Precision measurements with atomic co-magnetometer at the South Pole

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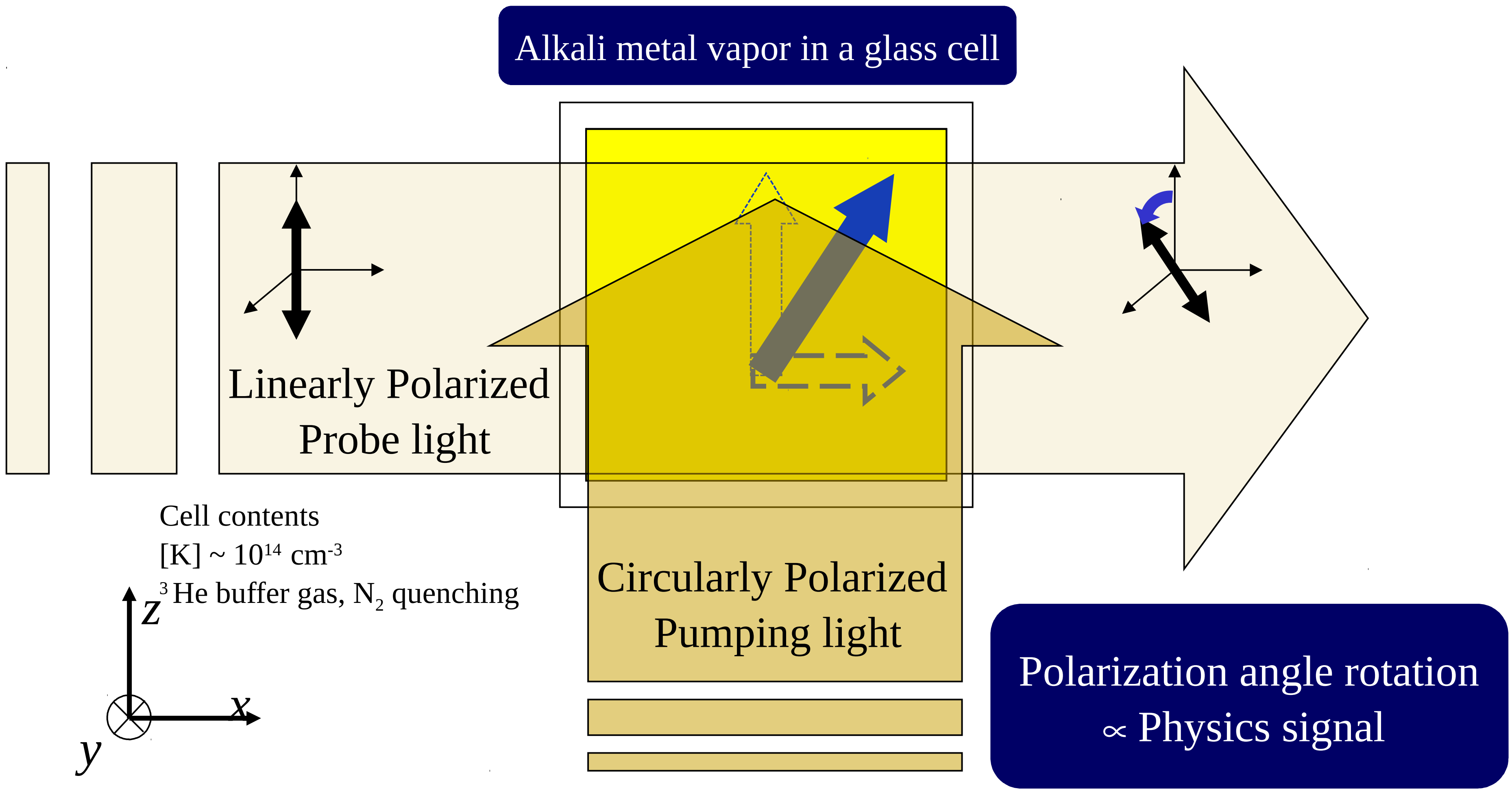
Outline

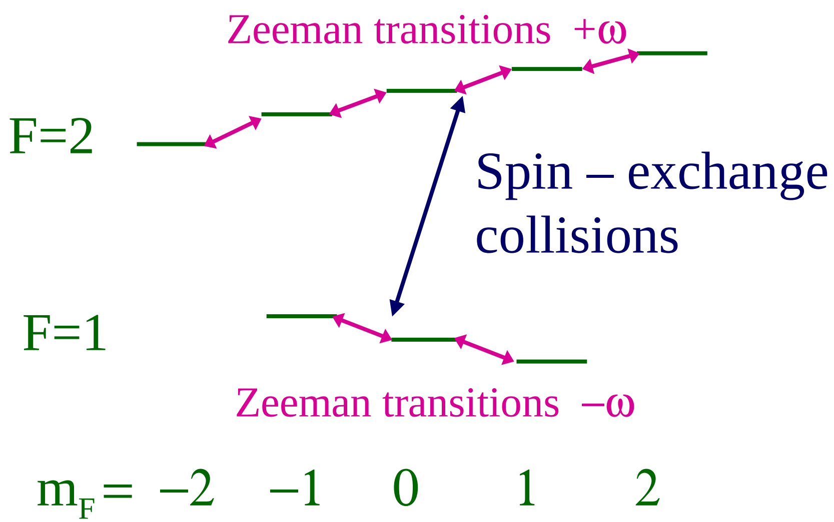
- Alkali metal - noble gas co-magnetometer
- Rotating co-magnetometer at the South Pole
- New Physics Constraints
  - ⇒Lorentz violation
  - ⇒Long-range spin-dependent forces
  - ⇒Slowly oscillating fields
- Current experiments
  - ⇒ Search for spin-mass interaction on 20 cm scale
  - ⇒ Search for spin-spin interactions

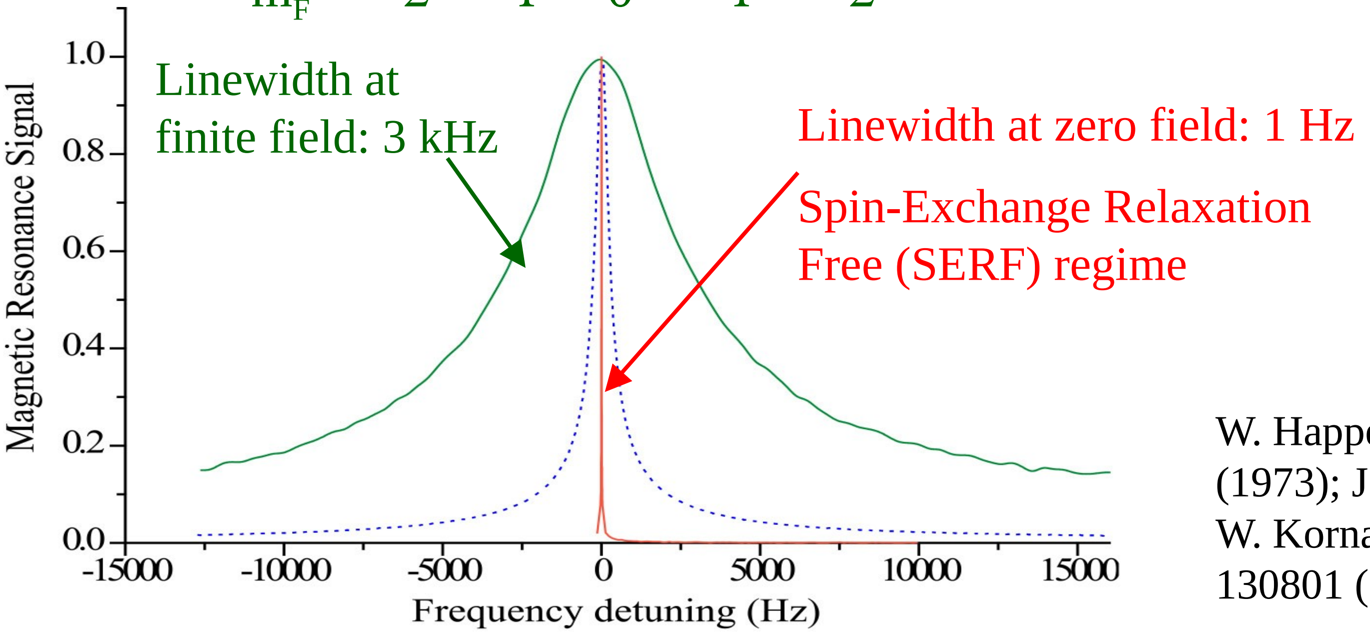
Operation of Atomic Co-Magnetometer



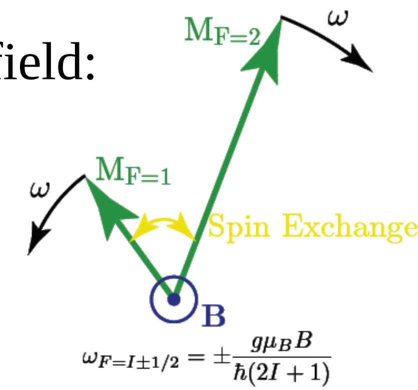
Elimination of spin-exchange broadening at zero field

Ground state Zeeman and hyperfine levels in K

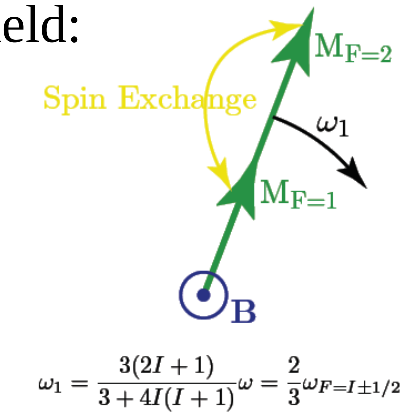




High field:



Low field:



W. Happer and H. Tang, PRL 31, 273 (1973); J. C. Allred, R. N. Lyman, T. W. Kornack, and MVR, PRL. 89, 130801 (2002)

K-^{3}He Co-magnetometer

1. Optically pump potassium atoms at high density (10^{13}-10^{14}/cm^3)
2. ^{3}He nuclear spins are polarized by spin-exchange collisions with K vapor
3. Polarized ^{3}He creates a magnetic field felt by K atoms

