Testing Lorentz Invariance with an Optical Ring Cavity

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Self-introduction

- Ando Group,
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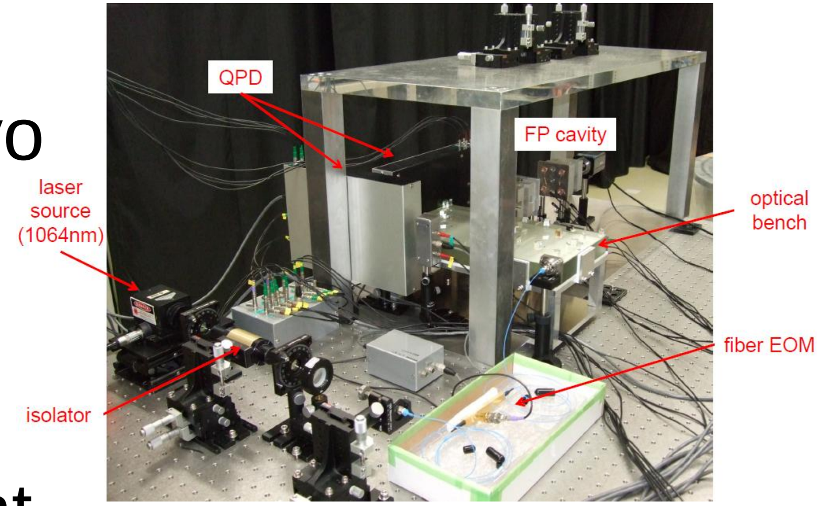
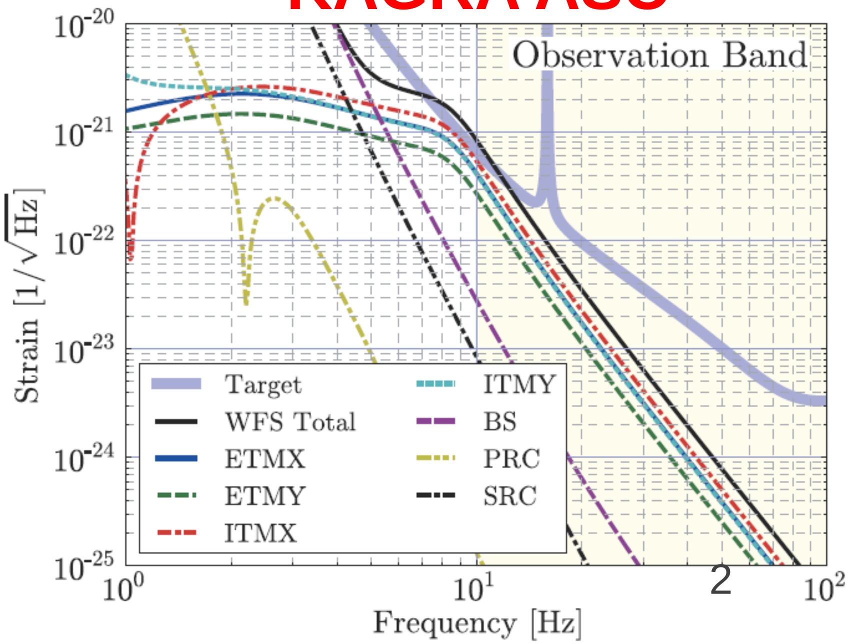
  graduate student
- what I have been doing
  - DECIGO Pathfinder
    prototype FP experiment
  - KAGRA (LCGT)
    ASC simulation
  - visit Caltech 40m
  - anisotropy search in the speed of light (this talk)

DPF prototype FP

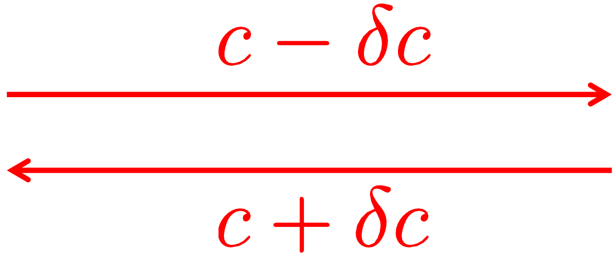


KAGRA ASC

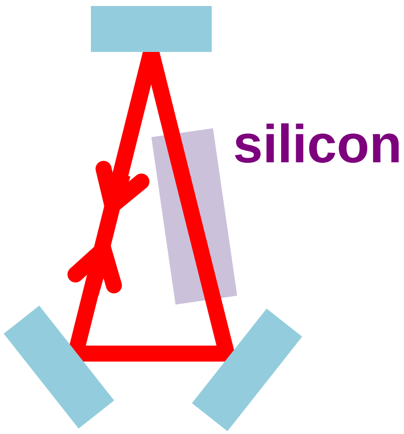


Abstract

- tested Special Relativity(Lorentz invariance in photons) by testing
  isotropy in the one-way speed of light



- new idea: use an asymmetric optical ring cavity

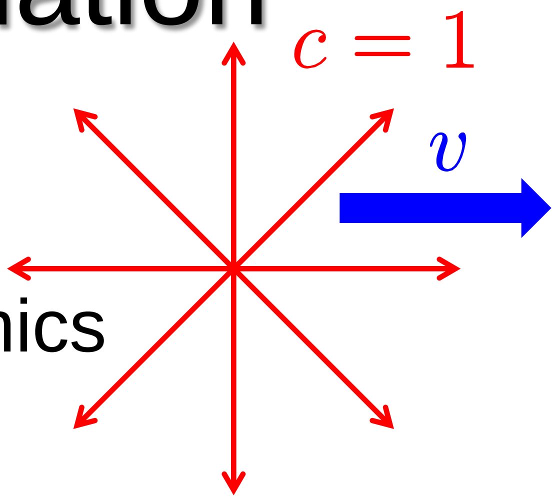


- got the world's best limit $|\delta c/c| \lesssim 1 \times 10^{-14}$

  [Y. Michimura *et al.*: Phys. Rev. Lett. 110, 200401 (2013)]
- got the first limits on higher order Lorentz violation

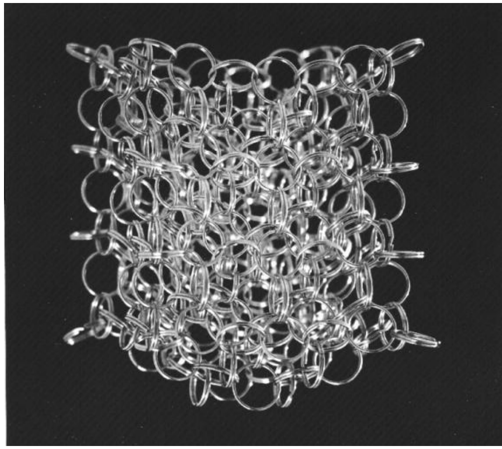
  [Y. Michimura *et al.*: Phys. Rev. D 88, 111101(R) (2013)]

SR and Lorentz violation

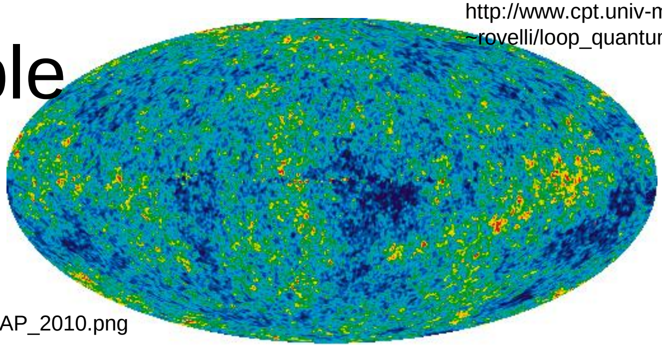


- Special Relativity (1905)
  speed of light is constant
- Lorentz invariance in electrodynamics
- no one could find any violation
- but…
  - quantum gravity theory suggests
    violation at some level
    e.g. $\delta c/c \sim 10^{-17}$
    D. Colladay and V. Alan Kostelecký: PRD 58 ,116002 (1998)
  - anisotropy in CMB
    CMB rest frame: possible
    preferred frame?

$\rightarrow$ we have to test SR !



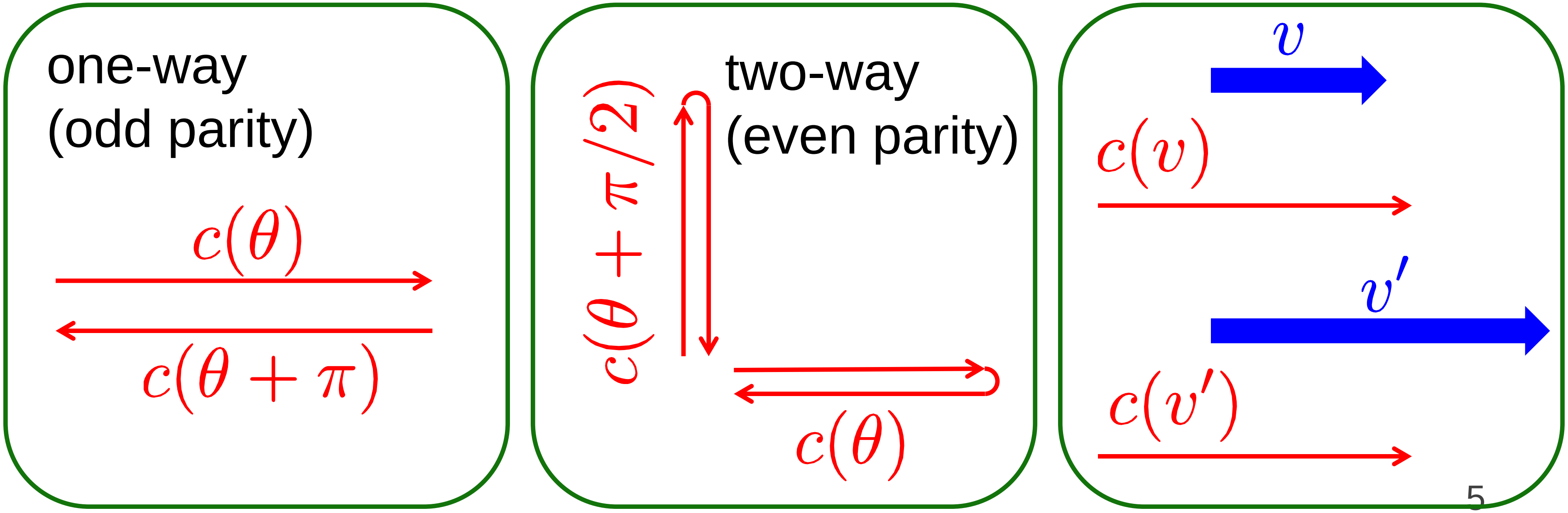
http://www.cpt.univ-mrs.fr/~rovelli/loop_quantum_gravity.jpg



