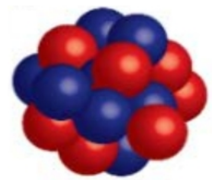
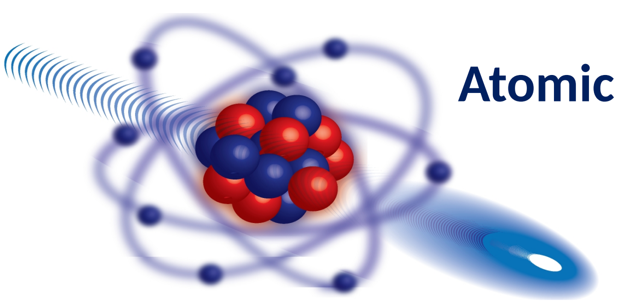
Exploring new physics with radioactive atoms and molecules



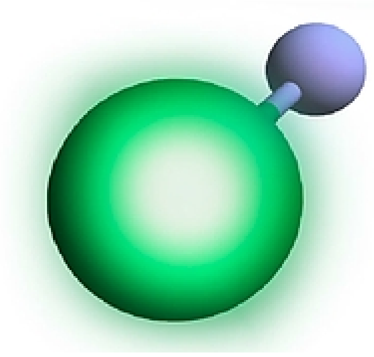
Ronald Fernando Garcia Ruiz

CERN



Atomic nuclei as laboratories for BSM physics

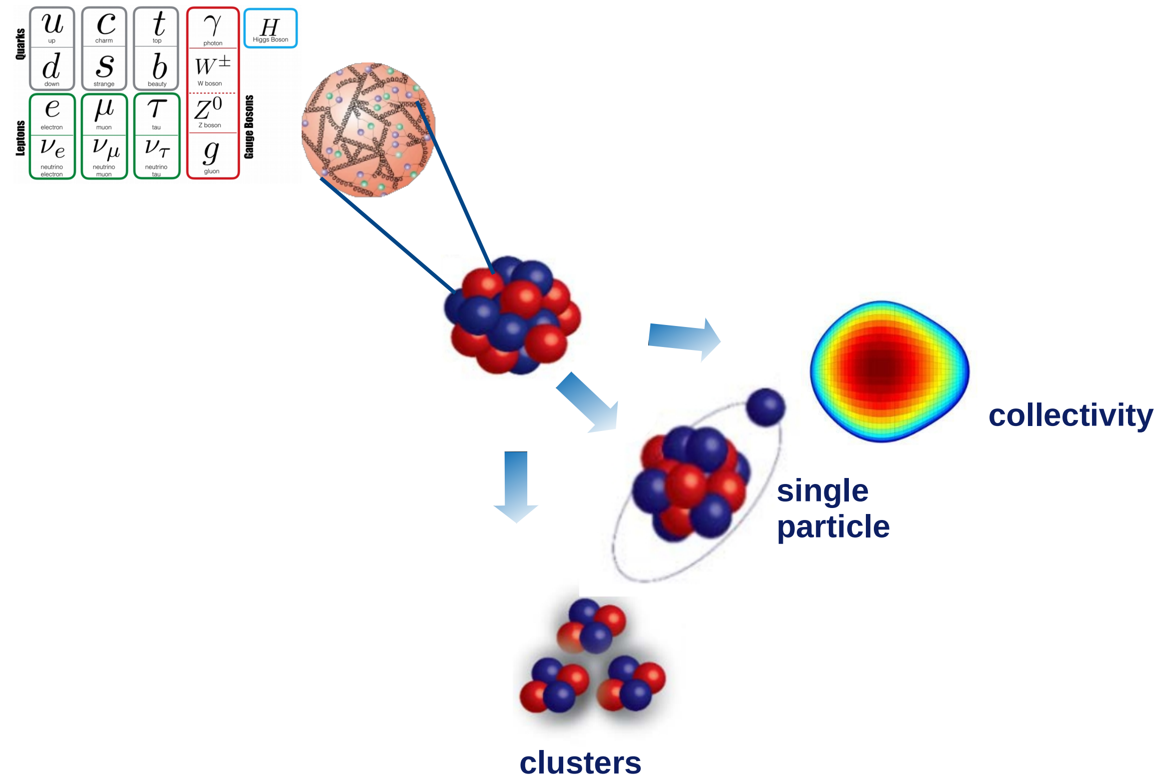
ECT*, Trento 2019



Motivation

Nuclear structure

- Nucleons/Nuclei from QCD
- Emergence of nuclear phenomena



How did visible matter come into being and how does it evolve?
How does subatomic matter organize itself and what phenomena emerge?

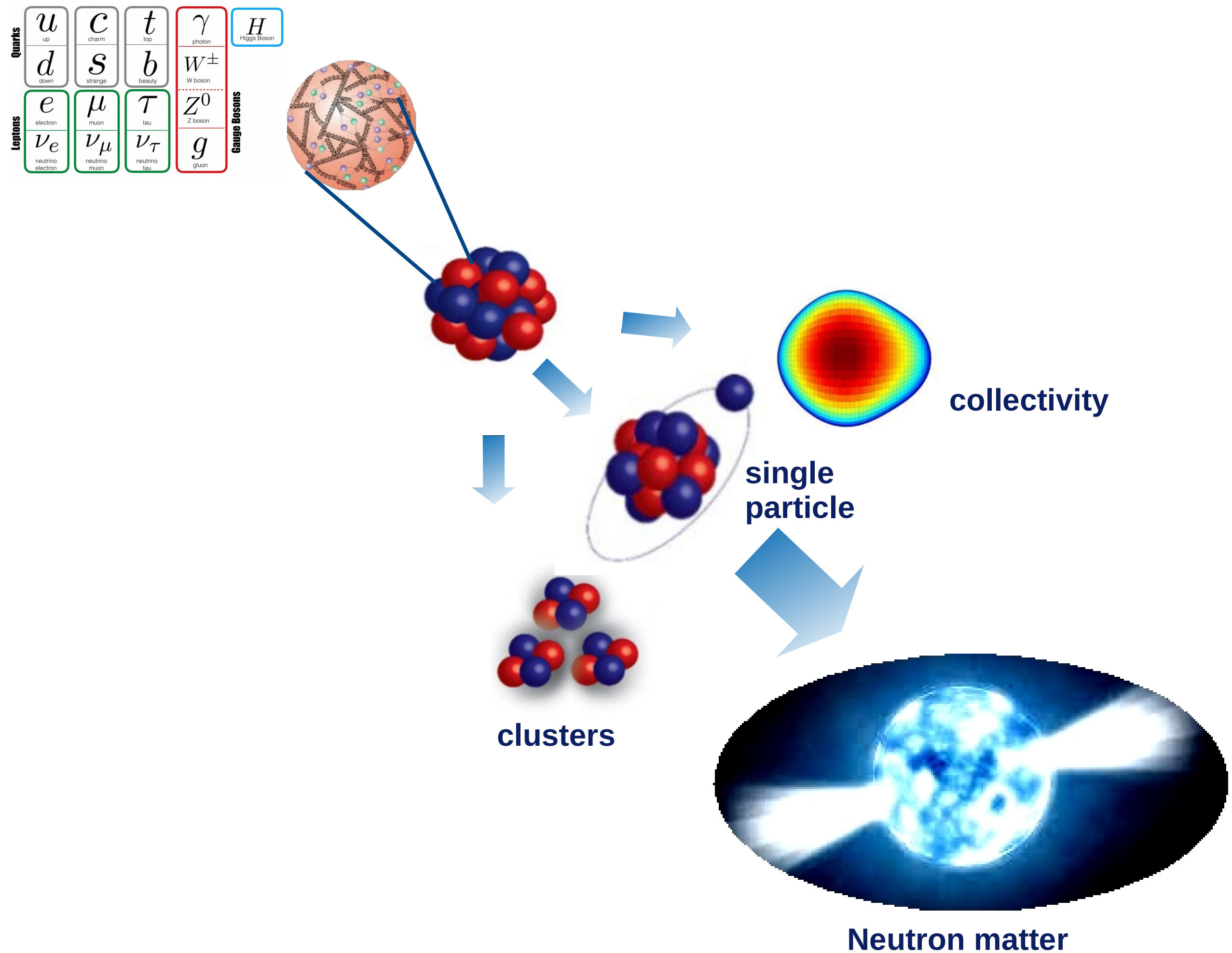
Motivation

Nuclear structure

- Nucleons/Nuclei from QCD
- Emergence of nuclear phenomena

Astrophysics

- Nature of neutron stars and dense nuclear matter
- Properties of nuclear matter



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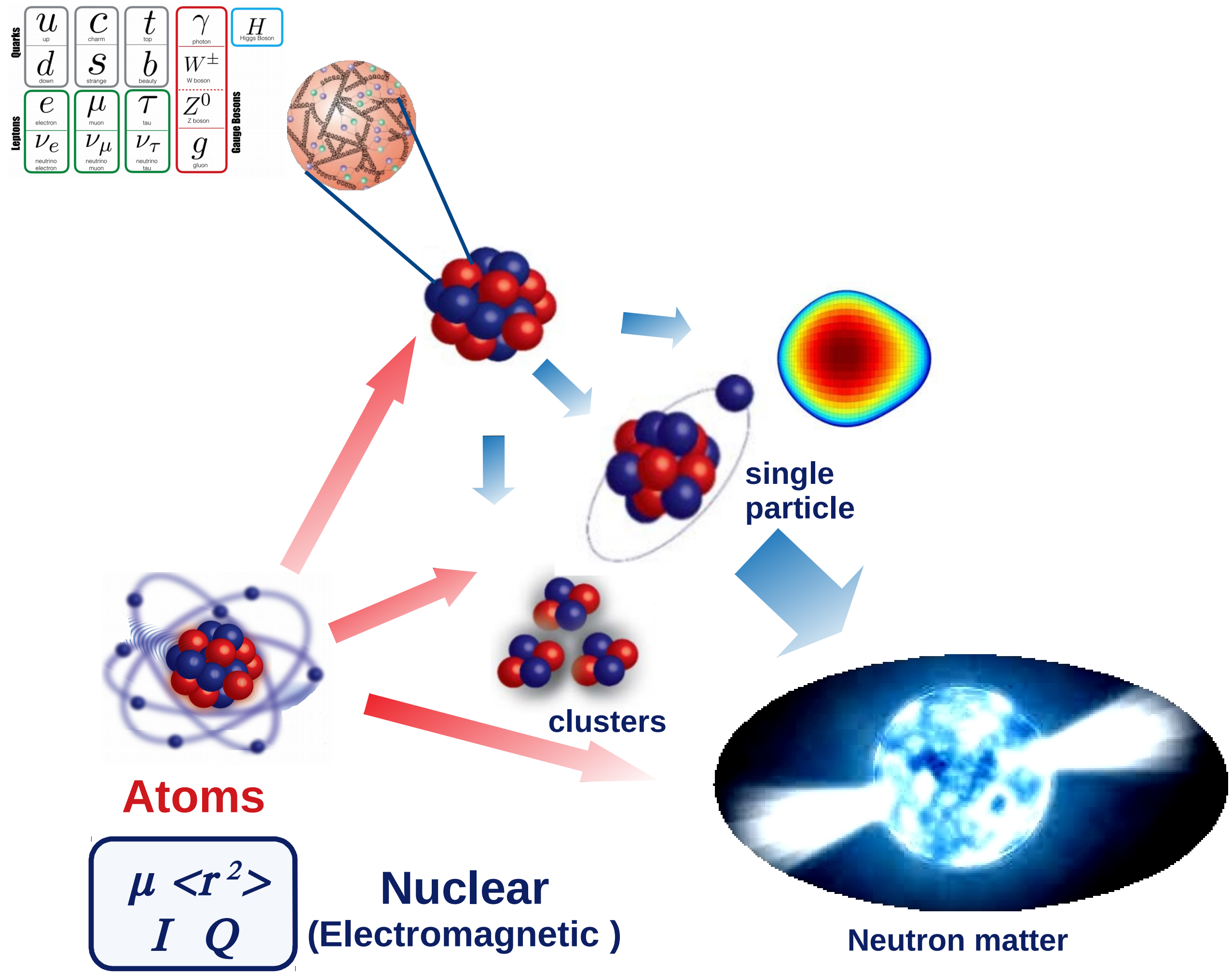


Motivation

BSM Physics

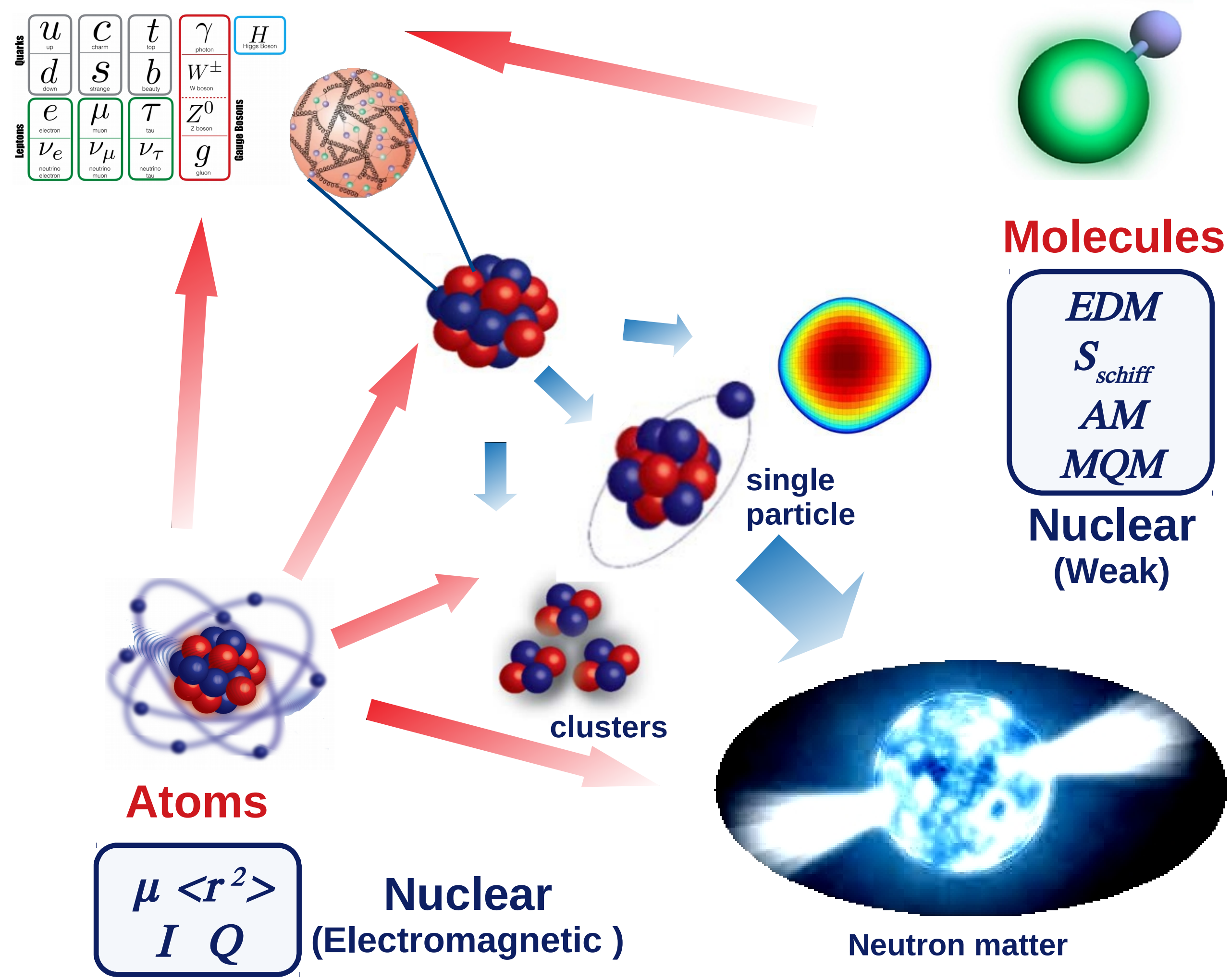
- Fundamental symmetries
- Matter – Antimatter
- Dark Matter / energy
- New forces/particles
- Neutrino properties

Nuclear structure

- Nucleons/Nuclei from QCD
- Emergence of nuclear phenomena

Astrophysics

- Nature of neutron stars and dense nuclear matter
- Properties of nuclear matter



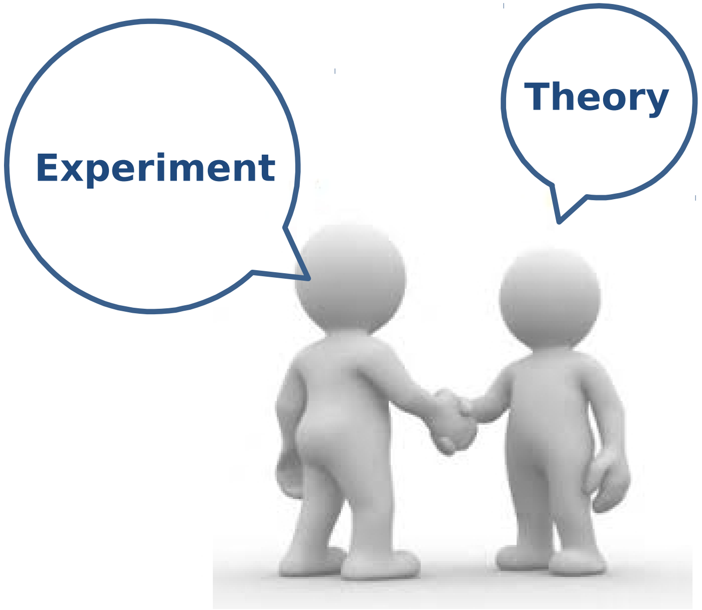
Radioactive atoms and molecules provide unique answers to these questions!

