Nonminimal CPT violation in neutral-meson oscillations

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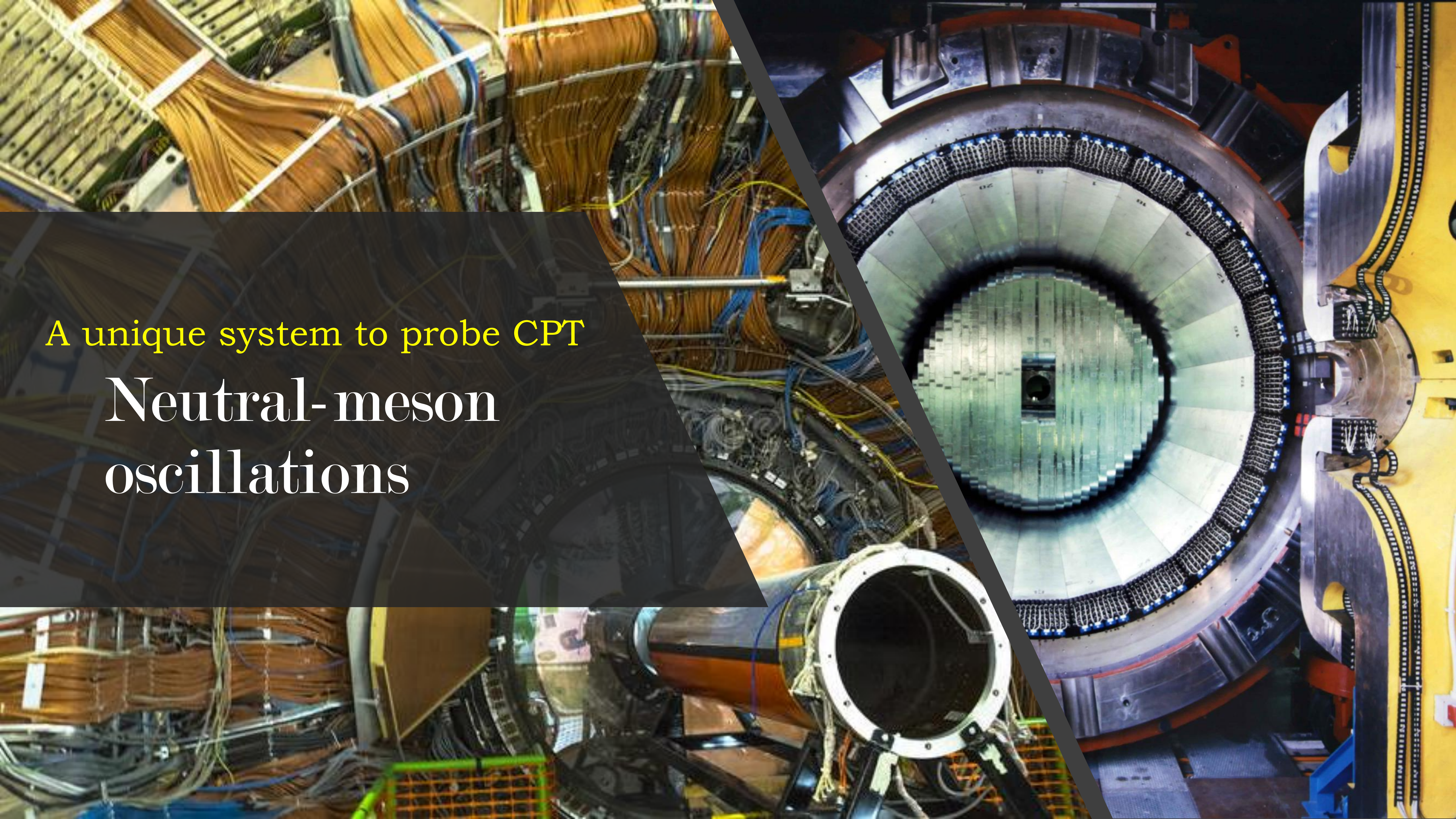
July 2019

Outline

- Neutral-meson oscillations
- CPT violation and the SME
- Effective field theory
- Experimental prospects

A unique system to probe CPT

Neutral-meson oscillations



Meson physics

- Formalism describing oscillations predates the Standard Model
- Includes parameter for CPT violation ξ
- Reasonable to assume ξ is just a constant in context of NRQM
- SME: a framework based on effective field theory to search for violations of CPT symmetry
- Surprisingly, a constant nonzero ξ is not possible in this framework
- Instead, it must depend on meson 3-velocity and energy

