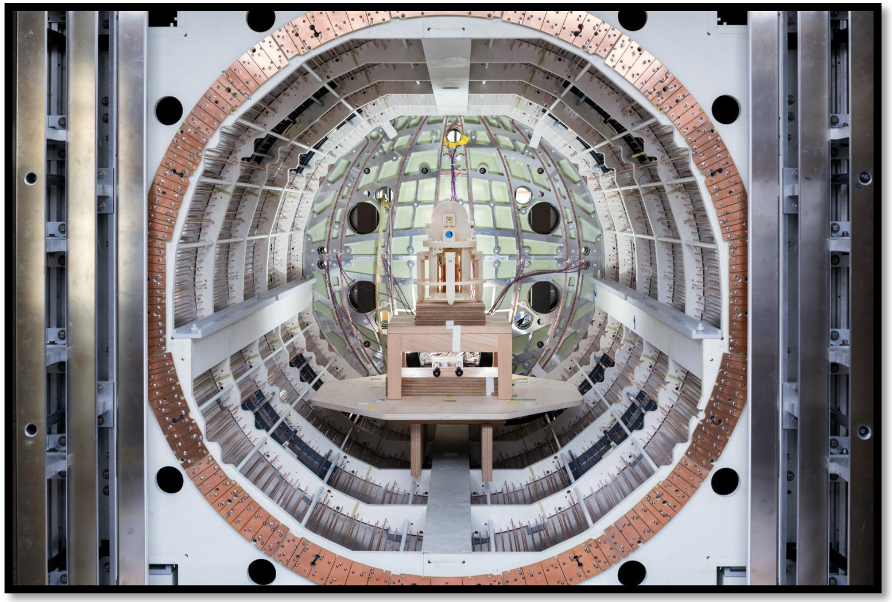
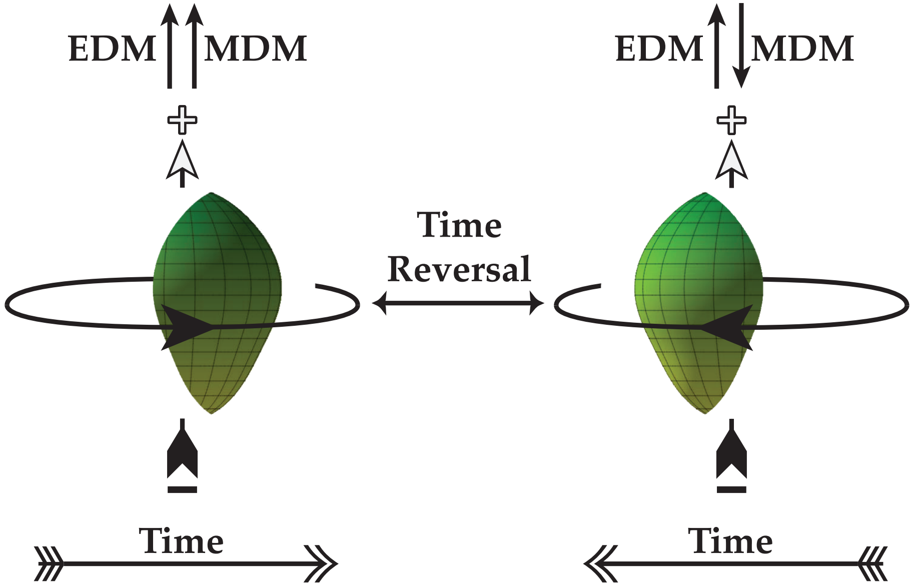
Testing Time-Reversal Symmetry Using Lasers, a Magic Room, and Pear-Shaped Nuclei

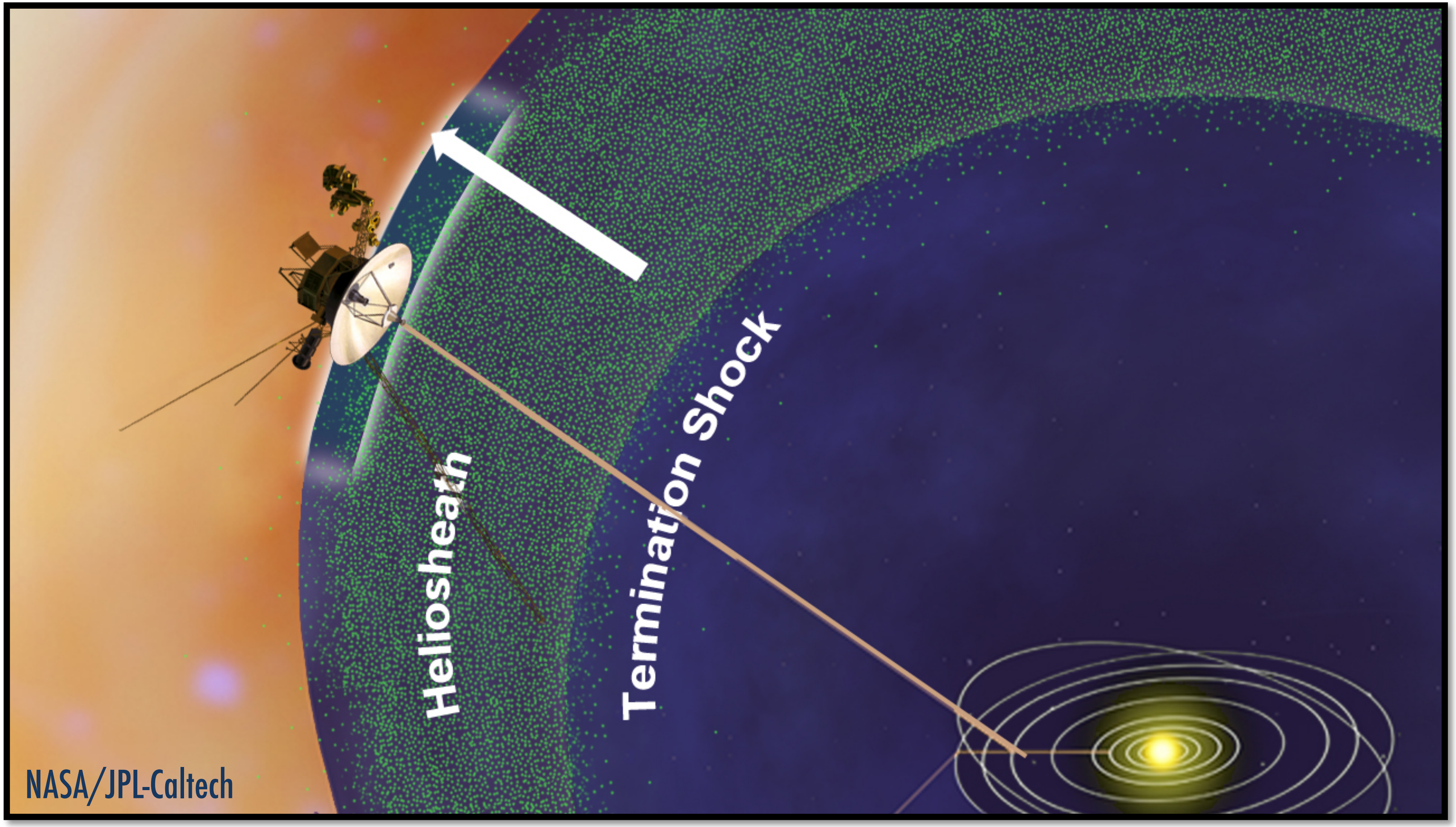




Jaideep Taggart Singh
National Superconducting Cyclotron Lab
Michigan State University

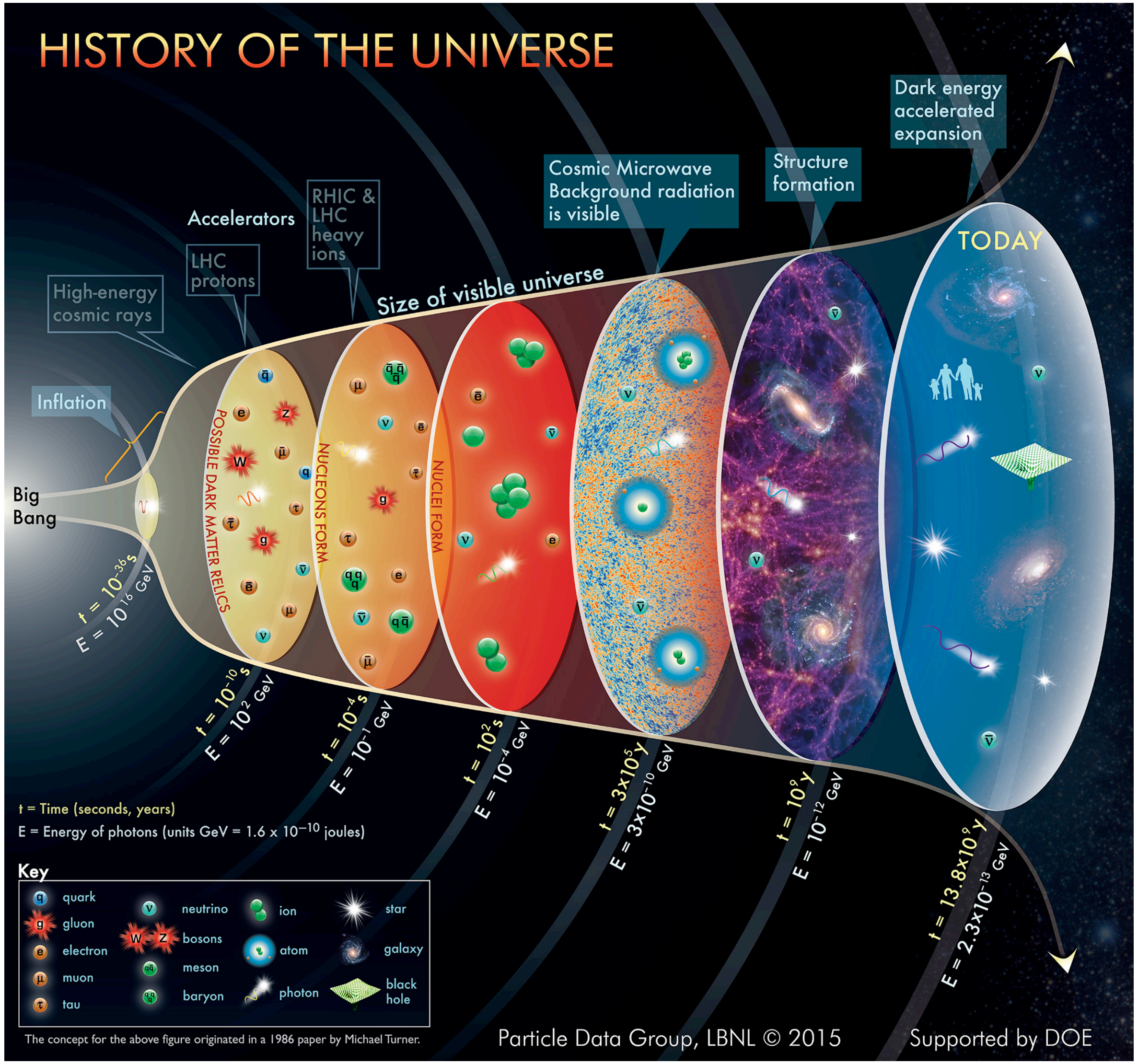
University of Toronto, Physics Colloquium, 2016-01-28

Voyager 1 is still OK!



Early History of the Universe

HOT &
DENSE



The concept for the above figure originated in a 1986 paper by Michael Turner.

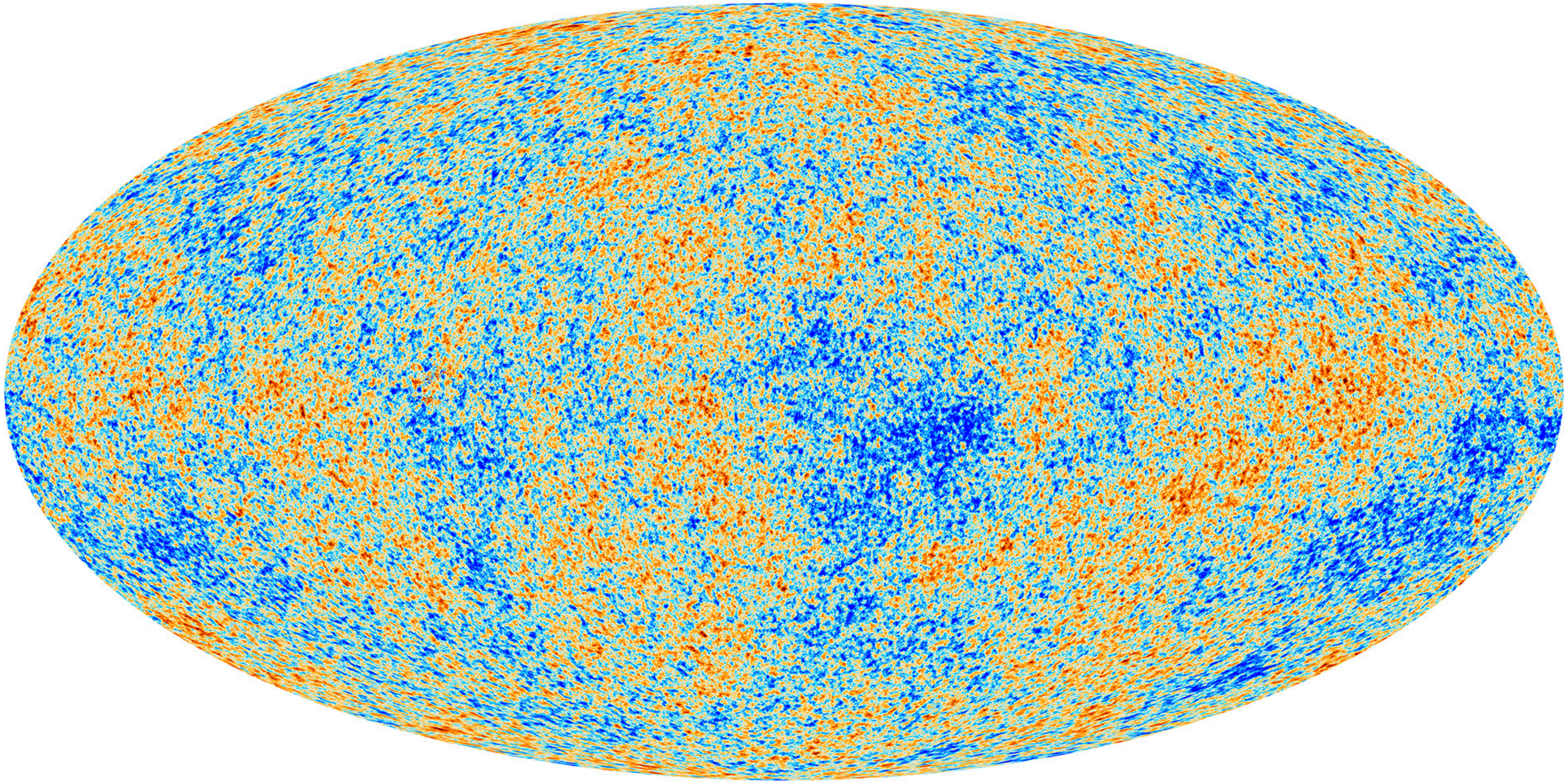
Particle Data Group, LBNL © 2015

Supported by DOE

cold &
dilute

http://www.particleadventure.org/history-universe.html

Cosmic Microwave Background Radiation

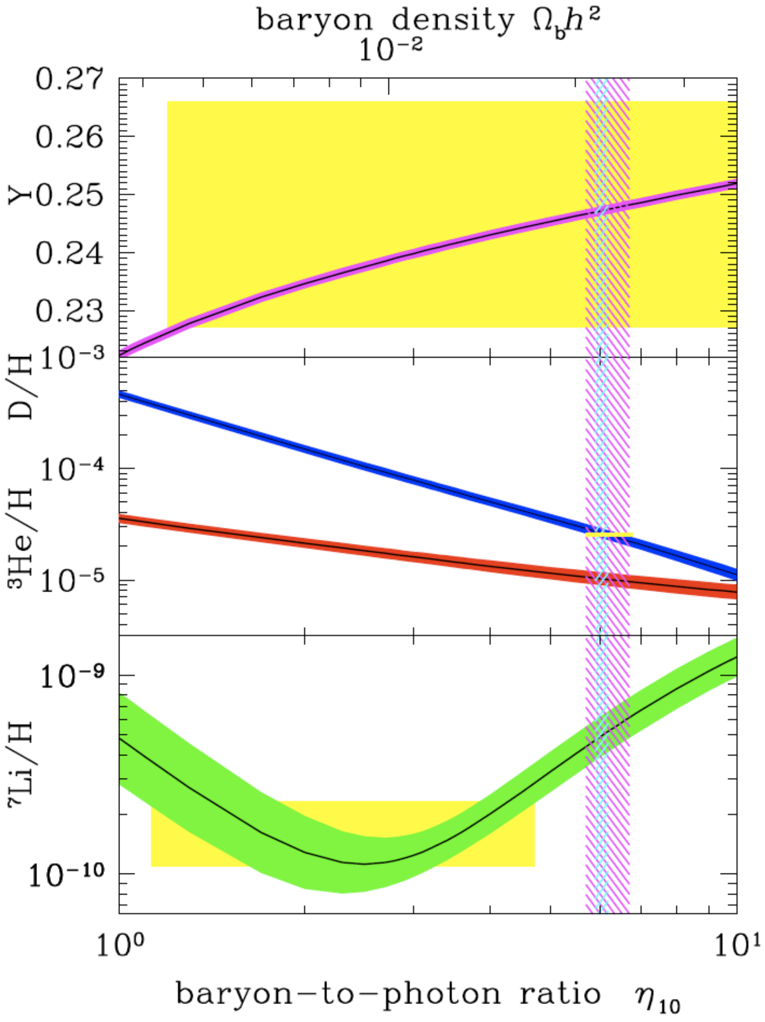


Planck 2013
http://www.esa.int/spaceinimages/Images/2013/03/Planck_CMB

Baryon Asymmetry of Universe

$$\frac{\text{(matter)} - \text{(antimatter)}}{\text{photons}}$$

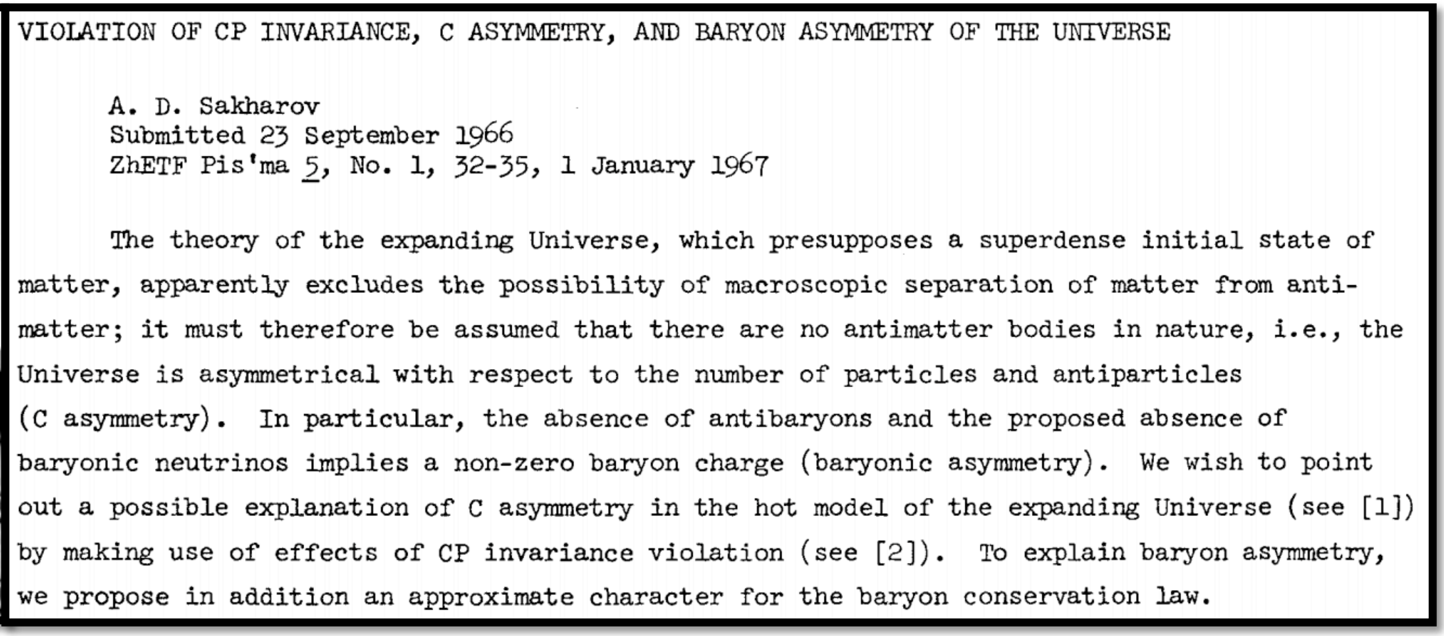
$$\begin{aligned}\eta_{10} &= (n_B - n_{\bar{B}})\frac{10^{10}}{n_\gamma} \\ &\approx 6.1 \pm 0.3 \\ &\gg 0\end{aligned}$$



PDG2014

Sakharov's Conditions

The Nobel Foundation



VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

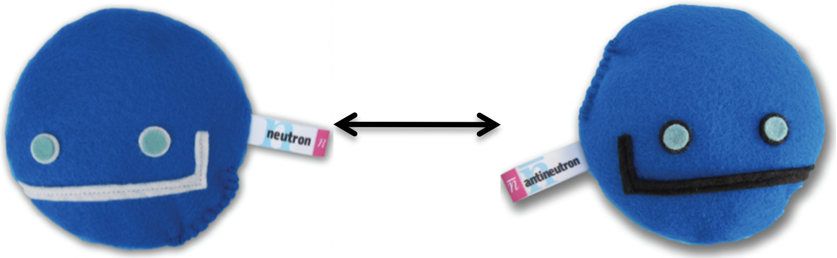
A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

1. A baryon number violating interaction exists.
2. Both *C*- & *CP*-symmetry must be violated.
3. Departure from thermal equilbrium

Discrete Transformations

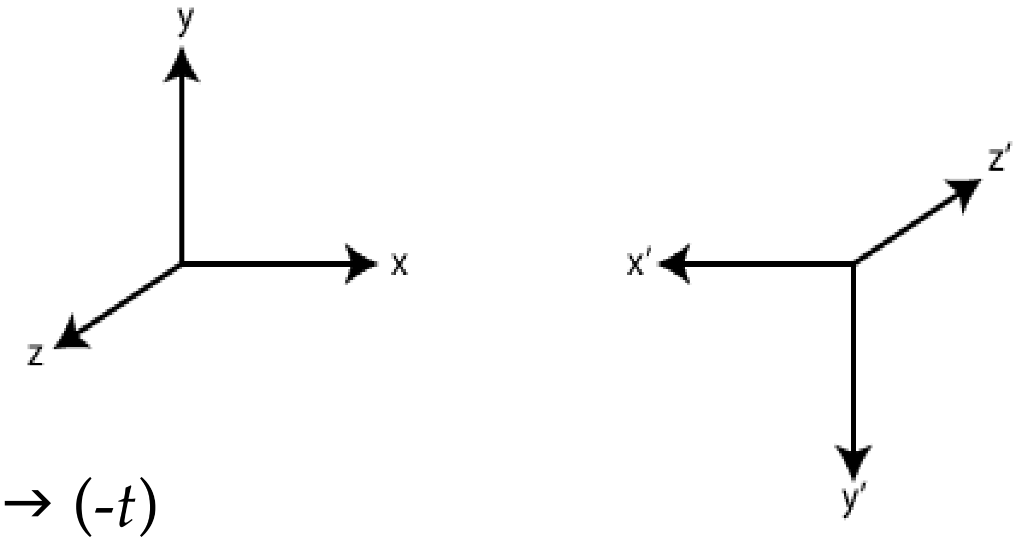
- C (charge): replace particle with antiparticle



http://www.particlezoo.net/

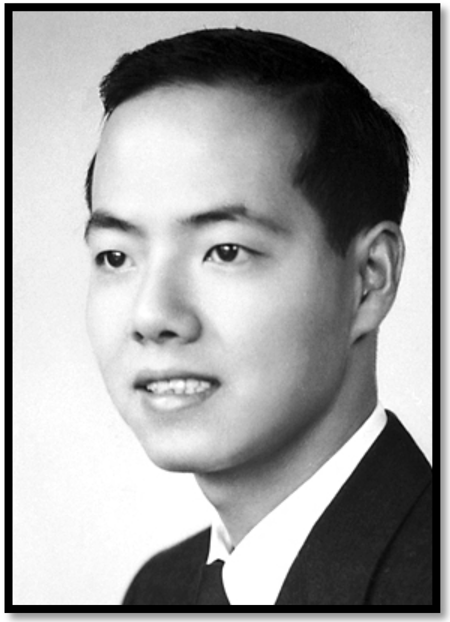
- P (parity): $(+x,+y,+z) \rightarrow (-x,-y,-z)$ mirror image + 180° rotation

http://www.quantumdiaries.org/2009/09/28/
symmetry-in-physics-pt-2-discrete
-symmetries-and-antimatter/

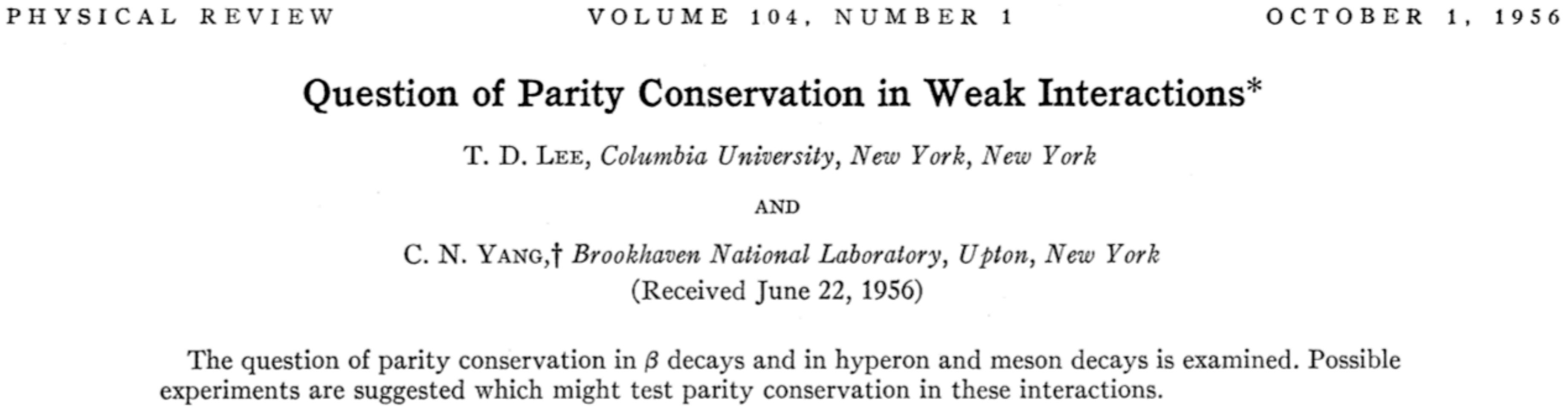


- T (time reversal): $(+t) \rightarrow (-t)$

1956: Is Parity conserved?


The Nobel Foundation


The Nobel Foundation


PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

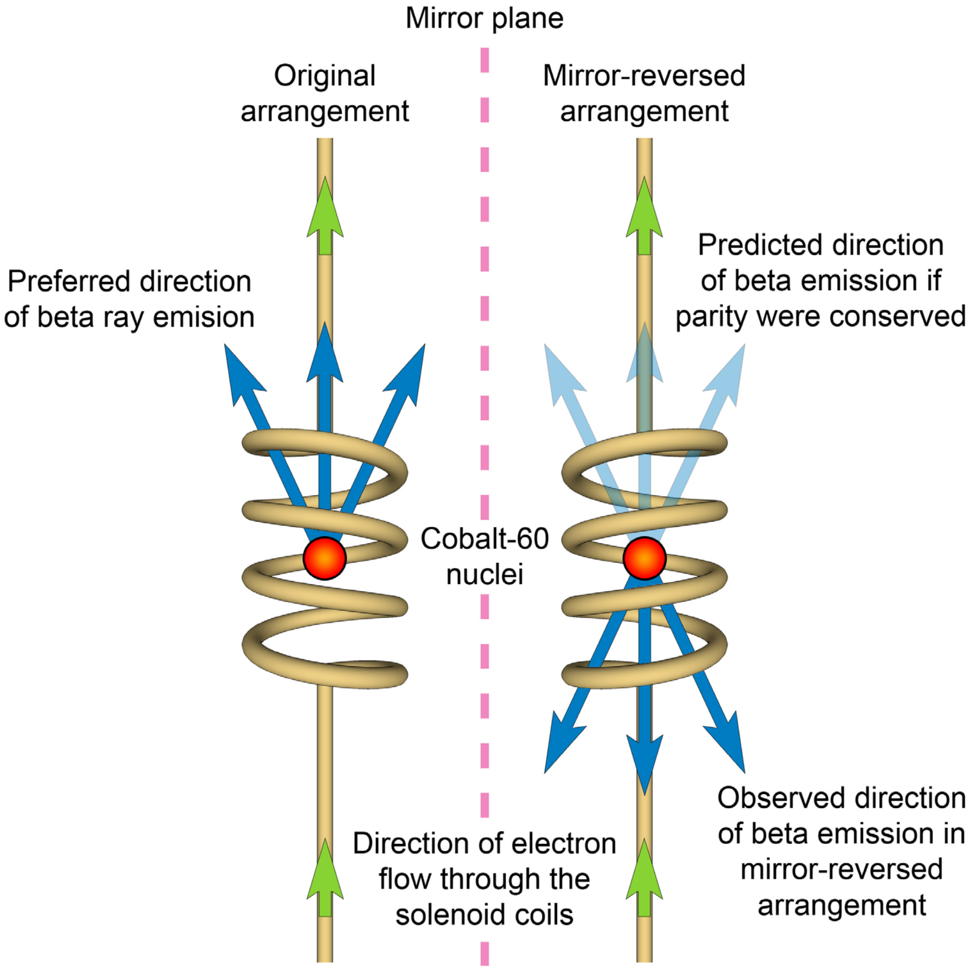
C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

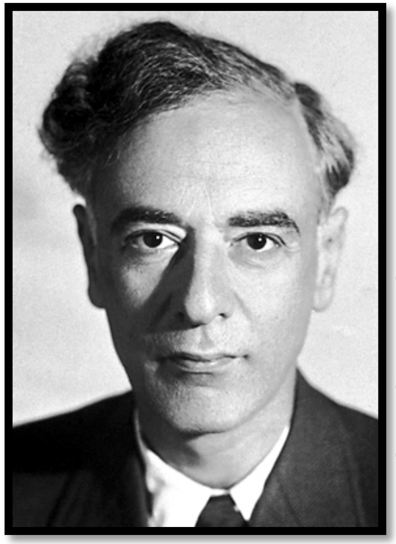
1957: Nope, Parity is violated (maximally)!

AIP Emilio Segre Visual Archives

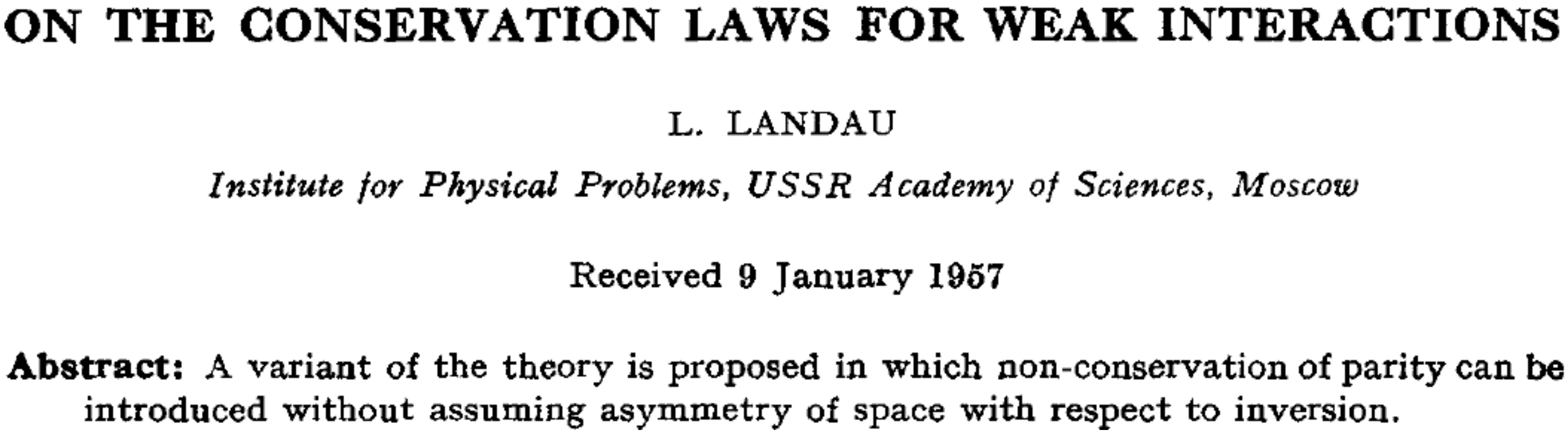


http://en.wikipedia.org/wiki/File:Wu_experiment.jpg

1957: Is CP conserved?



The Nobel Foundation



ON THE CONSERVATION LAWS FOR WEAK INTERACTIONS

L. LANDAU

Institute for Physical Problems, USSR Academy of Sciences, Moscow

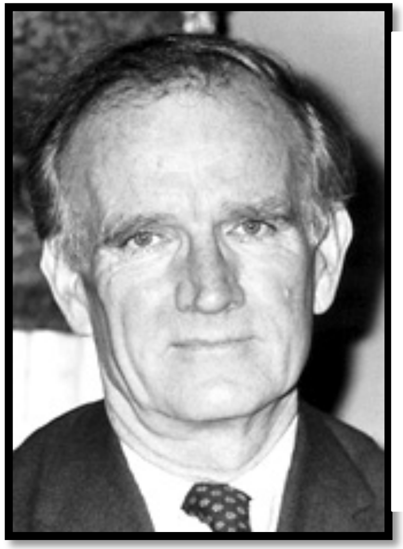
Received 9 January 1957

Abstract: A variant of the theory is proposed in which non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.

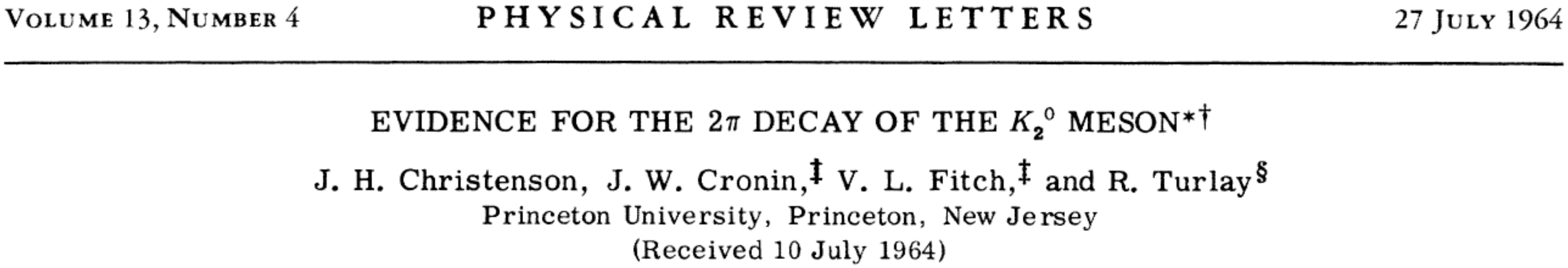
Nuclear Physics 3 (1957) 127–131

1964: Nope, CP is violated (just a little bit)!

The Nobel Foundation



The Nobel Foundation



VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

CKM Matrix: Weak Interaction for Quarks

http://en.wikipedia.org/wiki/File:Nicola_Cabibbo.jpg

C

The Nobel Foundation

K

The Nobel Foundation

M

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\delta = CP\text{-violating “phase”}$$

Standard Model CP - Violation

$$\eta \propto \frac{(\text{matter} \;-\; \text{antimatter})}{\text{total matter}} \propto \sin(\delta)$$

$$\eta_{\text{exp}} \approx 10^{-9}$$ PDG2014

$$\eta_{\text{CKM}} \approx 10^{-26}$$ Huet & Sather PRD 51 379 (1995)

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\delta = CP\text{-violating "phase"}$$

New Massive Particles = More Phases

$$\begin{aligned} \text{number of phases} &= (N_g - 1)(N_g - 2)/2 \\ \text{number of generations} &= N_g \end{aligned}$$

Hocker & Ligeti Annu. Rev. Nucl. Part. Sci. 2006. 56:501-67

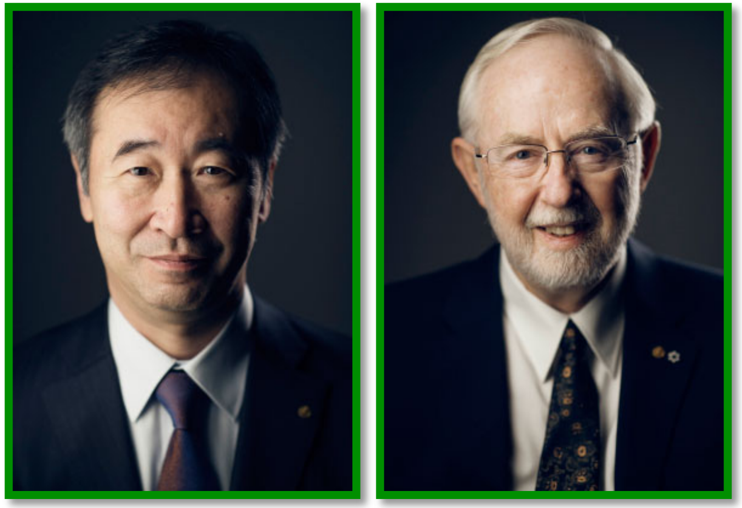
This is why things theories like Supersymmetry can produce more *CP* violation!

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\delta = CP\text{-violating “phase”}$$

Where do we look for more *CP*-violation?

The Nobel Foundation



The Nobel Foundation

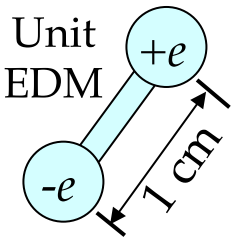
- Decays of B-mesons (like Kaons) [BABAR,KEK]:
- Neutrinos have mass! (PMNS matrix)
- rare decays at LHC
- *electric dipole moments: If CPT is good,* then *T*-violation can be used to search for new sources of *CP*-violation!

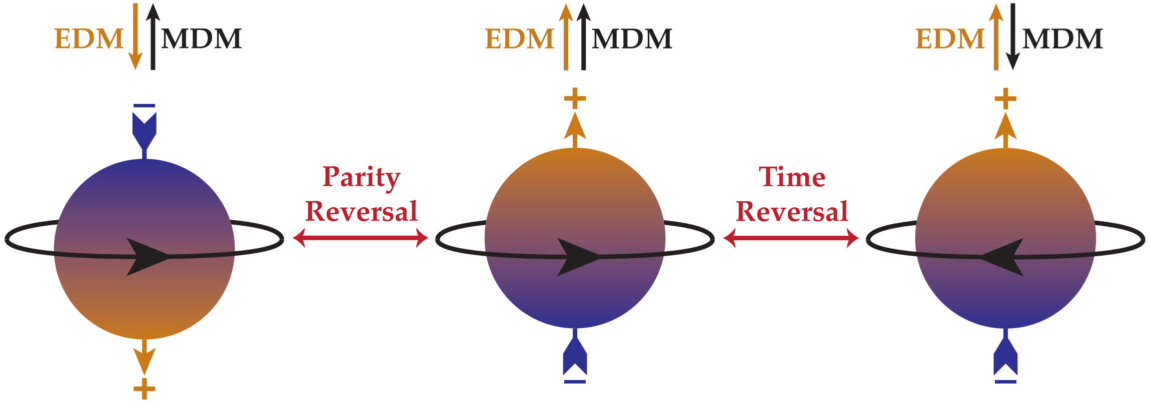
Electric Dipole Moments

$$\vec{d} = \int \vec{r}\left[\rho_{\text{charge}}(\vec{r}) - \left(\frac{Q}{M}\right)\rho_{\text{mass}}(\vec{r})\right] dV$$

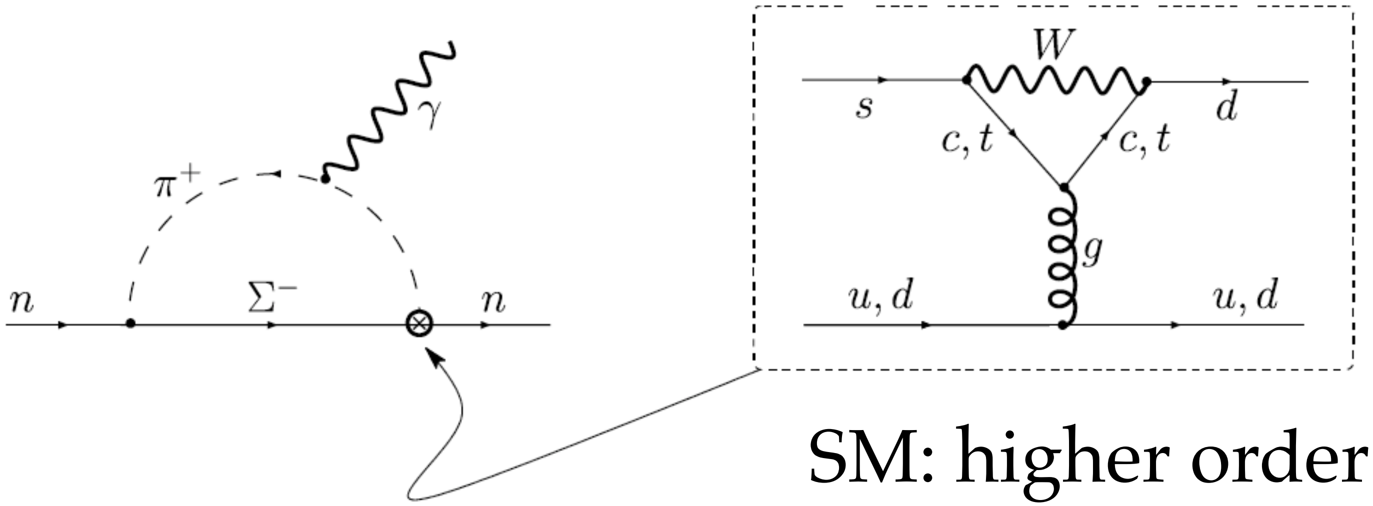
$$\mathcal{H} = -\mu\left(\frac{\vec{S}\cdot\vec{B}}{S}\right) - d\left(\frac{\vec{S}\cdot\vec{E}}{S}\right)$$

	P-parity	T-time reversal
$\vec{S}$	$+$	$-$
$\vec{B}$	$+$	$-$
$\vec{E}$	$-$	$+$
$\vec{S}\cdot\vec{B}$	$+$	$+$
$\vec{S}\cdot\vec{E}$	$-$	$-$

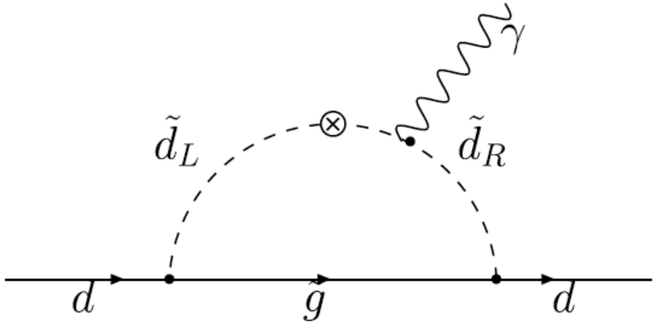




Standard Model vs. SUSY EDMs



SM: higher order "penguin" diagram

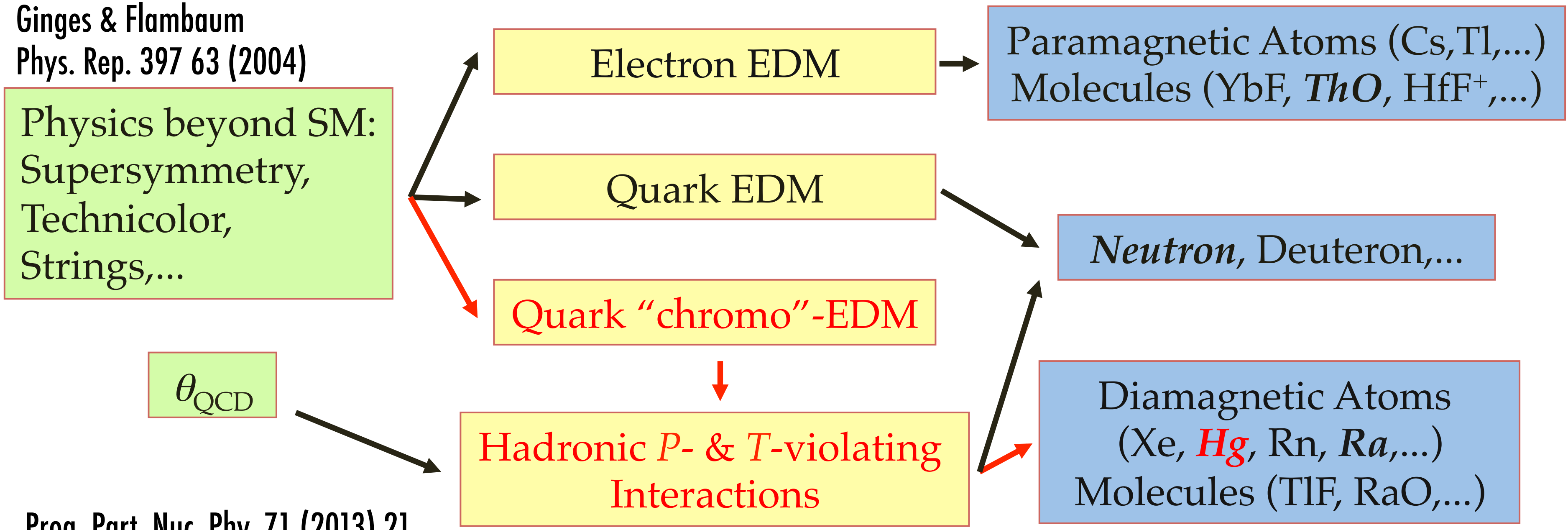


SUSY: lower order

Pospelov & Ritz
Ann. Phys. 318 119 (2005)

Sources of Signal

simplified from:
Ginges & Flambaum
Phys. Rep. 397 63 (2004)



Physics beyond SM:
Supersymmetry,
Technicolor,
Strings,...

