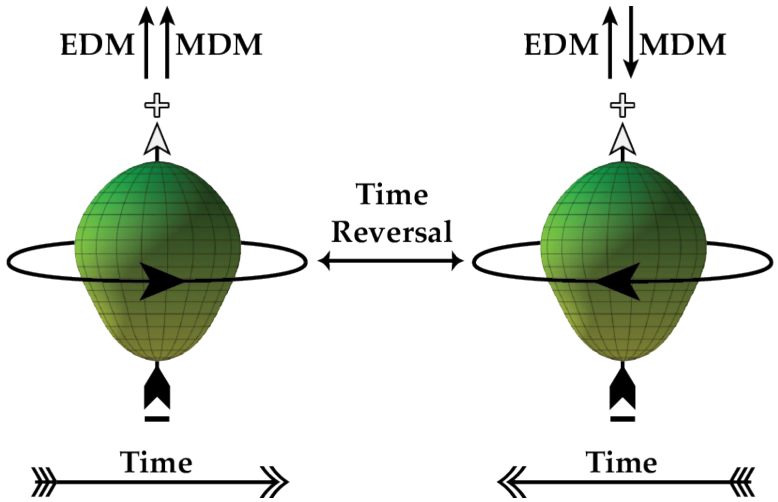
CUSTIPEN-IMP-PKU Workshop
on Physics of Exotic Nuclei

Huizhou, China
Dec.12-15, 2016

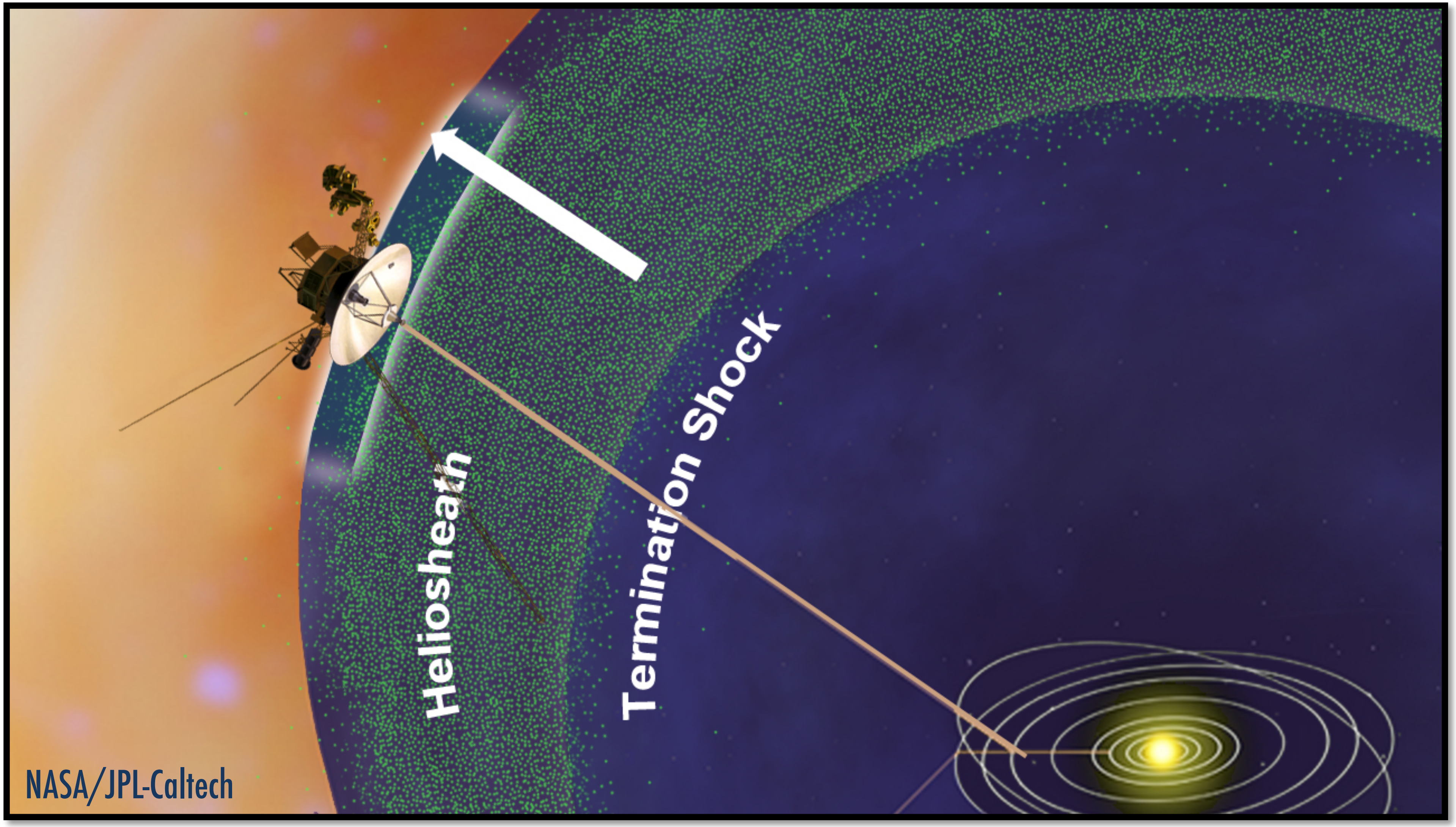
The Search for Electric Dipole Moments Using Octupole-Deformed Nuclei



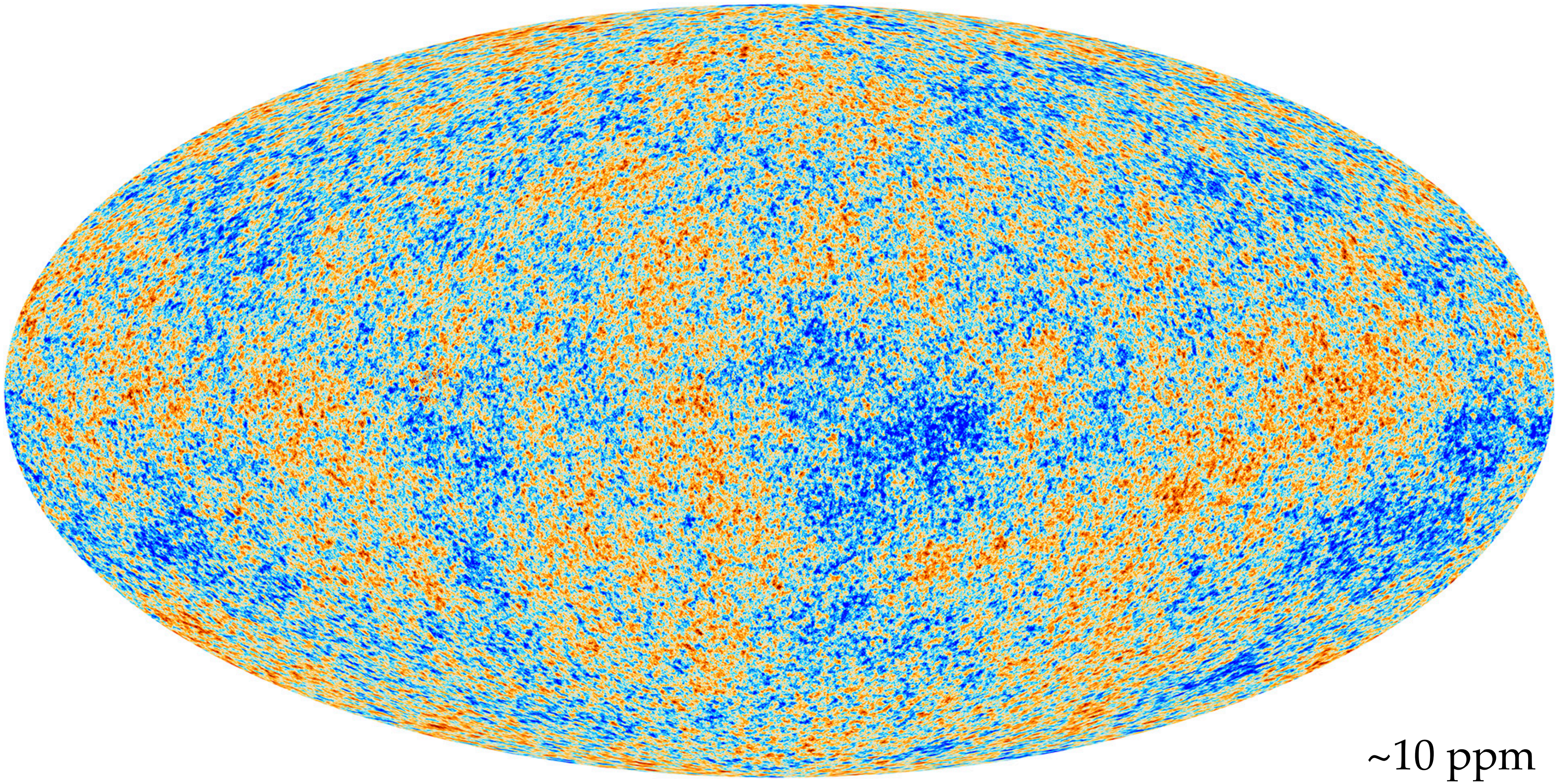
Jaideep Taggart Singh
National Superconducting Cyclotron Lab & Michigan State

CUSTIPEN-IMP-PKU Workshop on Physics of Exotic Nuclei
December 12-15, 2016 Huizhou, Guandong, China

Voyager 1 is still OK!



