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international atomic
energy agency

the
abdus salam
international centre for theoretical physics
40th anniversary 1964 2004

SMR.1580 - 13

CONFERENCE ON FUNDAMENTAL SYMMETRIES AND FUNDAMENTAL CONSTANTS

15 - 18 September 2004

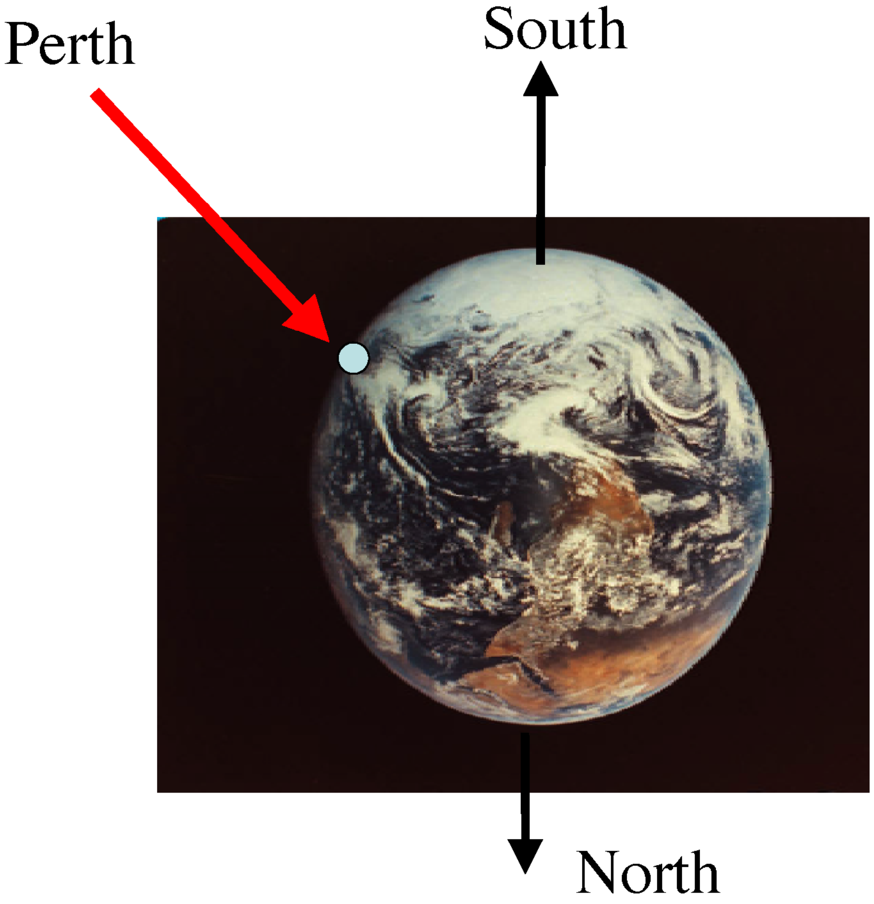
NEW TESTS OF LORENTZ INVARIANCE IN THE PHOTON SECTOR USING PRECISION MICROWAVE OSCILLATORS

M. Tobar
U. Western Australia

New Tests of Lorentz Invariance in the Photon Sector using Precision Oscillators and Interferometers

September 2004

Associate Professor Michael E. Tobar
School of Physics
University of Western Australia, Perth
Frequency Standards and Metrology Research Group


Perth
South
North

Outline

- Introduction to the Researchers Involved
- Testing Special Relativity
  - Tests of Lorentz Transform (Isotropy MM, Velocity KT)
  - Standard Model Extension (SME)
- Testing Lorentz Invariance Using Microwave Resonators
  - BNM/SYRTE - UWA Experiment (Stationary on earth)
  - UWA Experiment (Rotating)
- Parity-Odd and Scalar Lorentz Invariance Tests
  - Ives-Stilwell Experiments
  - Asymmetric Interferometers and Resonators

TESTING LORENTZ INVARIANCE USING MICROWAVE RESONATORS:
(The BNM-UWA Experiment)

Peter Wolf[1,2], **Sébastien Bize**[1], **André Clairon**[1], **Giorgio Santarelli**[1]
[1]SYRTE, Observatoire de Paris, France
[2]on leave from: Bureau International des Poids et Mesures

Michael E. Tobar[3], **André N. Luiten**[3]
[3]University of Western Australia

Phys. Rev. Lett., **90**, 6, 060402, (2003), update at gr-qc/0306047
Gen. Rel. and Grav., vol. 36, 10, pp. 2351-2373, (2004), also at gr-qc/0401017
Phys. Rev. D. Rap. Comm., accepted (2004), also at hep-ph/0407232

UWA: Rotating Michelson-Morley and SME Experiments

- Initial Operation -

Staff:

A/Prof. Michael Tobar
Dr. Eugene Ivanov
Dr. Frank van Kann
Dr. John Hartnett
Dr. John Winterflood

Ph.D. Student: Paul Stanwix
Honours Student: Mohamad Susli

Visiting Professor:

Peter Wolf (BNM-SYRTE - BIPM)

Based on a proposal published in Phys. Lett. A

ME Tobar, JG Hartnett, J Anstie, Physics Letters A, vol 300/1 pp. 33-39, 2002.

New methods of testing Lorentz violation in electrodynamics

Michael E. Tobar[1], Peter Wolf[2,3], Alison Fowler[1], John G. Hartnett[1]

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92312 Sèvres CEDEX, France**

arXiv: hep-ph/0408006

Submitted to PRD

Other Similar Experiments

Germany

Konstanz -> Berlin (Achim Peters)
Dusseldorf (Stephan Schiller)

Optical Cavity Experiments

Special Relativity

- Most modern tests of SR rely on atomic clocks and macroscopic resonators.
- We use sapphire resonator-oscillator and H-maser as reference frequency.
- We improve on previous tests by factor of 100

In principle there are three observable effects:

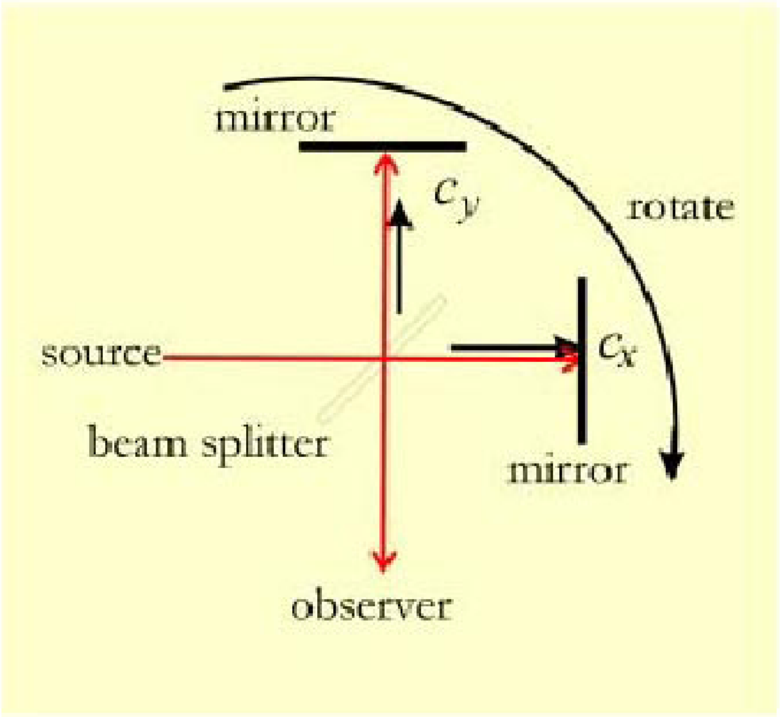
- Time/Frequency (→α) (= 1/2 in SR)
- Parallel length (→β) (= -1/2 in SR)
- Perpendicular length (→δ) (= 0 in SR)

Experiments realise one or a combination of these observables (Robertson Mansouri Sexl RMS):

- Light time/Doppler measurements (→α) [GPS, Doppler spect.] [IS]
- Length measurements in varying directions (→β -δ) [MM]
- Length measurements at varying velocities (→β -α) [KT]

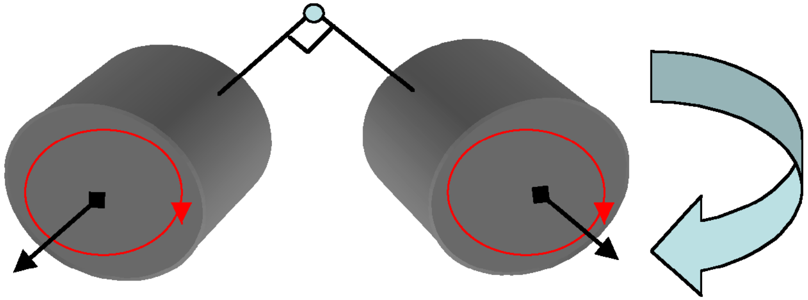
Michelson Morley Experiment New and Old

Michelson (1881, Potsdam)
Michelson & Morley (1887, Cleveland)

