Searching for New Spin-dependent Short-range Force Using Polarized ^{3}He Gas

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Outline

1. Motivation & Background
   - Beyond Standard Model
   - Axion-like particles & Dark matter
   - Three Effects induced by a Axion-Like particles
2. Experimental Studies
   - Monopole-Dipole
   - Dipole-Dipole
3. Summary

Motivation:
Extension of Standard Model ---Axion

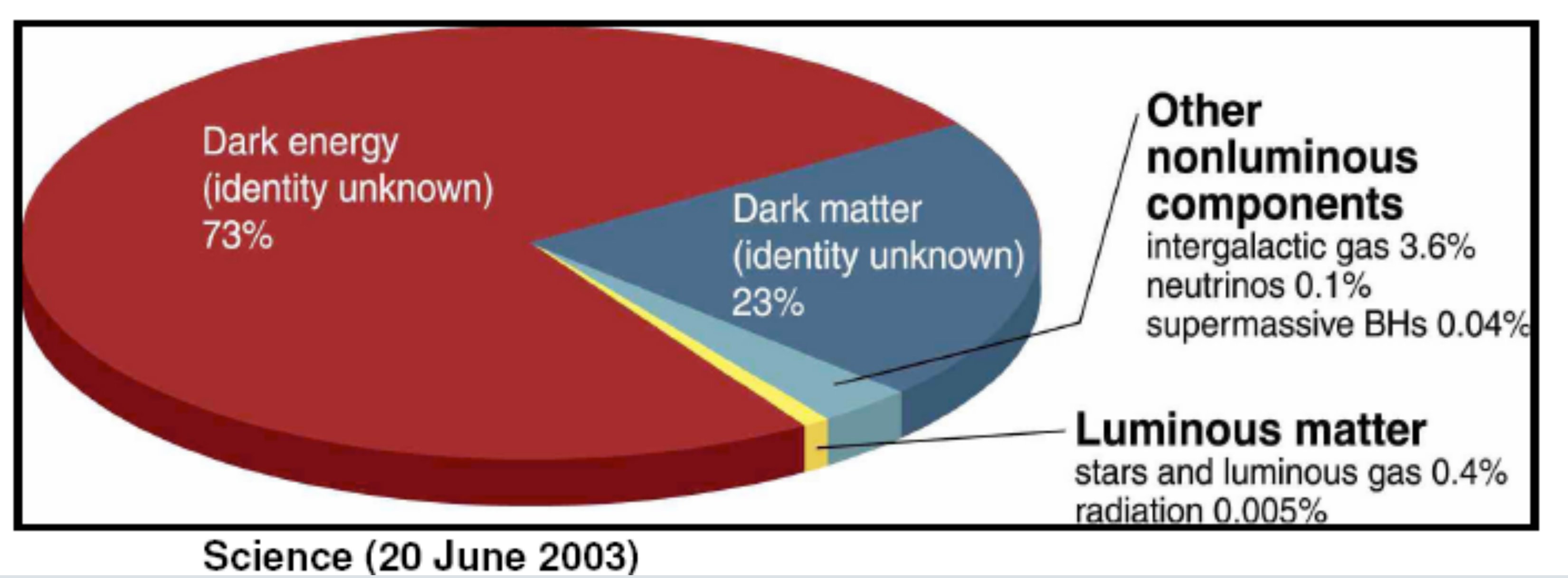
$$L_{eff} = L_{QCD} + \frac{\theta g_s^2}{32\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Strong CP Problem:
nEDM trillionth time smaller than SM predication