Cosmic Microwave Background Radiation



~10 ppm
fluctuations

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

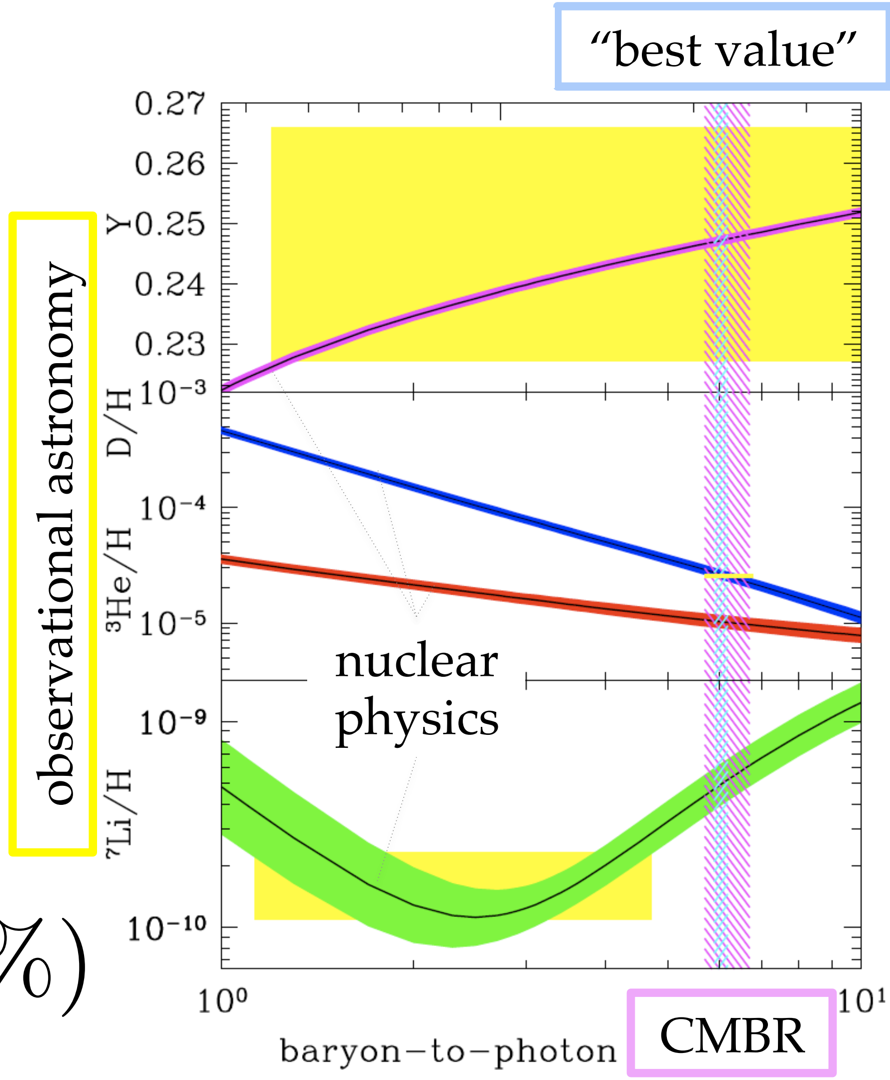
Baryon Asymmetry of Universe

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

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

$$= 0.0000000061(5\%)$$

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



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

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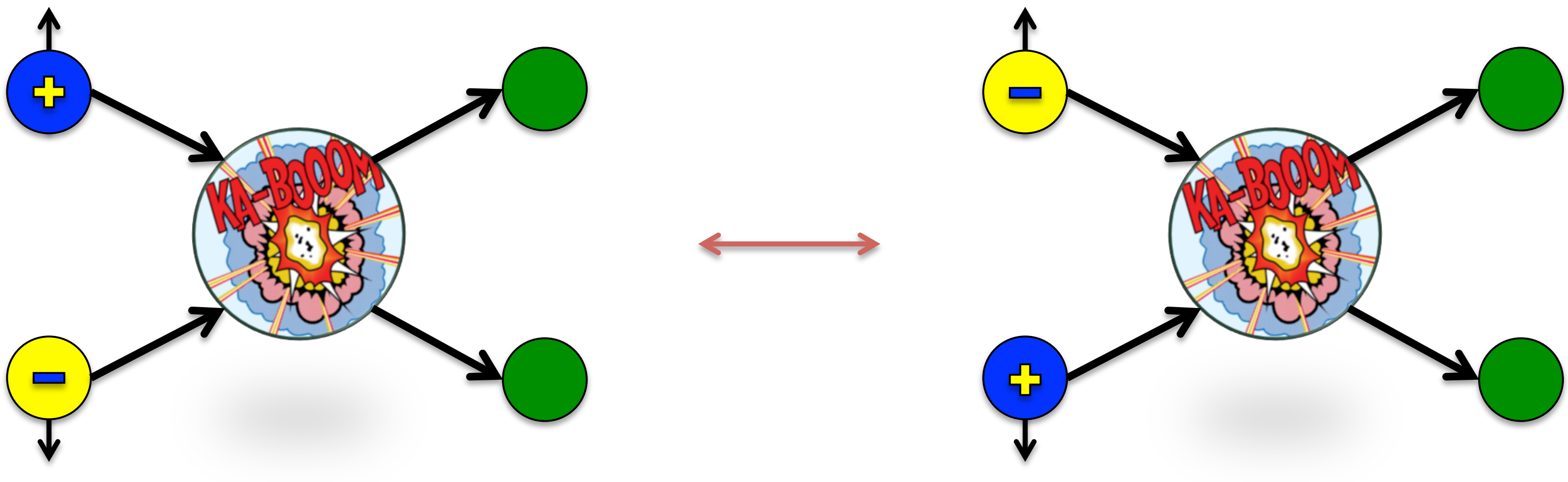
1. A baryon number violating interaction exists.
2. Departure from thermal equilbrium
3. ***Both C- & CP-symmetry must be violated.***

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

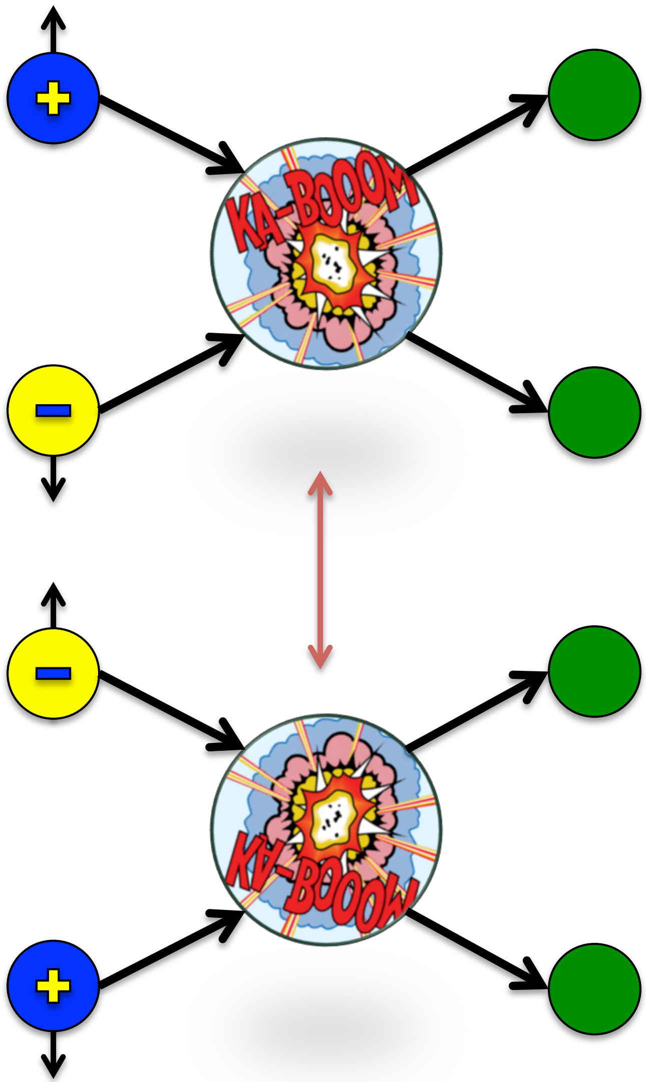
+

180º rotation

+x to –x

+y to –y

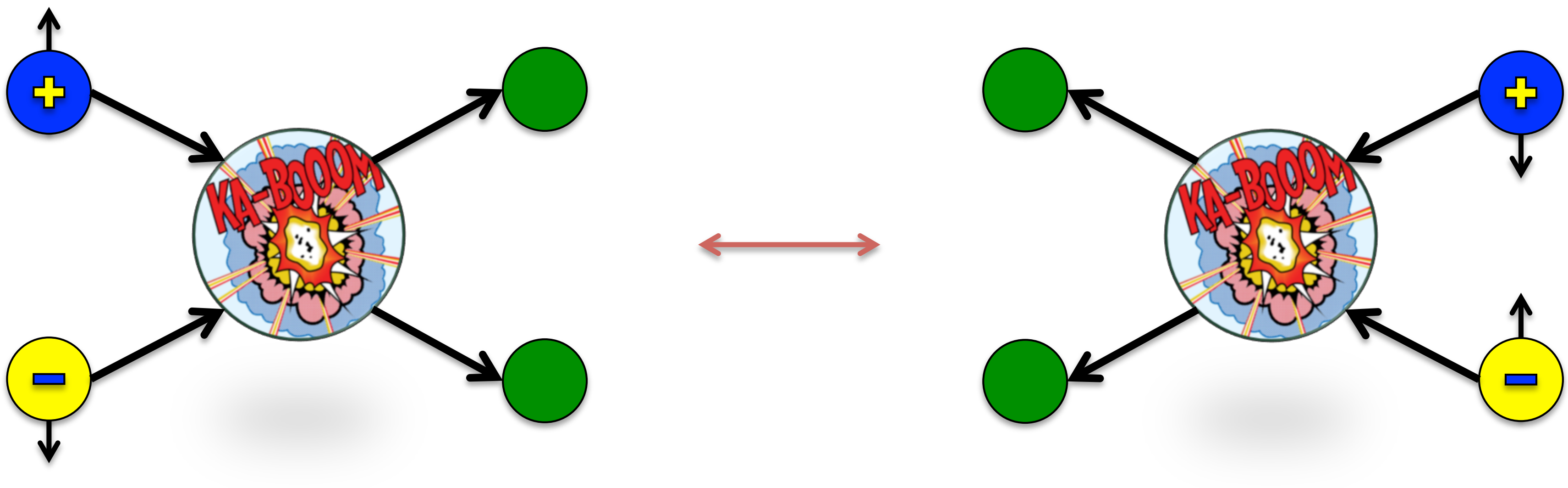
+z to -z



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

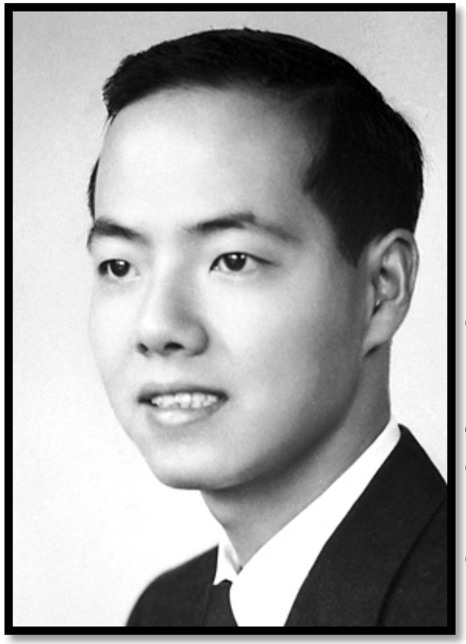
T: Time Reversal

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?



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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*

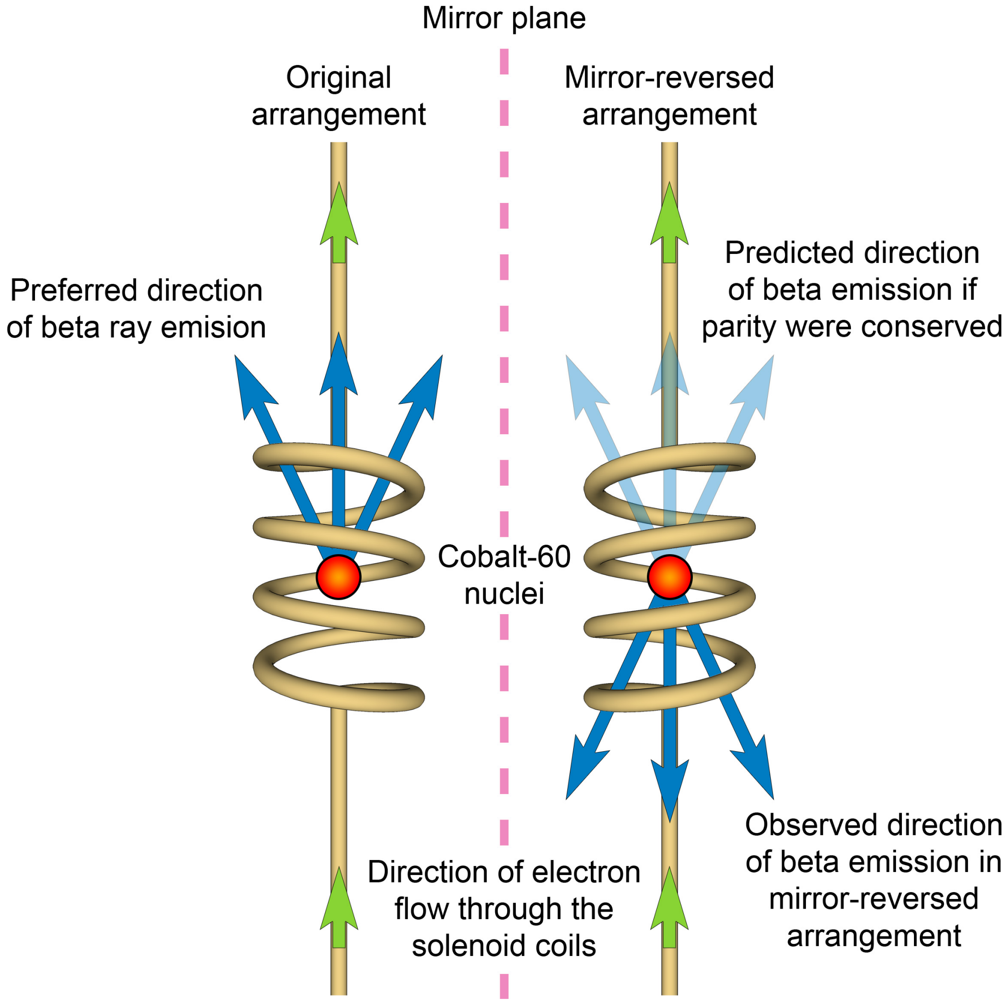
(Received June 22, 1956)

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)!

