# Pseudoscalar fields in the Universe:
## novel ways of Majorana neutrino mass generation and Leptogenesis

Nick E. Mavromatos
King's College London &
CERN-PH-TH

London Centre for Terauniverse Studies (LCTS)
AdV 267352

SCALARS 2015
03-07 December 2015
Warsaw, Poland

# OUTLINE

## MOTIVATION

- Matter asymmetry in Universe (Lepto/Baryogenesis) – **open issue**
- (Majorana) Neutrino mass generation – **open issue**
- νMSM: simplest extension of Standard Model with right-handed ν
- Lorentz- & CPT -Violating Backgrounds in the Early Universe: **WHY?**

## PART I

- String-Inspired Space-time Backgrounds with (Kalb-Ramond) **Torsion**
- Majorana neutrino mass generation due to torsion quantum fluctuations (even with zero background): **Novel role of axion fields coupled with the torsion – GEOMETRIC ORIGIN OF ν MASS**

## PART II

- Kalb-Ramond constant torsion backgrounds (**→ Lorentz, CPT & CP spontaneous violation**) in early Universe: Leptogenesis → Baryogenesis

# OUTLINE

General Relativity at 100

**Scalars from GEOMETRY:**
**Kalb-Ramond Torsion**
**as a pseudoscalar axion-like quantum field**

## MOTIVATION

- Matter asymmetry in Univer… ) – **open issue**
- (Majorana) Neutri…
- νMSM: s… t-handed ν
- Lorentz- … rse: **WHY?**

## PART I

- String-Insp… with (Kalb-Ramond) **Torsion**
- Majorana ne… ration due to torsion quantum fluctuations (e… zero background): **Novel role of axion fields coupled with the torsion – GEOMETRIC ORIGIN OF ν MASS**

## PART II

- Kalb-Ramond constant torsion backgrounds (→ **Lorentz, CPT & CP spontaneous violation**) in early Universe: Leptogenesis → Baryogenesis

# 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 lep
antileptons

escher

- ***Baryogenesis***: The corresponding p
produce an asymmetry between ba
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

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

T > 1 GeV

# 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

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

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

**Assume CPT**

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,
Gavela, Hernandez
Orloff, Pene, Quimbay

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

$$\boxed{\delta_{KM}^{CP} \sim \frac{D}{T^{12}} \sim 10^{-20}} \quad << \quad \boxed{\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4. - 8.9) \times 10^{-11}}$$

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

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

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,
Gavela, Hernandez
Orloff, Pene, Quimbay

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

$$\boxed{\delta_{KM}^{CP} \sim \frac{D}{T^{12}} \sim 10^{-20}} \quad << \quad \boxed{\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4. - 8.9) \times 10^{-11}}$$

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

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

**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 ν are **simplest** extension of SM
- Right-handed massive ν may provide extensions of SM with: **extra CP Violation**

# SM Extension with N extra right-handed neutrinos

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

# SM Extension with N extra right-handed neutrinos

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

Right-handed Massive **Majorana** neutrinos

Leptons

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

# SM Extension with N extra right-handed neutrinos

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

**Higgs scalar SU(2) Dual:**

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

# SM Extension with N extra right-handed neutrinos

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

**Yukawa couplings Matrix (N=? )**

# SM Extension with N extra right-handed neutrinos

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

**For Constraints (compiled ν oscillation data) on (light) sterile neutrinos**
**N=1** ***excluded by data***

**Yukawa couplings Matrix (N=? )**

# SM Extension with N extra right-handed neutrinos

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

**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

# SM Extension with N extra right-handed neutrinos

$\nu$MSM

**Boyarski, Ruchayskiy, Shaposhnikov**

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

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

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

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**

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

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

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

***If two of the heavy neutrinos are nearly degenerate → enhanced CP violation (Pilaftsis, Underwood...)***

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

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

Yukawa couplings
Matrix (N=3)

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

# SM Extension with N extra right-handed neutrinos

$\nu$MSM

**Boyarski, Ruchayskiy, Shaposhnikov**

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

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

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

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

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

**Majorana phases**

Mixing

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

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

# Right-handed neutrinos & SM neutrino masses

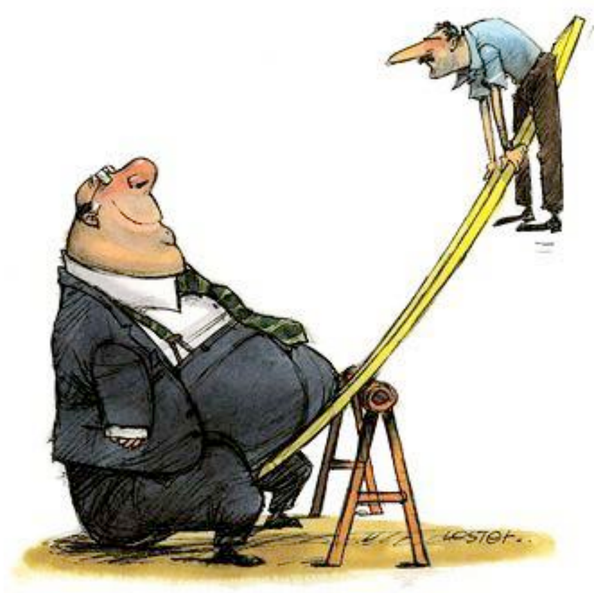
$$L = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2}\, \bar{N}_I^c N_I + \text{h.c.}$$

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

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

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

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



## Right-handed neutrinos & SM neutrino masses

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

**Minkowski,Yanagida,**
**Schecther, Valle**
**Mohapatra, Senjanovic**
**Lazarides, Shafi, Wetterich**

Light Neutrino Masses through see saw

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

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

$$v = \langle \phi \rangle \sim 175 \text{ GeV}$$

$$M_D \ll M_I$$

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

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

Light Neutrino Masses through see saw

**Minkowski, Yanagida,**
**Schecther, Valle**
**Mohapatra, Senjanovic**
**Lazarides, Shafi, Wetterich**

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

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

$$v = \langle \phi \rangle \sim 175 \text{ GeV}$$

$$M_D \ll M_I$$

# *Thermal Properties*

*Two distinct physics cases: $M_I > M_W$ & $M_I < M_W$*

# *Thermal Properties*

***Two distinct physics cases: $M_I > M_W$ & $M_I < M_W$***

**(i) $M_I > M_W$** (electroweak scale)

Decay of Right-handed fermions

$$T_{\rm decay} \simeq \left(\frac{m_{\rm atm} M_0}{24\pi v^2}\right)^{\frac{1}{3}} M_I \simeq 3 M_I$$

$$M_0 = \frac{M_{\rm Pl}}{1.66\sqrt{g_{\rm eff}}}$$

$g_{\rm eff}$ = d.o.f. in radiation era

$f_t$ = top-quark Yukawa coupl.

**Equilibrium Temp.**

$$T_{\rm eq} \simeq \frac{9\, f_t^2 m_{\rm atm} M_0}{64\pi^3\, v^2} M_I \simeq 5 M_I$$

**Out of equilibrium for:** $T > T_{\rm eq}$ or for $T < T_{\rm decay}$

$\boxed{\text{If } T_{\rm eq} > T_{\rm sph}}$

Decays of Right-handed Majorana fermions occur for period of active Sphaleron processes

$\boxed{T_{\rm decay} > T_{\rm sph}}$

# *Thermal Leptogenesis*

**Fukugita, Yanagida,**

# *(Conventional) Thermal Leptogenesis*

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

# *Thermal Leptogenesis*

***Independent of Initial Conditions @ T >>$T_{eq}$***

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

# *Thermal Leptogenesis*

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

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

**Lepton number Violation**
***@ 1-Loop***

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

***Out of Equilibrium Decays***

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

***Produce Lepton asymmetry***

**Fukugita, Yanagida,**

**Kuzmin, Rubakov, Shaposhinkov**

# Thermal Leptogenesis

***Independent of Initial Conditions @ T >> $T_{eq}$***

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

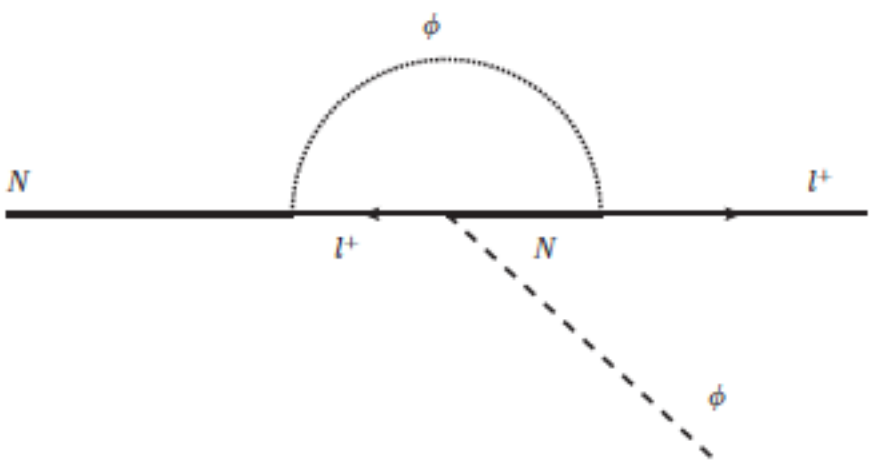
**Lepton number Violation**
***@ 1-Loop***