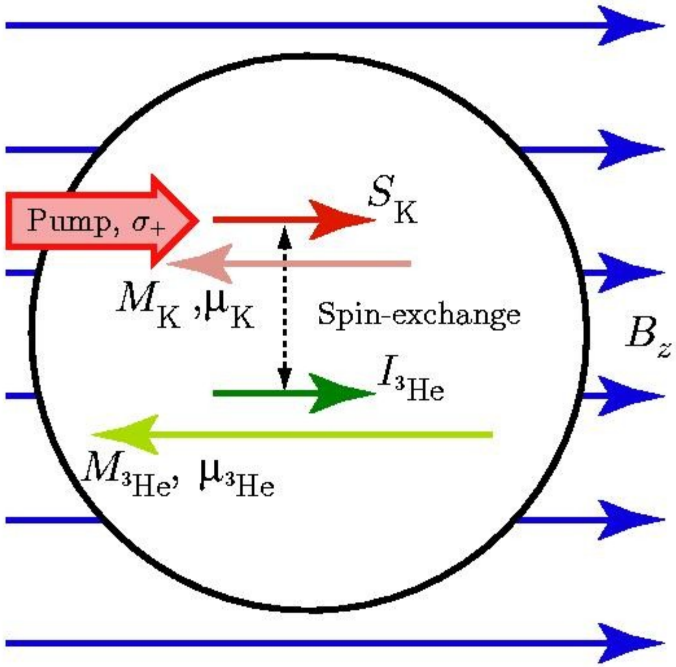
$$B_K = \frac{8\pi}{3}\kappa_0 M_{He}$$

4. Apply external magnetic field B_z to cancel field B_K

   ⇒K magnetometer operates near zero magnetic field

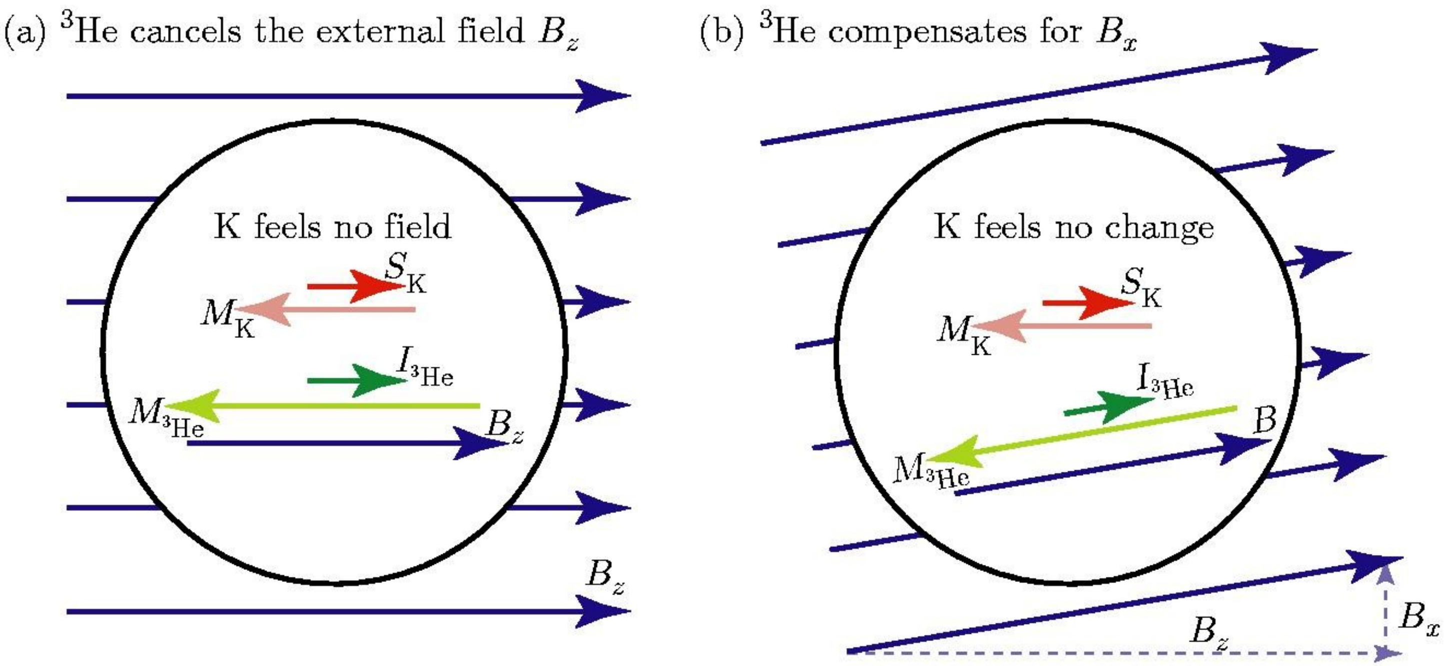
5. At zero field and high alkali density K-K spin-exchange relaxation is suppressed
6. Obtain high sensitivity of K to magnetic fields in spin-exchange relaxation free (SERF) regime

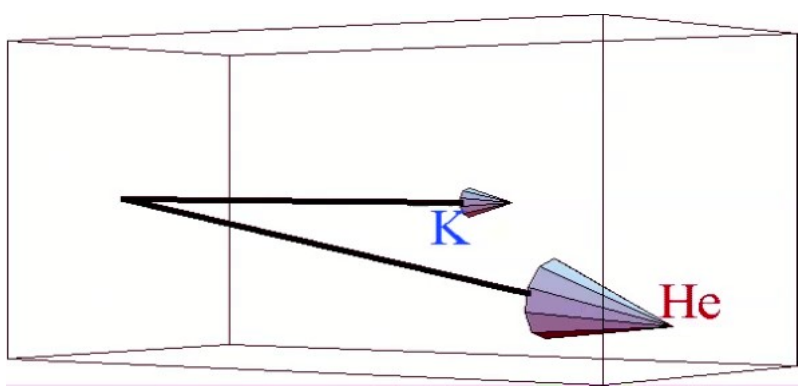
Turn most-sensitive atomic magnetometer into a co-magnetometer



J. C. Allred, R. N. Lyman, T. W. Kornack, and MVR, PRL **89**, 130801 (2002)
I. K. Kominis, T. W. Kornack, J. C. Allred and MVR, Nature **422**, 596 (2003)
T.W. Kornack and MVR, PRL 89, 253002 (2002)
T. W. Kornack, R. K. Ghosh and MVR, PRL **95**, 230801 (2005)

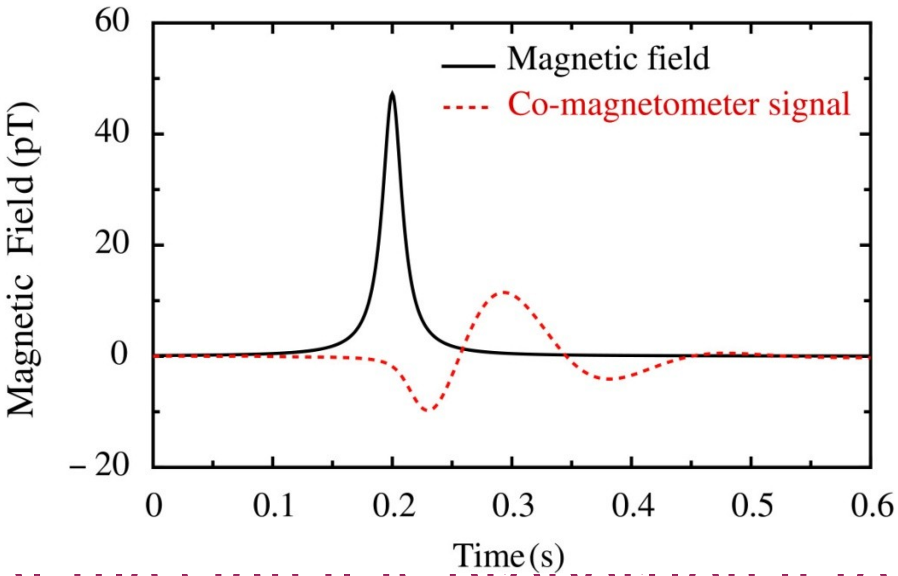
Magnetic field self-compensation





Response to transient signals

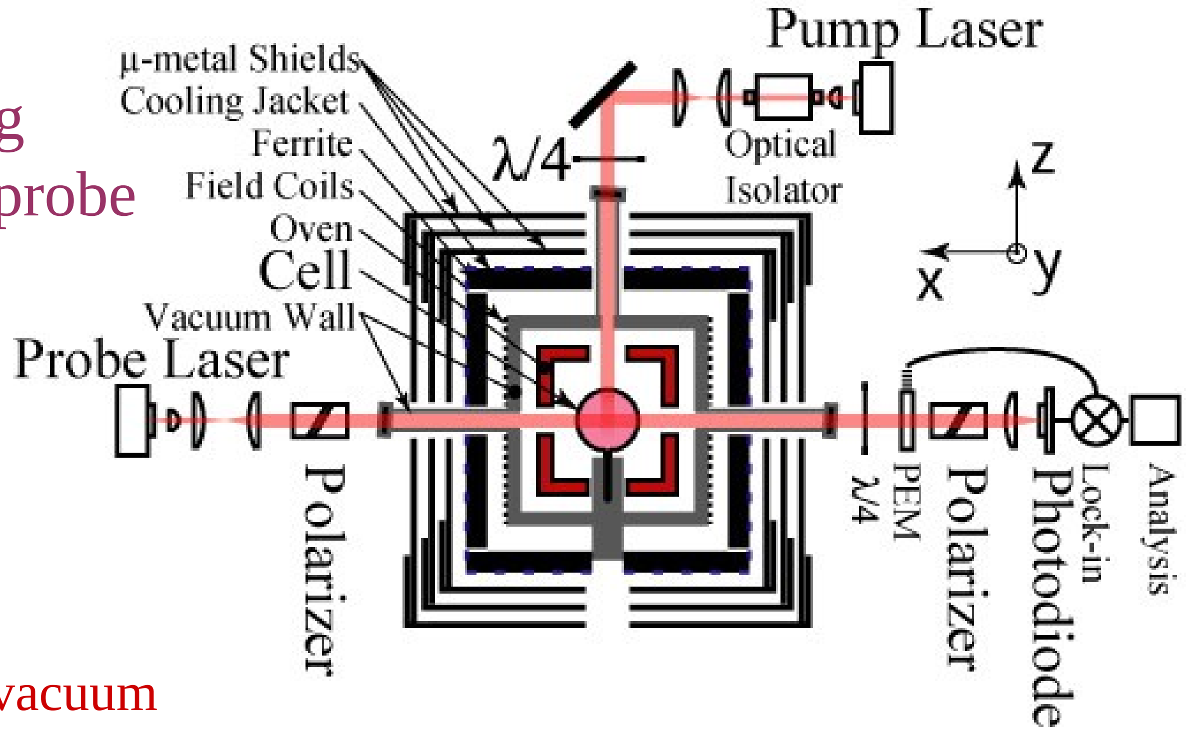
- Fast transient response
  - ⇒ ^{3}He has T_2 of 1000s of seconds
  - ⇒ Transient signals decay in 0.3 seconds
  - ⇒ Due to spin-damping coupling to K atoms



- Integral of the signal is proportional to spin rotation angle for arbitrary pulse shape

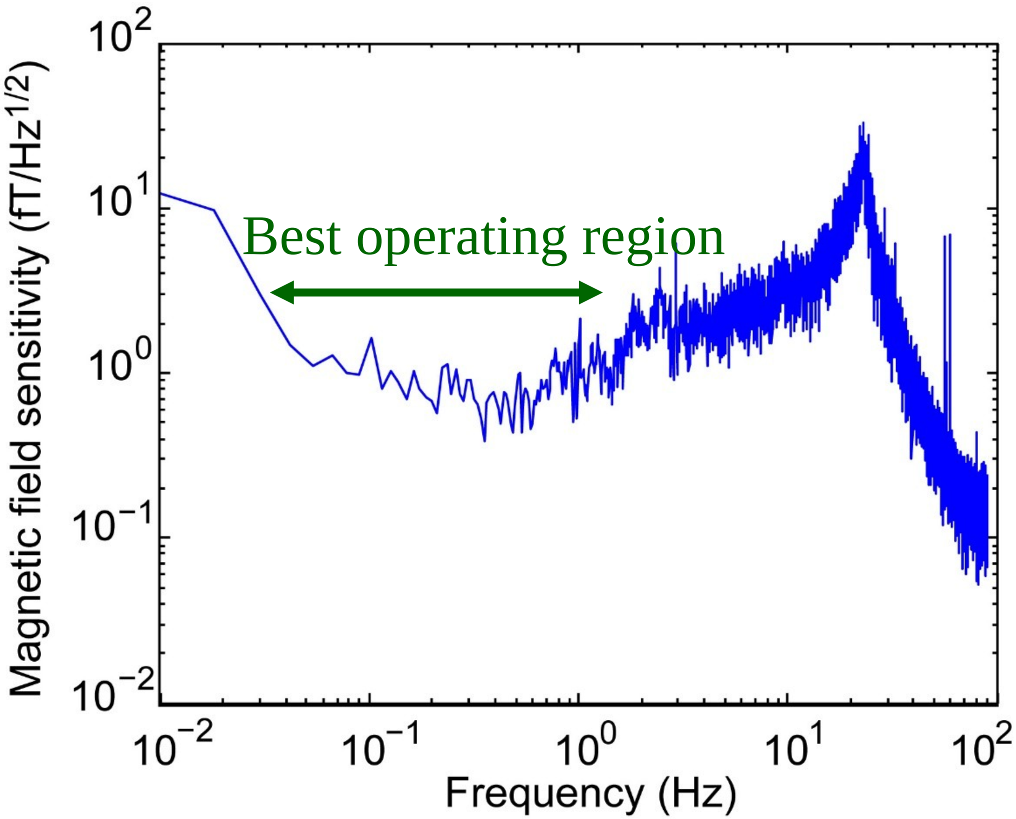
Co-magnetometer Setup

- Simple pump-probe arrangement
- Measure Faraday rotation of far-detuned probe beam
- Sensitive to spin coupling orthogonal to pump and probe



- Details:
  - ⇒ Ferrite inner-most shield
  - ⇒ 3 layers of μ-metal
  - ⇒ Cell and beams in mtorr vacuum
  - ⇒ Polarization modulation of probe beam for polarimetry at 10^{-7}rad/Hz$^{1/2}$
  - ⇒ Whole apparatus in vacuum at 1 Torr

