Light driven Nuclear-Particle physics and Cosmology 2017
(Pacifico Yokohama)

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Optical Cavity Tests of Lorentz Invariance

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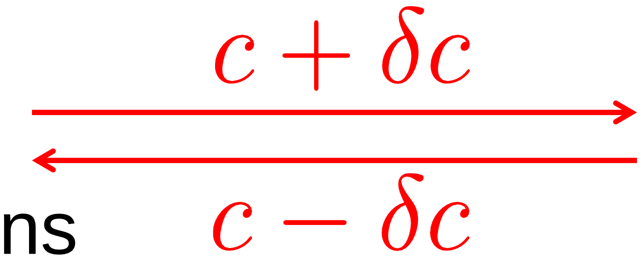
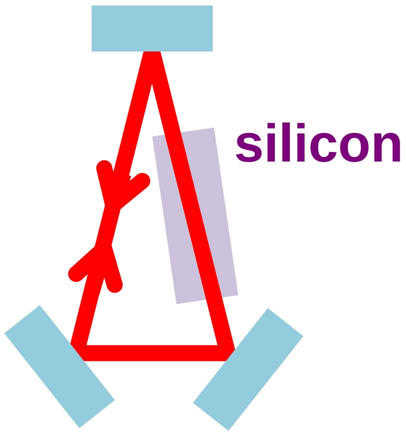
H. Takeda, Y. Sakai, N. Matsumoto, M. Masaki

Abstract



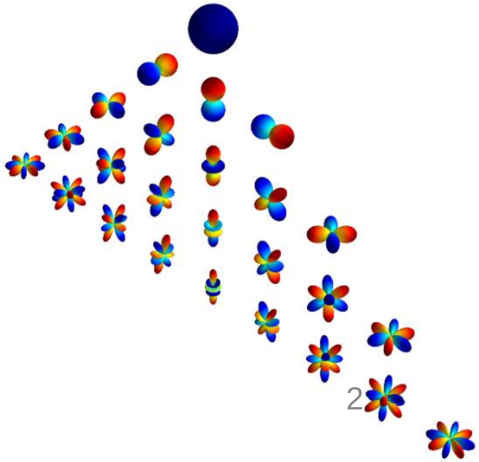
- compared the speed of light propagating in opposite directions
- using a double-pass optical ring cavity



- put most stringent limits

$$\left|\frac{\delta c}{c}\right| \lesssim 6 \times 10^{-15}$$

- put new limits on higher order Lorentz violation
- upgrade of apparatus underway

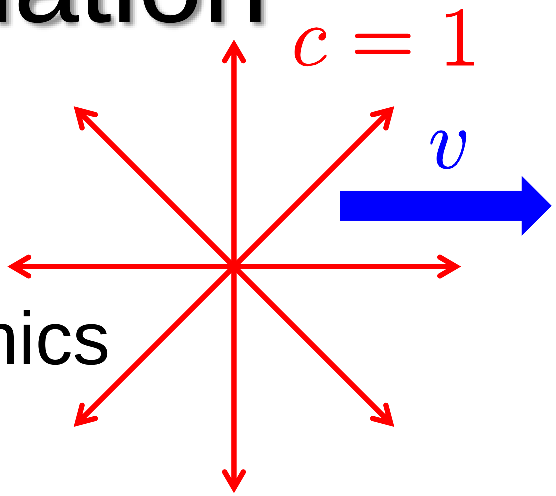


Y. Michimura *et al.*: Phys. Rev. Lett. 110, 200401 (2013)

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

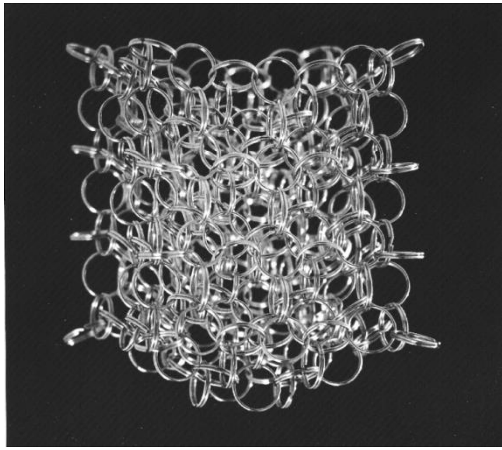
Y. Michimura *et al.*: arXiv:1602.00391

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 suggests
    violation at some level
    e.g. $\delta c/c \sim 10^{-17}$

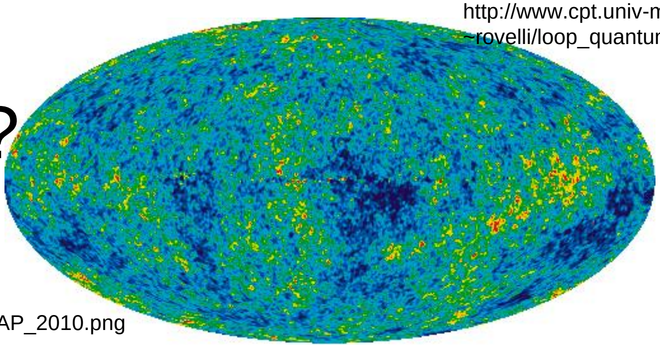
D. Colladay and V. Alan Kostelecký:PRD 58 (1998) 116002



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

- anisotropy in CMB
  possible preferred frame?

$\longrightarrow$ motivation for testing SR

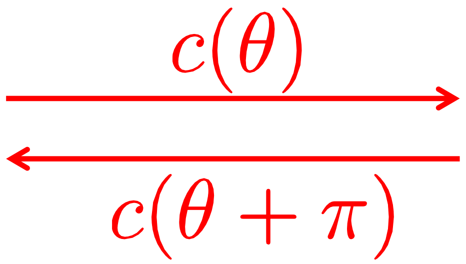


http://en.wikipedia.org/wiki/File:WMAP_2010.png

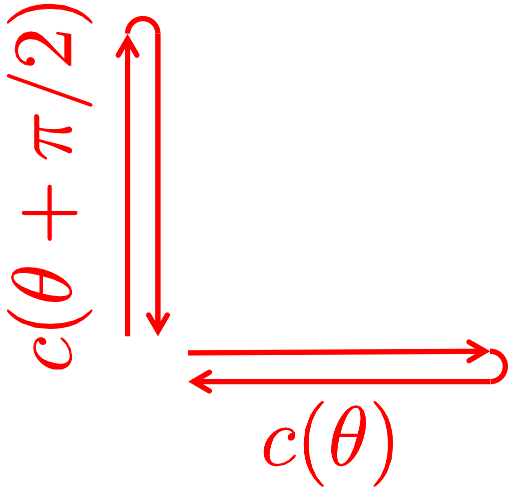
Test of Special Relativity

- test of constancy of speed of light
- two types of test: even-parity and odd-parity

odd-parity test
(Ives-Stilwell type test)

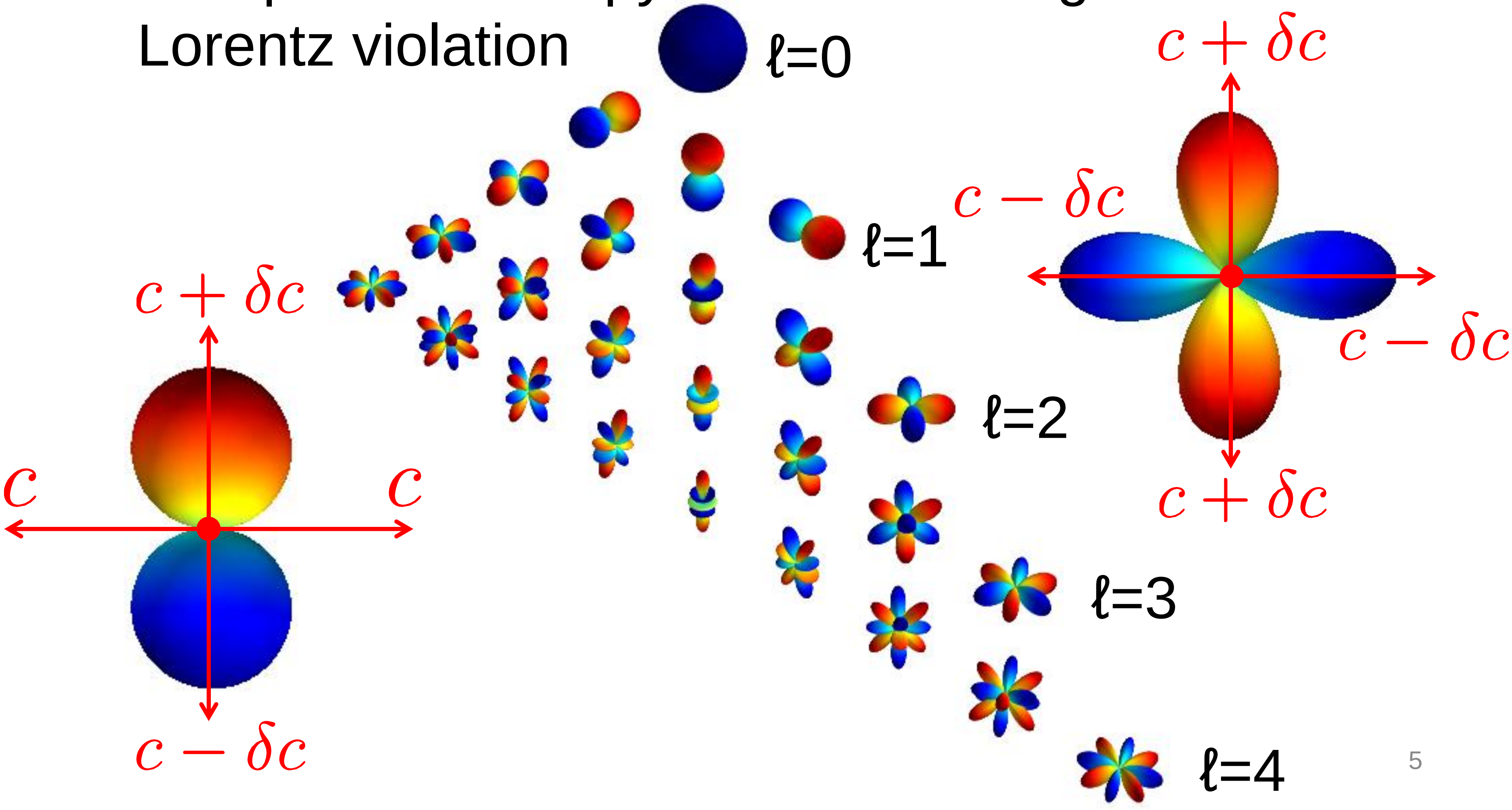


even-parity test
(Michelson-Morley type test)



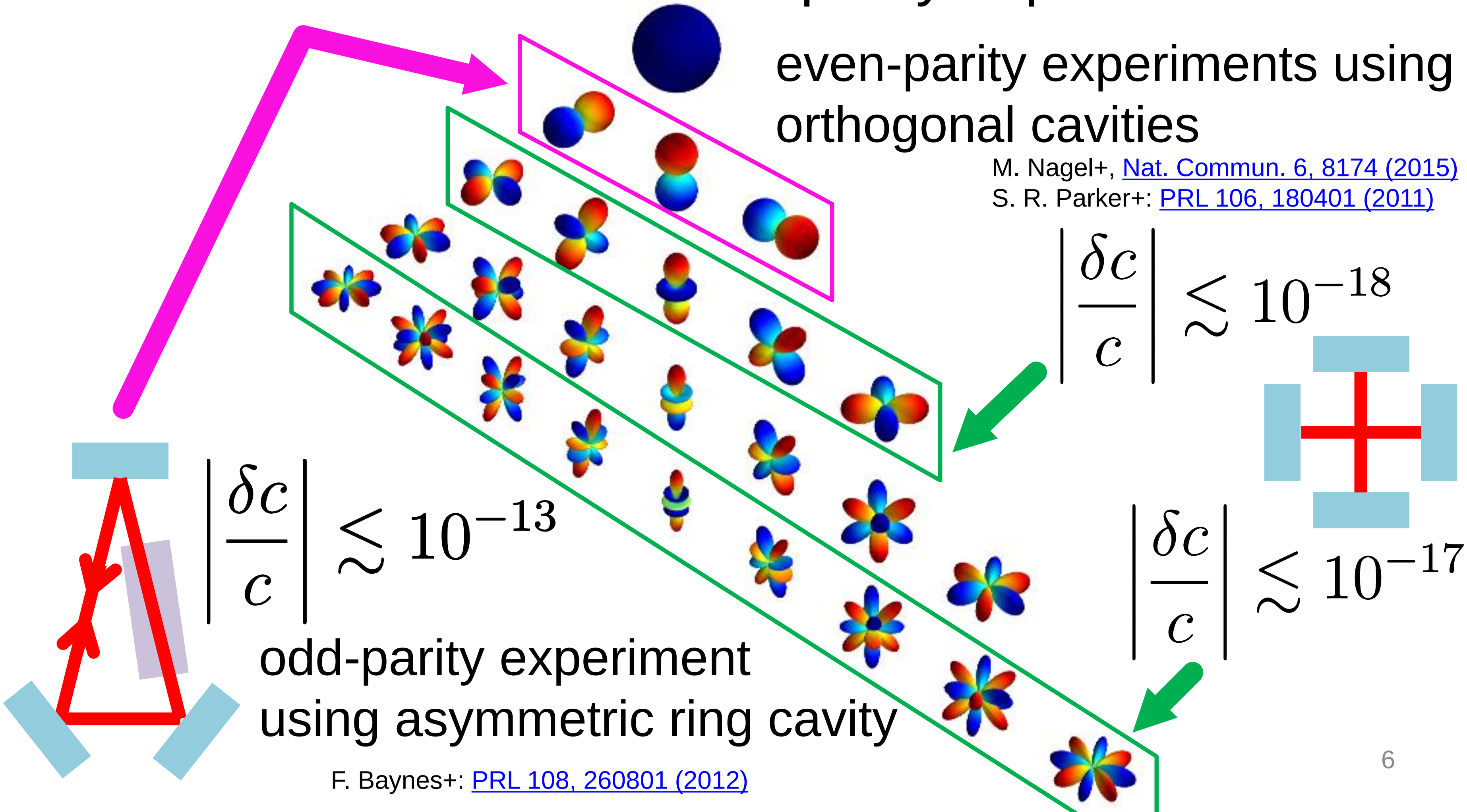
Anisotropy in the Speed of Light

- can be expanded with spherical harmonics
- multipole anisotropy comes from higher order Lorentz violation



