Search for Anisotropy in the One-Way Speed of Light Using an Optical Ring Cavity

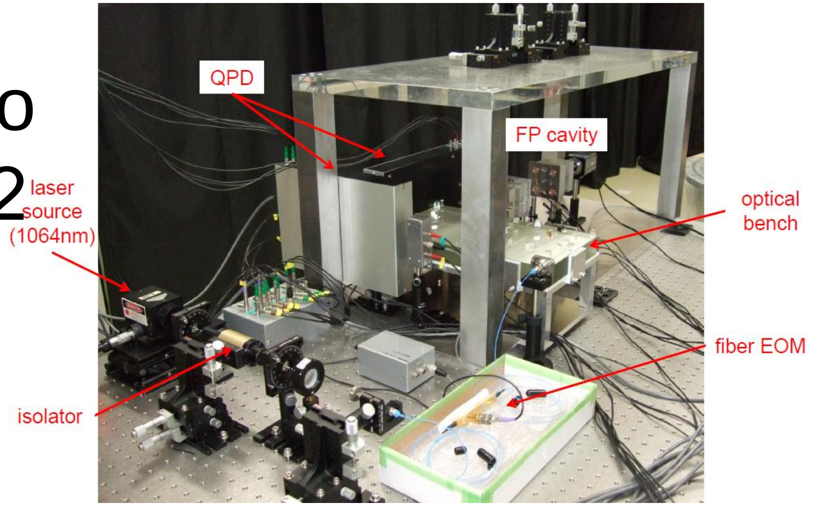
Yuta Michimura

Tsubono Group
University of Tokyo

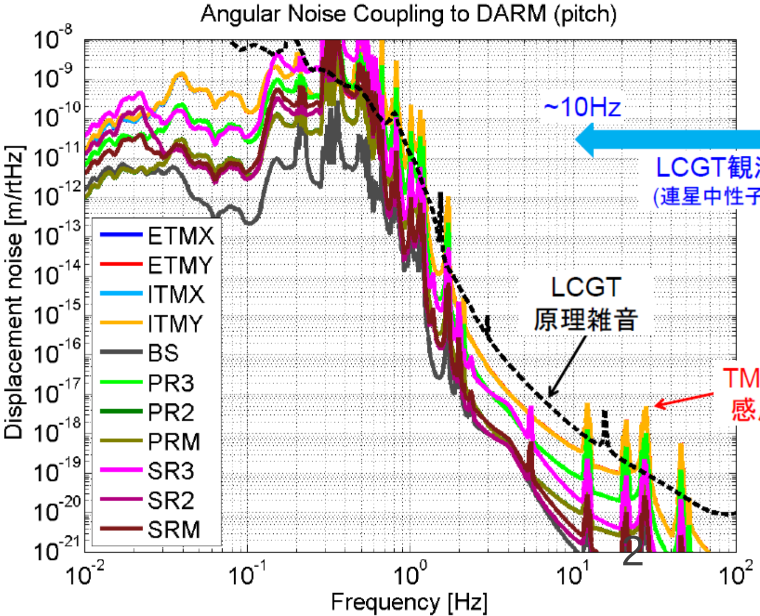
Self-introduction

- Tsubono Group,
  Dept. of Physics, U. of Tokyo
  got master's in March 2012
  starting Ph D
- what I have been doing
  - DECIGO Pathfinder
    prototype FP experiment
  - KAGRA (LCGT)
    ASC simulation
  - anisotropy search in the speed of light (master's thesis)
  - lock 40m IFO

DPF prototype FP



KAGRA ASC



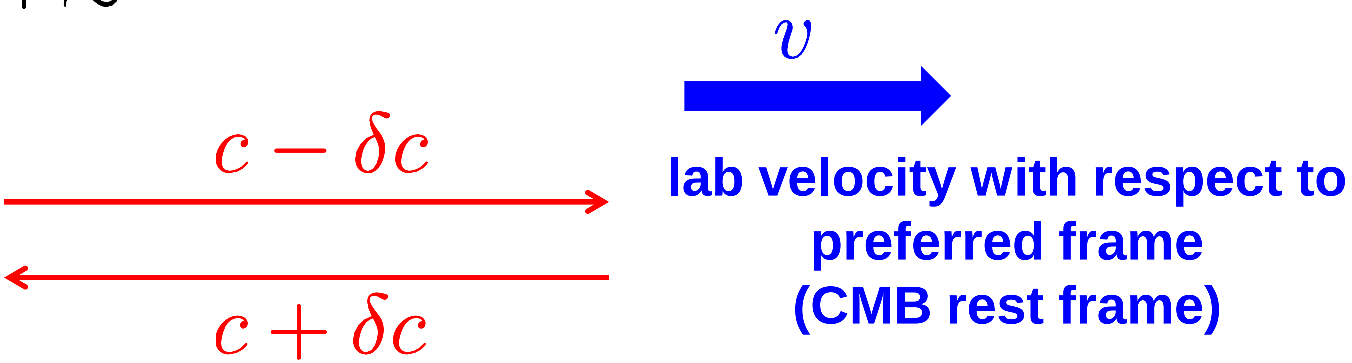
Abstract

- tested Special Relativity(Lorentz invariance in photons) by testing
  isotropy in the one-way speed of light
- new idea: use asymmetric optical ring cavity
- got the world's best limit (more than x2 better)

$$\hat{\alpha} = (-2.3 \pm 2.6) \times 10^{-10}$$

set upper limit on the anisotropy to a level of

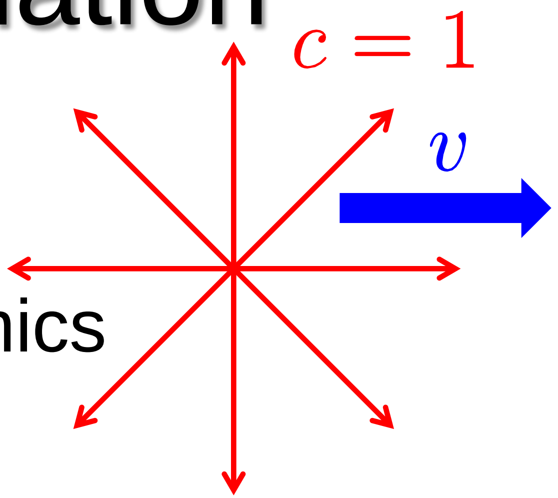
$$|\delta c / c| \lesssim 10^{-13}$$



Contents

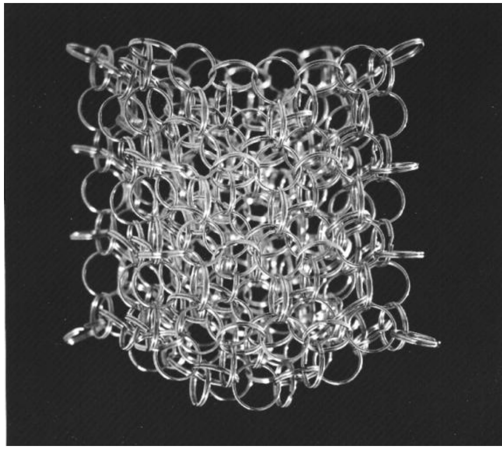
1. Background

SR and Lorentz violation

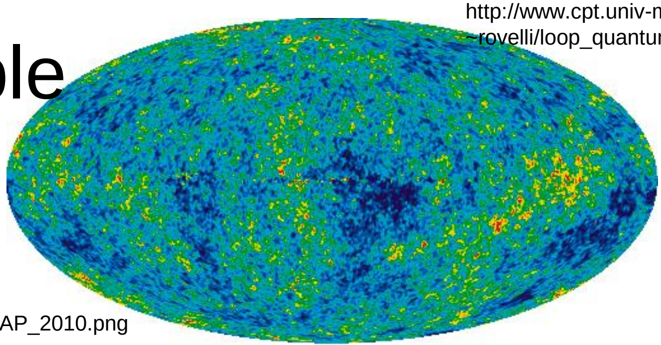


- Special Relativity (1905)
  speed of light is constant
- Lorentz invariance in electrodynamics
- no one could find any violation
- but…
  - quantum gravity theory suggests
    violation at some level
    e.g. $\delta c/c \sim 10^{-17}$
    D. Colladay and V. Alan Kostelecký:PRD 58 (1998) 116002
  -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

$\rightarrow$ we have to test SR !



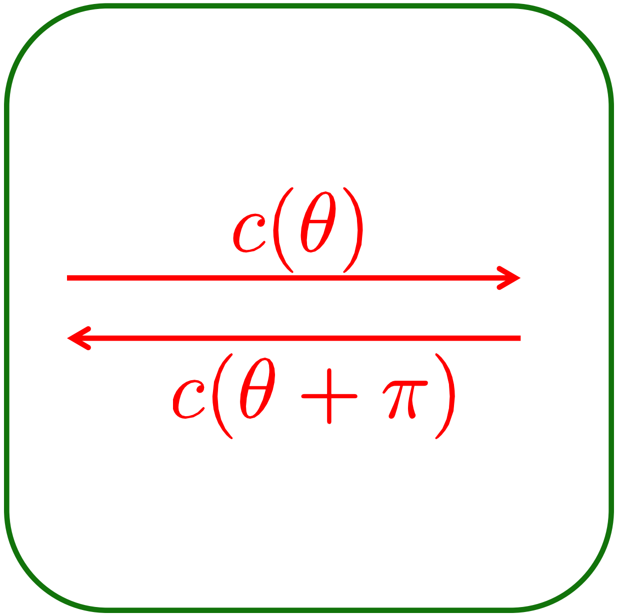
http://www.cpt.univ-mrs.fr/~rovelli/loop_quantum_gravity.jpg

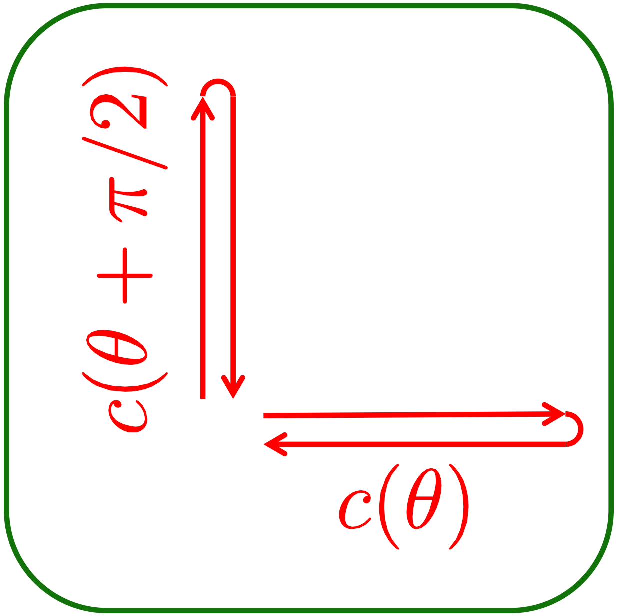


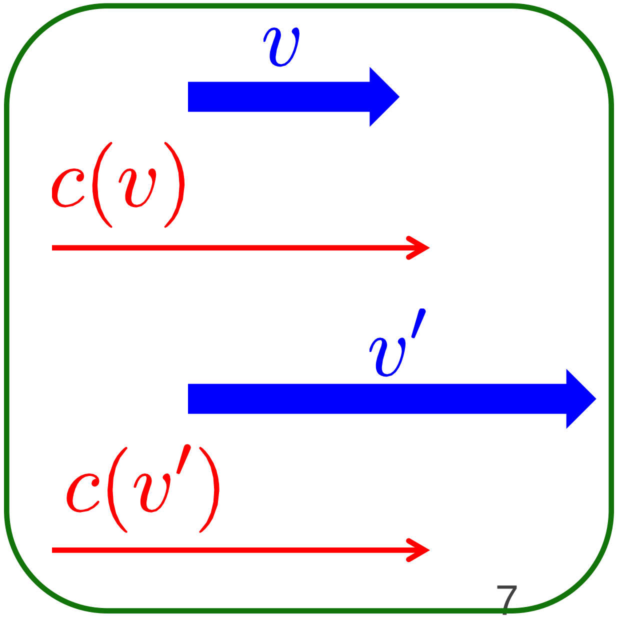
http://en.wikipedia.org/wiki/File:WMAP_2010.png

