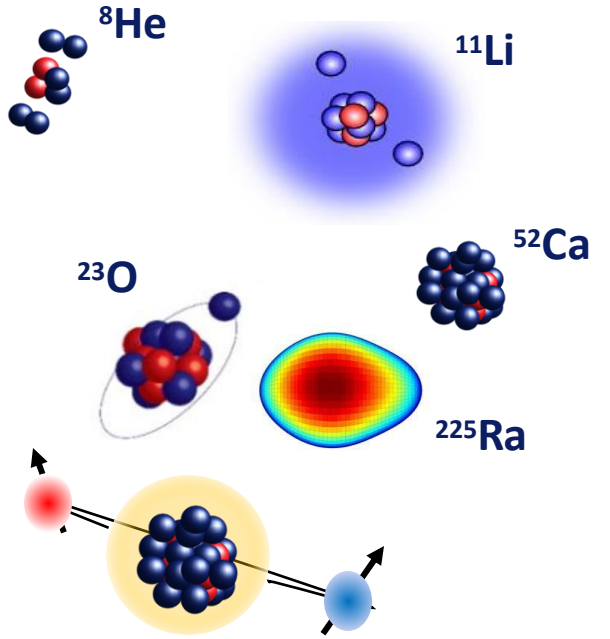
Radioactive Atoms and Molecules as Quantum Sensors for Nuclear Physics

Figure modified from https://sphereofinfluence360.com/



Ronald F. Garcia Ruiz, MIT

Quantum Information Science on the Intersections of Nuclear and AMO Physics

UMass Boston, January, 2025

Graduate Students

S. Udrescu
(-> U. Chicago)

A. Brinson
NSF Fellowship

H. Kakiota
Ezoe Memorial Fellowship

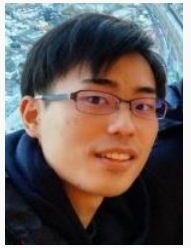
S. Moroch
Hertz Foundation Fellowship

F. Pastrana
Santo Domingo Fellowship

D. Gonzales
(Harvard)

J. Munoz
MIT Fellowship

M. Fulghieri



F. Shungo

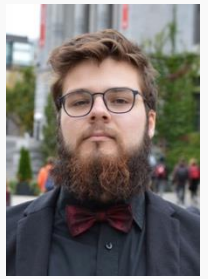
Postdoctoral Researchers

S. Wilkins

J. Karthein
Now Faculty at Texas A&M

S. Ebadi
Pappalardo Fellowship

A. Jadbabaie
NSF MPS Ascend Fellow



A. Belly
NSERC Fellow

PI

R.F. Garcia Ruiz

Undergraduate Students

K. Khusainova

S. Munoz

A. Fernandez

R. Hernandez

S. Becerra

FRIB

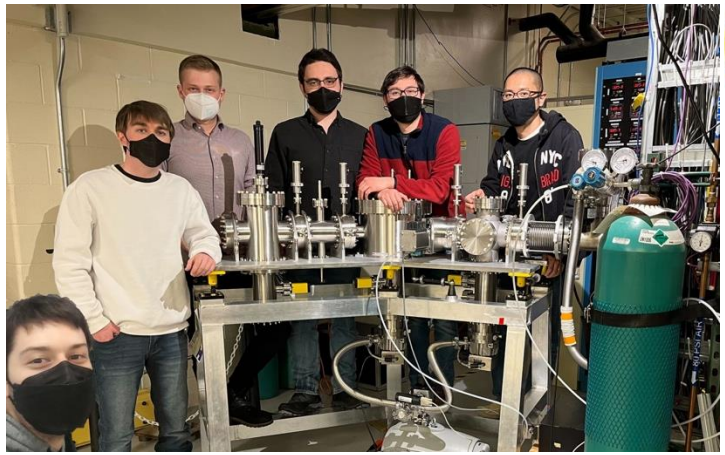
Bates Lab

Thanks to…

Nuclear & Atomic & Molecular Theory Experimen

J. Dobaczewski (York)
J. Holt (TRIUMF)
R. Stroberg (U ND)
W. Nazarewicz (FRIB/MSU)
R. Berger (Malbroune)
A. Borchevsky (Groningen)
L. Skripnikov (Petersburg)

RISE @ FRIB

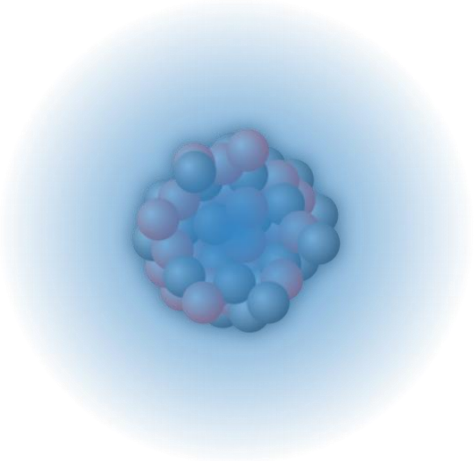


RaX Collaboration

NEPTUNE Project

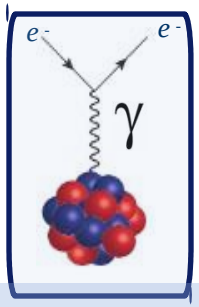
Why Atoms & Molecules?

Ra^+



Atom ($S_{1/2}$)

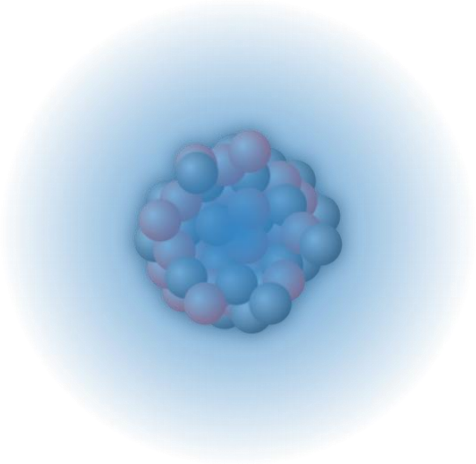
Long range (> 1 fm)



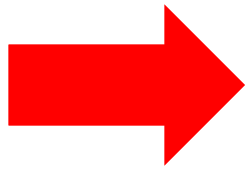
Electromagnetic nuclear properties $<r^2>, I, \mu, Q, ..$

Why Atoms & Molecules?

Ra^+

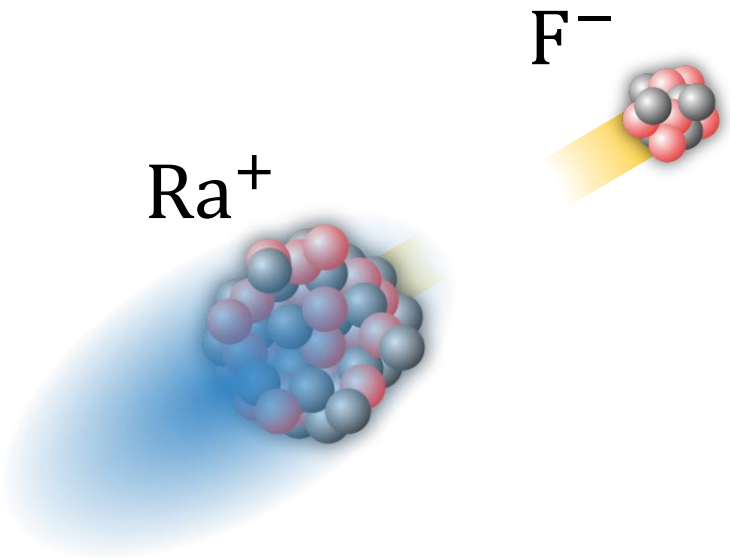


Atom ($S_{1/2}$)



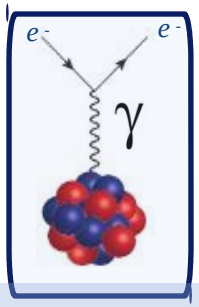
F^-

Ra^+

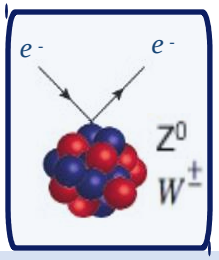


Molecule ($\Sigma_{1/2}$)

Long range (> 1 fm)



Short range (< 1 fm)

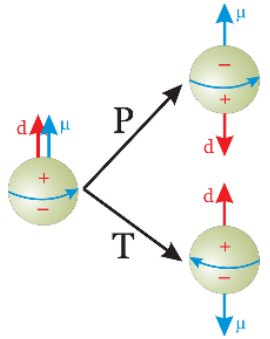


Electromagnetic nuclear properties $<r^2>, I, \mu, Q, ..$

Electroweak nuclear properties (P,T - violation)

Why Atoms & Molecules?

Eric Cornell's Talk
Tuesday at 10 am



[Sandars Phys. Rev. Lett. 18, 1396 (19
[Hudson et al. Nature 473 493 (2011)]

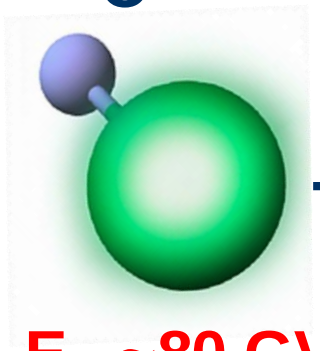
Nuclear spin = 0

[1 eV=241.8 THz]

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV} + d_e E_{eff}$$

eV ~ 2 10^{-2} 10^{-5} $<10^{-20}$

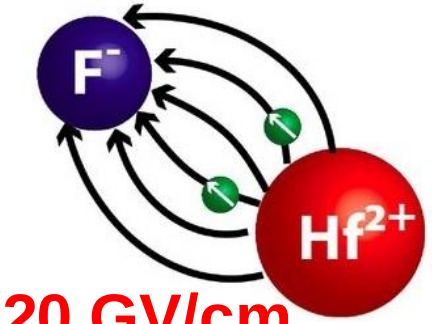
O^-



Th^+

E_{eff}~80 GV/cm

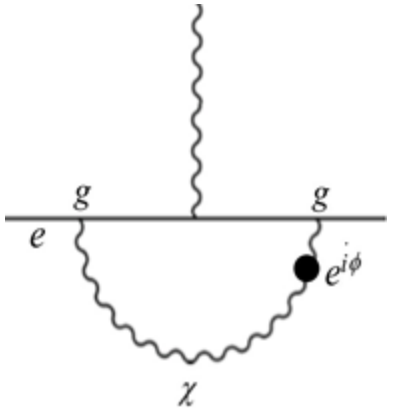
[ACME, Nature 562, 355 (2018)]



E_{eff}~20 GV/cm

$|d_e| \leq 4.1 \times 10^{-30}$ e · cm

[Roussy et al. Science 381, 46 (2023)]

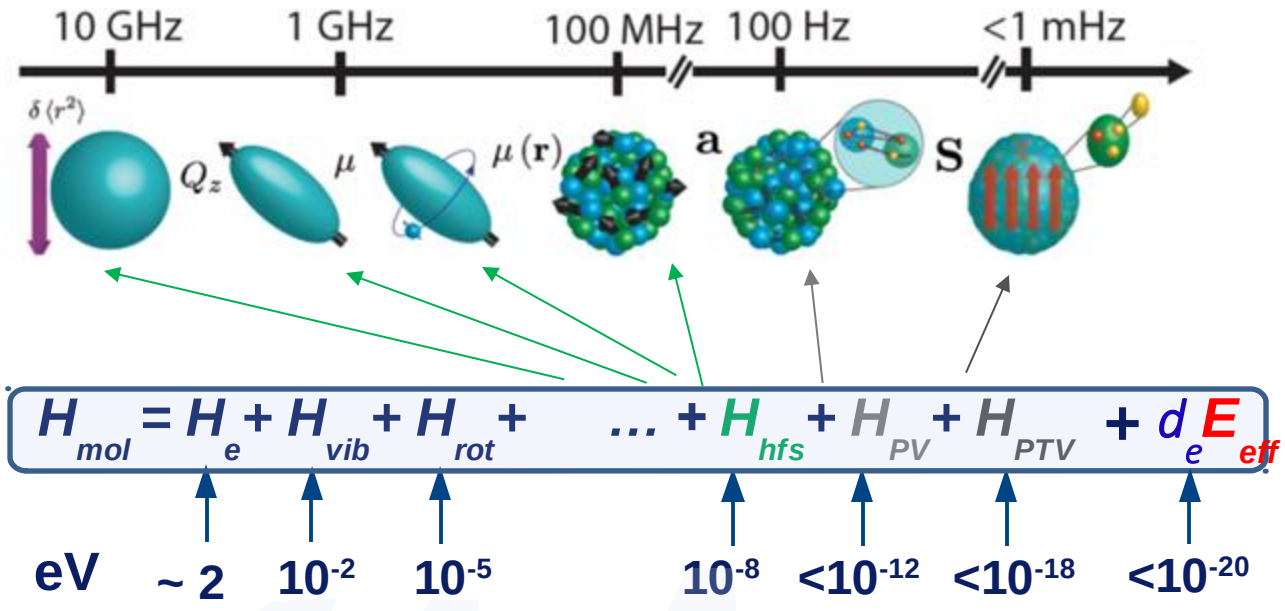


$$d_e \sim \mu_B \left(\frac{g^2}{2\pi}\right)^N \left(\frac{m_e}{m_\chi}\right)^2 \sin\phi$$

Probing physics @ TeV scale!

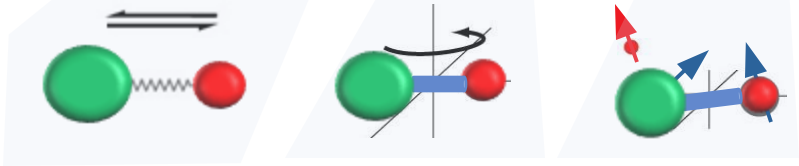
Why Atoms & Molecules?

Molecules with heavy, exotic nuclei: Ra(Z=88)



Nuclear spin > 0

[1 eV=241.8 THz]



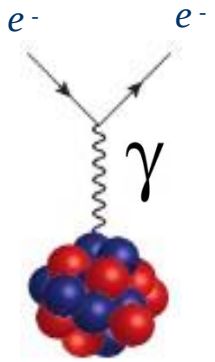
[Sandars Phys. Rev. Lett. 18, 1396 (19
[Hudson et al. Nature 473 493 (2011)]

Why atoms & molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

Dean Lee's Talk
Monday at 11:30 am

H_{hfs}



P,T-even

- Nuclear structure
- Nuclear matter

$< r^2 >, I, \mu, Q, ..$

How do nuclear phenomena emerge from QCD?

What are the properties of nuclear matter (e.g. neutron stars)?

Nuclei

?

Neutron star

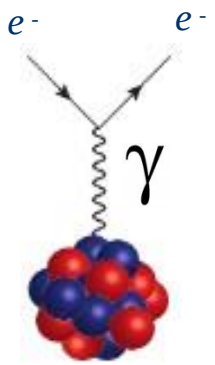
Recent highlights:

- Nature Physics 20,1719 (2024)
- Phys. Rev. Lett. 133, 033003 (2024)
- Nature Physics 20, 202 (2024)
- Physical Review Letters 132, 162502 (2024)
- Rep. Prog. Phys. 87 084301 (2024)
- Physical Review Letters 131, 222502 (2023)
- Nature 607, 260 (2022)
- Physical Review Letters 128, 022502 (2022)

Why atoms & molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

H_{hfs}



P,T-even

- Nuclear structure
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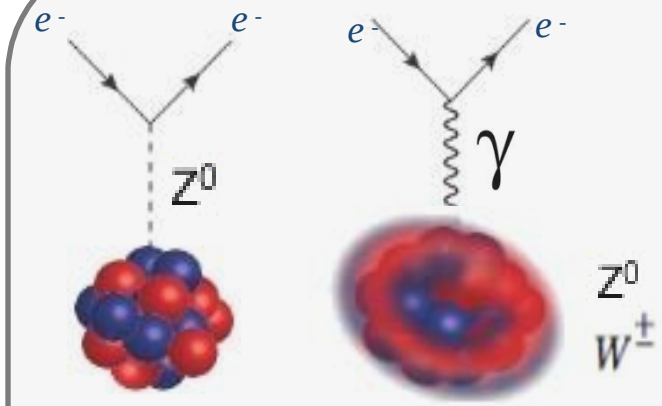
$< r^2 >, I, \mu, Q, ..$

H_{PV}

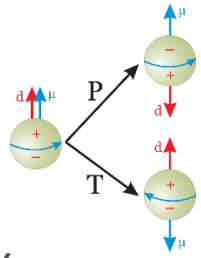


P-violation

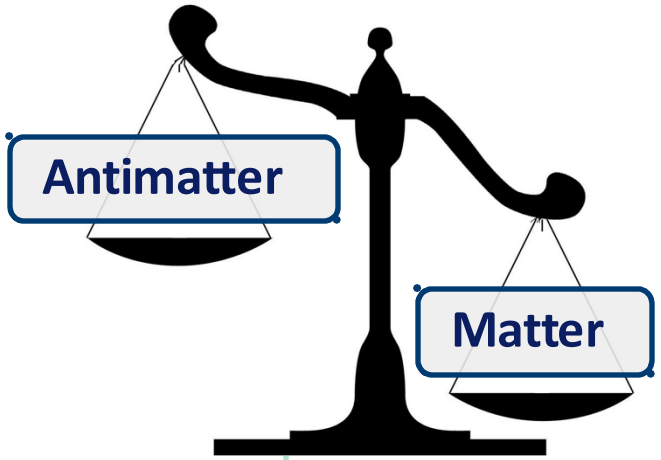
- Electro weak structure
- Precision Standard Model tests
- Dark Mater properties?
- New forces?

Why atoms & molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$



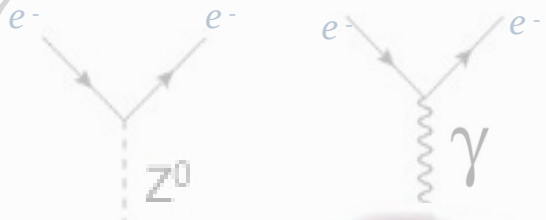
H_{hfs}



- Nuclear structure
- Nuclear matter

$< r^2 >, I, \mu, Q, ..$

H_{PV}

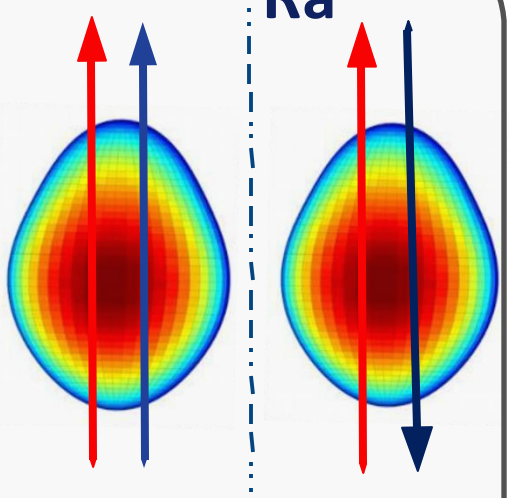


Strong CP problem

$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$

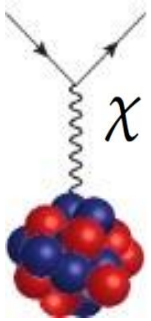
- Electro weak structure
- Precision Standard Model tests
- Dark Mater properties?
- New forces?

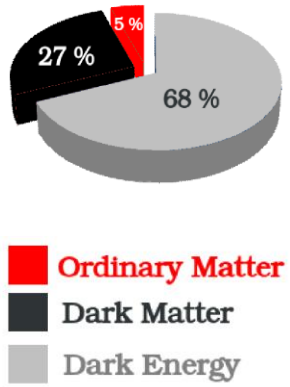
H_{PTV}



T-violation

- Matter-antimatter asymmetry
- New particles?

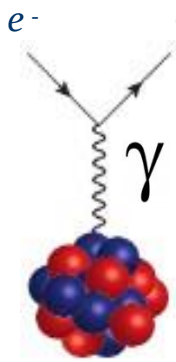




Why atoms & molecules?

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

H_{hfs}

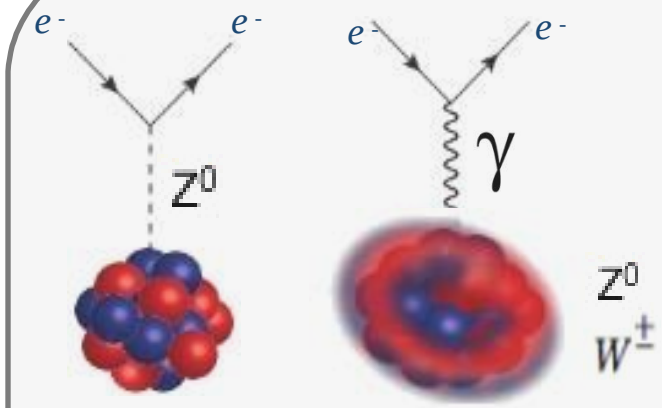


P,T-even

- Nuclear structure
- Nuclear matter

$\langle r^2 \rangle, I, \mu, Q, ..$

H_{PV}



P-violation

- Electro weak structure
- Precision Standard Model tests
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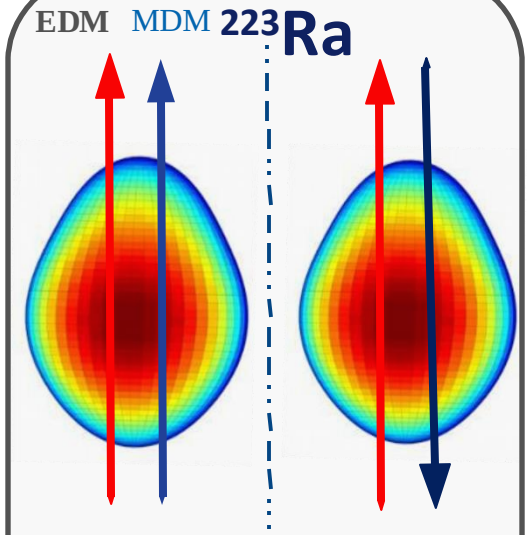
H_{PTV}



T-violation

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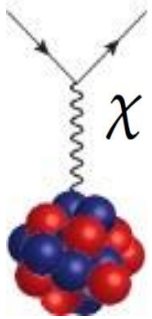
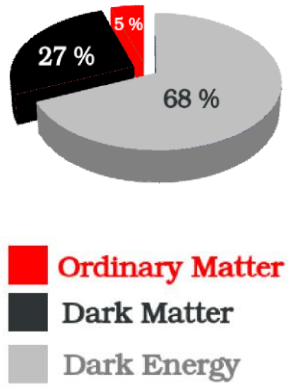




Why atoms & molecules?

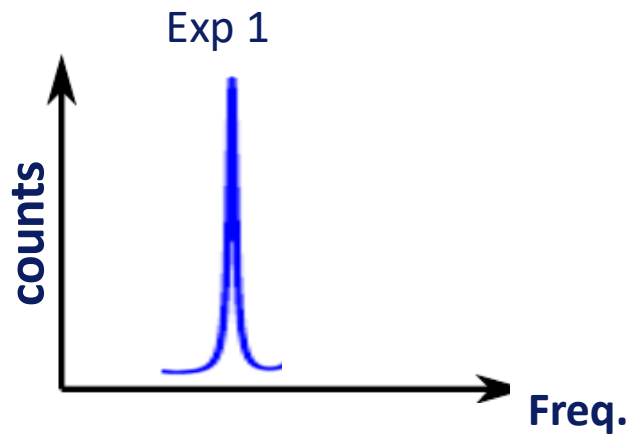
$\sim O_{Nucl}\, F_{mol}$

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

$$H_{mol} - H'_{mol} \sim O_{Nucl}\, F_{mol}$$

-> Direct measurements!



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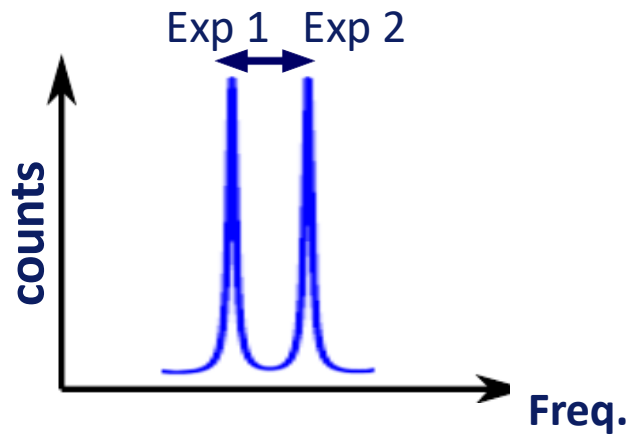


Why atoms & molecules?

$\sim O_{Nucl}\, F_{mol}$

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

	H_e	H_{vib}	H_{rot}	H_{hfs}	H_{PV}	H_{PTV}
eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-15}$

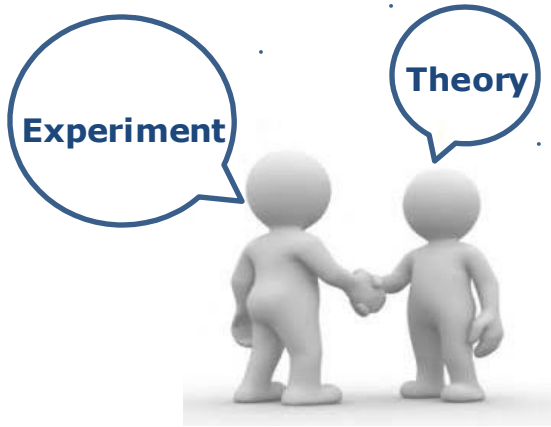
$H_{mol} - H'_{mol} \sim O_{Nucl}\, F_{mol}$ -> Direct measurements!