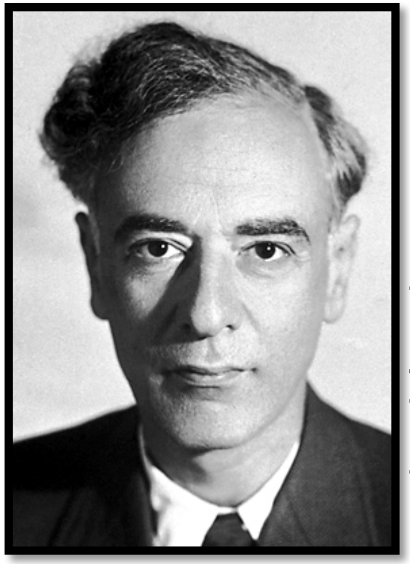
AIP Emilio Segre Visual Archives

My All Time Favorite Science Super Hero



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

1957: Is CP conserved?



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ON THE CONSERVATION LAWS FOR WEAK INTERACTIONS

L. LANDAU

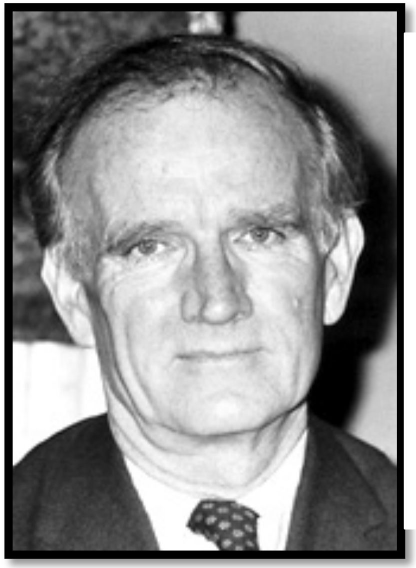
Institute for Physical Problems, USSR Academy of Sciences, Moscow

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)!



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

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C **K** **M**

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

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

Standard Model *CP*-Violation

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

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

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

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

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

New Massive Particles = More Phases

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

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

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

This is how things like Supersymmetry are expected to produce additional *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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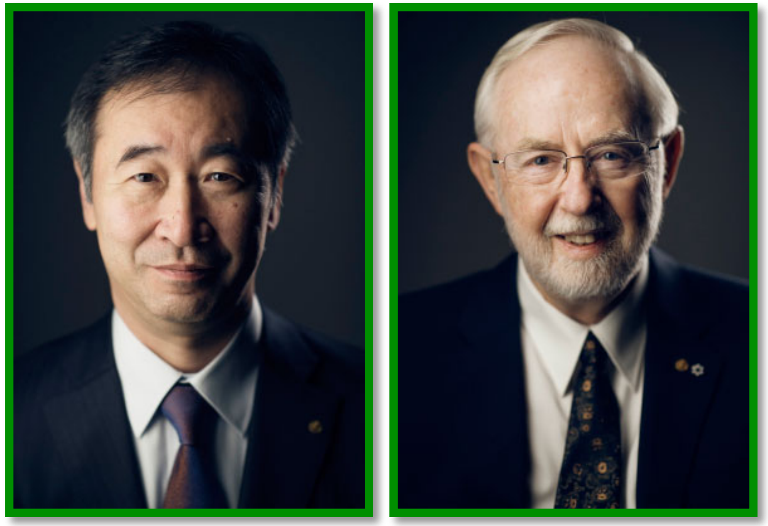

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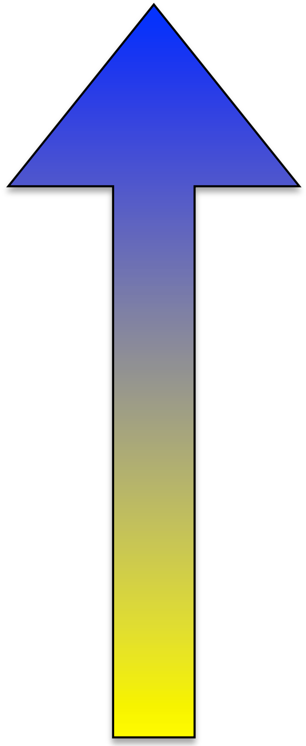
- Decays of B-mesons (like Kaons) [BABAR,KEK]
- Neutrinos have mass! (PMNS matrix)
- rare decays at LHC
- *electric dipole moments: If CPT is good,* **then *T*-violation can be used to search for new sources of *CP*-violation!**

EDM: Measures the Separation of Charges

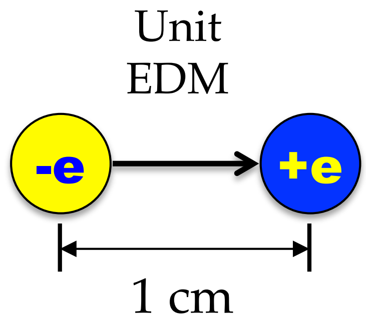


$$\vec{d}$$

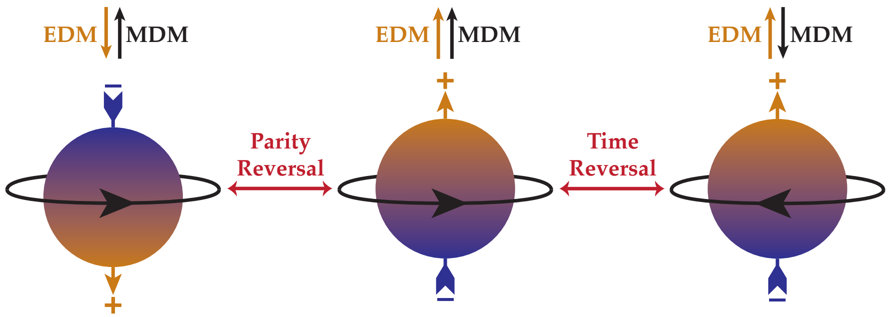
"Thunder Cloud as Generator #2" (1971) by Paterson Ewen [Art Gallery of Ontatrio]

EDMs to *E*-fields as MDMs to *B*-fields (somewhat)

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



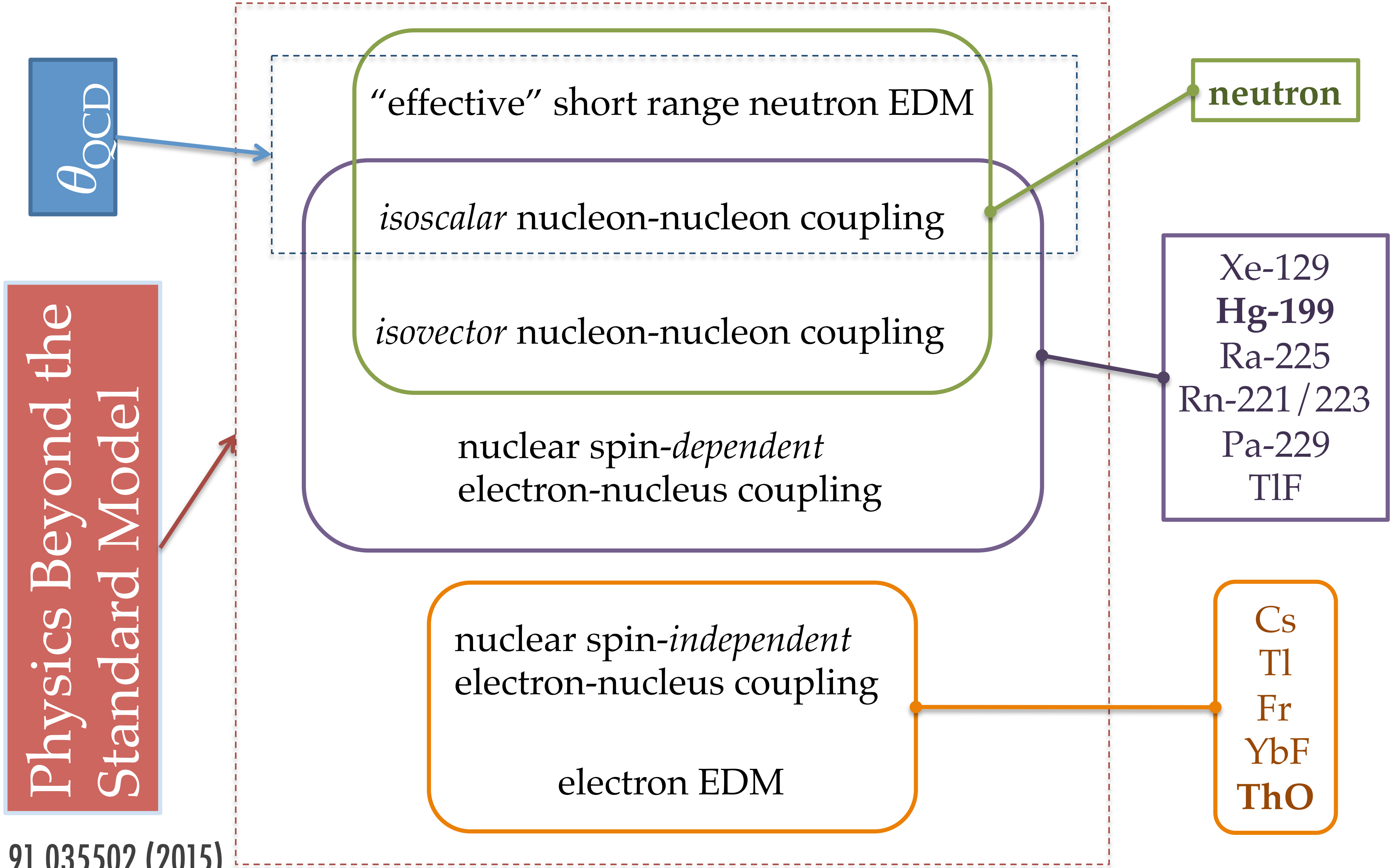
	P-parity	T-time reversal
$\vec{S}$	$+$	$-$
$\vec{B}$	$+$	$-$
$\vec{E}$	$-$	$+$
$\vec{S}\cdot\vec{B}$	$+$	$+$
$\vec{S}\cdot\vec{E}$	$-$	$-$



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

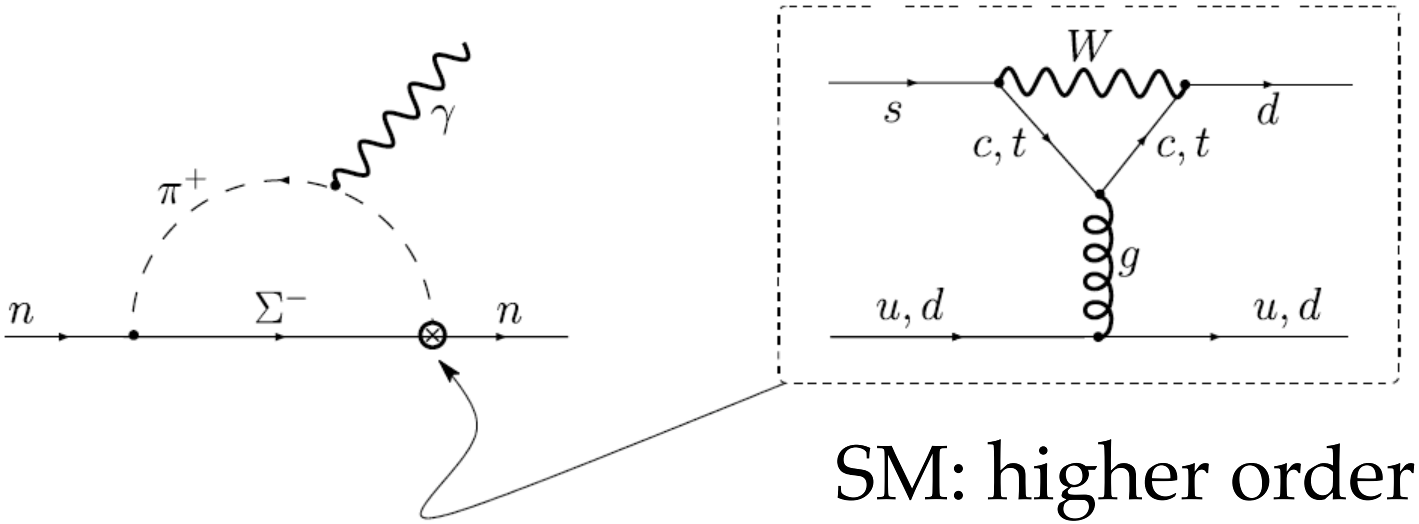
Experimentalist: ...blah blah blah Wigner-someone something…

