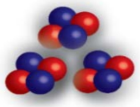
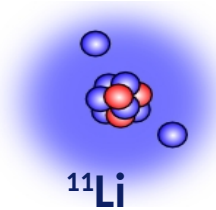
Exotic Atoms and Molecules for Nuclear Science

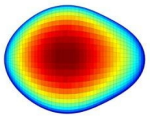


^{12}C



^{11}Li

^{23}O



^{224}Ra

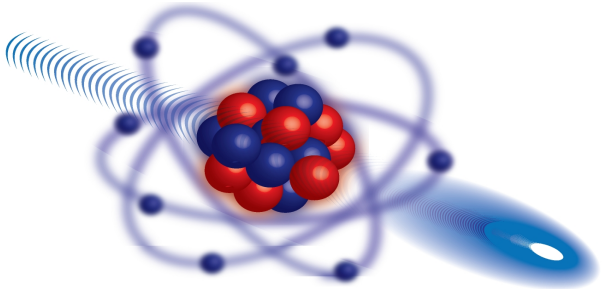
Ronald Fernando Garcia Ruiz

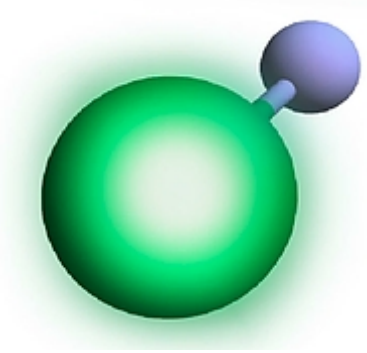
MIT

Institute for Nuclear Theory

University of Washington

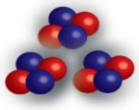
August 2020





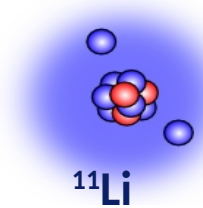
Exotic Atoms and Molecules for Nuclear Science

→ Containing nuclei with extreme proton/neutron ratios



^{12}C

Z=6, *N*=6
stable

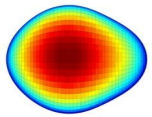


^{11}Li

Z=3, *N*=8
$T_{1/2}$=9 ms

^{23}O

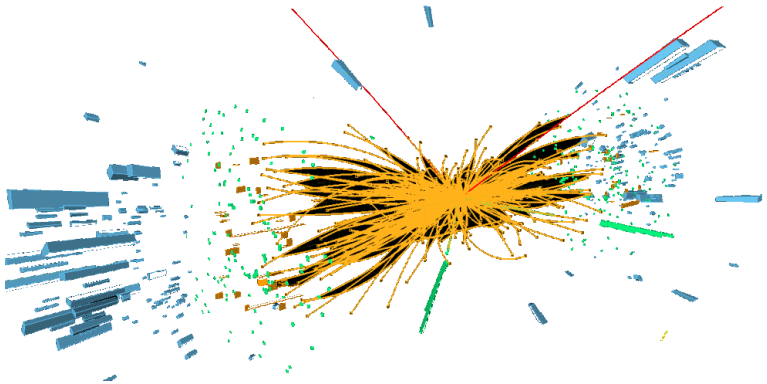
Z=8, *N*=15
$T_{1/2}$=97 ms



^{224}Ra

Z=88, *N*=136
$T_{1/2}$=3.6 days

Energy frontier



TeV

GeV

MeV

eV

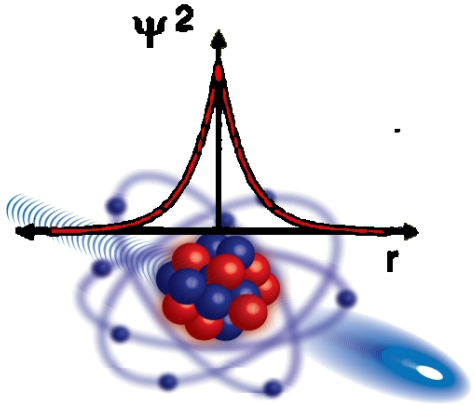
$<10^{-14}$

10^{-9}

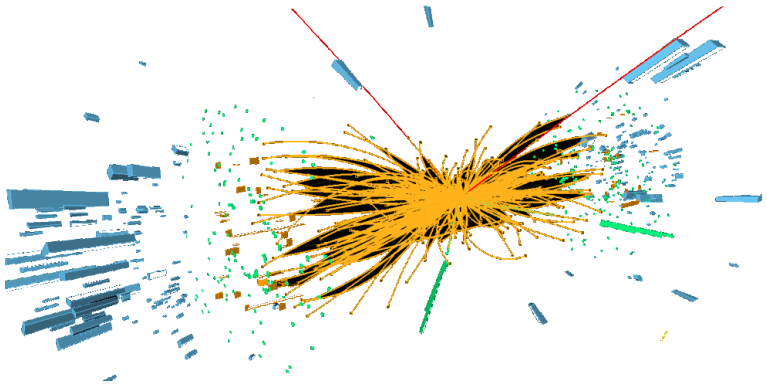
10^{-6}

10^{0}

Precision frontier



Energy frontier



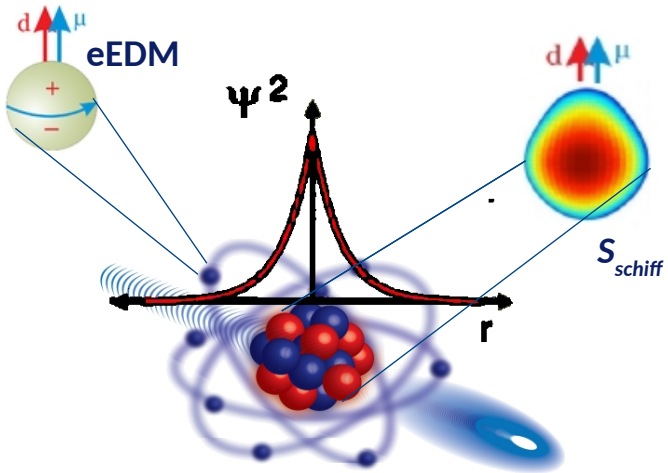
TeV $<10^{-14}$

GeV 10^{-9}

MeV 10^{-6}

eV 10^{0}

Precision frontier



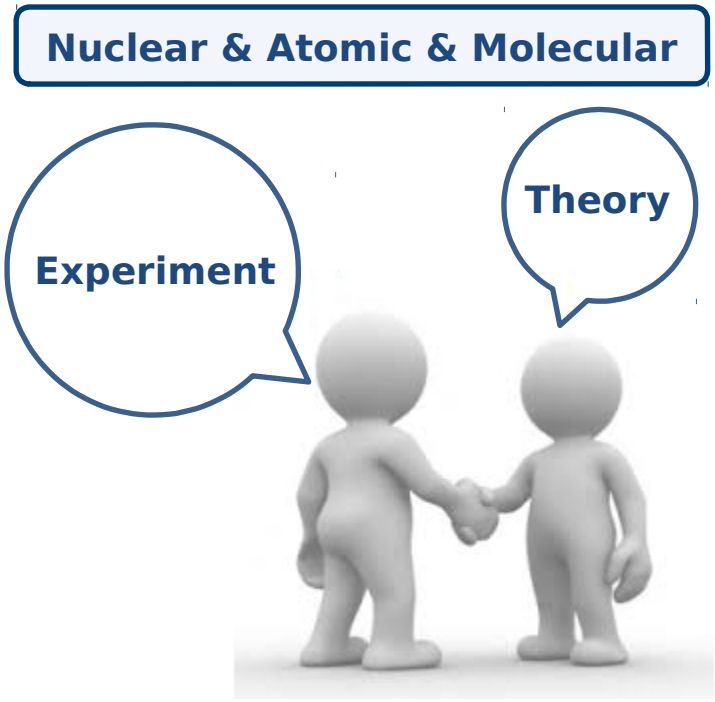
Exotic atoms & molecules offer a unique windows to study the nucleus, and the fundamental particles and interactions of nature!

Contents

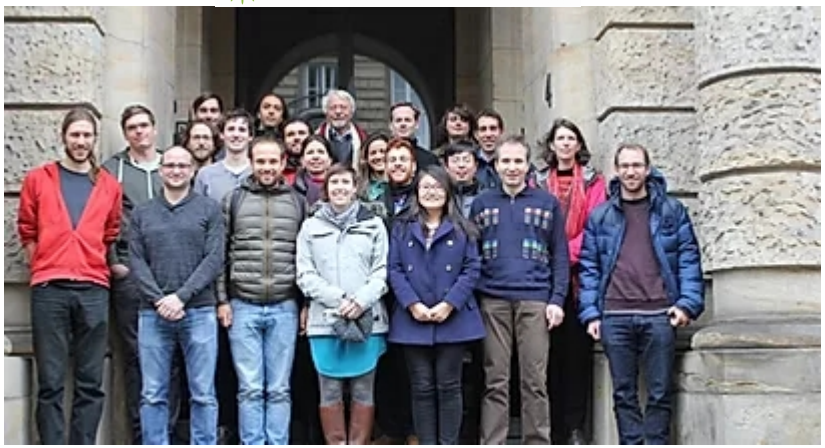
- Why (Exotic) atoms & molecules?
- Precision laser spectroscopy
- Exotic atoms: Recent highlights

  Ca (Z=20), Ni (Z=28), Sn (Z=50)
- Exotic molecules: Recent Results

  RaF molecules
- Summary & Outlook



Thanks to…



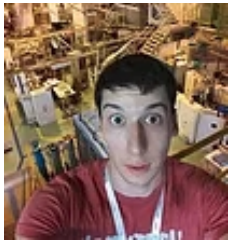
Nuclear theory: W. Nazarewicz (FRIB/MSU),
P.-G. Reinhard (Erlangen-Nürnberg),
G. Hagen (ORNL),
J. Holt (TRIUMF),
R. Stroberg (U. Washington)...

Atomic theory: B. *Sahoo (Navrangpura, India),*

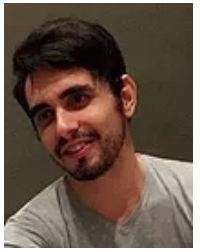
Quantum chemistry: *R. Berger (U. Marburg, Germany),*
T. Isaev (PNPI NRCKI, St. Petersburg)

ISOLTRAP (F. Wienholtz) , **RILIS** (S. Wilkins, K. Chrysalidis)
Target group (S. Rothe), **ISOLDE Technical group**

Graduate students @ MIT



A. Brinson



S. Udrescu

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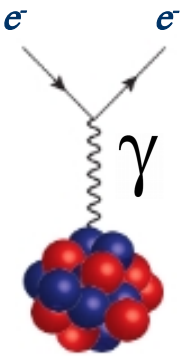
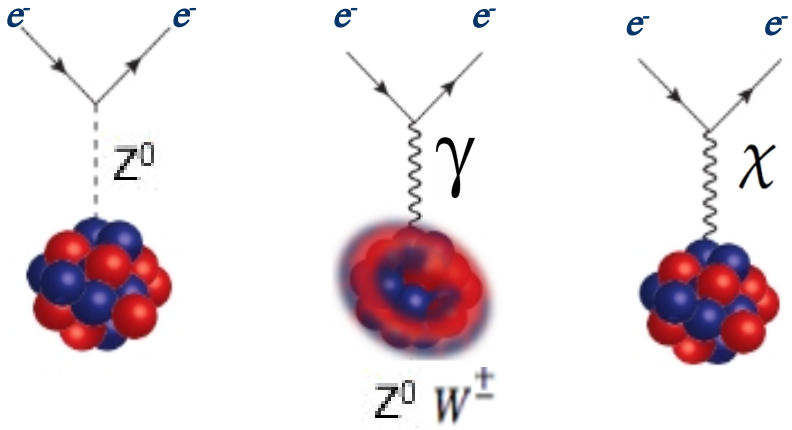
- Precision laser spectroscopy
- Exotic atoms: Recent highlights
- Exotic molecules: Recent Results
- Summary & Outlook

Why (Exotic) Atoms & Molecules?



Long range

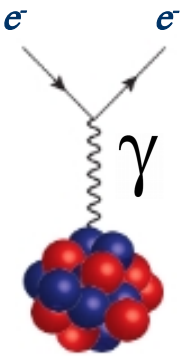
Electromagnetic structure

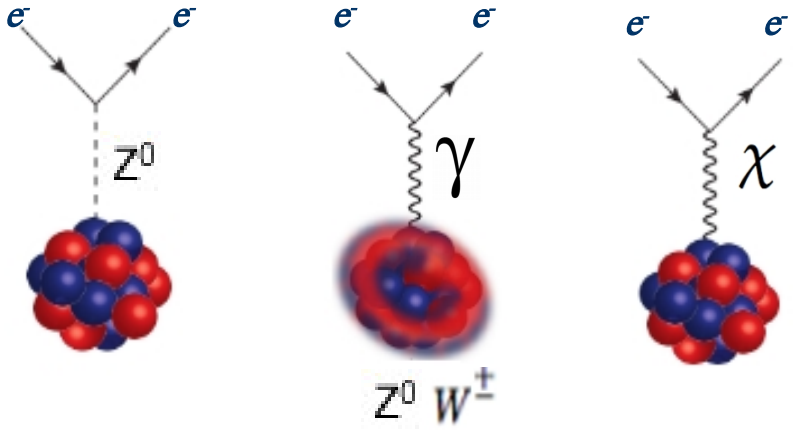


Short range (< 0.1 fm)

Electroweak structure

Why (Exotic) Atoms & Molecules?





Long range

Electromagnetic structure

Short range (< 0.1 fm)

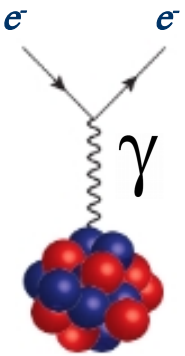
Electroweak structure

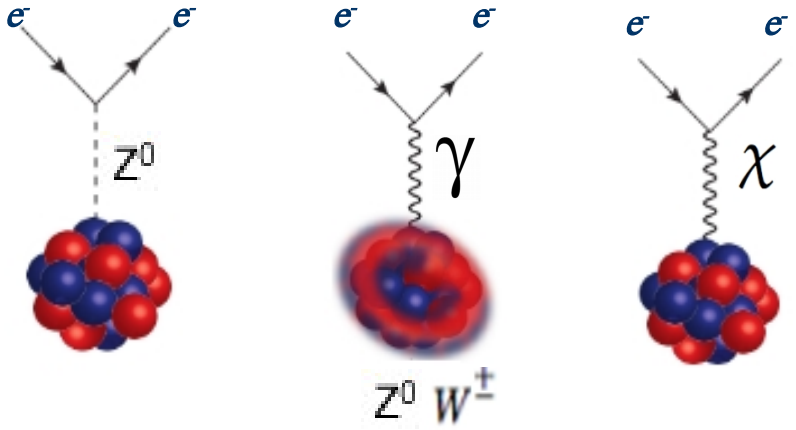
Atoms

- Nuclear force → QCD
- Emergence of nuclear phenomena
- Understanding of nuclear matter

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

Why (Exotic) Atoms & Molecules?





Long range

Electromagnetic structure

Short range (< 0.1 fm)

Electroweak structure

Atoms

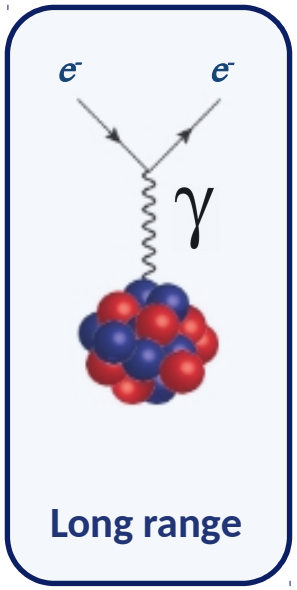
- Nuclear force → QCD
- Emergence of nuclear phenomena
- Understanding of nuclear matter

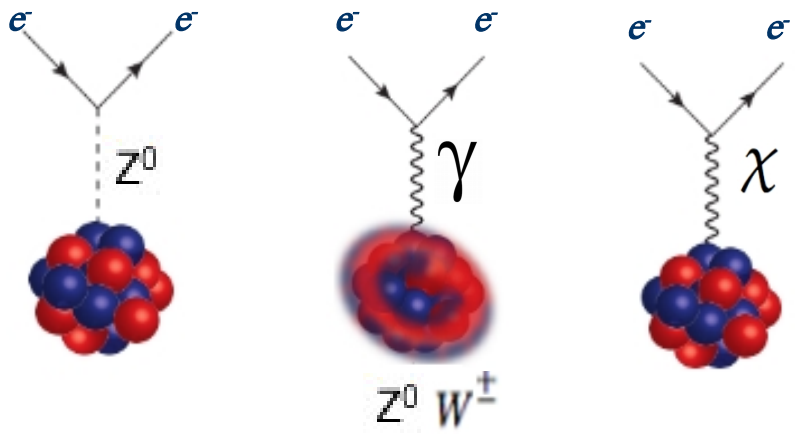
Molecules

- Fundamental symmetries, BSM physics
- Matter / Antimatter asymmetry
- Dark matter

$\langle r^2 \rangle$ $I, \mu, Q, \ldots$ A_{AM} , $eEDM$, S_{schiff} , MQM

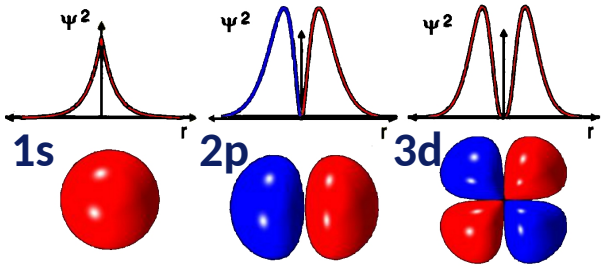
Why (Exotic) Atoms & Molecules?



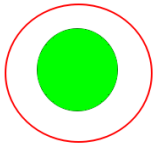


Short range (< 0.1 fm)

Atoms

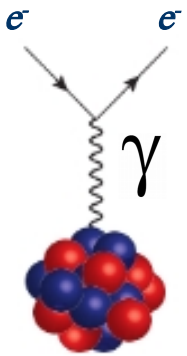


$\langle r^2 \rangle$ $I, \mu, Q, \ldots$

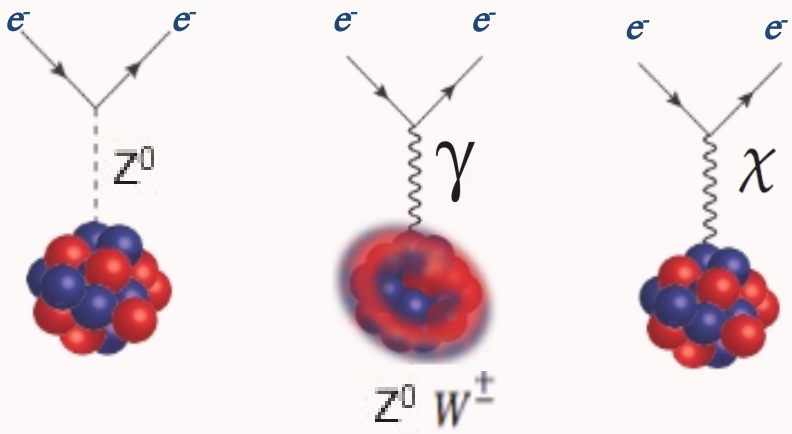


Ra^+

Why (Exotic) Atoms & Molecules?



Long range



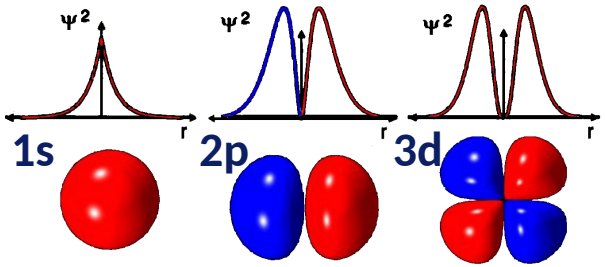
Short range (< 0.1 fm)

$\sim Z^n$

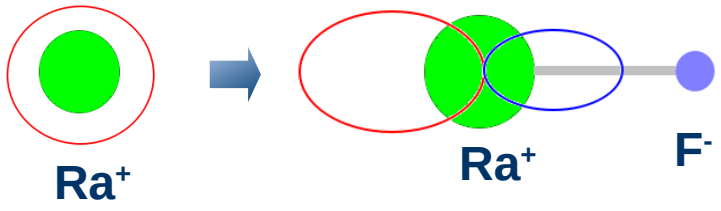
Atoms

- Parity violation > 10^{11}
- Parity and Time reversal violation > 10^3

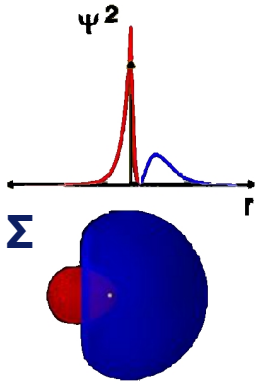
Molecules



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



A_{AM} , $eEDM$, S_{schiff} , MQM

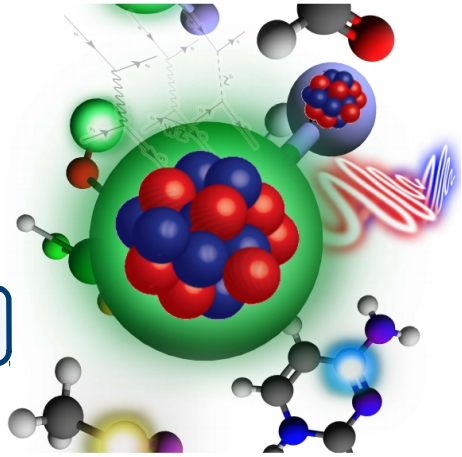


Contents

- Why (Exotic) atoms & molecules?
- **Precision laser spectroscopy**
- Exotic atoms: Recent highlights
- Exotic molecules: Recent Results
- Summary & Outlook