In 1977, Peccei-Quinn Symmetry;
When the PQ Symmetry breaks
----> **Axion**

- Good Theoretical Solution
- Good dark matter candidate

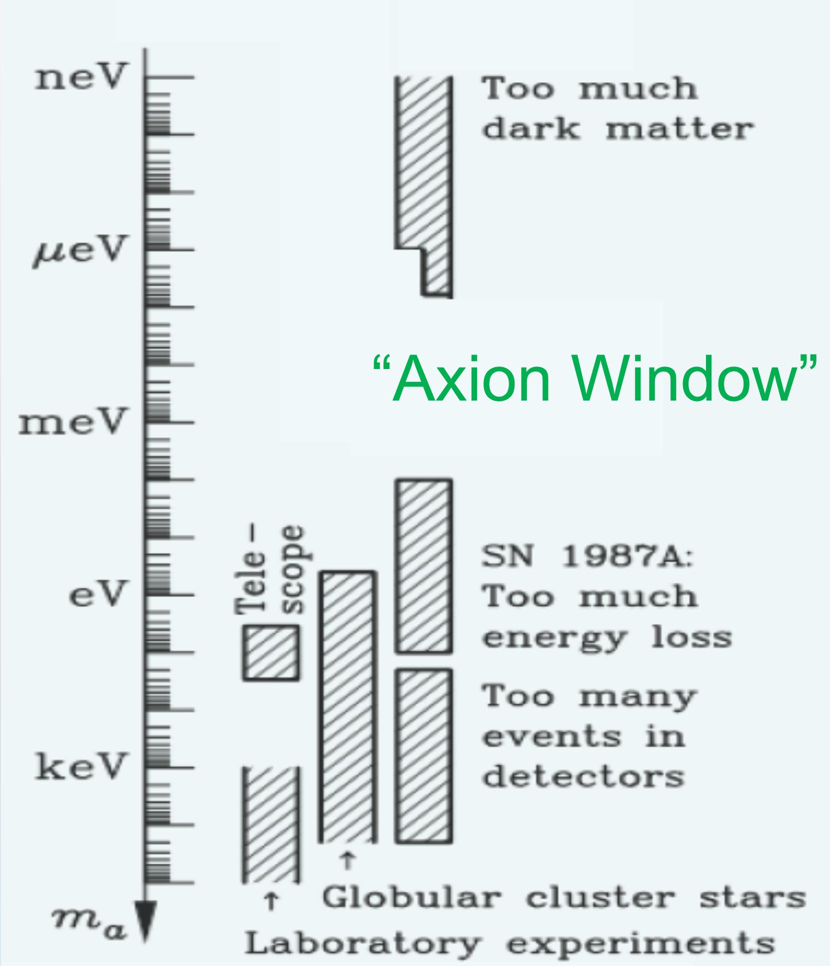
Dark Matter



Dark Matter Candidates:

- WIMPs (Weakly Interacting Massive Particles)
- WISPs (Weakly Interacting Sub-eV Particles, Axion-Like)
- …

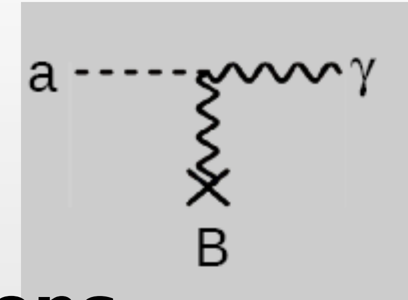
WISPs (Axion-Like Particles)

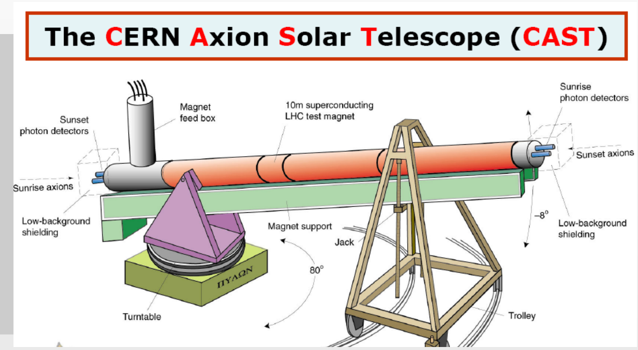


Raffelt, Stars as Laboratories for Fundamental Physics,
Univ. Chicago Press, Chicago (1996)

Search for Axions

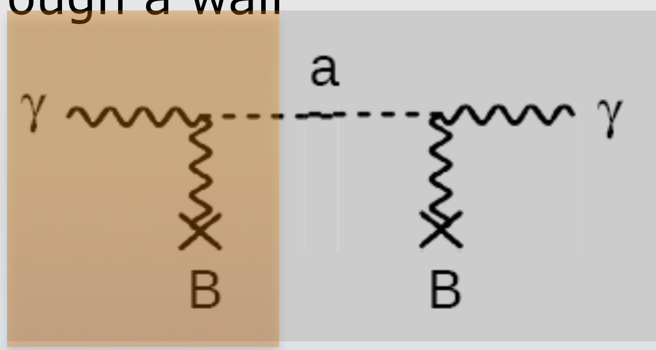
- **Helioscope**

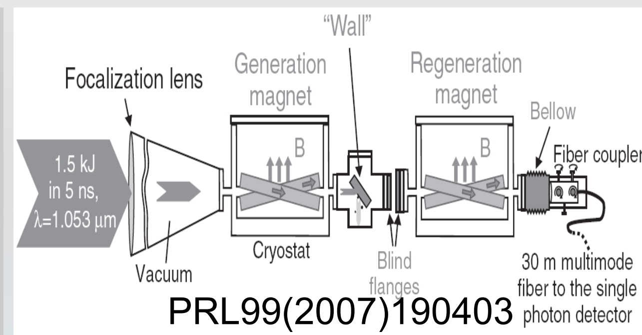




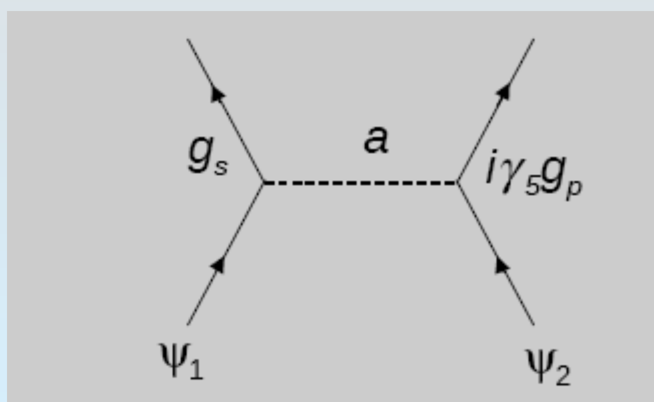
- **Make your own axions**

  "Shining light through a wall"