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

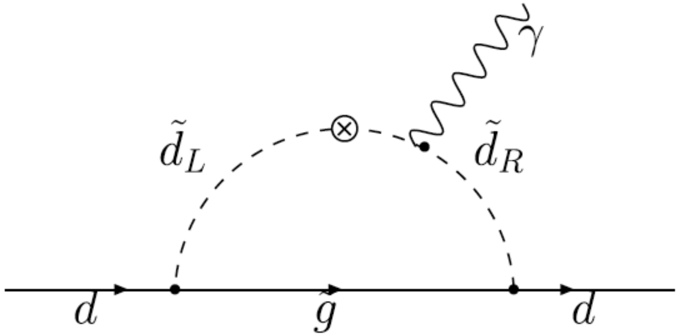


PRC 91 035502 (2015)

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	$\sim 10^{-10}$	cold ThO beam (Harvard/Yale)
Neutron	300	$\sim 10^{-4}$	UCN in bottle (ILL)
Nuclear	0.074	$\sim 10^{-7}$	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->Munich)
Ra-225	140000	1.000	0.001	Ra atoms in a laser trap (Argonne)

Summary – Part 1/3: Motivation

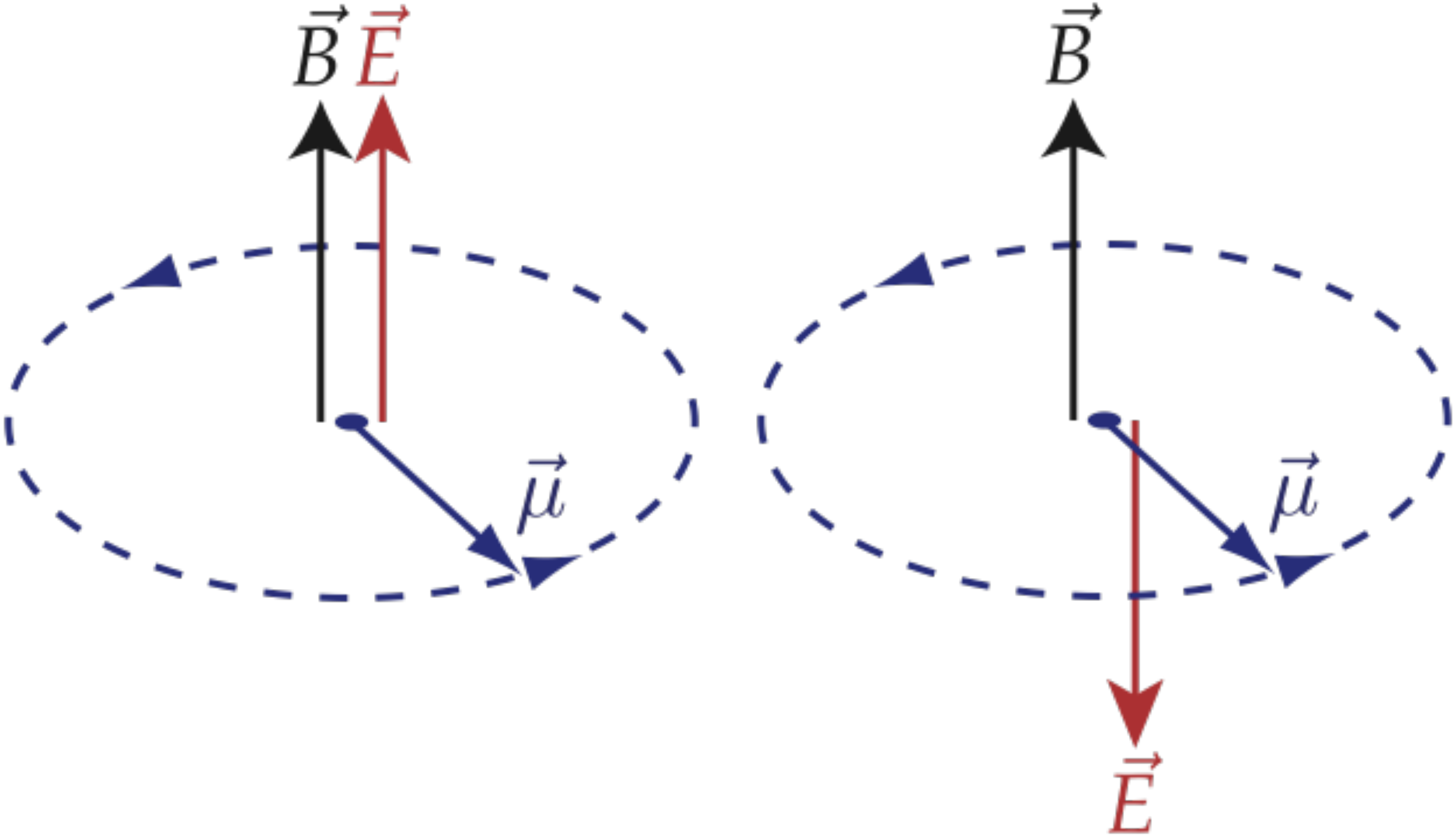
1. There is more (visible) matter than antimatter in the Universe.
2. ~~CP~~ is the key ingredient needed to explain this observation.
3. ~~CP~~ has even been observed…but it is too feeble!
4. New physics naturally and generically predicts more ~~CP~~.
5. EDMs are an unambiguous signature of ~~CP~~.
6. At the present & planned levels of experimental sensitivity, any observation of a nonzero EDM is due to New Physics.

From the 2015 US Nuclear Science Advisory Committee Long Range Plan:

"The observation of a nonzero EDM in any of the above searches would constitute a ***major discovery with significant implications for the origin of matter*** and the nature of new forces in the early universe. It would also have implications that go well beyond nuclear physics. Since we do not know where those forces might be hiding, ***a broad search strategy using a variety of systems is vital***." p. 74

"Improved sensitivities by [x30] would imply ***reach on the scale*** of CPV interactions in the 10–50 TeV range, ***inaccessible at high-energy colliders today*** ..." p. 72

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

"experimental efficiency"

integration time

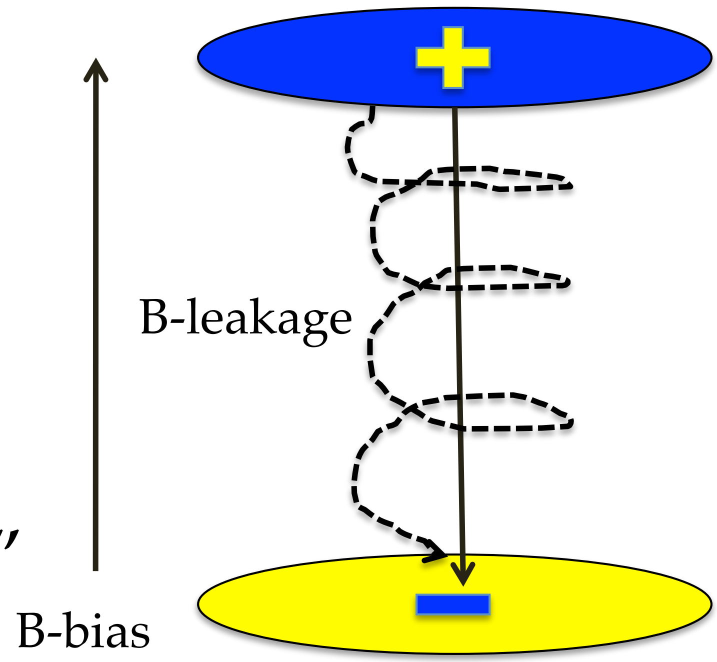
Magnetic Field Instabilities & False Effects!

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

challenge!

Instabilities adds noise & limits the statistical precision.

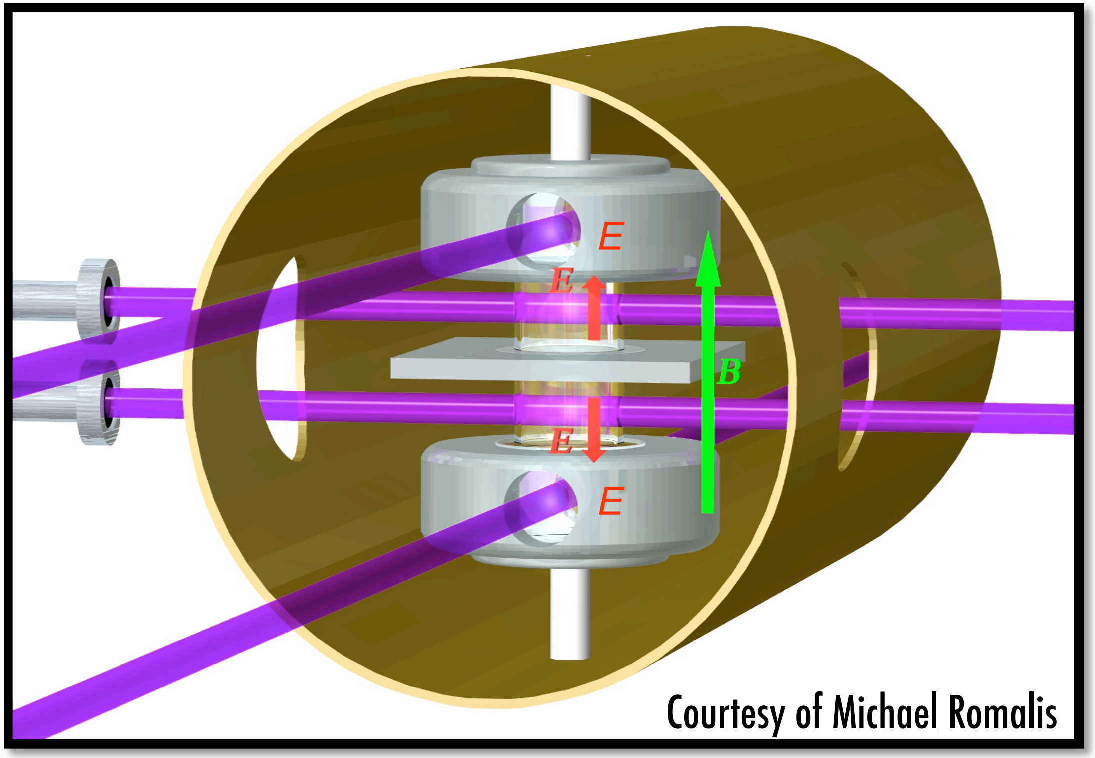
False effects, things which change sign with the electric field, are nasty: "leakage current"



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
Residual field inside of magnetic shield	1E-09
All of my clothes @ 10 cm	1E-10
Human Brain @ surface	1E-12
"SQUID" magnetometer noise floor (1 s)	1E-15
sensitivity of Hg-199 EDM experiment	1E-17

The Seattle Hg-199 EDM Search



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

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

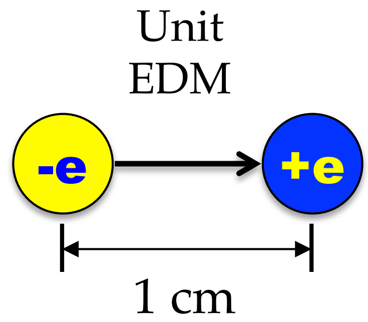
$$\bar{\nu} = 2\mu B/h = 16 \text{ Hz}$$

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

The best limit on atomic EDM:

EDM(^{199}Hg) < 7.4×10^{-30} *e*-cm (95% C.L.)