Electron EDM

Quark EDM

Quark "chromo"-EDM

θ_{QCD}

Hadronic *P*- & *T*-violating Interactions

Paramagnetic Atoms (Cs,Tl,...)
Molecules (YbF, ***ThO***, HfF$^+$,...)

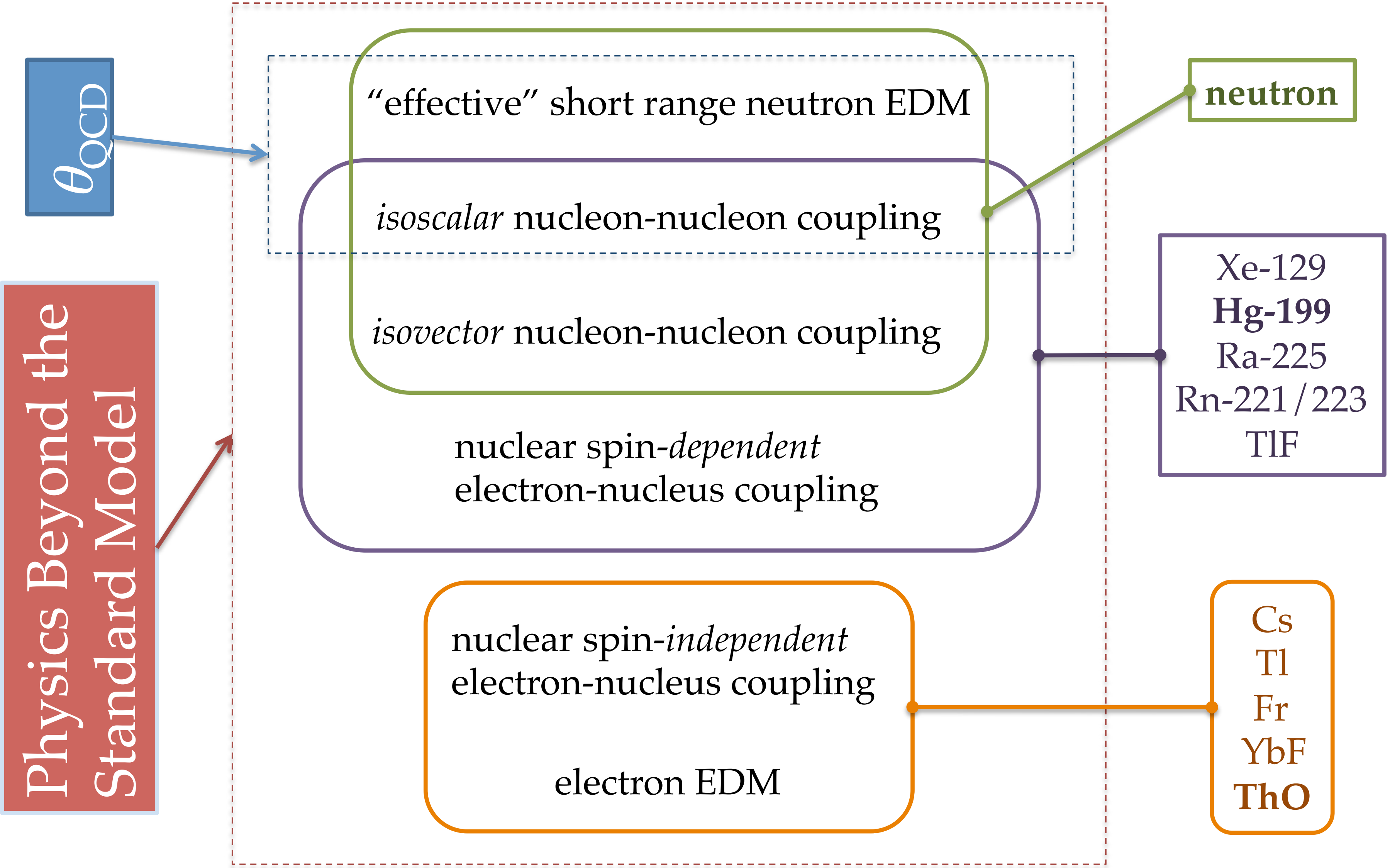
Neutron, Deuteron,...

Diamagnetic Atoms
(Xe, ***Hg***, Rn, ***Ra***,...)
Molecules (TlF, RaO,...)

Prog. Part. Nuc. Phy. 71 (2013) 21

System	Best Limit (2σ) 10^{-28} e*cm	SM estimate 10^{-28} e*cm	Method (Location)
Electron	0.9	$\sim10^{-10}$	cold ThO beam (Harvard / Yale)
Neutron	300	$\sim10^{-4}$	UCN in bottle (ILL)
Atoms	0.3	$\sim10^{-7}$	Hg atoms in vapor cell (Washington-Seattle)

"A Global Analysis": PRC 91 035502 (2015)



θ_{QCD}

Physics Beyond the Standard Model

"effective" short range neutron EDM

isoscalar nucleon-nucleon coupling

isovector nucleon-nucleon coupling

nuclear spin-*dependent*
electron-nucleus coupling

nuclear spin-*independent*
electron-nucleus coupling

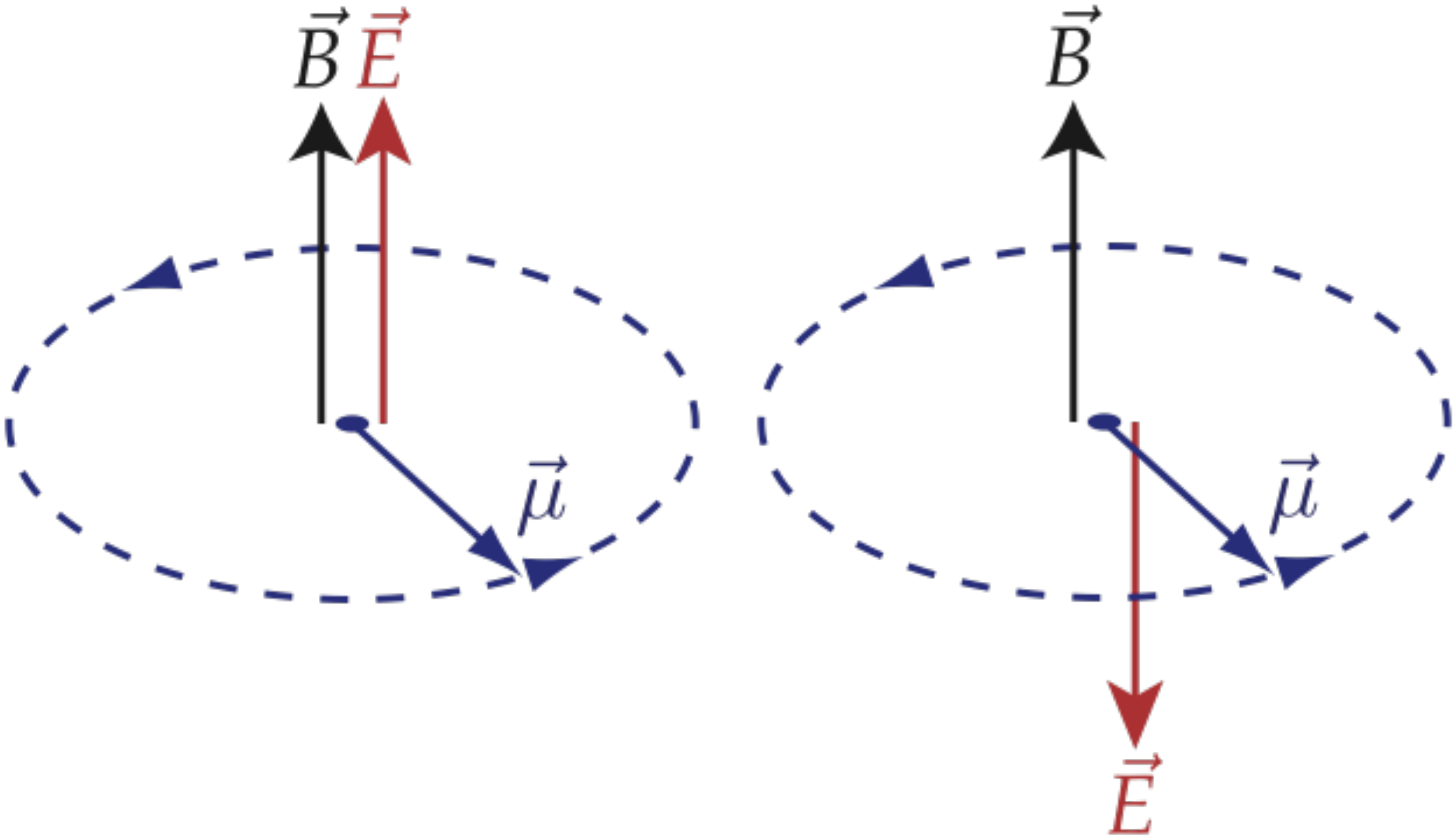
electron EDM

neutron

Xe-129
Hg-199
Ra-225
Rn-221/223
TlF

Cs
Tl
Fr
YbF
ThO

Always Measure Frequency: Spin Precession



$$h\nu_{\uparrow} = 2(\mu B_{\uparrow} + dE) \qquad h\nu_{\downarrow} = 2(\mu B_{\downarrow} - dE)$$

Ultimate Statistical Sensitivity

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \frac{4dE}{h}$$

interrogation
time

statistical sensitivity:

$$\frac{\sigma_d}{\sqrt{N}} = \left(\frac{n/\sqrt{\tau}}{S}\right)\frac{\hbar\sqrt{3}}{E\sqrt{\epsilon T\tau}}$$

signal-to-noise
ratio

Electric
field

integration
time

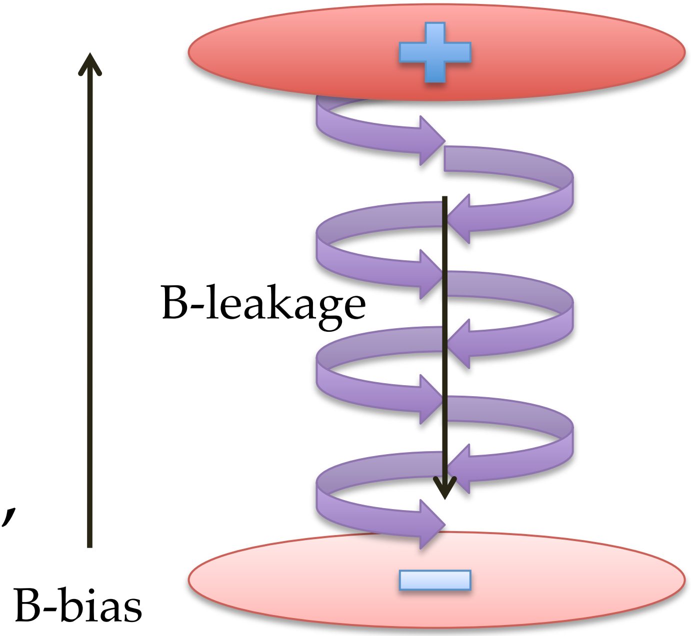
Magnetic Field Instabilities & False Effects!

$$\Delta\nu = \nu_{\uparrow} - \nu_{\downarrow} = \frac{4dE}{h} + \boxed{\frac{2\mu(B_{\uparrow} - B_{\downarrow})}{h}}$$

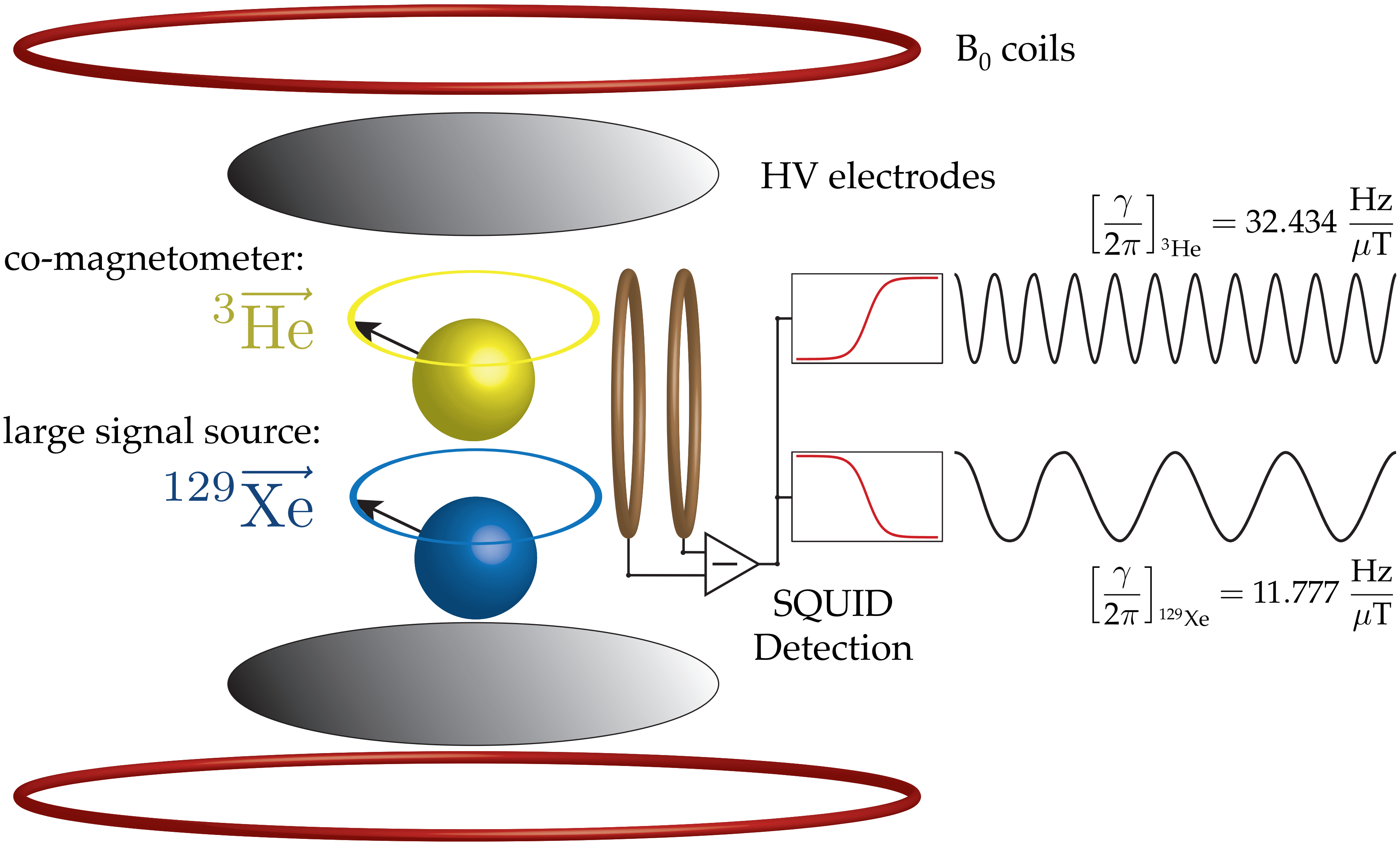
challenge!

Instabilities adds noise & limits the statistical precision.

False effects, things which change sign with the electric field, are nasty: "leakage current"



Munich: SQUID Detection of Noble Gases



B_0 coils

HV electrodes

co-magnetometer:

$^3\overrightarrow{\mathrm{He}}$

large signal source:

$^{129}\overrightarrow{\mathrm{Xe}}$

SQUID Detection

$$\left[\frac{\gamma}{2\pi}\right]_{^3\mathrm{He}} = 32.434\,\frac{\mathrm{Hz}}{\mu\mathrm{T}}$$

$$\left[\frac{\gamma}{2\pi}\right]_{^{129}\mathrm{Xe}} = 11.777\,\frac{\mathrm{Hz}}{\mu\mathrm{T}}$$

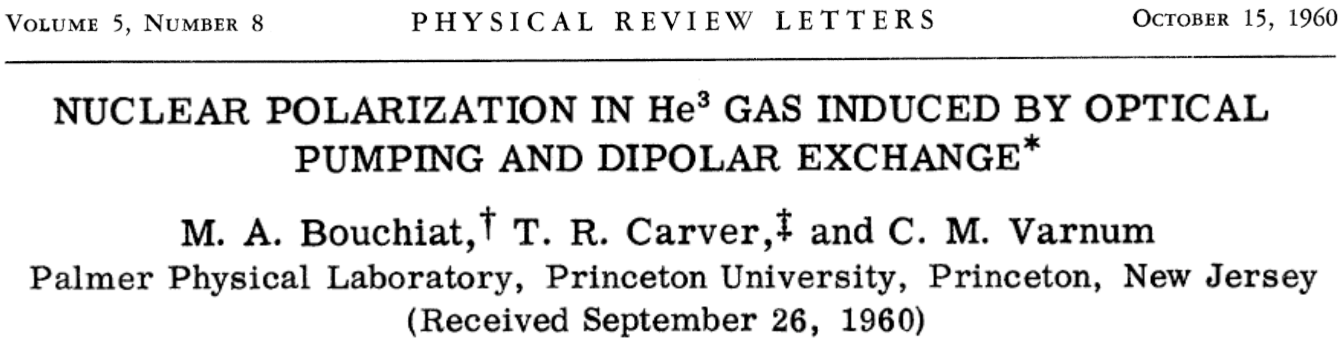
Ultimate Potential Statistical Sensitivity

$$\frac{\sigma_d}{\sqrt{N}} = \left(\frac{n/\sqrt{\tau}}{S}\right)\frac{\hbar\sqrt{3}}{E\sqrt{\epsilon T\tau}}$$

parameter	goal	Hg-199
S/n, SNR	3x10^6	~10^5
E, electric field	10 kV / cm	~10 kV / cm
τ, obs. time	10^3 sec	~10^2 sec
T, integration time	1 day	100 days
ε, efficiency	0.5	0.5

$$\frac{\sigma_d}{\sqrt{N}} = 5.5\times10^{-30}\ \frac{e\cdot\text{cm}}{\sqrt{\text{day}}}$$

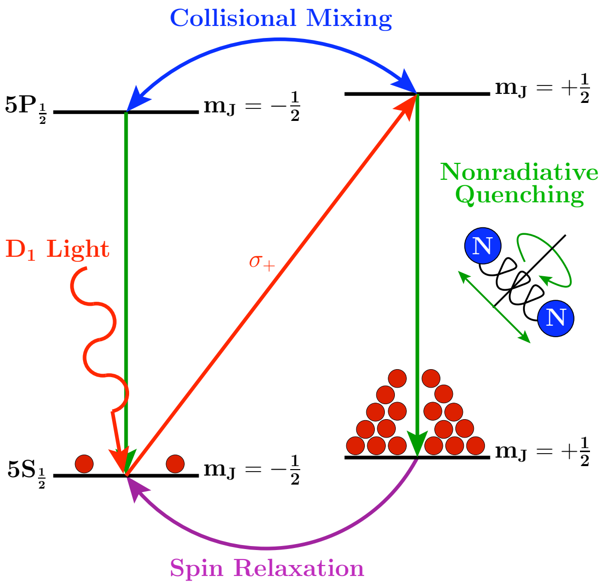
Spin-Exchange Optical Pumping (SEOP)



VOLUME 5, NUMBER 8 PHYSICAL REVIEW LETTERS OCTOBER 15, 1960

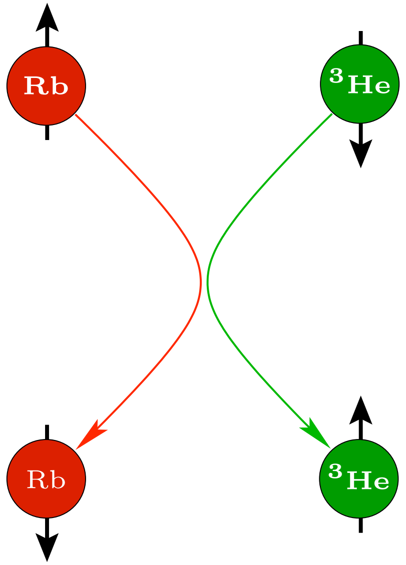
NUCLEAR POLARIZATION IN He^3 GAS INDUCED BY OPTICAL
PUMPING AND DIPOLAR EXCHANGE*

M. A. Bouchiat,† T. R. Carver,‡ and C. M. Varnum
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received September 26, 1960)



Optical Pumping

light (laser) to electron (Rb)



Spin Exchange

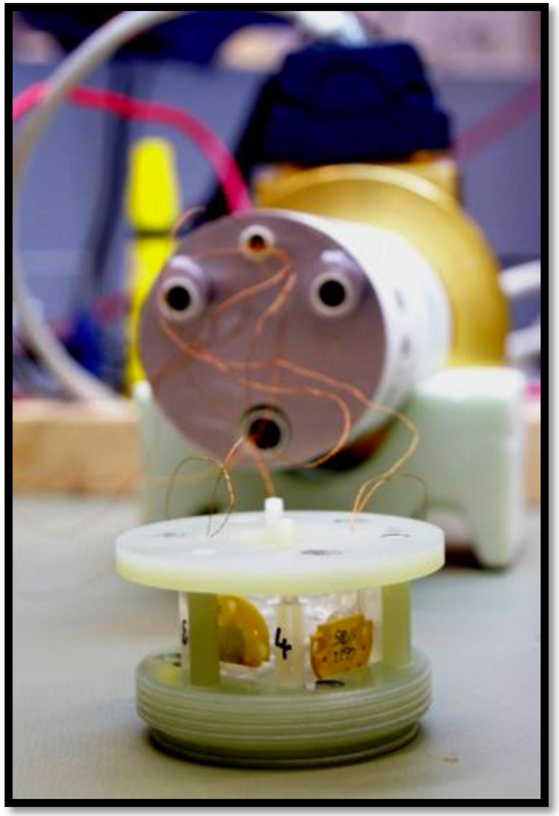
electron (Rb) to nucleus (^{3}He, ^{129}Xe)

Prototype EDM Cells

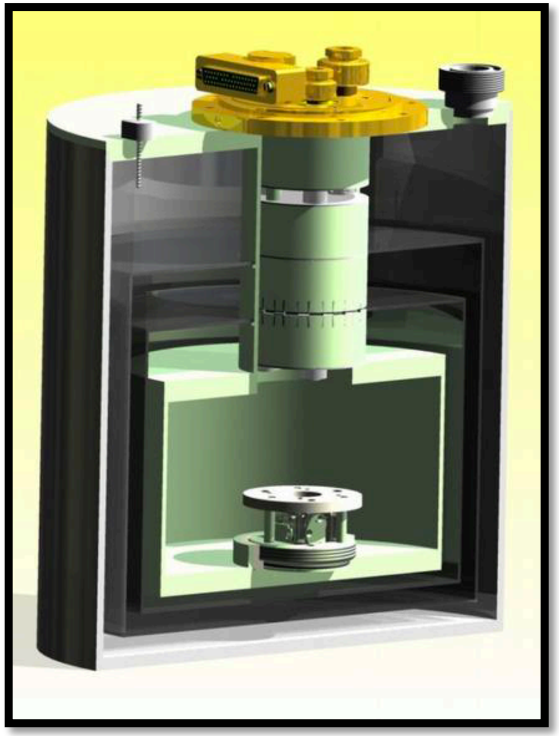
Silicon electrodes
+/- 10 kV/cm
1 atm He-3 @ 2% polarization
0.1 atm Xe-129 @ 20% polariation

Cells by:
S. Degenkolb (Michigan)
P. Pistel & E. Babcock (JCNS)

“SQUID” Magnetometers: Detectors



Two sensors in
each direction.
Cube side = 1 cm



LHe dewar
refill every 8 hrs

Nonmagnetic
wooden components

Magnetic field scales

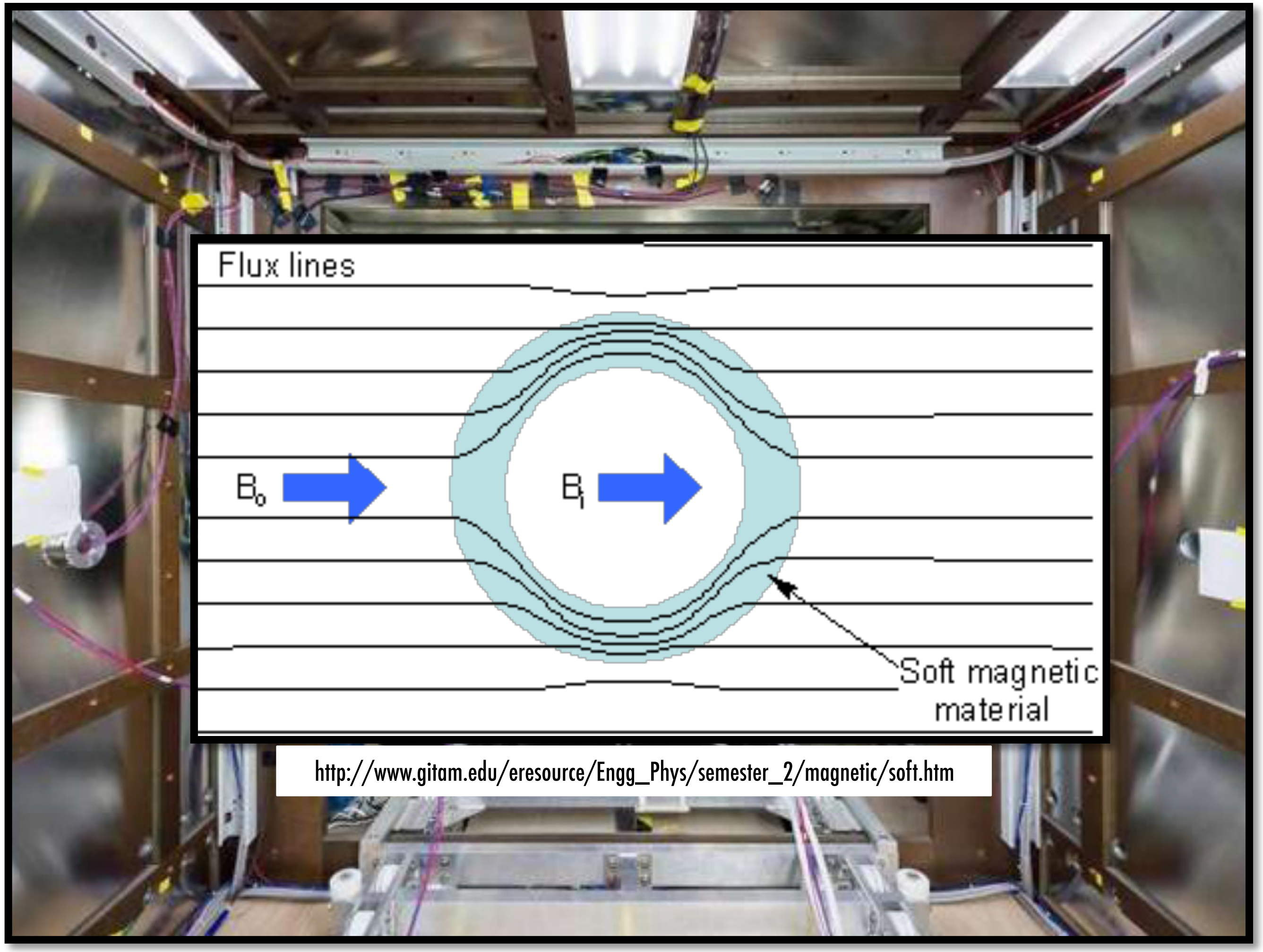
Object	B-Field (T)
MRI Machine	3E+00
Computer hard drive	2E+00
Loudspeaker	1E+00
Sun spots	2E-01
Refrigerator magnet	5E-03
Earth's magnetic field	5E-05
Cassette tape	2E-05
Bias field for EDM experiment	1E-06
Noble gas (100% @ 1 atm @ 1 mm)	1E-08
Residual field in magnetic shielded room	1E-09
My clothes @ 10 cm	1E-10
Human Brain	1E-12
"SQUID" magnetometer noise floor (1 s)	1E-15

SQUID Detection? Magic Room!

<1 nT residual B-field
<10 pT/cm B-field gradients
$>10^6$ low frequency shielding factors

Rev. Sci. Inst. 85:075106 (2014)
J. App. Phys. 117:183903 (2015)
J. App. Phys. 117:233903 (2015)

SQUID Detection? Magic Room!



http://www.gitam.edu/eresource/Engg_Phys/semester_2/magnetic/soft.htm

<1 nT residual B-field
<10 pT/cm B-field gradients
>10^6 low frequency shielding factors

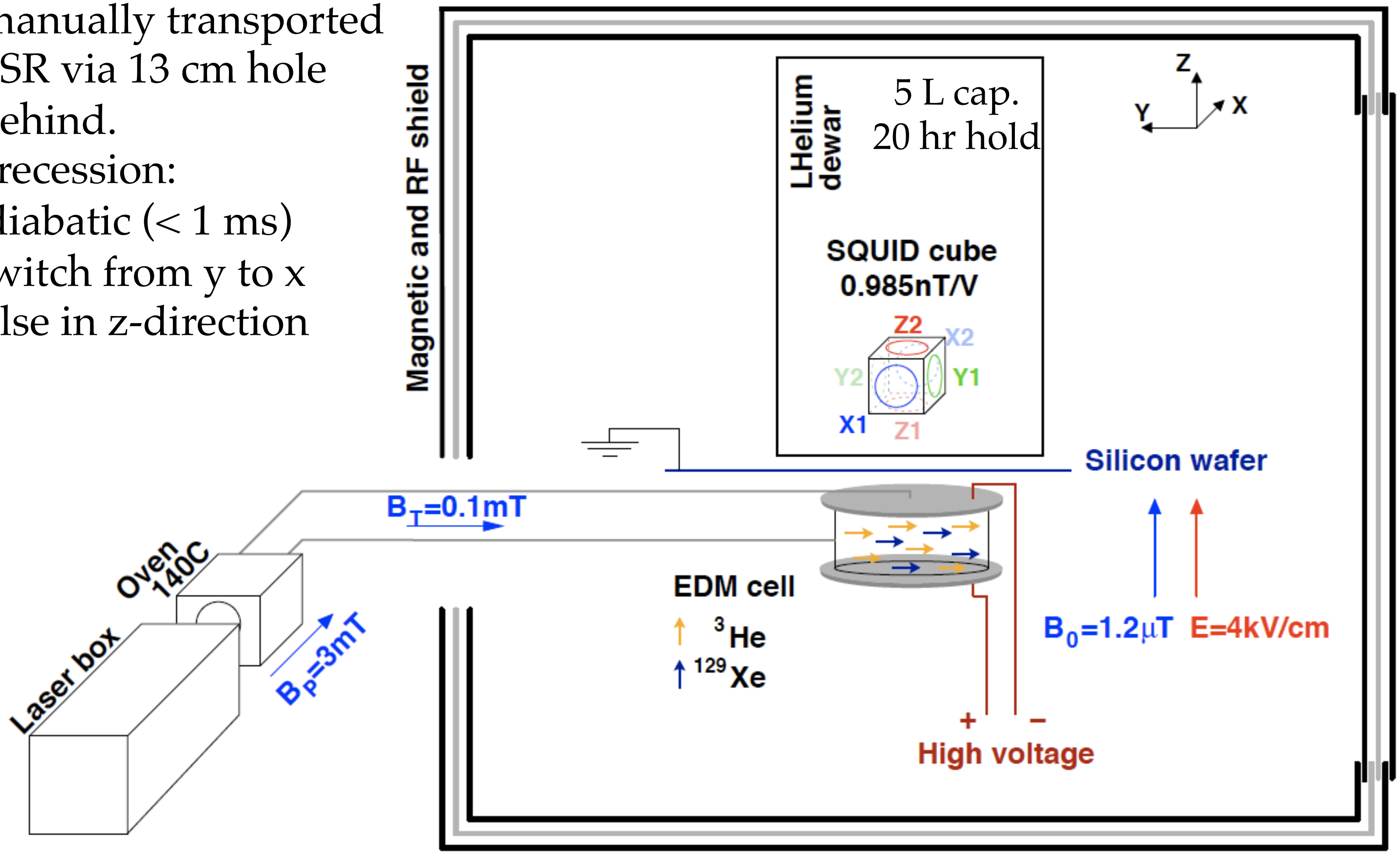
Rev. Sci. Inst. 85:075106 (2014)
J. App. Phys. 117:183903 (2015)
J. App. Phys. 117:233903 (2015)

Experimental Procedure

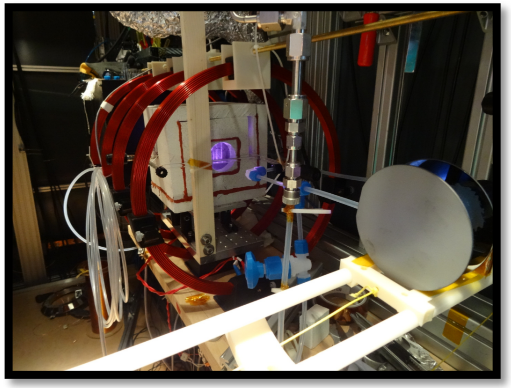
1. Cells polarized outside MSR.
2. MSR degaussed.
3. Cells manually transported into MSR via 13 cm hole from behind.
4. Spin precession:

- non-adiabatic (< 1 ms) field switch from y to x
- AC pulse in z-direction

From: Florian Kuchler thesis

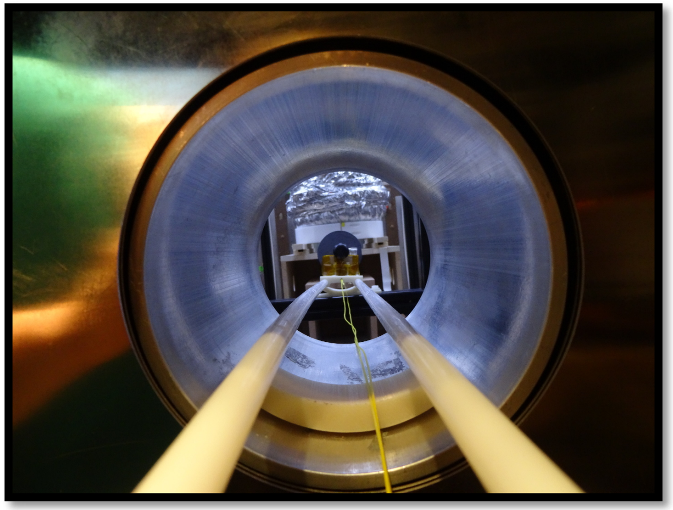


Experimental Layout

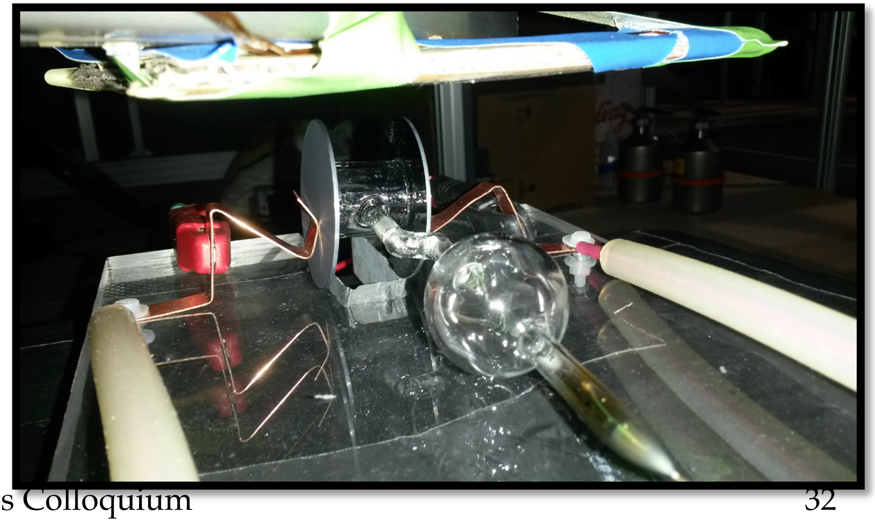


Noble gas polarizer
3 mT
100 W diode laser

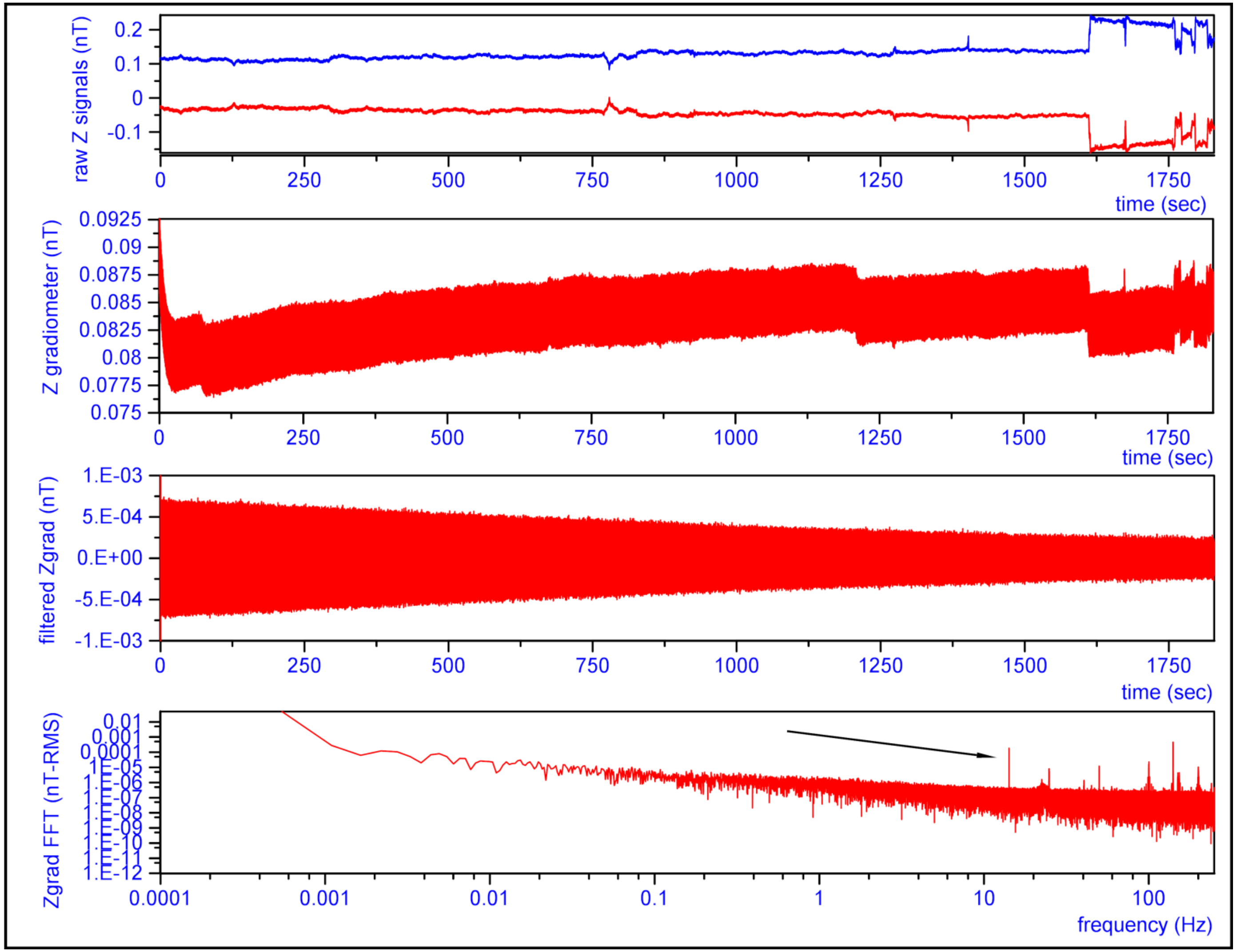
Non-human
Transport!



