CPT VIOLATION:

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

Nick E. Mavromatos

King's College London,

Physics Dept., London UK

7th Intl. Conf. on New Frontiers in Physics

ICNFP2018 , OAC (Kolymbari) 4-12 July 2018

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):

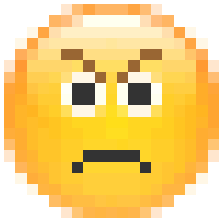
strong(?) in early Universe → CPT generator ill-defined

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

III(b). Connection to Baryogenesis

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 ?

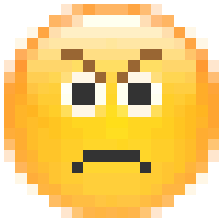
IS THIS CPTV ROUTE WORTH FOLLOWING? ….

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 ?

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

time

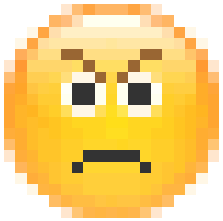
Baryogenesis @ T_D : direct
or through
Leptogenesis first @ $T'_D > T_D$

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

scale with T
(concrete
model)

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

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



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 ?

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

STANDARD MODEL INCOMPATIBLE WITH BARYOGENESIS

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

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

- But Universe consists only of matter

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

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

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

STANDARD MODEL INCOMPATIBLE WITH BARYOGENESIS

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

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

- But Universe consists only of matter

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

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

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

Assume CPT invariance

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

Assume CPT invariance

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

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

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

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

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

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

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

(**Baryogenesis through Leptogenesis**)

(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:

flavour SU(2)

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

Allowed Processes (change of B by multiples of 3)

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

→ L_i – B/3 Conserved

(three quantities)

BUT:
OBSERVED NEUTRINO FLAVOUR OSCILLATIONS

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

If neutrinos Majorana

→ **L not definite**

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''

OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

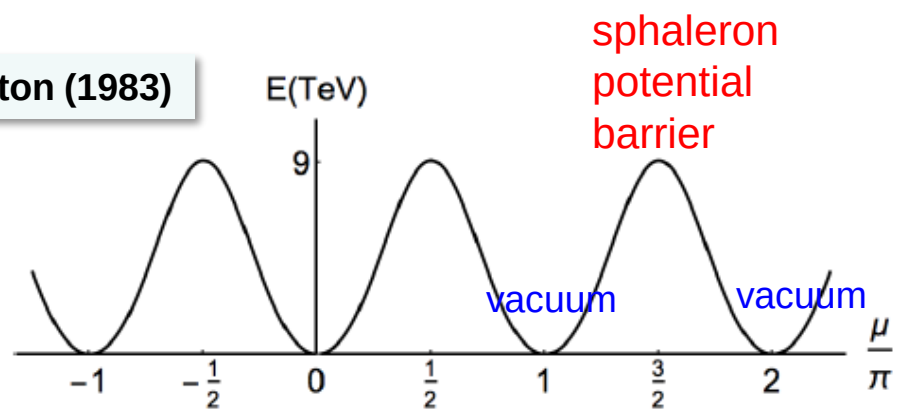
Kuzmin, Rubakov, Shaposhnikov

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''

Manton (1983)



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

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.

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

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:

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

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

LHC Expts (2012) $m_H \approx 126$ GeV

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

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

OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

Kuzmin, Rubakov, Shaposhnikov

Rate of B violation in Early Universe

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

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

Compute CP Violation Effects

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

LHC Expts (2012) $m_H \approx 126$ GeV

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

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

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

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

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

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

LHC Expts (2012) $m_H \approx 126$ GeV

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

Beyond the Standard Model

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

Beyond the Standard Model

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

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

CPT VIOLATION IN EARLY UNIVERSE ?

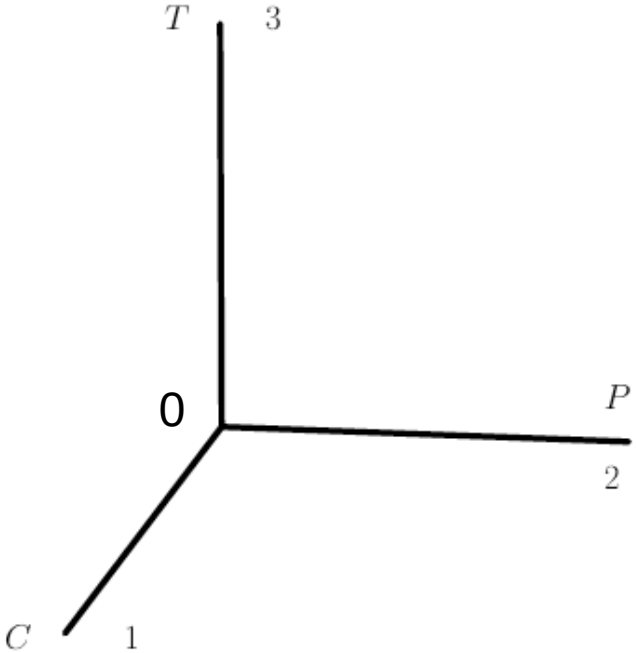
Consistency with stringent current constraints must be ensured

Part II

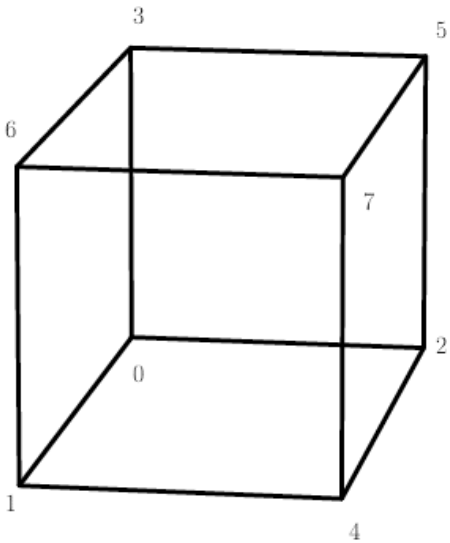
CPT Violation

THEORY

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



Lev Okun hep-ph/0210052v1



CPT mnemonic cube

Point 0: C even, P even, T even → CP, PT, TC, CPT even
1: C odd, P even, T even, → CP odd, PT even, CT odd, CPT odd
2: C even, P odd, T even → CP odd, PT odd, CT odd, CPT odd
3: C even, P even, T odd → CP even, PT odd, CT odd, CPT odd
4: C odd, P odd, T even → CP even, PT odd, CT odd, CPT even
etc

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

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

CPT Theorem

Schwinger 1951

Lüders 1954

J S Bell 1954

Pauli 1955

Res Jost 1958

CPT Theorem

Conditions for the Validity of CPT Theorem

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

i → f , **T**: f → i

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

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

Schwinger, Pauli, Luders, Jost, Bell

CPT Theorem

Conditions for the Validity of CPT Theorem

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

i → f , T: f → i

Schwinger, Pauli, Luders, Jost, Bell

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

e.g. for (Dirac) fermions:

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

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

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

CPT Theorem

Conditions for the Validity of CPT Theorem

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

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

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

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

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

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

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

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

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

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

(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

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

Lorentz & CPT Violation

Lorentz & CPT Violation

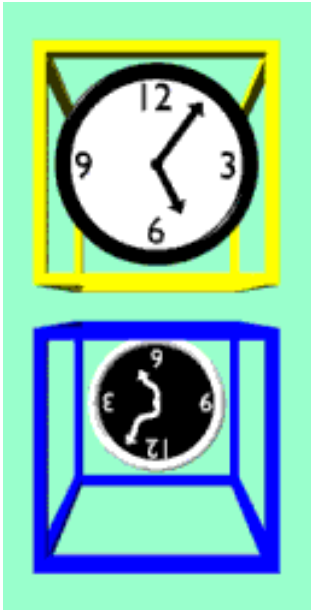
$[\,\Theta, H\,] \neq 0$

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



ONE POSSIBILITY:

particle-antiparticle mass differences

[Θ, H] ≠ 0 $\Rightarrow$ $m \neq \overline{m}$

physics.indiana.edu

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

(**|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

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

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

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

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

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

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

Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

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

Dolgov, Zeldovich
Dolgov (2009)

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

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

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

Dolgov (2009)

Current bound for proton-anti proton mass diff.

$$\delta m_p < 8 \times 10^{-10}\, m_{\rm e}$$

ASACUSA Coll. (2016)

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

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

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

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

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

Dolgov (2009)

Current bound for proton-anti proton mass diff.

$$\delta m_p < 8 \times 10^{-10}\, m_{\rm e}$$

ASACUSA Coll. (2016)

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

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

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

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.*

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

LV only

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

LV & CPTV

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

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

Axisymmetric Background

Geometries of the Early Universe

Torsionful Geometries (including strings…)

LV & CPTV

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

Microscopic Origin of SME coefficients?

Several ``Geometry-induced" examples:

Non-Commutative Geometries LV only

Axisymmetric Background

Geometries of the Early Universe

Torsionful Geometries (including strings…)

LV &
CPTV

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

STANDARD MODEL EXTENSION

Kostelecky *et al.*

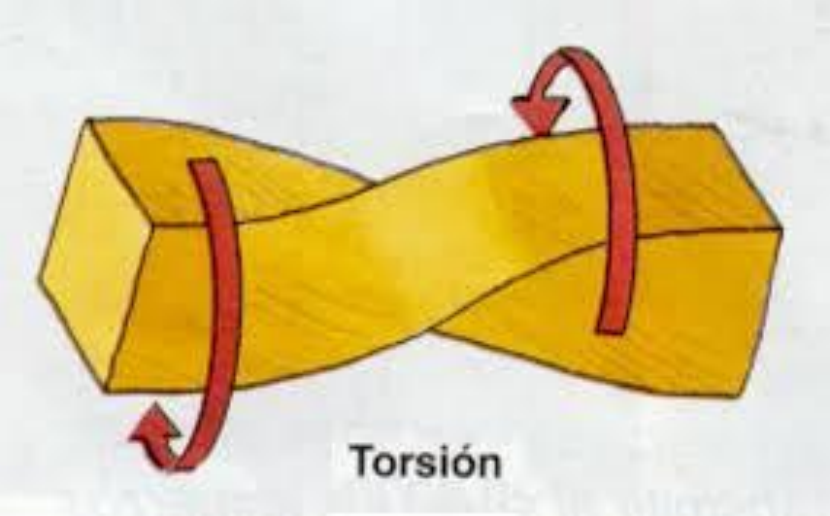
$$\mathcal{L} = \frac{1}{2}\mathrm{i}\bar{\psi}\Gamma^{\nu}\bar{\partial}_{\nu}\psi - \bar{\psi}M\psi,$$

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

LV & CPTV

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

In particular,
Space-times with



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

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

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

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

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

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

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

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

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

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

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

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

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

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

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

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

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

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

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

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

Gravitational covariant derivative including spin connection

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

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

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

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

Dirac Lagrangian (for concreteness, 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

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

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

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

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

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

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

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

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

$\kappa^2 = 8\pi G$

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

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

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

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

$\kappa^2 = 8\pi G$

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

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

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

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

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

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

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

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

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

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

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

$$H_{cab}$$

Non-trivial contributions to ***B*$^\mu$**

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

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

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

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

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

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

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

contorsion

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

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

$$H_{cab}$$

Non-trivial contributions to ***B*$^\mu$**

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

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

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

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

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

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

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

LV & CPTV

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

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

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

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

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

Lagrangian :

vacuum energy

$$\mathcal{L} = \sqrt{-g}\Big[\frac{1}{2\kappa^2}R - \frac{1}{2}(\partial_\mu b)^2 - \Omega + \sum_i [\overline{\psi}_i(i\gamma^\mu\partial_\mu - m_i)\psi_i + \frac{\kappa}{3\sqrt{6}}\partial_\mu b\,\overline{\psi}_i\gamma^\mu\gamma^5\psi_i] + \ldots\Big]$$

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

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

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

Eqs of motion for pseudoscalar:

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

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

i ≠ Majorana neutrinos

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

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

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**

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

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

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

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**

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**

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

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

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**

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

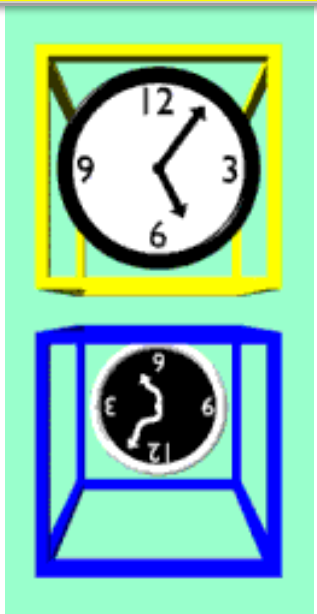
cf below...