http://en.wikipedia.org/wiki/File:WMAP_2010.png

Testing SR

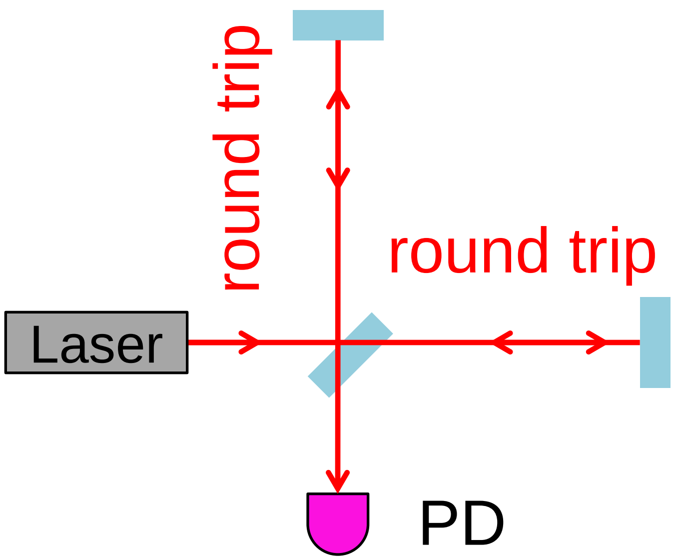
- most traditional way to test SR
- constancy of the speed of light consists from
  - isotropy in the one-way speed of light
  - isotropy in the two-way speed of light
  - independence of the speed of light from the lab. velocity

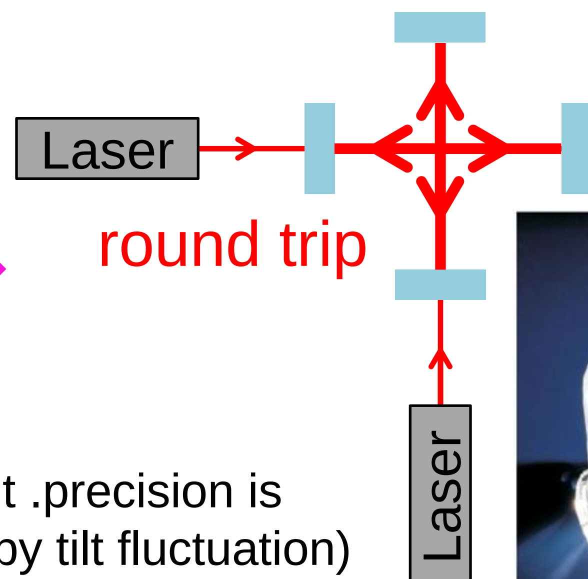


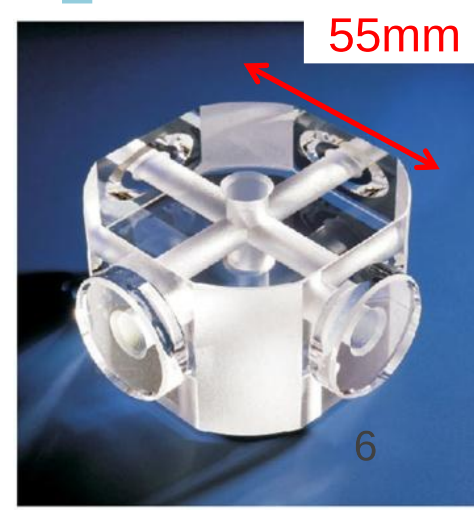
Previous Tests for Two-Way c

- Michelson-Morley experiment (1887)
  Michelson interferometer
- compare the resonant freqs of crossed FP in a single block (2009) $|\delta c/c| \lesssim 10^{-17}$

Ch. Eisele+: PRL 103, 090401 (2009)







(Current .precision is limited by tilt fluctuation)

S. Herrmann+: PRD 80, 105011 (2009)

Previous Tests for One-Way c

- Ives-Stilwel experiment (1938)
  measure Doppler shifted resonant freq of ions
- most recent IS-type experiment (2007)

$$|\delta c/c| \lesssim 10^{-10}$$

S. Reinhardt *et al.*: [Nat. Phys. 3, 861 (2007)]

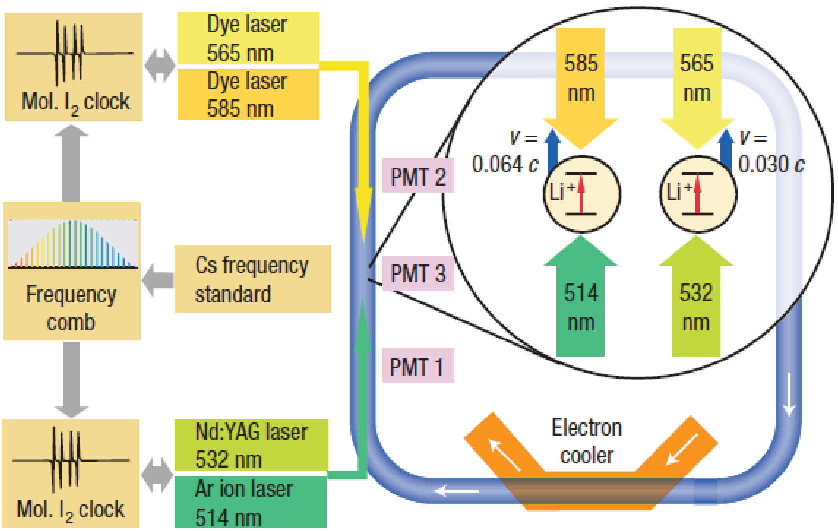
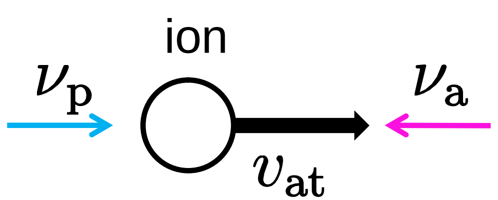


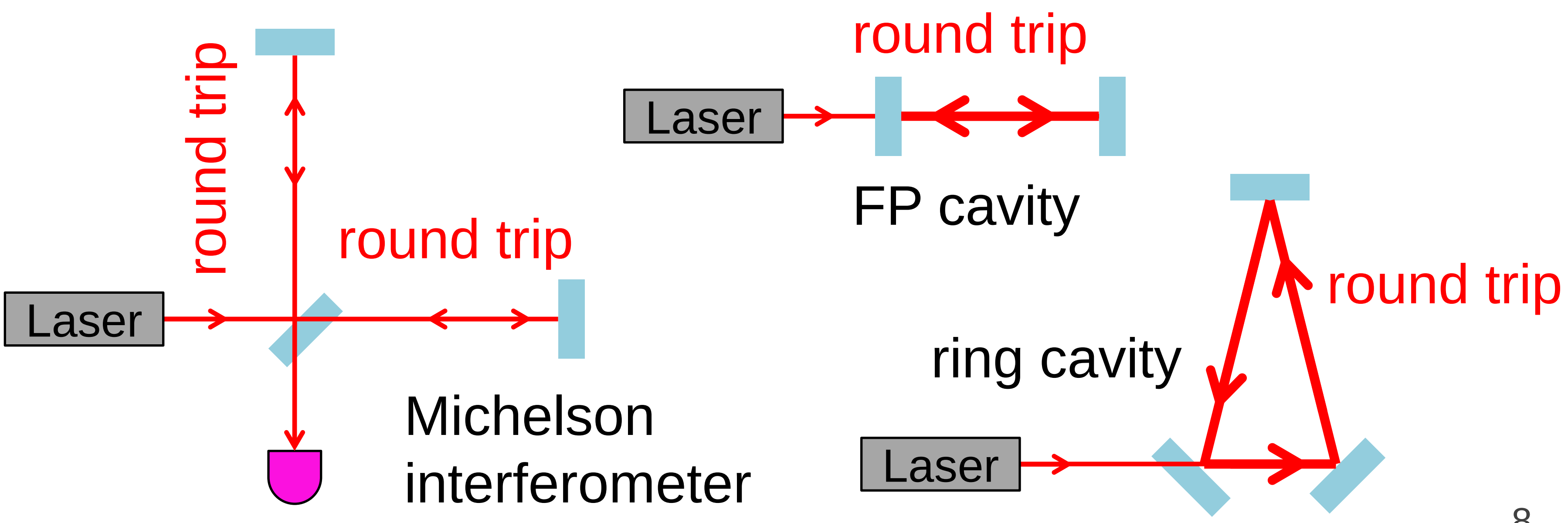
Figure 1 Schematic diagram of the TSR. Li^+ ions circulate in the 55-m-circumference ring. In the electron cooler, cold electrons are overlapped with the ions and provide cooling. The measurements at the two different velocities are carried out sequentially. In the experiment, the two lasers are coupled into the ring from the same side and are retro-reflected.



have to measure the absolute value of the resonant frequency

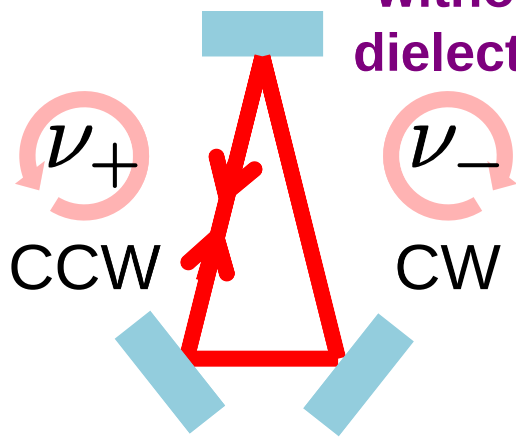
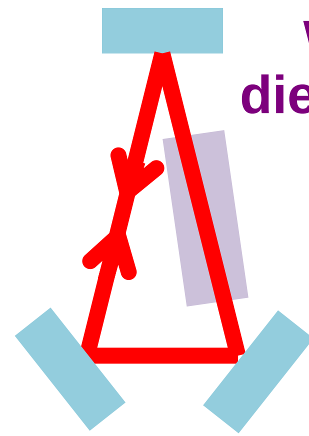
Starting Point

- one-way test is 7-orders of magnitude less precise than two-way test!
- can't test one-way c using ordinary interferometers
- one-way anisotropy term cancels in a closed loop
- Hmm……



Asymmetric Ring Cavity

- putting a dielectric makes an asymmetry
  $\rightarrow$ will be sensitive to one-way anisotropy

