Report on the Test of Lorentz Invariance

2017/11/17 ANDO GROUP SEMINAR

SAKAI YUZURU

Abstract

- Measuring **Lorentz violation signal** since Oct. 31st

- Data analysis in Mansouri-Sexl framework
  - ✓ I used a week-long data (Oct. 31st - Nov. 7th)
  - ✓ LV signal after Nov. 8th is very noisy (*why?*)

- Lorentz violation parameter:

$$\alpha + 1/2 = (-0.5 \pm 2.5)\times 10^{-12} \qquad \left(\frac{\delta c}{c} \sim 6\times 10^{-15}\right)$$

  - ✓ the same order of magnitude as world record

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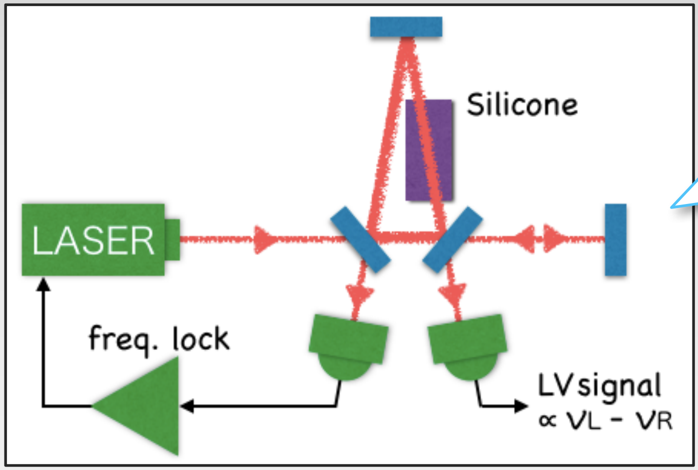
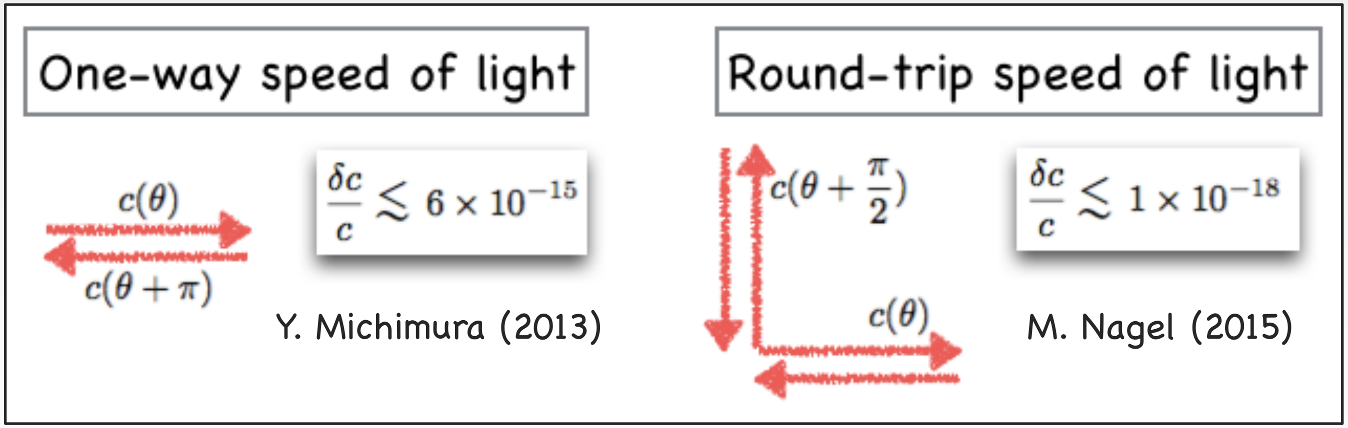
Introduction

- Purpose of our experiment: Test of Lorentz invariance



Especially,
we search for Anisotropy
in the one-way speed of light
using optical ring cavity.



Test Theory

➢ <u>3 frameworks</u>

✓ Mansouri-Sexl theory --- 道村さん修論
- test theory of special relativity with 3 parameters (α, β, δ)
- $\alpha + 1/2 = 0 \Leftrightarrow$ one-way speed of light is constant

✓ Standard model extension --- 道村さん(修論)・D論
- more general theory with many parameters
- can describe many particle (not only photon)

✓ Spherical harmonic decomposition --- 道村さんD論
- no theoretical assumptions or background
- $c(\theta, \phi) = 1 + \sum_{lm} \mathrm{Re}[(\bar{y}_l^m)^* Y_l^m(\theta, \phi)]$

Mansouri-Sexl Theory

- Special relativity

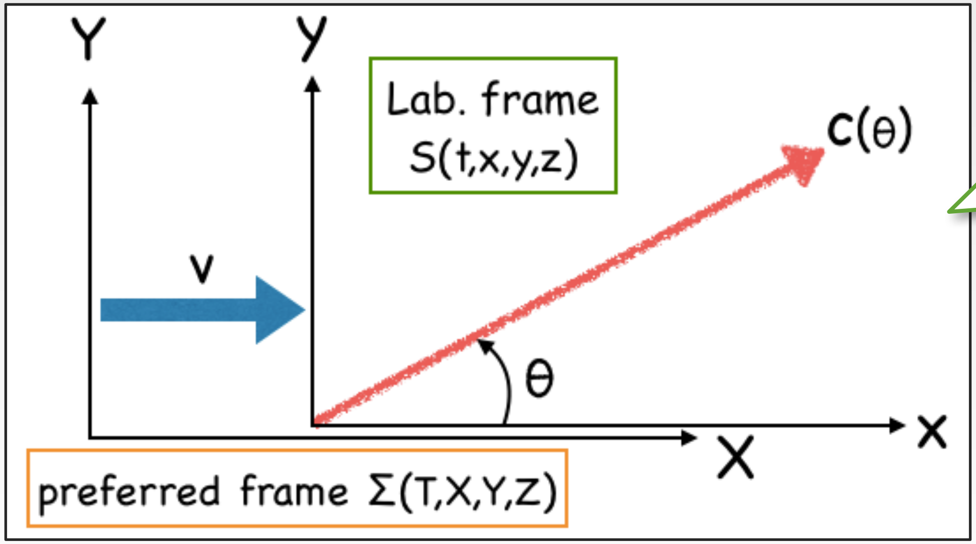
  ① Principle of relativity ② Invariance of c $\Rightarrow$ Lorentz Invariance

- Mansouri-Sexl theory

  ① There exists a preferred frame Σ, where c is constant

  ② There is no preferred direction in Σ

  \+ Clock synchronization by slow clock transport



c is not necessarily constant in lab. frame.

↑Natural candidate: CMB rest frame

Speed of Light in MS Theory

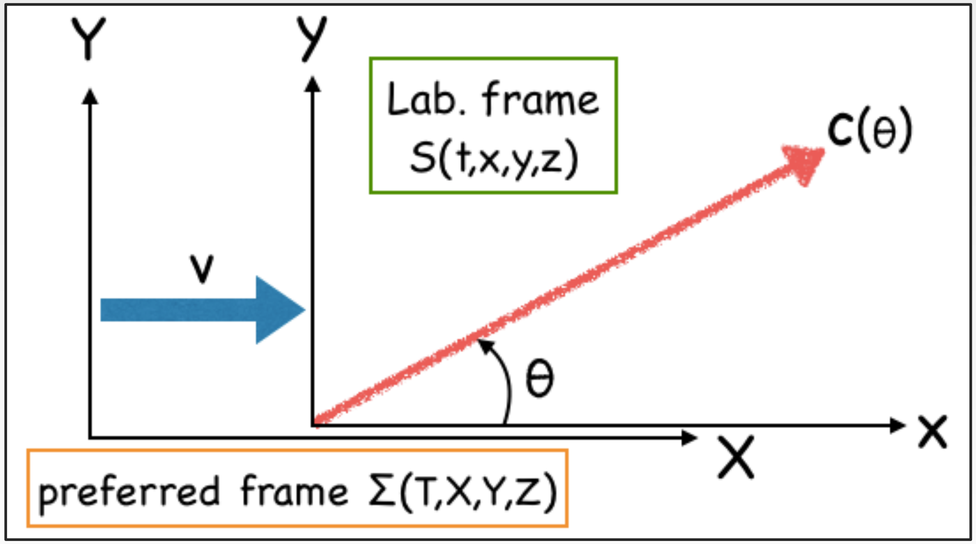
① preferred frame Σ ($c = \text{const.}$) + ② no preferred direction in Σ

