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

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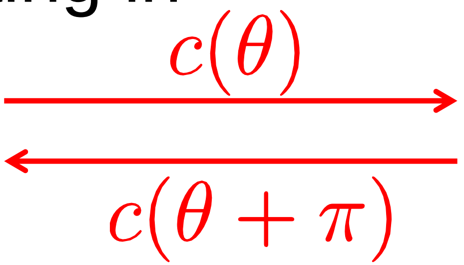
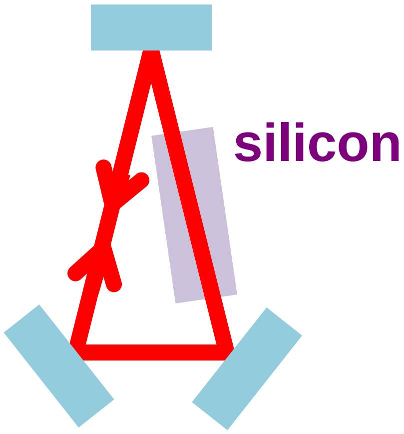
Summary

- compared the speed of light propagating in opposite directions



- using a double-pass optical ring cavity



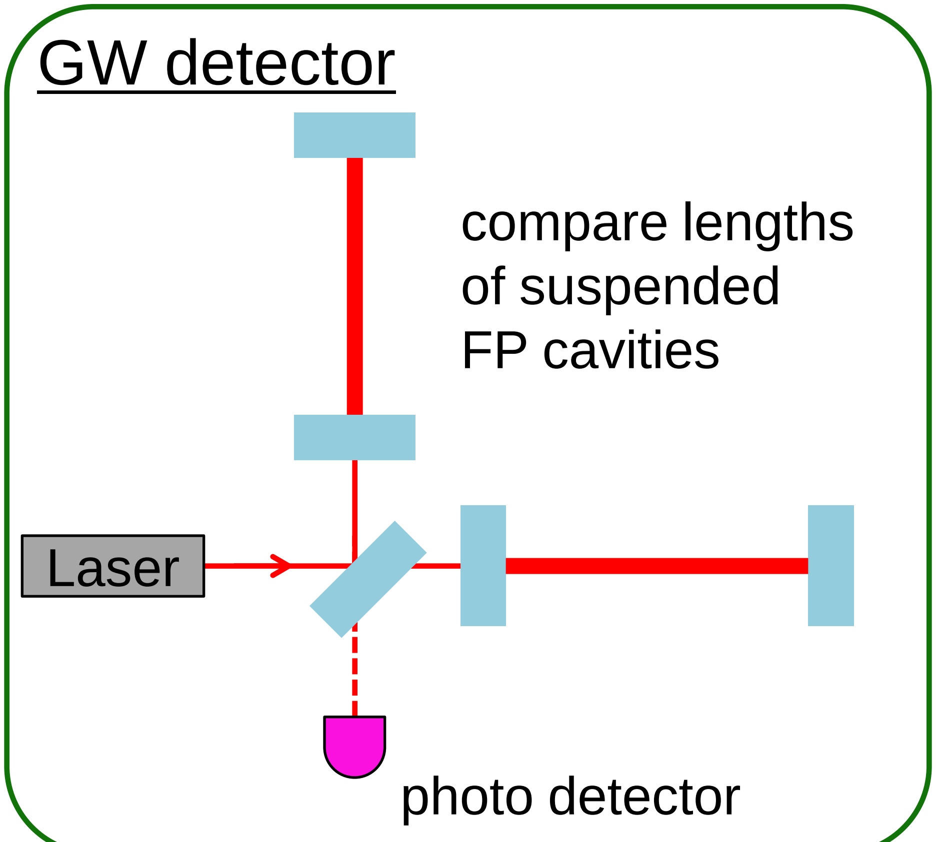
- put new limits on LV in photons

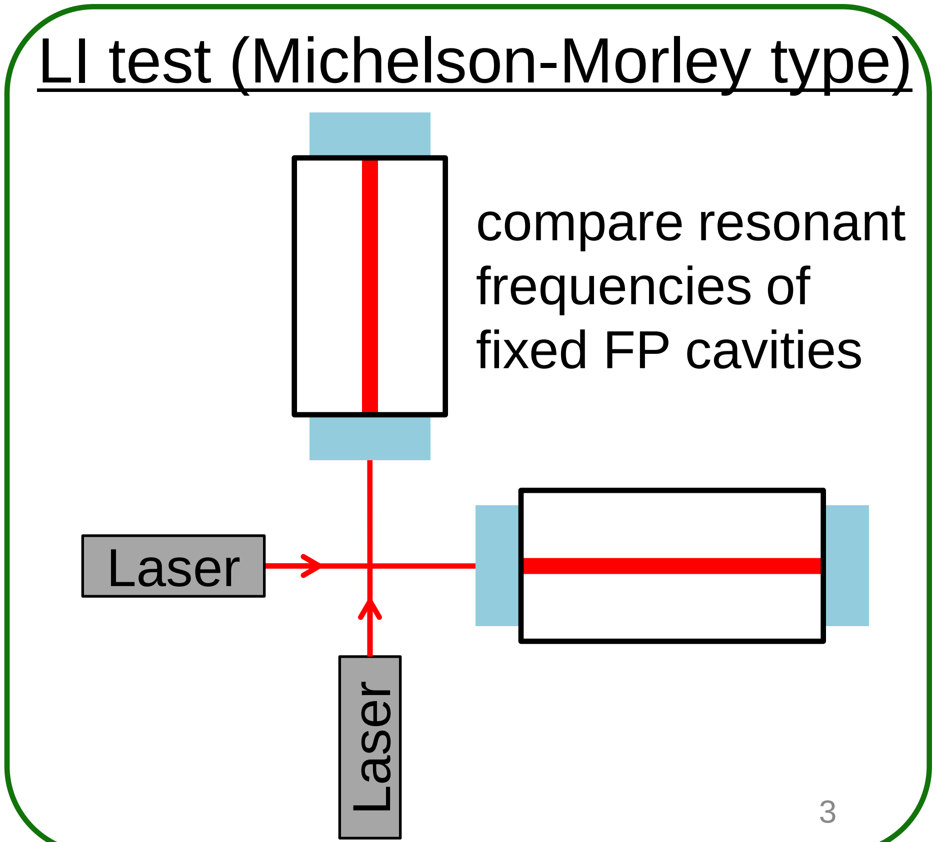
$$|\delta c/c| \lesssim 1 \times 10^{-14}$$

- Y. Michimura, N. Matsumoto, N. Ohmae, W. Kokuyama, Y. Aso, M. Ando, K. Tsubono: [Phys. Rev. Lett. 110, 200401 (2013)]

We are (eventual) GW Astronomers

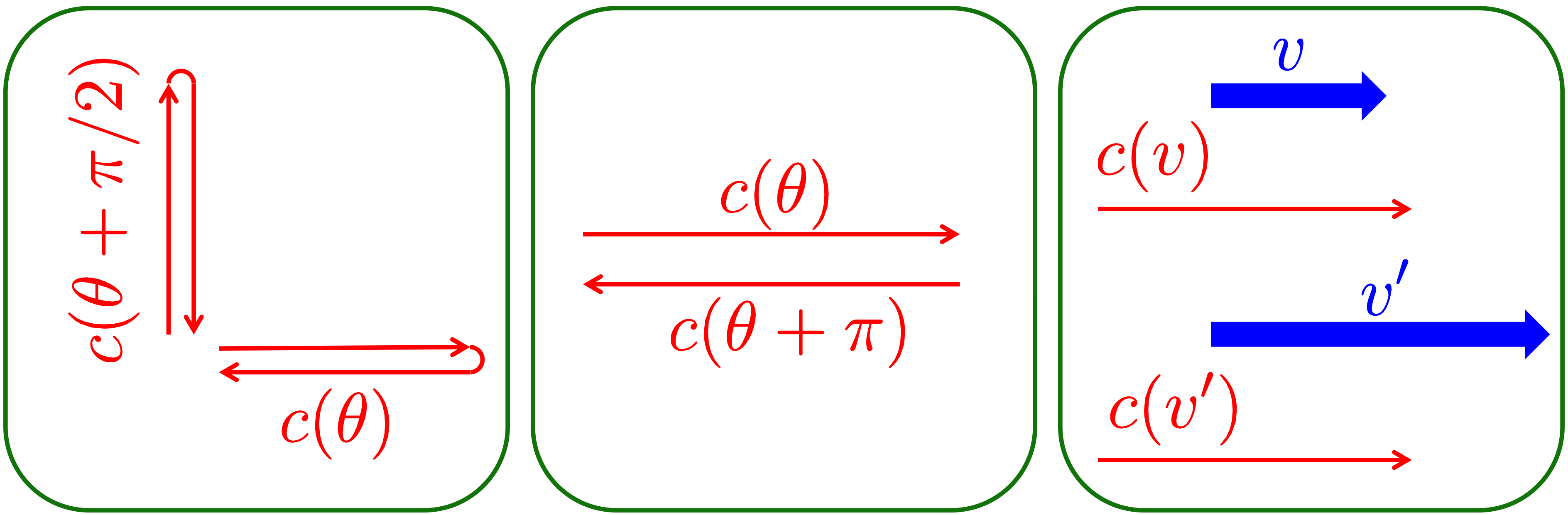
- laser interferometric gravitational wave detectors
  KAGRA (Japan), LIGO (US), Virgo (Italy) ......
- first detection within ~ 5 years