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

***Out of Equilibrium Decays***

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

***Produce Lepton asymmetry***




**Fukugita, Yanagida,**

**Kuzmin, Rubakov, Shaposhinkov**

# Thermal Leptogenesis

*Independent of Initial Conditions @ T >>$T_{eq}$*

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

**Lepton number Violation**
***@ 1-Loop***

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

***Out of Equilibrium Decays***

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

***Produce Lepton asymmetry***

**Equilibrated electroweak B+L violating sphaleron interactions**

**Fukugita, Yanagida,**

**Kuzmin, Rubakov, Shaposhinkov**

# Thermal Leptogenesis

**Independent of Initial Conditions @ T >>$T_{eq}$**

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

**Lepton number Violation**
***@ 1-Loop***

$N_I \to H$

***Out of Equilibrium Decays***

$T_{\rm sph}$

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

where

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

**Equilibrated**
**B+L violating**
**interactions**

**a, Yanagida,**

**n, Rubakov,**
**shinkov**

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

# *Thermal Leptogenesis*

***Independent of Initial Conditions @ T >>$T_{eq}$***

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

**Lepton number Violation**
***@ 1-Loop***

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

***Out of Equilibrium Decays***

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

***Produce Lepton asymmetry***

**Equilibrated electroweak B+L violating sphaleron interactions**

***Independent of Initial Conditions***

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

**Fukugita, Yanagida,**

**Kuzmin, Rubakov, Shaposhinkov**

# Thermal Leptogenesis

**Independent of Initial Conditions @ T >>$T_{eq}$**

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

**Lepton number Violation**
***@ 1-Loop***

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

***Out of Equilibrium Decays***

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

***Produce Lepton asymmetry***

**Equilibrated electroweak B+L violating sphaleron interactions**

***Independent of Initial Conditions***

**B-L conserved**

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

**Fukugita, Yanagida,**

**Kuzmin, Rubakov, Shaposhinkov**

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

**Pilafsis,**
**Buchmuller, di Bari** *et al.*

# *Thermal Properties*

*Two distinct physics cases: $M_I > M_W$ & $M_I < M_W$*

# *Thermal Properties*

**Ashaka, Shaposhnikov…**

νMSM

*Two distinct physics cases: $M_I > M_W$ & $M_I < M_W$*

**(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:

$$F_{\alpha I} \sim \frac{\sqrt{m_{\rm atm} M_I}}{v} \sim 4 \times 10^{-8}$$

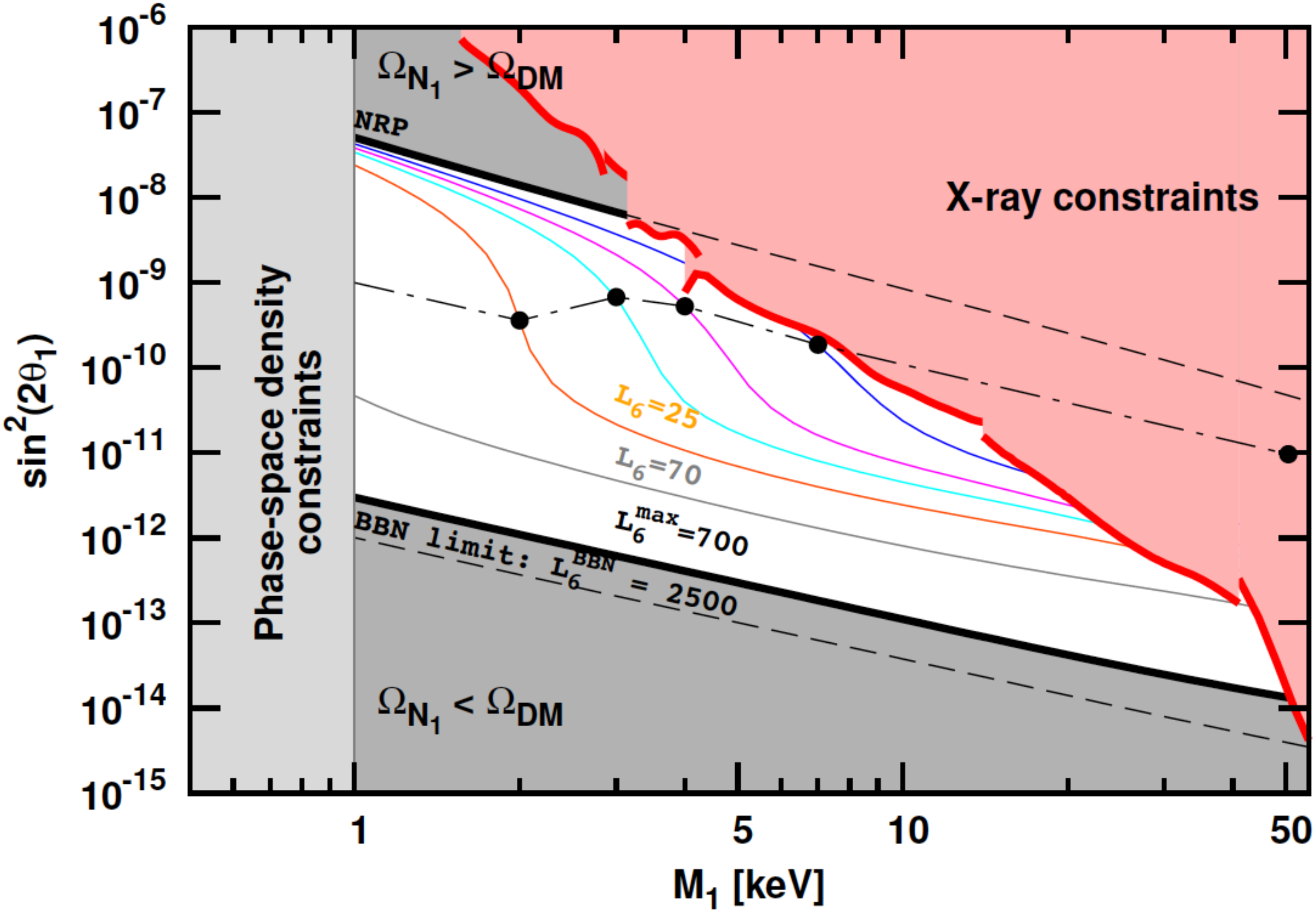
***Baryogenesis : various scenarios depending on detailed parameters of the model***

**Akhmedov, Rubakov, Smirnov, Canetti, Drewes, Frossard, Shaposhnikov,**

Boyarski, Ruchayskiy, Shaposhnikov…

# νMSM RH Neutrino Masses

MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS

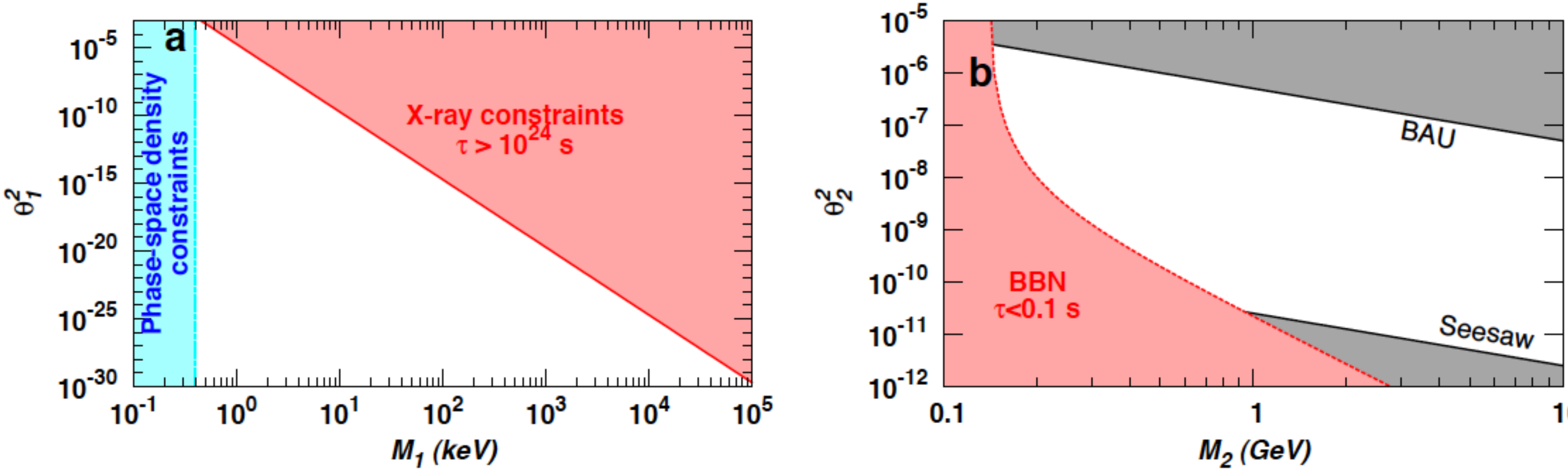


***More than one sterile neutrino needed to reproduce Observed oscillations***

## νMSM RH Neutrino Masses

**Boyarski, Ruchayskiy, Shaposhnikov…**

**Degenerate $N_{2,}$ $N_3$ RH Neutrinos, enhances CP violation**




Constraints on two heavy degenerate singlet neutrinos

$N_1$ DM production estimation in Early Universe must take into account its interactions with $N_{2,3}$ heavy neutrinos