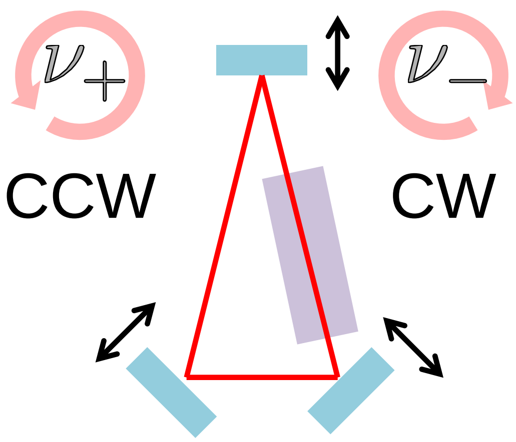
	without dielectric	with dielectric
		
without Lorentz violation	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu$ $\nu_- = \nu$
with Lorenz violation	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu - \delta\nu$ $\nu_- = \nu + \delta\nu$

freq. shift $\propto \hat{\alpha}$

Counter Propagating Modes

- comparing resonant frequencies of counter propagating modes
  → high CMRR to cavity length change
  no need for high vacuum, seismic isolation,
  tilt control of turn table,
  temperature control (or cryogenic)

W. S. N. Trimmer+: PRD 8, 3321 (1973)
M. E. Tobar+: PRD 71, 025004 (2005)
Q. Exirifard: arXiv:1010.2057
F. N. Baynes+: PRL 108, 260801 (2012)