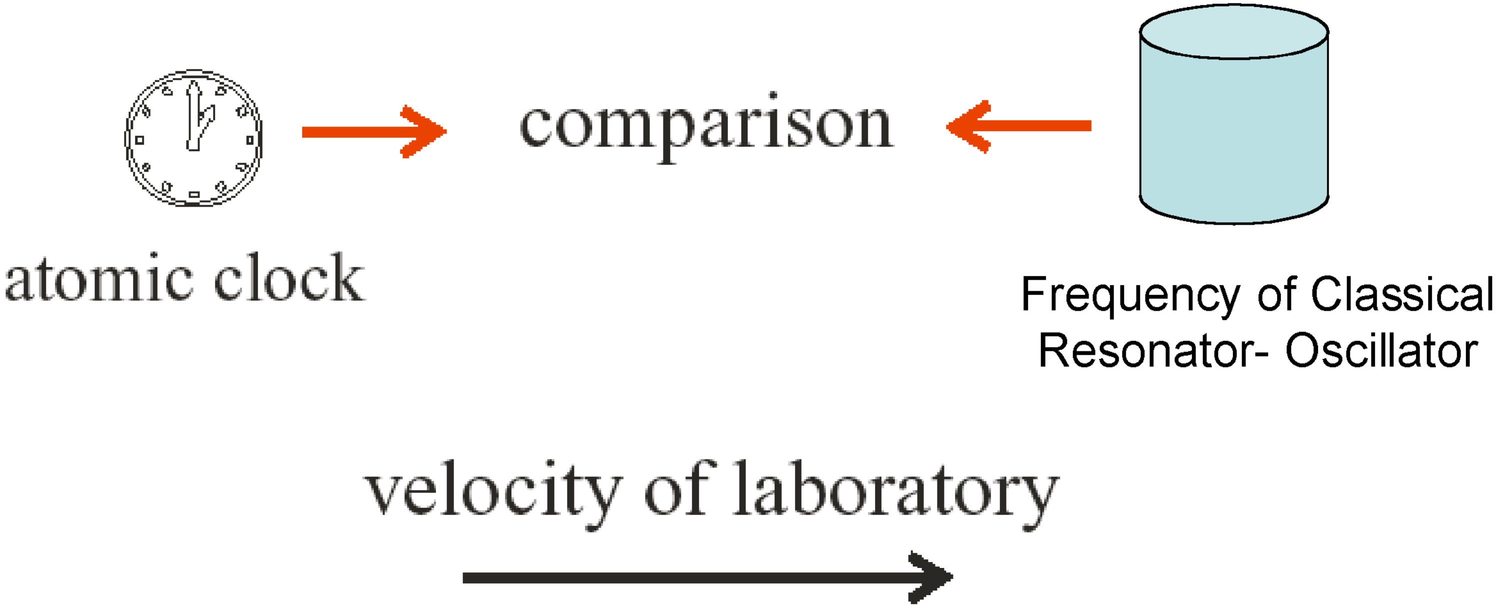


Modern Experiment

Compare the frequency of two resonant cavity oscillators



Kennedy-Thorndike Experiment



atomic clock

comparison

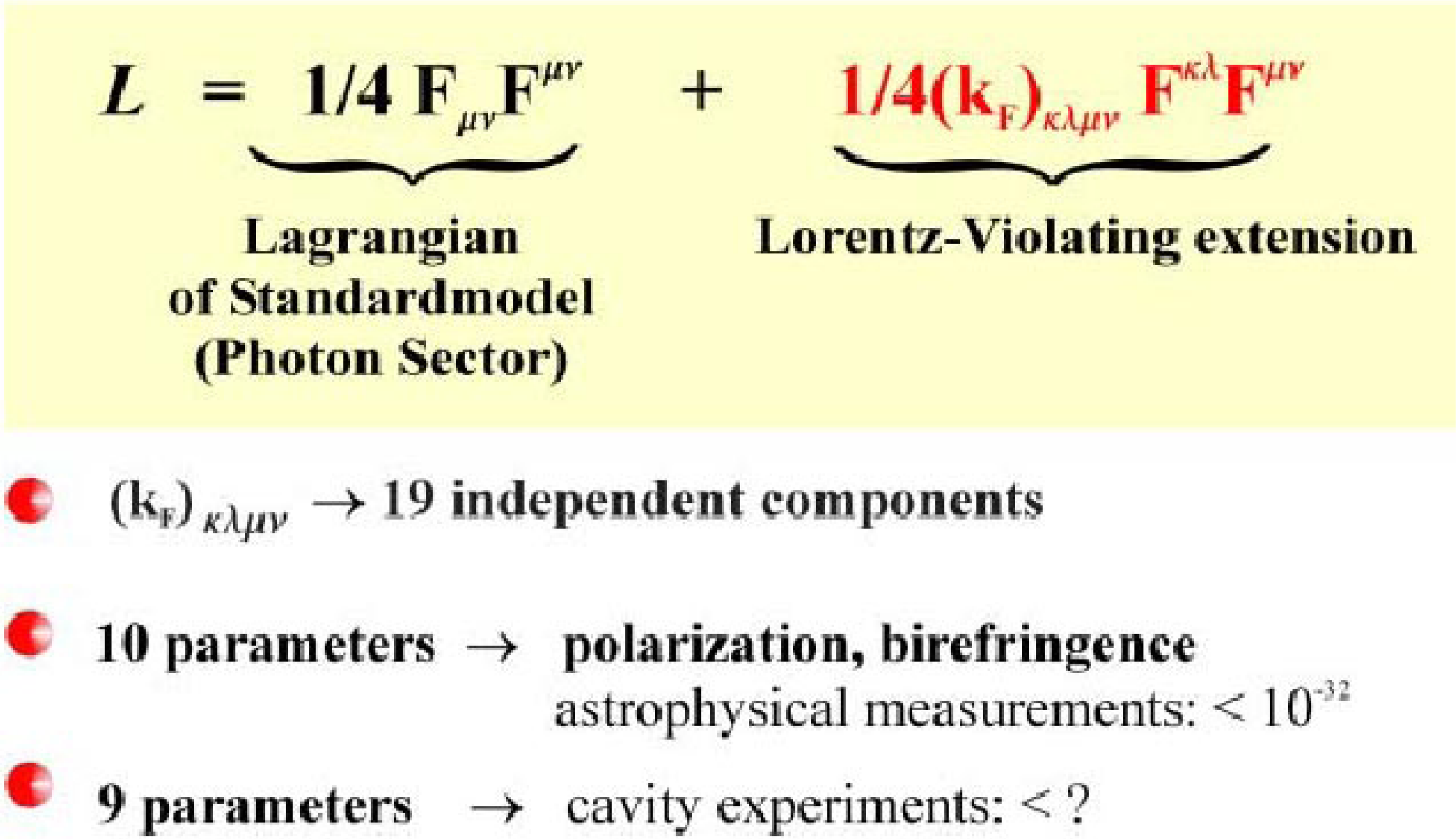
Frequency of Classical
Resonator- Oscillator

velocity of laboratory

Standard Model Extension (SME)

Most general low-energy model incorporating violations of the Standard Model (SM) of Physics

Electromagnetic Cavity -> Test the Photon Sector of the SM (Lorentz-Invariance)

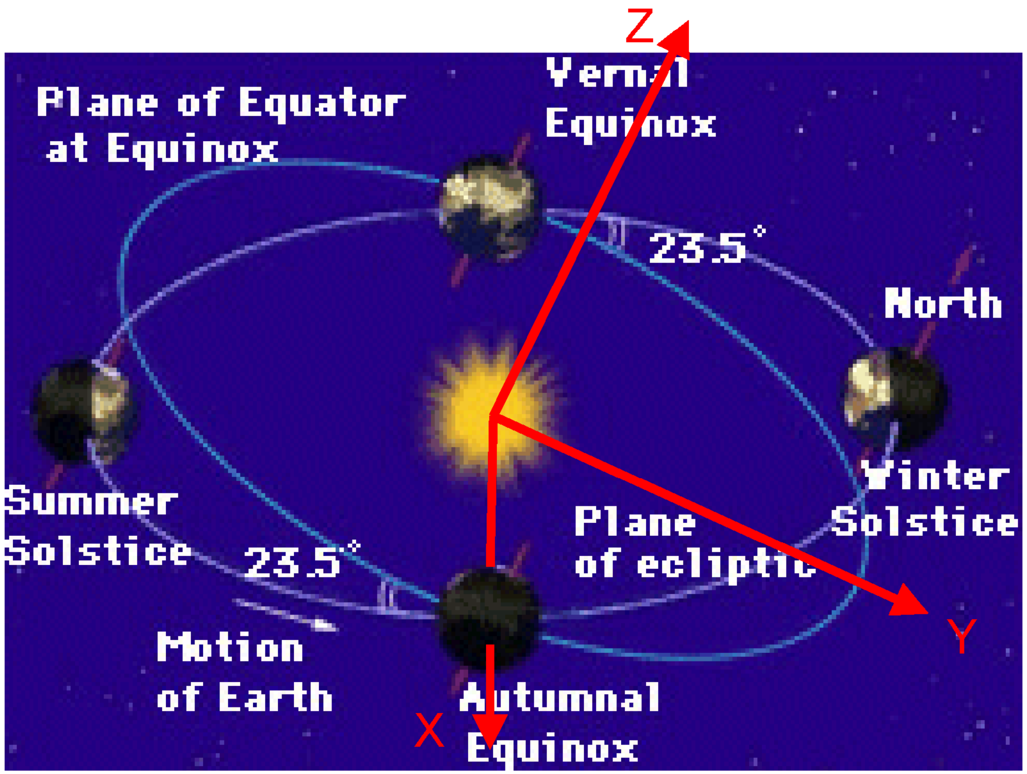


$$L = \underbrace{1/4\, F_{\mu\nu} F^{\mu\nu}}_{\substack{\textbf{Lagrangian} \\ \textbf{of Standardmodel} \\ \textbf{(Photon Sector)}}} + \underbrace{1/4(k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu}}_{\textbf{Lorentz-Violating extension}}$$

- $(k_F)_{\kappa\lambda\mu\nu}$ → **19 independent components**
- **10 parameters** → **polarization, birefringence**
  astrophysical measurements: $< 10^{-32}$
- **9 parameters** → cavity experiments: < ?

Co-ordinate System for SME

Sun Centred Celestial Equatorial Frame



Astrophysical constraints - 10 polarization components ~ 10^{-32}

$$\begin{bmatrix} \tilde{\kappa}_{e+}^{XX} & \tilde{\kappa}_{e+}^{XY} & \tilde{\kappa}_{e+}^{XZ} \\ \tilde{\kappa}_{e+}^{XY} & \tilde{\kappa}_{e+}^{YY} & \tilde{\kappa}_{e+}^{YZ} \\ \tilde{\kappa}_{e+}^{XZ} & \tilde{\kappa}_{e+}^{YZ} & -\tilde{\kappa}_{e+}^{XX} - \tilde{\kappa}_{e+}^{YY} \end{bmatrix}$$

$$\begin{bmatrix} \tilde{\kappa}_{o-}^{XX} & \tilde{\kappa}_{o-}^{XY} & \tilde{\kappa}_{o-}^{XZ} \\ \tilde{\kappa}_{o-}^{XY} & \tilde{\kappa}_{o-}^{YY} & \tilde{\kappa}_{o-}^{YZ} \\ \tilde{\kappa}_{o-}^{XZ} & \tilde{\kappa}_{o-}^{YZ} & -\tilde{\kappa}_{o-}^{XX} - \tilde{\kappa}_{o-}^{YY} \end{bmatrix}$$

Resonant Cavity Experiments

$$\begin{bmatrix} 0 & \tilde{\kappa}_{o+}^{XY} & \tilde{\kappa}_{o+}^{XZ} \\ -\tilde{\kappa}_{o+}^{XY} & 0 & \tilde{\kappa}_{o+}^{YZ} \\ -\tilde{\kappa}_{o+}^{XZ} & -\tilde{\kappa}_{o+}^{YZ} & 0 \end{bmatrix}$$

~ 10^{-11} suppressed by boost: 3 components

$$\begin{bmatrix} \tilde{\kappa}_{e-}^{XX} & \tilde{\kappa}_{e-}^{XY} & \tilde{\kappa}_{e-}^{XZ} \\ \tilde{\kappa}_{e-}^{XY} & \tilde{\kappa}_{e-}^{YY} & \tilde{\kappa}_{e-}^{YZ} \\ \tilde{\kappa}_{e-}^{XZ} & \tilde{\kappa}_{e-}^{YZ} & \boxed{-\tilde{\kappa}_{e-}^{XX} - \tilde{\kappa}_{e-}^{YY}} \end{bmatrix}$$

~ 10^{-15}

5 components

Not yet tested

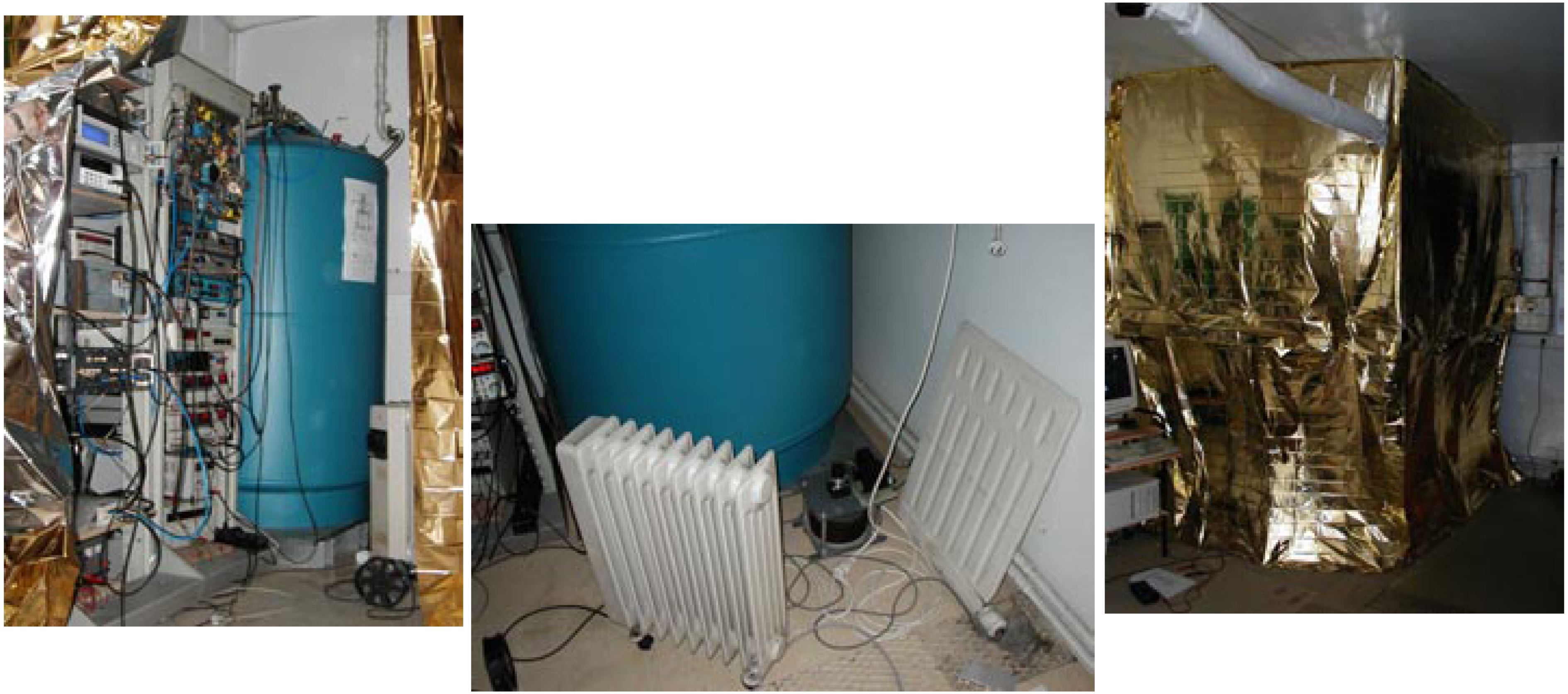
Scalar

$$\tilde{\kappa}_{tr}$$

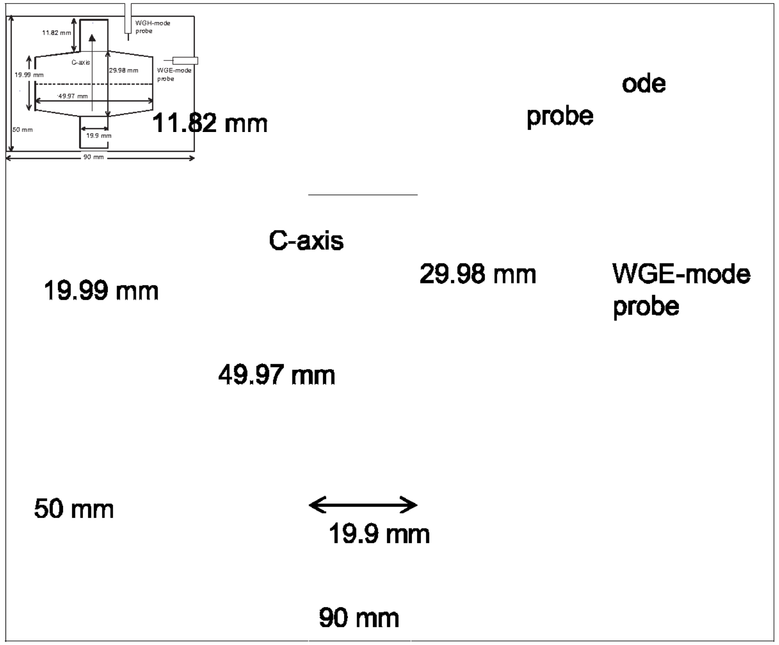
TESTING LORENTZ INVARIANCE USING MICROWAVE RESONATORS:

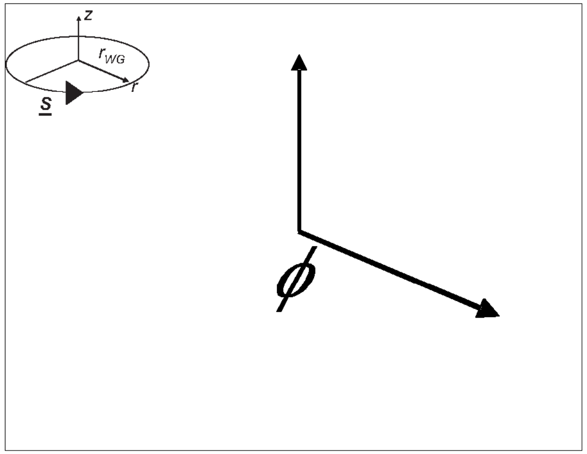
(The BNM-UWA Experiment)

