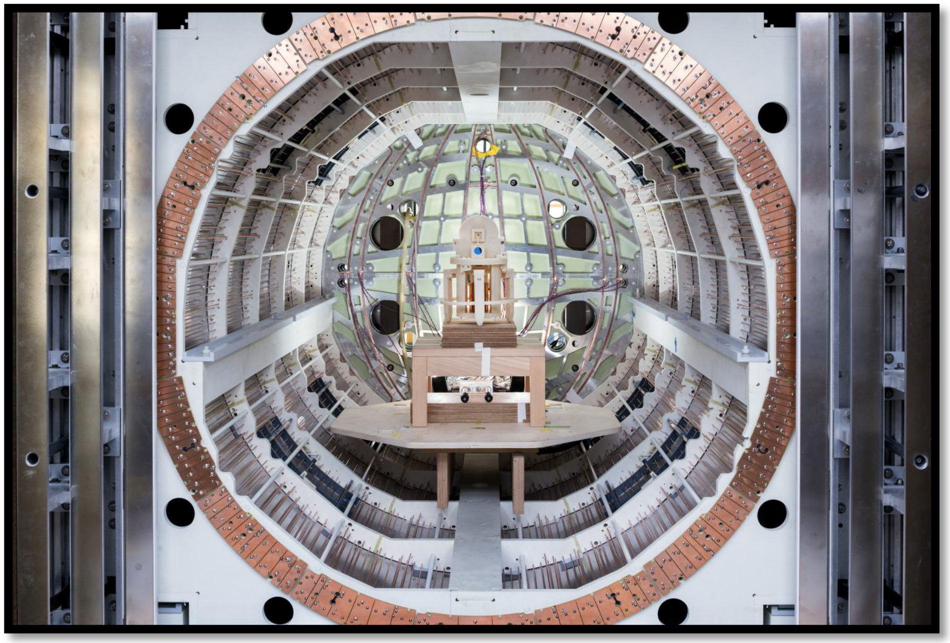
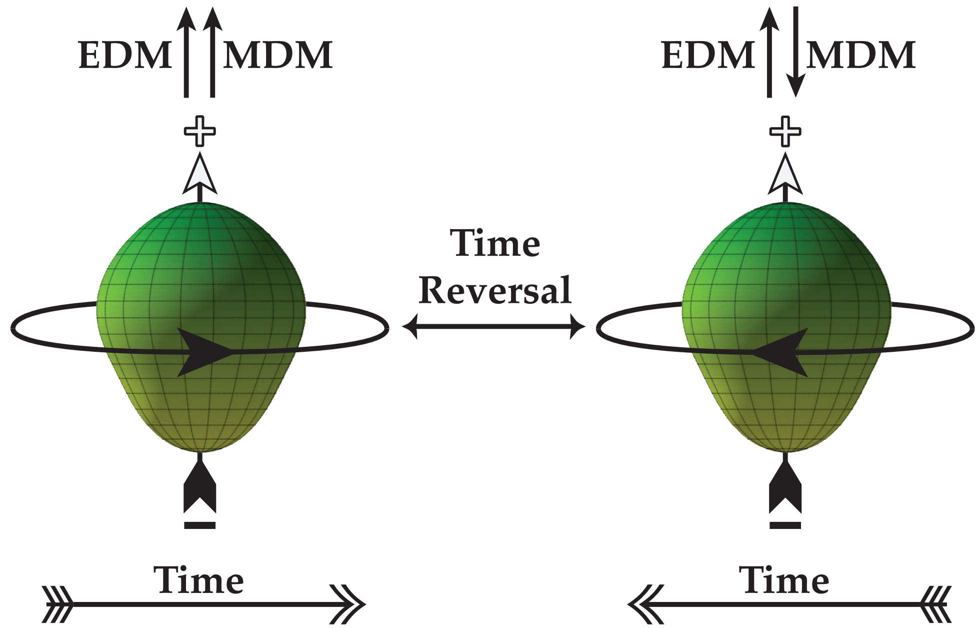
Testing Time-Reversal Symmetry Using Lasers, a Magic Room, and Pear-Shaped Nuclei



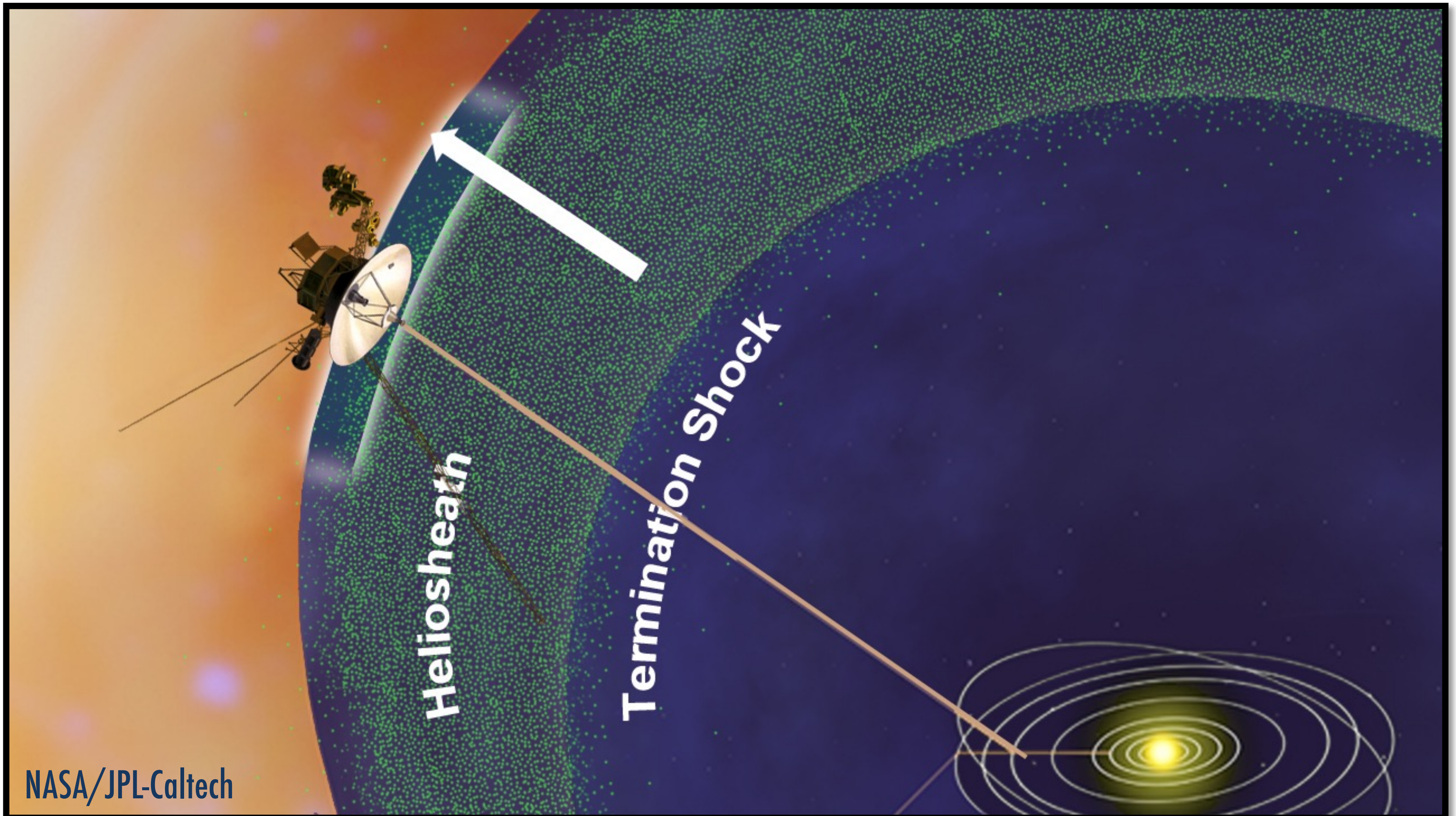


Jaideep Taggart Singh
National Superconducting Cyclotron Lab
Michigan State University

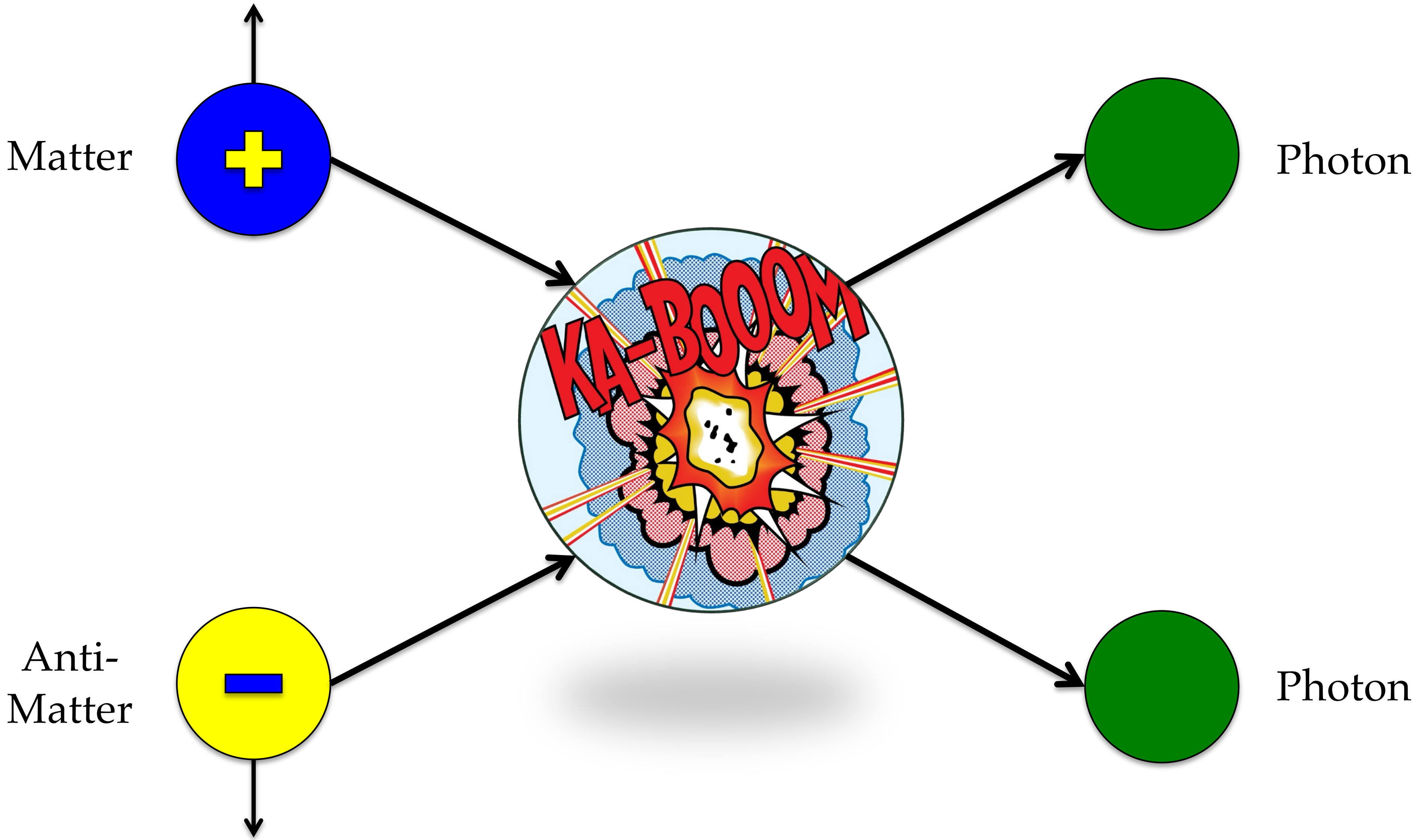
Texas Tech University, Physics Colloquium, 2016-02-04

NSCL

Voyager 1 is still OK!

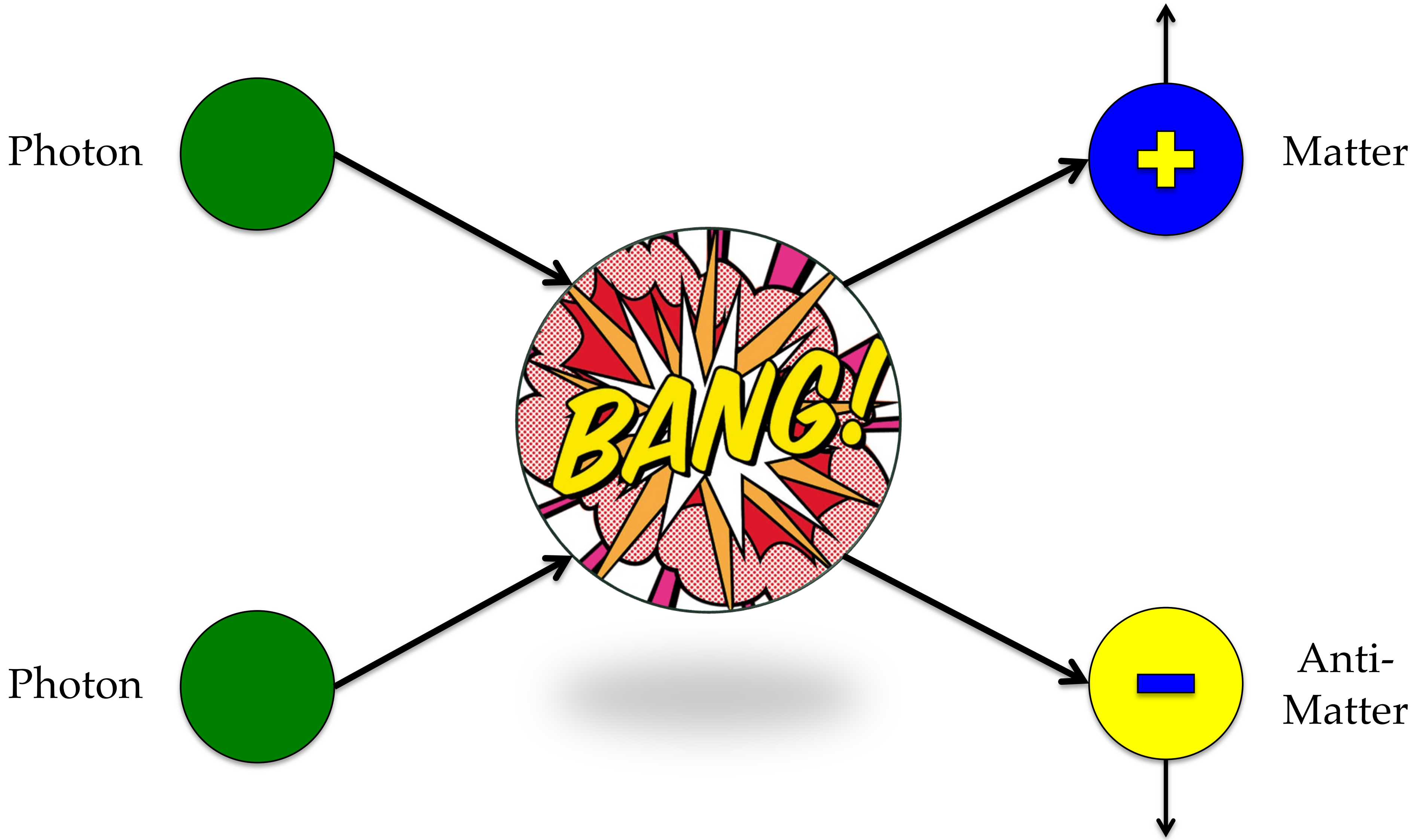


Stuff and Anti-Stuff disappears into Light.



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

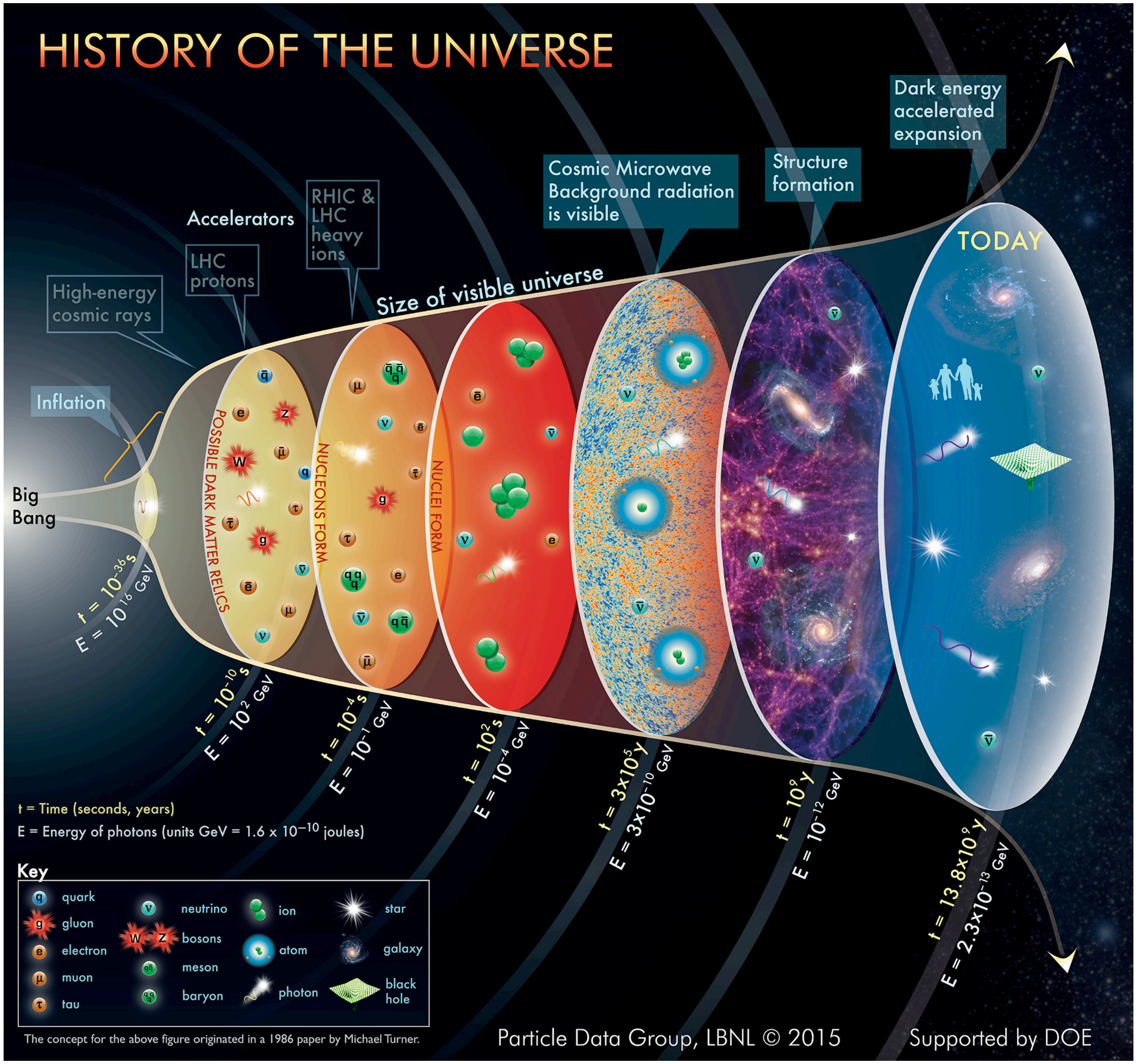
Light can be converted into Stuff and Anti-Stuff.



