Cosmological and Dynamical Aspects of Quantum Gravity with Torsion

Nick E. Mavromatos

King's College London &

CERN-PH-TH

London Centre for Terauniverse Studies (LCTS) AdV 267352

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organized by A. Bassi, C. Curceanu & D. Dürr

cost

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE AND TO ENRICO FERMI, "THE ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Frascati

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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- Conclusions & Outlook

Keep the Extension of SM minimal

Non SUSY but allow for Right-Handed (Majorana) Neutrinos

BUT

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 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

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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 $\vec{x} \to -\vec{x}$

$$X \overset{\leftarrow}{\rightarrow} \ell + \ldots$$

Ā = **antiparticle**

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

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

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

(ii) Directly generated out of equilibrium Baryogenesis

ELECTROWEAK THEORY & FERMION # NON-CONSERVATION

Classical conservations of EW theory: B, L_e , L_μ , L_τ

Quantum Anomalies:

$$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{n_f}{32\pi^2} \mathrm{Tr} F_{\mu\nu} \tilde{F}_{\mu\nu} + U(1) \quad \text{part}$$

Allowed Processes (change of B by multiples of 3)

$$\text{bosons} \leftrightarrow \text{bosons} + 9q + 3l$$

$\rightarrow$ L_i – B/3 Conserved

(three quantities)

BUT:
OBSERVED NEUTRINO FLAVOUR OSCILLATIONS

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

If neutrinos Majorana

$\rightarrow$ **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

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

α_W = SU(2) fine structure ``constant''

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Sphaleron Mass Scale (M_W/α_W) = height of energy Barrier separating SU(2) vacua with different topologies

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

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

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

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

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

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

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BAU COULD BE PRODUCED @ $\boxed{T \simeq T_{\rm sph}}$

Compute CP Violation Effects

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

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

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

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

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

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

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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 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

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

**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

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

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Higgs scalar SU(2) Dual: $\tilde{\phi}_i = \epsilon_{ij} \phi_j^*.$

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νMSM

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Yukawa couplings
Matrix (N=2 or 3)

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

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

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

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

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Boyarski, Ruchayskiy, Shaposhnikov

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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

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

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

SM Extension with N extra right-handed neutrinos

$$\nu\mathrm{MSM}$$

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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 $\langle\Phi\rangle = v \neq 0$ → Dirac mass term

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Light Neutrino Masses through see saw

Minkowski,
Yanagida,
Mohapatra, Senjanovic

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

$M_D = F_{\alpha I} v$

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

$M_D \ll M_I$

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

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

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Thermal Properties

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

$$|F|^2 \approx \frac{m_{\text{atm}} M_I}{v^2} \sim 2 \times 10^{-15} \frac{M_I}{\text{GeV}}$$

$$|\Delta m^2_{\text{atm}}| \equiv m^2_{\text{atm}} = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{eV}^2$$

(Decay) processes in Early Universe

$$Nt \leftrightarrow \nu t,\ H \leftrightarrow N\nu \text{ or } N \leftrightarrow H\nu$$

Rate: $9F^2 f_t^2 T/(64\pi^3)$

Akhmedov, Rubakov, Smirnov

f_t = top quark Yukawa coupling

Thermal equilibrium at temperatures

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

(for T_{eq} > 100 GeV)

$$M_0 = M_P/(1.66\sqrt{g_{eff}})$$
$$\text{time} = M_0^2/2T^2 \text{ (radiation era)}$$

Thermal Properties

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

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

Decay of Right-handed fermions

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

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 $T = T_{eq}$***

Thermal Leptogenesis

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

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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 @ $T \gg T_{eq}$

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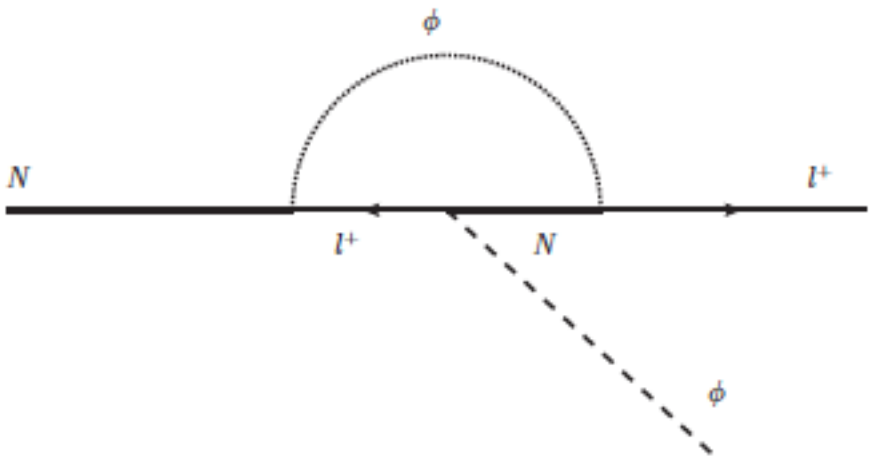

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov

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Equilibrated electroweak B+L violating sphaleron interactions

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov

Thermal Leptogenesis

Independent of Initial Conditions
@ T >>T$_{eq}$

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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}

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Fukugita, Yanagida,

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Equilibrated electroweak B+L violating sphaleron interactions

B-L conserved

Independent of Initial Conditions

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…

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 through coherent oscillations right-handed singlet fermions

Akhmedov, Rubakov, Smirnov

Assume ***Mass degeneracy*** $N_{2,3}$, hence enhanced CP violation

Coherent Oscillations between these singlet fermions

$$\omega \sim \frac{|M_2^2 - M_3^2|}{E_I} \sim \frac{M_2 \Delta M(T)}{T}$$

$$E_I \sim T$$

$$\Delta M(T) \ll M_2 \approx M_3$$

$N_2 - N_3$ MASS DIFF.

FOR CP VIOLATION TO OCCUR MUST HAVE: Oscillation rate > Hubble rate H(T)

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

Total Lepton zero but unevenly distributed between active & sterile v

Lepton number of active left-handed v transferred to Baryons due to equilibrated sphaleron processes conserving B-L

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Baryon Asymmetry in Universe ESTIMATES

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FOR CP VIOLATION TO OCCUR MUST HAVE: Oscillation rate > Hubble rate H(T)

Baryogenesis occurs @: $T_B \sim \left(M_I \Delta M(T) M_0\right)^{1/3}$

$$\boxed{\frac{n_B}{s} \simeq 1.7 \cdot 10^{-10}\, \delta_{CP} \left(\frac{10^{-5}}{\Delta M(T)/M_2}\right)^{\frac{2}{3}} \left(\frac{M_2}{10\ \ \mathrm{GeV}}\right)^{\frac{5}{3}}}$$

$$\delta_{CP} = 4 s_{R23} c_{R23} \Big[s_{L12} s_{L13} c_{L13} \left((c_{L23}^4 + s_{L23}^4) c_{L13}^2 - s_{L13}^2 \right) \cdot \sin(\delta_L + \alpha_2)$$
$$+ c_{L12} c_{L13}^3 s_{L23} c_{L23} \left(c_{L23}^2 - s_{L23}^2 \right) \cdot \sin \alpha_2 \Big] .$$

