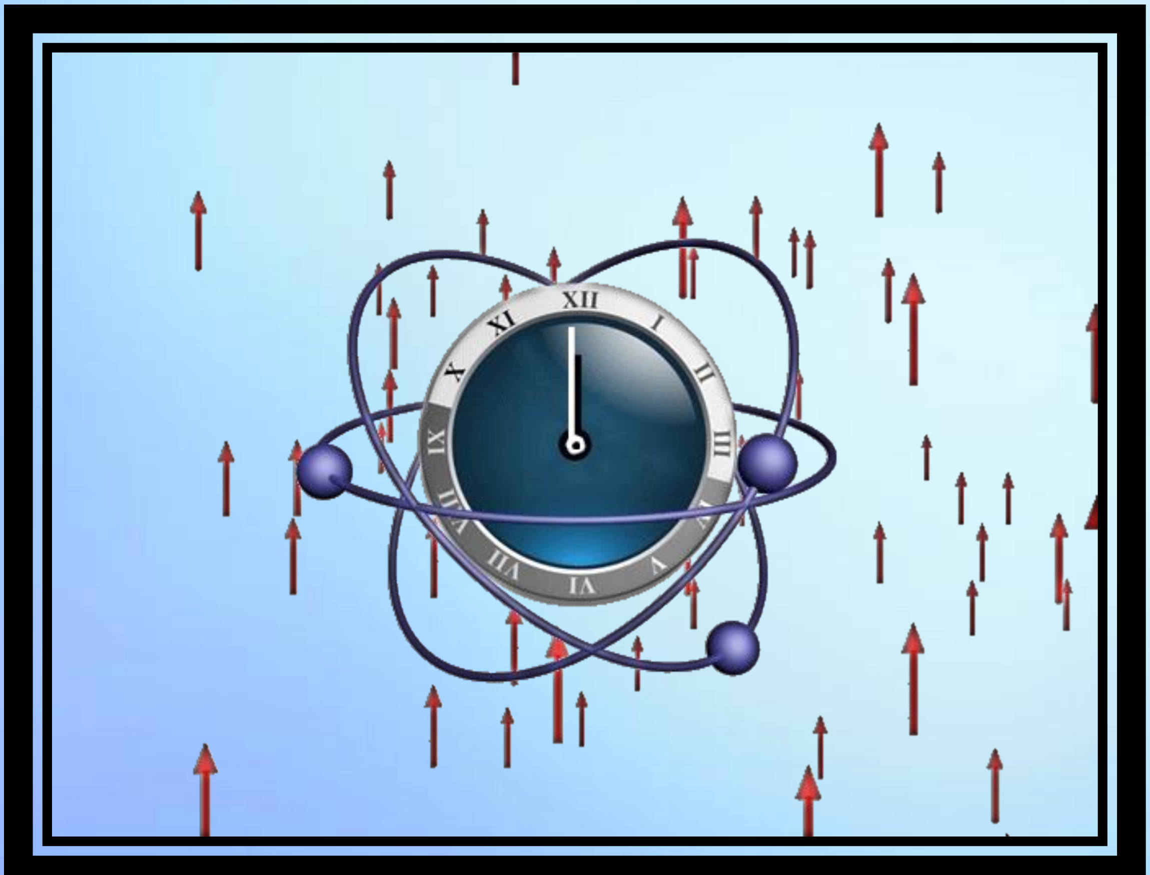
CPT violation, Lorentz violation, and low-energy antiprotons



Arnaldo Vargas

LOYOLA UNIVERSITY NEW ORLEANS

Why Lorentz violation?

Possible low-energy signature for theories beyond the Standard Model and General Relativity

Examples

String theory

Permits mechanisms for spontaneous Lorentz breaking compatible with gauge symmetries

Kostelecký and Samuel, PRD **39**, 683 (1989)

Non-commutative field theory

Different directions do not commute

Carroll *et al.,* PRL 87,141601 (2001)

Loop quantum gravity

The volume of a hypersurface is a field operator with a discrete spectrum

Florian *et al.,* SIGMA 8, 098 (2012)

Relation between CPT symmetry and Lorentz symmetry

Field operator

$$A^{\mu_1 \dots \mu_n} \overset{\text{CPT}}{\Rightarrow} (-1)^{\mathrm{n}} A^{\mu_1 \dots \mu_n}$$

Even # indexes ⇒ CPT even

Odd # indexes ⇒ CPT odd

Lorentz-invariant field theory

$$A^{\mu_1 \dots \mu_n} B_{\mu_1 \dots \mu_n} \overset{\text{CPT}}{\Rightarrow} (-1)^{2n} A^{\mu_1 \dots \mu_n} B_{\mu_1 \dots \mu_n} = A^{\mu_1 \dots \mu_n} B_{\mu_1 \dots \mu_n}$$

Lorentz-violating field theory

$$k_{\mu_1 \dots \mu_n} A^{\mu_1 \dots \mu_n} \overset{\text{CPT}}{\Rightarrow} (-1)^{n} k_{\mu_1 \dots \mu_n} A^{\mu_1 \dots \mu_n}$$

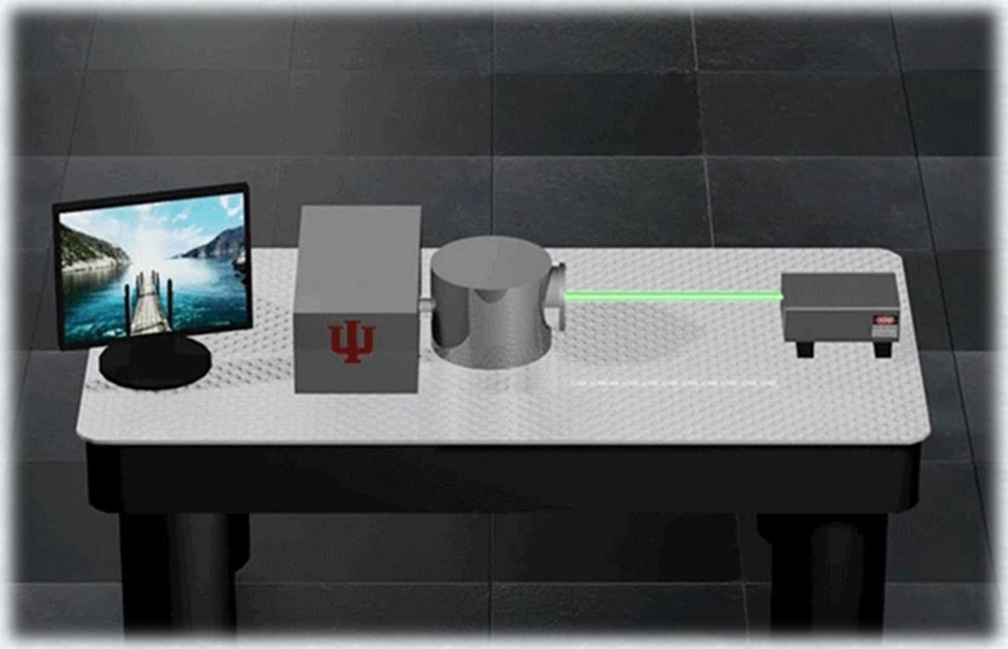
In an interacting quantum field theory CPT violation implies Lorentz violation

Greenberg, PRL **89**, 231602 (2002)

Lorentz symmetry

Experimental results are independent of the overall orientation and velocity of the experiment

Lorentz symmetry



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Lorentz symmetry

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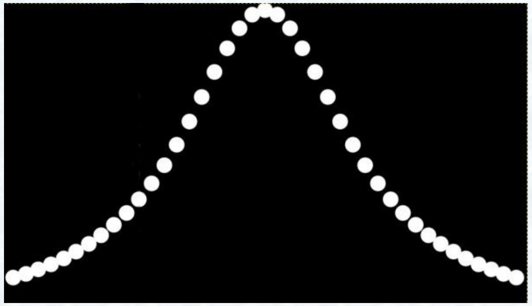
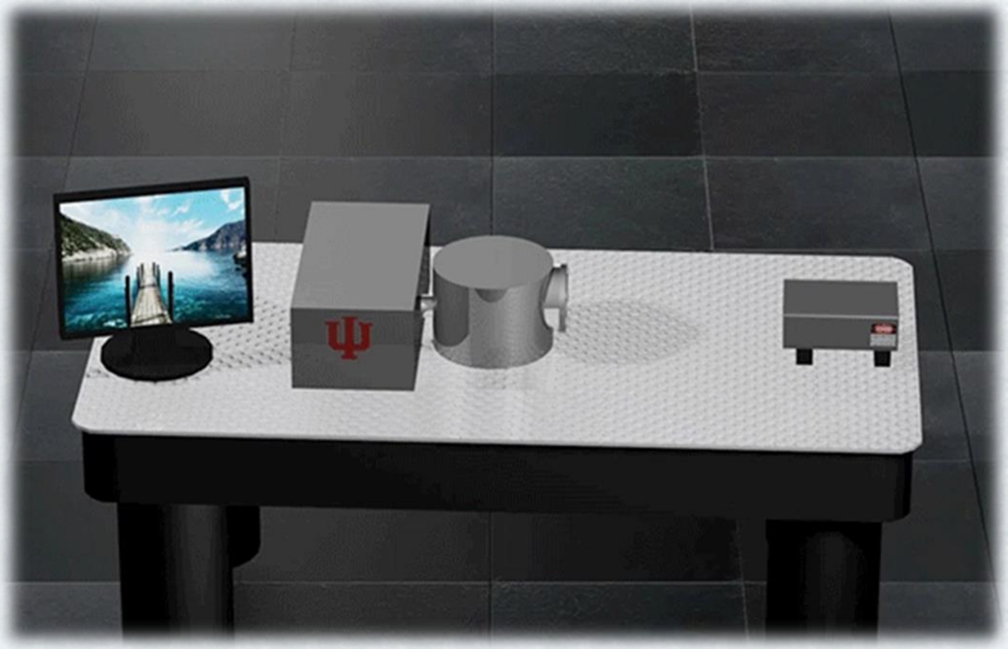
Original inertial reference frame



Lorentz symmetry



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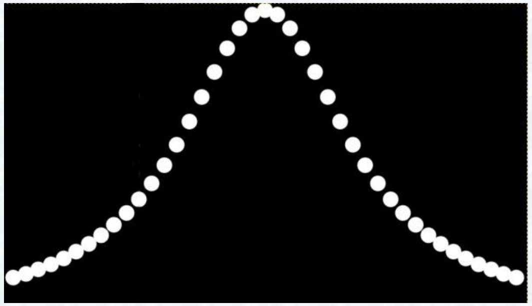

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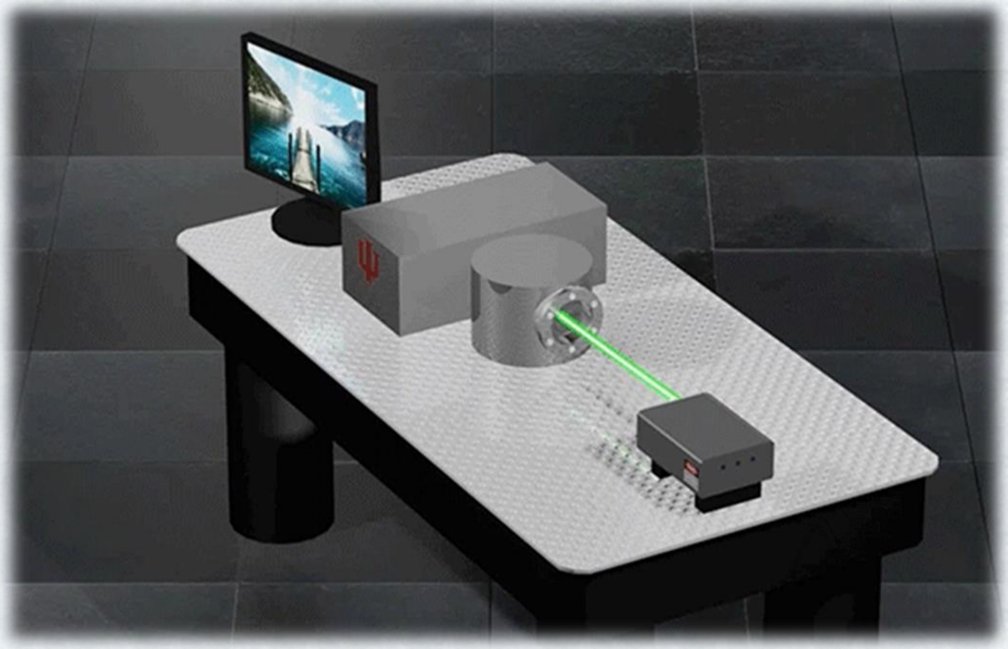

