CPT VIOLATION:

From MATTER-ANTIMATTER ASYMMETRY in the EARLY UNIVERSE to ENTANGLED QUANTUM STATES

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Workshop on the Standard Model and Beyond
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OUTLINE

I. Motivation – Insufficient CP Violation induced matter-antimatter asymmetry in Standard Model

→ must go beyond to reproduce observed baryon asymmetry....

II. Exotic scenarios: CPT Violation in early Universe?

(a) Lorentz Violating Background (flux) fields & Baryogenesis through Leptogenesis

→ matter-antimatter asymmetry of correct value:

→ evolution from early epochs to present day – current bounds

(b) Quantum Gravity Decoherence (QGD): strong(?) in early Universe → CPT generator ill-defined

III(a). Novel QGD-CPT Violating effects (ω-effect) in entangled states of particles, e.g. neutral mesons – bounds: Φ, B- factories searches

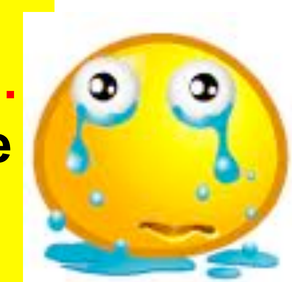
III(b). Connection to Baryogenesis (specific QGD models)

IV. Conclusions-Outlook

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

CPT Violation

Construct microscopic models with strong CPT Violation in Early Universe (due to background fields or quantum gravity), but weak today… Fit with all available data… in particular current stringent constraints → scale back in time
Estimate in this way matter-antimatter asymmetry in Universe
Does it agree with the expected phenomenological value ?



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time

Baryogenesis @ T_D : direct
or through
Leptogenesis first @ $T'_D > T_D$

CPTV
$\{b^i(T_D)\}$ parameters
phenomenology?

scale with T
(concrete
model)

CPT Violation parameter(s)
$\{b^i_0\}$: current-epoch bounds (experiment)

$\{b^i(T_0)\} \leq \{b^i_0\}$

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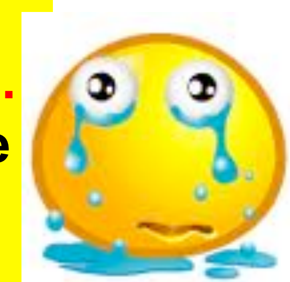

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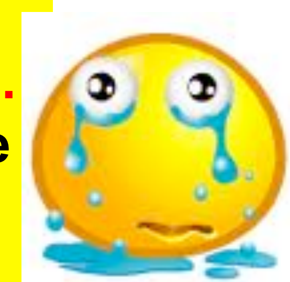

Part I
Motivation:
Matter-Antimatter Asymmetry
in
the Standard Model

STANDARD MODEL INCOMPATIBLE WITH BARYOGENESIS

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

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

- But Universe consists only of matter

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

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

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

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OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

Kuzmin, Rubakov, Shaposhnikov

Rate of B violation in Early Universe

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

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

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

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

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

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

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

Compute CP Violation Effects

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

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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

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

Shaposhnikov

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

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

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

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

Beyond the Standard Model

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

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- THIS TALK: TRY **EXOTIC** SCENARIOS WITH (SIMPLIFIED) MODELS OF

CPT VIOLATION IN EARLY UNIVERSE ?

Consistency with stringent current constraints must be ensured

Part II
CPT Violation
THEORY

CPT Theorem

Schwinger 1951

Lüders 1954

J S Bell 1954

Pauli 1955

Res Jost 1958

CPT Theorem

Conditions for the Validity of CPT Theorem

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

i → f , **T**: f → i

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

Schwinger, Pauli, Luders, Jost, Bell

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

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

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

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

CPT VIOLATION

Conditions for the Validity of CPT Theorem

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

(ii)-(iii) CPT V well-defined as Operator Θ does not commute with Hamiltonian
$[\Theta, H] \neq 0$

(iv) e.g. Quantum Gravity decoherence → CPT operator may not be well defined (Wald)
→ consequence for Entangled States (Bernabeu, NEM, Papavassiliou, ...)

CPT VIOLATION

Conditions for the Validity of CPT Theorem

This Talk

CPT Invariance Theorem :

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

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

(ii)-(iv) Independent reasons for violation

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

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

Lorentz & CPT Violation

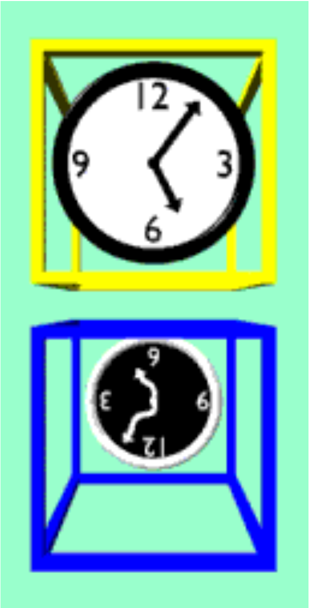
Lorentz & CPT Violation

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

CPT VIOLATION IN THE EARLY UNIVERSE

GENERATE Baryon and/or Lepton ASYMMETRY through CPT Violation

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



physics.indiana.edu

ONE POSSIBILITY:

particle-antiparticle mass differences

[Θ, H] ≠ 0 → $m \neq \overline{m}$

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

(**|m> = mass eigenstate**
Θ |m> = antimatter state)

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

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

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

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

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

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

Dolgov, Zeldovich
Dolgov (2009)

Assume dominant contributions to Baryon asymmetry from quarks-antiquarks

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

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Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

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

Dolgov, Zeldovich
Dolgov (2009)

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

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

Dolgov (2009)

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

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

Current bound for proton-anti proton mass diff.

$$\delta m_p < 7 \times 10^{-10}\, m_\mathrm{p}$$

$$C.L.\, 90\%$$

ASACUSA Coll. (2016)

$$\delta m_q \sim \delta m_p$$ → ***Too small $\beta^{T=0}$***

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

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

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

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

STANDARD MODEL EXTENSION

Kostelecky, Bluhm, Colladay, Lehnert, Potting, Russell *et al.*

LV only

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

LV & CPTV

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

LV only

Spontaneous Violation of Lorentz Symmetry

(*LV coefficients are v.e.v. of tensor-valued field quantities*)

Microscopic Origin of SME coefficients?

Several ``Geometry-induced” examples:

Microscopic Origin of SME coefficients?

$$\left[x^{\mu},\, x^{\nu}\right] = \theta^{\mu\nu} \neq 0$$

Several ``Geometry-induced" examples:

Non-Commutative Geometries LV only (*$H_{\mu\nu}$, $d_{\mu\nu}$, ...*)

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

Non-Commutative Geometries LV only

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

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

Microscopic Origin of SME coefficients?

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STANDARD MODEL EXTENSION

Kostelecky *et al.*

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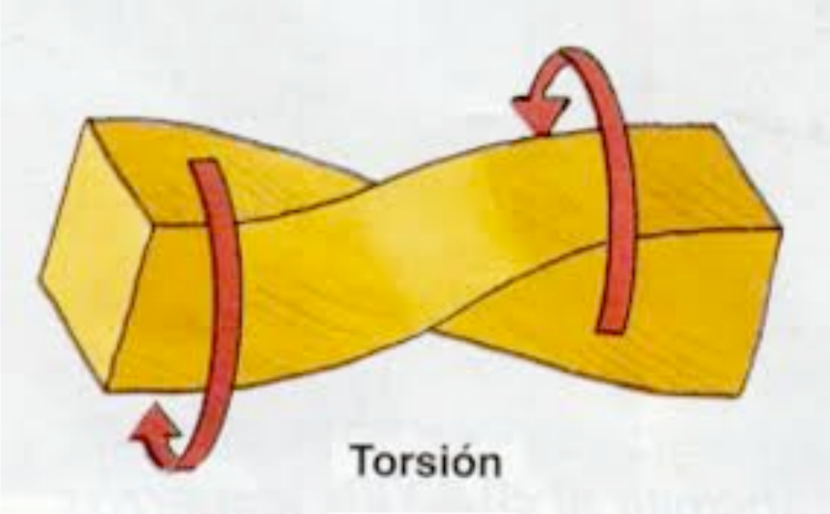
$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + e^{\nu} + \mathrm{i}f^{\nu}\gamma_5 + \frac{1}{2}g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

In particular, Space-times with



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

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

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

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

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

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

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

Gravitational covariant derivative including spin connection

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

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

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X

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

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

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

NEM & Sarben Sarkar, arXiv:1211.0968
John Ellis, NEM & Sarkar, arXiv:1304.5433
De Cesare, NEM & Sarkar arXiv:1412.7077
Bossingham, NEM & Sarkar, arXiv:1712.03312

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

Dirac Lagrangian (for concreteness, i

NEM & Sarben Sarkar, arXiv:1211.0968
John Ellis, NEM & Sarkar, arXiv:1304.5433
De Cesare, NEM & Sarkar arXiv:1412.7077
Bossingham, NEM & Sarkar, arXiv:1712.03312

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

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

Part IIa

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

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

NEM & Sarben Sarkar, arXiv:1211.0968
John Ellis, NEM & Sarkar, arXiv:1304.5433
De Cesare, NEM & Sarkar arXiv:1412.7077
Bossingham, NEM & Sarkar, arXiv:1712.03312

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

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

ROLE OF H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

4-DIM PART

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

$\kappa^2 = 8\pi G$

$\overline{R}(\overline{\Gamma})$

generalised curvature

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

Contorsion

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

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

4-DIM PART

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

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

$\kappa^2 = 8\pi G$

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

IN 4-DIM DEFINE DUAL OF H AS :

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

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

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

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

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

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

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

contorsion

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

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$$H_{cab}$$

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

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

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

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TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

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

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

contorsion

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

$$H_{cab}$$

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

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

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

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

When **db/dt = constant** → Torsion is constant

Covariant Torsion tensor

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

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

Constant

↓

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

constant ***B⁰*** $\propto \dot{b}$

When **db/dt = constant** → Torsion is constant

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

Covariant Torsion tensor

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

Antoniadis, Bachas, Ellis, Nanopoulos

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

Constant

↓

constant $\boldsymbol{B^0} \propto \dot{b}$

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

When **db/dt = constant** → Torsion is constant

Covariant Torsion tensor

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

Constant

↓

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

constant $B^0 \propto \dot{b}$

LV & CPTV

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

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

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

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

NB:

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

<0 | J^{05} |0> ≠ 0

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

Lagrangian :

vacuum energy

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

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

i = Standard Model fermionic species

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

higher derivative terms in strings

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

NB:

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

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

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

Eqs of motion for pseudoscalar:

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

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

i ≠ Majorana neutrinos

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 $T < T_c$**

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

weak torsion today, compatible with stringent experimental limits

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

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

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

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

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

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

Quite safe from stringent Experimental Bounds

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

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

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

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

CPTV Dispersion relations (B_0 = b_0)

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

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

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

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

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

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

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

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

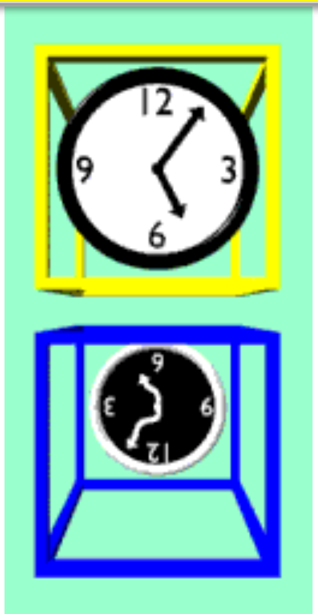
cf below...