Previous Limits

- $l = \mathrm{even}$ limits with even-parity experiments
- $l = \mathrm{odd}$ limits with odd-parity experiments



even-parity experiments using orthogonal cavities

M. Nagel+, Nat. Commun. 6, 8174 (2015)
S. R. Parker+: PRL 106, 180401 (2011)

$$\left|\frac{\delta c}{c}\right| \lesssim 10^{-18}$$

$$\left|\frac{\delta c}{c}\right| \lesssim 10^{-17}$$

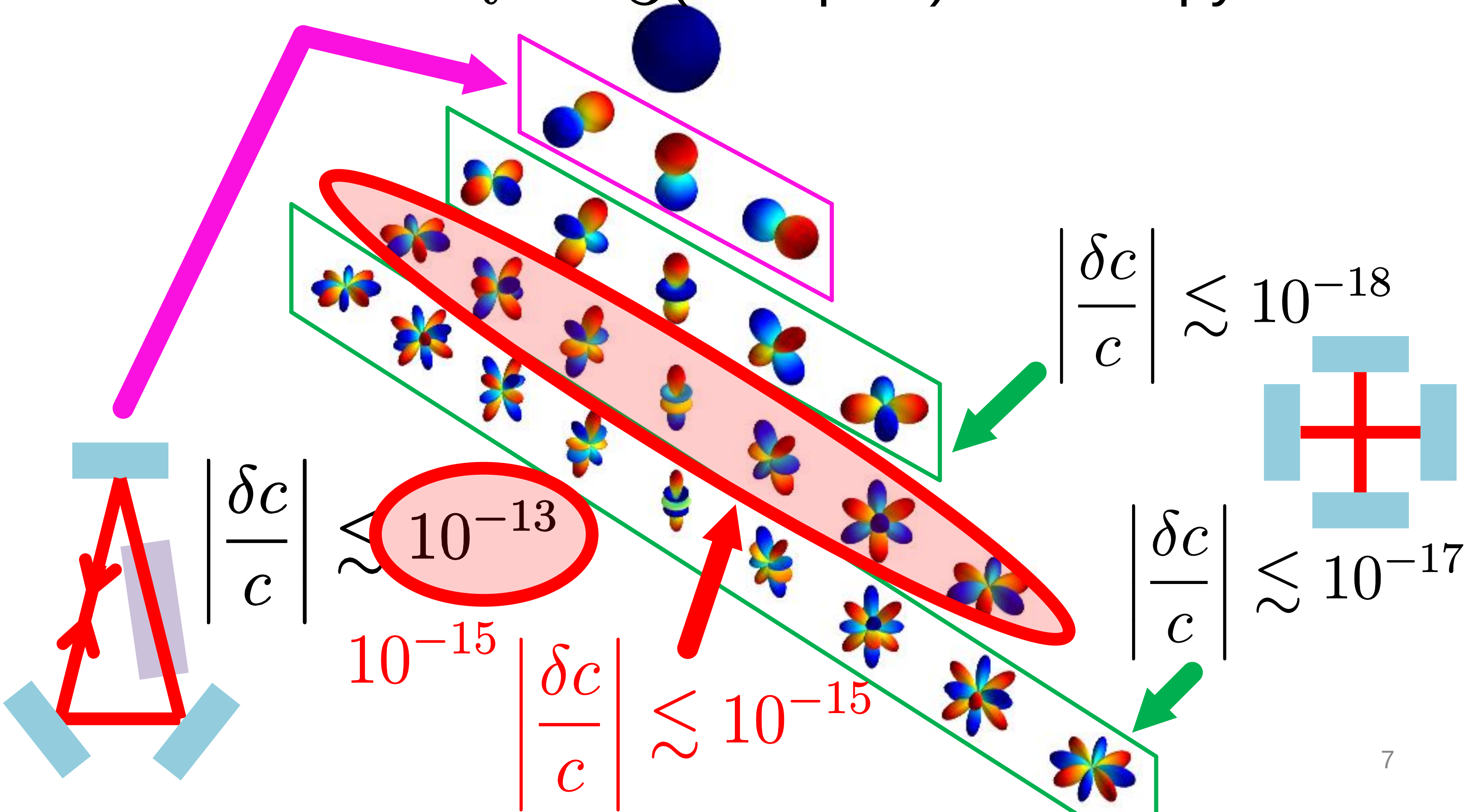
$$\left|\frac{\delta c}{c}\right| \lesssim 10^{-13}$$

odd-parity experiment using asymmetric ring cavity

F. Baynes+: PRL 108, 260801 (2012)

Our Limits

- improved limits on $l = 1$(dipole) anisotropy
- new limits on $l = 3$(hexapole) anisotropy



$$\left|\frac{\delta c}{c}\right| \lesssim 10^{-18}$$

$$\left|\frac{\delta c}{c}\right| \lesssim \boxed{10^{-13}}$$

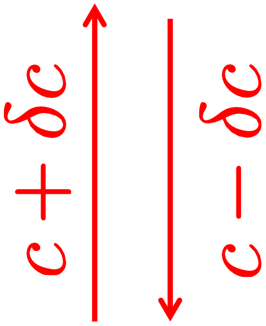
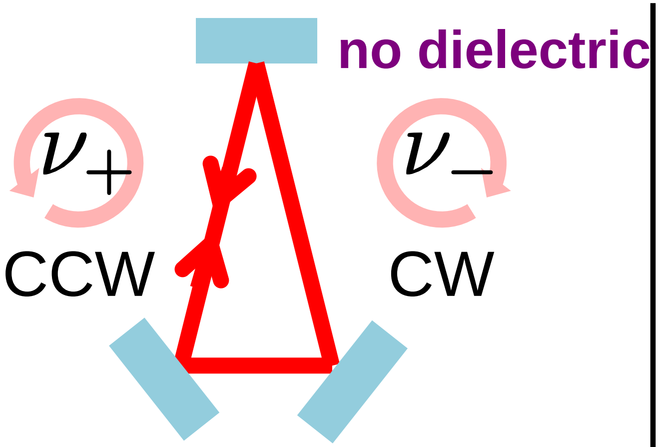
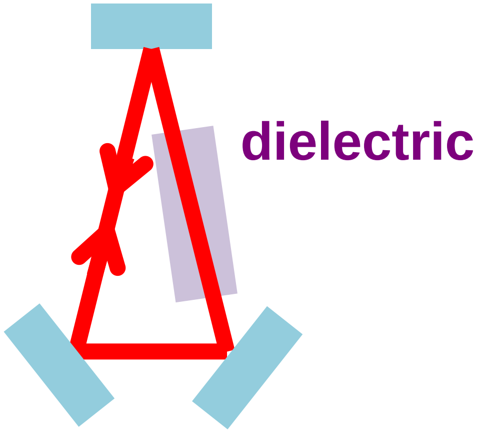
10^{-15}

$$\left|\frac{\delta c}{c}\right| \lesssim 10^{-15}$$

$$\left|\frac{\delta c}{c}\right| \lesssim 10^{-17}$$

Optical Ring Cavity

- sensitive to LV when a dielectric is contained

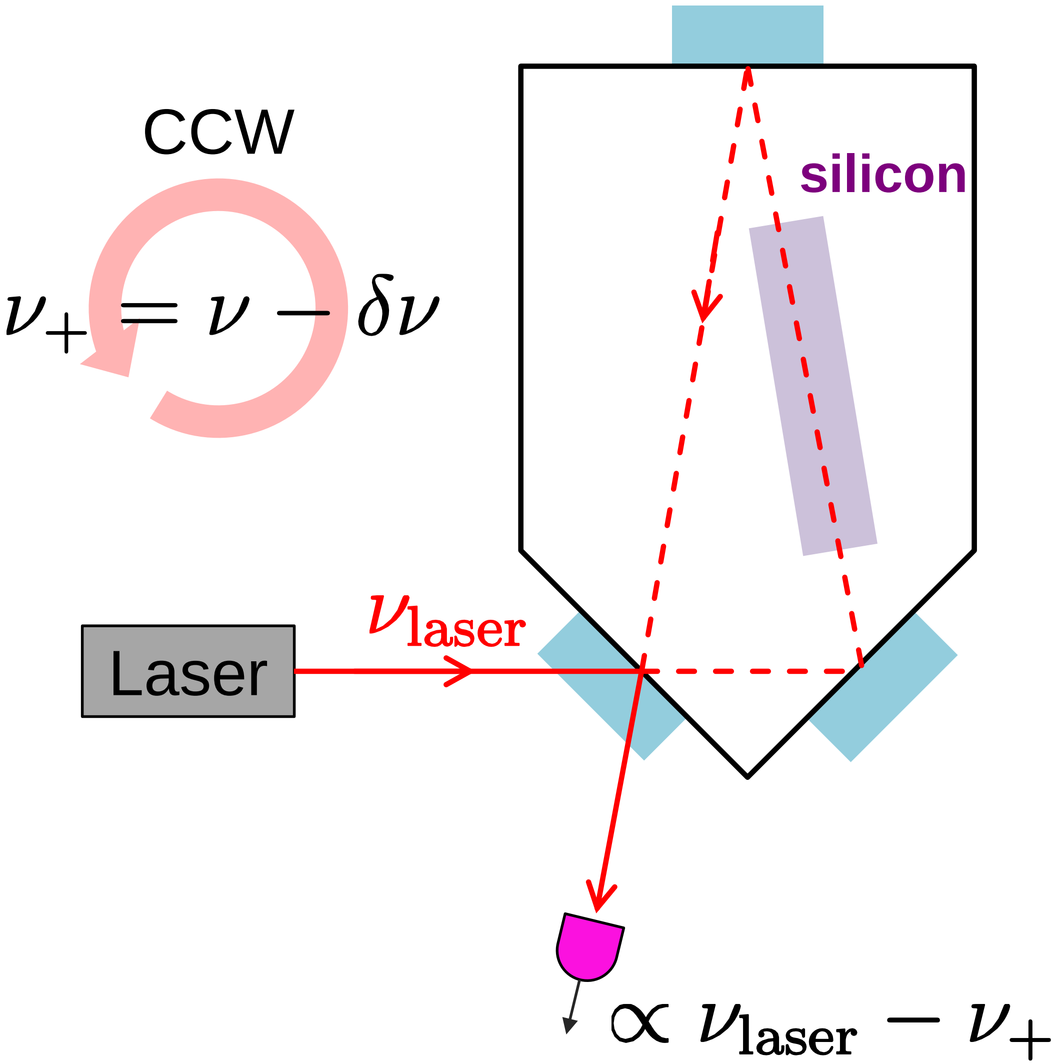
		
no LV	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu$ $\nu_- = \nu$
LV	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu - \delta\nu$ $\nu_- = \nu + \delta\nu$

freq. shift $\propto$ LV

- $\nu_+ - \nu_-$ gives LV signal (null measurement)

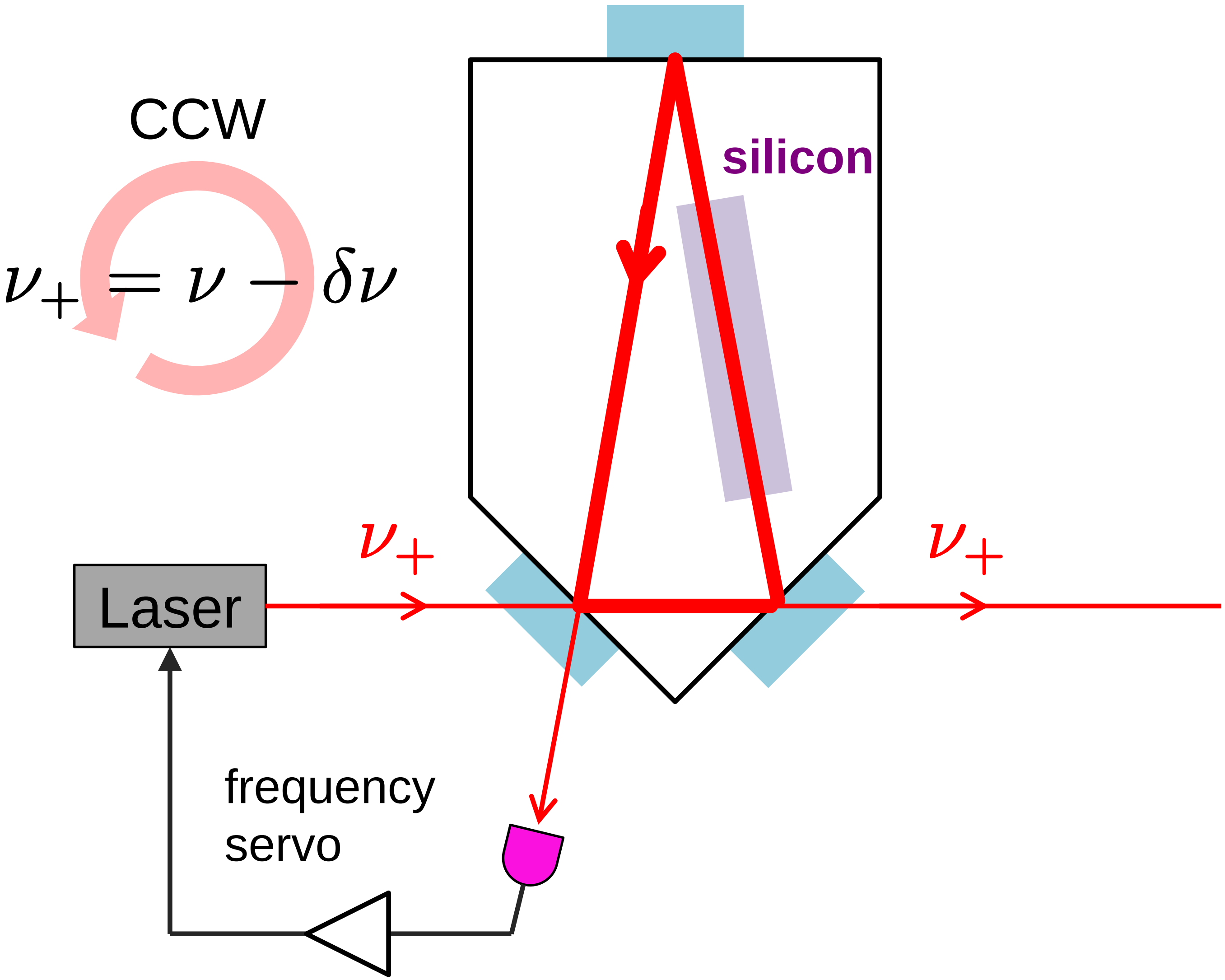
How Do We Measure 1/4

- inject laser beam in CCW



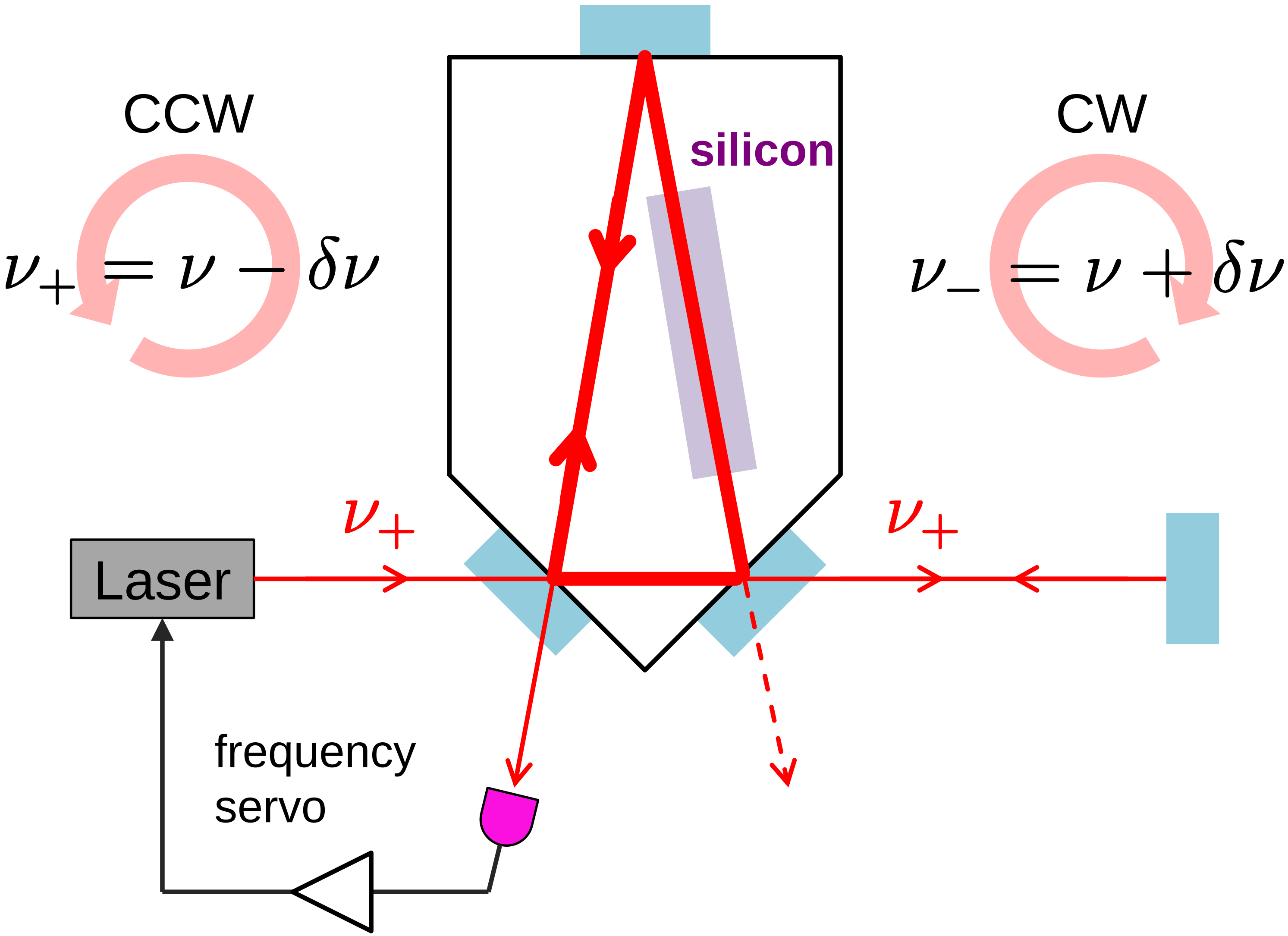
How Do We Measure 2/4

- lock laser frequency to CCW resonance ($\boldsymbol{\nu_+}$)



