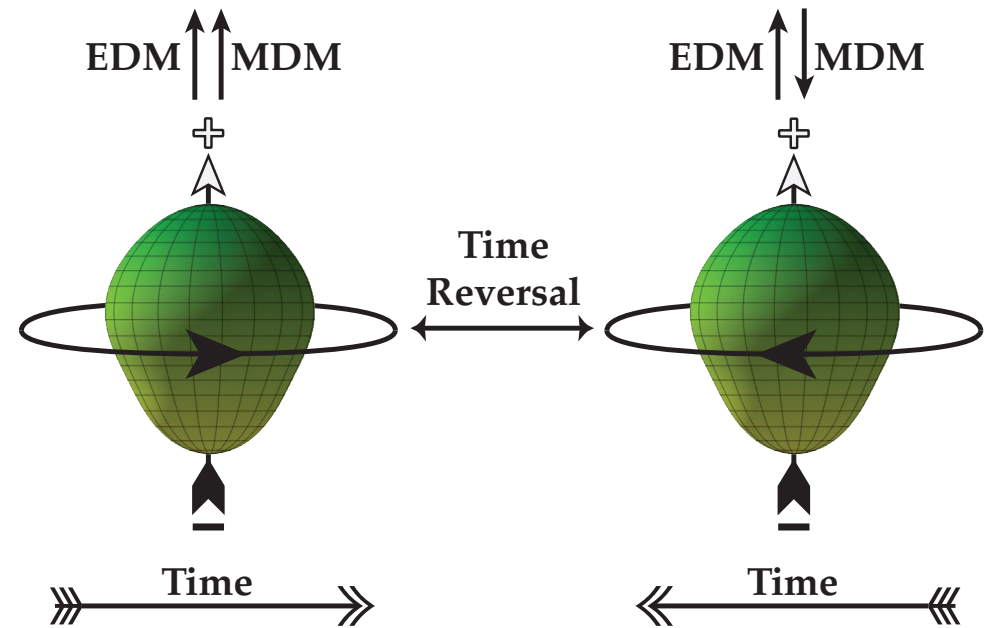
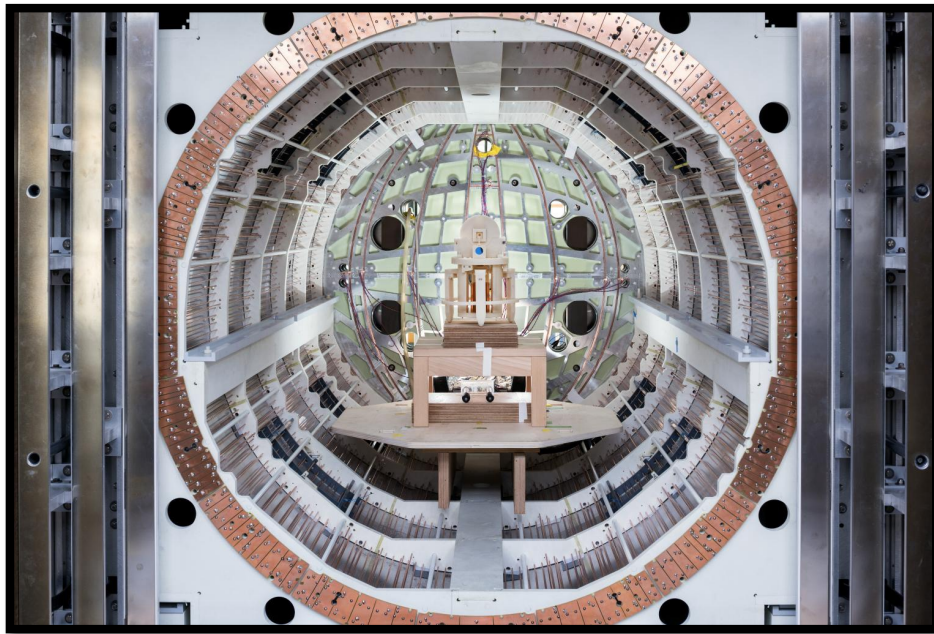


Testing Time-Reversal Symmetry Using Lasers, a Magic Room, and Pear-Shaped Nuclei



Jaideep Taggart Singh

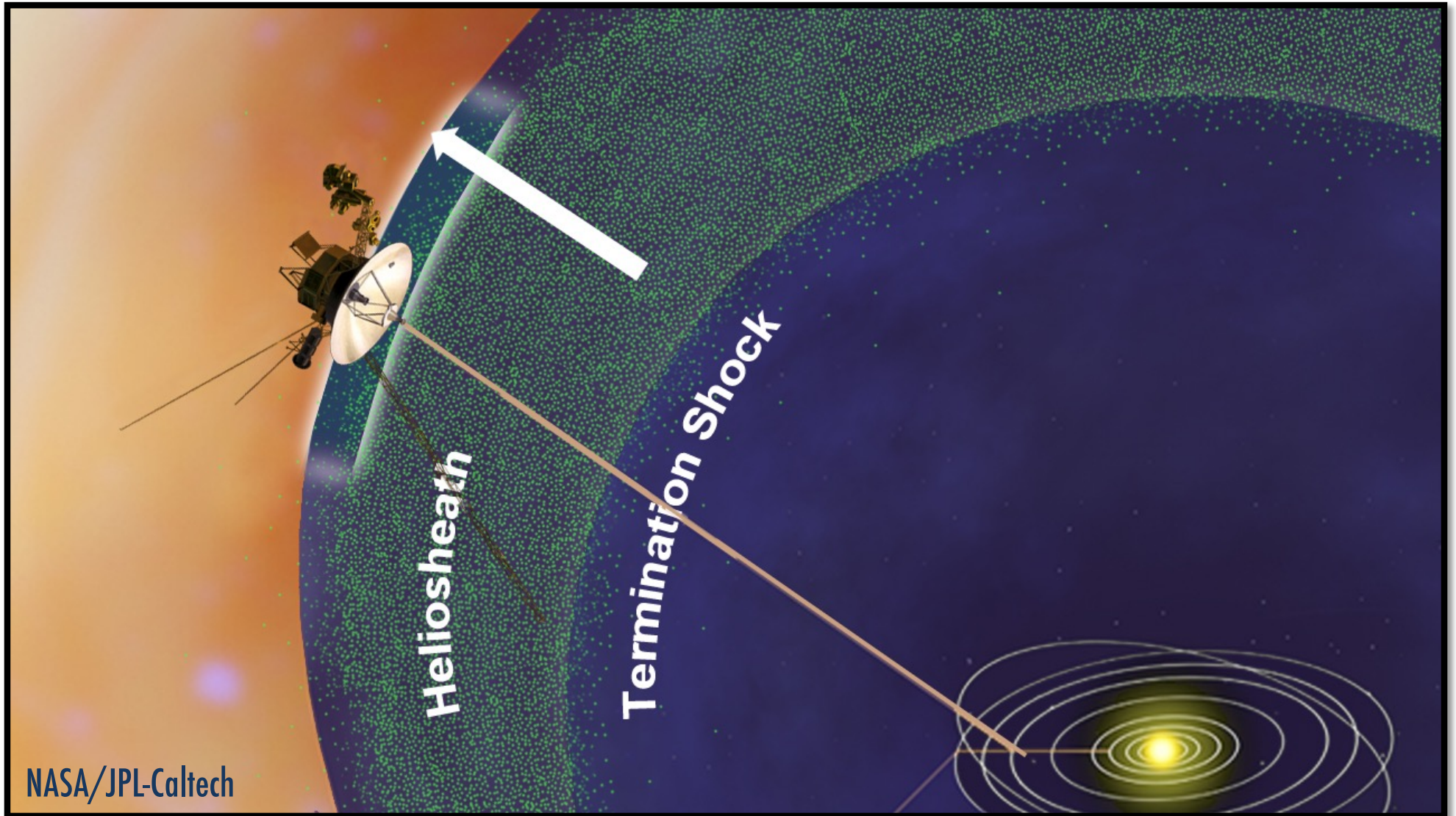
National Superconducting Cyclotron Lab

Michigan State University

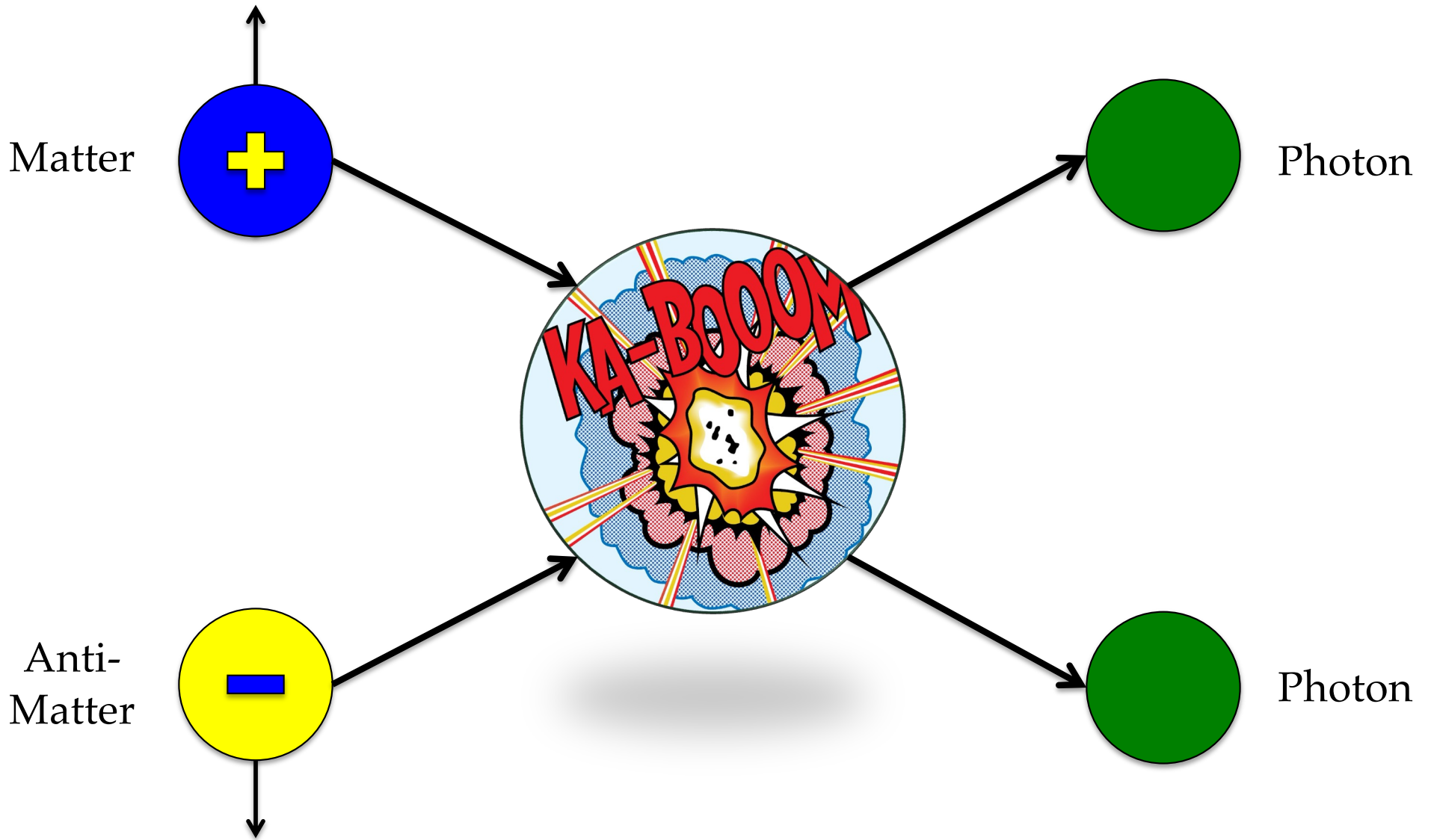
Texas Tech University, Physics Colloquium, 2016-02-04



Voyager 1 is still OK!

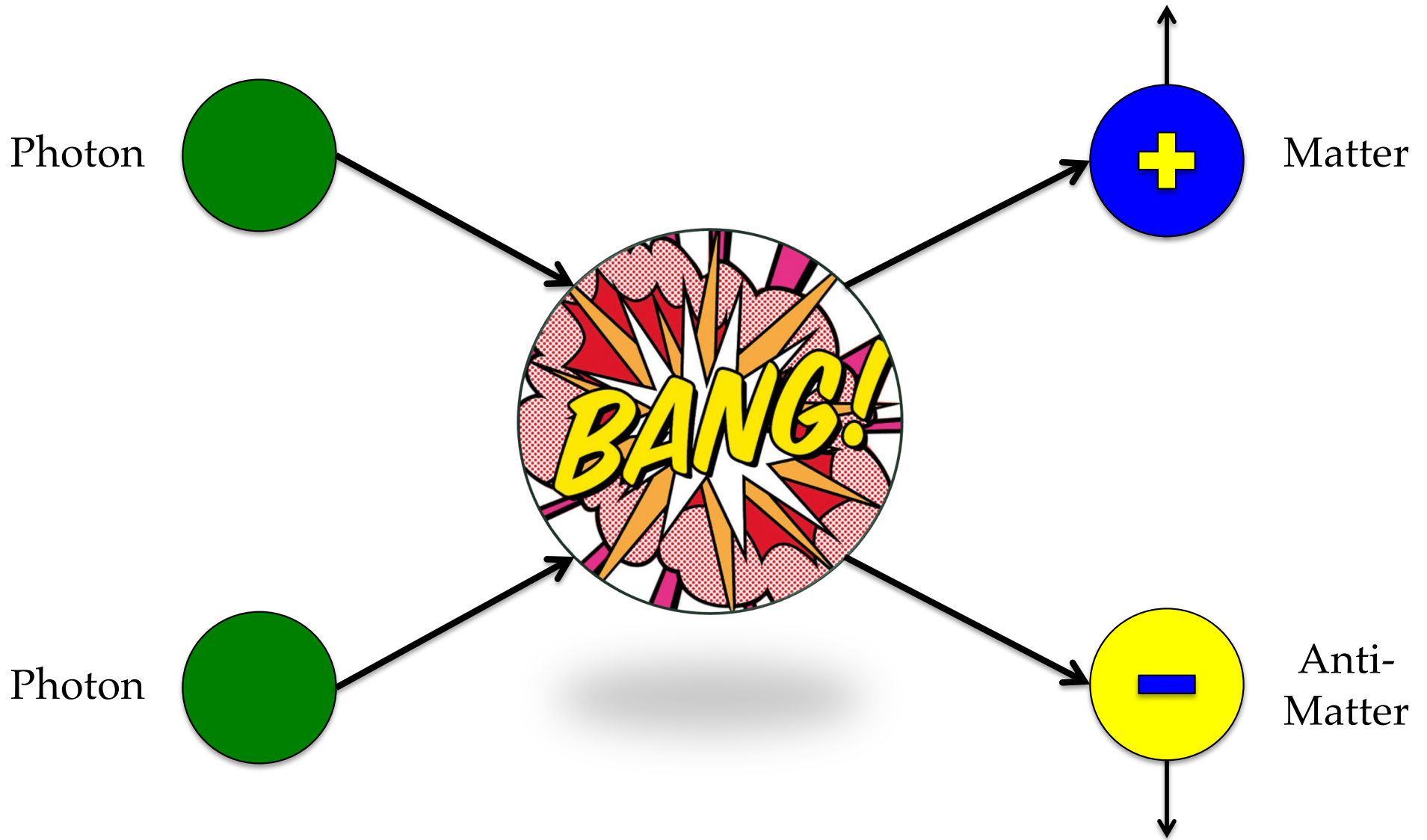


Stuff and Anti-Stuff disappears into Light.



<http://strangesounds.org/2013/08/mysterious-booms-in-the-usa-new-york-california-alaska-mississippi-utah-michigan.html>

Light can be converted into Stuff and Anti-Stuff.