Precision laser spectroscopy

Figure modified from https://sphereofinfluence360.com/



Production

Selection

Study

Precision laser spectroscopy

Light nucleus

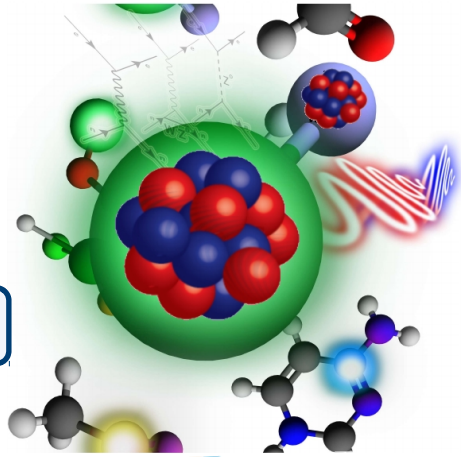
+

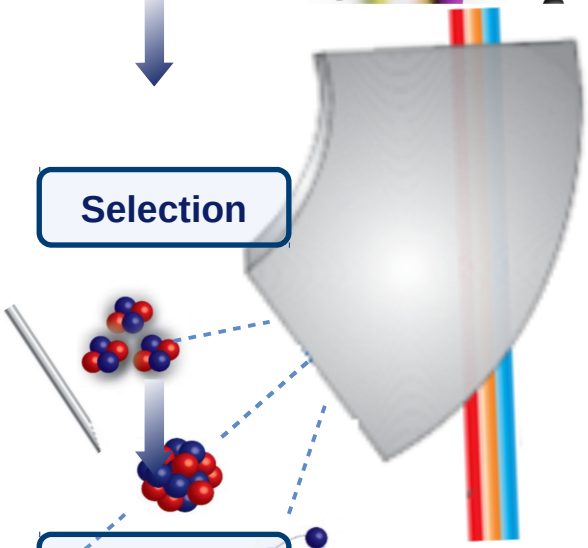
Heavy Nuclei

Production

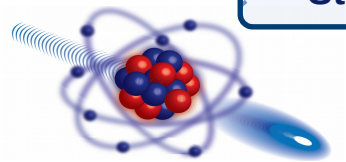
Selection

Study





Lasers
+
Electromagnetic fields

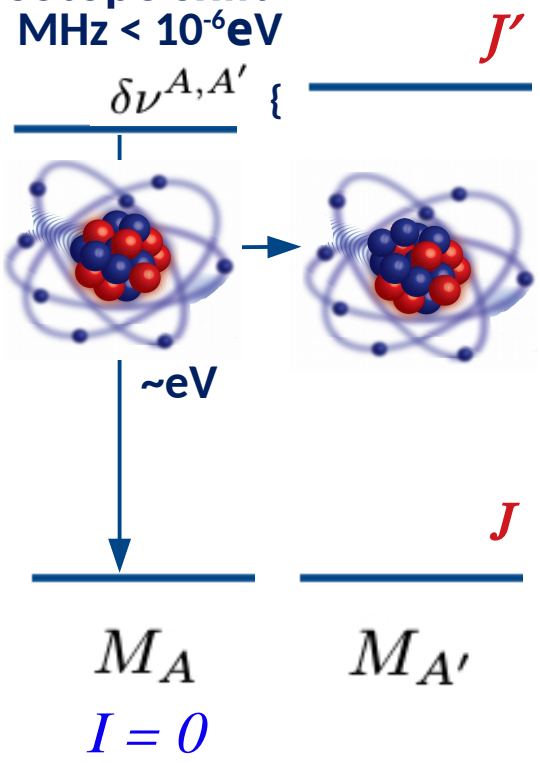


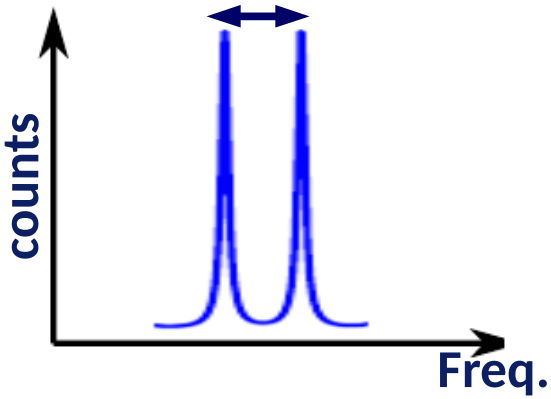
One atom at a time

Precision laser spectroscopy

Isotope shift

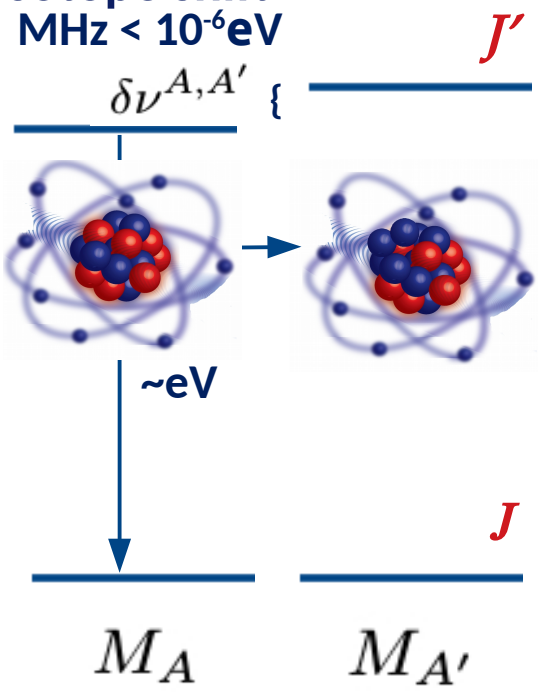
MHz < 10^{-6}eV





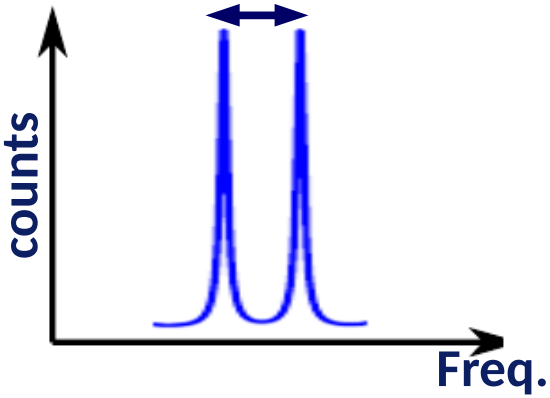
Precision laser spectroscopy

Isotope shift
MHz < 10^{-6}eV



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

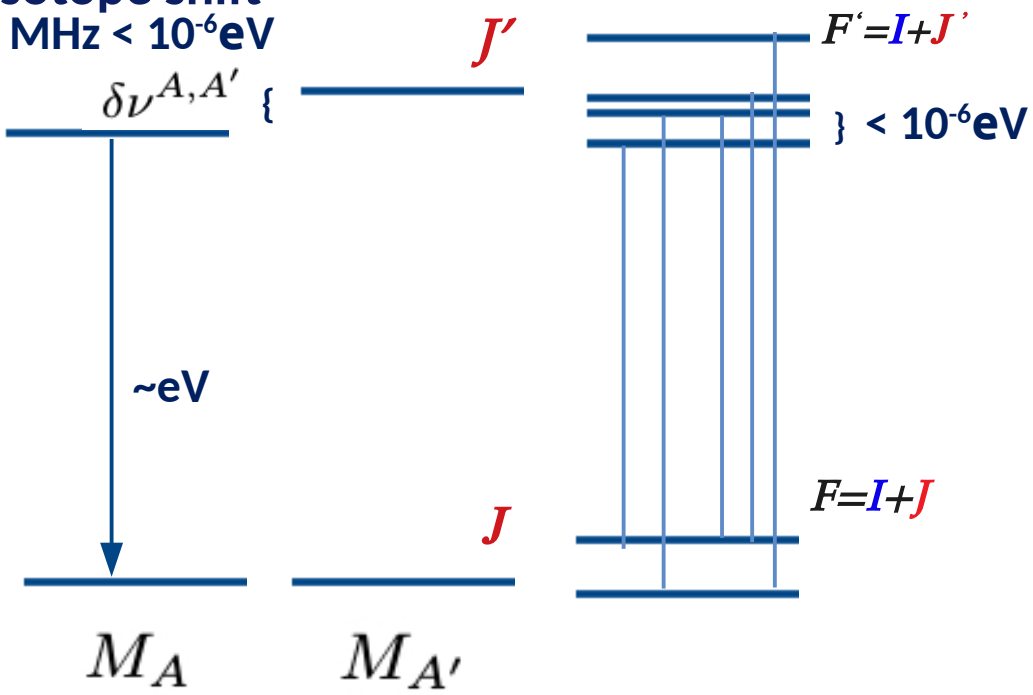
Atom/molecule
Nuclear



Electromagnetic structure
Rms charge radii: $\langle r^2 \rangle$

Precision laser spectroscopy

Isotope shift
MHz < 10^{-6}eV

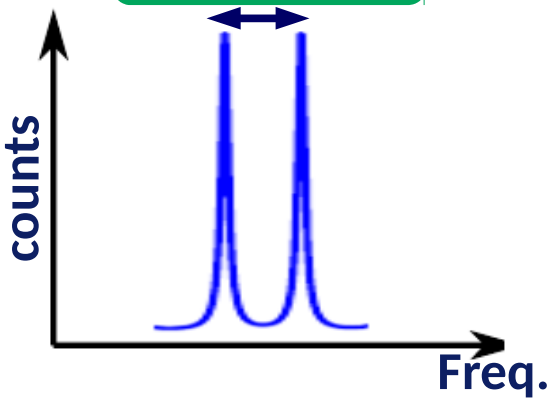


$I = 0$

$I > 0$

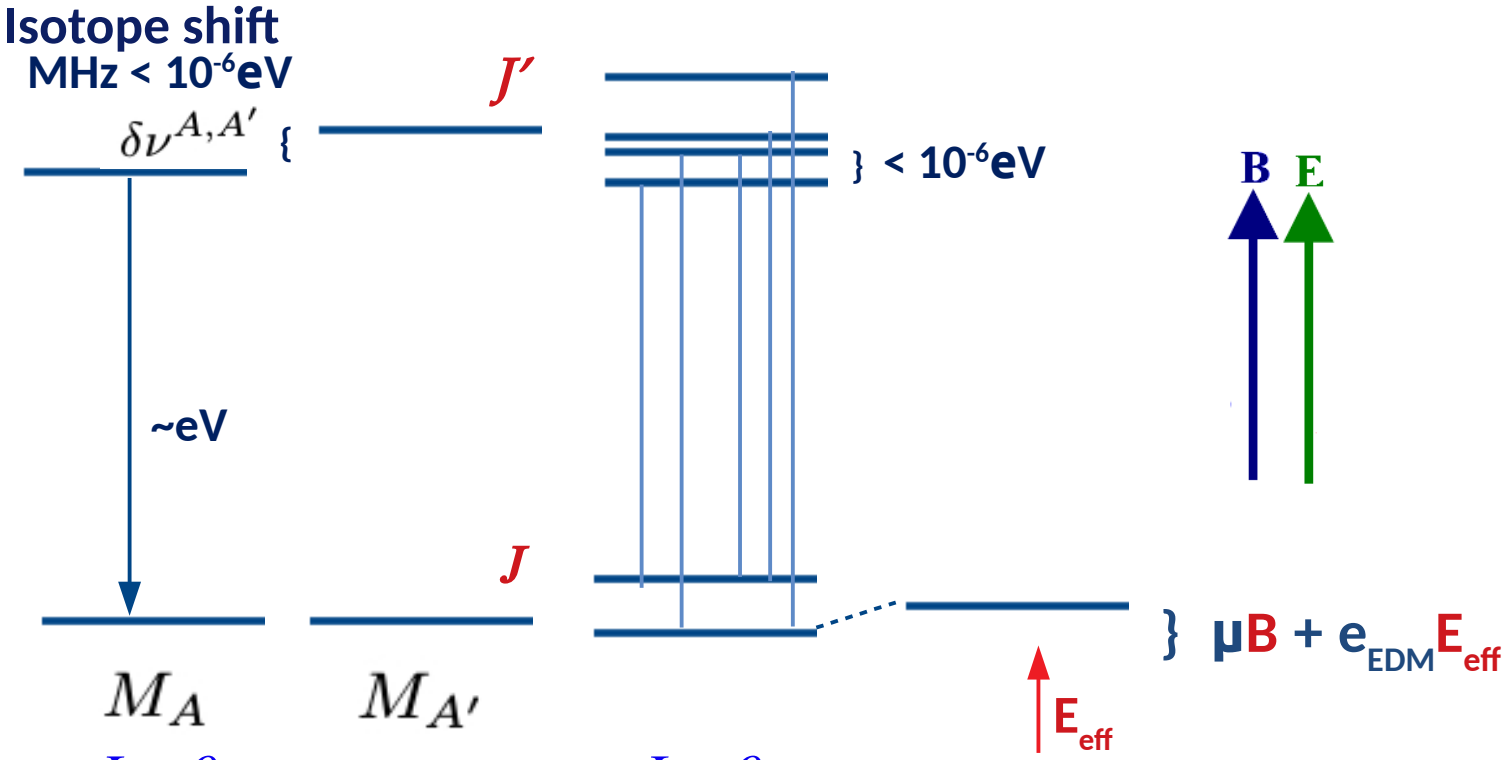
Atom/molecule
Nuclear

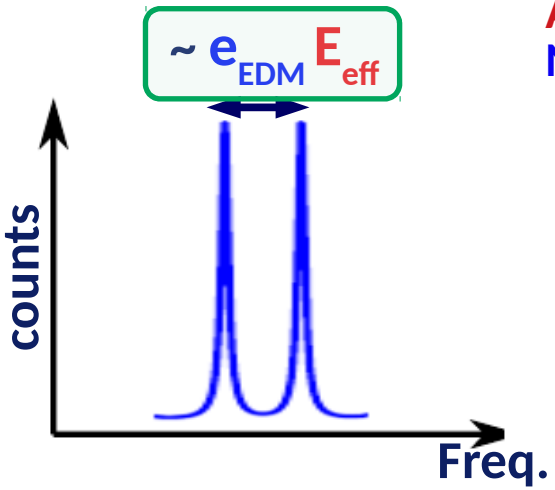
~ μB +Q ∇E



Electromagnetic structure
Rms charge radii: $\langle r^2 \rangle$
Nuclear spin: I
Magnetic moment: μ
Quadrupole moment : Q

Precision laser spectroscopy





Electromagnetic structure
Rms charge radii: $\langle r^2 \rangle$
Nuclear spin: I
Magnetic moment: μ
Quadrupole moment : Q

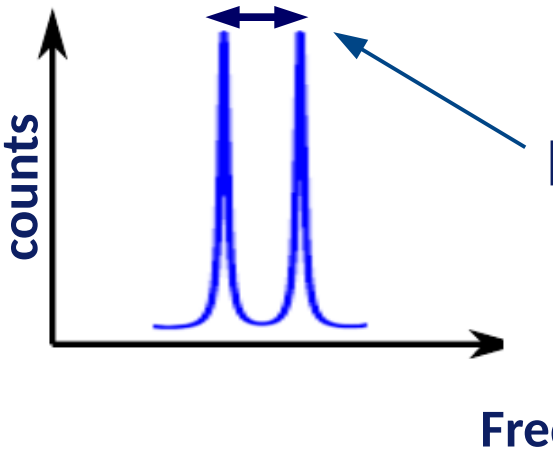
Symmetry violating moments:
Anapole (P-odd): A_{AM}
EDM (P,T-odd): $eEDM$, S_{schiff}
Magnetic quad. (P,T-odd): MQM

Precision laser spectroscopy

Nuclear

Atom/molecule

$\sim O_{Nucl} F_{atom/mol.}$



Experiment

Electromagnetic structure:

Rms charge radii: $\langle r^2 \rangle$

Nuclear spin: I

Magnetic moment: μ

Quadrupole moment : Q

Symmetry-violating properties:

Anapole (P-odd): A_{AM}

EDM (P,T-odd): $eEDM$, S_{schiff}

Magnetic quad. (P,T-odd): MQM

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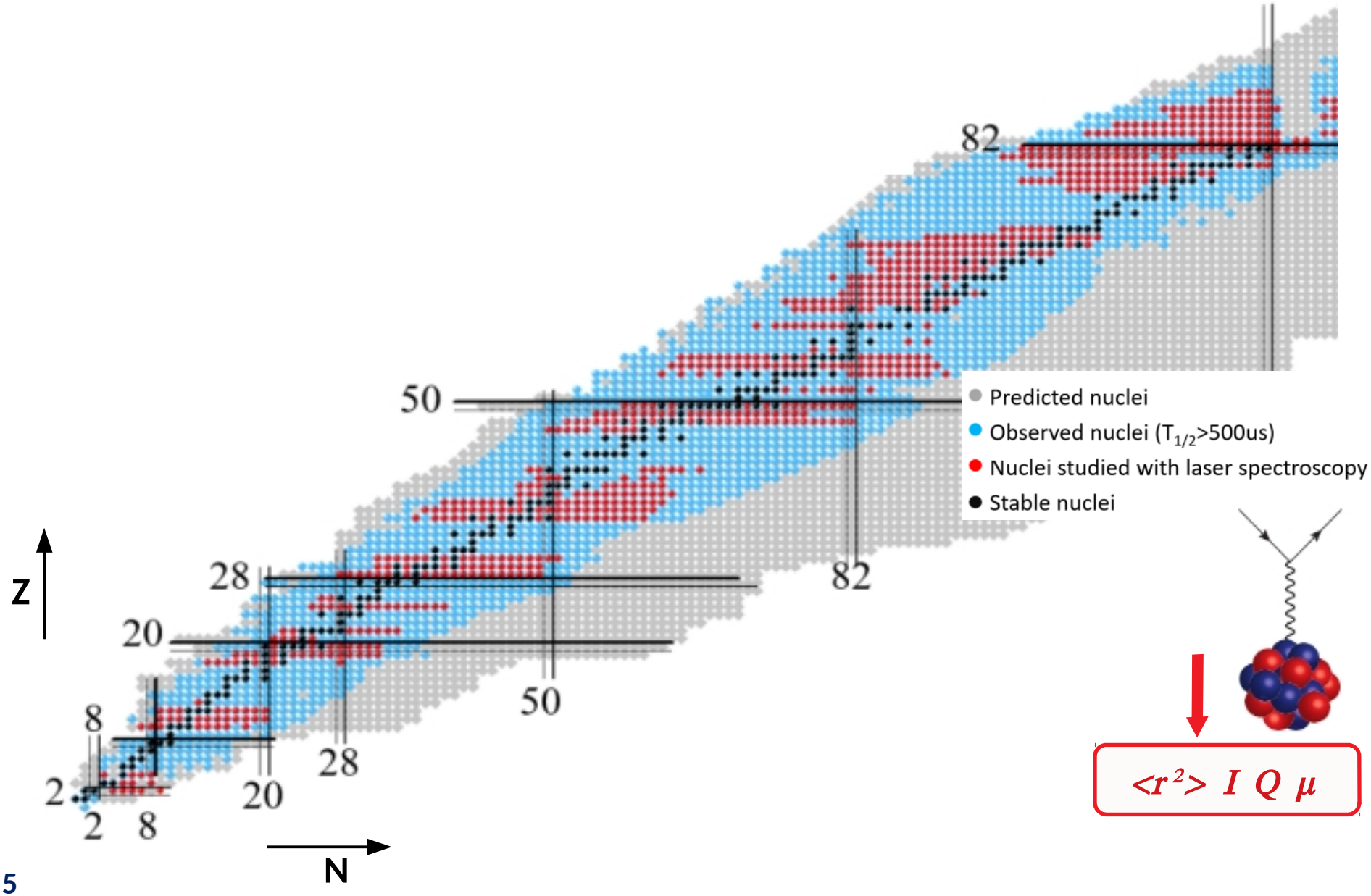
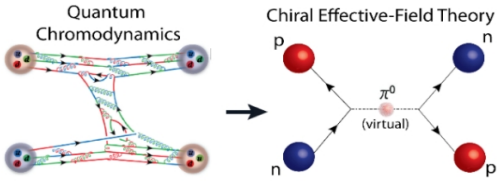
Theoretical/Experimental Progress

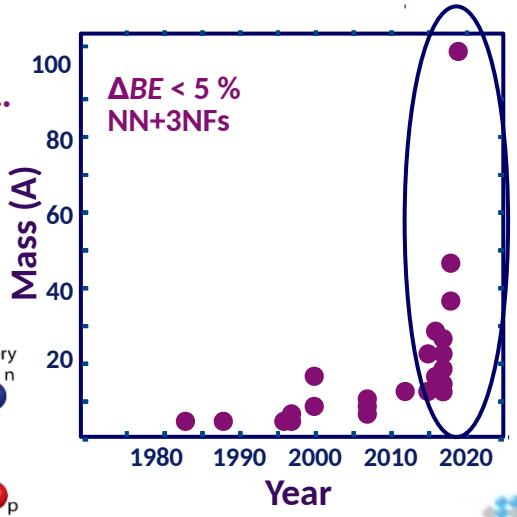


Theoretical/Experimental Progress

Ab-initio methods

QMC, GFMC, CC, IMSRG, GGF....

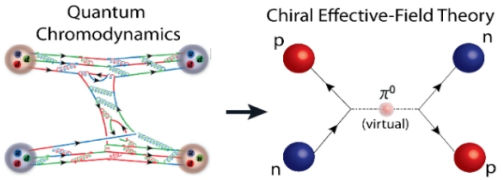


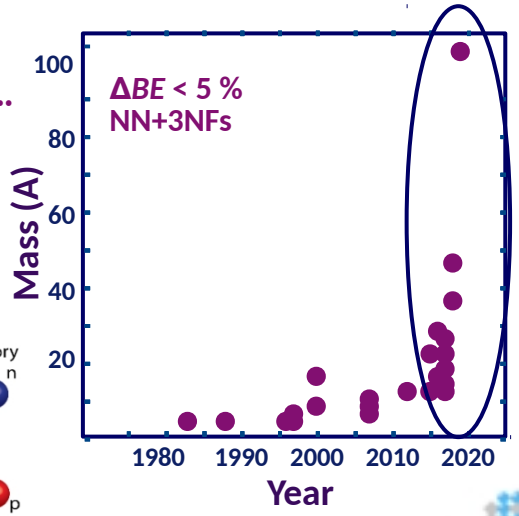


$\langle r^2 \rangle$ *I Q* μ

Theoretical/Experimental Progress

Ab-initio methods
QMC, GFMC, CC, IMSRG, GGF....





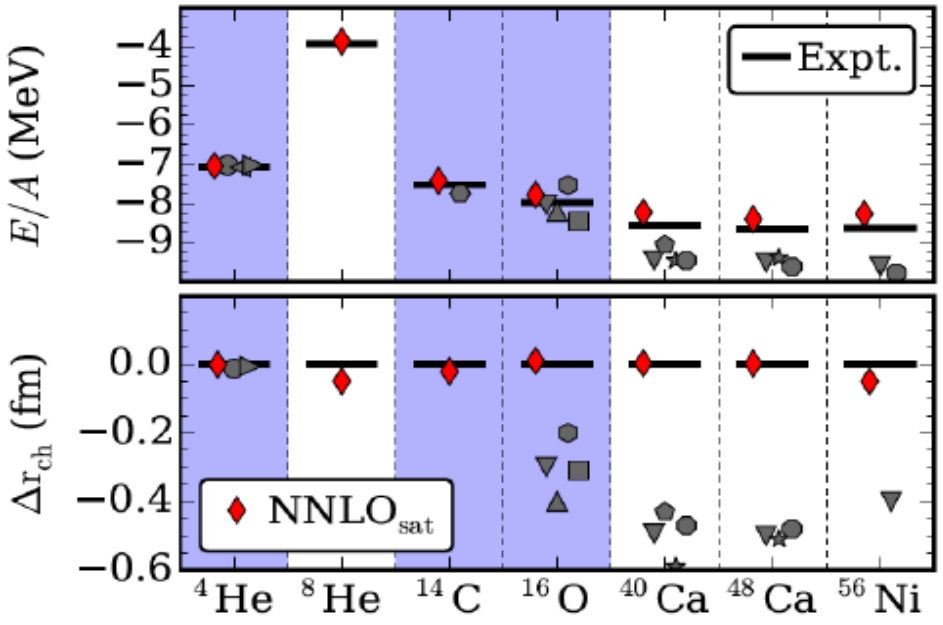
Main focus of our recent work!

Experimental challenges:
- **High efficiency (<100 ions/s)**
- **Short time scales (< 1 s)**
- **High precision/resolution (<10^{-6})**
- **High selectivity (>1/10^6)**

$\langle r^2 \rangle$ I Q μ

Nuclear Charge Radii

Simultaneous reproduction of charge radii and binding energies has been a long-standing challenges for nuclear theory.