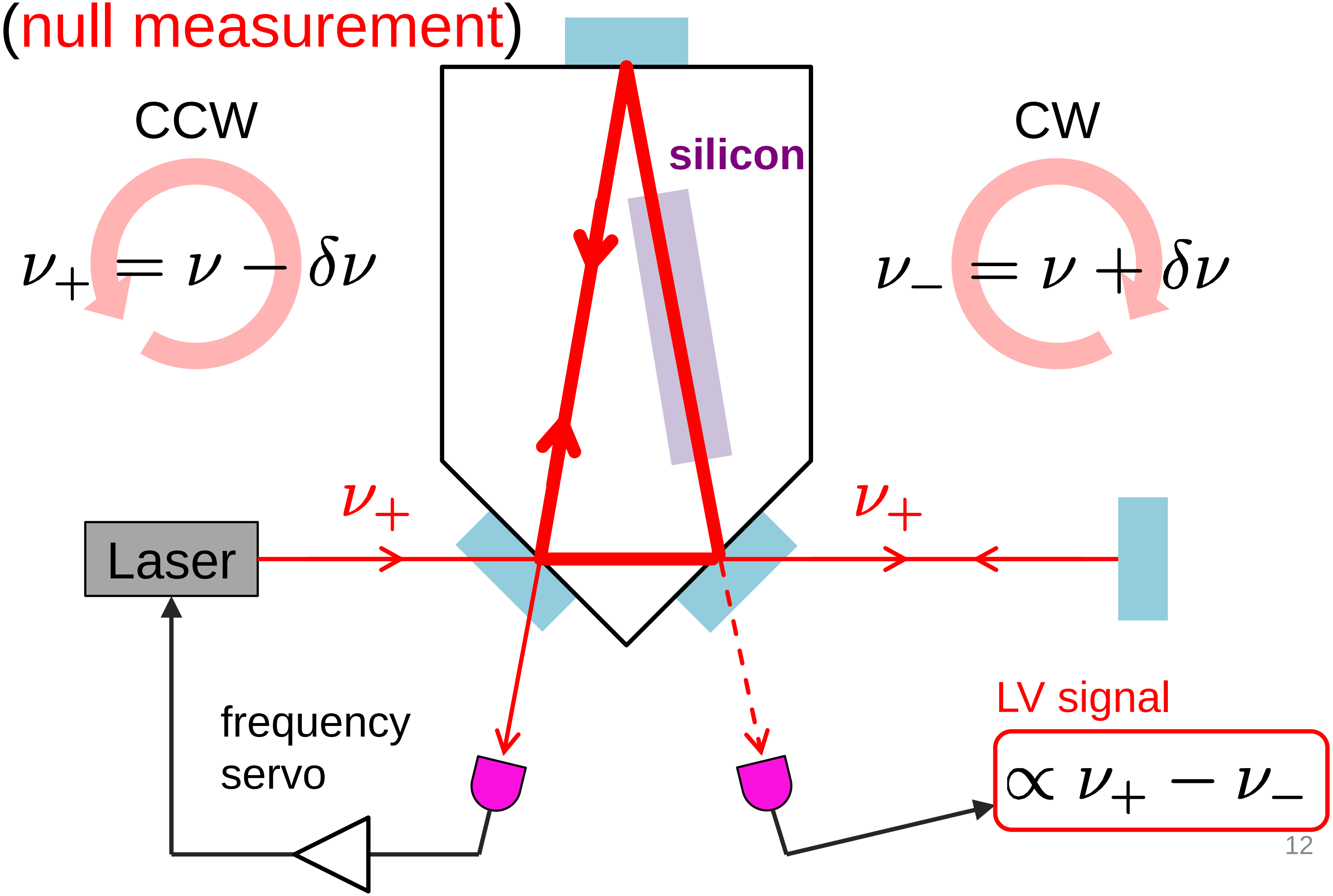
How Do We Measure 3/4

- reflect the beam back into the cavity in CW



How Do We Measure 4/4

- LV signal obtained from cavity reflection (null measurement)



Experimental Setup

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

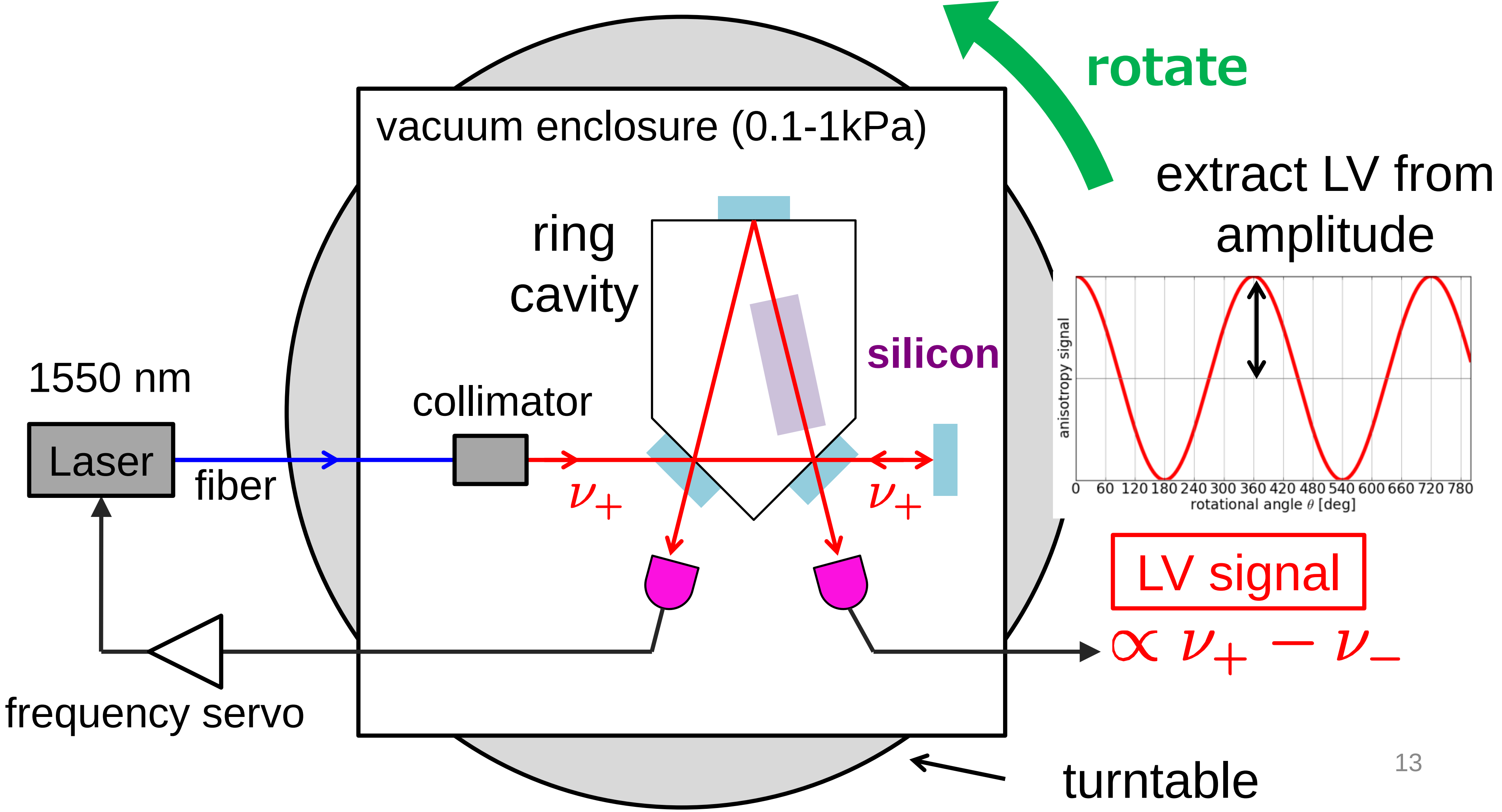
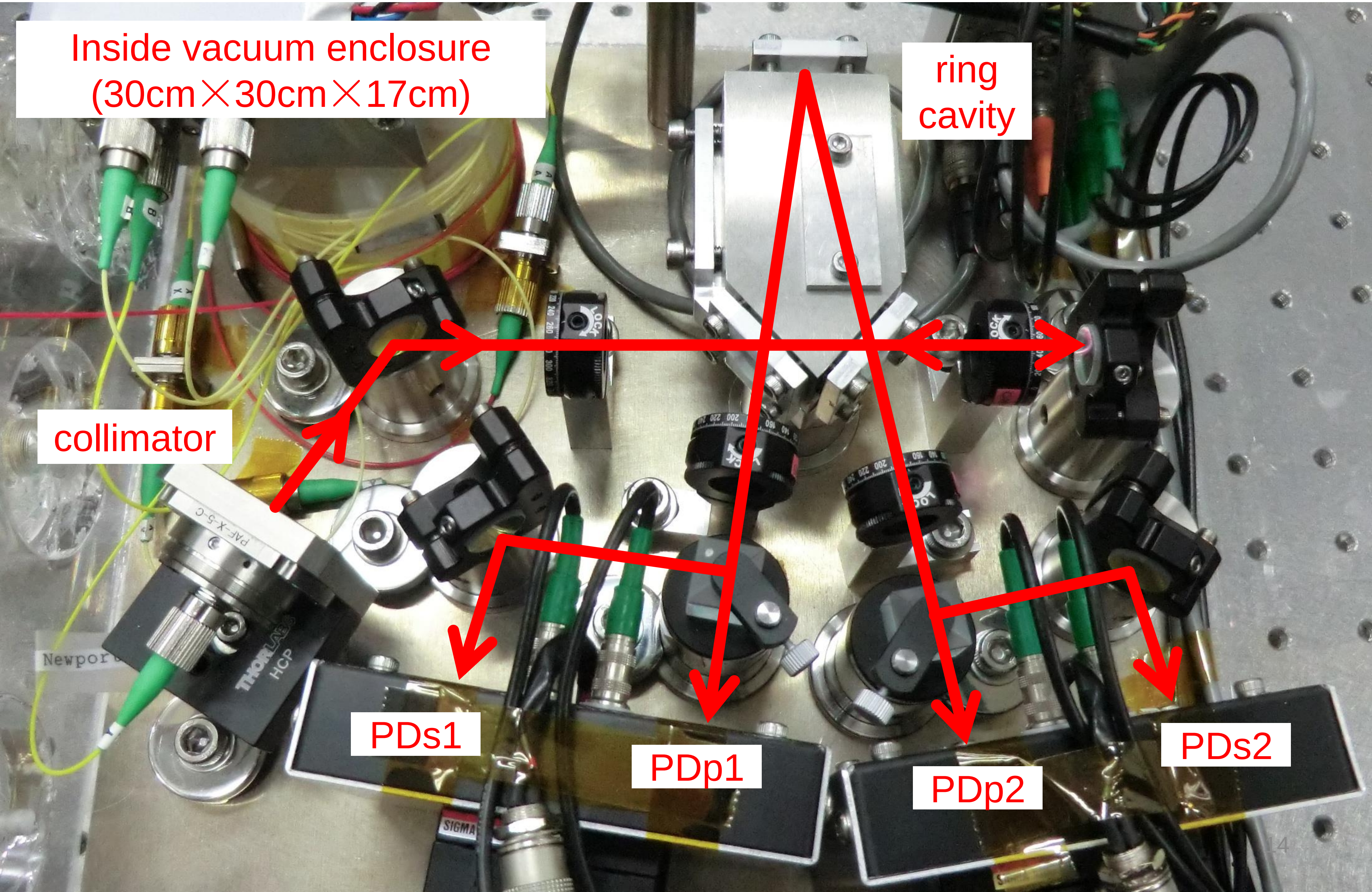


Photo of the Optics



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

ring
cavity

collimator

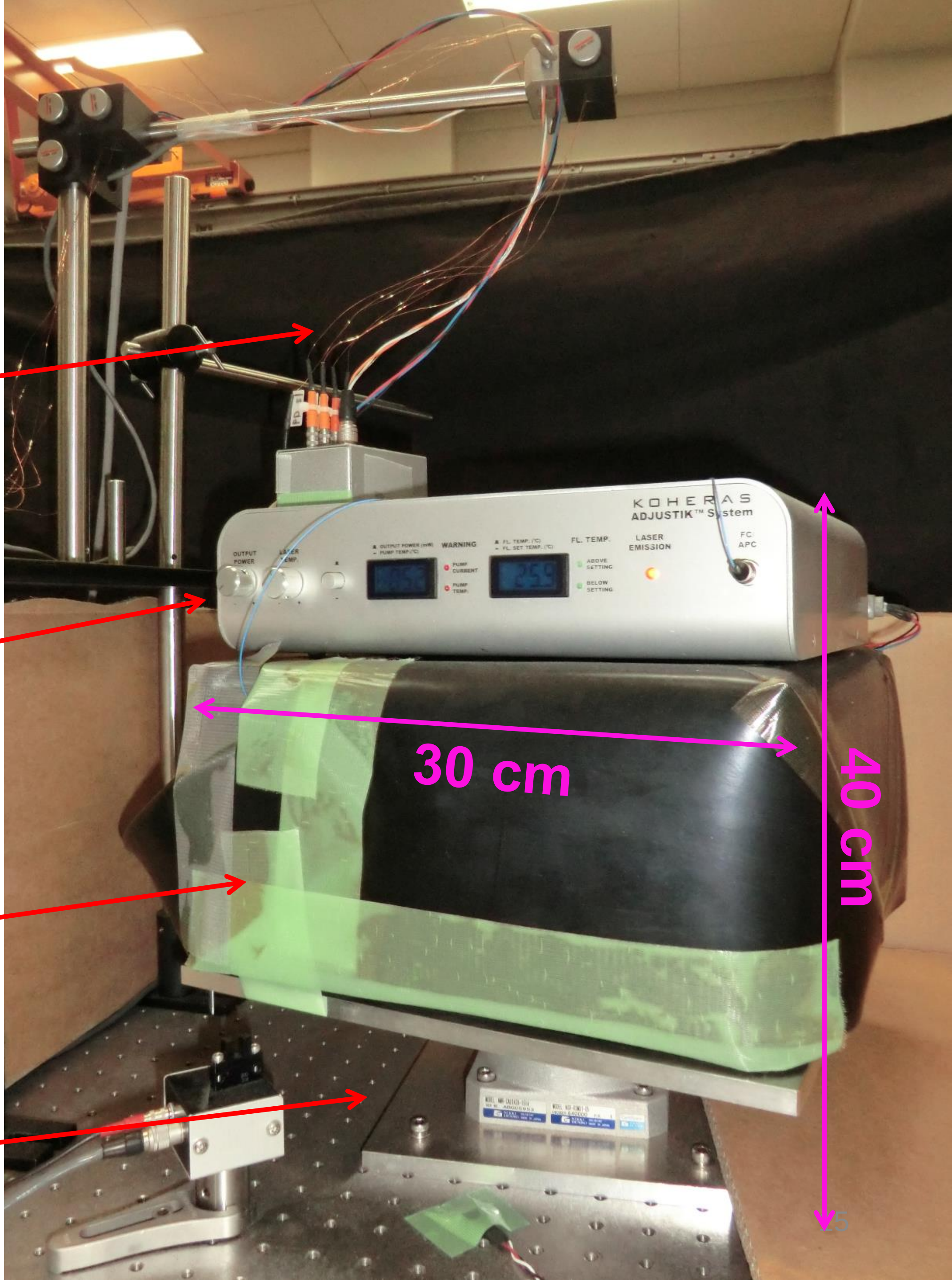
PDs1

PDp1

PDp2

PDs2

Photo of the Whole Setup



electrical cables

laser source

vacuum enclosure
+ shielding
(optics inside)

