New Limit on Lorentz Violation Using a Double-Pass Optical Ring Cavity

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Summary

• compared the speed of light propagating in opposite directions

• using a double-pass optical ring cavity

• put new limits on LV in photons

\[ |\delta c/c| \lesssim 1 \times 10^{-14} \]

We are (eventual) GW Astronomers

- laser interferometric gravitational wave detectors
  KAGRA (Japan), LIGO (US), Virgo (Italy) ……
- first detection within ~ 5 years

**GW detector**

- Laser
- compare lengths of suspended FP cavities
- photo detector

**LI test (Michelson-Morley type)**

- Laser
- compare resonant frequencies of fixed FP cavities
Lorentz Invariance in Photons

- constancy of speed of light
  - no directional dependence
  - no difference between opposite directions
  - no dependence from lab velocity

\[ \tilde{\kappa}_{e-}^{JK} \] (5 parameters)
\[ \tilde{\kappa}_{o+}^{JK} \] (3 parameters)
\[ \tilde{\kappa}_{tr} \] (1 parameter)
**Optical Ring Cavity**

- sensitive to LV when a dielectric is contained

<table>
<thead>
<tr>
<th></th>
<th>( \nu_+ = \nu_0 )</th>
<th>( \nu_- = \nu_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>no LV</td>
<td>( \nu_+ = \nu )</td>
<td>( \nu_- = \nu )</td>
</tr>
<tr>
<td>LV</td>
<td>( \nu_+ = \nu_0 )</td>
<td>( \nu_- = \nu + \delta \nu )</td>
</tr>
</tbody>
</table>

freq. shift \( \propto \) LV

- let’s compare the resonant frequencies!
How Do We Measure 1/4

- inject laser beam in CCW

\[ \nu_+ = \nu - \delta \nu \]
How Do We Measure 2/4

- lock laser frequency to CCW resonance ($\nu_+$)
How Do We Measure 3/4

- reflect the beam back into the cavity in CW

\[ \nu_+ = \nu - \delta \nu \quad \text{CCW} \]

\[ \nu_- = \nu + \delta \nu \quad \text{CW} \]

Laser

frequency servo
How Do We Measure 4/4

• LV signal obtained from cavity reflection (null measurement)

\[ \nu_+ = \nu - \delta\nu \]

\[ \nu_- = \nu + \delta\nu \]
Experimental Setup

- frequency comparison using double-pass setup
- rotate and modulate LV signal

1550 nm

Laser

fiber

Laser

collimator

vacuum enclosure (0.1-1kPa)

ring cavity

cavity

silicon

rotational angle $\theta$ [deg]

amplitude

extract LV from amplitude

$\propto \nu_+ - \nu_-$

turntable

frequency servo

$\nu_+$

$\nu_+$

LV signal
Photo of the Optics

Inside vacuum enclosure (30cm×30cm×17cm)

collimator

ring cavity

PDs1

PDb1

PDp2

PDs2
Parameters We Look for

- 3 odd-parity parameters

\[ \tilde{\kappa}_{o+}^{YZ} \leftarrow c \text{ difference in SCCEF X axis} \]

\[ \tilde{\kappa}_{o+}^{XZ} \leftarrow c \text{ difference in SCCEF Y axis} \]

\[ \tilde{\kappa}_{o+}^{XY} \leftarrow c \text{ difference in SCCEF Z axis} \]

- isotropic parameter

\[ \tilde{\kappa}_{tr} \leftarrow \text{isotropic shift in } c \] (lab. speed dependence)

Sun speed to CMB

\[ c(\theta) \]

\[ c(\theta + \pi) \]
Data Analysis 1/3

- demodulate each 1 rotation data with $\omega_{\text{rot}}$

\[ \tilde{\kappa}_{o+}, \tilde{\kappa}_{o-}, \tilde{\kappa}_{o+}, \tilde{\kappa}_{\text{tr}} \]
Data Analysis 2/3

• next, demodulate 1 day data with $\omega_{\oplus}$
then, fit whole data with $\Omega_\oplus$ using least squares fit
Result

- Rotated $3.7 \times 10^5$ times from Aug 2012 to Dec 2012
- no significance for LV

1 point from 1 day data
average over 104 days
New Limits

- By extracting annual modulation by fitting,
  \[ \tilde{\kappa}_{YZ}^{o+} = (0.5 \pm 1.0) \times 10^{-14} \]
  \[ \tilde{\kappa}_{XZ}^{o+} = (-0.6 \pm 1.2) \times 10^{-14} \]
  \[ \tilde{\kappa}_{XY}^{o+} = (0.7 \pm 1.0) \times 10^{-14} \]
  \[ \tilde{\kappa}_{tr} = (-0.4 \pm 0.9) \times 10^{-10} \]

- 1σ statistical errors are shown

- the speed of light difference propagating in opposite directions was \( \delta c/c \lesssim 10^{-14} \)

Previous best: S. Herrmann et al.: PRD 80, 105011 (2009)
# Systematic Errors

- 10% of statistical error at maximum
- sidereal tilt of turntable

<table>
<thead>
<tr>
<th>Cause</th>
<th>Amount</th>
<th>Ratio compared with stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotational speed fluctuation</td>
<td>&lt; 1 mrad/sec</td>
<td>&lt; 0.01 %</td>
</tr>
<tr>
<td>(Sagnac effect)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>turntable tilt</td>
<td>&lt; 0.2 mrad</td>
<td>&lt; 10 %</td>
</tr>
<tr>
<td>calibration</td>
<td>-</td>
<td>3 %</td>
</tr>
<tr>
<td>refractive index</td>
<td>-</td>
<td>&lt; 0.1 %</td>
</tr>
<tr>
<td>time</td>
<td>1 min</td>
<td>0.4 %</td>
</tr>
<tr>
<td>orientation</td>
<td>2 deg</td>
<td>3 %</td>
</tr>
</tbody>
</table>
Summary and Outlook

Summary
• compared the speed of light propagating in opposite directions
• using a double-pass optical ring cavity
• put new limits on LV in photons

Outlook
• we are still running the measurement from Aug 2012
• higher order coefficients?
• upgrade to monolithic optical system more common mode rejection
Thank you!

ありがとうございます！
Some Photos

spacer made of Super Invar

cavity mirrors

silicon inside

20 mm

70 mm
Time Series
from July 25, 2012
to April 25, 2013
Sensitivity Spectrum

![Graph showing sensitivity spectrum with frequency on the x-axis and relative frequency noise on the y-axis. The graph includes lines for free run, requirement, sensitivity in-loop, and sensitivity. A diagram of a laser setup is also included.]
Cheat Sheet

- rotation frequency $f_{rot} = 0.083$ Hz ($T_{rot} = 12$ sec)
- input power $P_{in} = 1$ mW
- finesse $F = 120$
- cavity length $L = 140$ mm
- silicon length $d = 20$ mm
- silicon refractive index $n = 3.69$
- silicon AR loss $l < 0.5\%$ / surface
- incident angle $\theta = 9.5$ deg
- FSR = 1.5 GHz
- FWHM = 12 MHz

- sensitivity $\sim 4e^{-13}/\text{rtHz}$
- shot noise $\sim 7e^{-14}/\text{rtHz}$ ($\propto 1/F$, $\propto 1/\sqrt{P_{in}}$)
- mirror thermal $\sim 5e^{-16}/\text{rtHz}$ (all @ 0.1 Hz)

- laser: Koheras AdjustiK C15
- motor: Nikki Denso $\tau$DISC (ND110-85-FC)