Study of RaF^- anions at CRIS

Ronald Fernando Garcia Ruiz

MIT

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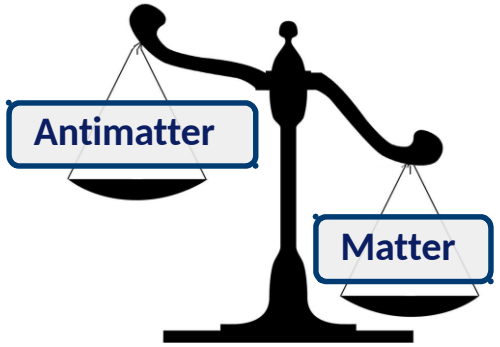
R. F. Garcia Ruiz[1], O. Ahmad [3], M. Au [8], J. Berbalk [3] R. Berger [2], A. Brinson[1], T. E. Cocolios[3], R. P. de Groote[3], S. Ebadi[1], K. T. Flanagan[4] C. Fajardo[3], K. Gaul[2], D. Gonzalez[1], D. Hanstorp[5], P. Imgram[3], A. Jadbabaie[1], J. Karthein [1], Á. Koszorús[3], L. Lalanne[6], S. Moroch[1] J. M. Munoz[1] W. C. Mei[7] G. Neyens[3], M. Nichols[5] F. C. Pastrana Cruz[1], H. Perrett[4], S. Udrescu[1], J. Warbinek[6], S. G. Wilkins[1], X. F. Yang[7], C. Zülch[2],

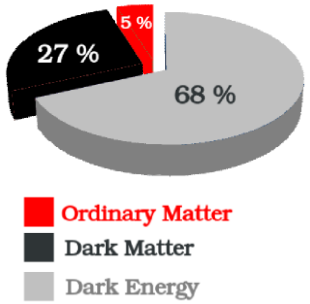
Spokesperson: R. F. Garcia Ruiz [rgarciar@mit.edu]
K. T. Flanagan [kieran.flanagan-2@manchester.ac.uk]
Contact person: Jessica Warbinek [jessica.warbinek@cern.ch]

Major Open Questions in Physics and Cosmology

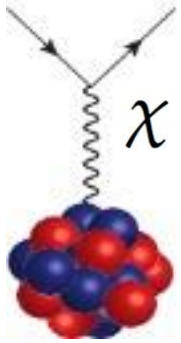
Why is there more matter?



What is Dark Matter?



Are there new particles?

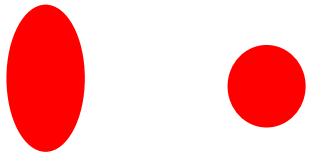


Strong CP problem

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

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

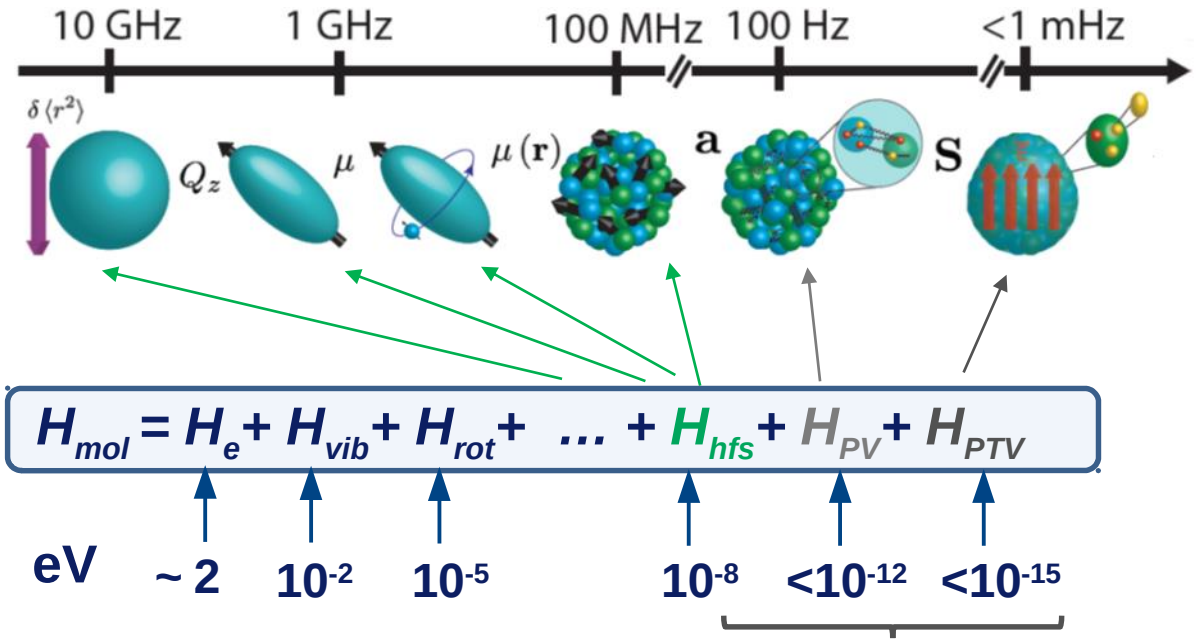
Time-reversal violation ⇄ **Electric Dipole Moment (EDM) Of fundamental particles**



EDM > 0 EDM=0

Why (Radioactive) Molecules?

Heavy exotic
Nuclei Ra(Z=88)



[1 eV=241.8 THz]

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

Nuclear

$\sim Z^a A^b \beta_2 \beta_3^2 / (E^N_+ - E^N_-)$

Molecule

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

Electric field ~ 100 GV/cm

Radioactive molecules => Best of all worlds!

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

Why (Radioactive) Molecules?

