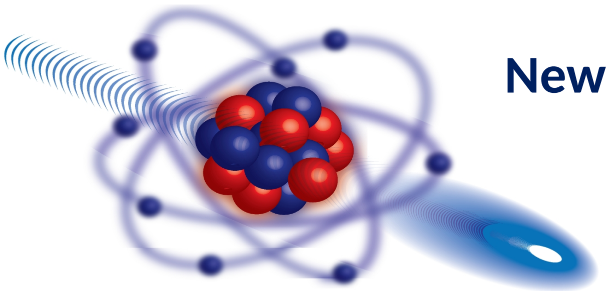
Opportunities for New Physics searches with exotic atoms and molecules

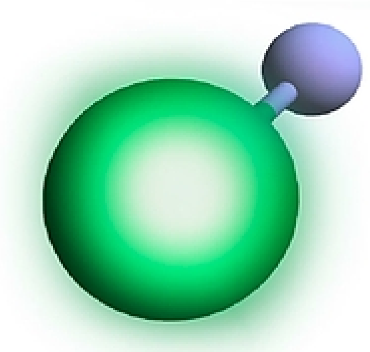
Ronald Fernando Garcia Ruiz

CERN/MIT



New Physics on the Low-Energy Precision Frontier

CERN, Geneva 2020



Thanks to…

CRIS Collaboration

COLLAPS Collaboration

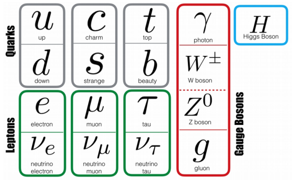
J. Billowes, C. Binnersley, A. Brinson, T.E. Cocolios, B. Cooper, K.T. Flanagan, S. Franchoo, V. Fedosseev, B.A. Marsh, M. Bissell, R.P. De Groote, R.F. Garcia Ruiz, A. Koszorus, G. Neyens, H. Perrett, F. Parnefjord Gustafsson, C. Ricketts, H.H. Stroke, S.M. Udrescu, A. Vernon, K. Wendt, S. Wilkins, X. Yang, ……

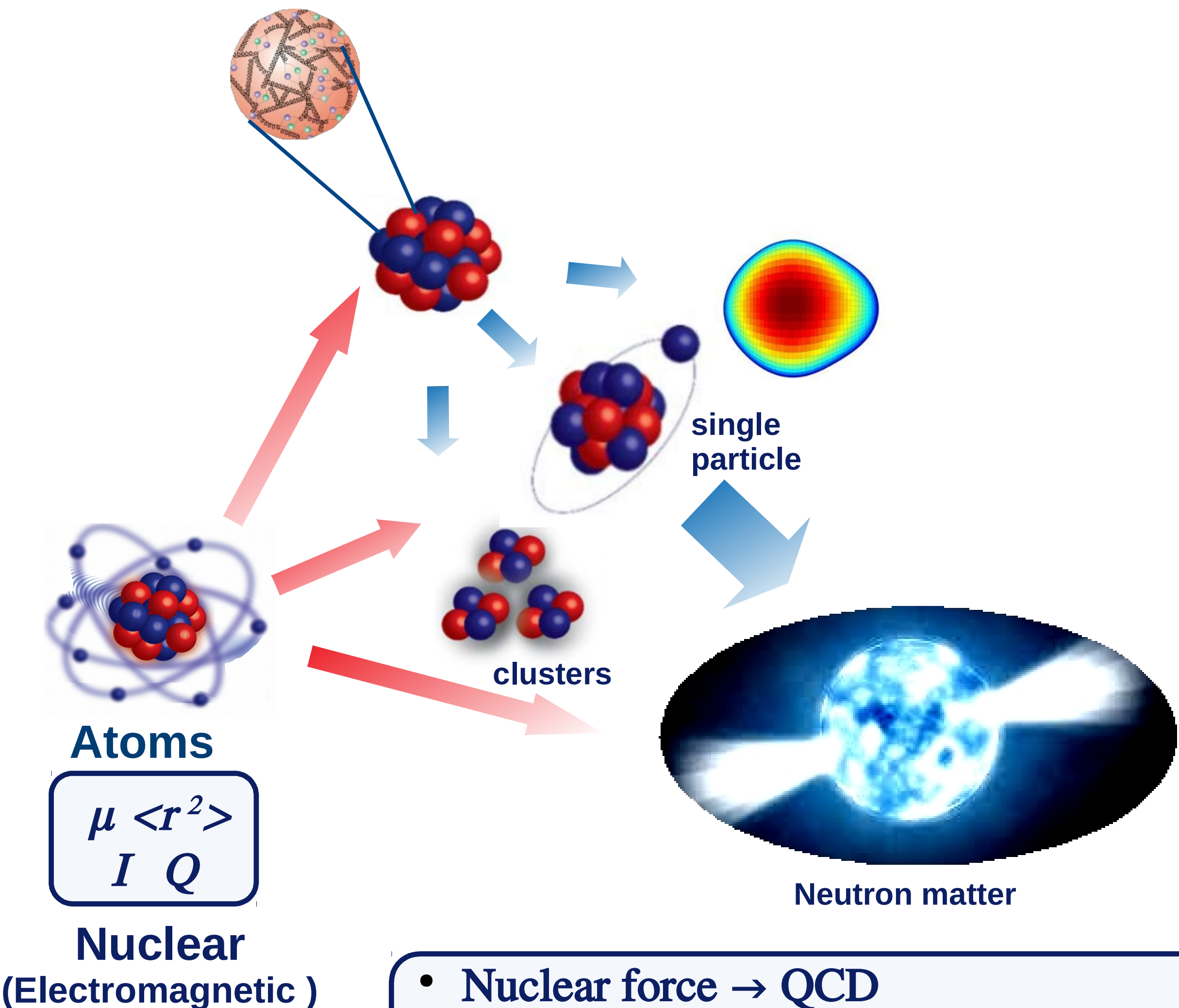
ISOLTRAP (F. Wienholtz) , **RILIS** (S. Wilkins, K. Chrysalidis)
Target group (S. Rothe), **ISOLDE Technical group**

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

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

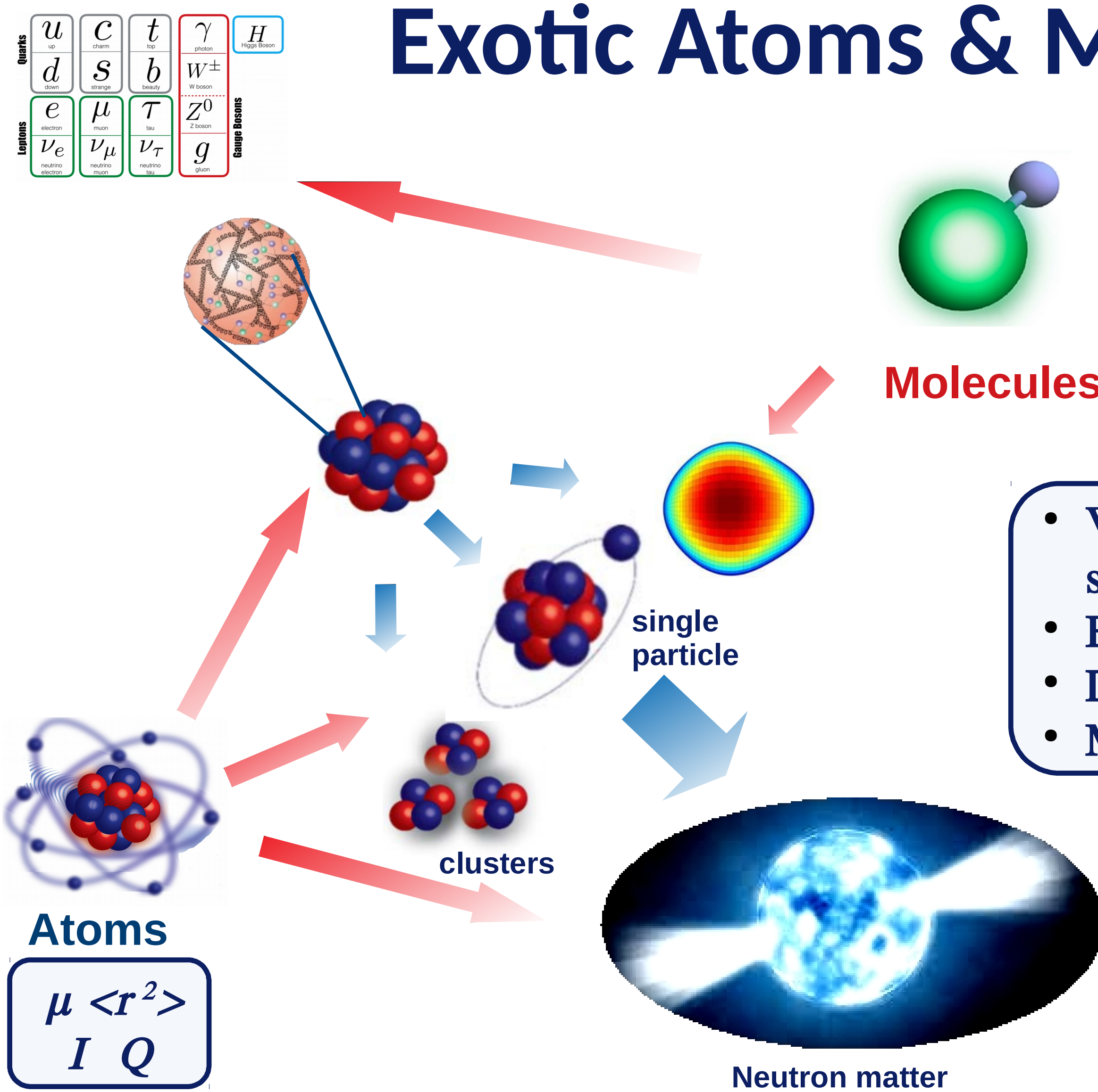
Exotic Atoms & Molecules





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

Exotic Atoms & Molecules



Nuclear
(Electromagnetic)

- Violation of fundamental symmetries
- BSM searches
- Dark matter
- Matter / Antimatter asymmetry

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

Opportunities for New Physics searches with exotic atoms and molecules

Contents

Opportunities for New Physics searches with exotic atoms and molecules

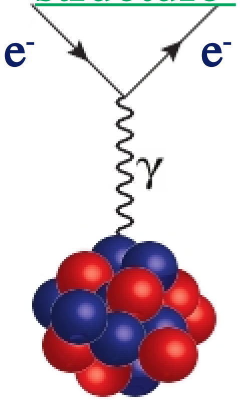
Contents

Why exotic atoms/molecules?

- Large Z, A
- Nuclear spins
- Isotopic chains
- Octupole deformation

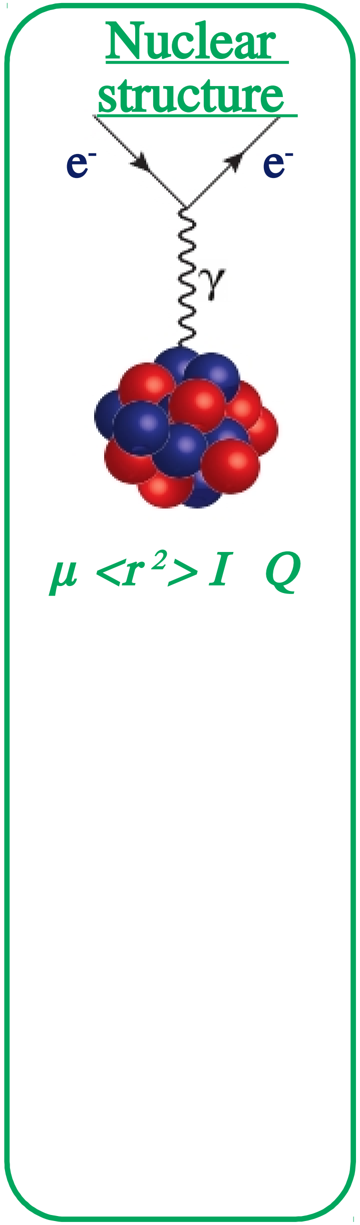
Precision studies in atoms and molecules

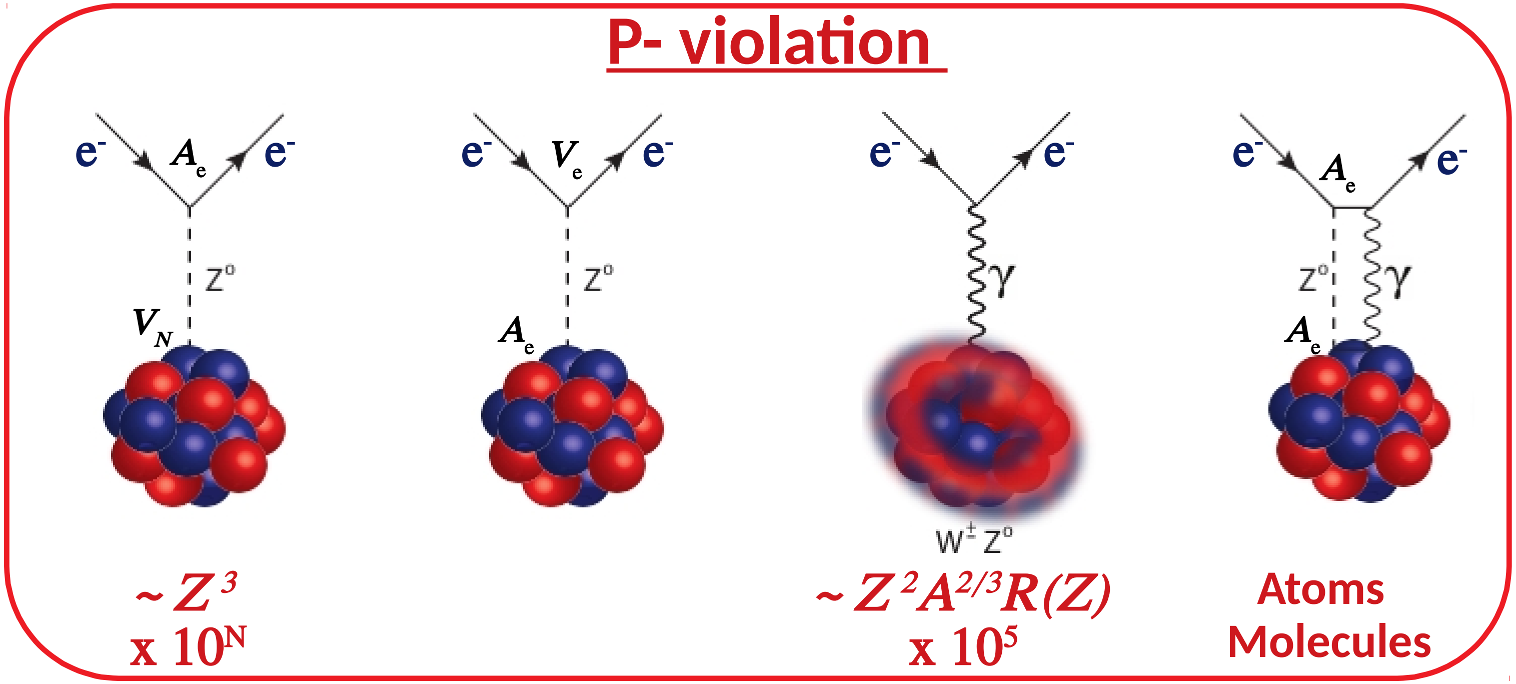
Nuclear structure



μ $<r^2>$ I Q

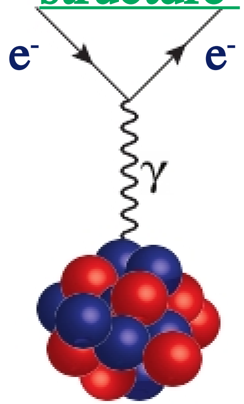
Precision studies in atoms and molecules





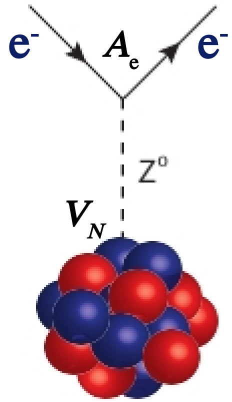
Precision studies in atoms and molecules

Nuclear structure

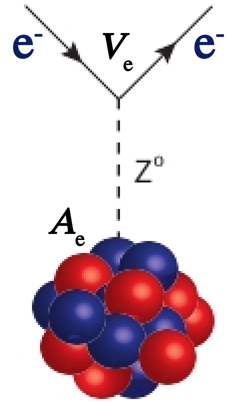


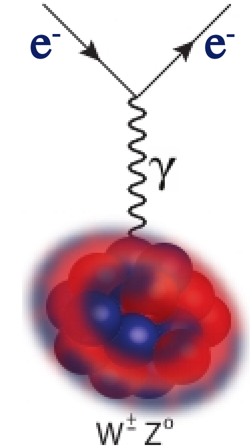
μ $\langle r^2 \rangle$ I Q

P- violation

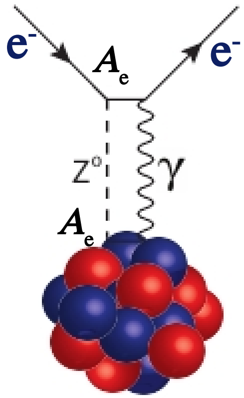


$\sim Z^3$
x 10^N





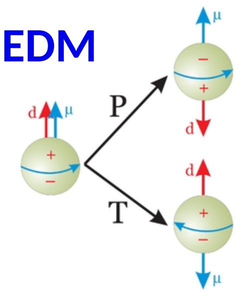
$\sim Z^2 A^{2/3} R(Z)$
x 10^5



Atoms
Molecules

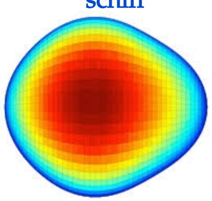
P,T- violation

EDM



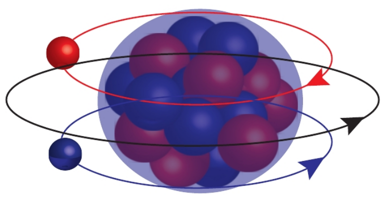
$\sim Z^2 R(Z)$
$> 10^3$

S_{schiff}



$S \sim Q_2 Q_3 Z A^{2/3} / (E_+ - E_-)$
($> 10^5$ Octupole)

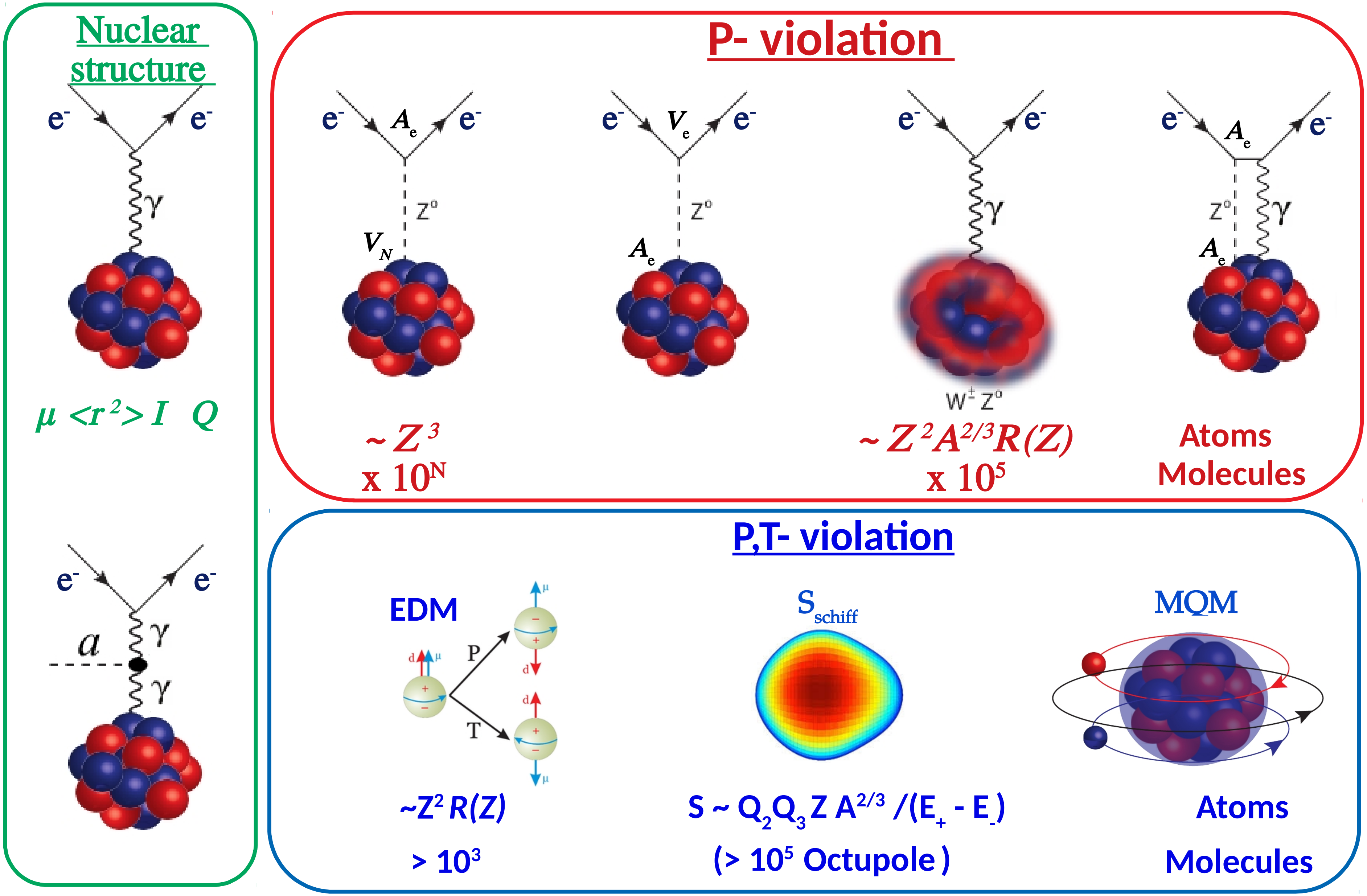
MQM



Atoms
Molecules

[Safronova et al. Rev. Mod. Phys. 90, 025008 (2018)]

Precision studies in atoms and molecules



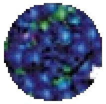
Best of all worlds → Radioactive molecules containing heavy and octupole deformed nuclei

Contents

- Precision studies in atoms and molecules
- **Nuclear structure / nuclear matter / new forces & particles**
- Parity violation
- Parity and time-reversal violation
- First results: RaF
- Summary

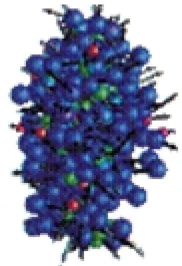
How do we create and study exotic atoms/molecules?

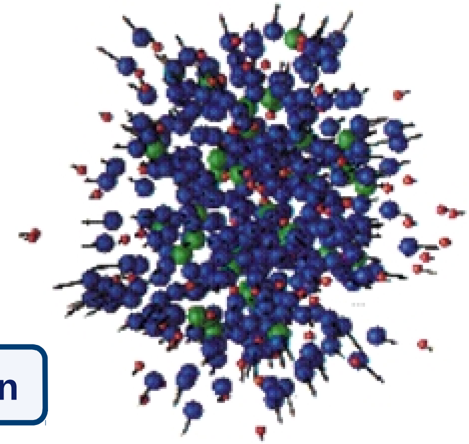
Light nucleus



+

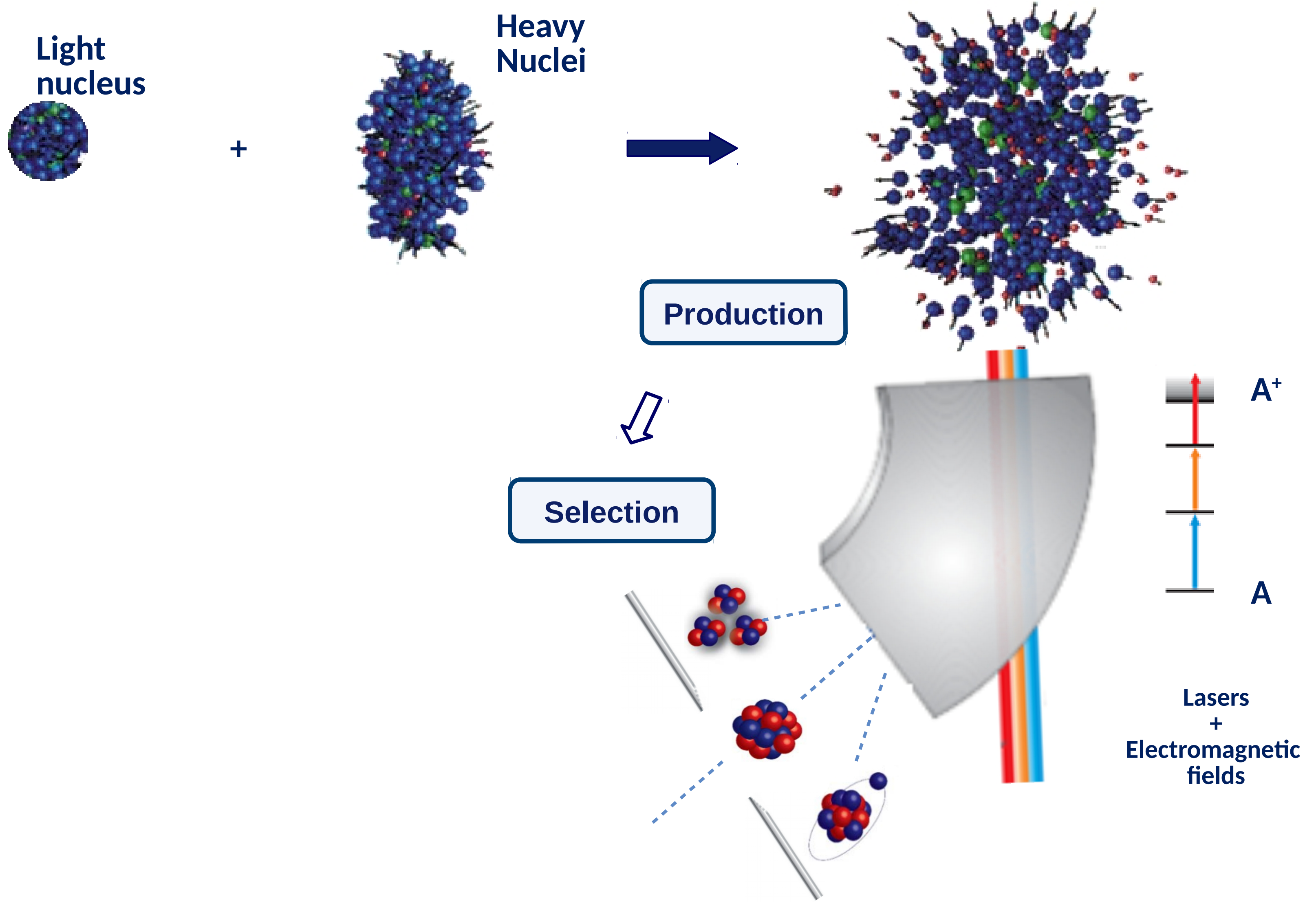
Heavy Nuclei





Production

How do we create and study exotic atoms/molecules?



