Searches for Exotic Interactions with Slow Neutrons

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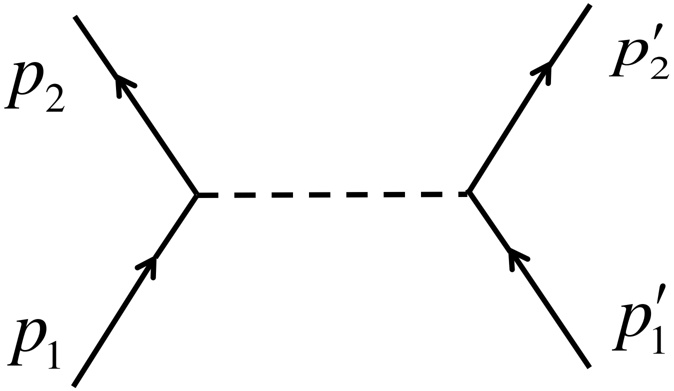
0. (General) Motivations to search for weakly-coupled, long range interactions
1. Searches for new Yukawa interactions at the nanometer scale
2. Searches for dark energy using neutron interferometry
3. Searches for exotic spin dependent interactions of the neutron

Thanks for slides to: H. Kamiya H. Abele, H. Shimizu, G. Pignol,…

Related talks: Wursten, Jaeckel, Abele, Kamiya
Related Posters: Ayres/Rawlik, Jenke, Rechberger, Thalhammer

Searches for light, weakly interacting particles: complementary to LHC



$$V(\vec{r}) = g^2 \frac{1}{r} e^{-\frac{r}{\lambda}}$$

(Most) high energy physics explores: g~1, λ as small as possible

This work emphasizes a different regime:

g small, λ "large" (millimeters-microns) but not infinite

New interactions with ranges from millimeters to microns… “Who ordered that?”

1. *Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries (Goldstone theorem)*

2. *Specific theoretical ideas (axions, extra dimensions for gravity) imply new interactions at ~mm-μm scales*

3. *Dimensional analysis: dark energy->100 microns*

Experiments should look!

Antionadis et al, Comptes Rendus Physique 12, 755-778 (2011)
***J. Jaeckel and A. Ringwald,** Ann. Rev. Nucl. Part. Sci. 60, 405 (2010).*

Why use slow neutrons to search?

1. *Zero electric charge, small magnetic moment, very small electric polarizability->low "background" from Standard Model interactions*

2. *Deep penetration distance into macroscopic amounts of matter*

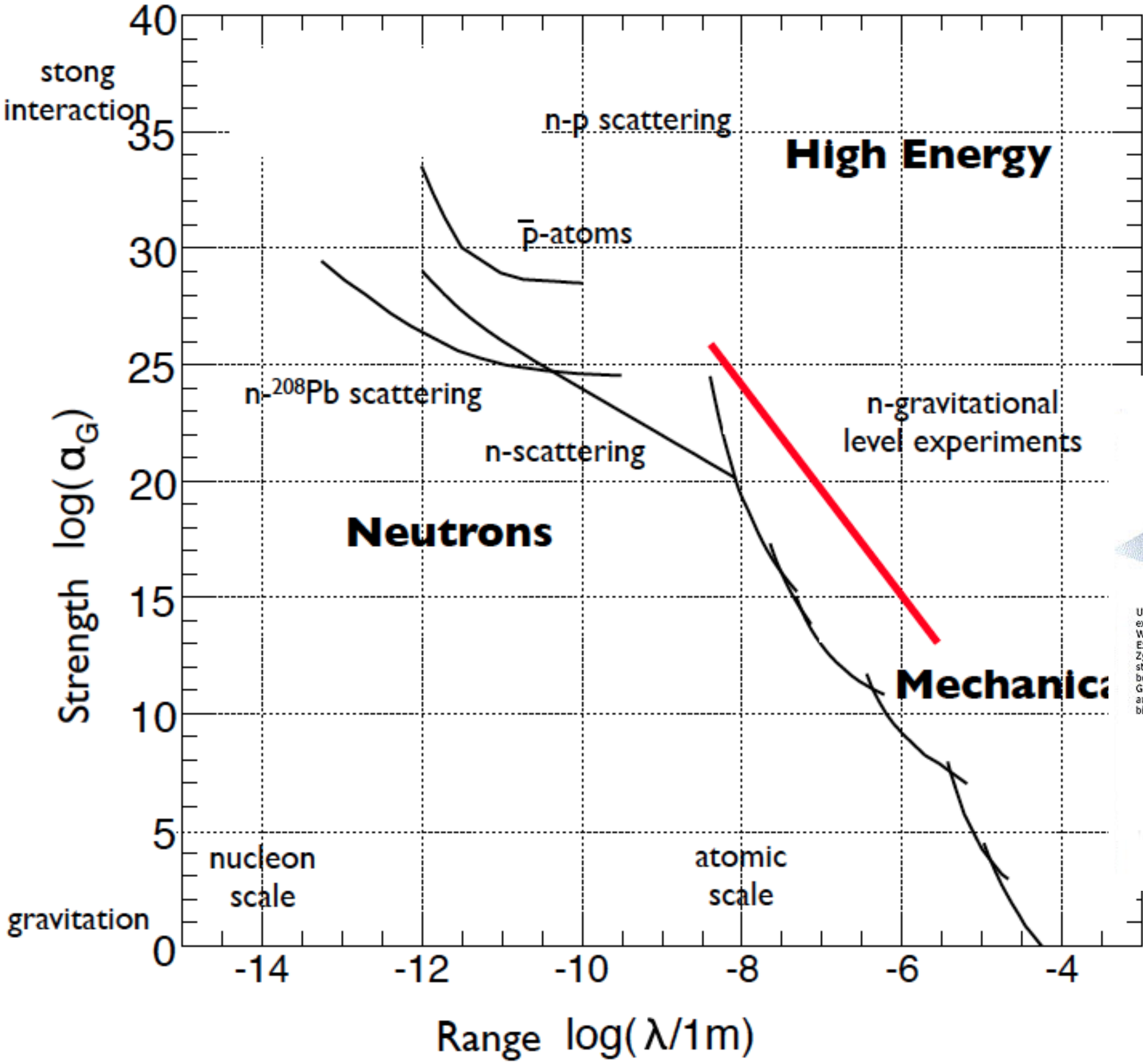
3. *Coherent interactions with matter->phase sensitive measurements possible*

4. *High neutron polarization (>~99%) routine for slow neutrons ->important in searching for spin-dependent interactions*

4. *A broad set of facilities for experimental work is available*

*J. Nico and W. M. Snow, Annual Reviews of Nuclear and Particle Science **55**, 27-69 (2005).*
*H. Abele, Progress in Particle and Nuclear Physics **60**, 1-81 (2008).*
D. Dubbers and M. Schmidt, Reviews of Modern Physics (2011).

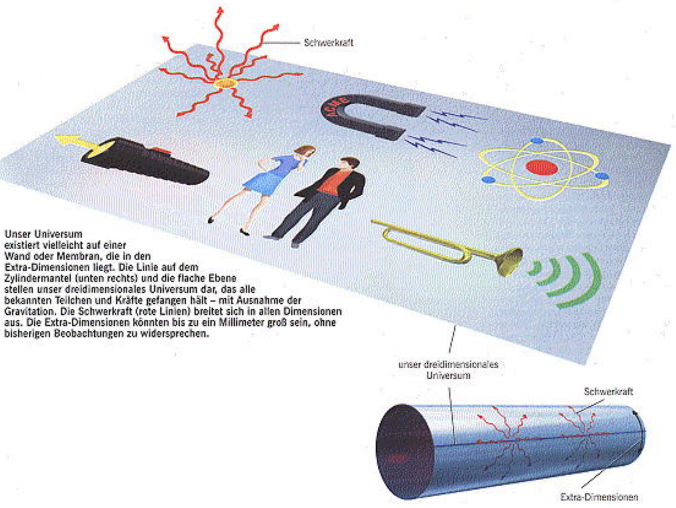
Searches for new Yukawa interactions



$$V(r) = G\frac{m_1 \cdot m_2}{r}(1 + \alpha \cdot e^{-r/\lambda})$$

Neutron measurements are the most sensitive from atomic to subnuclear scales

Continued work at atomic scales important to probe the idea of extra spacetime dimensions (Murata/Tanaka arXiv:1408.3588)



Unser Universum existiert vielleicht auf einer Wand oder Membran, die in den Extra-Dimensionen liegt. Die Linie auf dem Zylindermantel (unten rechts) und die flache Ebene stellen unser dreidimensionales Universum dar, das alle bekannten Teilchen und Kräfte gefangen hält – mit Ausnahme der Gravitation. Die Schwerkraft (rote Linien) breitet sich in allen Dimensionen aus. Die Extra-Dimensionen könnten bis zu ein Millimeter groß sein, ohne bisherigen Beobachtungen zu widersprechen.

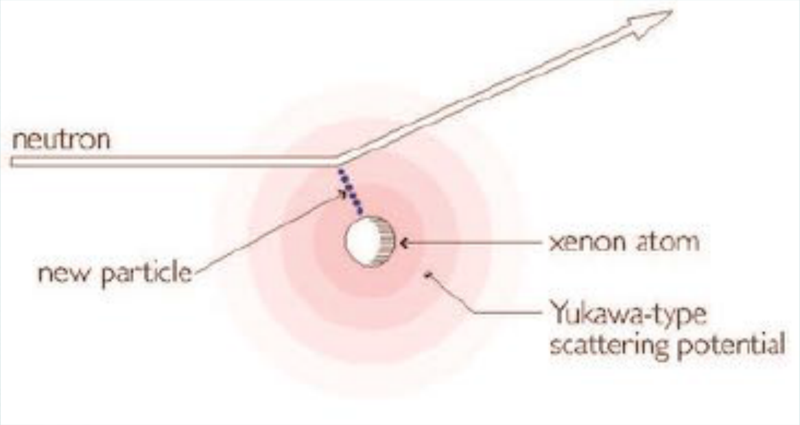
Recent theory to explain muon g-2 and p radius puzzle gives new Yukawa interaction with a boson mass as low as 100 keV (Liu/Miller PRL)

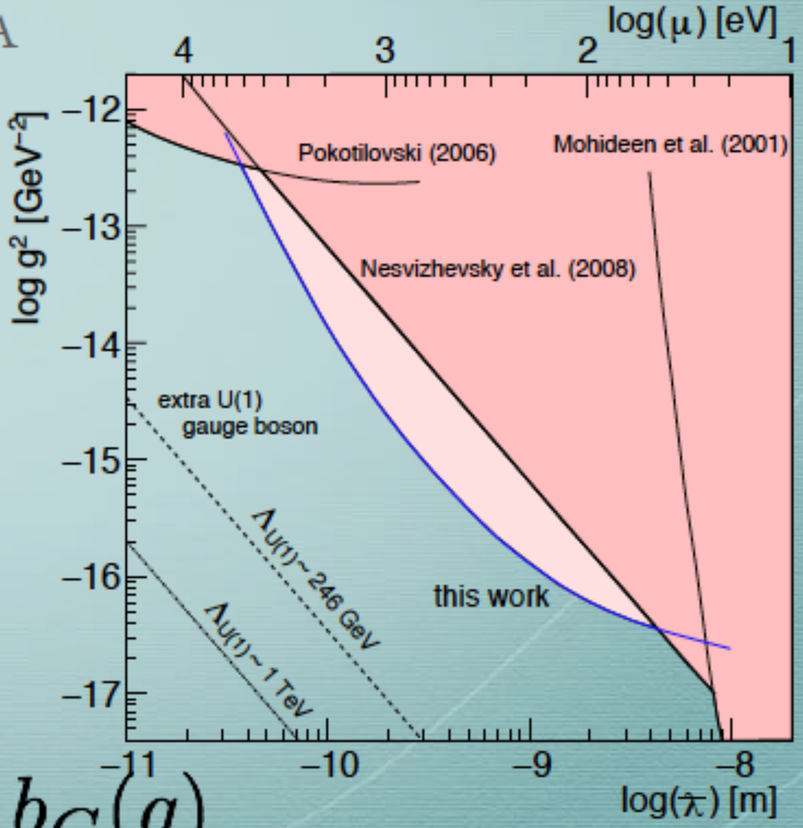
Search for new gravity-like interactions and test of the equivalence principle using slow neutrons

Yoshio Kamiya, Koji Yamada, Kenta Uchida, Yoshihiro Sasayama, Keita Itagaki,
Misato Tani, Sachio Komamiya, and Guinyun Kim

The Univ. of Tokyo / Kyngpook Nat. Univ.