Lorentz Invariance in Photons

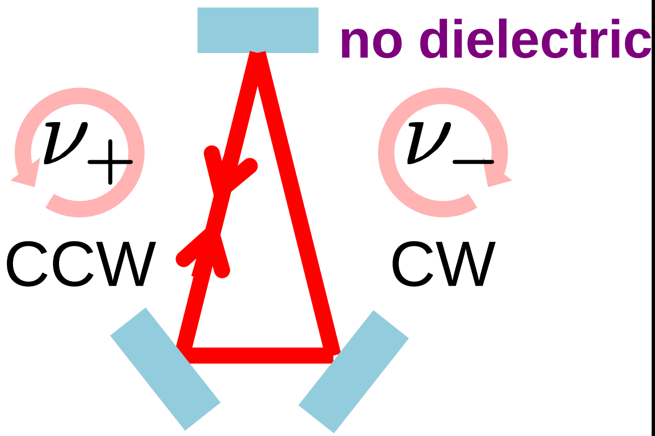
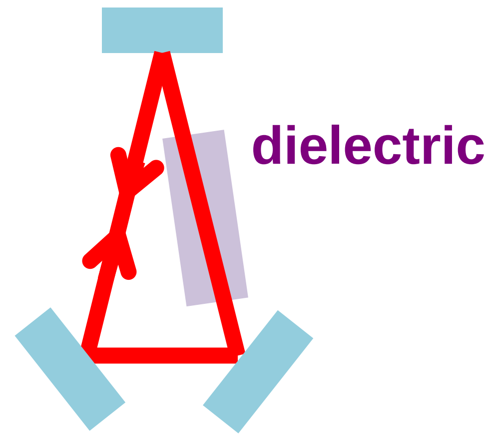
- constancy of speed of light
  - no directional dependence
  - no difference between opposite directions
  - no dependence from lab velocity



$\tilde{\kappa}_{e-}^{JK}$ (5 parameters) | $\tilde{\kappa}_{o+}^{JK}$ (3 parameters) | $\tilde{\kappa}_{\mathrm{tr}}$ (1 parameter)

Optical Ring Cavity

- sensitive to LV when a dielectric is contained

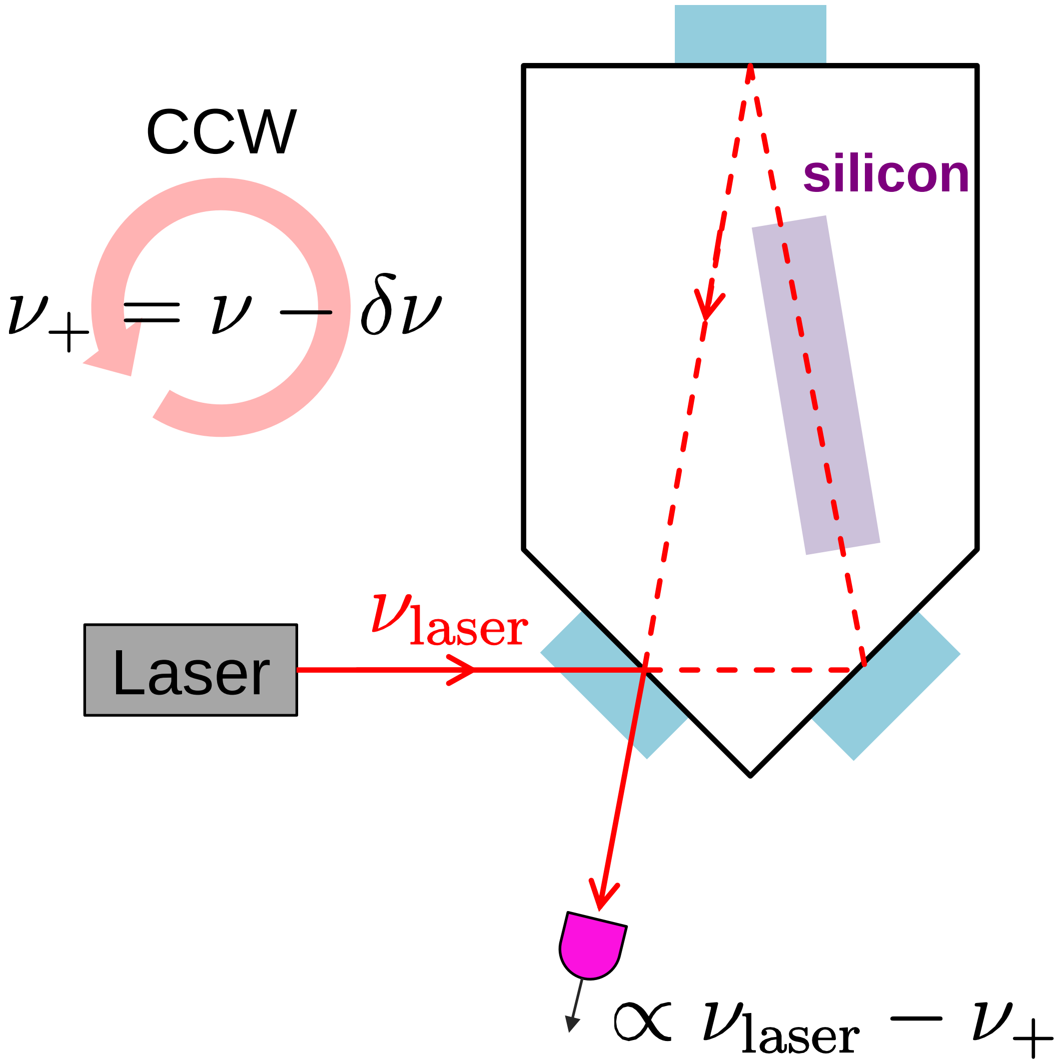
		
no LV	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu$ $\nu_- = \nu$
LV	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu - \delta\nu$ $\nu_- = \nu + \delta\nu$

freq. shift $\propto$ LV

- let's compare the resonant frequencies!