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

Big Bang…expanding Universe

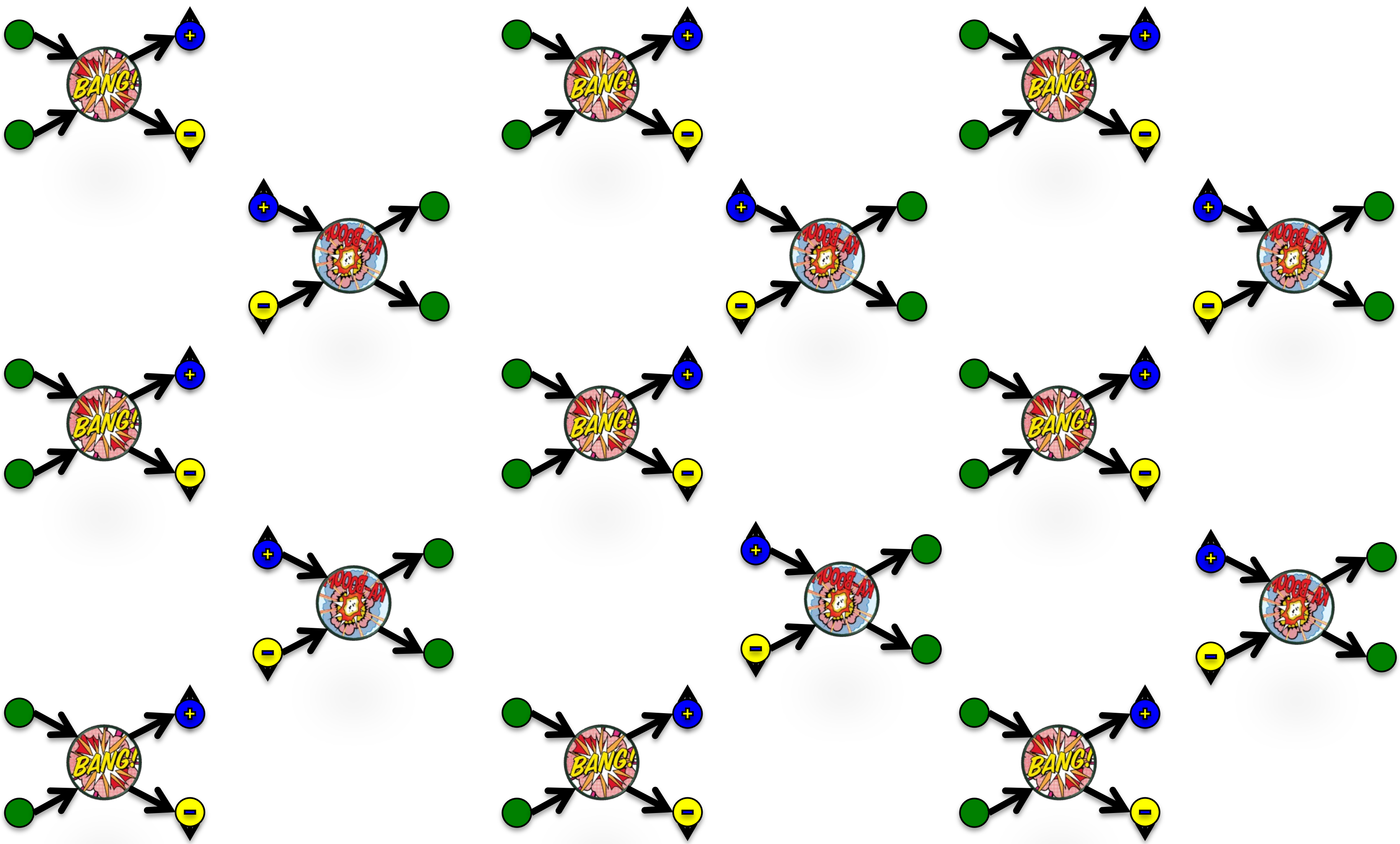
HOT & DENSE



cold & dilute

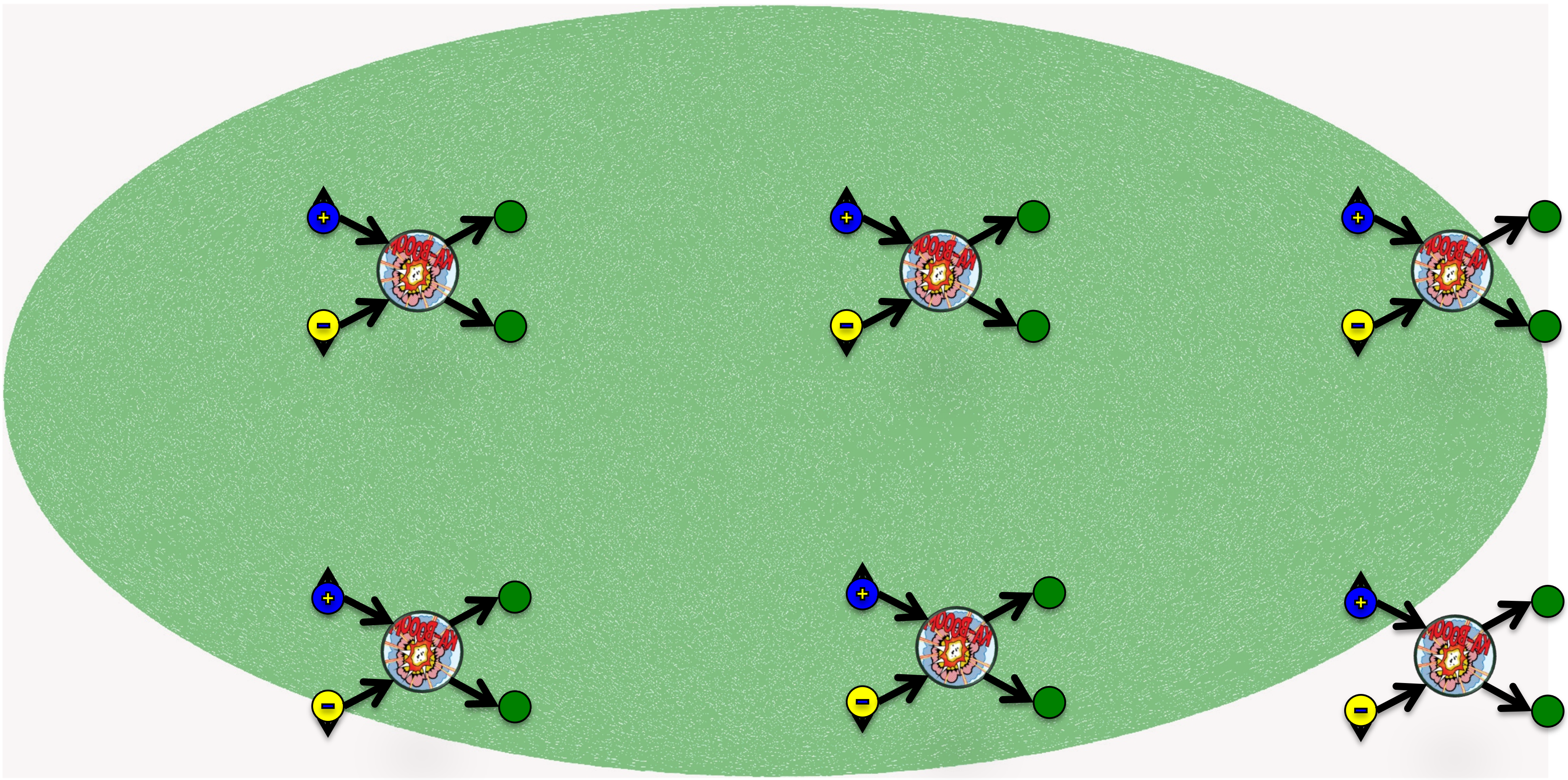
http://www.particleadventure.org/history-universe.html

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

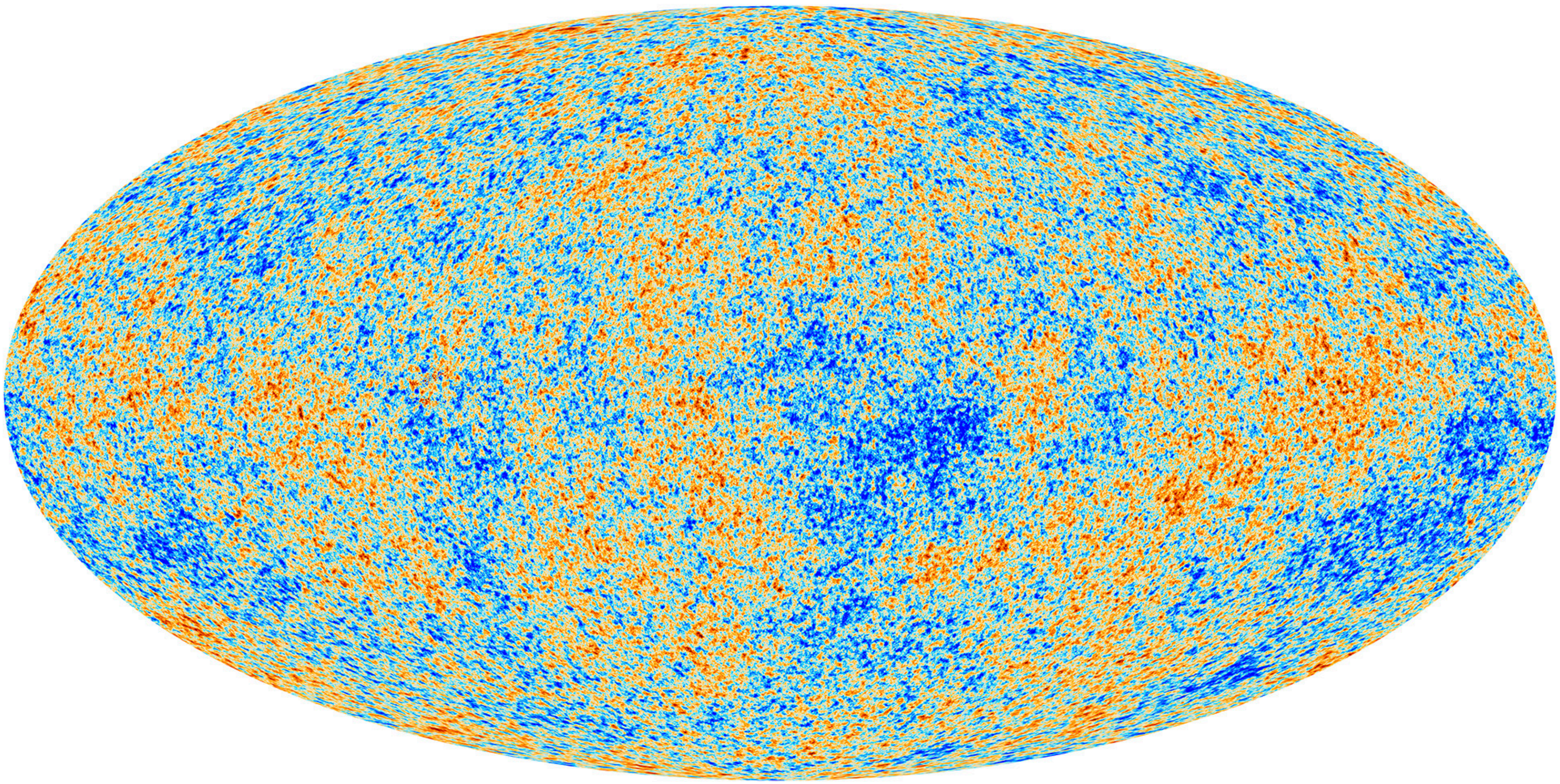


Planck 2013
http://www.esa.int/spaceinimages/Images/2013/03/Planck_CMB

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

Cosmic Microwave Background Radiation

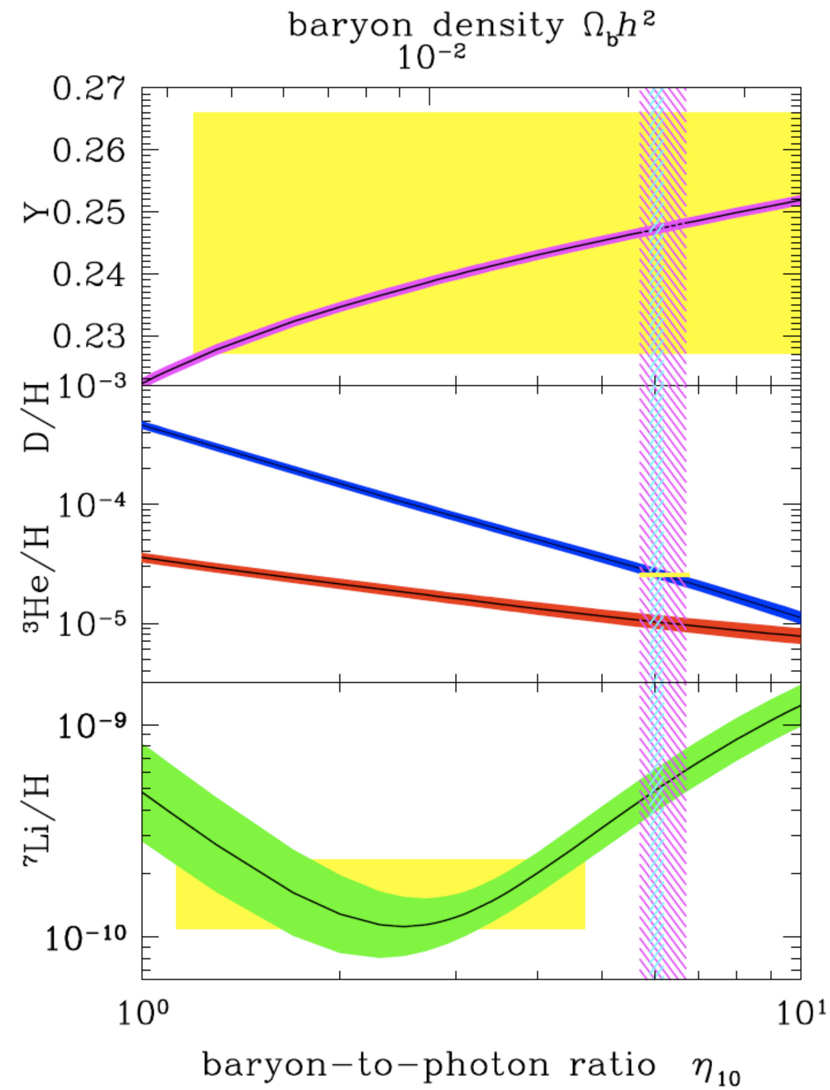


Planck 2013
http://www.esa.int/spaceinimages/Images/2013/03/Planck_CMB

Baryon Asymmetry of Universe

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

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$
$$= 0.0000000061(5\%)$$
$$\approx 10^{-9}$$



PDG2014

Sakharov's Conditions

The Nobel Foundation

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

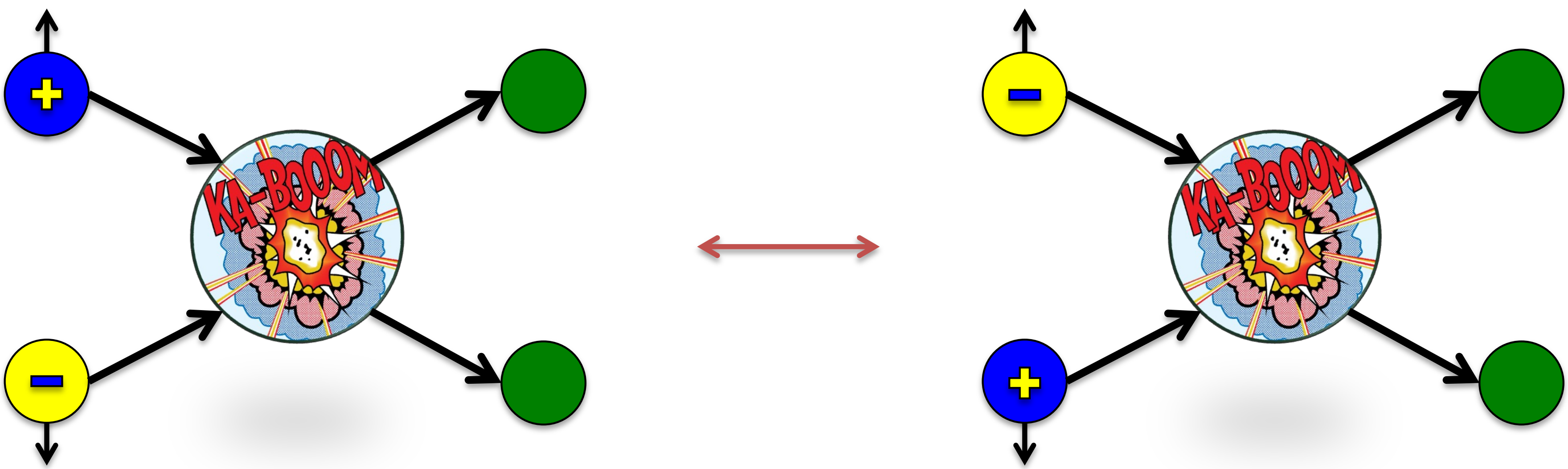
A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from 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.

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

Discrete Transformation: Charge Conjugation

Replace particle with antiparticle



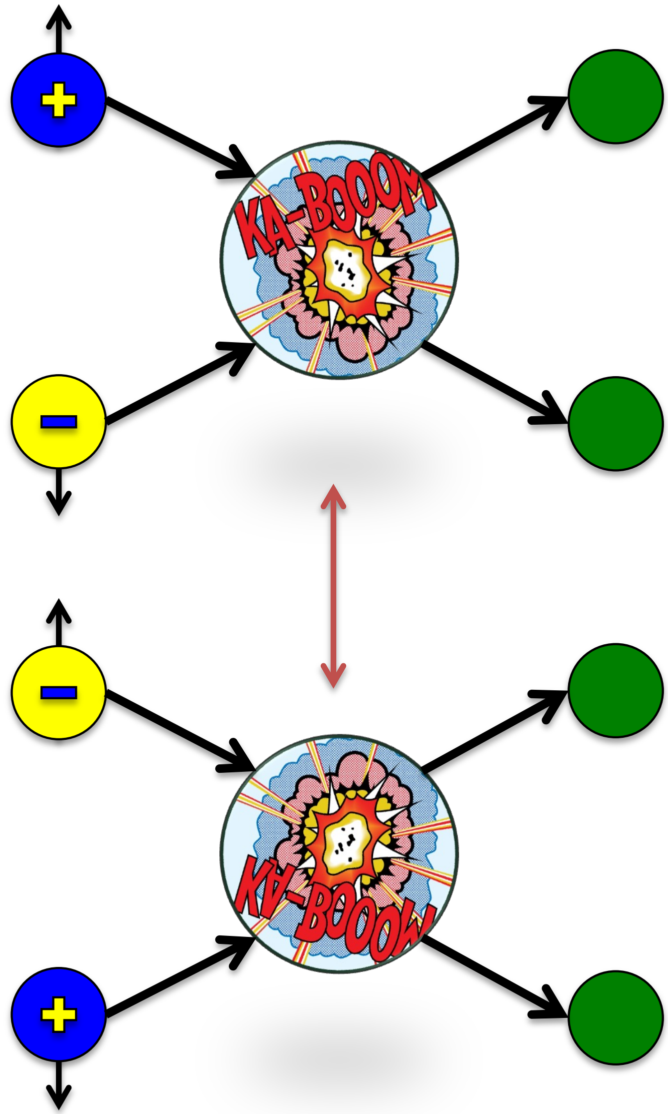
http://strangesounds.org/2013/08/mysterious-booms-in-the-usa-new-york-california-alaska-mississippi-utah-michigan.html

Discrete Transformation: Parity (Spatial Inversion)