Baryon Asymmetry in Universe ESTIMATES

Assume ***Mass degeneracy*** $N_{2,3}$, hence enhanced CP violation
Coherent Oscillations between these singlet fermions

$$\boxed{\omega \sim \frac{|M_2^2 - M_3^2|}{E_I} \sim \frac{M_2 \Delta M(T)}{T}}$$

$$E_I \sim T$$

$$\Delta M(T) \ll M_2 \approx M_3$$

FOR CP VIOLATION TO OCCUR MUST HAVE: Oscillation rate > Hubble rate H(T)

Baryogenesis occurs @: $T_B \sim \left(M_I \Delta M(T) M_0\right)^{1/3}$

Quite effective Mechanism: Maximal Baryon asymmetry $\Delta \equiv \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 1$

for $T_B = T_{sph} = T_{eq}$

Canetti, Frossart, Shaposhnikov, arXiv: 1208.4607

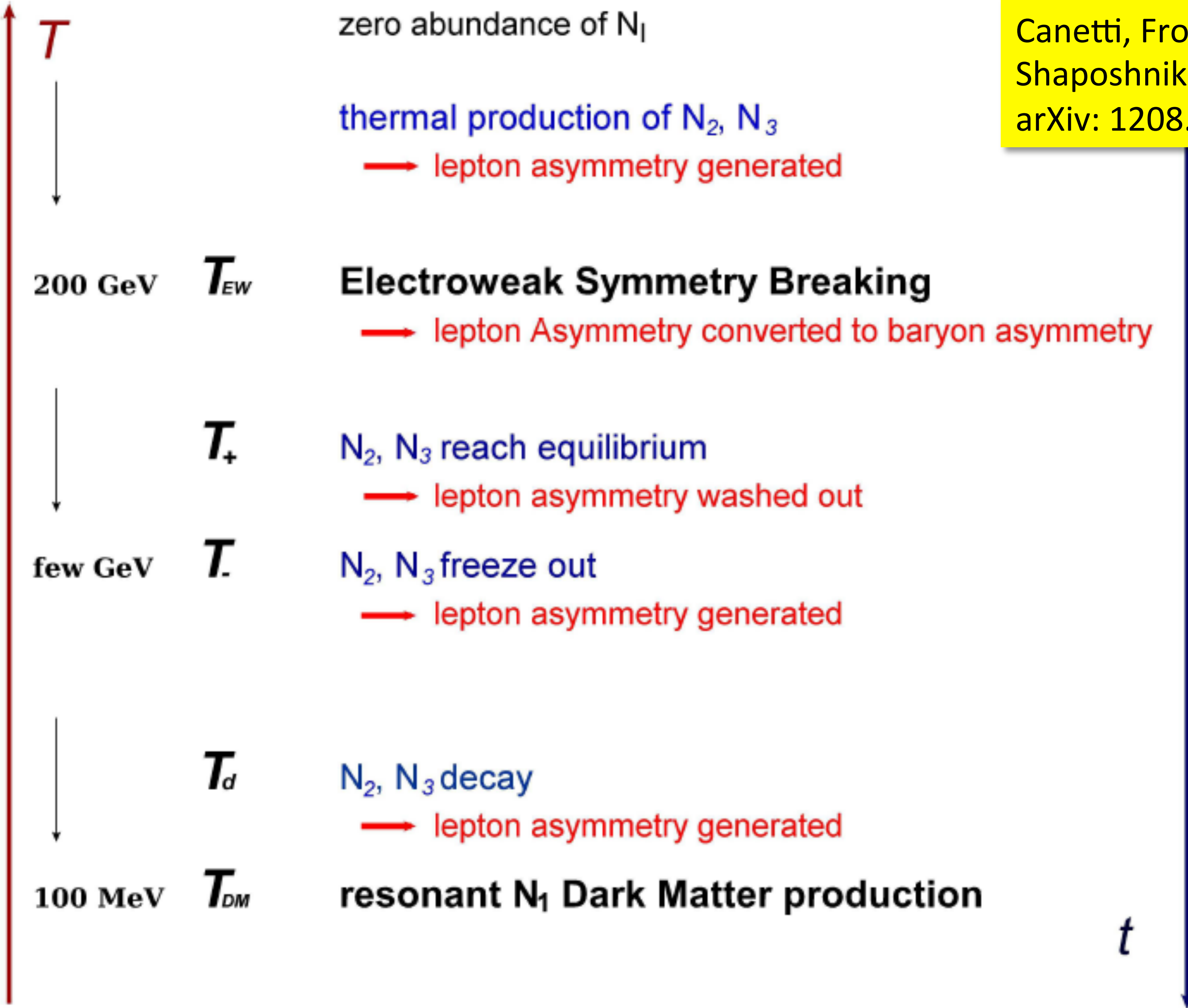
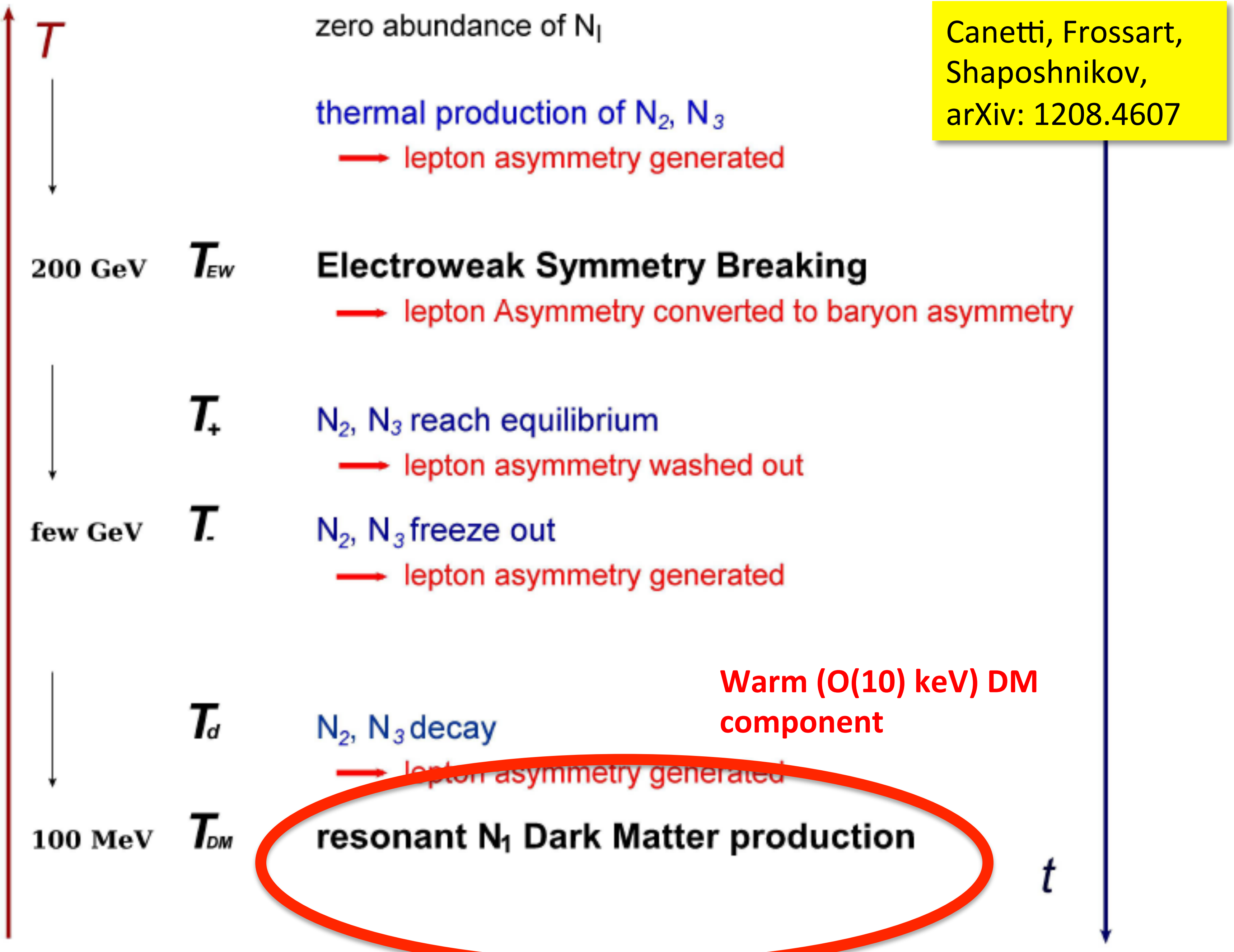


