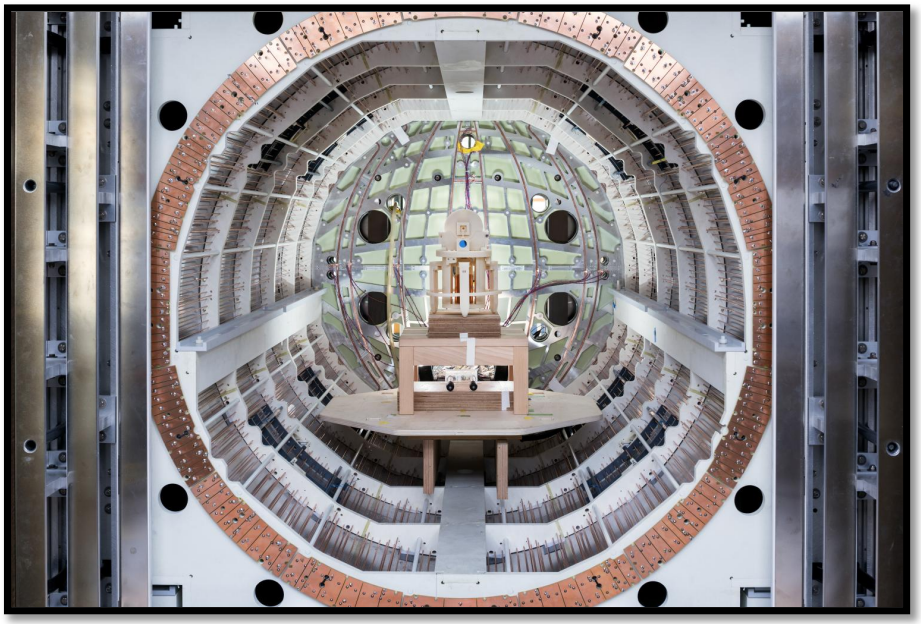
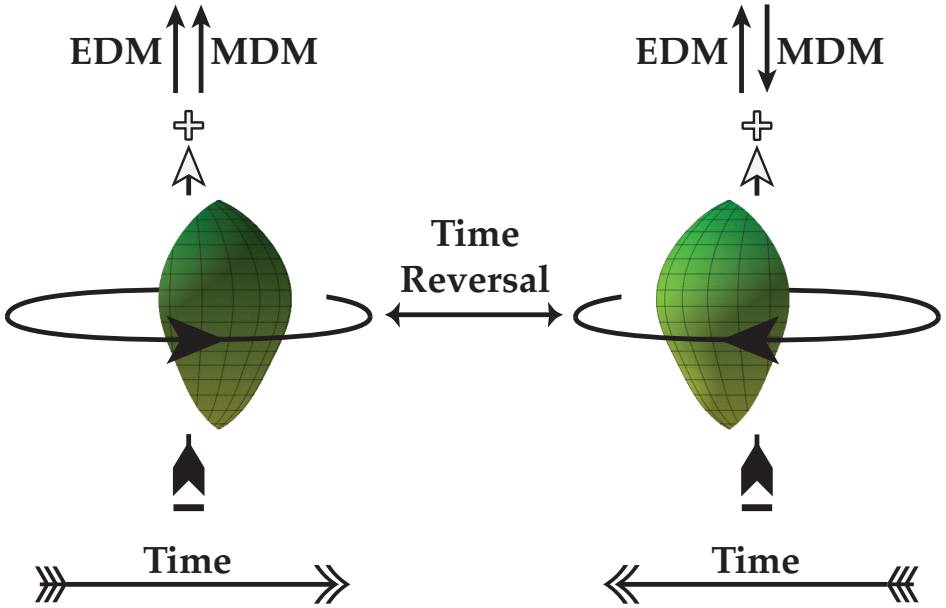
Testing Time-Reversal Symmetry Using Lasers, a Magic Room, and Pear-Shaped Nuclei

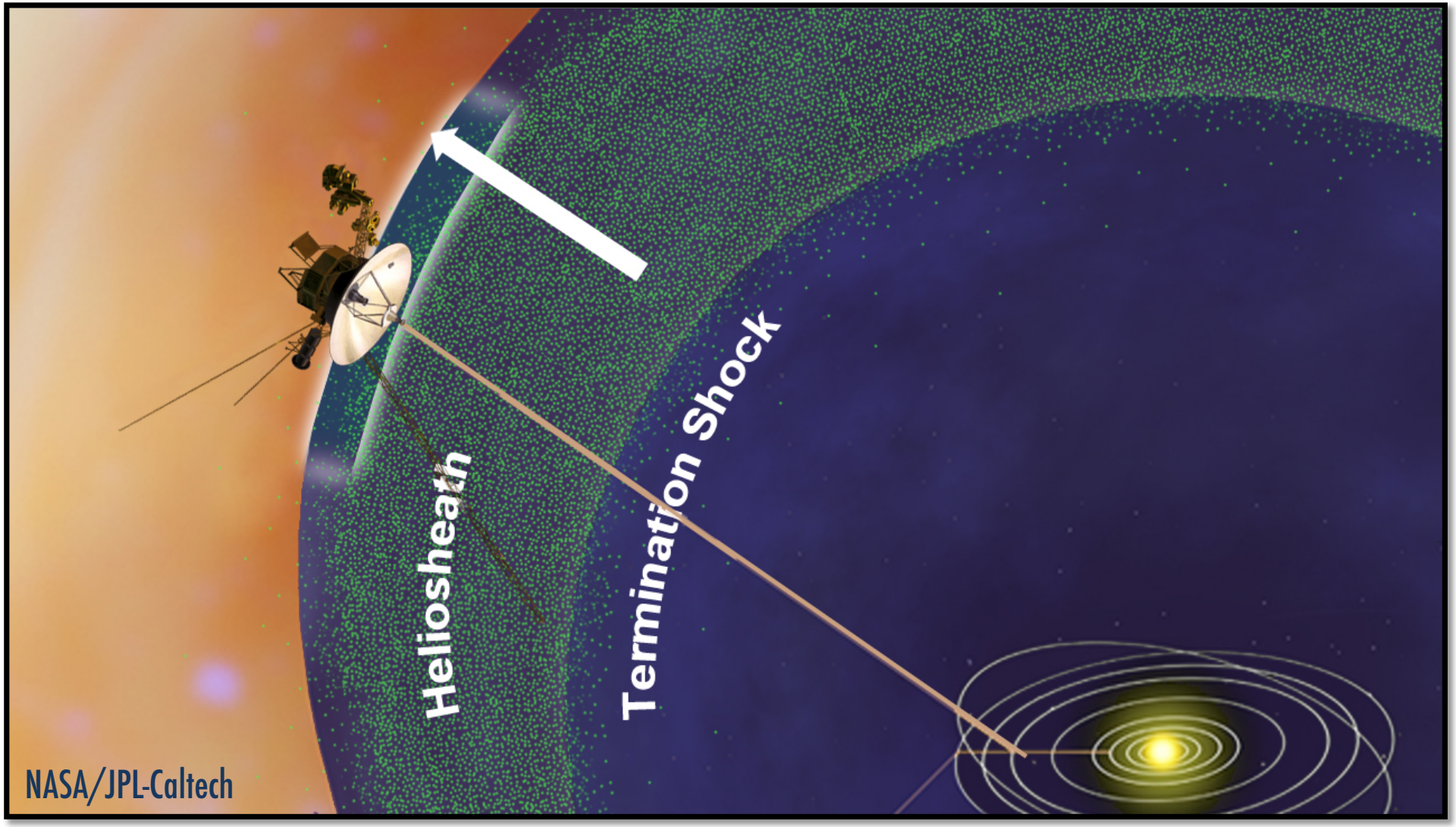




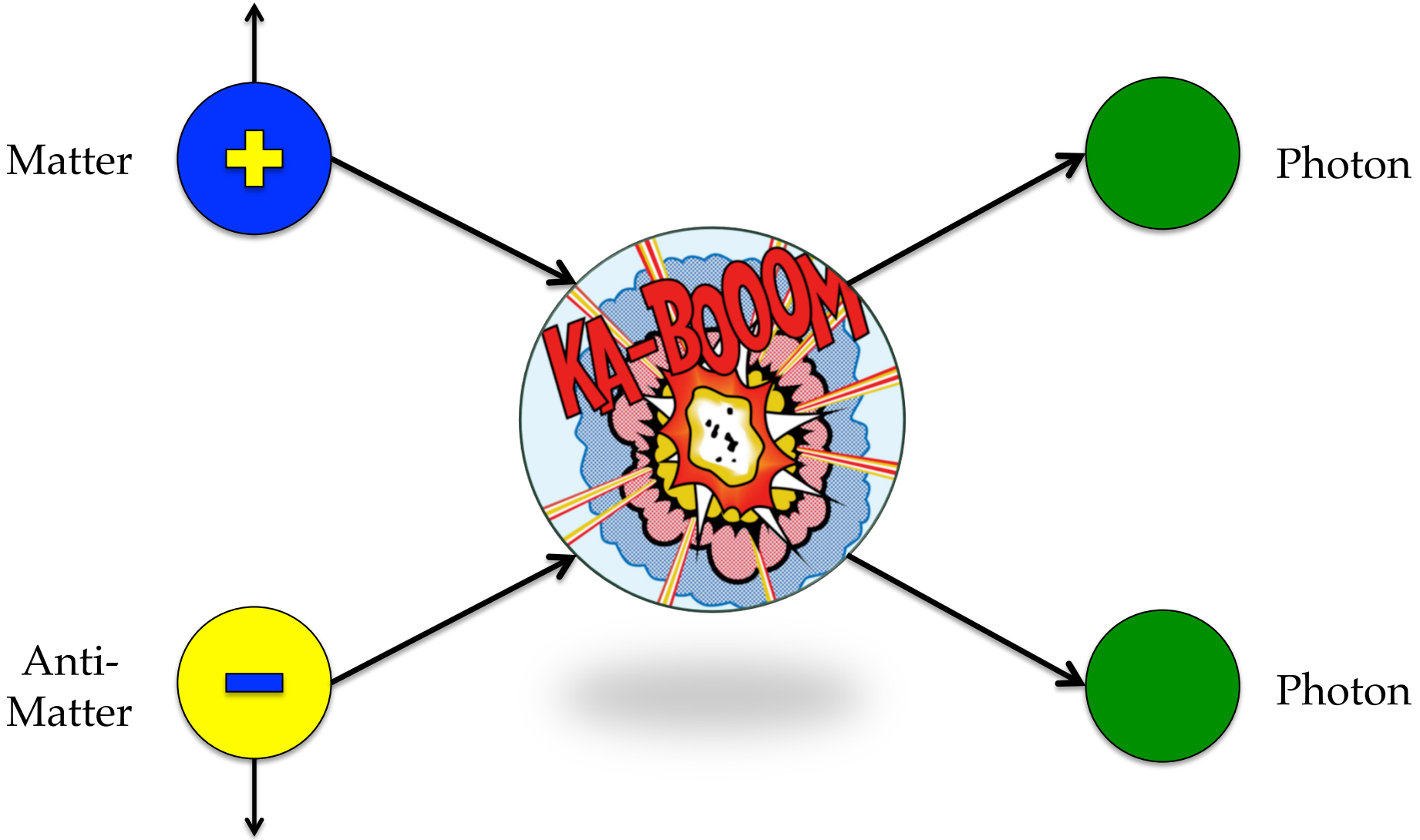
Jaideep Taggart Singh
National Superconducting Cyclotron Laboratory
Michigan State University
Bucknell University, Physics & Astronomy Seminar, 2017-02-23

NSCL

Voyager 1 is Still OK!

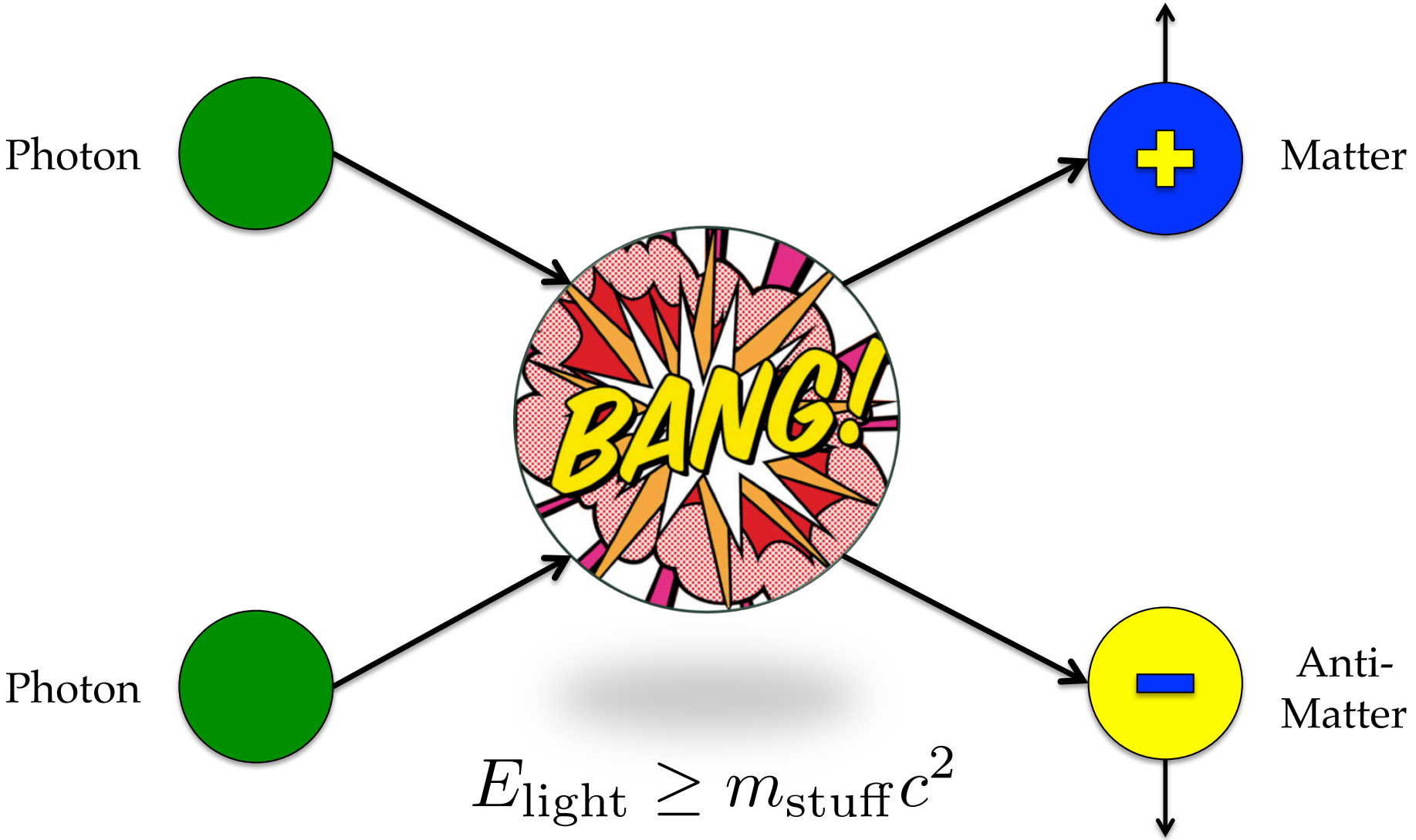


Stuff and Anti-Stuff disappears into Light.



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.