Graner et al., PRL 116, 161601 (2016)



Problem: Schiff Shielding in Diamagnetic Atoms

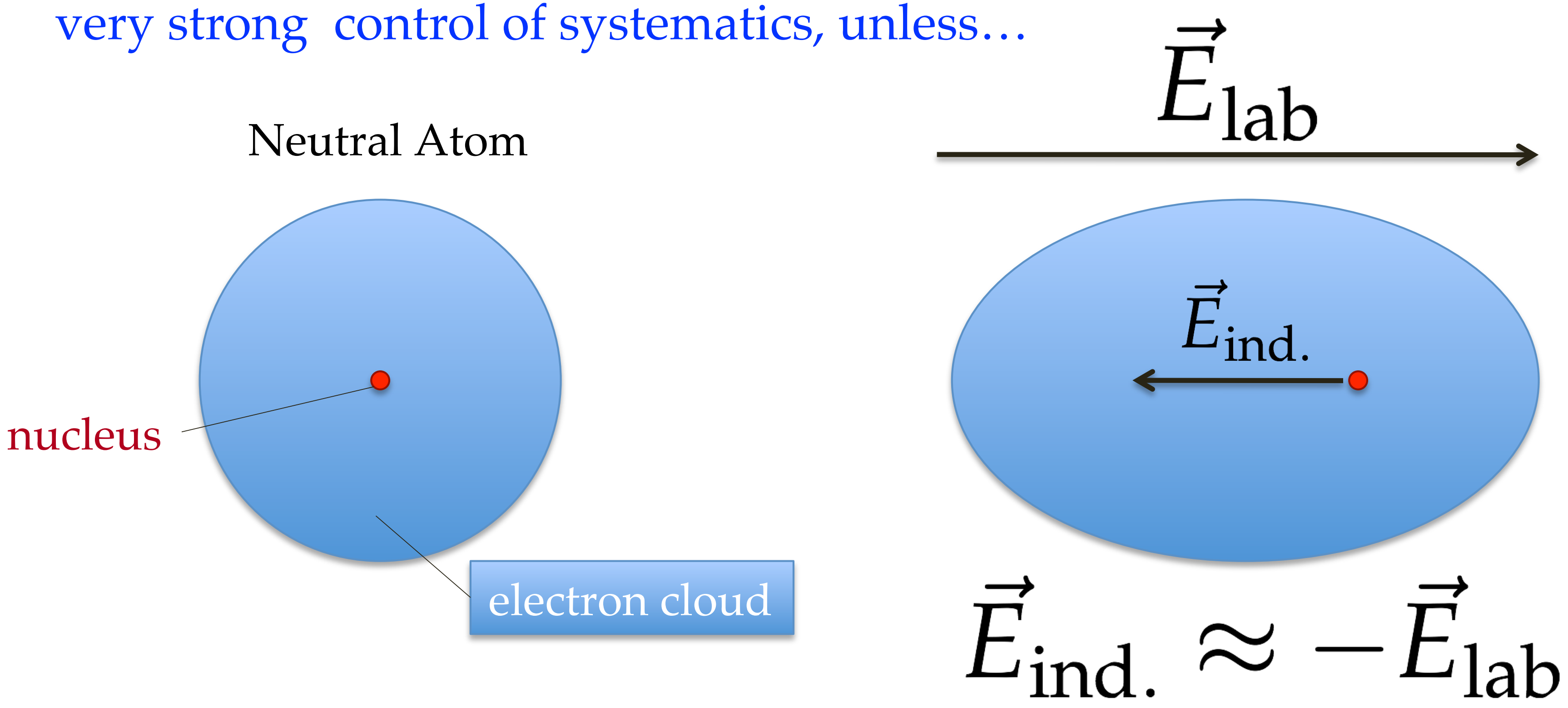
- Shielding in Diamagnetic Atoms

  Schiff PR 132, 2194 (1963)

- Nuclear CPV are suppressed by 10^{-2} to 10^{-6}
- Need ultra high frequency precision and very strong control of systematics, unless…

Schiff Moment

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



The Melancholy Tale of Effective *T*- & *P*-Violating Nucleon-Nucleon Isovector Couplings

$$\text{New Physics} \rightarrow d_{\text{chromo}-\text{EDM}}$$

$$d_{\text{chromo}-\text{EDM}} \times [\text{QCD}] = a_1$$

$$a_1 \times [\text{Nuclear Structure}] = S$$

$$S \times [\text{Atomic Structure}] = d_{\text{atom}}$$

Three New Lattice QCD Faculty Hires @ MSU
67% Interested in EDMs!

$$\text{New Physics} \rightarrow d_{\text{chromo-EDM}}$$

Theory calculations do not rule out [QCD] = 0!

$$\boxed{d_{\text{chromo-EDM}} \times [\text{QCD}] = a_1}$$

Andrea Shindler (NSCL) and Huey-Wen Lin (P&A)

$$a_1 \times [\text{Nuclear Structure}] = S$$

$$S \times [\text{Atomic Structure}] = d_{\text{atom}}$$

Nuclear Structure is Currently More Challenging than Atomic Structure for EDMs

$$\text{New Physics} \rightarrow d_{\text{chromo}-\text{EDM}}$$

$$d_{\text{chromo}-\text{EDM}} \times [\text{QCD}] = a_1$$

Theory calculations do not rule out [^{199}Hg Nuclear Structure] = 0!

$$a_1 \times [\text{Nuclear Structure}] = S$$

Witek Nazarewicz, Erik Olsen (Postdoc), Y. Maxwell Cao (Graduate Student)

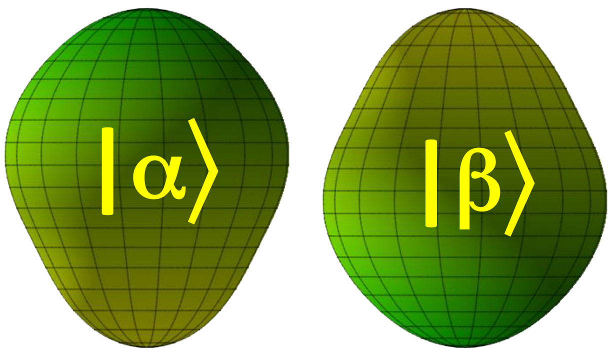
$$S \times [\text{Atomic Structure}] = d_{\text{atom}}$$

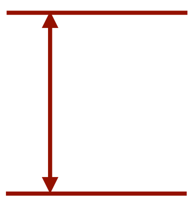
Octupole Deformation Equals Big Schiff Moment

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

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

Parity Doublet





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

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

ΔE

$$S \propto \frac{[\text{quadrupole deformation}] \times [\text{octupole deformation}]^2}{\Delta E}$$

- Nuclear analogy to diatomic molecules
- 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)
- Candidates include isotopes of Radium, Radon, and other neutron-rich lanthanides and actinides

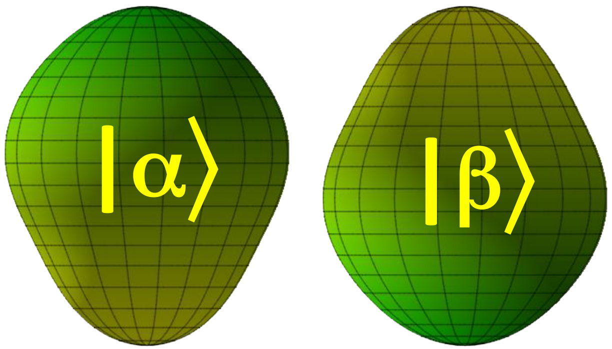
Candidate Isotopes?

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

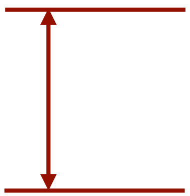
$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet

$$S \propto \frac{[\text{quadrupole deformation}] \times [\text{octupole deformation}]^2}{\Delta E}$$



Isotope	ΔE (keV)	half-life (sec)
Hg-199	1800	stable
Rn-221/223	~10^2?	10^3
Ra-225	55	10^6
Pa-229	(0.06 +/- 0.05)?	10^5



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

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

ΔE

Pa-229: I. Ahmad et al Phys. Rev. C **92**, 024313 (2015)

Theory Difficult = Discovery Potential!

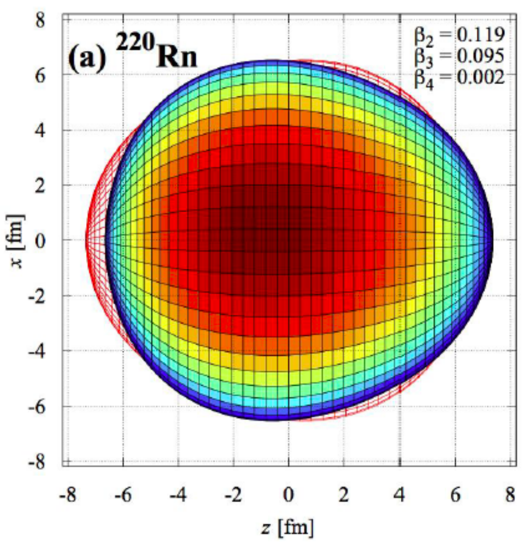
type	Hg-199	Ra-225	ratio*3	Hg-199 Ref
SIII	0.005	7.0	4300	PRC 82 015501 (2010)
SkM*	-0.027	21.5	-2400	PRC 82 015501 (2010)
SLy4	-0.006	16.9	-8600	PRC 82 015501 (2010)
SkO′		6.0		
DE05	0.071			PRC 72 045503 (2005)
DS03	0.055			PAN 66 1940 (2003)
“Best”	+/-(0.02)	6.0	+/-(900)?	Prog. PNP 71 21 (2013)

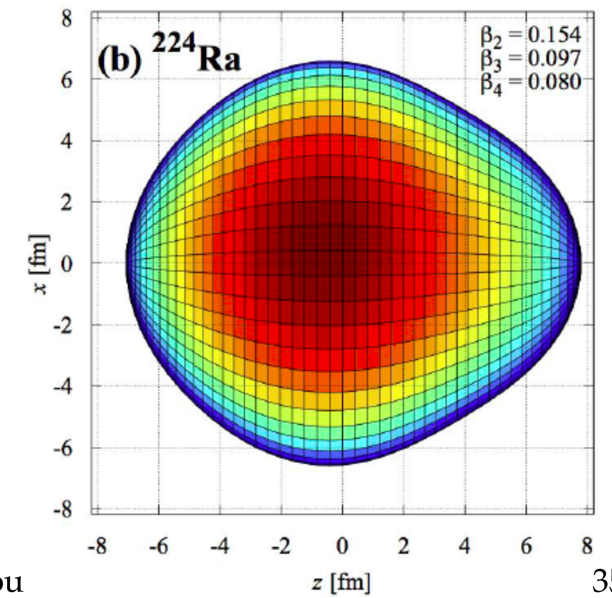
- Isovector coupling is given by “chromo”-EDMs
- Nuclei are the most sensitive to this source of new physics
- Opportunity for octupole-deformed nuclei

Summary – Part 2/3: Octupole-Deformed Nuclei

1. Atoms with octupole-deformed nuclei have orders of magnitude more "physics sensitivity" to ~~*CP*~~ than Hg-199.
2. "Low precision" searches without the need for tight control of systematics can be competitive and/or reach beyond Hg-199.
3. Interpretation of EDM result is more straightforward because of smaller theoretical uncertainties.
4. **Need both improved theory calculations and development of new experimental techniques to identify the best isotopes.**