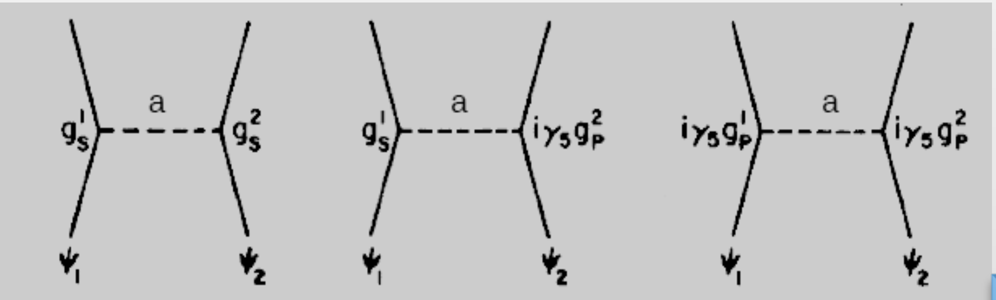


- **5th Forces**



Exchanging an Axion-Like Particle:

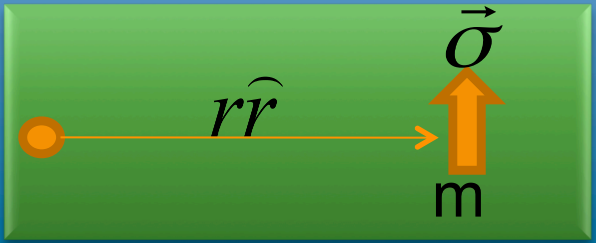
Possible New interaction



matter-matter | matter-spin | spin-spin

Moody et al., PRD30, 130(1984)

B. Dobrescuet al., J. High En. Phys. 11, 005(2006)



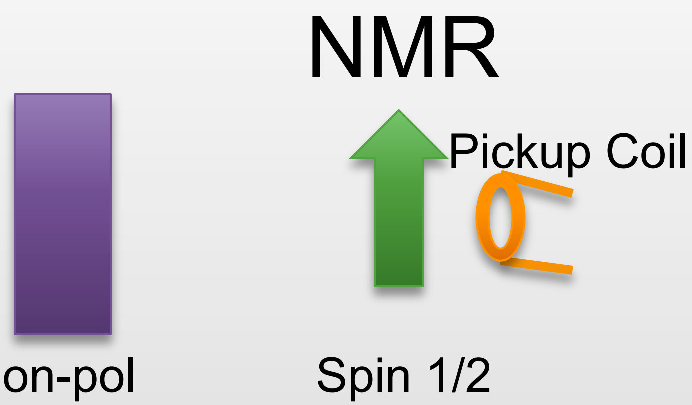
$$V(\vec{r}) = \vec{\sigma} \bullet \hat{r} \frac{\hbar g_s^n g_p^n}{8\pi mc}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}$$

$$V(\vec{r}) = -\vec{\sigma} \bullet \vec{B}$$

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

Three Measurable Effects:
induced by a monopole-dipole Interaction

$$\mathbf{B}_{\text{eff}} = -\frac{\hbar}{\mu_e}\frac{g_s g_p}{8\pi m_e c}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)\exp(-r/\lambda)\hat{\mathbf{r}}\,, \qquad (5)$$



1. Frequency shift
   - S. Baessler et al., PRD75, 075006(2006)
   - A. Youdin et al., PRL77, 2170(1996)
   - P.H. Chu, et al., PRD87,011105(2013)
   - W.Z. Zheng, et al., PRD85, 031505(2012)
2. T_1 (Longitudinal Relaxation Time Shift)
   - Y.N. Pokotilovski, Phys. Lett. B686, 114(2010)
   - A. Serebrov, Phys. Lett. B 680, 423(2009)
3. T_2 (Transverse Relaxation Time Shift)
   - Changbo Fu, T. Gentile, W. M. Snow, Arxiv:1007.5008(2010)
   - A. Pektukhov et al., PRL105, 170401(2010)
   - Changbo Fu, et al., PRD83, 031504(2011)

Classify the Potential between two particles

Dobrescu et al., J. High E Phys. 611 (2006)005

Mathematically, the 2-particle potential has 16 forms (ONLY). i.e. $V(\vec{r}) = \sum_{n=1}^{16} a_n V_n$

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

Mono-Mono

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

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

Di-Di

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

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

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

Classify the Potential between Two Particles (Continue)

Dobrescu et al, J. High E Phys. 611 (2006)005

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

Non.Pol-Dipole (Axion-Like)

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

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

v-dependent

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

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

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

Systematic Errors

We are try to spy Axion by a tiny small B-field,
But a lot of tiny small B-fields are living around!