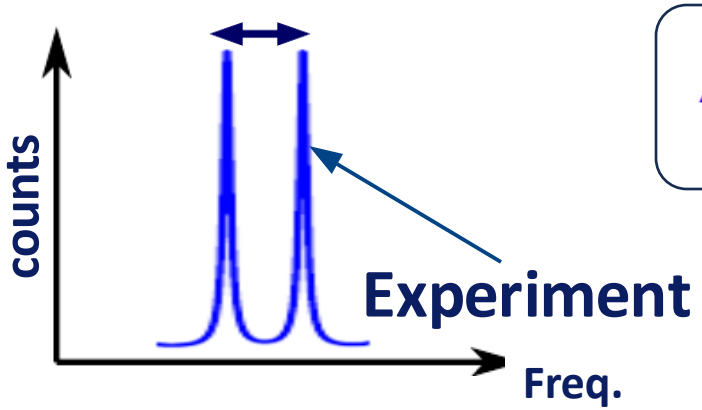
Nuclear

Atom/molecule

$\sim O_{Nucl}\, F_{mol}$

Nuclear & Atomic & *Molecular*

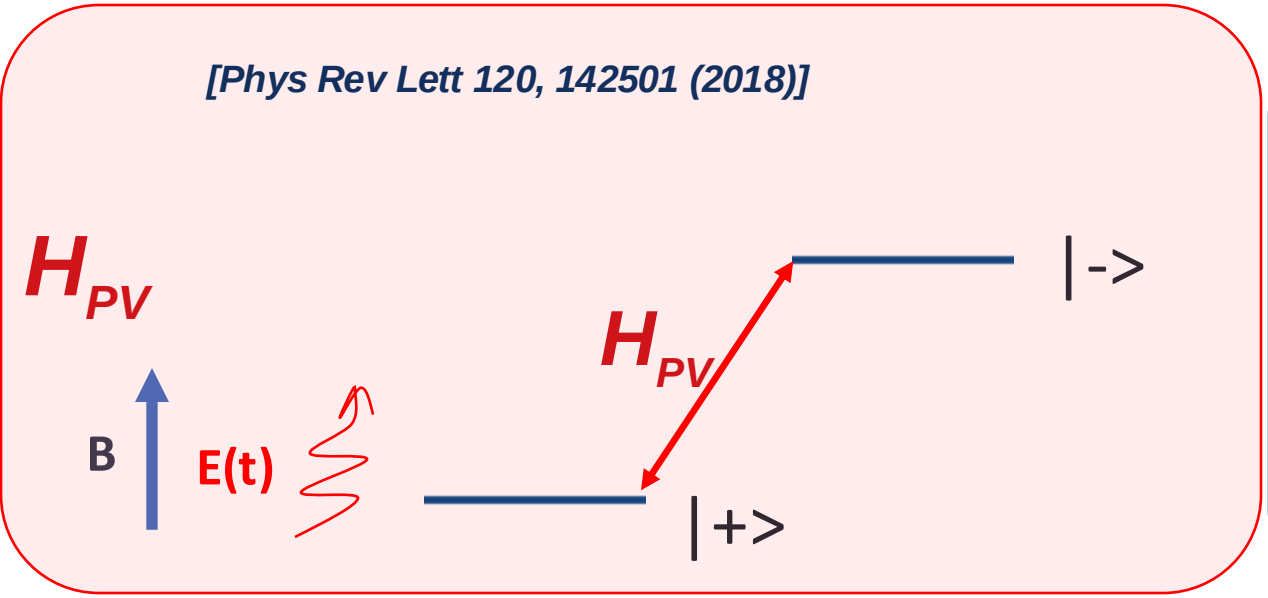




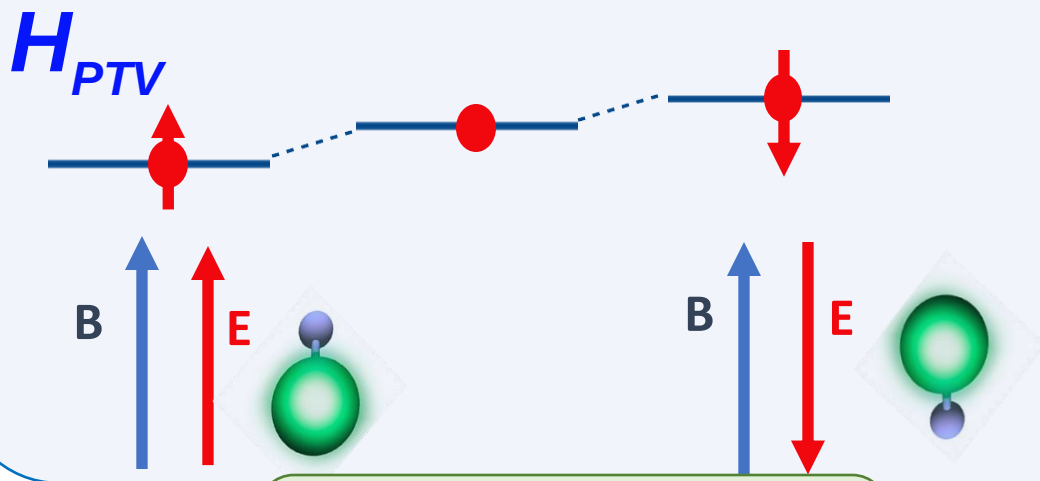
$$\Delta O \sim \frac{1}{F_{mol}\tau\sqrt{N}}$$

Molecules as “quantum sensors”

[Phys Rev Lett 120, 142501 (2018)]



[Nature 562, 355 (2018)] [Roussy et al. Science 381, 46 (2023)]

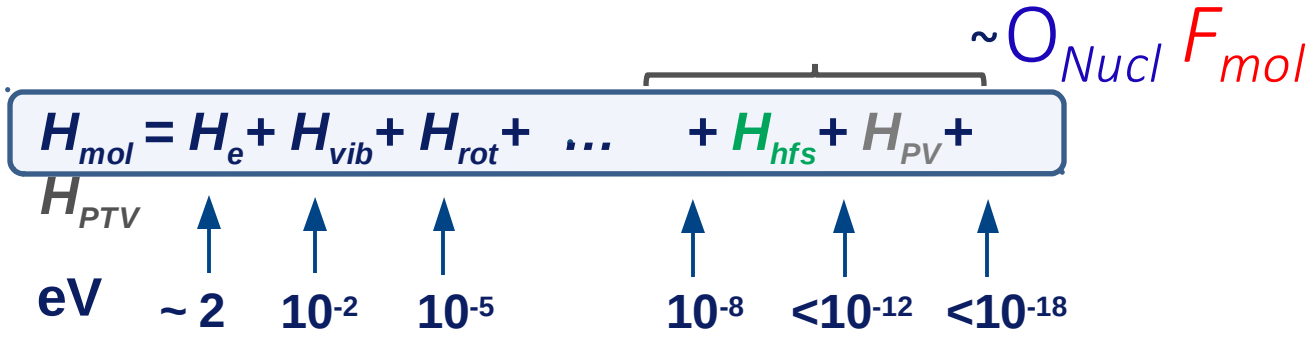


Eric Cornell’s Talk
Tuesday at 10 am

Recent reviews:

- *"Searches for new sources of CP violation using molecules as quantum sensors”.* Hutzler et al. arXiv:2010.08709 (2020)
- *“Opportunities for fundamental physics research with radioactive molecules”.* Arrowsmith-Kron et al. Rep. Prog. Phys. 87 084301 (2024)

Radioactive molecules as sensitive probes of P,T-violating nuclear properties



Radioactive Molecules for studies of P, T violation

^{225}Ra

- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ β_2 β_3 > 0

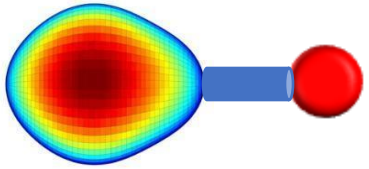
$>10^3$
Nuclear
$\sim Z^a A^b \beta_2 \beta_3^2 / (E_+^N - E_-^N)$

$>10^3$
Atom/molecule
$\sim Z^e / (E_+^e - E_-^e)$

$E_+^N - E_-^N \sim 10^{-5}$ eV

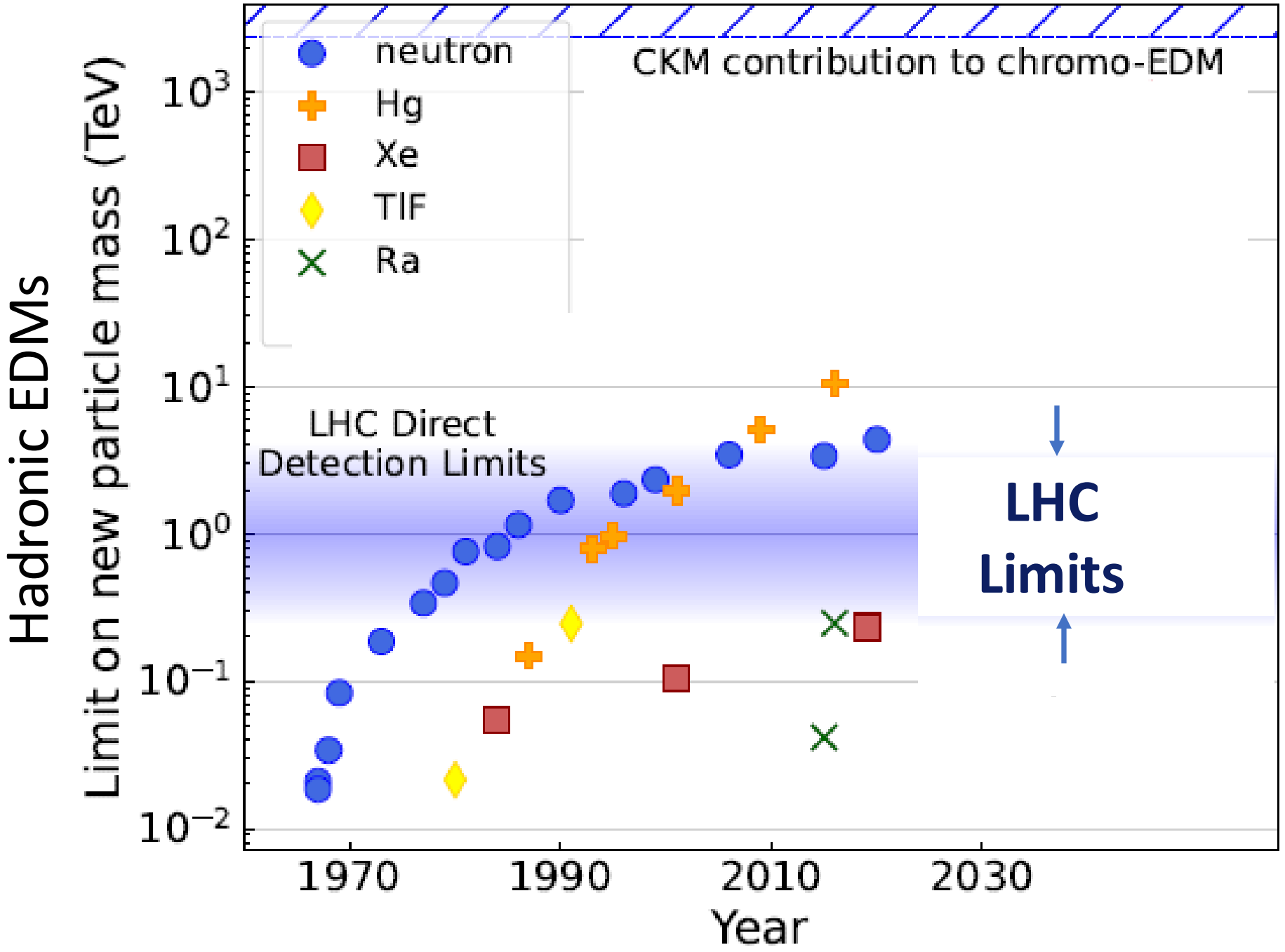
$\sim O_{Nucl} F_{mol}$

[Gaffney et al. Nature 497, 199 (2013)]
[Ra@ ANL: Parker et al. PRL 114, 233002 (2015)]

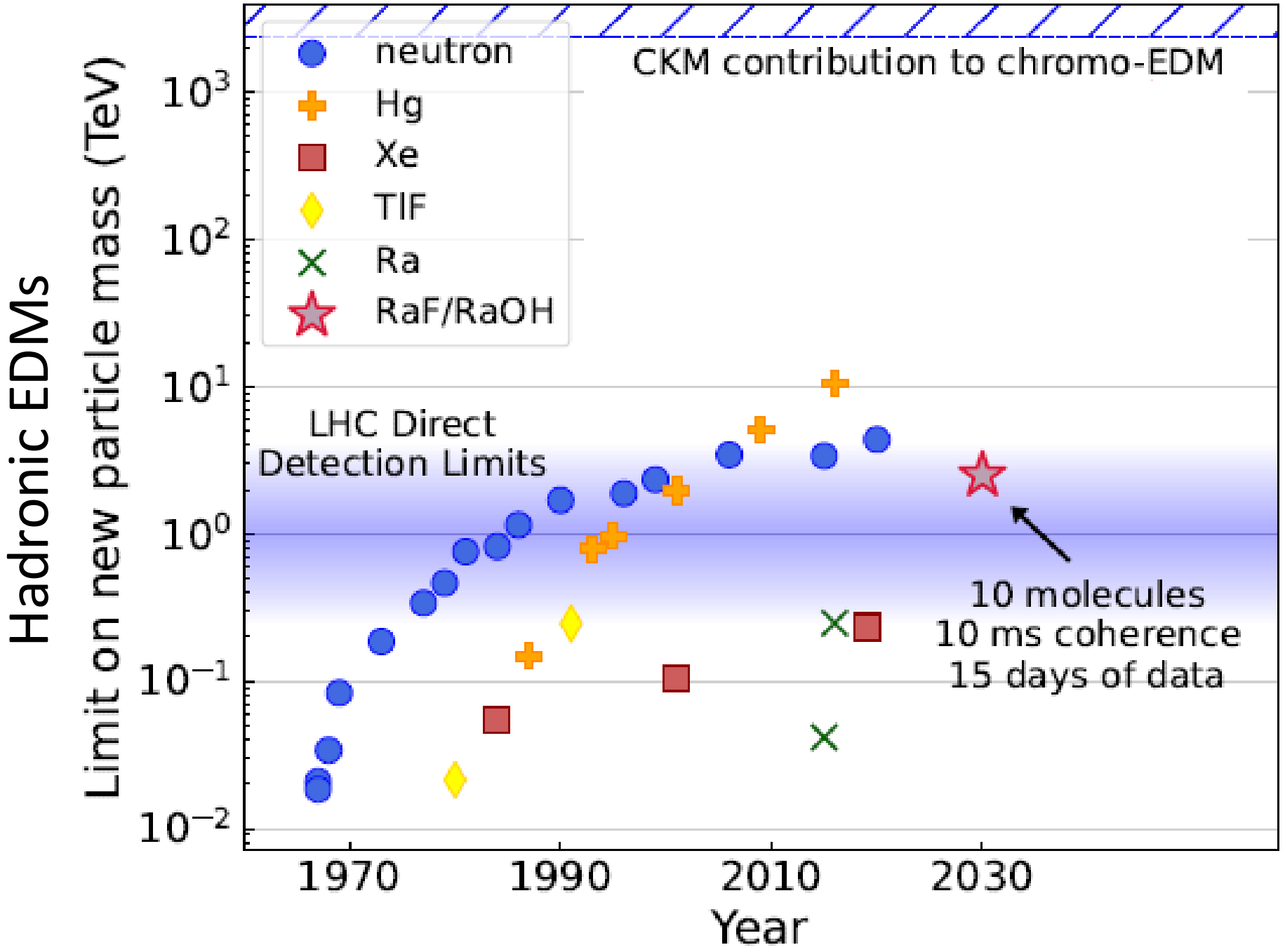


Radioactive molecules=> Best of all worlds!

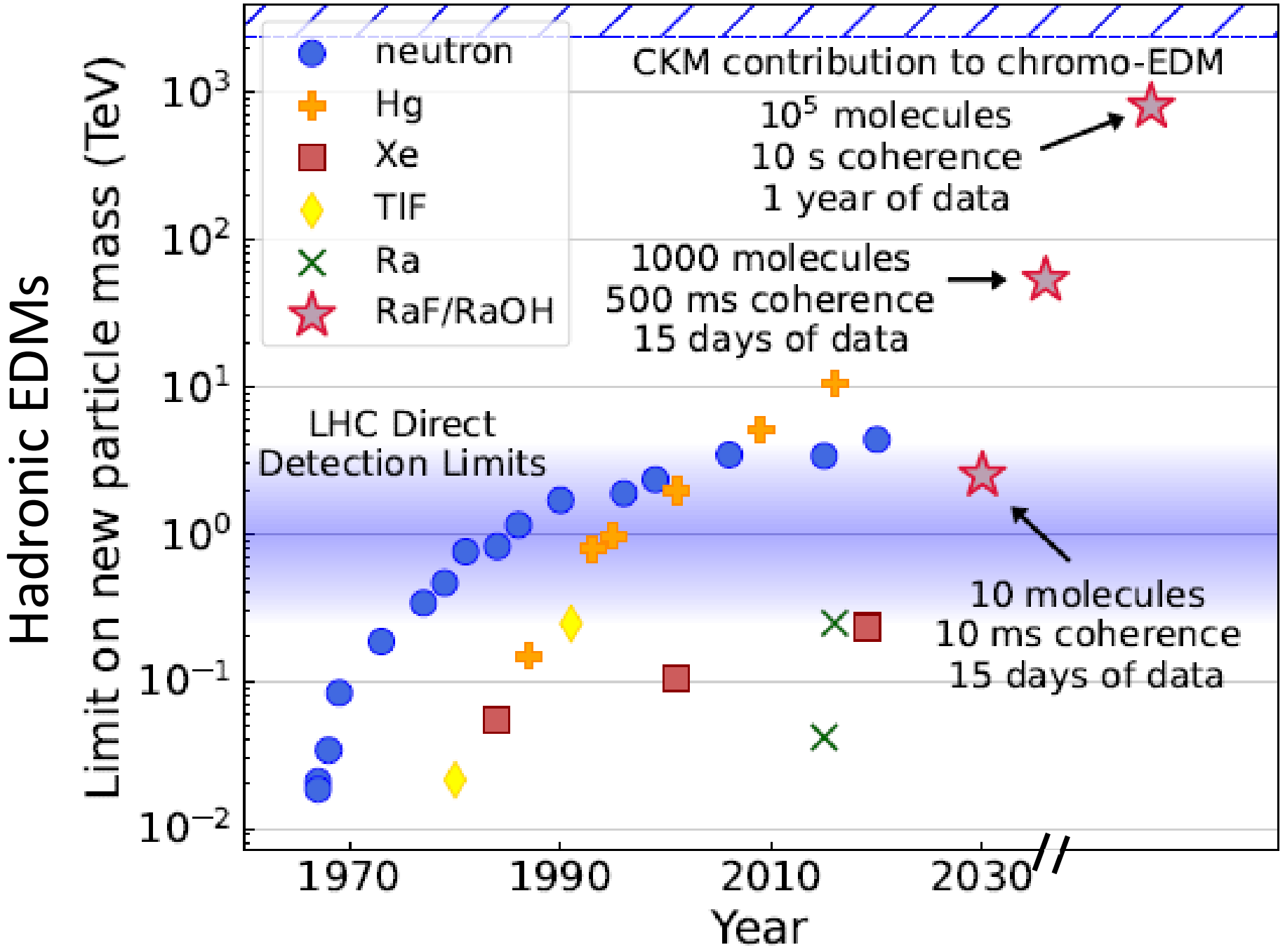
=> $>10^6$



Window of Discovery

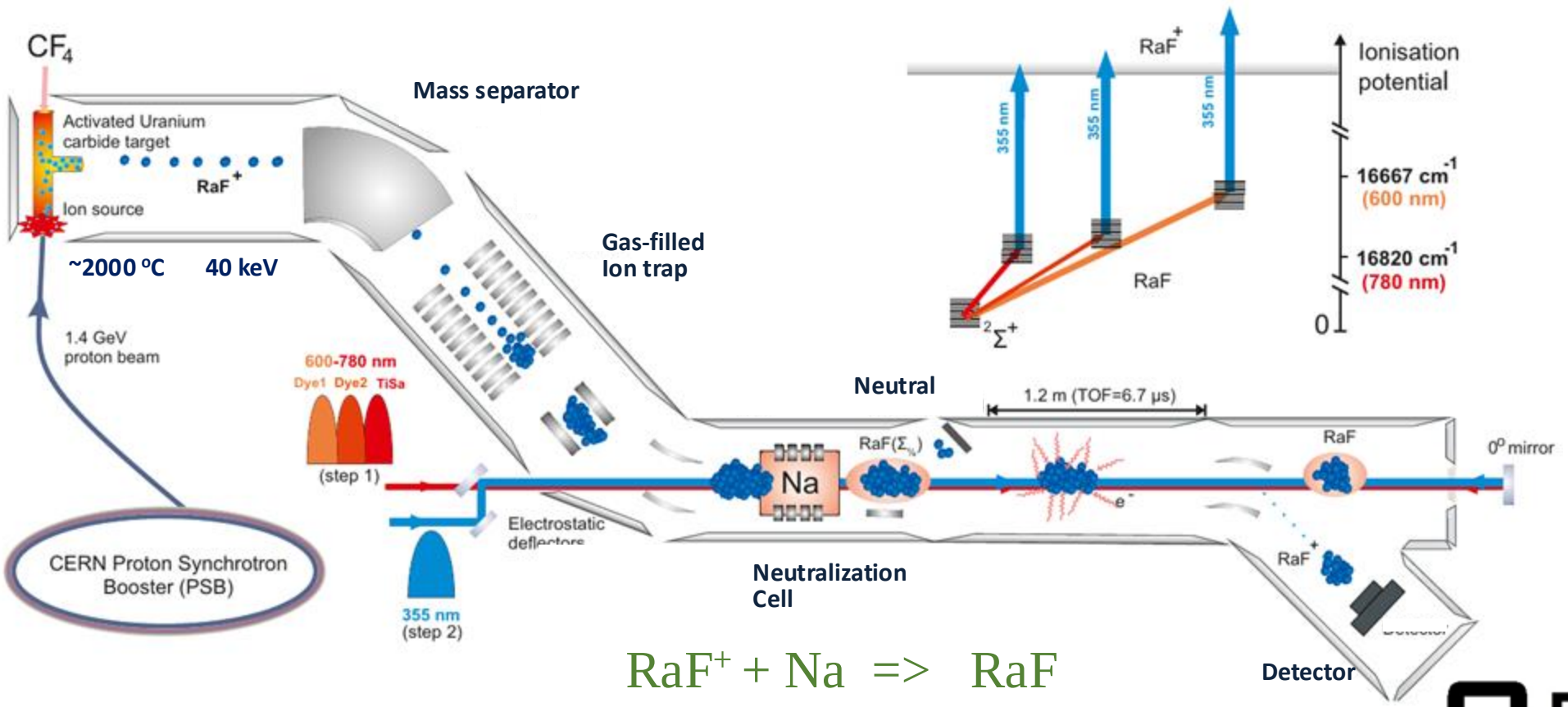


Window of Discovery



Window of Discovery

Recent Results (RaF)



$$RaF^+ + Na \Rightarrow RaF$$

Recent Results (RaF)

nature

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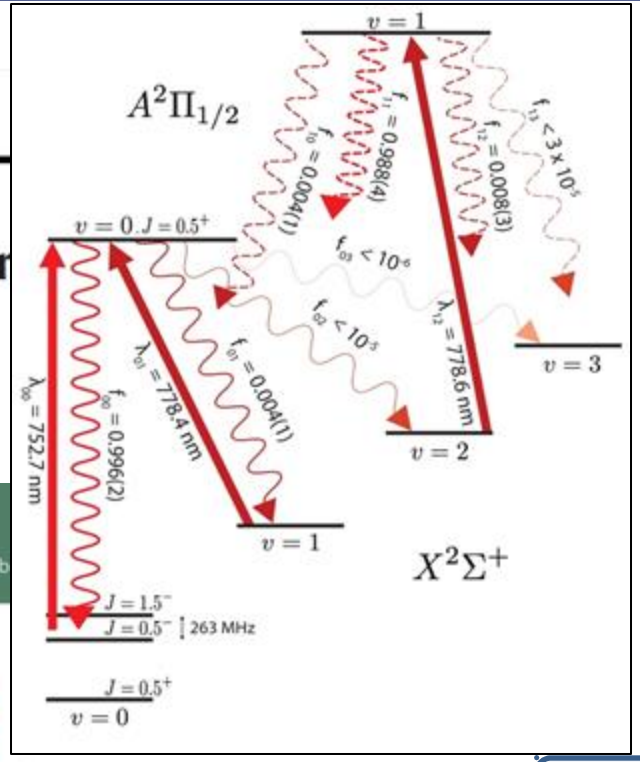
Spectroscopy of short-lived radioactive r

R. F. Garcia Ruiz ✉, R. Berger ✉, [...]

Nature **581**, 396–400 (2020) | Cite this article



PHYSICAL REVIEW LETTERS

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Isotope Shifts of Radium Monofluoride Molecules

S. M. Udrescu *et al.*

Phys. Rev. Lett. **127**, 033001 – Published 14 July 2021

PHYSICS See Viewpoint: Sizing up Exotic Nuclei with Radioactive Molecules

181 More

nature physics

nature > nature physics > articles > article

Article | Published: 09 January 2024

Precision spectroscopy and laser-cooling scheme of a radium-containing molecule

S. M. Udrescu ✉, S. G. Wilkins ✉, A. A. Breier, M. Athanasakis-Kaklamanakis, R. F. Garcia Ruiz ✉, M. Au, I.

+ Show authors

Nature Physics **20**, 202–207 (2024) | Cite this article

Nature 581, 396 (2020)
PRL 127, 033001 (2021)
Nature Phys 20, 202 (2024)
(2024) under review

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

H

eV ~ 2 10^{-2} 10^{-5} 10^{-8} $<10^{-12}$ $<10^{-15}$

Recent studies of RaF-

$RaF + Na \Rightarrow RaF^-$

S. Udrescu

S. Wilkins

M. Athanasakis

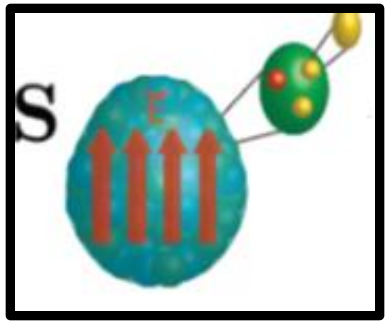
Recent Results (RaF)

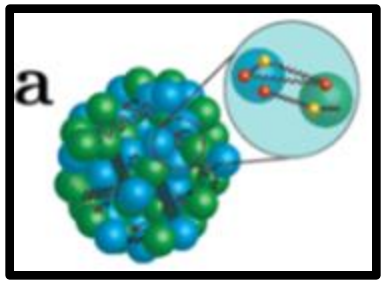
Nature 581, 396 (2020) ✓
PRL 127, 033001 (2021) ✓
Nature Phys 20, 202 (2024) ✓
(2024) Under review ✓

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

$$\Delta O \sim \frac{1}{F_{mol}\tau\sqrt{N}}$$

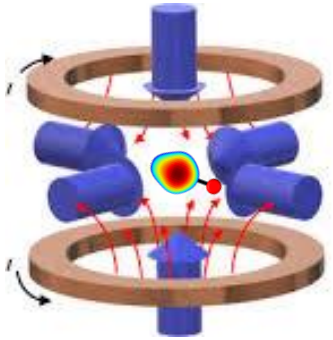


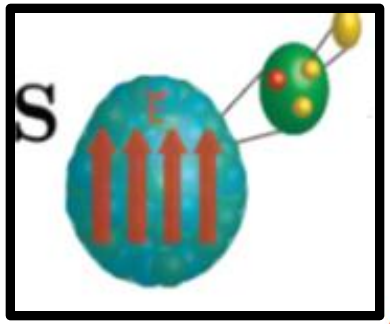


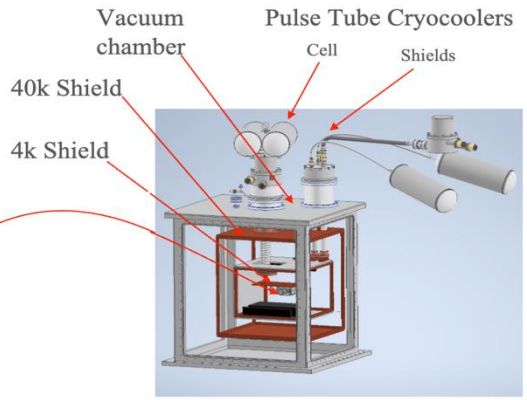
NEPTUNE Project

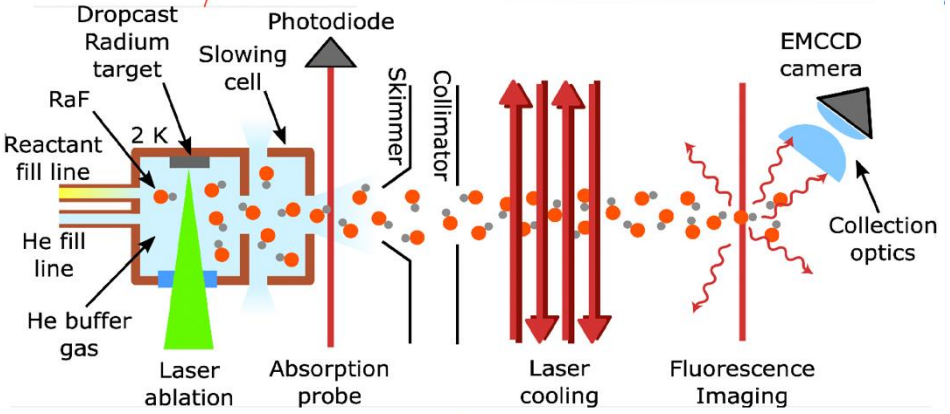
RaX Collaboration

P,T-violation measurements with RaX Molecules









RaX Collaboration

J. Doyle (Harvard), N. Hutzler (Caltech), R.F. Garcia Ruiz (MIT) & FRIB

FRIB

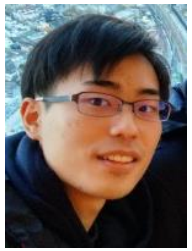
Caltech


S. Ebadi

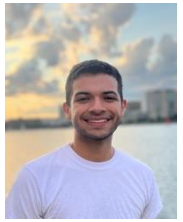

A. Jadbabaie


J. Munoz


M. Fulghieri

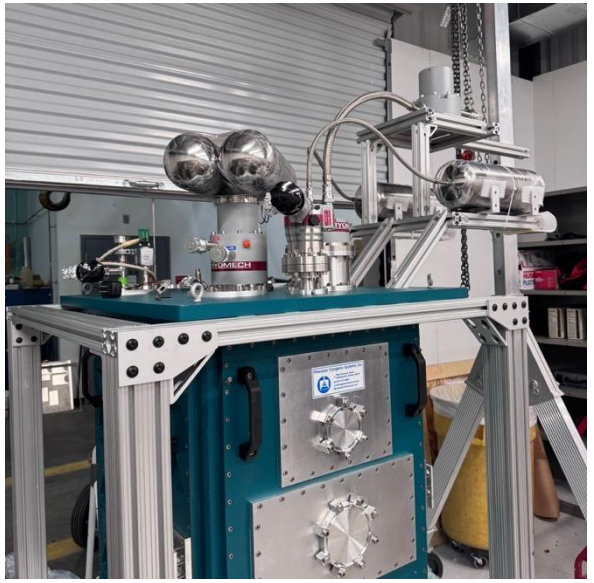

F. Shungo


K. Khusainova

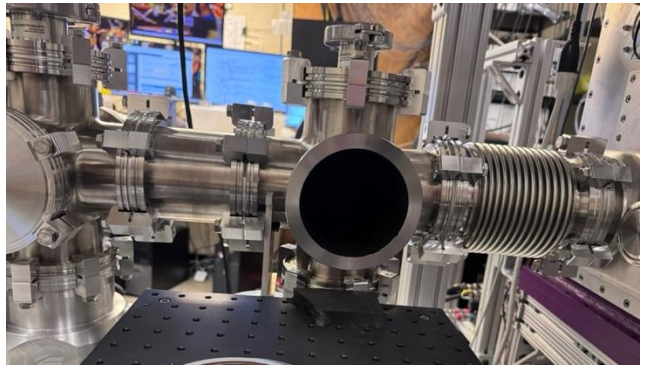

S. Munoz

RaX Collaboration

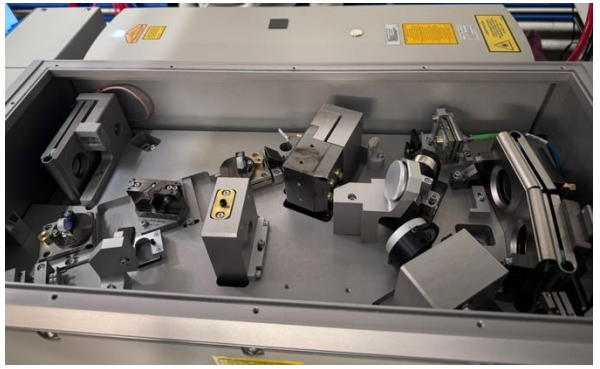
- ✓Beam box fabrication
- ✓Cryocooler testing
- ✓Laser Installation
- ✓Beamline construction



