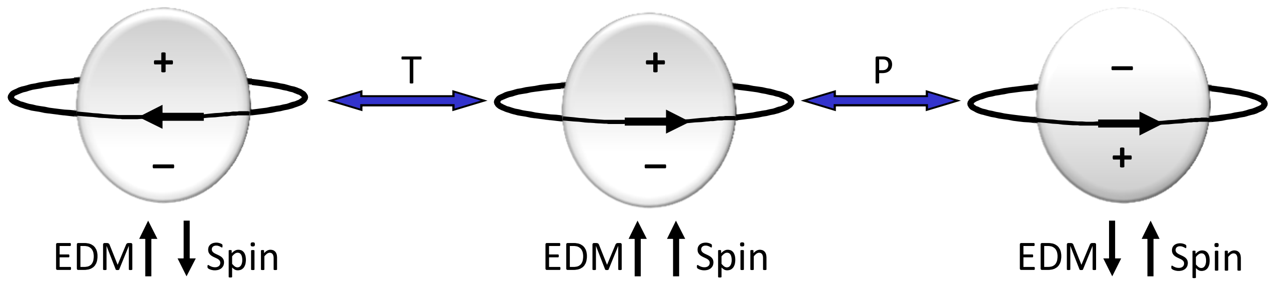


EDM Searches at the Intensity Frontier

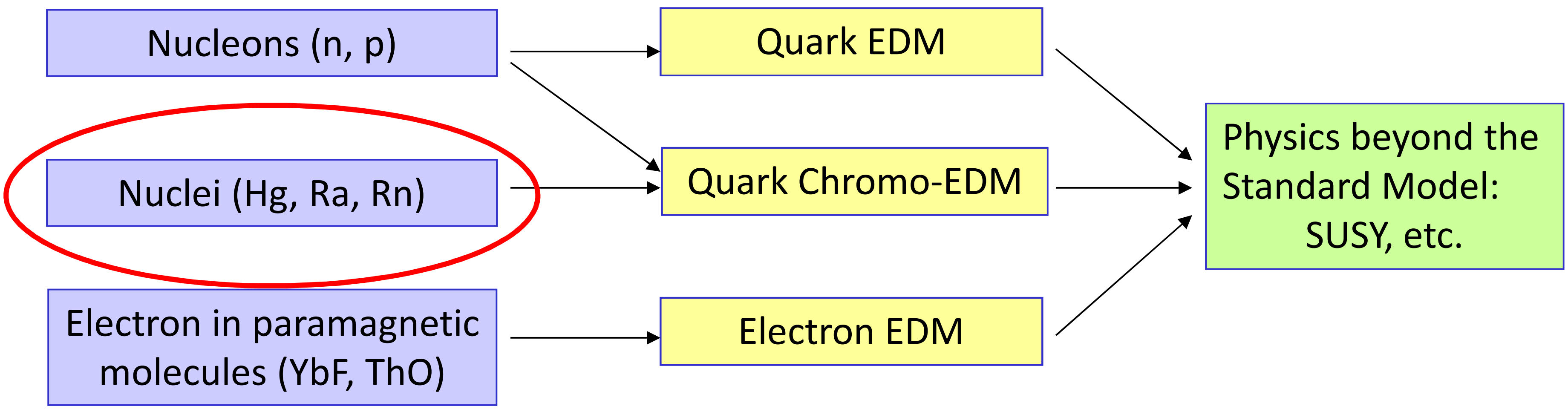
Zheng-Tian Lu

Physics Division, Argonne National Laboratory

Department of Physics, University of Chicago

EDM Searches in Three Sectors

Review article: *EDM of Nucleons, Nuclei, and Atoms*
Engel, Ramsey-Musolf, van Kolck, arXiv:1303.2371 (2013)



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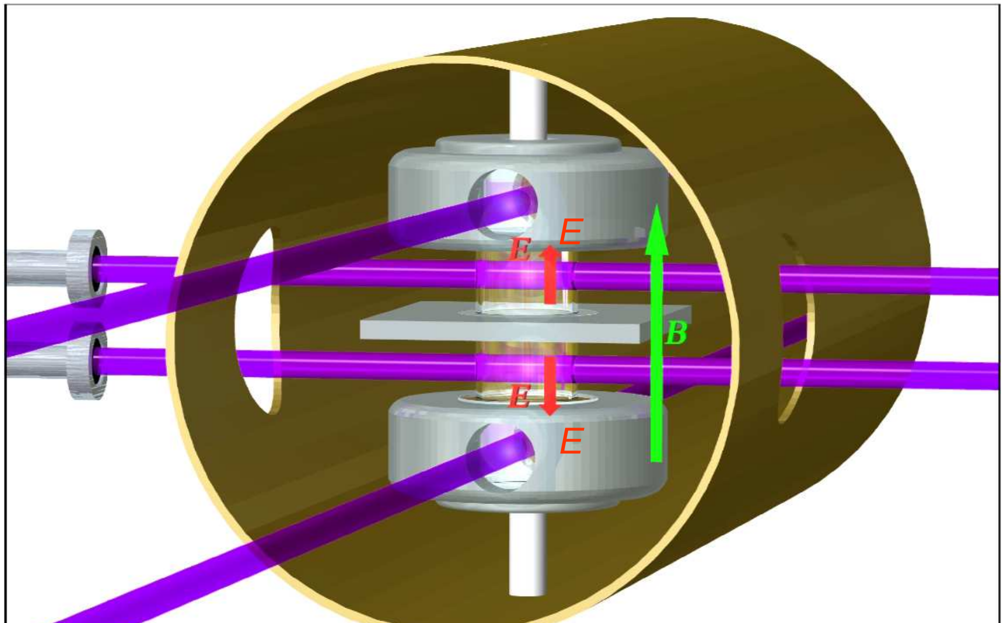
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)

The Seattle EDM Measurement (1980's - present)