EDM cell underneath SQUID
distance to sensor = 10 cm



Raw data



nT

two channels, A,B

pT

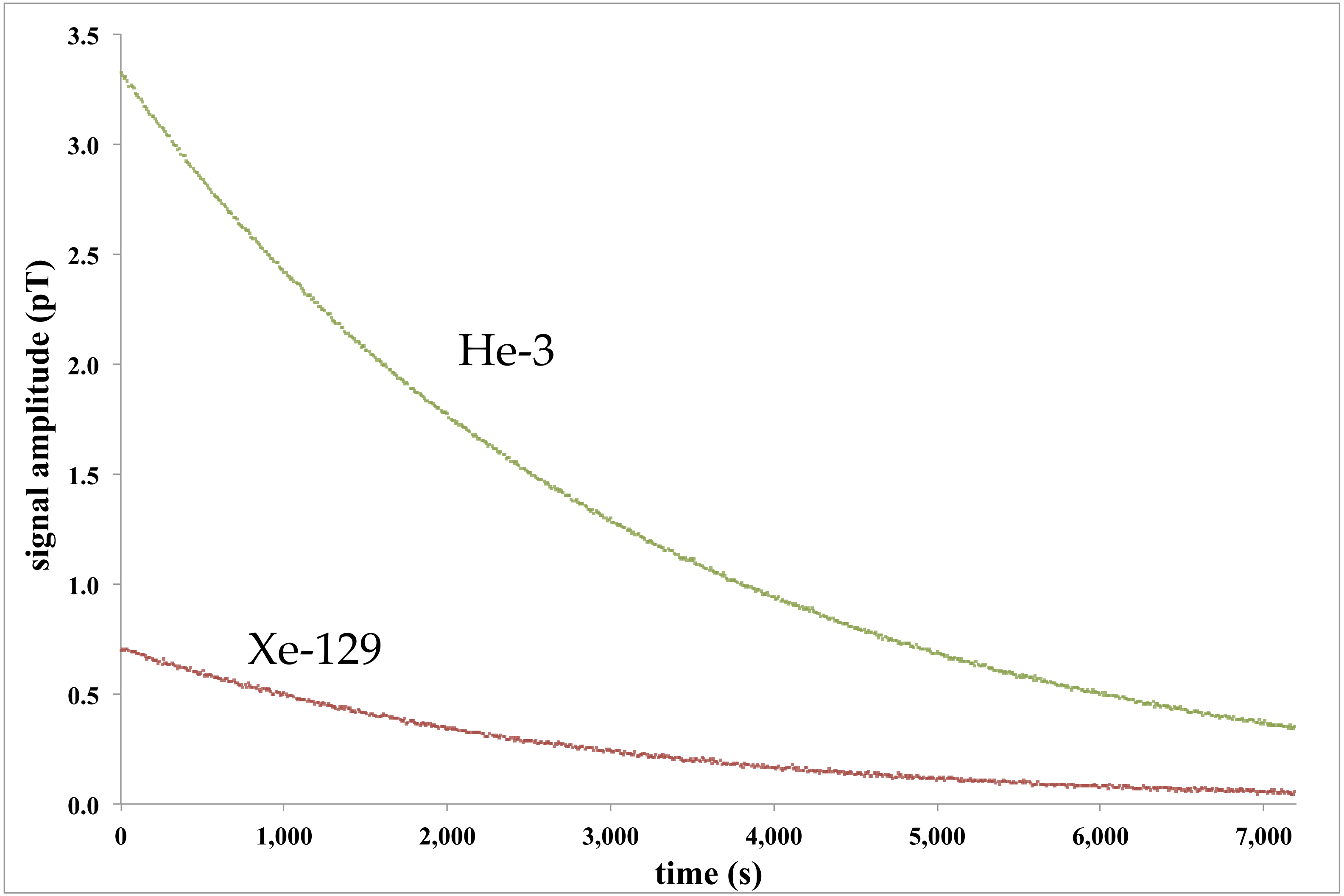
|A|-|B|, gradiometer

pT

filtered

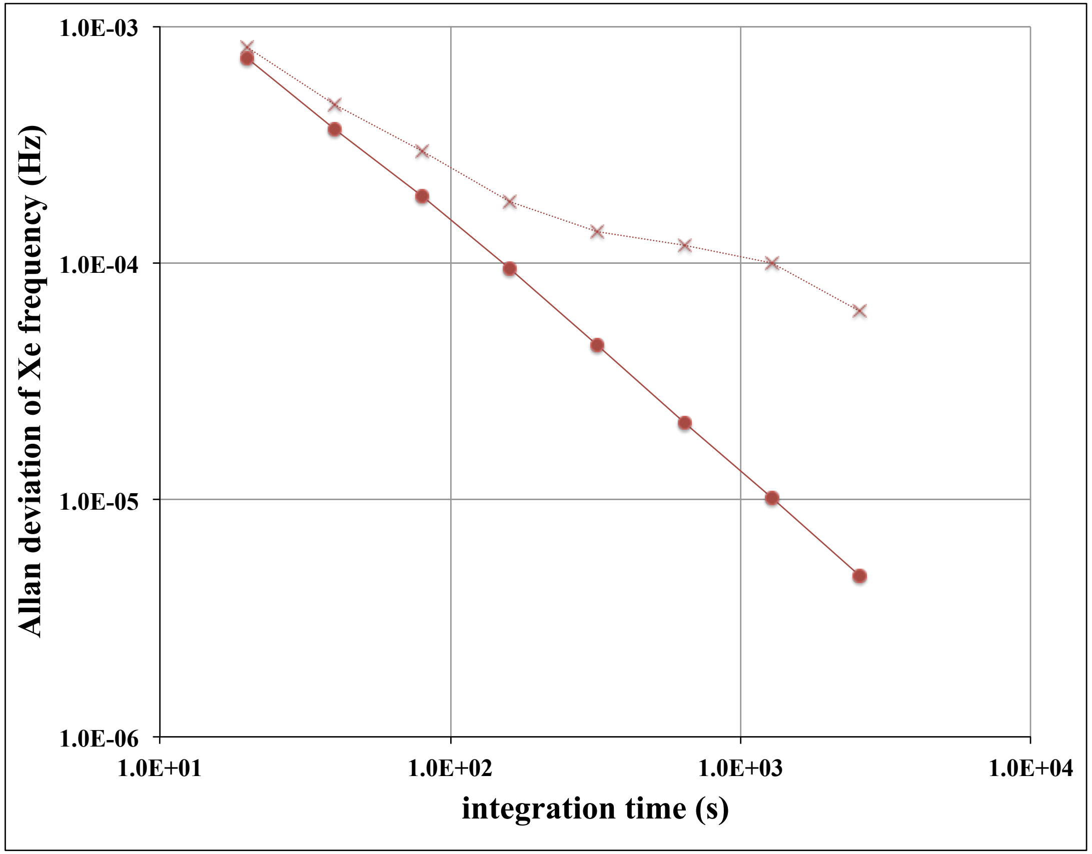
FFT

>1000 sec Spin Precession Times



Analysis by I. Fan (PTB)

He-3 Co-Magnetometer is helpful!



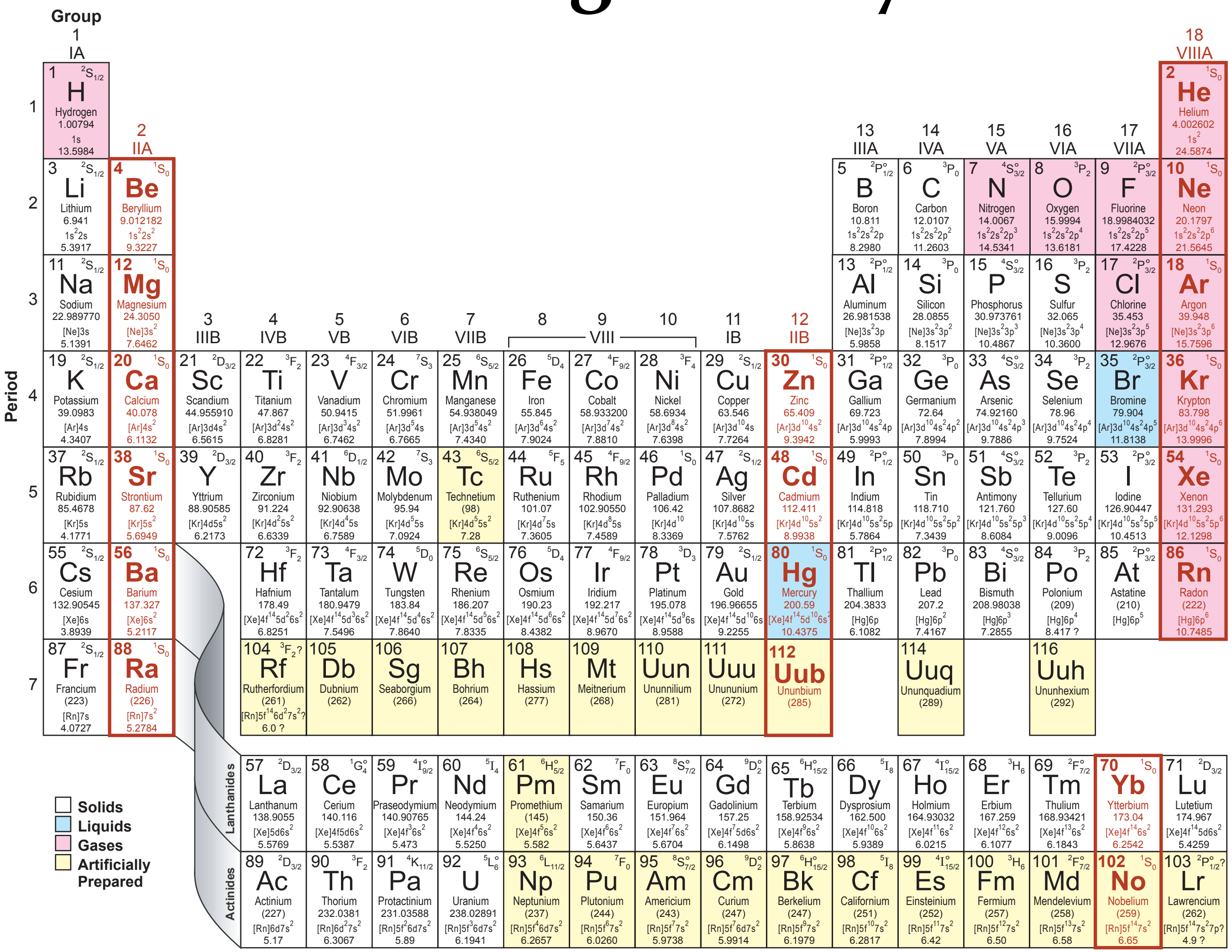
Need to reduce sensor-cell distance
Need to provide a stable time base to ADC card

Analysis by I. Fan (PTB)

"Magic Box" @ MSU/NSCL/FRIB

Photo by G.L. Kohuth.

Other Diamagnetic Systems?



Group

Period	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII
1	1 $^{2}S_{1/2}$ H Hydrogen 1.00794 $1s$ 13.5984								
2	3 $^{2}S_{1/2}$ Li Lithium 6.941 $1s^2 2s$ 5.3917	4 $^{1}S_{0}$ Be Beryllium 9.012182 $1s^2 2s^2$ 9.3227							
3	11 $^{2}S_{1/2}$ Na Sodium 22.989770 $[Ne]3s$ 5.1391	12 $^{1}S_{0}$ Mg Magnesium 24.3050 $[Ne]3s^2$ 7.6462							
4	19 $^{2}S_{1/2}$ K Potassium 39.0983 $[Ar]4s$ 4.3407	20 $^{1}S_{0}$ Ca Calcium 40.078 $[Ar]4s^2$ 6.1132	21 $^{2}D_{3/2}$ Sc Scandium 44.955910 $[Ar]3d4s^2$ 6.5615	22 $^{3}F_{2}$ Ti Titanium 47.867 $[Ar]3d^2 4s^2$ 6.8281	23 $^{4}F_{3/2}$ V Vanadium 50.9415 $[Ar]3d^3 4s^2$ 6.7462	24 $^{7}S_{3}$ Cr Chromium 51.9961 $[Ar]3d^5 4s$ 6.7665	25 $^{6}S_{5/2}$ Mn Manganese 54.938049 $[Ar]3d^5 4s^2$ 7.4340	26 $^{5}D_{4}$ Fe Iron 55.845 $[Ar]3d^6 4s^2$ 7.9024	27 $^{4}F_{9/2}$ Co Cobalt 58.933200 $[Ar]3d^7 4s^2$ 7.8810
5	37 $^{2}S_{1/2}$ Rb Rubidium 85.4678 $[Kr]5s$ 4.1771	38 $^{1}S_{0}$ Sr Strontium 87.62 $[Kr]5s^2$ 5.6949	39 $^{2}D_{3/2}$ Y Yttrium 88.90585 $[Kr]4d5s^2$ 6.2173	40 $^{3}F_{2}$ Zr Zirconium 91.224 $[Kr]4d^2 5s^2$ 6.6339	41 $^{6}D_{1/2}$ Nb Niobium 92.90638 $[Kr]4d^4 5s$ 6.7589	42 $^{7}S_{3}$ Mo Molybdenum 95.94 $[Kr]4d^5 5s$ 7.0924	43 $^{6}S_{5/2}$ Tc Technetium (98) $[Kr]4d^5 5s^2$ 7.28	44 $^{5}F_{5}$ Ru Ruthenium 101.07 $[Kr]4d^7 5s$ 7.3605	45 $^{4}F_{9/2}$ Rh Rhodium 102.90550 $[Kr]4d^8 5s$ 7.4589
6	55 $^{2}S_{1/2}$ Cs Cesium 132.90545 $[Xe]6s$ 3.8939	56 $^{1}S_{0}$ Ba Barium 137.327 $[Xe]6s^2$ 5.2117		72 $^{3}F_{2}$ Hf Hafnium 178.49 $[Xe]4f^{14}5d^2 6s^2$ 6.8251	73 $^{4}F_{3/2}$ Ta Tantalum 180.9479 $[Xe]4f^{14}5d^3 6s^2$ 7.5496	74 $^{5}D_{0}$ W Tungsten 183.84 $[Xe]4f^{14}5d^4 6s^2$ 7.8640	75 $^{6}S_{5/2}$ Re Rhenium 186.207 $[Xe]4f^{14}5d^5 6s^2$ 7.8335	76 $^{5}D_{4}$ Os Osmium 190.23 $[Xe]4f^{14}5d^6 6s^2$ 8.4382	77 $^{4}F_{9/2}$ Ir Iridium 192.217 $[Xe]4f^{14}5d^7 6s^2$ 8.9670
7	87 $^{2}S_{1/2}$ Fr Francium (223) $[Rn]7s$ 4.0727	88 $^{1}S_{0}$ Ra Radium (226) $[Rn]7s^2$ 5.2784		104 $^{3}F_{2}$? Rf Rutherfordium (261) $[Rn]5f^{14}6d^2 7s^2$? 6.0 ?	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)

Period	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1									2 $^{1}S_{0}$ He Helium 4.002602 $1s^2$ 24.5874
2				5 $^{2}P^{\circ}_{1/2}$ B Boron 10.811 $1s^2 2s^2 2p$ 8.2980	6 $^{3}P_{0}$ C Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603	7 $^{4}S^{\circ}_{3/2}$ N Nitrogen 14.0067 $1s^2 2s^2 2p^3$ 14.5341	8 $^{3}P_{2}$ O Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181	9 $^{2}P^{\circ}_{3/2}$ F Fluorine 18.9984032 $1s^2 2s^2 2p^5$ 17.4228	10 $^{1}S_{0}$ Ne Neon 20.1797 $1s^2 2s^2 2p^6$ 21.5645
3				13 $^{2}P^{\circ}_{1/2}$ Al Aluminum 26.981538 $[Ne]3s^2 3p$ 5.9858	14 $^{3}P_{0}$ Si Silicon 28.0855 $[Ne]3s^2 3p^2$ 8.1517	15 $^{4}S^{\circ}_{3/2}$ P Phosphorus 30.973761 $[Ne]3s^2 3p^3$ 10.4867	16 $^{3}P_{2}$ S Sulfur 32.065 $[Ne]3s^2 3p^4$ 10.3600	17 $^{2}P^{\circ}_{3/2}$ Cl Chlorine 35.453 $[Ne]3s^2 3p^5$ 12.9676	18 $^{1}S_{0}$ Ar Argon 39.948 $[Ne]3s^2 3p^6$ 15.7596
4	28 $^{3}F_{4}$ Ni Nickel 58.6934 $[Ar]3d^8 4s^2$ 7.6398	29 $^{2}S_{1/2}$ Cu Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^{1}S_{0}$ Zn Zinc 65.409 $[Ar]3d^{10}4s^2$ 9.3942	31 $^{2}P^{\circ}_{1/2}$ Ga Gallium 69.723 $[Ar]3d^{10}4s^2 4p$ 5.9993	32 $^{3}P_{0}$ Ge Germanium 72.64 $[Ar]3d^{10}4s^2 4p^2$ 7.8994	33 $^{4}S^{\circ}_{3/2}$ As Arsenic 74.92160 $[Ar]3d^{10}4s^2 4p^3$ 9.7886	34 $^{3}P_{2}$ Se Selenium 78.96 $[Ar]3d^{10}4s^2 4p^4$ 9.7524	35 $^{2}P^{\circ}_{3/2}$ Br Bromine 79.904 $[Ar]3d^{10}4s^2 4p^5$ 11.8138	36 $^{1}S_{0}$ Kr Krypton 83.798 $[Ar]3d^{10}4s^2 4p^6$ 13.9996
5	46 $^{1}S_{0}$ Pd Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^{2}S_{1/2}$ Ag Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 $^{1}S_{0}$ Cd Cadmium 112.411 $[Kr]4d^{10}5s^2$ 8.9938	49 $^{2}P^{\circ}_{1/2}$ In Indium 114.818 $[Kr]4d^{10}5s^2 5p$ 5.7864	50 $^{3}P_{0}$ Sn Tin 118.710 $[Kr]4d^{10}5s^2 5p^2$ 7.3439	51 $^{4}S^{\circ}_{3/2}$ Sb Antimony 121.760 $[Kr]4d^{10}5s^2 5p^3$ 8.6084	52 $^{3}P_{2}$ Te Tellurium 127.60 $[Kr]4d^{10}5s^2 5p^4$ 9.0096	53 $^{2}P^{\circ}_{3/2}$ I Iodine 126.90447 $[Kr]4d^{10}5s^2 5p^5$ 10.4513	54 $^{1}S_{0}$ Xe Xenon 131.293 $[Kr]4d^{10}5s^2 5p^6$ 12.1298
6	78 $^{3}D_{3}$ Pt Platinum 195.078 $[Xe]4f^{14}5d^9 6s$ 8.9588	79 $^{2}S_{1/2}$ Au Gold 196.96655 $[Xe]4f^{14}5d^{10}6s$ 9.2255	80 $^{1}S_{0}$ Hg Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 $^{2}P^{\circ}_{1/2}$ Tl Thallium 204.3833 $[Hg]6p$ 6.1082	82 $^{3}P_{0}$ Pb Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^{4}S^{\circ}_{3/2}$ Bi Bismuth 208.98038 $[Hg]6p^3$ 7.2855	84 $^{3}P_{2}$ Po Polonium (209) $[Hg]6p^4$ 8.417 ?	85 $^{2}P^{\circ}_{3/2}$ At Astatine (210) $[Hg]6p^5$	86 $^{1}S_{0}$ Rn Radon (222) $[Hg]6p^6$ 10.7485
7	110 Uun Ununnilium (281)	111 Uuu Unununium (272)	112 Uub Ununbium (285)		114 Uuq Ununquadium (289)		116 Uuh Ununhexium (292)		

Lanthanides	57 $^{2}D_{3/2}$ La Lanthanum 138.9055 $[Xe]5d6s^2$ 5.5769	58 $^{1}G^{\circ}_{4}$ Ce Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387	59 $^{4}I^{\circ}_{9/2}$ Pr Praseodymium 140.90765 $[Xe]4f^3 6s^2$ 5.473	60 $^{5}I_{4}$ Nd Neodymium 144.24 $[Xe]4f^4 6s^2$ 5.5250	61 $^{6}H^{\circ}_{5/2}$ Pm Promethium (145) $[Xe]4f^5 6s^2$ 5.582	62 $^{7}F_{0}$ Sm Samarium 150.36 $[Xe]4f^6 6s^2$ 5.6437	63 $^{8}S^{\circ}_{7/2}$ Eu Europium 151.964 $[Xe]4f^7 6s^2$ 5.6704	64 $^{9}D^{\circ}_{2}$ Gd Gadolinium 157.25 $[Xe]4f^7 5d6s^2$ 6.1498	65 $^{6}H^{\circ}_{15/2}$ Tb Terbium 158.92534 $[Xe]4f^9 6s^2$ 5.8638	66 $^{5}I_{8}$ Dy Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9389	67 $^{4}I^{\circ}_{15/2}$ Ho Holmium 164.93032 $[Xe]4f^{11}6s^2$ 6.0215	68 $^{3}H_{6}$ Er Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077	69 $^{2}F^{\circ}_{7/2}$ Tm Thulium 168.93421 $[Xe]4f^{13}6s^2$ 6.1843	70 $^{1}S_{0}$ Yb Ytterbium 173.04 $[Xe]4f^{14}6s^2$ 6.2542	71 $^{2}D_{3/2}$ Lu Lutetium 174.967 $[Xe]4f^{14}5d6s^2$ 5.4259
Actinides	89 $^{2}D_{3/2}$ Ac Actinium (227) $[Rn]6d7s^2$ 5.17	90 $^{3}F_{2}$ Th Thorium 232.0381 $[Rn]6d^2 7s^2$ 6.3067	91 $^{4}K_{11/2}$ Pa Protactinium 231.03588 $[Rn]5f^2 6d7s^2$ 5.89	92 $^{5}L^{\circ}_{6}$ U Uranium 238.02891 $[Rn]5f^3 6d7s^2$ 6.1941	93 $^{6}L_{11/2}$ Np Neptunium (237) $[Rn]5f^4 6d7s^2$ 6.2657	94 $^{7}F_{0}$ Pu Plutonium (244) $[Rn]5f^6 7s^2$ 6.0260	95 $^{8}S^{\circ}_{7/2}$ Am Americium (243) $[Rn]5f^7 7s^2$ 5.9738	96 $^{9}D^{\circ}_{2}$ Cm Curium (247) $[Rn]5f^7 6d7s^2$ 5.9914	97 $^{6}H^{\circ}_{15/2}$ Bk Berkelium (247) $[Rn]5f^9 7s^2$ 6.1979	98 $^{5}I_{8}$ Cf Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^{4}I^{\circ}_{15/2}$ Es Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.42	100 $^{3}H_{6}$ Fm Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^{2}F^{\circ}_{7/2}$ Md Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^{1}S_{0}$ No Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 $^{2}P^{\circ}_{1/2}$? Lr Lawrencium (262) $[Rn]5f^{14}7s^2 7p$? 4.9 ?

☐ **Solids**
🟦 **Liquids**
🟪 **Gases**
🟨 **Artificially Prepared**

NIST website

Schiff Shielding in Diamagnetic Atoms

- Shielding in Diamagnetic Atoms

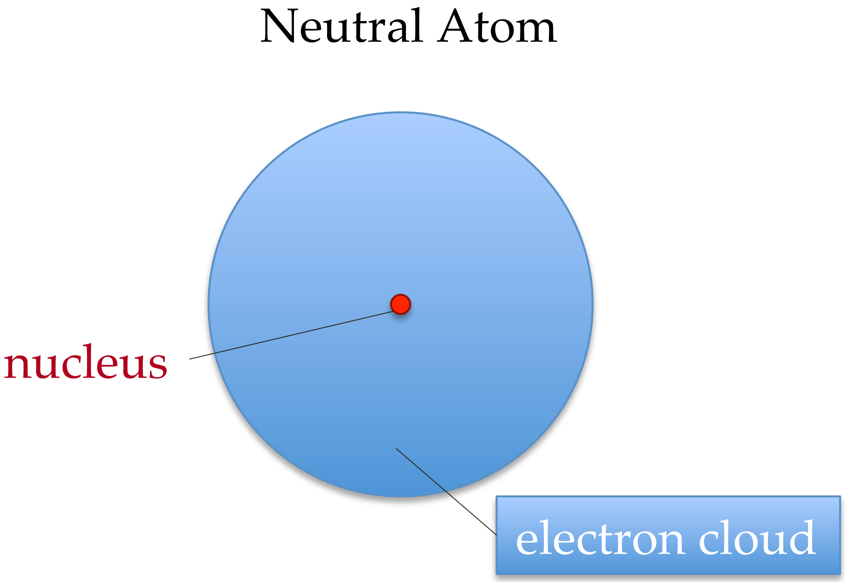
  Schiff PR 132, 2194 (1963)

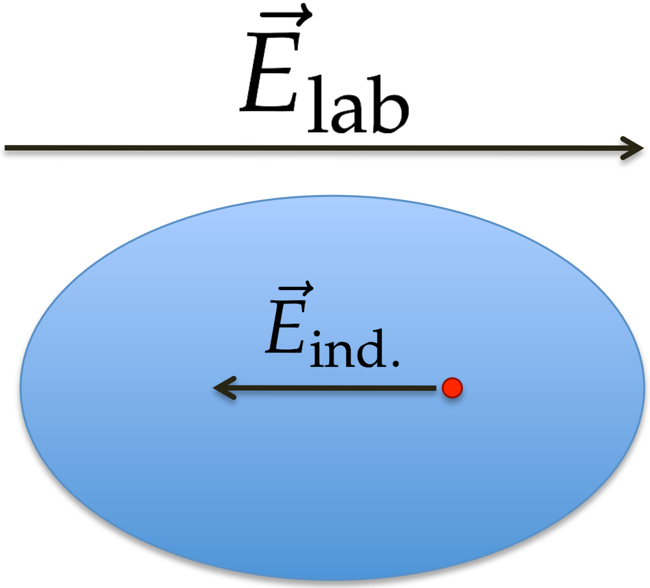
- Relativistic atomic structure ($^{225}\mathrm{Ra}/^{199}\mathrm{Hg} \sim 3$)

  Dzuba, Flambaum, Ginges, & Kozlov PRA 66, 012111 (2002)

Schiff Moment

$$\vec{S} = \frac{\langle e r^2 \vec{r} \rangle}{10} - \frac{\langle r^2 \rangle \langle e \vec{r} \rangle}{6}$$





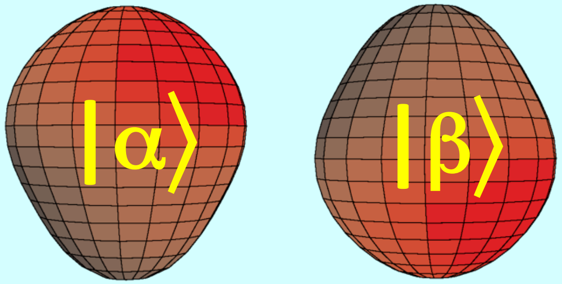
$$\vec{E}_{\mathrm{ind.}} \approx -\vec{E}_{\mathrm{lab}}$$

Enhanced Sensitivity in Ra-225

$$S_z = \frac{\langle e r^2 z\rangle}{10} - \frac{\langle r^2\rangle\langle e z\rangle}{6}$$

$$S \equiv \langle\Psi_0|\,S_z\,|\Psi_0\rangle = \sum_{k\neq 0}\frac{\langle\Psi_0|\,S_z\,|\Psi_k\rangle\langle\Psi_k|\,V_{PT}\,|\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet



$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

55 keV

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

- Nearly degenerate parity doublet

  Haxton & Henley PRL 51, 1937 (1983)

- Large intrinsic Schiff moment due to octupole deformation

  Auerbach, Flambaum, & Spevak PRL 76, 4316 (1996)

Total Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector
SIII	300	4000
SkM*	300	2000
SLy4	700	9000

^{225}*Ra:* Dobaczewski & Engel PRL 94 232502 (2005)
^{199}*Hg:* De Jesus & Engel PRC 72 045503 (2005)

Theory Difficult = Discovery Potential!

type	Hg-199	Ra-225	ratio*3	Hg-199 Ref
SIII	0.005	7.0	4300	PRC 82 015501 (2010)
SkM*	-0.027	21.5	-2400	PRC 82 015501 (2010)
SLy4	-0.006	16.9	-8600	PRC 82 015501 (2010)
SkO′		6.0		
DE05	0.071			PRC 72 045503 (2005)
DS03	0.055			PAN 66 1940 (2003)
“Best”	+/-(0.02)	6.0	+/-(900)?	Prog. PNP 71 21 (2013)

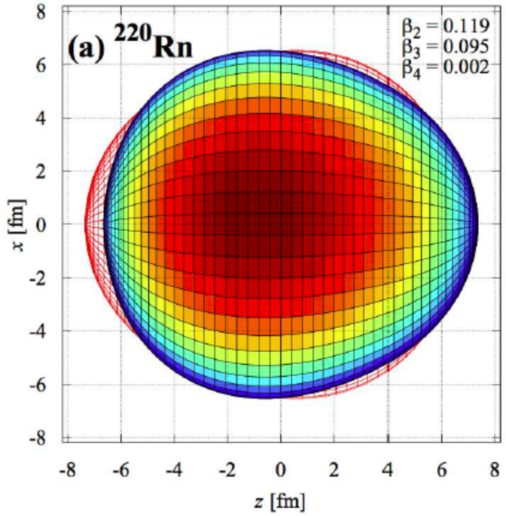
- Isovector coupling is given by “chromo”-EDMs
- Nuclei are the most sensitive to this source of new physics
- Opportunity for Ra-225 or Xe-129

Other "Deformed" Searches

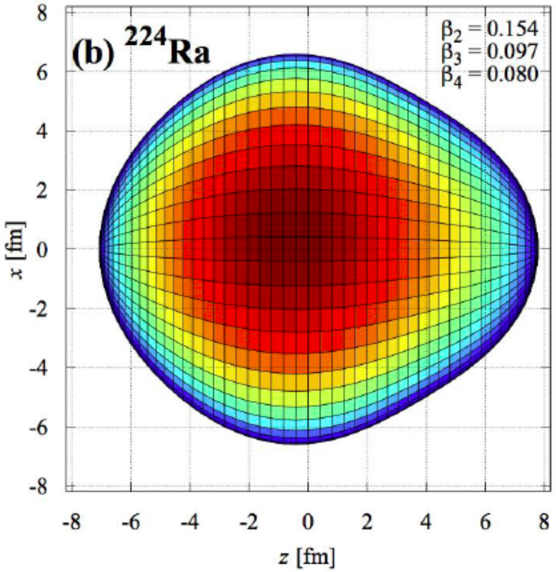
- Radon EDM @ TRIUMF (x20 to x200 vs. Hg)
- Protactinium EDM (Pa-229 is? x10^2 vs. Ra)
- Are there others? Stay tuned…

L. Gaffney et al. (Nature v497, p199, 2013)

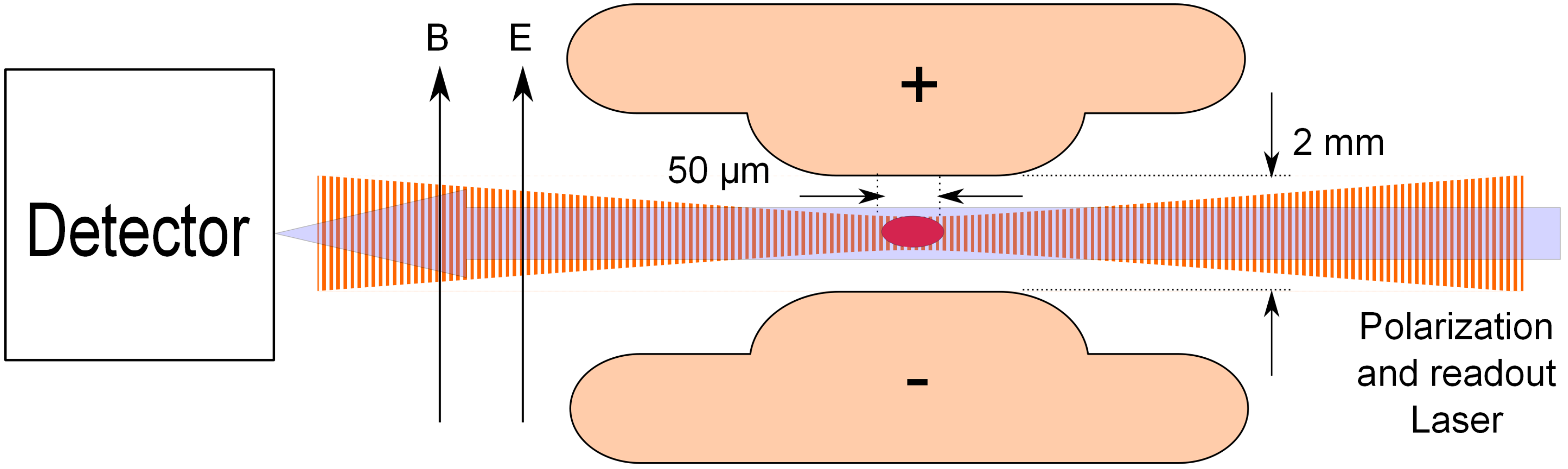
Vibrator



Permanent



Measurement Scheme



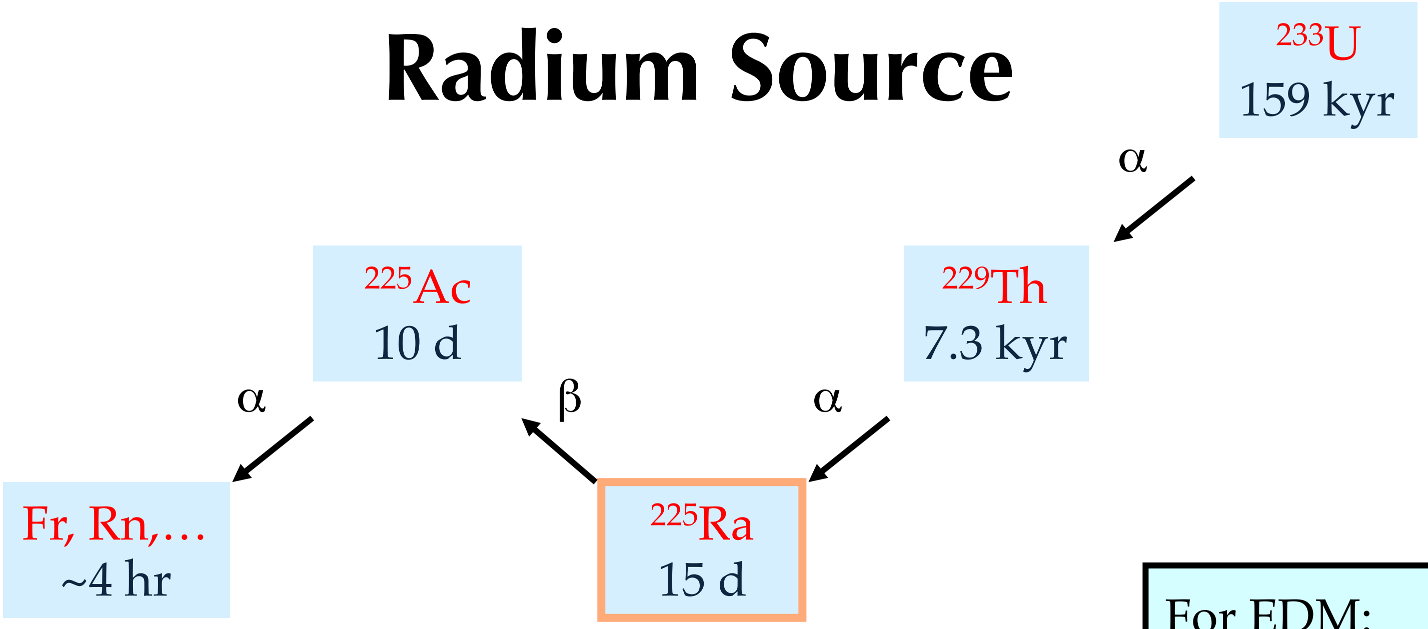
EDM search using atoms held in Optical Lattice

Romalis & Fortson PRA 59, 4547 (1999)
Chin et al. PRA 63, 033401 (2001)

^{225}Ra
Nuclear Spin = ½
Electronic Spin = 0
$t_{1/2}$ = 15 days
Low vapor pressure

- Trap allows the efficient use of ^{225}Ra
- Long coherence time (100 s)
- negligible “v x E” systematics
- High electric field (100 kV/cm) in vacuum
- Light-induced systematic effects can be controlled!

Radium Source



^{233}U
159 kyr

α

^{229}Th
7.3 kyr

α

^{225}Ra
15 d

β

^{225}Ac
10 d

α

Fr, Rn,…
~4 hr

- 2 mCi (50 ng) ^{225}Ra sources from:

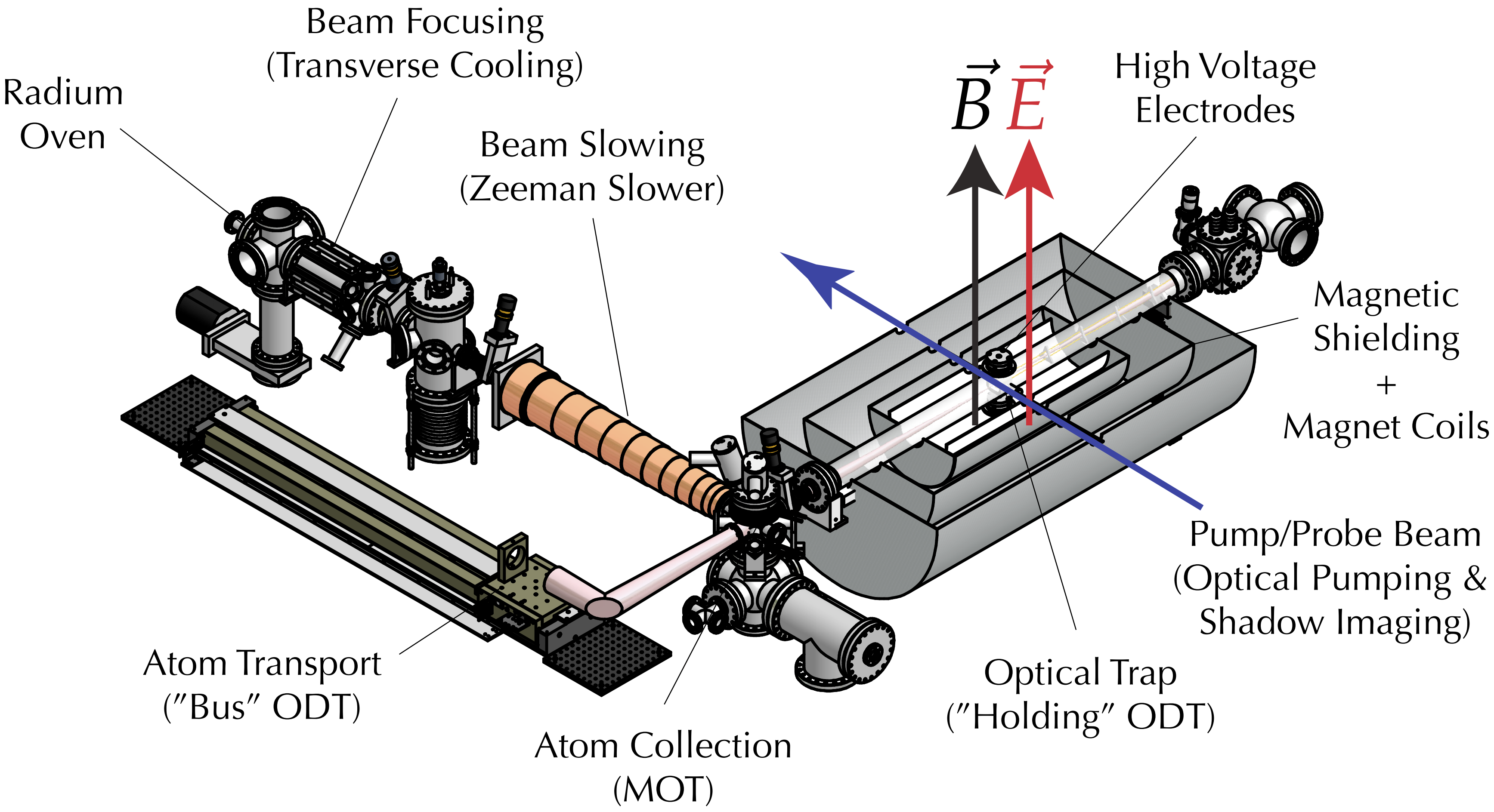
  National Isotope Development Center (Oak Ridge, TN)
- Test source: 1 μCi (1 mg) ^{226}Ra
- Integrated Atomic Beam Flux ~ 10^8/s

FRIB
Yield for ^{225}Ra ~ (10^9 to 10^{10})/s

For EDM:
^{225}Ra
Nuclear Spin = ½
$t_{1/2}$ = 15 days

For Testing:
^{226}Ra
Nuclear Spin = 0
$t_{1/2}$ = 1600 yrs

Experimental Layout



Radium Oven

Beam Focusing (Transverse Cooling)

Beam Slowing (Zeeman Slower)

$\vec{B}$ $\vec{E}$

High Voltage Electrodes

Magnetic Shielding + Magnet Coils

Pump/Probe Beam (Optical Pumping & Shadow Imaging)

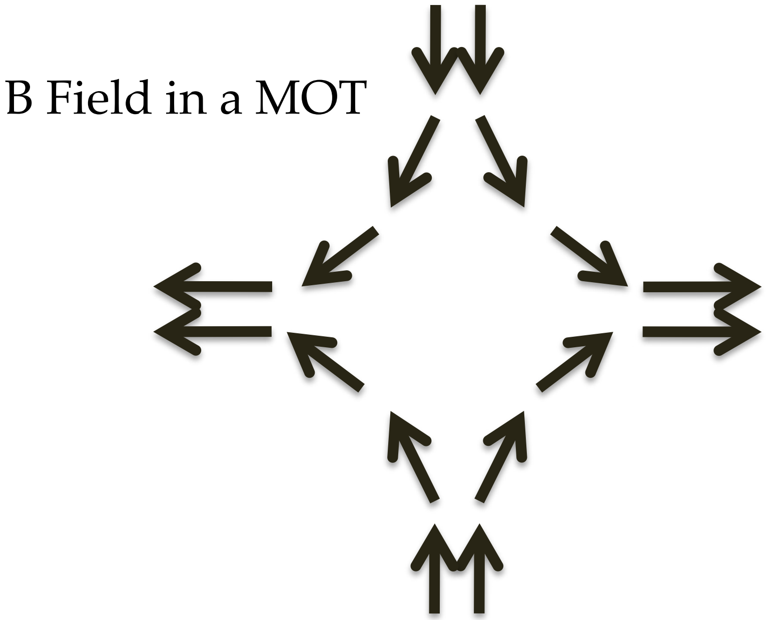
Optical Trap ("Holding" ODT)

Atom Collection (MOT)

Atom Transport ("Bus" ODT)

Neutral Atom Traps

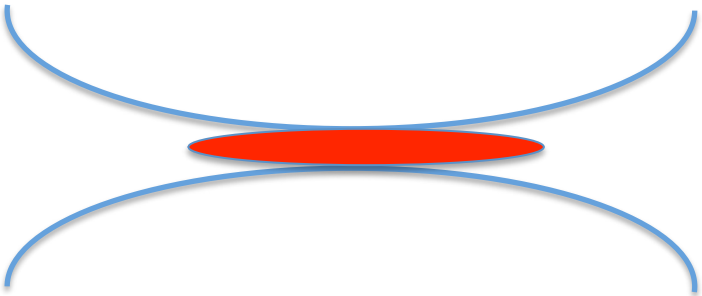
Magneto-Optical Trap (MOT)



- Large capture volume 1 cm^3
- Efficient Collection
- Unsuitable B-field region
- Capture velocity 6 cm/s = 30 μK
- Laser cool @ 714 nm
- Only 1 repump @ 1429 nm

Optical Dipole Trap (ODT)