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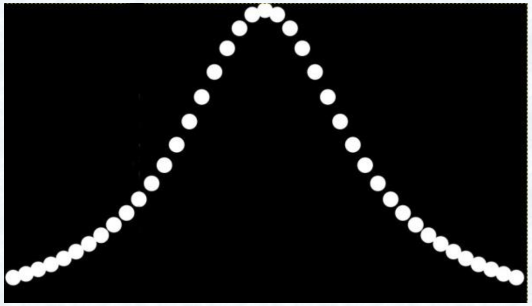

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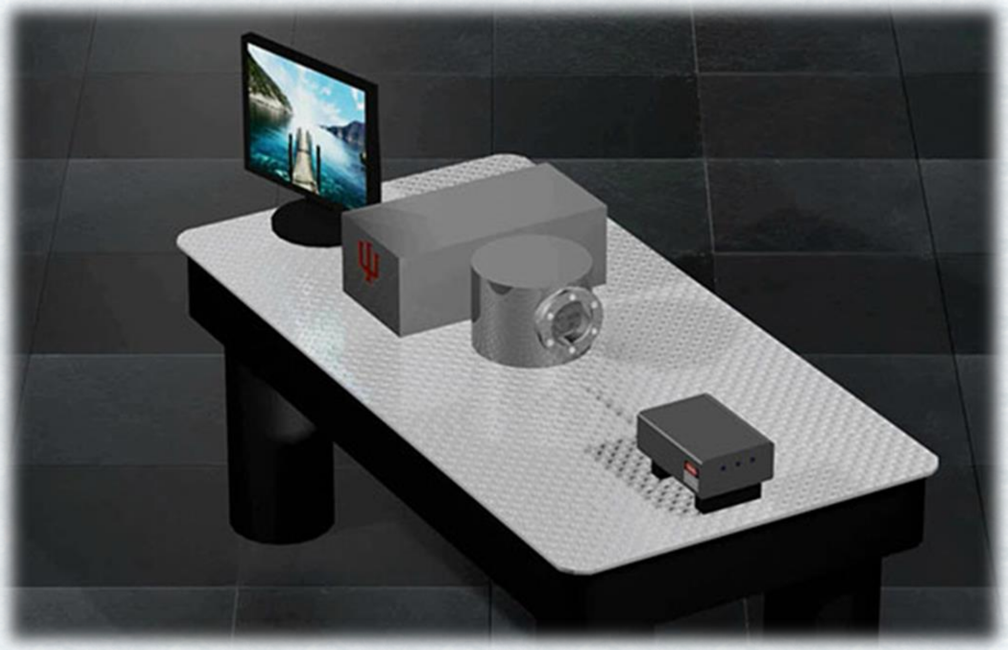
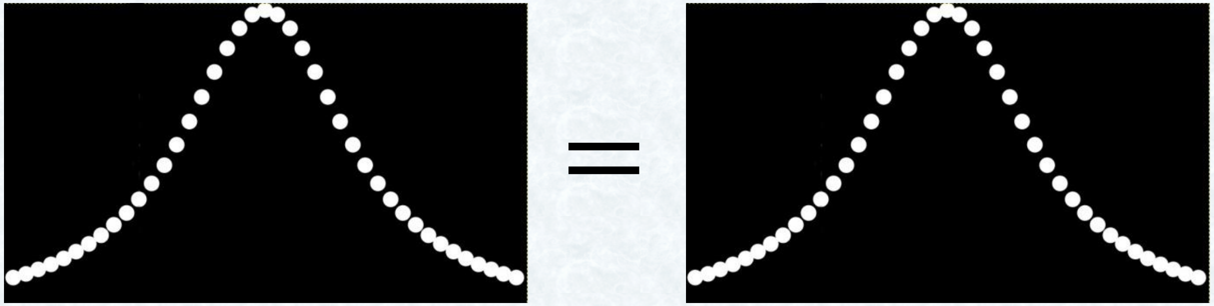


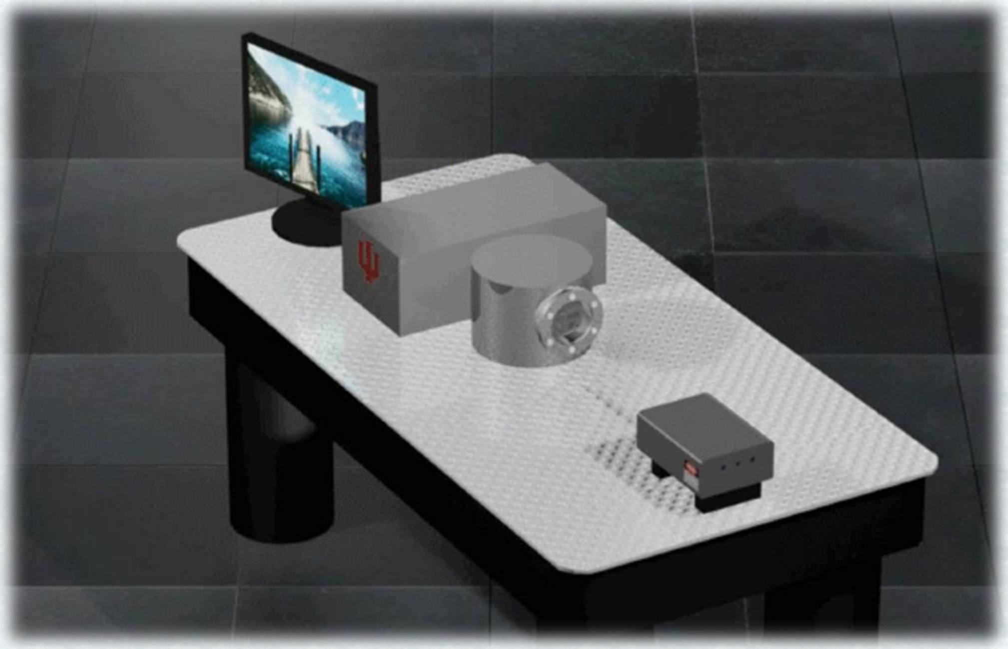
Experimental results are independent of the overall orientation and velocity of the experiment

Original inertial reference frame

Rotated reference frame

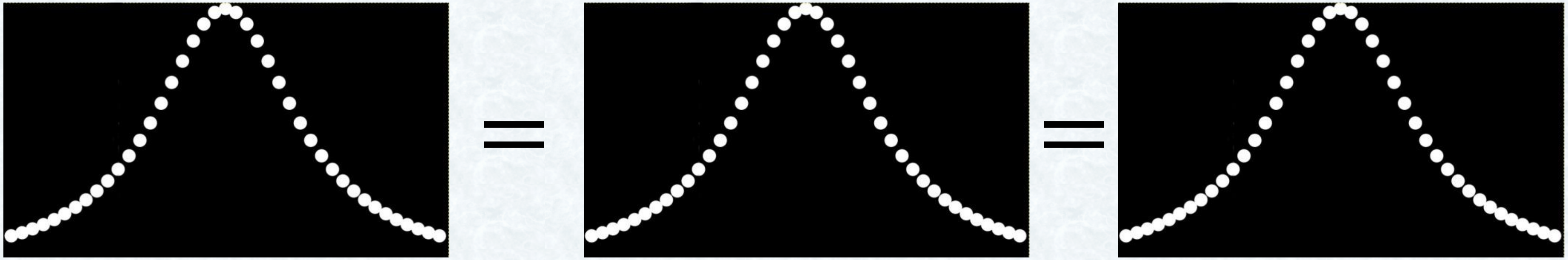


Lorentz symmetry



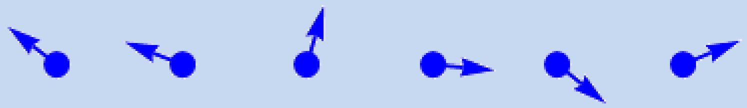
Experimental results are independent of the overall orientation and velocity of the experiment

Original inertial reference frame | Rotated reference frame | Boosted reference frame



How can we represent violations of Lorentz symmetry?

Representing Broken symmetries

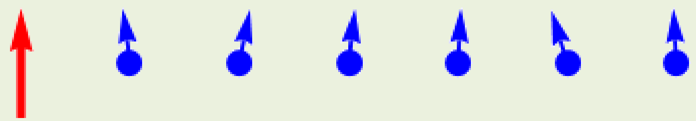


Symmetry: relative orientation of the magnetic dipoles

Representing Broken symmetries

Symmetry: relative orientation of the magnetic dipoles

Explicit symmetry breaking



Applied magnetic field

$$H = \cdots + c_i \, \vec{\boldsymbol{B}} \cdot \vec{\mu}_i + \cdots$$

The magnetic field explicitly selects a preferred orientation

Representing Broken symmetries

Symmetry: relative orientation of the magnetic dipoles

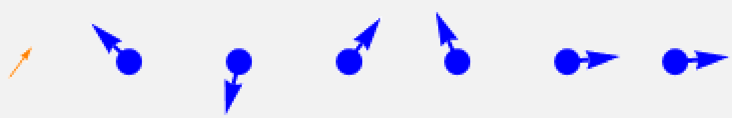
Explicit symmetry breaking

Applied magnetic field

$$H = \cdots + c_i \, \vec{\boldsymbol{B}} \cdot \vec{\mu}_i + \cdots$$

The magnetic field explicitly selects a preferred orientation

Spontaneous symmetry breaking



$T \to 0$

Magnetization

$$\mu_i = \vec{\boldsymbol{M}} + \delta\mu_i$$

$$H \simeq \cdots + c_i \, \vec{\boldsymbol{M}} \cdot \vec{\mu}_i + \cdots$$

The magnetization is a preferred orientation

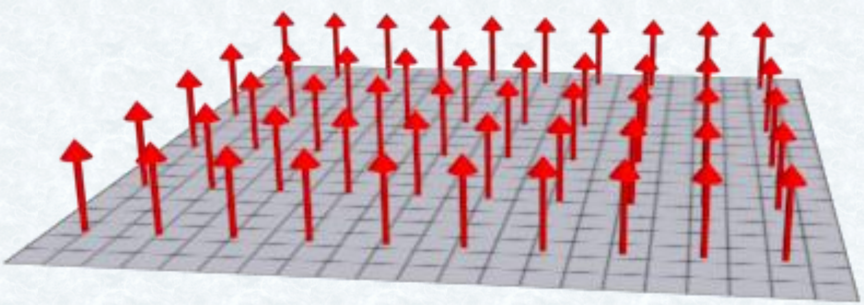
Lorentz violation as background fields

Lorentz-violation controlling coefficients **Field operator**

$$\mathcal{L} = \cdots + e^{\mu}\bar{\psi} i \partial_{\mu} \psi + \cdots$$

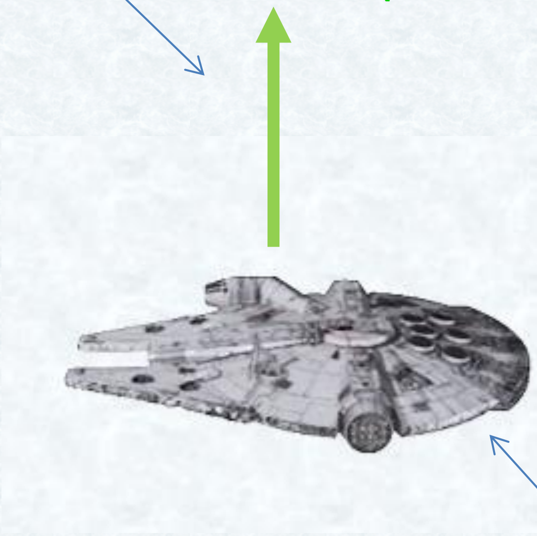
Lorentz-violation controlling coefficients can be understood as the components of constant uniform background fields that permeate Minkowski spacetime

Representation of e^{μ}



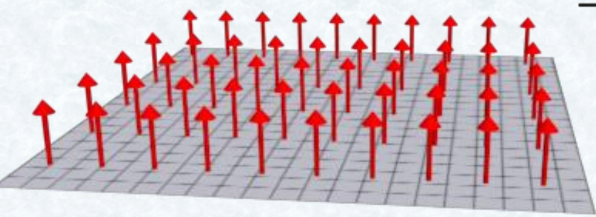
Fixed inertial reference frame

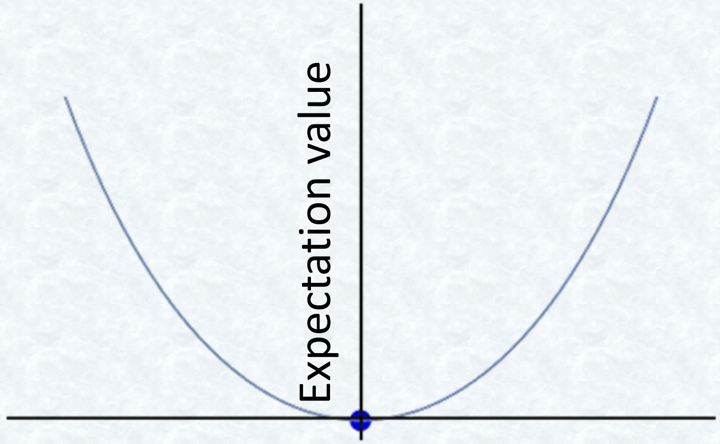
Representation of $\langle \bar{\psi} i \partial_{\mu} \psi \rangle$