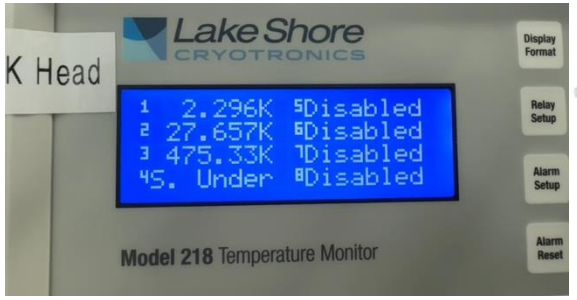
Lab @ Harvard

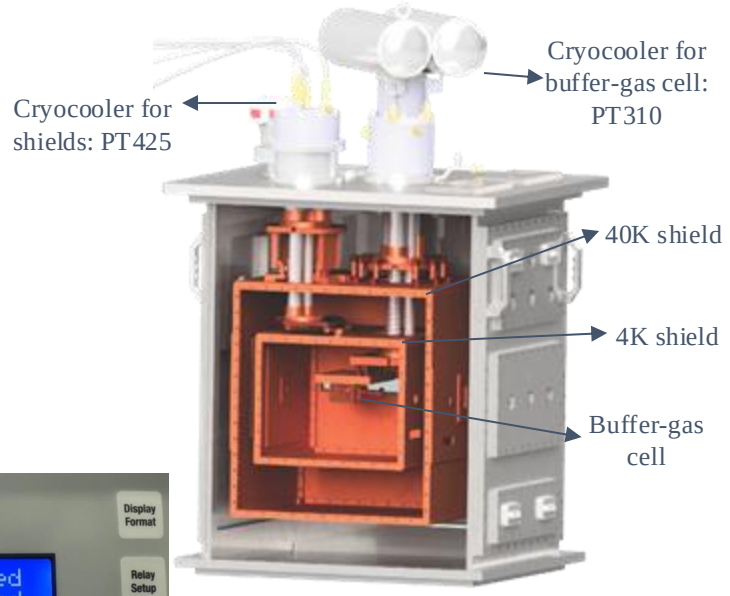


Blackened beamline for fluorescence collection



Ti:Sa laser installed





PT310 cryocooler:
2.2K base temp,
1W@3K, 51W@34K

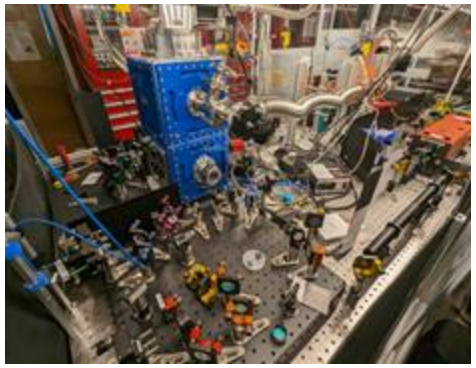
Radioactive Molecules for Fundamental-Symmetry Tests

→ **RaOH, $RaOH^+$ and $RaOCH_3^+$**

[Hutzler, Jayich, …]

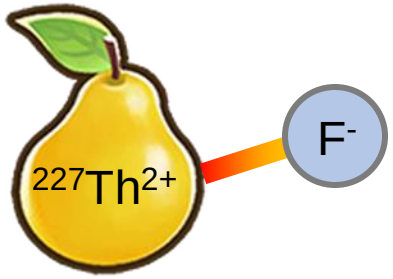
[Fan et al. Phys. Rev. Lett. 126, 023002 (2021)]
[Yu & Hutzler Phys. Rev. Lett. 126, 023003 (2021)]

Hutzler's group: RaOH @ Caltech



→ **$^{227}ThF^+$**

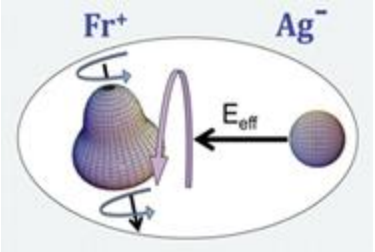
[Boon Ng, Cornell, Fang, Malbrunot …]



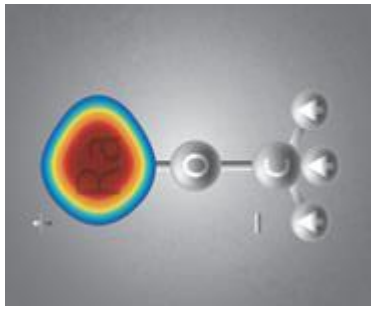
→ **Assembling molecules from cold atoms [Demille]**

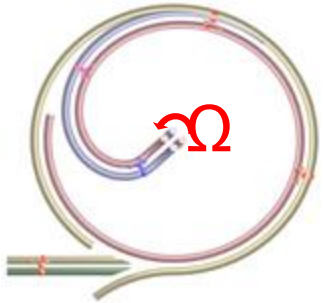
- **RaAg**
- **FrAg**

[New J. Phys. 23, 113039 (2021)]



→ **Centrifuge Deceleration**



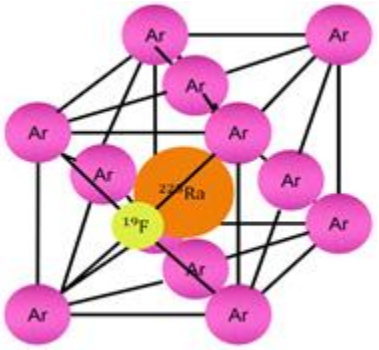


Xing Wu
$RaOCH_3$ @ FRIB/MSU

→ **Molecules in Noble Gas Solids (York/Toronto/MSU)**

[Singh, Vutha,…]

[Vutha et al. PRA 98:032513 (2018)]

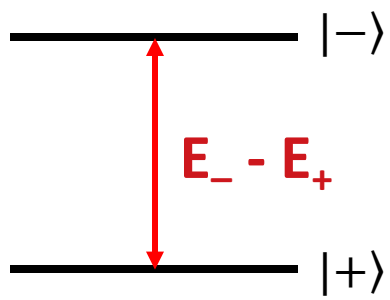


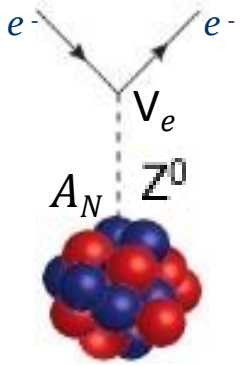
Molecules as sensitive probes of the nuclear electroweak (EW) structure

Molecules as sensitive probes of the nuclear EW structure

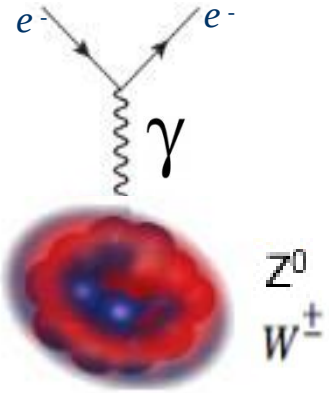
$H_{PV} \sim Z^c/(E_+ - E_-)$

$$|+\rangle' = |+\rangle + \frac{\langle +|V_{PV}|-\rangle}{E_+ - E_-}\,|-\rangle$$

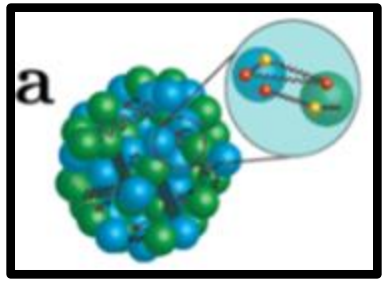




C_{2u}, C_{2d}



Anapole



Molecules as sensitive probes of the nuclear EW structure

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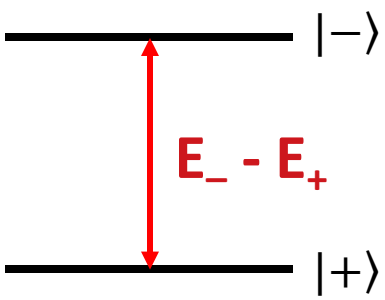
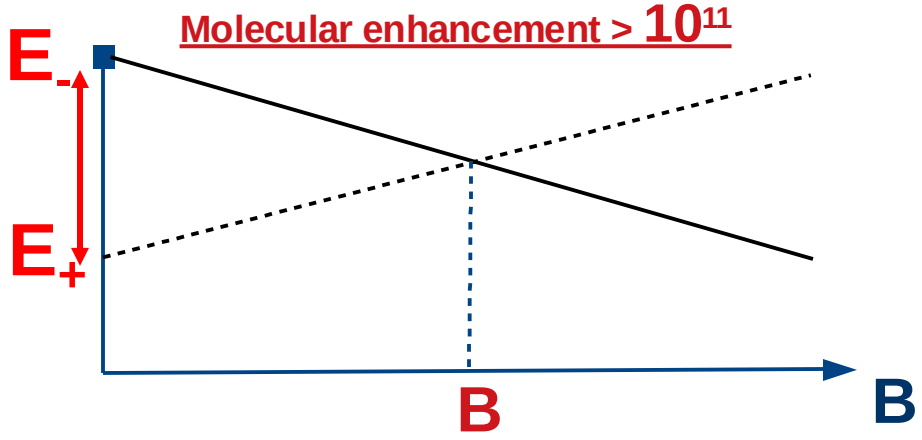


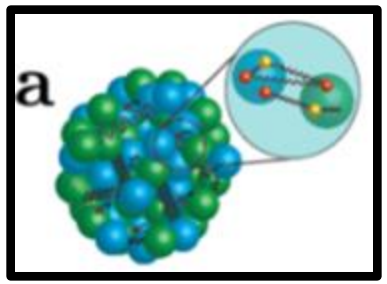


> 10^{11} Enhancement sensitivity to electroweak nuclear properties!

Demille's Group [Altunas et al. Phys. Rev. Lett. 120, 142501 (2018)]

NEPTUNE – Project

Nuclear Electroweak Measurements in a Penning Trap Using Near-degenerate Energy States of Molecules



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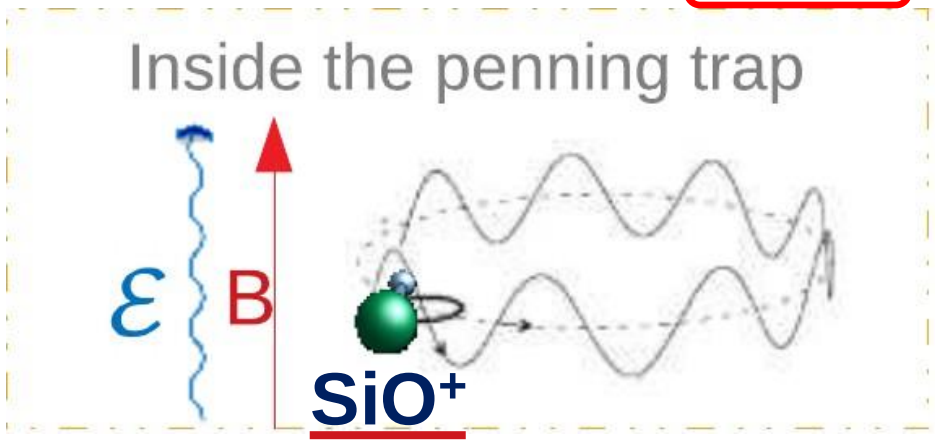

J. Karthein

S. Udrescu

S. Moroch

H. Kakiota

PHYSICAL REVIEW LETTERS

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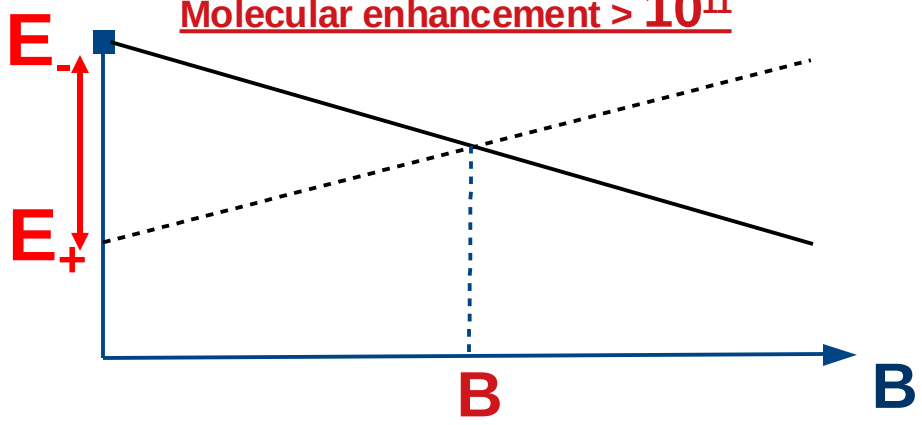
Electroweak Nuclear Properties from Single Molecular Ions in a Penning Trap

J. Karthein, S. M. Udrescu, S. B. Moroch, I. Belosevic, K. Blaum, A. Borschevsky, Y. Chamorro, D. DeMille, J. Dilling, R. F. Garcia Ruiz, N. R. Hutzler, L. F. Pašteka, and R. Ringle

Phys. Rev. Lett. **133**, 033003 – Published 19 July 2024

Molecular enhancement > 10^{11}



FRIB

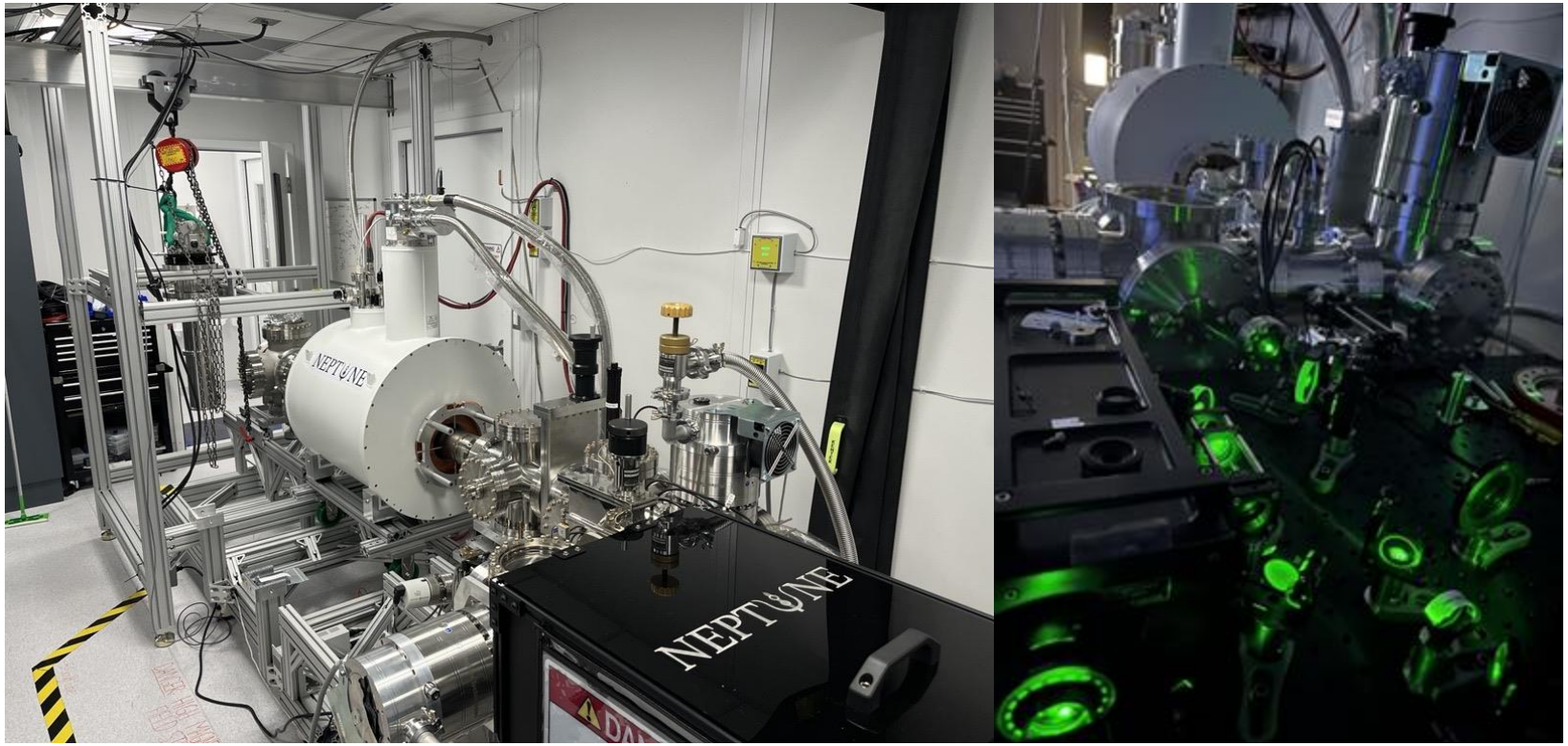
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

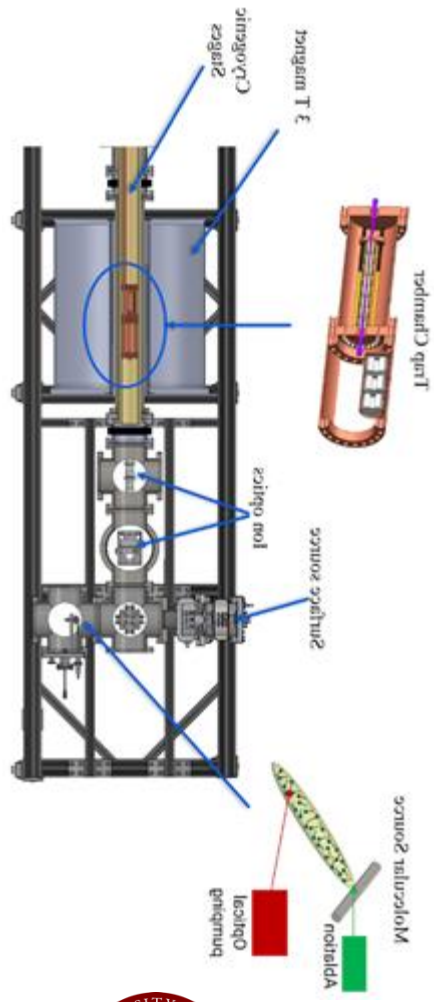
Caltech

NEPTUNE – Project

Nuclear Electroweak Measurements in a Penning Trap Using Near-degenerate Energy States of Molecules

Lab @MIT





DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

MIT

FRIB

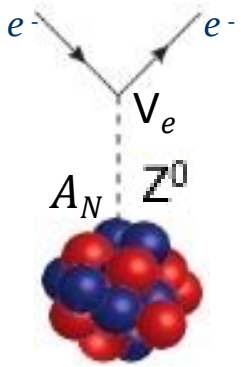
TAMU

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

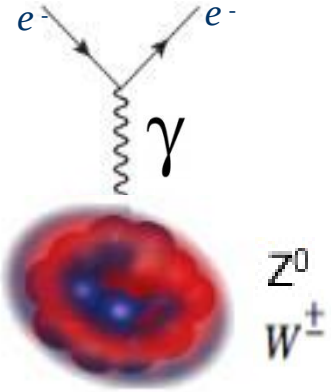
Caltech

THE UNIVERSITY OF CHICAGO 1890

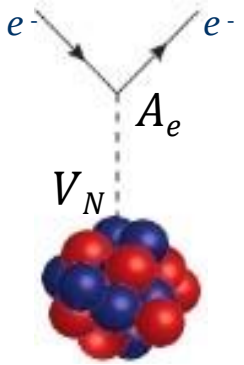
Molecules as sensitive probes of the nuclear EW structure



C_{2u}, C_{2d}



Anapole

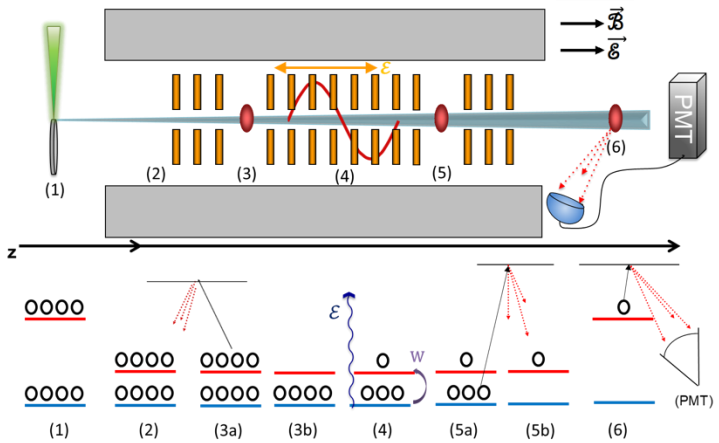


θ_w

Fr @ TRIUMF

[Zang et al. Phys. Rev. Lett. 115, 042501 (2015)]

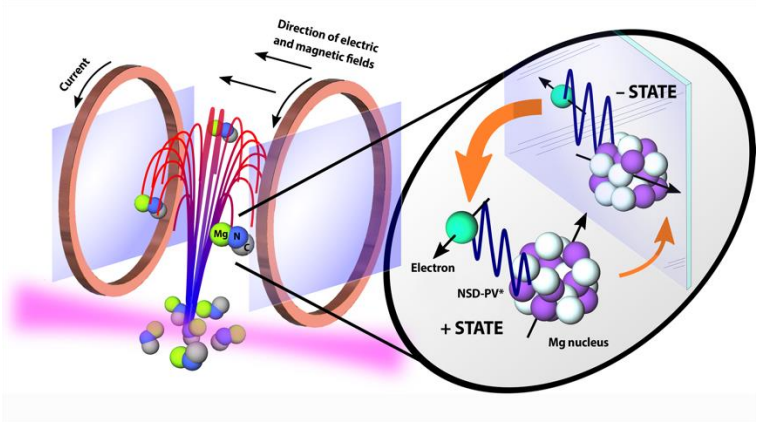
ZOMBIES



U Chicago, ANL

[Altunas et al. PRL 120, 142501 (2018)]

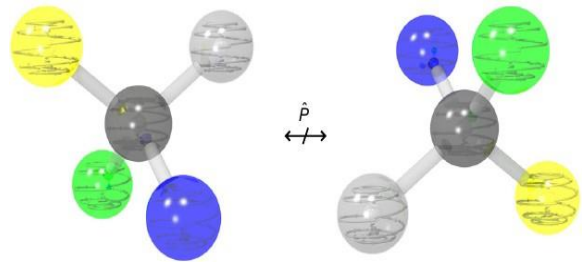
Molecular fountain



NIST

[Norrgard et al. Comm. Phys. 2, 77 (2019)]

$PV \sim Z^5$



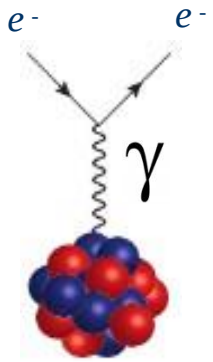
[Erez et al. arXiv:2206.03699 (2022)]

[Gaul et al. Phys. Rev. Lett. 125, 123004 (2

Summary and Outlook

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

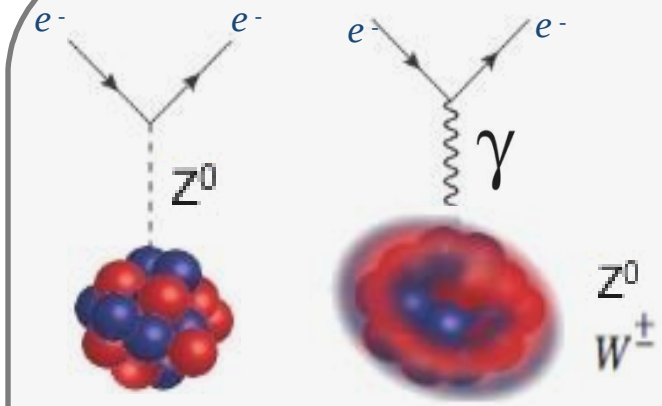
H_{hfs}



P,T-even

- Nuclear structure
- Nuclear matter

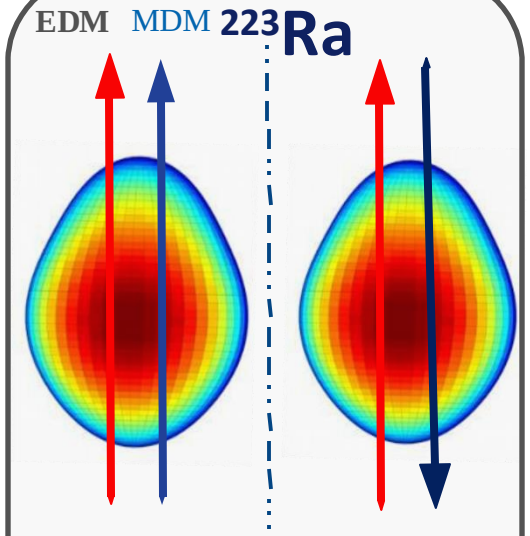
H_{PV}



P-violation

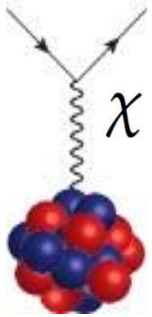
- Electro weak structure
- Precision Standard Model tests
- Dark Mater properties?
- New forces?

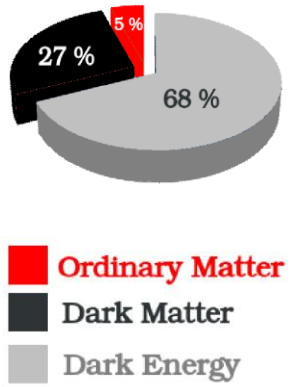
H_{PTV}



T-violation

- Matter-antimatter asymmetry
- New particles?