Dependence on v

$$c(\theta) = 1 - 2\left(\alpha + \frac{1}{2}\right) v \cos\theta - \left(\beta + \delta - \frac{1}{2}\right) v^2 \sin^2\theta - (\alpha - \beta + 1) v^2 + \mathcal{O}(v^3)$$

One-way speed of light

Round-trip speed of light



In Special relativity,

$$\alpha = -\frac{1}{2}, \quad \beta = \frac{1}{2}, \quad \delta = 0$$

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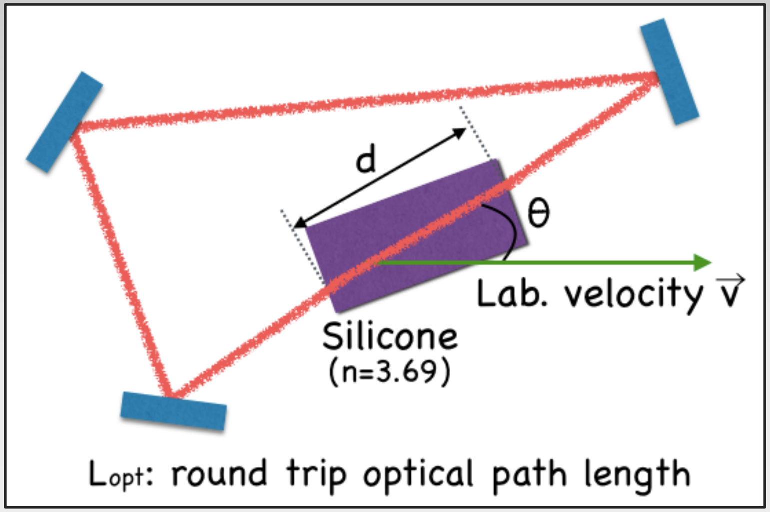
Optical Ring Cavity (1/2)



- Speed of light

$$c(\theta) = 1 - \underbrace{2\left(\alpha + \frac{1}{2}\right) v \cos\theta}_{\text{One-way speed of light}}$$

- Resonant frequency

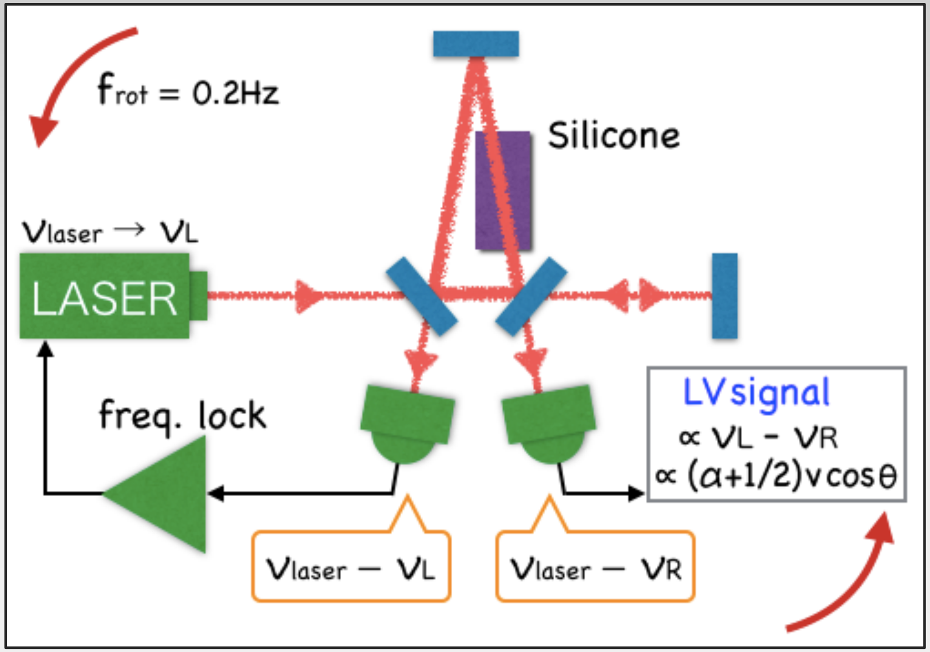
$$\begin{cases} \nu_L = \nu + \delta\nu/2 & \text{for clockwise} \\ \nu_R = \nu - \delta\nu/2 & \text{for counterclockwise} \end{cases}$$

where $\nu \equiv \frac{m}{L_{opt}} (m \in \mathbb{N})$, $\frac{\delta\nu}{2} \equiv -\nu \frac{2(n-1)d}{L_{opt}} \left(\alpha + \frac{1}{2}\right) v \cos\theta$

- Resonant frequency difference

$$\frac{\delta\nu}{\nu} = \frac{\nu_L - \nu_R}{\nu} = \frac{4(n-1)d}{L_{opt}} \left(\alpha + \frac{1}{2}\right) v \cos\theta$$

Optical Ring Cavity (2/2)



- Measuring $\nu_L - \nu_R$ using double-pass configuration.
- Getting the error signal ($\nu_{laser} - \nu_{L/R}$) by the Hänsch-Couillaud method.
  = 偏光解析法

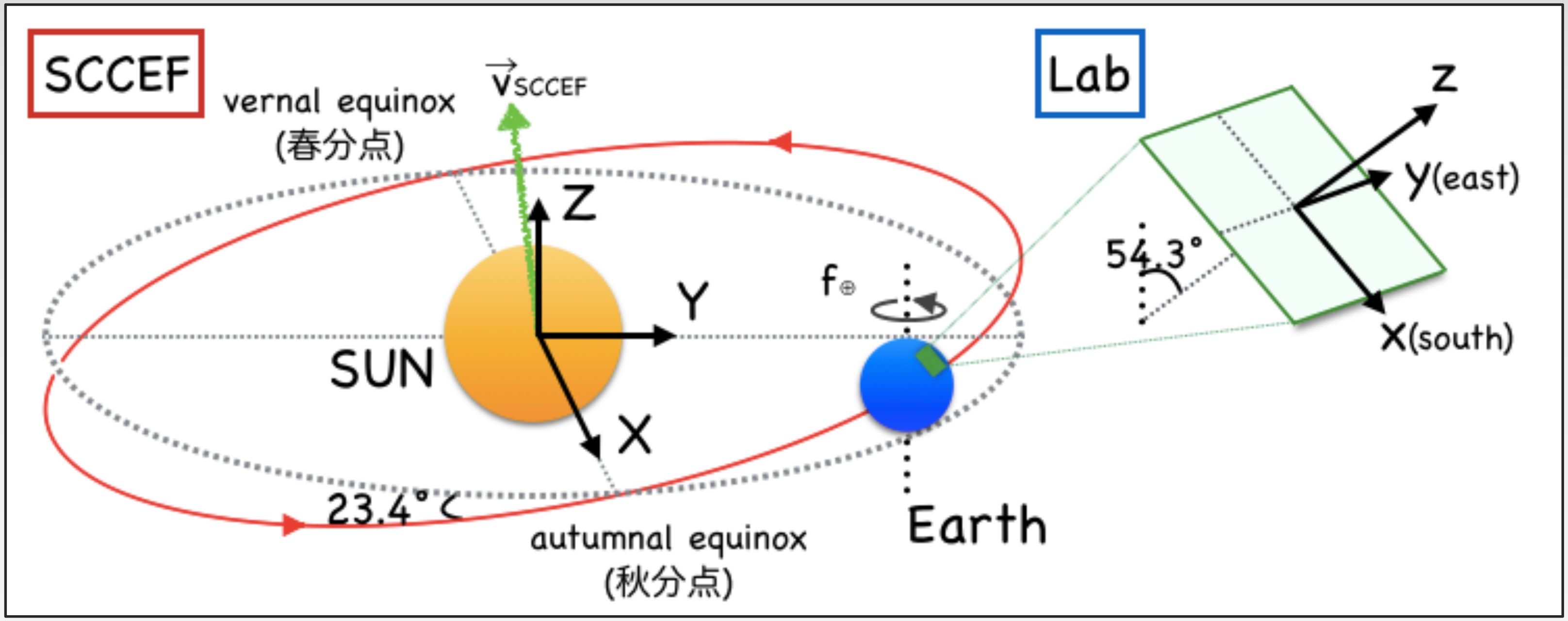
- Lorentz Violation signal → modulation by rotating the cavity
  ↳ $\theta = \omega_{rot} t$? --- This is not true because of the Earth's rotation.
- We have to define a frame moving at a constant velocity with respect to Σ. → SCCEF