Figure 1: *The thermal history of the universe in the νMSM.*



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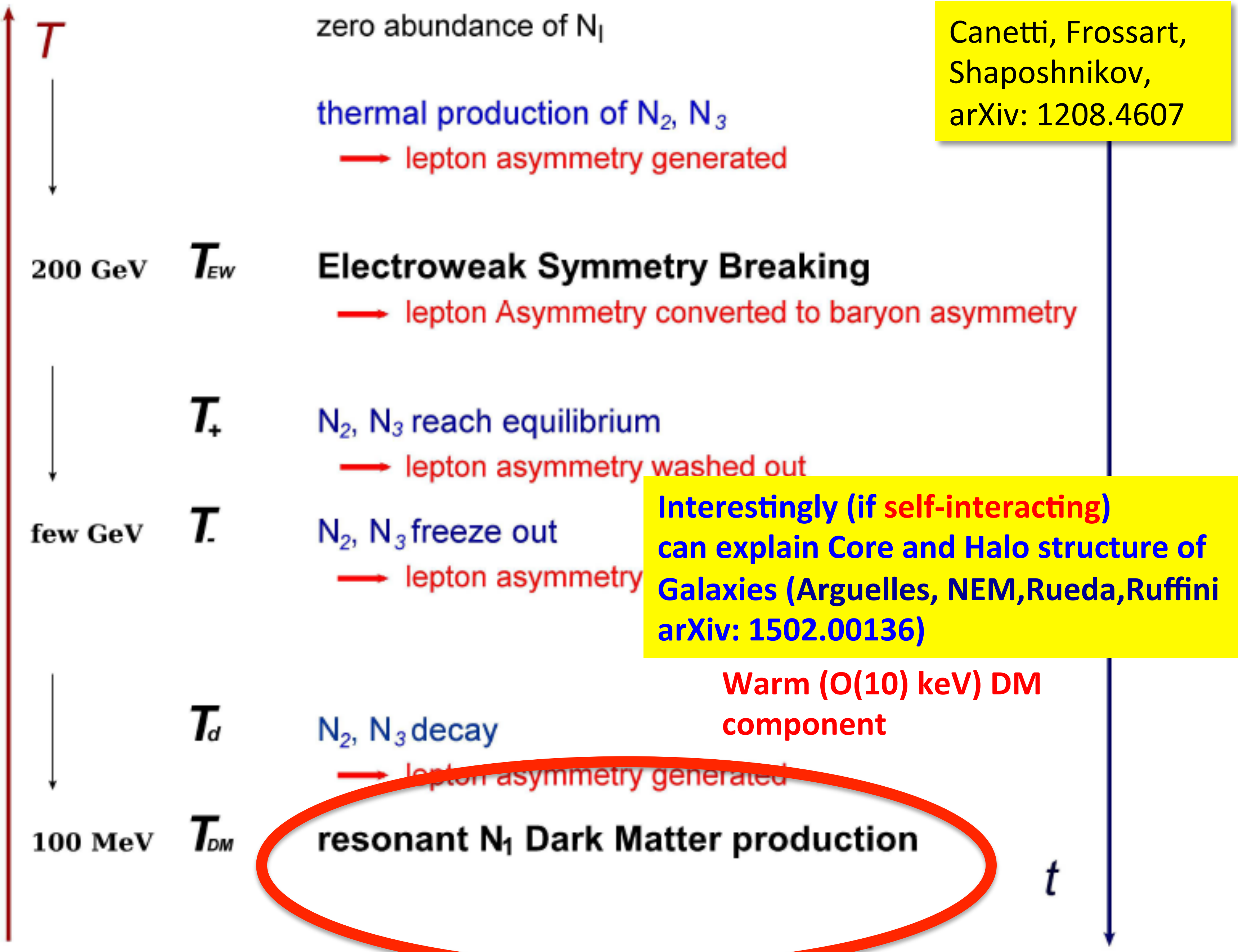
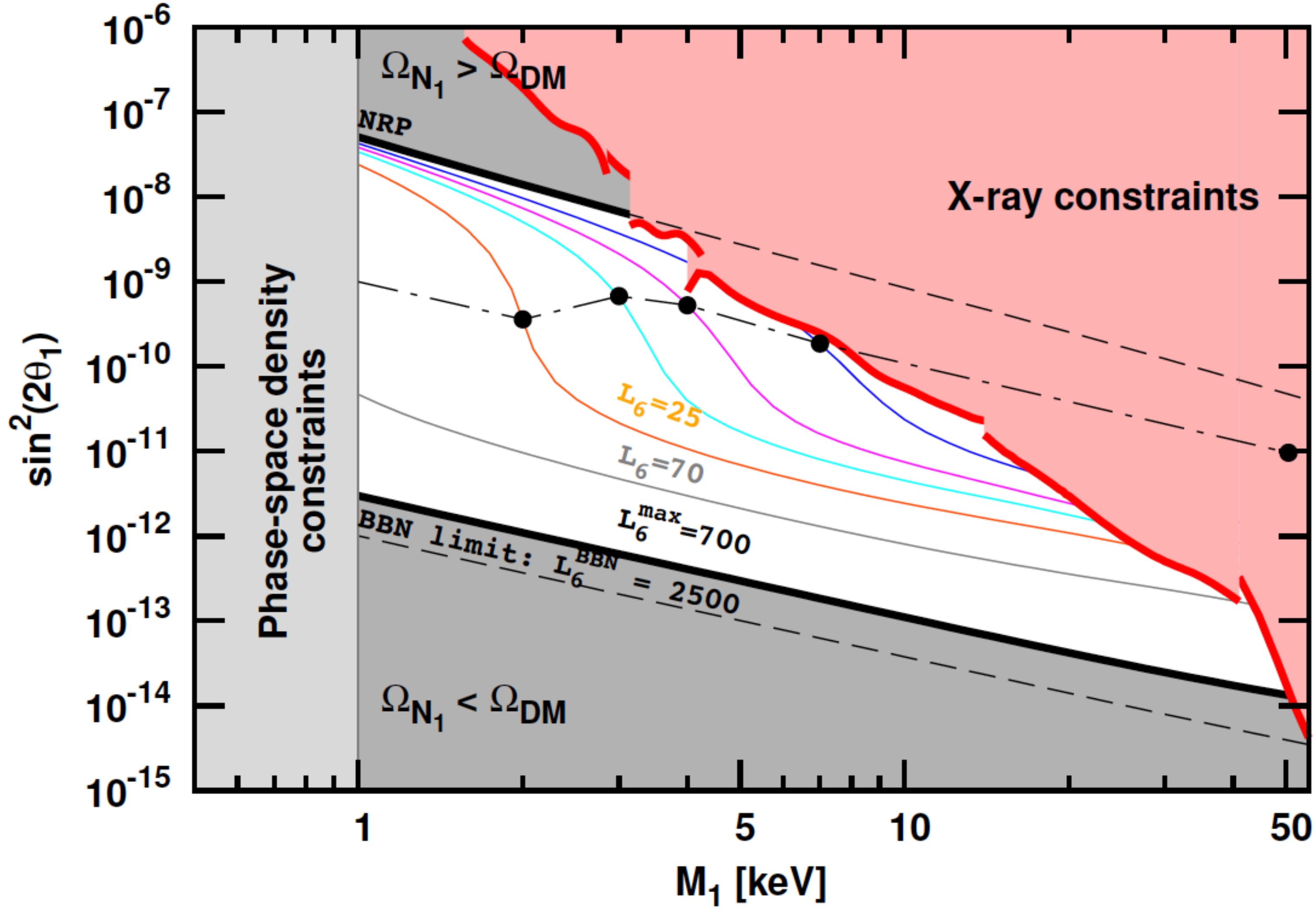