Exploring new physics with radioactive atoms and molecules

Contents

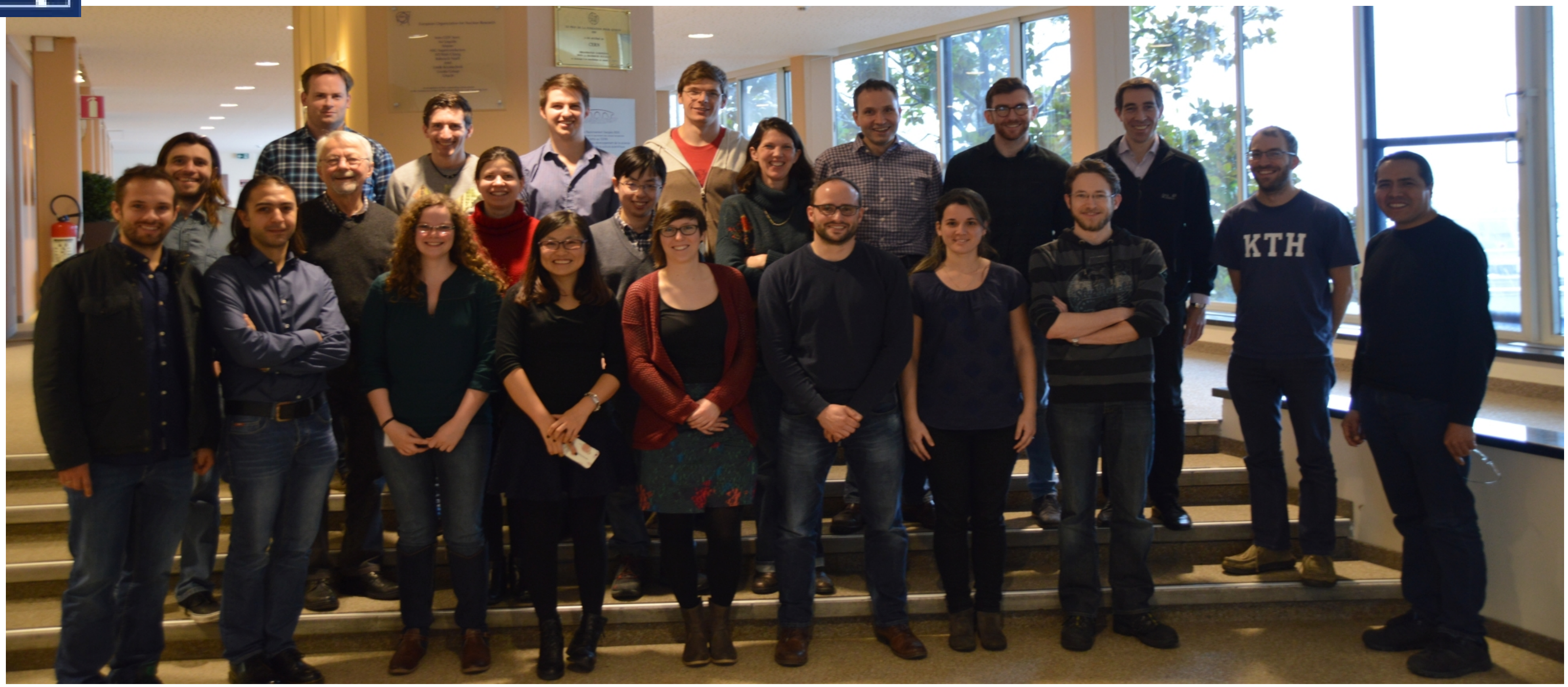
- Precision laser spectroscopy at ISOLDE-CERN
- Probing new forces/particles with atomic isotope shifts
  → Why radioactive atoms?
- Exploring nuclear electroweak properties with molecules
  → Fundamental symmetries / EDMs
  → Why radioactive molecules?
  → Recent results: RaF
- Summary

Nuclear & Atomic & Molecular



The COLLAPS Collaboration

Collinear Laser Spectroscopy



MAX-PLANCK-GESELLSCHAFT

KU LEUVEN

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TECHNISCHE UNIVERSITÄT DARMSTADT

M. Bissell, K. Blaum, B. Cheal, N. Frommgen, R.F. Garcia Ruiz, C. Gorges, M.Hammen, M. Kowalska, K. Kreim, S. Malbrunot-Ettenauer, R.Neugart, G. Neyens, W. Nortershauser, J. Papuga, X. Yang, D.Yordanov

The CRIS Collaboration

Collinear Resonance Ionization Spectroscopy

CERN ISOLDE

KU LEUVEN

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

MANCHESTER 1824

LPSC Grenoble

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

NEW YORK UNIVERSITY

CRIS

erc European Research Council Established by the European Commission

J. Billowes, C. Binnersley, 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, A. Vernon, K. Wendt, S. Wilkins, X. Yang

Nuclear theory: G. Hagen (ORNL), J. Holt (TRIUMF), W. Nazarewicz (FRIB/MSU), S. Gandolfi (LANL), D. Lonardoni (LANL)

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

Atomic theory: B. Sahoo (PRL, India)

ISOLTRAP (F. Wienholtz) , **RILIS** (S. Wilkins, K. Chrysalidis)

Target group (S. Rothe)

ISOLDE Technical group

Contents

- **Precision laser spectroscopy at ISOLDE-CERN**

- Probing new forces/particles with atomic isotope shifts
→ Why radioactive atoms?

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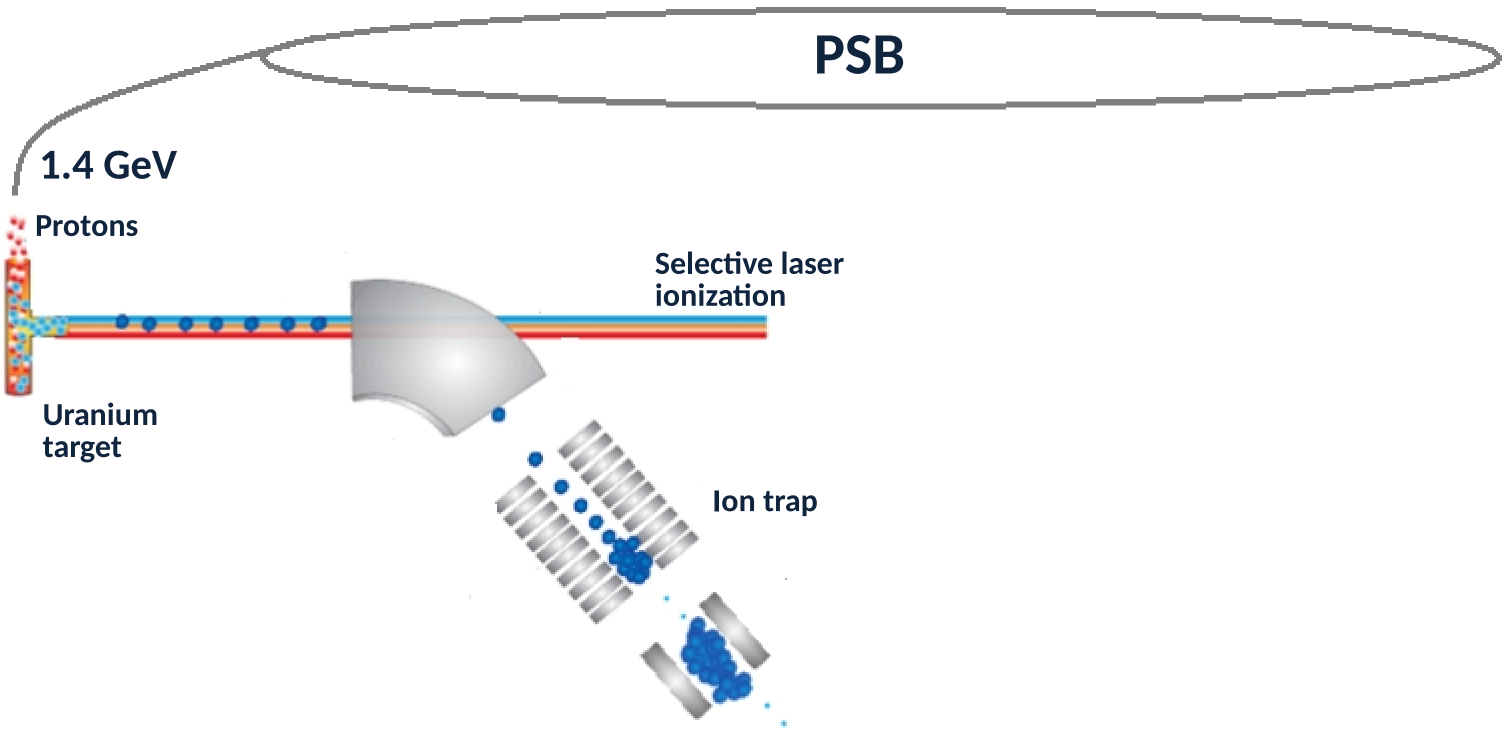
→ Fundamental symmetries / EDMs
→ Why radioactive molecules?
→ Recent results: RaF