^{199}Hg stable, high Z, groundstate $^1S_0$, I = ½, high vapor pressure



Courtesy of Michael Romalis

$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15\ \mathrm{Hz}$$

$$f_- = \frac{2\mu B - 2dE}{h} \approx 15\ \mathrm{Hz}$$

$$|f_+ - f_-| < 0.1\ \mathrm{nHz}$$

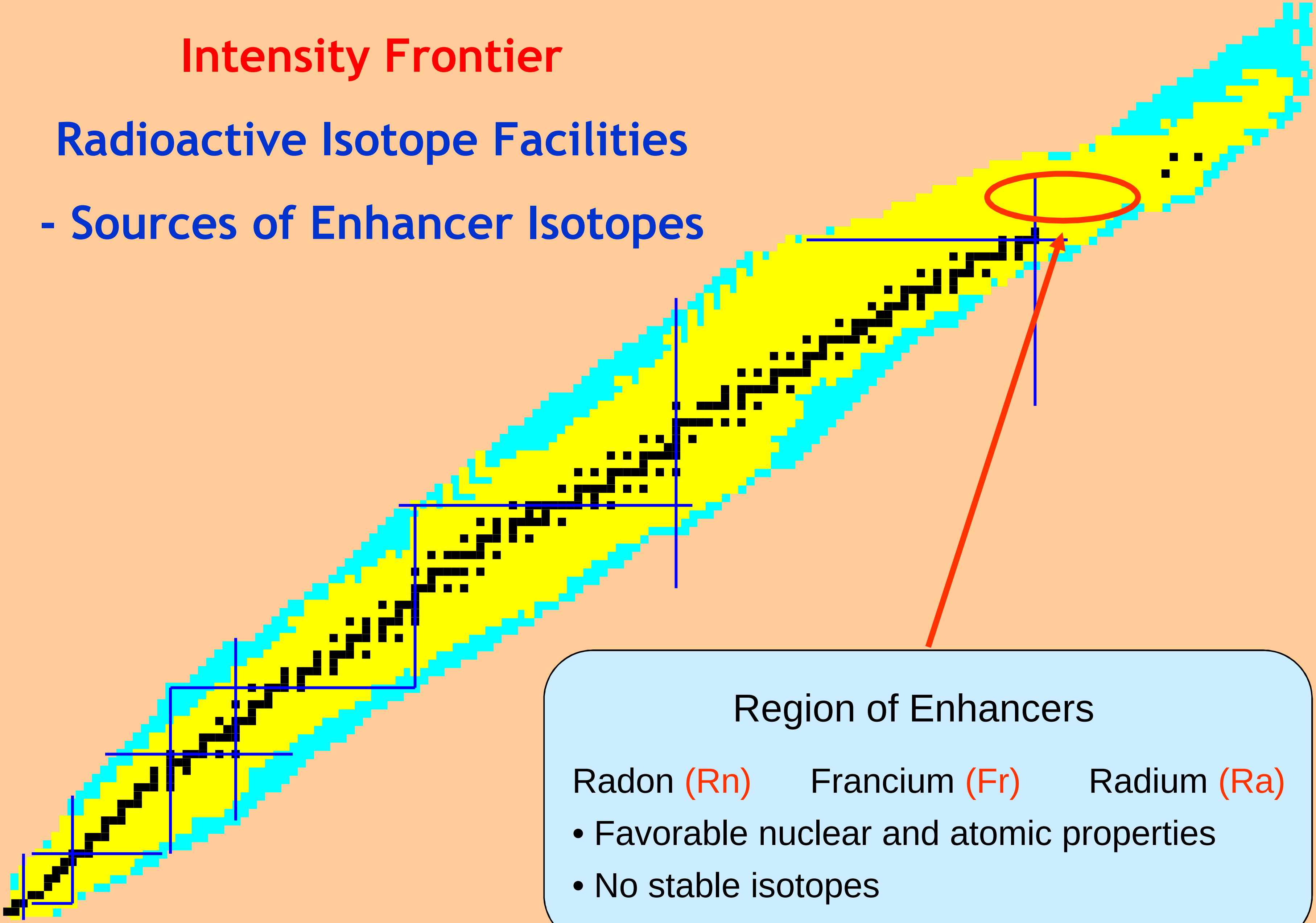
Limits and Sensitivities

- Current: < 0.3 x 10^{-28} e-cm   Griffith *et al.*, Phys. Rev. Lett. (2009)
- Next 5 years: 0.03 x 10^{-28} e-cm
- 2020 and beyond: 0.006 x 10^{-28} e-cm

Intensity Frontier

Radioactive Isotope Facilities

- Sources of Enhancer Isotopes



Region of Enhancers

Radon (Rn) Francium (Fr) Radium (Ra)

- Favorable nuclear and atomic properties
- No stable isotopes

EDM of ^{225}Ra enhanced

^{225}Ra:

I = ½

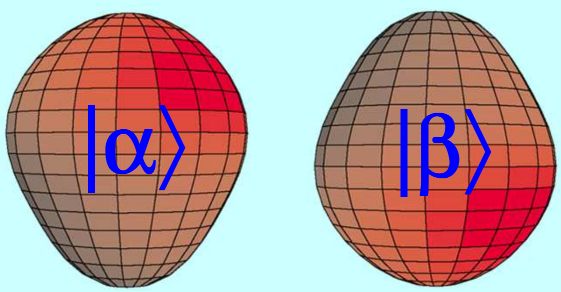
$t_{1/2}$ = 15 d

- Closely spaced parity doublet – *Haxton & Henley (1983)*
- Large intrinsic Schiff moment due to octupole deformation

  – *Auerbach, Flambaum & Spevak (1996)*
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3)

  – *Dzuba, Flambaum, Ginges, Kozlov (2002)*

Parity doublet



55 keV

$$\Psi^{-} = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

$$\Psi^{+} = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

$$S \equiv \langle \psi_0 | \hat{S}_z | \psi_0 \rangle = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

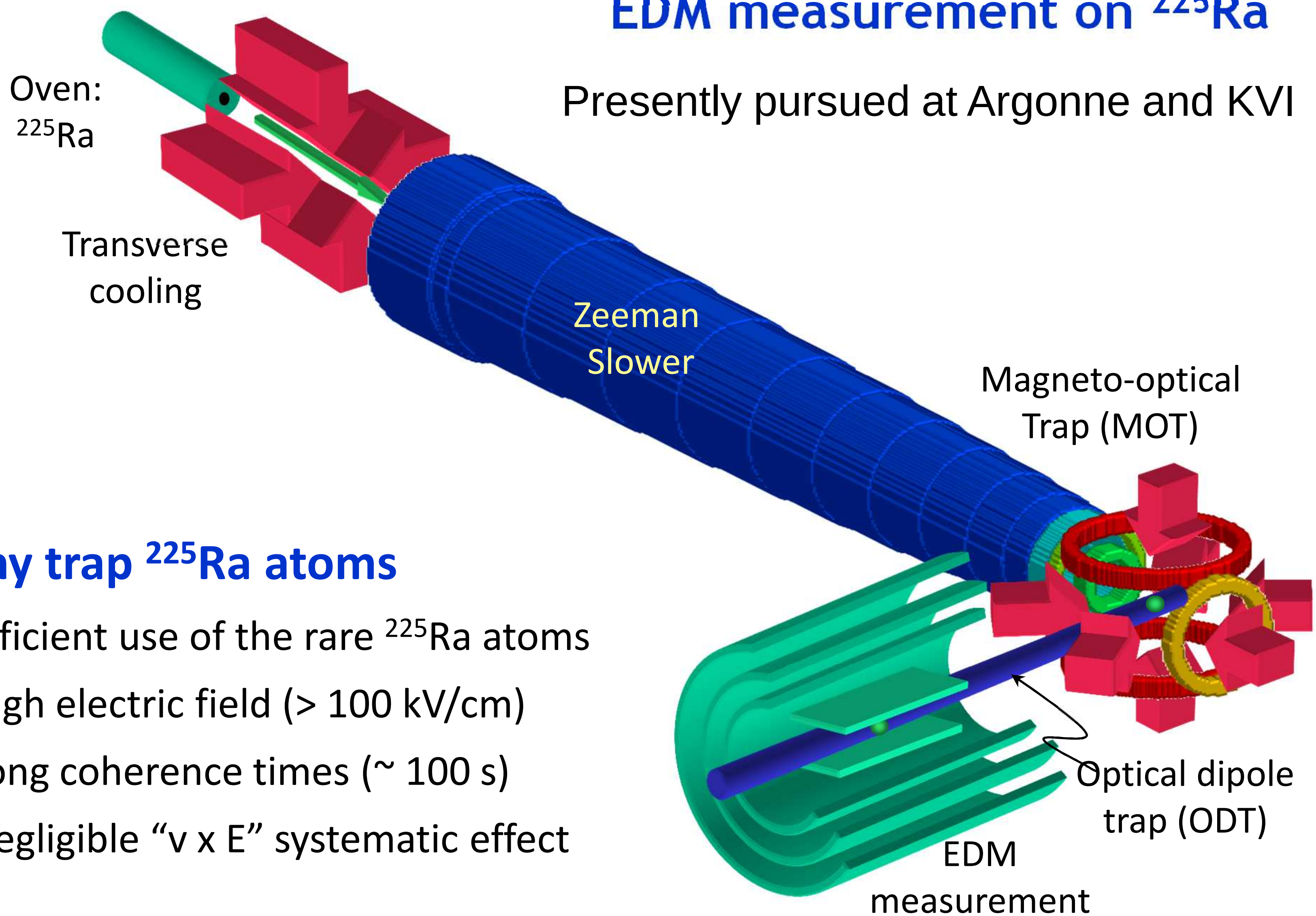
Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)

Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

EDM measurement on ^{225}Ra

Presently pursued at Argonne and KVI



Why trap ^{225}Ra atoms

- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible "v x E" systematic effect

Radium EDM Search at Argonne

Progress

- 2007 – Magneto-optical trap (MOT) of radium realized;

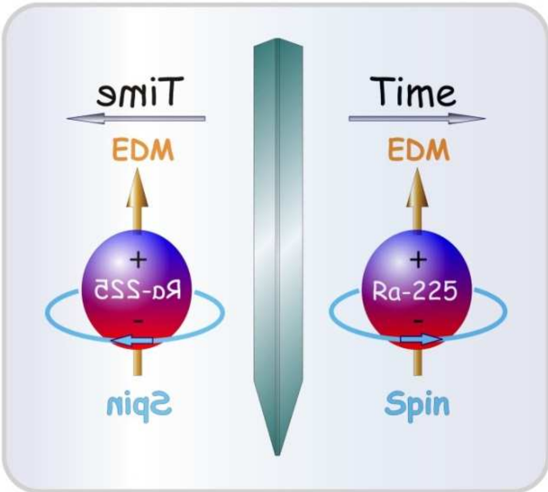
  J.R. Guest *et al.*, Phys. Rev. Lett. (2007)
- 2010 – Optical dipole trap (ODT) of radium realized;
- 2011 – Atoms transferred to the measurement trap;

  R.H. Parker *et al*. Phys. Rev. C (2012)
- 2012 – Spin precession of Ra-225 observed.