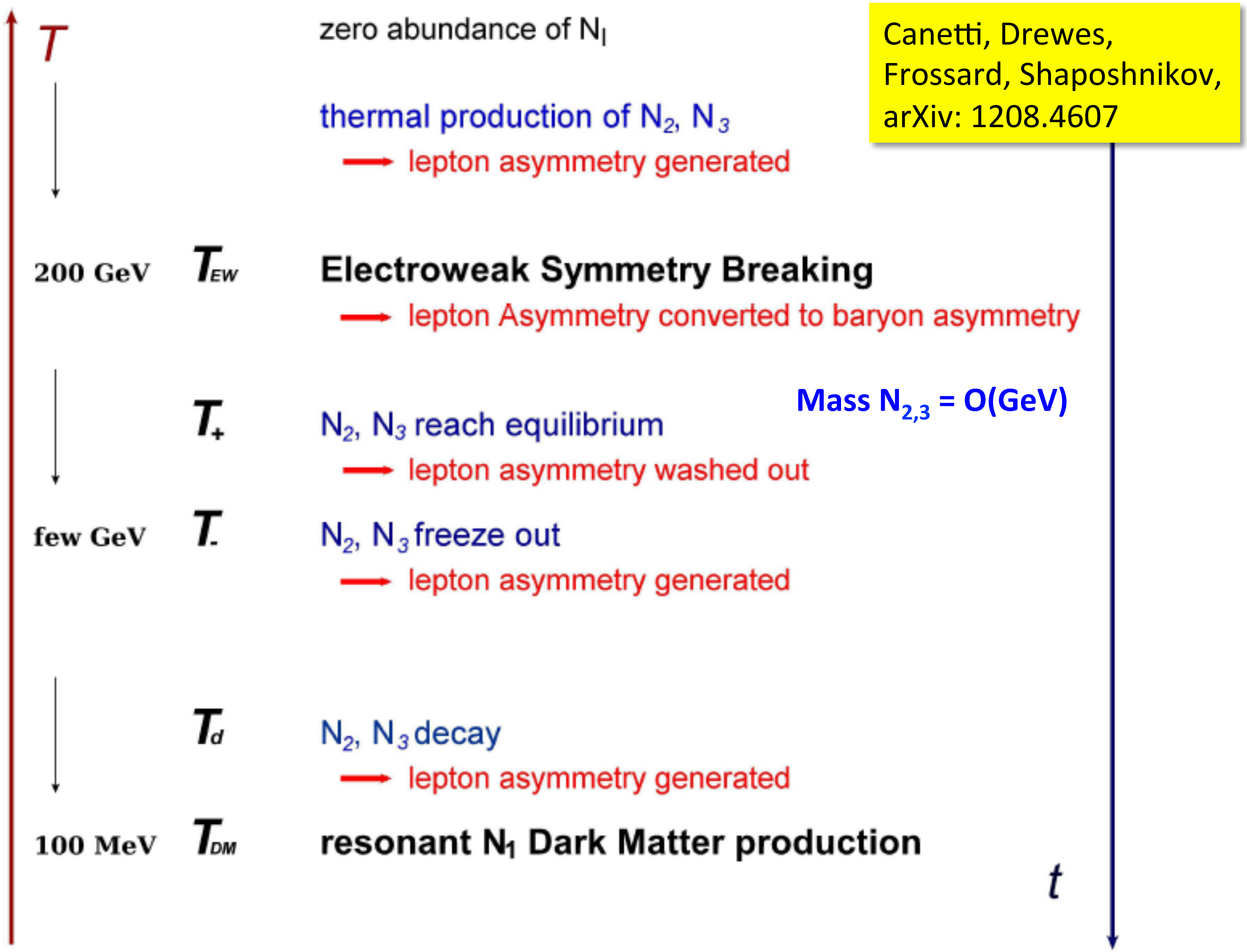



Figure 1: *The thermal history of the universe in the $\nu$MSM.*

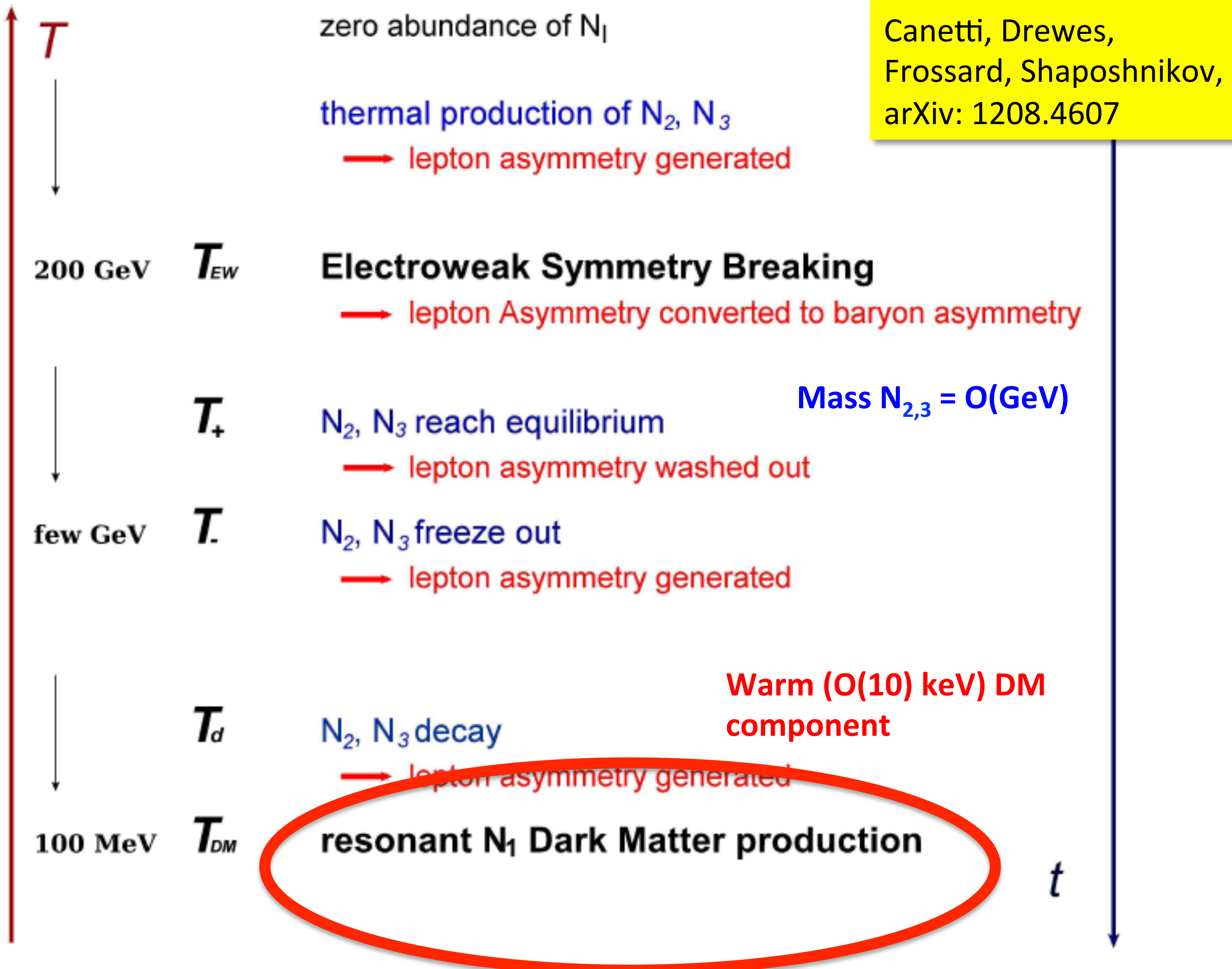



Figure 1: *The thermal history of the universe in the $\nu$MSM.*

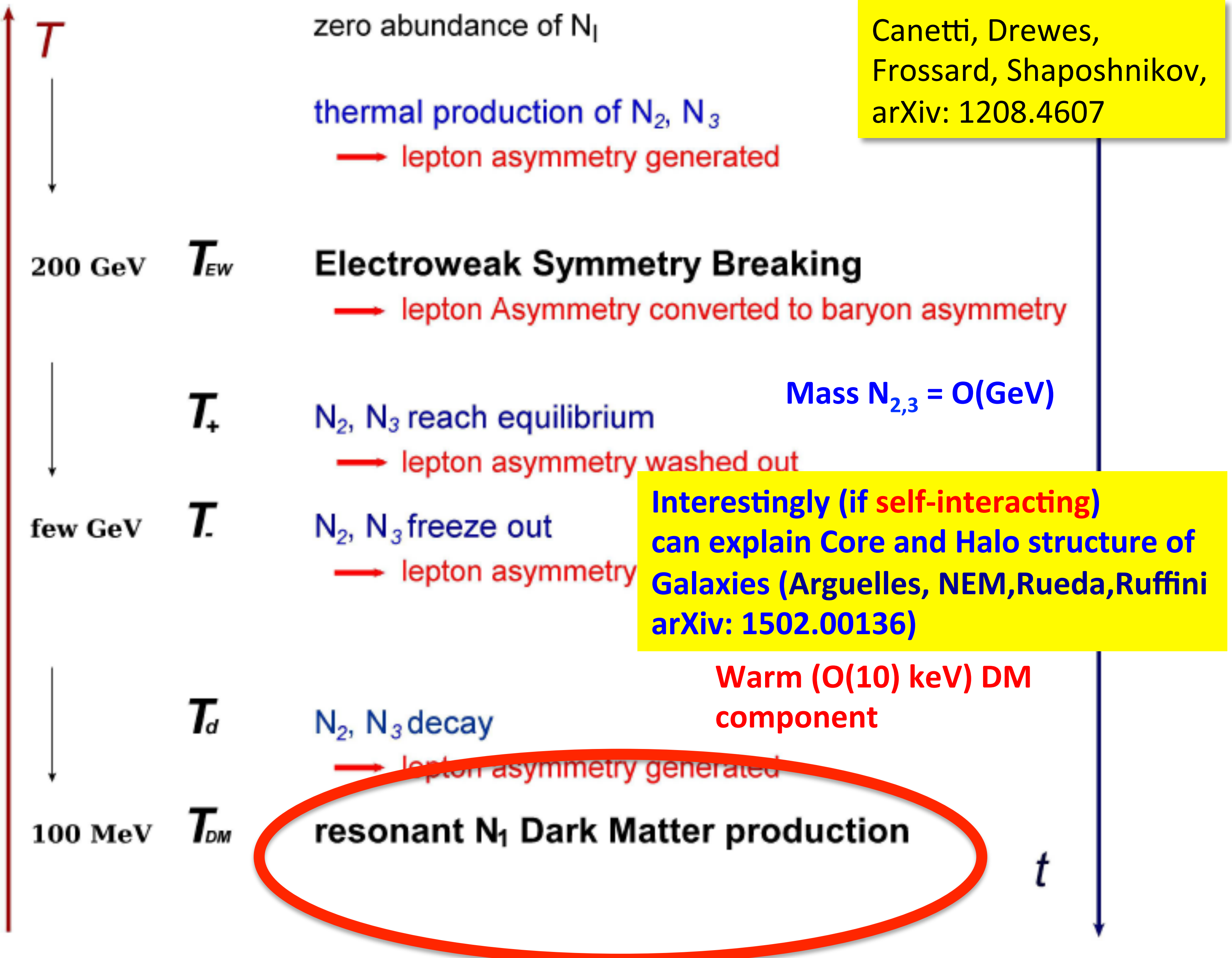
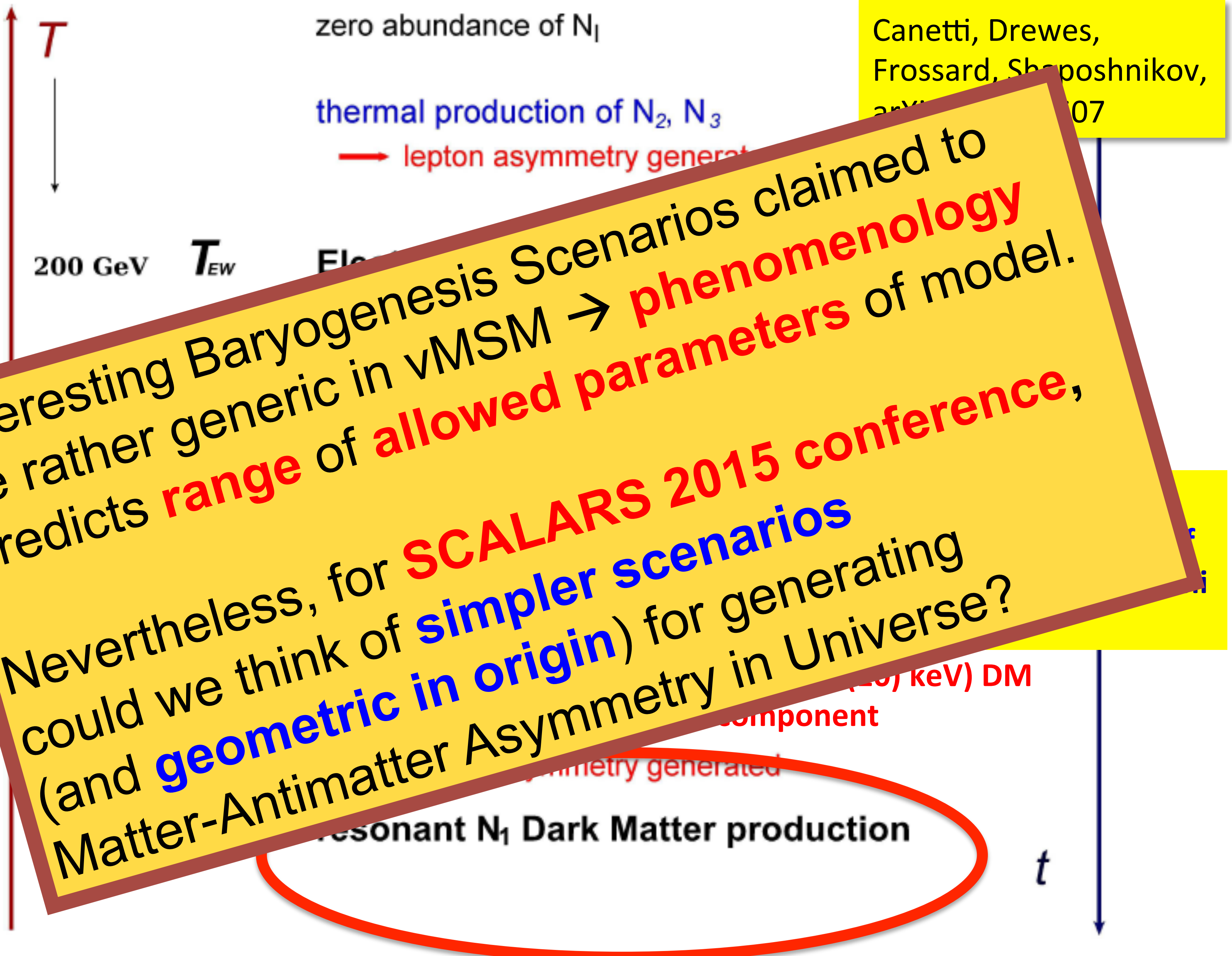



Figure 1: *The thermal history of the universe in the $\nu$MSM.*



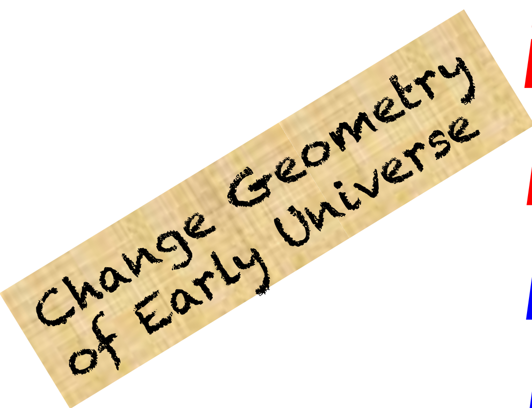

Interesting Baryogenesis Scenarios claimed to be rather generic in νMSM → **phenomenology** predicts **range** of **allowed parameters** of model.

Nevertheless, for **SCALARS 2015 conference**, could we think of **simpler scenarios** (and **geometric in origin**) for generating Matter-Antimatter Asymmetry in Universe?

Figure 1: *The thermal history of the universe in the νMSM.*

**IDEA:**

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



General Relativity at 100

**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**

**Yes…But unlike $\nu$ MSM**
heavy right-handed neutrinos
with **masses m ≳ 100 TeV** needed here

**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**

**Scalars** from **GEOMETRY:**
Kalb-Ramond **Torsion**
as a pseudoscalar **axion-like**
**quantum field**
**Background in Early Universe**

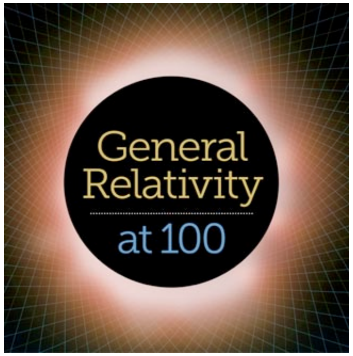
General Relativity at 100

**Yes…But unlike $\nu$ MSM**
heavy right-handed neutrinos
with **masses m ≳ 100 TeV** needed here