$$\nu_+ = \nu - \delta\nu$$
$$\nu_- = \nu + \delta\nu$$

Experimental Setup

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

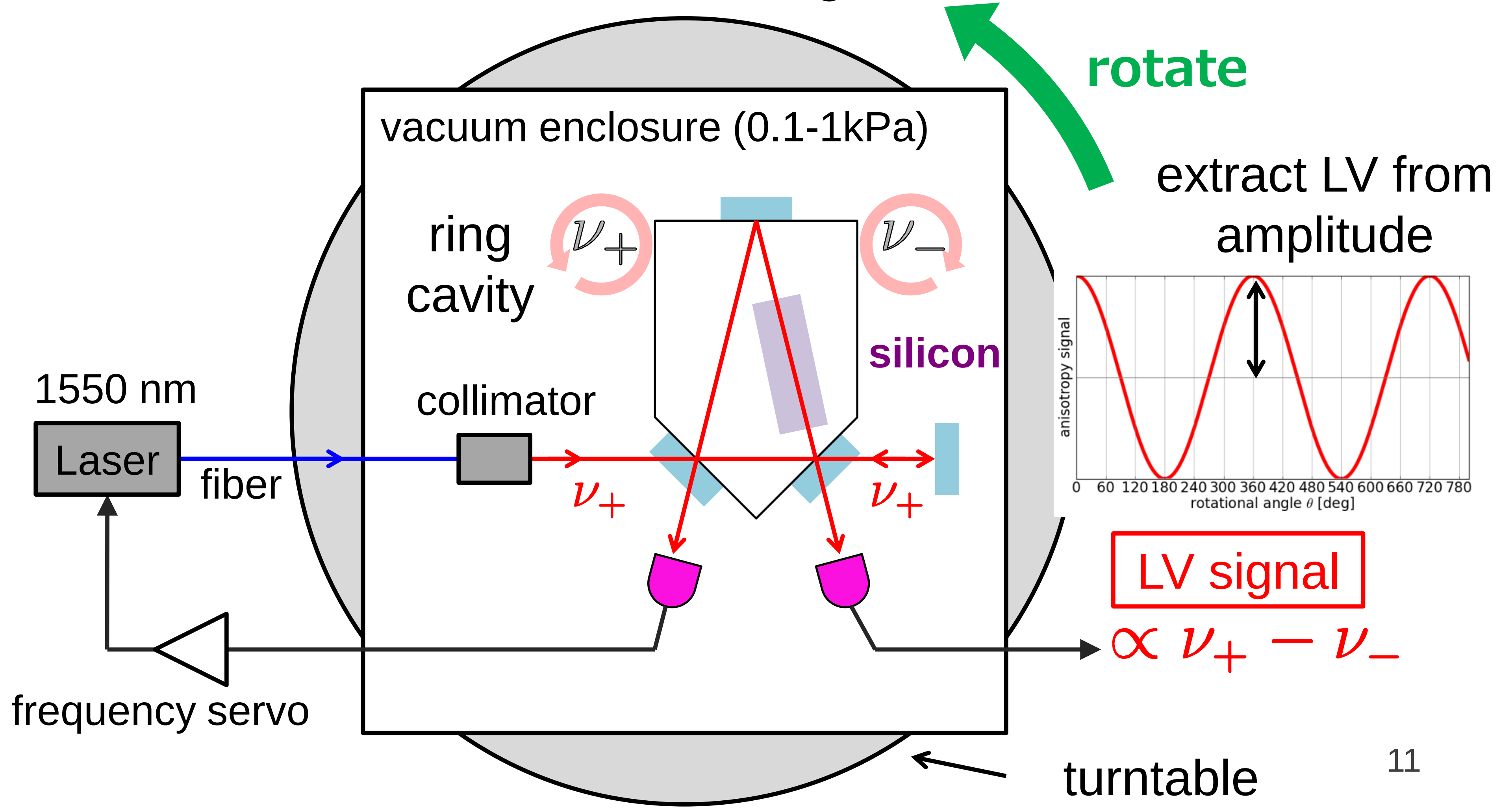


Photo of the Optics

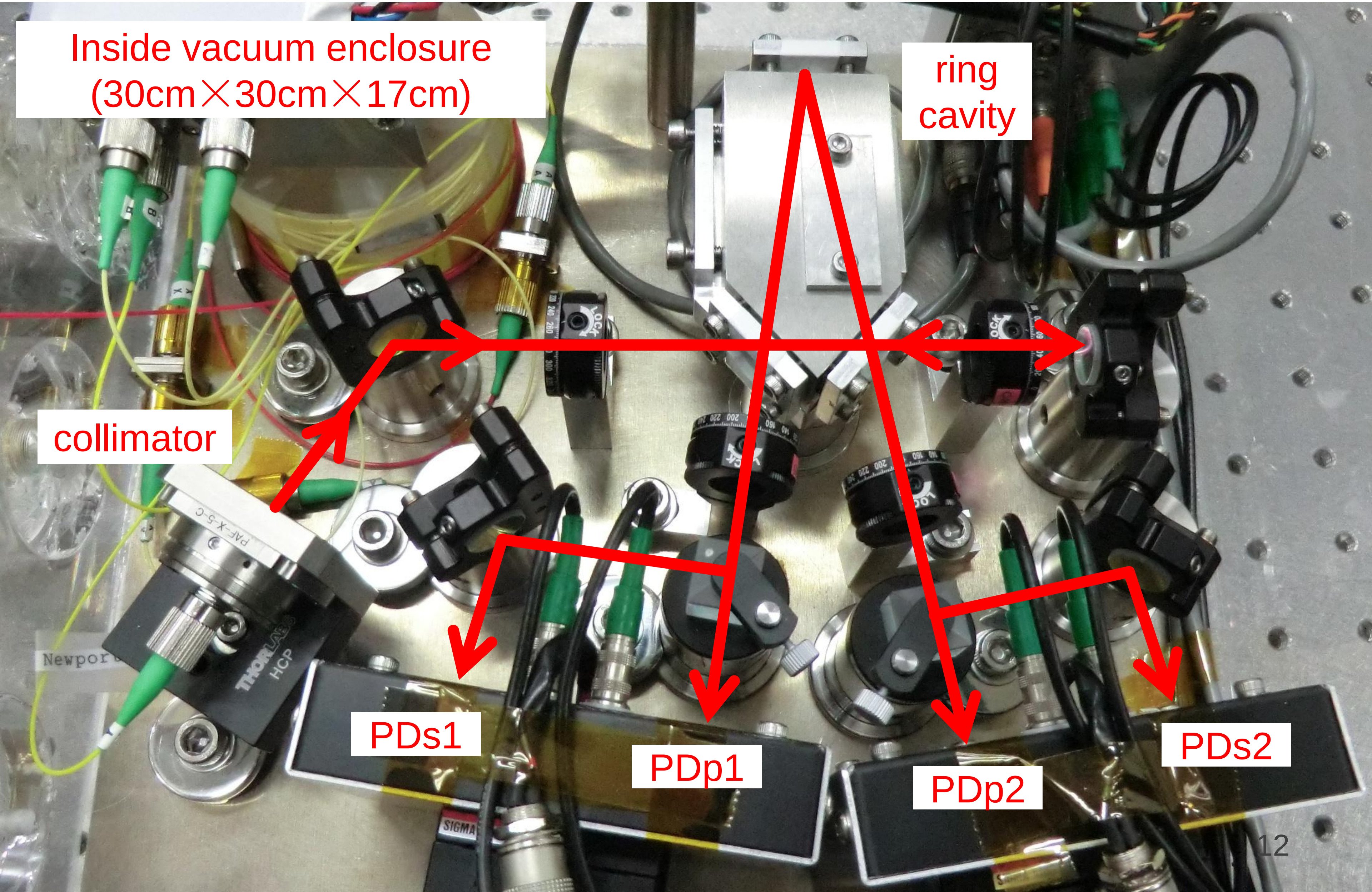


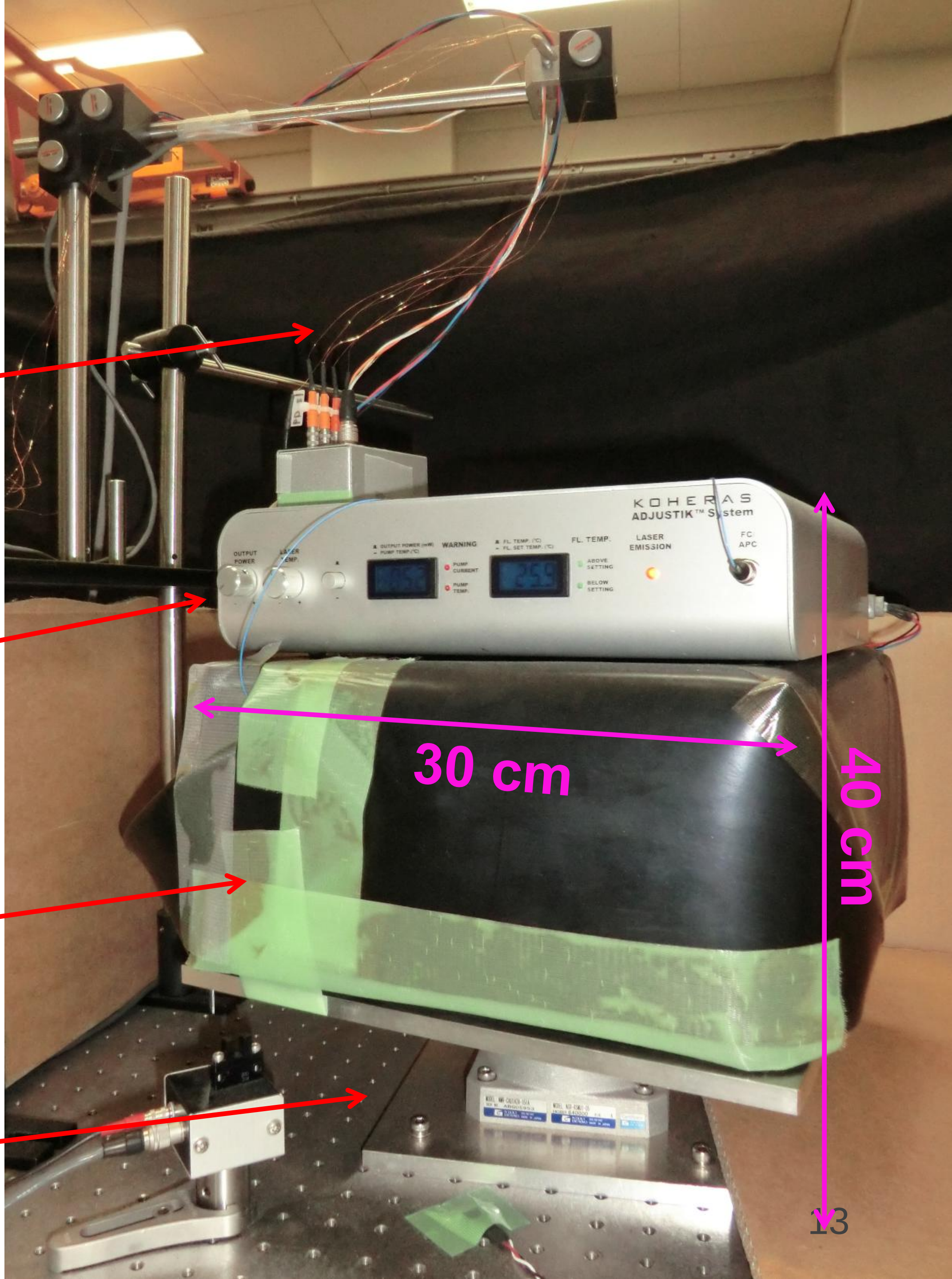
Photo of the Whole Setup

electrical cables

laser source

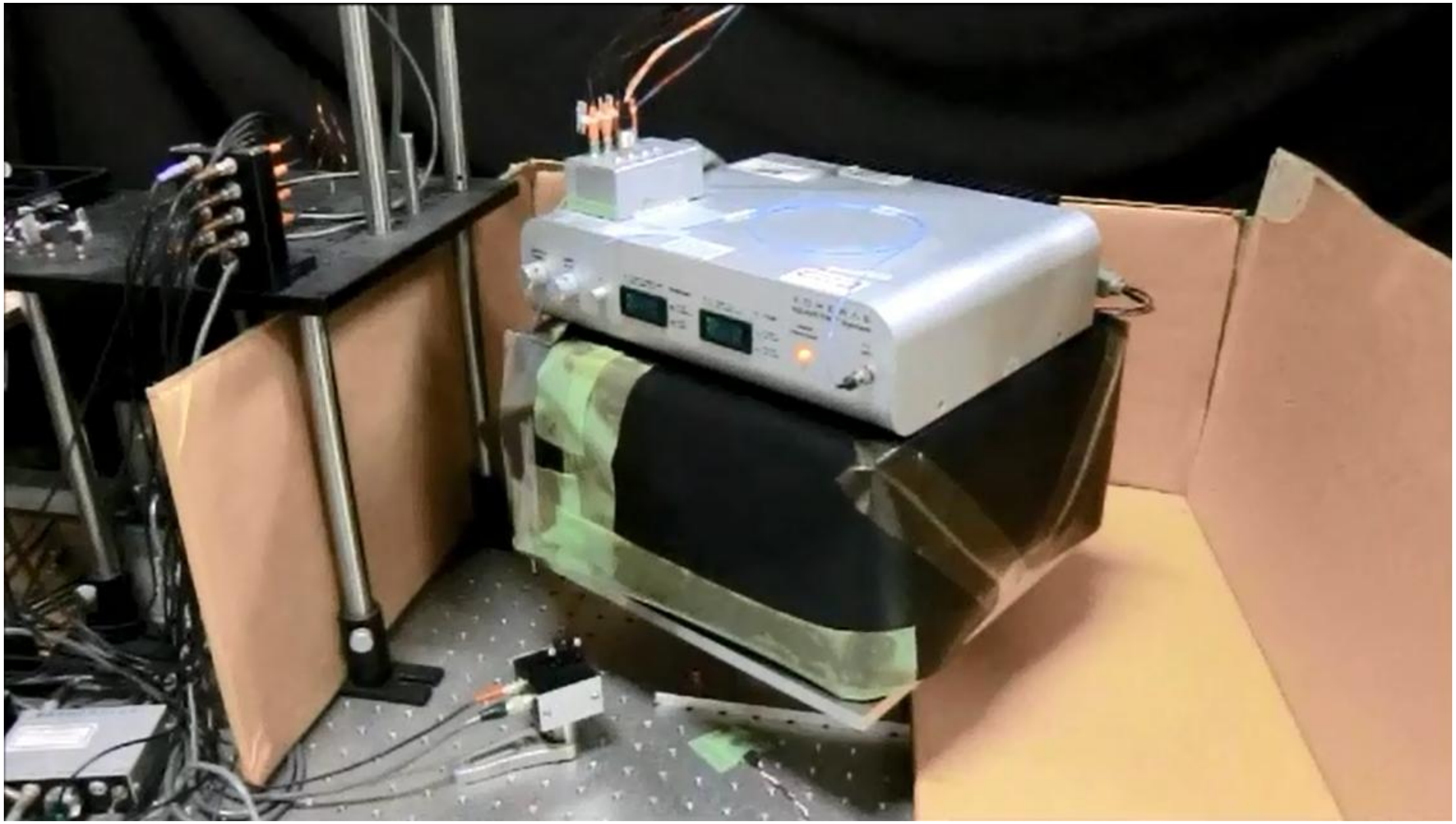
vacuum enclosure
+ shielding
(optics inside)