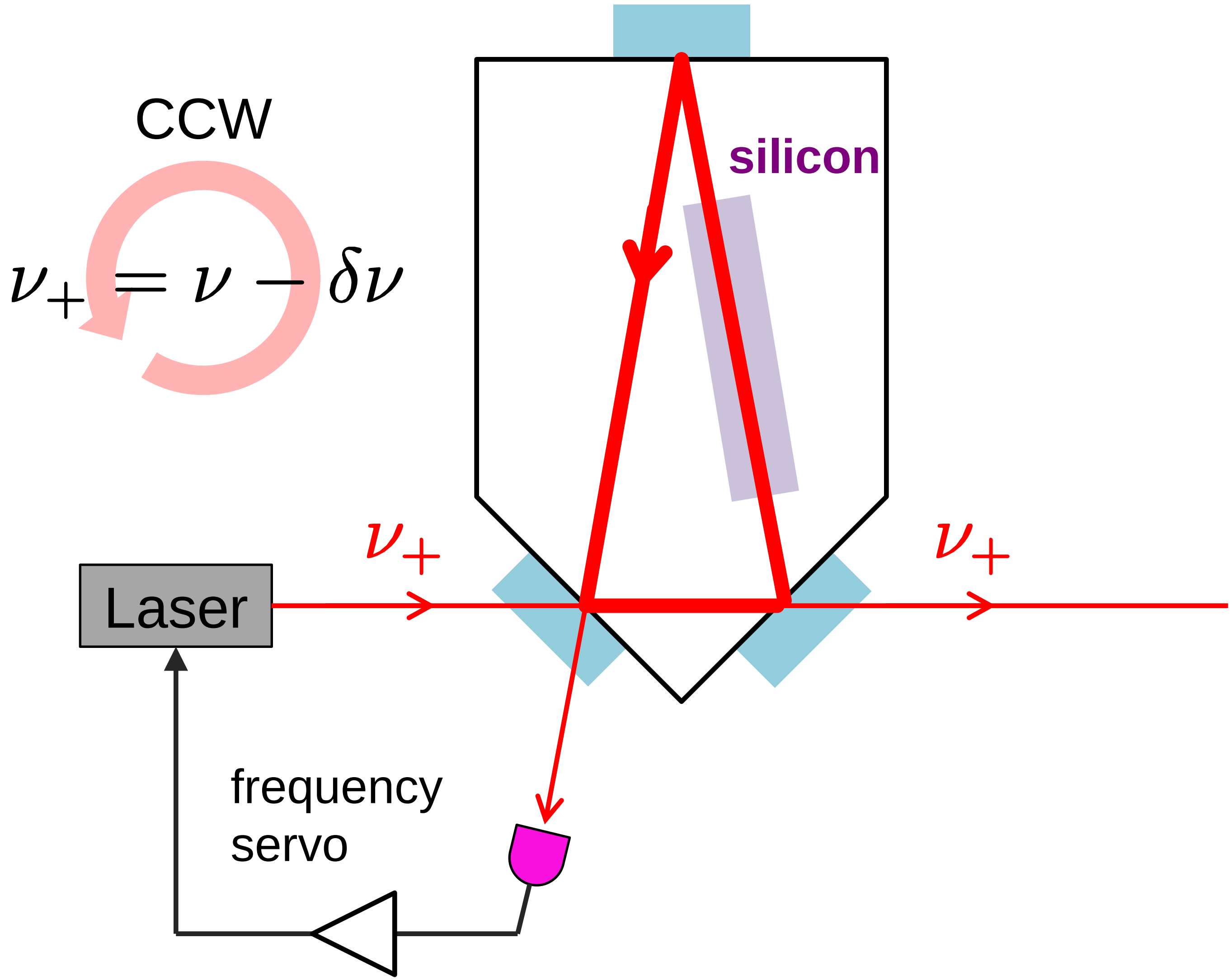
How Do We Measure 1/4

- inject laser beam in CCW



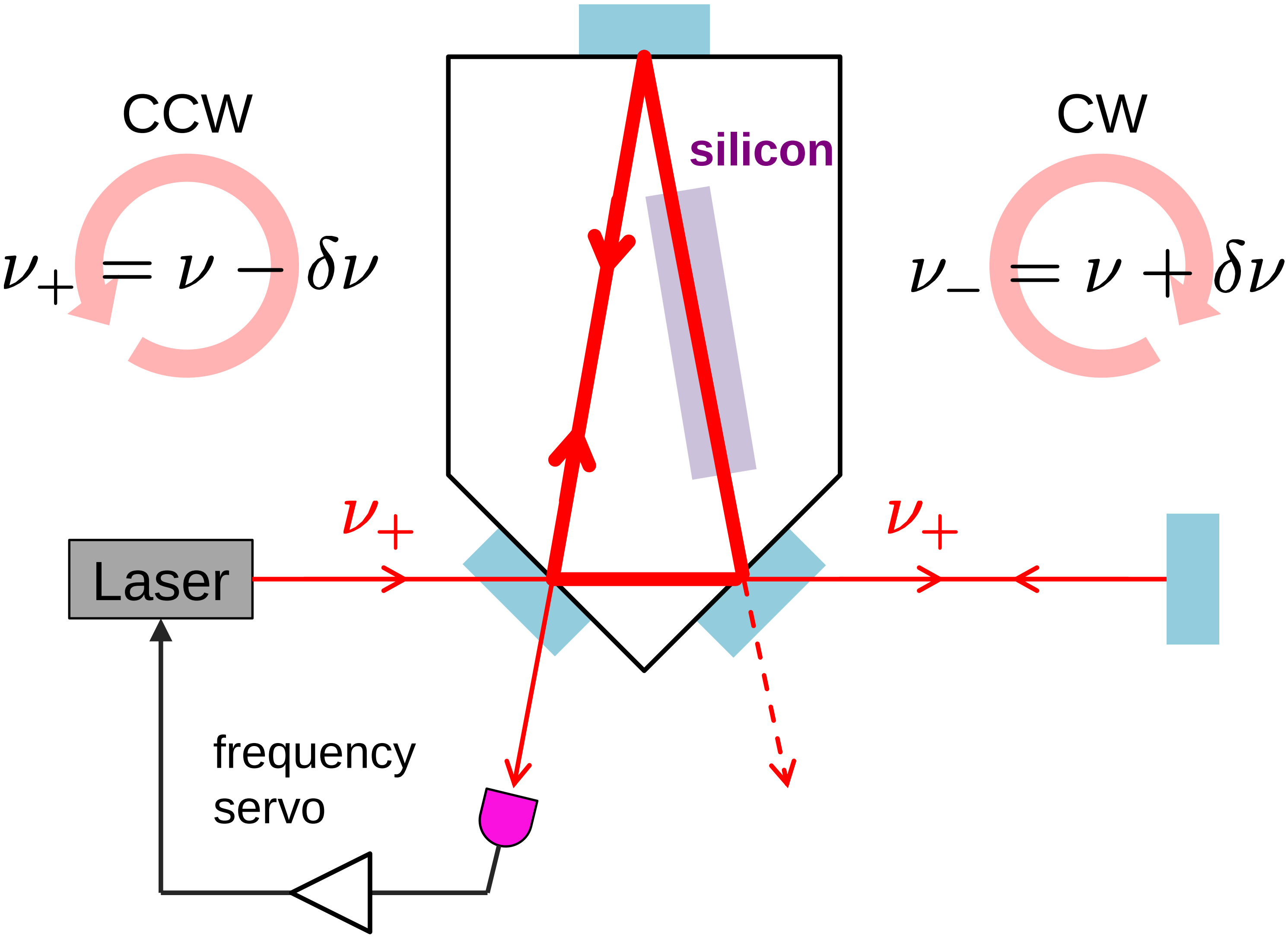
How Do We Measure 2/4

- lock laser frequency to CCW resonance (ν_+)



