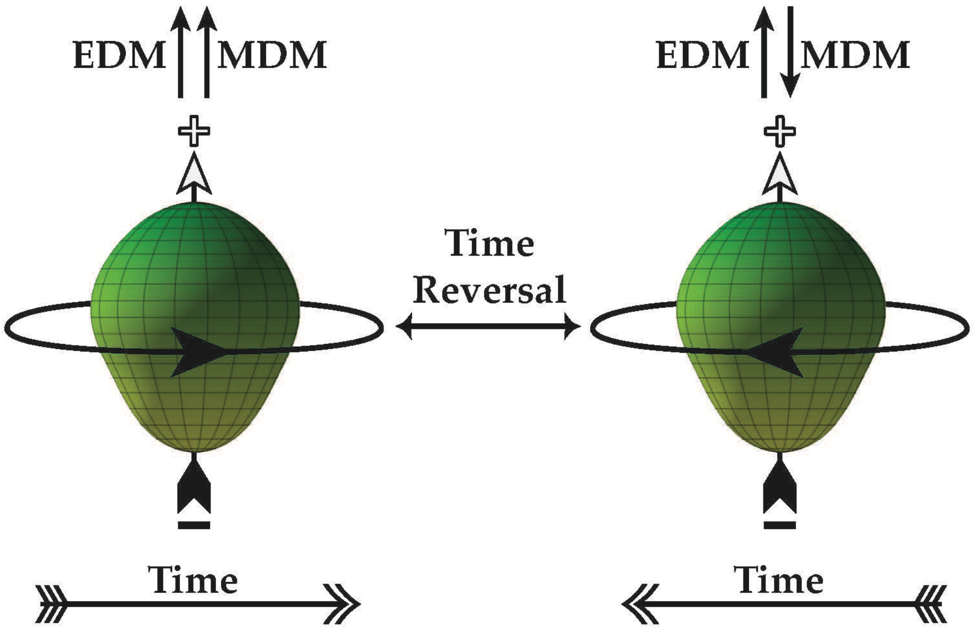
Electric Dipole Moment (1/2)

Today: Motivation & Background, The Atomic Ra EDM Experiment

Tomorrow: "Atomic" Parity Violation, Neutrons & Nuclei, & Radioactive Molecules



Carolyn Beatrice Parker
M.S. Physics MIT
1917-66

Jaideep Taggart Singh (he/him/his)
Michigan State University/FRIB

National Nuclear Physics Summer School 2024

Monday July 22, 2024 @ 14:00

Indiana University Bloomington

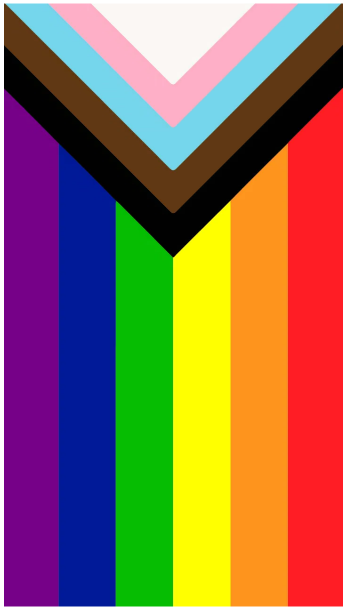
Swain Hall West 007 (Basement)

FRIB

SCAN ME

Introductions

- Theory
- Experiment
- Accelerator Physics
- Computational Physics
- Hadronic Physics
- Nuclear Structure
- Nuclear Astrophysics
- Fundamental Symmetries
- Neutrons
- Neutrinos
- Radiochemistry
- Other

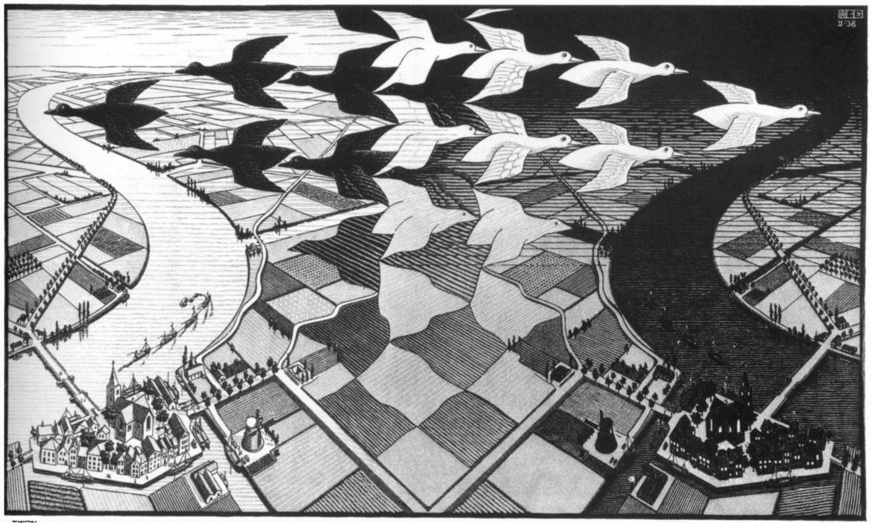


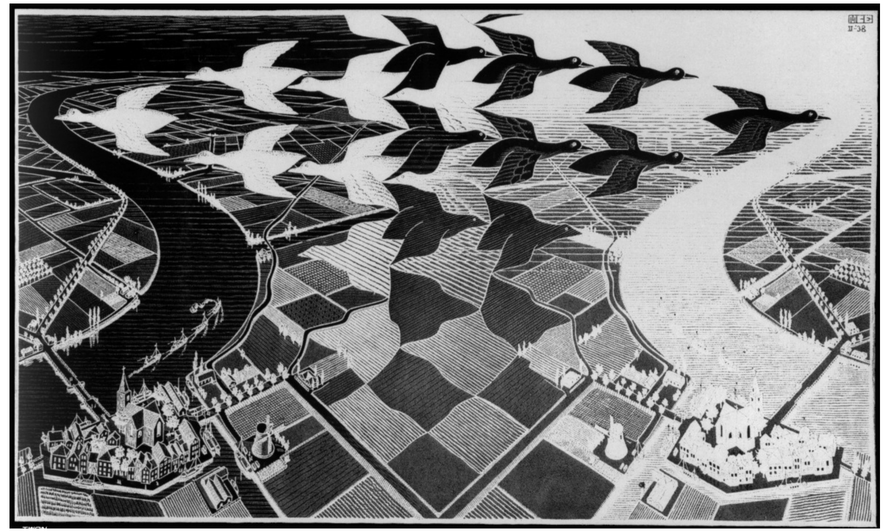
https://www.them.us/story/pride-flag-redesign

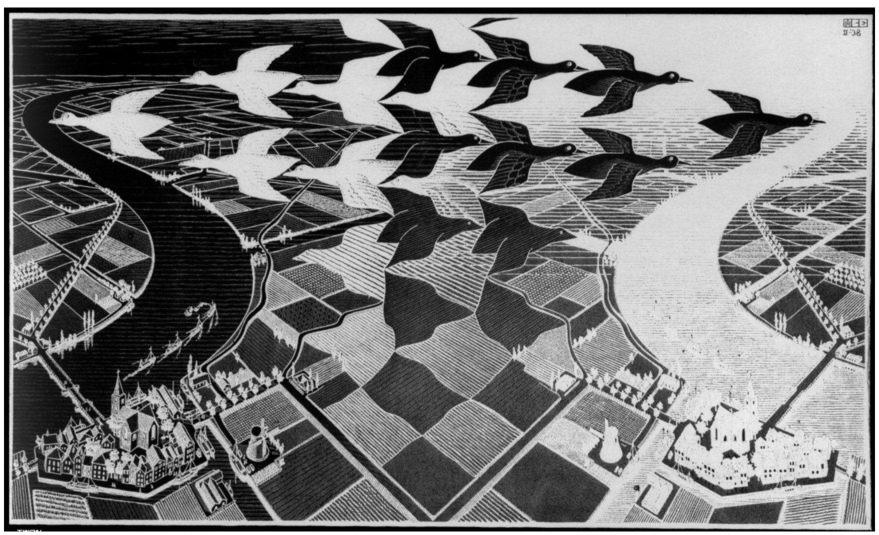
Benny (7 years old, they/them) @ DNP Hawaii 2023

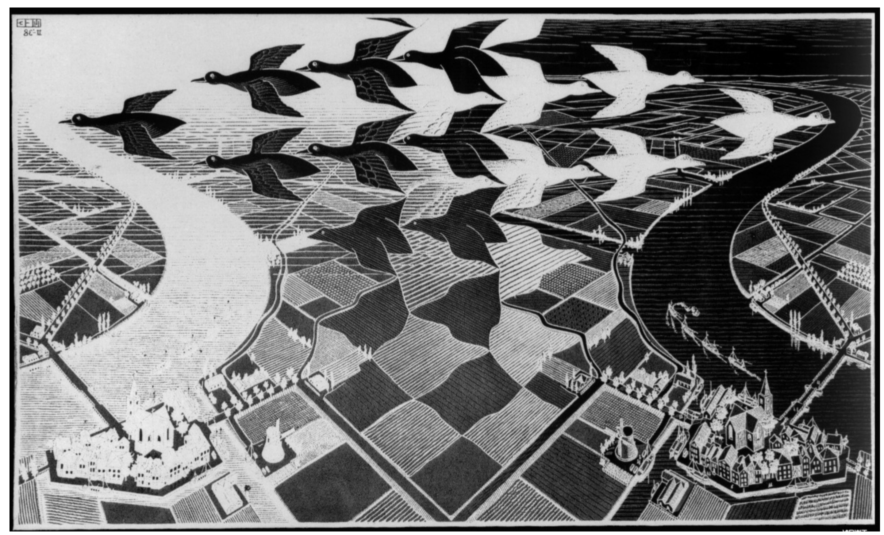
My Dad: Condensed Matter Theory (Pittsburgh) – Hindi Movies & Songs
My Wife: Artist from West Des Moines, Iowa
Me: New Delhi, India – Waterloo, Ontario, Canada – Lubbock, Texas – Pasadena, California – San Diego, California – Charlottesville, Virginia – JLab – Chicago, Illinois – Argonne National Lab – Garching/Munich, Germany – East Lansing, Michigan – National Superconducting Cyclotron Lab – Michigan State University – Facility for Rare Isotope Beams

Transformations and Symmetry: "Day and Night" by M.C. Escher (1938)



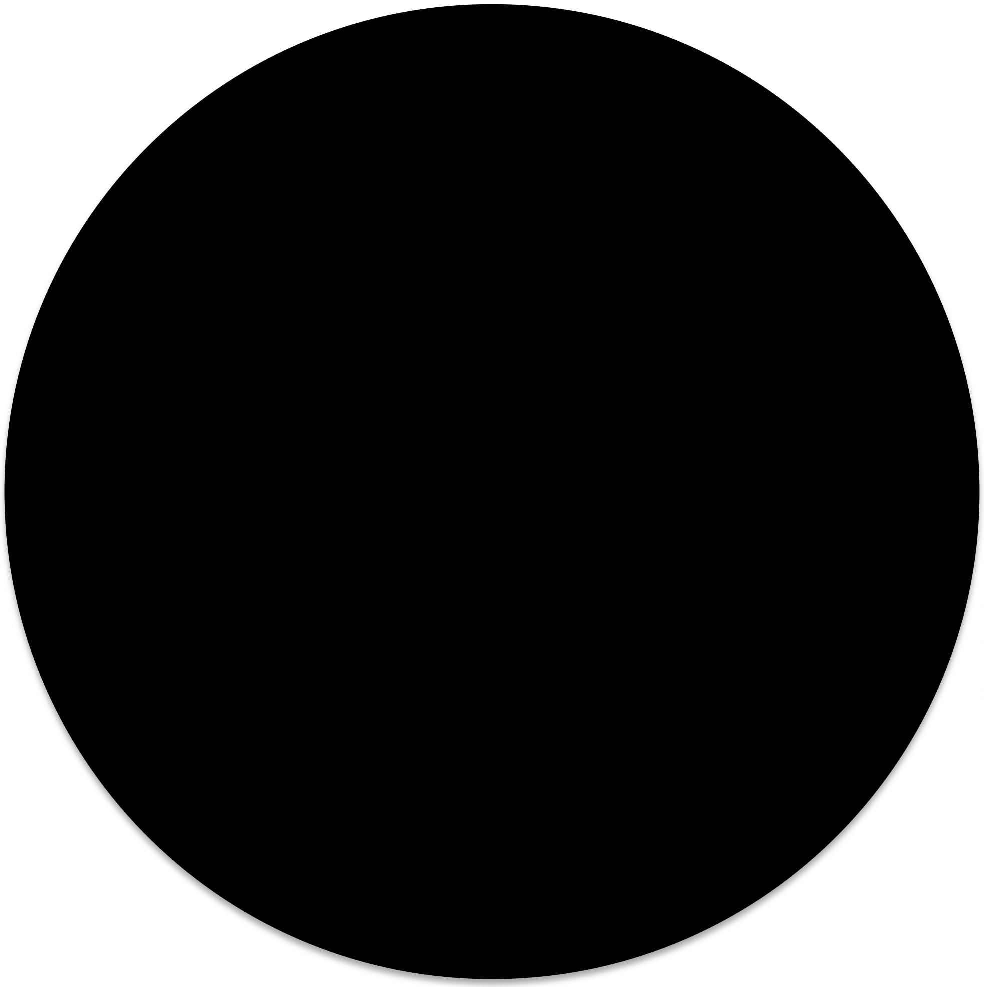






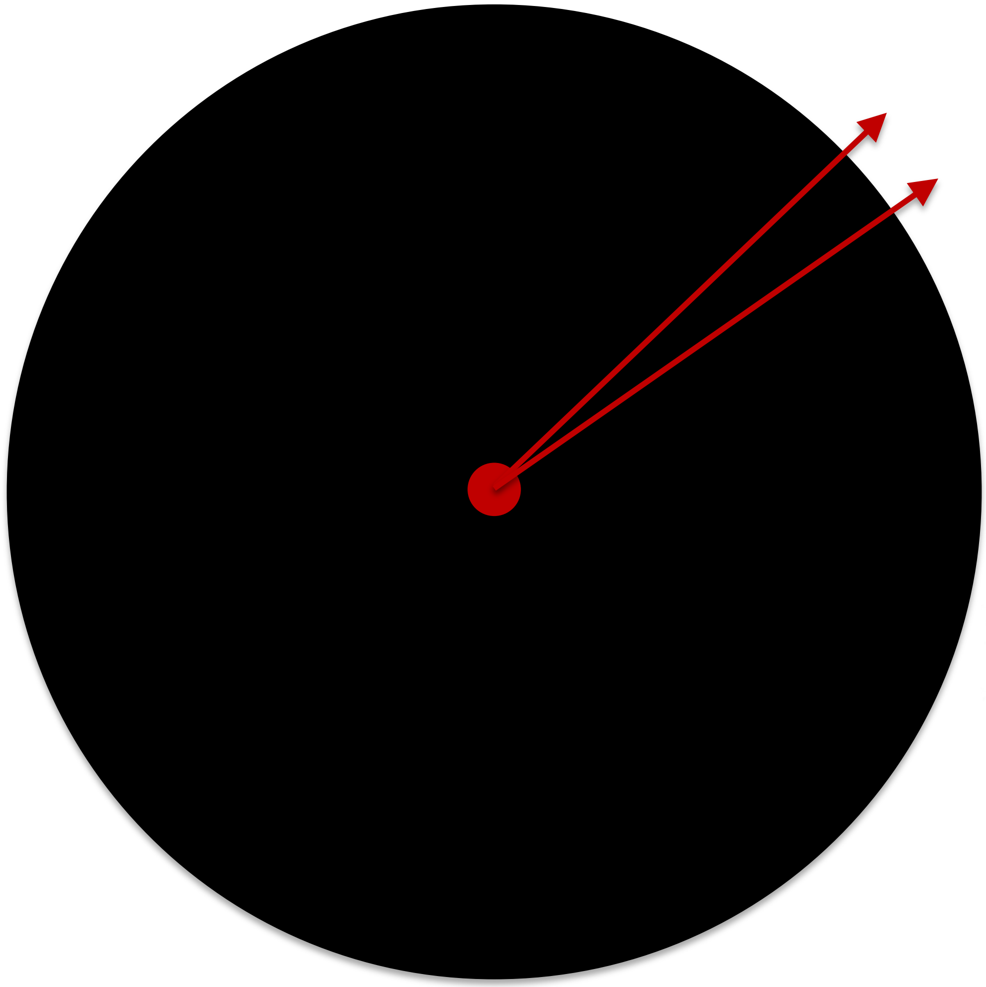
https://www.wikiart.org/en/m-c-escher/day-and-night

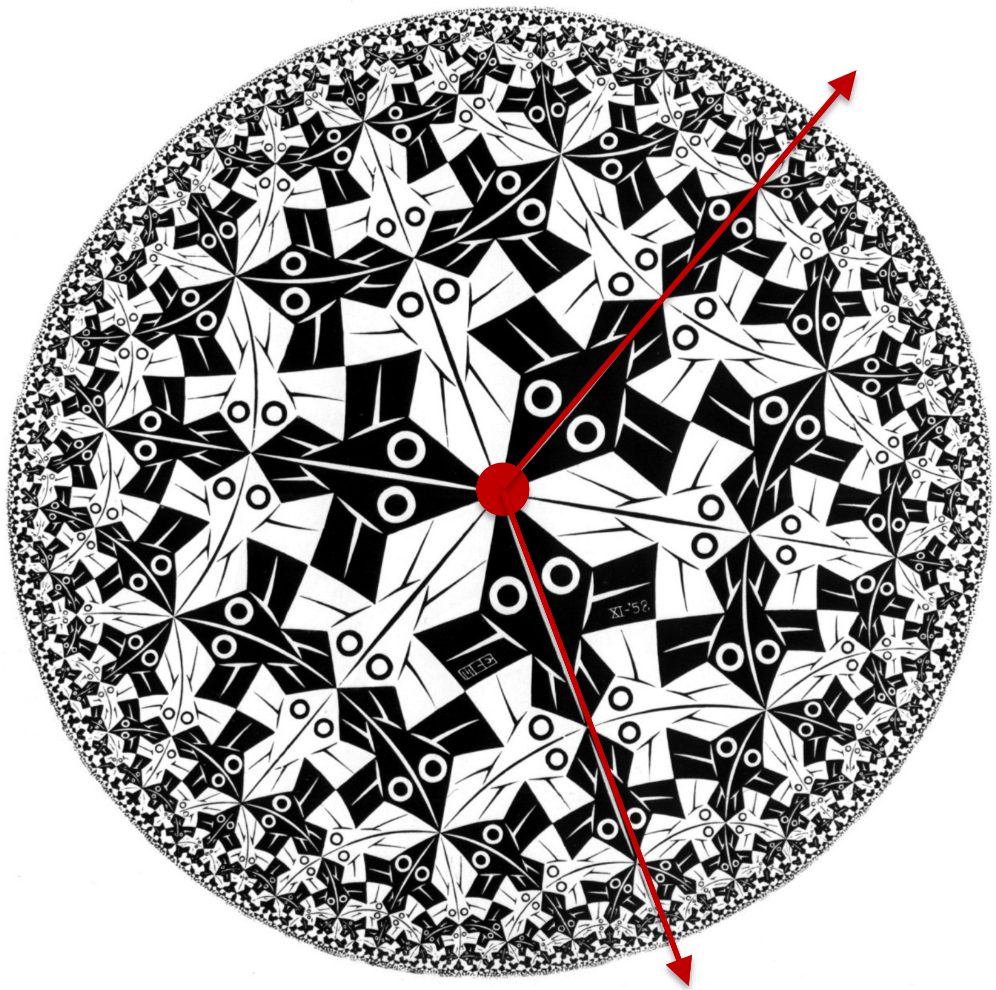
Continuous vs. Discrete Symmetries: "Circle Limit I" by M.C. Escher (1958)



https://www.wikiart.org/en/m-c-escher/circle-limit-i

Continuous vs. Discrete Symmetries: "Circle Limit I" by M.C. Escher (1958)





https://www.wikiart.org/en/m-c-escher/circle-limit-i

Noether's Theorem (1918)
(Only For Continuous Symmetries)

The presence of a continuous symmetry implies the existence of a conserved quantity.

Symmetry under temporal translations
➢ conservation of energy

Symmetry under spatial translations
➢ conservation of linear momentum

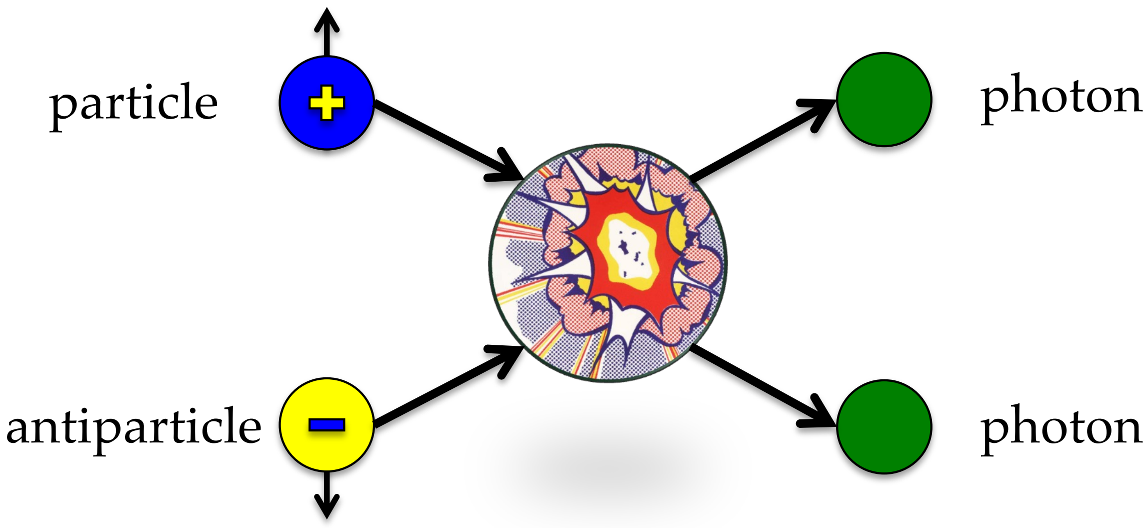
Symmetry under rotations
➢ conservation of angular momentum

SCAN ME

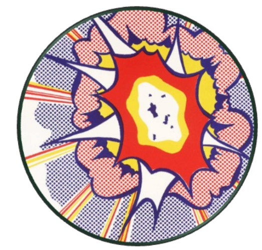
Emmy Noether:
My All-Time Favorite Theorist!

https://en.wikipedia.org/wiki/Emmy_Noether

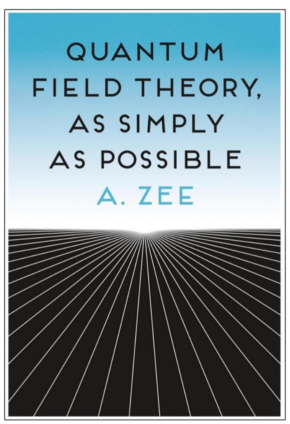
Quantum Field Theory Provides The Mathematical Apparatus Used To Calculate The Interaction Probability



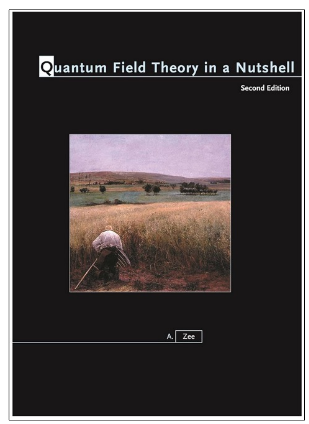
"Explosion" by
Roy Lichtenstein (1965-6)



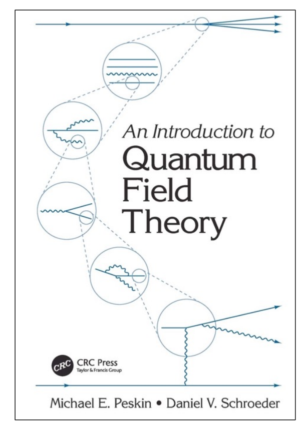
An infinite sum of
multidimensional integrals



Anthony Zee (2023)
For The Curious



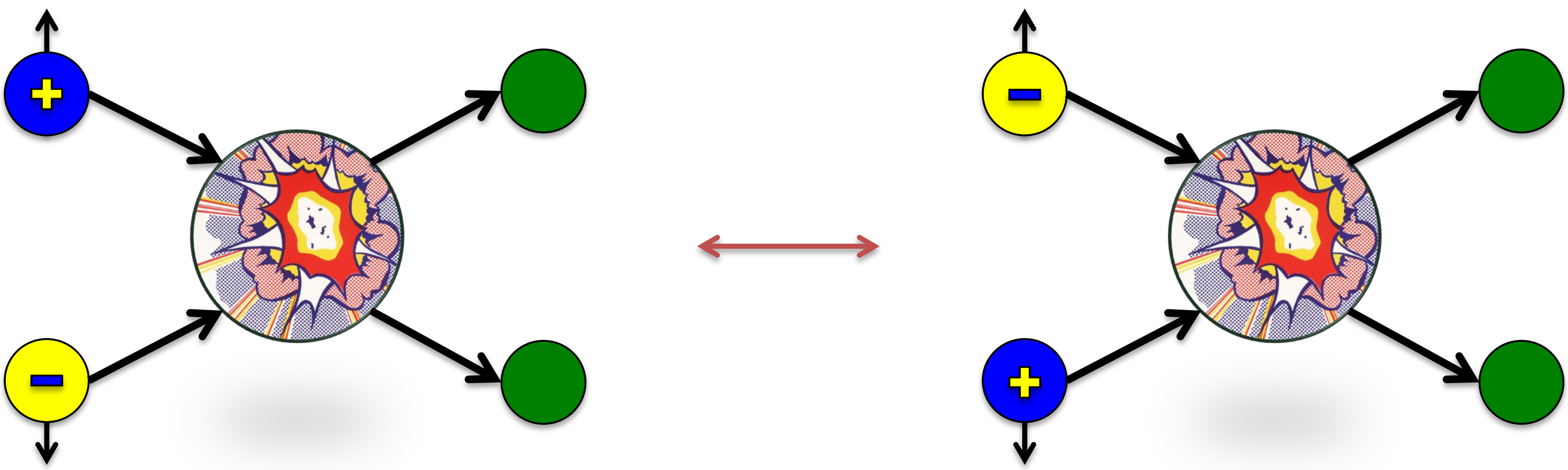
Anthony Zee (2010)
For Self-Study



Peskin & Schroeder (1995)
For QFT Practitioners

Discrete Symmetry Transformation
C: Charge Conjugation

Replace particle with antiparticle



https://www.tate.org.uk/kids/explore/who-is/who-roy-lichtenstein

Discrete Symmetry Transformation
P: Parity (Spatial Inversion)