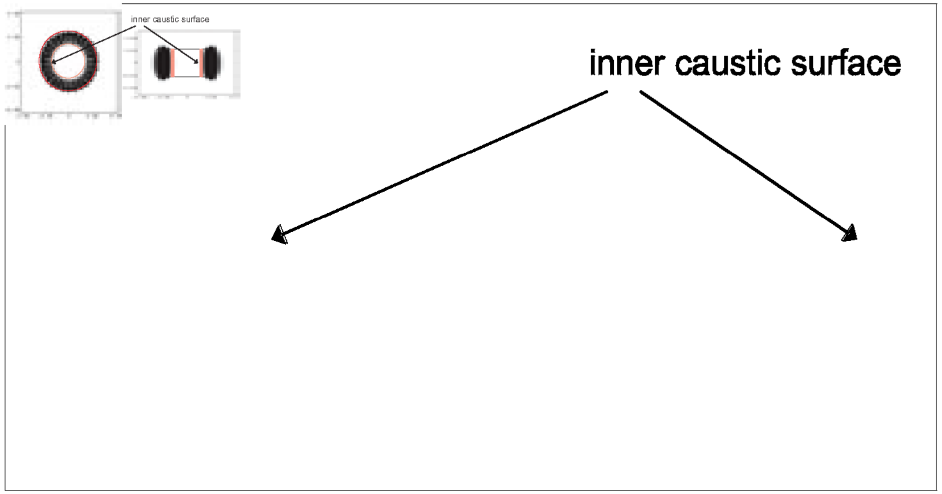
H-Maser versus Cryogenic Sapphire Oscillator



WG CRYOGENIC RESONATORS







Standard Model Extension (SME)

- The photon sector of the SME is equivalent to usual Maxwell equations with (in vacuum):

$$\begin{pmatrix} \vec{D} \\ \vec{H} \end{pmatrix} = \begin{pmatrix} \varepsilon_0 (1 + \kappa_{DE}) & \sqrt{\varepsilon_0 / \mu_0}\, \kappa_{DB} \\ \sqrt{\varepsilon_0 / \mu_0}\, \kappa_{HE} & \mu_0^{-1} (1 + \kappa_{DB}) \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{B} \end{pmatrix}$$

- The frequency of the e-m field inside a cavity is perturbed by

$$\frac{\Delta f}{f} = -\frac{1}{\langle U_0 \rangle} \int d^3x \begin{pmatrix} \varepsilon_0 \vec{E}_0^* \cdot \kappa_{DE} \cdot \vec{E}_0 - \mu_0^{-1} \vec{B}_0^* \cdot \kappa_{HB} \cdot \vec{B}_0 \\ + 2\,\mathrm{Re}\left[\sqrt{\varepsilon_0 / \mu_0}\, \vec{E}_0^* \cdot \kappa_{DB} \cdot \vec{B}_0 \right] \end{pmatrix}$$

Single Resonator Frame

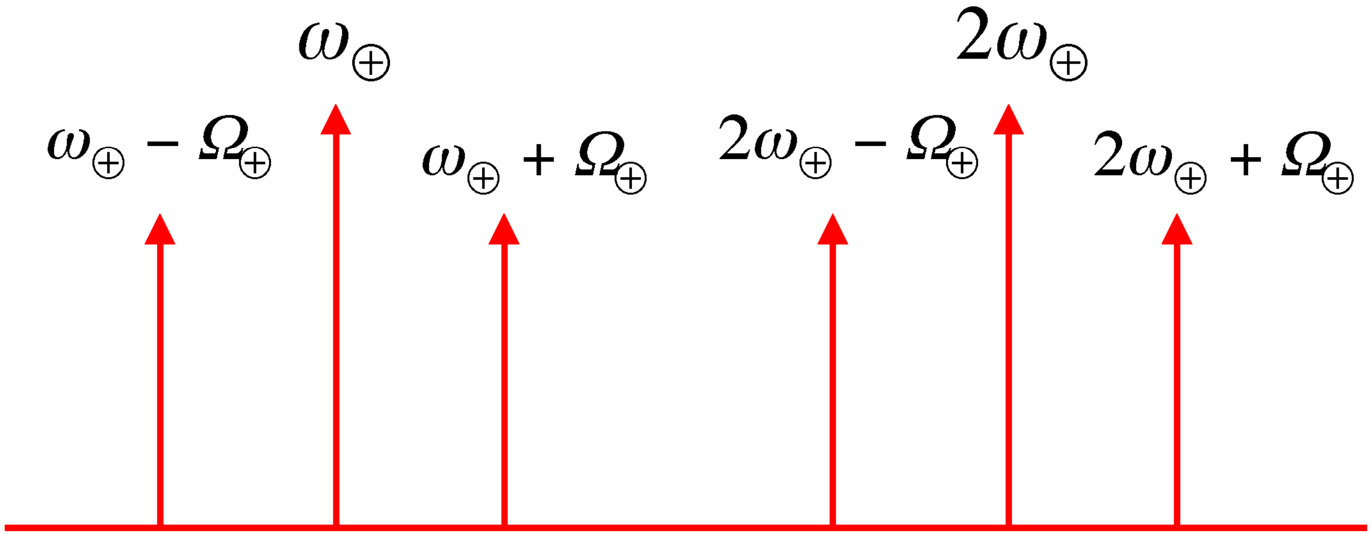
$$\Delta f = \left(\mathcal{M}_{DE}\right)_{lab}^{jk}\left(\kappa_{DE}\right)_{lab}^{jk} + \left(\mathcal{M}_{HB}\right)_{lab}^{jk}\left(\kappa_{HB}\right)_{lab}^{jk}$$

$$\left(\mathcal{M}_{DE}\right)_{res}^{jk} = \begin{bmatrix} -\frac{1}{4}\sum_{l=1}^{2}\frac{\left(P_{er,l}+P_{e\theta,l}\right)}{\varepsilon_l} & 0 & 0 \\ 0 & -\frac{1}{4}\sum_{l=1}^{2}\frac{\left(P_{er,l}+P_{e\theta,l}\right)}{\varepsilon_l} & 0 \\ 0 & 0 & -\frac{1}{2}\sum_{l=1}^{2}\frac{P_{ez,l}}{\varepsilon_l} \end{bmatrix}$$

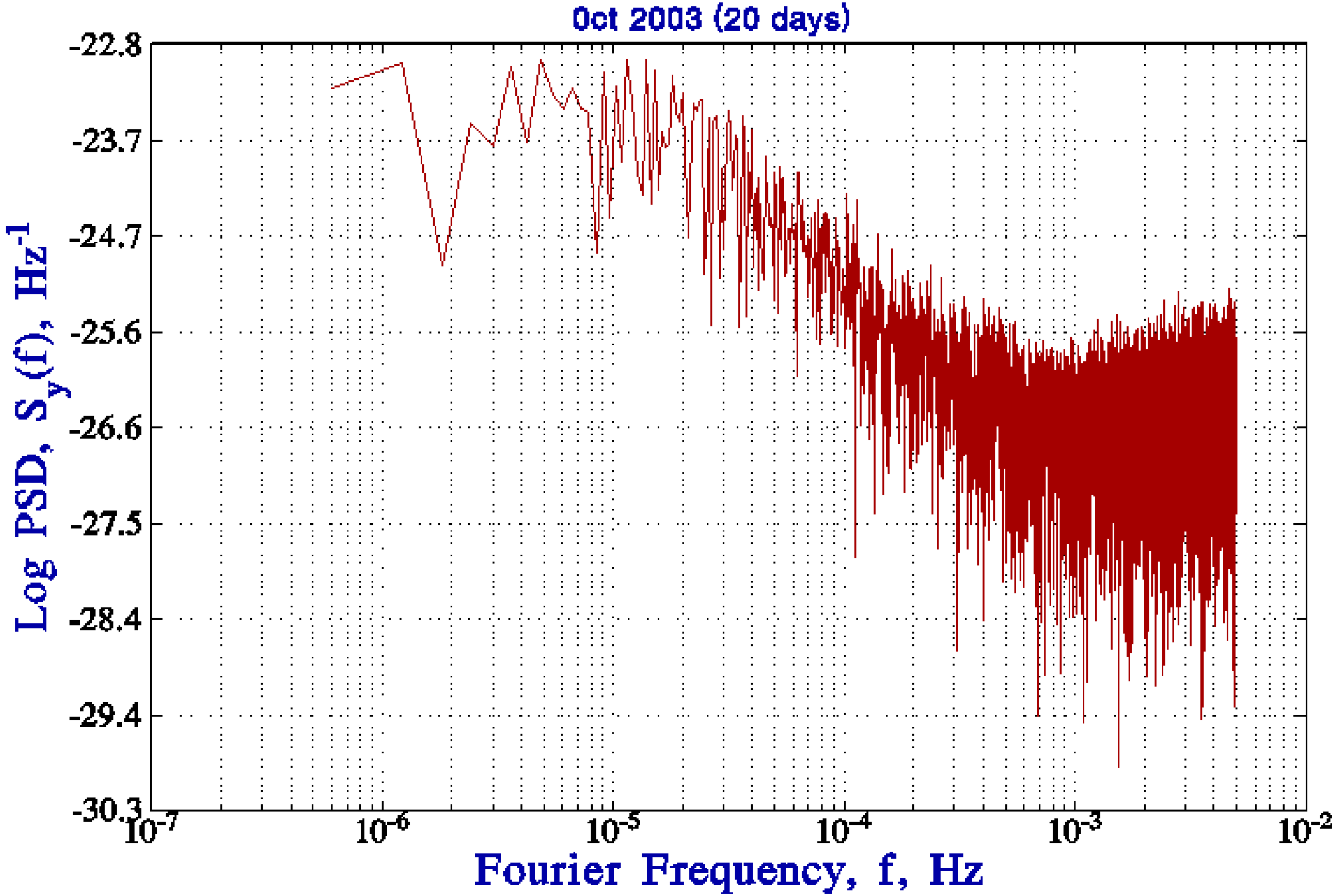
$$\left(\mathcal{M}_{HB}\right)_{res}^{jk} = \begin{bmatrix} \frac{1}{4}\sum_{l=1}^{2}\mu_l\left(P_{mr,l}+P_{m\theta,l}\right) & 0 & 0 \\ 0 & \frac{1}{4}\sum_{l=1}^{2}\mu_l\left(P_{mr,l}+P_{m\theta,l}\right) & 0 \\ 0 & 0 & \frac{1}{2}\sum_{l=1}^{2}\mu_l P_{mz,l} \end{bmatrix}$$

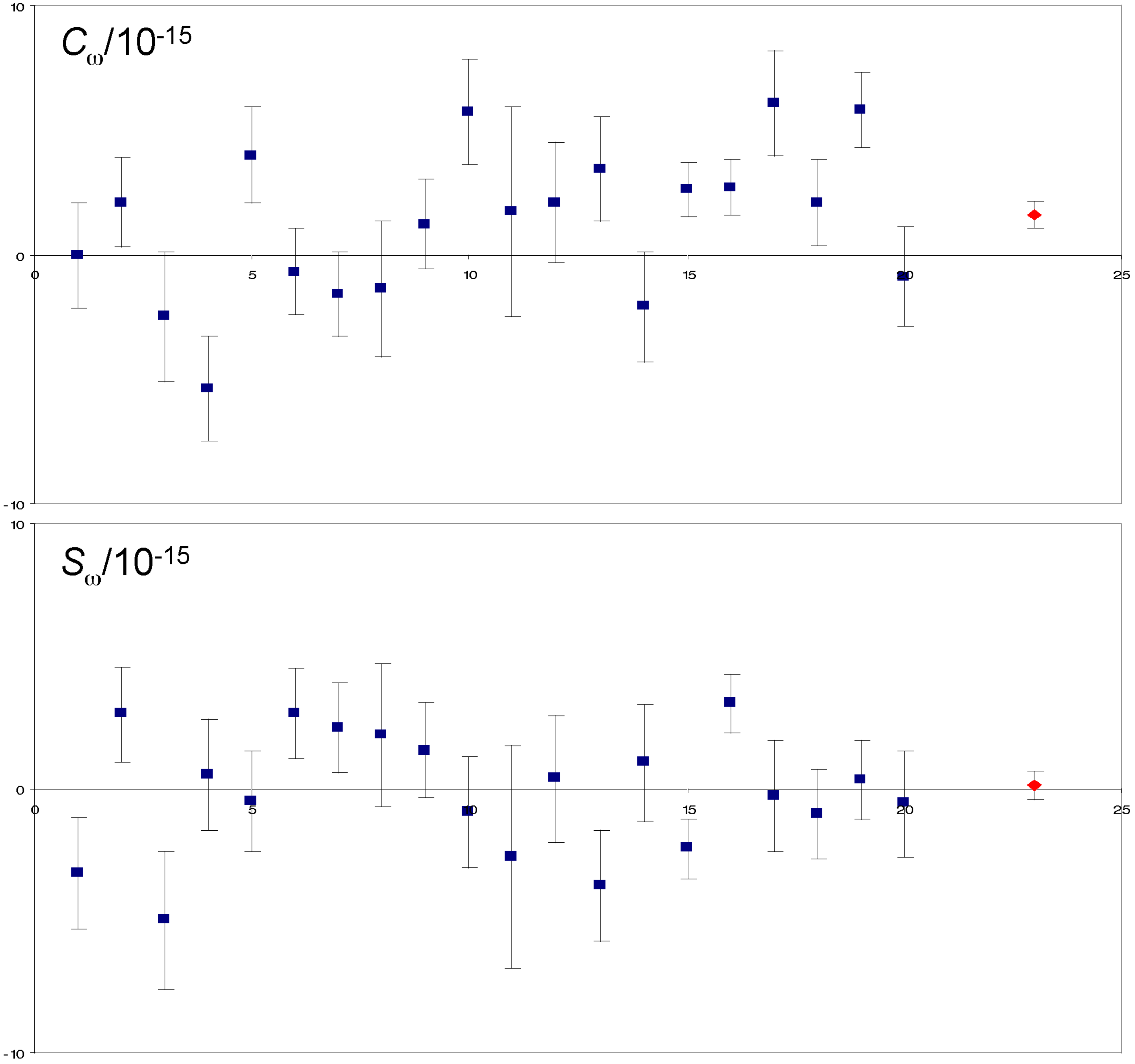
Calculate, electric and magnetic filling factors -> Allows numeric solution Gen. Rel. and Grav., vol. 36, 10, pp. 2351-2373, (2004), also at gr-qc/0401017

$$
\begin{aligned}
(\tilde{\kappa}_{e+})^{jk} &= \tfrac{1}{2}(\kappa_{DE} + \kappa_{HB})^{jk}, \\
(\tilde{\kappa}_{e-})^{jk} &= \tfrac{1}{2}(\kappa_{DE} - \kappa_{HB})^{jk} - \tfrac{1}{3}\delta^{kj}(\kappa_{DE})^{ll}, \\
(\tilde{\kappa}_{o+})^{jk} &= \tfrac{1}{2}(\kappa_{DB} + \kappa_{HE})^{jk}, \\
(\tilde{\kappa}_{o-})^{jk} &= \tfrac{1}{2}(\kappa_{DB} - \kappa_{HE})^{jk}, \\
\tilde{\kappa}_{tr} &= \tfrac{1}{3}(\kappa_{DE})^{ll}.
\end{aligned}
$$



