Title: Precision microwave oscillators and interferometers to test Lorentz Invariance and Local Position Invariance

Date: Jul 16, 2008 02:00 PM

URL: http://pirsa.org/08070025

Abstract: We present recent and ongoing work that uses precision frequency generation and phase measurement to test the constancy of the speed of light Local Position Invariance (LPI) and the Lorentz Invariance (LI) of the photon with respect to the Standard Model of Particle Physics under the frame work of the Standard Model Extension (SME). The first experiment consists of a pair of orthogonally orientated single crystal sapphire resonators cooled to cryogenic temperatures and configured as stable oscillators operating in Whispering Gallery Mode (Cryogenic Sapphire Oscillator). The experiment is continuously rotated at a period of about 20 seconds, and modulations are searched for with respect to an absolute frame of reference. Our experiment has confirmed Lorentz Invariance at sensitivity better than one order of magnitude than previous tests. The experiment is now being upgraded and has the potential to improve this result by further one and a half orders of magnitude. The second experiment consists of a Mach-Zender Interferometer with a magnetic material in one arm. This experiment allows us to measure odd parity and scalar Lorentz violating parameters predicted in the SME, in which the cavity experiment either exhibit suppressed or no sensitivity to. The experiment has been in continuous operation since September 2007 and has put a limit of order 10^-7 on the scalar Lorentz violating parameter, we show that an upgraded experiment can improve this result by a few more orders of magnitude. The final experiment measures over seven years the frequency comparison of a Cryogenic Sapphire Oscillator and a Hydrogen maser at the Paris Observatory. Amongst the data we search for signals correlated with the changing gravitational potential (test of LPI) and reference frame velocity (test of LI), with first results to be presented.

2:00 – 2:40	Michael Tobar	Precision microwave oscillators and interferometers to test Lorentz Invariance and Local Position Invariance	Bob Room

1. Collaboration with SYRTE
   - Variation of Fundamental Constants
   - LPI (Null red shift experiment)

2. Lorentz Invariance Tests
   - Michelson-Morley Even Parity Experiment
   - Ives-Stillwell Odd Parity Experiment

l'Observatoire de Paris — SYRTE

Systèmes de Référence Temps-Espace

Search for Temporal Variations in Fundamental Constants Using Hyperfine Transitions in Primary Atomic Clocks

LNE — Le progrès, une passion à partager

CNRS — Centre National de la Recherche Scientifique

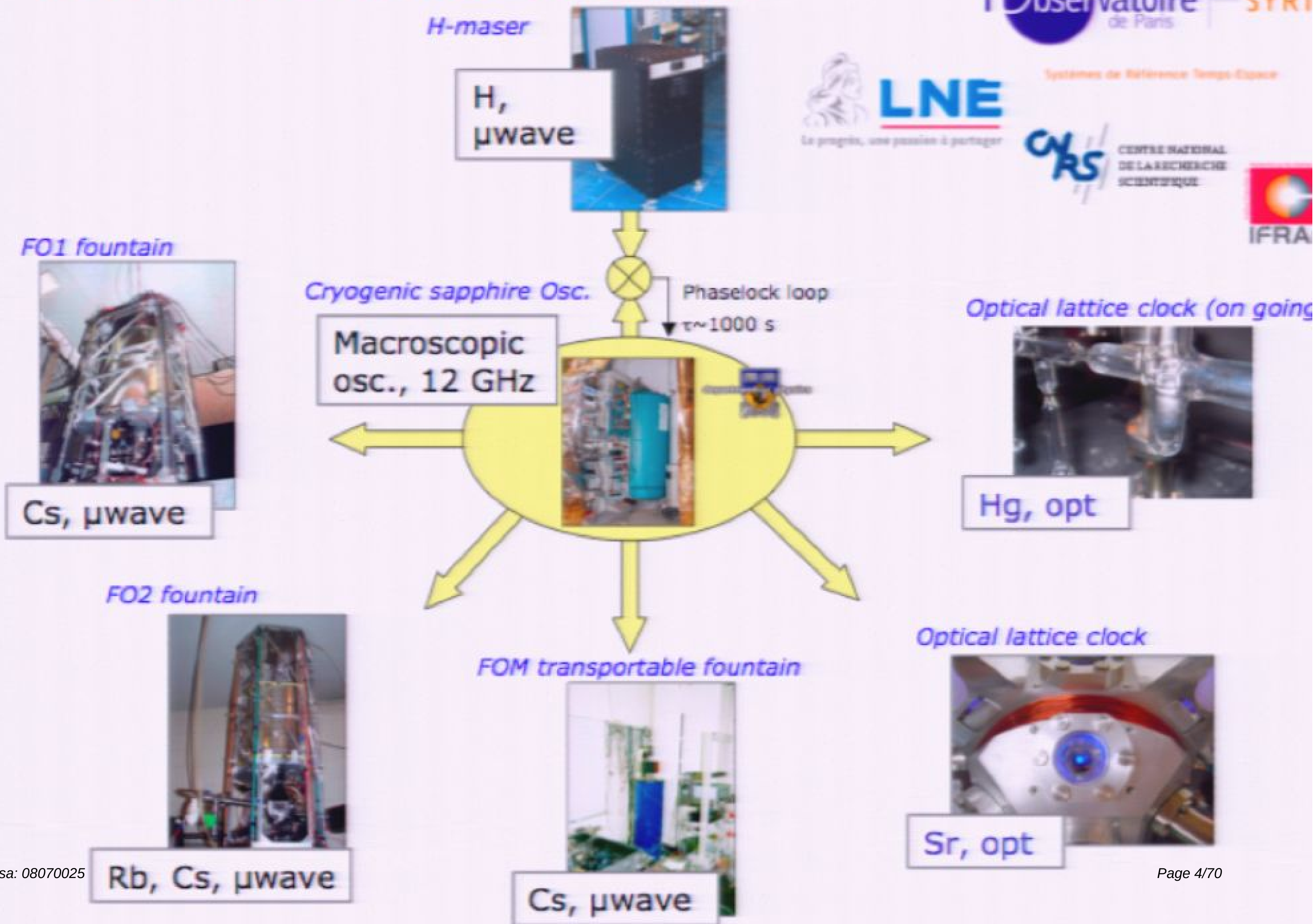
IFRAF

cnes — Centre National d'Études Spatiales

J. Guéna, F. Chapelet, P. Rosenbusch, P. Laurent, M. Abgrall, G. D. Rovera, G. Santarelli, M. E. Tobar, S. Bize and A. Clairon

DAMOP 2008
May 29th 2008, State College, PA, USA

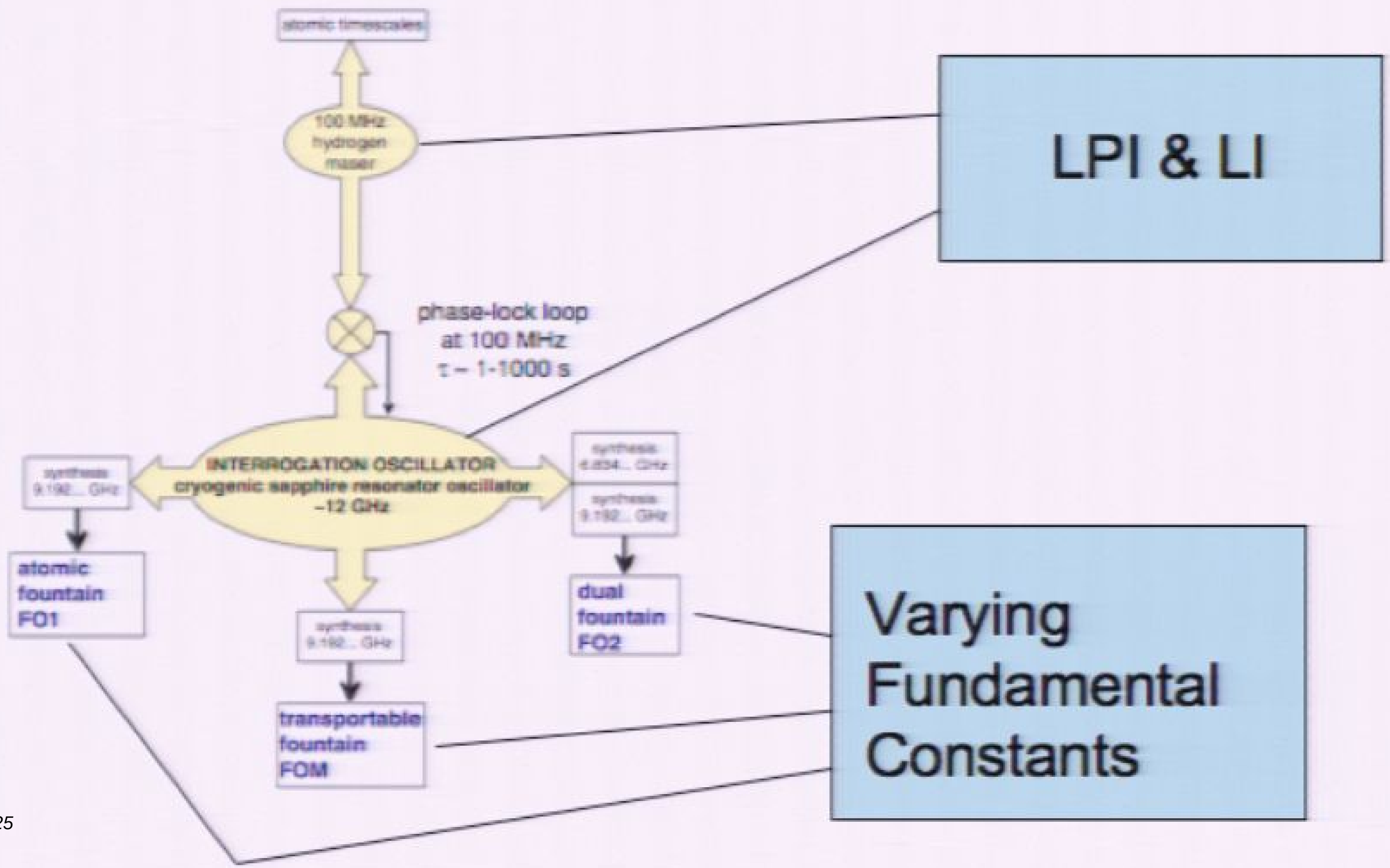
LNE-SYRTE CLOCK ENSEMBLE



Collaboration with SYRTE at Paris Observatory

l'Observatoire de Paris — SYRTE

FREQUENCY STANDARDS AND METROLOGY RESEARCH GROUP



How do fundamental constants vary?

- String theory inspired cosmological models suggest existence of additional massless (very light) scalar fields ϕ, eg. Dilaton [Damour 1994,…].
- Assuming that they couple differently to different low energy Lagrangian fields, they will lead to variation of fundamental constants in time and space.

- Assuming further that they are given by a field equation whose source is proportional to $T = T_\mu^{\ \mu}$ (the trace of the energy-momentum tensor)

$$\boxed{\phi = \phi_C + Q/r}$$ where it is reasonable to assume: $$\boxed{Q \propto GM/c^2}$$ [Flammbaum & Shuryak physics/0701220, (2007)]

- The "local" part (Q/r) will lead to a variation of fundamental constants as a function of the Newtonian potential, and can be parameterized:

$$\frac{\delta\alpha}{\alpha} = k_\alpha \delta\left(\frac{GM}{rc^2}\right); \ \frac{\delta(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} = k_q \delta\left(\frac{GM}{rc^2}\right); \ \frac{\delta(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})} = k_e \delta\left(\frac{GM}{rc^2}\right)$$

- This leads to two types of variation: long term drift (ϕ_C) and local (periodic) terms $\delta(GM/r)$. Can be distinguished in laboratory or space-borne experiments !!

Which constants vary?

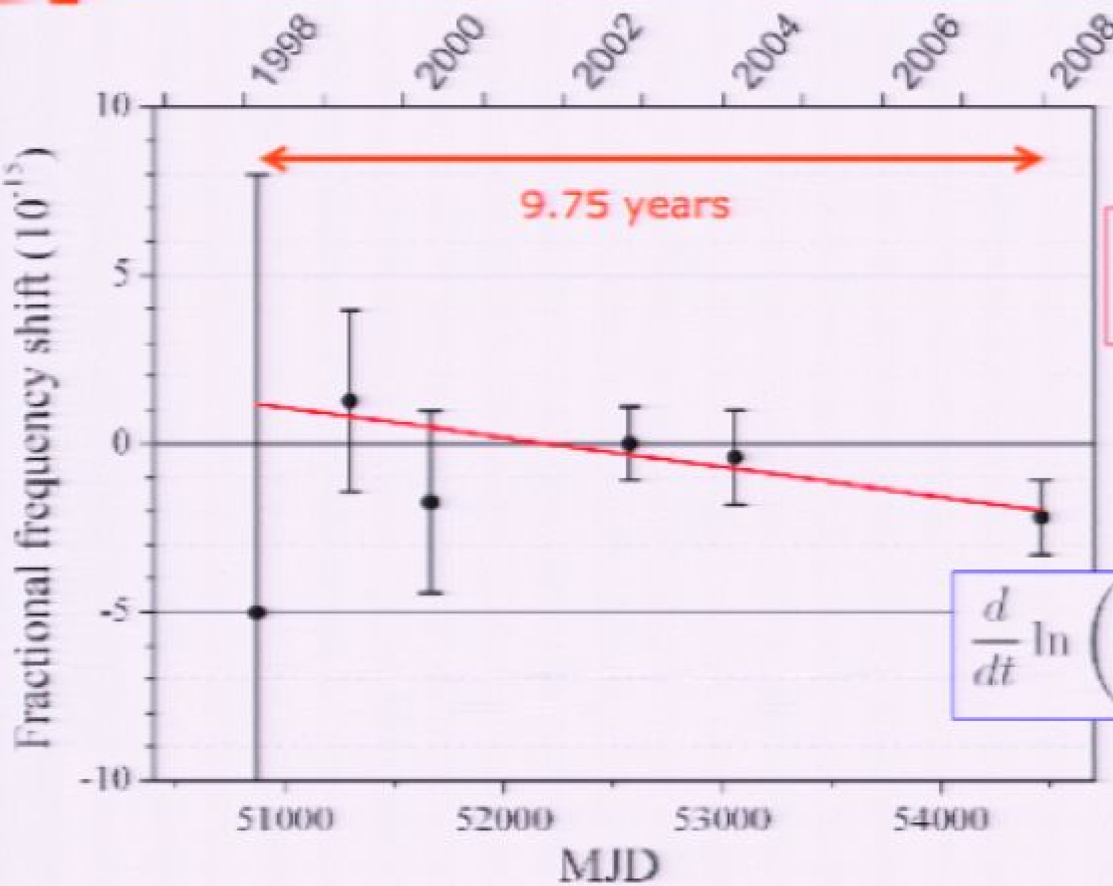
V. V. Flambaum and A. F. Tedesco, PR **C73**, 055501 (2006)

- Recent accurate calculations of sensitivities for many commonly used transitions can be found

$$\frac{\delta(\nu^{(i)}/Ry)}{(\nu^{(i)}/Ry)} = \kappa_{\alpha}^{(i)}\frac{\delta\alpha}{\alpha} + \kappa_{q}^{(i)}\frac{\delta(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} + \kappa_{e}^{(i)}\frac{\delta(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}$$

	κ_α	κ_q	κ_e
Rb hf	2.34	-0.064	1
Cs hf	2.83	-0.039	1
H opt	0	0	0
Yb^+ opt	0.88	0	0
Hg^+ opt	-3.2	0	0

Search for variation of constants



Weighted least square fit gives:

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-3{,}2 \pm 2{,}3) \times 10^{-16}\,\mathrm{an}^{-1}$$

With QED calculations:

J. Prestage, et al., PRL (1995), V. Dzuba, et al., PRL (1999)

$$\frac{d}{dt}\ln\left(\frac{g_{\mathrm{Rb}}}{g_{\mathrm{Cs}}}\alpha^{-0{,}49}\right) = (-3{,}2 \pm 2{,}3) \times 10^{-16}\,\mathrm{an}^{-1}$$

With QCD calculations:

V. V. Flambaum and A. F. Tedesco, PR C73, 055501 (2006)

$$\frac{d}{dt}\ln\left(\alpha^{-0.49}\left[m_q/\Lambda_{\mathrm{QCD}}\right]^{-0.025}\right) = (-3.2 \pm 2.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

Improves our 2002 result (PRL 90, 150801 (2003)) by a factor of 3

Overview of recent measurements

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-3.2\pm 2.3)\times 10^{-16}\,\mathrm{yr}^{-1} = -0.49\frac{d}{dt}\ln(\alpha) - 0.025\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}})$$

LNE-SYRTE, JPB (2004)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Hg+}}}{\nu_{\mathrm{Cs}}}\right) = (3.7\pm 3.9)\times 10^{-16}\,\mathrm{yr}^{-1} = -6.03\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

NIST, PRL (2007

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Yb-}}}{\nu_{\mathrm{Cs}}}\right) = (-7.8\pm 14)\times 10^{-16}\,\mathrm{yr}^{-1} = -1.95\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

PTB, arXiv (2006

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{H}}}{\nu_{\mathrm{Cs}}}\right) = (-32\pm 63)\times 10^{-16}\,\mathrm{yr}^{-1} = -2.83\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

MPQ
+ LNE-SYRTE
PRL (2004)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Dy}}}{\nu_{\mathrm{Cs}}}\right) = (-4\pm 3.9)\times 10^{-8}\,\mathrm{yr}^{-1} = 1.5\times 10^{7}\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

Berkley,
PRL (2007

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Sr}}}{\nu_{\mathrm{Cs}}}\right) = (-7\pm 18)\times 10^{-16}\,\mathrm{yr}^{-1} = -2.77\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

Tokyo
JILA
LNE-SYRT
arXiv (2008)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Hg-}}}{\nu_{\mathrm{Al+}}}\right) = (4.6\pm 6.7)\times 10^{-17}\,\mathrm{yr}^{-1} = -2.9\frac{d}{dt}\ln(\alpha)$$

NIST, Science (2008)

- All optical frequency measurements are against Cs
- Only 2 hyperfine transitions Rb and Cs
- Direct optical to optical comparisons to come

Laboratory Tests: Results

Using a weighted least squares fit to previous data:

$$\frac{d}{dt}\ln(\alpha) = (-0.18 \pm 0.23) \times 10^{-16}\,\mathrm{yr}^{-1}$$

$$\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) = (131 \pm 92) \times 10^{-16}\,\mathrm{yr}^{-1}$$

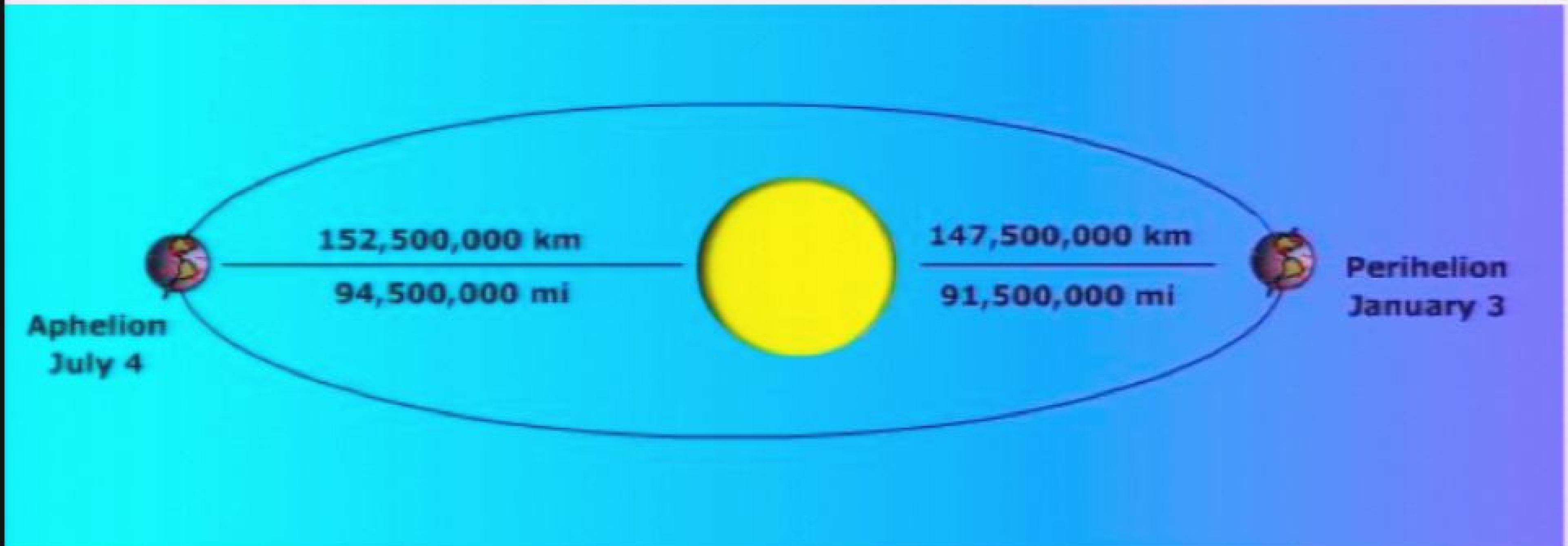
$$\frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}}) = (3.8 \pm 5.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

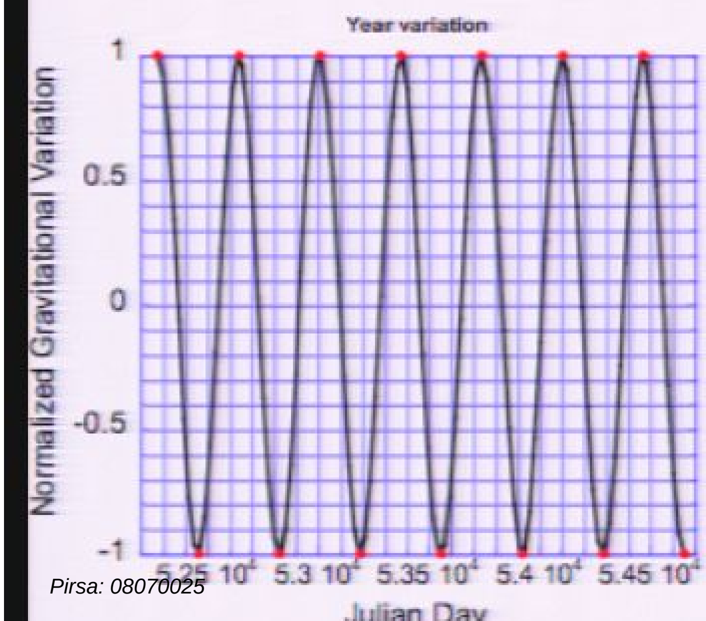
INDEPENDENT OF COSMOLOGICAL MODELS

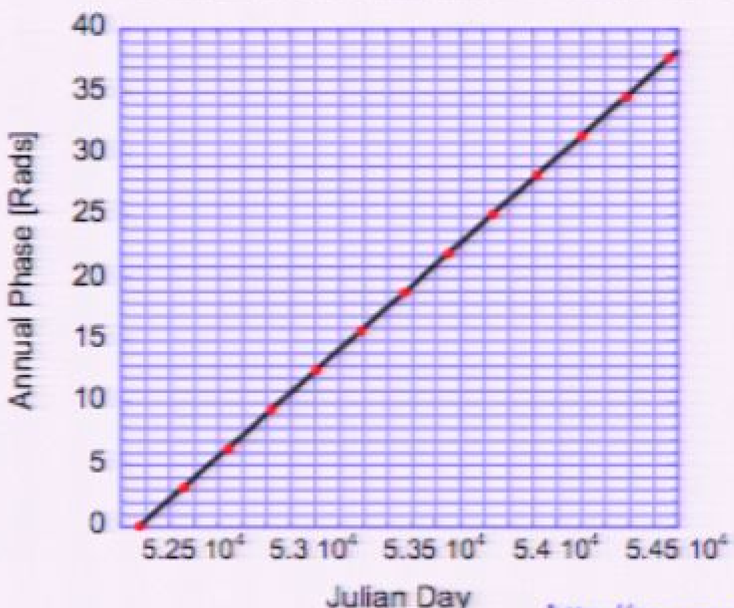
- Limit on α var. is becoming competitive with Oklo ($\sim 10^{-17} yr^{-1}$) and Quasar limits ($\sim 10^{-16} yr^{-1}$) assuming linear change.
- Assuming linear change, limits on m_q and m_e do not exclude the positive result on m_e/m_p (Reinhold et al. 2006)

- Correlation coefficients are quite high between m_q and m_e
- More accurate, and more diverse measurements are required!!