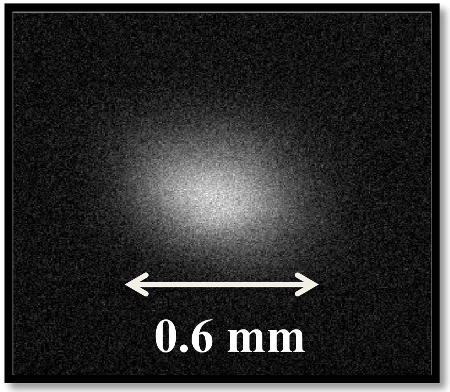
$$\mathcal{H} = -\vec{d}_{\text{ind}} \cdot \vec{E}_0 = \frac{\alpha}{4} E_0^2$$



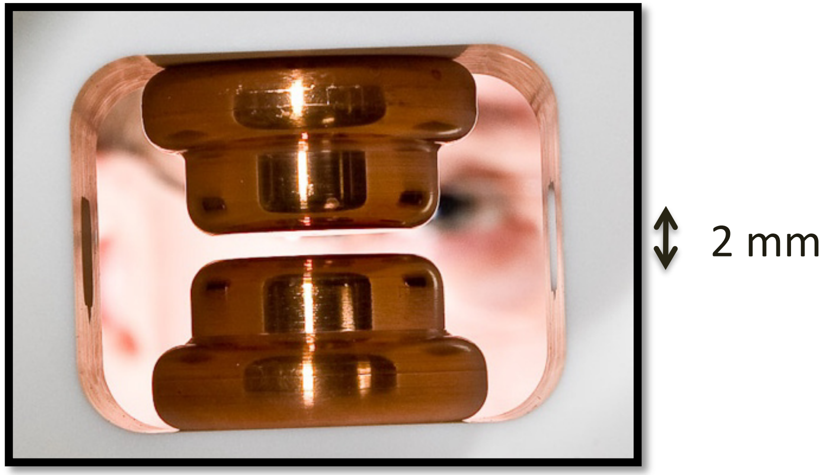
- Atoms trapped at beam focus
- 50 W @ 1550 nm
- 100 mm spot = Trap Depth of 400 μK
- Good for transporting atoms
- Good for spatially confining atoms

Collecting & Transporting Ra-225 Atoms

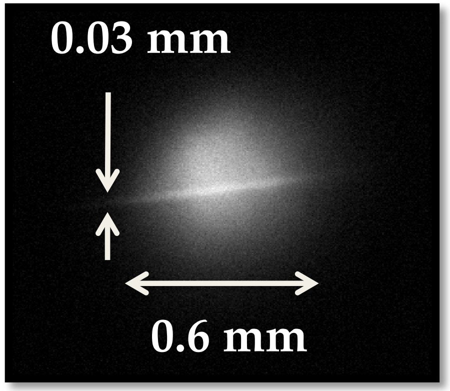
Guest et al., PRL 98 093001 (2007)



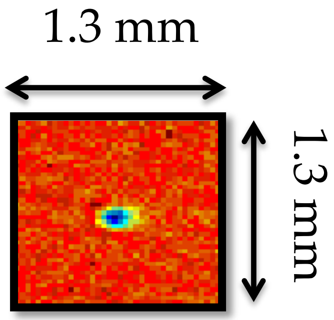
^{226}Ra MOT
20,000 atoms



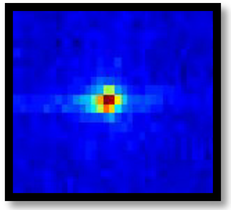
Parker et al., PRC 86 065503 (2012)



MOT + ODT
20,000 atoms



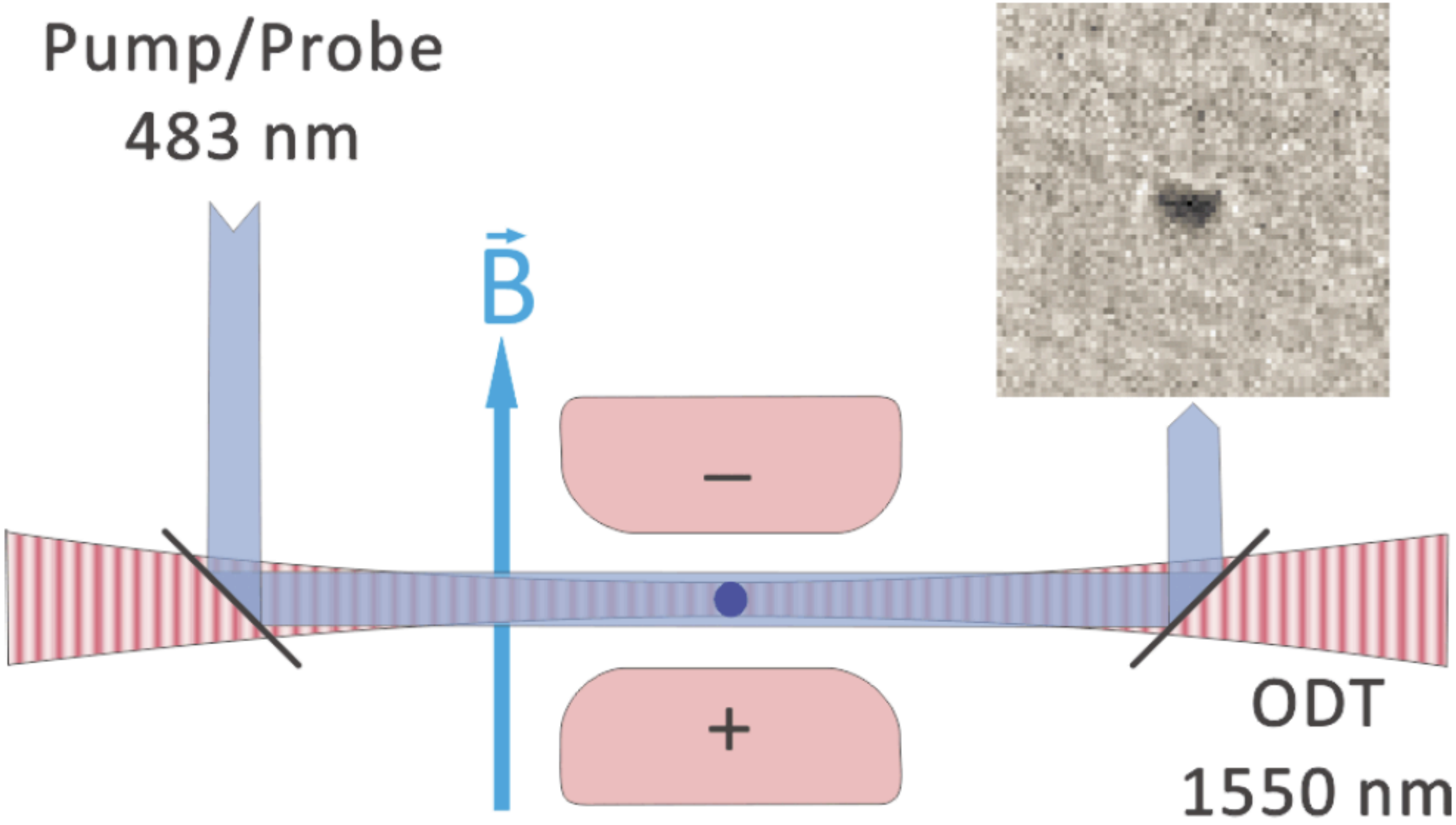
Absorption
Imaging



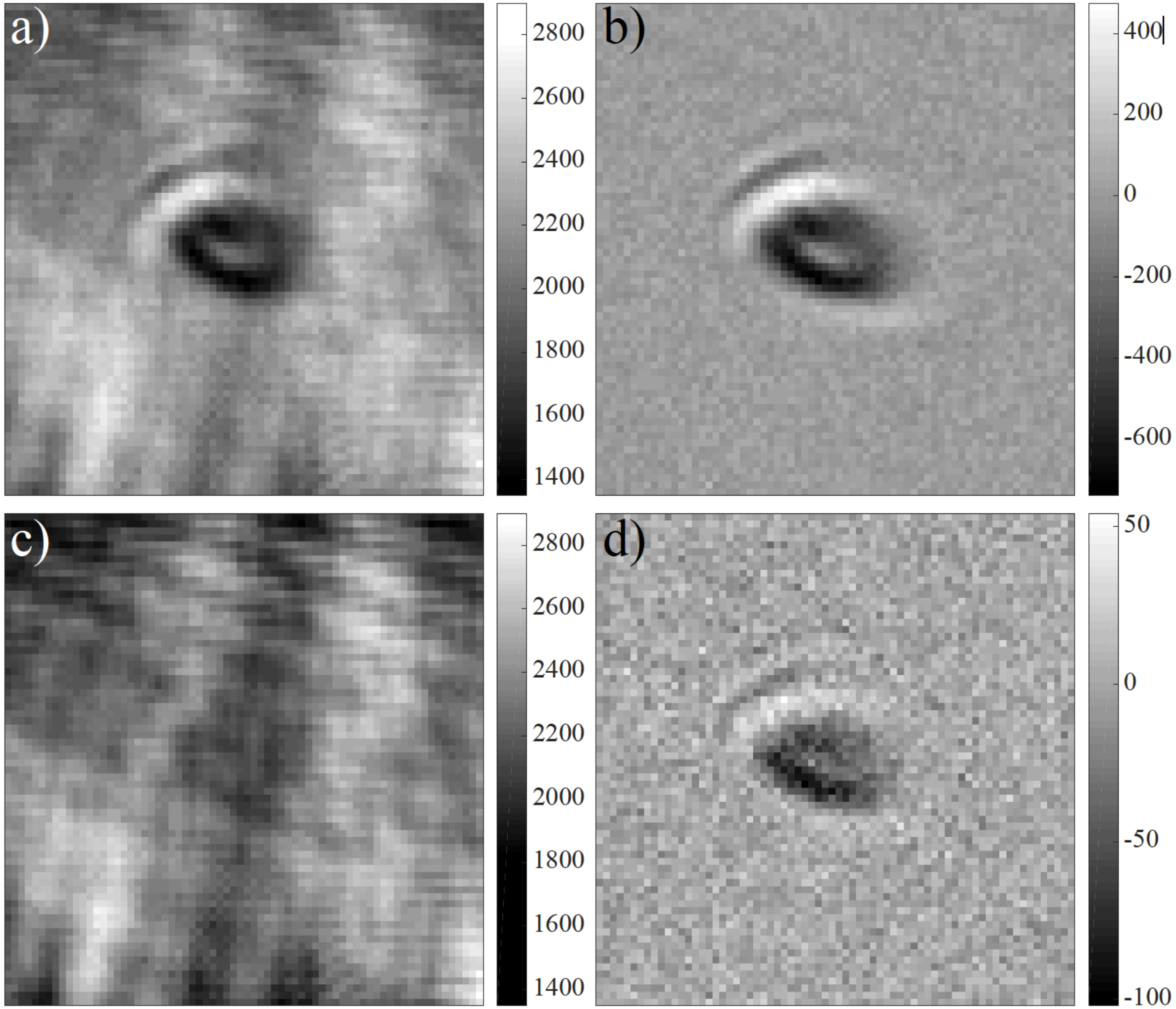
Fluoresence
Imaging

3000
atoms

Atoms create a shadow by absorption



Shadow Image Analysis: Background & Distortion Corrections



raw image
of Ra-226

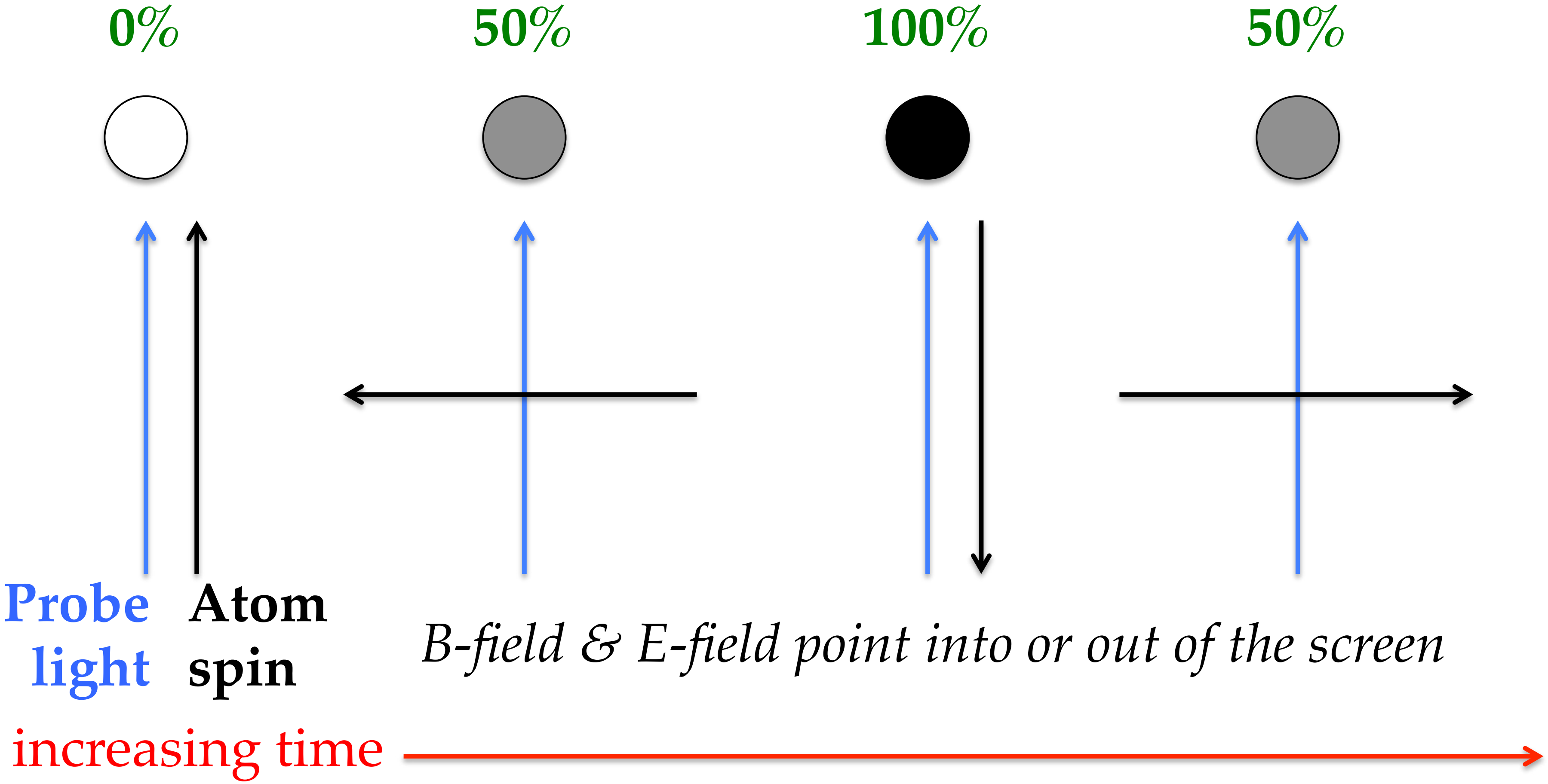
Ra-226
only

composite
background

Ra-225
only

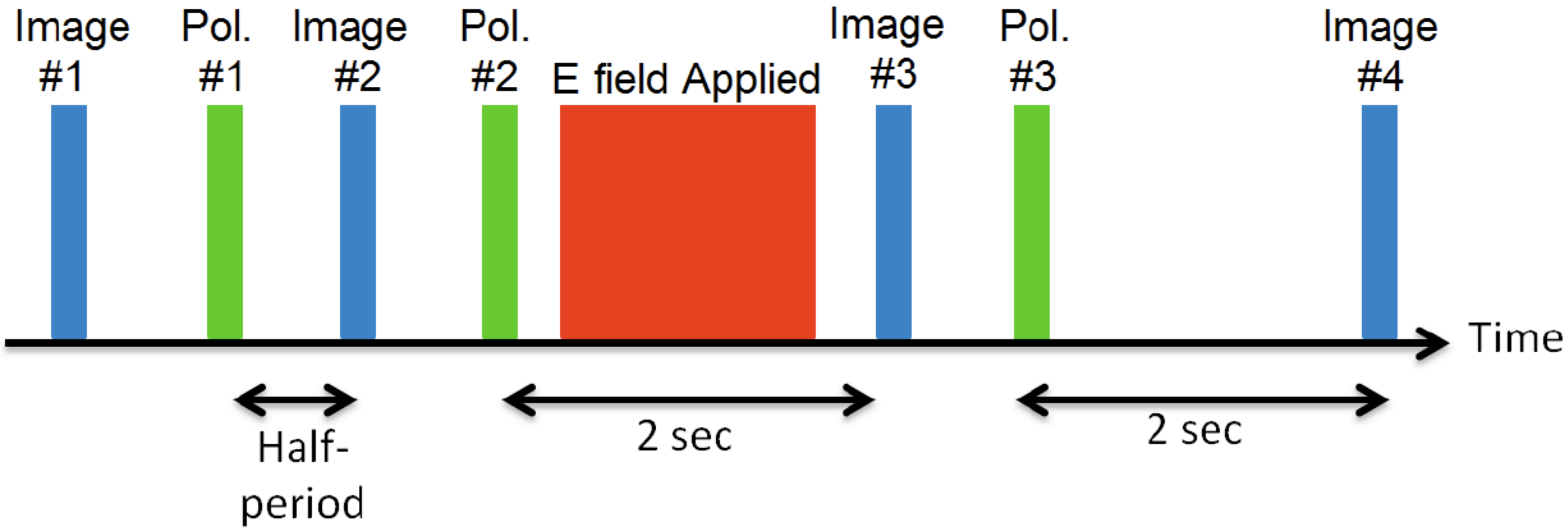
Absorption probability oscillates at ~20 Hz

probability of absorbing probe light and creating a shadow:



B-field & E-field point into or out of the screen

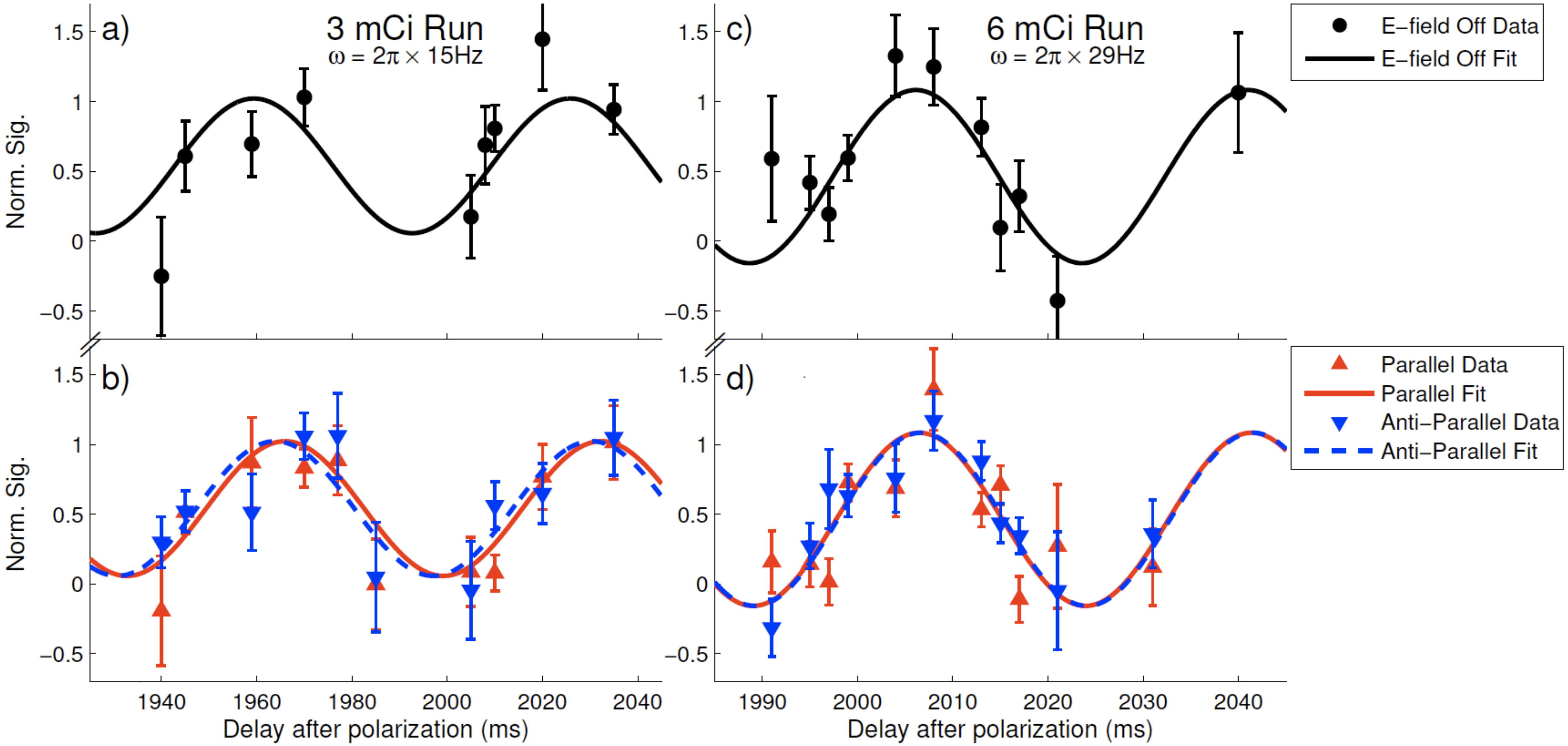
Several images are taken



Images taken to account for changes in atom number and probe light intensity.

Data taken for electric parallel, anti-parallel, and off for different time delays.

Ra-225 EDM, Proof of principle

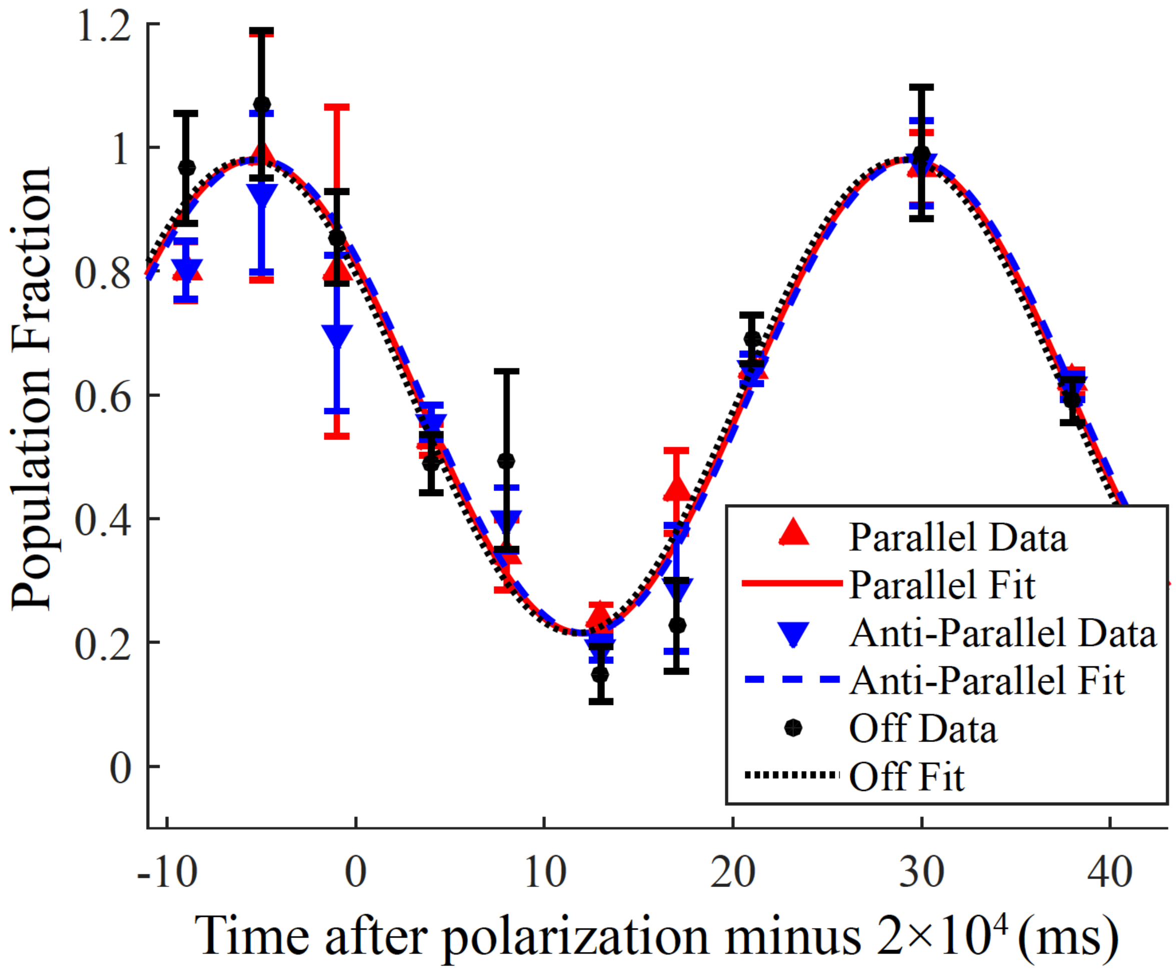


First Result & Systematics

parameter	central	uncertainty
Oct. 2014 (3 mCi)	-4.0	5.2
Dec. 2014 (6 mCi)	+0.6	2.9
E^2	+0.1	0.1
HV correlations	<0.001	<0.001
leakage current	<0.001	<0.001
vxE	<0.001	<0.001
laser trap	<0.001	<0.001

Parker *et al*. PRL 114, 233002 (2015)
$|d(\mathrm{Ra\text{-}225})| < 5\mathrm{x}10^{-22}$ *e* cm (95%)

New Preliminary Data! 2 to 20 s: x30 better



Next Steps & Upgrades

$$\frac{\sigma_d}{\sqrt{N}} = \left(\frac{n/\sqrt{\tau}}{S}\right)\frac{\hbar\sqrt{3}}{E\sqrt{\epsilon T\tau}}$$

parameter	present	~5 yrs	upgrades
Atom number	10^2	10^4	more atoms, better trapping
E, electric field	67 kV/cm	>100 kV/cm	new electrodes
τ, obs. time	20 sec	100 sec	better vacuum, stable laser
T, integration time	1 day	10 days	all better
ε, efficiency	10^{-4}	10^{-1}	better detection better DAQ

Systematics will be studied and controlled using a Yb-171 trap!

Yields of Enhancer Isotopes

Presently available

- Decay daughters of ^{229}Th, National Isotope Development Center, ORNL
  - ^{225}Ra: 10^{8} /s

Projected rates at FRIB (B. Sherrill, MSU)

- Beam dump recovery with a ^{238}U beam
  - Parasitic operation, available ~ 150 days per year
  - ^{225}Ra: 6 x 10^{9} /s ; ^{223}Rn: 8 x 10^{7} /s; $^{208\text{-}220}$Fr: 10^{9} -10^{10} /s.

- Dedicated running with a ^{232}Th beam
  - ^{225}Ra: 5 x 10^{10} /s ; ^{223}Rn: 1 x 10^{9} /s; $^{208\text{-}220}$Fr: 10^{10} /s;

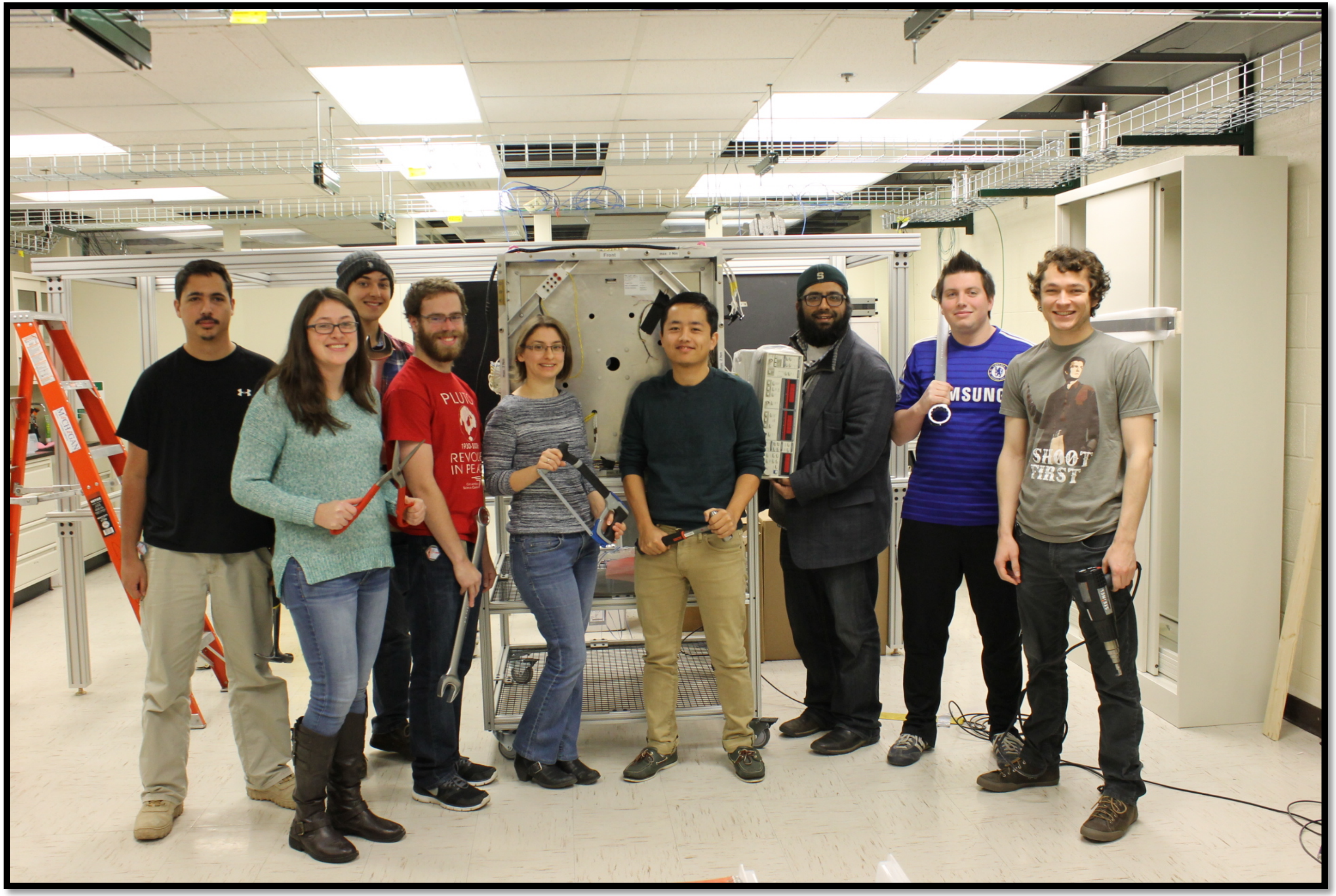
FRIB will produce isotopes with enhanced sensitivity to fundamental symmetries, and provide opportunities for discovering physics beyond the Standard Model.

Z.-T. Lu

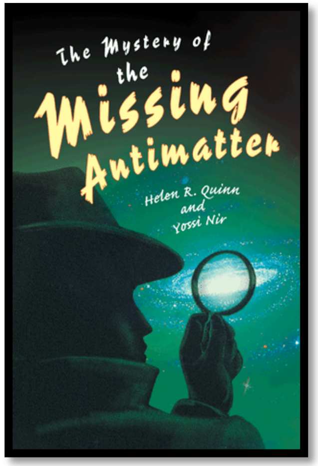
Ra EDM Team

Z.-T. Lu, **N.D. Lemke**, **M.R Dietrich**, T.P. O'Connor
P. Mueller, R.J. Holt, **M.R. Kalita**, J. Singh, **R.H. Parker**,
K.G. Bailey, W. Korsh, not pictured: **M. Bishof**

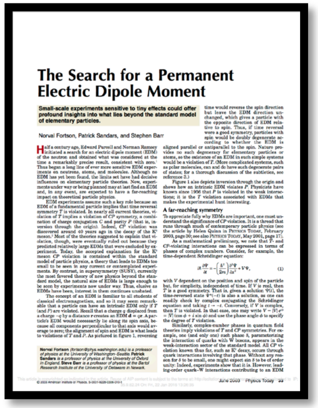
MSU Team: Thanks For Your Attention!



For more information…



The Mystery of the Missing Antimatter
by: Helen R. Quinn and Yossi Nir
Princeton University Press (2014)



The Search for a Permanent Electric Dipole Moment

Small-scale experiments sensitive to tiny effects could offer profound insights into what lies beyond the standard model of elementary particles.

Norval Fortson, Patrick Sandars, and Stephen Barr

Half a century ago, Edward Purcell and Norman Ramsey initiated a search for an electric dipole moment (EDM) of the neutron and obtained what was considered at the time a remarkably precise result, consistent with zero.[1] Thus began a long line of ever more sensitive EDM experiments on neutrons, atoms, and molecules. Although no EDM has yet been found, the limits set have had decisive influences on elementary particle theories. Now, experiments under way or being planned may at last find an EDM and, in any event, are expected to have a far-reaching impact on theoretical particle physics.

EDM experiments assume such a key role because an EDM of a fundamental particle implies that time reversal symmetry T is violated. In nearly all current theories, violation of T implies a violation of CP symmetry, a combination of charge conjugation C and parity P (that is, inversion through the origin). Indeed, CP violation was discovered around 40 years ago in the decay of the K^0 meson.[2] Most of the theories suggested to explain that violation, though, were eventually ruled out because they predicted relatively large EDMs that were excluded by experiment. Today, the accepted explanation for the K^0 meson CP violation is contained within the standard model of particle physics, a theory that leads to EDMs too small to be seen in any current or contemplated experiments. By contrast, in supersymmetry (SUSY), currently the most favored theory of new physics beyond the standard model, the natural size of EDMs is large enough to be seen by experiments now under way. Thus, elusive as EDMs have been, interest in them continues unabated.

The concept of an EDM is familiar to all students of classical electromagnetism, and so it may seem remarkable that a particle can have an intrinsic EDM only if T (and P) are violated. Recall that a charge q displaced from a charge $-q$ by a distance $\mathbf{r}$ creates an EDM $\mathbf{d} = q\mathbf{r}$. A particle's EDM would necessarily lie along its spin axis, because all components perpendicular to that axis would average to zero; the alignment of spin and EDM is what leads to violations of T and P. As pictured in figure 1, reversing time would reverse the spin direction but leave the EDM direction unchanged, which gives a particle with the opposite direction of EDM relative to spin. Thus, if time reversal were a good symmetry, particles with spin would be doubly degenerate according to whether the EDM is aligned parallel or antiparallel to the spin. Nature provides no such degeneracy for elementary particles or atoms, so the existence of an EDM in such simple systems would be a violation of T. (More complicated systems, such as polar molecules, can and do have such degenerate pairs of states; for a thorough discussion of the subtleties, see reference 3.)

Figure 1 also depicts inversion through the origin and shows how an intrinsic EDM violates P. Physicists have known since 1956 that P is violated in the weak interactions; it is the T violation associated with EDMs that makes the experimental hunt interesting.

A far-reaching symmetry

To appreciate fully why EDMs are important, one must understand the significance of CP violation. It is a thread that runs through much of contemporary particle physics (see the article by Helen Quinn in PHYSICS TODAY, February 2003, page 30; see also PHYSICS TODAY, May 2001, page 17).

As a mathematical preliminary, we note that T- and CP-violating interactions can be expressed in terms of phases of complex numbers. Consider, for example, the time-dependent Schrödinger equation:

$$i\hbar\frac{\partial\Psi}{\partial t} = -\left(\frac{\hbar^2}{2m}\right)\frac{\partial^2\Psi}{\partial x^2} + V\Psi, \qquad (1)$$

with V dependent on the position and spin of the particle but, for simplicity, independent of time. If V is real, then T is a good symmetry. That is, given a solution $\Psi(t)$, the time-reversed state $\Psi^*(-t)$ is also a solution, as one can readily check by complex conjugating the Schrödinger equation and taking $t \to -t$. Conversely, if V is complex, then T is violated. In that case, one may write $V = |V|\,e^{i\phi} = |V|\,(\cos\phi + i\sin\phi)$ and use the phase angle ϕ to specify the degree of T violation.

Similarly, complex-number phases in quantum field theories imply violations of T and CP symmetries. For example, one (and only one) such phase δ, parameterizing the interaction of quarks with W bosons, appears in the weak-interaction sector of the standard model. All CP violation known thus far, such as K^0 decay, occurs through quark interactions involving that phase. Without any reason for δ to be small, one might expect $\sin\delta$ to be of order unity. Indeed, experiments show that it is. However, leading-order quark–W interactions contributing to an EDM

Norval Fortson (fortson@phys.washington.edu) is a professor of physics at the University of Washington–Seattle. ***Patrick Sandars*** *is a professor of physics at the University of Oxford in England.* ***Steve Barr*** *is a professor of physics at the Bartol Research Institute of the University of Delaware in Newark.*

The search for a permanent electric dipole moment
Norval Fortson, Patrick Sandars & Stephen Barr
Physics Today, June 2003, page 33

REVIEWS OF MODERN PHYSICS, VOLUME 75, OCTOBER 2003

Colloquium: Measuring and understanding the universe

Wendy L. Freedman*
Observatories of the Carnegie Institution of Washington, 813 Santa Barbara St., Pasadena, California 91101, USA

Michael S. Turner
Center for Cosmological Physics and the Departments of Astronomy & Astrophysics and of Physics, The University of Chicago, 5640 S. Ellis Ave., Chicago, Illinois 60637-1433, USA, and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, MS 209, P.O. Box 500, Batavia, Illinois 60510-0500, USA

(Published 10 November 2003)

Revolutionary advances in both theory and technology have launched cosmology into its most exciting period of discovery yet. Unanticipated components of the universe have been identified, promising ideas for understanding the basic features of the universe are being tested, and deep connections between physics on the smallest scales and on the largest scales are being revealed.

CONTENTS

I. INTRODUCTION

Thirty years ago, cosmology was described as a search for two numbers: the current expansion rate (or Hubble constant) H_0, and its change over time, the deceleration parameter, q_0 (Sandage, 1970). But that was before the discovery of giant walls of galaxies, voids, dark matter, tiny variations in the cosmic microwave background radiation (CMB), dark energy, and the acceleration of the universe. Today, the subject has become vastly richer, and the numbers being sought are more numerous but more closely tied to fundamental theory. An overall picture has emerged that accounts for the origin of structure and geometry of the universe, as well as describing its evolution from a fraction of a second onward.

In this new and still-evolving picture rooted in elementary particle physics, in a tiny fraction of a second during the early history of the universe, there was an enormous burst of expansion called inflation. This burst smoothed out wrinkles and curvature in the fabric of spacetime, and stretched quantum fluctuations on subatomic scales to astrophysical scales. Following inflation was a phase when the universe was a hot thermal mixture of elementary particles, out of which arose all the forms of matter that exist today. Some 10 000 years into its evolution, gravity began to grow the tiny lumpiness in the matter distribution arising from quantum fluctuations into the rich cosmic structures seen today, from individual galaxies to the great clusters of galaxies and superclusters.

Recent observations of the universe have not only strengthened and expanded the big-bang model, but they have also revealed surprises. In particular, most of the universe is made of something fundamentally different from the ordinary matter of which we are made. (By ordinary matter, we mean matter made of neutrons and protons; the jargon for this is baryons, the technical term for particles made of quark triplets.) About 30% of the total mass energy is dark matter, composed of particles most likely formed early in the universe. Two-thirds is in a smooth "dark energy" whose gravitational effects began causing the expansion of the universe to speed up just a few billion years ago. Ordinary matter, the bulk of it dark, only accounts for the remaining 4% of the total mass-energy density of the universe. While the remnant (thermal) microwave background from the hot big bang contributes only about 0.01%, it encodes information about the spacetime structure of the universe, about its early history, and possibly even about its ultimate fate.

We have also learned much about the organization of the universe. In the nearby universe, galaxies are distributed in a "cosmic web" composed of sheets and sinuous filaments interspersed with voids (see Fig. 1). Though inhomogeneous on these apparently vast scales, the universe becomes more and more homogeneous when viewed on even larger scales from 100 Mpc out to the current horizon of 10 000 Mpc.

---

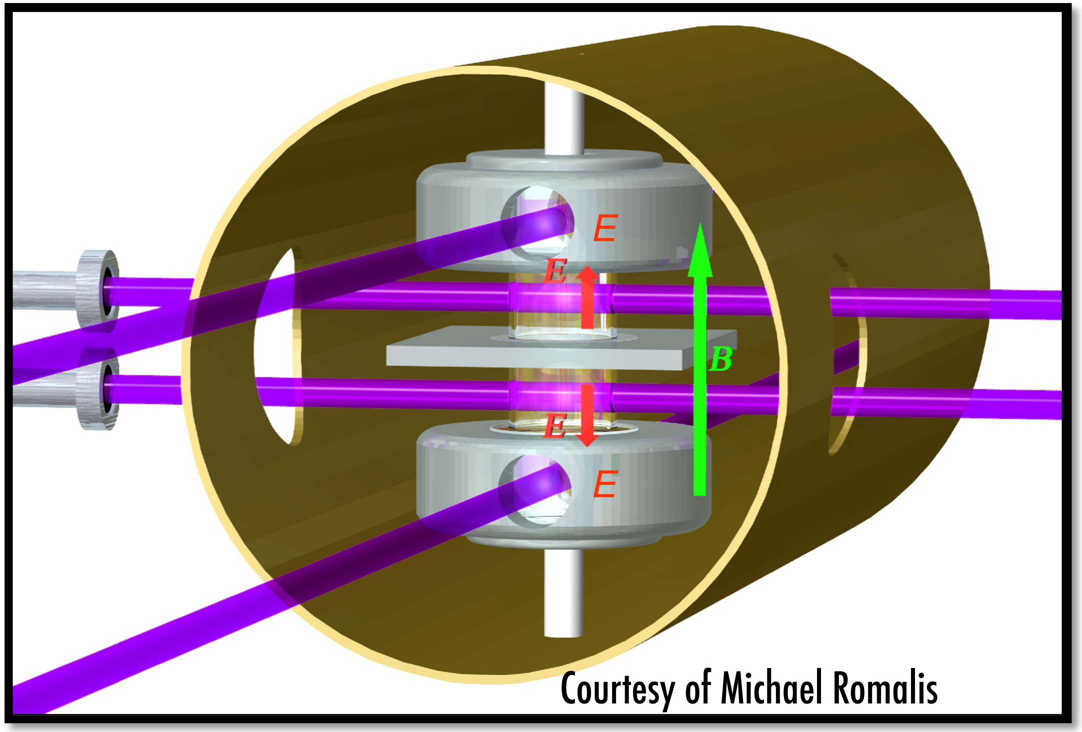
*Electronic address: wendy@ociw.edu

0034-6861/2003/75(4)/1433(15)/$35.00

Colloquium: Measuring and understanding the universe
Wendy L. Freedman and Michael S. Turner
Rev. Mod. Phys. 75, 1433 – Published 10 November 2003

Backup Slides

The Seattle Hg-199 EDM Search



Courtesy of Michael Romalis

- **diamagnetic**, $^1S_0$ ground state
- ***I* = ½**, no elect. quad. moment
- **high Z**, (80) rel. atomic struct.
- **stable**, (17% n.a.) 92% enriched
- **high vapor pressure**, (10^{13}/ cm^3)

$$h\nu_\pm = 2\mu B \pm 2dE$$

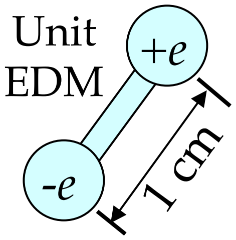
$$\bar{\nu} = 2\mu B/h = 16\text{ Hz}$$

$$\Delta\nu = 4dE/h \leq 0.1\text{ nHz}$$

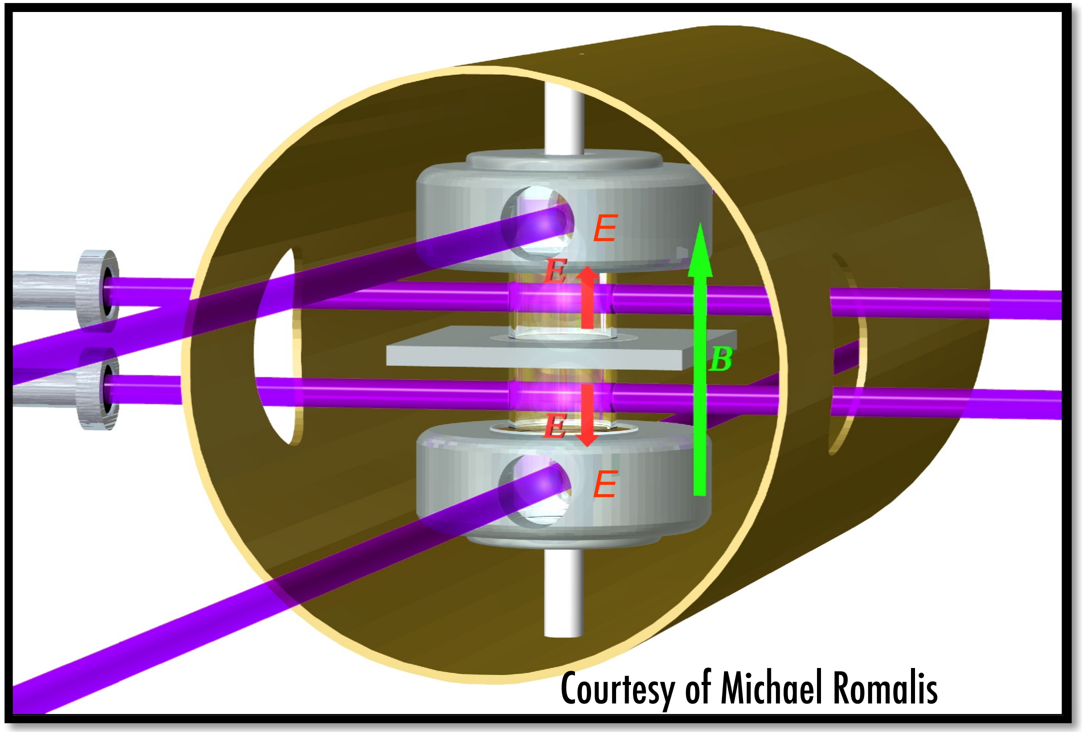
The best limit on atomic EDM:

EDM(^{199}Hg) < $3.1\text{x}10^{-29}$ *e*-cm (95% C.L.)