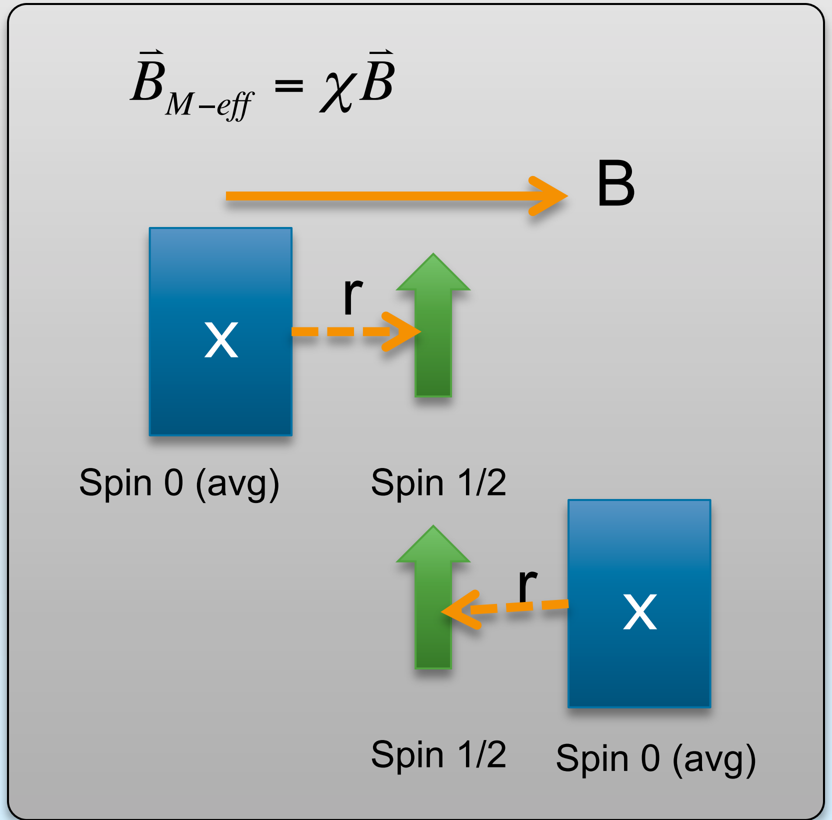
1. Non-zero magnetic susceptibility of the test mass block and Air.
2. Radiation damping effect. (interaction between dipole and induced current in pickup coils)
3. B-field induced by polarized ^{3}He itself.
4. Conductivity of the test mass block.
5. Slowly changing of polarization of the ^{3}He gas.
6. Limited T_1/T_2.
7. Electrons outside
8. …

Why ^{3}He?

- Noble gas
- Spin ½
- Being pumped *easily*. Extensive development in nuclear, HEP, neutron scattering
- High polarization (over 80%)
- Very long T_1/T_2 have been achieved

Choose Test Mass: Non-polarized Material

- Density
- Magnetic Susceptibility

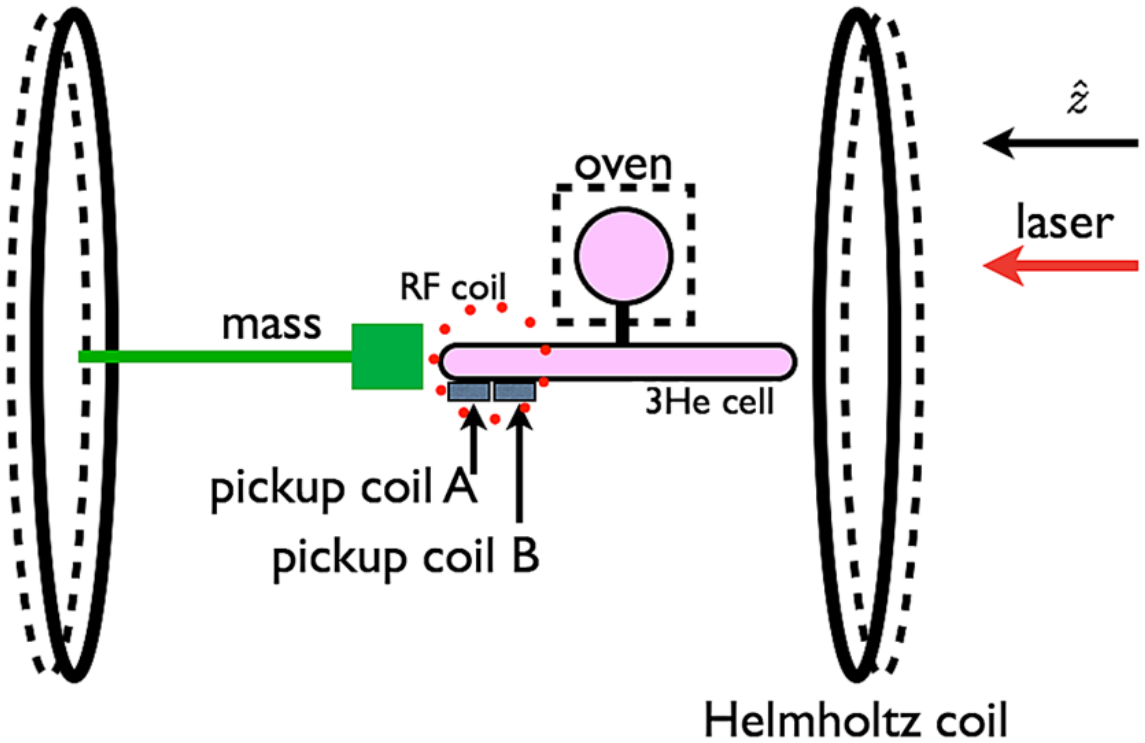


$$V(\vec{r}) = \vec{\sigma} \bullet \hat{r} \frac{\hbar g_s^n g_p^n}{8\pi mc} \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

Candidates

1. Ceramic
2. Pb
3. BGO
4. PbWO3

Spin-Exchange Optical Pumping: Experimental Setup



In the cell:

1. ^3He Gas (~7amgs@room temp.)
2. Rb (<0.1g)
3. N_2 gas (50 torr)

Polarization Transfer:

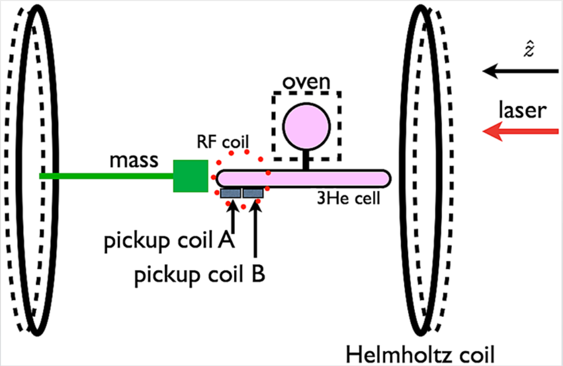
Linearly Polarized **Photon**

→ Circularly Polarized **Photon**

→ Atomically polarized **Rb**

→Nuclear Polarized **3He**

Experimental Procedure



1:Test Mass in:	Signal Ai1 & Bi1
1':Test Mass Out:	Signal Ao1& Bo1
2:Test Mass in:	Signal Ai2 & Bi2
2':Test Mass Out:	Signal Ai2 & Bi2

3,3'…

Flip B, S, Mass…

Data Analysis Procedure:

$$S(t)=a + b*t + c*t^2 + r$$

$$1*S[0]-3*S[1]+3*S[2] -1*S[3]$$
$$=\{a+r\}-3*\{a+b+c\}+3*\{a+2b+4c+r\}-\{a+3b+9c\}$$
$$=4r$$

Swanson et al. Meas. Sci. Technol. **21** (2010) 115104

4*df=1*[fAi1-fBi1]-3*[[fAo1-fBo1]]+3*[fAi2-fBi2]-1*[fAo2-fBo2]

A-B;	remove the background
In-Out:	Test Mass
1331:	remove Background fluc. in time
Flip B:	remove Test Mass B-Susceptibility