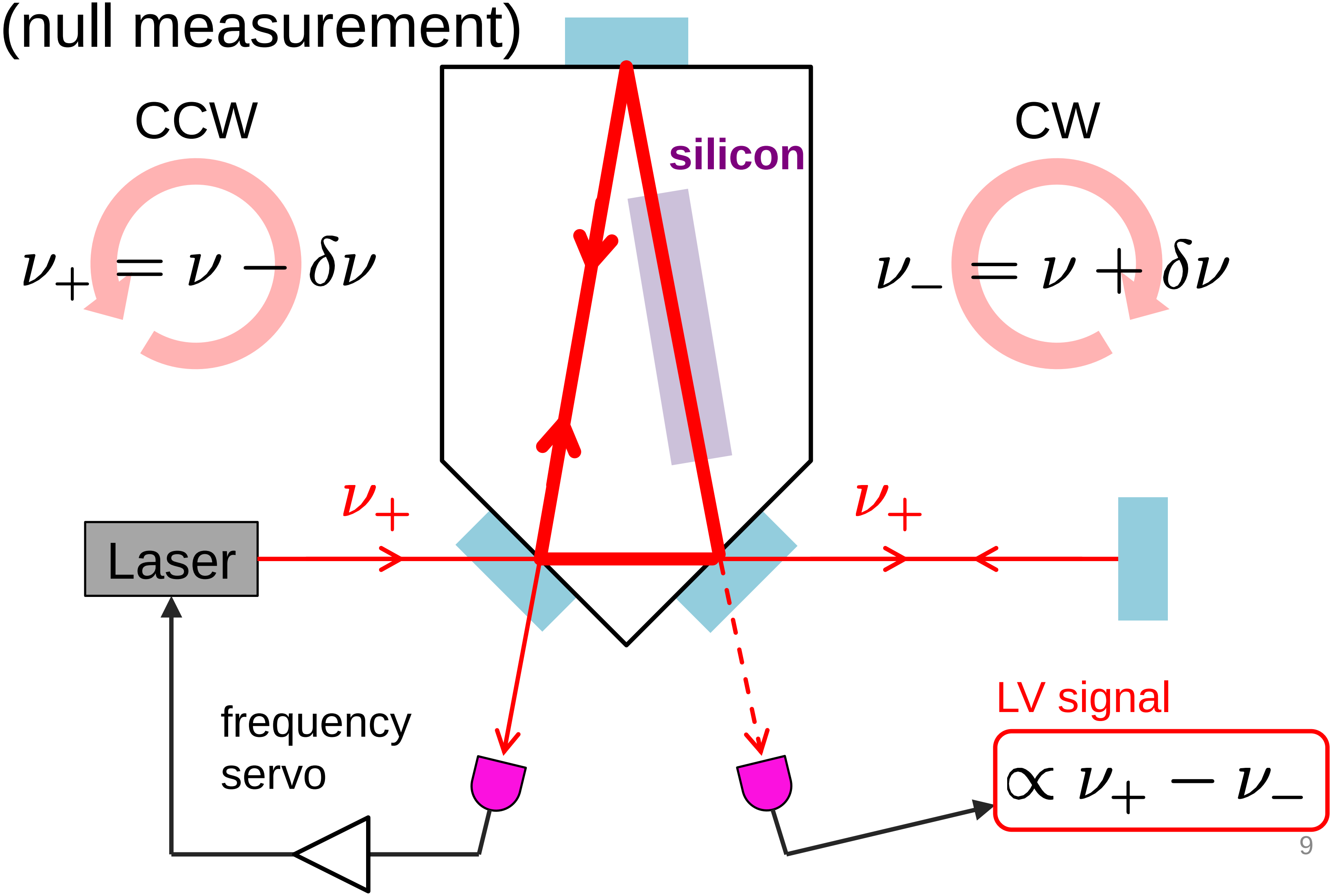
How Do We Measure 3/4

- 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

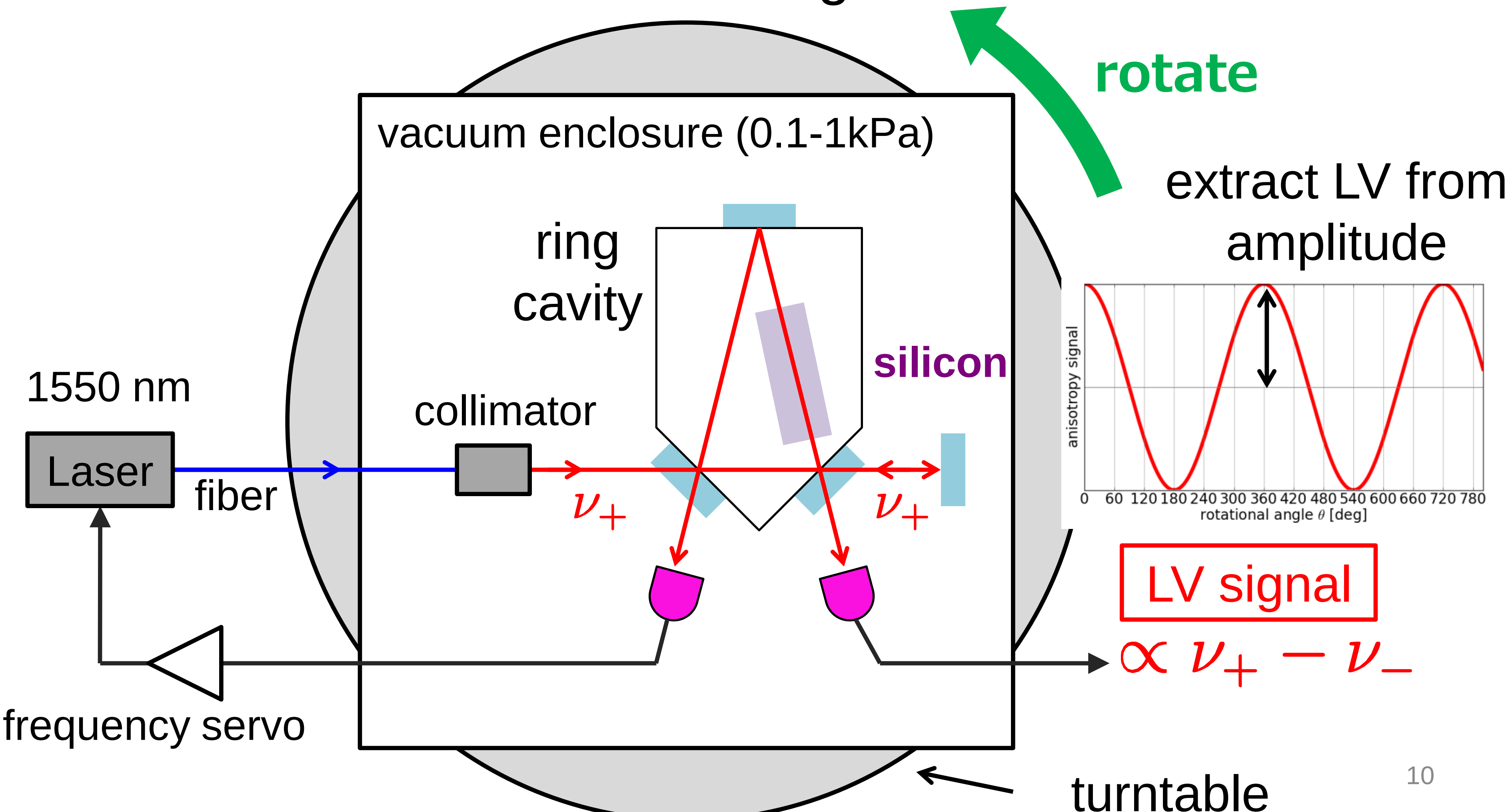


Photo of the Optics

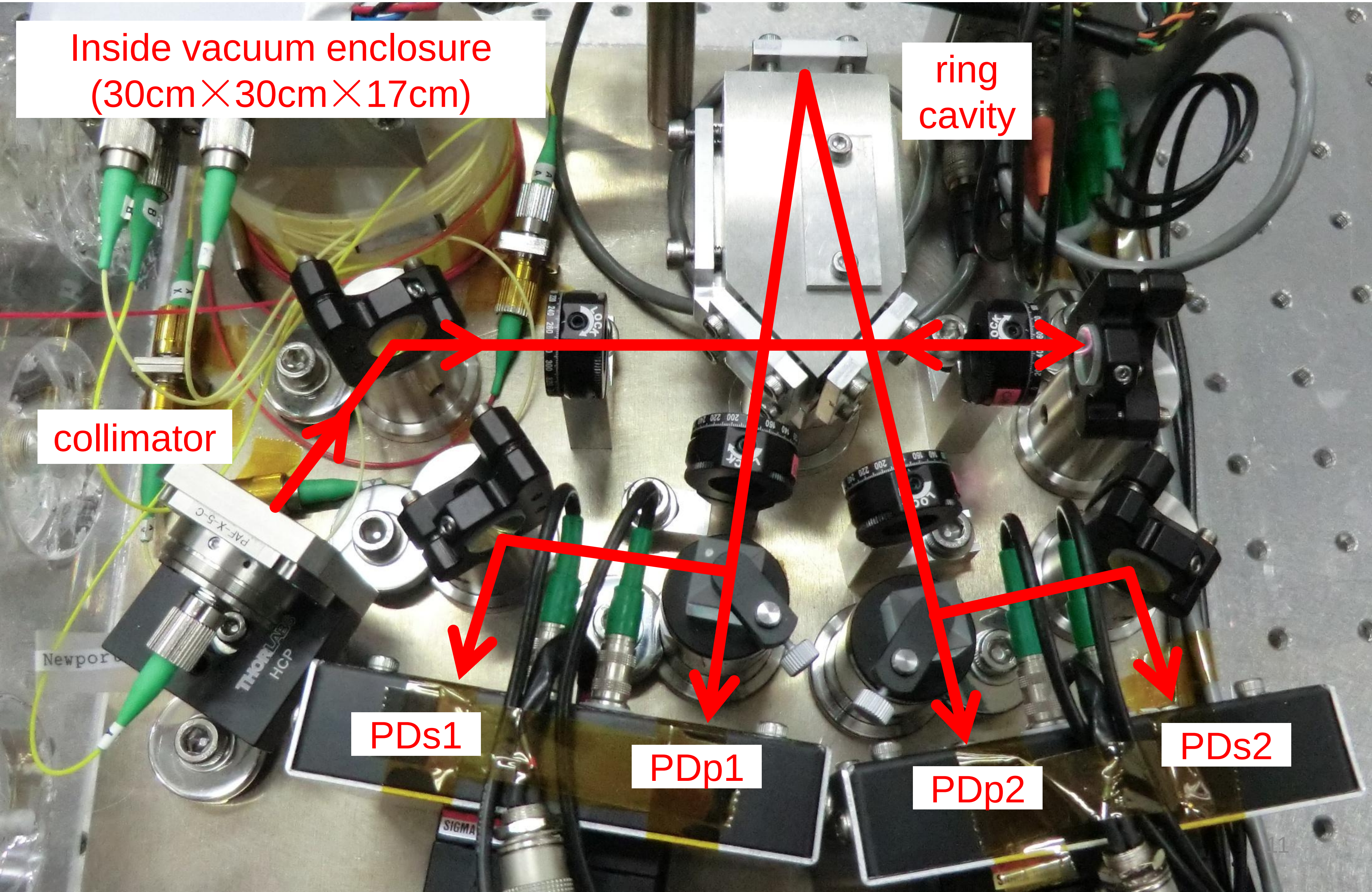


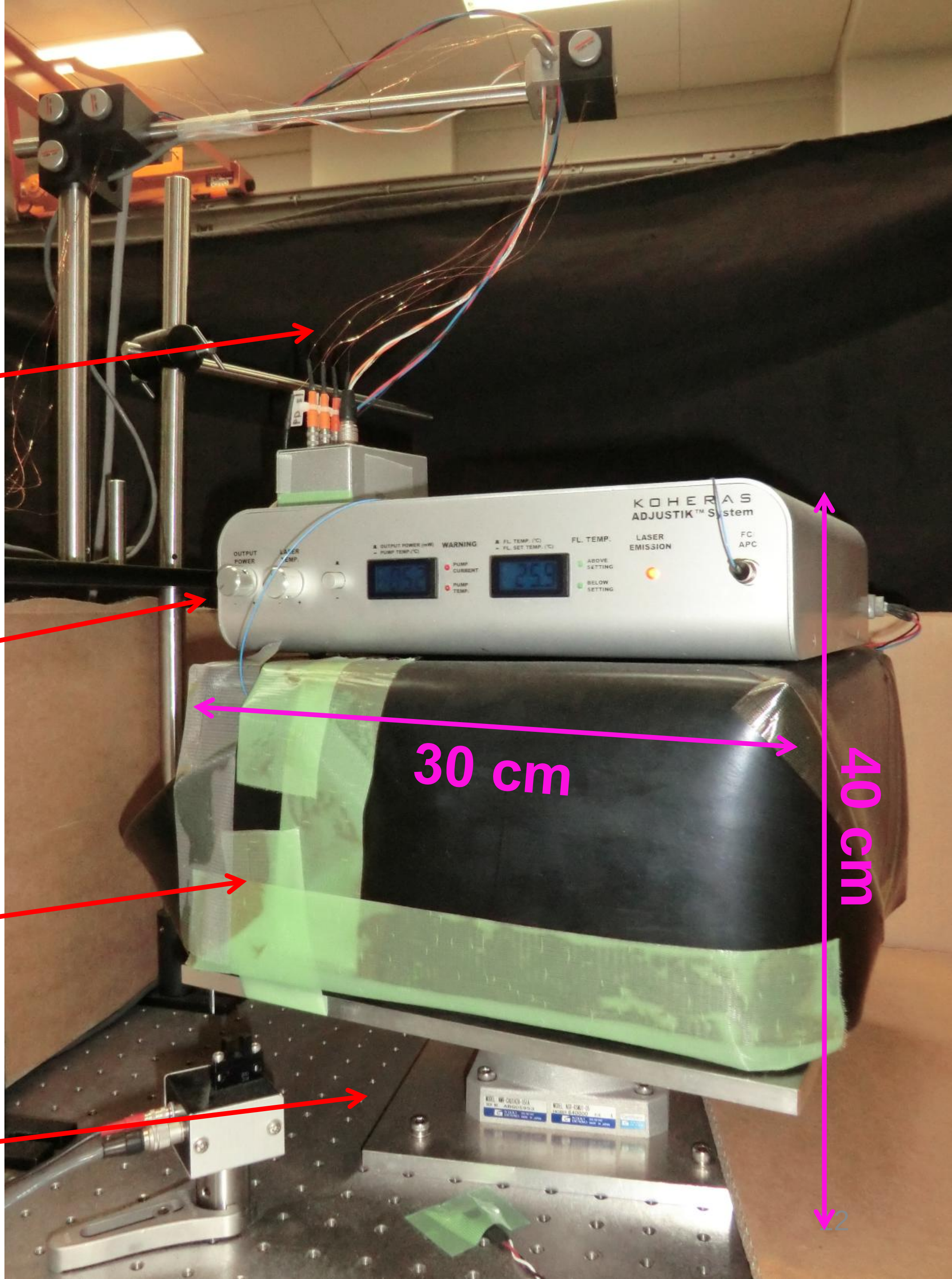
Photo of the Whole Setup

electrical cables

laser source

vacuum enclosure
+ shielding
(optics inside)

turntable



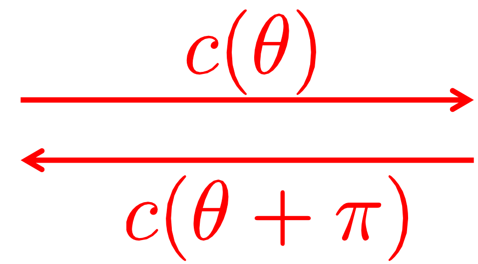
Parameters We Look for

- 3 odd-parity parameters

$\tilde{\kappa}_{o+}^{YZ}$ ⟵ c difference in SCCEF X axis

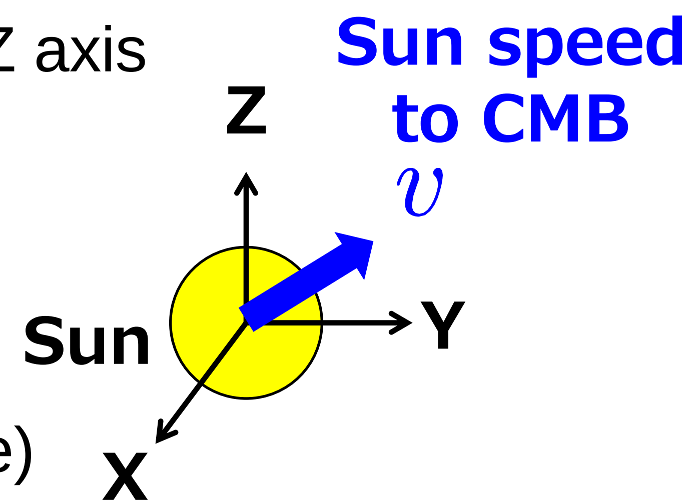
$\tilde{\kappa}_{o+}^{XZ}$ ⟵ c difference in SCCEF Y axis