Mirror reflection

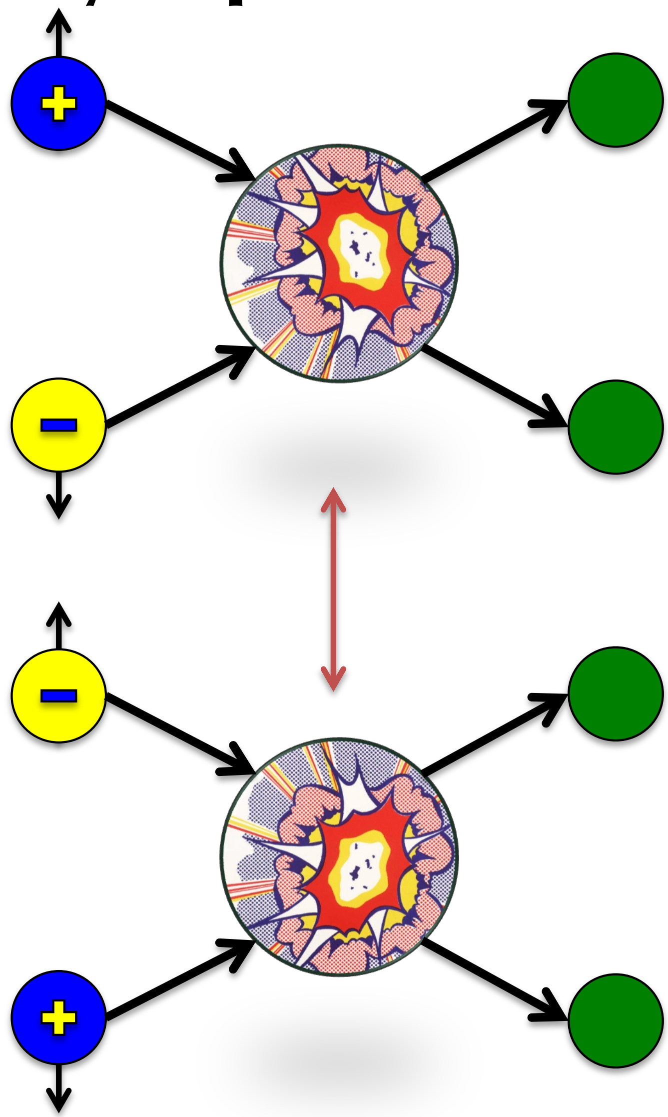
+

180º rotation

+x to –x

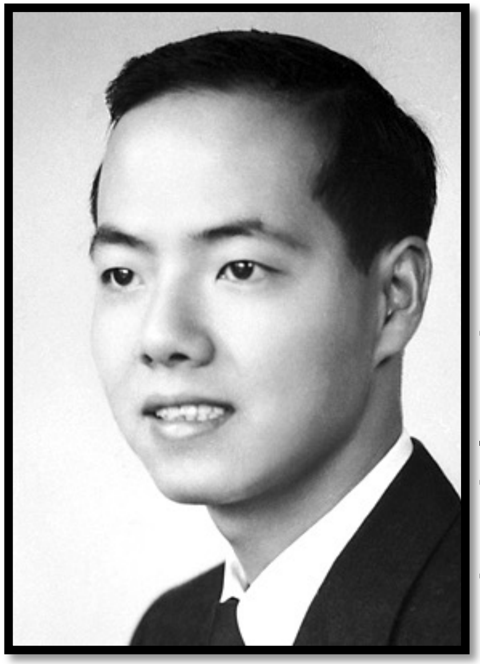
+y to –y

+z to -z



https://www.tate.org.uk/kids/explore/who-is/who-roy-lichtenstein

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*

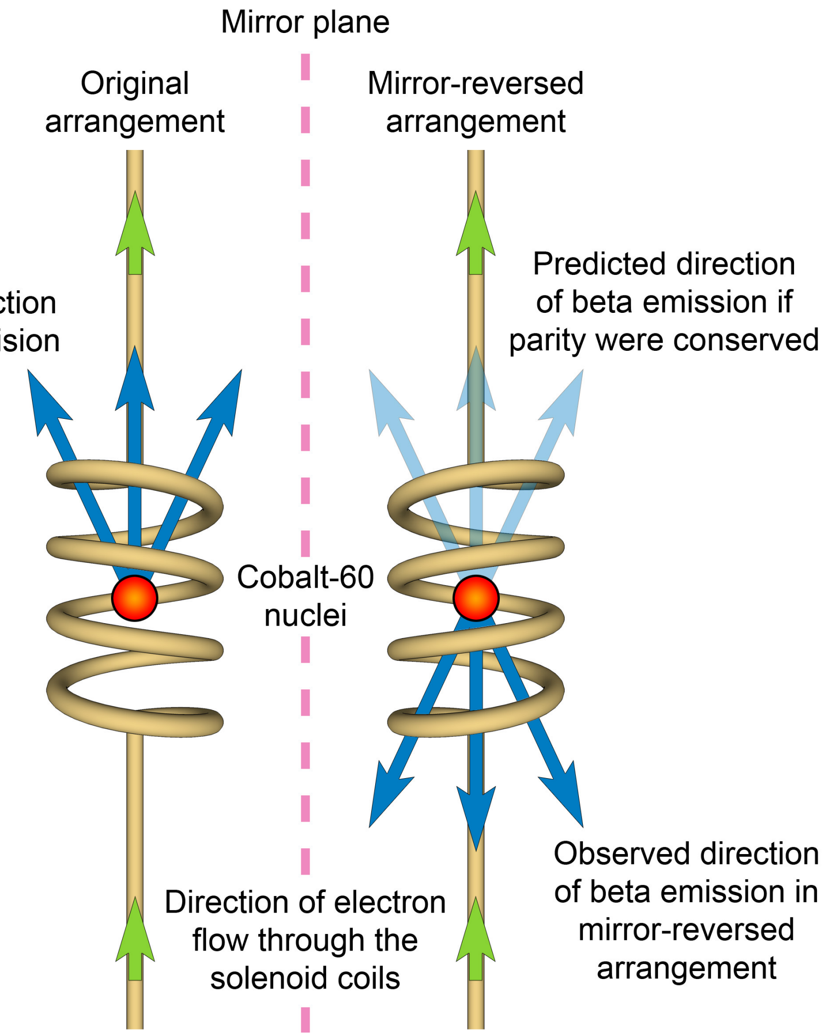
(Received June 22, 1956)

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

SCAN ME

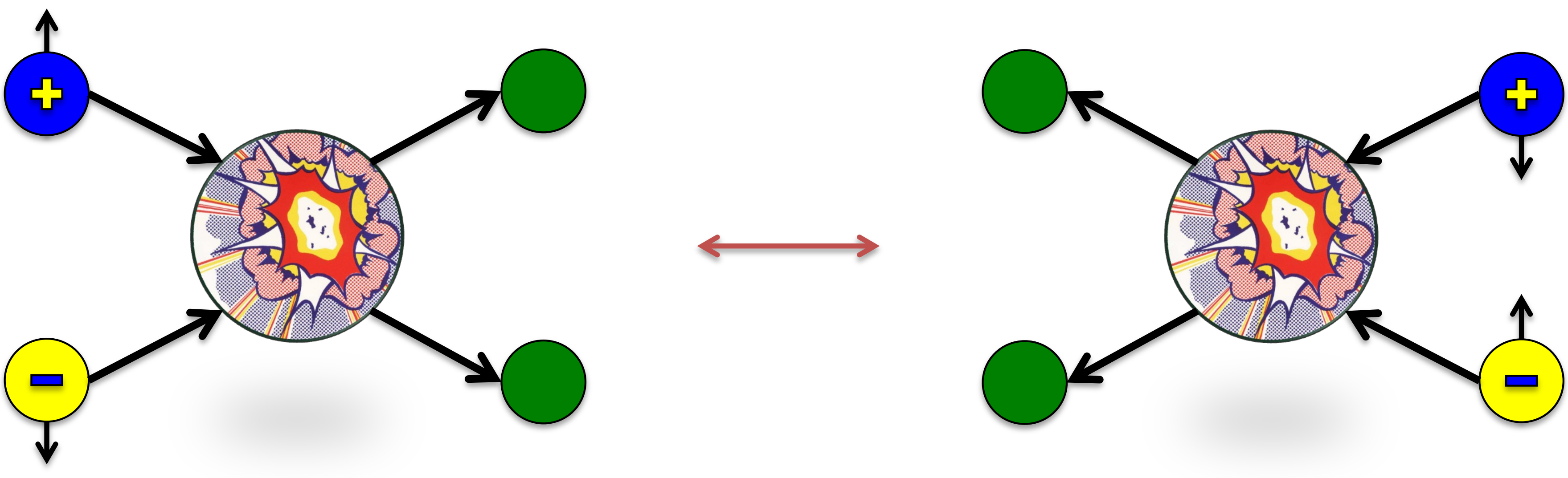


C.S. Wu: My All-Time Favorite Science Super-Hero!

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

Discrete Symmetry Transformation
T: Time-Reversal

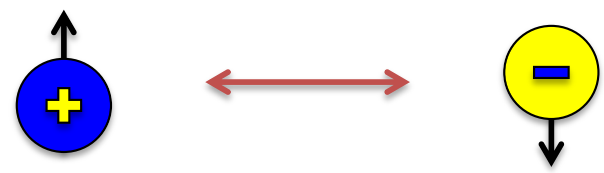
Reverse the arrow of time: +t to -t



https://www.tate.org.uk/kids/explore/who-is/who-roy-lichtenstein

Special Combinations of Discrete Symmetry Transformations

***CP*-transformation**
replace a "right-handed" particle with
its "left-handed" antiparticle counterpart

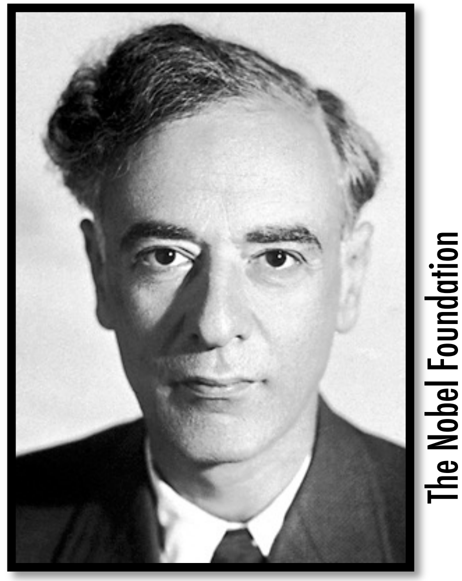


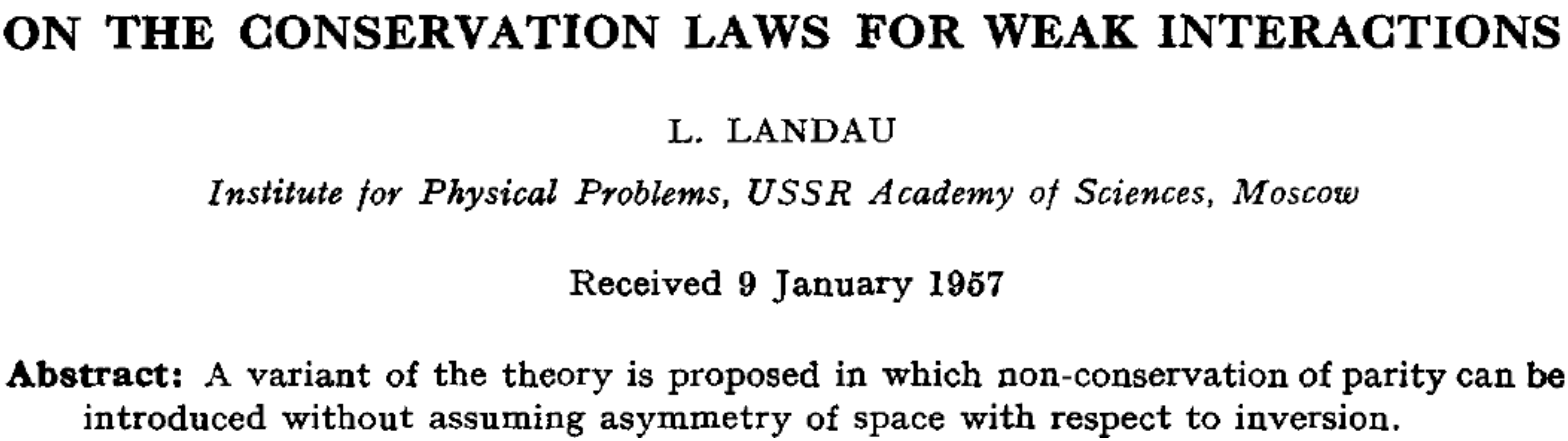
***CPT*-transformation**
replace a "right-handed" particle with its "left-handed" antiparticle counterpart moving in the opposite direction

The *CPT* Theorem (Taylor's Version):
The quantum interaction probability remains the same after a *CPT*-transformation if the underlying theory is consistent with special relativity.

https://en.wikipedia.org/wiki/Shake_It_Off#Lawsuits

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)!

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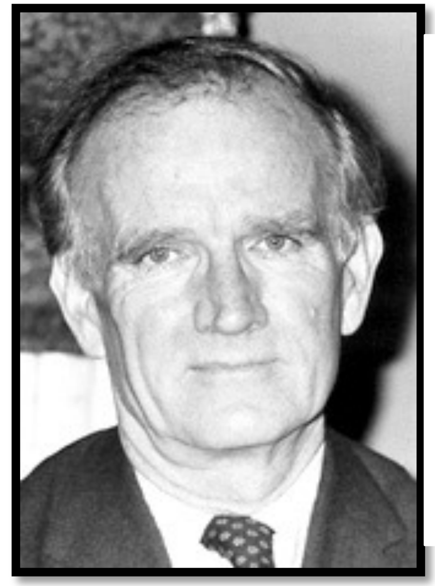


The Nobel Foundation

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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

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

Does The Quantum Interaction Probability Remain The Same Under A Discrete Symmetry Transformation?

	Strong Interaction	Weak Interaction	Electricity + Magnetism	Gravity	New Physics
C	Yup, so far	No, never	Yup, so far	Yup, so far	depends
P	Yup, so far	No, never	Yup, so far	Yup, so far	depends
T & CP	Yup, so far, (but we are ready for no: θ_{QCD} parameter)	Yes, most of the time, but… *occasionally* not when dealing with quarks (CKM matrix) and maybe also neutrinos (PMNS matrix)	Yup, so far	Yup, so far	depends
CPT	Yup, so far	Yup, so far	Yup, so far	Yup, so far	depends

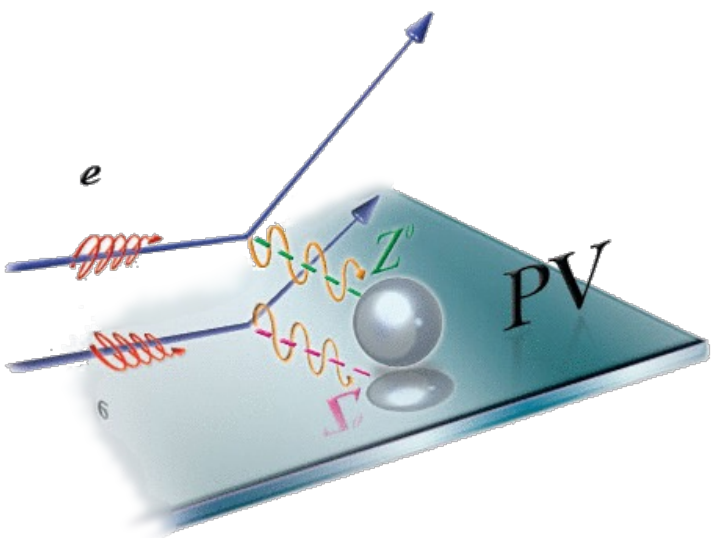
If the quantum interaction probability is not the same under a discrete symmetry transformation, then we say that discrete symmetry transformation is "violated."

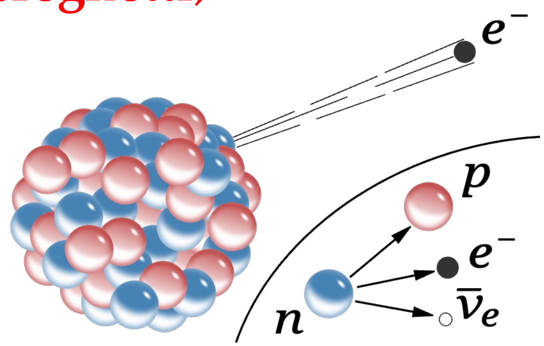
If the quantum interaction probability stays the same under *CPT*-transformations:

- then *T*-violation implies *CP*-violation and vice versa
- then *P*-violation implies *C*-violation or *T*-violation

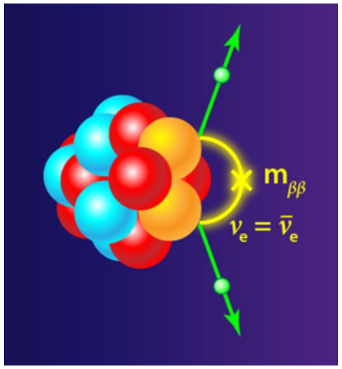
Testing "Fundamental Symmetries" (Discrete Symmetry Transformations) Provides Access to "New Physics"

Fundamental Symmetries (E. Mereghetti)





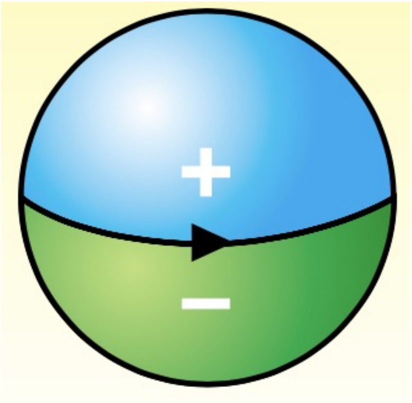
Nuclear Beta Decay (B. Jones & A. Holley)



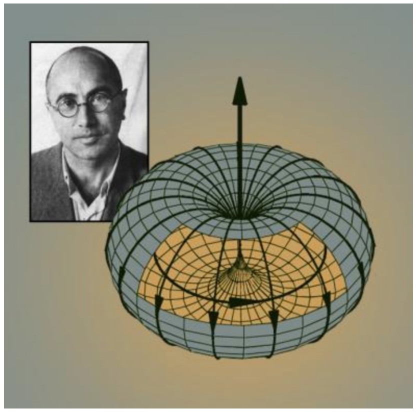
Neutrinoless Double Beta Decay (B. Jones)

Asymmetries in scattering and reaction rates (C. Palatchi)

https://hallaweb.jlab.org/parity/prex/prextalks.html
https://en.wikipedia.org/wiki/Beta_decay
https://physics.aps.org/articles/v11/30
https://www.eurekalert.org/multimedia/925121
Physics Today, June 2003



Electric Dipole Moments (JTS)



Nuclear Anapole Moments (JTS)

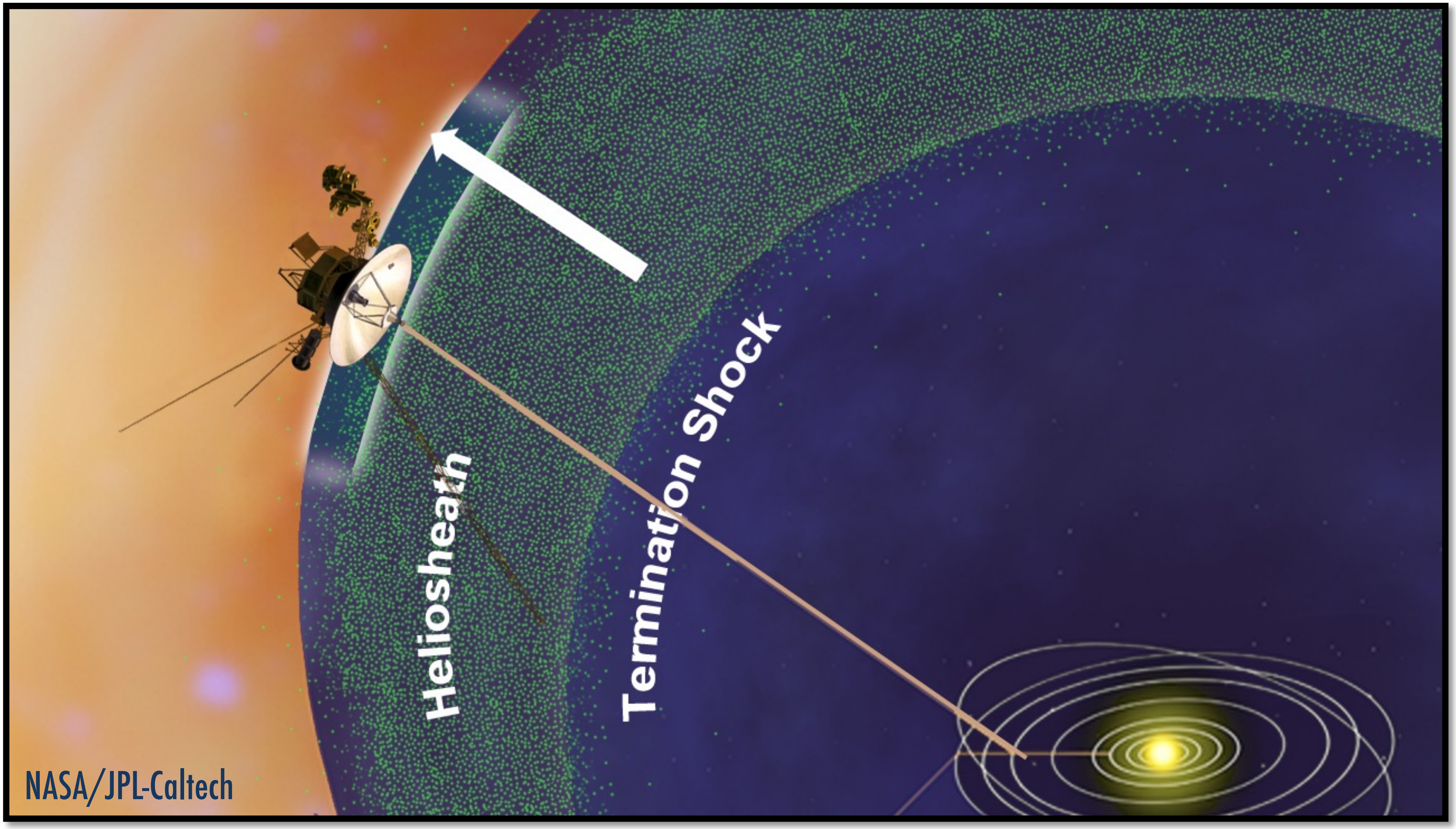
Intermission

Questions?