Magnetic field sensitivity



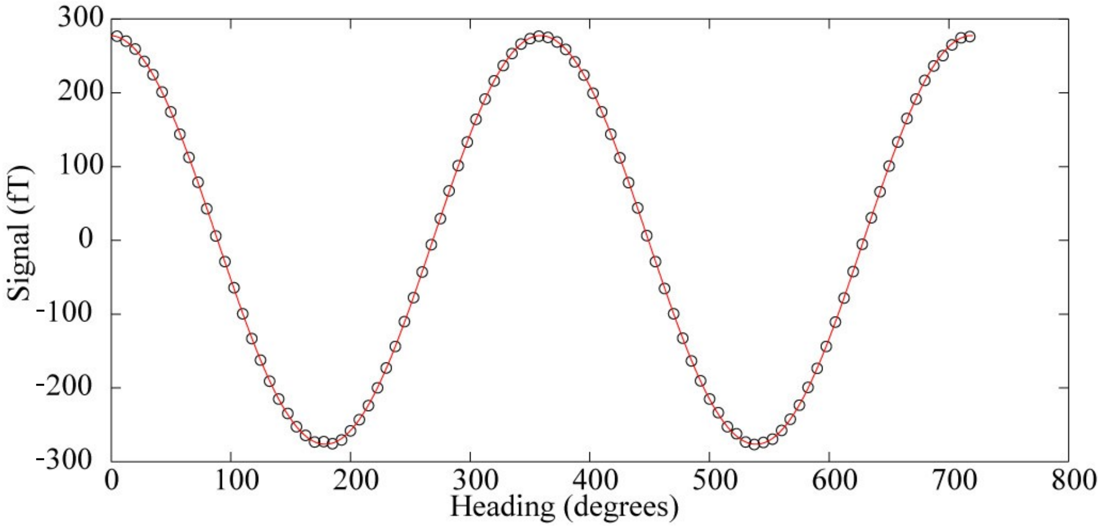
- Sensitivity of ~1 $fT/Hz^{1/2}$ for both electron and nuclear interactions
  ⇒Frequency uncertainty of 20 $pHz/month^{1/2}$ = 10^{-25} eV for ^3He
  20 $nHz/month^{1/2}$ = 10^{-22} eV for electrons
- So search for preferred spatial direction, reverse co-magnetometer orientation every 20 sec to operate in the region of best sensitivity

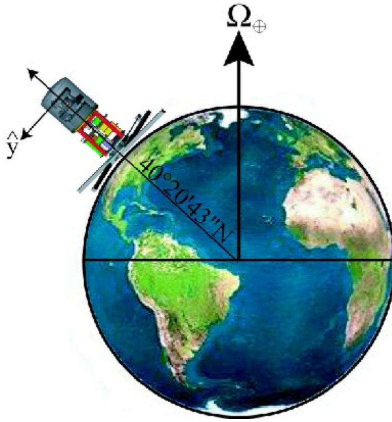
Rotating K-^{3}He co-magnetometer

- Rotate – stop – measure – rotate
  - ⇒ Fast transient response crucial
- Record signal as a function of magnetometer orientation

$$b^{eff} = \frac{\Omega}{\gamma}$$

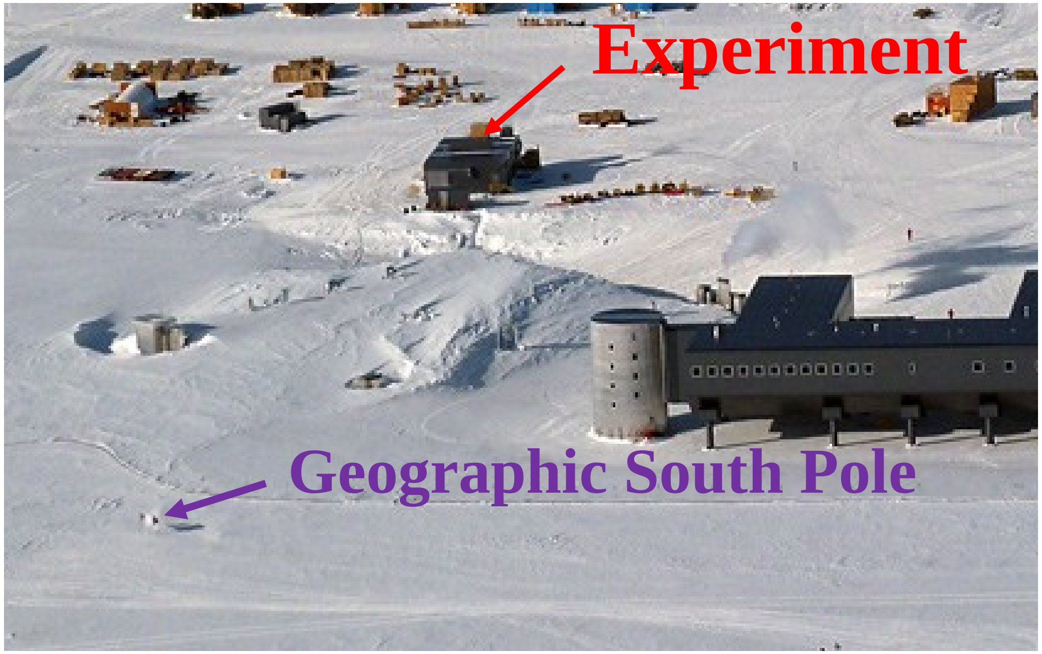
$$S = \frac{P_z \gamma_e \Omega_y}{R}\left(\frac{1}{\gamma_e} - \frac{1}{\gamma_n}\right)$$

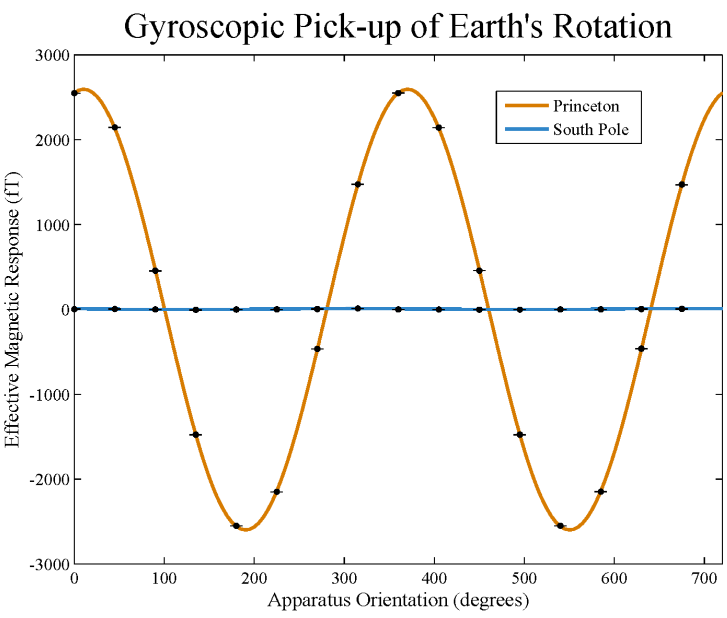




South Pole

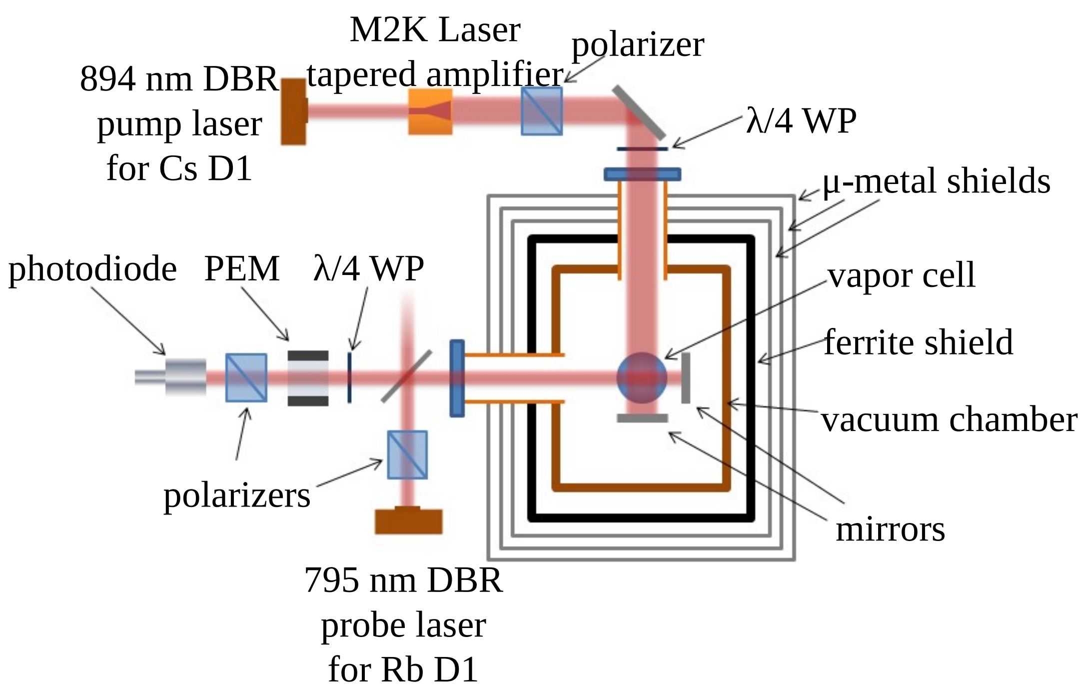
- Most systematic errors are due to two preferred directions in the lab: gravity vector and Earth rotation vector
- If the two vectors are aligned, rotation about that axis will eliminate most systematic errors
- Amundsen-Scott South Pole Station
  - ⇒ Lab location within 200 meters of geographic South Pole

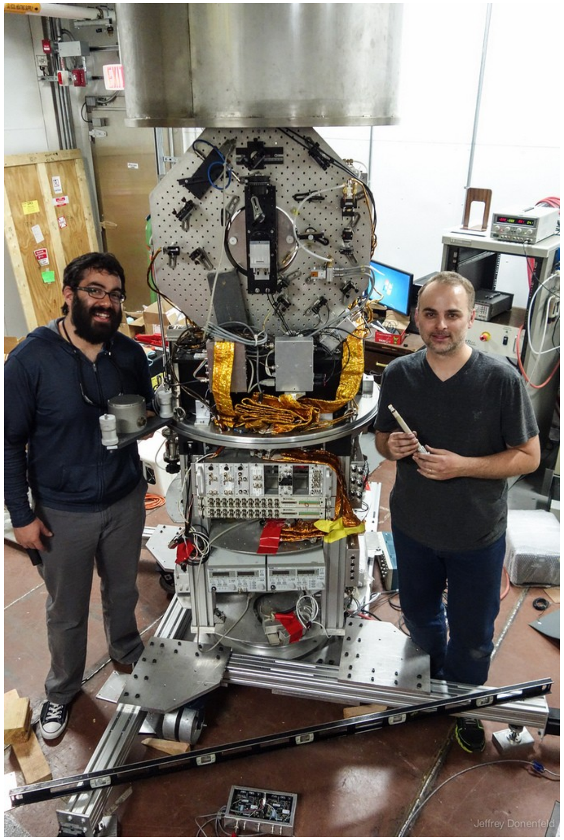


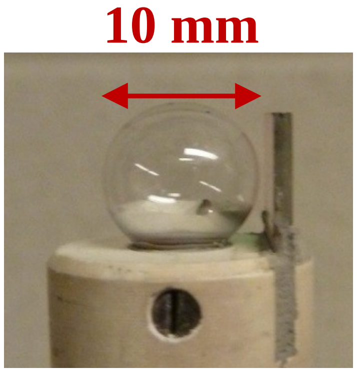


South Pole Setup

- Use ^{21}Ne with I=3/2 to look for tensor CPT-even Lorentz-violating effects
- Reliable operation with minimal human intervention:
  - Simple optical setup with DBR diode lasers
  - Whole apparatus in vacuum at 1 Torr
  - Automatic fine-tuning and calibration procedures
  - Remote-controlled mirrors, lasers, etc

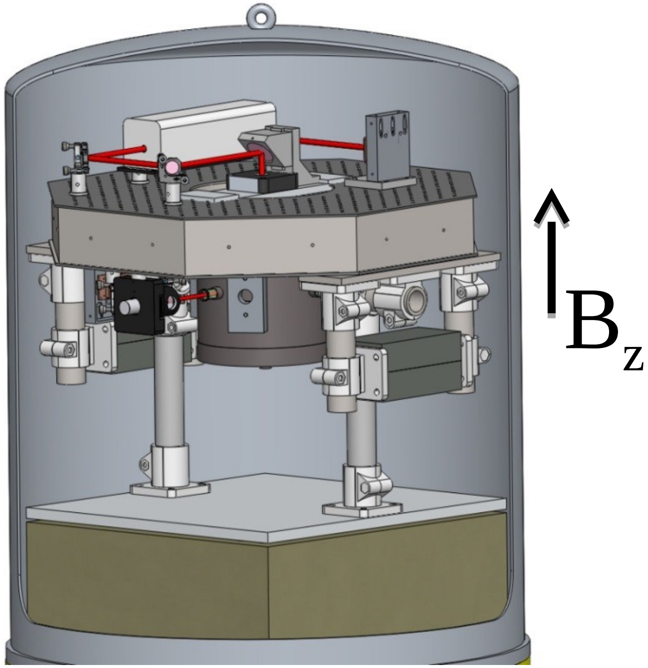




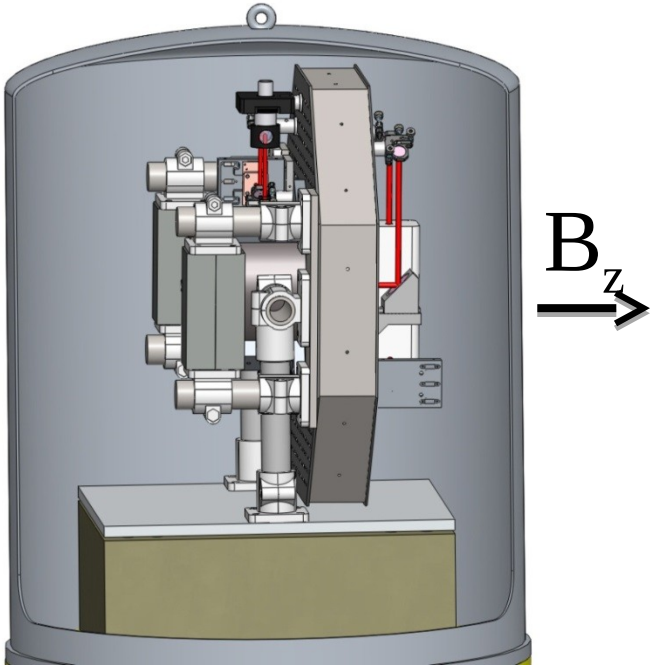


Apparatus Orientations

Dipole and quadrupole Lorentz violating coefficients are constrained by operating with the quantization axis in two orthogonal configurations