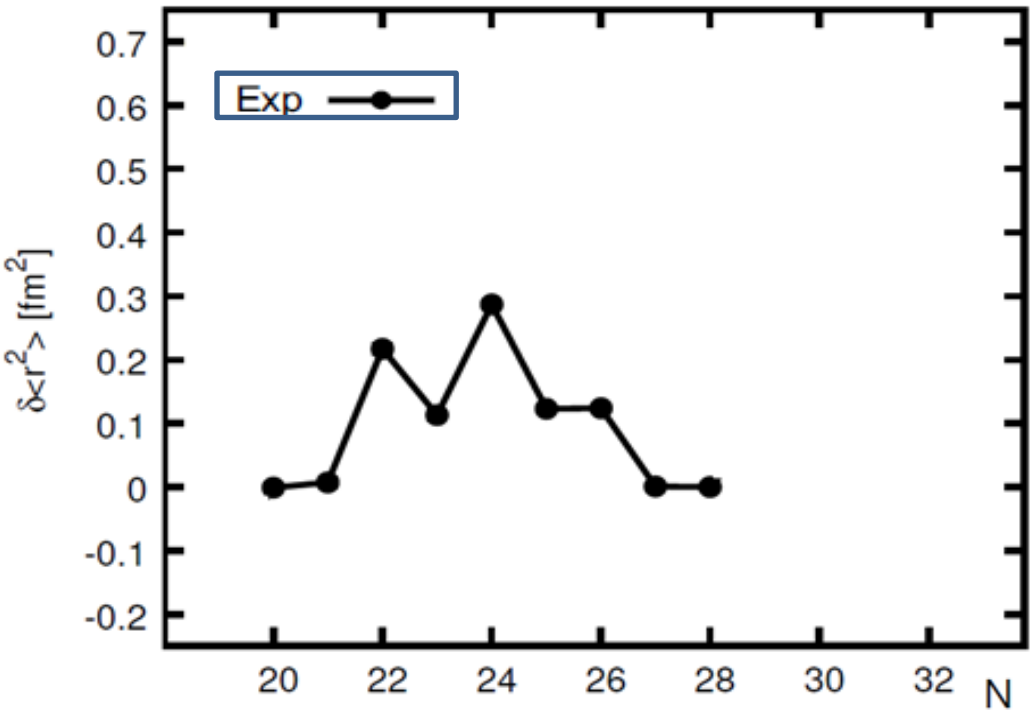
- Phys. Rev. Lett. 99 042501 (2007)
- Phys. Lett. B 736 119 (2014)
- Phys. Rev. Lett. 112 102501 (2014)
- Phys. Rev. Lett. 109 252501 (2012)
- Phys. Rev. C 90 014314 (2014)
- Phys. Rev. Lett. 94 212501 (2005)
- Phys. Rev. Lett. 108 242501 (2012)
- Phys. Rev. C 90 064619 (2014)
- Phys. Rev. Lett. 106 202502 (2011)
- Phys. Rev. C 89 061301 (2014)
- Phys. Rev. C 90 041302 (2014)
- Phys. Rev. C 91, 051301(R) (2015)

Nature Physics 12, 186 (2016)

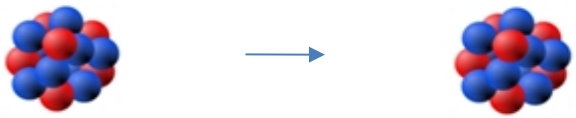
Charge radii of calcium (Z=20) isotopes

[R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]

The charge radii of Ca isotopes present additional challenges



^{40}Ca ^{48}Ca ^{52}Ca



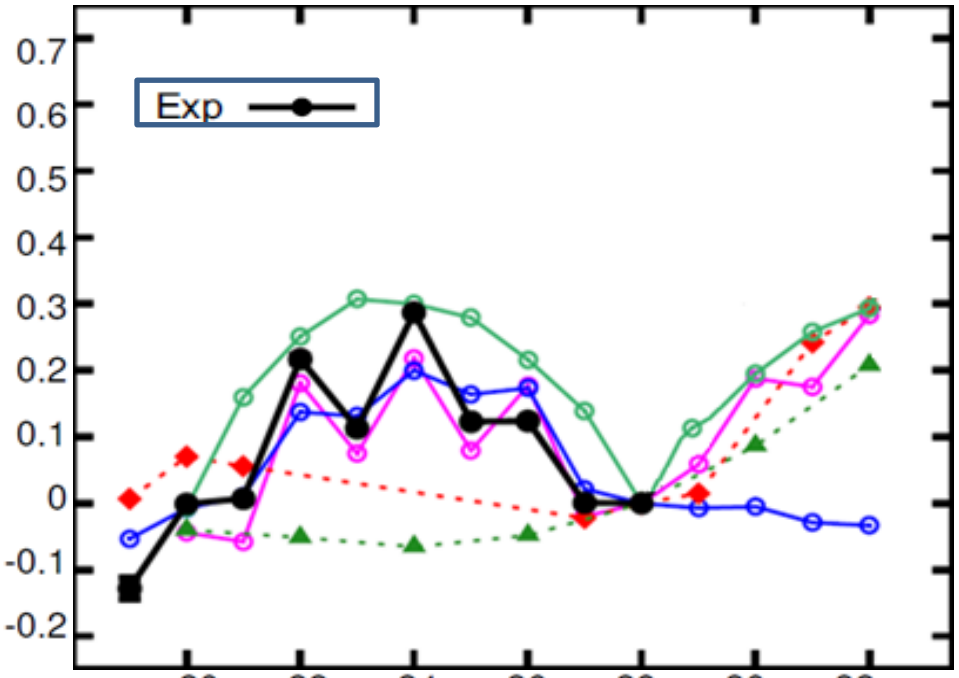
^{52}Ca → S_{2n} [Wienholtz et al. Nature 498, 346 (2013)]

^{54}Ca → *E2* [Steppenbeck et al. Nature 502, 207 (2013)]

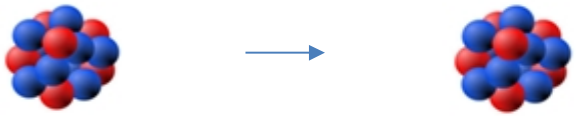
Charge radii of calcium (Z=20) isotopes

[R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]

The charge radii of Ca isotopes present additional challenges



^{40}Ca ^{48}Ca ^{52}Ca



NNLO$_{sat}$ — PRC 91, 051301 (2015); Nature Physics 12, 180 (2016)

ZBM2 — PLB 522, 240 (2001); PRL 113, 052502 (2014); PRC 92, 014305 (2015)

DF3-a — NPA 676, 49 (2000)

UNEDF0 — Nature 486, 509 (2012)

Wang et al. — PRC 88, 011301(R) (2013)

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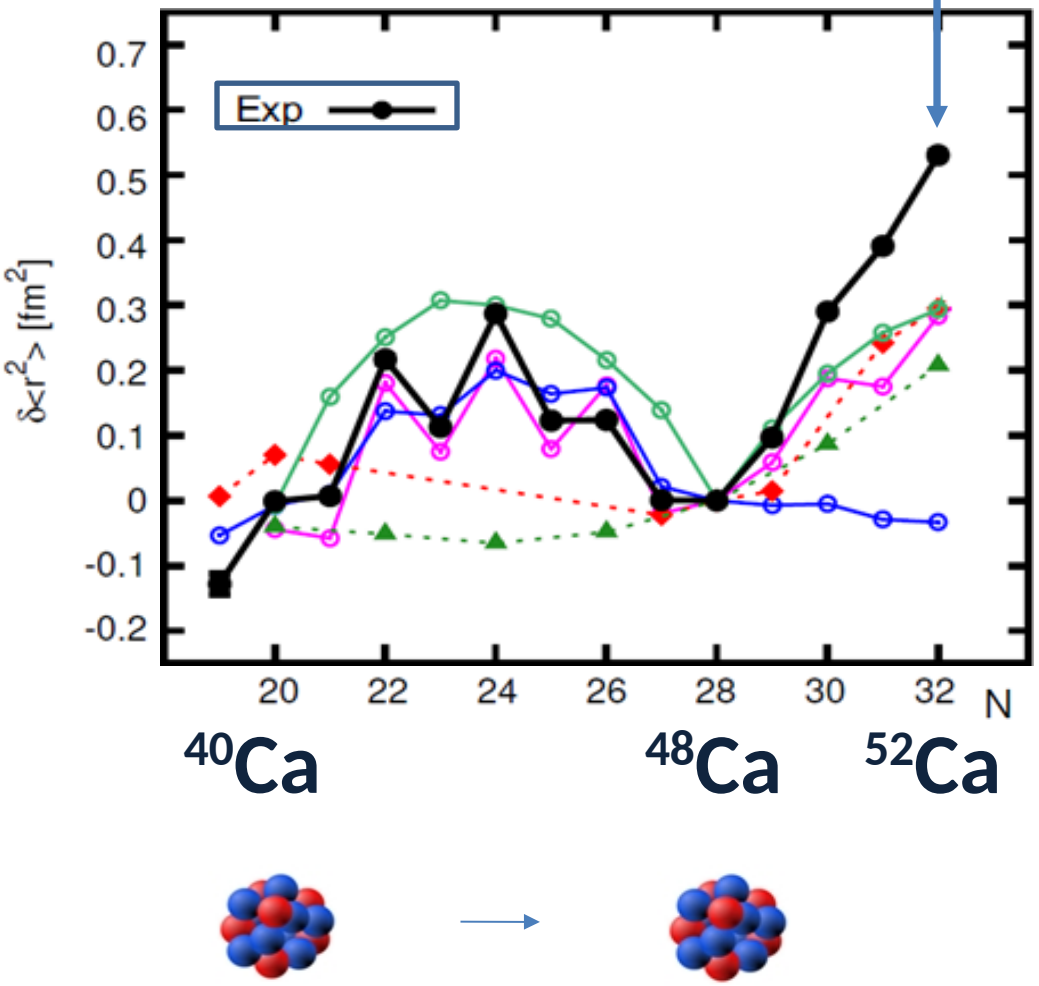
Charge radii of calcium (Z=20) isotopes

[R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]

Much larger than expected!



NNLO$_{sat}$ — PRC 91, 051301 (2015); Nature Physics 12, 180 (2016)

ZBM2 — PLB 522, 240 (2001); PRL 113, 052502 (2014); PRC 92, 014305 (2015)

DF3-a — NPA 676, 49 (2000)

UNEDF0 — Nature 486, 509 (2012)

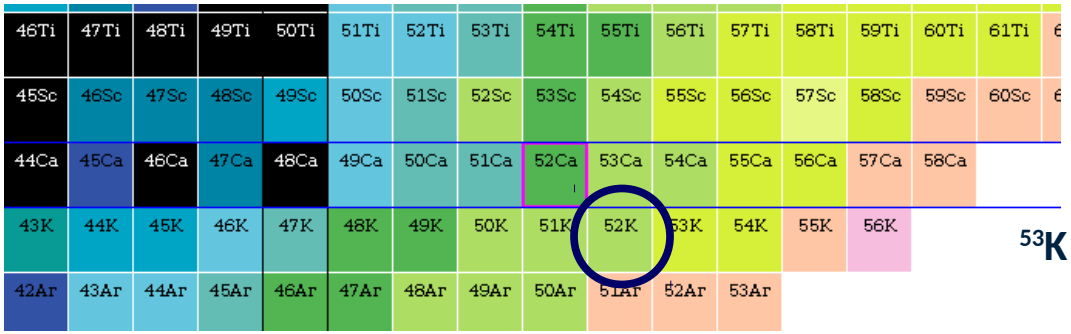
Wang et al. — PRC 88, 011301(R) (2013)

^{36}Ca → <r²> [Miller et al. Nature Phy., 15, 432 (2019)]

^{52}Ca → S_{2n} [Wienholtz et al. Nature 498, 346 (2013)]

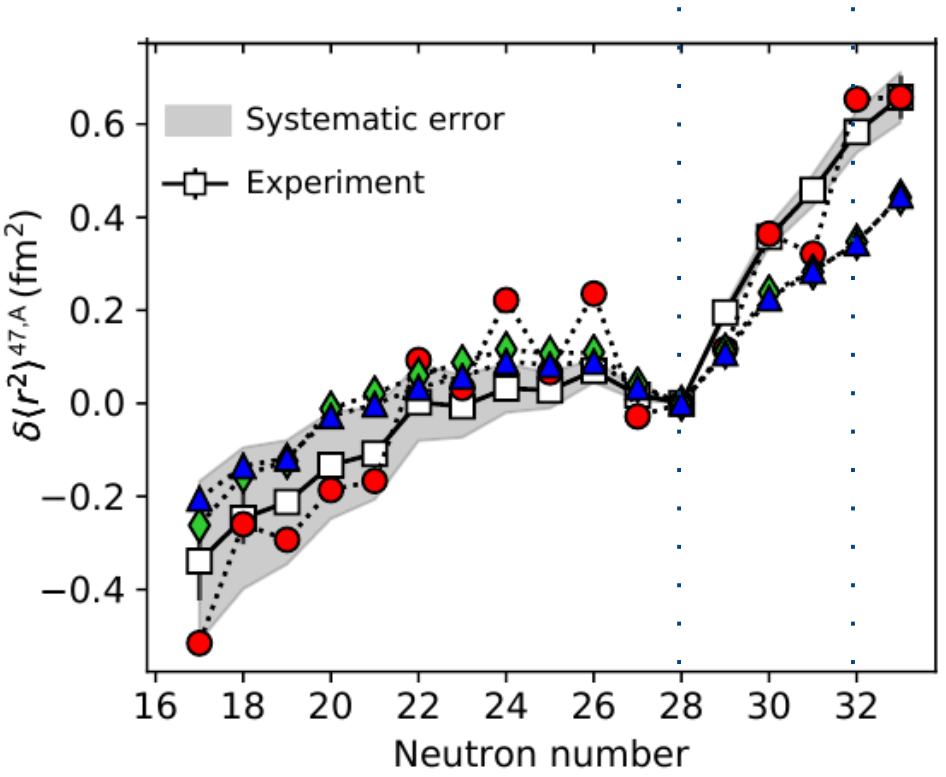
^{54}Ca → *E2* [Steppenbeck et al. Nature 502, 207 (2013)]

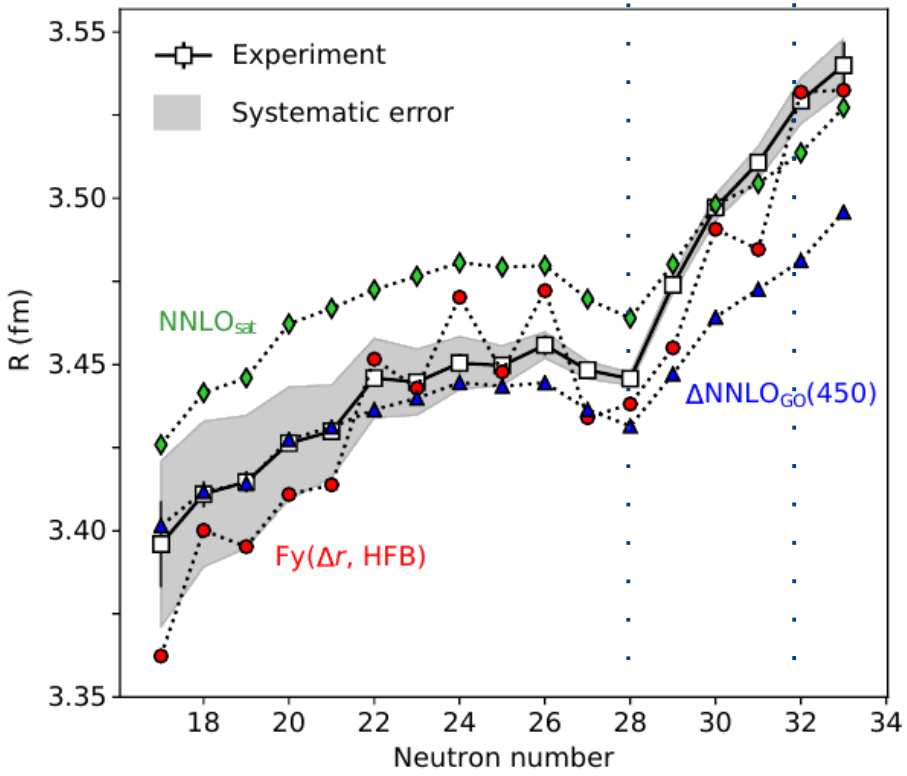
Charge radii of K (Z=19) isotopes



^{53}K ~ 100 ions/s
τ~ 110 ms

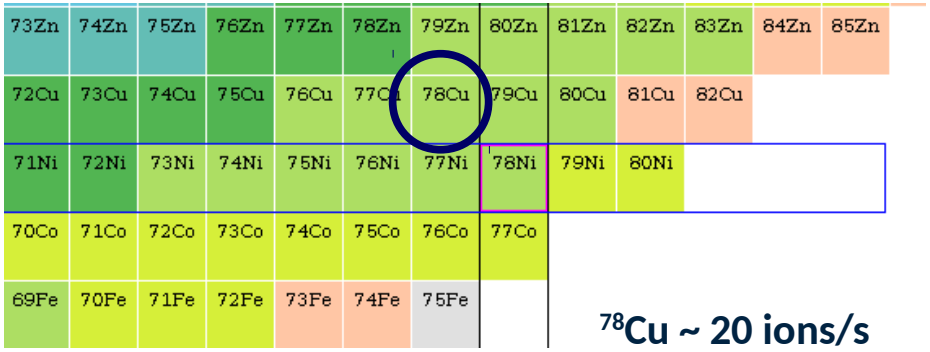
A. Koszorus



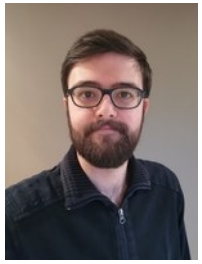


Koszorus et al. Submitted to Nature Phys. (2020)

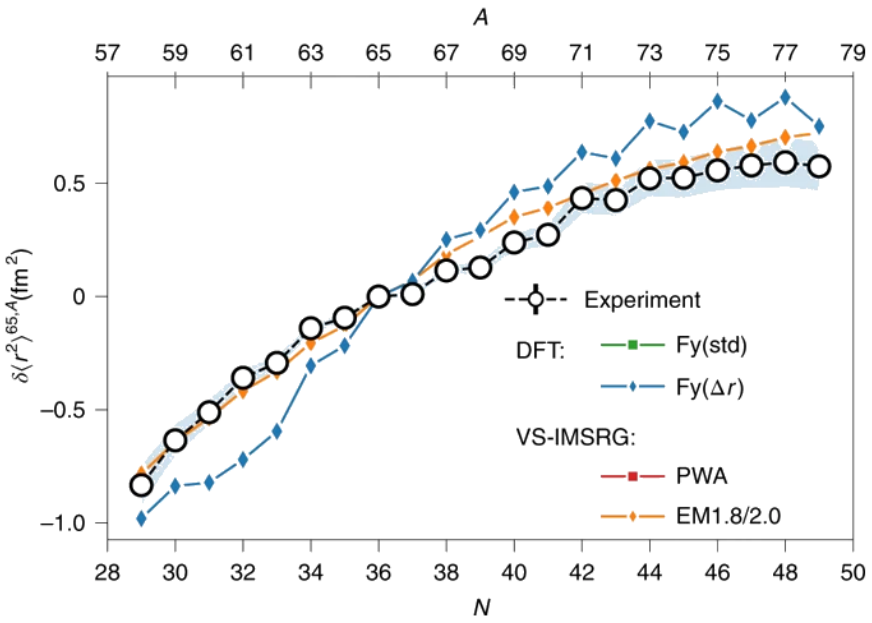
Charge radii of Cu (Z=29) isotopes

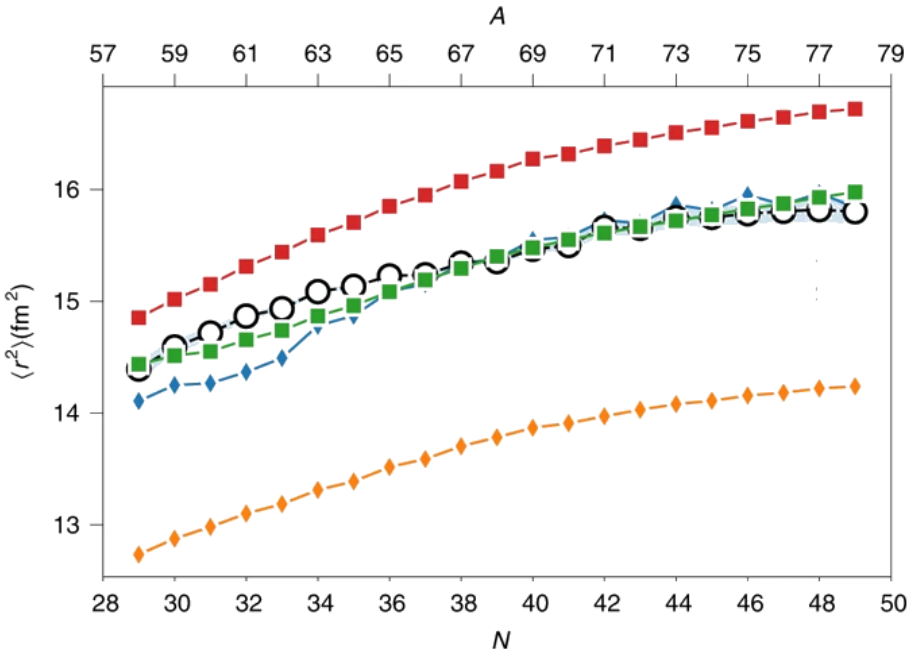


^{78}Cu ~ 20 ions/s



R. de Groote

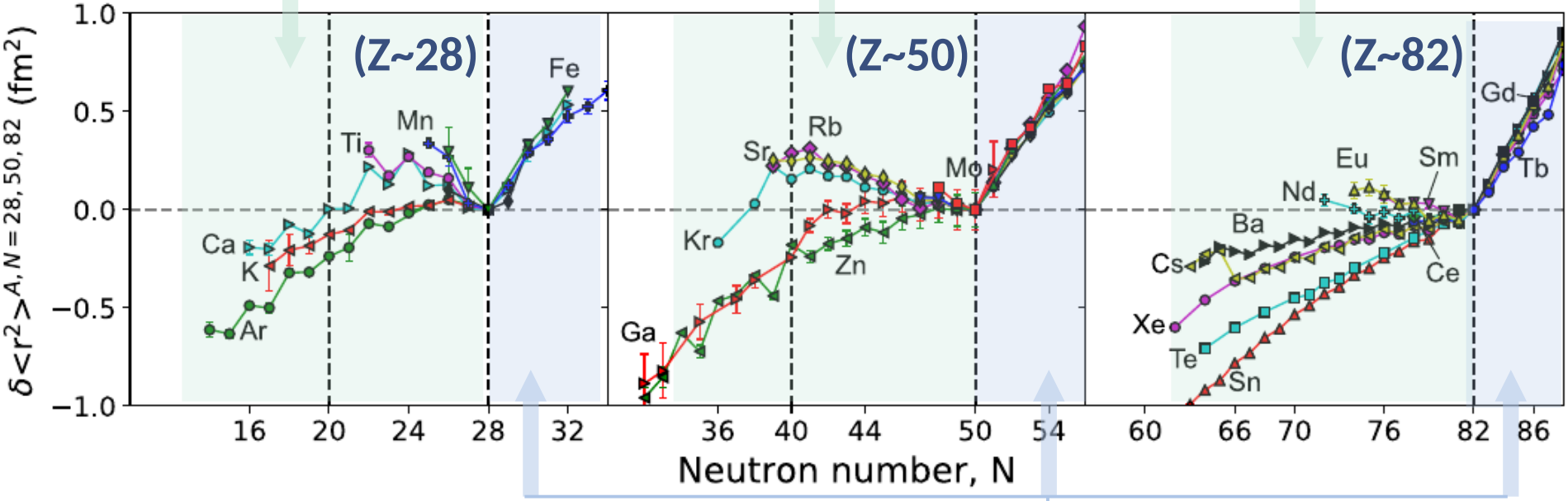




[Groote et al. Nature Physics 16, 620 (2020)]

Nuclear charge radii across closed-shells

Strong Z dependence



Similar trends for neutron-rich

[Garcia Ruiz & Vernon EPJ A 56, 136 (2020)]

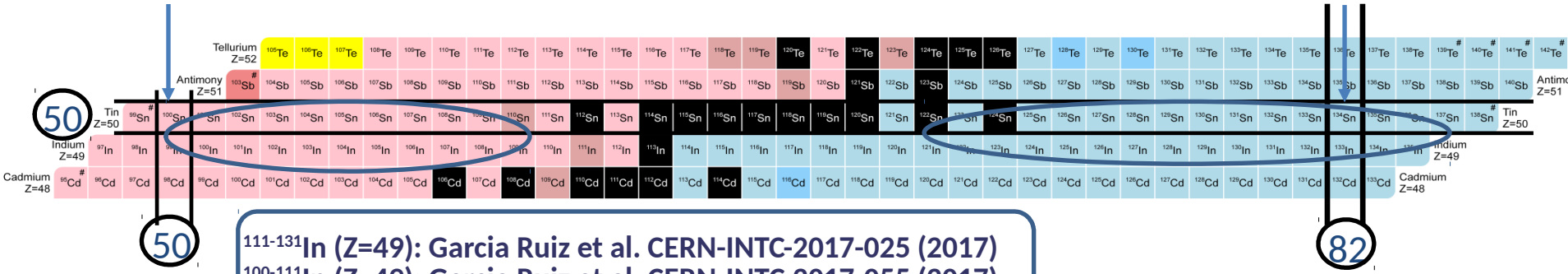
Nuclear structure around ^{100}Sn (Z=50) and ^{132}Sn

Doubly "magic" ^{100}Sn?