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







Test theory of SR: MS Theory

- test theory proposed by Mansouri & Sexl (1977)

R. Mansouri and R. U. Sexl: Gen. Relativ. Grav. 8 (1977) 497/515/809

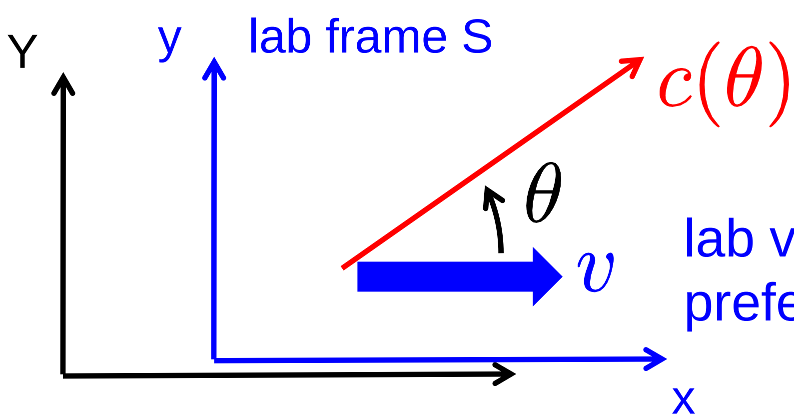
- speed of light in MS theory

$$c(\theta) = 1 - 2\hat{\alpha} v \cos\theta$$ one-way anisotropy

$$-(\hat{\beta} - \hat{\delta}) v^2 \sin^2\theta$$ two-way anisotropy

$$-(\hat{\alpha} - \hat{\beta}) v^2$$ independence of c from v

preferred frame Σ



lab velocity with respect to preferred frame (CMB rest frame)

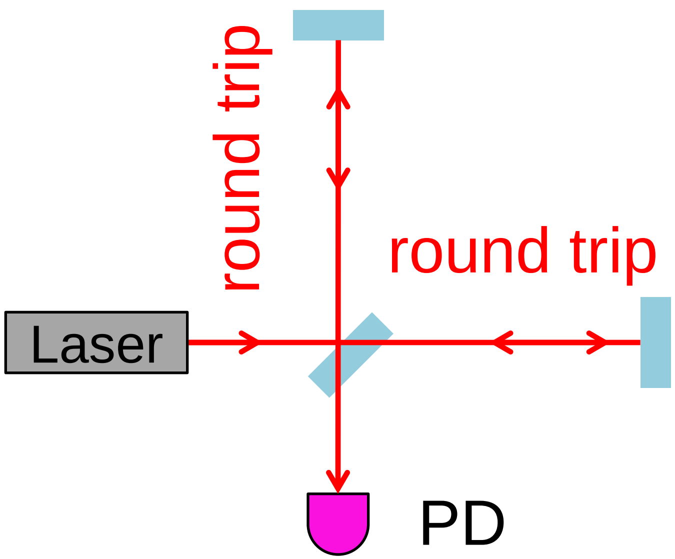
Previous Test for Two-Way c

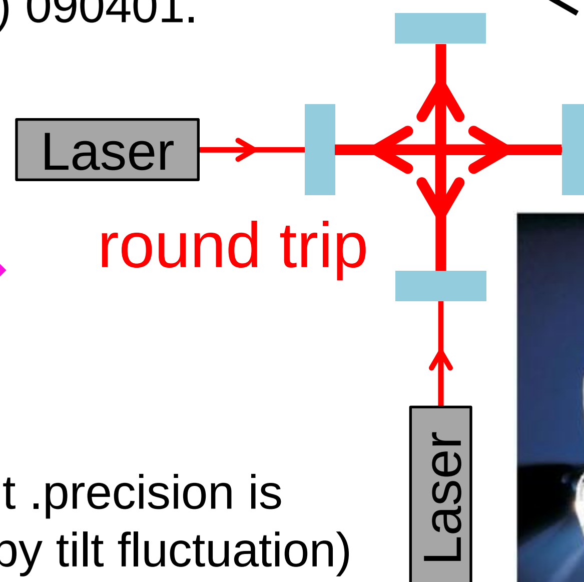
- Michelson-Morley experiment (1887)
  Michelson interferometer
- compare the resonant freqs of crossed FP in a single block(2009)

$$\hat{\beta} - \hat{\delta} = (-1.6 \pm 6 \pm 1.2) \times 10^{-12}$$

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

$$|\delta c / c| \lesssim 10^{-17}$$





(Current .precision is limited by tilt fluctuation)

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

Previous Test for One-Way c

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

$$\hat{\alpha} = (-4.8 \pm 8.4) \times 10^{-8}$$

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

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

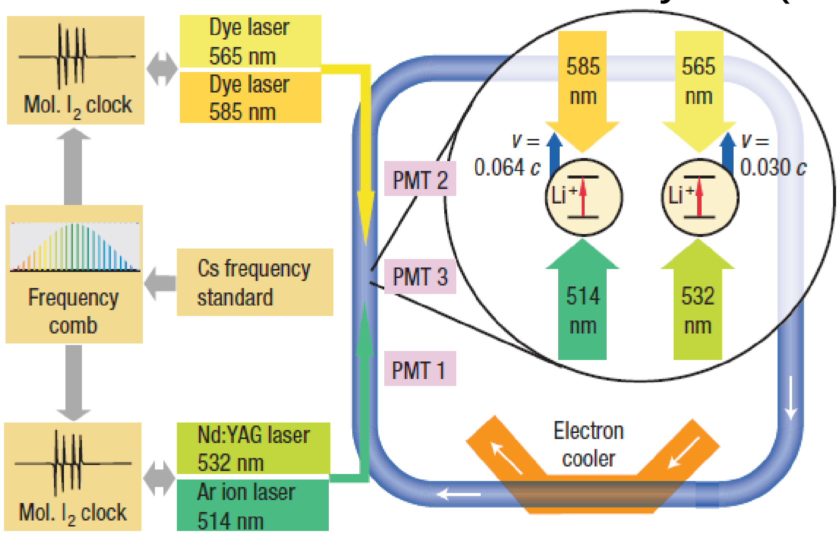
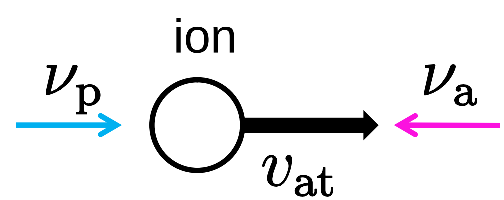


Figure 1 Schematic diagram of the TSR. Li^+ ions circulate in the 55-m-circumference ring. In the electron cooler, cold electrons are overlapped with the ions and provide cooling. The measurements at the two different velocities are carried out sequentially. In the experiment, the two lasers are coupled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



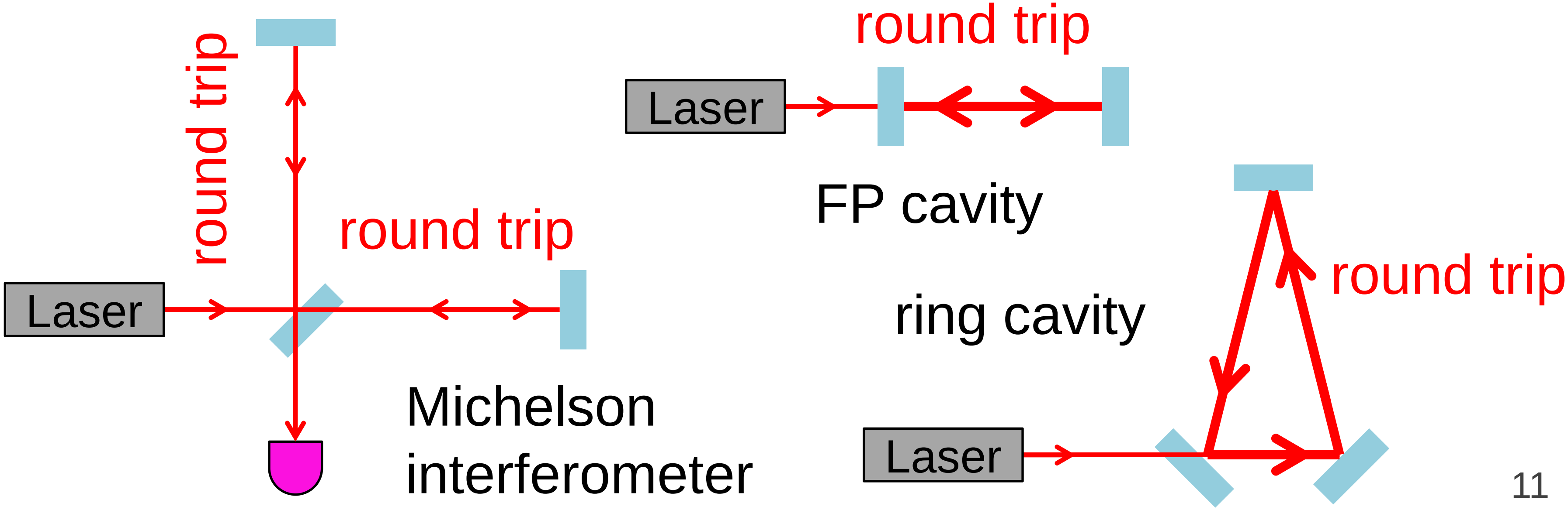
have to measure the absolute value of the resonant frequency

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

$$c(\theta) = 1 - 2\hat{\alpha}v\boxed{\cos\theta} + \mathcal{O}(v^2)$$

$\rightarrow$ how can we deal with it?