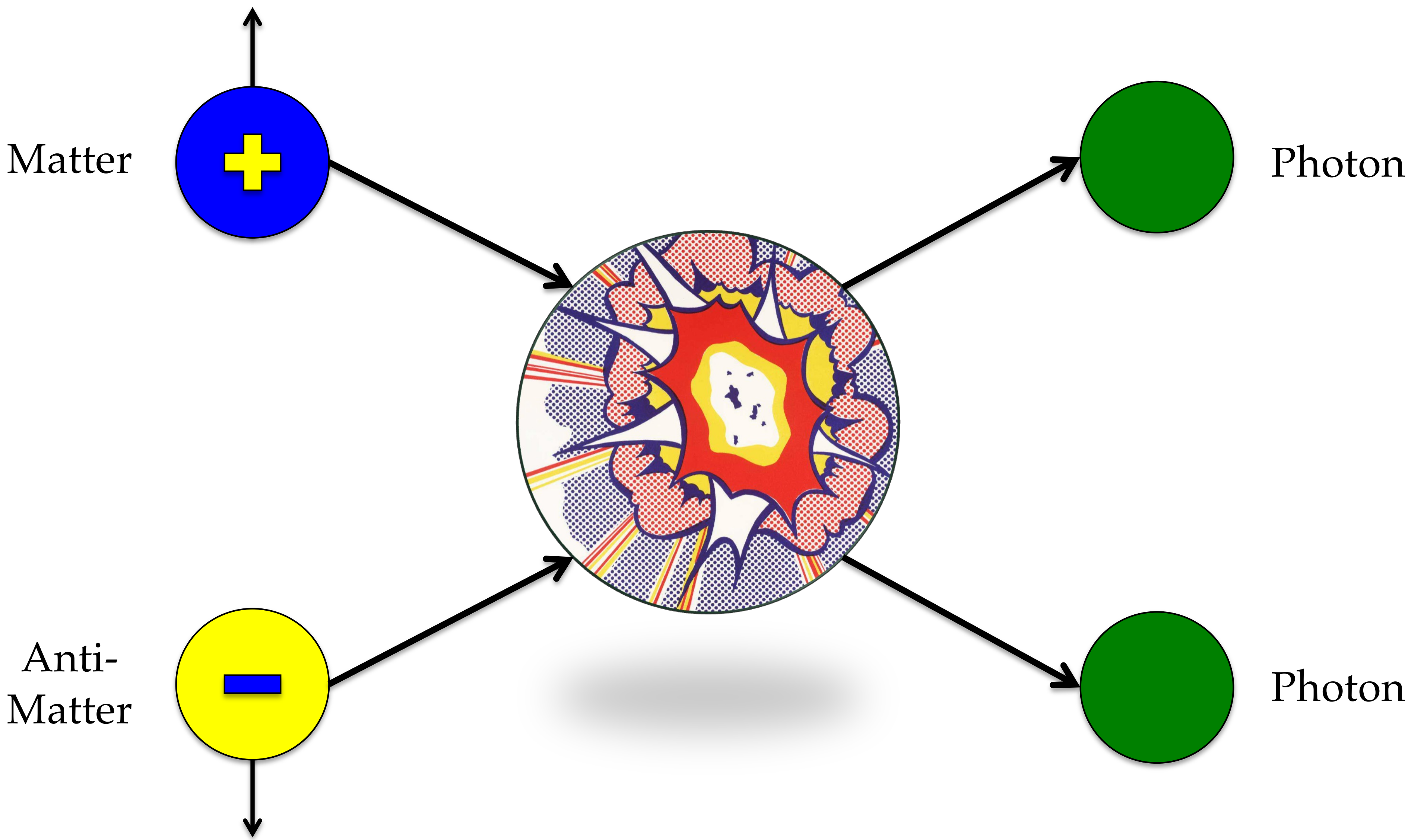
1. stuff

Voyager 1 is Still OK!

for the rest of the Universe: Annual Review of Astronomy and Astrophysics 14:339-372 (1976)

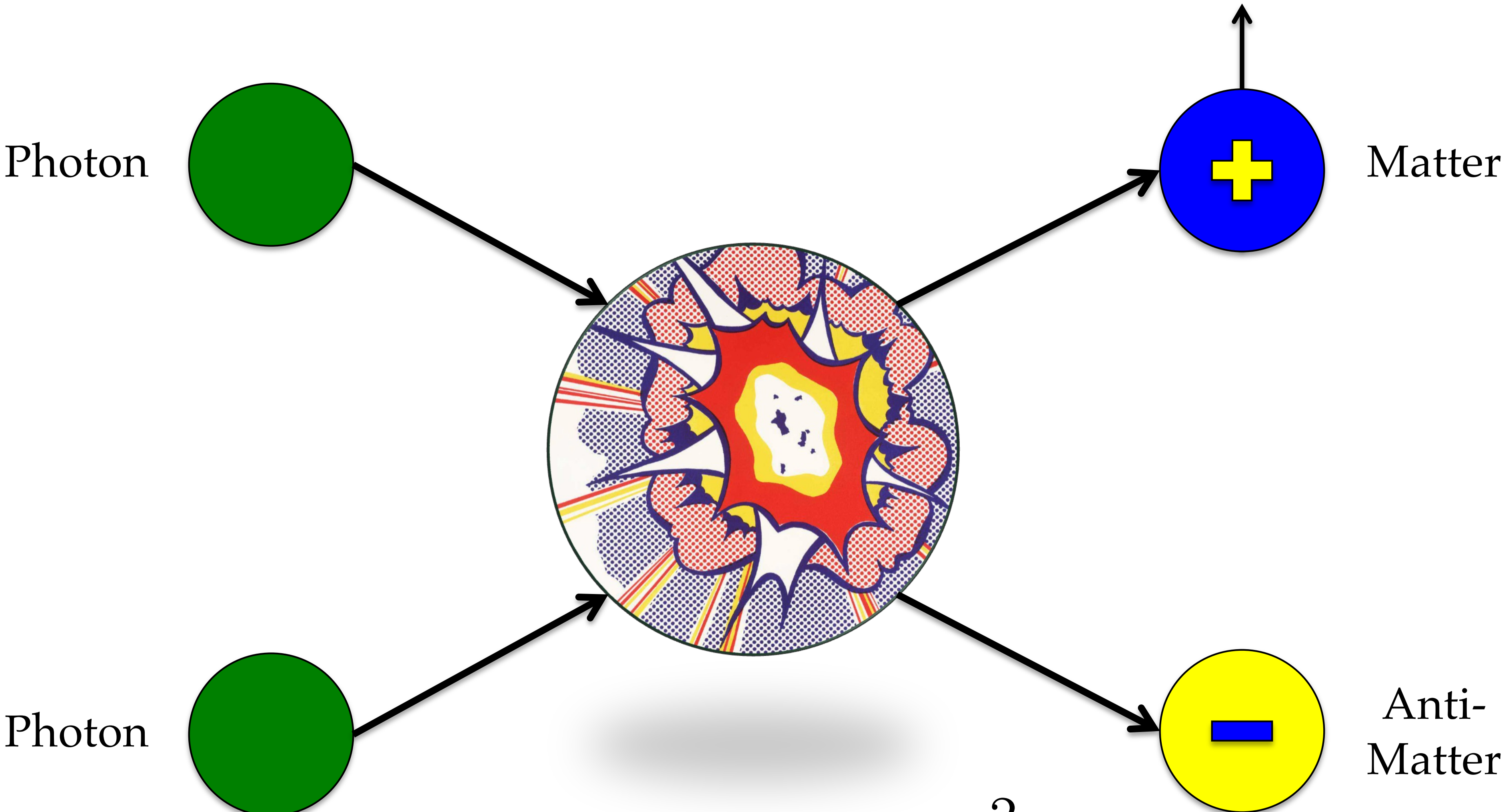


Matter & Antimatter Annihilate Into Photons



https://www.tate.org.uk/kids/explore/who-is/who-roy-lichtenstein

Photons Annihilate Matter & Antimatter

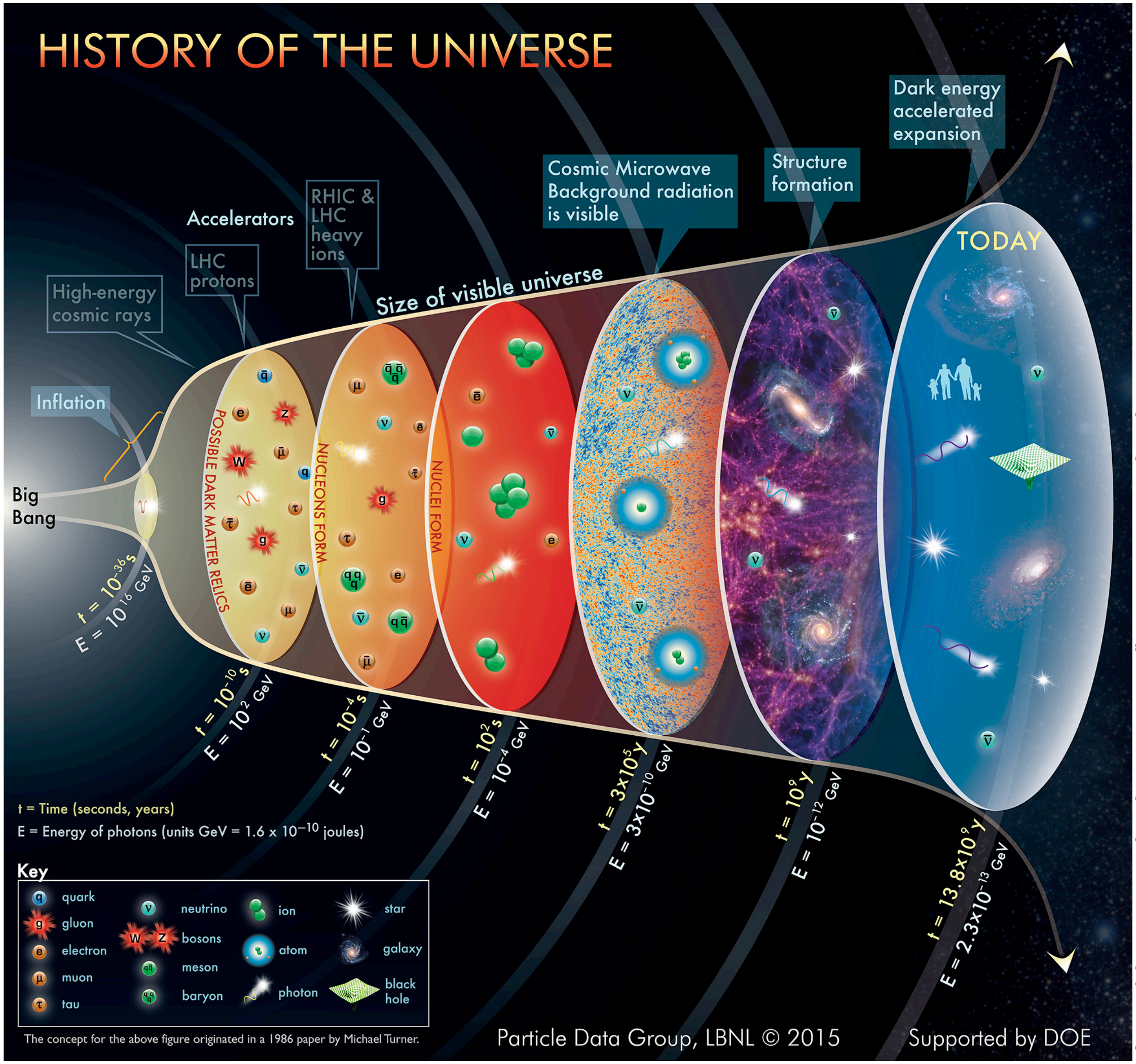


$$E_{\text{light}} \geq m_{\text{stuff}} c^2$$

https://www.tate.org.uk/kids/explore/who-is/who-roy-lichtenstein

Big Bang…Expanding Universe

HOT & DENSE

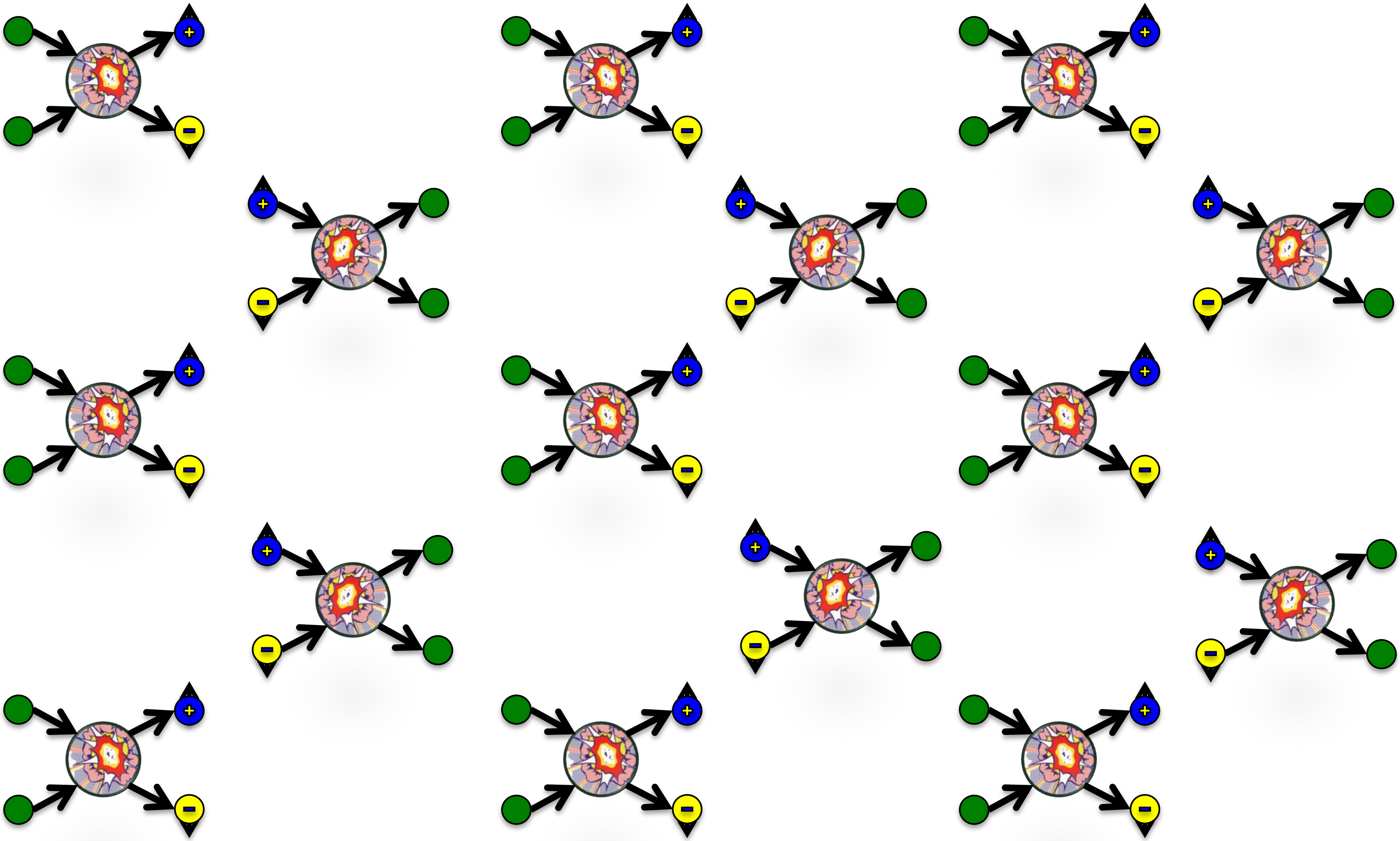


http://www.particleadventure.org/history-universe.html

cold & dilute

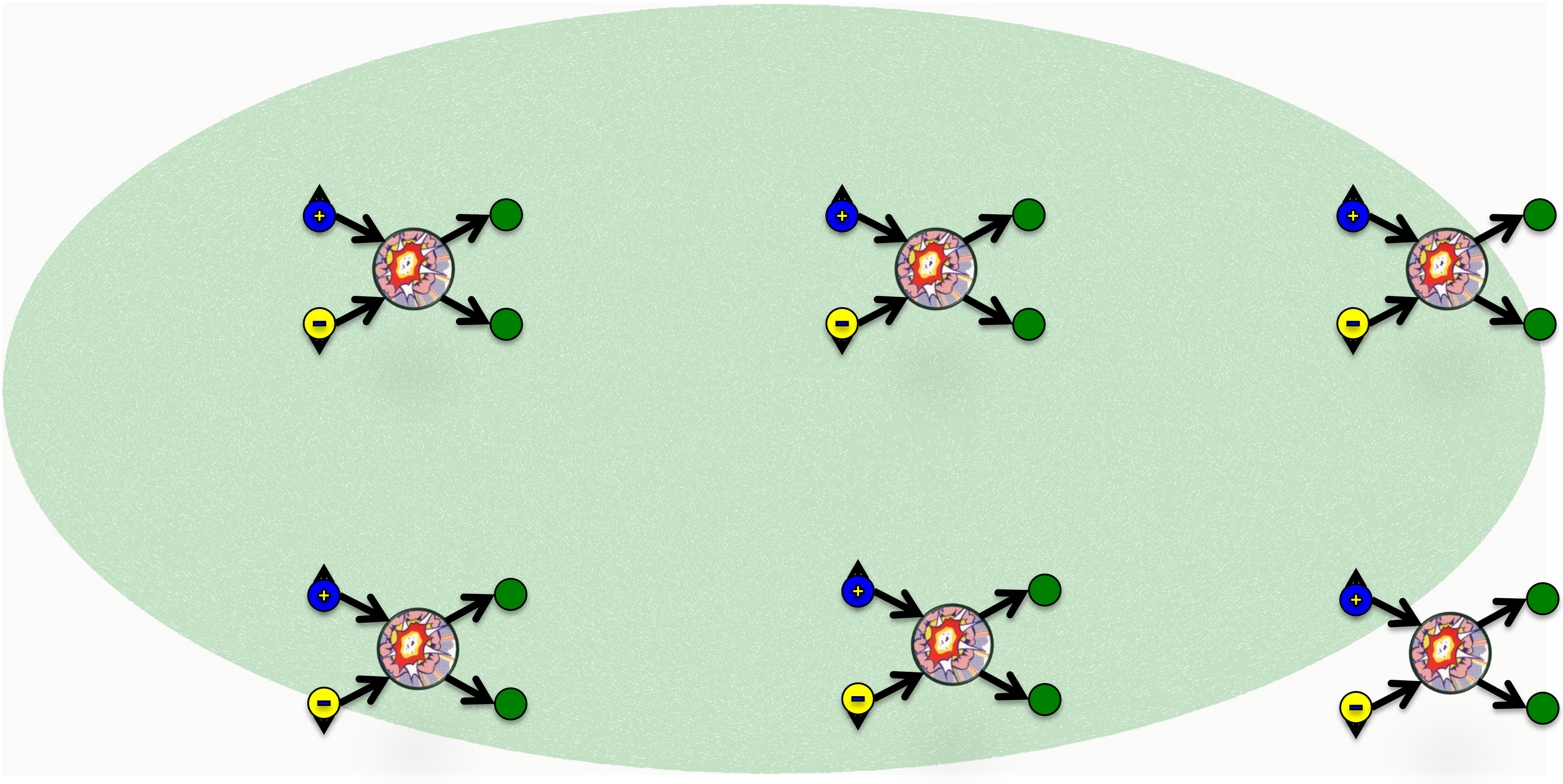
Everything Everywhere All At Once!

https://www.bbc.com/news/entertainment-arts-64938320



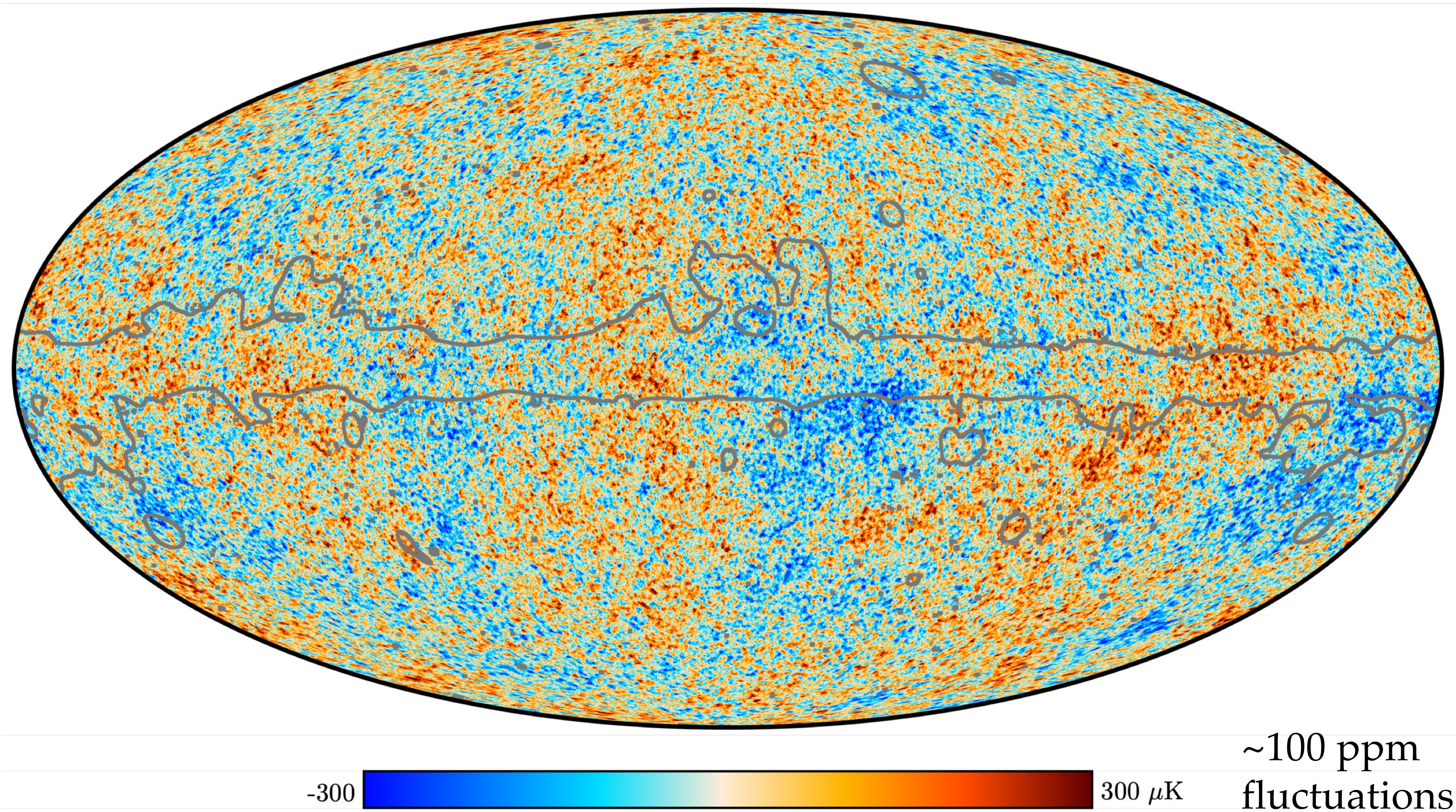
https://www.tate.org.uk/kids/explore/who-is/who-roy-lichtenstein

Expansion Means Cooling: 2.73 K Everywhere



https://www.tate.org.uk/kids/explore/who-is/who-roy-lichtenstein

Cosmic Microwave Background Anisotropy
"Baby Picture" of the Universe



~100 ppm fluctuations

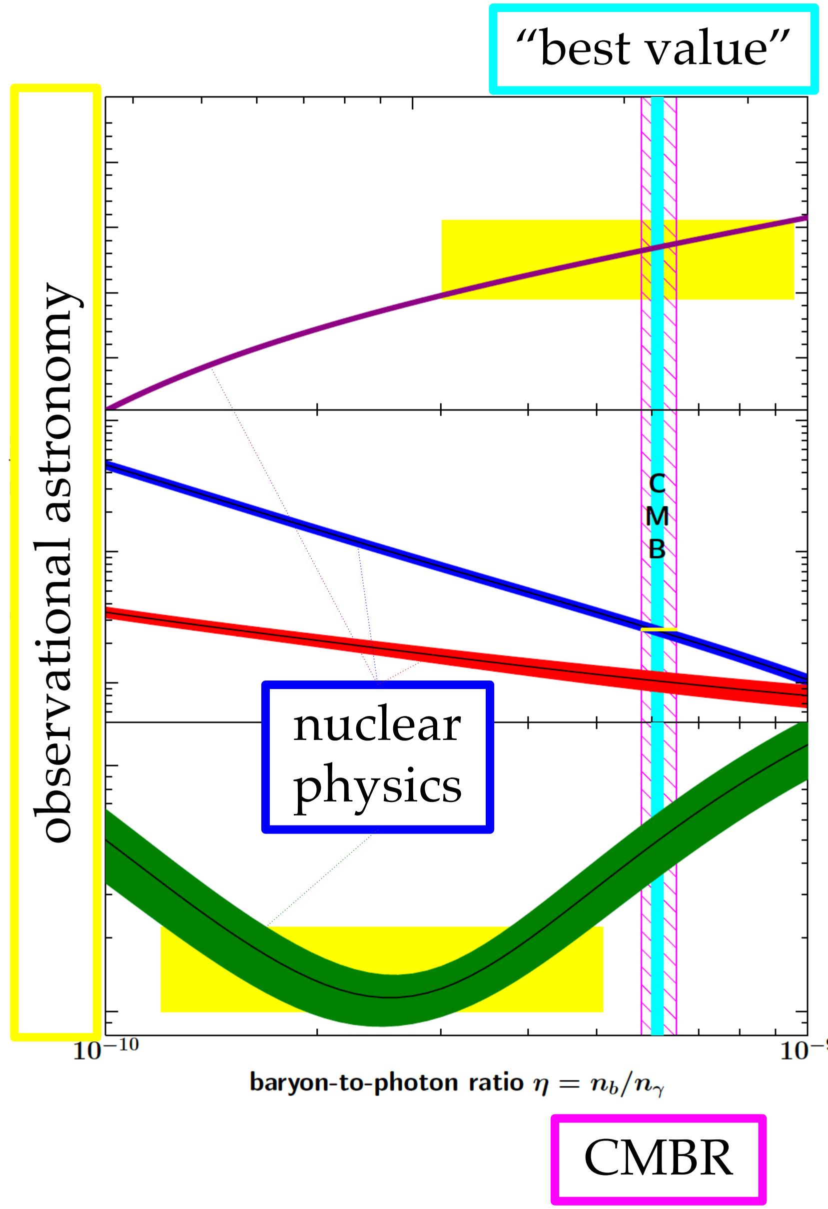
https://www.cosmos.esa.int/web/planck/picture-gallery

Planck 2018

There Is No Visible Antimatter In The Universe

$$\eta \ \text{“}=\text{”} \ \frac{(\text{matter}) - (\text{antimatter})}{\text{relic photons}}$$

$$\eta = 0.000000006129 \ (0.6\%) \quad \text{PDG2022}$$
$$\approx 10^{-9}$$



Sakharov's Conditions: Need *CP*-Violation

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

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

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

The Nobel Foundation

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

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: Not Enough

$$\eta = \frac{\text{(matter)} - \text{(antimatter)}}{\text{relic photons}} \propto \sin(\delta)$$

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

PDG2022

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

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

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

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

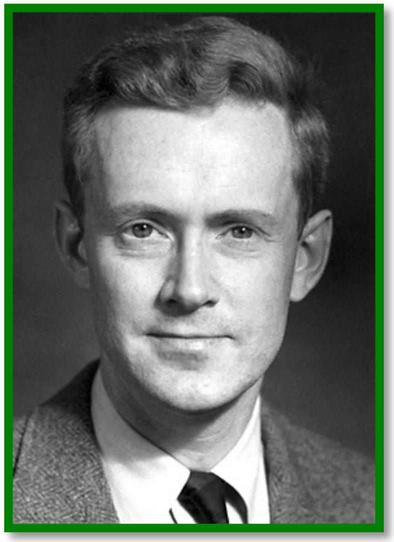
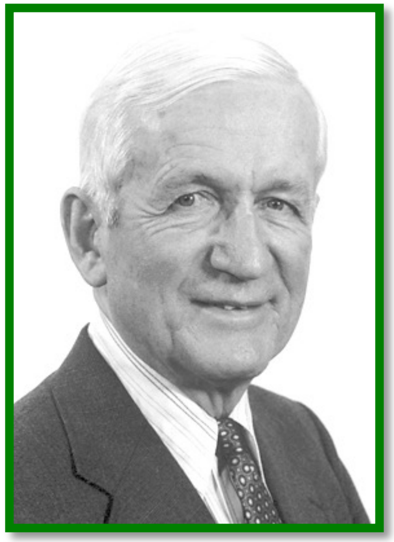
Hocker & Ligeti, Annu. Rev. Nucl. Part. Sci. 2006. 56:501–67

This is generically why "New Physics" can produce more *CP*-violation!