[Hinke *et al.* Nature 486, 341 (2012)]

Doubly "magic" ^{132}Sn

[Jones *et al.* Nature 465, 454 (2010)]



$^{111-131}$In (Z=49): Garcia Ruiz et al. CERN-INTC-2017-025 (2017)
$^{100-111}$In (Z=49): Garcia Ruiz et al. CERN-INTC-2017-055 (2017)
$^{103-121}$Sn (Z=50): Garcia Ruiz et al. CERN-INTC-2016-037 (2016)


A. Vernon


C. Binnersley


C. Rikketts

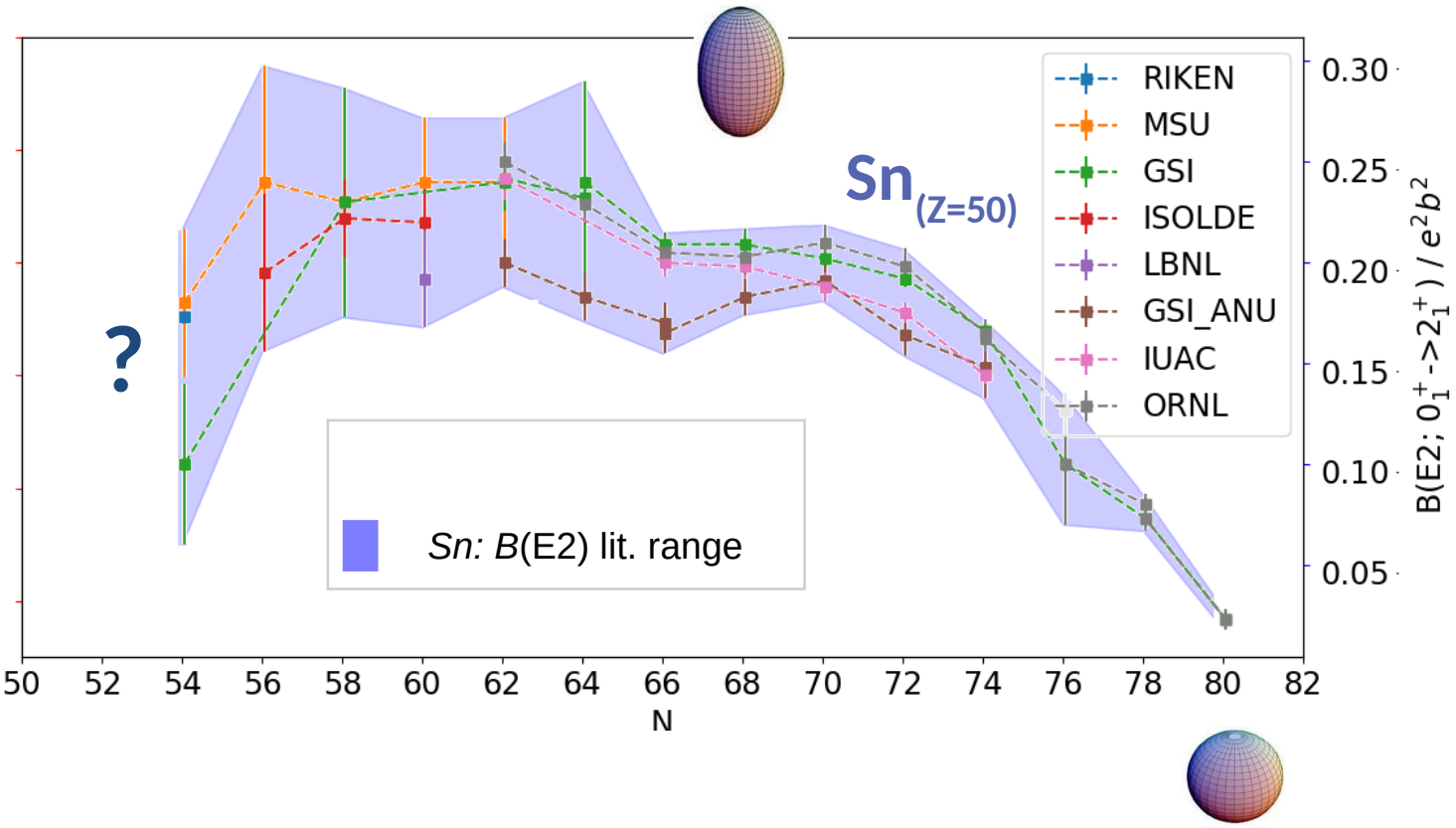

F. Parnefjord

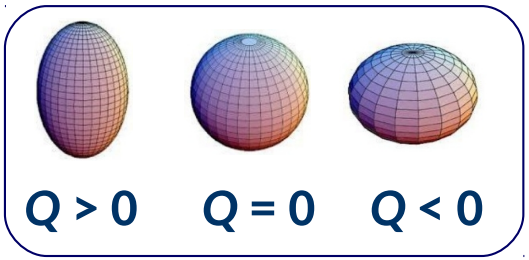
Evolution of collectivity towards ^{100}Sn and ^{132}Sn?

Sn (Z=50) region: Forefront of theoretical developments!

<u>Theoretical progress around ^{100}Sn:</u>
[Gysbergs et al. Nature Phys. 15, 428 (2019)]
[T. Morris et al. Phys. Rev. Lett. 120, 152503 (2018)]
[Togashi et al. Phys. Rev. Lett. 121, 062501 (2018)]

Nuclear structure around ^{100}Sn (Z=50) and ^{132}Sn





Nuclear structure around ^{100}Sn (Z=50) and ^{132}Sn

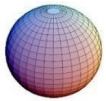
PRELIMINARY

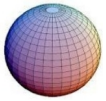
Sn$_{(Z=50)}$

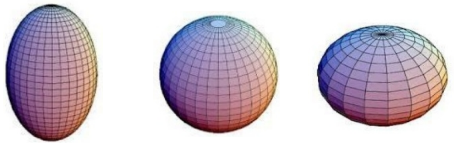
In$_{(Z=49)}$

In: Q_s This work I=9/2$^+$

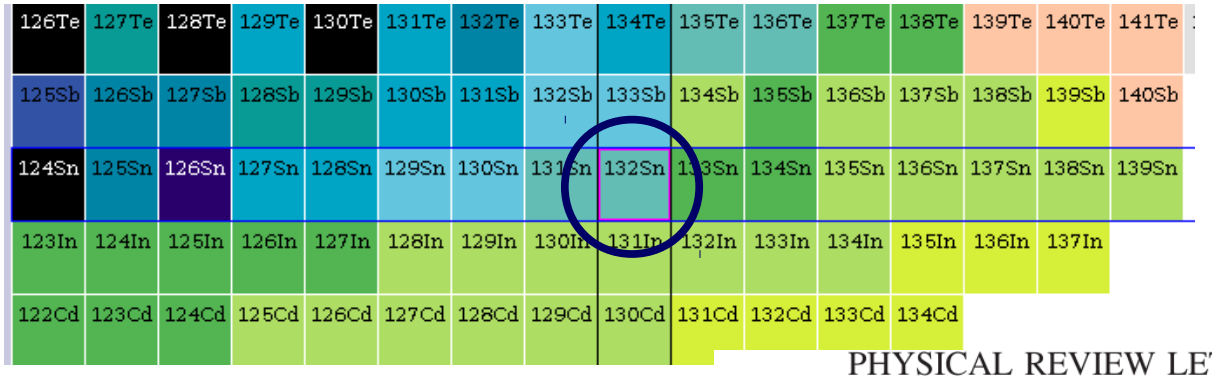
Sn: *B*(E2) lit. range







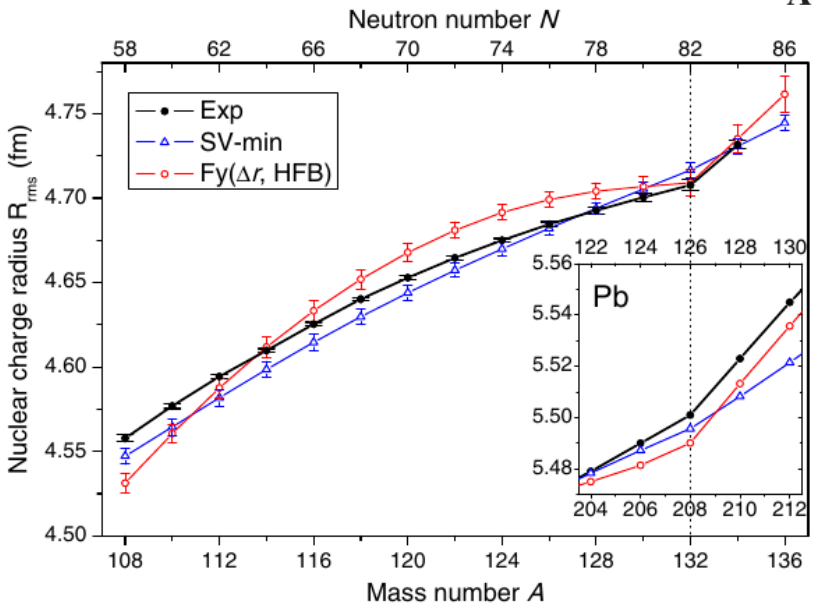
Charge radii of Sn (Z=50) isotopes



PHYSICAL REVIEW LETTERS **122,** 192502 (2019)

Editors' Suggestion Featured in Physics

Laser Spectroscopy of Neutron-Rich Tin Isotopes: A Discontinuity in Charge Radii across the $N = 82$ Shell Closure

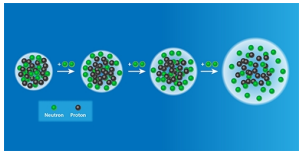


C. Gorges

Exotic atoms: Our recent highlights

Tin (Z=50) region

[Phys. Rev. Lett. 122, 192502 (2019)]
[Phys Rev X 8, 041005 (2018)]...

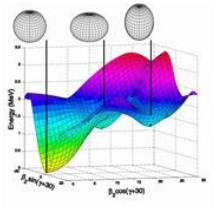


Physics VIEWPOINT
Editors' Suggestion
Featured in Physics

Physics VIEWPOINT
Featured in Physics

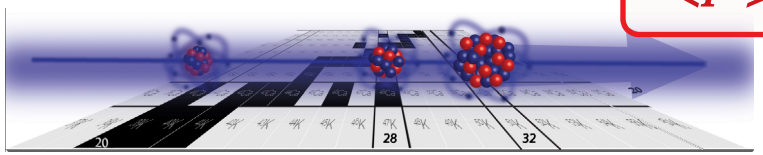
Nickel (Z=28) region

[^{78}Cu: Nature Phys. 16, 620 (2020)]
[Phys. Rev. Lett. 124, 132502 (2020)
[Phys Rev Lett 116, 182502 (2016)]
[Phys Lett B 771, 385 (2017)]
...



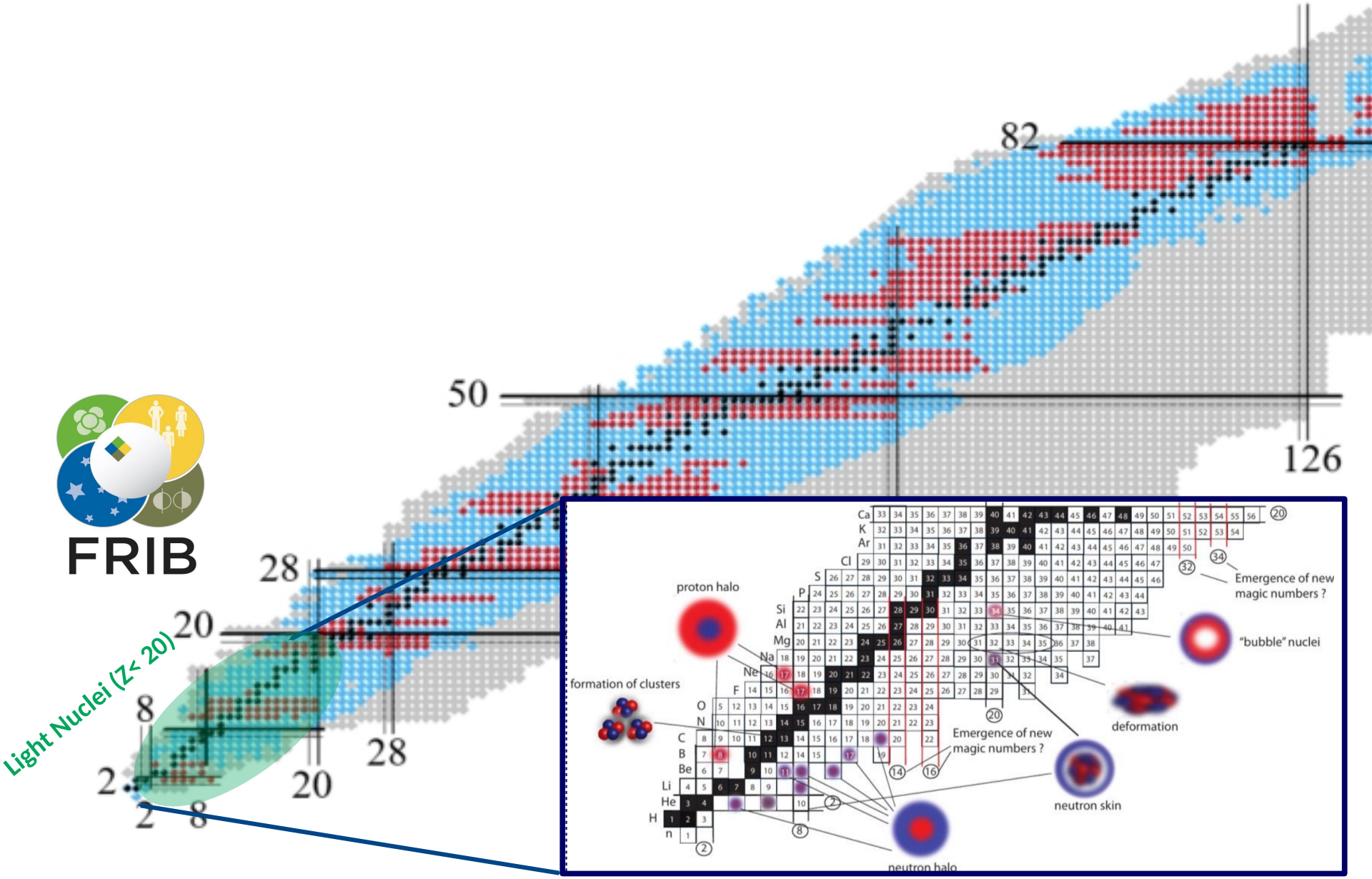
Calcium (Z=20) region

[Nature Physics 12, 594 (2016)]
[Phys Rev Lett 113, 052502 (2014)]
[Phys Rev Lett 110, 172503 (2013)]. . .



$\langle r^2 \rangle$ I Q μ

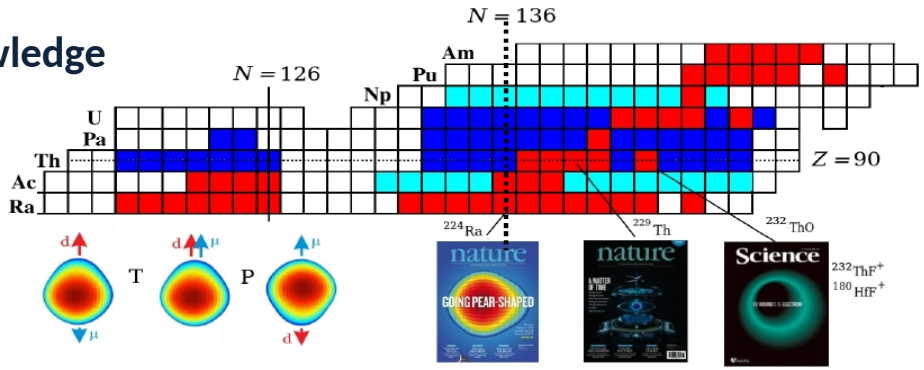
A bright future ahead!



FRIB

A bright future ahead!

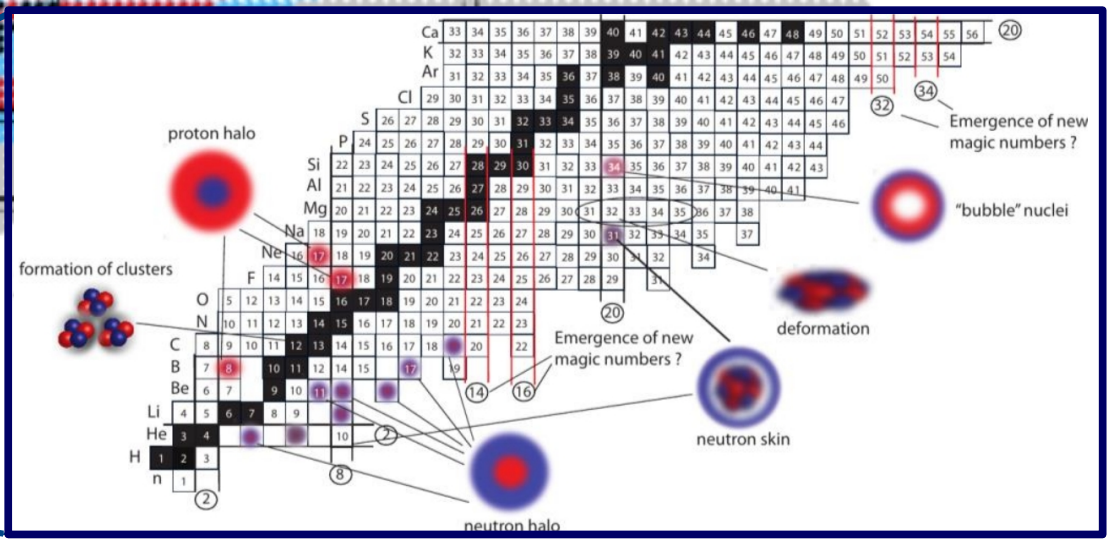
Experimental knowledge
FRIB year 1
FRIB > year 2



Actinides (Z>88)

50
126
28
20
8
2
28
20
8
2

Light Nuclei (Z< 20)



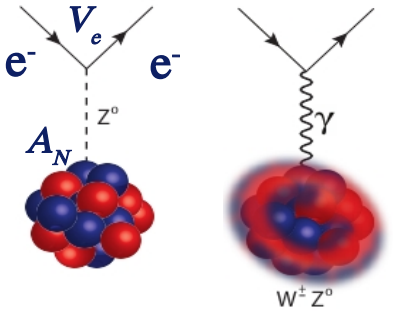
FRIB

Contents

- Why (Exotic) atoms & molecules?
- Precision laser spectroscopy
- Exotic atoms: Recent highlights
- **Exotic molecules: Recent Results**
- Summary & Outlook

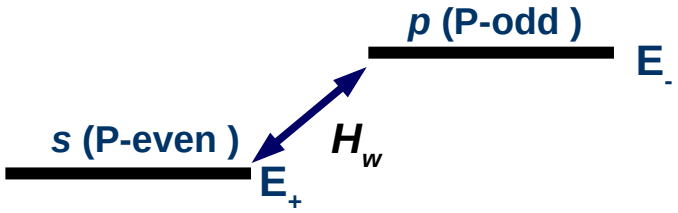
Parity violation

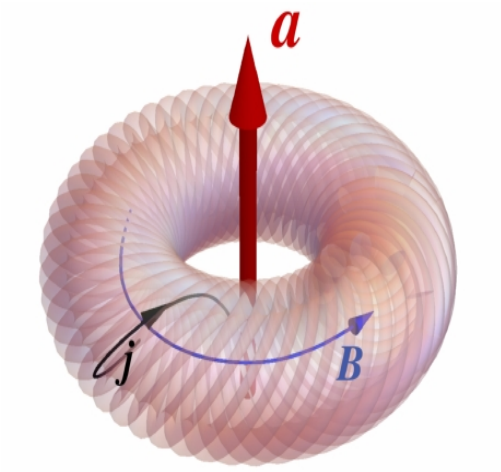
P- violation



$$E_{PNC} \sim \frac{\langle \text{P-odd}|H_w|\text{P-even}\rangle}{E_- - E_+}$$

Atoms: (E_+- E_-) ~ 1 eV

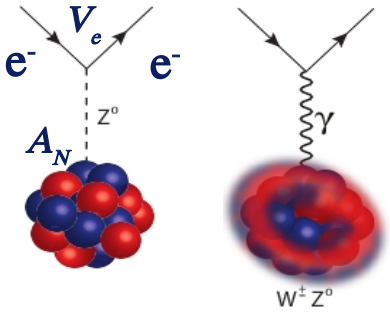




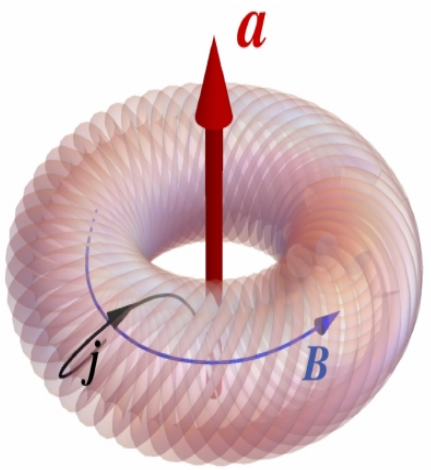
[Safronova et al. RMP 90, 025008 (2018)]
[Wood et al. Science 275, 1759 (1997)]

Parity violation

P- violation



$\sim Z^3$ $\sim Z^2A^{2/3}R(Z)$

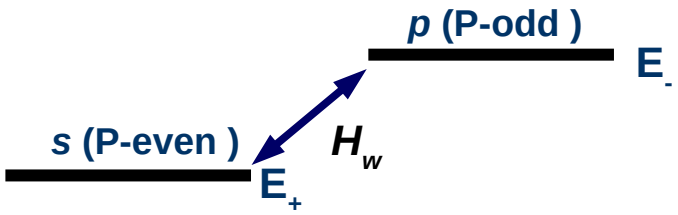


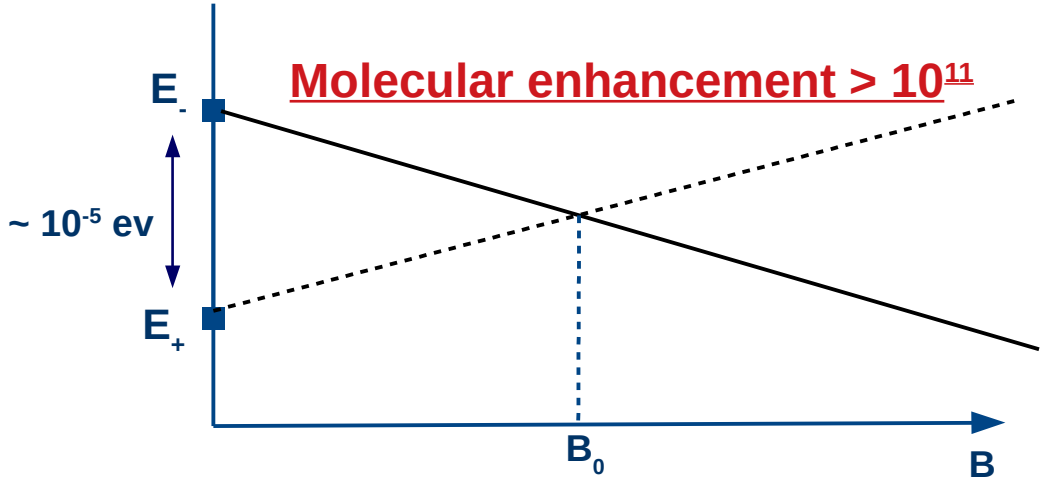
$$E_{PNC} \sim \frac{\langle \text{P-odd}|H_w|\text{P-even}\rangle}{E_- - E_+}$$

Atoms: (E_+- E_-) ~ 1 eV

Molecules: (E_+- E_-) ~ 10^{-5} ev

[Safronova et al. RMP 90, 025008 (2018)]
[Wood et al. Science 275, 1759 (1997)]





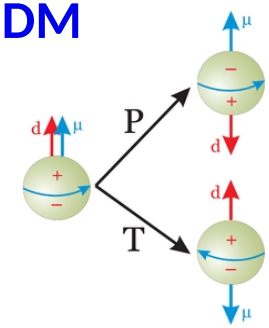
Molecular enhancement > 10^{11}

Demille's group@ Yale
[Phys Rev Lett 120, 142501 (2018)]
[Phys. Rev. Lett. 119, 223201 (2017)]