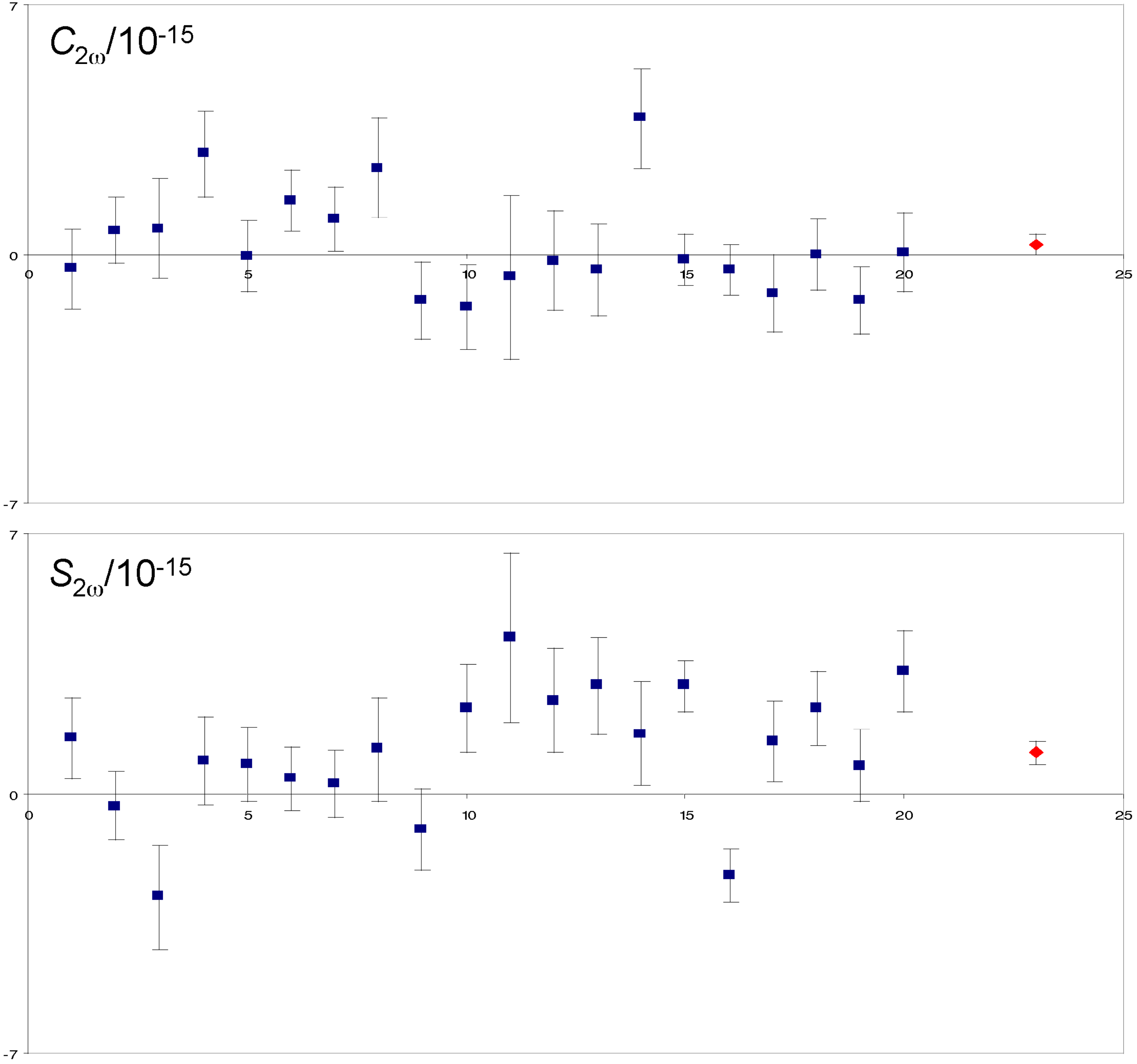
20 data sets 5 d to 20 d τ_0 = 2500 s
222 d total t_0 = 9/9/2002 45% of time (55% in 2003)
Sept. 2002 to Jan 2004.

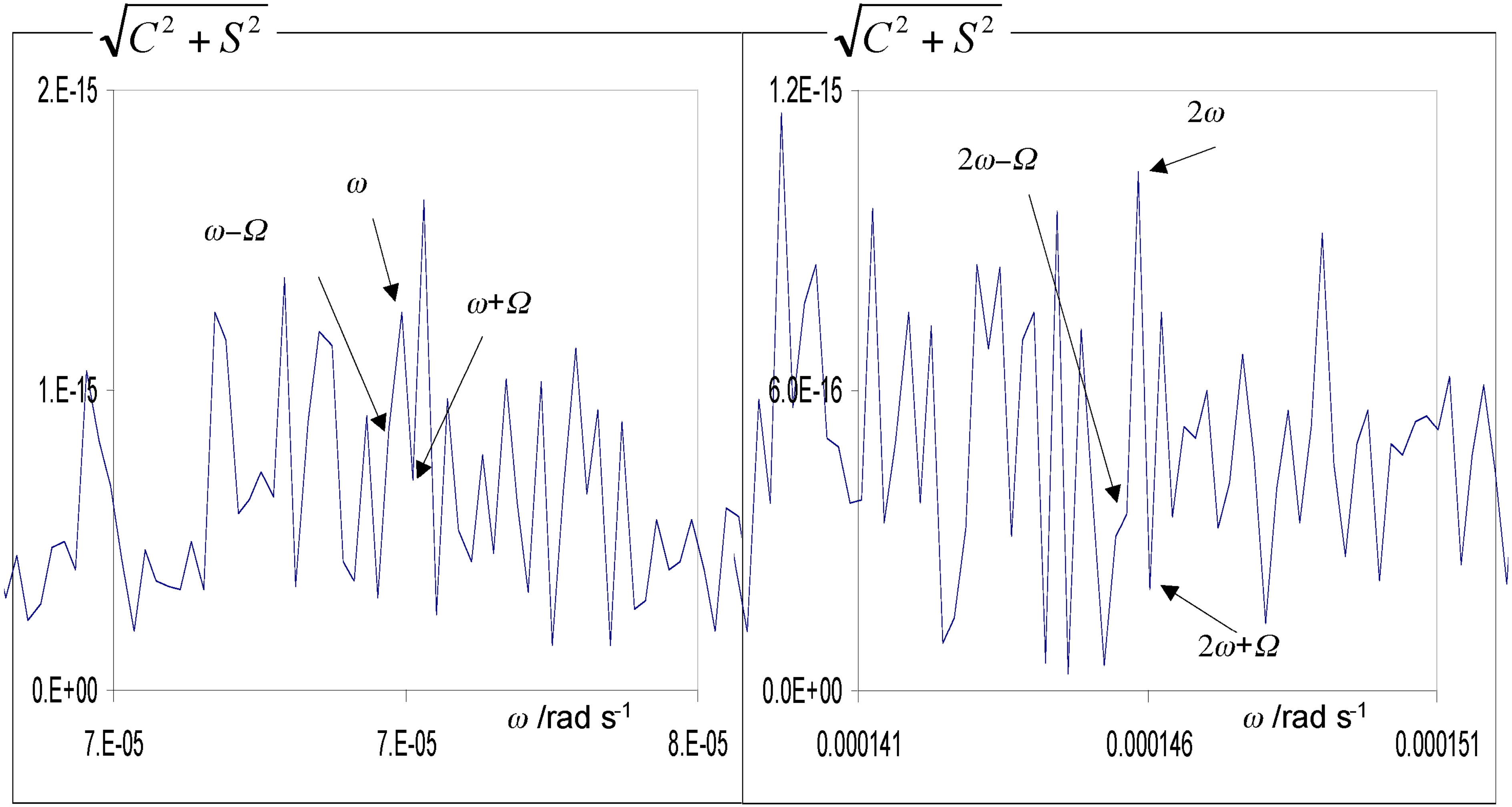




$C_\omega/10^{-15}$

$S_\omega/10^{-15}$


$C_{2\omega}/10^{-15}$
7
0
-7
0
5
10
15
20
25
$S_{2\omega}/10^{-15}$
7
0
-7
0
5
10
15
20
25


$\sqrt{C^2 + S^2}$
2.E-15
1.E-15
0.E+00
ω−Ω
ω
ω+Ω
ω /rad s^{-1}
7.E-05
7.E-05
8.E-05
$\sqrt{C^2 + S^2}$
1.2E-15
6.0E-16
0.0E+00
2ω
2ω−Ω
2ω+Ω
ω /rad s^{-1}
0.000141
0.000146
0.000151

Results in the SME

	Müller et. al.(2003)	This work
$\tilde{\kappa}_{e-}^{XZ}\ /10^{-15}$	**-6.3 ± 12.4**	**-3.2 ± 1.3**
$\tilde{\kappa}_{e-}^{YZ}\ /10^{-15}$	**3.6 ± 9.0**	**-0.5 ± 1.3**
$\tilde{\kappa}_{e-}^{XY}\ /10^{-15}$	1.7 ± 2.6	-5.7 ± 2.3
$(\tilde{\kappa}_{e-}^{XX}-\tilde{\kappa}_{e-}^{YY})\ /10^{-15}$	8.9 ± 4.9	-3.2 ± 4.6
$\tilde{\kappa}_{o+}^{XZ}\ /10^{-11}$	-1.2 ± 2.6	-1.4 ± 2.3
$\tilde{\kappa}_{o+}^{YZ}\ /10^{-11}$	0.1 ± 2.7	2.7 ± 2.2
$\tilde{\kappa}_{o+}^{XY}\ /10^{-11}$	**14 ± 14**	**-1.8 ± 1.5**

Results for RMS

Saathoff et al. 2003 Wolf & Petit (1997) Riis et al. (1988) R. Grieser et. al. (1994)	2.2 $\left|\alpha + \tfrac{1}{2}\right| < 8\times10^{-7}$	
Braxmaier et al. (2002) Hils & Hall (1990)	$\left|\beta - \alpha - 1\right| < 2\times10^{-5}$	P_{KT}
This experiment	$\left|\beta - \alpha - 1\right| < 2\times10^{-7}$	
Brillet & Hall (1979) Schiller (2003)	$\left|\beta - \delta - 1/2\right| < 3\times10^{-9}$	P_{MM}
This experiment	$\left|\beta - \delta - 1/2\right| < 2\times10^{-9}$	

PRL 2003, Wolf, Bize, Clairon, Luiten, Santarelli, Tobar
GRG 2004, Wolf, Tobar,Bize, Clairon, Luiten, Santarelli

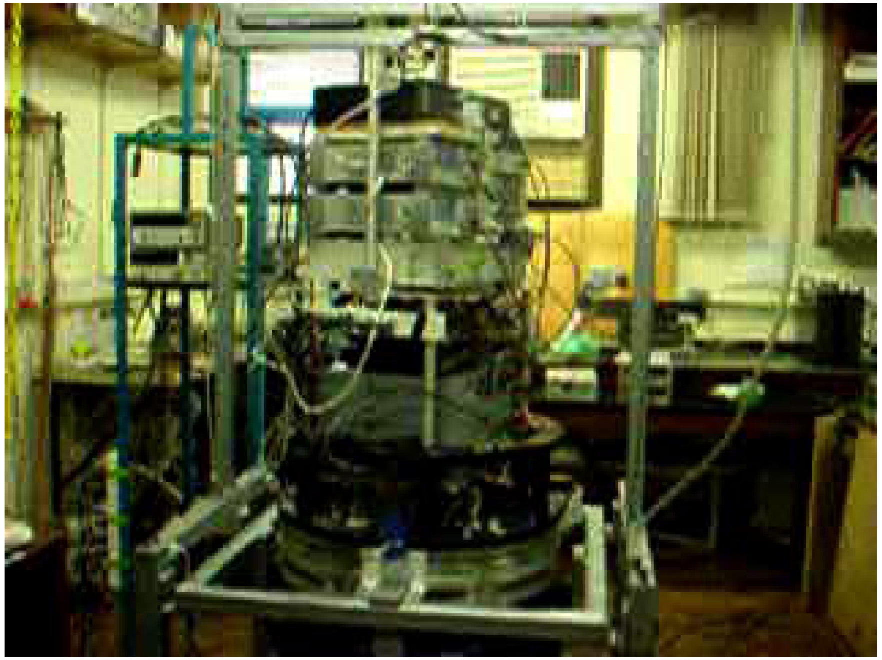
Discussion and Conclusion

Standard Model Extension (SME)

- Improvement by about a factor 7 to 10 for three SME parameters (slight improvement on the rest).
- Significant ($\approx 2\sigma$) results for two parameters.
- Not consistent with Müller et al. (except for $\tilde{\kappa}_{e-}^{XZ}$).
- Not supported by distribution of individual points, or fits at neighbouring frequencies.
- Most likely a statistical coincidence or an underestimated or neglected systematic effect.
- $\Rightarrow$ Experiment is continued….
- $\Rightarrow$ Rotating experiment at UWA (potentially > order of magnitude improvement).