Figure 1: *The thermal history of the universe in the νMSM.*

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

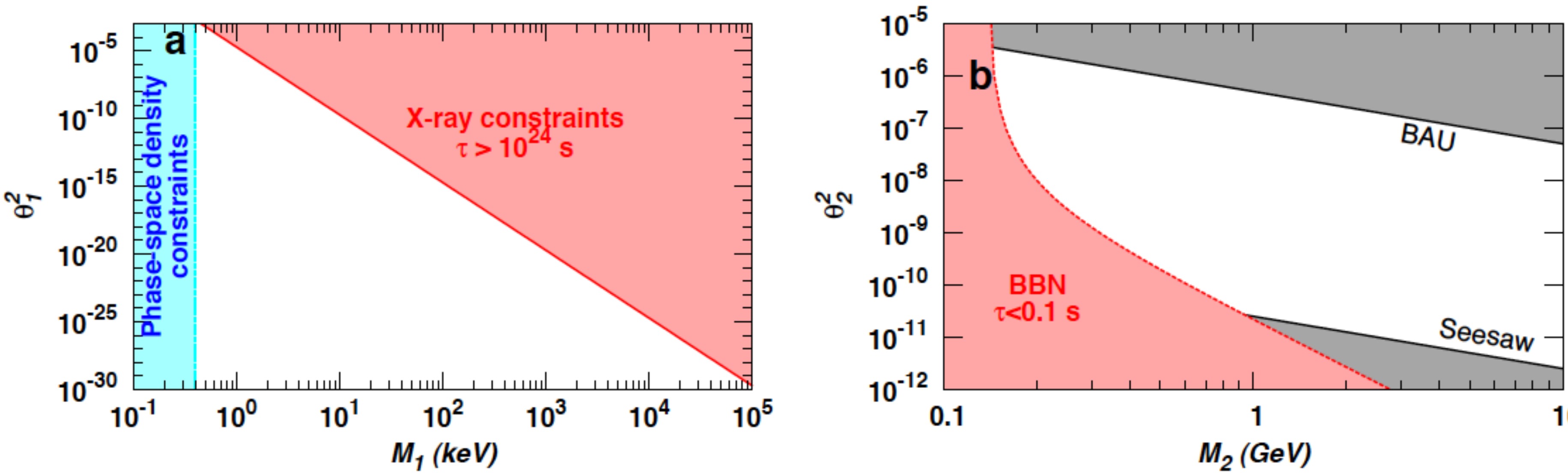
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS



More than one sterile neutrino needed to reproduce Observed oscillations

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…



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

Baryon Asymmetry in Universe ESTIMATES

Assume ***Mass degeneracy*** $N_{2,3}$, hence enhanced CP violation
Coherent Oscillations between these singlet fermions

$$\omega \sim \frac{|M_2^2 - M_3^2|}{E} \quad \ldots \quad M_3$$

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

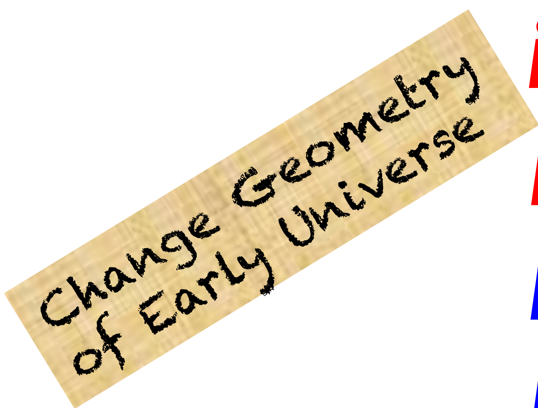
MAY BE DIFFICULT TO ACHIEVE

$$\ldots (T) M_0 \Big)^{1/3}$$

Q… …anism: Maximal Baryon asymmetry $\Delta \equiv \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 1$

for $T_B = T_{sph} = T_{eq}$

IDEA:



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

Can we maintain νMSM 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 νMSM (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

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

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)

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

Lorentz Violation

Lorentz & CPT Violation

(ii)-(iv) Independent reasons for violation

FIELD THEORY LV & CPTV FORMALISM.....

The Standard Model Extension (SME) (Kostelecky et al.)