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 νMSM

Boyarski, Ruchayskiy, Shaposhnikov

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

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

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

Early Universe
T > 10^5 GeV

CPT Violation

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;

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

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

CPTV Thermal

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

CPT Violation

Early Universe
T > 10^5 GeV

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

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

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

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

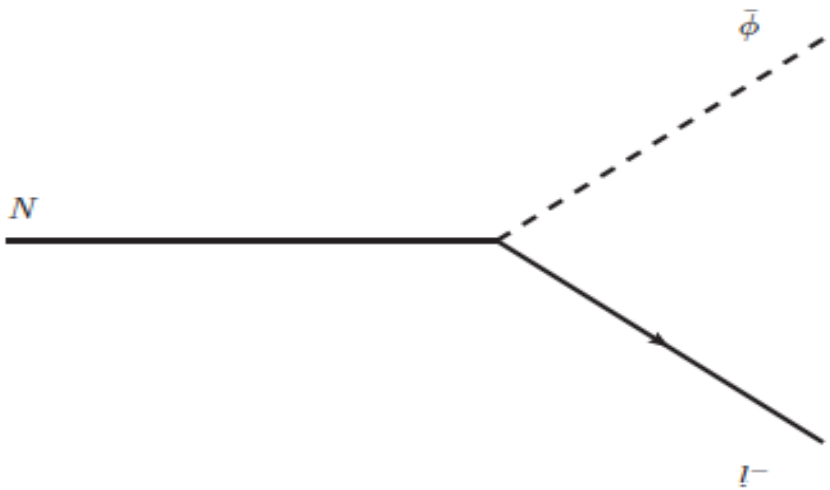
CPT Violation

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

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

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

Constant H-torsion

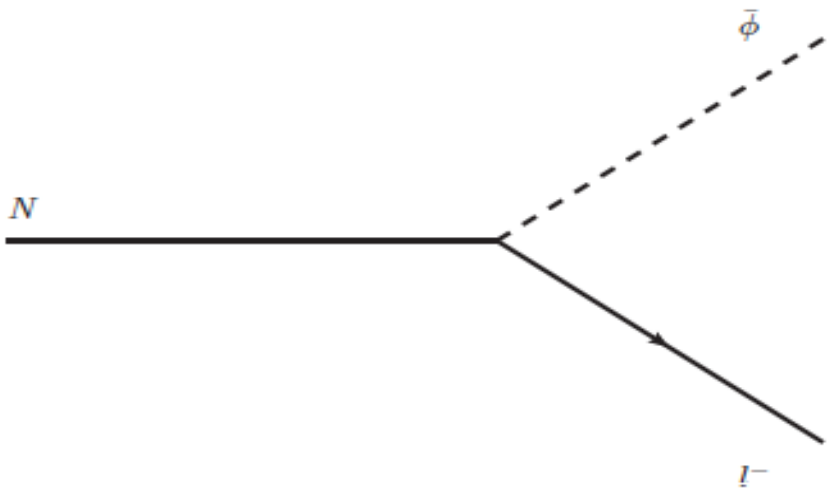
Early Universe
T > 10^5 GeV

CPT Violation

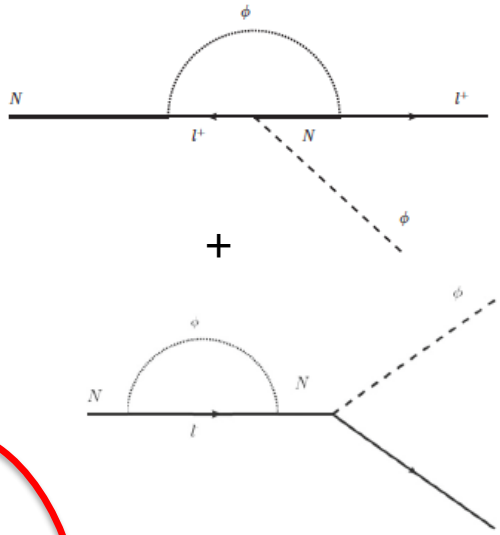
Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

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

Produce Lepton asymmetry



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



Fukugita, Yanagida,

CPTV Thermal

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

Constant H-torsion

Early Universe
T > 10^5 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

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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

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

* **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

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

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

CPTV Thermal

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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

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

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

Produce Lepton asymmetry

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

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

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

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

CPTV Thermal

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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

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

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

Produce Lepton asymmetry

?

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

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

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

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

CPTV Thermal

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

CPT Violation

Early Universe
$T > 10^5$ GeV

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

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

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

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

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

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

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

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

Produce Lepton asymmetry

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

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

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental Conditions Dependent

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

Observed Baryon Asymmetry In the Universe (BAU)

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

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

B^0 : (string) theory underwent a **phase transition**

@ $T \approx T_d = 10^5$ GeV, from B^0 = const = 1 MeV **to** :

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

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

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

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

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

Quite safe from stringent Experimental Bounds

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

CPTV Thermal

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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

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

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

Produce Lepton asymmetry

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

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

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental Conditions Dependent

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

Observed Baryon Asymmetry In the Universe (BAU)

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

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

CPTV Thermal

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

Early Universe
T > 10^5 GeV

CPT Violation

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

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

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

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

Produce Lepton asymmetry

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

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

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental Conditions Dependent

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

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

Observed Baryon Asymmetry In the Universe (BAU)

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

e.g. May Require Fine tuning of Vacuum energy

CPTV Thermal

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

CPT Violation

Early Universe
$T > 10^5$ GeV

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

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

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

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

Produce Lepton asymmetry

Equilibrated electroweak B+L violating sphaleron interactions

B-L conserved

Environmental Conditions Dependent

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

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

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

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

Observed Baryon Asymmetry In the Universe (BAU)

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

e.g. May Require Fine tuning of Vacuum energy

e.g. 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

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

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

$\kappa^2 = 8\pi G$

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

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

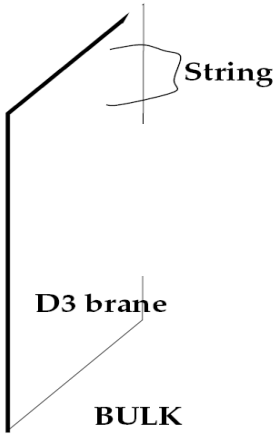
$$\sim \frac{1}{2}\partial^\mu b\, \partial_\mu b$$

4-DIM PART

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

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

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)

Part II(b)

Quantum-Gravity induced Decoherence

&

intrinsic CPT Violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

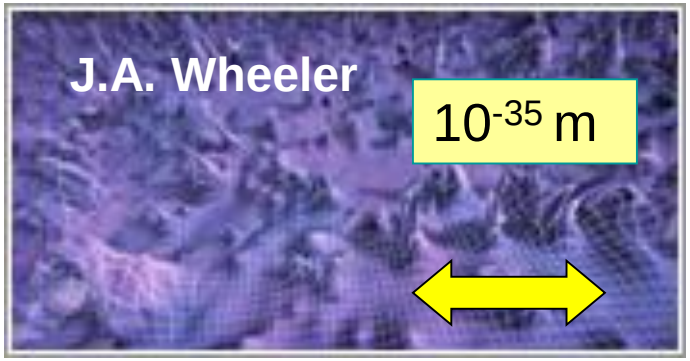
CPT Invariance Theorem :

(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***



CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

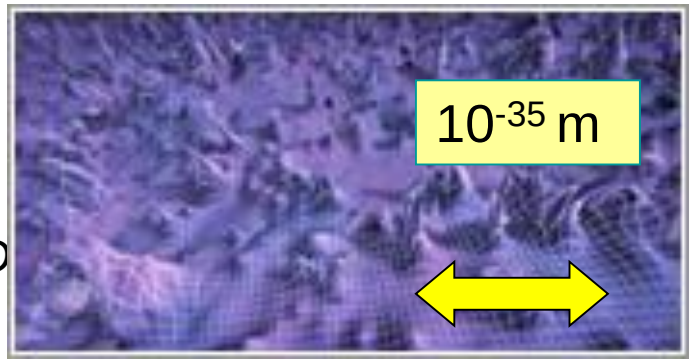
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

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

(ii)-(iv) Independent reasons for violation

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

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



CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

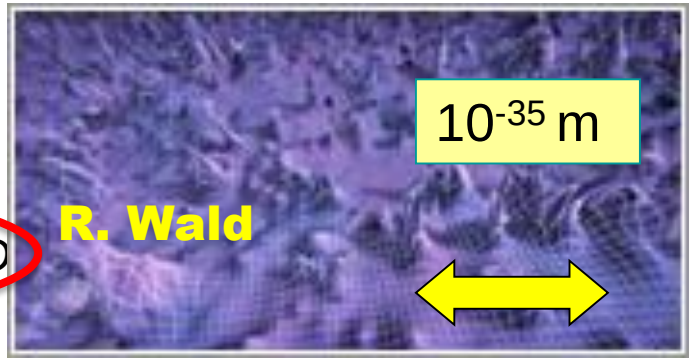
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

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

(ii)-(iv) Independent reasons for violation

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

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



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)

NB: Decoherence & CPTV

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

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

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

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

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

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

Bernabeu, NEM, Papavassiliou (04),…

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

Wald (79)

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

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

ω-effect

CPTV in Hamiltonian

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

NB: Decoherence & CPTV

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

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

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

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

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

Bernabeu, NEM, Papavassiliou (04),…

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

Wald (79)

NB: Decoherence & CPTV

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

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

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

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

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

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

Bernabeu, NEM, Papavassiliou (04),…

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

Wald (79)

If CPT ill-defined →

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

but...

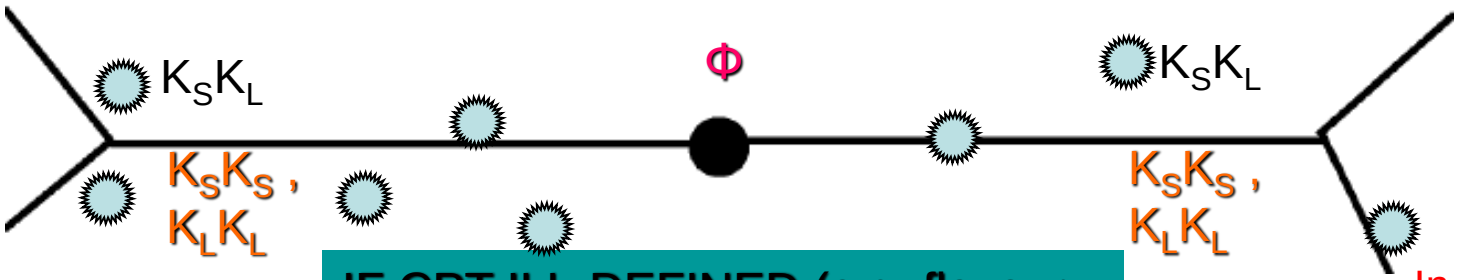
(i) observable effects in entangled (neutral) meson-states

ω-effect

- 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

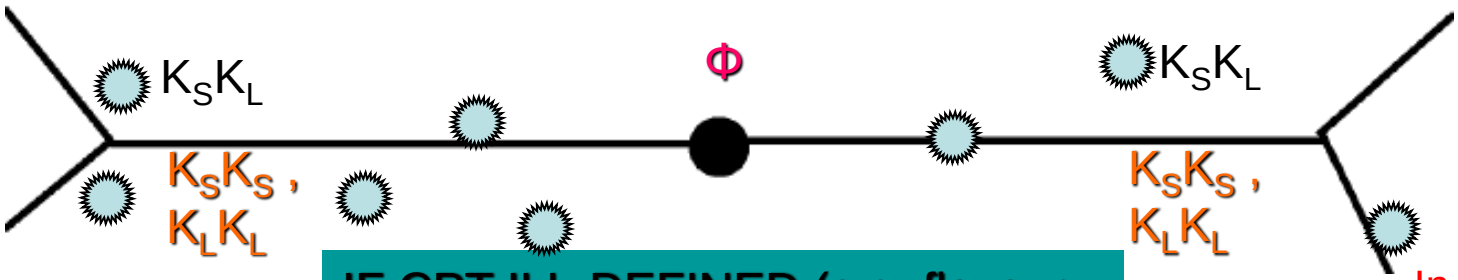
$$|\omega|^2 \sim \frac{\zeta^2\, k^4}{M_{\rm QG}^2 (m_1 - m_2)^2}, \Delta k = \zeta\, k\, (\text{particle momentum transfer})$$

If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for **M_{QG} ~ 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**)

- 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)

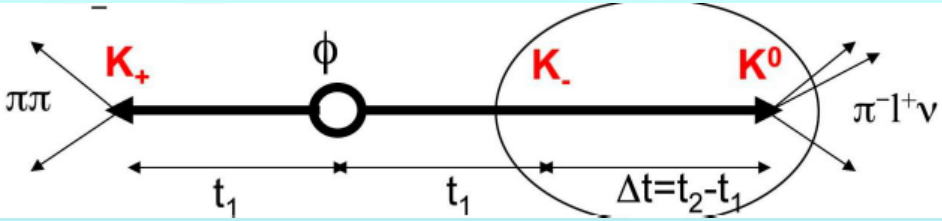
In a concrete model of space-time foam

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

If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for **M_{QG} ~ 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**)