- Summary

Laser Spectroscopy at ISOLDE-CERN



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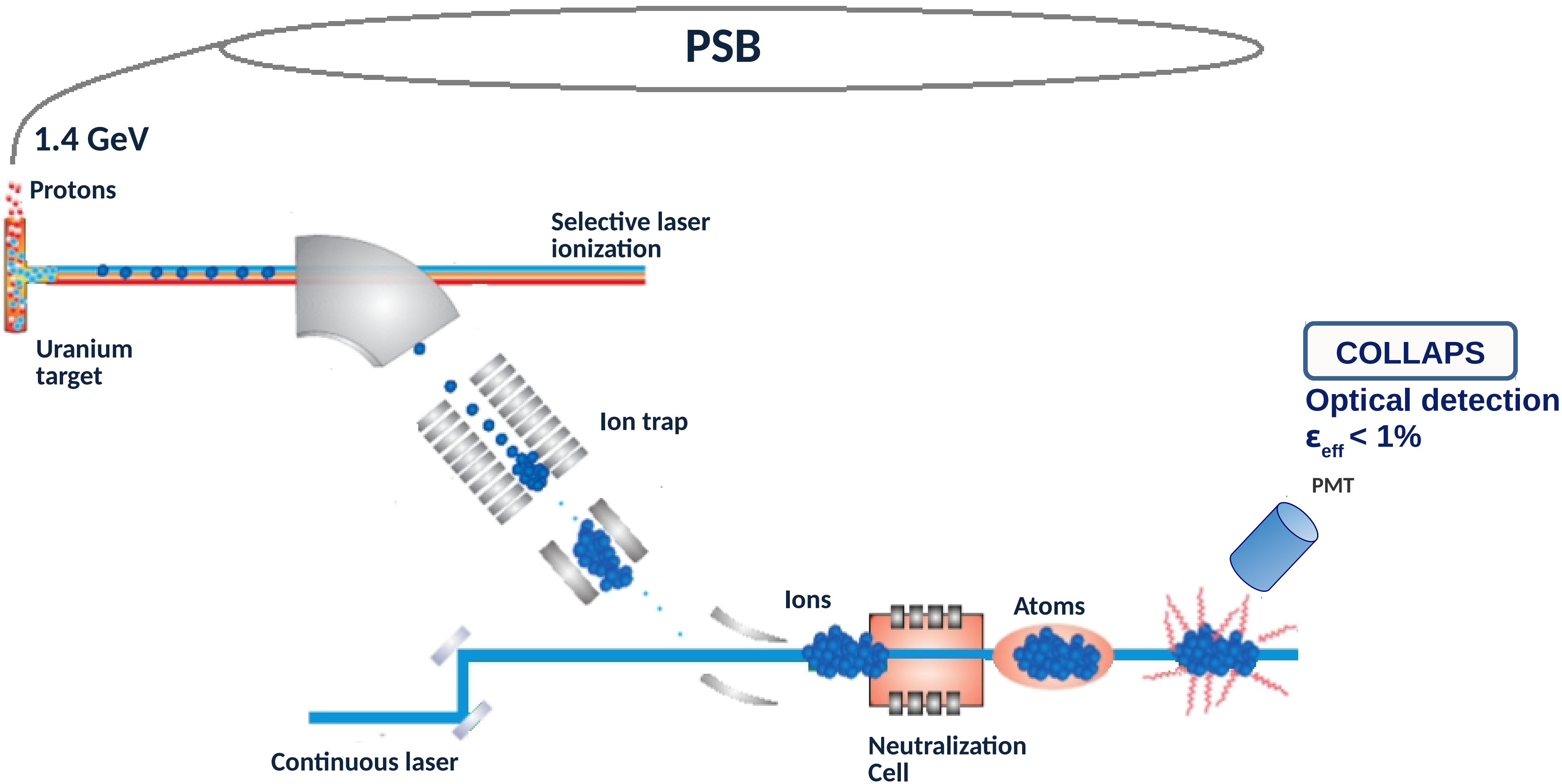
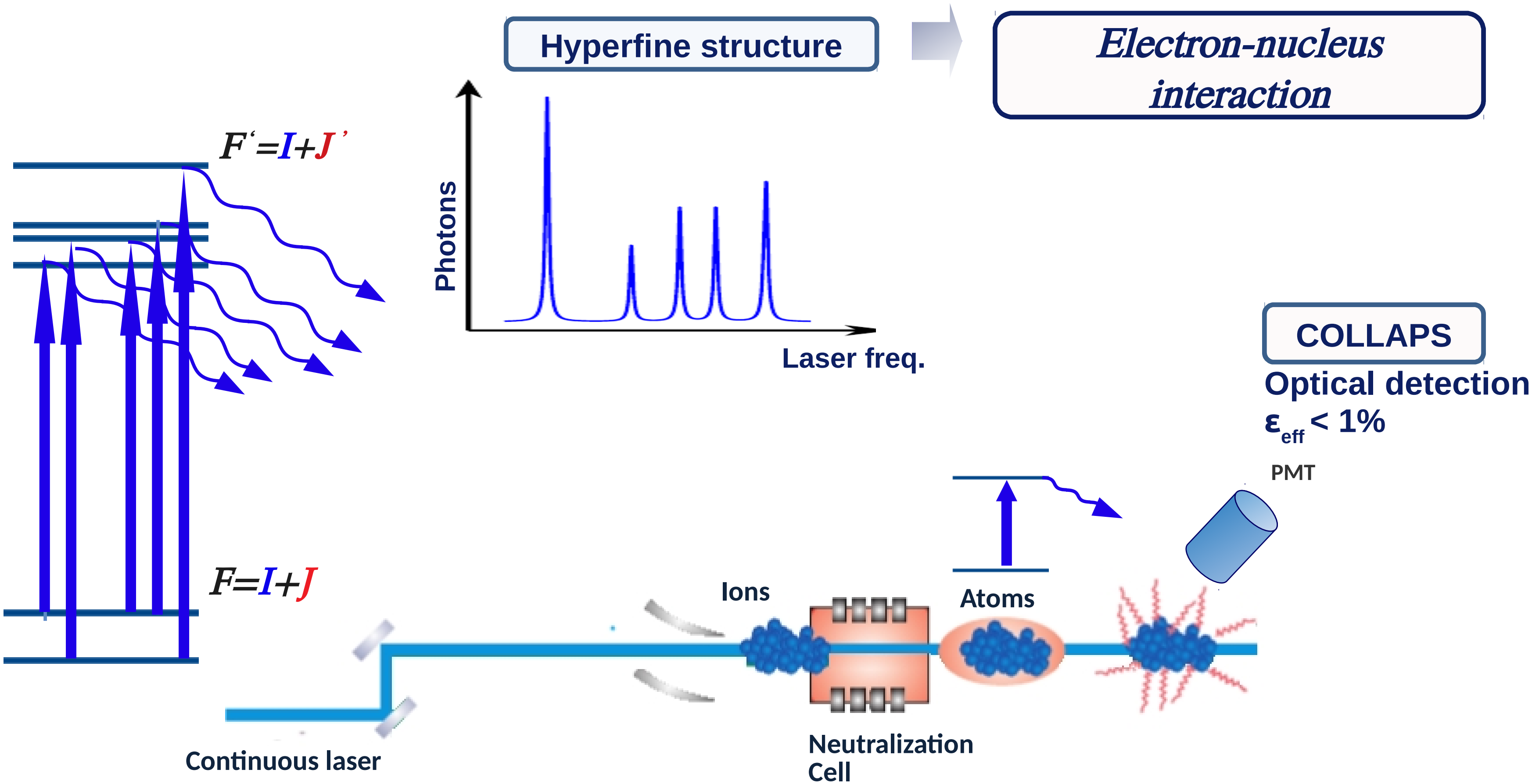
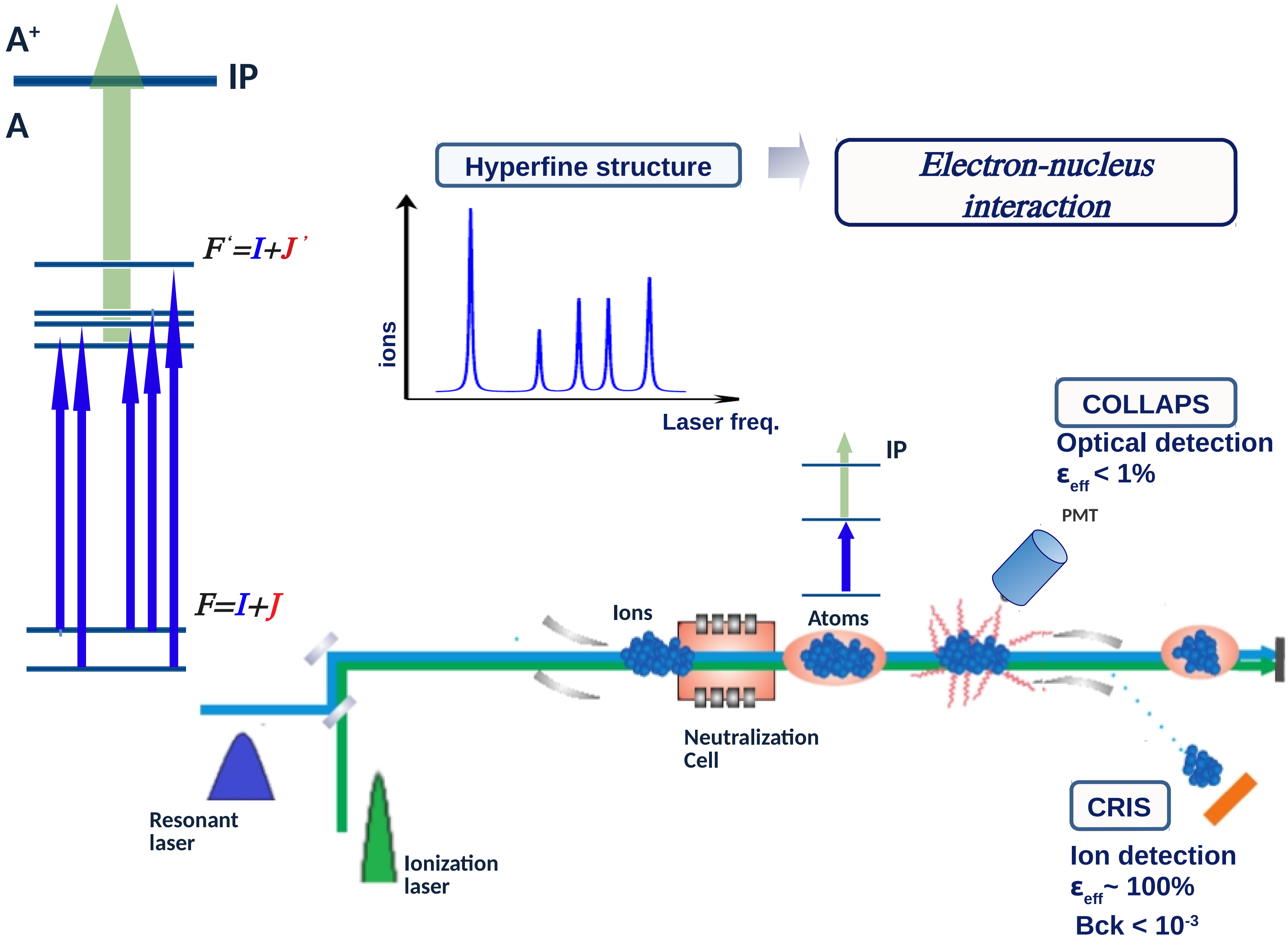


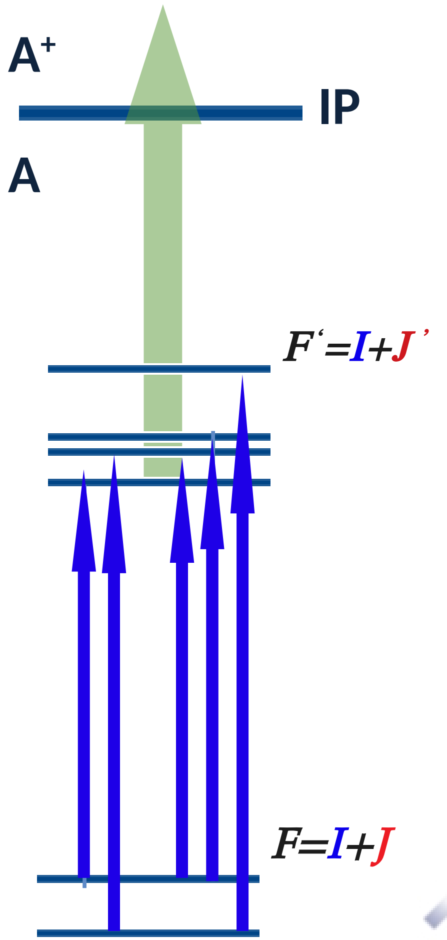
Laser Spectroscopy at ISOLDE-CERN



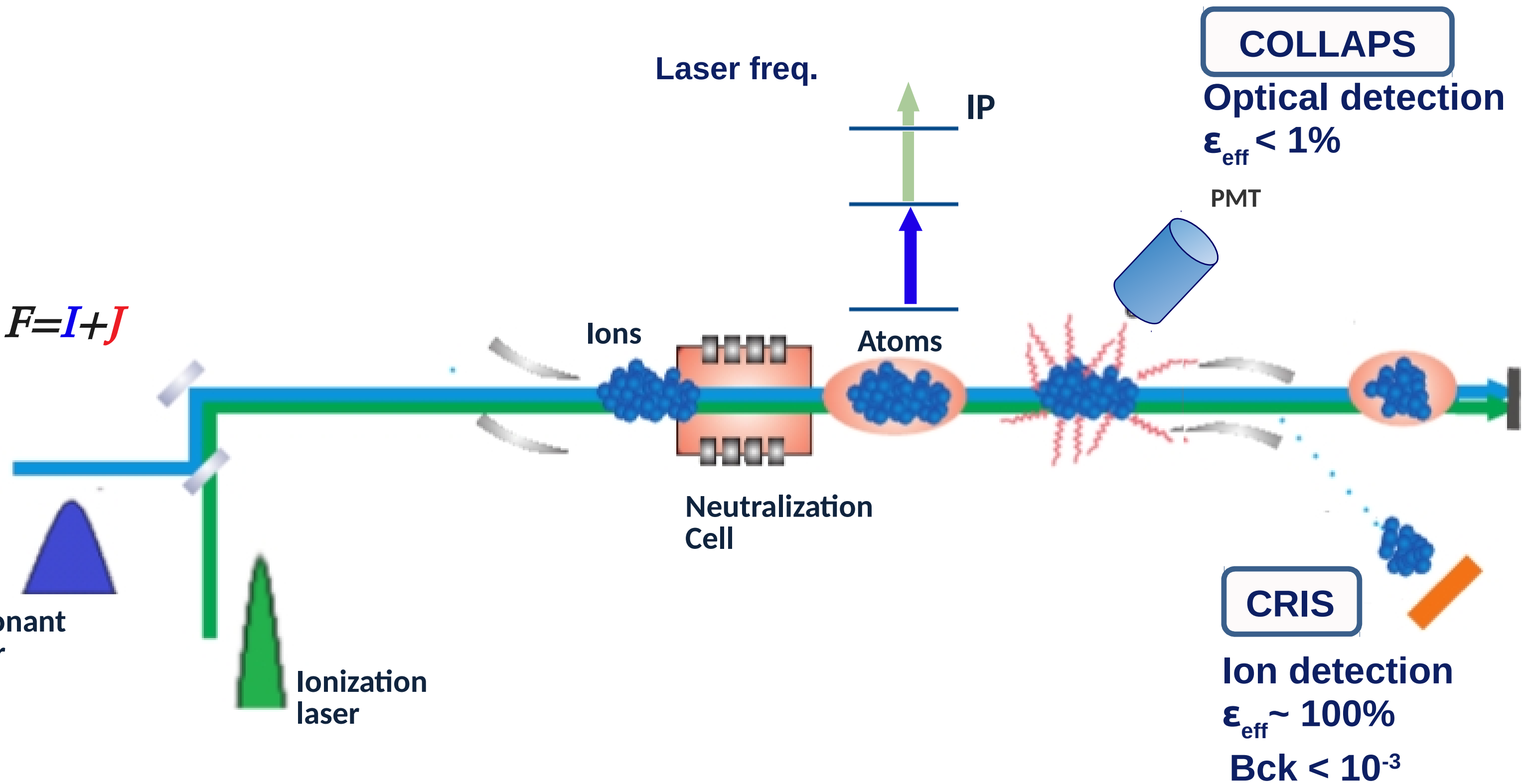
Laser Spectroscopy at ISOLDE-CERN



Laser Spectroscopy at ISOLDE-CERN



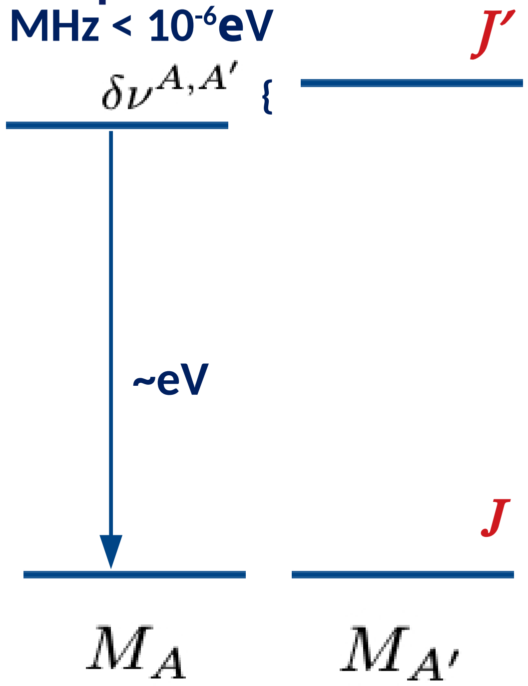
- High resolution (~MHz)
- High efficiency (<100 ions/s)
- High selectivity (>1/10^6)
- Short time scales (< 1 s)



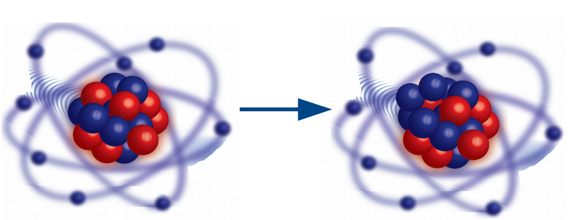
Precision Laser Spectroscopy

Isotope shift

MHz < 10^{-6}eV



$I = 0$



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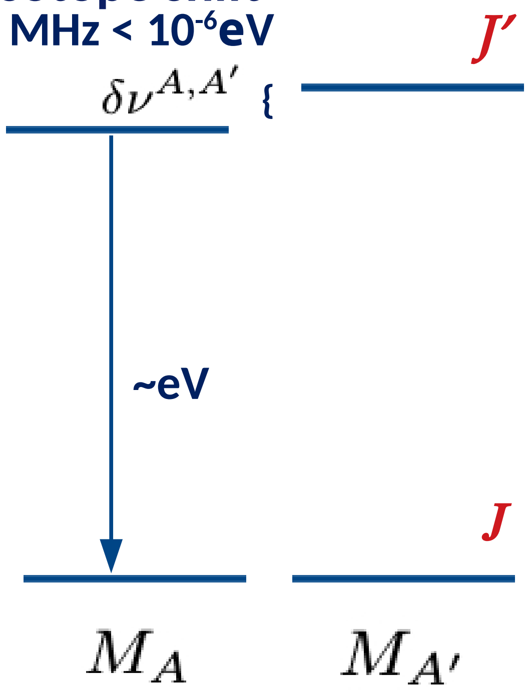

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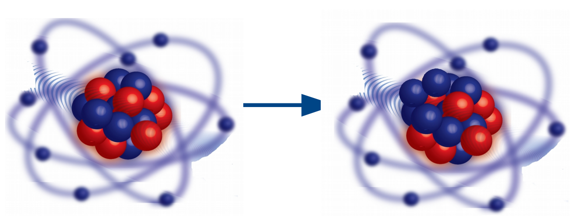