- CPT well-defined quantum mechanical operator Θ, not commuting with the Hamiltonian **$[\Theta, H] \neq 0$** ✔
- Field Theoretical Formalism:
  CPTV induced by Lorentz-violating backgrounds → **Standard Model Extension (SME)** ✔
- **Early Universe Lorentz-violating backgrounds with torsion → Leptogenesis → matter/antimmater asymmetry**

Torsion-background –induced SME with CPTV & Lorentz Violation

STANDARD MODEL EXTENSION

Kostelecky *et al.*

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

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

+ Gauge Sectors

$$\boxed{O^{\mathrm{SM}}_{\mu\nu\dots} C^{\mu\nu\dots} \to O^{\mathrm{SM}}_{\mu\nu\dots} \langle C^{\mu\nu\dots} \rangle}$$

Bolokhov, Pospelov 0703291.

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

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Lorentz & CPT - Violating

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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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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):

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

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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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

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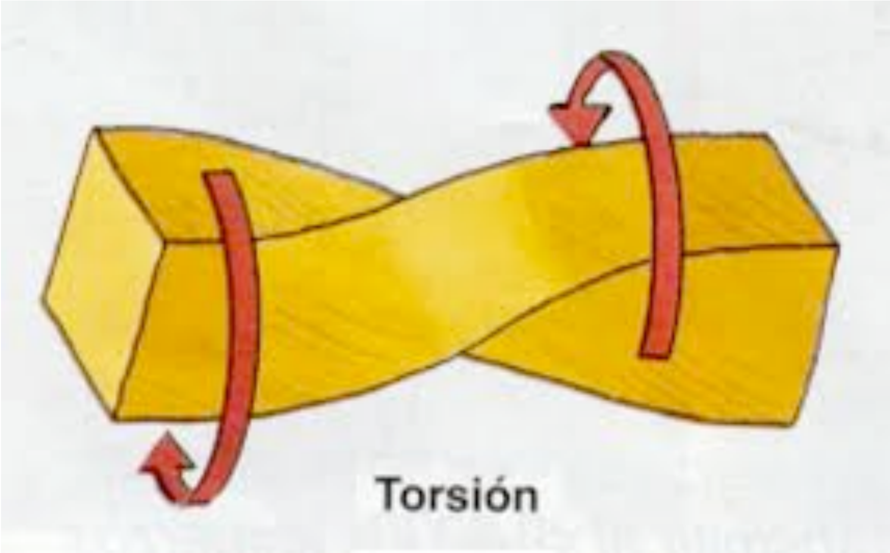
CPTV Effects of different Space-Time-Curvature/ Spin couplings between fermions/antifermions

B. Mukhopadhyay, U. Debnath, N. Dadhich, M. Sinha
Lambiase, Mohanty, NEM, Ellis, Sarkar, de Cesare

In particular, Space-times with



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

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

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

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

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

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

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

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:

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

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

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

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_μ , axial vector S_μ 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

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

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

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

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

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

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

ROLE OF H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

4-DIM PART

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

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

Contorsion

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT $\boxed{\sim \frac{1}{2}\partial^\mu b\, \partial_\mu b}$

4-DIM PART

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

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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 $\boldsymbol{B^\mu}$

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

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

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

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

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$$H_{cab}$$

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

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

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

$$<0 \,|\, J^{05} \,|0> \neq 0$$

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

De Cesare, NEM & Sarkar arXiv:1412.7077

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

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

Condensate may be subsequently destroyed at a temperature Tc $<0 \,|\, J^{05} \,|0> \to 0$

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 = 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 ***B⁰***

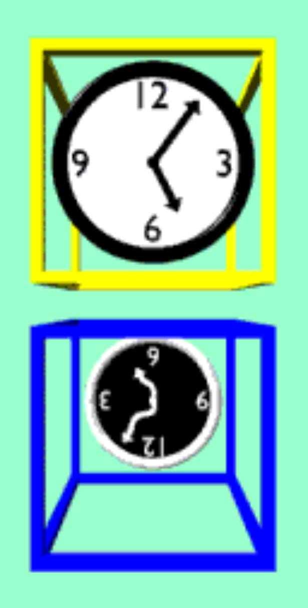
Standard Model Extension type with CPT and Lorentz Violating background b^0

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



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

Through B-L conserving Sphaleron processes In the standard model

Standard Thermal Leptogenesis

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

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

Lepton number & CP Violations @ 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

B-L conserved

Independent of Initial Conditions

Observed Baryon Asymmetry In the Universe (BAU)

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhnikov, Akhmedov, Smirnov,…

Estimate BAU by solving Boltzmann equations for Heavy Neutrino Abundances

Pilafsis, Buchmuller, di Bari *et al.*

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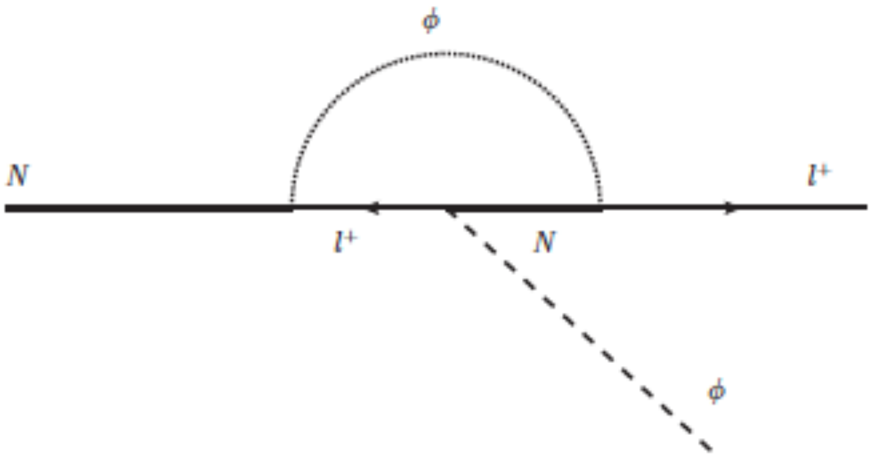

ymmetry

-L conserved

metry
U)