CPT VIOLATION IN THE EARLY UNIVERSE

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

Bossingham, NEM & Sarkar arXiv:1712.03312
(Eur.Phys.J. C78 (2018) 10, 113)

Right-Handed Heavy Majorana Neutrinos



physics.indiana.edu

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

Through B-L conserving
Sphaleron processes
In the standard model

SM Extension with N extra right-handed neutrinos

Non SUSY νMSM

Boyarski, Ruchayskiy, Shaposhnikov

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

SM Extension with N extra right-handed neutrinos

Non SUSY $\nu\mathrm{MSM}$

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Yukawa couplings
Matrix (N=2 or 3)

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

SM Extension with N extra right-handed neutrinos

νMSM

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

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

Yukawa couplings Matrix (N=2 or 3)

Minkowski,Yanagida, Mohapatra, Senjanovic Sechter, Valle …

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

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

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

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

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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

CPTV Thermal

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

Early Universe
$T > 10^5$ GeV

CPT Violation

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

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

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

CPTV Thermal

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

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

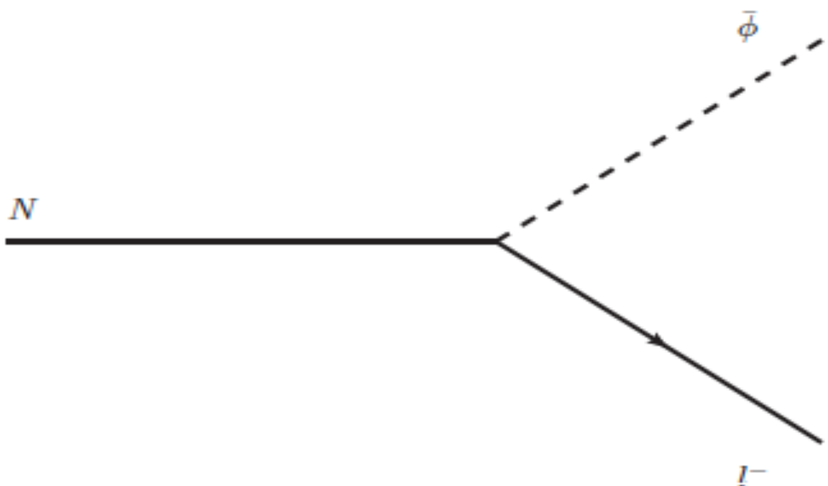
Early Universe
$T > 10^5$ GeV

CPT Violation

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

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

Produce Lepton asymmetry



CPTV Thermal

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

Constant H-torsion

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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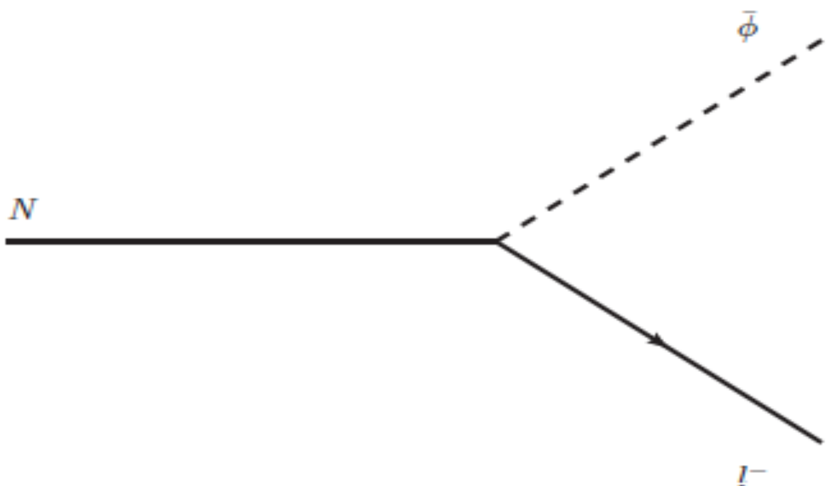
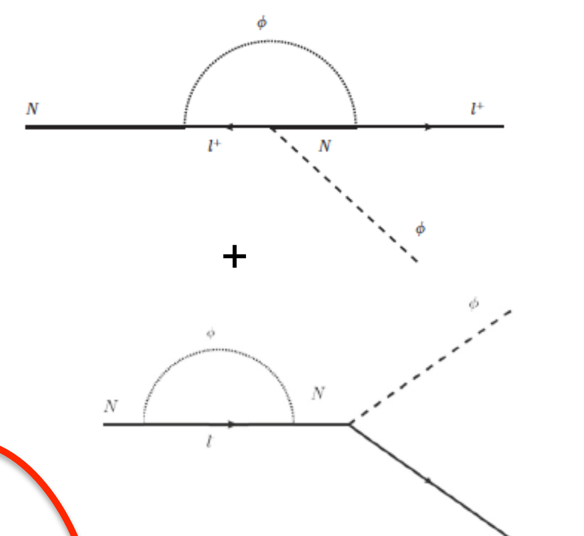


Contrast with one-loop conventional CPV Leptogenesis (in absence of H-torsion)



Fukugita, Yanagida,

CPTV Thermal

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Constant H-torsion

Early Universe
$T > 10^5$ GeV

CPT Violation

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Produce Lepton asymmetry

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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

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

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

* **Solving system of Boltzmann eqs**

Produce Lepton asymmetry

*

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

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

d.o.f.

assume standard cosmology

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

for one generation of RH heavy neutrino

$$\Omega = \sqrt{B_0^2 + m_N^2}\ .$$

Estimate: Total Lepton number asymmetry

$$\left(N \to \ell^- \phi^+, \nu\ \phi^0\right) - \left(N \to \ell^+ \phi^-, \overline{\nu}\ \phi^0\right)$$

via solving the appropriate system of **Boltzmann equations:**

CPTV Thermal

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

CPT Violation

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

Early Universe
$T > 10^5$ GeV

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

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

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

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

Produce Lepton asymmetry

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

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

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

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

CPTV Thermal

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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

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

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 Thermal

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

CPT Violation

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Constant H-torsion
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$$N_I \rightarrow H\nu,\ \bar{H}\bar{\nu}$$

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

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

Produce Lepton asymmetry

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental
Conditions Dependent

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

where

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

Observed Baryon Asymmetry
In the Universe (BAU)

Fukugita, Yanagida,

CPTV Thermal

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

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

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

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

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

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

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In the Universe (BAU)

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

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

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

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

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

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

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

Quite safe from stringent Experimental Bounds

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

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

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

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

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

4-DIM PART

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

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

IN 4-DIM DEFINE DUAL OF H AS :

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

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

e.g. May Require Fine tuning of Vacuum energy

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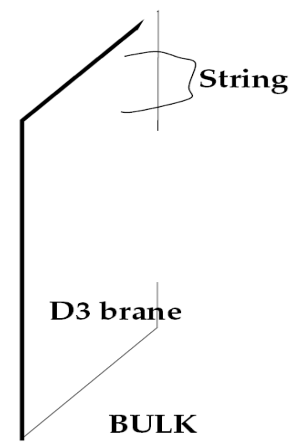
constant if $\dot{b} = \text{const}$



need to be cancelled by bulk contrib. in brane models

$\kappa^2 = 8\pi G$

IN 4-DIM DEFINE DUAL OF H AS :

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

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

Bossingham, NEM, Sarkar, to appear

Alternatively: B^0 approximately constant

Add chemical potential μ of fermions (e.g. quarks)

Eqs of motion for pseudoscalar:

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

Thermal (high T > m_N /10) average $\langle J^5_0 \rangle \simeq - \frac{2.722 g_q}{\pi^2} \mu B_0 T$

$$B_0(z) = B_0(z_D) \frac{\sqrt{z_D}(z_D + 3\epsilon)}{\sqrt{z}(z + 3\epsilon)}$$

$$0 < z = m_N / T \leq 10$$

$$\epsilon = \frac{2.722 g_q}{\pi} \frac{\mu m_N}{m_{pl}^2} \simeq 1.0062 \times 10^{-29}$$

Boltzmann equation solutions for **Leptogenesis**

$$B_0(z) \simeq (0.1399\,\mathrm{MeV}) z^{-3/2}$$

Consistent with current bounds

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

Part II(b)

Quantum-Gravity induced Decoherence & intrinsic CPT Violation

CPT VIOLATION

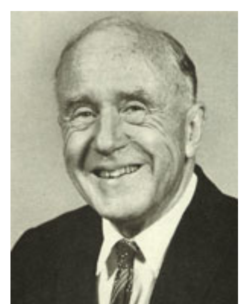
Conditions for the Validity of CPT Theorem

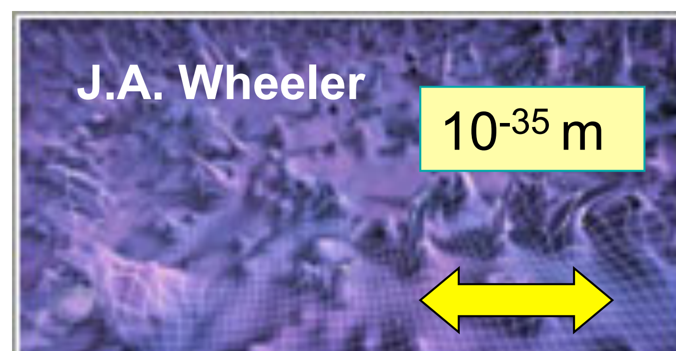
CPT Invariance Theorem :
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

This Talk

(ii)-(iv) Independent reasons for violation

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





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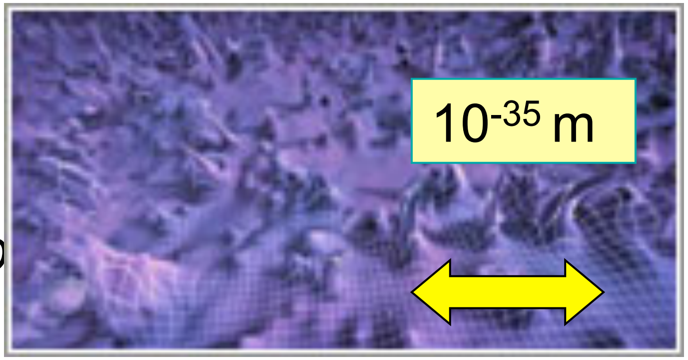
**Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…**

(ii)-(iv) Independent reasons for violation

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

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



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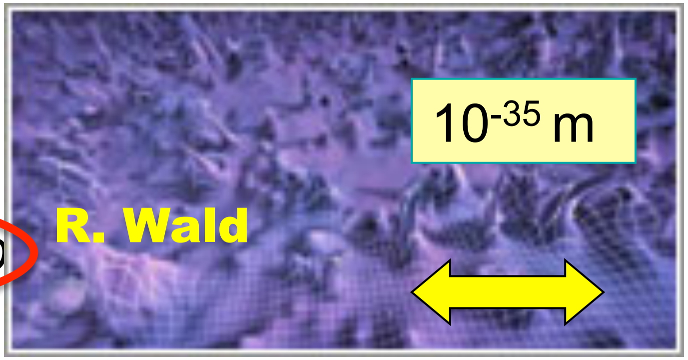

Decoherence & ill-defined CPT

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

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

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

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

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

QG May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined**

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

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

INCOMPATIBLE WITH DECOHERENCE !

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

Wald (79)

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

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

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

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

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

Wald (79)

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

Bernabeu, NEM, Papavassiliou (04),…

NB: Including conventional CPTV (θ) in the Hamiltonian

Bernabeu, Botella, NEM, Nebot (2018)

$$\mathbf{H}|B_H\rangle = \mu_H|B_H\rangle, \quad |B_H\rangle = p_H|B_d^0\rangle + q_H|\bar{B}_d^0\rangle,$$

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

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

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

ω-effect

CPTV in Hamiltonian

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

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Wald (79)

If CPT ill-defined →

tiny effect (if due to **Quantum Gravity decoherence**) → concept of antiparticle still well-defined,

but...