Griffith et al., PRL 102, 101601 (2009)



The Seattle Hg-199 EDM Search



Courtesy of Michael Romalis

- **diamagnetic**, $^1S_0$ ground state
- ***I* = ½**, no elect. quad. moment
- **high Z**, (80) rel. atomic struct.
- **stable**, (17% n.a.) 92% enriched
- **high vapor pressure**, (10^{13}/ cm^3)

$$h\nu_\pm = 2\mu B \pm 2dE$$

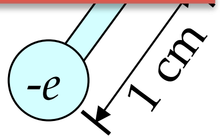
$$\bar{\nu} = 2\mu B/h = 16\text{ Hz}$$

$$\Delta\nu = 4dE/h \leq 0.1\text{ nHz}$$

note from Blayne Heckel (Jan. 2014): taking data now,
have the already collected enough data to surpass earlier limit,
can ultimately do x10 better than 2009 result

EDM(^{199}Hg) < 3.1x10^{-29} *e*-cm (95% C.L.)

Griffith et al., PRL 102, 101601 (2009)

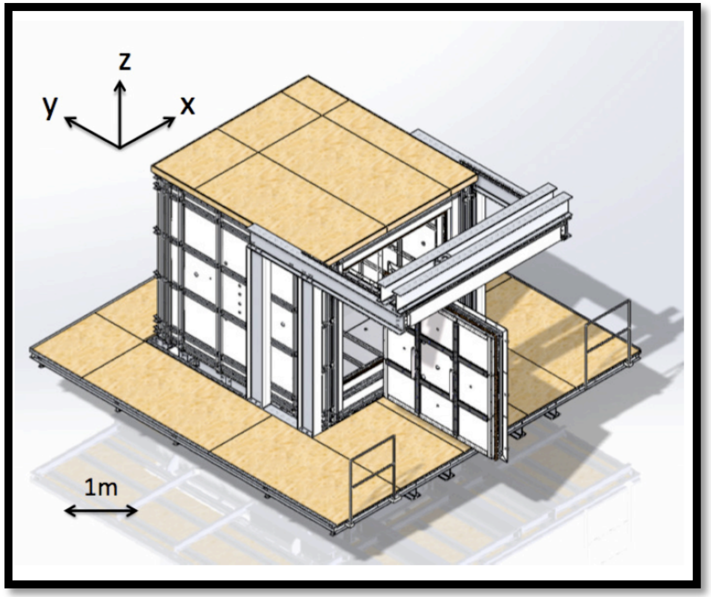


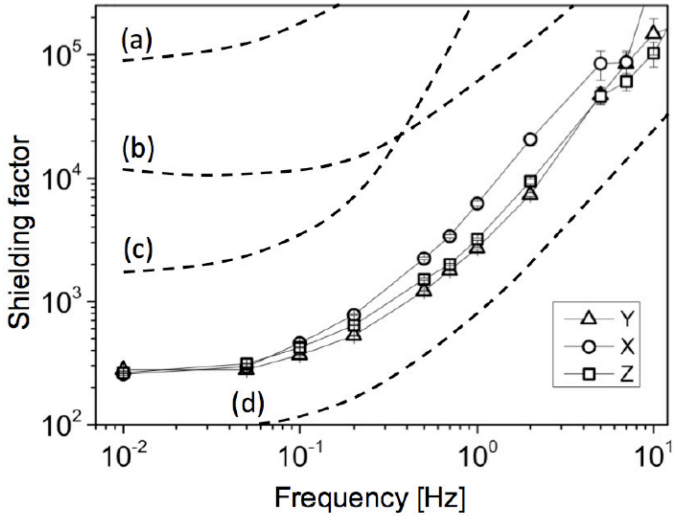
Potential Statistical Sensitivity

symbol, parameter	2001 Maser	long term potential	now (June 2015)	after detector upgrade
$S/(n/\sqrt{\tau})$, signal to noise	5×10^3	3×10^6	10^3	10^5
τ, obs. time (s)	1000	1000	2500	500
σ_ν, single-shot frequency precision (nHz)	300	0.2	5000	30
E, electric field (kV / cm)	3.6	10	4	5
T, integration time (days)	150	1		15
ε, efficiency	0.2	1		0.5
σ_d, stat. only (10^{-28} e cm)	33	0.04		3

$$\frac{\sigma_d}{\sqrt{N}} = \left(\frac{n/\sqrt{\tau}}{S}\right)\frac{\hbar\sqrt{3}}{E\sqrt{\epsilon T\tau}}$$

Magnetically Shielded Room





Altarev et al., Rev. Sci. Instrum. 85 075106 (2014)

- low residual fields ~ nT (50000 less than the Earth's field)
- very stable in time to 10 parts per million
- very uniform (1 pT/cm)
- Already demonstrated 10000 sec T_2 for He-3

Stepwise goals for Xe-129 EDM

system	upper limit in 10^{-28} *e* cm (95% C.L.)	reference
^{199}Hg	0.31 (~0.03, data analysis underway)	PRL **102**, 101601 (2009)
^{129}Xe	**66 (~0.6 goal, multiple groups)**	PRL **86**, 22 (2001)
^{225}Ra	5000000 (~5000 goal, ANL/MSU/UK)	PRL **114**, 233002 (2015)
neutron	350 (~3 goal, multiple groups)	PRL **97**, 131801 (2006)

- **x10 improvement**: potential co-magnetometer for next generation neutron EDM searches
- **x100 improvement**: constrains nuclear spin-*dependent* electron-nucleus couplings by x10
- **x1000 improvement**: constrains all parameters by at least x10 and provides independent verification of null Hg-199 EDM result

Advantages of Our Approach

Polarized Noble Gases

- large magnetizations (nT) using standard techniques
- polarized ^{3}He for co-magnetometry
- very long spin precession times (10^3 seconds)

SQUID Detectors

- very sensitive detection (1 fT/root-Hz noise floor)

Magnetically Shielded Room

- small (<1 nT) and uniform (<10 pT/cm) residual *B*-field
- high shielding factor (>10^6)
- low noise environment for electronics

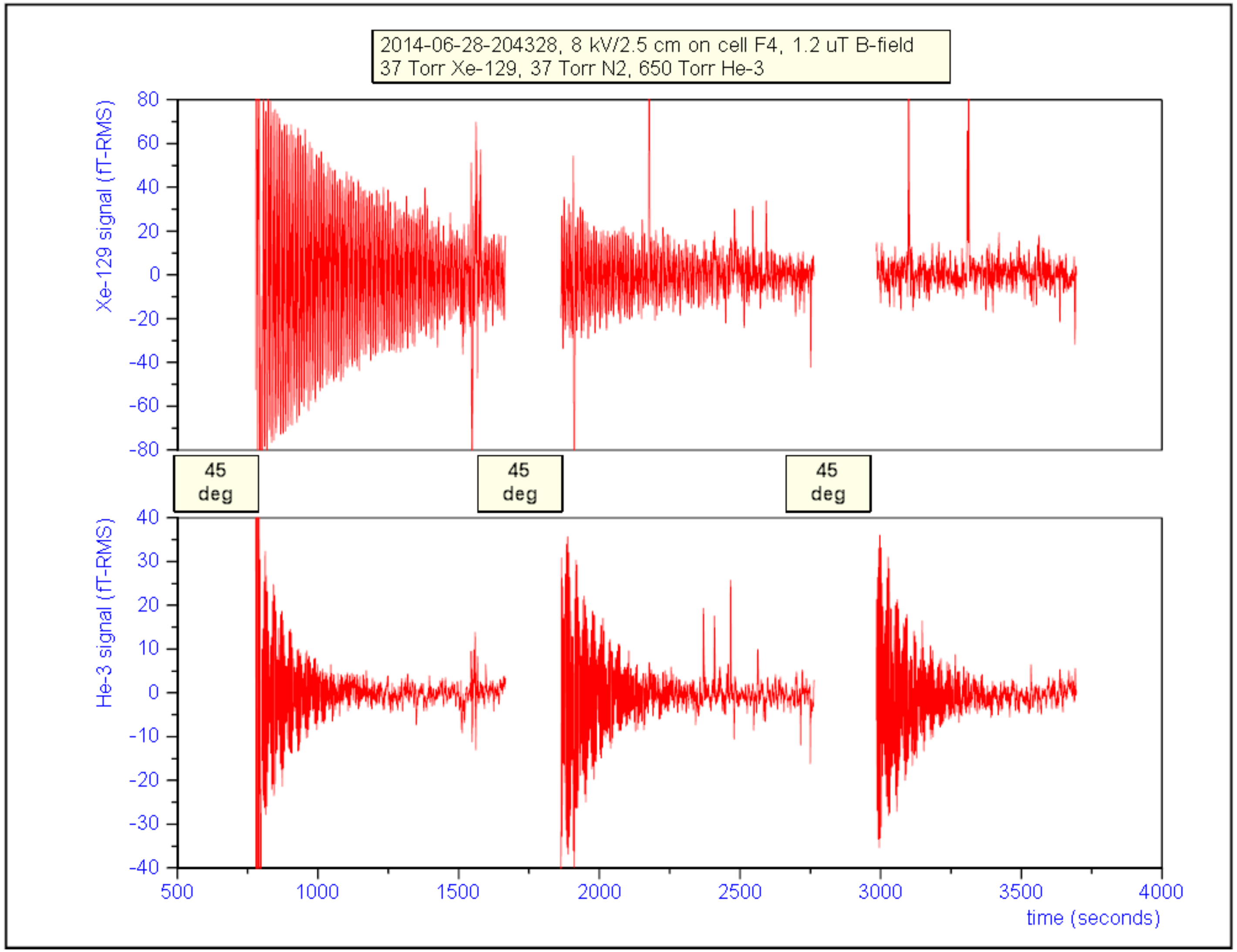
Precision Atomic Magnetometry

- Cs and Hg magnetometers monitor the *B*-field

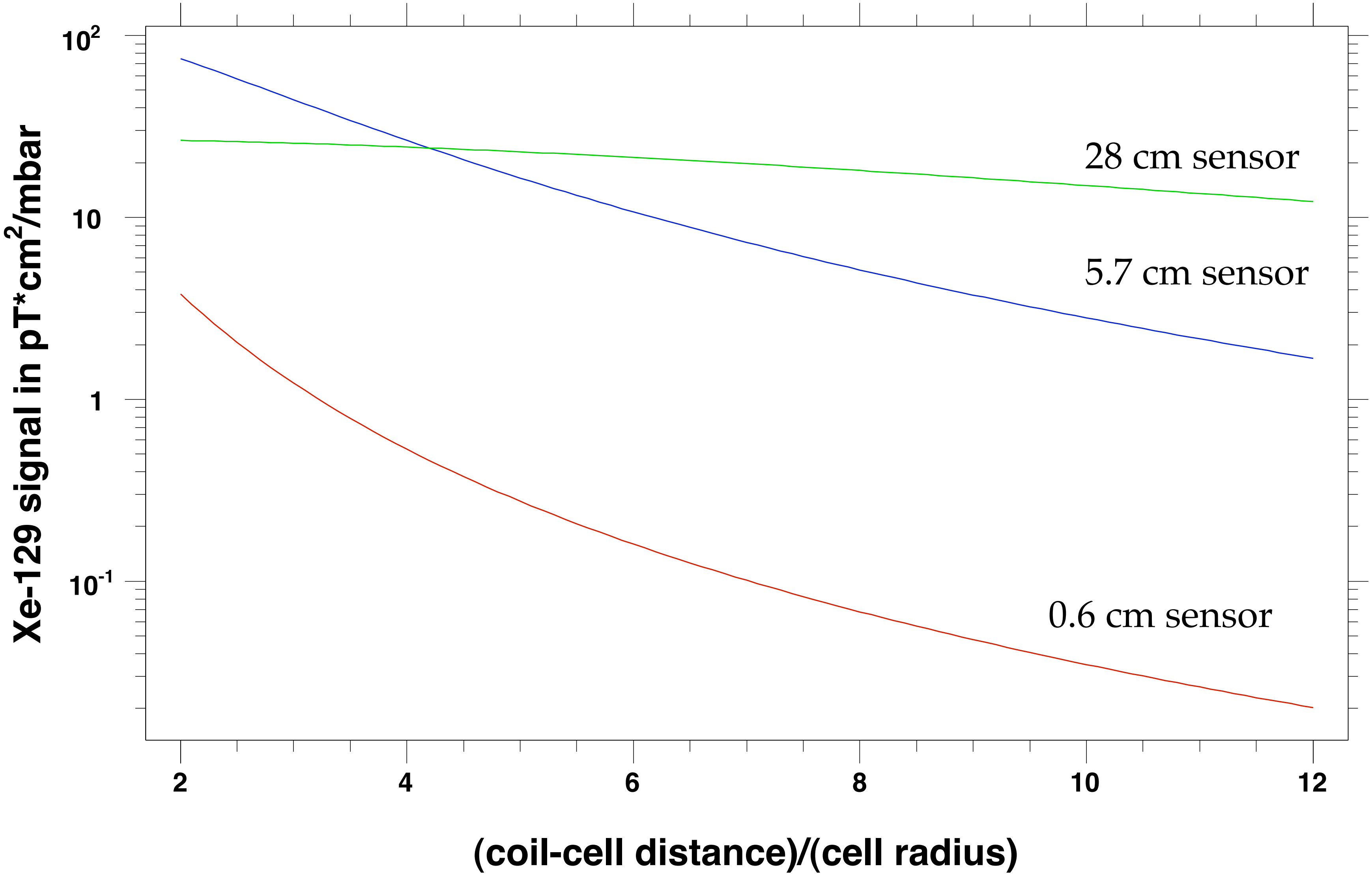
Pulse NMR with HV

Xe-129

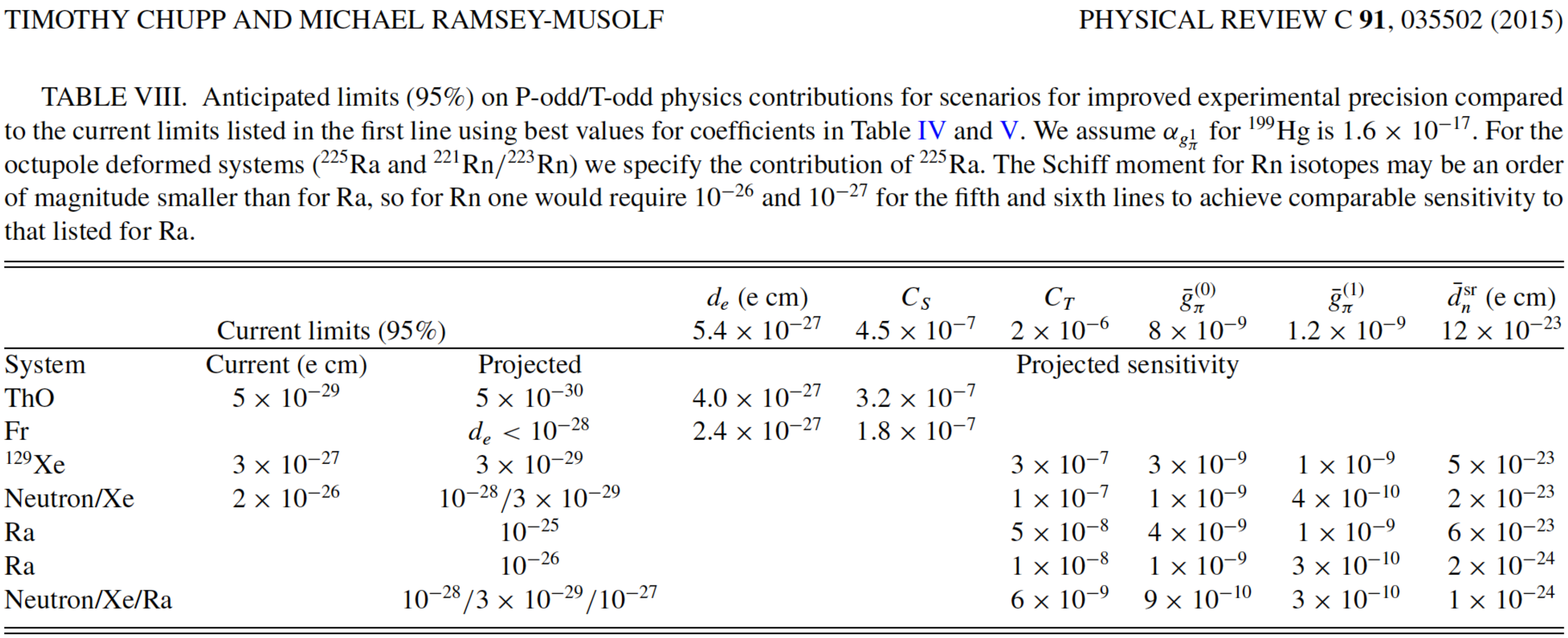
He-3



Decrease Sensor to Cell Distance



Improved Constraints



TIMOTHY CHUPP AND MICHAEL RAMSEY-MUSOLF PHYSICAL REVIEW C **91**, 035502 (2015)

TABLE VIII. Anticipated limits (95%) on P-odd/T-odd physics contributions for scenarios for improved experimental precision compared to the current limits listed in the first line using best values for coefficients in Table IV and V. We assume $\alpha_{g_\pi^1}$ for ^{199}Hg is 1.6×10^{-17}. For the octupole deformed systems (^{225}Ra and ^{221}Rn/^{223}Rn) we specify the contribution of ^{225}Ra. The Schiff moment for Rn isotopes may be an order of magnitude smaller than for Ra, so for Rn one would require 10^{-26} and 10^{-27} for the fifth and sixth lines to achieve comparable sensitivity to that listed for Ra.

	Current limits (95%)		d_e (e cm)	C_S	C_T	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n^{\mathrm{sr}}$ (e cm)
			5.4×10^{-27}	4.5×10^{-7}	2×10^{-6}	8×10^{-9}	1.2×10^{-9}	12×10^{-23}
System	Current (e cm)	Projected	Projected sensitivity					
ThO	5×10^{-29}	5×10^{-30}	4.0×10^{-27}	3.2×10^{-7}				
Fr		$d_e < 10^{-28}$	2.4×10^{-27}	1.8×10^{-7}				
^{129}Xe	3×10^{-27}	3×10^{-29}			3×10^{-7}	3×10^{-9}	1×10^{-9}	5×10^{-23}
Neutron/Xe	2×10^{-26}	$10^{-28}/3 \times 10^{-29}$			1×10^{-7}	1×10^{-9}	4×10^{-10}	2×10^{-23}
Ra		10^{-25}			5×10^{-8}	4×10^{-9}	1×10^{-9}	6×10^{-23}
Ra		10^{-26}			1×10^{-8}	1×10^{-9}	3×10^{-10}	2×10^{-24}
Neutron/Xe/Ra		$10^{-28}/3 \times 10^{-29}/10^{-27}$			6×10^{-9}	9×10^{-10}	3×10^{-10}	1×10^{-24}

Next Steps

text

2012-2013 Summary

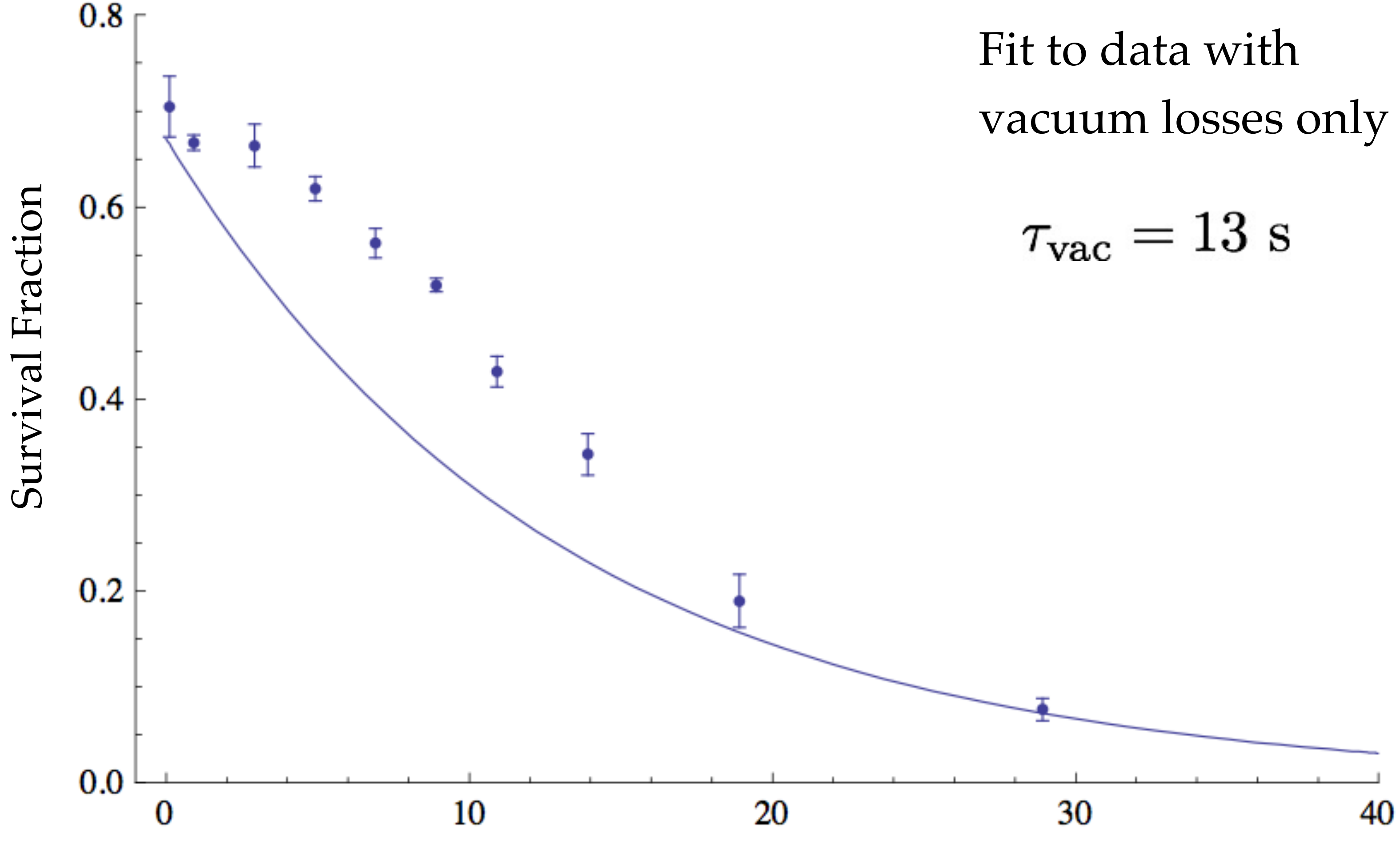
2012: Started major vacuum upgrade + Ra-225

- trapped Ra-225 for the first time in 5 years
- observed spin precession in high *B*-field

2013: Finished major vacuum upgrade and assembly of experiment:

- MOT Lifetime increased from ~10 s to ~50 s
- ODT Lifetime stayed the same ~3 s

Trap Lifetime



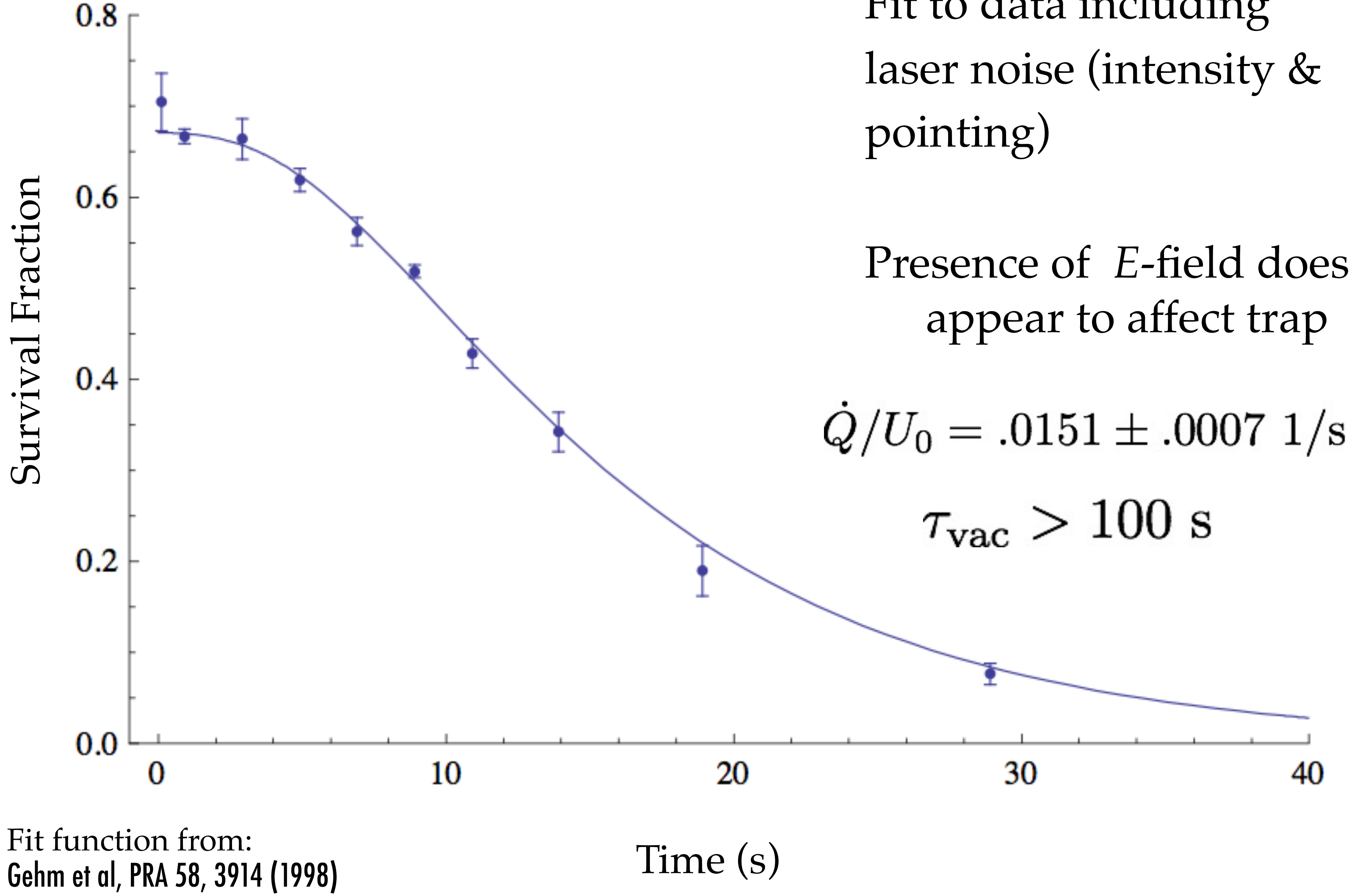
Fit to data with
vacuum losses only

$$\tau_{\text{vac}} = 13 \text{ s}$$

Time (s)

Fit function from:
Gehm et al, PRA 58, 3914 (1998)

Trap Lifetime



Fit to data including laser noise (intensity & pointing)

Presence of *E*-field does not appear to affect trap

$$\dot{Q}/U_0 = .0151 \pm .0007\ 1/\mathrm{s}$$

$$\tau_{\mathrm{vac}} > 100\ \mathrm{s}$$

Fit function from:
Gehm et al, PRA 58, 3914 (1998)

Present Status

2014: Two Ra-225 runs with assembled experiment:

- improved stability of lasers using Zerodur cavity
- repaired noisy "Bus" beam lens translation stage

- observed spin precession with low *B*-field
- ODT Lifetime (Ra-226) is not affected by *E*-field
- discovered that Ra-225/Ra-226 ratio at oven is too low!

Next run: ~Sept./Oct. 2014

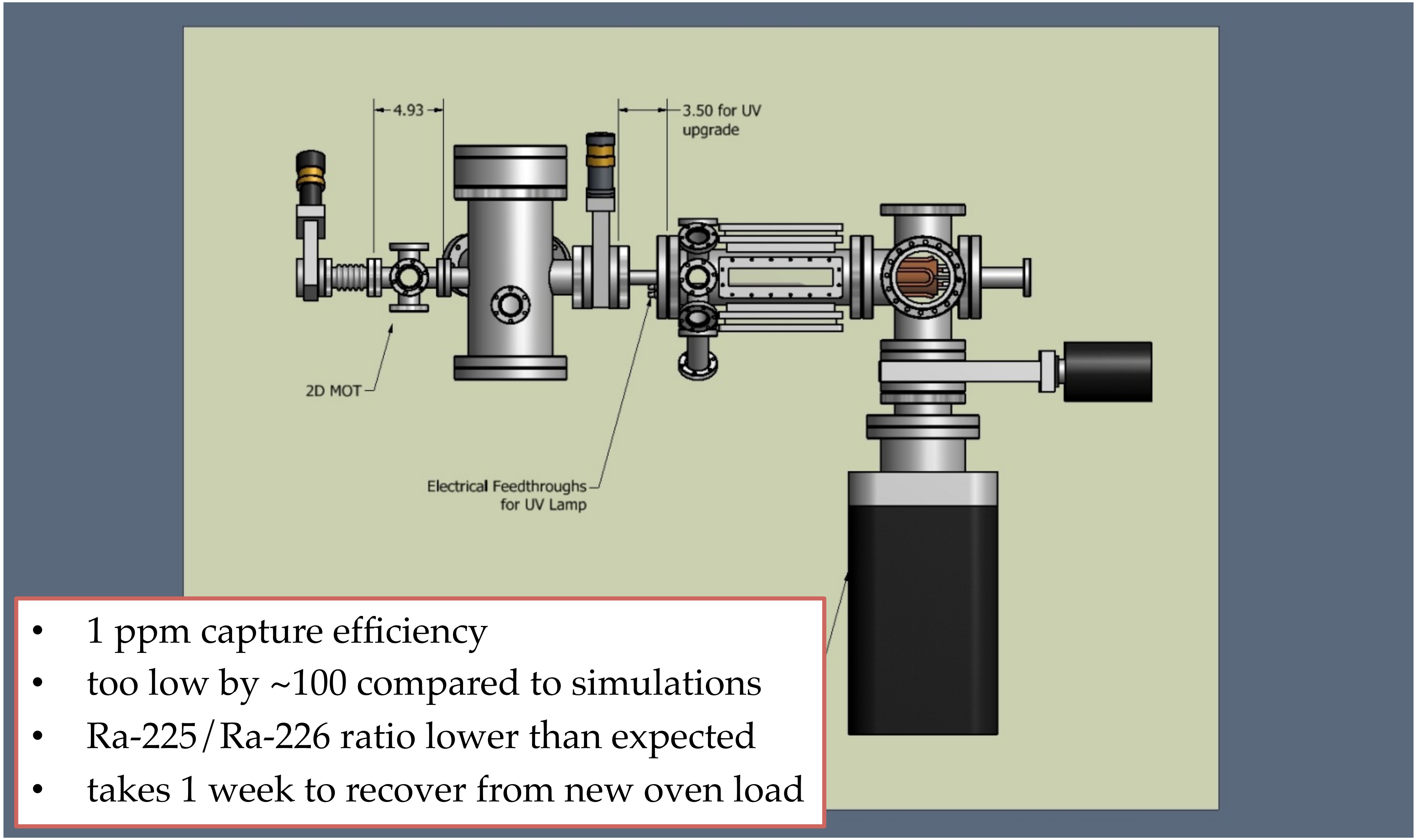
- stabilize laser intensity of ODT
- apply *E*-field to Ra-225 during spin precession

Sensitivity Goals

$$\sigma_d^{\text{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon N \tau T}}$$

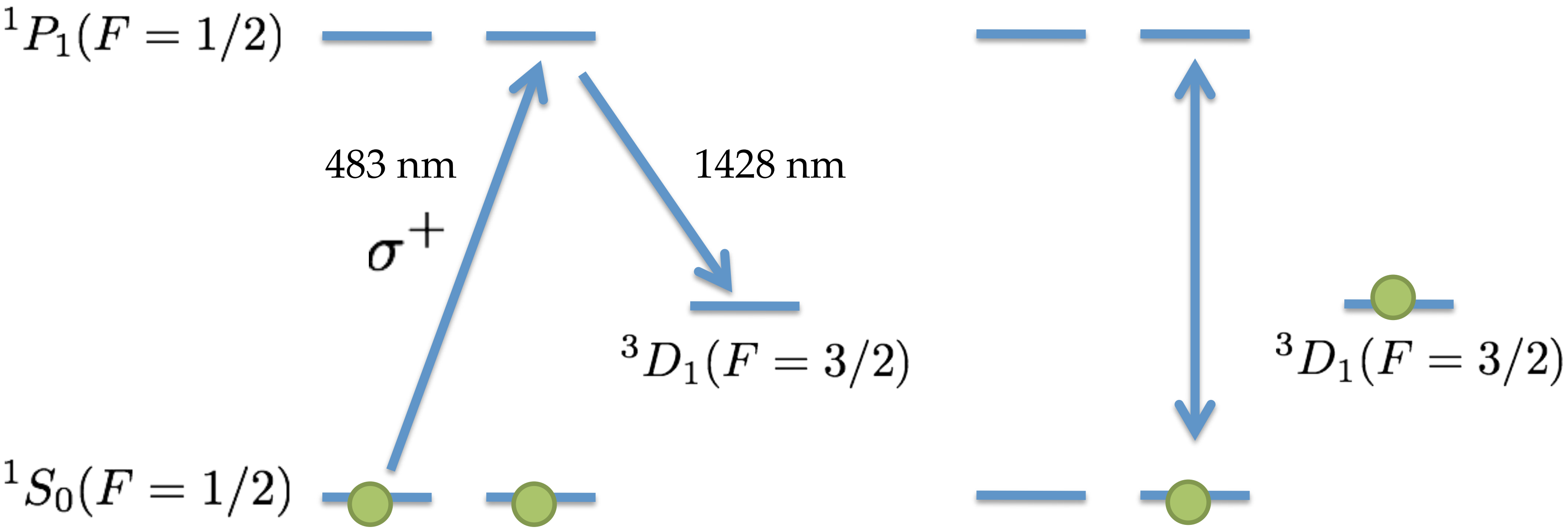
parameter	now	phase 0	phase 1	comments
E, electric field (kV/cm)	75	75	100	new HV electrodes
e, efficiency	0.003	0.01	0.1	optimize detection
N, # of atoms	10^2	10^3	10^4	use more atoms, optimize transfer, optimize oven
t, storage time (s) coherence time (s)	3	10	10^2	optimize holding beam
T, integration time (days)		3	10	
sensitivity (1σ) e*cm		10^{-24}	10^{-26}	

Ra Atomic Source Upgrade



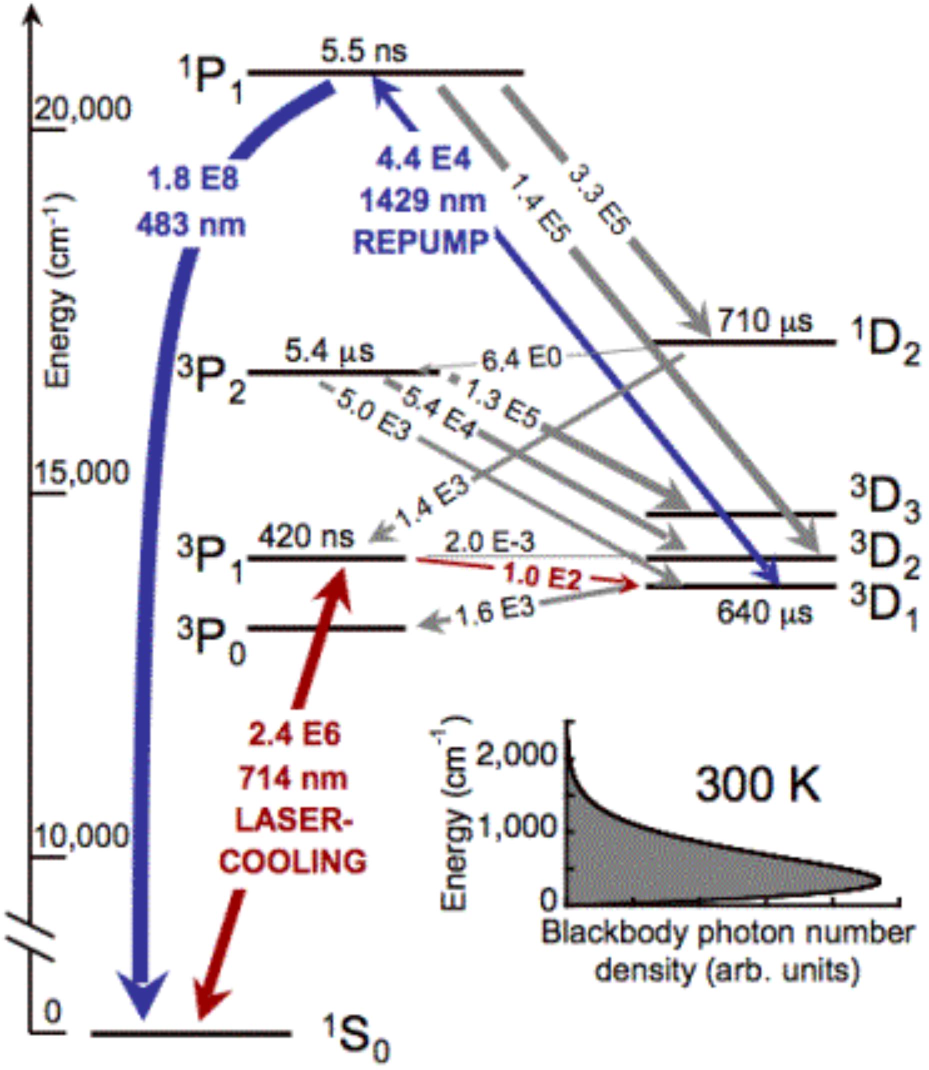
- 1 ppm capture efficiency
- too low by ~100 compared to simulations
- Ra-225/Ra-226 ratio lower than expected
- takes 1 week to recover from new oven load

Improve Detection Scheme

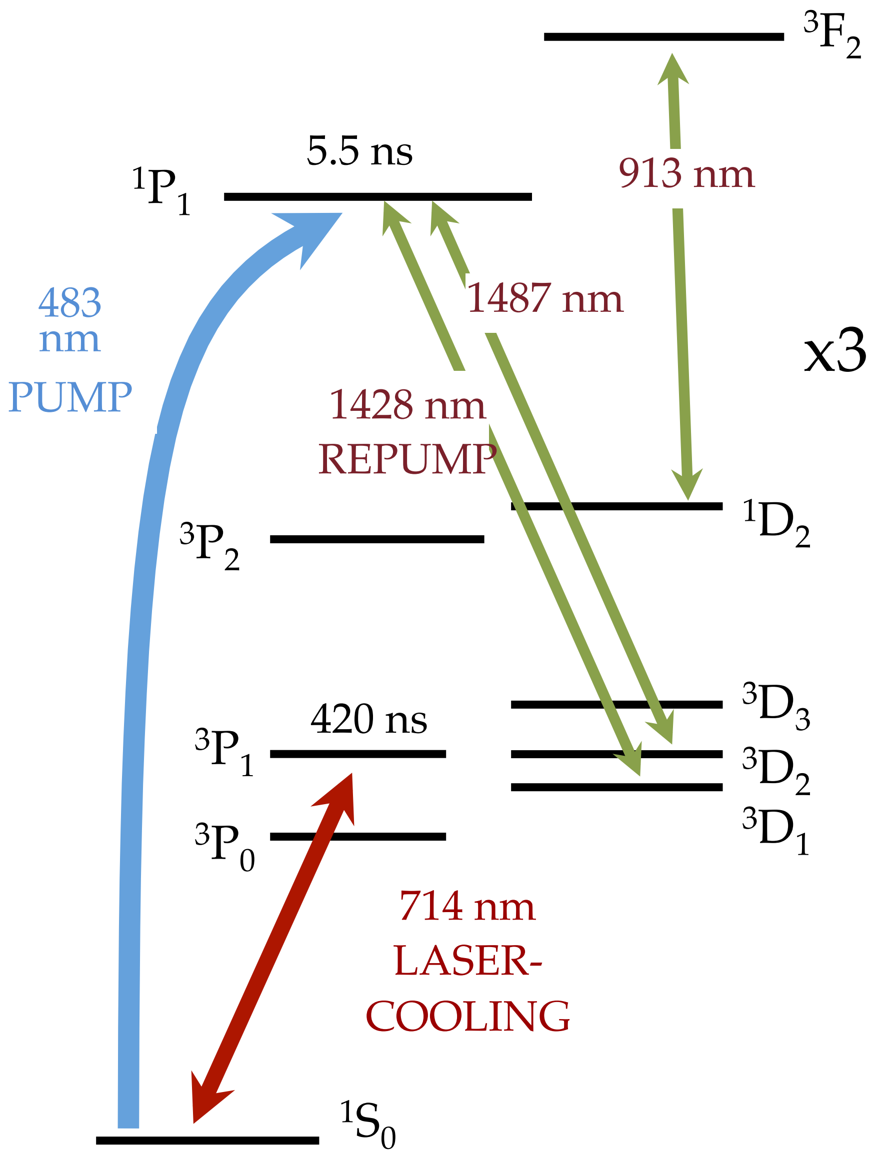


- “STIRAP” suggested M. Dietrich
- old scheme – scatter a few photons per atom
- new scheme – scatter thousands of photons per atom