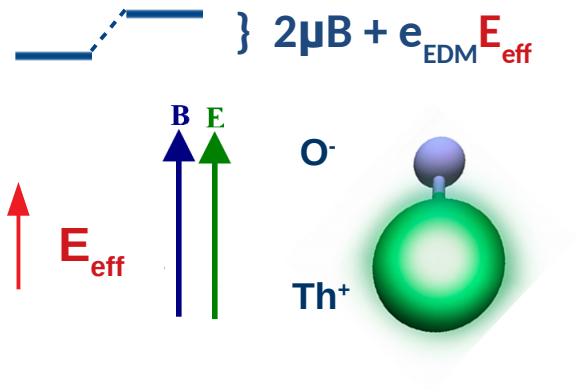
Parity & Time reversal violation

P,T- violation

EDM

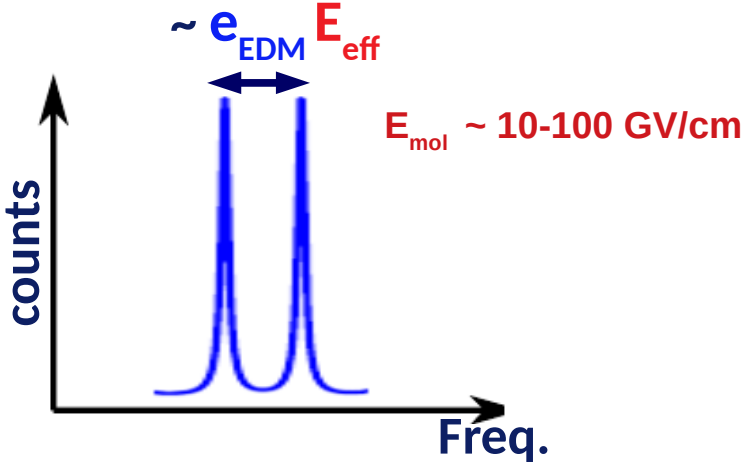


$\sim Z^3 R(Z)$

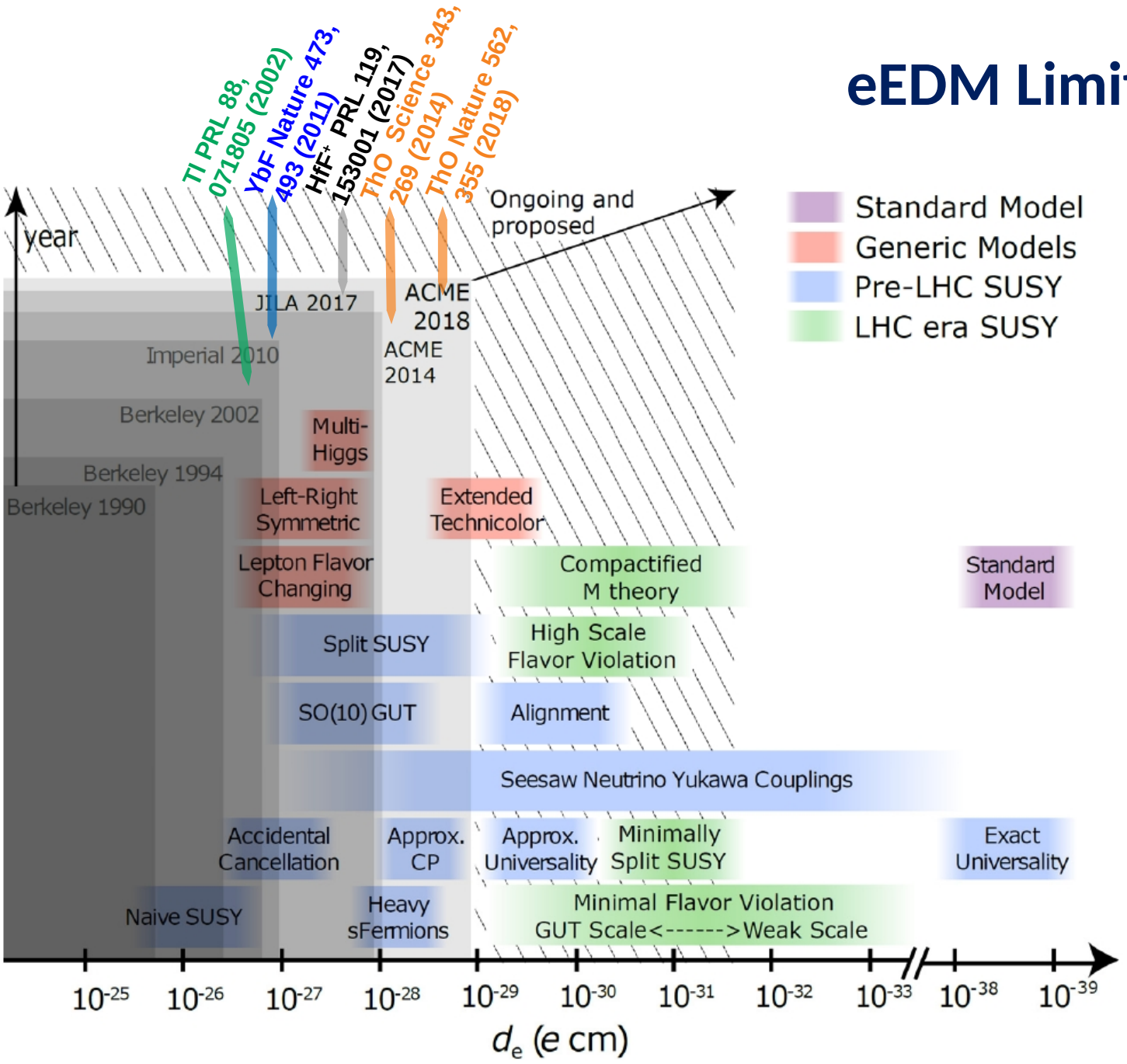


E_{ext} ~1 V/cm

E_{eff} ~80 GV/cm



eEDM Limits

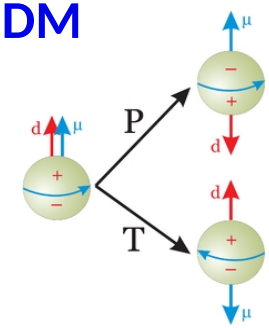


[Source: D. DeMille. Manipulating Quantum Systems: An Assessment of Atomic,Molecular, and Optical Physics in the United States (2019)]

Parity & Time reversal violation

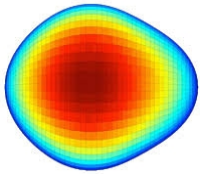
P,T- violation

EDM



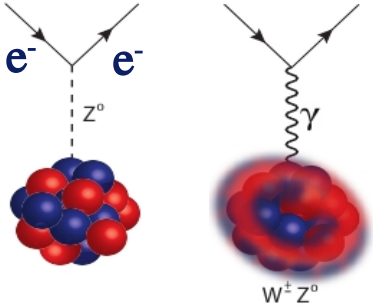
$\sim Z^3 R(Z)$

S_{schiff}



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

P- violation

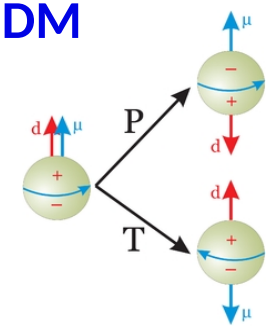


$\sim Z^3$ $\sim Z^2 A^{2/3} R(Z)$

Parity & Time reversal violation

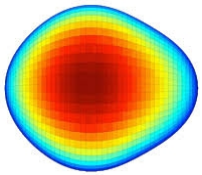
P,T- violation

EDM



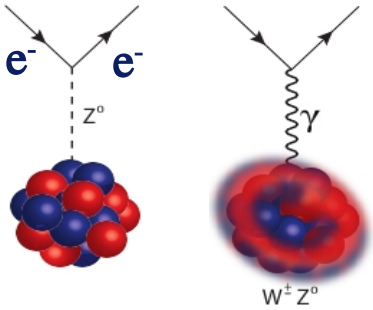
$\sim Z^3 R(Z)$

S_{schiff}



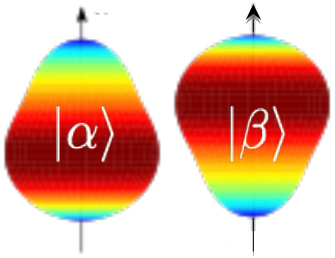
$\sim Z^3 \beta_2\beta_3 A^{2/3} / (E_+ - E_-)$

P- violation



$\sim Z^3$ $\sim Z^2 A^{2/3} R(Z)$

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



^{225}Ra

$\Delta E = 55$ keV

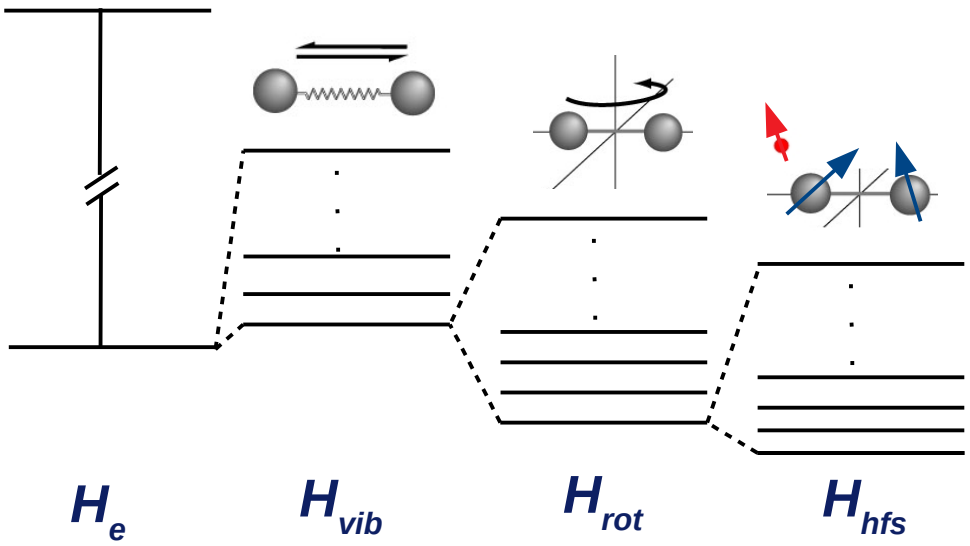
Exotic nuclei →

- Max. Z, A, *I*>0
- Max. β_2, β_3
- Min. $(E^N_+ - E^N_-)$

Exotic molecules: Best of all worlds

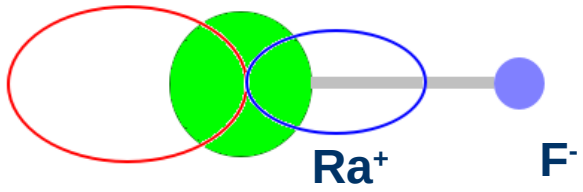
Recent Results (RaF)

Collinear resonance ionization spectroscopy of RaF molecules
[Garcia Ruiz, Berger et al. CERN-INTC-2018-017 (2018)]



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

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



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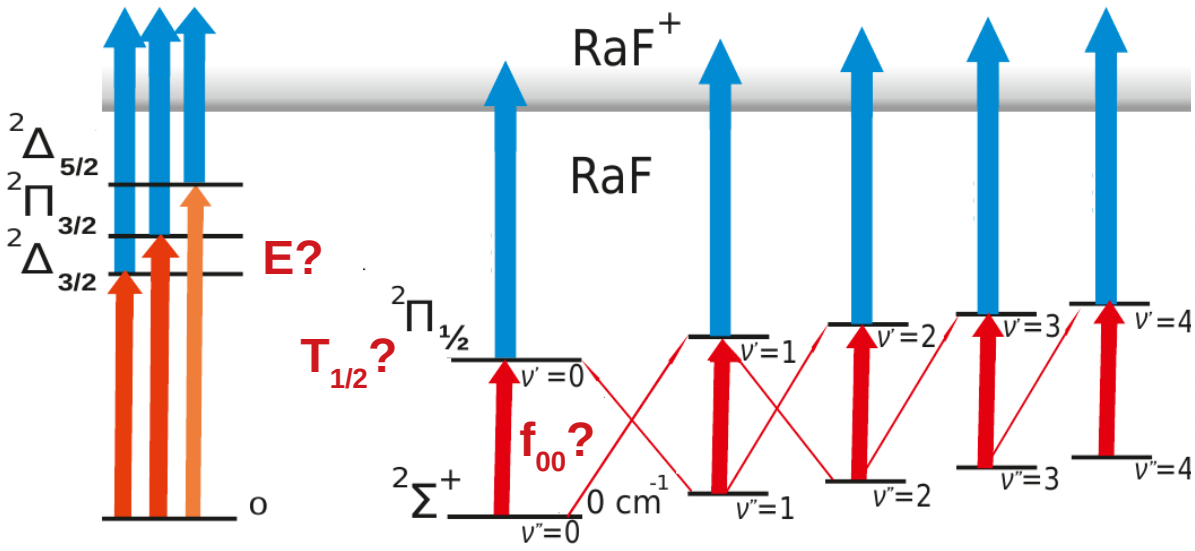


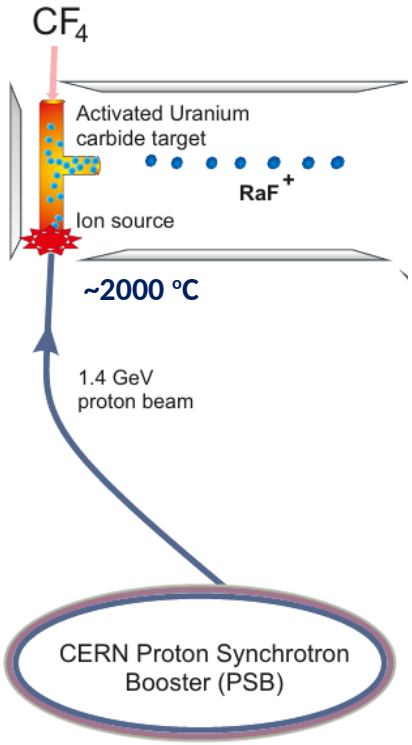
I. **Low-lying structure?**
II. **Feasibility of laser cooling?**
   1. **Dominant f_{00}?**
   2. **Short-lived excited state ($T_{1/2}$)?**
   3. **Electronic states of lower energy (E)?**

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

SrF: First evidence of laser cooling
[Shuman et al. Nature 467, 820-823 (2010)]

[Isaev et al. Phys. Rev. A 82, 052521(2010)]

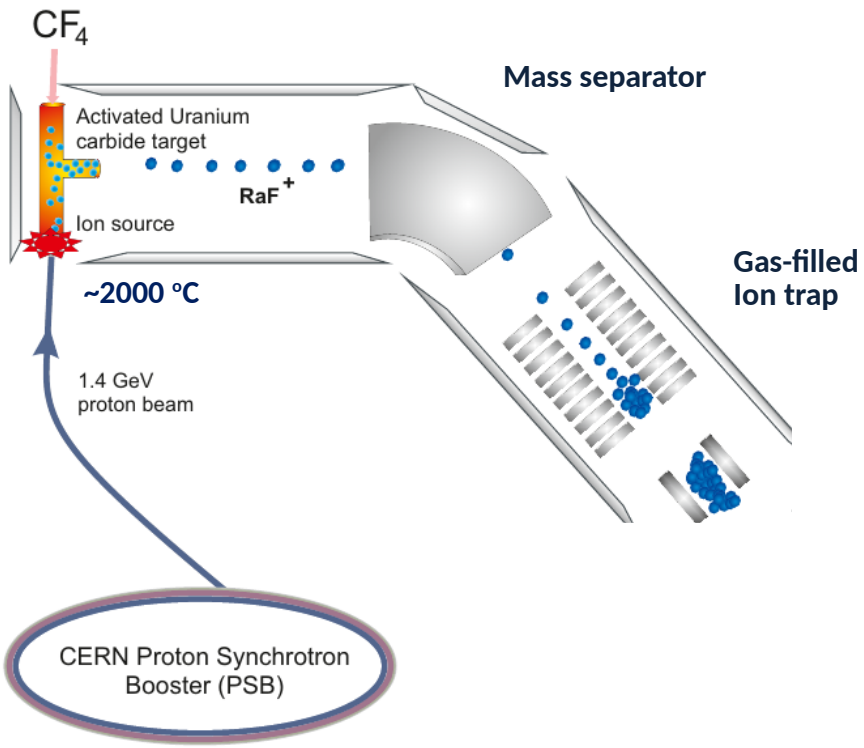
Recent Results (RaF)



$$Ra^+ \xrightarrow{CF_4} RaF^+$$

[Garcia Ruiz et al. Nature 581, 396 (2020)]

Recent Results (RaF)



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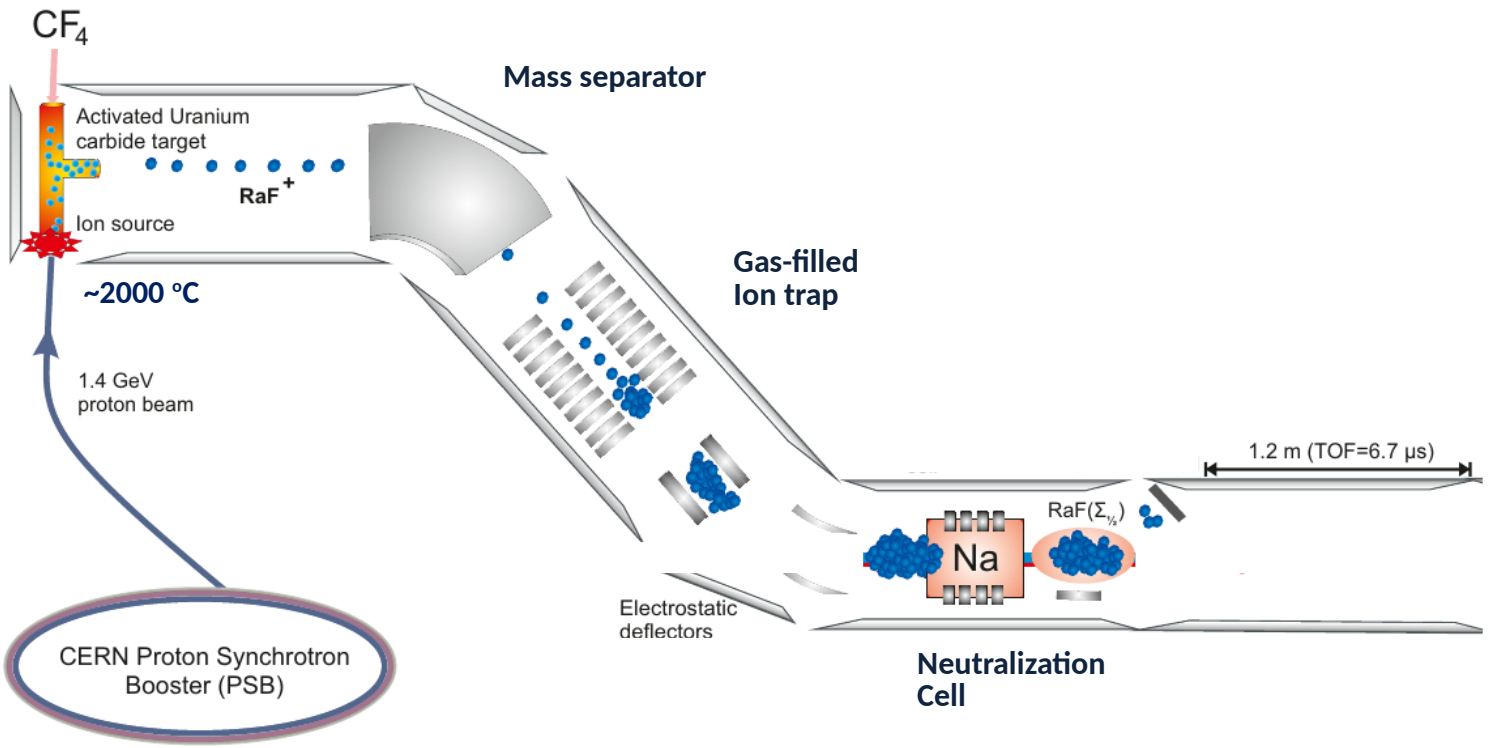

$$\mathrm{Ra}^+ \xrightarrow{\mathrm{CF_4}} \mathrm{RaF}^+ \xrightarrow{\mathrm{Na}} \mathrm{RaF}(^2\Sigma)$$

[Garcia Ruiz et al. Nature 581, 396 (2020)]

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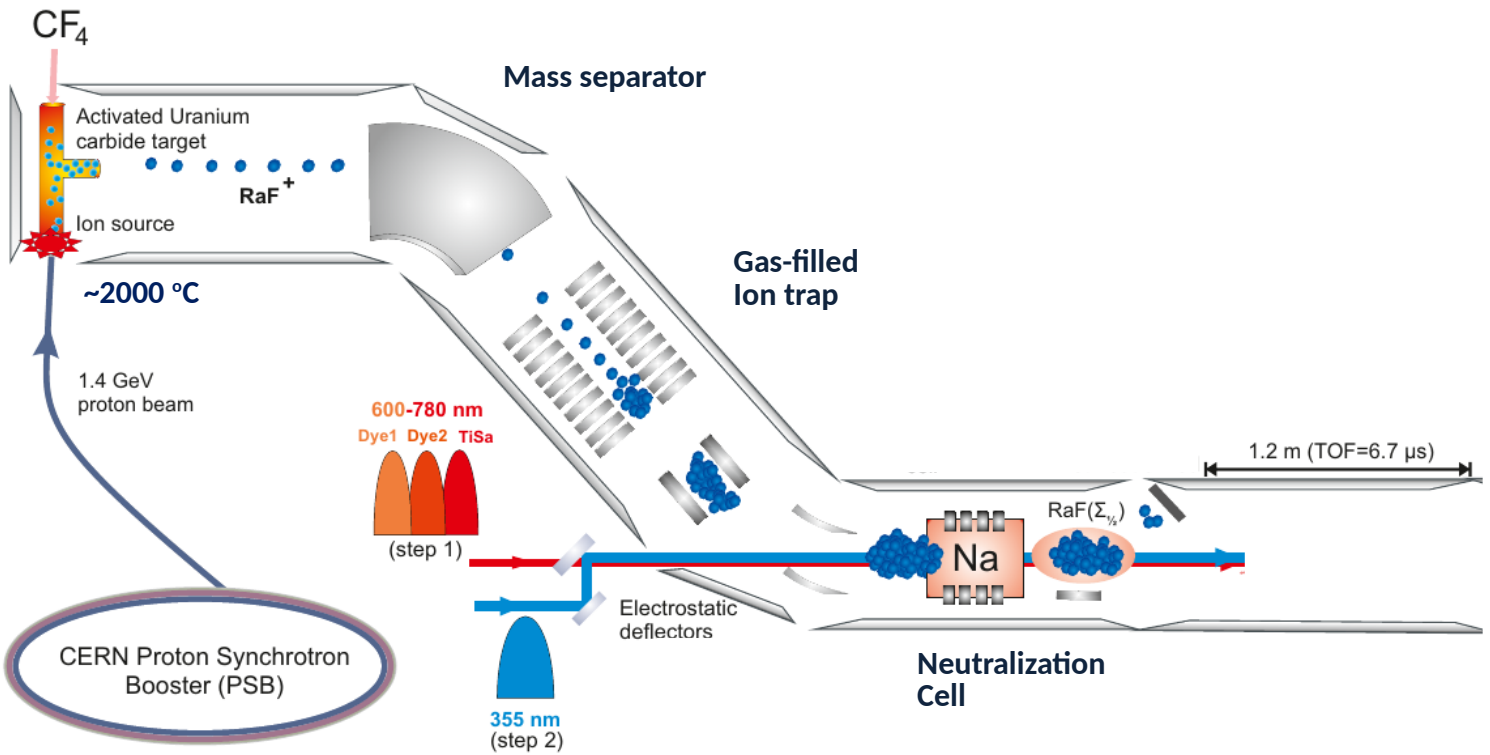

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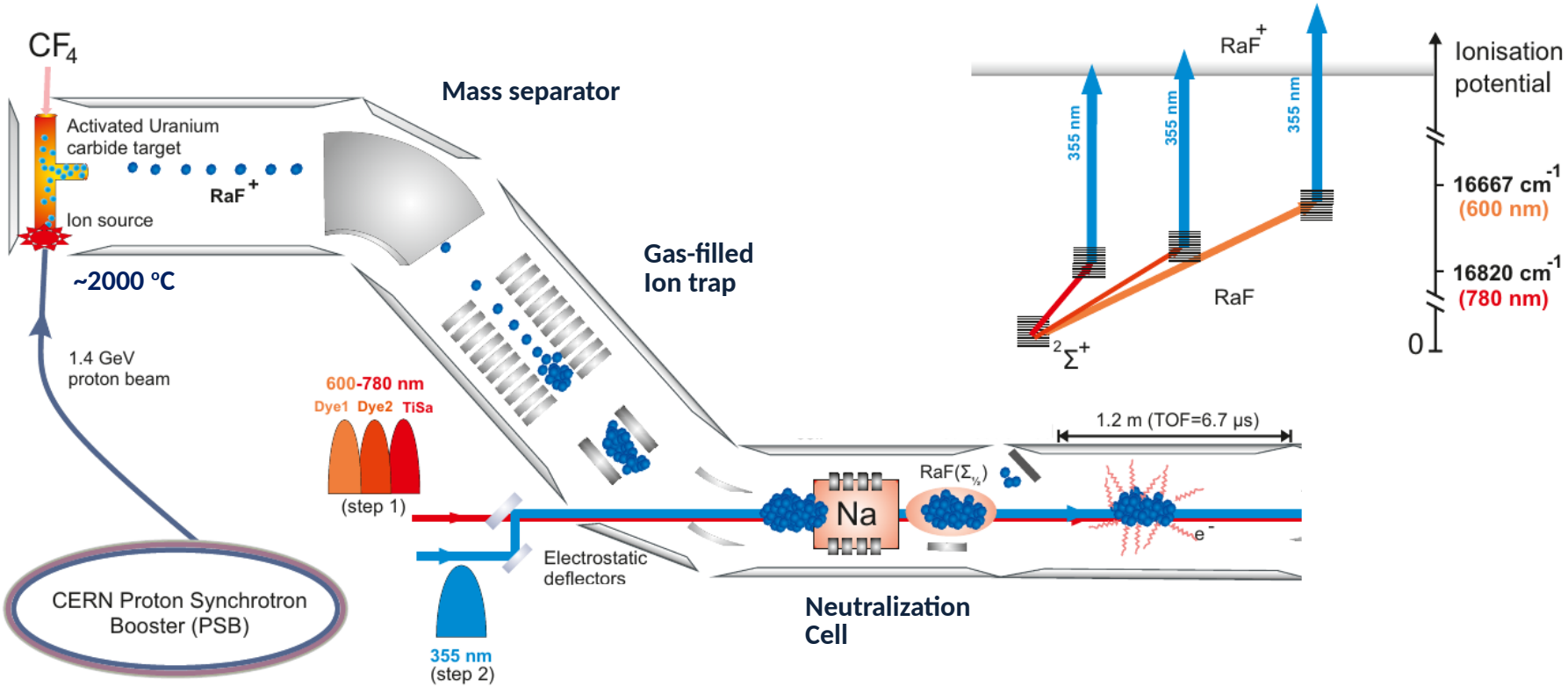

