New Constraints on Possible 5th Forces Using SERF Magnetometer

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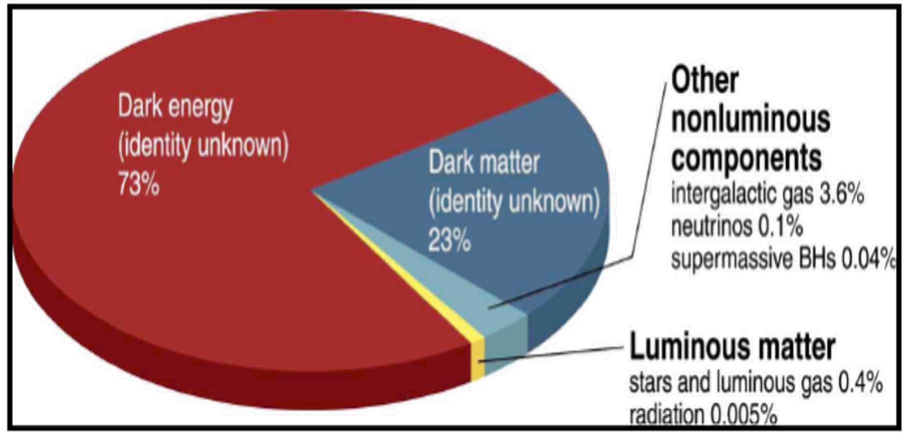
Outline

1. Introduction
    - New Particles as media of 5th Force?
    - Classifying the New Interactions (or the 5th Force)
    - The SERF (Spin Exchange Relaxation Free) Magnetometer
2. Exp1: Spin-Dependent 5th Force
3. Exp2: Spin-Velocity-Dependent 5th force
4. Summary

New particles, wanted?

- Dark Matter
- Strong CP problem

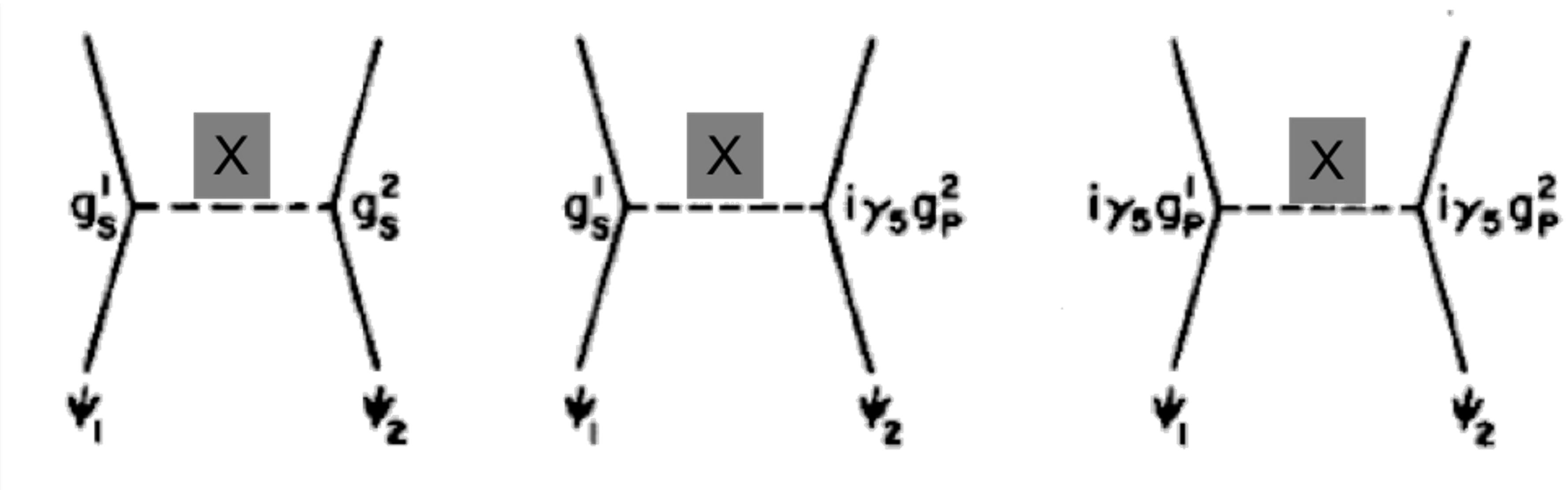


Science (20 June 2003)

  - Baryon asymmetry: Baryon/ photon~10^{-10} , compared with CP violation in kaon&B-meson experimentally: Baryon/photon~10^{-18}
- EDM(Electric Dipole Moment)
- WIMPs, Axion, Dark Photon, Gravitino……

New Medium Bosons means New Forces

- "The 5th Force "



Yukawa-Like Potential between the two Vertexes must be function of:

$$U(m_1, m_2, S_1, S_2, r_{12}, V_{12})$$

Classifying the Interactions (I)

$U(m_1, m_2, S_1, S_2, r_{12}, V_{12})$

$$\mathcal{V}_1 = \frac{1}{r}\, y(r) \ ,$$

$$\mathcal{V}_2 = \frac{1}{r}\, \vec{\sigma}\cdot\vec{\sigma}\,'\, y(r) \ ,$$

$$\mathcal{V}_3 = \frac{1}{m^2\, r^3}\left[\vec{\sigma}\cdot\vec{\sigma}\,'\left(1 - r\frac{d}{dr}\right) - 3\left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right)\right] y(r) \ ,$$

$$\mathcal{V}_{4,5} = -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}\,'\right)\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr}\right) y(r) \ ,$$

$$\mathcal{V}_{6,7} = -\frac{1}{2m\, r^2}\left[\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right) \pm \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}\,'\cdot\vec{v}\right)\right]\left(1 - r\frac{d}{dr}\right) y(r) \ ,$$

$$\mathcal{V}_8 = \frac{1}{r}\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}\,'\cdot\vec{v}\right)\, y(r) \ ,$$

B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. 11, 005 (2006).

Classifying of Interactions (II)

$$\boxed{\mathcal{V}_{9,10} = -\frac{1}{2m\,r^2}\,(\vec{\sigma} \pm \vec{\sigma}\,') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr}\right) y(r) \;\;,}$$

$$\mathcal{V}_{11} = -\frac{1}{m\,r^2}\,(\vec{\sigma} \times \vec{\sigma}\,') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr}\right) y(r) \;\;,$$

$$\boxed{\mathcal{V}_{12,13} = \frac{1}{2r}\,(\vec{\sigma} \pm \vec{\sigma}\,') \cdot \vec{v}\, y(r) \;\;,}$$

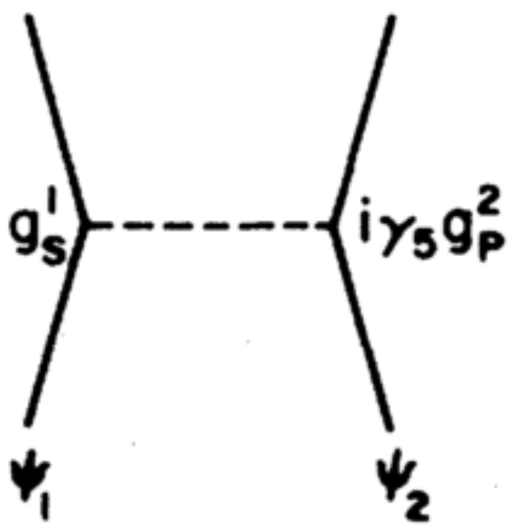
$$\mathcal{V}_{14} = \frac{1}{r}\,(\vec{\sigma} \times \vec{\sigma}\,') \cdot \vec{v}\, y(r) \;\;,$$