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

Current Measurement Status of ω-effect



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

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

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

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

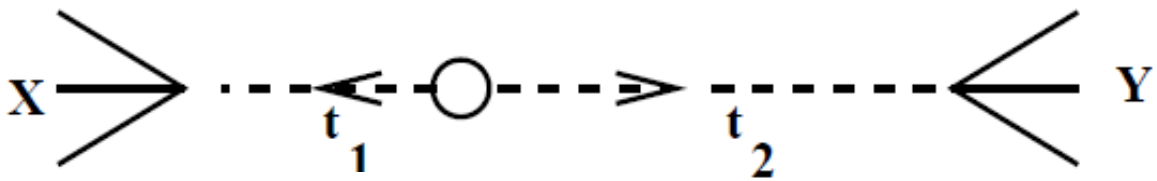
Neutral Kaons

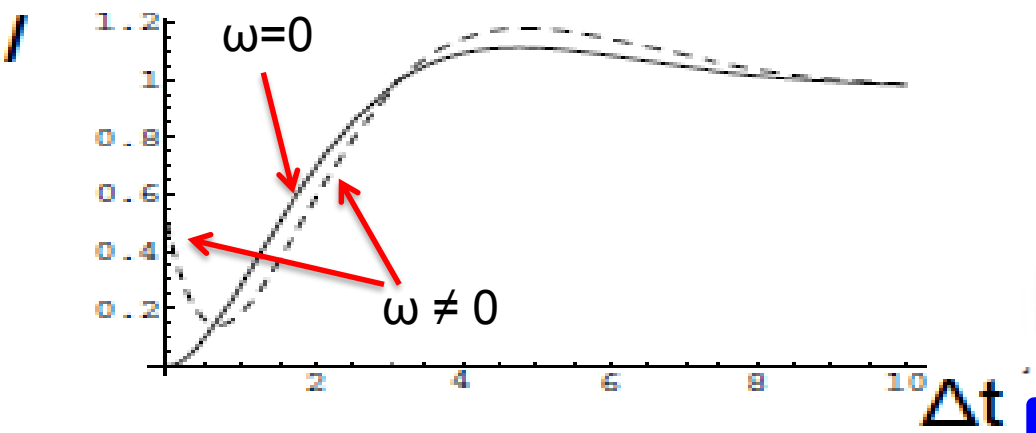
Prospects KLOE-2 Re(ω), Im(ω) → 2 x 10^{-5}

ω-effect observables/current bounds

ϕ Decays and the ω Effect

Consider the ϕ decay amplitude: final state X at t_1 and Y at time t_2 ($t = 0$ at the moment of ϕ decay)





I(Δt=0) ≠ 0
if ω-effect present

The "intensity" $I(\Delta t)$: $(\Delta t = t_1 - t_2)$ is an observable

$$I(\Delta t) \equiv \frac{1}{2} \int_{|\Delta t|}^{\infty} dt \, |A(X,Y)|^2$$

ω-Effect & Intensities

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

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

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

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 (04),…

ω-Effect & Intensities

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

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

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

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

$$I_{12}(\Delta t) = -\frac{4}{4(\Delta M)^2 + (3\Gamma_S + \Gamma_L)^2}\frac{|\omega|}{|\eta_{+-}|} \times$$

$$\Big[2\Delta M \Big(e^{-\Gamma_S \Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t) \Big)$$

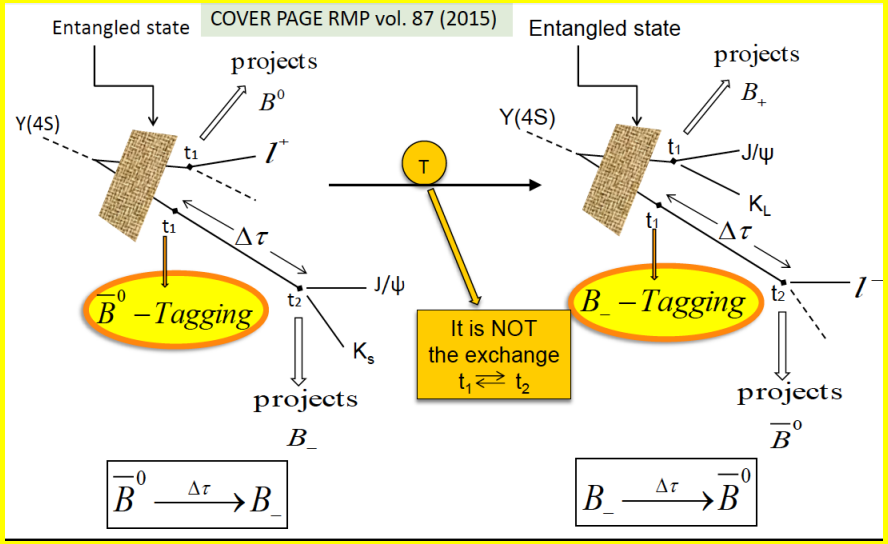
$$-(3\Gamma_S + \Gamma_L)\Big(e^{-\Gamma_S \Delta t}\cos(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\phi_{+-} - \Omega + \Delta M \Delta t) \Big) \Big]$$

$\Delta M = M_S - M_L$ 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 (04),…

Current Measurement Status of ω-effect



Neutral B-mesons

Equal Sign Dilepton Asymmetry

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

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

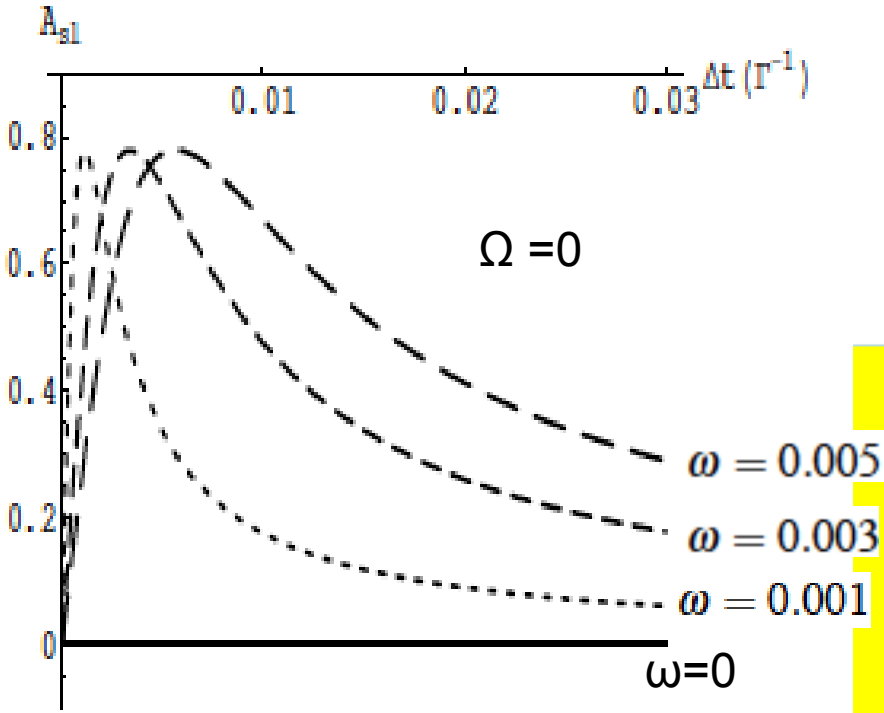
Current Measurement Status of ω-effect

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

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

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

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



Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 027)

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

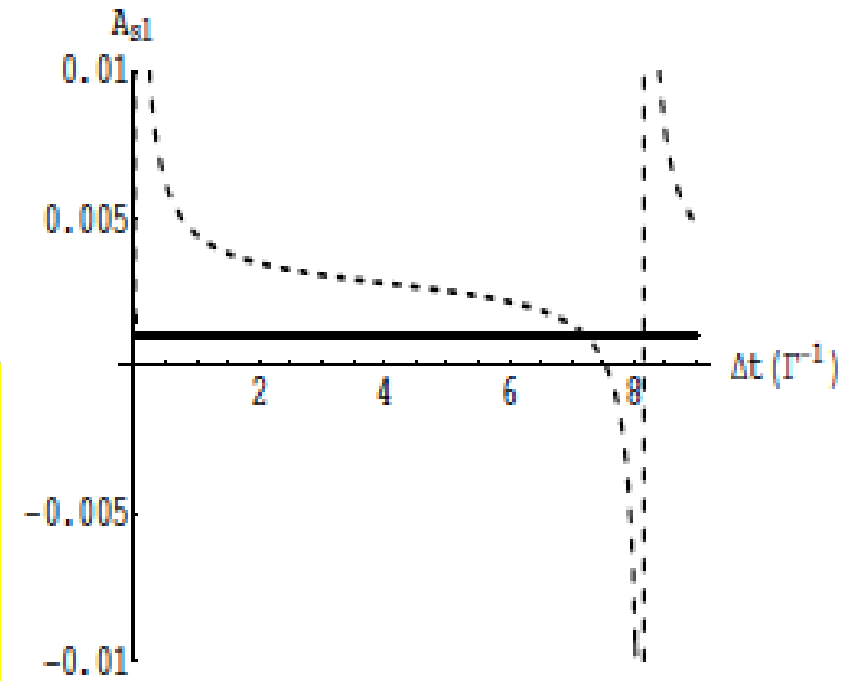
Neutral B-mesons

Current Measurement Status of ω-effect

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

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

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



Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 027)

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

Neutral B-mesons

Current Measurement Status of ω-effect

$$\Delta\Gamma = 0$$

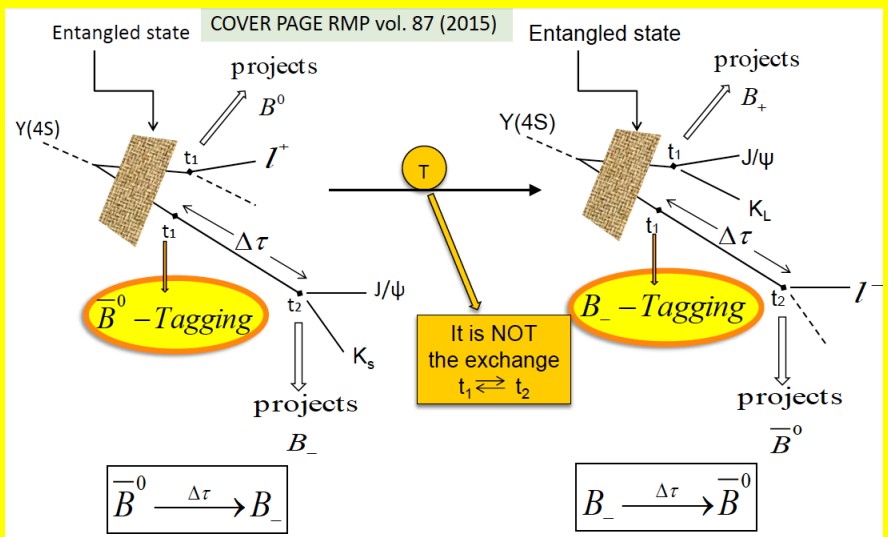
$$I(f,g;t) = \int_0^\infty dt_0\, |\langle f, t_0; g, t+t_0|T|\Psi_0\rangle|^2 = \frac{\langle\Gamma_f\rangle\langle\Gamma_g\rangle}{\Gamma} e^{-\Gamma t}\{\mathscr{C}_h^\omega[f,g] + \mathscr{C}_c^\omega[f,g]\cos(\Delta M t) + \mathscr{S}_c^\omega[f,g]\sin(\Delta M t)\}$$

Observables

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

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

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



Neutral B-mesons

Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 027)

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

Novel signal from (f,g) ←→ (g,f)

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

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

Current Measurement Status of ω-effect

$$\Delta\Gamma = 0$$

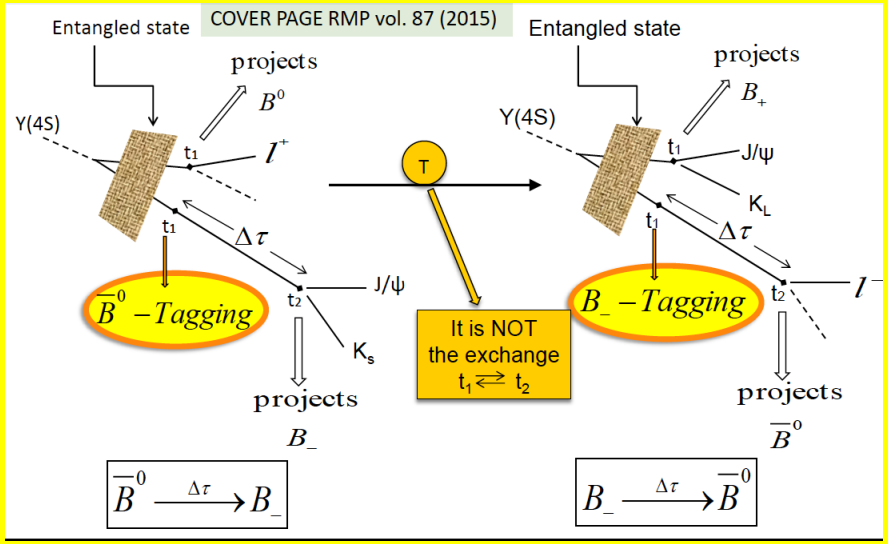
$$I(f,g;t) = \int_0^\infty dt_0\, |\langle f, t_0; g, t+t_0|T|\Psi_0\rangle|^2 = \frac{\langle\Gamma_f\rangle\langle\Gamma_g\rangle}{\Gamma} e^{-\Gamma t}\{\mathscr{C}_h^\omega[f,g] + \mathscr{C}_c^\omega[f,g]\cos(\Delta M t) + \mathscr{S}_c^\omega[f,g]\sin(\Delta M t)\}.$$