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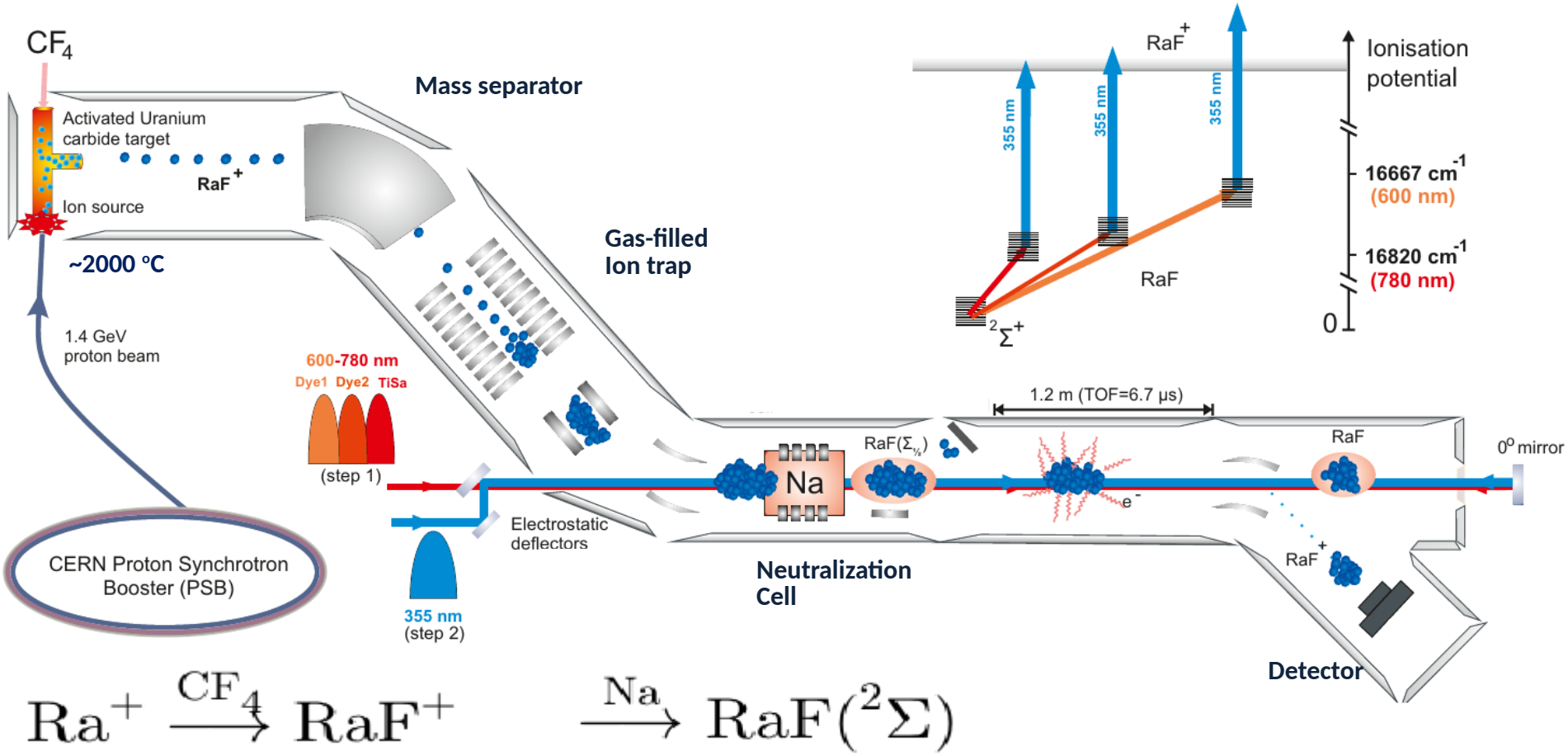

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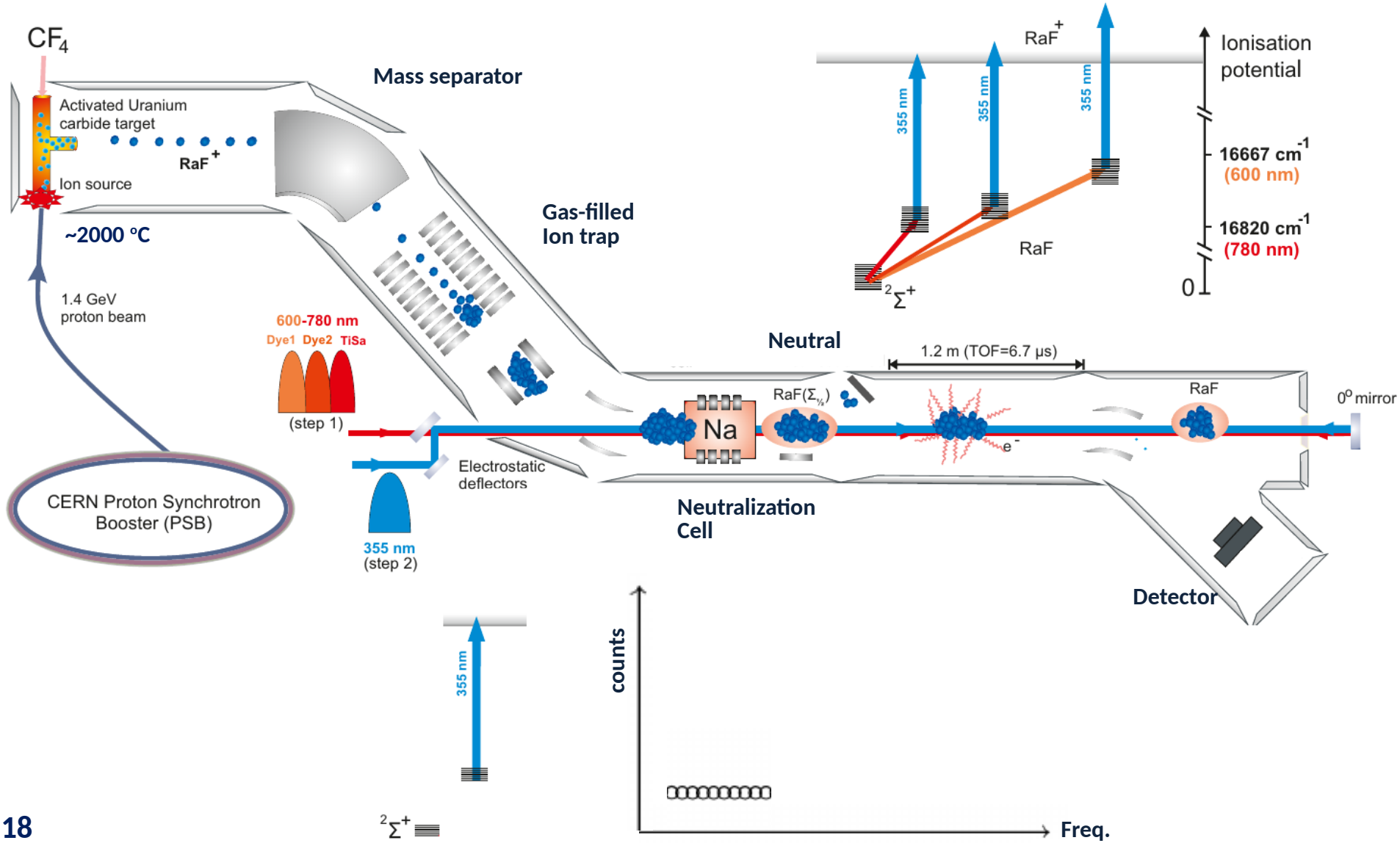

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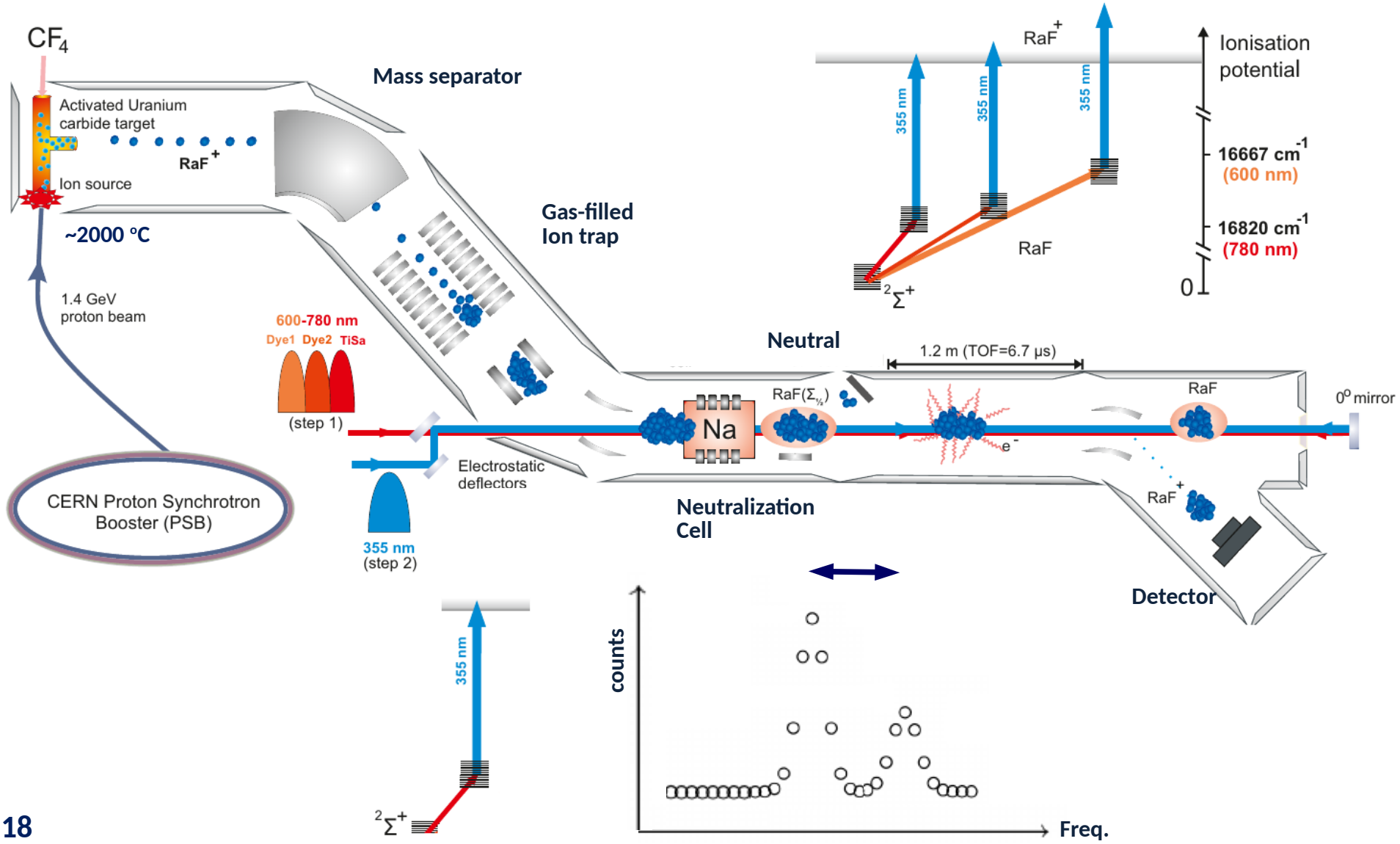

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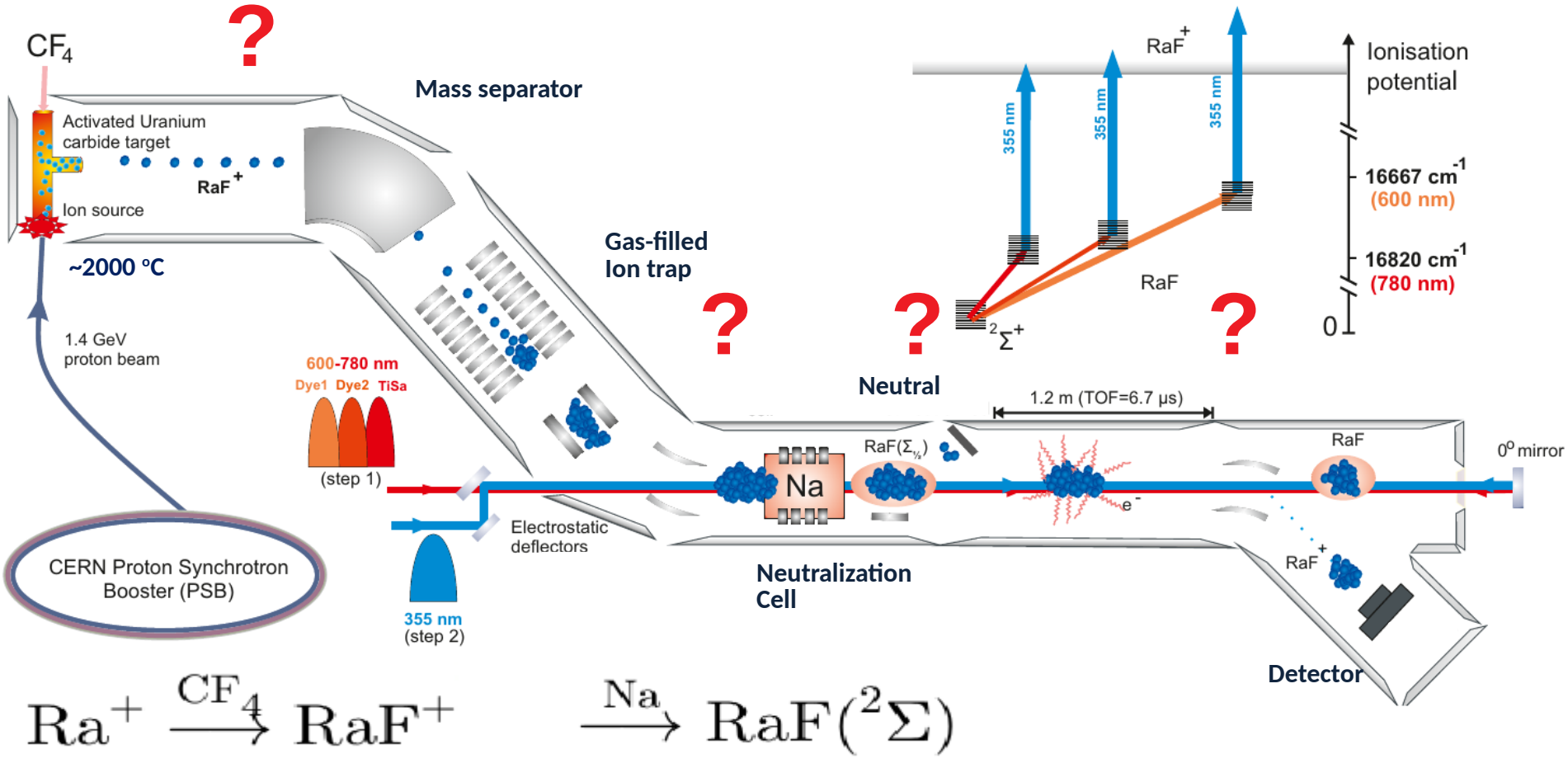

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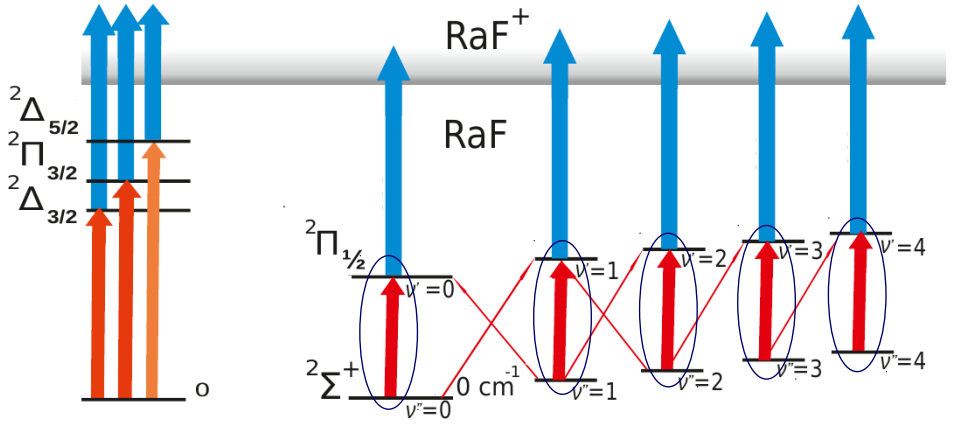

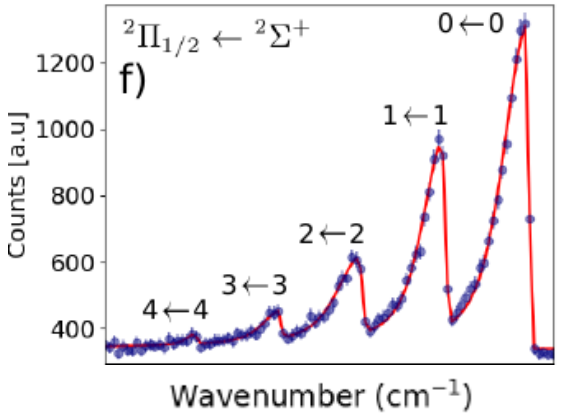

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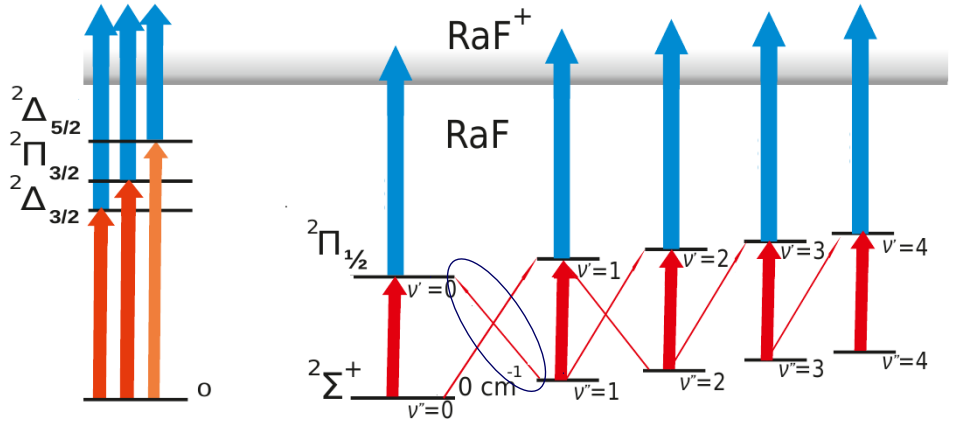

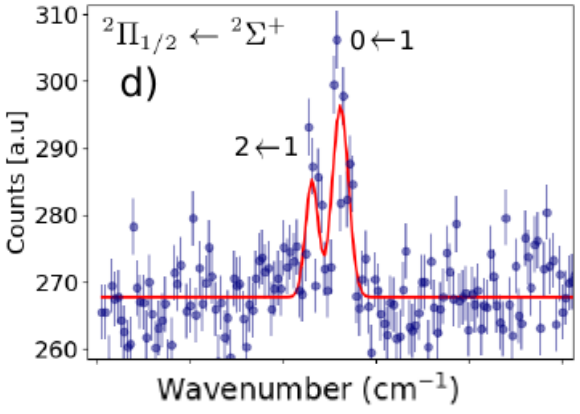

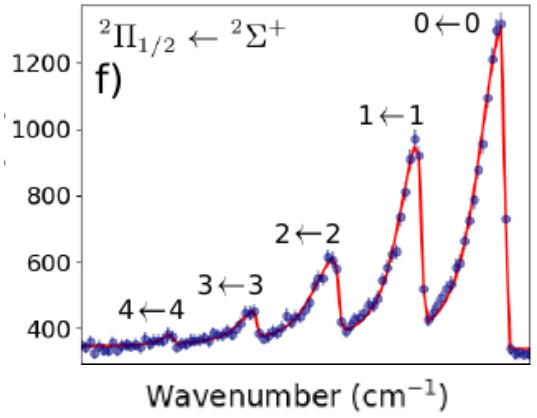

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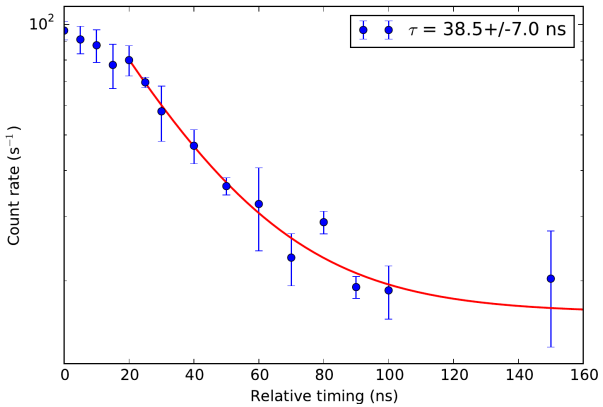

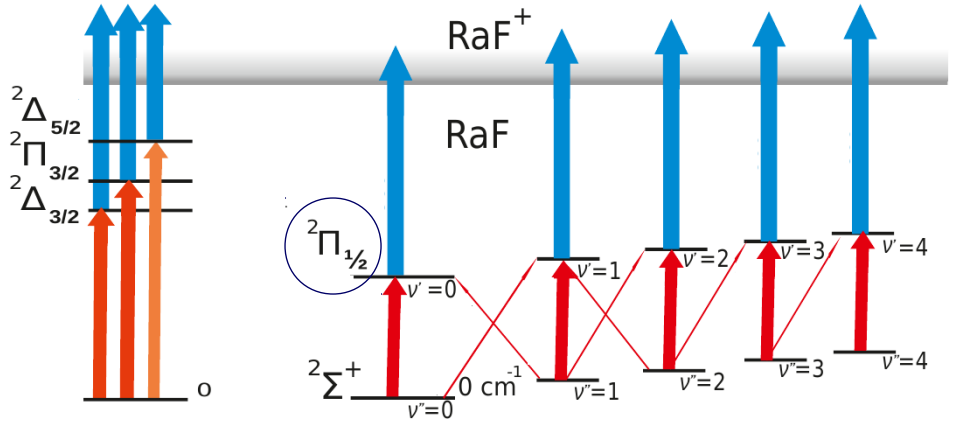

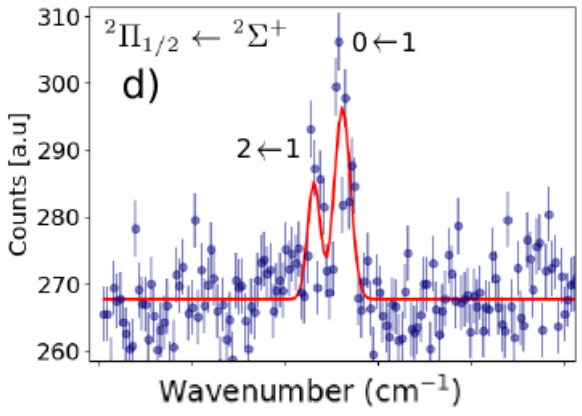

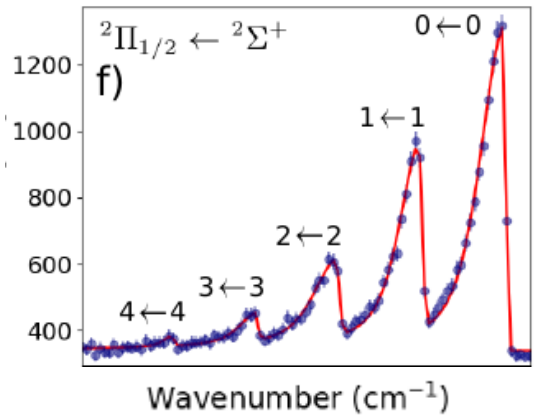

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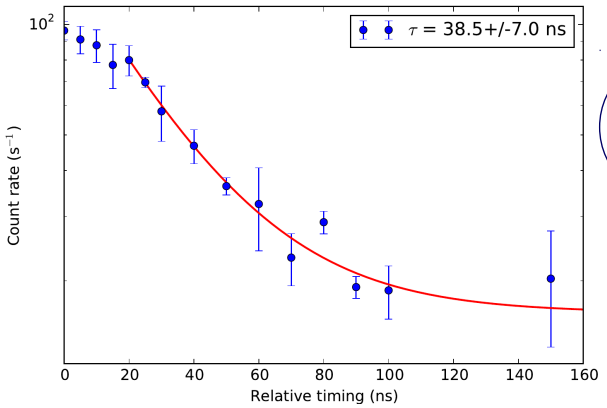