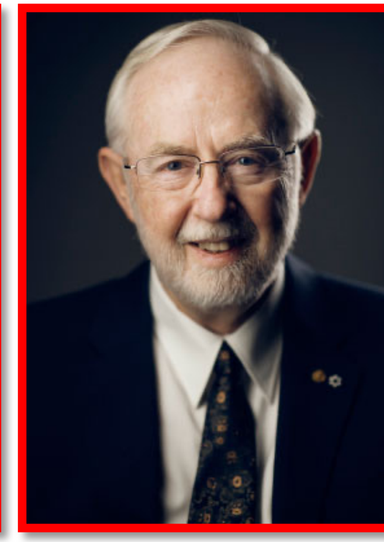
$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

Where Do We Look For More *CP*-Violation?

The Nobel Foundation

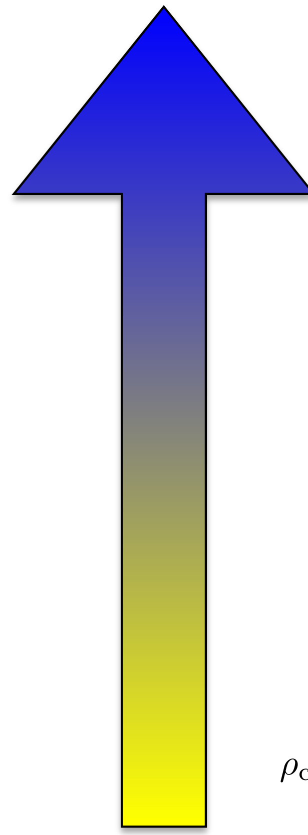
The Nobel Foundation

- Decays of *B*-mesons [Belle II]
- Rare decays of b-hadrons [LHCb]
- Angular decay correlations of positronium [Wittenberg/MSU]
- D-coefficient in nuclear beta-decay [The MORA Project]
- Nuclear magnetic quadrupole moments [Caltech, UNLV, ODU]
- Double polarized neutron transmission [**NOPTREX – Mike Snow @ Indiana**]
- Neutrinos have mass! (PMNS matrix) [neutrino oscillations + $0\nu2\beta$: *B. Jones*]
- ***electric dipole moments: If CPT is good,*** **then *T*-violation can be used to search for new sources of *CP*-violation!**

Electric Dipole Moment (EDM): Measures the Separation of Charges

$$\vec{d} = \int \rho_{\mathrm{charge}} \left(\vec{r} - \vec{R}_{\mathrm{CM}} \right) \, d^3 r = \langle \rho_{\mathrm{charge}} \vec{r} \rangle - Q \vec{R}_{\mathrm{CM}}$$

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



$$\vec{d}$$

ρ_{charge} = charge distribution

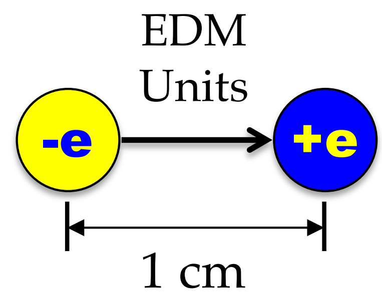
$\vec{r}$ = position vector

$\vec{R}_{\mathrm{CM}}$ = center of mass

Q = net charge

Electric Dipole Moments Couple to E-fields
Magnetic Dipole Moments Couple to B-fields

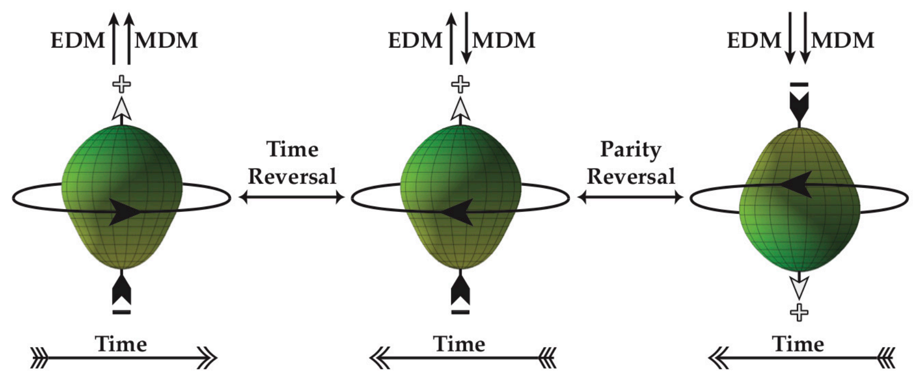
$$\mathcal{H} = -\mu\left(\frac{\vec{S}\cdot\vec{B}}{S}\right) - d\left(\frac{\vec{S}\cdot\vec{E}}{S}\right)$$



adapted from B. Filippone:

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

$\vec{S} = \text{spin}$

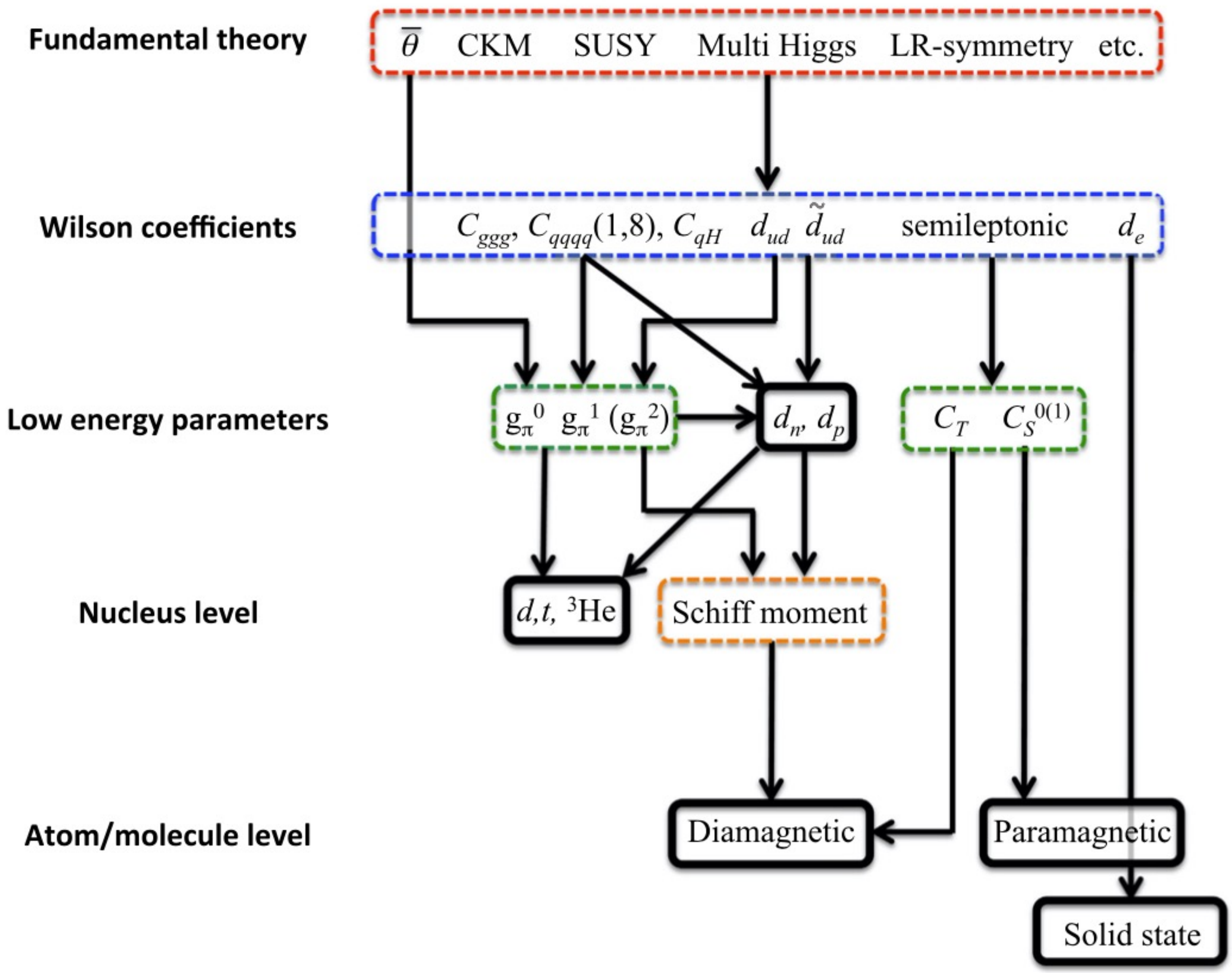


Theorist: …trivial application of the Wigner-Eckart Theorem…

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

Connecting New Physics to EDMs

T.E. Chupp, P. Fierlinger, M. Ramsey-Musolf, JTS, RMP 91:015001



Sources of *CP*-violation

Particle Physics Theory

Effective Field Theory

Lattice QCD Theory

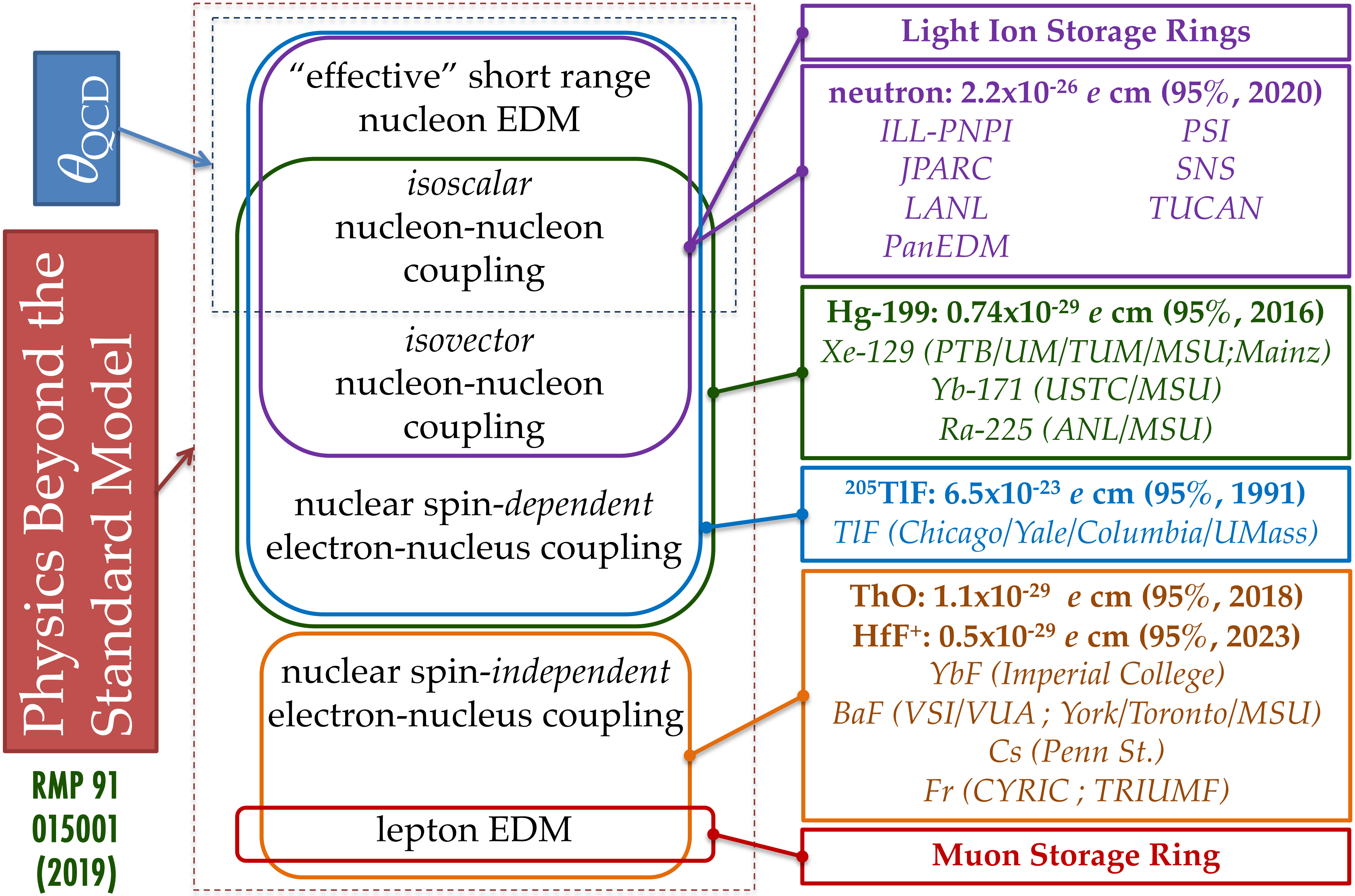
Nuclear Theory
+
Nuclear Experiment

Atomic Theory
+
Atomic Experiment

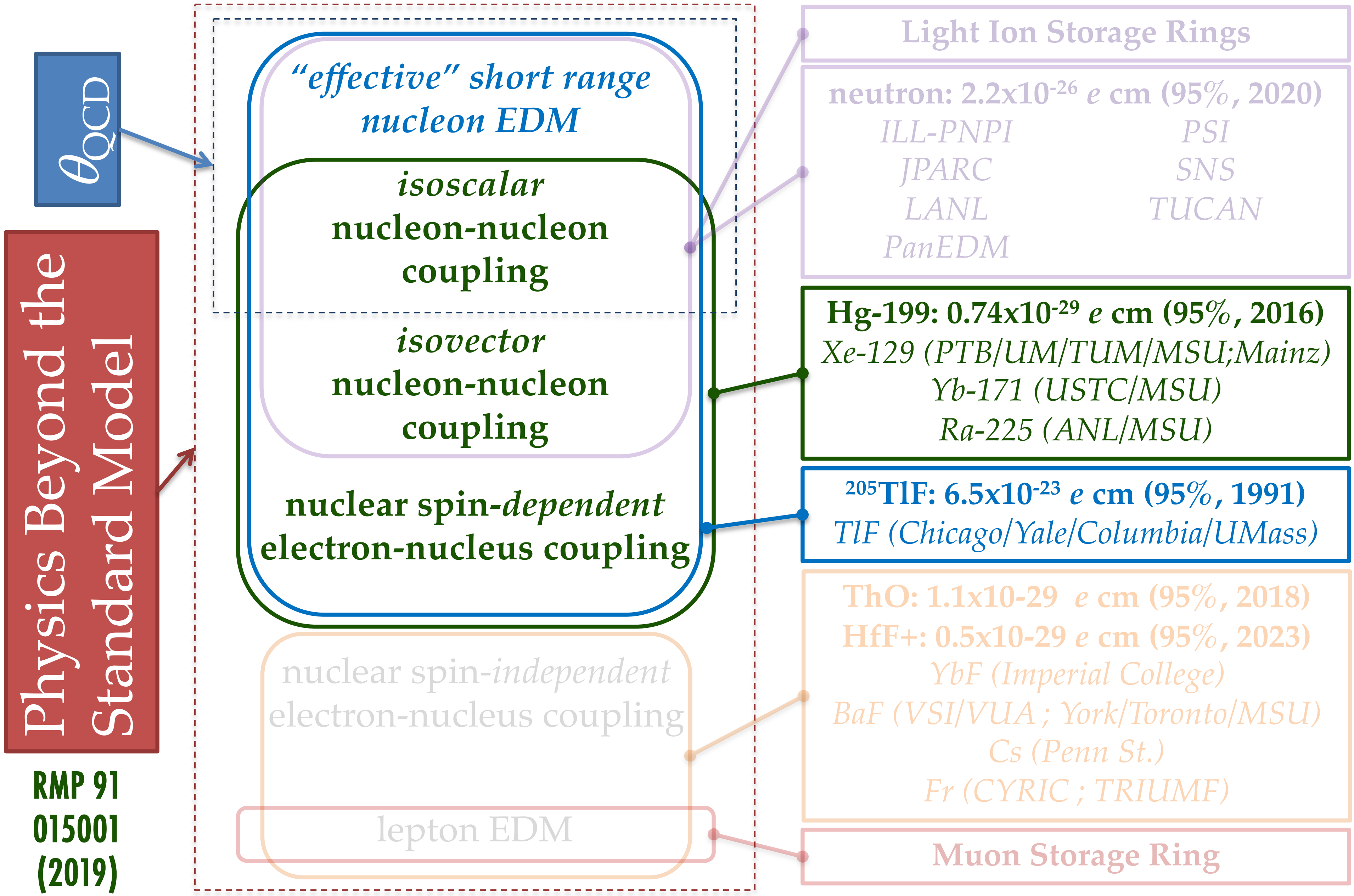
Molecular Theory
+
Molecular Experiment

Radiochemistry
...EDMs

Different Sources of $\not{T}$ ↔ EDM of Different Systems



Different Sources of $\not{T}$ ↔ EDM of Different Systems



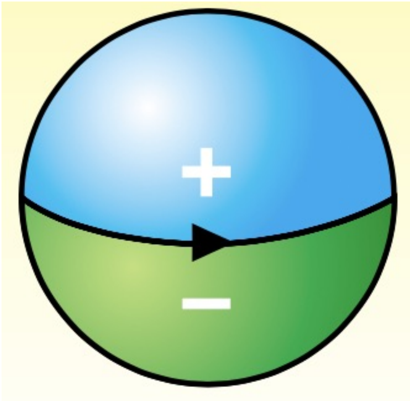
RMP 91 015001 (2019)

2023 EDM Limits: "Free" of Standard Model (SM) "Backgrounds"

Chupp, Fierlinger, Ramsey-Musolf, JTS RMP 91:015001 (2019) & Nature 562:355 (2018) & PRL 124:081803 (2020) & PRL 129:231801 (2022) & Science 381:46 (2023)

System	Best Limit (95%) 1E-28 *e* cm	SM estimate 1E-28 *e* cm	Method (Location)
Neutron	220	$\sim 10^{-4}$	ultracold neutrons in a bottle (PSI)
"Electron"	0.11 0.05	$\sim 10^{-7}$	cold ThO beam (Chicago/Harvard/Northwestern) trapped HfF^{+} (JILA/Boulder)
Hg-199	0.074	$\sim 10^{-6}$	atoms in vapor cell (UW-Seattle)

Imagine a Hg-199 atom that is composed of two oppositely charged hemispherical shells each with charge magnitude *e*...



Physics Today, June 2003

2023 EDM Limits:
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Chupp, Fierlinger, Ramsey-Musolf, JTS RMP 91:015001 (2019) & Nature 562:355 (2018)
& PRL 124:081803 (2020) & PRL 129:231801 (2022) & Science 381:46 (2023)

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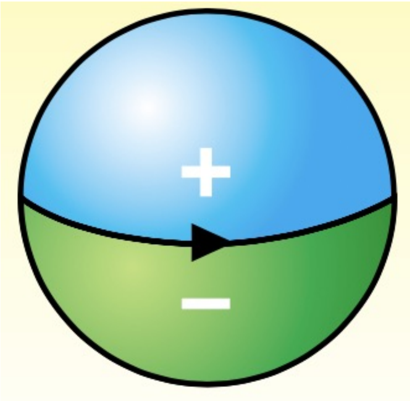
Hg-199	0.074	$\sim 10^{-6}$	atoms in vapor cell (UW-Seattle)

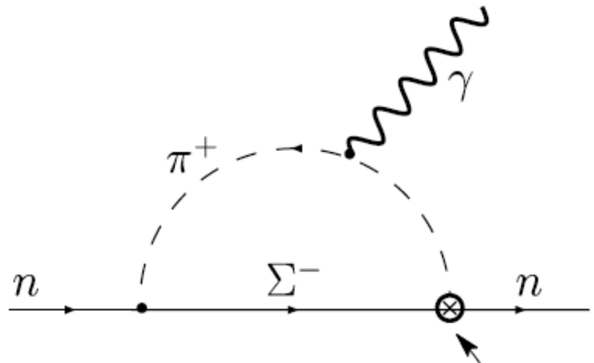
Imagine a Hg-199 atom that is composed of two oppositely charged hemispherical shells each with charge magnitude *e*…

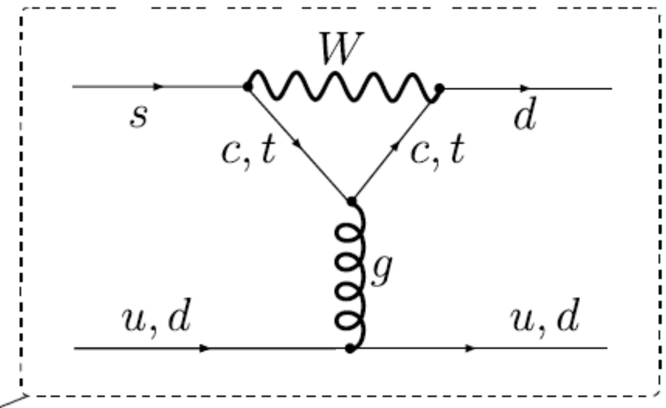
…if the Hg-199 atom was the size of the Earth, then the maximum thickness of these shells would be less than the diameter of a strand of human hair.