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





EDM Experiments Are Like 皮蛋

1. Produce rare atoms with octupole-deformed nuclei.

http://www.souschef.co.uk/century-eggs.html

2. Filter, collect, concentrate, and store atoms.

http://dreamstime.com/royalty-free-stock-images-century-eggs-image13199369

3. Interrogate with high "experimental efficiency" and **integrate for a long time**.

http://foododdity.com/century-eggs-preserving-pre-conceptions/

4. Report a null (0) measurement.

http://www.tastehongkong.com/tag/century-egg/

Some Practical Experimental Considerations

- Produce/collect as many atoms as possible
  - harvesting from FRIB beam dump (new faculty: Greg Severin)
  - **is this a possibility at HIAF?**
- Interrogate atoms for as long as possible
  - spin-1/2 is ideal but not necessary
- Use as high of an electric field as possible
  - neutral atoms in a vacuum
  - ions in an optical crystal (large residual crystal field)
  - **fully stripped atoms in a storage ring (no Schiff Shielding!)**
- High "experimental efficiency"
  - optical is usually best (many photons per atom)
  - **beta decay or spin-dependent scattering (low analyzing power)**

ultimate 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

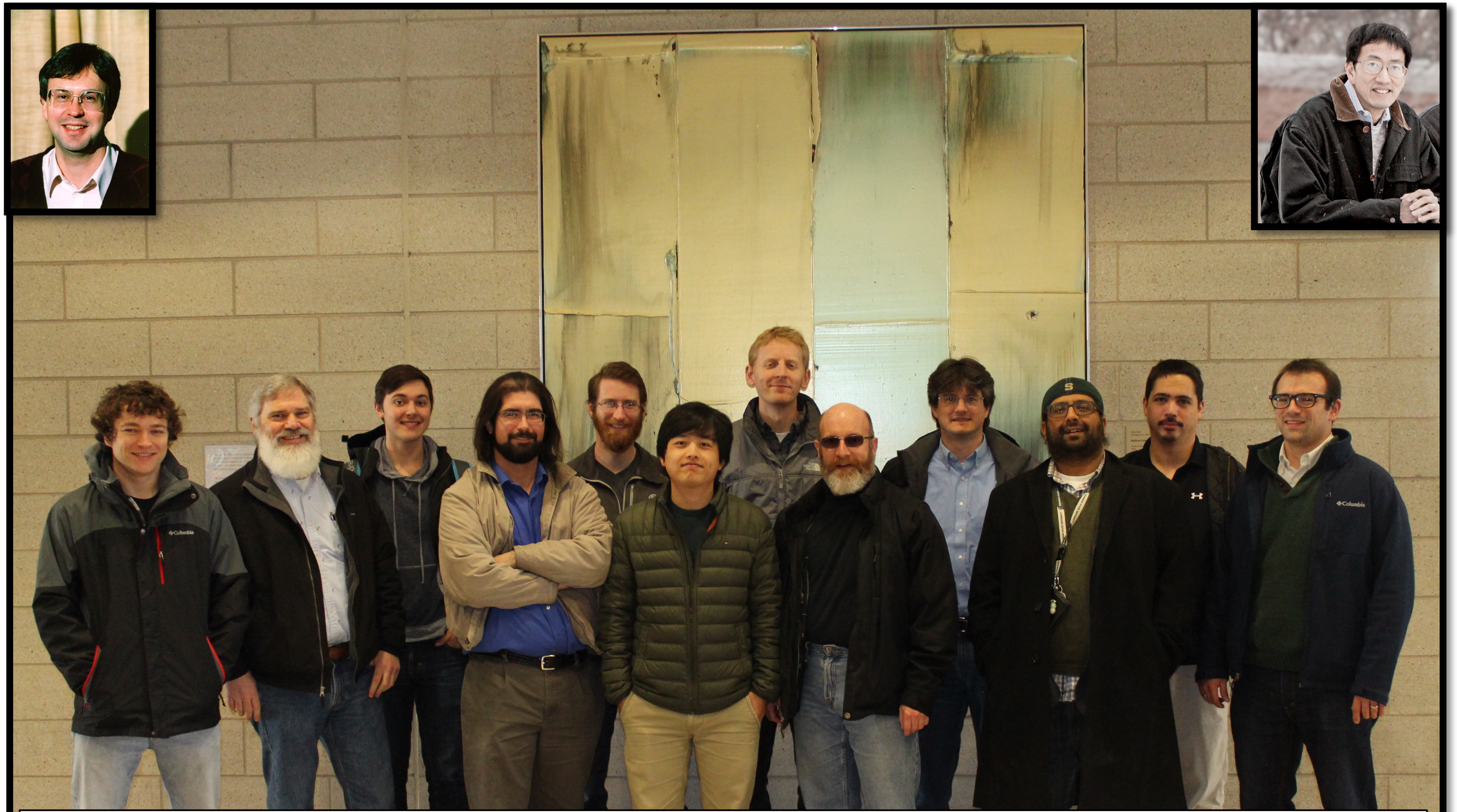
E, Electric field

ε, "experimental efficiency"

T, integration time

τ, interrogation time

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

Source of Radium Atoms

^{233}U
159 kyr

α →

^{229}Th
7.3 kyr

α →

^{225}Ra
15 d

β →

^{225}Ac
10 d

α →

Fr, Rn,…
~4 hr

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

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

FRIB

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

For EDM:

^{225}Ra

Nuclear Spin = ½

$t_{1/2}$ = 15 days

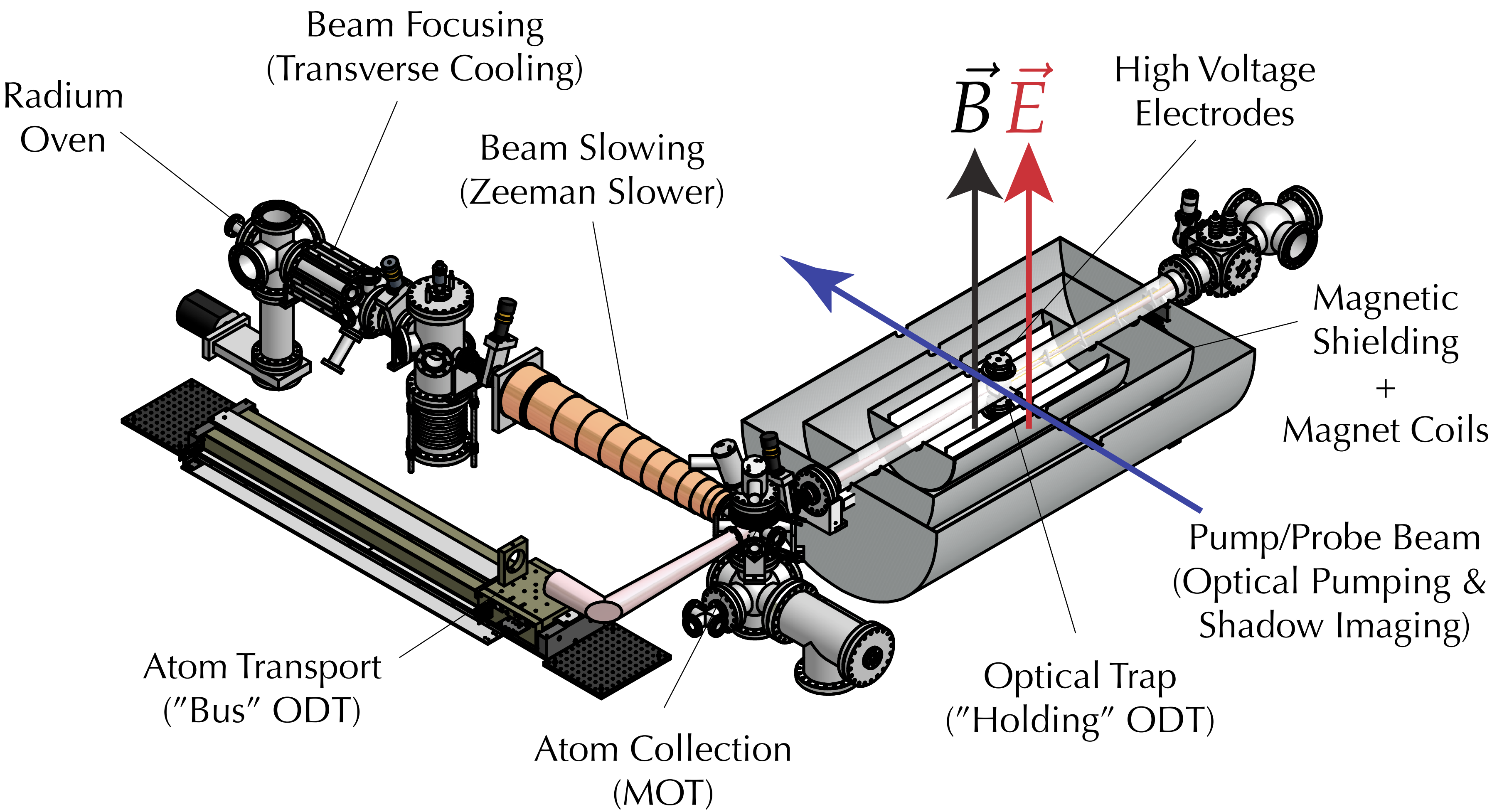
For Testing:

^{226}Ra

Nuclear Spin = 0

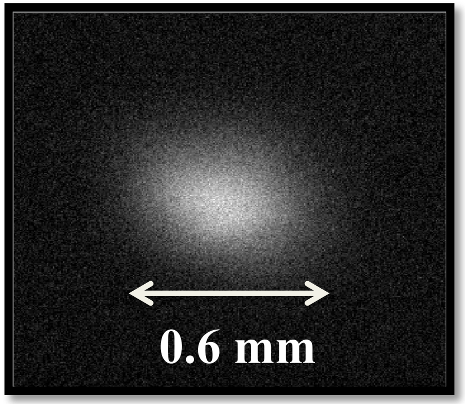
$t_{1/2}$ = 1600 yrs

Laser Trap Ra EDM Experimental Layout

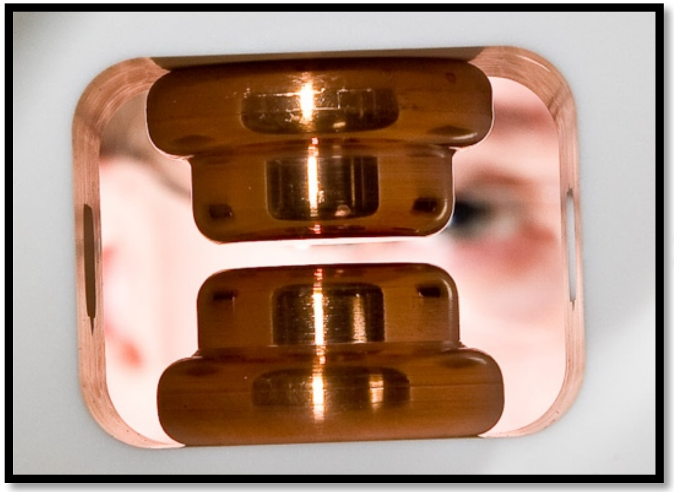


Collecting & Transporting Ra-225 Atoms

Guest et al., PRL 98 093001 (2007)

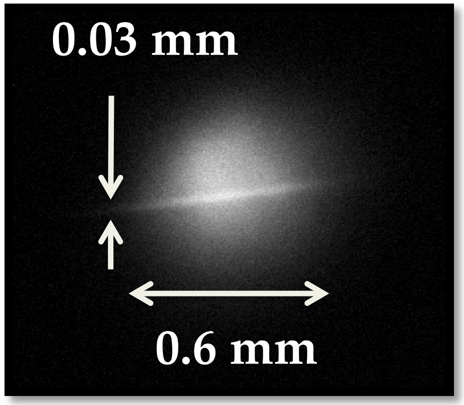


^{226}Ra MOT
20,000 atoms



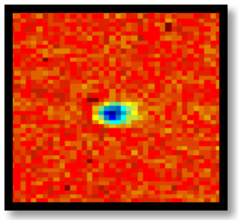
2 mm

Parker et al., PRC 86 065503 (2012)