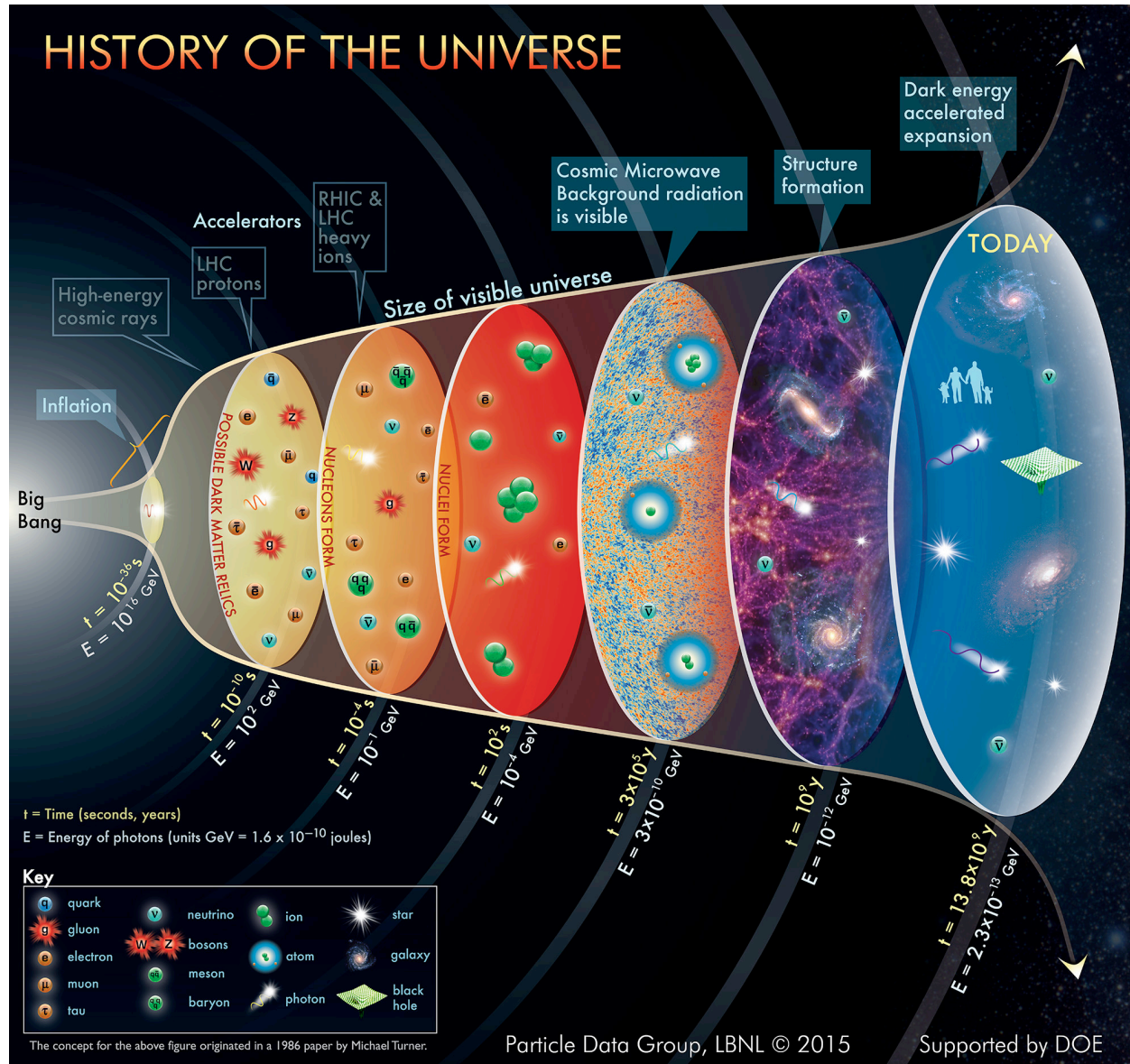


<http://www.bing-bang-mag.com/Le-premier-Comic-street-dijonnais.html>

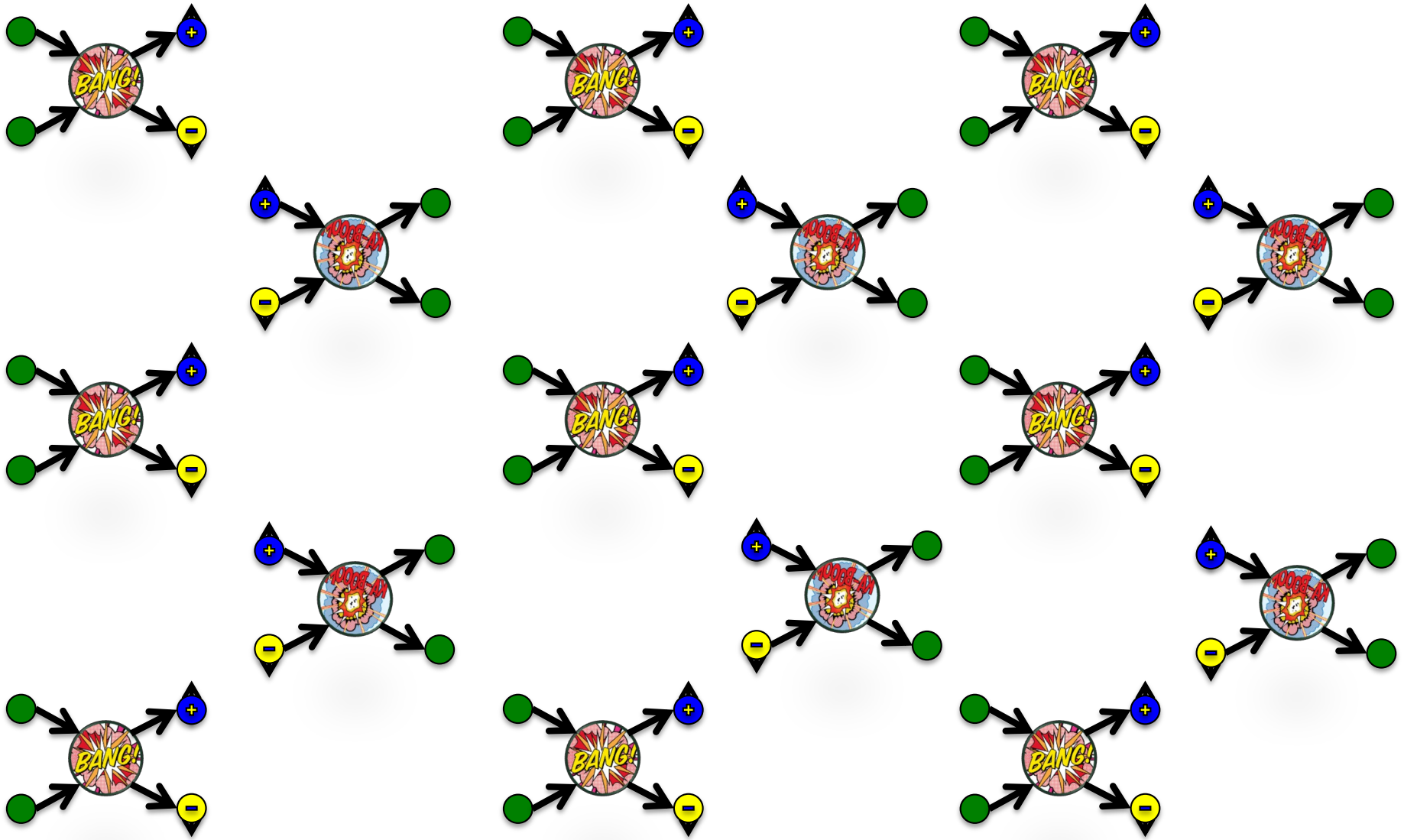
Big Bang...expanding Universe

**HOT &
DENSE**

**cold &
dilute**



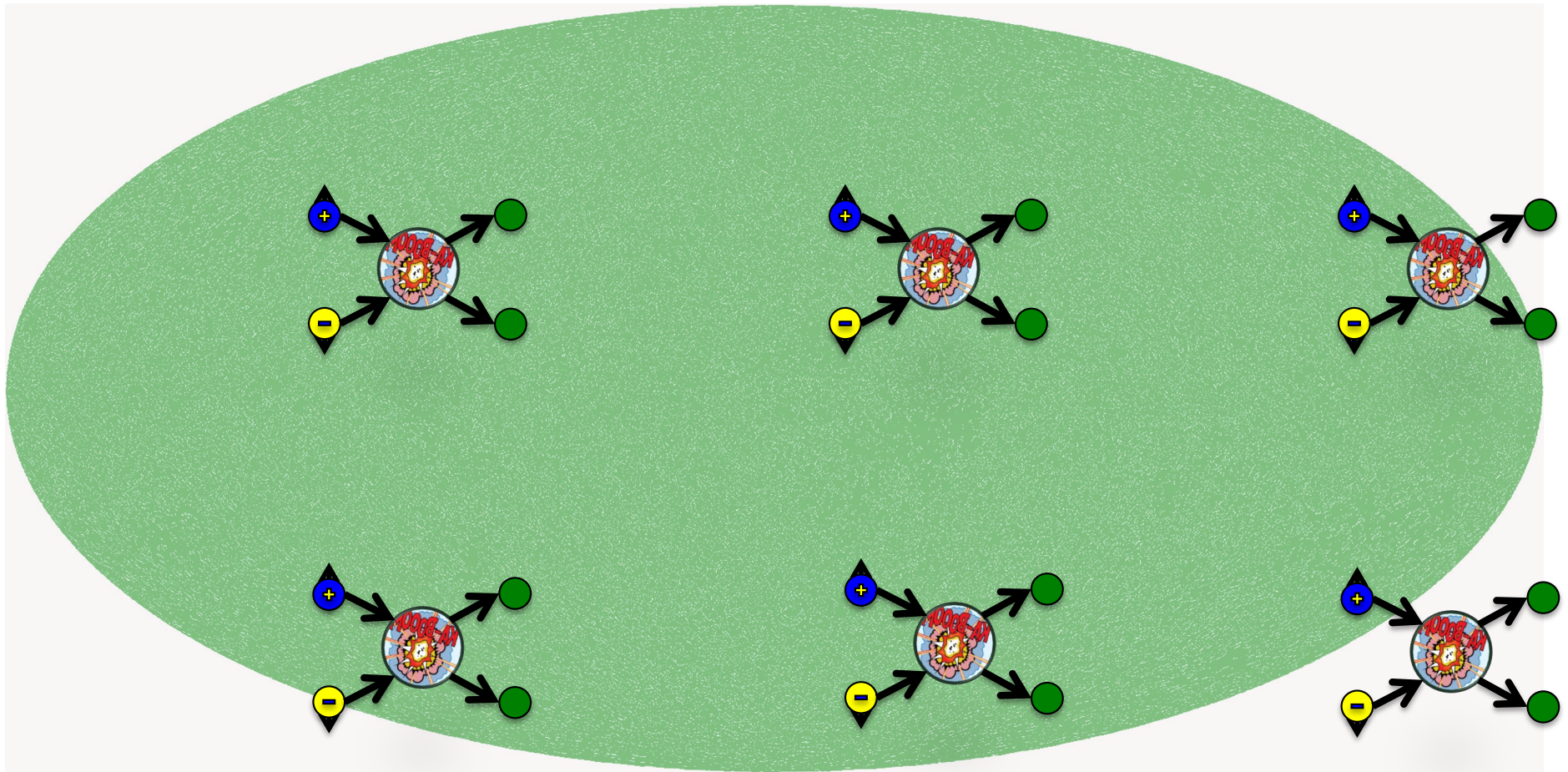
All the things happening all the time everywhere



<http://strangesounds.org/2013/08/mysterious-booms-in-the-usa-new-york-california-alaska-mississippi-utah-michigan.html>

<http://www.bing-bang-mag.com/Le-premier-Comic-street-dijonnais.html>

Expansion means cooling



Planck 2013

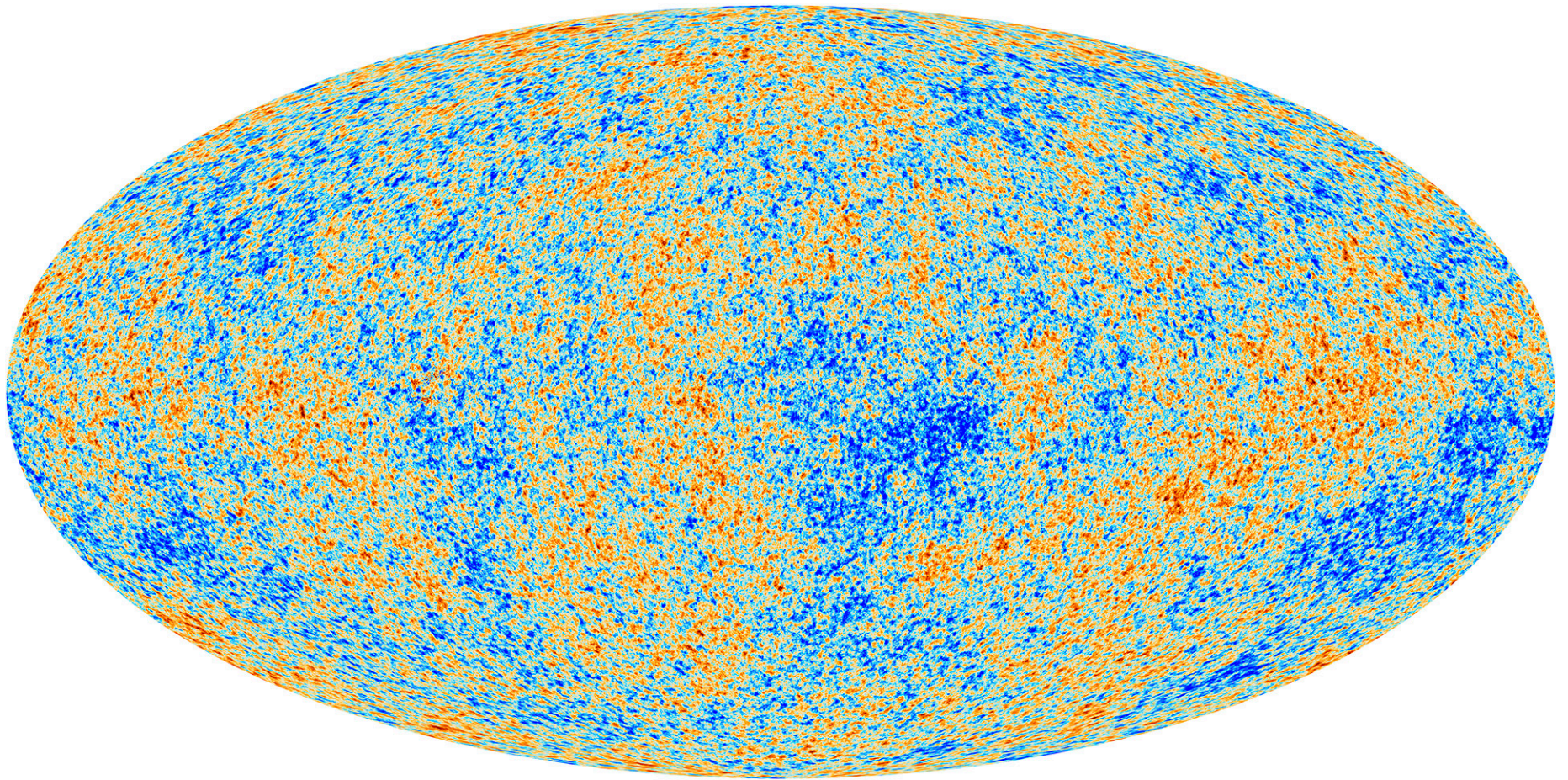
http://www.esa.int/spaceinimages/Images/2013/03/Planck_CMB

<http://strangesounds.org/2013/08/mysterious-booms-in-the-usa-new-york-california-alaska-mississippi-utah-michigan.html>

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

TTU Physics Colloquium

Cosmic Microwave Background Radiation



Planck 2013

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

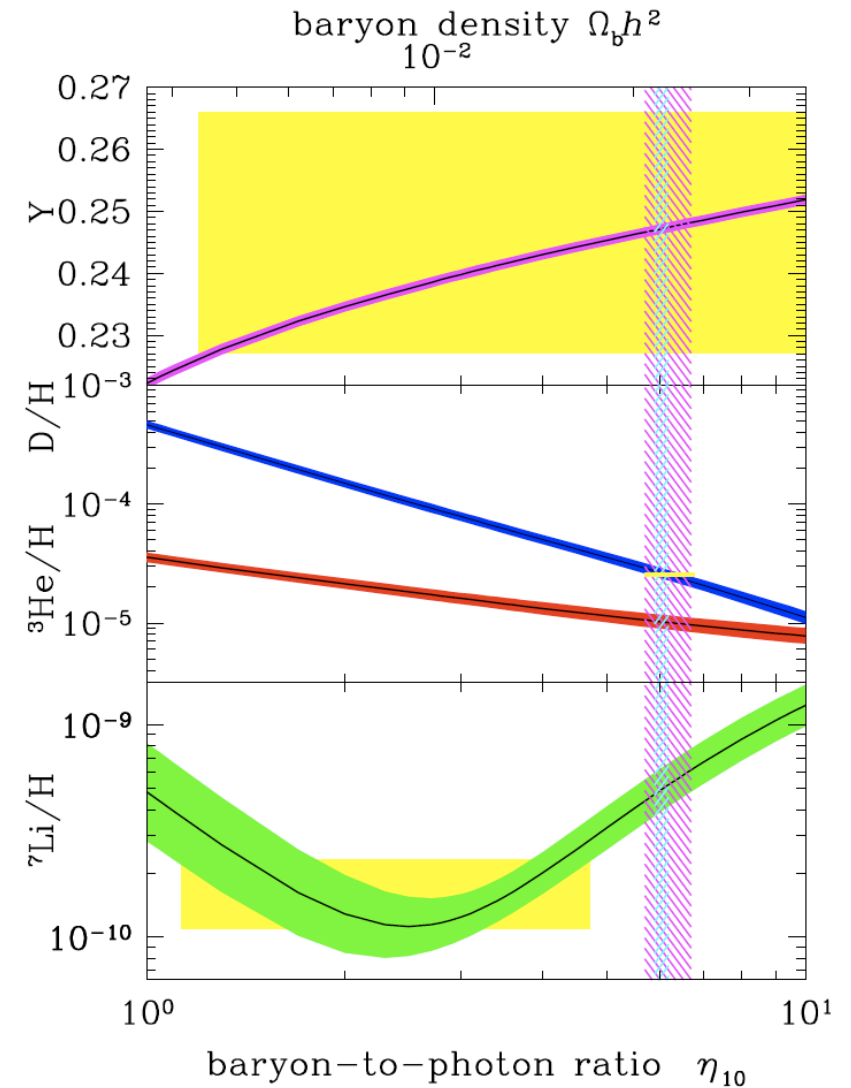
Baryon Asymmetry of Universe

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

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

$$= 0.000000000061 (5\%)$$

$$\approx 10^{-9}$$



PDG2014

Sakharov's Conditions



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

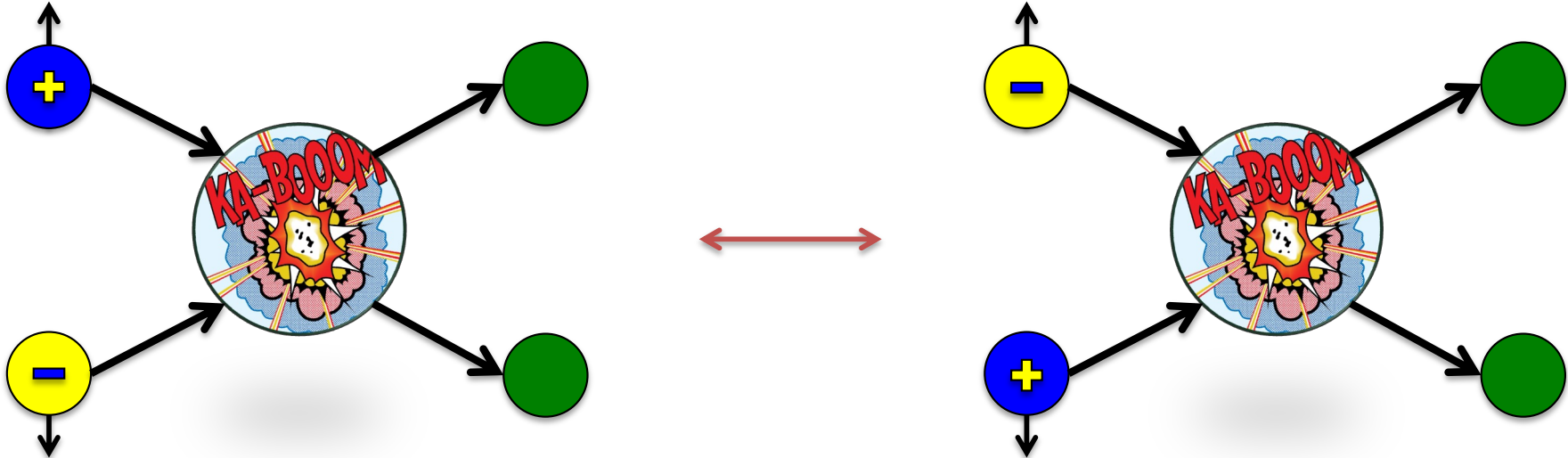
The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect 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.

The Nobel Foundation

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

Discrete Transformation: Charge Conjugation

Replace particle with antiparticle



Discrete Transformation: Parity (Spatial Inversion)

*Mirror
reflection*

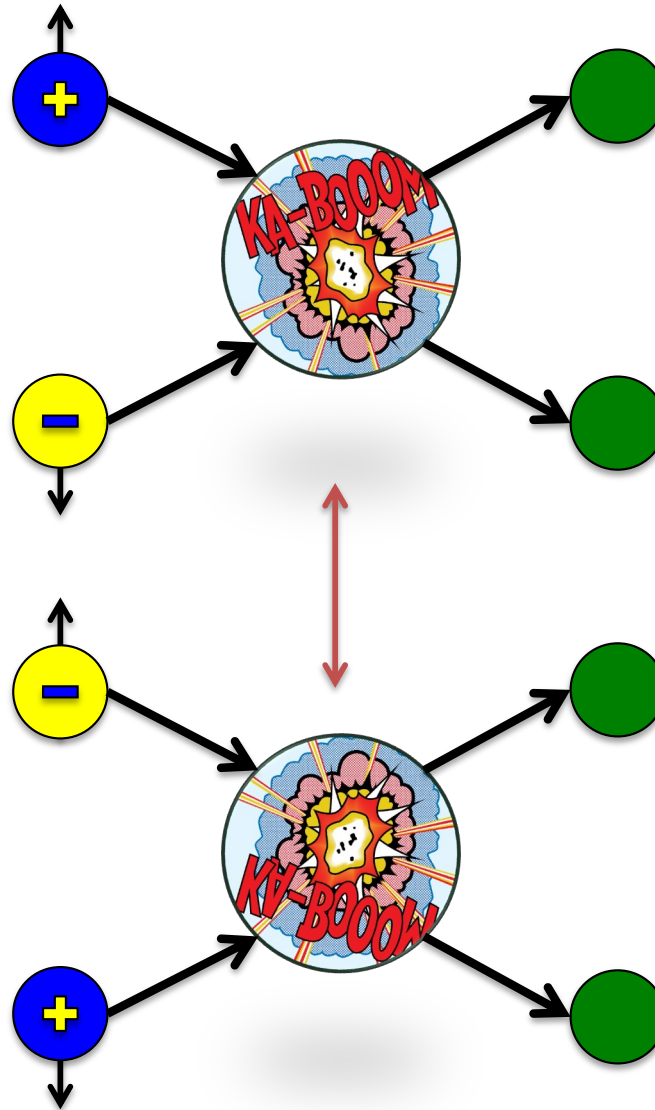
+

*180°
rotation*

+x to -x

+y to -y

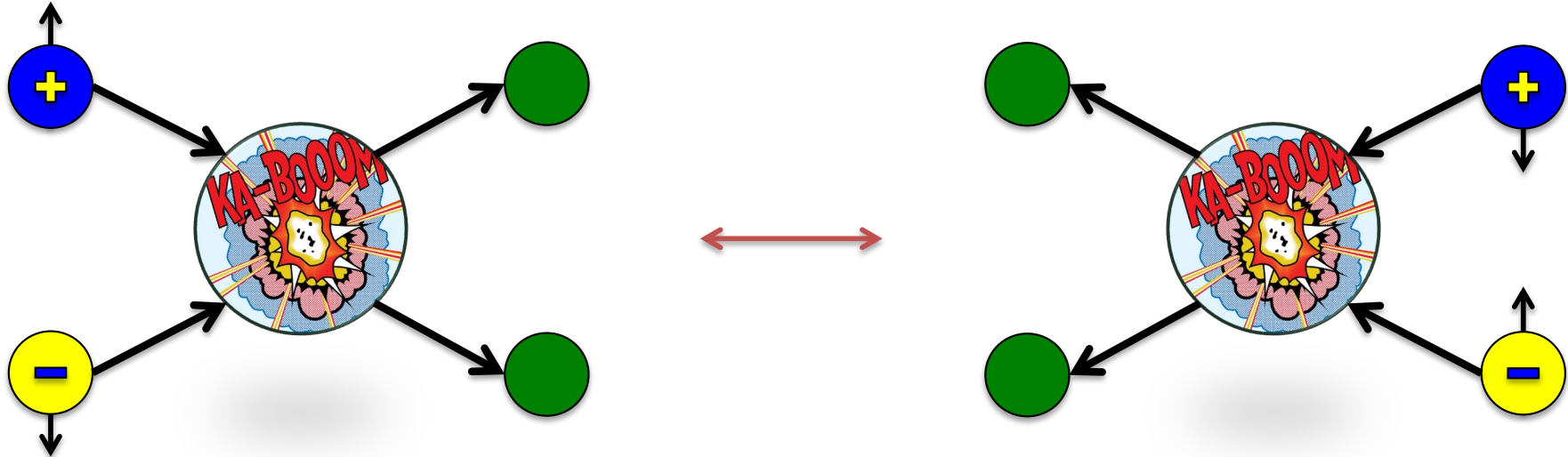
+z to -z



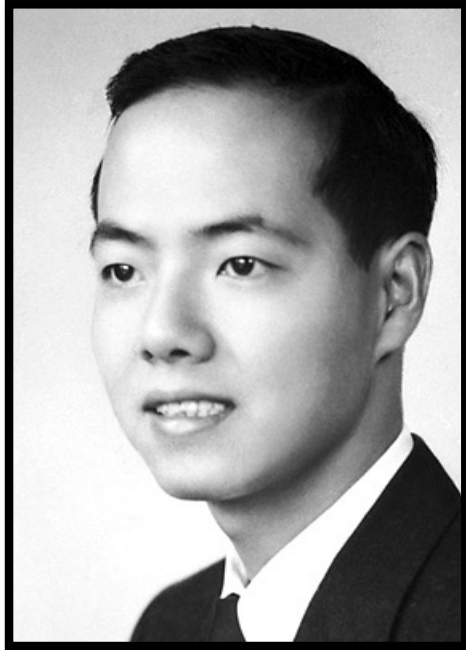
<http://strangesounds.org/2013/08/mysterious-booms-in-the-usa-new-york-california-alaska-mississippi-utah-michigan.html>

Discrete Transformation: Time Reversal

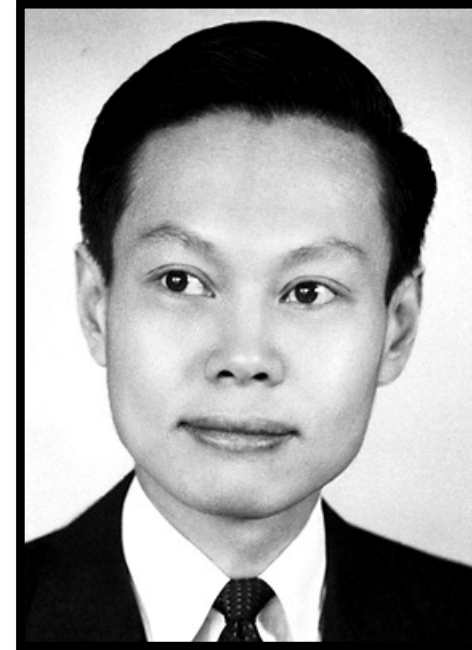
Reverse the arrow of time, $+t$ to $-t$



1956: Is Parity conserved?