↓

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

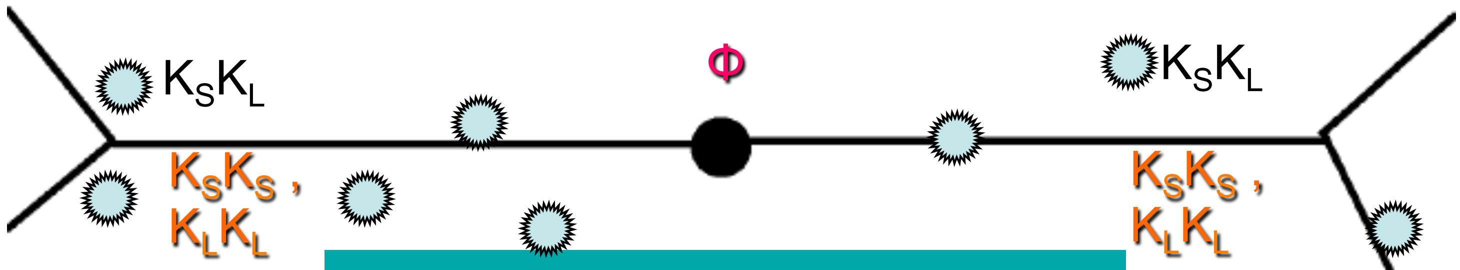
ω-effect

Part III(a)
ω-effect searches
in
Entangled Neutral Meson Systems

- Neutral mesons **no** longer **indistinguishable** particles, initial entangled state:

$$|i> \;=\; \mathcal{N}\Big[\Big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\Big) + \omega\Big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\Big)\Big]$$

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



IF CPT ILL-DEFINED (e.g. flavour violating (FV) D-particle Foam)

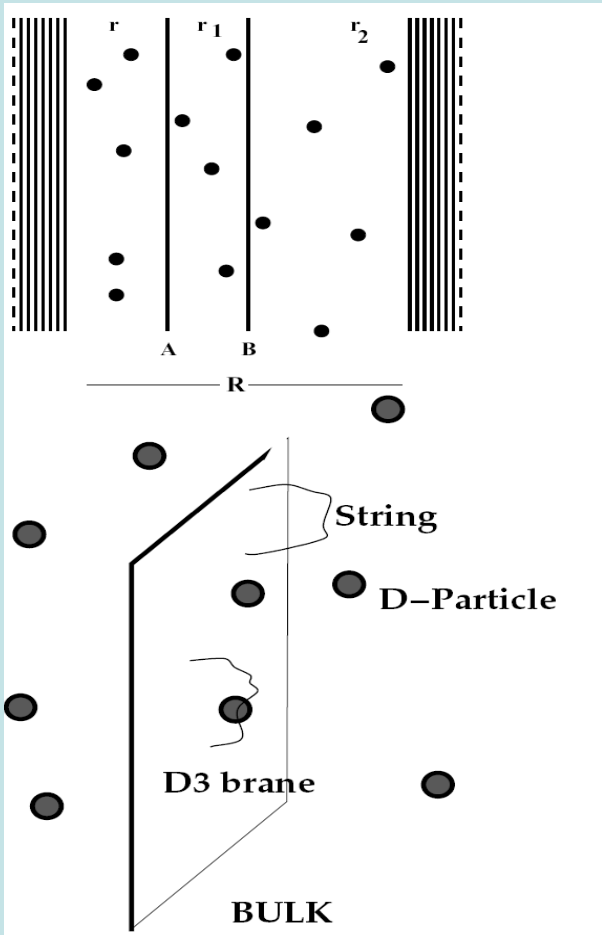
In a concrete model of space-time foam

$$|\omega|^2 \sim \frac{\zeta^2 \, k^4}{M_{\rm QG}^2 (m_1 - m_2)^2}, \; \Delta k = \zeta \, k \,(\text{particle momentum transfer})$$

If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for **$M_{QG} \sim 10^{18}$ GeV** the estimate for ω: **$|\omega| \sim 10^{-4}$ $|\zeta|$,** for $1 > |\zeta| > 10^{-2}$ (natural)
Not far from sensitivity of upgraded meson factories (e.g. **KLOE2**)

Bernabeu, Sarkar, NEM
Phys.Rev. D74 (2006) 045014

D-particle recoil and entangled Meson States



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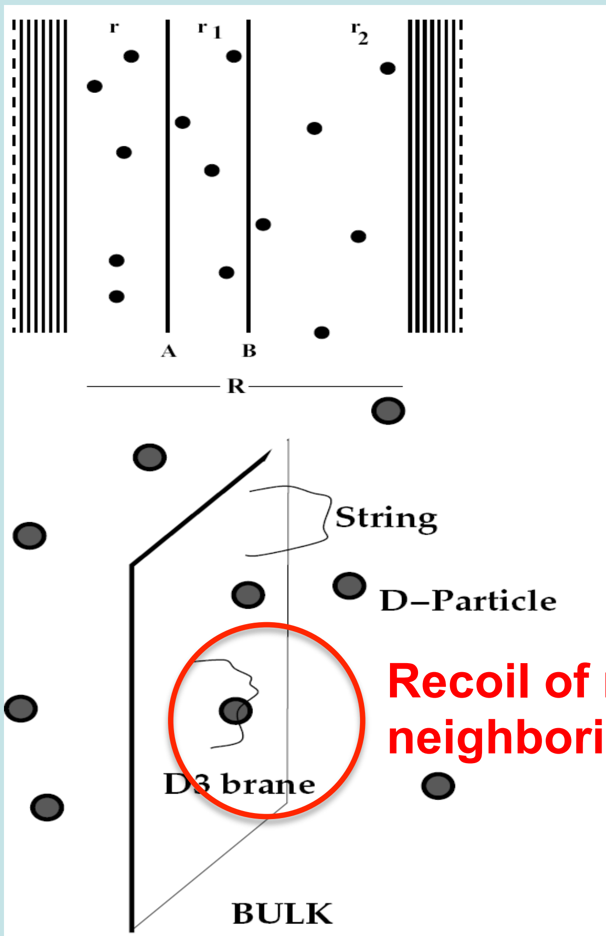

Gravitationally dressed quantum states viewed as quantum mechanically perturbed

propagation of matter string in curved background interaction with metric

Recoil of massive Defect distorts neighboring space-time on brane world

Bernabeu, Sarkar, NEM
Phys.Rev. D74 (2006) 045014

D-particle recoil and entangled Meson States

- Apply non-degenerate perturbation theory to construct "gravitationally dressed" states from $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)} \alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\left\langle \uparrow, k^{(i)}\right| \widehat{H_I} \left|k^{(i)},\downarrow\right\rangle^{(i)}}{E_2 - E_1}$$

$$\widehat{H} = -\left(r_1\sigma_1 + r_2\,\sigma_2\right)\widehat{k}$$

$$\left(g^{ab}\,\nabla_a\nabla_b - m^2\right)\Phi = 0$$

FLAVOUR FLIP
Perturbation due to recoil distortion of space-time

$$g_{0i} \propto \Delta k_i/M_P \otimes (\text{flavour} - \text{flip})$$

$$\Delta k_i = r_i k,\ << r_i >>= 0, << r_i r_j >>= \Delta\delta_{ij}$$

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$$\begin{aligned}
&|k,\uparrow\rangle_{QG}^{(1)}|-k,\downarrow\rangle_{QG}^{(2)} - |k,\downarrow\rangle_{QG}^{(1)}|-k,\uparrow\rangle_{QG}^{(2)} = \\
&|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} \\
&+|k,\downarrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}\left(\beta^{(1)}-\beta^{(2)}\right) + |k,\uparrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)}\left(\alpha^{(2)}-\alpha^{(1)}\right) \\
&+\beta^{(1)}\alpha^{(2)}|k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)}|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}
\end{aligned}$$

Bernabeu, Sarkar, NEM
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&+ |k,\downarrow\rangle^{(1)} |-k,\downarrow\rangle^{(2)} \left(\beta^{(1)} - \beta^{(2)}\right) + |k,\uparrow\rangle^{(1)} |-k,\uparrow\rangle^{(2)} \left(\alpha^{(2)} - \alpha^{(1)}\right) \\
&+ \beta^{(1)}\alpha^{(2)} |k,\downarrow\rangle^{(1)} |-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)} |k,\uparrow\rangle^{(1)} |-k,\downarrow\rangle^{(2)}
\end{aligned}$$

ω-effect

Bernabeu, Sarkar, NEM
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$$\begin{aligned}
&|k,\uparrow\rangle^{(1)}_{QG}|-k,\downarrow\rangle^{(2)}_{QG} - |k,\downarrow\rangle^{(1)}_{QG}|-k,\uparrow\rangle^{(2)}_{QG} = \\
&|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} \\
&+|k,\downarrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}\left(\beta^{(1)}-\beta^{(2)}\right) + |k,\uparrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)}\left(\alpha^{(2)}-\alpha^{(1)}\right) \\
&+\beta^{(1)}\alpha^{(2)}|k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)}|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}
\end{aligned}$$

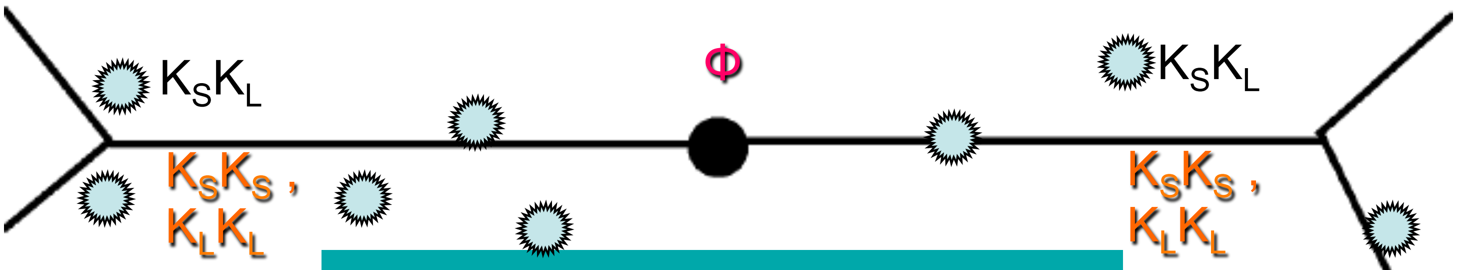
ω-effect

)

- Neutral mesons **no** longer **indistinguishable** particles, initial entangled state:

$$
\begin{aligned}
|i> &= \mathcal{N}\Big[\left(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\right) \\
&+ \omega\left(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\right)\Big]
\end{aligned}
$$

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



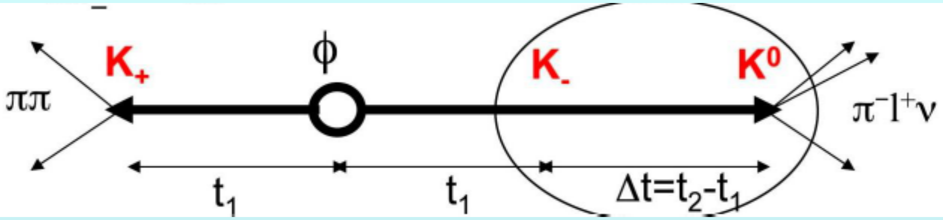
IF CPT ILL-DEFINED (e.g. flavour violating (FV) D-particle Foam)

In a concrete model of space-time foam

$$|\omega|^2 \sim \frac{\zeta^2\, k^4}{M_{\rm QG}^2 (m_1 - m_2)^2}, \Delta k = \zeta\, k \,(\text{particle momentum transfer})$$

If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for $M_{QG} \sim 10^{18}$ **GeV** the estimate for ω: **$|\, \omega \,| \sim 10^{-4}\ \ |\zeta|$,** for $1 > |\zeta| > 10^{-2}$ (natural)
Not far from sensitivity of upgraded meson factories (e.g. **KLOE2**)