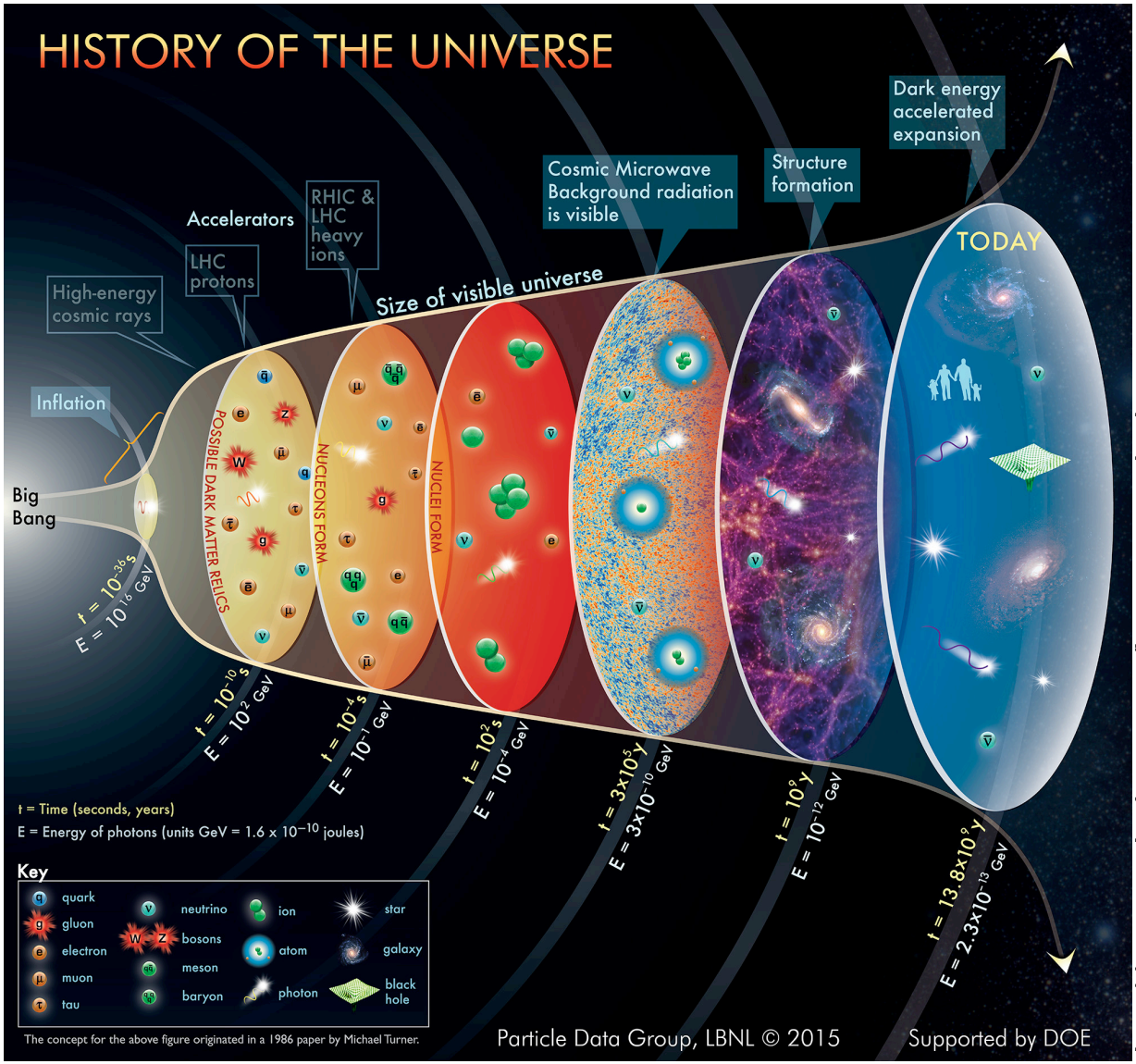


$$E_{\text{light}} \geq m_{\text{stuff}} c^2$$

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

Big Bang…expanding Universe

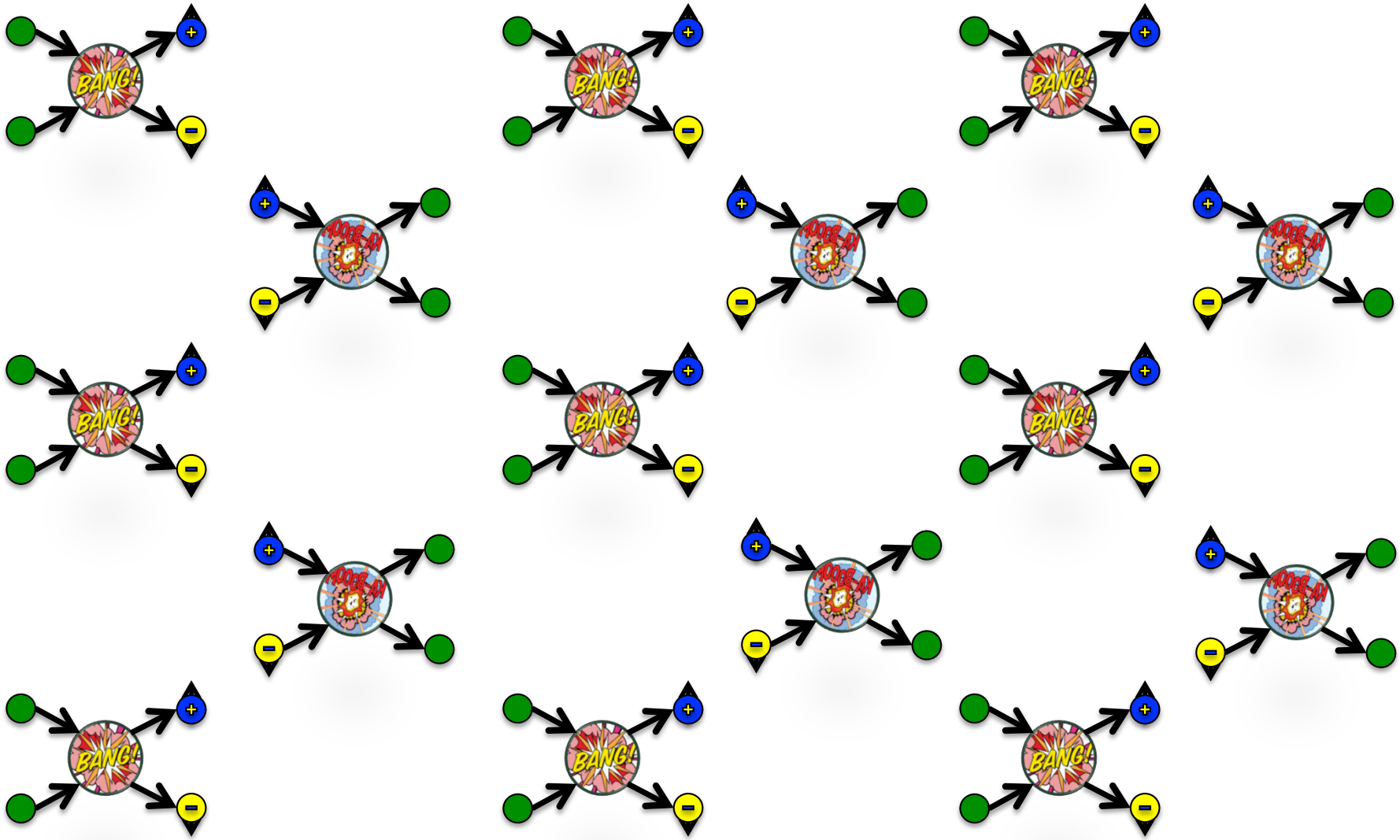
HOT & DENSE



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

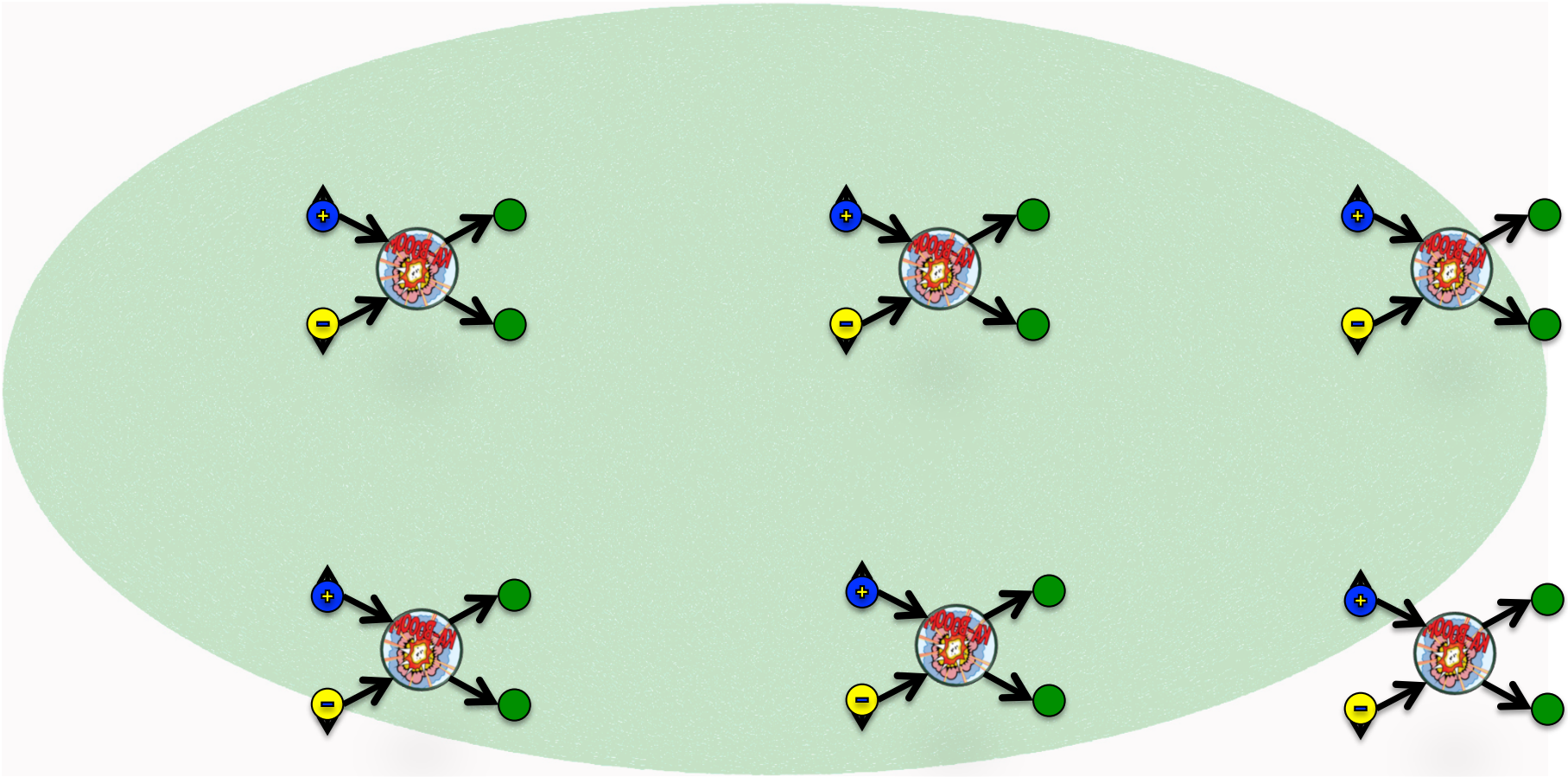
cold & dilute

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

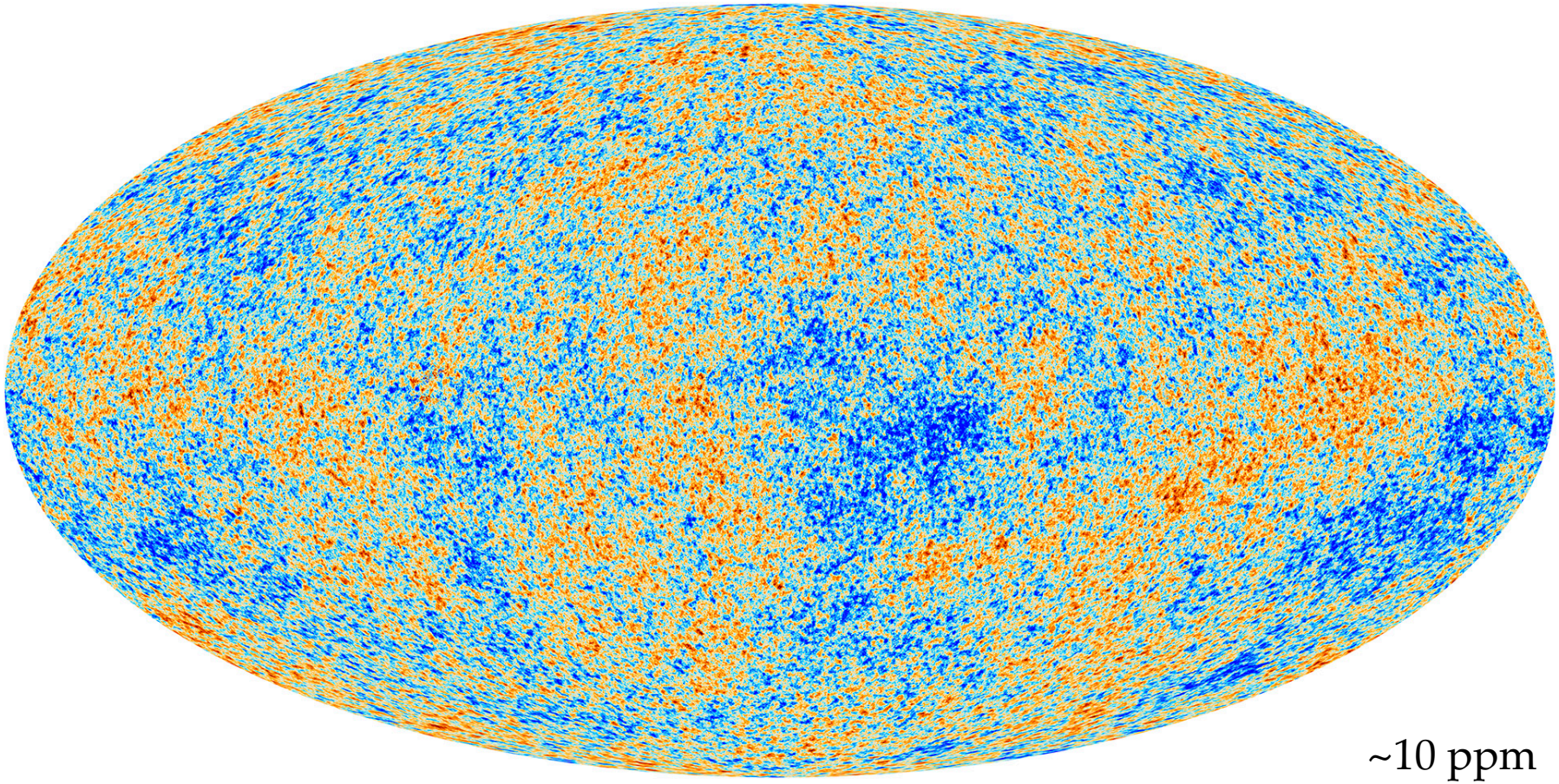
Expansion means cooling: 2.73 K everywhere



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



~10 ppm
fluctuations

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

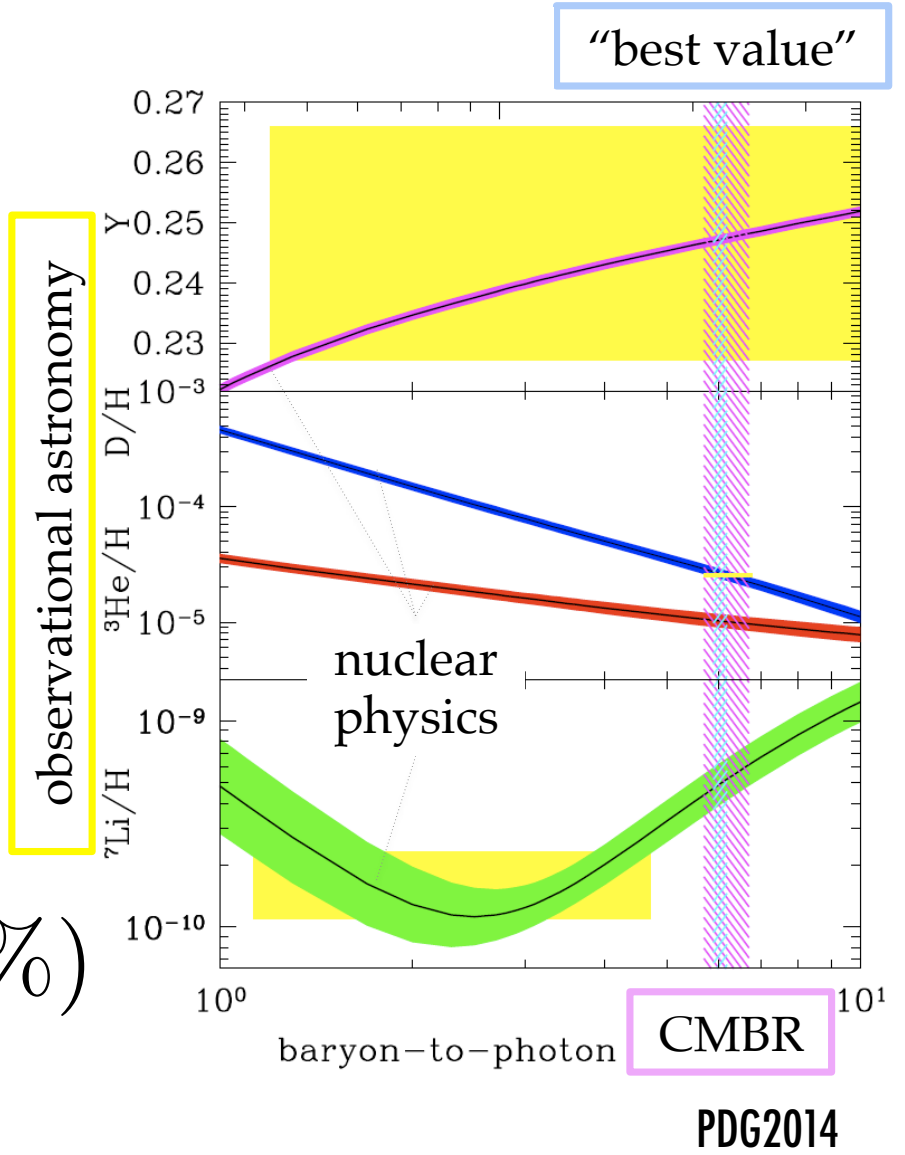
Baryon Asymmetry of Universe

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

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

$$= 0.00000000061(5\%)$$

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



PDG2014

Sakharov's Conditions

The Nobel Foundation

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

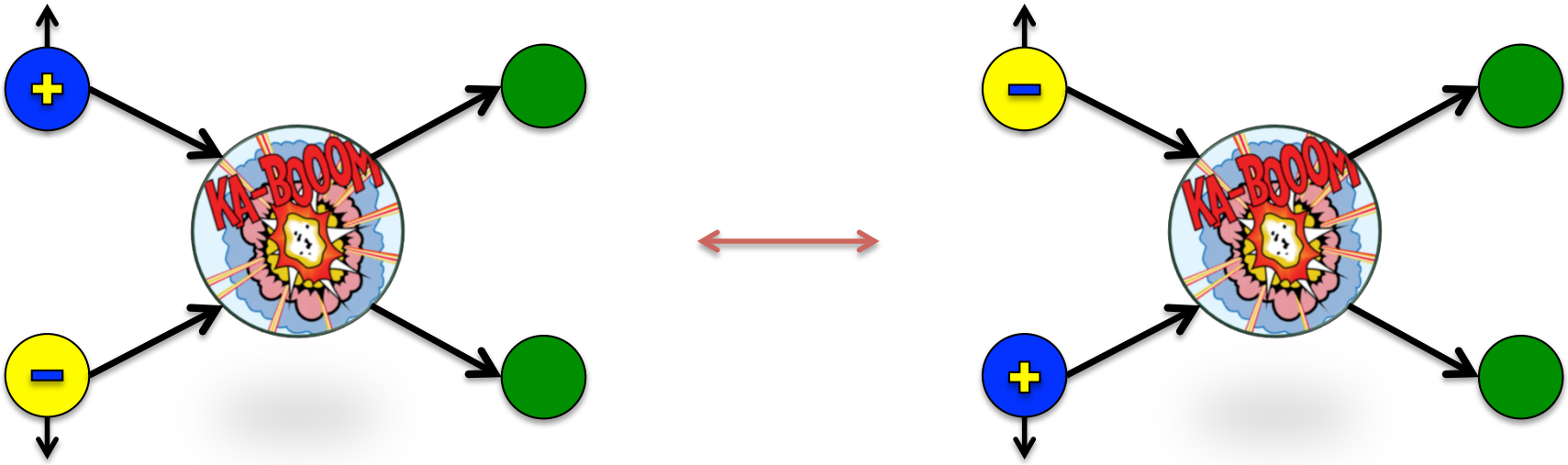
A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