Kostelecký PRL 1998, Colladay, Kostelecký PRD 1998, 1997

Meson physics

flavor eigenstates

$$\Psi = \begin{pmatrix} P^0 \\ \overline{P}^0 \end{pmatrix}$$

$$P^0 = \{K^0, D^0, B_d^0, B_s^0\}$$

time evolution

$$i\partial_t \Psi = \Lambda\Psi$$

$$|P_{a,b}(t)\rangle = \exp(-i\lambda_{a,b}t)|P_{a,b}\rangle$$

$$\lambda_{a,b} \equiv m_{a,b} - \tfrac{1}{2}i\gamma_{a,b}$$

- Propagating eigenstates are not flavor eigenstates
- In meson/antimeson subspace, hamiltonian is not hermitian
- Time evolution not unitary

Lee, Wu Annu. Rev. Nucl. Sci. 1966

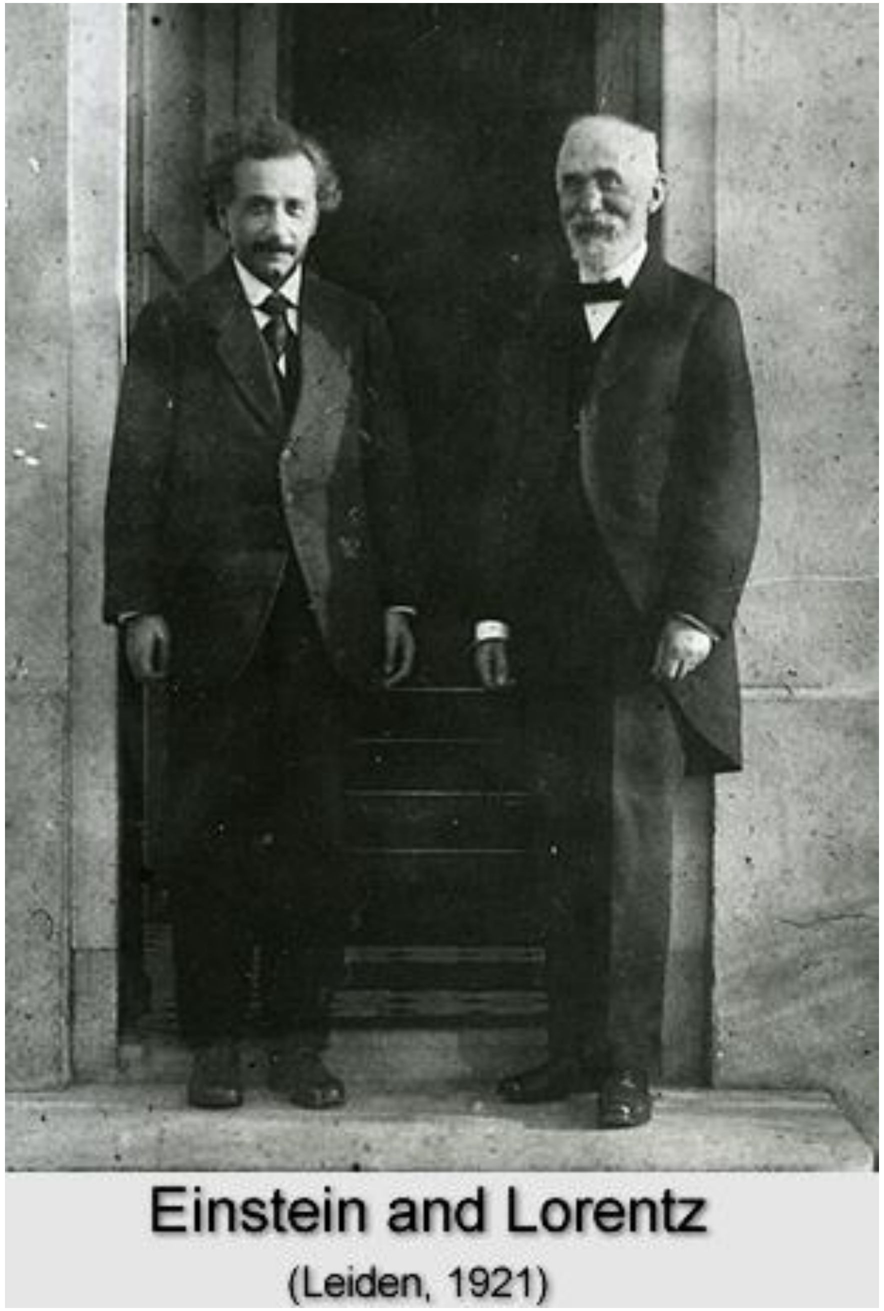
Meson physics

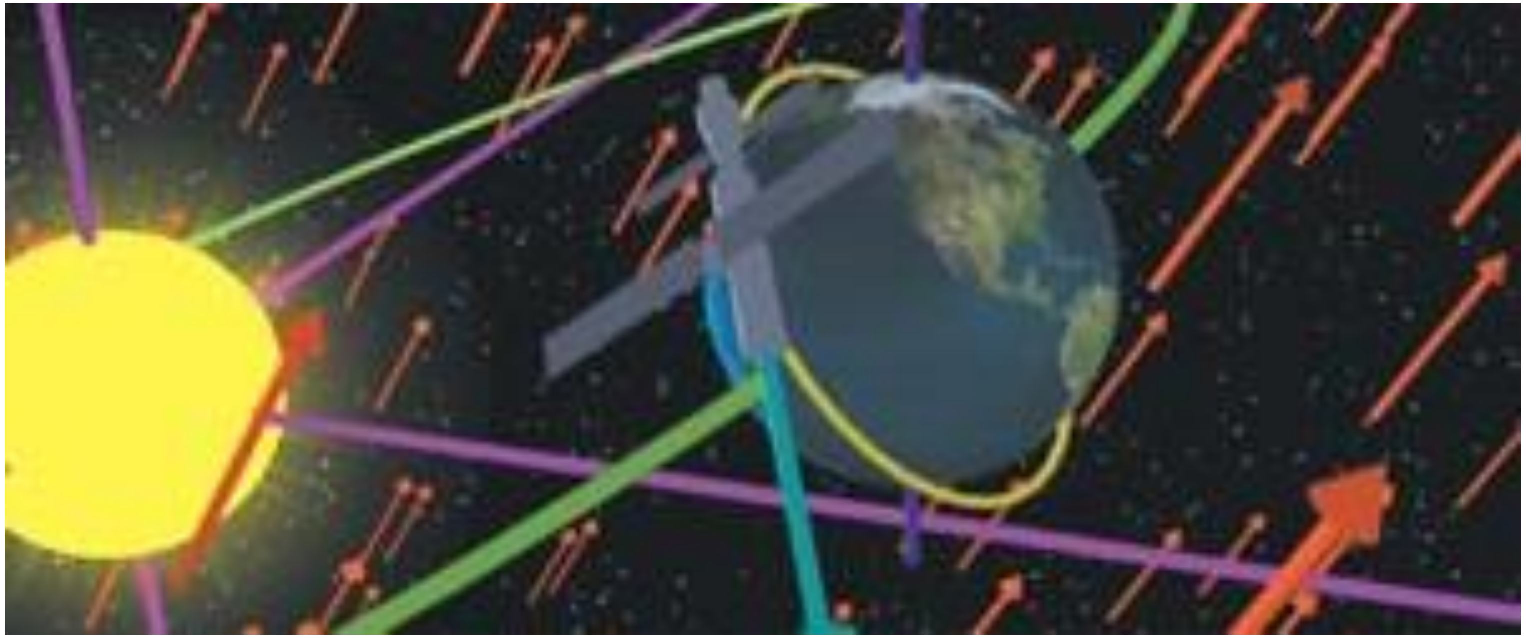
$$\Lambda = \frac{1}{2}\Delta\lambda \begin{pmatrix} U+\xi & VW^{-1} \\ VW & U-\xi \end{pmatrix}$$

- 8 parameters:
  - 2 masses, 2 decay rates
  - 1 T violation
  - 2 CPT violation
  - 1 overall phase