$\tilde{\kappa}_{o+}^{XY}$ ⟵ c difference in SCCEF Z axis



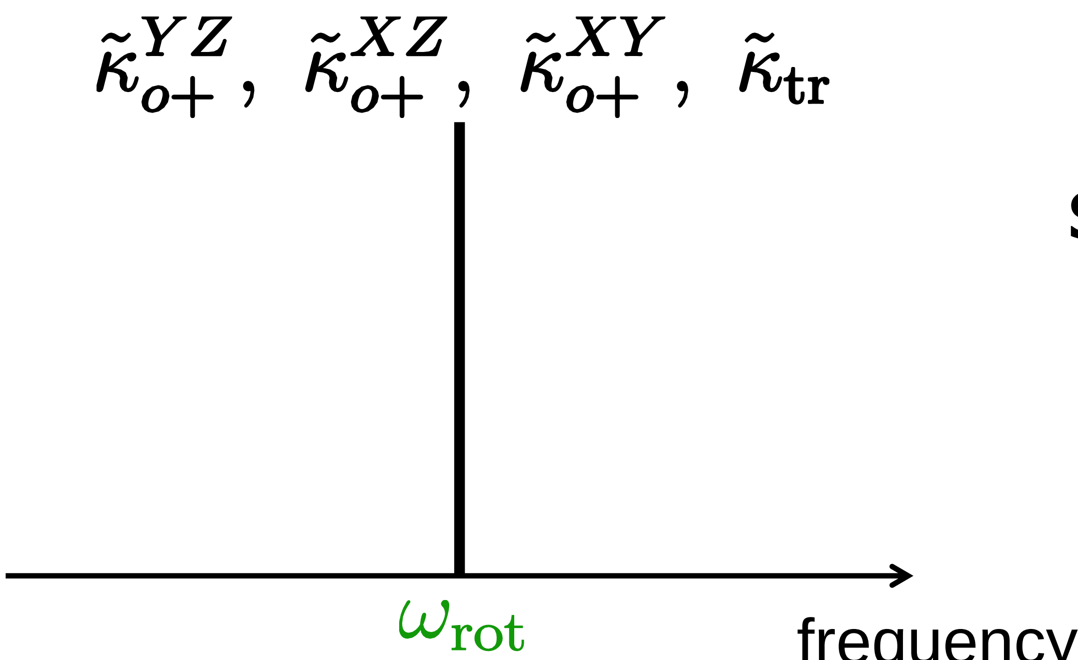
- isotropic parameter

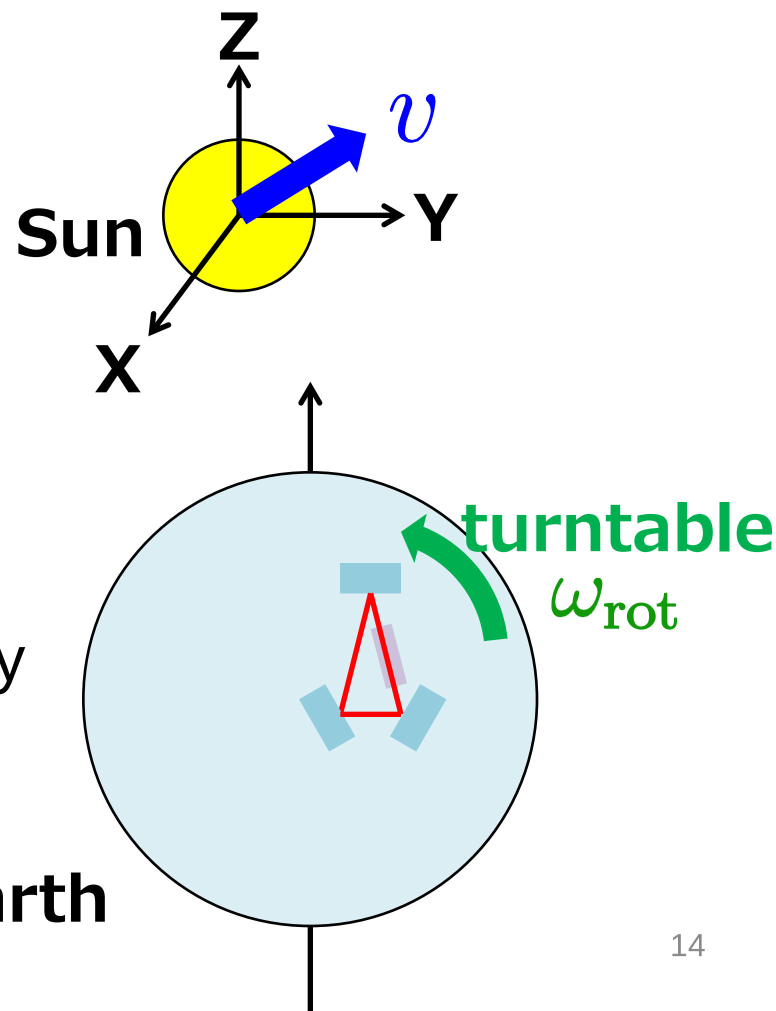
$\tilde{\kappa}_{\mathrm{tr}}$ ⟵ isotropic shift in c
(lab. speed dependence)



Data Analysis 1/3

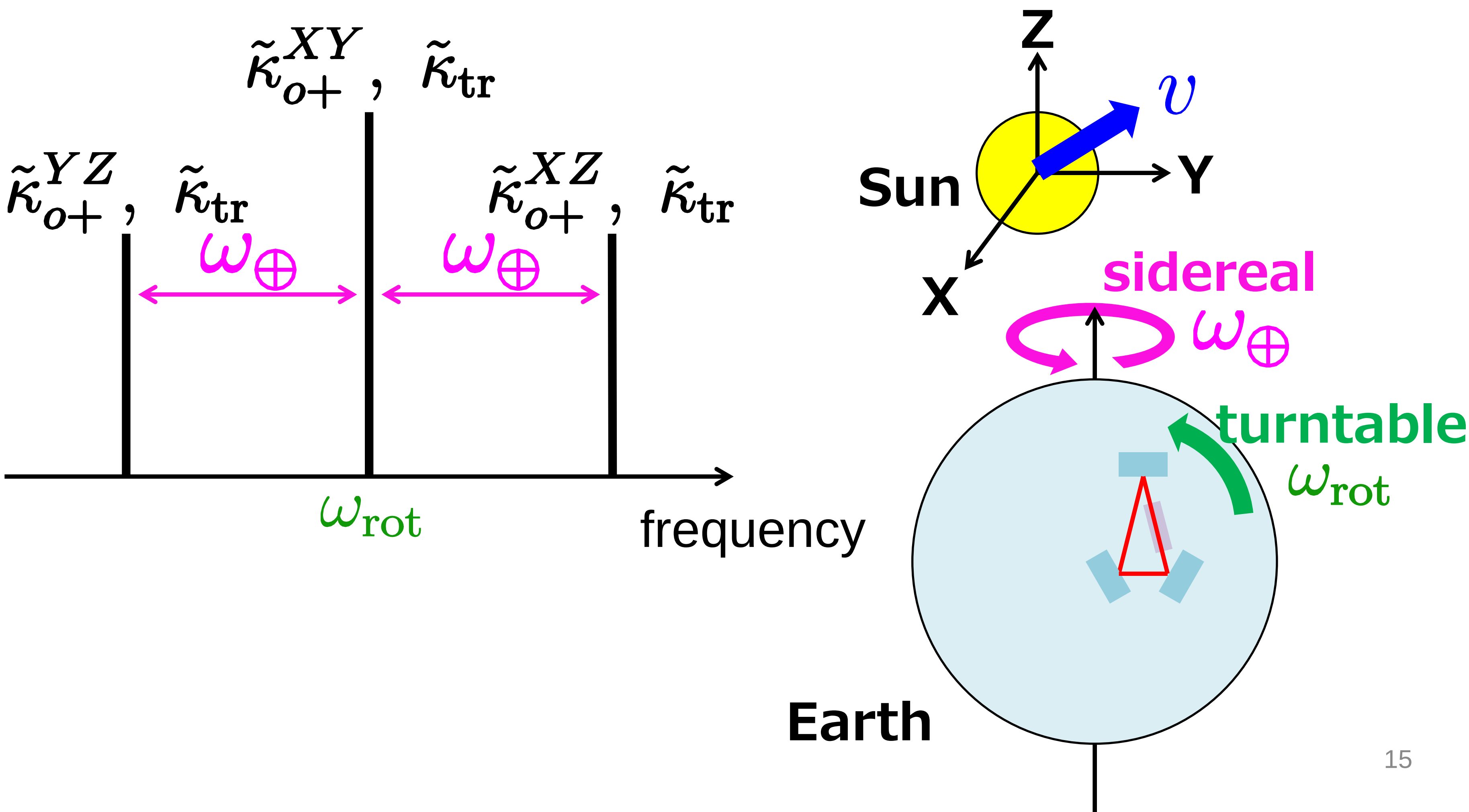
- demodulate each 1 rotation data with ω_{rot}