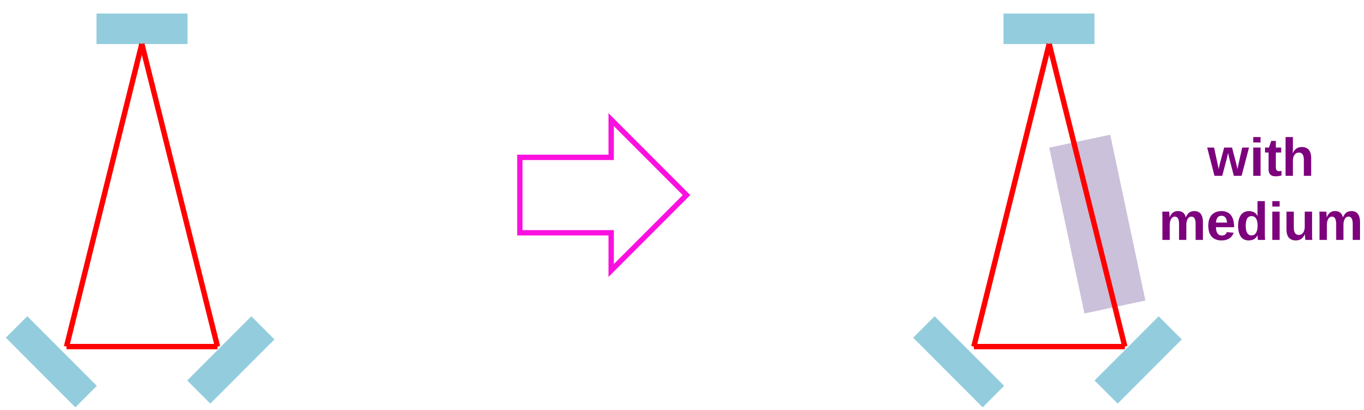


2. Experimental Principle

Asymmetric Ring Cavity

- putting a medium in the optical path makes an asymmetry
  → ring cavity will be sensitive to the one-way anisotropy
- asymmetric Sagnac experiment was first done by Trimmer+ (1973) W. S. N. Trimmer+: PRD 8 (1973) 3321
- cavity type proposed by Exirifard (2010)

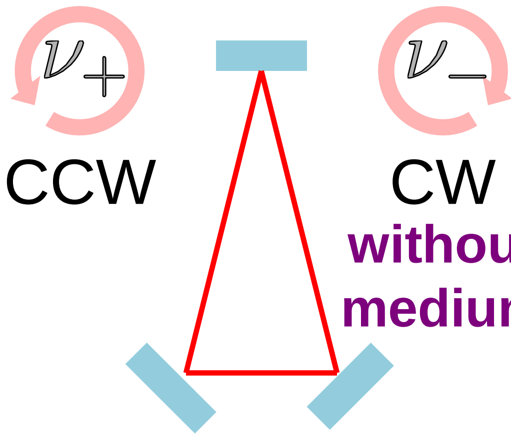
Q. Exirifard: arXiv:1010.2057.

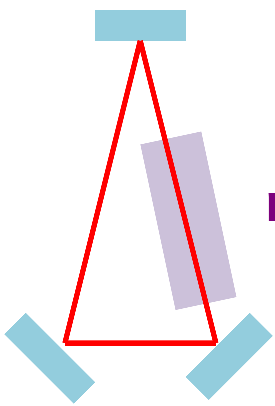


Resonant Frequencies

- one-way term remains because of asymmetry

$$c(\theta) = 1 - 2\hat{\alpha} v \boxed{\cos\theta} + \mathcal{O}(v^2)$$





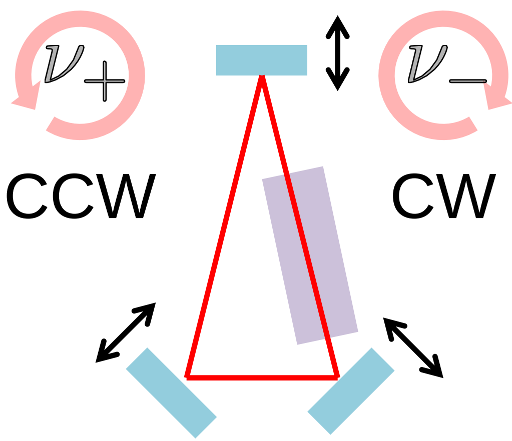
	without medium	with medium
no anisotropy	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu$ $\nu_- = \nu$
anisotropy	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu - \delta\nu$ $\nu_- = \nu + \delta\nu$

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

Counter Propagating Modes

- comparing resonant frequencies of counter propagating modes
  $\rightarrow$ high CMRR to cavity length change
  no need for high vacuum
  seismic isolation
  temperature control (or cryogenic)
- first experiment done by Baynes+ (Oct 2011)

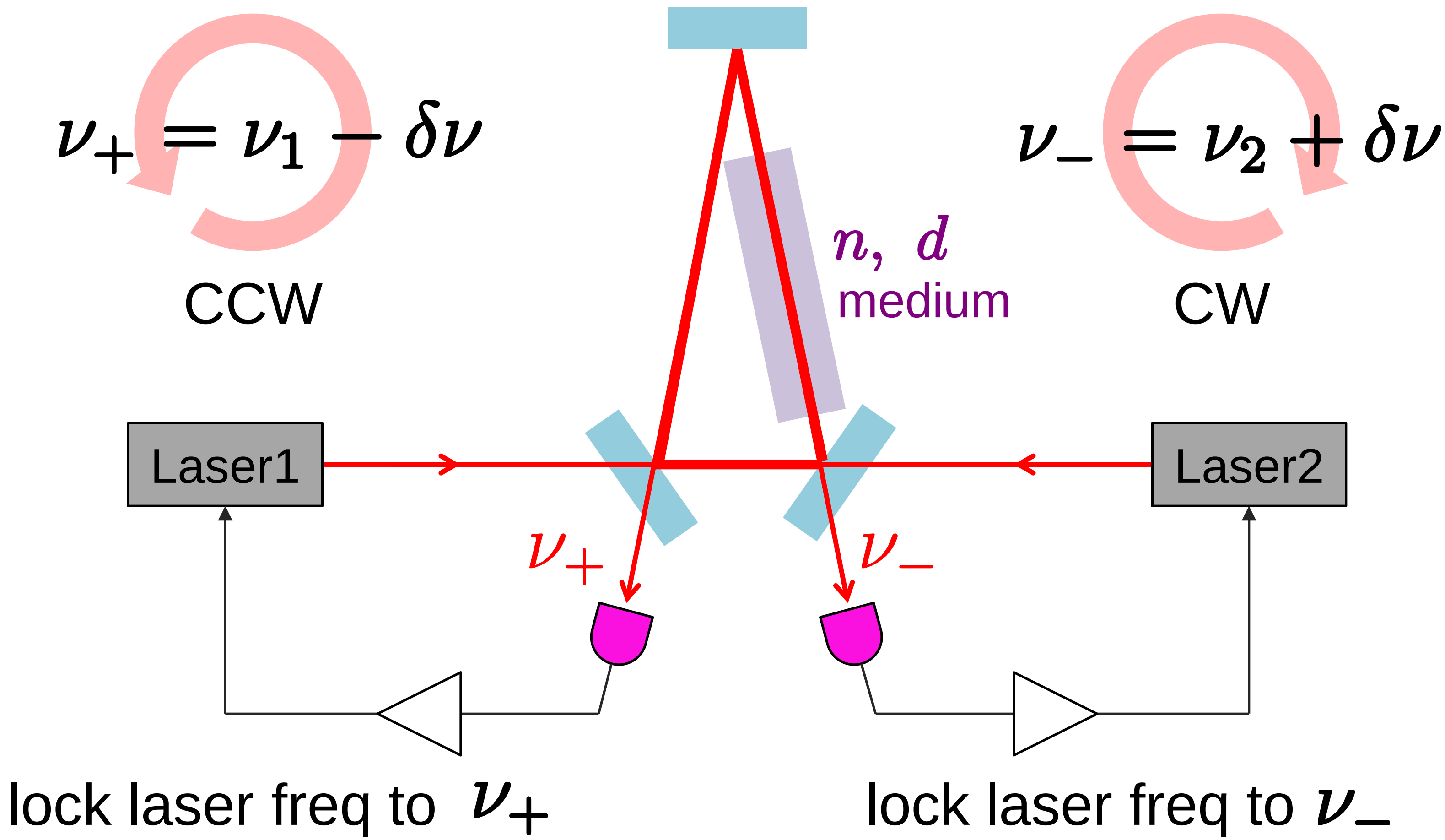
F. Baynes+: PRD 84 (Oct 2011) 0811021.



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

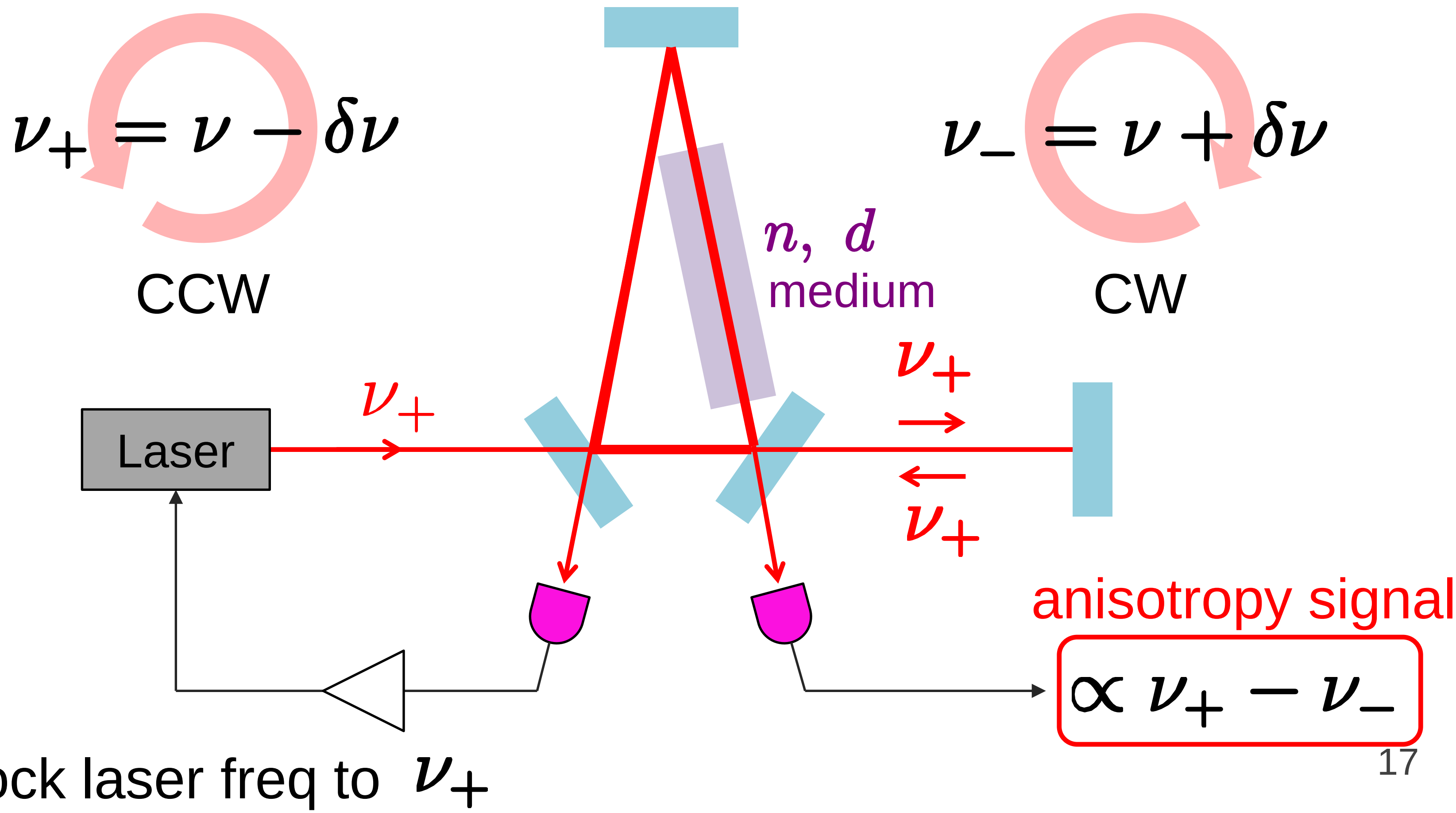
Optical Setup of Baynes+(2011)