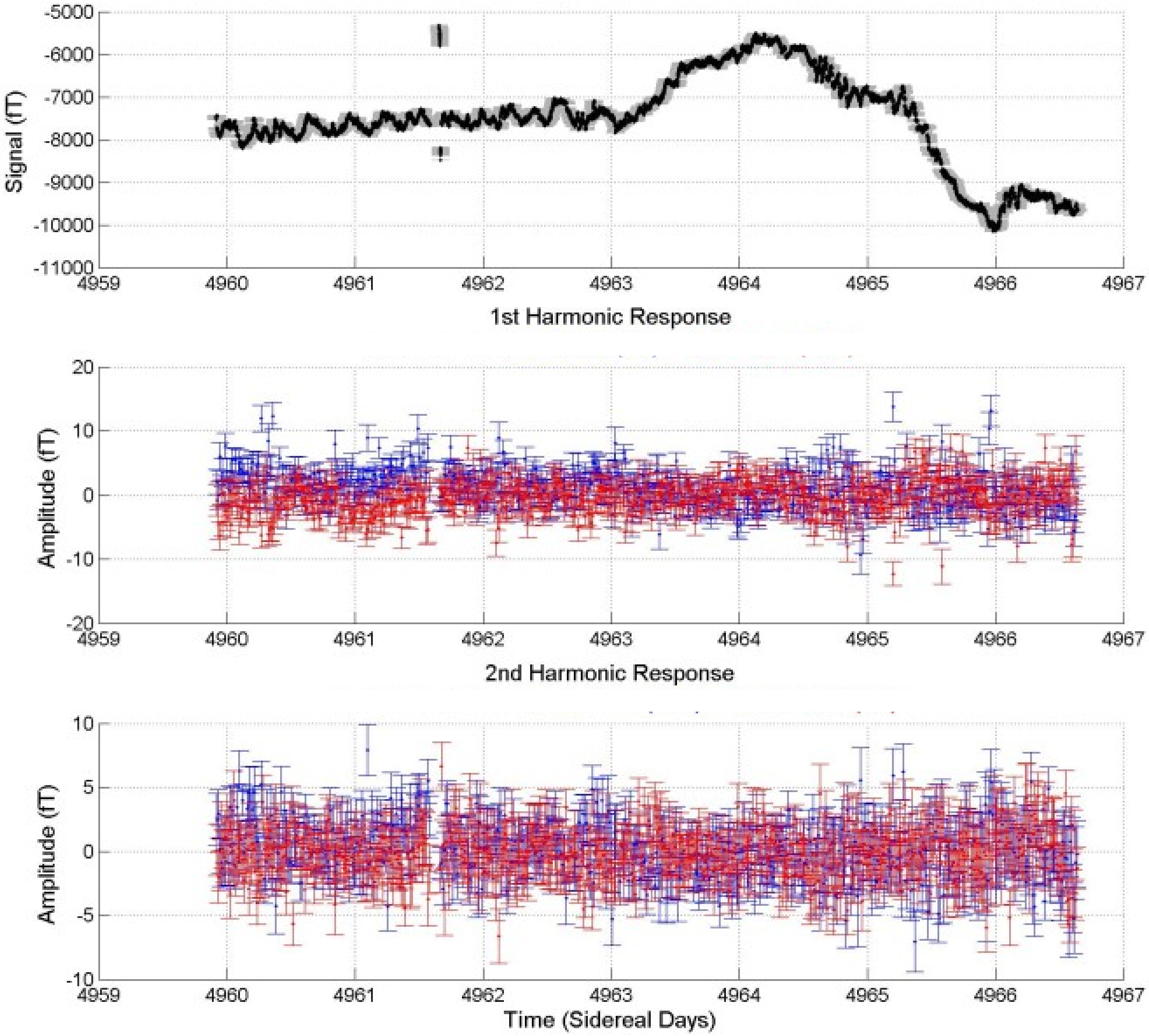


B_z Vertical
1st Harmonic: c_X, c_Y, $\tilde{b}_X$, $\tilde{b}_Y$
2nd Harmonic: none



B_z Horizontal
1st Harmonic: $\tilde{b}_X$, $\tilde{b}_Y$
2nd Harmonic: c_-, c_Z

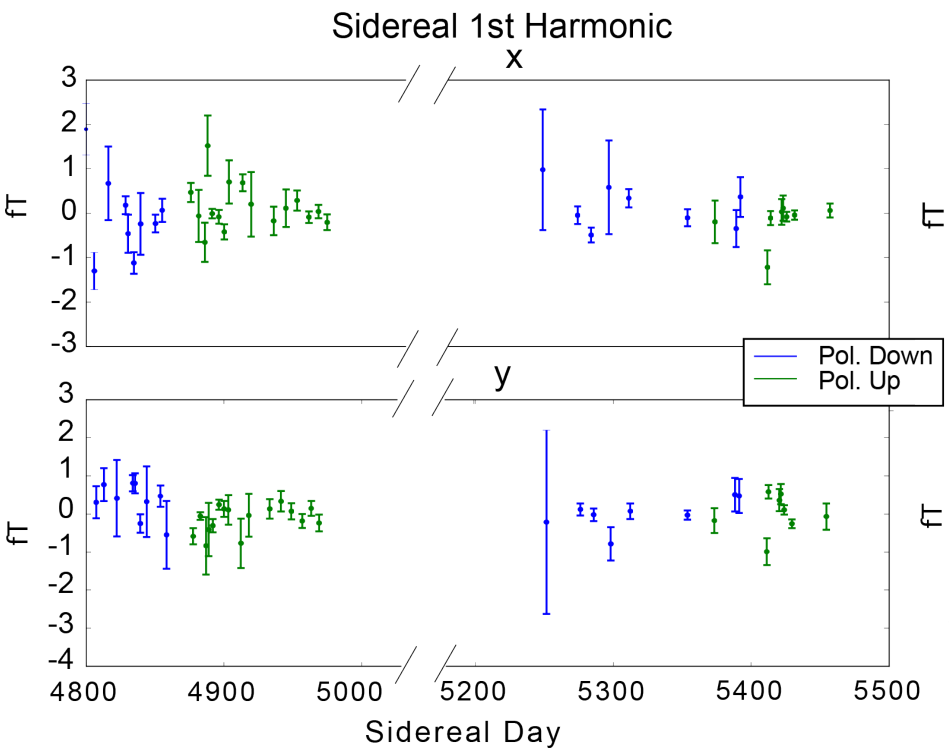
South pole data sample

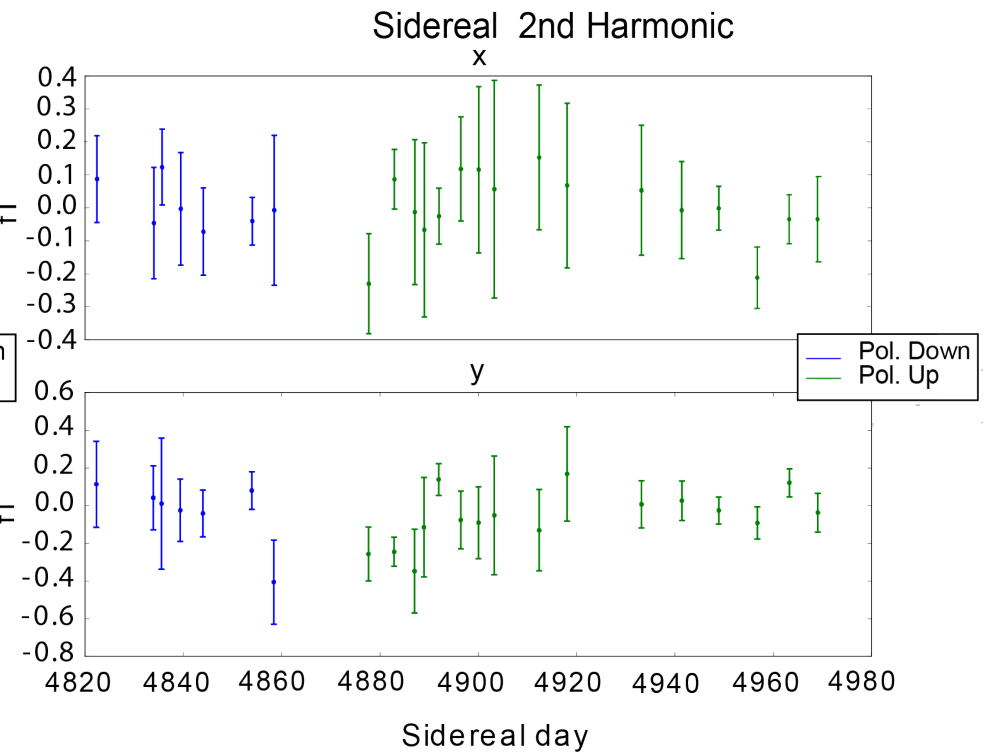


χ^2=1.7

χ^2=1.1

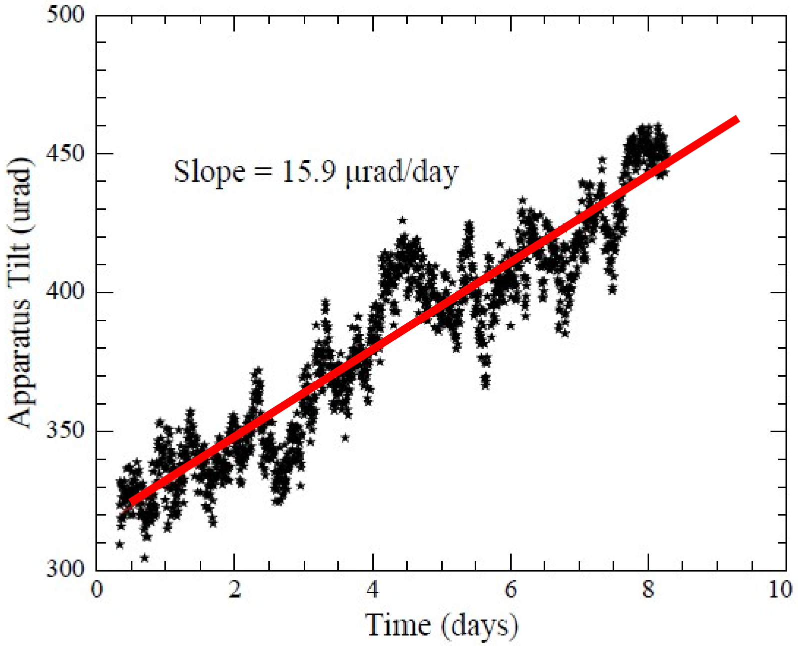
Summary of Lorentz-violation data

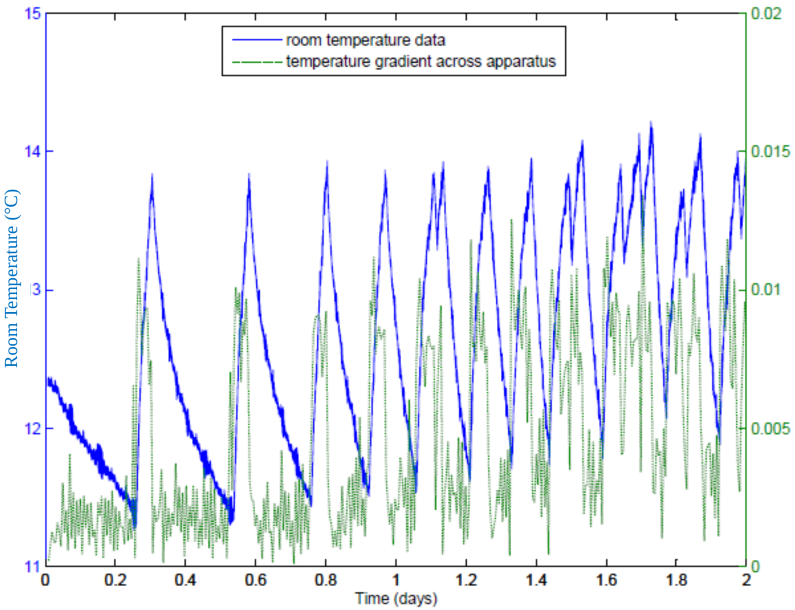




- Two years of data taking
- About 60% duty factor

Challenges at the Pole





The building's tilt on ice is slowly drifting
Requires regular automatic leveling