Summary & Outlook

"Terra incognita"

Sensitivity (ions/s)

10^{-8}

10^{-6}

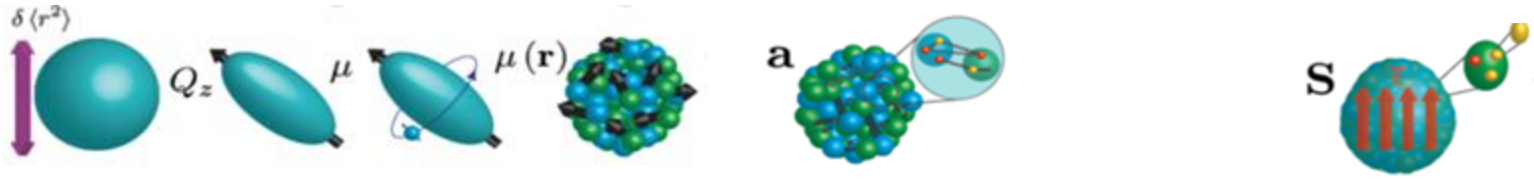
10^{-4} ← *Super Heavy Elements*

10^{-2} ← *Neutron Dripline*

10^{0} ← *Proton Dripline*

10^{2}

⋮



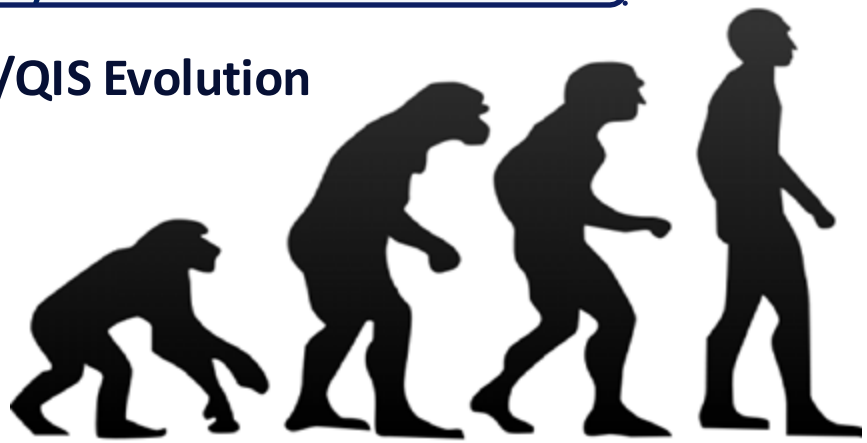
… 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}

Precision [eV]

"Access to new fundamental properties"

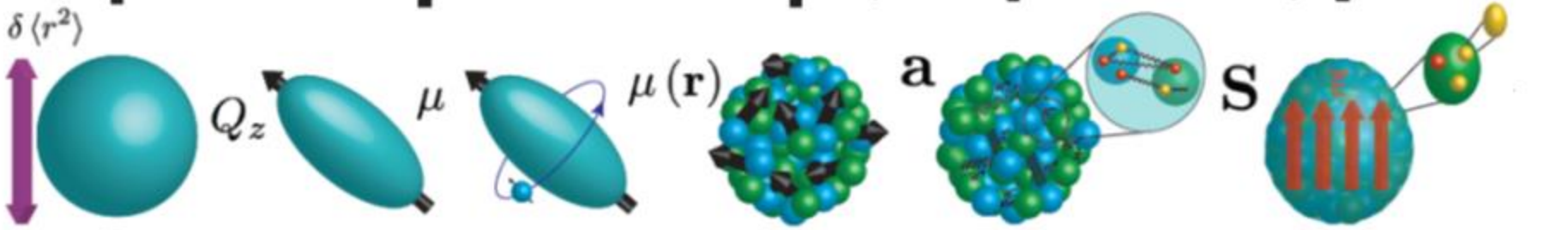
Summary and Outlook

AMO/QIS Evolution



We are here!

10 GHz | 1 GHz | 100 MHz | 100 Hz | <1 mHz



$$H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

	eV	~ 2	10^{-2}	10^{-5}	10^{-6}	10^{-8}	$<10^{-12}$	$<10^{-15}$

Summary and Outlook

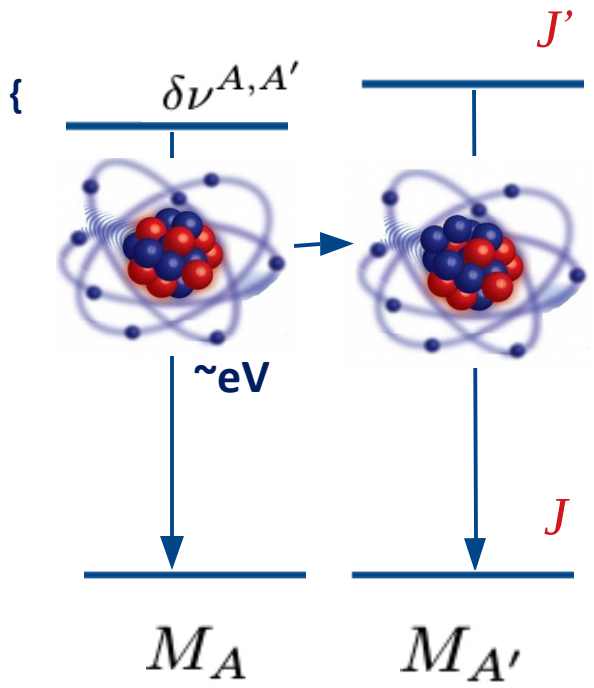
New opportunities!

- **New Facilities (FRIB, TRIUMF, ISOLDE, FAIR,….)**
- **New Era of Precision (Atomic, Molecular, Nuclear) Physics**

Isotope Shifts for Nuclear Structure and BSM Physics

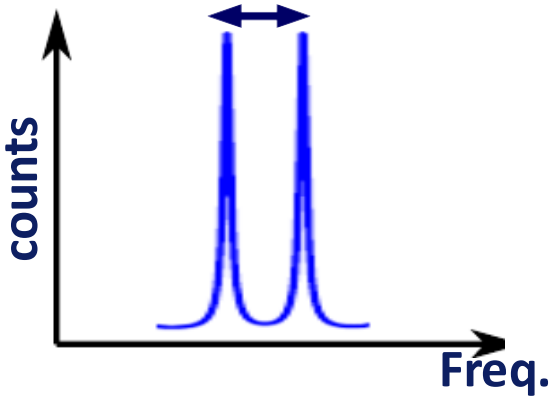
Isotope Shifts for Nuclear Structure and BSM Physics

Isotope shift
MHz < 10^{-6}eV



$I = 0$

$\sim F\delta\langle r^2\rangle^{A,A'}$



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Isotope Shifts for Nuclear Structure and BSM Physics

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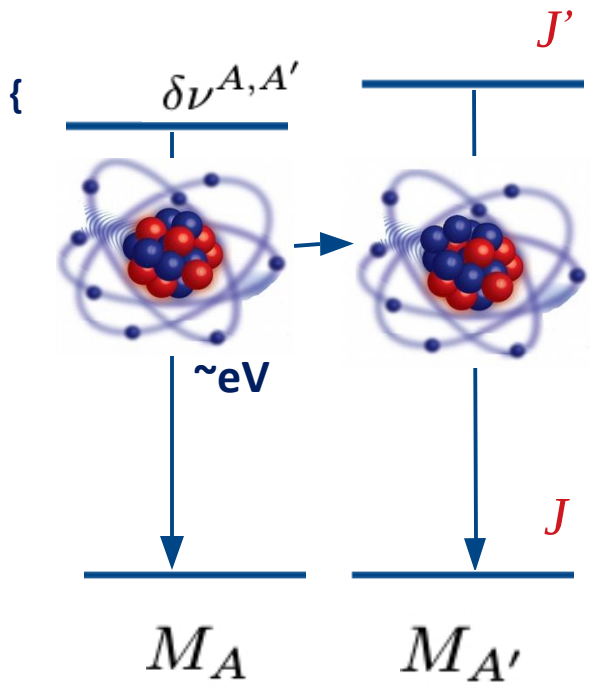

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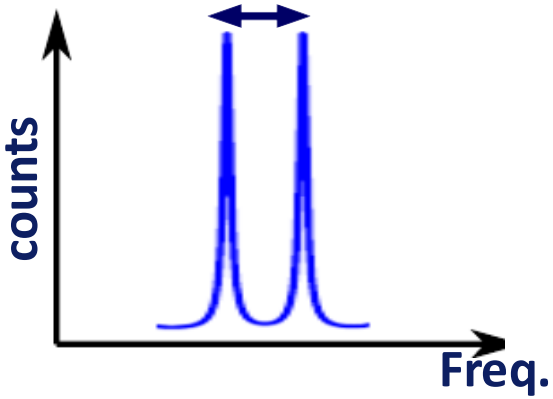

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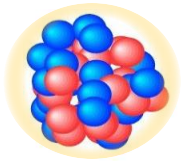

Si(Z=14)

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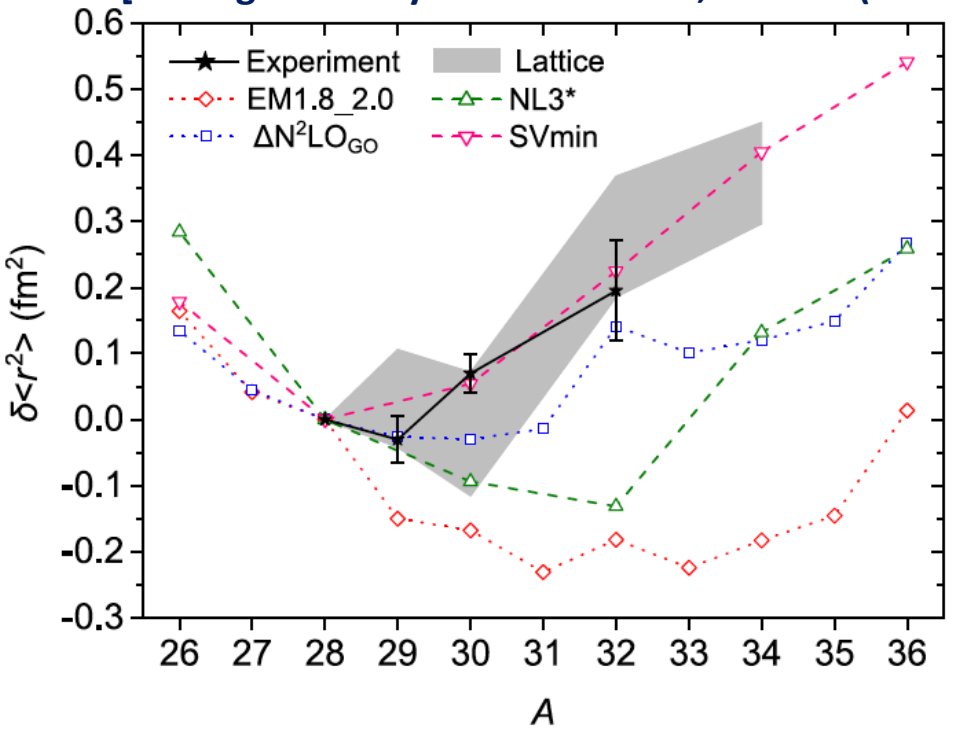
[Koning et al. Phys. Rev. Lett. 132, 162502 (2024)]



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Dean Lee's Talk
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Isotope Shifts for Nuclear Structure and BSM Physics

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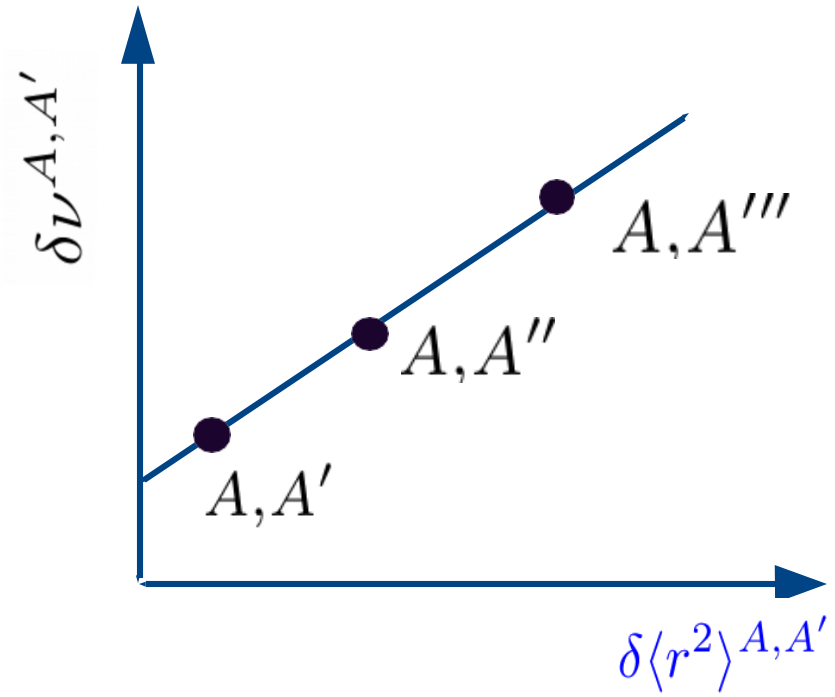

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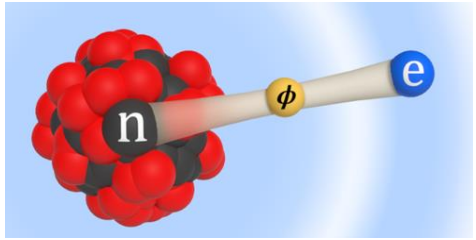
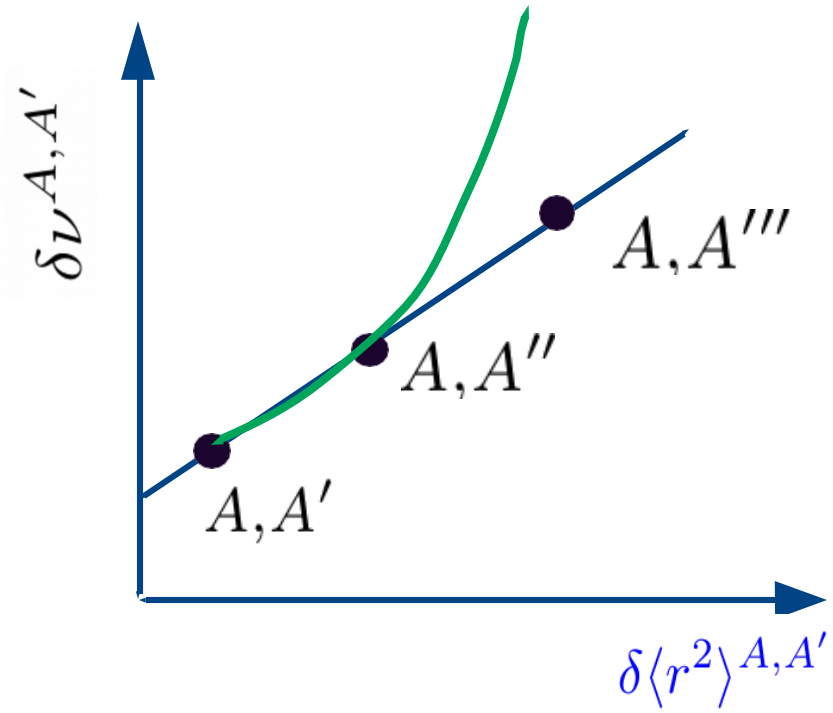
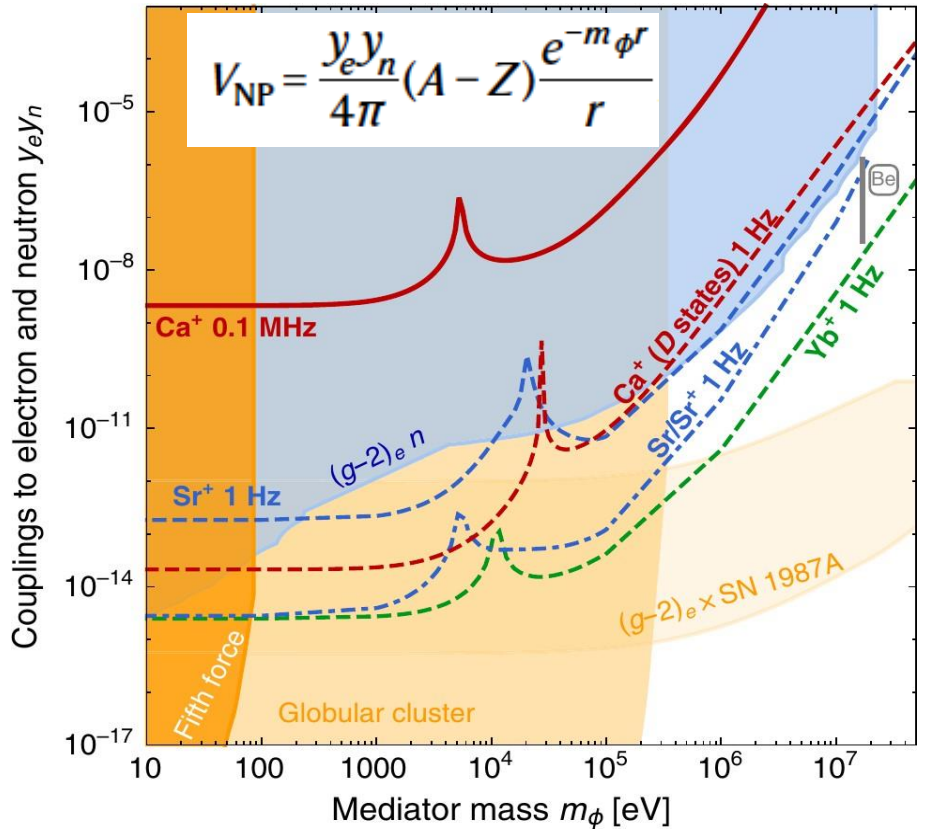


New physics





[Berengutet al. Phys. Rev. Lett 120, 091801 (2018)]

Isotope Shifts for Nuclear Structure and BSM Physics

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Yb^+ → Vuletic's group at MIT

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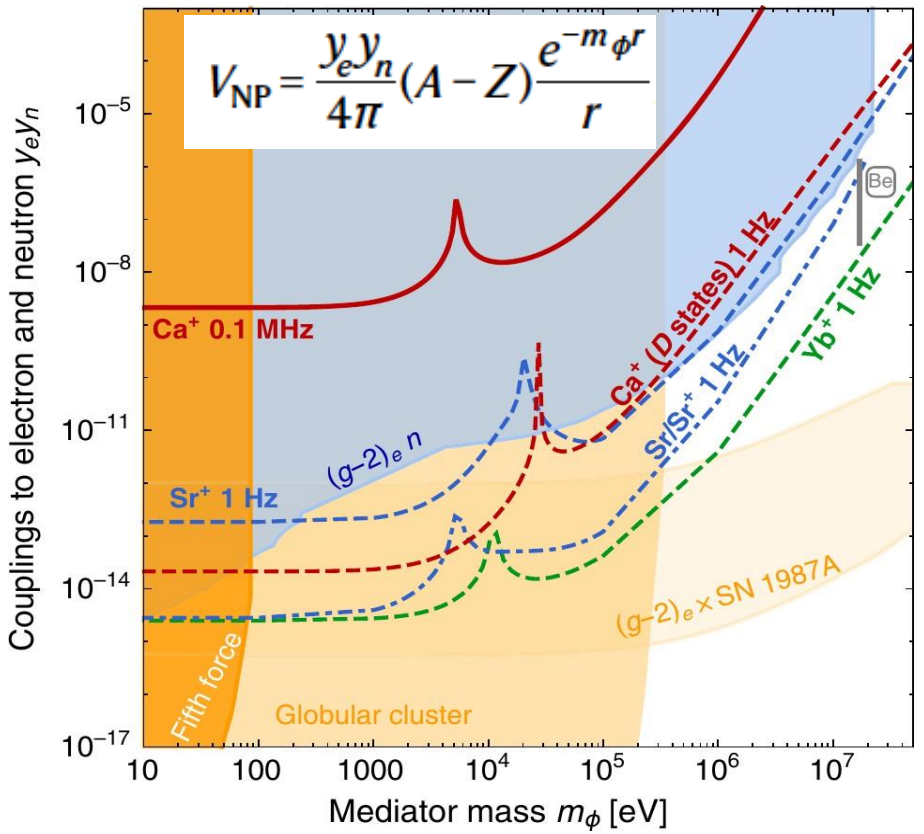
[Counts et al. Phys. Rev. Lett. 125, 123002 (2020)]
[J. Hur et al. Phys. Rev. Lett. 128, 163201 (2022)]
[Door et al. arXiv:2403.07792 (2024)]

$\delta\langle r^4\rangle^{A,A'}$ → **Related to the surface thickness of the nuclear density**

[Reinhard et atl . Phys. Rev. C 101, 021301(R) (2020)]



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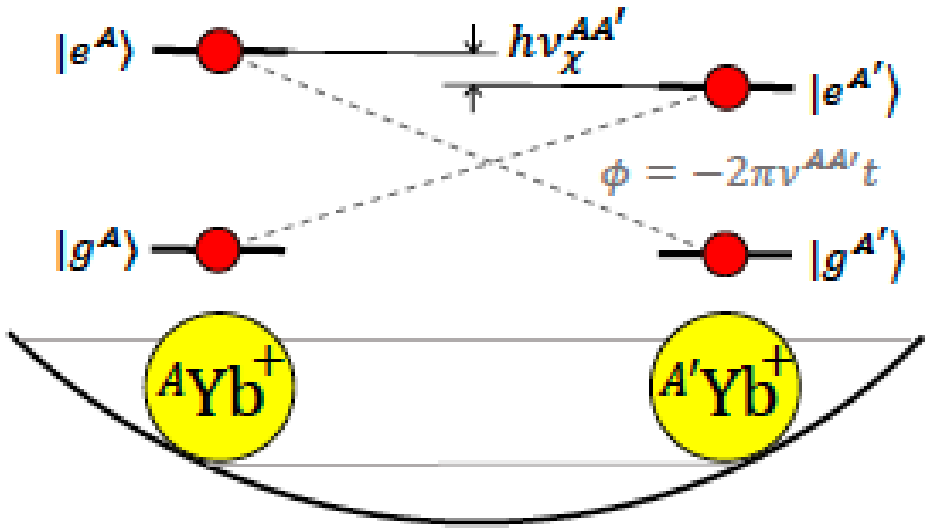

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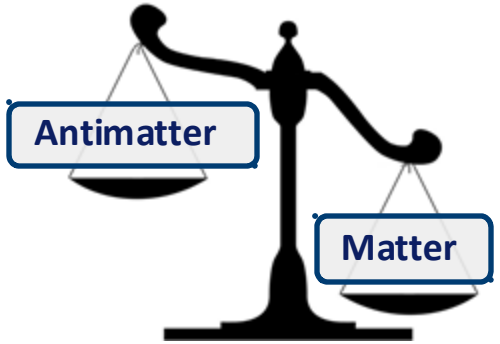
[T. Manovitz et al., PRL 123, 203001 (2019)]

Sr^+: Uncertainty ~ 10 mHz (stable)

Major Open Questions in Physics and Cosmology

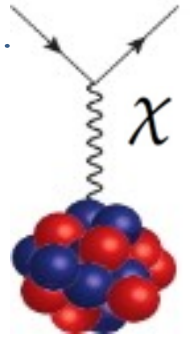
Why is there more matter?



Strong CP problem

$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$

Are there new particles?



New sources of Time-reversal (CP) violation in nuclei can provide answers to these problems

Fundamental Symmetries

Parity (P): $r \rightarrow -r$

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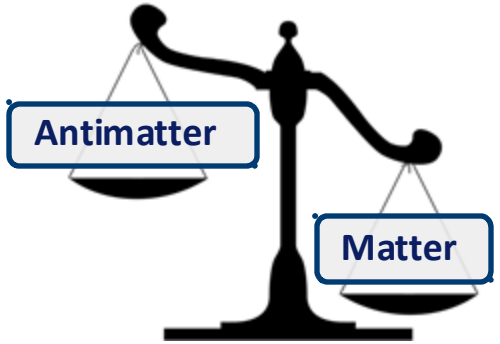

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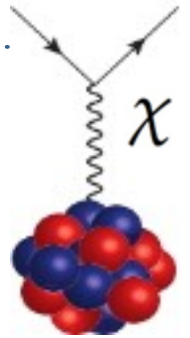

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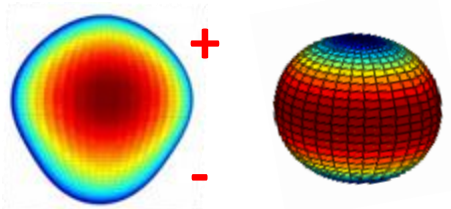
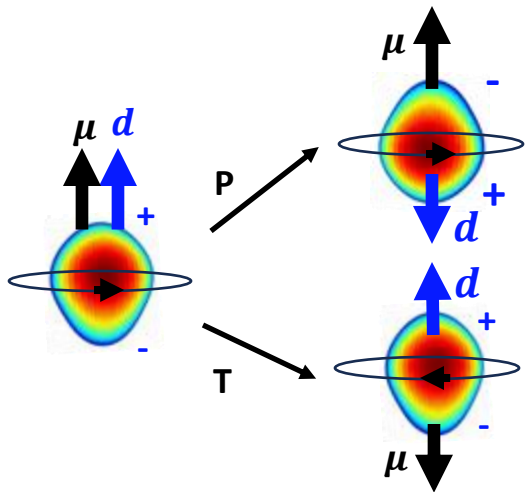
Electric Dipole Moment (EDM) ⇄ **Time-reversal violation**



EDM > 0

EDM=0



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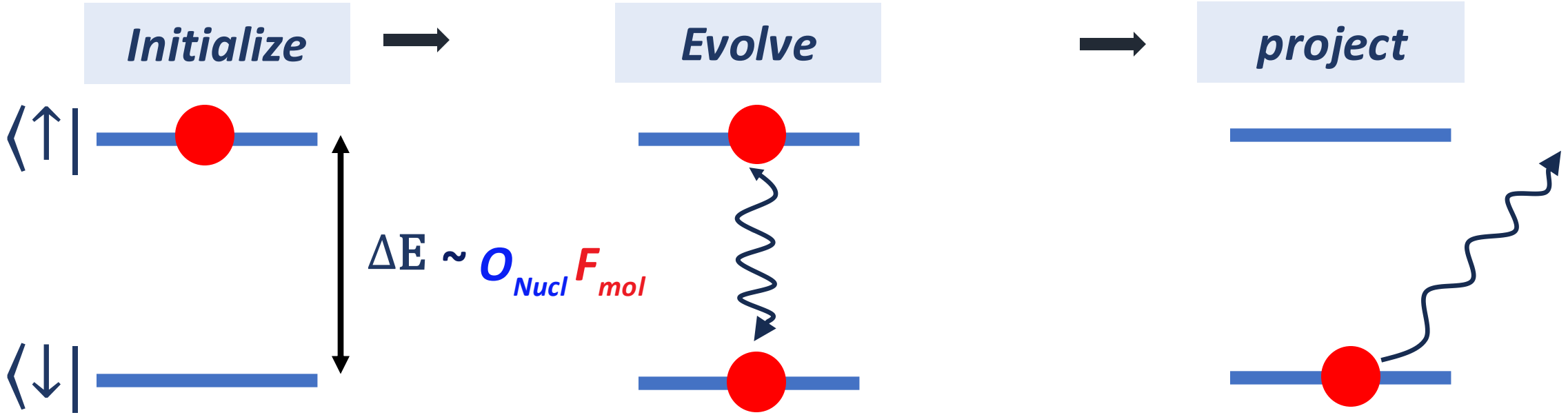
Molecules as “quantum sensors”