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

where

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

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CPTV Thermal Leptogenesis

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

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

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Constant H-torsion

CPT Violation

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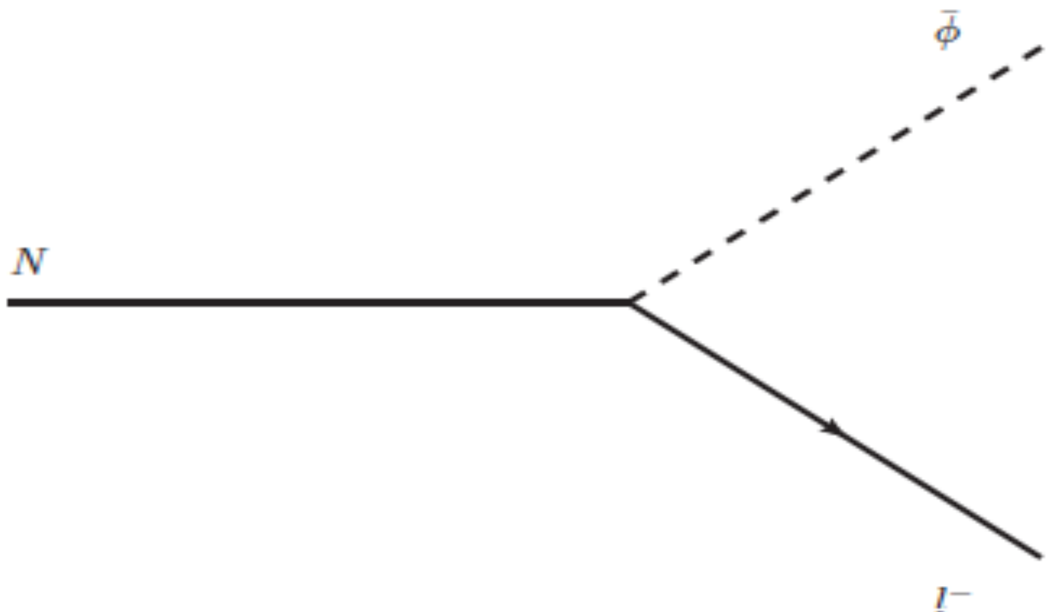

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Early Universe

T > 10^5 GeV

CPT Violation

Constant H-torsion

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

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

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

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

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

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

$$T_D \simeq m$$

Produce Lepton asymmetry

CPTV Thermo

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

Early Universe

T > 10^5 GeV

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Produce Lepton asymmetry

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Produce Lepton asymmetry

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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

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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

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

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

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

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental
Conditions Dependent

Observed Baryon Asymmetry
In the Universe (BAU)

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

e.g. May Require
Fine tuning of
Vacuum energy

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_μ

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 it 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 ***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

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

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Condensate may be **subsequently destroyed** at a temperature Tc **$\langle 0 \,|\, J^{05} \,|0\rangle \to 0$**

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

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

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

$$B_0 = c_0 T^3$$

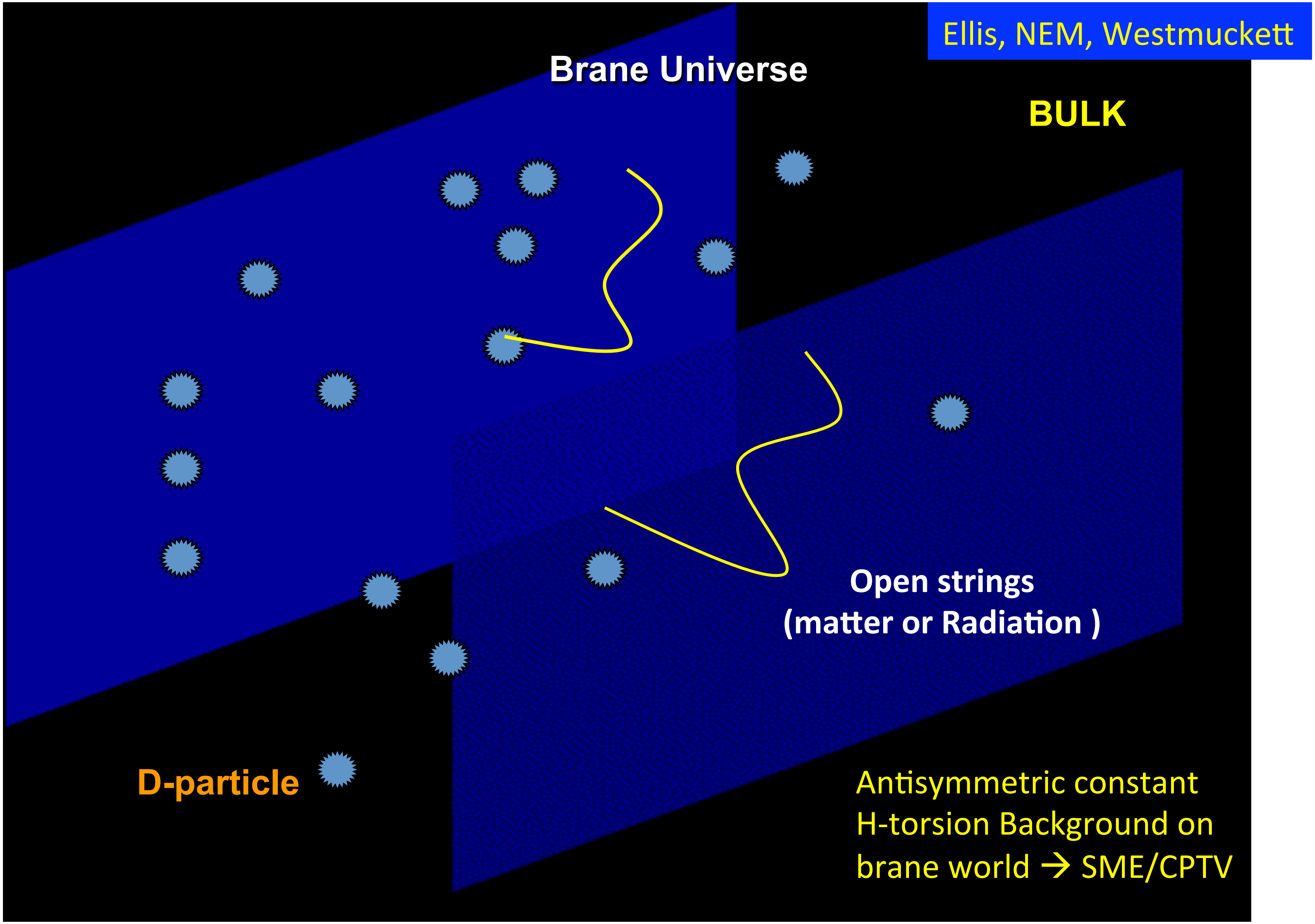
$$c_0 = 10^{-42}\,\mathrm{meV}^{-2}$$

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

Quite safe from stringent Experimental Bounds

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

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



A stringy (microscopic) model for the T_c phase transition → fluctuations of D-particles also induce quantum decoherence

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

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

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Torsion-Quantum Fluctuations & Neutrino Mass Generation