Aggressive temperature cycling
Temperature gradient across apparatus

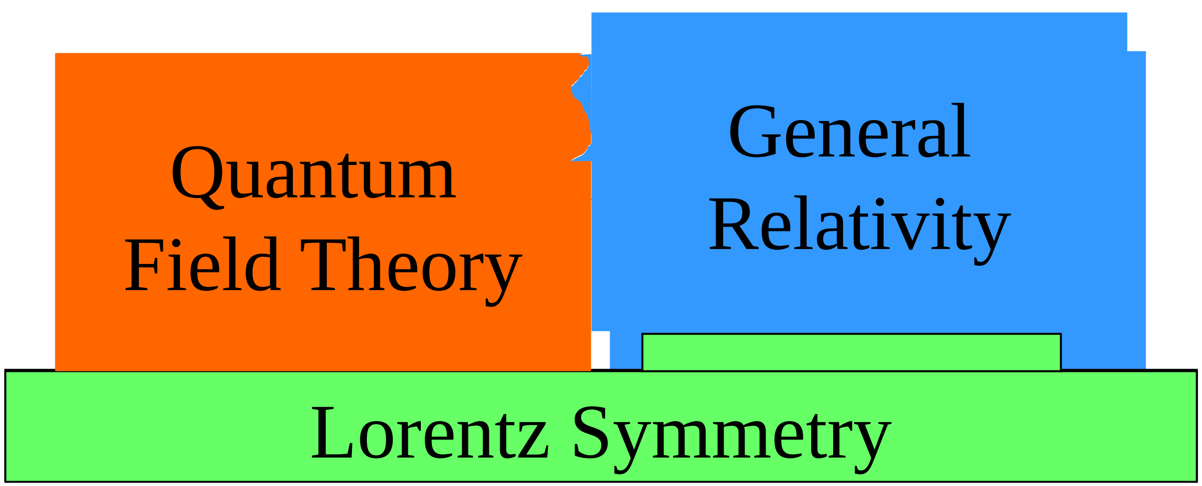
<u>Other challenges:</u>

Isolation platform damping failed, probe laser burned out, air-bearing rotation stage got stuck, etc… Need spares for everything.

First atomic physics experiment operated at the South Pole
First experiment to take advantage of geographic pole location

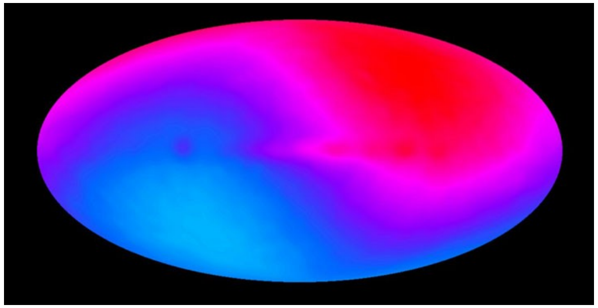
Tests of Lorentz symmetry

- Lorentz symmetry is at the foundation of two very successful but mutually incompatible theories:
  - ⇒ General Relativity
  - ⇒ Quantum Field Theory
- One approach for resolving this problem is to modify Lorentz symmetry



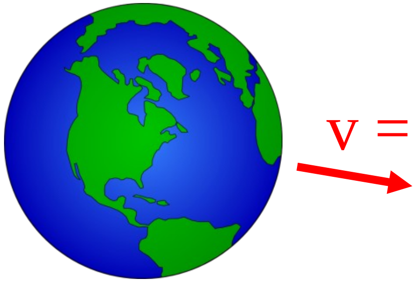
Is the space really isotropic?

- Cosmic Microwave Background Radiation Map



⇒The universe appears warmer on one side!

- Well, we are actually moving relative to CMB rest frame



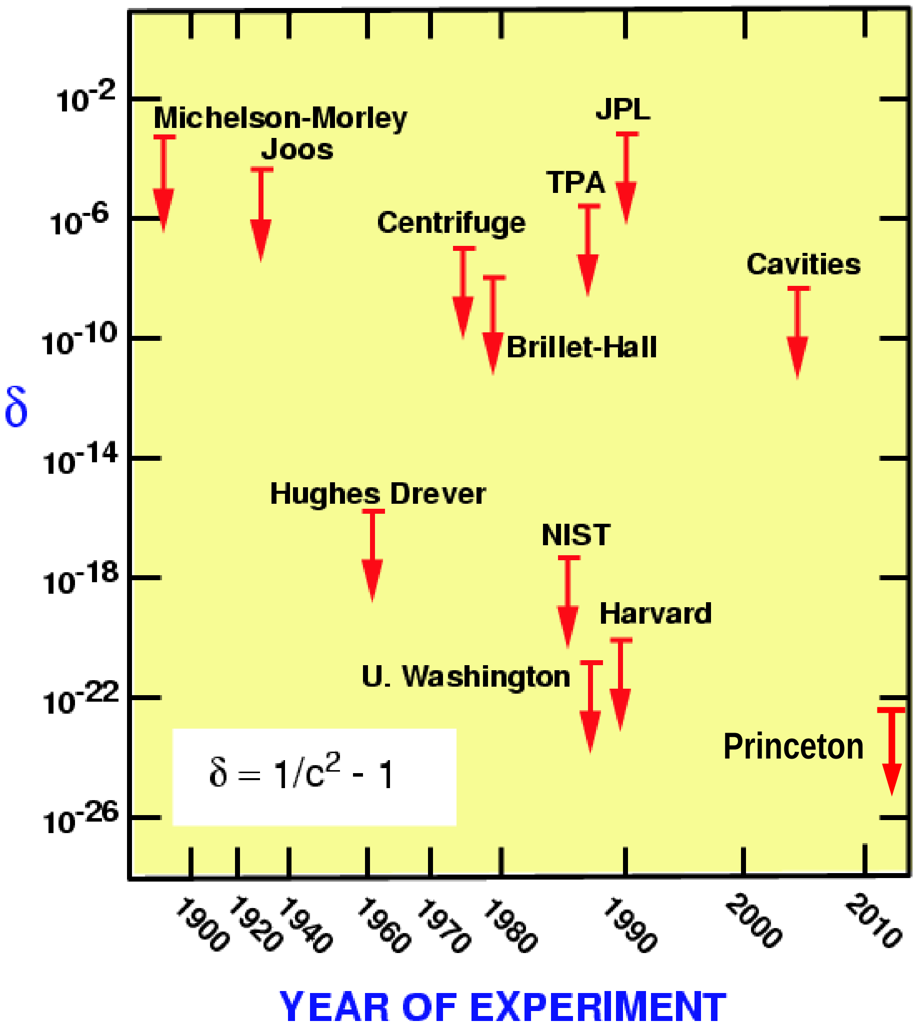
$v = 369$ km/sec $\sim 10^{-3}$ c

⇒Space and time vector components mix by Lorentz transformation

⇒A test of spatial isotropy becomes a true test of Lorentz invariance (i.e. equivalence of space and time)

Local Lorentz Invariance

- Is the speed of light (photons) rotationally invariant in our moving frame?
  - ⇒ First established by Michelson-Morley experiment as a foundation of Special Relativity
- Is the speed of "light" as it enters into particle Lorentz transformation rotationally invariant in the moving frame?
  - ⇒ Best constrained by Hughes-Drever experiments due to finite kinetic energy of nucleons



From Clifford M. Will, *Living Rev. Relativity* **9**, (2006)

Parametrization of Lorentz violation

$$L = -\bar{\Psi}(m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu)\psi + \frac{i}{2}\bar{\Psi}(\gamma_\nu + c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma_5\gamma^\mu)\overleftrightarrow{\partial}^\nu \psi$$

a,b - *CPT-odd*
c,d - *CPT-even*
Alan Kostelecky

⇒ $a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}$ are vector fields in space with non-zero expectation value

⇒ Vector and tensor analogues to the scalar Higgs vacuum expectation value

- Maximum attainable particle velocity

$$v_{MAX} = c(1 - c_{00} - c_{0j}\hat{v}_j - c_{jk}\hat{v}_j\hat{v}_k)$$

⇒ Implications for ultra-high energy cosmic rays, Cherenkov radiation, etc

⇒ Many laboratory limits (optical cavities, cold atoms, etc)

- Something special needs to happen when particle momentum reaches Planck scale

⇒ Doubly-special relativity

⇒ Horava-Lifshitz gravity

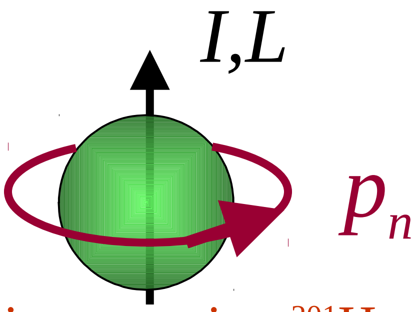
⇒ Your favorite recent theory

Search for CPT-even Lorentz violation with nuclear spin

- Need nuclei with orbital angular momentum and total spin >1/2
- Quadrupole energy shift due to angular momentum of the valence nucleon:

$$E_Q \sim (c_{11} + c_{22} - 2c_{33})\left\langle p_x^2 + p_y^2 - 2p_z^2 \right\rangle$$

$$p_x^2 + p_y^2 - 2p_z^2 > 0$$



- Previously has been searched for in experiments using ^{201}Hg and ^{21}Ne with sensitivity of about 0.5 μHz

Sidereal Variation — Semi-sidereal Variation

$$\Delta E(t) = E_0 + E_{1X}\cos\Omega t + E_{1Y}\sin\Omega t + E_{2X}\cos 2\Omega t + E_{2Y}\sin 2\Omega t$$

$$c_{\mu\nu} = \begin{pmatrix} c_{TT} & c_{TX} & c_{TY} & c_{TZ} \\ c_{XT} & c_{XX} & c_{XY} & c_{XZ} \\ c_{YT} & c_{YX} & c_{YY} & c_{YZ} \\ c_{ZT} & c_{ZX} & c_{ZY} & c_{ZZ} \end{pmatrix}$$

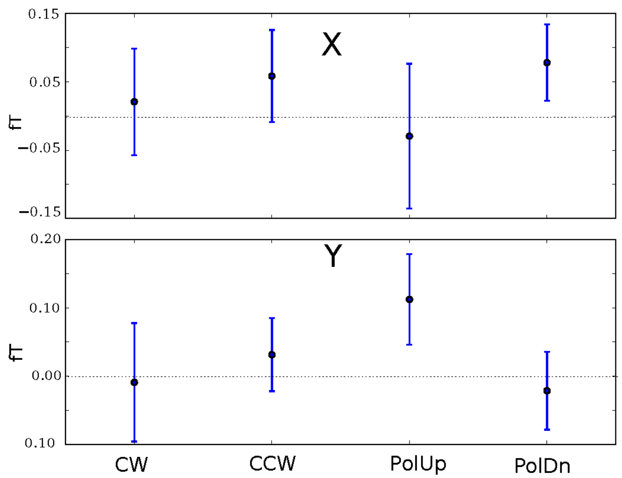
} 2nd Harmonic

} 1st Harmonic

Suppressed by v_{Earth}

Preliminary Results

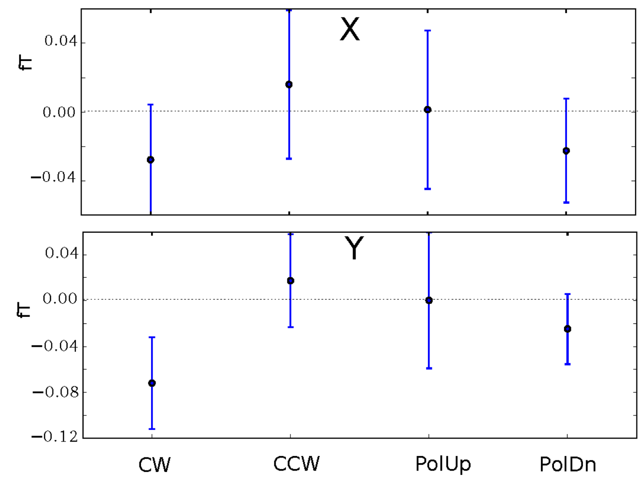
Subsets, 1st Harmonic



1H:

X	-58 ± 51 aT
Y	19 ± 46 aT

Subsets, 2nd Harmonic

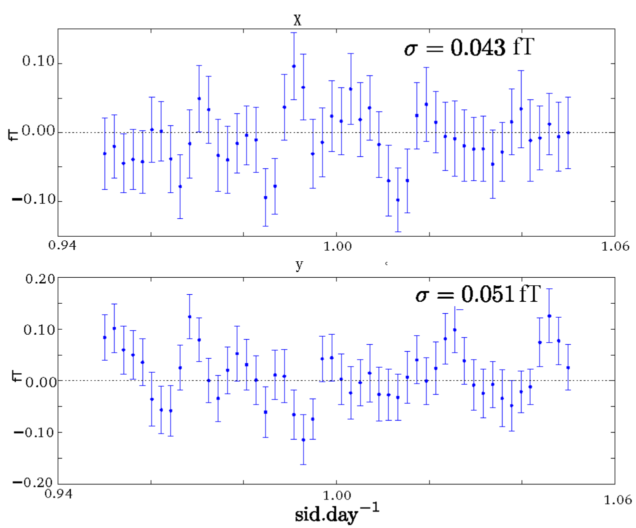


2H:

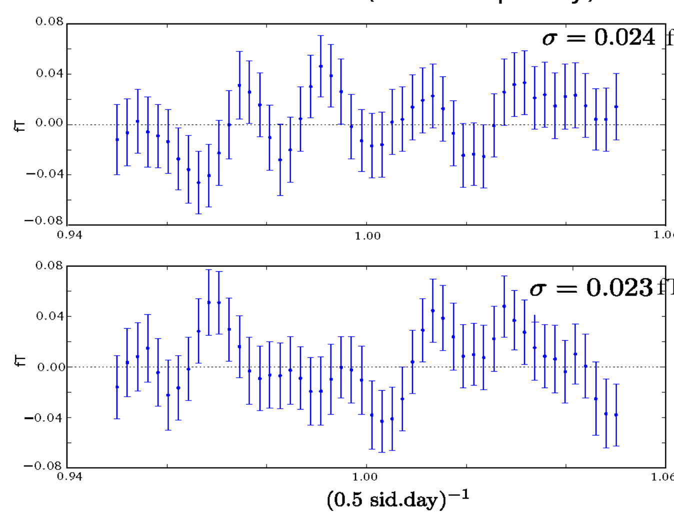
X	-15 ± 25 aT
Y	-25 ± 27 aT

Vary frequency of the fit around sidereal period to independently estimate errors

1H (fit frequency)



2nd Harmonic (vs fit frequency)



Constrains on SME coefficients

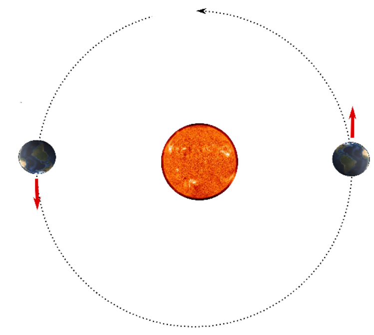
Spatial

SME coeff	$\bar{x}$	σ	units	Improve
$c^n_{yz}+c^n_{zy}$	2.6	4.5	x 10^{-30}	x 10 [1]
$c^n_{xz}+c^n_{zx}$	2.2	4.8	x 10^{-30}	x 10 [1]
$c^n_{xy}+c^n_{yx}$	-1.9	3.1	x 10^{-30}	x 3 [1]
$c^n_{xx}-c^n_{yy}$	3.0	2.9	x 10^{-30}	x 3 [1]
$\tilde{b}_x$	-1.0	1.5	x 10^{-33} GeV	x 1 [2]
$\tilde{b}_y$	0.5	1.6	x 10^{-33} GeV	x 1 [2]

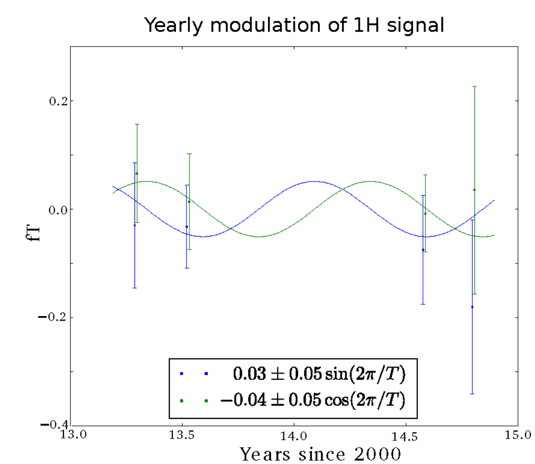
Boost (suppressed by V_{earth}/c)

coeff	$\bar{x}$	σ	units	Improve
$c^n_{tx}+c^n_{xt}$	0.1	3.0	x 10^{-26}	-
$c^n_{ty}+c^n_{yt}$	0.4	3.2	x 10^{-26}	-
$c^n_{tz}+c^n_{zt}$	-2.9	4.9	x 10^{-26}	-
$\tilde{b}_t$	-0.25	1.6	x 10^{-29} GeV	x 50 [3]

Boost



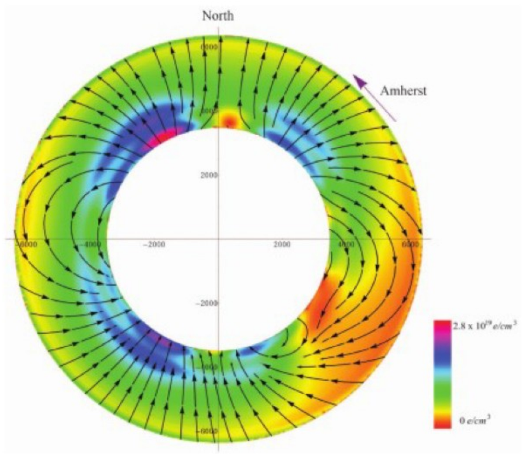
Look for yearly modulation of correlation signal. Suppressed by v_{earth}/c

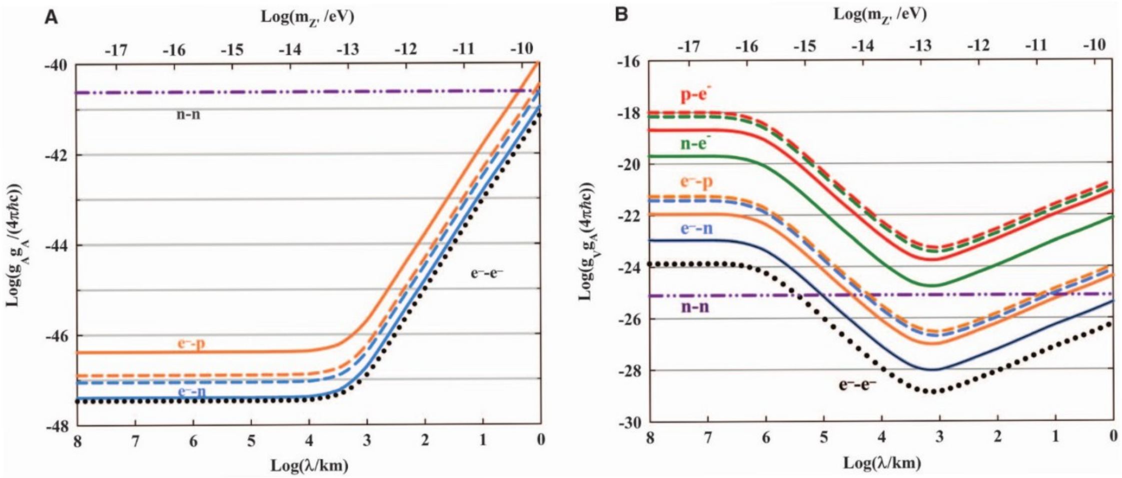


[1] Smiciklas et al., PRL. 107, 171604 (2011)
[2] Brown et al. PRL 105, 151604 (2010)
[3] Cane et. al. PRL 93, 230801 (2004)

Long-range spin-spin interactions with Geo-electrons

Earth spin-density map





Cause a static lab-frame interaction
No Earth's rotation background at South Pole

Larry Hunter et al, Science **339**, 928 (2013)

	$\bar{x}$	σ	units	Imprv.
$\frac{g_A^e g_A^n}{4\pi\hbar c}$	-1.2	0.7	x 10^{-49}	x 30 [1]
$\frac{g_V g_A^n}{4\pi\hbar c}$	-5	-2.8	X 10^{-25}	X 20 [1]

Interactions that scale as 1/r or 1/r^2
- Vector bosons mediated,
- Unparticles

Slowly-modulated signals: light axions, dark photons

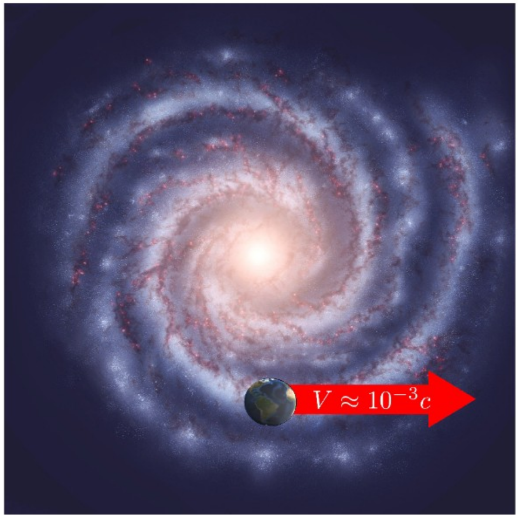
Look for modulation of the sidereal frame signal, i.e. amplitude modulation of the correlation signal

$$\delta E = A \sin(\omega t)\ \left(\cos(\omega_{sd} t)\hat{\mathbf{X}} + \sin(\omega_{sd} t)\hat{\mathbf{Y}}\right)$$

For e.g. axion-wind:

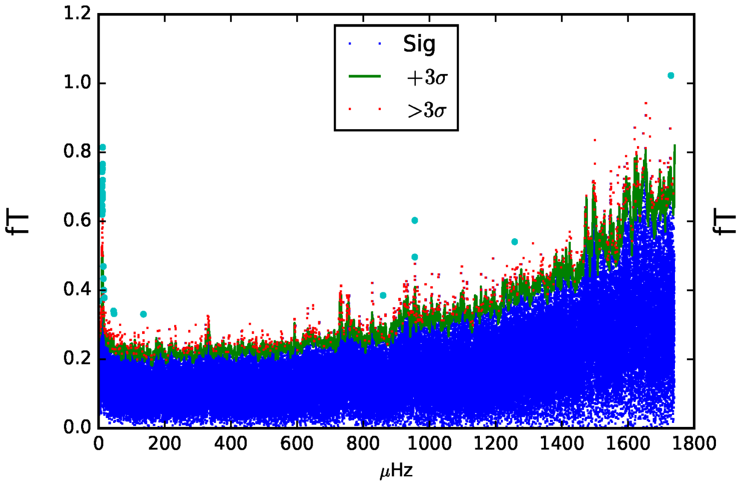
$$\omega = m_a c^2 / \hbar$$

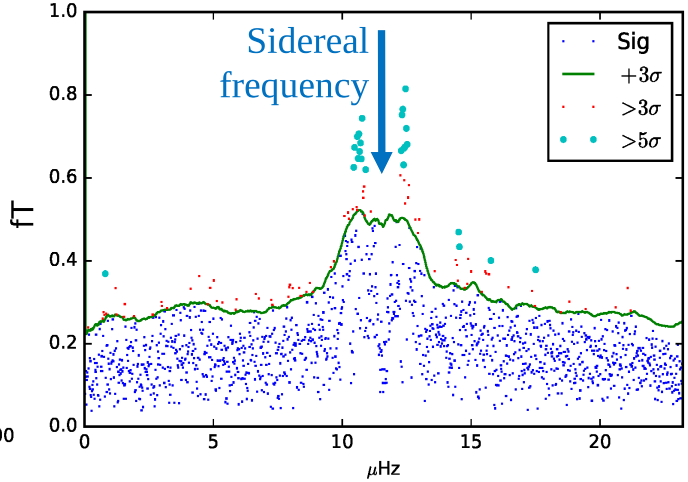
$$A = \frac{(C_N a_0)}{(2 f_a)} (p_a \cdot \sigma_N)$$



Careful:
Look-elsewhere effects
Interference with sidereal frequency giving rise to slow drifts

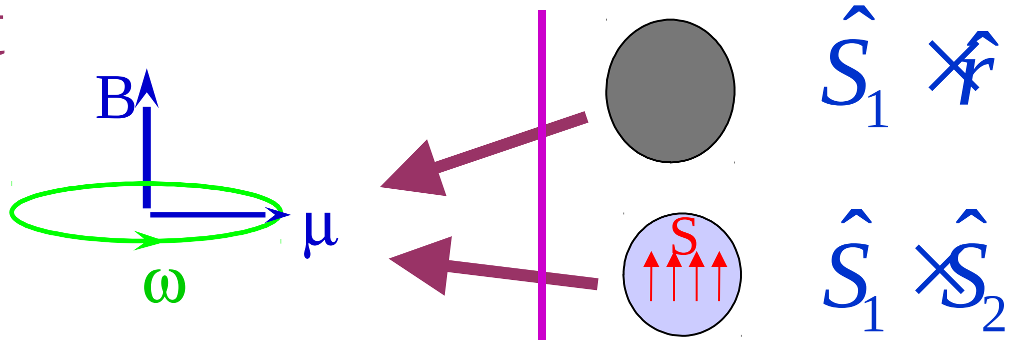
General sensitivity to δE on the order of 10^{-32} GeV in the frequency range 0.1-1500 μHz