Atomic
Nuclear

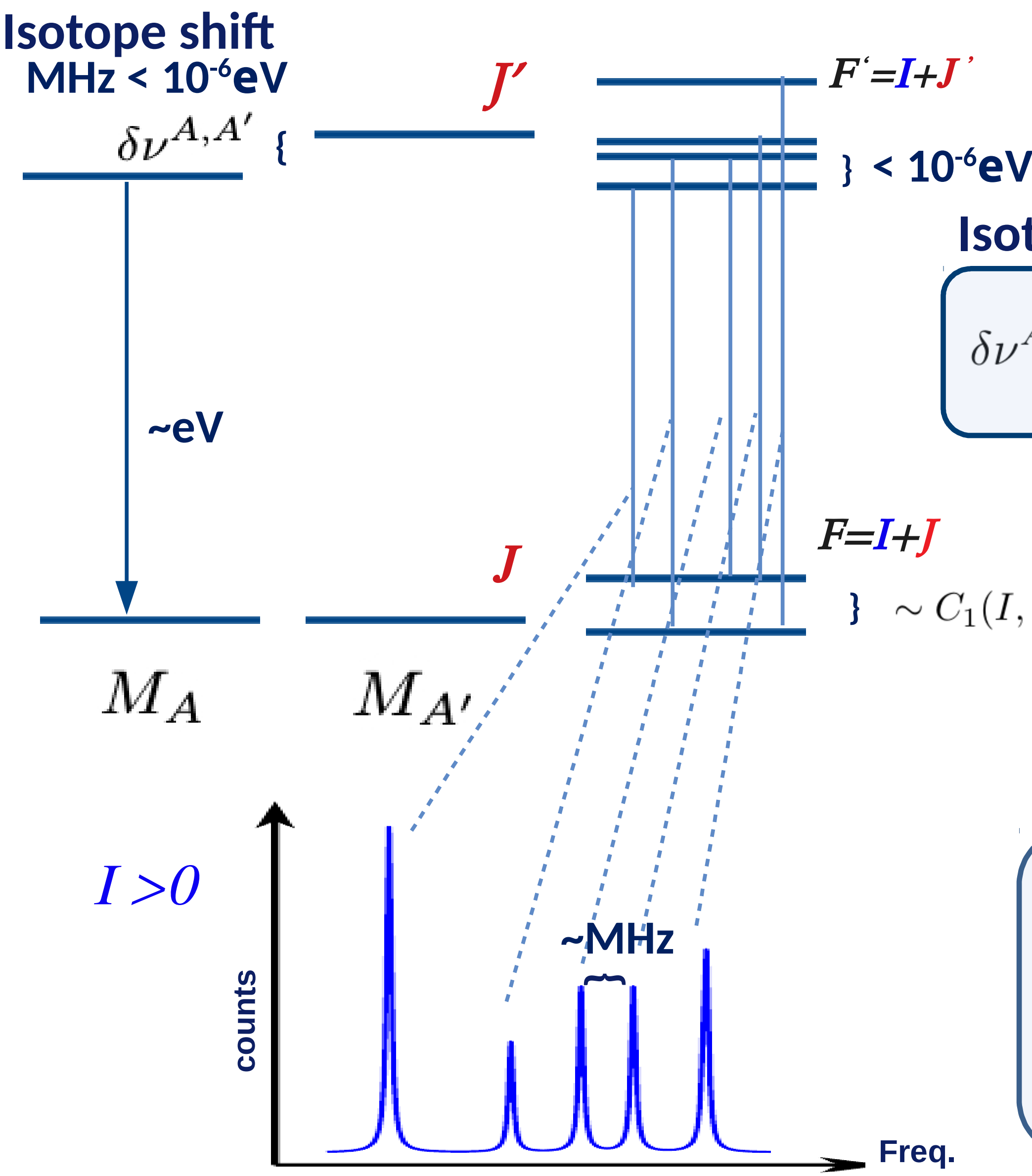
Isotope shift:

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

Electromagnetic structure

- Rms charge radii: $<r^2>$

Precision Laser Spectroscopy



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Nuclear

Isotope shift:

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

Atomic hyperfine structure

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

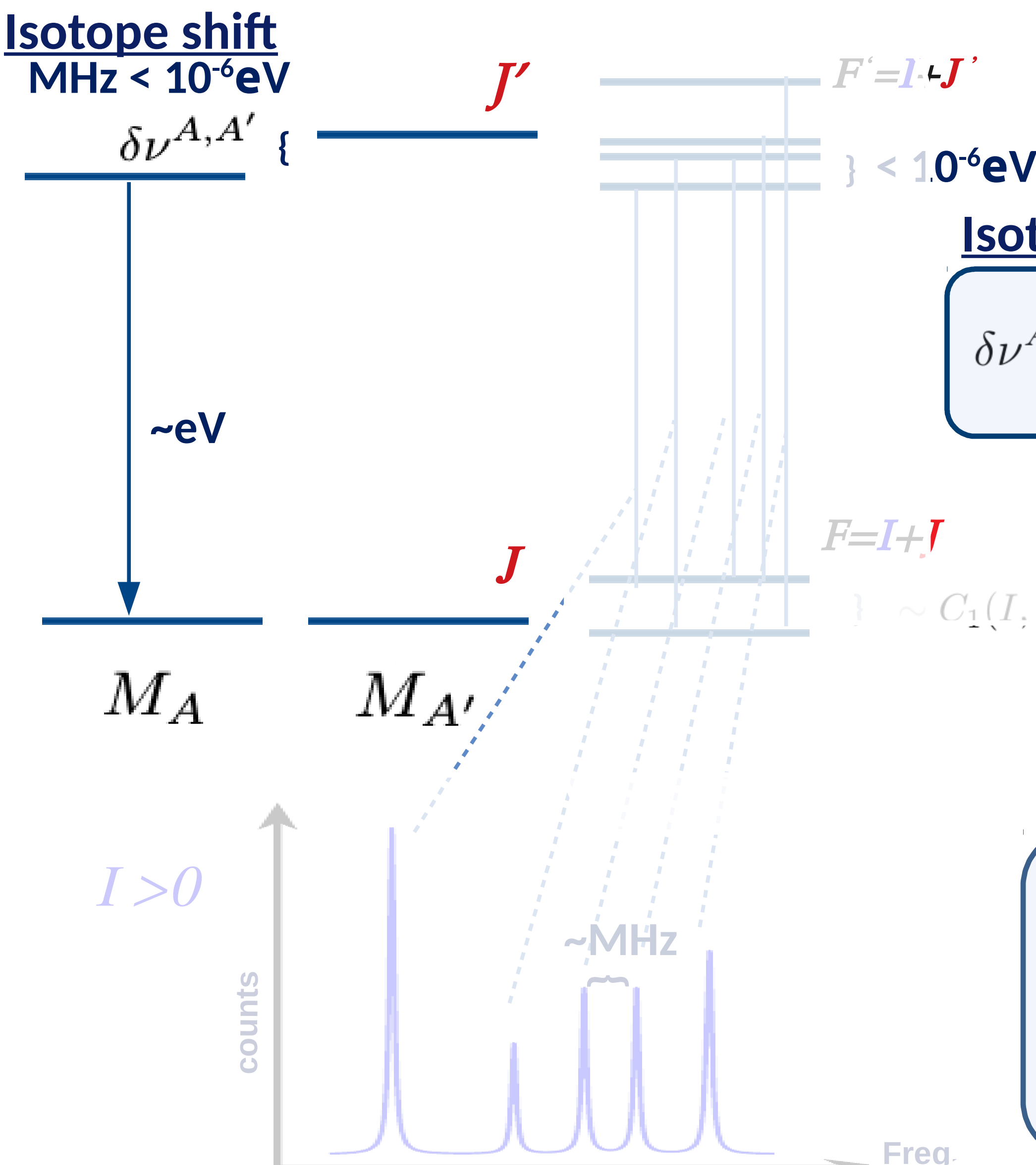
$$A_{\text{hfs}} = \frac{\mu B}{IJ}$$

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

Electromagnetic structure

- Rms charge radii: $<r^2>$
- Nuclear spin: I
- Electromagnetic moments: μ
- Quadrupole moment : Q

Precision Laser Spectroscopy



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- Rms charge radii: $<r^2>$
- Nuclear spin: I
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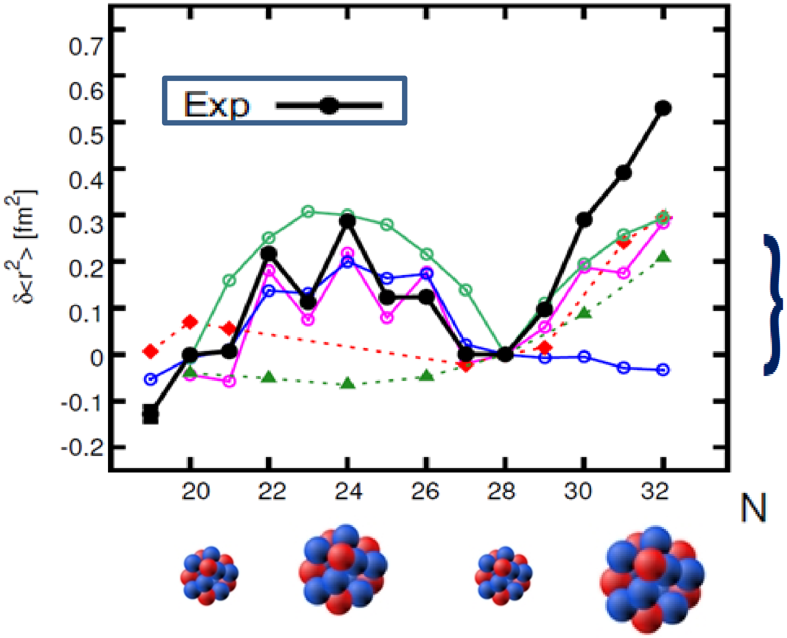
- Quadrupole moment : Q

An example: exotic calcium isotopes

Atom
Nucleus

[Ca: <r²> @CERN: Nature Physics 12, 594 (2016)]

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



Nuclear theory / forces

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

^{36}Ca → <r²> @NSCL
[Nature Physics, Accepted (2019)]

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

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

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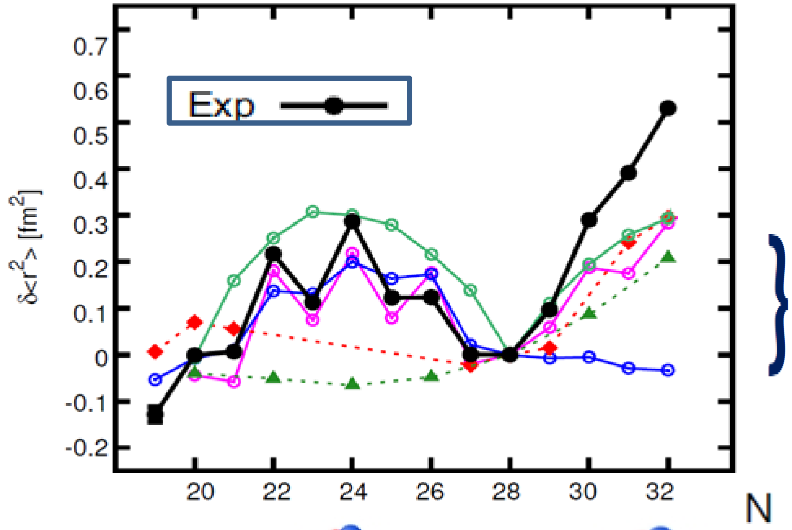
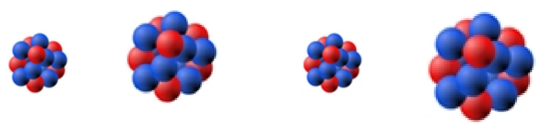


Nuclear theory / forces



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[Nature 498, 346 (2013)]

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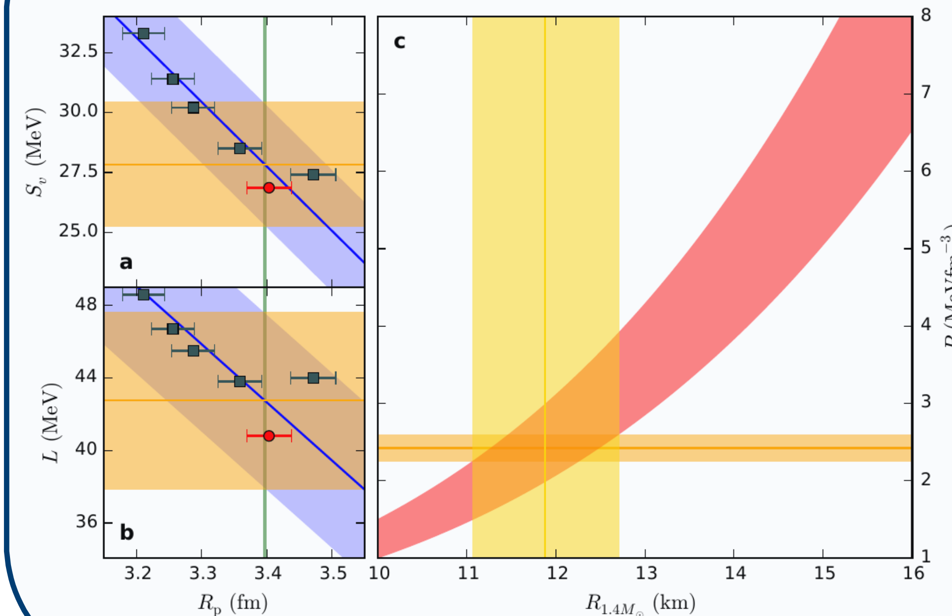
[Nature 502, 207(2013)]

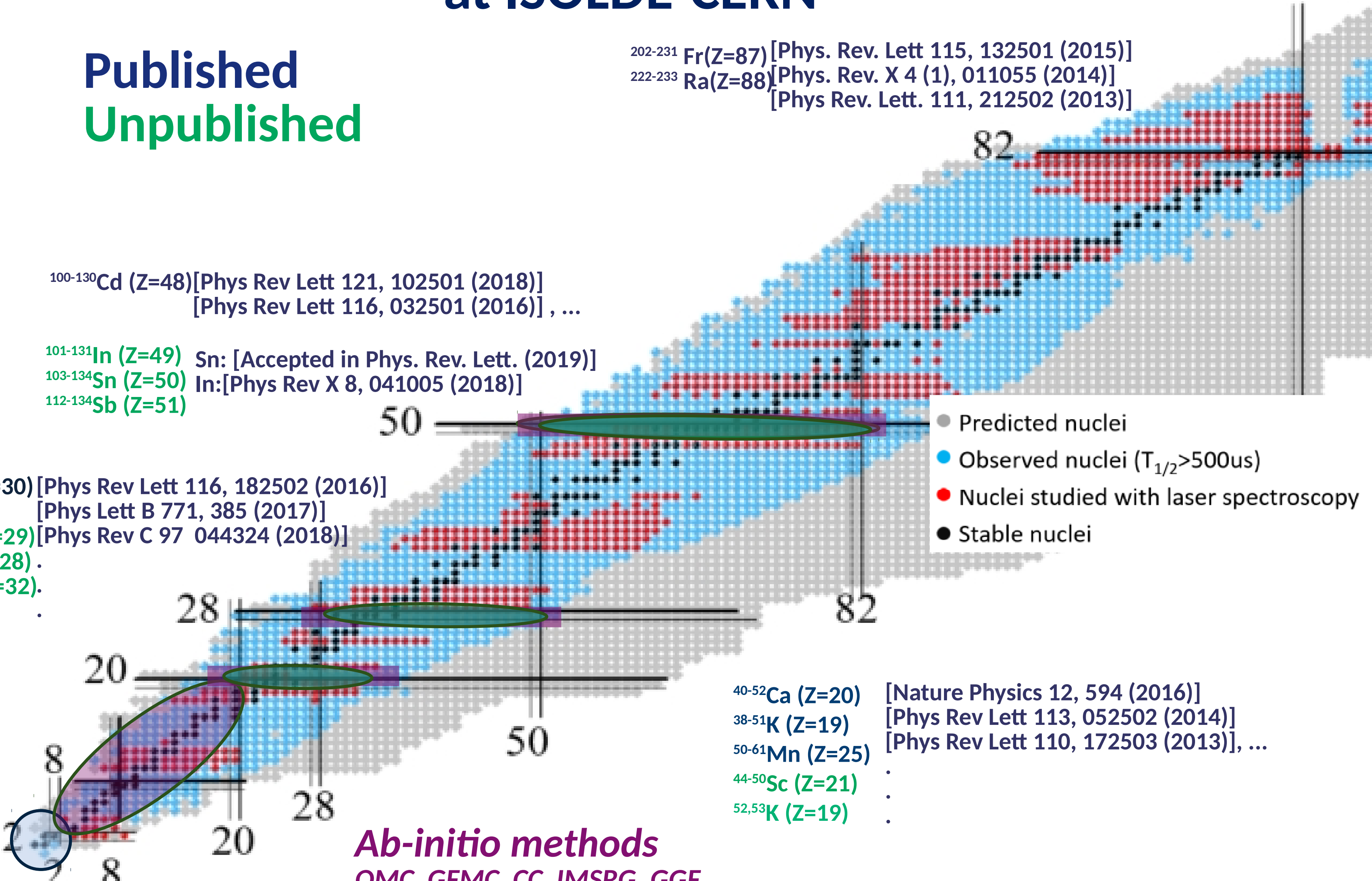
Nuclear charge radii (^{48}Ca): Constrain to properties of nuclear matter



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

Recent results from collinear laser spectroscopy at ISOLDE-CERN

Published
Unpublished



$^{202-231}$Fr(Z=87) [Phys. Rev. Lett 115, 132501 (2015)]
$^{222-233}$Ra(Z=88) [Phys. Rev. X 4 (1), 011055 (2014)]
[Phys Rev. Lett. 111, 212502 (2013)]

$^{100-130}$Cd (Z=48) [Phys Rev Lett 121, 102501 (2018)]
[Phys Rev Lett 116, 032501 (2016)] , …

$^{101-131}$In (Z=49)
$^{103-134}$Sn (Z=50)
$^{112-134}$Sb (Z=51)
Sn: [Accepted in Phys. Rev. Lett. (2019)]
In:[Phys Rev X 8, 041005 (2018)]

$^{65-80}$Zn (Z=30) [Phys Rev Lett 116, 182502 (2016)]
[Phys Lett B 771, 385 (2017)]
$^{58-78}$Cu (Z=29) [Phys Rev C 97 044324 (2018)]
$^{56-68}$Ni (Z=28) .
$^{68-74}$Ge (Z=32).
.