We report on a new constraint on gravity-like interactions obtained by measuring the angular distribution of 5 A neutrons scattering off atomic Xe gas.





$$b_c(q) = (b_c - b_e Z(1 - f(q)) + b_G(q)$$

Y. Kamiya et al., Phys. Rev. Lett. Done at HANARO (Korea) see Kamiya talk

Neutron-Xenon Gas Scattering Search for Yukawa Interaction at J-PARC Spallation Neutron Source H. M. Shimizu, K. Hirota, M. Kitaguchi, C. Haddock,W. M. Snow, K. Mishima, T. Yoshioka, T. Ino, S. Matsumoto, T. Shima

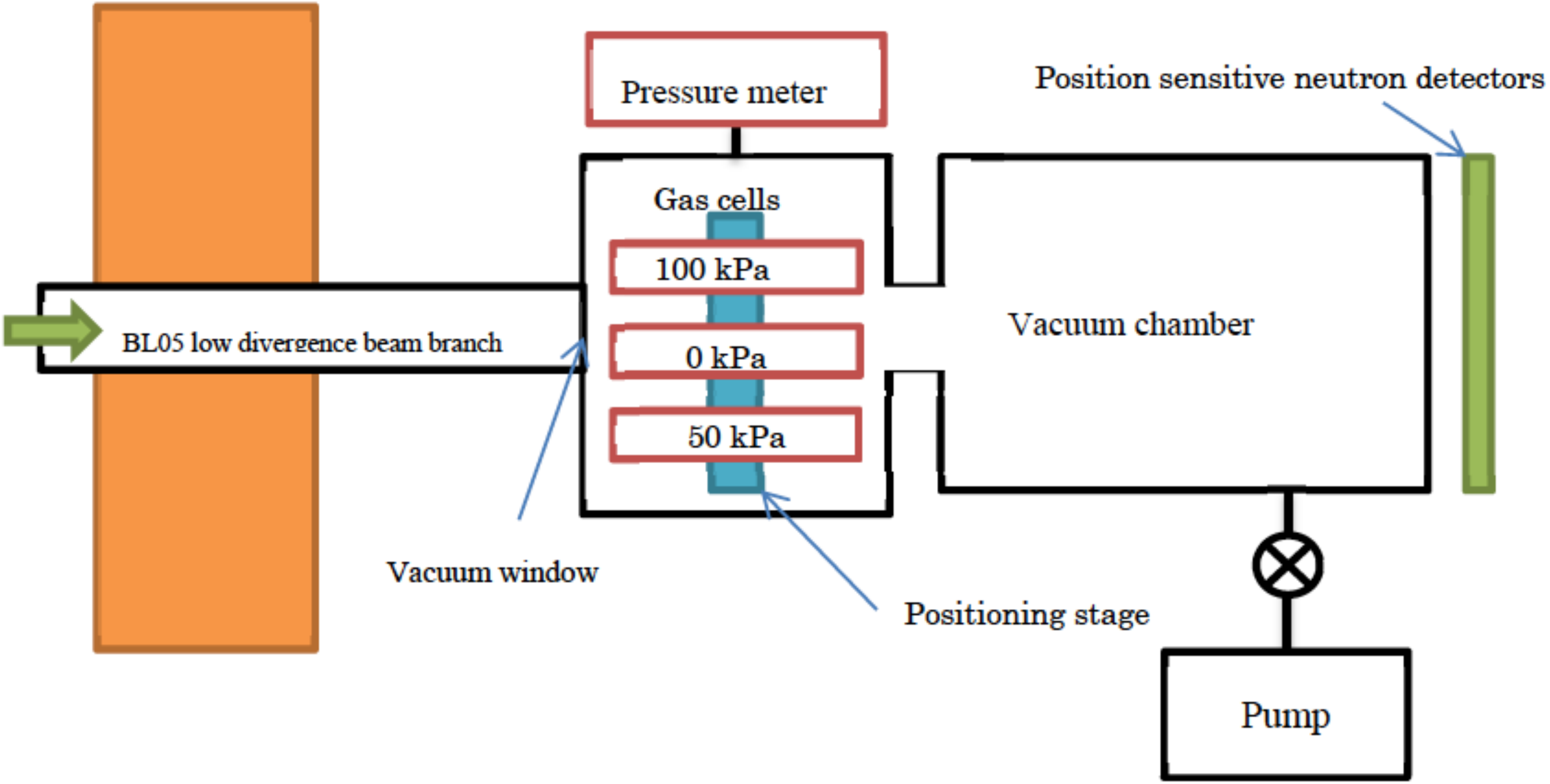
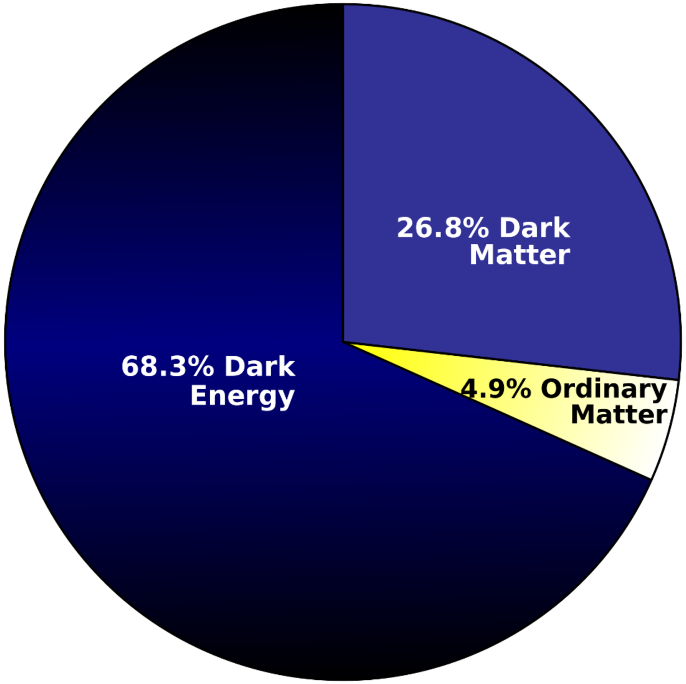


Figure.4. Experimental apparatus.

Use angular distribution on n-Xe scattering to search for Yukawa Interaction at very short ranges Experiment in progress at JPARC

Chameleon scalar field

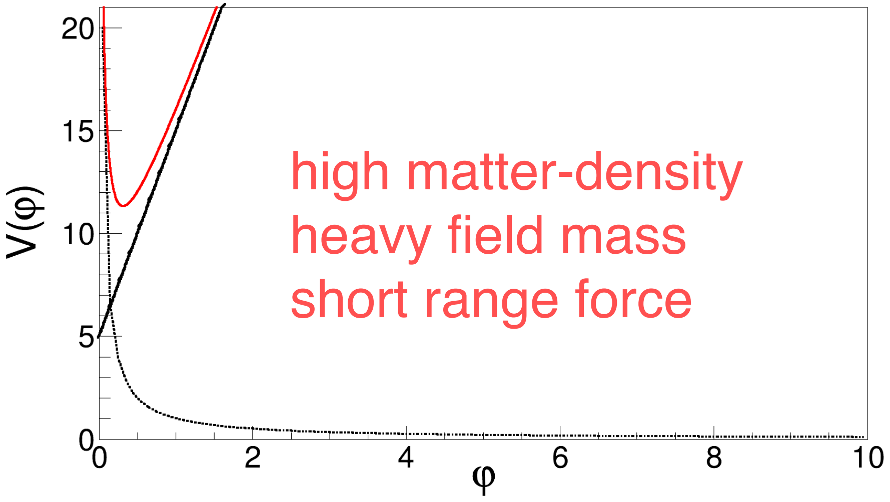
J. Khoury and A. Weltman, PRL **93**, 044026 (2004)



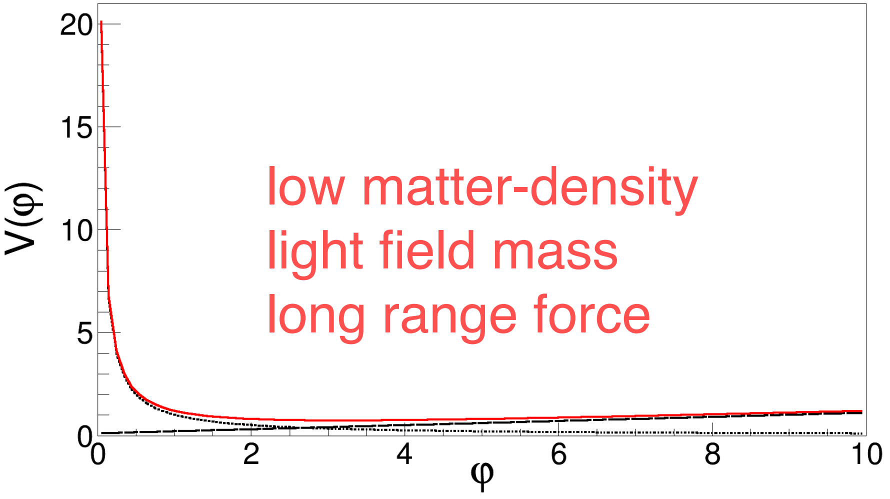
One proposed form of Dark Energy: a new scalar field (quintessence)

Chameleon field is engineered to be:

- Massless on cosmological scales
- Massive field in laboratory



high matter-density
heavy field mass
short range force



low matter-density
light field mass
long range force

Chameleon field

Effective potential: $V(\varphi)_{eff} = V(\varphi) + \rho A(\varphi)$

Runaway potential   Coupling to matter

Ratio of pressure to energy density evolves to w=-1 dynamically

$$A(\varphi) = \sum e^{\beta_i \varphi / M_{PI}} \approx \beta\varphi / M_{PI}$$

$$w_q = \frac{p_q}{\rho_q} = \frac{\frac{1}{2}\dot{Q}^2 - V(Q)}{\frac{1}{2}\dot{Q}^2 + V(Q)}$$