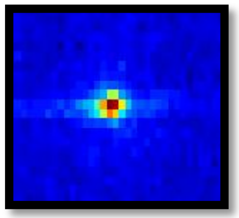


MOT + ODT
20,000 atoms

1.3 mm



1.3 mm

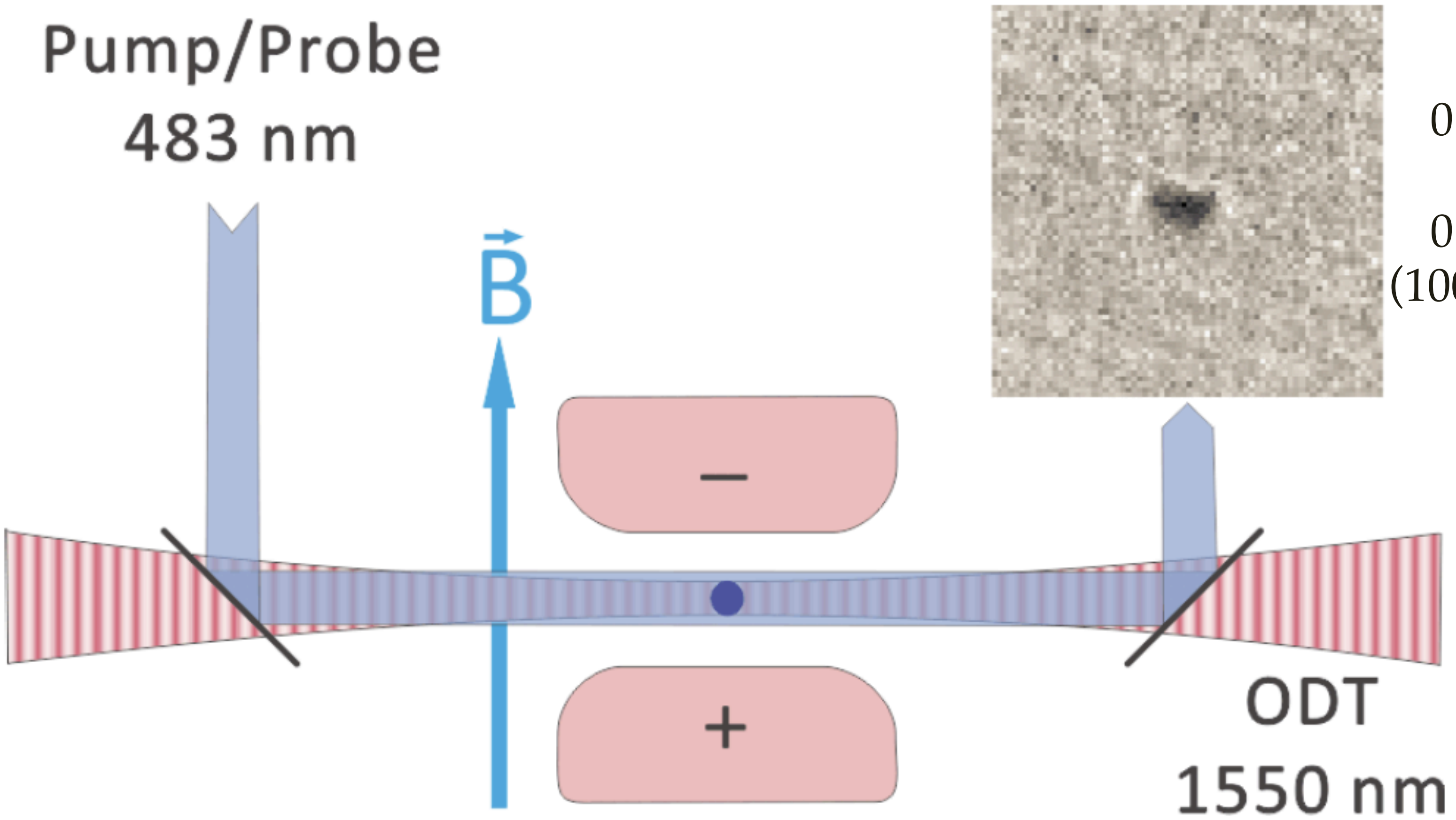


3000
atoms

Absorption
Imaging

Fluorescence
Imaging

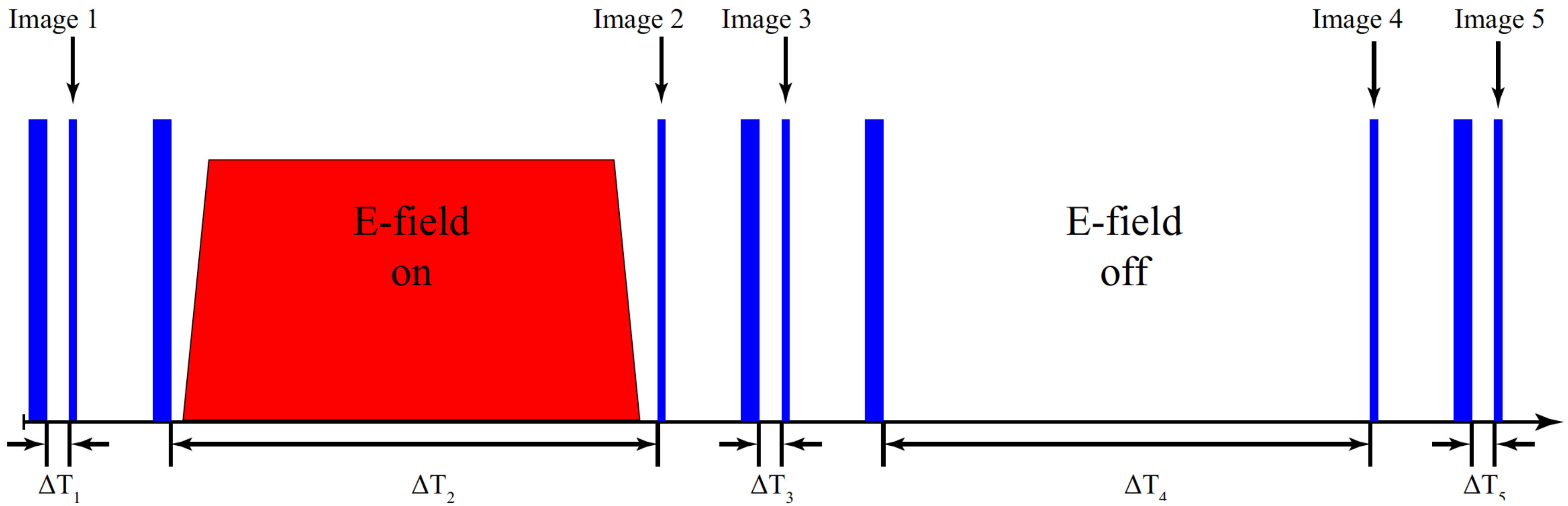
Image of Shadow Created by Atomic Absorption



0.5 mm
by
0.5 mm
(100 atoms)

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

Several Images are Taken During One Cycle



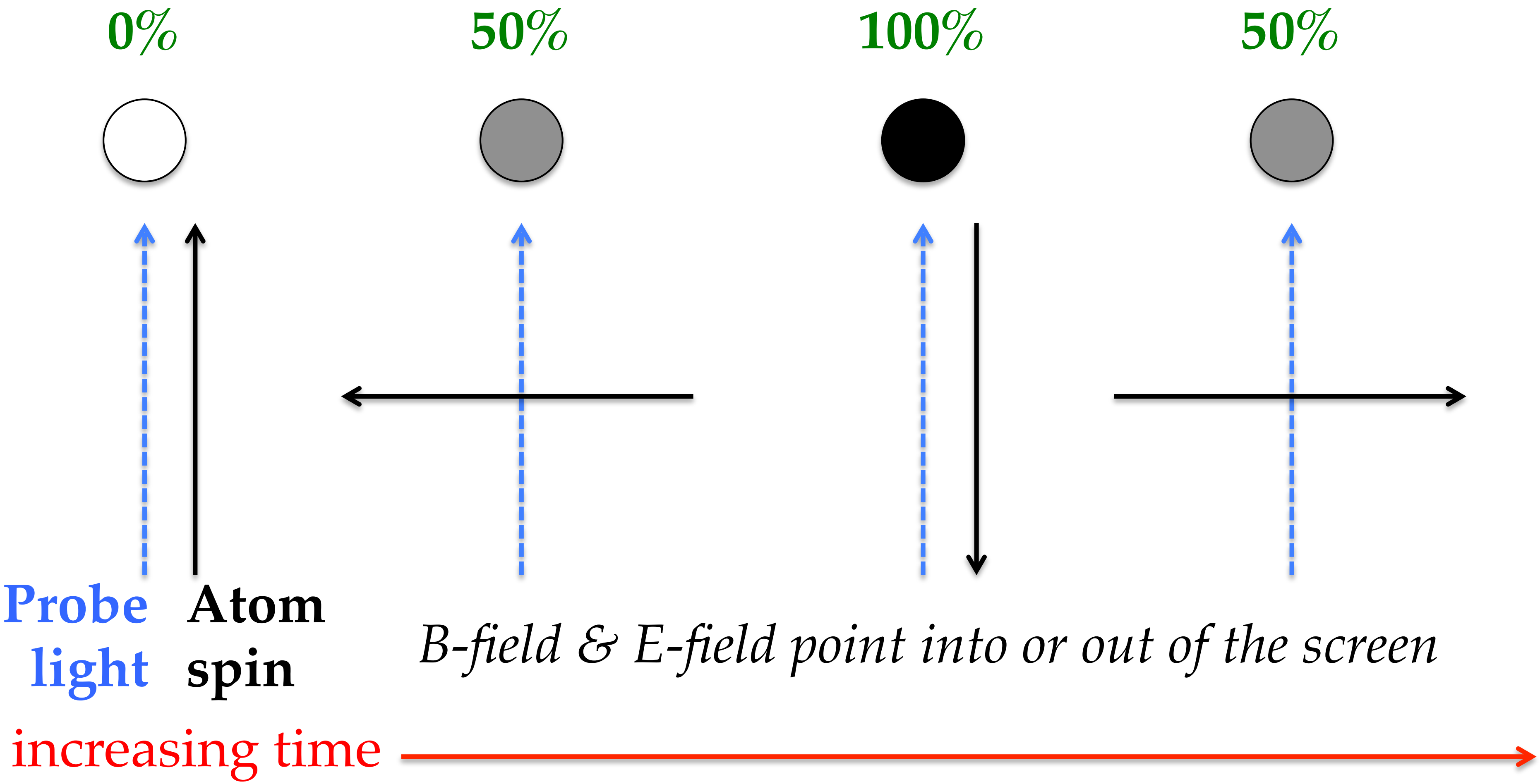
M. Bishof et al., Phys. Rev. C 94, 025501 (2016)

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

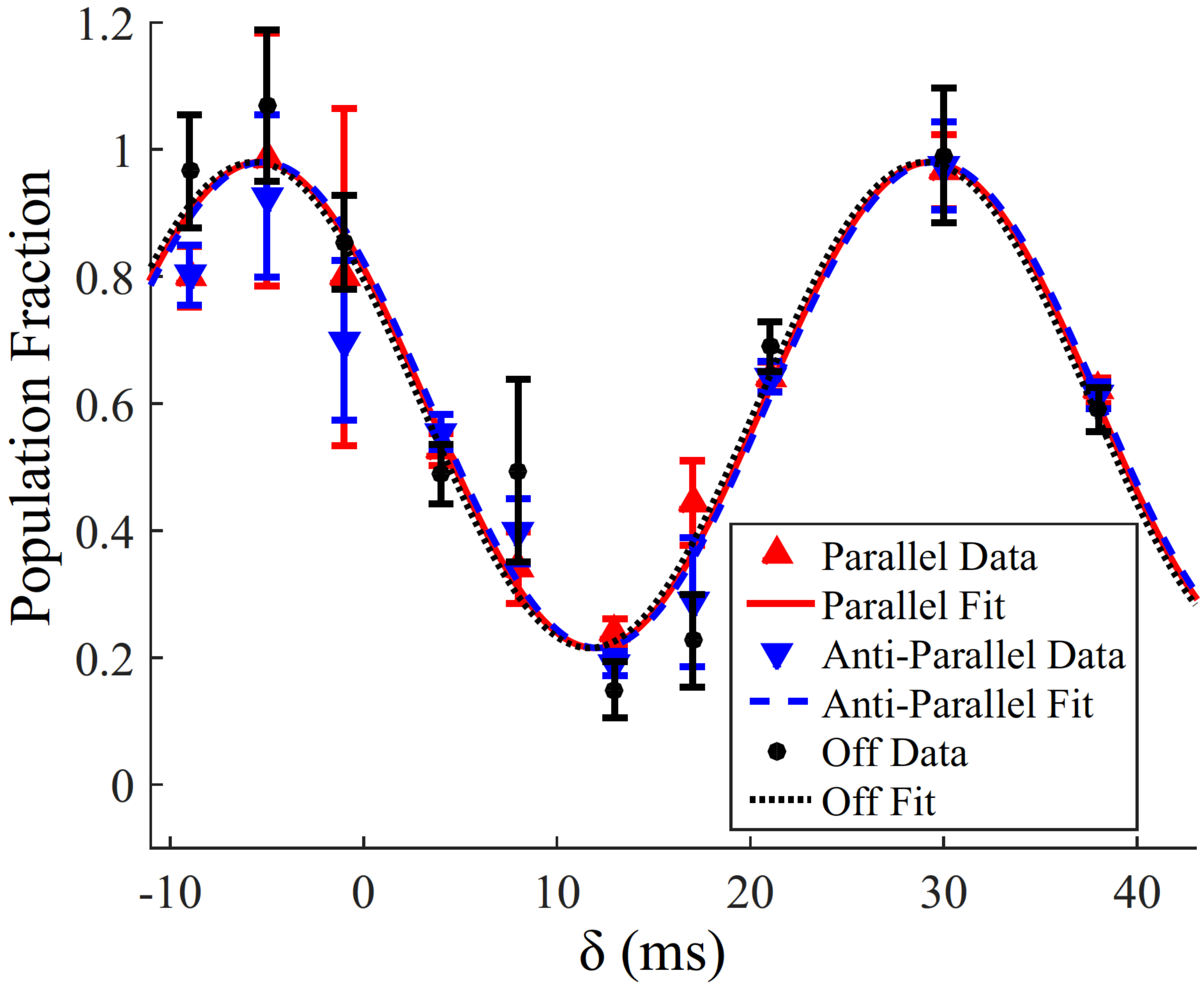
Data taken for electric parallel, anti-parallel, and off for different time delays.