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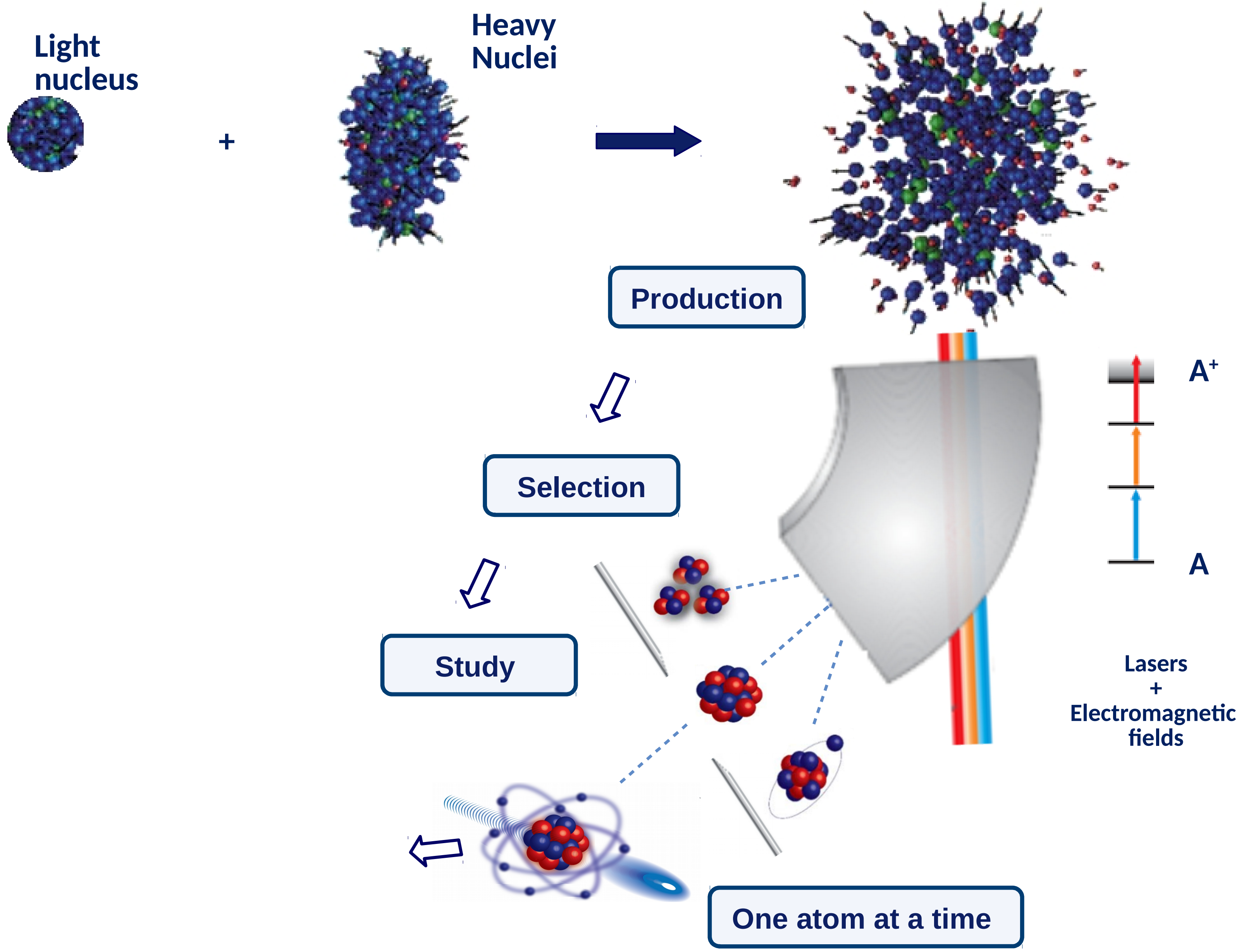

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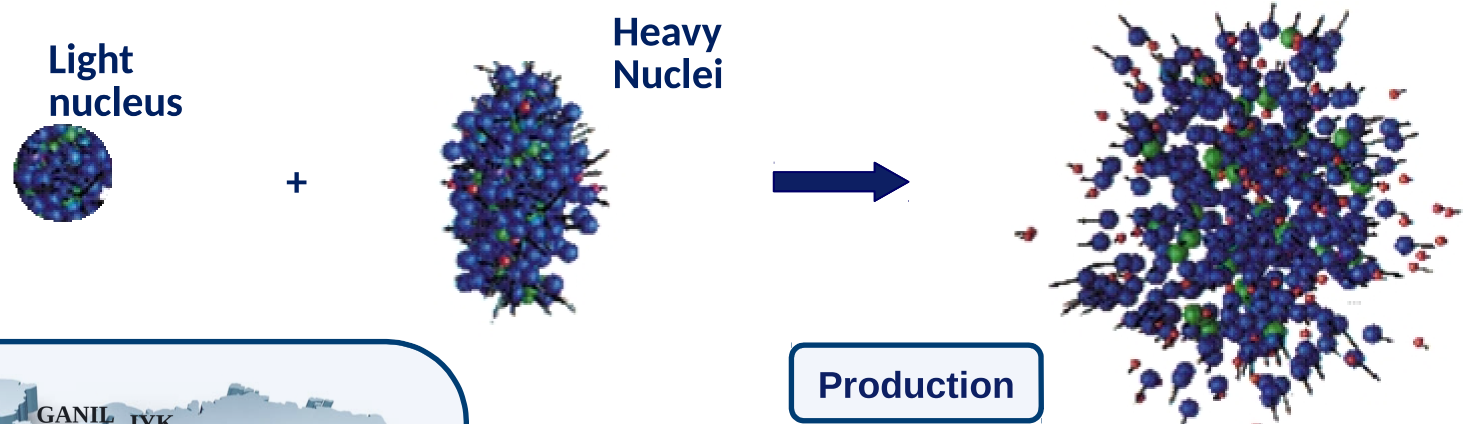
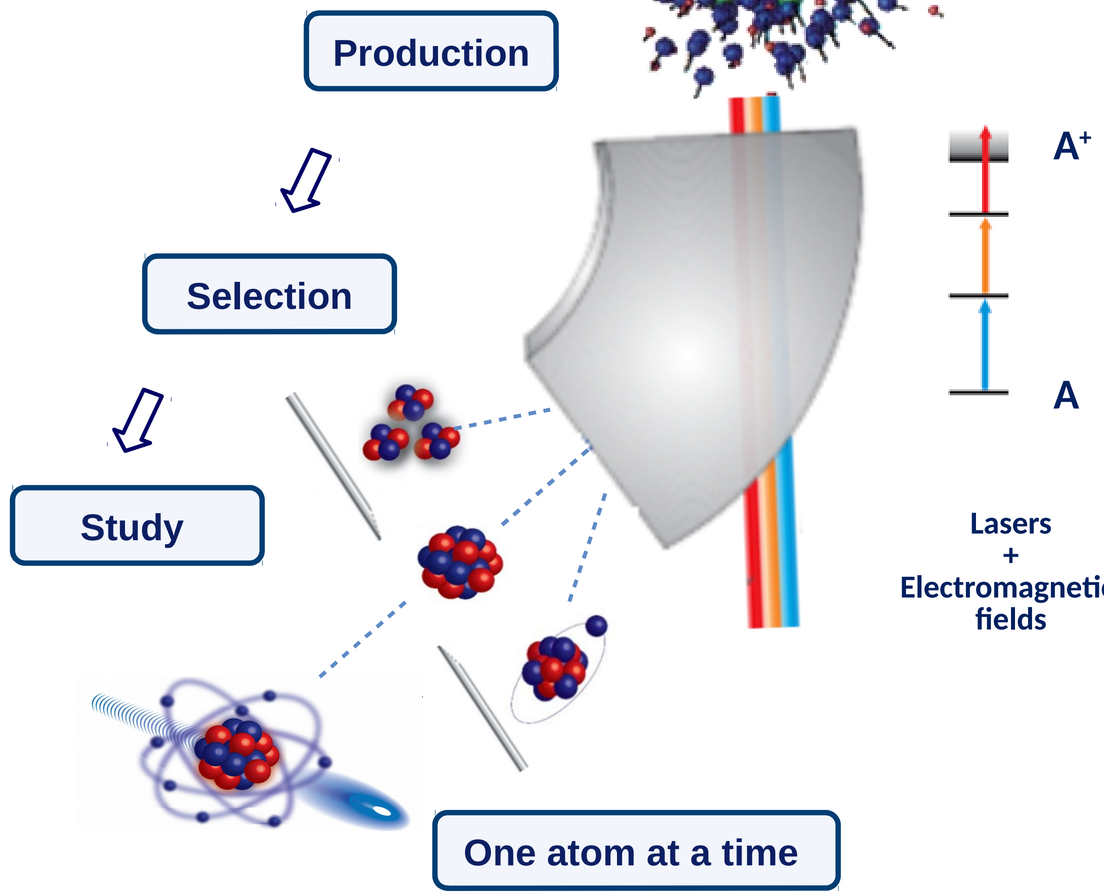


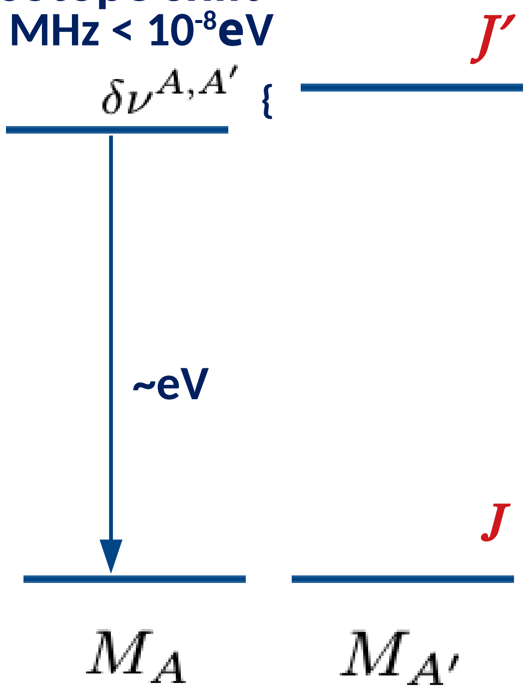


Experimental challenges:

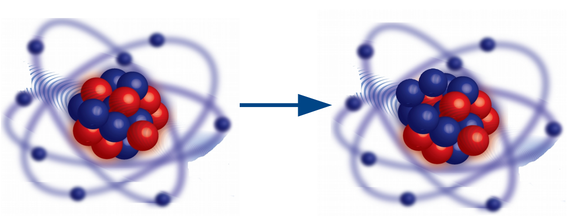
- High selectivity (>1/10^6)
- Short time scales (< 1 s)
- High efficiency (<100 ions/s)
- High precision/resolution (~MHz)

Exotic atoms & Nuclear structure

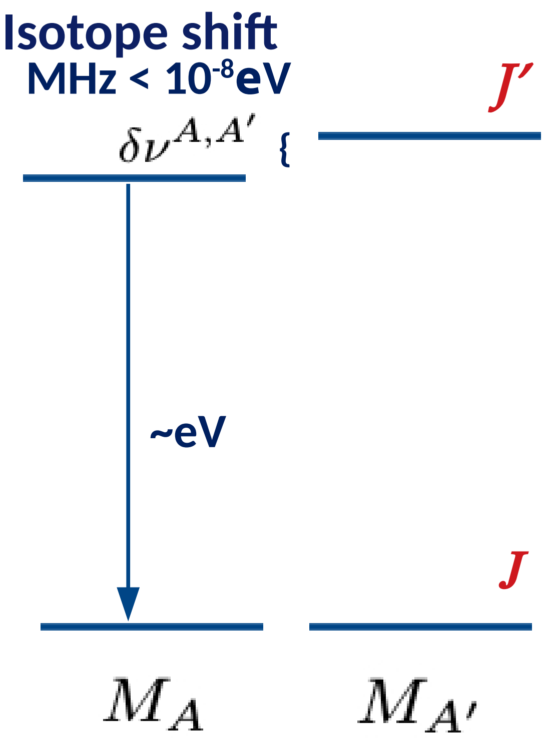
Isotope shift
MHz < 10^{-8}eV



$I = 0$



Exotic atoms & Nuclear structure



Electromagnetic structure

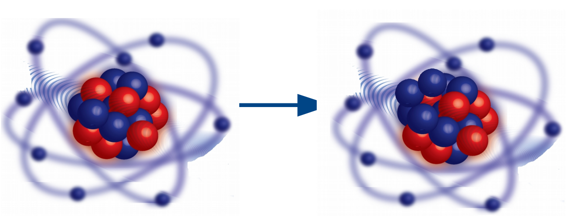
- Rms charge radii: $\langle r^2 \rangle$

Atomic

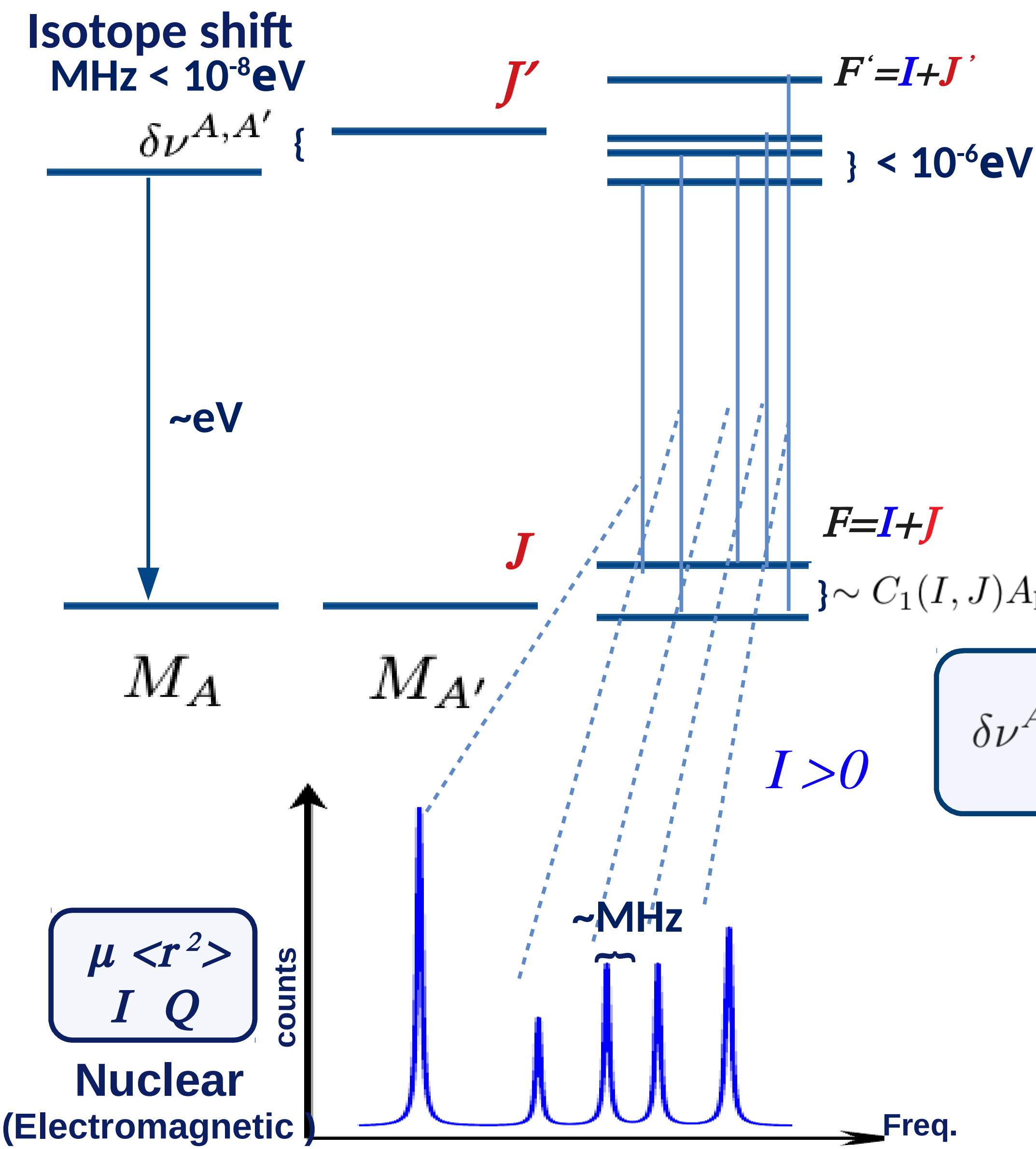
Nuclear

$I = 0$

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$



Exotic atoms & Nuclear structure



$\sim C_1(I,J)A_{\rm hfs} + C_2(I,J)B_{\rm hfs}$

Atomic hyperfine structure

Electromagnetic structure

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

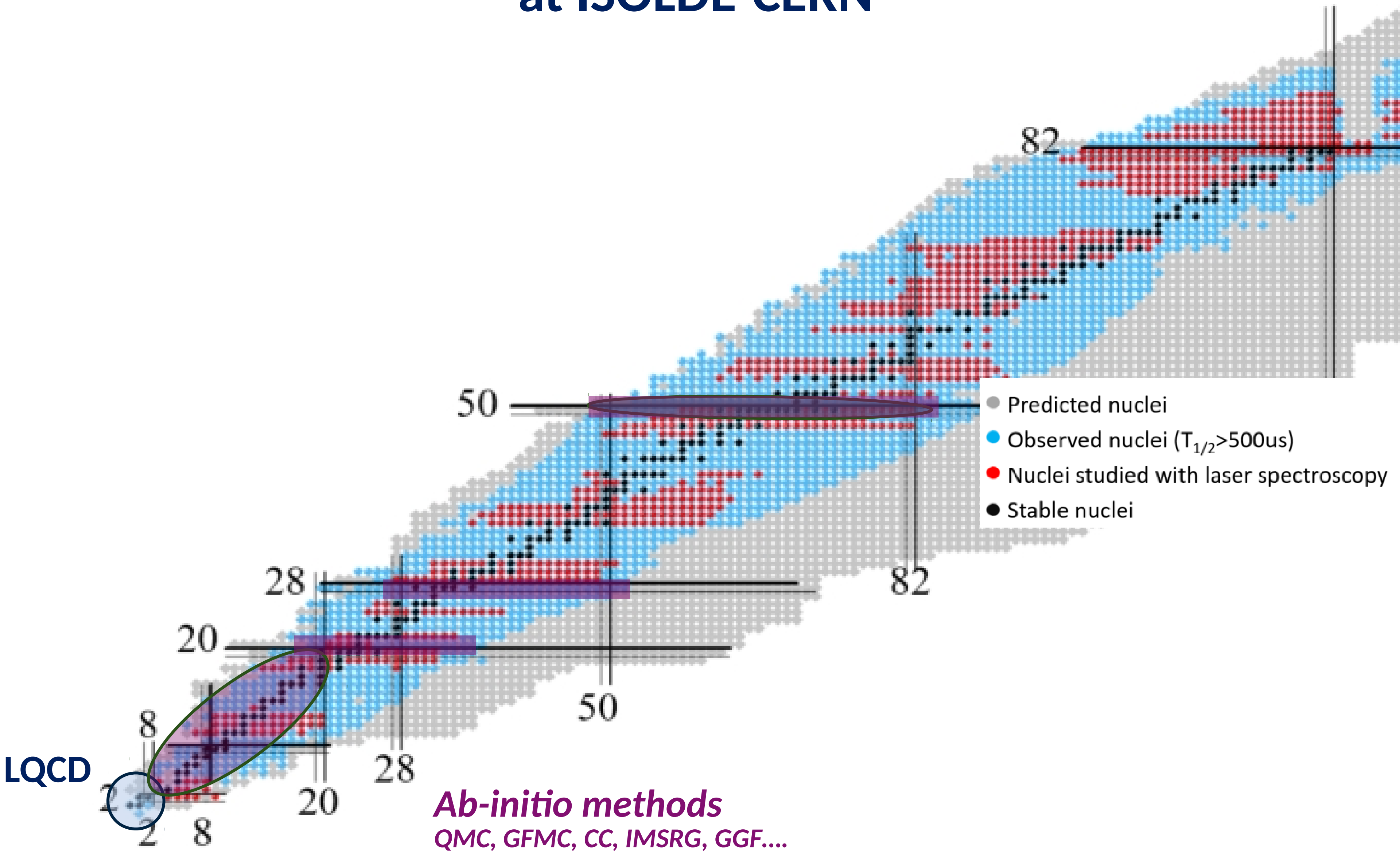
Atomic
Nuclear

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'}-M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

$$A_{\rm hfs} = \frac{\mu B}{IJ}$$

$$B_{\rm hfs} = eQ\frac{\partial^2 V}{\partial^2 z}$$

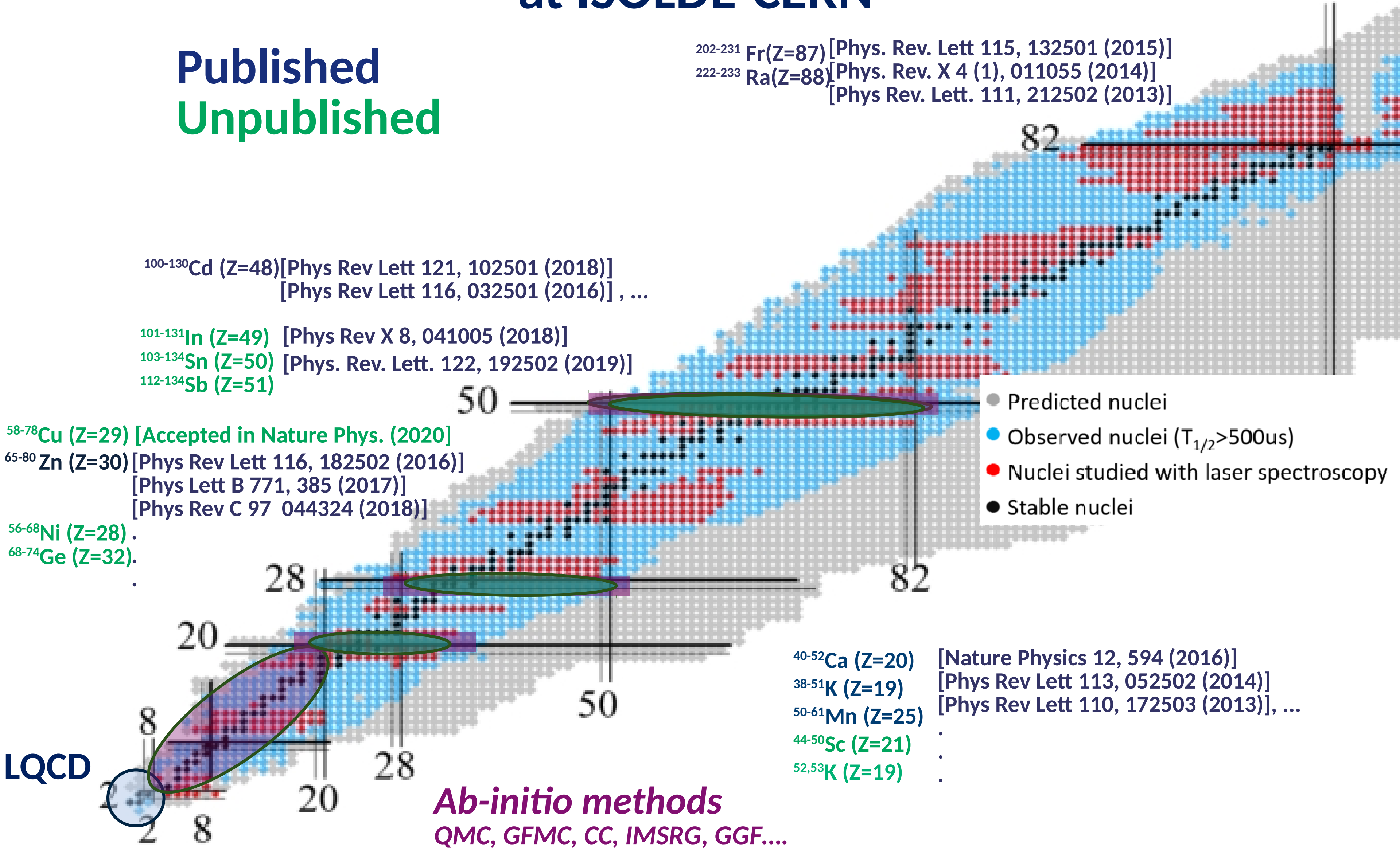
Recent results from collinear laser spectroscopy at ISOLDE-CERN



Ab-initio methods

QMC, GFMC, CC, IMSRG, GGF….

Recent results from collinear laser spectroscopy at ISOLDE-CERN

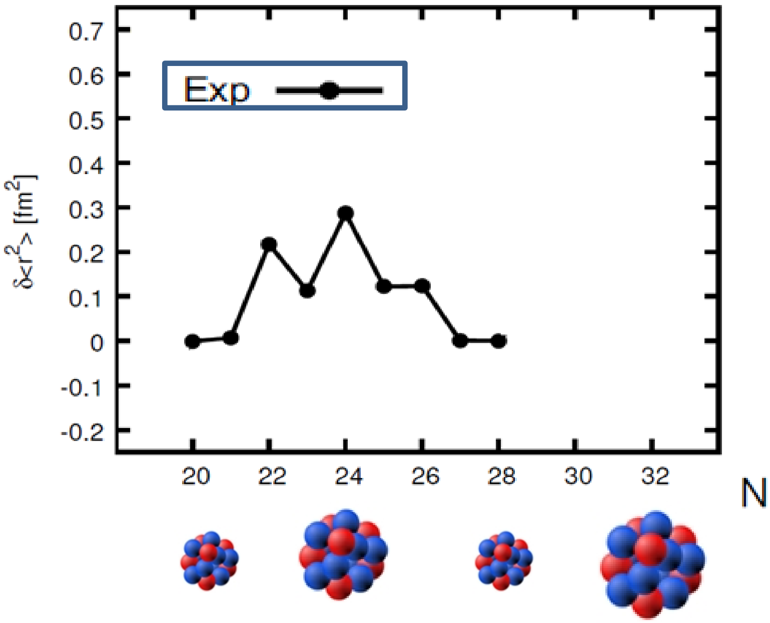


An example: exotic calcium isotopes

Atom
Nucleus

[Ca: <r^2>: Garcia Ruiz et al. Nature Phys. 12, 594 (2016)]

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$



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

^{36}Ca → <r^2> @NSCL
[Miller et al. Nature Phy, 15, 432 (2019)]

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

^{54}Ca → $E(2^+)$ @RIKEN
[Steppenbeck et al. Nature 502, 207(2013)]

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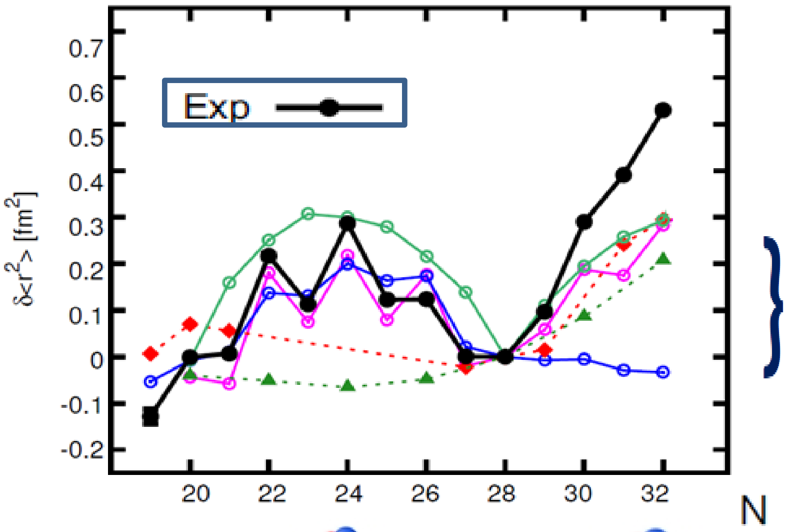
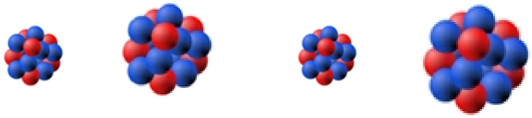


Nuclear theory / forces



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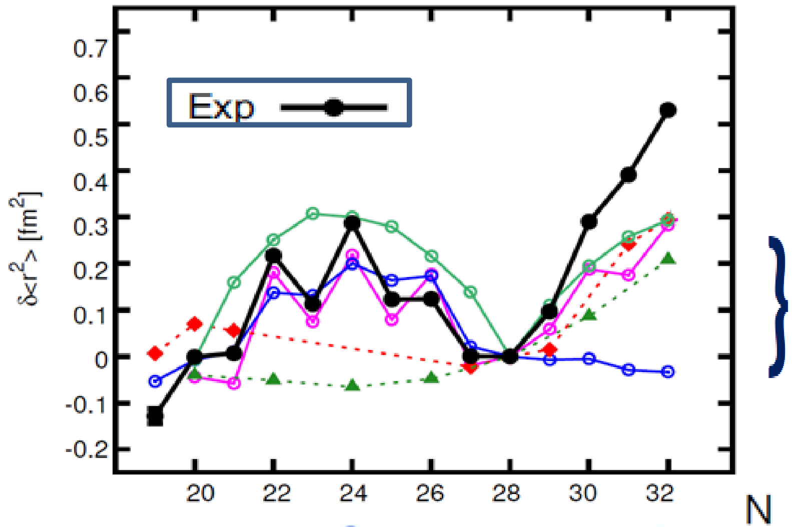
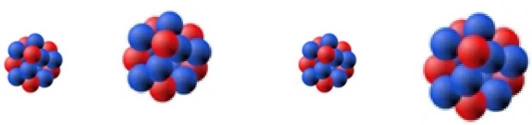