Local Position Invariance





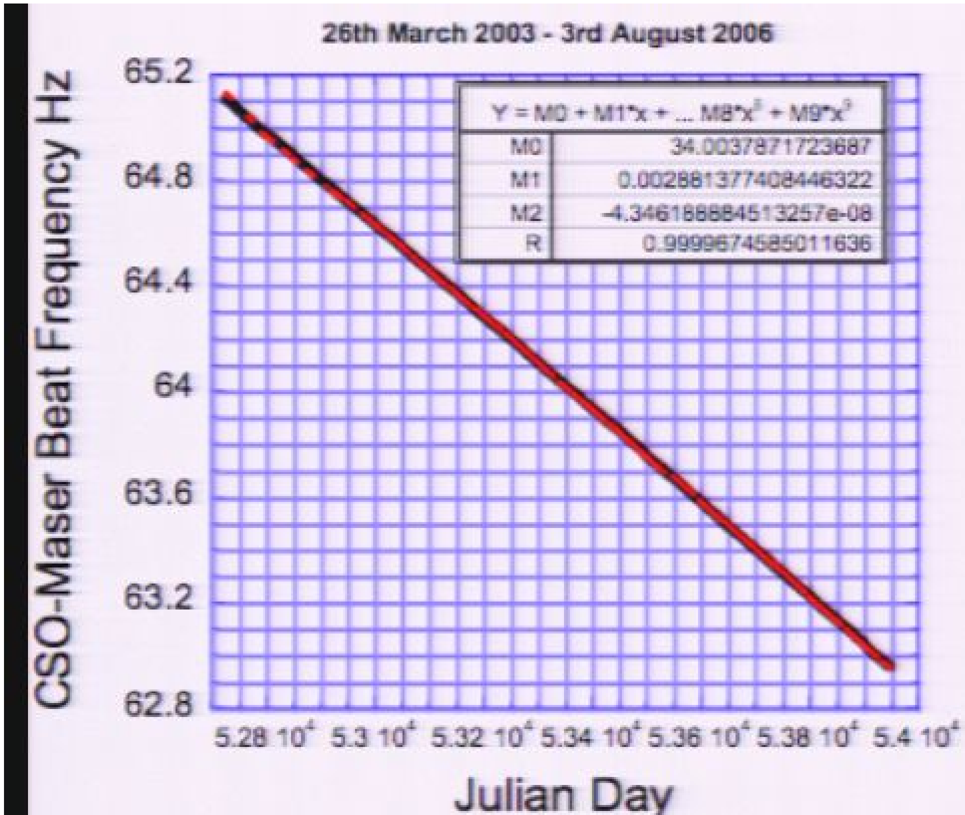


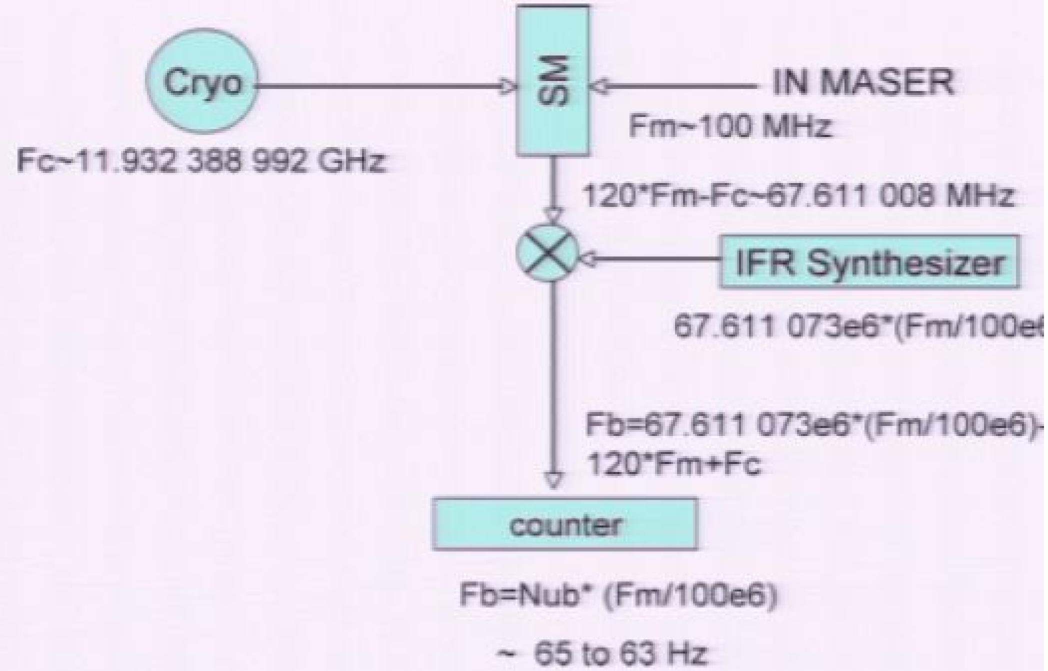
$$\frac{GM_S e}{c^2 a} \approx 1.65 \times 10^{-10}$$

$$ACos[\Omega_{\oplus} t]$$

$$BSin[\Omega_{\oplus} t]$$

http://aa.usno.navy.mil/data/docs/EarthSeasons.php



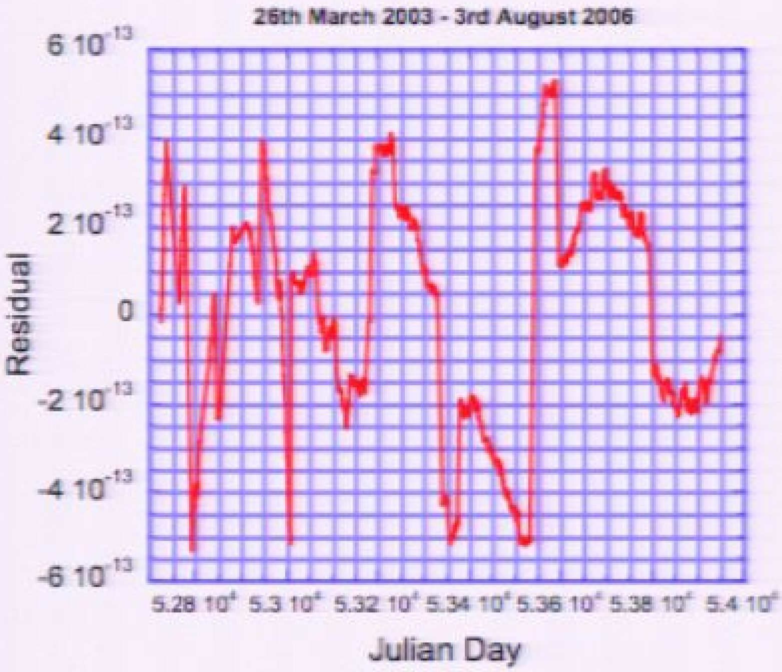


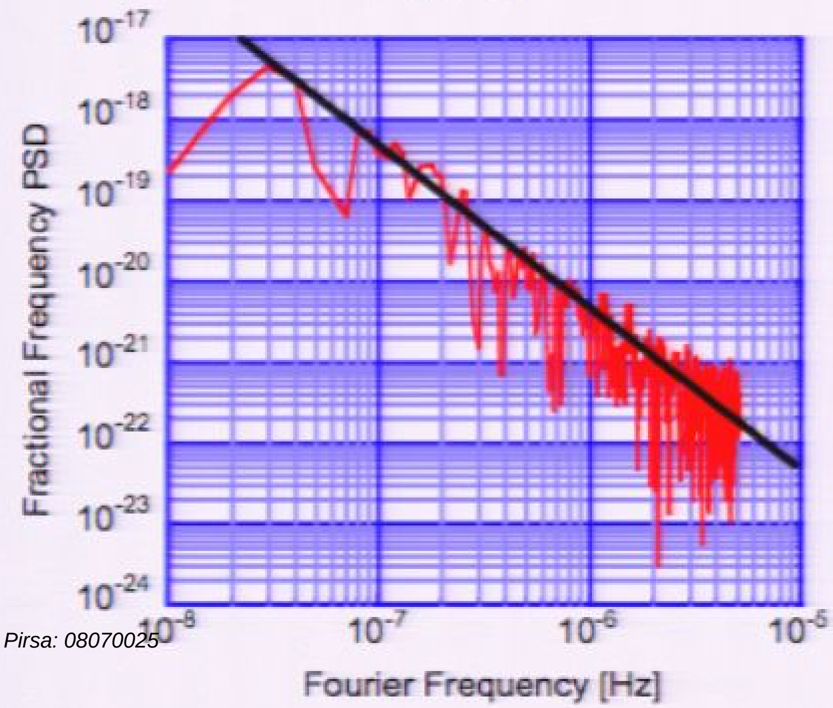
.Search for yearly variations of LPI.
'requency is sampled every 100 s -> Data is averaged over 95,000 s intervals (1.1 day
'wo ways the data is analysed.

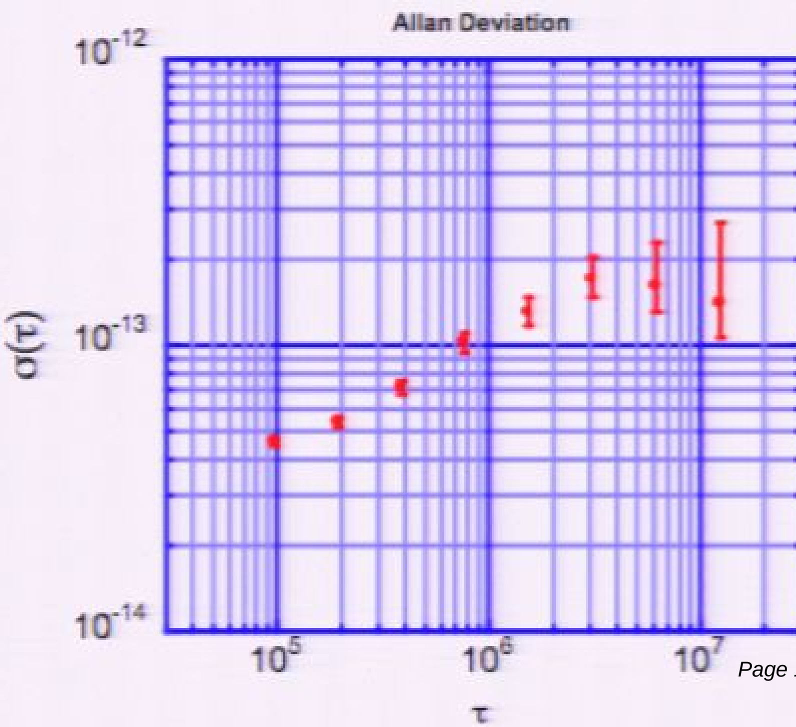
) From the residuals between a quadratic and the measured beat frequency with respe
o 12 GHz. (susceptible to technical systematics)

) From the derivative of the experimental data, which filters out systematic jumps
etween cryogenic refills and relocking of the CSO

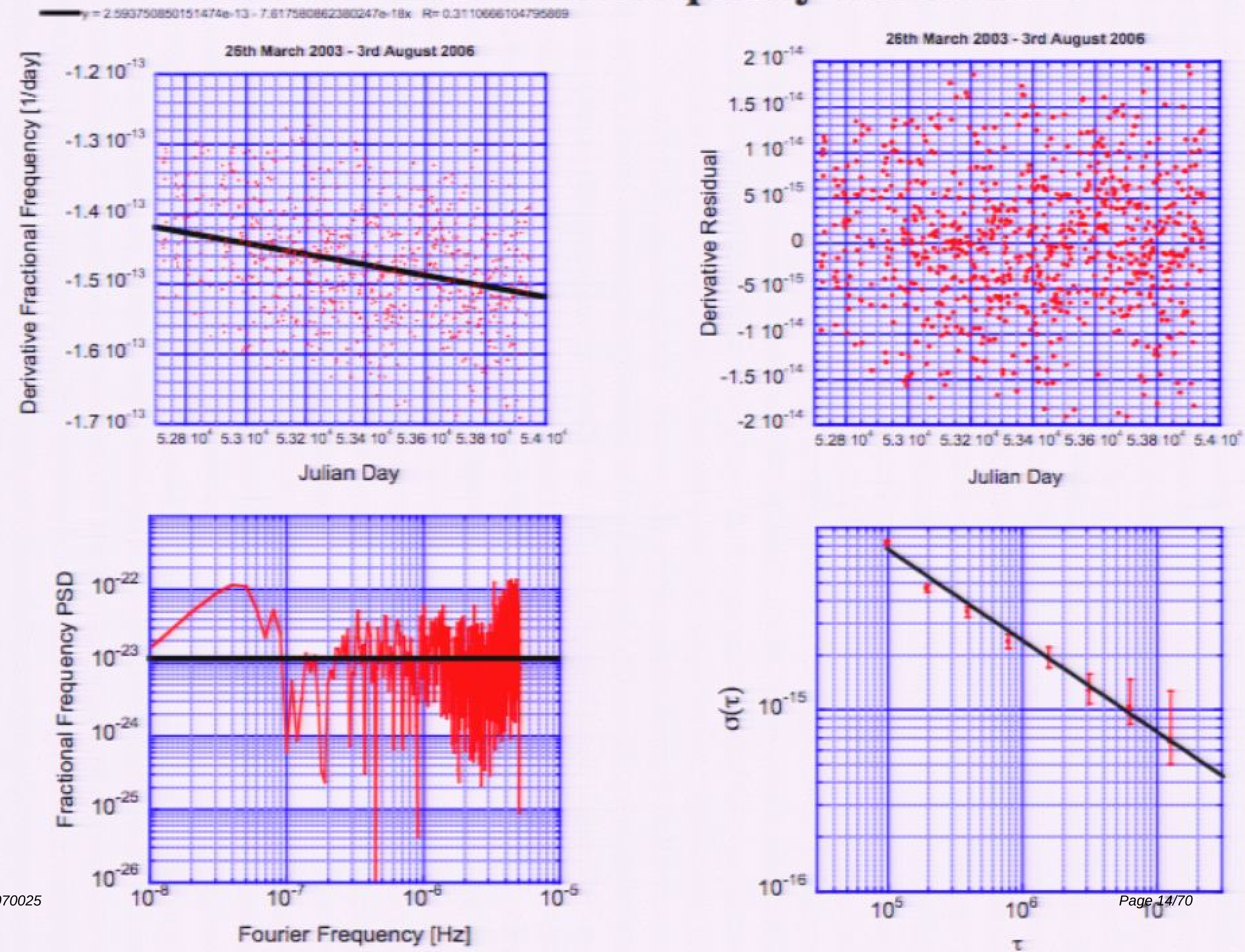
Residuals of the Beat Frequency wrt 12 GHz







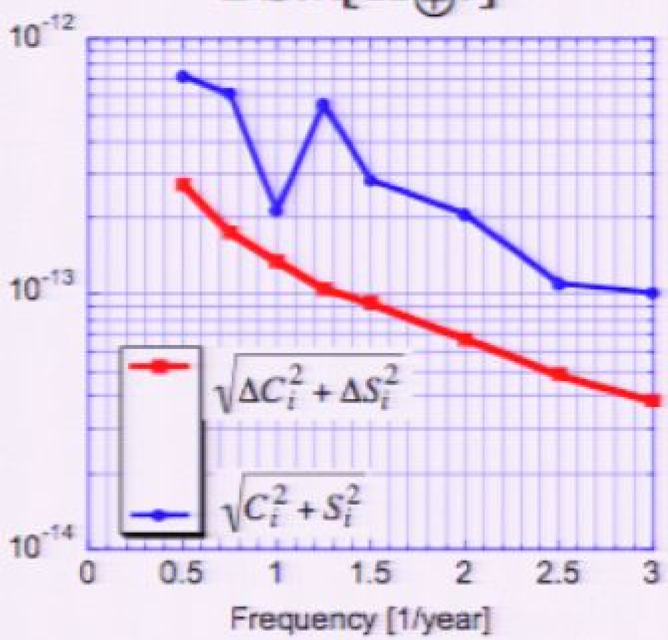
Derivative of the Beat Frequency wrt 12 GHz



Data Analysis

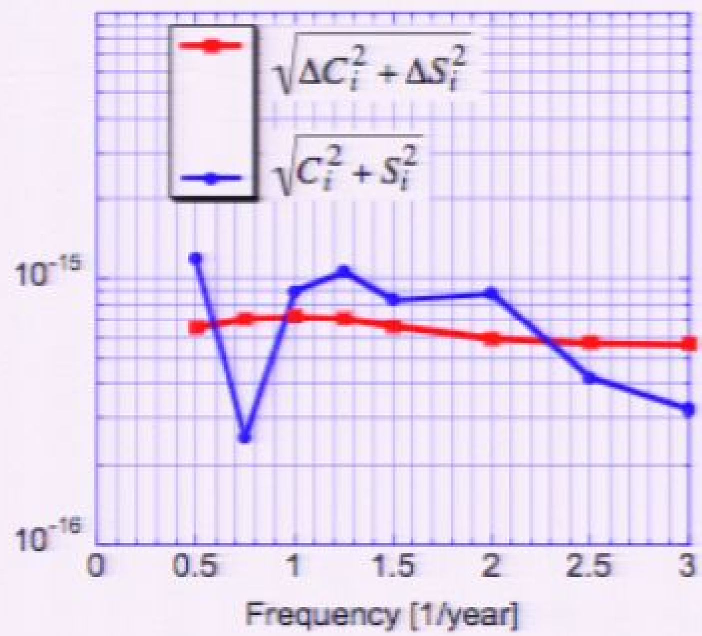
WLS analysis on the residuals of the beat frequency

$$A Cos[\Omega_{\oplus} t]$$
$$B Sin[\Omega_{\oplus} t]$$



OLS analysis on the residuals of the derivative

$$-\Omega_{\oplus} A Sin[\Omega_{\oplus} t]$$
$$\Omega_{\oplus} B Cos[\Omega_{\oplus} t]$$



$\Omega_{\oplus}$ Annual frequency = 0.017203 rads/day

In general, the amplitudes at $\Omega_\oplus$ do not show any significance much greater than the standard error, and/or much greater than the other nearby frequencies.

Method	A	B
1. WLS (Beat)	$-2.06\ (0.98) \times 10^{-13}$	$-0.51\ (0.92) \times 10^{-13}$
2. OLS (Derivative)	$0.24(0.31) \times 10^{-13}$	$-0.46\ (0.28) \times 10^{-13}$
Weighted Mean of 1 and 2	$0.3(2.9) \times 10^{-14}$	$-4.7(2.7) \times 10^{-14}$
Weighted Mean/ $\frac{GM_{se}}{c^2 a}$	$0.18(1.8) \times 10^{-4}$	$-2.8(1.65) \times 10^{-4}$

Data before March 2003 left out
> large systematic shifts and small duty cycle.

Analysis after August 2006 is yet to be included.
> H-maser was changed and the beat frequency underwent a large shift.
Data will be included in the near future. (5.4 years in total)

Will include diurnal analysis to improve statistics (nearly finished)

Compare with other resonator experiments

Cs vs Resonator (Superconducting cavity): Limit 1.7×10^{-2}

Phys. Rev. D 27, 1705 (1983), Test of the principle of equivalence by a null gravitational red-shift experiment, John P. Turneaure, Clifford M. Will, Brian F. Farrell, Edward M. Mattison, and Robert F. Vessot

I_2 vs FP resonator: Limit 4×10^{-2}

Tests of Relativity Using a Cryogenic Optical Resonator, C. Braxmaier, H. Müller, O. Pradl, J. Mlynek, A. Peters, and S. Schiller, Physical Review Letters 88 010401 (2001)

This work H-maser vs CSO resonator: Limit $\sim10^{-4}$

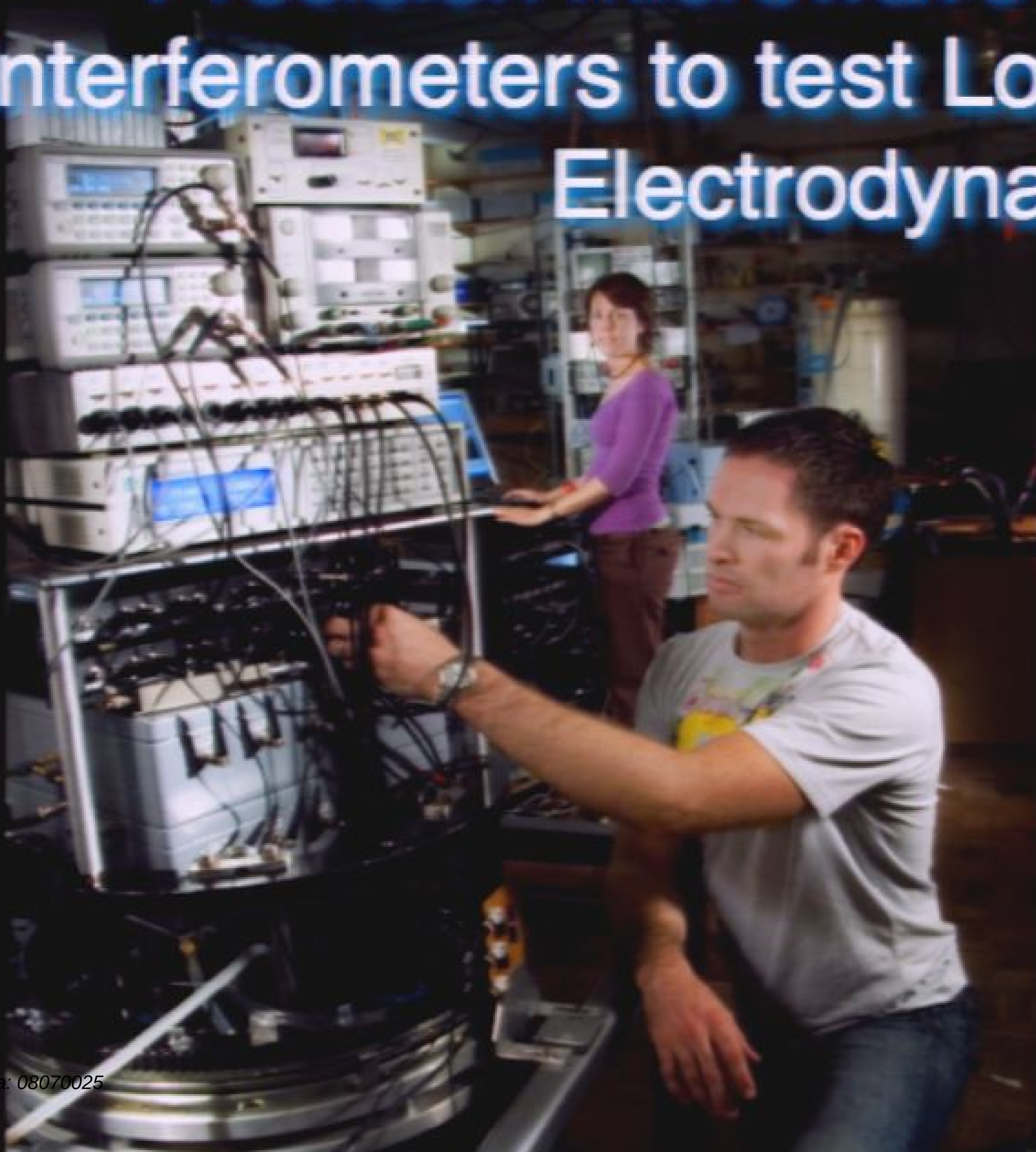
Note: H-Maser vs Cs best limit $\sim10^{-6}$ Ashby et. al. PRL 98, 070802 (2007)

With respect to fundamental constants?

$$\frac{\nu_{H\,(Hyperfine)}}{\nu_{CSO}} = \alpha^3 \frac{m_e}{m_p} g_p = \alpha^3 \frac{m_e}{m_p}\left(\frac{m_q}{\Lambda_{QCD}}\right)^{-0.1}$$

$$\frac{\Delta \frac{\nu_{H\,(Hyperfine)}}{\nu_{CSO}}}{\frac{\nu_{H\,(Hyperfine)}}{\nu_{CSO}}} = 3\frac{\Delta\alpha}{\alpha} + \frac{\Delta \frac{m_e}{m_p}}{\frac{m_e}{m_p}} - 0.1\,\frac{\Delta \frac{m_q}{\Lambda_{QCD}}}{\frac{m_q}{\Lambda_{QCD}}}$$

Precision microwave oscillators and Interferometers to test Lorentz Invariance i Electrodynamics



Michael Tobar [1]
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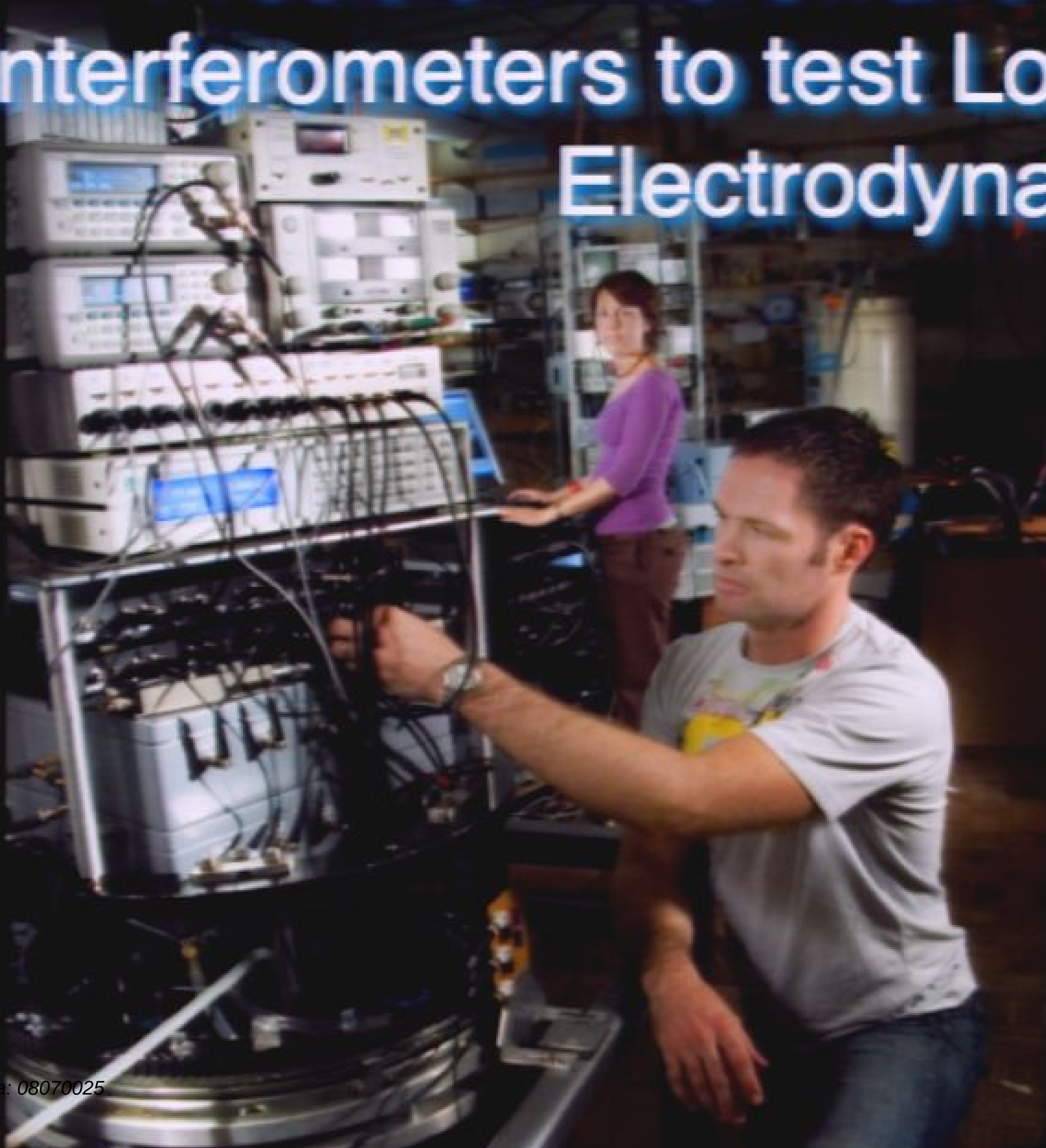