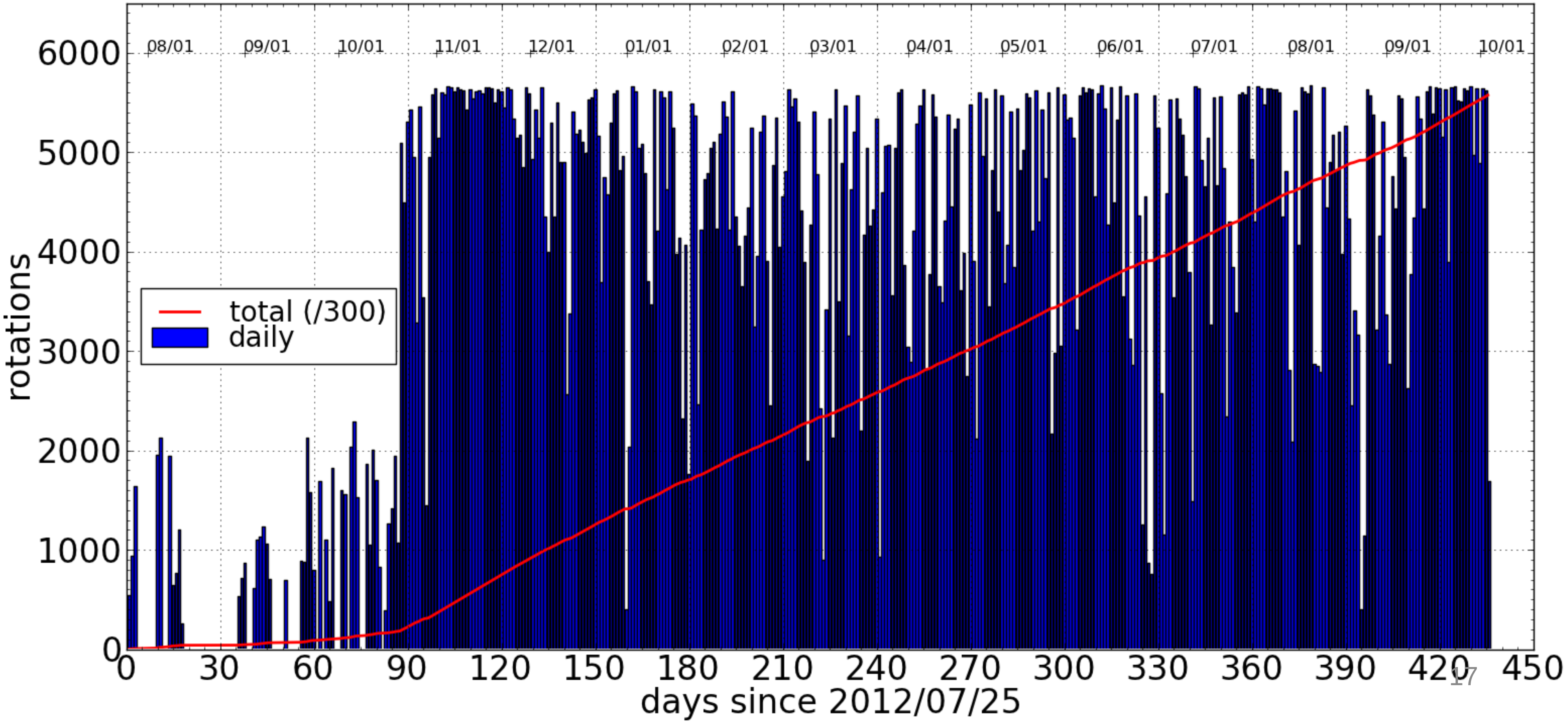
turntable

Rotation

- 12 sec / rotation, alternately

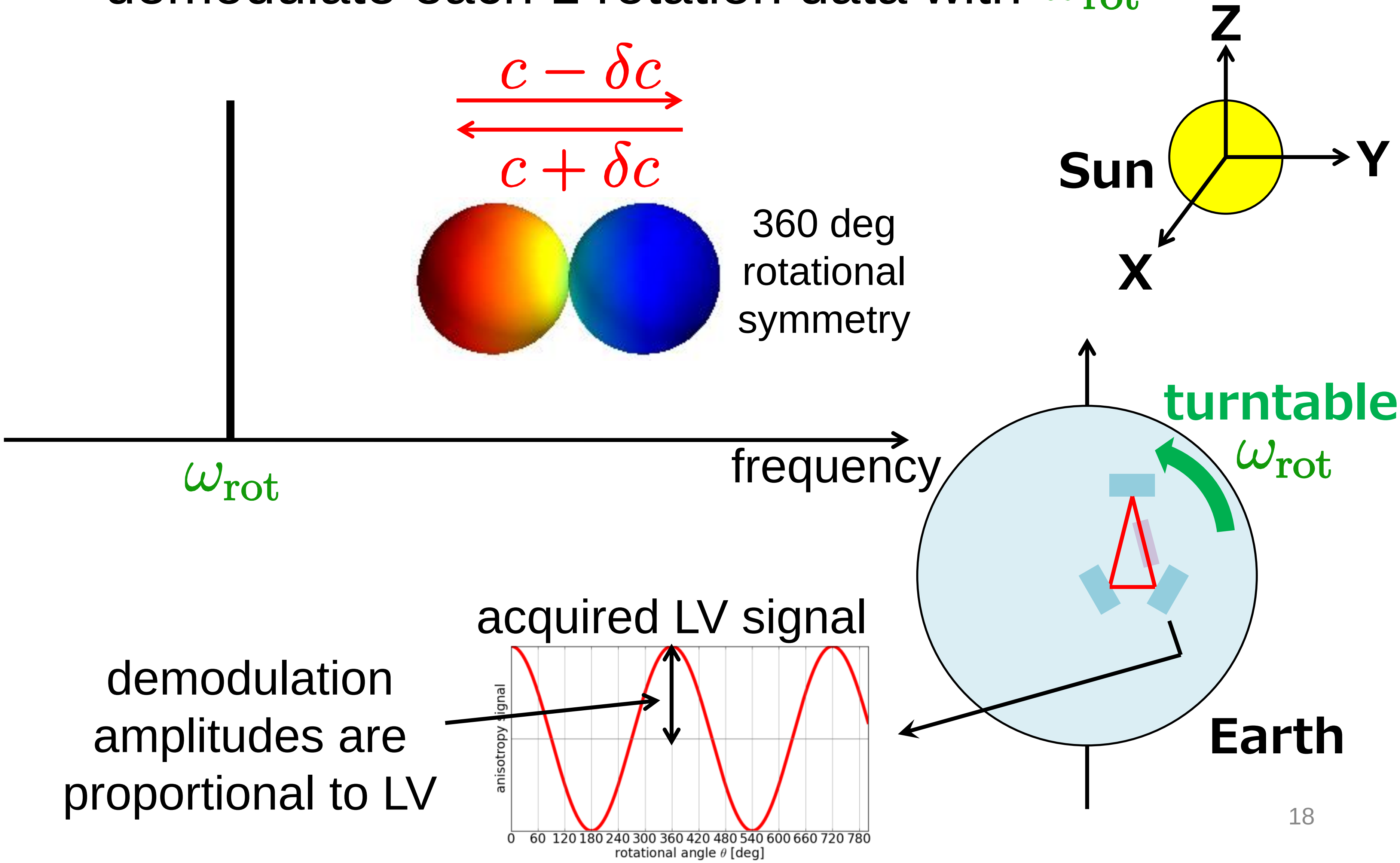
Observation Data

- from July 2012 to October 2013
- 393 days, 1.67 million rotations
- duty cycle: 53% (64% after Oct 2012)



Data Analysis 1/3

- demodulate each 1 rotation data with ω_{rot}



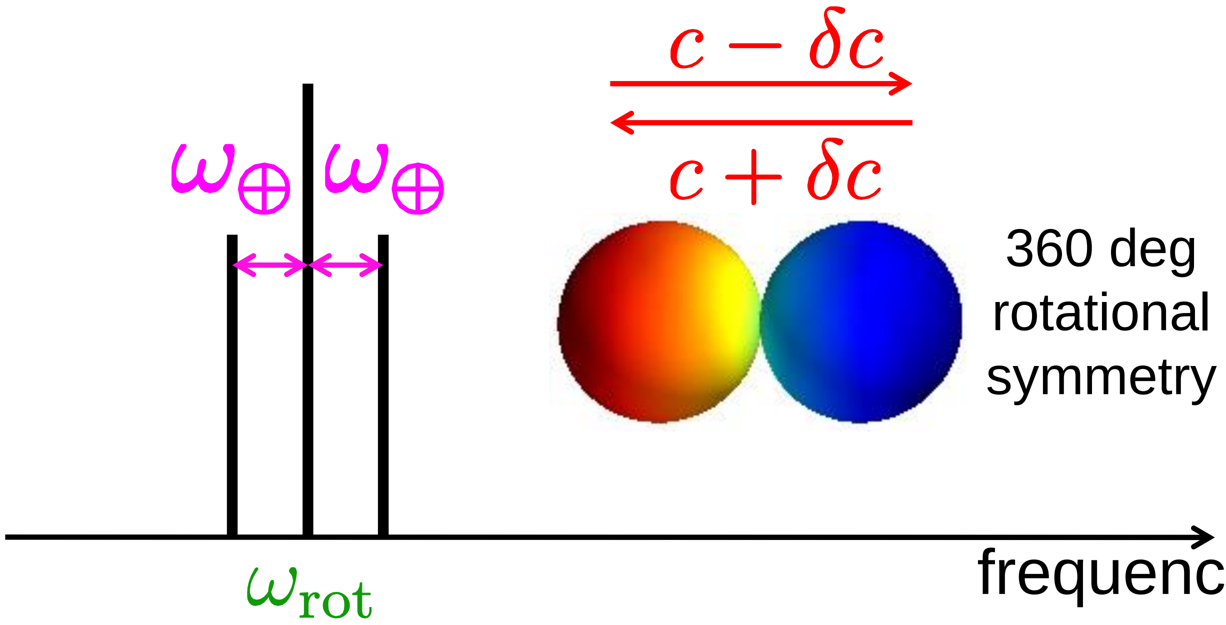
360 deg rotational symmetry

acquired LV signal

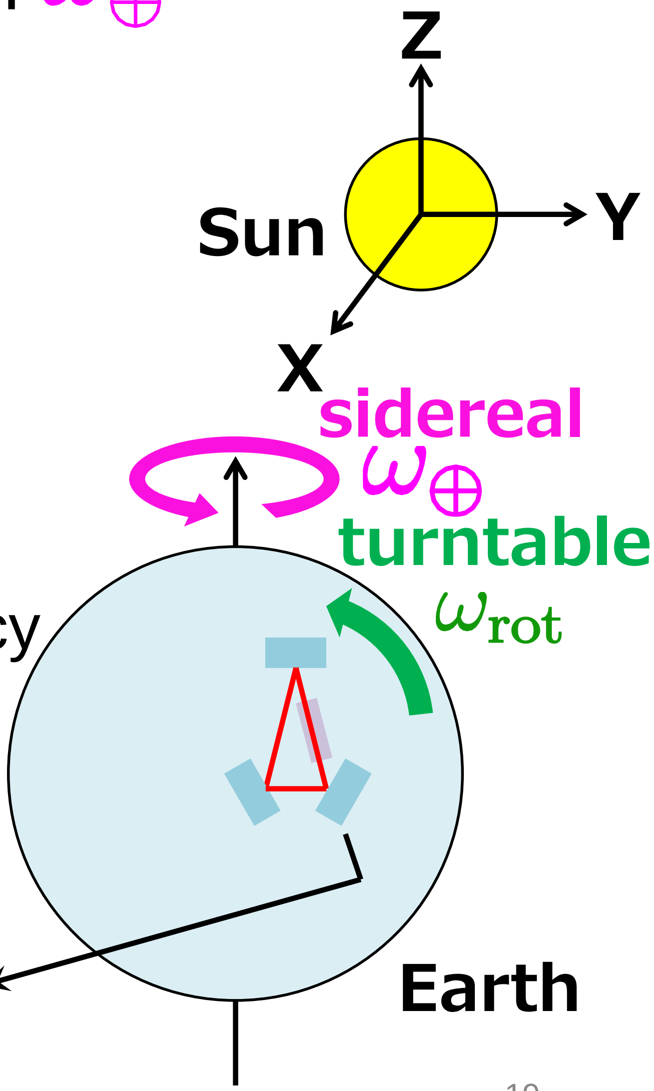
demodulation amplitudes are proportional to LV

Data Analysis 2/3

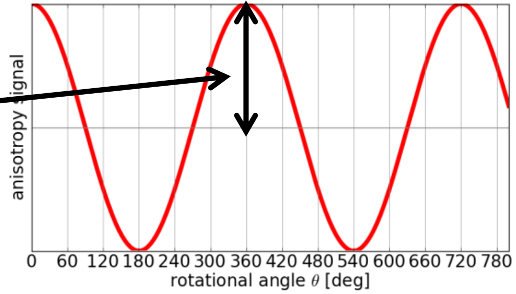
- next, demodulate 1 day data with $\omega_\oplus$