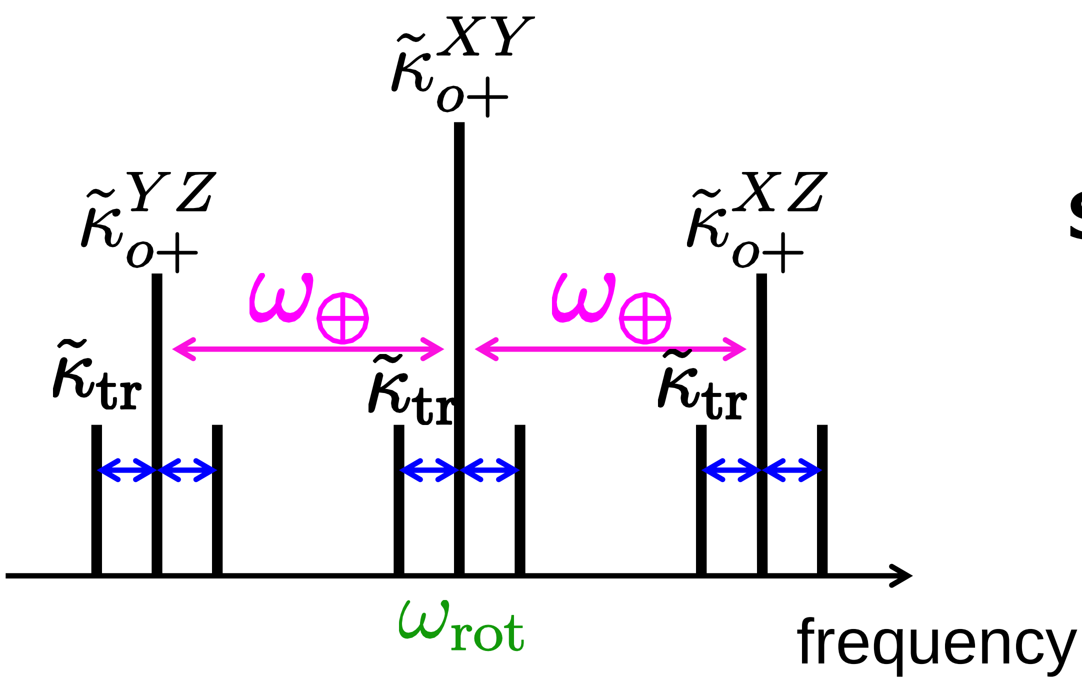
Data Analysis 2/3

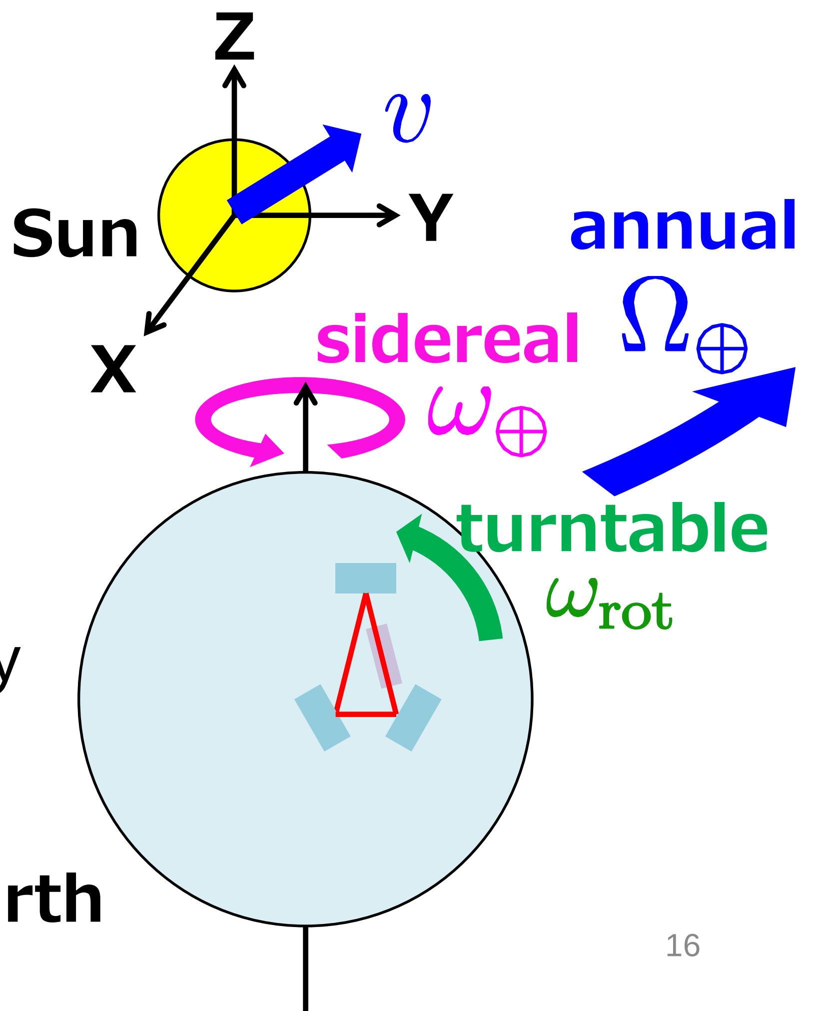
- next, demodulate 1 day data with $\omega_\oplus$



Data Analysis 3/3

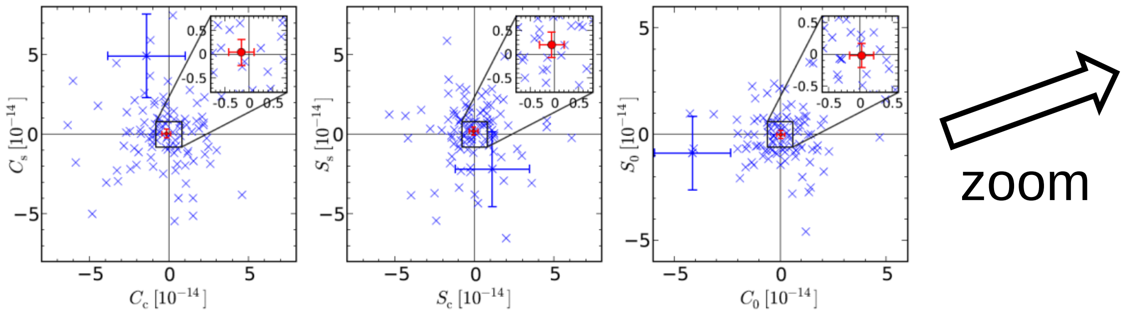
- then, fit whole data with $\Omega_\oplus$ using least squares fit