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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*

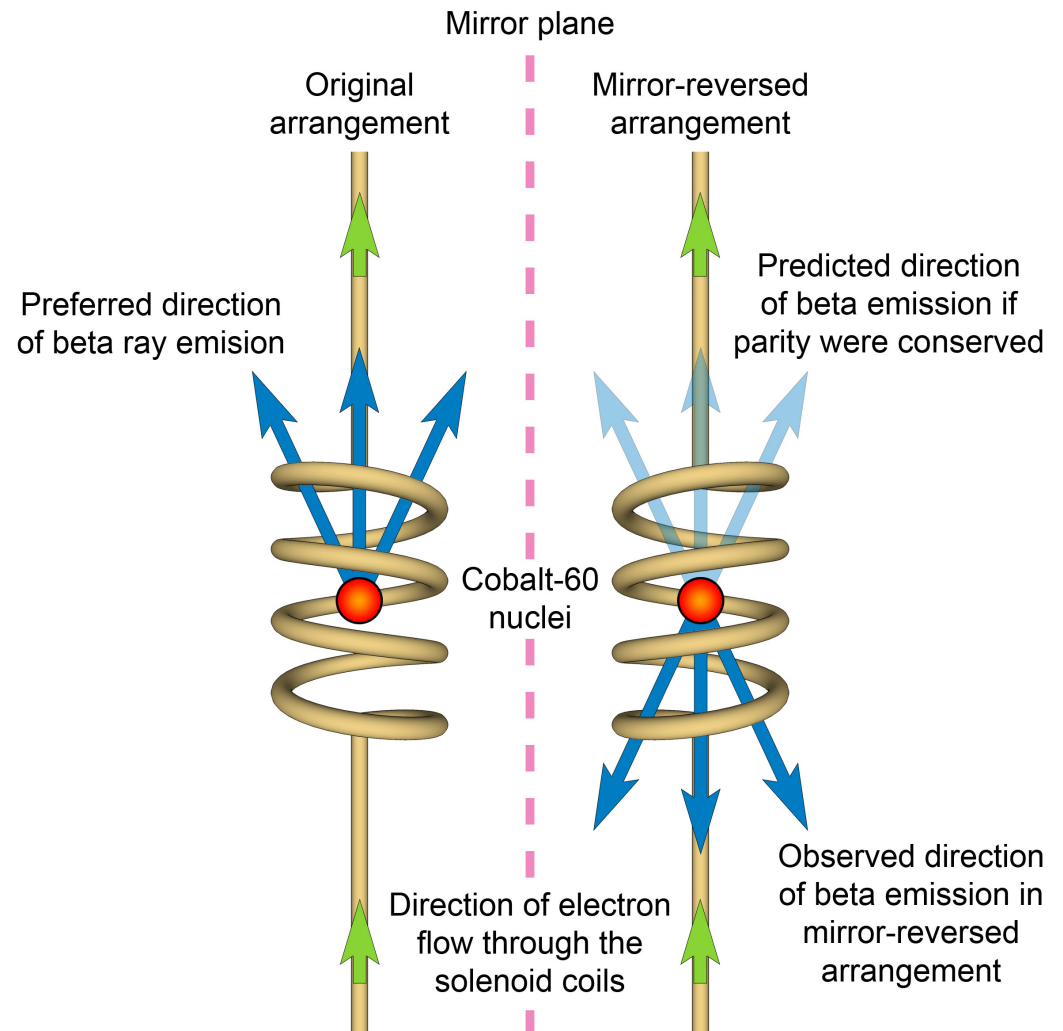
(Received June 22, 1956)

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)!

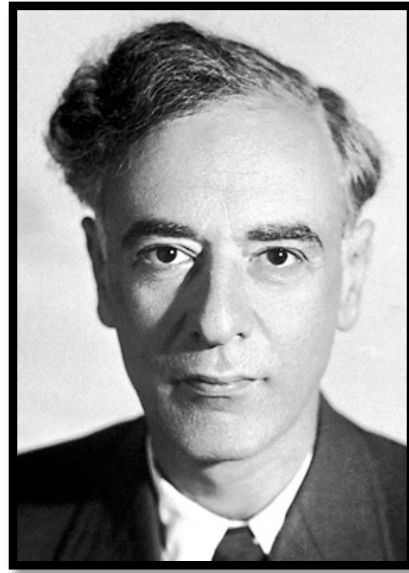


AIP Emilio Segre Visual Archives



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

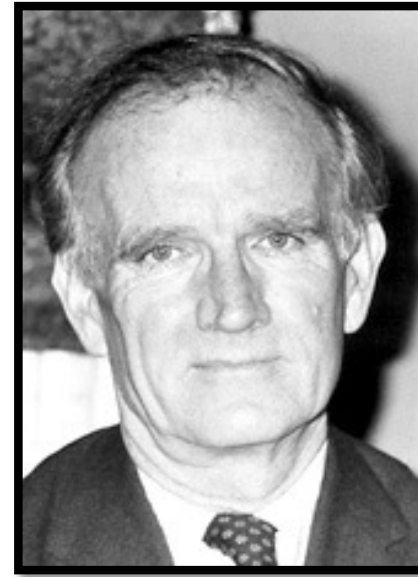
Abstract: A variant of the theory is proposed in which non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.

Nuclear Physics 3 (1957) 127-131

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



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VOLUME 13, NUMBER 4

PHYSICAL REVIEW LETTERS

27 JULY 1964

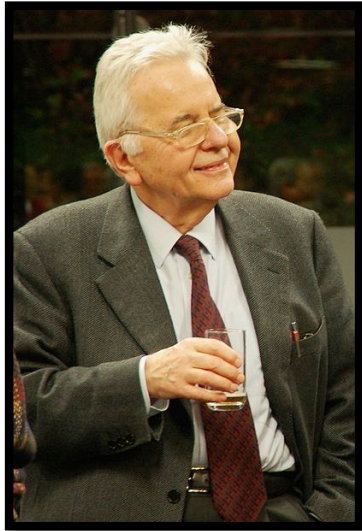
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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

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

$\delta = CP$ -violating “phase”

Standard Model CP - Violation

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

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

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

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

$\delta = CP$ -violating “phase”

New Massive Particles = More Phases

$$\text{number of phases} = (N_g - 1)(N_g - 2) / 2$$

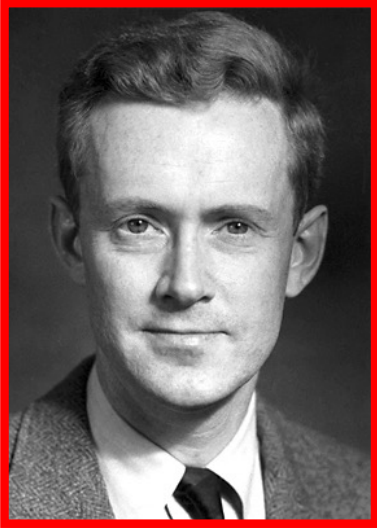
$$\text{number of generations} = N_g \quad \text{Hocker \& Ligeti Annu. Rev. Nucl. Part. Sci. 2006. 56:501-67}$$

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

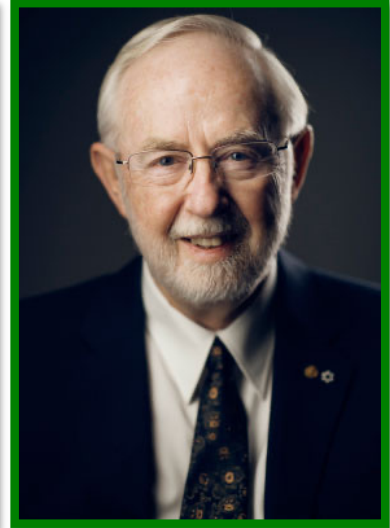
$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$\delta = CP$ -violating “phase”

Where do we look for more CP -violation?



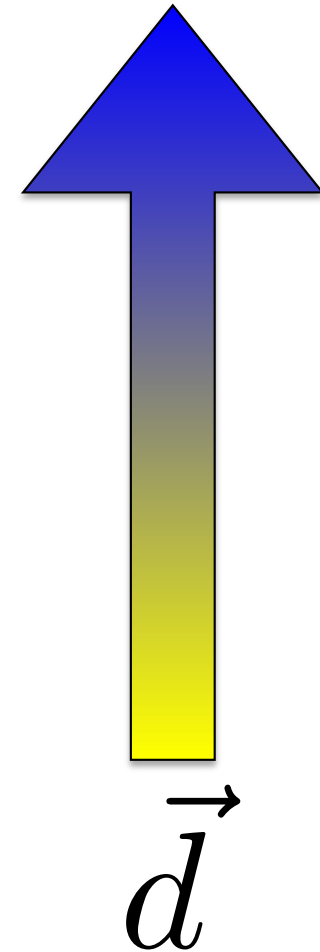
The Nobel Foundation



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!*

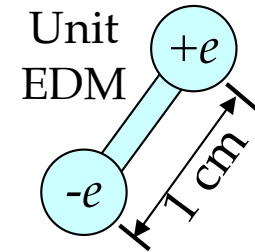
EDM: Measures the Separation of Charges



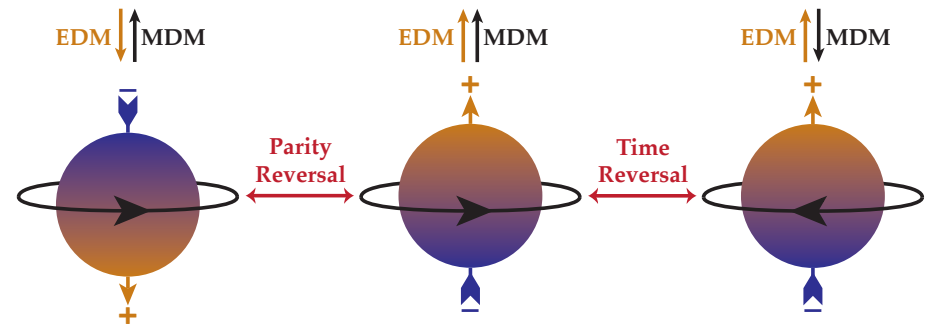
"Thunder Cloud as Generator #2" (1971) by Paterson Ewen [Art Gallery of Ontario]

EDMs to E-fields as MDMs to B-fields (sorta)

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



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



Theorist: ...trivial application of the Wigner-Eckart Theorem...

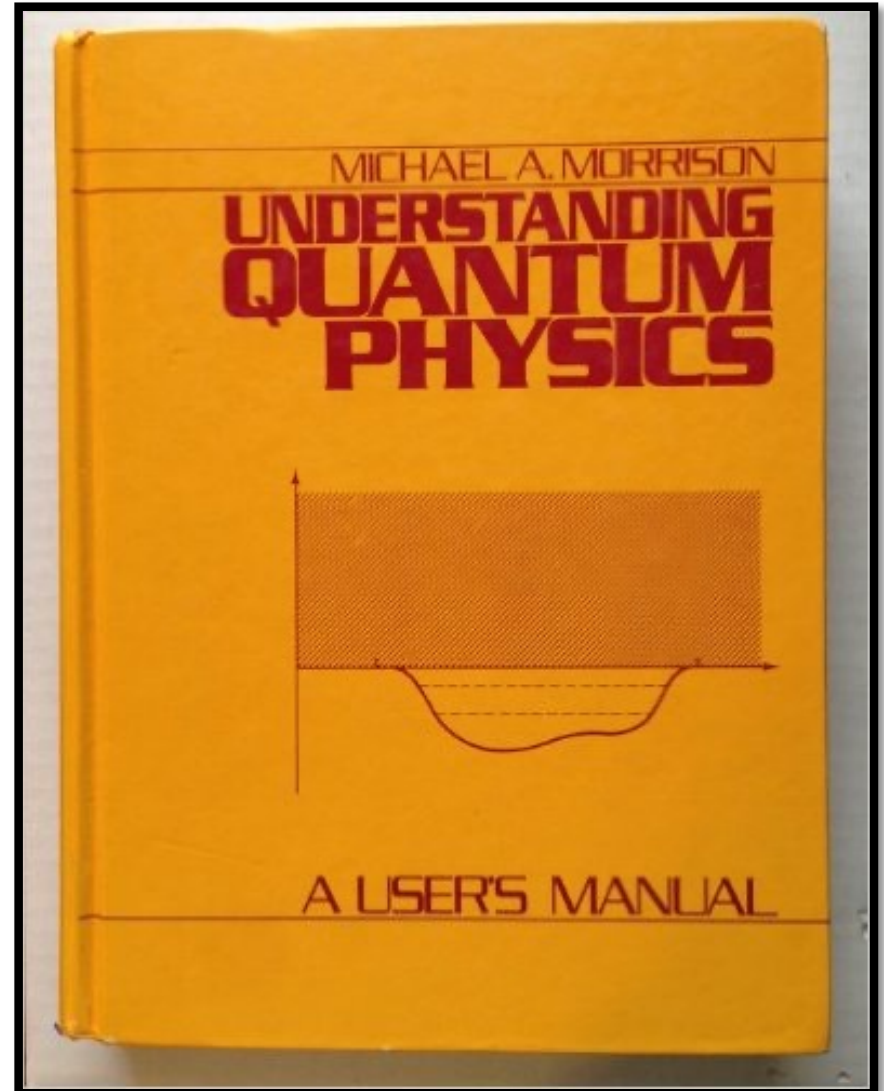
Experimentalist: ...blah blah blah Wigner-someone something...

Wigner-Eckart Theorem? Just ask Prof. Gibson!



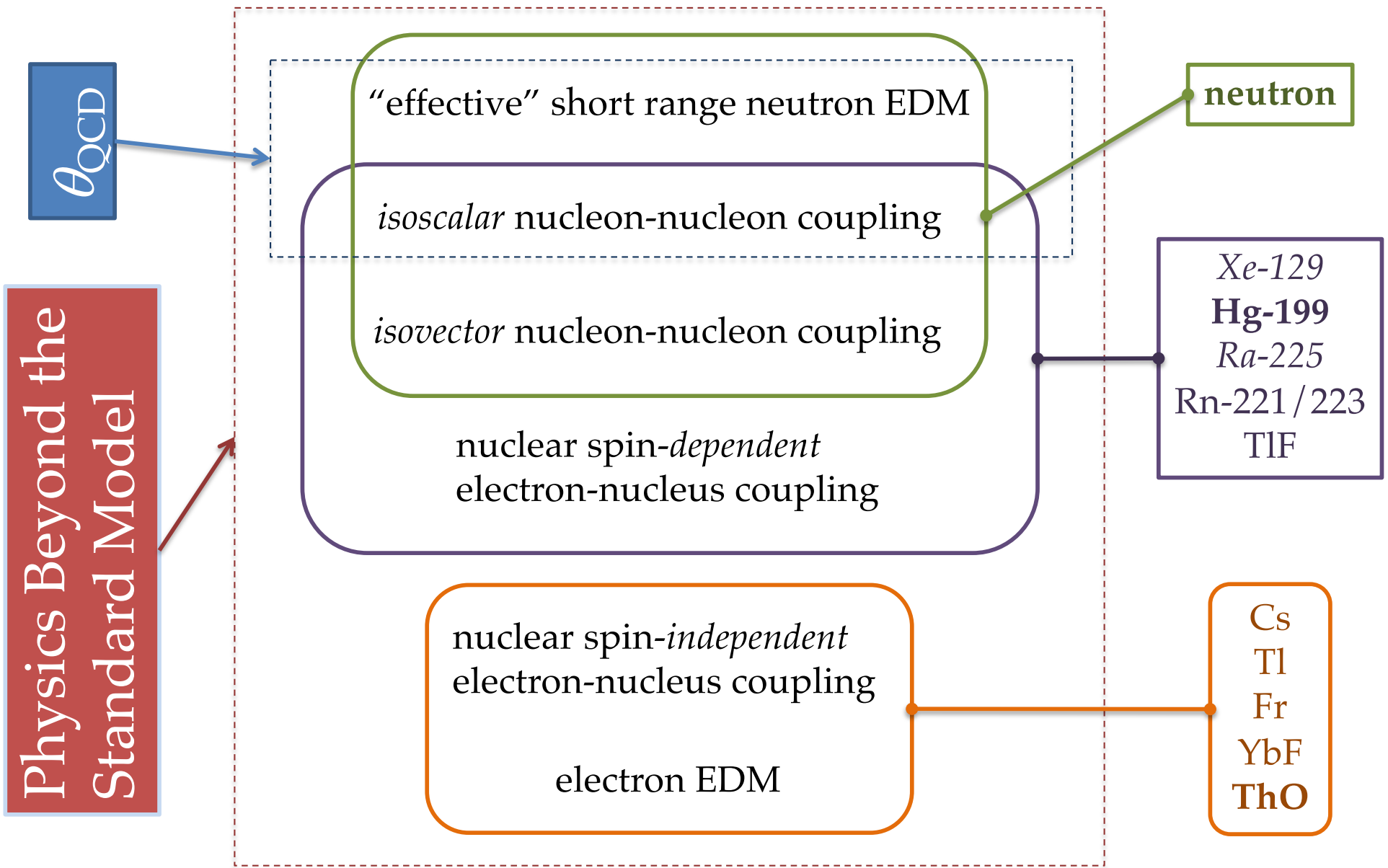
2016-02-03 Texas Tech, Lubbock, TX (Photo by T. Maccarone)

TTU Physics Colloquium

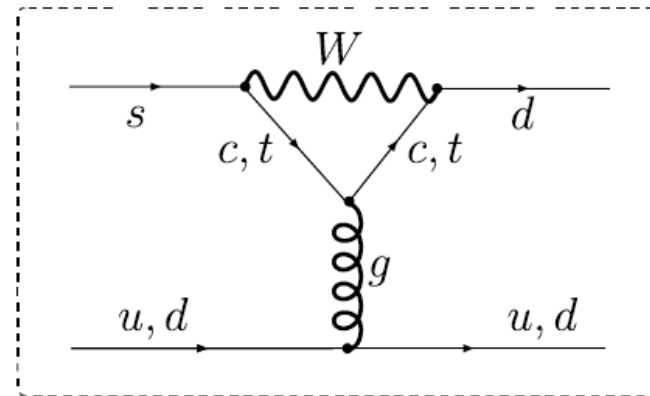
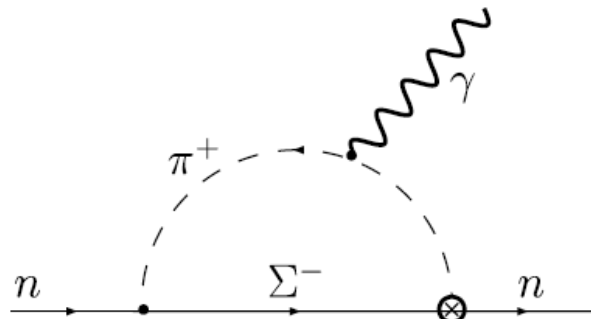