Lab frame

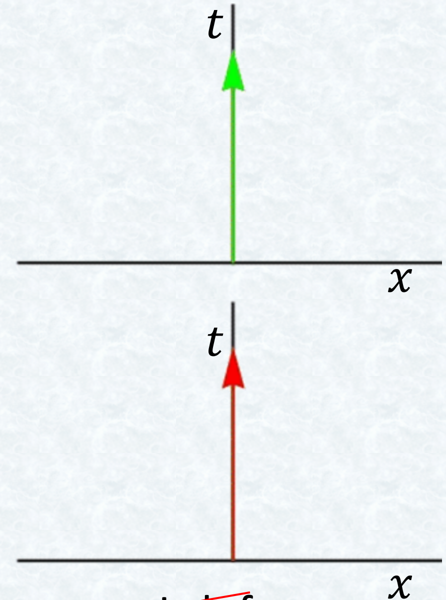
$$\langle e^{\mu}\bar{\psi} i \partial_{\mu} \psi \rangle$$





Relative velocity between lab frame and fixed frame

Fixed inertial frame



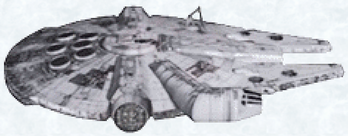
~~Lab frame~~

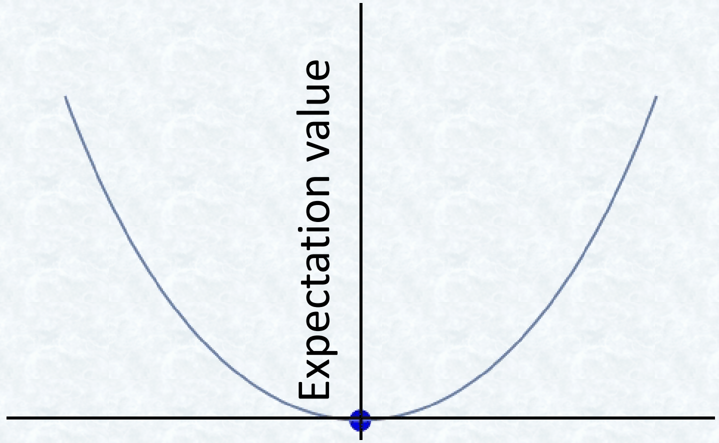
Chewie's

Yoda's

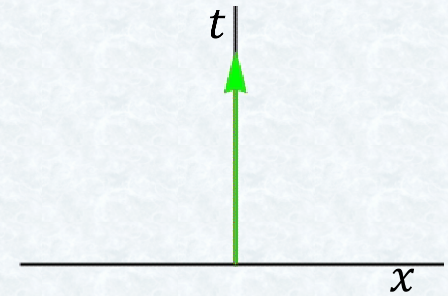
~~Fixed inertial~~ frame

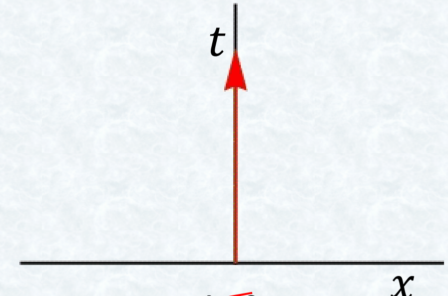
$$\langle e^{\mu}\bar{\psi} i \partial_{\mu} \psi \rangle$$





Relative velocity between lab frame and fixed frame

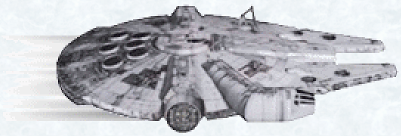


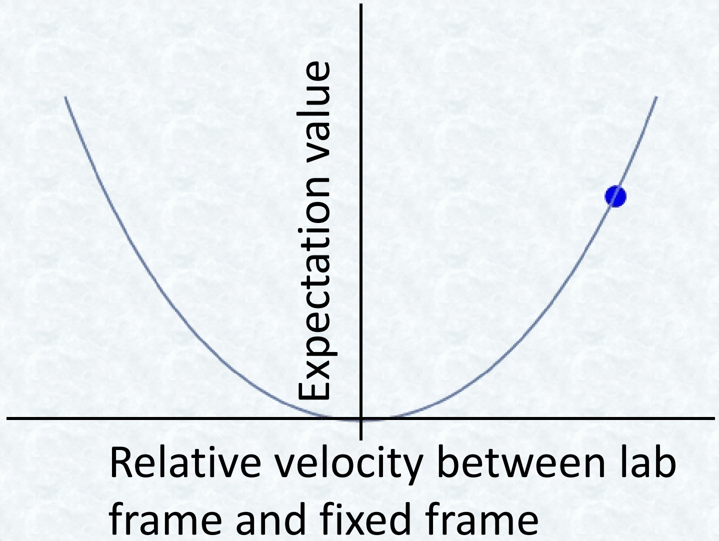


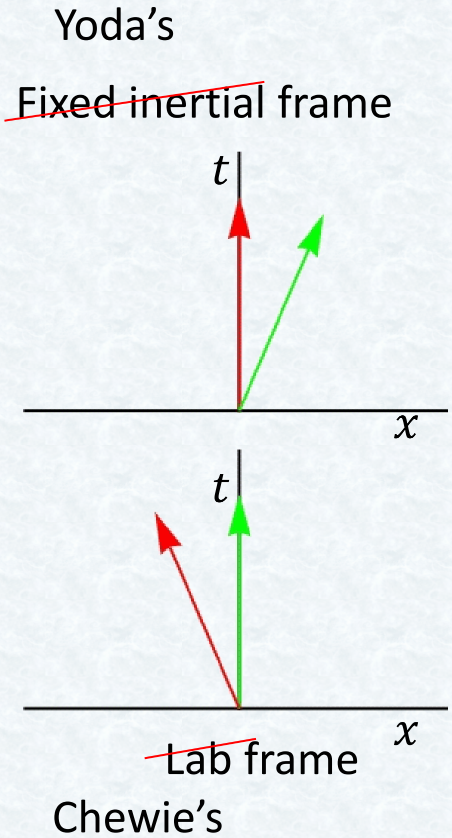
~~Lab~~ frame

Chewie's

$$\langle e^{\mu}\bar{\psi} i\partial_{\mu}\psi\rangle$$







- Yoda and Chewie agree about $\langle e^{\mu}\bar{\psi} i\partial_{\mu}\psi\rangle$ (observer independent)
- The result depends on the velocity of the experiment (Lorentz violation)

Lorentz violation as background fields

The SME Lagrangian

Colladay and Kostelecký, PRD **55**, 6760 (1997)
Colladay and Kostelecký, PRD **58**, 116002 (1998)
Kostelecký, PRD **69**, 105009 (2004)

$$\mathcal{L}_{SME} = \mathcal{L}_{SM} + \mathcal{L}_{GR} + \mathcal{L}_{LV}$$

Conventional physics → $\mathcal{L}_{SM}$, $\mathcal{L}_{GR}$

Lorentz violation → $\mathcal{L}_{LV}$

Facilitates the systematic test of Lorentz and CPT symmetry

- Models for Lorentz violation applicable to diverse physical scenarios
- Compare and classify tests of Lorentz symmetry
- Predicts signals for Lorentz and CPT violation

Systems used in Lorentz symmetry tests

Atomic experiments

- Clock comparison
- Atomic spectroscopy
- Ion spectroscopy
- Masers
- Atom interferometry
- Doppler-shift experiment

Spin-precession experiments

- Penning traps
- Ultra-cold neutrons
- g-2 experiments

Neutrino experiments

- Neutrinos oscillations
- Neutrinos time of flight
- Neutrino-antineutrino comparison
- Atmospheric neutrinos

Polarized matter

- Torsion pendulums
- Magnetometer

Astrophysical observations

- Astrophysical dispersion
- Astrophysical birefringence
- Lunar laser ranging
- Gravitational waves
- Pulsars
- CMB polarization
- Cosmic particles

Gravity tests

- Free-fall WEP tests
- Force-comparison WEP tests
- Space-based WEP tests
- Short-range gravity

Collider experiments

- Scattering cross-sections
- Baryon decays
- Meson decays
- Quark pair production
- Meson oscillations

Light experiments

- Rotating resonators
- Cavity oscillators
- Light Interferometry

Data Tables for Lorentz and CPT Violation

arXiv:0801.0287 [hep-ph] (update annually)

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Collaborations

- ALPHA
- ASACUSA
- ATRAP
- BASE
- AEgIS
- GBAR

What they want to observe

- Gravitational acceleration of antimatter
- Magnetic moment of the antiprotons
- Antimatter spectroscopy

Atomic spectroscopy

$n\mathrm{S}_{1/2}$ atomic state of hydrogen in the hyperfine-Zeeman regime

energy of the atomic state → $\epsilon = \epsilon_0 + \boldsymbol{\delta\epsilon}$

ϵ_0: conventional case

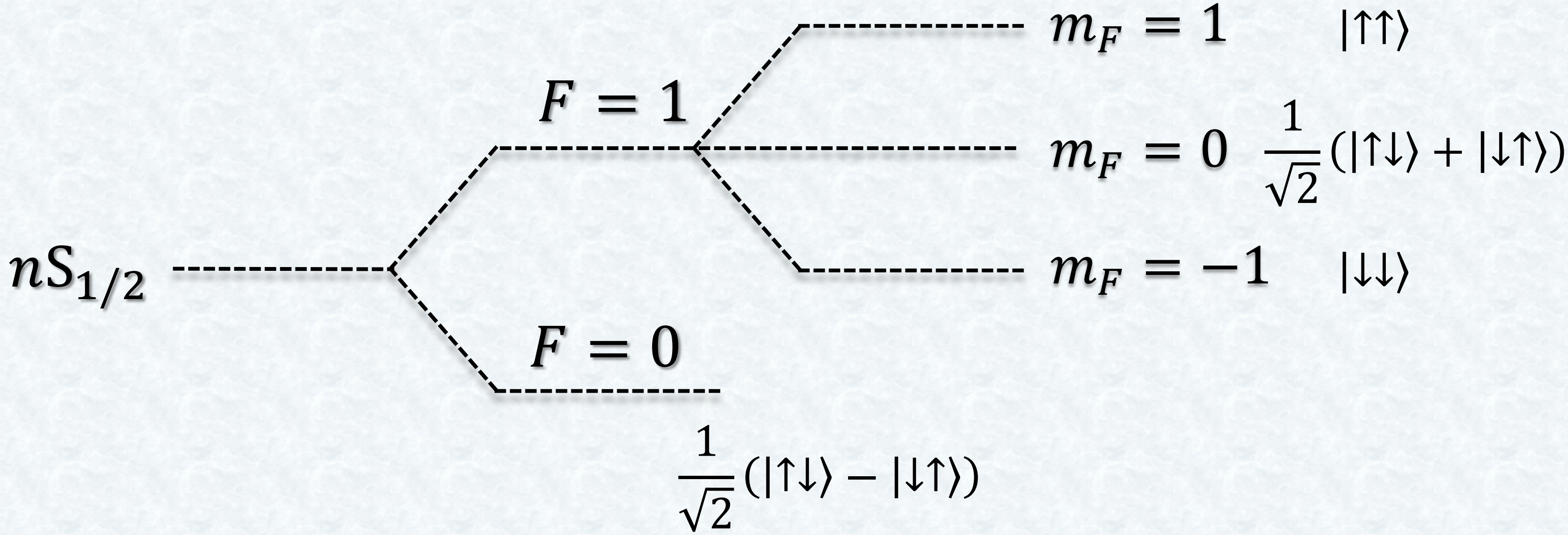
$\delta\epsilon$: Lorentz-violating contribution

$$\delta\epsilon \simeq S + \vec{\beta}\cdot\vec{V} + \frac{m_F}{B}\left(\vec{B}\cdot\vec{A} + B^I T_{IK}\beta^K\right)$$