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Content

1. **Rotating Cryogenic Sapphire Oscillators (Even Parity Test)**

2. **Odd Parity Tests of Lorentz Invariance**

Tests of Lorentz Invariance

Standard Model Extension (SME)

Mathematical framework for analyzing experiments

Incorporates Lorentz and CPT violations into existing Standard Model of Physics

Colladay and Kostelecky PRD 55(11) 6760, 1997

The Photon Sector of the SME

Electromagnetic Tests ⇒ Photon Sector ⇒ Modified Maxwell Equations

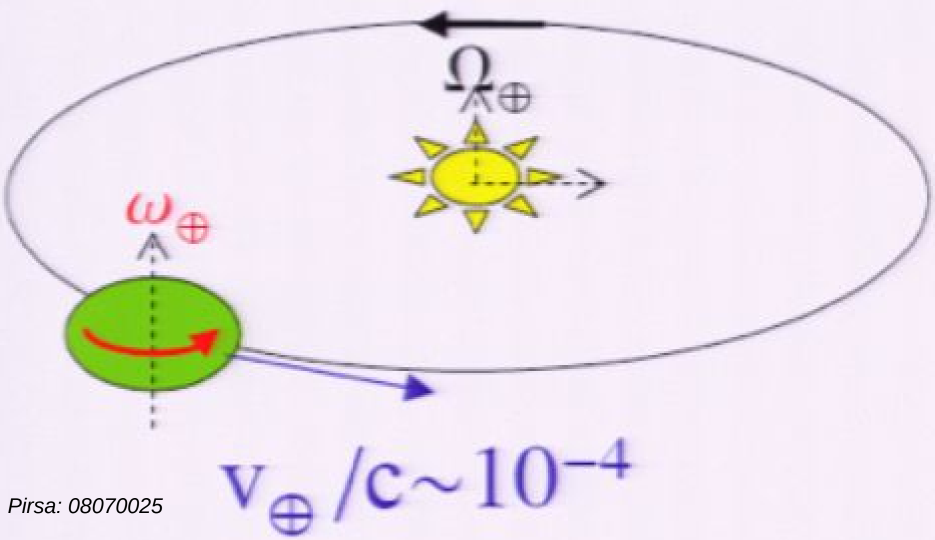
$$\begin{pmatrix} D \\ H \end{pmatrix} = \begin{pmatrix} \varepsilon_0(\varepsilon_r + \kappa_{DE}) & \sqrt{\frac{\varepsilon_0}{\mu_0}}\kappa_{DB} \\ \sqrt{\frac{\varepsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\mu_r^{-1} + \kappa_{HB}) \end{pmatrix} \begin{pmatrix} E \\ B \end{pmatrix} \longrightarrow$$

Linear combinations:

$\kappa_{e+}{}^{jk}$, $\kappa_{e-}{}^{jk}$,

$\kappa_{o+}{}^{jk}$, $\kappa_{o-}{}^{jk}$,

$\kappa_{trace} = 1/3\,\mathrm{Tr}(\kappa_{DE})$



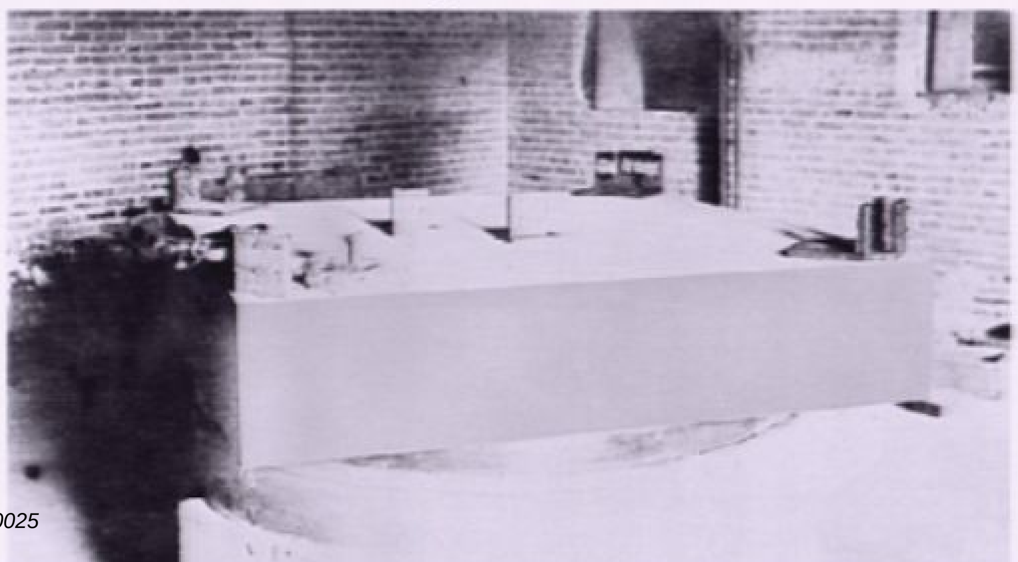
Existing Limits in sun-centred frame:

$\kappa_{e+}{}^{jk}$, $\kappa_{o-}{}^{jk} < 2\text{x}10^{-37}$

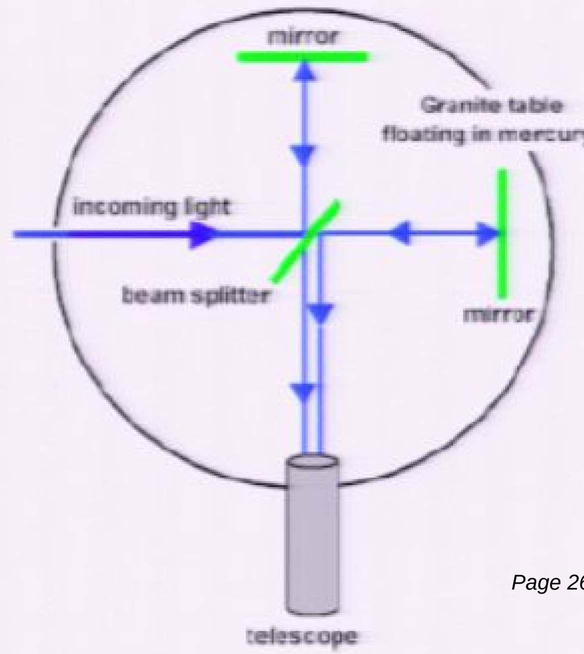
$\kappa_{e-}{}^{jk} < 10^{-16}$, $\kappa_{o+}{}^{jk} < 10^{-12}$

Introduction:
Michelson-Morley Experiments

- MM experiments generally compare the speed of light in orthogonal directions using an interferometer (phase) or cavities (frequency) (For cavities, $f \sim c / L$)
- Rotation of the experiment, using either the Earth's rotation or active rotation, modulates a putative Lorentz violating effect



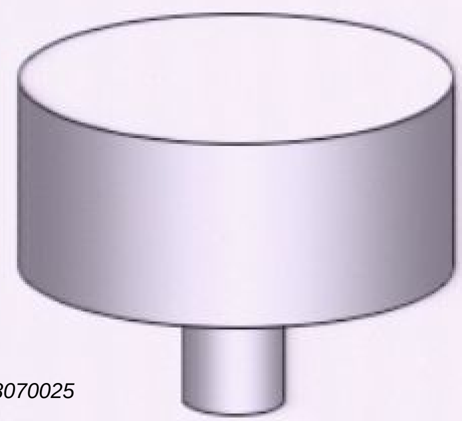
(A. Michelson and E.W. Morley, Am. J. Sci. 34, 1887)

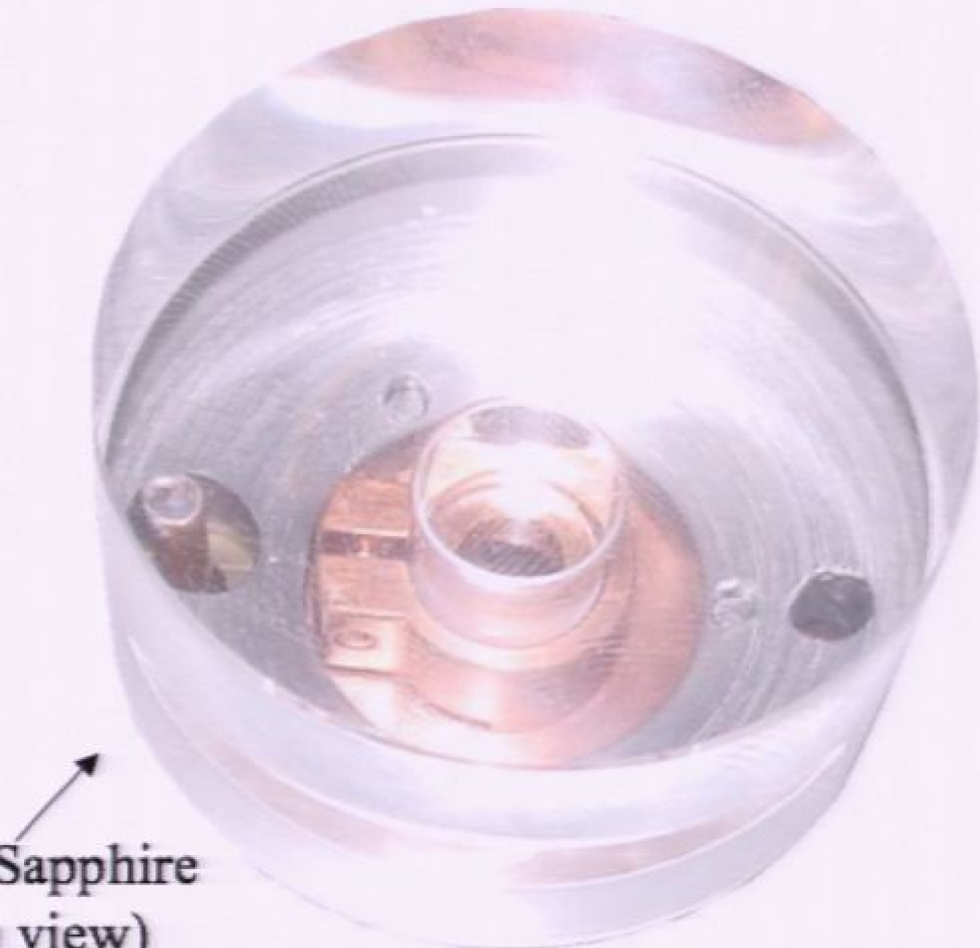


UWA Sapphire Clock:

Most Accurate clock to measure 0.1 seconds to a few hours

- Single crystal Sapphire at cryogenic temperature (4~10K):





Single crystal Sapphire Resonator (top view)

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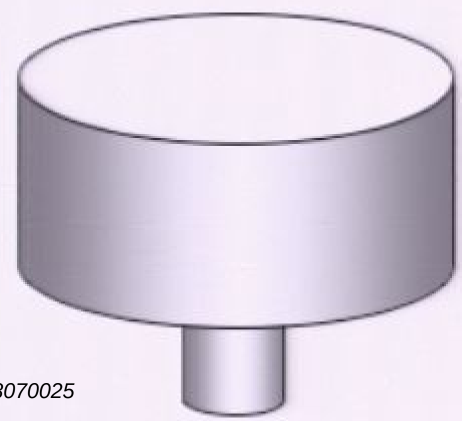
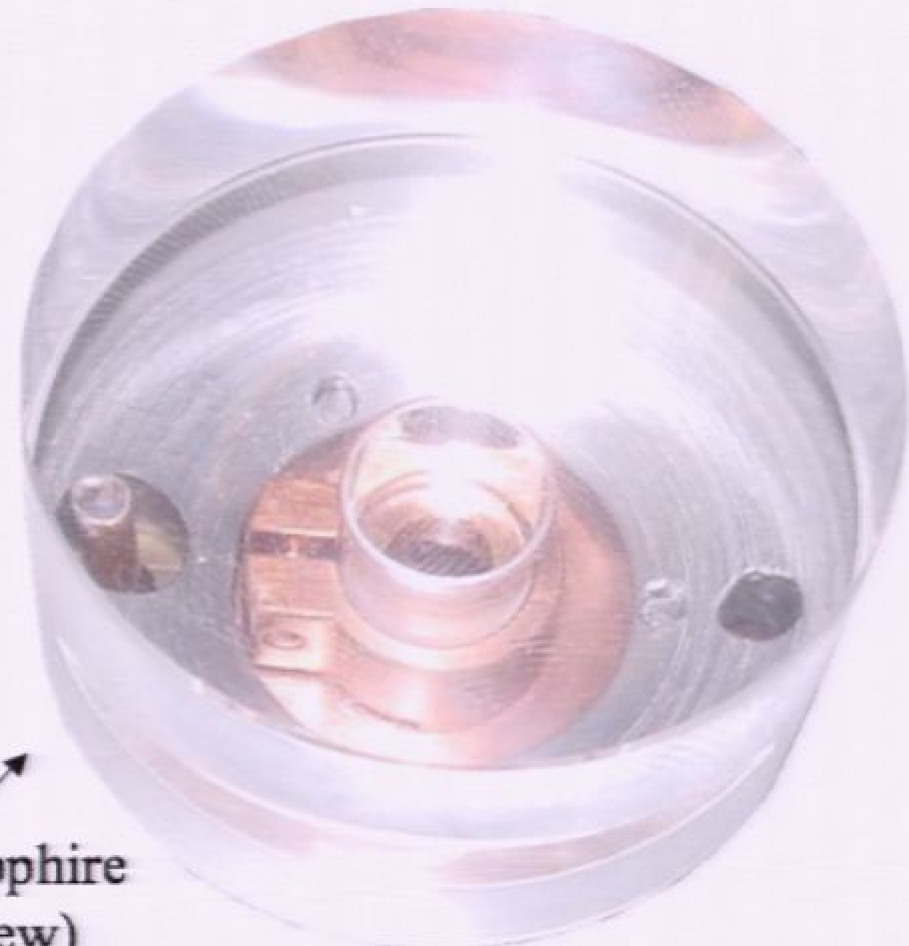
- Single crystal Sapphire at cryogenic temperature (4~10K):

- Supporting whispering gallery (WG) modes





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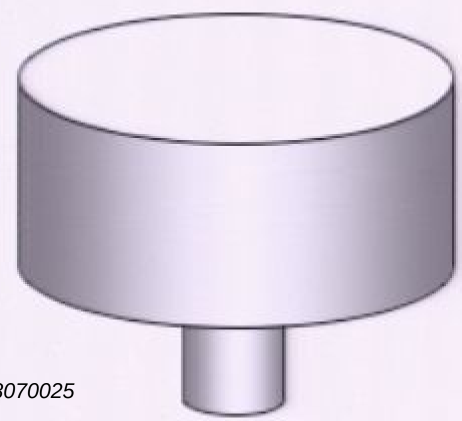

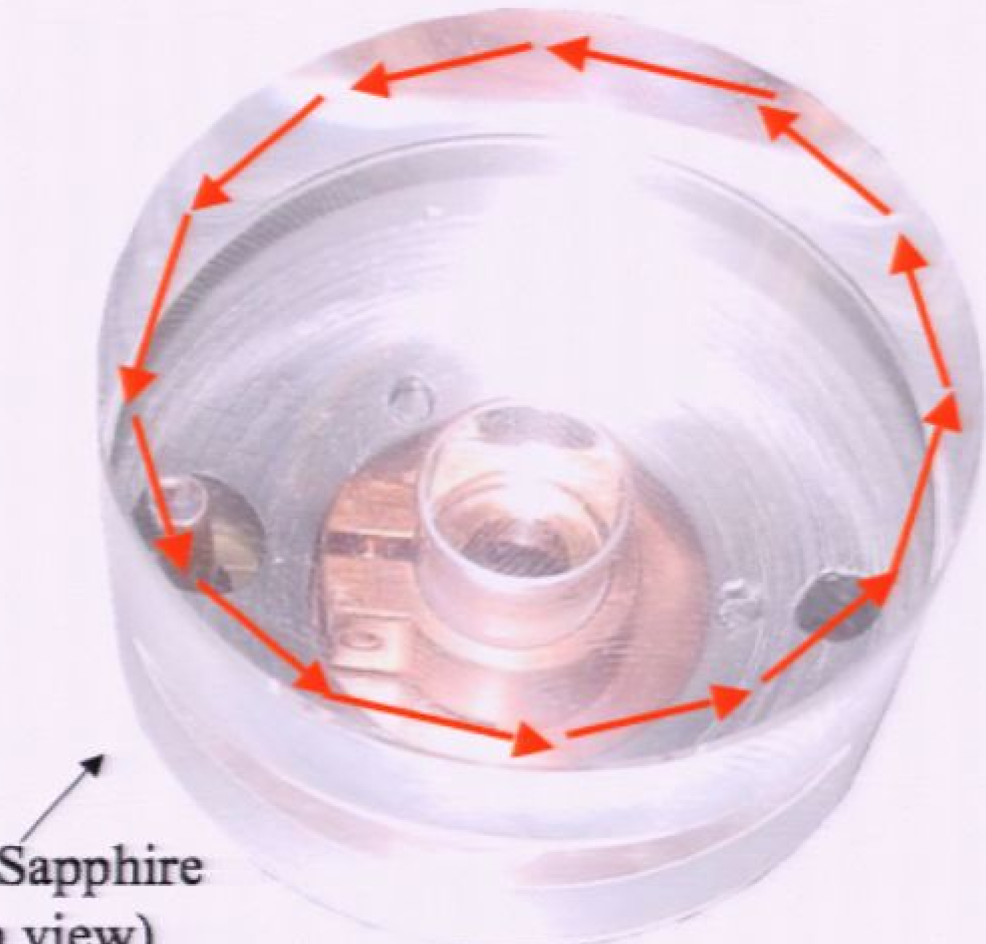

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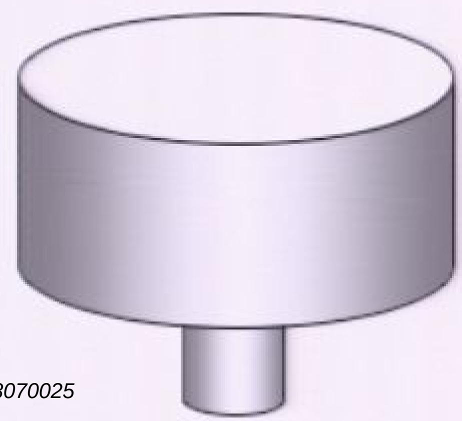