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. Departure from thermal equilibrium
3. ***Both C- & CP-symmetry must be violated.***

C: Charge Conjugation

Replace particle with antiparticle



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

P: Parity (Spatial Inversion)

Mirror reflection

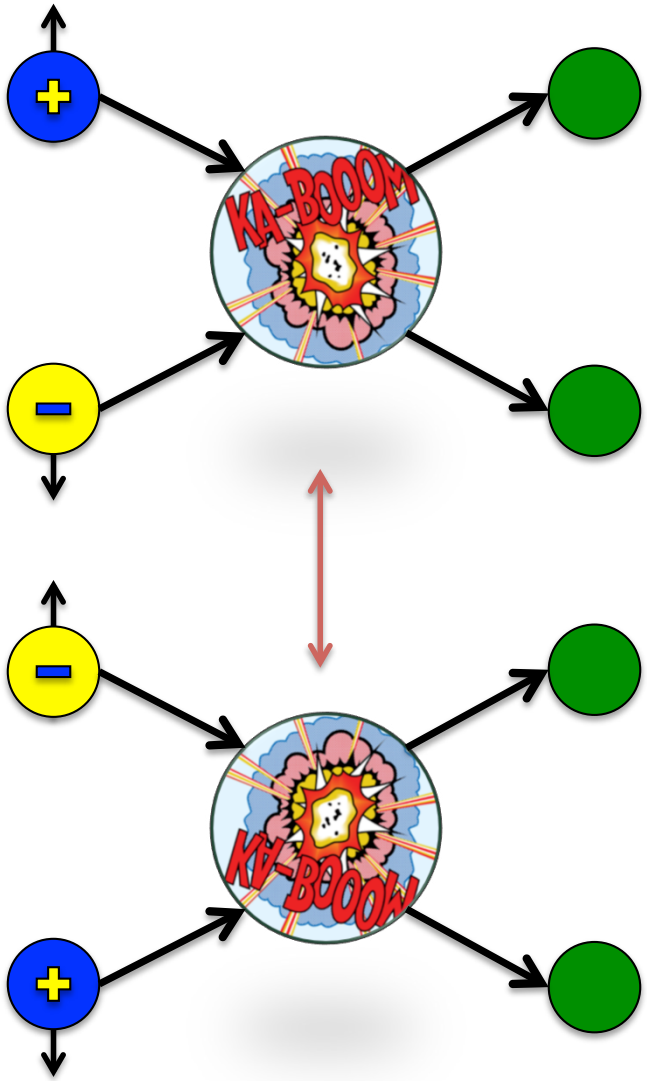
+

180° rotation

+x to –x

+y to –y

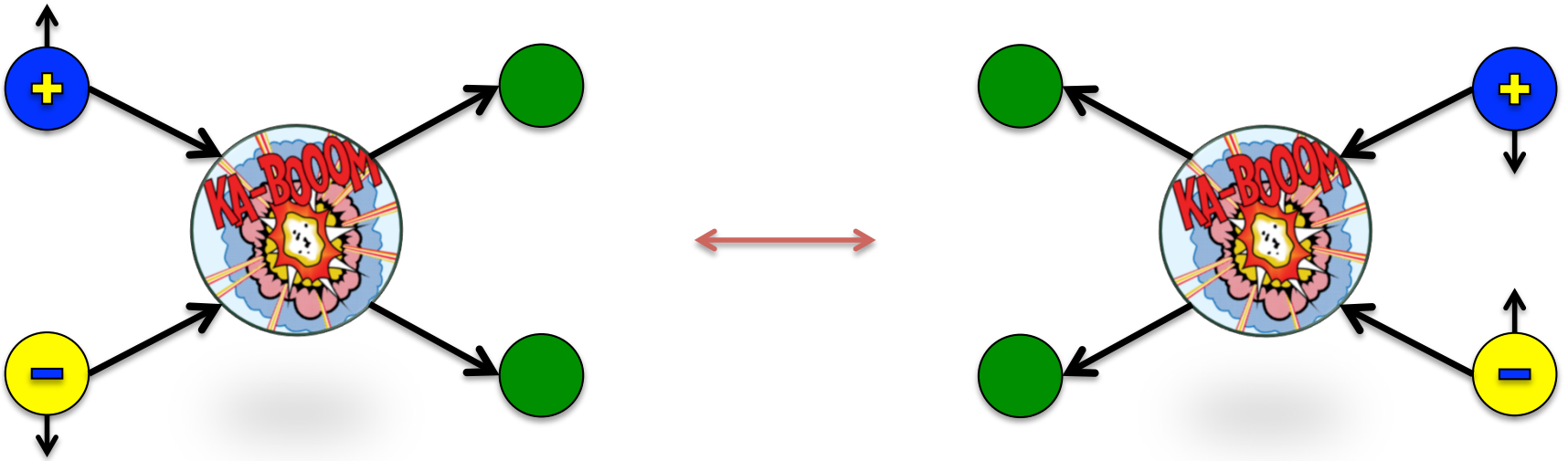
+z to -z



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

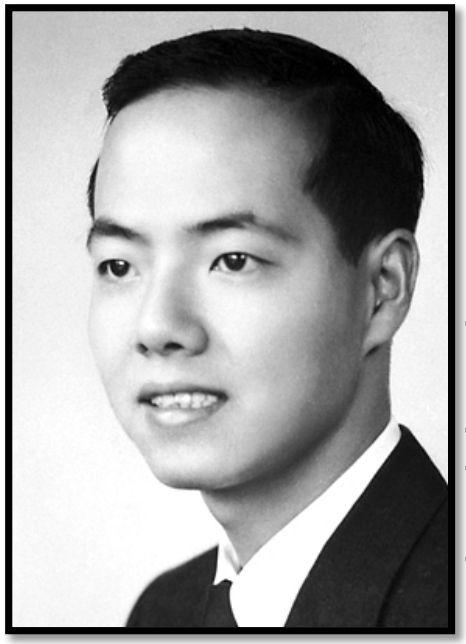
T: Time Reversal

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?



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

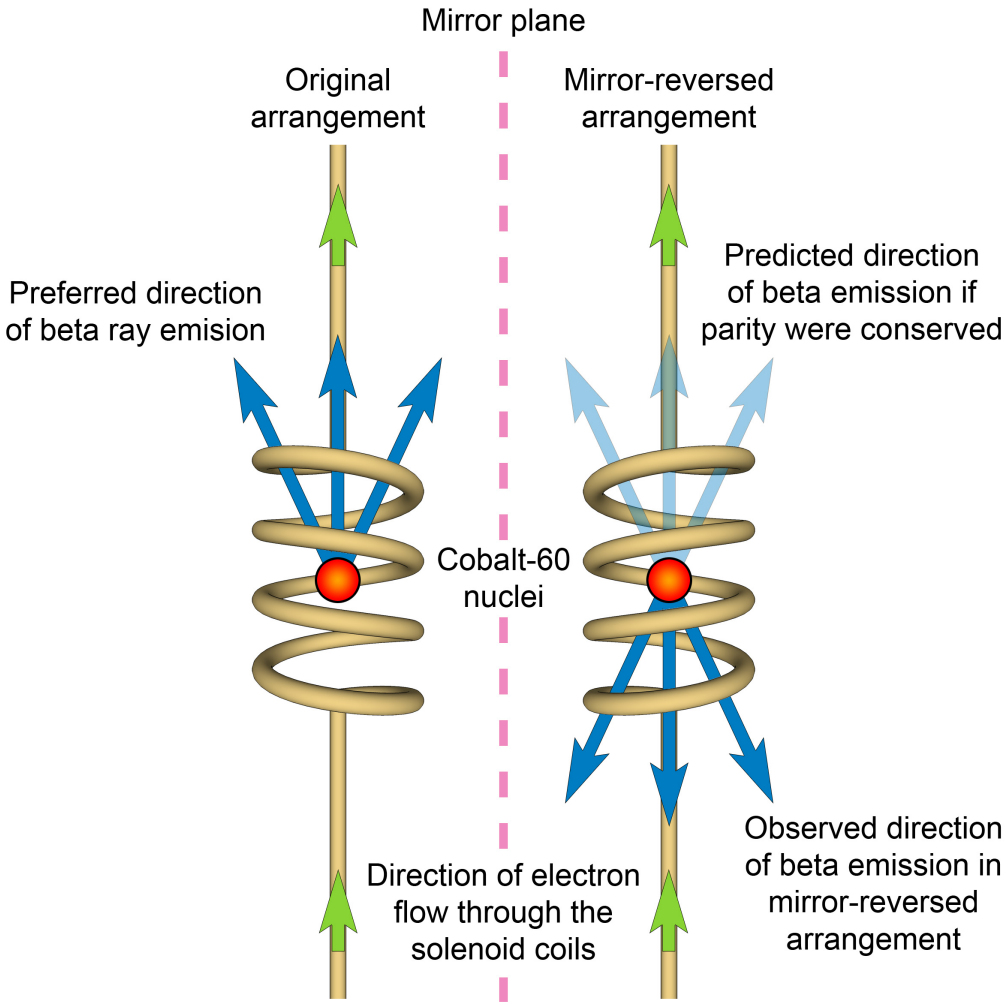
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(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)!

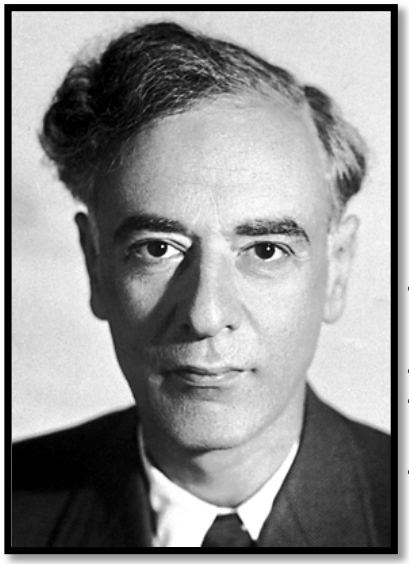
AIP Emilio Segre Visual Archives



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

My All Time Favorite Science Super Hero

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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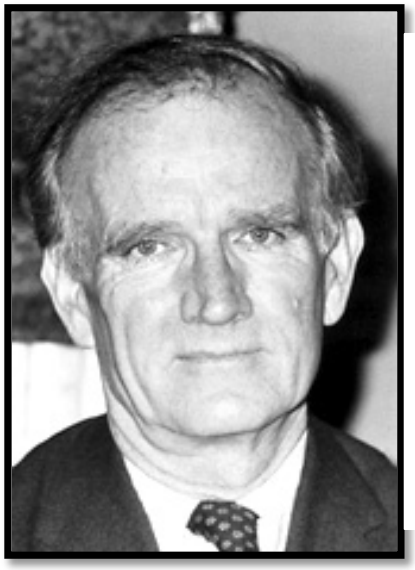

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VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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

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

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

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)

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

$\delta = CP$-violating "phase"

New Massive Particles = More Phases

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

$$\text{number of generations} = N_g$$

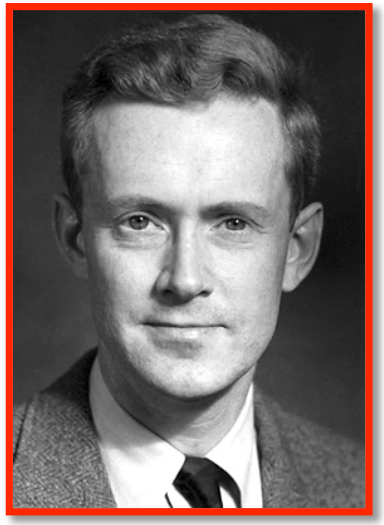
Hocker & Ligeti Annu. Rev. Nucl. Part. Sci. 2006. 56:501–67

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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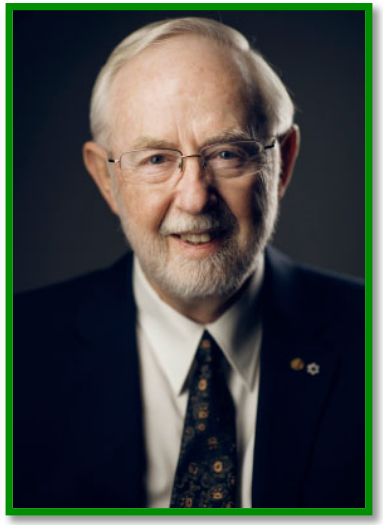
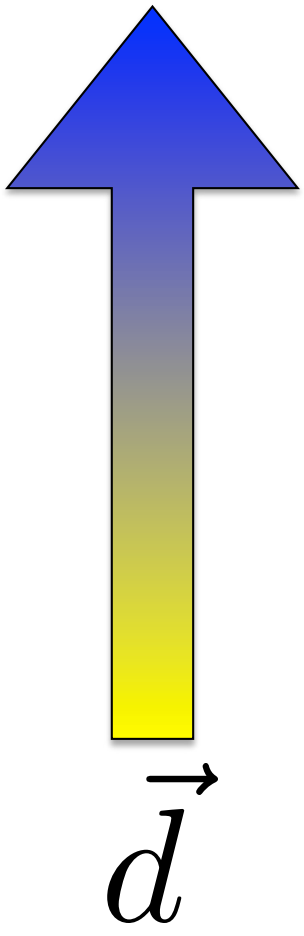

The Nobel Foundation

- 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!

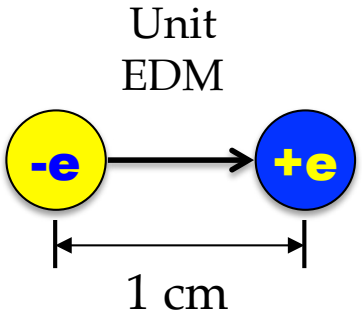
EDM: Measures the Separation of Charges



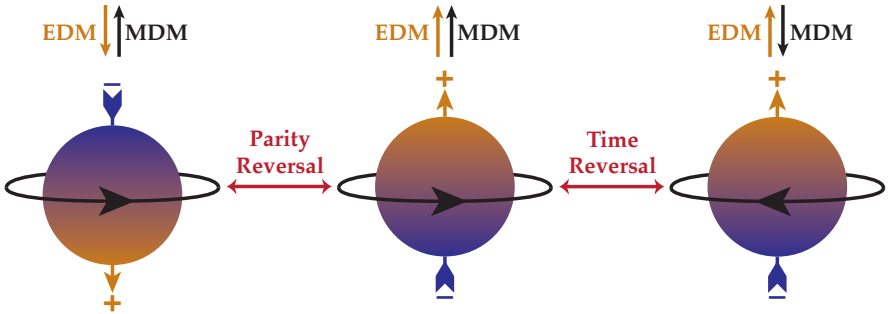
"Thunder Cloud as Generator #2" (1971) by Paterson Ewen [Art Gallery of Ontatrio]

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

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



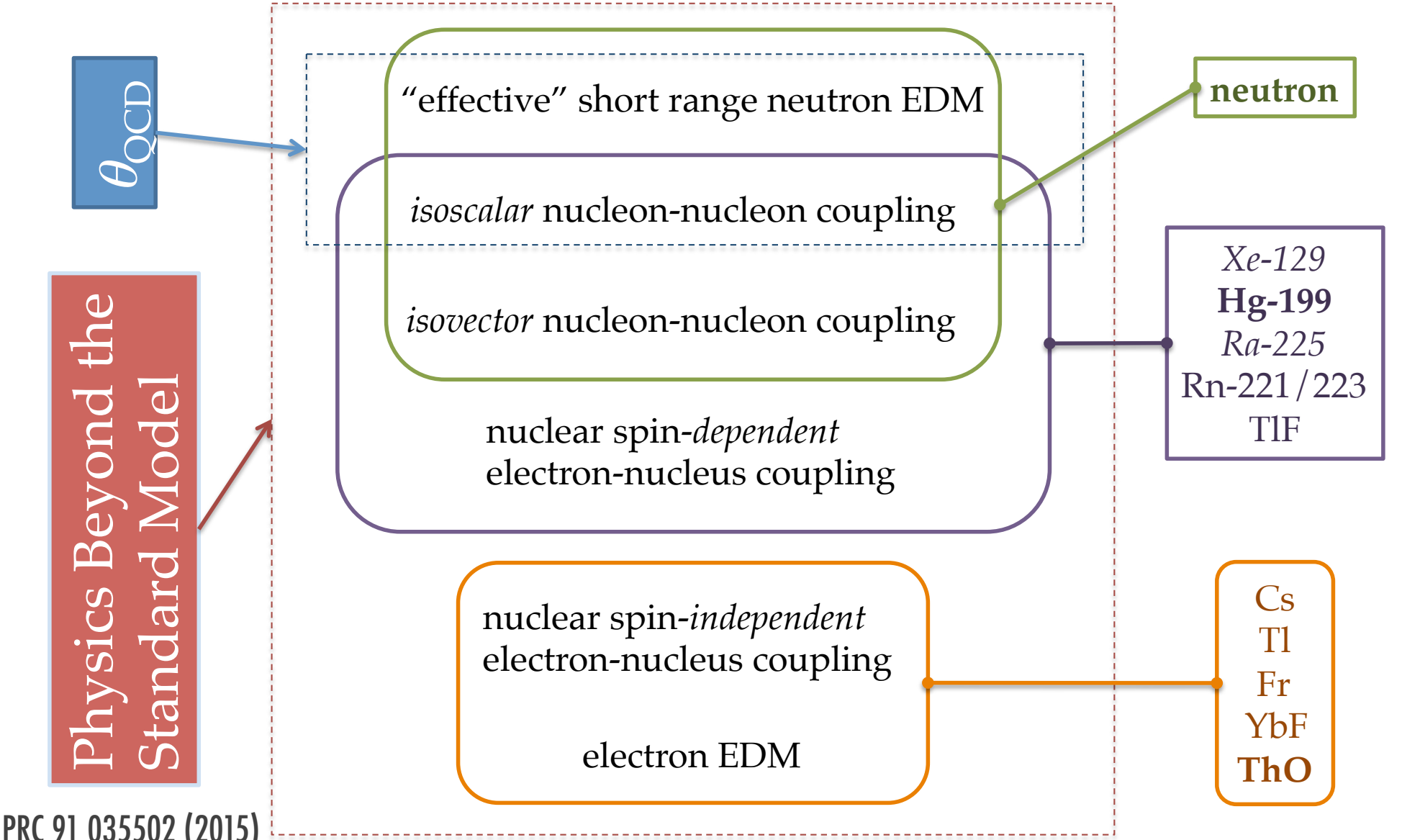
	P-parity	T-time reversal
$\vec{S}$	+	−
$\vec{B}$	+	−
$\vec{E}$	−	+
$\vec{S}\cdot\vec{B}$	+	+
$\vec{S}\cdot\vec{E}$	−	−