Test Experiment for Monopole-dipole interaction

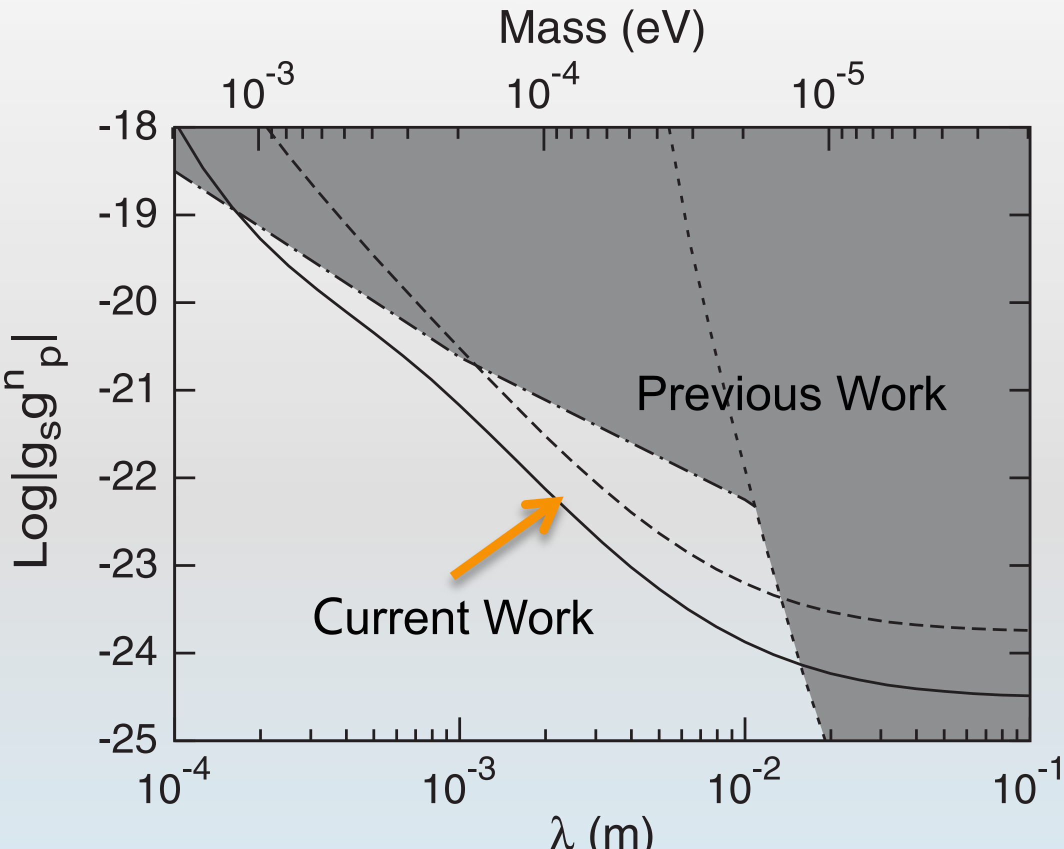


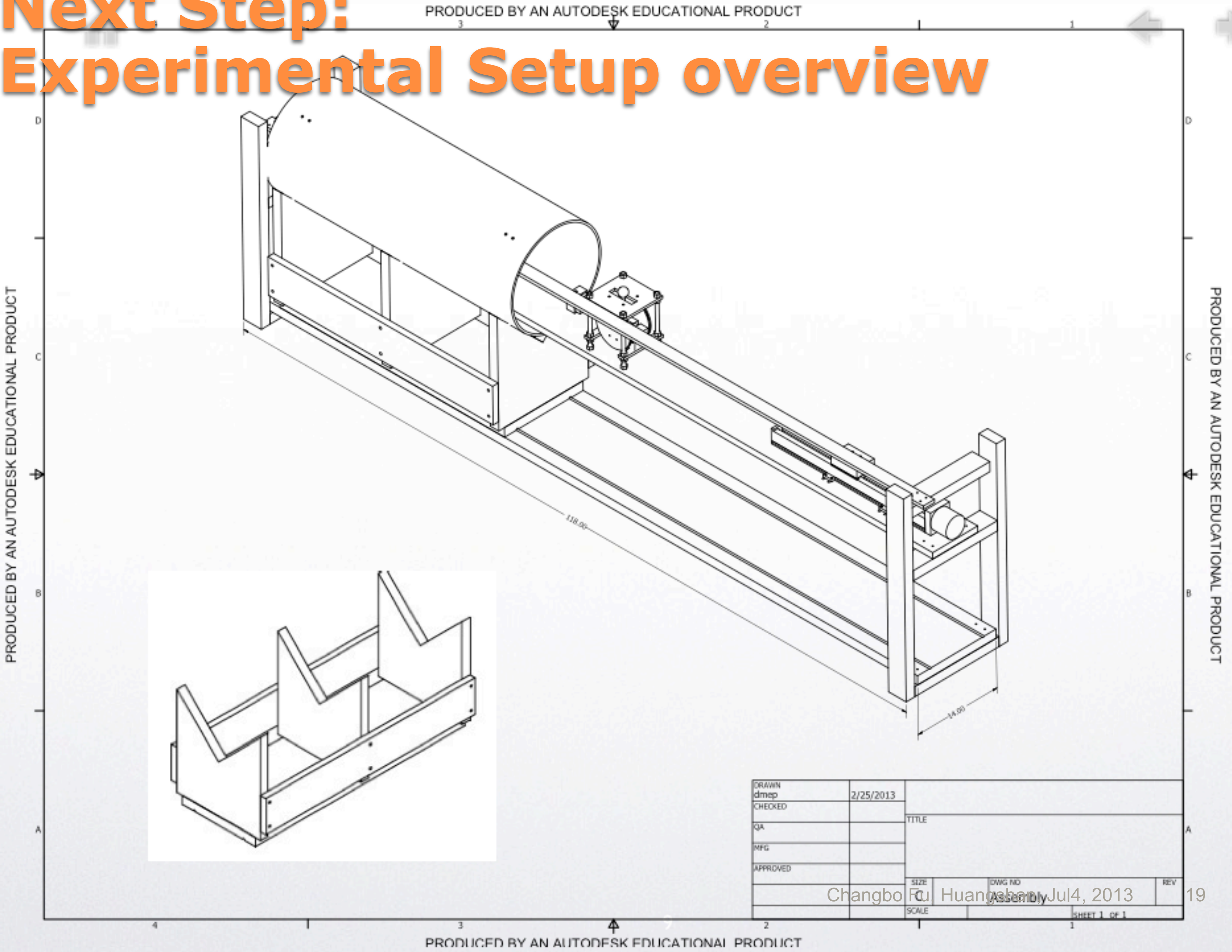
FIG. 3. Constraints on the coupling strength $g_s g_p^n$ as a function of the force range λ and the equivalent mass of the ALPs. The dark gray area is the region excluded by previous works. The dotted curve is from Ref. [19] and the dash-dotted curve is from Ref. [17]. The dashed (solid) curve is the constraint of the salt water (ceramic) sample within one standard deviation.

P.-H. Chu, et al., PRD87,011105(2013)

Next Step:
Will Focus on the following

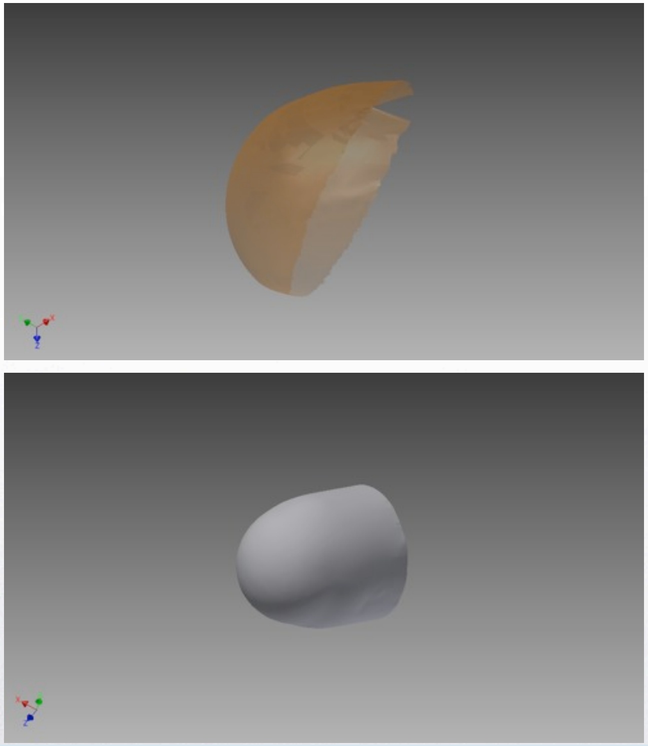
1. Specially Designed Cell
2. Solenoid & mu-metal Shielding
3. Higher density Test mass and Better curvature Matching