CPT violation when

$$\mathrm{Re}\,\xi \neq 0 \quad , \quad \mathrm{Im}\,\xi \neq 0$$

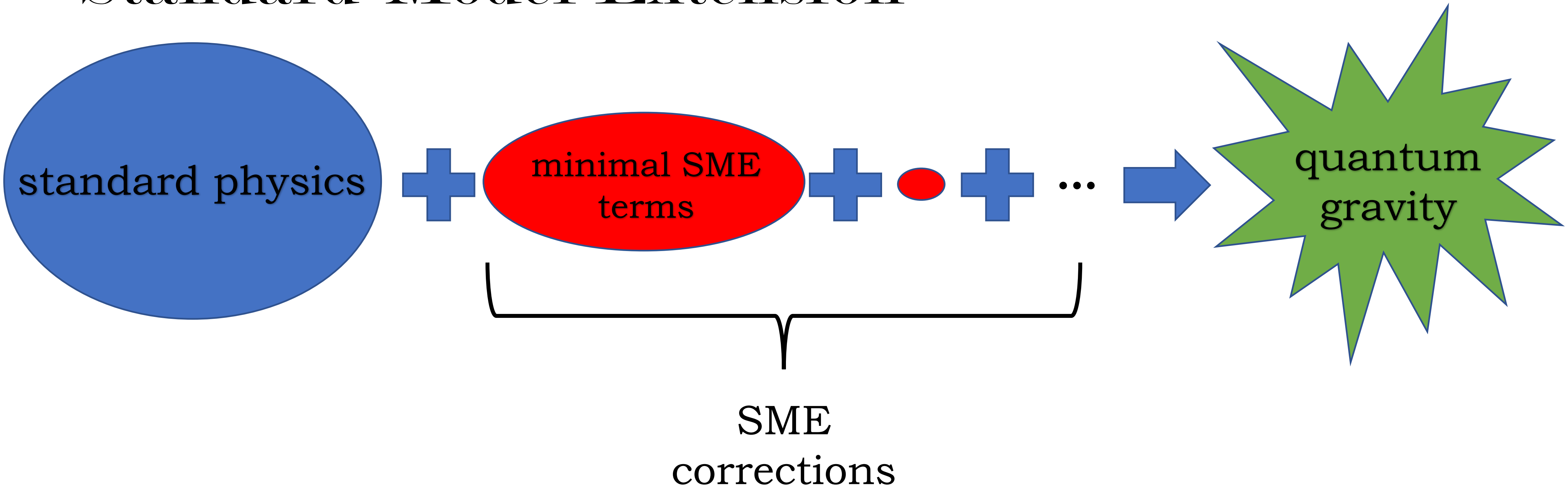




The Standard-Model Extension

A framework for CPT violation

Standard-Model Extension



- Minimal SME refers to mass dimension 3 and 4
- Nonminimal SME refers to $d > 4$

A framework for CPT violation: The Standard-Model Extension

- Want perturbations of known physics that
  - keep general coordinate invariance
  - incorporate CPT violation

$$\mathcal{L} \supset \tfrac{1}{2} i \overline{\psi} \Gamma^{\mu} \overleftrightarrow{\partial}_{\mu} \psi - \overline{\psi} M \psi$$

$$\Gamma^{\mu} \supset \gamma^{\mu} + e^{\mu} + i f^{\mu} \gamma_5 + \tfrac{1}{2} g^{\mu\nu\lambda} \sigma_{\nu\lambda} \qquad M \supset m + a_{\mu} \gamma^{\mu} + b_{\mu} \gamma_5 \gamma^{\mu}$$

- These terms violate Lorentz symmetry as expected

The SME and neutral-meson oscillations

- Extensive study of CPT violation using the SME framework

LHCb Collaboration, Aaij *et al.* PRL 2016
D0 Collaboration, Abazov *et al.* PRL 2015
KLOE Collaboration, Babusci *et al.* PLB 2014
BaBar Collaboration, Aubert *et al.* PRL 2008
FOCUS Collaboration, Link *et al.* PLB 2003
KTeV Collaboration, Nguyen hep-ex/0112046