**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**

**Scalars** from **GEOMETRY:**
Kalb-Ramond **Torsion**
as a pseudoscalar **axion-like**
**quantum field**
**Background in Early Universe**




**Yes…But unlike $\nu$ MSM**
heavy right-handed neutrinos
with **masses m ≳ 100 TeV** needed here

**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 → quantum axion-like field**

General Relativity at 100

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 → **quantum axion-like field**

**NEXT**

# PART I
# Torsion-Quantum Fluctuations
# &
# Neutrino Majorana Mass Generation
# (beyond seesaw)

SCALARS 2015

03-07 December 2015

Warsaw, Poland

# CPT THEOREM IN RELATIVISTIC QFT

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

**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)**

$$\mathcal{L} \ni \dots + \overline{\psi}^f \Big( i\gamma^\mu \nabla_\mu - m_f \Big) \psi^f + \underbrace{a_\mu \overline{\psi}^f \gamma^\mu \psi^f}_{\text{Lorentz Violation}} + \underbrace{b_\mu \overline{\psi}^f \gamma^\mu \gamma^5 \psi^f}_{\text{Lorentz \& CPT Violation}} + \dots$$

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

# 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

# Microscopic Origin of SME coefficients?

**Several ``Geometry-induced'' examples:**

**Non-Commutative Geometries**

**Axisymmetric Background Geometries of the Early Universe**

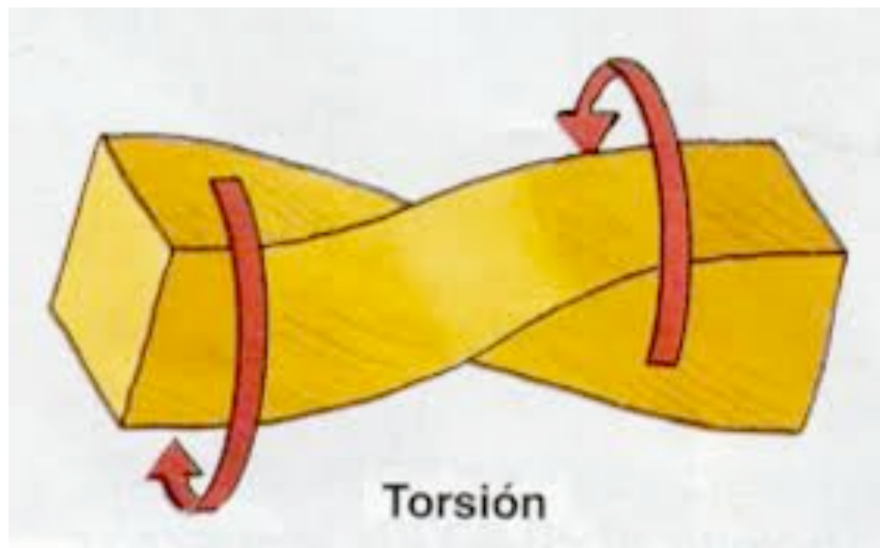
**Torsionful Geometries (including strings…)**