Radium Atomic Energy Diagram

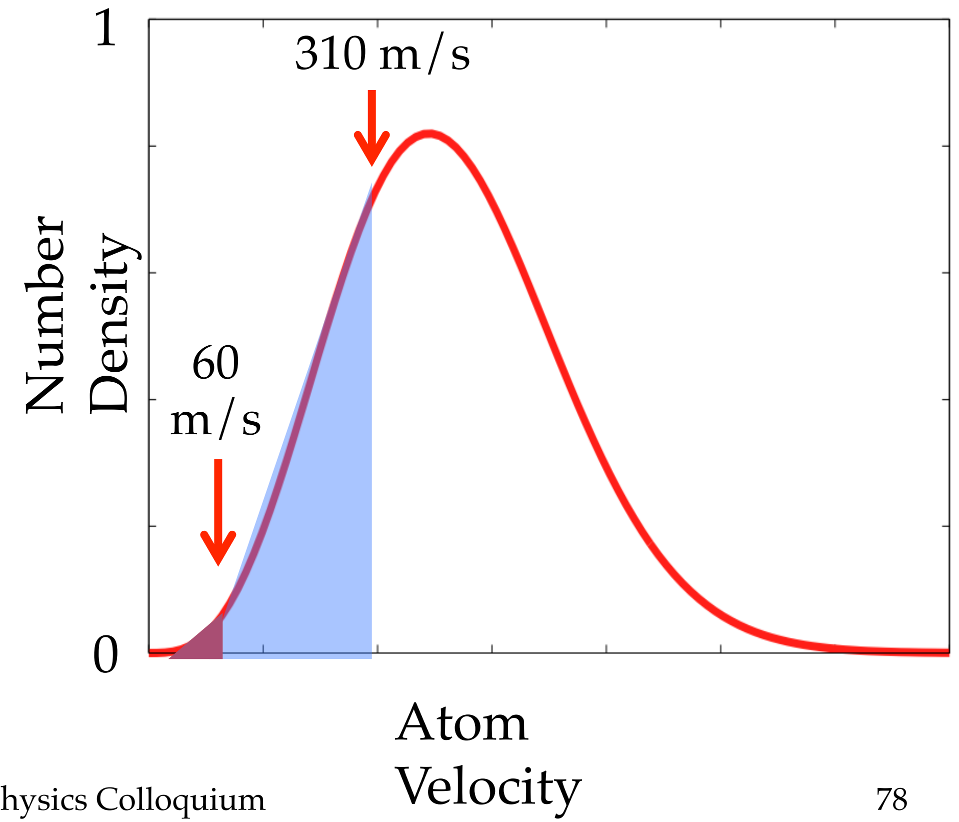


“Blue” Upgrade



$$\sigma_d^{\text{stat}} \geq \frac{\hbar}{2E\sqrt{\varepsilon \enclose{circle}{N} \tau T}}$$

x30 – x100 Atom Capture Efficiency

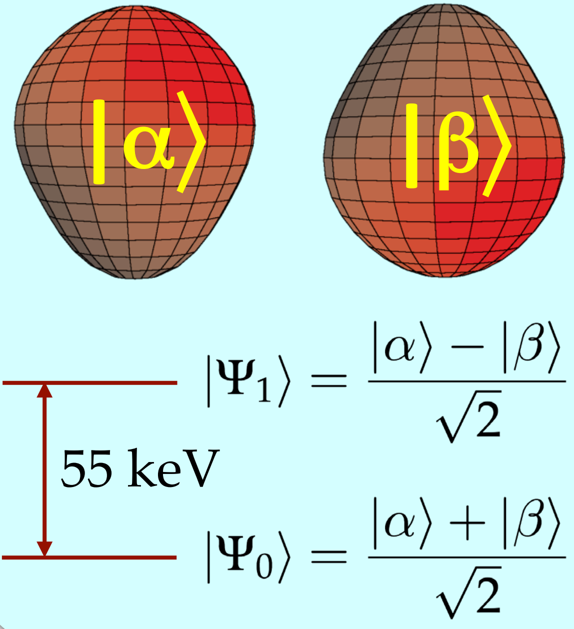


^{225}Ra EDM Search

- Relativistic atomic structure + deformed nuclear shape makes ^{225}Ra a few 100 to a few 1000 times more sensitive than ^{199}Hg to EDM physics

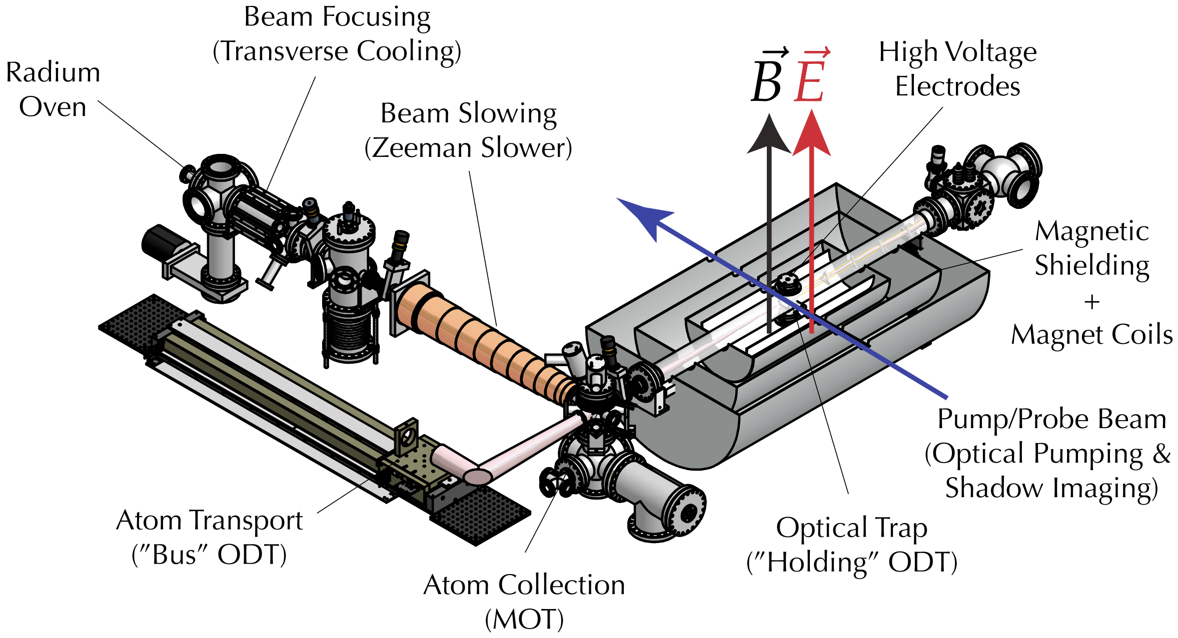
- Our initial goal of d(^{225}Ra)$<3\times10^{-26}$ *e*-cm would provide constraints on *CP*-violating interactions between nucleons that would already be competitive with the present best limits derived from d(^{199}Hg)$<3\times10^{-29}$ *e*-cm!

^{225}Ra Parity Doublet



$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$



Trap Beam Induced Zeeman Shifts

3. Parity mixing of the hyperfine states in the excited level

- misalignment of the trap beam allows for a frequency shift linear in *E*-field
- only coupling that mimics an EDM signal
- controlling the alignment to within 1 degree gives < 10^{-28} *e*-cm

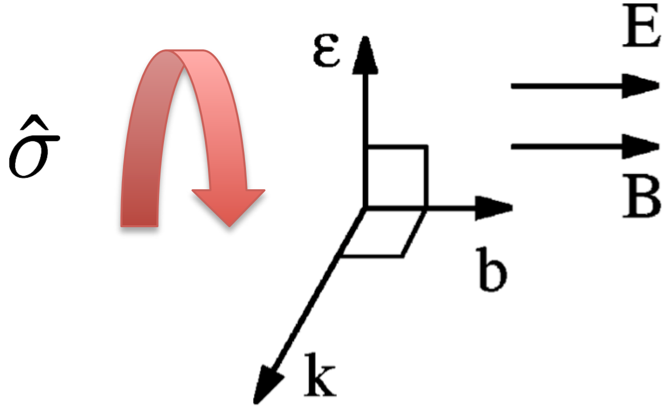


FIG. 16. Relative orientation of the magnetic field ***B***, static electric field ***E***, the trapping beam wave vector ***k*** and the polarization ***ε*** that minimizes the shifts due to parity mixing induced by the electric field as well as the vector light shift.

Romalis & Fortson PRA 59, 4547 (1999)

$$\left(\hat{b}\cdot\hat{\sigma}\right)\left(\hat{\varepsilon}\cdot\hat{E}\right)$$

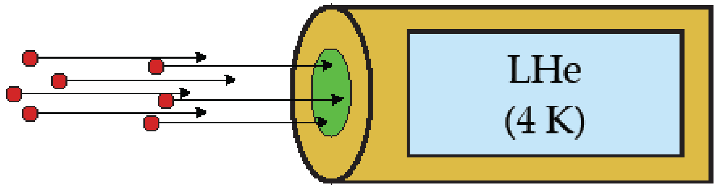
$$\left(\hat{b}\cdot\hat{E}\right)\left(\hat{\varepsilon}\cdot\hat{\sigma}\right)$$

Atoms in Noble Gas Solids

Our goal is to spin-polarize nuclei of neutral atoms trapped in noble gas solids:

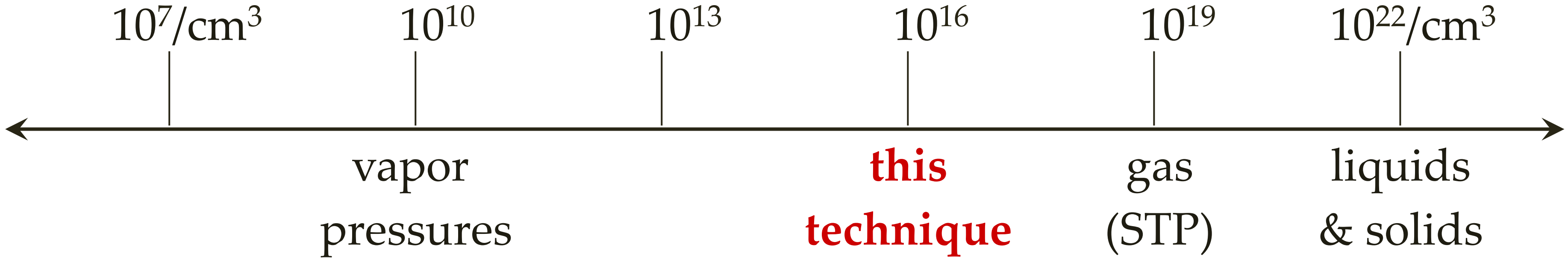
- unselective, stable, & inert confinement of atoms
- long nuclear spin relaxation times
- tunable atom number/nuclear spin densities
- atomic transitions are broad (~nm) but homogenous

Xu et al. PRL 107, 093001 (2011)



Applications include:

- Tests of fundamental symmetries
- Rare nuclear reaction cross sections measurements
- Electromagnetic moments of exotic isotopes



10^7/cm^3 | 10^{10} | 10^{13} | 10^{16} | 10^{19} | 10^{22}/cm^3

vapor pressures

this technique

gas (STP)

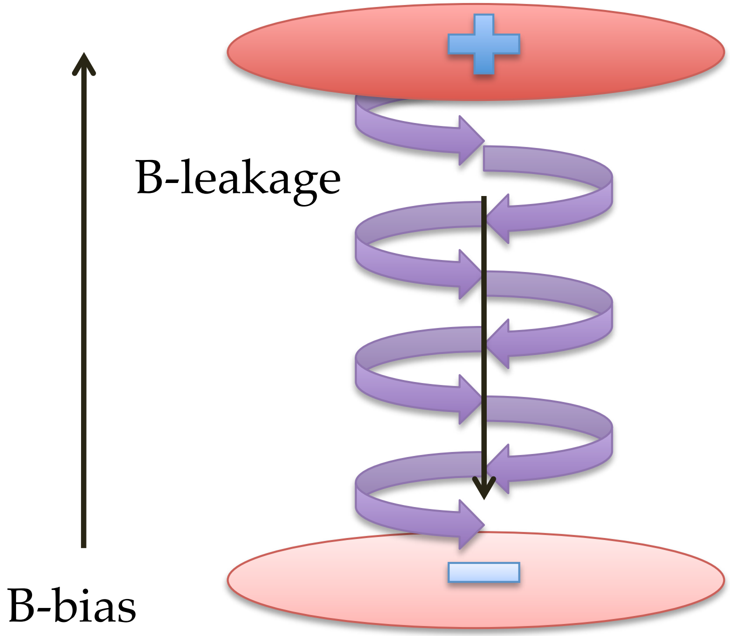
liquids & solids

Summary

- EDMs are excellent probes of new physics
- Different systems are needed!
  - sensitive to different sources of new physics
  - can be used as co-magnetometers
  - different techniques have different types of systematics
- Limits are projected to improve by at least an order of magnitude in the next 5 years, stay tuned!

Systematic Leakage Current

- Leakage current was 1/3 dominant systematic uncertainties for ^{199}Hg = 0.42 pA
- Leakage current generates small magnetic field that couples to MDM and has the same signature as an EDM (changes sign under *E*-field reversal)
- Leakage *B*-field must be aligned with bias *B*-field to cause problems
- Toy model assumes that the current travels in a helical path from one electrode to the other
- For our exp: 100 pA of leakage current corresponds to 1.5x10^{-26} *e*-cm



$$d_{\mathrm{leak}} = \frac{\mu}{E} B_{\mathrm{leak}} \approx \frac{\mu(^{225}\mathrm{Ra})\mu_0}{R_{\mathrm{path}}}$$

Systematic: "v x E"

- This can be a major systematic for "beam"-type experiments.
- A particle with velocity *v* in a transverse E-field see a *B*-field in its rest frame
- Ideally, this effective *B*-field is perpendicular to the bias *B*-field. When added in quadrature, this effect is does not change sign under *E*-field reversal.
- The problem occurs when the *E*- & *B*-fields are not perfectly parallel.
- For the RMS thermal velocity at T=40 mK, this corresponds to $5.4\text{x}10^{-26}$ *e*-cm per degree misalignment
- In our trap, however, the mean velocity averaged over all motions is essentially zero. This argument is also true for ^{199}Hg and they estimated $2\text{x}10^{-31}$ *e*-cm.

$$d_{\mathrm{v}\times\mathrm{E}} = \frac{\mu}{E} B_{\mathrm{v}\times\mathrm{E}} \approx \mu(^{225}\mathrm{Ra}) \frac{v \sin(\theta)}{c^2}$$

Trap Beam Induced Zeeman Shifts

1. Vector light shifts are due to a circularly polarized trap beam
- couples laser intensity noise to the spin precession frequency of the atoms
- adds effective *B*-field noise to the measurement
- laser intensity gradients result in a reduction to T_2
- can be suppressed by a linearly polarized trap beam
  & orienting the trap beam perpendicular to the bias *B*-field

2. Tensor light shifts have similar problems
- totally absent for diamagnetic atoms with I=1/2 (^{199}Hg & ^{225}Ra)

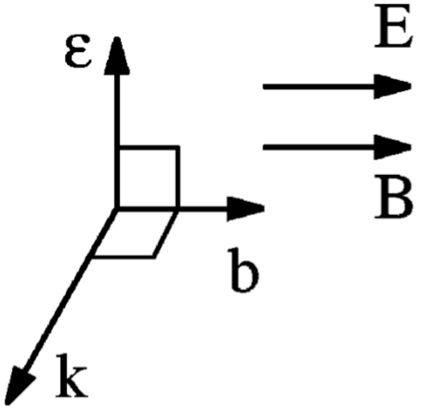


FIG. 16. Relative orientation of the magnetic field ***B***, static electric field ***E***, the trapping beam wave vector ***k*** and the polarization ***ε*** that minimizes the shifts due to parity mixing induced by the electric field as well as the vector light shift.

Romalis & Fortson PRA 59, 4547 (1999)

A New EDM Search in Xe-129

Polarized Noble Gases

- large magnetizations (nT) using standard techniques
- polarized ^{3}He for co-magnetometry
- very long spin precession times (10^3 seconds)

SQUID Detectors

- very sensitive detection (1 fT/root-Hz noise floor)

Magnetically Shielded Room

- small (<1 nT) and uniform (<10 pT/cm) residual *B*-field
- high shielding factor ($>10^6$)
- low noise environment for electronics

Collaboration of World Leading Experts:

- TU Munich, PTB (Germany), Michigan State, Michigan

Stepwise Physics Goals

system	upper limit in 10^{-28} e cm (95% C.L.)	reference
^{199}Hg	0.31 (~0.03, data taking underway)	PRL **102**, 101601 (2009)
^{129}Xe	**66 (~0.1 goal, multiple groups)**	PRL **86**, 22 (2001)
neutron	350 (~3 goal, multiple groups)	PRL **97**, 131801 (2006)

- A **10x**-improvement in ^{129}Xe would make it a **potential co-magnetometer** for next generation neutron EDM searches.
- A **100x**-improvement in ^{129}Xe would **improve the limits** on *CP*-violating interactions between electron and nucleons by an order of magnitude and provide **independent confirmation** of the null result for ^{199}Hg.
- Is a **1000x (or more)**-improvement in ^{129}Xe possible? Needs long term research and development effort!

Spin Polarization

$$P\,(J=1/2)=\frac{n_+-n_-}{n_++n_-}$$

1. **Spin polarization is angular momentum.**
2. **Spin polarization generates a magnetic field.**

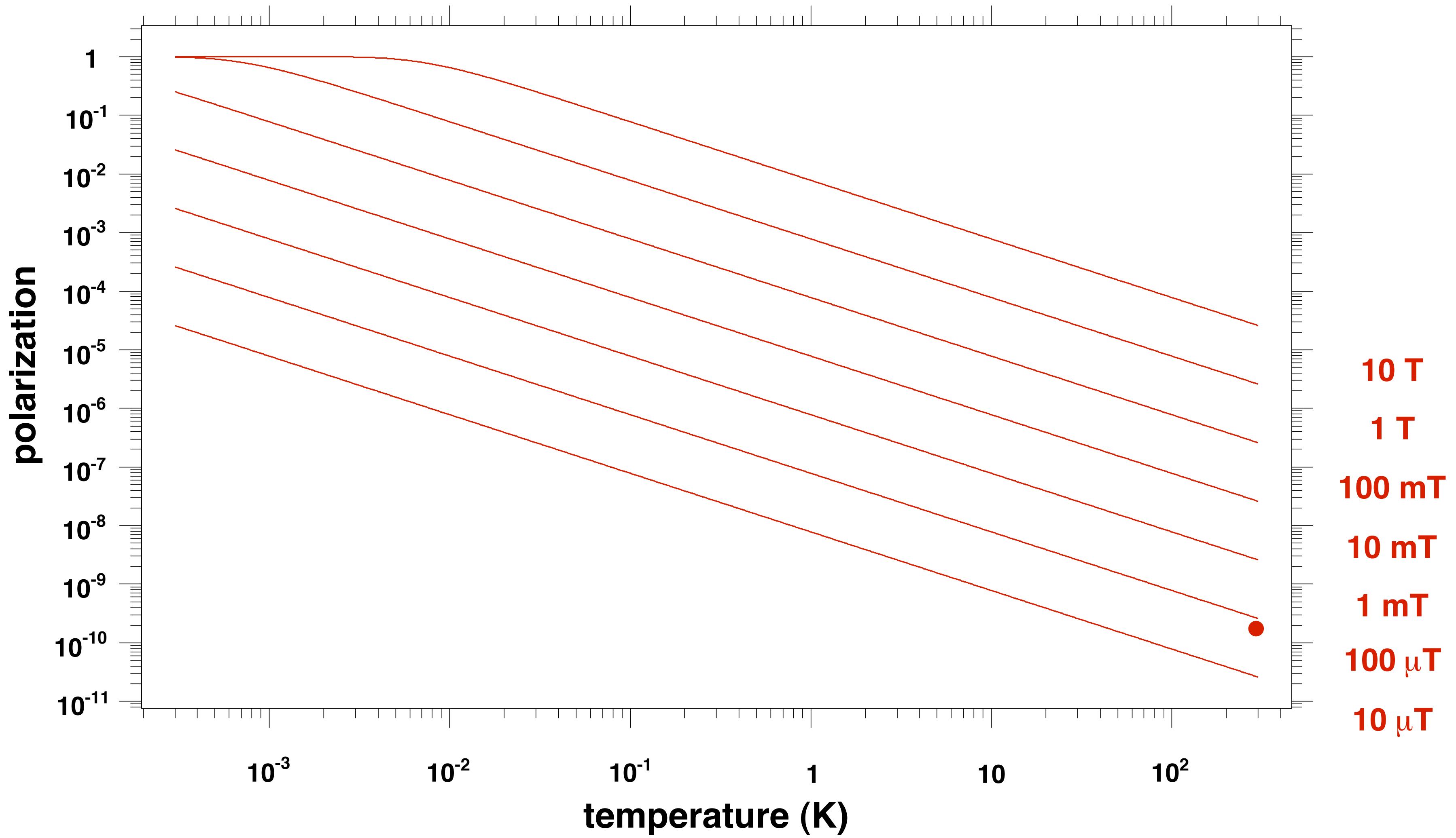
$$\vec{M}=\mu\vec{P}\,[\mathrm{N}] \qquad \text{(magnetization)}$$

$$\vec{A}(\vec{r})=\frac{\mu_0}{4\pi}\int\frac{\vec{M}(\vec{u})\times(\vec{r}-\vec{u})}{|\vec{r}-\vec{u}|^3}d^3u \qquad \text{(vector potential)}$$

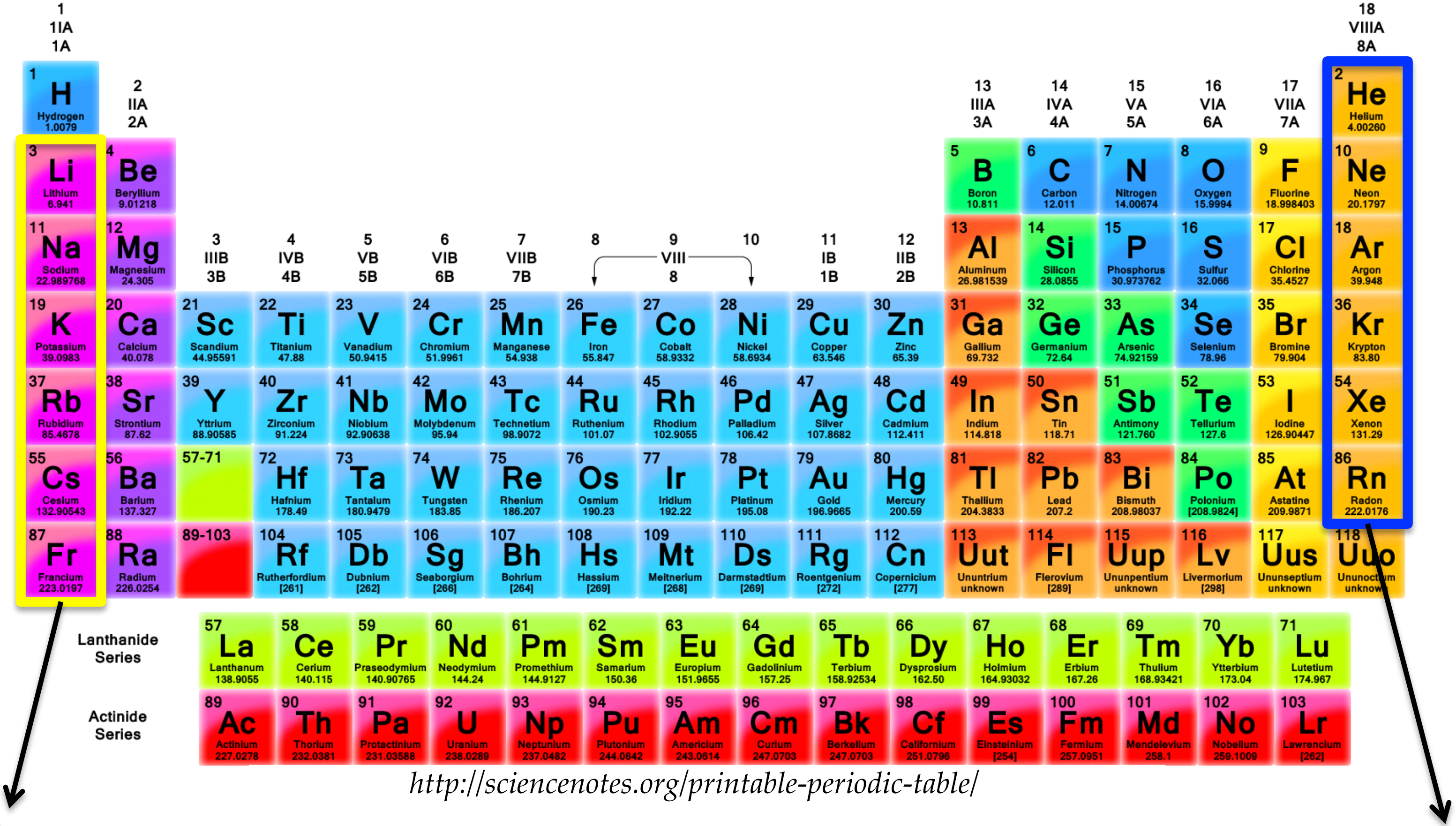
- population imbalance
- total number of spins
- intrinsic magnetic moment
- distance between spin sample and magnetometer

$$\vec{B}=\vec{\nabla}\times\vec{A} \qquad \text{(magnetic field)}$$

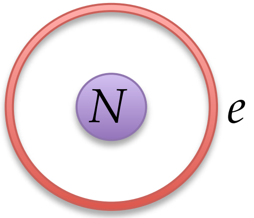
Brute Force: Thermal Polarization of ^{3}He



Alkali Atoms & Noble Gases



http://sciencenotes.org/printable-periodic-table/



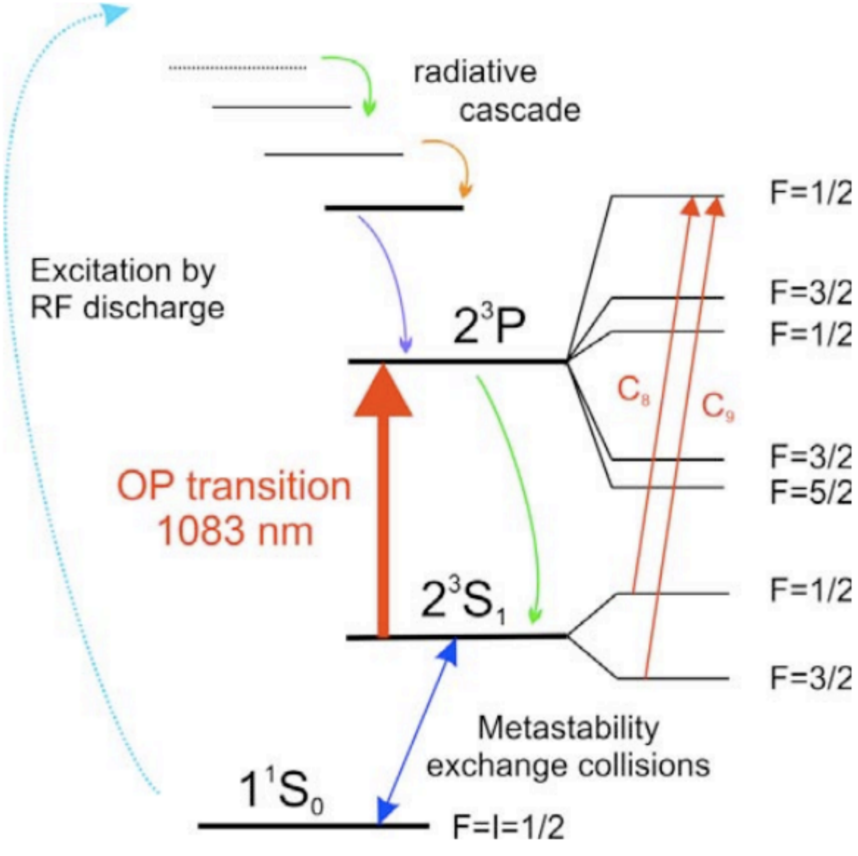
$$\frac{e}{N} \to \frac{\mu_B}{\mu_N} = \frac{M_p}{m_e} \approx 2000$$

Metastability Exchange Optical Pumping

E. Otten MSU P&A Colloquium

October 21, 1997

	SEOP	MEOP
polarization timescale	~hours	~seconds
polarization volume	~liters	~milliliters
Typical Modern Production Rate	~0.3 liter/hr @ 50% (P=0.5)	~0.3 liter/hr @ 50% (P=0.5)



Guilhem Collier Ph.D. Thesis, KRAKÓW (2011)

Basic Schematic of SEOP Polarizer

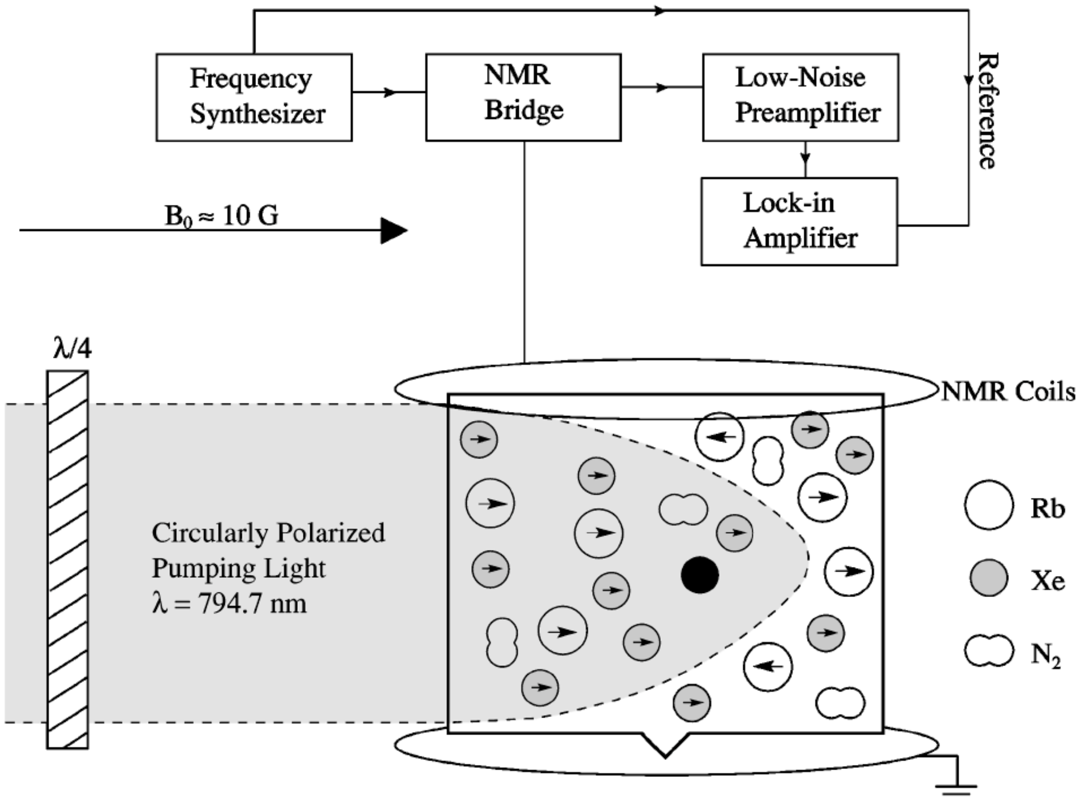


FIG. 2. Experimental arrangement for spin-exchange optical pumping.

Rev. Mod. Phys., Vol. 69, No. 2, April 1997

SEOP ^{3}He Performance

Year	Volume	Pol.	Simple Rate Pol.	Light Power	Spin Exchange Rate (Hrs)	Spin Relaxation Rate (Hrs)
1960	100 mL	0.01%	0.01%	1 mW	100	1
2000	1.5 L	40%	83%	30 W	20	100
2010	3 L	70%	90%	90 W	3	100

- No improvement for decades until lasers!

  Chupp et al. PRC 36 2244 (1987)
- Previously unknown glass/alkali correlated relaxation rate called "X"-factor limits the maximum polarization, which is now thought to be 90%.

  Babcock et al. PRL 96 083003 (2006)

$$P = \frac{1}{1+\Gamma_{\mathrm{sr}}/\gamma_{\mathrm{se}}} \to \frac{1}{1+X+\Gamma^0_{\mathrm{sr}}/\gamma_{\mathrm{se}}}$$

Spin Exchange is Very Slow

particle species	cross section (cm^2) @ 150 ^oC	relative velocity (cm/s) @ 150 ^oC	number density (cm^{-3}) @ 150 ^oC	rate (Hz)
Rb-Rb	1.7E-14	4.6E4	1.0E14	7.8E4 (13 μs)
^{3}He-Rb	3.7E-25	1.8E5	1.0E14	6.7E-6 (41 hrs)
^{129}Xe-Rb	8.8E-21	4.2E4	1.0E14	3.7E-2 (27 sec)

spin exchange cross section depends on:

- square of product of magnetic moments
- degree of overlap between wave functions
- the phase space available to conserve energy

compare to physical cross section of atom pairs: 3E-15 cm^2

A New EDM Search in Xe-129

Polarized Noble Gases

- large magnetizations (nT) using standard techniques
- polarized ^{3}He for co-magnetometry
- very long spin precession times (10^3 seconds)

SQUID Detectors

- very sensitive detection (1 fT/root-Hz noise floor)

Magnetically Shielded Room

- small (<1 nT) and uniform (<10 pT/cm) residual *B*-field
- high shielding factor ($>10^6$)
- low noise environment for electronics

Collaboration of World Leading Experts:

- TU Munich, PTB (Germany), Michigan State, Michigan

Stepwise Physics Goals

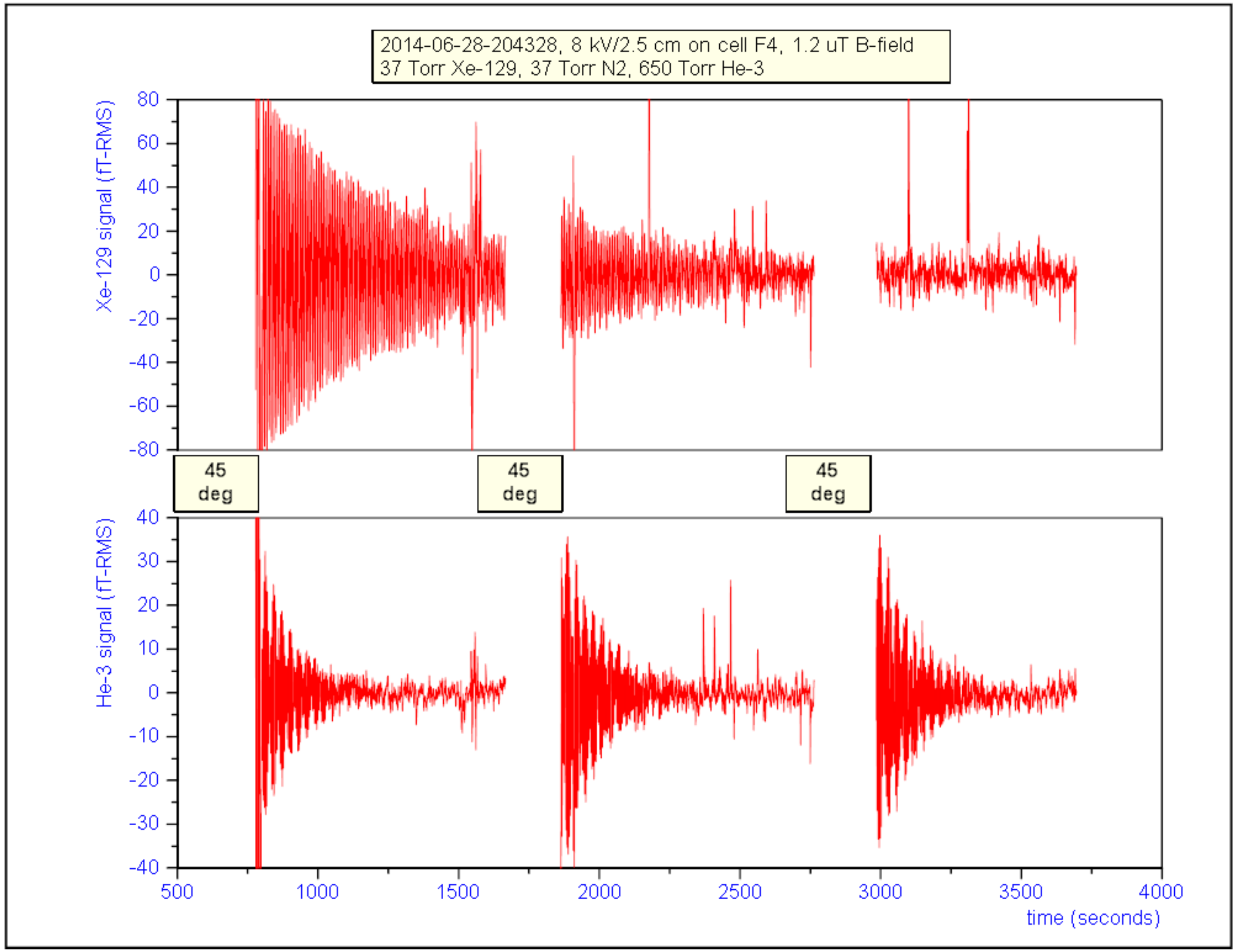
system	upper limit in 10^{-28} *e* cm (95% C.L.)	reference
^{199}Hg	0.31 (~0.03, data taking underway)	PRL **102**, 101601 (2009)
^{129}Xe	**66 (~0.1 goal, multiple groups)**	PRL **86**, 22 (2001)
neutron	350 (~3 goal, multiple groups)	PRL **97**, 131801 (2006)

- A **10x**-improvement in ^{129}Xe would make it a **potential co-magnetometer** for next generation neutron EDM searches.
- A **100x**-improvement in ^{129}Xe would **improve the limits** on *CP*-violating interactions between electron and nucleons by an order of magnitude and provide **independent confirmation** of the null result for ^{199}Hg.
- Is a **1000x (or more)**-improvement in ^{129}Xe possible? Needs long term research and development effort!

S/N of ~10^3 with E-Field ON!

Xe-129

He-3



Potential Statistical Sensitivity

$$\frac{\sigma_d}{\sqrt{N}} = \left(\frac{n/\sqrt{\tau}}{S}\right)\frac{\hbar\sqrt{3}}{E\sqrt{\epsilon T\tau}}$$

parameter	goal	achieved
S/n, SNR	3x10^6	~10^3
E, electric field	10 kV/cm	~4 kV/cm
τ, obs. time	10^3 sec	~3x10^2 sec
T, integration time	1 day	
ε, efficiency	0.5	

$$\frac{\sigma_d}{\sqrt{N}} = 5.5\times10^{-30}\ \frac{e\cdot\text{cm}}{\sqrt{\text{day}}}$$

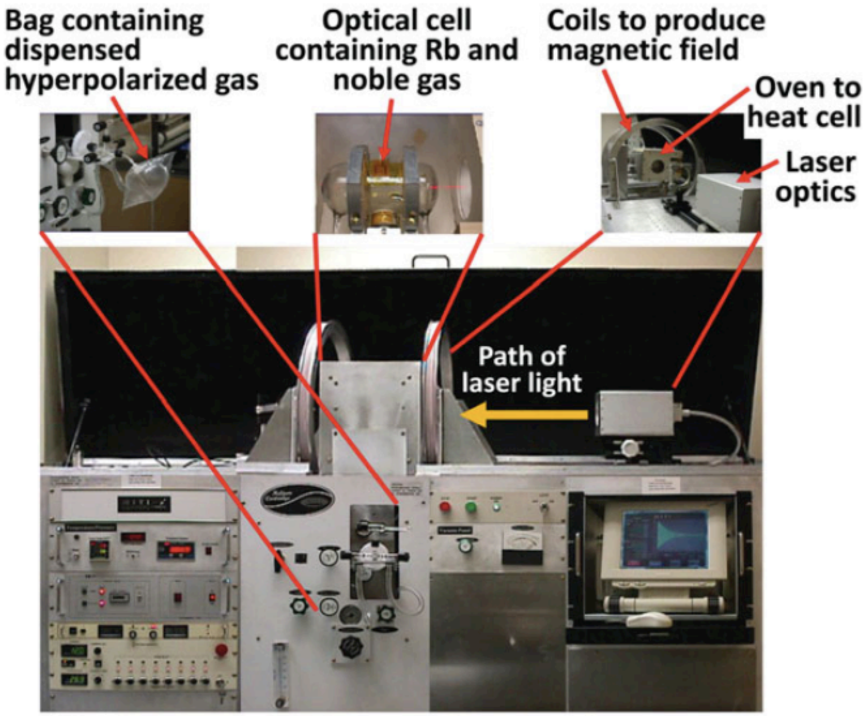
Magnetic Resonance Imaging (MRI)

- Spin precession frequency is given by strength of magnetic field.
- Spatially varying magnetic field encodes position information into frequency.
- Lots of protons in the body!
- Thermal polarization time scale ~ 1 second
- Thermal polarization at T level B-field is ppm

G. Wilson Miller UVa Radiology

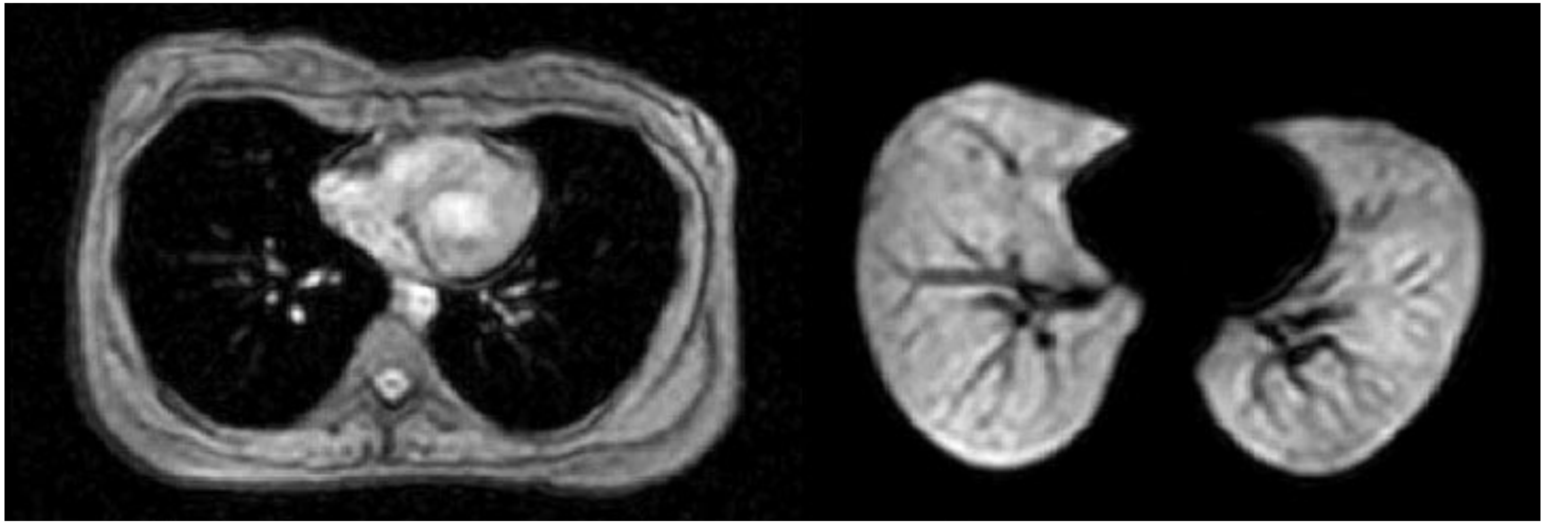
“Hyperpolarized” Gas MRI

- ^{3}He and ^{129}Xe are more or less harmless to the body.
- Density is about 10^3 less, but polarizations are up to 10^5 more
- Polarization process is exactly the same, but instead of sealed glass cells, refillable “baggies” are used.
- Technique developed world-wide, but will focus on UVa Radiology
- Patented in 1995 by collaborators at Princeton and Stony Brook (but now with Polarean).