$^{40-52}$Ca (Z=20) [Nature Physics 12, 594 (2016)]
$^{38-51}$K (Z=19) [Phys Rev Lett 113, 052502 (2014)]
$^{50-61}$Mn (Z=25) [Phys Rev Lett 110, 172503 (2013)], …
$^{44-50}$Sc (Z=21) .
^{52,53}K (Z=19) .
.

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

Contents

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- **Probing new forces/particles with atomic isotope shifts**
  → Why radioactive atoms?

- **Exploring nuclear electroweak properties with molecules**
  → Fundamental symmetries / EDMs
  → Why radioactive molecules?

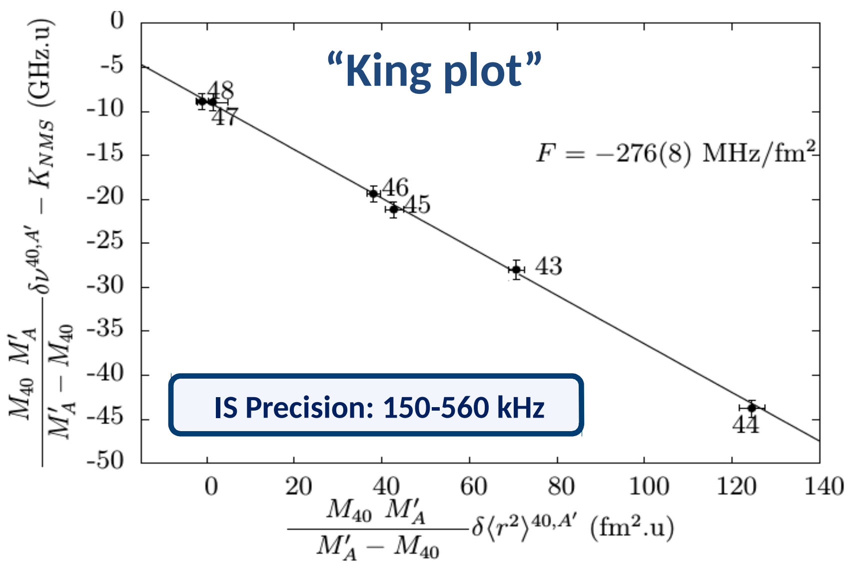
- **Summary**

Atomic
Nuclear

Probing New Forces from Isotope Shifts

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

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



Atomic
Nuclear

Atomic physics results:

- [Garcia Ruiz et al. Phys Rev X 8, 041005 (2018)]
- [Sahoo, Vernon, Garcia Ruiz et al. *Submitted to PRL (2019)*]

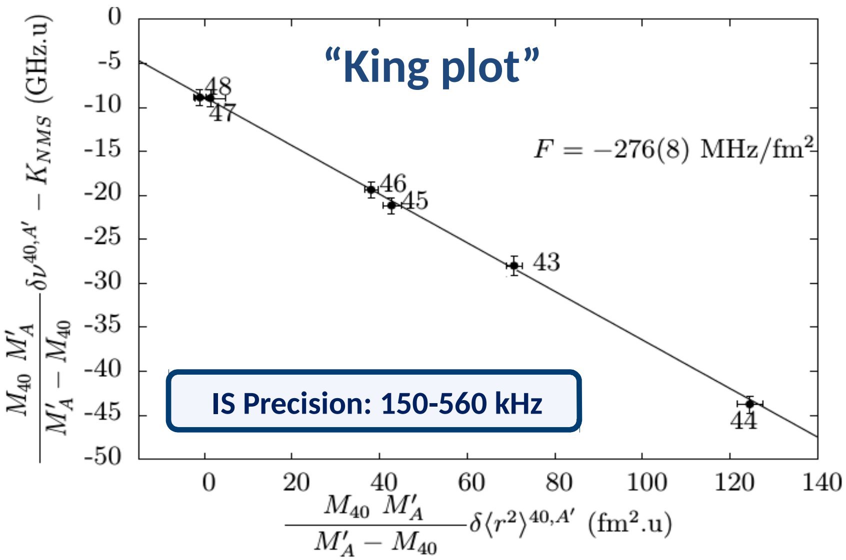
Atomic
Nuclear

Probing New Forces from Isotope Shifts

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

$+$ ***New nucleon-electron force***

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



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

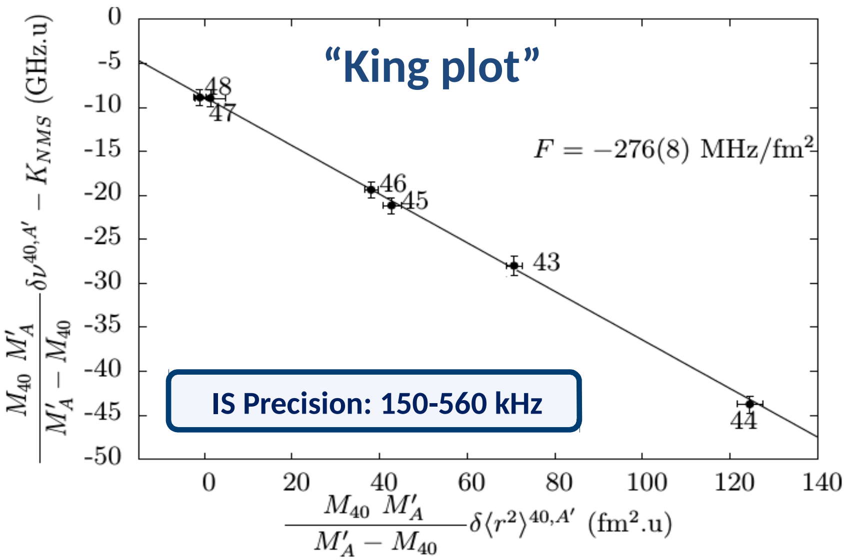
[Stadnik et al. Phys Rev Lett 120, 223202 (2018)]
[Flambaum et al. Phys Rev A 97, 032510 (2018)]
[Frugiuele et al. Phys Rev D 96, 015011 (2017)]
[Berengut et al. Phys Rev Lett 120, 091801 (2018)]

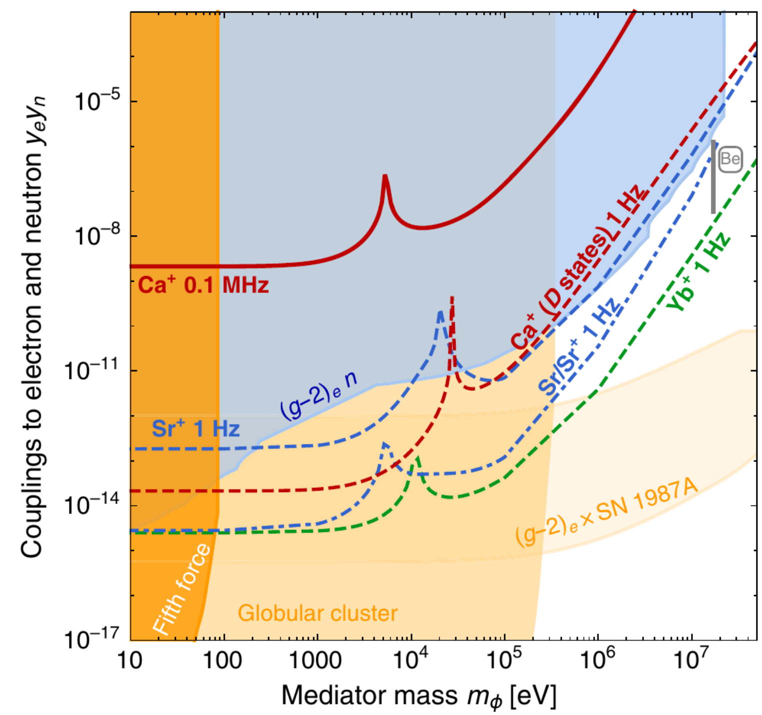
Probing New Forces from Isotope Shifts

Atomic
Nuclear

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'}-M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} \quad + \quad \alpha_{\rm NP}X_i\gamma_{AA'}$$

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





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

$$V_\phi(r) = -\alpha_{\rm NP}(A-Z)e^{-m_\phi r}/r$$

$$\alpha_{\rm NP} = (-1)^s y_e y_n/4\pi$$

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

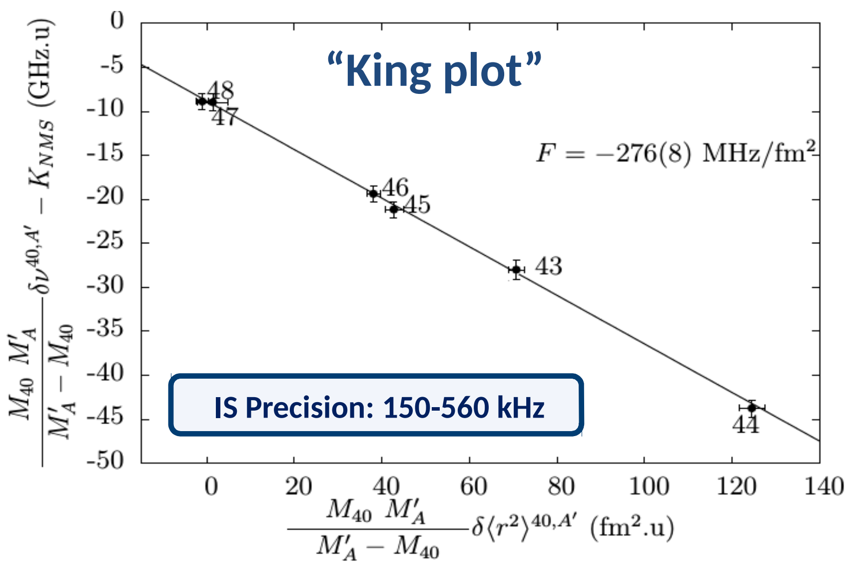
Probing New Forces from Isotope Shifts

Atomic
Nuclear

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

$+$ ***New nucleon-electron force*** $+$ ***Nuclear corrections***

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



A main limitation in heavy atoms
→ Nuclear polarizability

[Flambaum et al. Phys. Rev. A 97, 032510 (2018)]

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

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

PHYSICAL REVIEW D **96,** 015011 (2017)

Constraining new physics models with isotope shift spectroscopy

Claudia Frugiuele, Elina Fuchs, Gilad Perez, and Matthias Schlaffer
Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel
(Received 14 May 2017; published 12 July 2017)

PHYSICAL REVIEW A **97**, 032510 (2018)

Isotope shift, nonlinearity of King plots, and the search for new particles

V. V. Flambaum,[1,2] A. J. Geddes,[1] and A. V. Viatkina[2]
[1]*School of Physics, University of New South Wales, Sydney 2052, Australia*
[2]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*
(Received 7 December 2017; published 19 March 2018)

PHYSICAL REVIEW LETTERS **120,** 091801 (2018)

Probing New Long-Range Interactions by Isotope Shift Spectroscopy

Julian C. Berengut,[1,*] Dmitry Budker,[2,3,4,†] Cédric Delaunay,[5,‡] Victor V. Flambaum,[1,§] Claudia Frugiuele,[6,||]

PHYSICAL REVIEW LETTERS **120,** 223202 (2018)

Probing Long-Range Neutrino-Mediated Forces with Atomic and Nuclear Spectroscopy

Yevgeny V. Stadnik
Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, 55128 Mainz, Germany
(Received 18 November 2017; published 1 June 2018)

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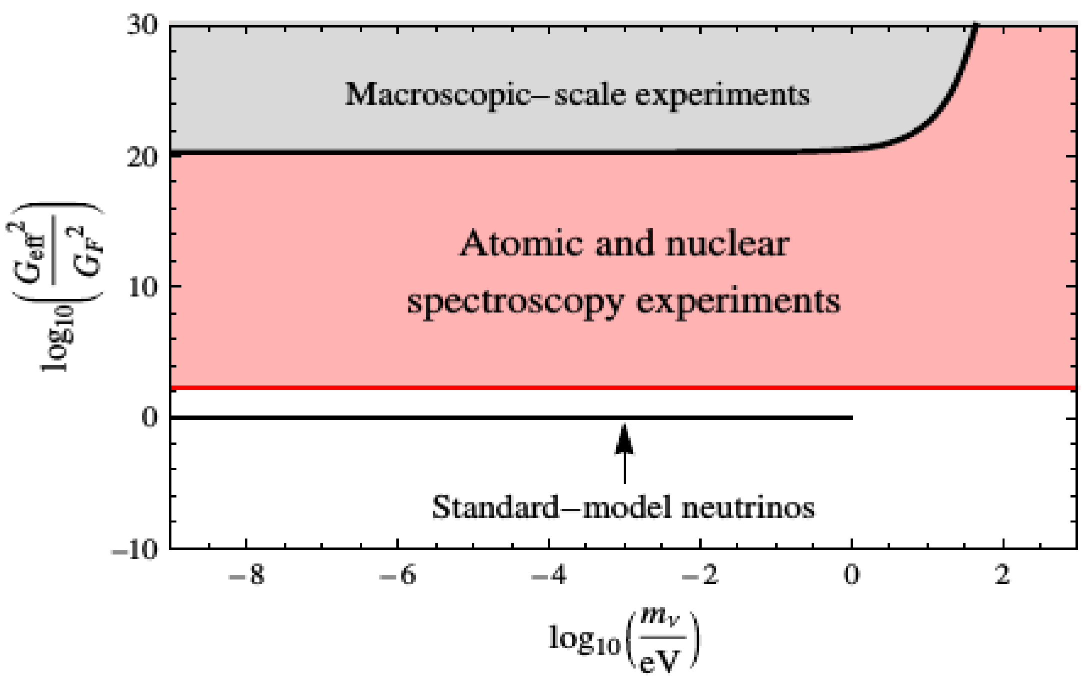
Yevgeny V. Stadnik
Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, 55128 Mainz, Germany

(Received 18 November 2017; published 1 June 2018)

Limits on the neutrino-mediated potential



$$\nu_1^{AA'} \approx K_1 \mu_{AA'} + F_1 \delta\langle r^2\rangle_{AA'} - \delta E_{\kappa=-1}^{AA'}$$

Atomic
Nuclear

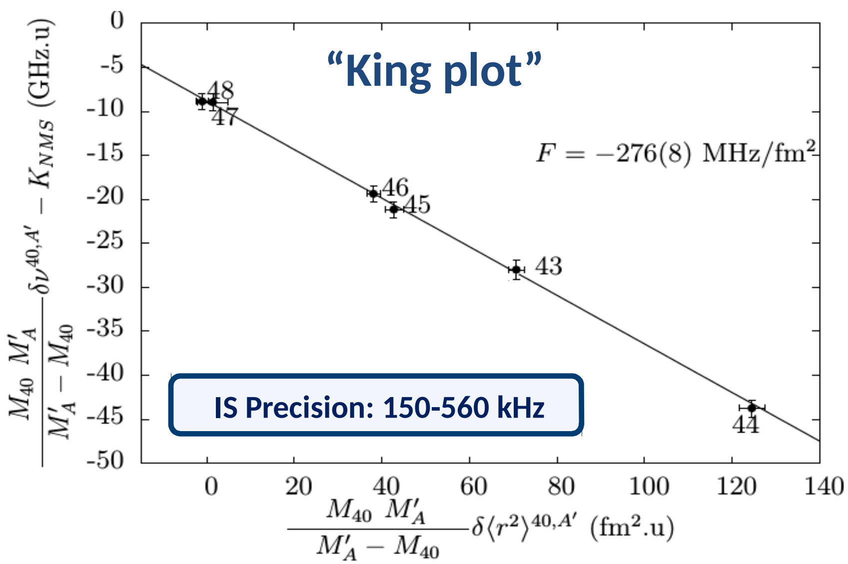
Probing New Forces from Isotope Shifts

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

+ *New nucleon-electron force*

+ *Nuclear corrections*

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



A main limitation in heavy atoms
→ Nuclear polarizability

[Flambaum et al. Phys. Rev. A 97, 032510 (2018)]

Why radioactive atoms?