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

# 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, de Cesare

In particular,
Space-times with




General Relativity at 100

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

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

***$B^d$ may be constant in a given frame***
***In some (torsionful) background***
***Geometries → SME***

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

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

***$B^d$ may be constant in a given frame***
***In some (torsionful) background***
***Geometries → SME***

# 3. Fermions in Gravity with TORSION

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

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

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

# Fermions and Torsion

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

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

$$\overline{\omega}_\mu{}^{ab} = e^a_\nu \partial_\mu e^{\nu b} + e^a_\nu e^{\sigma b}\Gamma^\nu_{\sigma\mu} = e^a_\nu e^{\nu b}{}_{;\mu}$$

$$K_\mu^{ab} = e^a_\nu e^b_\rho K^{\nu\rho}_{\ \ \mu} \; , \quad K^{\nu\rho}_{\ \ \mu} = -K^{\rho\nu}_{\ \ \mu}$$

Contorsion tensor

Torsion $T^\mu_{\nu\rho}$

$$K^\nu_{\ \rho\mu} = \frac{1}{2}\left(T^\nu_{\ \rho\mu} - T_\rho{}^\nu{}_\mu - T_\mu{}^\nu{}_\rho\right)$$

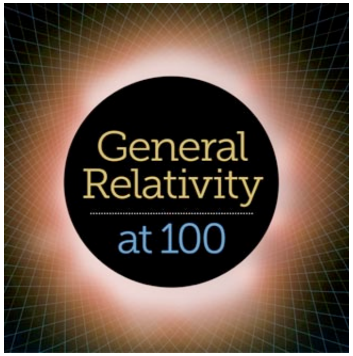
**Torsion decomposes in vector, $T_\mu$ , axial vector $S_\mu$ and tensor $q_{\mu\nu\rho}$ parts**

Curvature tensor in first order torsionful formalism

$$R^{ab}_{\ \ \mu\nu} = 2\partial_{[\mu,}\omega^{ab}_{\ \ \nu]} + 2\omega^a_{\ c[\mu}\omega^{cb}_{\ \ \nu]}$$

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

**NEM & Sarben Sarkar, arXiv:1211.0968**
**John Ellis, NEM & Sarkar, arXiv:1304.5433**
**De Cesare, NEM & Sarkar arXiv:1412.7077**



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

**NEM & Sarben Sarkar, arXiv:1211.0968**
**John Ellis, NEM & Sarkar, arXiv:1304.5433**
**De Cesare, NEM & Sarkar arXiv:1412.7077**

**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

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

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

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

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

4-DIM PART

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

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

IN 4-DIM DEFINE DUAL OF H AS :

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

***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 $B^\mu$

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

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

## 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

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

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

**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***

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

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

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

**Antoniadis, Bachas, Ellis, Nanopoulos**

**Strings in Cosmological backgrounds**

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

$$a(t) = t$$

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

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

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

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**

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

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

constant ***B*⁰**

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

What About the Quantum Fluctuations of the H-torsion ?
In the absence of a (or very small ) non-trivial H-background

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

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

What About the Quantum Fluctuations of the H-torsion ?
In the absence of a (or very small ) non-trivial H-background

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

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

Geometric origin
due to KR-Torsion flcts

What About the Quantum Fluctuations of the H-torsion ?
In the absence of a (or very small ) non-trivial H-background

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

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

**Geometric origin**
**due to KR-Torsion flcts**

Even at **zero KR-Torsion background**

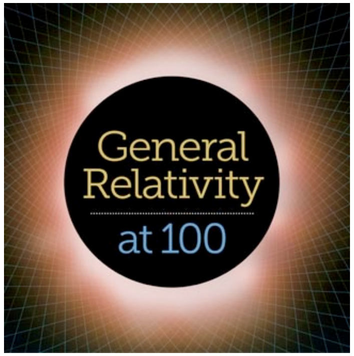
***$\langle B_\mu \rangle \to 0$***

***only quantum 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:**

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

+ standard Dirac terms without torsion

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

$$S_d = \frac{1}{3!}\epsilon^{abc}{}_d T_{abc}$$

$$T_{abc} \to H_{cab} = \epsilon_{cabd}\,\partial^d b$$

Bianchi identity

$$\mathbf{d}\,{}^\star\mathbf{S} = 0$$

classical

conserved ``torsion " charge

$$Q = \int {}^\star\mathbf{S}$$

Postulate conservation at quantum level by adding counterterms

Implement $\mathrm{d}\,{}^\star\mathrm{S} = 0$ via $\delta(d\,{}^\star\mathrm{S})$ constraint
→ lagrange multiplier in Path integral → b-field

## Fermionic Field Theories with H-Torsion
## EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

**Fermions:**

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

+ standard Dirac terms without torsion

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

$$S_d = \frac{1}{3!}\epsilon^{abc}{}_d T_{abc}$$

$$T_{abc} \to H_{cab} = \epsilon_{cabd}\,\partial^d b$$

Bianchi identity

$$\mathrm{d}\,{}^\star\mathbf{S} = 0$$

classical

conserved ``torsion " charge

$$Q = \int {}^\star\mathbf{S}$$

Postulate conservation at quantum level by adding counterterms

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

$$
\int D\mathbf{S}\, Db \exp\left[i \int \frac{3}{4\kappa^2}\mathbf{S}\wedge {}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge {}^\star\mathbf{J}^5 + \left(\frac{3}{2\kappa^2}\right)^{1/2} b\, d{}^\star\mathbf{S}\right]
$$

$$
= \int Db \exp\left[-i \int \frac{1}{2}\mathrm{d}b\wedge {}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge {}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5\wedge {}^\star\mathbf{J}^5\right]
$$

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

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

$$\int D\mathbf{S}\, Db \exp\left[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge{}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge{}^\star\mathbf{J}^5 + \left(\frac{3}{2\kappa^2}\right)^{1/2} b\, d^\star\mathbf{S}\right]$$

$$= \int Db \exp\left[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge{}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5\wedge{}^\star\mathbf{J}^5\right]$$

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

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

$$\int DS\, Db\, \exp\left[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge{}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge{}^\star\mathbf{J}^5 + \left(\frac{3}{2\kappa^2}\right)^{1/2} b\, d^\star\mathbf{S}\right]$$

$$= \int Db\, \exp\left[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge{}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5\wedge{}^\star\mathbf{J}^5\right]$$

partial integrate

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

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

$$\int DS\, Db\, \exp\Big[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge{}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge{}^\star\mathbf{J}^5 + \Big(\frac{3}{2\kappa^2}\Big)^{1/2} b\, d^\star\mathbf{S}\Big]$$

$$= \int Db\, \exp\Big[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge{}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5\wedge^\star\mathbf{J}^5\Big]$$

partial integrate

Use chiral anomaly equation (one-loop) in curved space-time:

$$\begin{aligned}\nabla_\mu J^{5\mu} &= \frac{e^2}{8\pi^2}F^{\mu\nu}\widetilde{F}_{\mu\nu} - \frac{1}{192\pi^2}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma}\\ &\equiv G(\mathbf{A},\omega)\,.\end{aligned}$$

Hence, effective action of torsion-full QED

$$\int Db\, \exp\Big[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b - \frac{1}{f_b}bG(\mathbf{A},\omega) + \frac{1}{2f_b^2}\mathbf{J}^5\wedge^\star\mathbf{J}^5\Big]\,.$$

$$\int DS\, Db\, \exp\Big[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge{}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge{}^\star\mathbf{J}^5 + \Big(\frac{3}{2\kappa^2}\Big)^{1/2} b\, d^\star\mathbf{S}\Big]$$

$$= \int Db\, \exp\Big[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge{}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5\wedge{}^\star\mathbf{J}^5\Big]$$

partial integrate

Use chiral anomaly equation (one-loop) in curved space-time:

$$\nabla_\mu J^{5\mu} = \frac{e^2}{8\pi^2}F^{\mu\nu}\widetilde{F}_{\mu\nu} - \frac{1}{192\pi^2}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma}$$
$$\equiv G(\mathbf{A},\omega)\ .$$

$$\boxed{bR\widetilde{R} - bF\widetilde{F}}$$

coupling

Hence, effective action of torsion-full QED

$$\int Db\, \exp\Big[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b - \frac{1}{f_b}bG(\mathbf{A},\omega) + \frac{1}{2f_b^2}\mathbf{J}^5\wedge{}^\star\mathbf{J}^5\Big]\ .$$

# Fermionic Field Theories with H-Torsion
# EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} + \frac{1}{2f_b^2} J^5_\mu J^{5\mu} \; +$$