Implemented by a Ratra/Peebles potential

$$V(\varphi) = \Lambda^4 + \frac{\Lambda^{n+4}}{\varphi^n}$$

Parameters:

$$M_{PI} = 2.44 \times 10^{18} Gev$$

$$\Lambda = 2.4 meV$$

Chameleon field on neutron interferometer

The phase shift will be

$$\Delta\Phi = \int dx \frac{m^2 \beta\varphi(x)}{M_{PI} k}$$

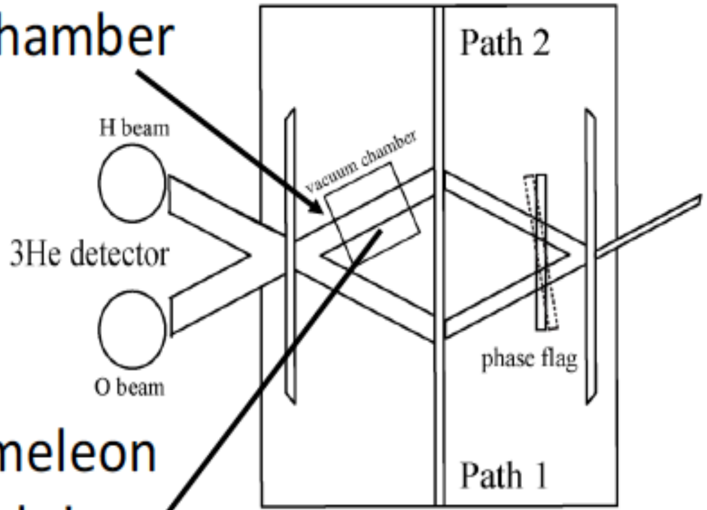
m is the mass of neutron

k is the magnitude of neutron wave-vector

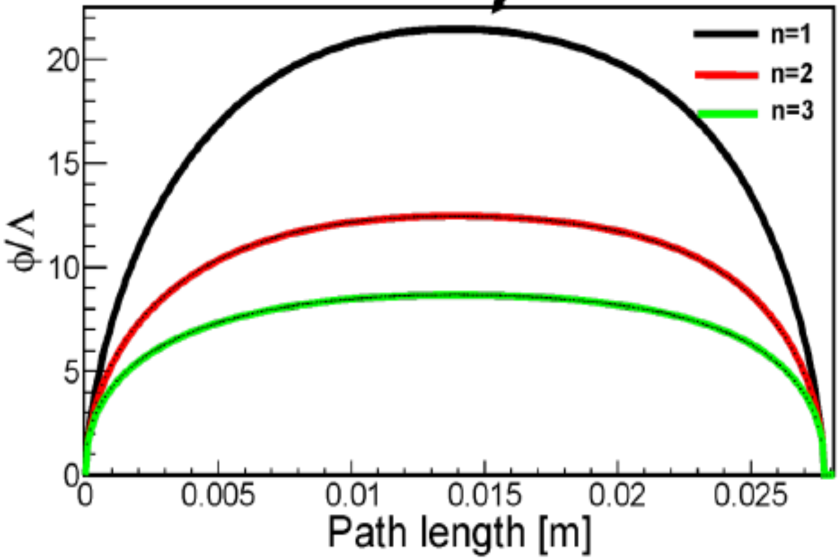
Vary gas pressure to make chameleon field appear and disappear. A few mbar of helium is enough to kill the field

Look for phase shift on the neutron. β is neutron-matter coupling, n is Ratra-Peebles index

vacuum chamber



Chameleon bubble!



INDEX Collaboration

K. Li, W. M. Snow, CEEM, Indiana University

M. Arif, M. G. Huber, NIST Center for Neutron Research

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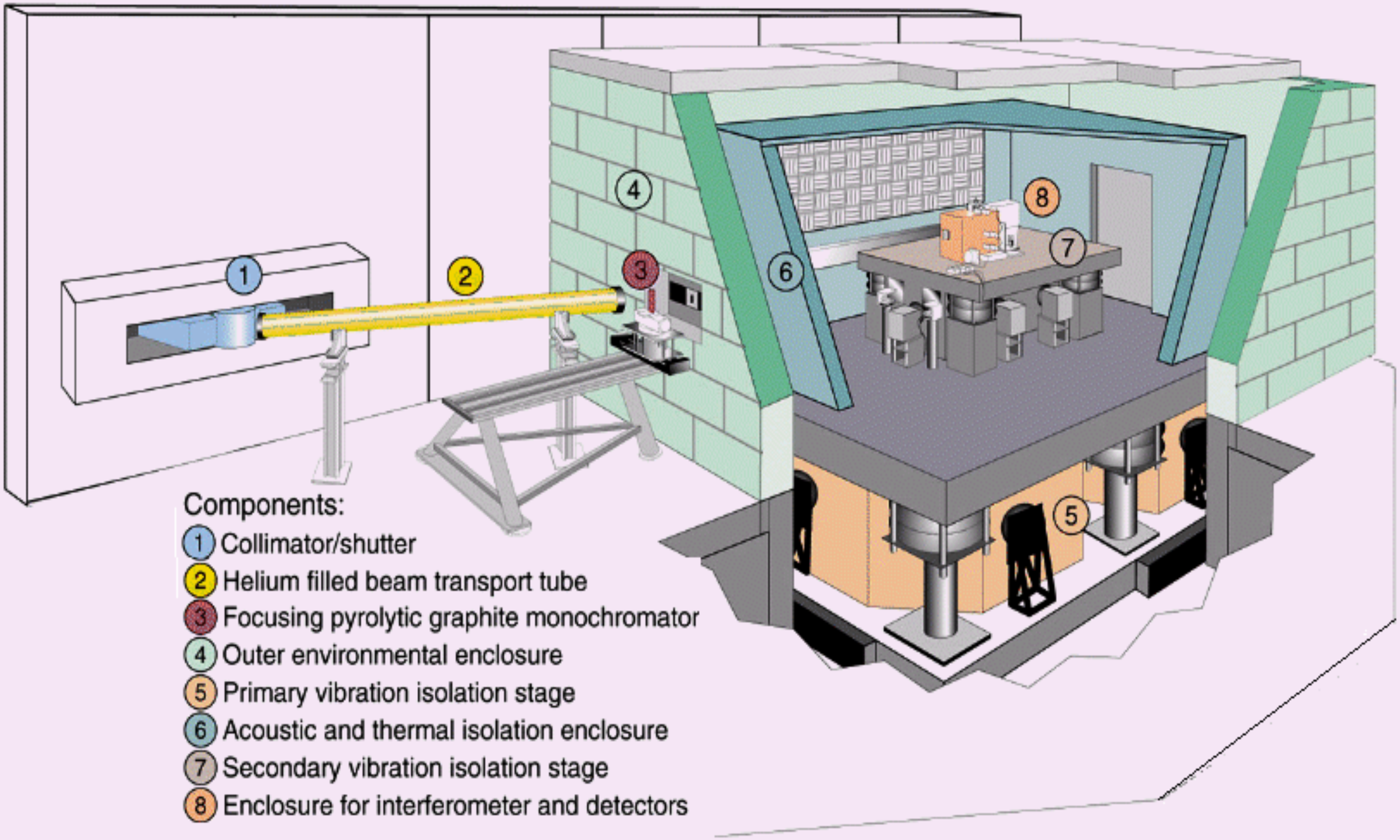
B. Heacock, V. Skavysh, A. R. Young, North Carolina State University

J. Nsofini, P. Saggu, D. Sarenac, University of Waterloo

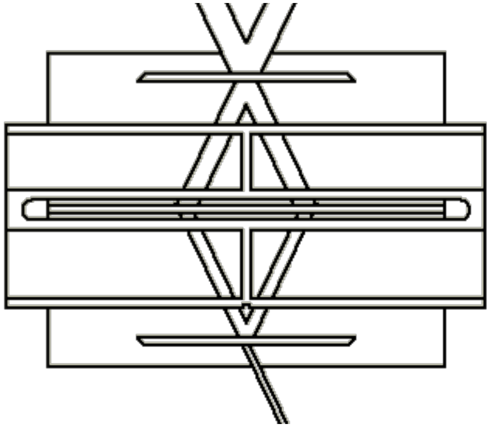
Neutron Interferometer and Optics Facility



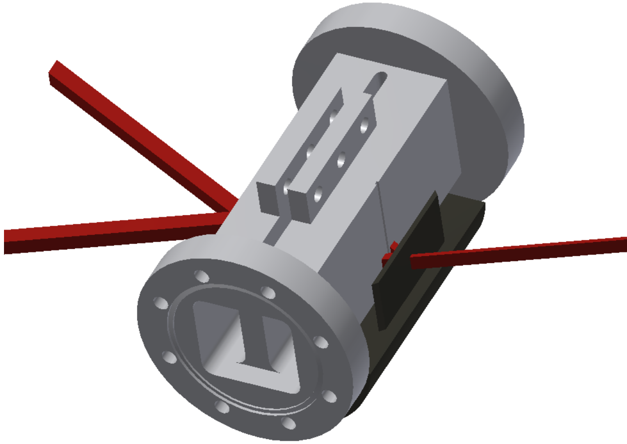
Components:

1. Collimator/shutter
2. Helium filled beam transport tube
3. Focusing pyrolytic graphite monochromator
4. Outer environmental enclosure
5. Primary vibration isolation stage
6. Acoustic and thermal isolation enclosure
7. Secondary vibration isolation stage
8. Enclosure for interferometer and detectors

