Single Ion Spectroscopy: Towards Measuring Atomic Parity Violation

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E. Dijck, A. Mohanty, N. Valappol, K. Jungmann, C.J.G. Onderwater, R.G.E. Timmermans, L. Willmann, H.W. Wilschut

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FOM

Test of Standard Model

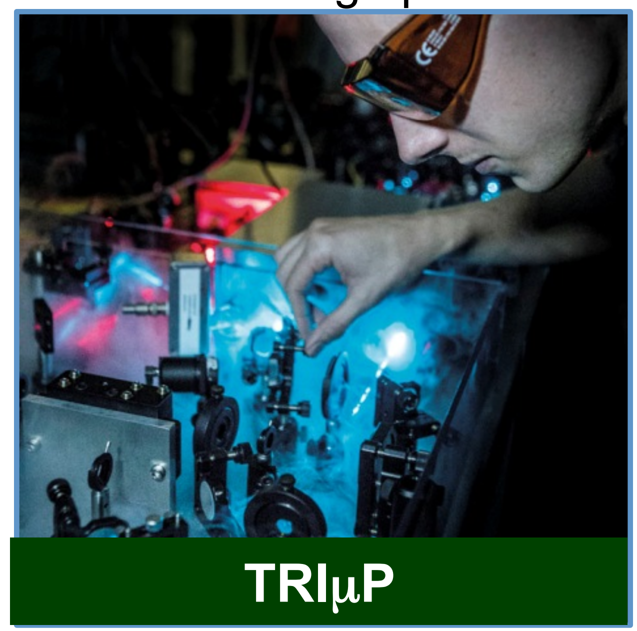
The Standard Model (SM) of particle physics is “incomplete” ⇒ searches for physics “beyond the SM” at two, complementary, fronts:

High energy collider experiments:
Direct observation of new particles

e.g. Discovery of Higgs

Complementary

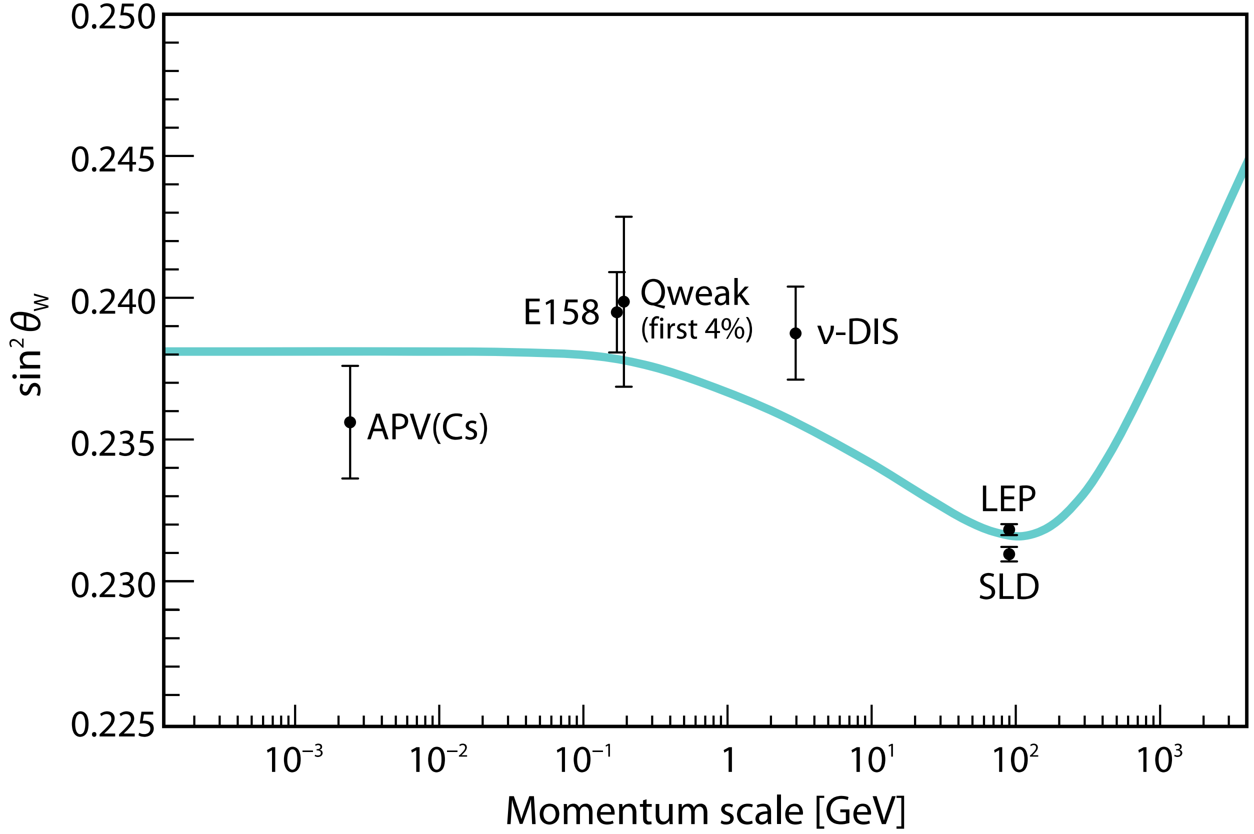
Low energy searches:
Indirect with high precision