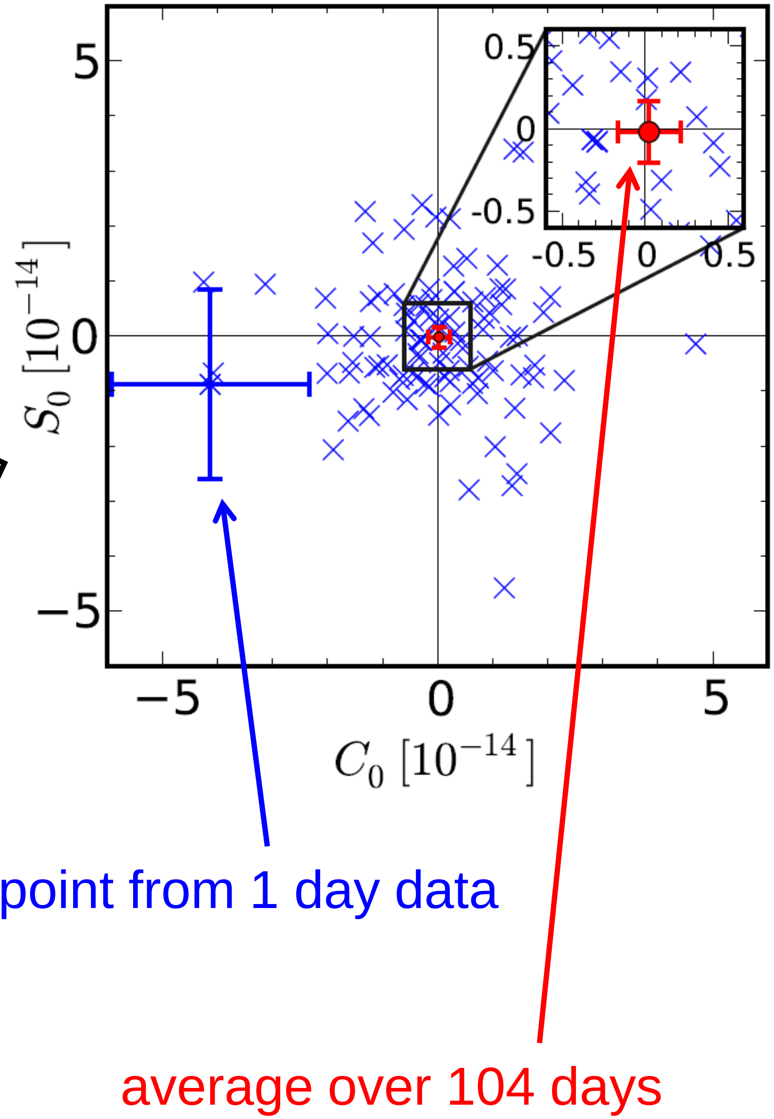


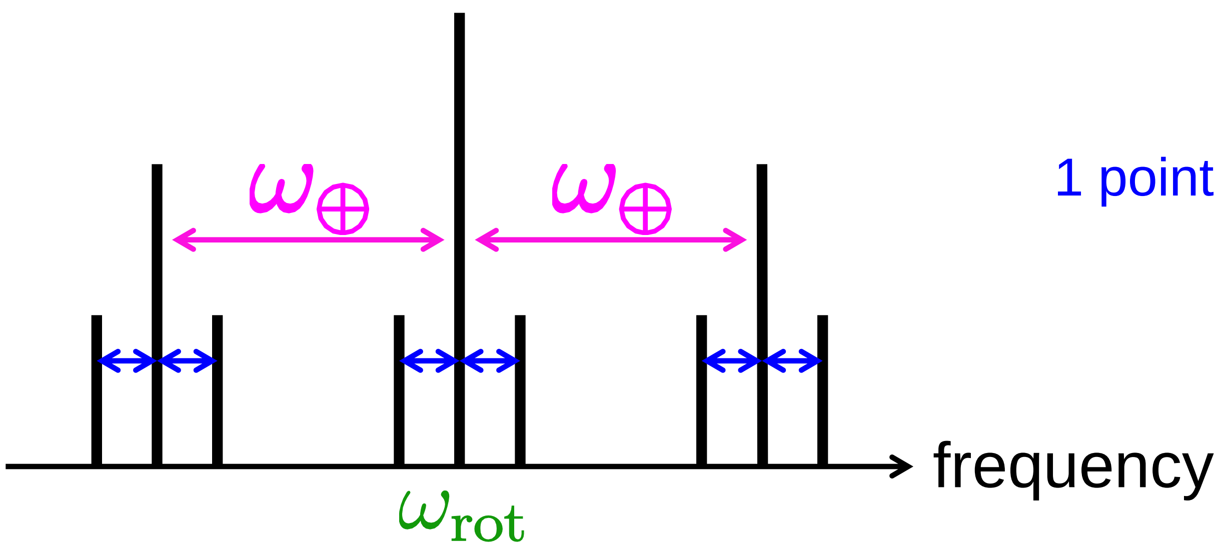


Result

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







New Limits

- By extracting annual modulation by fitting,

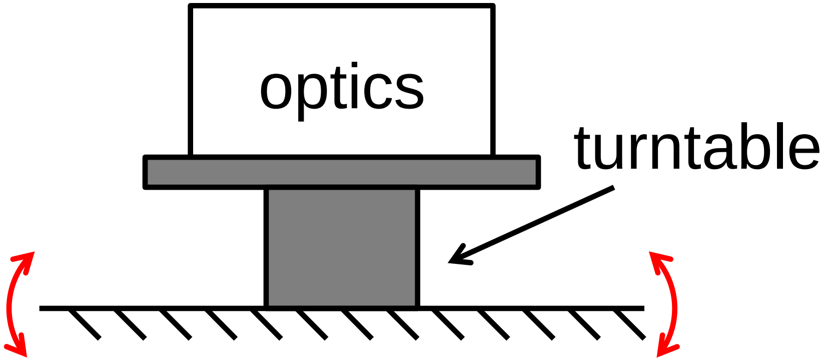
$$
\begin{aligned}
\tilde{\kappa}_{o+}^{YZ} &= (0.5 \pm 1.0) \times 10^{-14} \\
\tilde{\kappa}_{o+}^{XZ} &= (-0.6 \pm 1.2) \times 10^{-14} \\
\tilde{\kappa}_{o+}^{XY} &= (0.7 \pm 1.0) \times 10^{-14} \\
\tilde{\kappa}_{\mathrm{tr}} &= (-0.4 \pm 0.9) \times 10^{-10}
\end{aligned}
$$

- 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)
F. N. Baynes *et al.*: PRL **108**, 260801 (2012)

Systematic Errors

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

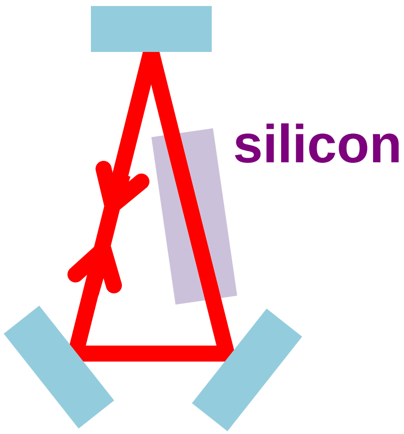


Cause	Amount	Ratio compared with stat.
rotational speed fluctuation (Sagnac effect)	< 1 mrad/sec	< 0.01 %
turntable tilt	< 0.2 mrad	< 10 %
calibration	-	3 %
refractive index	-	< 0.1 %
time	1 min	0.4 %
orientation	2 deg	3 %

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



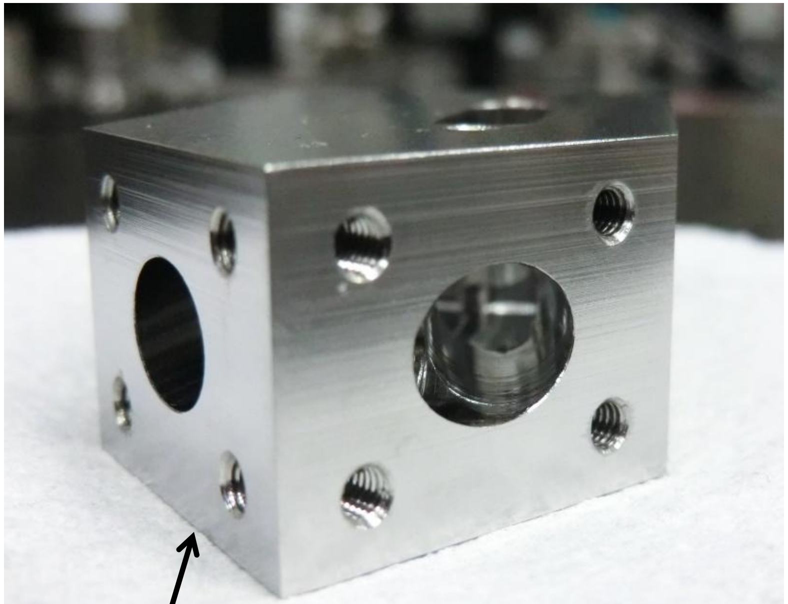
Outlook

- we are still running the measurement
  from Aug 2012
- higher order coefficients?
- upgrade to monolithic optical system
  more common mode rejection

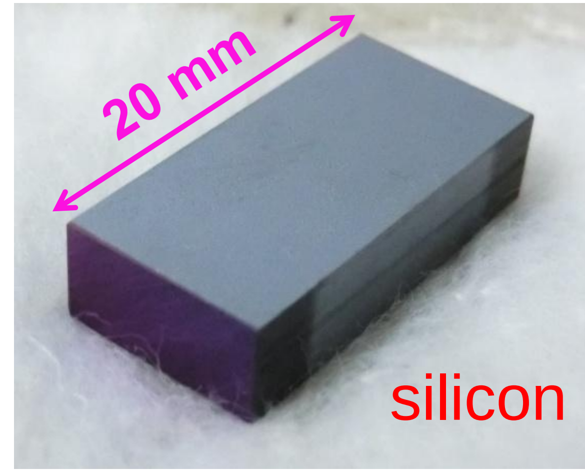
Thank you!