Outlook

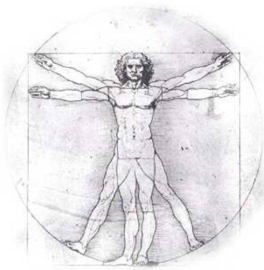
- Next 5 years: 10 – 100 x 10^{-28} e-cm
- 2020 and beyond: 1 x 10^{-28} e-cm *

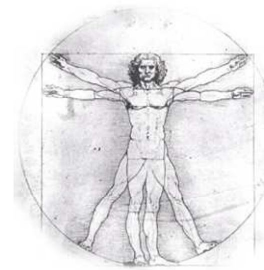
  * at an accelerator-based isotope production facility



We acknowledge support by DOE, Office of Nuclear Physics

Radon-EDM Experiment





TRIUMF E929

Spokesmen: Timothy Chupp & Carl Svensson

E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)

TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

Funding: NSF-Focus Center, DOE, NRC (TRIUMF), NSERC

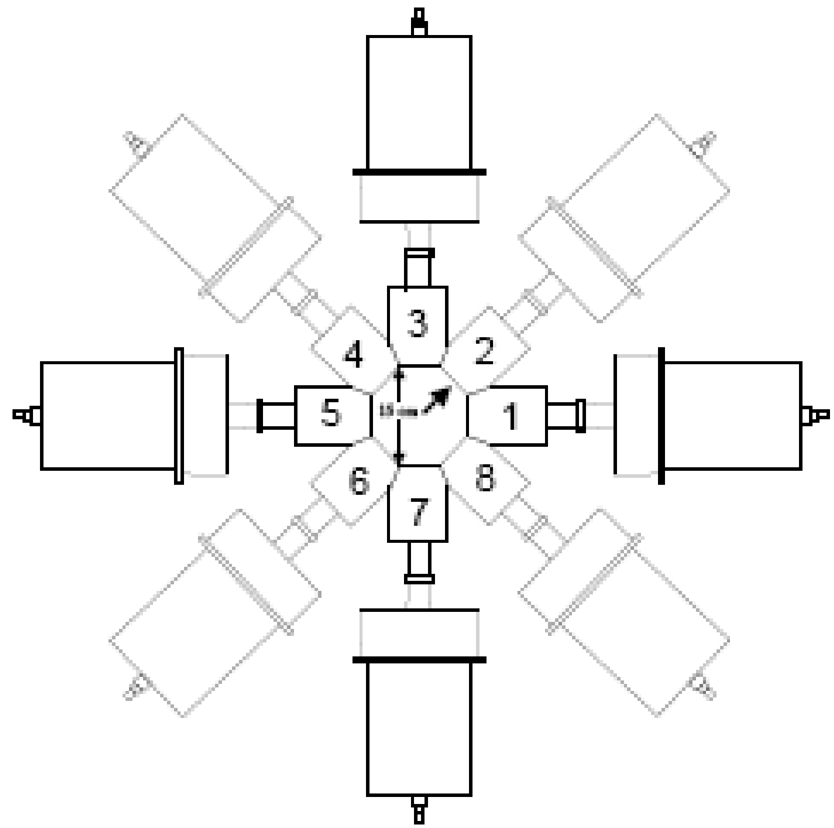
Techniques:

Produce rare ion radon beam

Collect in cell

Comagnetometer

Measure free precesion
(γ anisotropy/β asymmetry/laser)



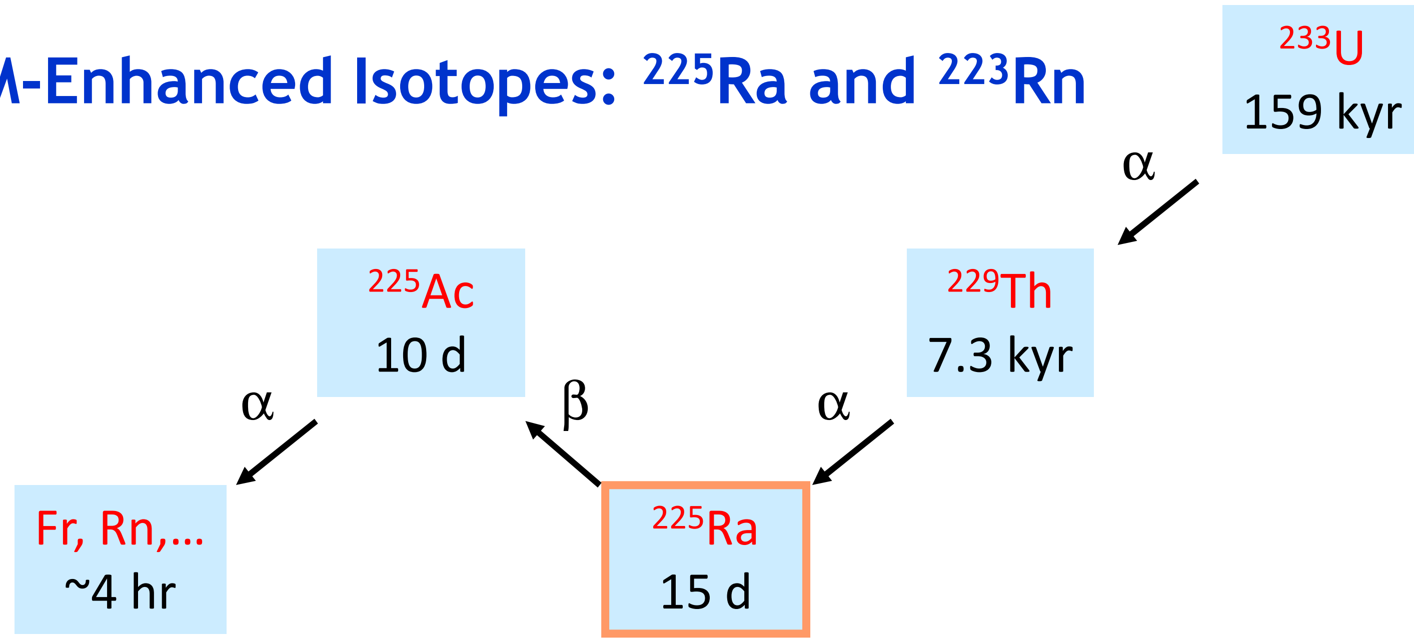
$^{221/223}$Rn EDM projected sensitivity

Facility	Detection	S_d (100 d)
ISAC	g anisotropy	200 x 10^{-28} e-cm
ISAC	b asymmetry	10 x 10^{-28} e-cm
FRIB	b asymmetry	2 x 10^{-28} e-cm

→ **~ 5x10^{-30} for ^{199}Hg**

T. Chupp, Michigan

Yields of EDM-Enhanced Isotopes: ^{225}Ra and ^{223}Rn



Presently available

- National Isotope Development Center, ORNL
  - Decay daughters of ^{229}Th ^{225}Ra: $10^7 – 10^8$ /s