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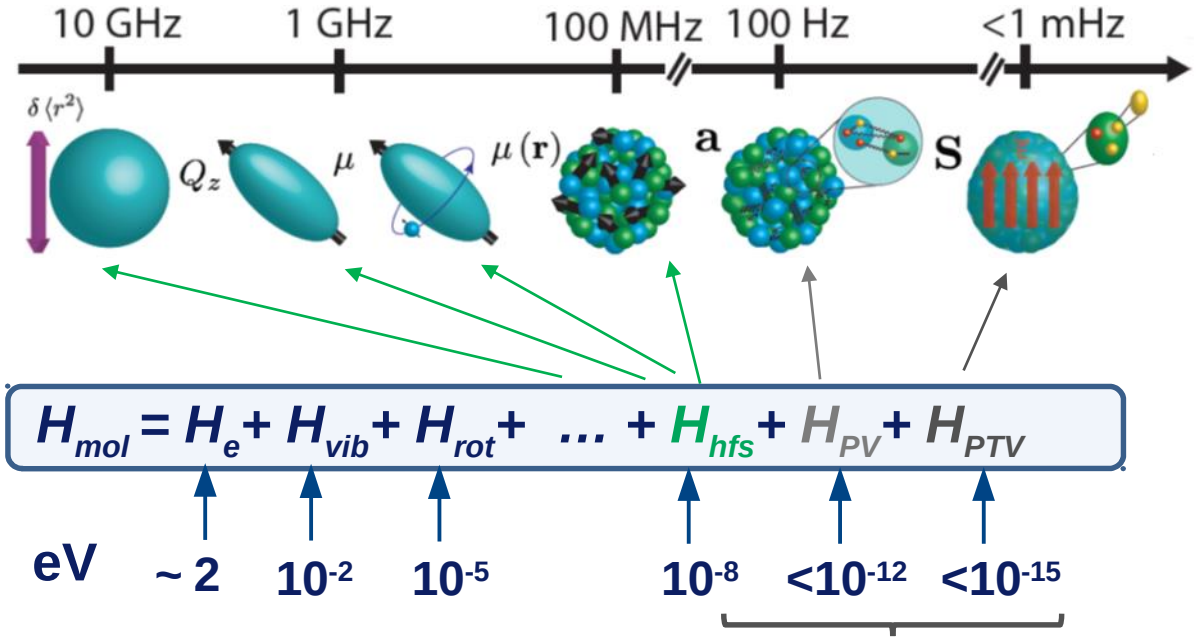


[1 eV=241.8 THz]

^{225}Ra

- ✓ Large Z, A
- ✓ Nuclear spin I >0
- ✓ $|\beta_2 \beta_3| > 0$

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

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

$(x\ 10^3)$ Nuclear

$\sim Z^a A^b \beta_2^2 \beta_3 / (E^N_+ - E^N_-)$

protons
nuclear mass
nuclear deformation
nuclear levels

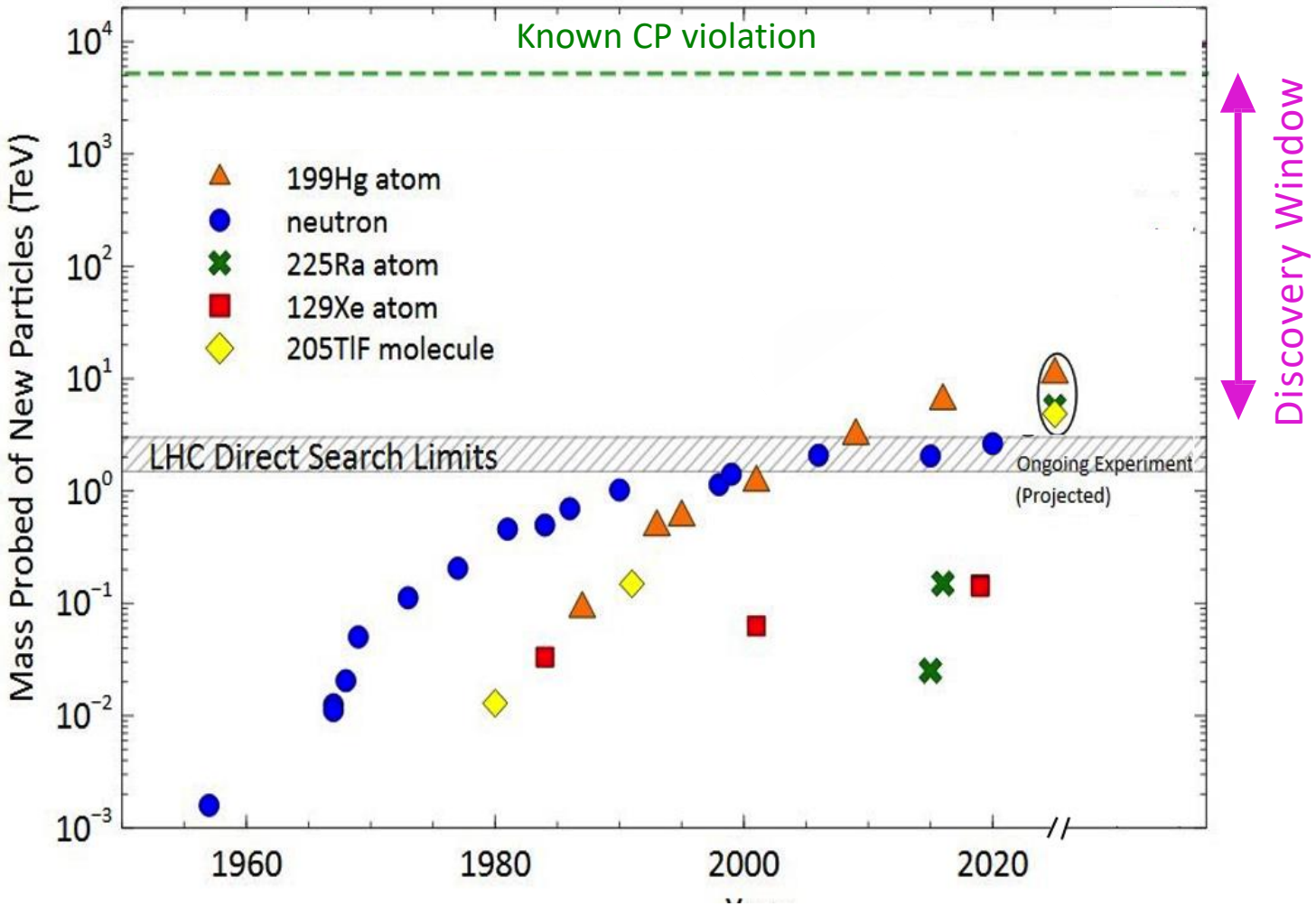
$(x\ 10^3)$ Molecule

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

[RaF: Isaev et al. PRA 82, 052521 (2010)]

Radioactive molecules => Best of all worlds!