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

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

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

Contents

Molecules

Great! Why are they important?

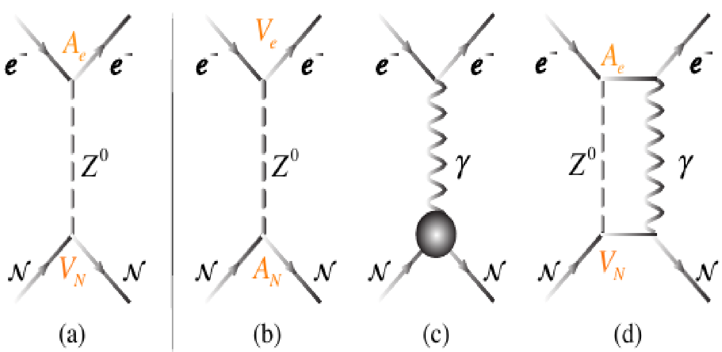
→ <u>New window to the atomic nucleus</u>

P- and P,T- odd effects

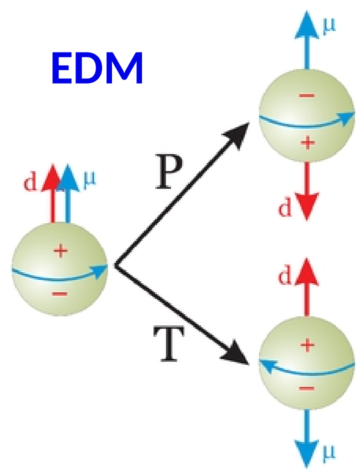
Molecules: <u>Electroweak structure</u>

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

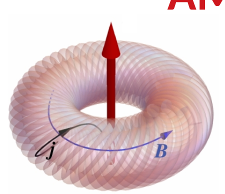
- Matter/antimatter asymmetry?
- Origin of Dark Matter?
- Physics BSM?



EDM

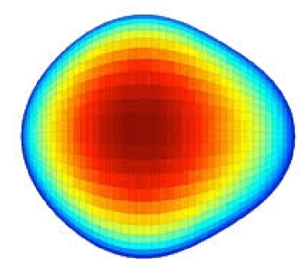


AM



$$\boldsymbol{a} = -\pi \int d^3r\, r^2\, \boldsymbol{j}(\boldsymbol{r})$$

S_{schiff}



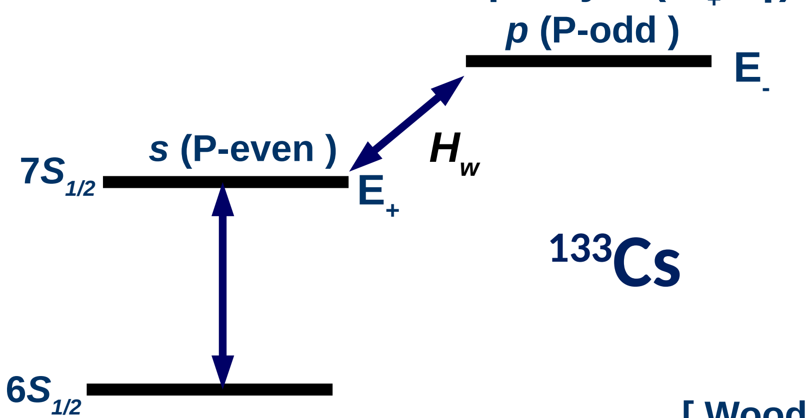
[Safronova et al. Rev. Mod. Phys. 90, 025008 (2018)]

Atoms vs Molecules

Atoms

PV → Mix states of different parity ~ $(E_+ - E_-)^{-1}$

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



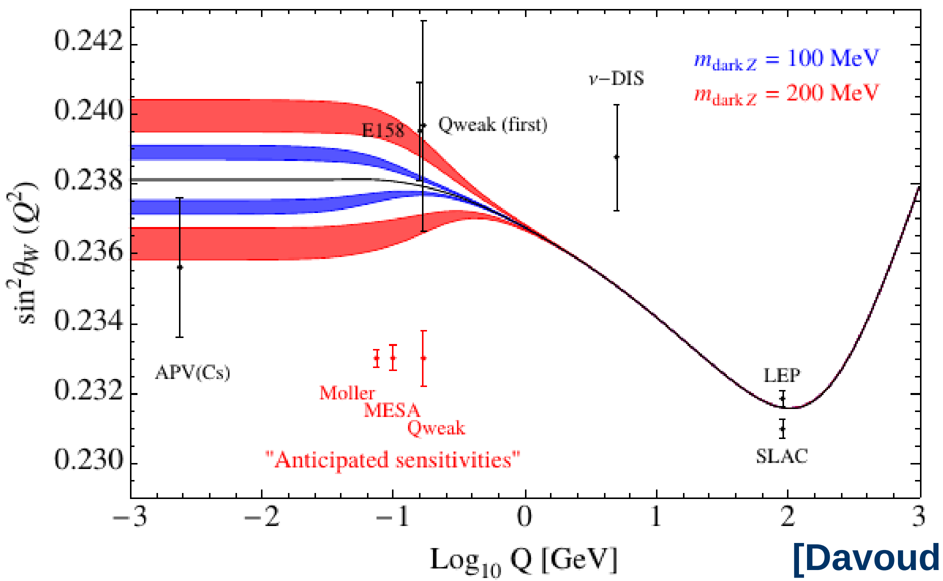
^{133}Cs

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

measure — atomic calculation — Nuclear weak charge

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

[Wood et al. Science 275, 1759 (1997)]
[Porsev et al. PRL 102, 181601 (2009)]



[Davoudias et al. Phys. Rev. D 89, 095006 (2014)]

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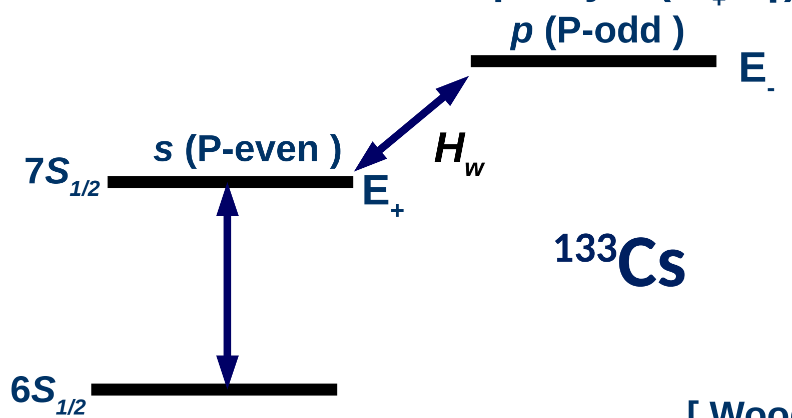

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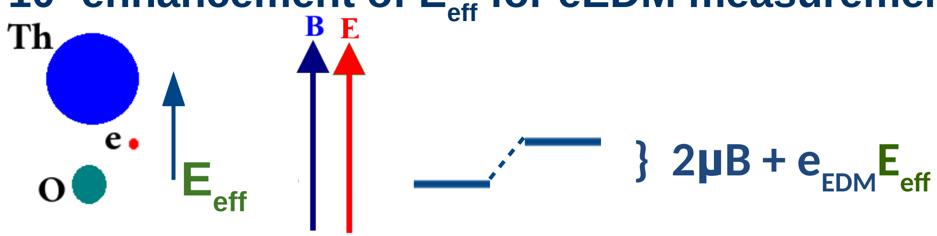
Molecules

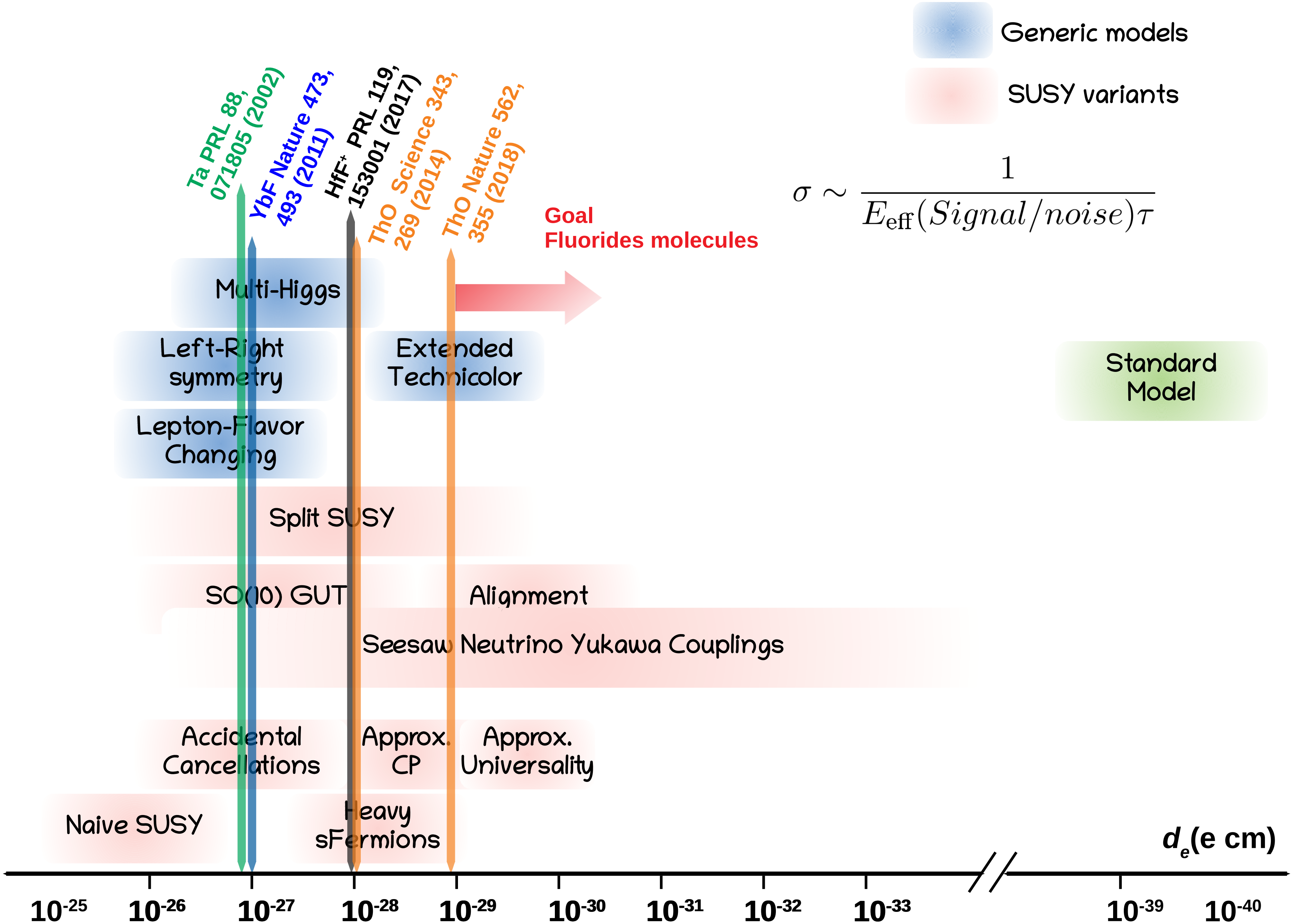
- ✓ $(E_+ - E_-) \sim 0$ About 10^5 enhancement
  [Dzuba et al. Phys. Rev. Lett. 119, 223201 (2017)]
- ✓ Nuclear-Spin-Dependent PV / Anapole moment (BaF)
  [Altunas et al. Phys Rev Lett 120, 142501 (2018)]
- ✓ >10^5 enhancement of E_{eff} for eEDM measurements



[Baron et al. Science 343, 269 (2014)]
[Hardvard-Yale Nature 562, 355 (2018)]

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

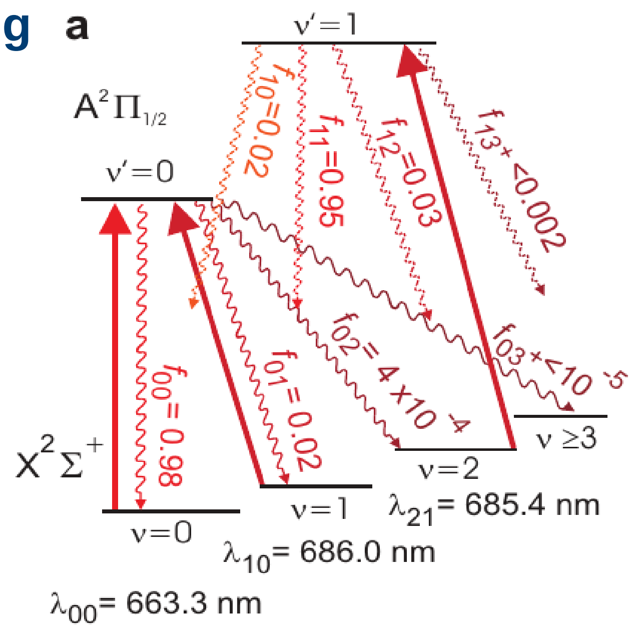
eEDM Limits



Generic models
SUSY variants
$$\sigma \sim \frac{1}{E_{\text{eff}}(Signal/noise)\tau}$$
Ta PRL 88, 071805 (2002)
YbF Nature 473, 493 (2011)
HfF^+ PRL 119, 153001 (2017)
ThO Science 343, 269 (2014)
ThO Nature 562, 355 (2018)
Goal
Fluorides molecules
Multi-Higgs
Left-Right symmetry
Extended Technicolor
Lepton-Flavor Changing
Standard Model
Split SUSY
SO(10) GUT
Alignment
Seesaw Neutrino Yukawa Couplings
Accidental Cancellations
Approx. CP
Approx. Universality
Naive SUSY
Heavy sFermions
d_e(e cm)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-39}
10^{-40}

Fluoride molecules

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



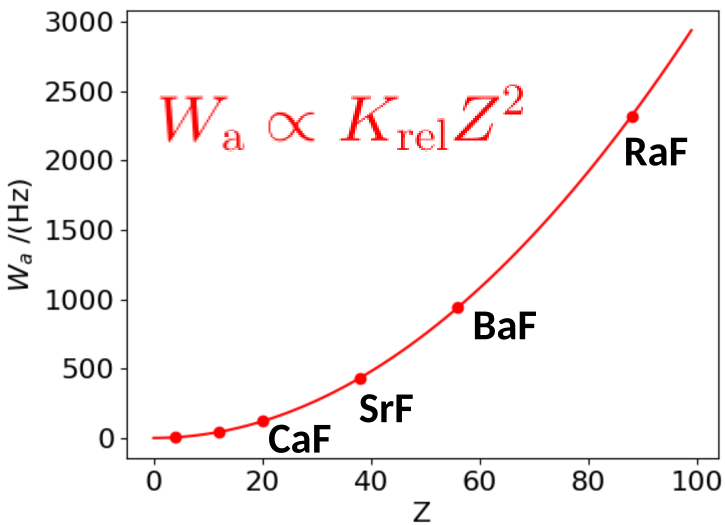
- **.**
- **.**
- **.**
- **SrF → Nature Physics 13, 1173(2017)**
- **YbF → Phys. Rev. Lett. 120, 123201 (2018)**
- **CaF → Nature Physics 14, 890 (2018)**
  Phys. Rev. Lett. 120, 163201 (2018)
- **RaF → Radioactive**
  Coming soon … Is it needed?