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

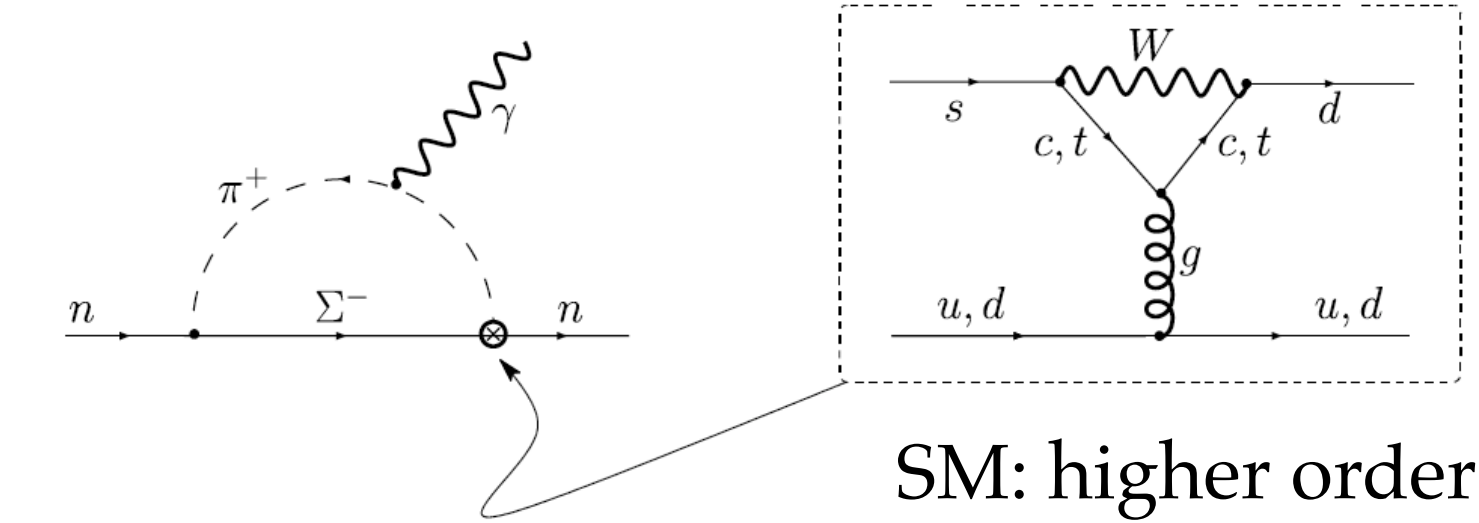
Experimentalist: ...blah blah blah Wigner-someone something…

Different Sources of ~~CP~~ ⇔ EDMs of Different Systems

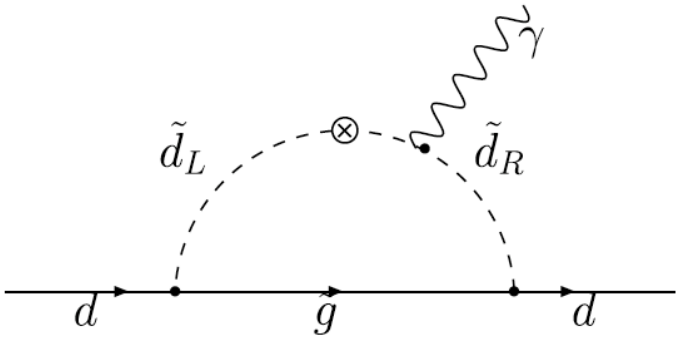


PRC 91 035502 (2015)

EDMS from Standard Model vs. Supersymmetry



SM: higher order "penguin" diagram



SUSY: lower order

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

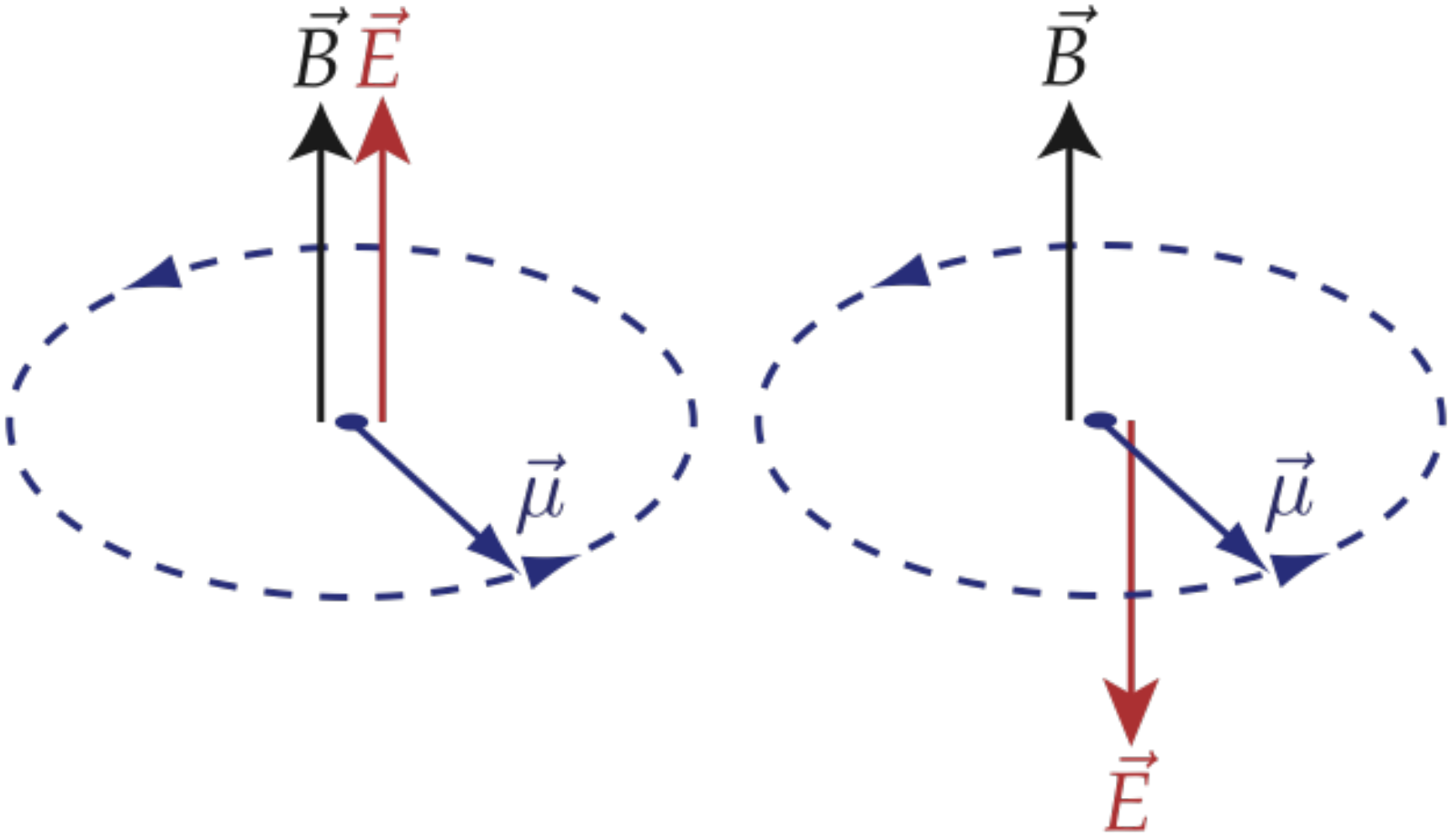
2016 EDM Limits

Prog. Part. Nuc. Phy. 71 (2013) 21; PHYSICAL REVIEW C 94, 025501 (2016) , Phys. Rev. Lett. 116, 161601 (2016)

System	Best Limit (2σ) 10^{-28} e*cm	SM estimate 10^{-28} e*cm	Method (Location)
Electron	0.9	~10^{-10}	cold ThO beam (Harvard/Yale)
Neutron	300	~10^{-4}	UCN in bottle (ILL)
Nuclear	0.074	~10^{-7}	Hg atoms in vapor cell (Washington-Seattle)

Nuclear	Best Limit (2σ) 10^{-28} e*cm	Long Term Goal	Goal on "Hg scale"	Method (Location)
Hg-199	0.074	0.010	0.010	Hg atoms in vapor cell (Washington-Seattle)
Xe-129	66	0.001	0.010	Xe/He gas mixture cell (Michigan)
Ra-225	140000	1.000	0.001	Ra atoms in a 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:

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

interrogation time

signal-to-noise ratio

Electric field

integration time

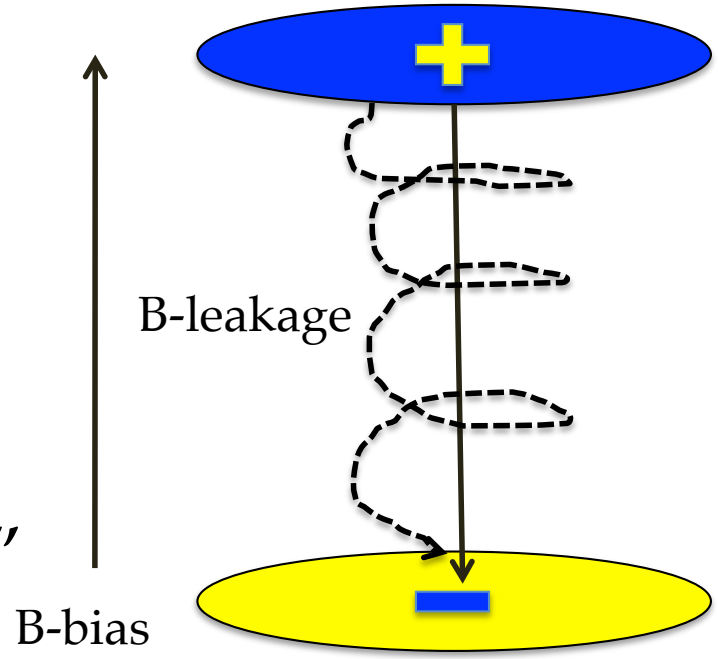
Magnetic Field Instabilities & False Effects!

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

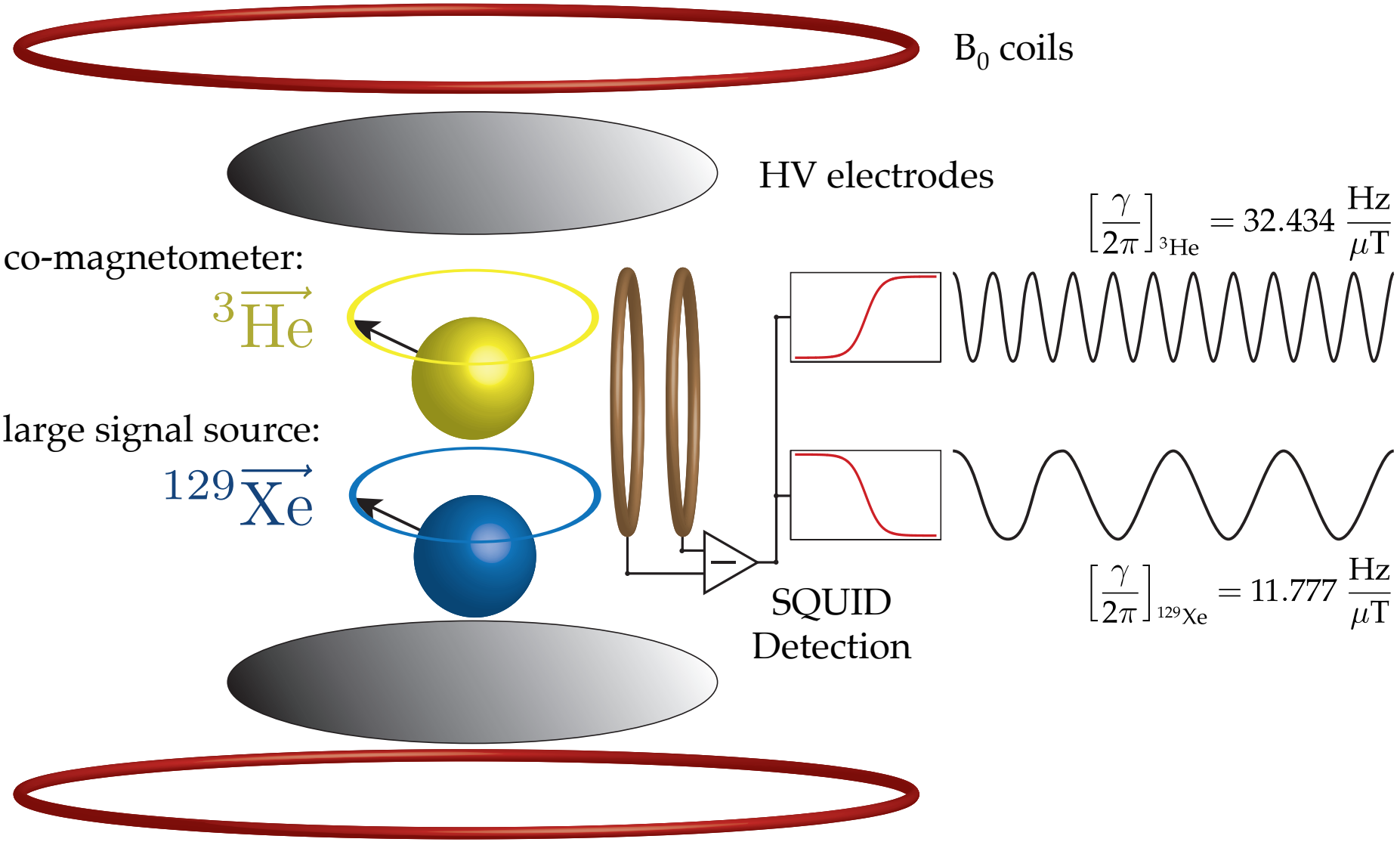
challenge!

Instabilities adds noise & limits the statistical precision.

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

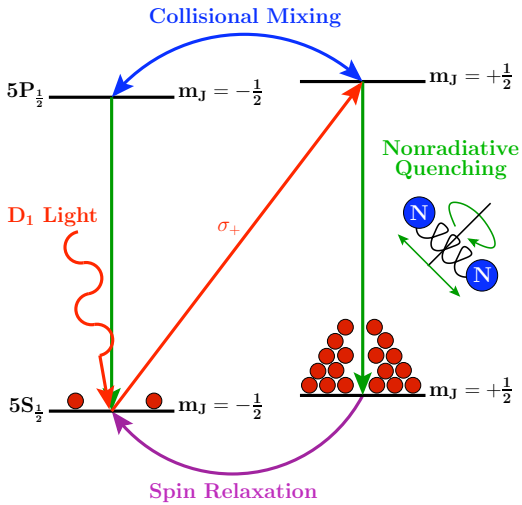


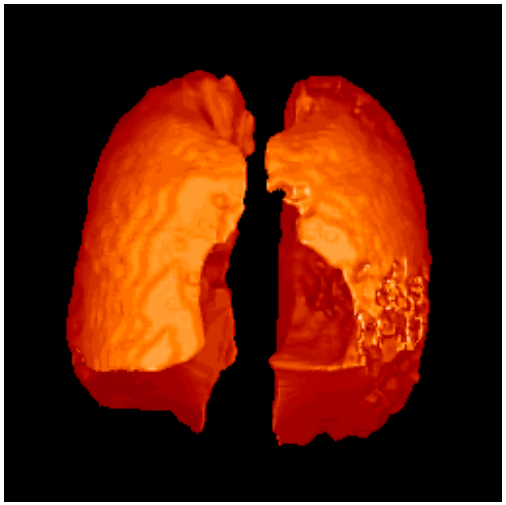
Munich: SQUID Detection of Noble Gases



Spin-Exchange Optical Pumping (SEOP)

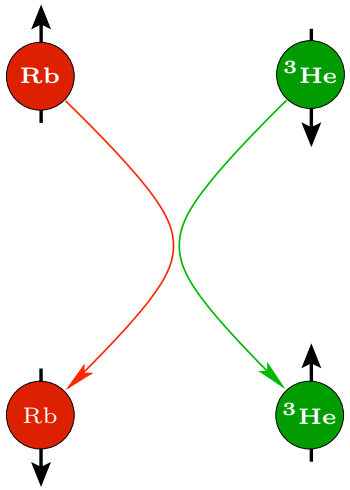
Optical Pumping
light (laser)
to electron (Rb)



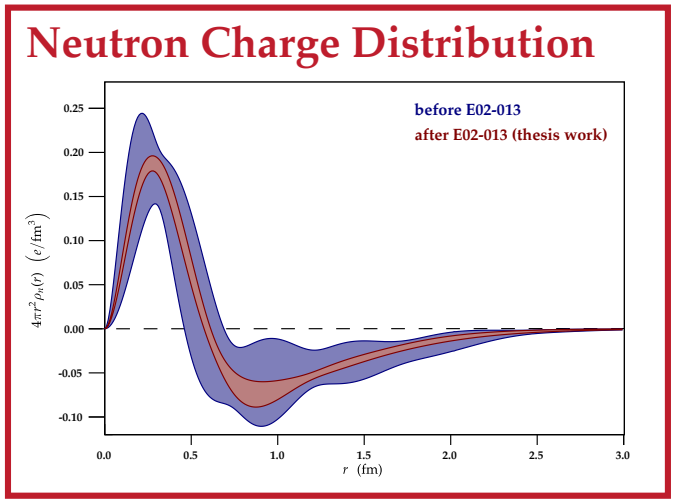


University of Virginia Radiology

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

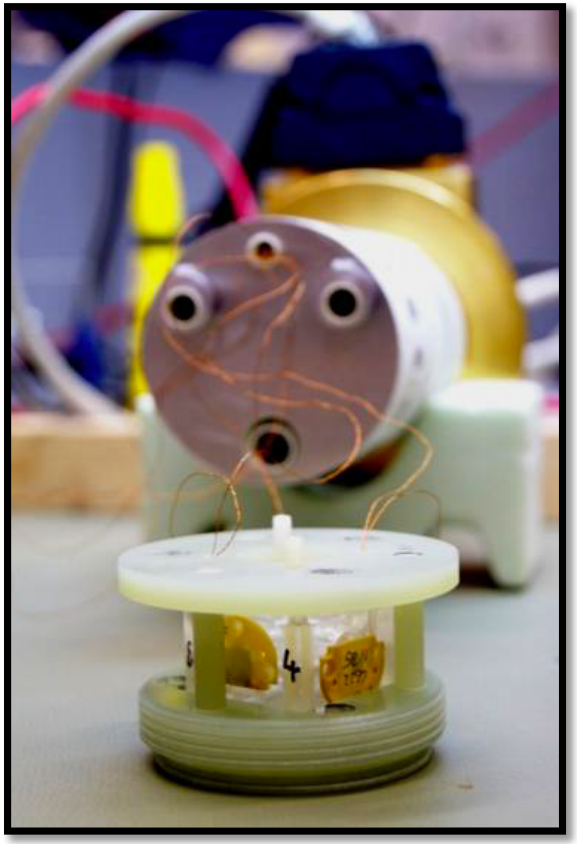


Singh et al.
PRC 91 055205 (2015)