Observables

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

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

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



Neutral B-mesons

Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 027)

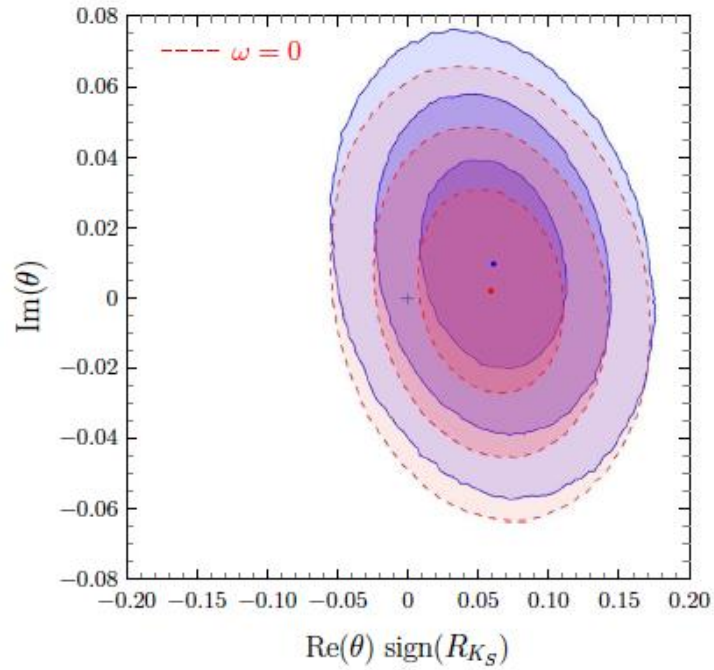
$$-0.0084 \le Re(\omega) \le 0.0100 \qquad 95\%\text{C.L}$$

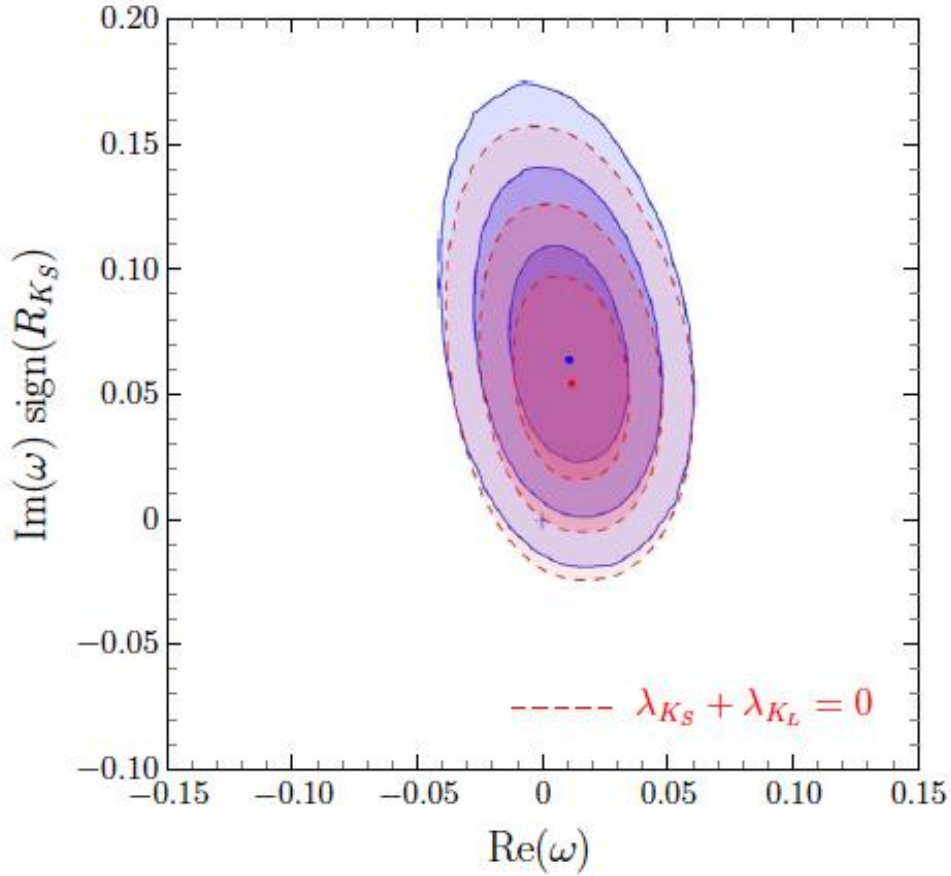
Novel signal from (f,g) ←→ (g,f)

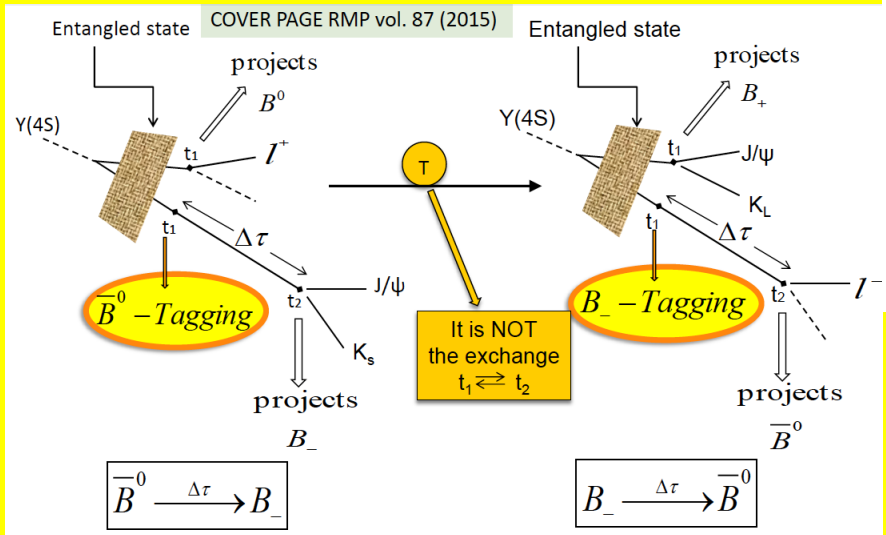
(Bernabeu, Botella, NEM, Nebot (2018))

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

Current Measurement Status of ω-effect





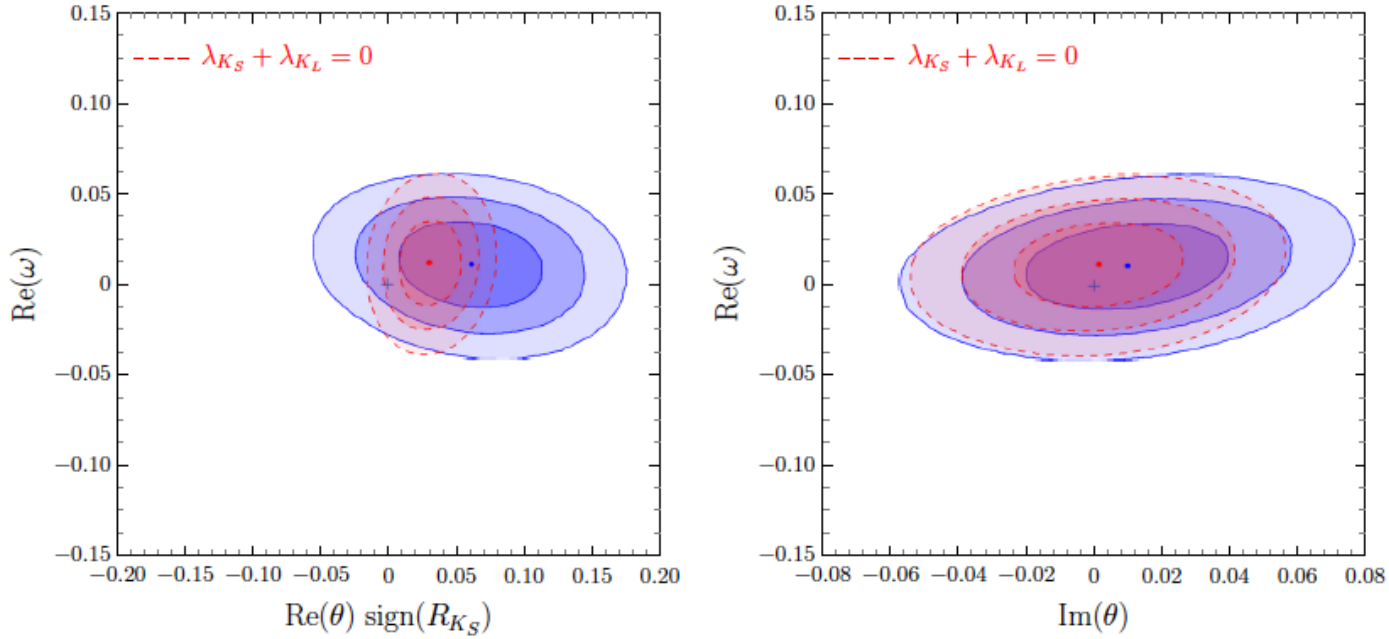


Neutral B-mesons

Novel signal from (f,g) ←→ (g,f)
(Bernabeu, Botella, NEM, Nebot (2018))

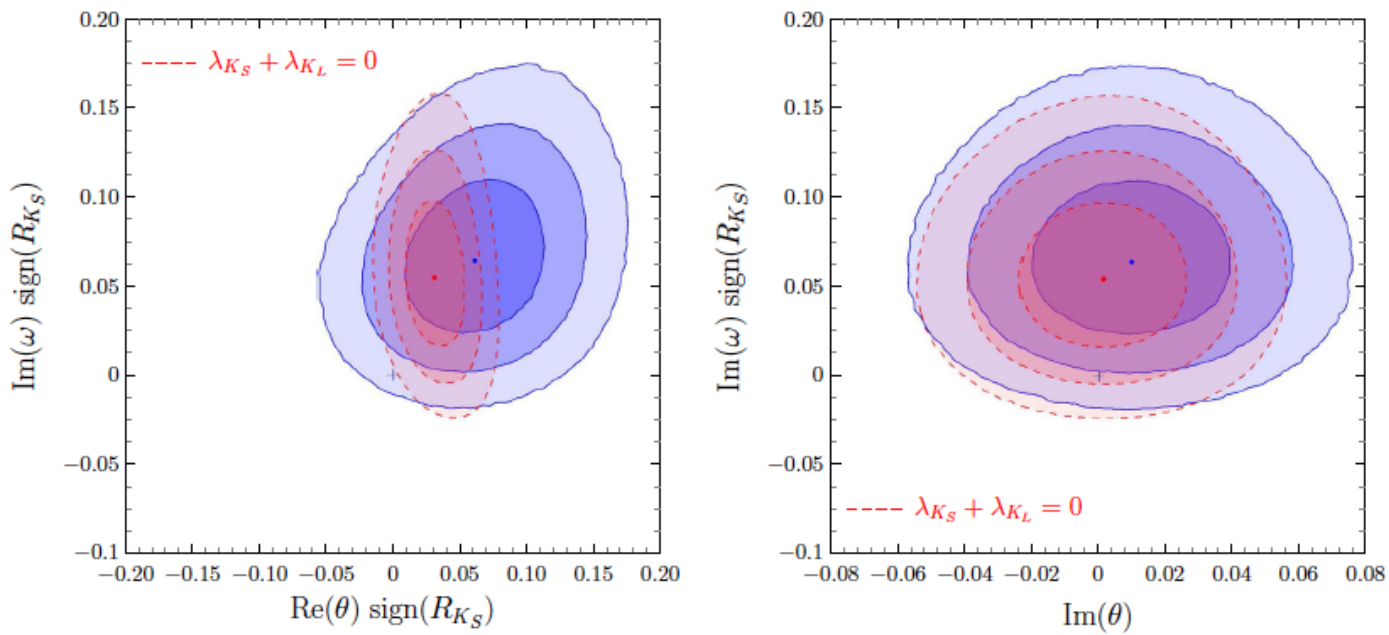
$\mathrm{Im}\ (\theta)$	$(0.99 \pm 1.98)10^{-2}$
$\mathrm{Im}\ (\omega)$	$\pm(6.40 \pm 2.80)10^{-2}$

Correlations among ω & θ



(a) Re (ω) vs. Re (θ).