Physics Today, June 2003

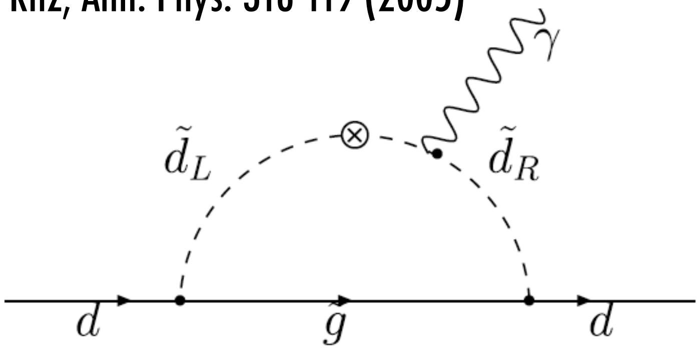
EDMs From Standard Model vs. New Physics





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

Standard Model: higher order "penguin" diagram

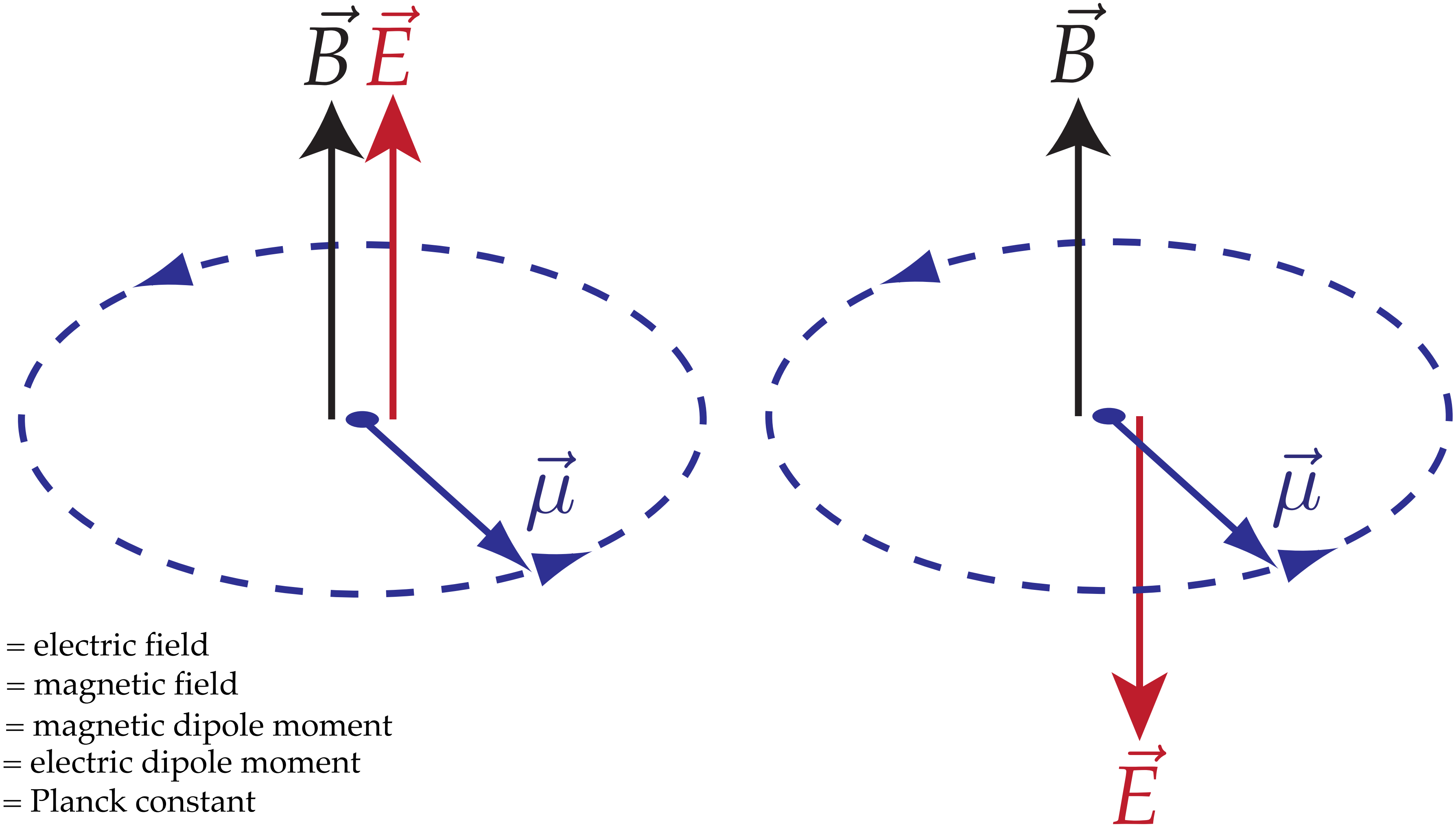


Supersymmetry: lower order

RMP 91:015001 (2019)

$$\frac{d}{10^{-28}\ e\ \mathrm{cm}} \approx \sin(\phi_{CP}) \left[\frac{1\ \mathrm{TeV}}{\text{mass scale of new particles}} \right]^2$$

Always Measure Frequency = ν
Example: Spin Precession of a Spin-1/2 Particle



E = electric field
B = magnetic field
μ = magnetic dipole moment
d = electric dipole moment
h = Planck constant

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

Statistics & Systematics

$$\sigma_\nu = \frac{\Gamma_{\text{linewidth}}}{\texttt{SNR}}$$

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

Quantum Projection Noise (100% efficiency):

$$\frac{\sigma_d}{\sqrt{N_m}} = \frac{\hbar}{4E\sqrt{N_d T \tau}}$$

Electric field

number of detected particles

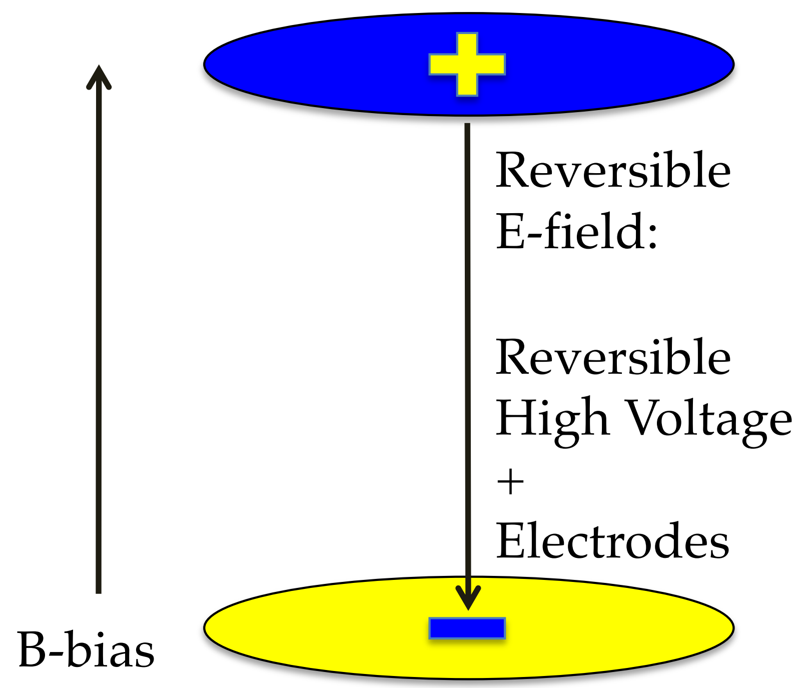
integration time

interrogation time

Magnetic Field Instabilities: Annoying

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

Instabilities adds noise &
limits the statistical precision.



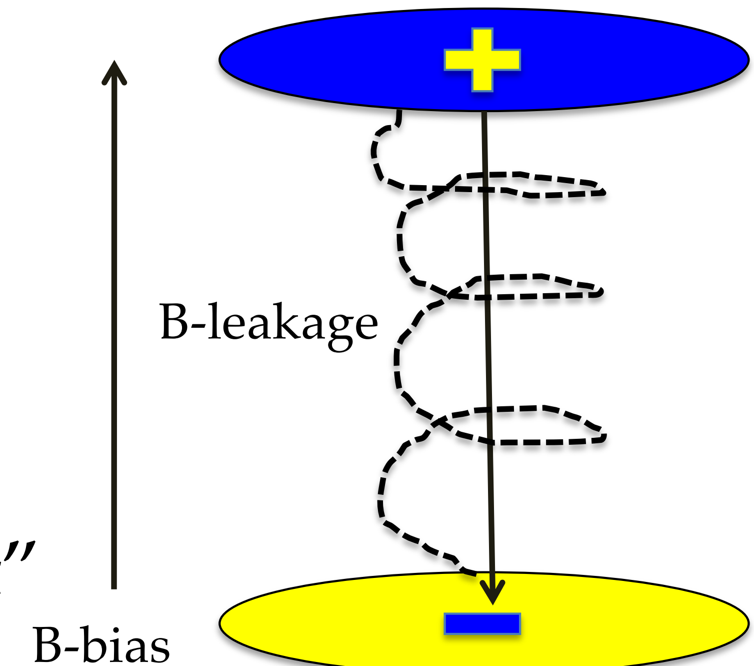
Electric Field-Correlated Systematic: Killer

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

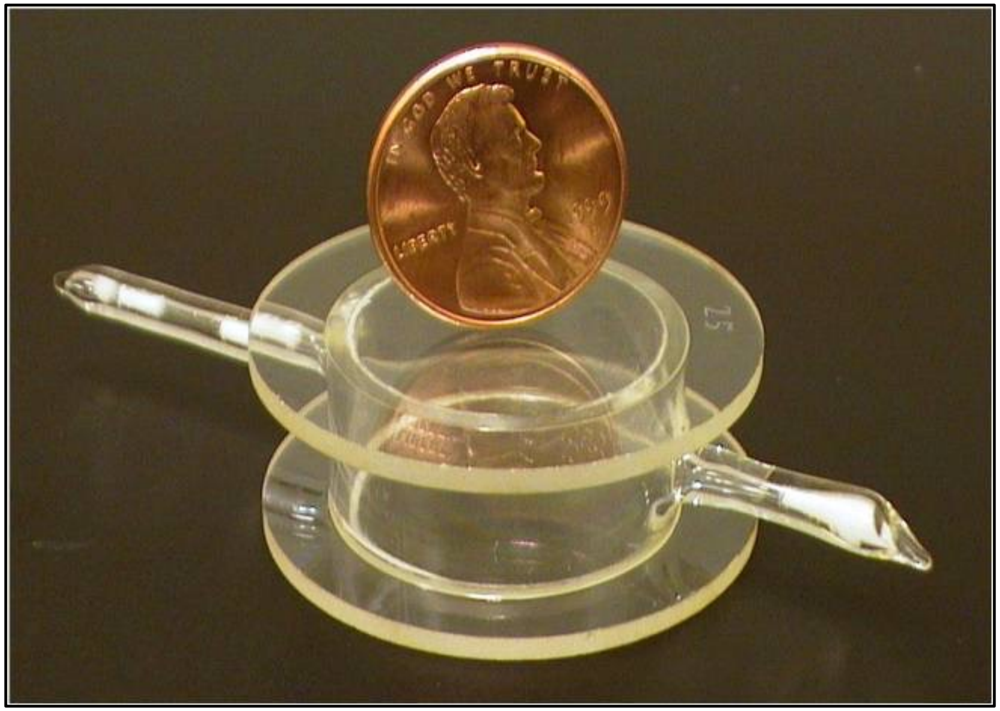
challenge!

Instabilities adds noise & limits the statistical precision.

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



The Gold Standard: Hg-199 EDM Search



B. Graner

- **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)
- **modest electric field,** 10 kV/cm
- **30+ year old experiment!**

$$\nu = 8.3 \text{ Hz}$$

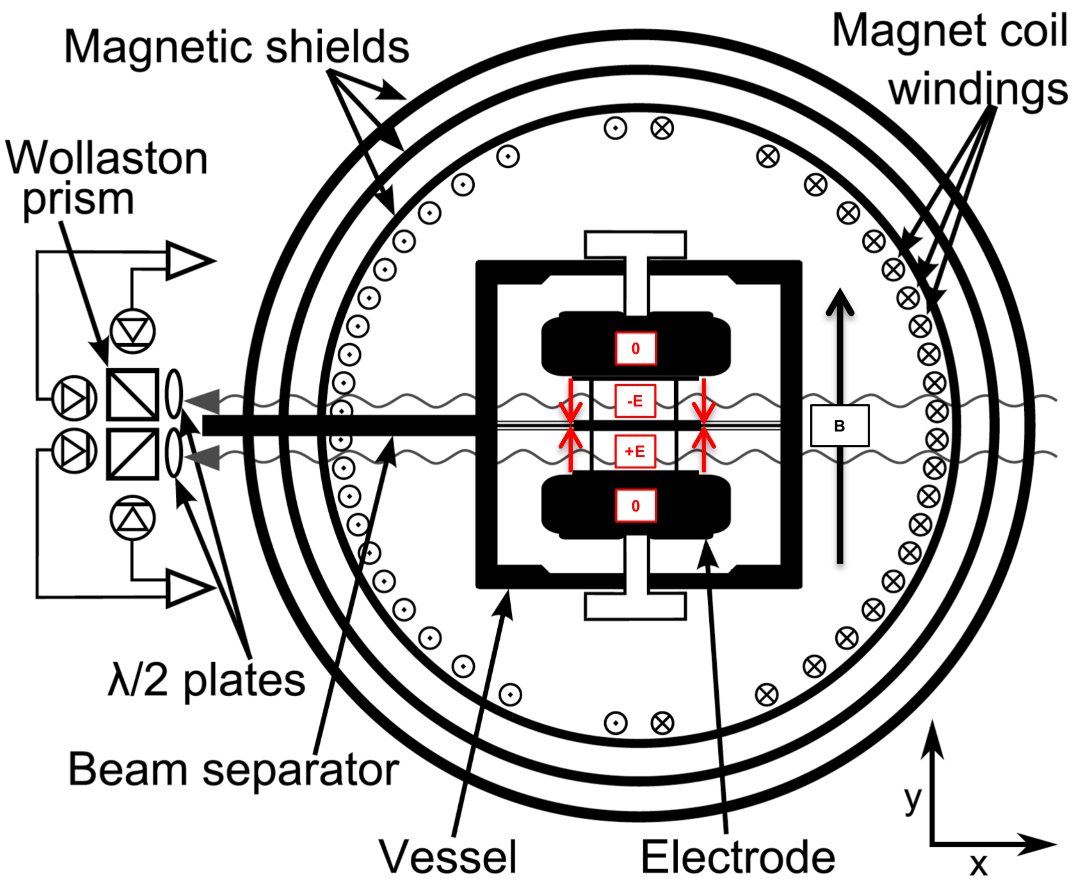
$$\Delta\nu \leq 0.1 \text{ nHz}$$

The best limit on atomic EDM:

EDM(^{199}Hg) < 0.74x10^{-29} *e*-cm (95% C.L.)

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

The Gold Standard: Hg-199 EDM Search



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- **stable**, (17% n.a.) 92% enriched
- **high vapor pressure**, (10^{13}/cm^3)
- **modest electric field,** 10 kV/cm
- **30+ year old experiment!**

Limiting systematic appears to be ~10 nm scale motion of vapor cells when HV is switched in the presence of 2nd order *B*-field gradients.

$$\nu = 8.3 \text{ Hz}$$

$$\Delta\nu \leq 0.1 \text{ nHz}$$

The best limit on atomic EDM:

EDM(^{199}Hg) < $0.74\text{x}10^{-29}$ *e*-cm (95% C.L.)

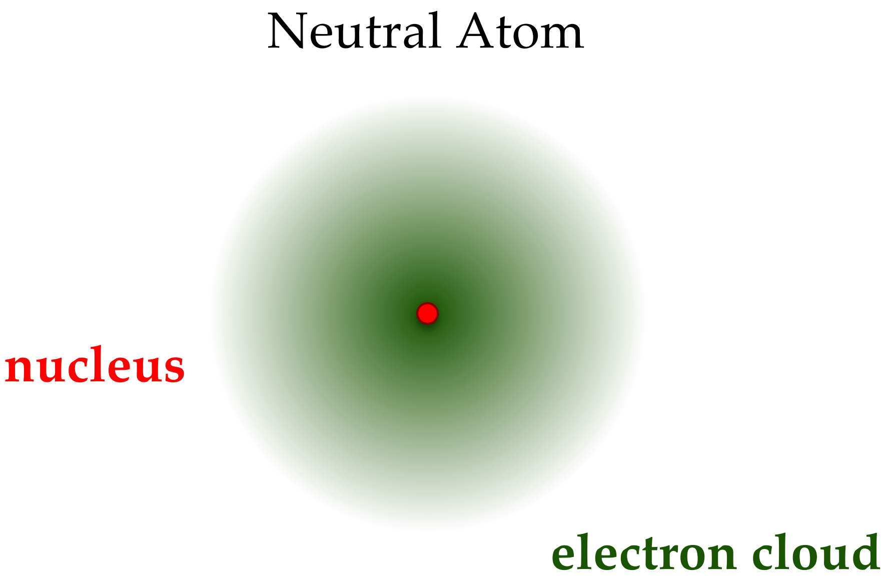
Graner et al., PRL 116:161601 (2016)

Intermission

Questions?

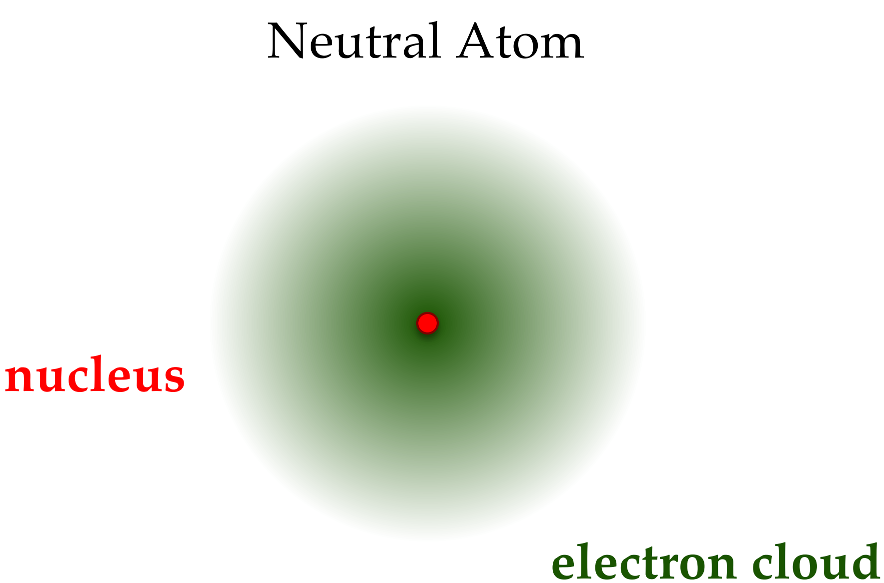
1. stuff

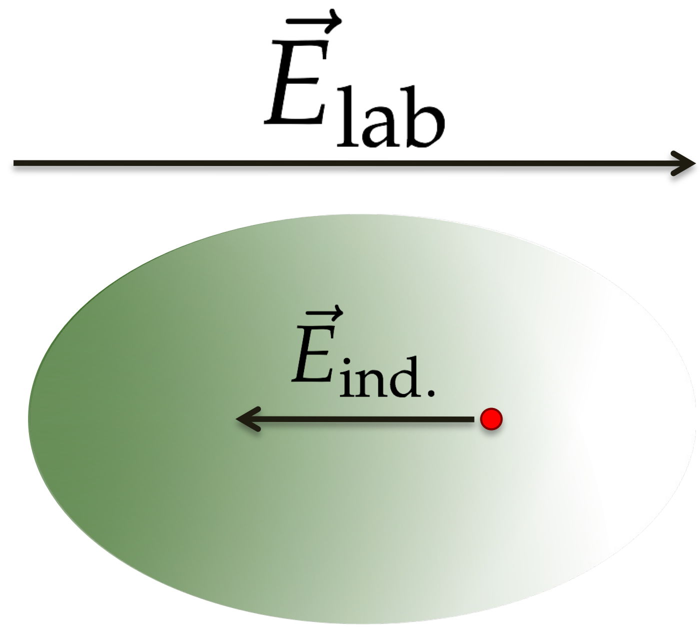
Diamagnetic Atoms: All Electrons Are Paired



Schiff Shielding in Diamagnetic Atoms

- **Shielding in Diamagnetic Atoms**
  Schiff PR 132:2194 (1963)





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

Shielding Imperfect in Relativistic Atoms With Nonzero Nuclear Size

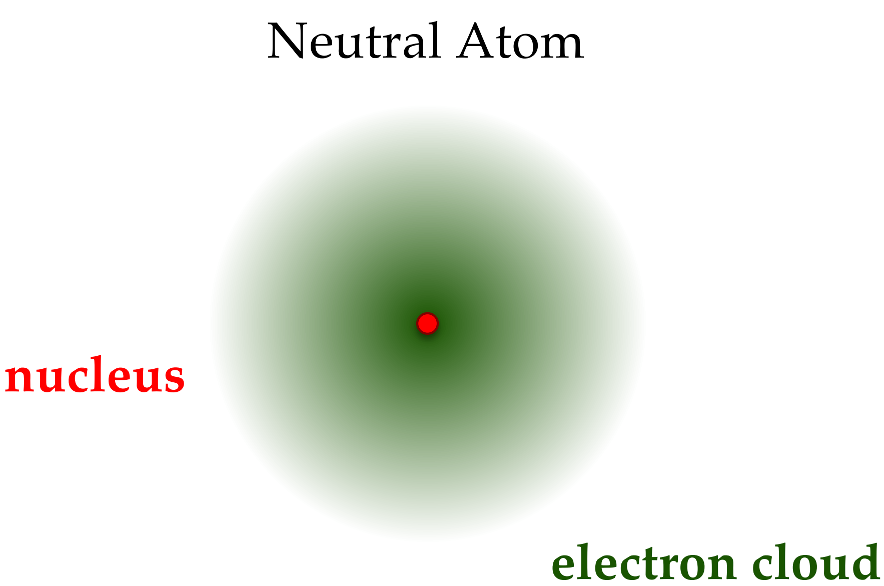
- **Shielding in Diamagnetic Atoms**
  Schiff PR 132:2194 (1963)

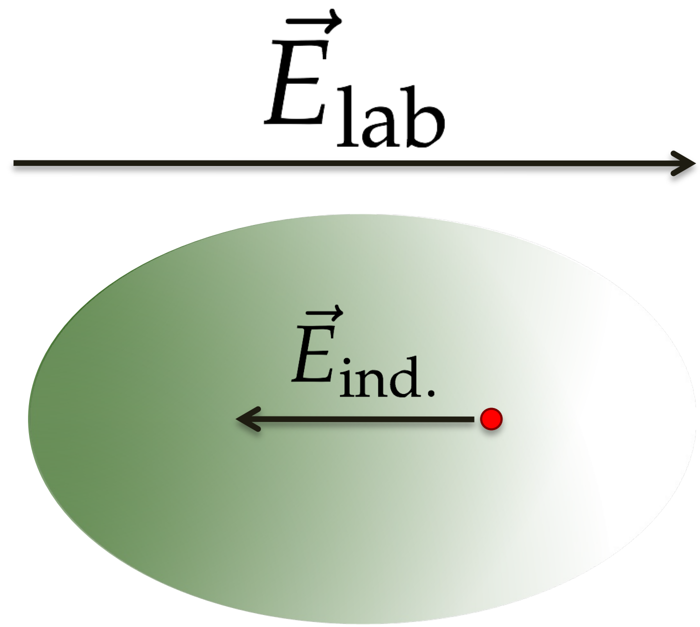
- **Relativistic atoms: The Sandars-Bouchiat Z^3 "Law"**
  Physics Letters 22:290 (1966) & Physics Letters 48B:111 (1974)

- **^{225}Ra vs ^{199}Hg vs. ^{3}He: 2.8 to 1 to 10^{-5}**
  JPB:AMOP 53:195004 (2020) & Phys. Rev. A 106, 022817 (2022)

Madame Professor Marie-Anne Bouchiat

SCAN ME





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

Residual Ᵽ & Ŧ Observable: Nuclear Schiff Moment

- **Shielding in Diamagnetic Atoms**
  Schiff PR 132:2194 (1963)
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- **^{225}Ra vs ^{199}Hg vs. ^{3}He: 2.8 to 1 to 10^{-5}**
  JPB:AMOP 53:195004 (2020) & Phys. Rev. A 106, 022817 (2022)

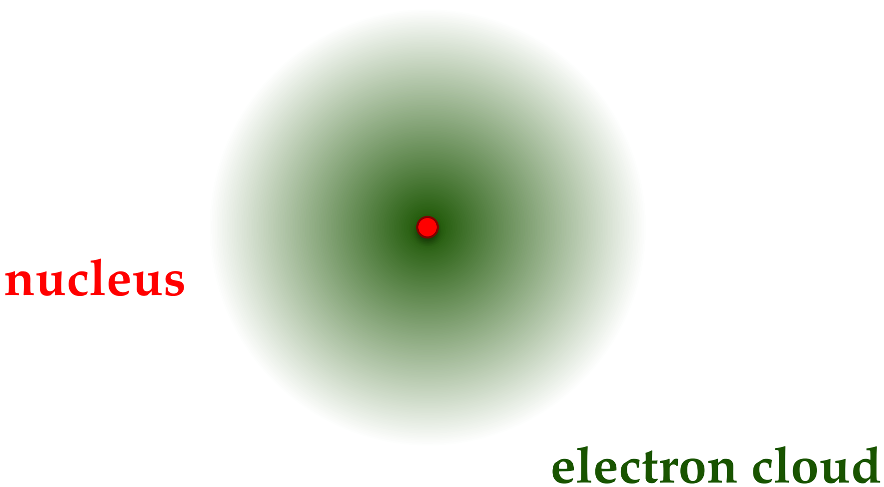
$$\vec{d}_{\mathrm{atom}} = \kappa_{\mathrm{atom}} Z^3 \vec{S}$$

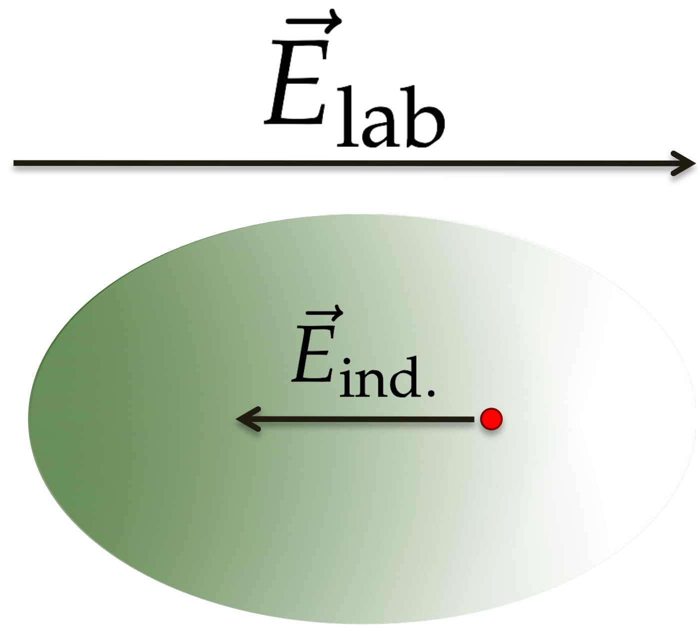
Schiff Moment

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

Zh. Eksp. Teor. Fiz. 87, 1521-1540 (1984)

Neutral Atom





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

P̶ & T̶ Physics: First Order Perturbation Theory

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

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{\not{P}\not{T}} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

- The P̶ and T̶ physics that we seek (unknown & common to all isotopes)

Isotopes With Nearly Degenerate Nuclear States

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

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{\not P \not T} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

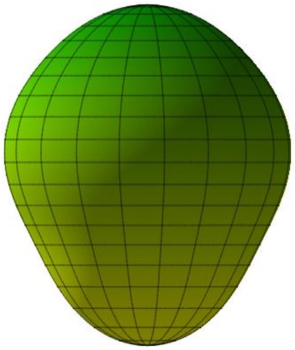
- Difference in lab-frame nuclear energy levels
- The $\not P$ and $\not T$ physics that we seek (unknown & common to all isotopes)