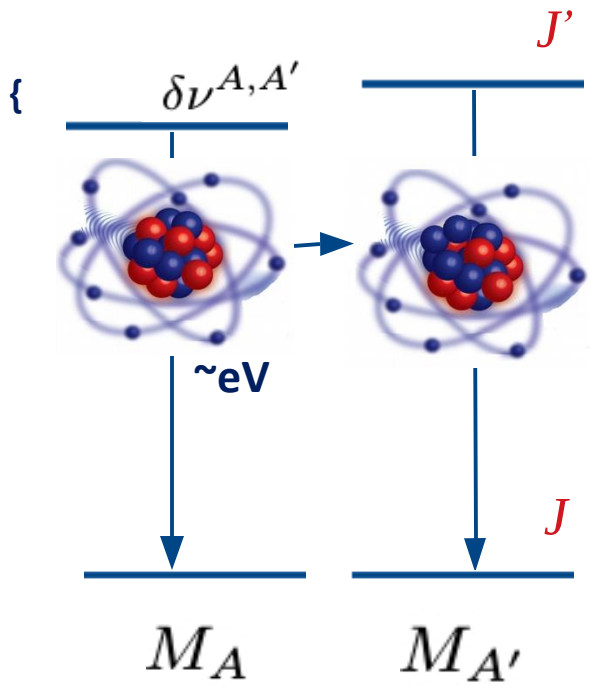
$|\psi\rangle_0$ → $|\psi\rangle_= \hat{U}(\Delta E, t)|\psi\rangle_0$ → $|\langle\uparrow|\psi\rangle|^2$, $|\langle\downarrow|\psi\rangle|^2$

Recent reviews:

- *"Searches for new sources of CP violation using molecules as quantum sensors".* Hutzler et al. arXiv:2010.08709 (2020)
- *“Opportunities for fundamental physics research with radioactive molecules”.* Arrowsmith-Kron et al. Rep. Prog. Phys. 87 084301 (2024)

Isotope Shifts for Nuclear Structure and BSM Physics

Isotope shift
MHz < 10^{-6}eV



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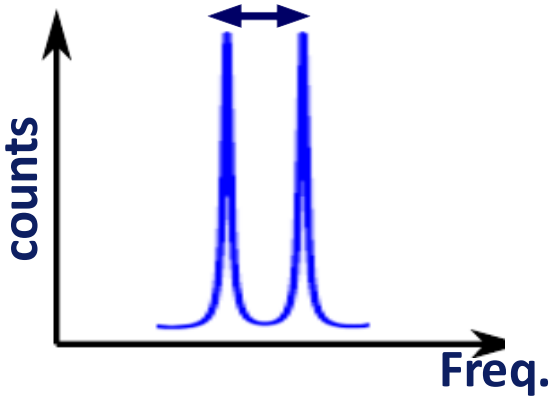

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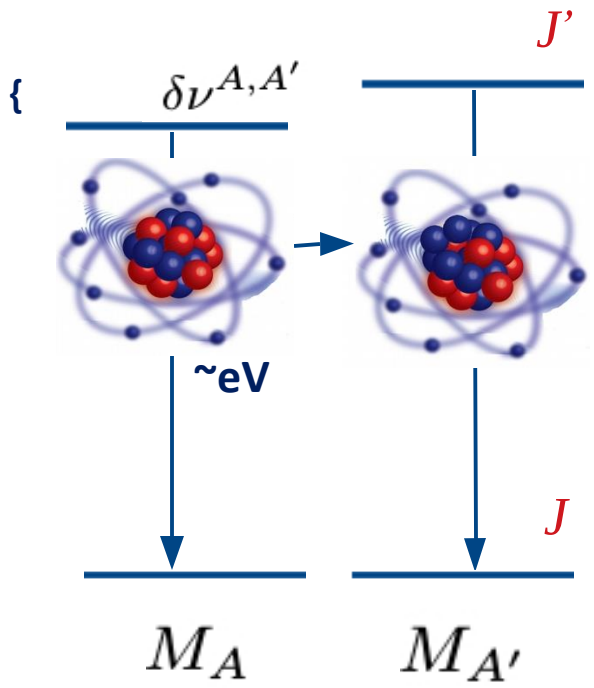

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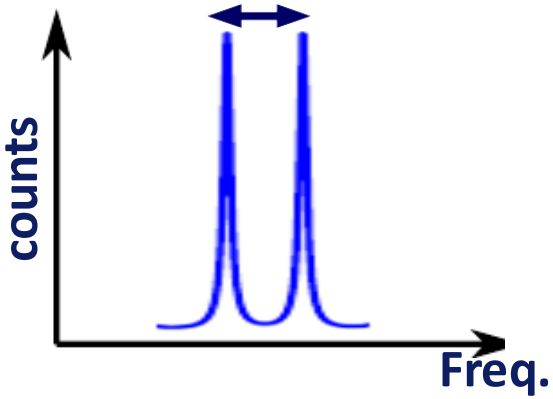

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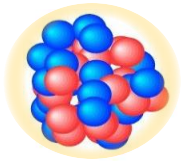

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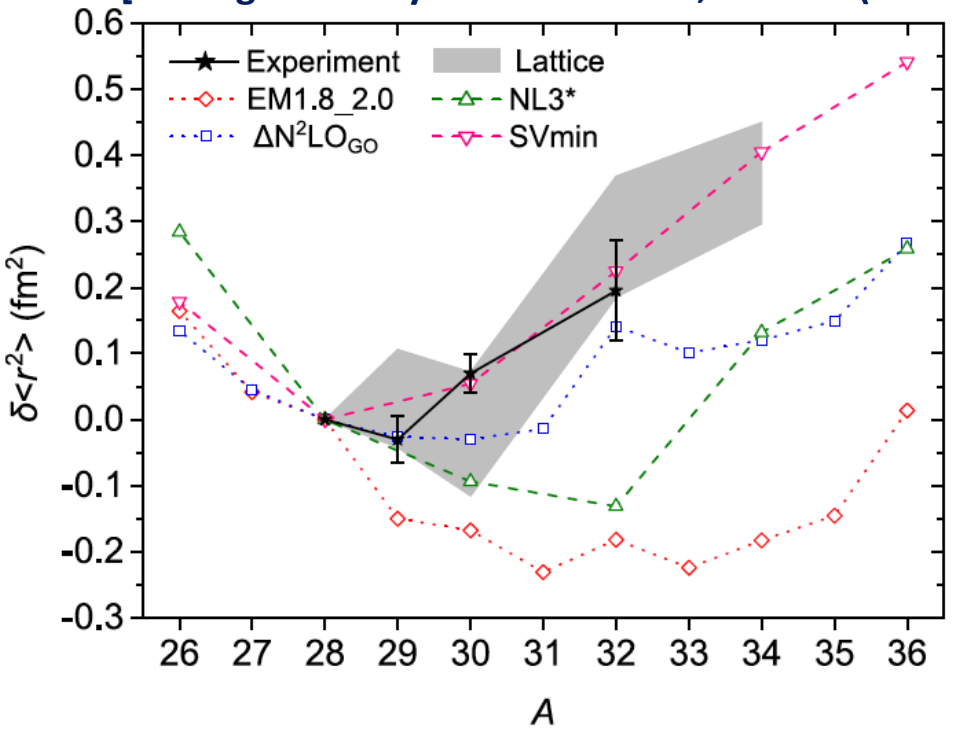

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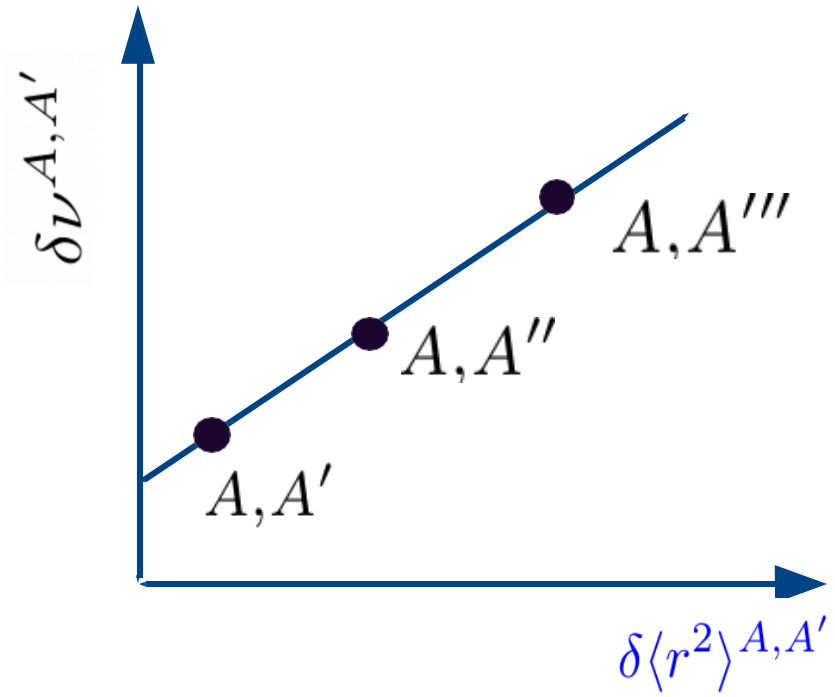

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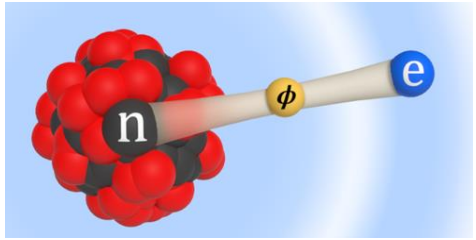

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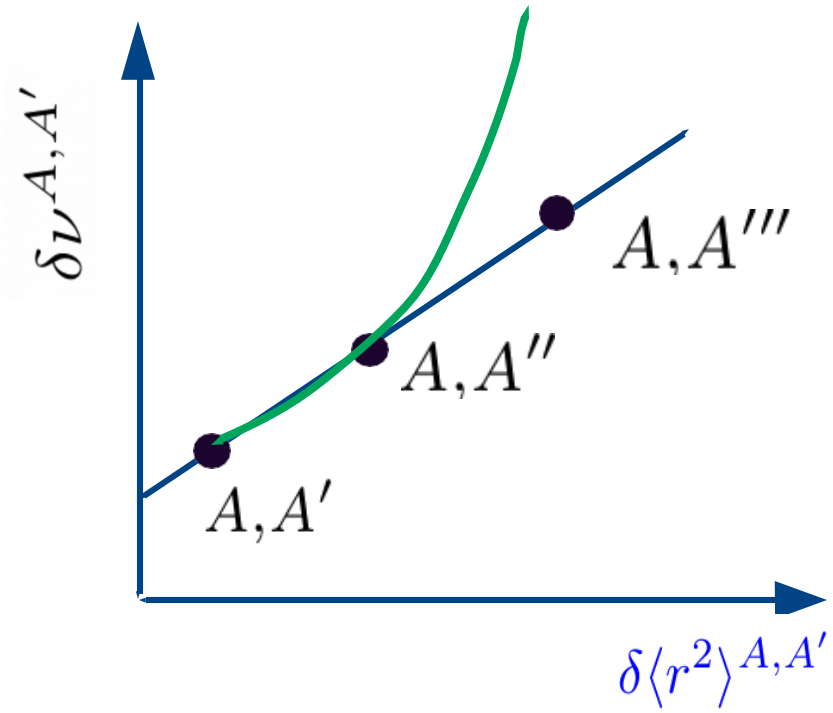

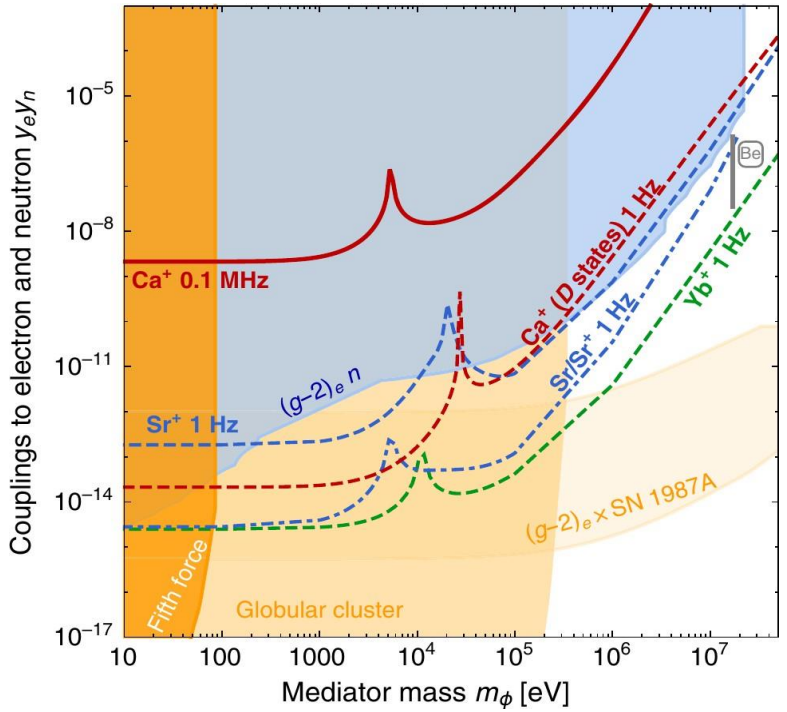

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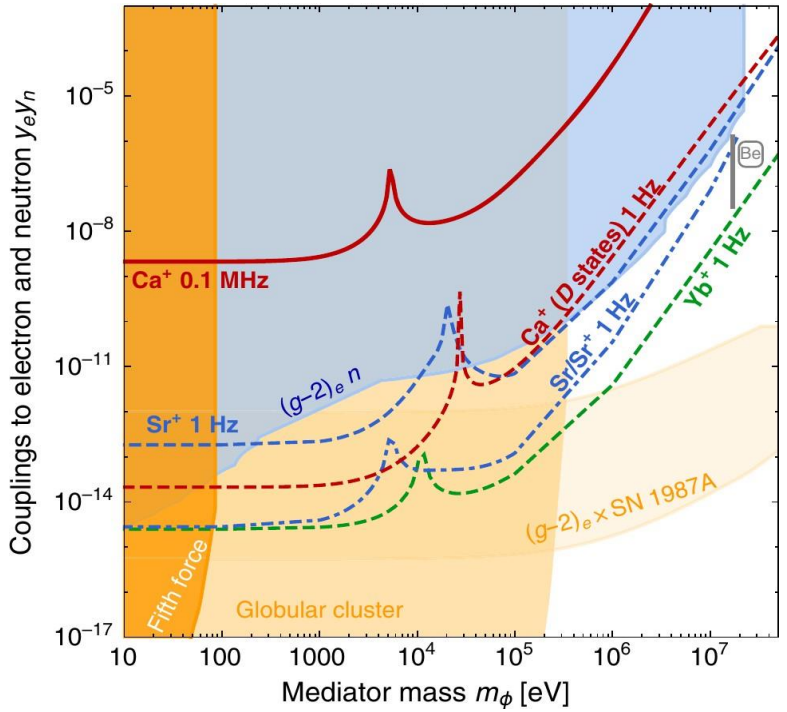

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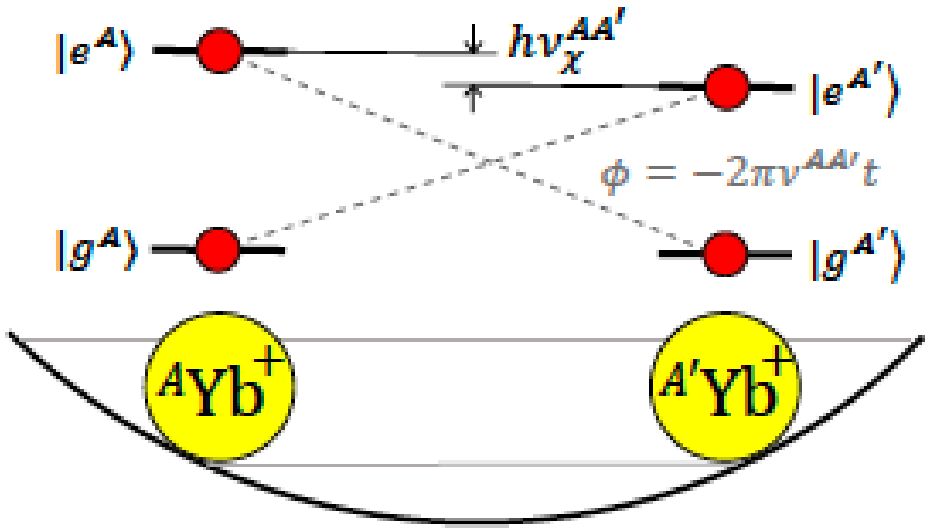

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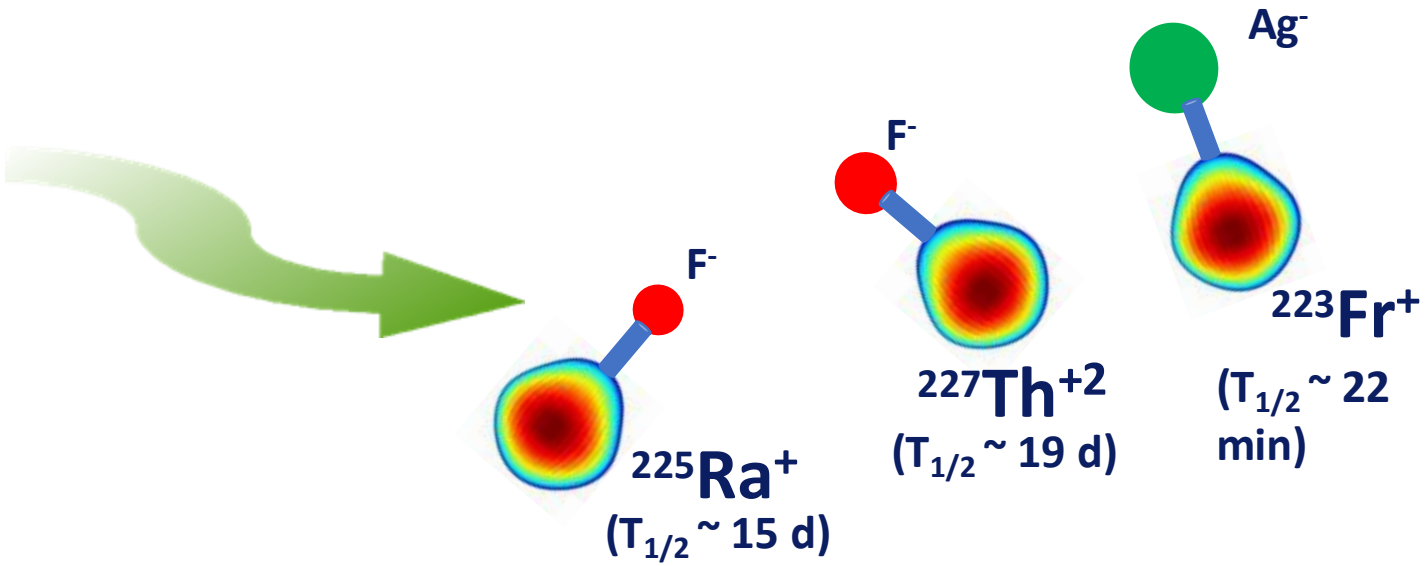
Buckup Slides

Probing Symmetry-Violating Nuclear Properties with Molecules

Figure modified from https://sphereofinfluence360.com/

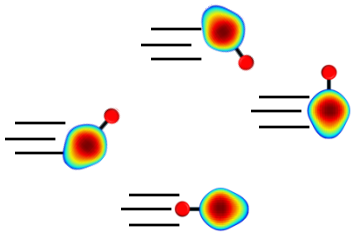


Radioactive molecule production

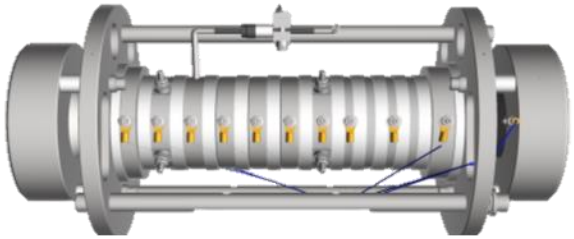
$$\delta H_{PTV} \propto \frac{1}{\tau \sqrt{\dot{N}\, T}}$$

RaF^+

T>1000 K

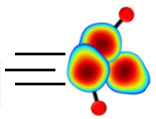


Gas filled ion Cooler and buncher



RaF^+

T~300 K



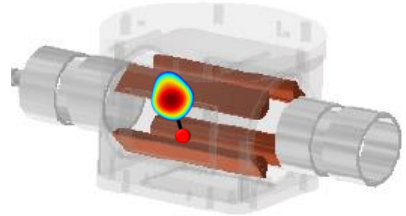
$RaF^+ + Na \Rightarrow RaF$

(Charge exchange)

RaF

T > 300 K

$RaF + Na \Rightarrow RaF^-$



$RaF^- + \gamma \Rightarrow RaF + e$

T > 1000 K

T~300 K

RaF^- Experiment @ CRIS-CERN

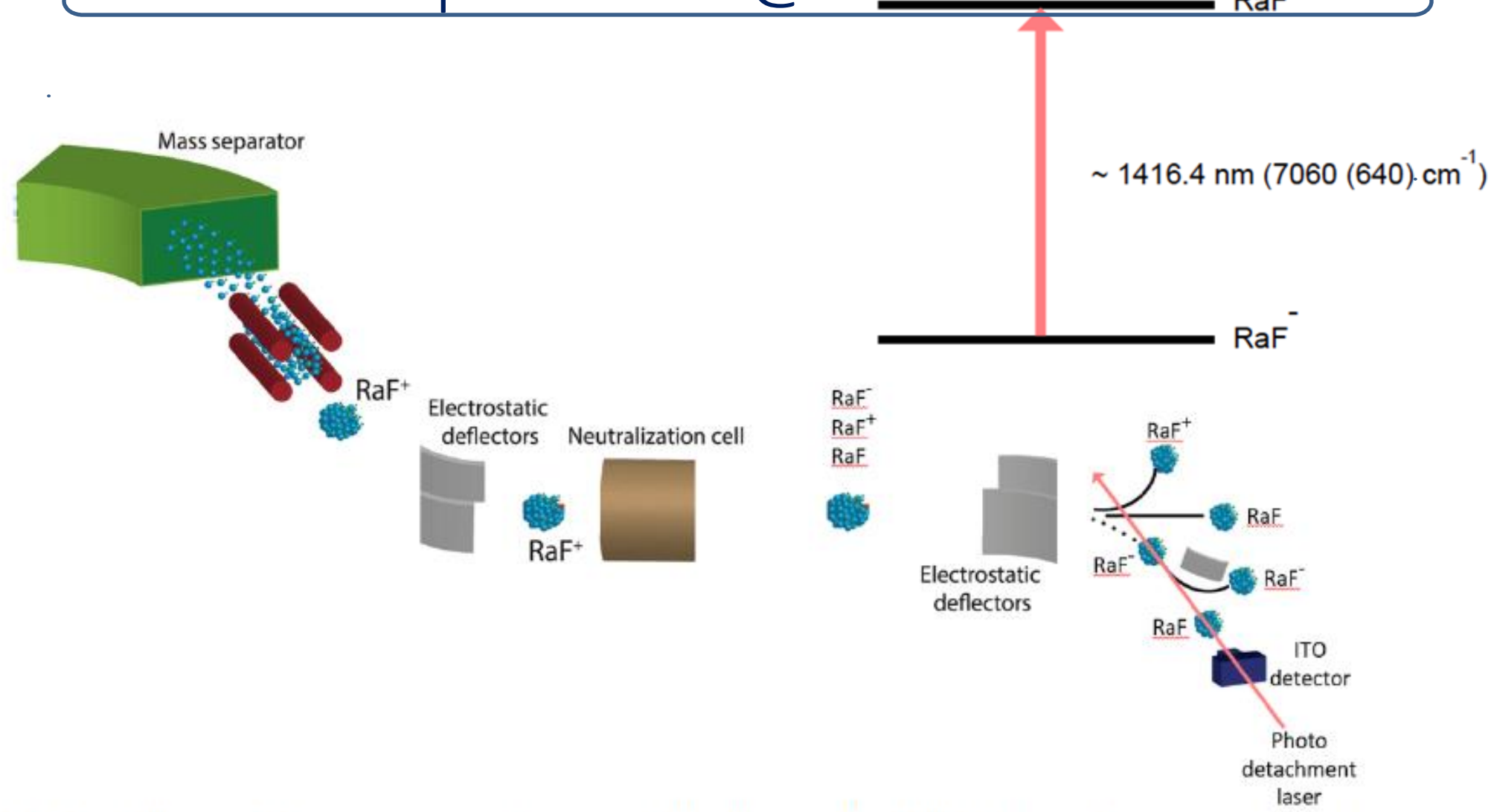


Fig 2. Schematic for anion production and colinear photodetachment measurements.