360 deg rotational symmetry



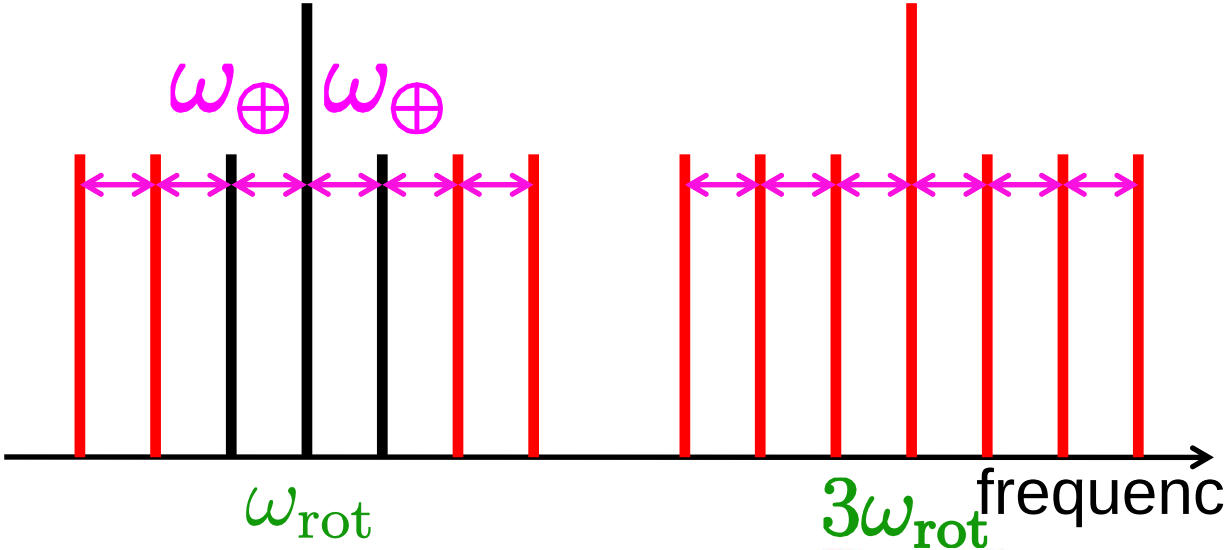
acquired LV signal

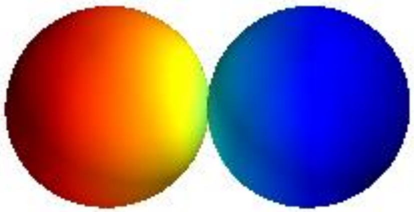


demodulation amplitudes are modulated by sidereal frequency

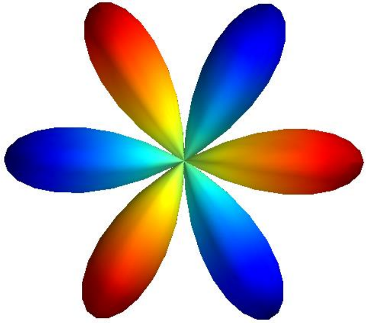
Data Analysis 3/3

- higher order LV appear at higher harmonics

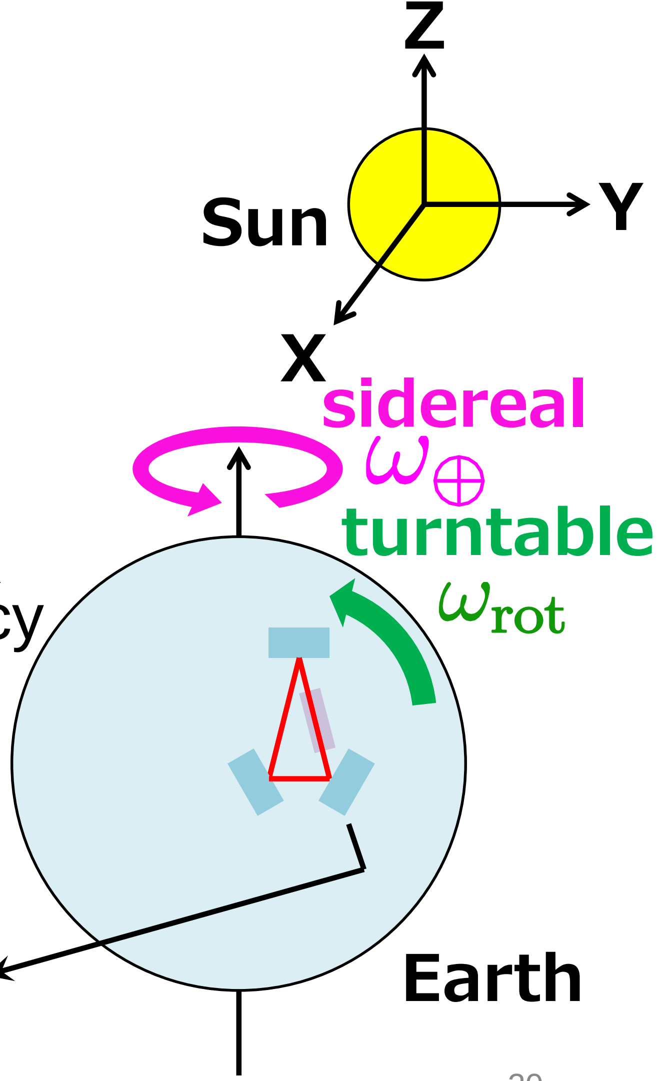




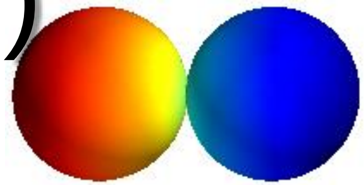
360 deg
rotational symmetry



120 deg
rotational symmetry

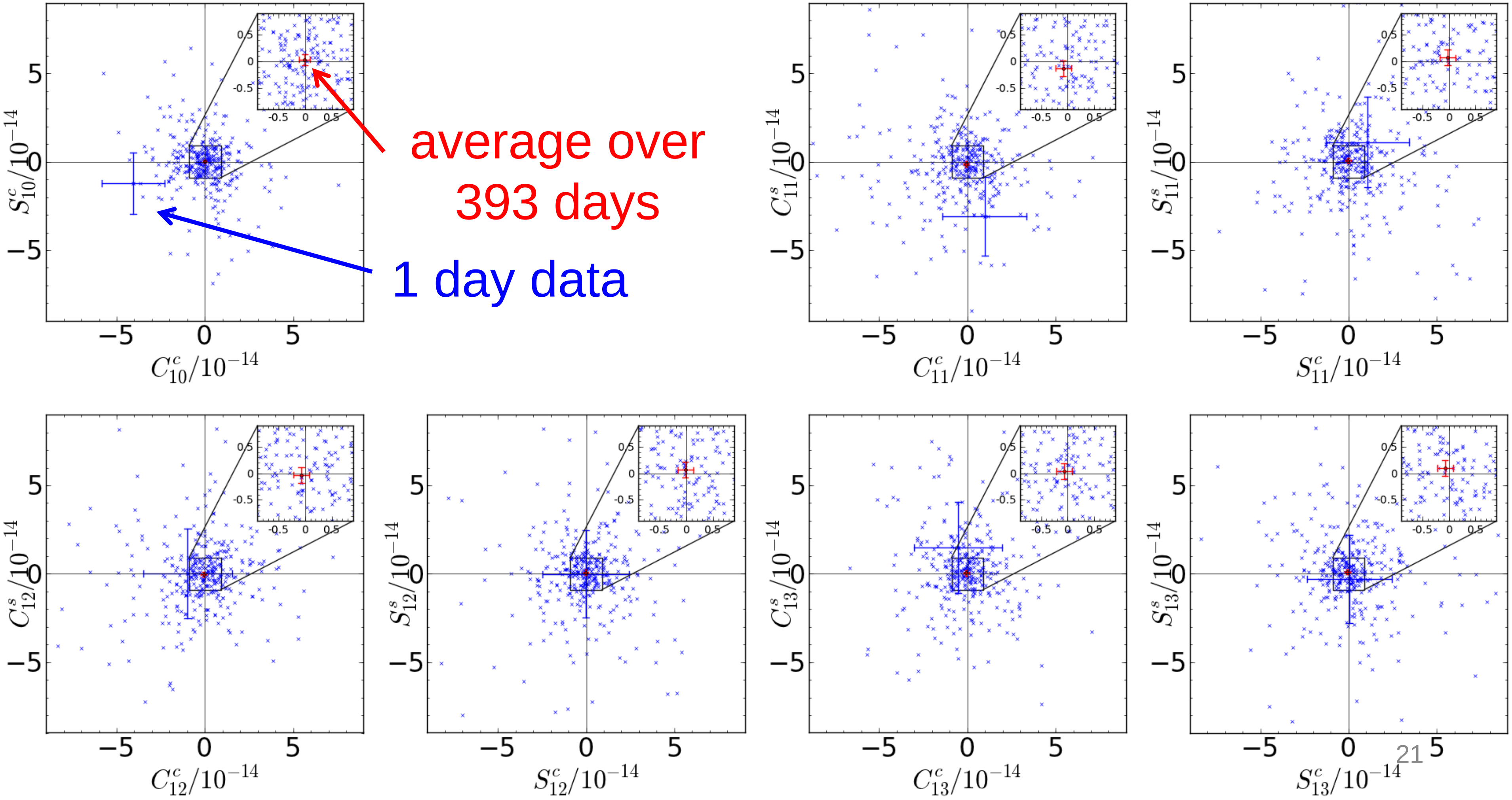


Demodulation Amps($\omega_{\rm rot}$)



- zero consistent at 2σ

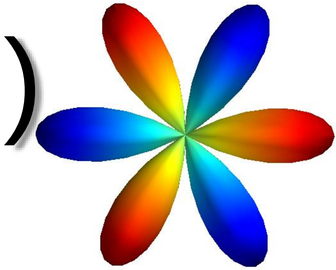
  ⟶ no significant LV can be claimed



average over 393 days

1 day data

Demodulation Amps($3\omega_{\mathrm{rot}}$)



- zero consistent at 2σ

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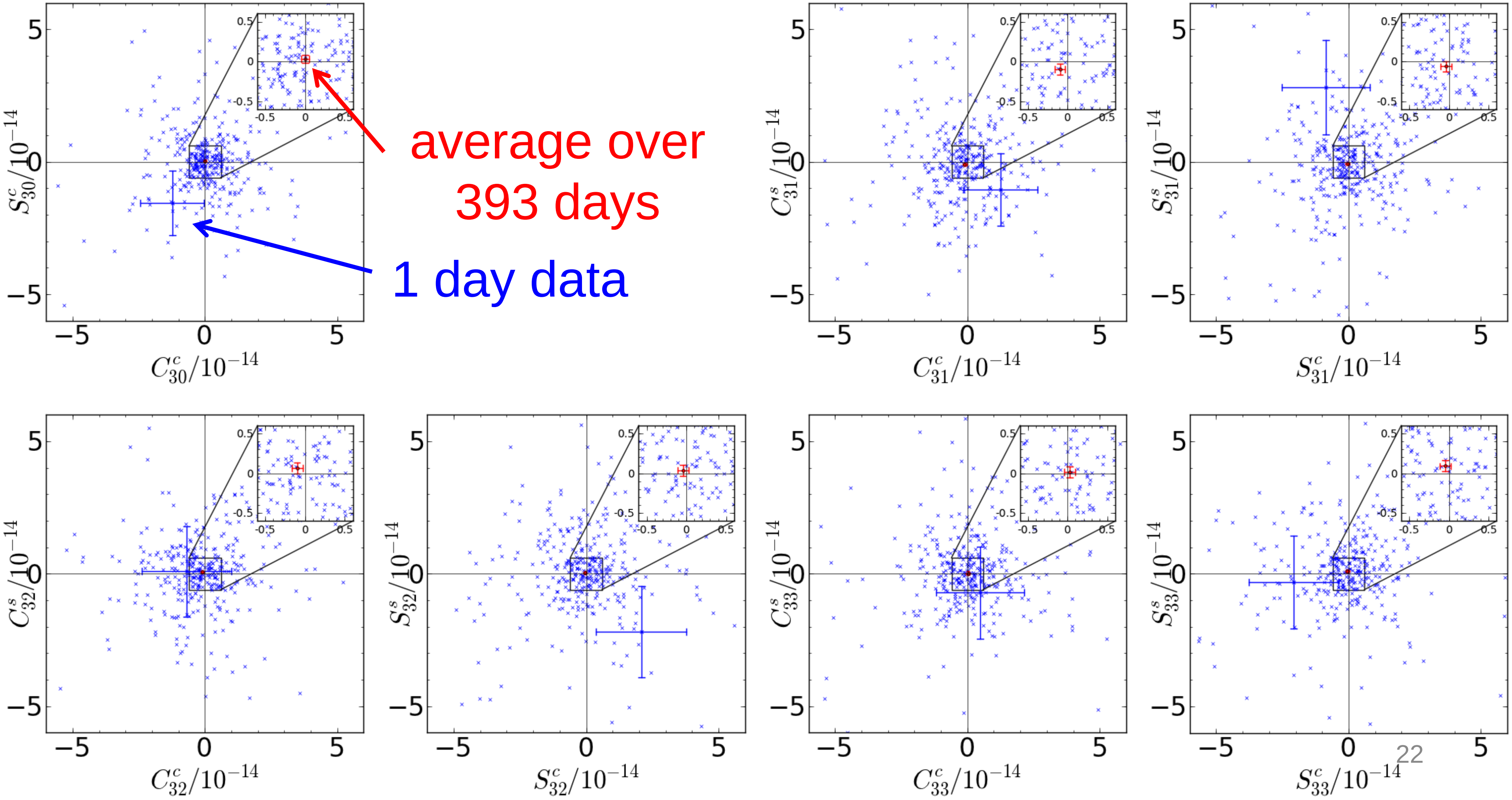


average over 393 days

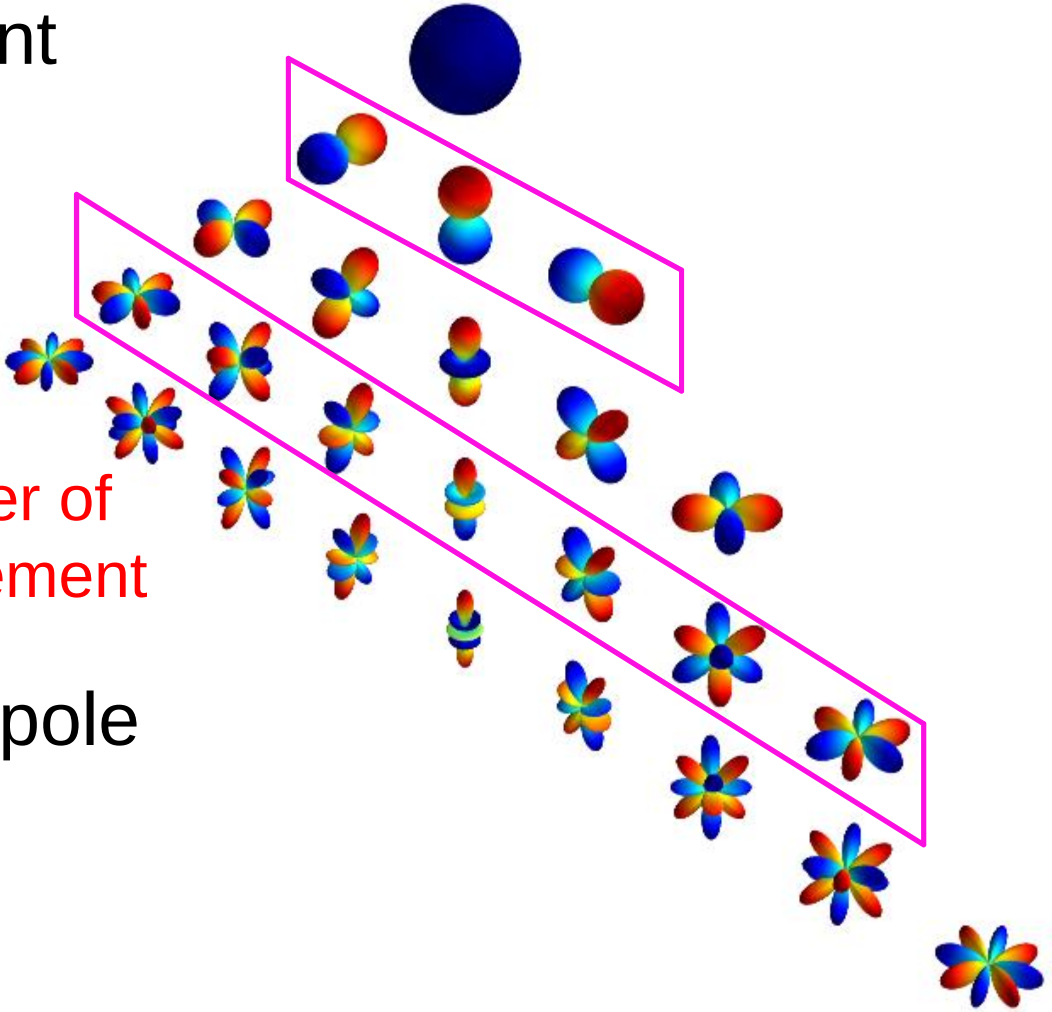
1 day data

Our Limits on Anisotropy

- each demodulation amplitude is related to each anisotropy component
- limits three dipole ($l = 1$) components

$$\left|\frac{\delta c}{c}\right| \lesssim 6 \times 10^{-15}$$

more than an order of magnitude improvement



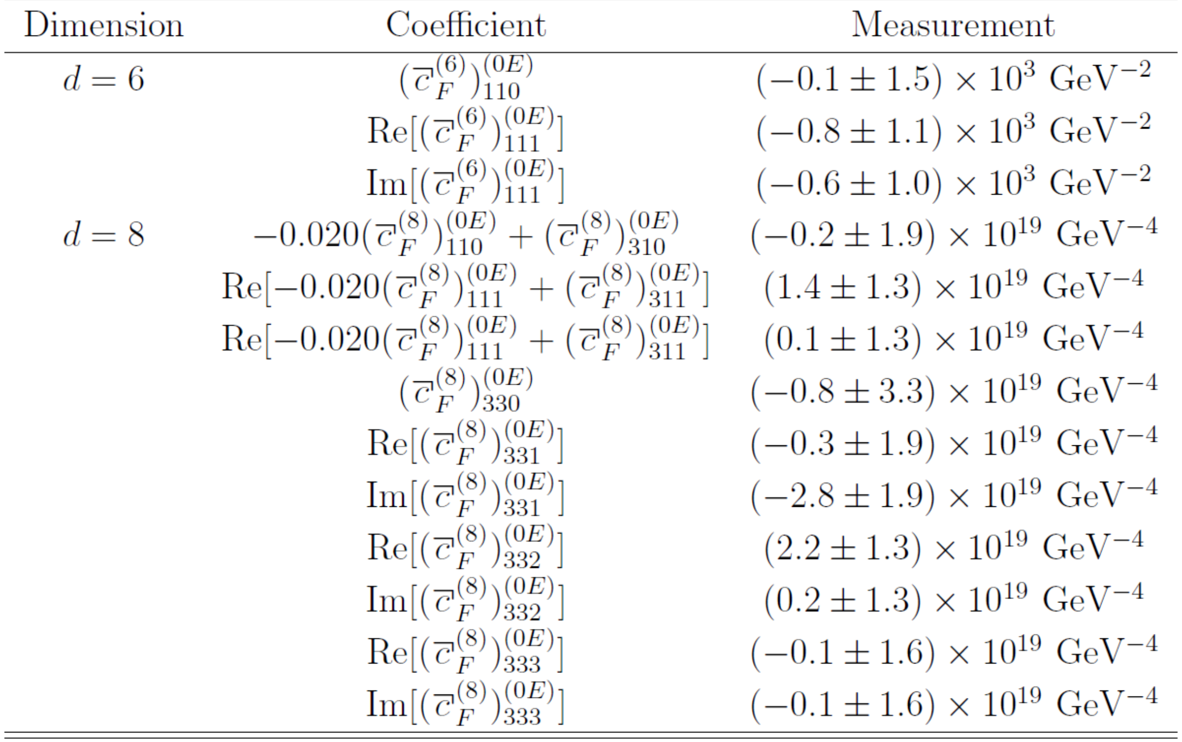
- limits on seven hexapole ($l = 3$) components

$$\left|\frac{\delta c}{c}\right| \lesssim 2 \times 10^{-15}$$

new limit

Our Limits on SME Coefficients

- Standard Model Extension (SME)
  [D. Colladay and V. Alan Kostelecký: [PRD 58, 116002 (1998)]()]
- test theory with all realistic Lorentz violation
- our result put new limits on "camouflage coefficients" of LV in photon sector