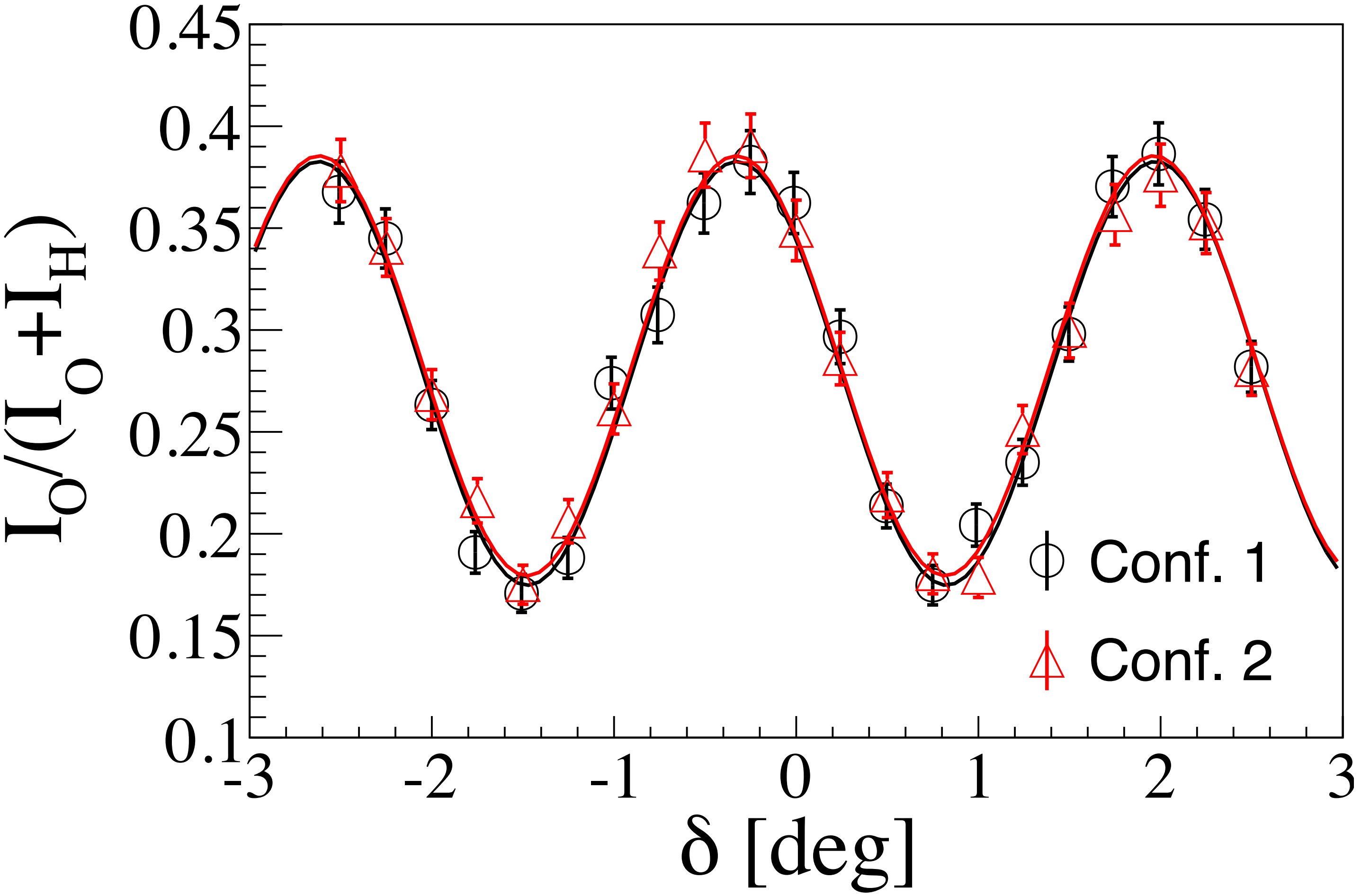
Vacuum cell for Chameleon Experiment



Allows addition of gas at different pressures on each subbeam

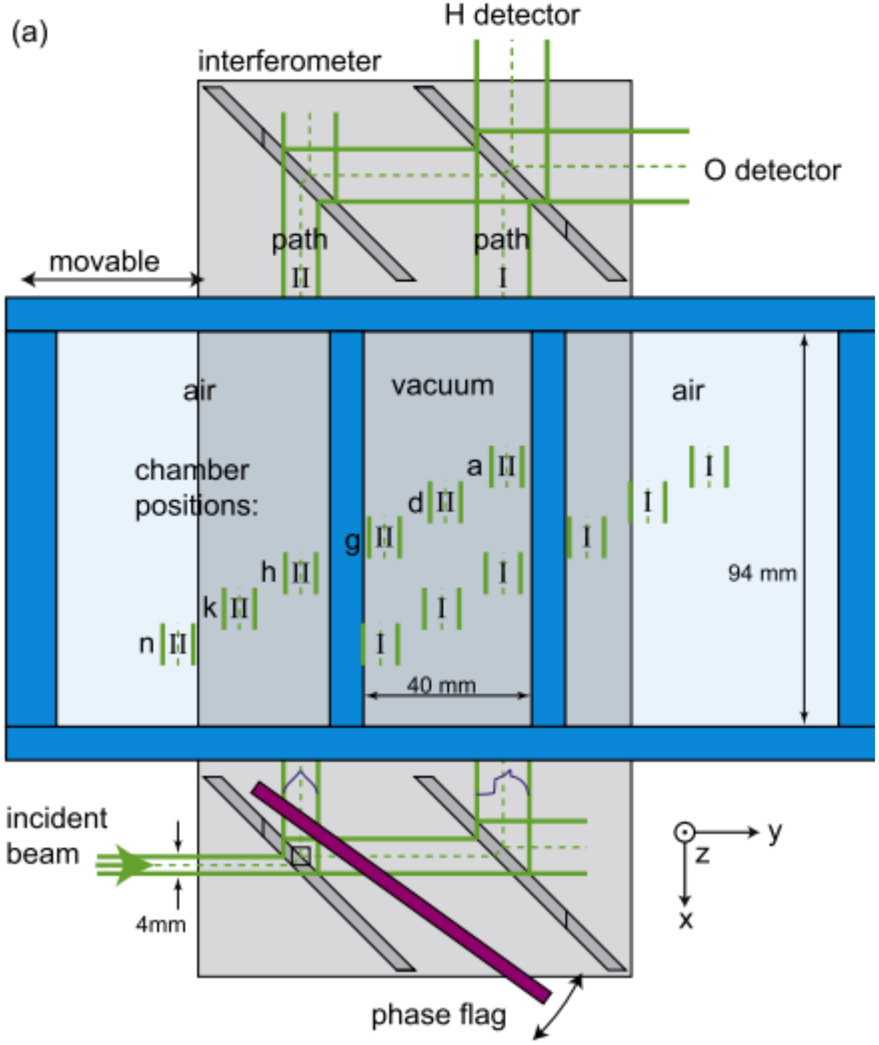


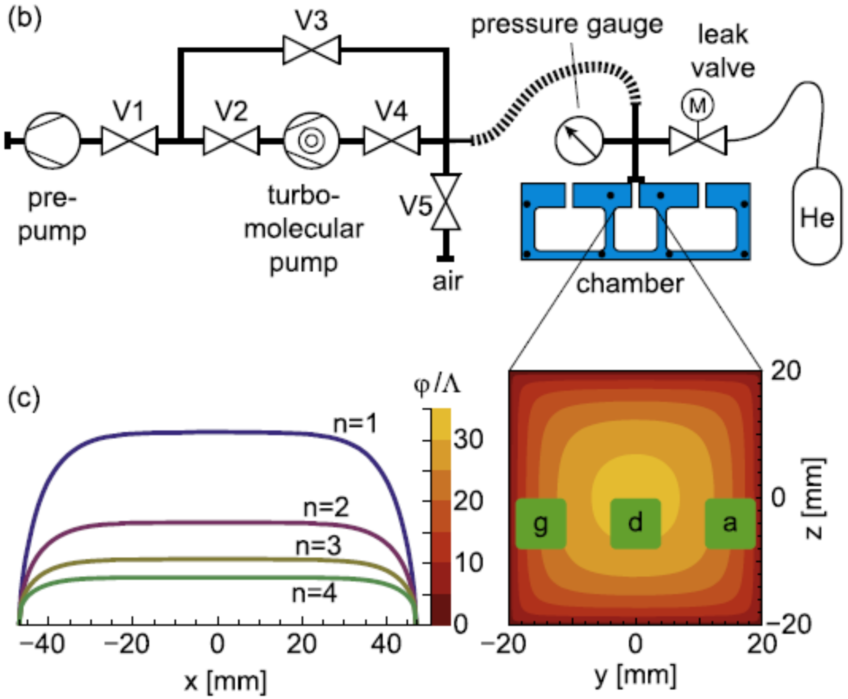
Some Experimental Data from NIST



No evidence for chameleon dark energy

Neutron interferometer experiment at ILL





Physics Letters B 743 (2015)
See poster by T. Jenke

Other recent chameleon experiments:

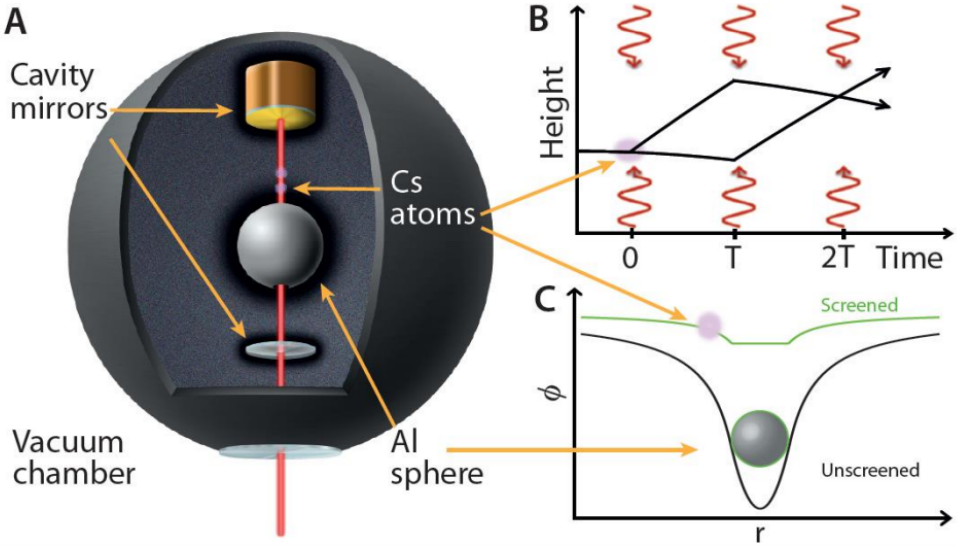
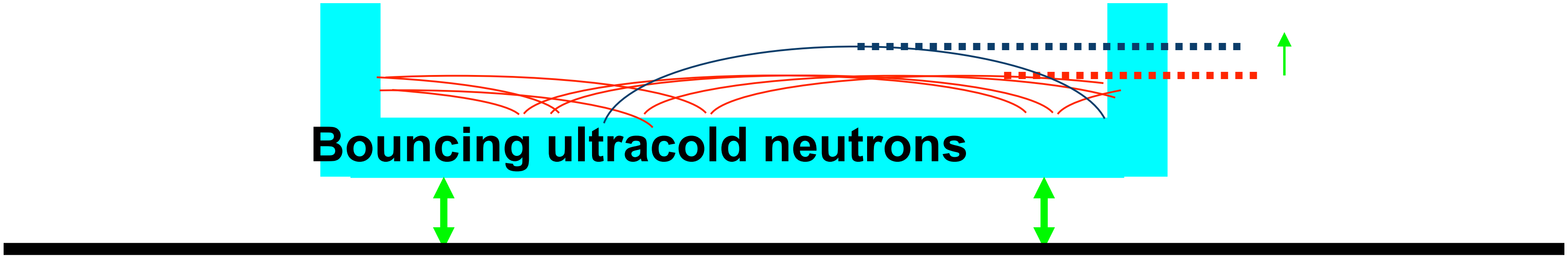


Fig. 1. **Screened fields in our experiment** (**A**) The vacuum chamber (radius 5 cm, pressure ~6× 10^{-10} Torr, mostly hydrogen) holds a pair of mirrors forming a Fabry-Perot cavity and the aluminum (Al) source sphere. Laser beams pass a 1.5-mm radius hole in the r_s = 9.5-mm radius sphere. A Mach-Zehnder interferometer is formed using cold cesium atoms at an effective distance of 8.8 mm from the sphere surface from a magneto-optical trap (not shown). (**B**): Photons in three flashes of laser radiation resonant in the cavity impart momentum to the atoms, directing each atomic matter wave on two paths. (**C**) Potential generated by a macroscopic sphere as function of distance from the center.

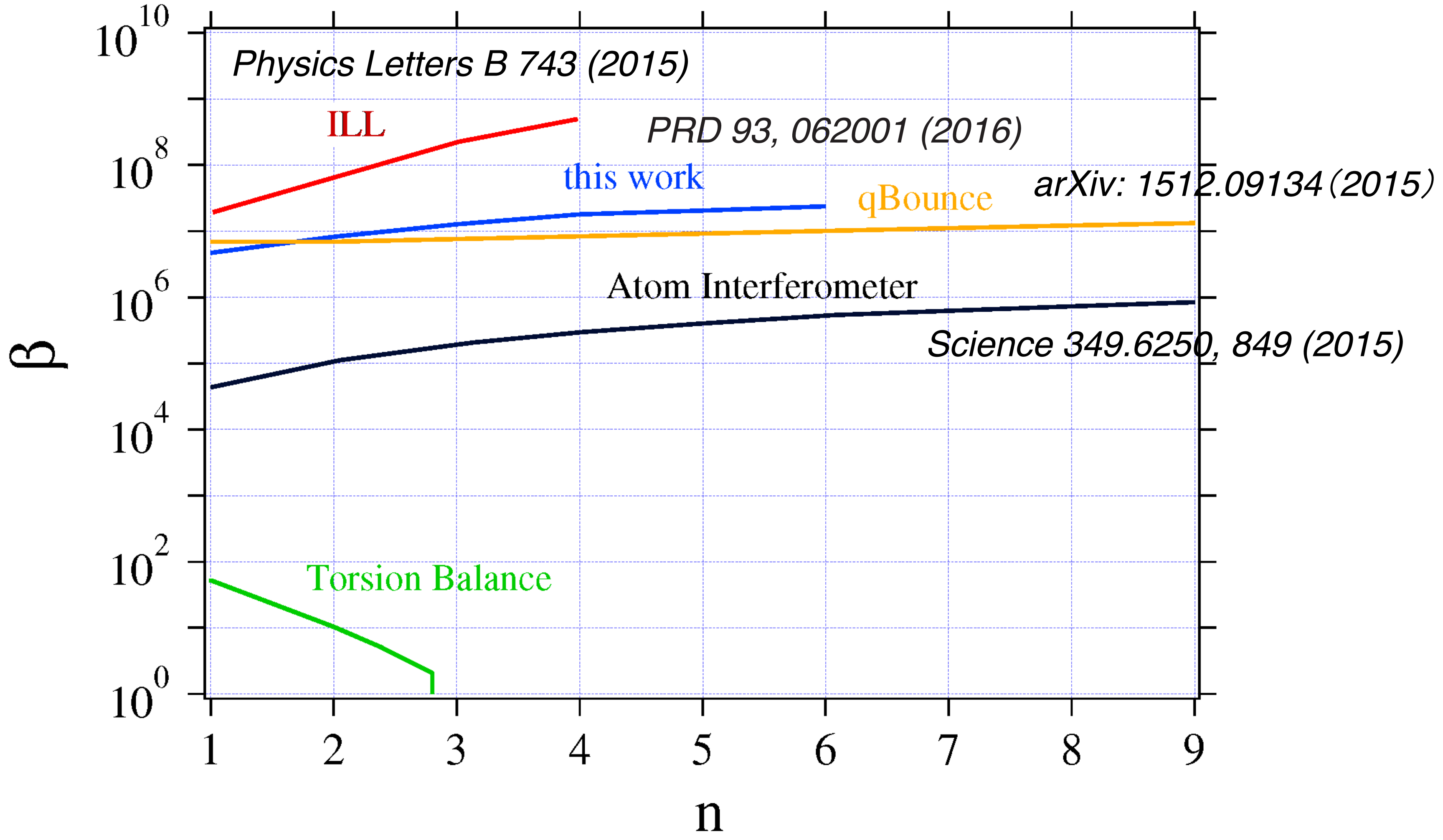
Atom interferometer
(see H. Mueller talk)