Current Measurement Status of ω-effect



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

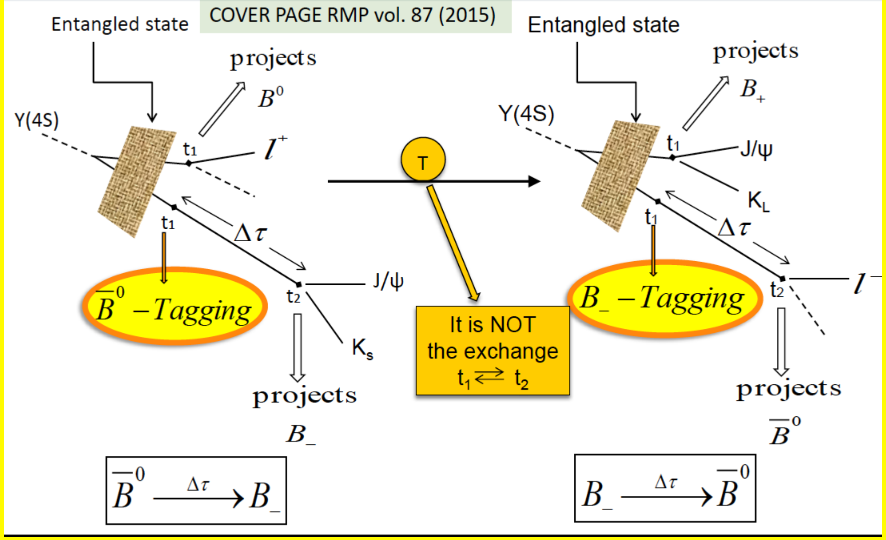
$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$

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

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

Neutral Kaons

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



Nautral B-mesons

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

$$-0.0084 \leq Re(\omega) \leq 0.0100 \qquad 95\%C.L$$

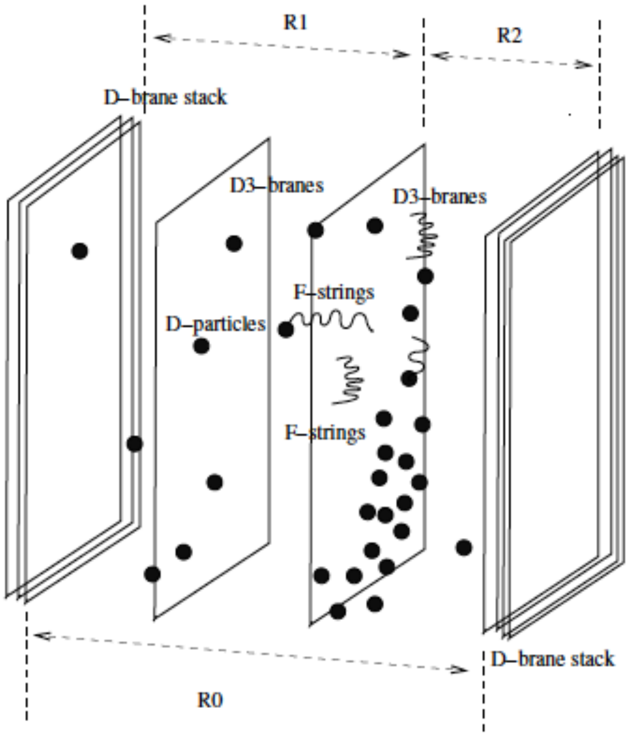
Novel signal from (f,g) ←→ (g,f)
(Bernabeu, Botella, NEM, Nebot
EPJC 77 (2017) 865)

$\text{Im}(\theta)$	$(0.99 \pm 1.98)10^{-2}$
$\text{Im}(\omega)$	$\pm(6.40 \pm 2.80)10^{-2}$

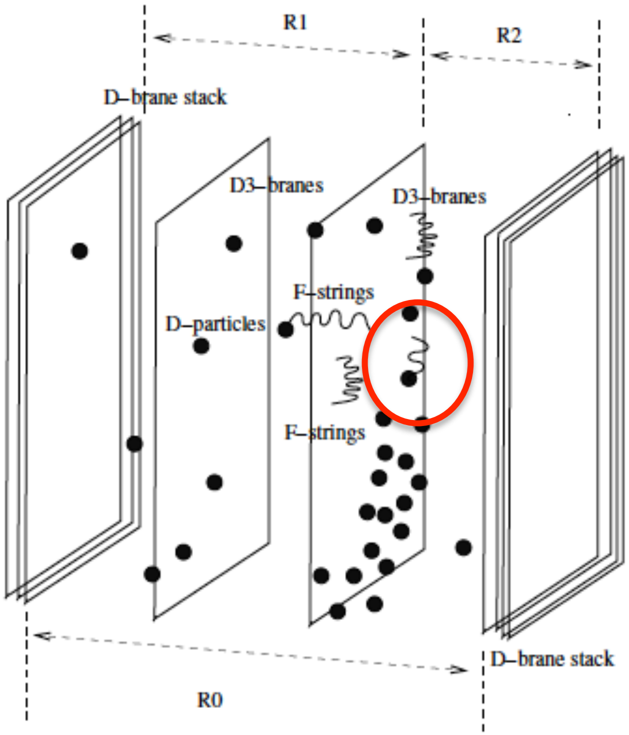
Part III(b)

Connection to Baryogenesis

Connection to Baryogenesis



Connection to Baryogenesis



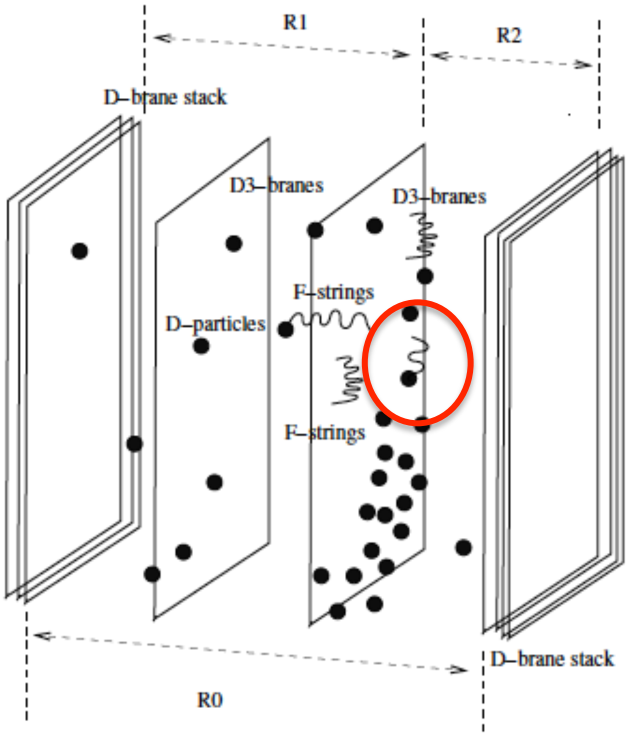
Effective metric due to LV foam medium

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = (\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu \ , \qquad h_{0i} = (u^a_{i\,\parallel}\sigma_a)$$

Stochastic media

$$\ll u_{i\,\parallel} \gg = 0 \ , \qquad \ll u_{i\,\parallel} u_{j\,\parallel} \gg = \sigma^2 \delta_{ij} \ .$$

Connection to Baryogenesis



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Energy differences between matter-antimatter

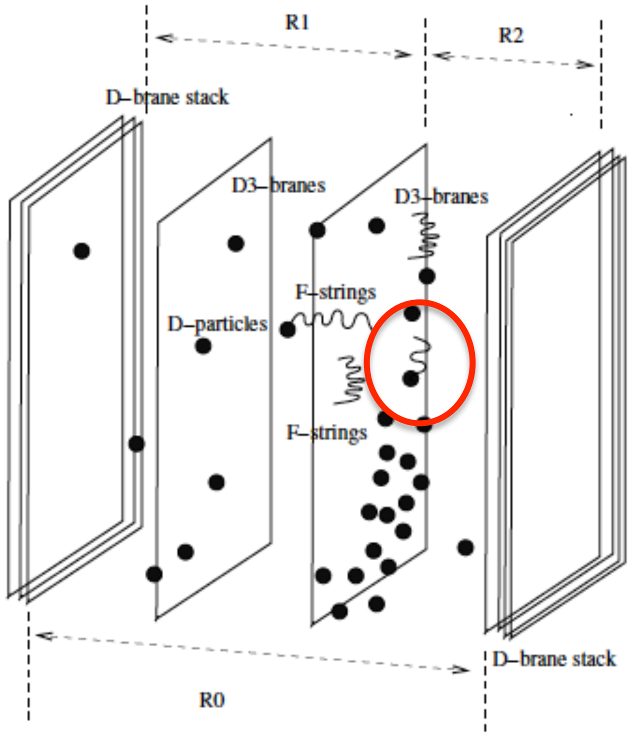
$$\ll E \gg = \sqrt{p^2 + m^2} + \frac{p^2\,\sigma^2}{2\,\sqrt{p^2+m^2}} - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

$$\ll \overline{E} \gg = \sqrt{p^2 + m^2} + \frac{p^2\,\sigma^2}{2\,\sqrt{p^2+m^2}} + \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

situation equivalent to an induced chemical potental

$$\frac{1}{2}\frac{M_s}{g_s}\sigma^2 \equiv \mu_{\rm CPTV} > 0$$

Connection to Baryogenesis



Effective metric due to LV foam medium

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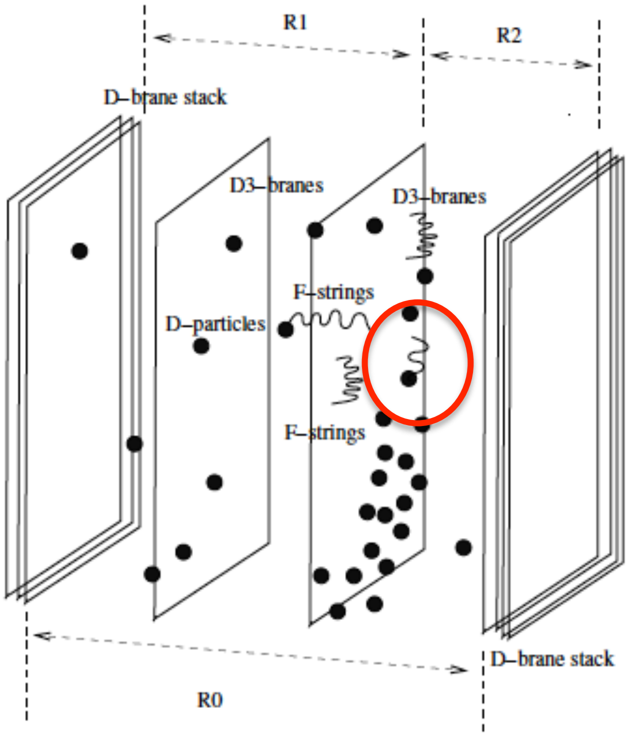
Baryon asymmetry in Universe

$$\Delta n_q \equiv \ n - \overline{n} = g_{d.o.f.} \int \frac{d^3p}{(2\pi)^3}[f(E,\mu) - f(\overline{E},\overline{\mu})]$$

$$\sim \frac{T^2}{2}\left(\frac{M_s\sigma^2}{g_s}\right)$$

Connection to Baryogenesis



Effective metric due to LV foam medium

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = (\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu \ , \qquad h_{0i} = (u^a_{i\,\|}\sigma_a)$$

Stochastic media

$$\ll u_{i\,\|} \gg = 0 \ , \qquad \ll u_{i\,\|} u_{j\,\|} \gg = \sigma^2 \delta_{ij} \ .$$

Energy differences between matter-antimatter

$$\ll E \gg = \sqrt{p^2 + m^2} + \frac{p^2\,\sigma^2}{2\,\sqrt{p^2+m^2}} - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

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Baryon asymmetry in Universe @ T_D

$$s \sim \frac{2\pi^2}{45} g_\star(T)\,T^3$$

$$\Delta n(T < T_D) = \frac{\Delta n_q}{s} \sim \frac{M_s}{g_s}\,\frac{45\,\sigma^2}{g_\star(T_D)\,T_D}$$

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

time ↓

Baryogenesis @ T_D : direct
or through
Leptogenesis first @ $T'_D > T_D$

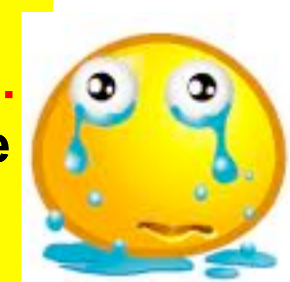
CPTV
$\{b^i(T_D)\}$ parameters
phenomenology?

scale with T (concrete model)

CPT Violation parameter(s)
$\{b^i_0\}$: current-epoch bounds (experiment)

$\{b^i(T_0)\} \leq \{b^i_0\}$

Construct microscopic models with strong CPT Violation in Early Universe (due to background fields or quantum gravity), but weak today… Fit with all available data… in particular current stringent constraints → scale back in time
Estimate in this way matter-antimatter asymmetry in Universe
Does it agree with the expected phenomenological value ?