SCCEF

天の赤道

- SCCEF = Sun-Centered Celestial Equatorial Frame

  ⇒ Velocity with respect to Σ (CMB rest frame) is approximately constant.



- Velocity of SCCEF

$$\vec{v}_{\mathrm{SCCEF}} = 369\ \mathrm{km/s} \times \begin{pmatrix} -0.970 \\ 0.206 \\ 0.126 \end{pmatrix}$$

We can neglect

- orbital speed $\sim 30\ \mathrm{km/s}$
- rotational speed $\sim 0.5\ \mathrm{km/s}$

Lorentz Violation Signal

- <u>Coordinate transformation matrix</u> (SCCEF → Lab.)

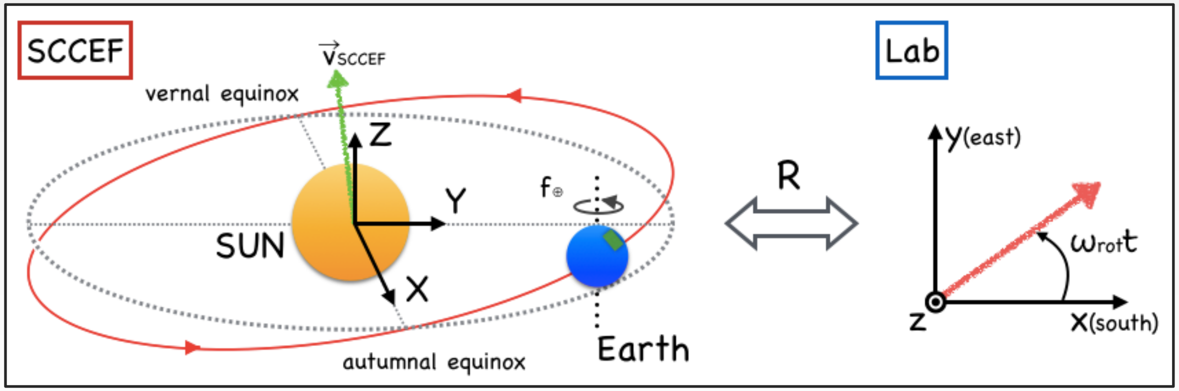
$$R = \begin{pmatrix} \cos\chi\cos\omega_\oplus t & \cos\chi\sin\omega_\oplus t & -\sin\chi \\ -\sin\omega_\oplus t & \cos\omega_\oplus t & 0 \\ \sin\chi\cos\omega_\oplus t & \sin\chi\sin\omega_\oplus t & \cos\chi \end{pmatrix}$$

- <u>LV signal</u>

$$\frac{\delta\nu}{\nu} = \frac{4(n-1)d}{L_{\mathrm{opt}}}\left(\alpha + \frac{1}{2}\right) v\cos\theta$$

$$= \frac{4(n-1)d}{L_{\mathrm{opt}}}\left(\alpha + \frac{1}{2}\right) \vec{v}\cdot R^{\mathrm{T}} \begin{pmatrix} \cos\omega_{\mathrm{rot}} t \\ \sin\omega_{\mathrm{rot}} t \\ 0 \end{pmatrix}$$

Unit vector along the light propagating in silicone
(in Lab. frame)



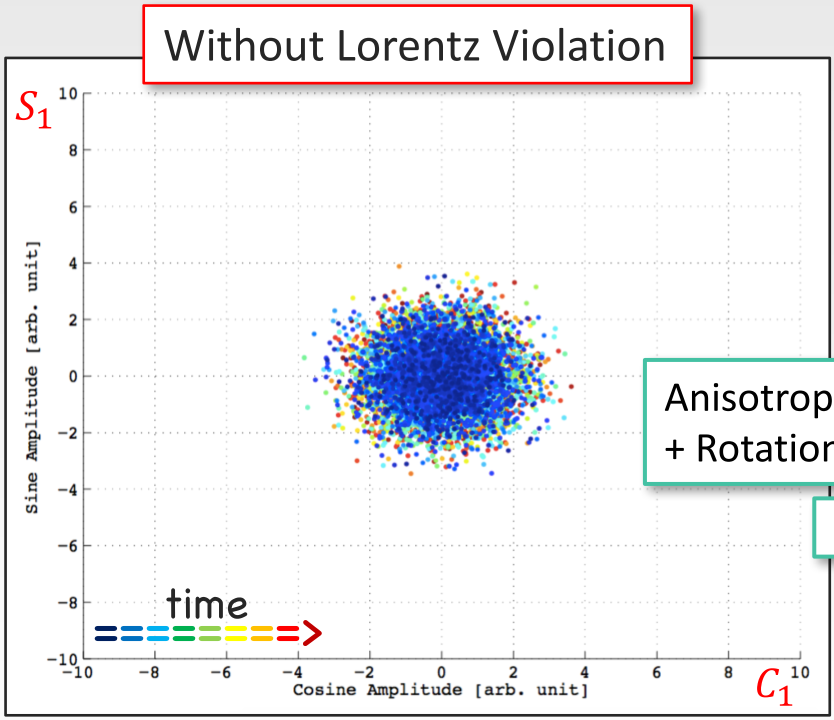
$\chi = 54.3°$ (Colatitude of Lab.)

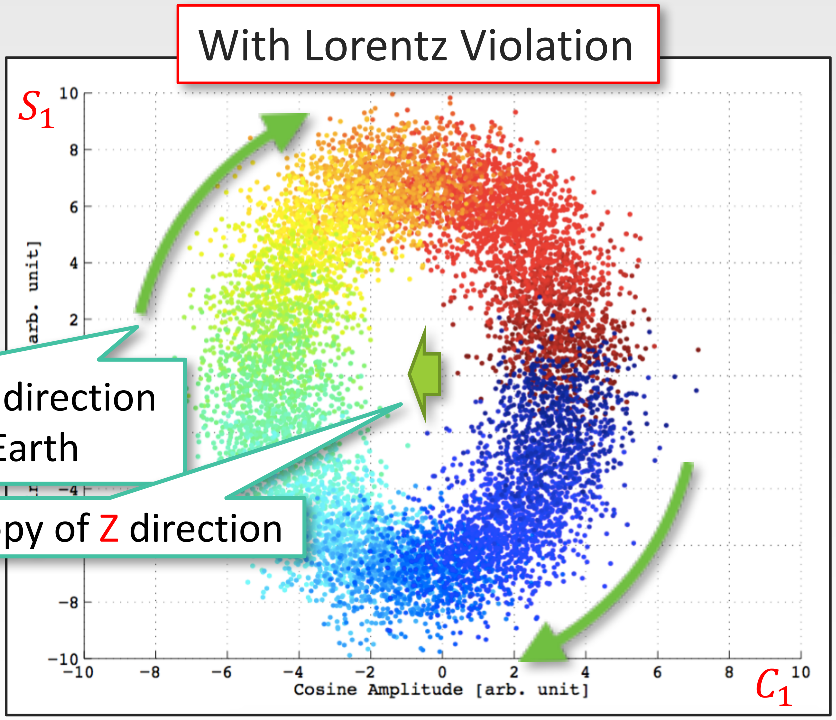
$$\frac{\omega_\oplus}{2\pi} = \frac{1}{23\mathrm{h}\ 56\mathrm{m}\ 4\mathrm{s}}$$