Nuclear Schiff Moment in the Lab Frame

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

$$S \equiv \langle\Psi_0| S_z |\Psi_0\rangle = \sum_{k\neq 0} \frac{\langle\Psi_0| S_z |\Psi_k\rangle \langle\Psi_k| V_{\not{P}\not{T}} |\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

- Body-frame Schiff moment – large when there are intrinsic nuclear deformations
- Difference in lab-frame nuclear energy levels
- The $\not{P}$ and $\not{T}$ physics that we seek (unknown & common to all isotopes)



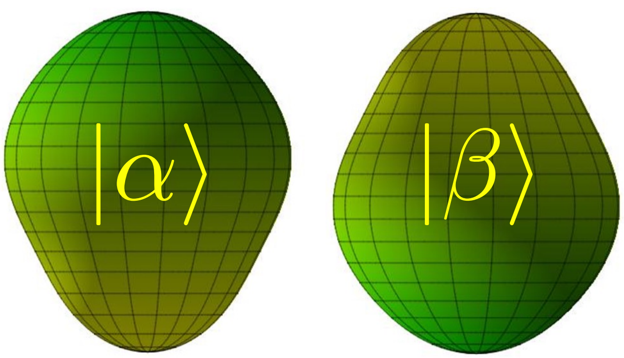
Example of large intrinsic Schiff moment: Pear-shaped nucleus in the "body-frame"

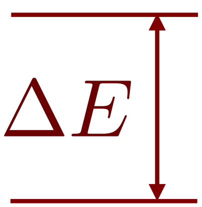
Pear-Shaped Nuclei = Nearly Degenerate Parity Doublets

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

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

Parity Doublet





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

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

- **Nearly degenerate parity doublet**

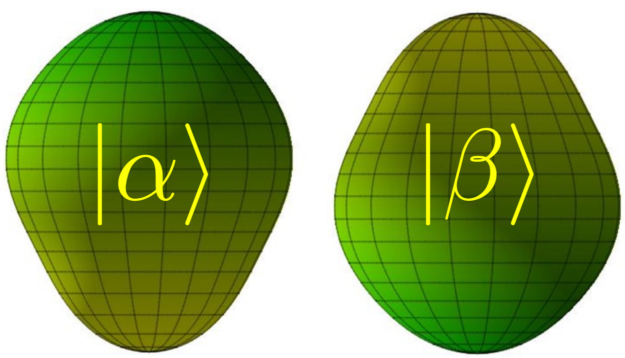
Haxton & Henley PRL 51:1937 (1983)

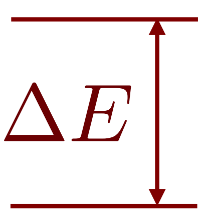
Pear-Shaped Nuclei = Enhanced Intrinsic Schiff Moments

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

$$S \equiv \langle\Psi_0|\, S_z \,|\Psi_0\rangle = \sum_{k\neq 0} \frac{\langle\Psi_0|\, S_z \,|\Psi_k\rangle \langle\Psi_k|\, V_{\not{P}\not{T}} \,|\Psi_0\rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet





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

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- **Nearly degenerate parity doublet**

  Haxton & Henley PRL 51:1937 (1983)

- **Large intrinsic Schiff moment due to octupole deformation**

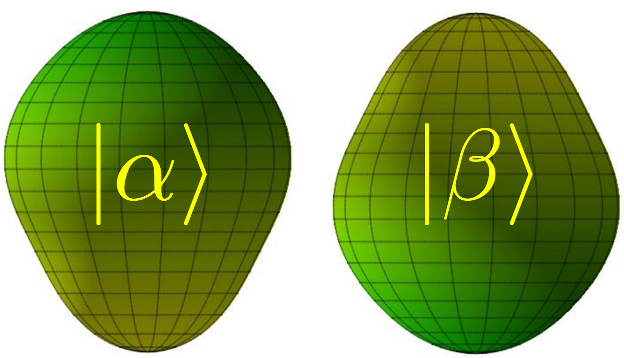
  Auerbach, Flambaum, & Spevak PRL 76:4316 (1996)

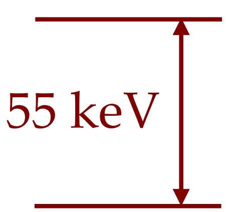
Example: Enhanced Sensitivity in Radium-225

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

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{\not{P}\not{T}} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet





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  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: Ban et al. PRC 82:015501 (2010)

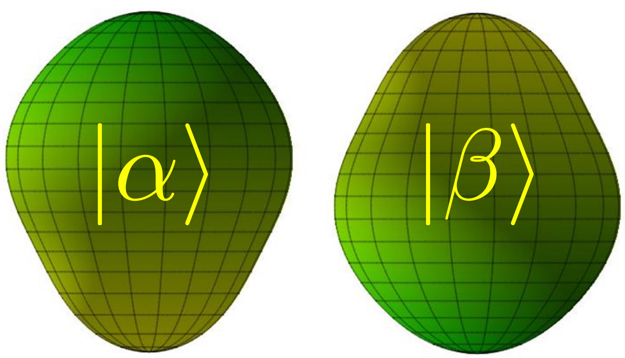
Protactinium-229 *May* Be Unusually Sensitive!

Choose an isotope with large deformations

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{\not{P}\not{T}} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

Unknown

Parity Doublet



ΔE

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

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

Pa-229: Haxton & Henley PRL 51:1937 (1983)
I. Ahmad et al Phys. Rev. C 92:024313 (2015)
Dobaczewski et al PRL 121, 232501 (2018)

Isotope	ΔE (keV)	$\tau_{1/2}$ (sec)	sensitivity
Hg-199	1800	stable	1
Rn-223	~10^2?	10^3	10^2
Ra-225	55	10^6	10^3
Pa-229	**(0.06 +/- 0.05)?**	**10^5**	**10^6**

FRIB will make lots of Pa-229!

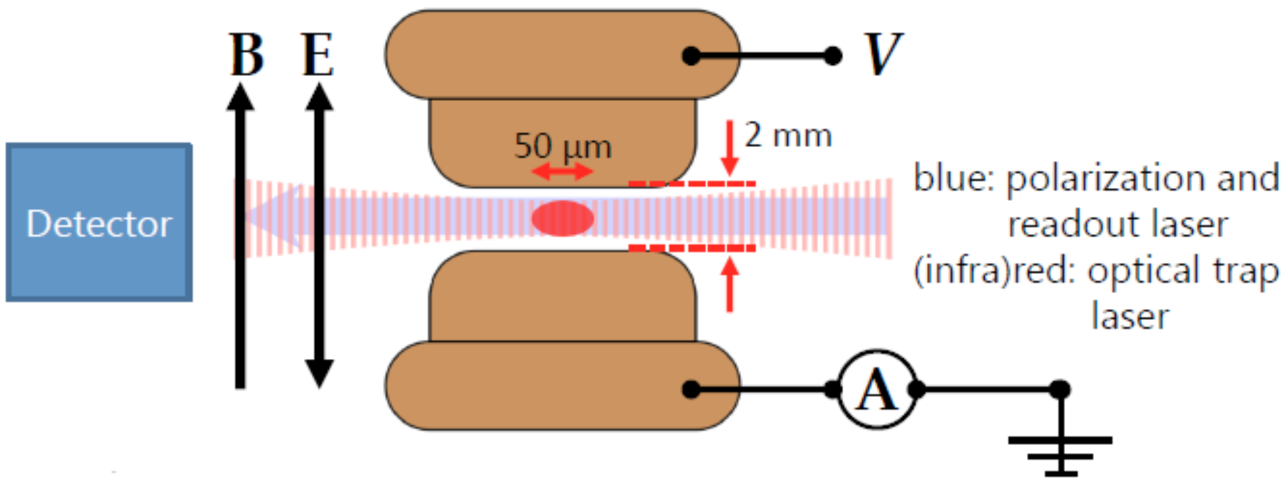
Intermission

Questions?

1. stuff

The Search For The Atomic EDM of Radium

|d(^{225}Ra)| < 50x10^{-23} *e*-cm (95%)
PRL 114:233002 (2015)
|d(^{225}Ra)| < 1.4x10^{-23} *e*-cm (95%)
equivalent to ~1000xEDM(^{199}Hg)
PRC 94:025501 (2016)
Upgrades underway to improve sensitivity by x1000
Spectrochimica Acta Part B 172 105967 (2020)



EDM search using atoms held in Optical Lattice

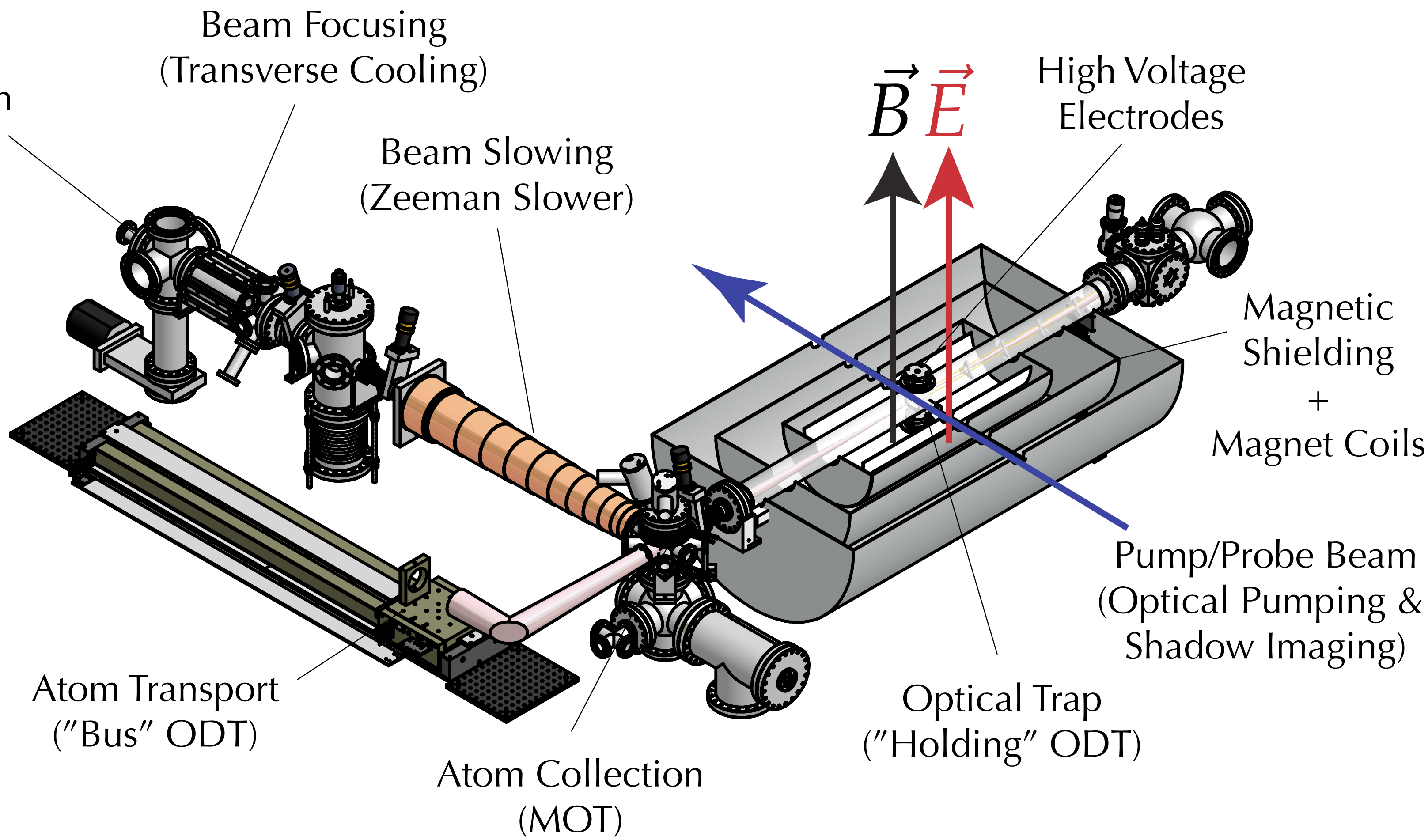
Romalis & Fortson PRA 59:4547 (1999)
Chin et al. PRA 63:033401 (2001)
Bishof et al. PRC 94:025501 (2016)

^{226}Ra
nuclear spin = 0
$t_{1/2}$ = 1600 years
Low vapor pressure

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

- Atoms concentrated in a very small region
- Long coherence time (100 s) PRL 129, 083001 (2022)
- negligible "v x E" systematics
- High electric field (>300 kV/cm) in vacuum NIMA 1014 165738 (2021)
- Light-induced systematic effects can be controlled!

Laser Cooling & Trapping of Neutral Ra Atoms



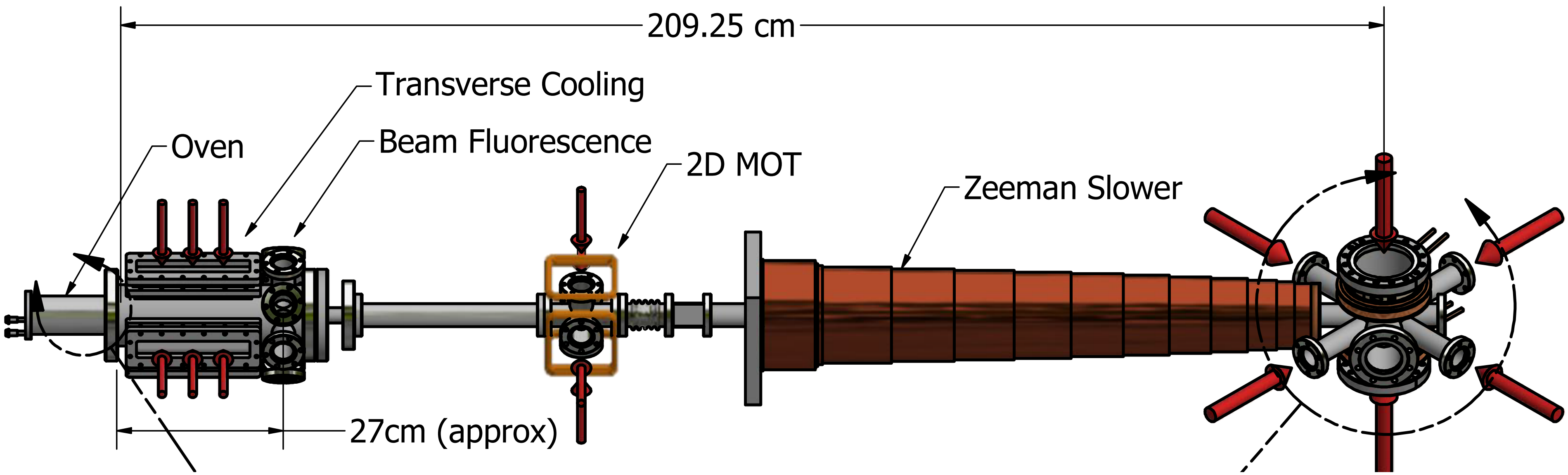
PRC 94:025501

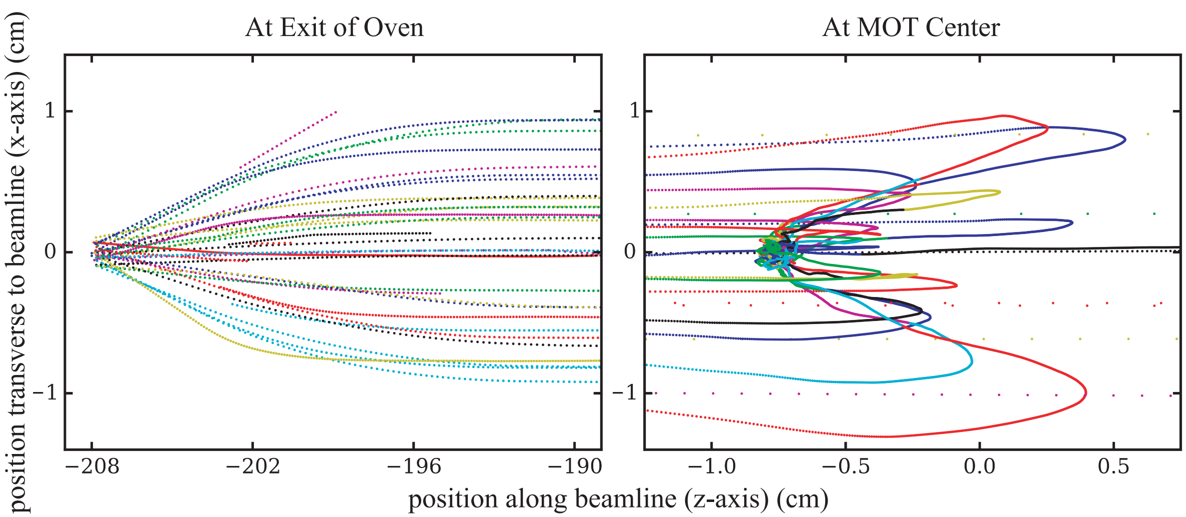
|d(Ra-225)| < $1.4\text{x}10^{-23}$ *e* cm (95%)

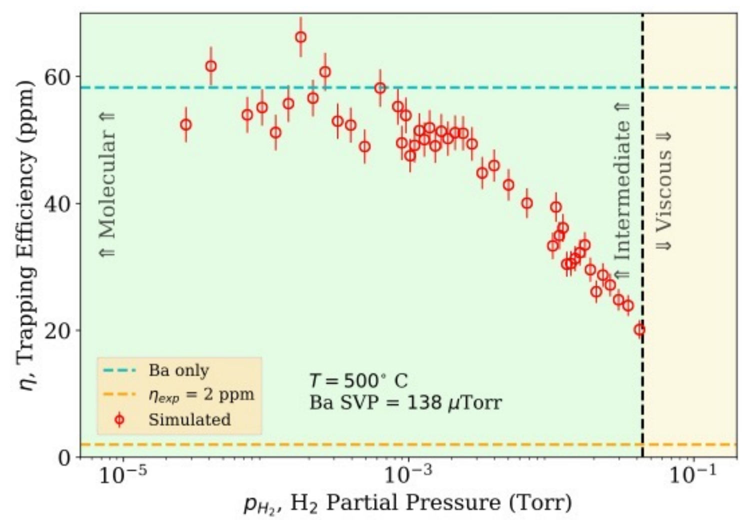
completely statistics limited

several upgrades underway

Current Laser Trapping Efficiency: 2 ppm





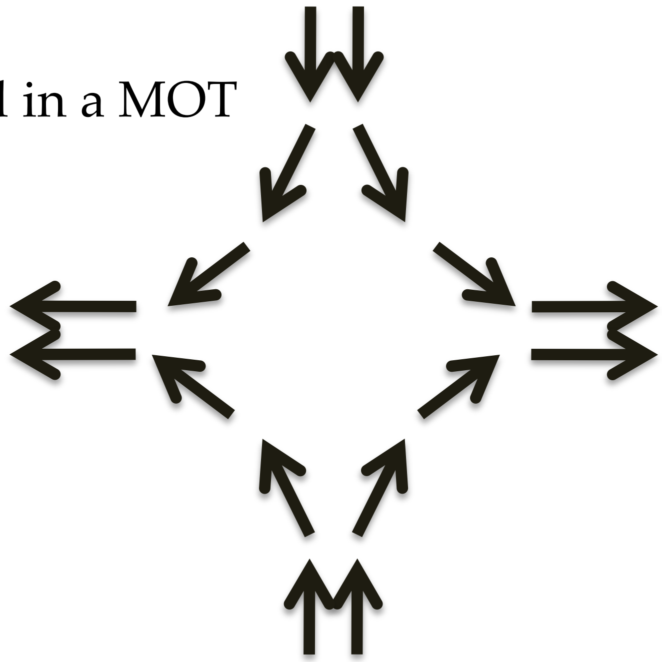


D. A. Potterveld, S. A. Fromm et al. (under review with PRA)

Neutral Atom Traps Using Lasers

Magneto-Optical Trap (MOT)

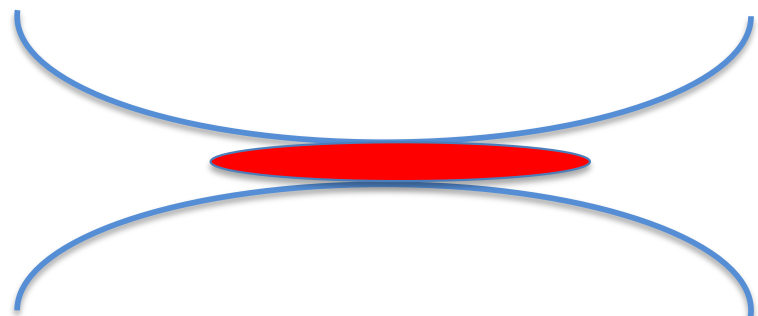
B Field in a MOT



- 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)

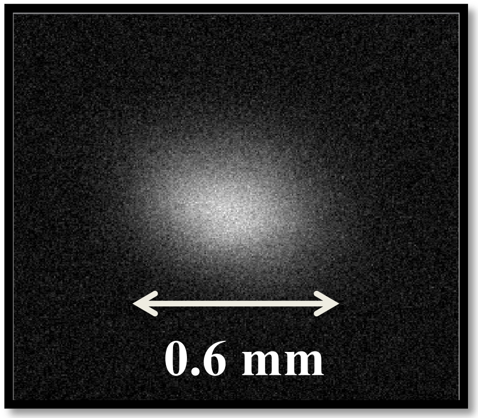
$$\mathcal{H} = -\vec{d}_{\text{ind}} \cdot \vec{E}_0 = \frac{\alpha}{4} E_0^2$$



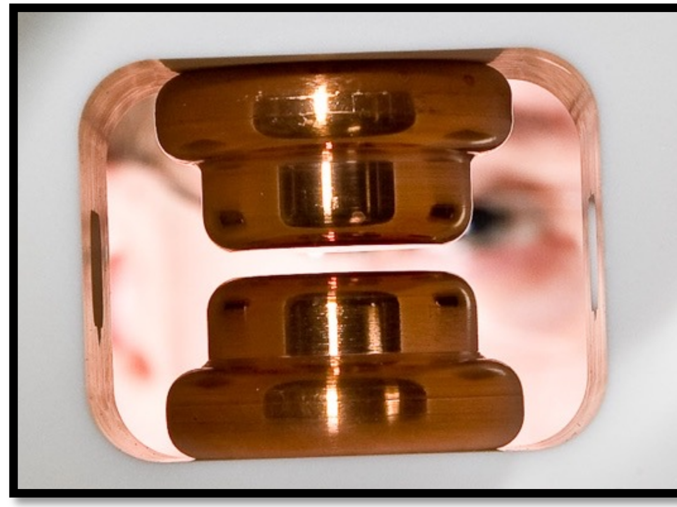
- Atoms trapped at beam focus
- 50 W @ 1550 nm
- 100 mm spot = Trap Depth of 400 μK
- Good for transporting atoms
- Good for spatially confining atoms

Collecting & Transporting Ra-225 Atoms

Guest et al., PRL 98 093001 (2007)

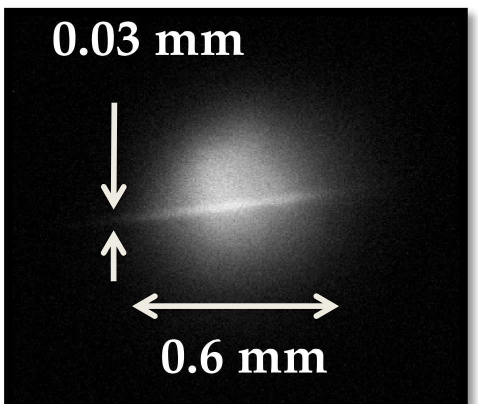


^{226}Ra MOT
20,000 atoms



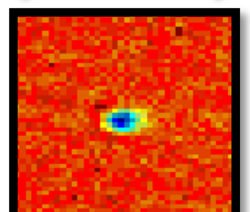
Copper
2.3 mm

Parker et al., PRC 86 065503 (2012)