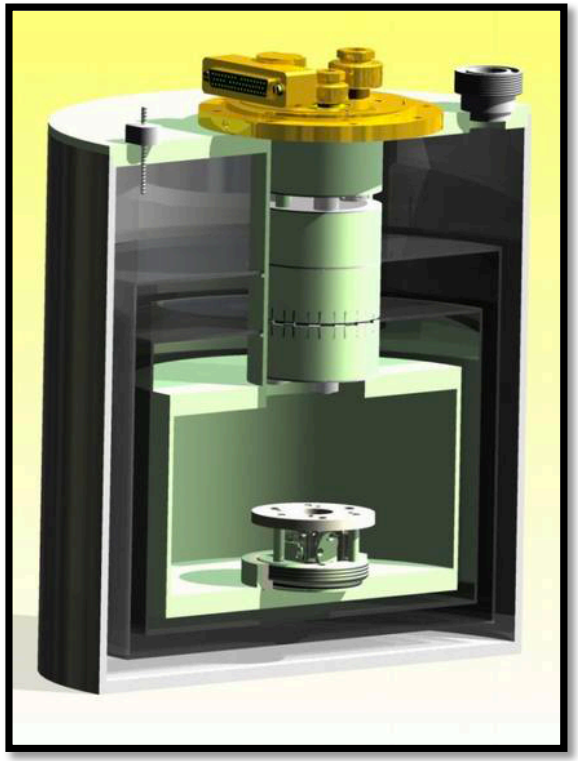


PRL 105 262302 (2010)

"SQUID" Magnetometers: Detectors



Two sensors in
each direction.
Cube side = 1 cm



LHe dewar
refill every 8 hrs

Nonmagnetic
wooden components

Magnetic Field Scales

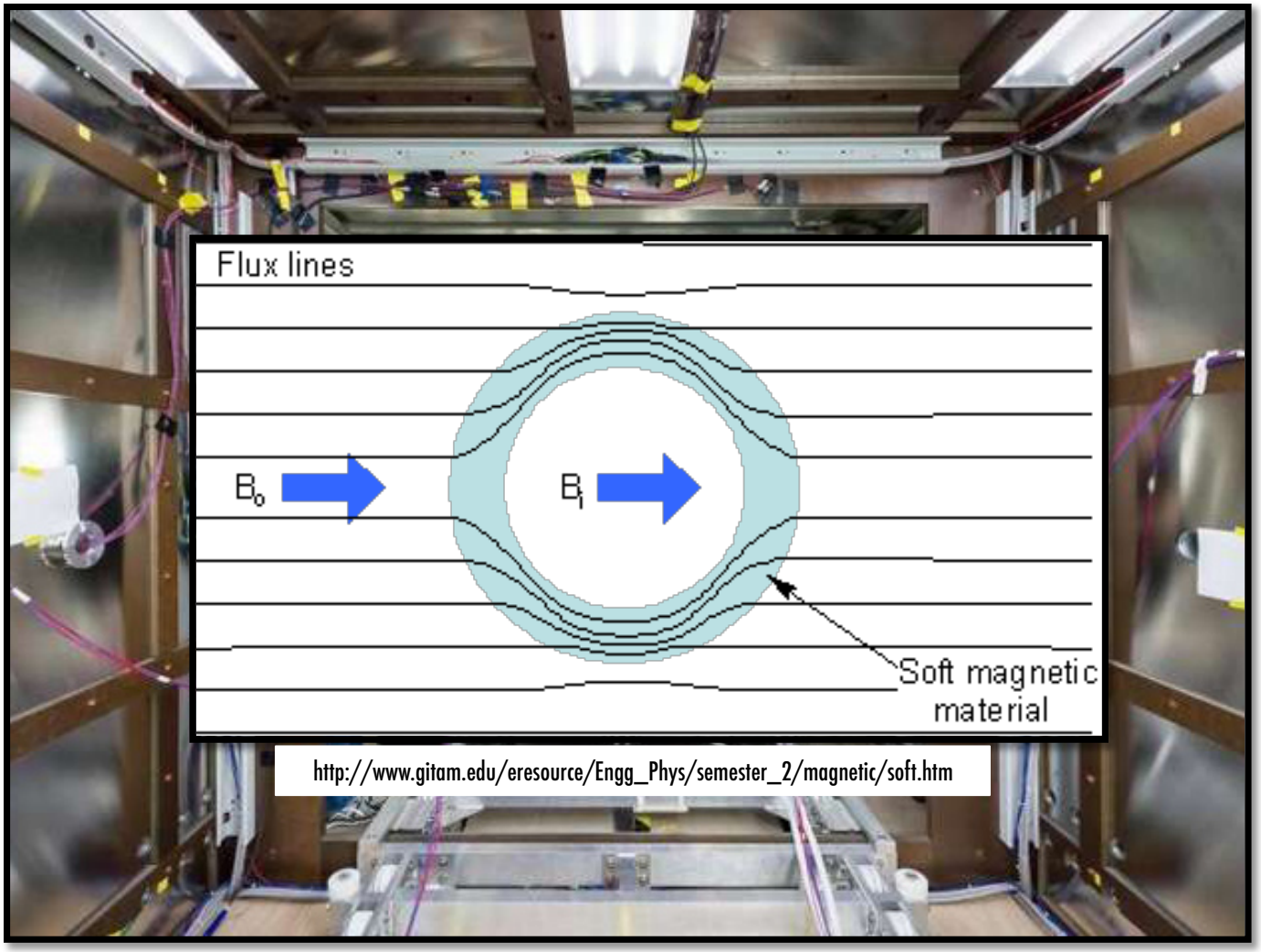
Object	B-Field (T)
MRI Machine	3E+00
Computer hard drive	2E+00
Loudspeaker	1E+00
Sun spots	2E-01
Refrigerator magnet	5E-03
Earth's magnetic field	5E-05
Cassette tape	2E-05
Bias field for EDM experiment	1E-06
Noble gas (100% @ 1 atm @ 1 mm)	1E-08
Residual field in magnetic shielded room	1E-09
All of my 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)

Magic Room? Boundary Conditions!



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

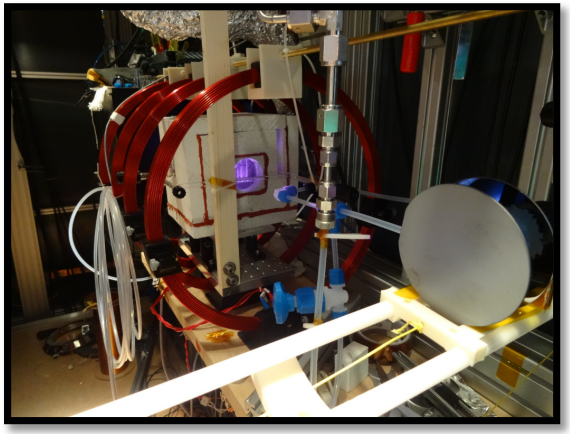
Rev. Sci. Inst. 85:075106 (2014)
J. App. Phys. 117:183903 (2015)
J. App. Phys. 117:233903 (2015)

Experimental Layout

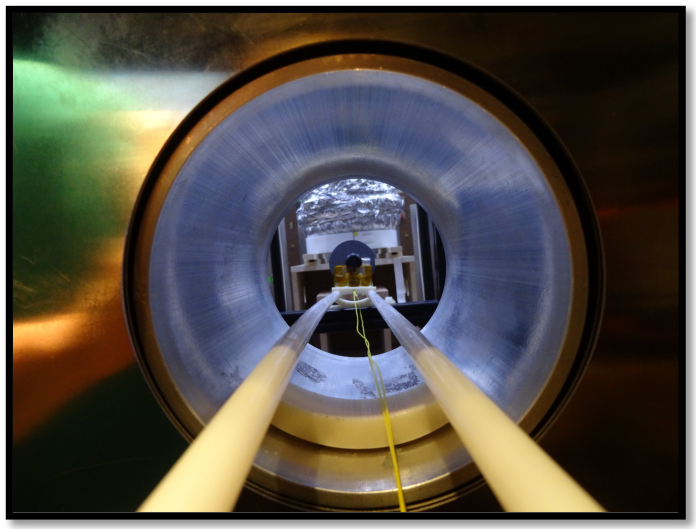
1 cm tall

2.5 cm diameter

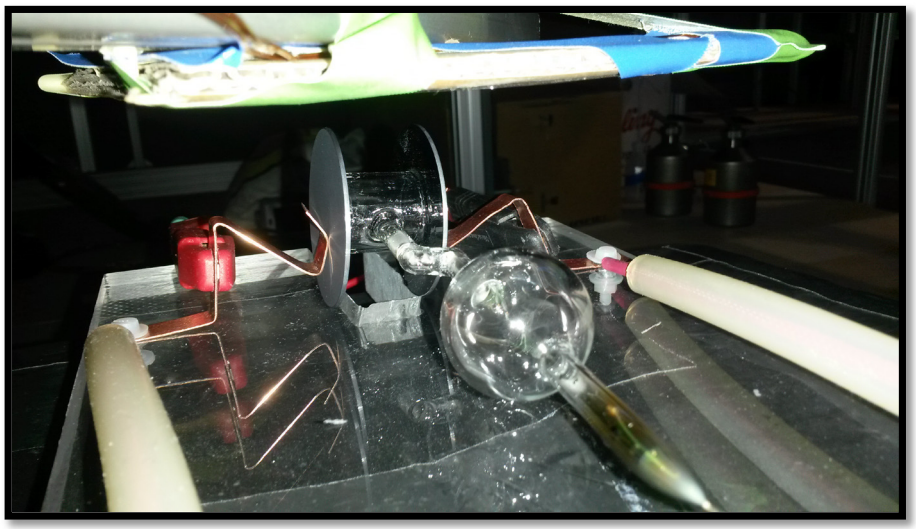
Noble gas polarizer
3 mT
100 W diode laser



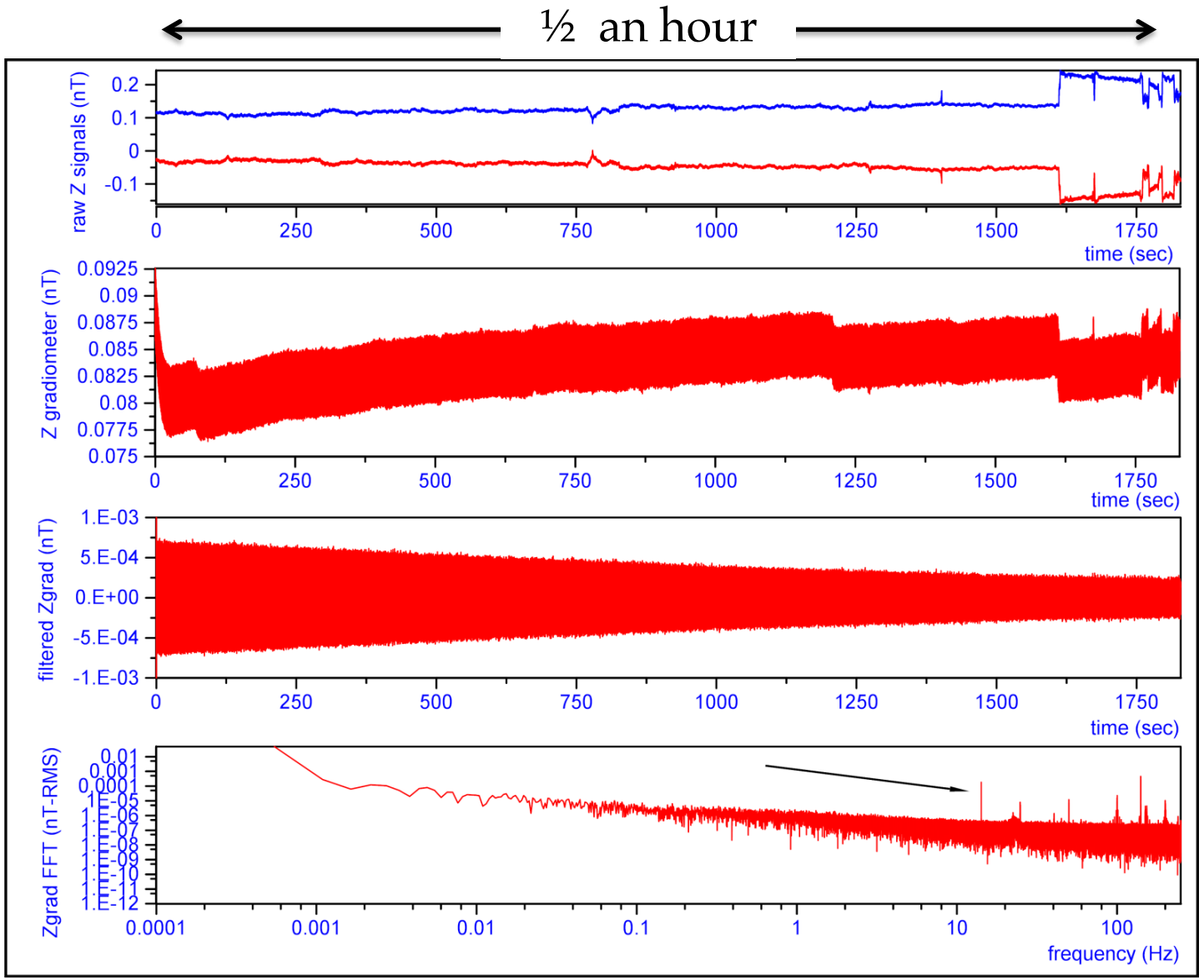
Non-human Transport!



EDM cell underneath SQUID
distance to sensor = 10 cm



Raw Spin Precession Data From SQUIDs



nT

pT

pT

2 channels: A,B

|A|-|B|, gradiometer

high pass filter

FFT

Schiff Shielding in Diamagnetic Atoms

- Shielding in Diamagnetic Atoms

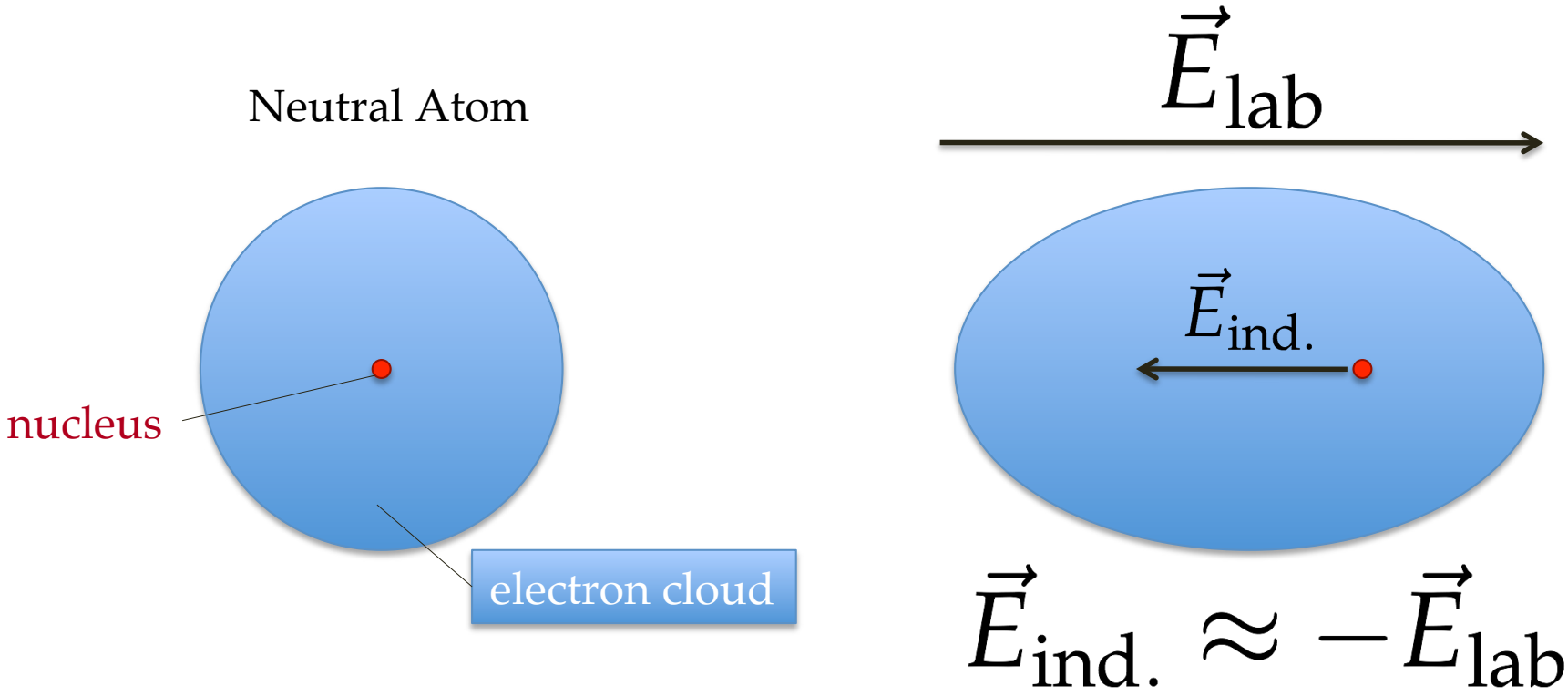
  Schiff PR 132, 2194 (1963)