Exploring The Entire New Physics Discovery Window With Standard Model Sensitivity Within Our Lifetime



CKM

θ_{QCD}

BSM

Figure thanks to Demille, Hutzler, Jayich, …

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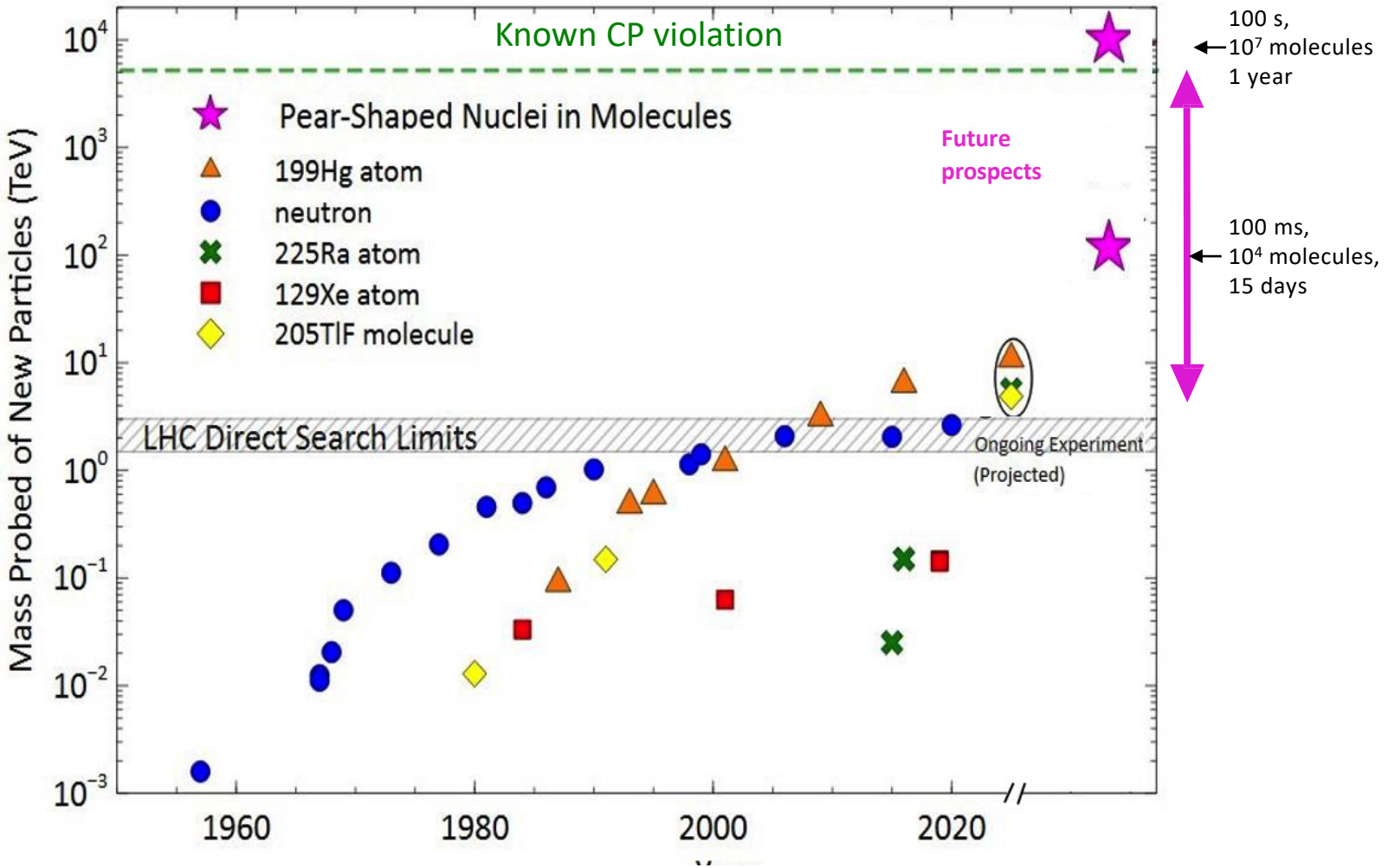