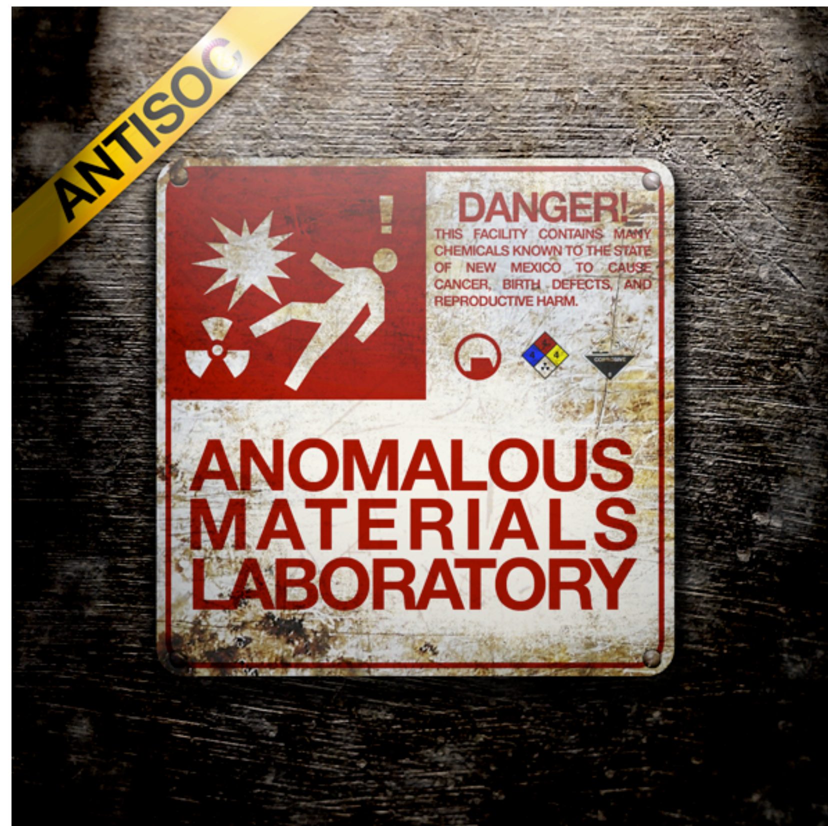
What About the Quantum Fluctuations of the H-torsion ?
Even in the absence of a non-trivial H-background

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

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

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

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

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

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

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

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

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

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partial integrate

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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

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

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

coupling

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+ 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)

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

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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

Field redefinition

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

so, effective action becomes

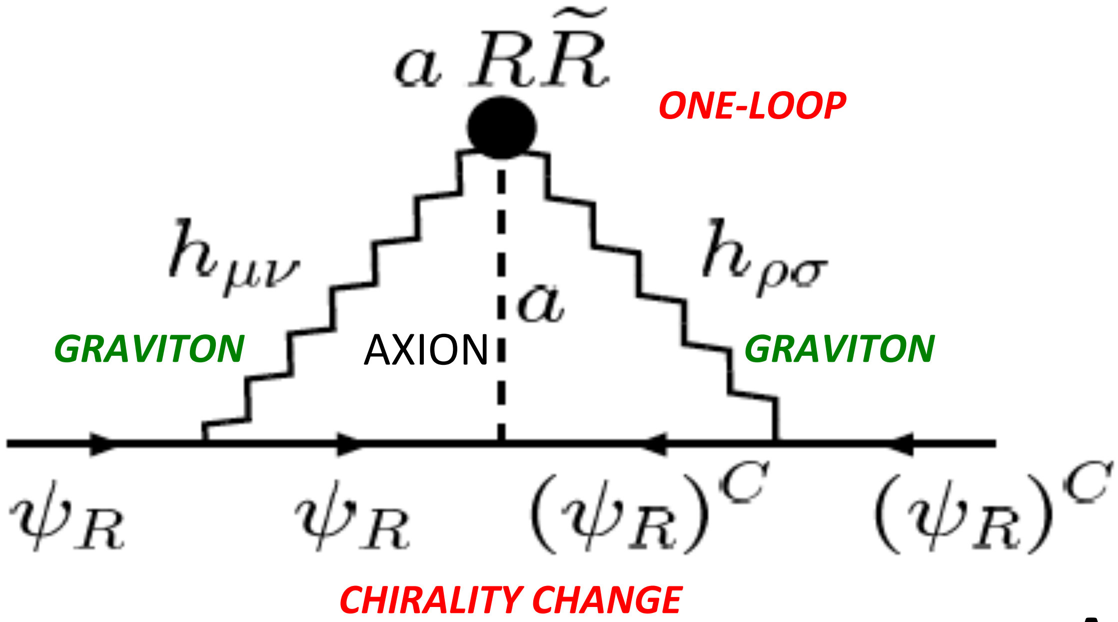
$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b')^2 + \frac{1}{2}\left(1-\gamma^2\right)(\partial_\mu a)^2 + \frac{1}{2f_b^2}J^5_\mu J^{5\mu} + \frac{b'(x)-\gamma a(x)}{192\pi^2 f_b}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} - y_a i a\left(\overline{\psi}_R^{\,C}\psi_R -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

must have $|\gamma| < 1$ *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

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

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,

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

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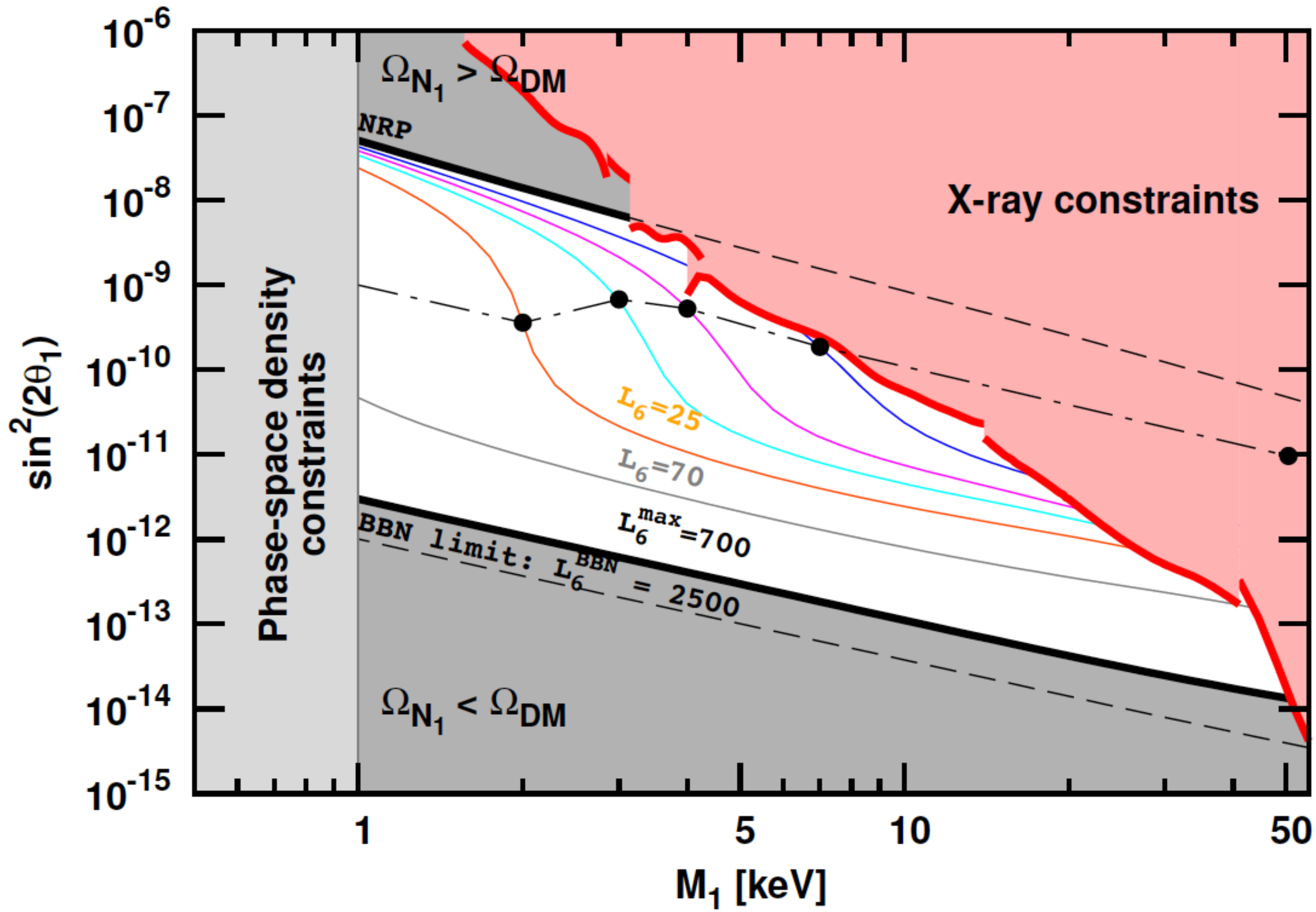
INTERESTING WARM DARK MATTER REGIME