UWA: Rotating Michelson-Morley and SME Experiments

- Initial Operation -

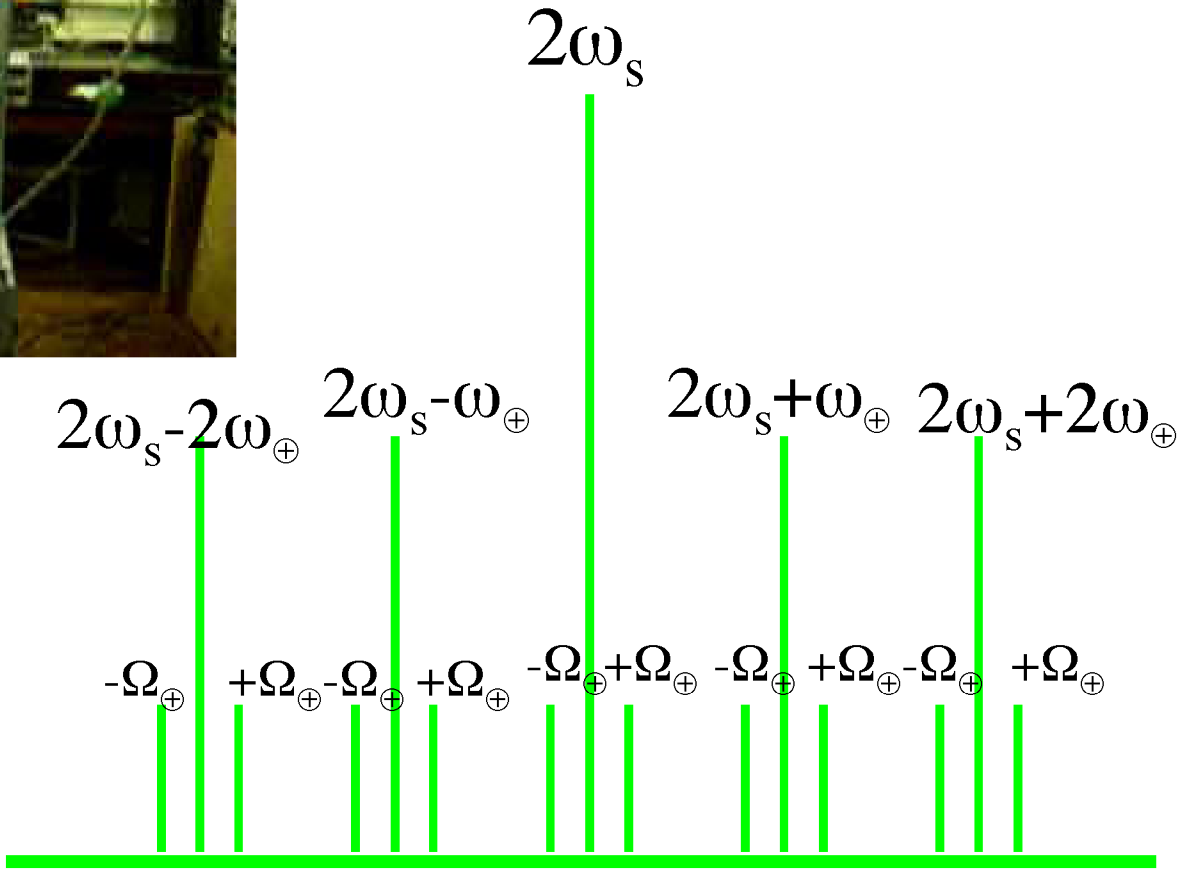


ω_s:Spin

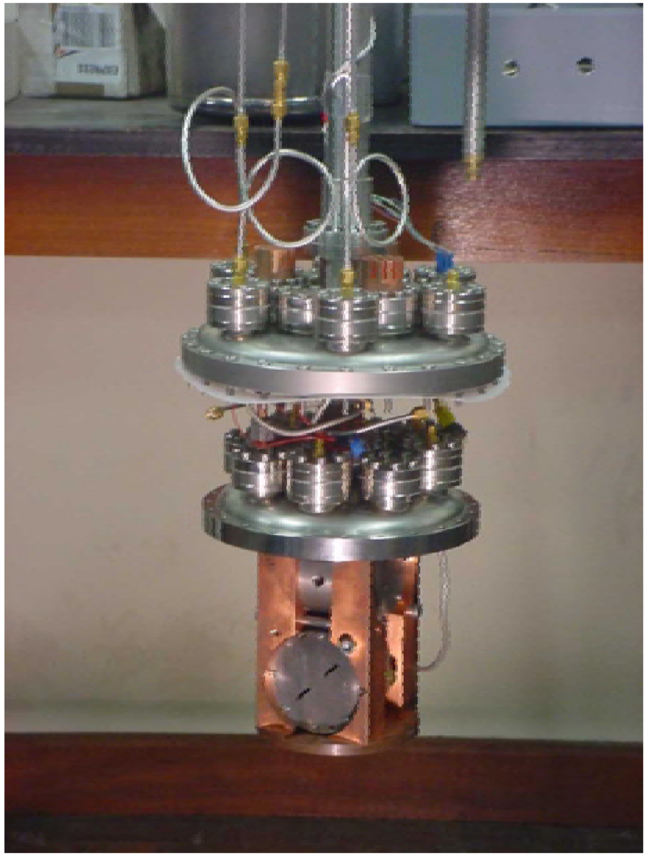
$\omega_\oplus$:Sidereal

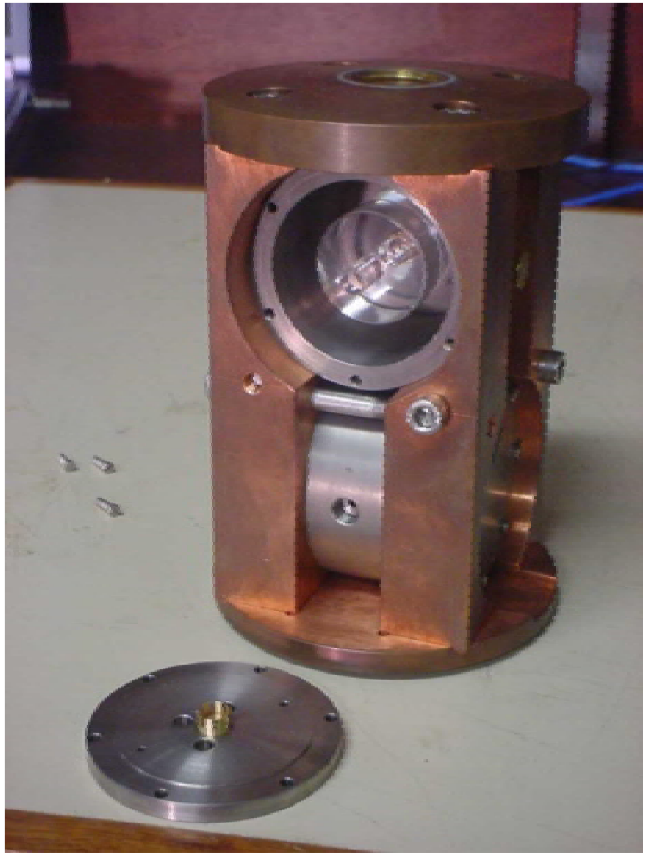
$\Omega_\oplus$:Annual

15 frequencies



WG Mode Experiment





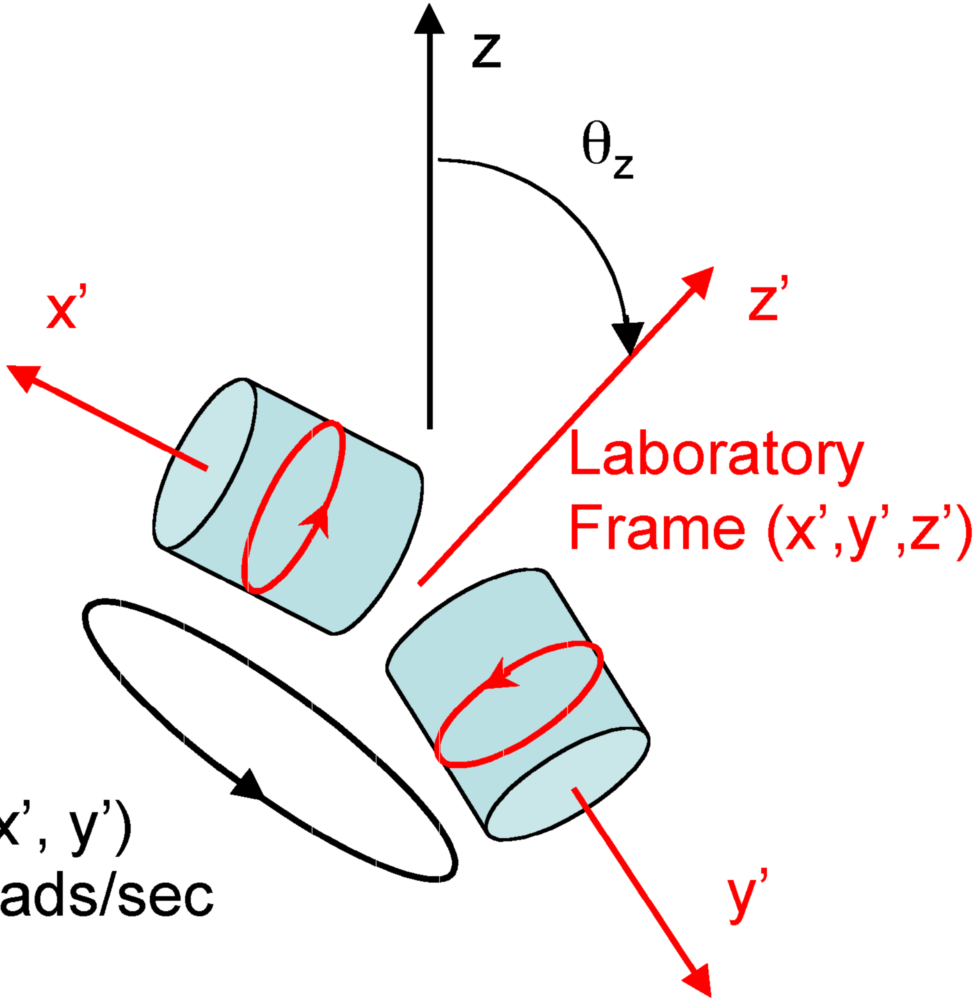
Initial experiments use 3cm diameter sapphire clocks -> fit in current dewar.