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

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

Schiff Moment

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

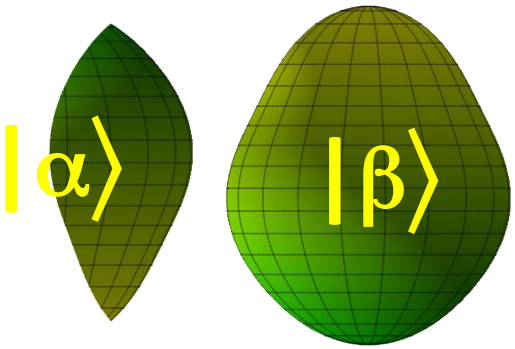


Enhanced Sensitivity in Radium-225

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

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

Parity Doublet



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

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

55 keV << 1 MeV

- 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

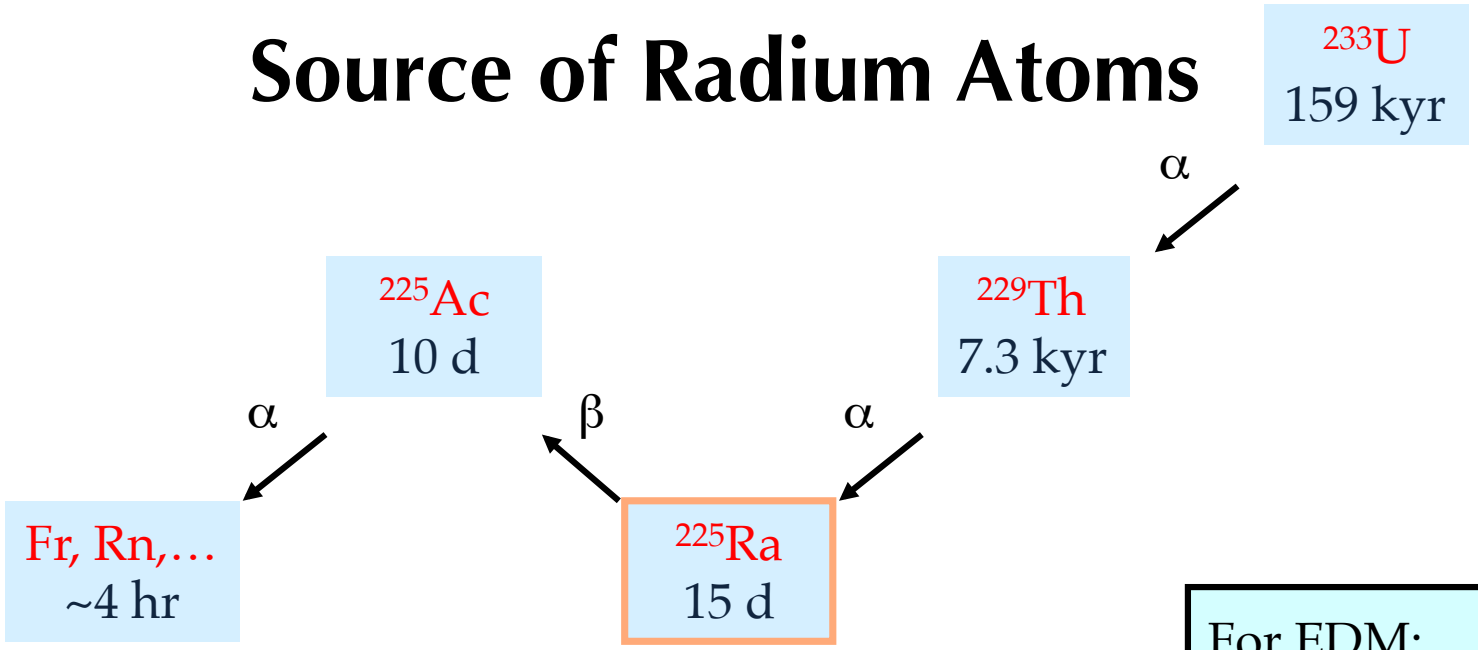
^{225}Ra: Dobaczewski & Engel PRL 94 232502 (2005)
^{199}Hg: De Jesus & Engel PRC 72 045503 (2005)

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

Source of Radium Atoms



- 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

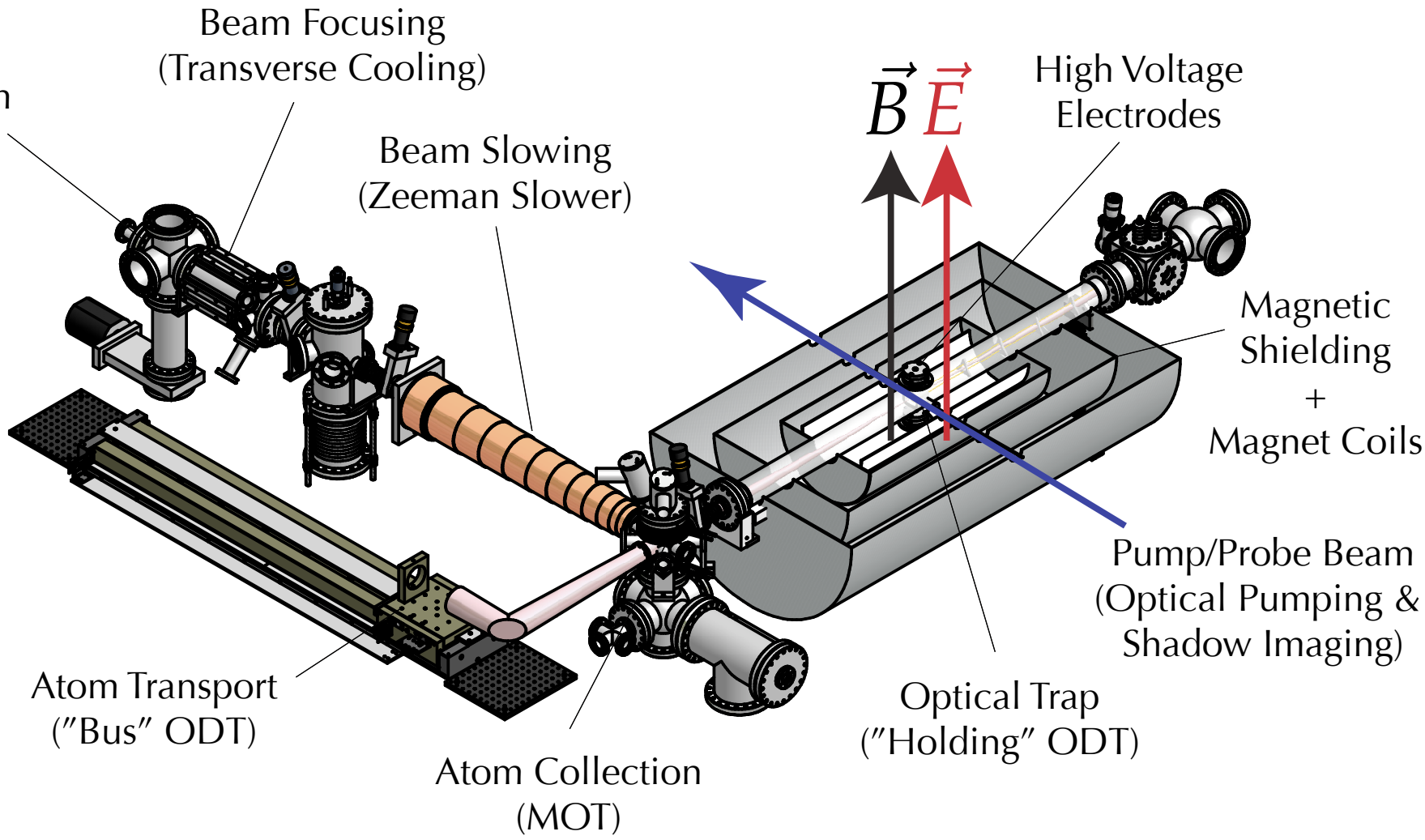
Yield for ^{225}Ra ~ (10^9 to 10^{10})/s

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

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

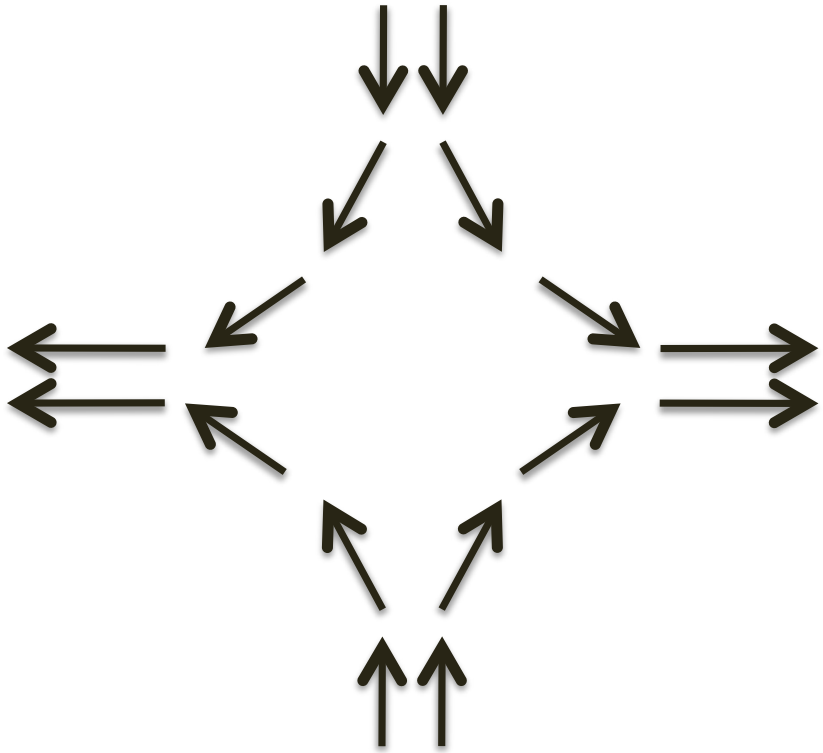
Ultracold-Atom Trappers or Ultracold Atom-Trappers

Experimental Layout



Neutral Atom Traps

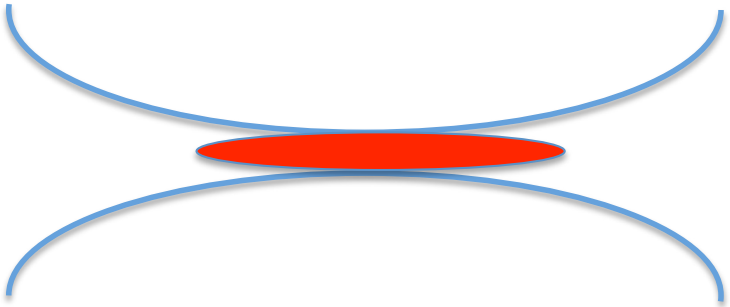
Magneto-Optical Trap (MOT)



B Field in a MOT
Atoms trapped in "zero-field" volume

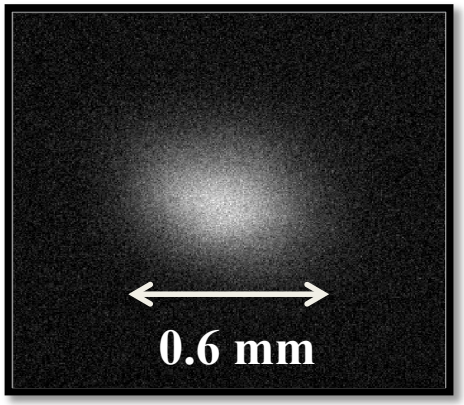
Optical Dipole Trap (ODT)

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

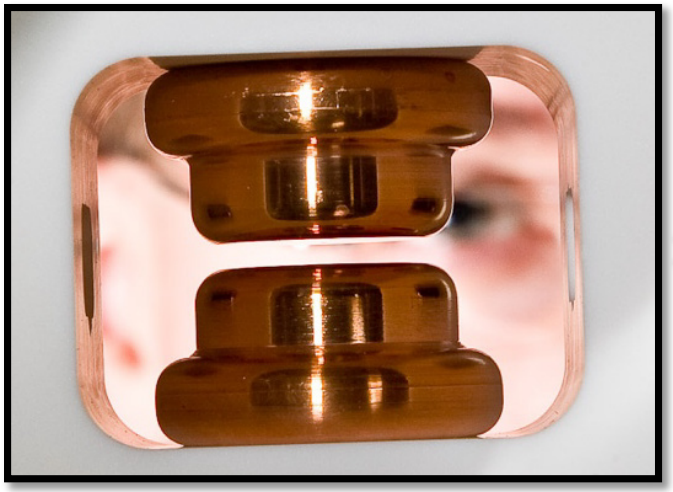


Collecting & Transporting Ra-225 Atoms

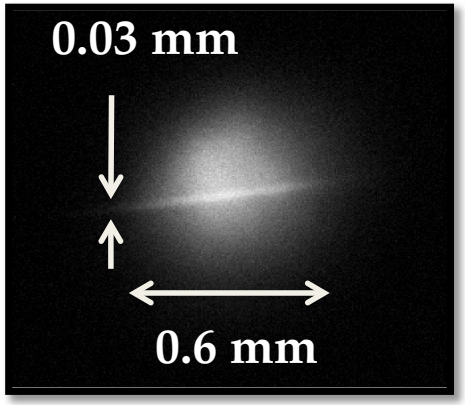
Guest et al., PRL 98 093001 (2007)



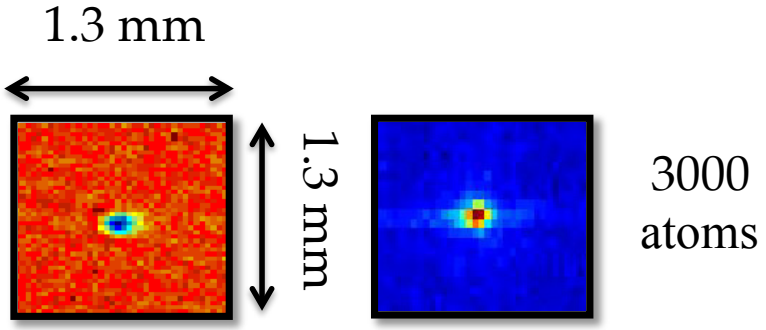
^{226}Ra MOT
20,000 atoms



Parker et al., PRC 86 065503 (2012)



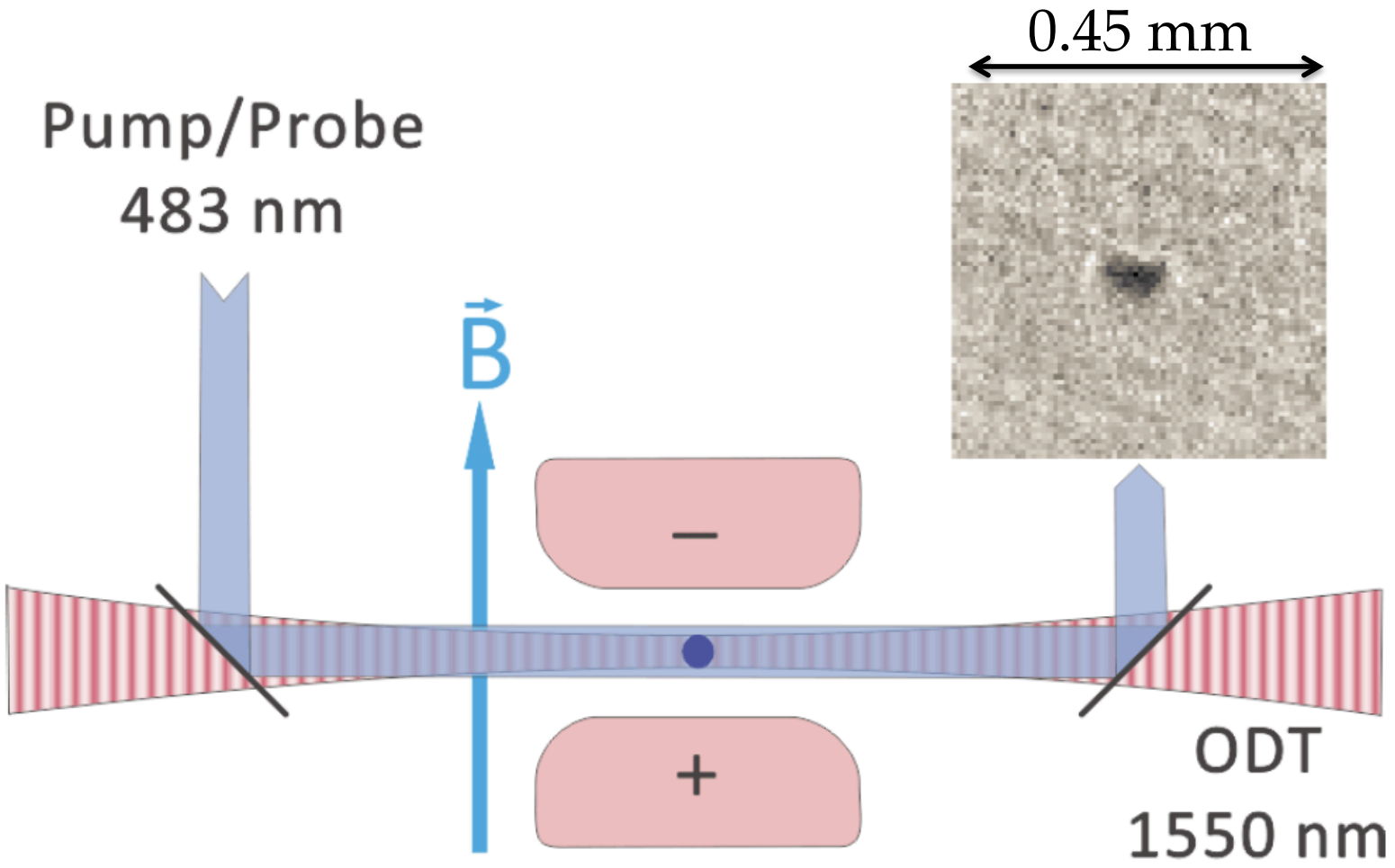
MOT + ODT
20,000 atoms



Absorption Imaging

Fluorescence Imaging

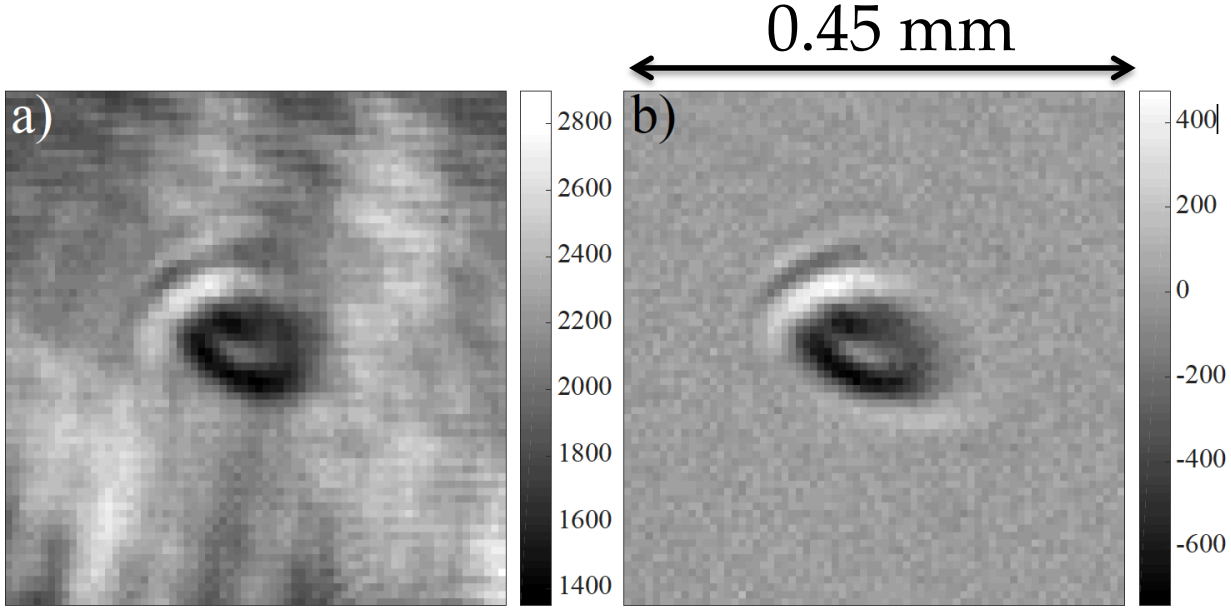
Atoms Create a Shadow by Absorption



Parker et al. Phys. Rev. Lett. 114, 233002 (2015)