Radioactive Molecules: Ra(Z=88)F Results

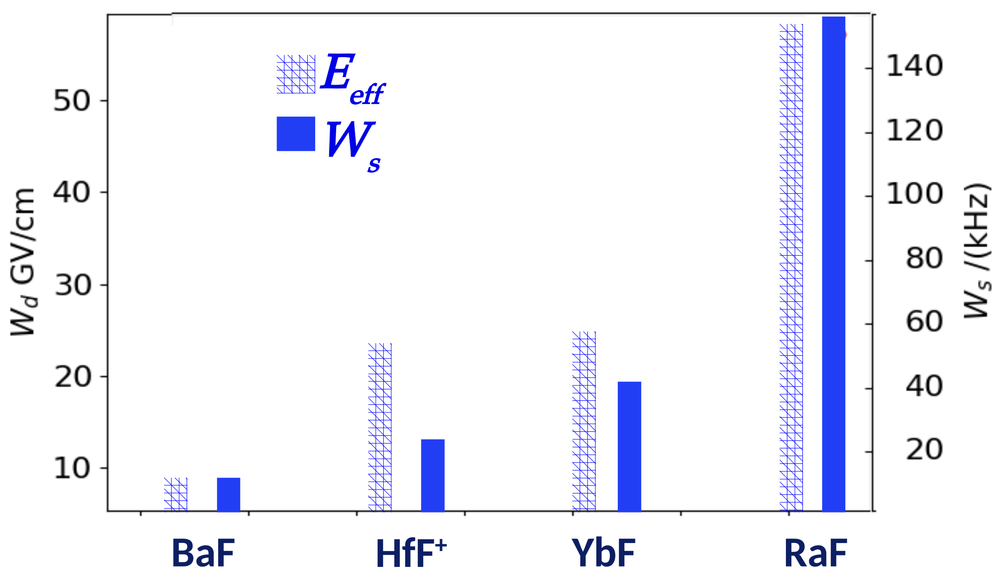
$$\widehat{H}_{\mathrm{sr}} = B\vec{\mathcal{N}}^2 + \gamma\,\vec{\mathbf{S}}^{\mathrm{eff}}\cdot\vec{\mathcal{N}} + \vec{\mathbf{S}}^{\mathrm{eff}}\cdot\widehat{\mathbf{A}}\cdot\vec{\mathbf{I}} + \vec{\mathcal{N}}\cdot\widehat{\mathbf{C}}\cdot\vec{\mathbf{I}} + \;\cdots$$

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

P-odd and P,T -odd effects



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



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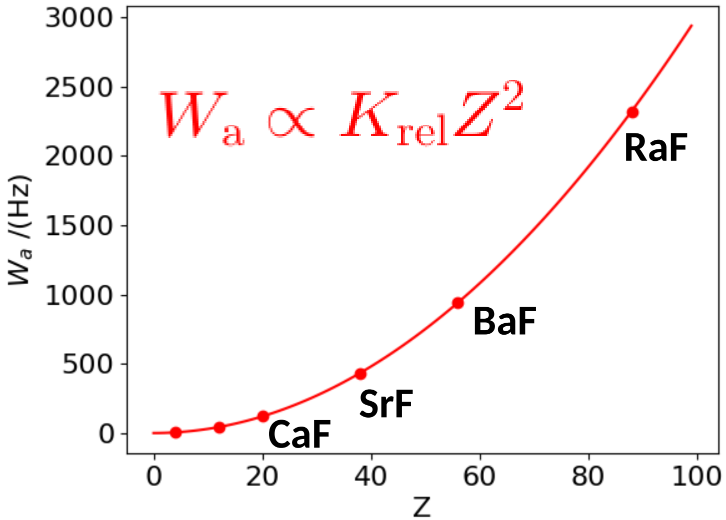

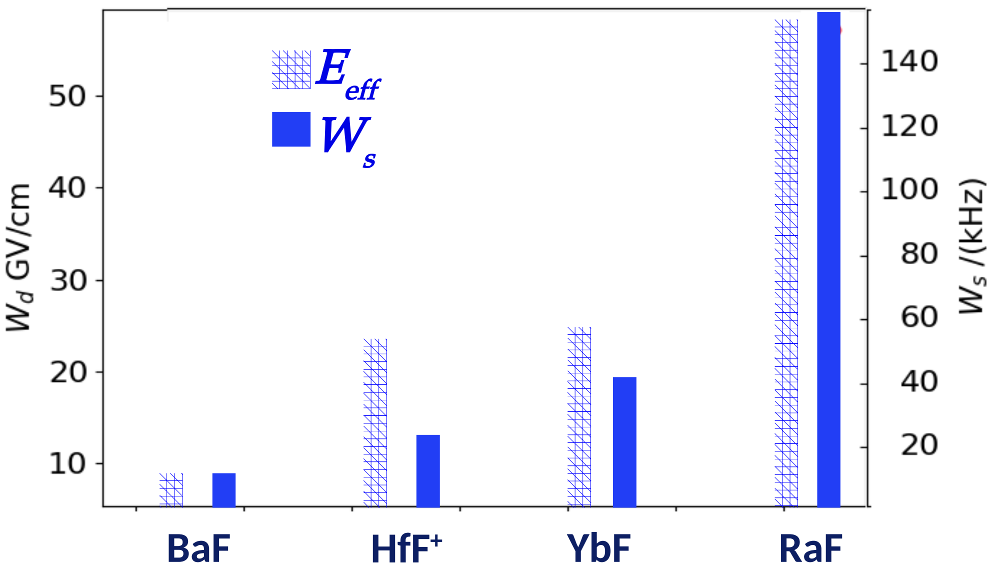

[Gaul & Berger J. Chem. Phys 147, 014109(2017)]
[Fleig. Phys. Rev. A 96, 040502 (2017)]

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

... BUT all parameters experimentally unknown!

Radioactive Molecules

→ <u>New window to study the atomic nucleus</u>

[Garcia Ruiz, Berger et al. CERN-INTC-2018-017 (2018)]

[Garcia Ruiz, Berger et al. In preparation (2019)]

Molecules: <u>Electroweak structure</u>

- Anapole moment: AM
- Magnetic Quadrupole Moment: MQM
- Schiff Moment: S_{schiff}
- eEDM, nEDM, ...

⬇

P- and P,T- odd effects

⬇

- Matter/antimatter asymmetry?
- Origin of Dark Matter?
- Physics beyond the standard model of particle physics?

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

↓

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Octupole deformed nuclei?
Ra @ CERN

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

[Hardvard-Yale Nature 562, 355 (2018)]
[Altunas et al. Phys Rev Lett 120, 142501 (2018)]
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Why radioactive molecules?

- ✓ Large Z → E_{ef} (x 5)
- ✓ Deformed nuclei (>10^2)
- ✓ Large enhancement of the MQM (>10^2)
- ✓ Study of NSD interactions (I>0)

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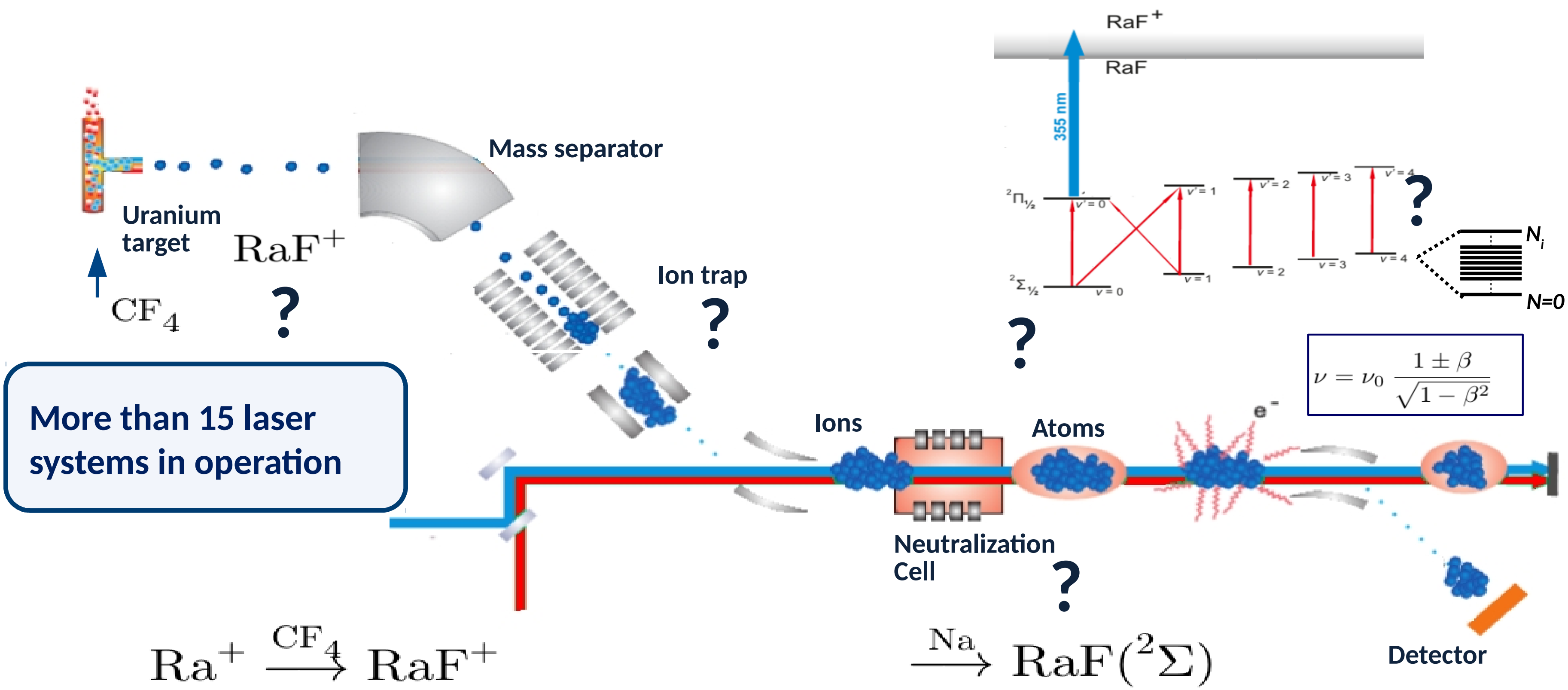
Radioactive Molecules: RaF Results

Collinear resonance ionization spectroscopy of RaF molecules

[Garcia Ruiz, Berger et al. CERN-INTC-2018-017 (2018)]

<u>Molecules can be 10^5 times more exciting but are 10^6 more challenging!</u>



More than 15 laser systems in operation

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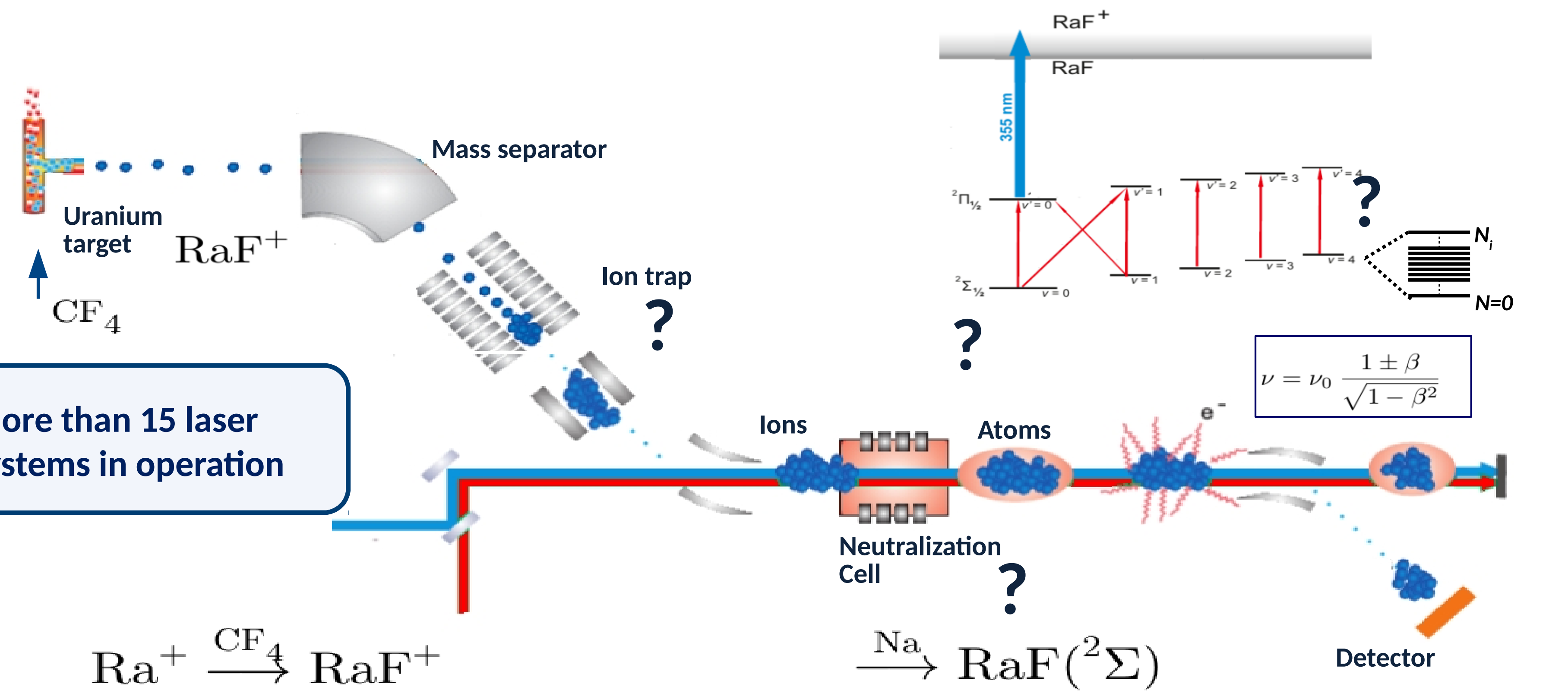
Molecules can be 10^5 times more exciting but are 10^6 more challenging!

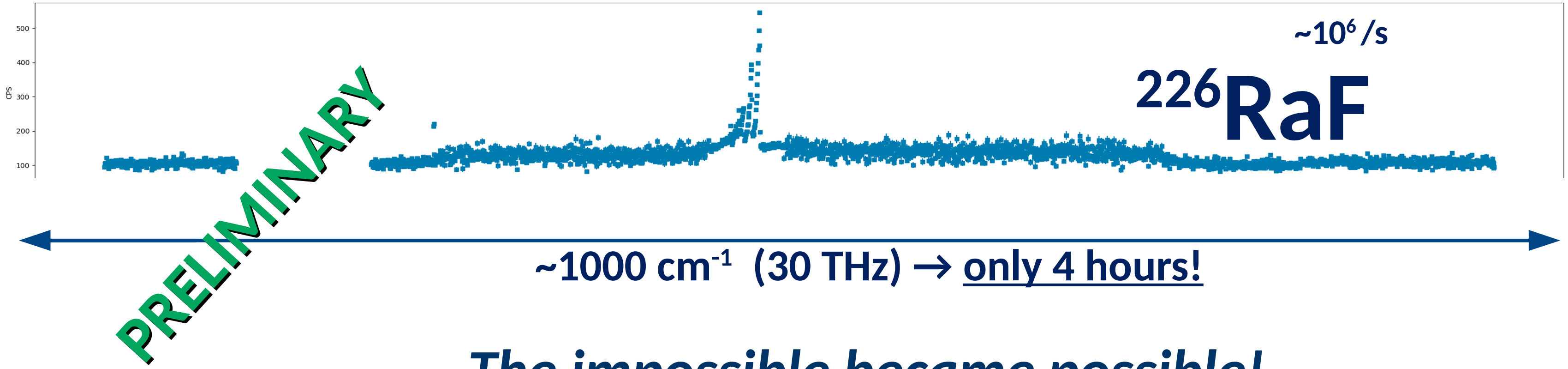
Molecules have complex structures
→ More than 10^4 states can be populated
Vibrational / rotational / hyperfine
Impossible with a hot (> 300 K) molecule?