} Nuclear theory / forces



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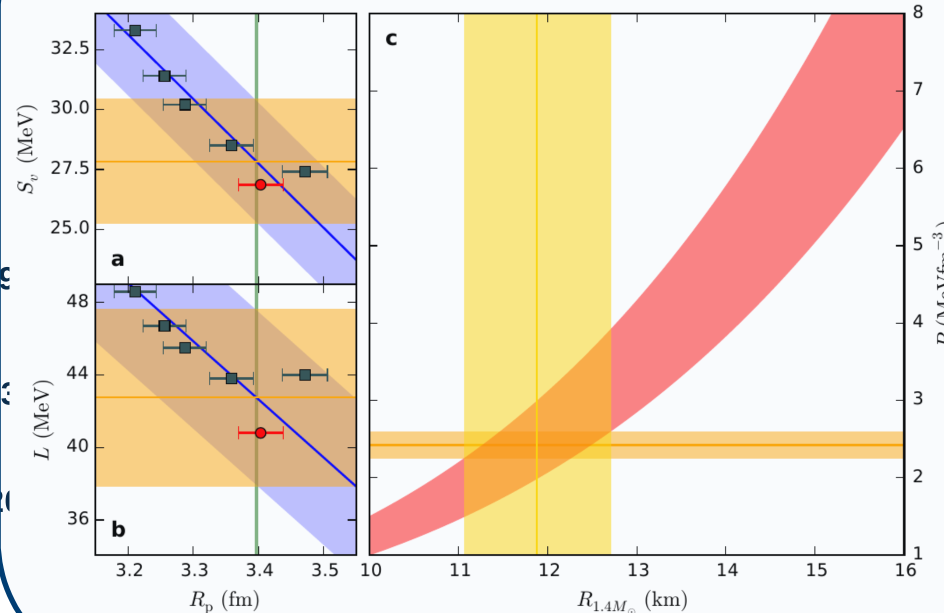
[Steppenbeck et al. Nature 502, 207(2

Neutron-rich nuclei:
"Quantum simulators" of neutron starts

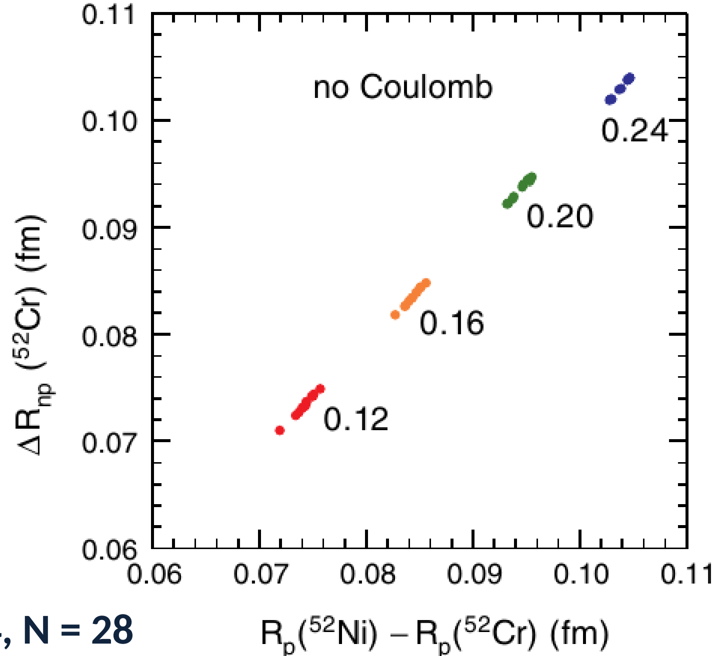
Nuclear charge radii (^{48}Ca): Constrain to properties of nuclear matter



[Hagen et al., Nature Physics 12, 186 (2016)]

Isotope shifts & "Skins"

[Brown. PRL 119, 122502 (2017)]



"Neutron skin"

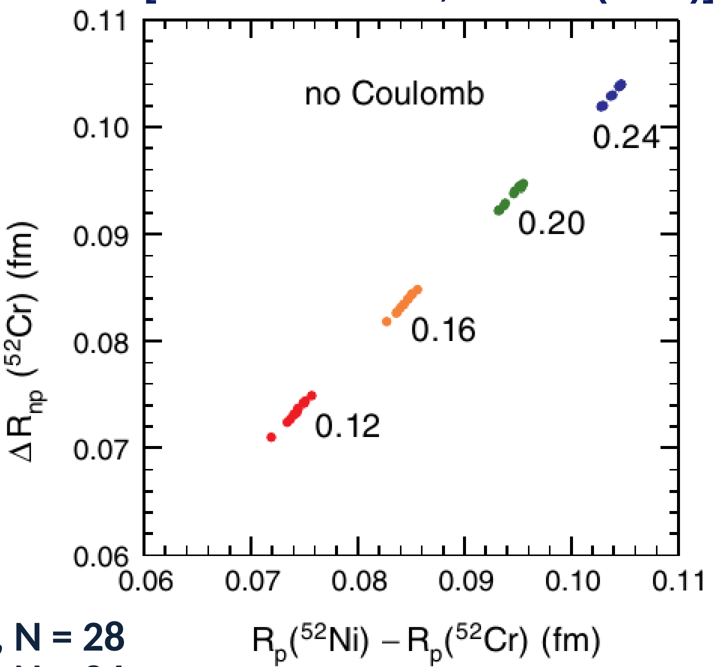
Z = 24, N = 28
Z = 28, N = 24

"Mirror skin"

Isotope shifts & "Skins"

[Brown. PRL 119, 122502 (2017)]

"Neutron skin"



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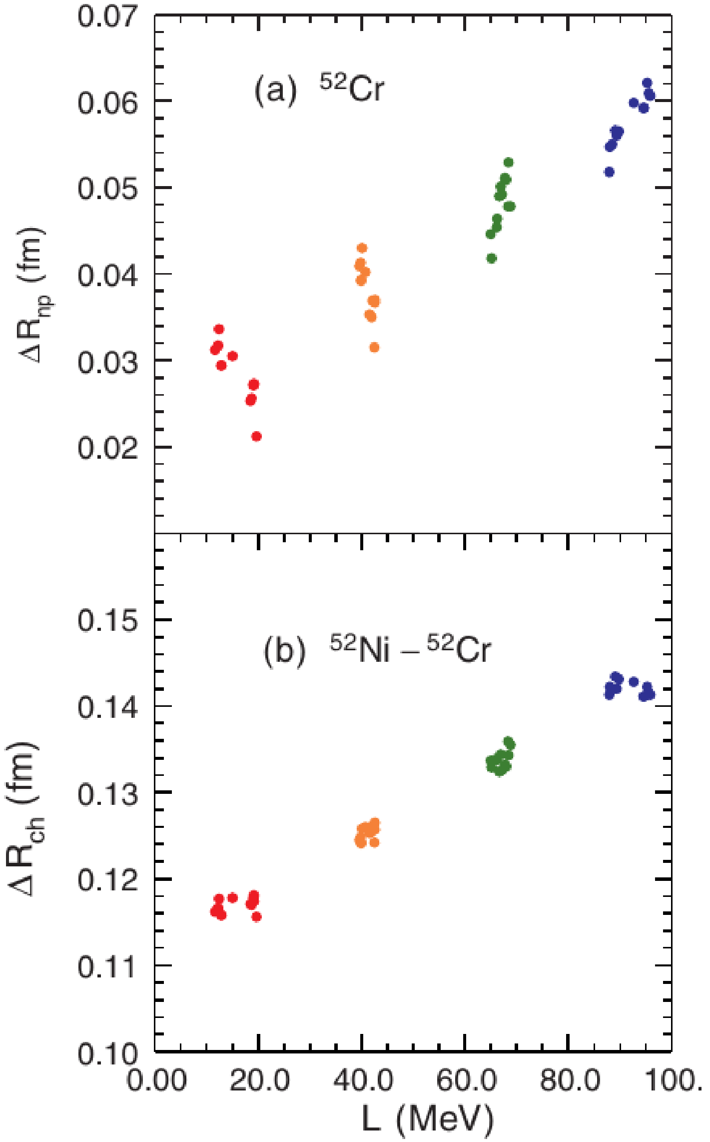

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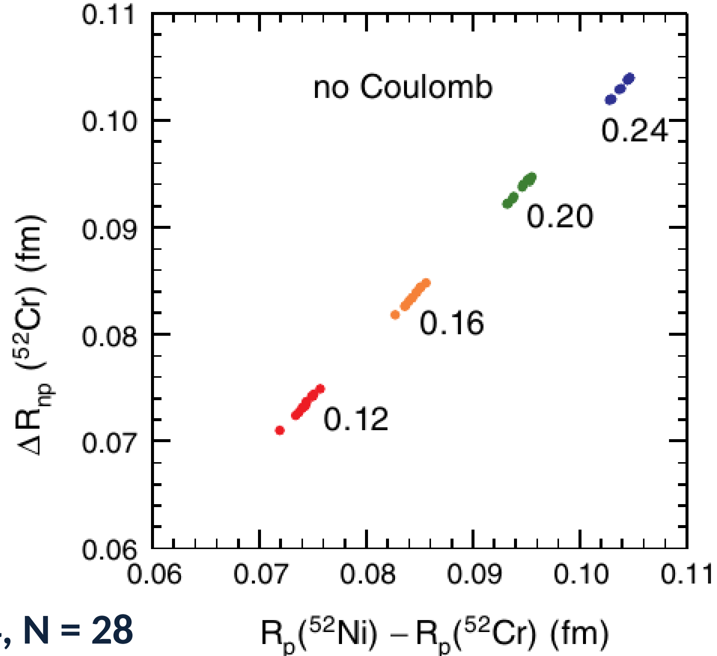

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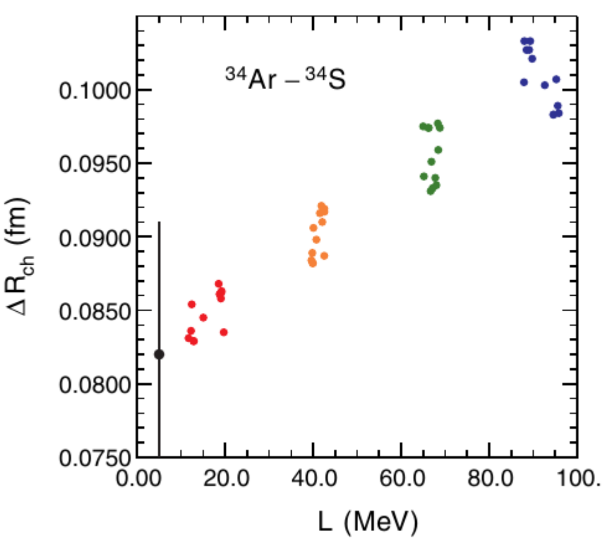
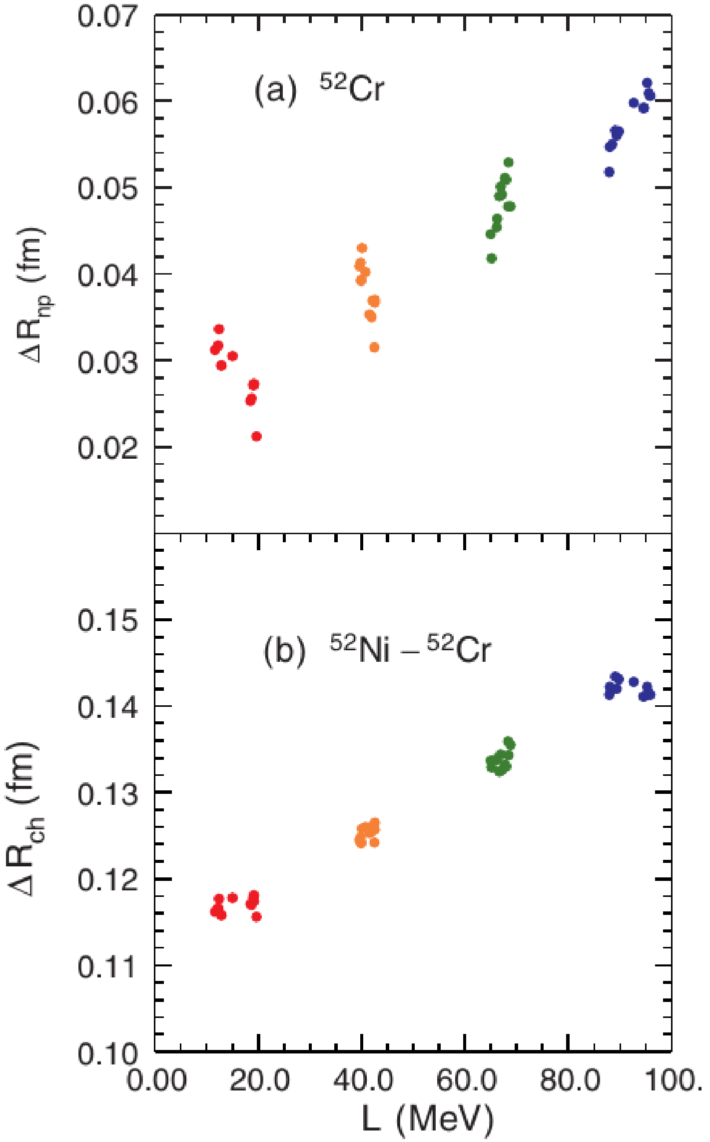




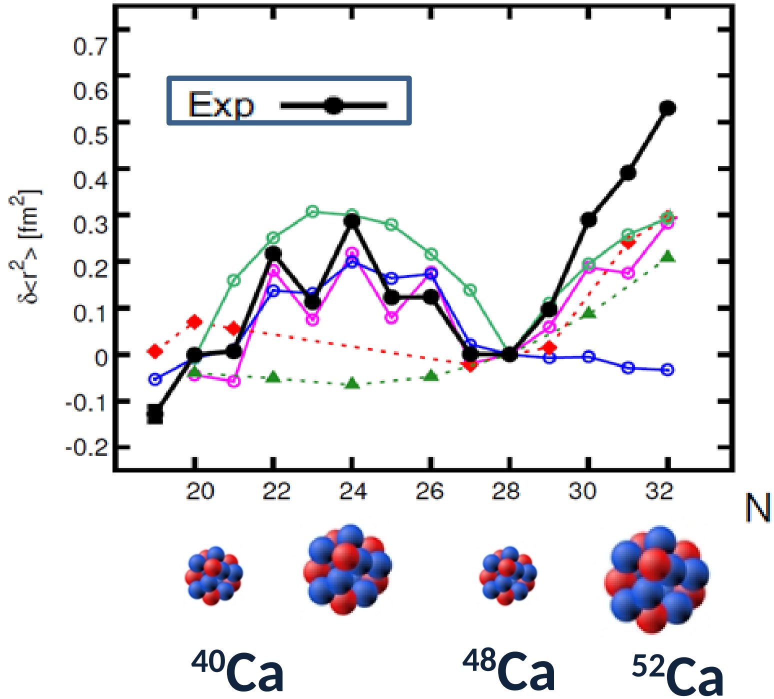
^{32}Si (Z = 14, N = 18) & ^{32}Ar (Z=18, N=14)
[Garcia Ruiz, Minamisono et al. NSCL PAC 20002 (2020)]

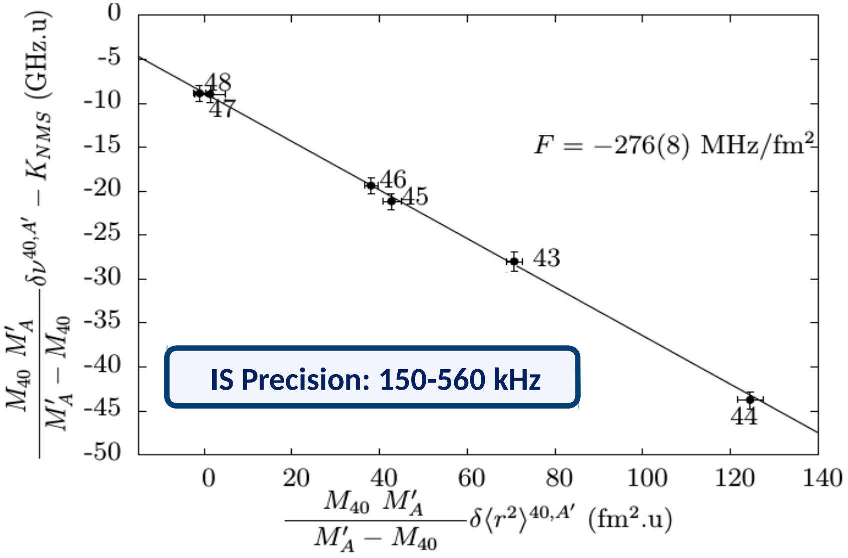
Isotope shifts & New Physics

Atom
Nucleus

[Ca: <r²>: Garcia Ruiz et al. Nature Phys. 12, 594 (2016)]

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$





Isotope shifts & New Physics

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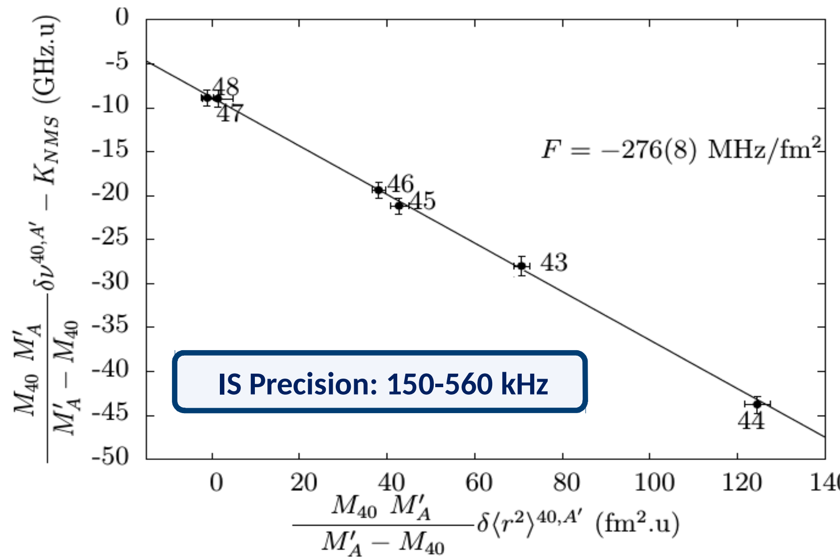

A new force between electrons and nucleons will cause a "King plot" non-linearity

[Berengut et al. Phys Rev Lett 120, 091801 (2018)]
[Stadnik et al. Phys Rev Lett 120, 223202 (2018)]
[Flambaum et al. Phys Rev A 97, 032510 (2018)]
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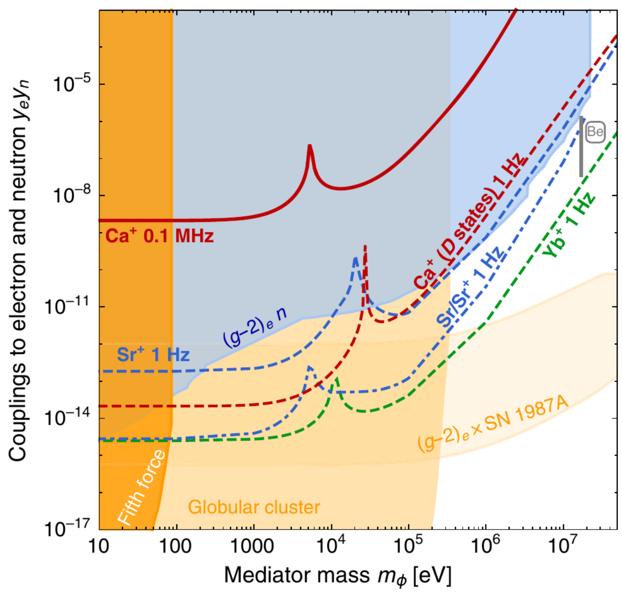

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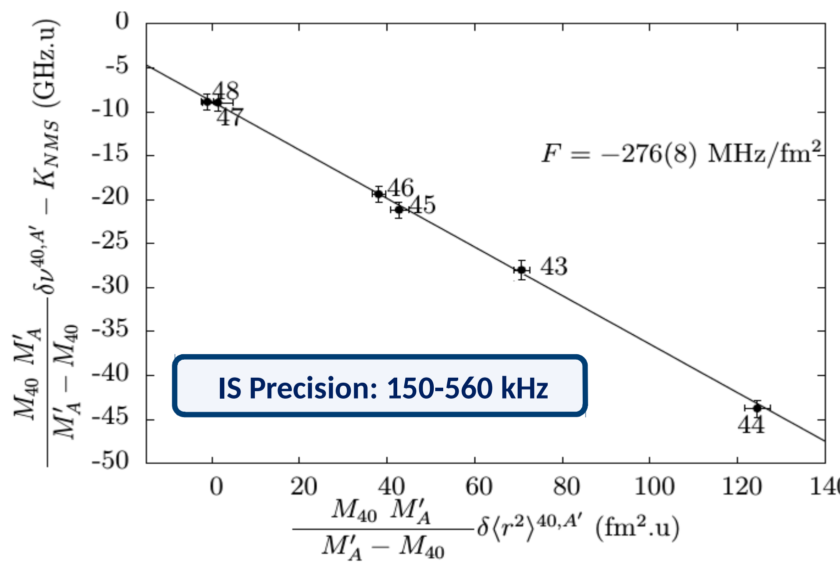

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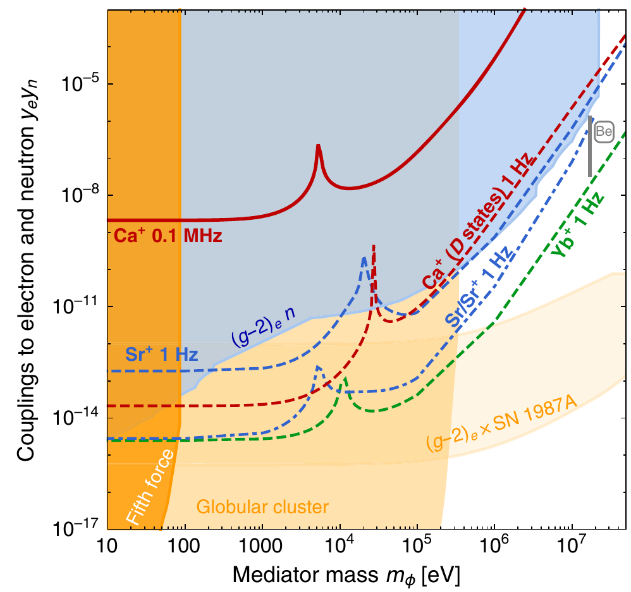
Sr^+ → mHz (Weizmann Institute)
[Manovitz et al. Phys. Rev. Lett. 123, 203001 (2019)]
Yb → < kHz (MIT, V. Vuletic group)



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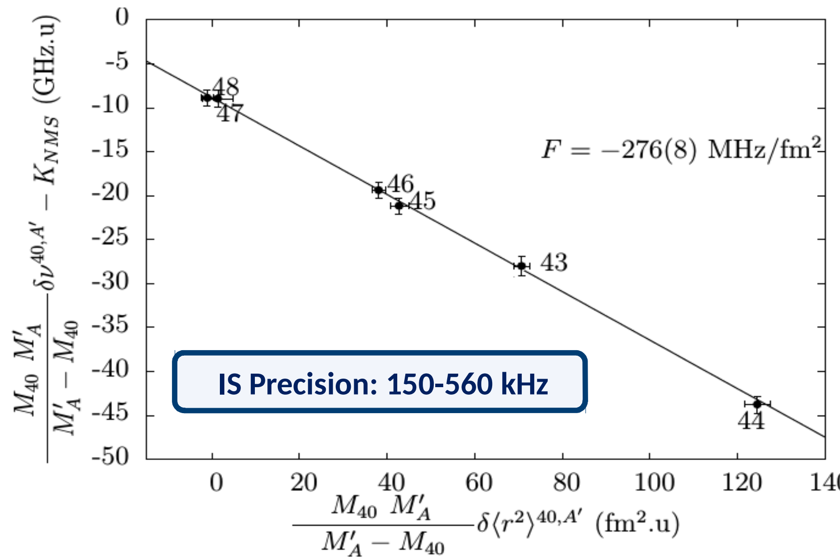


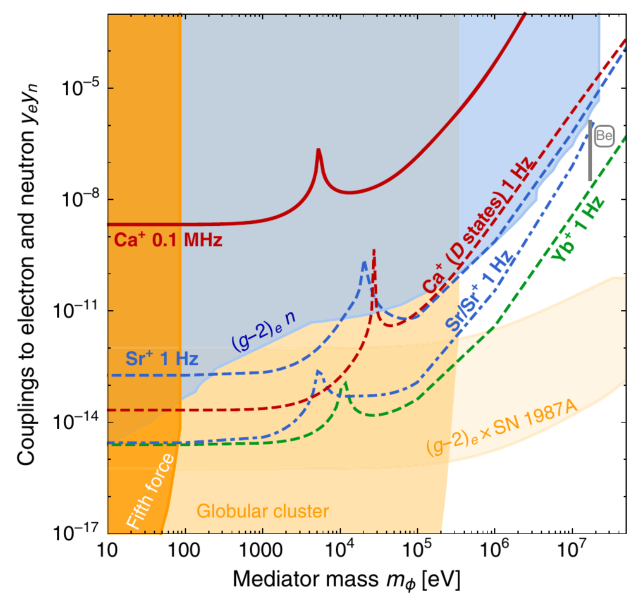
Opportunities with exotic atoms (?):

- ✓ Access to long isotopic chains
- ✓ Nuclear isomers ($M'_A \sim M_A$)
- ✓ Heavy nuclei

A new force between electrons and nucleons will cause a "King plot" non-linearity

[Berengut et al. Phys Rev Lett 120, 091801 (2018)]
[Stadnik et al. Phys Rev Lett 120, 223202 (2018)]
[Flambaum et al. Phys Rev A 97, 032510 (2018)]
[Frugiuele et al. Phys Rev D 96, 015011 (2017)]

Sr^+ → mHz (Weizmann Institute)
[Manovitz et al. Phys. Rev. Lett. 123, 203001 (2019)]
Yb → < kHz (MIT, V. Vuletic group)

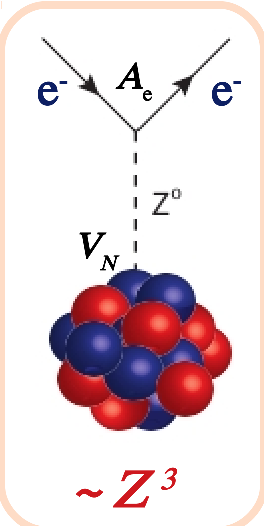


Contents

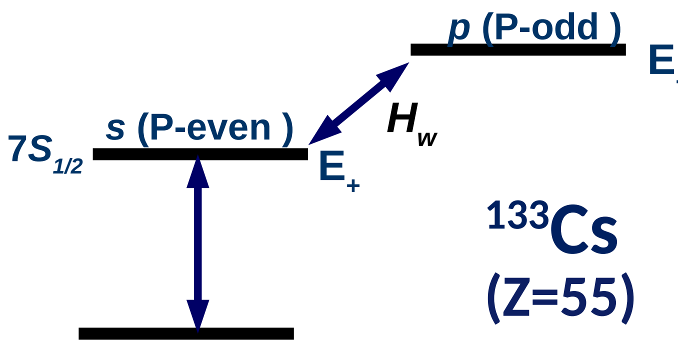
- Precision studies in atoms and molecules
- Nuclear structure / nuclear matter / new forces & particles
- **Parity violation**
- Parity and time-reversal violation
- First results: RaF
- Summary