Published by Prentice-Hall 1990

Different Sources of $CP \Leftrightarrow$ EDMs of Different Systems

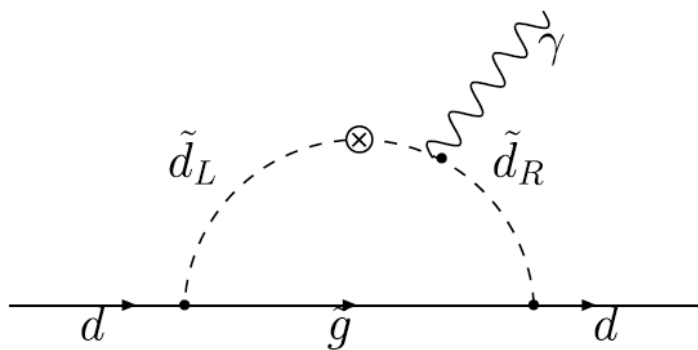


Standard Model vs. Supersymmetry EDMs



SM: higher order
“penguin” diagram

SUSY: lower order



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

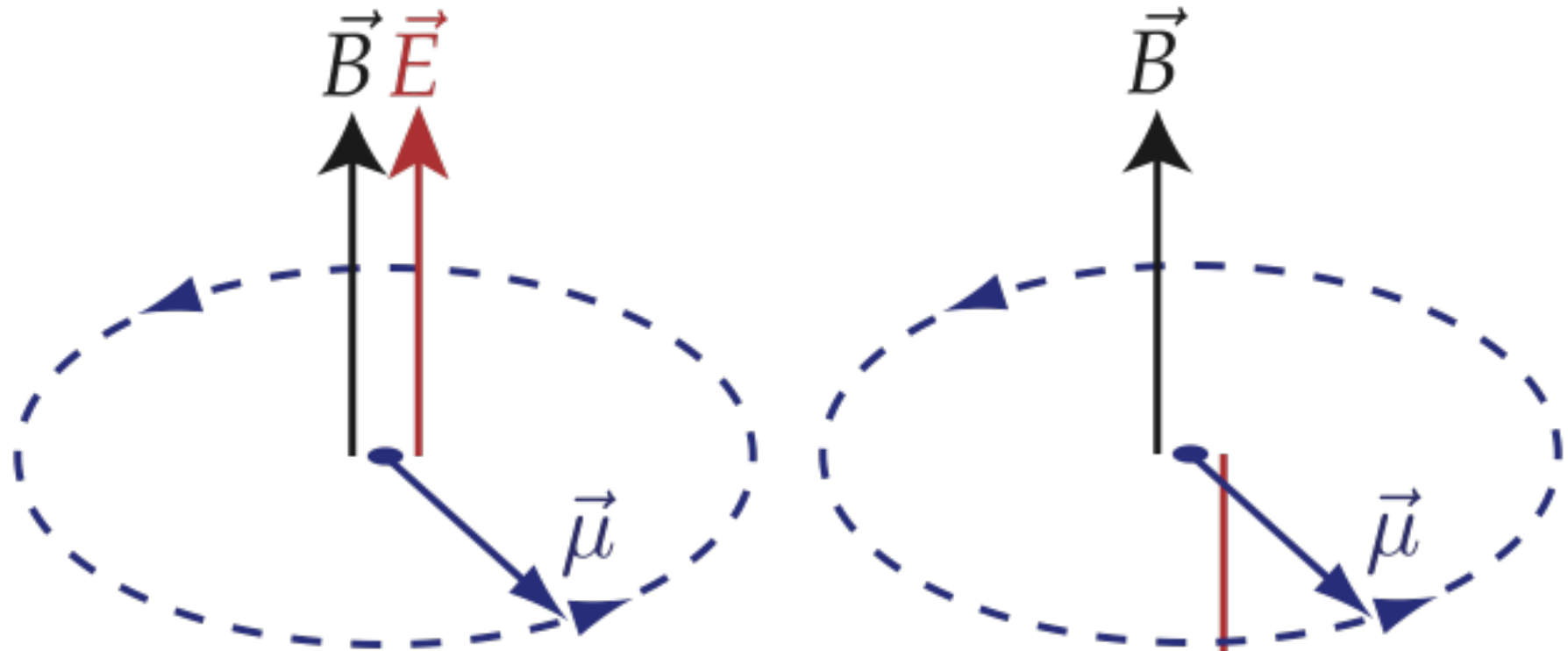
Current Limits

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

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

System	Best Limit (2σ) $10^{-28} \text{ e}^* \text{ cm}$	Goal	Goal on "Hg scale"	Method (Location)
Hg-199	0.3	0.01	0.01	Hg atoms in vapor cell (Washington-Seattle)
Xe-129	66	0.001	0.01	Gas cell (Munich)
Ra-225	5000000	1	0.001	Laser trap (Argonne)

Always Measure Frequency: Spin Precession



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

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

Ultimate Statistical Sensitivity

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

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

interrogation
time

integration
time

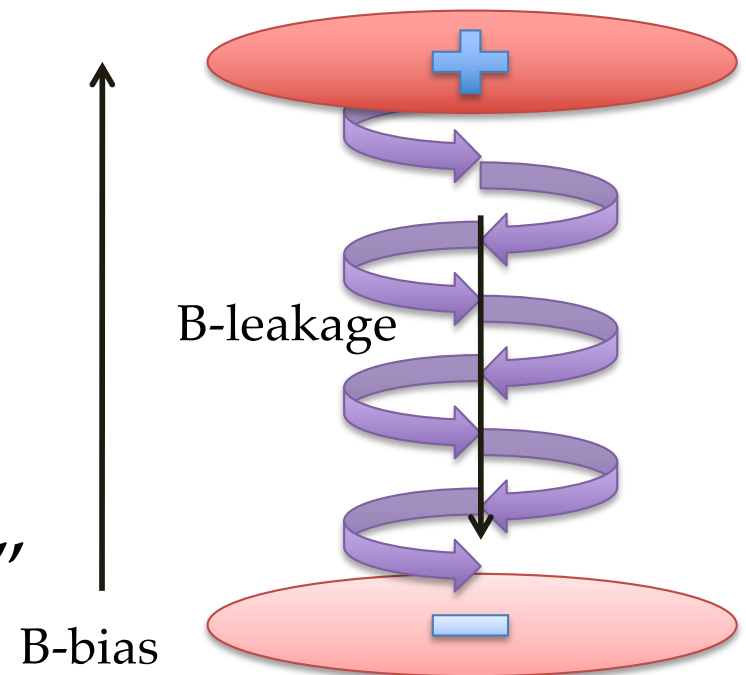
Magnetic Field Instabilities & False Effects!

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

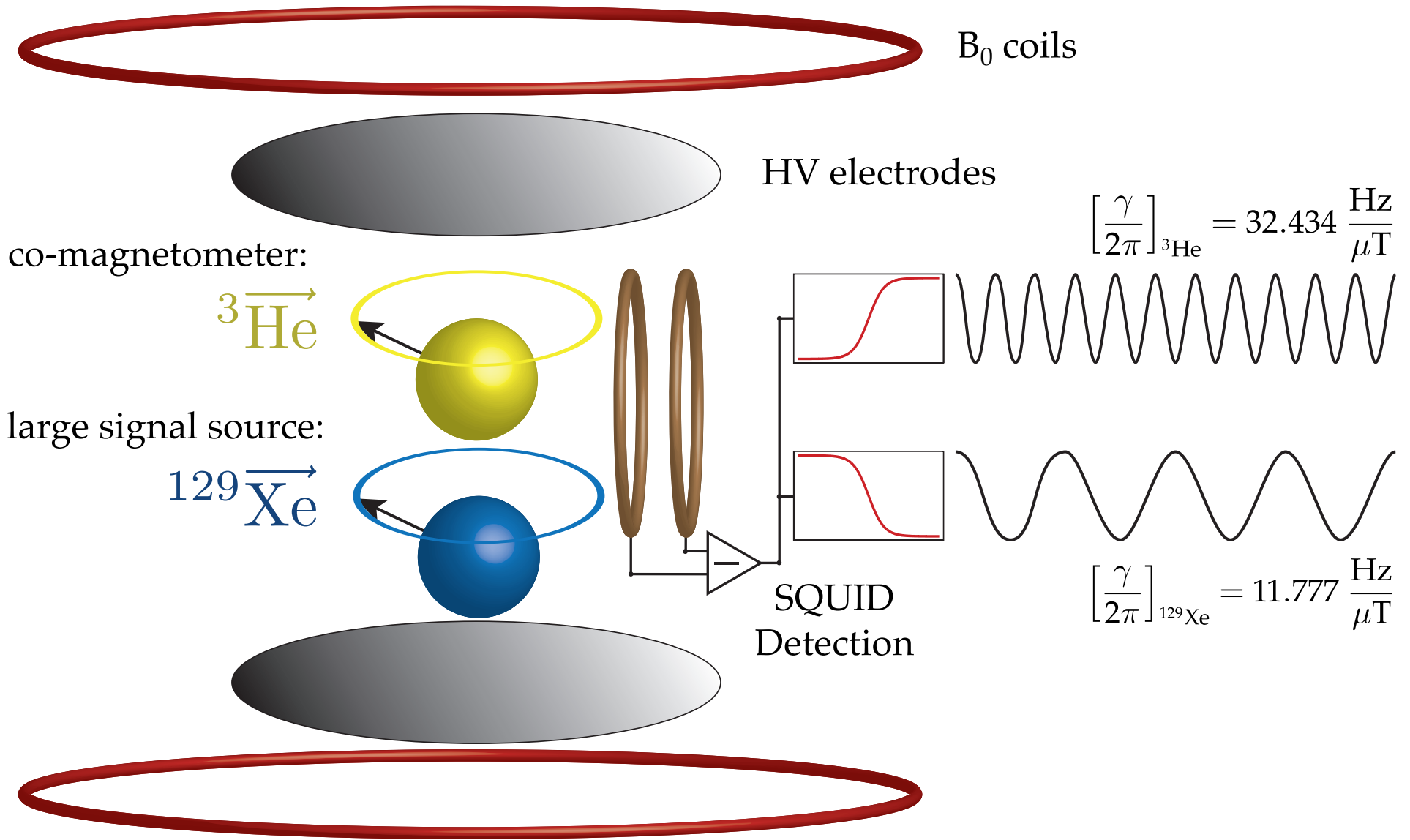
challenge!

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



Spin-Exchange Optical Pumping (SEOP)

VOLUME 5, NUMBER 8

PHYSICAL REVIEW LETTERS

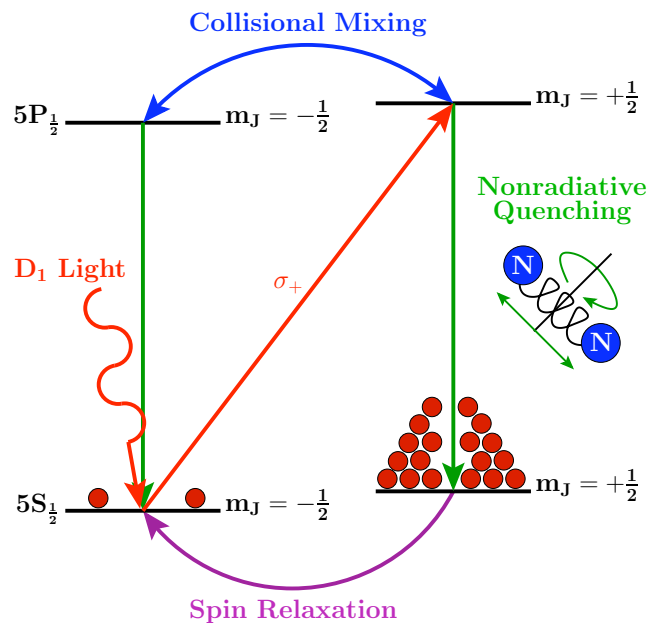
OCTOBER 15, 1960

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

M. A. Bouchiat,[†] T. R. Carver,[‡] and C. M. Varnum

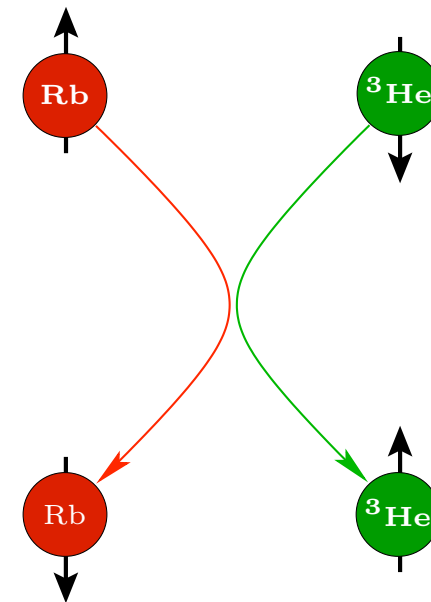
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received September 26, 1960)



Optical Pumping

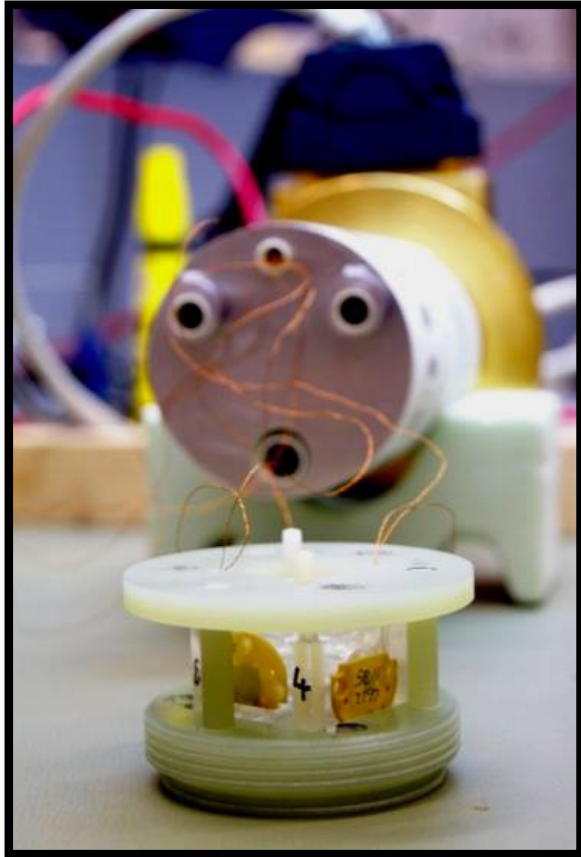
light (laser) to electron (Rb)



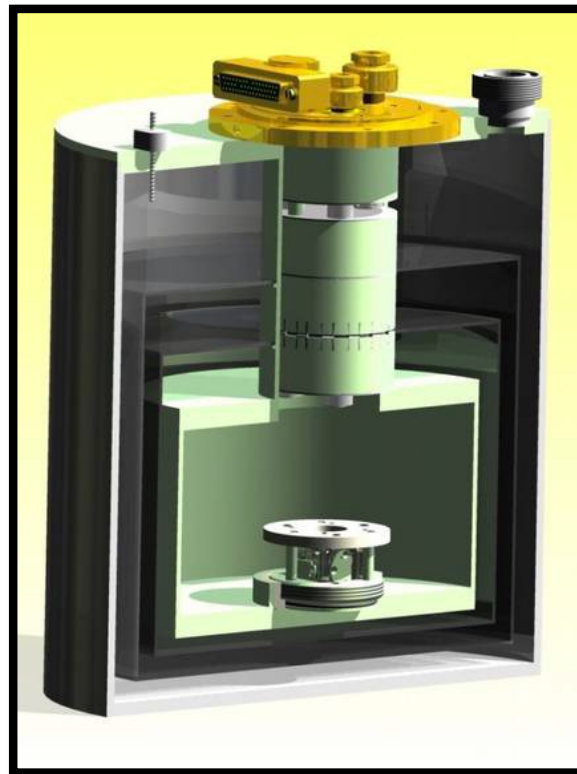
Spin Exchange

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

“SQUID” Magnetometers: Detectors



Two sensors in
each direction.
Cube side = 1 cm



LHe dewar
refill every 8 hrs

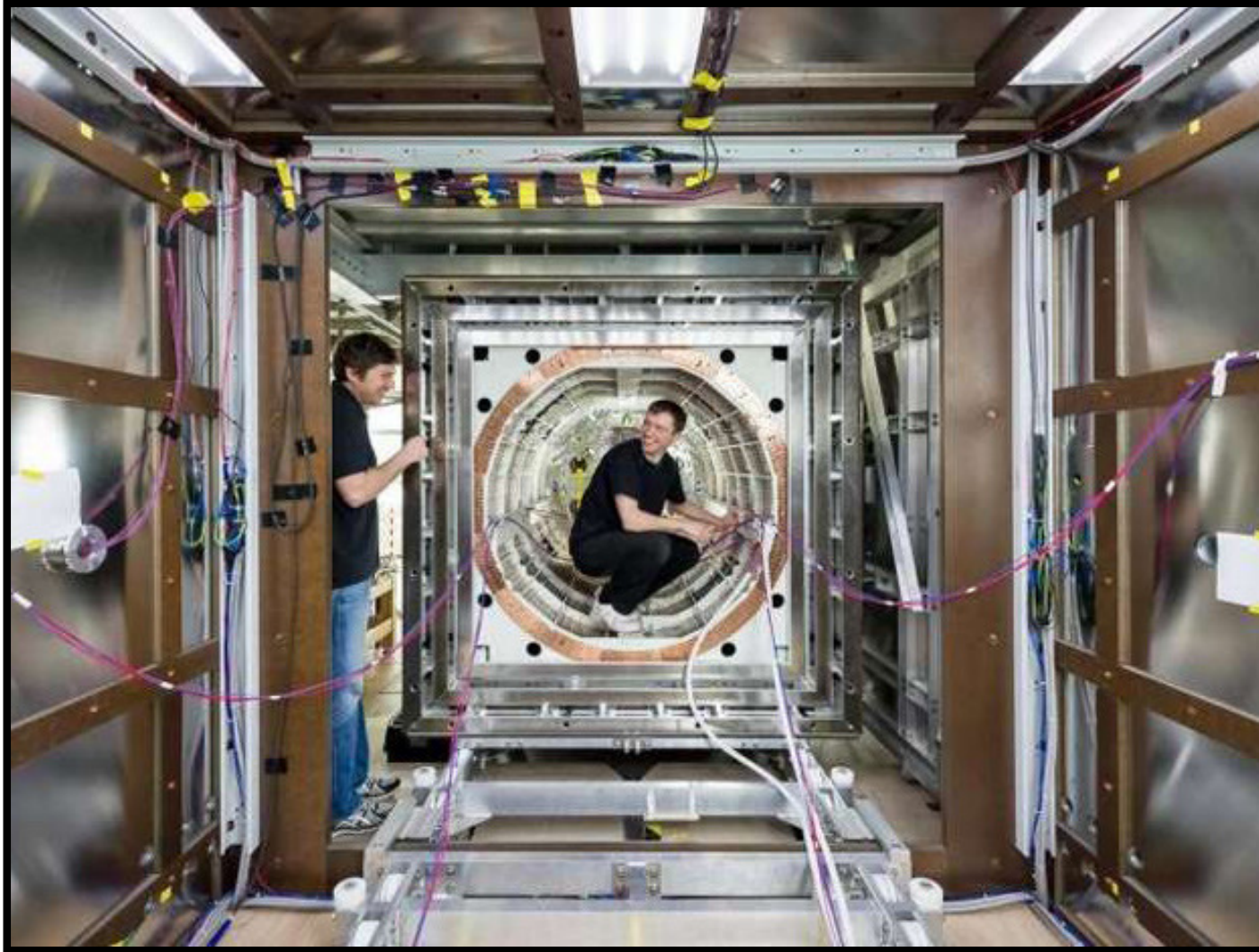
Nonmagnetic
wooden components



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
All of my clothes @ 10 cm	1E-10
Human Brain	1E-12
"SQUID" magnetometer noise floor (1 s)	1E-15