Theory: $13300(1000)\mathrm{cm}^{-1}$
Scanning 1000 cm^{-1} at 10 MHz/min (1 cm^{-1} = 30 GHz)
→ 2080 days!!!
Impossible with a radioactive molecules? (<10^6 molecules/s)



More than 15 laser systems in operation

RaF: Results (November 2018)



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

...The impossible became possible!

Strategy → <u>Take advantage of all possible disadvantages</u> in precision spectroscopy (laser linewidths, power broadening, energy spread, ...)

[Garcia Ruiz et al. In preparation (2019)]

Contents

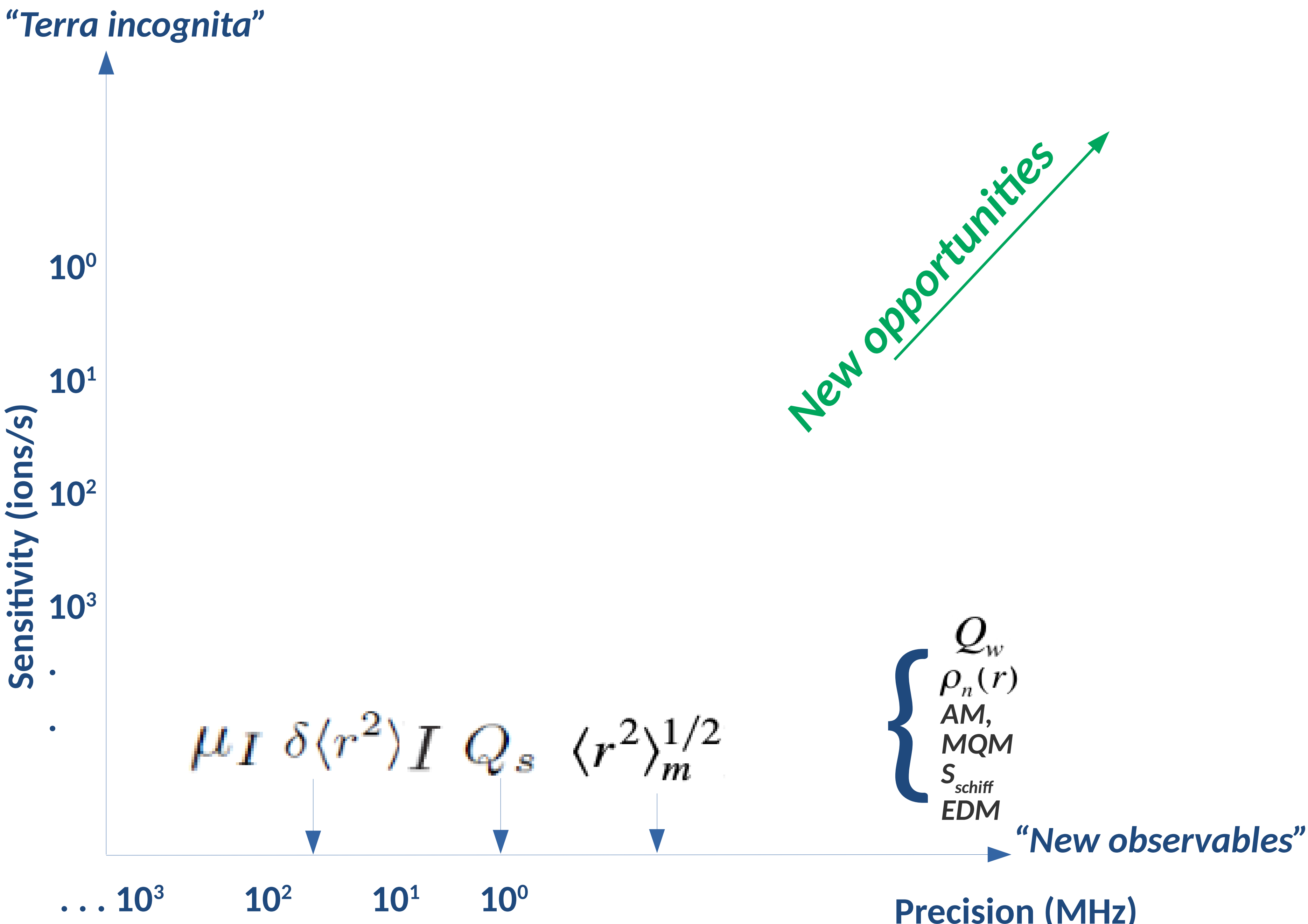
- Precision laser spectroscopy

- Probing new forces/particles with atomic isotope shifts
  → Why radioactive atoms?

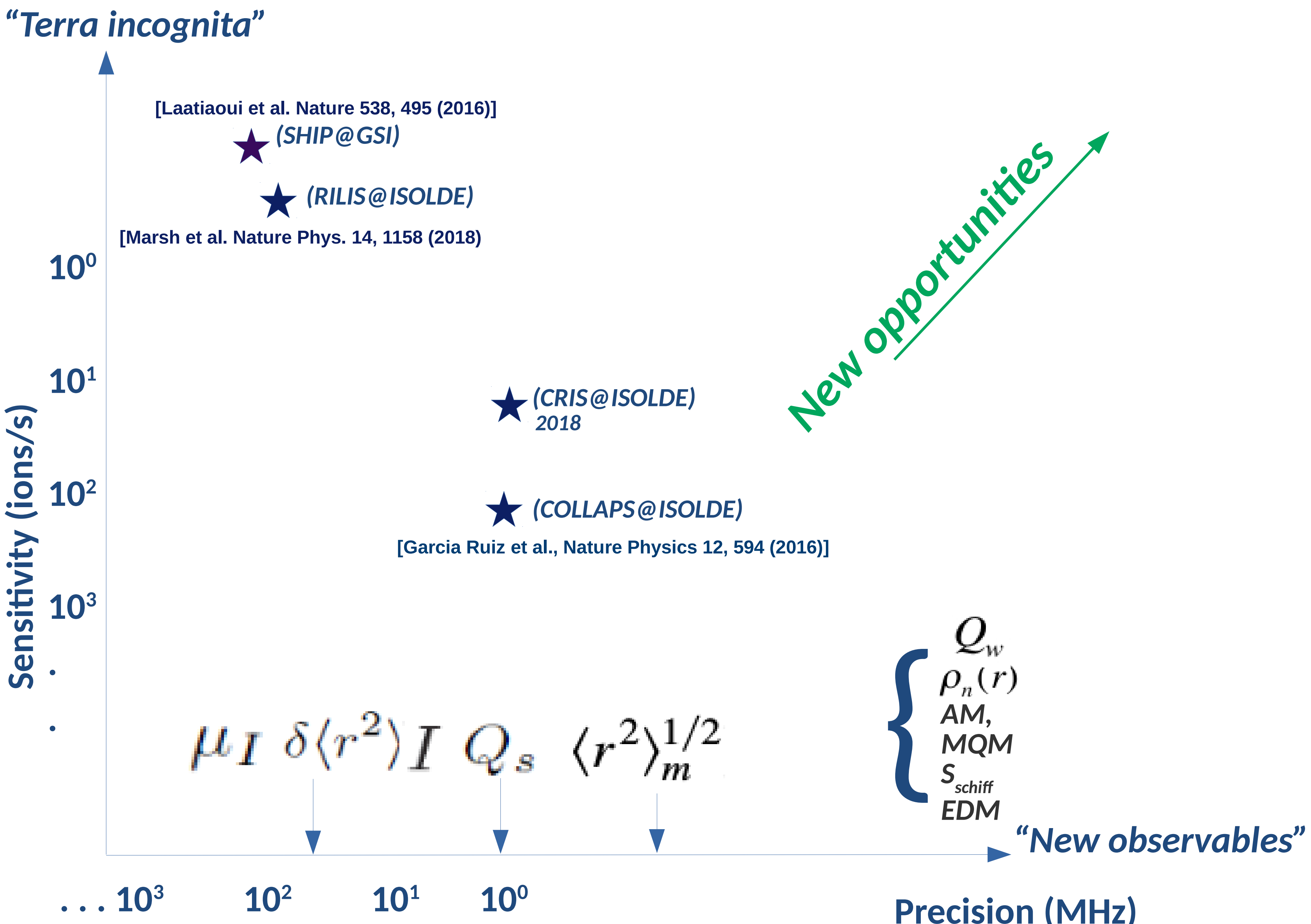
- Exploring nuclear electroweak properties with molecules
  → Fundamental symmetries / EDMs
  → Why radioactive molecules?

- Summary

Present achievements / future opportunities



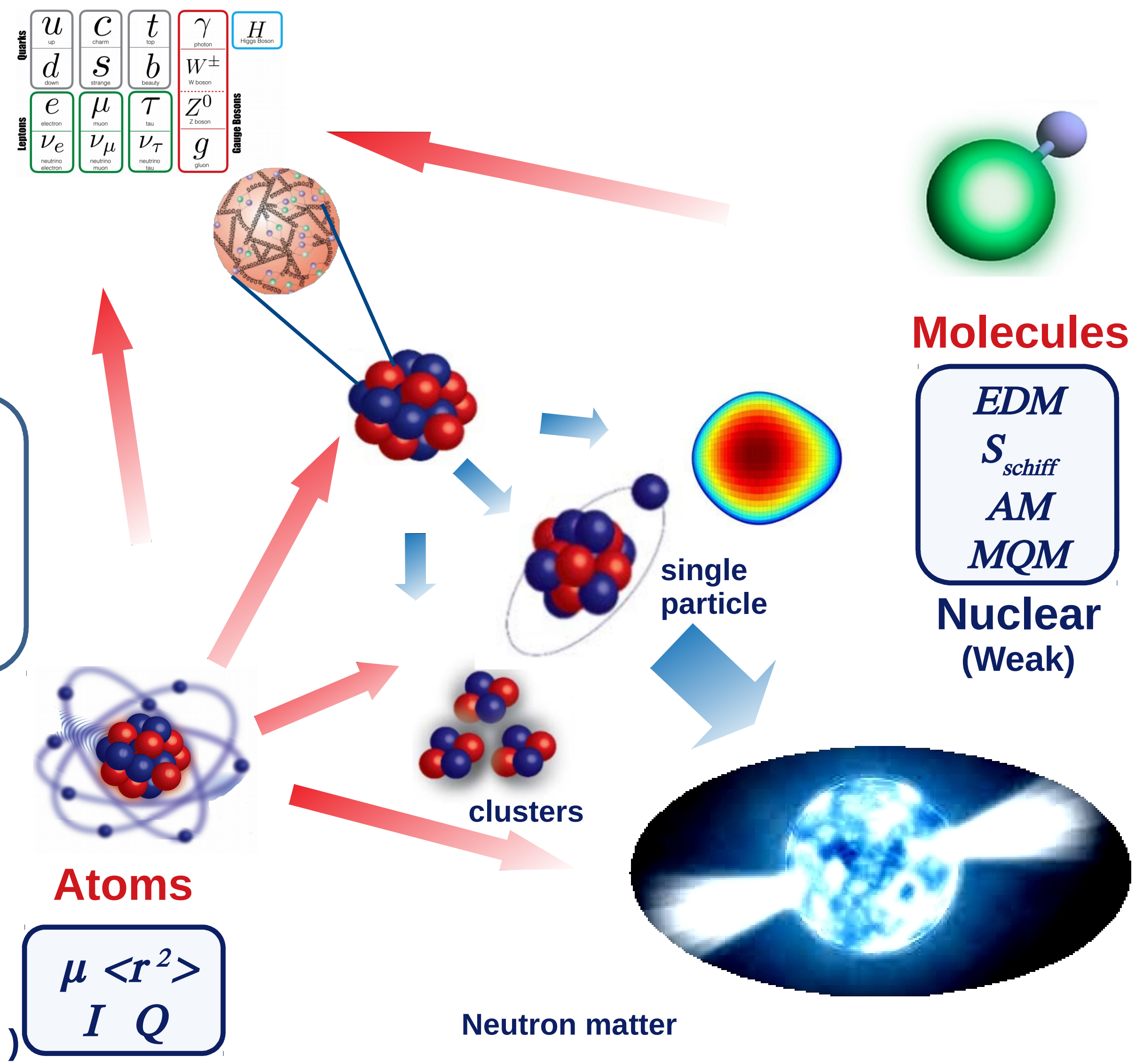
Present achievements / future opportunities



Conclusions

Isotope shifts:
Are there new particles/forces?

Molecules
- **CP and PT violation?**
- **What is the origin of matter-antimatter asymmetry?**
- **What are the properties of dark matter?**



Radioactive atoms and molecules provide unique answers to these questions!

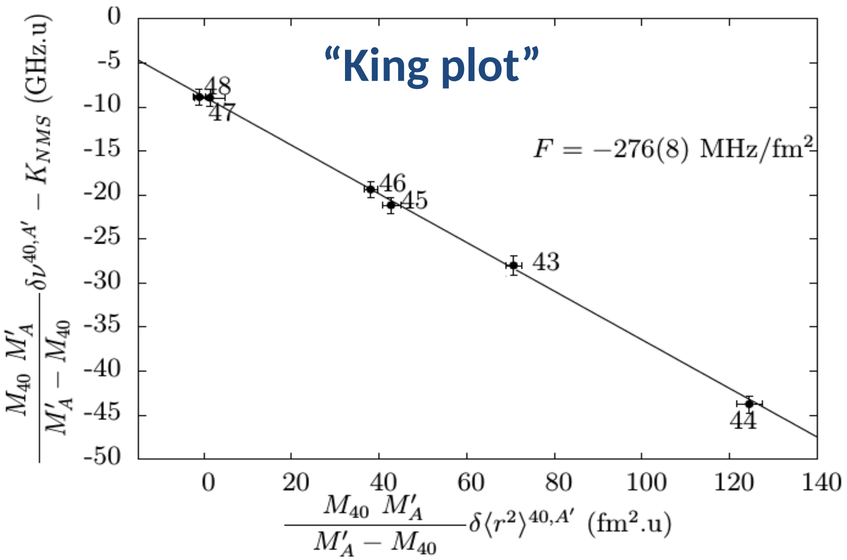
Conclusions

Isotope shifts:
Are there new particles/forces?

Radioactive atom:

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

Nuclear theory → dipole polarizability



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

+ ***New nucleon-electron force*** + **Nuclear corrections**

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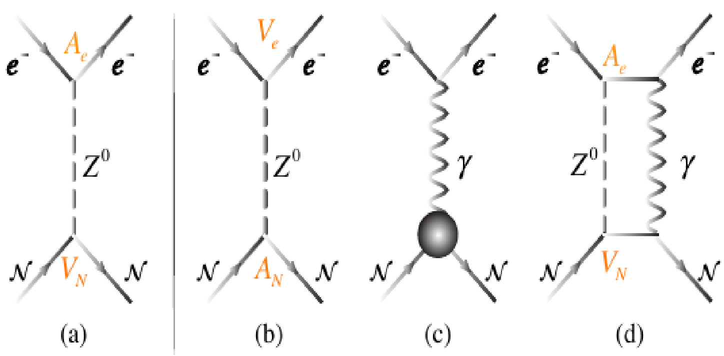

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- ✓ Measurements of ^{223}RaF, ^{224}RaF, ^{225}RaF, ^{226}RaF, ^{228}RaF
- ✓ Hyperfine structure of ^{223}Ra(I=3/2)F, Ionization potential....

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... this is just the beginning!

Thanks for your attention!