Mirror reflection

+

180^o rotation



+x to –x

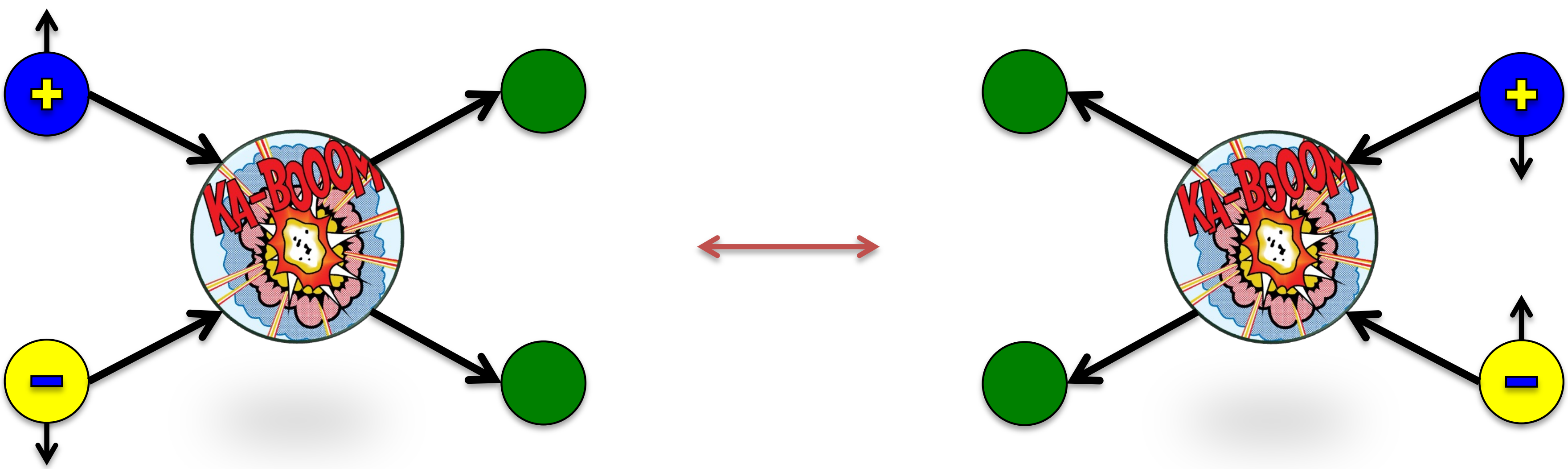
+y to –y

+z to -z

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

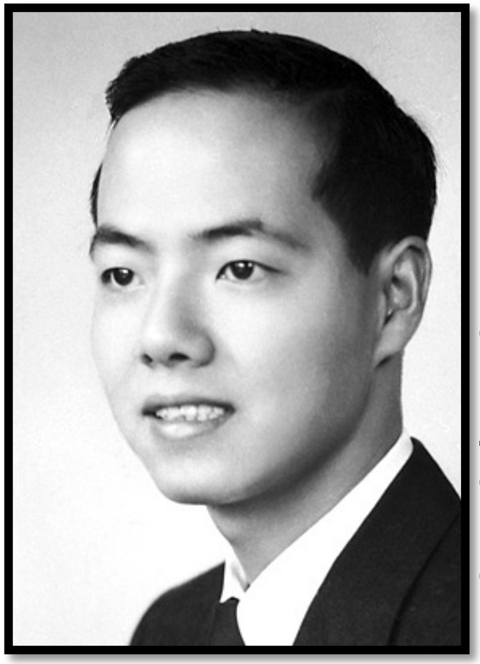
Discrete Transformation: Time Reversal

Reverse the arrow of time, +t to -t

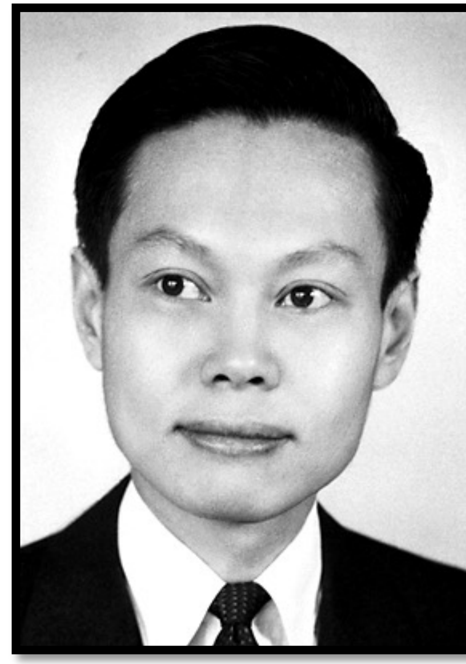


http://strangesounds.org/2013/08/mysterious-booms-in-the-usa-new-york-california-alaska-mississippi-utah-michigan.html

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

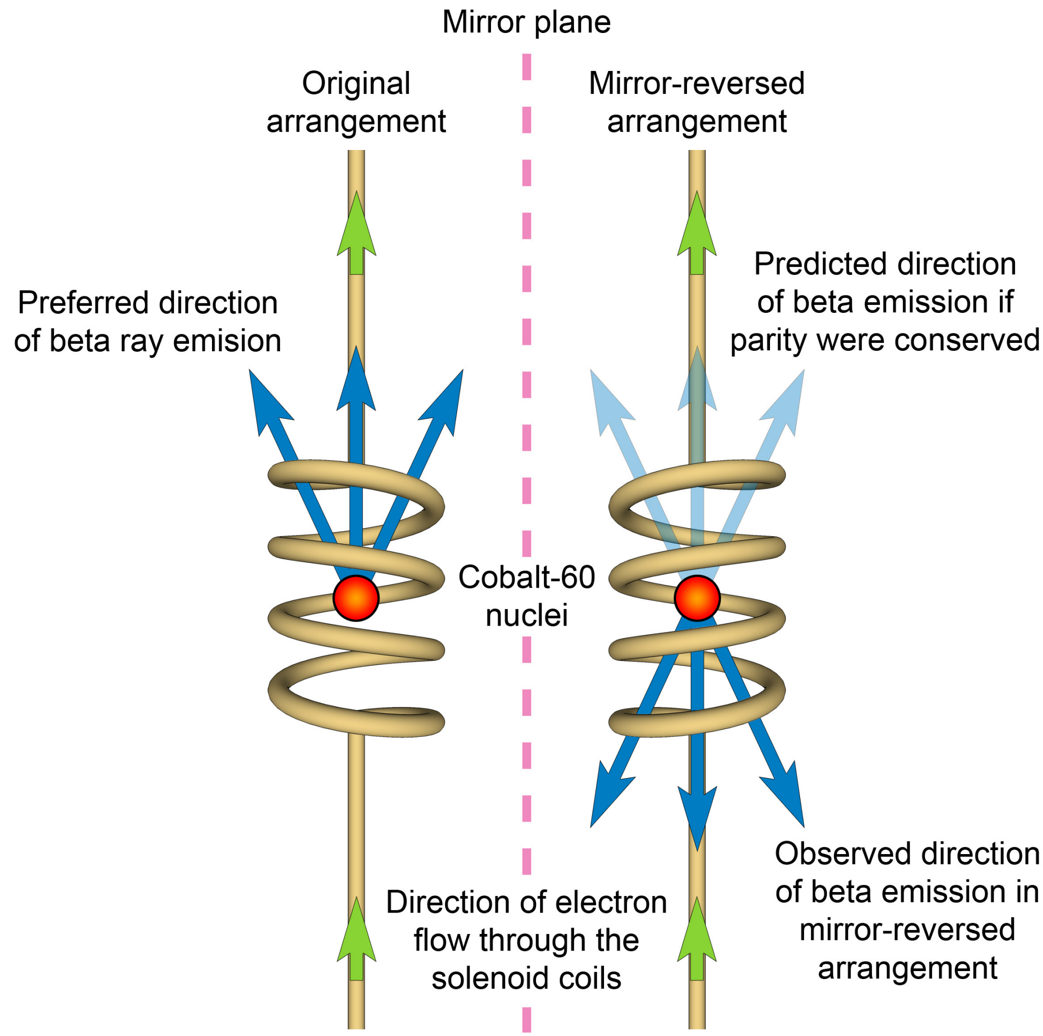
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(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.

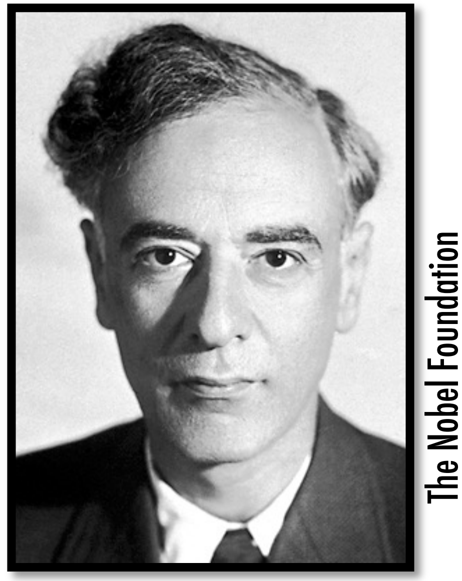
1957: Nope, Parity is violated (maximally)!

AIP Emilio Segre Visual Archives



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

1957: Is CP conserved?



ON THE CONSERVATION LAWS FOR WEAK INTERACTIONS

L. LANDAU

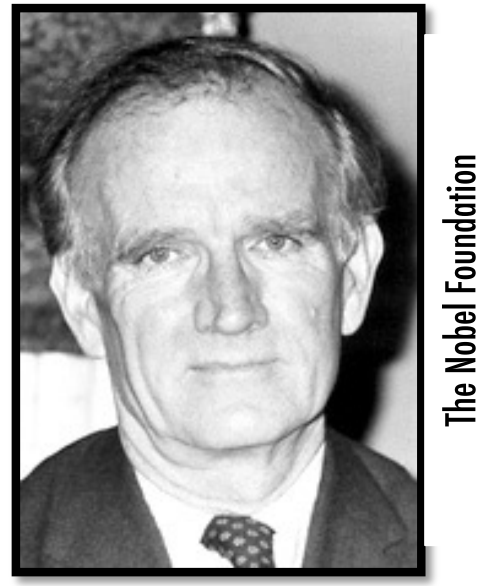
Institute for Physical Problems, USSR Academy of Sciences, Moscow

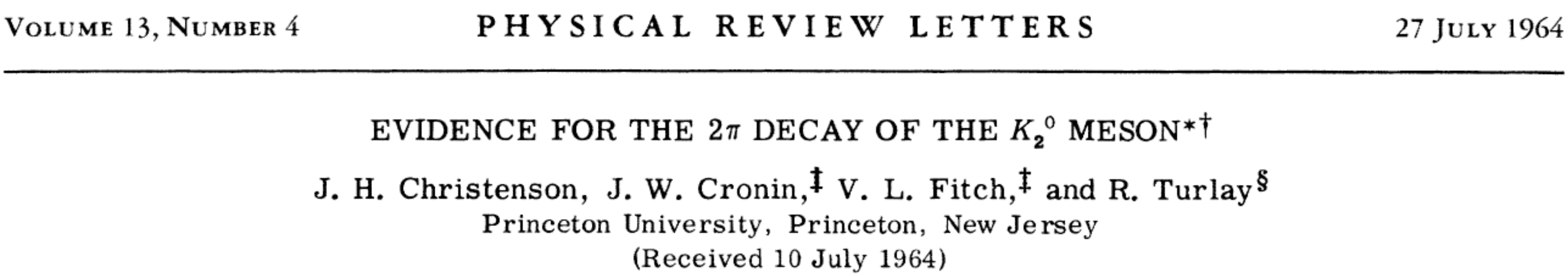
Received 9 January 1957

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)!





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

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

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

$$\eta_{\rm CKM} \approx 10^{-26}$$ 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

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

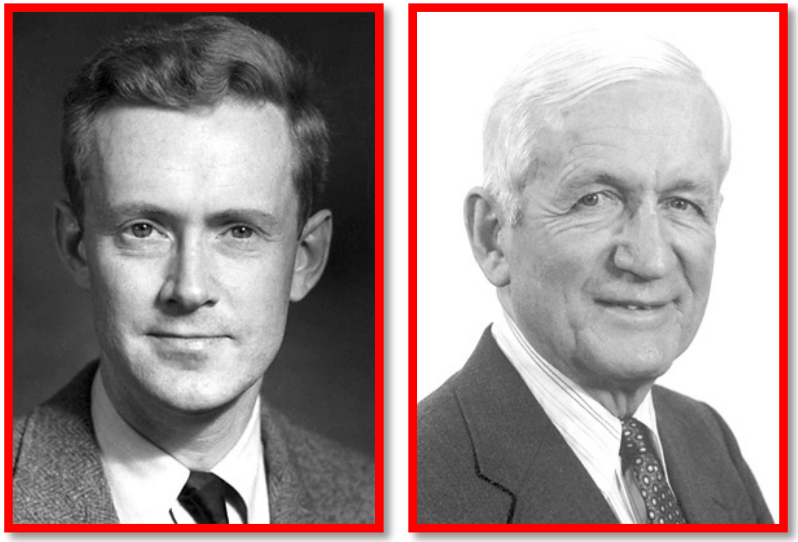
Hocker & Ligeti Annu. Rev. Nucl. Part. Sci. 2006. 56:501-67

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?



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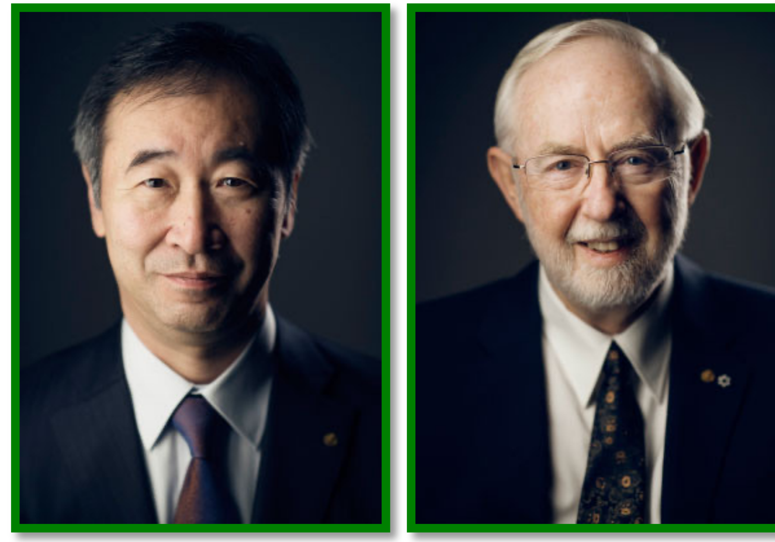
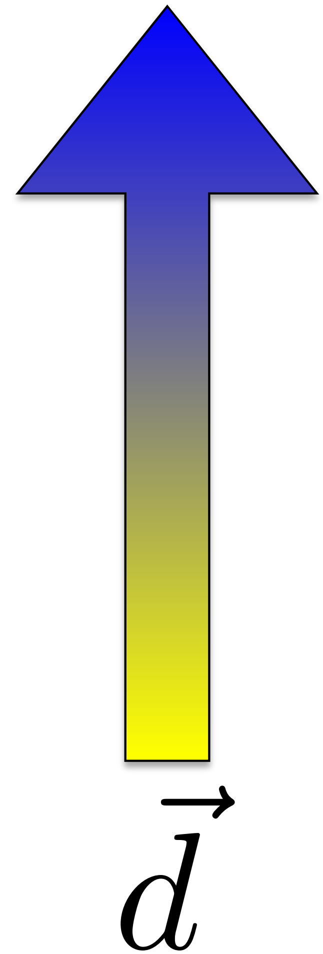


The Nobel Foundation

- 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!

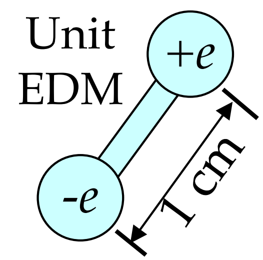
EDM: Measures the Separation of Charges



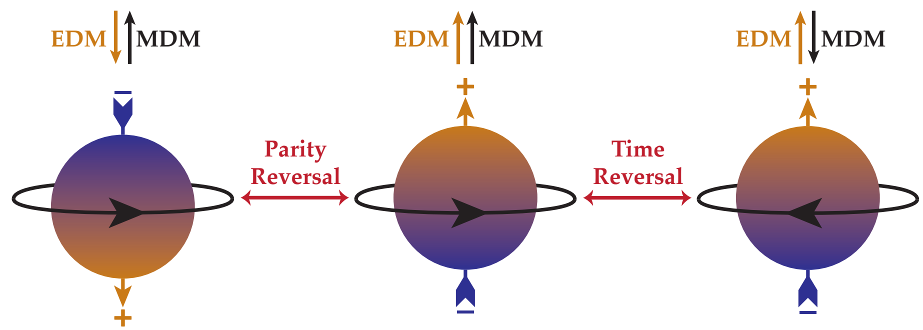
"Thunder Cloud as Generator #2" (1971) by Paterson Ewen [Art Gallery of Ontatrio]

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

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



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

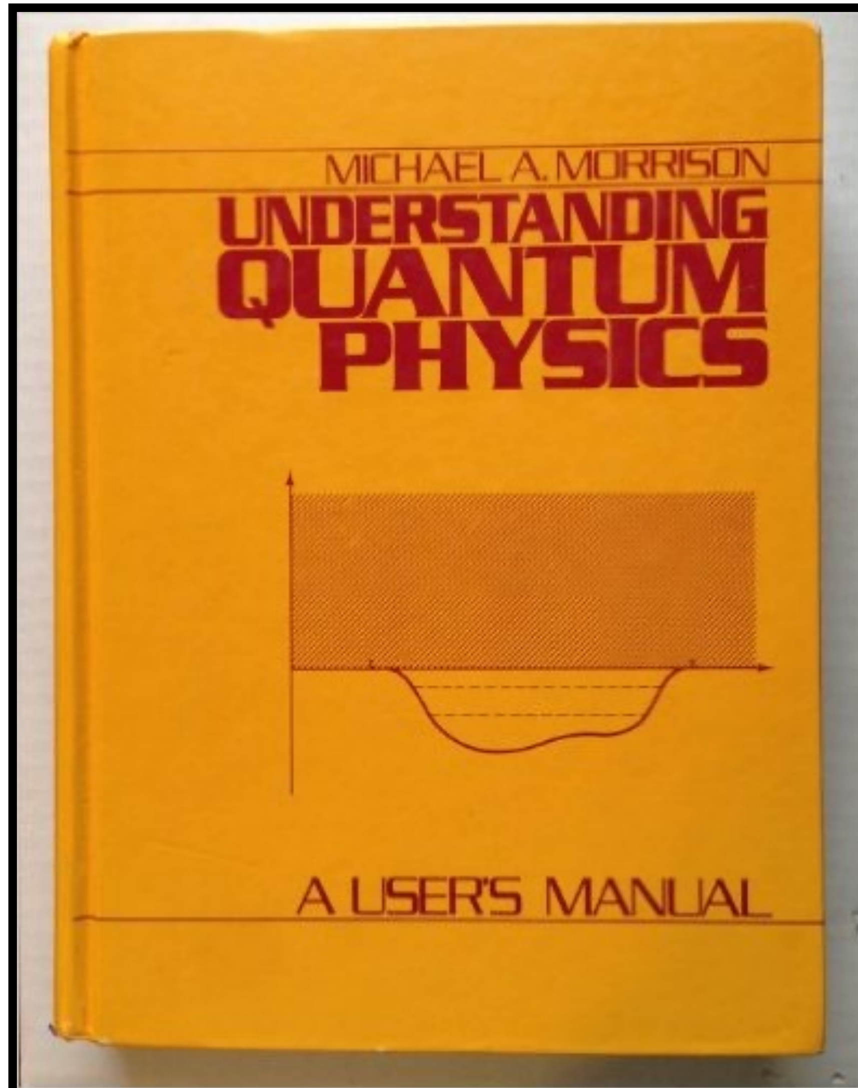


Theorist: …trivial application of the Wigner-Eckart Theorem…

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

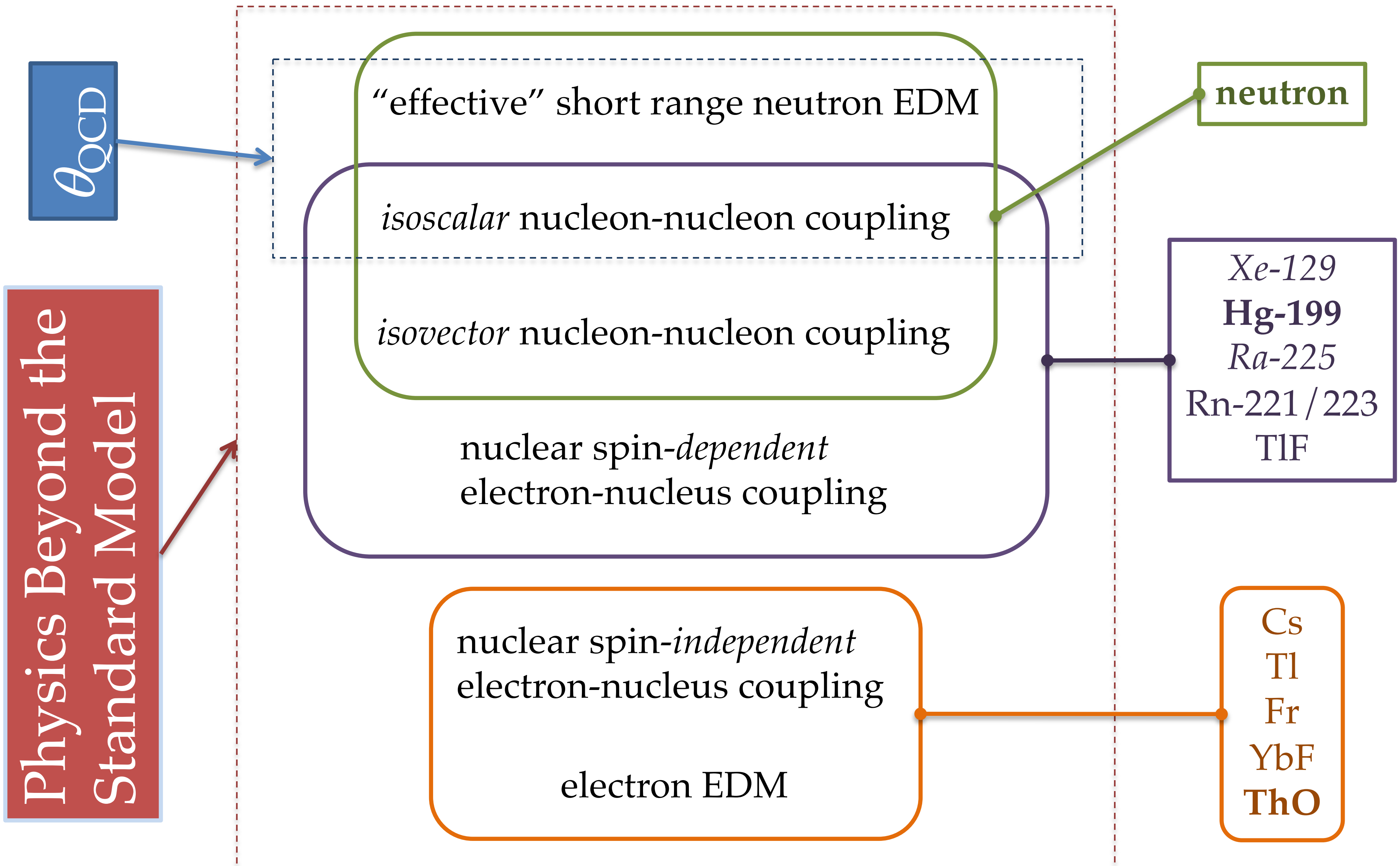
Wigner-Eckart Theorem? Just ask Prof. Gibson!