turntable



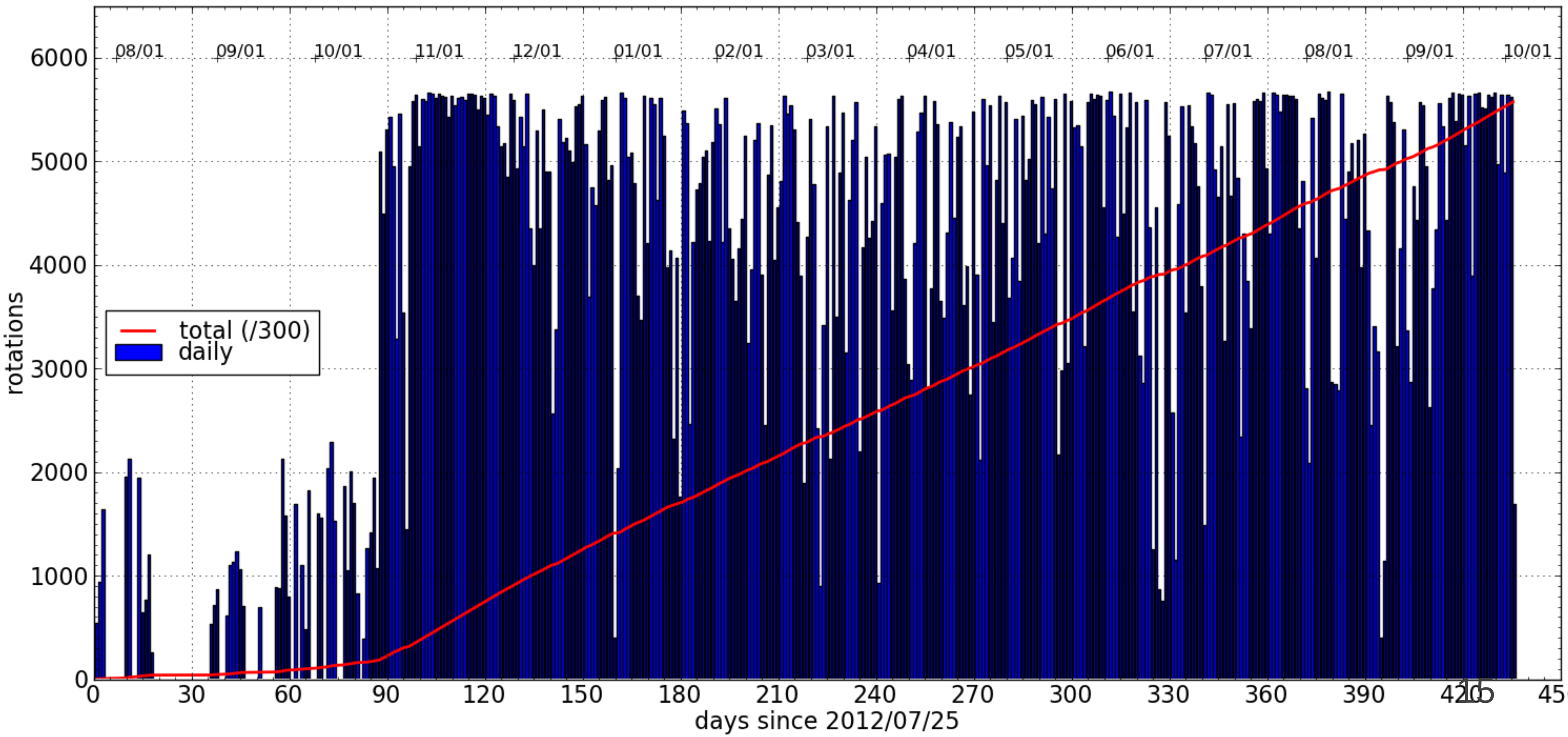
It Rotates

- movie



Rotated for 1 Year

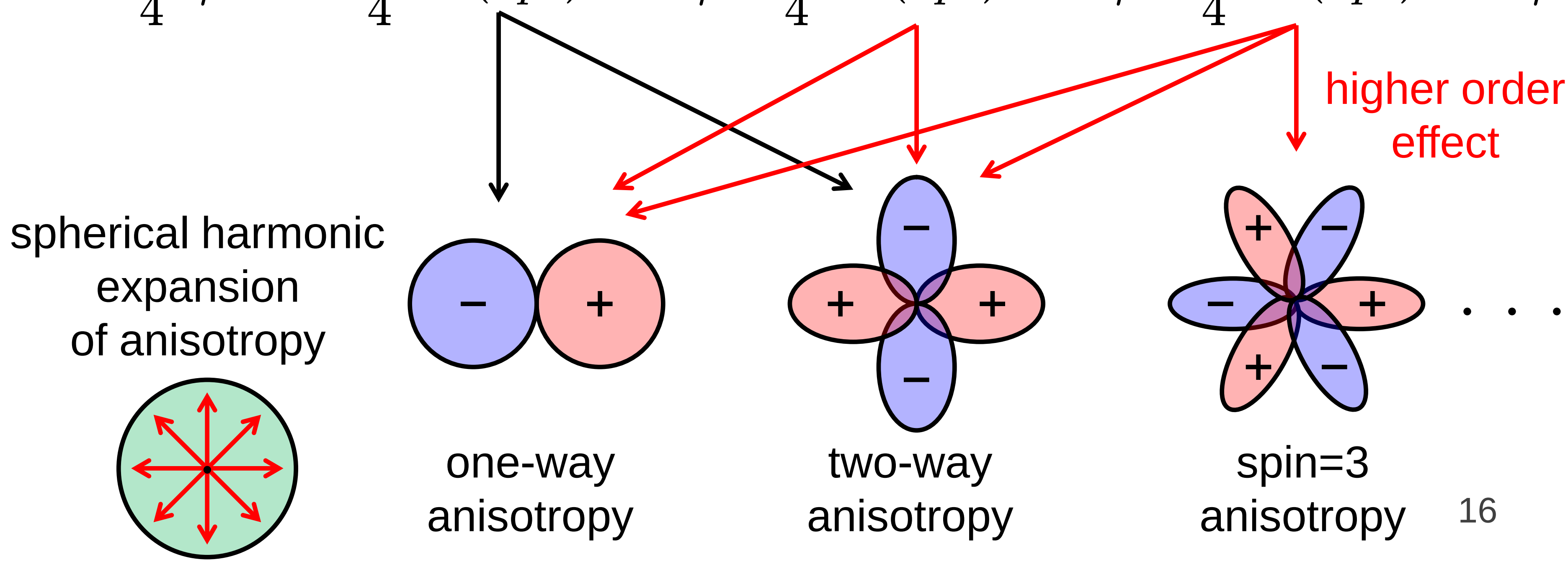
- from August 2012 to September 2013
- 393 days
- 1.7 million rotations



Test Model for Data Analysis

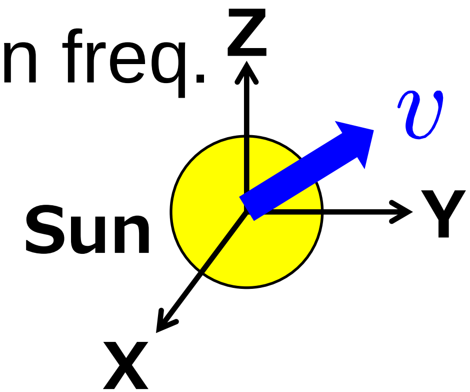
- Standard Model Extension (SME)
  D. Colladay and V. Alan Kostelecký: [PRD 58, 116002 (1998)]
- add LV terms in the electromagnetic Lagrangian

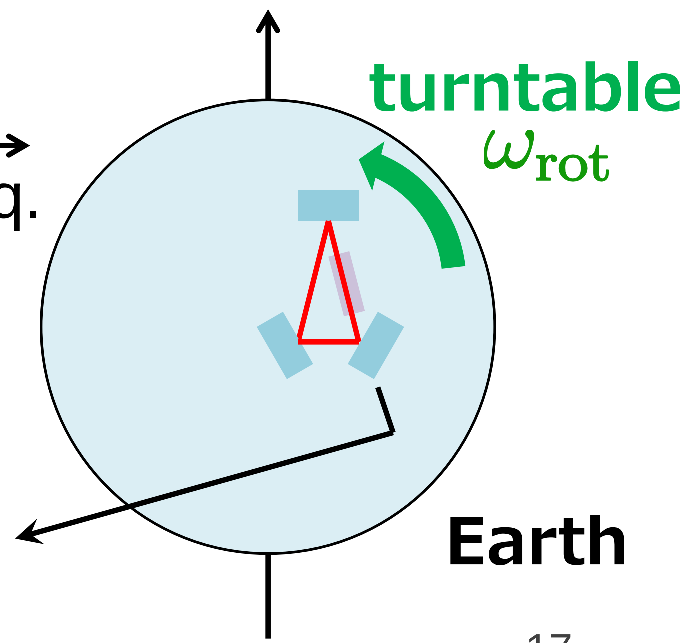
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}F_{\kappa\lambda}(\hat{k}_F^{(4)})^{\kappa\lambda\mu\nu}F_{\mu\nu} + \frac{1}{4}F_{\kappa\lambda}(\hat{k}_F^{(6)})^{\kappa\lambda\mu\nu}F_{\mu\nu} + \frac{1}{4}F_{\kappa\lambda}(\hat{k}_F^{(8)})^{\kappa\lambda\mu\nu}F_{\mu\nu} \cdots$$



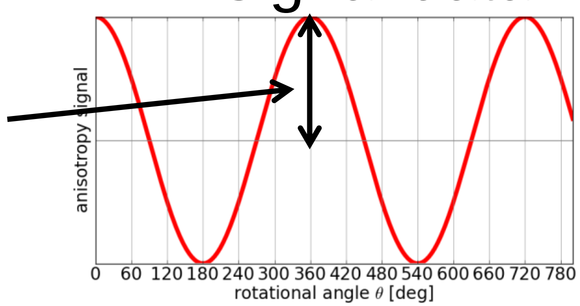
Data Analysis 1

- demodulate data with turntable rotation freq.





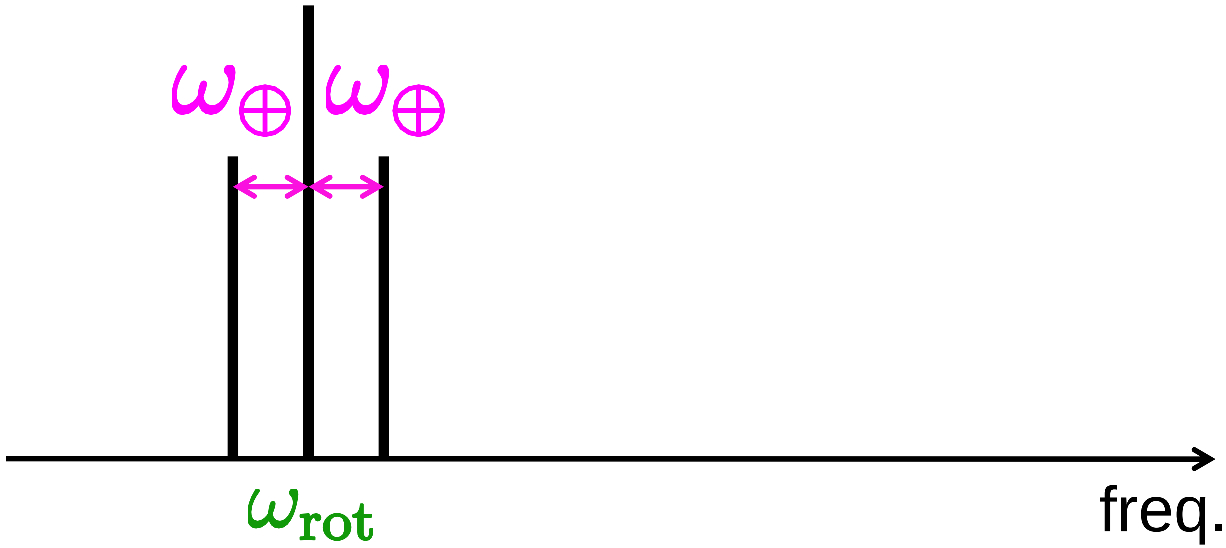
LV signal data

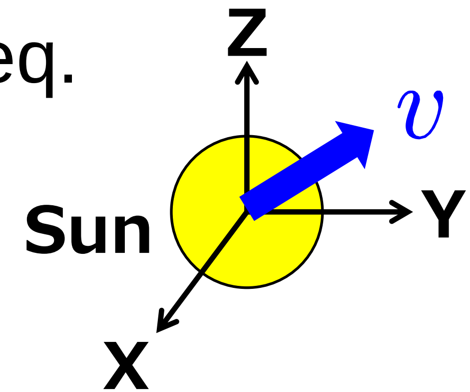


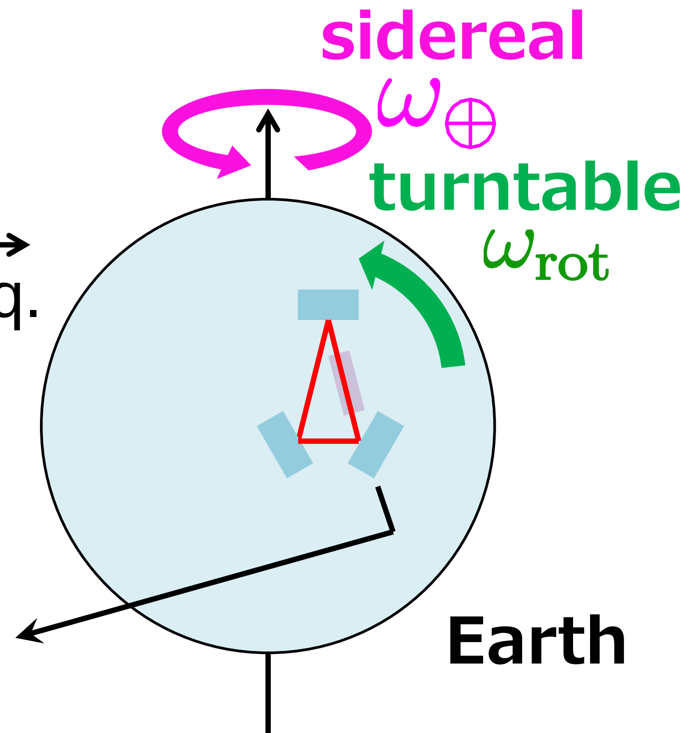
demodulation amplitude $\propto$ LV

Data Analysis 2

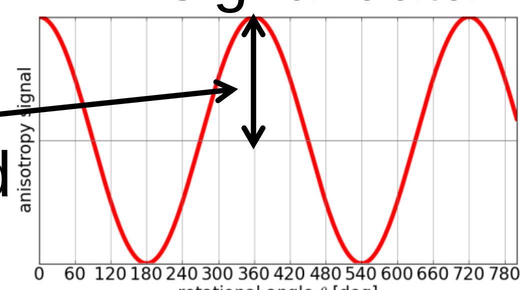
- then demodulate data with sidereal freq.