Next Step: Experimental Setup overview



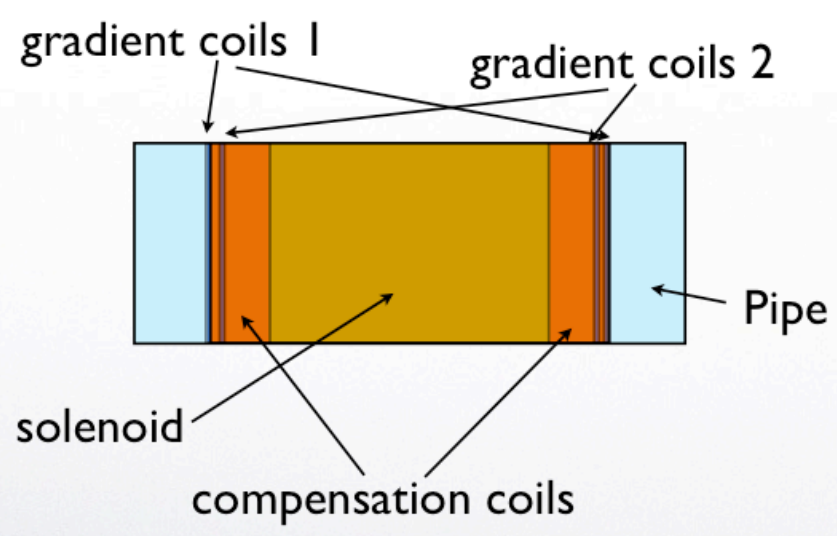
Next Step: Cell "Tiny"

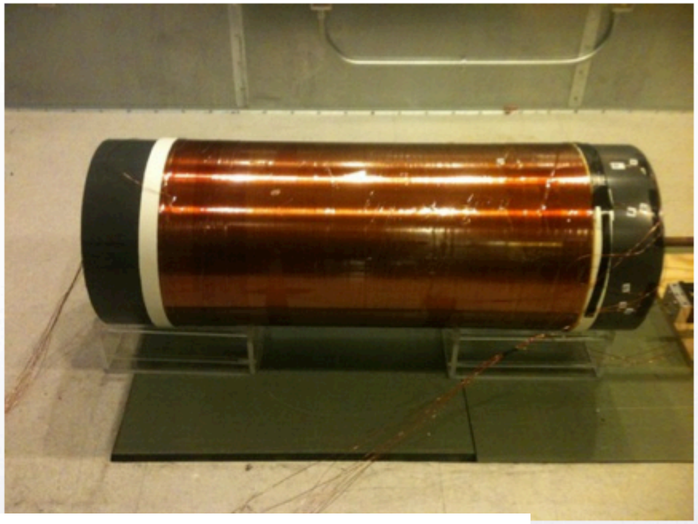
Next Step: Cell 3D Map

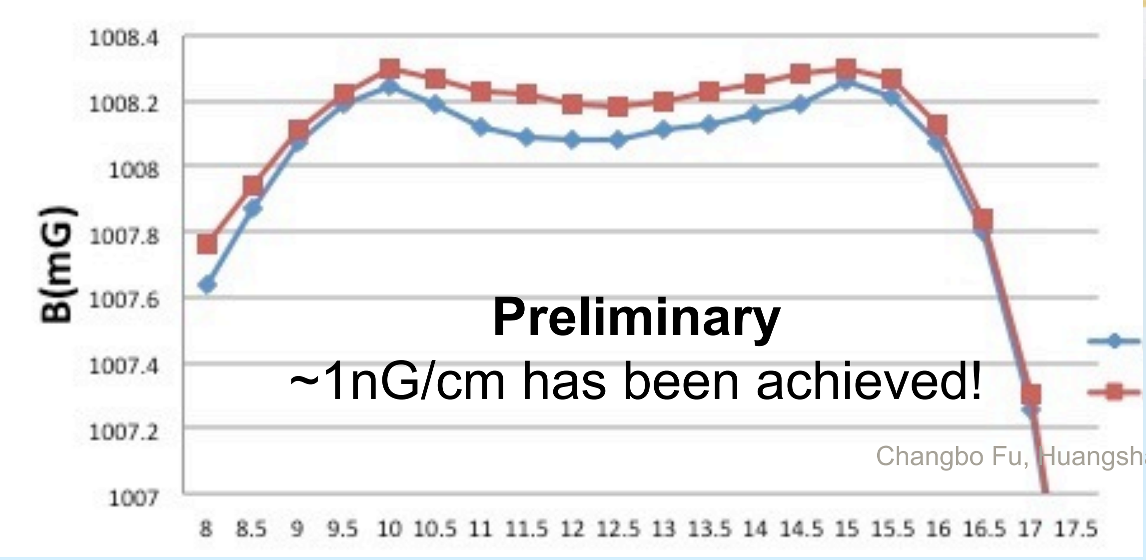


Try to bring the Test Mass closer!