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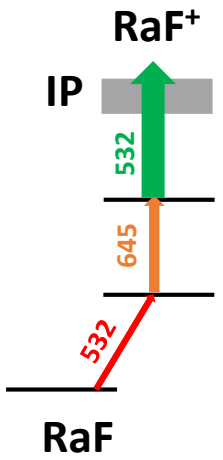
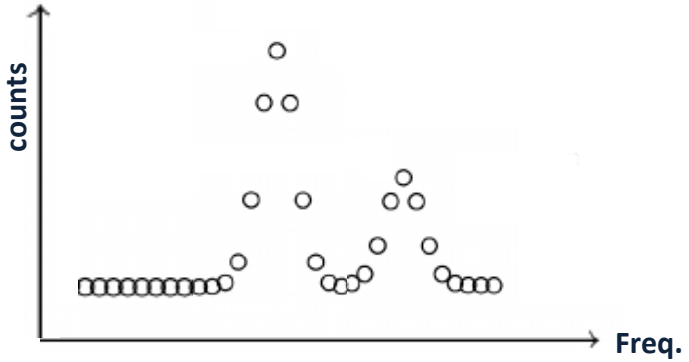
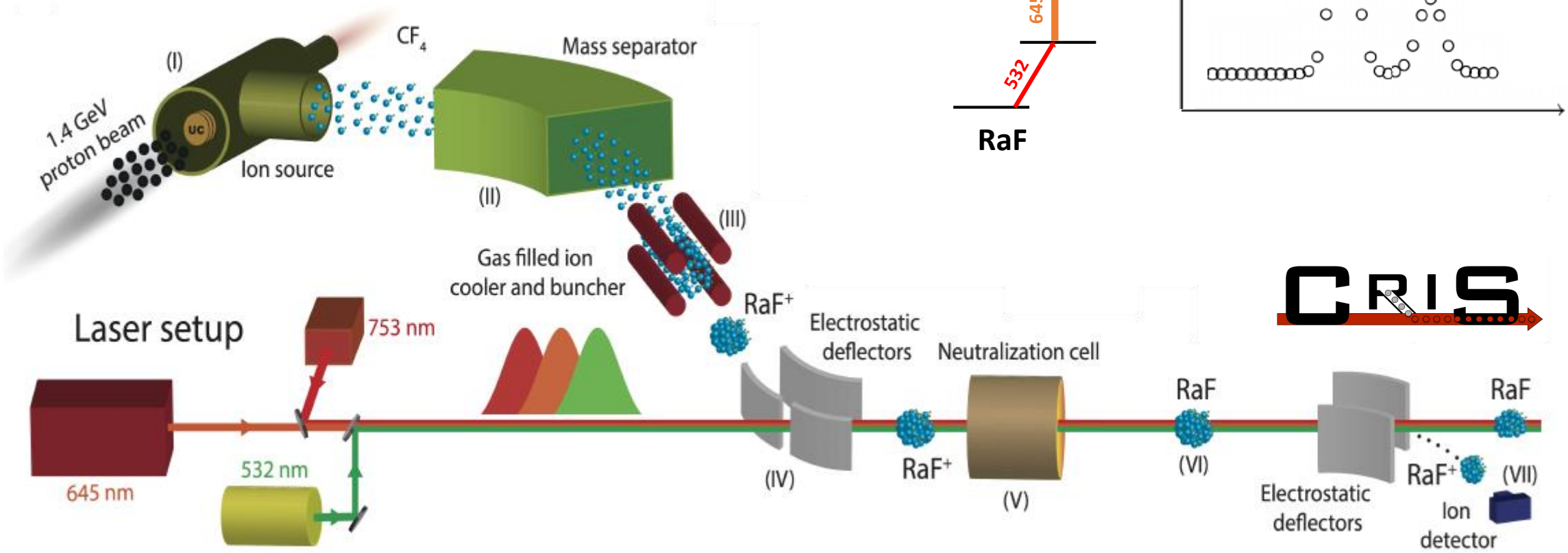
Recent Results (RaF)







RaF Molecules @ CRIS/ISOLDE

- CERN-INTC-2018-017 / INTC-P-546 (2018)
- CERN-INTC-P-555 (2020)
- CERN-INTC-P-555-ADD-1 (2023)

Recent Results (RaF)

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R. F. Garcia Ruiz, R. Berger, […]

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11 Jun 2020 in Research & Technology

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}	$<10^{-12}$	$<10^{-15}$

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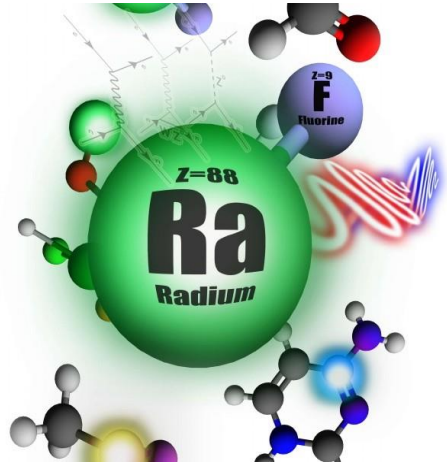

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Phys. Rev. Lett. **127**, 033001 – Published 14 July 2021

Physics See Viewpoint: Sizing up Exotic Nuclei with Radioactive Molecules

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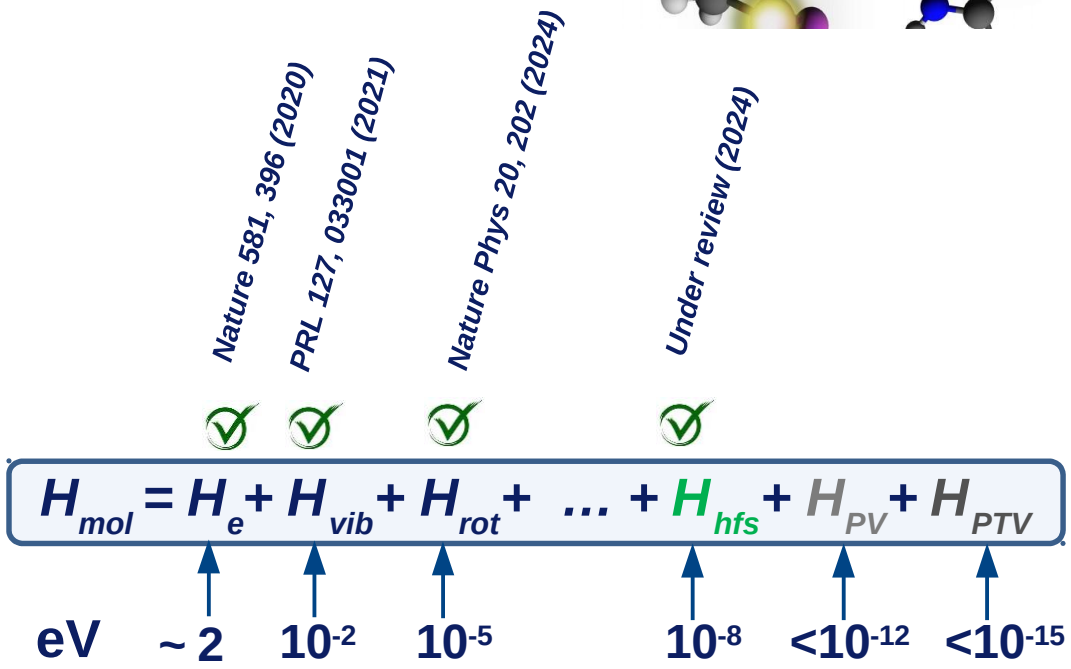