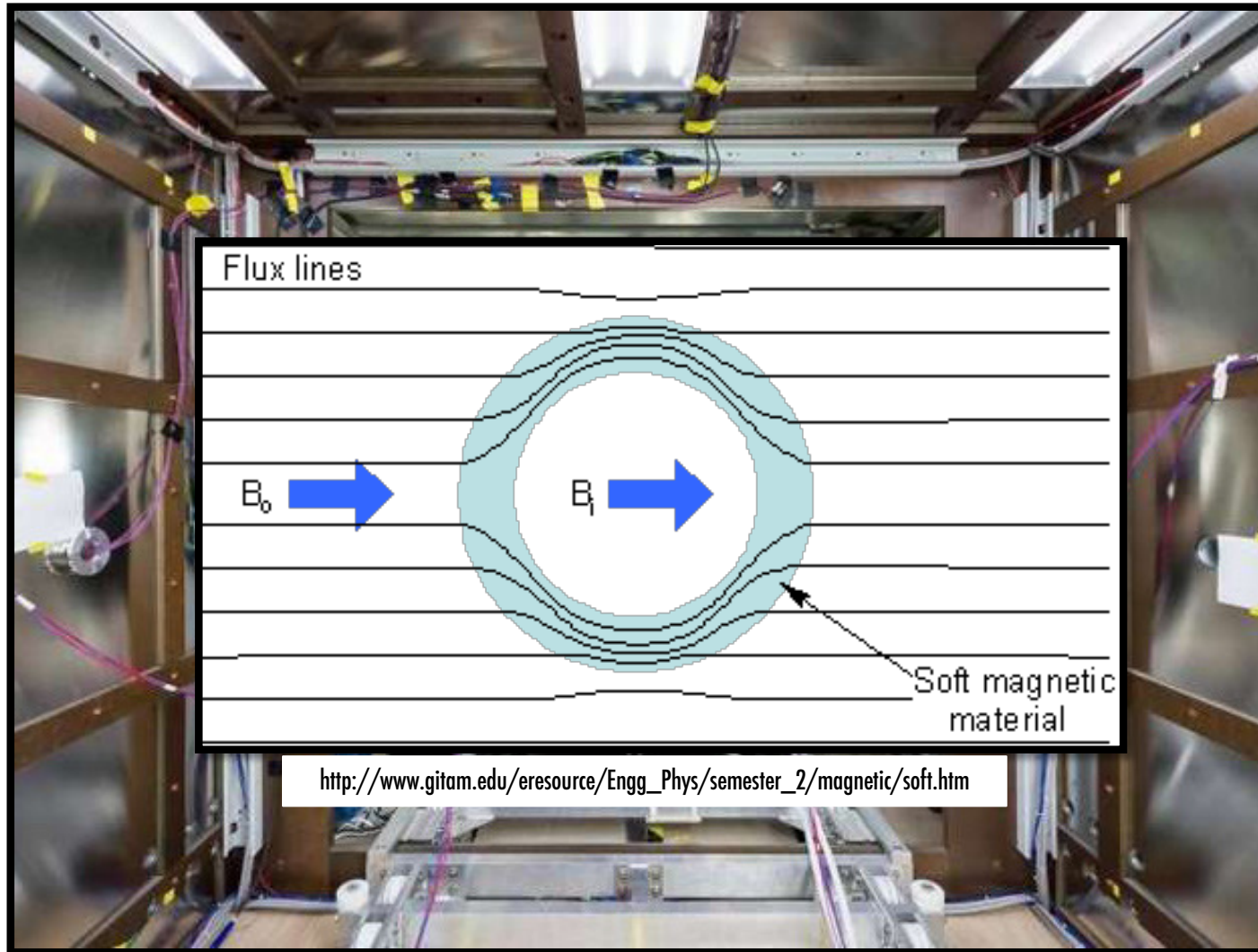
SQUID Detection? Magic Room!



<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!



<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)

Prototype EDM Cells



1 cm tall



2.5 cm diameter

Silicon electrodes

+/- 10 kV / cm

1 atm He-3 @ 2% polarization

0.1 atm Xe-129 @ 20% polarization

Cells by:

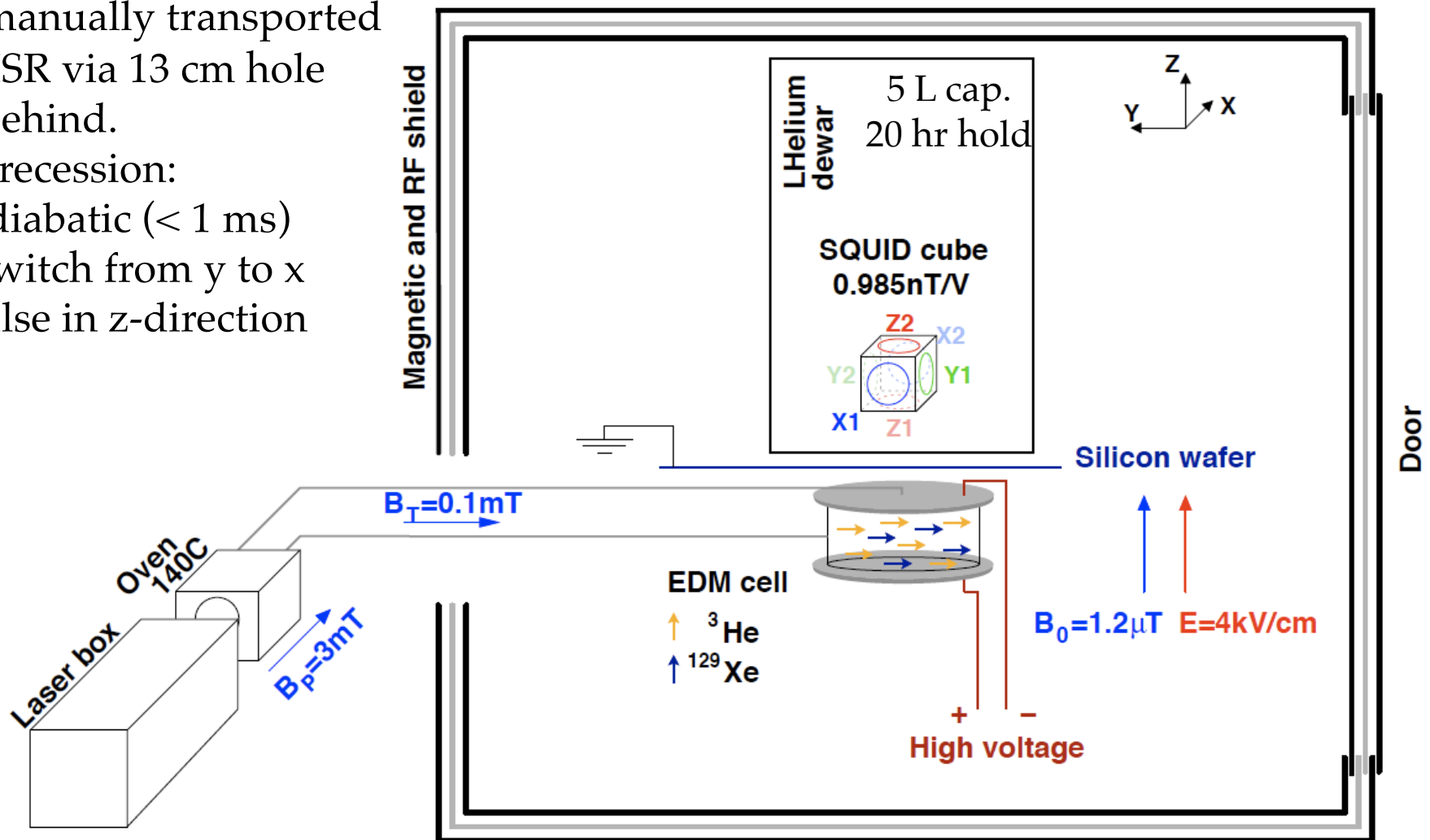
S. Degenkolb (Michigan)

P. Pistel & E. Babcock (JCNS)

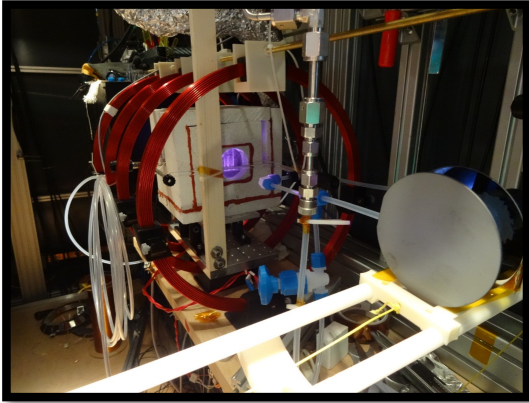
Experimental Procedure

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

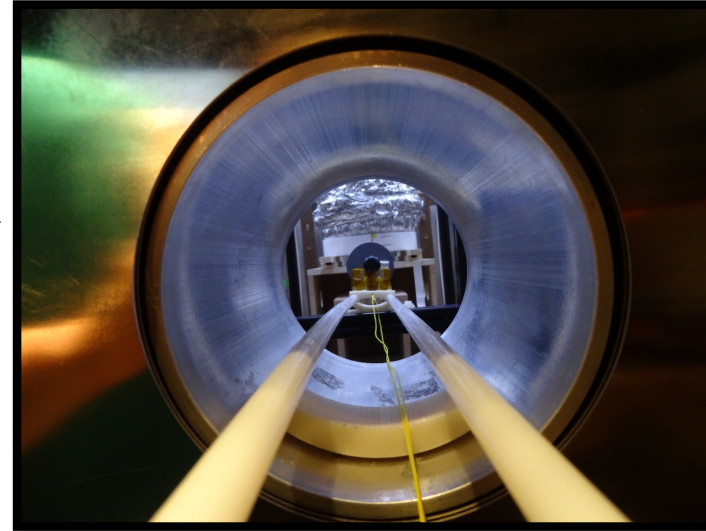
From: Florian Kuchler thesis



Experimental Layout

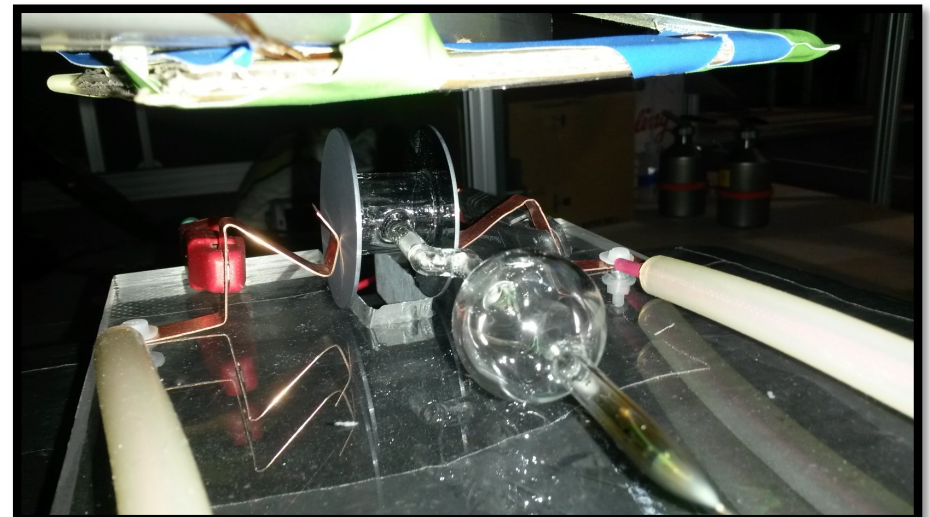


Non-human
Transport!



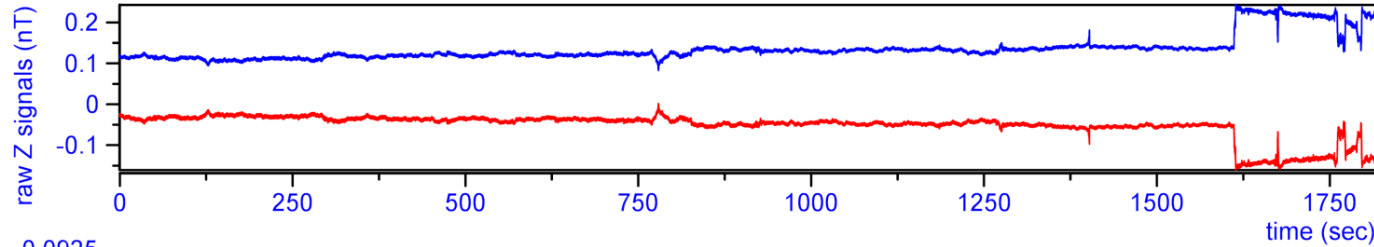
Noble gas polarizer
3 mT
100 W diode laser

EDM cell underneath SQUID
distance to sensor = 10 cm



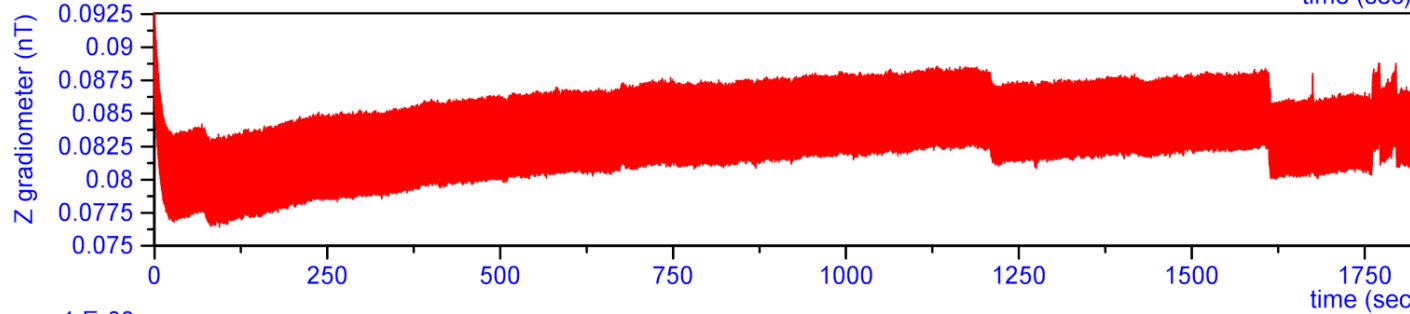
Raw data

nT



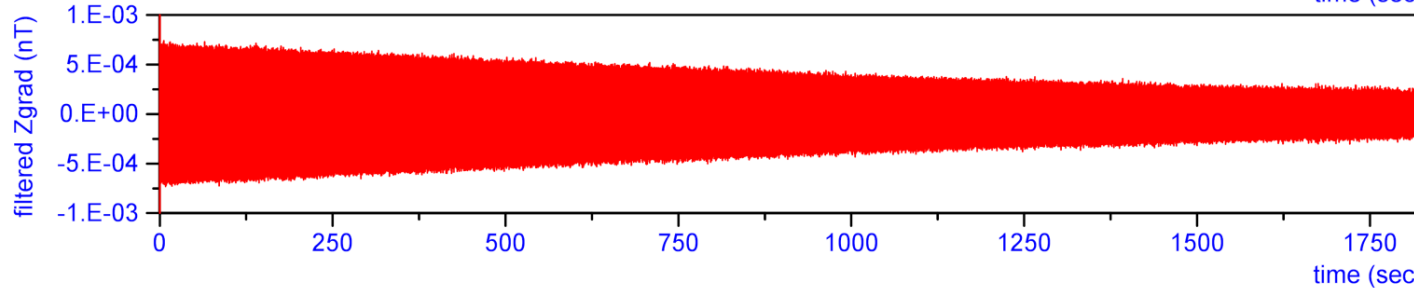
two channels, A,B

pT

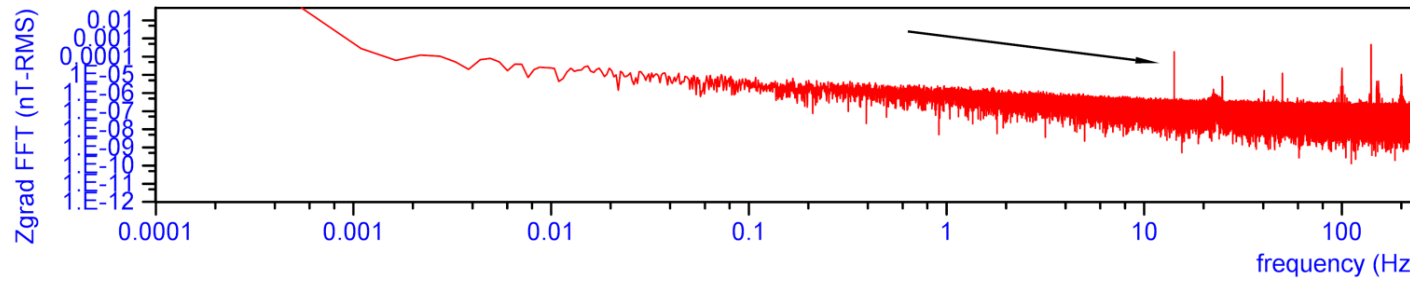


$|A| - |B|$,
gradiometer

pT

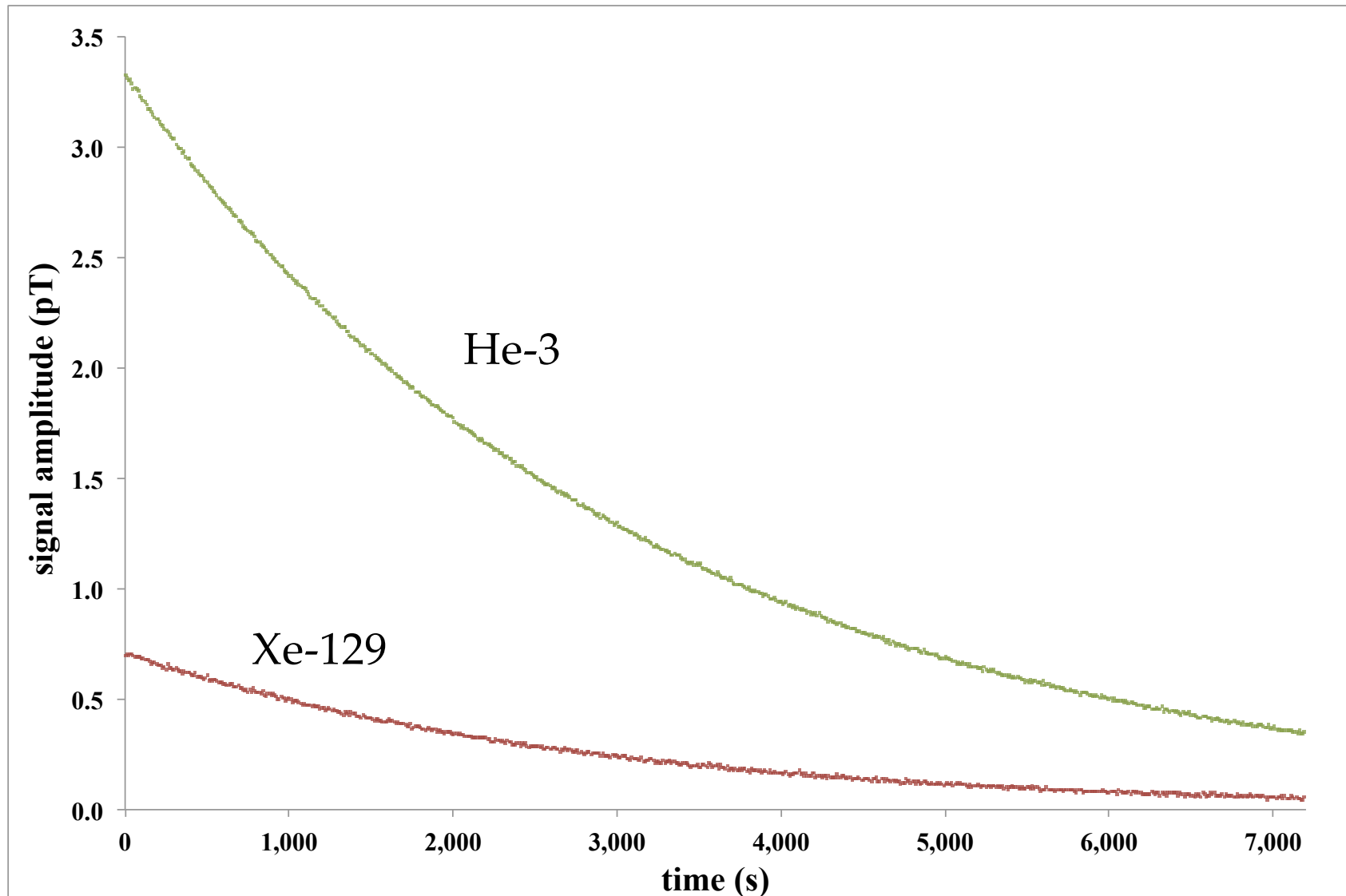


filtered



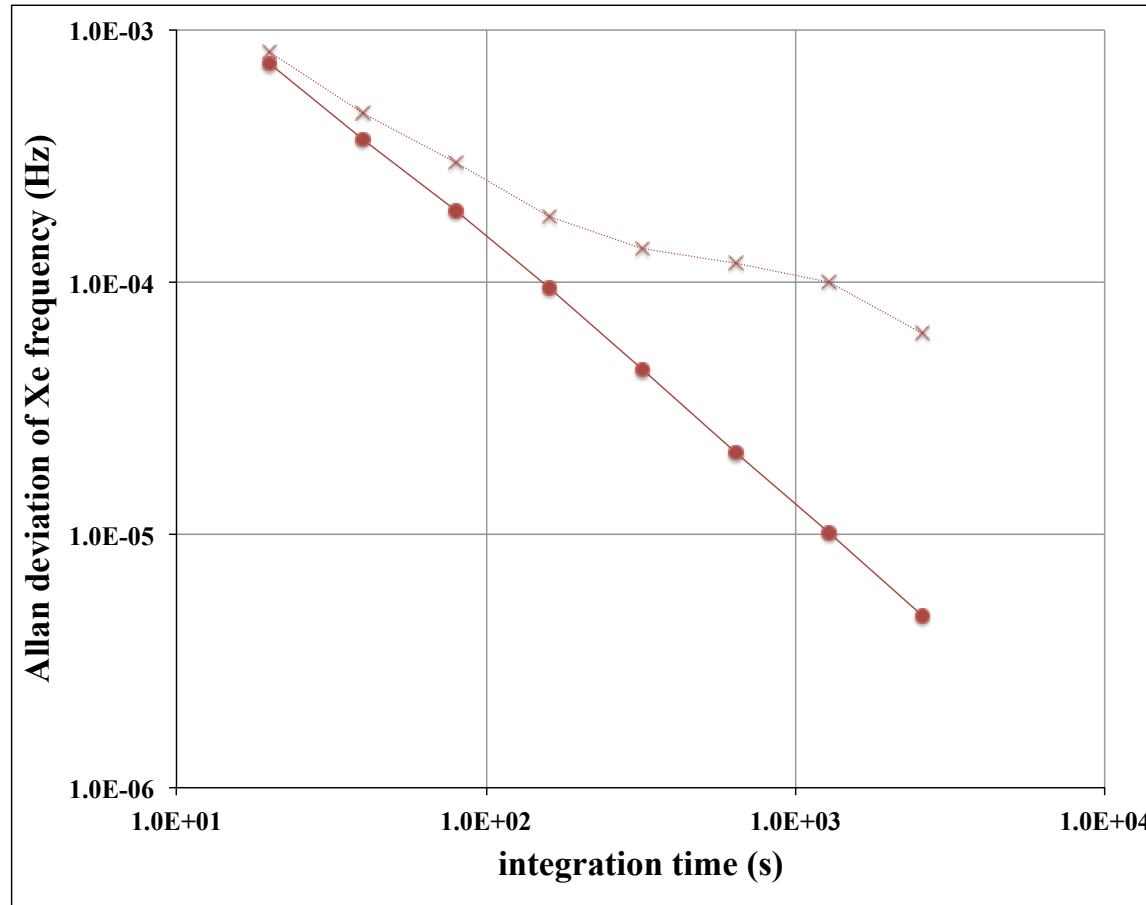
FFT

>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



Other Diamagnetic Systems?