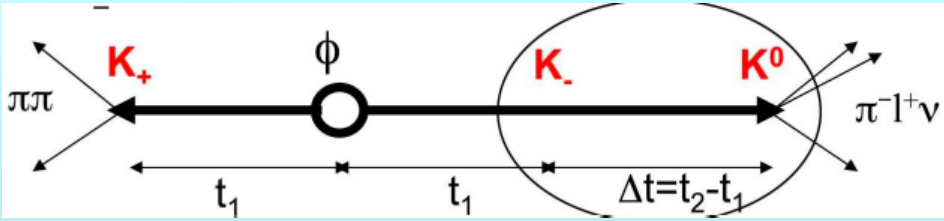
(b) Re (ω) vs. Im (θ).



(c) Im (ω) vs. Re (θ).

(d) Im (ω) vs. Im (θ).

Current Measurement Status of ω-effect



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

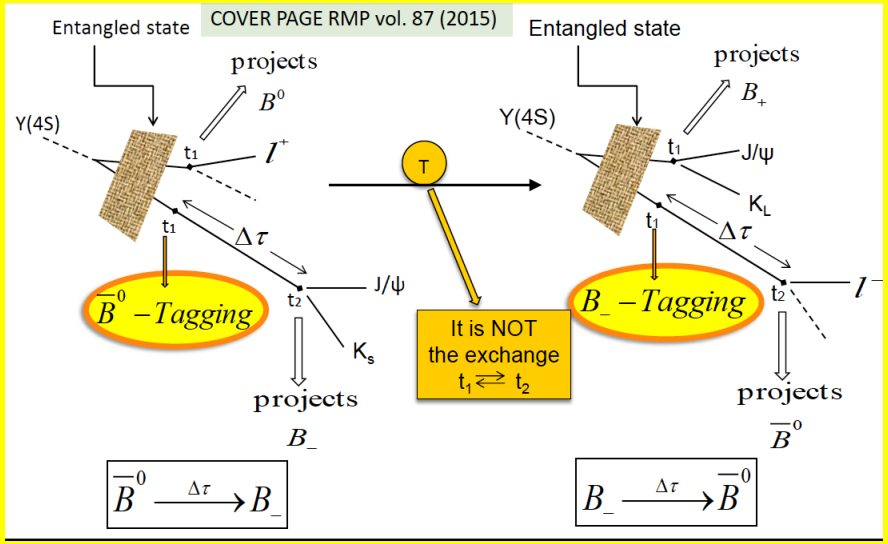
$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$

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

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

Neutral Kaons

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



Nautral B-mesons

Equal Sign Dilepton Asymmetry

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

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

Novel signal from (f,g) ←→ (g,f)

(Bernabeu, Botella, NEM, Nebot

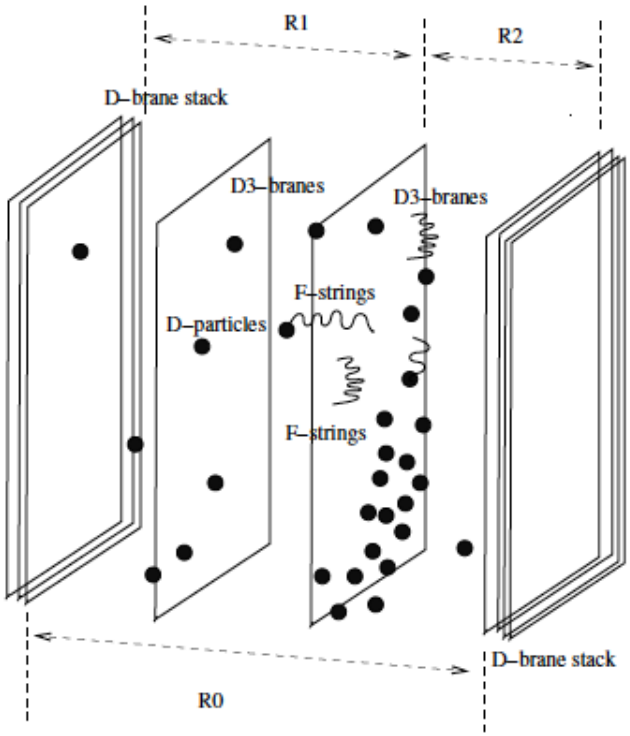
EPJC 77 (2017) 865)

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

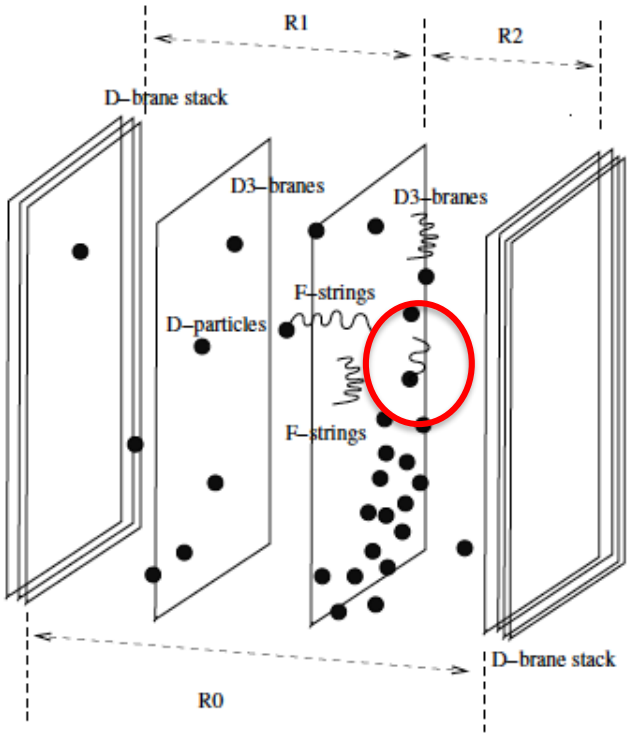
Part III(b)

Connection to Baryogenesis

Connection to Baryogenesis



Connection to Baryogenesis



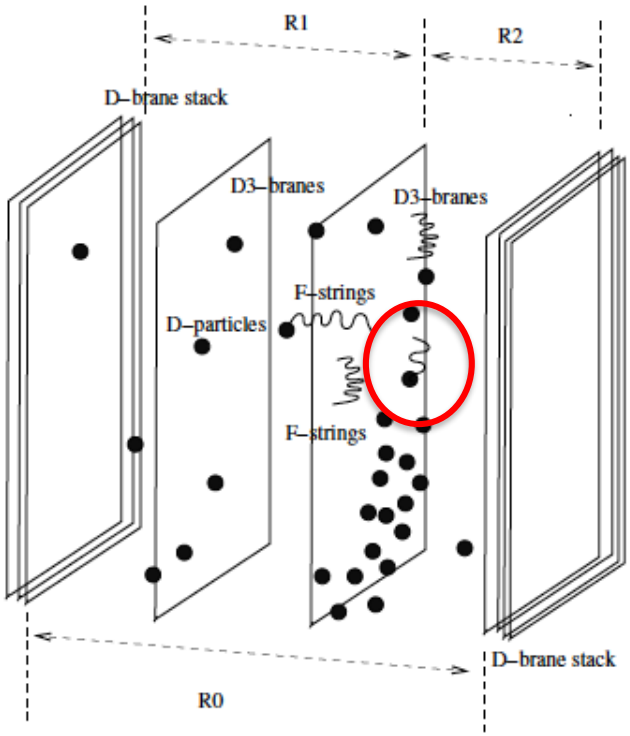
Effective metric due to LV foam medium

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

Stochastic media

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

Connection to Baryogenesis



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

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

Energy differences between matter-antimatter

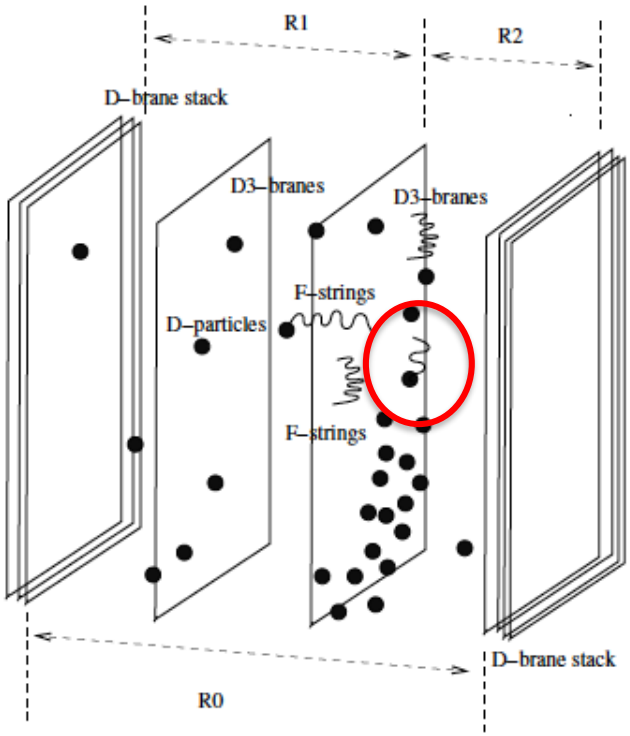
$$\ll E \gg = \sqrt{p^2 + m^2} + \frac{p^2 \sigma^2}{2\sqrt{p^2 + m^2}} - \frac{1}{2} \frac{M_s}{g_s} \sigma^2$$

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

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

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

Stochastic media

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

Energy differences between matter-antimatter

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

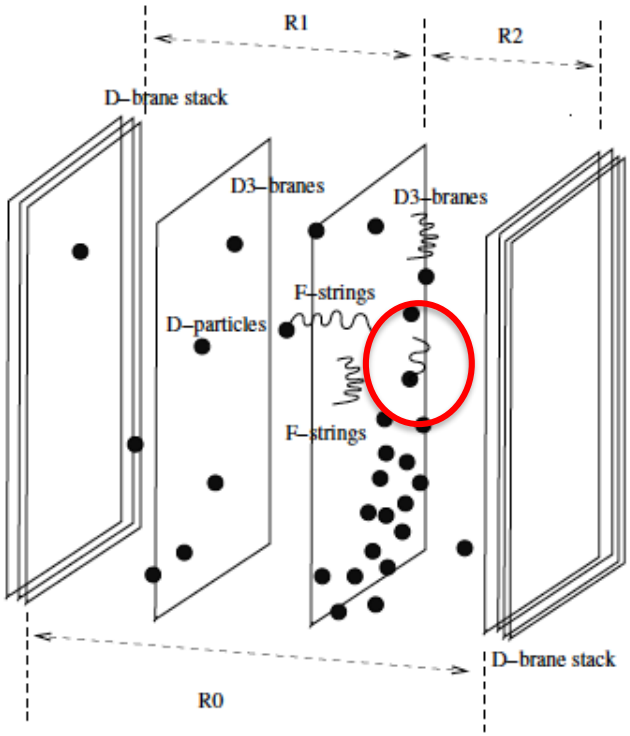
$$\ll \overline{E} \gg = \sqrt{p^2 + m^2} + \frac{p^2\,\sigma^2}{2\sqrt{p^2+m^2}} + \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

Baryon asymmetry in Universe

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

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

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

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

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

Baryon asymmetry in Universe @ T_D

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

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

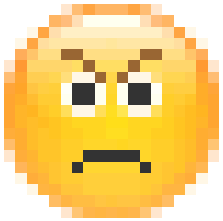
IS THIS CPTV ROUTE WORTH FOLLOWING? ….

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 ?

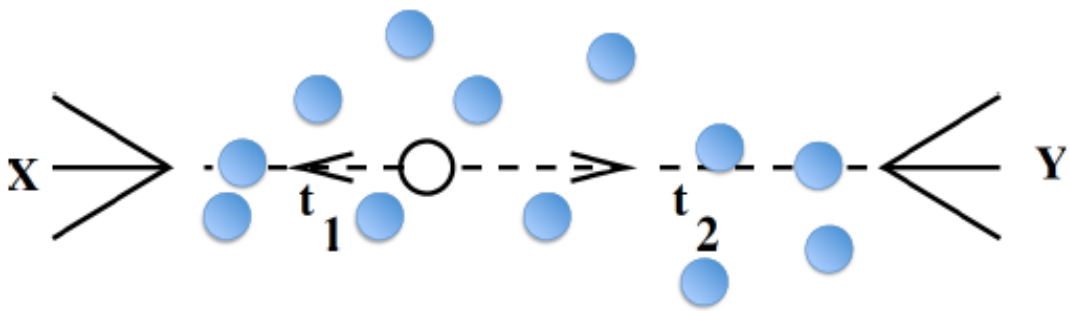
Φ-factories Current Limits → Baryogenesis?