(Rotational frequency of the Earth)

Cos/Sin Amplitude of LV Signal

- LV signal $$\frac{\delta\nu}{\nu} = \frac{4(n-1)d}{L_{\mathrm{opt}}}\left(\alpha+\frac{1}{2}\right)\vec{v}\cdot R^{\mathrm{T}}\begin{pmatrix}\cos\omega_{\mathrm{rot}}t\\ \sin\omega_{\mathrm{rot}}t\\ 0\end{pmatrix}$$
$$= C_1\cos\omega_{\mathrm{rot}}t + S_1\sin\omega_{\mathrm{rot}}t$$
- Simulation (made by random number)





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2. Optical Ring Cavity
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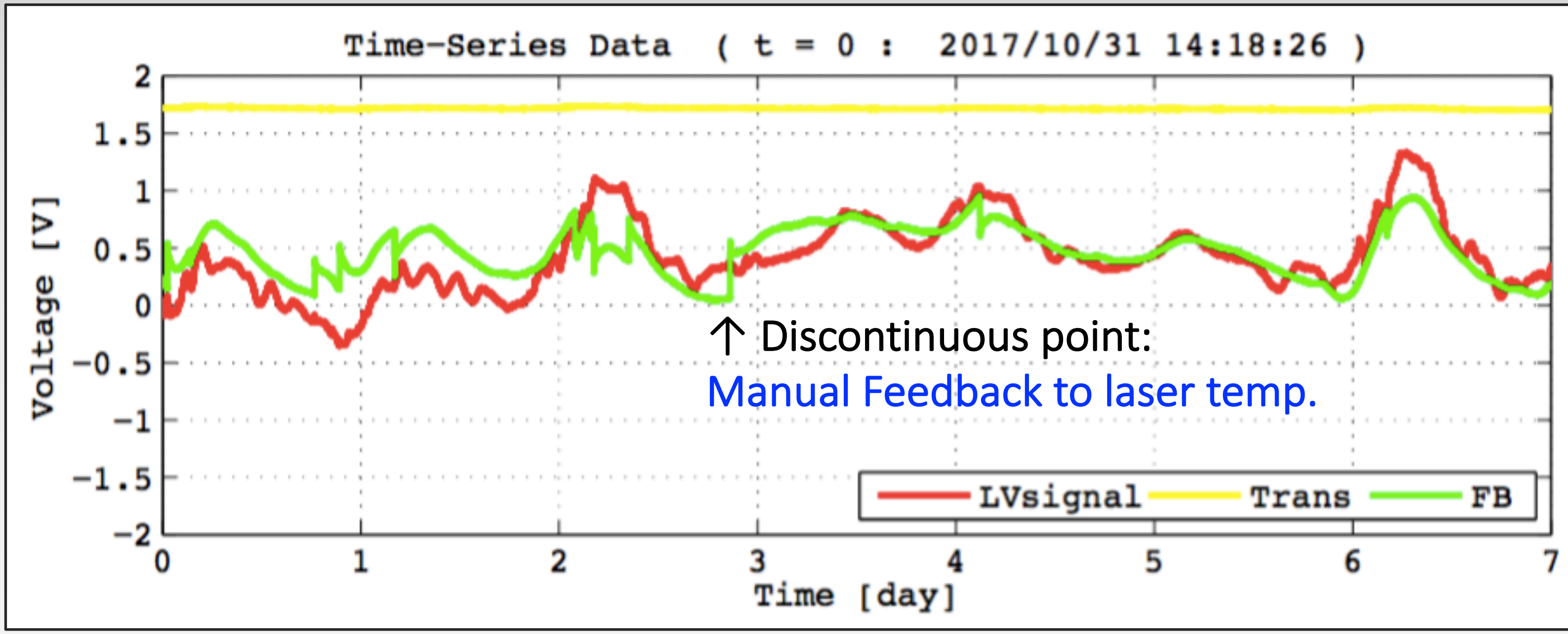
4. Conclusion

Time-Series Data (1/2)

- Freq. lock had continued for 7 days.

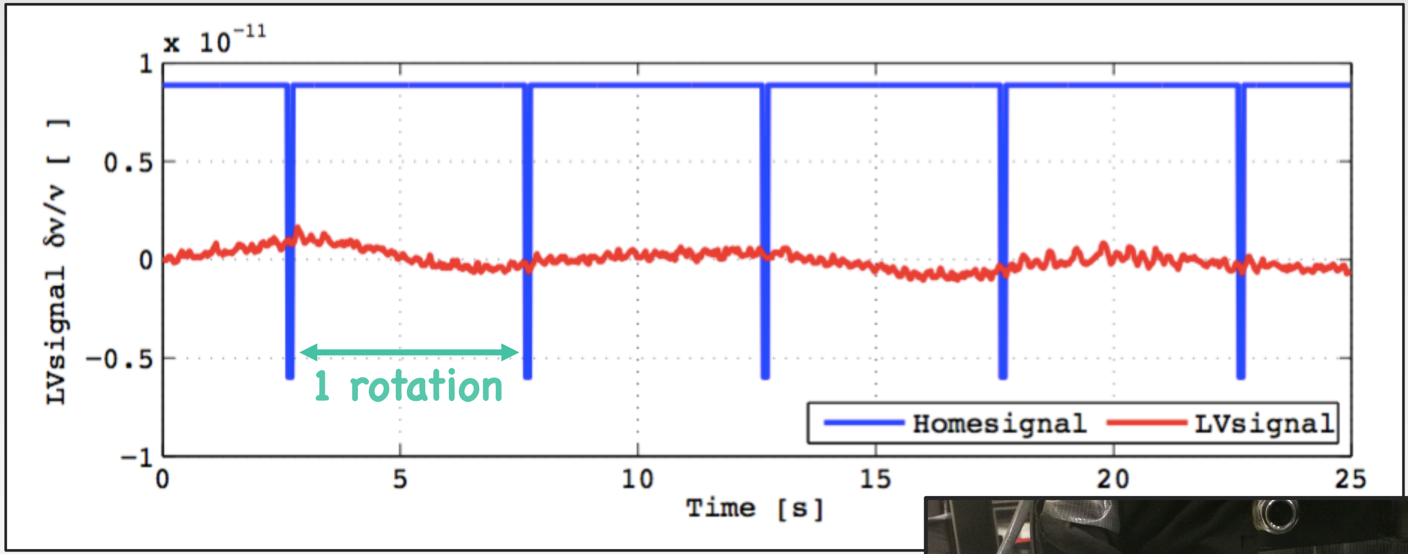


- Some correlation between LV and FB
  ⇒ If caused by cavity length change, $\mathrm{CMRR} \lesssim 10^{-3}$