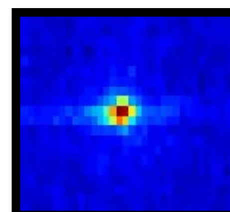


MOT + ODT
20,000 atoms

1.3 mm



1.3 mm

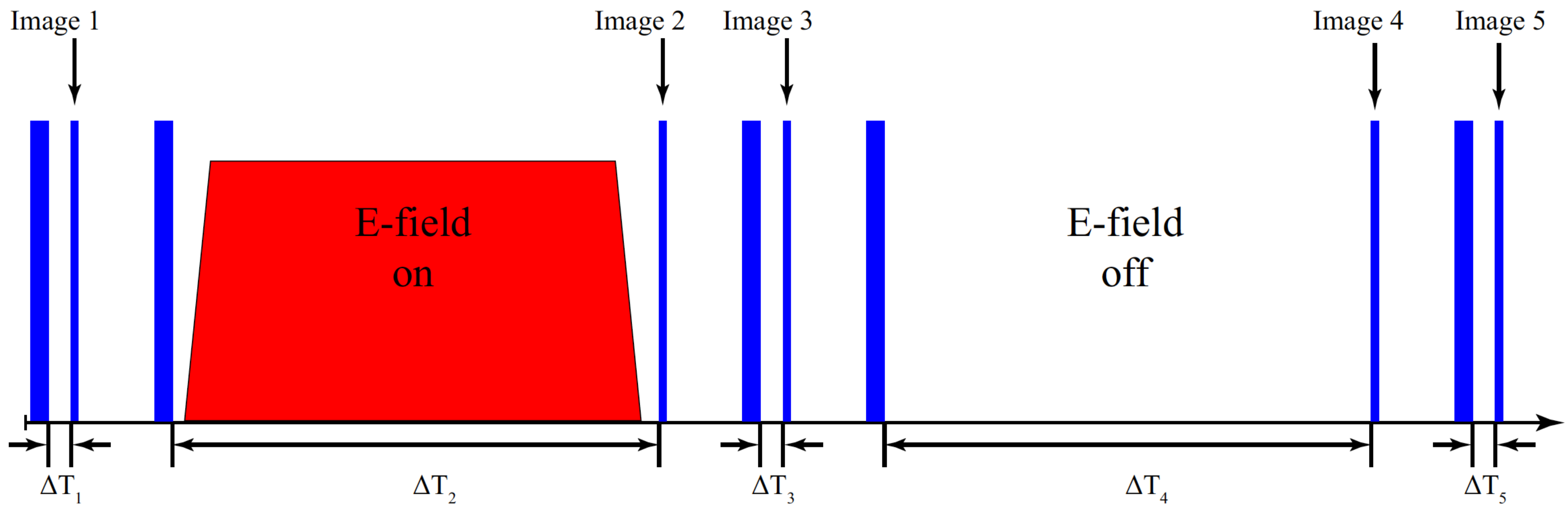


3000 atoms

Absorption Imaging

Fluorescence Imaging

Several Images Are Taken During One Cycle



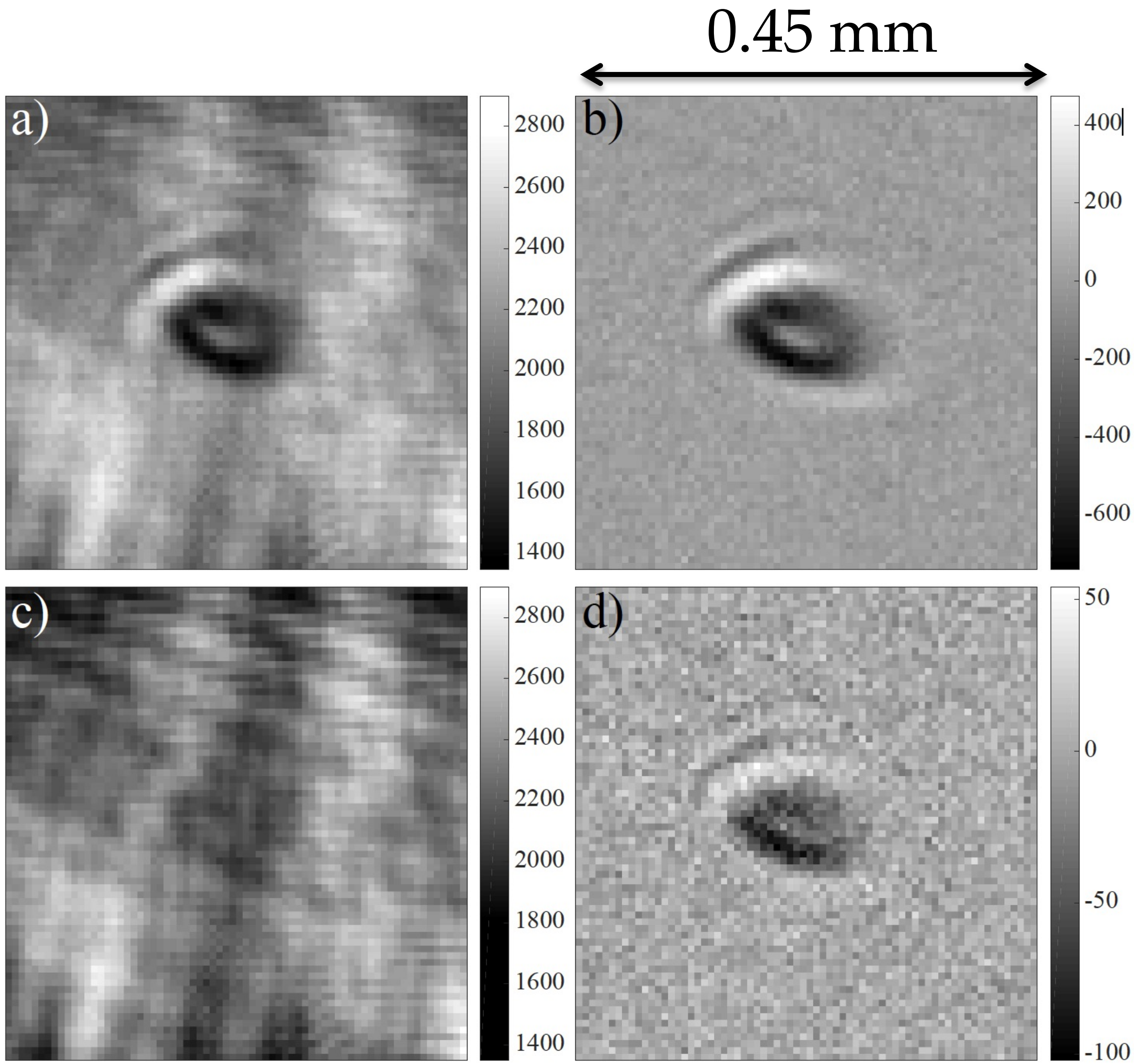
Images taken to account for changes in atom number and probe light intensity.

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

Image Background & Distortion Corrections

average of 8 raw images of Ra-226

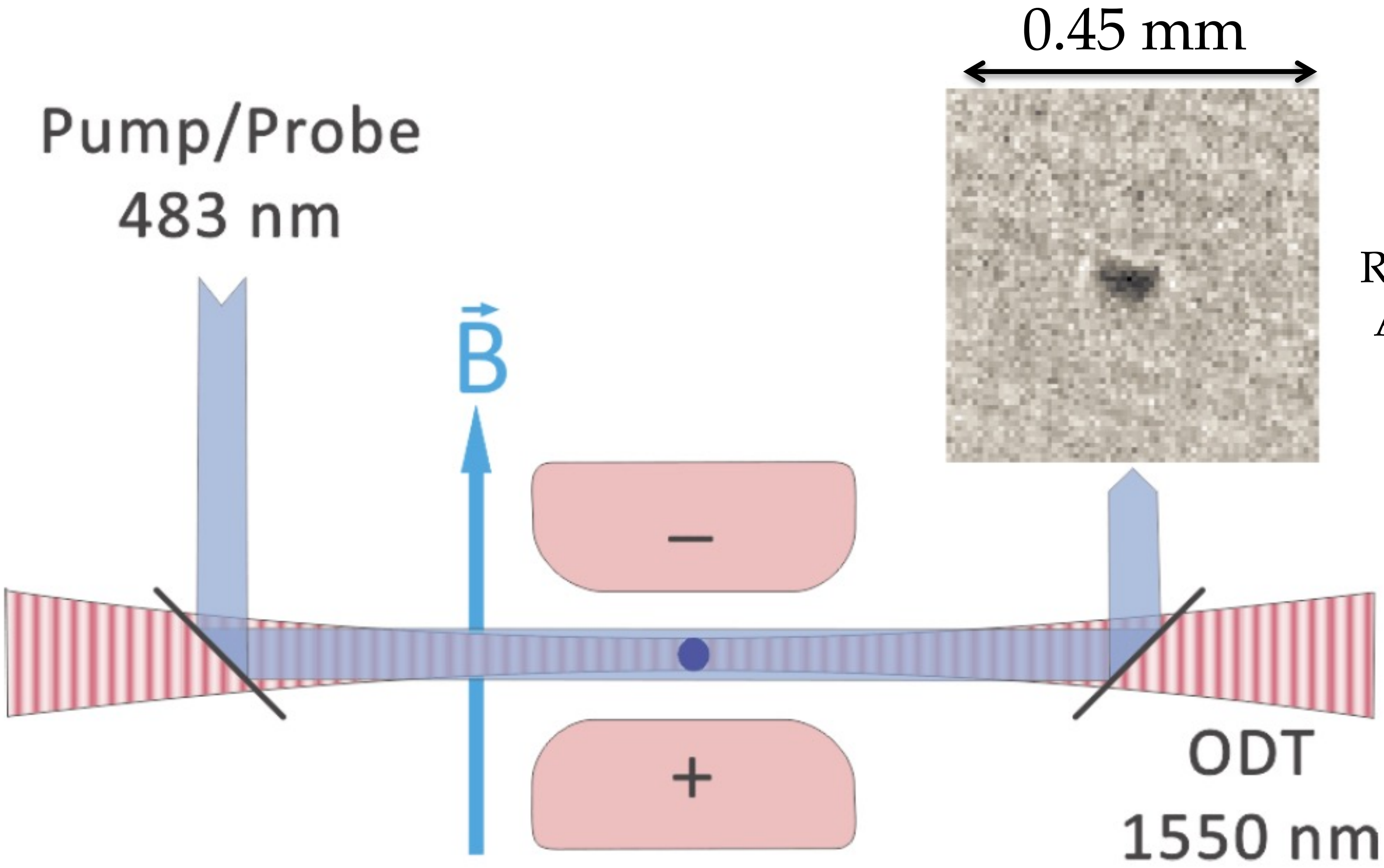
average of 63 raw images of Ra-225



"clean" Ra-226 image 10^4 atoms

"clean" Ra-225 image 10^2 atoms

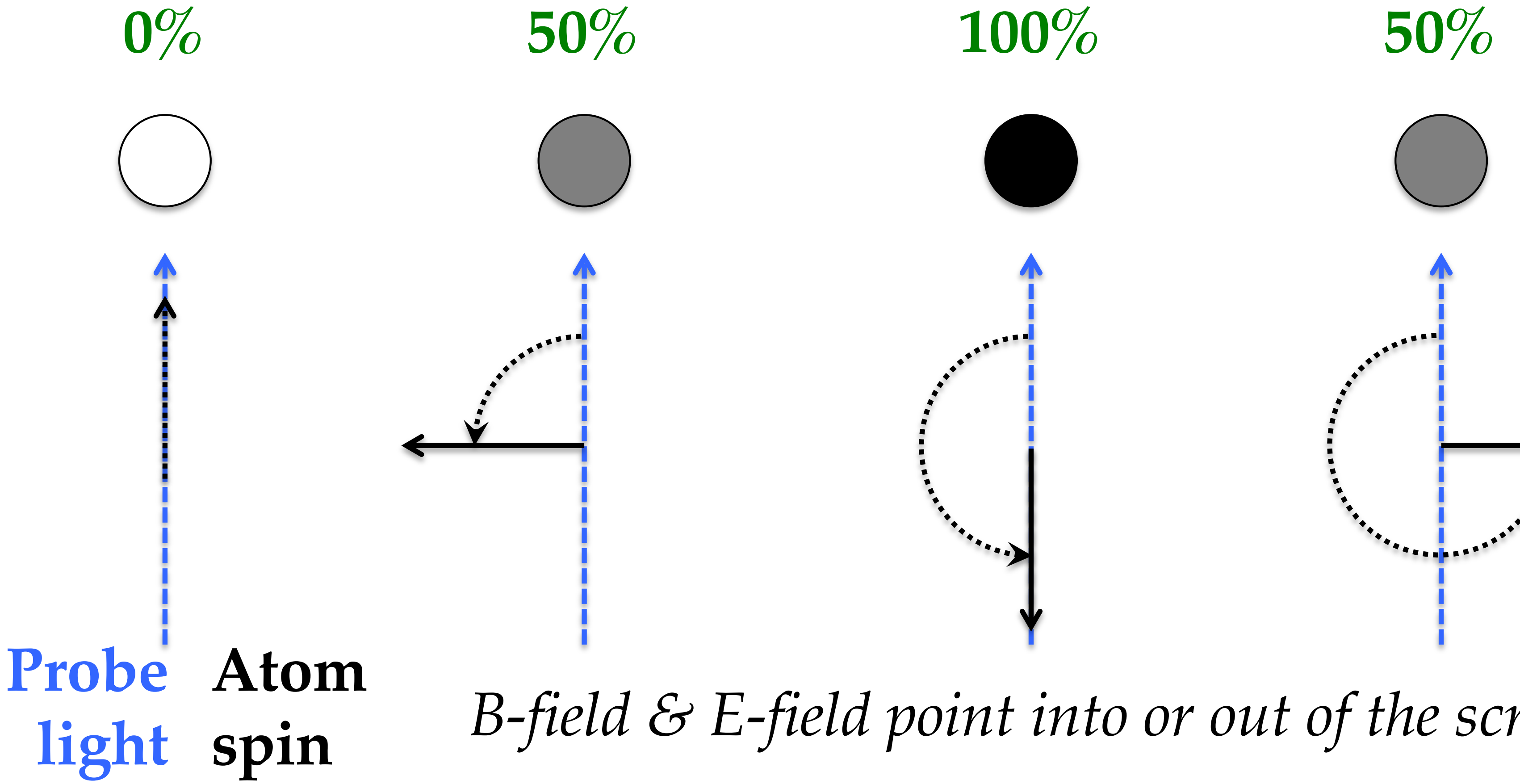
Radium Atoms Create a Shadow by Absorption



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

The Absorption Probability Oscillates at the Spin Precession Frequency (~20 Hz)

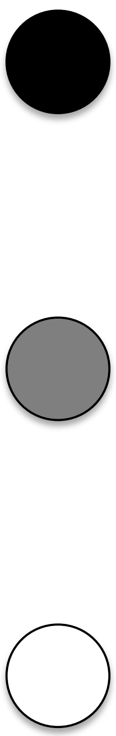
probability of absorbing probe light and creating a shadow:

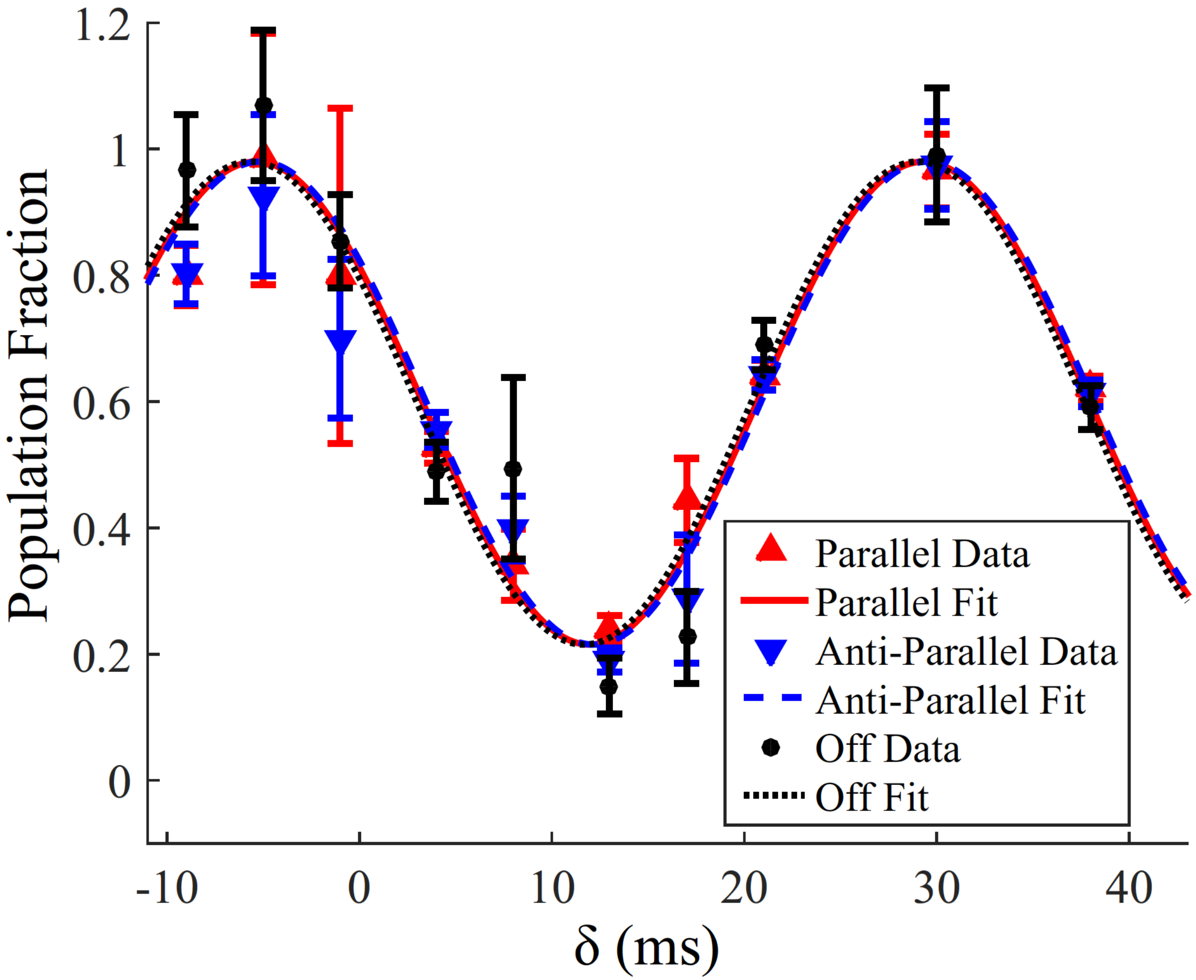


B-field & E-field point into or out of the screen

increasing time

Reconstructed Spin Precession Curve After τ = 20 s (Shadow Measurements Taken At Different Time Delays)





$$d = \frac{h(\Delta\phi)}{4E\tau}$$

$\Delta\phi$ = phase shift between red and blue curves

Ra EDM: Completely Statistics Limited

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.

More efficient detection of atoms: optical cycling

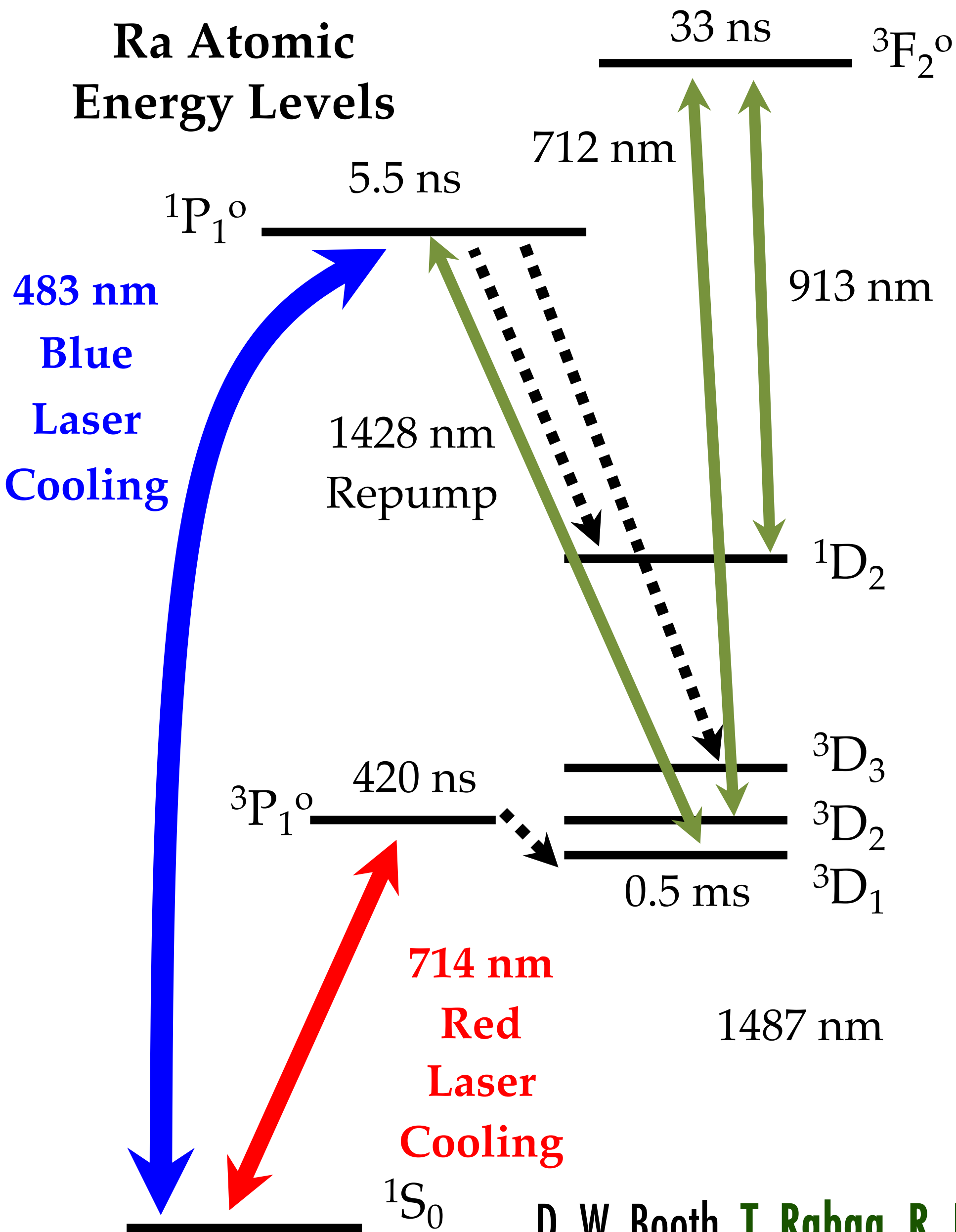
More efficient laser cooling and trapping: 1 ppm to 100 ppm

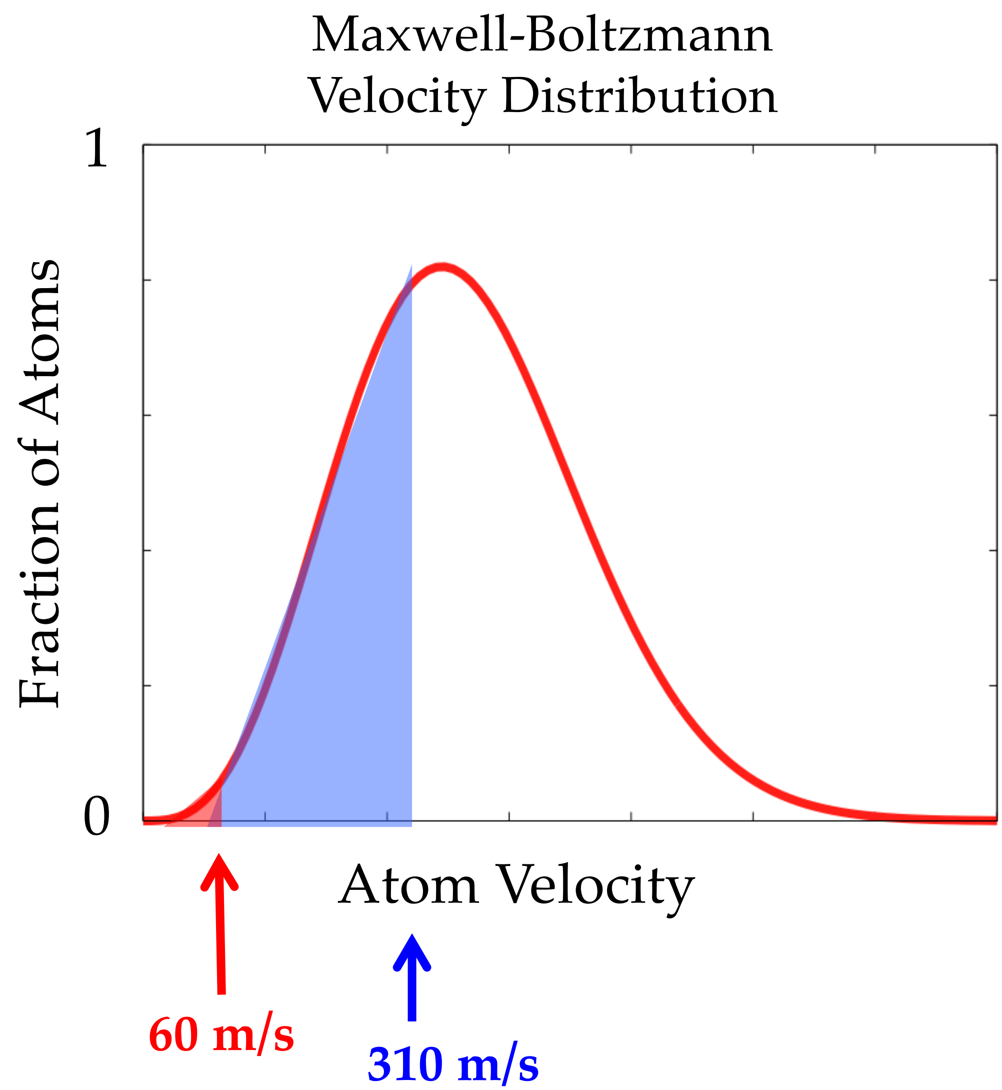
Higher electric field: 70 kV/cm to >350 kV/cm