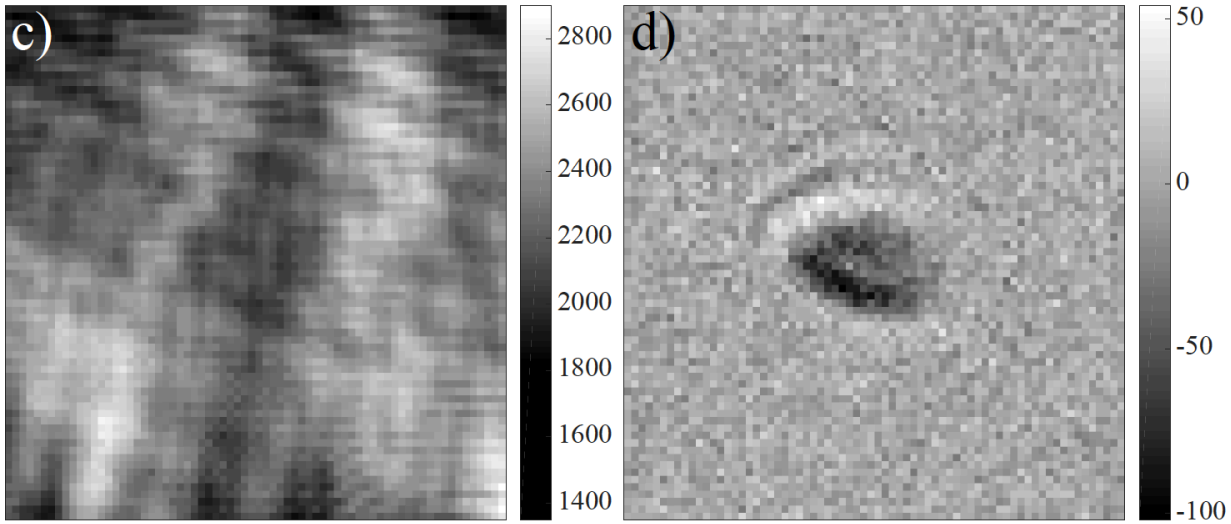
Image Background & Distortion Corrections

average of 8 raw images of Ra-226



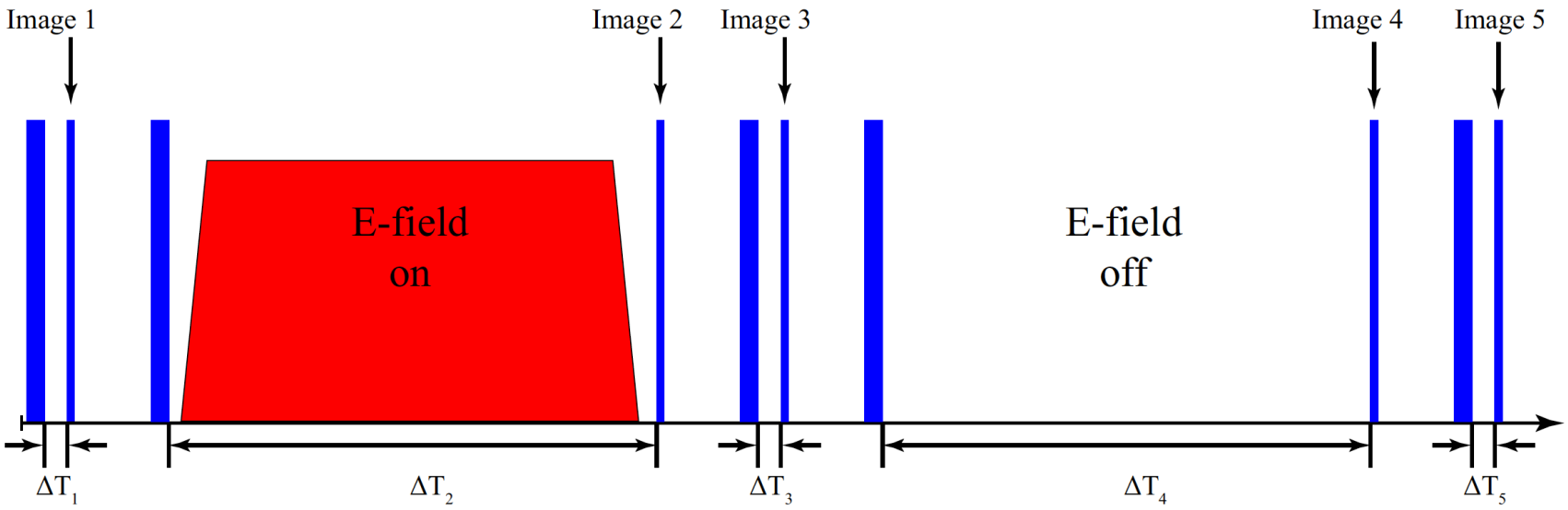
"clean" Ra-226 image

average of 63 raw images of Ra-225



"clean" Ra-225 image

Several Images Are Taken During One Cycle

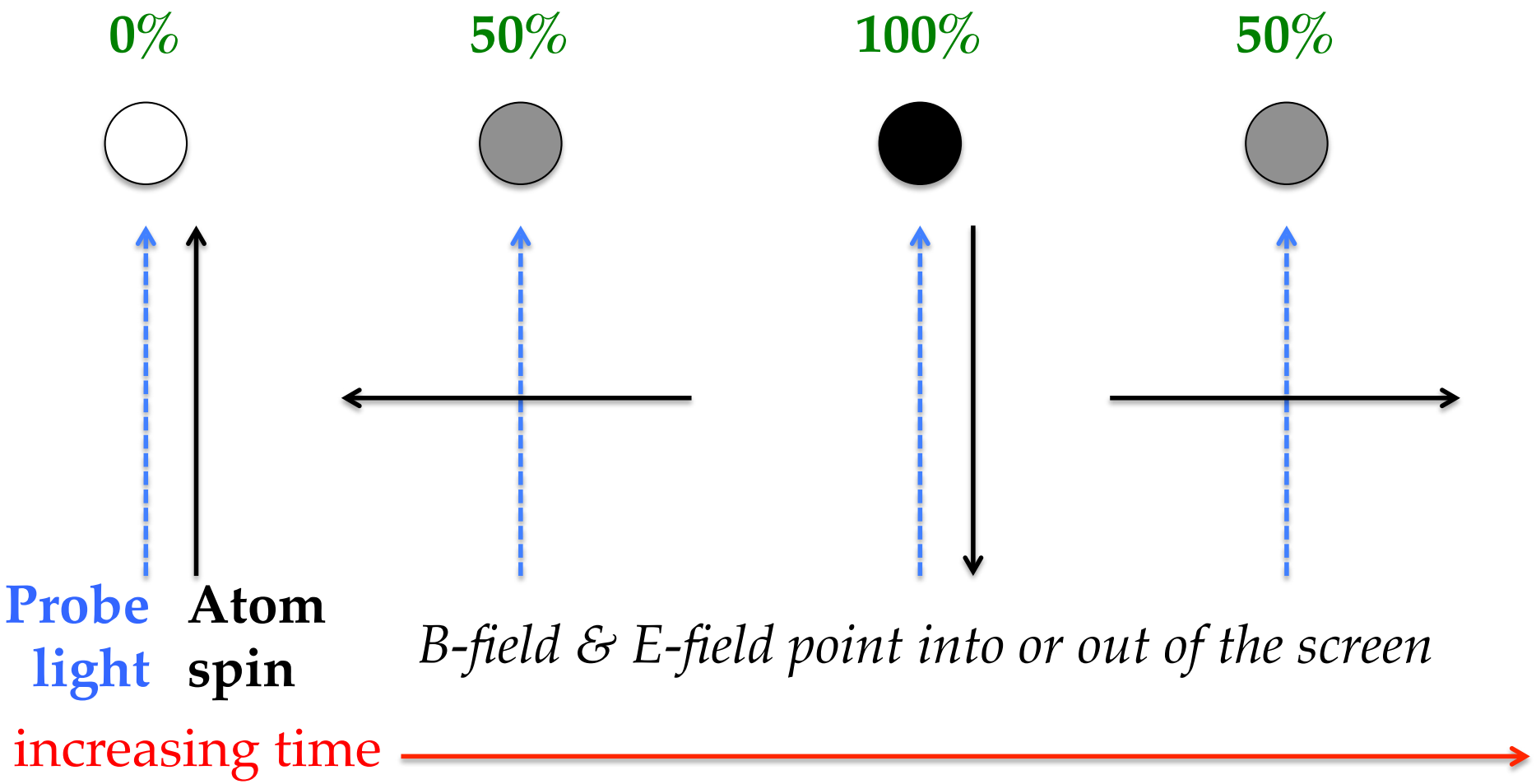


Images taken to account for changes in atom number and probe light intensity.

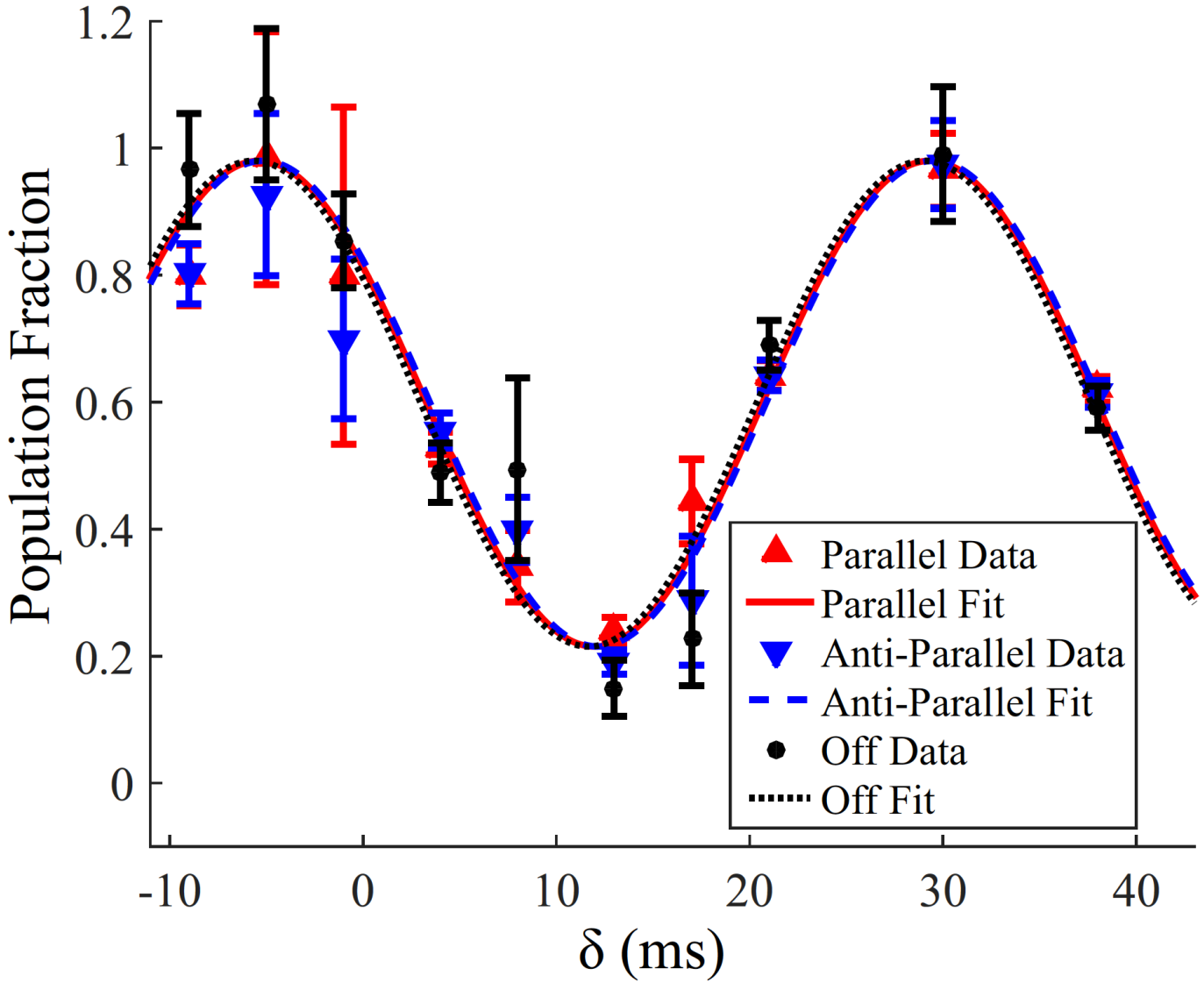
Data taken for electric parallel, anti-parallel, and off for different time delays.

Absorption probability oscillates at ~20 Hz

probability of absorbing probe light and creating a shadow:



Reconstructed Spin Precession Curve



Towards More Statistics

Dec 2014: PRL 114, 233002: $|d(\text{Ra-225})| < 50\text{x}10^{-23}\ e$ cm (95%)

June 2015: PRC 94, 025501: $|d(\text{Ra-225})| < 1.4\text{x}10^{-23}\ e$ cm (95%)

Effect	Current uncertainty	α scenario uncertainty	β scenario uncertainty
E-squared effects	1×10^{-25}	7×10^{-29}	7×10^{-31}[a]
B-field correlations	1×10^{-25}	5×10^{-27}	3×10^{-29}[a]
Holding ODT power correlations	6×10^{-26}	9×10^{-30}	9×10^{-32}[a]
Stark interference	6×10^{-26}	2×10^{-27}	3×10^{-29}[a]
E-field ramping	9×10^{-28}	2×10^{-29}	N/A
Blue laser power correlations	7×10^{-28}	1×10^{-31}	1×10^{-31}
Blue laser frequency correlations	4×10^{-28}	8×10^{-30}	8×10^{-30}
$\mathbf{E} \times \mathbf{v}$ effects	4×10^{-28}	7×10^{-30}	N/A
Leakage current	3×10^{-28}	9×10^{-29}	N/A
Geometric phase	3×10^{-31}	7×10^{-30}	5×10^{-33}
Total	2×10^{-25}	5×10^{-27}	4×10^{-29}[a]

[a]This uncertainty will improve with the statistical sensitivity of the experiment.