Parity violation

Atoms



PV → Mix states of different parity



^{133}Cs
(Z=55)

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

$$E1_{APV} = \langle 7\tilde{S}_{1/2} | D | 6\tilde{S}_{1/2} \rangle = k\, Q_W$$

measure — atomic calculation

Expt: $Q_W(^{133}\text{Cs}) = -72.06(28)_{exp}(34)_{th}$

$Q_W = -N + (1-4\sin^2\theta_W)Z$

[Wood et al. Science 275, 1759 (1997)]
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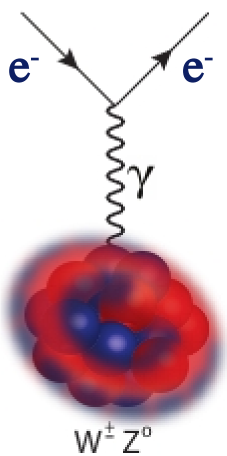
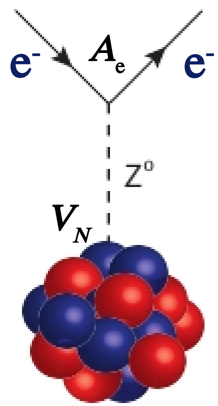


$\sim Z^2 A^{2/3} R(Z)$

$$H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5\, \rho(r)$$

Parity violation

Atoms



$\sim Z^3$

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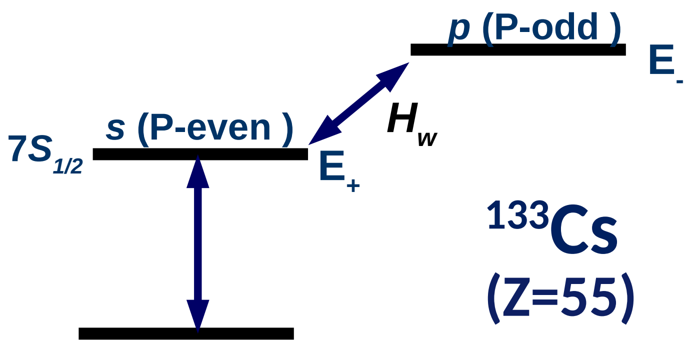

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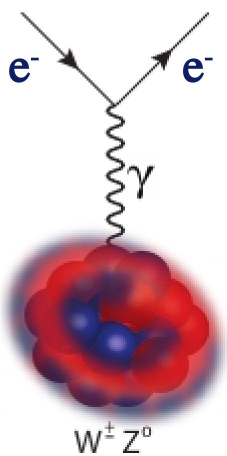

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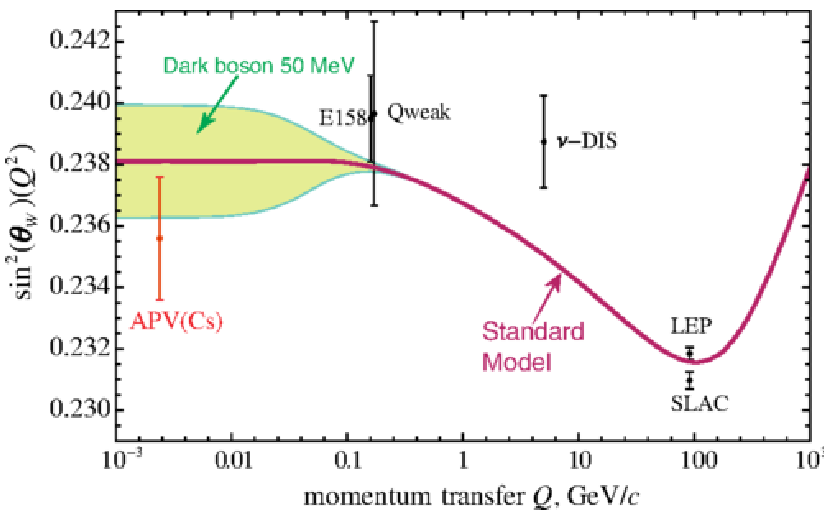

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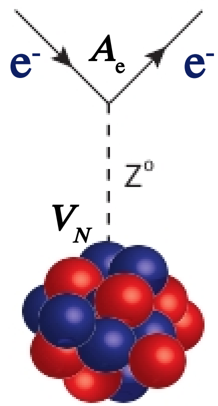
[Rev. Mod. Phys. 90, 025008 (2018)]

Parity violation

Atoms



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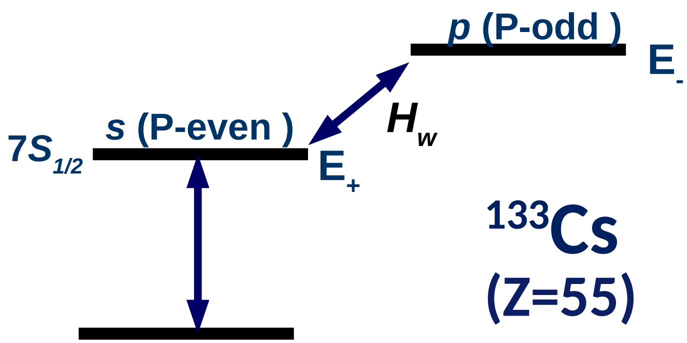

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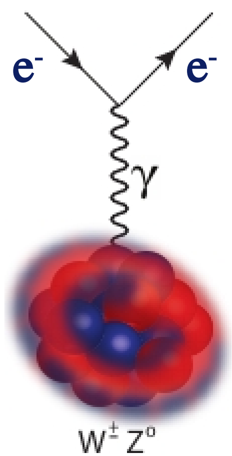

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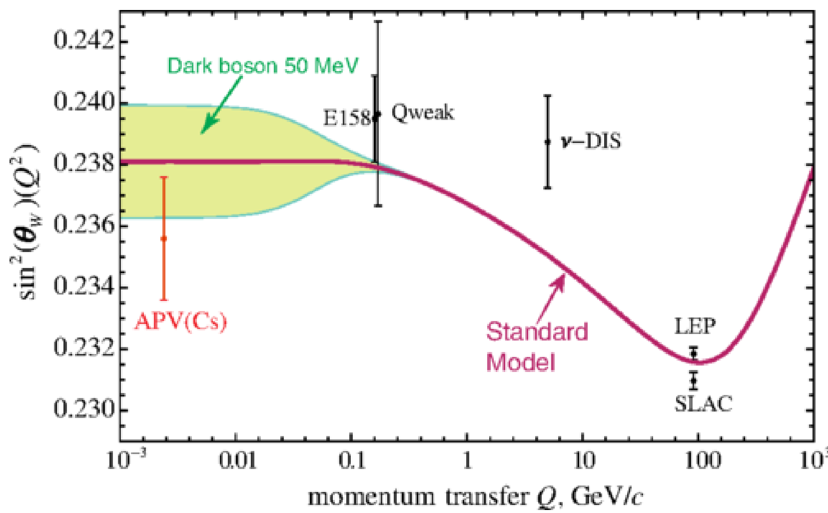

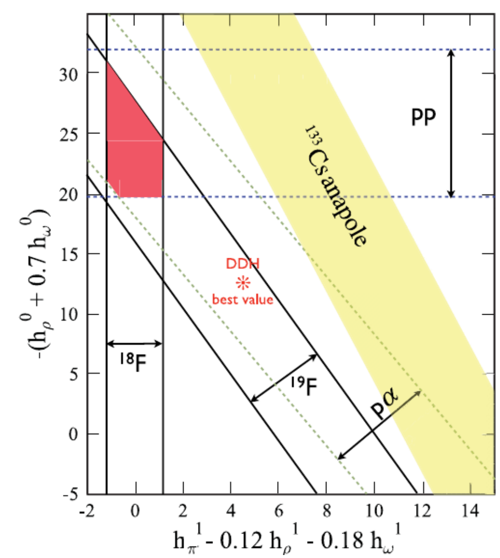

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Parity violation

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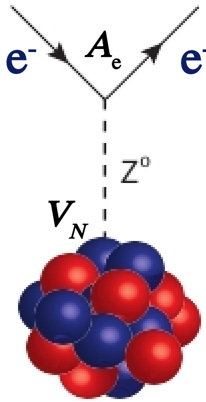

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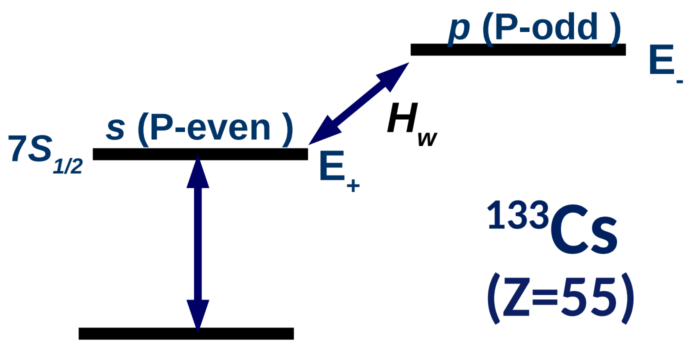

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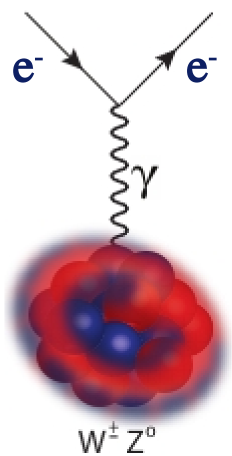

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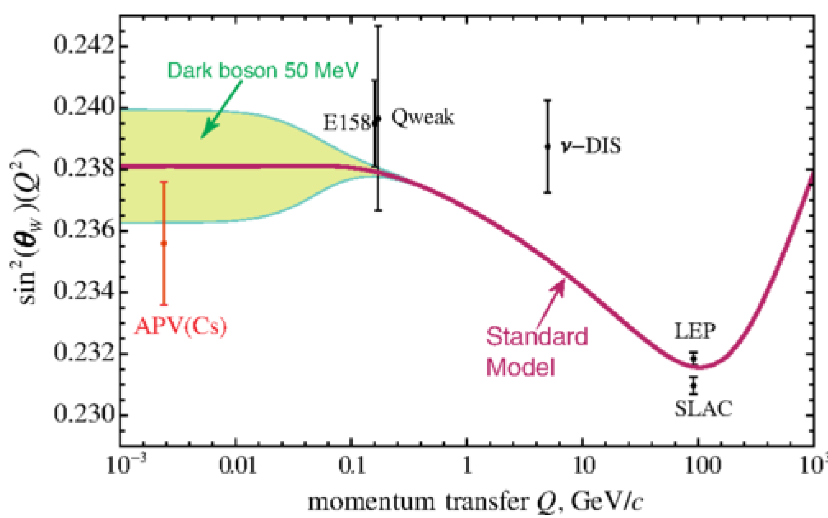
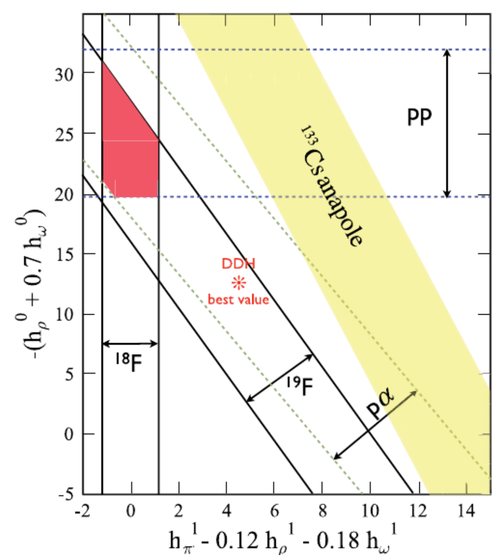




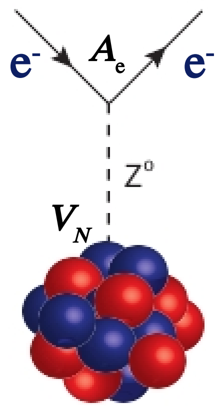
[Rev. Mod. Phys. 90, 025008 (2018)]

Yb (Z=70) stable @ Mainz → Isotopic ratios [Nature Phys. 15, 120 (2019)]

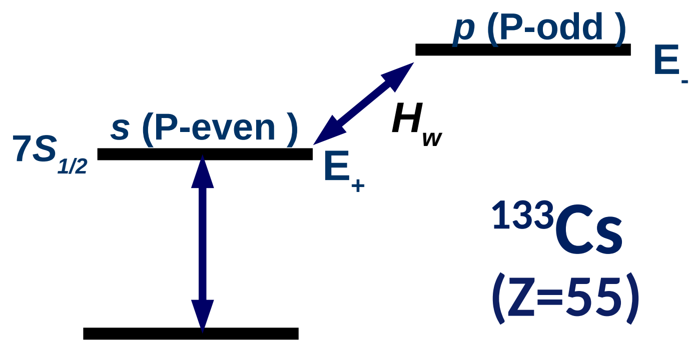
Parity violation

Atoms | **Why exotic atoms?**

PV → Mix states of different parity



~ Z^3



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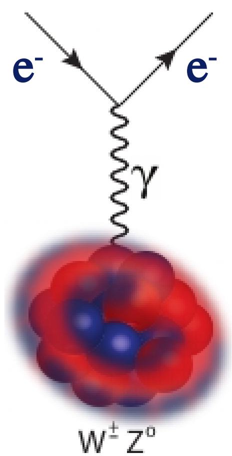

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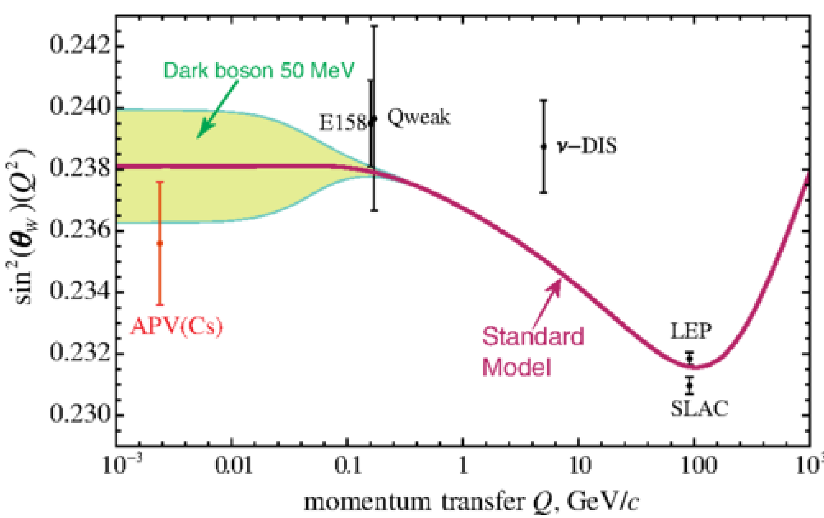

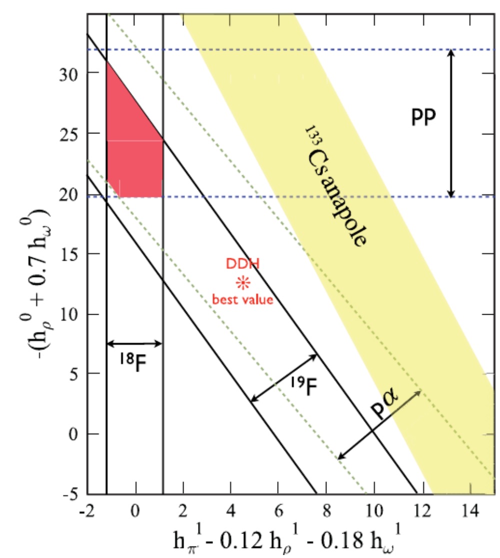

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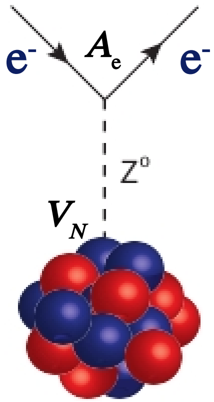

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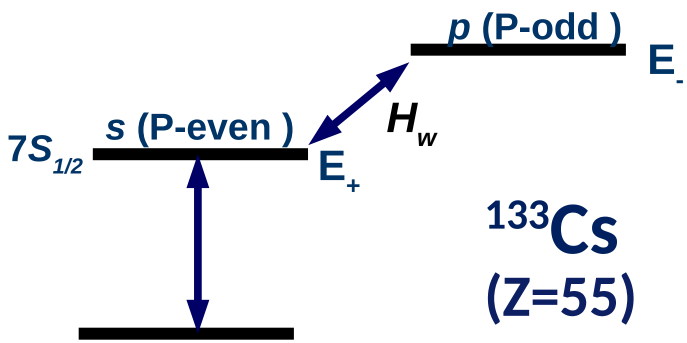

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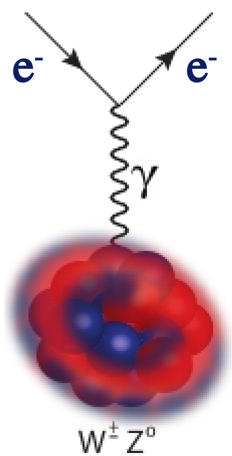
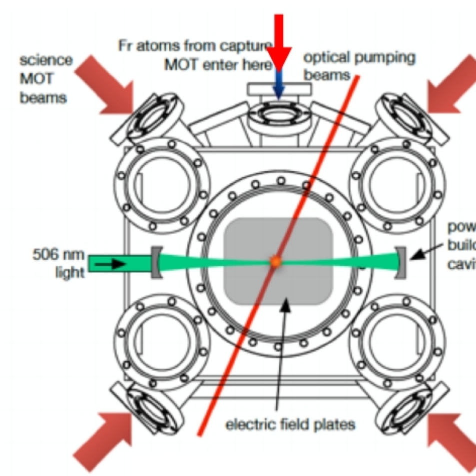


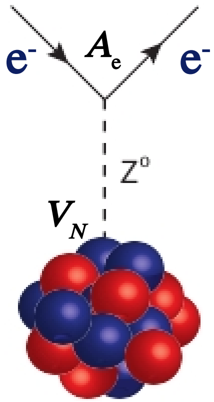
$\sim Z^2 A^{2/3} R(Z)$

Fr (Z=87) @ TRIUMF

[Zang et al. Phys. Rev. Lett. 115, 042501 (2015)]
[Kalita et al. Phys. Rev. A 97, 042507 (2018)]



Parity violation



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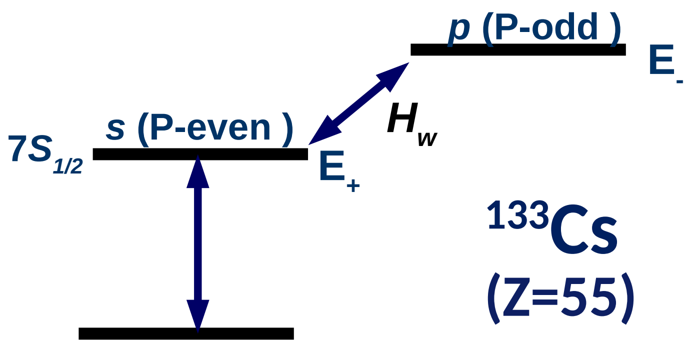

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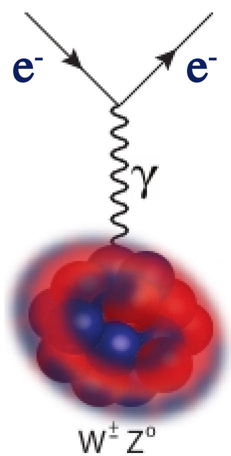
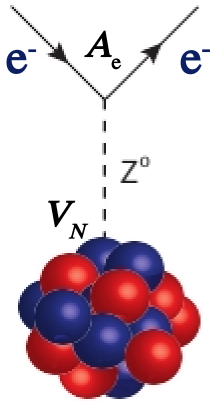


$\sim Z^2 A^{2/3} R(Z)$

Molecules | **Why (exotic) molecules?**

Parity violation



$\sim Z^3$

Atoms

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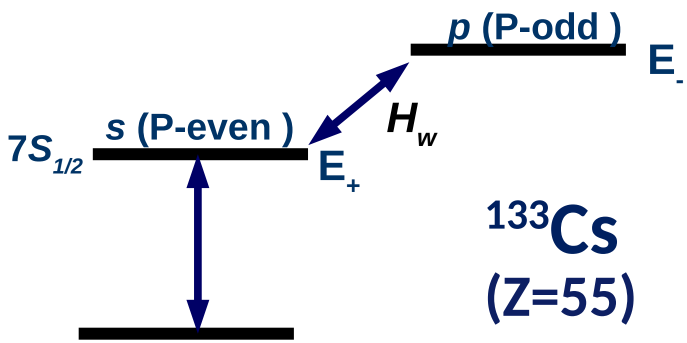

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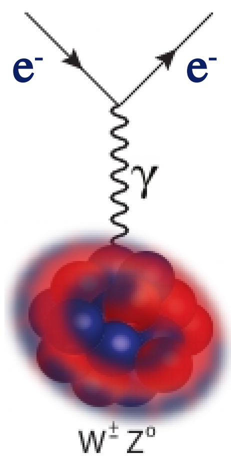


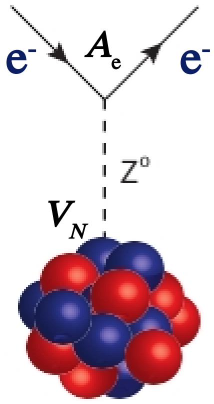
$\sim Z^2 A^{2/3} R(Z)$

Molecules

Why (exotic) molecules?

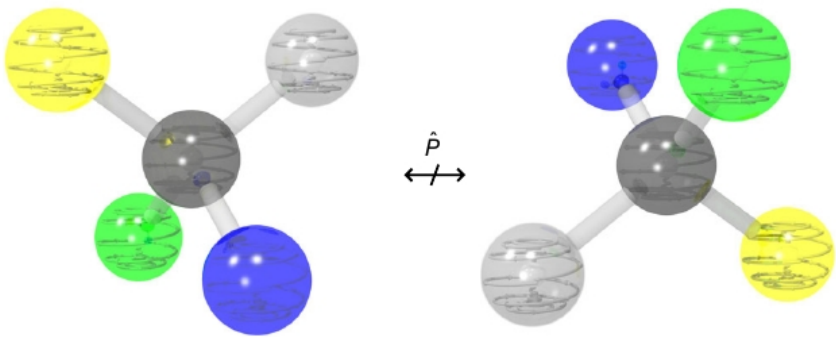
- ✓ $(E_+ - E_-) \sim 0$ About 10^3 enhancement
  [Dzuba et al. Phys. Rev. Lett. 119, 223201 (2017)]
- ✓ Nuclear-Spin-Dependent PV / Anapole moment (BaF)
  [Altunas et al. Phys Rev Lett 120, 142501 (2018)]

Parity violation

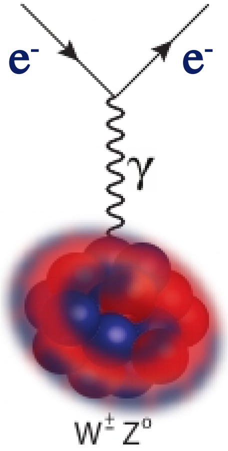


$\sim Z^5$

Chiral molecules



[Berger & Stohner. WIREs Comput. Mol. Sci. e1396, 1 (2018)]
[Laerdahl et al. Phys. Rev. Lett. 84, 3811 (2000)]



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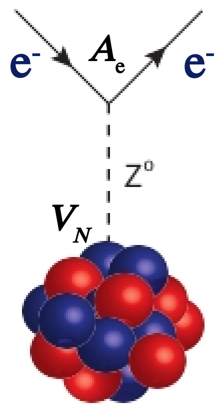
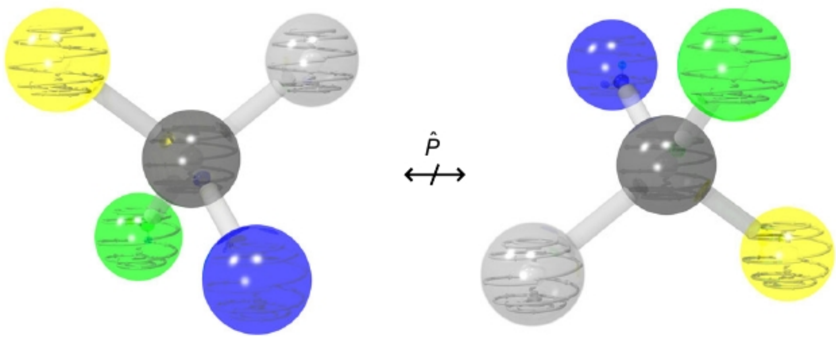
Parity violation



$\sim Z^5$

Chiral molecules



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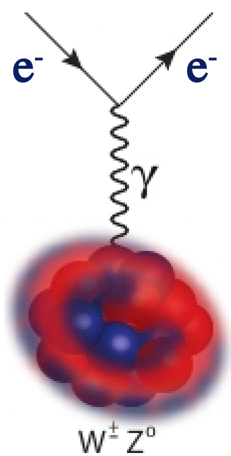

$\sim Z^2 A^{2/3} R(Z)$

$\Delta\nu_{pv}/\nu$ (x 10^{-16})

Molecule	HF	B3LYP	B–LYP	LDA
CHBrClF	+0.72	+1.01	+0.93	+0.98
CHBrFI	+17.8	+22.9	+22.1	+24.1
CHClFI	+9.35	+8.96	+6.94	+7.38
CHAtFI	−1072	−1008	−850	−946

[Berger et al. Mol. Phys. 105, 41 (2007)]

$$H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \, \rho(r)$$

^{211}At (Z=85, $T_{1/2}$~7.2 h) → Freq. shift ~ 3-10 Hz

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- Precision studies in atoms and molecules
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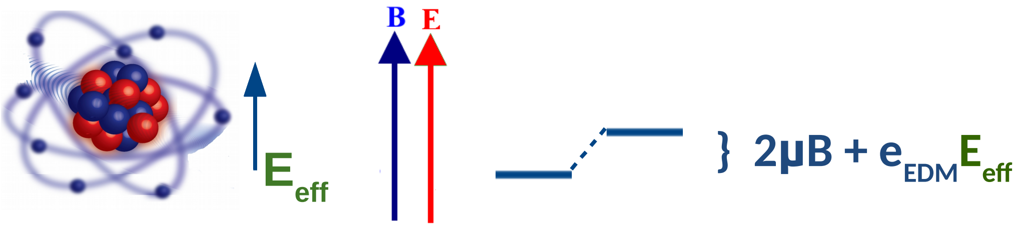
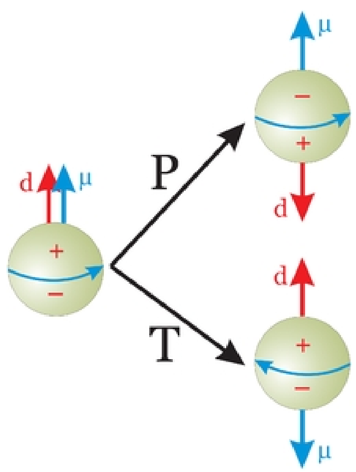
Parity and Time-reversal Violation

Atoms



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



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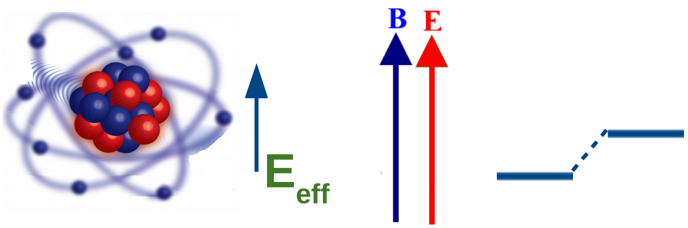