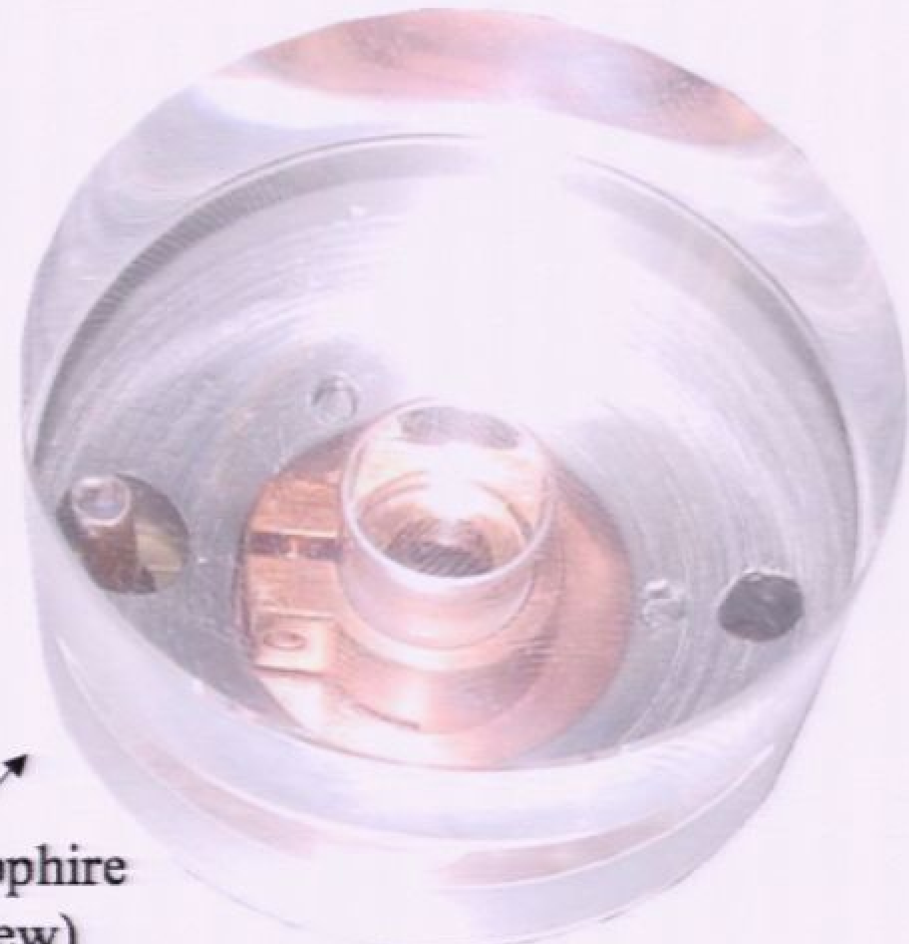

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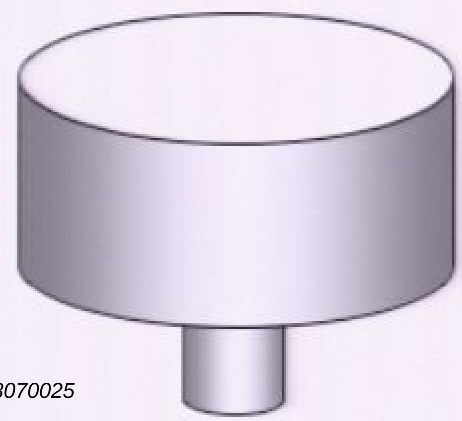
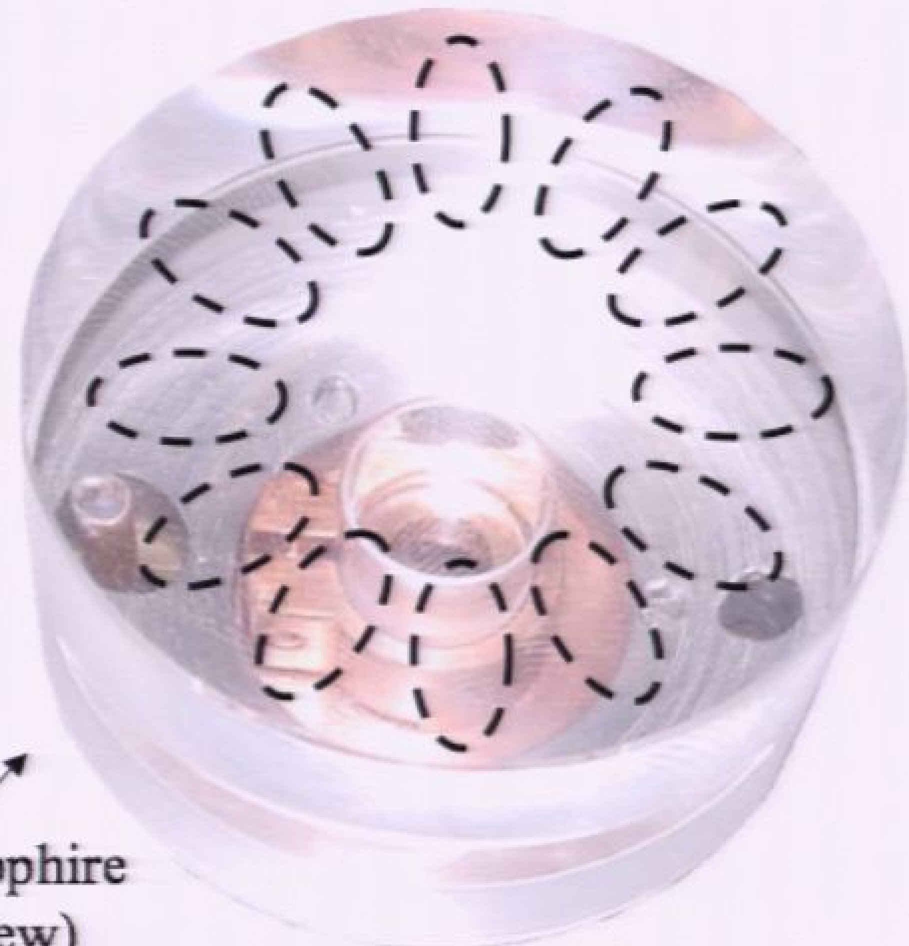
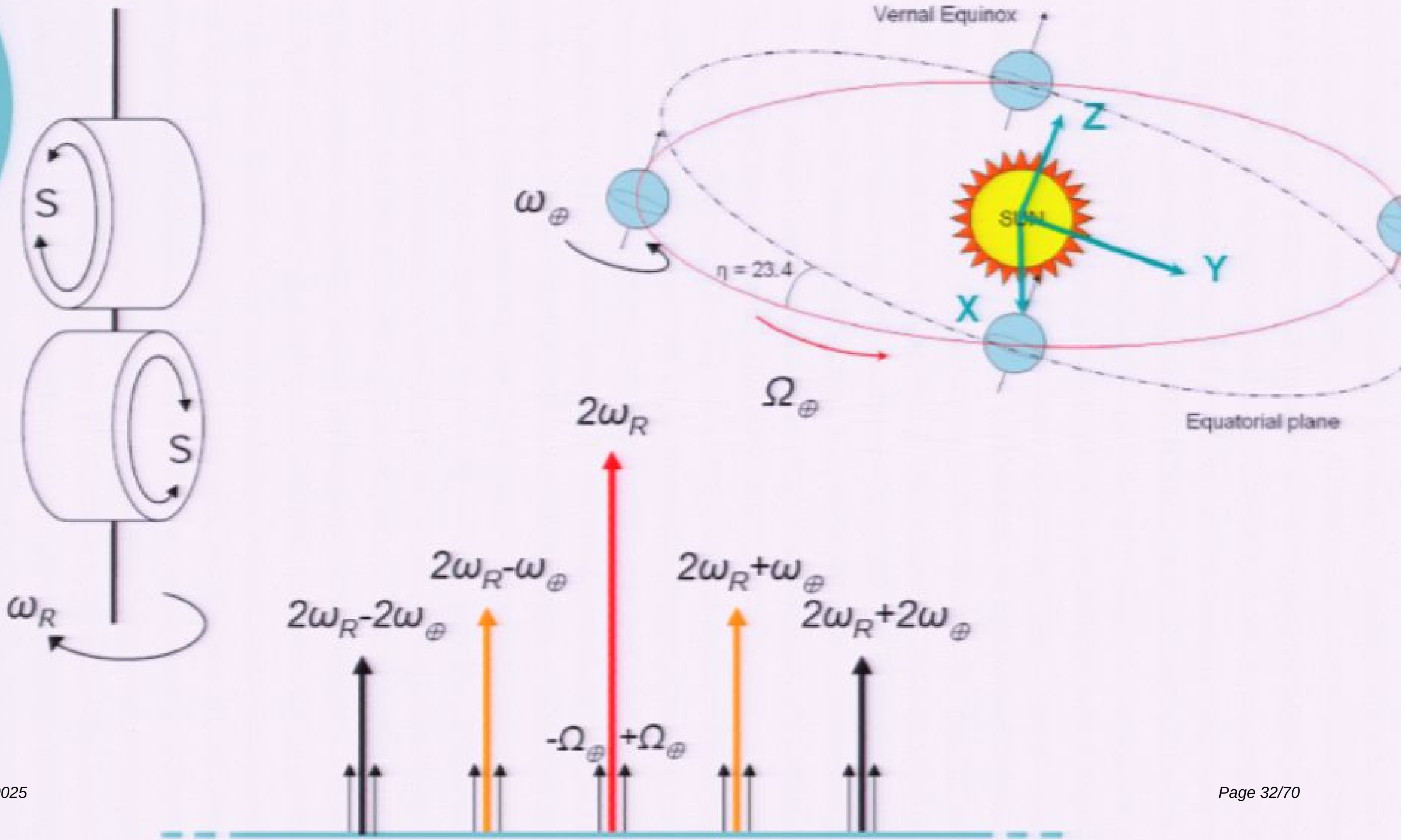
- Supporting whispering gallery (WG) modes



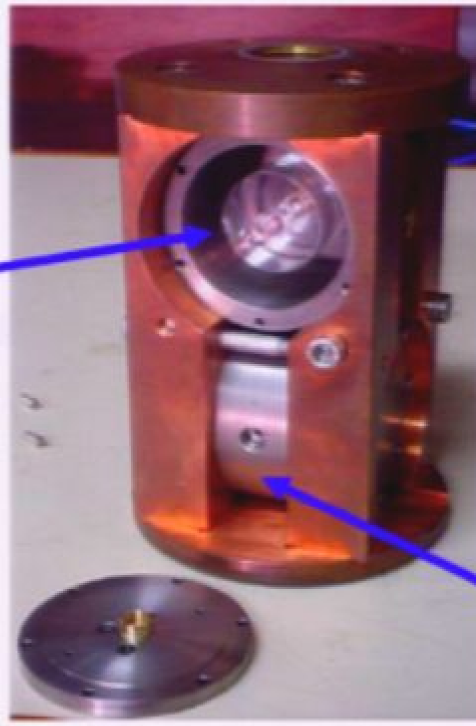


Single crystal Sapphire Resonator (top view)

Theory:
Frequencies of interest

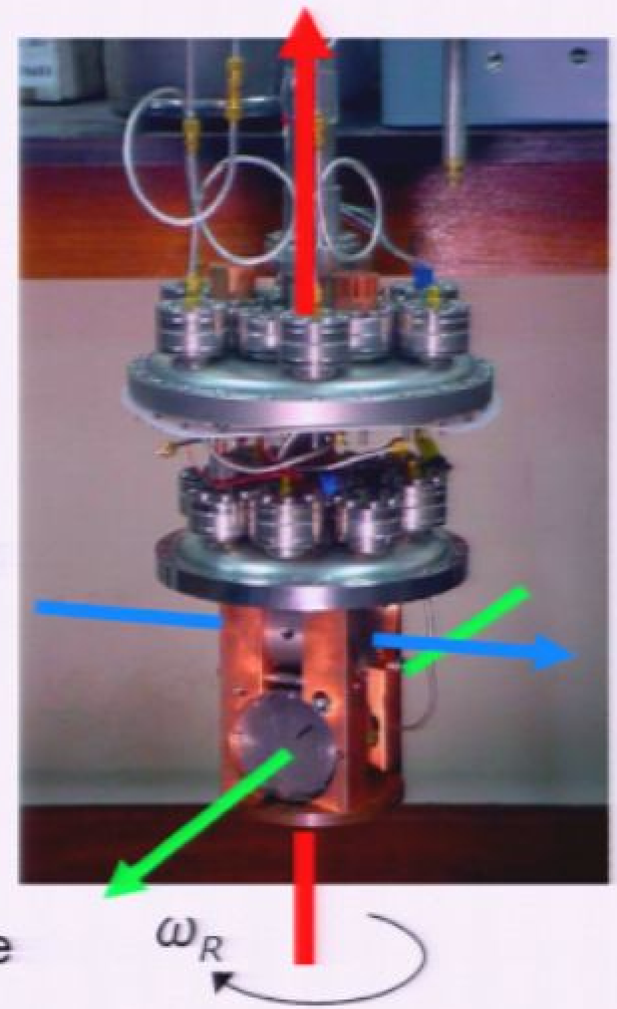


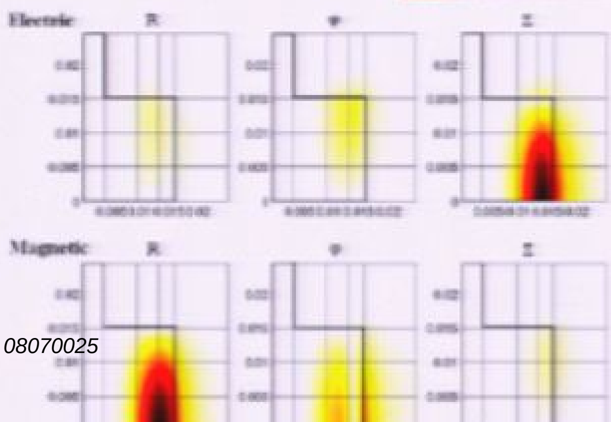
Experiment:
Resonators



Cylindrical Sapphire crystal

Superconducting Niobium Cavity

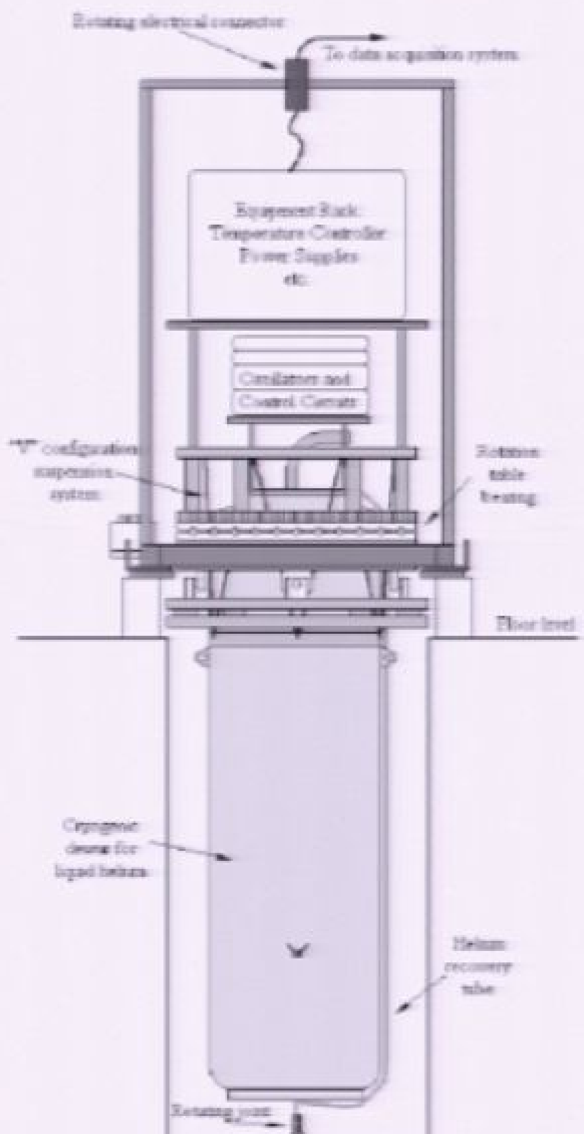




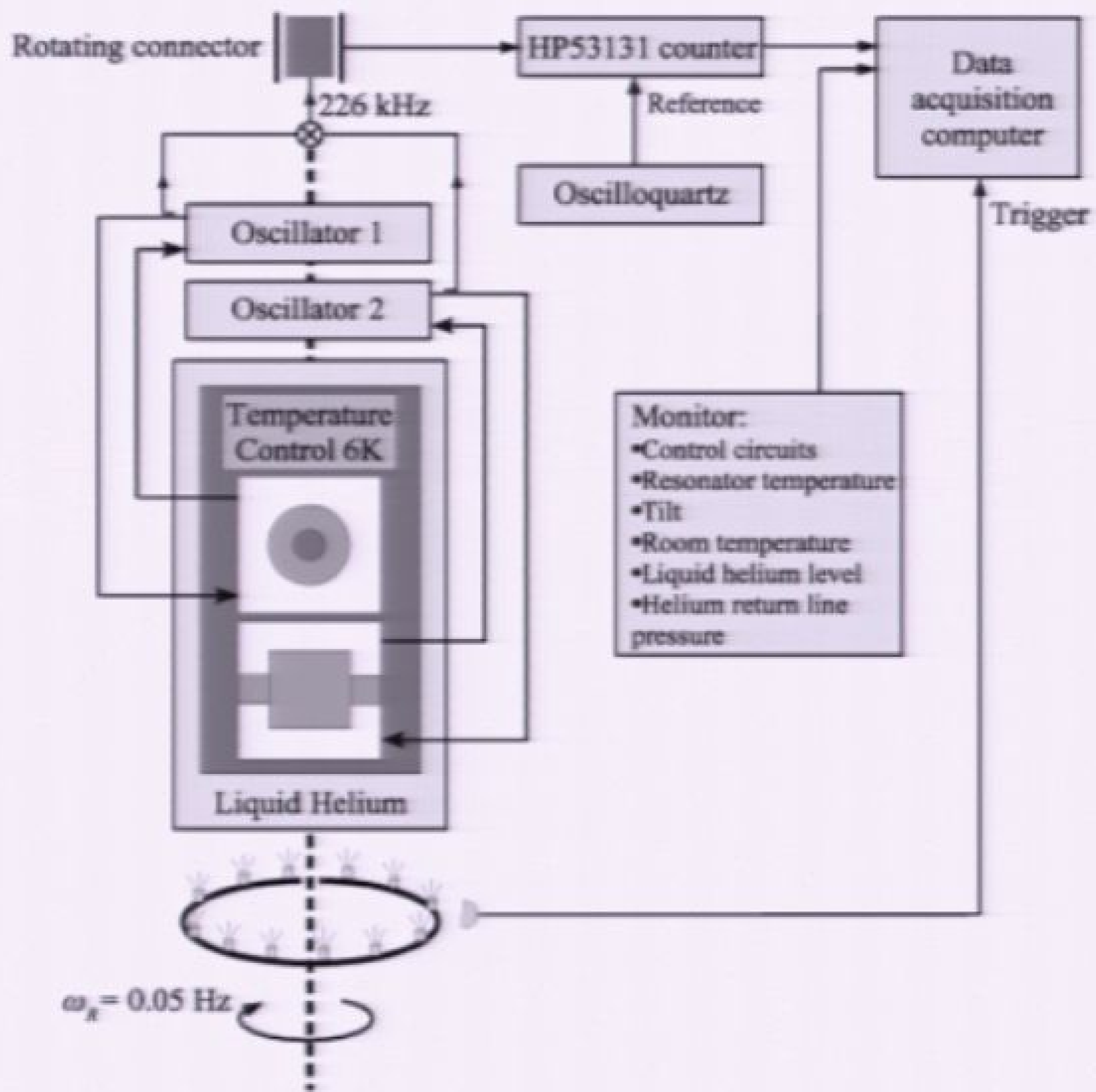
Operate the E8,1,1 mode
Frequency ~ 10GHz
Q ~ 1 x 10^8

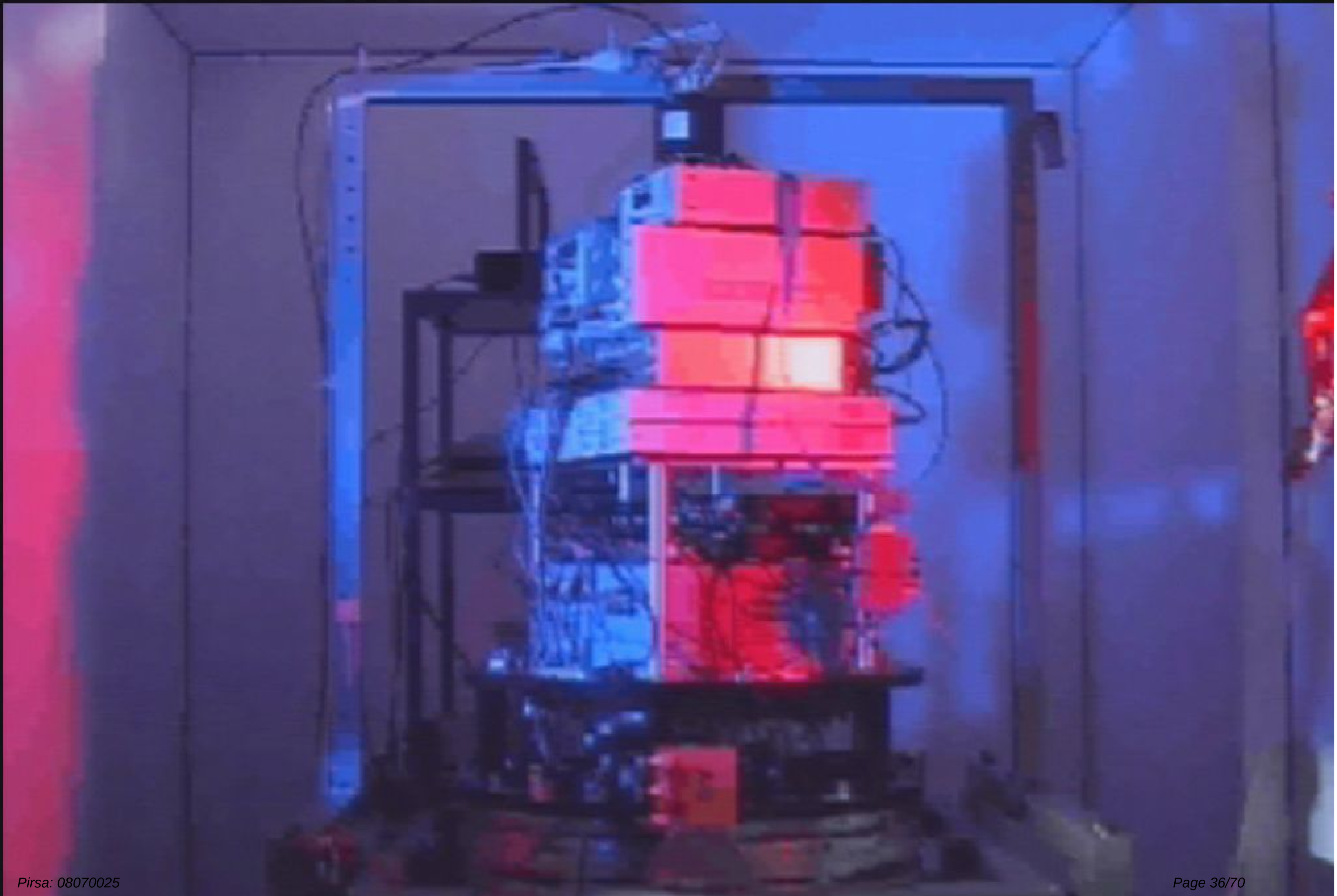
Experiment:

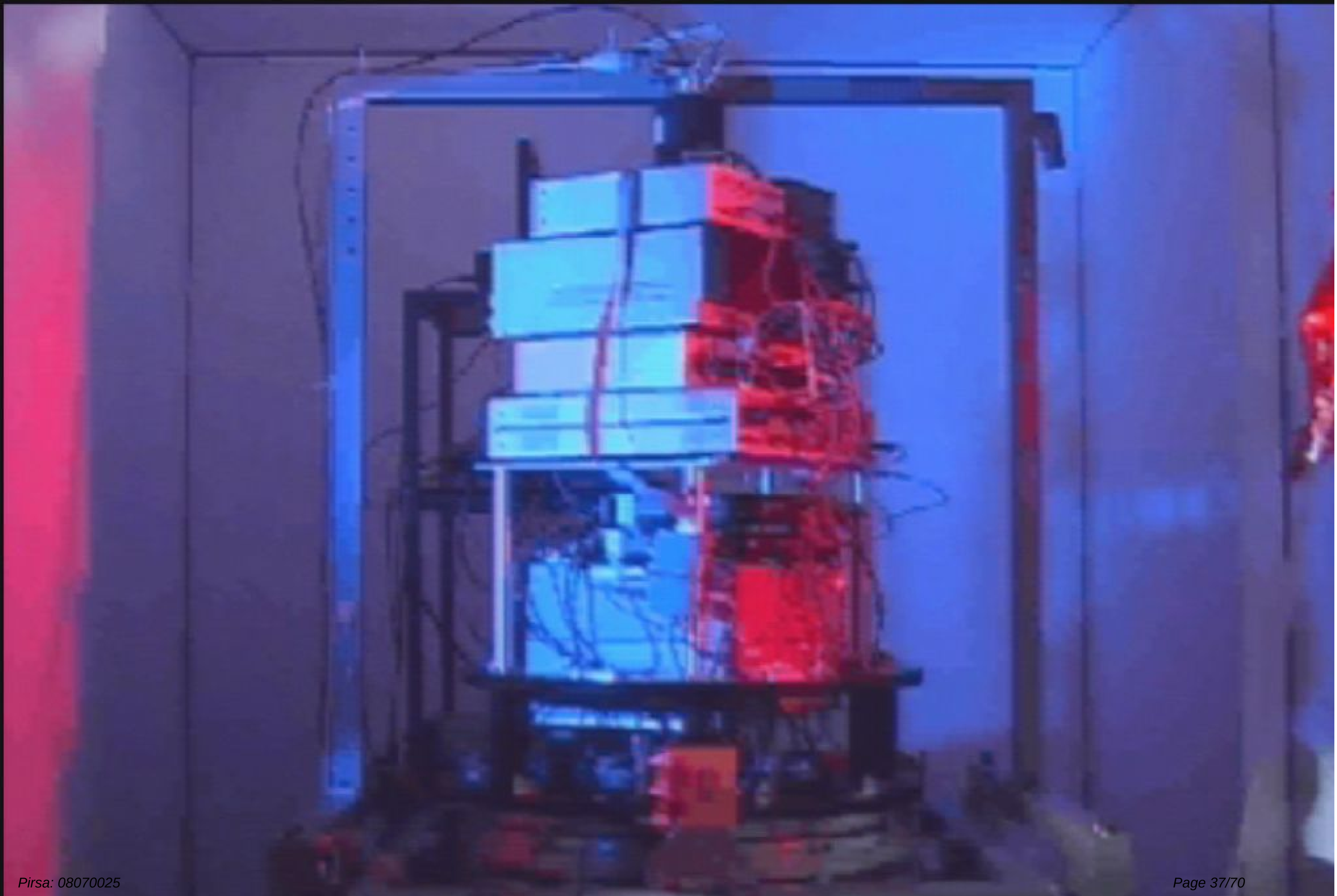
Rotation system

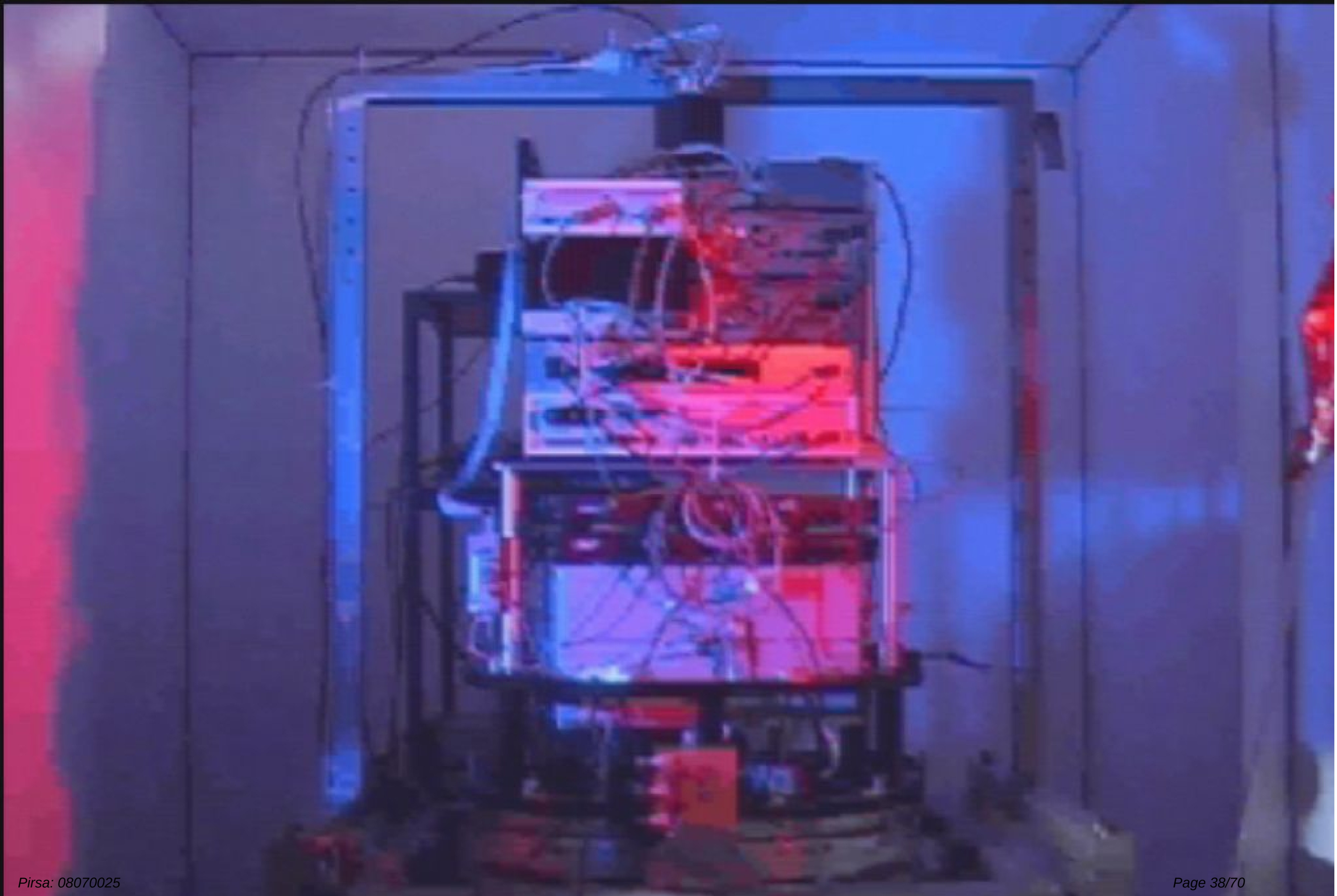


Experiment:
Overview

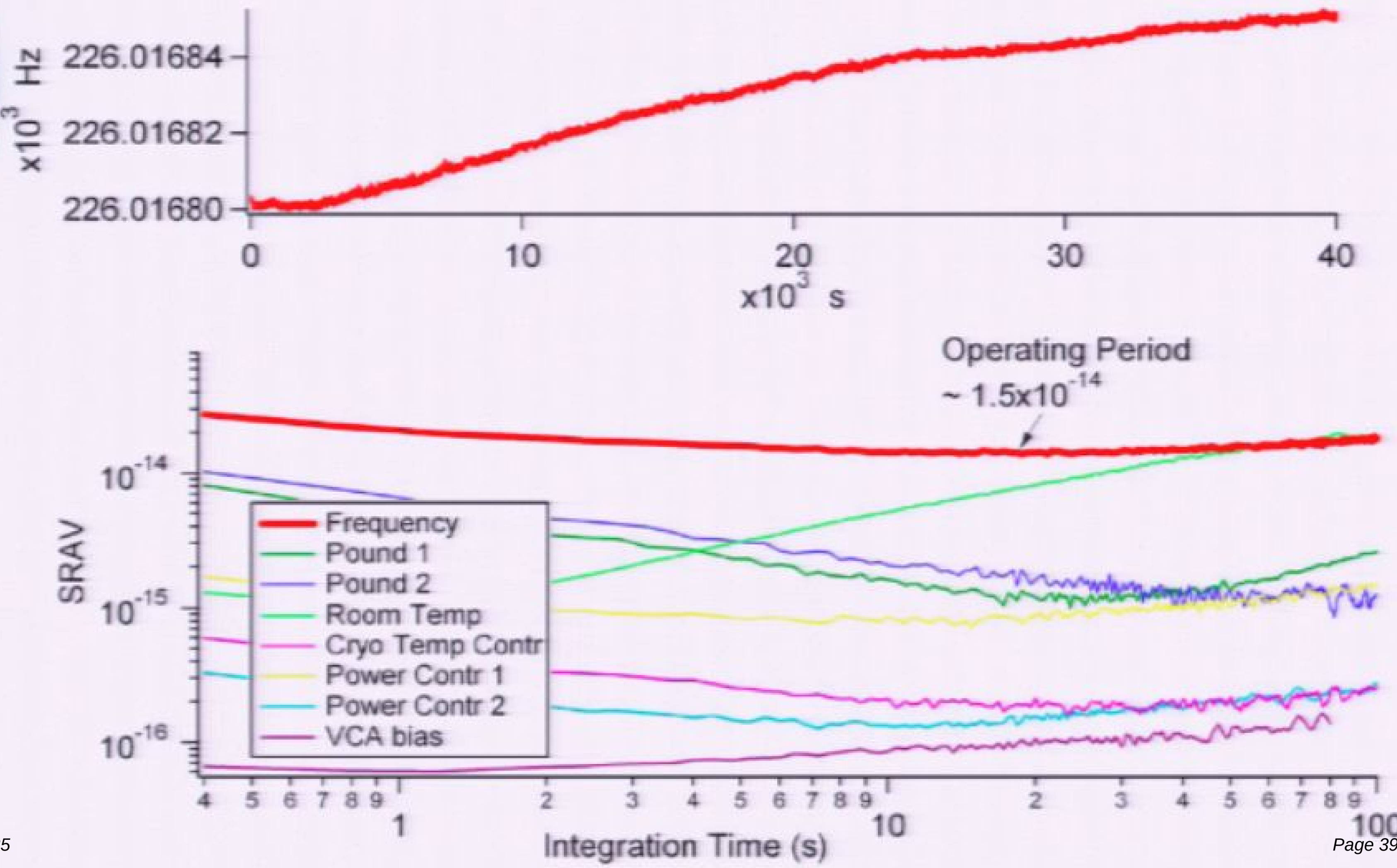




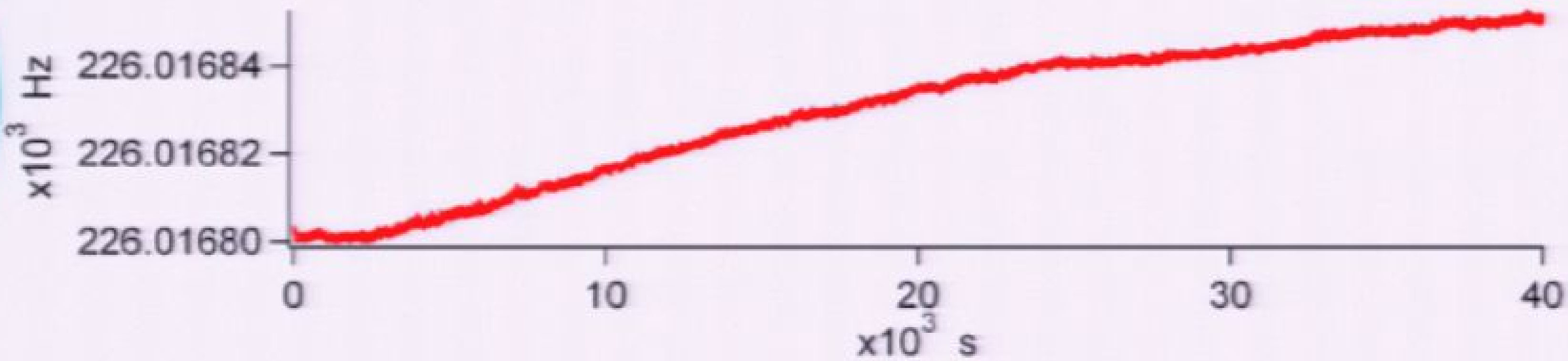


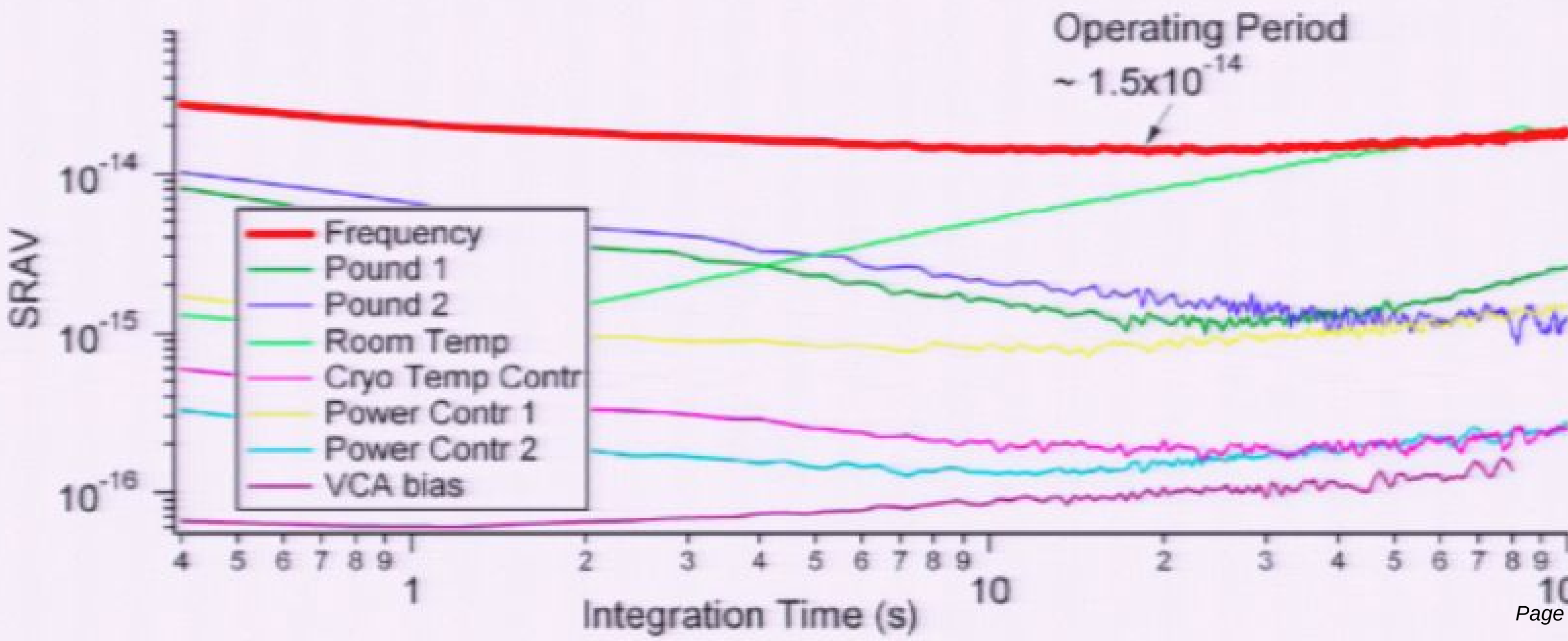


Experiment:
Fractional frequency instabilty



Experiment:
Fractional frequency instabilty





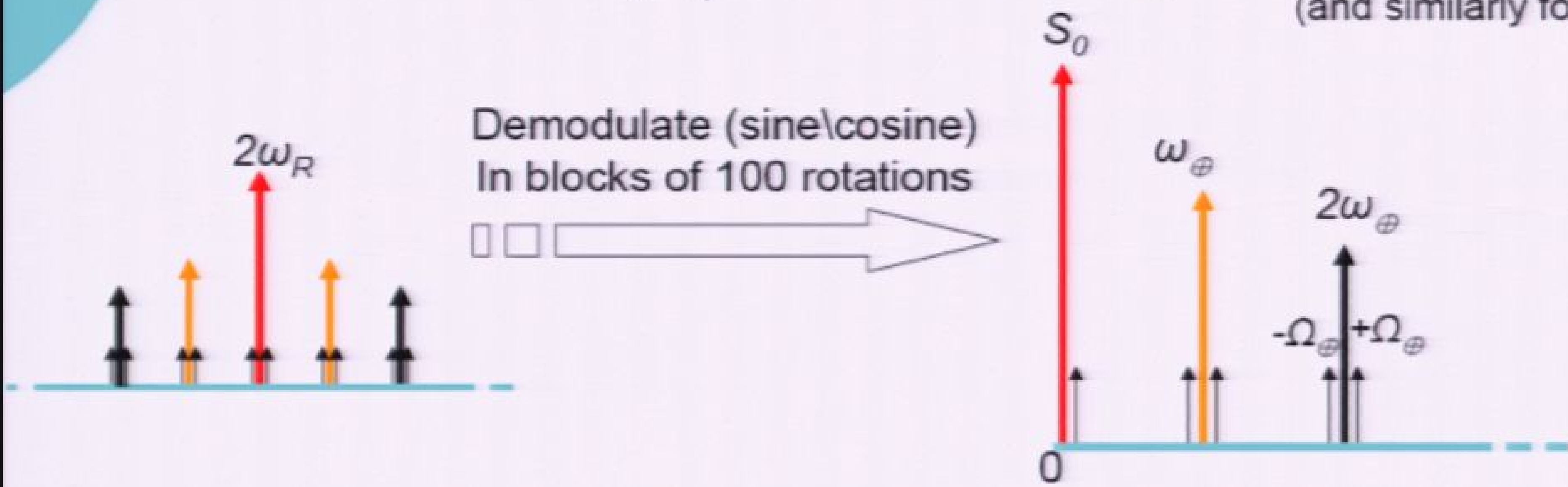
Results:

Analysis 2

$$\frac{\Delta f(t)}{f} = A + Bt + C(t)\cos(2\omega_R t) + S(t)\sin(2\omega_R t)$$

$$S(t) = S_0 + \sum_i S_{S,i}\cos(\omega_i t) + S_{C,i}\sin(\omega_i t)$$

(and similarly for cosine



$$C_{C,2\omega_\oplus+\Omega_\oplus} \sim \frac{1}{2}\kappa_{o+}^{XZ}(3+\cos[2\chi])\sin\left[\frac{\eta}{2}\right]^2 \beta_{op}$$

$$C_{S,\omega_\oplus+\Omega_\oplus} \sim \sin\left[\frac{\eta}{2}\right]\left(\kappa_{o+}^{XZ}\cos\left[\frac{\eta}{2}\right] + \kappa_{o+}^{XY}\sin\left[\frac{\eta}{2}\right]\right)\sin[2\chi]\beta_{op}$$

Results:

Standard Model Extension

Parameter	**Complete Analysis [1]**	Previous Analysis [2]	Recent Short Analysis [3]
κ_{e-}^{XY}	**2.9 (2.3)**	-57 (23)	-3.1 (2.5)
κ_{e-}^{XZ}	**-6.9 (2.2)**	-32 (13)	-1.9 (3.7)
κ_{e-}^{YZ}	**2.1 (2.1)**	-5 (13)	-4.5 (3.7)
$\kappa_{e-}^{XX} - \kappa_{e-}^{YY}$	**-5.0 (4.7)**	-32 (46)	5.4 (4.8)
κ_{e-}^{ZZ}	**143 (179)**	.....	-19 (52)
K_{o+}^{XY}	**-0.9 (2.6)**	18 (15)	2.0 (2.1)
K_{o+}^{XZ}	**-4.4 (2.5)**	-14 (23)	-3.6 (2.7)
K_{o+}^{YZ}	**-3.2 (2.3)**	27 (22)	2.9 (2.8)

x10-1 (rows κ_{e-})

x10-1 (rows K_{o+})

Analysis assumes no cancellation

[1] P. Stanwix et al., Phys. Rev. D 74, 081101(R), (2006), [2] P. Wolf et al., Phys. Rev. D 70, 051902(R), (2004

Results:
RMS

- Our experiment is inherently insensitive to the boost term $P_{KT} = \beta - \alpha - 1$ so there is no benefit from a full year analysis
- Take a weighted average of P_{MM} determined from each data set

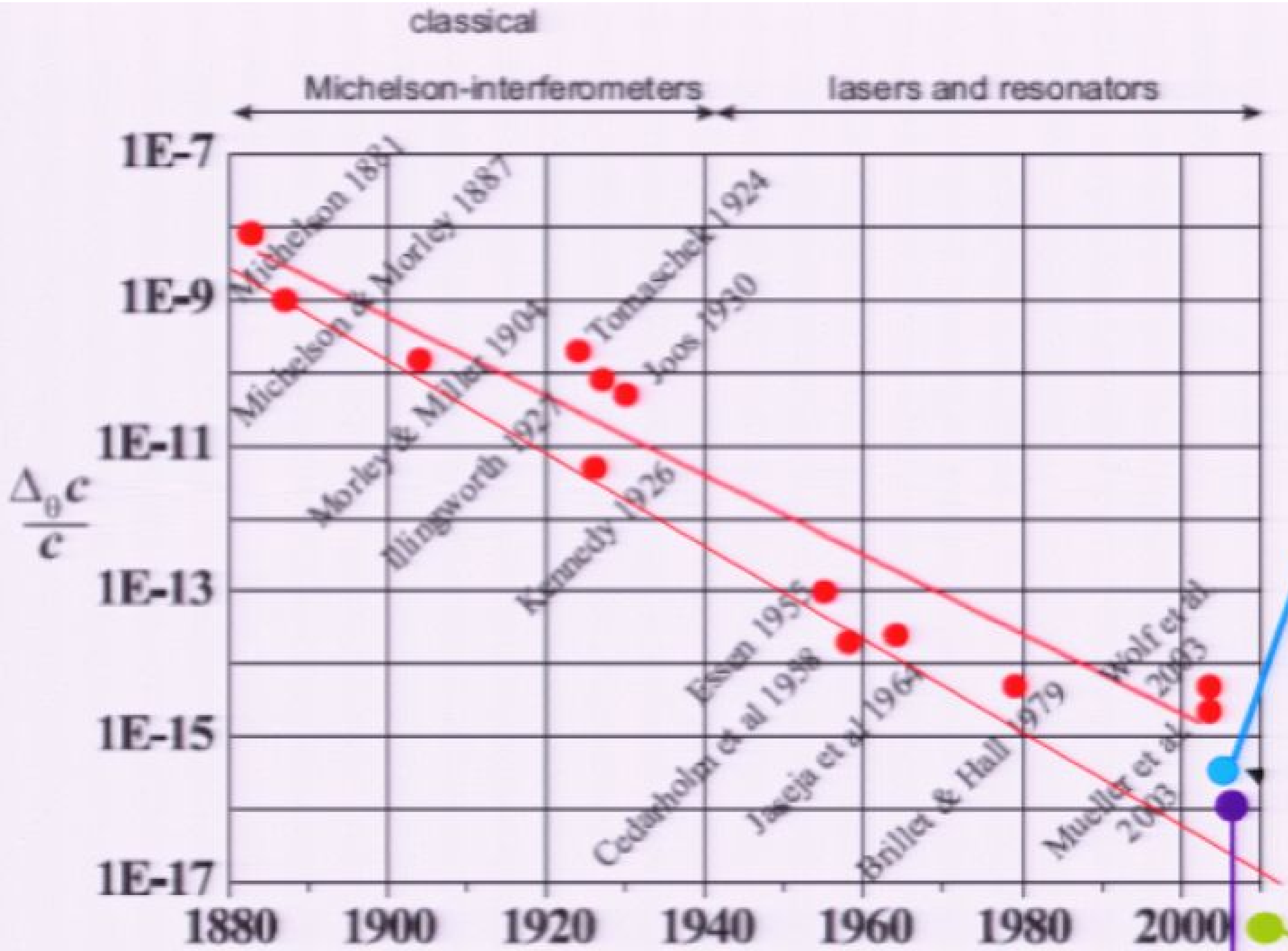
Eg.

$$C_{2\omega_R + 2\omega_\oplus} = P_{MM}[4.6\times10^{-7} - 1.4\times10^{-8}\cos(\Phi_0) - 7.1\times10^{-8}\sin(\Phi_0)]$$

(Φ_0 is the annular phase of the earth's orbit)

RMS Parameter	This work [1]	Previous Best Result [2]
	x 10^{-11}	
$P_{MM} = {}^1/_2 - \beta + \delta$	9.4 (8.1)	-21 (19)

([1] P. Stanwix et al., Phys. Rev. D 74, 081101(R), (2006),
[2] S. Herrmann et al., Phys. Rev. Lett. 95, 150401, (2004).)



Stanwix, Tobar et. al. 2005, PRL
Herrmann et. al. 2005
Antonini et. al. 2005

Future

Stanwix, Tobar et. al. PHYSICAL REVIEW D 74, 081101(R) (2006)

Hartnett et. al. Applied Physics Letters (Vol.89, No.20)

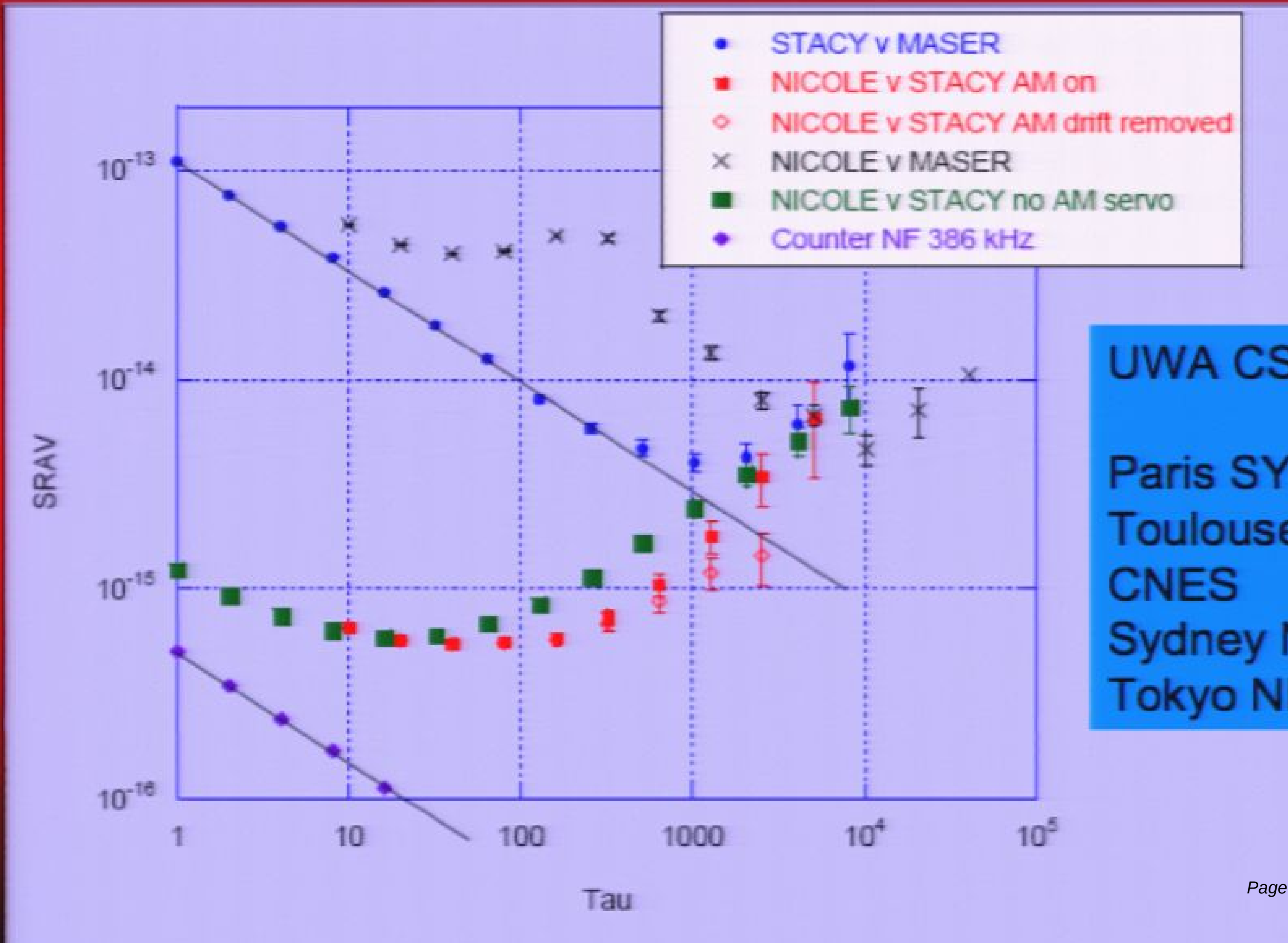
Sapphire Resonator

WGE and WGH modes
are spatially orthogonal

Crystal Diameter: 51mm

Whispering Gallery Modes
excited in crystal near dielectric
vacuum interface

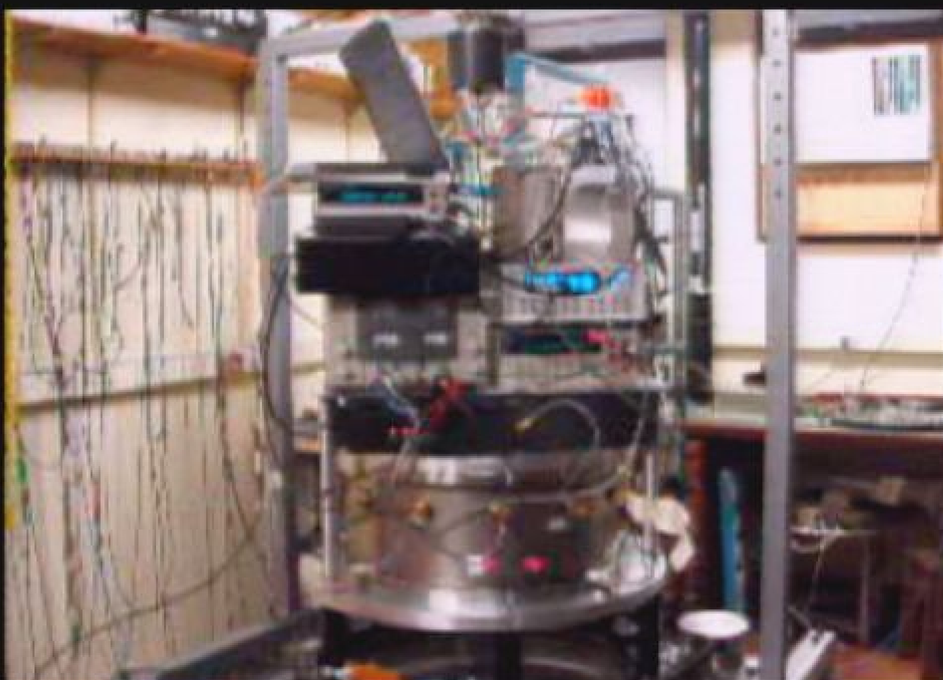
Stability



UWA CSOs

Paris SYRTE
Toulouse
CNES
Sydney NMI
Tokyo NICT

Continuous Operation of an Odd Parity Lorentz Invariance Test in Electrodynamics Using a Microwave Interferometer