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

limits on LV of dimension 6

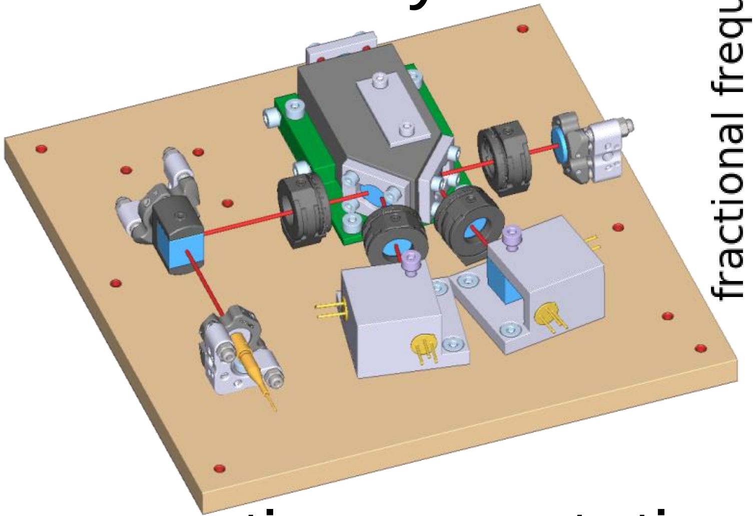
$$10^3\ \mathrm{GeV}^{-2}$$

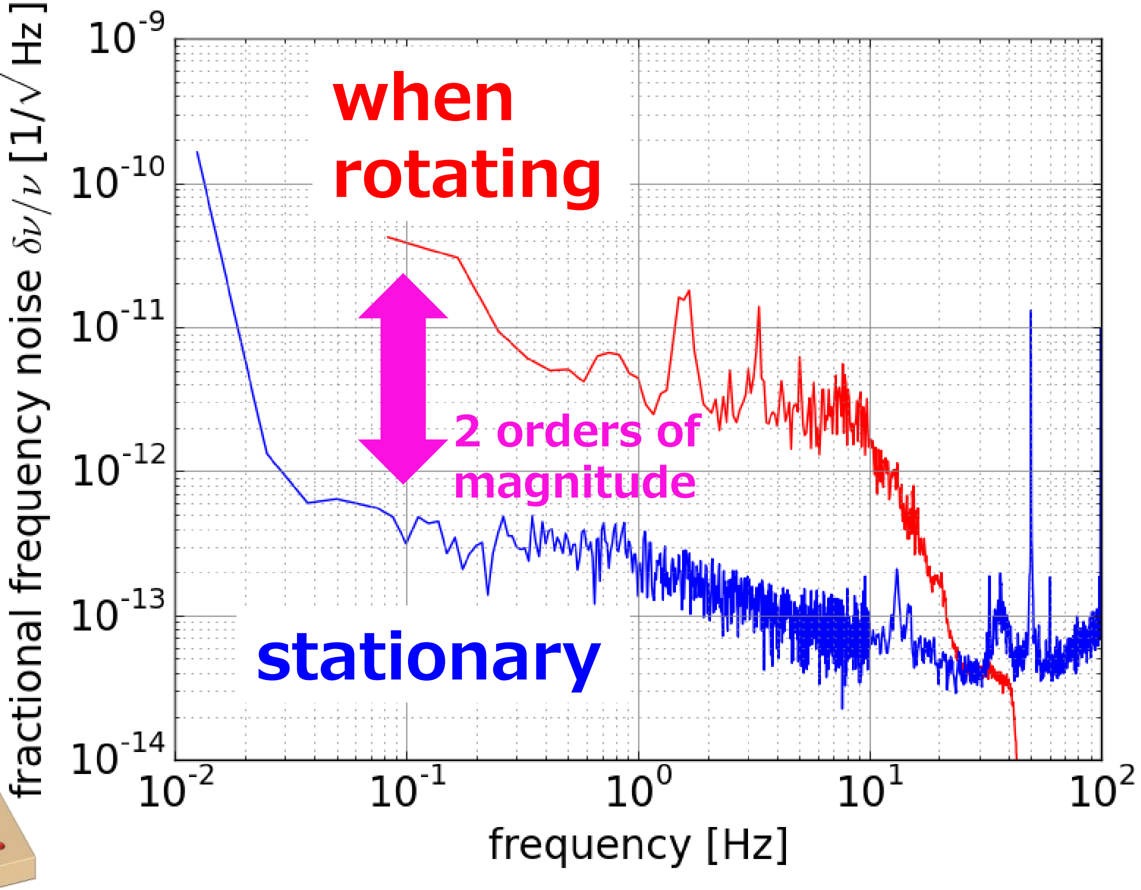
limits on LV of dimension 8

$$10^{19}\ \mathrm{GeV}^{-4}$$

Upgrade of the Apparatus

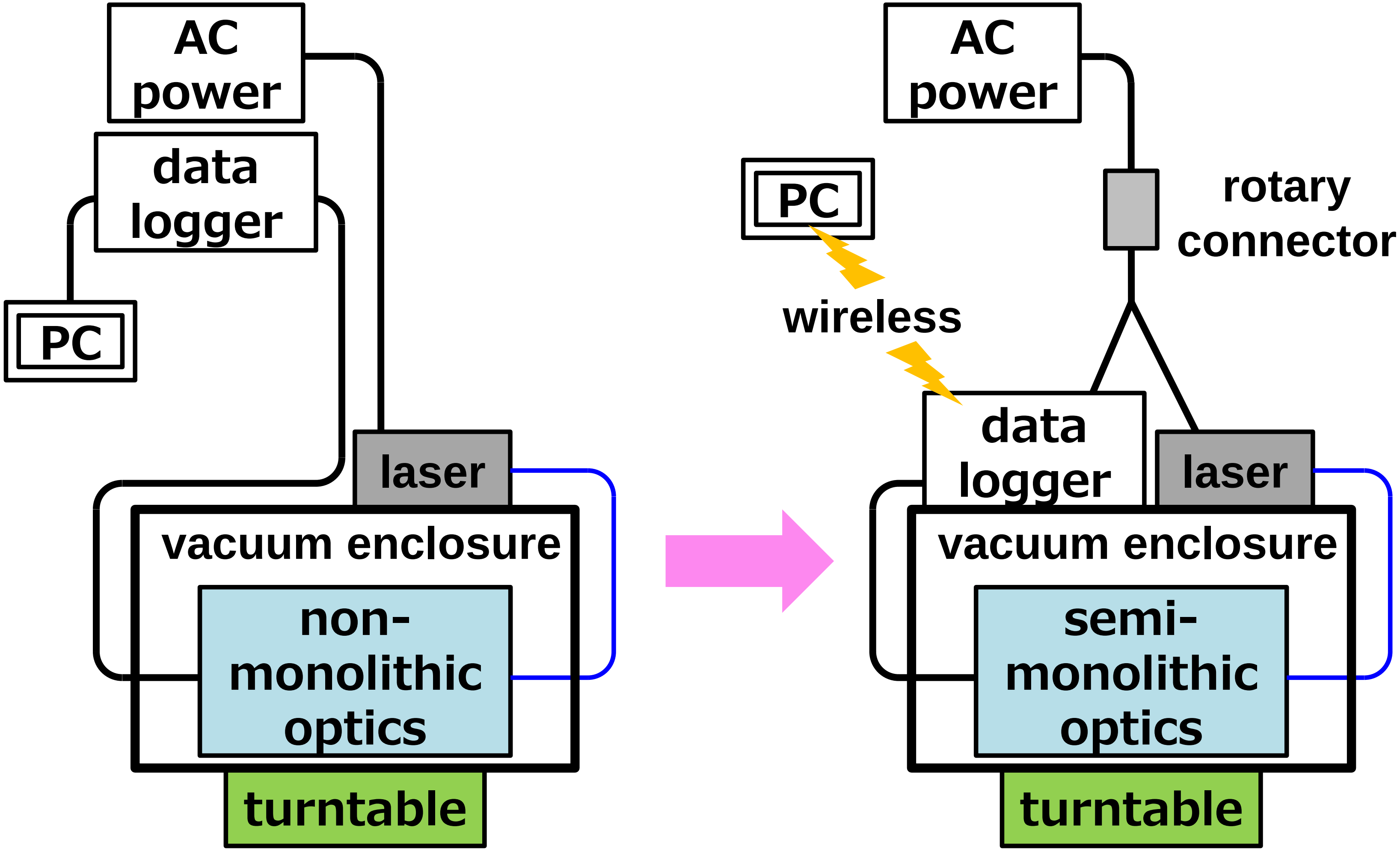
- current noise level is limited by noise from rotation
- semi-monolithic optical bench to reduce vibration sensitivity





- continuous rotation for more stable operation

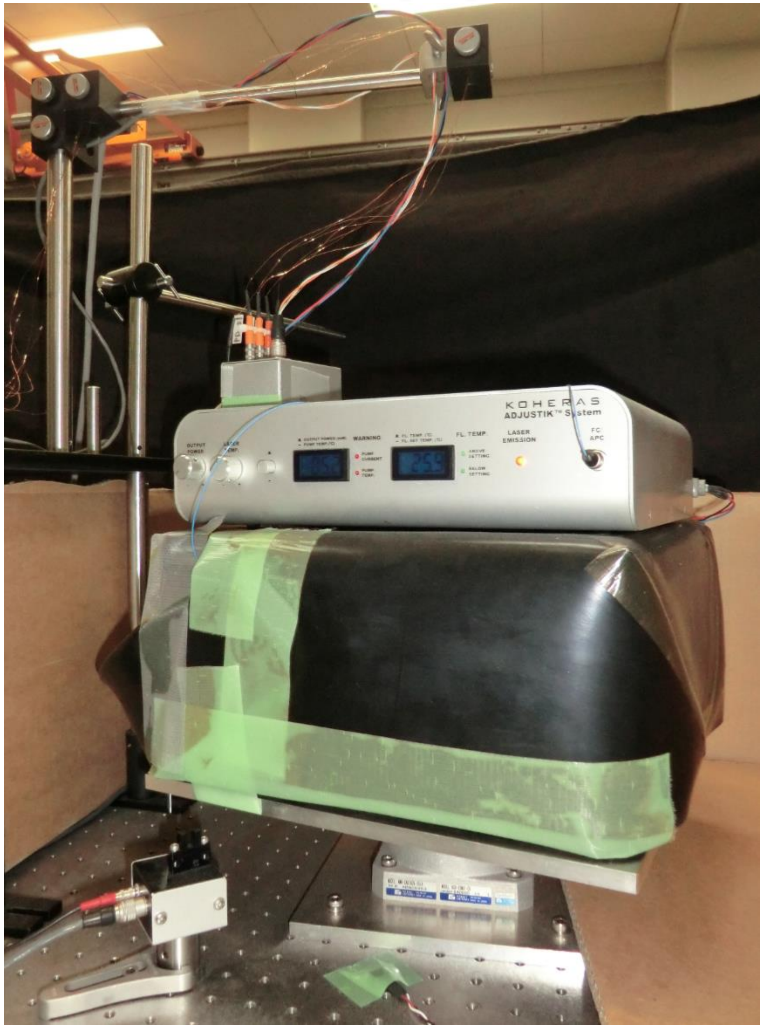
Apparatus Comparison



Previous Model
- non-monolithic optics
- alternative rotation

New Model
- semi-monolithic optics
- continuous rotation

Apparatus Comparison



Previous Model
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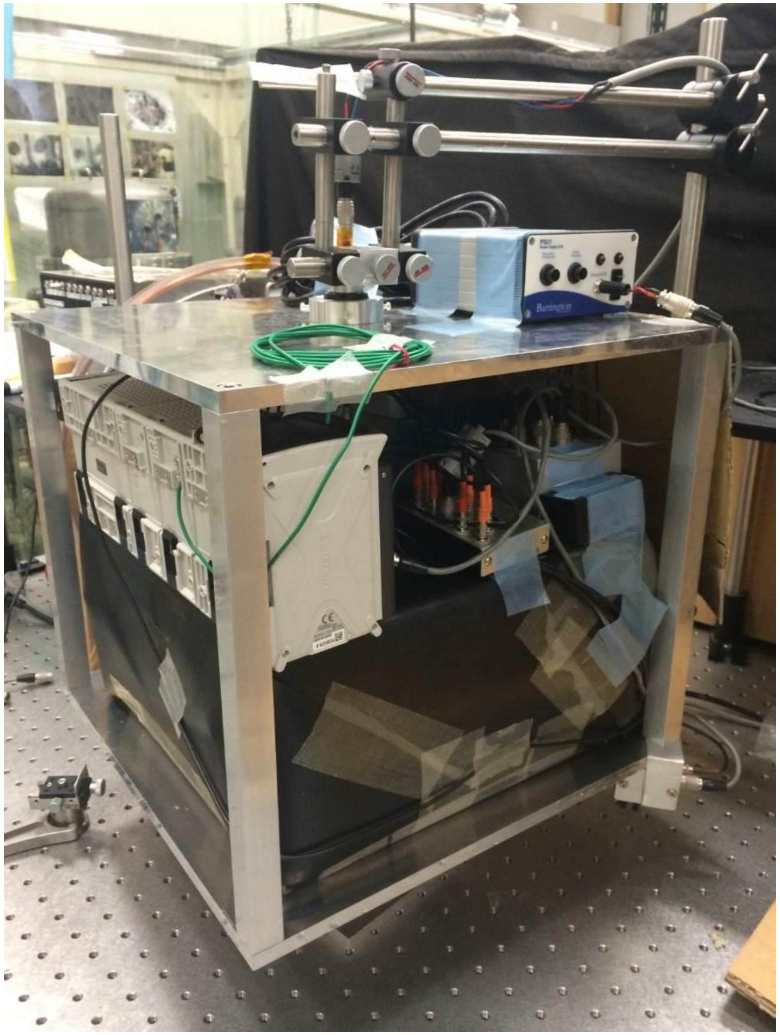
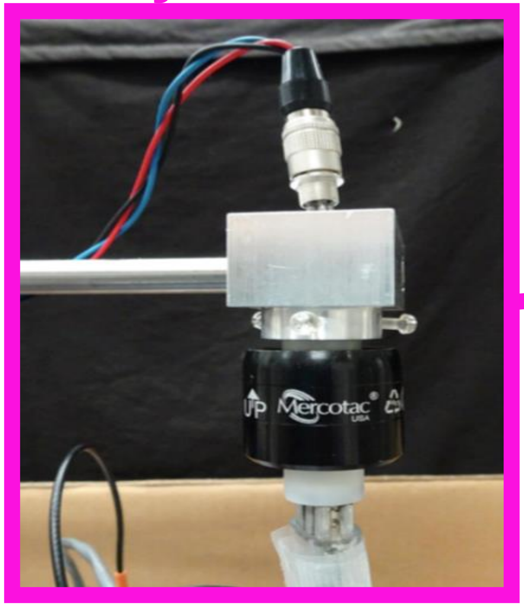


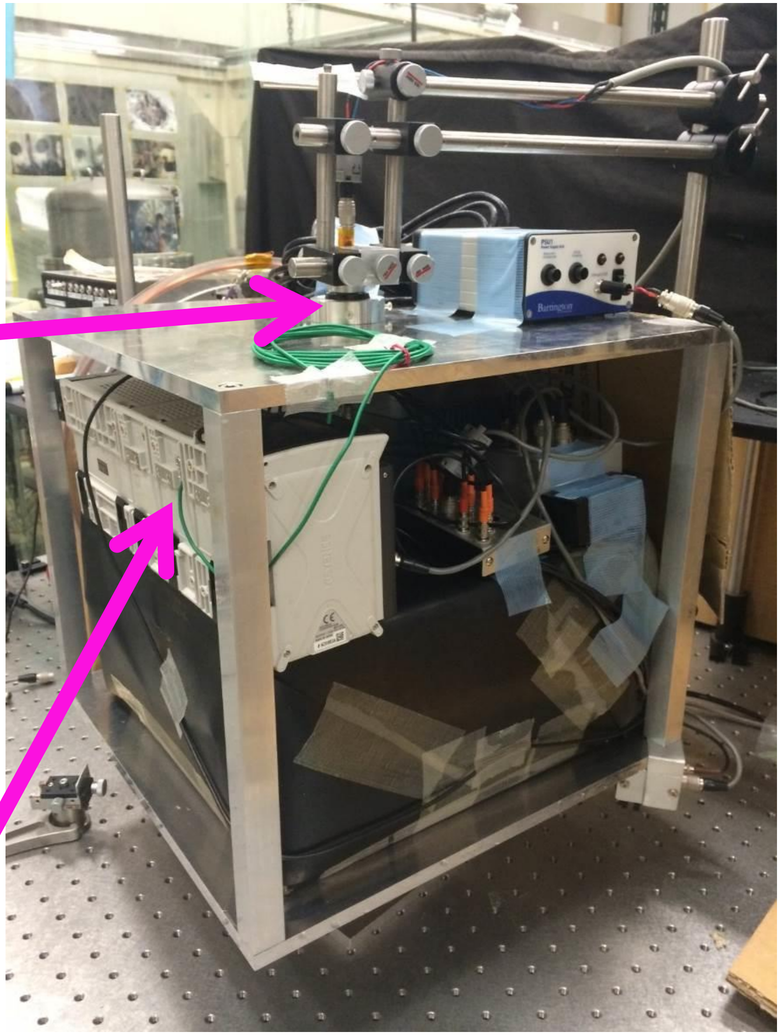
New Model
- semi-monolithic optics
- continuous rotation