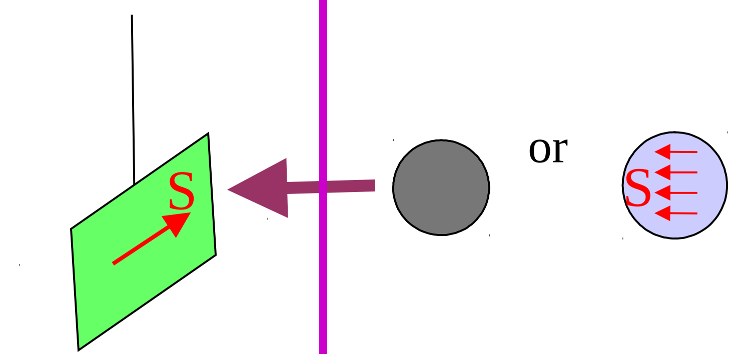


Searches for spin-dependent forces

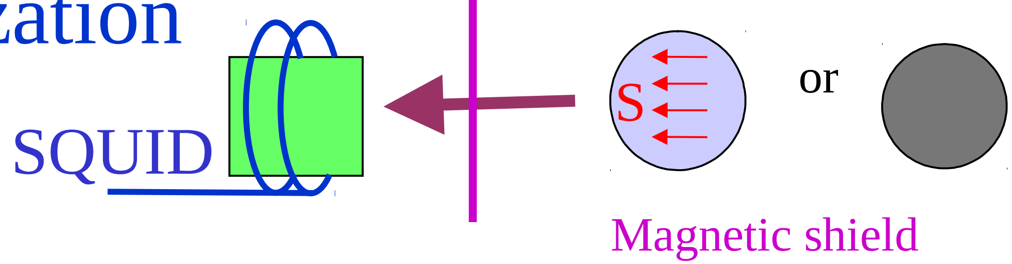
- Frequency shift



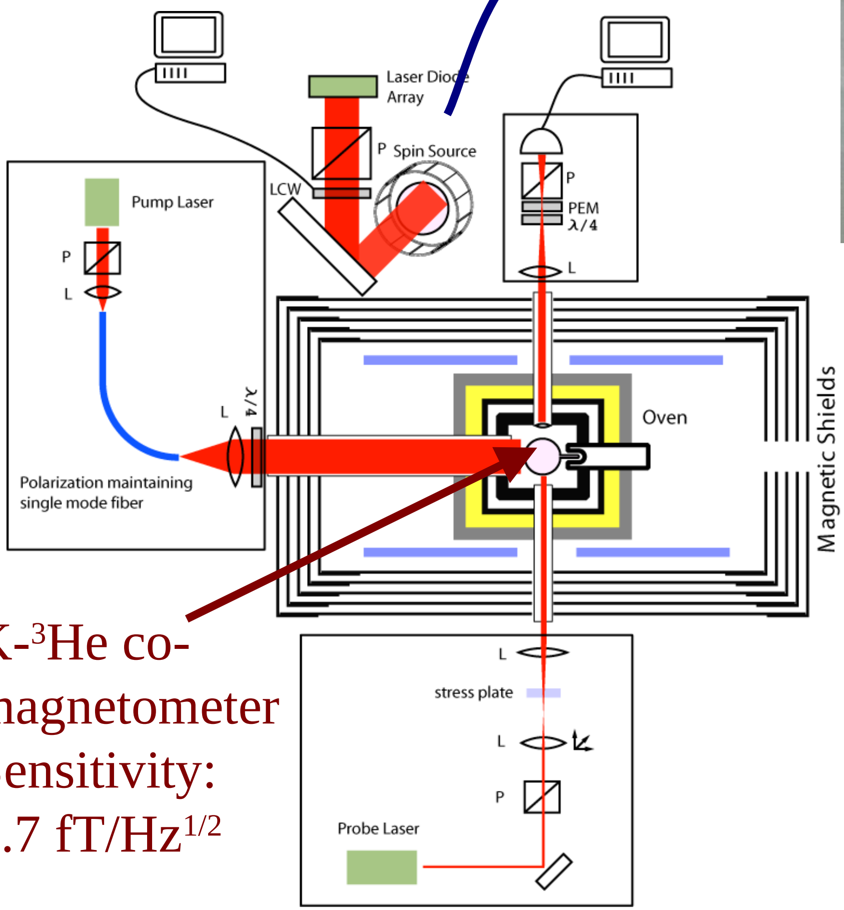
- Acceleration

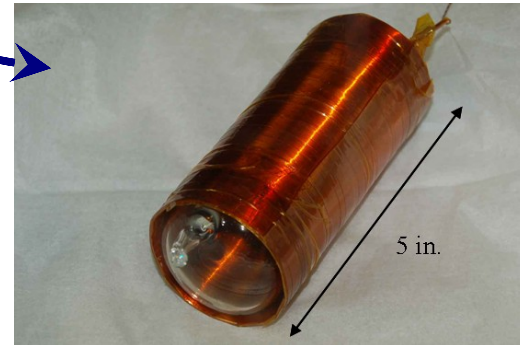


- Induced magnetization



Search for nuclear spin-dependent forces

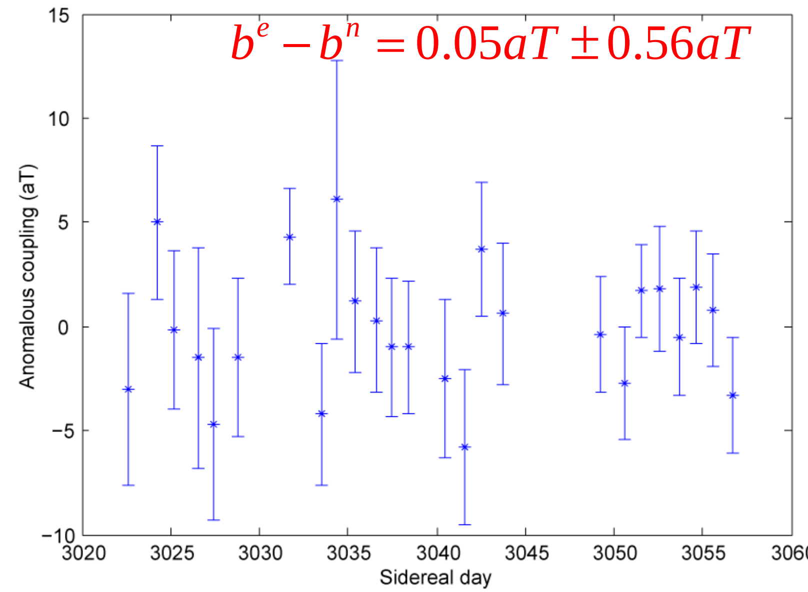




Spin Source:

10^{22} ^{3}He spins at 20 atm.

Spin direction reversed every 3 sec with Adiabatic Fast Passage



K-^{3}He co-magnetometer

Sensitivity: 0.7 fT/Hz$^{1/2}$

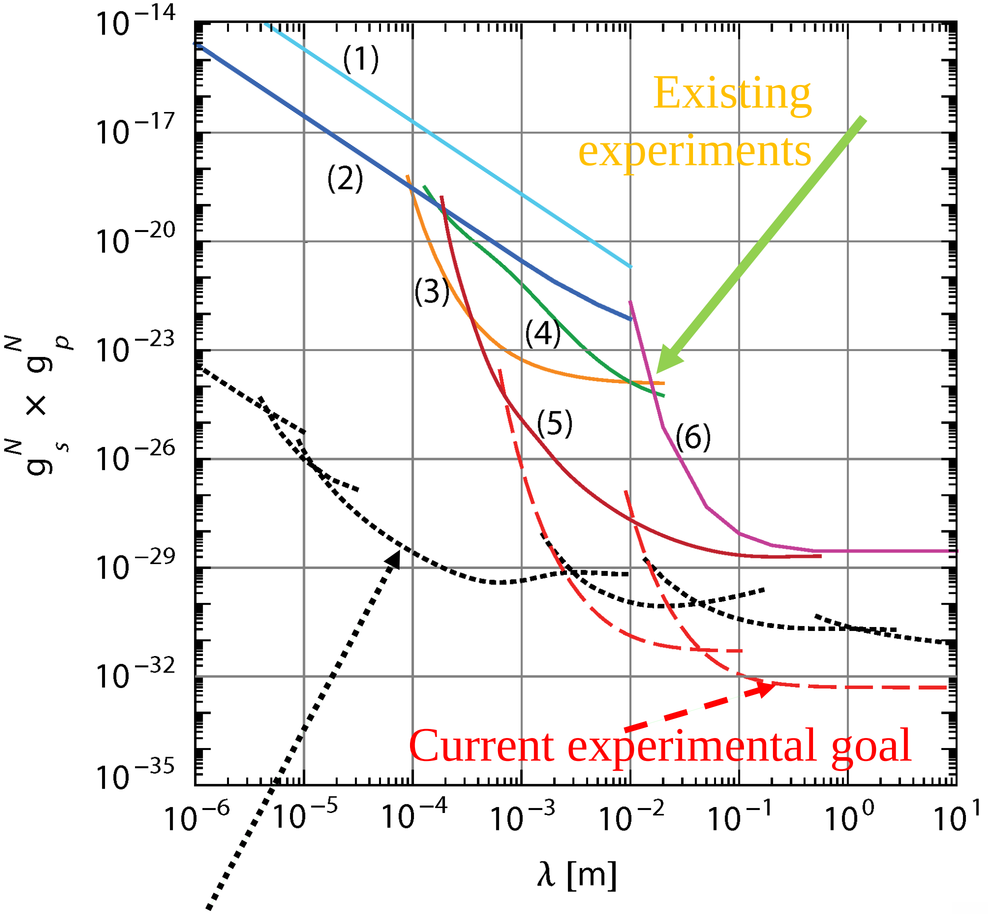
G. Vasilakis, J. M. Brown, T. W. Kornack, MVR, Phys. Rev. Lett. **103**, 261801 (2009)

Uncertainty (1σ) = 18 pHz or $4.3\cdot10^{-35}$ GeV ^{3}He energy after 1 month

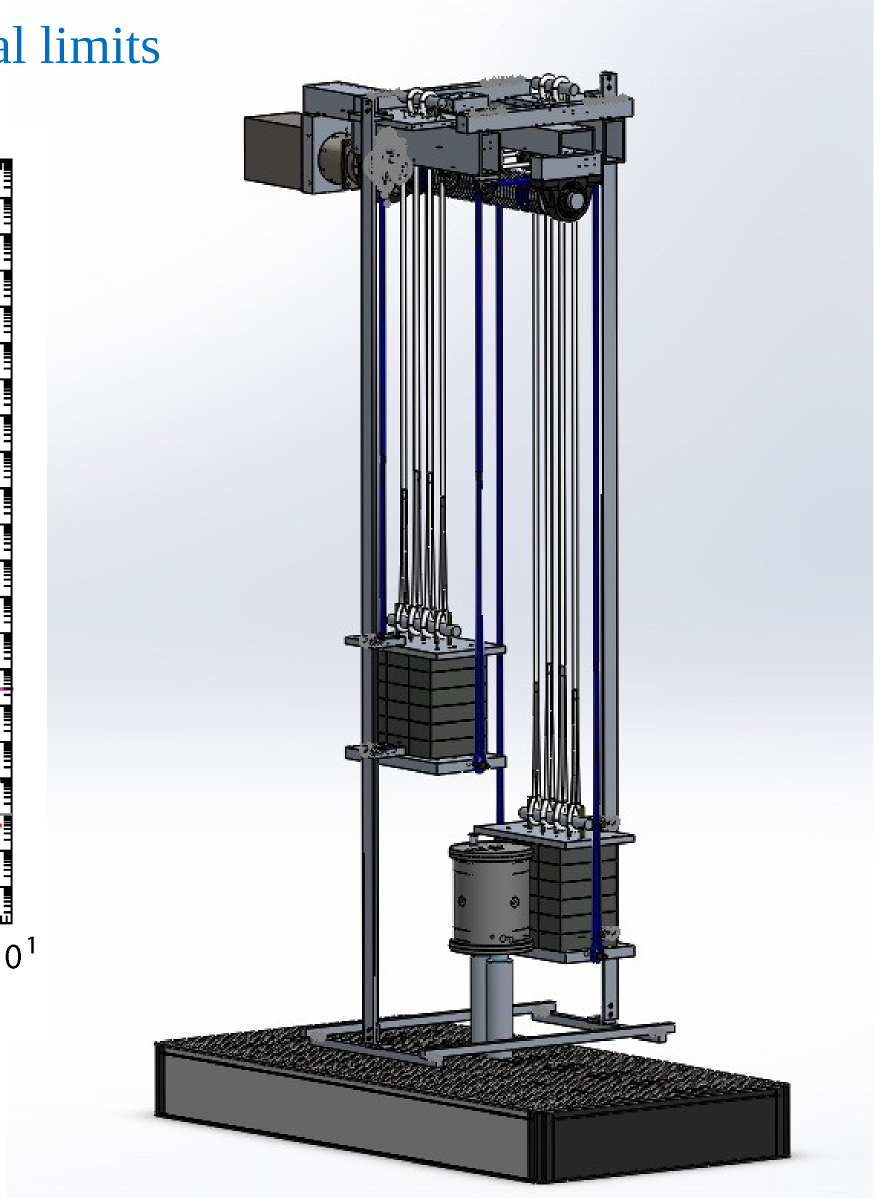
Smallest energy shift ever measured

Spin-mass searches with co-magnetometer

- Will be more sensitive than astrophysical limits



Astrophysical × gravitational limits from G. Raffelt
Phys. Rev. D **86**, 015001 (2012)