Michael Tobar
Paul Stanwix
Eugene Ivanov
John Hartnett
Jean-Michel le Floch

[1]FSM Group, The University of Western Australia

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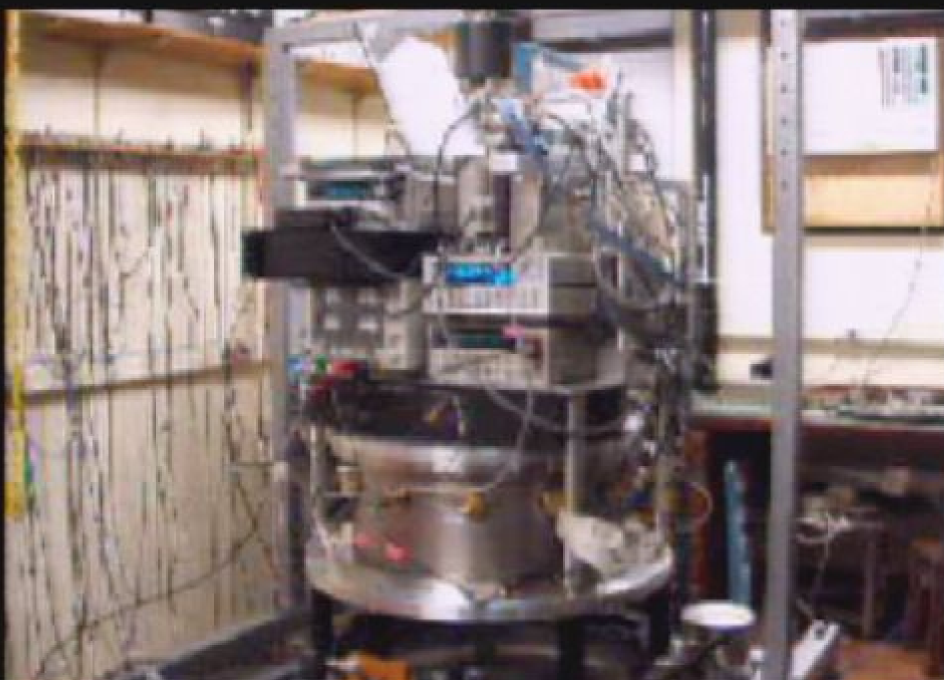

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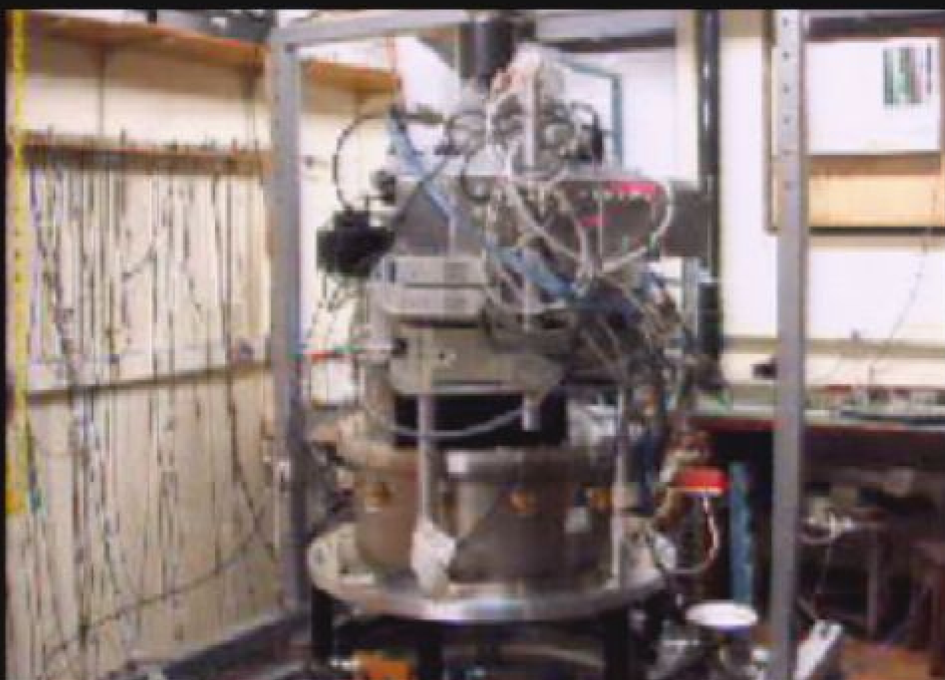

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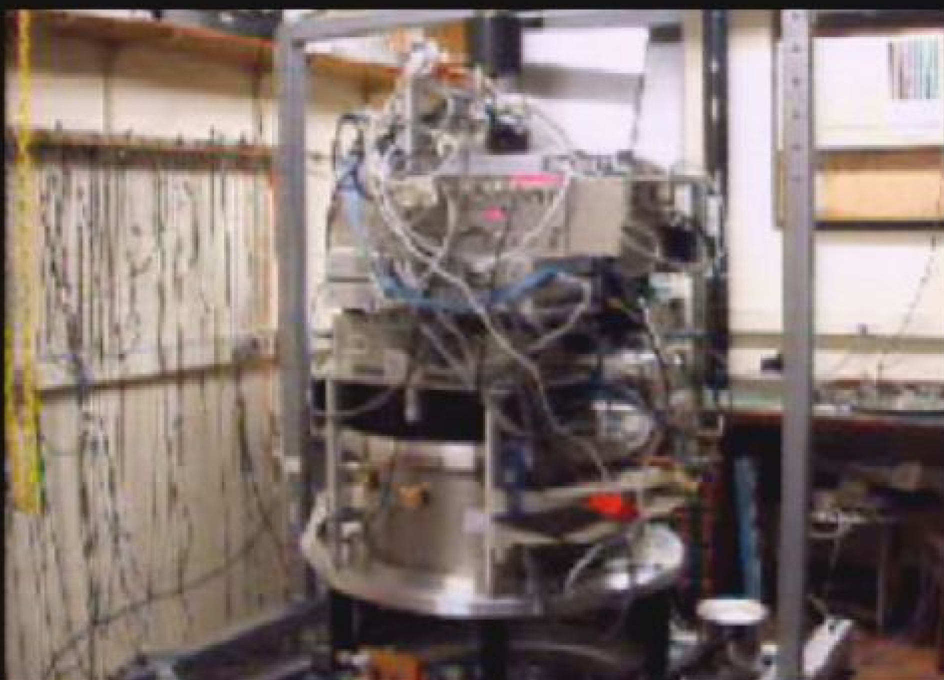

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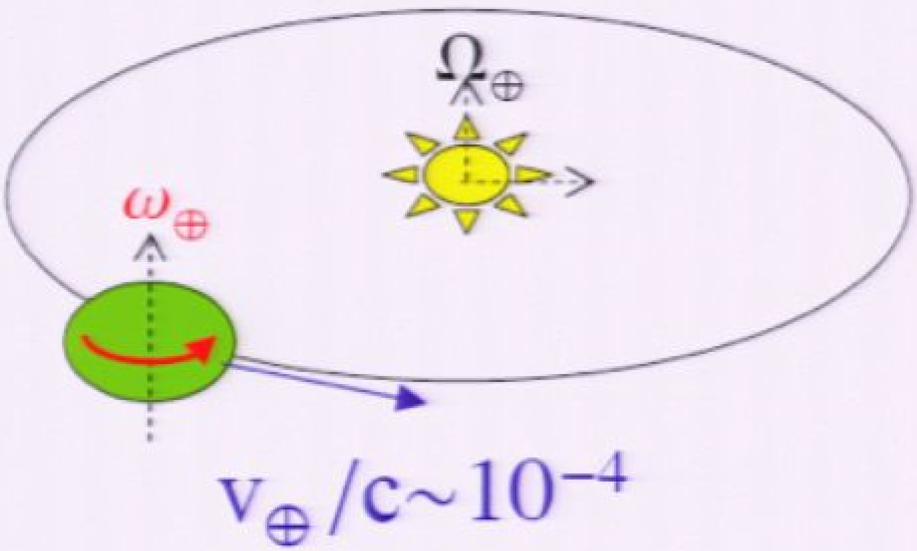
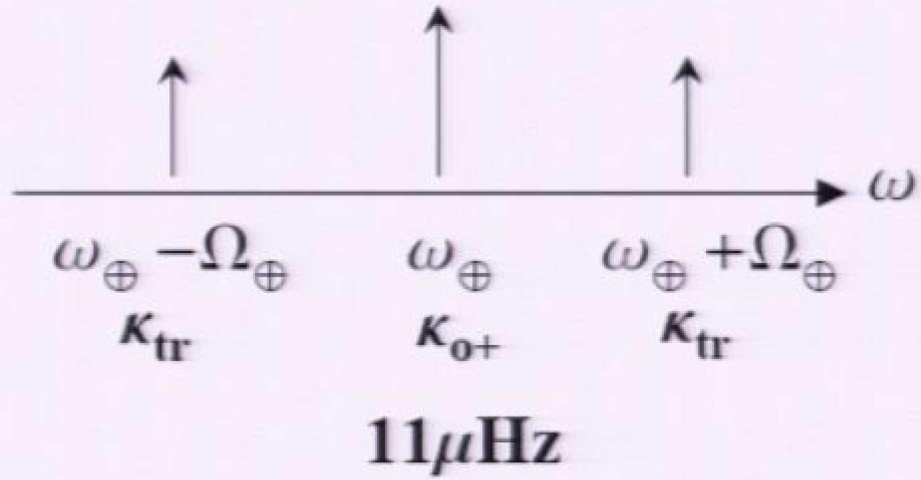
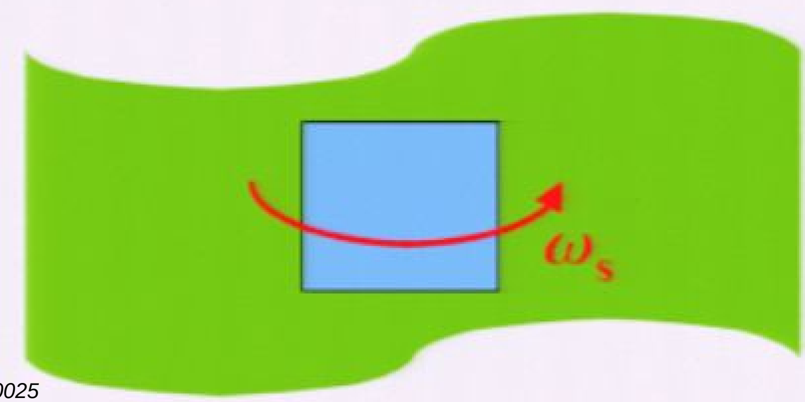
Frequencies of Interest

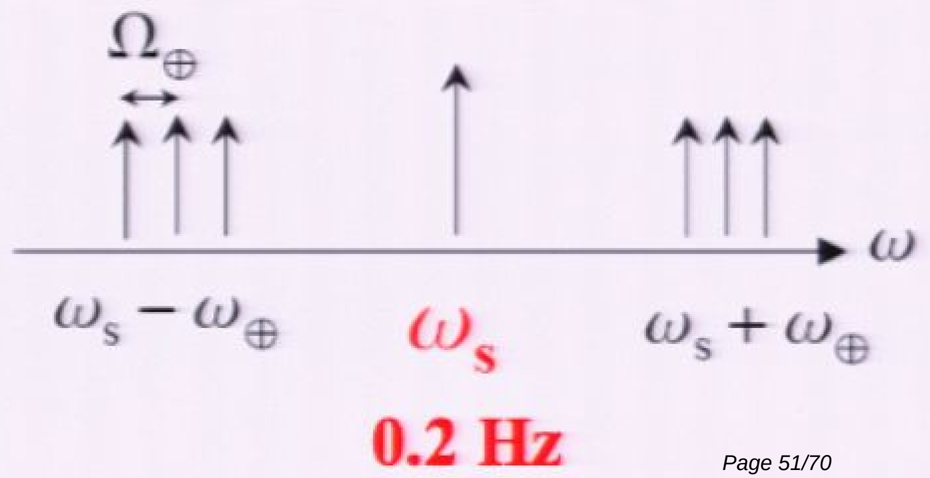


For odd-parity tests:

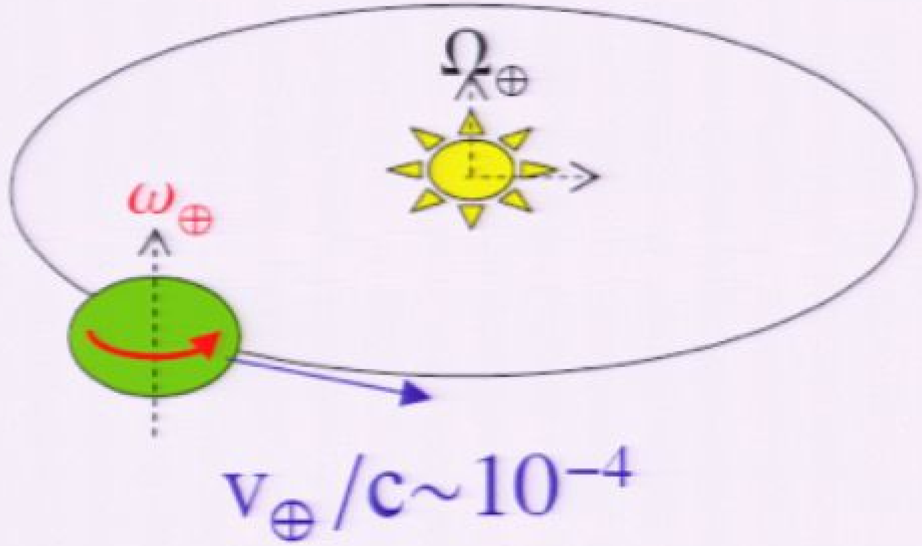


Rotation in Lab:

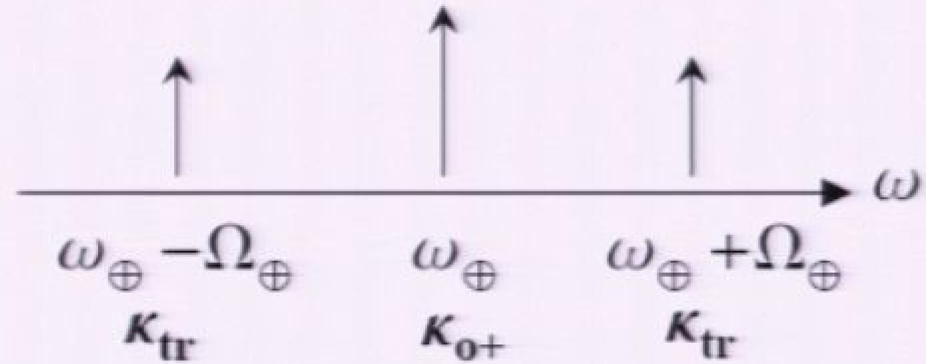




Frequencies of Interest

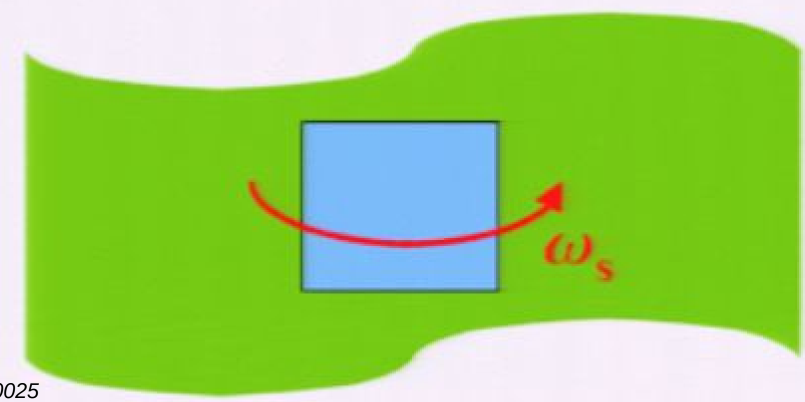


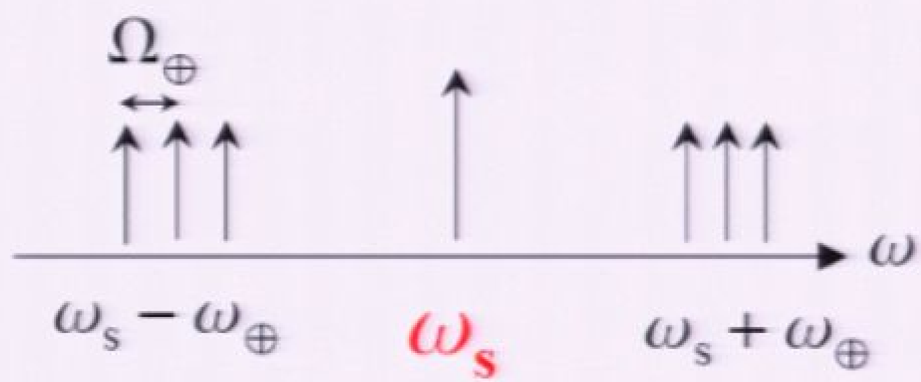
For odd-parity tests:



11μHz

Rotation in Lab:





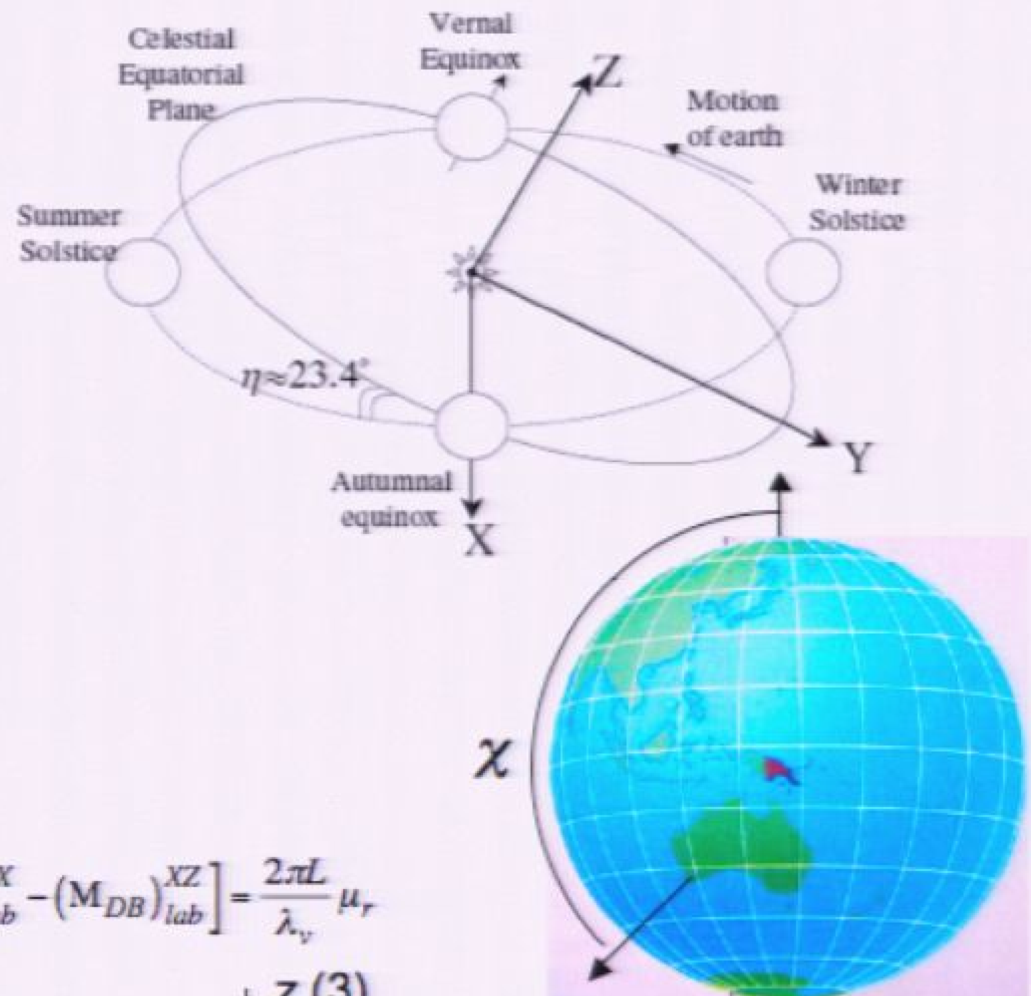
0.2 Hz

ABLE IV. Sensitivity coefficients of $(v_\oplus/c)/\tilde{\kappa}_{tr}$ at the rele-
nt modulation frequencies (rotating experiment).

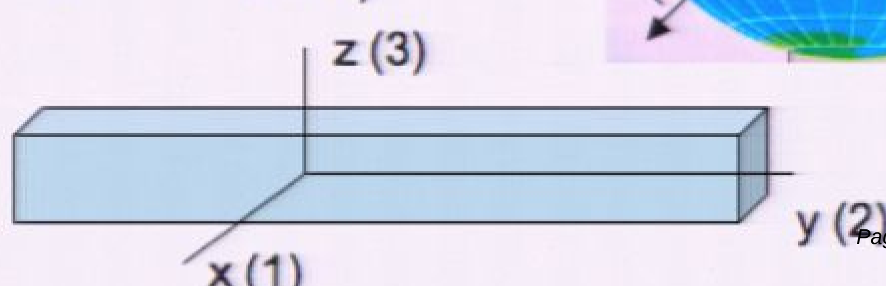
Modulation	Coefficient
$\cos(\omega_s T_s)$	$-2\frac{v_{\rm sp}}{v_\oplus}\sin\chi\times [(\mathcal{M}_{DB})^{XZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZX}_{\rm lab}]$
$\sin(\omega_s T_s)$	$-2\frac{v_{\rm sp}}{v_\oplus}\sin\chi\times [(\mathcal{M}_{DB})^{YZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZY}_{\rm lab}]$
$\cos(\omega_s T_s+\Omega_\oplus T)$	$\sin\eta\sin\chi\times [(\mathcal{M}_{DB})^{YZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZY}_{\rm lab}]$
$\sin(\omega_s T_s+\Omega_\oplus T)$	$-\sin\eta\sin\chi\times [(\mathcal{M}_{DB})^{XZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZX}_{\rm lab}]$
$\cos(\omega_s T_s-\Omega_\oplus T)$	$\sin\eta\sin\chi\times [(\mathcal{M}_{DB})^{YZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZY}_{\rm lab}]$
$\sin(\omega_s T_s-\Omega_\oplus T)$	$-\sin\eta\sin\chi\times [(\mathcal{M}_{DB})^{XZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZX}_{\rm lab}]$
s$(\omega_s T_s+\omega_\oplus T_\oplus+\Omega_\oplus T)$	$-\frac{1}{2}(1-\cos\eta)(1-\cos\chi)\times [(\mathcal{M}_{DB})^{XZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZX}_{\rm lab}]$
n$(\omega_s T_s+\omega_\oplus T_\oplus+\Omega_\oplus T)$	$-\frac{1}{2}(1-\cos\eta)(1-\cos\chi)\times [(\mathcal{M}_{DB})^{YZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZY}_{\rm lab}]$
s$(\omega_s T_s+\omega_\oplus T_\oplus-\Omega_\oplus T)$	$\frac{1}{2}(1+\cos\eta)(1-\cos\chi)\times [(\mathcal{M}_{DB})^{XZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZX}_{\rm lab}]$
n$(\omega_s T_s+\omega_\oplus T_\oplus-\Omega_\oplus T)$	$\frac{1}{2}(1+\cos\eta)(1-\cos\chi)\times [(\mathcal{M}_{DB})^{YZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZY}_{\rm lab}]$
s$(\omega_s T_s-\omega_\oplus T_\oplus+\Omega_\oplus T)$	$\frac{1}{2}(1+\cos\eta)(1+\cos\chi)\times [(\mathcal{M}_{DB})^{XZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZX}_{\rm lab}]$
n$(\omega_s T_s-\omega_\oplus T_\oplus+\Omega_\oplus T)$	$\frac{1}{2}(1+\cos\eta)(1+\cos\chi)\times [(\mathcal{M}_{DB})^{YZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZY}_{\rm lab}]$
s$(\omega_s T_s-\omega_\oplus T_\oplus-\Omega_\oplus T)$	$-\frac{1}{2}(1-\cos\eta)(1+\cos\chi)\times [(\mathcal{M}_{DB})^{XZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZX}_{\rm lab}]$
n$(\omega_s T_s-\omega_\oplus T_\oplus-\Omega_\oplus T)$	$-\frac{1}{2}(1-\cos\eta)(1+\cos\chi)\times [(\mathcal{M}_{DB})^{YZ}_{\rm lab}-(\mathcal{M}_{DB})^{ZY}_{\rm lab}]$