$\vec{\beta}$ velocity of the laboratory

$\vec{B}$ applied magnetic field

Conventional case



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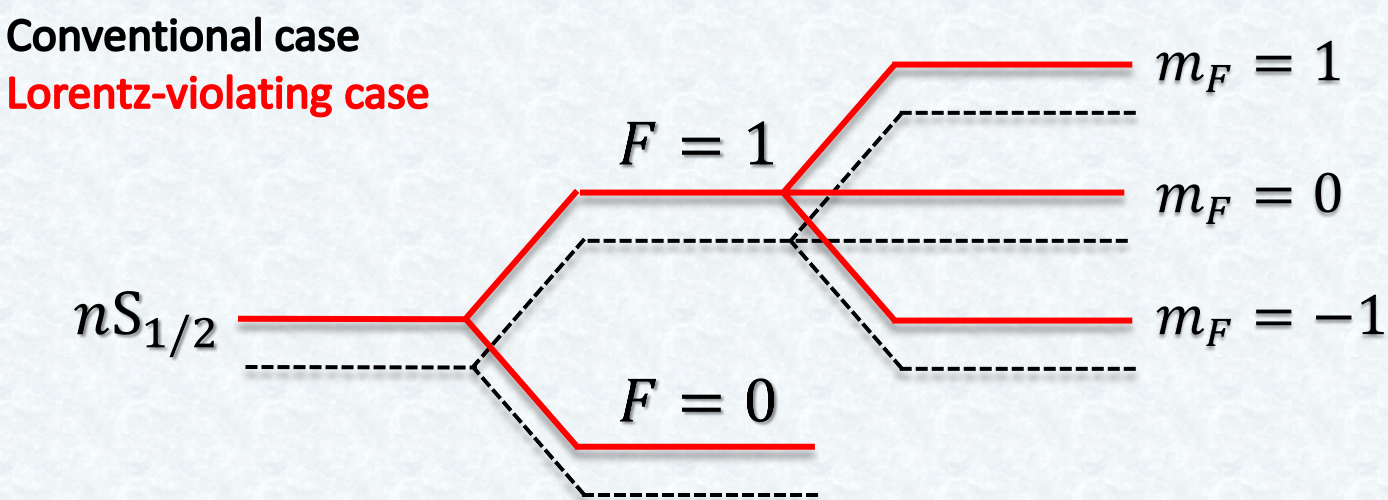

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- energy of the atomic state → ϵ
- conventional case → ϵ_0
- Lorentz-violating contribution → $\delta\epsilon$

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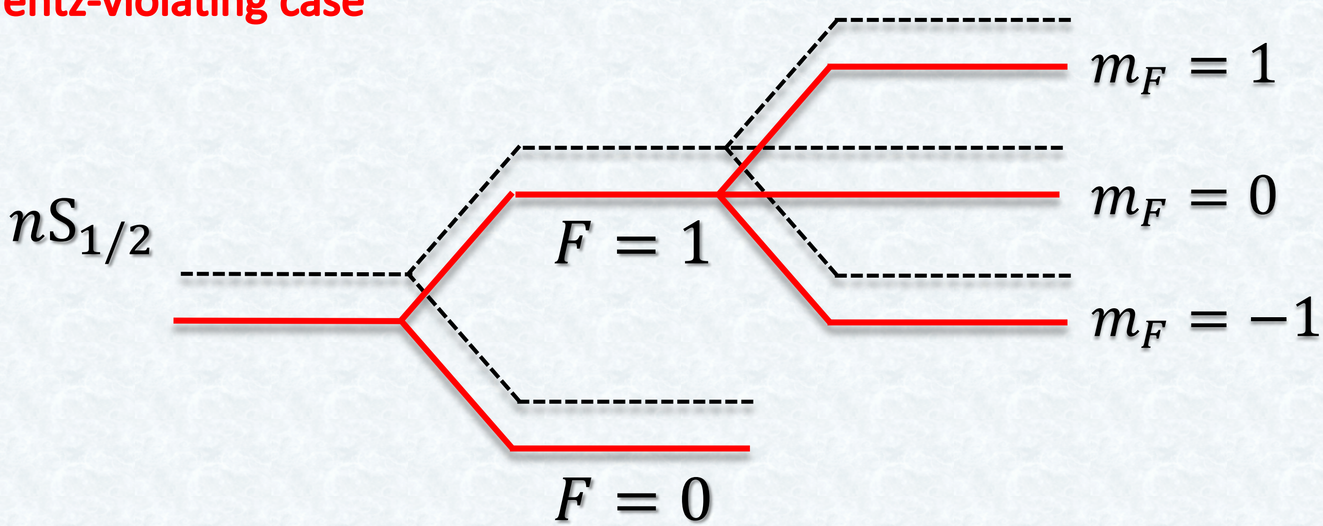
Conventional case

Lorentz-violating case



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energy of the atomic state → ϵ; conventional case → ϵ_0; Lorentz-violating contribution → $\delta\epsilon$

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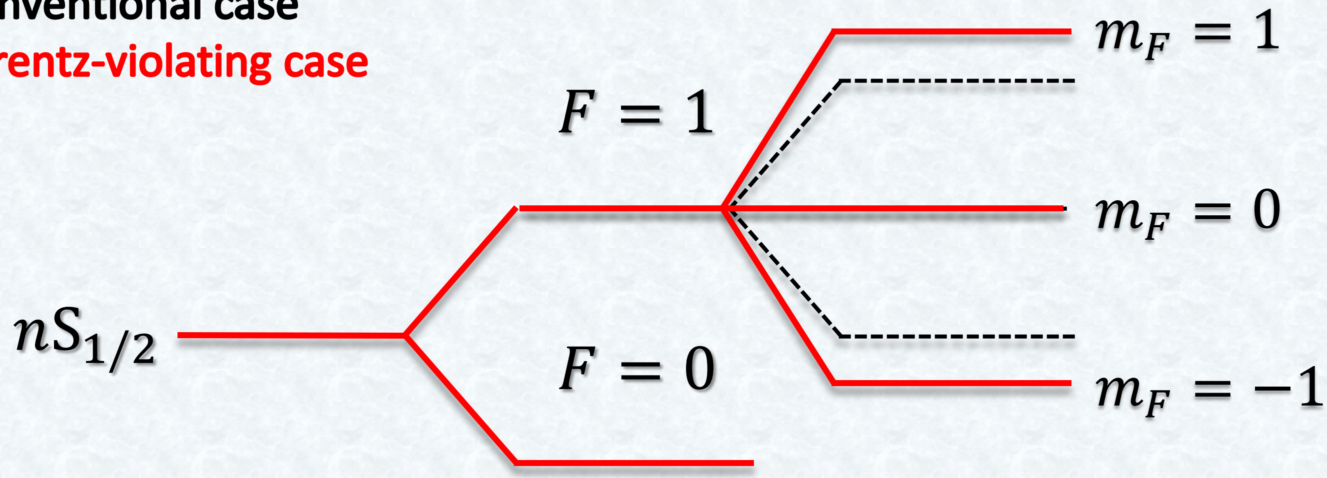

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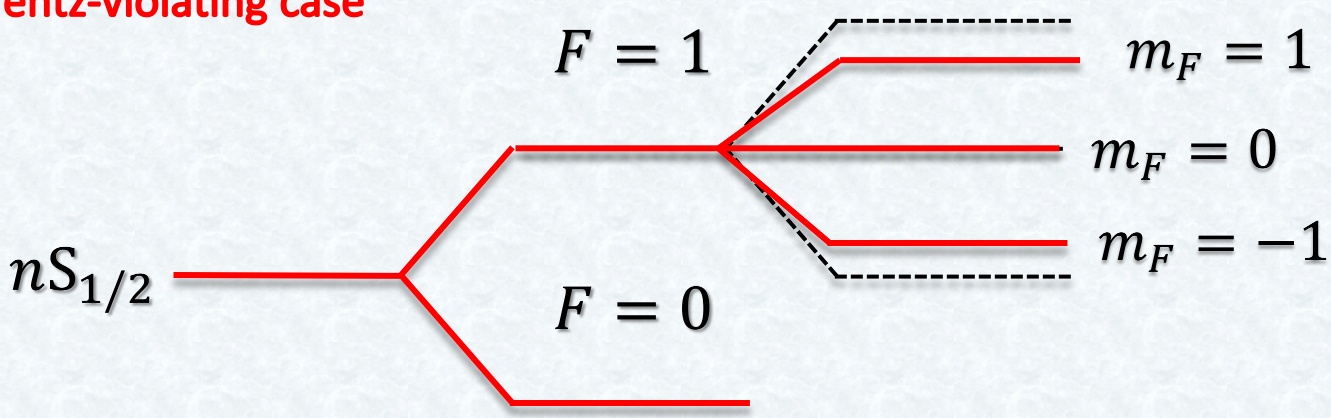

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ϵ_0 ← conventional case

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$\vec{\beta}$ velocity of the laboratory

$\vec{B}$ applied magnetic field

$$S(n) = \cdots \left(\frac{\alpha m_r}{n}\right)^2 \left(c_{200}^{\mathrm{NR}} - a_{200}^{\mathrm{NR}}\right) \ldots$$

α fine-structure constant
m_r reduced mass of hydrogen
n principal quantum number

${c_w}_{200}^{\mathrm{NR}}$ and ${a_w}_{200}^{\mathrm{NR}}$ are the coefficients to be measured

Atomic spectroscopy

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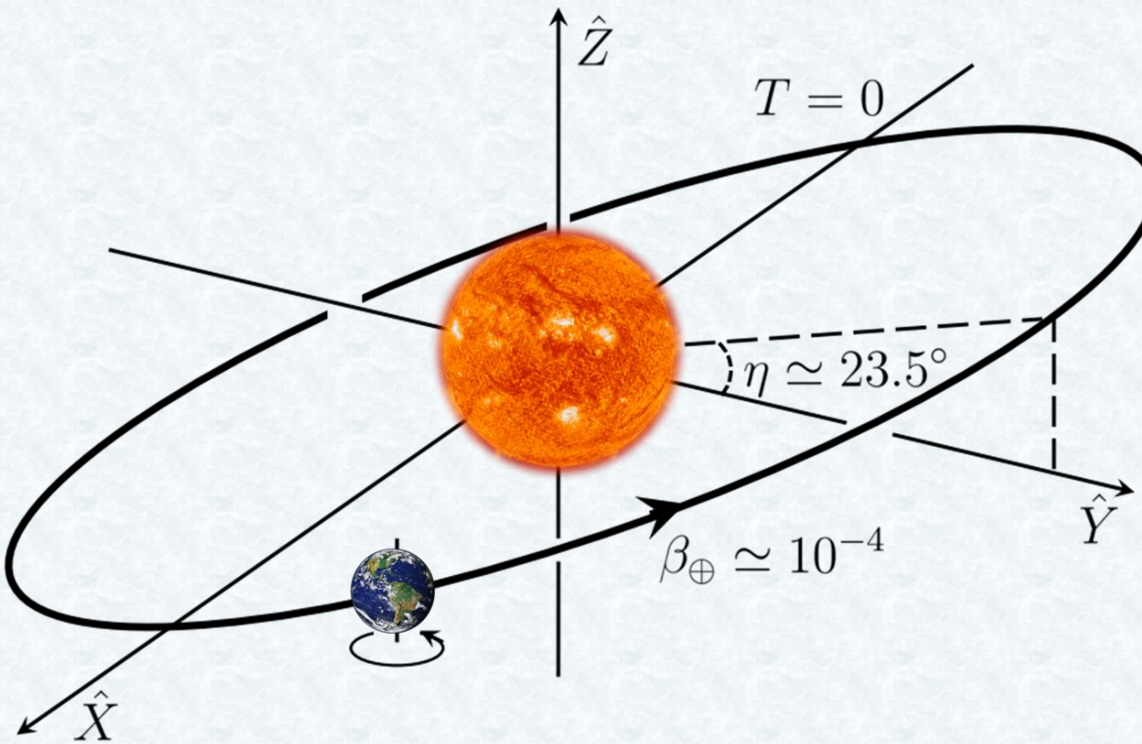