- lock freqs of two lasers to $\nu_+, \ \nu_-$
- have to shift two laser freqs to avoid the lock-in problem (not a null experiment)



Our New Idea: Double-Pass

- double-pass makes null measurement
- only one beam; no need to care about lock-in



Anisotropy Signal

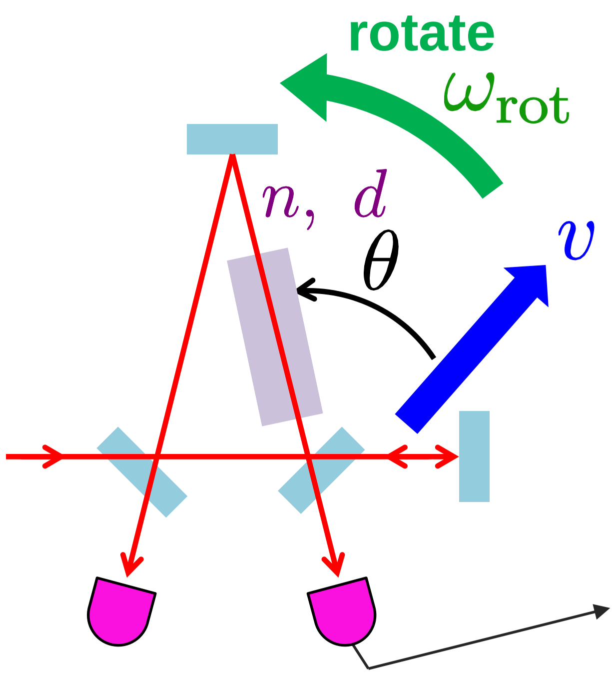
- $\delta\nu \equiv \nu_+ - \nu_-$

lab speed with respect to CMB
$v \simeq 10^{-3}$

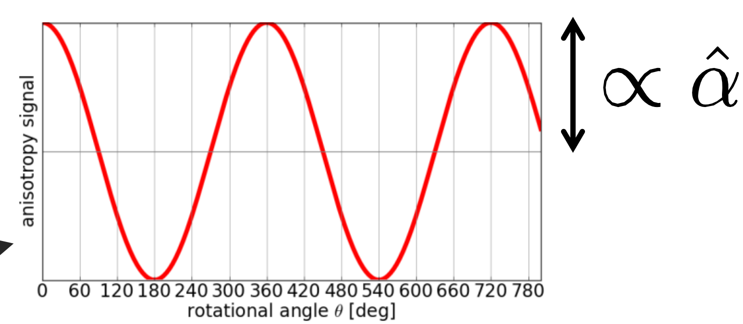
$$\frac{\delta\nu}{\nu} = -\frac{4(n-1)d}{L+(n-1)d}\boxed{\hat{\alpha}}\,v\cos\theta$$

round trip length

rotate cavity to modulate

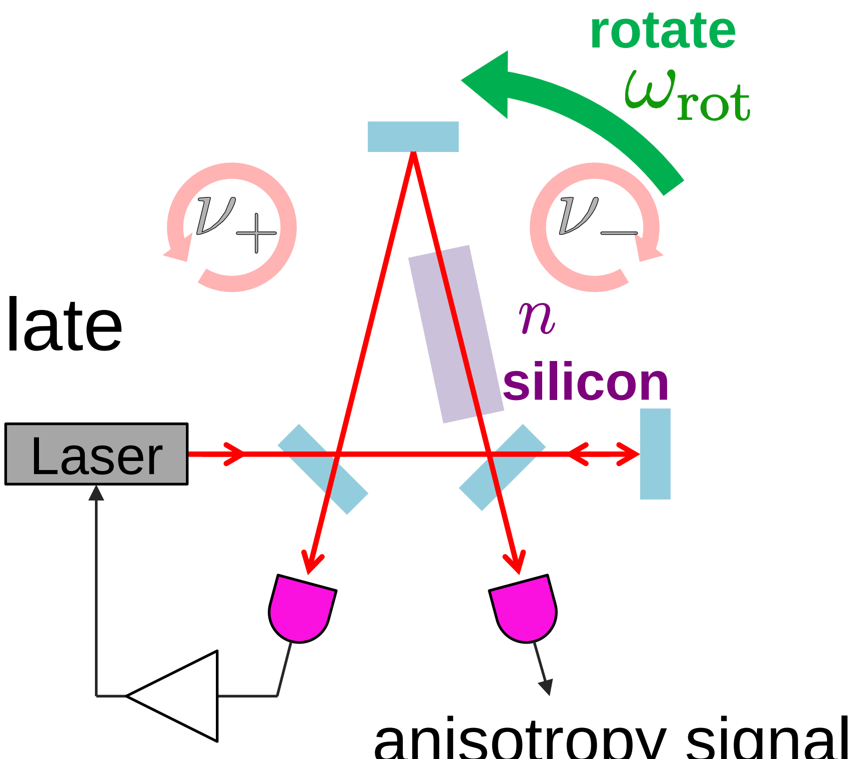


putting a medium is essential
larger n, bigger signal
$\longrightarrow$ let’s use silicon with 1550nm (n=3.69)



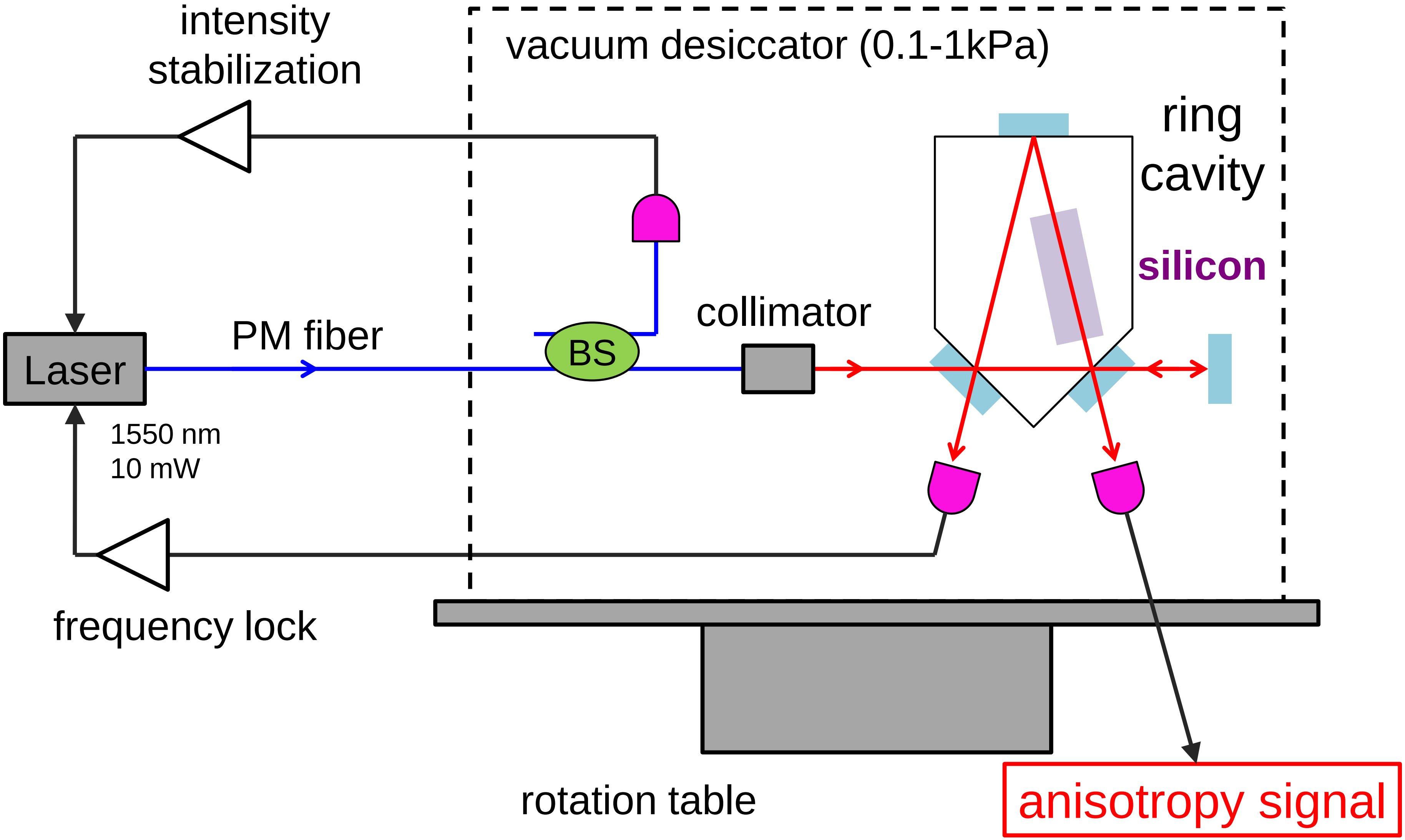
Summary (first half)

- measure anisotropy in one-way speed of light using a ring caviy
  - silicon inside
  - compare counter-propagating resonant freqs
    high CMMR
  - double pass
    null measurement
- rotate the cavity to modulate anisotropy signal