Frequencies of Interest wrt SCF

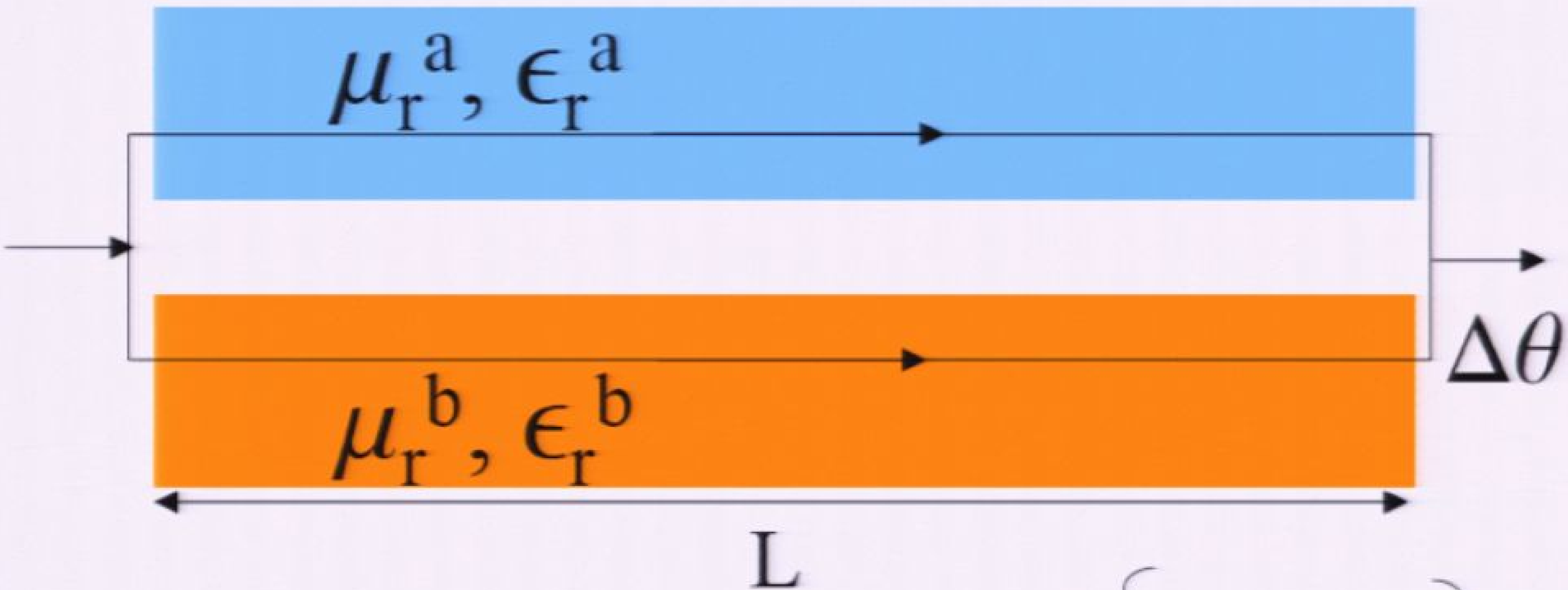
Tobar et. al. PRD, 71, 025004, 2005



$$\left[(\mathrm{M}_{DB})^{ZX}_{lab}-(\mathrm{M}_{DB})^{XZ}_{lab}\right]=\frac{2\pi L}{\lambda_v}\mu_r$$



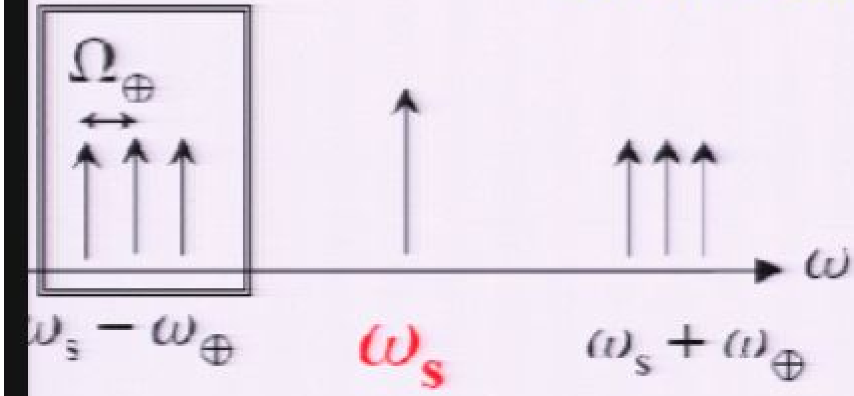
Asymmetric Interferometer



$$\Delta\theta_{odd} \sim \frac{2\pi L}{\lambda_0} (\mu_r^a - \mu_r^b) \begin{Bmatrix} \kappa_{o+} \\ 10^{-4}\kappa_{tr} \end{Bmatrix}$$

Direction dependent ⇒ Standing waves cancel

Short Data Set Approximation at Perth



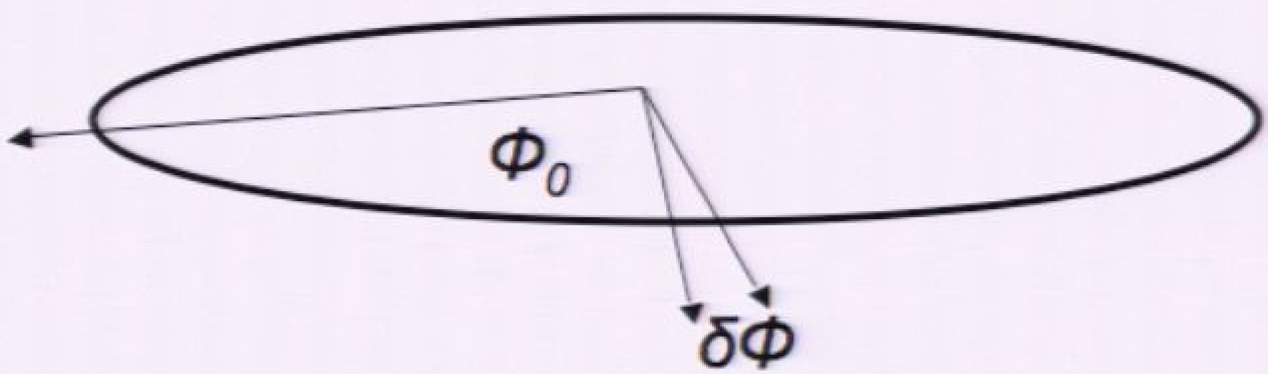
$$\theta = (\omega_s \pm \omega_\oplus)T$$

$$\phi_o + \delta\phi = \Omega_\oplus T$$

$$\delta\phi << 1$$

$$\sin(\theta \pm (\delta\Phi + \Phi_0)) \approx \sin(\theta)\cos(\Phi_0) \pm \cos(\theta)\sin(\Phi_0)$$

$$\cos(\theta \pm (\delta\Phi + \Phi_0)) \approx \cos(\theta)\cos(\Phi_0) \mp \sin(\theta)\sin(\Phi_0)$$



Four Measurements to Make (Improve Statistics)

$$\left[(\mathrm{M}_{DB})_{lab}^{ZX} - (\mathrm{M}_{DB})_{lab}^{XZ}\right] = 4.55$$

$A_{S+}Sin[(\omega_S + \omega_{\oplus})T]$: $-1.5272\ \beta o\ \kappa_{tr}\ Sin[\Phi o]\ \frac{2\pi L}{\lambda_v}\Delta\mu_r$

$-6.9 \times 10^{-4} \kappa_{tr}\ Sin[\Phi_0]$ [rads]

$A_{S-}Sin[(\omega_S - \omega_{\oplus})T]$: $0.472797\beta o\ \kappa_{tr}\ Sin[\Phi o]\ \frac{2\pi L}{\lambda_v}\Delta\mu_r$

$2.14 \times 10^{-4} \kappa_{tr}\ Sin[\Phi_0]$ [rads]

$A_{C+}Cos[(\omega_S + \omega_{\oplus})T]$: $-1.5272\ \beta o\ \kappa_{tr}\ 0.918629\ Cos[\Phi o]\ \frac{2\pi L}{\lambda_v}\Delta\mu_r$

$-6.34 \times 10^{-4} \kappa_{tr}\ Cos[\Phi_0]$ [rads]

$A_{C-}Cos[(\omega_S - \omega_{\oplus})T]$: $-0.472797\ \beta o\ \kappa_{tr}\ 0.918629\ Cos[\Phi o]\ \frac{2\pi L}{\lambda_v}\Delta\mu_r$

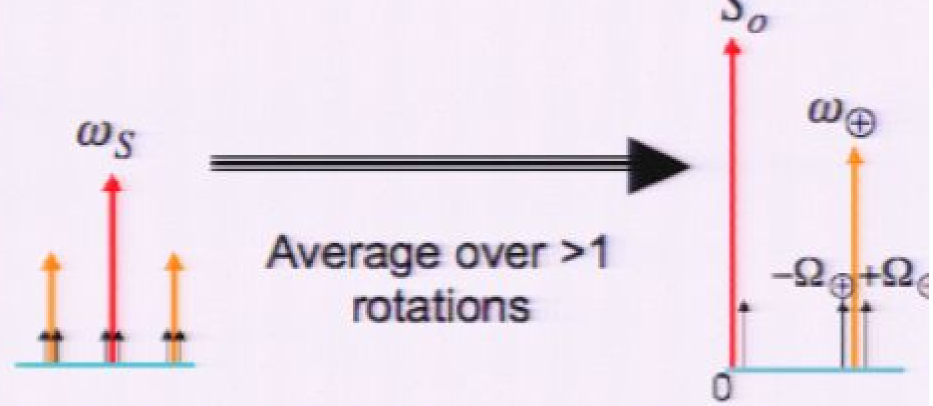
$-2.0 \times 10^{-4} \kappa_{tr}\ Cos[\Phi_0]$ [rads]

Demodulated Least Squares (DLS): Minimize Narrow and Broad Band Noise

$$\delta\theta = A + Bt + C(t)Cos(\omega_S T) + S(t)Sin(\omega_S T)$$

$$S(t) = S_o + \sum_i S_{s,i}Sin(\omega_i T) + S_{c,i}Cos(\omega_i T)$$

$$C(t) = C_o + \sum_i C_{s,i}Sin(\omega_i T) + C_{c,i}Cos(\omega_i T)$$



-> Find Optimum number of rotations to reduce standard error

-> Equivalent to optimum filter that minimizes combined effect o NBN BBN

Combine Short Data Set Approx with DLS

$$\omega_S + \omega_\oplus, \omega_S - \omega_\oplus \Longrightarrow \omega_\oplus$$

$$i = \omega_\oplus \Longrightarrow S_{s,\omega_\oplus}, S_{c,\omega_\oplus}, C_{s,\omega_\oplus}, C_{c,\omega_\oplus}$$

Fit 4 components to set limit on κ_{tr} only (assume other κ's are zero)

Numerical Values to Search for κ_{tr}

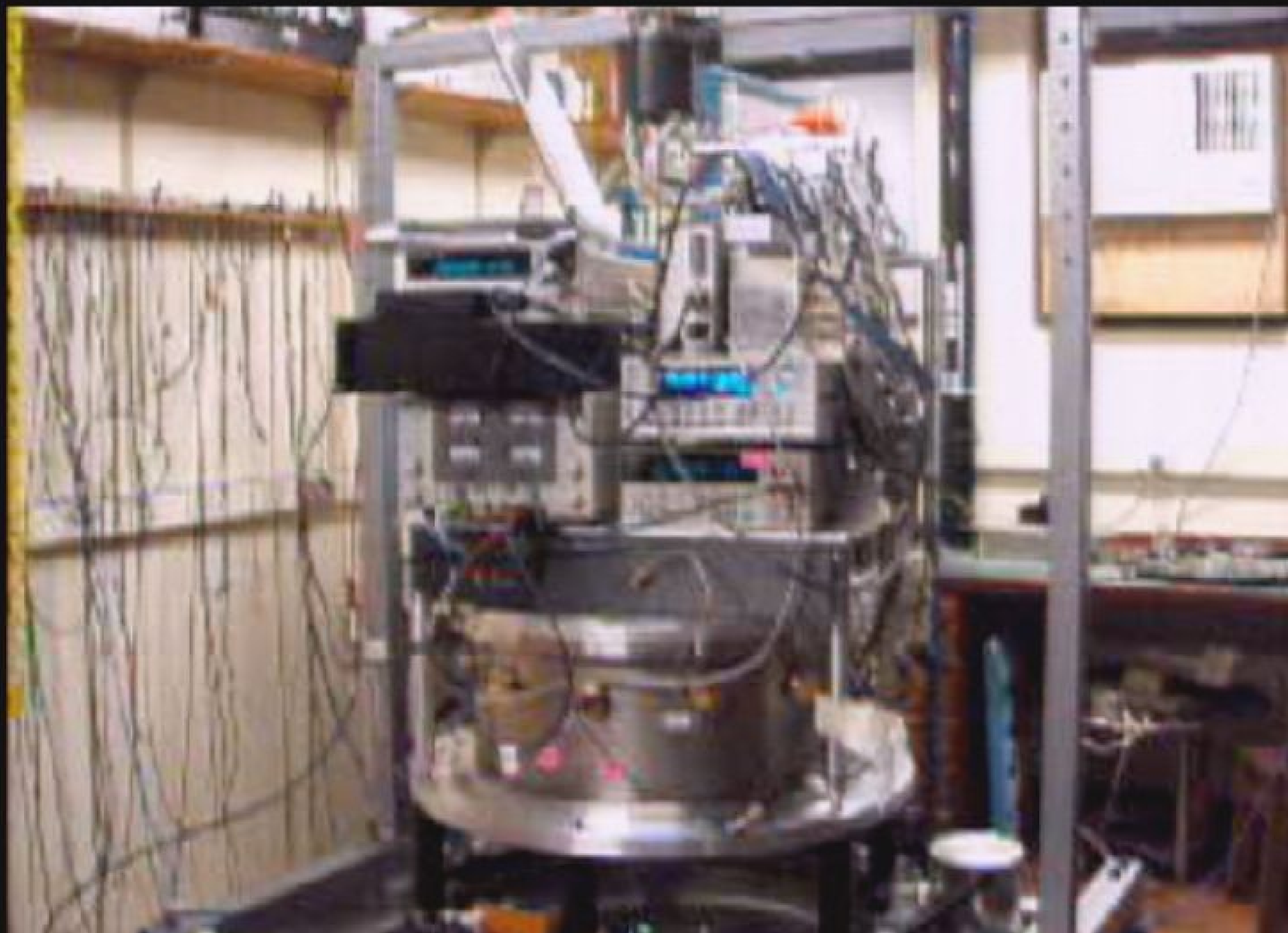
$$S_{s,\omega_\oplus} = 4.4 \times 10^{-3} \kappa_{tr} Cos[\Phi_o]$$

$$S_{c,\omega_\oplus} = -9.0 \times 10^{-3} \kappa_{tr} Sin[\Phi_o]$$

$$C_{s,\omega_\oplus} = -4.8 \times 10^{-3} \kappa_{tr} Sin[\Phi_o]$$

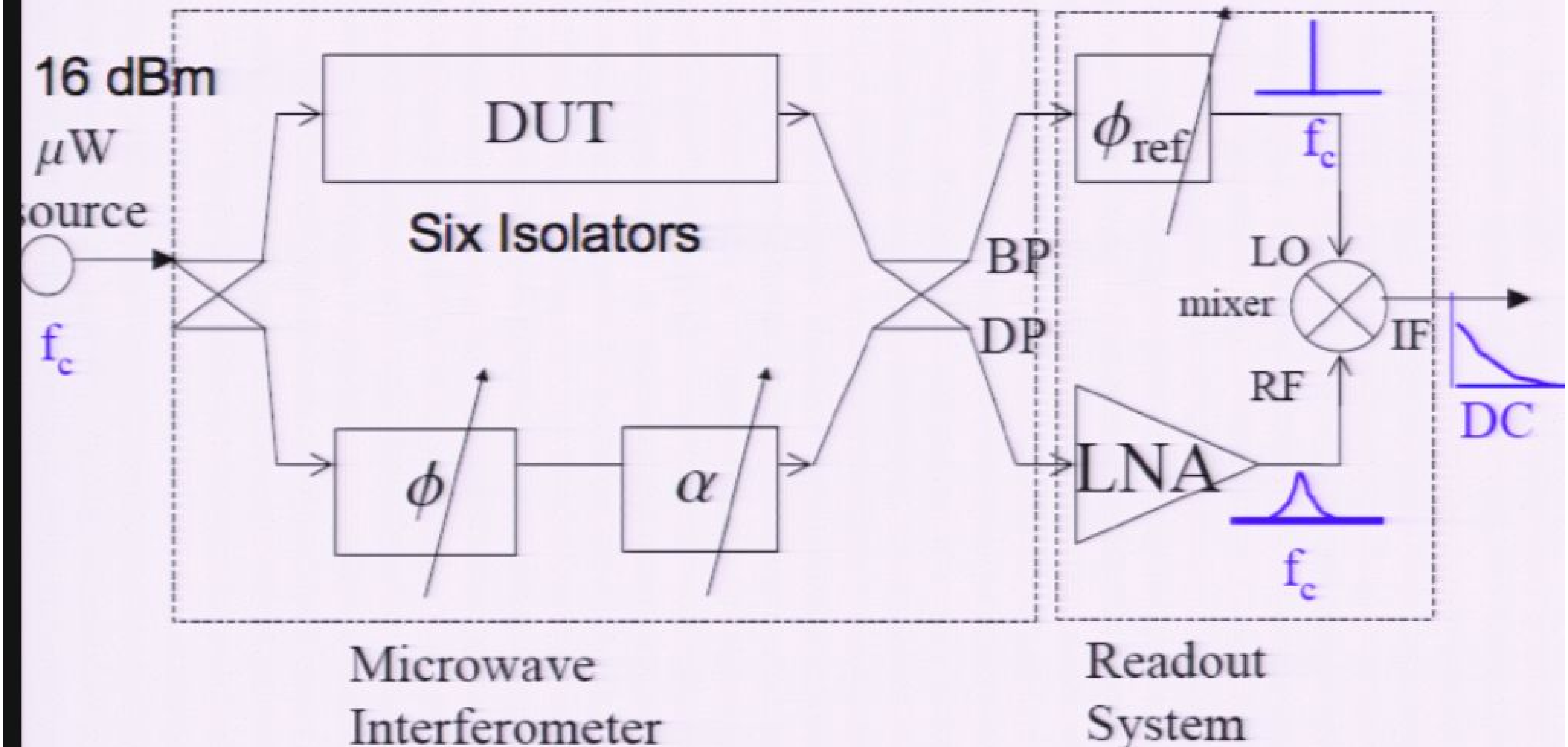
$$C_{c,\omega_\oplus} = -8.3 \times 10^{-3} \kappa_{tr} Cos[\Phi_o]$$

First Operation August 2006 Continuous Since September 2007



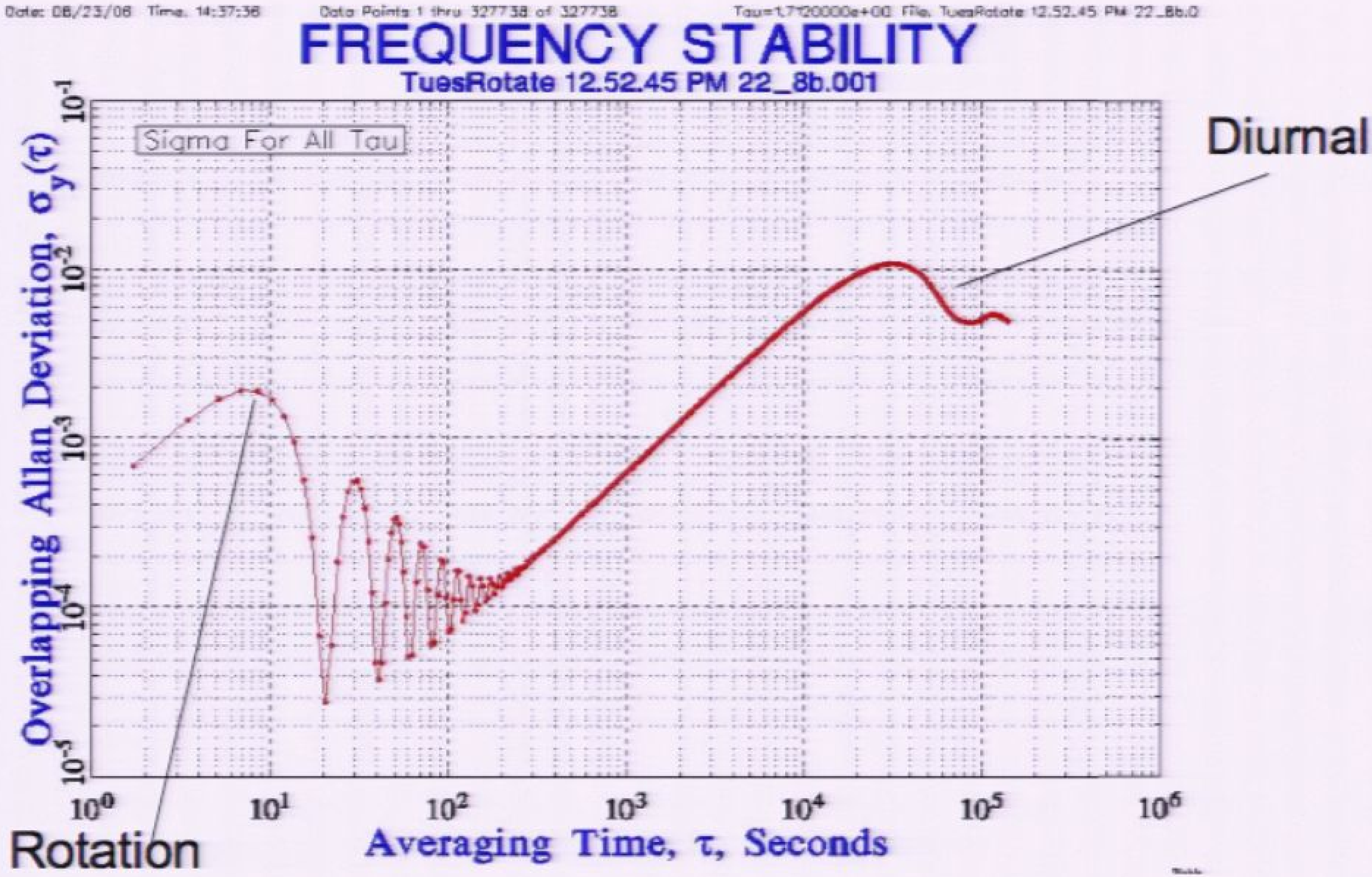
Mu Metal Shielding

Microwave Interferometer



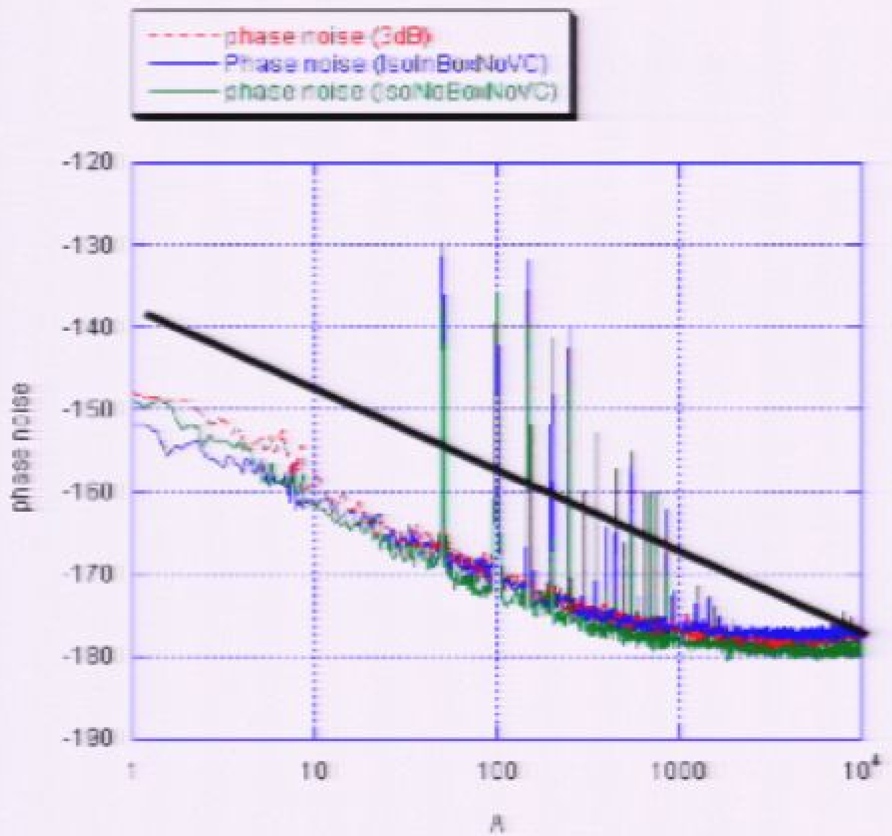
$$\delta u_{out} = \delta u_{SOURCE} + \delta u_{READOUT} + S_{PD}(\delta\phi_{DUT} + \Delta\theta_{odd})$$

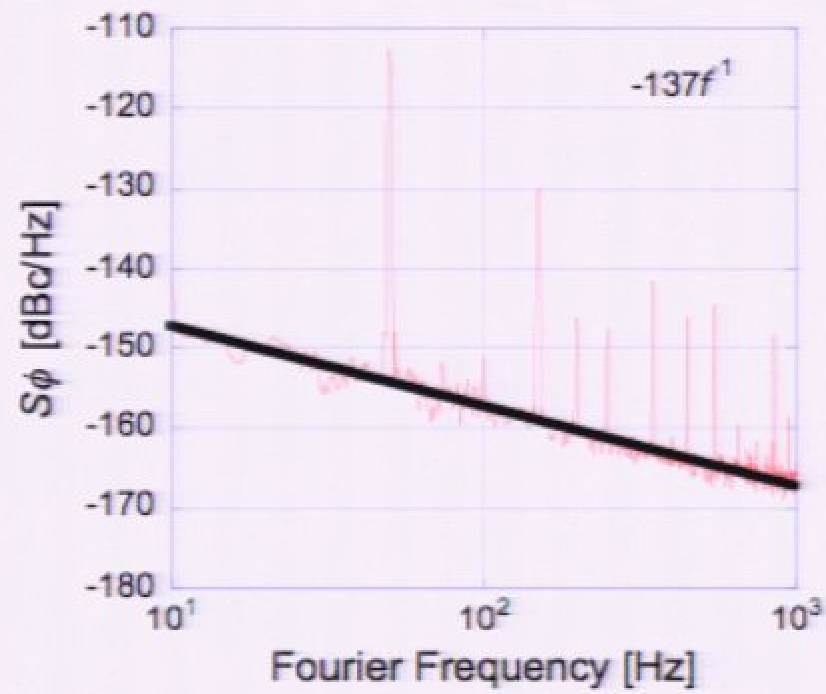
Measure output with DVM, Sample ~ 0.4 second