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

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

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

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



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

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

$$0 < \Delta < 1$$

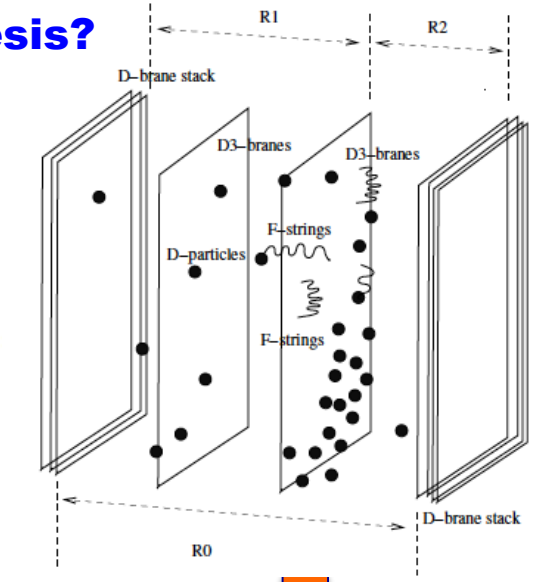
T-dependence of Δ depends on details of QG model

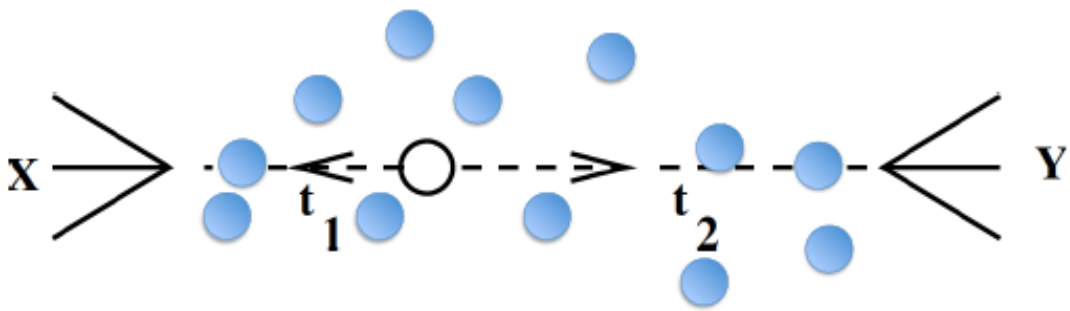
Φ-factories Current Limits → Baryogenesis?

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

$$\langle r_i \rangle = 0,\ \langle r_i\, r_j \rangle$$

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





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

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

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

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

Neutral Kaons in Φ-factories

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

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

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

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

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

$$\langle r^2 \rangle = \Delta \qquad \langle r \rangle = \hat{0}$$

$$0 < \Delta < 1$$

Neutral Kaons in Φ-factories

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

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

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

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

$$\langle r^2 \rangle = \Delta \qquad \langle r \rangle = \hat{0}$$

$$0 < \Delta < 1$$

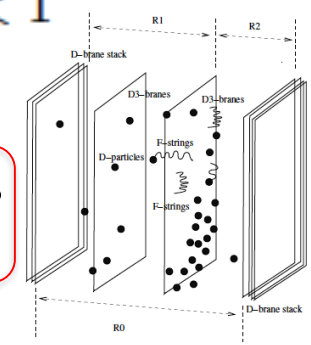
$$\Delta_{\mathrm{today}} < 10^{-38}$$

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

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

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

$$\Rightarrow \quad \frac{\Delta_{100\ \mathrm{GeV}}}{\Delta_{\mathrm{today}}} \sim \frac{M_s}{g_s}\,\frac{1}{\mathrm{GeV}} \times 10^{26} \sim \left(\frac{T = 100\,\mathrm{GeV}}{T^0_{\mathrm{CMB}} = 0.2\,\mathrm{meV}}\right)^3 \sim 10^{44}$$

$$\Rightarrow \quad \frac{M_s}{g_s} \sim 10^{18}\ \mathrm{GeV}$$

Consistent string model !

Neutral Kaons in Φ-factories

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

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

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

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

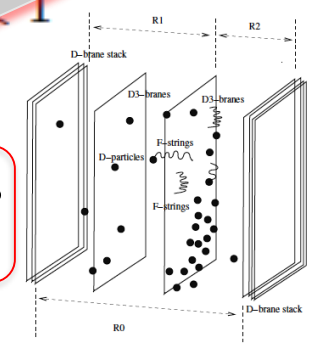
$$\Delta_{\mathrm{today}} < 10^{-38}$$

D-particle induced Baryogenesis

Scaling with Temperature T in D-particle foam model

D-particles = dark-matter

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



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

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

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

NB: RHN leptogenesis also consistent

$$\sigma \ldots \frac{}{M_s^2}\,\Delta \;\Rightarrow\; \Delta n \sim \frac{g_s}{M_s}\,T\,\Delta$$

$$\Rightarrow \frac{\Delta_{100\ \mathrm{GeV}}}{\Delta_{\mathrm{today}}} \sim \frac{M_s}{g_s}\frac{1}{\mathrm{GeV}} \times 10^{26} \sim \left(\frac{T = 100\,\mathrm{GeV}}{T^0_{\mathrm{CMB}} = 0.2\,\mathrm{meV}}\right)^3 \sim 10^{44}$$

$$\Rightarrow \frac{M_s}{g_s} \sim 10^{18}\ \mathrm{GeV}$$

Consistent 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

- CPT Violation (CPTV) due to (strong) quantum fluctuati ne at early eras or LV early Universe Geometries (with b

  is a possibility and may explain the observed y in the cosmos, consistently with current-e

- One framework for early universe sion (SME)
- A string-inspired model of t PT and Lorentz Violation due to Kalb-R ground geometries – Consistent phenc

  ...to expl with Early Universe c ion etc

- Quan n early Universe might be strong → Decoh uantum 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

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

Proper Treatment through solving Boltzmann Eqs.

T. Bossingham, N.E.M., Sarka

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 $B_0/T << 1$**) :

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

Proper Treatment through solving Boltzmann Eqs.

T. Bossingham, N.E.M., Sarka

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 $B_0/T << 1$**) :

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

Proper Treatment through solving Boltzmann Eqs.

T. Bossingham, N.E.M., Sarka

Boltzmann equation in presence of CPTV & LV Background B_0

RHN Helicity specific λ_r :

$$\mathrm{d}n_r/\mathrm{d}t + 3Hn_r - \frac{g}{2\pi^2} 2\lambda_r \frac{B_0}{T} T^3 \int \mathrm{d}u\, u\, f(E(B_0=0), u)$$
$$= \frac{g}{8\pi^3} \int \frac{d^3p}{E(B_0 \neq 0)} C[f] + \mathcal{O}(B_0^2)$$

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

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

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

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

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

Proper Treatment through solving Boltzmann Eqs.

T. Bossingham, N.E.M., Sarka

Boltzmann equation in presence of CPTV & LV Background B_0

RHN Helicity specific λ_r :

$$\lambda\, I$$

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

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

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

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

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

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

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

* Proper Treatment through solving Boltzmann Eqs.

T. Bossingham, N.E.M., Sarka

$$Y_x = n_x/s$$

$$z = m_N/T$$

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

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., Sarka

$$Y_x = n_x/s$$

$$z = m_N/T$$

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

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

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

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

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

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

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

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

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

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

* 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:

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

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

*

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

at freezeout temperature

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

*

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

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

$$\Omega = \sqrt{B_0^2 + m_N^2}\ . \qquad Y_k \sim 10^{-5}$$

*

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

at freezeout temperature

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

Pheno

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

*

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

at freezeout temperature

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

Pheno

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

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

at freezeout temperature

Proof of Ill-defined CPT in decoherent situations

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

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

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

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

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

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

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

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

Proof of ill-defined CPT in decoherent situations

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

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

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

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

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

NB: CPT is **antiunitary** (due to T) when acting on |ψ> but **unitary** when **acting on |ψ><ψ|**

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

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

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

Proof of Ill-defined CPT in decoherent situations

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

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

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

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

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

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

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

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

CPT symmetry without CPT invariance ?

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

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

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

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

In terms of superscattering matrix \$:

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

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

CPT symmetry without CPT invariance ?

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

of time

measu

Probab

ϕ =fin

where

$\Theta\rho =$

In tern

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

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

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

In principle this question can be settled experimentally

CPT symmetry without CPT invariance ?

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

of time

measu

Probab

ϕ =fin

where

$\Theta\rho =$

In tern

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

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

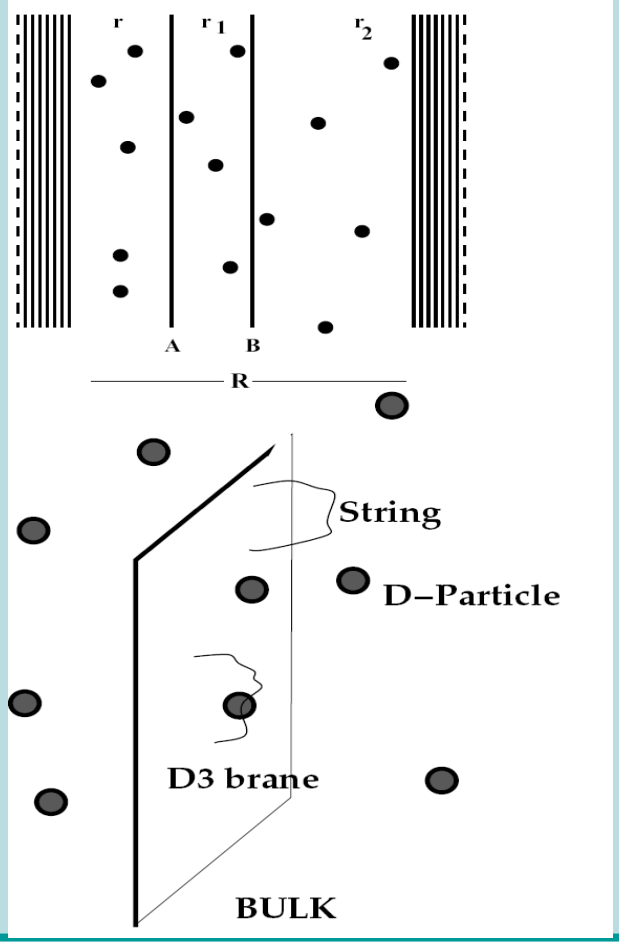
Supporting evidence for Weak CPT from Black-hole thermodynamics: *Although white holes do not exist (strong CPT violation), nevertheless the CPT reverse of the most probable way of forming a black hole is the most probable way a black hole will evaporate:* **the states resulting from black hole evaporation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

In principle this question can be settled experimentally

The Model

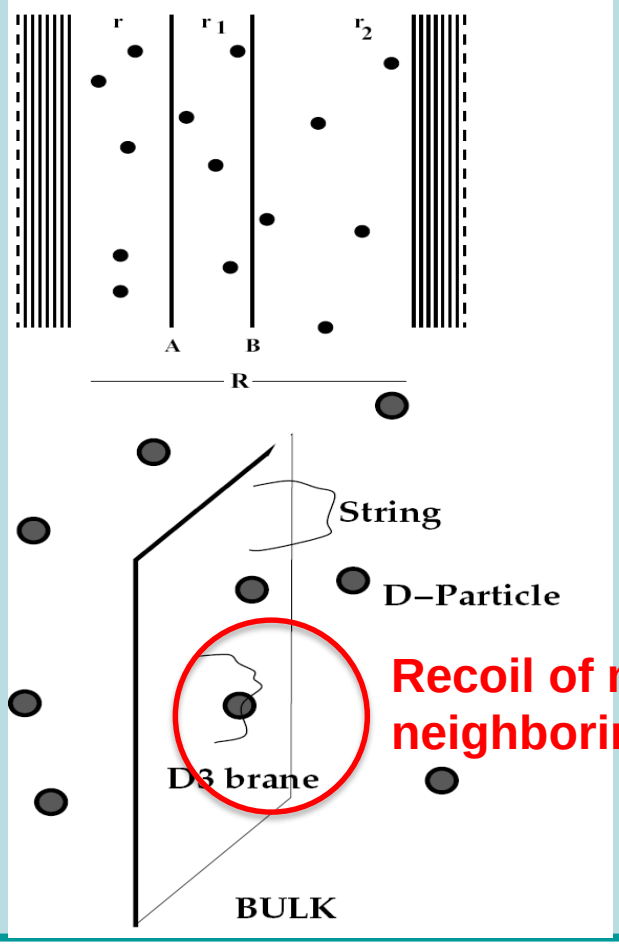
Bernabeu, Sarkar, NEM
Phys.Rev. D74 (2006) 045014