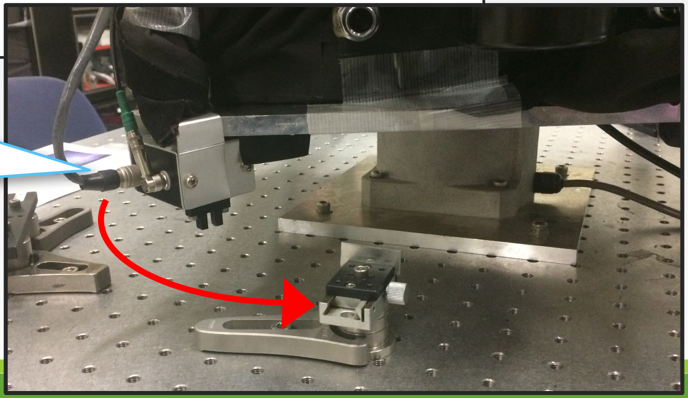
  $\nu_{\mathrm{L}} - \nu_{\mathrm{R}}$

Time-Series Data (2/2)

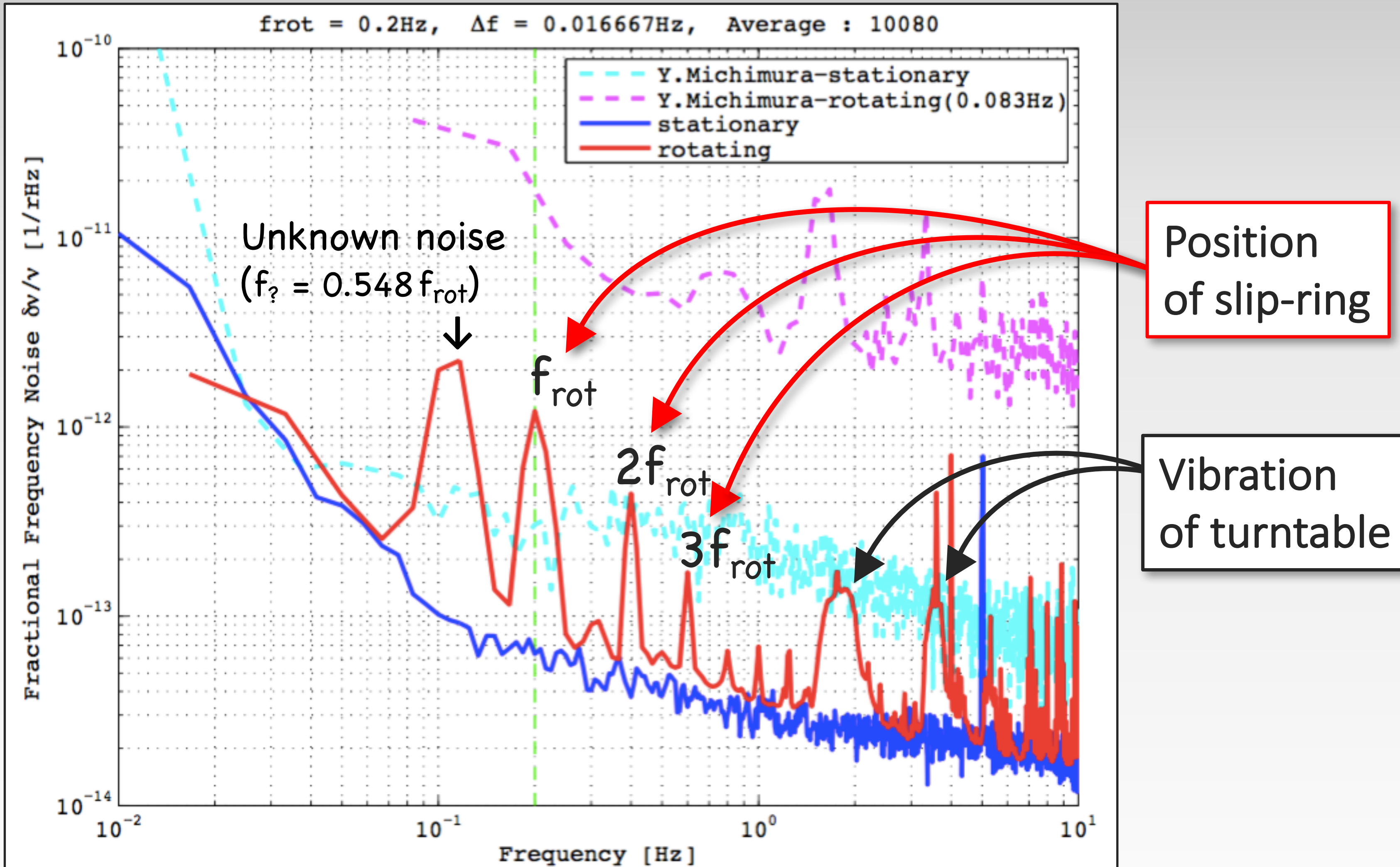
- Enlarged view of LV signal
  - Cannot find rotational frequency noise visually
  - Unknown noise with ~2-rotation period



We can get "home signal" using a photo-interrupter.



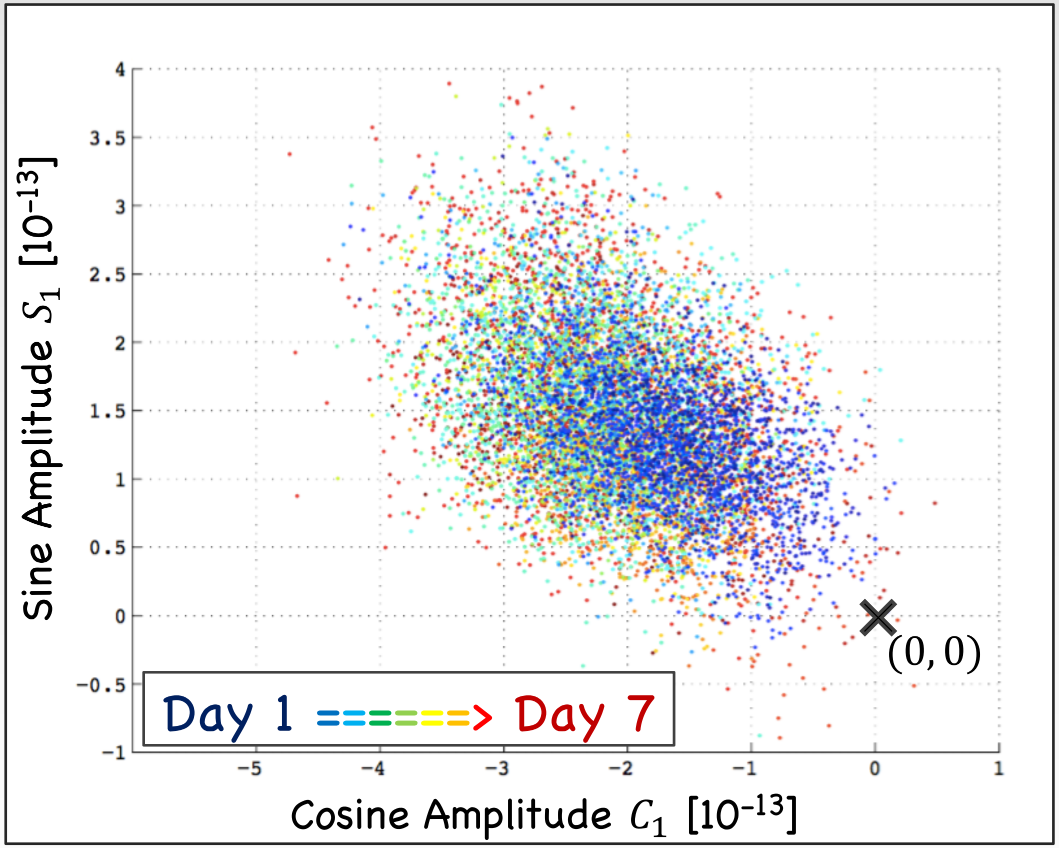
Power Spectrum of LV signal



Cos/Sin Amplitudes (1/2)