Voltage Control to limit diurnal effect(VCA and VCP)

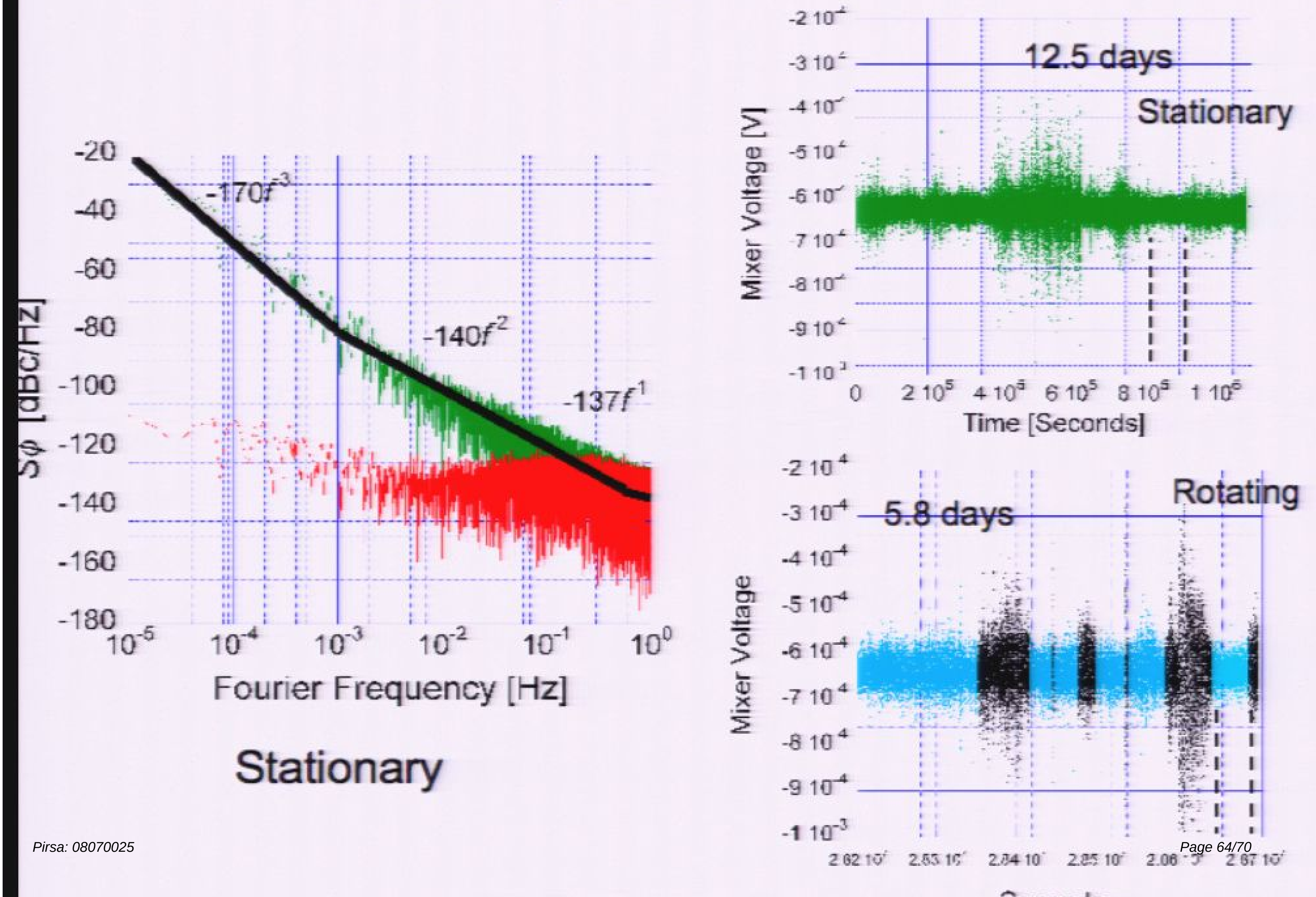
String of Ferrite Isolators does not have any measurable noise (well shielded)
Noise limited by voltage controlled phase shifter.



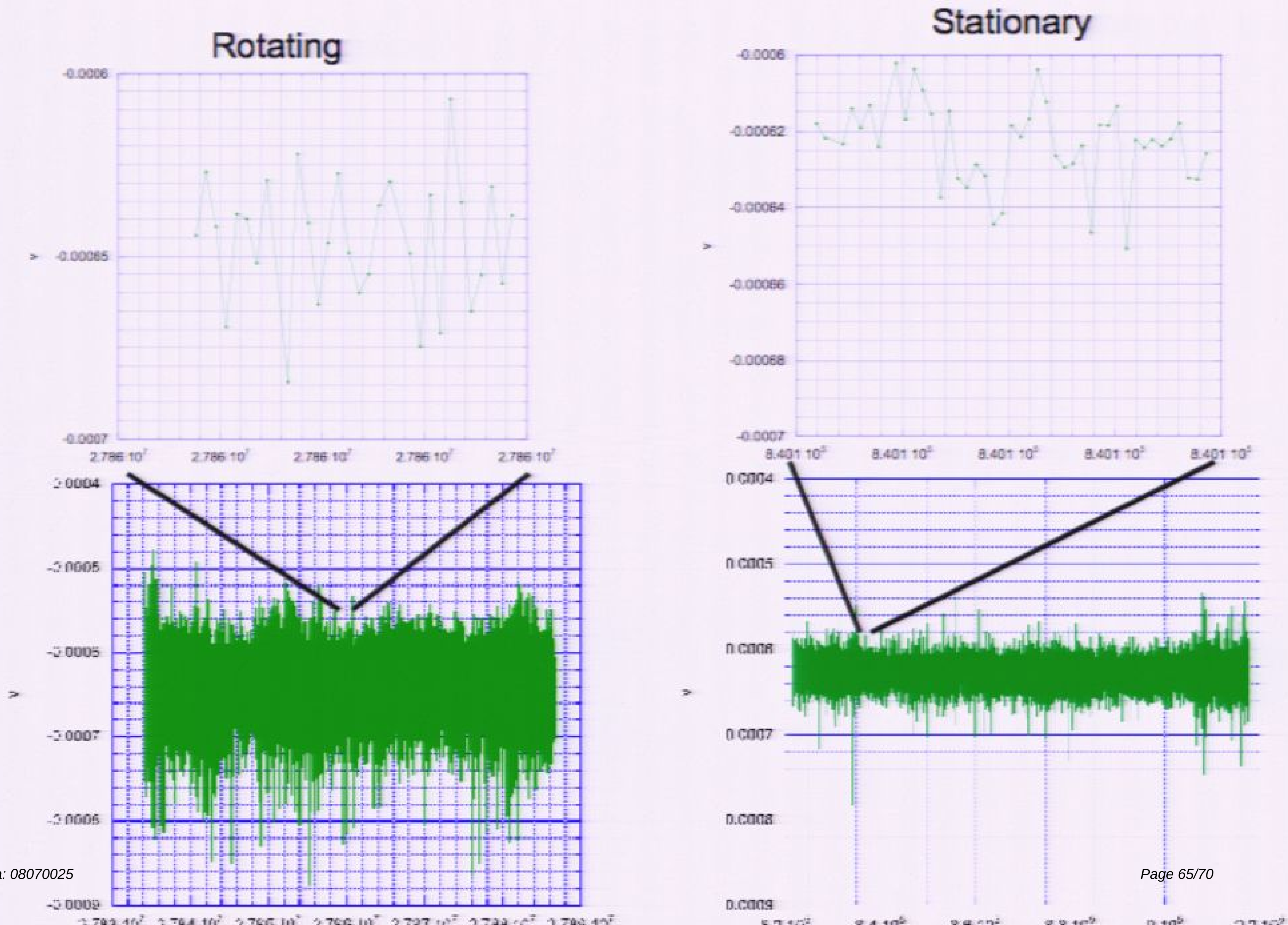


Measure >1 Hz with Spectrum Analyzers

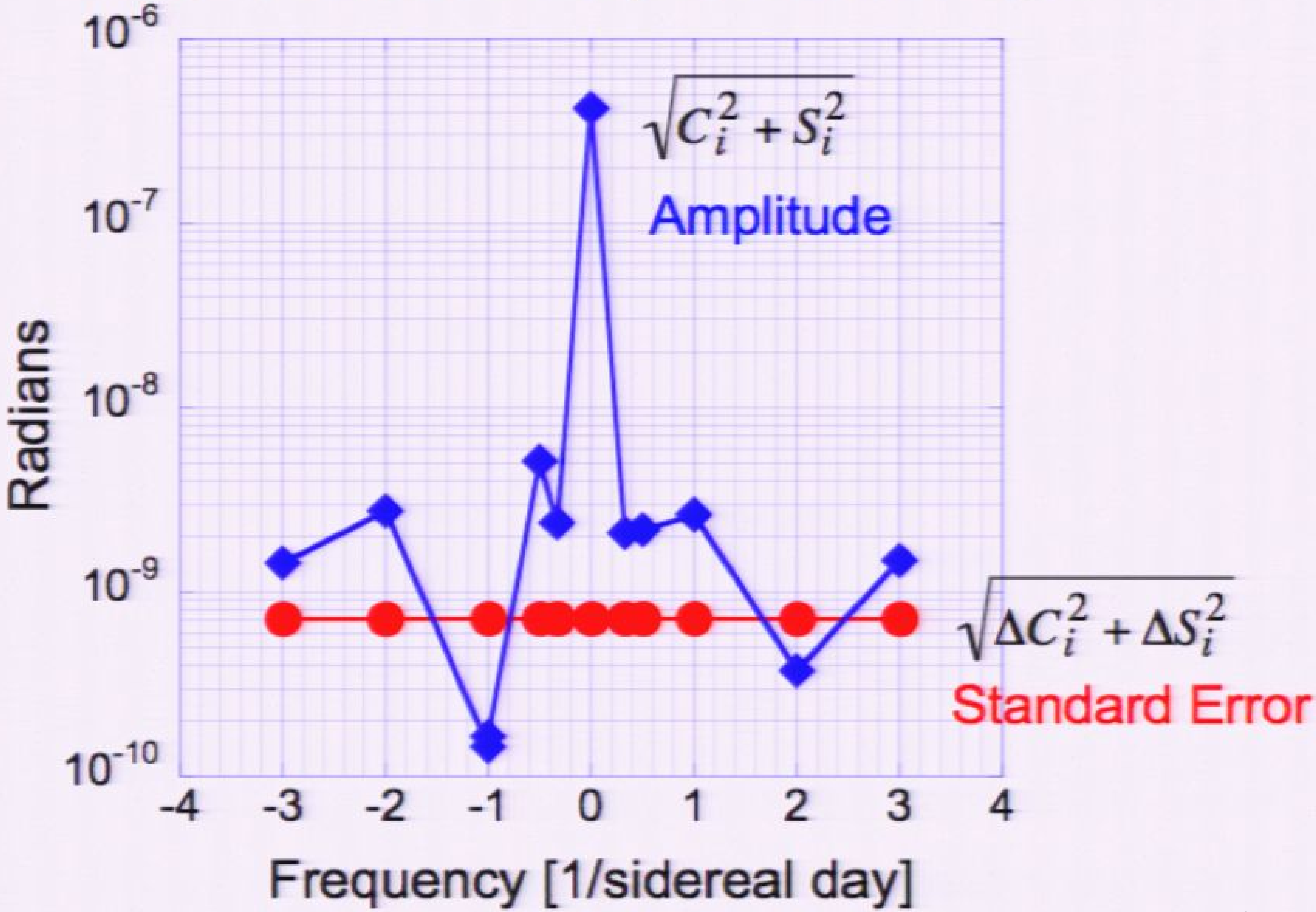
Noise Properties < 1 Hz



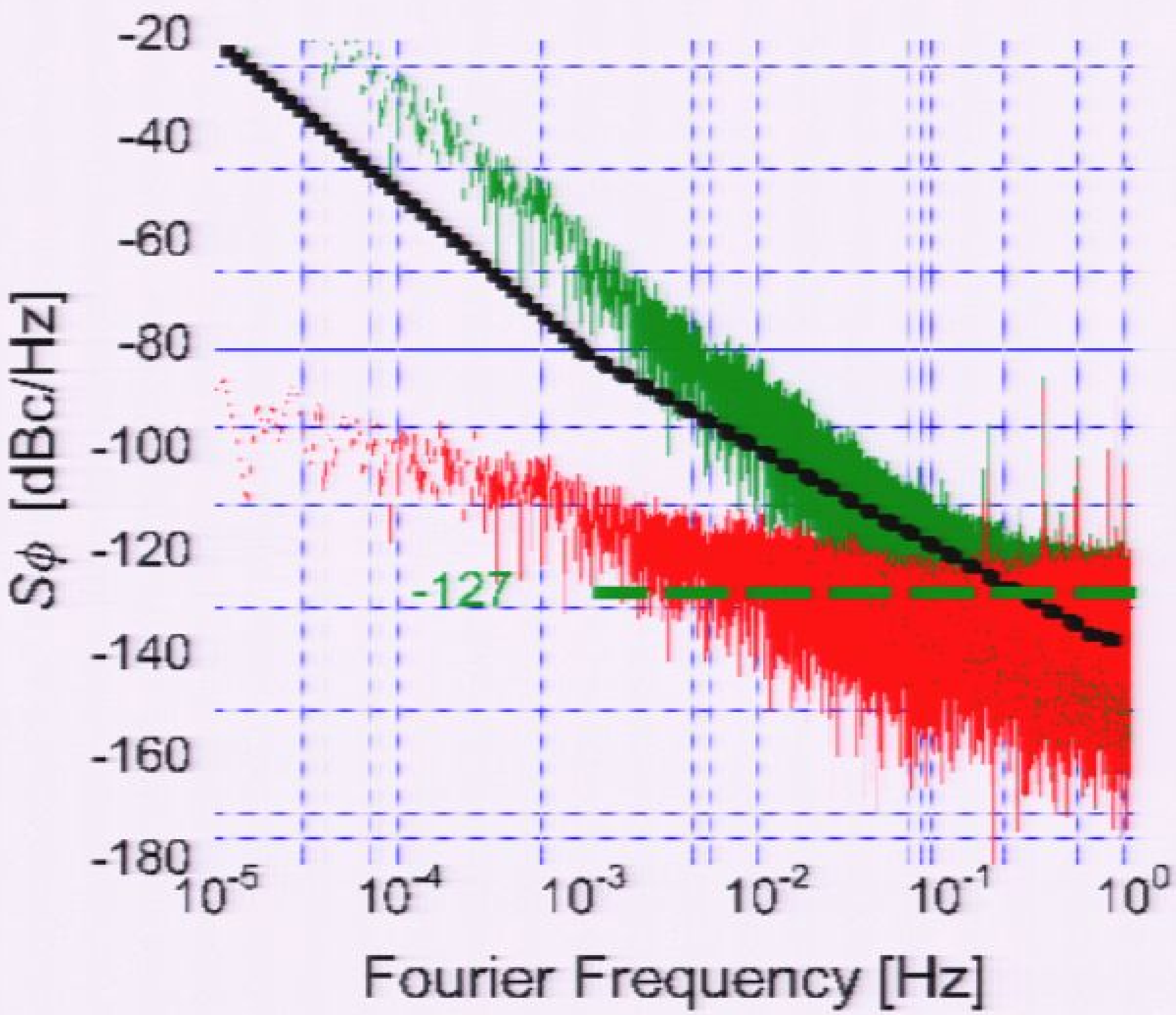
Mixer Voltage Noise vs Time (Rotating and Stationary)



Systematic Effects
Data set starts at Sep 14 for 13.2 days

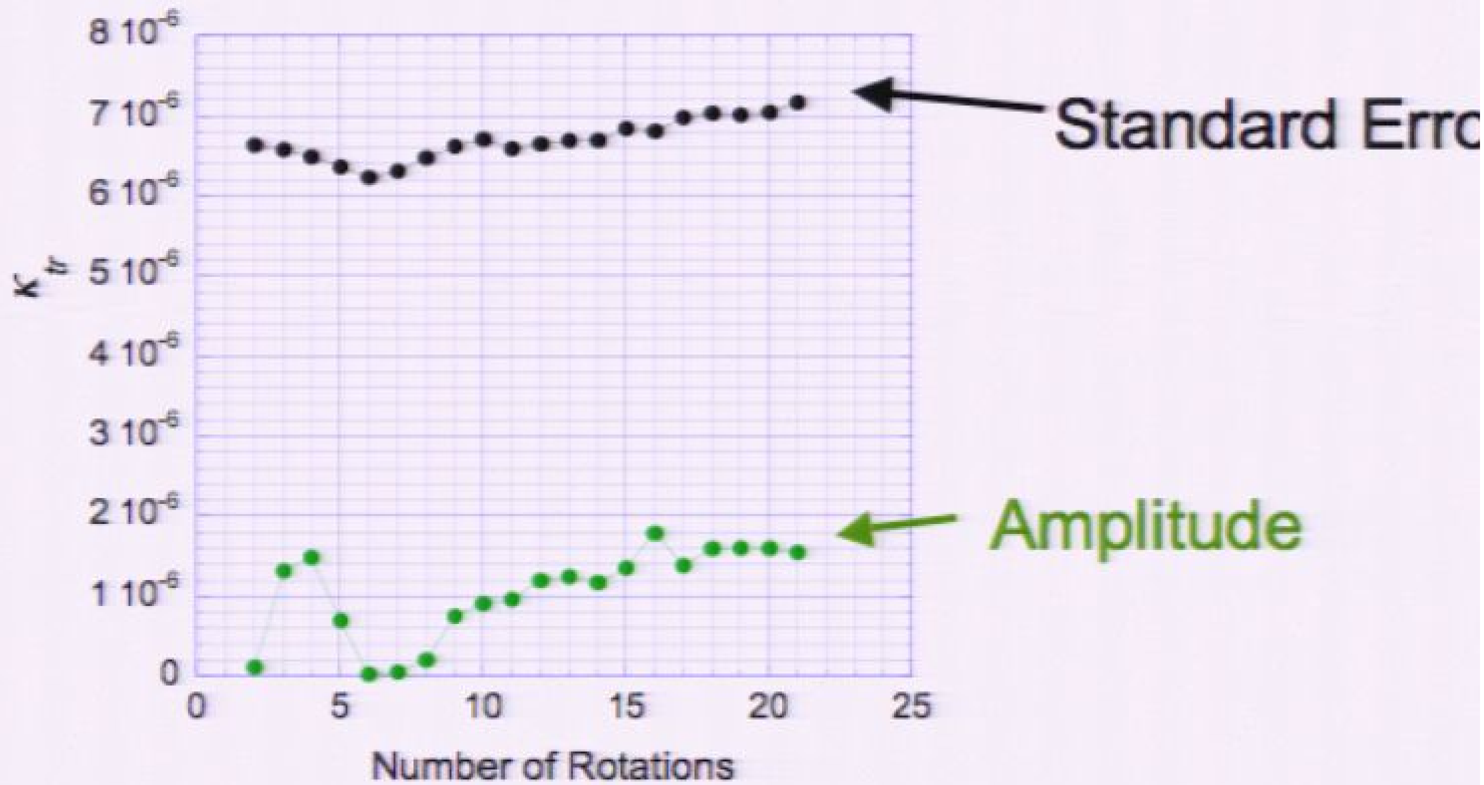


Sep 14 data set Phase Noise

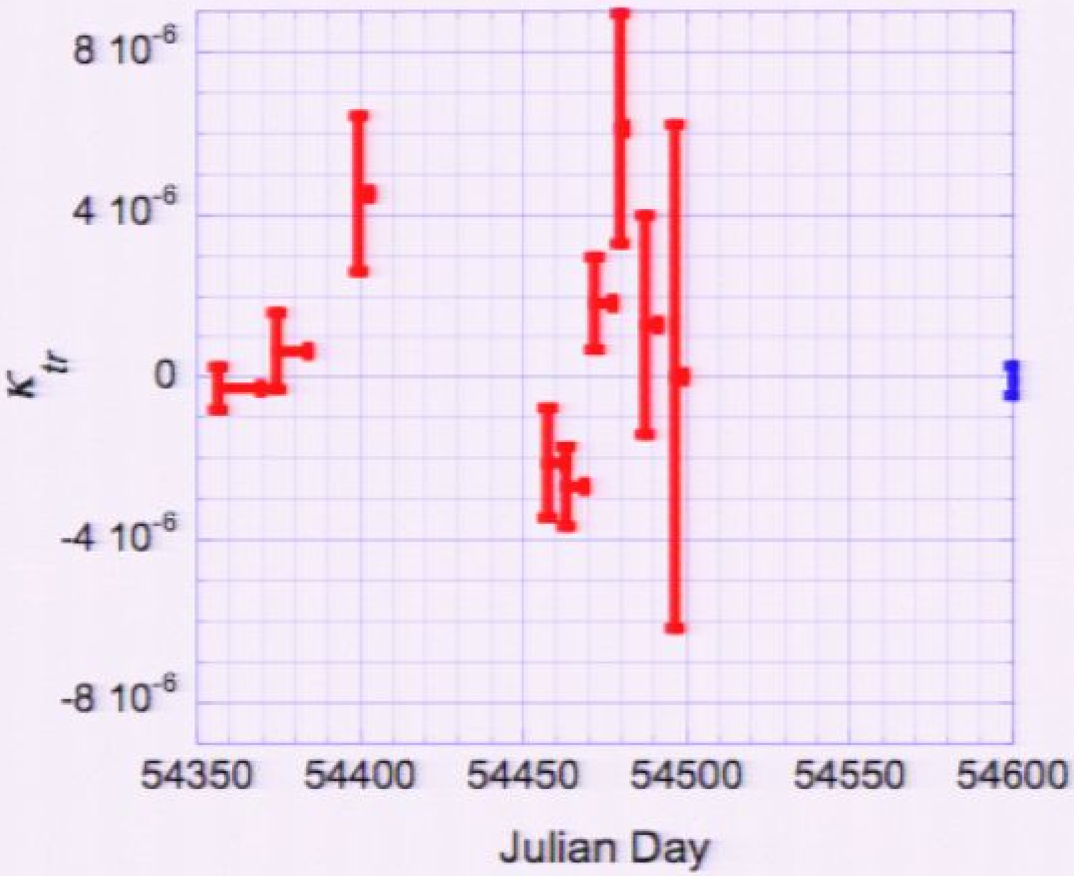


Demodulated Least Squares Optimization

Example: 3 day data set starting January 31st



Blocks of Data Analysed with DLS



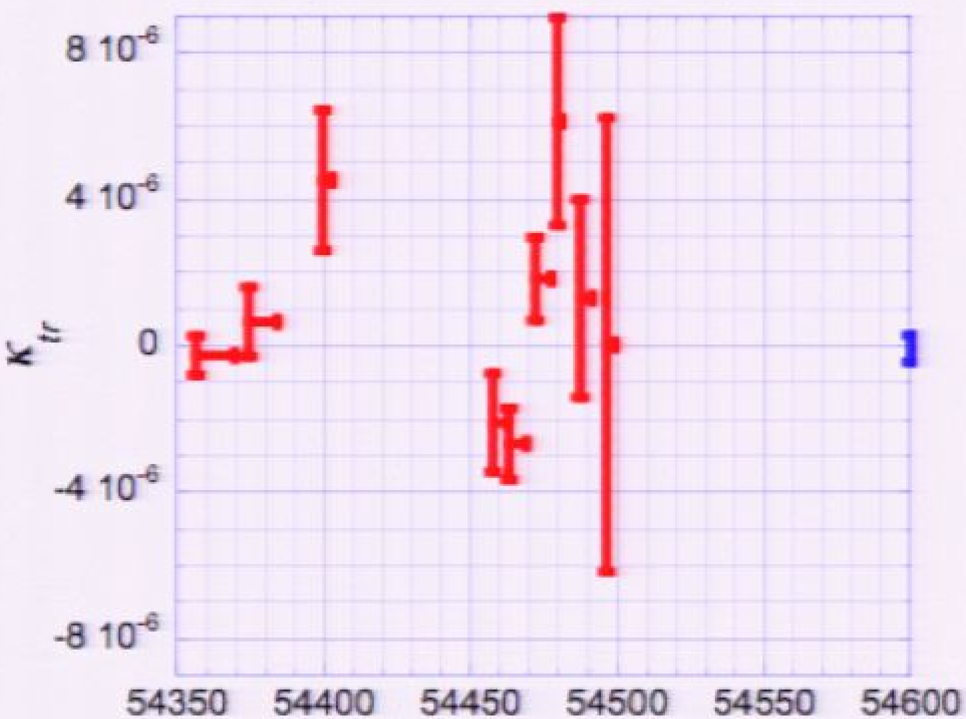
No. of Rotations for Demodulation: 2 to 7

$-0.8 \pm 3.6 \times 10^{-7}$

Improve Phase Noise: High Power Recycling

Limit -155-20Log[f] => 20 dB improvement

Blocks of Data Analysed with DLS



No. of Rotations for Demodulation: 2 to 7

$-0.8 \pm 3.6 \times 10^{-7}$