+ Standard Model terms for fermions

***SHIFT SYMMETRY*** b(x) → b(x) + c

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

Mavromatos, Pilaftsis arXiv: 1209.6387

# 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)

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

Mavromatos, Pilaftsis arXiv: 1209.6387

# 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)

$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} + \frac{1}{2f_b^2}J^5_\mu J^{5\mu} + \gamma(\partial_\mu b)\,(\partial^\mu a) + \frac{1}{2}(\partial_\mu a)^2 - y_a i a\Big(\overline{\psi}_R^{\,C}\psi_R - \overline{\psi}_R\psi_R^{\,C}\Big)\Big]\,,$$

Mavromatos, Pilaftsis arXiv: 1209.6387

# 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)

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

Yukawa

neutrino fields

Generated through, e.g.
**non-perturbative effects**
in string/brane theory

## Field redefinition

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

**so, effective action becomes**

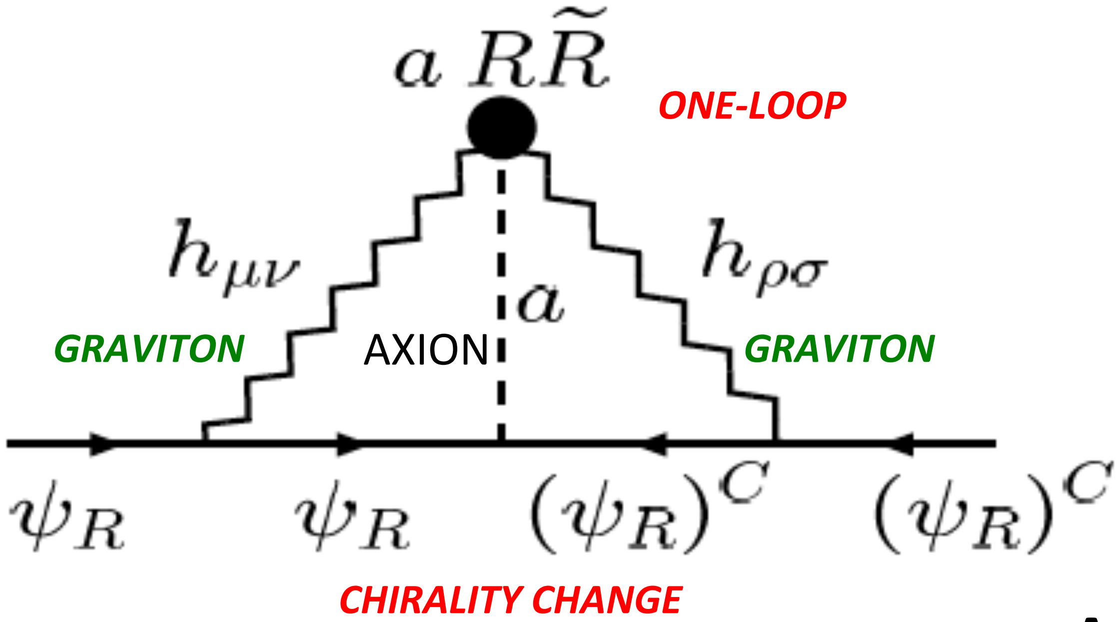
$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b')^2 + \frac{1}{2}\left(1-\gamma^2\right)(\partial_\mu a)^2 + \frac{1}{2f_b^2}J^5_\mu J^{5\mu} + \frac{b'(x) - \gamma a(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} - y_a i a\left(\overline{\psi}_R^C \psi_R -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

*must have* $\boxed{|\gamma| < 1}$ *otherwise axion field a(x) appears as a ghost → canonically normalised kinetic terms*

$$\boxed{\mathcal{S}_a = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu a)^2 - \frac{\gamma a(x)}{192\pi^2 f_b\sqrt{1-\gamma^2}} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} - \frac{i y_a}{\sqrt{1-\gamma^2}}\, a\left(\overline{\psi}_R^C \psi_R - \overline{\psi}_R \psi_R^C\right) + \frac{1}{2f_b^2}J^5_\mu J^{5\mu}\Big] .}$$

*CHIRALITY CHANGE*

# THREE-LOOP ANOMALOUS FERMION MASS TERMS




**Λ = UV cutoff**

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

# SOME NUMBERS

$\Lambda = 10^{17}$ GeV

$\gamma = 0.1$

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

$\Lambda = 10^{16}$ GeV

$M_R \sim 16$ keV,

$y_a = \gamma = 10^{-3}$

# SOME NUMBERS

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

$$\gamma = 0.1$$

$M_R$ is at the TeV

for $y_a = 10^{-3}$

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

$M_R \sim 16$ keV,

$\bar{y}_a = \gamma = 10^{-3}$

***INTERESTING***
***WARM DARK MATTER***
***REGIME*** **(*eg*. νMSM)**

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

# SOME NUMBERS

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

$$\gamma = 0.1$$

$M_R$ is at the TeV

for $y_a = 10^{-3}$

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

$M_R \sim 16$ keV,

$y_a = \gamma = 10^{-3}$

May be (discrete) **symmetry** reasons
(**cf Leontaris-Vlachos**)
force **two** of the heavier **RH neutrinos**
to be **degenerate** → dictate patterns
for the axion-RH-neutrino
Yukawa couplings $y_a$

***INTERESTING WARM DARK MATTER REGIME*** **(*eg*. νMSM)**

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

# FINITENESS OF THE MASS

Arvanitaki, Dimopoulos *et al.*

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

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

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

positive mass spectrum for all axions

simplifying all mixing equals

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

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

## FINITENESS OF THE MASS

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

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

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

positive mass spectrum
for all axions

simplifying all mixing equals

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

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

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


**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**


**Yes…But unlike $\nu$MSM**
heavy right-handed neutrinos
with **masses m ≳ 100 TeV** needed here

**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**

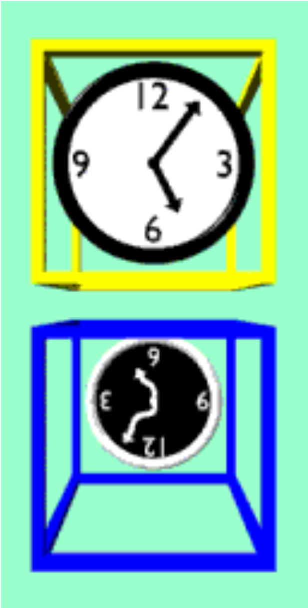
# PART II
# Kalb-Ramond Torsion-Induced Leptogenesis

SCALARS 2015
03-07 December 2015
Warsaw, Poland

# *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




physics.indiana.edu

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

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

# *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 L

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

**Early Universe**
**$T > 10^5$ GeV**

# CPT Violation

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

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

# CPTV Thermal L

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

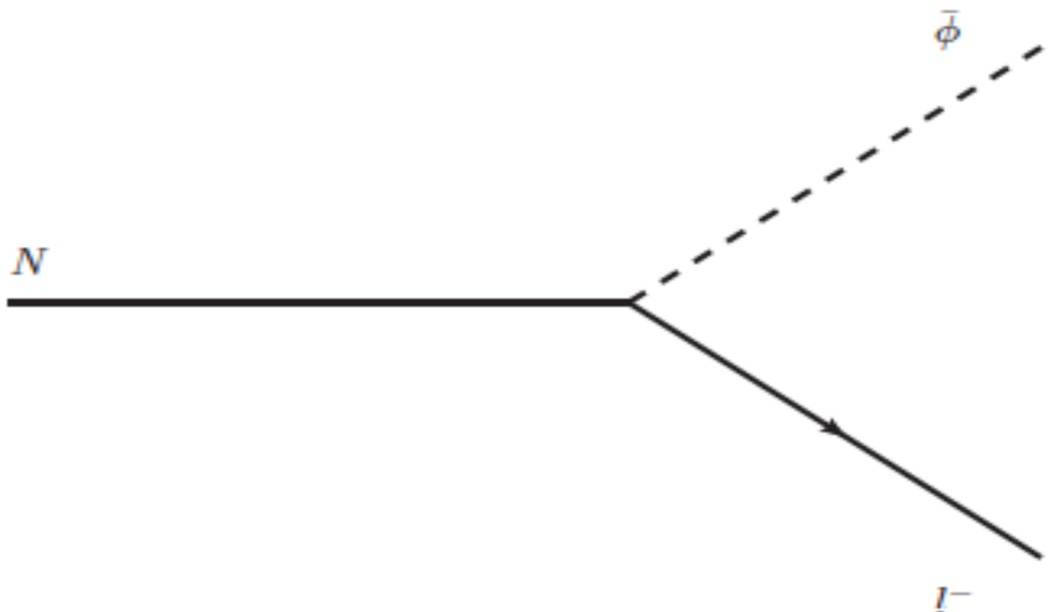
Constant H-torsion

Early Universe
$T > 10^5$ 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 L