- Cos/Sin amplitudes (calculated every 12 rotations = 1min.)

$$\delta\nu/\nu = C_1 \cos\omega_{\mathrm{rot}}t + S_1 \sin\omega_{\mathrm{rot}}t$$

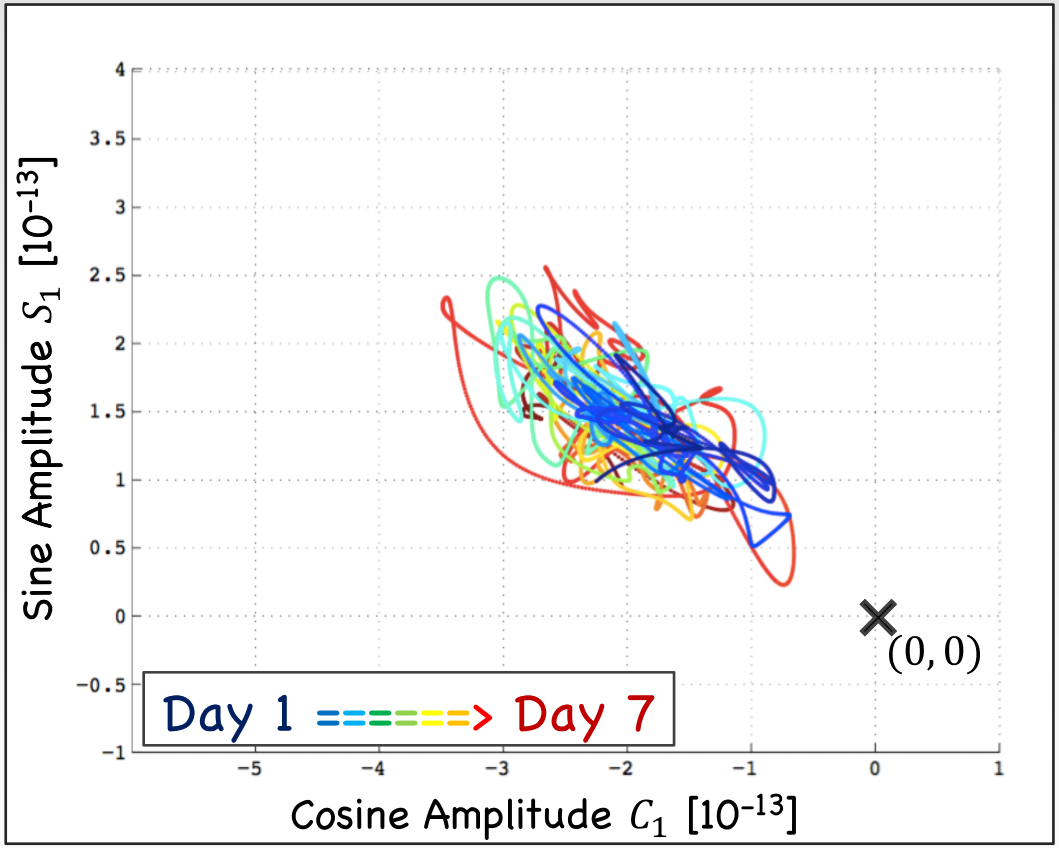


$\overline{C_1}, \overline{S_1} \neq 0$
··· Rot. freq. noise

(If this gap is caused by anisotropy, $\delta c/c \sim 10^{-12}$)

Cos/Sin Amplitudes (2/2)

- Taking moving average (time constant ~ 1 hour)   前後1時間のデータと移動平均をとってみる
- Local mean value changes with time --- *Big problem!!!*



because we cannot distinguish mean value change by anisotropy with by noise.

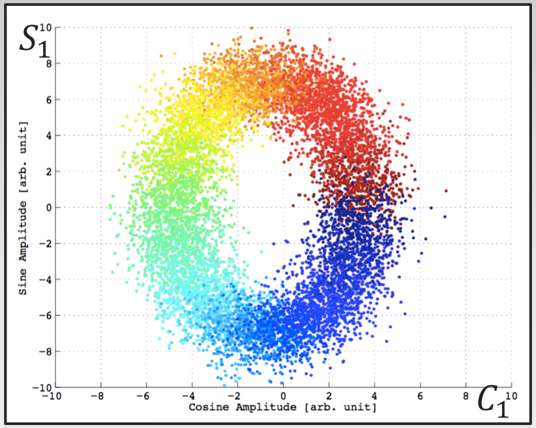
Current sensitivity is limited by this effect.

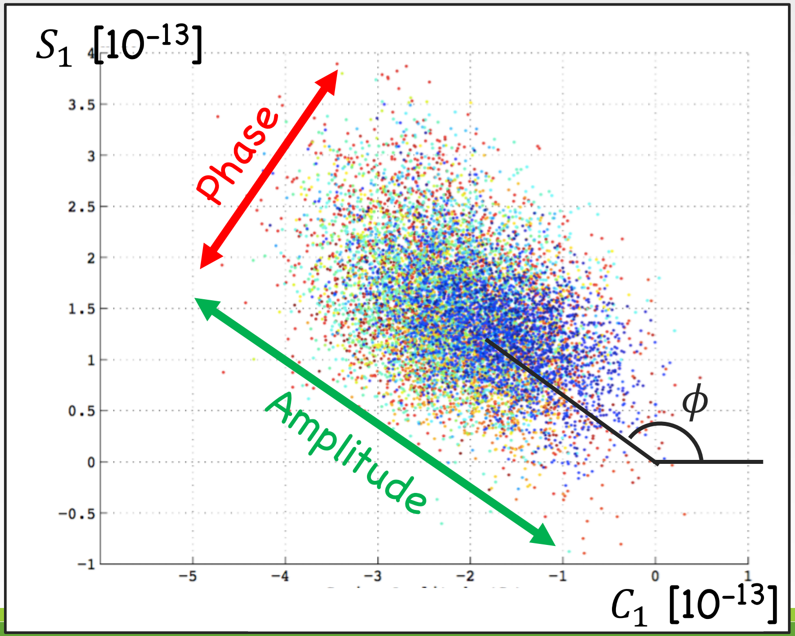
(noise at $f_{\mathrm{rot}} \pm f_{\oplus}$)

How to calculate $\alpha + 1/2$

- If anisotropy exists,
  - C_1 is drifted — Anisotropy of Z direction
  - C_1 changes @ $f_\oplus$
  - S_1 changes @ $f_\oplus$ — Anisotropy of X, Y direction + Rotation of the Earth

  $\Rightarrow$ These 3 components has the same information about $\alpha + 1/2$.





- I used "phase component"

$$p_1 \equiv -\sin\phi\,(C_1 - \overline{C_1}) + \cos\phi\,(S_1 - \overline{S_1})$$