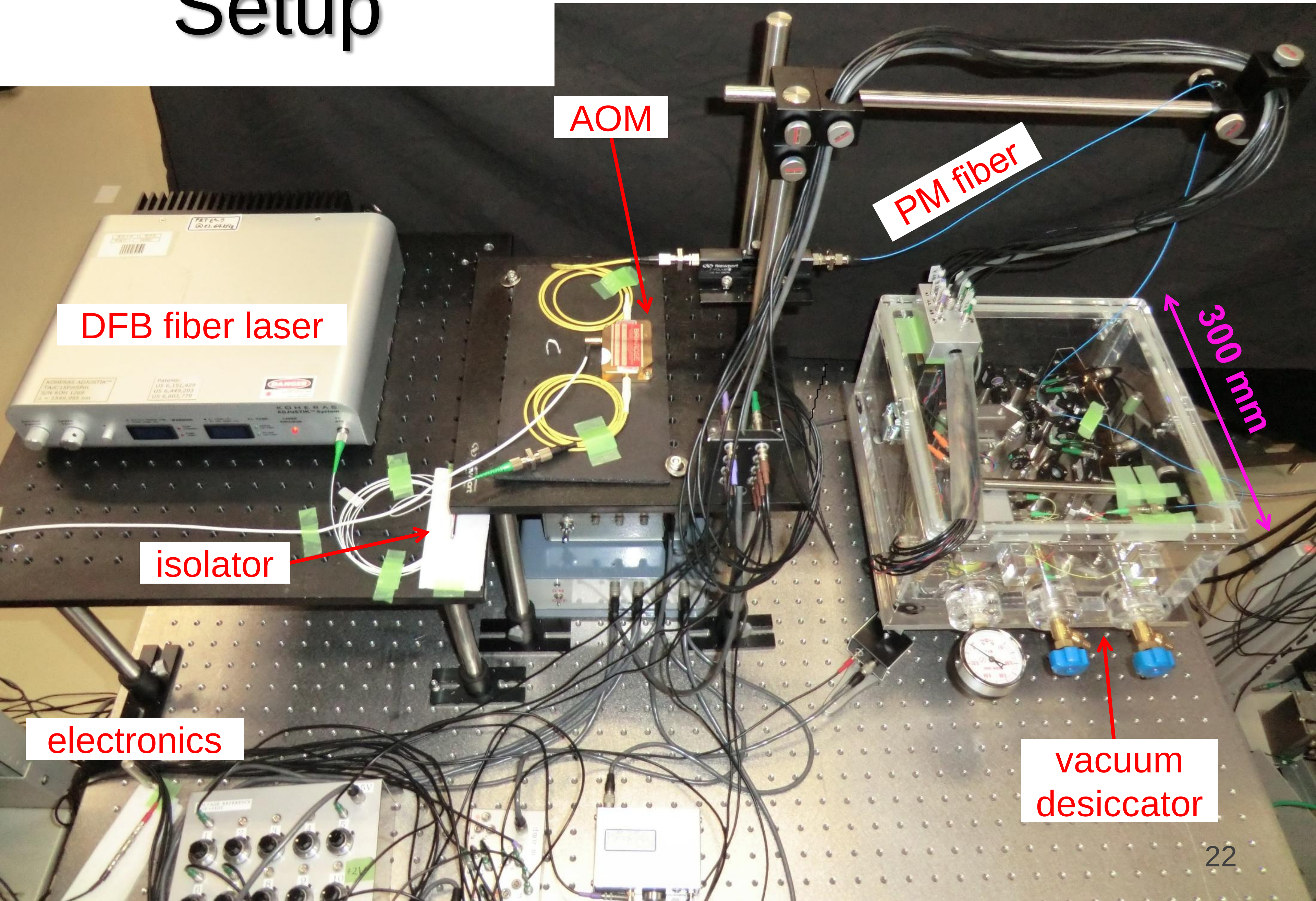


3. Experimental Setup

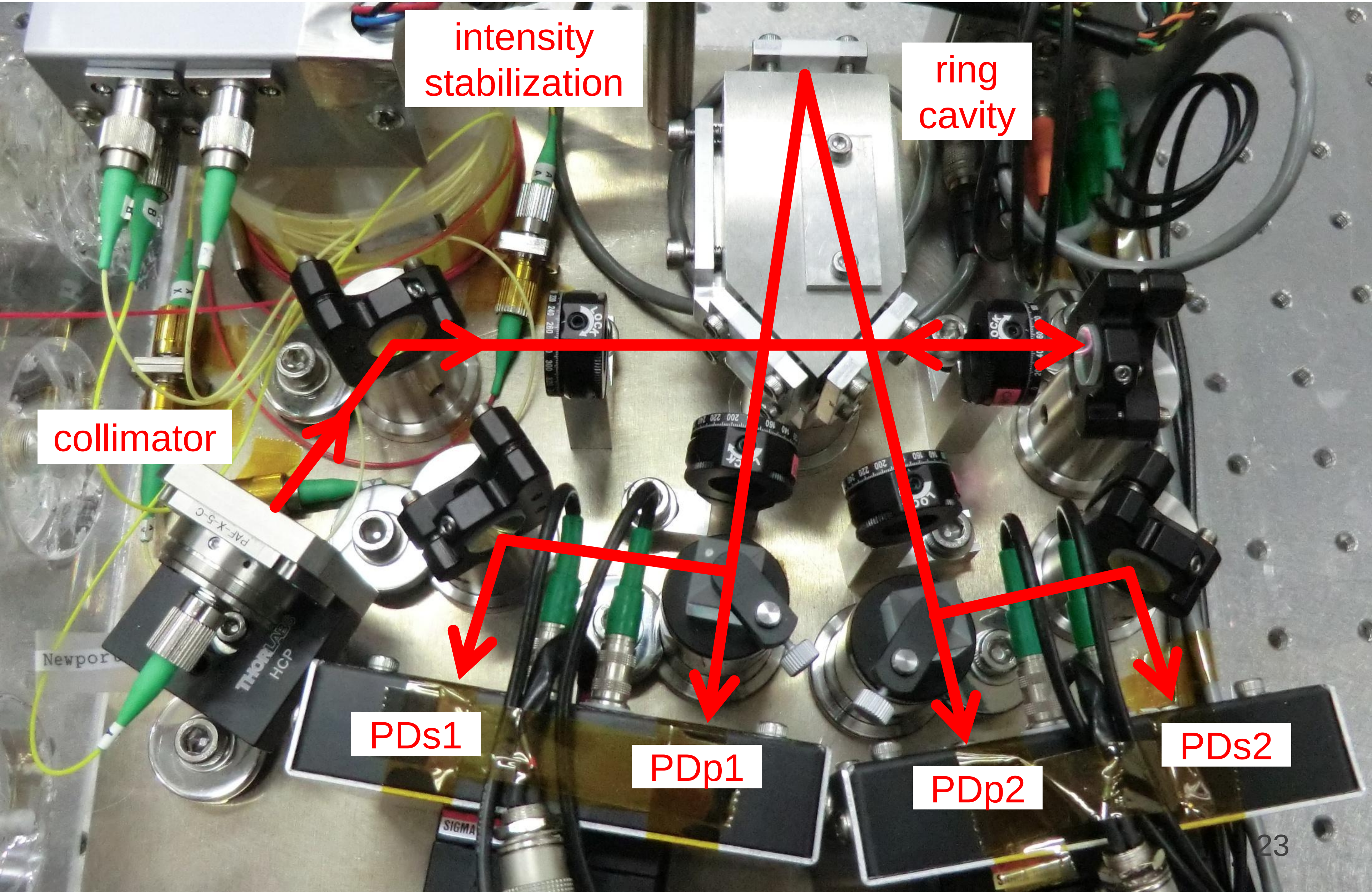
Whole Setup


intensity
stabilization
vacuum desiccator (0.1-1kPa)
ring
cavity
silicon
PM fiber
BS
collimator
Laser
1550 nm
10 mW
frequency lock
rotation table
anisotropy signal