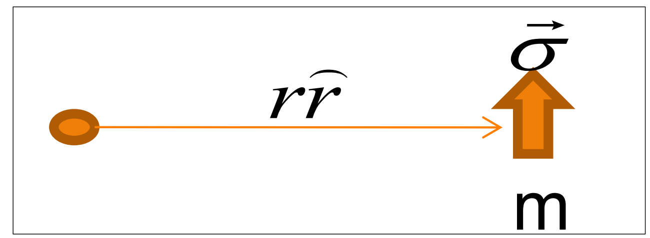
$$\mathcal{V}_{15} = -\frac{3}{2m^2\,r^3}\left\{ \left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] \left(\vec{\sigma}\,' \cdot \hat{\vec{r}}\right) + \left(\vec{\sigma} \cdot \hat{\vec{r}}\right) \left[\vec{\sigma}\,' \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] \right\}$$
$$\times \left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right) y(r) \;\;,$$

$$\mathcal{V}_{16} = -\frac{1}{2m\,r^2}\left\{ \left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] (\vec{\sigma}\,' \cdot \vec{v}) + (\vec{\sigma} \cdot \vec{v}) \left[\vec{\sigma}\,' \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right] \right\} \left(1 - r\frac{d}{dr}\right) y(r)$$

B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. 11, 005 (2006).

Det. New Particle by NMR





$$V(\vec{r}) = \hbar g_s^n g_p^n \frac{\vec{\sigma}\bullet\hat{r}}{8\pi mc}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

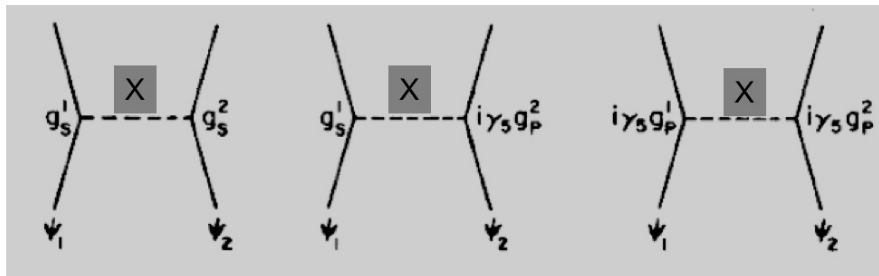
V=μ•B

Moody et al., PRD30, 130(1984)
B. Dobrescuet al., J. High En. Phys. 11, 005(2006)

$$\vec{B}_{eff} = \hbar g_s^n g_p^n \frac{\hat{r}}{8\pi mc}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

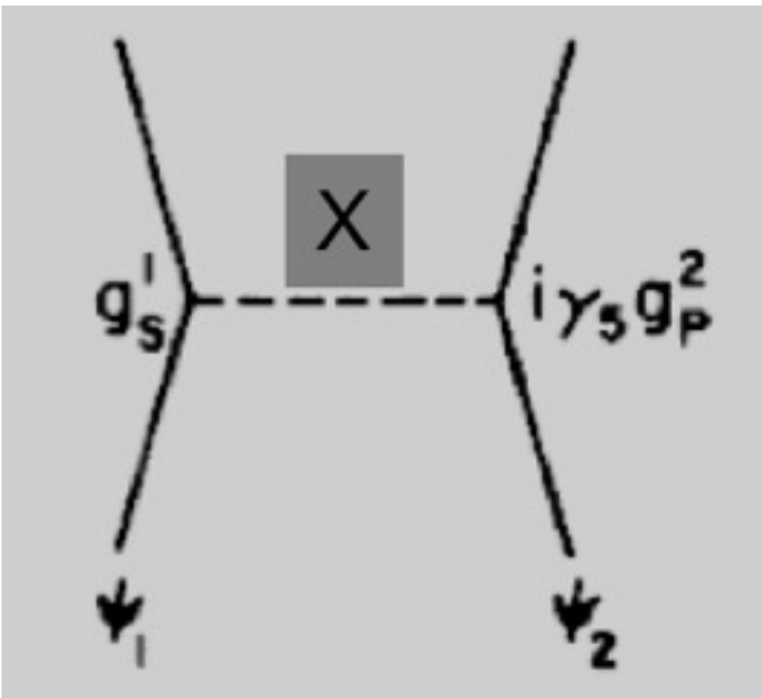
New Particle→NewForces → Behave of NMR

“Model Independent” Exp



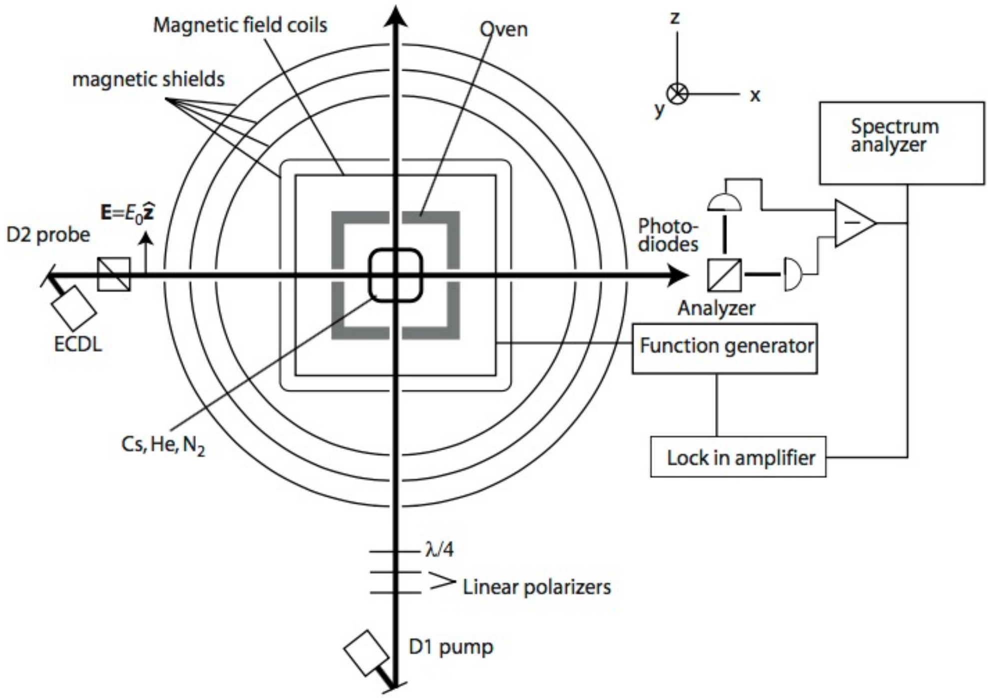
- Interaction: function of $m_{1,2}$, R_{12}, $Spin_{1,2}$, V_{12}.
- Complete Set for “All” Interactions
- The medium Boson could be:
  - Scale Boson
  - Vector Boson
  - Axial-Vector Boson