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



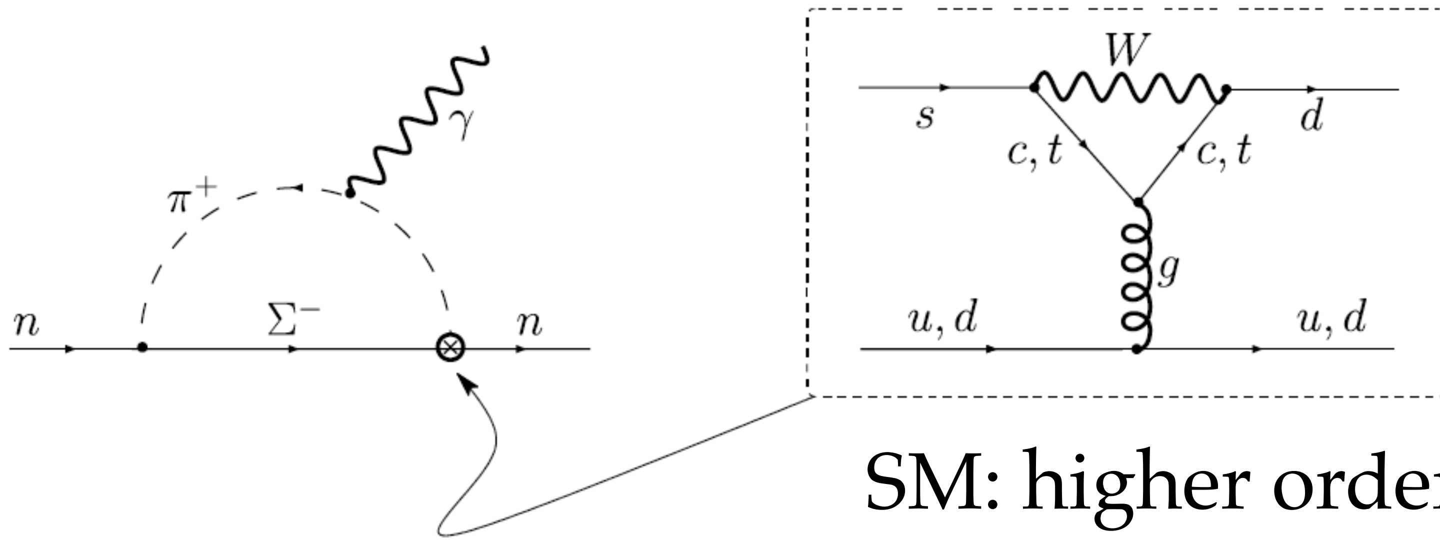
Published by Prentice-Hall 1990

Different Sources of $\not{CP}$ ⇔ EDMs of Different Systems

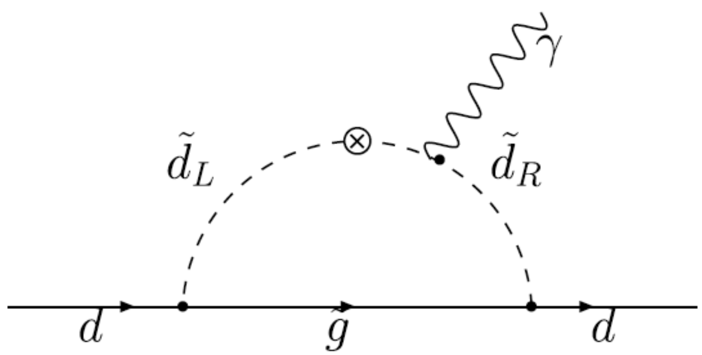


PRC 91 035502 (2015)

Standard Model vs. Supersymmetry EDMs



SM: higher order
"penguin" diagram



SUSY: lower order

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

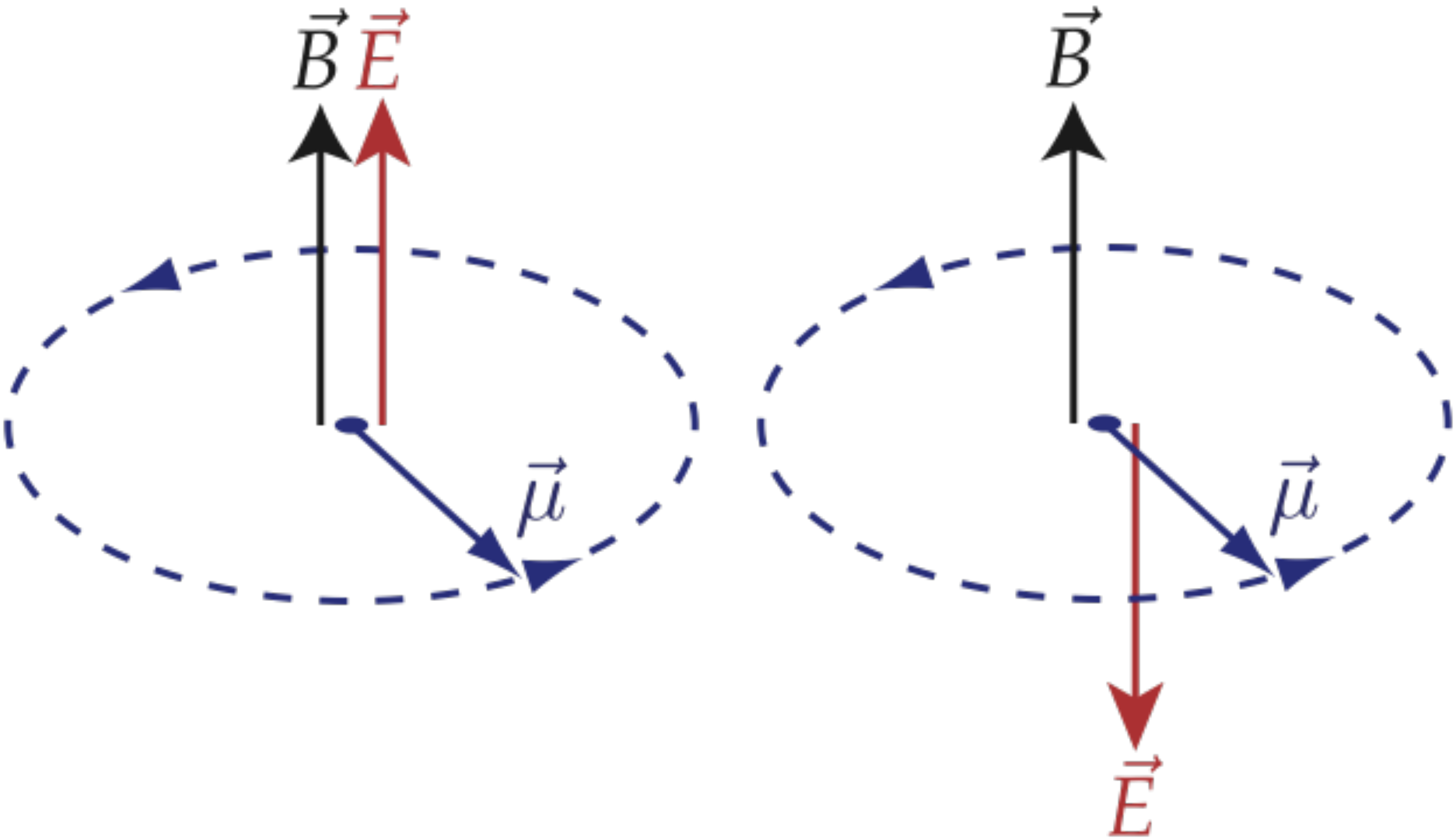
Current Limits

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

System	Best Limit (2σ) 10^{-28} e*cm	SM estimate 10^{-28} e*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} e*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



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

Ultimate Statistical Sensitivity

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

statistical sensitivity:

interrogation
time

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

signal-to-noise
ratio

Electric
field

integration
time

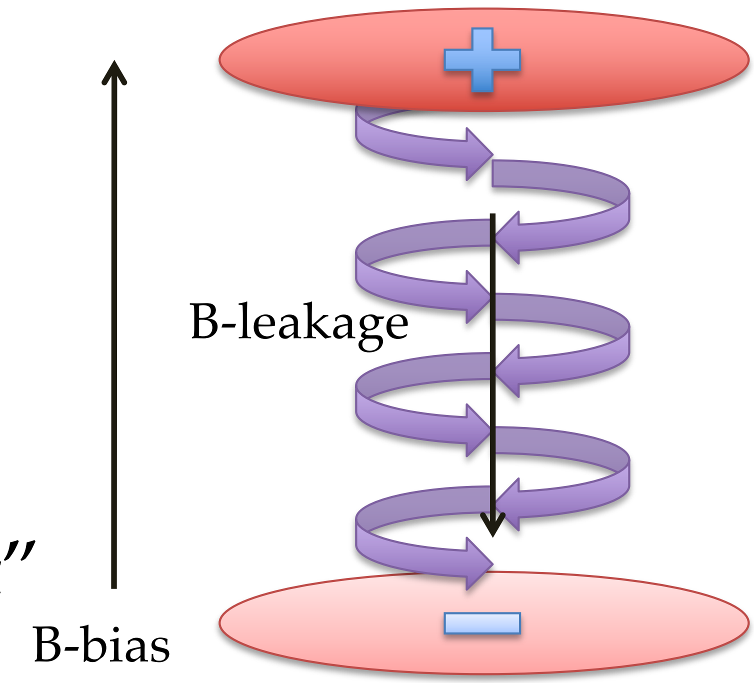
Magnetic Field Instabilities & False Effects!

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

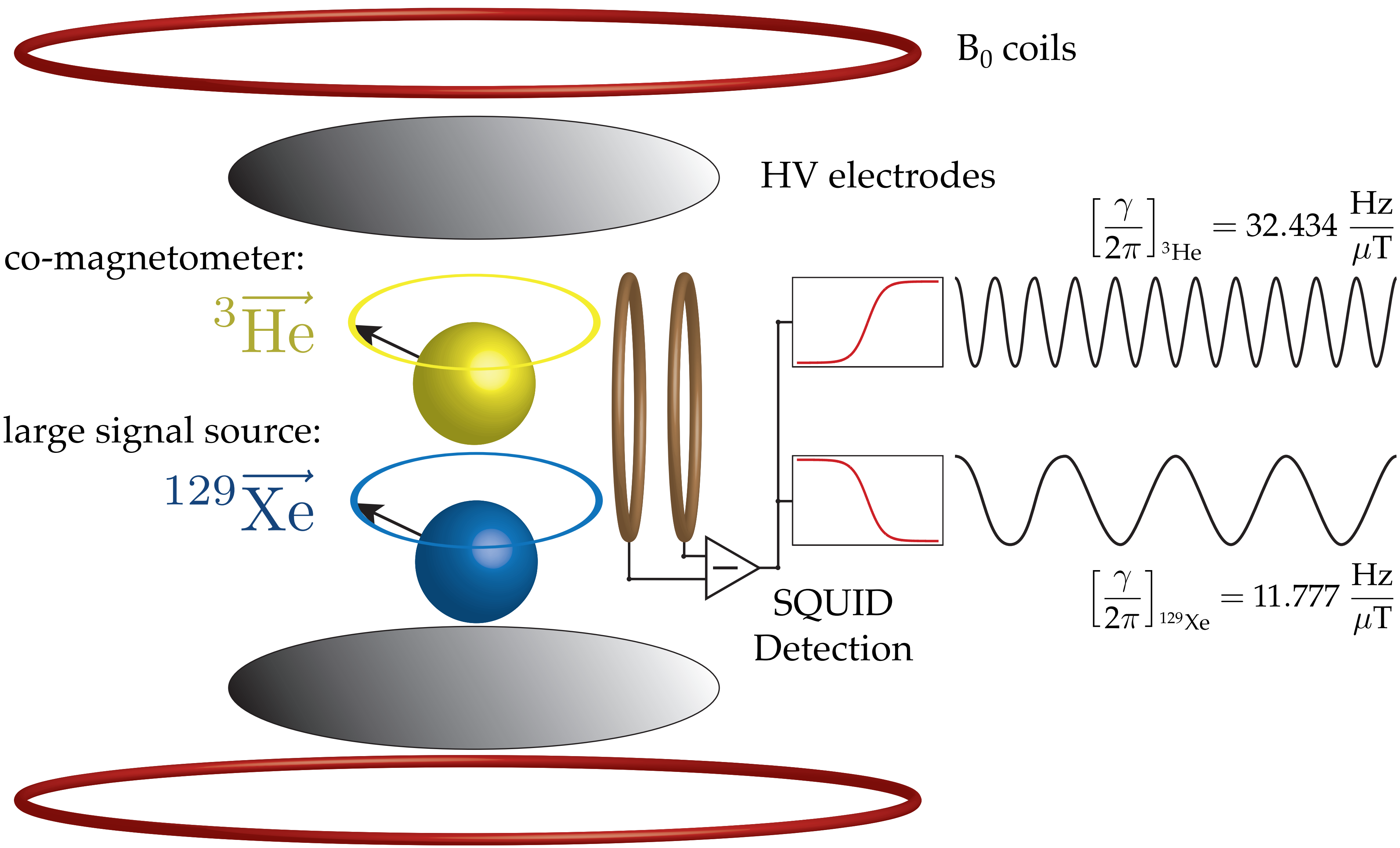
challenge!

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

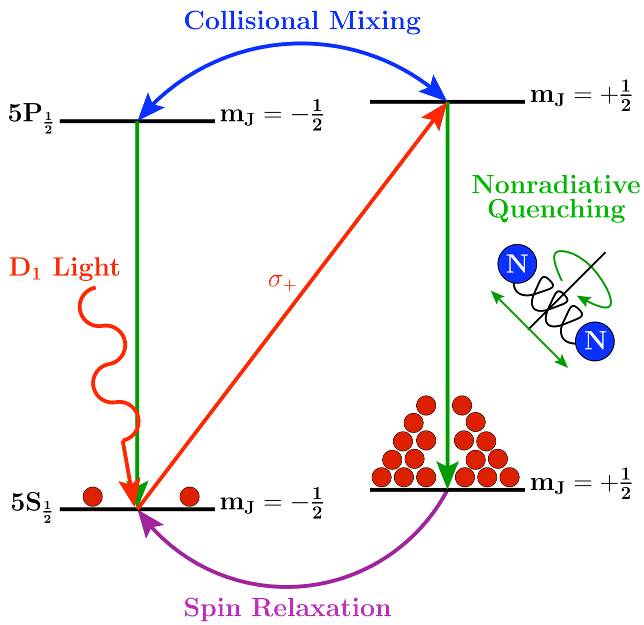


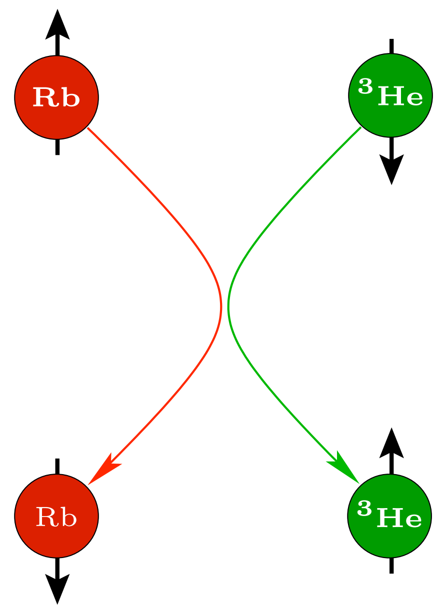
Spin-Exchange Optical Pumping (SEOP)

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)





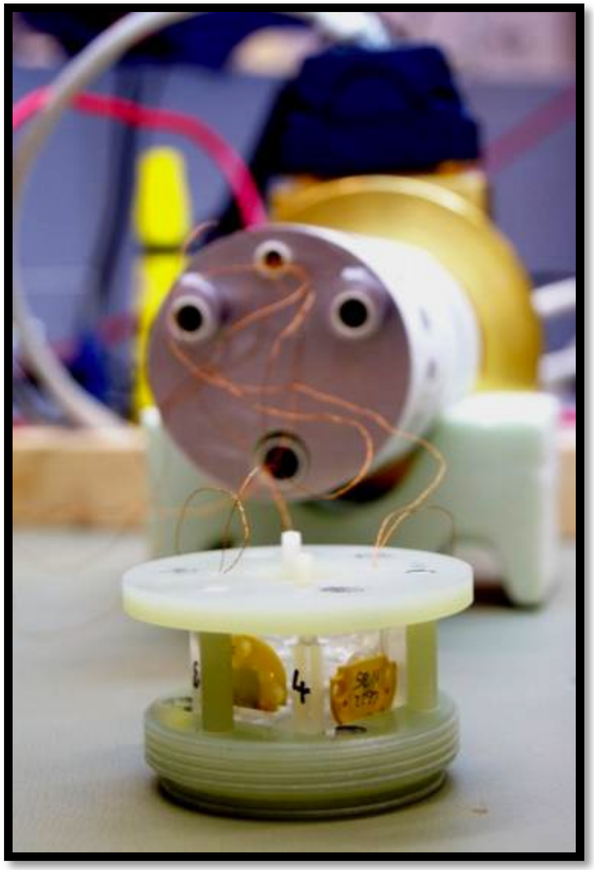
Optical Pumping

light (laser) to electron (Rb)