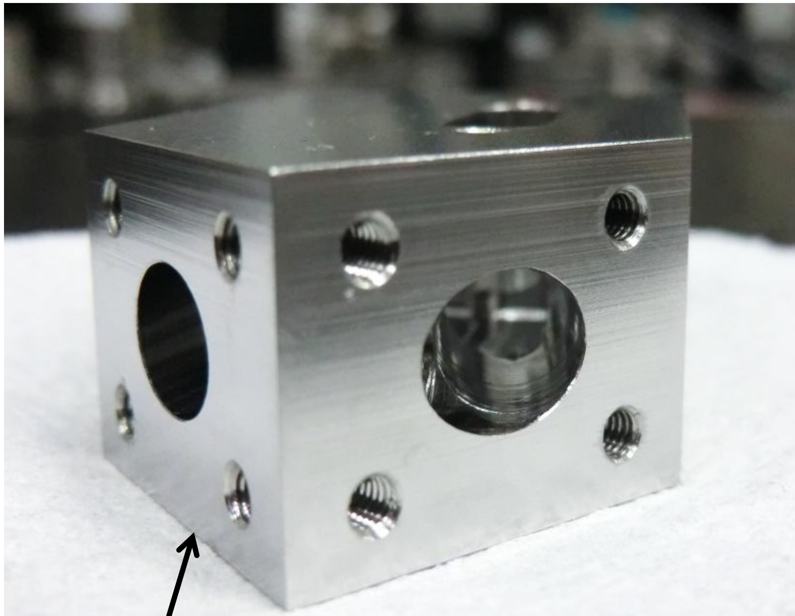
Setup


AOM
PM fiber
DFB fiber laser
300 mm
isolator
electronics
vacuum desiccator

Optics Inside Desiccator

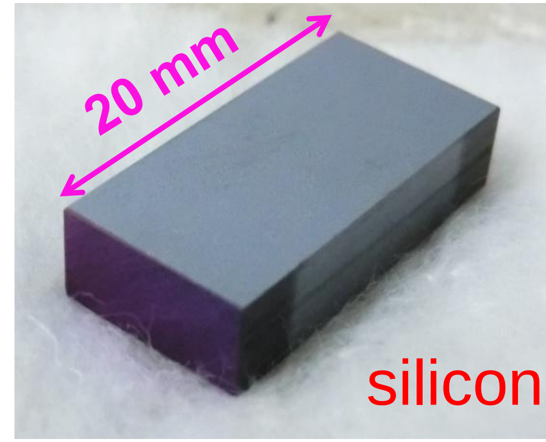


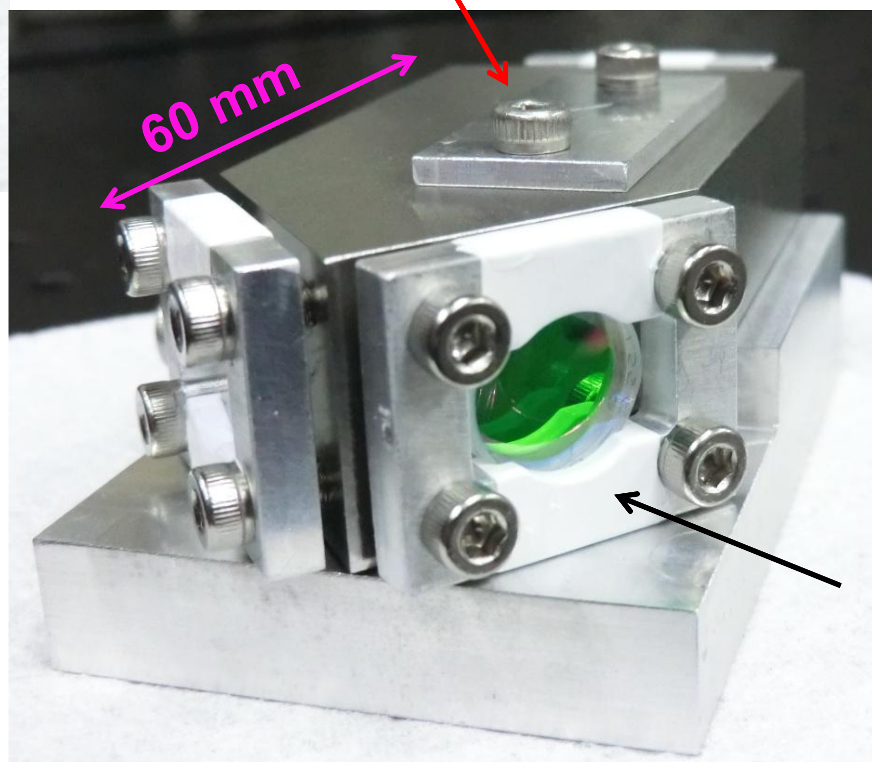
Ring Cavity



spacer made of Super Invar

silicon inside





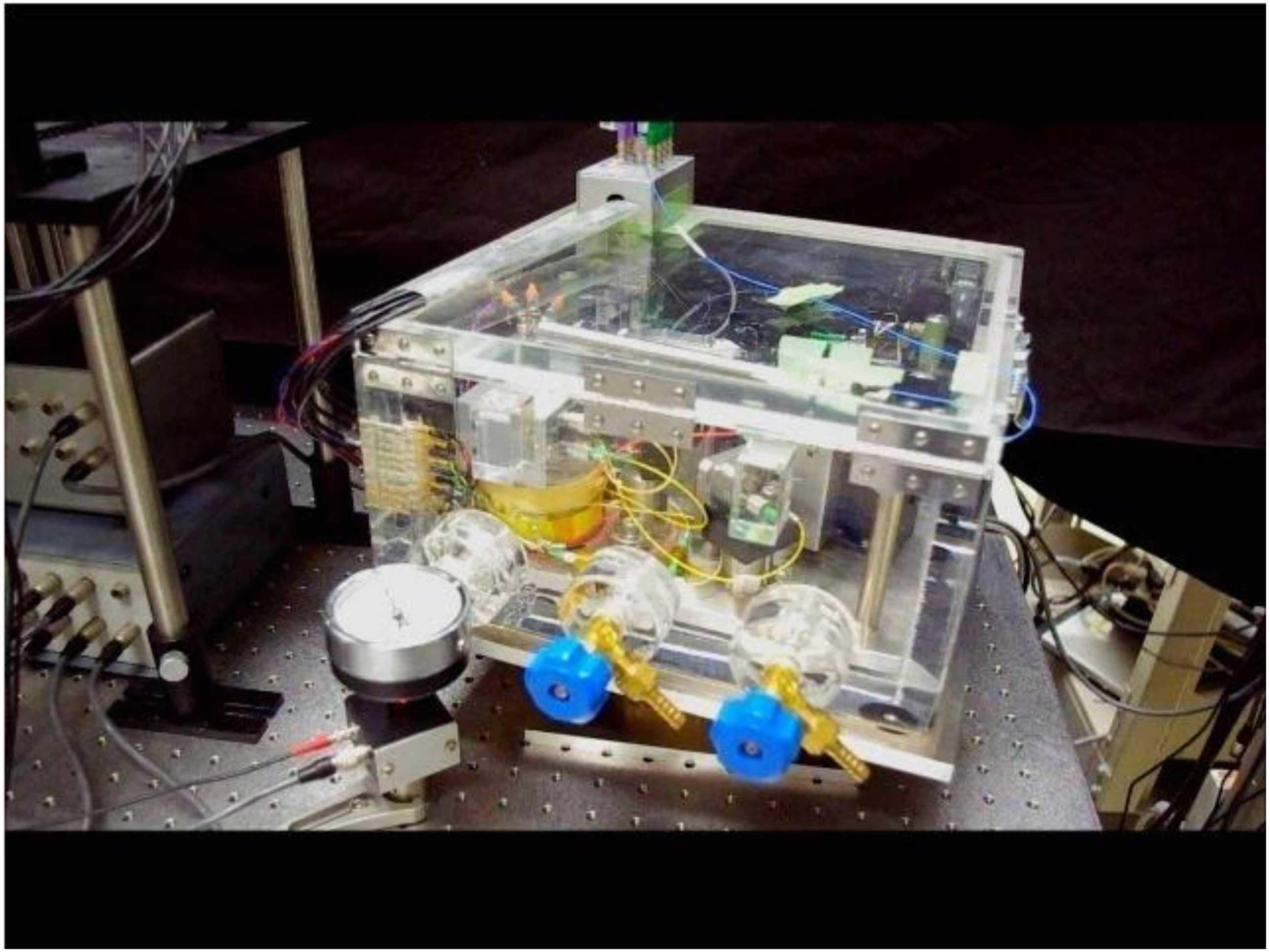
mirrors

ring cavity spec

- incident power: ～1 mW
- finesse: ～125
- round-trip length: 140 mm
- silicon length: 20 mm
- end mirror RoC: 200 mm

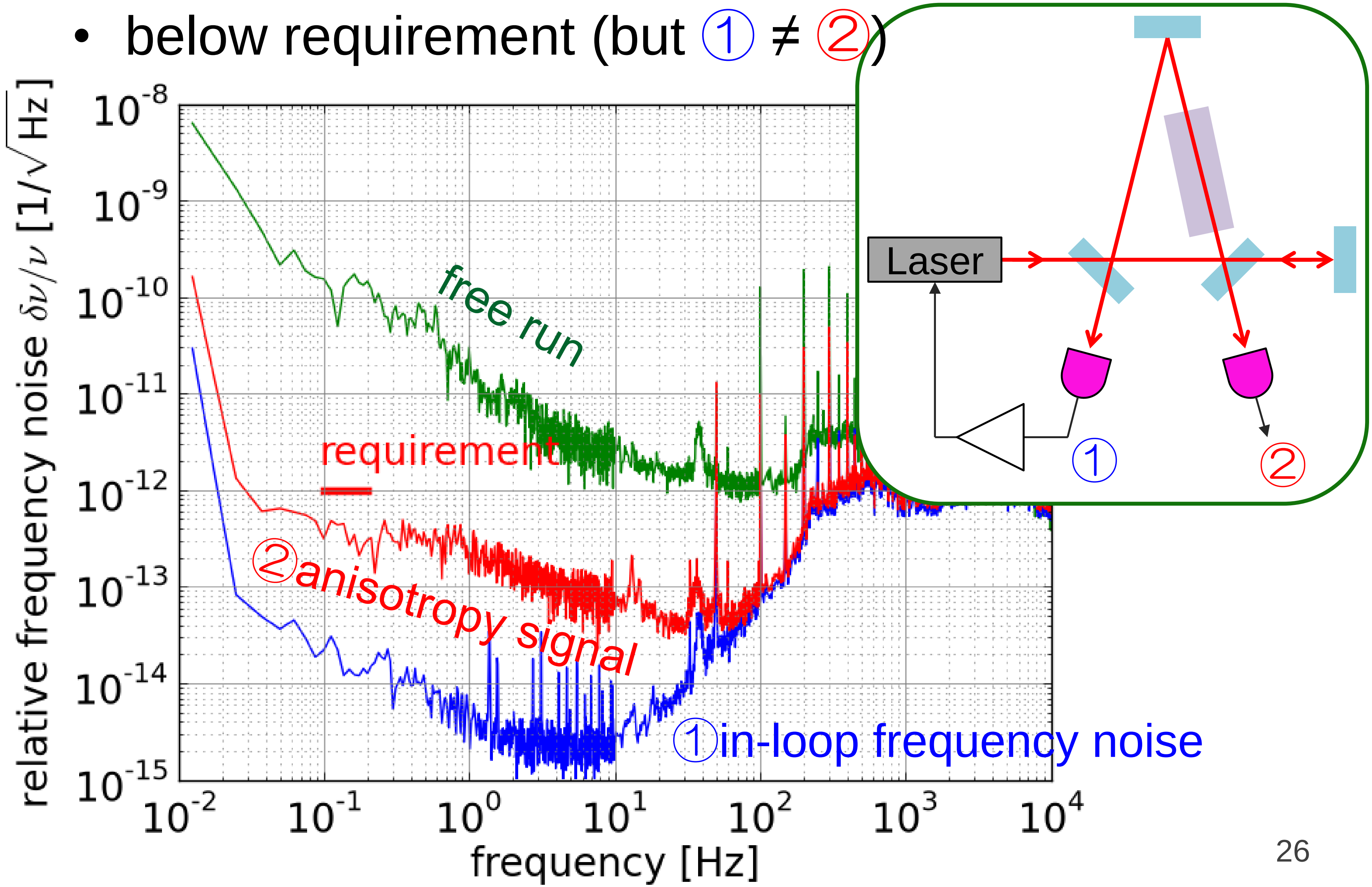
It’s Rotating

- movie



Sensitivity

- below requirement (but ① ≠ ②)