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

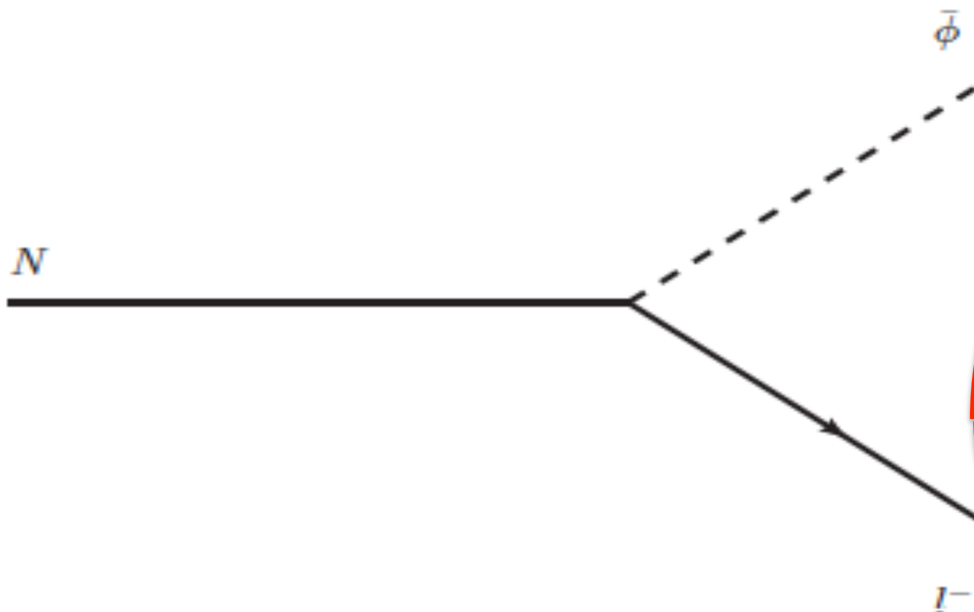
Constant H-torsion

**Early Universe**
**T > $10^5$ GeV**

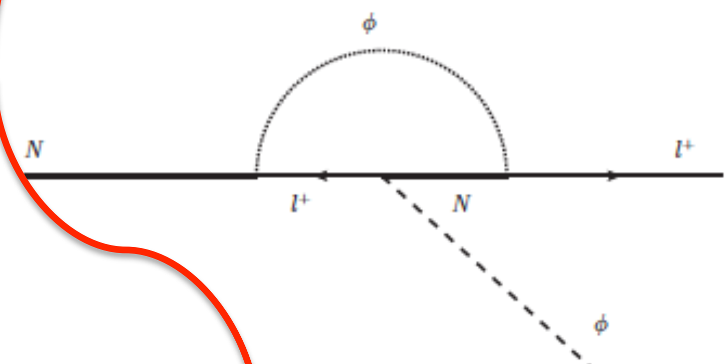
## CPT Violation

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

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




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



## CPTV Thermal L

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

Constant H-torsion

**Early Universe**
**T > $10^5$ GeV**

# CPT Violation

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

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

***Produce Lepton asymmetry***

## CPTV Thermo

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

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

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

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

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

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

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

$$T_D \simeq m$$

*Produce Lepton asymmetry*

# CPTV Thermo

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

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

**Early Universe**
**$T > 10^5$ GeV**

# CPT Violation

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

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

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

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

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

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

*Produce Lepton asymmetry*

$$T_D \simeq m$$

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

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

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

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

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

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

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

# CPTV Thermo

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

**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**

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

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

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

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

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

*Produce Lepton asymmetry*

$$T_D \sim m$$

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

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

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

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

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

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

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


**Hence… unlike $\nu$ MSM, for leptogenesis heavy $M$ > 100 TeV, right-handed Neutrinos N are needed**

## CPTV Thermo

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

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

Early Universe
$T > 10^5$ GeV

# CPT Violation

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

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

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10}, \quad \to \quad \frac{B_0}{m} \simeq 10^{-8}$$

*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 Thermo

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

**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***

**?**

$$Y_k \sim 10^{-5}$$
$$m \geq 100\text{TeV} \to$$
$$B^0 \sim 1\text{MeV}$$
$$T_D \simeq m \sim 100\ \text{TeV}$$

# CPTV Thermo

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

**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***

**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)***

## CPTV Therm

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

**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**

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

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10}, \qquad \frac{B_0}{m} \simeq 10^{-8}$$

***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 ....***

## 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**
**$B^0 \neq 0$ backgroumd**

**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***

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

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

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

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

**Equilibrated electroweak**
**B+L violating sphaleron interactions**

**B-L conserved**

***Environmental***
***Conditions Dependent***

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

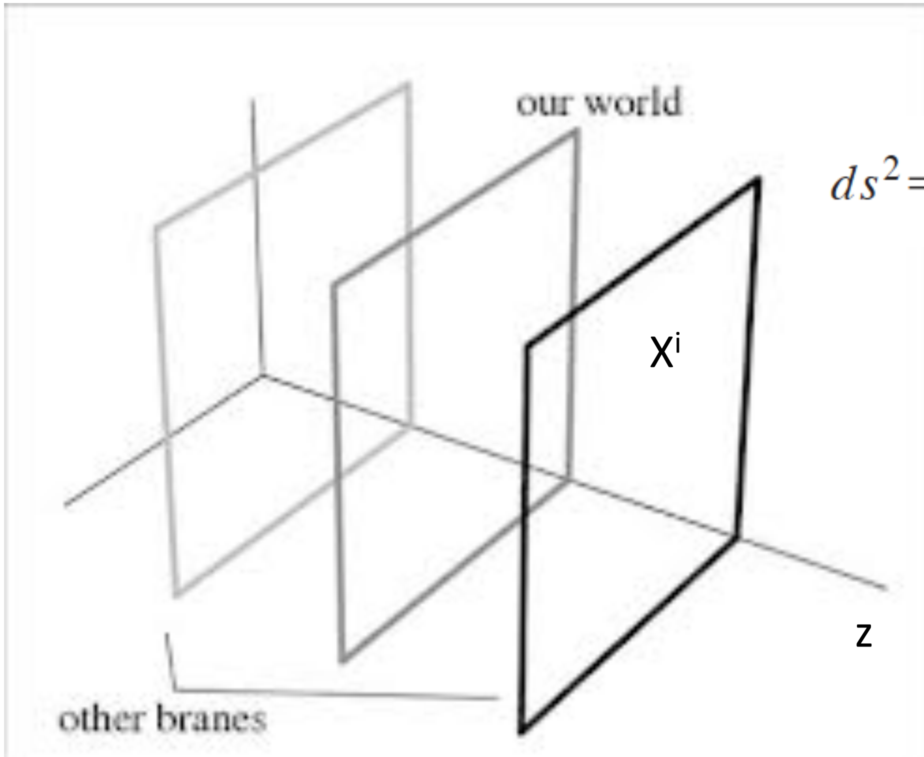
***Estimate BAU by fixing CPTV background parameters***
***In some models this means fine tuning ….***

**e.g. May Require**
**Fine tuning of**
**Vacuum energy**

(

# e.g. Gauss Bonnet in Randall-Sunderum Brane World Scenarios

J. Rizos and NEM




**warped metrics**

$$ds^2 = e^{-2\sigma(z)} \eta_{ij} dX^i dX^j + dz^2, \quad i,j = 0,1,\ldots,3.$$

$$\boxed{S = S_5 + S_4}$$

$$S_4 = \sum_i \int d^4x \sqrt{-g_{(4)}} e^{\omega\Phi} v(z_i)$$

$$g_{(4)}^{\mu\nu} = \begin{cases} g^{\mu\nu}, & \mu,\nu < 5, \\ 0 & \text{otherwise}, \end{cases}$$

**Matching conditions (Israel type) at our brane world from left- and right-bulk**

$$S_5 = \int d^5x \sqrt{-g} \Big[ -R - \frac{4}{3}(\nabla_\mu \Phi)^2 + f(\Phi)(\alpha R^2 + \beta R^2_{\mu\nu}$$

$$+ \gamma R^2_{\mu\nu\rho\sigma}) + \xi(z) e^{\zeta\Phi} + c_2 \; f(\Phi)(\nabla_\mu \Phi)^4 + \cdots \Big],$$

# Brane World Effective Action

$$\sqrt{-g}R(x) = \sqrt{-g^{(4)}(x)}(e^{-2\sigma(z)}R^{(4)}(x) + e^{-4\sigma(z)}\mathcal{R}),$$

$$\lambda e^{-\frac{4}{3}\Phi(z)}\sqrt{-g}R_{\rm GB}(x) = \sqrt{-g^{(4)}(x)}\lambda e^{-\frac{4}{3}\Phi(z)}(4e^{-2\sigma(z)}(3\sigma'(z)^2 - 2\sigma''(z))R^{(4)}(x) - 2(R^2_{\mu\nu\rho\sigma} - R^2_{\mu\nu}) + e^{-4\sigma(z)}\mathcal{R}_{\rm GB}),$$

$$\sqrt{-g}(\nabla_\mu\Phi)^2 = \sqrt{-g^{(4)}(x)}(e^{-4\sigma(z)}\Phi'(z)^2 + e^{-2\sigma(z)}(\nabla_i\Phi^{(4)}(x))^2),$$

where

$$\mathcal{R} = 4(5\sigma'(z)^2 - 2\sigma''(z)),$$

$$\mathcal{R}_{\rm GB} = 24(5\sigma'(z)^4 - 4\sigma'(z)^2\sigma''(z))$$

**Planck Mass**

$$M_P^2 = M_s^3\int_{-\infty}^{\infty} dz\, e^{-2\sigma(z)}\left(1 - 4\lambda e^{-\frac{4}{3}\Phi(z)}(3(\sigma'(z))^2 - 2\sigma''(z))\right).$$

**Cosmo. Constant**

$$\Lambda_{\rm total}(z_i) = \Omega + V_{\rm brane}(z_i),$$

$$\Omega = \int_{-\infty}^{+\infty} dz\, e^{-4\sigma(z)}\Big[\xi e^{\frac{4}{3}\Phi(z)} - \frac{4}{3}(\Phi'(z))^2 - 20(\sigma'(z))^2 + 8\sigma''(z) + \lambda e^{-\frac{4}{3}\Phi(z)}(24(5(\sigma'(z))^4 - 4(\sigma'(z))^2\sigma''(z)) + c_2(\Phi'(z))^4)\Big].$$