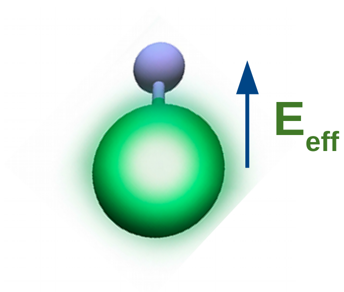
} $2\mu B + e_{EDM}E_{eff}$

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

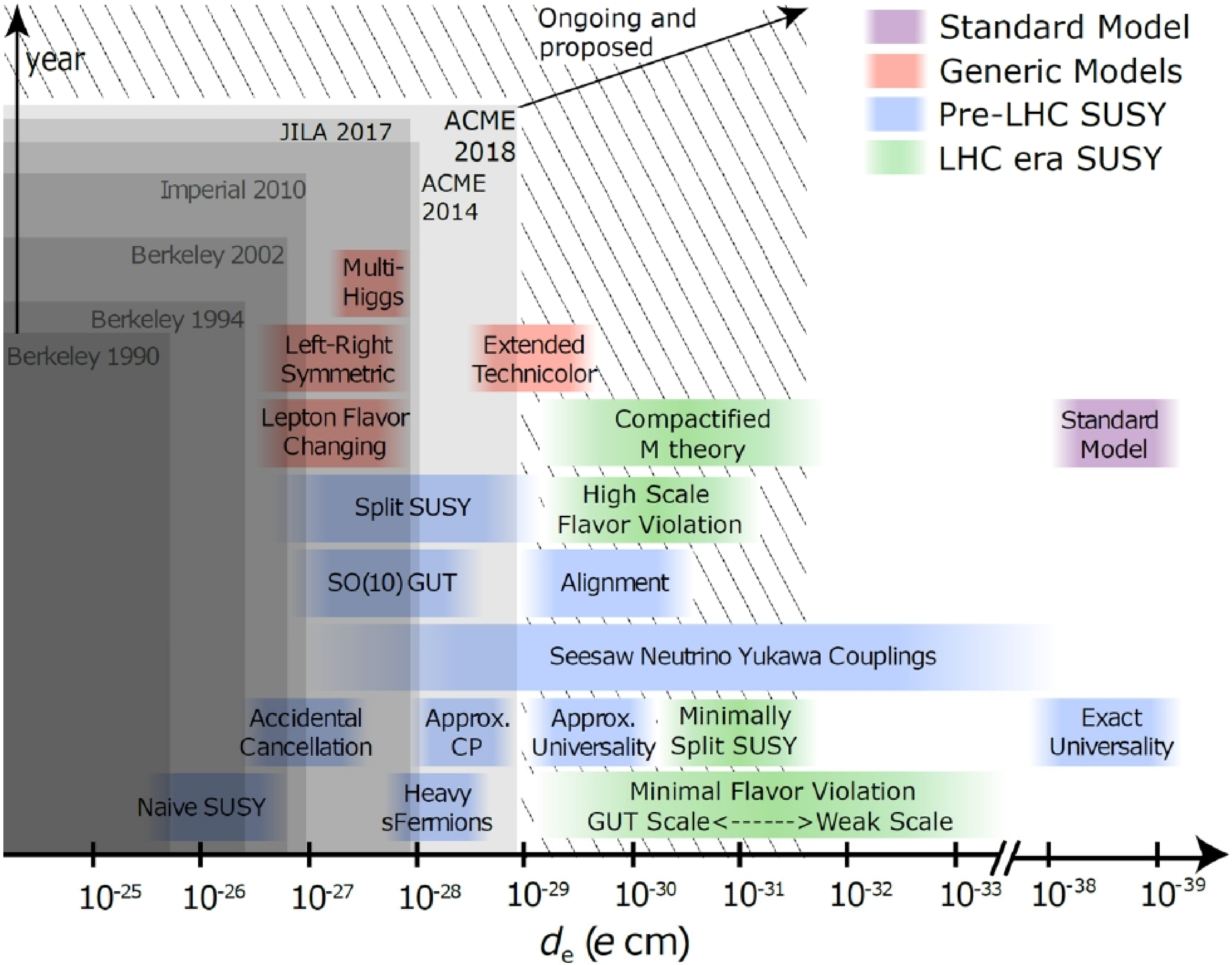
Molecules

- ✓ $>10^3$ enhancement of E_{eff} for EDM measurements

[ACME, Nature 562, 355 (2018)]
[Baron et al. Science 343, 269 (2014)]
[Sandars Phys. Rev. Lett. 18, 1396 (1967)]



E_{ext} ~1 V/cm
E_{eff} ~80 GV/cm



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

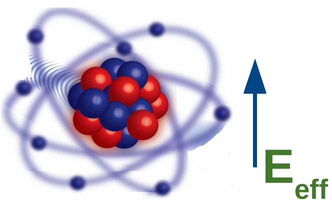
Why radioactive nuclei?

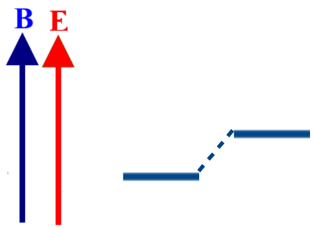
- Large Z → E_{ef} (>>)
- Deformed nuclei (>10^2)
- Large enhancement of the MQM (>10^2)
- Study of NSD interactions (I>0)

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

Why radioactive nuclei?

Atoms





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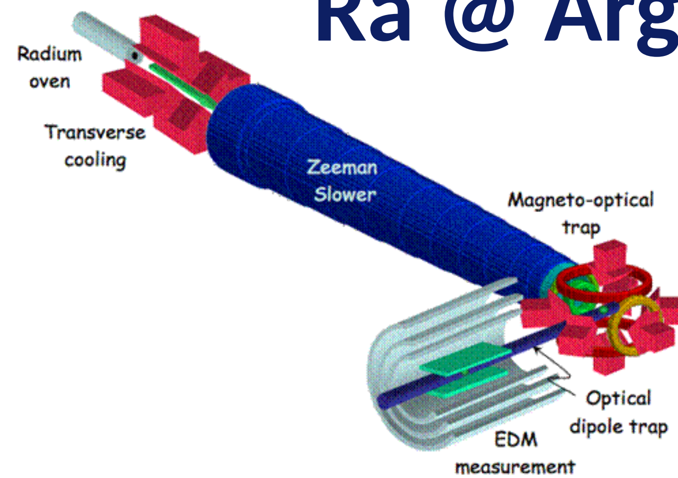
$$\sigma_d \sim \frac{1}{E_{\text{eff}}\tau\sqrt{\dot{N}T}}$$

Ra @ Argonne



$$|d(^{225}\text{Ra})| < 5.0 \times 10^{-22}\ e\,\text{cm}$$

Phys. Rev. Lett. 114, 233002 (2015)

Why radioactive nuclei?

P,T-odd nucleon-nucleon interaction

Schiff Moments

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

Nuclear structure

Experiment

ΔE: Energy splitting of opposite parity states

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Theory + Experiment

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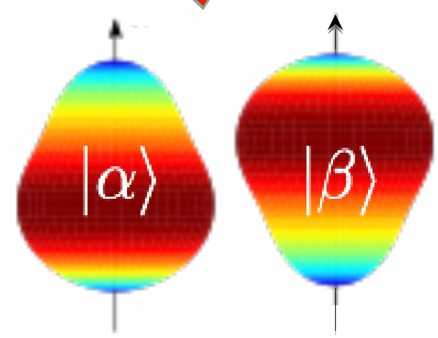

^{225}Ra

ΔE = 55 keV

Slide from L. Gaffney

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

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

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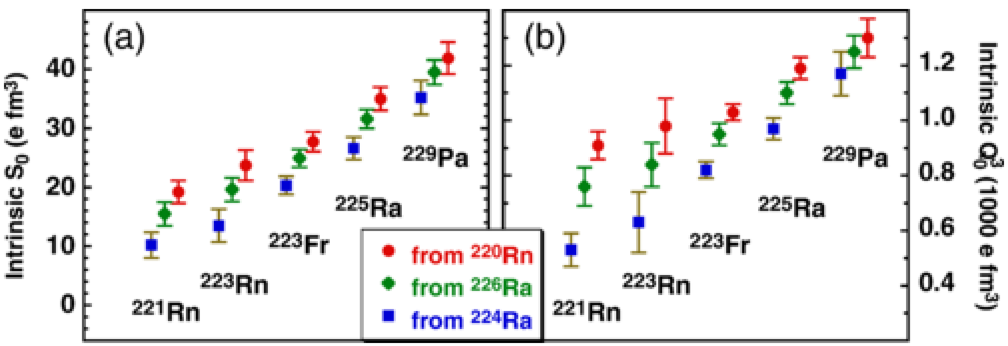
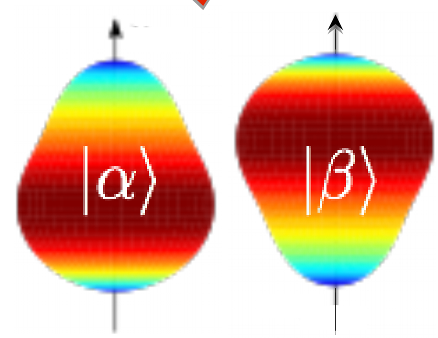


Dobaczewski et al. Phys. Rev. Lett. **121**, 232501 (2018)
Chupp et al. Rev. Mod. Phys. **91**, 015001 (2019)

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



^{225}**Ra**
ΔE = 55 keV

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

Contents

RaF → Nuclear x Molecular Enhancement

- ✓ Large Z → E_{ef} (>>)
- ✓ Deformed nuclei (>10^2)
- ✓ Large enhancement of the MQM (>10^2)
- ✓ Study of NSD interactions (I>0)

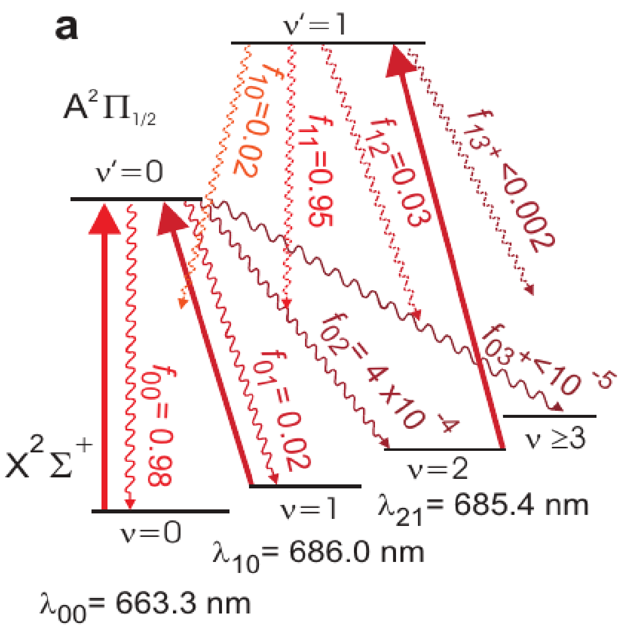
P- and P,T- odd effects

Enhanced sensitivity in radioactive molecules
(composed of heavy and octupole deformed nuclei)

Molecules: Electroweak structure
- Anapole moment: AM
- Magnetic Quadrupole Moment: MQM
- Schiff Moment: S_{schiff}
- eEDM, nEDM, …

Fluoride molecules

- **SrF → First evidence of laser cooling**
  [Nature 467, 820-823 (2010)]
- **YbF → Nature 473, 493 (2011)**
- **.**
- **.**
- **.**



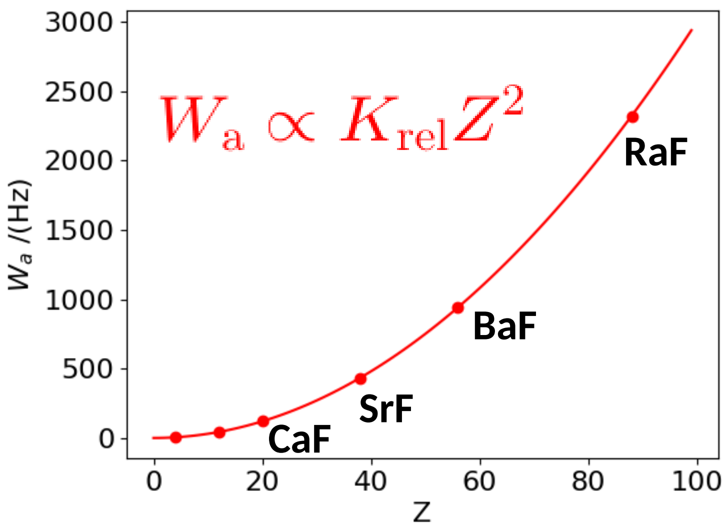
- **.**
- **.**
- **.**
- **SrF → Nature Physics 13, 1173(2017)**
- **YbF → Phys. Rev. Lett. 120, 123201 (2018)**
- **CaF → Nature Physics 14, 890 (2018)**
  Phys. Rev. Lett. 120, 163201 (2018)
- **RaF → Radioactive**
  Coming soon …

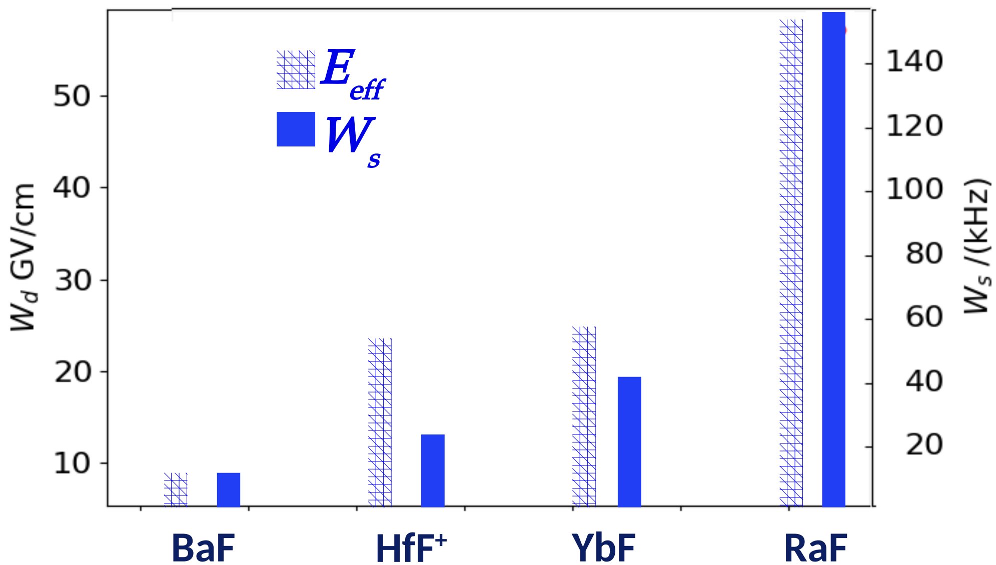
Radioactive Molecules: Ra(Z=88)F Results

$$\widehat{H}_{\rm sr} = B\vec{\mathcal{N}}^2 + \gamma\,\vec{\mathbf{S}}^{\rm eff}\cdot\vec{\mathcal{N}} + \vec{\mathbf{S}}^{\rm eff}\cdot\widehat{\mathbf{A}}\cdot\vec{\mathbf{I}} + \vec{\mathcal{N}}\cdot\widehat{\mathbf{C}}\cdot\vec{\mathbf{I}} + \cdots$$

$$+W_a(K_A/2)[\vec{\lambda}\times\vec{S}^{\rm eff}].\vec{I} + (W_s k_s + E_{\rm eff} d_e)\vec{\lambda}.\vec{S}^{\rm eff}$$

P-odd and P,T -odd effects





[Gaul & Berger J. Chem. Phys 147, 014109(2017)]
[Fleig. Phys. Rev. A 96, 040502 (2017)]

RaF → Superior sensitivity for both P- and P,T- odd effects

... BUT all parameters experimentally unknown!

Results: Radium fluoride (RaF)

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

I. Low-lying structure?
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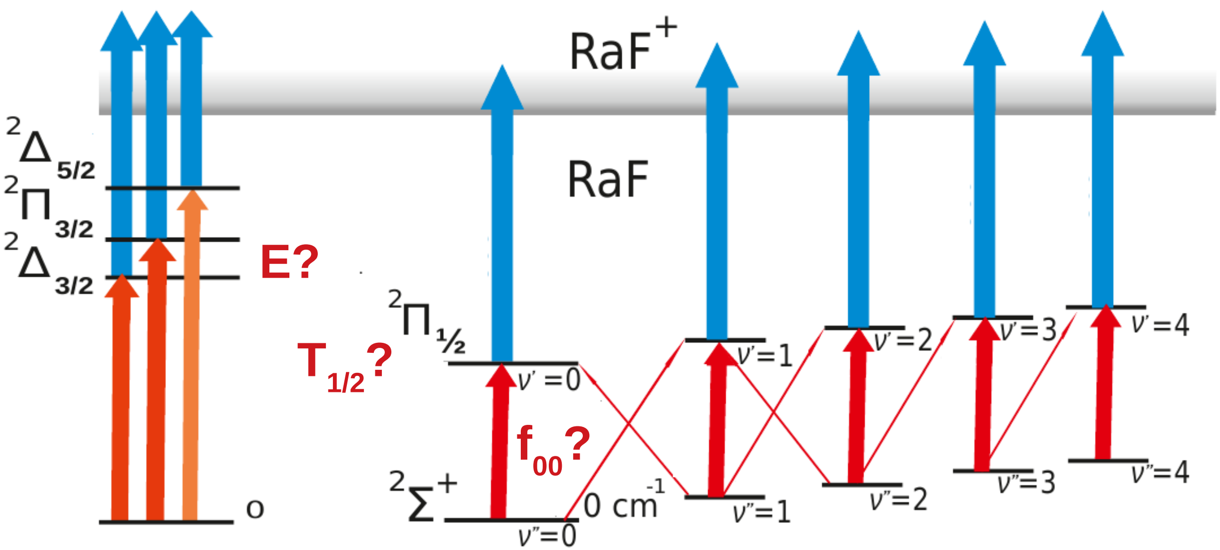

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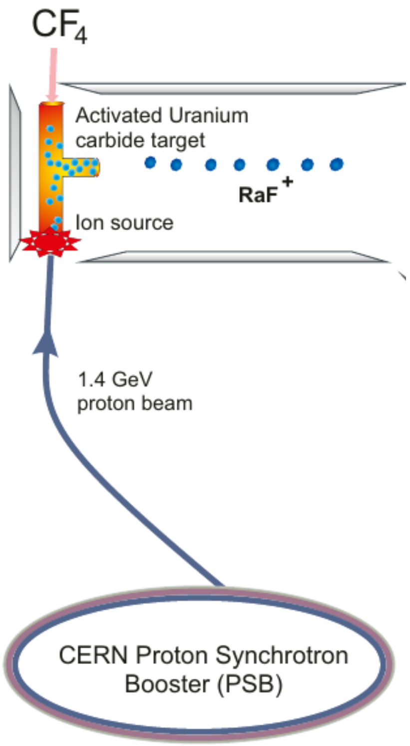

$$\mathrm{Ra}^{+} \xrightarrow{\mathrm{CF}_4} \mathrm{RaF}^{+}$$

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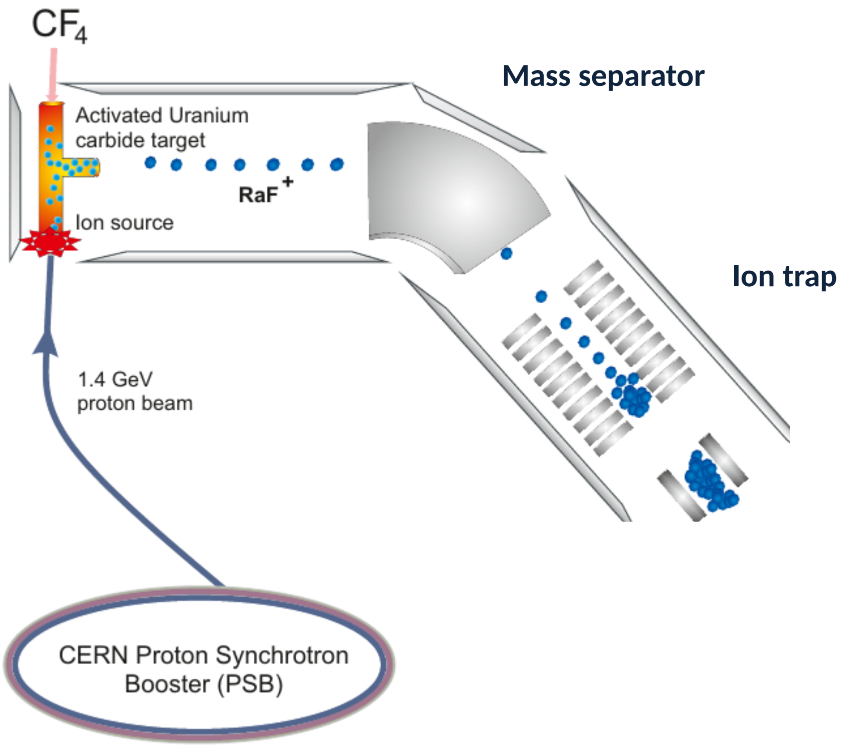

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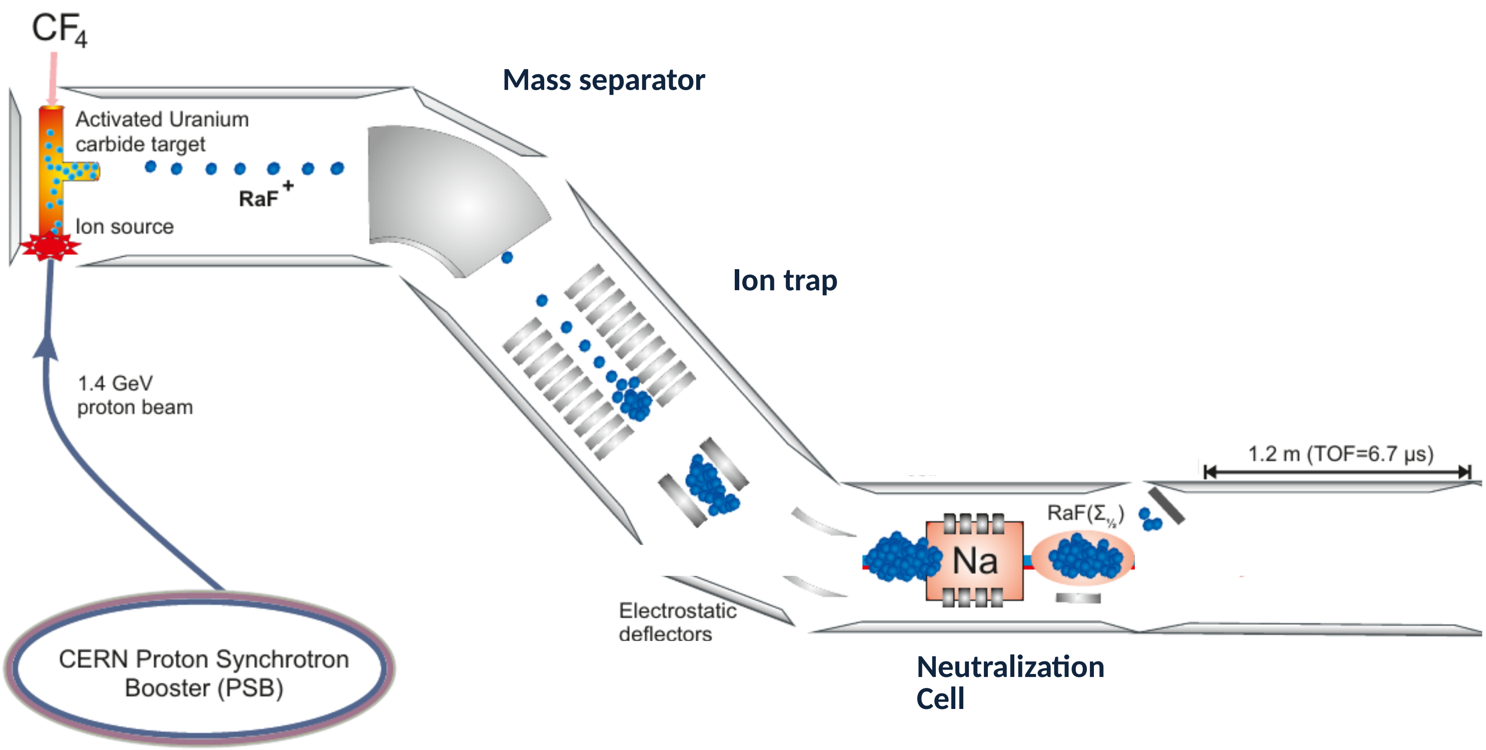

$$Ra^+ \xrightarrow{CF_4} RaF^+ \xrightarrow{Na} RaF(^2\Sigma)$$

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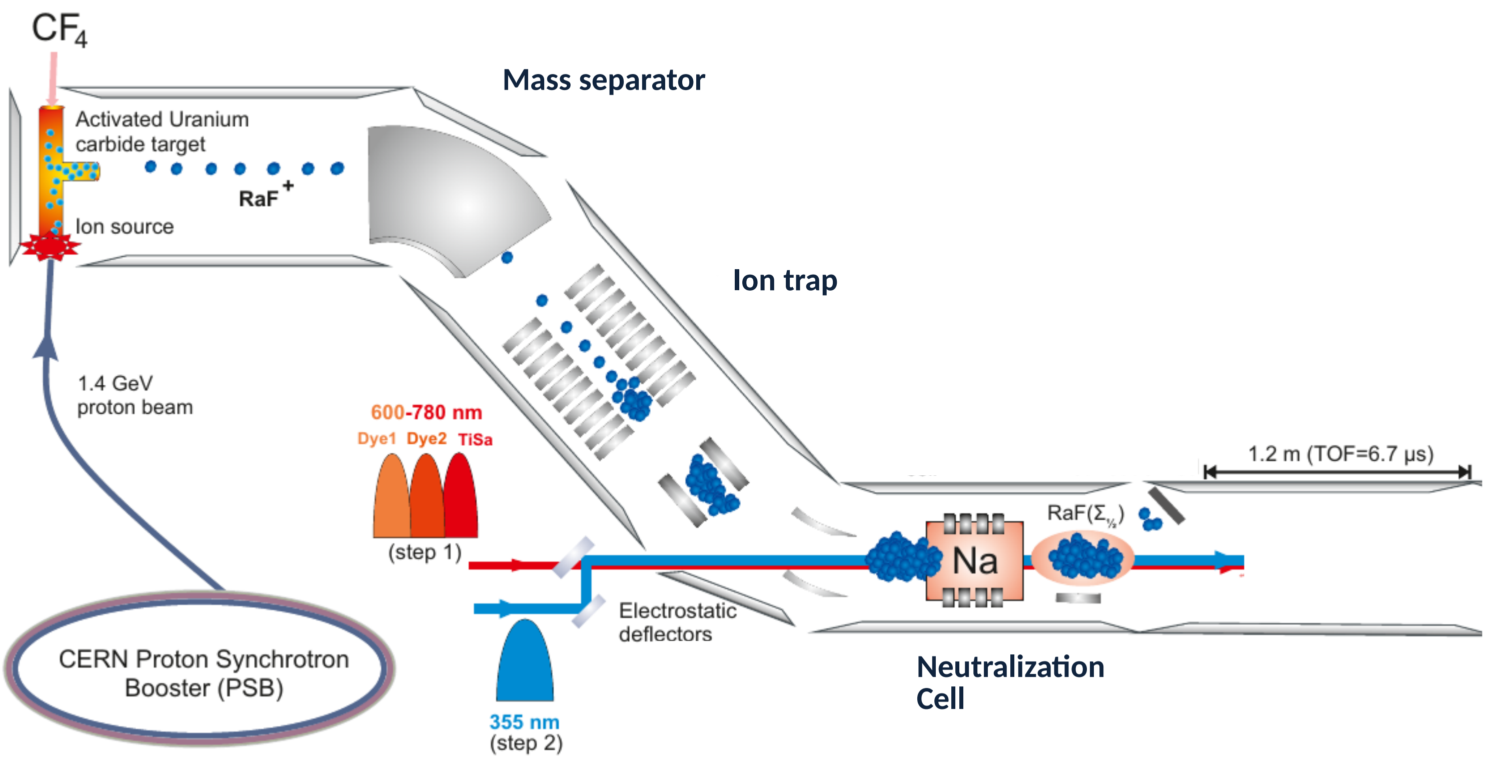