Gravitational spectroscopy
with ultracold neutrons
(see H. Abele talk,
posters by T. Rechberger,
M. Thalhammer)



Bouncing ultracold neutrons

Constraints in Chameleon-Matter coupling/ Ratra-Peebles index space



Spin-dependent macroscopic interactions meditated by light bosons: general classification

$$\mathcal{O}_1 = 1 \ ,$$

$$\mathcal{O}_2 = \vec{\sigma} \cdot \vec{\sigma}' \ ,$$

$$\mathcal{O}_3 = \frac{1}{m^2} (\vec{\sigma} \cdot \vec{q}) \ (\vec{\sigma}' \cdot \vec{q}) \ ,$$

$$\mathcal{O}_{4,5} = \frac{i}{2m^2} (\vec{\sigma} \pm \vec{\sigma}') \cdot \left(\vec{P} \times \vec{q}\right) \ ,$$

$$\mathcal{O}_{6,7} = \frac{i}{2m^2} \left[\left(\vec{\sigma} \cdot \vec{P}\right) (\vec{\sigma}' \cdot \vec{q}) \pm (\vec{\sigma} \cdot \vec{q}) \left(\vec{\sigma}' \cdot \vec{P}\right)\right] \ ,$$

$$\mathcal{O}_8 = \frac{1}{m^2} \left(\vec{\sigma} \cdot \vec{P}\right) \left(\vec{\sigma}' \cdot \vec{P}\right) \ .$$

$$\mathcal{O}_{9,10} = \frac{i}{2m} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{11} = \frac{i}{m} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{12,13} = \frac{1}{2m} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{P} \ ,$$

$$\mathcal{O}_{14} = \frac{1}{m} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{P} \ ,$$

$$\mathcal{O}_{15} = \frac{1}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] (\vec{\sigma}' \cdot \vec{q}) + (\vec{\sigma} \cdot \vec{q}) \left[\vec{\sigma}' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\}$$

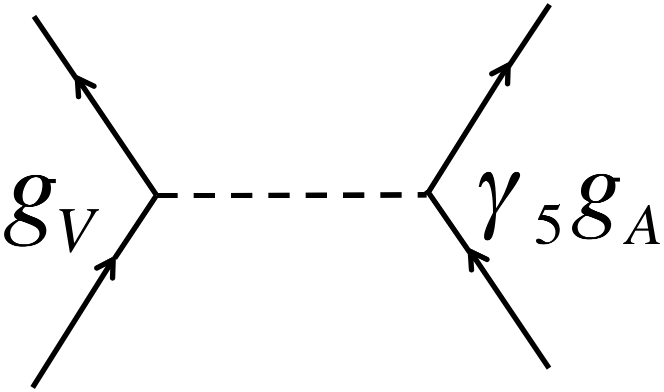
$$\mathcal{O}_{16} = \frac{i}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] \left(\vec{\sigma}' \cdot \vec{P}\right) + \left(\vec{\sigma} \cdot \vec{P}\right) \left[\vec{\sigma}' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\} .$$

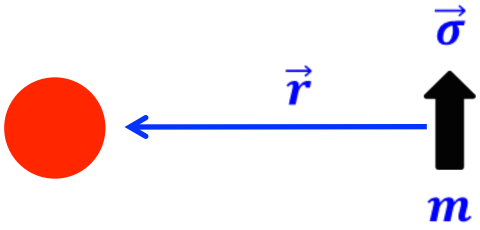
- *16 independent scalars can be formed: 8 P-even, 8 P-odd*
- *15/16 depend on spin*
- *Traditional "fifth force" searches constrain O_1*

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

Example of a nonstandard P-odd interaction from spin 1 boson exchange:

[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]





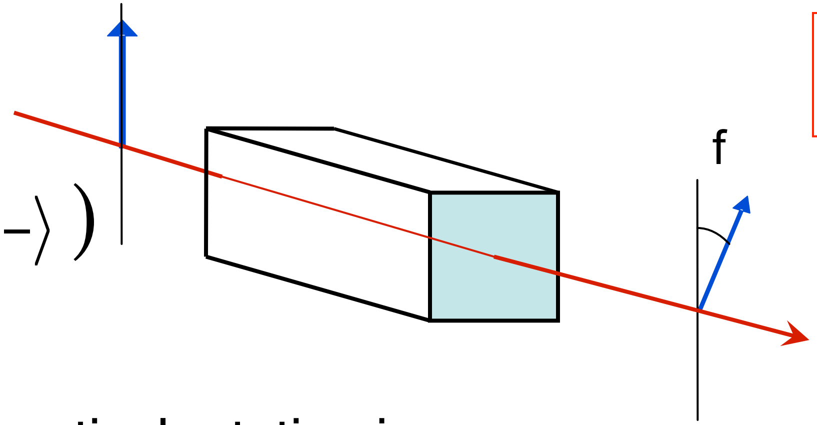
$$V(\vec{\sigma},\vec{r},\vec{v}) = \frac{\hbar}{8\pi mc^2} g_A g_V \vec{\sigma} \bullet \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}}$$

- *Induces an interaction between polarized and unpolarized matter*
- *Violates P symmetry*
- *Not very well constrained over “mesoscopic” ranges(millimeters to microns)*
- *Best investigated using a beam of polarized particles*

Parity-odd Neutron Spin Rotation

$$f(0) = f_{PC} + f_{PV}\left(\vec{\sigma}\cdot\vec{k}\right)$$

$$|\uparrow\rangle_i = \frac{1}{\sqrt{2}}\left(|+\rangle + |-\rangle\right)$$



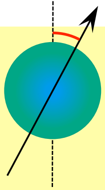
Refractive index dependent on neutron helicity

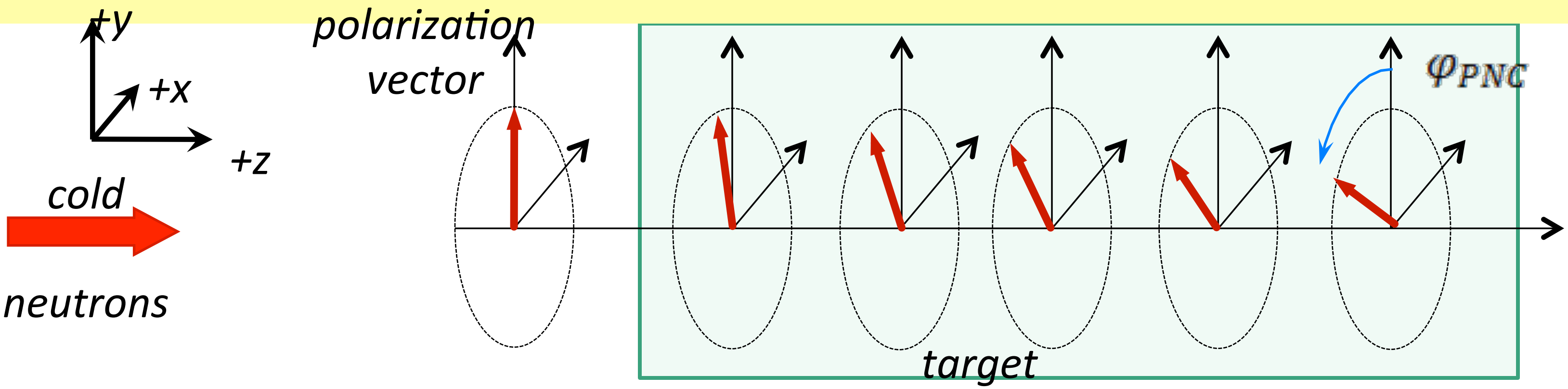
- Analogous to optical rotation in an “handed” medium.
- Transversely-polarized neutrons corkscrew from any parity-odd interaction
- *PV Spin Angle* is independent of incident neutron energy in cold neutron regime,
- $d\phi_{PV}/dx \sim 10^{-6}$ rad/m sensitivity achieved so far

$$\frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PV})}|z\rangle + e^{-i(\phi_{PC}-\phi_{PV})}|-z\rangle\right)$$

$$\varphi_{PV} = \phi_+ - \phi_- = 2\varphi_{PV} = 4\pi l\rho f_{PV}$$

Parity-odd interaction of neutron with matter will produce neutron spin rotation:





$$f(0) \;= f_{strong} + f_{P-odd}(\vec{\sigma}\cdot\vec{p})$$

Forward scattering amplitude of neutron in matter sensitive to all neutron-matter interactions

$$f_{P-odd} = g_A g_V \lambda^2$$

Parity-odd interaction gives helicity-dependent phase shift and therefore rotation of plane of polarization vector

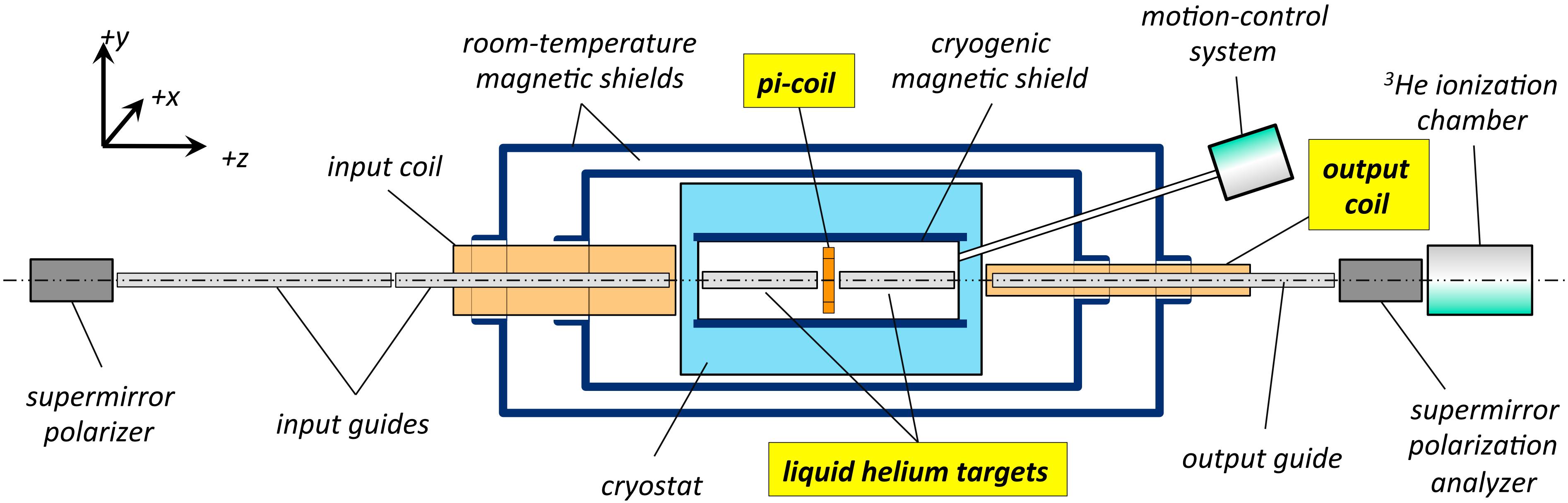
$$\phi_{\pm} = \phi_{strong} \pm \phi_{P-odd}$$