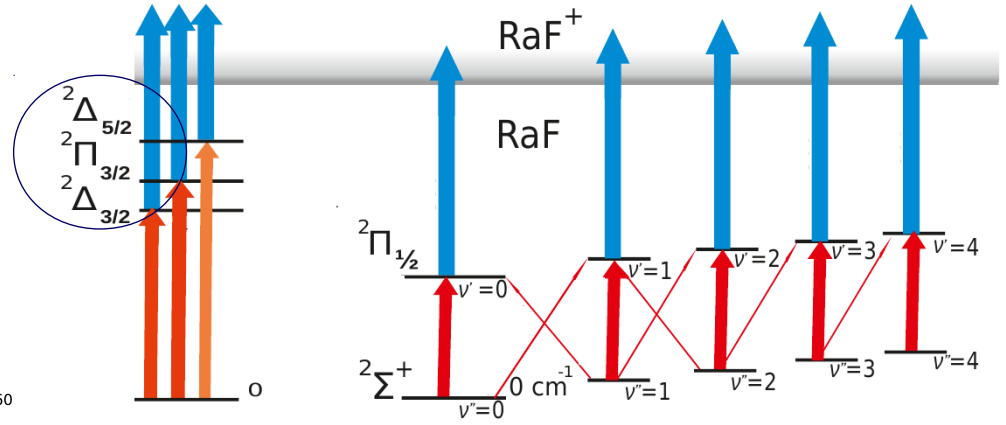

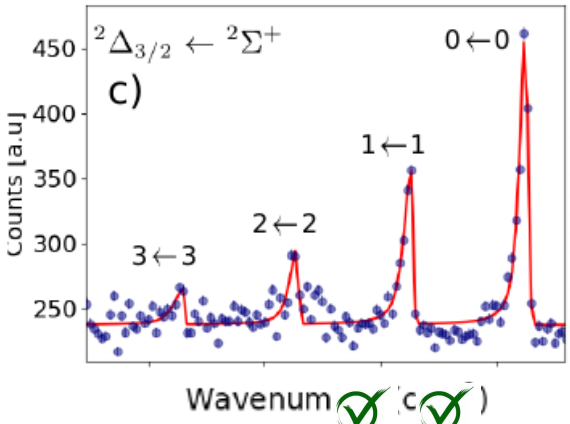

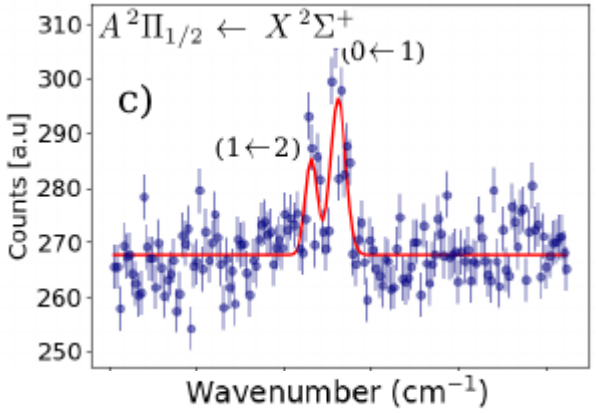

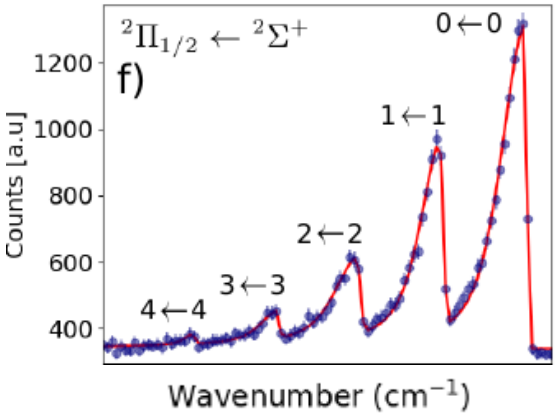

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"Hot" molecules can be super cool!

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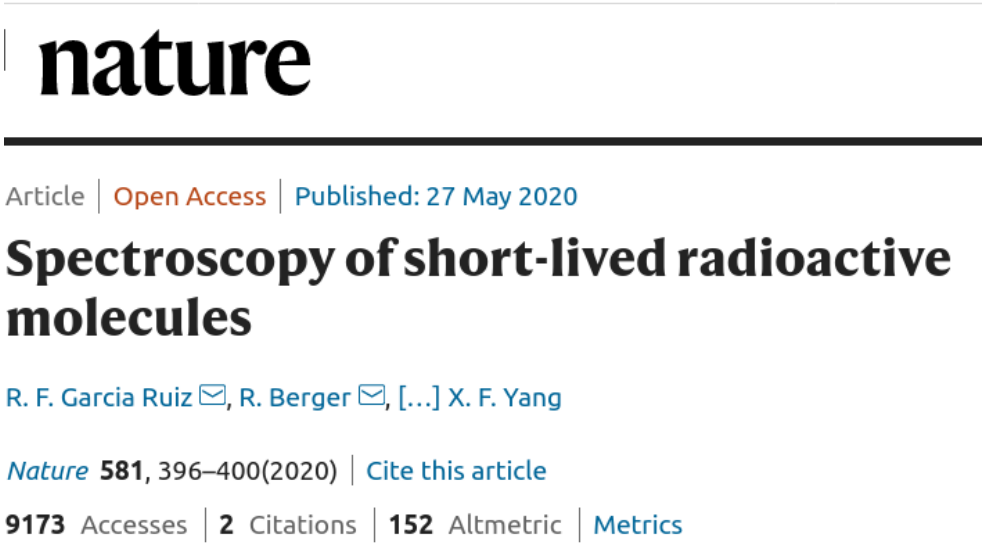

nature

Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz ✉, R. Berger ✉, […] X. F. Yang

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

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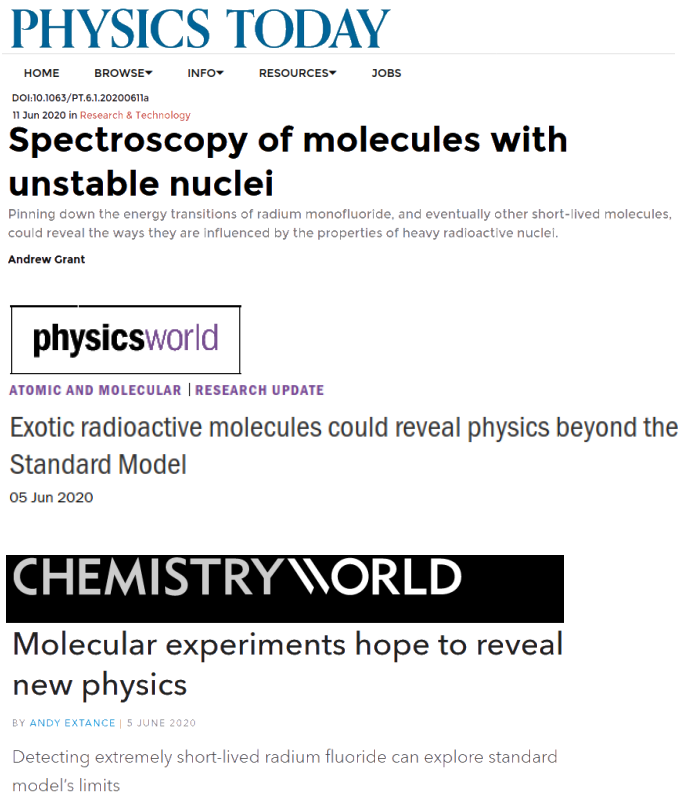

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DOI:10.1063/PT.6.1.20200611a
11 Jun 2020 in Research & Technology

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

physicsworld

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Exotic radioactive molecules could reveal physics beyond the Standard Model

05 Jun 2020

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

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

[Garcia Ruiz et al. Nature 581, 396 (2020)]

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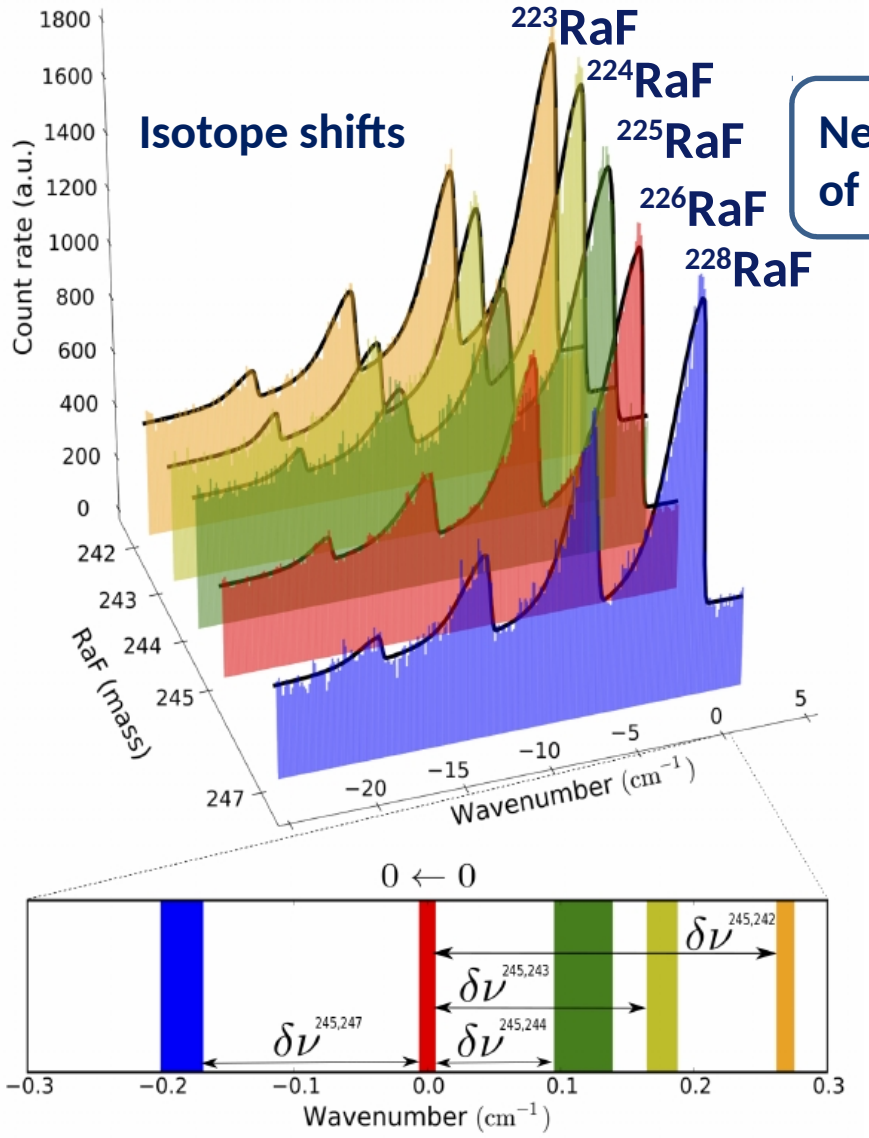
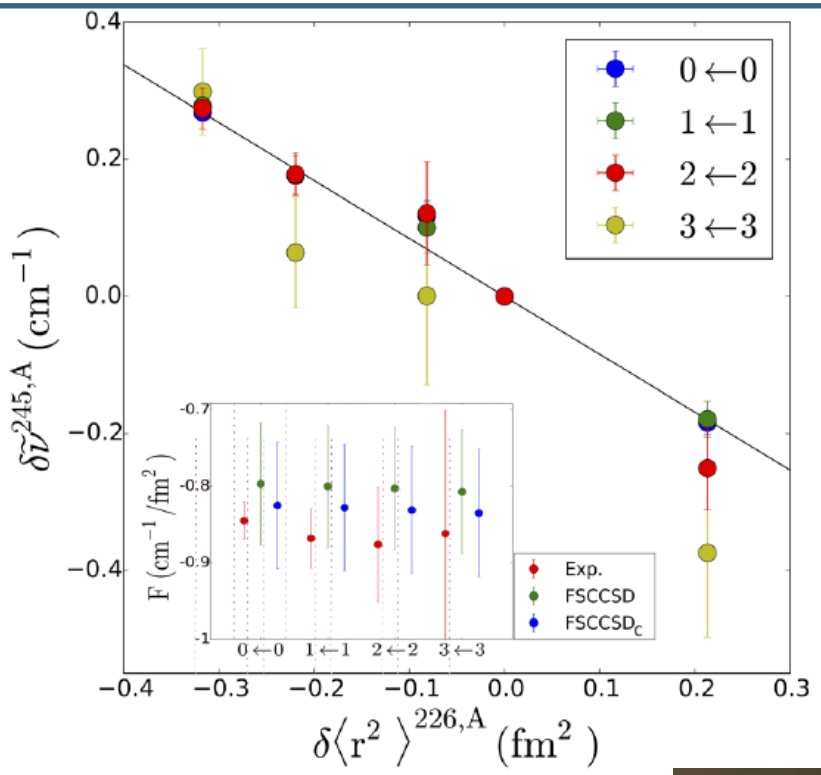
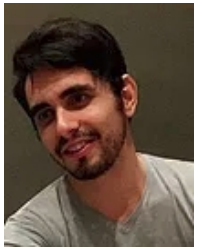


New opportunities for nuclear structure studies of the heaviest elements (e.g. ThO, PaO,...)



[Udrescu et al. *In preparation* (2020)]



S. Udrescu

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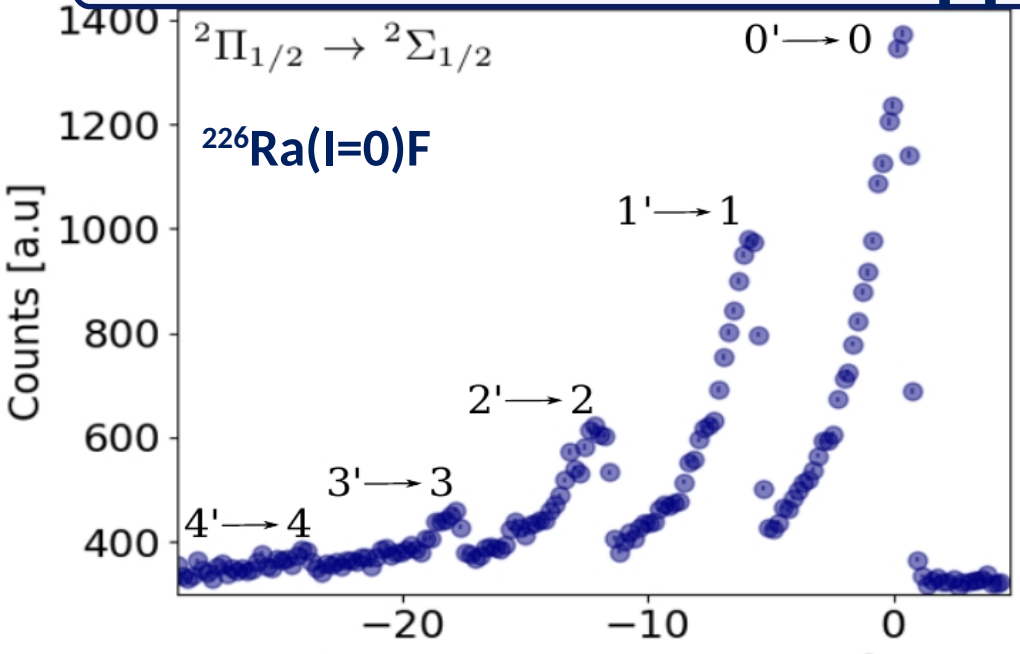
Recent results: Sub-Doppler spectroscopy (RaF)



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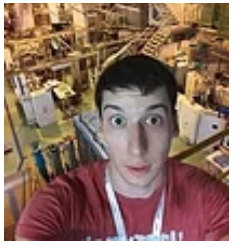
Graduate students @ MIT



A. Brinson

S. Udrescu

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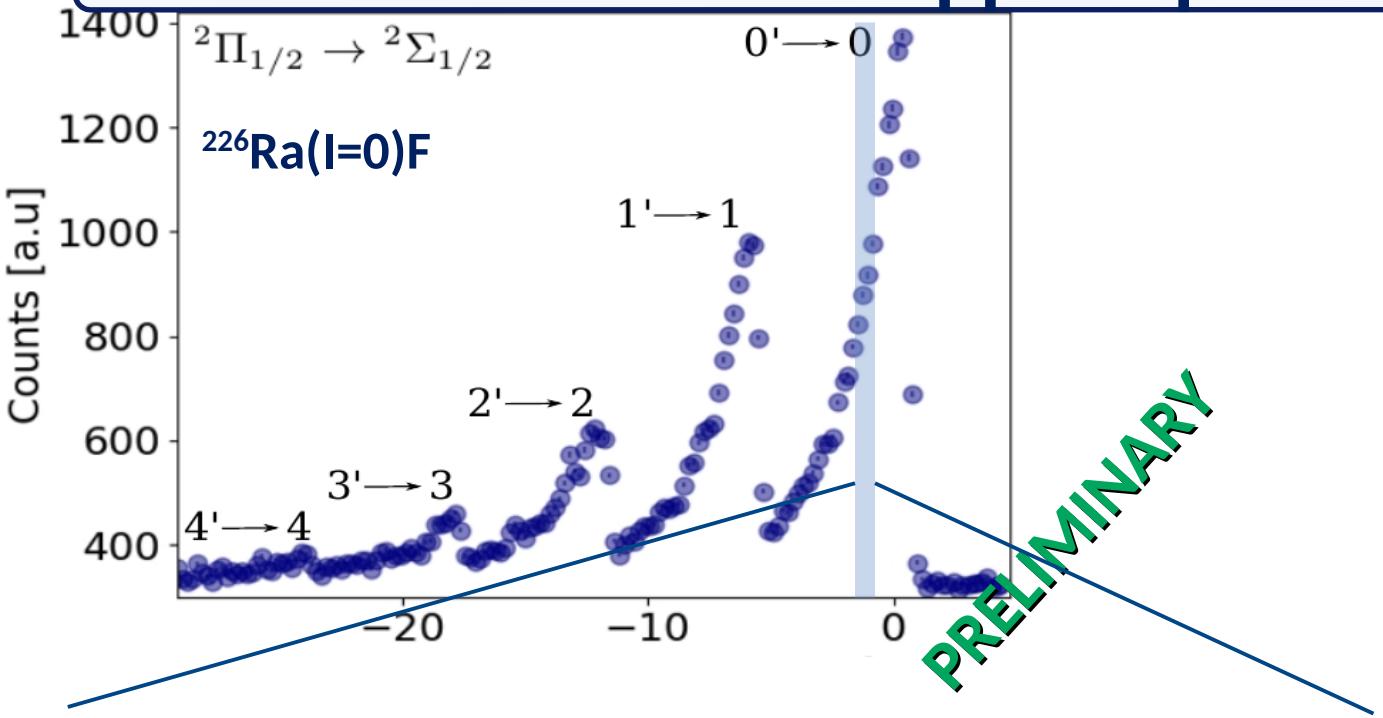

^{226}Ra(I=0)F

Rotational Structure

Wavenumber (cm^{-1})

~ 15 GHz

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

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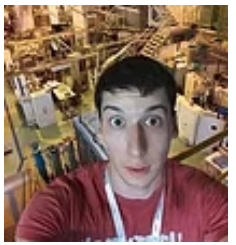

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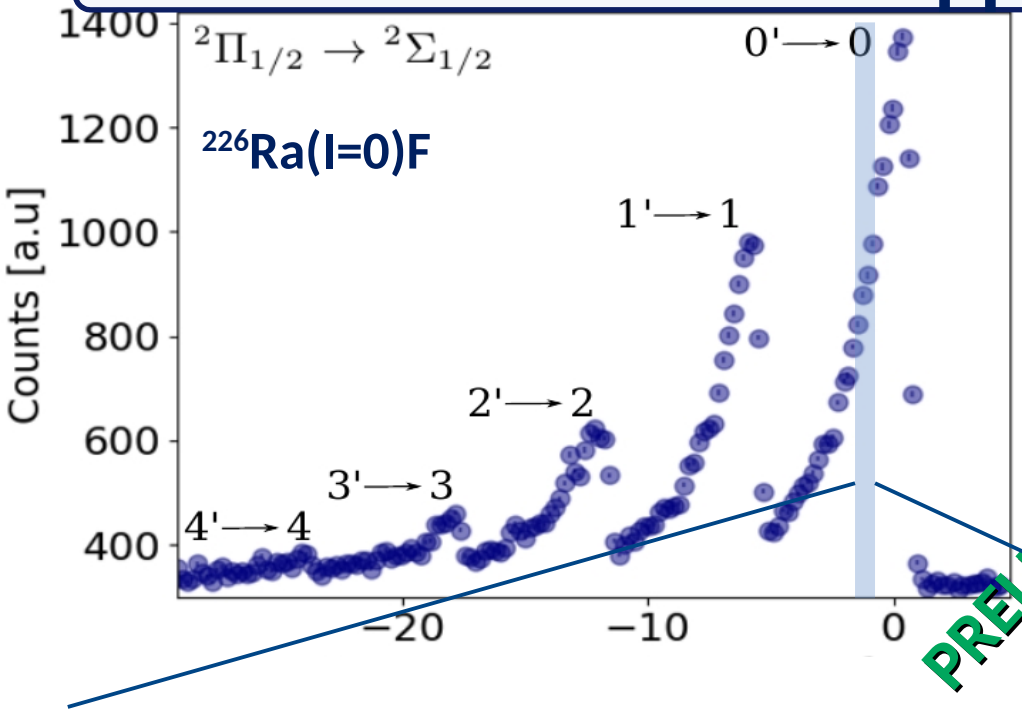

Hyperfine structure

PRELIMINARY

^{223}Ra(I=3/2)F

300 MHz

^{226}Ra(I=0)F

Rotational Structure

Wavenumber (cm^{-1})

~ 15 GHz

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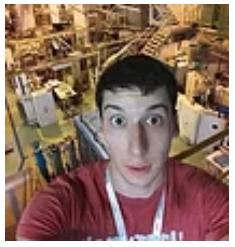
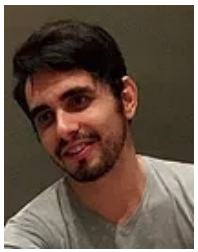
Graduate students @ MIT



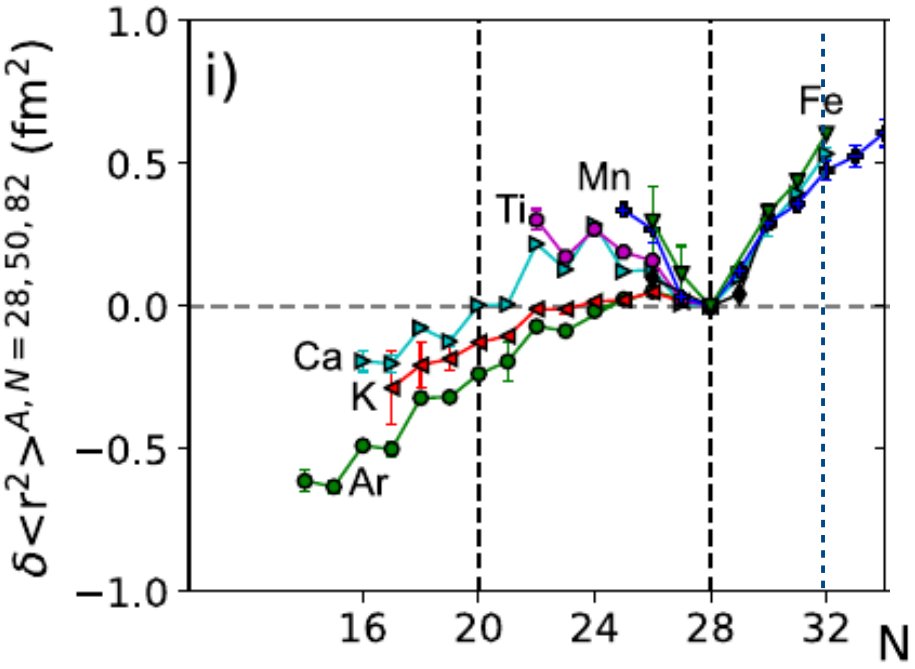
A. Brinson



S. Udrescu

Opportunities: Nuclear structure

→ New opportunities for nuclear structure

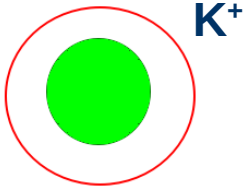


Nuclear charge radii:

[Koszorus et al. Submitted to Nature Phys. (2020)]
[Miller et al. Nature Phys. 432, 15 (2019)]
[Garcia Ruiz et al., Nature Phys. 12, 594 (2016)]

^{52}Ca(N=32)→ S_{2n} [Wienholtz et al. Nature 498, 346 (2013)]
^{54}Ca(N=34)→ *E2* [Steppenbeck et al. Nature 502, 207 (2013)]

Nuclear Q-moments
K(Z=19)?