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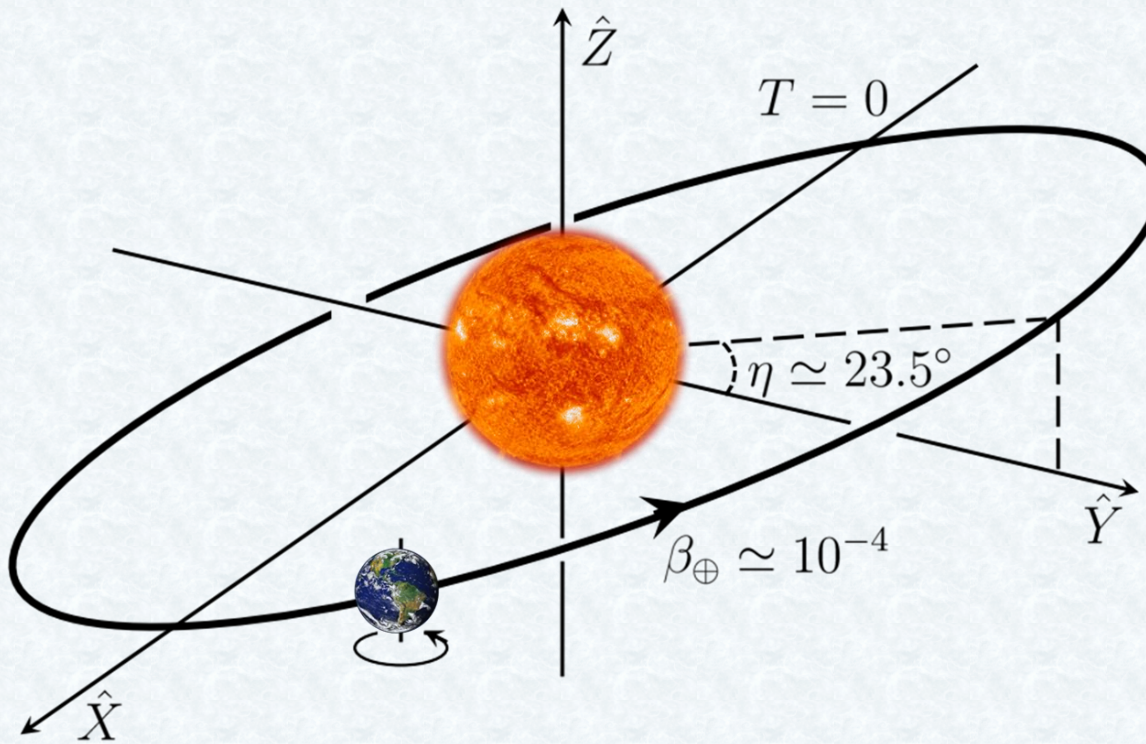
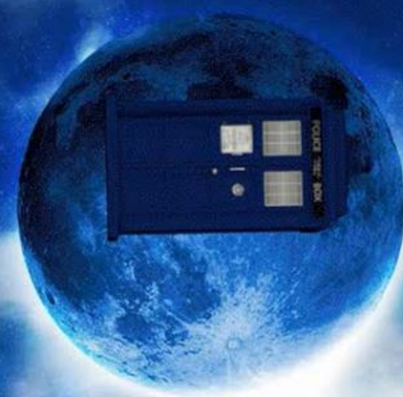
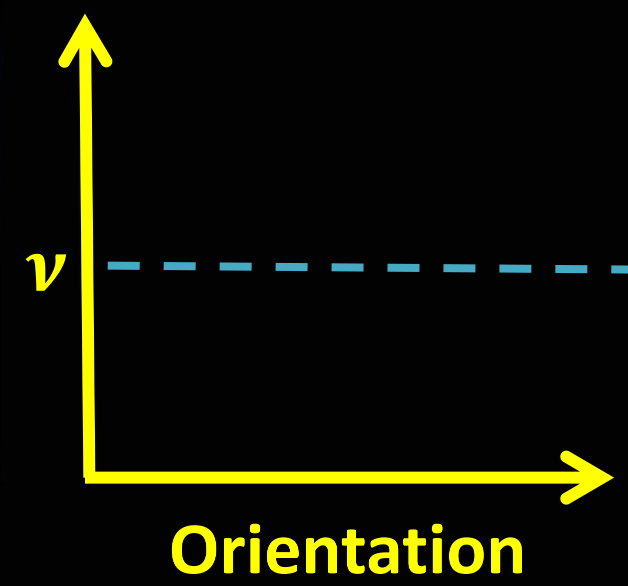


T.A.R.D.I.S.