e.g. Atomic Parity Violation

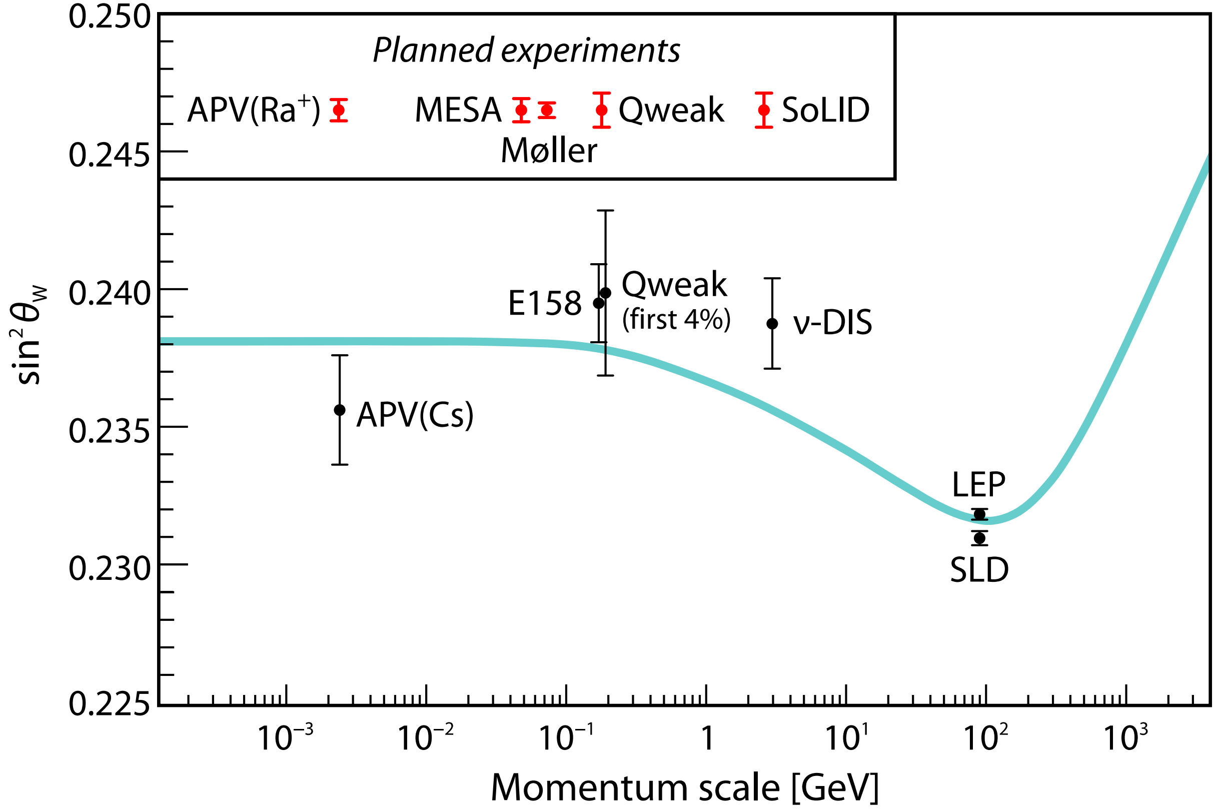
Test of Standard Model

Weak Interaction