- Constraints on minimal CPT odd quark coefficients

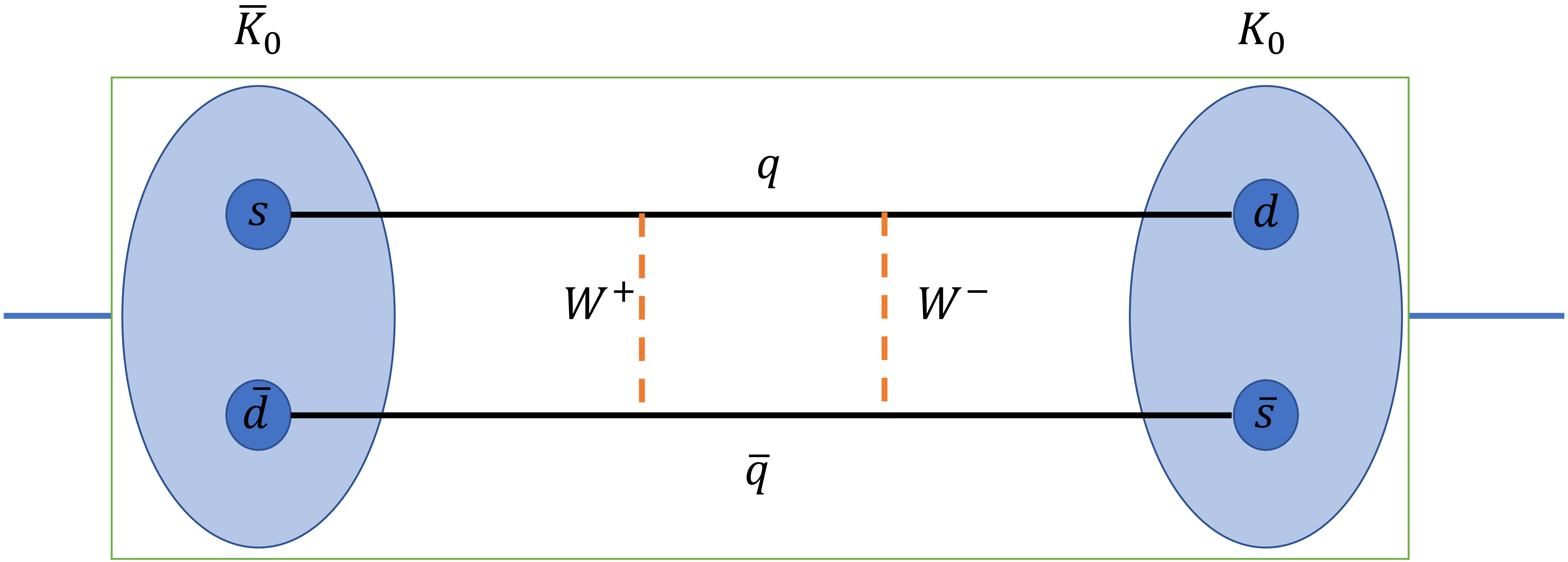
- What about contributions from nonminimal SME?

Effective scalar field theory

Extending the existing formalism

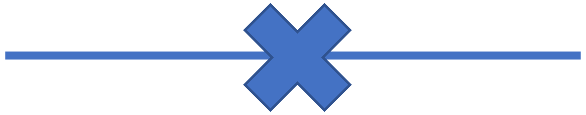
Standard picture

- Complications due to sea particles, interactions
- Many different LV insertions



Effective scalar field theory

- Propagation of meson effectively described by scalar φ
- Effects of nonminimal Lorentz violation can be inferred
- Exact match to SME can be done later



Effective scalar field theory

$$\mathcal{L}(\phi,\phi^\dagger) = \partial^\mu\phi^\dagger\partial_\mu\phi - m^2\phi^\dagger\phi - \tfrac{1}{2}[\underbrace{i\phi^\dagger(\widehat{k}_a)^\mu\partial_\mu\phi}_{} + \text{h.c.}] + \cdots$$

odd number of derivatives

$$(\widehat{k}_a)^\mu = \sum_{d=3}(i)^{d-3}(k_a^{(d)})^{\mu\alpha_1\alpha_2\cdots\alpha_{d-3}}\partial_{\alpha_1}\partial_{\alpha_2}\cdots\partial_{\alpha_{d-3}}$$

- Coefficients have constant cartesian components in defining frame
- Flavor *U(1)* breaking incorporated
- Can be taken as traceless and symmetric… $(d-1)^2$ components