# Brane World Effective Action

$$\sqrt{-g}R(x) = \sqrt{-g^{(4)}(x)}(e^{-2\sigma(z)}R^{(4)}(x) + e^{-4\sigma(z)}\mathcal{R})\,,$$

$$\lambda e^{-\frac{4}{3}\Phi(z)}\sqrt{-g}R_{\rm GB}(x) = \sqrt{-g^{(4)}(x)}\lambda e^{-\frac{4}{3}\Phi(z)}(4e^{-2\sigma(z)}(3\sigma'(z)^2 - 2\sigma''(z))R^{(4)}(x) - 2(R^2_{\mu\nu\rho\sigma} - R^2_{\mu\nu}) + e^{-4\sigma(z)}\mathcal{R}_{\rm GB})\,,$$

$$\sqrt{-g}(\nabla_\mu\Phi)^2 = \sqrt{-g^{(4)}(x)}(e^{-4\sigma(z)}\Phi'(z)^2 + e^{-2\sigma(z)}(\nabla_i\Phi^{(4)}(x))^2)\,,$$

where

$$\mathcal{R} = 4(5\sigma'(z)^2 - 2\sigma''(z))\,,$$

$$\mathcal{R}_{\rm GB} = 24(5\sigma'(z)^4 - 4\sigma'(z)^2\sigma''(z))$$

**Planck Mass**

$$M_P^2 = M_s^3\int_{-\infty}^{\infty} dz\, e^{-2\sigma(z)}(1 - 4\lambda e^{-\frac{4}{3}\Phi(z)}(3(\sigma'(z))^2 - 2\sigma''(z)))$$

**Cosmo. Constant**

$$\Lambda_{\rm total}(z_i) = \Omega + V_{\rm brane}(z_i)\,,$$

$$\Omega = \int_{-\infty}^{+\infty} dz\, e^{-4\sigma(z)}\Big[\xi e^{\frac{4}{3}\Phi(z)} - \frac{4}{3}(\Phi'(z))^2 - 20(\sigma'(z))^2 + 8\sigma''(z) + \lambda e^{-\frac{4}{3}\Phi(z)}(24(5(\sigma'(z))^4 - 4(\sigma'(z))^2\sigma''(z)) + c_2(\Phi'(z))^4)\Big]\,.$$

there are negative contributions

Inclusion of constant KR torsion on 4-dim world -→ contribution to 4-D vacuum energy on brane

$$V_4 \ni \int d^4x \sqrt{-g^{(4)}}\, e^{\mathrm{const}\,\Phi(t)} \left(\frac{1}{2}(\dot{b})^2 + \Omega\right)$$

Inclusion of constant KR torsion on 4-dim world -→ contribution to 4-D vacuum energy on brane

$$V_4 \ni \int d^4x \sqrt{-g^{(4)}}\, e^{\text{const}\,\Phi(t)} \left(\frac{1}{2}(\dot{b})^2 + \Omega\right)$$


Small vacuum energy during leptogenesis guaranteed if **negative** contributions from **bulk-induced** Ω **set** to cancel the large KR kinetic term contributions

**Complete analysis : Should Include of course higher order KR torsion terms**

)

**$B^0$** : (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 …

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

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)

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

**If a small $B^a$ is present today**

Standard Model Extension type coupling $b_\mu$

Kostelecky, Mewes, Russell, Lehnert …

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

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)

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

Can these small **current values of Torsion** be **connected smoothly**, with some form of temperature T dependence, to the **$B^0$ of O(1 MeV)** in our case, required for **Leptogenesis at T=$10^5$ GeV ?**

# NB:

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

**$<0 \mid J^{05} \mid 0> \neq 0$**

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

**De Cesare, NEM & Sarkar arXiv:1412.7077**

**Eqs of motion for pseudoscalar:**

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

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

Condensate may be **subsequently destroyed** at a temperature Tc **$<0 \mid J^{05} \mid 0> \rightarrow 0$**

by relevant operators so eventually in an expanding FRW Universe **for $T < T_c$**

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

**NB:**

Perturbatively we may also have such a constant ***B⁰*** 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

**De Cesare, NEM & Sarkar arXiv:1412.7077**

**Eqs of motion for pseudoscalar:**

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

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

Condensate may be **subsequently destroyed** at a temperature Tc **<0 | $J^{05}$ |0> → 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**

De Cesare, NEM, Sarkar arXiv:1412.7077

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

**$B^0$ small today but non zero, scales with scale factor as $a^{-3} \approx$ const x $T^3$**

$$B_0 = c_0\, T^3$$

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

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

Quite safe from stringent Experimental Bounds

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

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

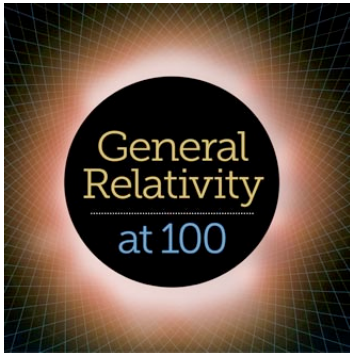
De Cesare, NEM, Sarkar arXiv:1412.7077

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

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

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


**BUT... unlike $\nu$ MSM, for leptogenesis heavy $M$ > 100 TeV, right-handed (RH) Neutrinos N are needed...**
**Even one RH neutrino generation suffices for Leptogenesis,** but we may need 3 RH neutrinos for seesaw active ν mass generation



# Conclusions

# &

# Outlook

SCALARS 2015

03-07 December 2015

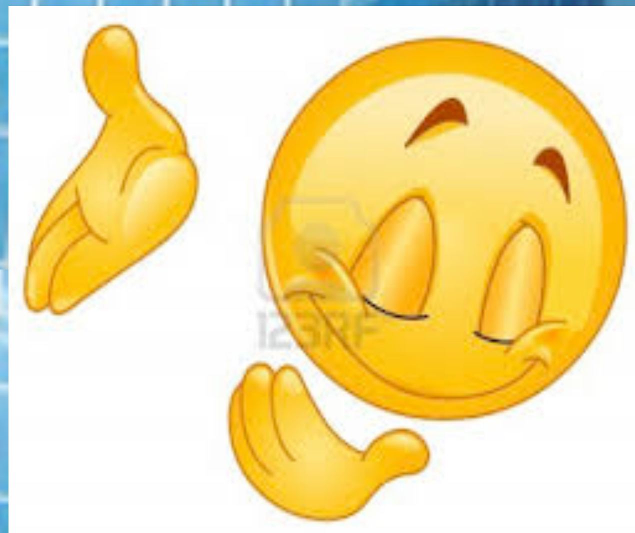
Warsaw, Poland

# 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**

General Relativity at 100



Thank you for your attention !

# SCALARS 2015

03-07 December 2015
Warsaw, Poland

# 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) $\rightarrow$ 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 $\psi$ reps. electrons, quarks etc. with charge $q$

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

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

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

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

NB2: In general $a_\mu, b_\mu \ldots$ 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

# Non-commutative effective field theories

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

Moyal $\star$ products

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

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

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

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

$$\widehat{A}_\mu = A_\mu - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha(\partial_\beta A_\mu + F_{\beta\mu}),$$

$$\widehat{\psi} = \psi - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha \partial_\beta \psi.$$

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

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

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**)

# Non-commutative effective field theories

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

Moyal $\star$ products

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

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

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

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

$$\widehat{A}_\mu = A_\mu - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha (\partial_\beta A_\mu + F_{\beta\mu}),$$
$$\widehat{\psi} = \psi - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha \partial_\beta \psi.$$

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

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

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

Kostelecky *et al.*

**Lorentz Violating**

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

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

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

# + Gauge Sectors

$$\boxed{O^{\rm SM}_{\mu\nu\ldots} C^{\mu\nu\ldots} \to O^{\rm SM}_{\mu\nu\ldots} \langle C^{\mu\nu\ldots} \rangle}$$

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 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***

# 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):

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

**Non-conserved Baryon number**

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

**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***

**LIKE A CHEMICAL POTENTIAL FOR FERMIONS**

# 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):

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

**Non-conserved Baryon number**

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

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

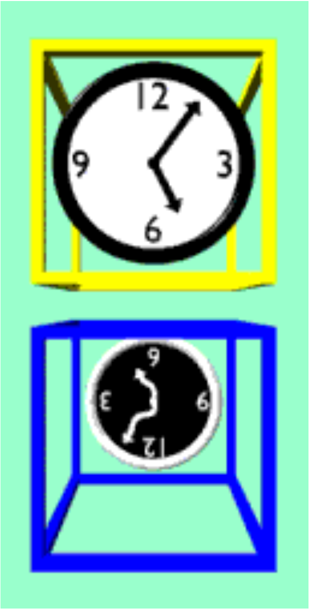
Calculate for various w in some scenarios

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

# *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

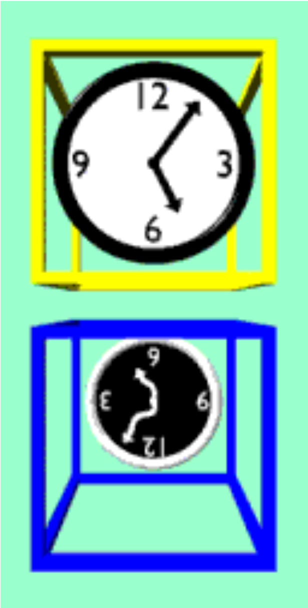



**physics.indiana.edu**

# 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




**physics.indiana.edu**

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

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

**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***

$$m(T) \sim gT$$ $\Rightarrow$ 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***

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

**Dolgov, Zeldovich**
**Dolgov (2009)**

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

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

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

**Dolgov (2009)**

Current bound for proton-anti proton mass diff.

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

**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

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

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

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

Dolgov (2009)

Current bound for proton-anti proton mass diff.

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

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***