Next Step: Solenoid



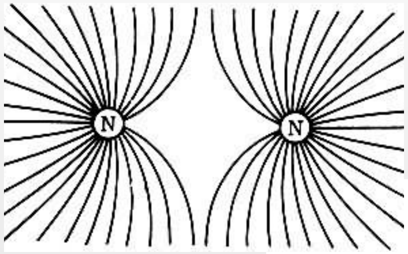




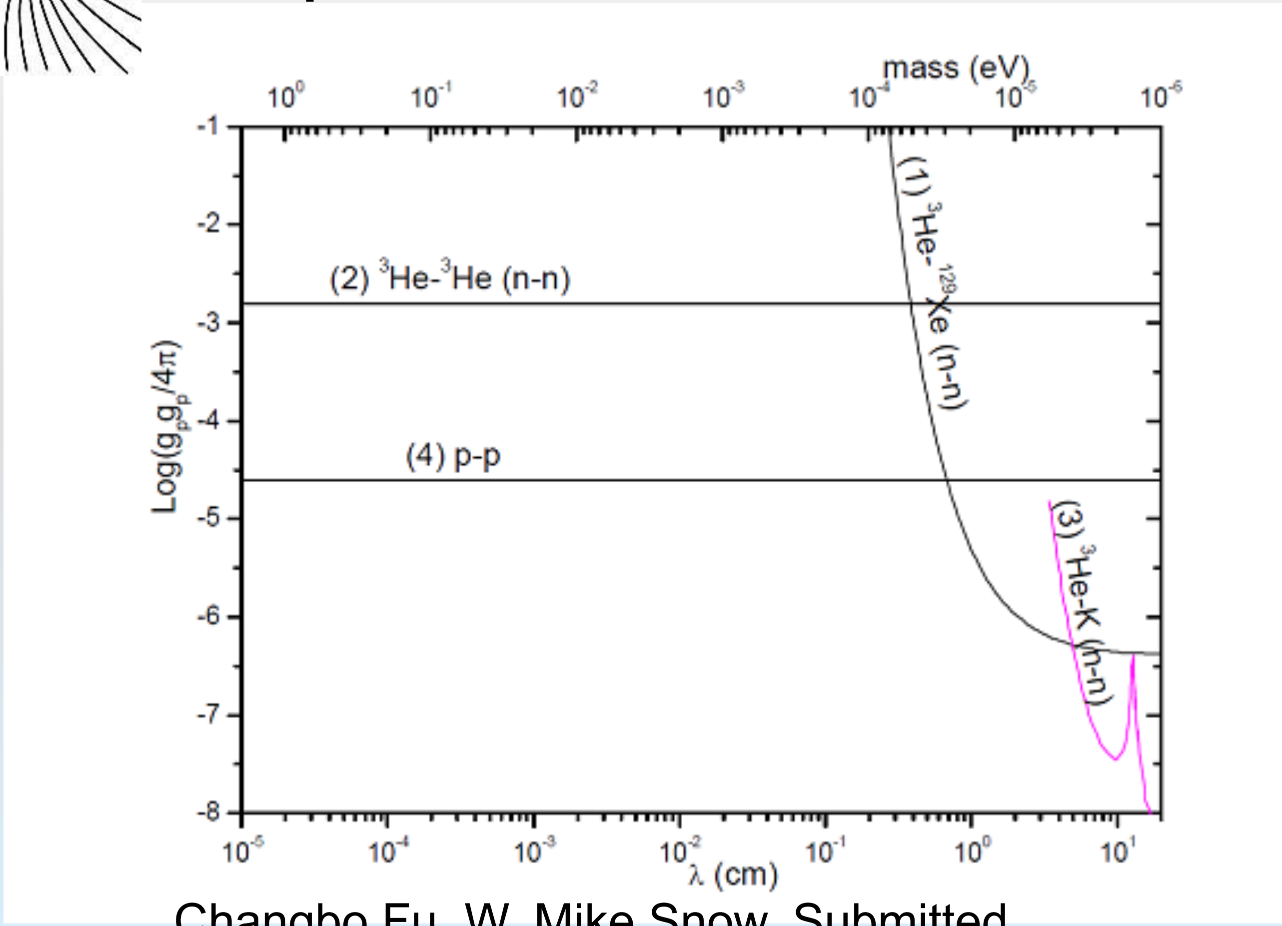
Preliminary

~1nG/cm has been achieved!

New Possible Dipole-Dipole Constrain



Dipole Relaxation time



Changbo Fu, W. Mike Snow, Submitted

Summary

1. We are using polarized ^{3}He to detect the possible new ***Mo-Di*** interaction. New constraints on Axion-like particles interactions are obtained.
2. By improving our experimental setup, we expect higher sensitivity in near future.
3. We constrain the possible new ***dipole-dipole*** interaction by using ^{3}He polarized gas.
4. It's possible that new Velocity Dependent Force could be obtained with this way.

Collaborators:

Duke University

- Pinghan Chu
- G. Laskaris
- Wangzhi Zheng
- Haiyan Gao

Indiana University

- W. Mike Snow
- Haiyang Yan
- Erick Smith
- Rakshya Khatiwada

Shanghai Jiaotong University

- Changbo Fu