RaF^- Experiment @ CRIS-CERN

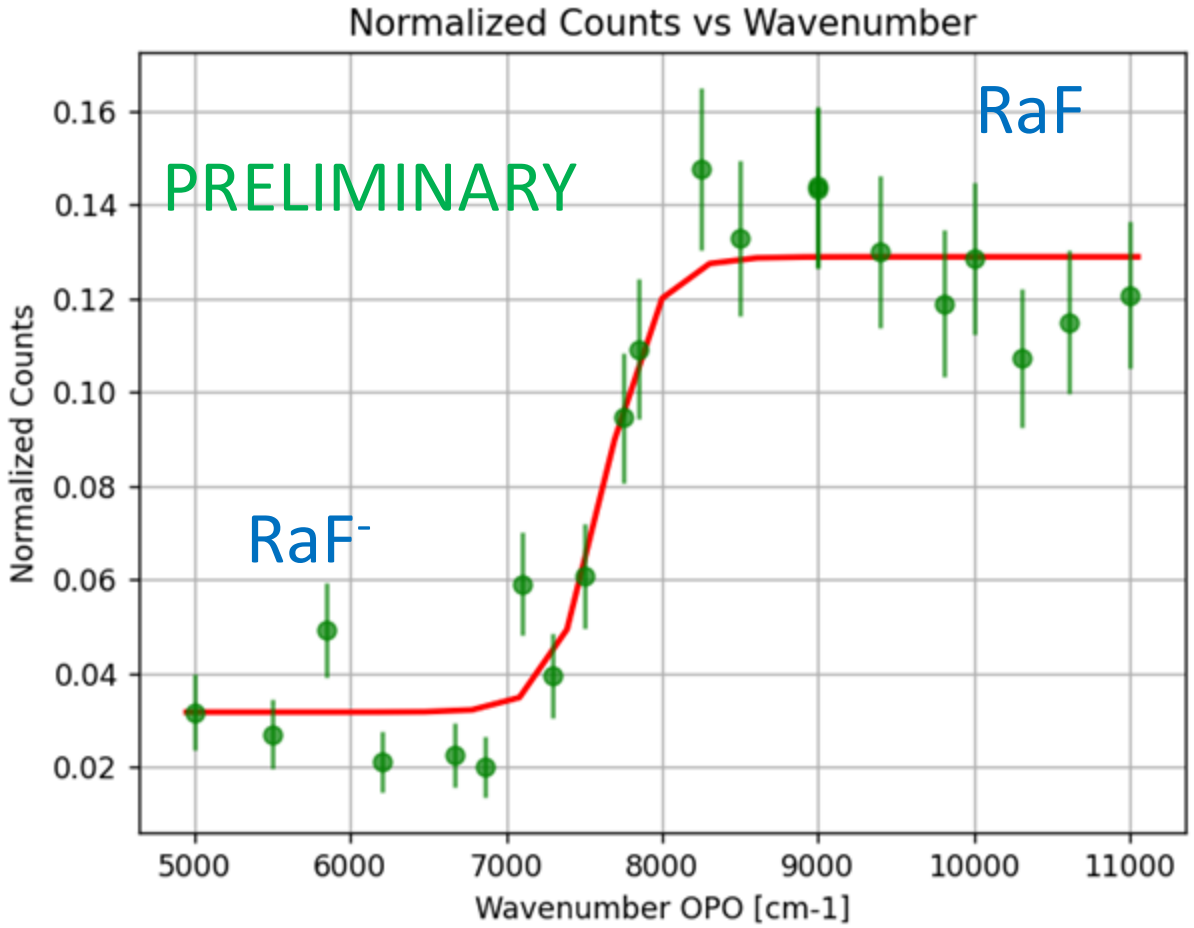
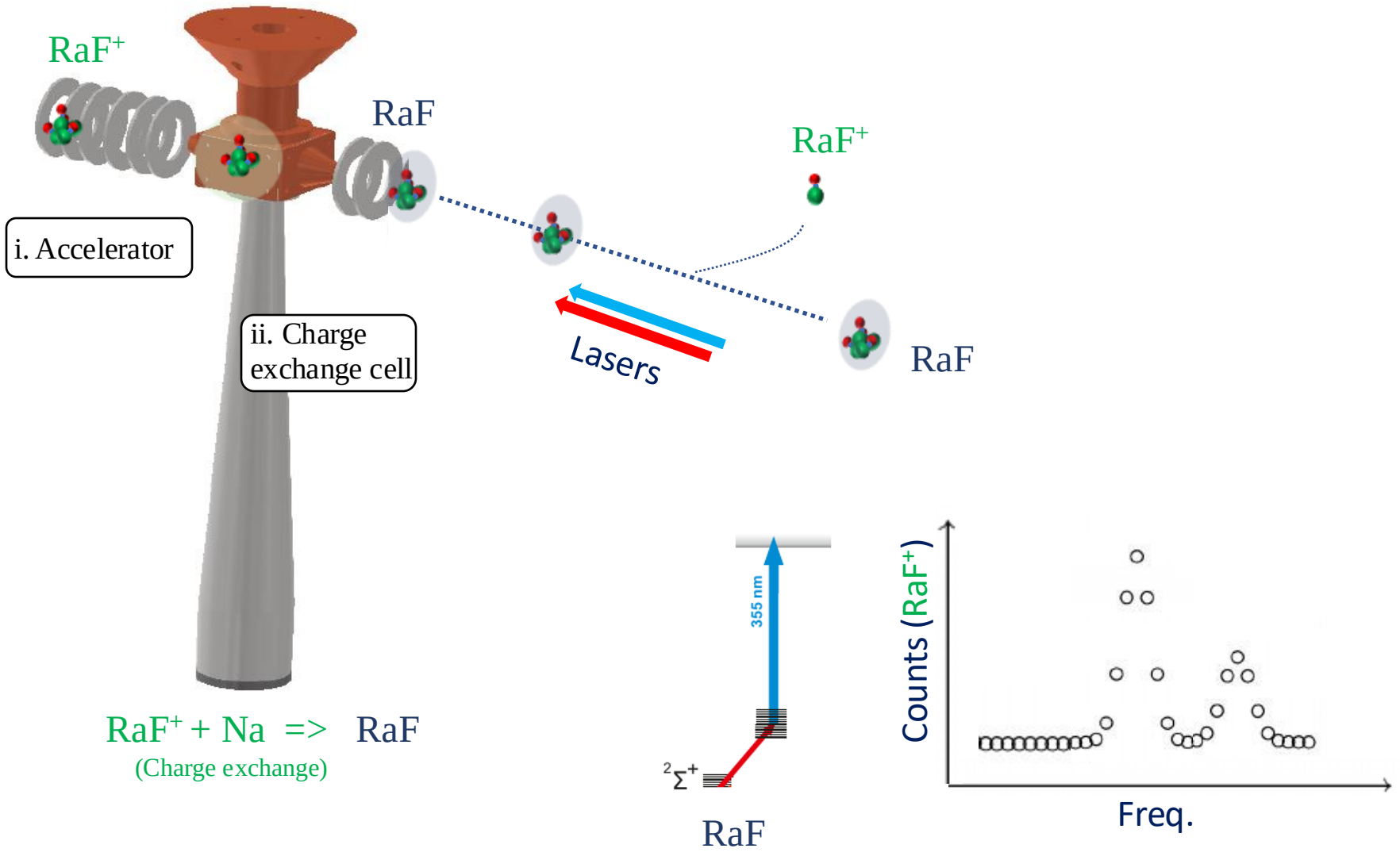


Table I. Dissociation wavenumbers $\tilde{D}_e$, adiabatic photoelectron detachment wavenumbers (ADW), equilibrium bond length r_e and harmonic vibrational wavenumber $\tilde{\omega}_e$ of MF^- computed at the level of RECP-CCSD(T)

Molecule	$\tilde{D}_e/cm^{-1}$	ADW/cm^{-1}	$r_e/Å$	$\tilde{\omega}_e/cm^{-1}$
BeF^-	28 700	8590	1.42	1060
MgF^-	21 600	10 800	1.82	577
CaF^-	26 200	8300	2.01	516
SrF^-	25 000	7950	2.15	434
BaF^-	26 800	6770	2.27	439
RaF^-	23 600	7210	2.36	401

Gaul, Garcia Ruiz, Berger. arXiv:2403.09320 (2024)

Symmetry-violating measurements with RaF



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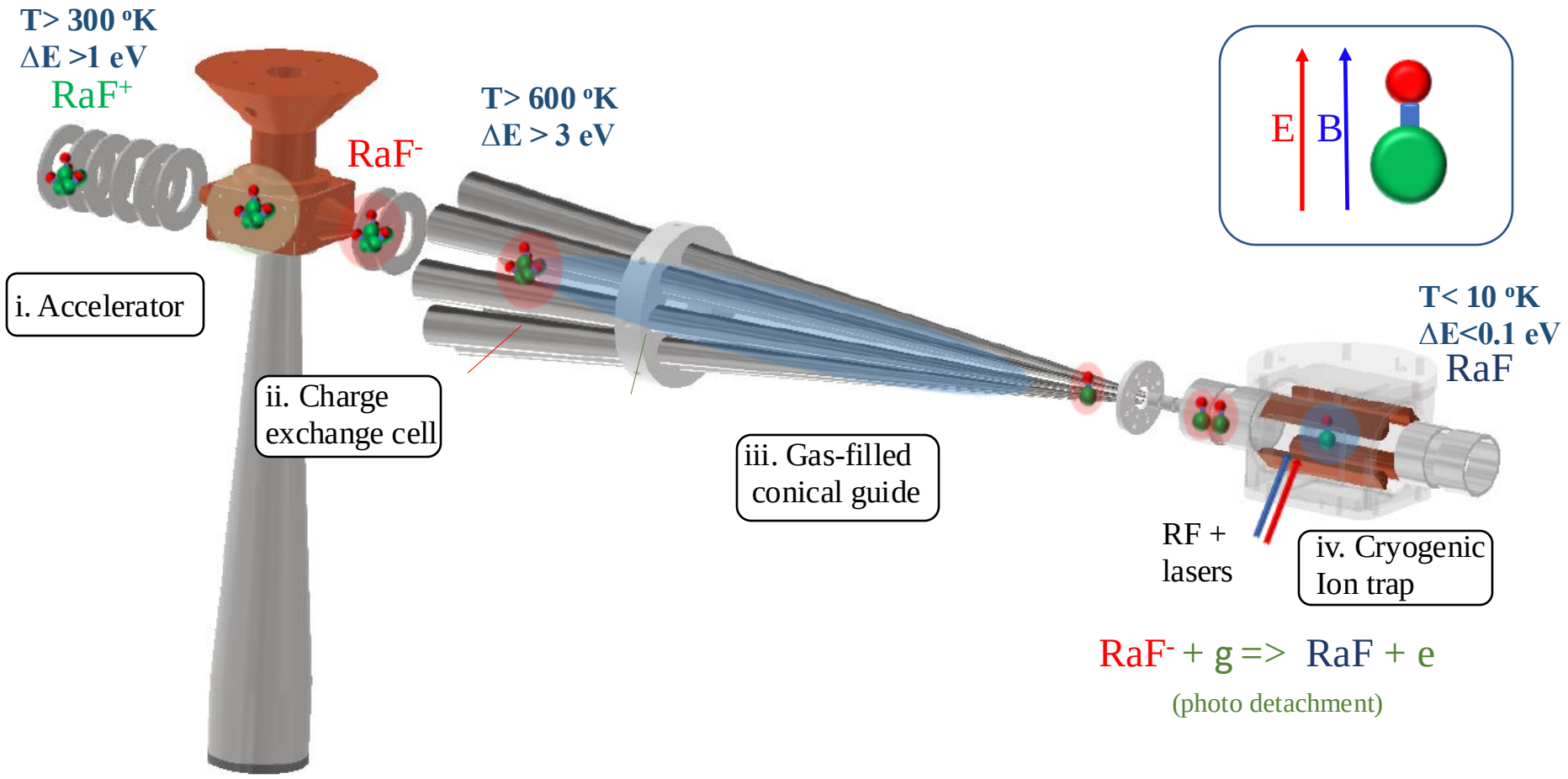


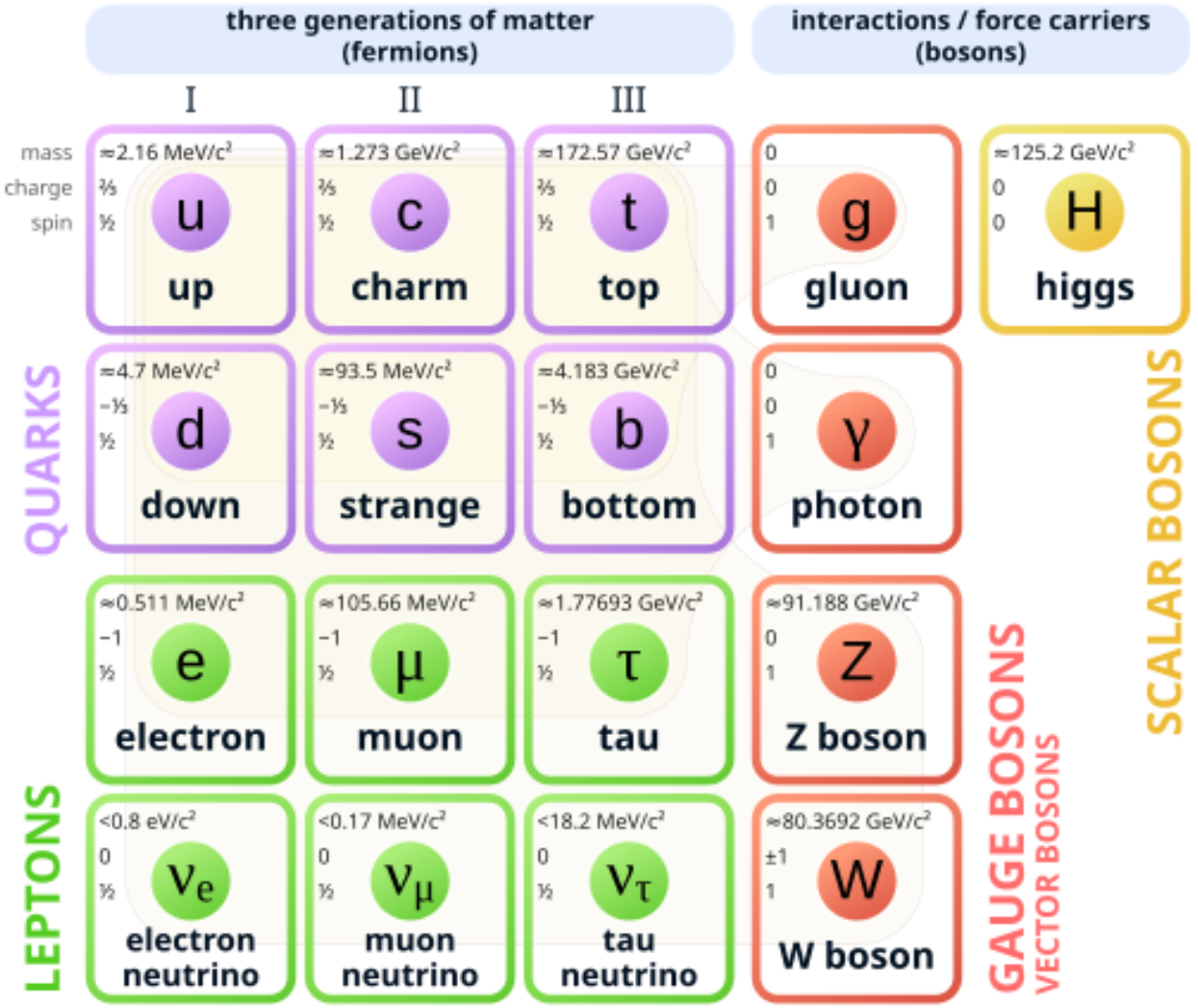
$RaF^+ + 2(Na) \Rightarrow RaF^- + 2(Na^+)$

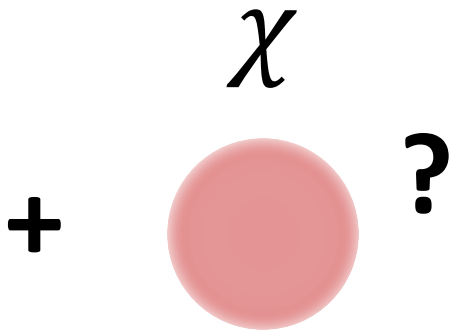
(Charge exchange)

$RaF^- + g \Rightarrow RaF + e$

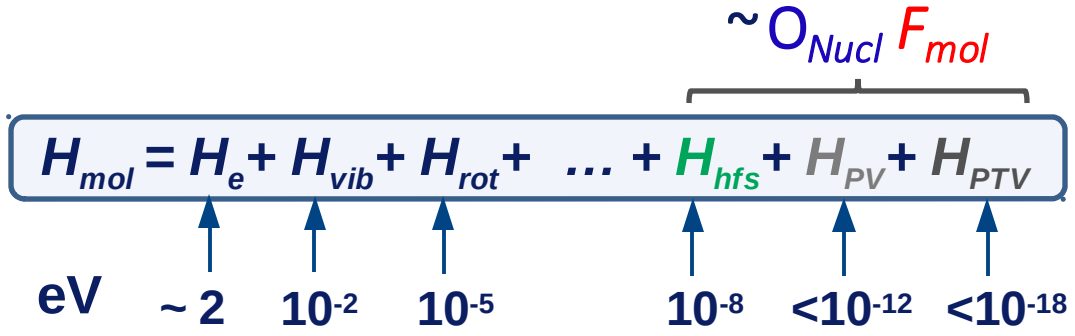
(photo detachment)

What are the fundamental particles and forces of nature?

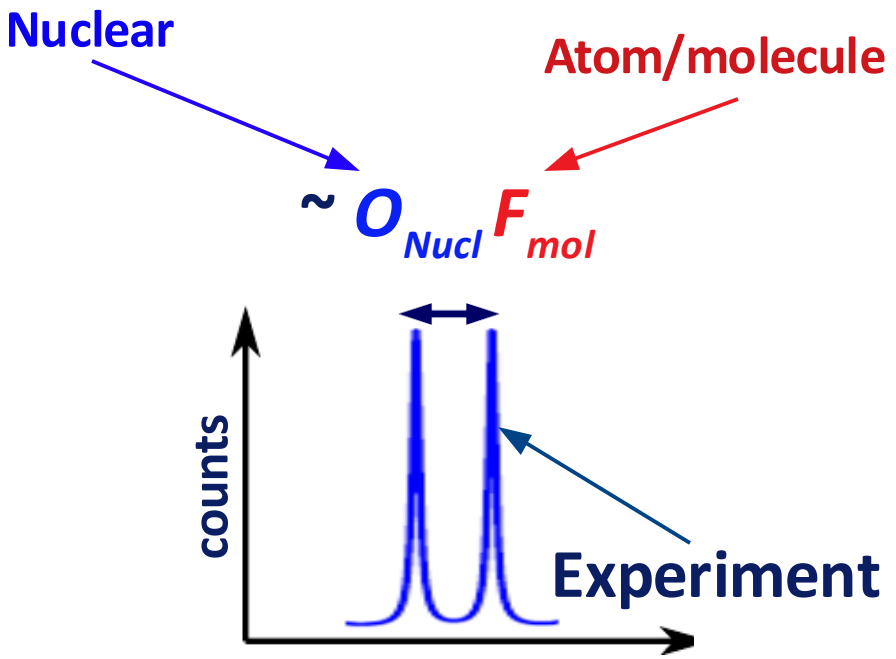




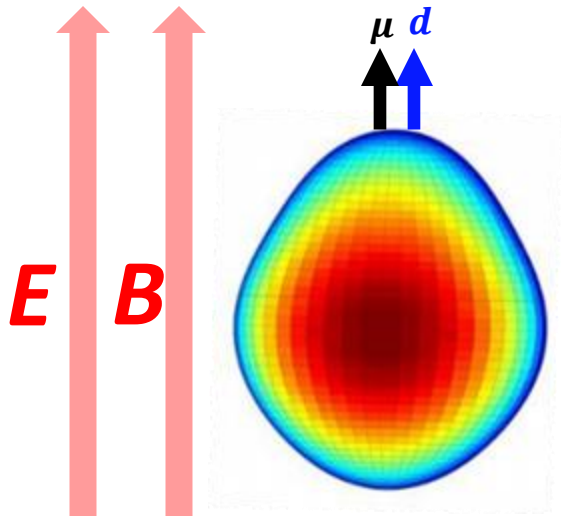
Why radioactive molecules?



$H_{mol} - H'_{mol} \sim O_{Nucl} F_{mol}$ -> Direct measurements!



Electromagnetic properties of a charge distribution



(Produced by the electrons)

Atom/molecule

Nuclear

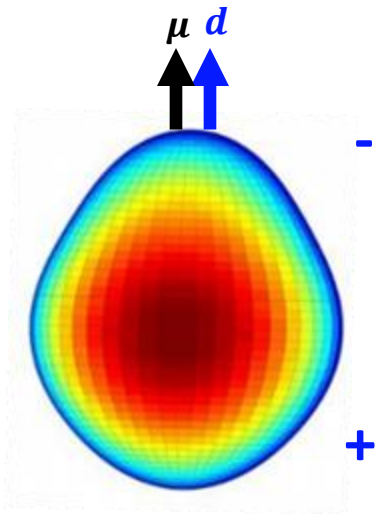
Transient fields in reaction
B ~ 10^3 Tesla
∇E ~ 10^{21} V/cm^2

Atom
B ~ 3 Tesla
∇E ~ 10^{18} V/cm^2

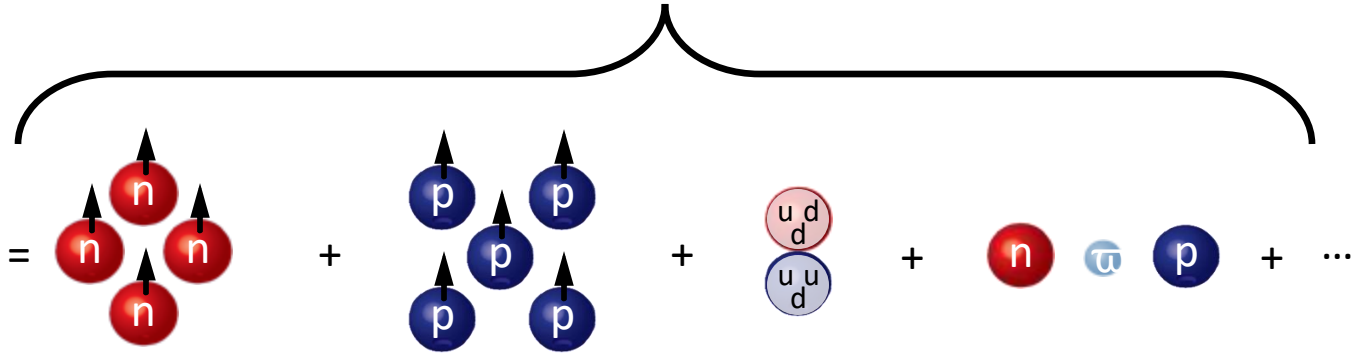
Violate Parity and Time reversal

$$H_{sym} = \ldots + c^{1}_{(I,J)}\, \mu.B + c^{1'}_{(I,J)}\, d.E_{eff} + c^{2}_{(I,J)}\, Q.\nabla E + c^{2'}_{(I,J)}\, Q_m.\, \nabla B + \ldots$$

Nuclei as a Rich Source of CP Violation



Nucleus



Neutron EDM

Proton EDM

Quark EDM

Nucleon-nucleon interactions

Why radioactive atoms & molecules?

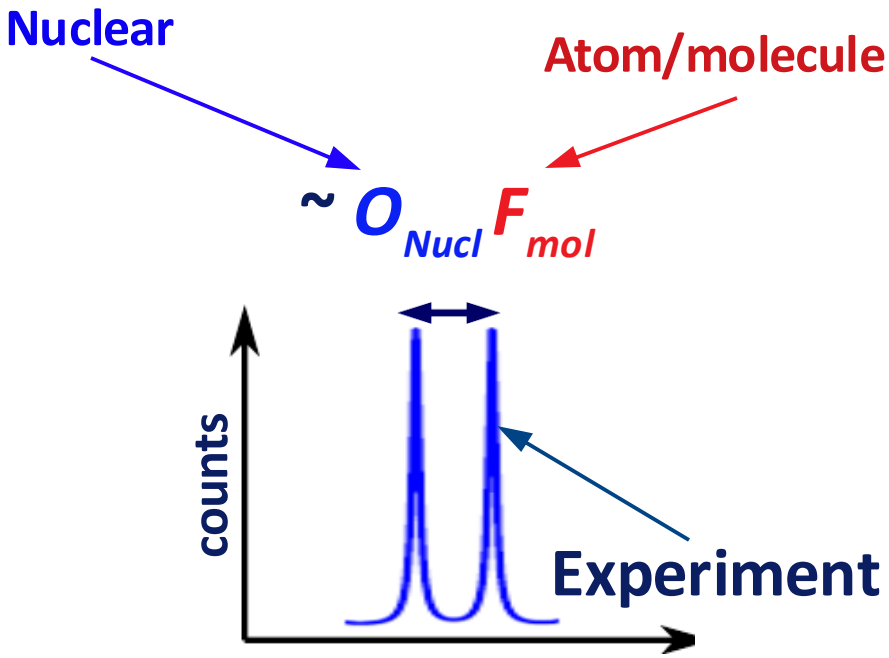
$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

$\sim O_{Nucl}\, F_{mol}$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

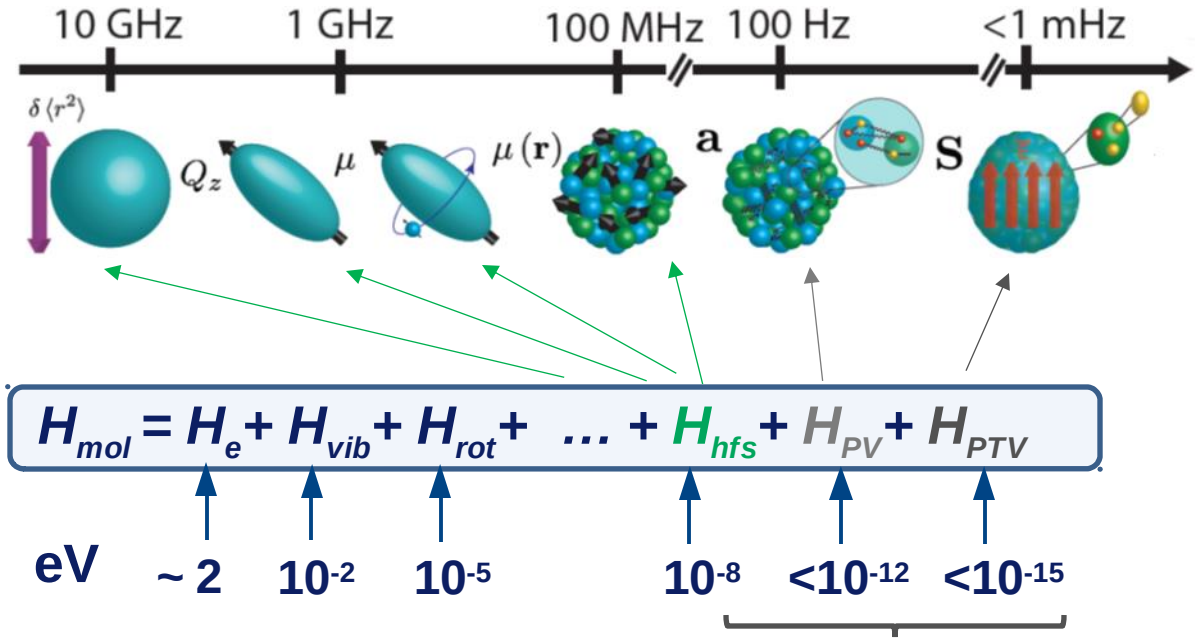
$$H_{mol} - H'_{mol} \sim O_{Nucl}\, F_{mol}$$

-> Direct measurements!



Why (Radioactive) Molecules?

Heavy exotic
Nuclei Ra(Z=88)



[1 eV=241.8 THz]

$\sim O_{Nucl}\, E_{mol}$

Nuclear

$\sim Z^3 A^{1/3} \beta_2 \beta_3^2 / (E^N_+ - E^N_-)$

Molecule

$\sim Z^3 / (E^e_+ - E^e_-)$

Electric field ~ 100 GV/cm

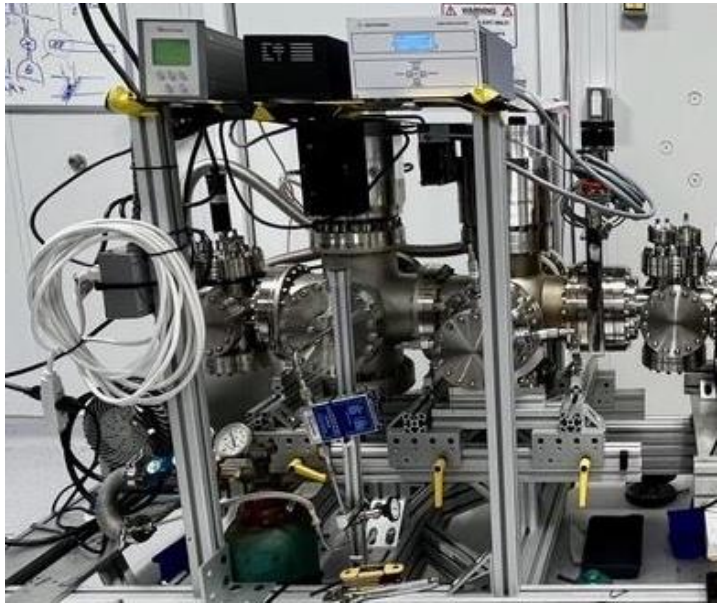
[Sandars Phys. Rev. Lett. 18, 1396 (1967)]
[ACME, Nature 562, 355 (2018)]
[Roussy et al. Science 381, 46 (2023)]

Radioactive molecules => Best of all worlds!