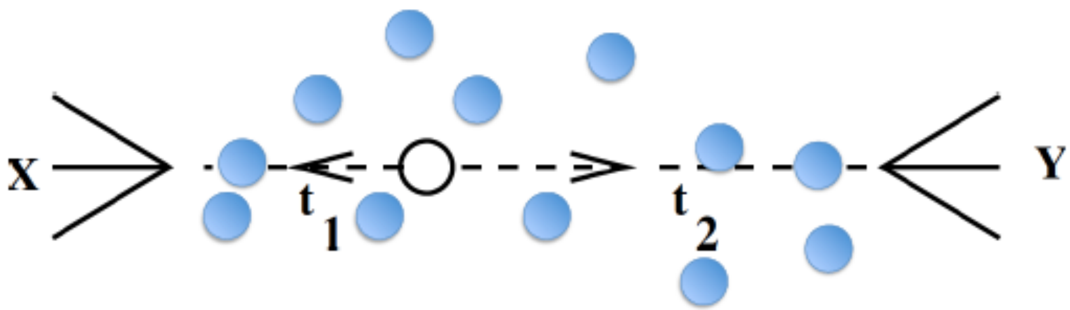
Φ-factories Current Limits → Baryogenesis?

$$|\omega|^2 = \frac{k^2\,\Delta_2}{(m_1 - m_2)^2} \qquad \Delta_2 = \Delta_L - \Delta_R = \xi^2\,\frac{k^2}{M_P^2}\,, \qquad 0 < \Delta_{R(L)} < 1$$

$$\langle r_i \rangle = 0,\ \langle r_i\, r_j \rangle = \Delta_{L(R)}\,\delta_{ij},$$

$$|\omega|^2 = \xi^2\,\frac{k^4}{(m_1 - m_2)^2\,M_P^2}$$

$$u_i = g_s r_i \frac{k_i}{M_s}$$



$$\sigma^2 = g_s^2\,\Delta_{\mathrm{R(L)}}\,\frac{k^2}{M_s^2}$$

Evolution of σ^2 with the **cosmic temperature T** can lead to interesting phenomenology on Baryogenesis models through such QG effects by tests of QGD CPTV ω-effect in current era :

Scaling with Temperature T $k \sim \sqrt{3T\,m_b}$ $\qquad \sigma^2 \sim 3g_s^2\,\frac{m_b T}{M_s^2}\,\Delta$ $\qquad \langle r^2 \rangle = \Delta$, $\langle r \rangle = 0$

for low T < m_b ~ GeV $\qquad 0 < \Delta < 1$

T-dependence of Δ depends on details of QG model

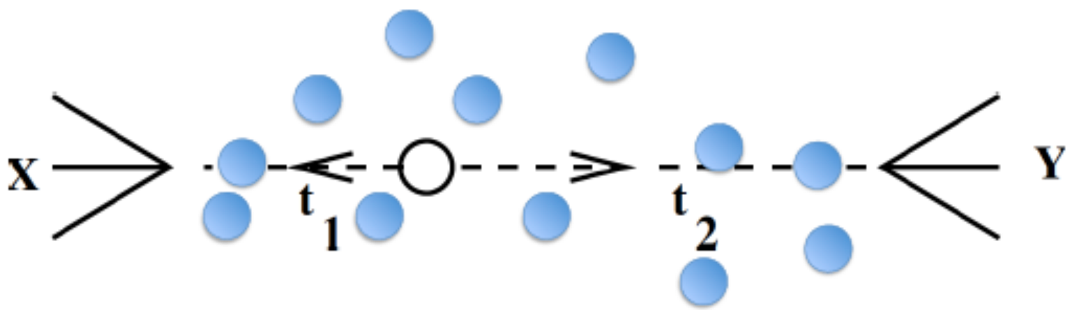
Φ-factories Current Limits → Baryogenesis?

$$|\omega|^2 = \frac{k^2 \Delta_2}{(m_1 - m_2)^2} \qquad \Delta_2 = \Delta_L - \Delta_R = \xi^2 \frac{k^2}{M_P^2}, \qquad 0 < \Delta_{R(L)} < 1$$

$$\langle r_i \rangle = 0, \ \langle r_i r_j \rangle = \Delta_{L(R)} \delta_{ij},$$

$$|\omega|^2 = \xi^2 \frac{k^4}{(m_1 - m_2)^2 M_P^2}$$

$$u_i = g_s r_i \frac{k_i}{M_s}$$



$$\sigma^2 = g_s^2 \Delta_{\mathrm{R(L)}} \frac{k^2}{M_s^2}$$

Evolution of **σ^2** with the **cosmic temperature T** can lead to interesting phenomenology on Baryogenesis models through such QG effects by tests of QGD CPTV ω-effect in current era :

Scaling with Temperature T

$k \sim T$

for high $T > m_b \sim$ GeV

$$\sigma^2 = g_s^2 \frac{T^2}{M_s^2} \Delta$$

$$0 < \Delta < 1$$

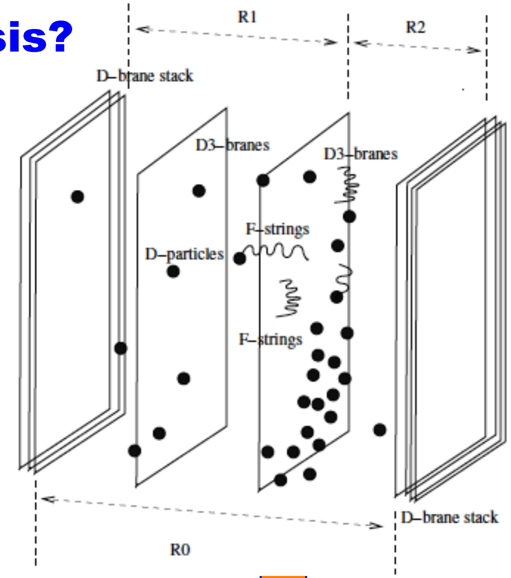
$$\langle r^2 \rangle = \Delta$$

$$\langle r \rangle = 0$$

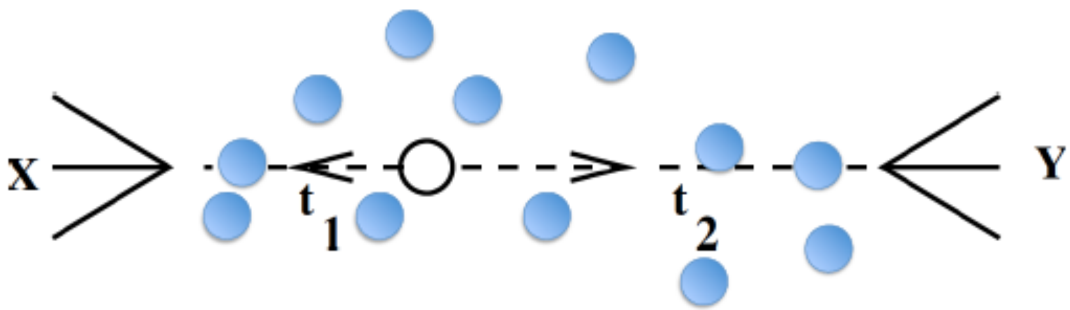
T-dependence of Δ depends on details of QG model

Φ-factories Current Limits → Baryogenesis?

$$|\omega|^2 = \frac{k^2\,\Delta_2}{(m_1 - m_2)^2} \qquad \Delta_2 = \Delta_L - \Delta_R = \xi^2 \frac{k^2}{M_P^2}$$



$$|\omega|^2 = \xi^2 \frac{k^4}{(m_1 - m_2)^2\, M_P^2} \qquad \langle r_i \rangle = 0,\ \langle r_i\, r_j \rangle$$



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Evolution of σ^2 with the **cosmic temperature T** can lead to interesting phenomenology on Baryogenesis models through such QG effects by tests of QGD CPTV ω-effect in current era :

Scaling with Temperature T $\quad k \sim T \quad \sigma^2 = g_s^2 \frac{T^2}{M_s^2} \Delta \quad \langle r^2 \rangle = \Delta \quad \langle r \rangle = 0$

D-particles in brane models if dark-matter like:

$$\Delta \propto n_{d-particles-density} \sim T^3$$

Neutral Kaons in Φ-factories

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

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

$$|m_1 - m_2| \sim 10^{-15}\ \mathrm{GeV} \qquad k \sim 1\ \mathrm{GeV}$$

$$\Delta_{\mathrm{today}} < 10^{-38}$$

$$|\omega|^2 \sim \frac{k^2}{|m_1 - m_2|^2}\,\Delta$$

$$\langle r^2 \rangle = \Delta \qquad \langle r \rangle = 0$$

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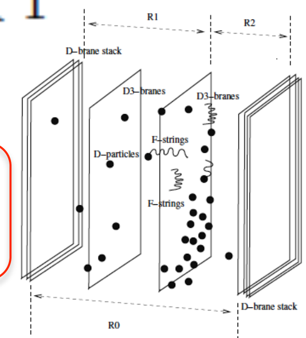
D-particle induced Baryogenesis

Scaling with Temperature T in D-particle foam model

D-particles = dark-matter like

$$\Delta \propto n_{d-particles-density} \sim T^3$$



$$\Delta n(T < T_D) = \frac{\Delta n_q}{s} \sim \frac{M_s}{g_s}\,\frac{45\,\sigma^2}{g_\star(T_D)\,T_D}$$

e.g. for quarks $T_D \approx 100$ GeV

$$\Delta n(T = 100\,\mathrm{GeV}) \sim 10^{-10}$$

$$\sigma^2 = g_s^2\,\frac{T^2}{M_s^2}\,\Delta \quad \Rightarrow \quad \Delta n \sim 0.45\,\frac{g_s}{M_s}\,T_D\,\Delta(T_D)$$

$T_D \sim 100$ GeV

$$\frac{\Delta_{100\ \mathrm{GeV}}}{\Delta_{\mathrm{today}}} \sim \frac{M_s}{g_s}\,\frac{1}{1.3\,\mathrm{GeV}} \times 10^{28} \sim \left(\frac{T = 100\,\mathrm{GeV}}{T^0_{\mathrm{CMB}} = 0.2\,\mathrm{meV}}\right)^3 \sim 10^{44}$$

$$\Rightarrow \quad \frac{M_s}{g_s} \sim 4.5 \times 10^{17}\ \mathrm{GeV}$$

Consistent perturbative string model !