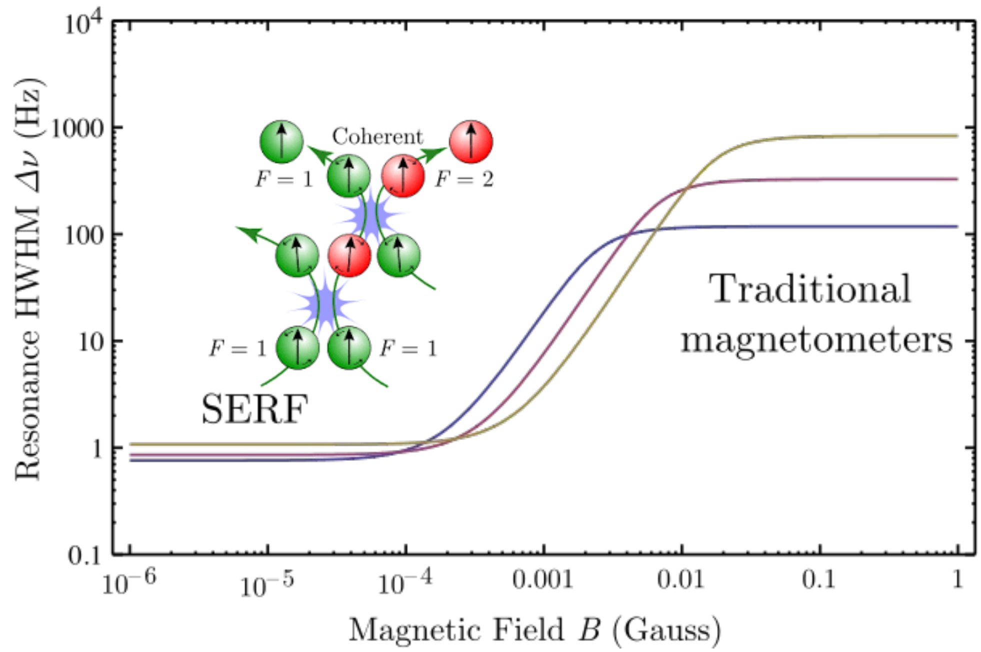
How to Improve the Exp Sensitivity?



- Higher Sensitive, B_{eff}
  - SERF, SQUID…
- Higher Densities of
  - Materials
  - Spins (SmCo5)
- Lower Noise

SERF Magnetometer



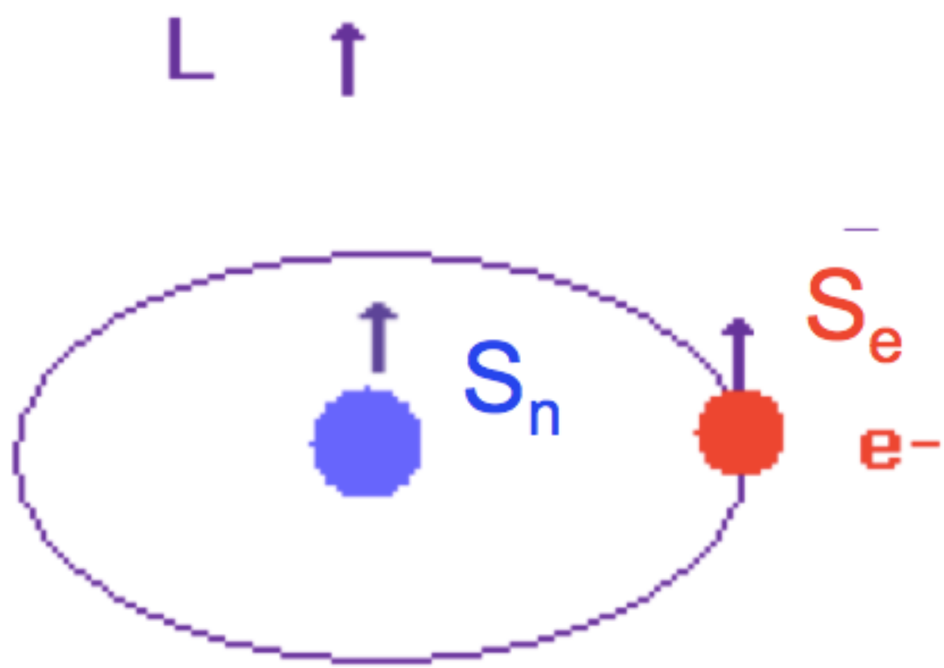


Phys. Rev. A **77**, 033408 2008

Phys Rev Lett. 89 (13): 130801

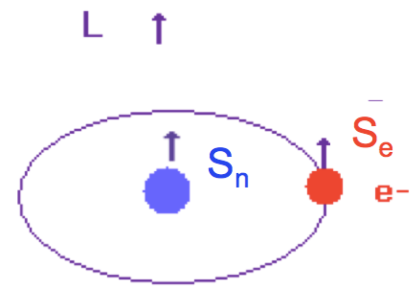
- Sensitivity <10 aT/Hz$^{1/2}$ has been achieved.

High Spin Density Source



- $n = L + S_e + S_n$

Spin Density of SmCo5



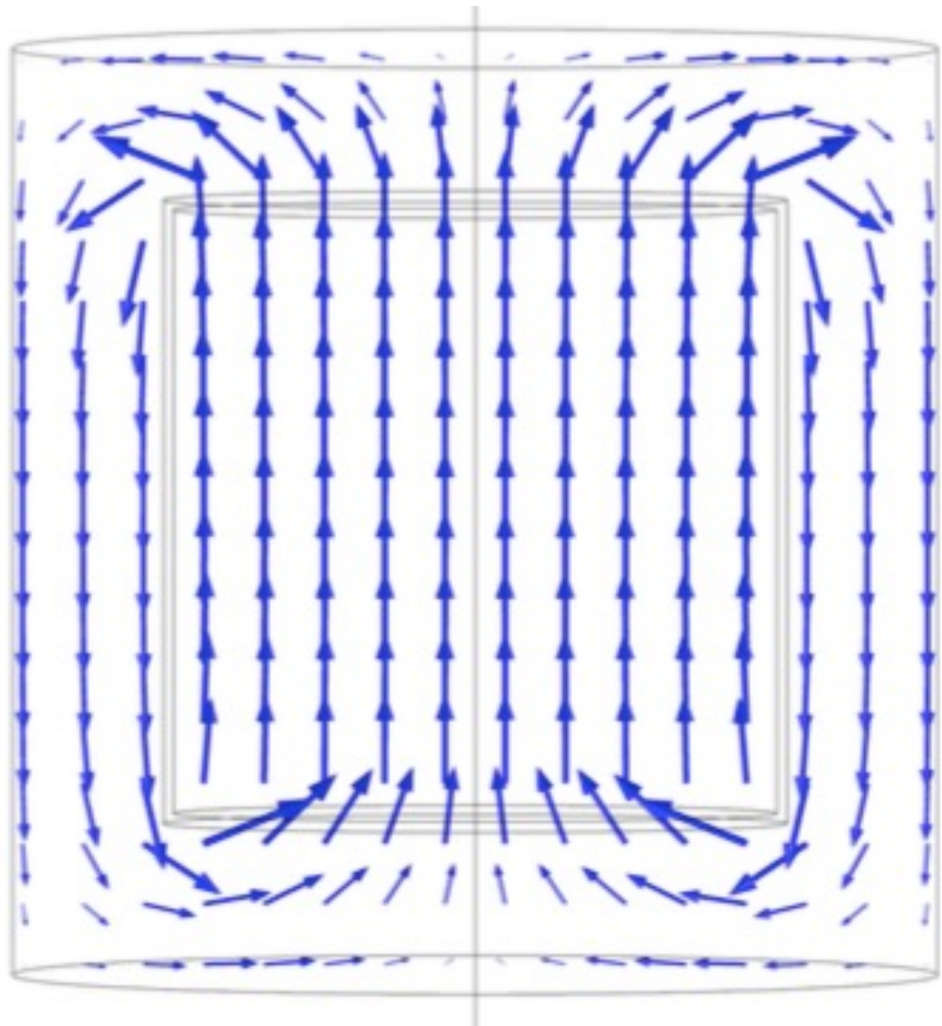
- $$n_{SmCo} = \frac{f_{Co}(1+R)}{\mu_B}\mathbf{M}_{Co}$$
  - $\mathbf{M}_{Co}$ is the magnetization of Co,
  - $R = -0.36$
  - f_{Co} is e-spin contr. to the mag. momen. of Co.
  - $f_{Co} = 0.80$
- For SmCo5 magnetized to 1T, its spin density is about $n_{SmCo} = 4.5E22/cc$
- Alnico, dyprosium iron garnet (DyIG), and GGG etc. have been investigated.