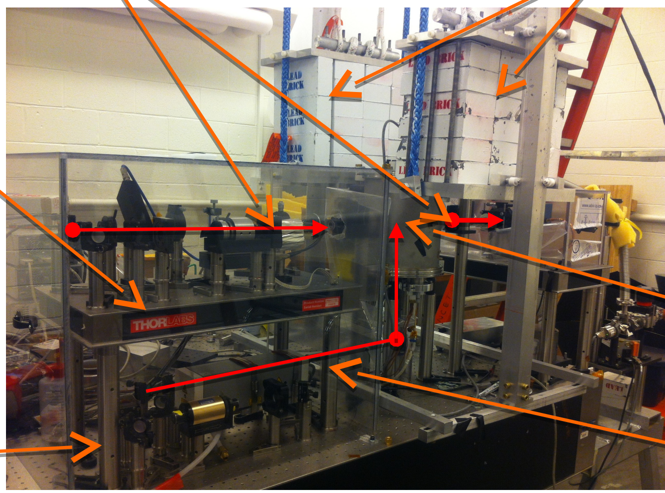
Movable mass constructed and tested

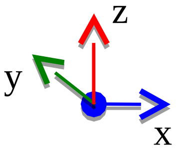
Probe beam

Pb Masses (~ 210 kg each)

Probe Beam Optics

Pump Beam Optics

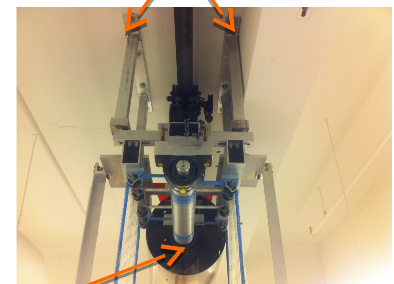




Glass cell (within vacuum chamber)

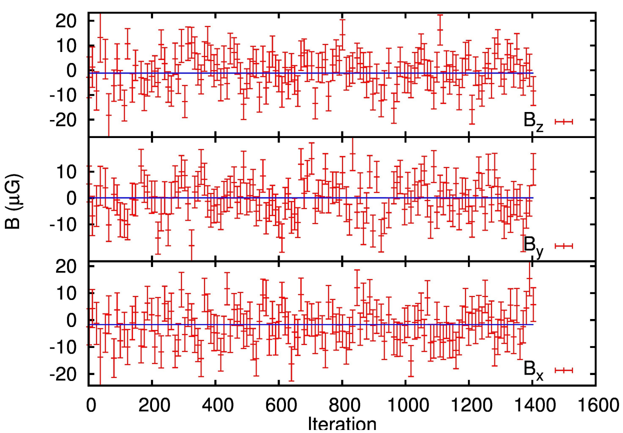
Pump beam

Apparatus is suspended from ceiling to reduce mechanical coupling to optical table

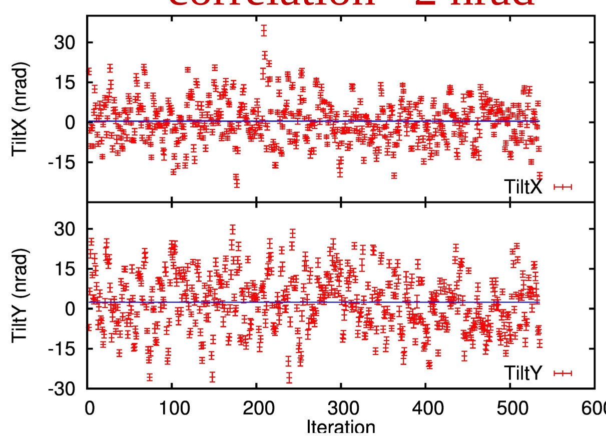


A Yaskawa 4kW servo motor smoothly raise/lower the two 210 kg Pb weights through a distance of 0.5m in 1s.

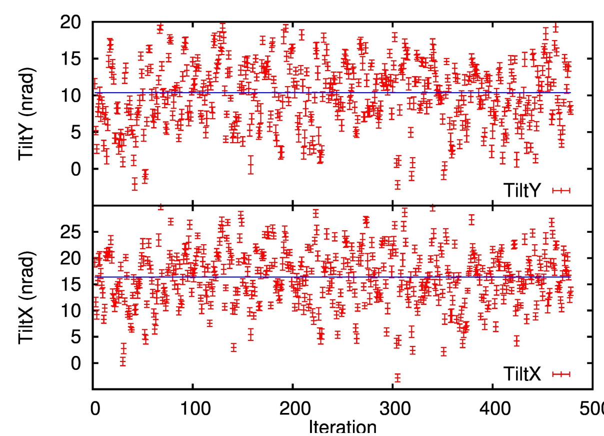
Magnetic correlation ~ 2 μG



Optical table tilt correlation ~2 nrad

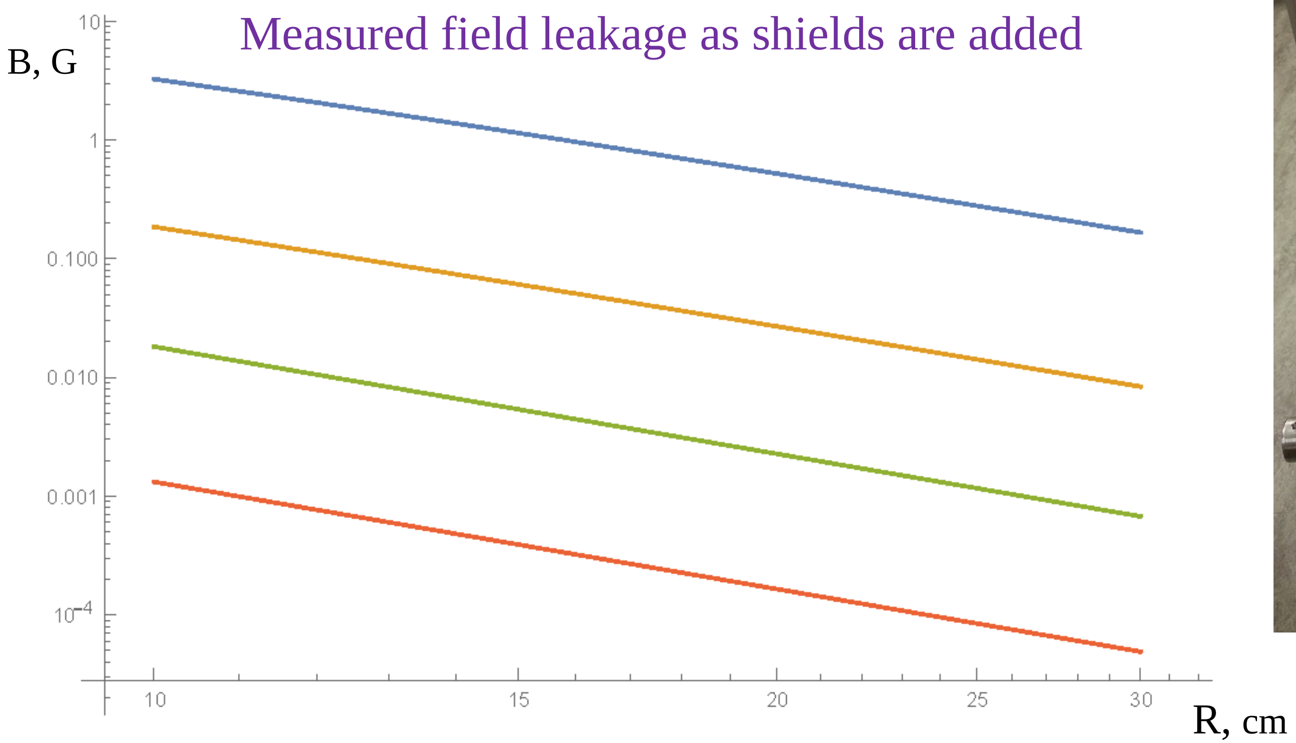


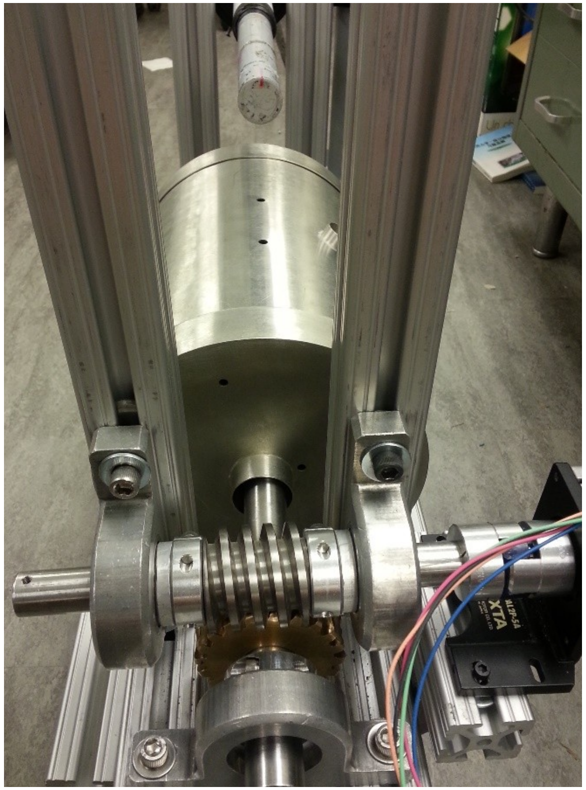
Gravitational effect on Tiltmeter 19.4 ± 0.5 nrad



Spin-spin long-range force

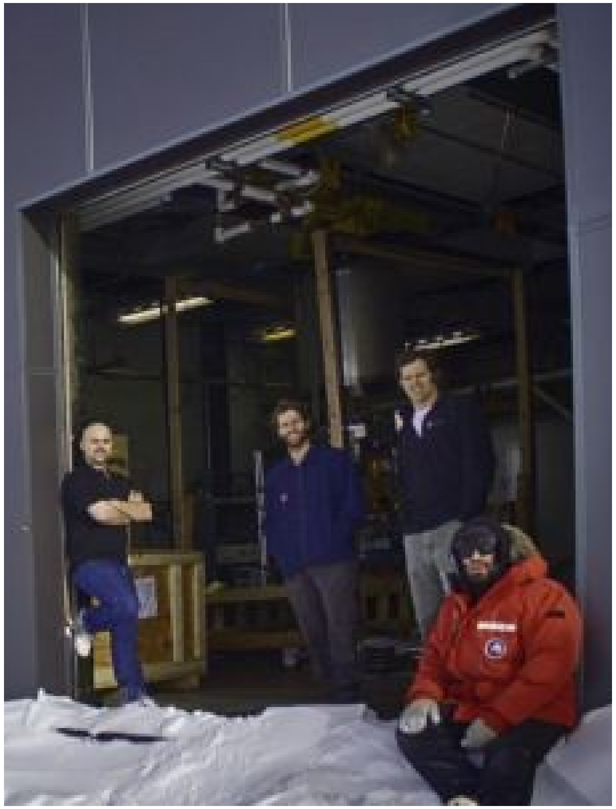
- Use a permanent magnet spin source with 10^{24} polarized electrons (Eöt-Wash approach)
- Use co-magnetometer as spin sensor
- Limits both e-e and e-n interactions
- Expect $g_p \sim 10^{-9}$, better than current laboratory limits but not quite reaching astrophysics limits
- Currently testing magnetic field leakage with 3 shields





Conclusions

- Atomic co-magnetometers set the most stringent limits on both CPT-odd and CPT-even Lorentz –violation coefficients
- Set limits on spin-dependent forces at 20 pHz level, the most sensitive energy shift measurements
- Can place limits on oscillating spin couplings in the μHz-Hz range
- Search for spin-mass coupling under way, should exceed astrophysical limits.



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