$$\frac{d\phi_{P-odd}}{dL} = 4 g_A g_V \rho\lambda^2$$

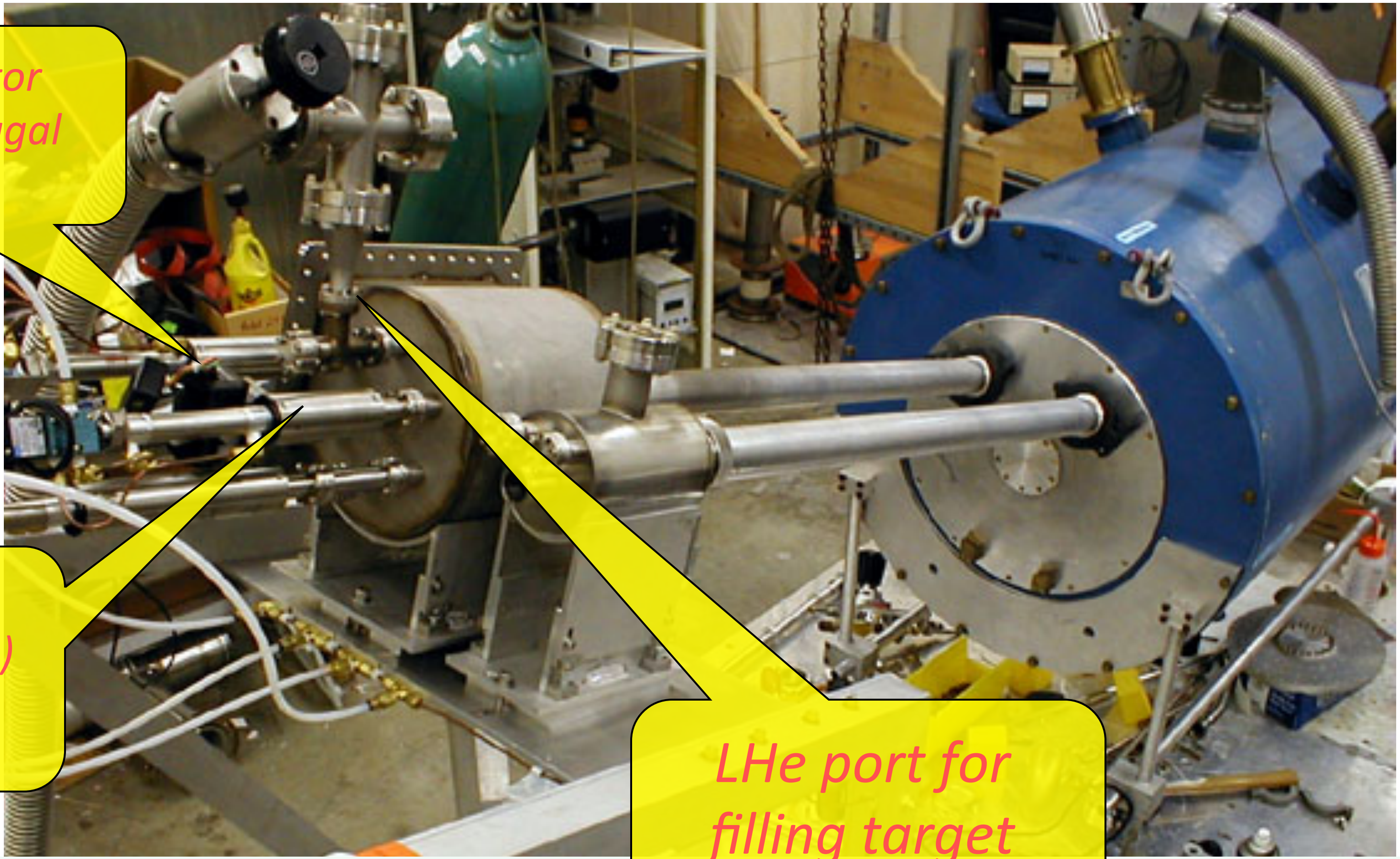
An upper bound on $f_{P\text{-}odd}$ places a constraint on possible new P-odd interactions between neutrons and matter over a broad set of distance scales

Neutron Spin Rotation in Liquid Helium

Apparatus measures the horizontal component of neutron spin generated in the liquid target starting from a vertically-polarized beam



Liquid Helium Cryostat and Motion Control



Stepper motor turns centrifugal pump

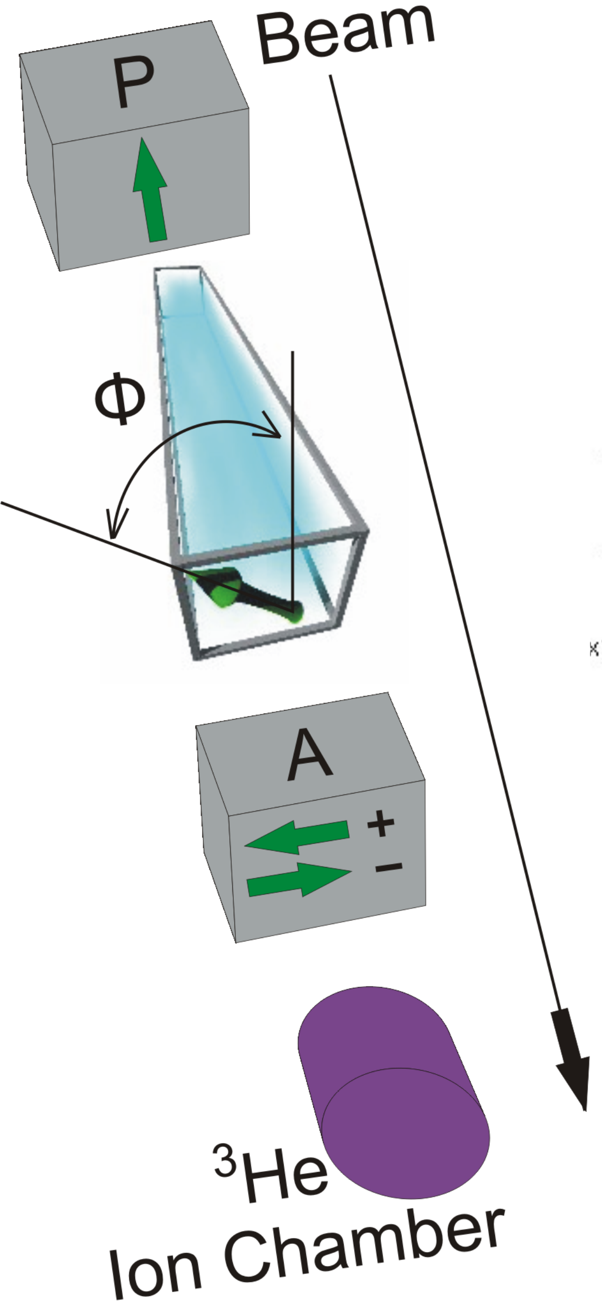
Pneumatic actuators (x4) raise/lower drainpipes

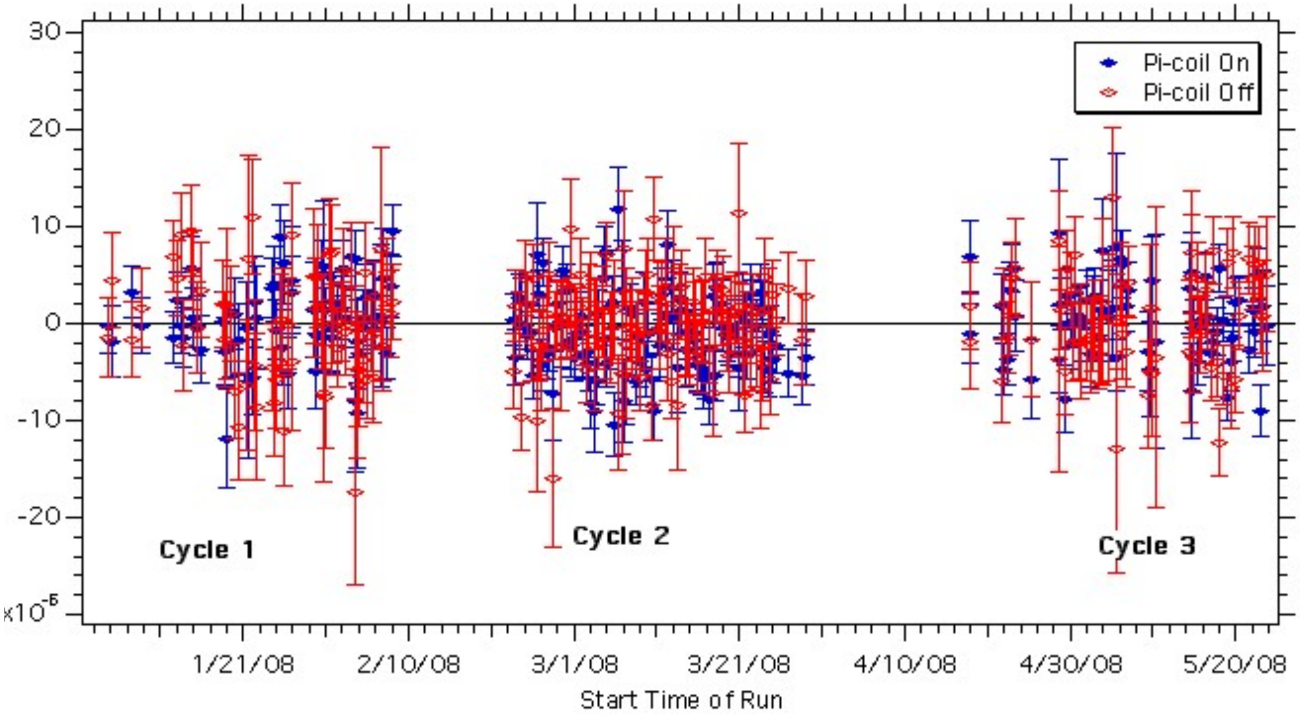
LHe port for filling target helium bath

- *Nonmagnetic movement of liquid helium.*
- *Cryogenic target of 4K helium, volume~10 liters*