Continuous Rotation System

rotary connector



wireless data logger

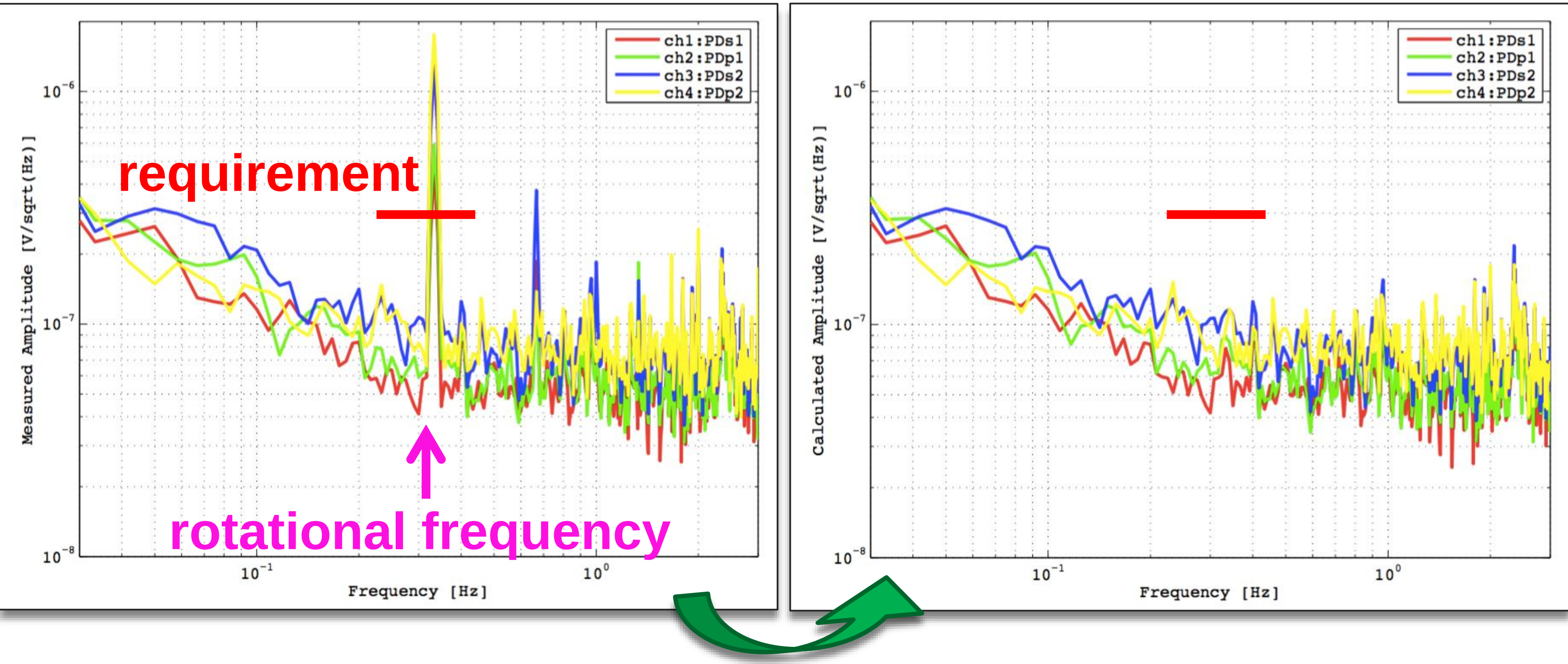


New Model

- semi-monolithic optics
- continuous rotation

Magnetic Noise

- environmental magnetic field noise couple into electronics noise
- can be subtracted by magnetic field measurement

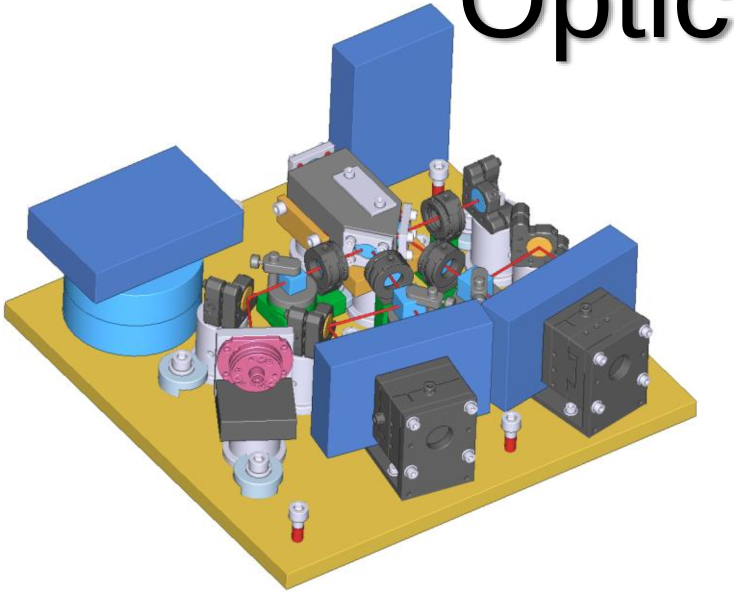


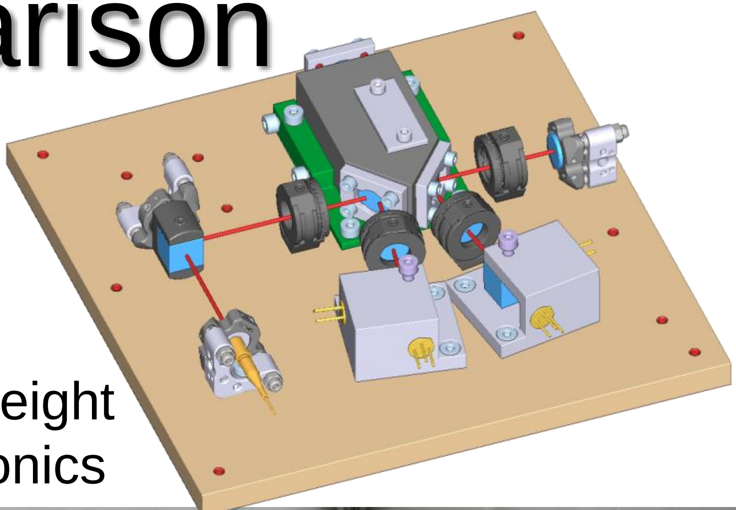
requirement

rotational frequency

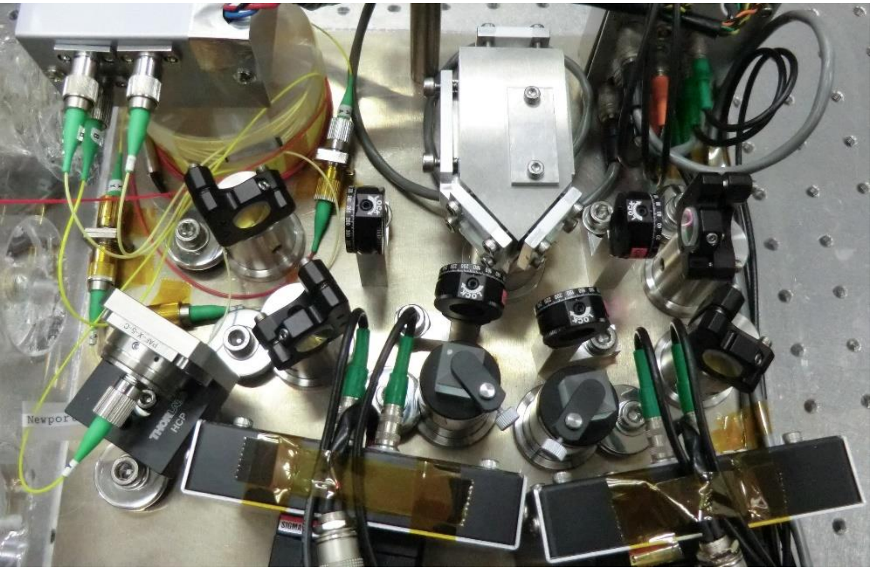
magnetic field noise subtraction

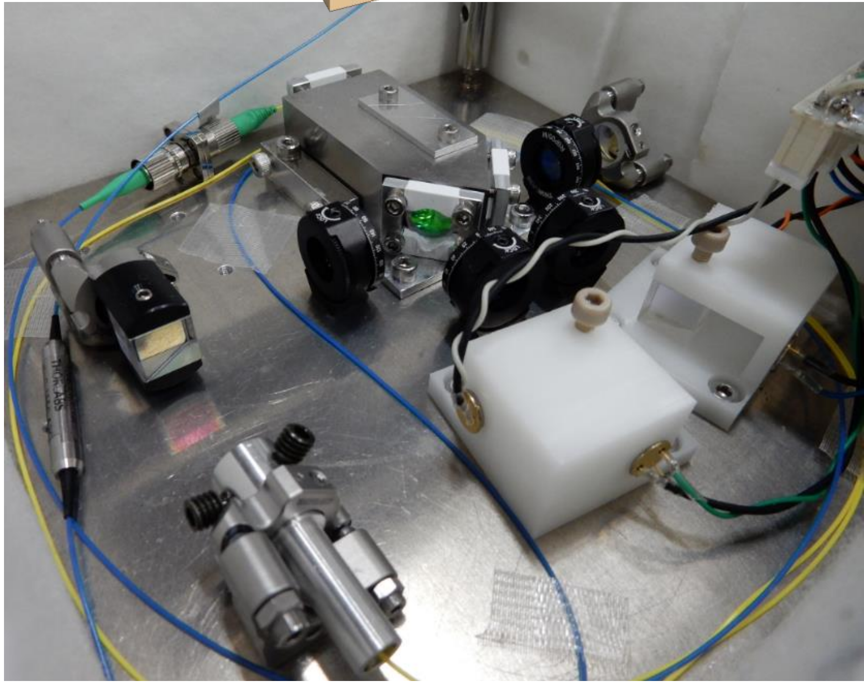
Optics Comparison





reduced beam height
simplified electronics

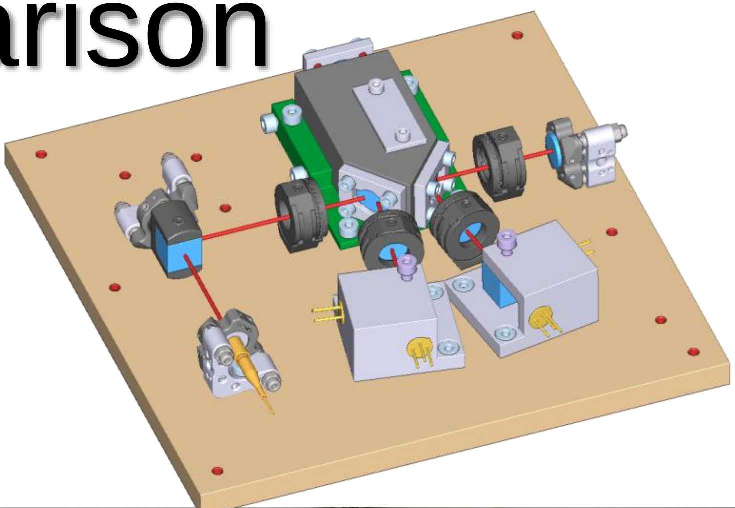




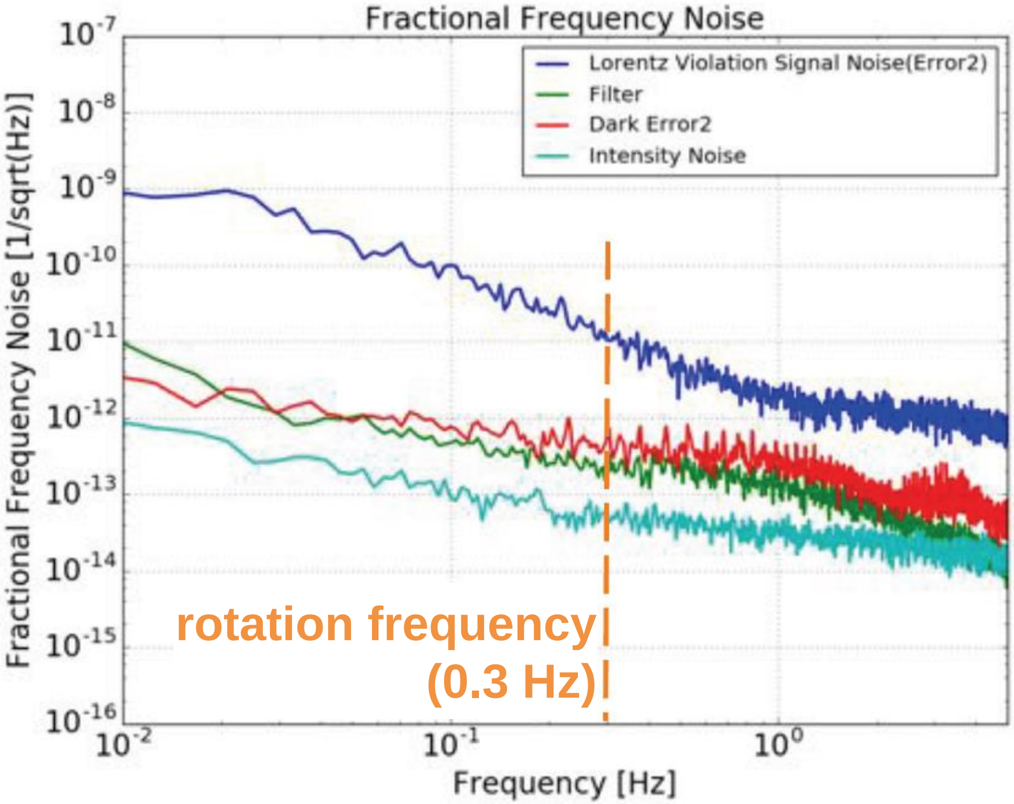
Previous Model
- non-monolithic optics

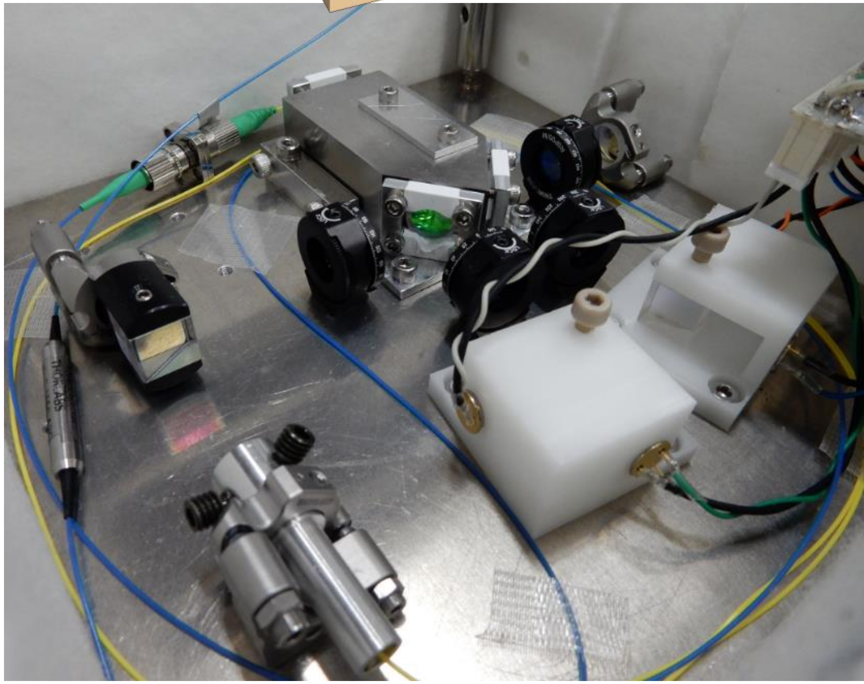
New Model
- semi-monolithic optics

Optics Comparison



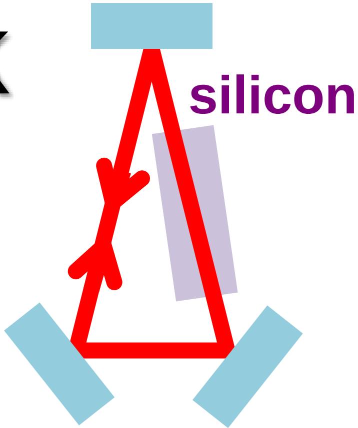
preliminary noise measurement
noise analysis ongoing