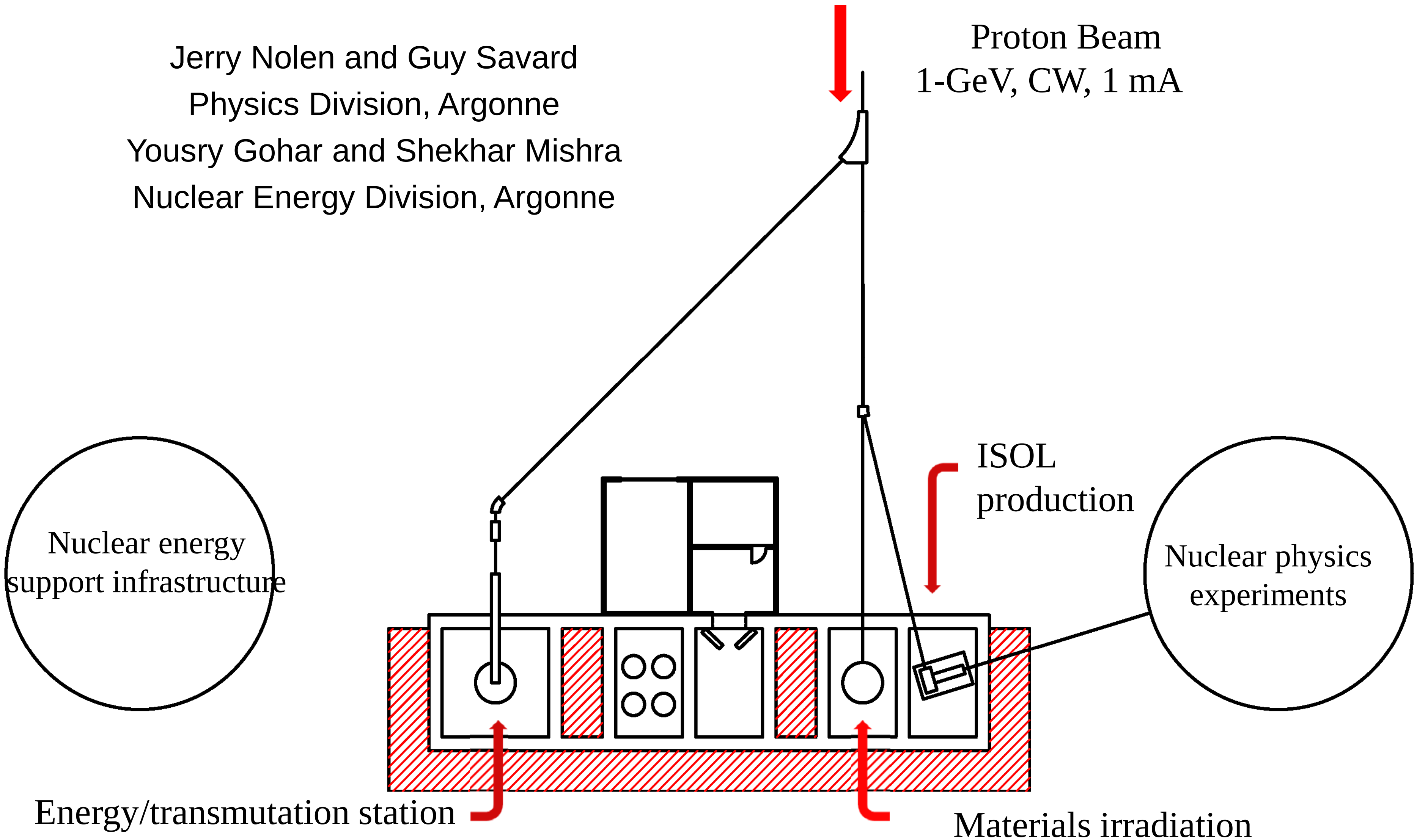
Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam ^{225}Ra: 6 x 10^9 /s
  - Dedicated running with a ^{232}Th beam ^{225}Ra: 5 x 10^{10} /s

- ISOL@FRIB, Project-X (I.C. Gomes and J. Nolen, Argonne)
  - Protons on thorium target, 1 mA x 1 GeV = 1 MW
  - ^{225}Ra: 10^{13} /s, ^{223}Rn: 10^{11} /s

Draft Layout of the Project X Joint Nuclear Facility

Jerry Nolen and Guy Savard
Physics Division, Argonne
Yousry Gohar and Shekhar Mishra
Nuclear Energy Division, Argonne



Project X Joint Nuclear Facility,
August, 2010

J. Nolen, Argonne

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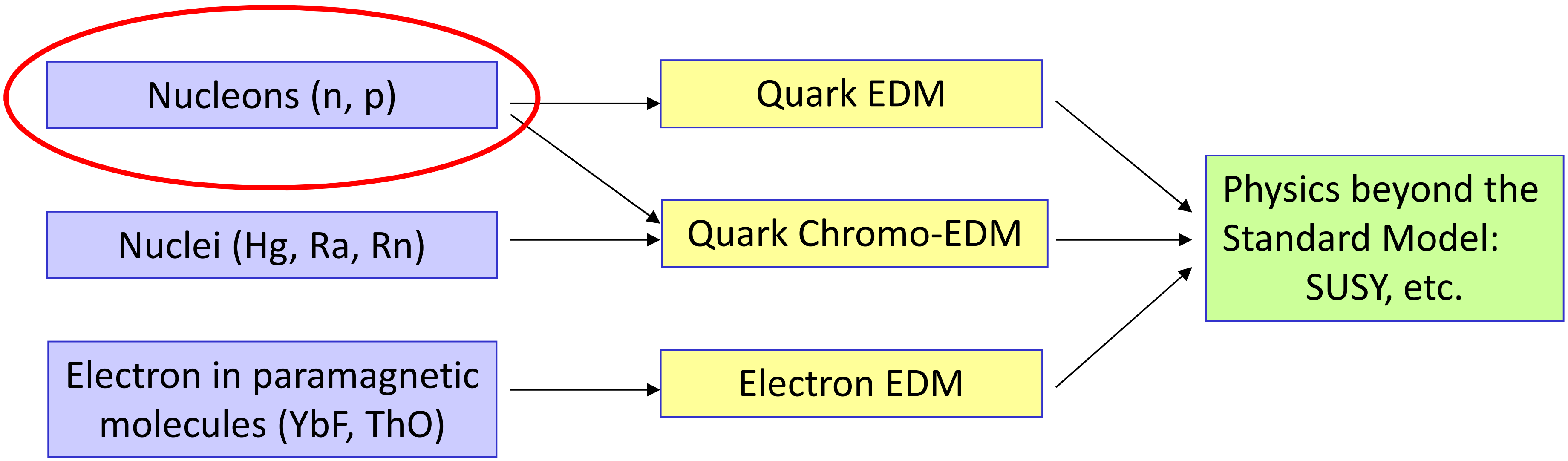

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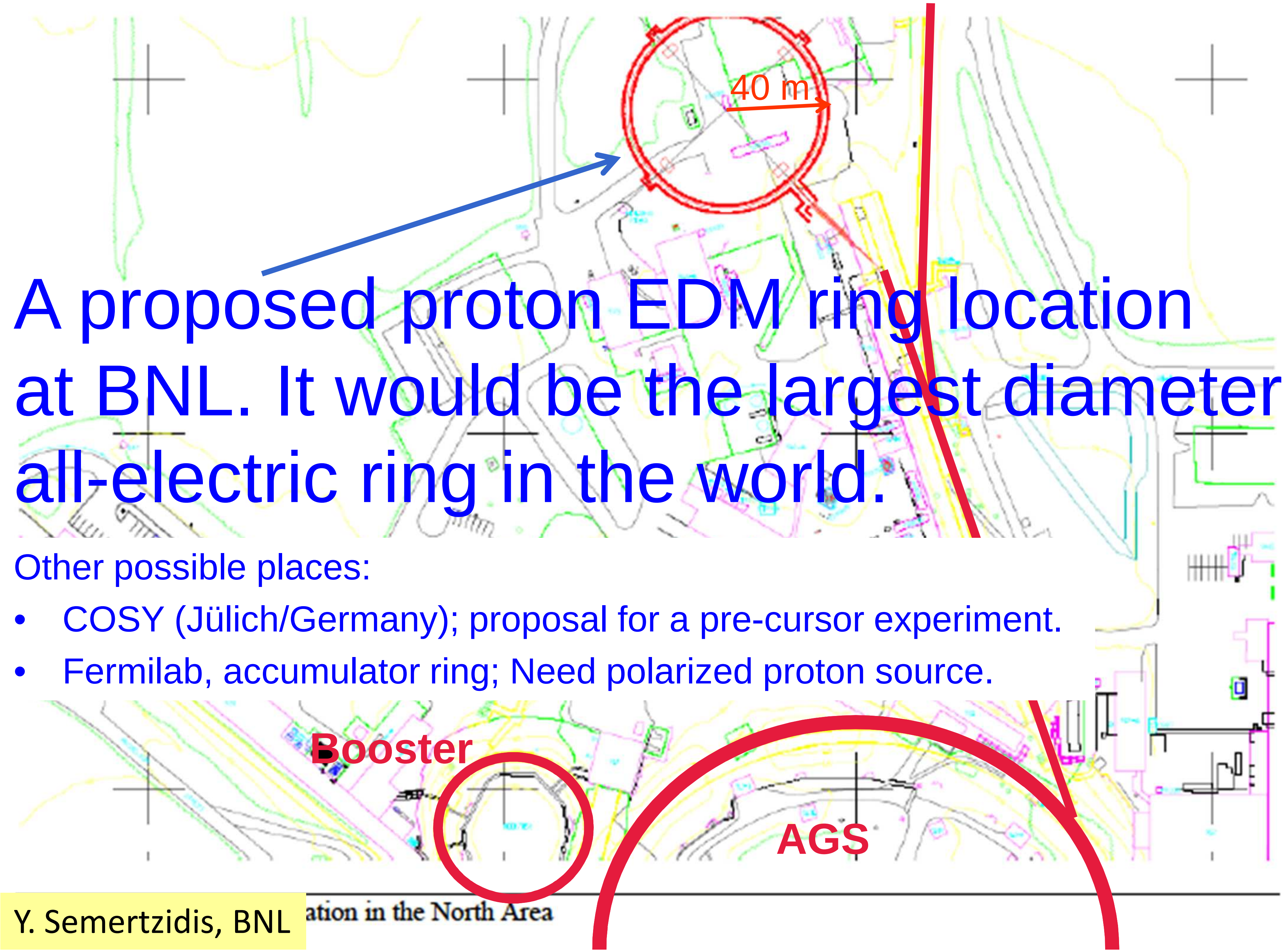
M. Ramsey-Musolf (2009)

A proposed proton EDM ring location at BNL. It would be the largest diameter all-electric ring in the world.