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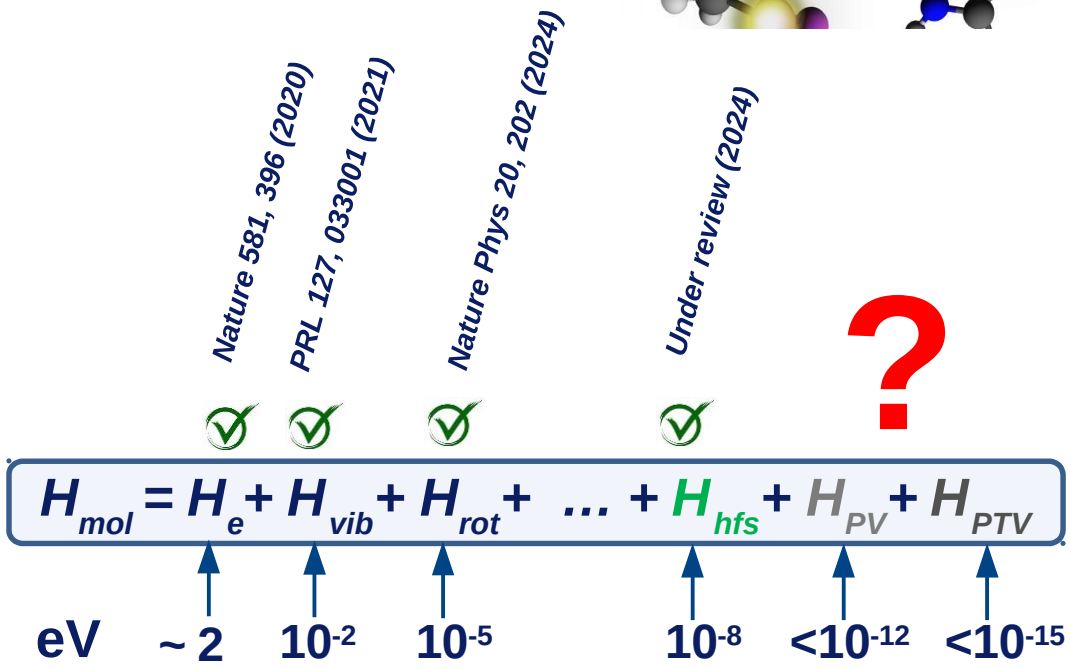
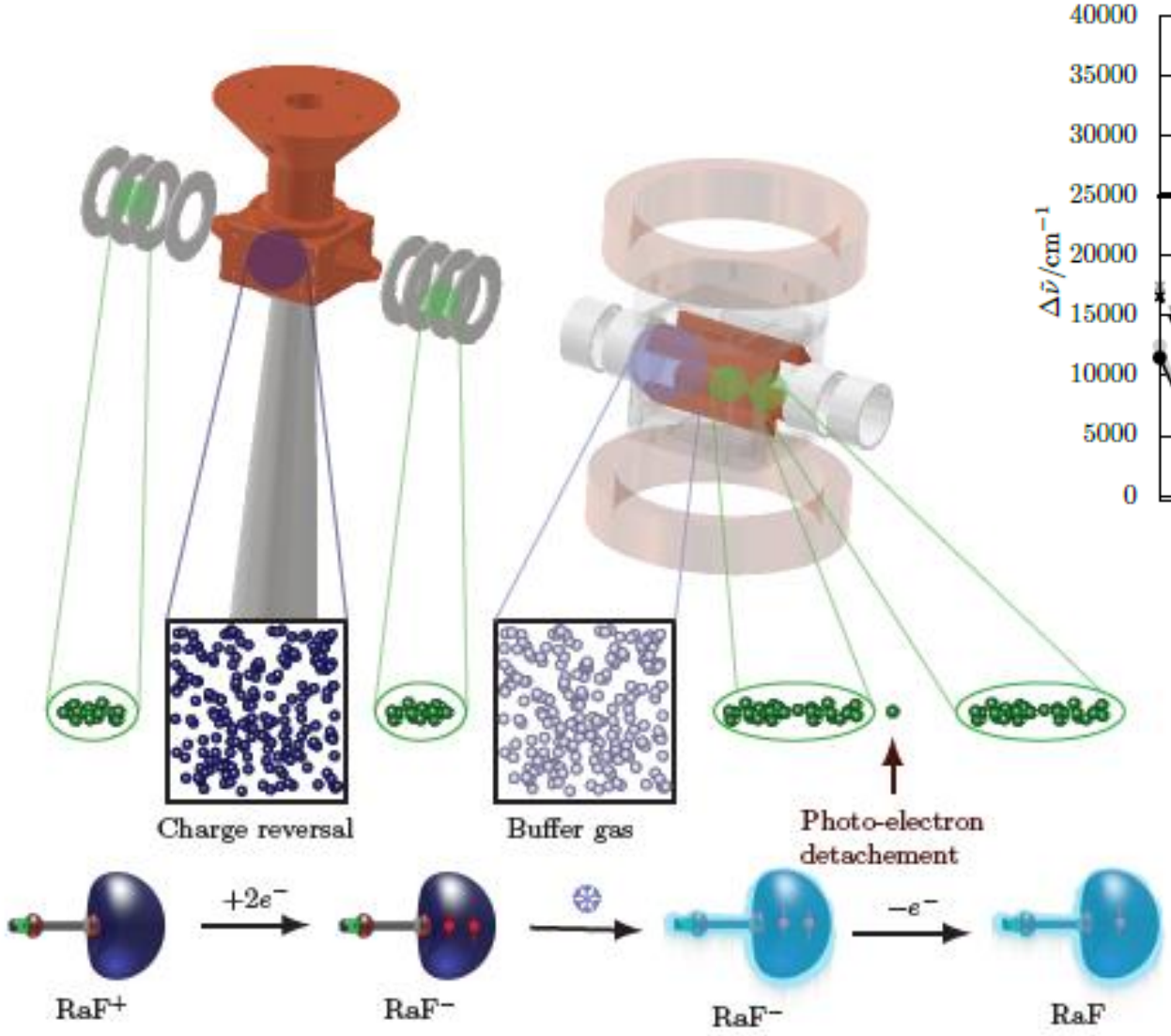
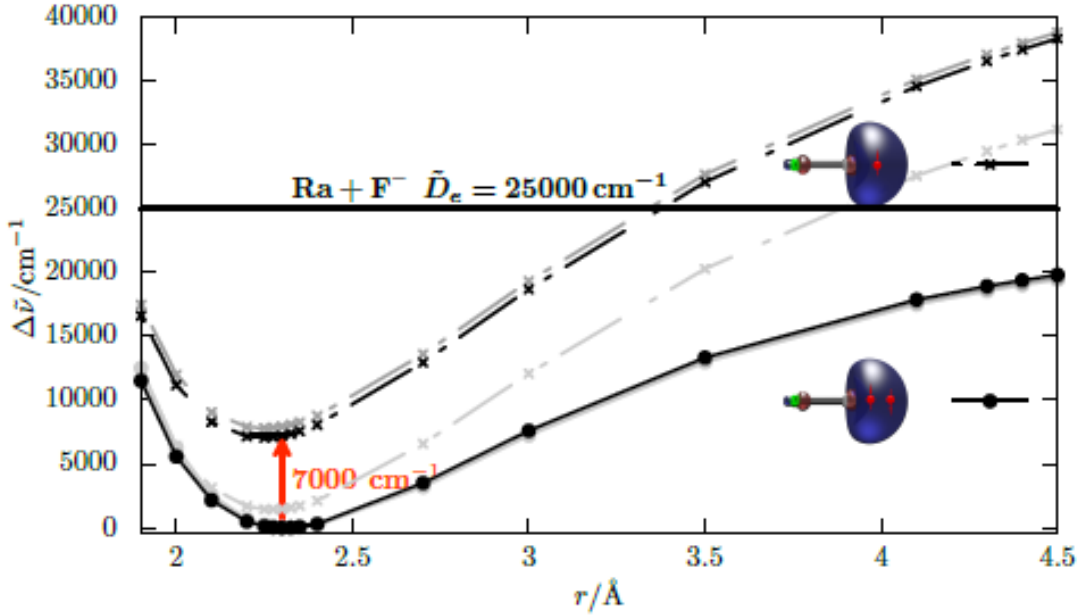