C. D. Bass et al, Nucl. Inst. Meth. A612, 69-82 (2009).

Neutron Spin Rotation in n+4He



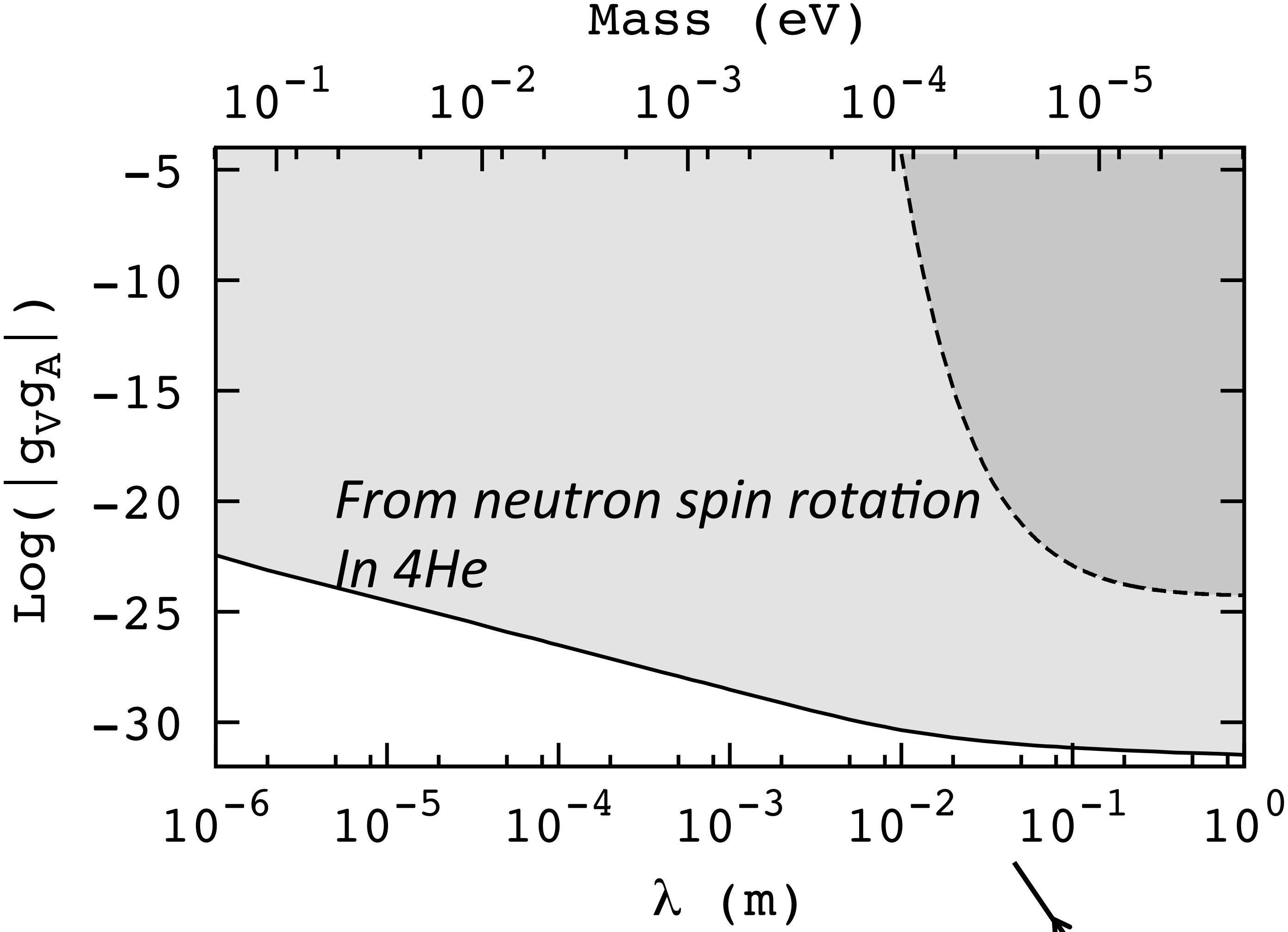


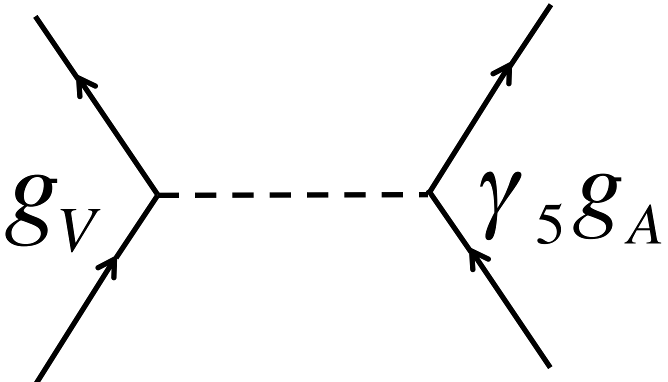
ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

Result analyzed to constrain short-range gravitational torsion: R. Lehnert, H. Yan, W. M. Snow, Phys. Lett ***B730****, 353 (2014),* ***B744****, 415 (2015), arXiv:1311.0467*

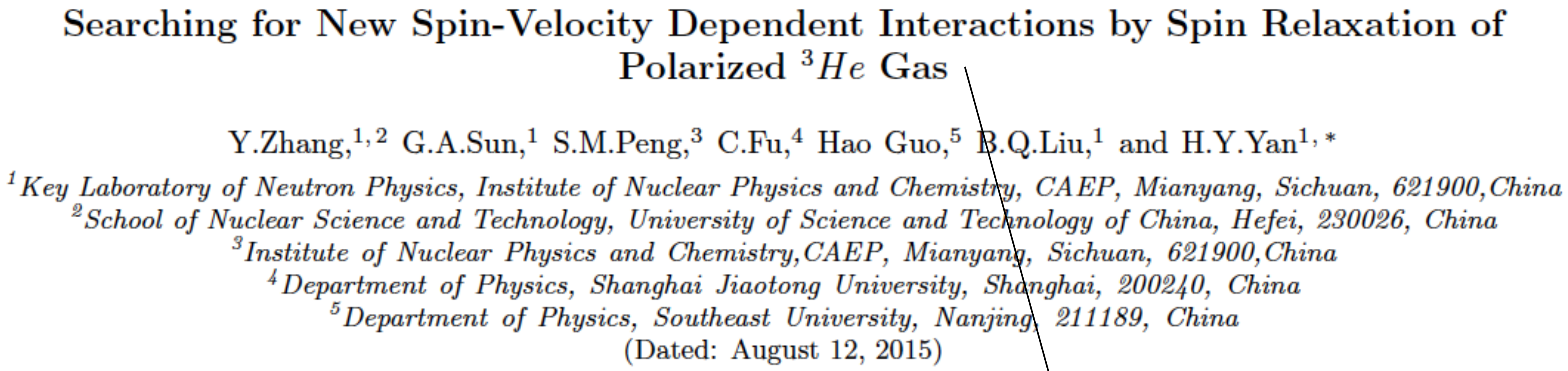
Constraints on exotic V-A interactions





H. Yan, and W. M. Snow, PRL 110, 082003 (2013).

More Constraints on exotic V-A interactions

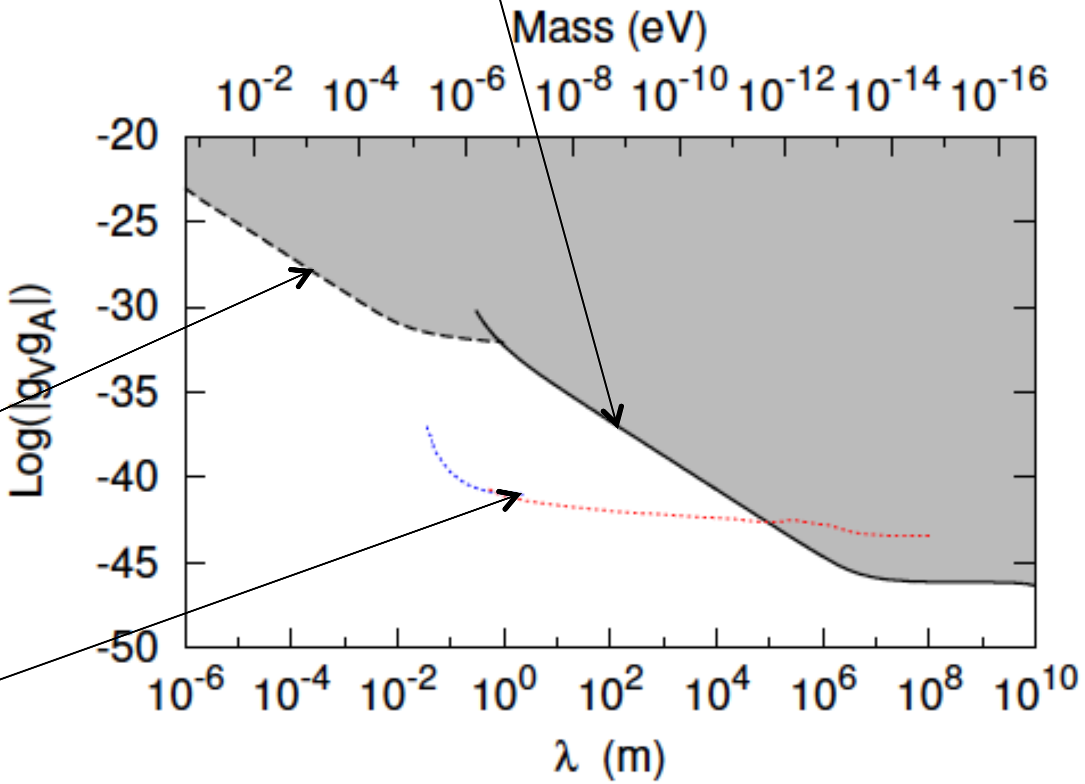


Searching for New Spin-Velocity Dependent Interactions by Spin Relaxation of Polarized ^3He Gas

Y.Zhang,[1,2] G.A.Sun,[1] S.M.Peng,[3] C.Fu,[4] Hao Guo,[5] B.Q.Liu,[1] and H.Y.Yan[1,*]

[1] *Key Laboratory of Neutron Physics, Institute of Nuclear Physics and Chemistry, CAEP, Mianyang, Sichuan, 621900,China*
[2] *School of Nuclear Science and Technology, University of Science and Technology of China, Hefei, 230026, China*
[3] *Institute of Nuclear Physics and Chemistry,CAEP, Mianyang, Sichuan, 621900,China*
[4] *Department of Physics, Shanghai Jiaotong University, Shanghai, 200240, China*
[5] *Department of Physics, Southeast University, Nanjing, 211189, China*
(Dated: August 12, 2015)

This led to more work to constrain parity-odd interactions of the neutron



H. Yan and W. M. Snow, PRL 110, 082003 (2013)

E. G. Adelberger and T. A. Wagner, PRD 88, 031101 (2013)

A Spin-1 Boson Axial Coupling Search

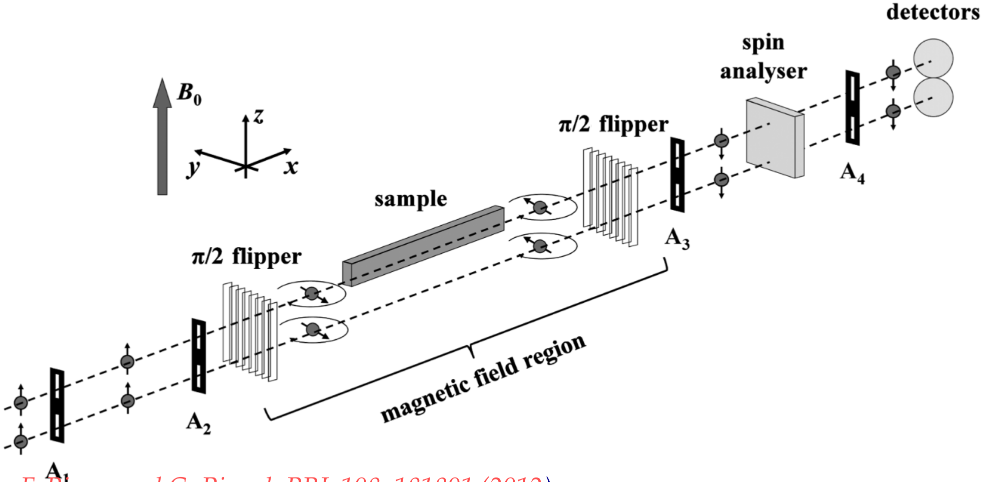
F. Piegsa and G. Pignol placed a first upper bound on the axial coupling constant for a beyond-the-Standard-Model light spin-1 boson in the millimeter range by passing polarized neutrons near one side of a non-magnetic mass and looking for an induced rotation of the polarization direction.