Mugler & Altes, JMRI 37 313 (2013)

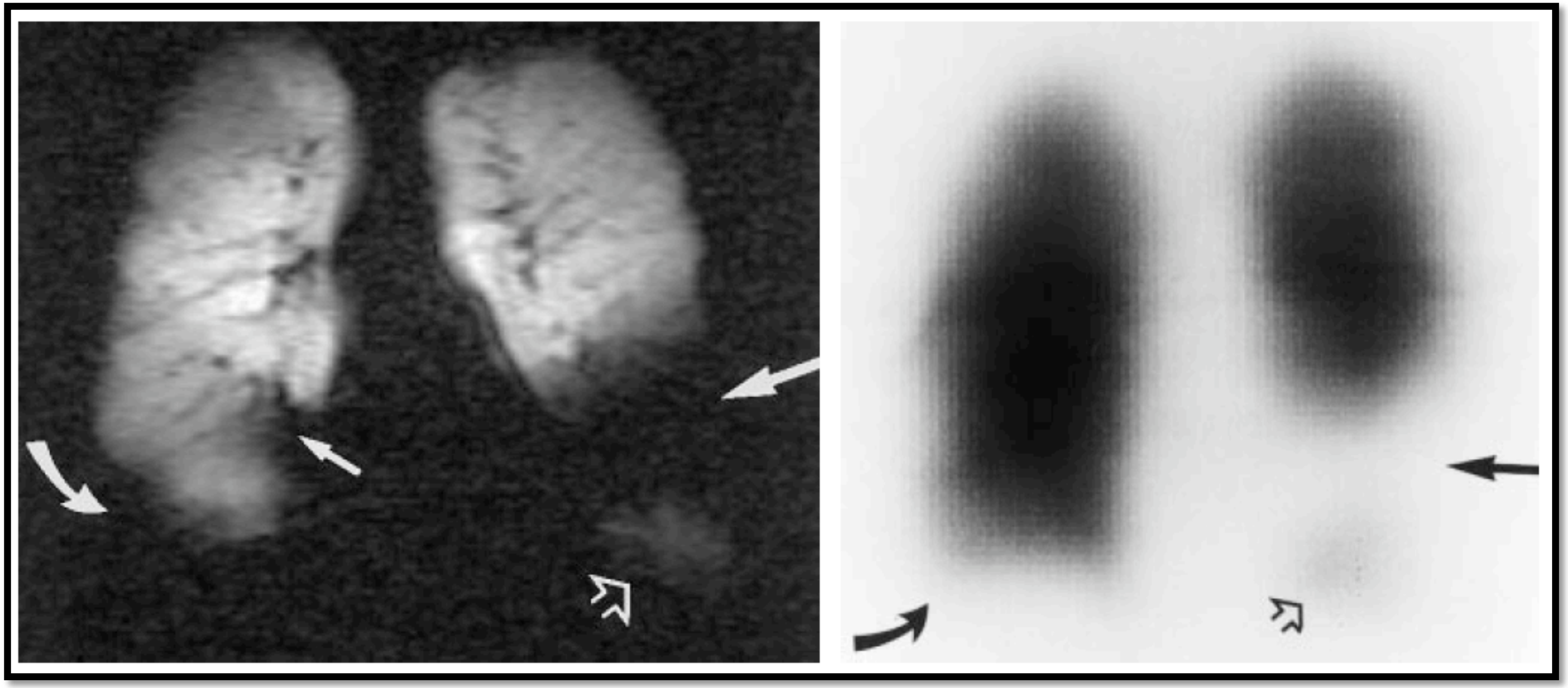
Detailed Images Of Lung Structure



Conventional Axial ^{1}H MRI Axial ^{3}He MRI

EE de Lange EE et al. Chest 130:1055-1062 (2006).

Noble Gases Have Been Used Before

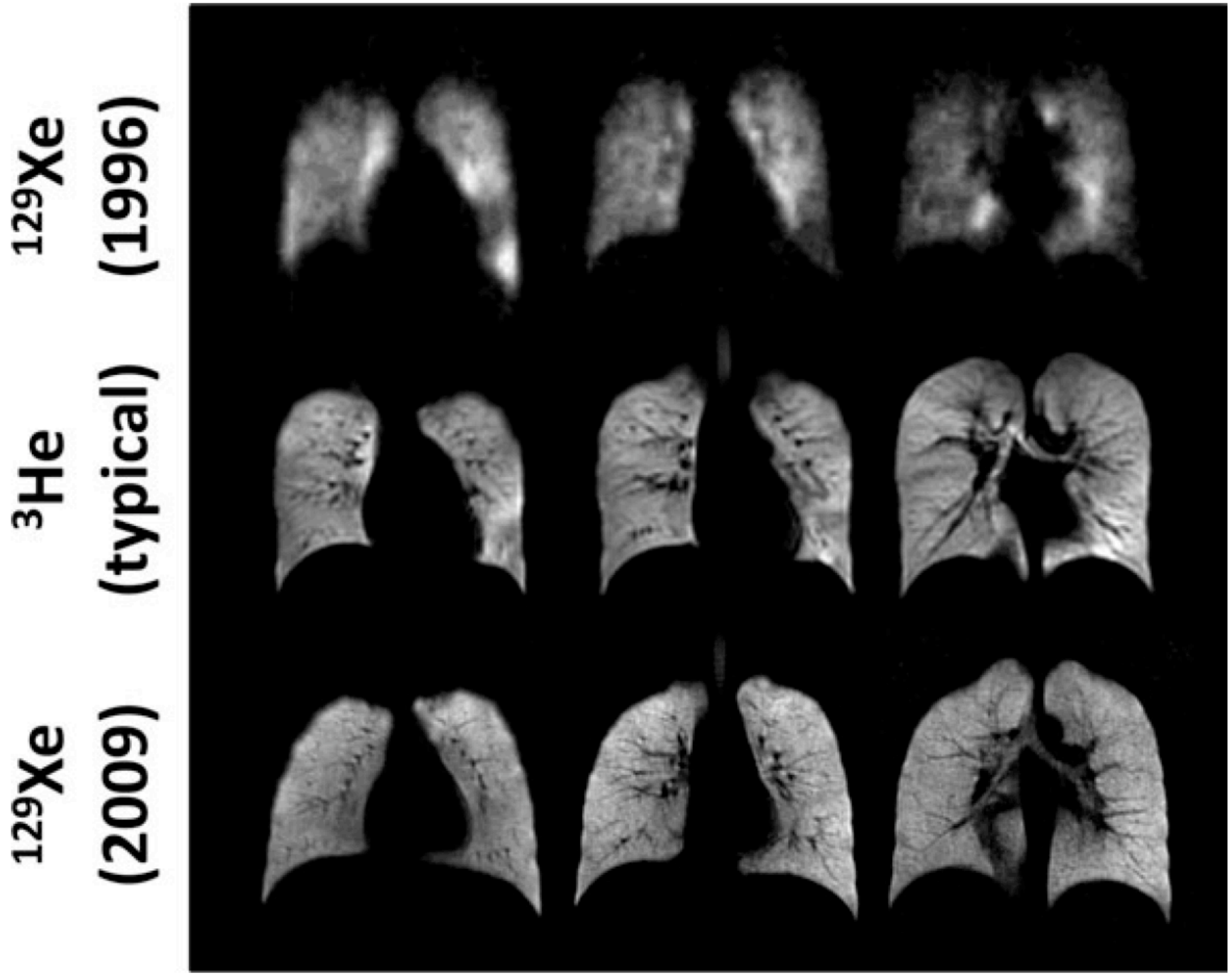


^{129}Xe (Stable)

^{133}Xe (5.3d, β)

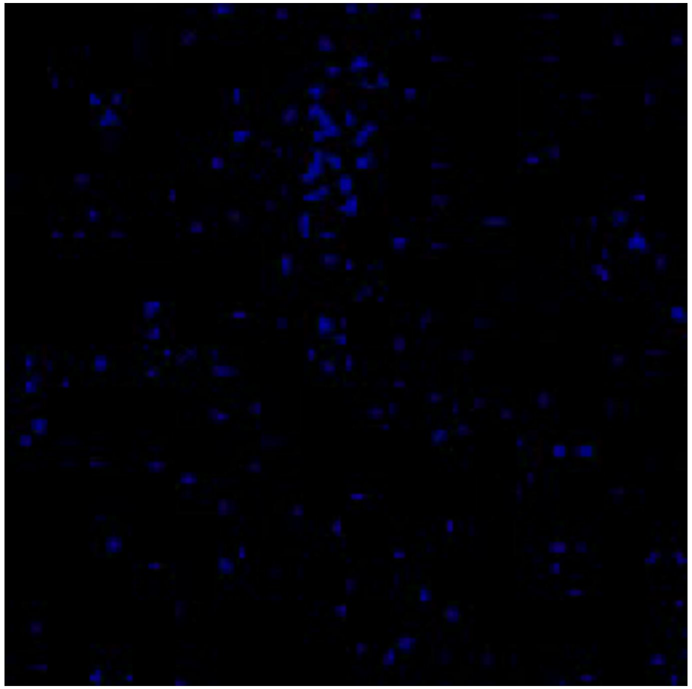
EE de Lange et al Radiology 210:3 (1999).

Big Improvements In Imaging



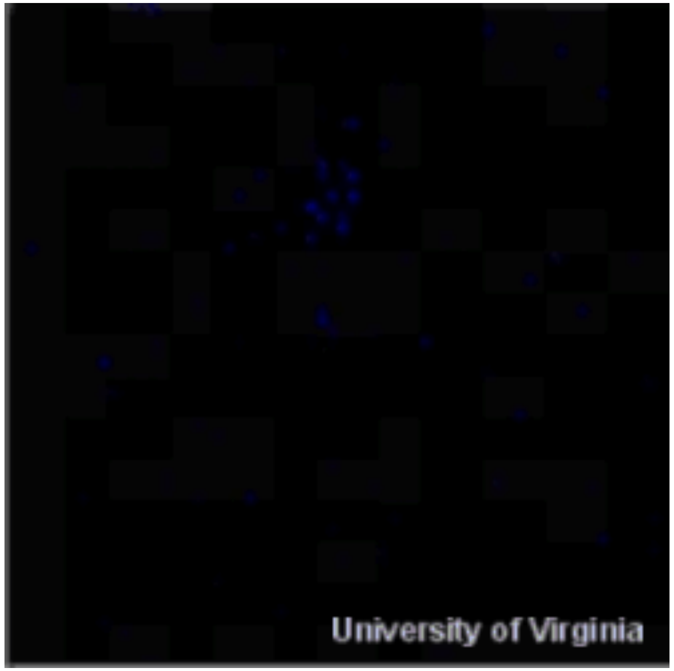
Mugler & Altes, JMRI 37 313 (2013)

Dynamic Visualizations: Healthy



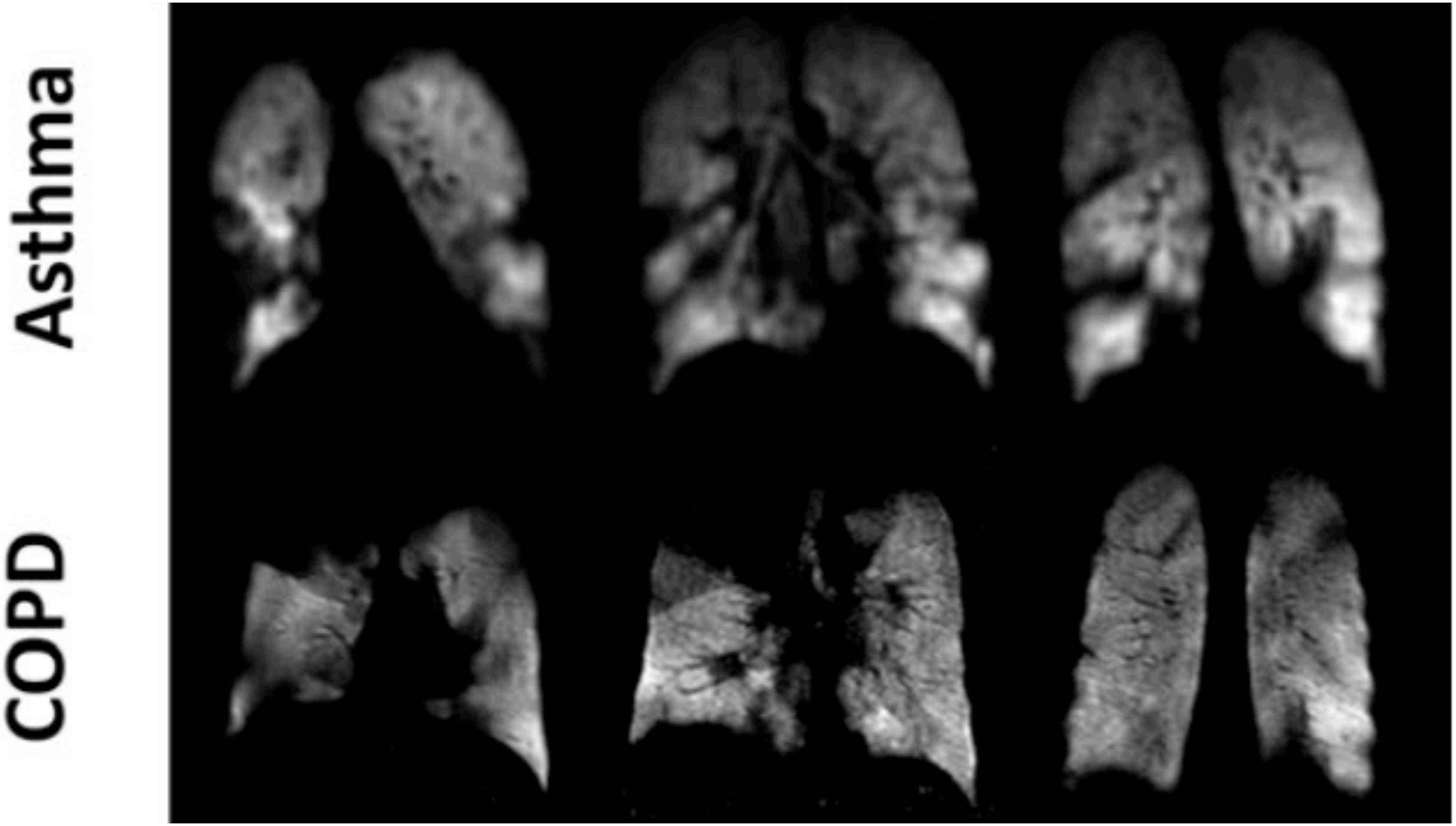
University of Virginia Radiology

Dynamic Visualizations: Unhealthy



University of Virginia Radiology

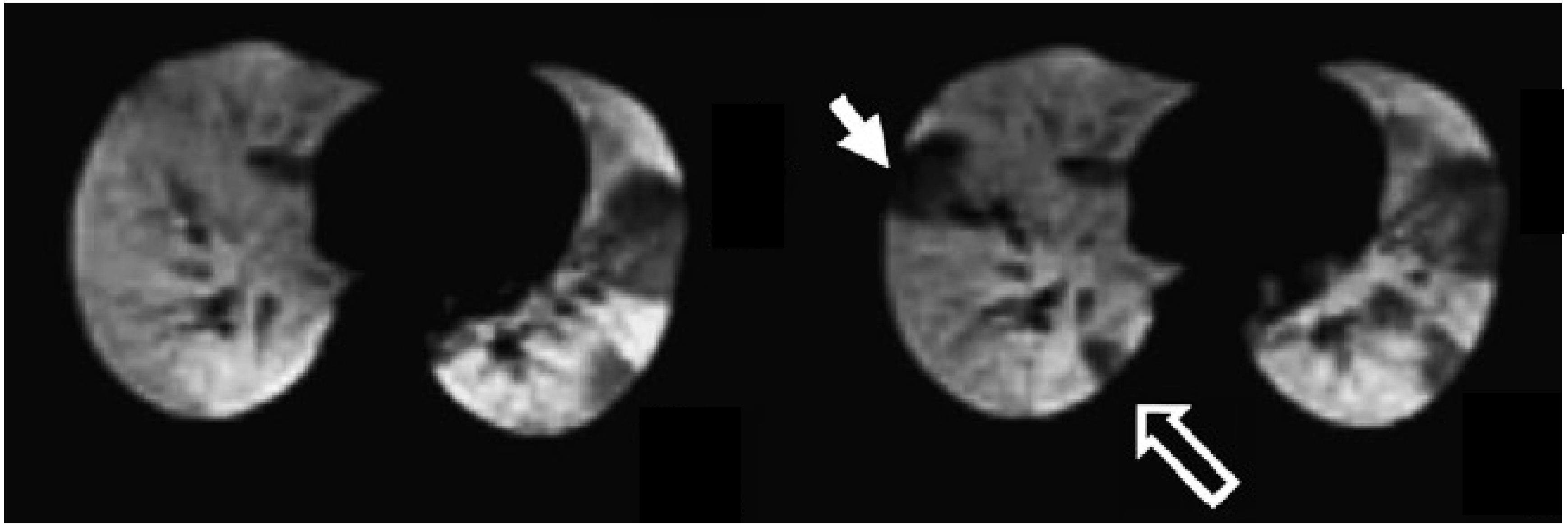
Problems Areas Clearly Visible



Mugler & Altes, JMRI 37 313 (2013)

How Sensitive Is the Subject?

Mild-intermittent asthmatic:



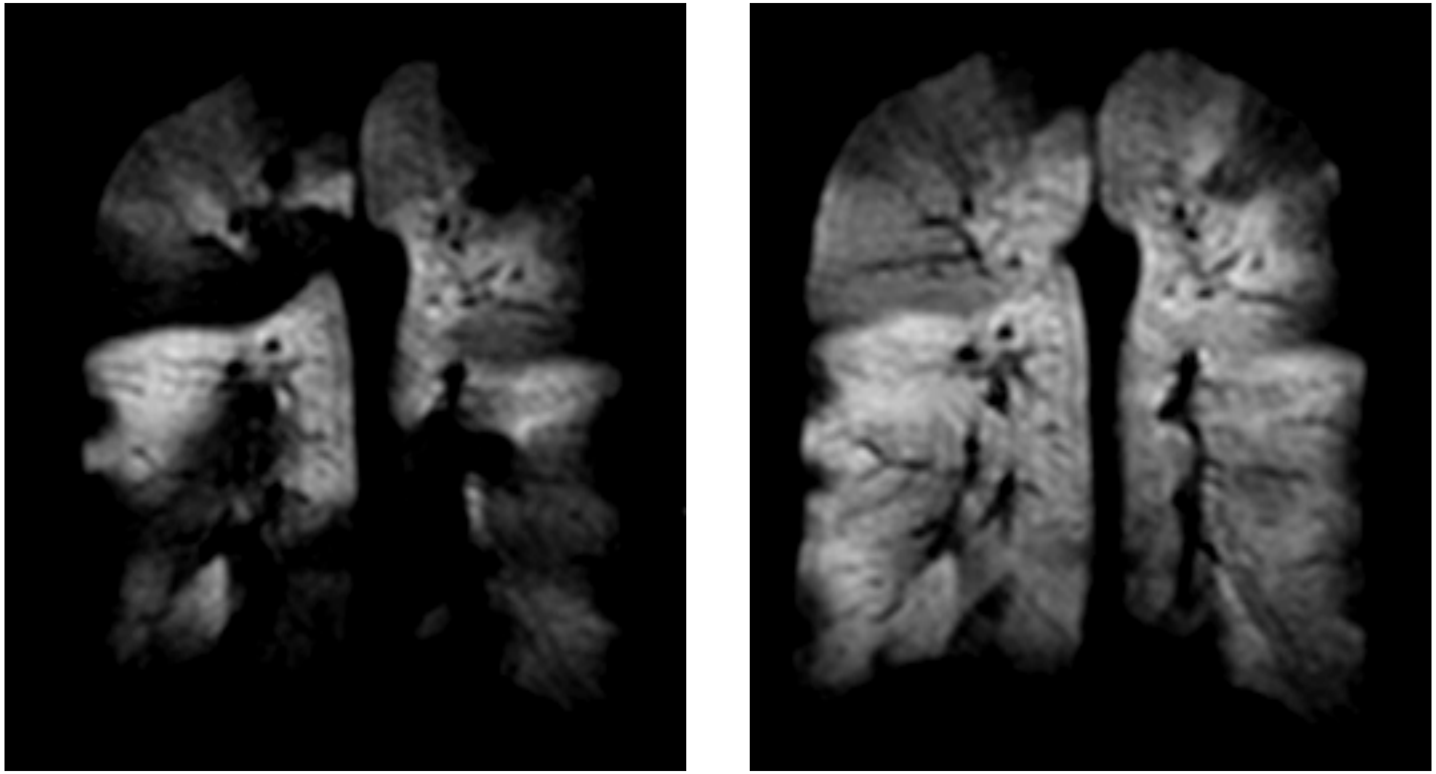
Pre Methacholine

Post Methacholine

EE de Lange et al. J. Allergy Clin Immunol 119:1072-1078 (2007).

How Effective is the Treatment?

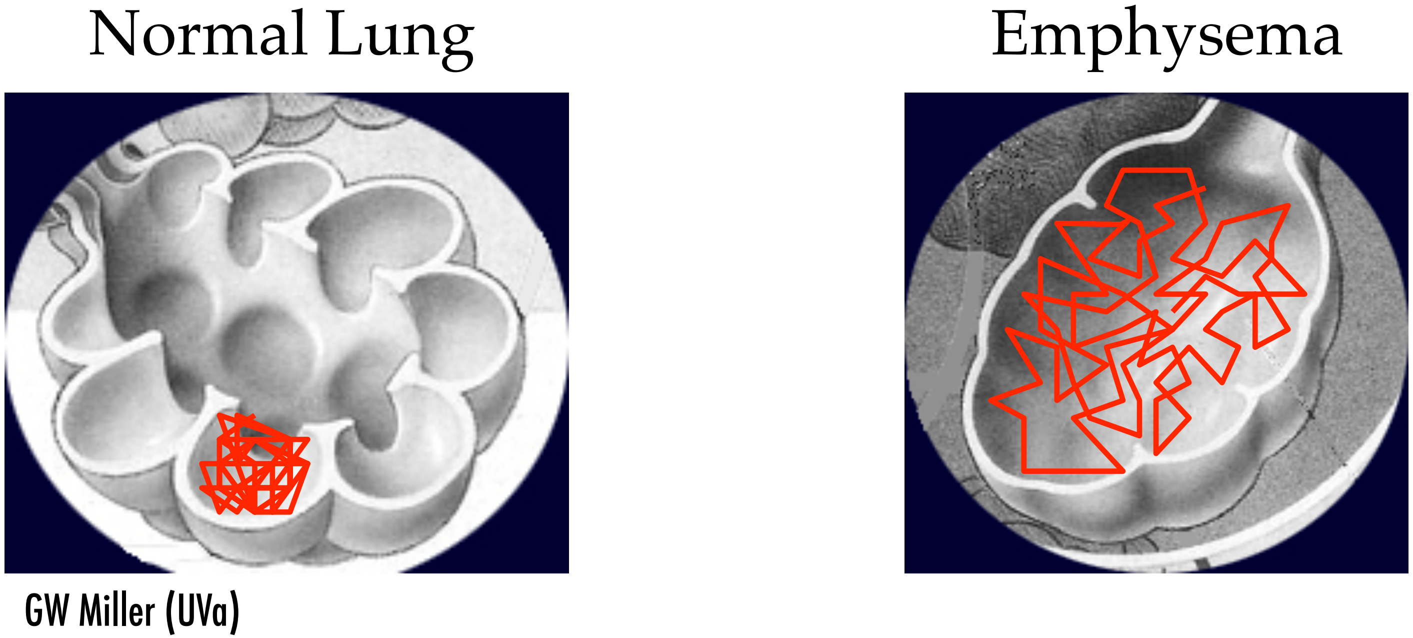
Severe-persistent asthmatic:



Pre Albuterol Post Albuterol

TA Altes et al. JMRI 2001;13:378-84

Microscopic Lung Structure



GW Miller (UVa)

Alveoli – lots of surface area for gas exchange with blood!

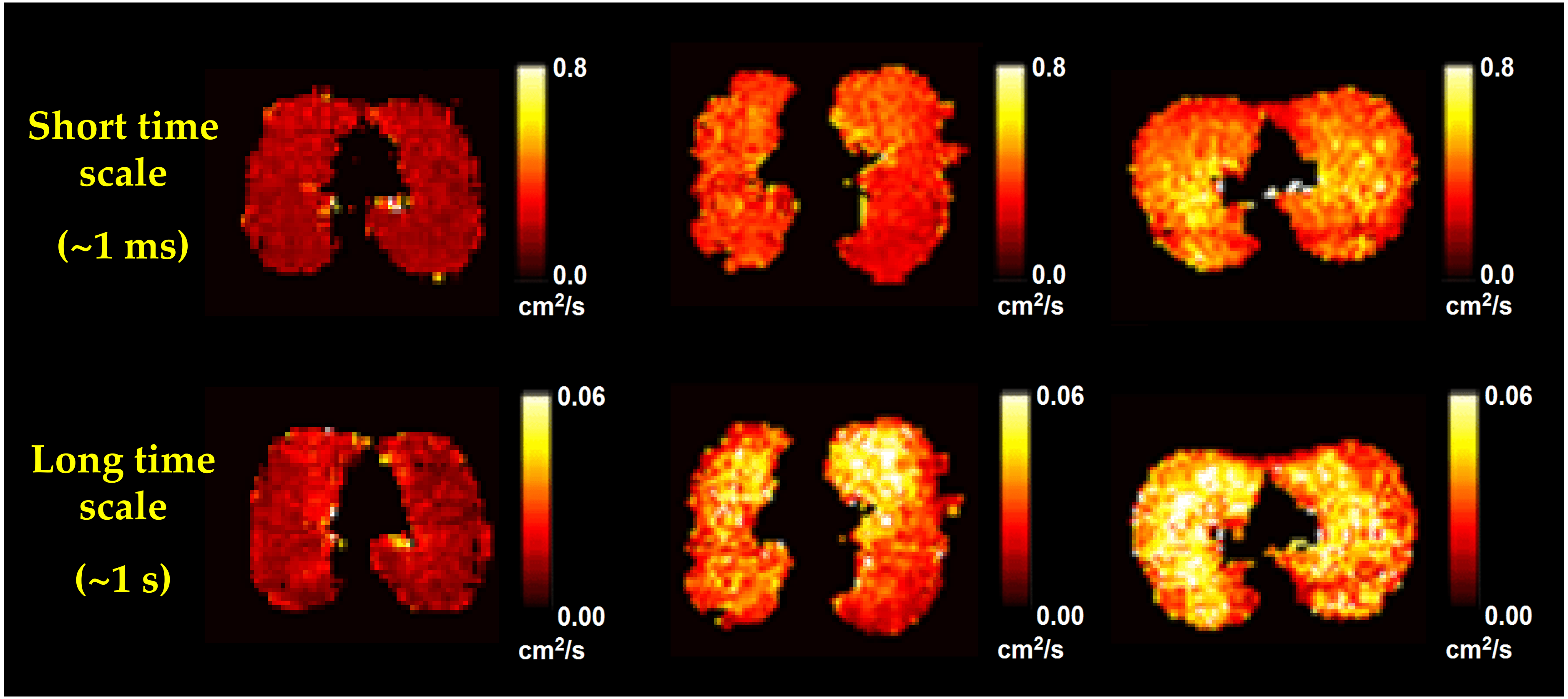
"Apparent Diffusion Coefficient"
is an indirect probe of Alveolar size.

The Effect of Second Hand Smoke

Low Exposure

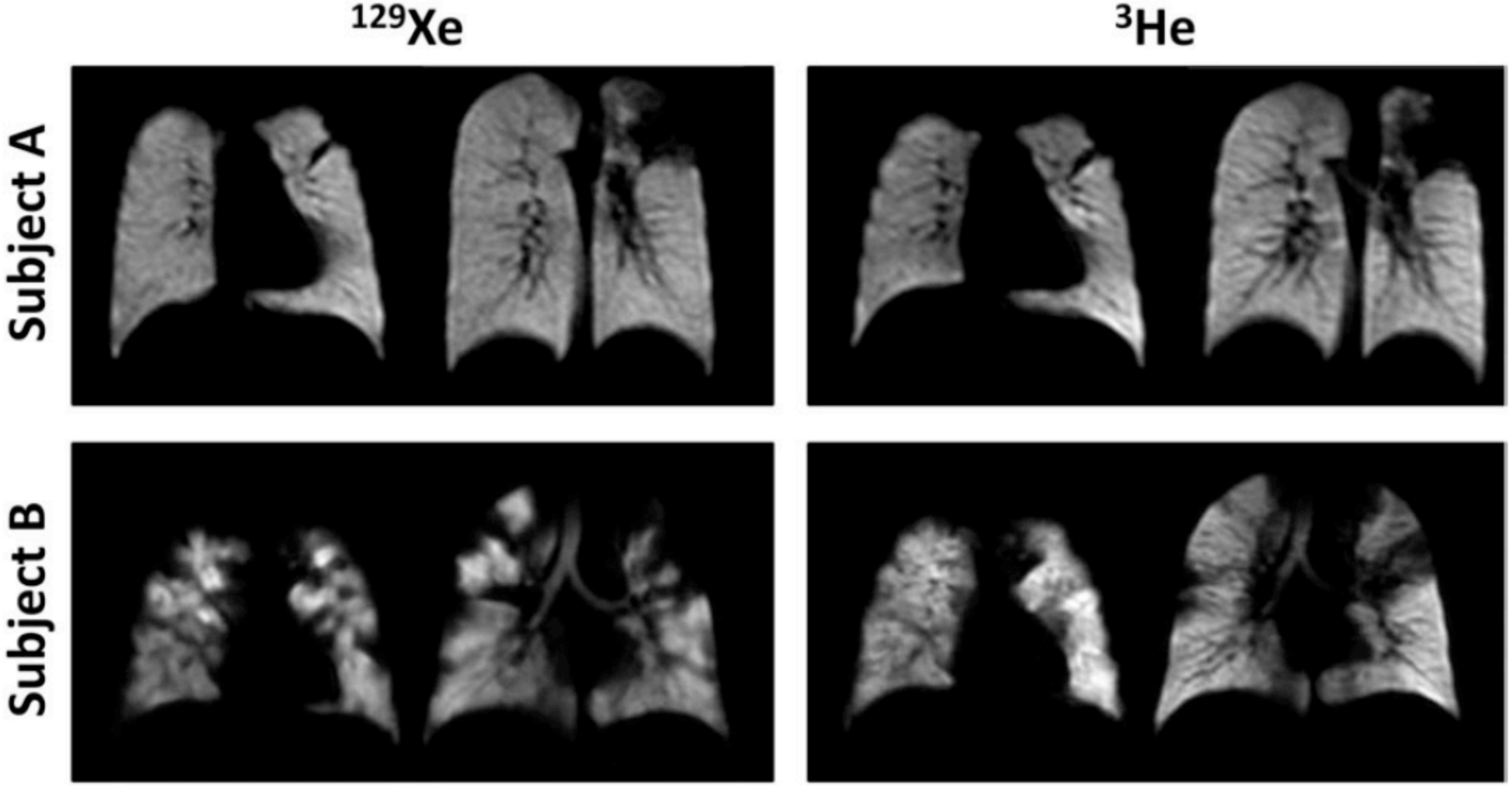
High Exposure

Smoker



C Wang et al. RSNA 93 (Chicago, 2007).

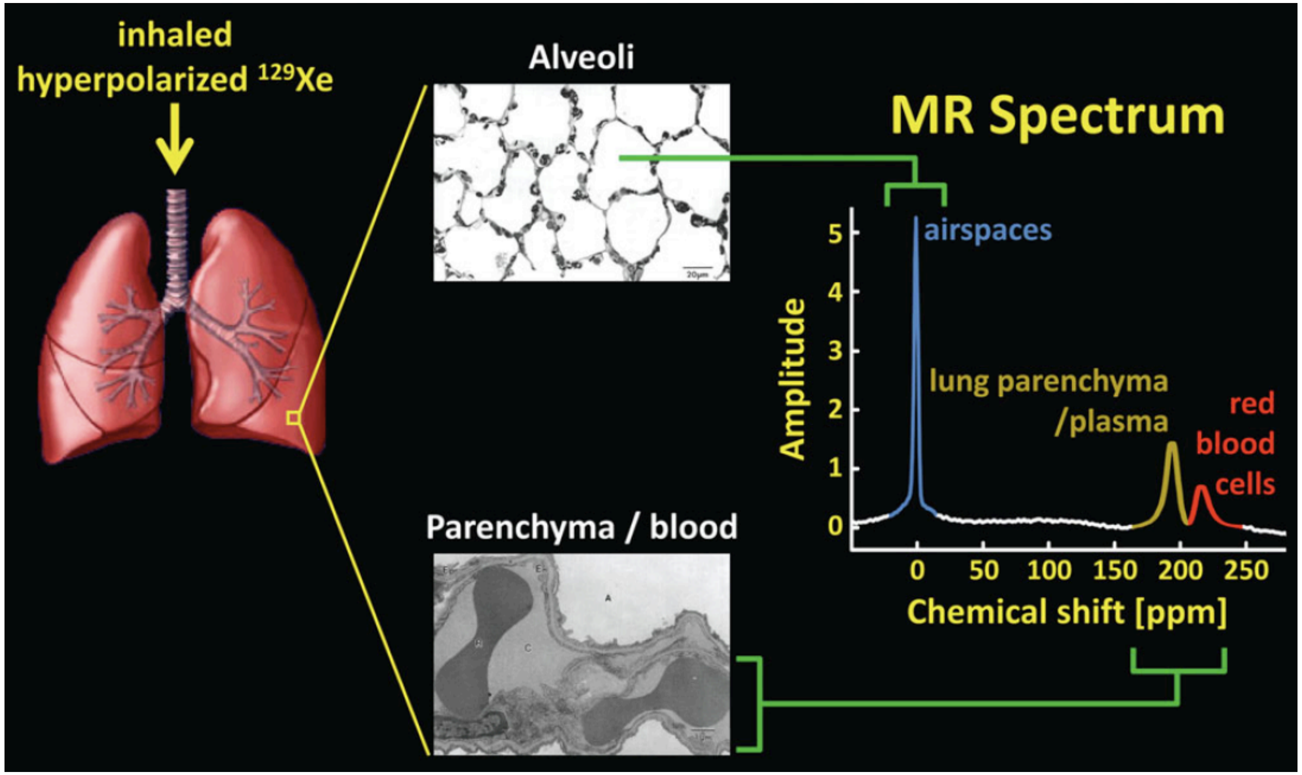
^{3}He vs. ^{129}Xe



Mugler & Altes, JMRI 37 313 (2013)

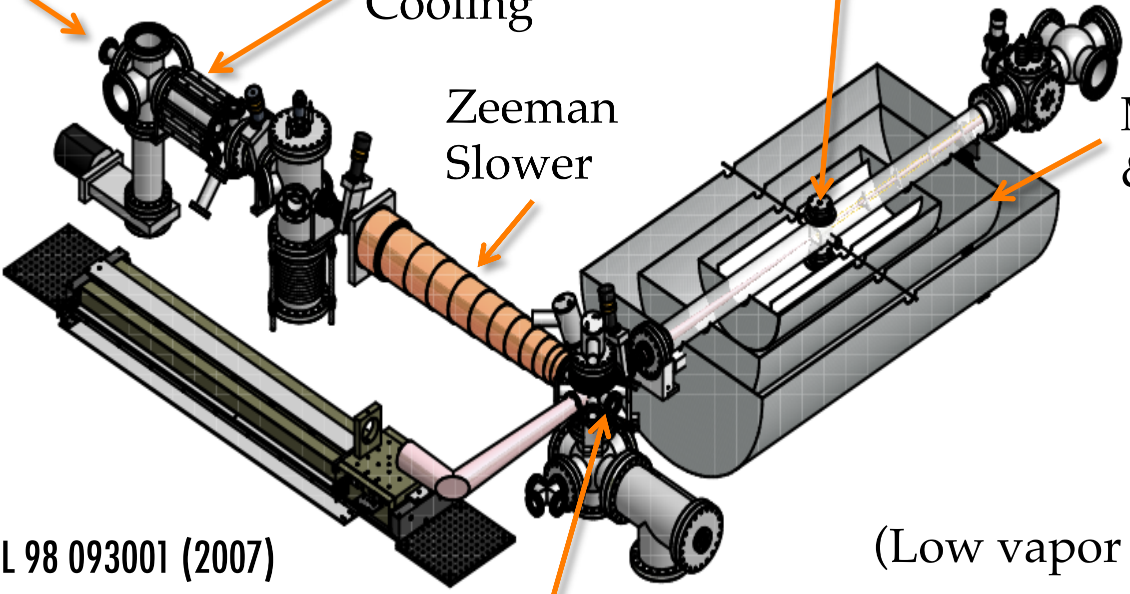
^{3}He – produced from tritium beta decay, 3.0k$/L
^{129}Xe – natural component of air, 0.3k$/L

Potential Advantages of ^{129}Xe



Great so far as a research tool, but still unclear if this will ever be a clinical tool.