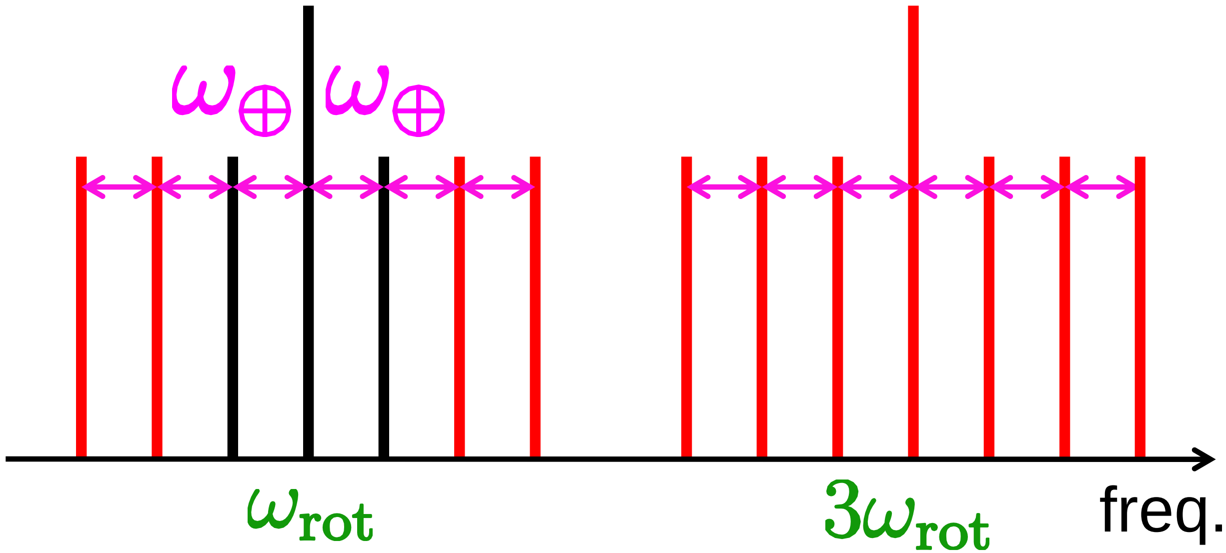
LV signal data

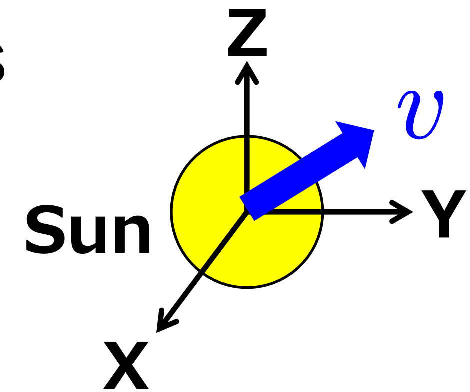


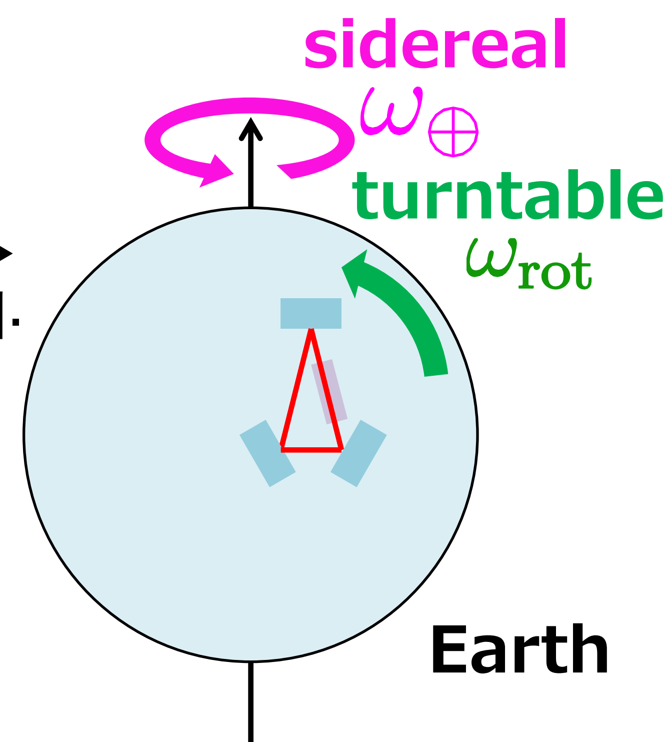
demodulation amplitude is modulated by sidereal freq.

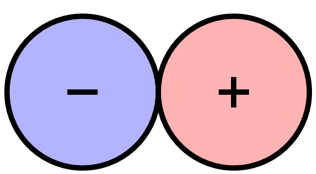
Data Analysis 3

- demodulate at odd number harmonics to get odd-parity higher order LV

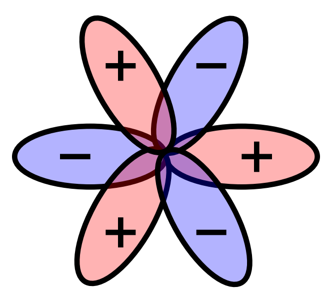






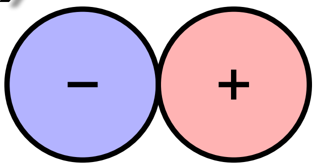


360 degrees rotational symmetry

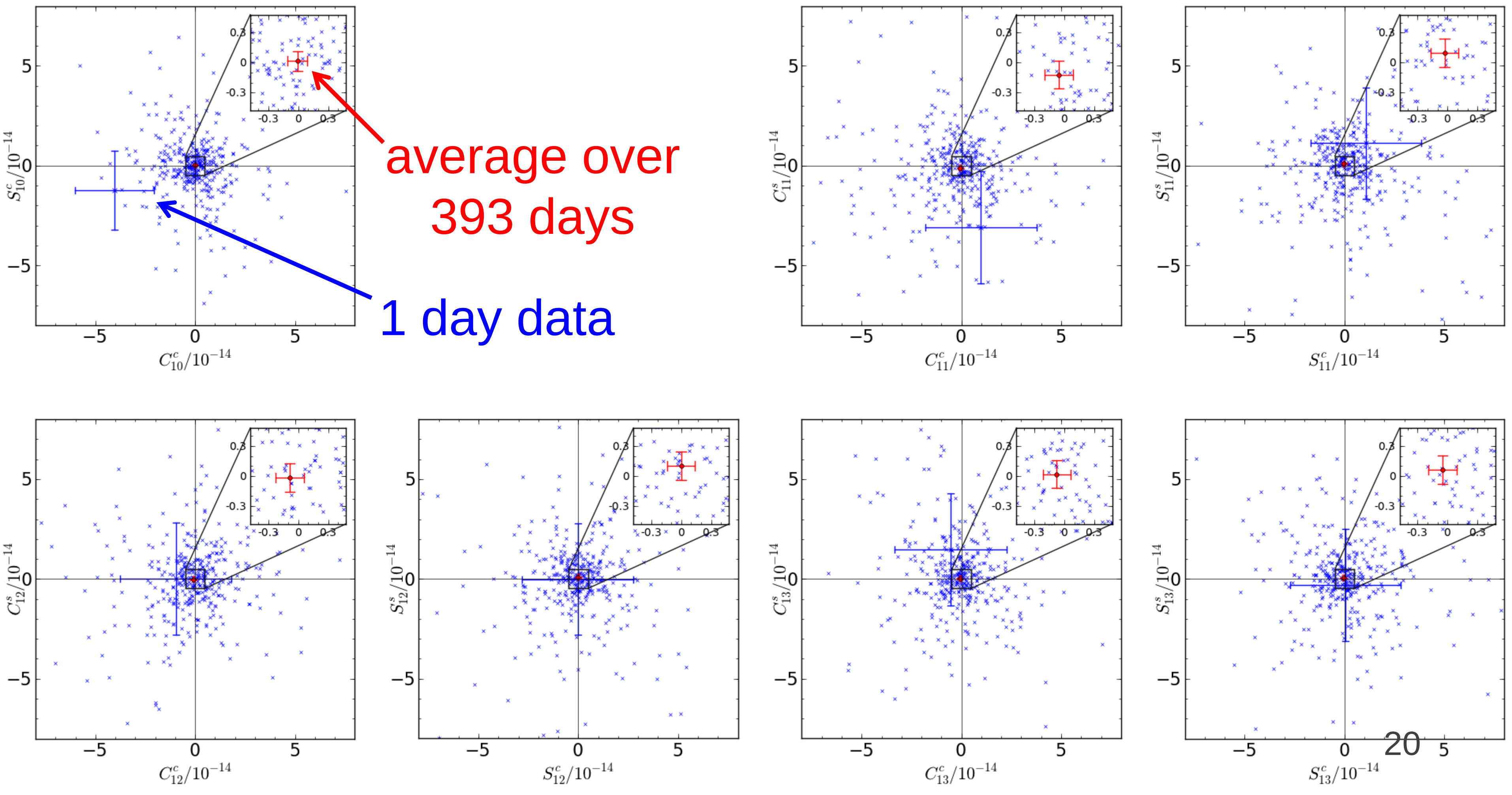


120 degrees rotational symmetry

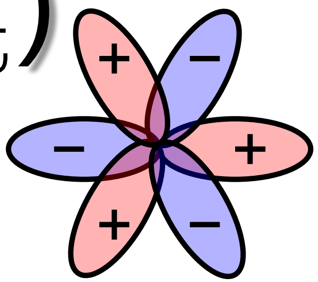
Demod. Amplitudes(ω_{rot})