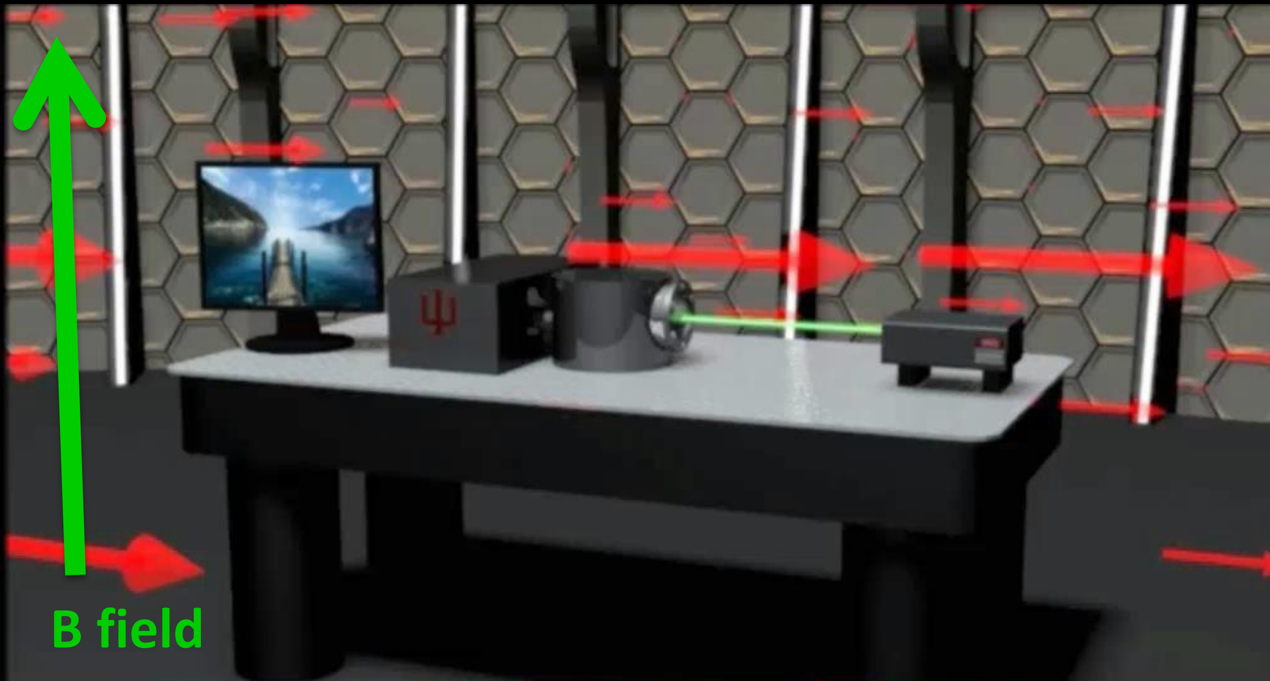
Lab Frame



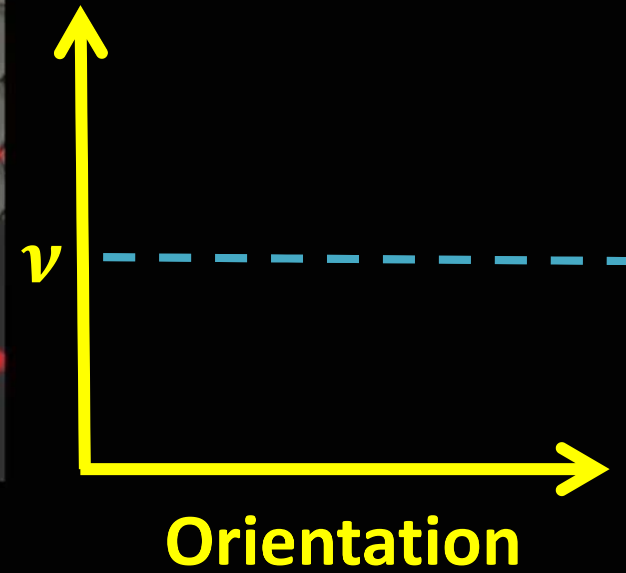
Lorentz invariance

The frequency ν is independent of the orientation

Fixed frame

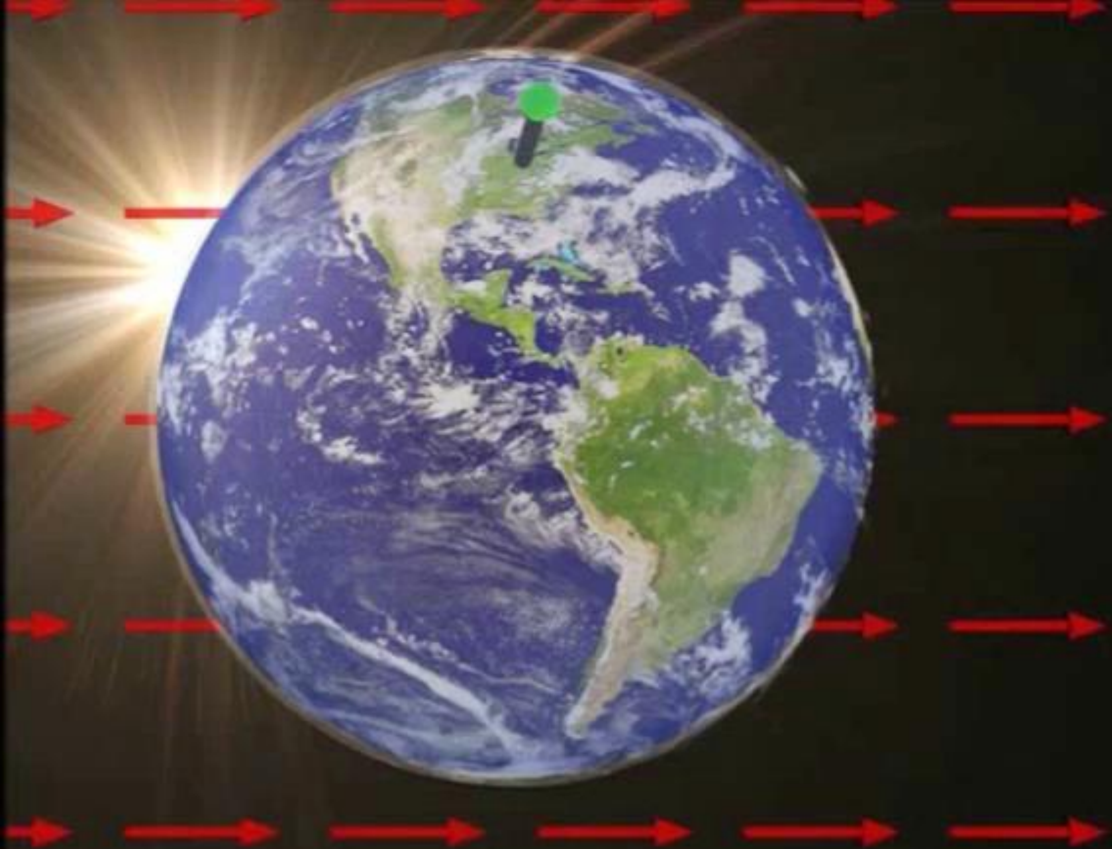


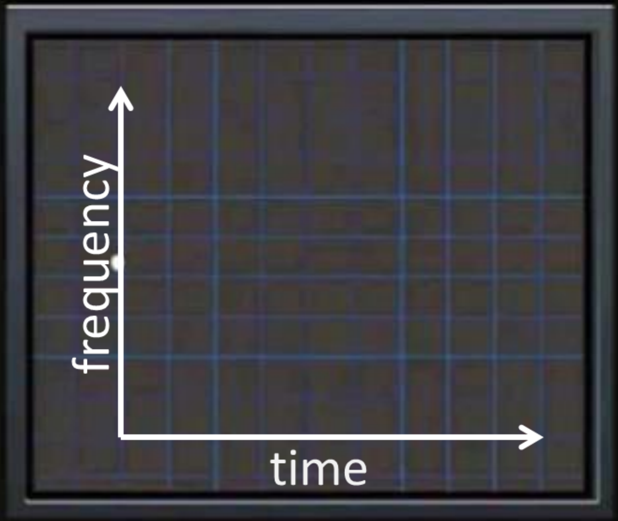
Lab Frame



$$\delta\nu = \frac{\Delta m_F}{B}\vec{A}\cdot\vec{B}$$

Fixed frame





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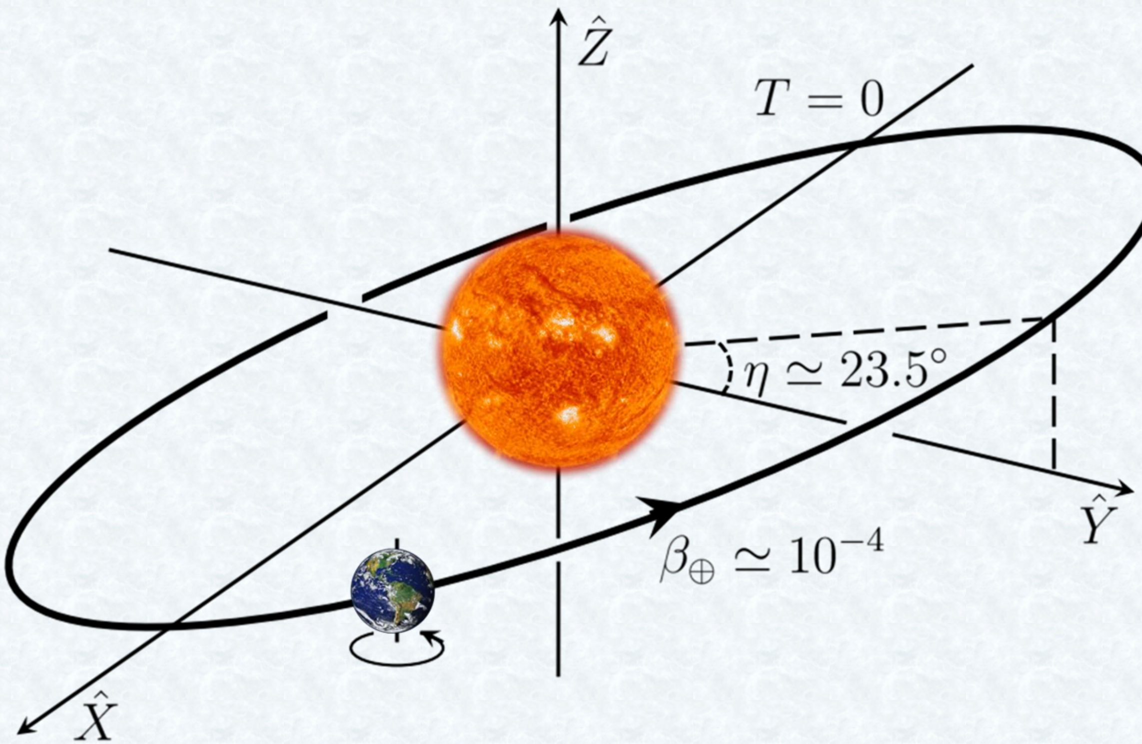
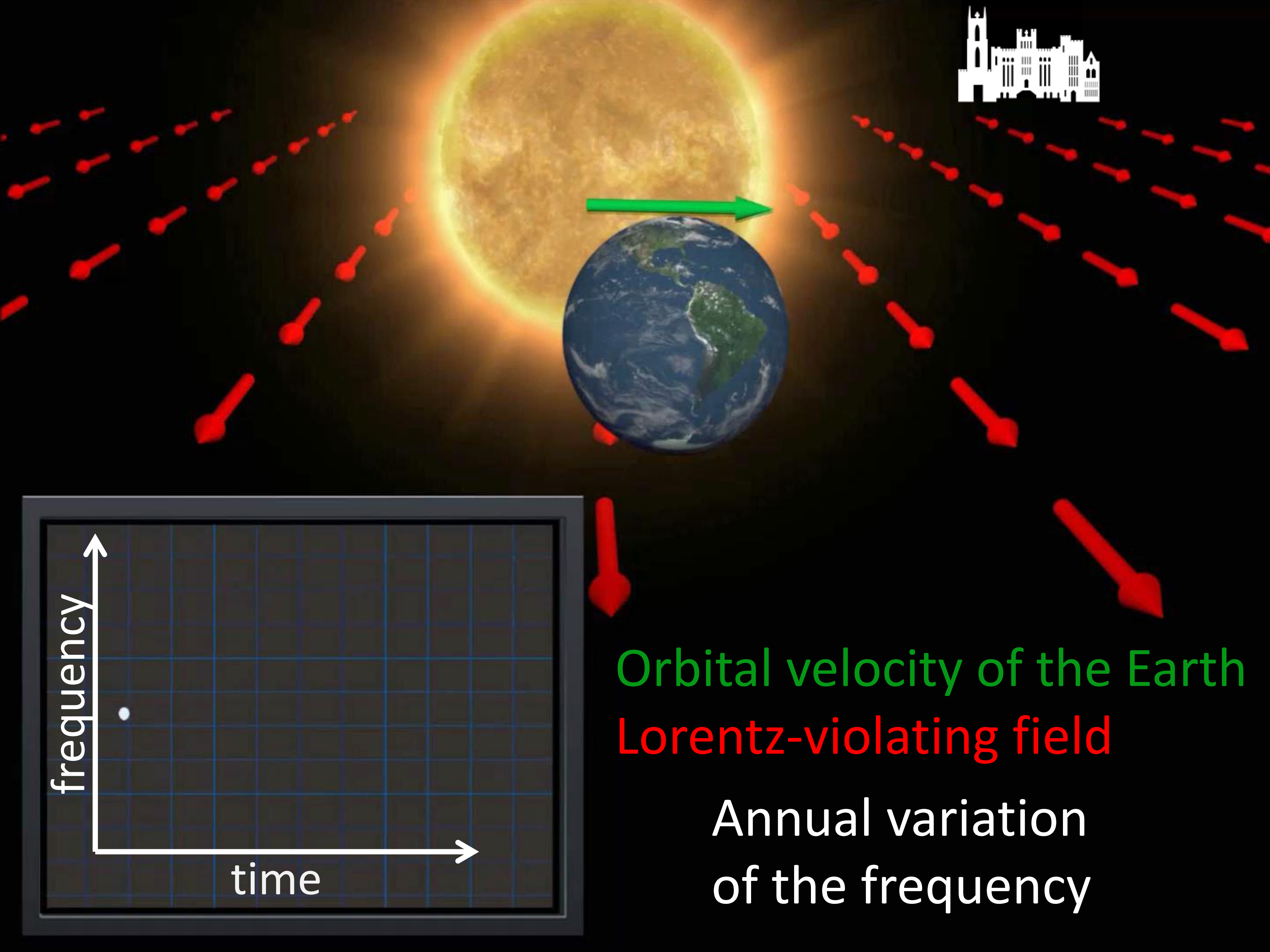
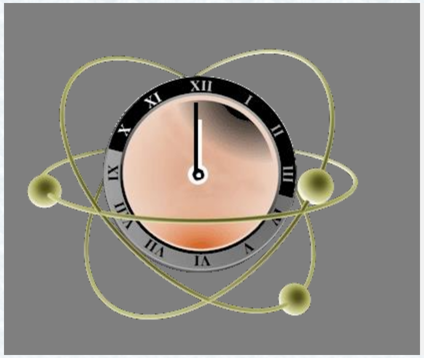
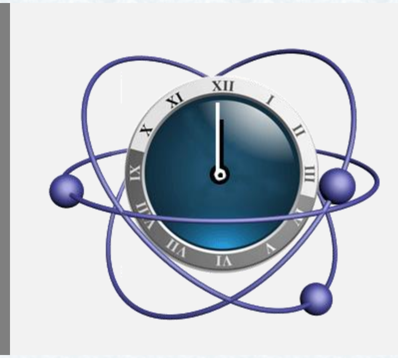
$\vec{\beta}$ **velocity of the laboratory**

$\vec{B}$ **applied magnetic field**




frequency
time
Orbital velocity of the Earth
Lorentz-violating field
Annual variation
of the frequency

The SME allows clocks and anti-clocks to tick at different rates

Lorentz-violating energy shift for hydrogen

$$\delta\epsilon \simeq S + \vec{\beta}\cdot\vec{V} + \frac{m_F}{B}\left(\vec{B}\cdot\vec{A} + B^I T_{IK}\beta^K\right)$$

$$S(n) = \cdots\left(\frac{\alpha m_r}{n}\right)^2\left(\boldsymbol{c}_{200}^{\mathrm{NR}} \ominus \boldsymbol{a}_{200}^{\mathrm{NR}}\right)\ldots$$

Lorentz-violating energy shift for antihydrogen

Coefficients for CPT violation

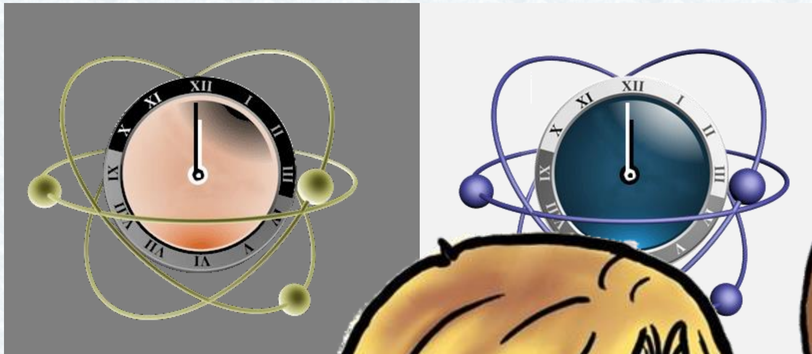
Coefficients of CPT invariant operators

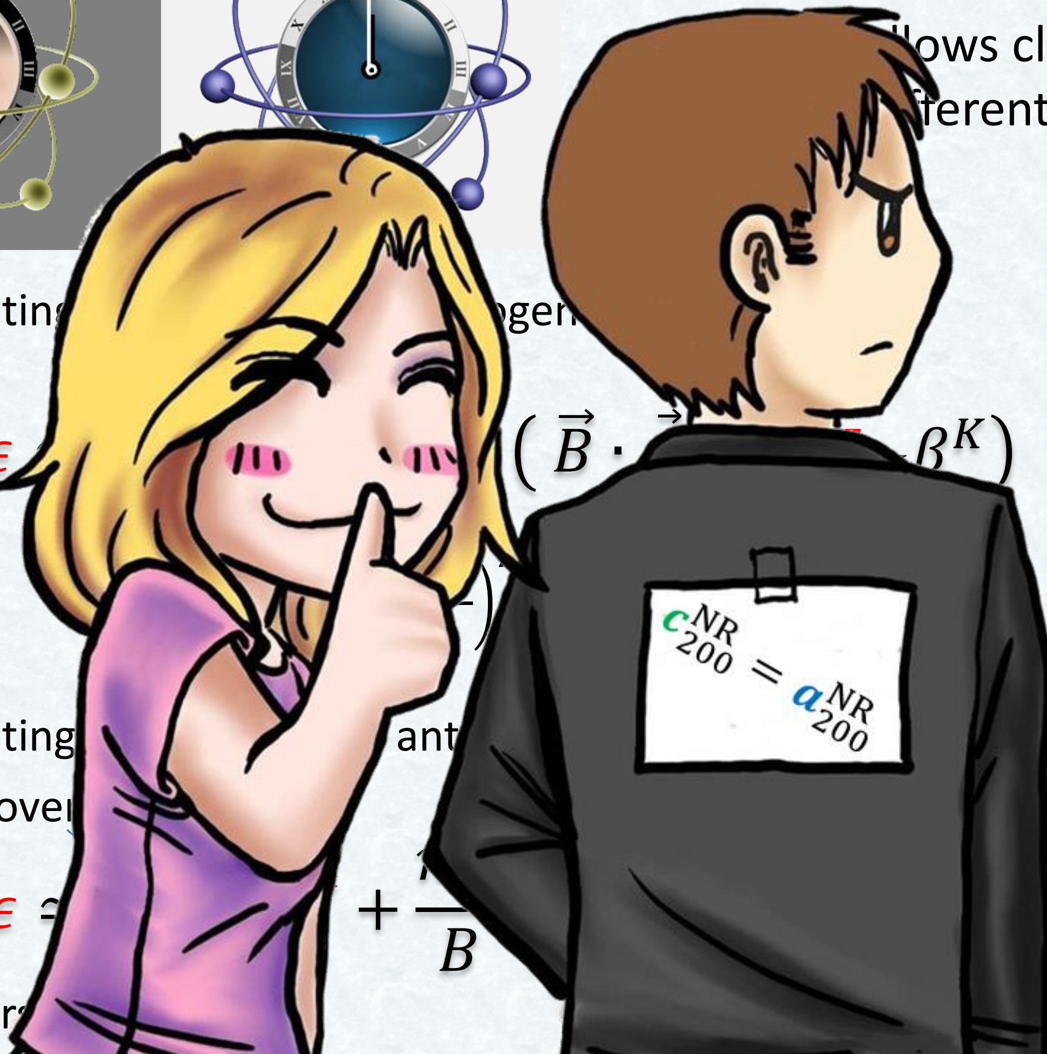
overbars

$$\delta\epsilon \simeq \bar{S} + \vec{\beta}\cdot\vec{\bar{V}} + \frac{m_F}{B}\left(\vec{B}\cdot\vec{\bar{A}} + B^I \bar{T}_{IK}\beta^K\right)$$

overbars

$$\bar{S}(n) = \cdots\left(\frac{\alpha m_r}{n}\right)^2\left(\boldsymbol{c}_{200}^{\mathrm{NR}} \oplus \boldsymbol{a}_{200}^{\mathrm{NR}}\right)\ldots$$





...lows clocks and anti-clocks
...fferent rates

Lorentz-violatin... ...ogen...