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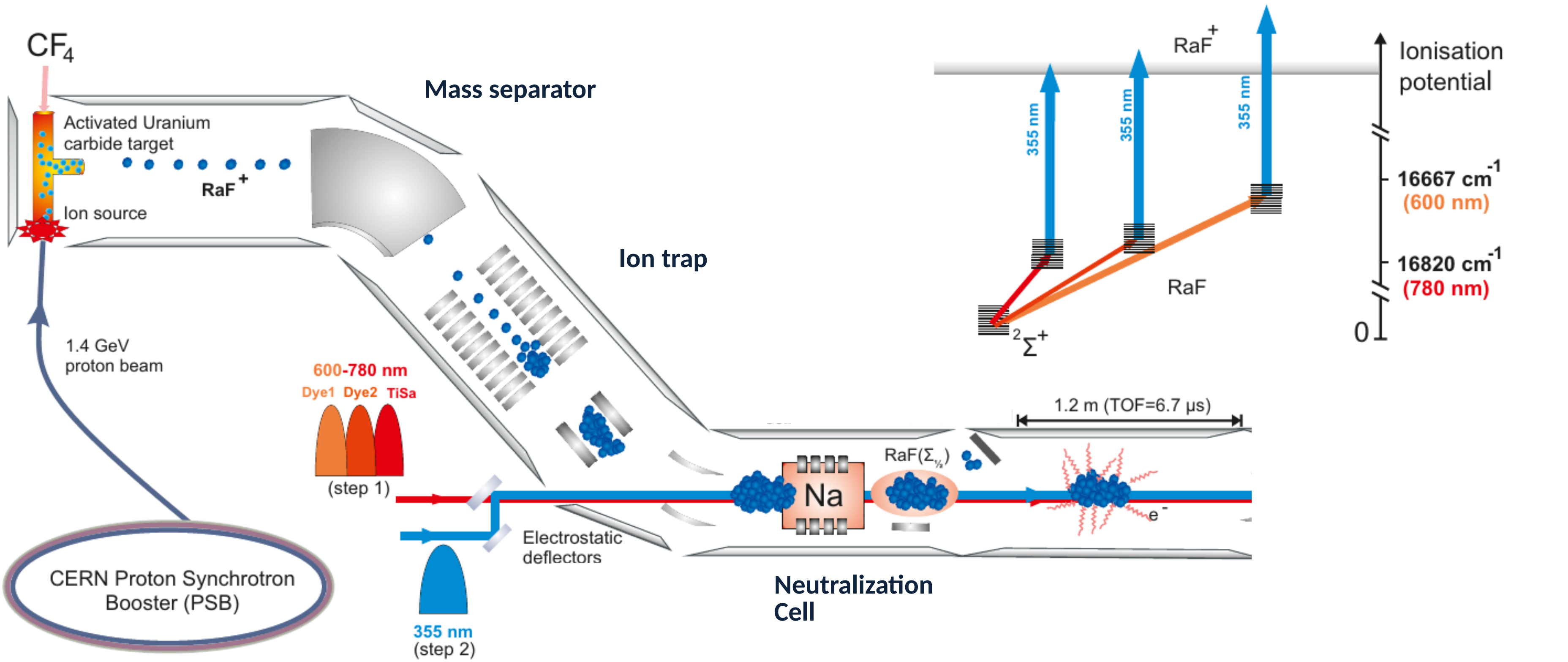

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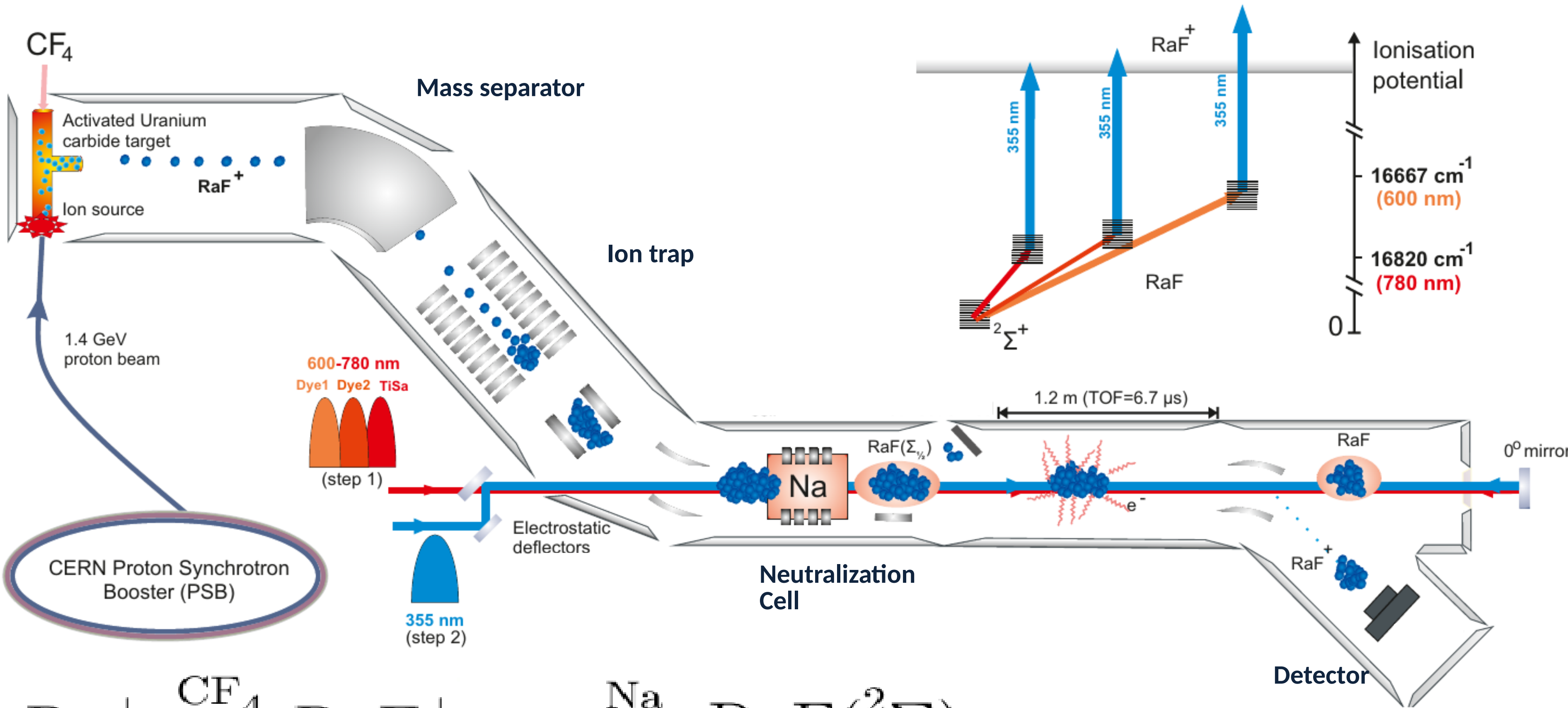

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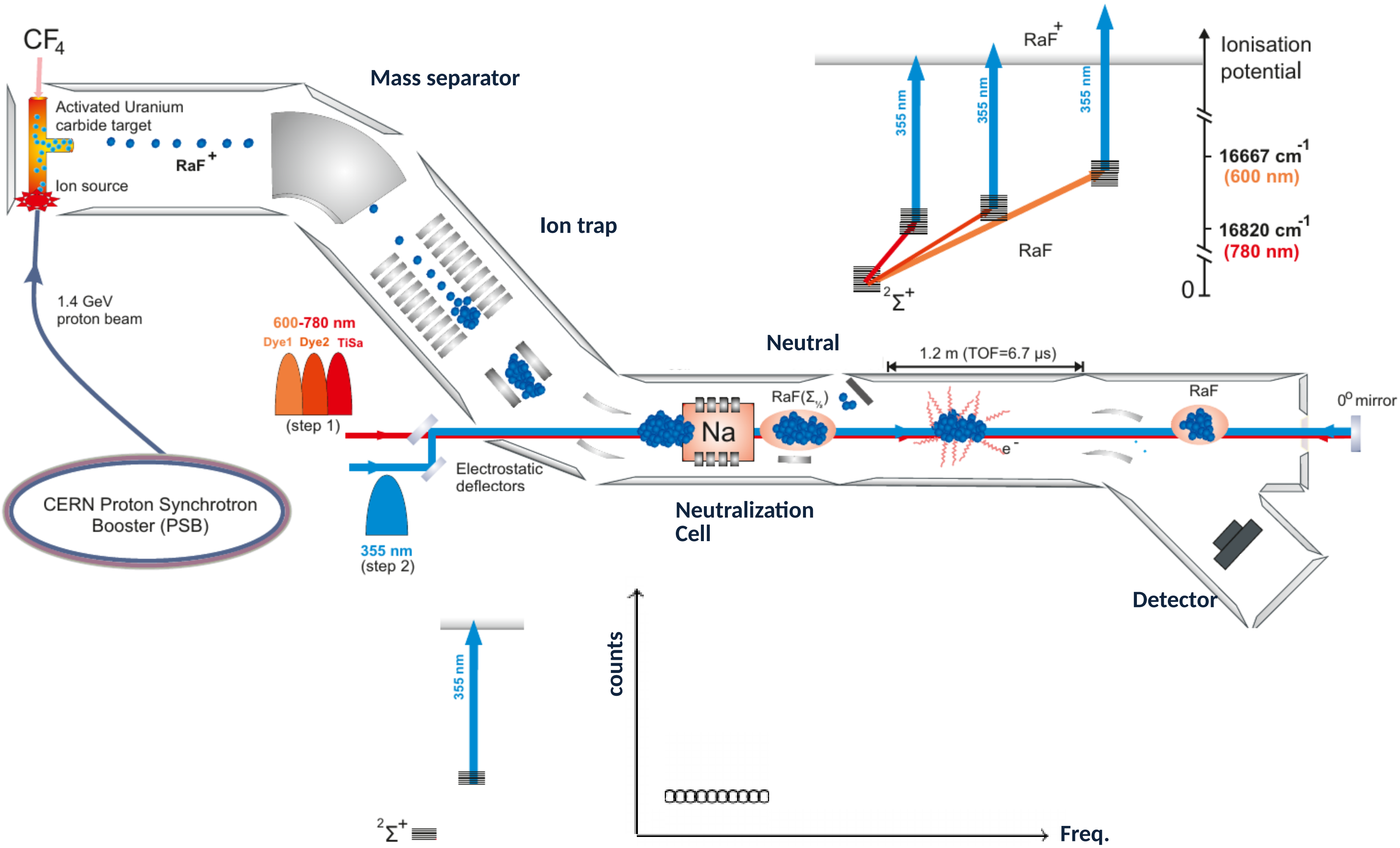

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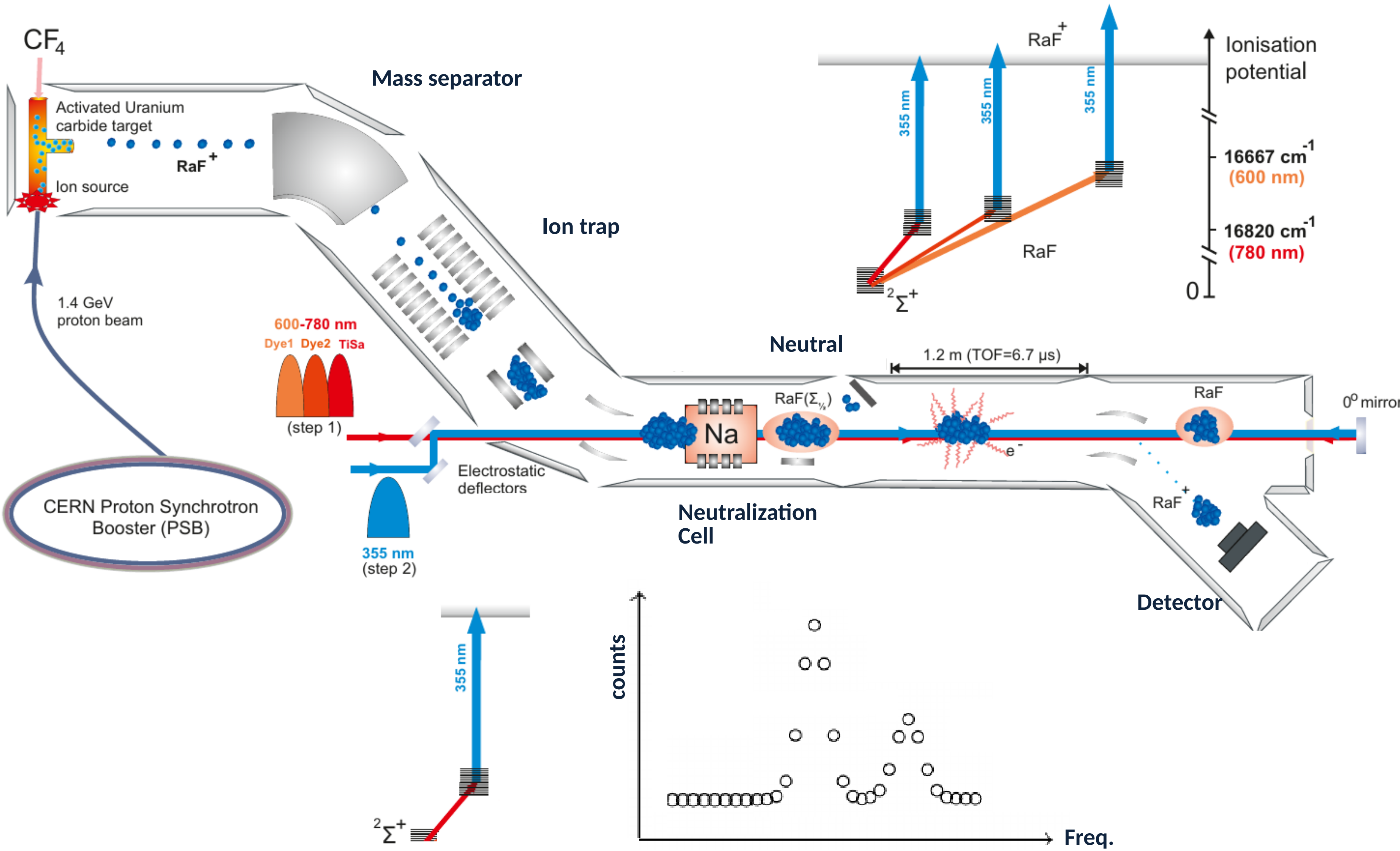

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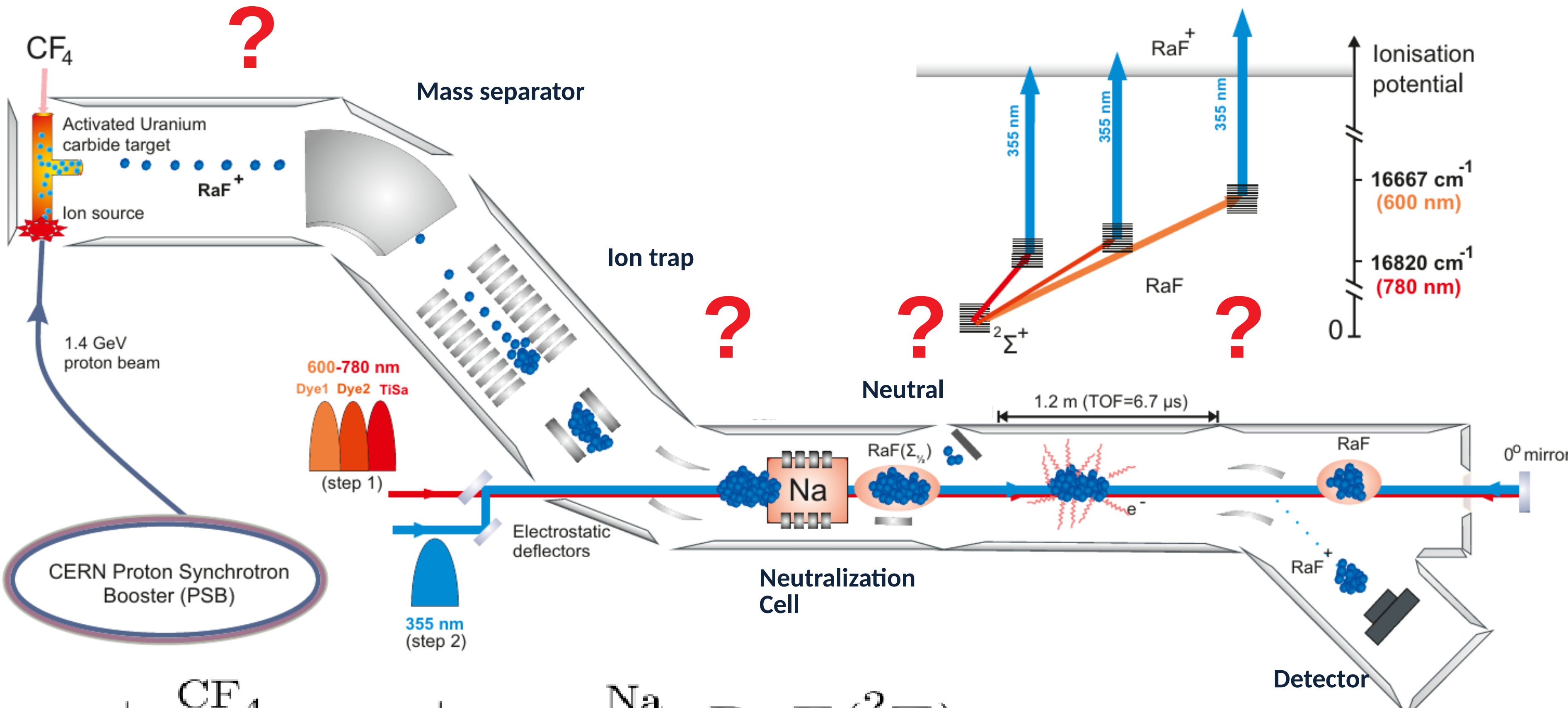

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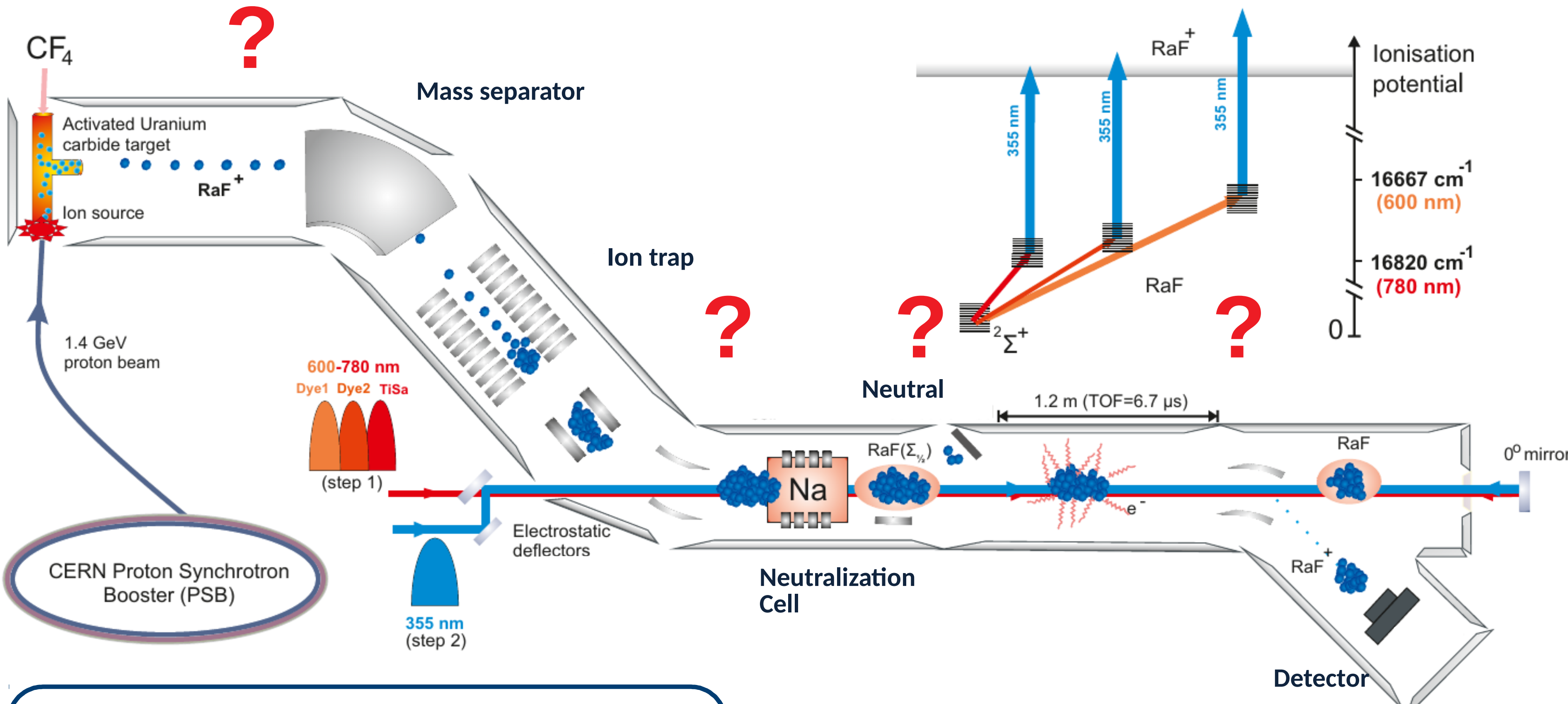

Molecules have complex structures
→ More than 10^4 states can be populated
Vibrational / rotational / hyperfine
Impossible with a hot (> 300 K) molecule?

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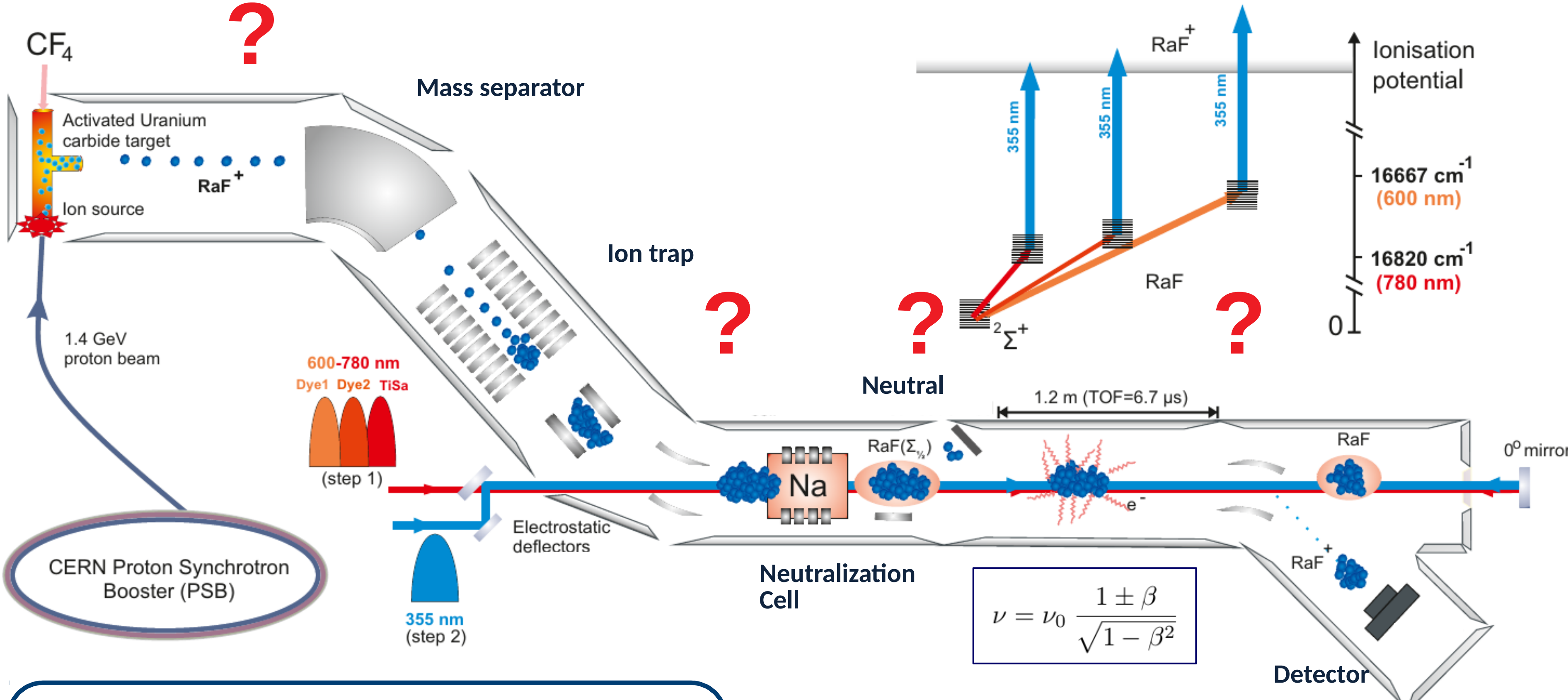


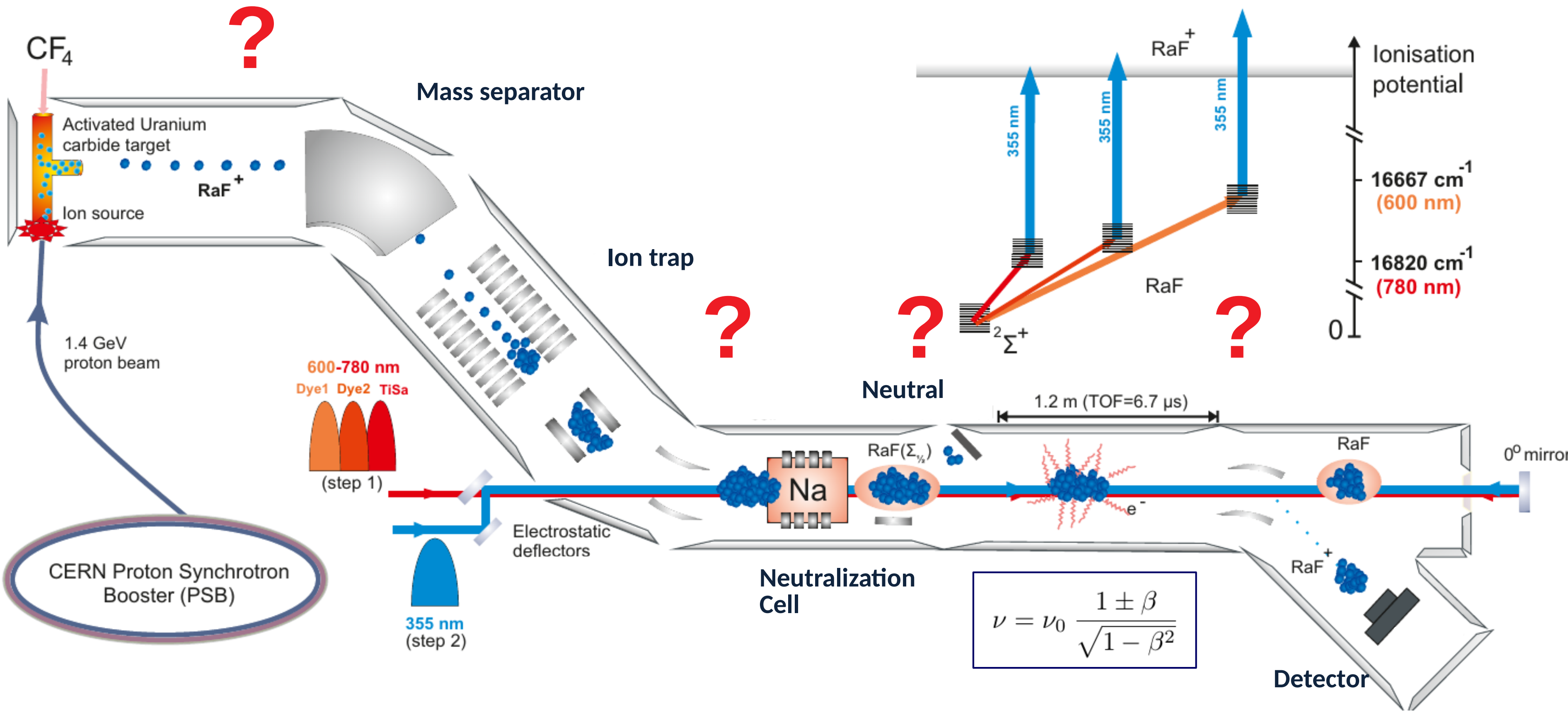
$$\nu = \nu_0 \frac{1 \pm \beta}{\sqrt{1-\beta^2}}$$

Molecules have complex structures
→ More than <u>10^4 states</u> can be populated
***Vibrational* / rotational / hyperfine**
Impossible with a hot (> 300 K) molecule?