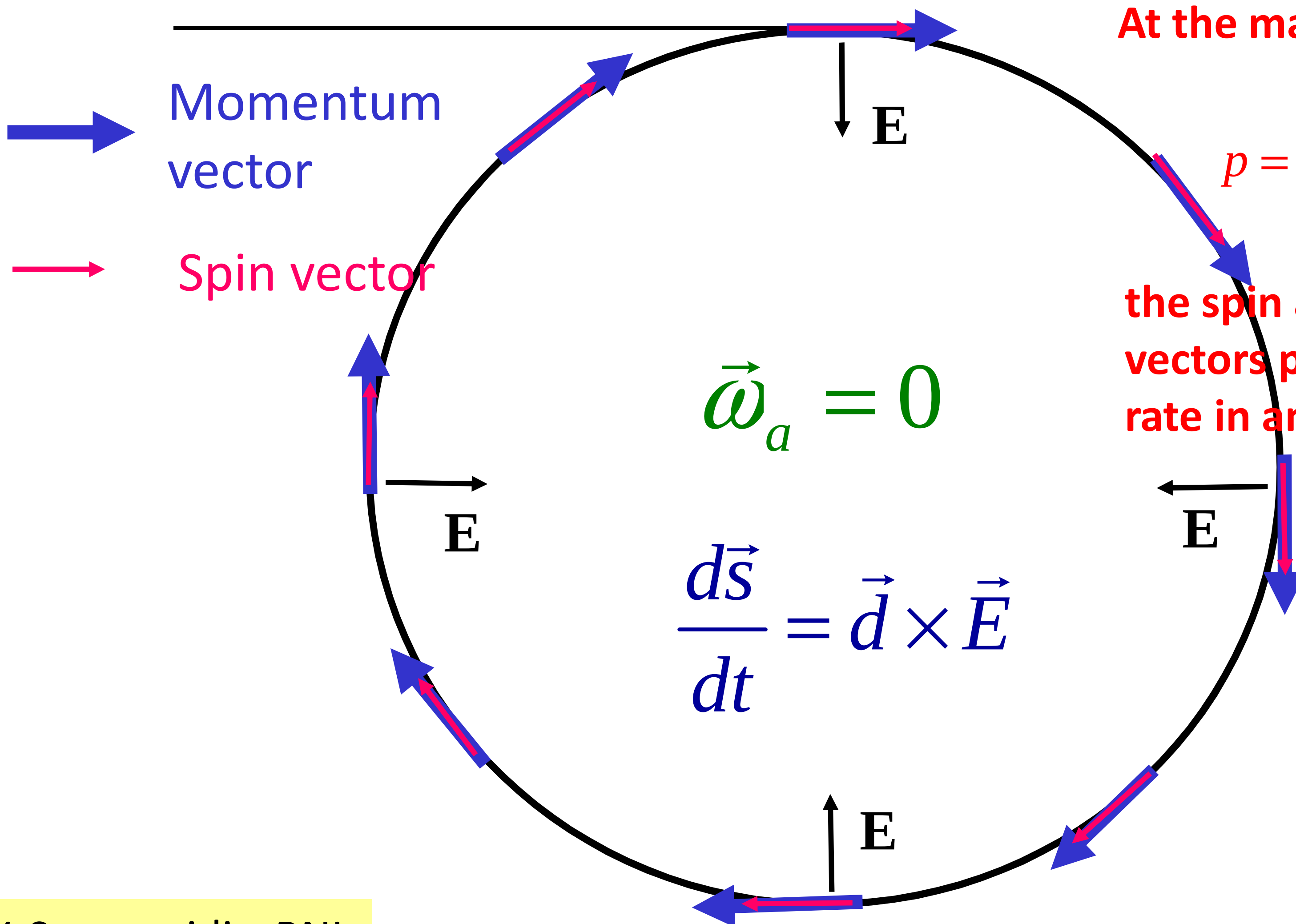


Other possible places:

- COSY (Jülich/Germany); proposal for a pre-cursor experiment.
- Fermilab, accumulator ring; Need polarized proton source.

Y. Semertzidis, BNL

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector



At the magic momentum

$$p = \frac{m}{\sqrt{a}} = 0.7 GeV / c$$

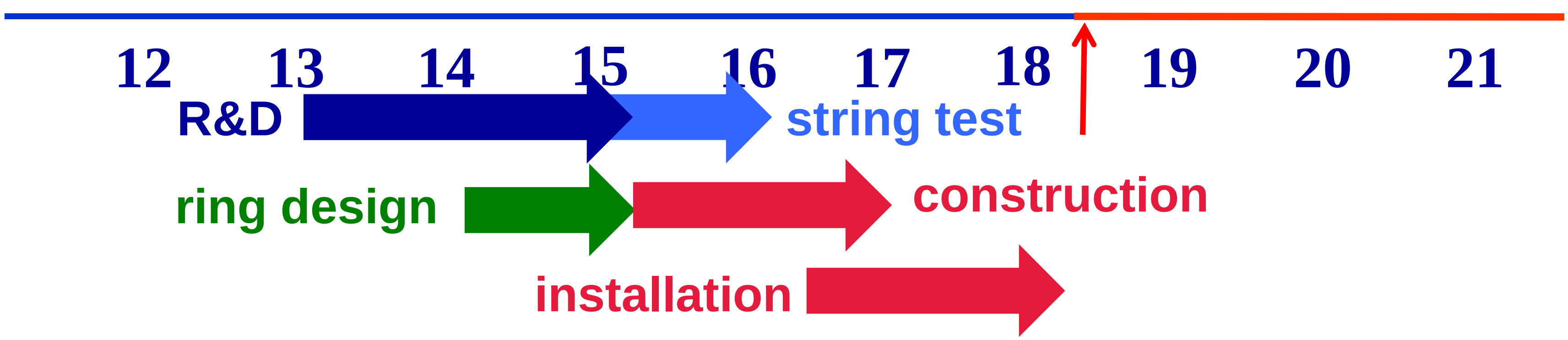
the spin and momentum vectors precess at same rate in an E-field

Y. Semertzidis, BNL

Current status

- Have developed R&D plans (need $1M/year for two years) for
  1) Beam Position Measurement magnetometers (need to test in rings)
  2) Spin Coherence Time tests at COSY (benchmark estimations)
  3) E-field development (first phase R&D done)
  4) Polarimeter prototype (first phase R&D done)
- Two successful technical reviews: Dec. 2009 and Mar. 2011.
- Sent proposal to DOE-NP for a proton EDM experiment at BNL: Nov. 2011

Technically driven pEDM timeline



Limits and Sensitivities

- 2020: 0.1 x 10^{-28} e-cm
- Ultimate: 0.01 x 10^{-28} e-cm

Y. Semertzidis, BNL

Next Generation nEDM Experiments

Cryogenic UCN source, room temperature storage cells

- Intitut Laue-Langevin, PNPI/ILL
- Paul Scherrer Institute
- Munich reactor
- TRIUMF-Japan collaboration