$\delta\epsilon$ ... $(\vec{B} \cdot$ ... $\beta^K)$

Lorentz-violating ... ant...

CPT violation

CPT invariant operators

over...

$\delta\epsilon$ ... $+ \frac{\ldots}{B}$

overbar...

$$\bar{S}(n) = \cdots \left(\frac{\alpha m_r}{n}\right)^2 \left(c^{\mathrm{NR}}_{200} \oplus a^{\mathrm{NR}}_{200}\right) \ldots$$

Coefficients for CPT violation that shift the atomic spectrum in the laboratory frame

$g_{010}^{\mathrm{NR}(0B)}$	$g_{010}^{\mathrm{NR}(1B)}$	a_{000}^{NR}	$g_{450}^{\mathrm{NR}(0B)}$	$g_{450}^{\mathrm{NR}(1B)}$
$g_{011}^{\mathrm{NR}(0B)}$	$g_{011}^{\mathrm{NR}(1B)}$	a_{200}^{NR}	$g_{451}^{\mathrm{NR}(0B)}$	$g_{451}^{\mathrm{NR}(1B)}$
$g_{210}^{\mathrm{NR}(0B)}$	$g_{210}^{\mathrm{NR}(1B)}$	a_{400}^{NR}	$g_{452}^{\mathrm{NR}(0B)}$	$g_{452}^{\mathrm{NR}(1B)}$
$g_{211}^{\mathrm{NR}(0B)}$	$g_{211}^{\mathrm{NR}(1B)}$	a_{220}^{NR}	$g_{453}^{\mathrm{NR}(0B)}$	$g_{453}^{\mathrm{NR}(1B)}$
$g_{410}^{\mathrm{NR}(0B)}$	$g_{410}^{\mathrm{NR}(1B)}$	a_{221}^{NR}	$g_{454}^{\mathrm{NR}(0B)}$	$g_{454}^{\mathrm{NR}(1B)}$
$g_{411}^{\mathrm{NR}(0B)}$	$g_{411}^{\mathrm{NR}(1B)}$	a_{222}^{NR}	$g_{455}^{\mathrm{NR}(0B)}$	$g_{455}^{\mathrm{NR}(1B)}$
$g_{230}^{\mathrm{NR}(0B)}$	$g_{230}^{\mathrm{NR}(1B)}$	a_{420}^{NR}		
$g_{231}^{\mathrm{NR}(0B)}$	$g_{231}^{\mathrm{NR}(1B)}$	a_{421}^{NR}		
$g_{232}^{\mathrm{NR}(0B)}$	$g_{232}^{\mathrm{NR}(1B)}$	a_{422}^{NR}		
$g_{232}^{\mathrm{NR}(0B)}$	$g_{233}^{\mathrm{NR}(1B)}$	a_{440}^{NR}		
$g_{430}^{\mathrm{NR}(0B)}$	$g_{430}^{\mathrm{NR}(1B)}$	a_{441}^{NR}		
$g_{431}^{\mathrm{NR}(0B)}$	$g_{431}^{\mathrm{NR}(1B)}$	a_{442}^{NR}		
$g_{432}^{\mathrm{NR}(0B)}$	$g_{432}^{\mathrm{NR}(1B)}$	a_{443}^{NR}		
$g_{433}^{\mathrm{NR}(0B)}$	$g_{433}^{\mathrm{NR}(1B)}$	a_{444}^{NR}		

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$g_{011}^{\mathrm{NR}(0B)}$	$g_{011}^{\mathrm{NR}(1B)}$	a_{200}^{NR}	$g_{451}^{\mathrm{NR}(0B)}$	$g_{451}^{\mathrm{NR}(1B)}$
$g_{210}^{\mathrm{NR}(0B)}$	$g_{210}^{\mathrm{NR}(1B)}$	a_{400}^{NR}	$g_{452}^{\mathrm{NR}(0B)}$	$g_{452}^{\mathrm{NR}(1B)}$
$g_{211}^{\mathrm{NR}(0B)}$	$g_{211}^{\mathrm{NR}(1B)}$	a_{220}^{NR}	$g_{453}^{\mathrm{NR}(0B)}$	$g_{453}^{\mathrm{NR}(1B)}$
$g_{410}^{\mathrm{NR}(0B)}$	$g_{410}^{\mathrm{NR}(1B)}$	a_{221}^{NR}	$g_{454}^{\mathrm{NR}(0B)}$	$g_{454}^{\mathrm{NR}(1B)}$
$g_{411}^{\mathrm{NR}(0B)}$	$g_{411}^{\mathrm{NR}(1B)}$	a_{222}^{NR}	$g_{455}^{\mathrm{NR}(0B)}$	$g_{455}^{\mathrm{NR}(1B)}$
$g_{230}^{\mathrm{NR}(0B)}$	$g_{230}^{\mathrm{NR}(1B)}$	a_{420}^{NR}		
$g_{231}^{\mathrm{NR}(0B)}$	$g_{231}^{\mathrm{NR}(1B)}$	a_{421}^{NR}		
$g_{232}^{\mathrm{NR}(0B)}$	$g_{232}^{\mathrm{NR}(1B)}$	a_{422}^{NR}		
$g_{232}^{\mathrm{NR}(0B)}$	$g_{233}^{\mathrm{NR}(1B)}$	a_{440}^{NR}		
$g_{430}^{\mathrm{NR}(0B)}$	$g_{430}^{\mathrm{NR}(1B)}$	a_{441}^{NR}		
$g_{431}^{\mathrm{NR}(0B)}$	$g_{431}^{\mathrm{NR}(1B)}$	a_{442}^{NR}		
$g_{432}^{\mathrm{NR}(0B)}$	$g_{432}^{\mathrm{NR}(1B)}$	a_{443}^{NR}		
$g_{433}^{\mathrm{NR}(0B)}$	$g_{433}^{\mathrm{NR}(1B)}$	a_{444}^{NR}		

Hyperfine transitions of the ground state with $\Delta m_F \neq 0$ (ASACUSA)

The hyperfine transition with $\Delta m_F = 0$ is insensitive to CPT violation at leading order

1st harmonic sidereal frequency

H vs. $\overline{H}$ comparison

$$\delta\nu \simeq \frac{\Delta m_F}{B}\left(\vec{B}\cdot\vec{\vec{A}} + B^I \overline{T}_{IK}\beta^K\right)$$

1st & 2nd harmonic sidereal frequency
Annual variation

Each one of these signals are sensitive to different sets of coefficients

Coefficients for CPT violation that shift the atomic spectrum in the laboratory frame

$g_{010}^{\mathrm{NR}(0B)}$	$g_{010}^{\mathrm{NR}(1B)}$	a_{000}^{NR}	$g_{450}^{\mathrm{NR}(0B)}$	$g_{450}^{\mathrm{NR}(1B)}$
$g_{011}^{\mathrm{NR}(0B)}$	$g_{011}^{\mathrm{NR}(1B)}$	a_{200}^{NR}	$g_{451}^{\mathrm{NR}(0B)}$	$g_{451}^{\mathrm{NR}(1B)}$
$g_{210}^{\mathrm{NR}(0B)}$	$g_{210}^{\mathrm{NR}(1B)}$	a_{400}^{NR}	$g_{452}^{\mathrm{NR}(0B)}$	$g_{452}^{\mathrm{NR}(1B)}$
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$g_{410}^{\mathrm{NR}(0B)}$	$g_{410}^{\mathrm{NR}(1B)}$	a_{221}^{NR}	$g_{454}^{\mathrm{NR}(0B)}$	$g_{454}^{\mathrm{NR}(1B)}$
$g_{411}^{\mathrm{NR}(0B)}$	$g_{411}^{\mathrm{NR}(1B)}$	a_{222}^{NR}	$g_{455}^{\mathrm{NR}(0B)}$	$g_{455}^{\mathrm{NR}(1B)}$
$g_{230}^{\mathrm{NR}(0B)}$	$g_{230}^{\mathrm{NR}(1B)}$	a_{420}^{NR}		
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$g_{232}^{\mathrm{NR}(0B)}$	$g_{232}^{\mathrm{NR}(1B)}$	a_{422}^{NR}		
$g_{232}^{\mathrm{NR}(0B)}$	$g_{233}^{\mathrm{NR}(1B)}$	a_{440}^{NR}		
$g_{430}^{\mathrm{NR}(0B)}$	$g_{430}^{\mathrm{NR}(1B)}$	a_{441}^{NR}		
$g_{431}^{\mathrm{NR}(0B)}$	$g_{431}^{\mathrm{NR}(1B)}$	a_{442}^{NR}		
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$1S_{1/2} \leftrightarrow 2S_{1/2}$ transition (ATRAP, ALPHA)

The $\Delta m_F = 0$ transition is sensitive to CPT violation at leading order

H vs. $\overline{H}$ comparison

$$\delta\nu \simeq \Delta S + \vec{\beta}\cdot\Delta\vec{V}$$

1st harmonic sidereal frequency

Annual variation

Comparing sensitivity to isotropic electron coefficients

Antihydrogen ($\sim$100 kHz) [1]	Positronium
$a_{220}^{\mathrm{NR}} \sim 10^{-7}\ \mathrm{GeV}^{-1}$	$c_{220}^{\mathrm{NR}} \sim 10^{-6}\ \mathrm{GeV}^{-1}$ [2]

1. Ahmadi *et. al.*, nature **541**, 506 (2017)
2. Kostelecký and AJV, PRD **92**, 056002 (2015).

Coefficients for CPT violation that shift the atomic spectrum in the laboratory frame

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$g_{011}^{\mathrm{NR}(0B)}$	$g_{011}^{\mathrm{NR}(1B)}$	a_{200}^{NR}	$g_{451}^{\mathrm{NR}(0B)}$	$g_{451}^{\mathrm{NR}(1B)}$
$g_{210}^{\mathrm{NR}(0B)}$	$g_{210}^{\mathrm{NR}(1B)}$	a_{400}^{NR}	$g_{452}^{\mathrm{NR}(0B)}$	$g_{452}^{\mathrm{NR}(1B)}$
$g_{211}^{\mathrm{NR}(0B)}$	$g_{211}^{\mathrm{NR}(1B)}$	a_{220}^{NR}	$g_{453}^{\mathrm{NR}(0B)}$	$g_{453}^{\mathrm{NR}(1B)}$
$g_{410}^{\mathrm{NR}(0B)}$	$g_{410}^{\mathrm{NR}(1B)}$	a_{221}^{NR}	$g_{454}^{\mathrm{NR}(0B)}$	$g_{454}^{\mathrm{NR}(1B)}$
$g_{411}^{\mathrm{NR}(0B)}$	$g_{411}^{\mathrm{NR}(1B)}$	a_{222}^{NR}	$g_{455}^{\mathrm{NR}(0B)}$	$g_{455}^{\mathrm{NR}(1B)}$
$g_{230}^{\mathrm{NR}(0B)}$	$g_{230}^{\mathrm{NR}(1B)}$	a_{420}^{NR}		
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Hyperfine transitions of the ground state with $\Delta m_F \neq 0$ (ASACUSA)

$1S_{1/2} \leftrightarrow 2S_{1/2}$ transition (ATRAP, ALPHA)

$2S_{1/2} - nD_{5/2}$ transition

Signals for Lorentz violation

- Hydrogen vs antihydrogen discrepancies
- Sidereal variations (1st , 2nd , 3rd , 4th , 5th and 6th harmonic)
- Annual variation

Going beyond antihydrogen?