Theory: $13300(1000)\mathrm{cm}^{-1}$
Scanning 1000 cm^{-1} at 100 MHz/min (1 cm^{-1} = 30 GHz)
→ <u>208 days!!</u>

<u>**Impossible with radioactive molecules (< 10^6 molecules/second)?**</u>

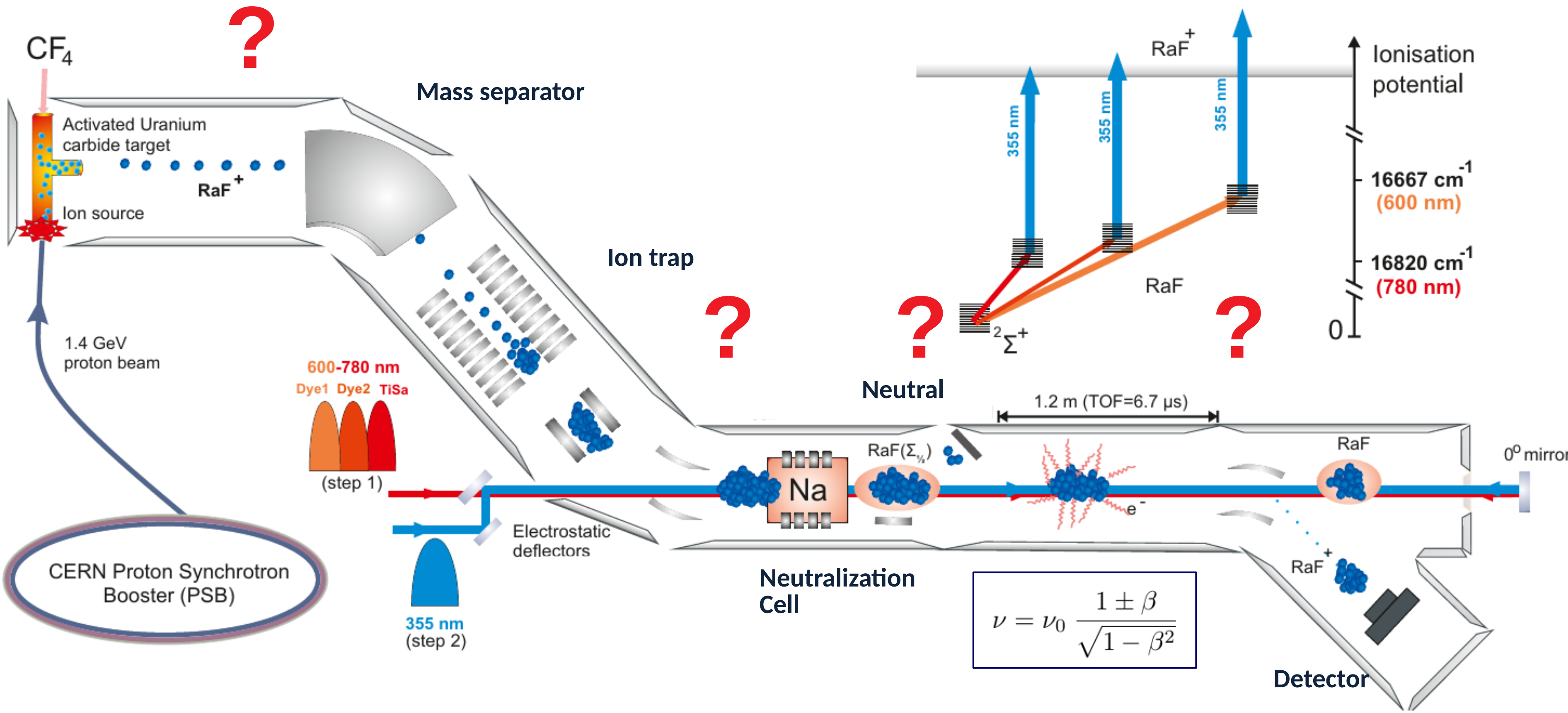
Results: Radium fluoride (RaF)



$$\nu = \nu_0 \frac{1 \pm \beta}{\sqrt{1-\beta^2}}$$

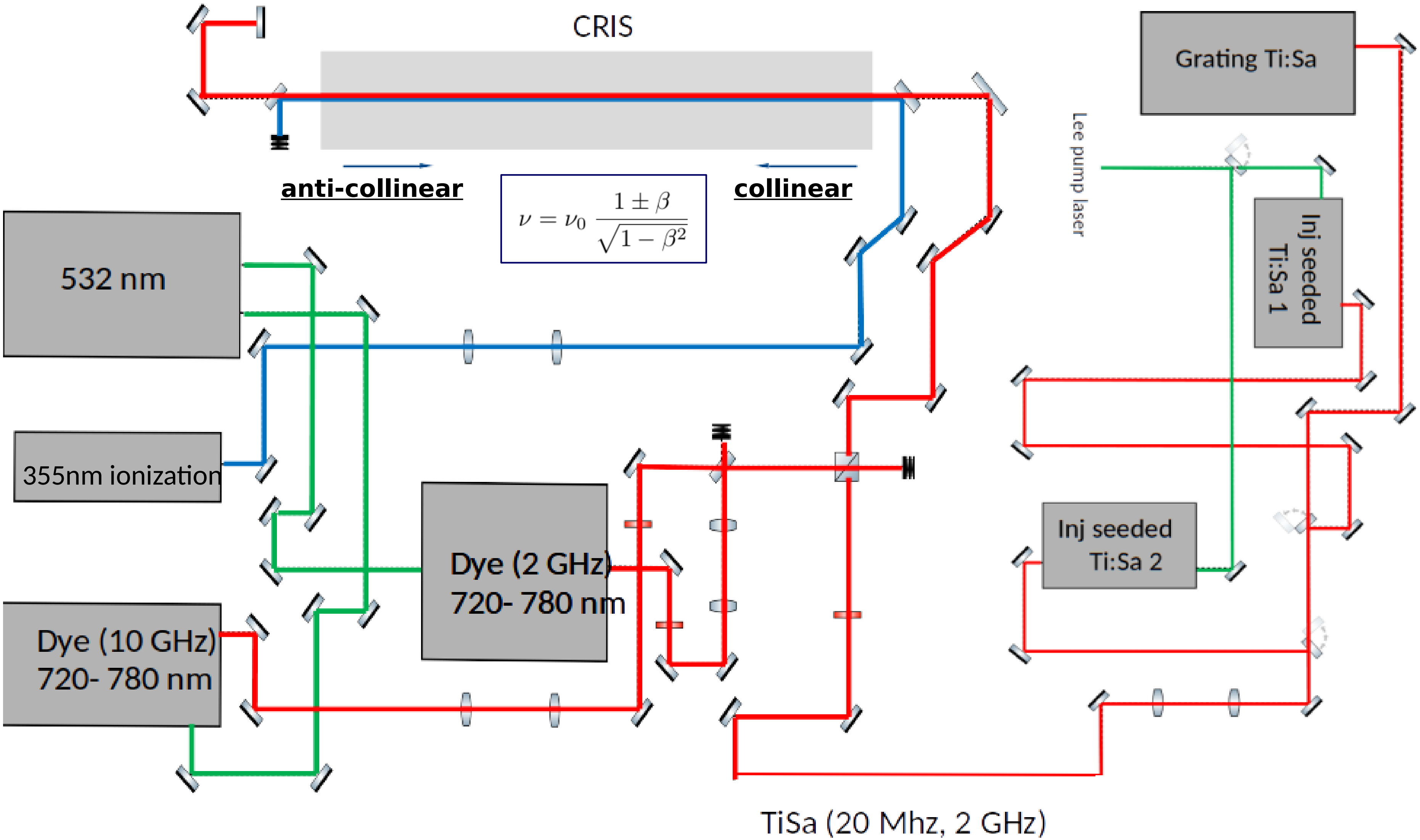
"We shall send to the moon, 240,000 miles away from the control station in Houston, a giant rocket more than 300 feet tall, made of new metal alloys, some of which have not yet been invented, capable of standing heat and stresses several times more than have ever been experienced,on an untried mission, to an unknown celestial body, and then return it safely to Earth, reentering the atmosphere at speeds of over 25,000 miles per hour, causing heat about half that of the temperature of the sun, and do all this, and do it right, and do it first before this decade is out—then we must be bold." J.F. Kennedy (1962).

Results: Radium fluoride (RaF)



"We shall send to the ~~moon~~ ISOLDE, 240,000 ~~miles~~ mm away from the control station in ~~Houston~~ CERN, a giant ~~rocket~~ molecule more than 300 ~~feet~~ fm tall, made of new metal alloys, some of which have not yet been ~~invented~~ studied, capable of standing heat and stresses several times more than have ever been experienced,on an untried mission, to an unknown ~~celestial body~~ gas-filled ion trap, and then return it safely to (neutral) Earth, reentering the ~~atmosphere~~ neutralization cell at speeds of over ~~25,000~~ 400,000 miles per hour, causing heat about half that of the temperature of the sun, and do all this, and do it right, and do it first before ~~this decade is out~~ Long Shutdown 2—then we must be bold." J.F. Kennedy (1962).

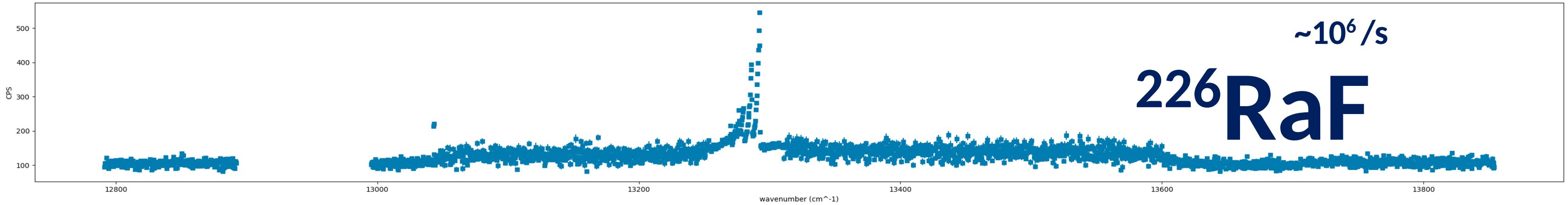
Results: Radium fluoride (RaF)



About 20 laser systems

(simplified scheme)

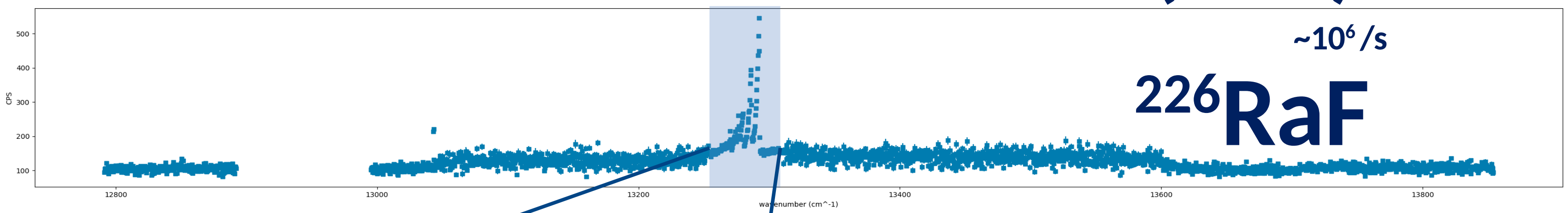
Results: Radium fluoride (RaF)



~1000 cm^{-1} (30 THz) → <u>only 4 hours!</u>

[Garcia Ruiz, Berger et al. Submitted (2019) (arXiv:1910.13416)]

Results: Radium fluoride (RaF)



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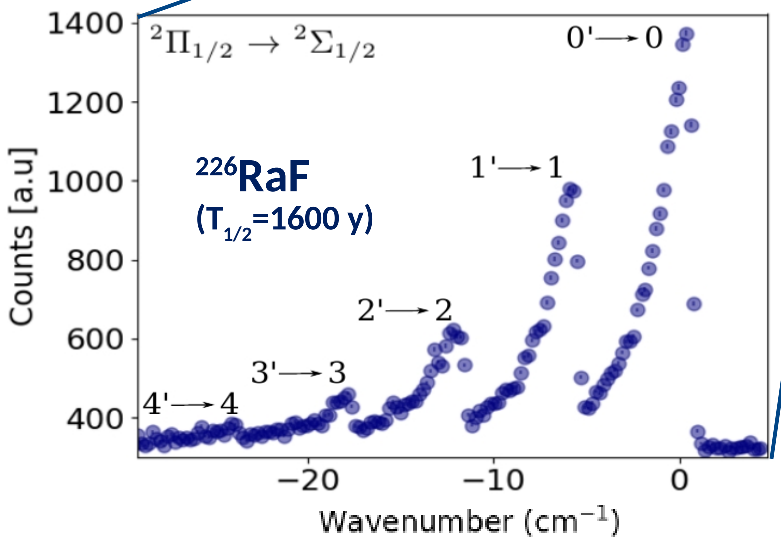

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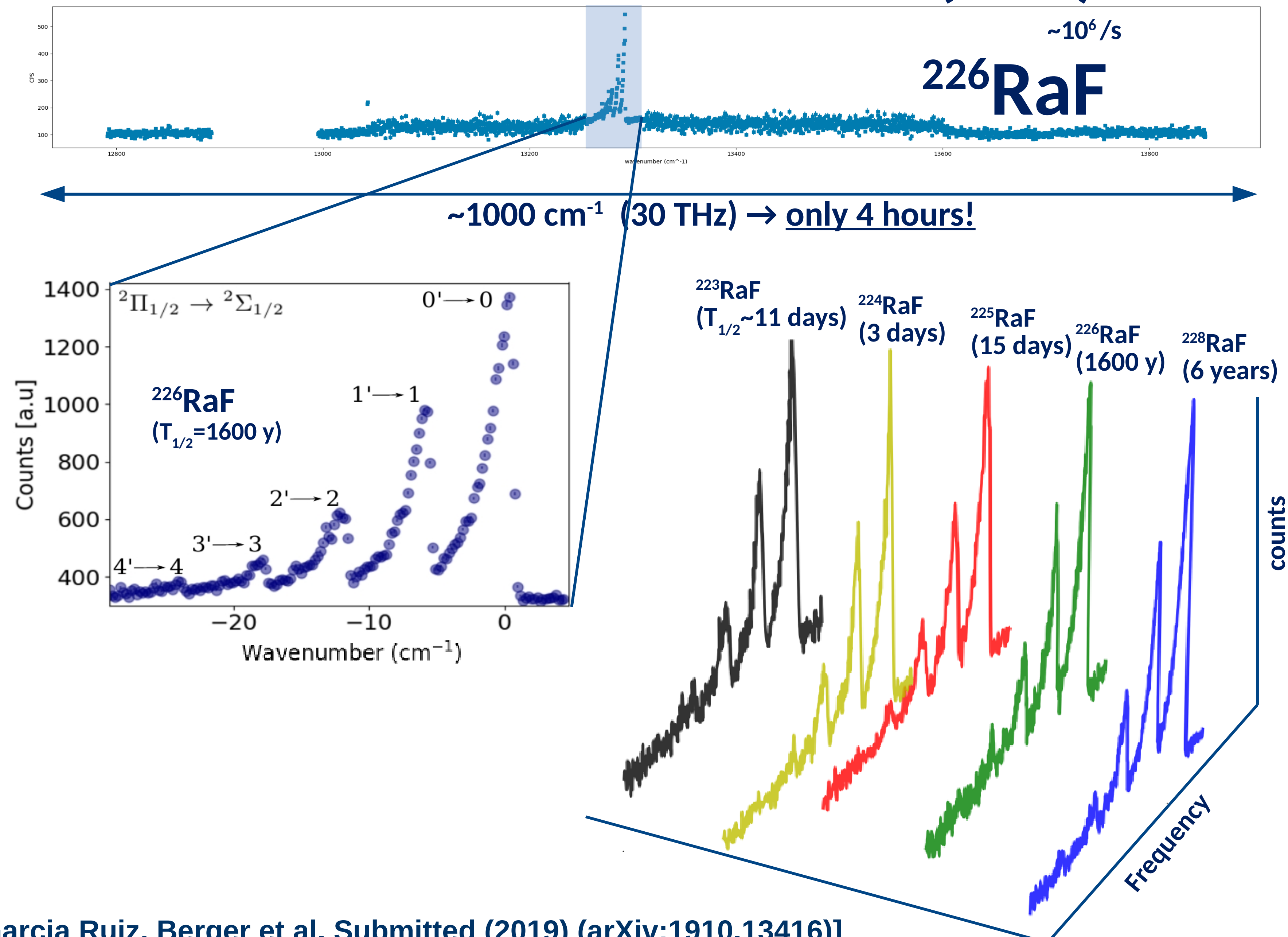

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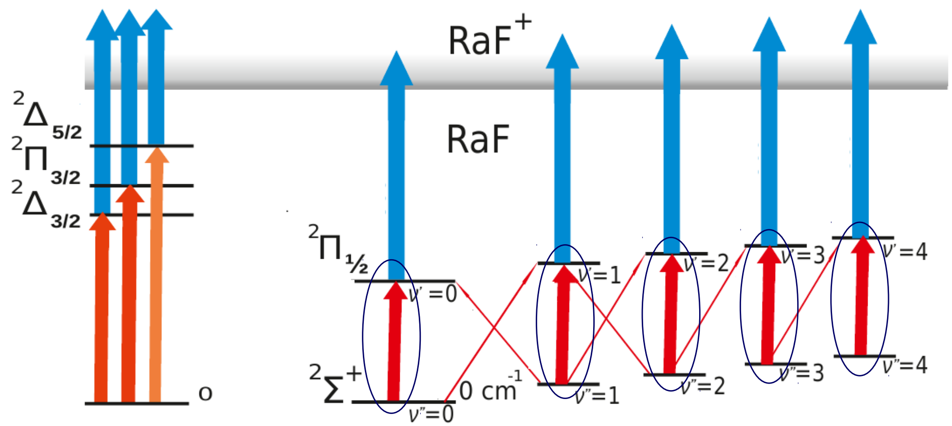

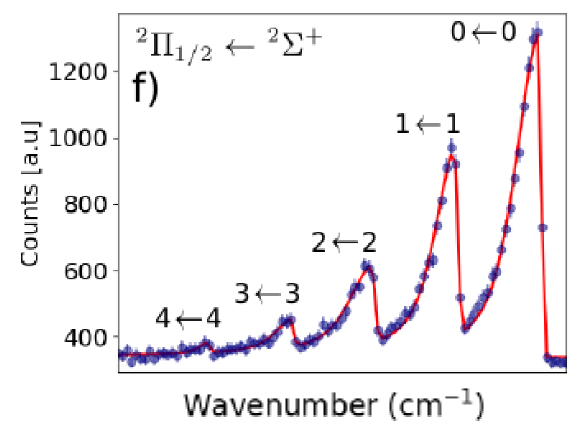

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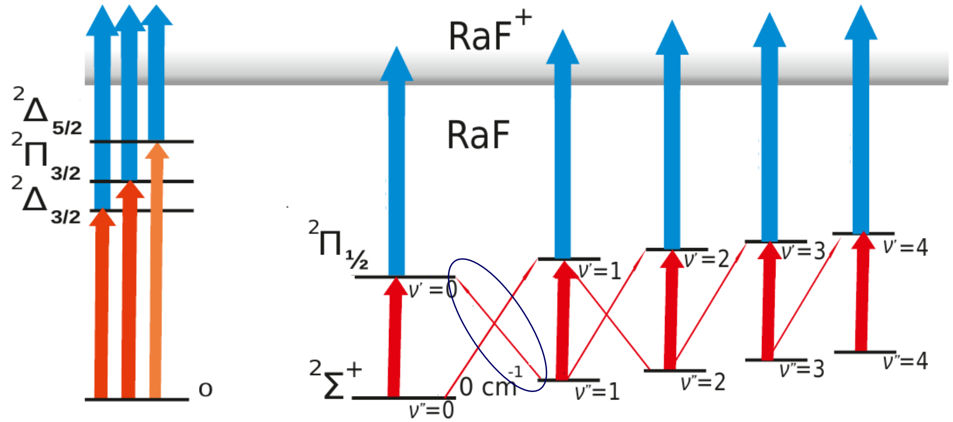

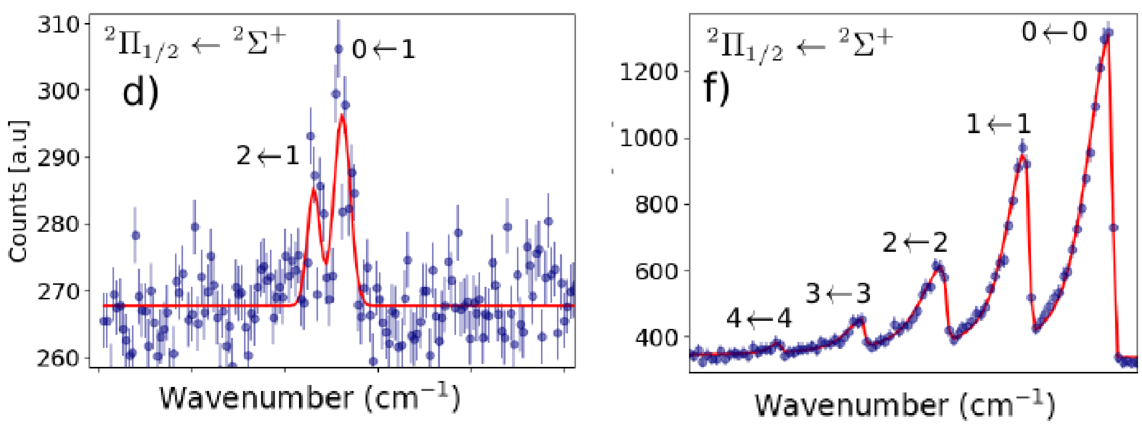

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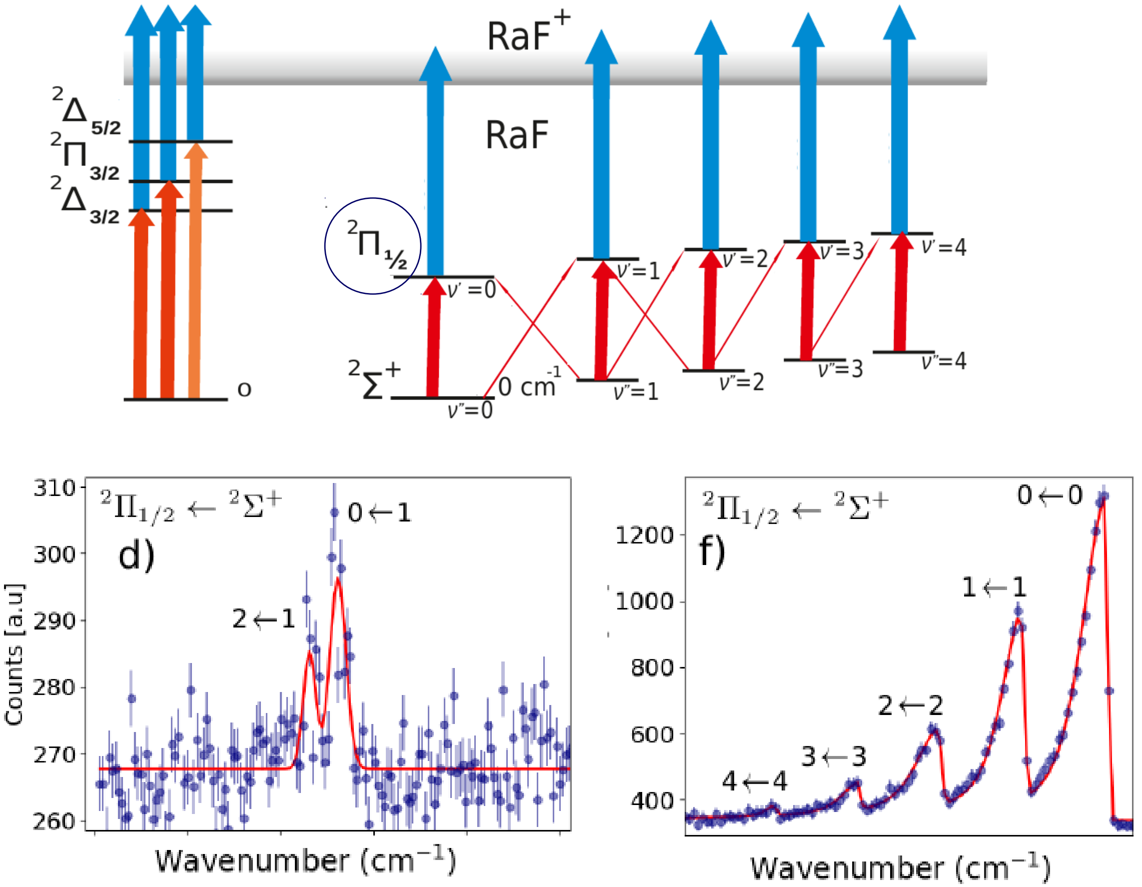
1. Dominant f_{00}? → $f_{00}/f_{ij} > 0.97$ ✓
2. Short-lived excited state ($T_{1/2}$)? → $T_{1/2} < 50$ ns ✓
3. Electronic states of lower energy (E)?