1990 Giles, Jones, Blair, Buckingham Physica B , 9×10^{-15} @10 to 300 s

Initial Operation Began Mid June 2004

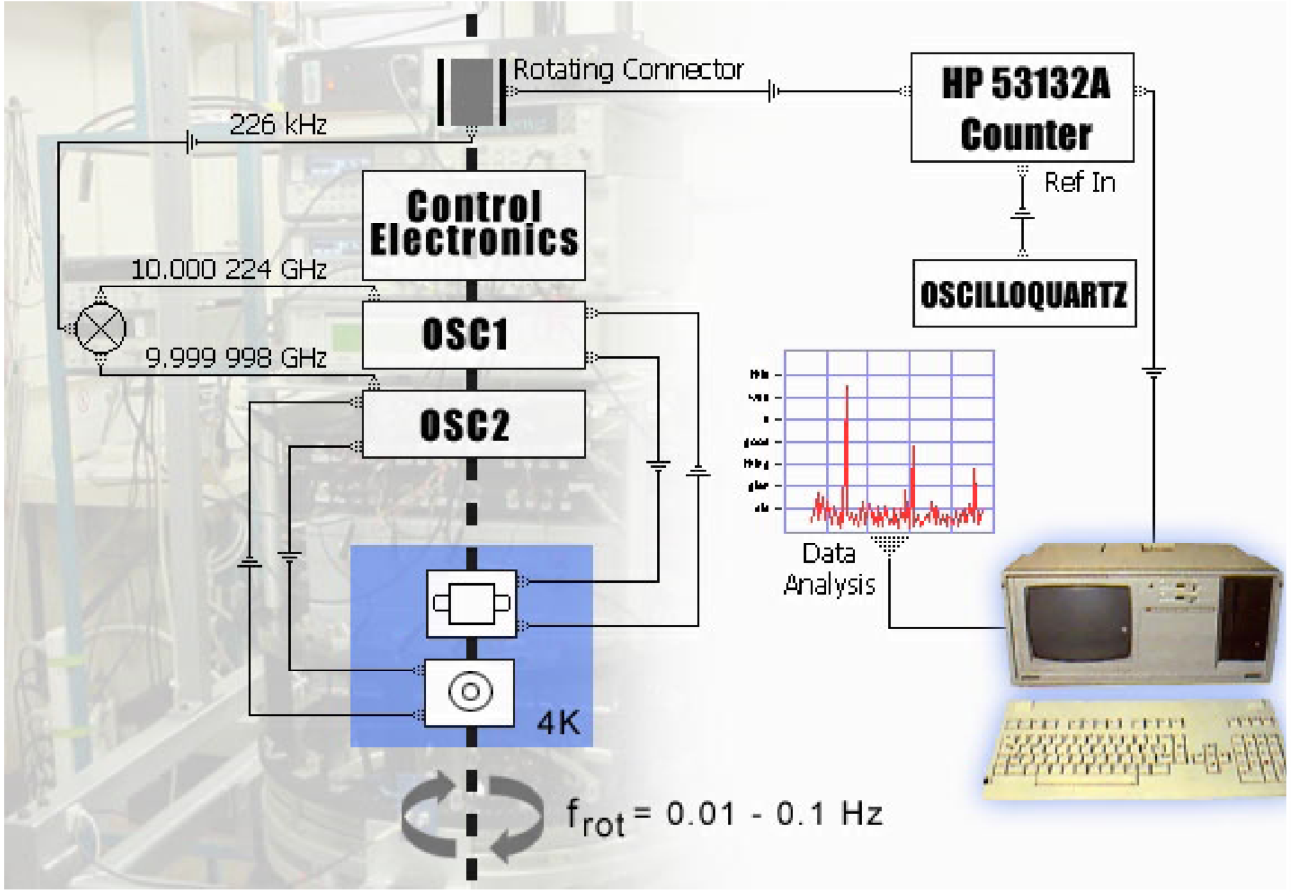
Two WG mode cylinder resonators

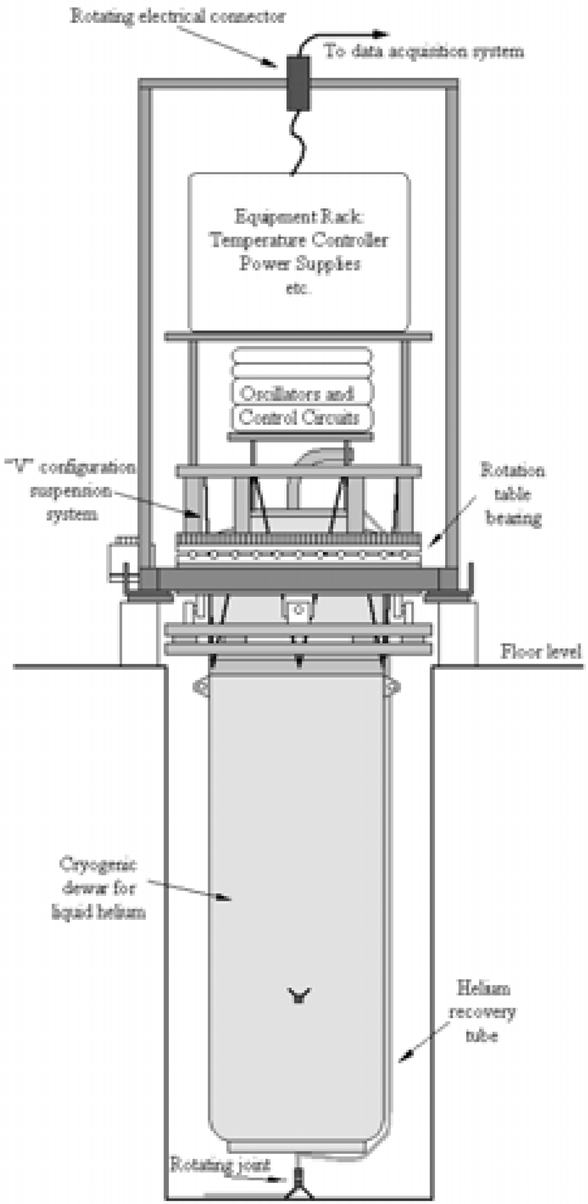
Absolute Frame (x,y,z)

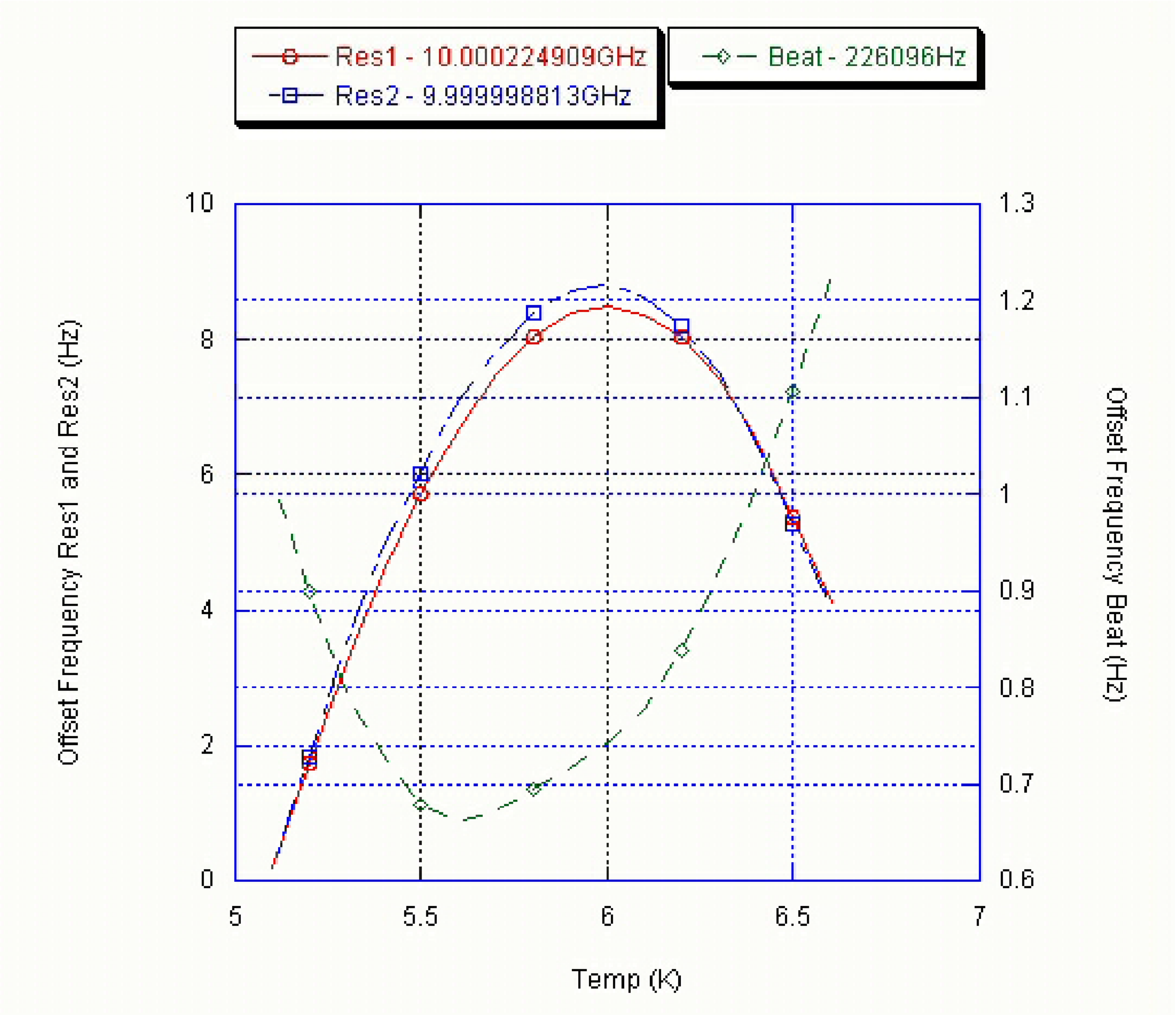


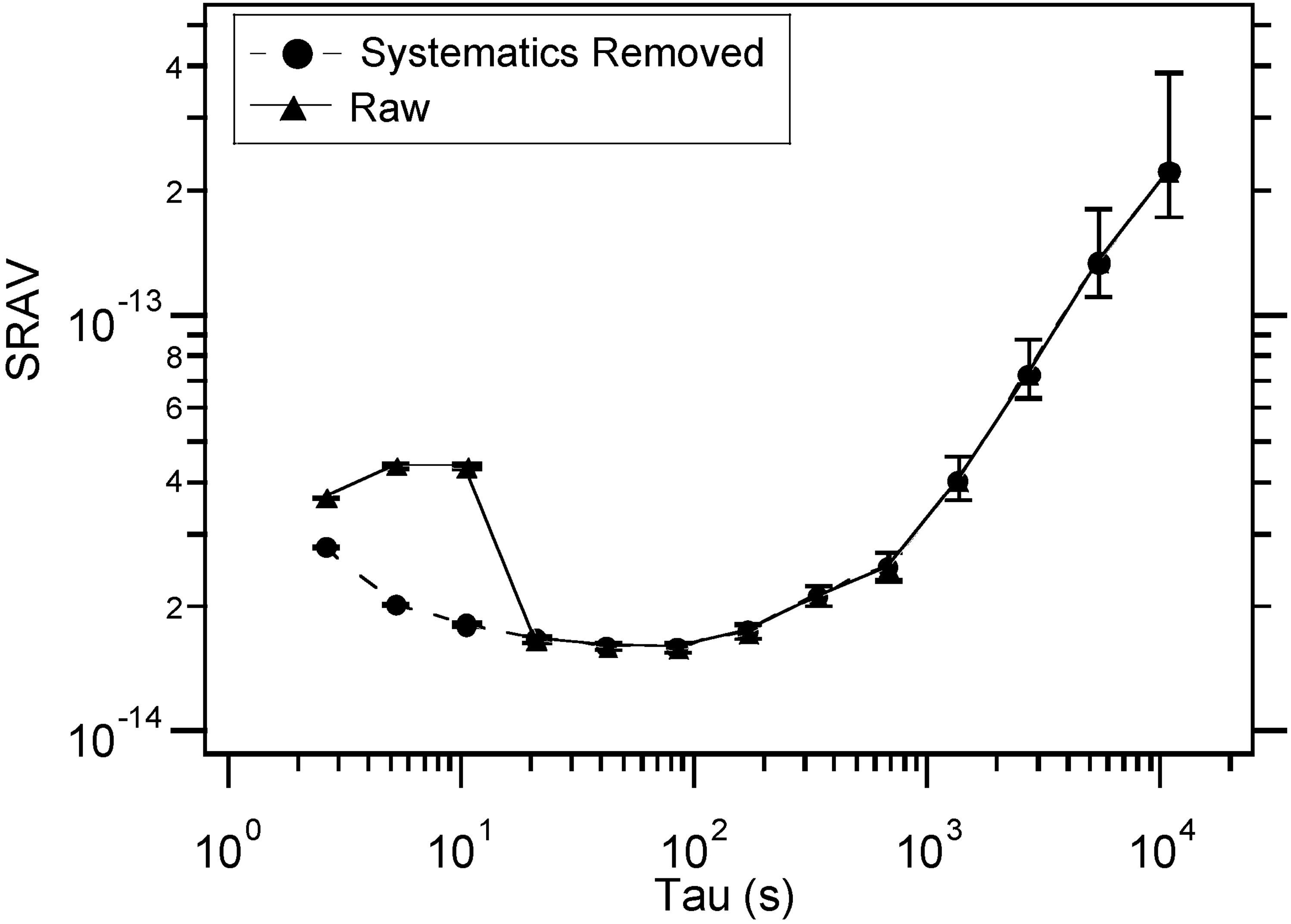
Laboratory Frame (x',y',z')

Spin (x', y')
at ω_s rads/sec

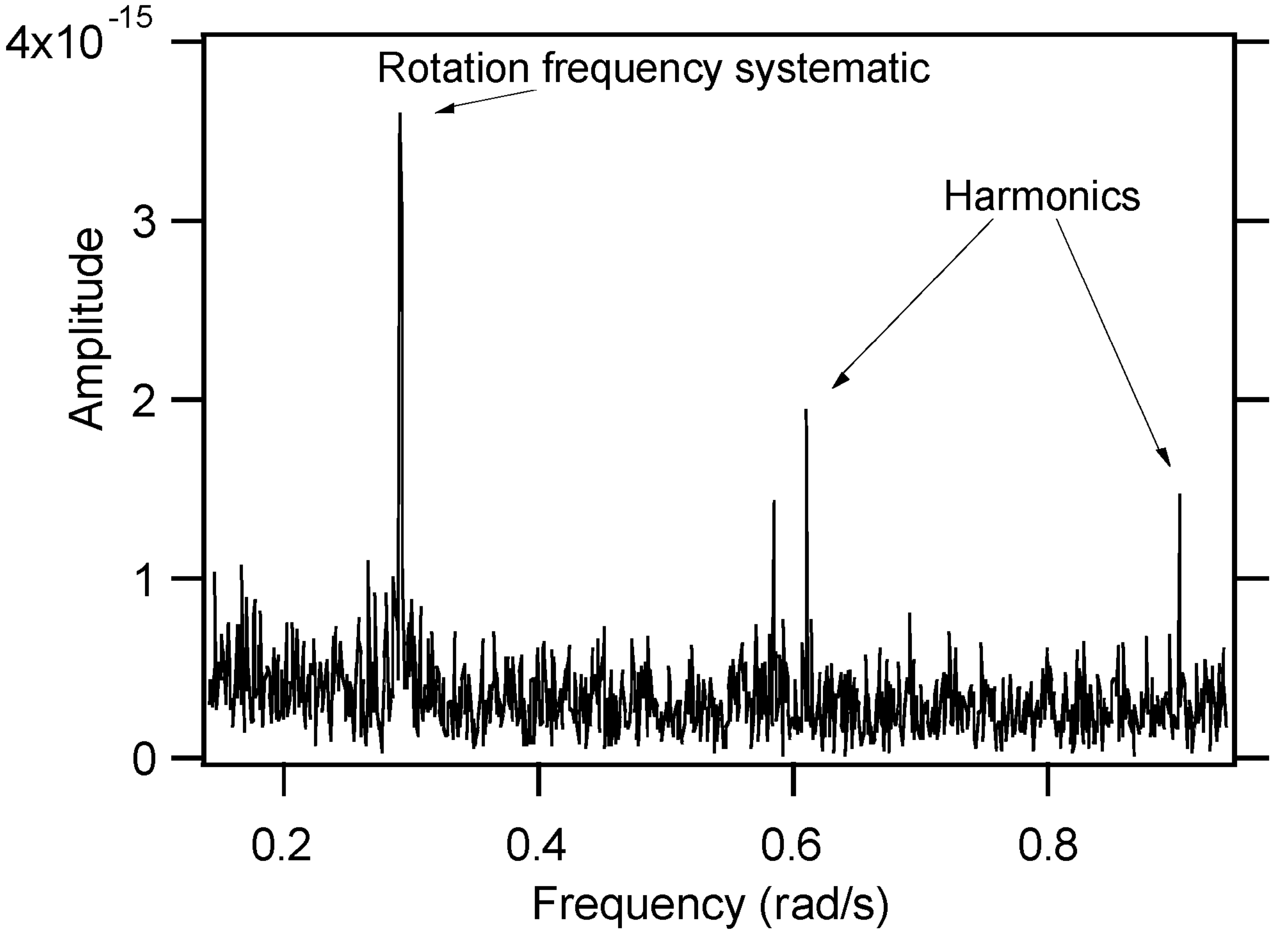

Rotating Connector
226 kHz
HP 53132A Counter
Ref In
Control Electronics
OSCILLOQUARTZ
10.000 224 GHz
OSC1
9.999 998 GHz
OSC2
Data Analysis
4K
f_{rot} = 0.01 - 0.1 Hz