Molecules as sensitive probes of electroweak nuclear properties

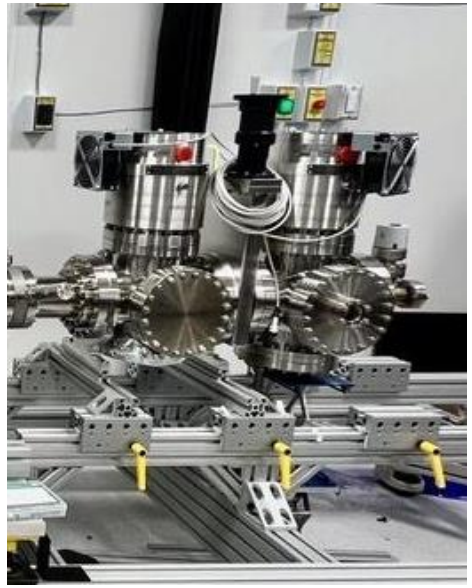
Setup @ MIT

~3 m

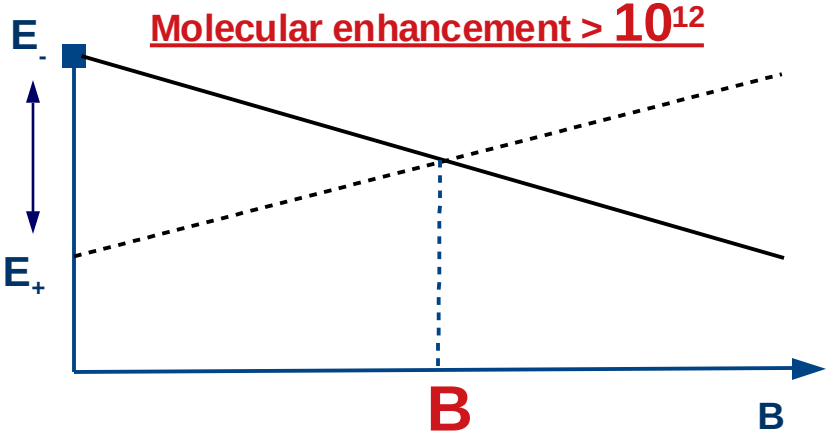


Paul trap

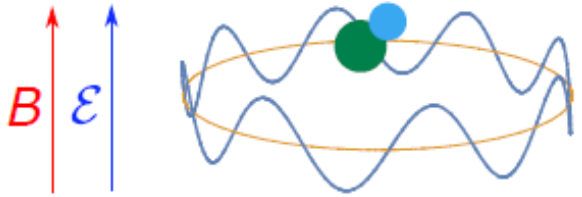
Penning trap



Ion source

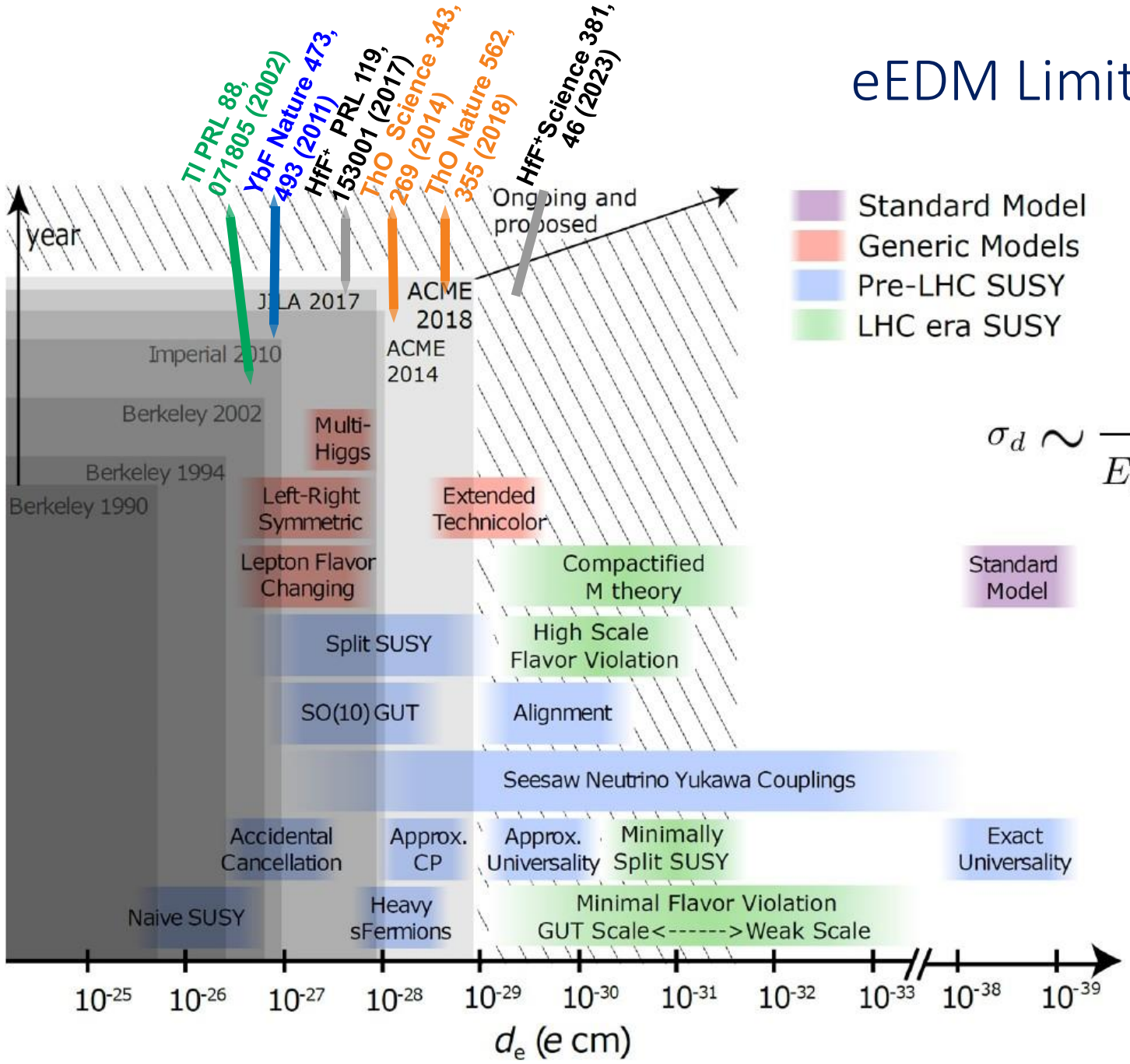


Inside Penning trap

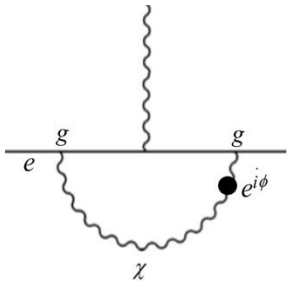


[*Kartehin, Udrescu, Moroch et al.* Under review in *Physical Review Letters* (arXiv:2310.11192) (2023)]

eEDM Limits



$$\sigma_d \sim \frac{1}{E_{\text{eff}}\tau\sqrt{\dot{N}T}}$$

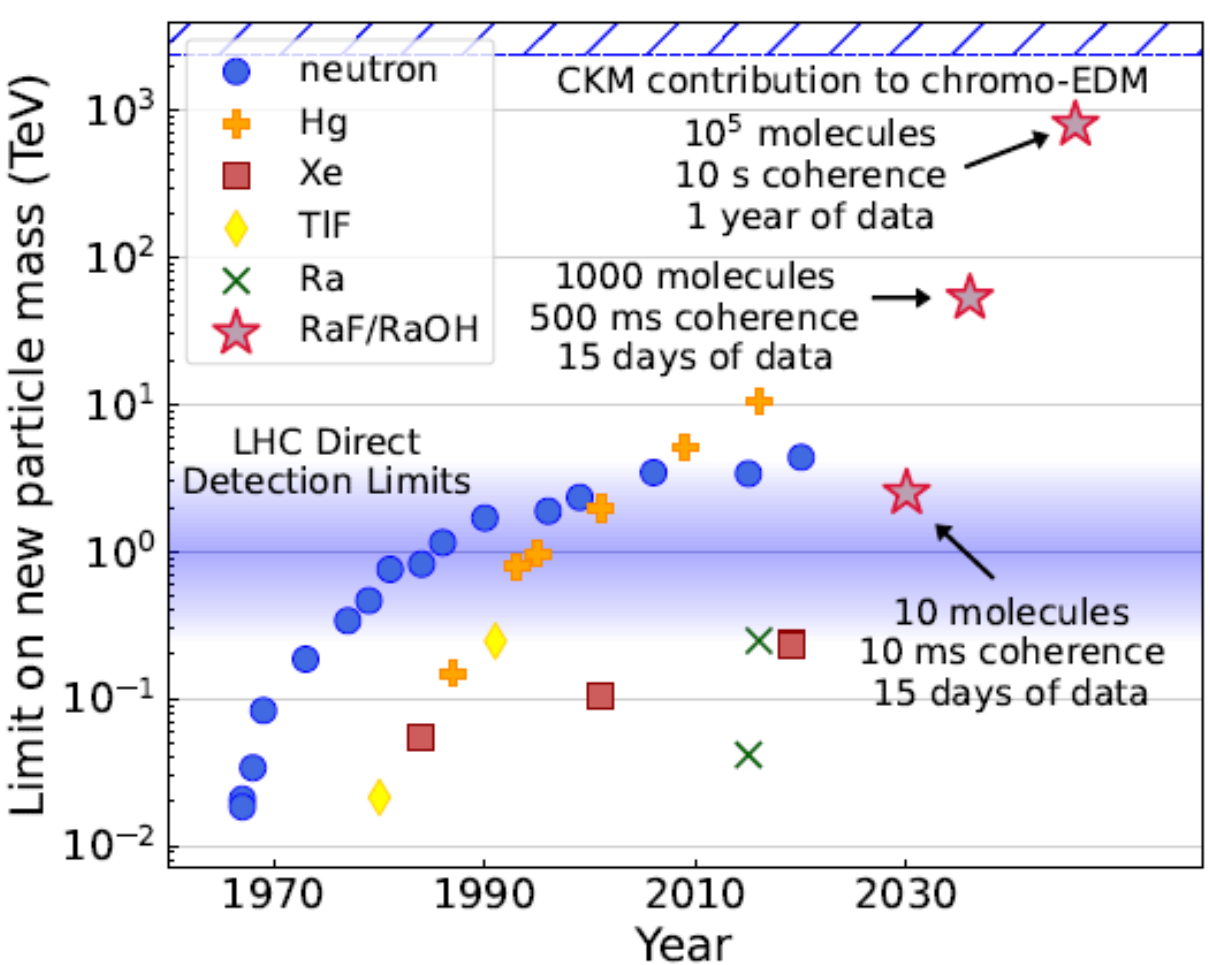


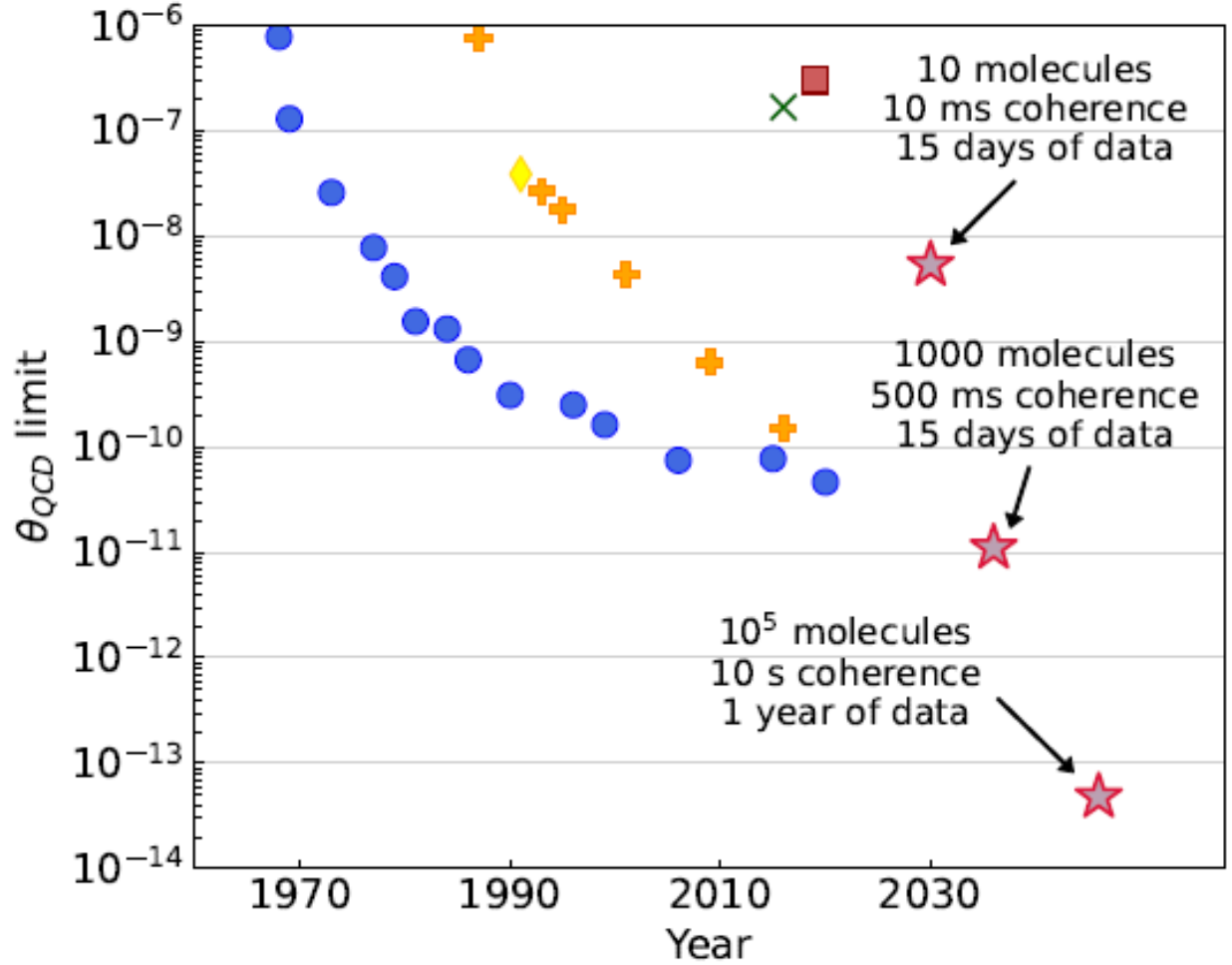
$$d_e \sim \mu_B \left(\frac{g^2}{2\pi}\right)^N \left(\frac{m_e}{m_\chi}\right)^2 \sin\phi$$

Probing physics @ TeV scale!

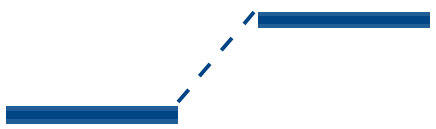
[Source: D. DeMille. Manipulating Quantum Systems: An Assessment of Atomic,Molecular, and Optical Physics in the United States (2019)]

Hadronic EDM Limits



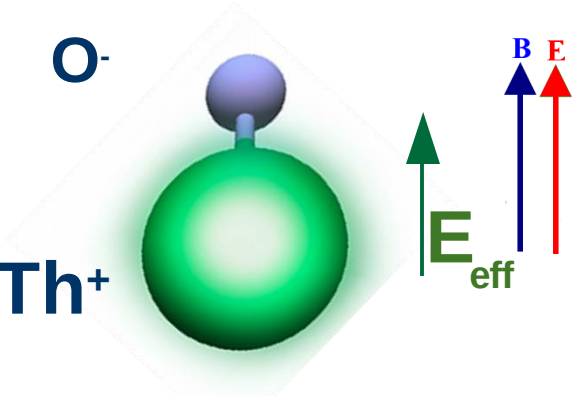


Molecules for studies of P, T violation



~d E_{eff}

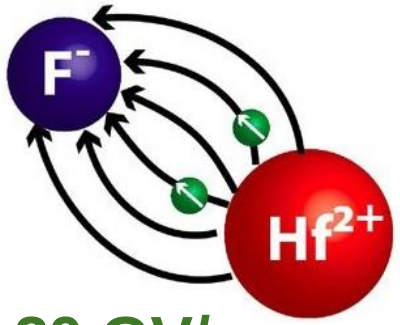
(< 10 μHz)



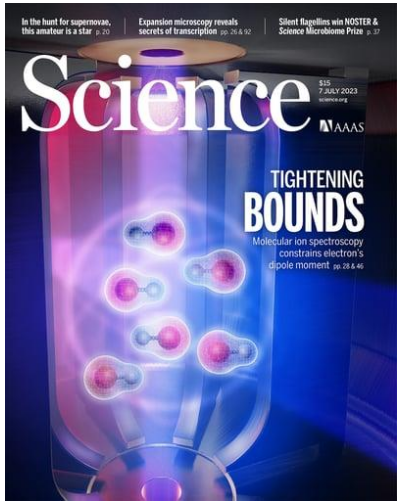
E_{ext} ~1-10 V/cm

E_{eff}~80 GV/cm

[ACME, Nature 562, 355 (2018)]



E_{eff}~20 GV/cm

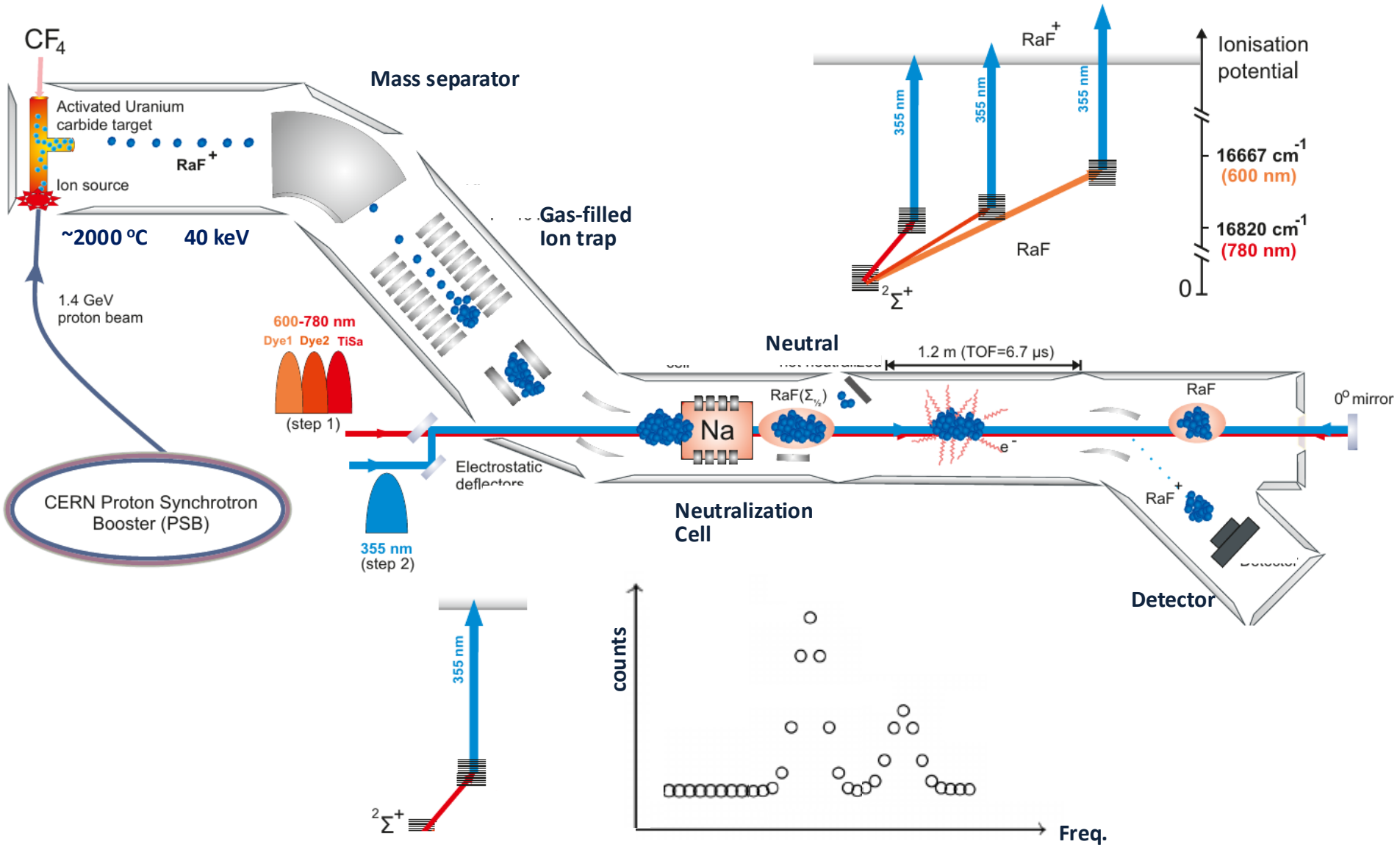


$|d_e| \leq 4.1 \times 10^{-30}$ e · cm

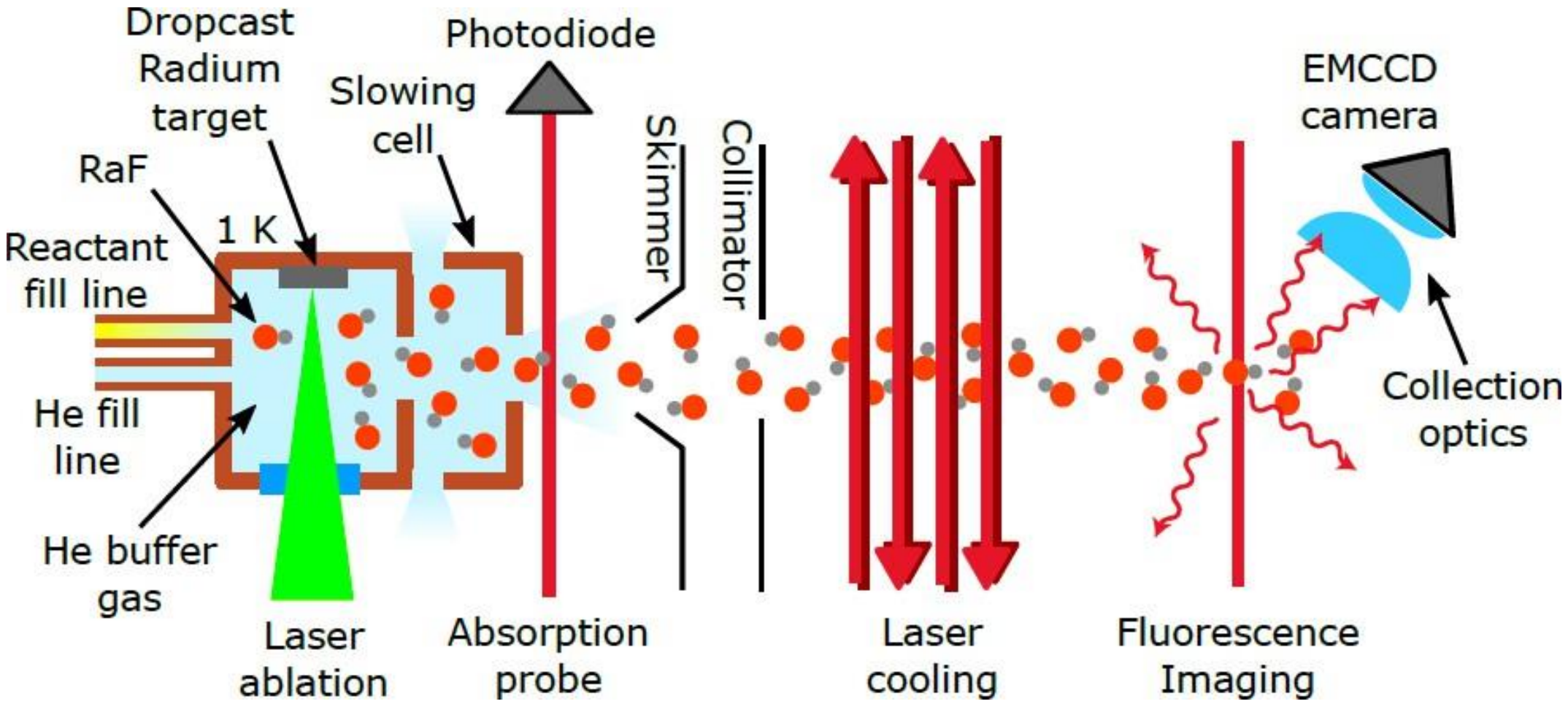
[Roussy et al. Science 381, 46 (2023)]

[Baron et al. Science 343, 269 (2014)]
[Sandars Phys. Rev. Lett. 18, 1396 (1967)]

Recent Results (RaF)



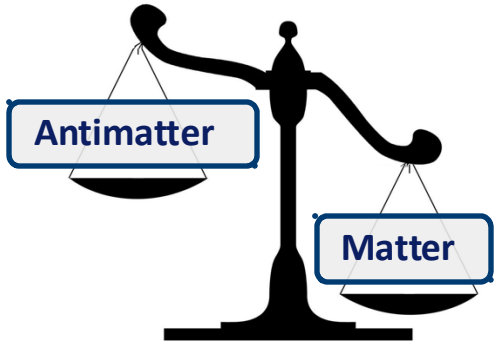
Laser Cooling of RaX Molecules



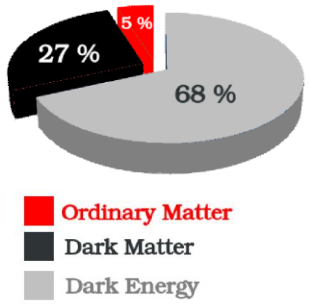
In Collaboration with J. Doyle (Harvard) & N. Hutzler (Caltech)

Major Open Questions in Physics and Cosmology

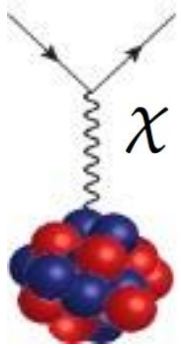
Why is there more matter?



What is Dark Matter?



Are there new particles?

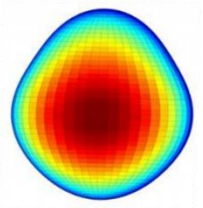


Strong CP problem

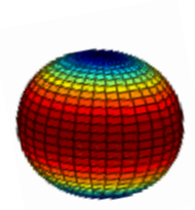
$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$

New sources of Time-reversal (CP) violation in nuclei can solve all of these problems

Time-reversal violation ⇄ **Electric Dipole Moment (EDM) Of fundamental particles**



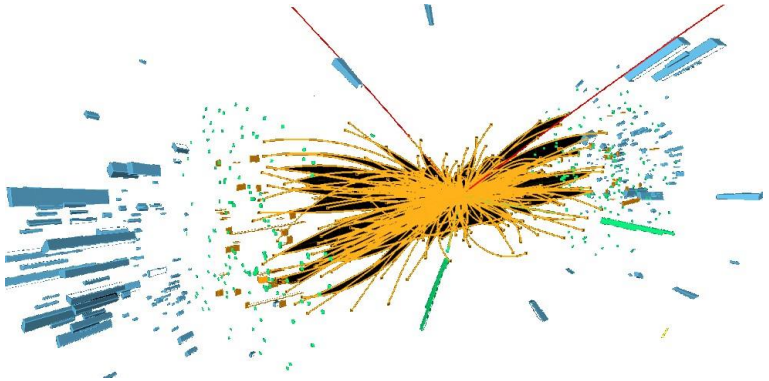
EDM > 0



EDM=0

Major Open Questions in Physics and Cosmology

Energy frontier



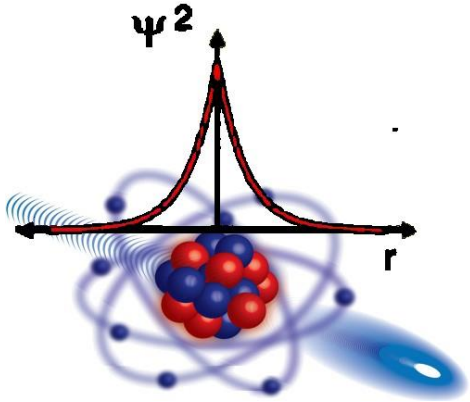
TeV <10^{-14}

GeV 10^{-9}

MeV 10^{-6}

eV 10^{0}

Precision frontier



Recent Results (RaF)

nature

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Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz, R. Berger, [...]

Nature **581**, 396–400 (2020) | Cite this article

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Spectroscopy of molecules with unstable nuclei

Pinning down the energy transitions of radium monofluoride, and eventually other short-lived molecules, could reveal the ways they are influenced by the properties of heavy radioactive nuclei.