F. Piegsa and G. Pignol, PRL 108, 181801 (2012)

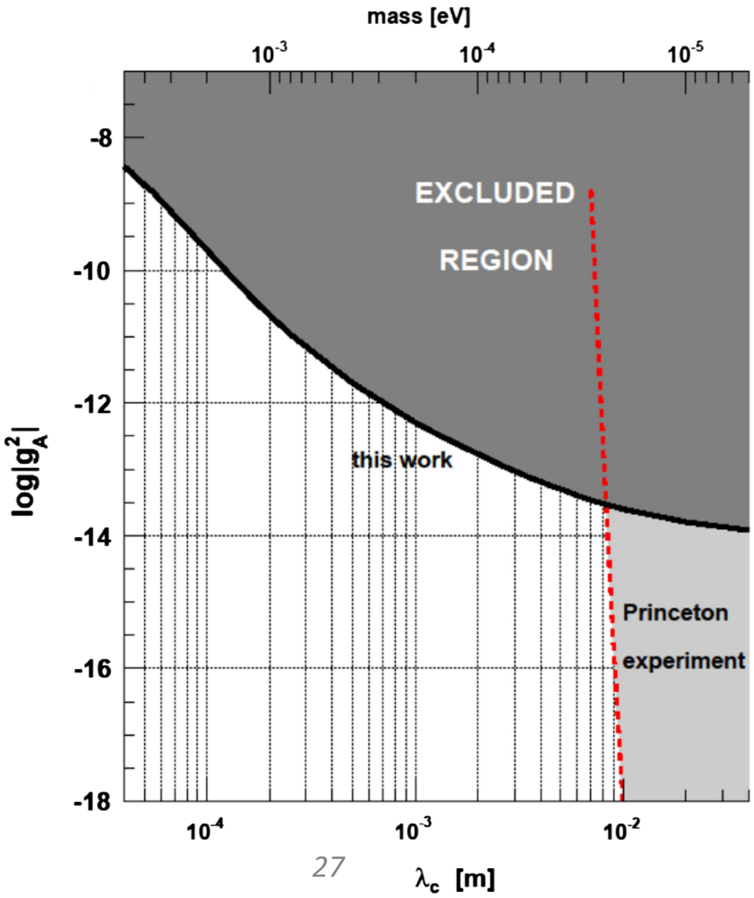
$$\mathcal{L} = \overline{\psi}\left(g_V \gamma^\mu + g_A \gamma^\mu \gamma^5\right)\psi\, X_\mu$$

$$V_{AA} \propto g_A^2\, \vec{\sigma}\cdot(\vec{v}\times\hat{r})\left(\frac{1}{\lambda}+\frac{1}{r}\right)\frac{e^{-r/\lambda}}{r}$$

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



F. Piegsa and G. Pignol, PRL 108, 181801 (2012)



Measurement performed at PSI

Neutron Spin Rotation (NSR) Collaboration

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A search for very light exotic vector bosons using slow neutrons

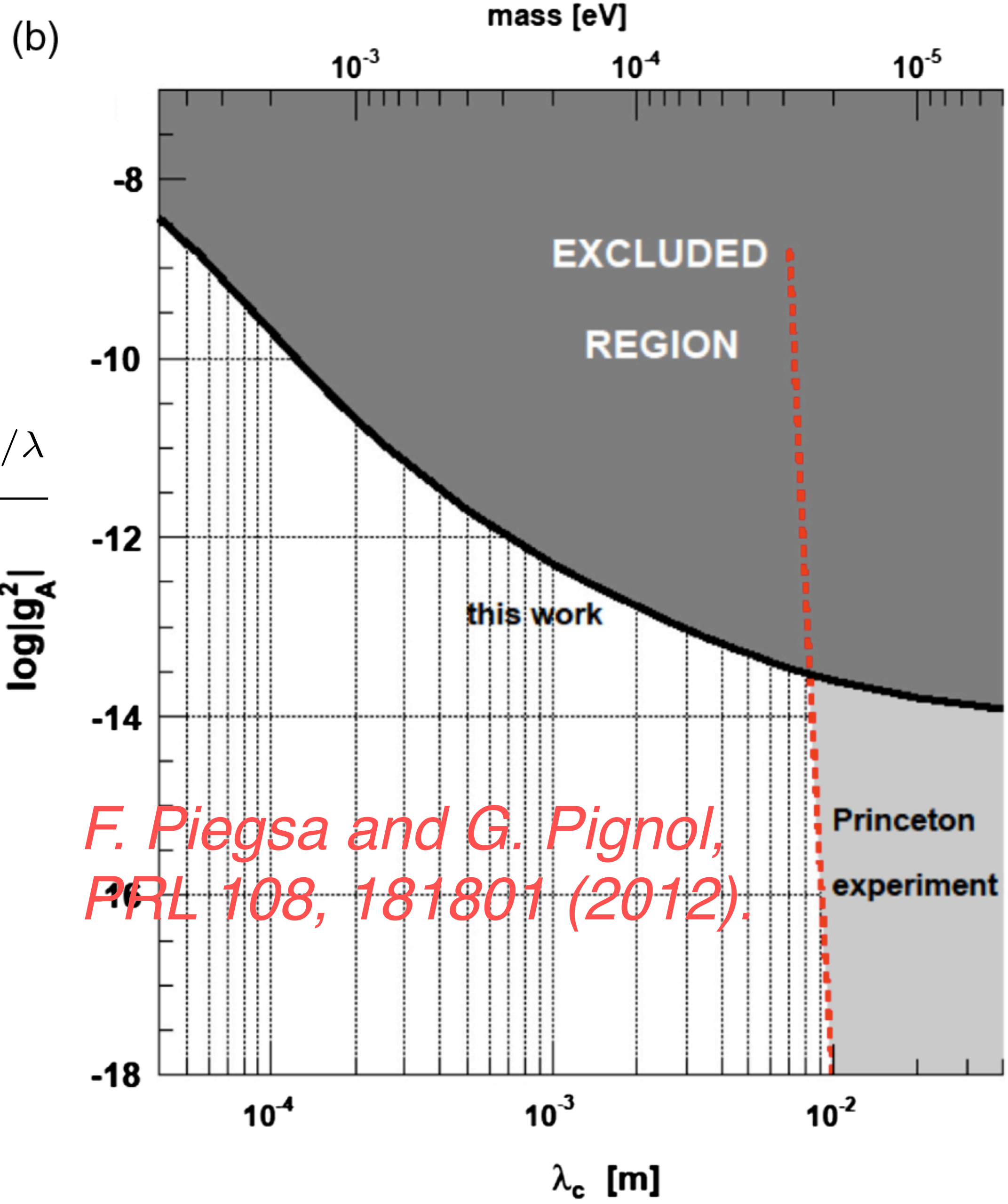
$$\mathcal{L} = \overline{\psi}\left(g_V\gamma^\mu + g_A\gamma^\mu\gamma^5\right)\psi\, X_\mu$$

$$V_{AA} \propto g_A^2\,\vec{\sigma}\cdot(\vec{v}\times\hat{r})\left(\frac{1}{\lambda}+\frac{1}{r}\right)\frac{e^{-r/\lambda}}{r}$$

Rotates neutron spin forward by an angle

$$\phi = l\frac{g_A{}^2}{4}N\frac{\hbar}{mc}\lambda_c e^{-\frac{\Delta y}{\lambda_c}}$$

Goal for fall 2016: complete experiment, improve previous search by ~3 orders of magnitude

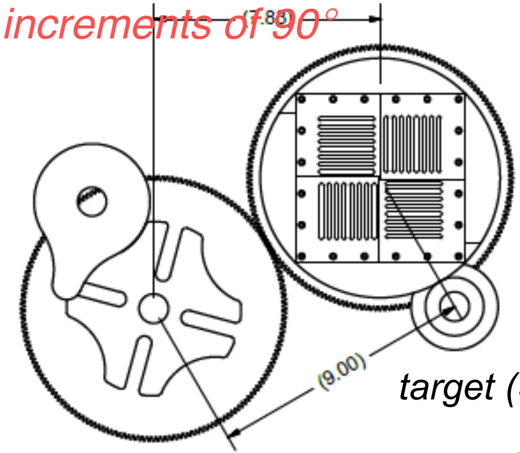


F. Piegsa and G. Pignol, PRL 108, 181801 (2012).

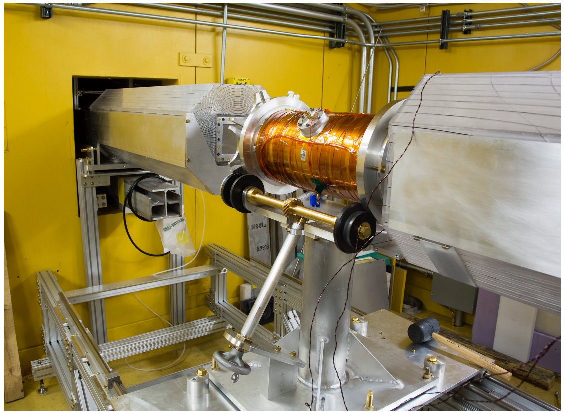
Neutron Polarimetry Apparatus on FP12 at LANSCE

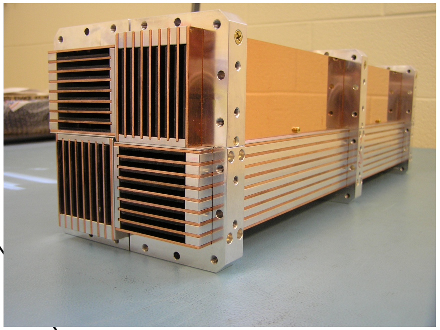
Geneva Mechanism:

Rotate the target by increments of 90°

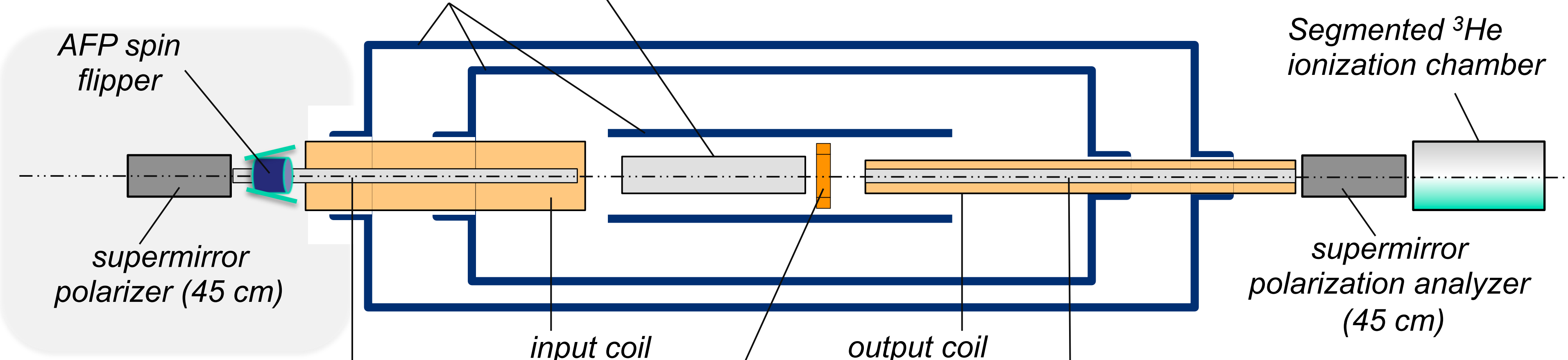


View inside FP12 cave showing input/output supermirror guides and coils and target vacuum chamber. Neutron supermirror polarizer/analyzer, ion chamber, magnetic shielding not shown.





Plates of different nucleon density N are assembled so that the polarized neutrons traveling between the gaps will always see a density gradient.



target (50 cm)

magnetic shields

AFP spin flipper

Segmented ^{3}He ionization chamber

supermirror polarizer (45 cm)

supermirror polarization analyzer (45 cm)

input coil

output coil

non-magnetic SM (m=2) input guide (125 cm)

non-magnetic SM (m=2) output guide (200 cm)

pi/2 turner

Conclusions

Experimental searches for weakly-coupled interactions with ranges from the millimeter to the atomic scale are actively pursued experimentally and appear in various theoretical scenarios

The properties of slow neutrons are well-suited to search for new interactions in this regime

Rapid experimental progress has occurred over the last few years, with the first measurements for certain spin-dependent interactions over sub-millimeter ever conducted.

New results and ongoing experiments have appeared at several neutron facilities throughout the world