Rotating electrical connector
To data acquisition system
Equipment Rack:
Temperature Controller
Power Supplies
etc.
Oscillators and
Control Circuits
"V" configuration suspension system
Rotation table bearing
Floor level
Cryogenic dewar for liquid helium
Helium recovery tube
Rotating joint


Res1 - 10.000224909GHz
Res2 - 9.999998813GHz
Beat - 226096Hz
Offset Frequency Res1 and Res2 (Hz)
Offset Frequency Beat (Hz)
Temp (K)
10
8
6
4
2
0
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
5
5.5
6
6.5
7


Systematics Removed
Raw
SRAV
4
2
10^-13
8
6
4
2
10^-14
10^0
10^1
10^2
10^3
10^4
Tau (s)

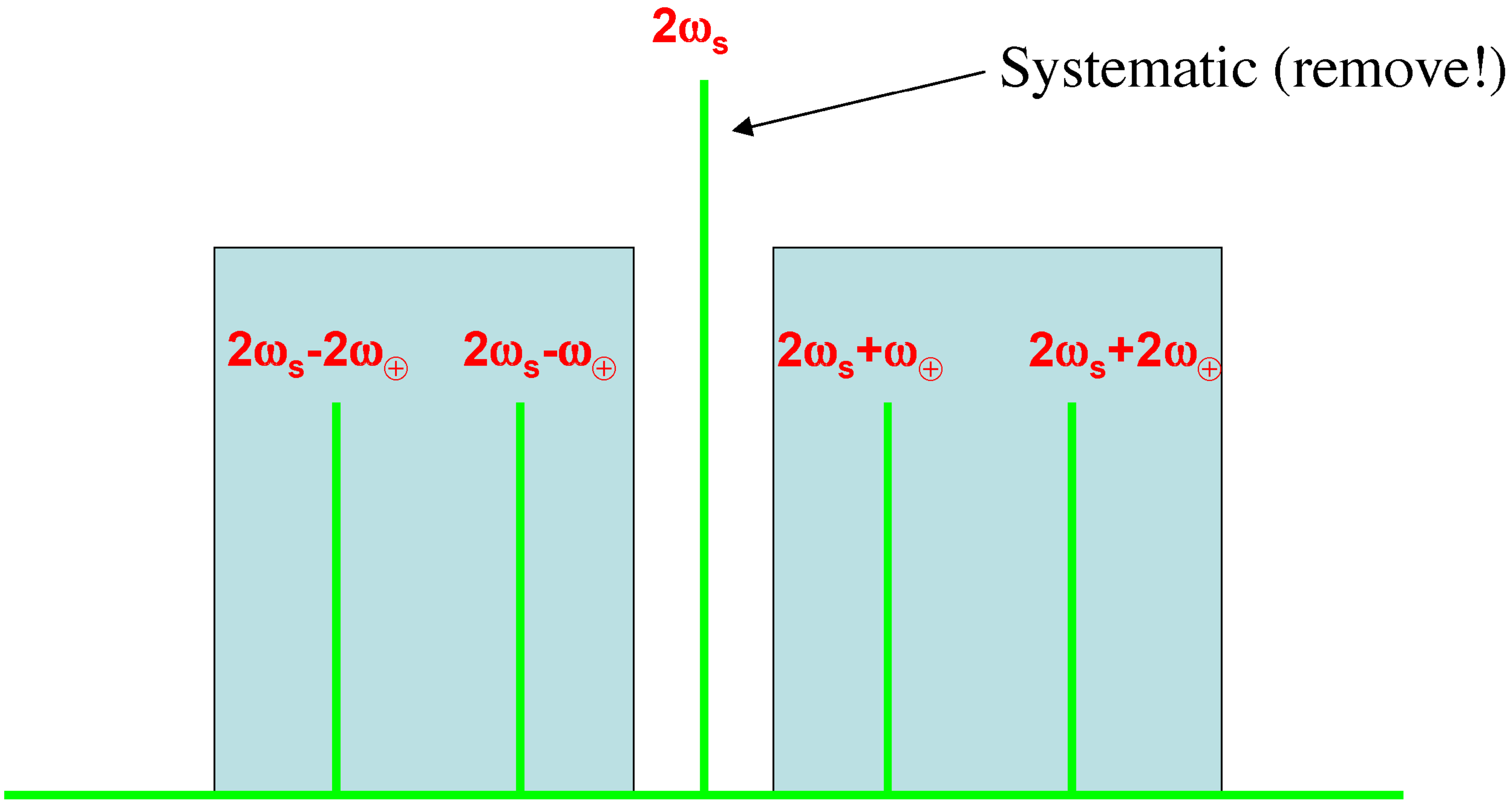
Data (~16.6 hrs Continuous)

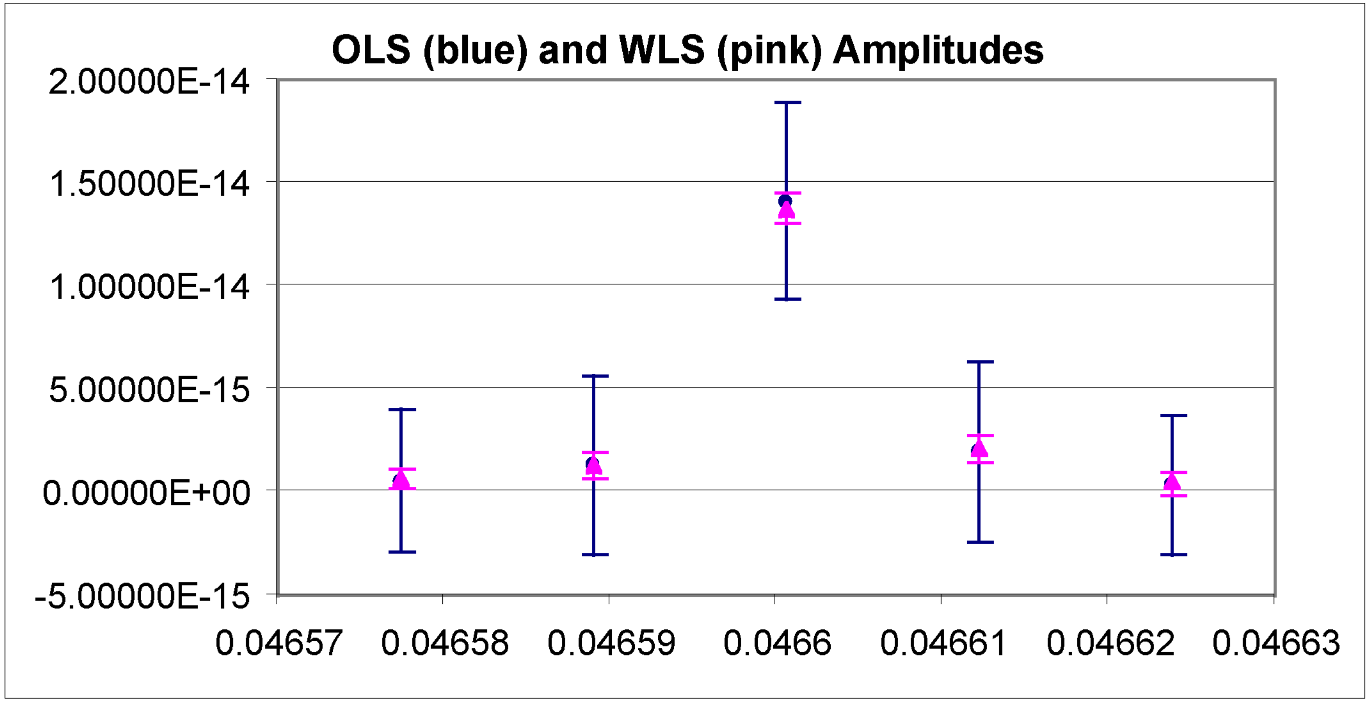


- OLS fit of noise at rotation frequency

Sensitivities

- If we look at sidebands, and sum the annular term (which will look like a drift):




OLS (blue) and WLS (pink) Amplitudes
2.00000E-14
1.50000E-14
1.00000E-14
5.00000E-15
0.00000E+00
-5.00000E-15
0.04657
0.04658
0.04659
0.0466
0.04661
0.04662
0.04663

Future plans:

-New Helium transfer tube => faster turn around time and less disturbance to exp

-Additional rotating connector and data acquisition card to monitor
tilt, temp in and out of exp, helium level, control systems

-Shield against magnetic fields

The data acquisition will run with 3 files:

1. The beat frequency counter with 2-2.5sec integration time and ~5ms dead time
2. The position as indicated by infra-red led sensors (probably triggering a measurement)
3. All the other monitored signals (for systematic analysis)

Rotation rate will be around 20 seconds.

New methods of testing Lorentz violation in electrodynamics

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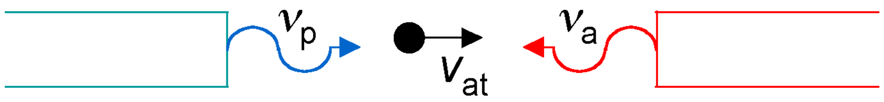
92312 Se`vres CEDEX, France

arXiv: hep-ph/0408006
Submitted to PRD

Doppler experiments in the SME



Ives – Stilwell experiment

- To first order:

$$\boxed{\frac{\nu_a \nu_p}{\nu_0^2} = 1 + \frac{v_{at}}{c_p} - \frac{v_{at}}{c_a}}$$

with the phase velocities in the lab frame $c_i \equiv |\omega_i / \beta_i|$

- The most recent version (Saathoff et al. 2003) uses $^7\mathrm{Li}^+$ ions at $v_{at} = 0.064\, c$ and sets a limit:

$$\frac{\nu_a \nu_p}{\nu_0^2} = 1 + \varepsilon \quad \text{with} \quad |\varepsilon| \leq 1.8 \times 10^{-9}$$

Doppler experiments in the SME

- In the SME photon sector, when imposing already known limits:

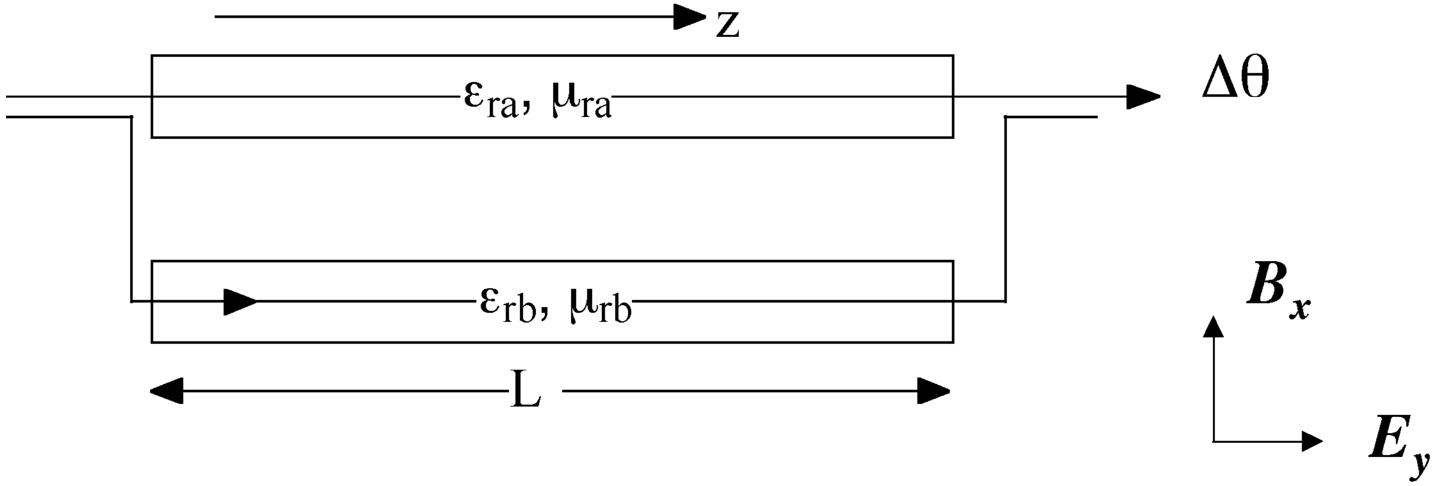
$$\frac{\nu_a \nu_p}{\nu_0^2} = 1 + 4\tilde{\kappa}_{tr}\frac{v_{at}}{c}\left[\begin{array}{l} \cos(\phi)\dfrac{v_\oplus}{c}\left(\begin{array}{l}\cos(\Omega_\oplus T)\big(\sin(\eta)\sin(\chi) - \cos(\eta)\cos(\chi)\sin(\omega_\oplus T_\oplus)\big) \\ + \sin(\Omega_\oplus T)\cos(\chi)\cos(\omega_\oplus T_\oplus)\end{array}\right) \\ + \sin(\phi)\left(\dfrac{v_r}{c} - \dfrac{v_\oplus}{c}\big(\cos(\Omega_\oplus T)\cos(\eta)\cos(\omega_\oplus T_\oplus) + \sin(\Omega_\oplus T)\sin(\omega_\oplus T_\oplus)\big)\right)\end{array}\right]$$

- Depending on the precise values of the experimental parameters (ϕ, T, etc…) the experiment by Saathoff et al. implies a limit of:

$$\boxed{\left|\tilde{\kappa}_{tr}\right| \leq \left(10^{-5} - 10^{-4}\right)}$$

- Analysing other experiments of this type (Two photon spectroscopy, GPS clock comparisons, etc…) in the SME yields additional, but less stringent limits on $\tilde{\kappa}_{tr}$.