Iron Shielded SmCo5

- B comes from (S+L)
- B can be canceled to ZERO outside, but not the Spins

$$n_{Fe} = \frac{f_{Fe}}{\mu_B}\mathbf{M}_{Fe}$$

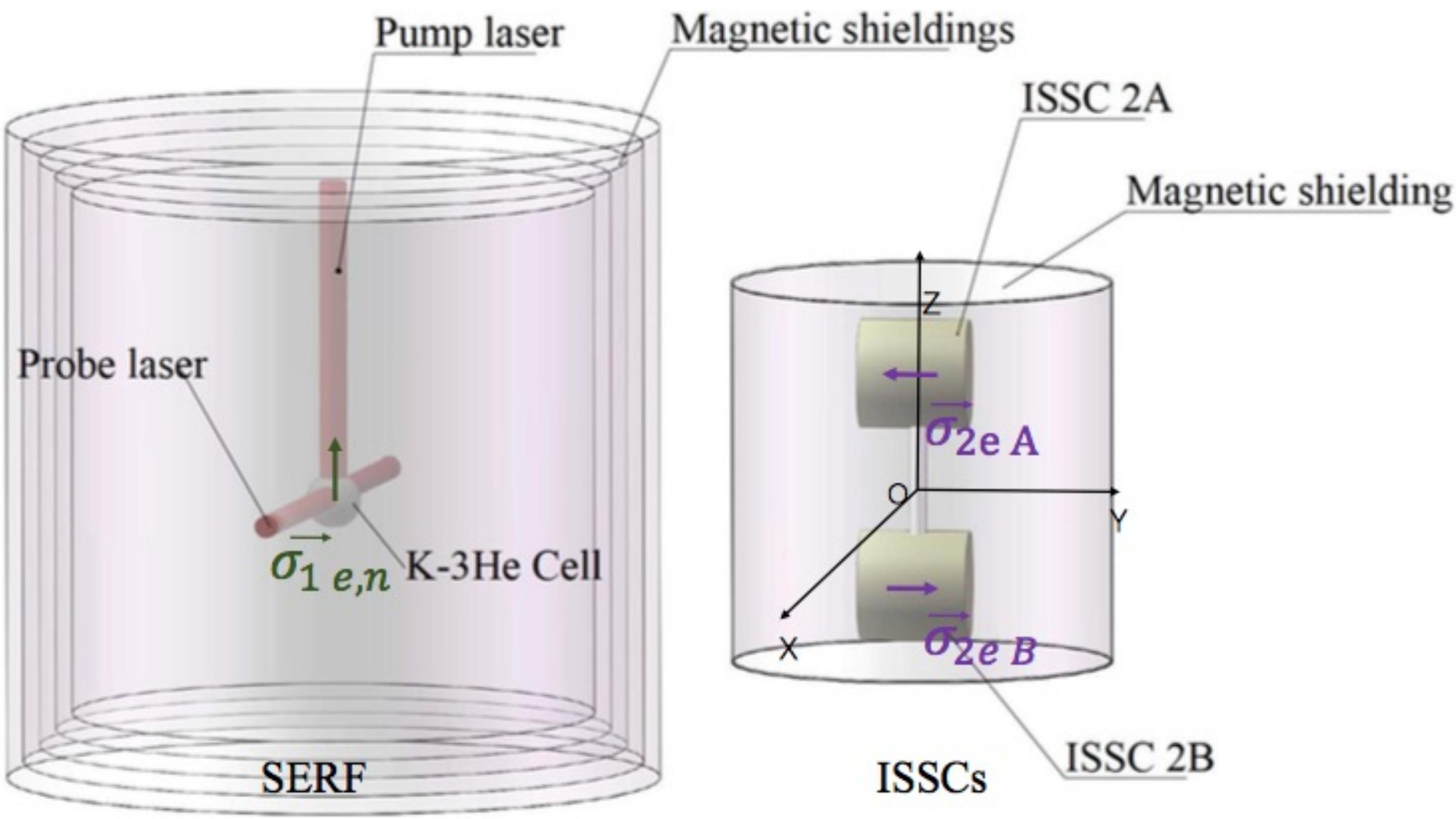
$$f_{Fe} = 0.957$$



Simulation of Iron-Shielded SmCo5 (ISSC)

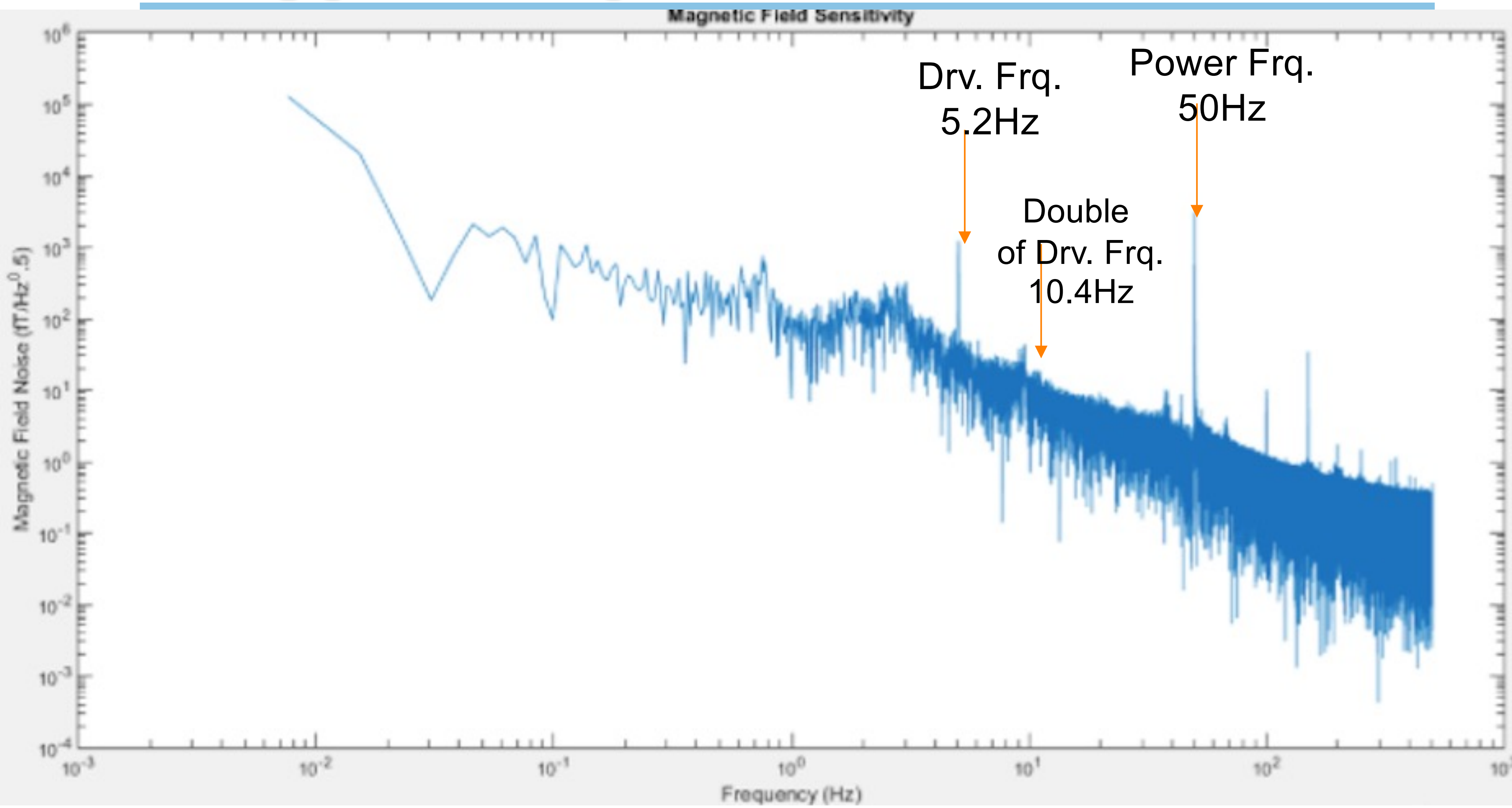
Parameter	value
The SERF's center to the ISSCs' center	0.7 m
Distance between the two ISSCs	0.6 m
Rotating frequency	5 Hz
Soft iron's relative permeability	12000
$SmCo_5$ Magnetization	10 kGs
The SERF's sensitivity	1 fT/Hz$^{1/2}$
Data taking time	2 weeks
The soft Iron's Nucleon density	4.7×10^{24} cm^{-3}
The $SmCo_5$'s Nucleon density	5.1×10^{24} cm^{-3}