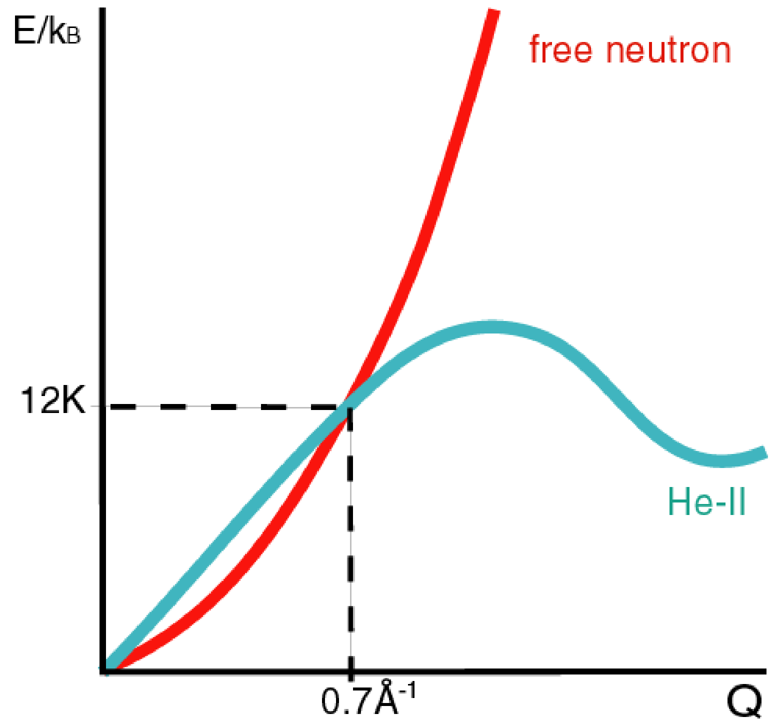
Super-fluid He source/storage cell

- Intitut Laue-Langevin, CyroEDM
- Spallation Neutron Source, nEDM

Limits and Sensitivities

- Current: 300 x 10^{-28} e-cm
- Next 5 years: 50 – 100 x 10^{-28} e-cm
- 2020 and beyond: 3 – 5 x 10^{-28} e-cm

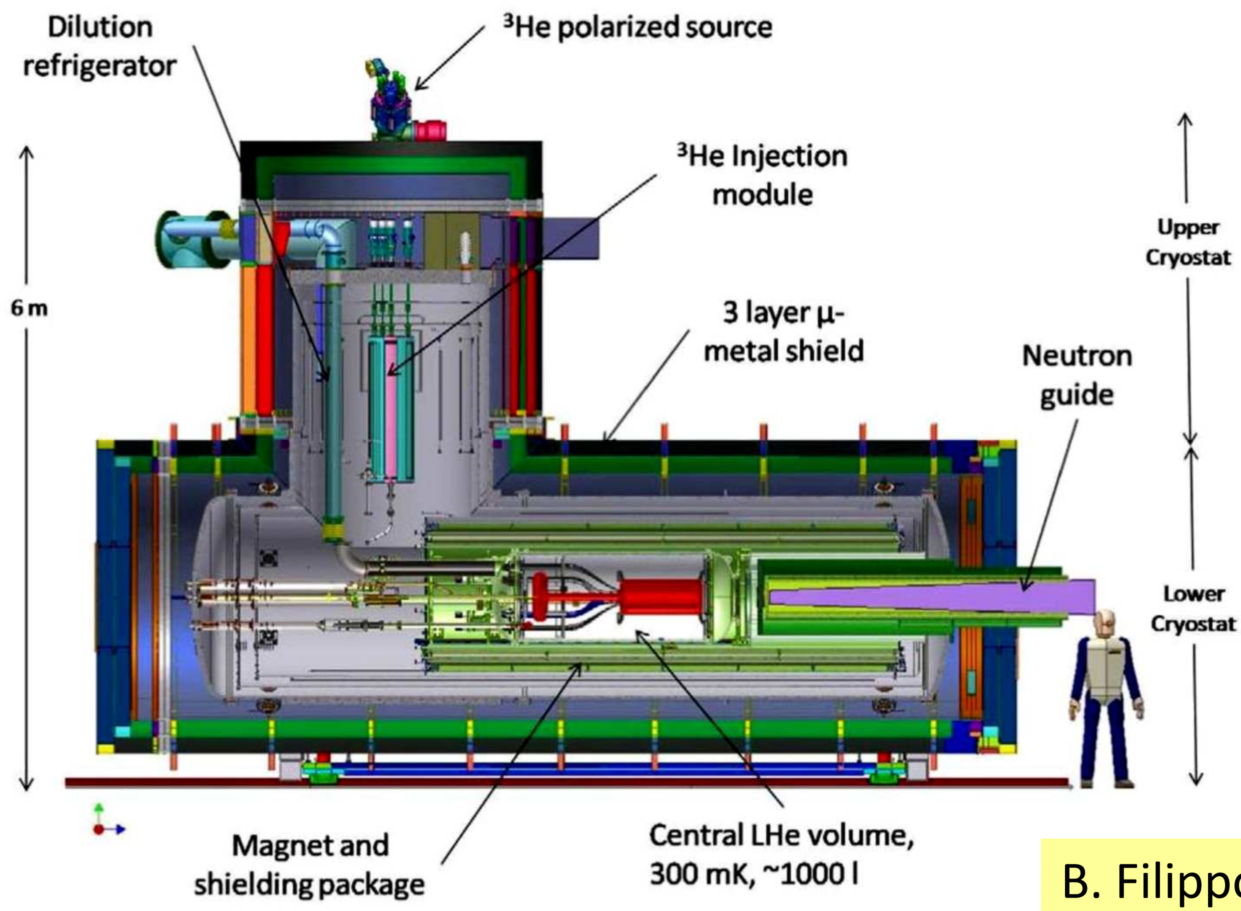
Dispersion curves for He-II and free neutrons



Golub & Pendlebury, Phys. Lett. (1977)

Neutron EDM @ SNS

1 Arizona State University
2 Brown University
3 Boston University
4 University of California, Berkeley
5 California Institute of Technology
6 Duke University
7 Harvard University
8 Indiana University
9 University of Illinois, Urbana-Champaign
10 University of Kentucky
11 Los Alamos National Laboratory
12 Massachusetts Institute of Technology
13 Mississippi State University
14 North Carolina State University
15 Oak Ridge National Laboratory
16 Simon Fraser University
17 University of Tennessee
18 Valparaiso University
19 University of Virginia



B. Filippone, Caltech

Active R&D:

- Demonstrate high E-field in superfluid LHe
- Identify novel electrode materials
- Demonstrate highly uniform B-field inside superconducting shield with reduced B-field noise
- Developing a polarized neutron & ^{3}He source for spin precession studies at NCSU research reactor
- Studies of polarized ^{3}He transport

Status and Plans:

- Complete initial R&D program: 2012-13
- Begin construction of experiment: 2013-18
- Begin operation of experiment: 2019

B. Filippone, Caltech

Summary of EDM Searches on Nucleons and Nuclei

EDM units: 1 x 10^{-28} e-cm

Sector	Experiment	Current Limit	5-year goal	Beyond 2020	Standard Model	Notes
Neutron	UCN general	300	50 – 100	3 – 5	0.001	No Schiff shielding
Neutron	SNS nEDM			3	0.001	No Schiff shielding
Proton	BNL Storage ring	8,000*		0.01 – 0.1	0.001	No Schiff shielding
Nucleus	Seattle ^{199}Hg cell	0.3	0.03	0.006	0.000,01	
Nucleus	ANL ^{225}Ra trap		10 – 100	1	0.01	Octupole enhanced
Nucleus	Michigan ^{223}Rn cell			2	< 0.01	Octupole enhanced

* Indirect limit derived from the ^{199}Hg measurement.

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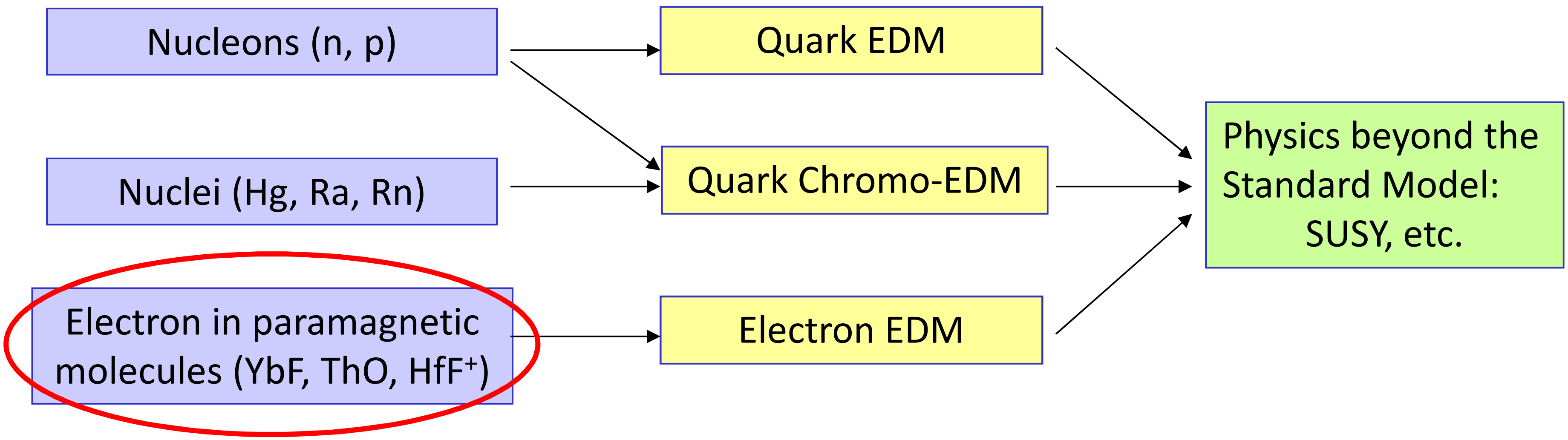