NEW MAGNETIC INTERFEROMETER EXPERIMEMT

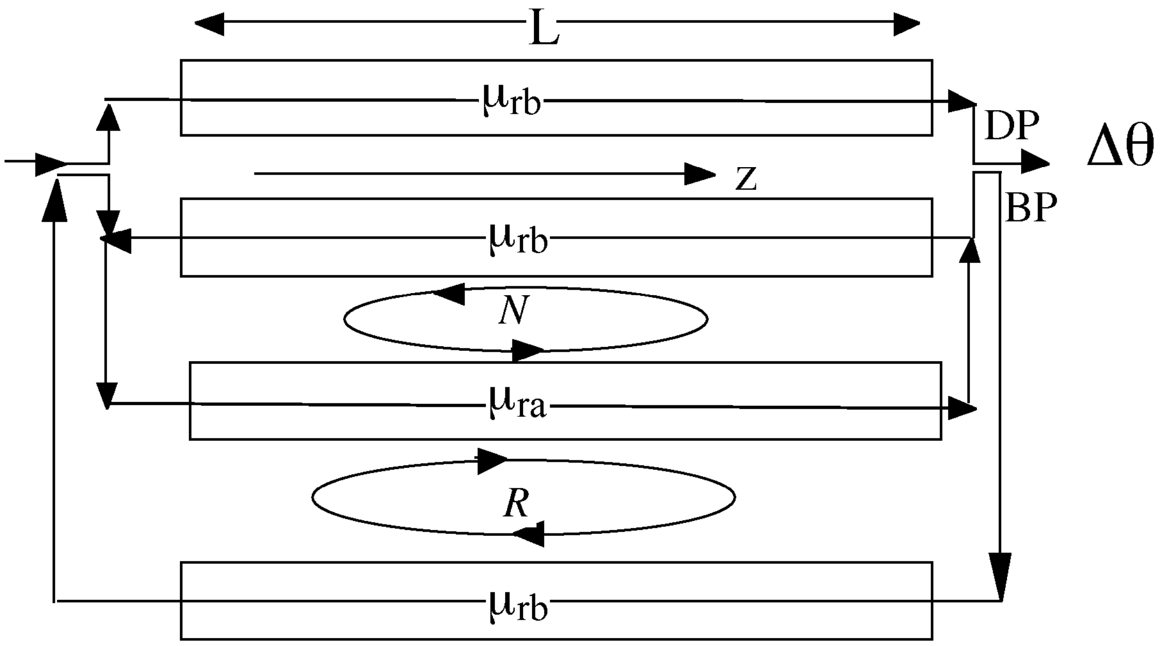


Plane wave solution ->
κ_{DB} term independent of
guiding technique

$$\Delta\theta^{+}_{yx} = \theta^{+}_{yx,a} - \theta^{+}_{yx,b} =$$

$$\frac{2\pi L}{\lambda_v}\left[\begin{array}{l}\left(\sqrt{\mu_{ra}\varepsilon_{ra}}-\sqrt{\mu_{rb}\varepsilon_{rb}}\right)-\left(\mu_{ra}-\mu_{rb}\right)\kappa^{yx}_{DBlab}+\\ \frac{1}{2}\left(\sqrt{\frac{\mu_{ra}}{\varepsilon_{ra}}}-\sqrt{\frac{\mu_{rb}}{\varepsilon_{rb}}}\right)\kappa^{yy}_{DElab}-\frac{1}{2}\left(\sqrt{\mu^{3}_{ra}\varepsilon_{ra}}-\sqrt{\mu^{3}_{rb}\varepsilon_{rb}}\right)\kappa^{xx}_{HBlab}\end{array}\right]$$

WITH RECYCLING



$$\delta\theta\big|_{SNR=1} = \frac{\sqrt{S_\phi}}{\sqrt{\tau_{obs} N_c}}$$

$$\delta\left(\kappa_{DB}\right)^{jk}_{lab}\Big|_{SNR=1} = \frac{\lambda_v}{2\pi L(N+1)(R+1)(\mu_{ra}-1)}\frac{\sqrt{S_\phi}}{\sqrt{\tau_{obs} N_c}}$$

YIG @ 10 GHz: $\mu_r \sim 0.9$; $Tan\delta \sim 10^{-4}$

$L = 1$ meter; $R+1 = N+1 \sim 100$

$\sqrt{S_\phi} \sim 10^{-10}$ radians/√Hz $N_c = 0.05$

$$\delta(\kappa_{DB})^{jk}_{lab}\Big|_{SNR=1} = \frac{2.10^{-14}}{\sqrt{\tau_{obs}}}$$

$\tau_{obs} \sim 450$ seconds -> sensitivity $\sim 10^{-15}$

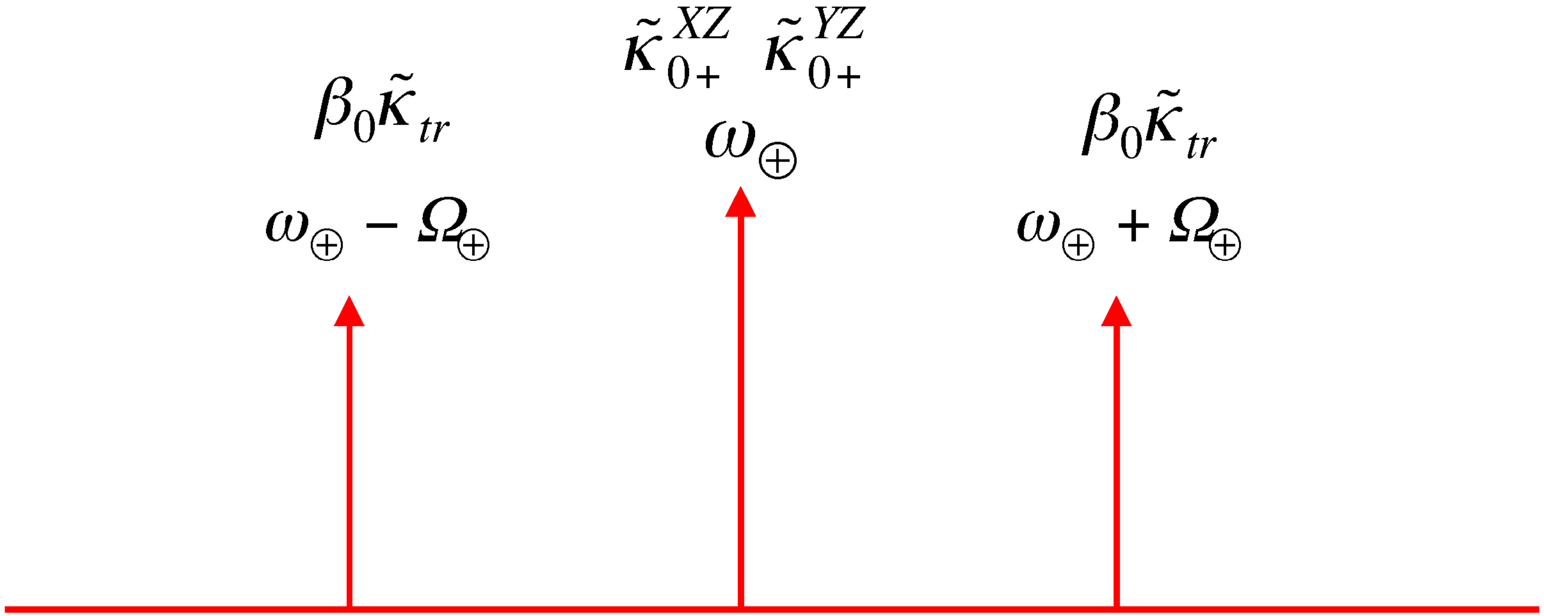
$\tilde{\kappa}_{0+} \sim 10^{-15}$ Direct Measurement

$\tilde{\kappa}_{tr} \sim 10^{-11}$ Boost Suppression (10^{-4})

$N_c = 1.157\times10^{-5}$ (one day rotation period), same sensitivity in 22.5 days

Stationary Laboratory Experiment
(direct and first order terms)

Cannot Measure $\tilde{\kappa}_{0+}^{XY}$



$\beta_0 \tilde{\kappa}_{tr}$

$\omega_\oplus - \Omega_\oplus$

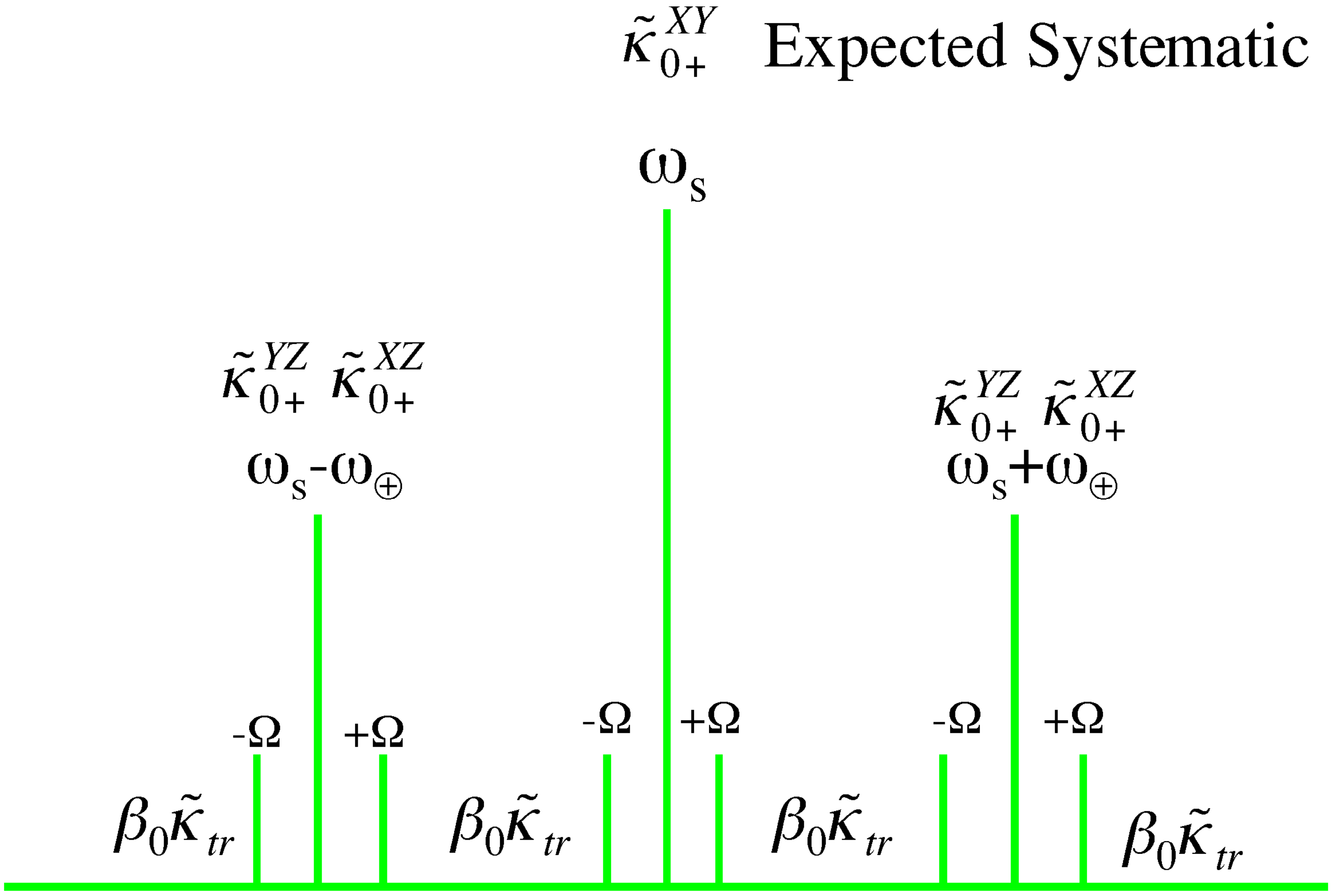
$\tilde{\kappa}_{0+}^{XZ} \quad \tilde{\kappa}_{0+}^{YZ}$

$\omega_\oplus$

$\beta_0 \tilde{\kappa}_{tr}$

$\omega_\oplus + \Omega_\oplus$

Rotating Laboratory Experiment



THE END