More consistent supply of atoms: Isotope Harvesting @ FRIB

Goal is <10^{-26} *e* cm over 4 years and then 10^{-28} *e* cm long term

"Blue" Upgrade: 2 ppm to >200 ppm





D. W. Booth, T. Rabga, R. Ready, et al. Spectrochimica Acta Part B 172 (2020) 105967

Towards Higher Electric Field: Bench Tests @ MSU

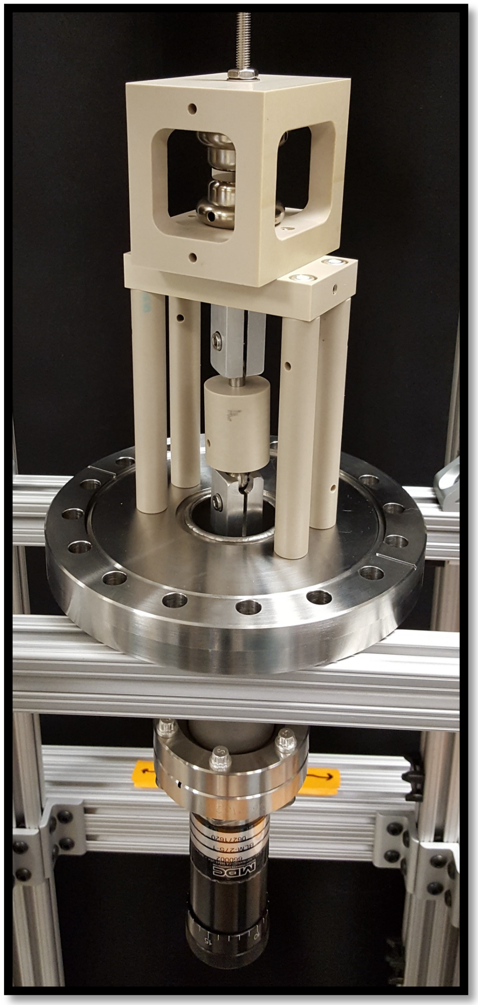
Increase E-field from 67 kV/cm without systematics:

- higher voltage (15 kV to 25 kV)
- smaller gap (2.3 mm to 0.4 mm)
- **achieved >500 kV/cm = 50 MV/m with Nb + High Pressure Rinse**

For the next run ($\leq 10^{-26}$ e*cm)

<1 pA leakage current

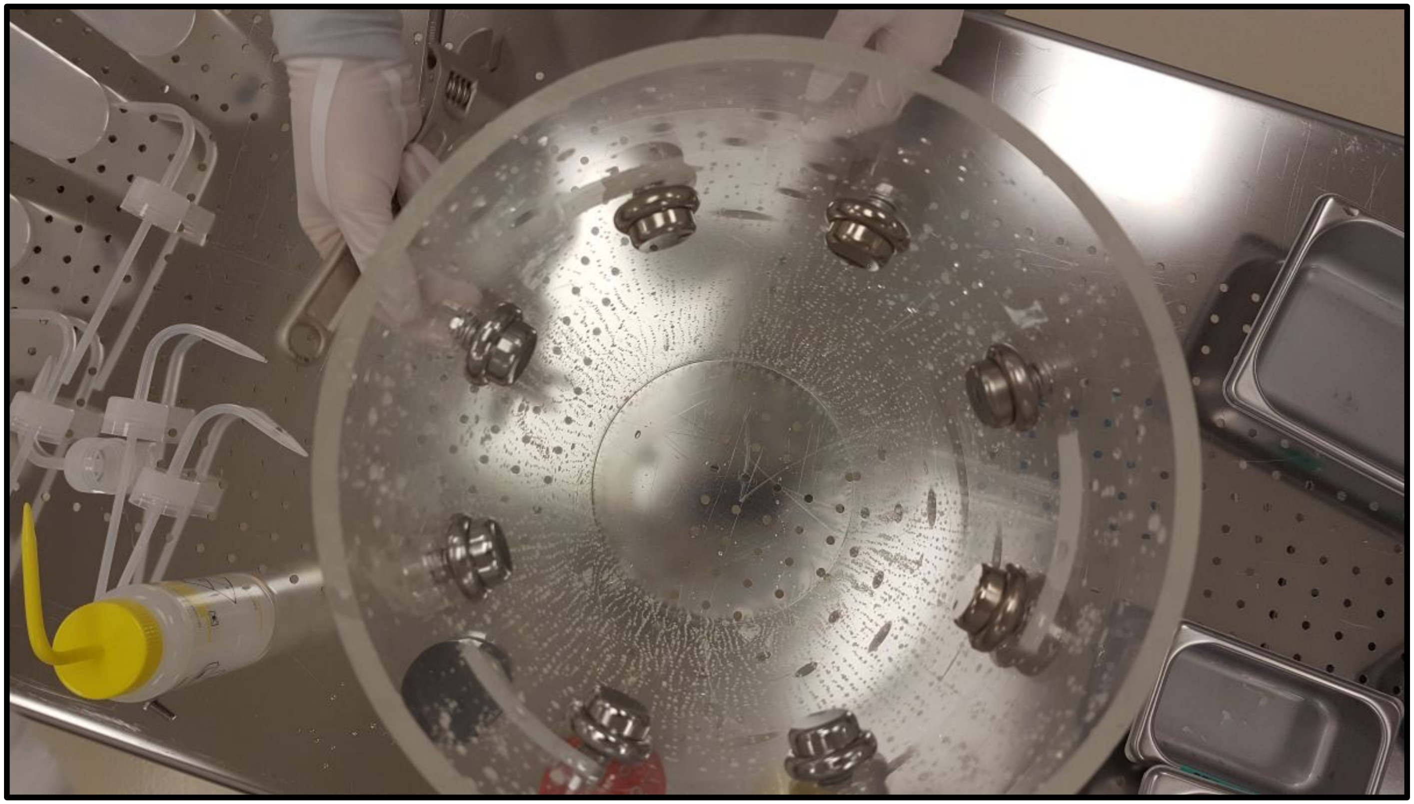
<10 pT residual magnetization



Cu, Nb, Ti Electrodes (below) and Adjustable Gap Mount (right)

2 cm

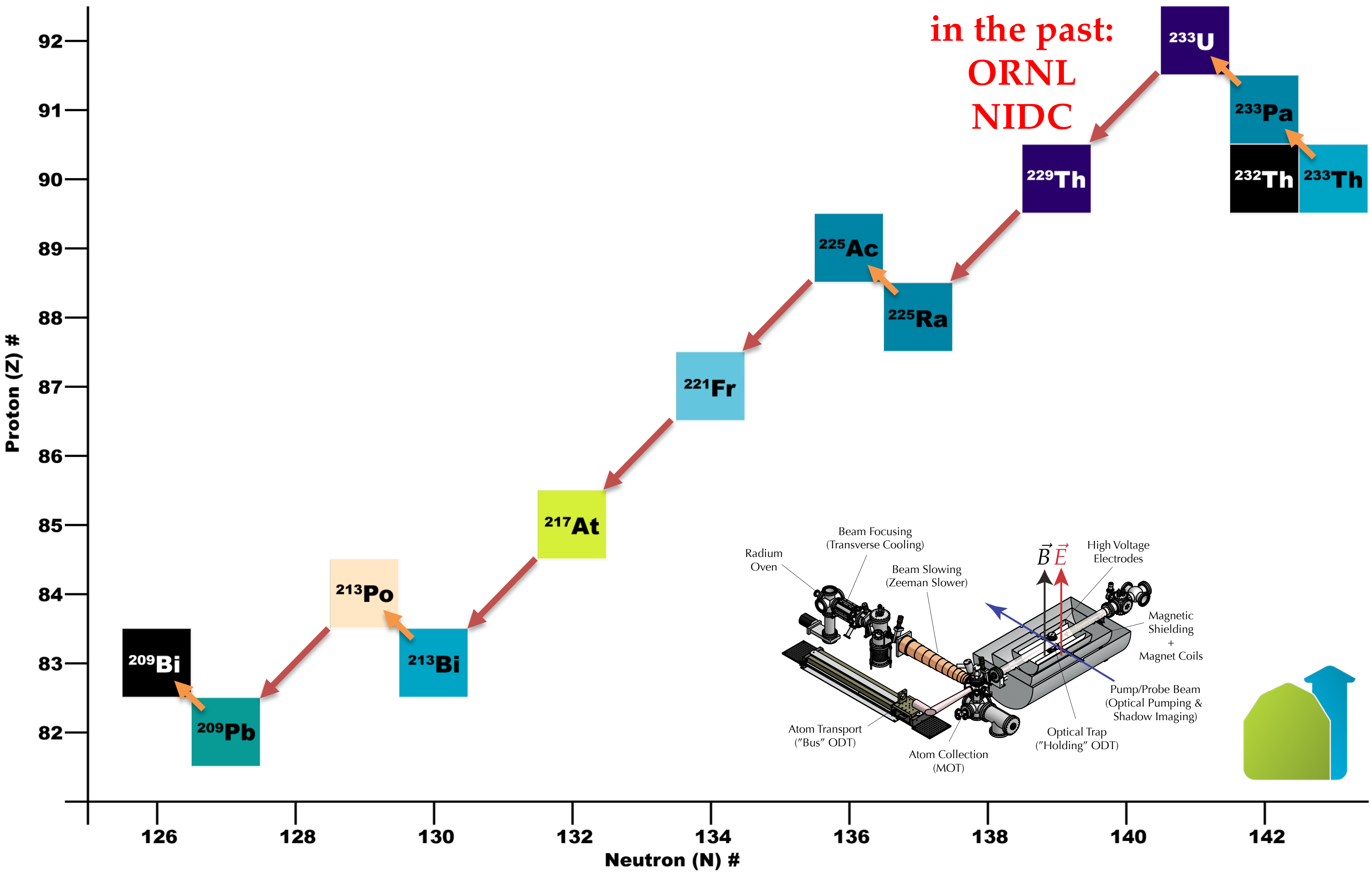
High Pressure Rinse Removes Particulate Contamination



- 1200 psi for 20 minutes
- 18.1 MΩ-cm rinse resistivity
- Rinse & installation performed in class 100 environments

R. Ready, et al. NIMA 1014 165738 (2021)

Source of Radium-225 Atoms ($\tau_{1/2}$ = 15 days)

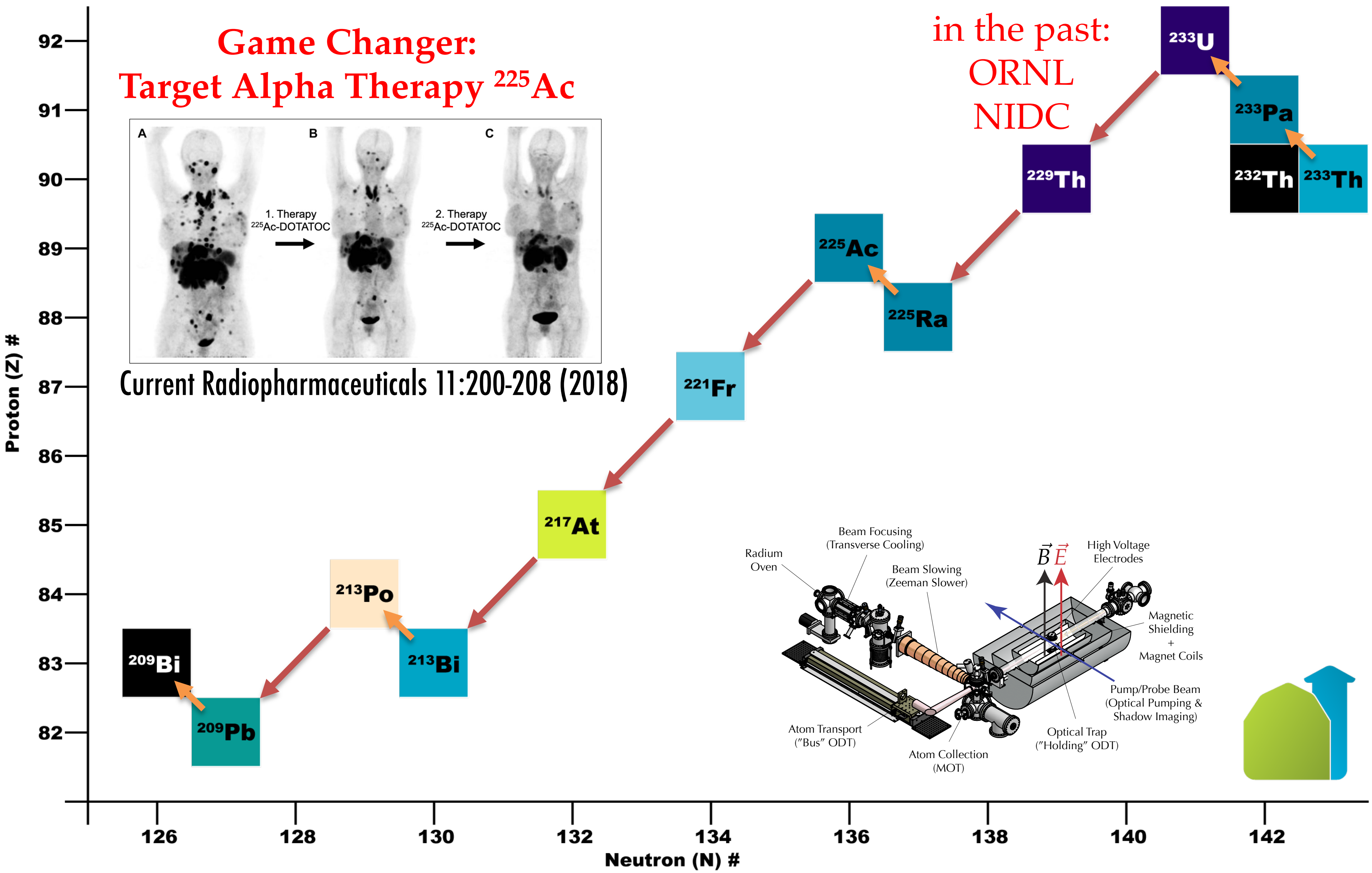


~~Source of Radium-225 Atoms ($\tau_{1/2}$ = 15 days)~~

Game Changer:
Target Alpha Therapy ^{225}Ac

Current Radiopharmaceuticals 11:200-208 (2018)

in the past:
ORNL
NIDC

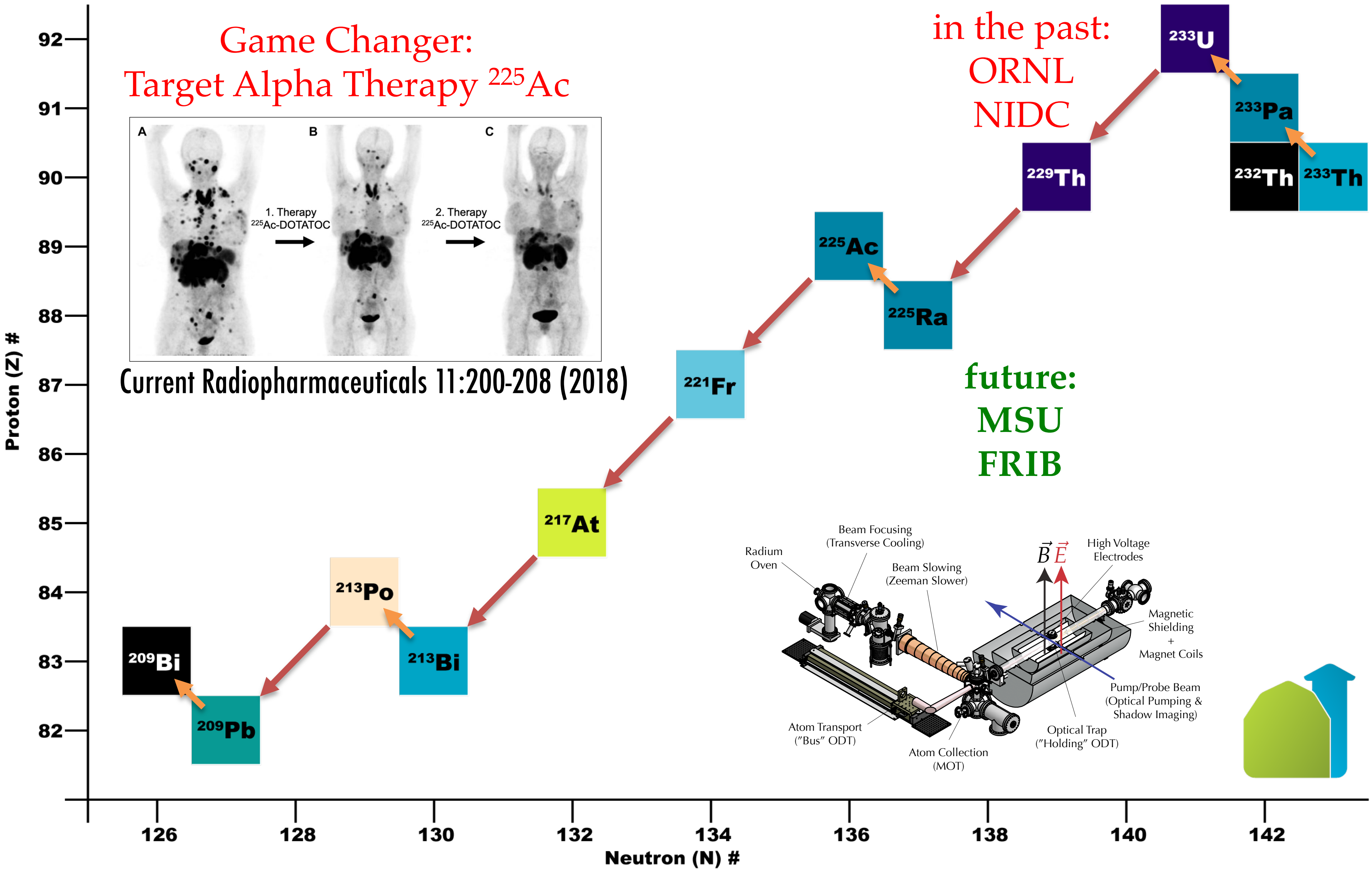


Source of Radium-225 Atoms ($\tau_{1/2}$ = 15 days)

Game Changer:
Target Alpha Therapy ^{225}Ac

in the past:
ORNL
NIDC

future:
MSU
FRIB



Current Radiopharmaceuticals 11:200-208 (2018)

Facility for Rare Isotope Beams @ MSU

Michigan State University
East Lansing, MI
Very Bad at American Football
Home of FRIB

Google Maps & Wikipedia Commons

Facility for Rare Isotope Beams @ MSU

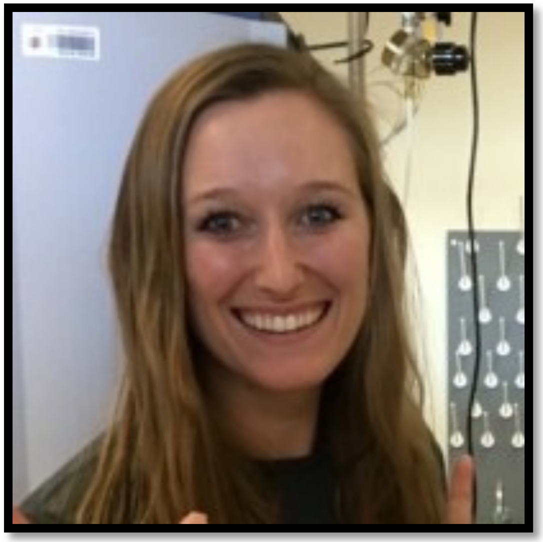
Michigan State University
East Lansing, MI
Very Bad at American Football
Home of FRIB

University of Michigan
Ann Arbor, MI
Very Good at American Football
no FRIB

Google Maps & Wikipedia Commons

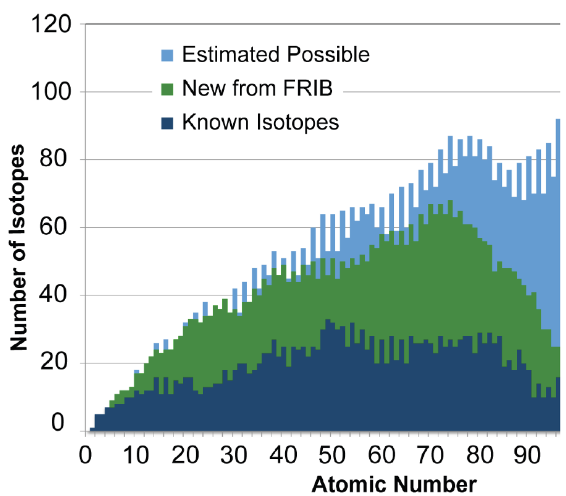
“Isotope Harvesting” at
The Facility for Rare Isotope Beams (MSU/East Lansing)

Prof. Greg Severin

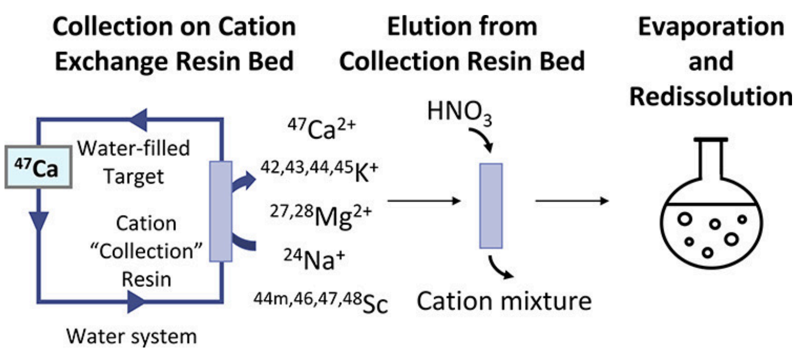


Prof. Alyssa Gaiser

Prof. Katharina Domnanich



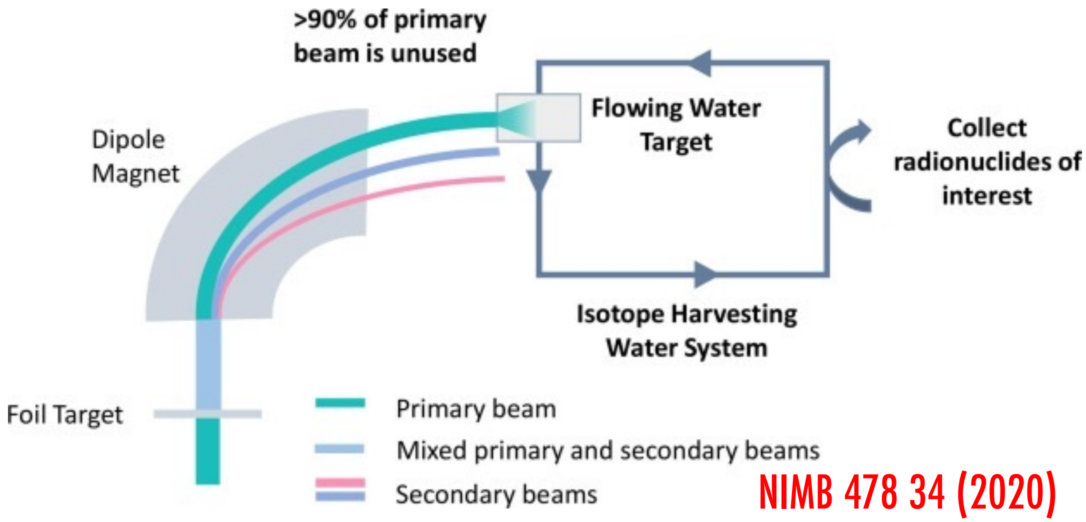
Nature 486, 509–512 (2012)



Recovery of 92% to 99% of ^{47}Ca (surrogate for Radium)

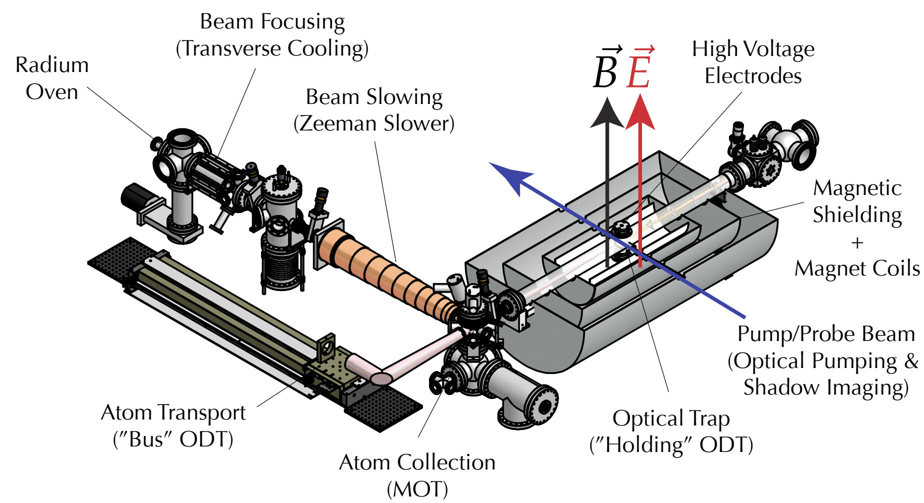
Abel et al., ACS Omega 5(43) 27864 (2020)

$upport Needed For "Beaker to Experiment"



NIMB 478 34 (2020)

- FRIB Operations is supported by DOE-NP
- Isotope Harvesting @ FRIB is supported by DOE-Isotopes



Thanks For Your Attention! More Questions?

1. Tests of fundamental symmetries provide access to New Physics.
2. The discovery of a nonzero electric dipole moment would indicate the presence of New Physics which could explain the Baryon Asymmetry of the Universe.
3. Pear-shaped (octupole-deformed) nuclei have enhanced sensitivity to symmetry violations.
4. FRIB will provide access to rare heavy pear-shaped nuclei.
5. Tomorrow:
   - Other symmetry-violating static electromagnetic moments
   - Some New Physics context
   - Other systems including Radioactive Molecules

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U.S. DEPARTMENT OF ENERGY | Office of Science

DOE Early Career Award 2018
DE-SC0019015 (EDM3)
DE-SC0019455 (Ra EDM)

GORDON AND BETTY MOORE FOUNDATION

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