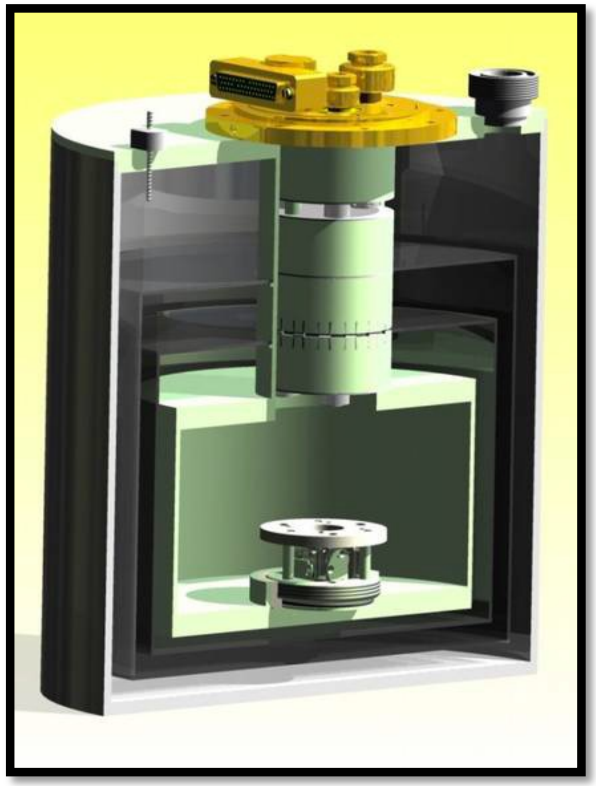
Spin Exchange

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

“SQUID” Magnetometers: Detectors



Two sensors in
each direction.
Cube side = 1 cm



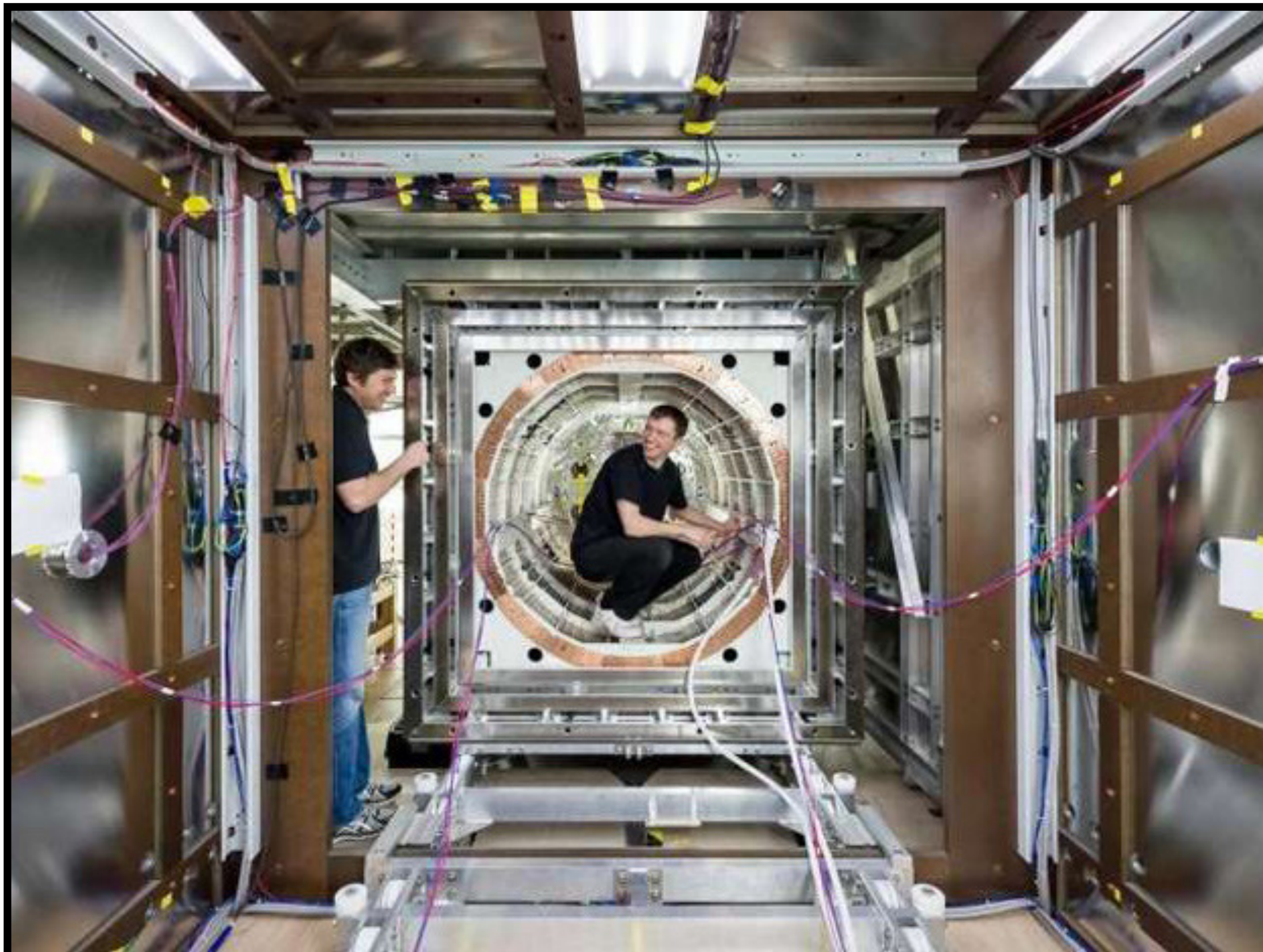
LHe dewar
refill every 8 hrs

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

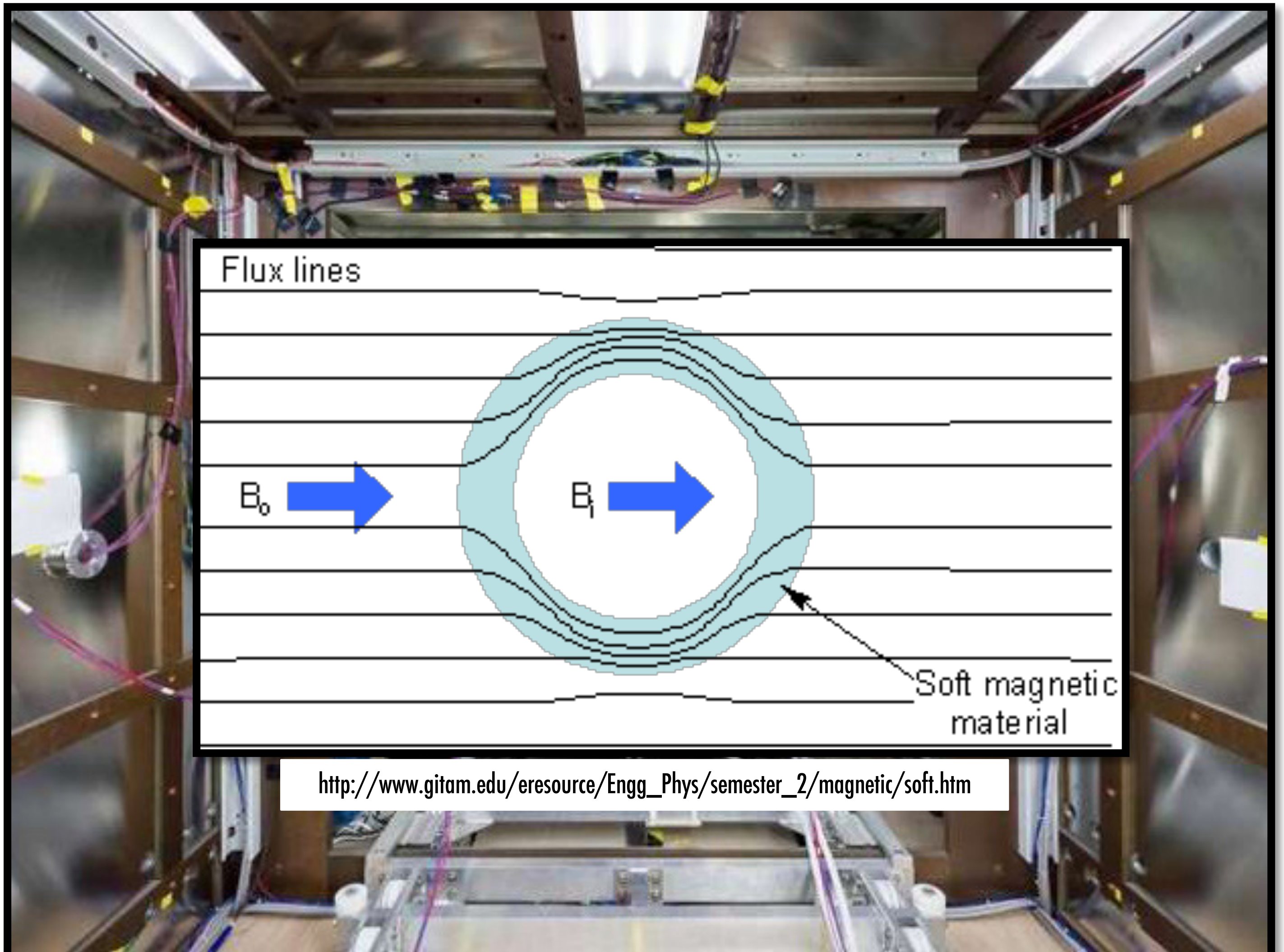
SQUID Detection? Magic Room!



<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% polariation

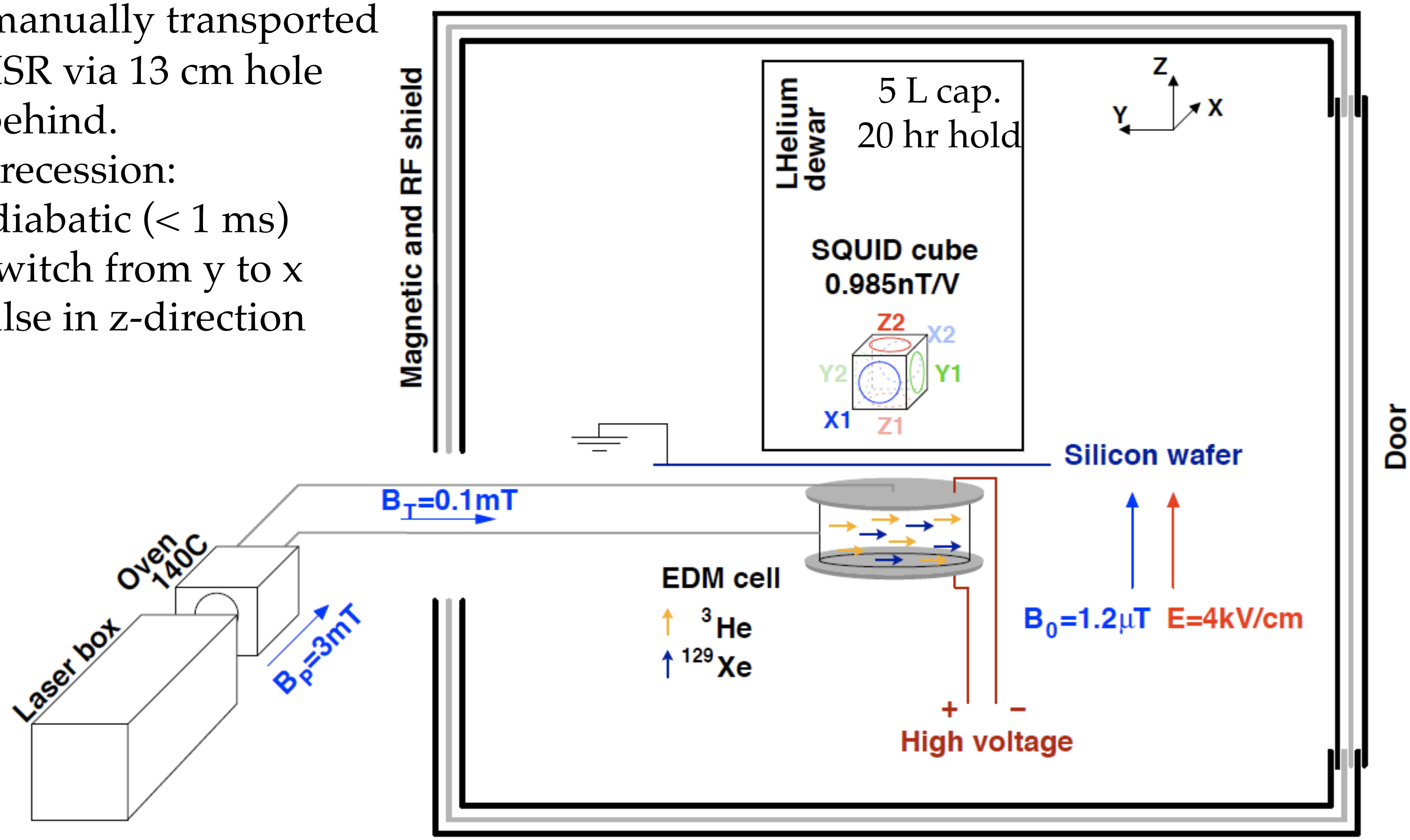
Cells by:
S. Degenkolb (Michigan)
P. Pistel & E. Babcock (JCNS)

Experimental Procedure

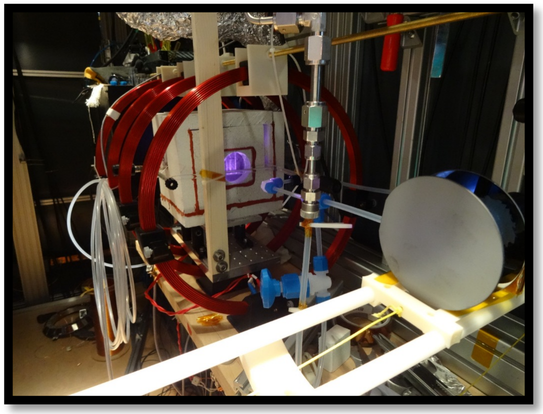
1. Cells polarized outside MSR.
2. MSR degaussed.
3. Cells manually transported into MSR via 13 cm hole from behind.
4. Spin precession:

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

From: Florian Kuchler thesis

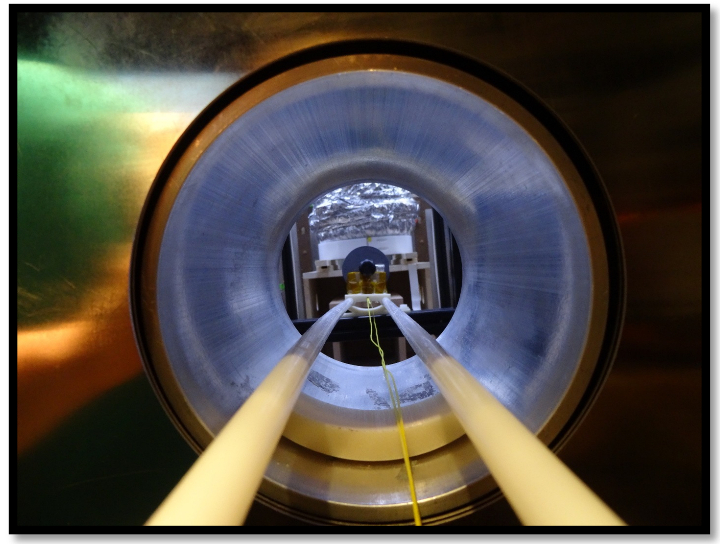


Experimental Layout

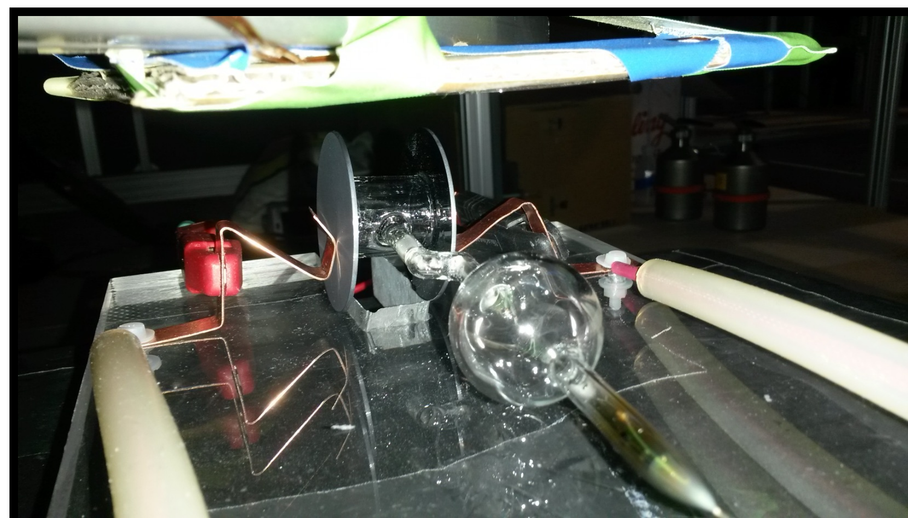


Noble gas polarizer
3 mT
100 W diode laser

Non-human
Transport!