Absorption Probability Oscillates at ~20 Hz

probability of absorbing probe light and creating a shadow:



Latest Ra-225 EDM Result (published August 3!)



Ra EDM: Towards More Statistics

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

June 2015: PRC 94, 025501: |d(Ra-225)| < 1.4×10^{-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.

Better control of experiment alignment: ANL

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

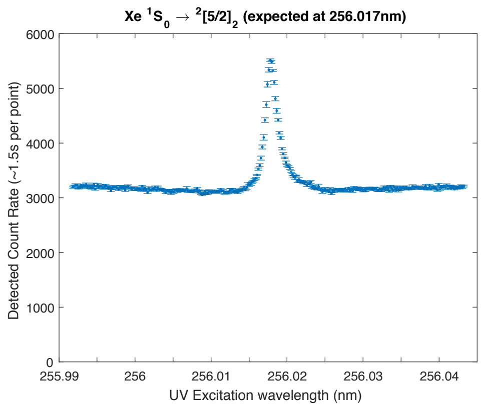
Under Development: Rn-221/223 & Pa-229

Radon EDM (PI: T. Chupp-Michigan)

Opportunities
- Easy to harvest (noble gas)
- Two-photon laser detection
- 100x intrinsic sensitivity of Hg-199
- stable surrogate: Xenon

Challenges
- Nuclear structure less well known
- spin-7/2 (short interrogation times)
- 25 min half-life
- 0.1x intrinsic sensitivity of Ra-225

first Xenon two photon detection using CW UV laser (Sept. 2016 @ MSU)



Protactinium EDM (Singh-MSU)

Opportunities
- Embed in a solid (half-life limited trap times and efficient trapping)
- Optical detection (unusually narrow optical transitions in solid)
- 100x intrinsic sensitivity of Ra-225
- 10^5x intrinsic sensitivity of Hg-199
- Optical single atom manipulation demonstrated for similar systems
- stable surrogate: Pr^{3+} in crystals
- many techniques already developed by Quantum Information community

Challenges
- Inhomogenous broadening
- 1.5 day half-life

Opportunity For Collaboration: Nuclear Storage Ring EDM

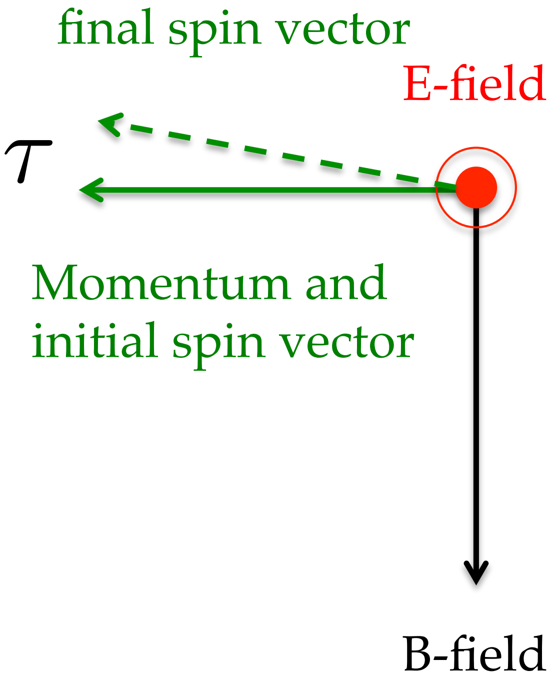
Opportunities

- Fully stripped ions – no Schiff Shielding (100x intrinsic sensitivity to neutral Ra-225)
- Could be used for many octupole-deformed species

Challenges

- low analyzing power from beta decay or spin-dependent scattering
- probably many things that I don't know about storage rings

$$\theta = dE\tau$$



Principle

1. Lock spin to momentum with appropriate *B*/*E*-fields
2. EDM would result in out of plane spin-precession
3. Out-of-plane (transverse) spin polarization is measured

References:

Khriplovich, I., Physics Letters B 444(12), 98 (1998)
Farley, F. *et al.* Phys. Rev. Lett. 93, 052001 (2004)

FRIB-CSC Postdoc: Come to MSU, learn about EDMs, teach me about storage rings!

Summary – Part 3/3

EDM searches using octupole-deformed species have enormous discovery potential relating to the origin of visible matter.

We need:

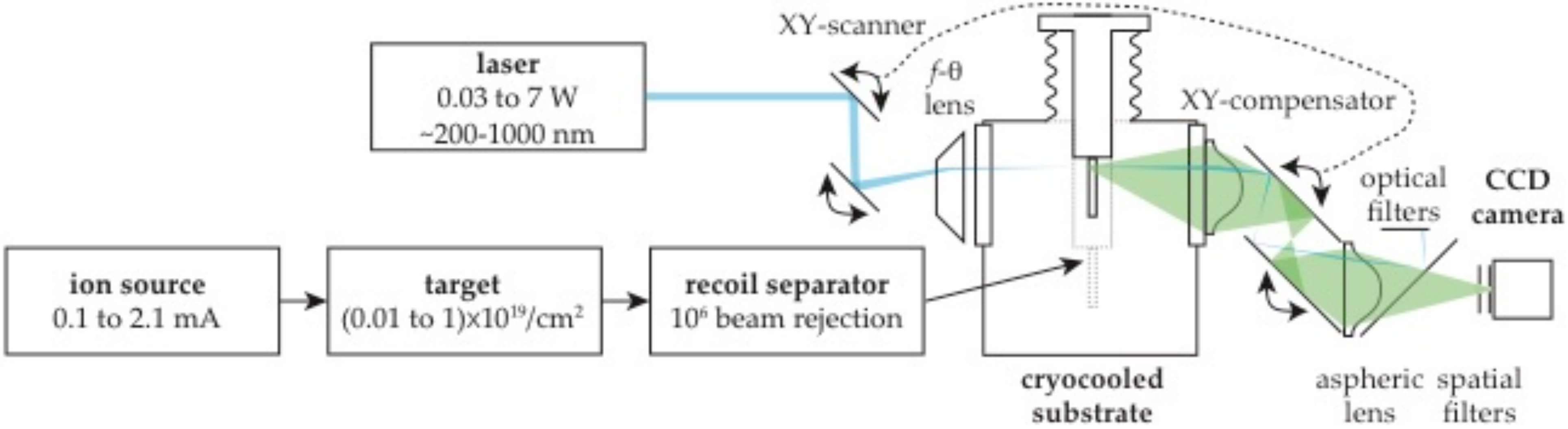
- a source of these rare isotopes (FRIB, HIAF,…)
- theory support to select isotopes and interpret results
- new experimental techniques (two photon magnetometry, ions in optical crystals, **storage rings**)

Ra-225 EDM (ANL/MSU/Kentucky/USTC) is making rapid progress – plans are underway for a new measurement in 2017!

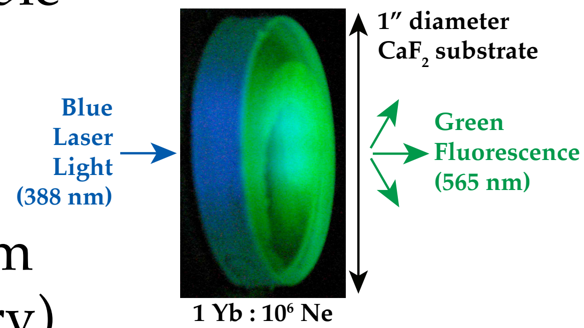
Alternative techniques for Rn/Pa are being developed at MSU.

Is a nuclear storage ring EDM feasible? Let's find out together!

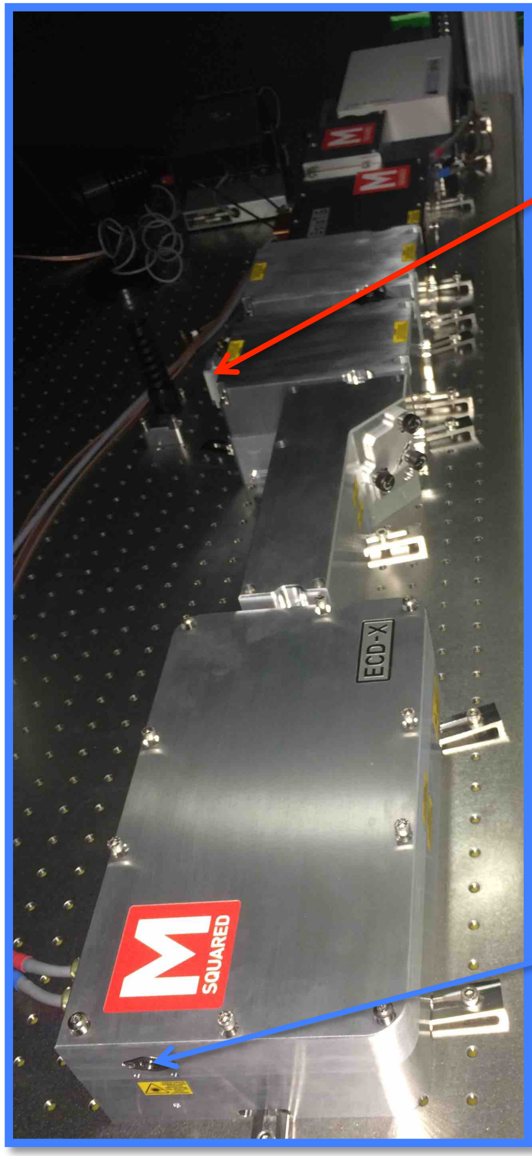
Single Atom Microscope (SAM) for Nuclear Astrophysics



- Efficient: cryogenic Ne film captures everything (both products and beam)
- Selective: product atoms identified by localized resonant laser excitation
- Sensitive: large shift (few nm to 100's of nm) between **excitation spectrum** and **emission spectrum** coupled with spatial & optical filtering makes optical single atom detection feasible
- Recoil separator is needed to:
  - minimize heat load on Ne film from beam
  - discriminate between isotopes
- Borrow off-the-shelf tools & existing techniques from Single Molecule Spectroscopy (2014 Nobel Chemistry)



We Have Fancy Lasers & SAM Should be Funded Soon!



Ti:Sapphire Laser
7 W & 5 W
700-1000 nm
computer tunable

Sum Frequency
Mixing Module
1 W @ 500-600 nm
computer tunable

Frequency Doubling
3 W @ 350-500 nm
0.2 W @ 250-300 nm
computer scannable