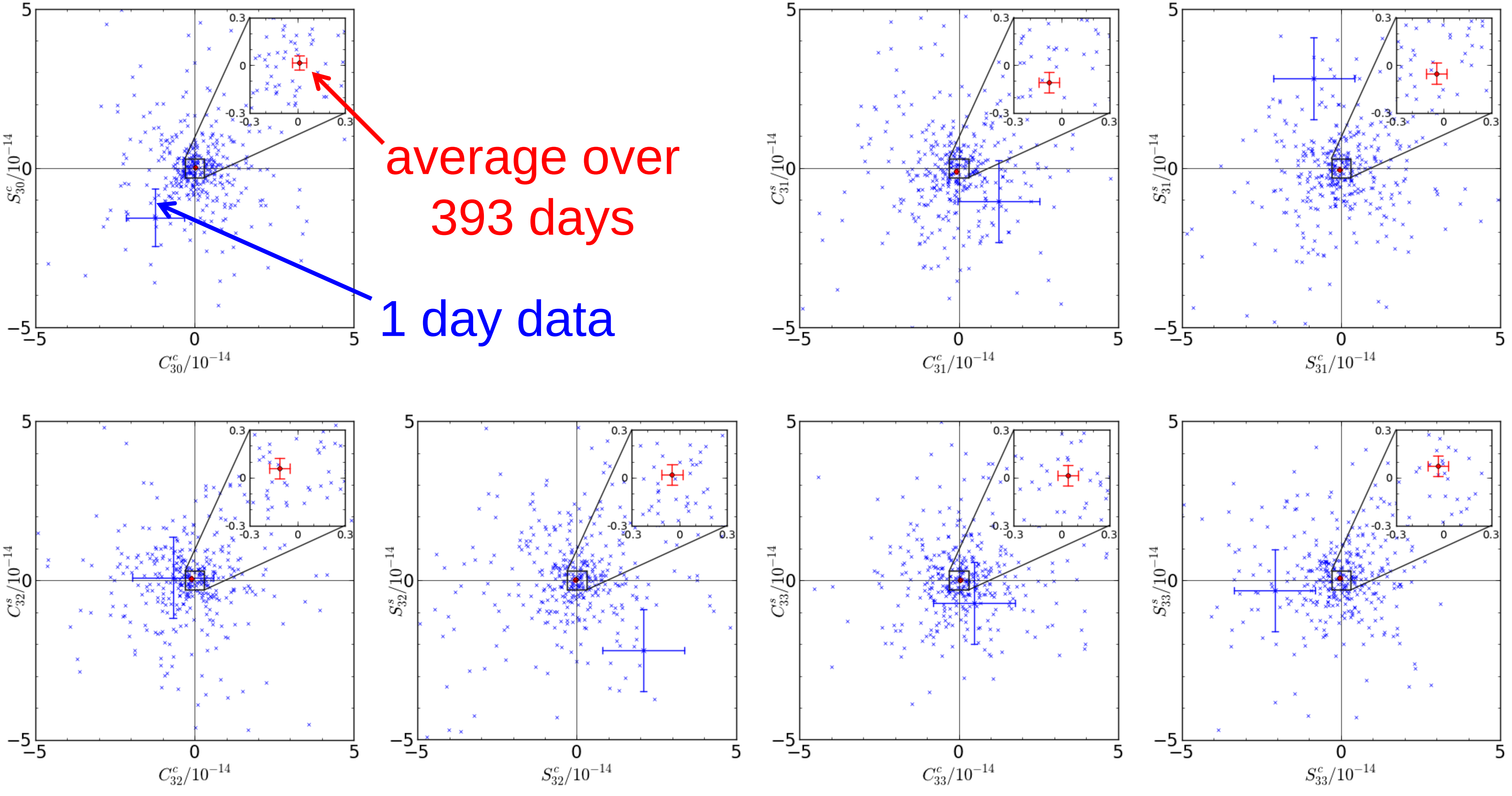
- zero consistent within 2σ
  → no significant LV found



Demod. Amplitudes($3\omega_{\mathrm{rot}}$)



- zero consistent within 2σ
  → no significant LV found



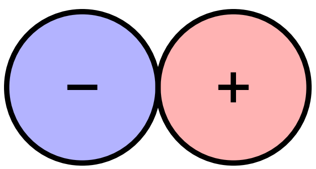
Limits on Higher-Order LV

- d=6 odd-parity LV parameters (3 of 3)

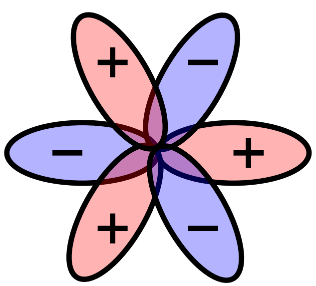
$$\lesssim 1 \times 10^{3}\ \mathrm{GeV}^{-2}$$

- d=8 odd-parity LV parameters (10 of 13)

$$\lesssim 1 \sim 3 \times 10^{19}\ \mathrm{GeV}^{-4}$$



$$|\delta c/c| \lesssim 7 \times 10^{-15}$$

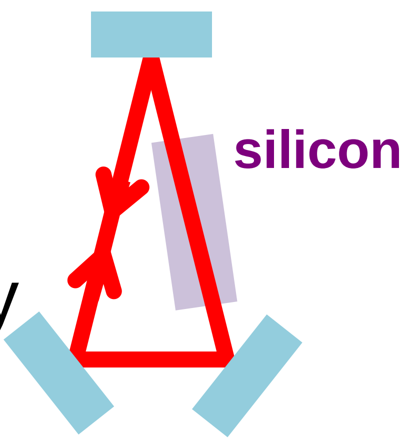


$$|\delta c/c| \lesssim 3 \times 10^{-15}$$

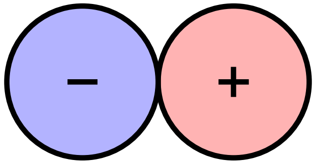
Coefficient	Measurement
$(\overline{c}_F^{(6)})^{(0E)}_{110}$	$(-0.1 \pm 1.5) \times 10^3\ \mathrm{GeV}^{-2}$
$\mathrm{Re}[(\overline{c}_F^{(6)})^{(0E)}_{111}]$	$(0.8 \pm 1.1) \times 10^3\ \mathrm{GeV}^{-2}$
$\mathrm{Im}[(\overline{c}_F^{(6)})^{(0E)}_{111}]$	$(-0.6 \pm 1.0) \times 10^3\ \mathrm{GeV}^{-2}$
$(\overline{c}_F^{(8)})^{(0E)}_{310} - 0.020(\overline{c}_F^{(8)})^{(0E)}_{110}$	$(-0.2 \pm 1.9) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Re}[(\overline{c}_F^{(8)})^{(0E)}_{311} - 0.020(\overline{c}_F^{(8)})^{(0E)}_{111}]$	$(1.4 \pm 1.3) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Im}[(\overline{c}_F^{(8)})^{(0E)}_{311} - 0.020(\overline{c}_F^{(8)})^{(0E)}_{111}]$	$(0.1 \pm 1.3) \times 10^{19}\ \mathrm{GeV}^{-4}$
$(\overline{c}_F^{(8)})^{(0E)}_{330}$	$(-0.8 \pm 3.3) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Re}[(\overline{c}_F^{(8)})^{(0E)}_{331}]$	$(-0.3 \pm 1.9) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Im}[(\overline{c}_F^{(8)})^{(0E)}_{331}]$	$(-2.8 \pm 1.9) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Re}[(\overline{c}_F^{(8)})^{(0E)}_{332}]$	$(2.2 \pm 1.3) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Im}[(\overline{c}_F^{(8)})^{(0E)}_{332}]$	$(0.2 \pm 1.3) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Re}[(\overline{c}_F^{(8)})^{(0E)}_{333}]$	$(-0.1 \pm 1.6) \times 10^{19}\ \mathrm{GeV}^{-4}$
$\mathrm{Im}[(\overline{c}_F^{(8)})^{(0E)}_{333}]$	$(-0.1 \pm 1.6) \times 10^{19}\ \mathrm{GeV}^{-4}$

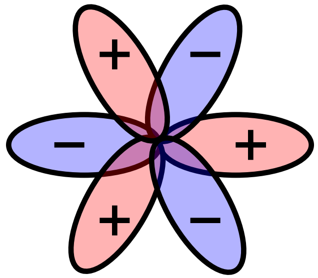
Summary

- asymmetric optical ring cavity with double-pass configuration



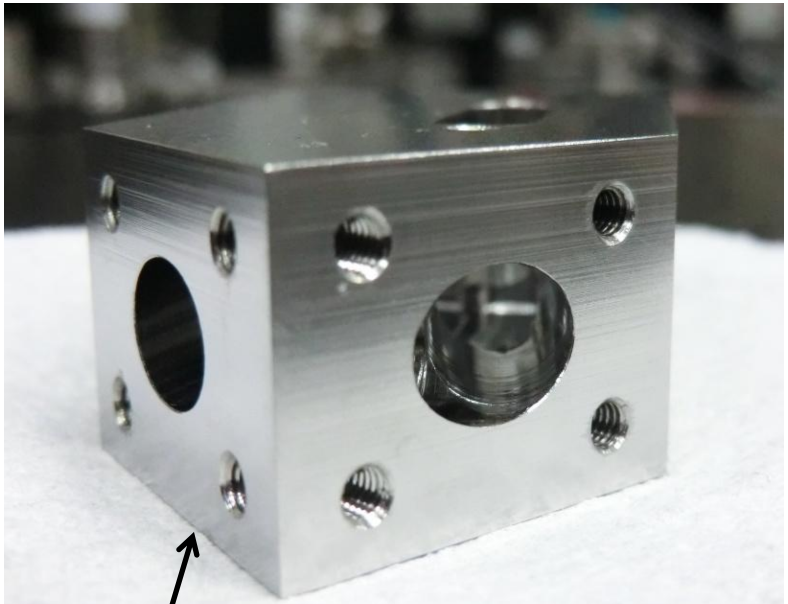
- searched anisotropy for 1 year
  393 days, 1.7 million rotations
- put the best limit on one-way anisotropy
  $$|\delta c/c| \lesssim 7 \times 10^{-15}$$
- put the first limits on odd-parity higher-order Lorentz violations