EDM cell underneath SQUID
distance to sensor = 10 cm

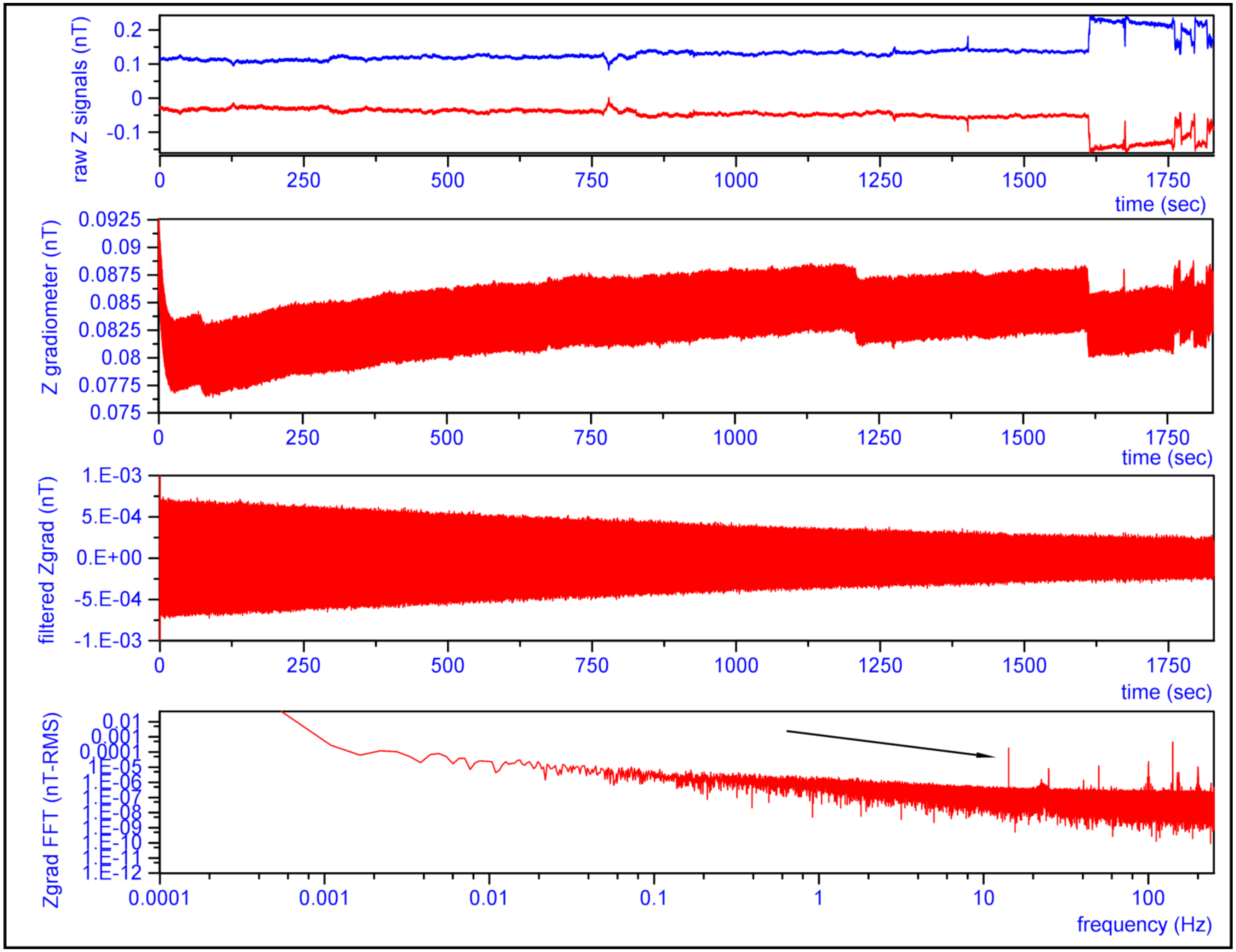


Raw data

nT

pT

pT



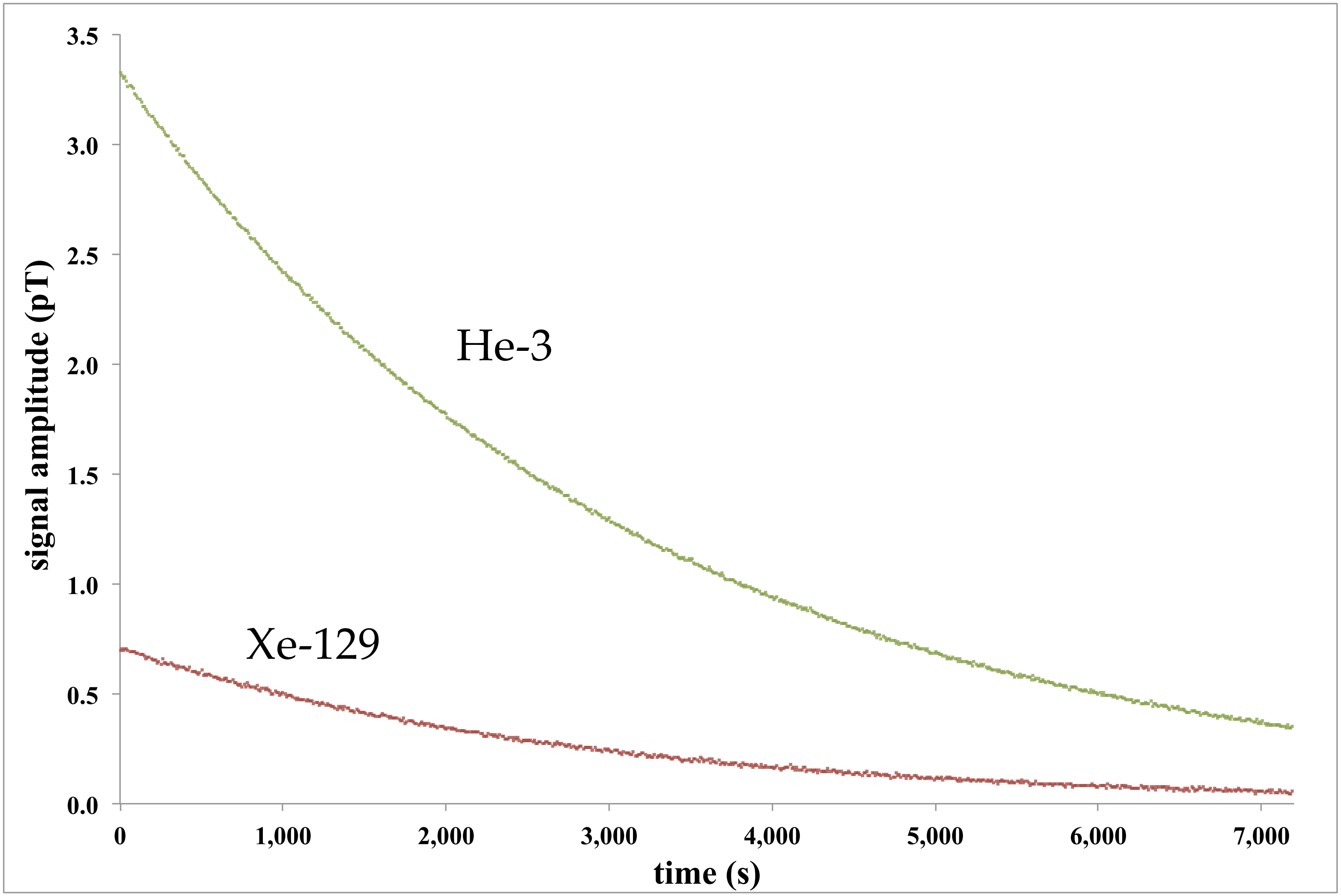
two channels, A,B

|A|-|B|, gradiometer

filtered

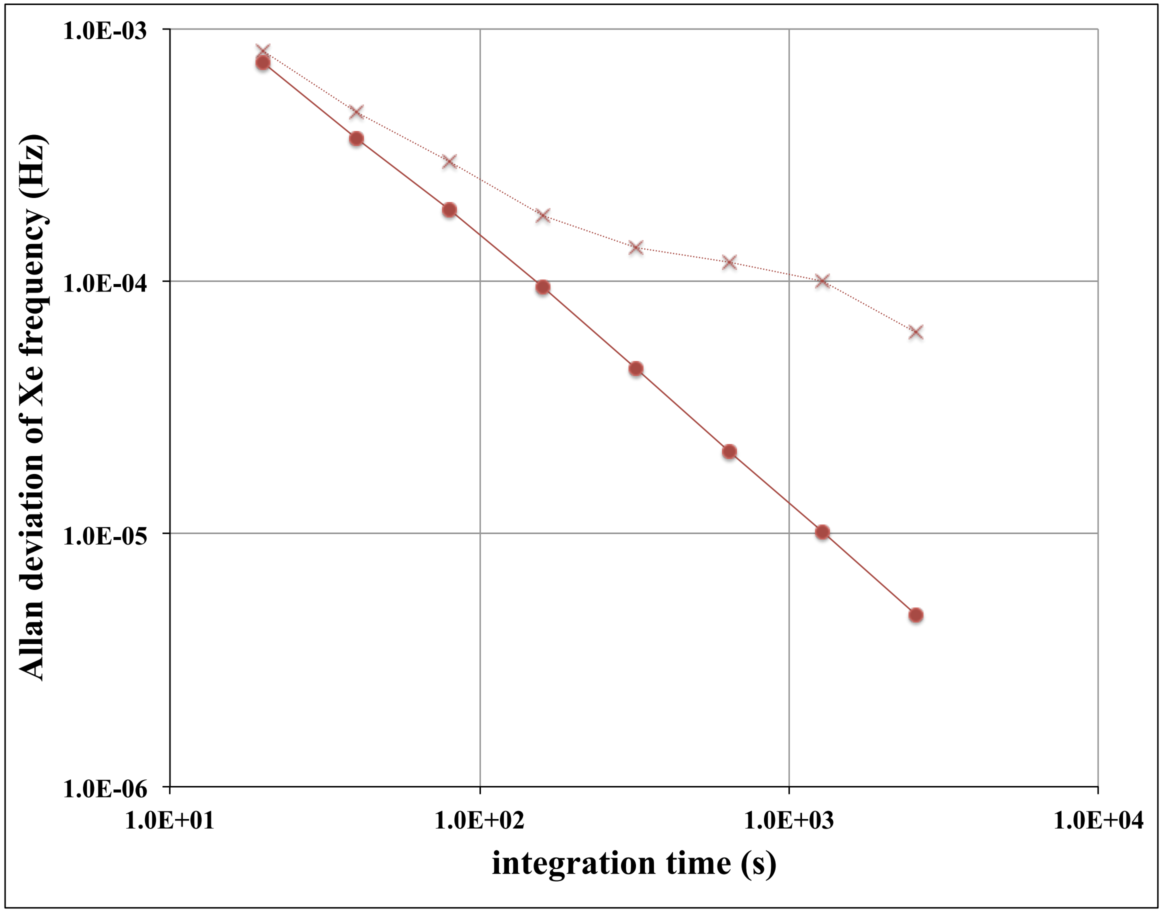
FFT

>1000 sec Spin Precession Times



Analysis by I. Fan (PTB)

He-3 Co-Magnetometer is helpful!



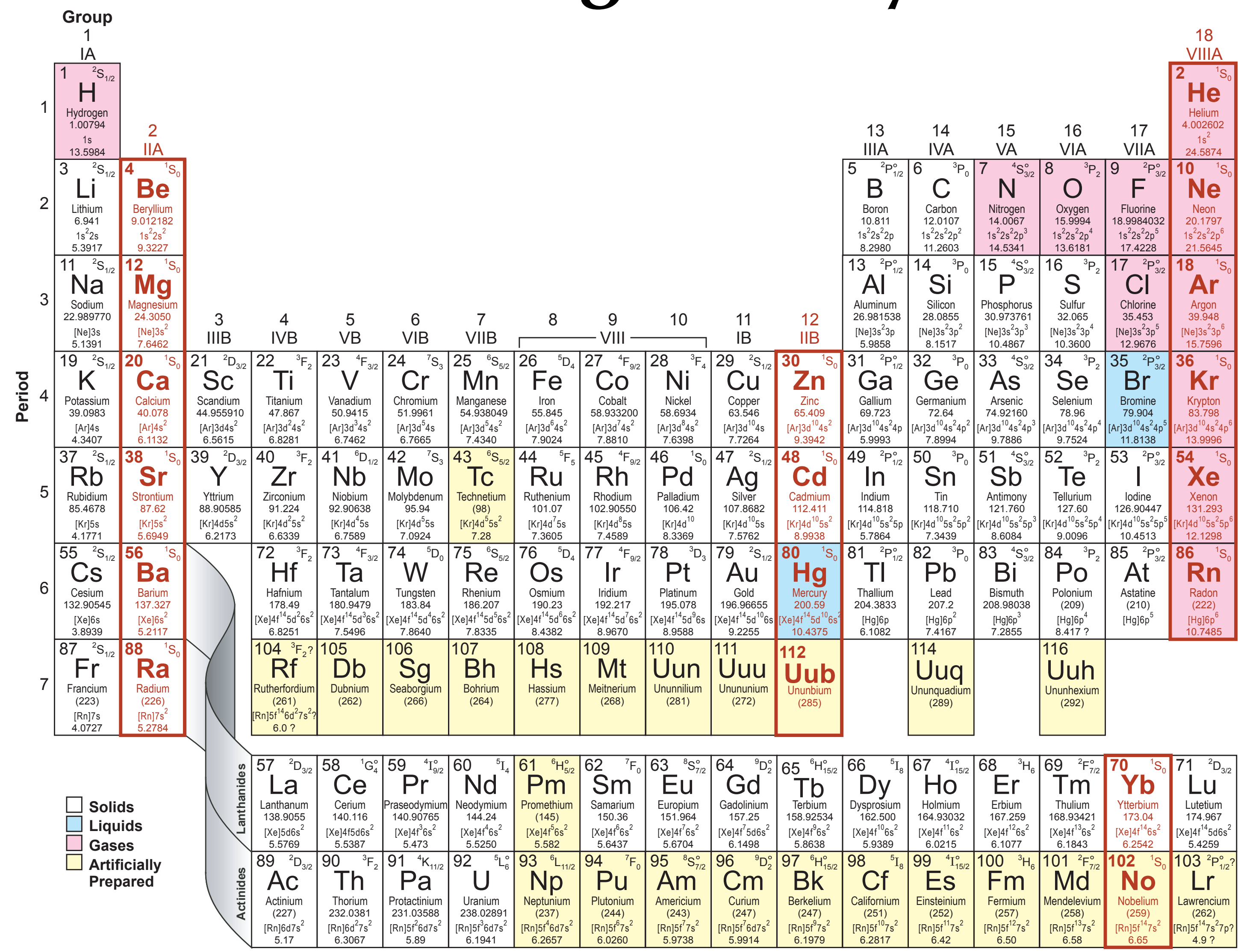
Need to reduce sensor-cell distance
Need to provide a stable time base to ADC card

Analysis by I. Fan (PTB)

"Magic Box" @ MSU/NSCL/FRIB

Photo by G.L. Kohuth.

Other Diamagnetic Systems?



NIST website

Schiff Shielding in Diamagnetic Atoms

- Shielding in Diamagnetic Atoms

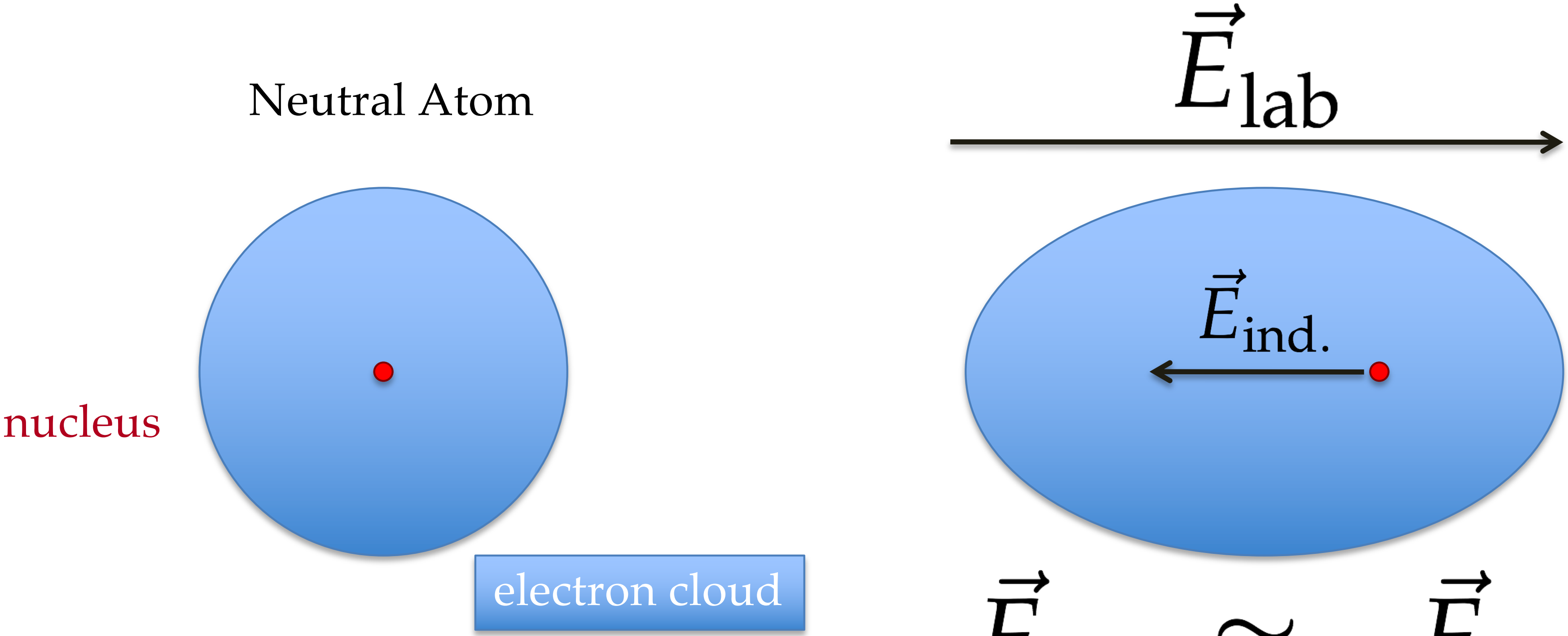
  Schiff PR 132, 2194 (1963)

- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3)

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

Schiff Moment

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



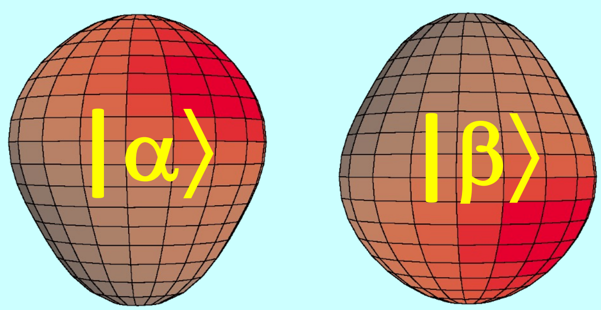
$$\vec{E}_{\mathrm{ind.}} \approx -\vec{E}_{\mathrm{lab}}$$

Enhanced Sensitivity in Ra-225

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

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

Parity Doublet



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

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!

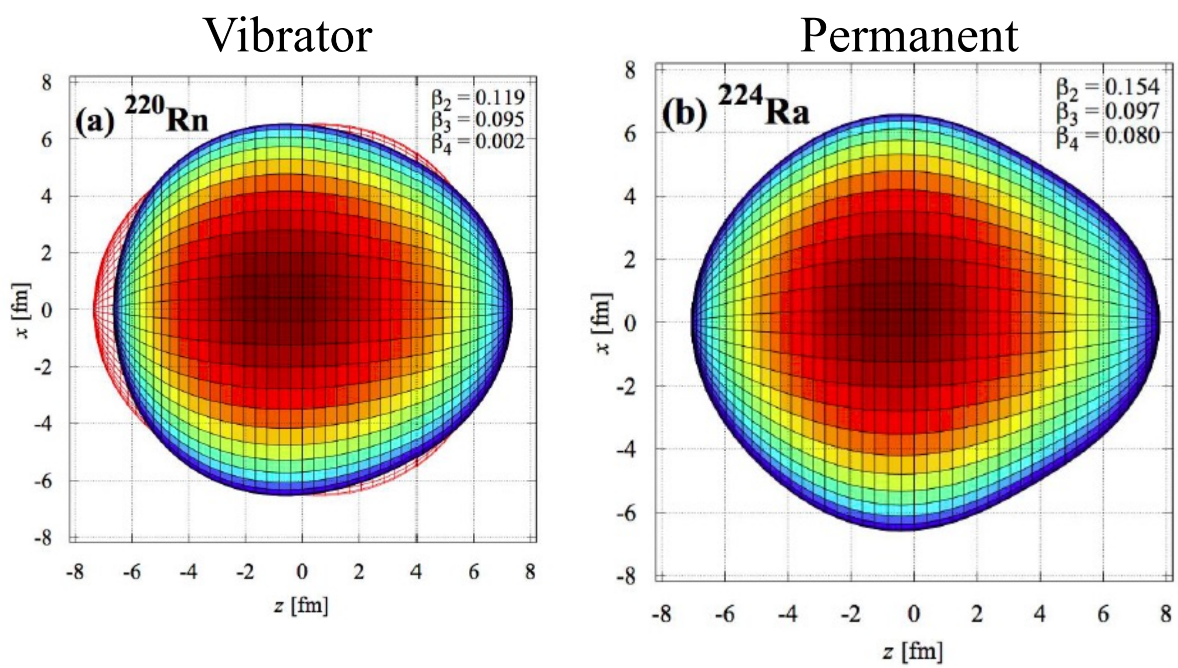
type	Hg-199	Ra-225	ratio*3	Hg-199 Ref
SIII	0.005	7.0	4300	PRC 82 015501 (2010)
SkM*	-0.027	21.5	-2400	PRC 82 015501 (2010)
SLy4	-0.006	16.9	-8600	PRC 82 015501 (2010)
SkO′		6.0		
DE05	0.071			PRC 72 045503 (2005)
DS03	0.055			PAN 66 1940 (2003)
"Best"	+/-(0.02)	6.0	+/-(900)?	Prog. PNP 71 21 (2013)

- 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

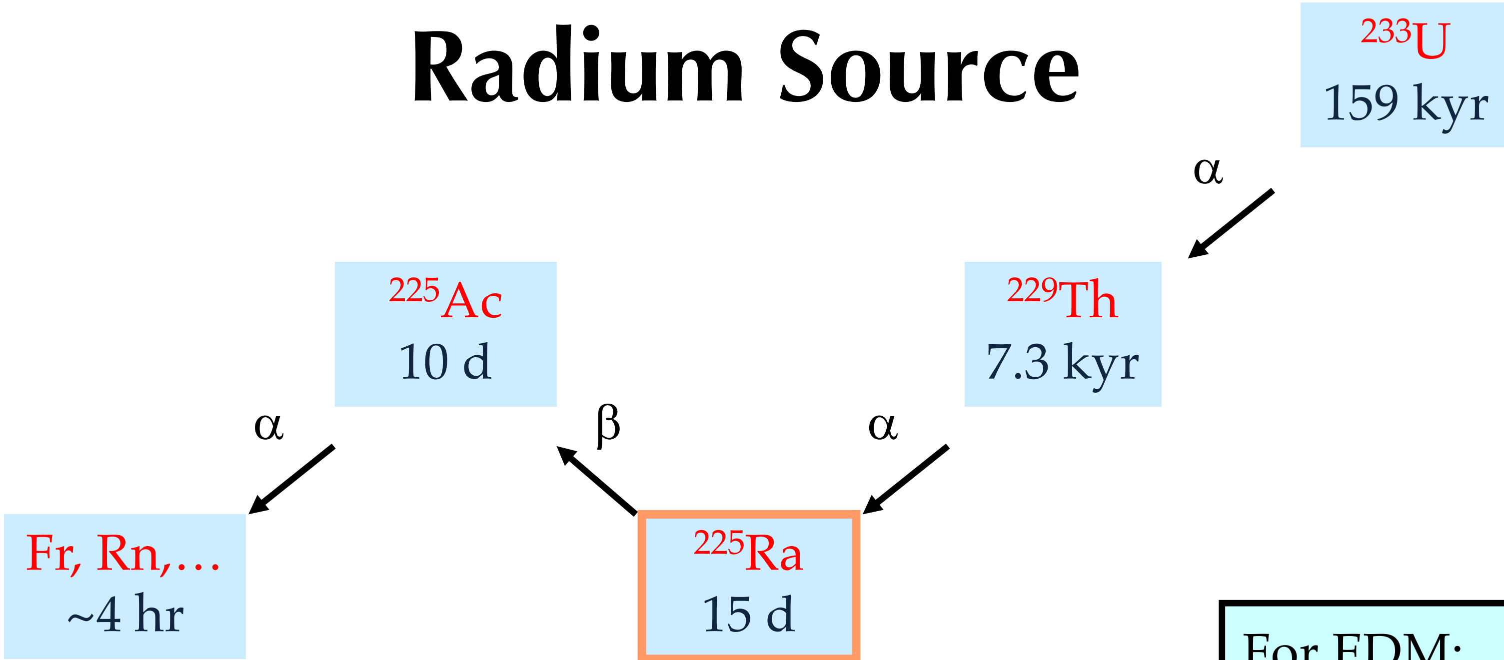
Other "Deformed" Searches

- 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)