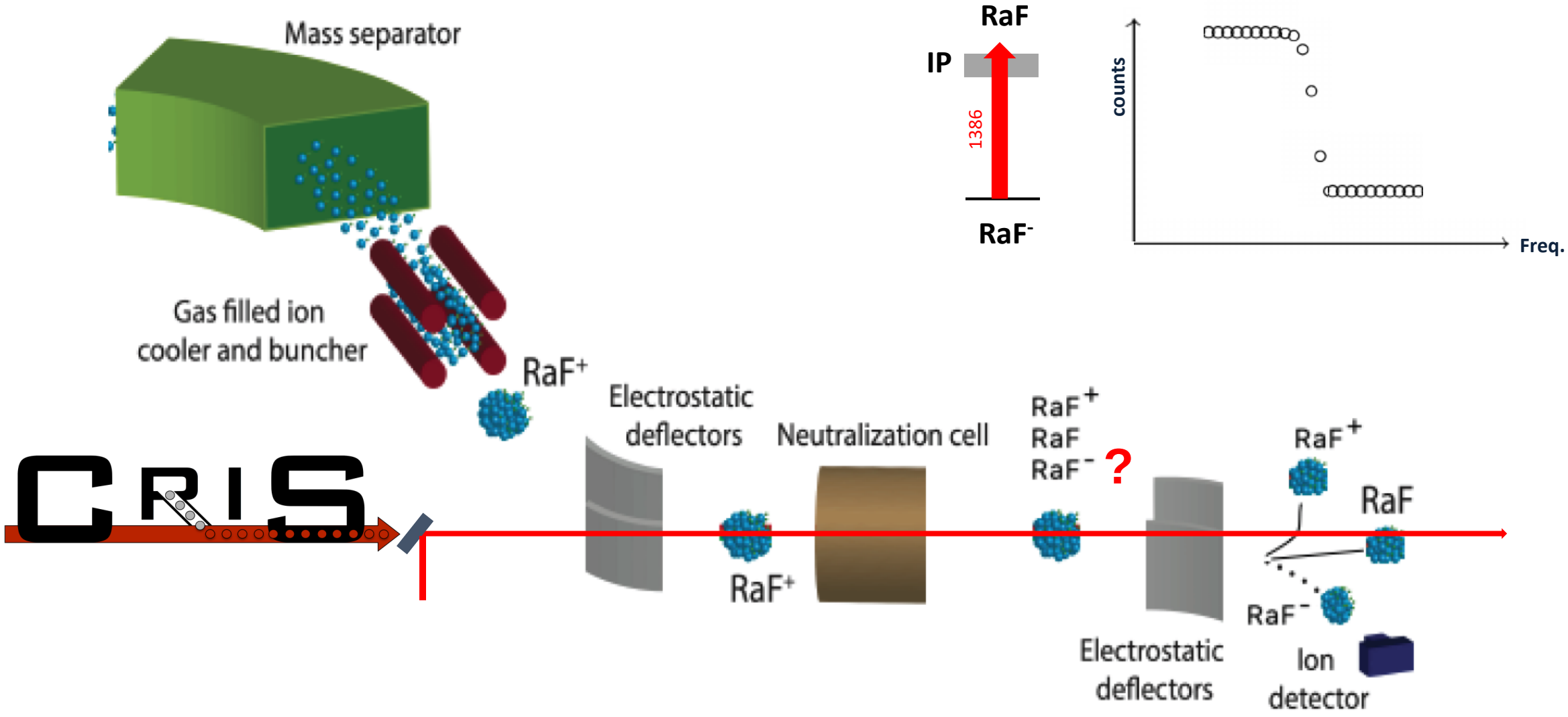
A possible path to cool and trap RaF





[Konstantin et al 2403.09320v2 (2024)]