Neutral Kaons in Φ-factories

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

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

$$|\omega|^2 \sim \frac{k^2}{|m_1 - m_2|^2}\,\Delta$$

$\langle r^2 \rangle$ … 0

$$|m_1 - m_2| \sim 10^{-15}\ \mathrm{GeV} \qquad k \sim 1\ \mathrm{GeV}$$

… < 1

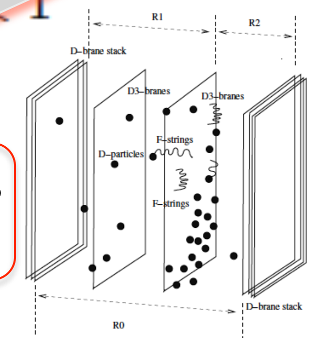
$$\Delta_{\mathrm{today}} < 10^{-38}$$

NB: RHN leptogenesis also consistent

D-particle induced Baryogenesis

Scaling with Temperature T in D-particle foam model

$$\Delta \ldots \text{…cles-density} \sim T^3$$



D-particles = dark-matter …

$$\Delta n(T < T_{\ldots}) \ldots \frac{\ldots}{g_s}\,\frac{45\,\sigma^2}{g_\star(T_D)\,T_D}$$

e.g. for quarks $T_D \approx 100$ GeV

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Consistent perturbative string model !

V. CONCLUSIONS

- CPT Violation (CPTV) due to (strong) quantum fluctuations in space-time at early eras or LV early Universe Geometries (with background flux fields)

  is a possibility and may explain the observed matter-antimatter asymmetry in the cosmos, consistently with current-era bounds of CPTV

- One framework for early universe CPTV: Standard Model Extension (SME)

- A string-inspired model of the Early Universe entailing CPT and Lorentz Violation due to Kalb-Ramond-axion- modified background geometries – Consistent phenomenology in current era

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

- **Quantum Gravity Flcts in early Universe might be strong → Decoherence of quantum matter**

  CPT operator in effective theory ill-defined

  → affects EPR entangled states → current bounds from meson factories → explore link with early Universe in concrete models of space-time foam from string/brane theory

V. CONCLUSIONS

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  …to exp… …with Early Universe C… …ion etc

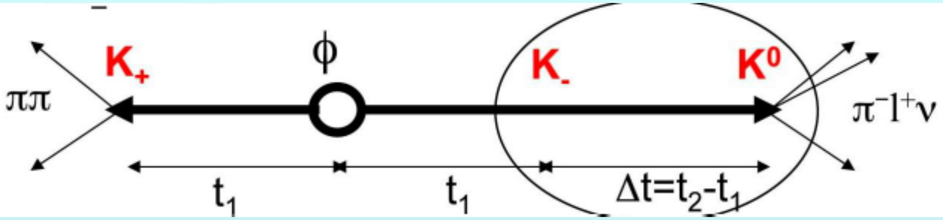
- Quan… …n early Universe might be strong → Decoh… …antum matter

  CPT ope… …n effective theory ill-defined → affects EPR entangled states → current bounds from meson factories → explore link with early Universe in concrete models of space-time foam from string/brane theory

Thank you !

SPARES

Current Measurement Status of ω-effect



KLOE result: PLB 642(2006) 315
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$$|\omega| < 1.0 \times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$

Neutral Kaons

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

ω-Effect & Intensities

$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt \, |A(\pi^+\pi^-, \pi^+\pi^-)|^2 = |\langle \pi^+\pi^- | K_S\rangle|^4 |\mathcal{N}|^2 |\eta_{+-}|^2 \Big[I_1 + I_2 + I_{12} \Big]$$

$$I_1(\Delta t) = \frac{e^{-\Gamma_S \Delta t} + e^{-\Gamma_L \Delta t} - 2 e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \cos(\Delta M \Delta t)}{\Gamma_L + \Gamma_S}$$

$$I_2(\Delta t) = \frac{|\omega|^2}{|\eta_{+-}|^2} \frac{e^{-\Gamma_S \Delta t}}{2\Gamma_S}$$

enhancement factor due to CP violation compared with, eg, B-mesons

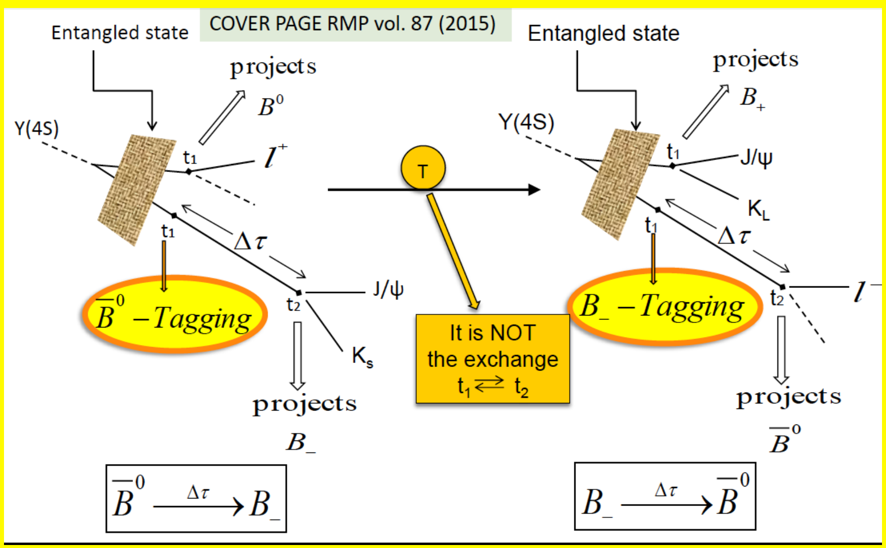
$$I_{12}(\Delta t) = -\frac{4}{4(\Delta M)^2 + (3\Gamma_S + \Gamma_L)^2} \frac{|\omega|}{|\eta_{+-}|} \times$$
$$\Big[2\Delta M \Big(e^{-\Gamma_S \Delta t} \sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \sin(\phi_{+-} - \Omega + \Delta M \Delta t) \Big)$$
$$-(3\Gamma_S + \Gamma_L) \Big(e^{-\Gamma_S \Delta t} \cos(\phi_{+-} - \Omega) - e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \cos(\phi_{+-} - \Omega + \Delta M \Delta t) \Big) \Big]$$

$\Delta M = M_S - M_L$ and $\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}}$.

NB: sensitivities up to $|\omega| \sim 10^{-6}$ in ϕ factories, due to enhancement by $|\eta_{+-}| \sim 10^{-3}$ factor.

Bernabeu, NEM, Papavassiliou (PRL 04), …

Current Measurement Status of ω-effect



Neutral B-mesons

Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 087)

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

Current Measurement Status of ω-effect

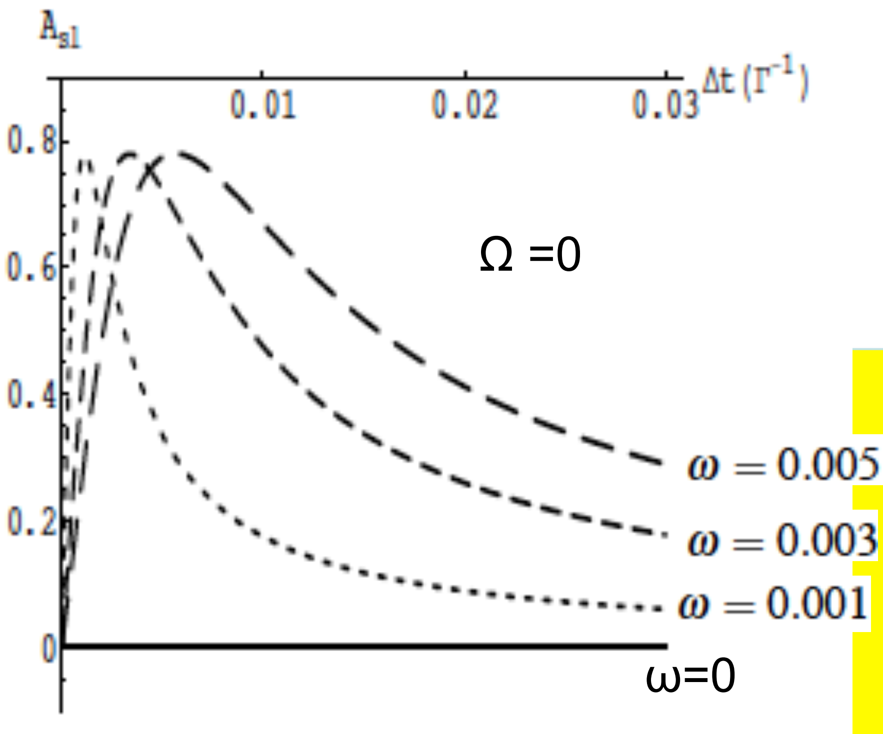
$$A_{sl} = \left.\frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)}\right|_{\omega=0} = 4\frac{Re(\varepsilon)}{1+|\varepsilon|^2} + \mathcal{O}((Re\,\varepsilon)^2)$$

→ $\omega = |\omega| e^{i\Omega} \neq 0$

↓

$$\Delta t_{peak} = \frac{1}{\Gamma} 1.12 |\omega|$$

$$A_{sl}(\Delta t_{peak}) = 0.77 \cos(\Omega)$$



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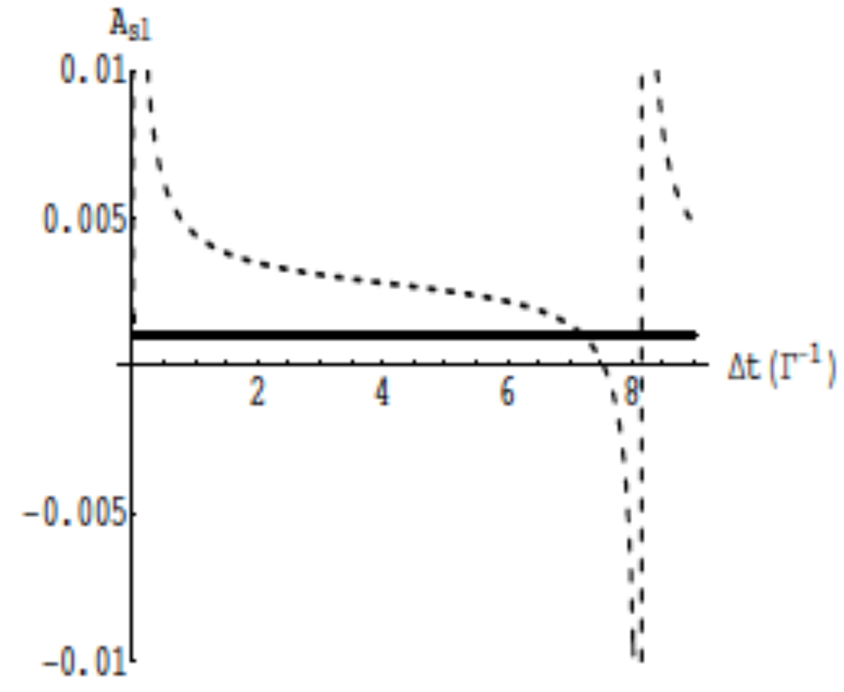
Current Measurement Status of ω-effect

$$A_{sl} = \left. \frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)} \right|_{\omega=0} = 4\frac{Re(\varepsilon)}{1+|\varepsilon|^2} + \mathcal{O}((Re\,\varepsilon)^2)$$

$\omega = |\omega| e^{i\Omega} \neq 0$

$$\Delta m \Delta t \approx 2\pi \; (\Delta t \approx 8.2\Gamma^{-1}),$$



Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 087)