Effective scalar field theory

- Produces the parameter for CPT violation in terms of velocities measured in the lab

$$\xi^{(d)} = \frac{m^{d-3}\gamma^{d-2}}{\Delta\lambda} \sum_k \binom{d-2}{k} \beta^k (k_a^{(d)})_{T\cdots T J_1 \cdots J_k} \hat{\beta}'^{J_1} \cdots \hat{\beta}'^{J_k}$$

$$\begin{aligned}
\hat{\beta}'^X &= (\hat{\beta}^x \cos\chi + \hat{\beta}^z \sin\chi) \cos\Omega T - \hat{\beta}^y \sin\Omega T \\
\hat{\beta}'^Y &= \hat{\beta}^y \cos\Omega T - (\hat{\beta}^x \cos\chi + \hat{\beta}^z \sin\chi) \sin\Omega T \\
\hat{\beta}'^Z &= \hat{\beta}^z \cos\chi - \hat{\beta}^x \sin\chi
\end{aligned}$$

Parameter for CPT violation

$$\xi^{(d)} = \frac{m^{d-3}\gamma^{d-2}}{\Delta\lambda} \sum_k \binom{d-2}{k} \beta^k (k_a^{(d)})_{T\cdots T J_1 \cdots J_k} \hat{\beta}'^{J_1} \cdots \hat{\beta}'^{J_k}$$

mass dimension $d = 5$

$$\xi^{(5)} = \frac{m^2\gamma^3}{\Delta\lambda} \Big[\mathcal{A}_0 + \mathcal{A}_1 \cos \Omega T + \mathcal{B}_1 \sin \Omega T + \mathcal{A}_2 \cos 2\Omega T + \mathcal{B}_2 \sin 2\Omega T + \mathcal{A}_3 \cos 3\Omega T + \mathcal{B}_3 \sin 3\Omega T \Big]$$

Parameter for CPT violation

mass dimension $d = 5$

$$\xi^{(5)} = \frac{m^2\gamma^3}{\Delta\lambda}\Big[\,\mathcal{A}_0 + \mathcal{A}_1\cos\Omega T + \mathcal{B}_1\sin\Omega T + \mathcal{A}_2\cos 2\Omega T + \mathcal{B}_2\sin 2\Omega T + \mathcal{A}_3\cos 3\Omega T + \mathcal{B}_3\sin 3\Omega T\Big]$$

$$\begin{aligned}\mathcal{A}_0 = {} & (k_a^{(5)})_{TTT} + 3(\beta^z\cos\chi - \beta^x\sin\chi)\big[(k_a^{(5)})_{TTZ} + (\beta^z\cos\chi - \beta^x\sin\chi)(k_a^{(5)})_{TZZ}\big] \\ & + \frac{3}{2}\big((\beta^x\cos\chi + \beta^z\sin\chi)^2 + (\beta^y)^2\big)\big[(k_a^{(5)})_{TXX} + (k_a^{(5)})_{TYY}\big] \\ & + \frac{3}{2}(\beta^z\cos\chi - \beta^x\sin\chi)\big((\beta^x\cos\chi + \beta^z\sin\chi)^2 + (\beta^y)^2\big)\big[(k_a^{(5)})_{XXZ} + (k_a^{(5)})_{YYZ}\big] \\ & + (\beta^z\cos\chi - \beta^x\sin\chi)^3(k_a^{(5)})_{ZZZ}\end{aligned}$$

Parameter for CPT violation

- CPT parameter measured using asymmetries in minimal case
- Nonminimal contributions can be measured using the same asymmetries!

$$P_f(t, T, \vec{p}) \equiv |\langle f|\hat{O}|P(t), T, \vec{p}\rangle|^2$$

$$\mathcal{A}_{CPT} = \frac{\bar{P}_{\bar{f}} - P_f}{\bar{P}_{\bar{f}} + P_f}$$

dependence on
sidereal time and
momentum from §

Edwards, Kostelecký PLB 2019; Kostelecký PRD 2001

Experimental prospects

Future possibilities and estimated bounds

Future investigations

- Each $d = 5$ coefficient has 16 independent components
- 4 meson species gives total of 64 unexplored observables
- Need experiments to test each of the 4 meson species
- High-boost experiments benefit from higher powers of gamma
- Correlated-meson experiments can yield better refinement

Inferred constraints

- Previous experiments assumed the form of $d = 3$ type coefficients
- Results can be translated into constraints on $d = 5$ coefficients
- Need to make assumptions due to the fundamentally different form of nonminimal coefficients

1. Eliminate $k_{\mu ZZ}$ with trace conditions

2. Assume only $k_{\mu TT} \neq 0$

3. Assume conservative average values for any velocity dependent prefactors

Attainable sensitivities (GeV^{-1})