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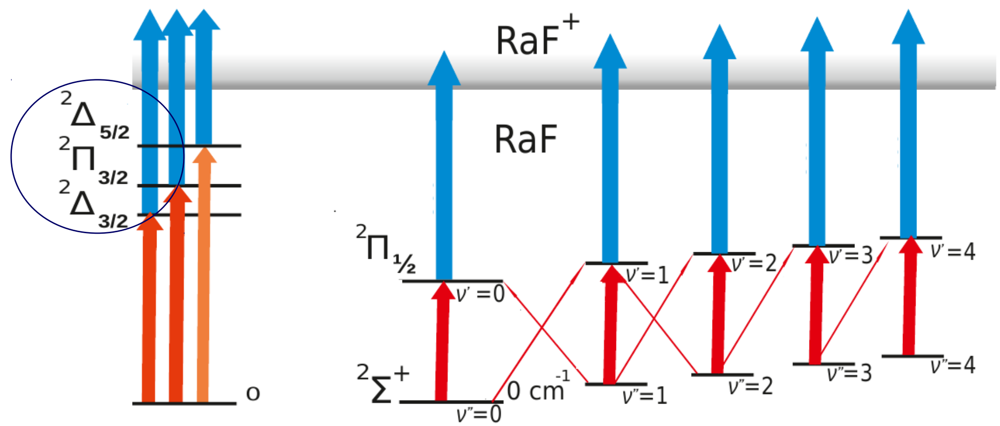
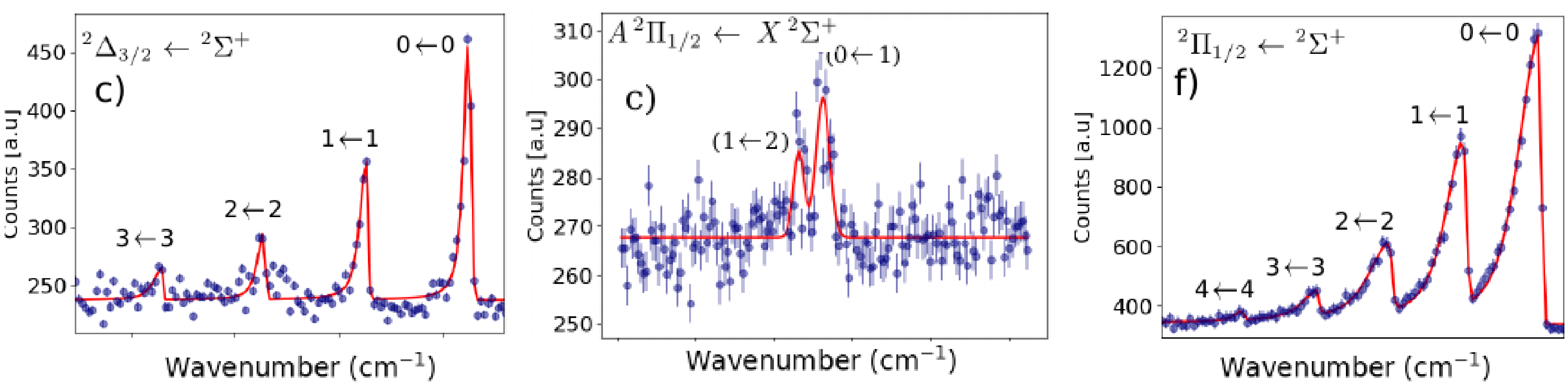
   3. Electronic states of lower energy (E)? → 2000 cm^{-1} above ✓





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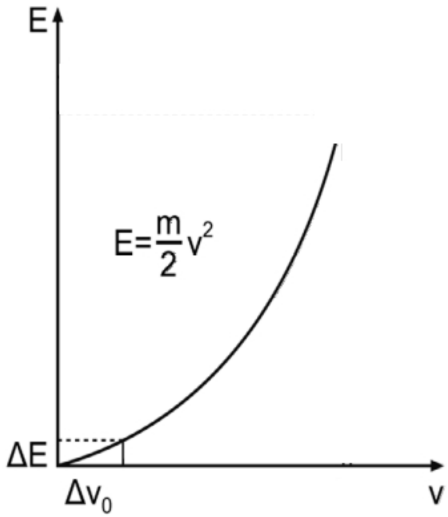
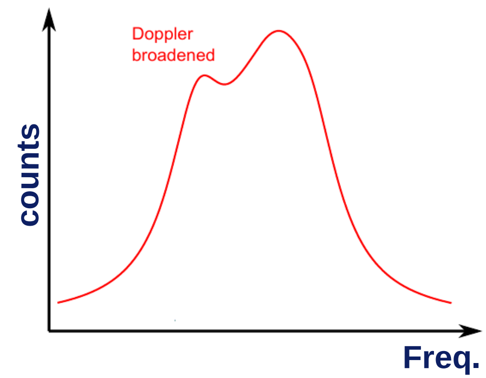
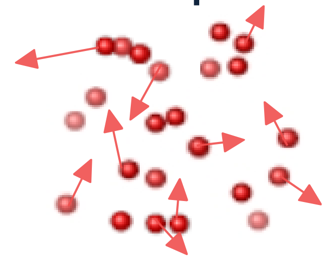
Precision Laser Spectroscopy



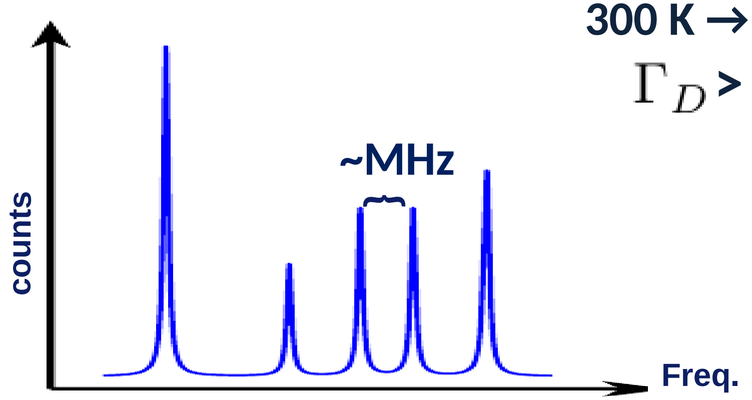


Room temperature



300 K → 25 meV

Γ_D > GHz



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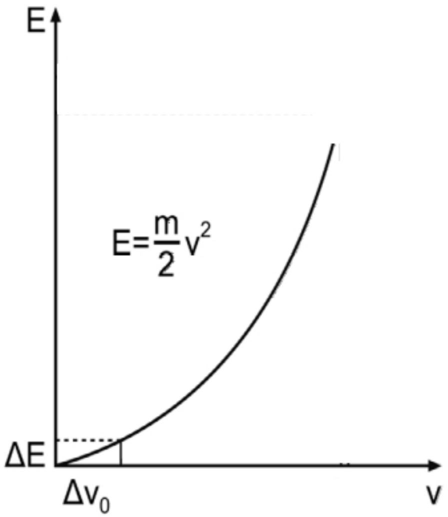

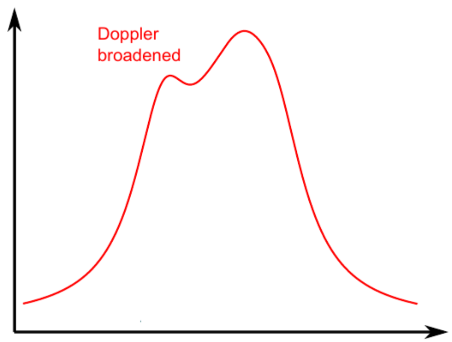

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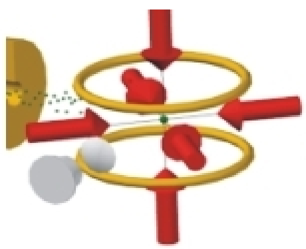
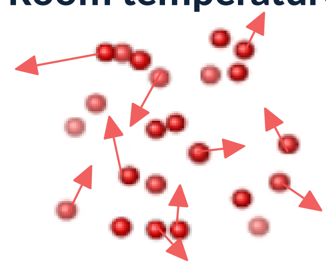




T < μK

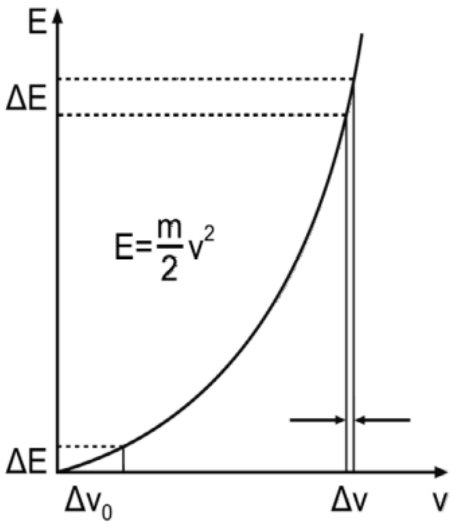
Γ_D **< MHz**

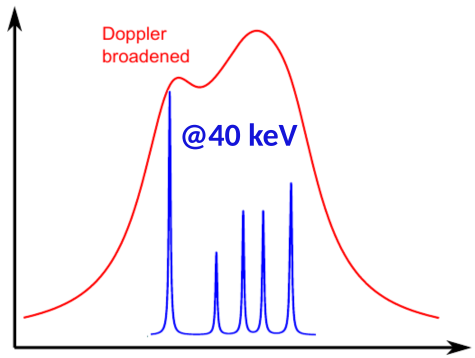
300 K → 25 meV

Γ_D **> GHz**

- ✔ High resolution (< MHz)
- High efficiency (<100 ions/s) ?
- High selectivity (>1/10^6) ?
- Short time scales (< 1 s)?

Precision Laser Spectroscopy

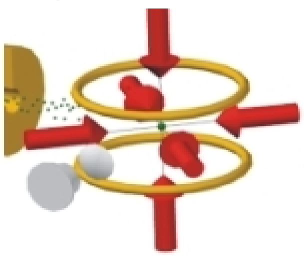




Energy spread

$$\Gamma_D = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}}$$

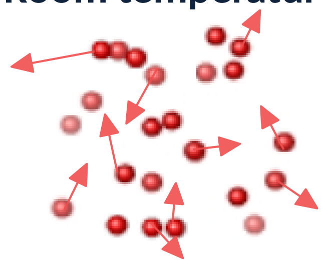
Ion beam energy



T < μK

Γ_D < MHz

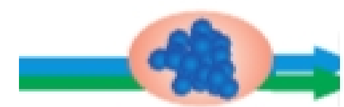
Room temperature



300 K → 25 meV

Γ_D > GHz

Fast beam



$\vec{v}$

@ 40 keV

Γ_D ~ MHz

- ✔ High resolution (< MHz)
- High efficiency (<100 ions/s) ?
- High selectivity (>1/10^6) ?
- Short time scales (< 1 s)?

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- ✔ High efficiency (<100 ions/s)
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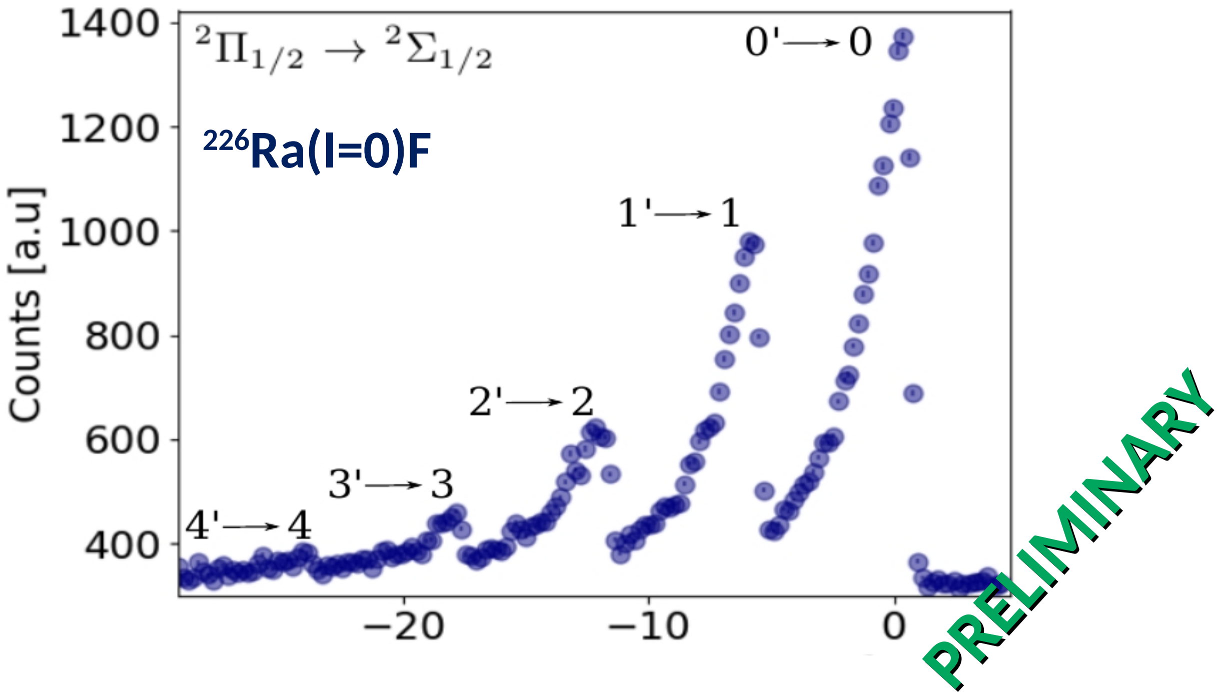
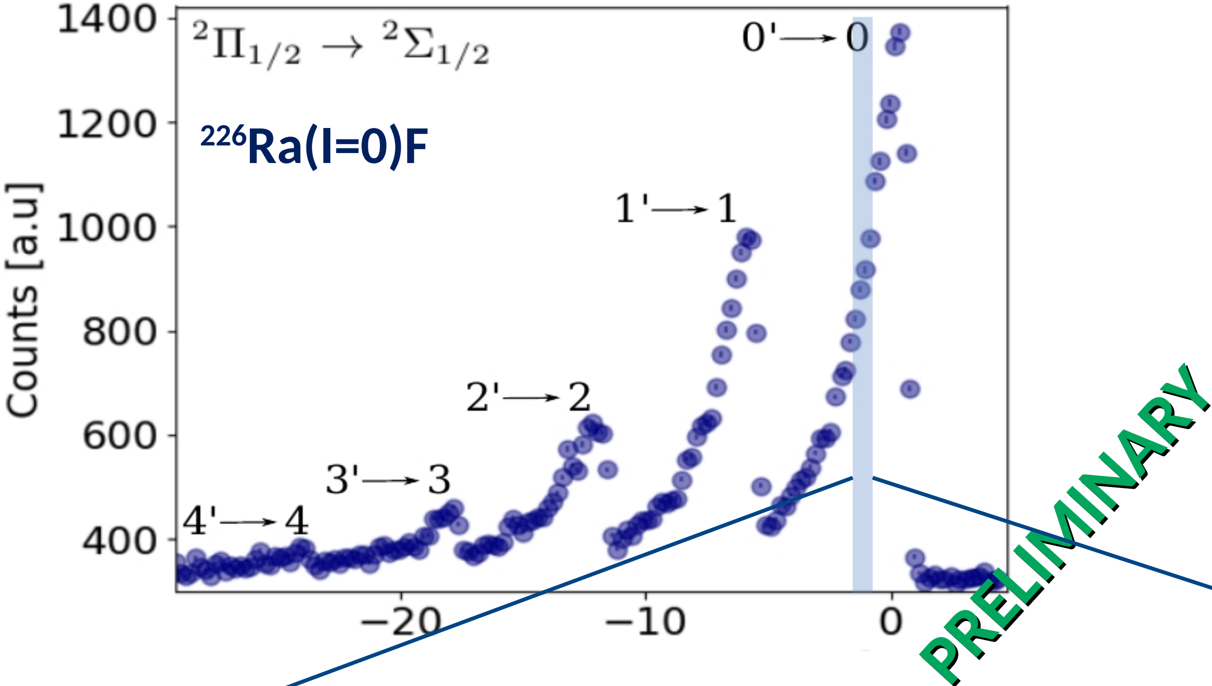
RaF: Hyperfine Structure



RaF: Hyperfine Structure

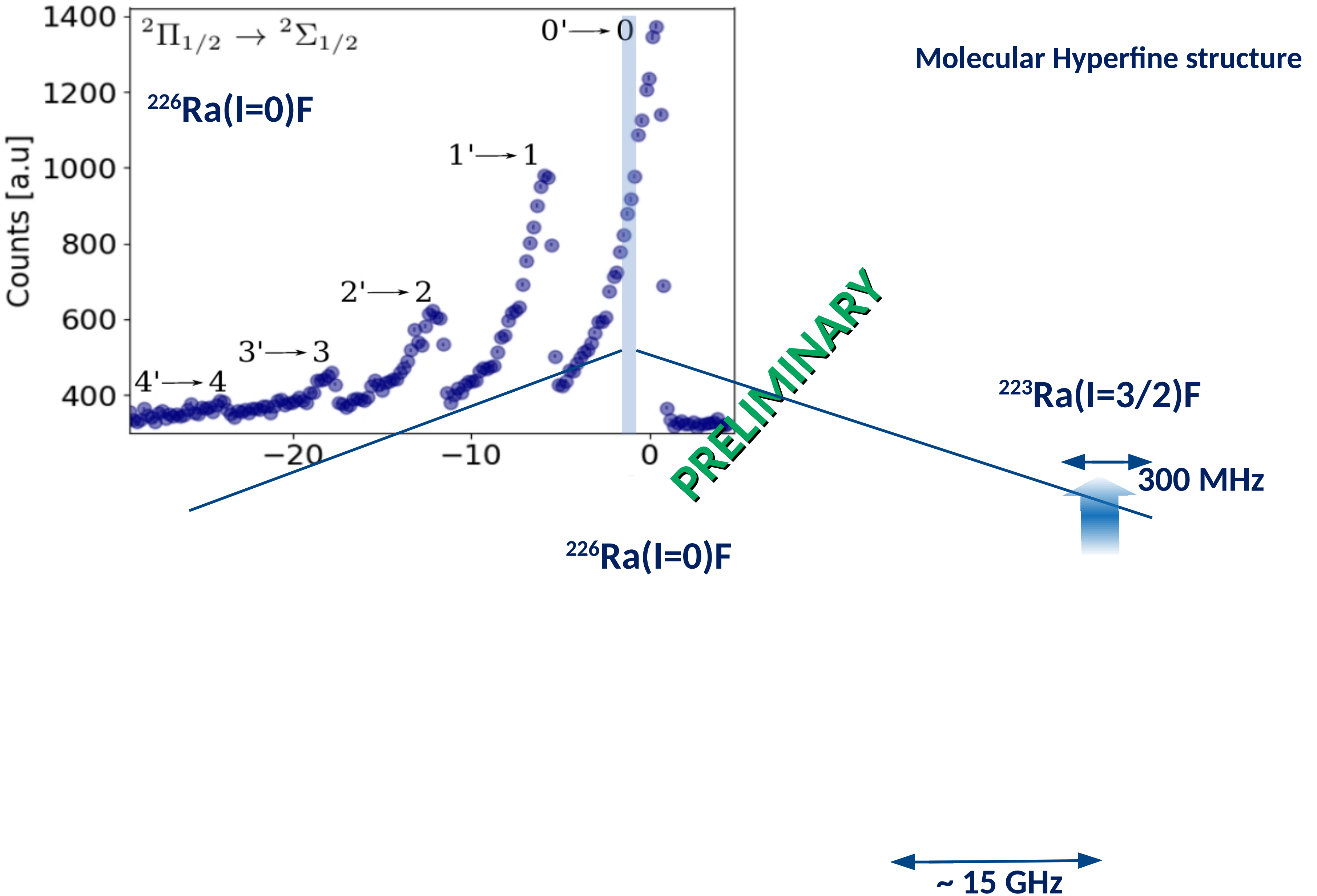


^{226}Ra(I=0)F

Wavenumber (cm^{-1})

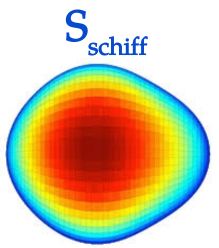
~ 15 GHz

RaF: Hyperfine Structure



From THz to MHz

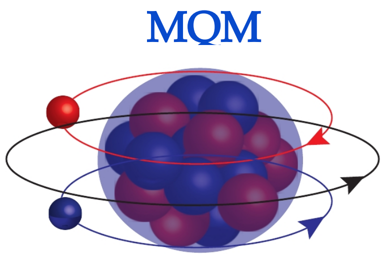
Opportunities with radioactive molecules



- **Axion dark matter produces oscillating S_{schiff}, MQM**

  Amplified in molecules with respect to atoms:

$$(M_{mol}/m_e)^2 \sim 10^6 - 10^8$$



→ AcF, RaO, PaN
[Flambaum & Feldmeier . Phys. Rev. C 101, 015502 (2020)]

- **Time reversal violating MQM**
  → ^{229}ThO and ^{229}ThF^{+} **[Lackenby & Flambaum. Phys. Rev. D 98, 115019 (2018)]**
  [Skripnikov, et al. Phys. Rev. Lett. 113, 263006 (2014)]

- **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"

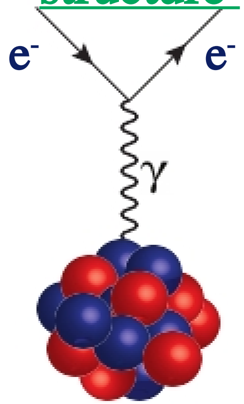
($T_{1/2}$= 7.17 10^5 years)

Contents

- Precision studies in atoms and molecules
- Nuclear structure / nuclear matter / new forces & particles
- Parity violation
- Parity and time-reversal violation
- First results: RaF
- **Summary**

Summary

<u>Nuclear structure</u>

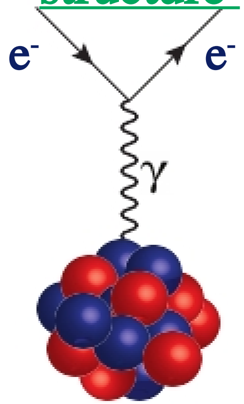


μ $<r^2>$ I Q

- Nuclear structure
- Nuclear matter
- New particle/ forces

Summary

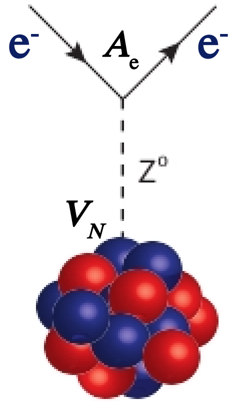
Nuclear structure



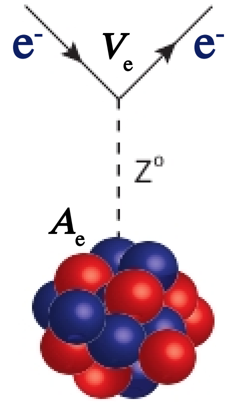
$\mu <r^2> I \quad Q$

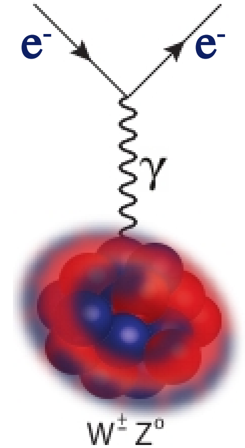
- Nuclear structure
- Nuclear matter
- New particle/ forces

P- violation

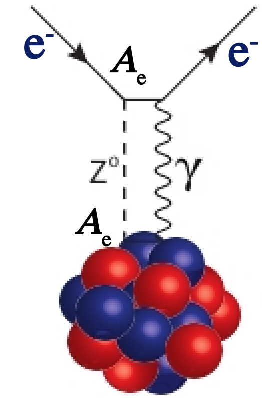


$\sim Z^3$
x 10^N





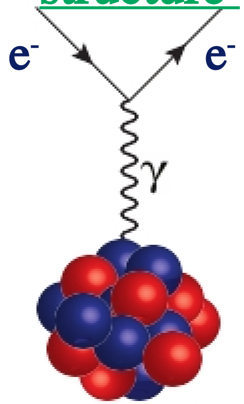
$\sim Z^2 A^{2/3} R(Z)$
x 10^5



Atoms
Molecules

Summary

Nuclear structure



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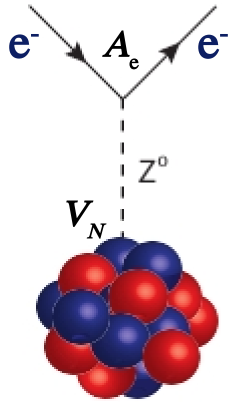
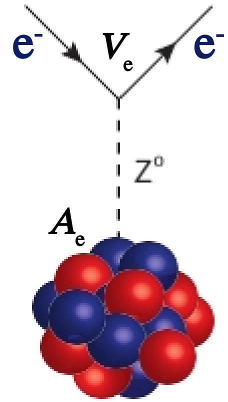
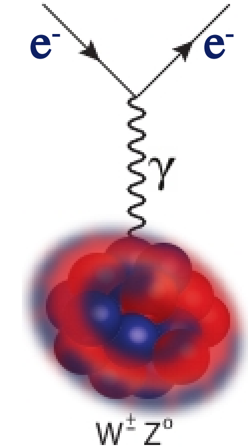
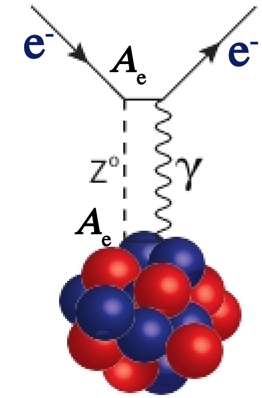








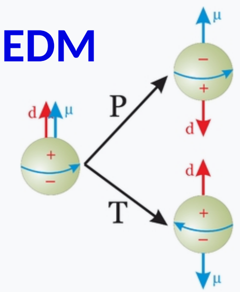
$\sim Z^3$
x 10^N

$\sim Z^2 A^{2/3} R(Z)$
x 10^5

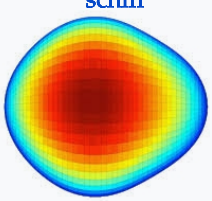
Atoms
Molecules

P,T- violation

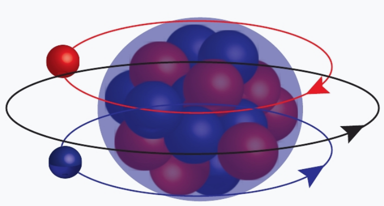
EDM



S_{schiff}



MQM



$\sim Z^2 R(Z)$
$> 10^3$

$S \sim Q_2 Q_3 Z A^{2/3} / (E_+ - E_-)$
($> 10^5$ Octupole)

Atoms
Molecules

Summary

- Radioactive molecules → New window to study the atomic nucleus

Molecules: Electroweak structure

- Anapole moment: AM
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- eEDM, nEDM, …

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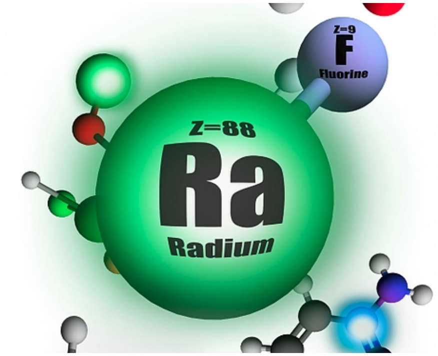
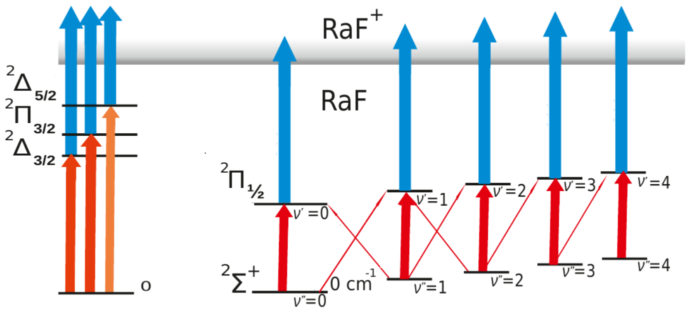


- First ever laser spectroscopy of a short-lived radioactive molecule (RaF)!

- ✓ RaF → eEDM, Schift moments, Anapole moments, MQM
- ✓ ^{223}RaF, ^{224}RaF, ^{225}RaF, ^{226}RaF, ^{228}RaF
- ✓ Strong experimental evidence for the laser cooling scheme
- ✓ Precision spectroscopy ^{223}Ra(I=3/2)F, lifetime, IP, …



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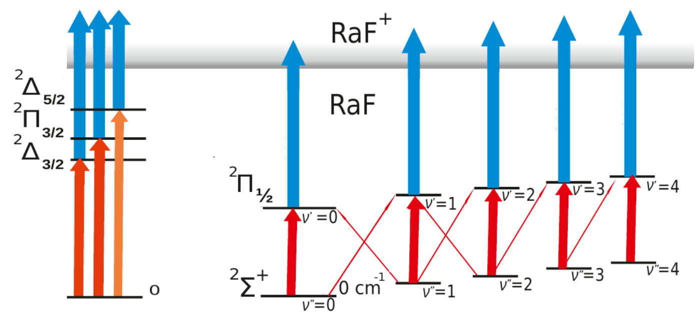

- “Hot” molecules can be super cool!

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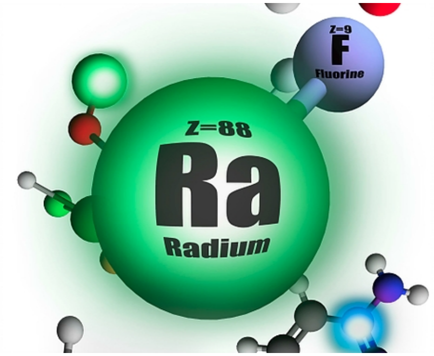

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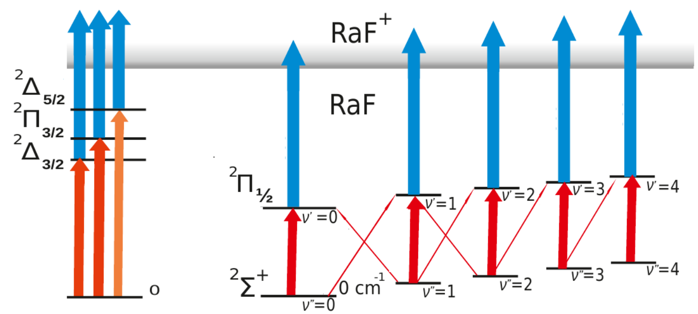

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… this is just the beginning!