Study of RaF^- anions at CRIS



Beam time request

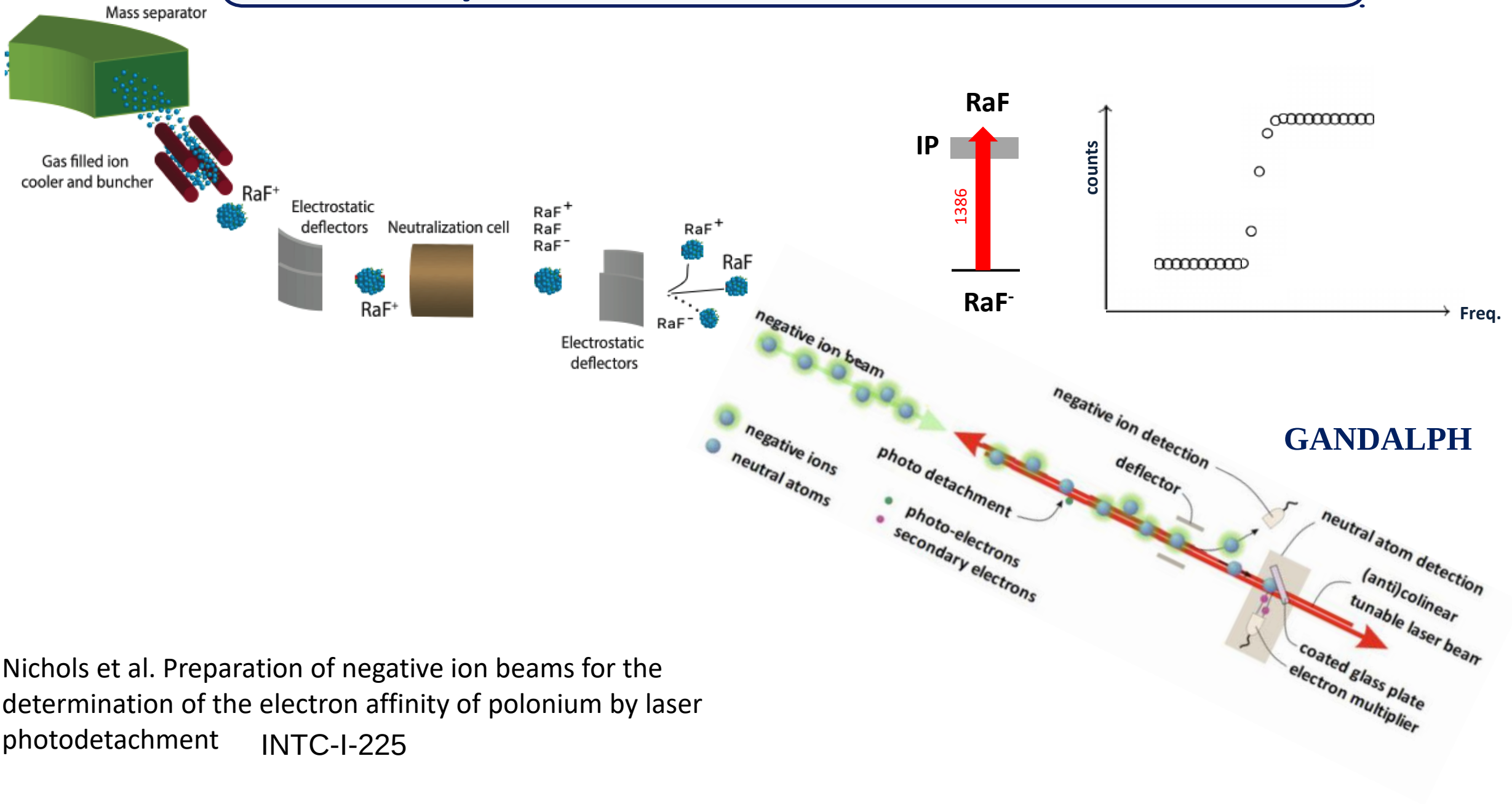
Molecule	Half life	Yield (ions/second)	Shifts
$^{226}RaF^{+}$	1600 yr	10^{7}	12

- 2 shifts to obtain a CRIS resonance with RaF and to optimize the beam tuning andlaser setup.
- 3 shifts to perform systematic studies of RaF with varying target and CEC temperature.
- 4 shifts to study the production of RaF^- after the CEC. This includes systematic studies of the CEC temperature.
- 3 shifts to study the photodetachment of RaF^- into RaF.

TAC recommendation:

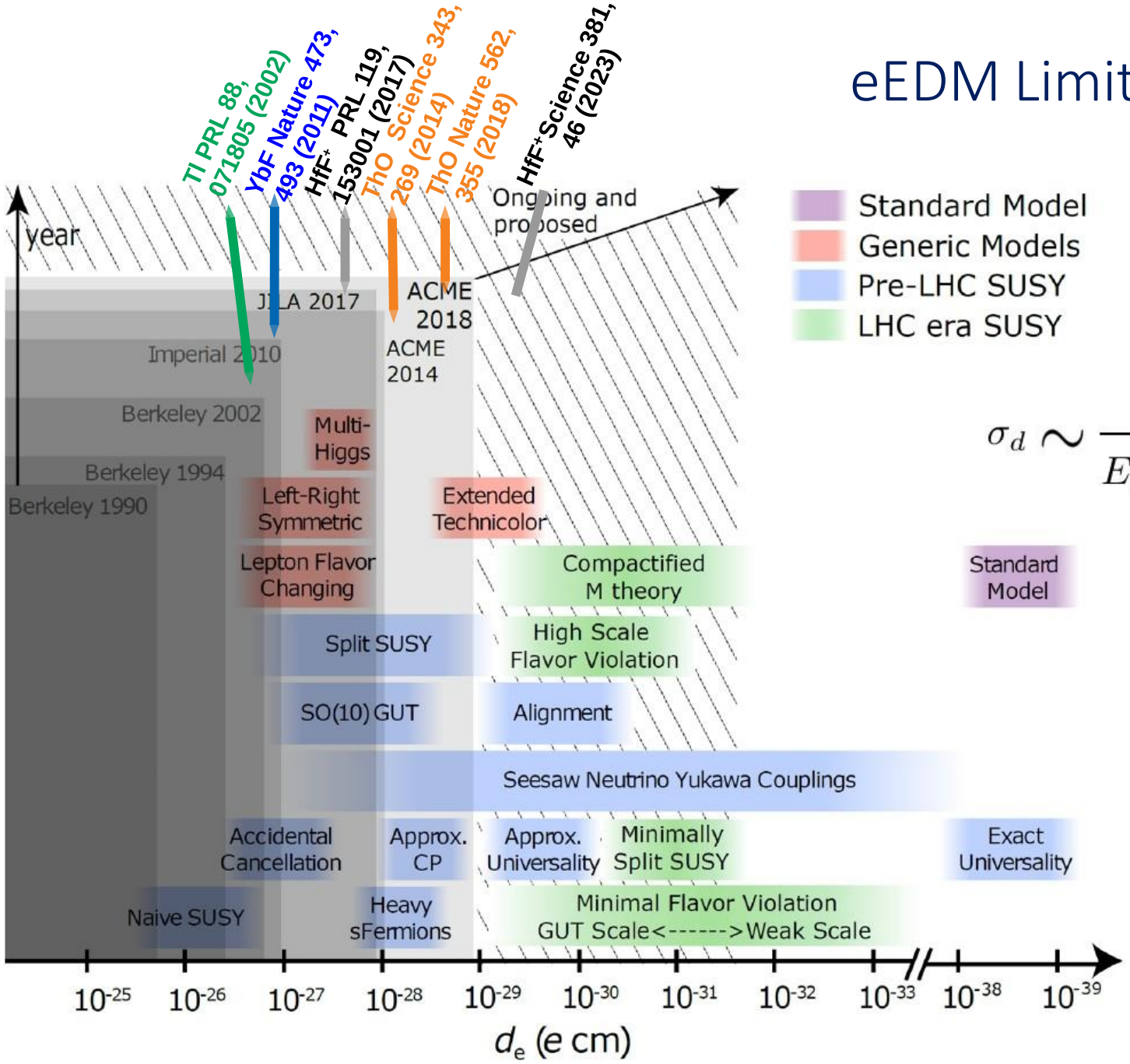
- RaF done before, no concerns.
- The TAC does not see any particular issues with this proposal

Study of RaF^- anions at CRIS - II

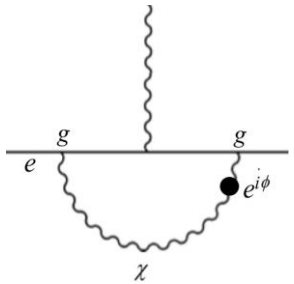


Nichols et al. Preparation of negative ion beams for the determination of the electron affinity of polonium by laser photodetachment INTC-I-225

eEDM Limits



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

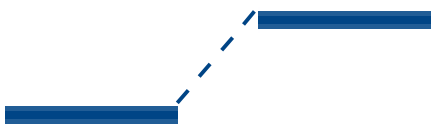


$$d_e \sim \mu_B \left(\frac{g^2}{2\pi}\right)^N \left(\frac{m_e}{m_\chi}\right)^2 \sin\phi$$

Probing physics @ TeV scale!

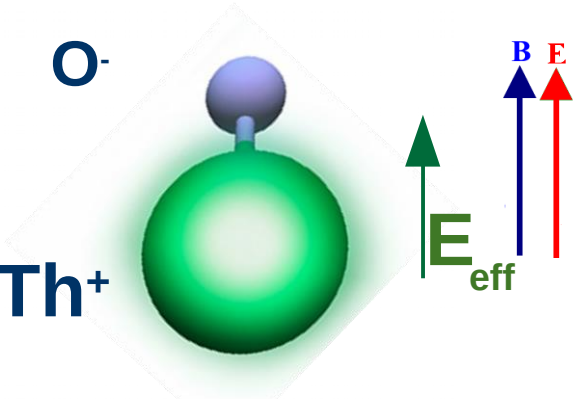
[Source: D. DeMille. Manipulating Quantum Systems: An Assessment of Atomic,Molecular, and Optical Physics in the United States (2019)]

Molecules for studies of electron EDM



$\sim d\, E_{eff}$

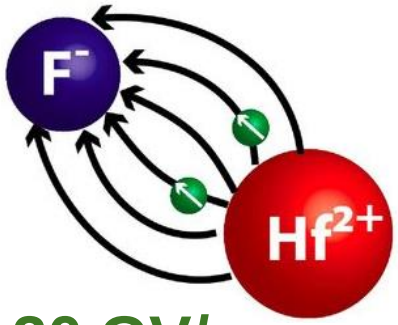
(< 10 μHz)



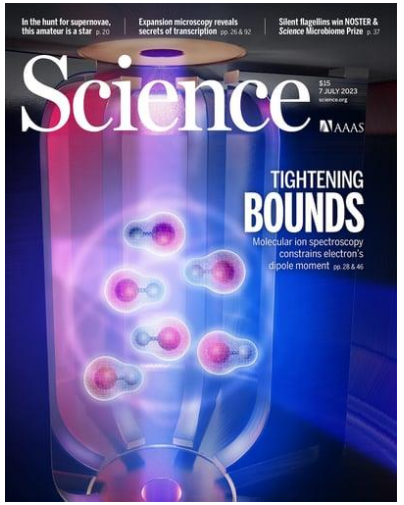
E_{ext} ~1-10 V/cm

E_{eff}~80 GV/cm

[ACME, Nature 562, 355 (2018)]



E_{eff}~20 GV/cm



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

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

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