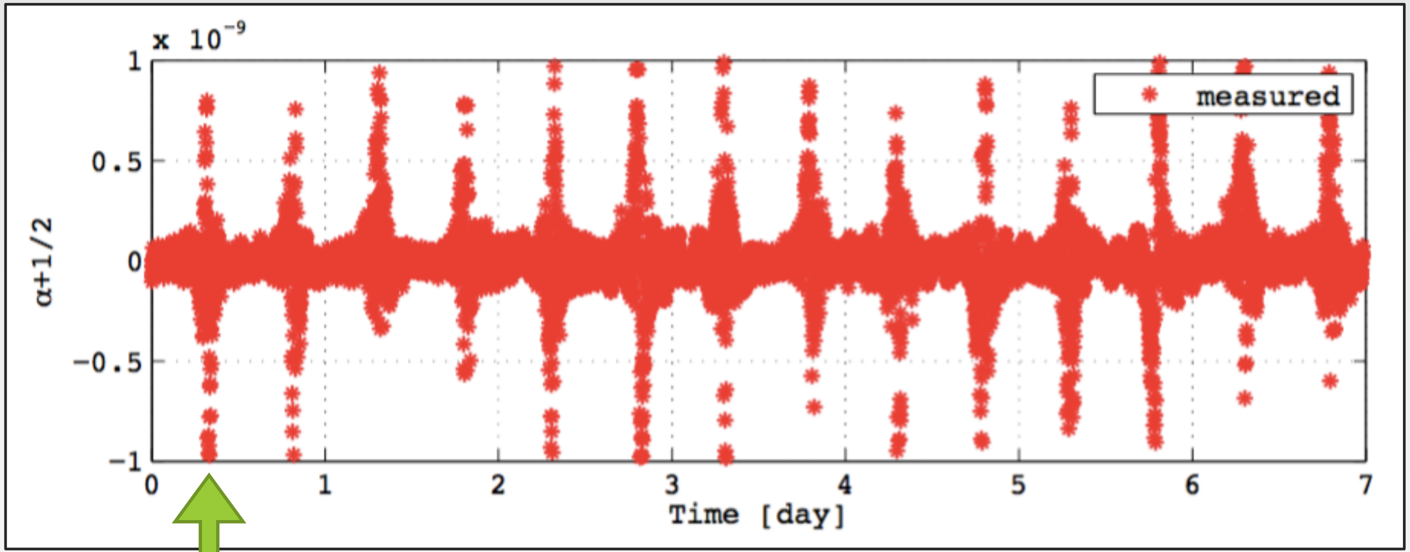
(ϕ: phase of rot. Freq. noise)

$$p_1 = A\left(\alpha + \frac{1}{2}\right)\cos(\omega_\oplus t - \psi)$$

$\alpha + 1/2$

- I calculated $\alpha + 1/2$ every 12 rotations

$$\alpha + \frac{1}{2} = \frac{p_1}{A\cos(\omega_\oplus t - \psi)}$$



Very high noise at $\cos(\omega_\oplus t - \psi) = 0$

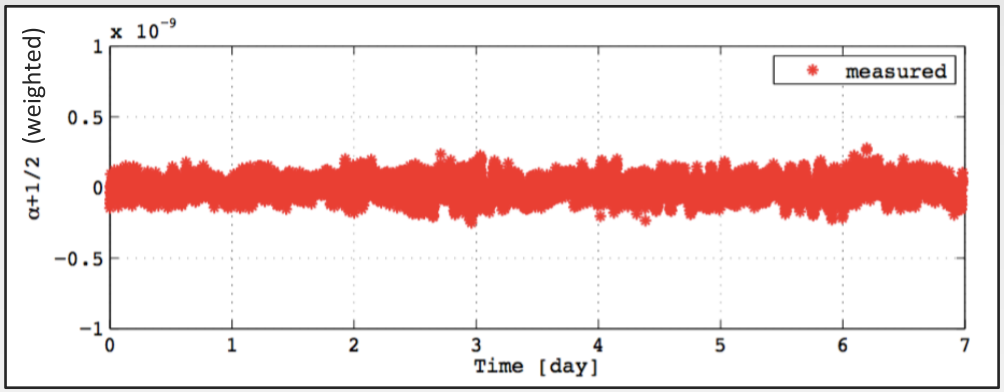
- <u>Need to take weighted average</u> (Normal average → Sensitivity↓)

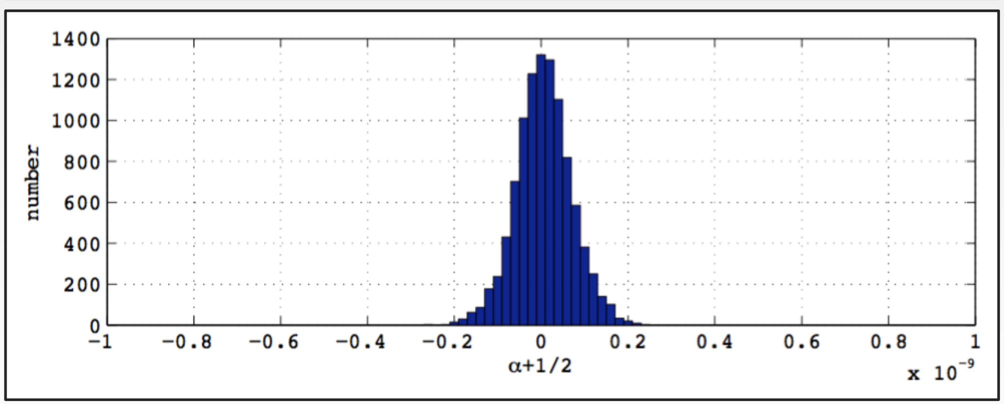
Weighted $\alpha + 1/2$

- Taking weighted average

$$\alpha + \frac{1}{2} = \frac{p_1}{A\cos(\omega_\oplus t - \psi)}$$

Weight $\propto \left|\cos(\omega_\oplus t - \psi)\right|$





- Weighted average:

$$\overline{\left(\alpha + \frac{1}{2}\right)_{\mathrm{w}}} = 5\times10^{-13}$$

- Standard deviation:

$$\delta\left(\alpha + \frac{1}{2}\right)_{\mathrm{w}} \sim 10^{-10}$$

Number of data: $N \sim 10^5$

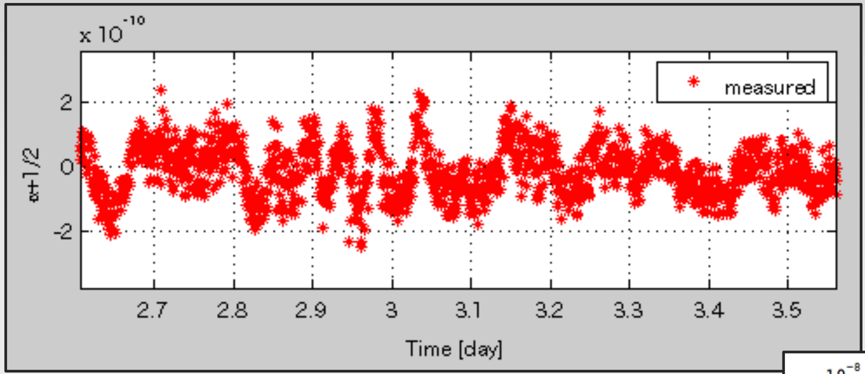
- Sensitivity:

$$\delta\,\overline{\left(\alpha + \frac{1}{2}\right)_{\mathrm{w}}} \neq \frac{\delta\left(\alpha+\frac{1}{2}\right)_{\mathrm{w}}}{\sqrt{N}} \sim 3\times10^{-13}$$

(?)

Really Independent?

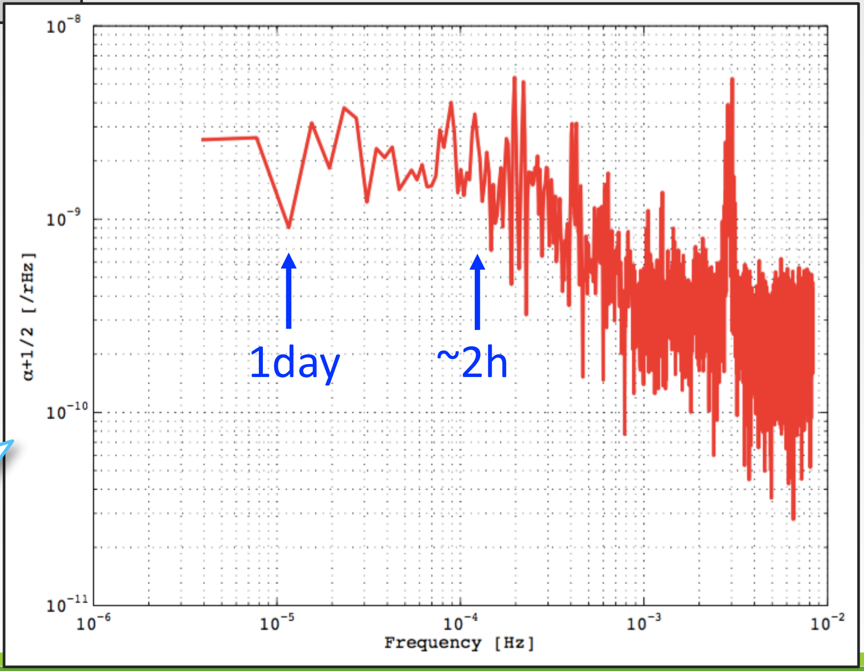
- Enlarged view of weighted $\alpha + 1/2$



There is some trend!