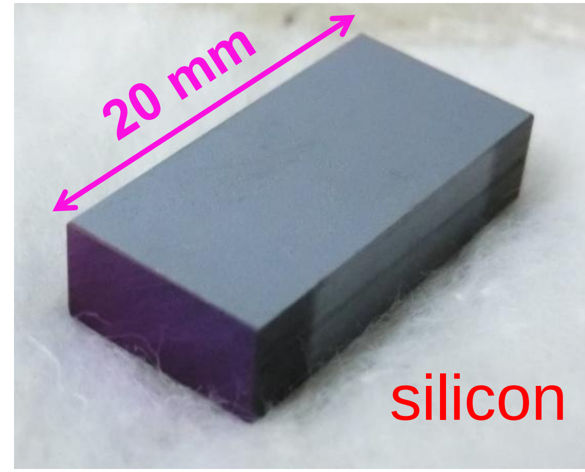


Additional Slides

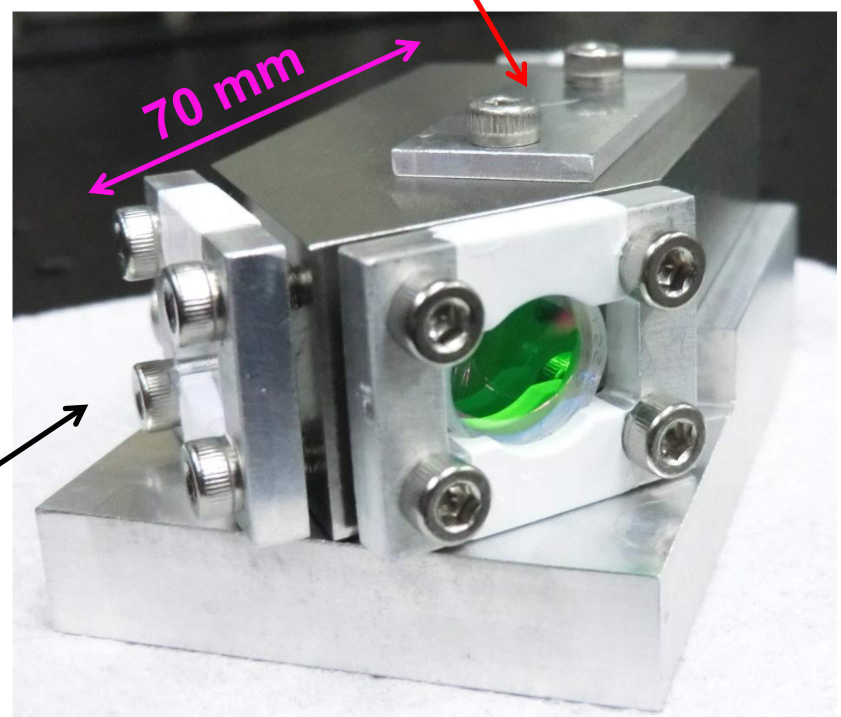
Some Photos of the Cavity



spacer made of
Super Invar

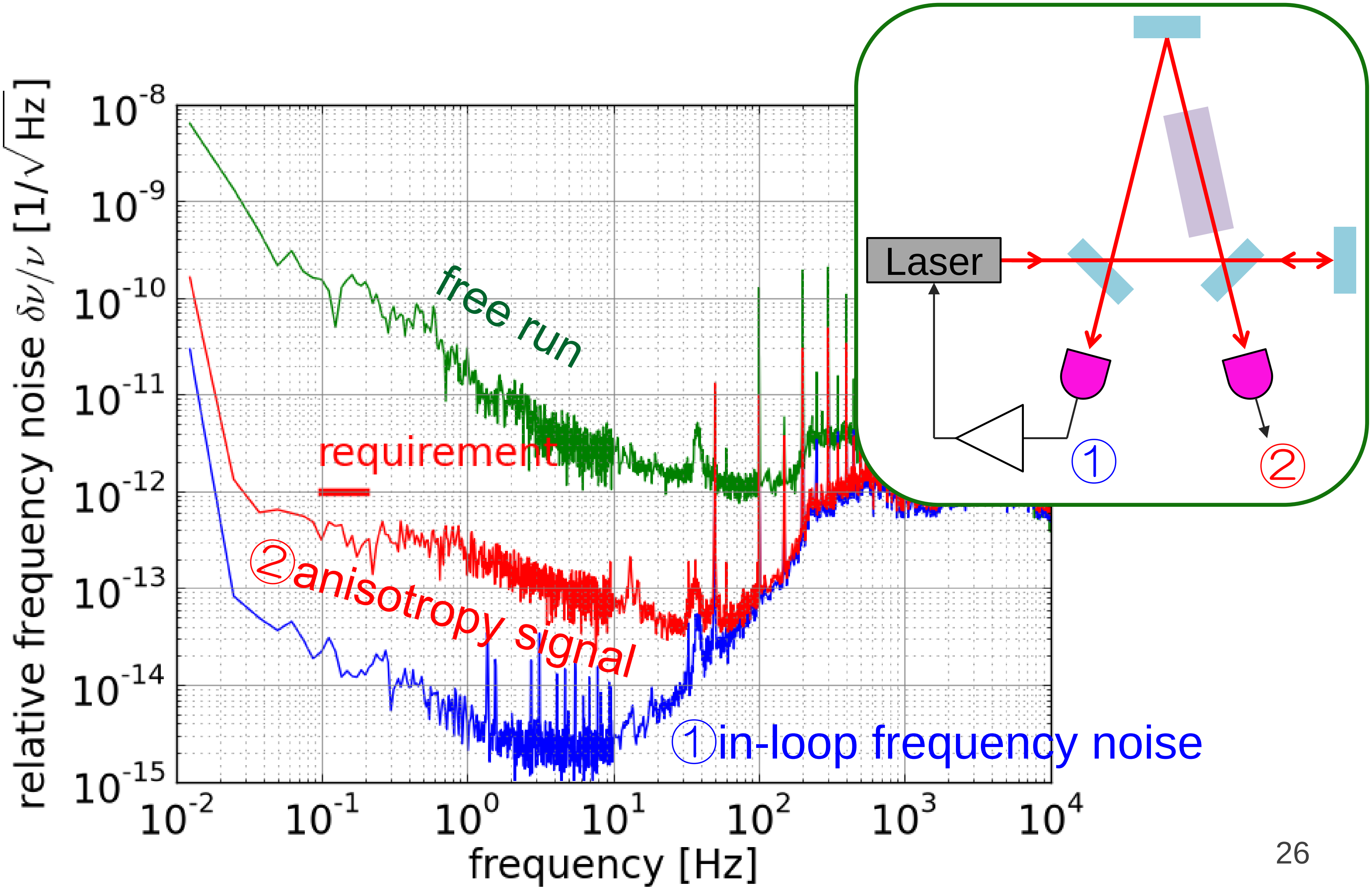


silicon inside



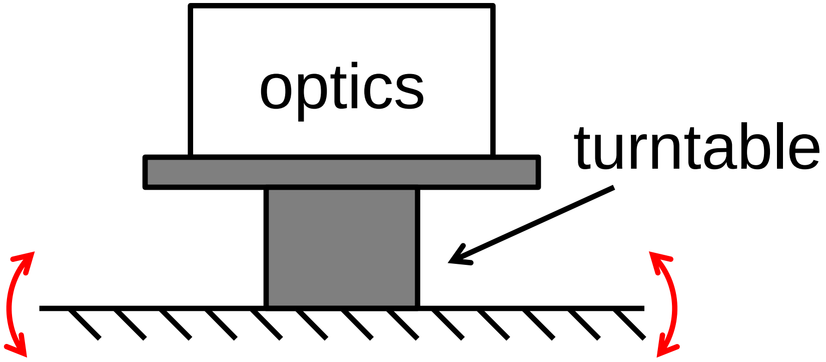
cavity mirrors

Sensitivity Spectrum



Systematic Errors

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



Cause	Amount	Ratio compared with stat.
rotational speed fluctuation (Sagnac effect)	< 1 mrad/sec	< 0.01 %
turntable tilt	< 0.2 mrad	< 10 %
calibration	-	3 %
refractive index	-	< 0.1 %
time	1 min	0.4 %
orientation	2 deg	3 %

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 θ = 9.5 deg
- FSR = 1.5 GHz
- FWHM = 12 MHz

- laser: Koheras AdjustiK C15
- motor: Nikki Denso τDISC
  (ND110-85-FC)

- sensitivity ~ 4e-13 /rtHz
- shot noise ~ 7e-14 /rtHz
  ($\propto$ 1/F, $\propto$ 1/sqrt(P_{in}))
- mirror thermal ~ 5e-16 /rtHz

(all @ 0.1 Hz)

Previous Limits on HOLV

- first limits odd-parity coefficients
- cf. previous limits for even-parity coefficients

  d=6: $\sim 10^6 \ \mathrm{GeV}^{-2}$

  d=8: $\sim 10^{31} \sim 10^{35} \ \mathrm{GeV}^{-4}$

[S. R. Parker *et al.*: PRL 106, 180401 (2011)]

Coefficient	Measurement
$(\overline{c}_F^{(6)})_{110}^{(0E)}$	$(-0.1 \pm 1.5) \times 10^3 \ \mathrm{GeV}^{-2}$
$\mathrm{Re}\big[(\overline{c}_F^{(6)})_{111}^{(0E)}\big]$	$(0.8 \pm 1.1) \times 10^3 \ \mathrm{GeV}^{-2}$
$\mathrm{Im}\big[(\overline{c}_F^{(6)})_{111}^{(0E)}\big]$	$(-0.6 \pm 1.0) \times 10^3 \ \mathrm{GeV}^{-2}$
$(\overline{c}_F^{(8)})_{310}^{(0E)} - 0.020(\overline{c}_F^{(8)})_{110}^{(0E)}$	$(-0.2 \pm 1.9) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Re}\big[(\overline{c}_F^{(8)})_{311}^{(0E)} - 0.020(\overline{c}_F^{(8)})_{111}^{(0E)}\big]$	$(1.4 \pm 1.3) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Im}\big[(\overline{c}_F^{(8)})_{311}^{(0E)} - 0.020(\overline{c}_F^{(8)})_{111}^{(0E)}\big]$	$(0.1 \pm 1.3) \times 10^{19} \ \mathrm{GeV}^{-4}$
$(\overline{c}_F^{(8)})_{330}^{(0E)}$	$(-0.8 \pm 3.3) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Re}\big[(\overline{c}_F^{(8)})_{331}^{(0E)}\big]$	$(-0.3 \pm 1.9) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Im}\big[(\overline{c}_F^{(8)})_{331}^{(0E)}\big]$	$(-2.8 \pm 1.9) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Re}\big[(\overline{c}_F^{(8)})_{332}^{(0E)}\big]$	$(2.2 \pm 1.3) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Im}\big[(\overline{c}_F^{(8)})_{332}^{(0E)}\big]$	$(0.2 \pm 1.3) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Re}\big[(\overline{c}_F^{(8)})_{333}^{(0E)}\big]$	$(-0.1 \pm 1.6) \times 10^{19} \ \mathrm{GeV}^{-4}$
$\mathrm{Im}\big[(\overline{c}_F^{(8)})_{333}^{(0E)}\big]$	$(-0.1 \pm 1.6) \times 10^{19} \ \mathrm{GeV}^{-4}$