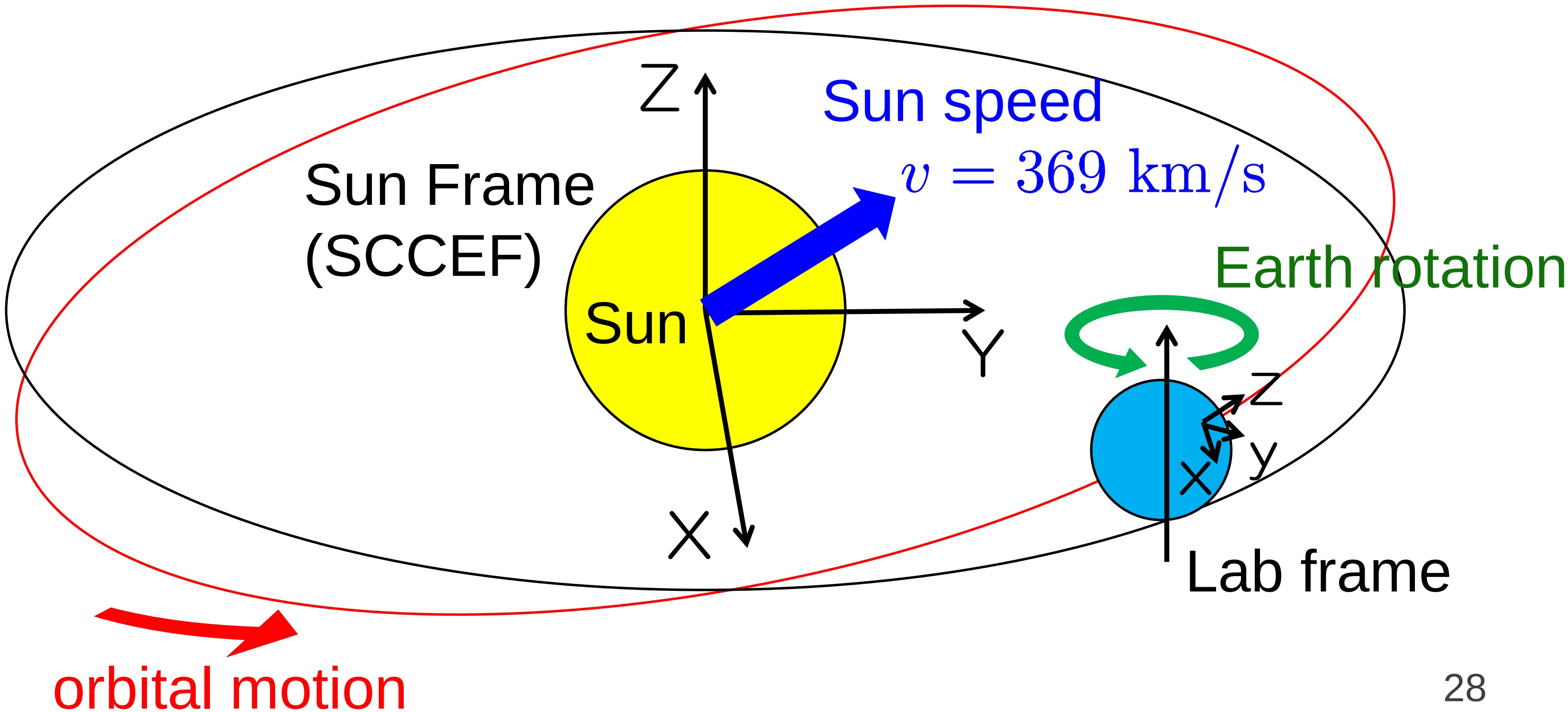


4. Data Analysis

Data Analysis Flow

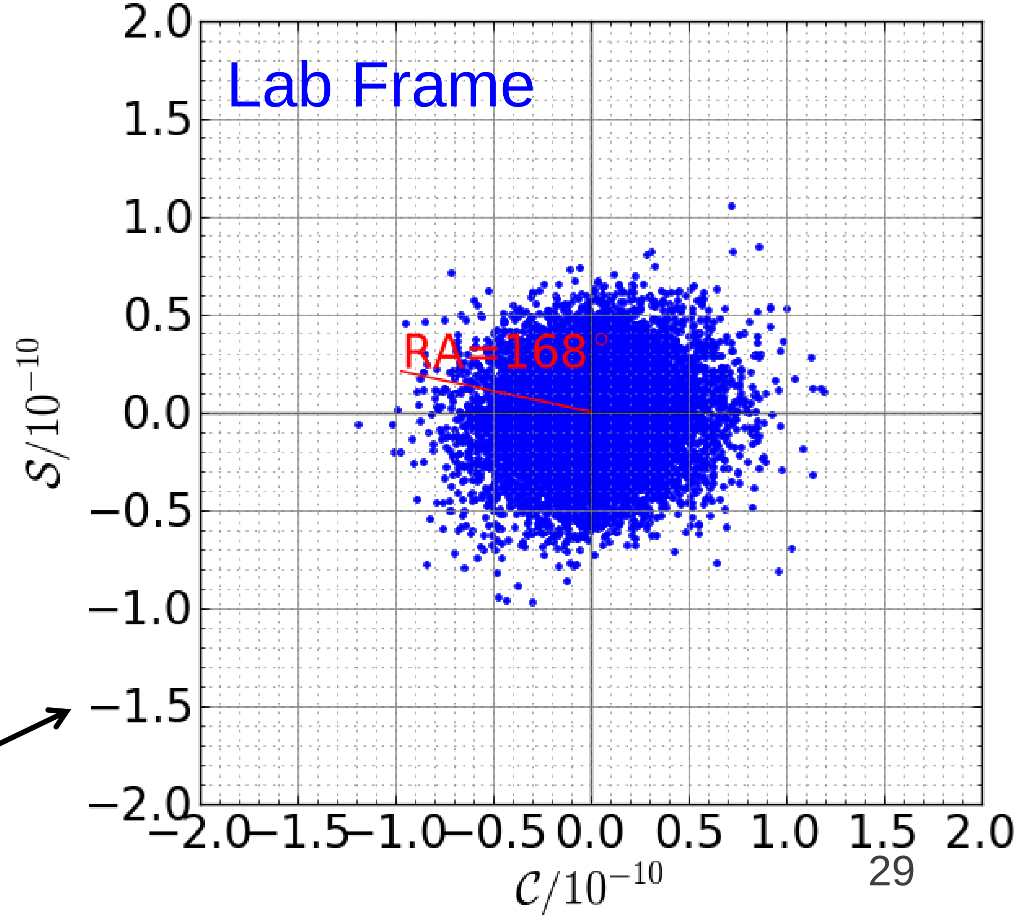
- FFT the signal in rotation frequency (0.125 Hz)
- eliminate the effect of Earth rotation

  (convert Fourier amplitudes from Lab to Sun Frame)
- derive $\hat{\alpha}$ for each cavity rotation



Result of the Analysis

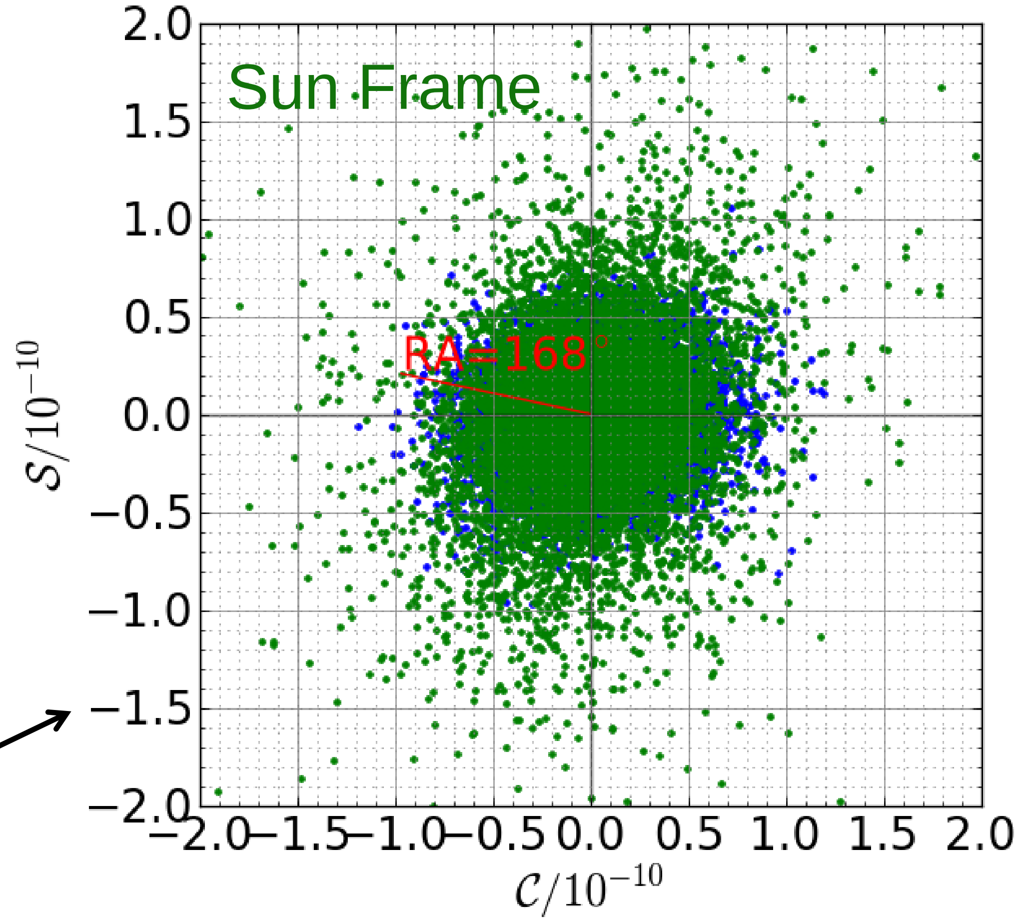
- ~26,000 rotation for 2 weeks in Nov 2011
- used quiet ~10,000 rotation for data analysis



10,000 Fourier complex amplitudes in Lab Frame

Result of the Analysis

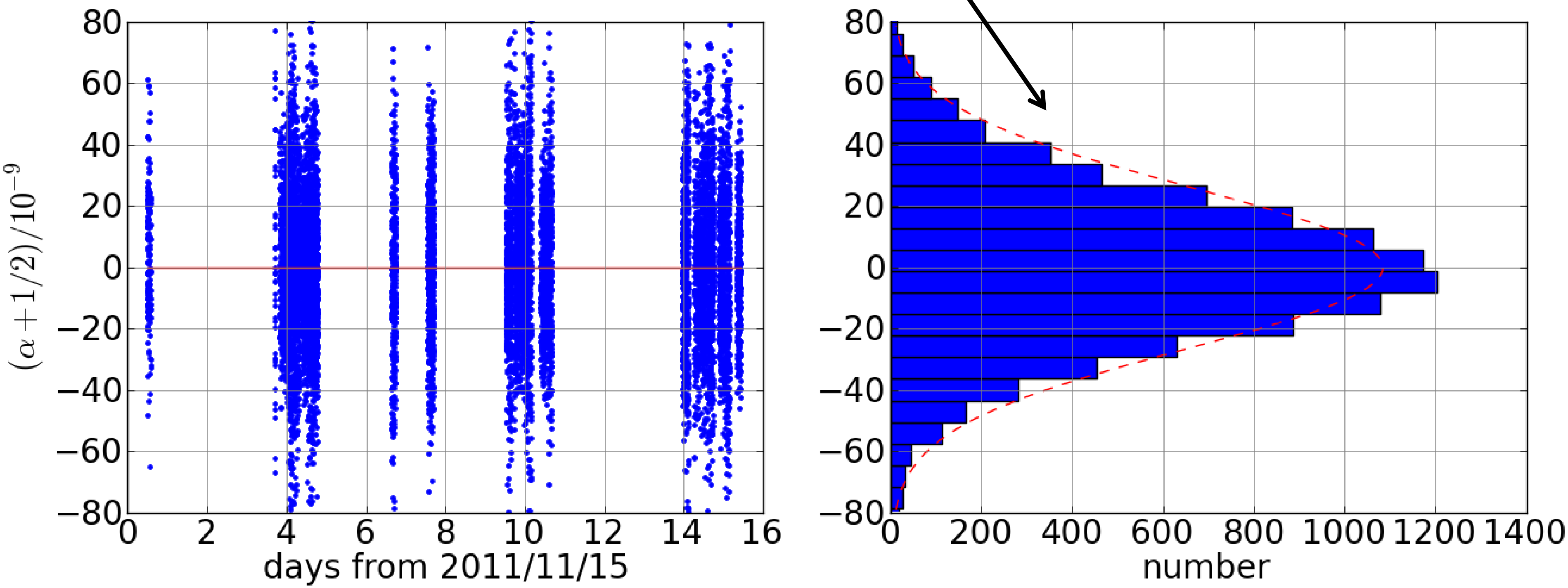
- ~26,000 rotation for 2 weeks in Nov 2011
- used quiet ~10,000 rotation for data analysis