More efficient detection of atoms: ANL

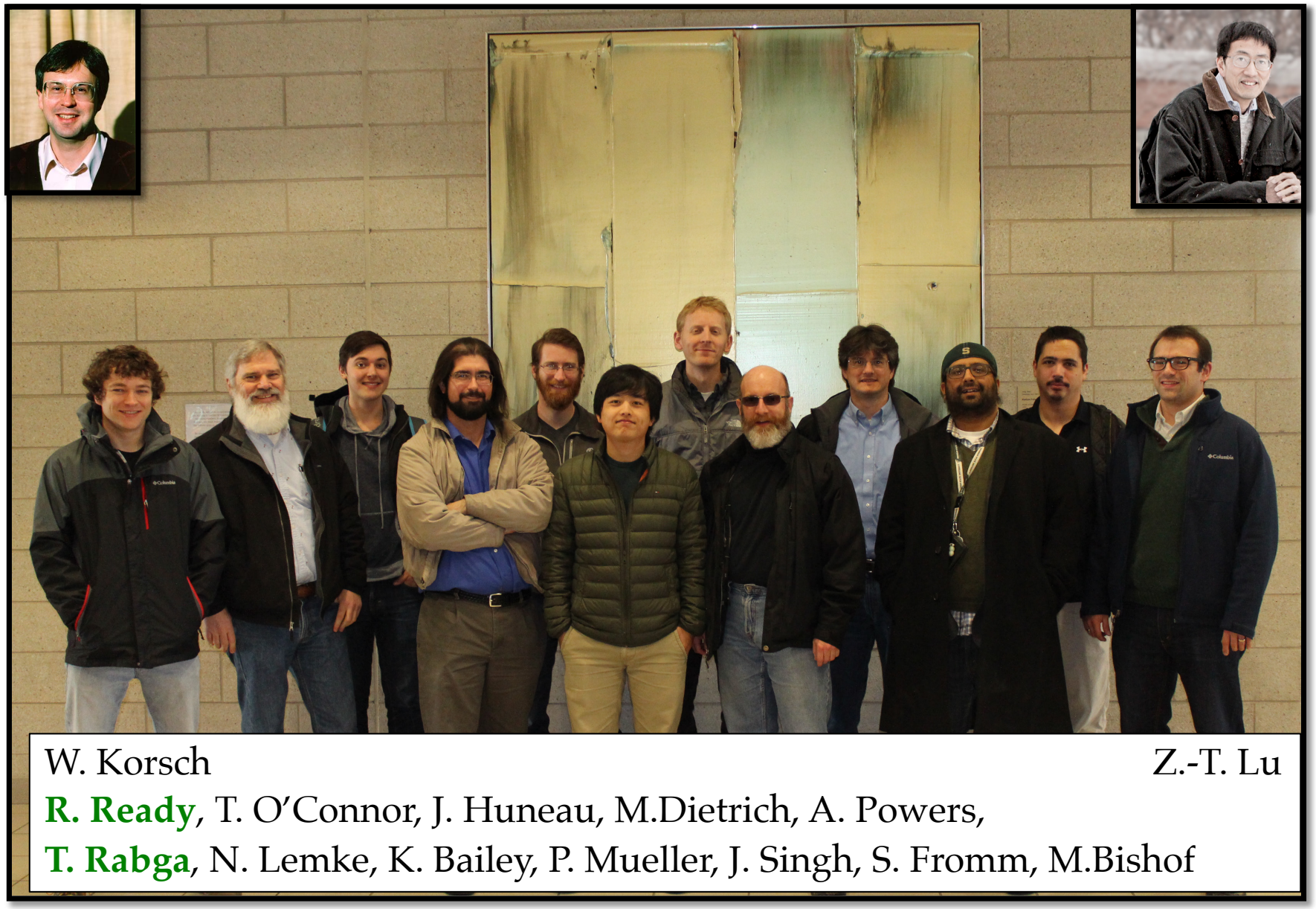
More efficient laser cooling and trapping: ANL

Higher electric field and more exact reversal of E-field: MSU

High activity atomic beam source: MSU

Yb laser trap for studying systematics: USTC

Ra EDM: Argonne/MSU/Kentucky/UST-China

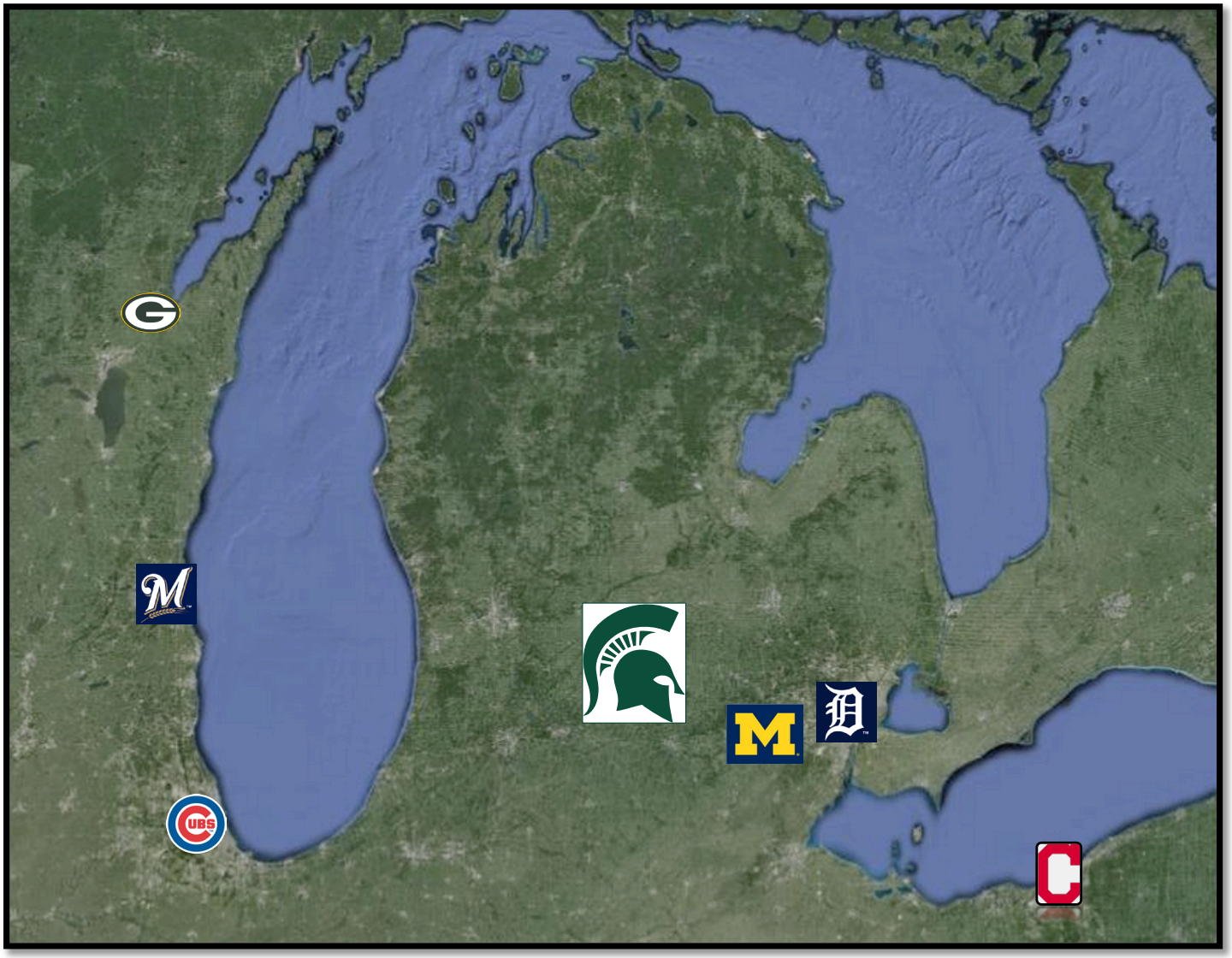


W. Korsch Z.-T. Lu

R. Ready, T. O'Connor, J. Huneau, M.Dietrich, A. Powers,

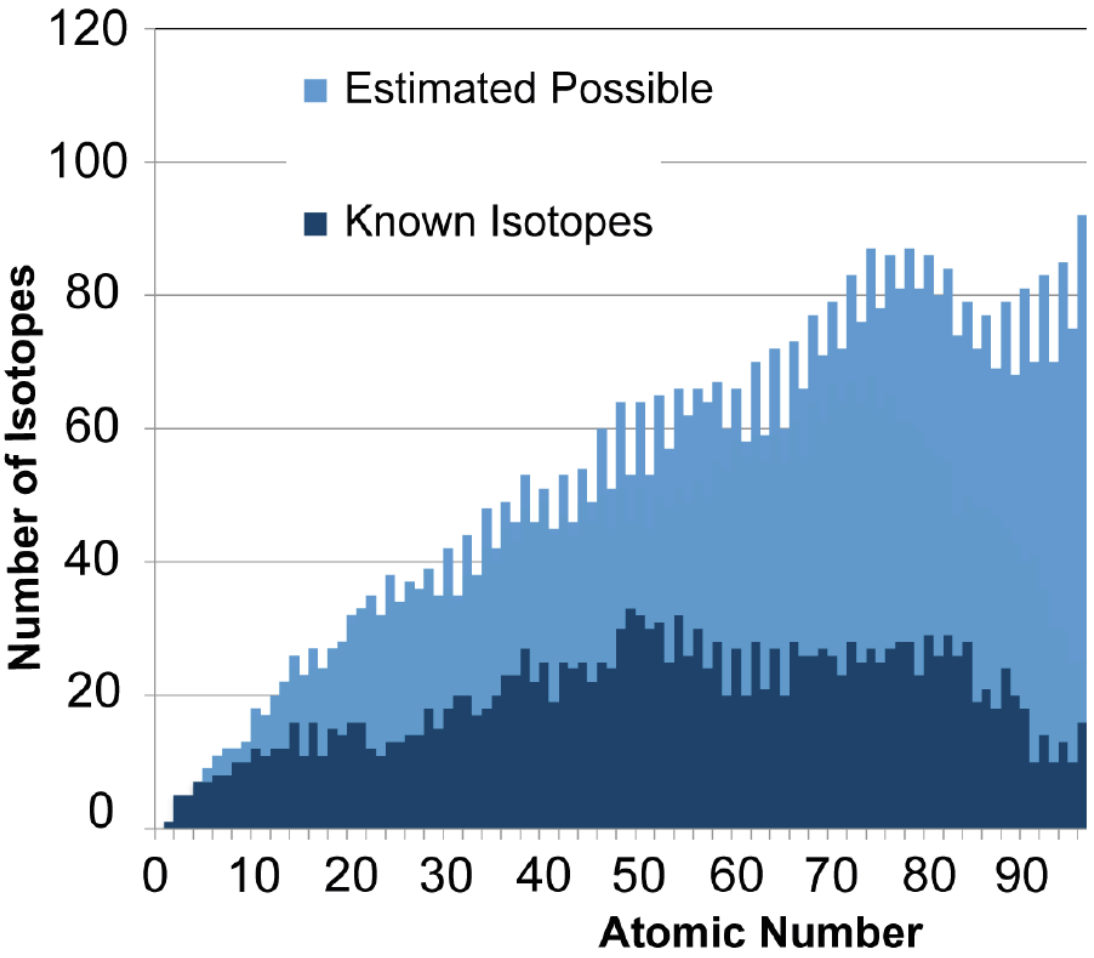
T. Rabga, N. Lemke, K. Bailey, P. Mueller, J. Singh, S. Fromm, M.Bishof

Michigan State University, East Lansing, MI



Google Maps & Wikipedia Commons

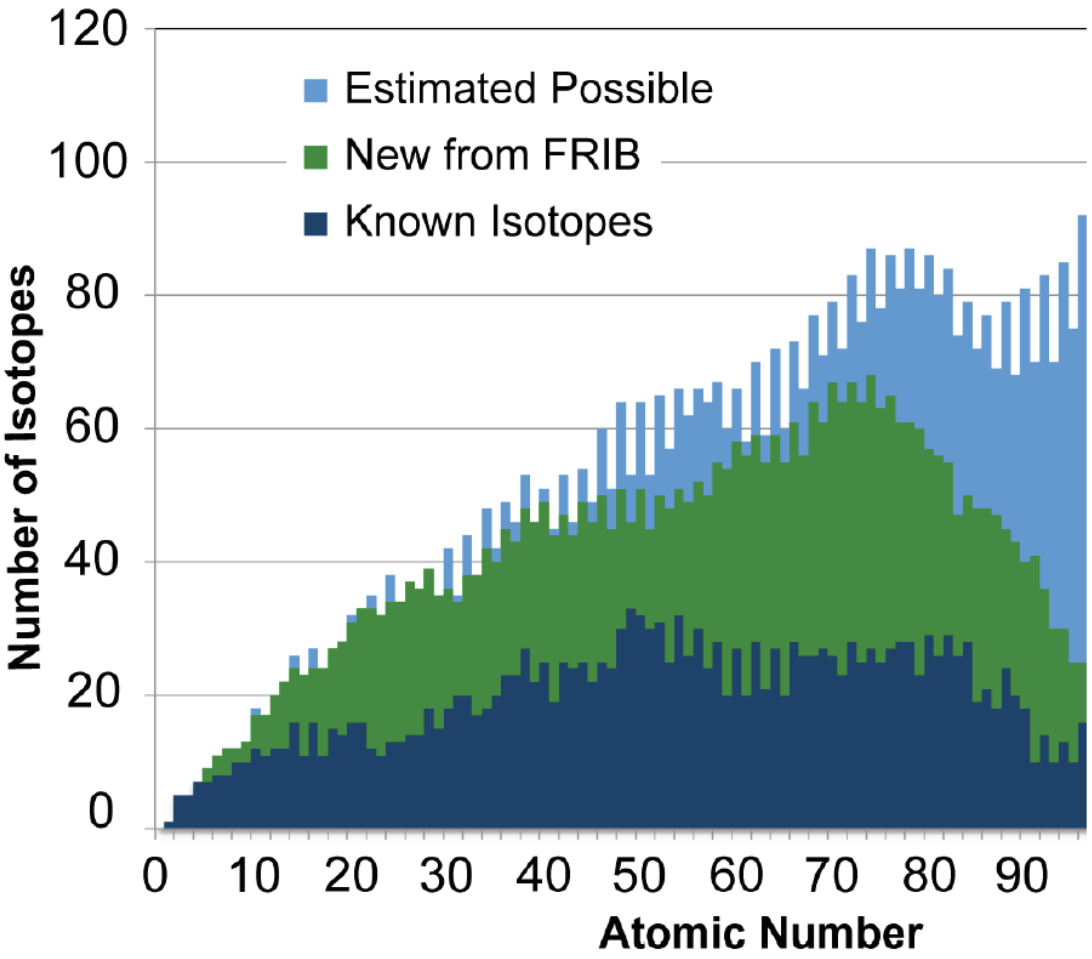
Facility for Rare Isotope Beams



- 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

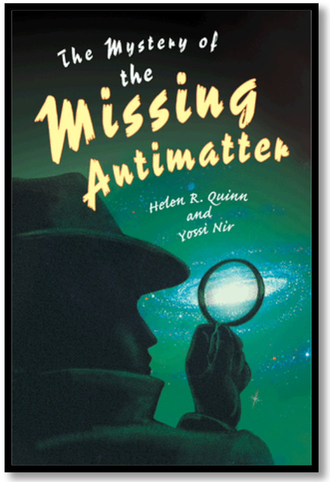
1000x production rate for Ra-225!



- 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

For more information…

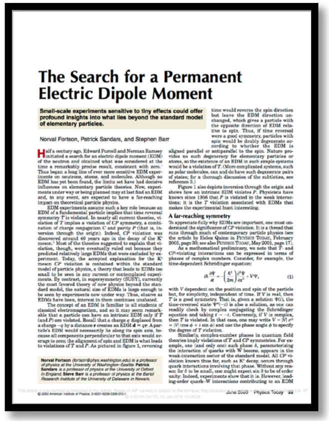


The Mystery of the Missing Antimatter
by: Helen R. Quinn and Yossi Nir
Princeton University Press (2014)


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


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

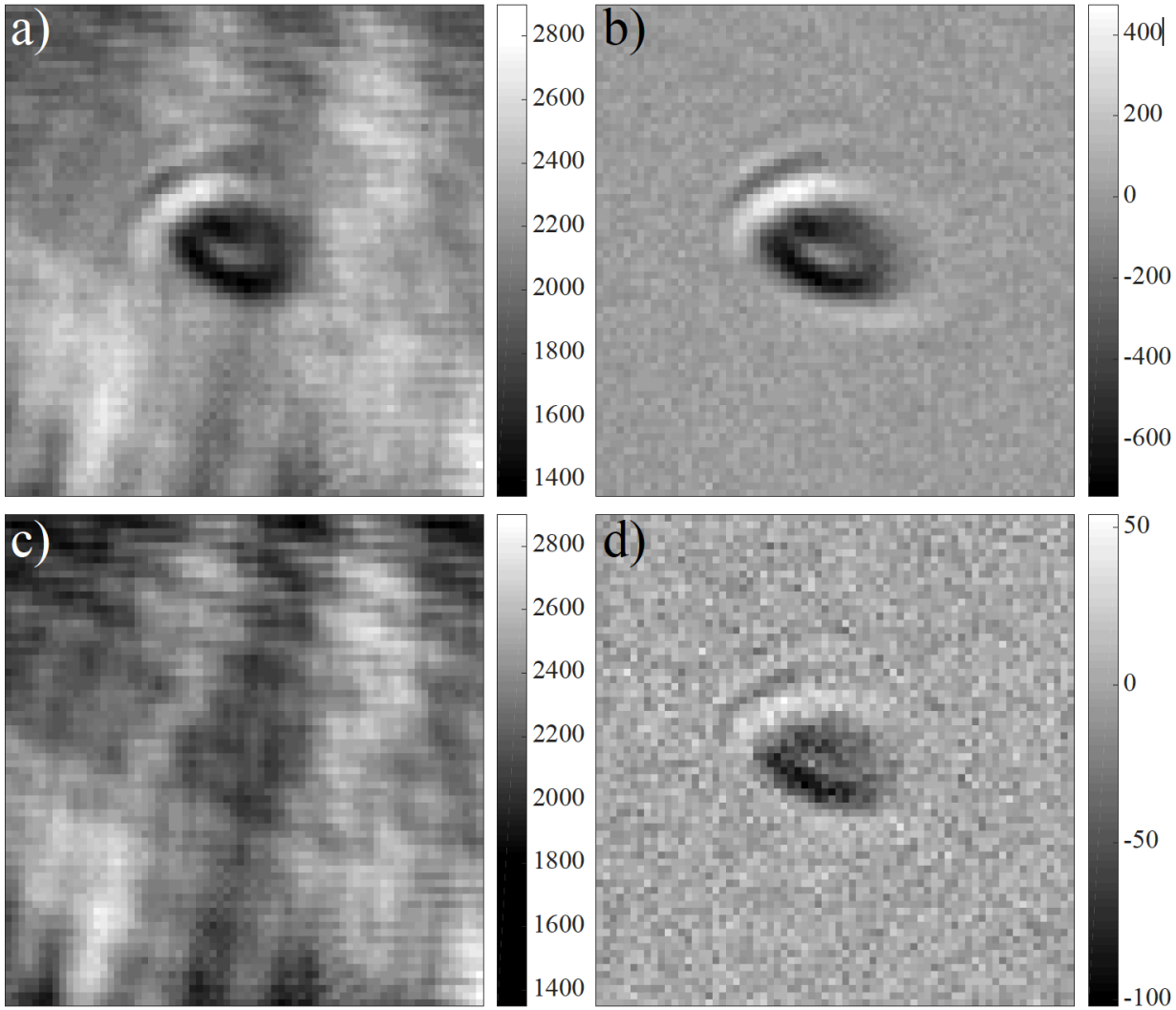
The search for a permanent electric dipole moment
Norval Fortson, Patrick Sandars & Stephen Barr
Physics Today, June 2003, page 33

Backup Slides

Shadow Image Analysis: Background & Distortion Corrections

raw image of Ra-226

composite background



Ra-226 only

Ra-225 only