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

Neutral B-mesons

Current Measurement Status of ω-effect

$\Delta\Gamma = 0$

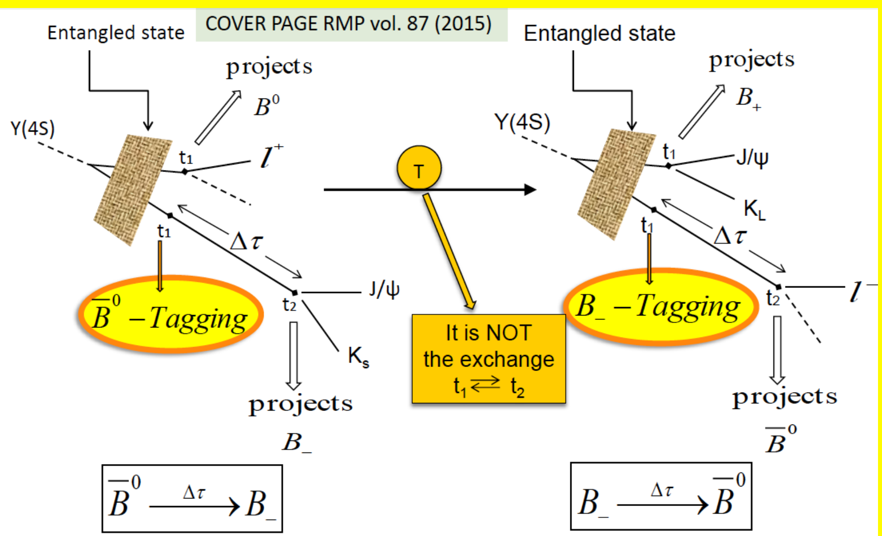
$$I(f,g;t) = \int_0^\infty dt_0\, |\langle f, t_0; g, t+t_0 | T | \Psi_0 \rangle|^2 = \frac{\langle \Gamma_f \rangle \langle \Gamma_g \rangle}{\Gamma} e^{-\Gamma t} \{ \mathscr{C}_h^\omega[f,g] + \mathscr{C}_c^\omega[f,g] \cos(\Delta M t) + \mathscr{S}_c^\omega[f,g] \sin(\Delta M t) \}$$

Observables

$$C[f,g] = \frac{\mathscr{C}_c^\omega[f,g]}{\mathscr{C}_h^\omega[f,g]} \quad \text{and} \quad S[f,g] = \frac{\mathscr{S}_c^\omega[f,g]}{\mathscr{C}_h^\omega[f,g]},$$

$$C[\ell^\pm, g] - C[g, \ell^\pm] = \frac{1}{1+(x/2)^2} \{ [x S_g \mp 2(C_g^2 - 1) \mp x C_g S_g] \mathrm{Re}\,(\omega) + x R_g [C_g \pm 1] \mathrm{Im}\,(\omega) \}$$

$$x = \frac{\Delta M}{\Gamma} \simeq 0.77$$



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Novel signal from (f,g) ←→ (g,f)

(Bernabeu, Botella, NEM, Nebot (2018))

$\mathrm{Im}\,(\theta)$	$(0.99 \pm 1.98)10^{-2}$
$\mathrm{Im}\,(\omega)$	$\pm(6.40 \pm 2.80)10^{-2}$

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$$\mathrm{S}[\ell^\pm, g] + \mathrm{S}[g, \ell^\pm] = \frac{1}{1+(x/2)^2} \{ [x C_g \pm x(1-S_g^2) \mp 2 C_g S_g] \mathrm{Re}(\omega) + R_g [x S_g \mp 2] \mathrm{Im}(\omega) \}.$$

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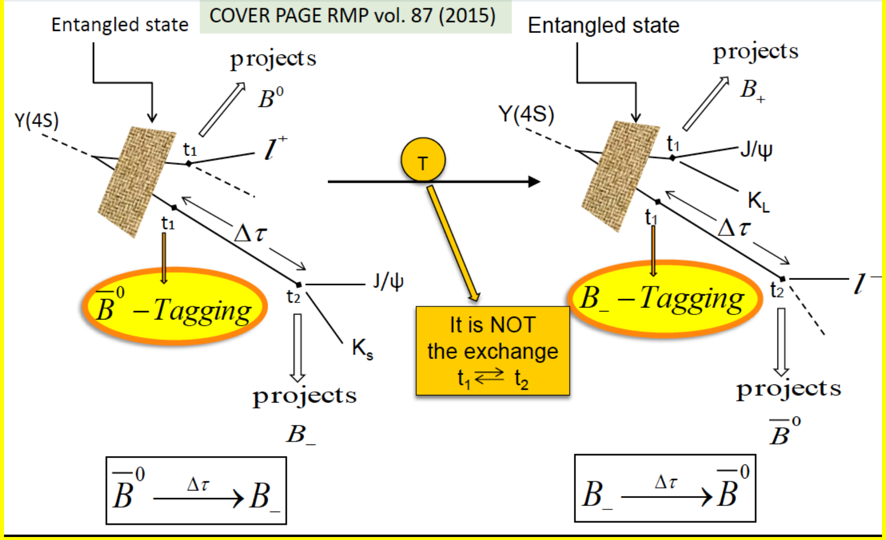

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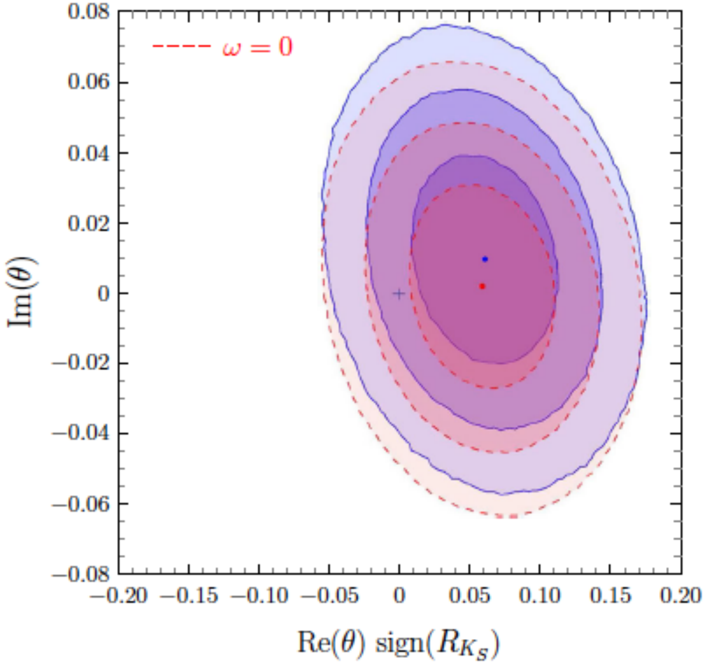