ありがとう！

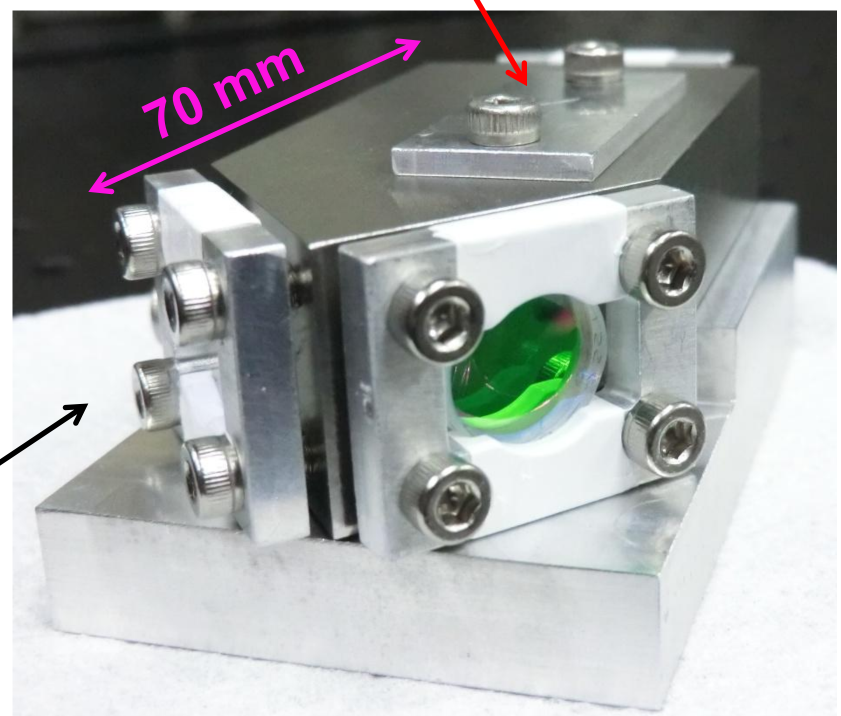
Some Photos



spacer made of
Super Invar



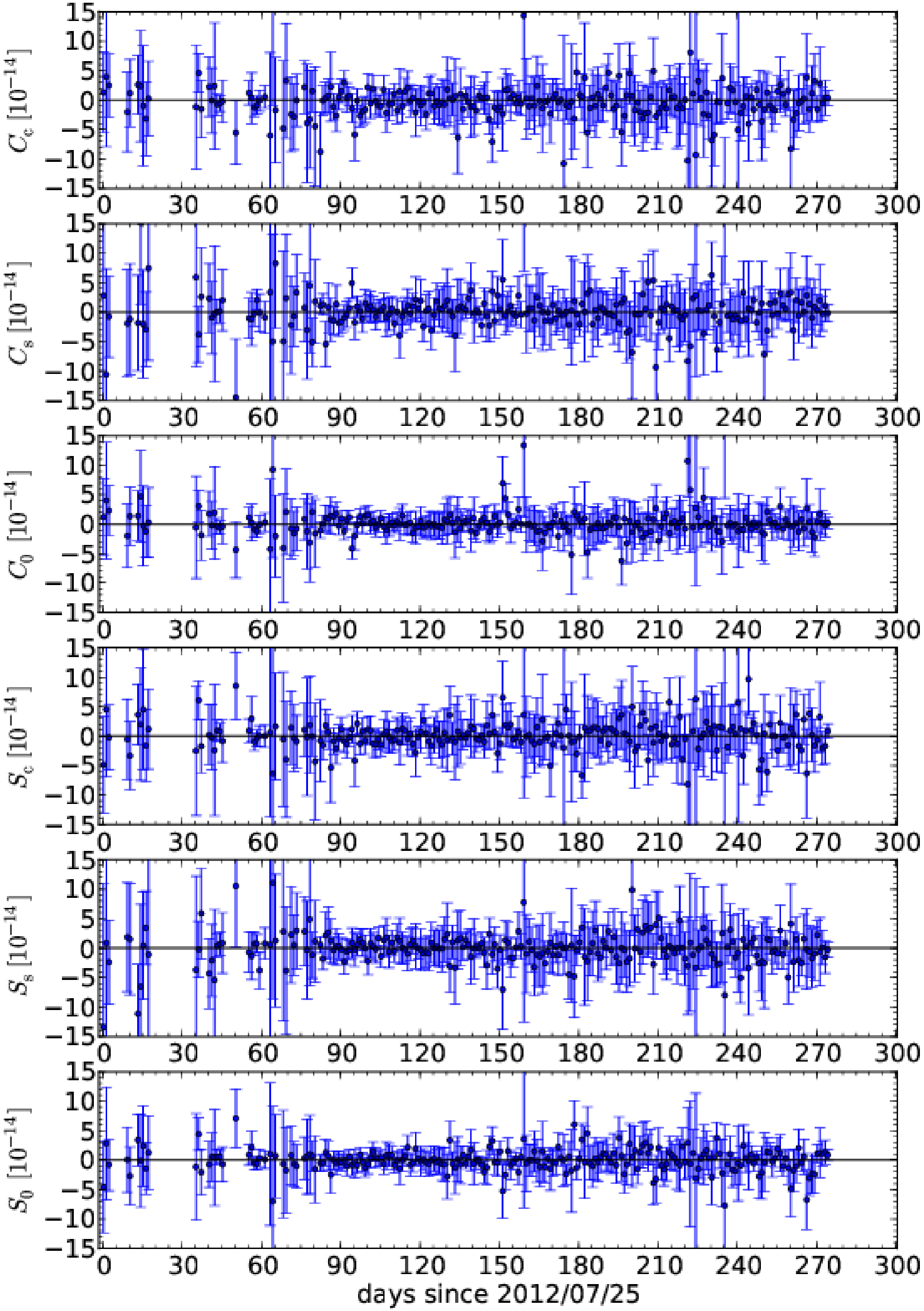
silicon inside



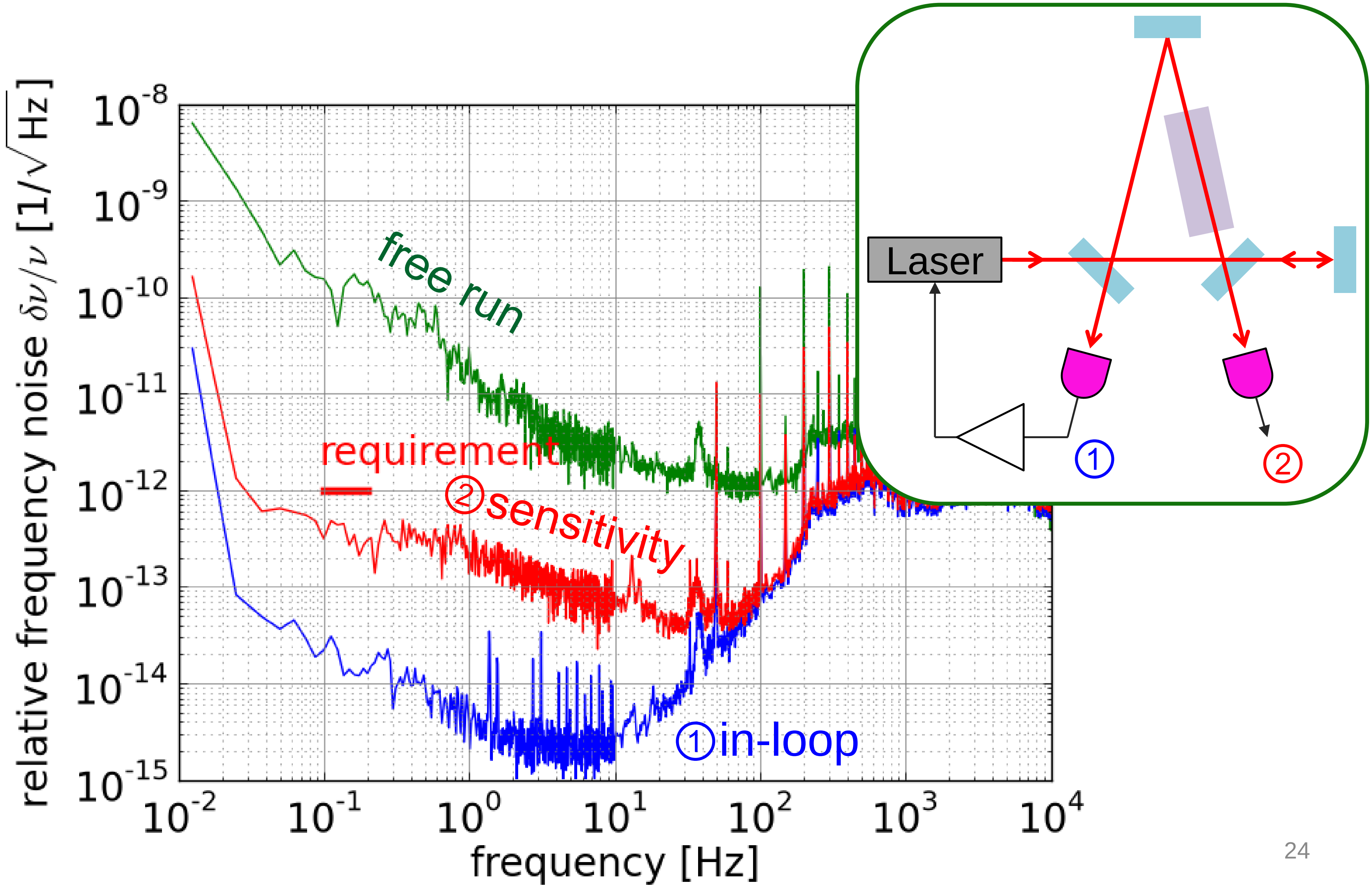
cavity mirrors

Time Series

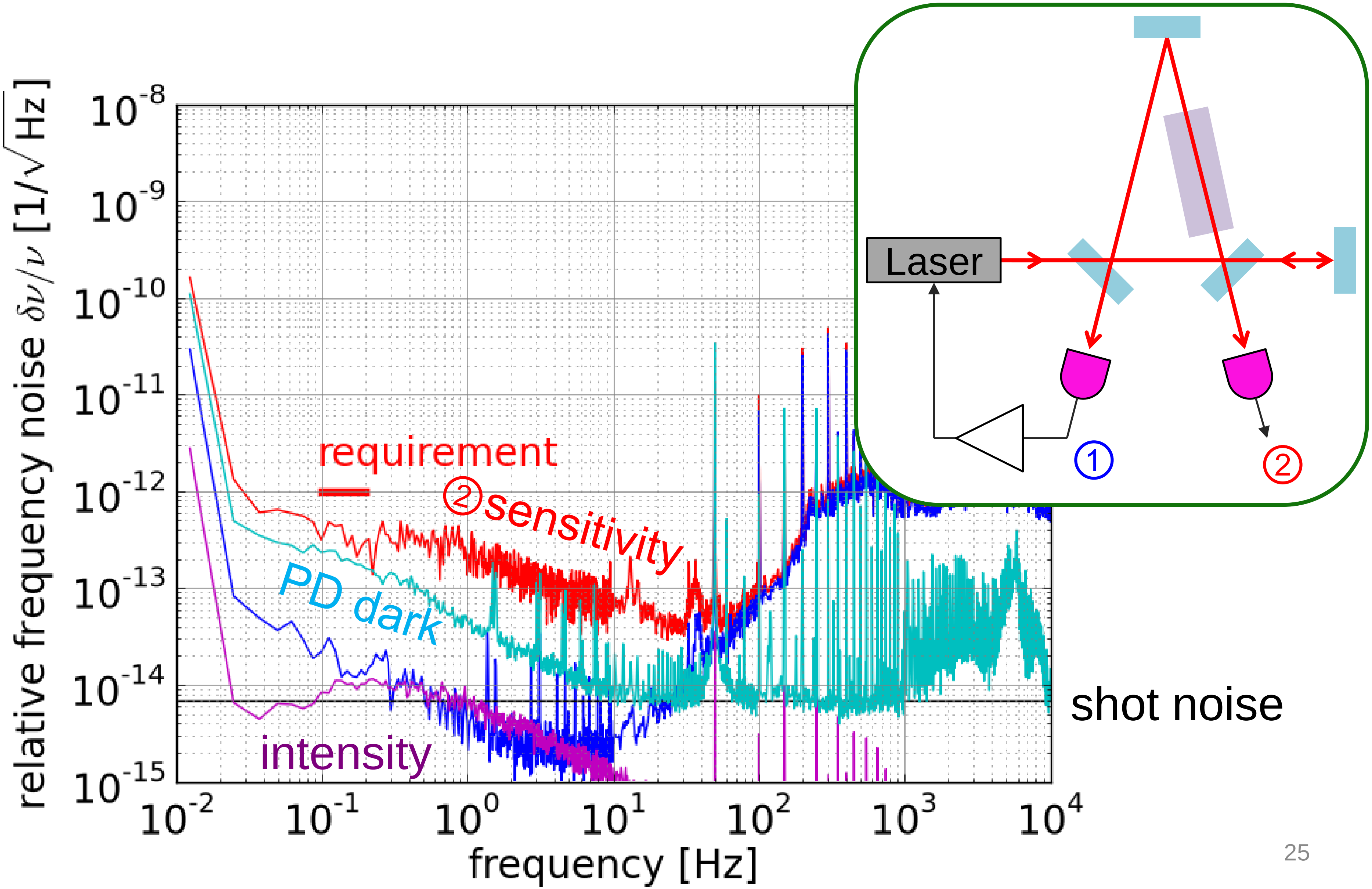
from July 25, 2012
to April 25, 2013



Sensitivity Spectrum



Noise Source



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)