Andrew Grant

CHEMISTRY WORLD

Molecular experiments hope to reveal new physics

BY ANDY EXTANCE | 5 JUNE 2020

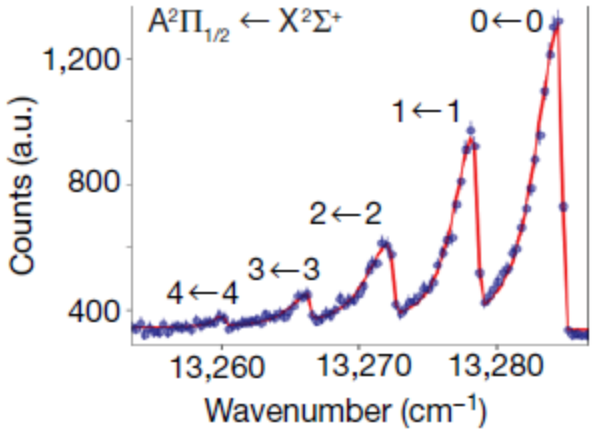
Detecting extremely short-lived radium fluoride can explore standard model's limits

physicsworld

ATOMIC AND MOLECULAR | RESEARCH UPDATE

Exotic radioactive molecules could reveal physics beyond the Standard Model

05 Jun 2020

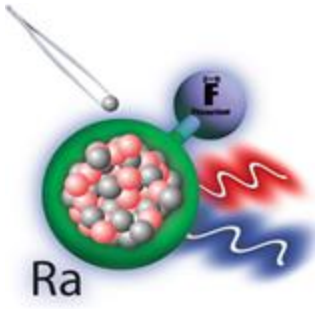


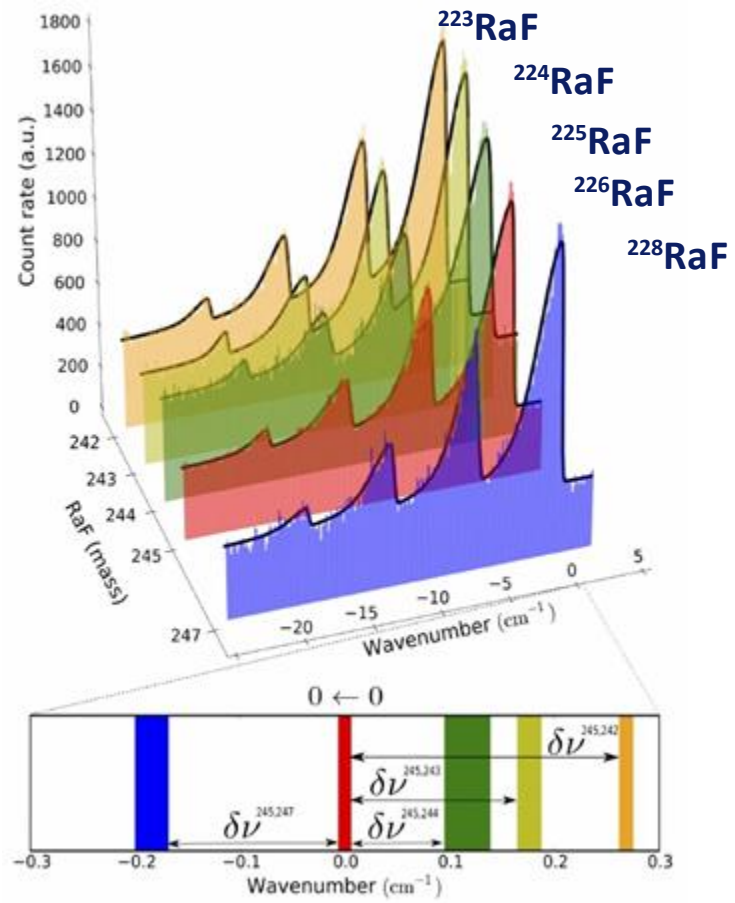
Nature 581, 396 (2020)

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

Recent Results (RaF)





Nature 581, 396 (2020)
PRL 127, 033001 (2021)

$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

Recent Results (RaF)

nature physics

nature > nature physics > articles > article

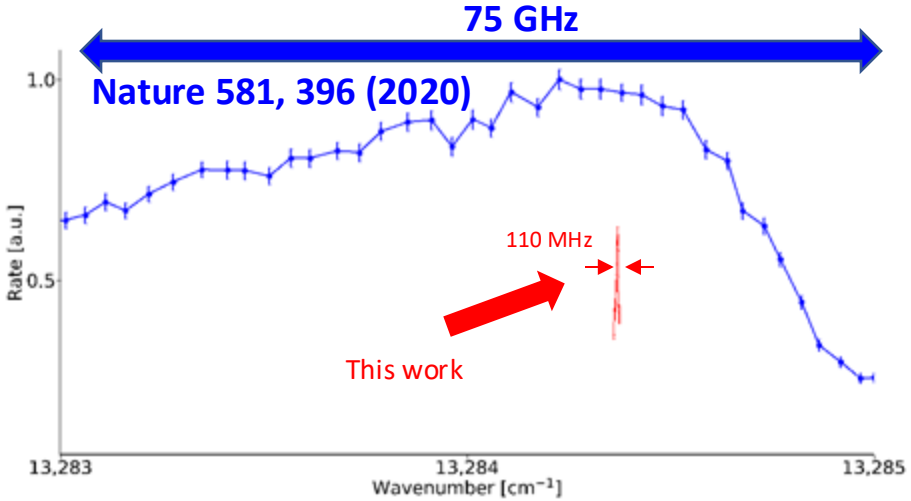
Article | Published: 09 January 2024

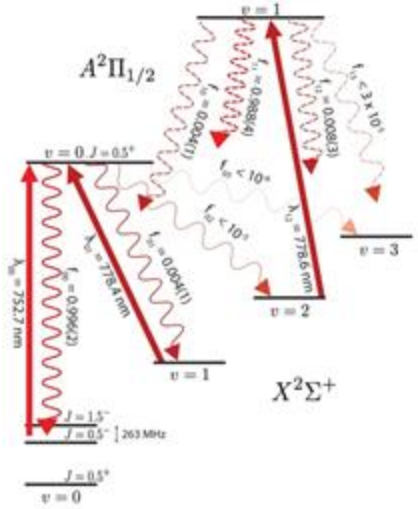
Precision spectroscopy and laser-cooling scheme of a radium-containing molecule

S. M. Udrescu, S. G. Wilkins, A. A. Breier, M. Athanasakis-Kaklamanakis, R. F. Garcia Ruiz, M. Au, I.

+ Show authors

Nature Physics **20**, 202–207 (2024) | Cite this article





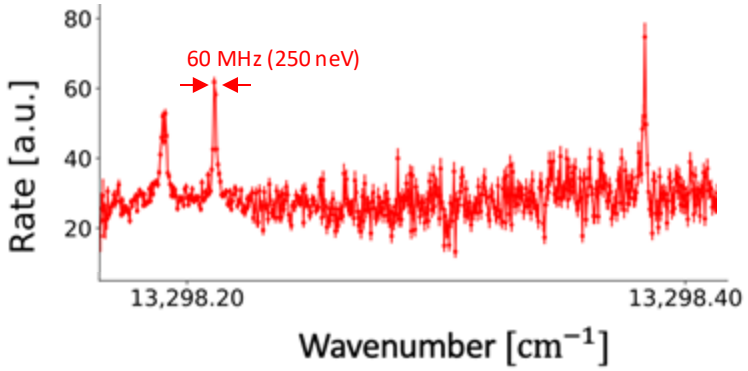
Nature 581, 396 (2020)
PRL 127, 033001 (2021)
Nature Phys 20, 202 (2024)

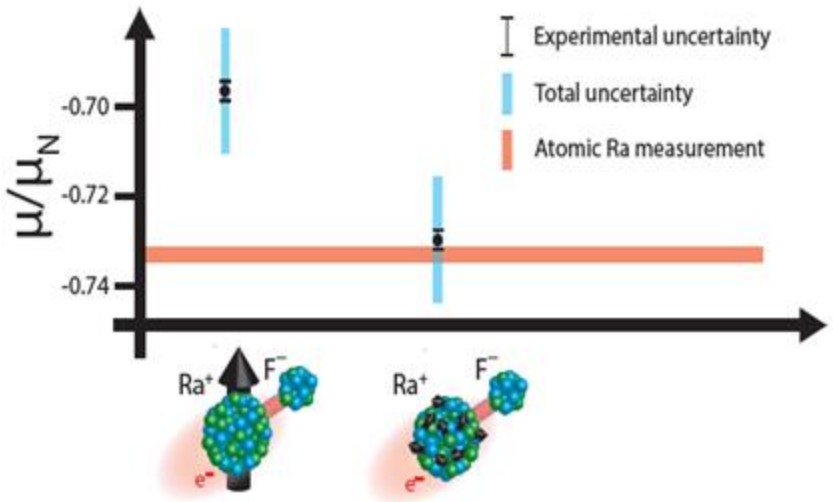
$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$

eV	~ 2	10^{-2}	10^{-5}	10^{-8}	$<10^{-12}$	$<10^{-18}$

Recent Results (RaF)

^{225}RaF hyperfine spectrum





$$\int B_e \, d\mu \neq \mu B_e$$

Nature 581, 396 (2020)
PRL 127, 033001 (2021)
Nature Phys 20, 202 (2024)
(2024) Science

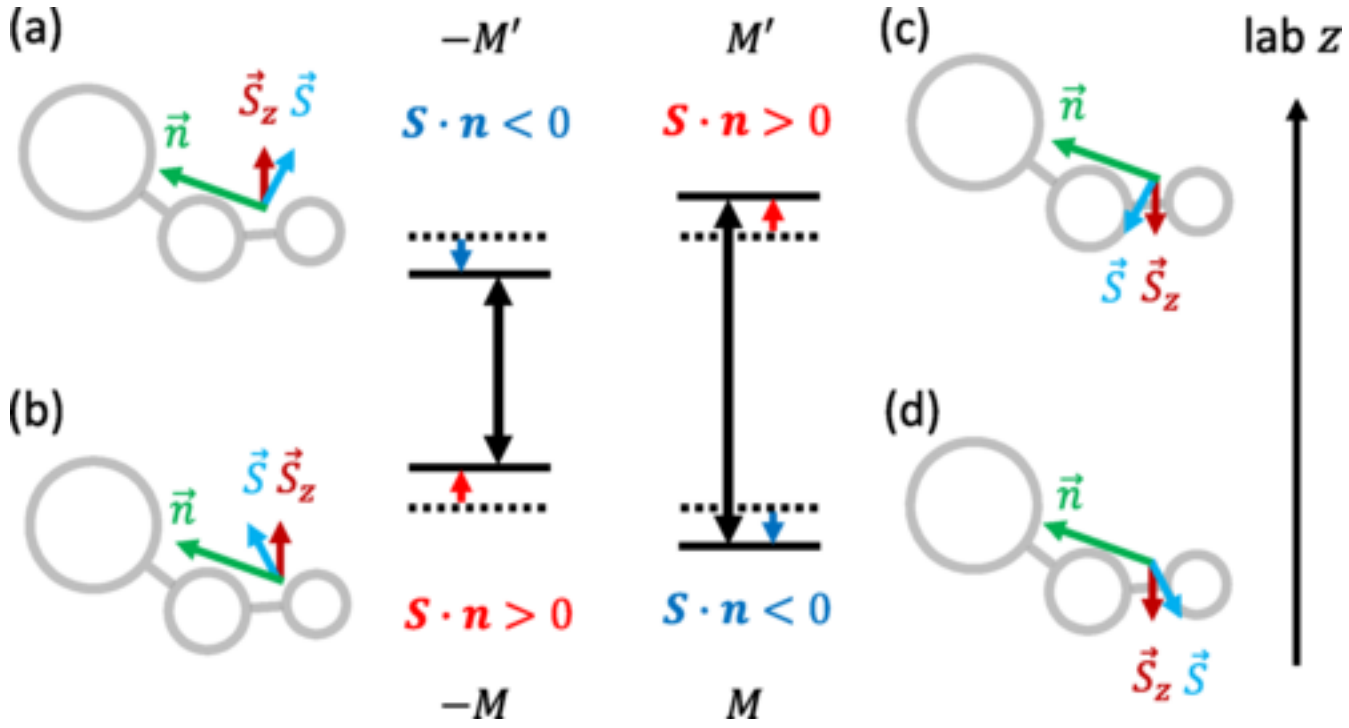
$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

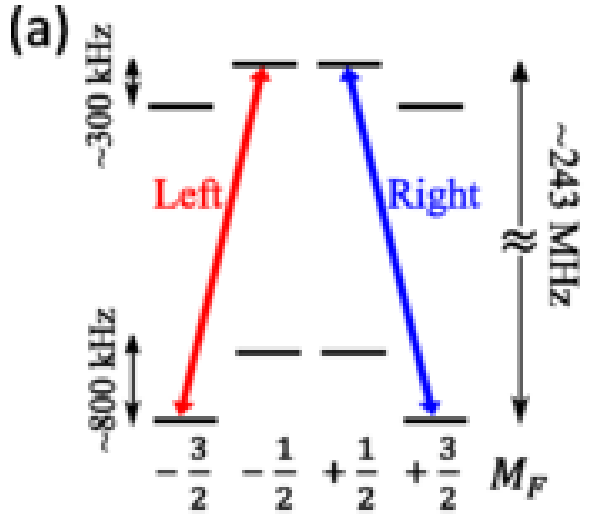
eV ~ 2 10^{-2} 10^{-5} 10^{-8} $<10^{-12}$ $<10^{-18}$

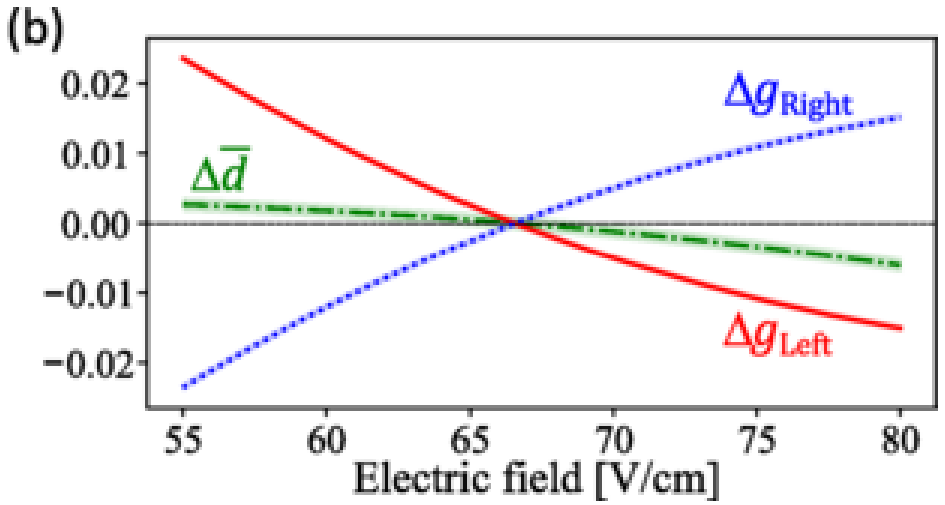
[Wilkins, Udrescu et al. arxiv:2311.04121 (2024)]

Engineering field-insensitive molecular clock transitions for symmetry violation searches

Takahashi, Zhang, Jadbabaie, Hutzler [Phys. Rev. Lett. 131, 183003 (2023)]

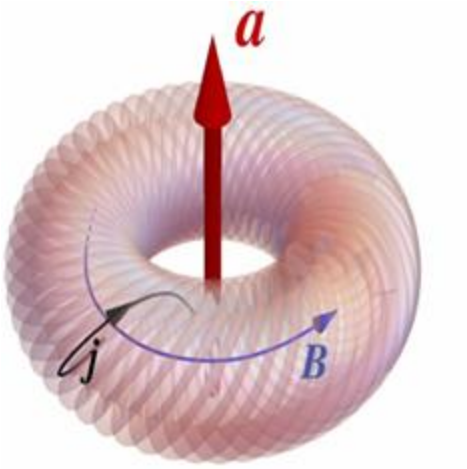






$$H = -Dn \cdot E - g\mu_B S \cdot B + W_d d_e S \cdot n + W_Q \frac{Q}{I} I \cdot n - W_M \frac{M}{2I(2I-1)} S \hat{T} n.$$

Nuclear Anapole Moment



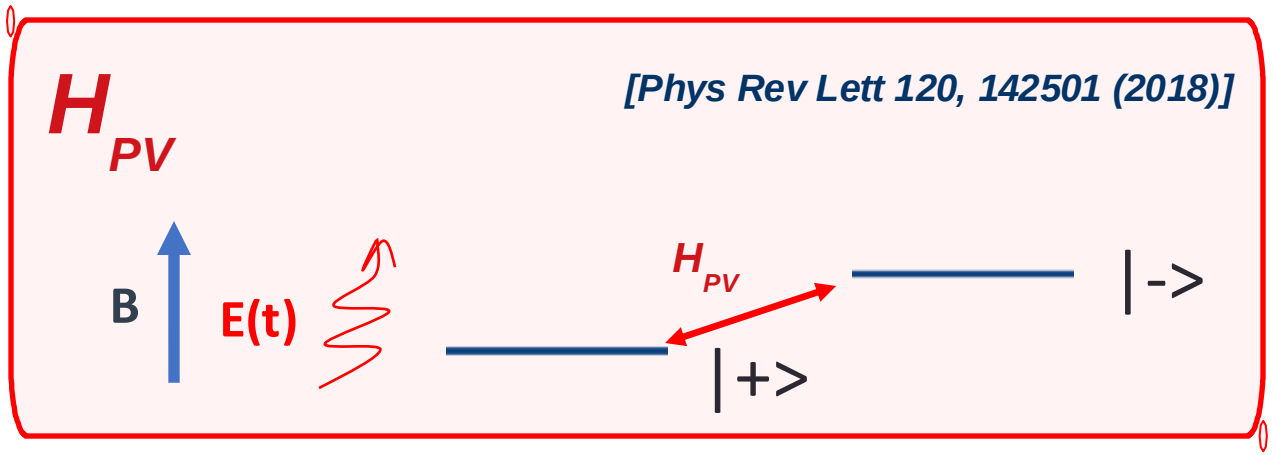
$$\sigma_d \sim \frac{1}{E_{\text{eff}}\tau\sqrt{\dot{N}T}}$$

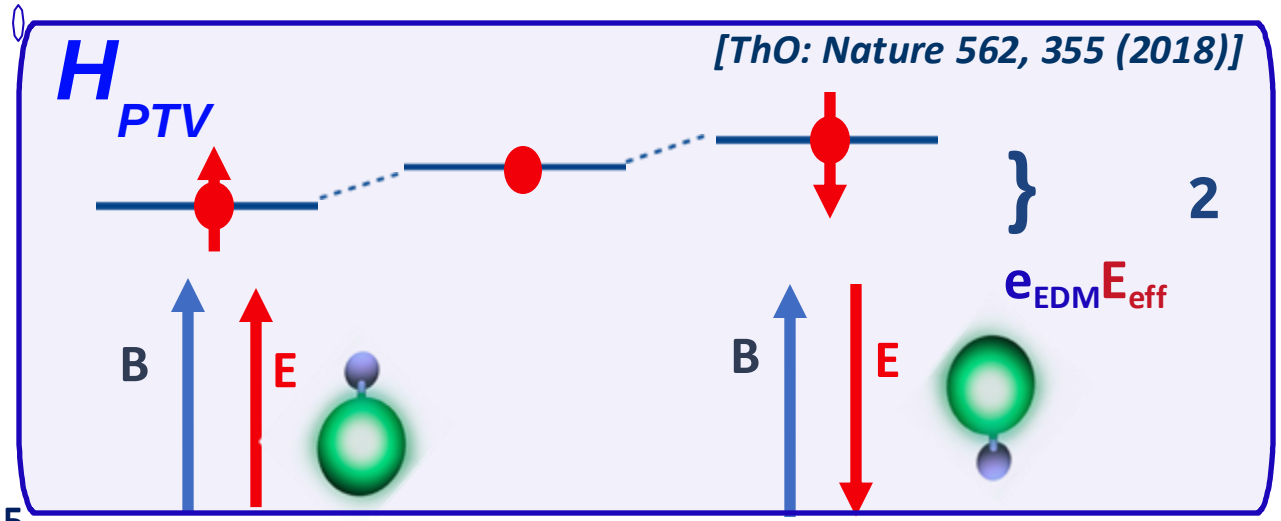
[Desplanques, Donoghue, Holstein et a. Ann. Phys. 124, 449495 (1980)]

Can we achieve efficient cooling & trapping?

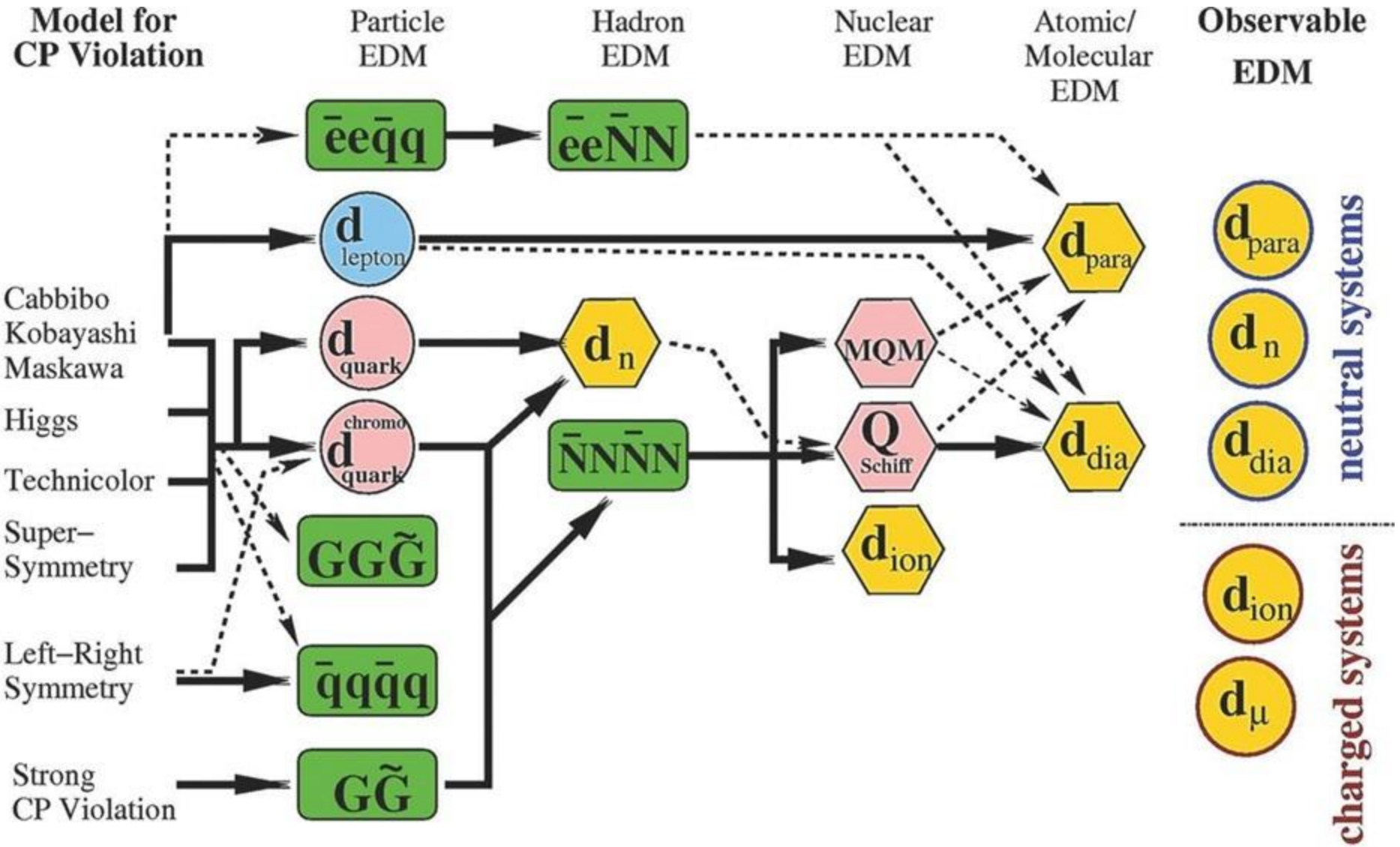
$$H_{mol} = H_e + H_{vib} + H_{rot} + \ldots + H_{hfs} + H_{PV} + H_{PTV}$$

?





[HfF⁺: PRL 119, 153001 (2017)]



[Jungmann et al. Ann. Phys. 525, 550 (2013)]

Why radioactive nuclei?

Schiff Moments

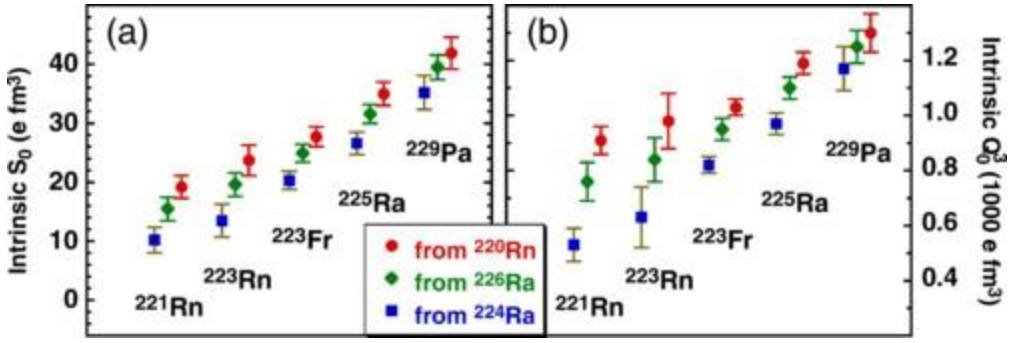
$$S = \langle \Psi_0 | S_z | \Psi_0 \rangle = \frac{\langle \Psi_+ | S_z | \Psi_- \rangle \langle \Psi_+ | V_{PT} | \Psi_- \rangle}{E_+ - E_-}$$

P,T-odd nucleon-nucleon interaction

Nuclear structure

Theory + Experiment

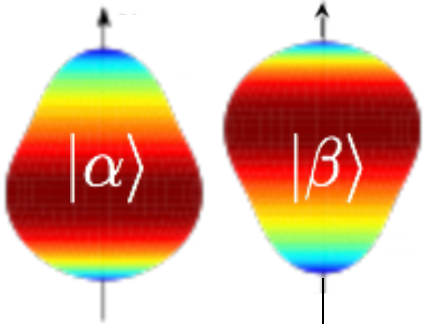
Experiment



Dobaczewski et al. Phys. Rev. Lett. **121**, 232501 (2018)
Chupp et al. Rev. Mod. Phys. **91**, 015001 (2019)

$$\hat{S}_0 = \frac{e}{10}\sqrt{\frac{4\pi}{3}}\sum_i \left(r_i^3 - \frac{5}{3}\overline{r_{\rm ch}^2} r_i\right) Y_0^1(\Omega_i) + \dots .$$

DE: Energy splitting of opposite parity states

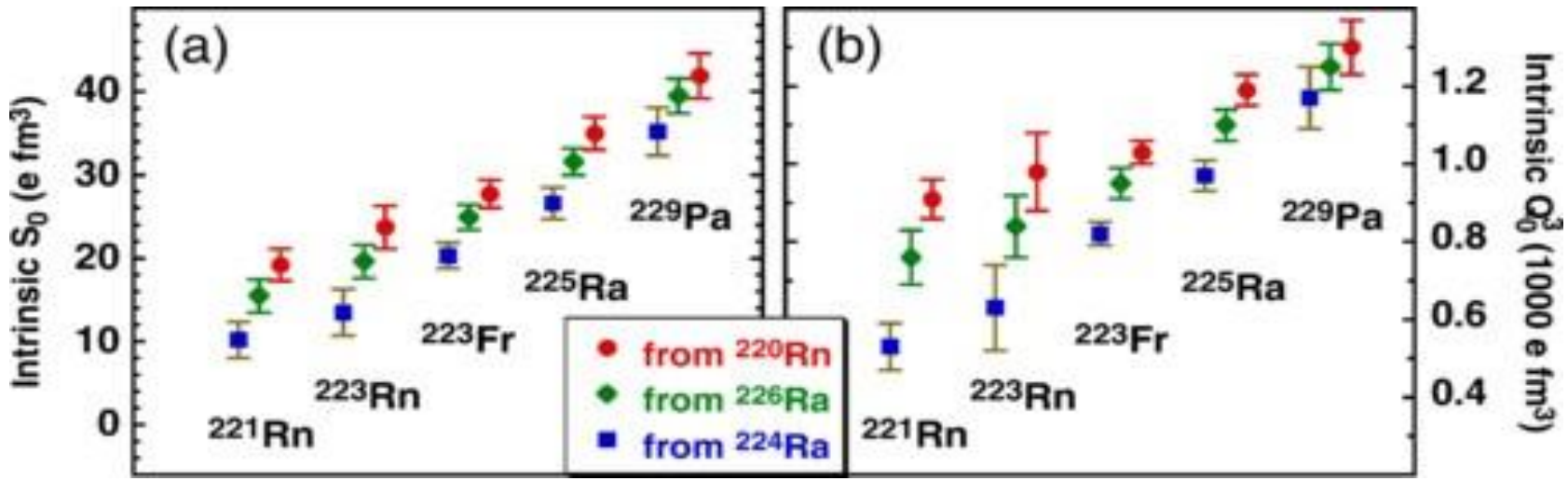


^{225}Ra

DE = 55 keV

Slide from L. Gaffney

[Gaffney et al. Nature 497, 199 (2013)]



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