Atom Collection



Ra+Ba Oven

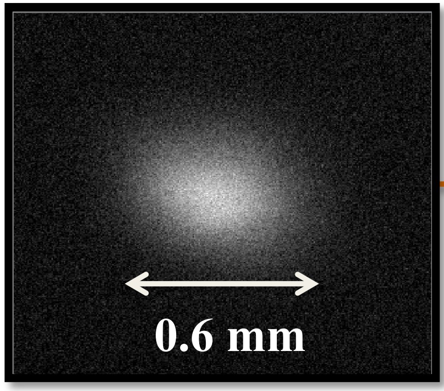
Transverse Cooling

HV Electrodes

Zeeman Slower

Magnetic Shielding & Magnet Coils

Guest et al., PRL 98 093001 (2007)

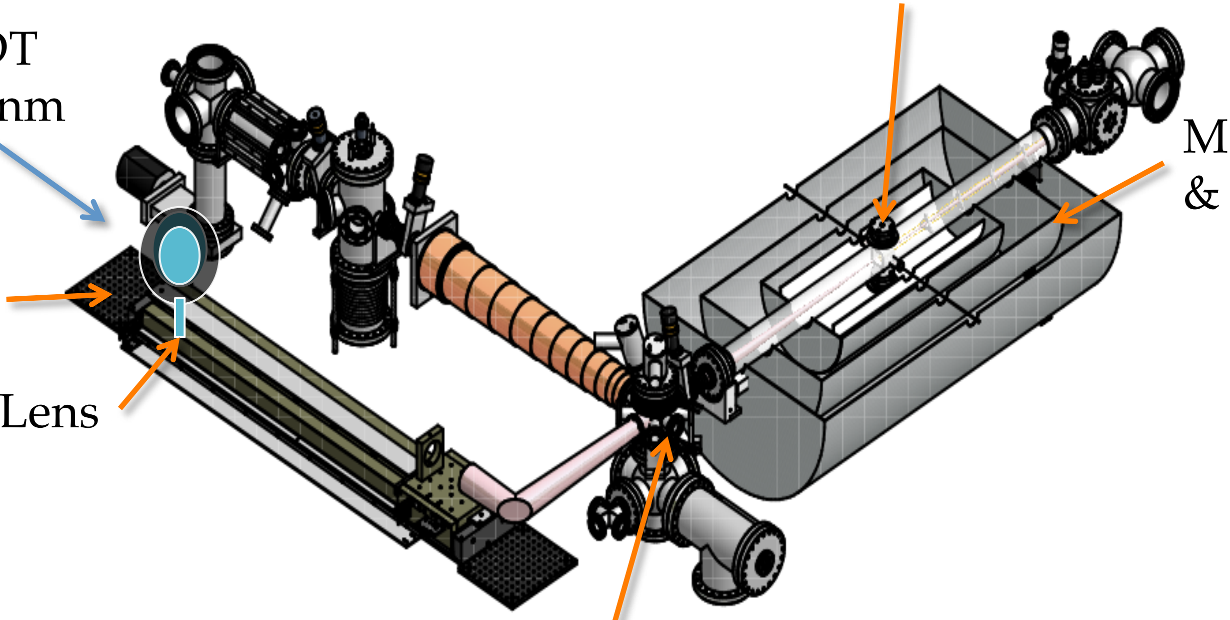


^{226}Ra MOT
20,000 atoms

(Low vapor pressure)

For EDM:	For Testing:
Ra-225	Ra-226
$I = 1/2, J = 0$	$I = 0, J = 0$
$t_{1/2} = 15$ days	$t_{1/2} = 1600$ yrs

Transfer into "Bus"



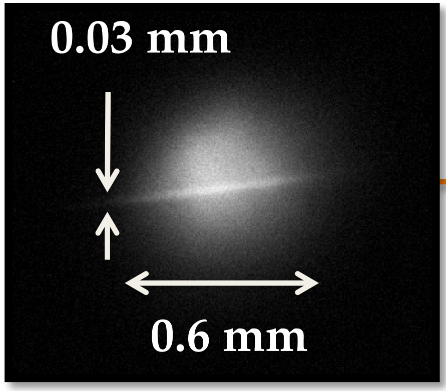
HV Electrodes

"Bus" ODT
50 W 1550 nm

Magnetic Shielding
& Magnet Coils

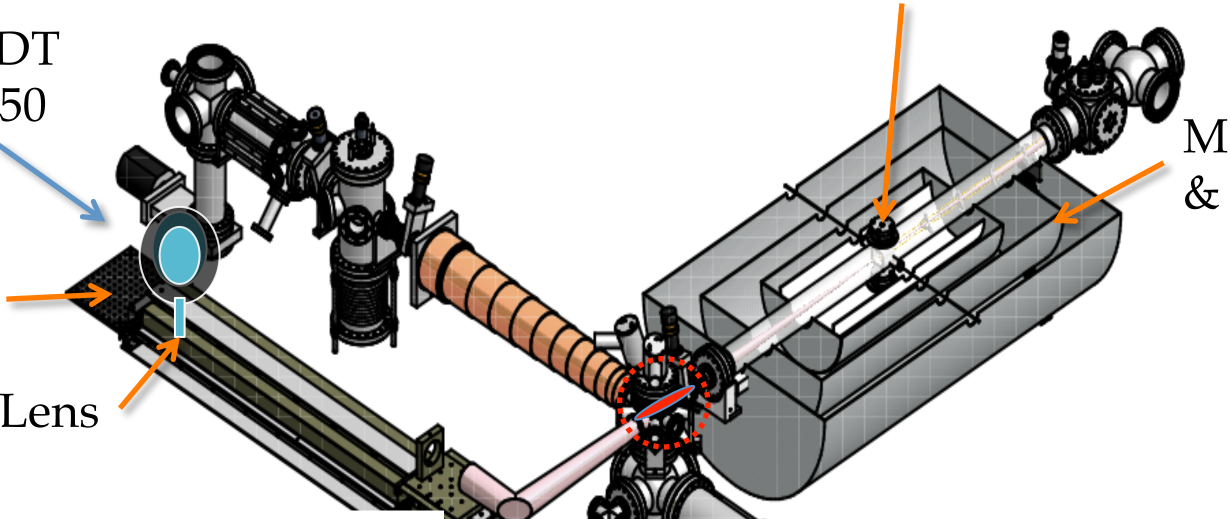
Translation
Stage

Lens



MOT + ODT
20,000 atoms

Transport into Science Region



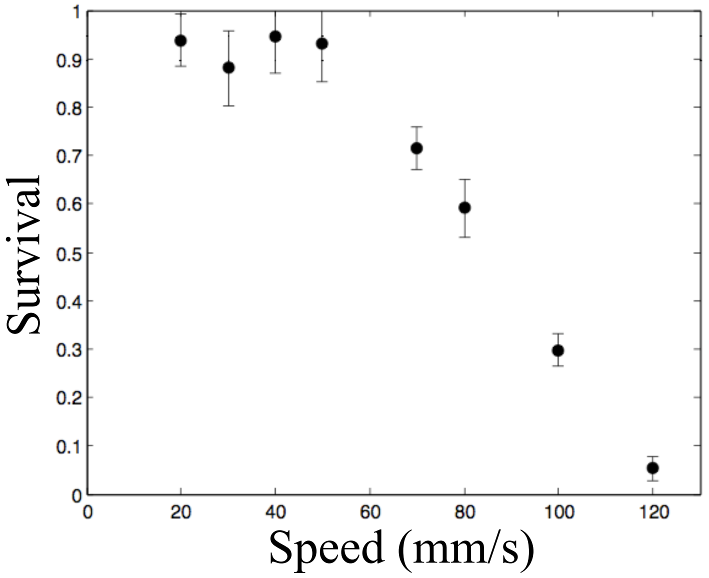
HV Electrodes

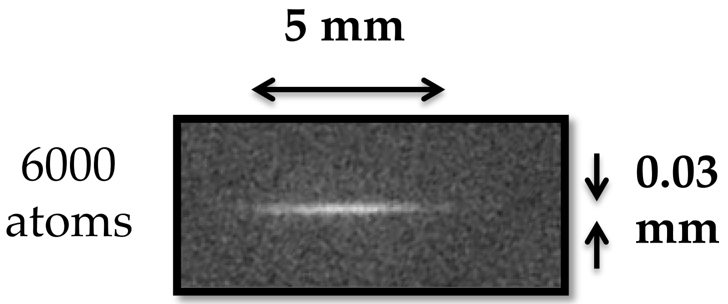
"Bus" ODT
50 W 1550
nm

Magnetic Shielding
& Magnet Coils

Translation
Stage

Lens



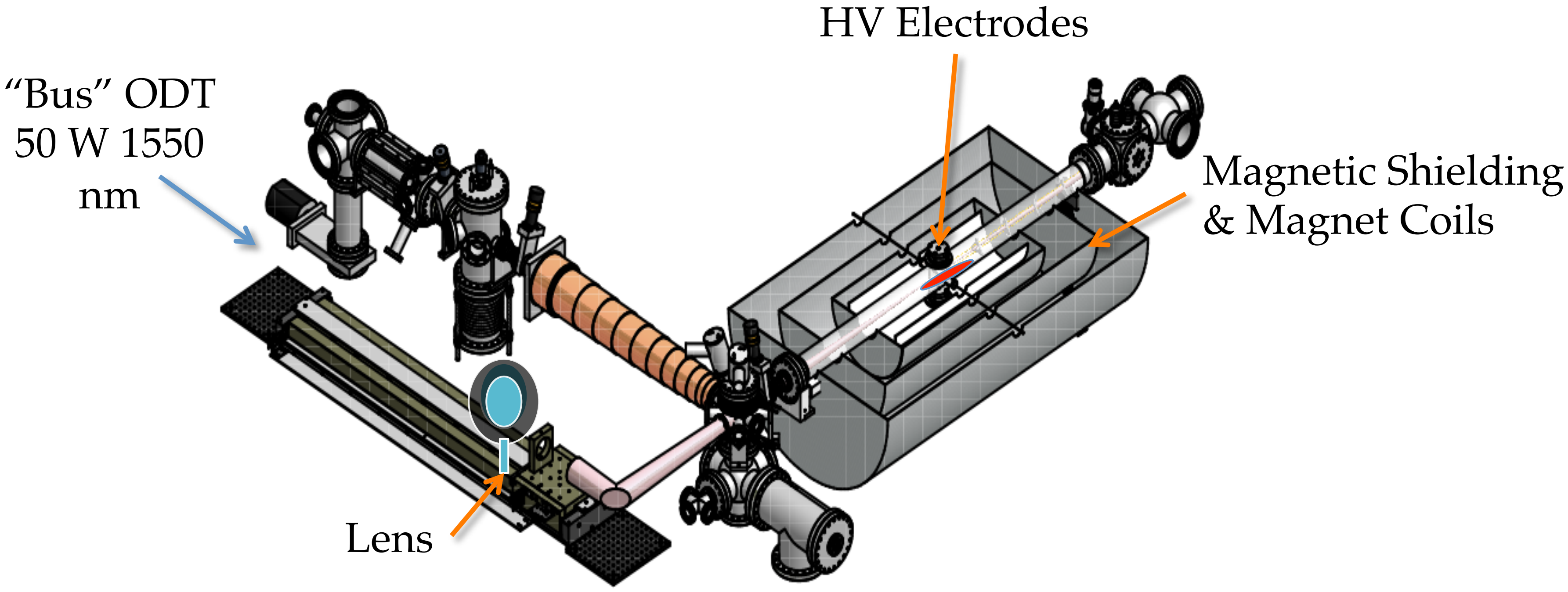


5 mm

6000
atoms

0.03
mm

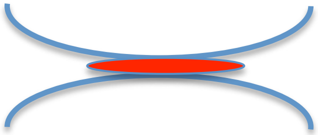
Transfer into "Holding" Trap



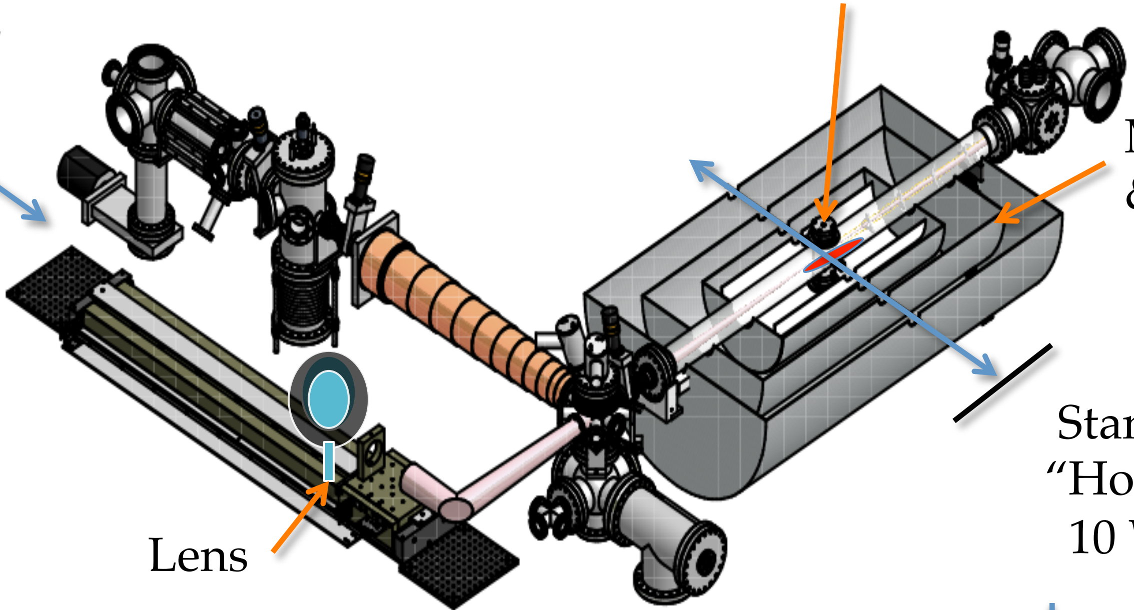
"Traveling Wave" ODT

- Tight confinement transverse to beam
- Weak confinement along beam axis
- Atoms can leak out of trap
- Field gradients must be very small
- Light induced systematics larger

Traveling Wave
"Bus" ODT



Transfer into "Holding" Trap



"Bus" ODT
50 W 1550
nm

HV Electrodes

Magnetic Shielding
& Magnet Coils

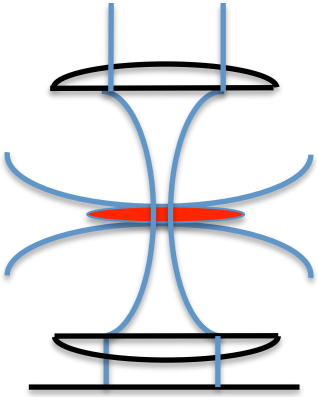
Standing Wave
"Holding" ODT
10 W 1550 nm

Lens

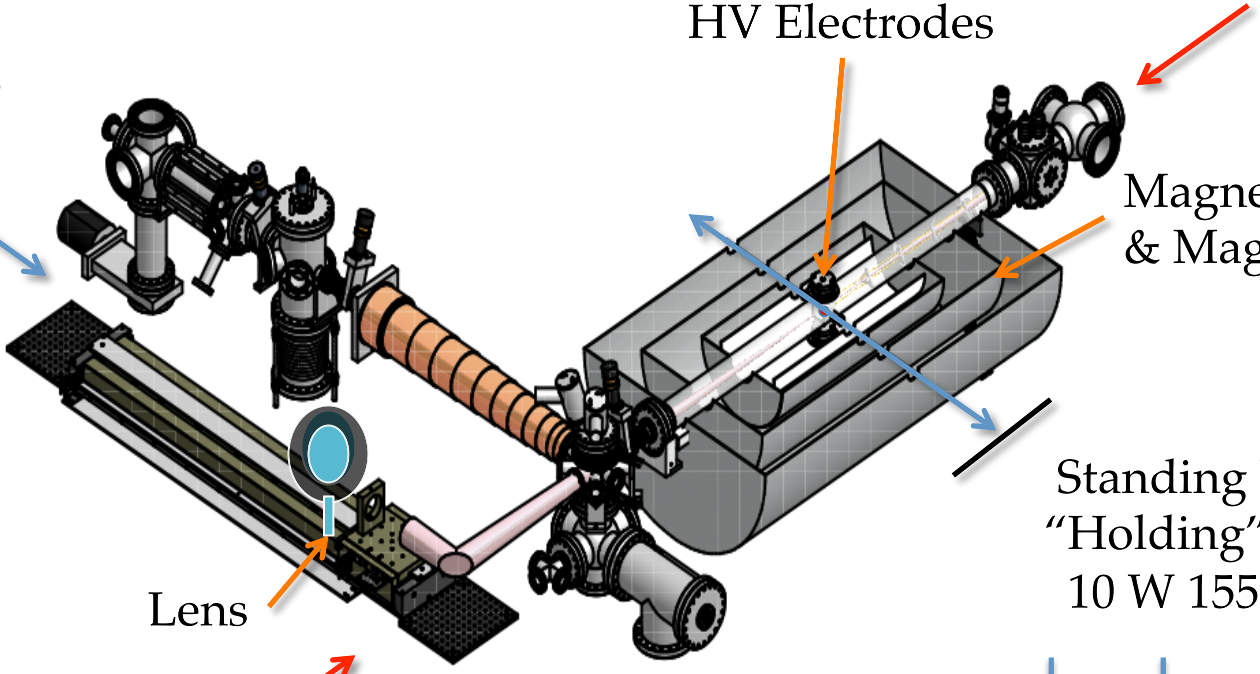
"Standing Wave" ODT

- Tight confinement transverse to beam
- Tight confinement along beam axis
- Atoms trapped in "pancakes"
- Field gradients more tolerable
- Light induced systematics smaller

Traveling Wave
"Bus" ODT



Transfer into “Holding” Trap



HV Electrodes

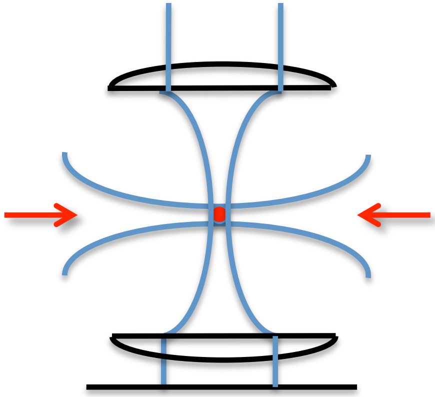
“Bus” ODT
50 W 1550
nm

Magnetic Shielding
& Magnet Coils

Standing Wave
“Holding” ODT
10 W 1550 nm

Lens

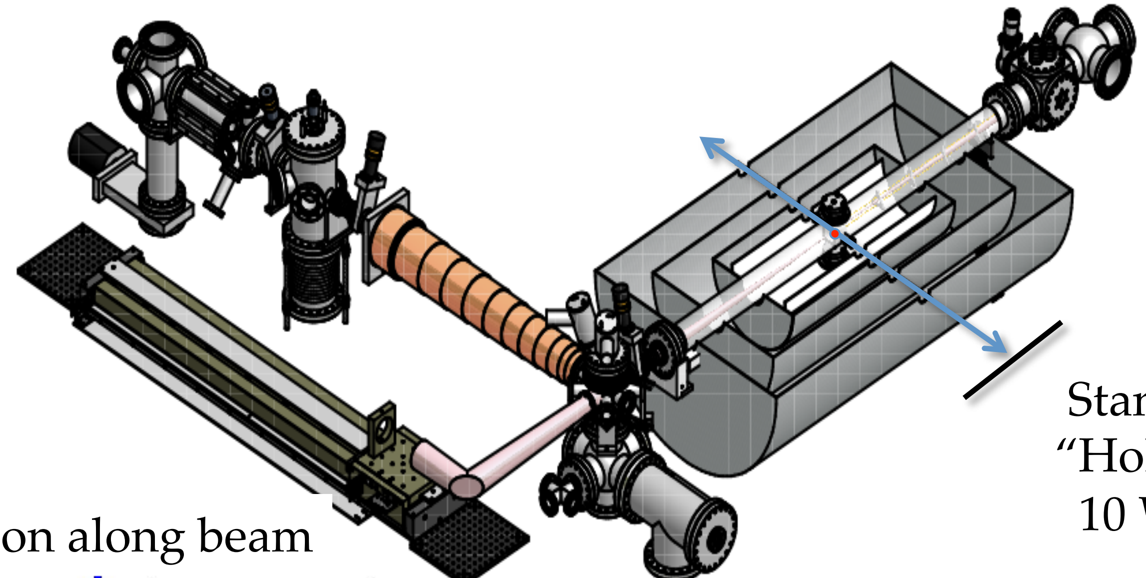
Laser Cooling
100 μW 714 nm



Traveling Wave
“Bus” ODT

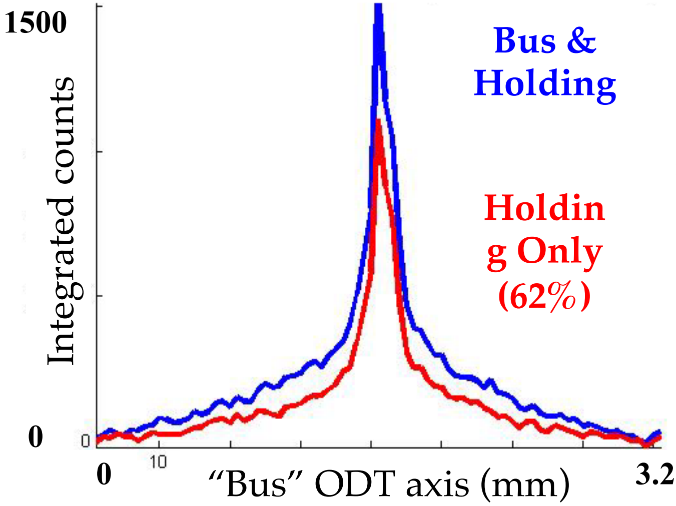
Laser
Cooling

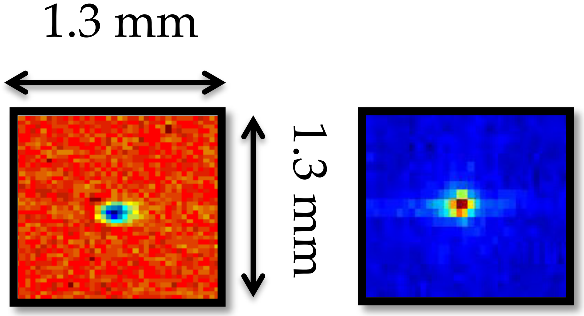
Transfer into “Holding” Trap



Standing Wave
“Holding” ODT
10 W 1550 nm

Projection along beam





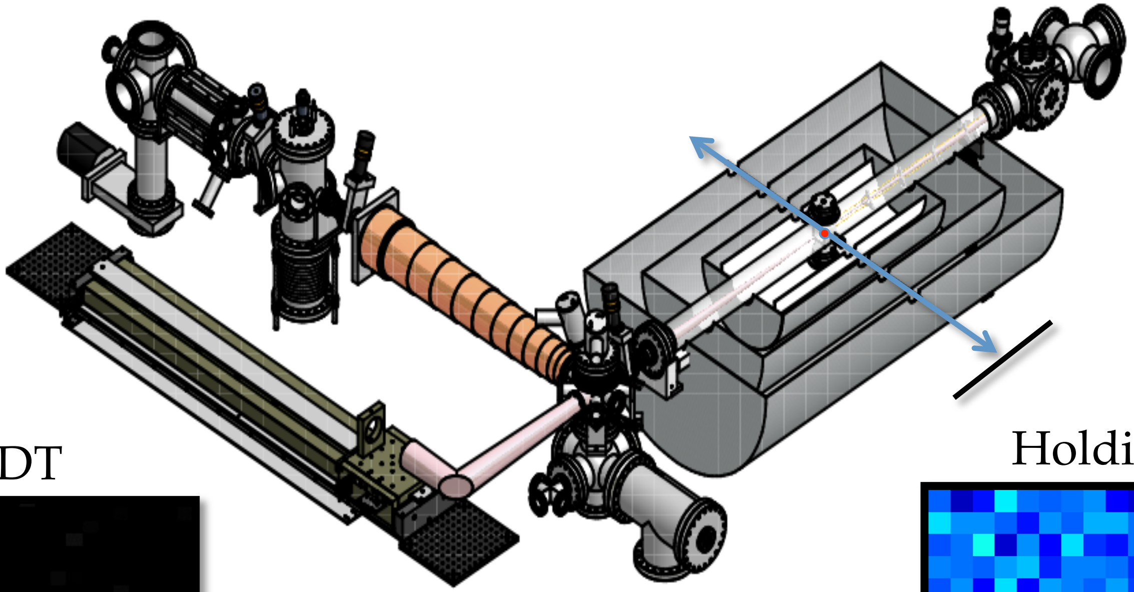
700 atoms
1.4% abs

3000
atoms

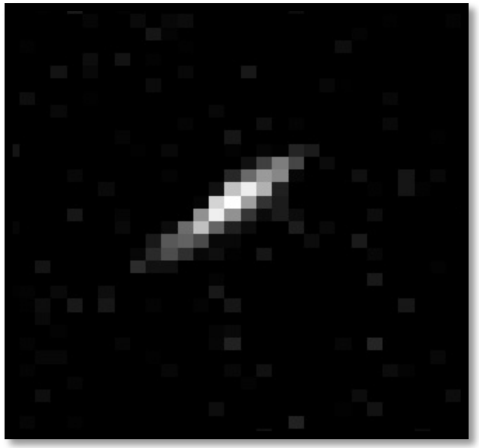
Absorption
Imaging

Fluoresence
Imaging

Now with Ra-225



Bus ODT

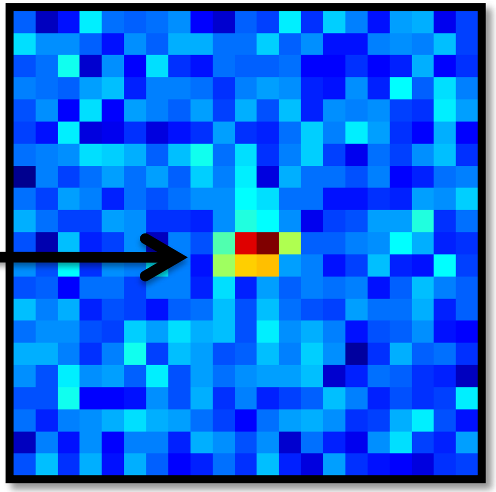


~150 Ra-225 Atoms

Atoms in a
$(50\ \mu m)^3$ spot

Alignment between two
beams is challenging

Holding ODT



~75 Ra-225 Atoms

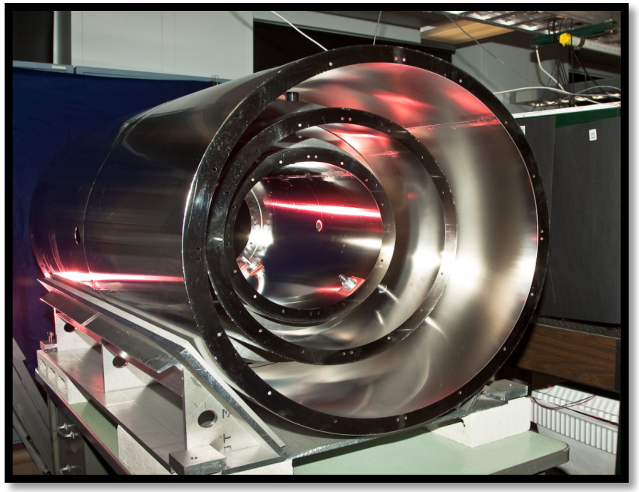
Stable Magnetic Fields

Design Goals Achieved!

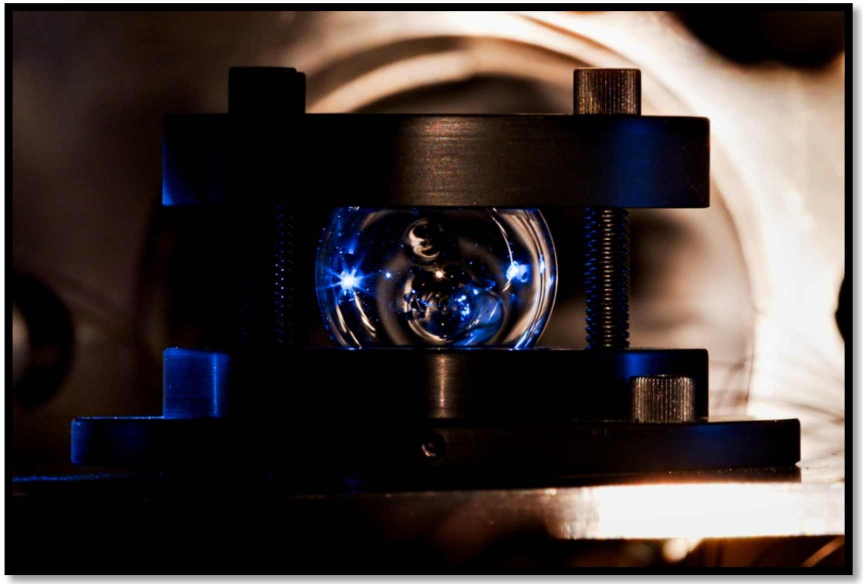
$B = 1\ \mu T$

Stability: < 1 ppm in 100 sec

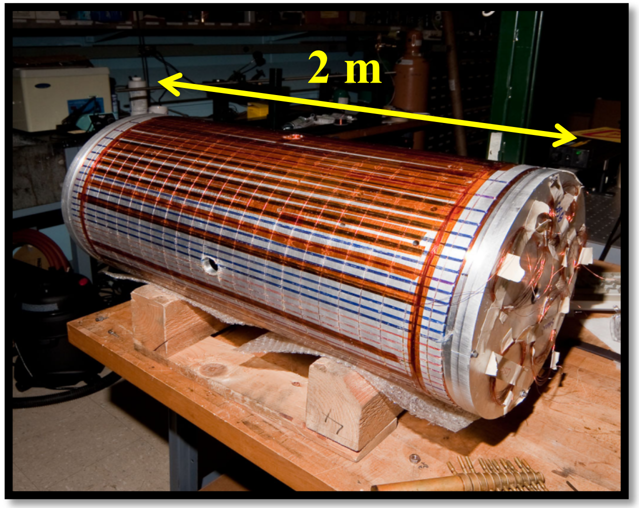
Uniformity: $< 0.1\%$ per cm



μ-shields: Shielding factor = 2×10^4



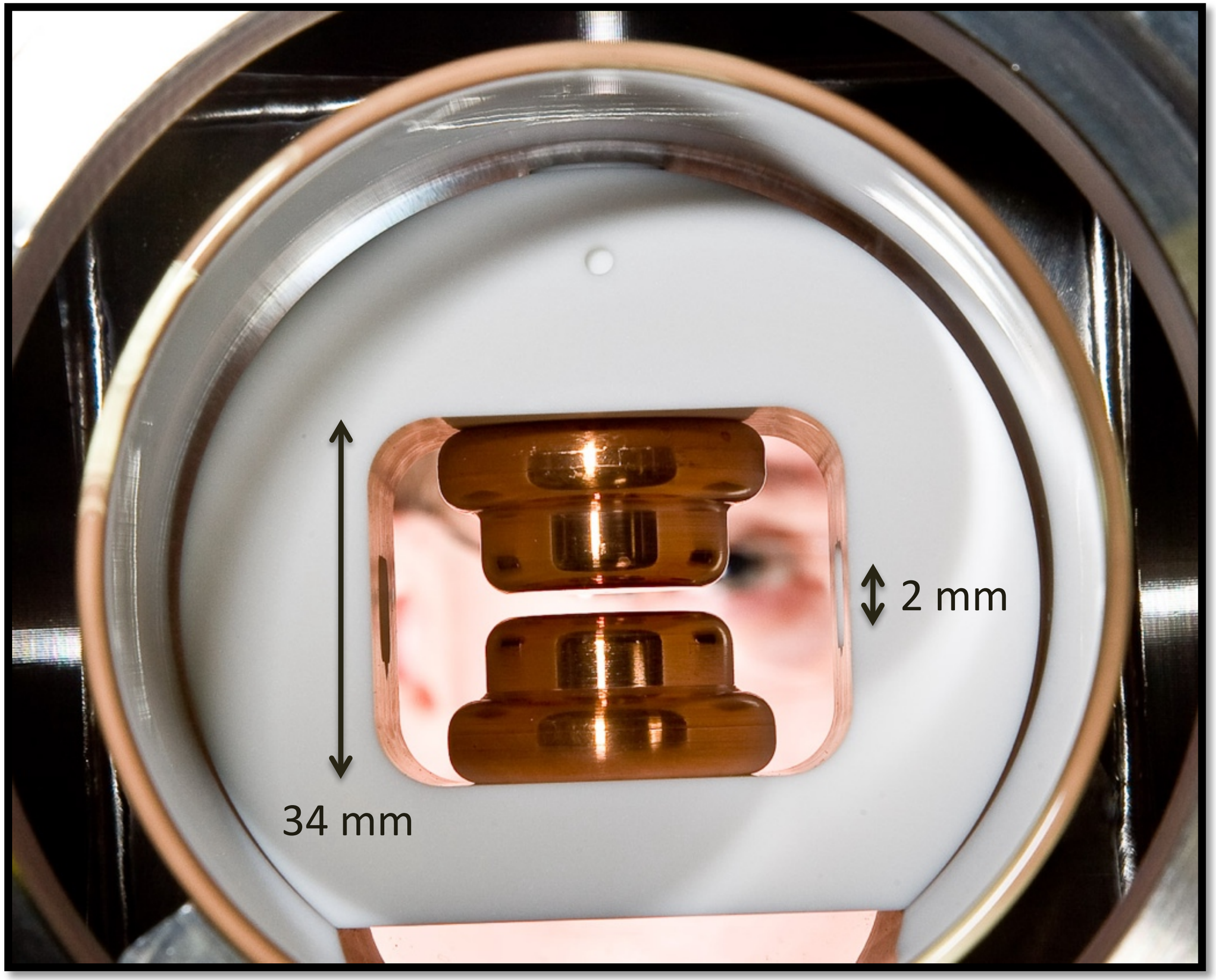
Rb cell magnetometer:
Higbie et al. Rev. Sci. Inst. 77, 113106 (2006)



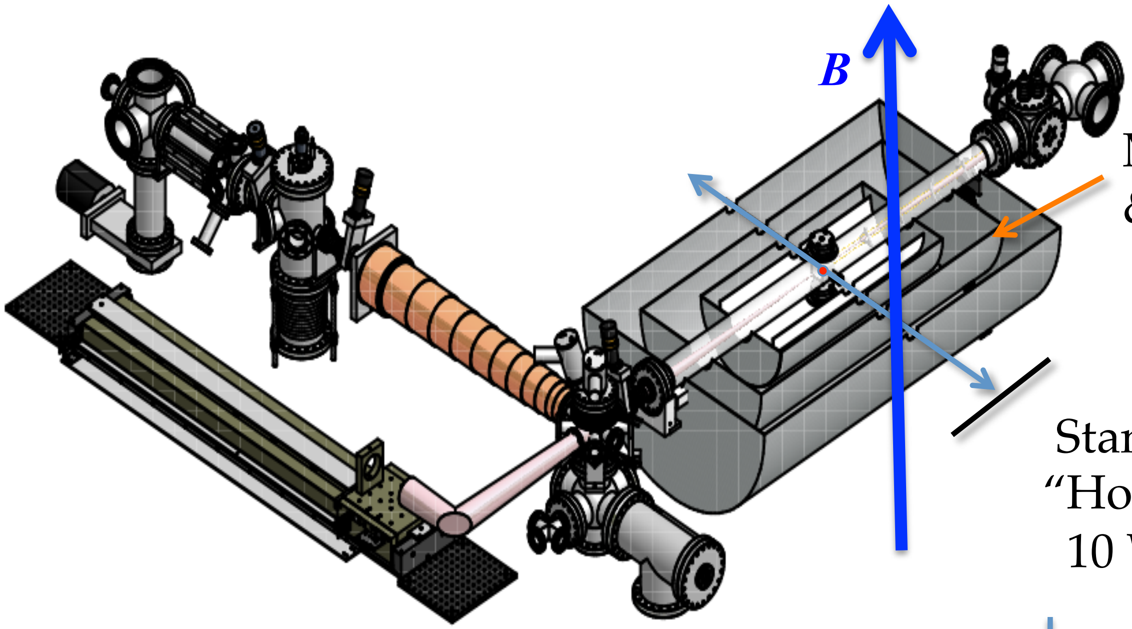
B gradient < 1 nT/cm

Electric Fields

- 15 kV over 2 mm vacuum gap (x4 higher than ^{199}Hg experiment)
- <50 pA leakage currents observed

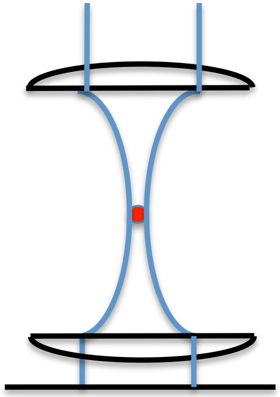


Apply B-field & Optically Pump



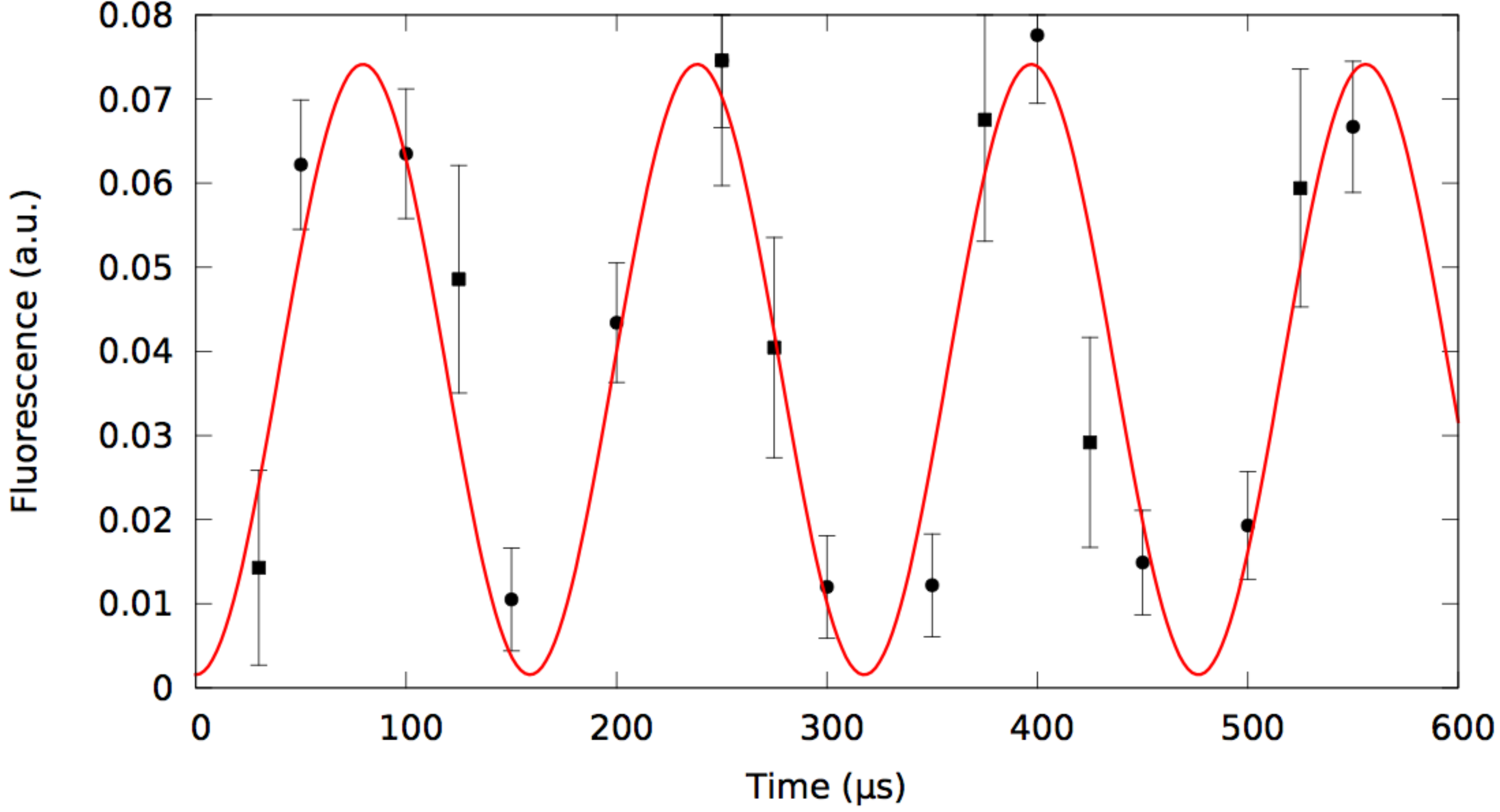
Magnetic Shielding
& Magnet Coils

Standing Wave
“Holding” ODT
10 W 1550 nm

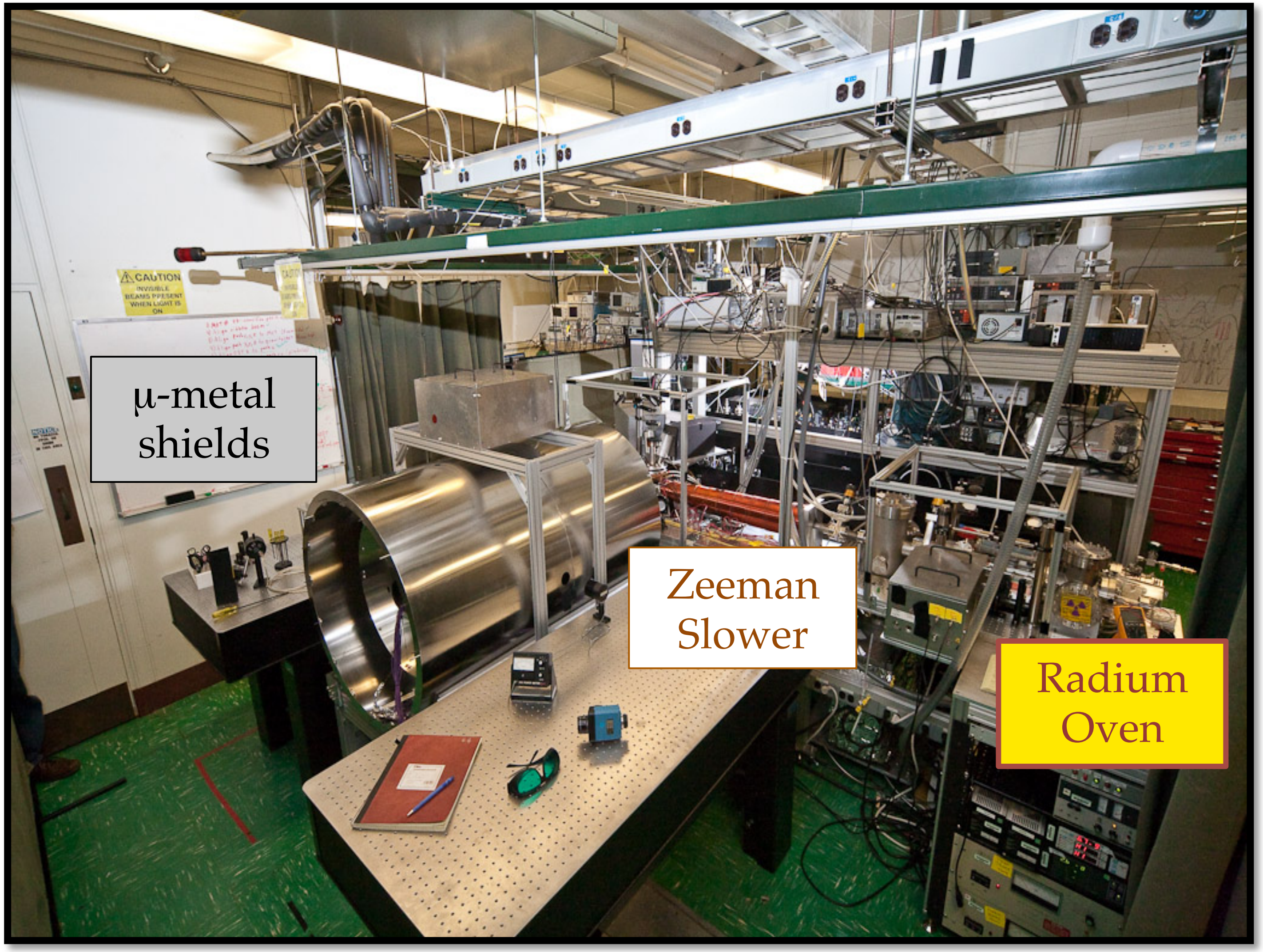


Spin Precession @ 570 μT

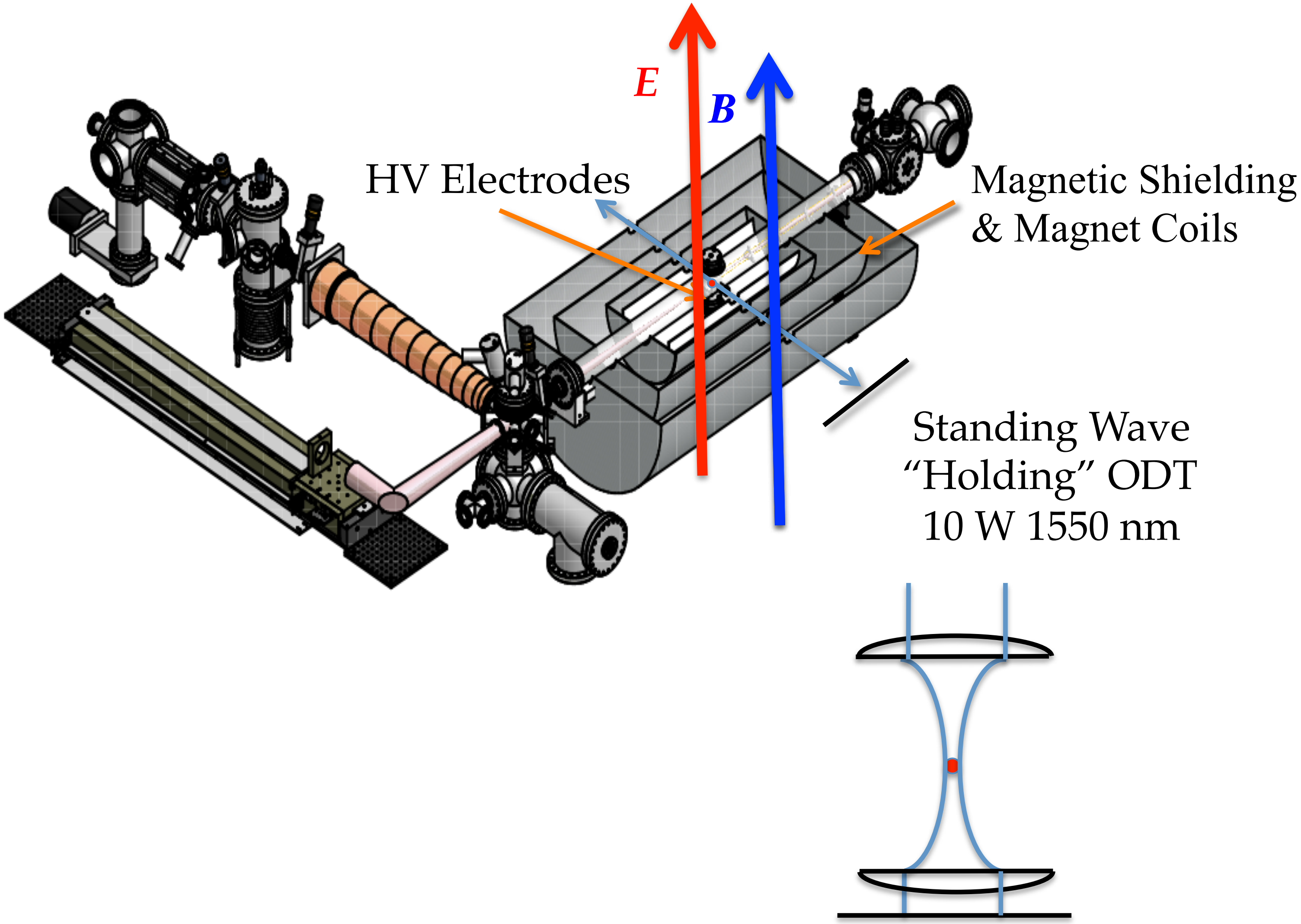
Polarization 96(10)%
Frequency 6.30(4) kHz
Reduced χ^2 19.0/15



Assembled Experiment



Apply *B*- & *E*-fields & Take Data



HV Electrodes

Magnetic Shielding
& Magnet Coils

Standing Wave
“Holding” ODT
10 W 1550 nm