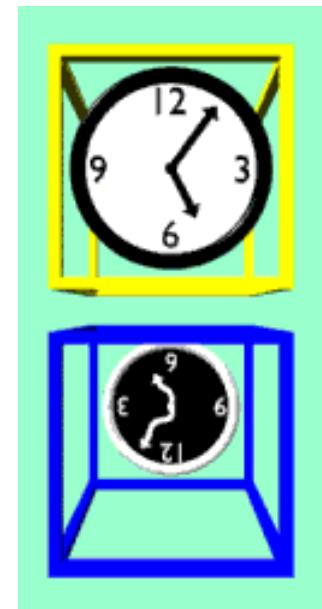
Calculate for  
various w in  
some scenarios

@  $T < T_D$  ,  
 $T_D$  = Decoupling T

# **CPT VIOLATION IN THE EARLY UNIVERSE**

*GENERATE Baryon and/or Lepton ASYMMETRY  
in the Universe via CPT Violation*

Assume CPT Violation.  
e.g. due to **Quantum Gravity** fluctuations,  
**strong** in the Early Universe



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# CPT VIOLATION IN THE EARLY UNIVERSE

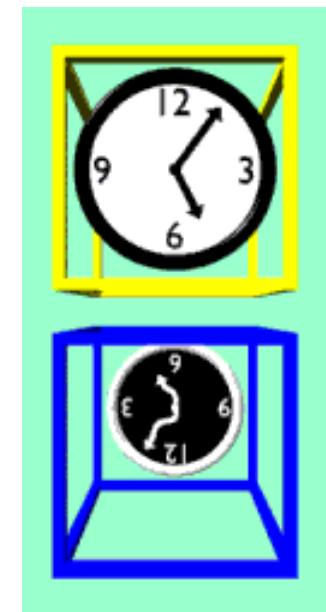
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**ONE POSSIBILITY:**  
particle-antiparticle mass differences

$$m \neq \bar{m}$$



**physics.indiana.edu**

Equilibrium Distributions different between particle-antiparticles  
*Can these create the observed matter-antimatter asymmetry?*

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

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

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

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

Dolgov, Zeldovich  
 Dolgov (2009)

*Assume dominant contributions to Baryon asymmetry from quarks-antiquarks*

$$m(T) \sim gT \quad \rightarrow$$

High-T quark mass >> Lepton mass

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

Dolgov, Zeldovich  
Dolgov (2009)

$$n_\gamma = 0.24T^3 \quad \text{photon equilibrium density at temperature T}$$

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Current bound  
for proton-anti  
proton mass diff.

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

ASACUSA Coll. (2011)

Reasonable to take:

$$\delta m_q \sim \delta m_p$$



**Too small**  
 $\beta^{T=0}$

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

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

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