D-particle recoil and entangled Meson States



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

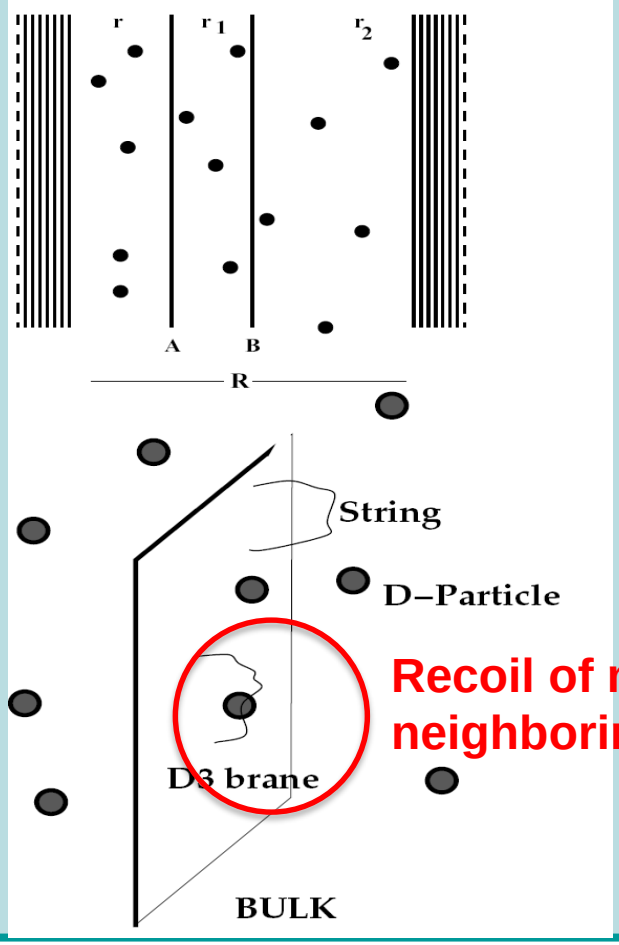
D-particle recoil and entangled Meson States



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

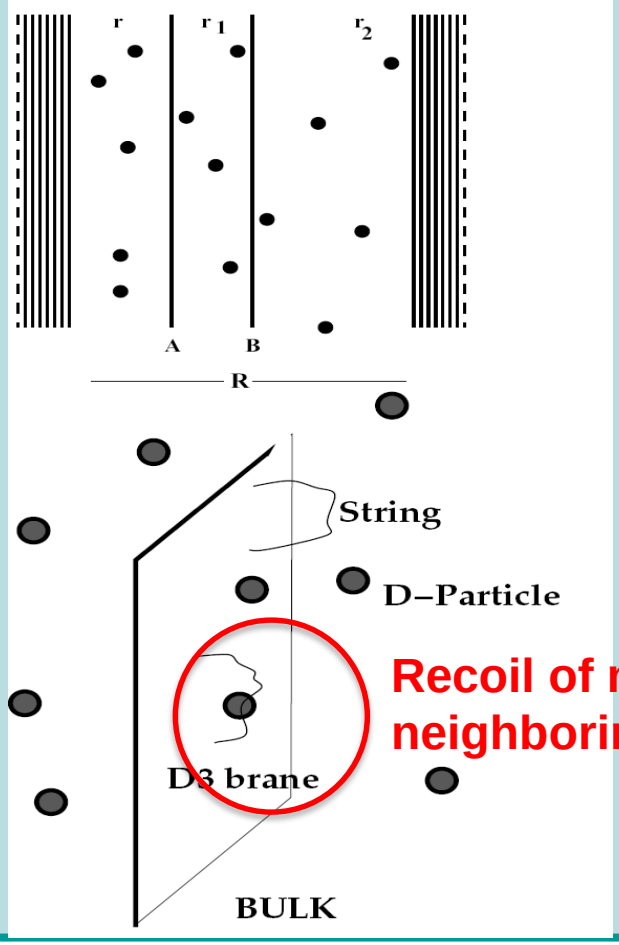


propagation of matter string in curved background interaction with metric

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

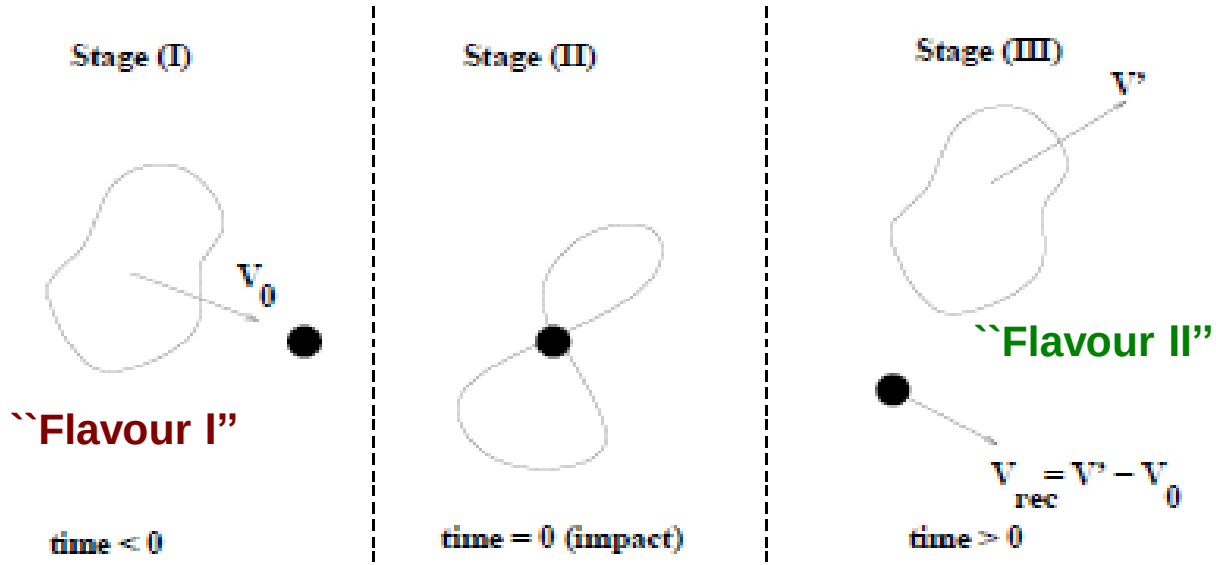


Gravitationally dressed quantum states viewed as quantum mechanically perturbed

propagation of matter string in curved background interaction with metric

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

D-particle Recoil & the ω-effect



Logarithmic conformal field theory describes the impulse at stage (II)

For neutral mesons: Consider Klein-Gordon in curved background due to recoil-induced metric distortions with two "flavours'' corresponding to mass eigenstates, e.g. for Kaons K_L , K_S .

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$(g^{\alpha\beta} D_\alpha D_\beta - m^2)\Phi = 0$$

$$g^{01} = g^{10} = r_0 1 + r_1 \sigma_1 + r_2 \sigma_2$$

$$\mathcal{U}_i \Rightarrow \frac{r}{M_P}\widehat{p}$$

mass matrix $m = \frac{1}{2}(m_1 + m_2)\,1 + \frac{1}{2}(m_1 - m_2)\,\sigma_3$

$$\langle r_\mu \rangle = 0, \ \langle r_\mu r_\nu \rangle = \Delta_\mu \delta_{\mu\nu}$$

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 $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

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 $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

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

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

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

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

FLAVOUR FLIP
Perturbation due to
recoil distortion of space-time

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

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

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 $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

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

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

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

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

FLAVOUR FLIP
Perturbation due to
recoil distortion of space-time

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

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

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 $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

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

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

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \to \beta$

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

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

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 $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

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

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

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \to \beta$

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

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

ω-effect

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 $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

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

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

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \to \beta$

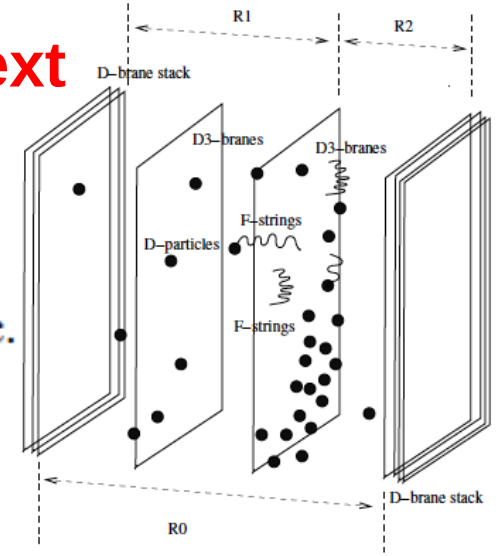
$$\beta^{(i)} = \frac{{}^{(i)}\langle\downarrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\uparrow\rangle^{(i)}}{E_1-E_2}$$

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

ω-effect

)

RHN Leptogenesis in D-particle foam context



$$\mathcal{L} = L_{\rm SM} + i\overline{N_R}\partial\!\!\!/ N_R - \frac{M_N}{2}(\overline{N_R^c}N_R + \overline{N_R}N_R^c) - Y_k\,\overline{L}_k\,\tilde{\phi}\,N_R + \text{h.c.}$$

$$\mathcal{N} \equiv N_R + N_R^c$$

$$\mathcal{L} = L_{\rm SM} + i\frac{1}{2}\overline{\mathcal{N}}\,\partial\!\!\!/\,\mathcal{N} - \frac{M_N}{2}\overline{\mathcal{N}}\,\mathcal{N} - Y_1\overline{L}_1\tilde{\phi}\,\frac{1}{2}(1+\gamma_5)\mathcal{N} - Y_1^\star\overline{\mathcal{N}}\,\frac{1}{2}(1-\gamma_5)\tilde{\phi}^\dagger\,L_1$$

$$\mathcal{L}_{D-foam/RHN-matter} = \mu_{\rm CPTV}\,N_R^\dagger\,N_R \qquad \mu_{\rm CPTV} = \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2$$

$$\mathcal{L}_{D-foam/RHN-matter} = \frac{1}{2}\,B_\mu\,\overline{\mathcal{N}}\,\gamma^\mu\,\gamma^5\,\mathcal{N}\,, \quad B_\mu = \delta_{\mu\,0}\,\mu_{\rm CPTV} = \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2 > 0$$

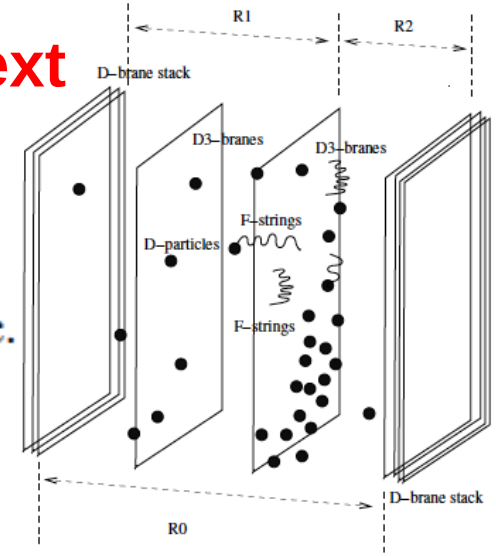
$$\sigma^2 = g_s^2\,\frac{T^2}{M_s^2}\,\Delta$$

$$E_r^2 = M_N^2 + (B_0 + \lambda_r\,|\vec{p}|)^2$$

$$\lambda_r = \pm 1,\; r = +,-$$

$$B_0 \sim \frac{g_s}{2\,M_s}\,T^2\,\Delta$$

RHN Leptogenesis in D-particle foam context



$$\mathcal{L} = L_{\rm SM} + i\overline{N_R}\partial\!\!\!/ N_R - \frac{M_N}{2}(\overline{N_R^c}N_R + \overline{N_R}N_R^c) - Y_k\,\overline{L}_k\,\tilde{\phi}\,N_R + \text{h.c.}$$

$$\mathcal{N} \equiv N_R + N_R^c$$

$$\mathcal{L} = L_{\rm SM} + i\frac{1}{2}\overline{\mathcal{N}}\,\partial\!\!\!/\,\mathcal{N} - \frac{M_N}{2}\overline{\mathcal{N}}\,\mathcal{N} - Y_1\overline{L}_1\tilde{\phi}\,\frac{1}{2}(1+\gamma_5)\mathcal{N} - Y_1^\star\overline{\mathcal{N}}\,\frac{1}{2}(1-\gamma_5)\tilde{\phi}^\dagger\,L_1$$

$$\mathcal{L}_{D-foam/RHN-matter} = \mu_{\rm CPTV}\,N_R^\dagger\,N_R \qquad \mu_{\rm CPTV} = \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2$$

$$\boxed{\mathcal{L}_{D-foam/RHN-matter} = \frac{1}{2}\,B_\mu\,\overline{\mathcal{N}}\,\gamma^\mu\,\gamma^5\,\mathcal{N}\,, \quad B_\mu = \delta_{\mu\,0}\,\mu_{\rm CPTV} = \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2 > 0}$$