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

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

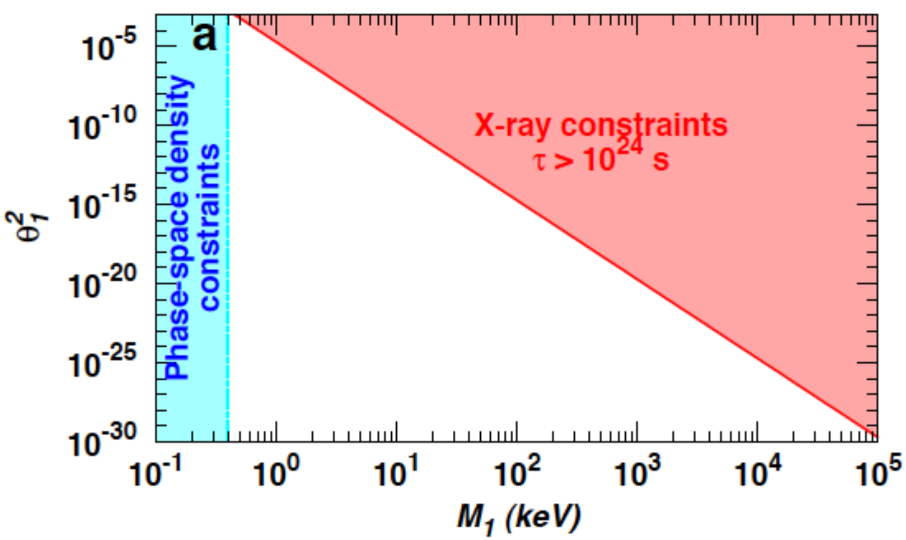
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS

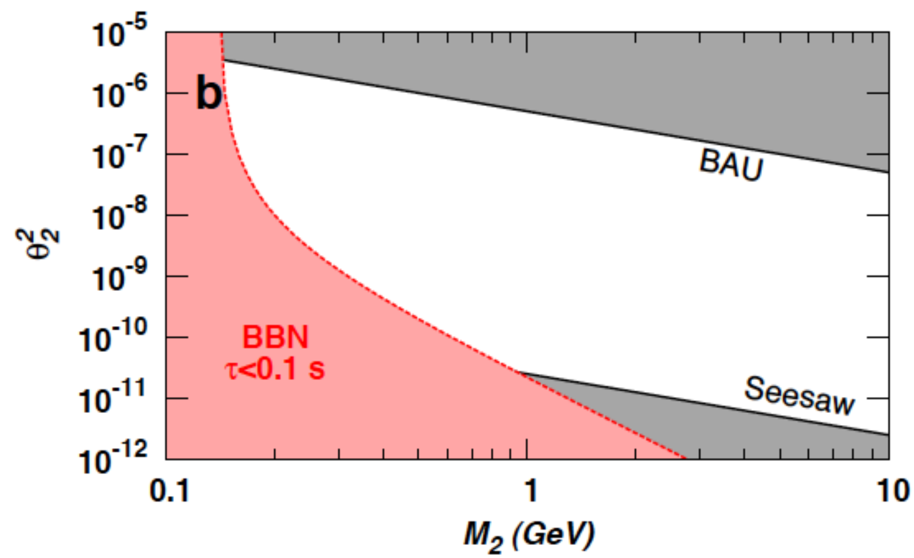


More than one sterile neutrino needed to reproduce Observed oscillations

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…





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

FINITENESS OF THE MASS

Arvanitaki, Dimopoulos *et al.*

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

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

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

positive mass spectrum
for all axions

simplifying all mixing equals

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

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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**

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

CPT Violation

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


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

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

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

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

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

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

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

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

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)

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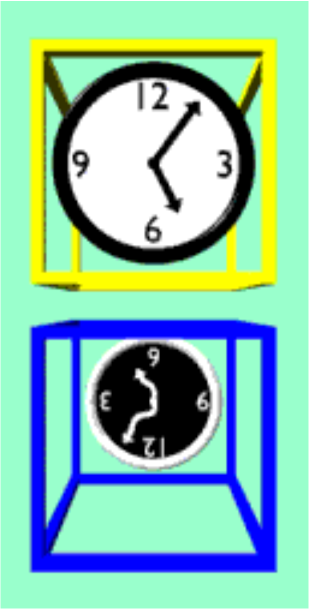
CPT VIOLATION IN THE EARLY UNIVERSE

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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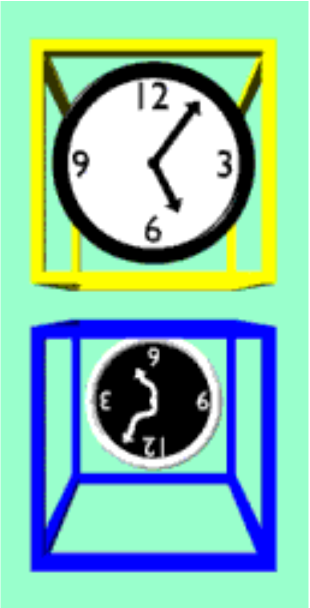

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ONE POSSIBILITY:
particle-antiparticle mass differences

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

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

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

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

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

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

Dolgov, Zeldovich
Dolgov (2009)

Assume dominant contributions to Baryon asymmetry from quarks-antiquarks

$$m(T) \sim gT$$ → High-T quark mass >> Lepton mass

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

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

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Current bound for proton-anti proton mass diff.

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

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

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

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