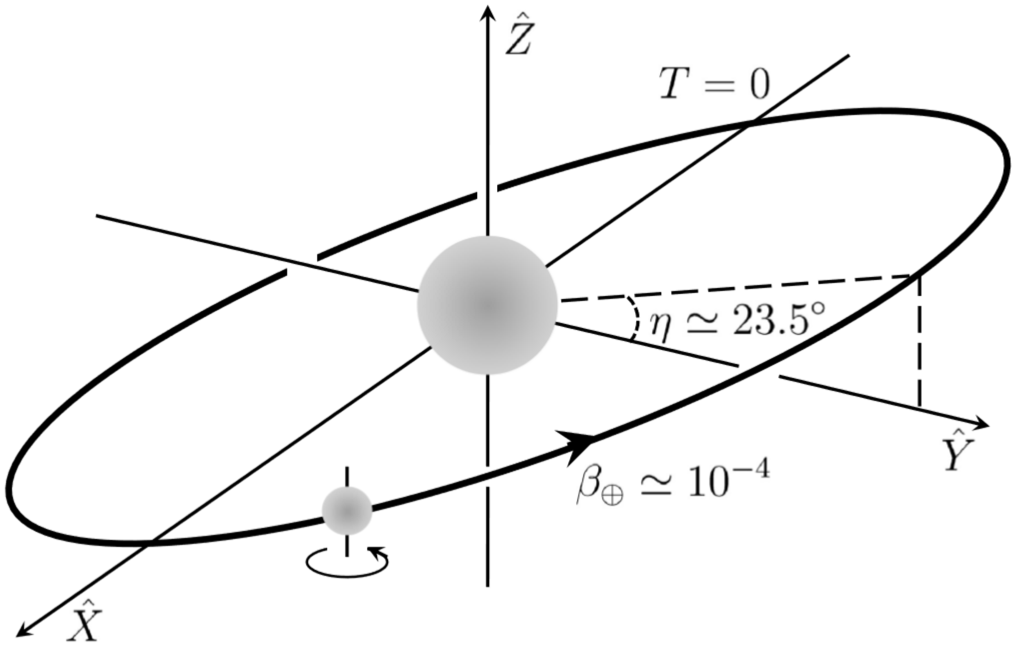
Coefficient	K^0 system	D^0 system	B_d^0 system	B_s^0 system
$(k_a^{(5)})_{TTT}$	10^{-17}	10^{-20}	10^{-20}	10^{-18}
$(k_a^{(5)})_{TTJ}$	10^{-18}	10^{-20}	10^{-20}	10^{-18}
$(k_a^{(5)})_{TJK}$	???	???	???	???
$(k_a^{(5)})_{JKL}$	???	???	???	???
Experiment	KLOE	LHCb, …	LHCb, …	D0, LHCb, …

Summary

- Neutral mesons are excellent systems for studying CPT
- Using EFT we can find nonminimal contributions to ξ
- 64 new observable types of CPT violation for $d = 5$
- First bounds on 16 of 64 types of nonminimal CPT violation in neutral mesons
- Experimental analyses needed to measure the other 48!

Sun-centered frame

- SCF:
  - T measured from vernal equinox 2000
  - Z-axis parallel to north pole
  - X-axis tied to vernal equinox 2000
  - Y-axis completes right-handed system