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 ~ 10^8/s

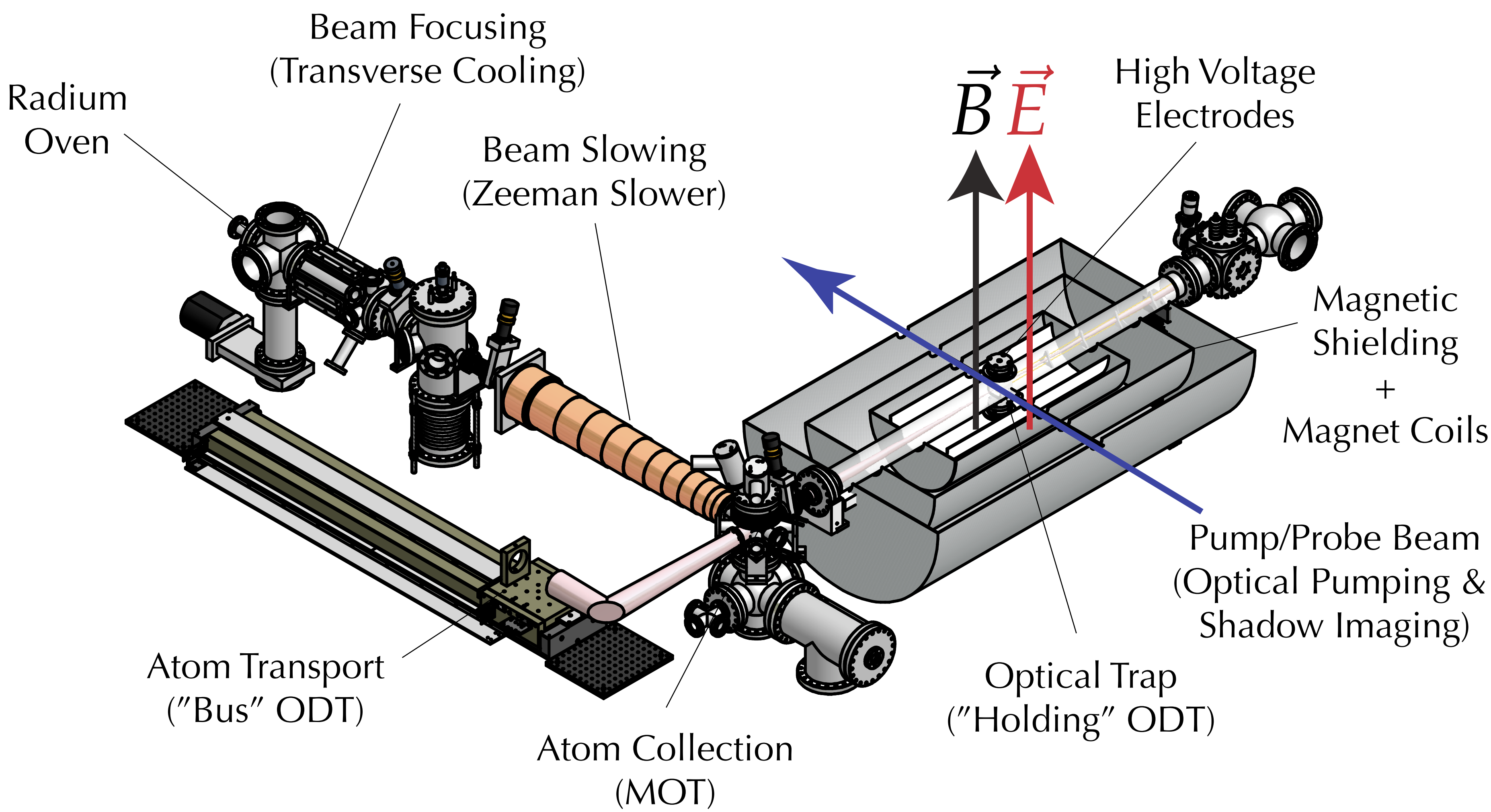
FRIB

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

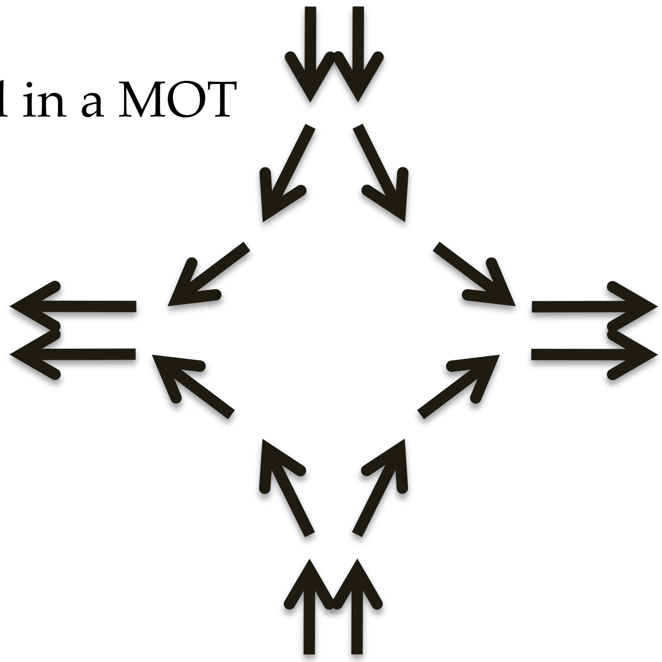
Experimental Layout



Neutral Atom Traps

Magneto-Optical Trap (MOT)

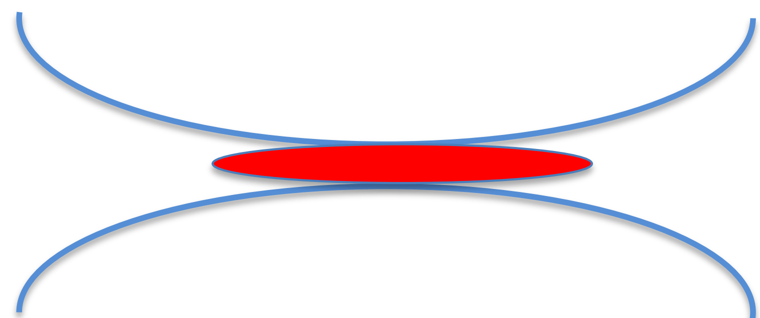
B Field in a MOT



- 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)

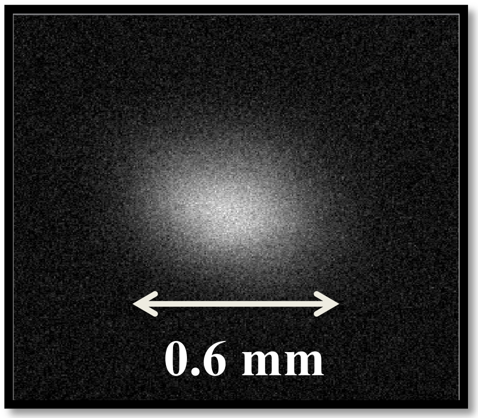
$$\mathcal{H} = -\vec{d}_{\text{ind}} \cdot \vec{E}_0 = \frac{\alpha}{4} E_0^2$$



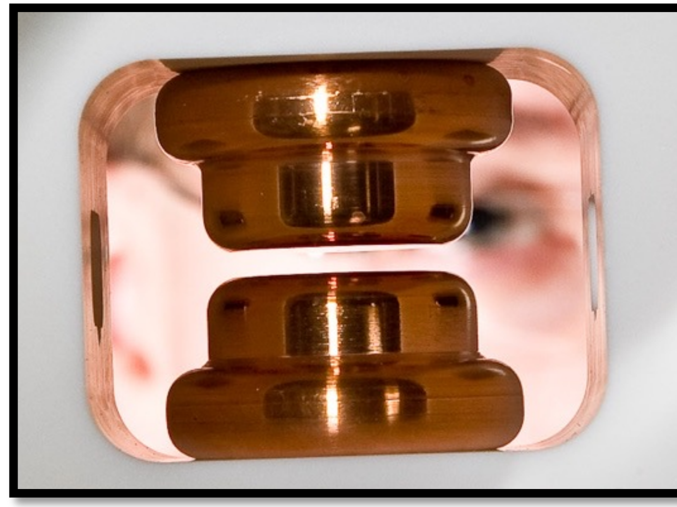
- Atoms trapped at beam focus
- 50 W @ 1550 nm
- 100 mm spot = Trap Depth of 400 μK
- Good for transporting atoms
- Good for spatially confining atoms

Collecting & Transporting Ra-225 Atoms

Guest et al., PRL 98 093001 (2007)

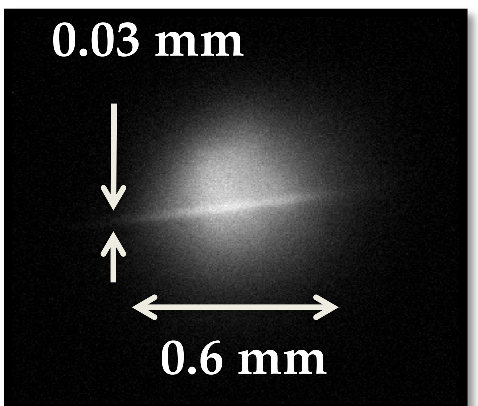


^{226}Ra MOT
20,000 atoms



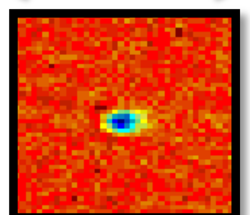
2 mm

Parker et al., PRC 86 065503 (2012)



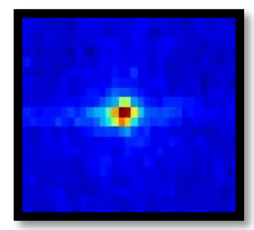
MOT + ODT
20,000 atoms

1.3 mm



1.3 mm

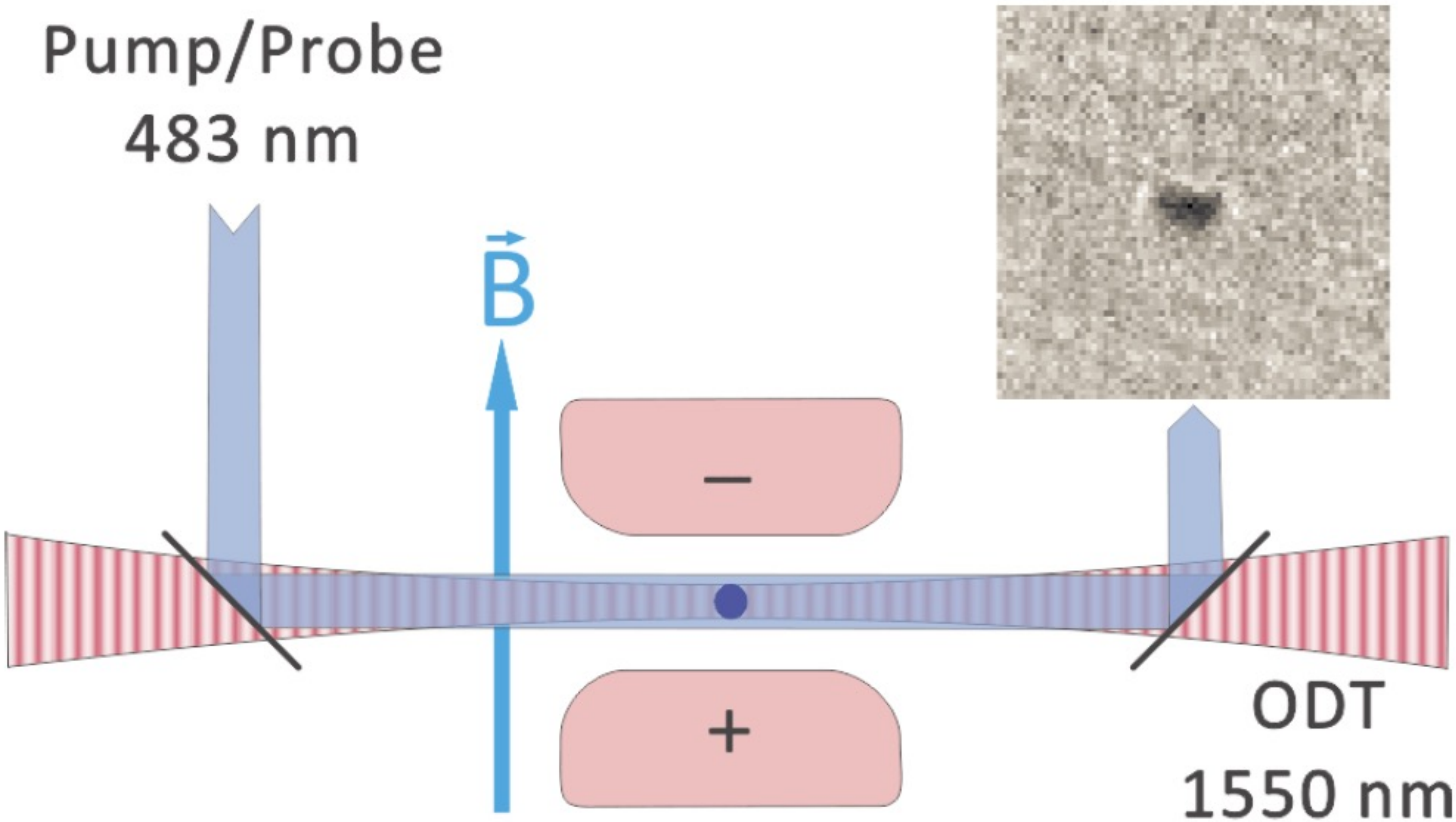
Absorption Imaging



3000 atoms

Fluoresence Imaging

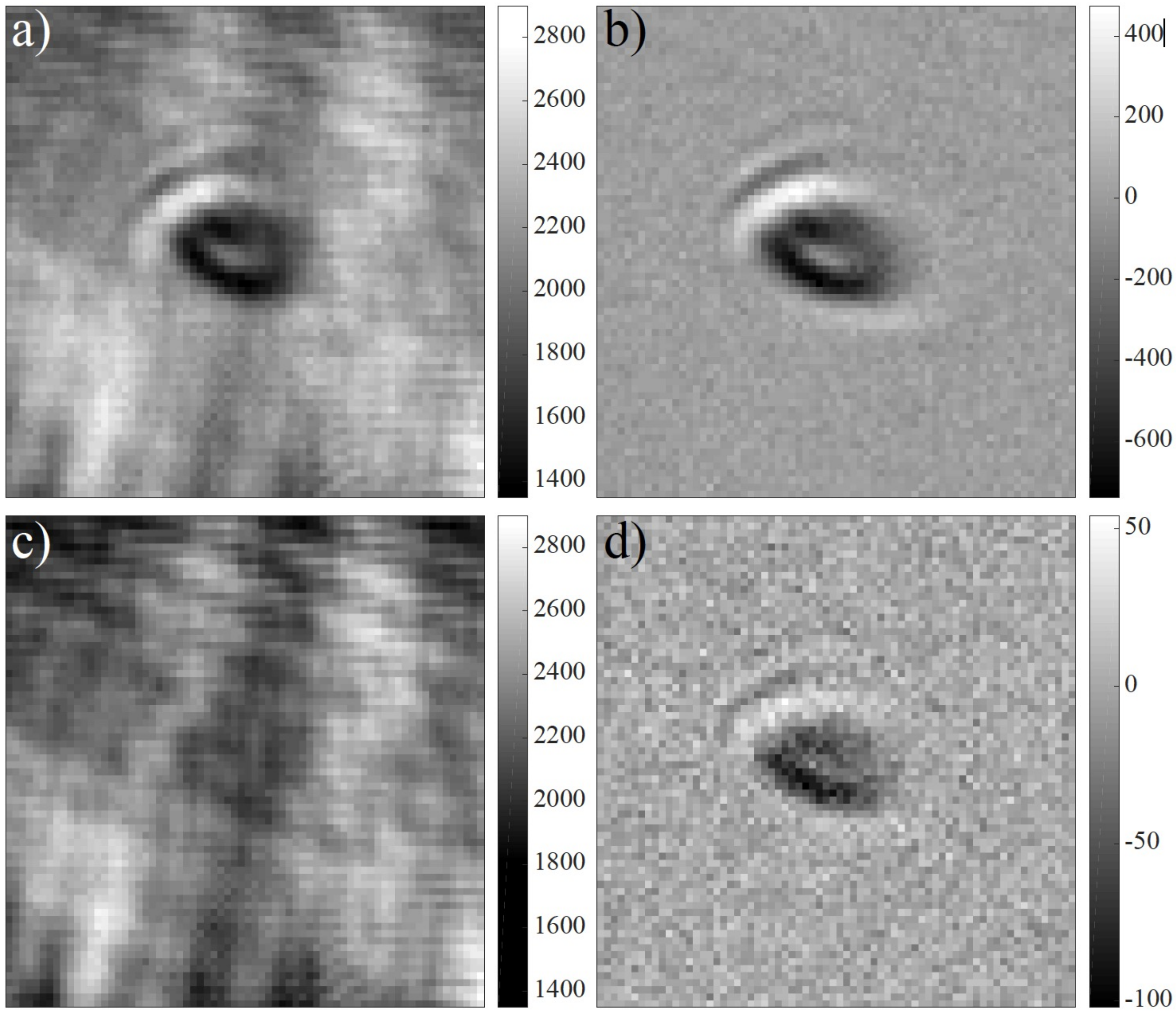
Atoms create a shadow by absorption



Shadow Image Analysis: Background & Distortion Corrections

raw image of Ra-226

Ra-226 only



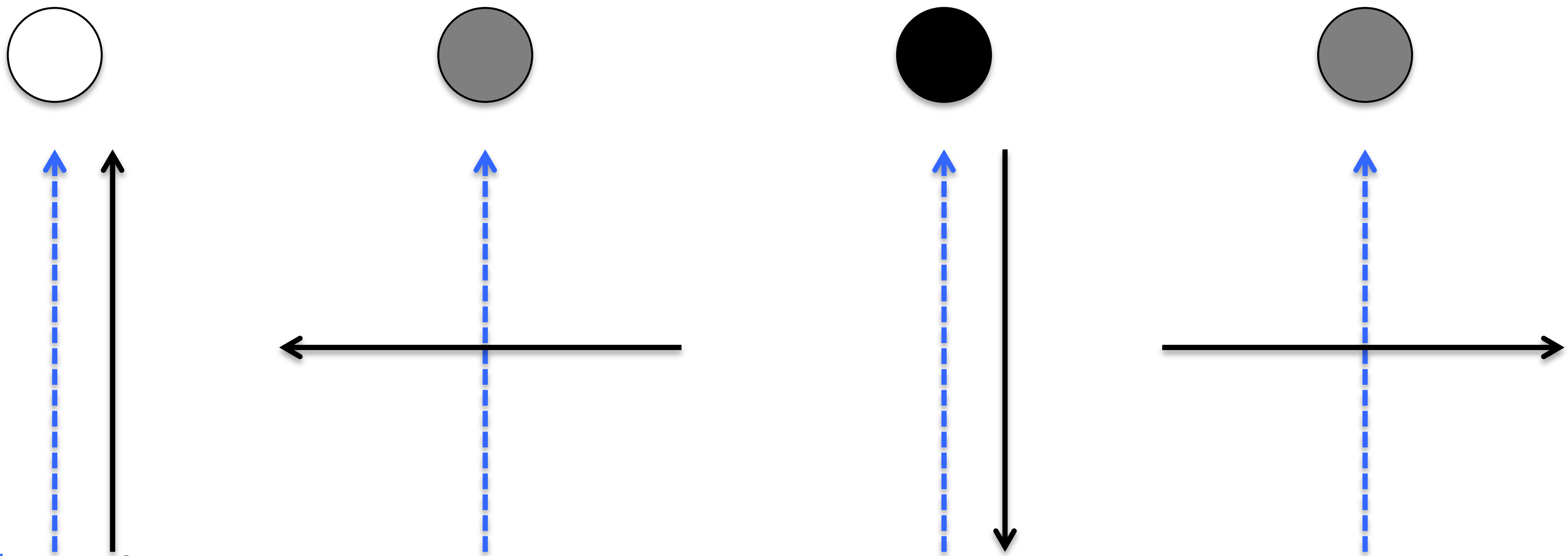
composite background

Ra-225 only

Absorption probability oscillates at ~20 Hz

probability of absorbing probe light and creating a shadow:

0% **50%** **100%** **50%**

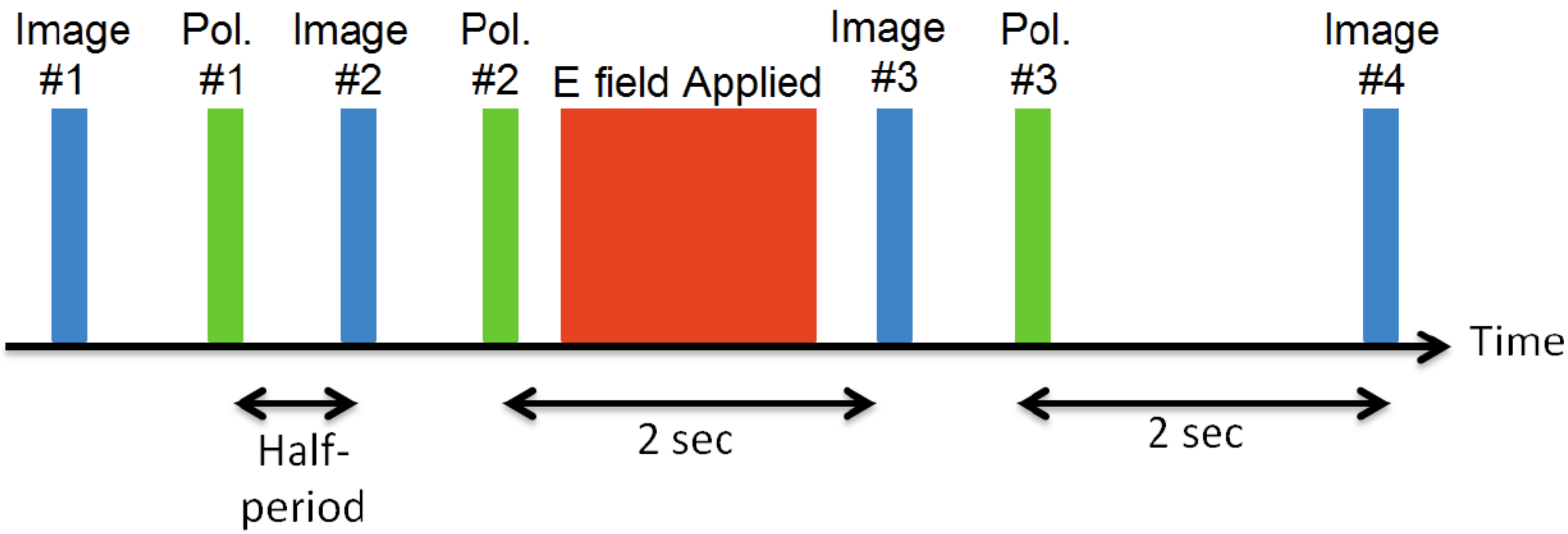


Probe light **Atom spin**

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

increasing time

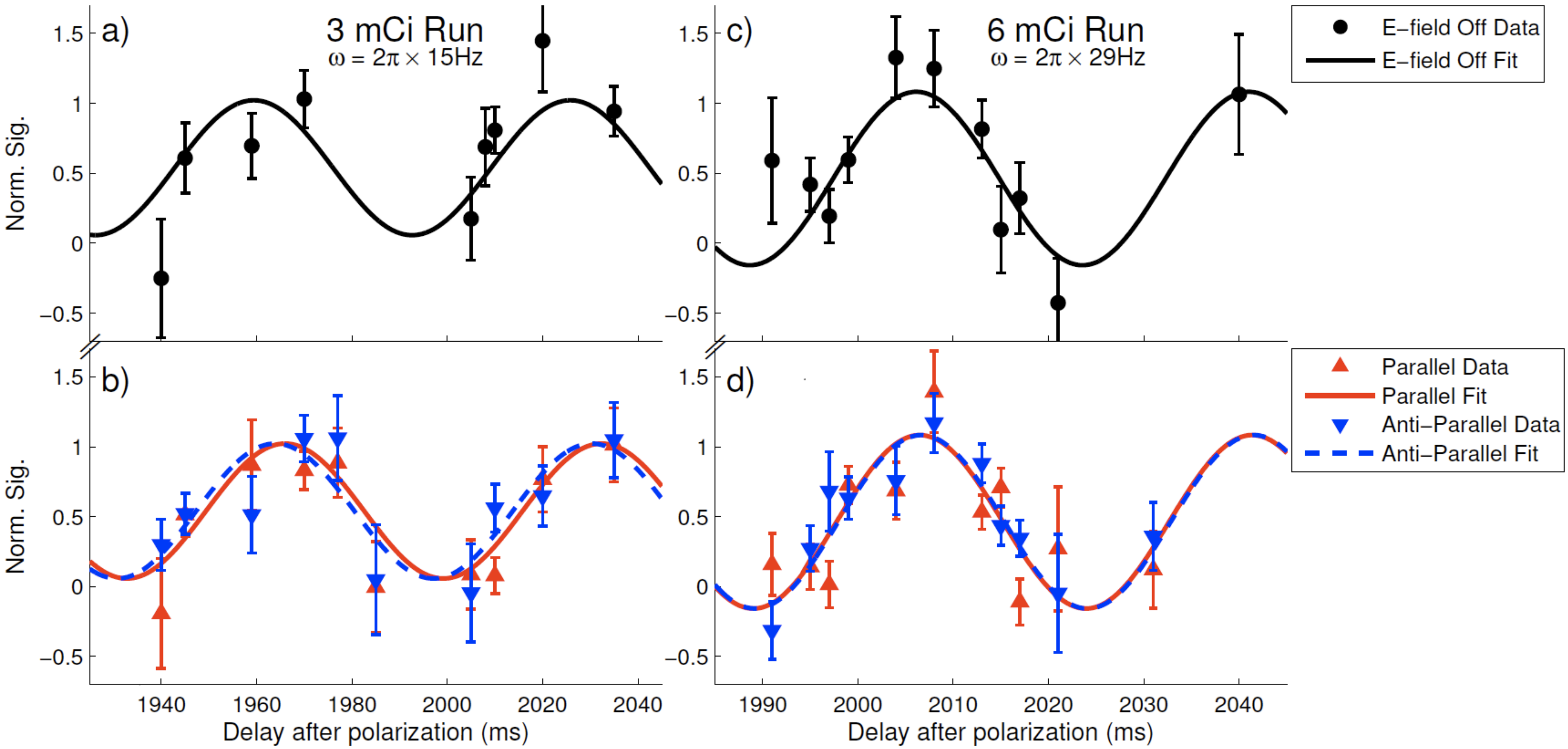
Several images are taken



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



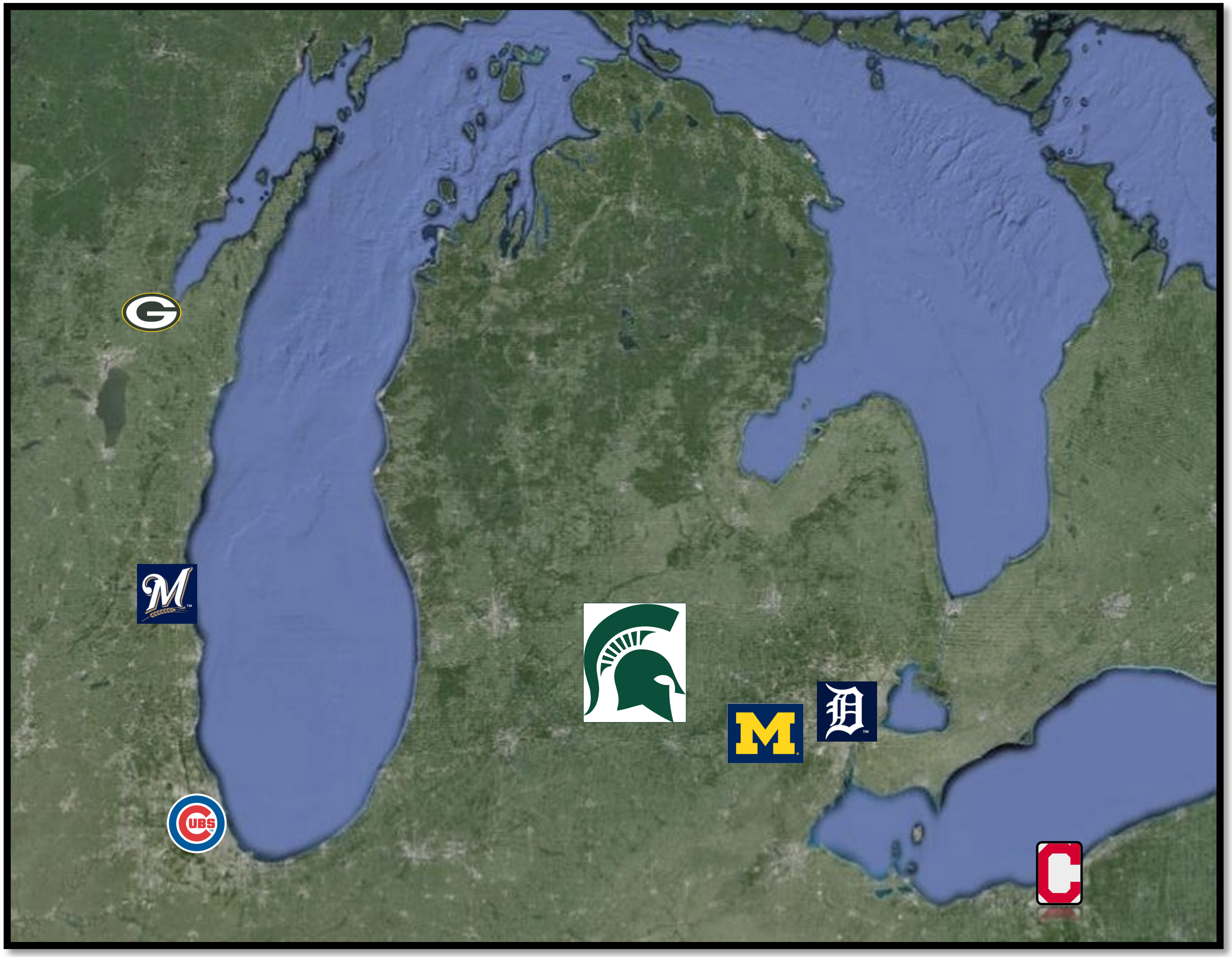
First Result & Systematics

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
vxE	<0.001	<0.001
laser trap	<0.001	<0.001

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

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

Michigan State University, East Lansing, MI

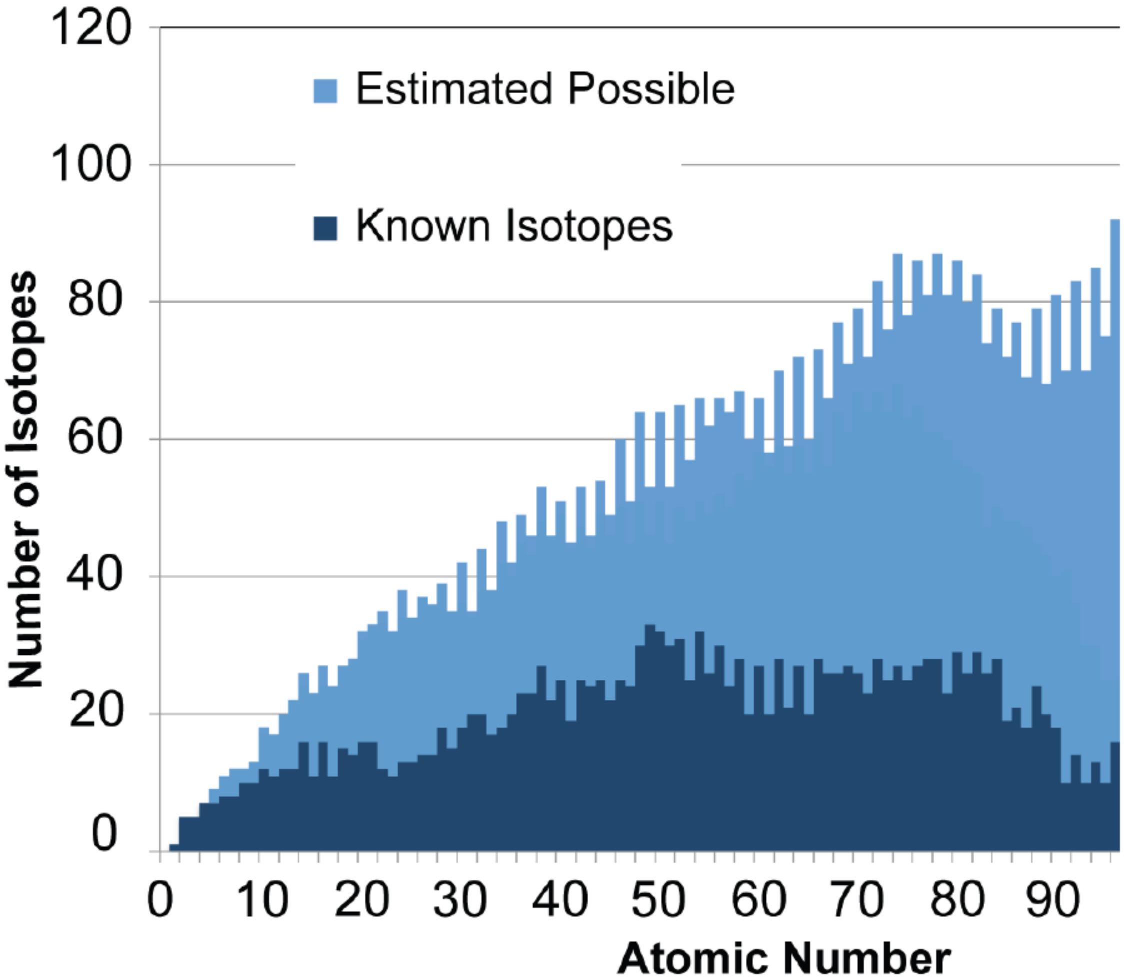


Google Maps & Wikipedia Commons

Facility for Rare Isotope Beams

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

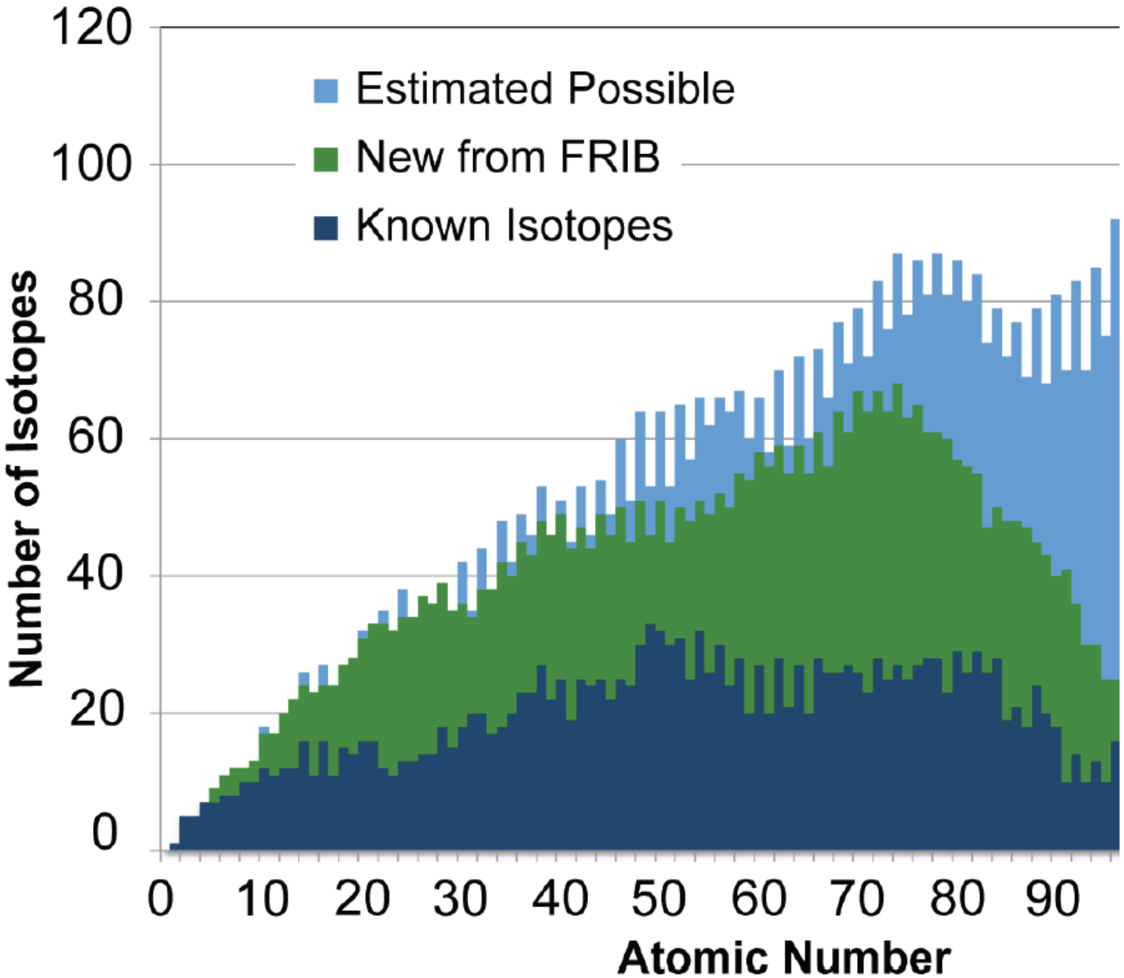
Facility for Rare Isotope Beams



- 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!



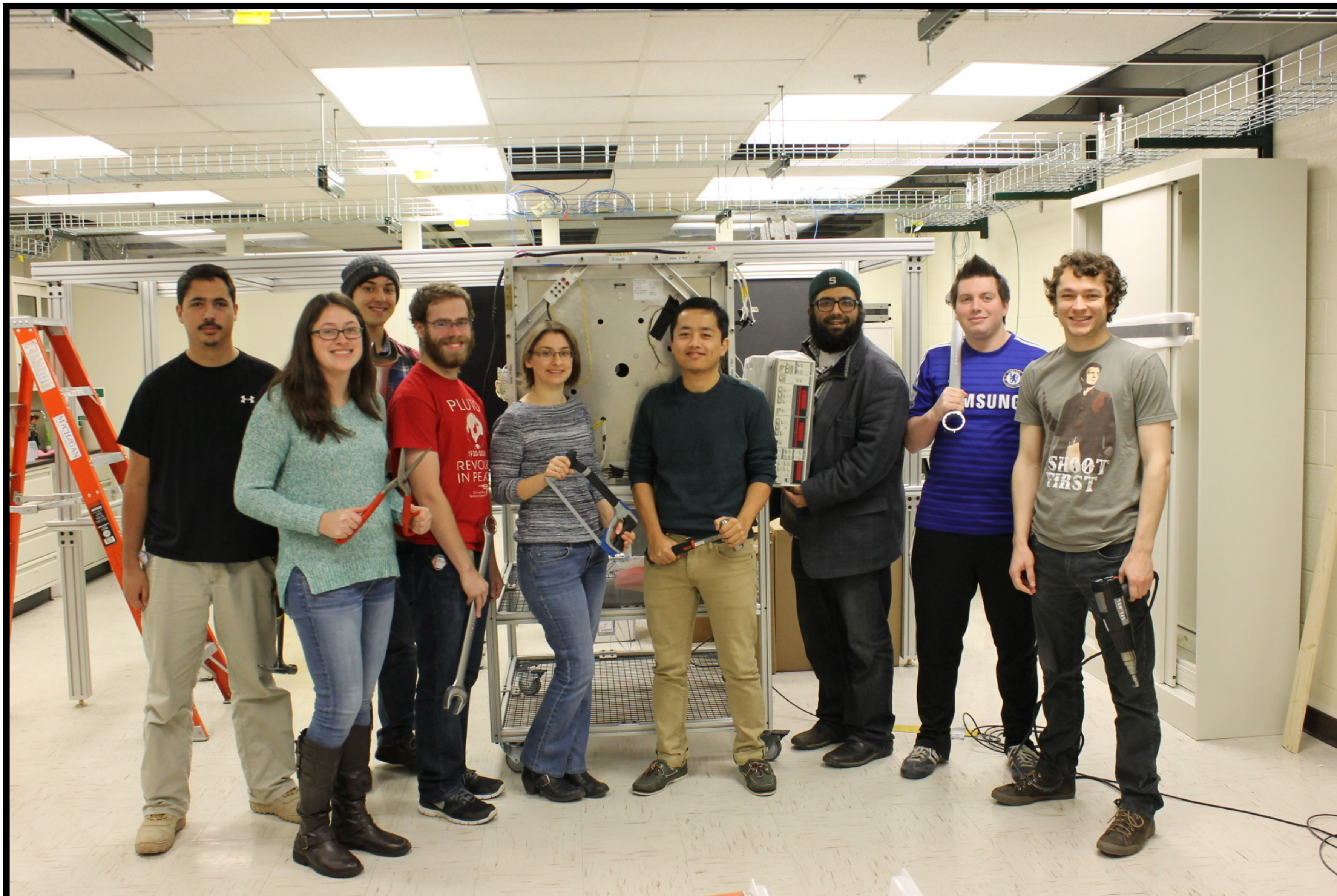
- Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models
- "Known" defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)
- For Z<90 FRIB is predicted to make > 80% of all possible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

B. Sherrill

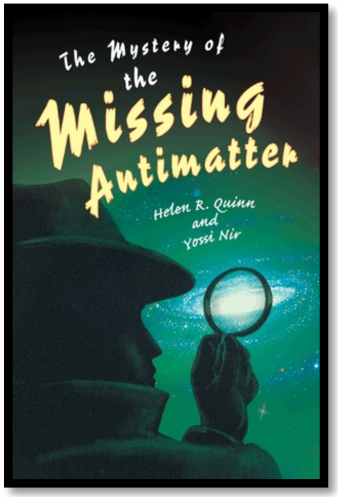
Ra EDM Team

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**

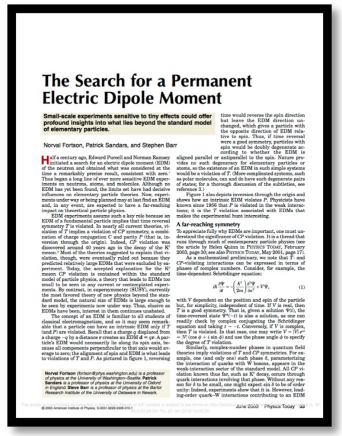
MSU Team: Thanks For Your Attention!



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

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

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

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