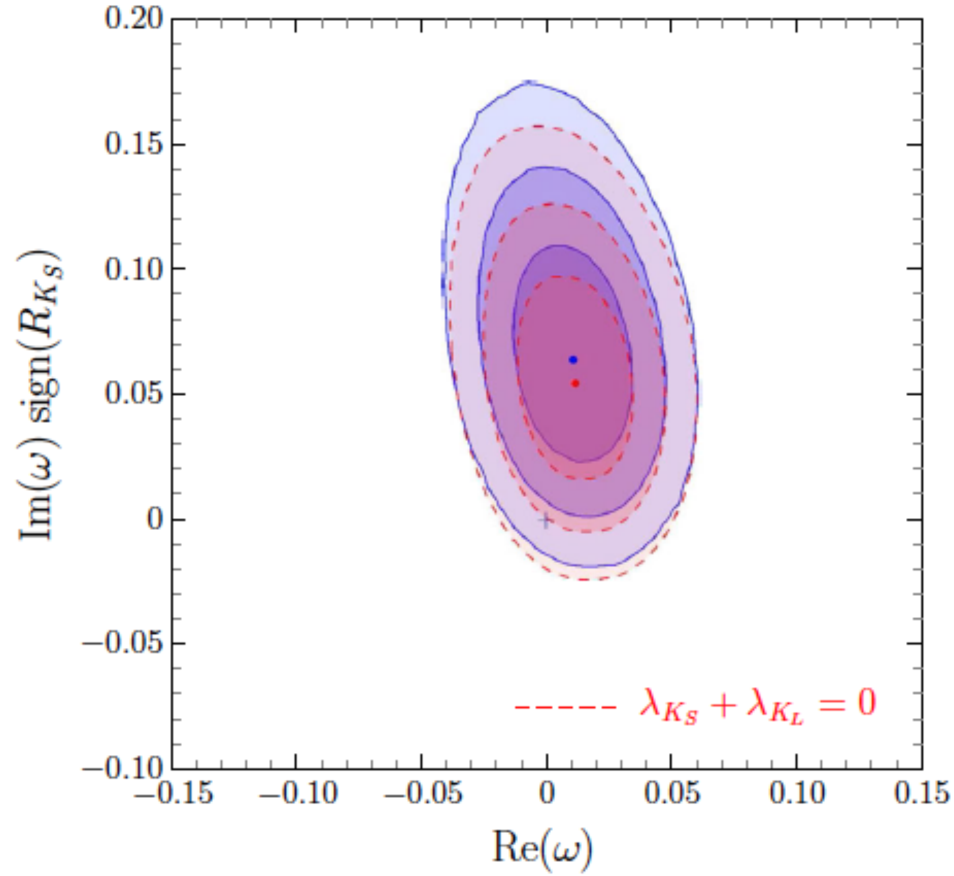

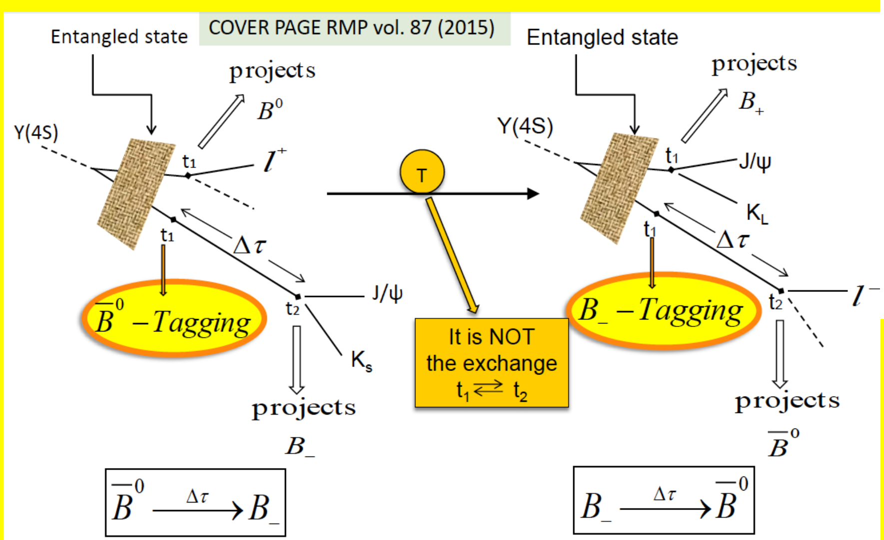

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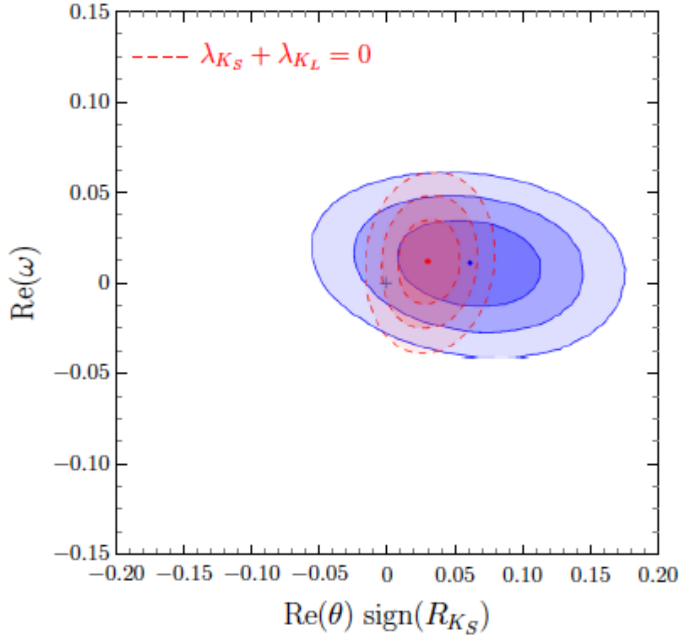
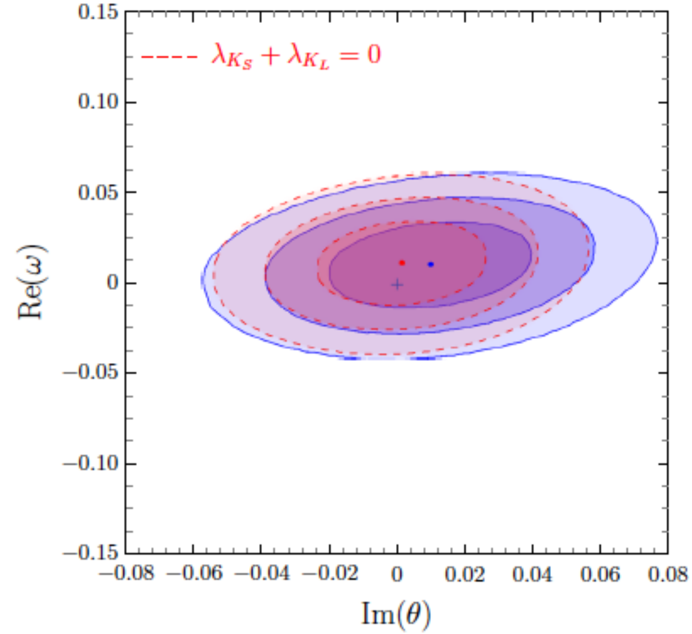
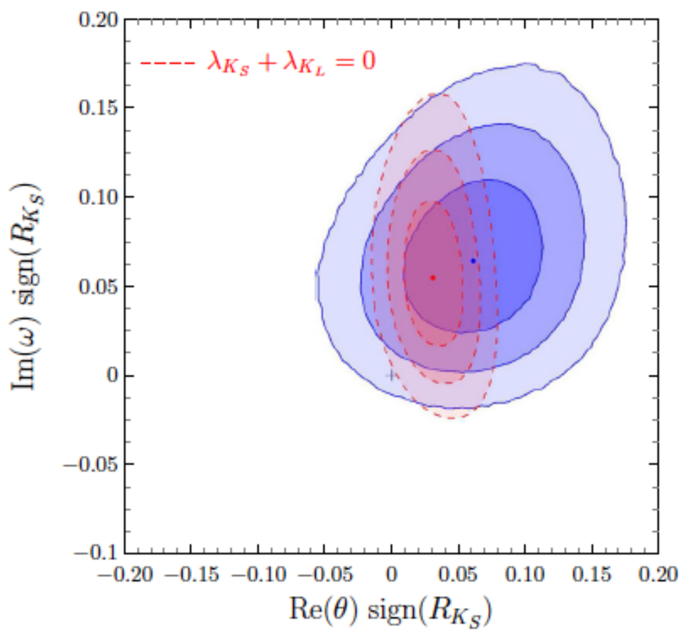
Correlations among ω & θ



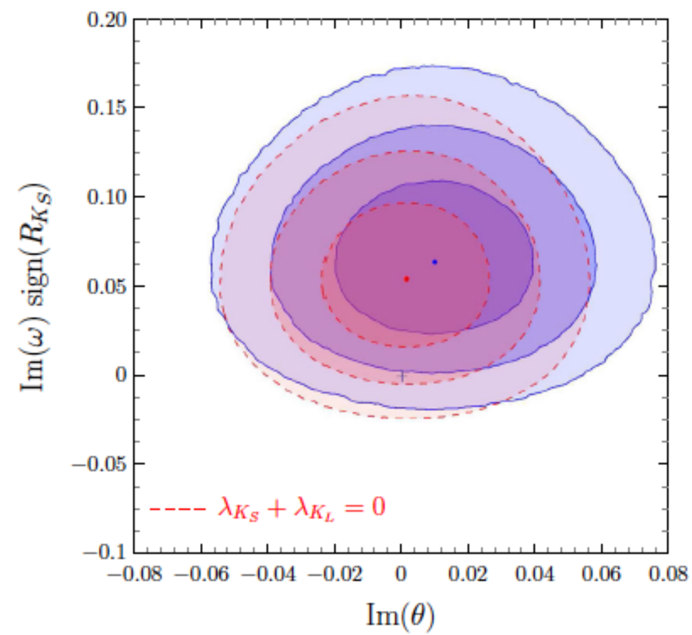
(a) Re (ω) vs. Re (θ).



(b) Re (ω) vs. Im (θ).



(c) Im (ω) vs. Re (θ).



(d) Im (ω) vs. Im (θ).

* **Proper Treatment through solving Boltzmann Eqs.**

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

Boltzmann equation in presence of CPTV & LV Background B_0

RHN Helicity specific λ_r :

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

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

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

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

*

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

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

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

⚠

*

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$\lambda\, I$

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

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

$$Y_x = n_x/s$$

$$z = m_N/T$$

Y^{eq} : Thermal Equilibrium Distributions (at high T)

Standard Cosmology at early eras (radiation era) $T \sim a^{-1} \Rightarrow s \sim T^3, \quad a \sim t^{1/2}$

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

Averaged (over helicities) heavy (right-handed) neutrino abundance $\bar{Y}_N \equiv \frac{Y_N^{(-)} + Y_N^{(+)}}{2};$

Lepton Asymmetry: $\mathcal{L} = \bar{Y}_{l^-} - \bar{Y}_{l^+}$

$$\mathcal{L} \equiv Y_{l^-}^{(-)} - Y_{l^+}^{(+)} = 2\left[\bar{Y}_{l^-} - \bar{Y}_{l^+}\right],$$

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

*

Proper Treatment through solving Boltzmann Eqs.

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

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

$$\frac{\Delta L^{TOT}}{s} \equiv \frac{Y_{l^-}^{(-)} - Y_{l^+}^{(+)}}{Y_{l^-}^{(-)} + Y_{l^+}^{(+)}} = \frac{\mathcal{L}}{2\bar{Y}_N}$$

* Proper Treatment through solving Boltzmann Eqs.

Heavy (right-handed) neutrino abundance

$$
\begin{aligned}
zHs\frac{dY_N^{(\lambda)}}{dz} - \lambda I = -\Bigg\{ & \left[\gamma^{eq,(\lambda)}(N \to l^- h^+)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}} - \gamma^{eq,(\lambda)}(l^- h^+ \to N)\frac{Y_{l^-}^{(\lambda)}}{Y_{l^-}^{(\lambda),eq}}\frac{Y_{h^+}}{Y_{h^+}^{eq}}\right] \\
& + \left[\gamma^{eq,(\lambda)}(N \to l^+ h^-)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}} - \gamma^{eq,(\lambda)}(l^+ h^- \to N)\frac{Y_{l^+}^{(\lambda)}}{Y_{l^+}^{(\lambda),eq}}\frac{Y_{h^-}}{Y_{h^-}^{eq}}\right] \\
& + \left[\gamma^{eq,(\lambda)}(N \to \nu h^0)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}} - \gamma^{eq,(\lambda)}(\nu h^0 \to N)\frac{Y_\nu^{(\lambda)}}{Y_\nu^{(\lambda),eq}}\frac{Y_{h^0}}{Y_{h^0}^{eq}}\right] \\
& + \left[\gamma^{eq,(\lambda)}(N \to \bar{\nu} h^0)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}} - \gamma^{eq,(\lambda)}(\bar{\nu} h^0 \to N)\frac{Y_{\bar{\nu}}^{(\lambda)}}{Y_{\bar{\nu}}^{(\lambda),eq}}\frac{Y_{h^0}}{Y_{h^0}^{eq}}\right]\Bigg\}.
\end{aligned}
$$

* Proper Treatment through solving Boltzmann Eqs.

Heavy (right-handed) neutrino abundance

$$zHs\frac{dY_N^{(\lambda)}}{dz} - \lambda I = -\left\{\left[\gamma^{eq,(\lambda)}(N \to l^- h^+)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}} - \gamma^{eq,(\lambda)}(l^- h^+ \to N)\frac{Y_{l^-}^{(\lambda)}}{Y_{l^-}^{(\lambda),eq}}\frac{Y_{h^+}}{Y_{h^+}^{eq}}\right]\right.$$

$$\gamma^{eq,(-)}(N \leftrightarrow l^- h^+) = \gamma^{eq,(-)}(N \leftrightarrow \nu h^0)$$

$$\gamma^{eq,(+)}(N \leftrightarrow l^+ h^-) = \gamma^{eq,(+)}(N \leftrightarrow \bar{\nu} h^0)$$

$$\left.+\left[\gamma^{eq,(\lambda)}(N \to \bar{\nu} h^0)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}} - \gamma^{eq,(\lambda)}(\bar{\nu} h^0 \to N)\frac{Y_{\bar{\nu}}^{(\lambda)}}{Y_{\bar{\nu}}^{(\lambda),eq}}\frac{Y_{h^0}}{Y_{h^0}^{eq}}\right]\right\}.$$

* **Proper Treatment through solving Boltzmann Eqs.**

Heavy (right-handed) neutrino abundance

$$zHs\frac{dY_N^{(\lambda)}}{dz}-\lambda I=-\Bigg\{\bigg[\gamma^{eq,(\lambda)}(N\to l^-h^+)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}}-\gamma^{eq,(\lambda)}(l^-h^+\to N)\frac{Y_{l^-}^{(\lambda)}}{Y_{l^-}^{(\lambda),eq}}\frac{Y_{h^+}}{Y_{h^+}^{eq}}\bigg]$$

$$\gamma^{eq,(-)}(N\leftrightarrow l^-h^+)=\gamma^{eq,(-)}(N\leftrightarrow \nu h^0)$$

$$\gamma^{eq,(+)}(N\leftrightarrow l^+h^-)=\gamma^{eq,(+)}(N\leftrightarrow \bar\nu h^0)$$

$$+\bigg[\gamma^{eq,(\lambda)}(N\to\bar\nu h^0)\frac{Y_N^{(\lambda)}}{Y_N^{(\lambda),eq}}-\gamma^{eq,(\lambda)}(\bar\nu h^0\to N)\frac{Y_{\bar\nu}^{(\lambda)}}{Y_{\bar\nu}^{(\lambda),eq}}\frac{Y_{h^0}}{Y_{h^0}^{eq}}\bigg]\Bigg\}.$$

Lepton Asymmetry:

$$2zHs\frac{d\mathcal{L}}{dz}+4I=-2\bigg[\gamma^{eq,(-)}(N\leftrightarrow l^-h^+)\bigg\{\frac{Y_{l^-}^{(-)}}{Y_{l^-}^{(-),eq}}-\frac{Y_N^{(-)}}{Y_N^{(-),eq}}\bigg\}$$

$$-\gamma^{eq,(+)}(N\leftrightarrow l^+h^-)\bigg\{\frac{Y_{l^+}^{(+)}}{Y_{l^+}^{(+),eq}}-\frac{Y_N^{(+)}}{Y_N^{(+),eq}}\bigg\}\bigg]$$

*

$$\frac{\Delta L^{TOT,\text{complete}}}{s} \simeq (0.016 - 0.019)\,\frac{B_0}{m_N}$$

at freezeout temperature

$$T = T_D : \quad m_N / T_D \simeq (1.44 - 1.77)$$

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

d.o.f.

assume standard cosmology

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

for one generation of RH heavy neutrino

$$\Omega = \sqrt{B_0^2 + m_N^2}\,.$$

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

*

$$\frac{\Delta L^{TOT,\text{complete}}}{s} \simeq (0.016 - 0.019)\,\frac{B_0}{m_N}$$

at freezeout temperature

$$T = T_D: \quad m_N/T_D \simeq (1.44 - 1.77)$$

Pheno

$$\frac{\Delta L^{TOT,\text{complete}}}{s} \simeq \mathcal{O}(8 \times 10^{-11})$$

$$\frac{B_0}{m_N} \sim 5.0 \times 10^{-9} - 4.2 \times 10^{-9},$$

at freezeout temperature