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M. Ramsey-Musolf (2009)

Probing eEDM in a neutral atom or molecule

$$H = -d_{atom} \cdot E_{ext} = -\langle d_e \cdot E_{int} \rangle \xrightarrow{define} -d_e \cdot E_{eff}$$

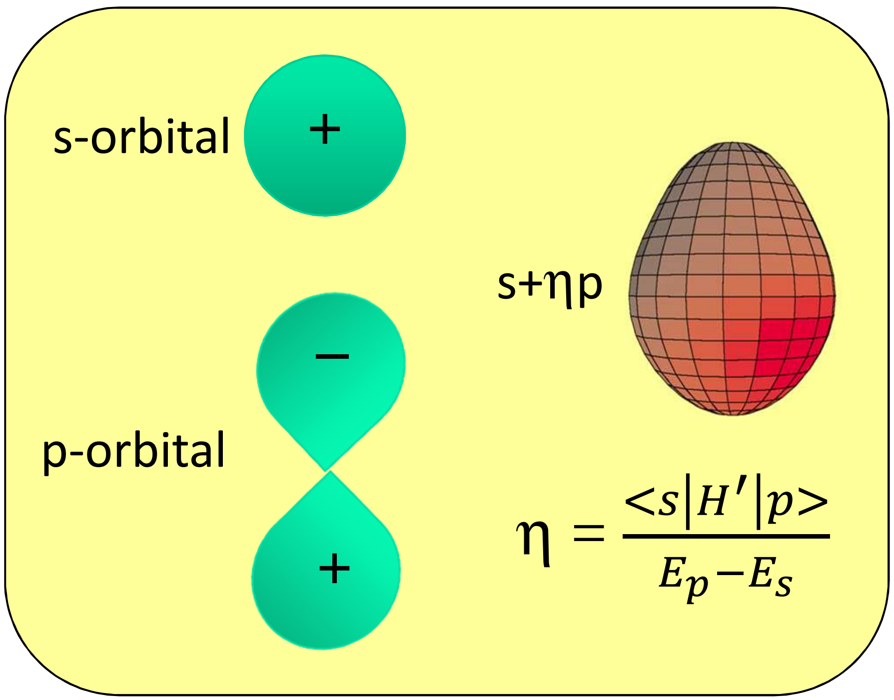
Problem: $\langle E_{int} \rangle = 0$

Insight: $\langle d_e \cdot E_{int} \rangle \neq d_e \cdot \langle E_{int} \rangle$

Enhancement factor! - P.G.H. Sandars, Phys. Lett. (1965)

Commins, Jackson, DeMille, Am. J. Phys. (2007)

$$|E_{eff}| \approx Z^3 \alpha^2 (e/a_0^2) \cdot \mathcal{P} \quad \sim \mathcal{P} \cdot 10^{11}\ \text{V/cm} \ @ \ Z \sim 80$$



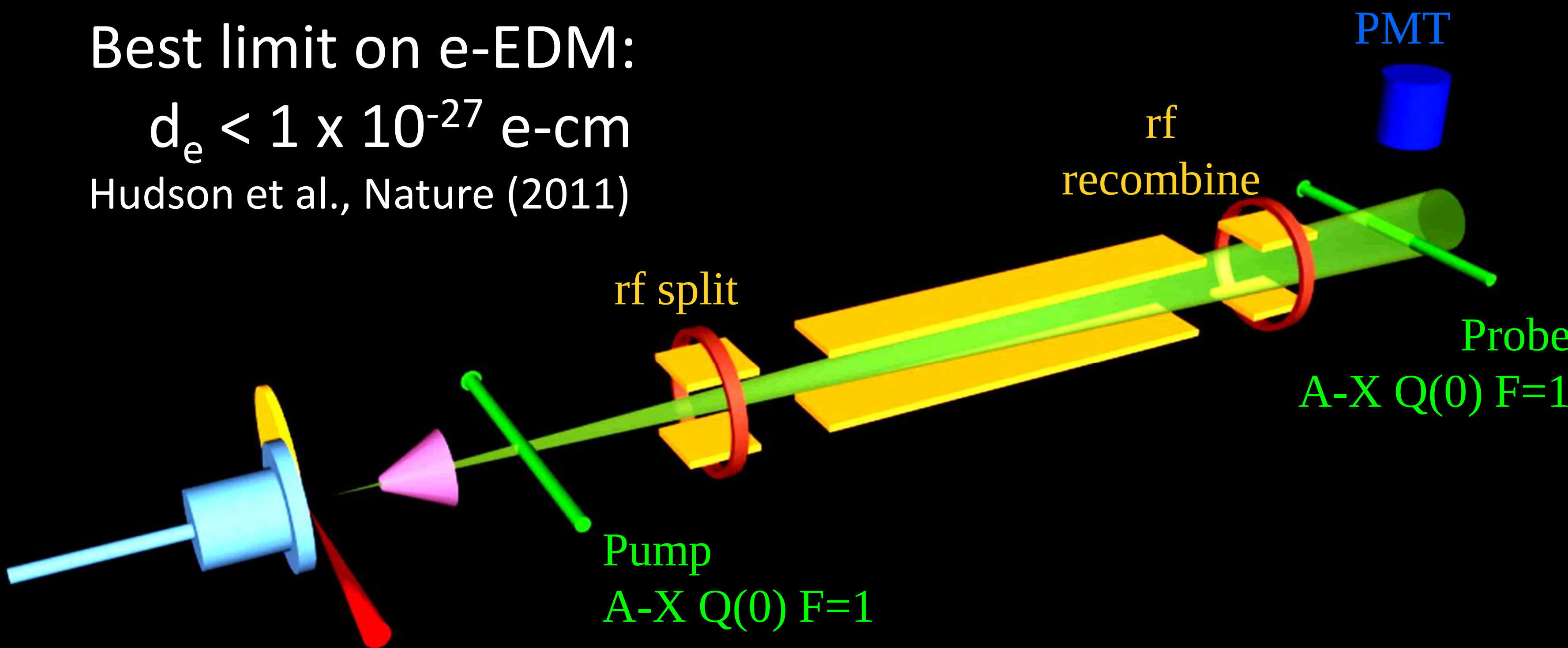
$$\eta = \frac{\langle s|H'|p\rangle}{E_p - E_s}$$

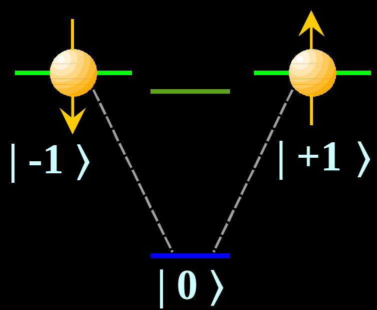
	Tl atom	YbF	ThO
Mixing	s-p	Rotational levels	Ω-doublet
E_ext	100 kV/cm	20 kV/cm	10 V/cm
$\mathcal{P}$	10^{-3}	1	1
E_eff	70 MV/cm	18 GV/cm	80 GV/cm

Best limit on e-EDM:

$d_e < 1 \times 10^{-27}$ e-cm

Hudson et al., Nature (2011)





Limits and Sensitivities

- Current: 10×10^{-28} e-cm
- Next 5 years: 1×10^{-28} e-cm
- 2020 and beyond: 0.01×10^{-28} e-cm