The Experimental Setup

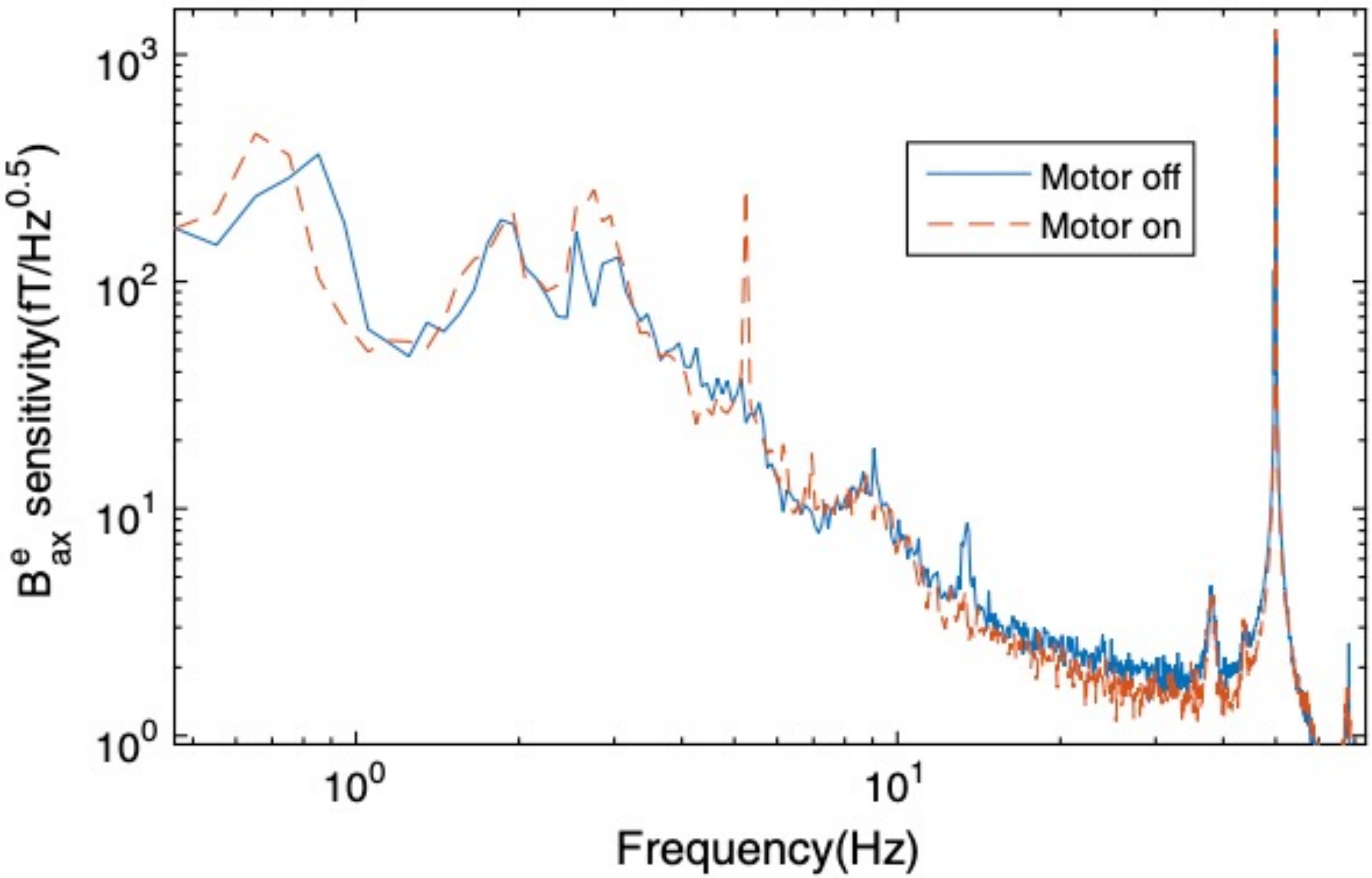


Terms	V_2	V_3	V_{9+10}	V_{11}	V_{6+7}	V_{14}	V_{15}	V_{16}
Rotating axis	y	y	x	y	x	y	y	y
$\vec{\sigma}_{2e}^{A}$	$+z$	$+x$	$+z$	$+z$	$+y$	$+y$	$+z$	$+x$
$\vec{\sigma}_{2e}^{B}$	$+z$	$+x$	$+z$	$+z$	$-y$	$-y$	$+z$	$-x$