New Model
- semi-monolithic optics

Summary and Outlook

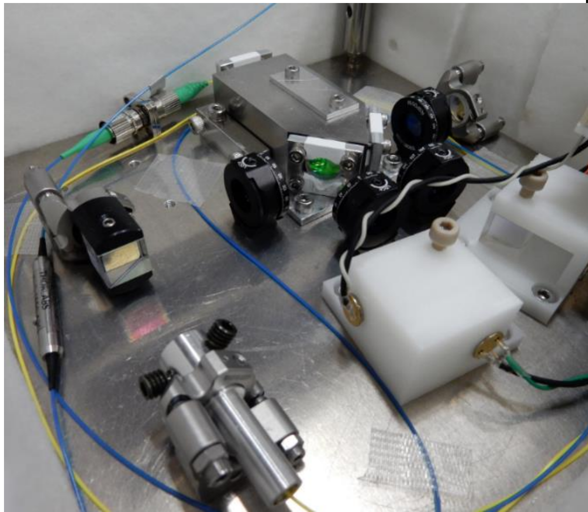


Summary

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

Outlook

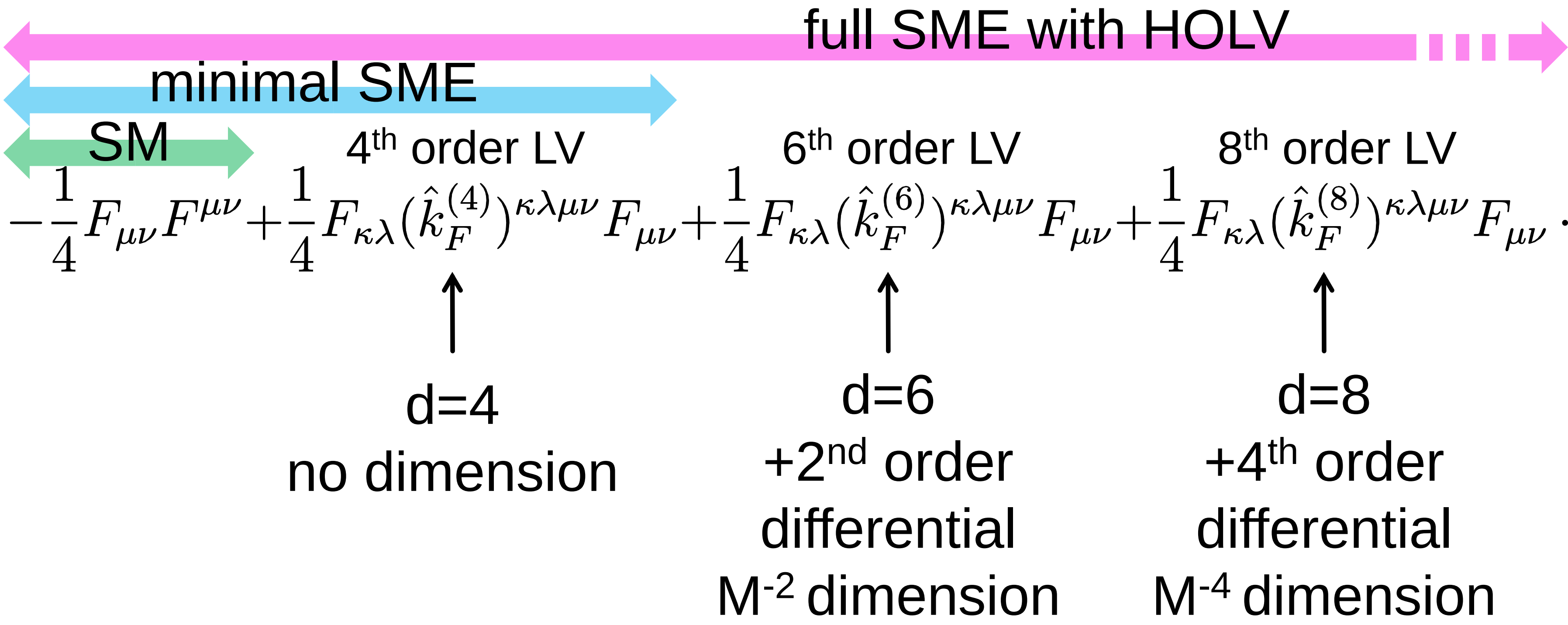
- currently upgrading the apparatus
  (Y. Sakai and H. Takeda)
- semi-monolithic optics
- continuous rotation



Additional Slides

Higher Order Lorentz Violation

- Standard Model Extention
- add LV term in Lagrangian for electromagnetic field
- $\hat{k}_F^{(d)}$ is zero for non-LV, d is mass dimension



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

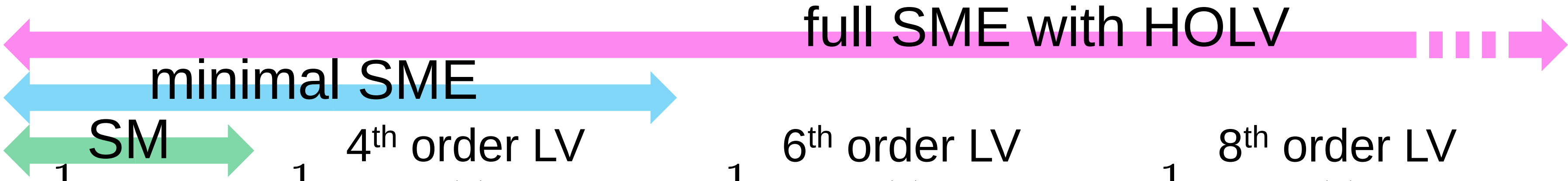
d=4
no dimension

d=6
+2nd order
differential
M^{-2} dimension

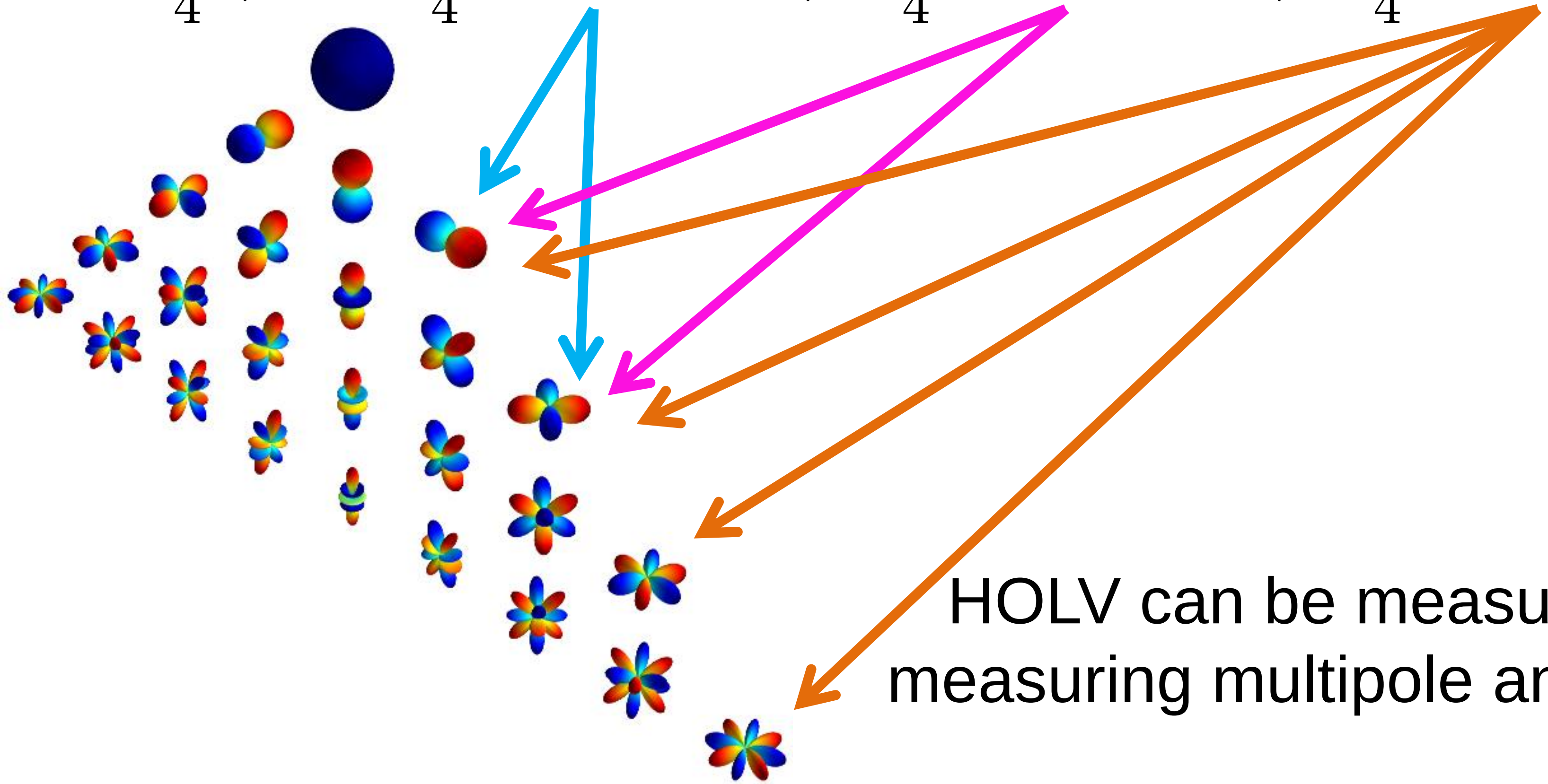
d=8
+4th order
differential
M^{-4} dimension

Higher Order LV and Anisotropy

- HOLV gives multipole anisotropy



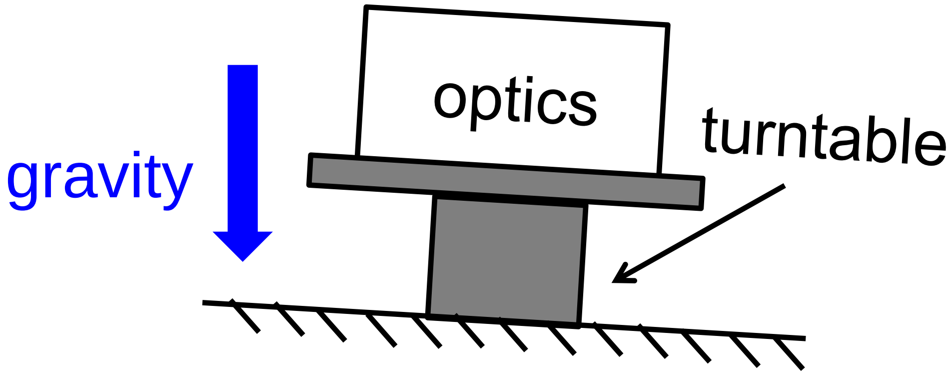
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}F_{\kappa\lambda}(\hat{k}_F^{(4)})^{\kappa\lambda\mu\nu}F_{\mu\nu} + \frac{1}{4}F_{\kappa\lambda}(\hat{k}_F^{(6)})^{\kappa\lambda\mu\nu}F_{\mu\nu} + \frac{1}{4}F_{\kappa\lambda}(\hat{k}_F^{(8)})^{\kappa\lambda\mu\nu}F_{\mu\nu} \cdot$$



HOLV can be measured by measuring multipole anisotropy

Systematic Errors

- 10% of statistical error at maximum

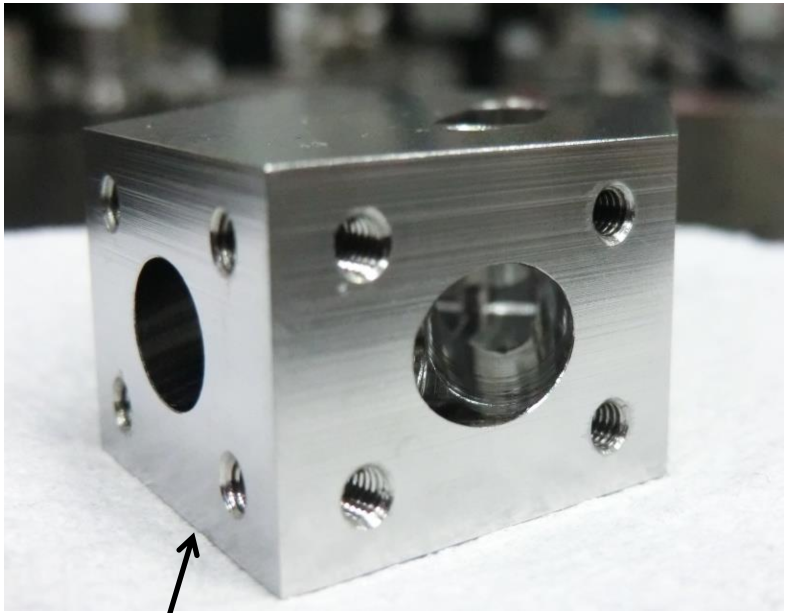


Cause	Amount	Ratio
Sagnac effect	< 1mrad/sec	<2%
turntable tilt	< 0.2 mrad	<10%
detuning	-	3%
TF meas.	-	3%
laser frequency actuation meas.	12.9±0.6 MHz/V	5%
refractive index	3.69±0.01	0.4%
cavity length	192±1 mm	0.5%

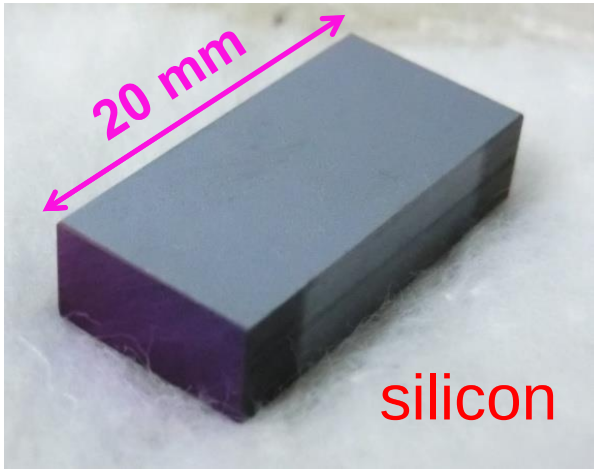
offset

calibration

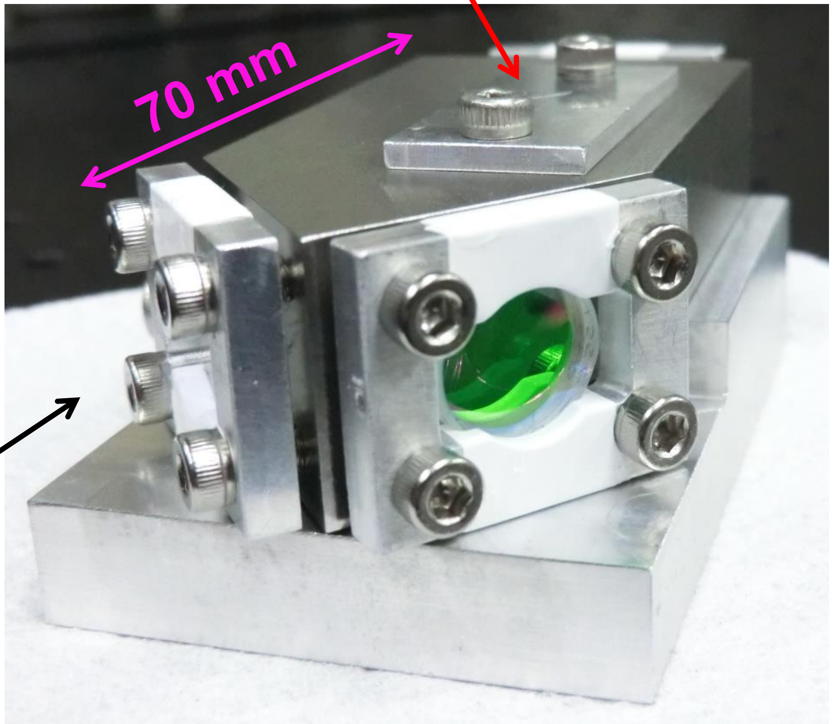
Some Photos



spacer made of
Super Invar



silicon inside



cavity mirrors

Cheat Sheet

- rotation frequency f_rot = 0.083 Hz
  (T_rot = 12 sec)
- wavelength λ = 1550 nm
- laser frequency v = 1.9e14 Hz
- input power P0 = 1 mW
- finesse F = 120
- cavity length L = 140 mm
- silicon length d = 20 mm
- silicon refractive index n = 3.69
- silicon dn/dT = 2e-4 /K
- silicon thermal expansion = 3e-6 /K
- Super Invar thermal exp. = ~ 1e-7 /K
- silicon AR loss l < 0.5 % / surface
- incident angle θ = 9.5 deg
- FSR = 1.5 GHz
- FWHM = 12 MHz

- current sensitivity ~ 6e-13 /rtHz
  (~ 4e-11 /rtHz when rotated)
- shot noise ~ 6e-16 /rtHz
- thermal noise ~ 8e-16 /rtHz

(all @ 0.1 Hz)

- Sun speed in CMBR = 369 km/s
- orbital speed of Earth = 30 km/s
- rotational speed of Earth = 0.4 km/s

- History
  Jul 2011: idea
  Nov 2011: first run (10hour)
  Jul 2012: data taking started
  Oct 2012: continuous data taking
  Oct 2013: shut down
- cost < ~200万円