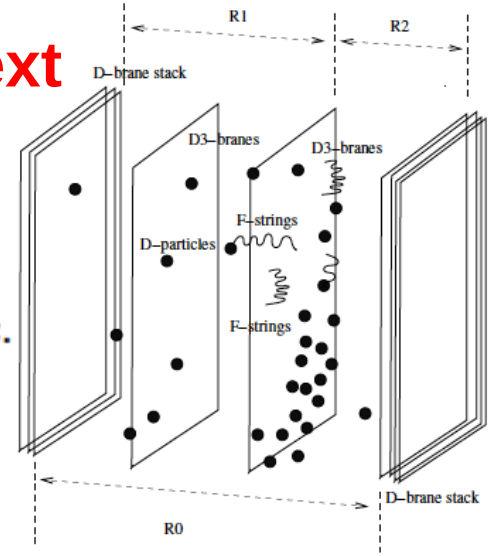
non constant B_0 in general,

Leptogenesis understanding pending or not relevant in this context

depends on Δ

$$B_0 \sim \frac{g_s}{2\,M_s}\,T^2\,\Delta$$

RHN Leptogenesis in D-particle foam context



$$\mathcal{L} = L_{\rm SM} + i\overline{N_R}\partial\!\!\!/ N_R - \frac{M_N}{2}(\overline{N_R^c}N_R + \overline{N_R}N_R^c) - Y_k\,\overline{L}_k\,\tilde{\phi}\,N_R + \text{h.c.}$$

$$\mathcal{N} \equiv N_R + N_R^c$$

$$\mathcal{L} = L_{\rm SM} + i\frac{1}{2}\overline{\mathcal{N}}\,\partial\!\!\!/\,\mathcal{N} - \frac{M_N}{2}\overline{\mathcal{N}}\,\mathcal{N} - Y_1\overline{L}_1\tilde{\phi}\,\frac{1}{2}(1+\gamma_5)\mathcal{N} - Y_1^\star\overline{\mathcal{N}}\,\frac{1}{2}(1-\gamma_5)\tilde{\phi}^\dagger\,L_1$$

$$\mathcal{L}_{D-foam/RHN-matter} = \mu_{\rm CPTV}\,N_R^\dagger\,N_R \qquad \mu_{\rm CPTV} = \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2$$

$$\boxed{\mathcal{L}_{D-foam/RHN-matter} = \frac{1}{2}\,B_\mu\,\overline{\mathcal{N}}\,\gamma^\mu\,\gamma^5\,\mathcal{N}\,, \quad B_\mu = \delta_{\mu\,0}\,\mu_{\rm CPTV} = \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2 > 0}$$

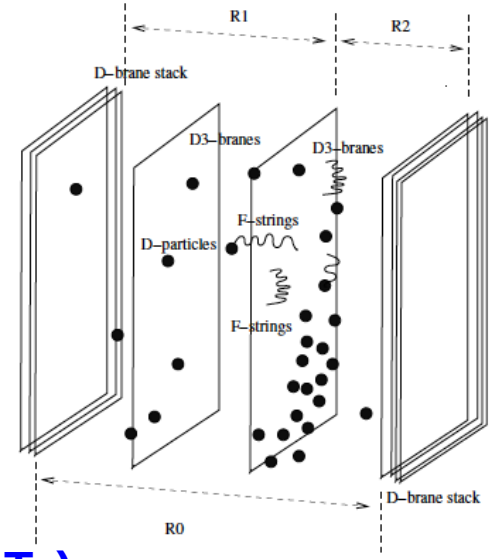
BUT may be approx. constant B_0 during leptegenesis (RHN freezeout) period

$$B_0 \sim \frac{g_s}{2\,M_s}\,T^2\,\Delta$$

RHN Leptogenesis as for constant B_0

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

for phenomenologically acceptable baryogenesis through leptogenesis



Assume Δ ~ constant during RHN freezeout period ($T \sim T_D$)
due to constant density of D-particles on brane world, due to influx from bulk

$$\frac{\dot{B}}{M_P\, B_0} \simeq -\frac{H}{M_P} \ll 1$$

BUT approx. constant B_0

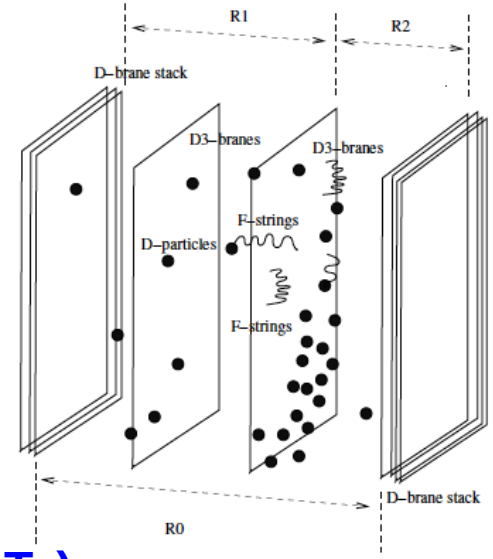
If D-particles on brane world dark-matter like → $\Delta \sim T^3$ ($T < T_D$)

$$B_0 \sim \frac{g_s}{2\, M_s}\, T^2\, \Delta$$

RHN Leptogenesis as for constant B_0

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

for phenomenologically acceptable baryogenesis through leptogenesis



Assume Δ ~ constant during RHN freezeout period ($T \sim T_D$)

$$\frac{\dot{B}}{M_P\, B_0} \simeq -\frac{H}{M_P} \ll 1$$

$$\Delta(T \sim T_D \simeq M_N) \sim 2 \times 10^{-8}\, \frac{M_s}{g_s\, M_N} < 1$$

$$\Rightarrow \frac{M_s}{g_s} < 5 \times 10^{-9}\, M_N,$$

$$M_N \sim 10^2\ \mathrm{TeV} \Rightarrow \frac{M_s}{g_s} < 10^{13}\ \mathrm{GeV}$$

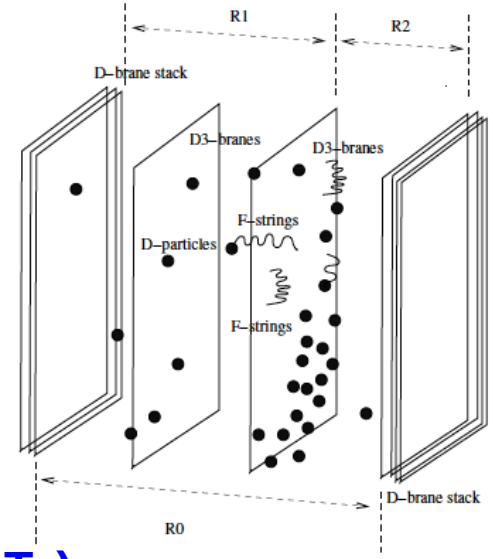
BUT approx. constant B_0

$$B_0 \sim \frac{g_s}{2\, M_s}\, T^2\, \Delta$$

RHN Leptogenesis as for constant B_0

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

for phenomenologically acceptable baryogenesis through leptogenesis



Assume Δ ~ constant during RHN freezeout period ($T \sim T_D$)

$$\frac{\dot{B}}{M_P\, B_0} \simeq -\frac{H}{M_P} \ll 1$$

$$\frac{\Delta(T \sim T_D \simeq M_N \simeq 10^2\,\mathrm{TeV})}{\Delta_{\mathrm{today}}} \sim \left(\frac{T_D}{T_{\mathrm{CMB}}}\right)^3 \sim 1.13 \times 10^{53}$$

BUT approx. constant B_0

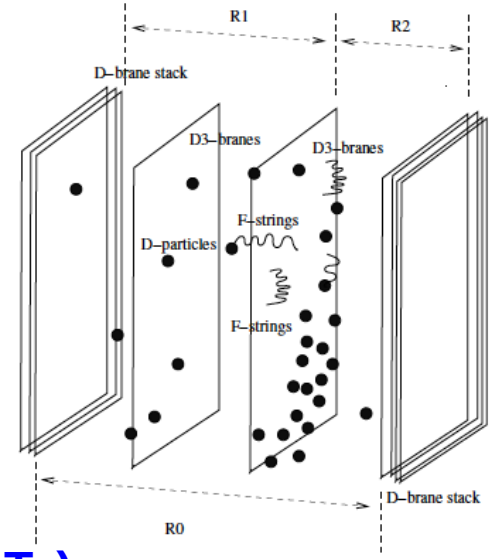
If D-particles on brane world dark-matter like → $\Delta \sim T^3$ ($T < T_D$)

$$B_0 \sim \frac{g_s}{2\, M_s}\, T^2\, \Delta$$

RHN Leptogenesis as for constant B_0

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

for phenomenologically acceptable baryogenesis through leptogenesis



Assume Δ ~ constant during RHN freezeout period (T ~ T_D)

$$\frac{\dot{B}}{M_P\, B_0} \simeq -\frac{H}{M_P} \ll 1$$

$$\frac{\Delta(T \sim T_D \simeq M_N \simeq 10^2\,\mathrm{TeV})}{\Delta_{\mathrm{today}}} \sim \left(\frac{T_D}{T_{\mathrm{CMB}}}\right)^3 \sim 1.13 \times 10^{53}$$

Neutral Kaons in Φ-factories

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

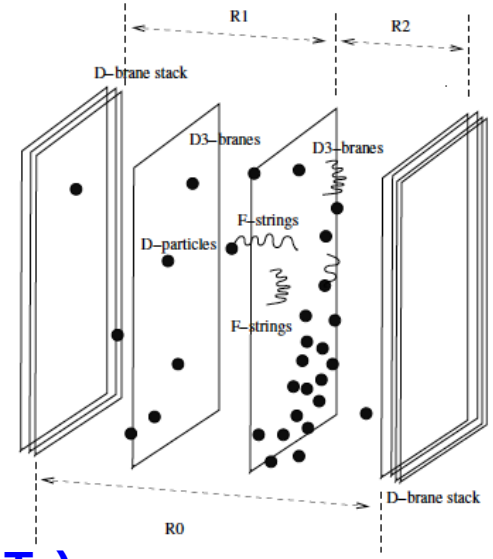
$$\Delta(T \sim T_D \simeq M_N \simeq 10^2) \sim 1.13 \times 10^{53}\, \Delta_0$$

$$\text{But } \Delta(T = M_N \simeq 10^2\,\mathrm{TeV}) < 1 \;\Rightarrow\; \Delta_0 < 8 \times 10^{-53}$$

RHN Leptogenesis as for constant B_0

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

for phenomenologically acceptable baryogenesis through leptogenesis



Assume Δ ~ constant during RHN freezeout period (T ~ T_D)

$$\frac{\dot{B}}{M_P\, B_0} \simeq -\frac{H}{M_P} \ll 1$$

$$\frac{\Delta(T \sim T_D \simeq M_N \simeq 10^2\ \mathrm{TeV})}{\Delta_{\mathrm{today}}} \sim \left(\frac{T_D}{T_{\mathrm{CMB}}}\right)^3 \sim 1.13 \times 10^{53}$$

Neutral Kaons in Φ-factories

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

$$\Delta(T \sim T_D \simeq M_N \simeq 10^2) \sim 1.13 \times 10^{53}\, \Delta_0$$

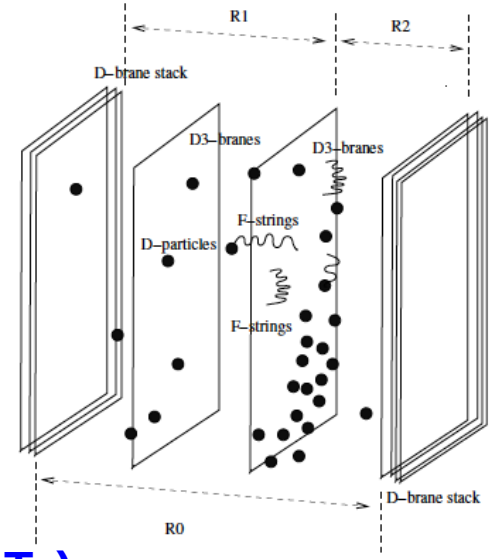
$$\text{But } \Delta(T = M_N \simeq 10^2\ \mathrm{TeV}) < 1 \Rightarrow \Delta_0 < 8 \times 10^{-53}$$

Far below current sensitivities !

RHN Leptogenesis as for constant B_0

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

for phenomenologically acceptable baryogenesis through leptogenesis



Assume Δ ~ constant during RHN freezeout period (T ~ T_D)

$$\frac{\dot{B}}{M_N B} \simeq -\frac{H}{}$$

$$\Delta(T \sim T \qquad) \sim \left(\frac{T_D}{T_{\rm CMB}}\right)^3$$

But of course this is one crude model of QG, we do not have a concrete theory yet → hence cannot tell ....

$$\Delta(T \sim T_D \simeq M_N \simeq 10^2) \sim 1.13 \times 10^{53}\, \Delta_0$$

$$\text{But } \Delta(T = M_N \simeq 10^2\ \text{TeV}) < 1 \Rightarrow \boxed{\Delta_0 < 8 \times 10^{-53}}$$

Far below current sensitivities !