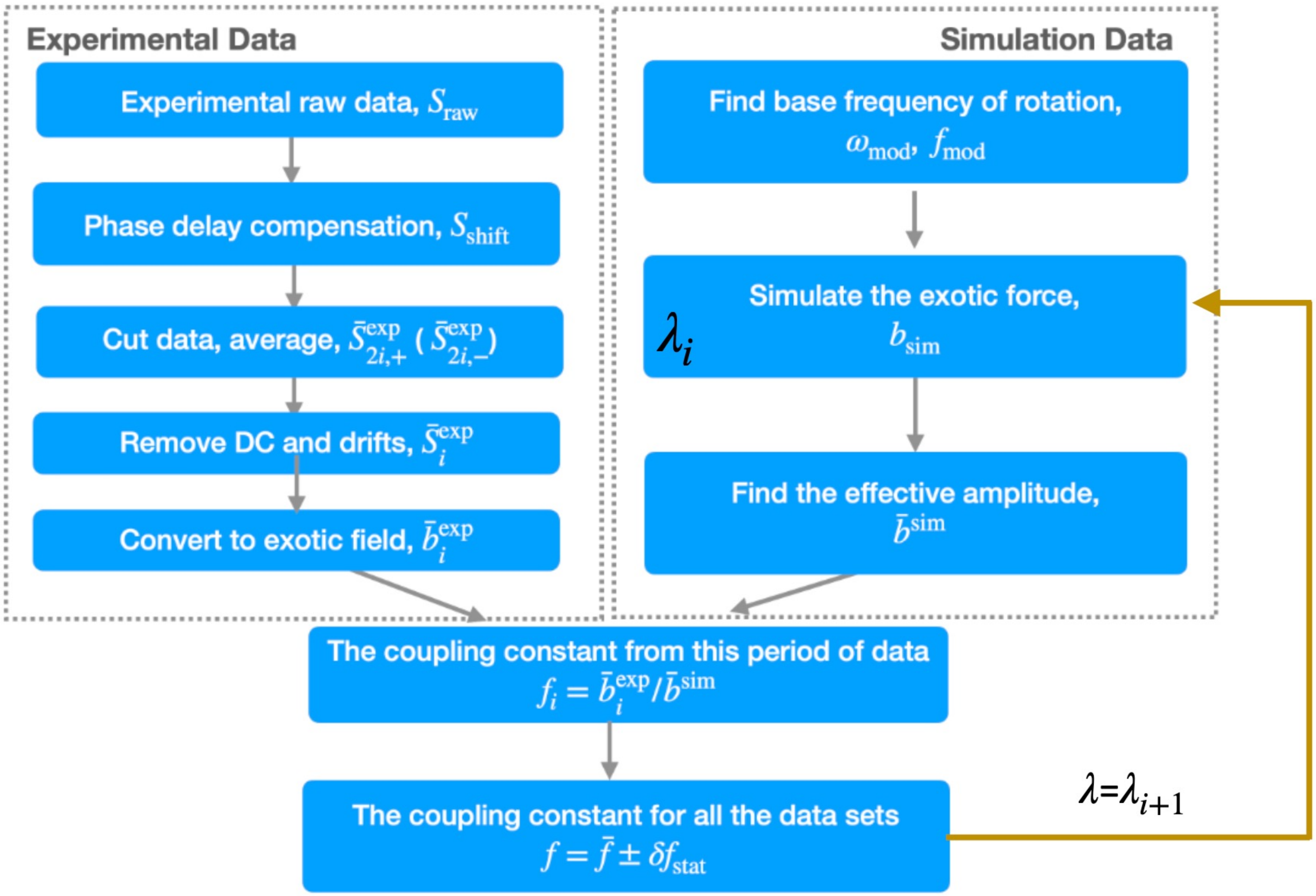
Typical Spectra



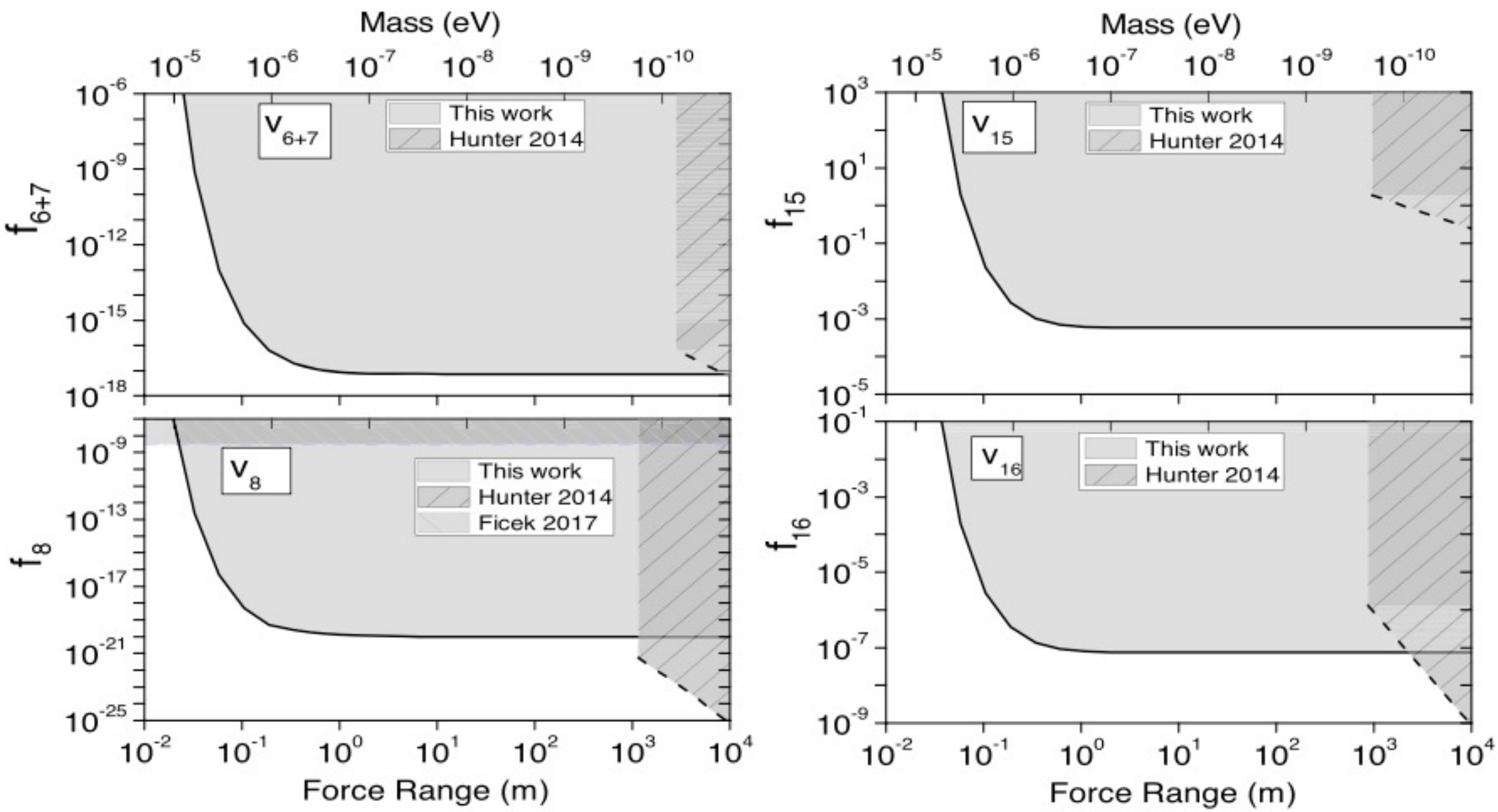
Typical Power Spctua



Data Processing



The expected Sensitivities



PHYSICAL REVIEW LETTERS 121, 261803 (2018)

Systematic Errors

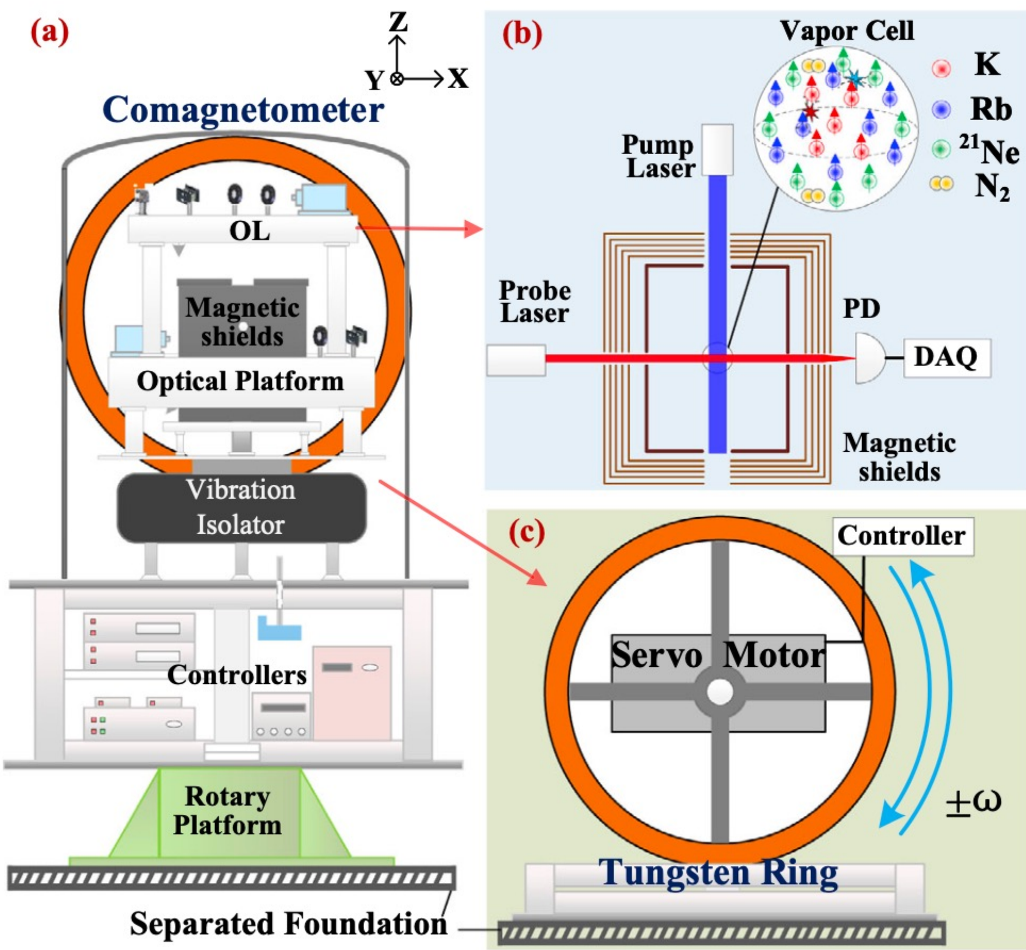
- Residue B field.
  - From static shielding
  - From the rotation of the ISSC.
  - Frq. Filter
- Moto which drives ISSCs rotating.
- Electronic noise