E. Hinds, Imperial London

ACME Electron Electric Dipole Moment search

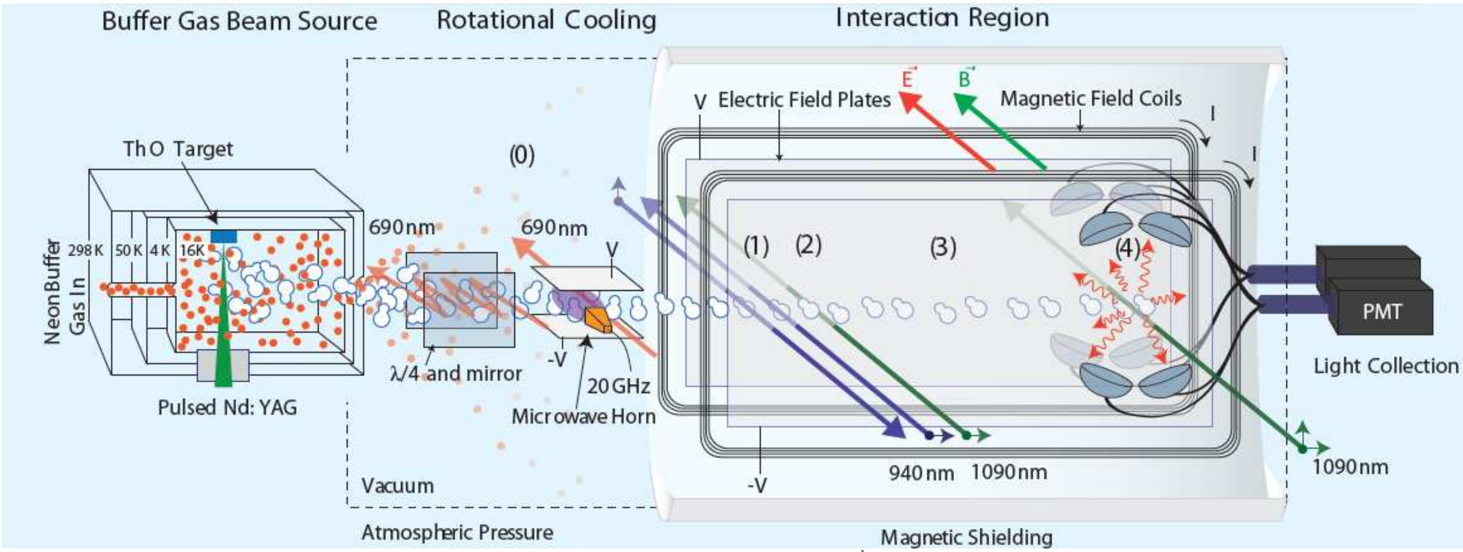
Yale/Harvard

Funding: NSF

KEY FEATURES

- New cryogenic molecular beam source: 1000 × brightness
- New molecule species (ThO*): largest effective E-field, suppression of systematics
- Larger collaboration (3 PI's): more resources, faster progress

Experiment Schematic

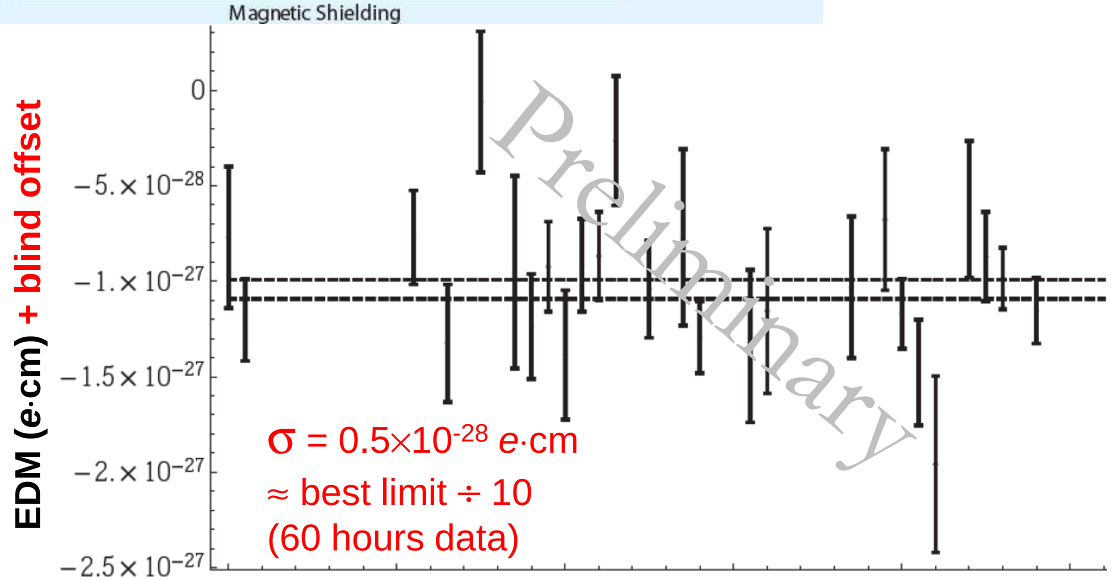


Molecular beam with

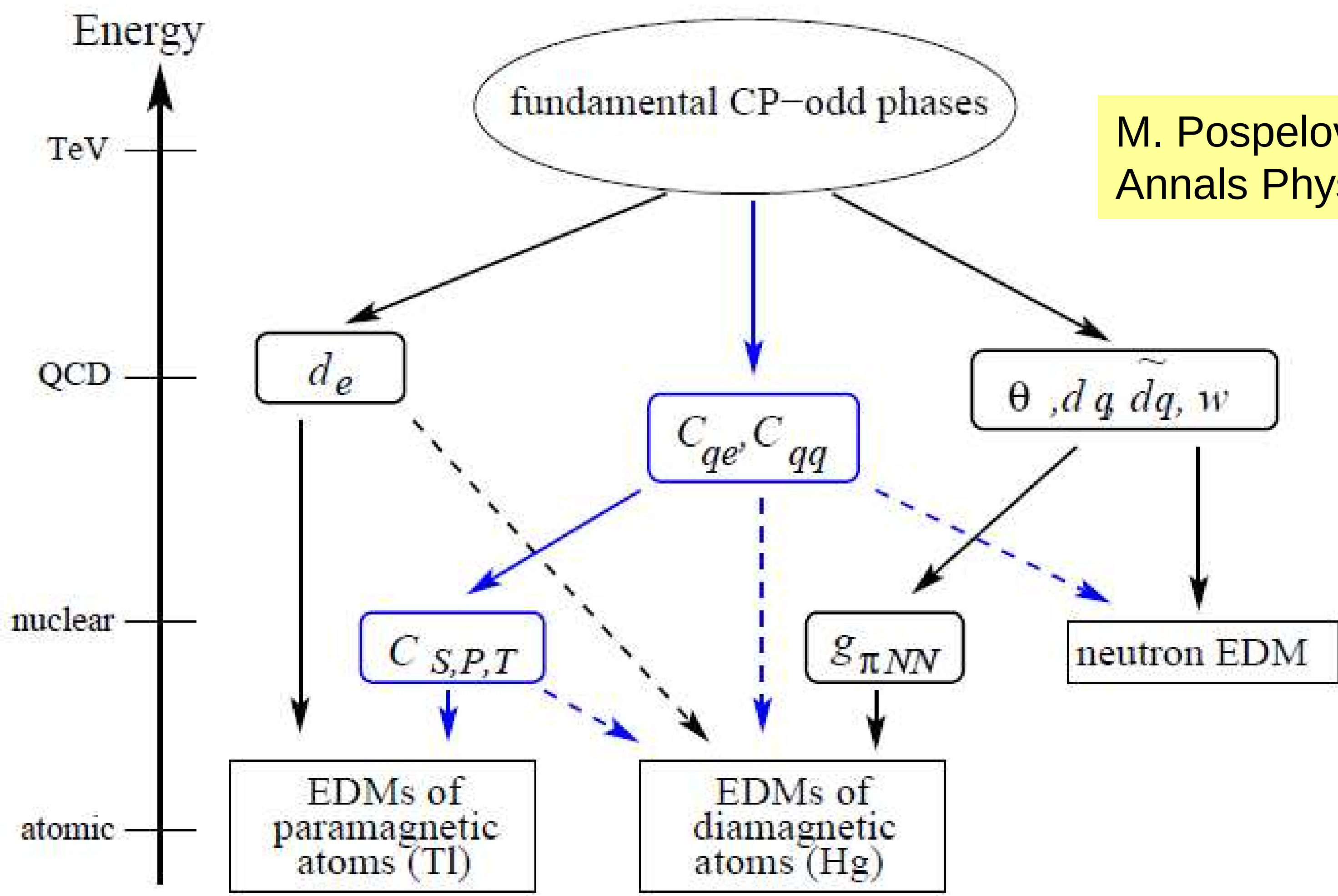
lasers for state prep & readout

STATUS

- Taking data since ~ Jun 2012
- Statistical sensitivity
  = best limit in ~ 30 min
- Extensive systematics tests
  underway
- Upgrades with ~ 300 × improved
  statistical sensitivity planned



Origin of elementary EDMs



M. Pospelov, A. Ritz, Annals Phys.(2005)

"Clearly, if EDM is found, we will need multiple systems to identify the origin of new CP violation." -- B. Filippone, Caltech