Group	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA									
1	H Hydrogen 1.00794 $1s$ 13.5984																		He Helium 4.002602 $1s^2$ 24.5874								
2	Li Lithium 6.941 $1s^2 2s$ 5.3917	Be Beryllium 9.012182 $1s^2 2s^2$ 9.3227											B Boron 10.811 $1s^2 2s^2 2p$ 8.2980	C Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603	N Nitrogen 14.0067 $1s^2 2s^2 2p^3$ 14.5341	O Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181	F Fluorine 18.9984032 $1s^2 2s^2 2p^5$ 17.4228	Ne Neon 20.1797 $1s^2 2s^2 2p^6$ 21.5645									
3	Na Sodium 22.989770 $[Ne]3s$ 5.1391	Mg Magnesium 24.3050 $[Ne]3s^2$ 7.6462											Al Aluminum 26.981538 $[Ne]3s^2 3p$ 5.9858	Si Silicon 28.0855 $[Ne]3s^2 3p^2$ 8.1517	P Phosphorus 30.973761 $[Ne]3s^2 3p^3$ 10.4867	S Sulfur 32.065 $[Ne]3s^2 3p^4$ 10.3600	Cl Chlorine 35.453 $[Ne]3s^2 3p^5$ 12.9676	Ar Argon 39.948 $[Ne]3s^2 3p^6$ 15.7596									
4	K Potassium 39.0983 $[Ar]4s$ 4.3407	Ca Calcium 40.078 $[Ar]4s^2$ 6.1132	Sc Scandium 44.955910 $[Ar]3d^1 4s^2$ 6.5615	Ti Titanium 47.867 $[Ar]3d^2 4s^2$ 6.8281	V Vanadium 50.9415 $[Ar]3d^3 4s^2$ 6.7462	Cr Chromium 51.9961 $[Ar]3d^5 4s^1$ 7.4340	Mn Manganese 54.938049 $[Ar]3d^5 4s^2$ 7.4340	Fe Iron 55.845 $[Ar]3d^6 4s^2$ 7.8810	Co Cobalt 58.933200 $[Ar]3d^7 4s^2$ 7.8810	Ni Nickel 58.6934 $[Ar]3d^8 4s^2$ 7.6398	Cu Copper 63.546 $[Ar]3d^{10} 4s^1$ 7.7264	Zn Zinc 65.409 $[Ar]3d^{10} 4s^2$ 9.3942	Ga Gallium 69.723 $[Ar]3d^{10} 4s^2 4p$ 5.9993	Ge Germanium 72.64 $[Ar]3d^{10} 4s^2 4p^2$ 7.8994	As Arsenic 74.92160 $[Ar]3d^{10} 4s^2 4p^3$ 9.7886	Se Selenium 78.96 $[Ar]3d^{10} 4s^2 4p^4$ 9.7524	Br Bromine 79.904 $[Ar]3d^{10} 4s^2 4p^5$ 11.8138	Kr Krypton 83.798 $[Ar]3d^{10} 4s^2 4p^6$ 13.9996									
5	Rb Rubidium 85.4678 $[Kr]5s$ 4.1771	Sr Strontium 87.62 $[Kr]5s^2$ 5.6949	Y Yttrium 88.90585 $[Kr]4d^5 5s^2$ 6.2173	Zr Zirconium 91.224 $[Kr]4d^2 5s^2$ 6.6339	Nb Niobium 92.90638 $[Kr]4d^4 5s^1$ 6.7589	Mo Molybdenum 95.94 $[Kr]4d^5 5s^1$ 7.0924	Tc Technetium (98) 98.906250 $[Kr]4d^5 5s^2$ 7.28	Ru Ruthenium 101.07 $[Kr]4d^7 5s^1$ 7.3605	Rh Rhodium 102.90550 $[Kr]4d^8 5s^1$ 7.4589	Pd Palladium 106.42 $[Kr]4d^10$ 8.3369	Ag Silver 107.8682 $[Kr]4d^10 5s^1$ 7.5762	Cd Cadmium 112.411 $[Kr]4d^10 5s^2$ 8.9938	In Indium 114.818 $[Kr]4d^10 5s^2 5p$ 5.7864	Sn Tin 118.710 $[Kr]4d^10 5s^2 5p^2$ 7.3439	Sb Antimony 121.760 $[Kr]4d^10 5s^2 5p^3$ 8.6084	Te Tellurium 127.60 $[Kr]4d^10 5s^2 5p^4$ 9.0096	I Iodine 126.90447 $[Kr]4d^10 5s^2 5p^5$ 10.4513	Xe Xenon 131.293 $[Kr]4d^10 5s^2 5p^6$ 12.1298									
6	Cs Cesium 132.90545 $[Xe]6s$ 3.8939	Ba Barium 137.327 $[Xe]6s^2$ 5.2117		Hf Hafnium 178.49 $[Xe]4f^{14} 5d^2 6s^2$ 6.8251	Ta Tantalum 180.9479 $[Xe]4f^{14} 5d^3 6s^2$ 7.5496	W Tungsten 183.84 $[Xe]4f^{14} 5d^4 6s^2$ 7.8640	Re Rhenium 186.207 $[Xe]4f^{14} 5d^5 6s^2$ 8.4382	Os Osmium 190.23 $[Xe]4f^{14} 5d^6 6s^2$ 8.9670	Ir Iridium 192.217 $[Xe]4f^{14} 5d^7 6s^2$ 8.9588	Pt Platinum 195.078 $[Xe]4f^{14} 5d^9 6s^1$ 8.9588	Au Gold 196.96655 $[Xe]4f^{14} 5d^{10} 6s^1$ 9.2255	Hg Mercury 200.59 $[Xe]4f^{14} 5d^{10} 6s^2$ 10.4375	Tl Thallium 204.3833 $[Hg]6p$ 6.1082	Pb Lead 207.2 $[Hg]6p^2$ 7.4167	Bi Bismuth 208.98038 $[Hg]6p^3$ 7.2855	Po Polonium (209) $[Hg]6p^4$ 8.417 ?	At Astatine (210) $[Hg]6p^5$	Rn Radon (222) $[Hg]6p^6$ 10.7485									
7	Fr Francium (223) $[Rn]7s$ 4.0727	Ra Radium (226) $[Rn]7s^2$ 5.2784		Rf Rutherfordium (261) $[Rn]5f^{14} 6d^2 7s^2$ 6.0 ?	Db Dubnium (262)	Sg Seaborgium (266)	Bh Bohrium (264)	Hs Hassium (277)	Mt Meitnerium (268)	Uun Ununnilium (281)	Uuu Ununquadium (272)	Uub Ununhexium (285)		Uuq Ununquadium (289)		Uuh Ununhexium (292)											
			Lanthanides										57 La Lanthanum 138.9055 $[Xe]5d^1 6s^2$ 5.5769	58 Ce Cerium 140.116 $[Xe]4f^1 5d^1 6s^2$ 5.5387	59 Pr Praseodymium 140.90765 $[Xe]4f^3 6s^2$ 5.473	60 Nd Neodymium 144.24 $[Xe]4f^4 6s^2$ 5.5250	61 Pm Promethium (145) 144.9128 $[Xe]4f^5 6s^2$ 5.582	62 Sm Samarium 150.36 $[Xe]4f^6 6s^2$ 5.6437	63 Eu Europium 151.964 $[Xe]4f^7 6s^2$ 5.6704	64 Gd Gadolinium 157.25 $[Xe]4f^7 5d^1 6s^2$ 6.1498	65 Tb Terbium 158.92534 $[Xe]4f^9 6s^2$ 5.8638	66 Dy Dysprosium 162.500 $[Xe]4f^10 6s^2$ 5.9389	67 Ho Holmium 164.93032 $[Xe]4f^11 6s^2$ 6.0215	68 Er Erbium 167.259 $[Xe]4f^12 6s^2$ 6.1077	69 Tm Thulium 168.93421 $[Xe]4f^13 6s^2$ 6.1843	70 Yb Ytterbium 173.04 $[Xe]4f^14 6s^2$ 6.2542	71 Lu Lutetium 174.967 $[Xe]4f^14 5d^1 6s^2$ 5.4259
			Actinides										89 Ac Actinium (227) $[Rn]6d^1 7s^2$ 5.17	90 Th Thorium 232.0381 $[Rn]6d^2 7s^2$ 6.3067	91 Pa Protactinium 231.03588 $[Rn]5f^2 6d^1 7s^2$ 5.89	92 U Uranium 238.02891 $[Rn]5f^3 6d^1 7s^2$ 6.1941	93 Np Neptunium (237) 237.04817 $[Rn]5f^4 6d^1 7s^2$ 6.2657	94 Pu Plutonium (244) 244.0642 $[Rn]5f^6 7s^2$ 6.0260	95 Am Americium (243) 243.0613 $[Rn]5f^7 7s^2$ 5.9738	96 Cm Curium (247) 247.0764 $[Rn]5f^7 6d^1 7s^2$ 5.9914	97 Bk Berkelium (247) 247.0713 $[Rn]5f^9 7s^2$ 6.1979	98 Cf Californium (251) 251.0833 $[Rn]5f^10 7s^2$ 6.2817	99 Es Einsteinium (252) 252.0833 $[Rn]5f^11 7s^2$ 6.42	100 Fm Fermium (257) 257.1037 $[Rn]5f^12 7s^2$ 6.50	101 Md Mendelevium (258) 258.1052 $[Rn]5f^13 7s^2$ 6.58	102 No Nobelium (259) 259.1089 $[Rn]5f^14 7s^2$ 6.65	103 Lr Lawrencium (262) 262.1053 $[Rn]5f^14 7p^1 7s^2$ 4.9 ?

- Solids
- Liquids
- Gases
- Artificially Prepared

NIST
website

Schiff Shielding in Diamagnetic Atoms

- Shielding in Diamagnetic Atoms

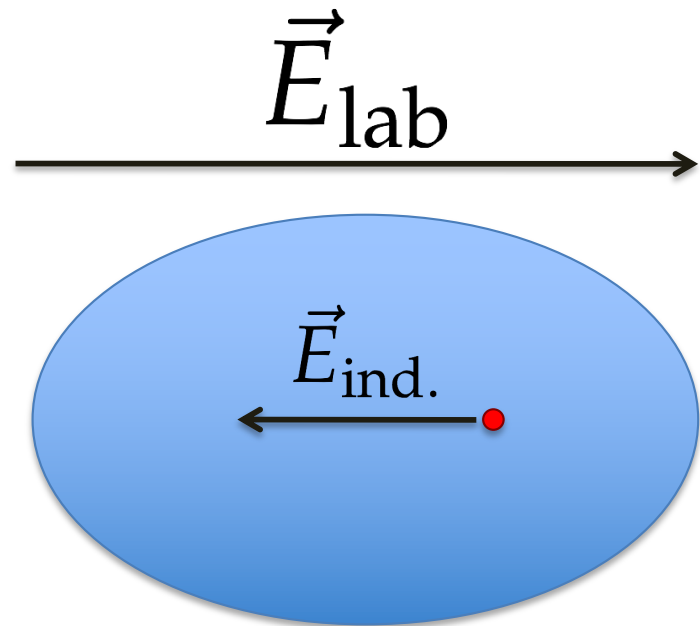
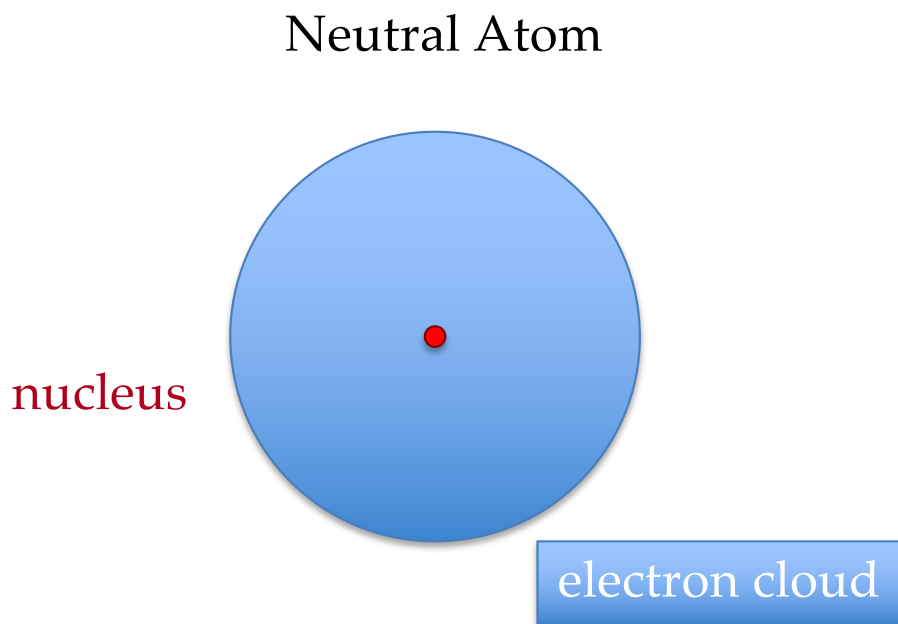
Schiff PR 132, 2194 (1963)

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

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

Schiff Moment

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



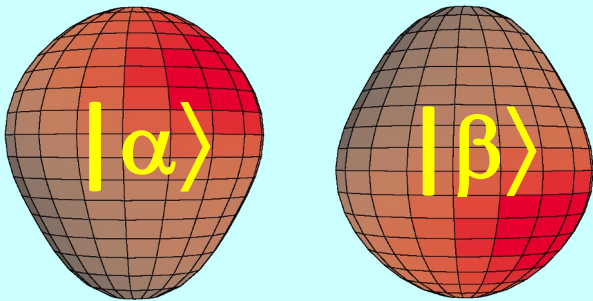
$$\vec{E}_{\text{ind.}} \approx -\vec{E}_{\text{lab}}$$

Enhanced Sensitivity in Ra-225

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

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

Parity Doublet



$$\begin{array}{l}
 \text{---} | \Psi_1 \rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}} \\
 \updownarrow 55 \text{ keV} \\
 \text{---} | \Psi_0 \rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}
 \end{array}$$

- 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 (²²⁵Ra) / EDM (¹⁹⁹Hg)

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

²²⁵Ra: Dobaczewski & Engel PRL 94 232502 (2005)

¹⁹⁹Hg: De Jesus & Engel PRC 72 045503 (2005)

Theory Difficult = Discovery Potential!

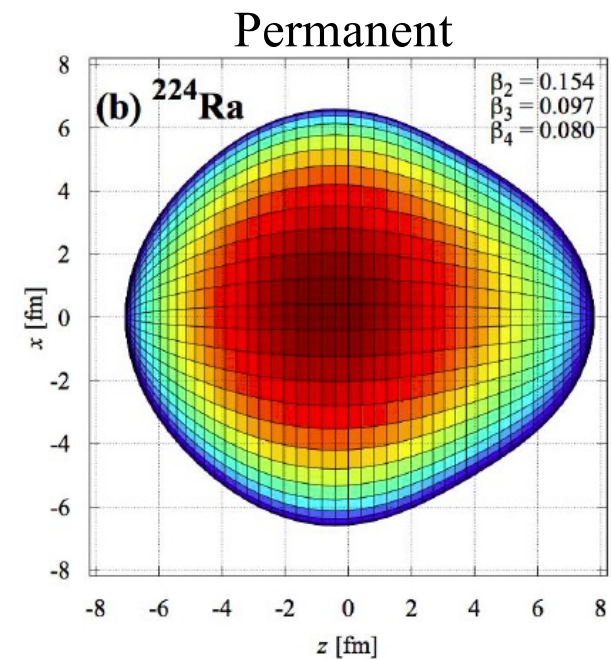
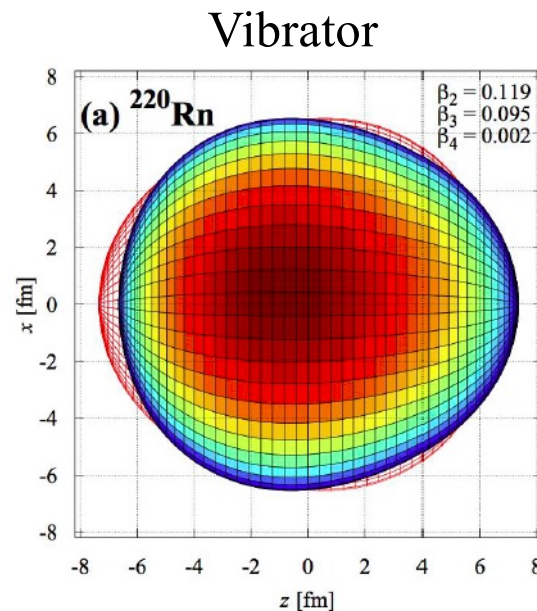
type	Hg-199	Ra-225	ratio*3	Hg-199 Ref
SIII	0.005	7.0	4300	PRC 82 015501 (2010)
SkM*	-0.027	21.5	-2400	PRC 82 015501 (2010)
SLy4	-0.006	16.9	-8600	PRC 82 015501 (2010)
SkO'		6.0		
DE05	0.071			PRC 72 045503 (2005)
DS03	0.055			PAN 66 1940 (2003)
"Best"	+/- (0.02)	6.0	+/- (900)?	Prog. PNP 71 21 (2013)

- 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

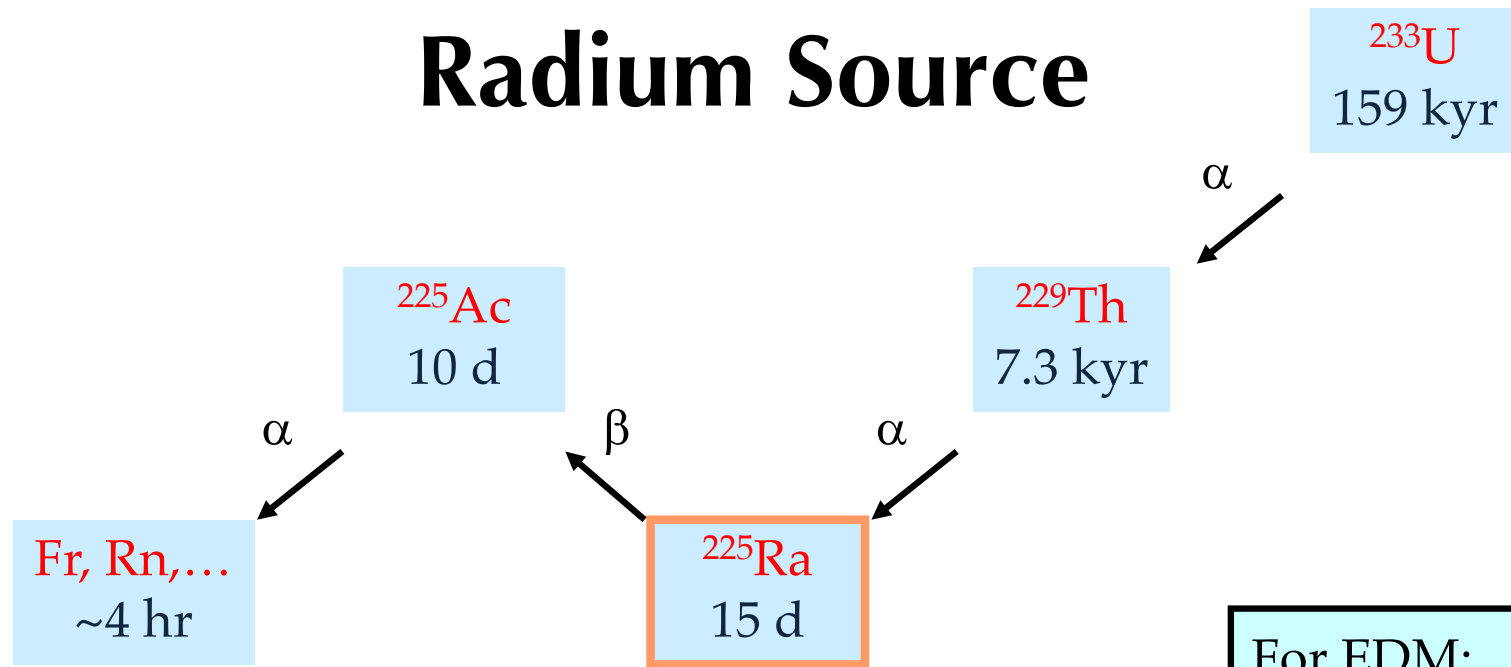
Other “Deformed” Searches

- Radon EDM @ TRIUMF (x20 to x200 vs. Hg)
- Protactinium EDM (Pa-229 is? x10² vs. Ra)
- Are there others? Stay tuned...