Spin-Velcity-Depend. Force

$$V_{4+5} = \frac{-f_{4+5}\hbar^2}{8\pi mc}\left[\left(\hat{\boldsymbol{\sigma}} \cdot (\boldsymbol{v} \times \hat{\mathbf{r}}\right)\right]\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\mathrm{e}^{-r/\lambda},$$

$$\mathbf{B}_{\mathrm{psd}} \equiv \frac{f_{4+5}\hbar^2}{8\pi mc\mu}\int \rho_N(\mathbf{r})(\boldsymbol{v} \times \hat{\mathbf{r}})\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\mathrm{e}^{-r/\lambda}\mathrm{d}\mathbf{r},$$

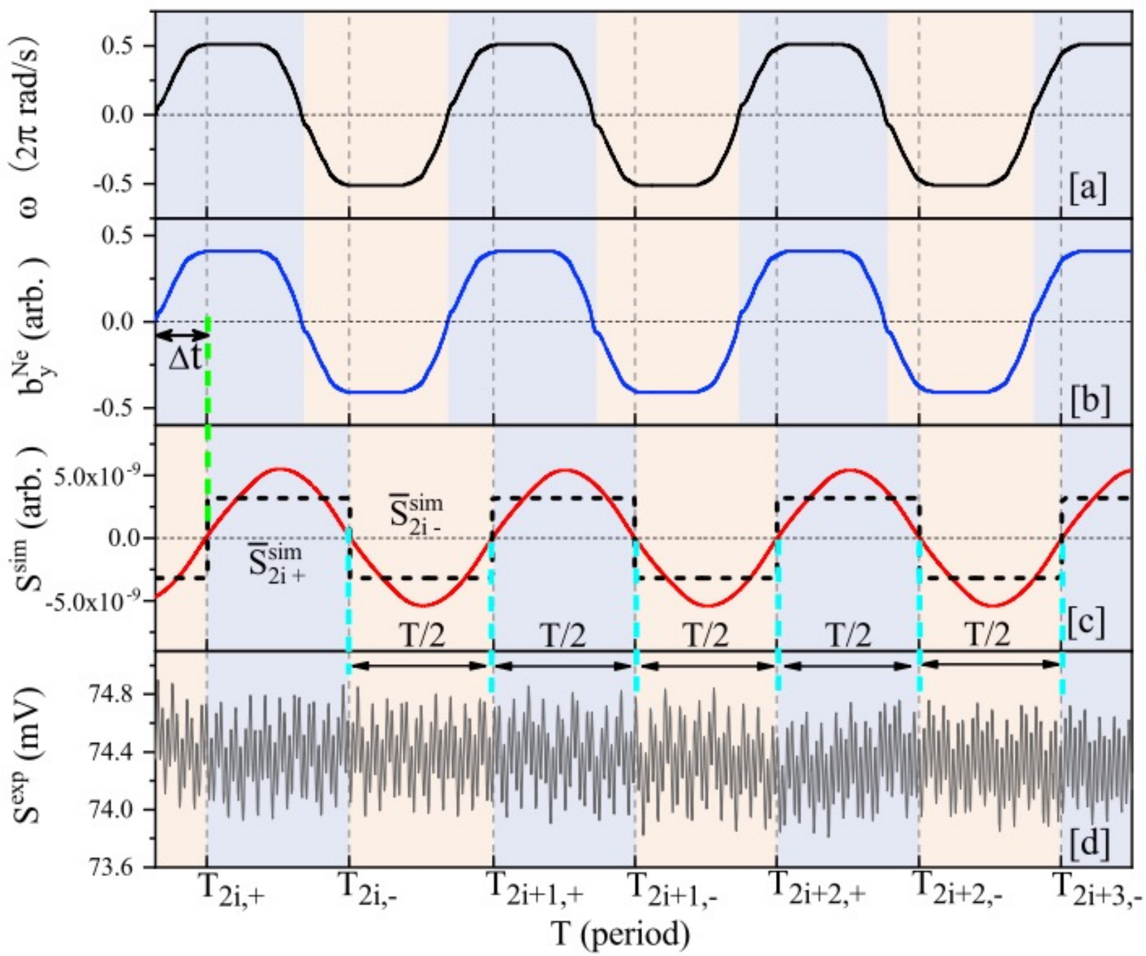
Setup for S-V-dependent F



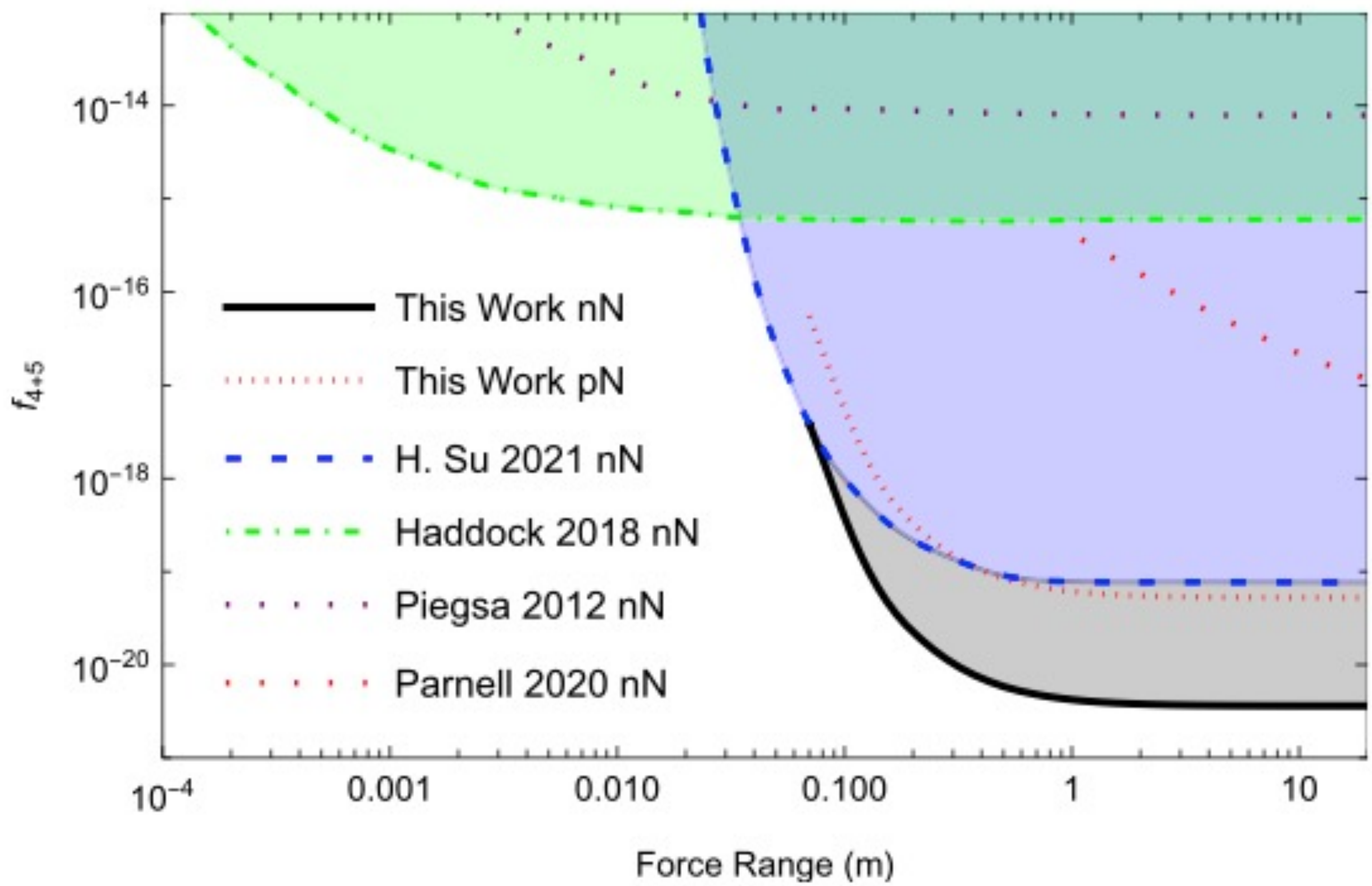
$$\frac{\partial \mathbf{P}^e}{\partial t} = \frac{\gamma_e}{Q}\left(\mathbf{B} + \lambda M_0^n \mathbf{P}^n + \mathbf{b}^e + \boldsymbol{\Omega}\frac{Q}{\gamma_e}\right) \times \mathbf{P}^e + \frac{P_{z0}^e \hat{z} - \mathbf{P}^e}{Q\{T_{1e}, T_{2e}, T_{2e}\}},$$