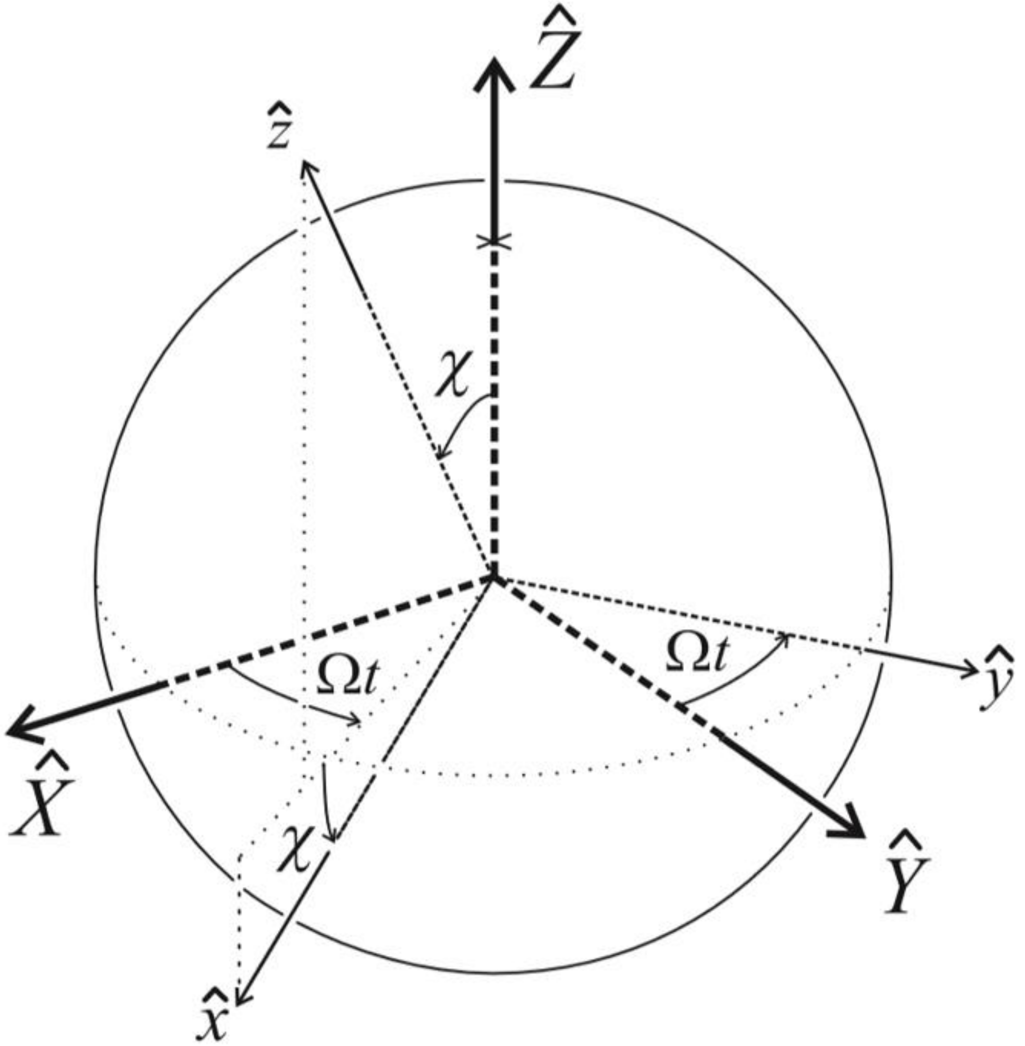


Sun-centered frame to lab frame

- Need two parameters to convert between

- Sidereal frequency $\Omega = \left(\frac{2\pi}{23.93}\right)\frac{rad}{hr}$

- $\cos\chi = \hat{z}\cdot\hat{Z}$



Effective field theory

- Terms that break both CPT and U(1) are total derivatives
- Terms that preserve CPT but break U(1) appear off-diagonal
- Terms that preserve both CPT and U(1) contribute equally to diagonal components
- Only one kind of term contributes!

$$\mathcal{L} \supset \tfrac{1}{2} i\phi^\dagger (\widehat{k}_a)^\mu \partial_\mu \phi + \text{h.c.}$$

Symmetric and traceless means $(d-1)^2$ independent components

Minimal vs. nonminimal

$$\xi^{(d)} = \frac{1}{\Delta\lambda} \sum_k \binom{d-2}{k} m^{d-3} \gamma^{d-2} \beta^k (k_a^{(d)})_{0\cdots 0 j_1 \cdots j_k} \hat{\beta}'^{j_1} \cdots \hat{\beta}'^{j_k}$$

mass dimension $d = 3$

one power of gamma...

$$\xi^{(3)} = \frac{\gamma}{\Delta\lambda} \Big[(k_a^{(3)})_T + (\beta^z \cos\chi - \beta^x \sin\chi)(k_a^{(3)})_Z$$
$$+ \big((\beta^z \sin\chi + \beta^x \cos\chi)(k_a^{(3)})_Y - \beta^y (k_a^{(3)})_X \big) \sin \Omega T$$
$$+ \big(\beta^y (k_a^{(3)})_Y + (\beta^z \sin\chi + \beta^x \cos\chi)(k_a^{(3)})_X \big) \cos \Omega T \Big]$$

dependence on sidereal time