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



Radium Source



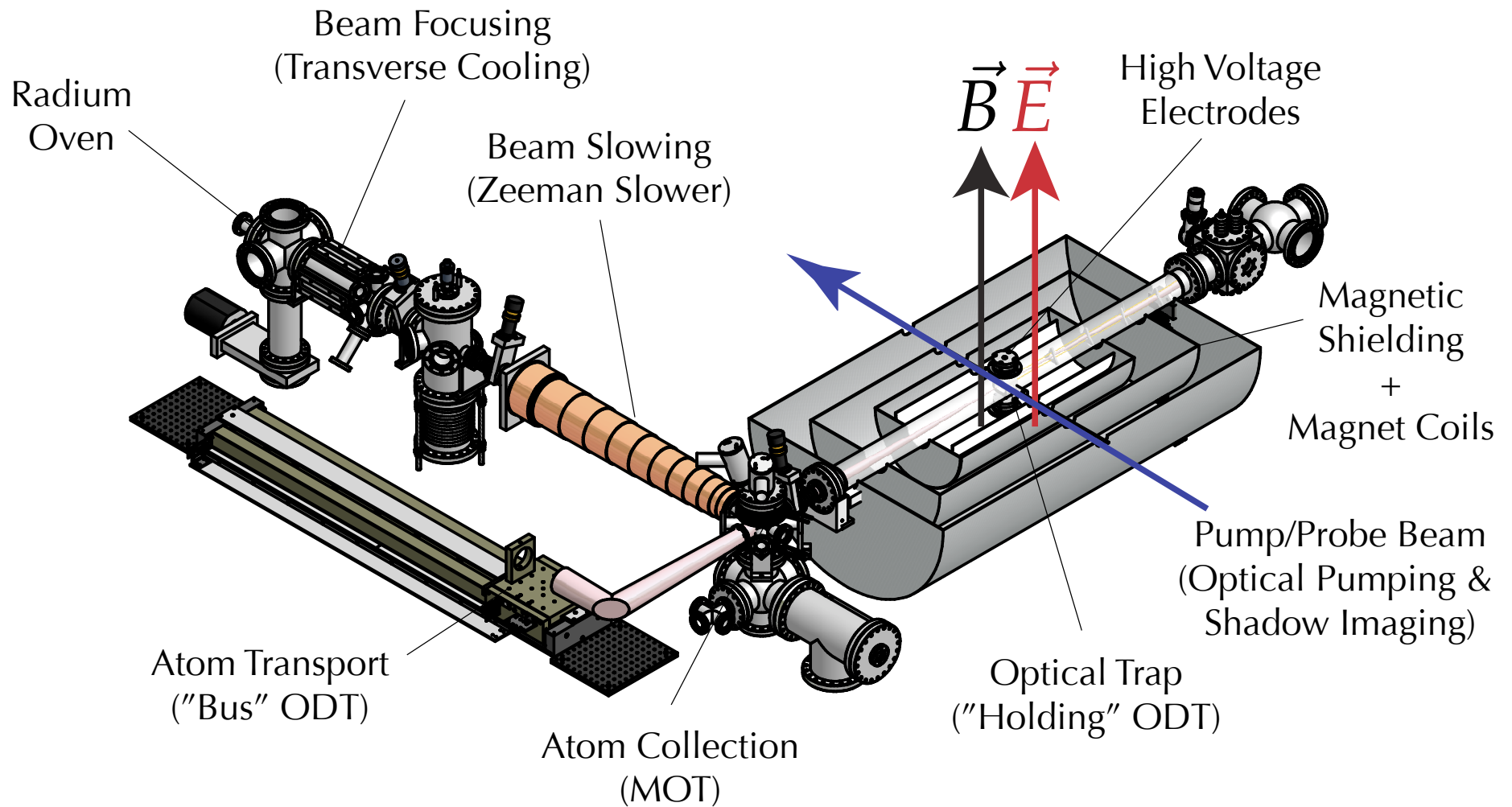
- 2 mCi (50 ng) ^{225}Ra sources from:
National Isotope Development Center (Oak Ridge, TN)
- Test source: 1 μCi (1 mg) ^{226}Ra
- Integrated Atomic Beam Flux $\sim 10^8/\text{s}$

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

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

FRIB
Yield for $^{225}\text{Ra} \sim (10^9 \text{ to } 10^{10})/\text{s}$

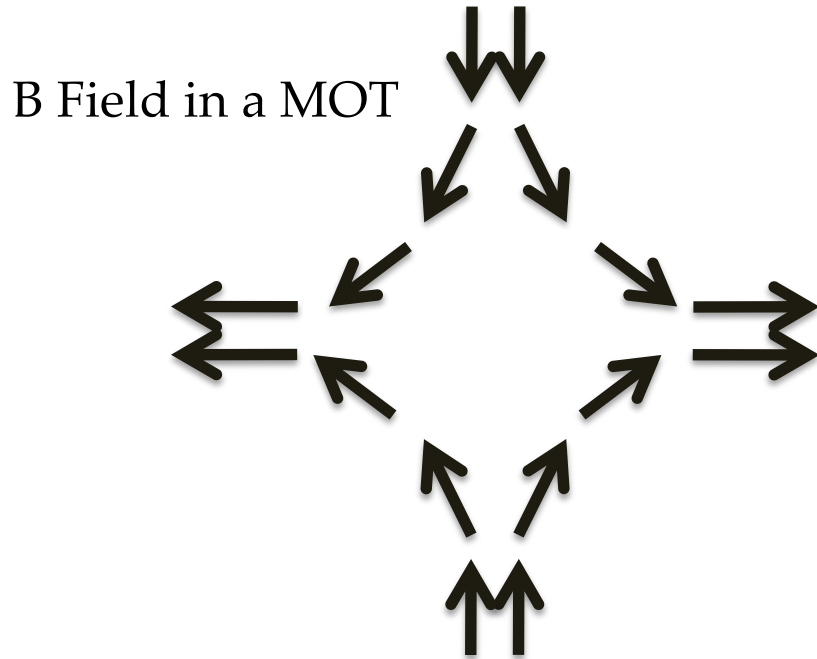
Experimental Layout



Neutral Atom Traps

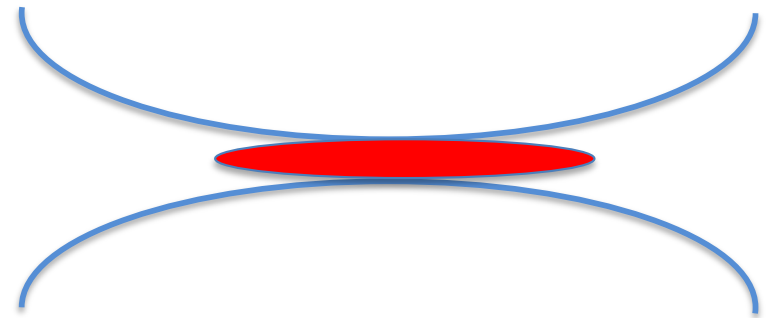
Magneto-Optical Trap (MOT)

Optical Dipole Trap (ODT)



- Large capture volume 1 cm^3
- Efficient Collection
- Unsuitable B-field region
- Capture velocity $6 \text{ cm/s} = 30 \mu\text{K}$
- Laser cool @ 714 nm
- Only 1 repump @ 1429 nm

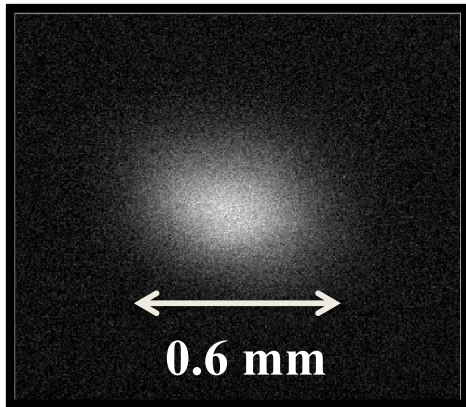
$$\mathcal{H} = -\vec{d}_{\text{ind}} \cdot \vec{E}_0 = \frac{\alpha}{4} E_0^2$$



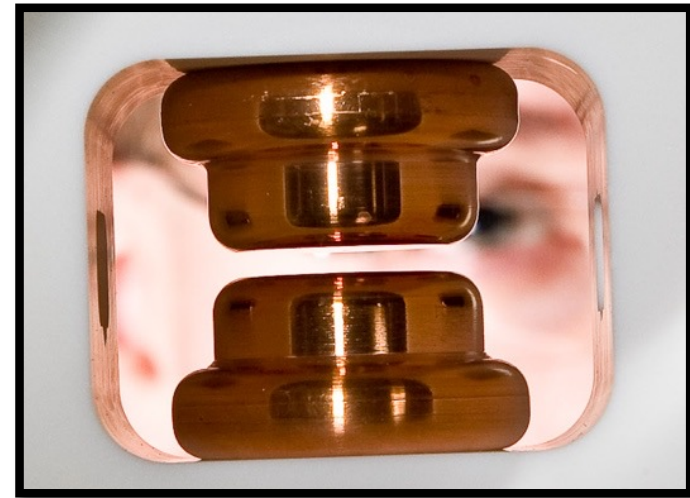
- Atoms trapped at beam focus
- 50 W @ 1550 nm
- 100 mm spot = Trap Depth of $400 \mu\text{K}$
- Good for transporting atoms
- Good for spatially confining atoms

Collecting & Transporting Ra-225 Atoms

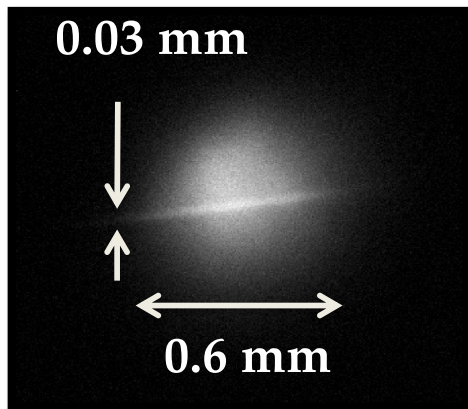
Guest et al., PRL 98 093001 (2007)



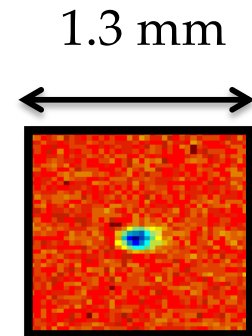
^{226}Ra MOT
20,000 atoms



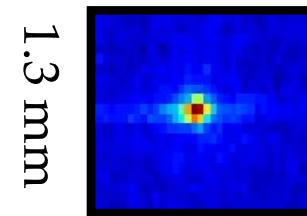
Parker et al., PRC 86 065503 (2012)



MOT + ODT
20,000 atoms



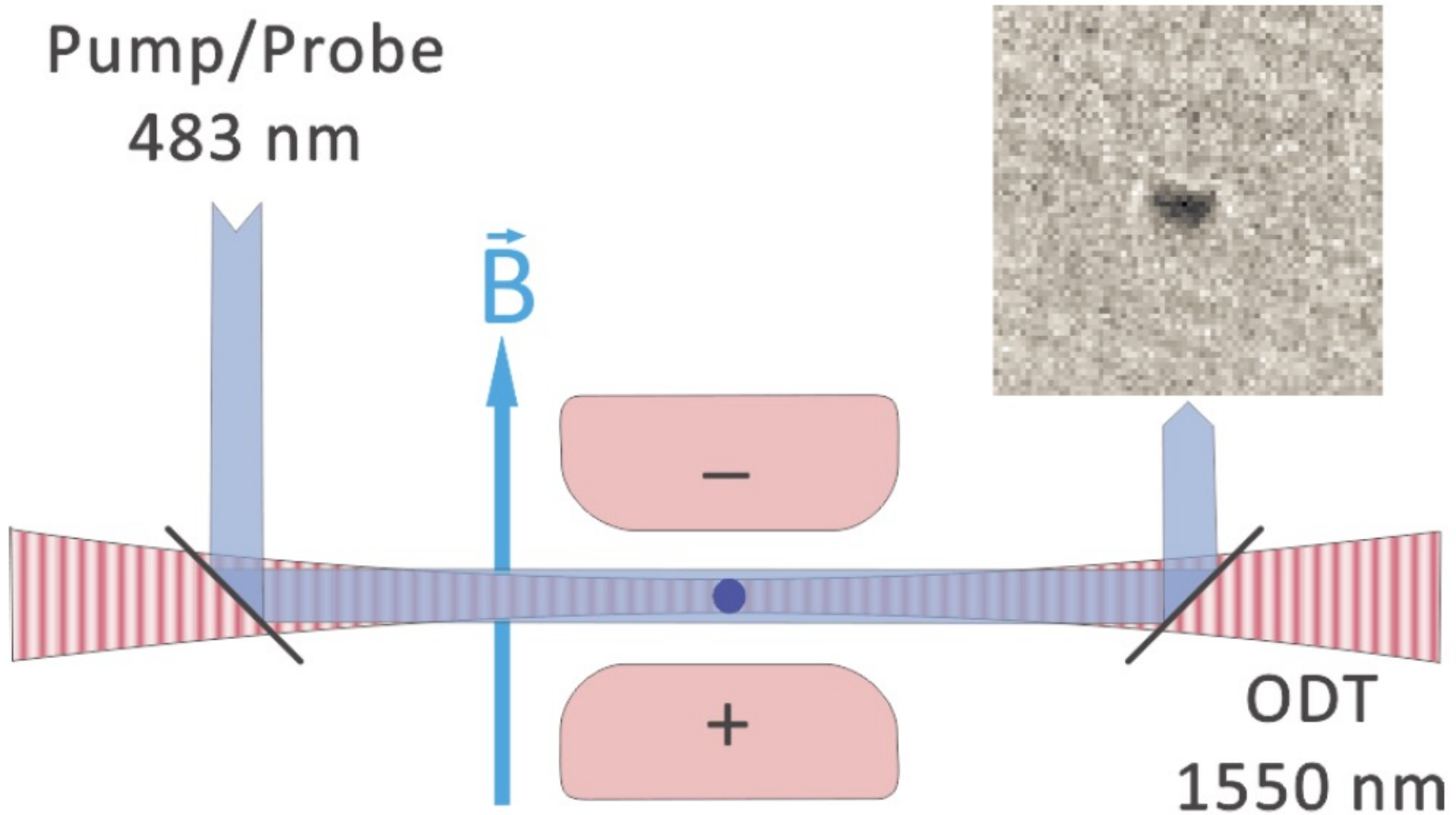
Absorption
Imaging



Fluorescence
Imaging

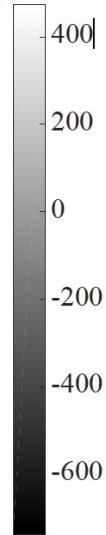
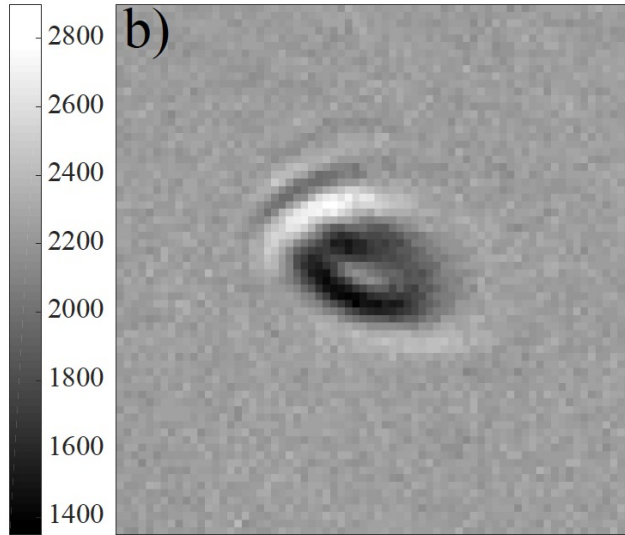
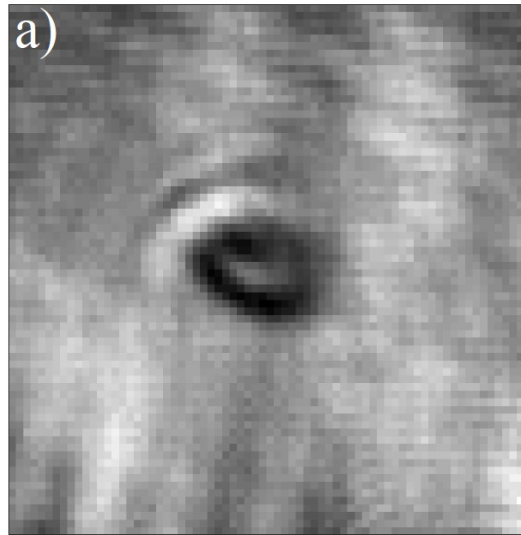
3000
atoms

Atoms create a shadow by absorption



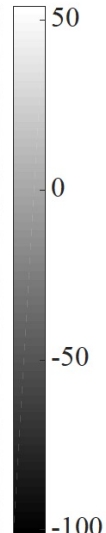
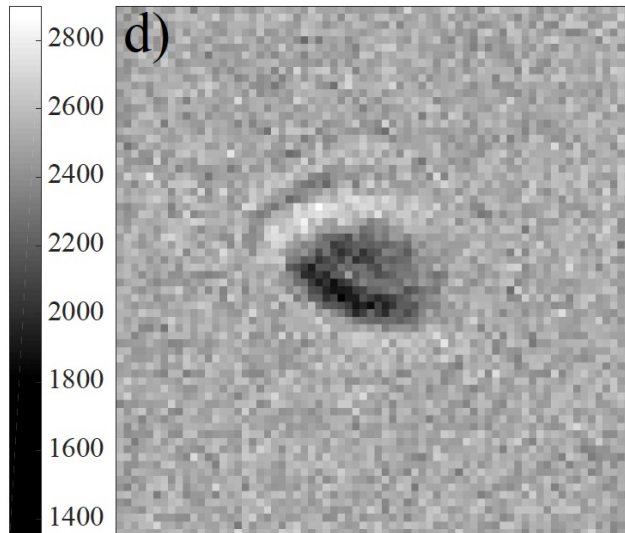
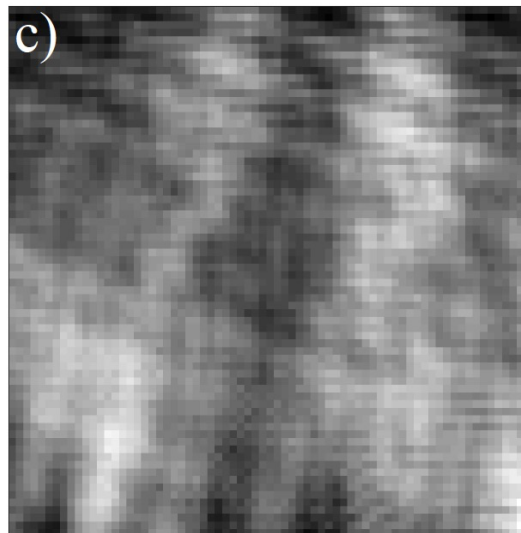
Shadow Image Analysis: Background & Distortion Corrections

raw image
of Ra-226



Ra-226
only

composite
background

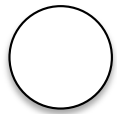


Ra-225
only

Absorption probability oscillates at ~ 20 Hz

probability of absorbing probe light and creating a shadow:

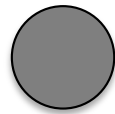
0%



Probe
light

Atom
spin

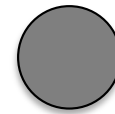
50%



100%



50%

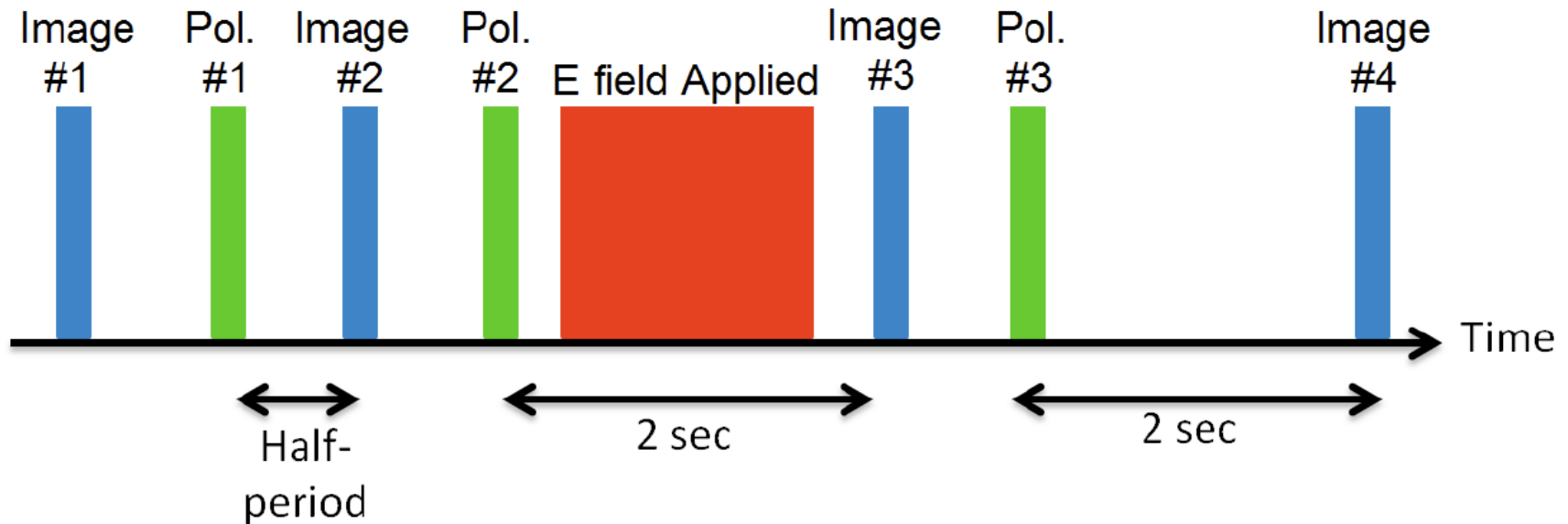


B-field & E-field point into or out of the screen

increasing time



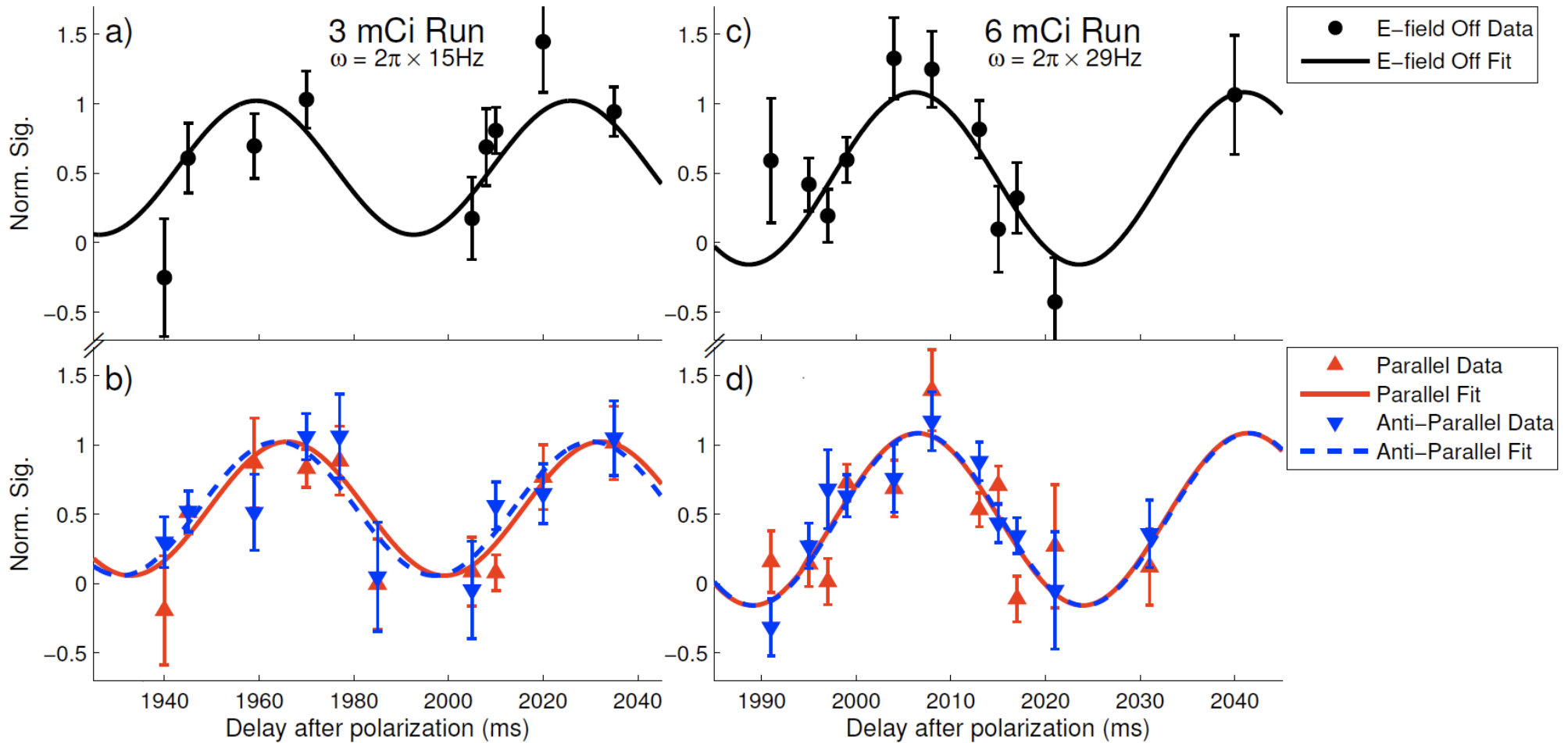
Several images are taken



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
$v \times E$	<0.001	<0.001
laser trap	<0.001	<0.001

Parker *et al.* PRL 114, 233002 (2015)

$|d(\text{Ra-225})| < 5 \times 10^{-22} e \text{ cm (95\%)}$

Michigan State University, East Lansing, MI



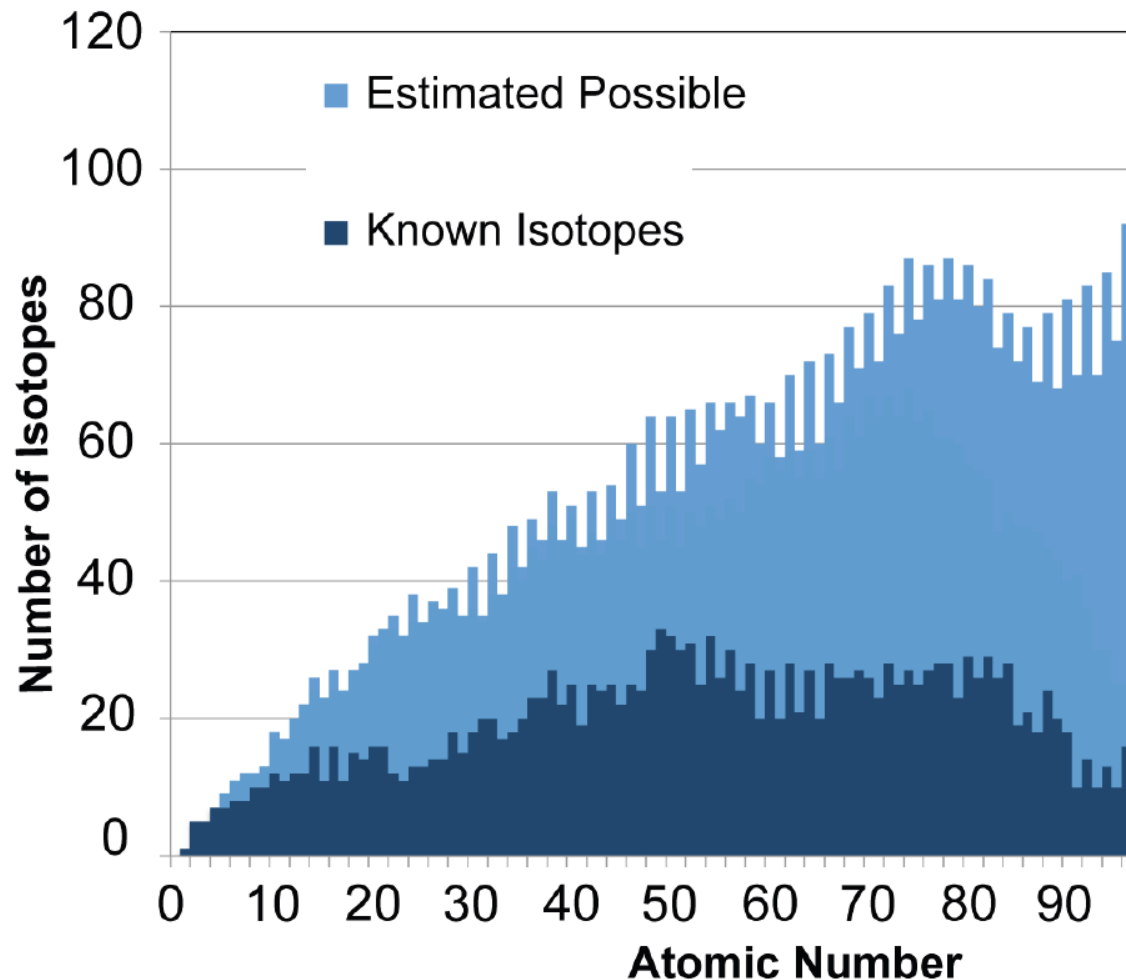
Google Maps & Wikipedia Commons

Facility for Rare Isotope Beams



**FRIB receives CD-3b from DOE on August 26, 2014
Start construction! (completion ~2020)**

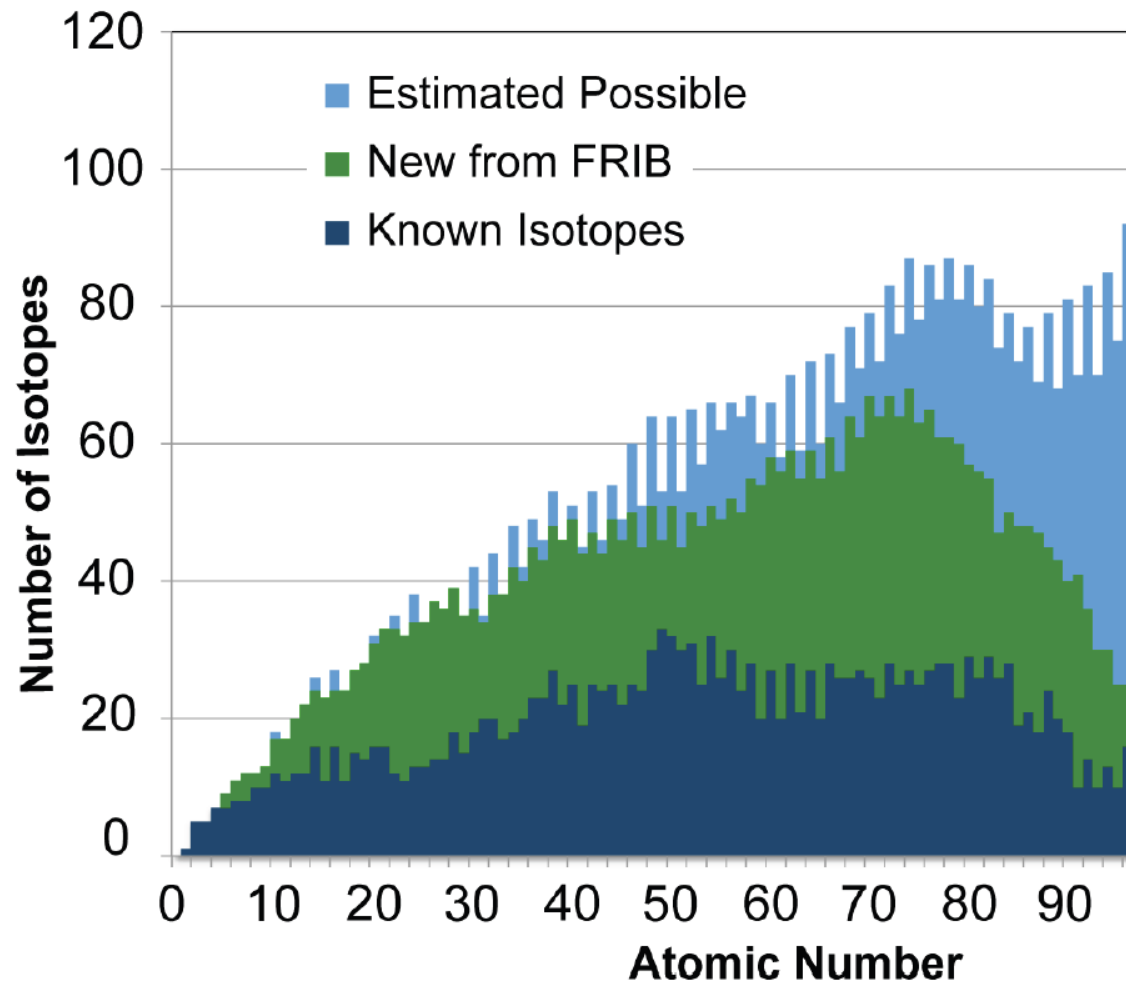
Facility for Rare Isotope Beams



- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012), based on a study of EDF models
- “Known” defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- Represents what is possible now

B. Sherrill

1000x production rate for Ra-225!



- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012), based on a study of EDF models
- “Known” defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- For $Z < 90$ FRIB is predicted to make $> 80\%$ of all possible isotopes

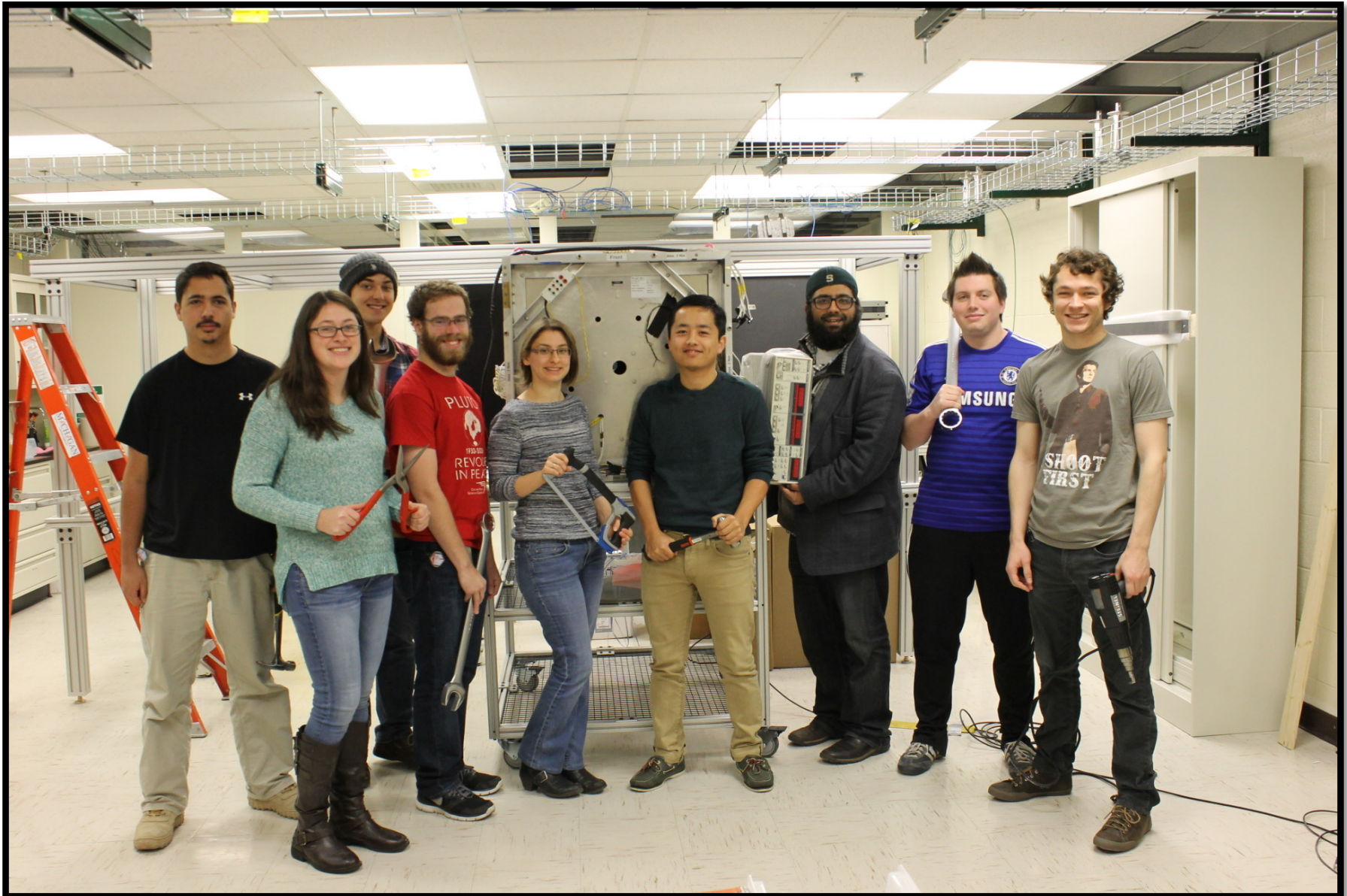
B. Sherrill

Ra EDM Team

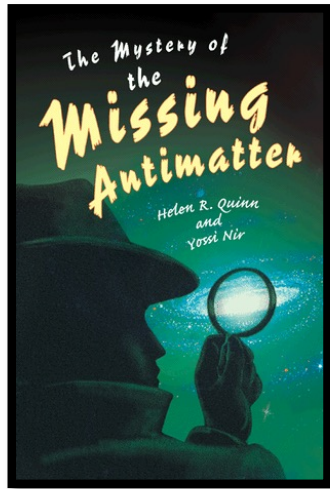


**Z.-T. Lu, N.D. Lemke, M.R. Dietrich, T.P. O'Connor
P. Mueller, R.J. Holt, M.R. Kalita, J. Singh, R.H. Parker,
K.G. Bailey, W. Korsh, not pictured: M. Bishof**

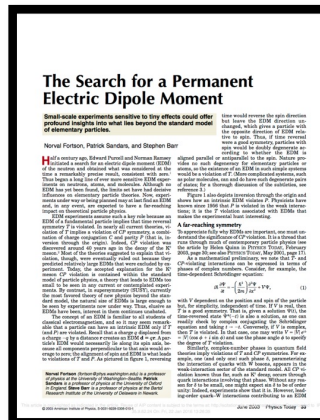
MSU Team: Thanks For Your Attention!



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
Norval Fortson, Patrick Sandars & Stephen Barr
Physics Today, June 2003, page 33



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