Q-int=>0

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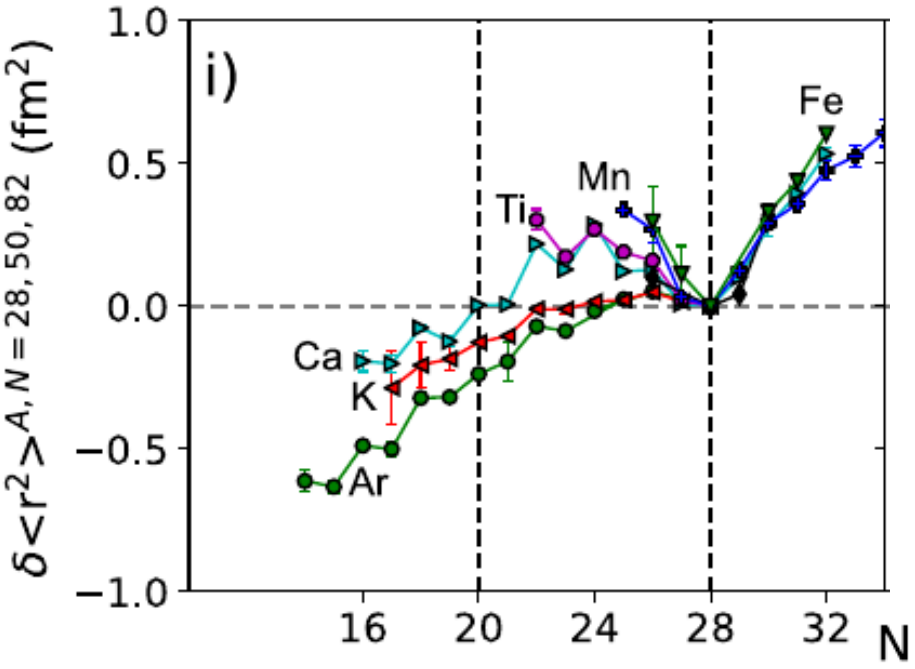

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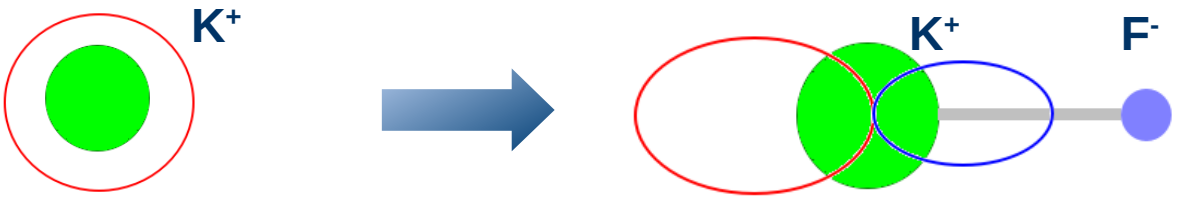
[Garcia Ruiz et al., Nature Phys. 12, 594 (2016)]

^{52}Ca(N=32)→ S_{2n} [Wienholtz et al. Nature 498, 346 (2013)]
^{54}Ca(N=34)→ *E2* [Steppenbeck et al. Nature 502, 207 (2013)]

Nuclear Q-moments K(Z=19)?

→ **Molecules could do the job!**



[Paquette et al. J. Mol. Struct. 190, 143 (1988)]

Q-int=>0

|Q-int|>0

Opportunities: Astrophysics

- **Quantum chemistry, astrophysics, ….**

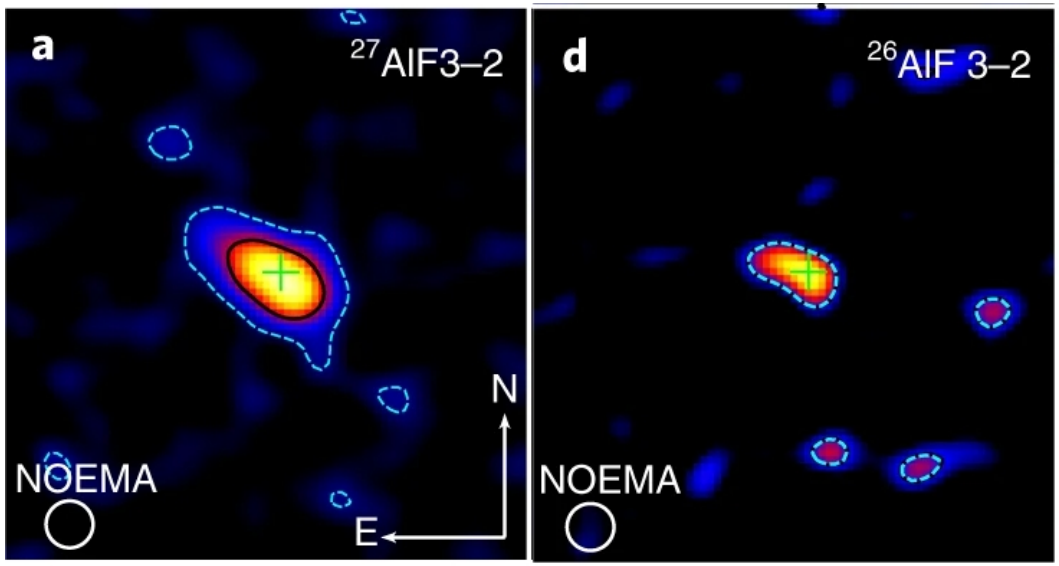
nature astronomy LETTERS
https://doi.org/10.1038/s41550-018-0541-x

Astronomical detection of radioactive molecule ^{26}AlF in the remnant of an ancient explosion

[Kaminski et al. Nature Astronomy 2, 778 (2018)]

"Spectroscopic laboratory studies of rare radioactive materials such as ^{26}AlF would be very challenging"

($T_{1/2}$= 7.17 10^5 years)



	Exp	Cal.
	$^{27}Al^{19}F$	$^{26}Al^{19}F$
$B \times 10^{-4}$	1.64883599(17)	1.67485239(18)
$D \times 10^{2}$	3.1398(59)	3.2399(61)
$H \times 10^{9}$	-9.14(28)	-9.58(29)
eQq_0(Al)	-37.53(9)	-67.8(83)
c_I(Al) $\times 10^{3}$	8(6)	3(2)

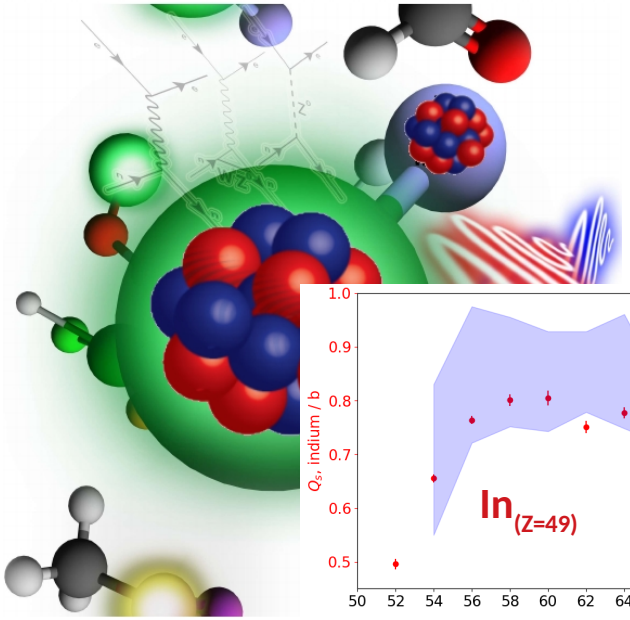
Contents

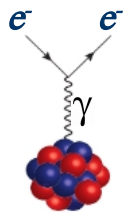
- Why (Exotic) atoms & molecules?
- Precision laser spectroscopy
- Exotic atoms: Recent highlights
- Exotic molecules: Recent Results
- **Summary & Outlook**

Summary and Outlook

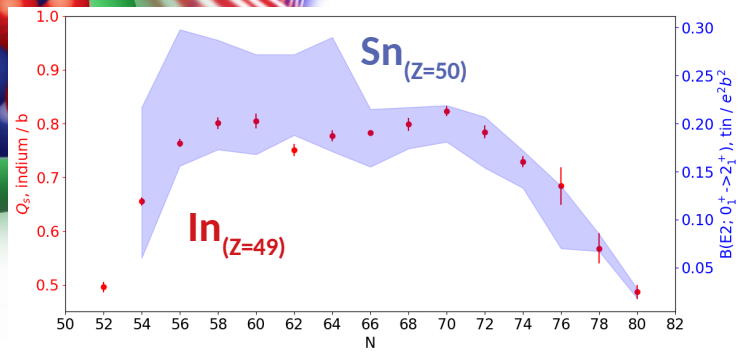
Exotic atoms and molecules

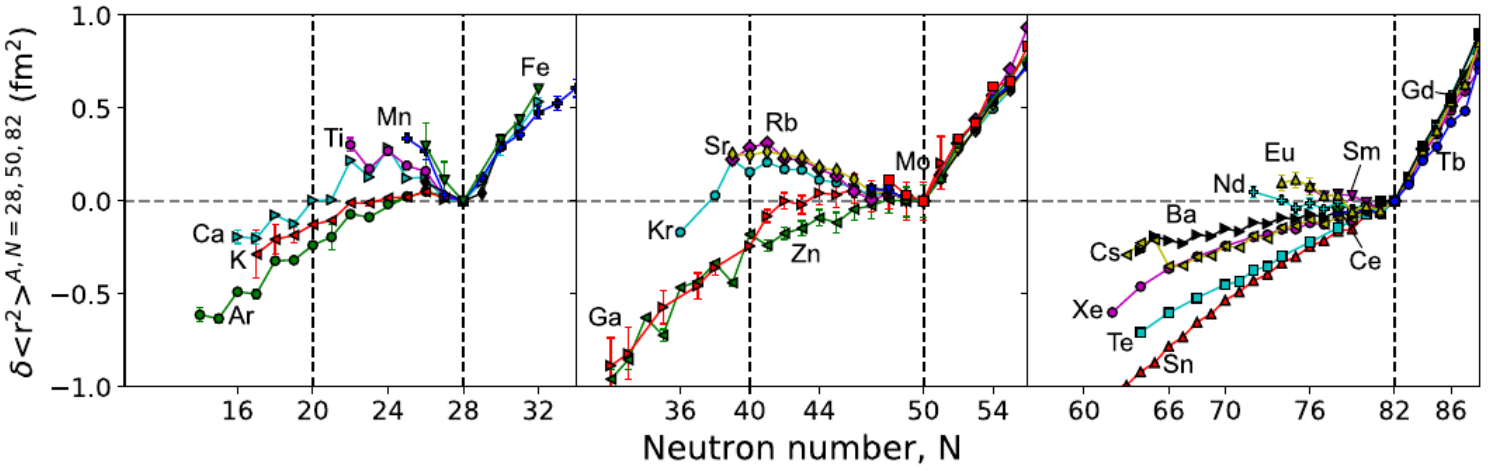
Nuclear EM structure





$\langle r^2 \rangle$ I Q μ

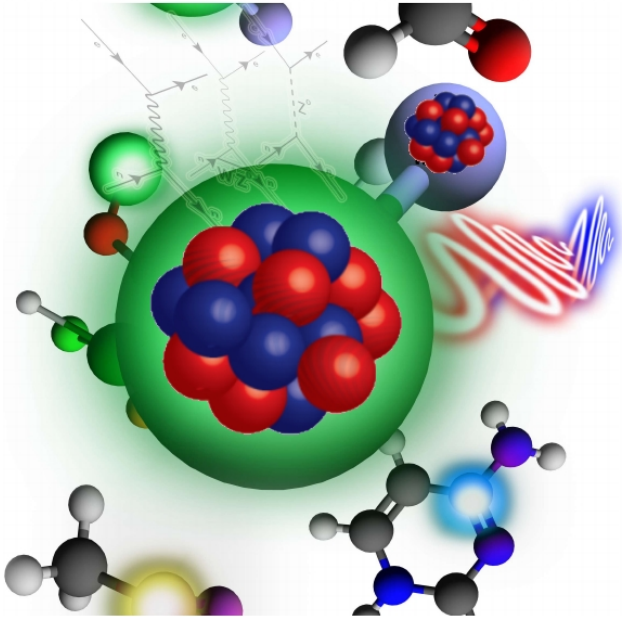


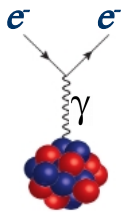


Summary and Outlook

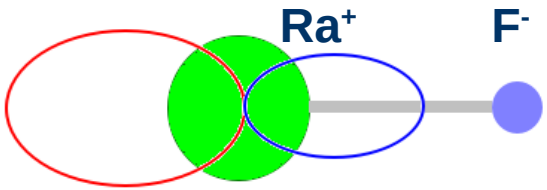
Exotic atoms and molecules

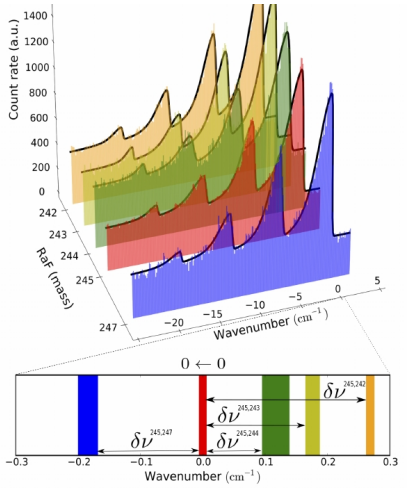
Nuclear EM structure





$\langle r^2 \rangle \; I \; Q \; \mu$





- First ever laser spectroscopy of a short-lived radioactive molecule (RaF)!

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

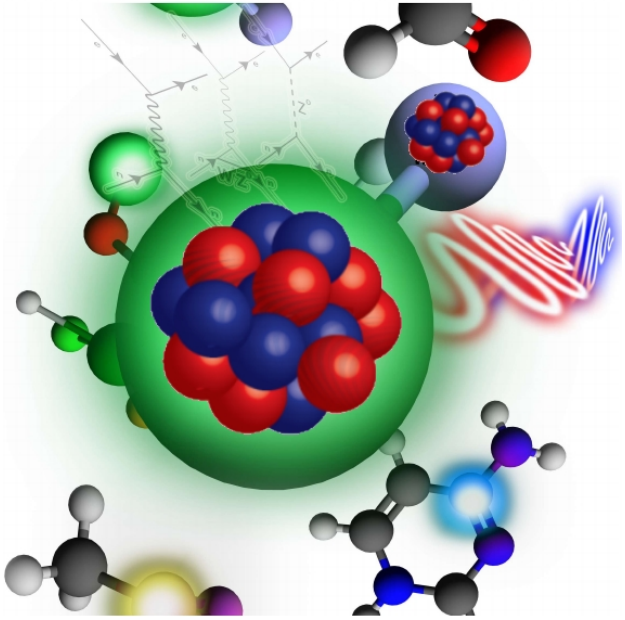
10^{-2} 10^{-5} 10^{-6} 10^{-8} $<10^{-12}$ $<10^{-15}$

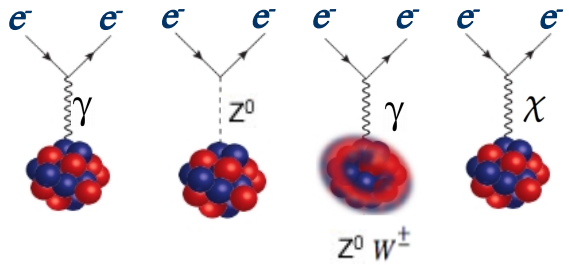
Summary and Outlook

Exotic atoms and molecules

Nuclear EM structure

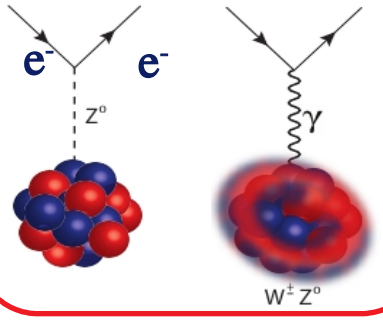
Nuclear EW structure





$\sim Z^a A^b \beta_2\beta_3 / (E_+ - E_-)$

P- violation



$$E_{PNC} \sim \frac{\langle \text{P-odd}|H_w|\text{P-even}\rangle}{E_- - E_+}$$

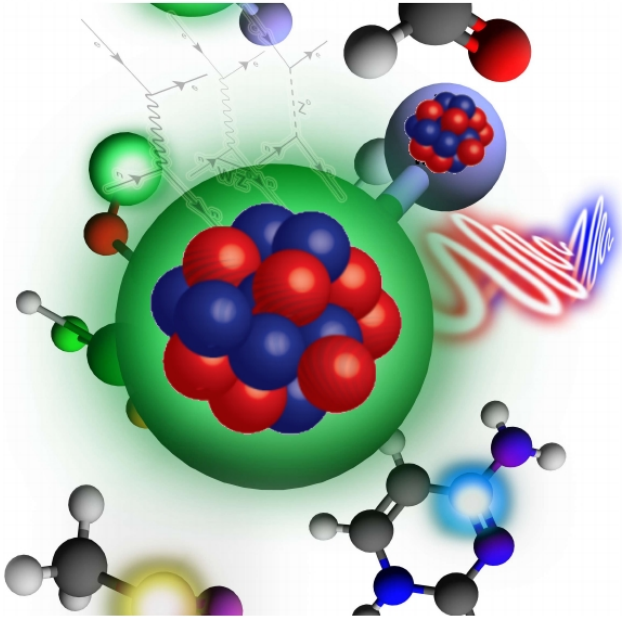
Molecular enhancement > 10^{11}

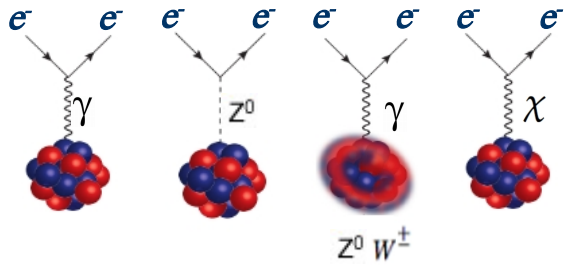
Summary and Outlook

Exotic atoms and molecules

Nuclear EM structure

Nuclear EW structure





$\sim Z^a A^b \beta_2\beta_3 / (E_+ - E_-)$

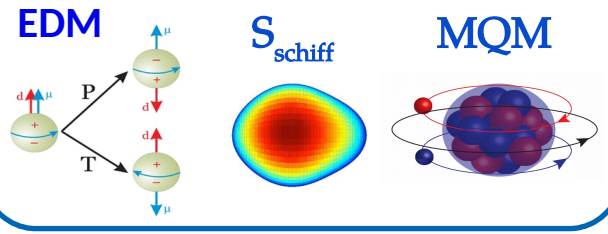
→ Max. Z, A

→ Max. β_2, β_3

→ Min. $(E_+ - E_-)$

Fundamental symmetries

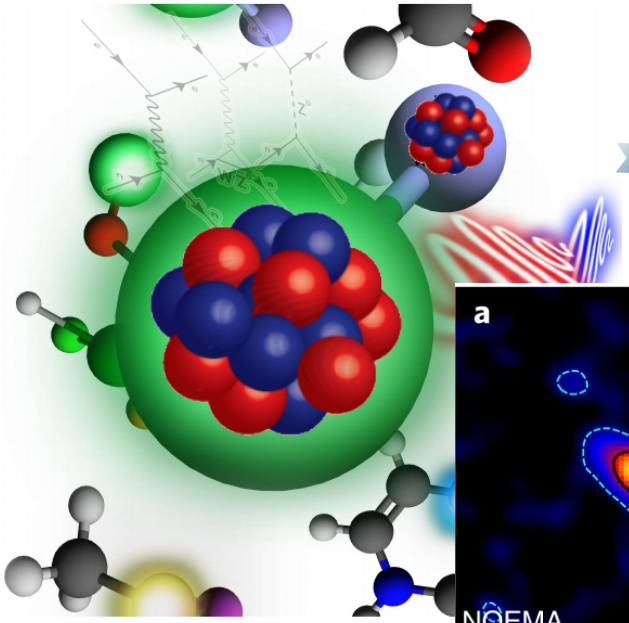
P,T- violation



Molecular + Nuclear amplification
→ E_{eff} > 50 GV/cm

Summary and Outlook

Exotic atoms and molecules

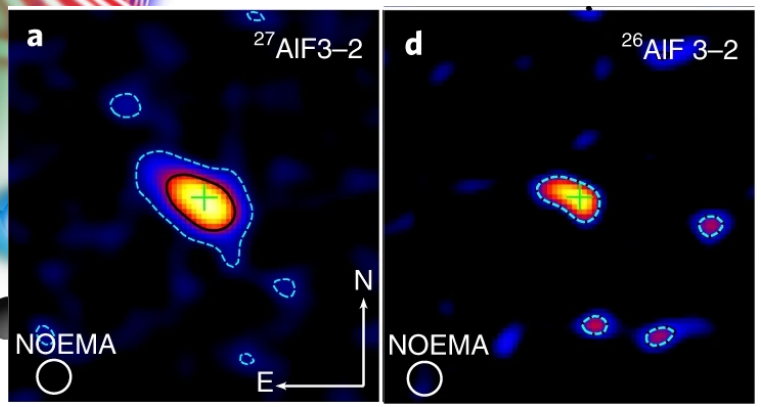


Nuclear EM structure

Nuclear EW structure

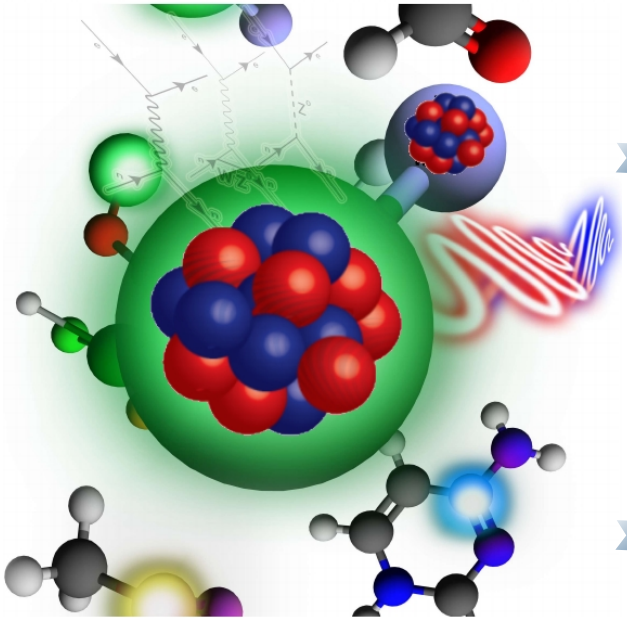
Fundamental symmetries

Astrophysics



Summary and Outlook

Exotic atoms and molecules



Nuclear EM structure

Astrophysics

Nuclear EW structure

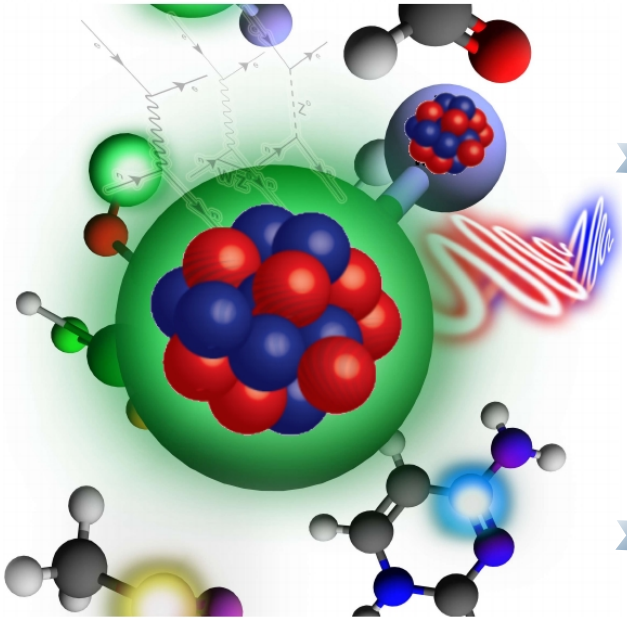
Nuclear chemistry

Fundamental symmetries

Quantum chemistry

Summary and Outlook

Exotic atoms and molecules



Nuclear EM structure

Astrophysics

Nuclear EW structure

Nuclear chemistry

Fundamental symmetries

Quantum chemistry

… this is just the beginning!