$$\frac{\partial \mathbf{P}^n}{\partial t} = \gamma_{\mathrm{Ne}}\left(\mathbf{B} + \lambda M_0^e \mathbf{P}^e + \mathbf{b}^{\mathrm{Ne}} + \frac{\boldsymbol{\Omega}}{\gamma_{\mathrm{Ne}}}\right) \times \mathbf{P}^n + \frac{P_{z0}^n \hat{z} - \mathbf{P}^n}{\{T_{1n}, T_{2n}, T_{2n}\}},$$

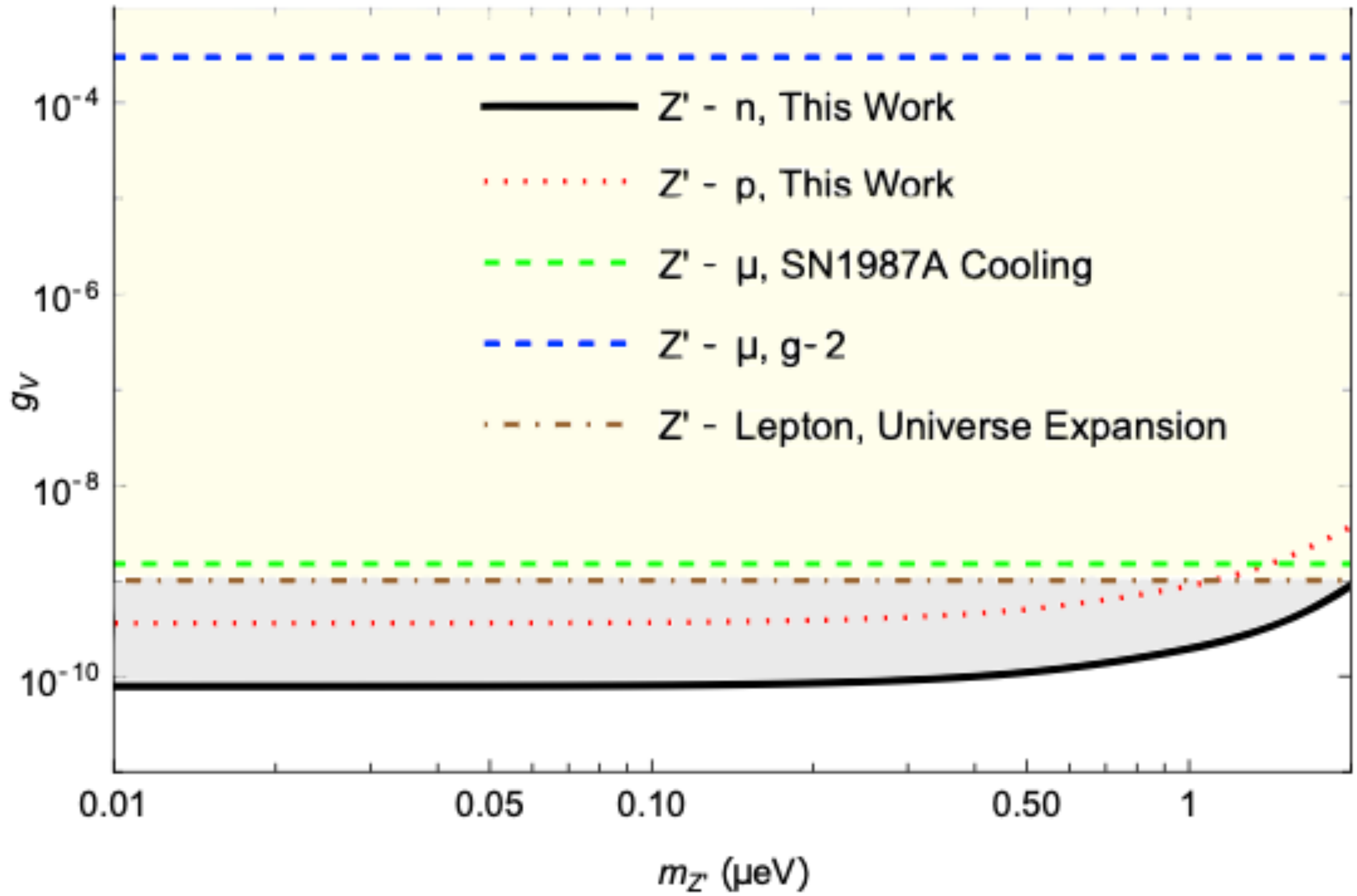
Signal Modulation



Experimal Results



Experimal Results



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Summary

- Spin-Dependent 5th Force searching: Taking advantages of High Spin densities of ISSC+SERF, we provided a new way to detecting the possible new bossions.
- Spin-Velocity-D 5th Force searching: 2 order of magnitude improvement on the constrain of f_{4+5}; as well as g_V of Z'
- In future, GNOME(global network of optical magnetometers for exotic) network, Satellite ...

Collaborators

- C.B. Fu (Fudan Univ. U.)
- W. Ji (THU)
- Kai Wei (Beihang U.)
- Y.Cheng (XTJU)
- H.Y. Gao (Duke)
- J.C. Fang (BHU)
- H.Y. Yan (CIAP)