10,000 Fourier complex amplitudes in Sun Frame

Upper Limit on the Anisotropy

- histogram of $\hat{\alpha}$ from our data



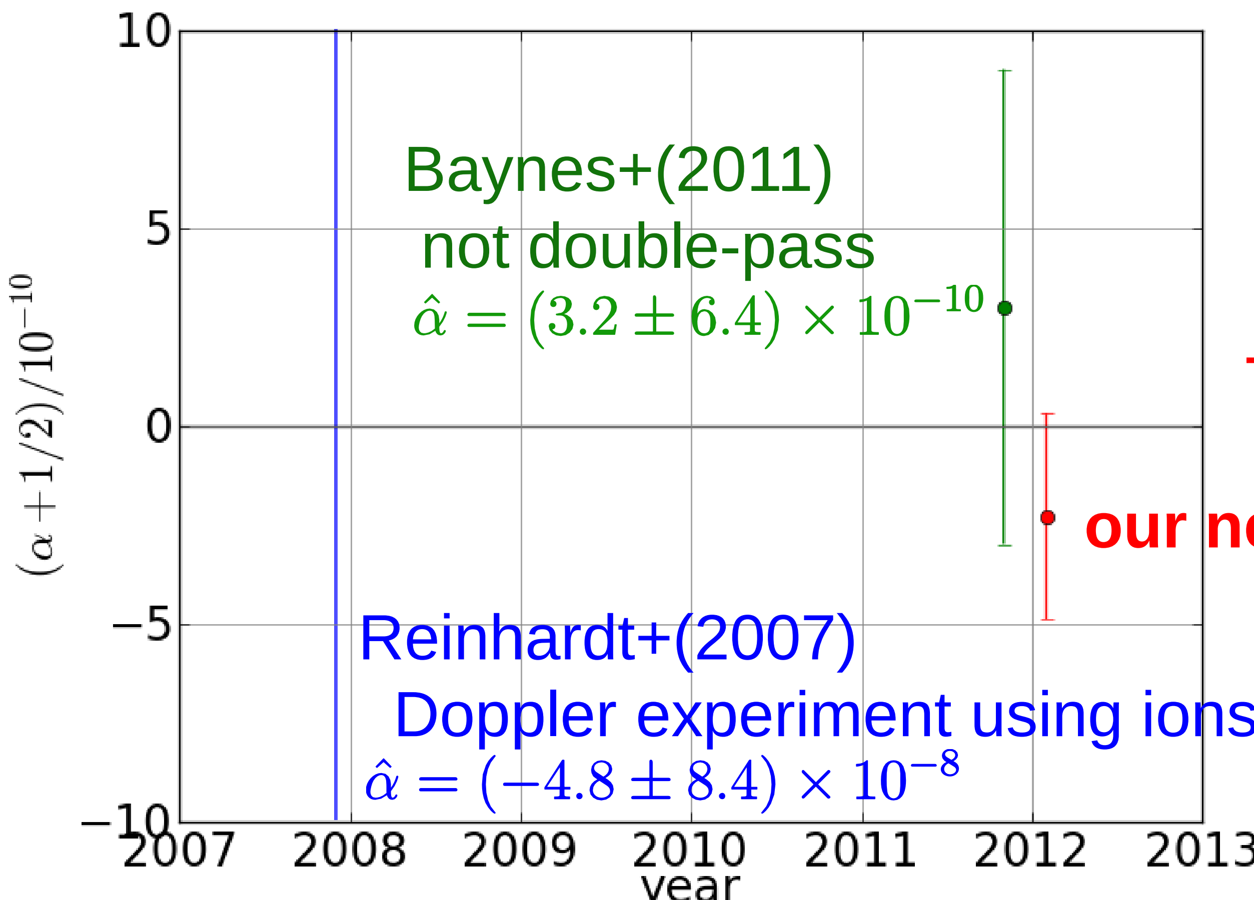
$$\rightarrow \boxed{\hat{\alpha} = (-2.3 \pm 2.6) \times 10^{-10}}$$

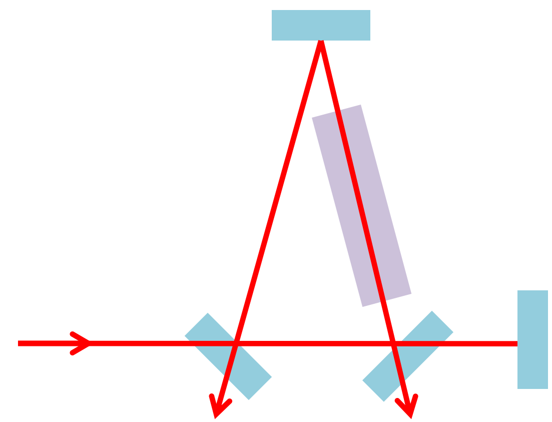
statistical error (1σ)

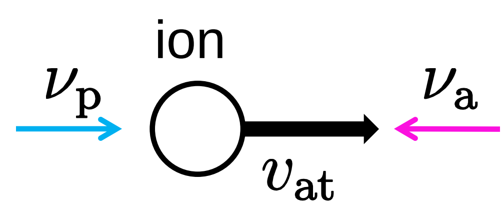
Comparison with Previous Exp.

- more than factor of 2 better

$$\hat{\alpha} = (-2.3 \pm 2.6) \times 10^{-10}$$



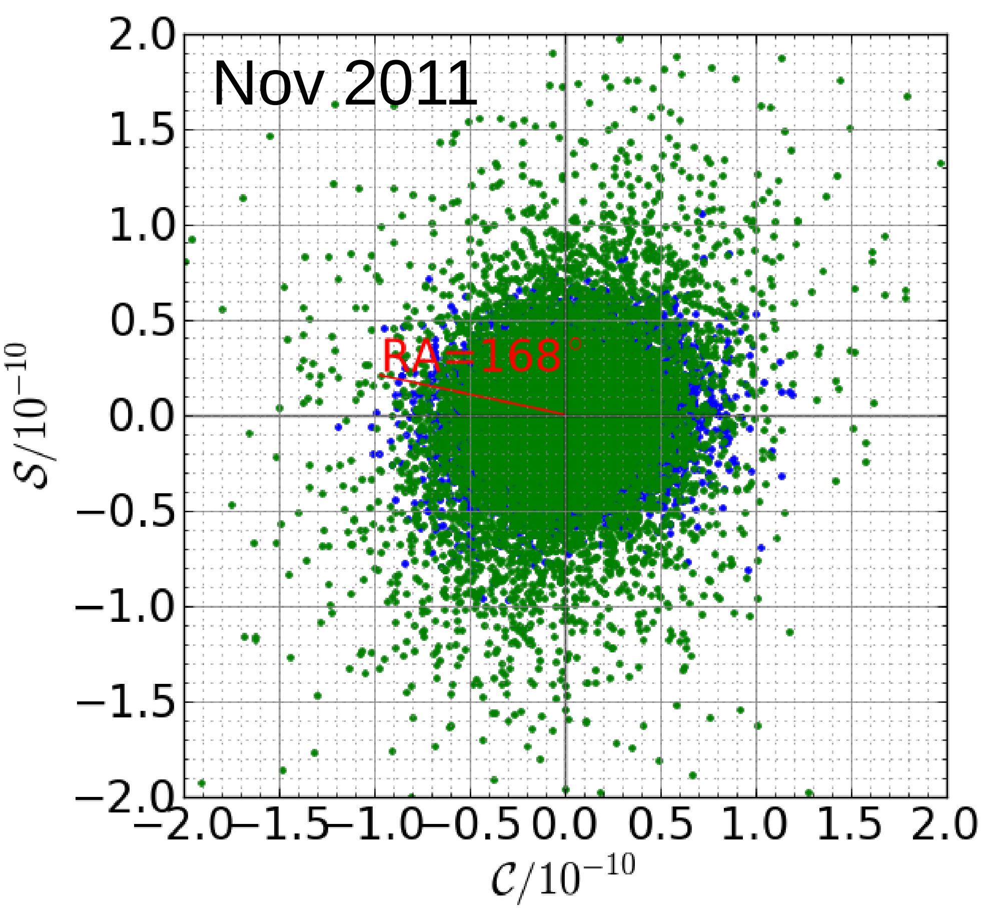


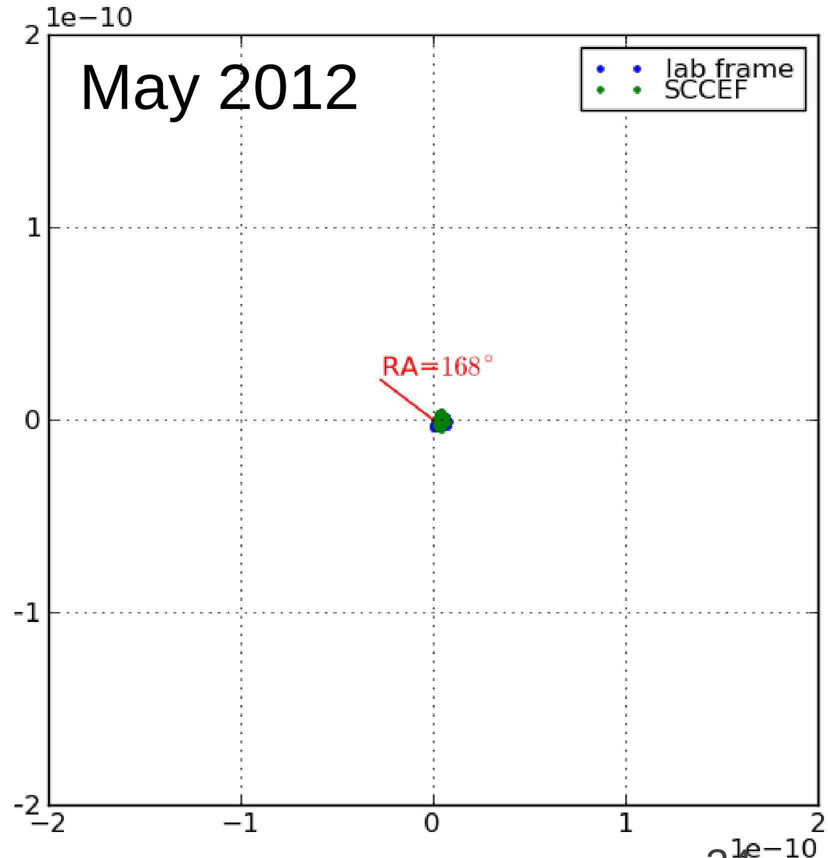


5. Current Status and Summary

Current Status

- reduced noise! (ADC noise was the limiting source…)
- now we have systematic errors > statistic error
  lab light, polarization, tilt of optical table





Summary

- tested SR (Lorentz invariance in photons) by testing isotropy of one-way speed of light
- developed new setup for the anisotropy search
  silicon inside ring cavity
  double-pass configuration
- took anisotropy signal data for ~10,000 rotations (1.2 days)
- analyzed data, and got the world's best limit

$$\hat{\alpha} = (-2.3 \pm 2.6) \times 10^{-10}$$

- already reduced noise by an order of magnitude
- working on making it insensitive to tilt