Antihelium and antideuterium can offer a significance enhancement (around 10^8)

Lorentz-violating shift to the anomalous frequency of the antiproton

1st harmonic sidereal frequency

p vs. $\bar{p}$ comparison

$$\omega_a = \left(\frac{g}{2} - 1\right)\omega_c - \frac{2}{B}\left(\tilde{b}^{*J} B^J - \tilde{b}_F^{*JK} B^J B^K \right)$$

1st & 2nd harmonic sidereal frequency

Ding and Kostelecký, PRD 94, 056008 (2016)

Lorentz-violating shift to the anomalous frequency of the antiproton

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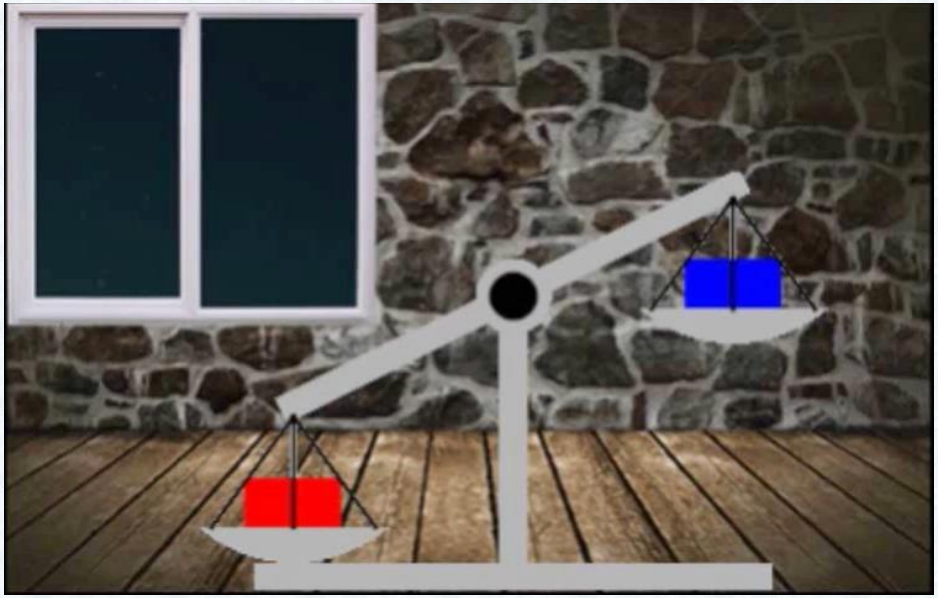
1st & 2nd harmonic sidereal frequency

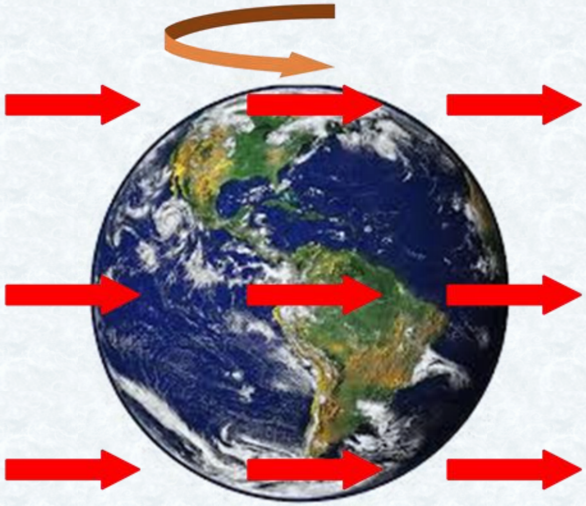
Ding and Kostelecký, PRD 94, 056008 (2016)

Coefficient	ATRAP 2013 & BASE 2014[1]	BASE 2014 & 2016 [2]
$\lvert\tilde{b}_p^Z\rvert$	$< 2 \times 10^{-21}$ GeV	$< 2.1 \times 10^{-22}$ GeV
$\lvert\tilde{b}_p^{*Z}\rvert$	$< 6 \times 10^{-21}$ GeV	$< 2.5 \times 10^{-22}$ GeV
$\lvert\tilde{b}_{F,p}^{XX} + \tilde{b}_{F,p}^{YY}\rvert$	$< 1 \times 10^{-5}$ GeV^{-1}	$< 1.2 \times 10^{-6}$ GeV^{-1}
$\lvert\tilde{b}_{F,p}^{ZZ}\rvert$	$< 1 \times 10^{-5}$ GeV^{-1}	$< 8.8 \times 10^{-7}$ GeV^{-1}
$\lvert\tilde{b}_{F,p}^{*XX} + \tilde{b}_{F,p}^{*YY}\rvert$	$< 2 \times 10^{-5}$ GeV^{-1}	$< 8.3 \times 10^{-7}$ GeV^{-1}
$\lvert\tilde{b}_{F,p}^{*ZZ}\rvert$	$< 8 \times 10^{-6}$ GeV^{-1}	$< 3.0 \times 10^{-6}$ GeV^{-1}

1. Ding and Kostelecký, PRD 94, 056008 (2016)
2. H. Nagahama et al., Nature Commun. 8, 14084 (2017)

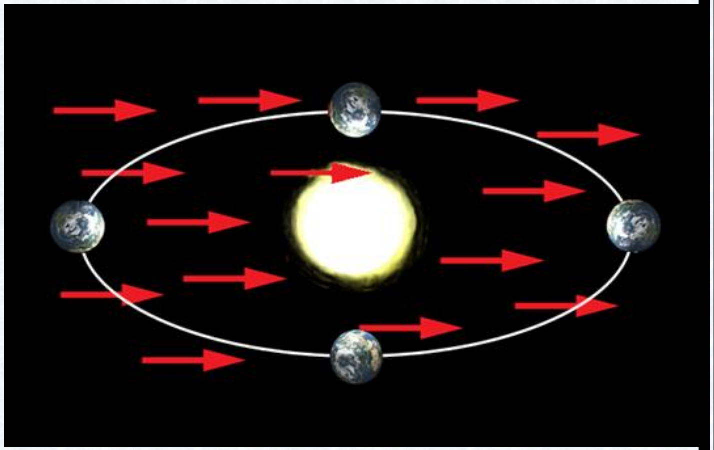
Who much antimatter weights?

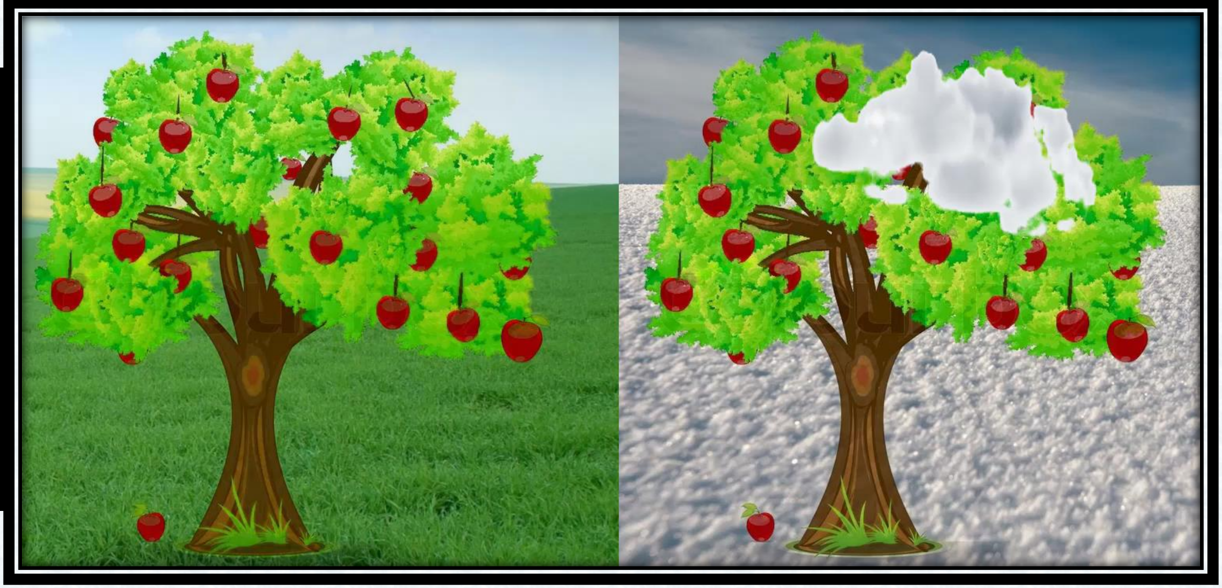




The effective weight of matter and antimatter might differ at different times of the day

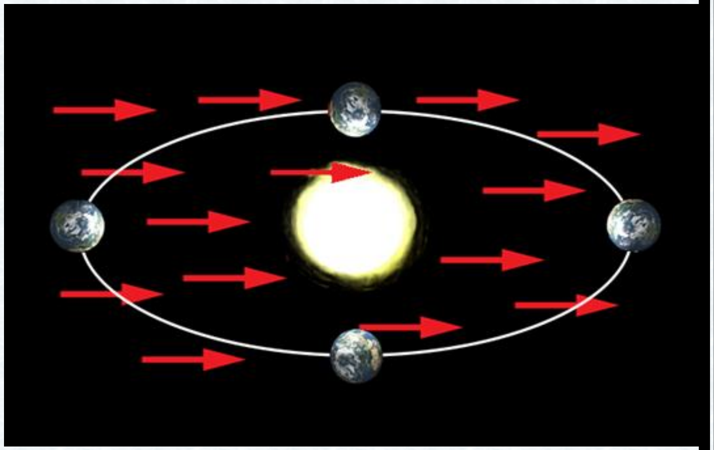
Kostelecký and Tasson, PRD **83**, 016013 (2011)

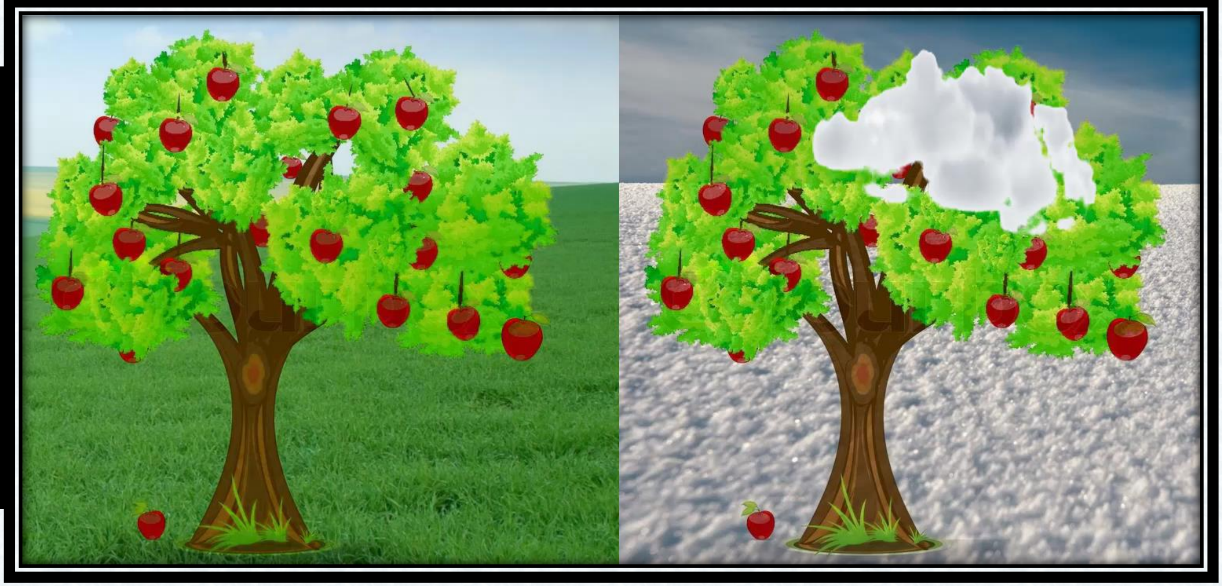




The free-falling acceleration of an object might depend on the relative orientation between orbital velocity of the Earth and the LV background field

Kostelecký and Tasson, PRD **83**, 016013 (2011)





The free-falling acceleration of an object might depend on the relative orientation between orbital velocity of the Earth and the LV background field

Kostelecký and Tasson, PRD **83**, 016013 (2011)

Testing that the acceleration of antimatter is $9.81\ \mathrm{m/s^2}$ is important, but it is not enough.

Does the acceleration changes at different times of the day or at different times of the year?

Isotropic parachute model

Kostelecký and Tasson, PRD **83**, 016013 (2011)

For matter

$$a = g$$

$$m_{\mathrm{i,eff}} = m_{\mathrm{g,eff}}$$

For antimatter

$$a \neq g$$

$$m_{\mathrm{i,eff}} \neq m_{\mathrm{g,eff}}$$

The IPM suggest that there is nothing wrong with a theory for which the acceleration of antimatter is not $9.81\ \mathrm{m/s^2}$.

Final Comments

- The Standard-Model Extension is a natural test framework for testing CPT symmetry

- Tests of Lorentz and CPT symmetry with antimatter are sensitive to unique combinations of coefficients for Lorentz violation

- Matter vs antimatter comparison is important, but it is not enough.

    - It might be possible that antimatter experiments are more sensitive to Lorentz violation than matter experiments. Looking for sidereal and annual variations is crucial.

- Any experiment that you could imagine with antimatter probably can be used to test Lorentz symmetry