Nearby data points are NOT independent.

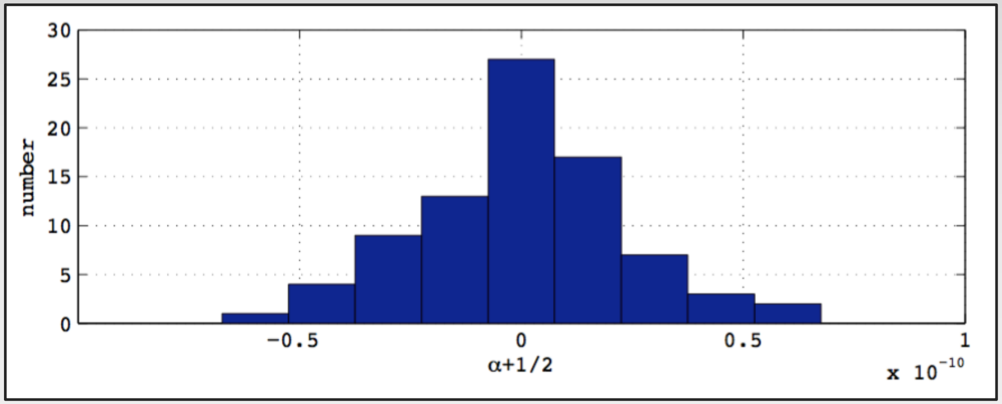
- Power spectrum of weighted $\alpha + 1/2$



2 points are independent if more than 2 hours away from each other.

Result

- Taking average every 2 hours



- Standard deviation:

$$\delta\left(\alpha+\frac{1}{2}\right)_{\mathrm{w}} = 2.3\times10^{-11}$$

Number of data: $N\sim84$

- Sensitivity:

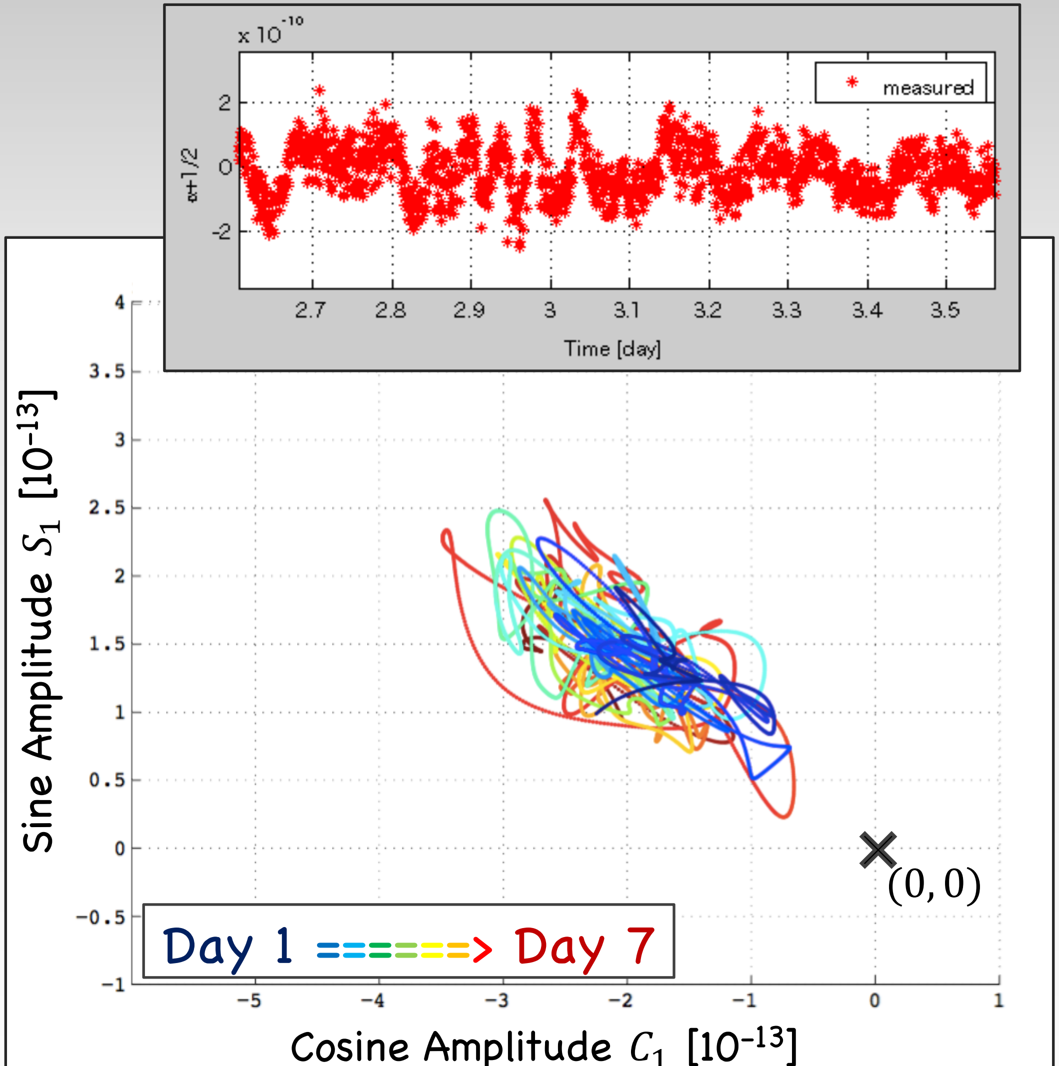
$$\delta\overline{\left(\alpha+\frac{1}{2}\right)_{\mathrm{w}}} = \frac{\delta\left(\alpha+\frac{1}{2}\right)_{\mathrm{w}}}{\sqrt{N}} \sim 2.5\times10^{-12}$$

Result

$$\alpha+\frac{1}{2} = (-0.5\pm2.5)\times10^{-12}$$

$$\frac{\delta c}{c} \sim 2\left(\alpha+\frac{1}{2}\right)v_{\mathrm{SCCEF}} \sim 6\times10^{-15}$$

Discussion



- Noise level is reduced, but now noise at $f_{\mathrm{rot}} \pm f_{\oplus}$ limits the sensitivity.
- In the framework of spherical harmonic decomposition, anisotropy of Z direction cannot be measured unless rot. freq. noise is reduced by 3 order of magnitude.

今の装置では限界？吊るしかない？

Contents

Conclusion

- Data analysis in Mansouri-Sexl framework
  (using a week-long data: Oct. 31st - Nov. 7th)

$$\alpha + 1/2 = (-0.5 \pm 2.5)\times 10^{-12} \quad \left(\frac{\delta c}{c} \sim 6\times 10^{-15}\right)$$

✓ The same order of magnitude as world record
✓ Noise at $f_{\mathrm{rot}} \pm f_{\oplus}$ is big problem

✓ 来年の異方性実験のテーマ: 光学系を吊った状態で回せる連続回転機構(傾き制御付き)の開発

ほそく：回転周波数依存性

- 回転周波数ノイズ・謎のノイズとも振幅は変わらない