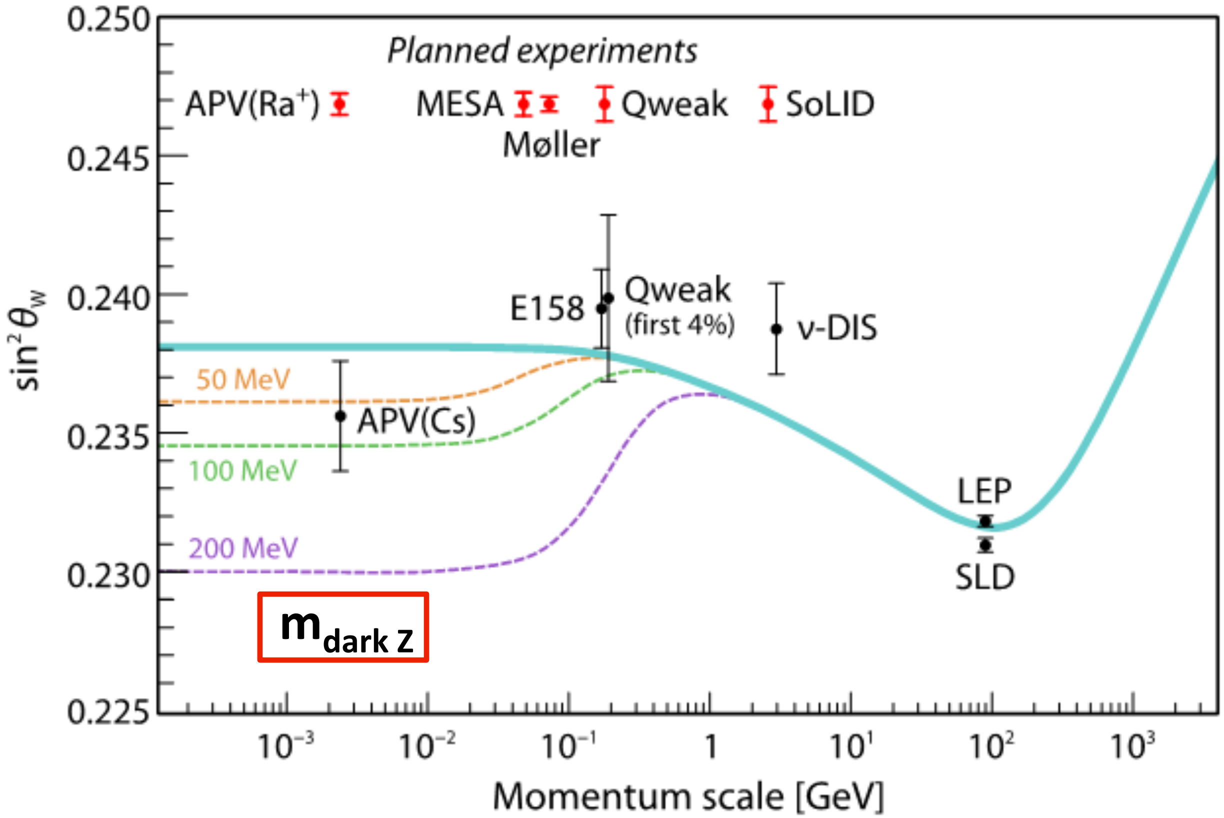


Test of Standard Model

Weak Interaction



Test of Standard Model
Weak Interaction



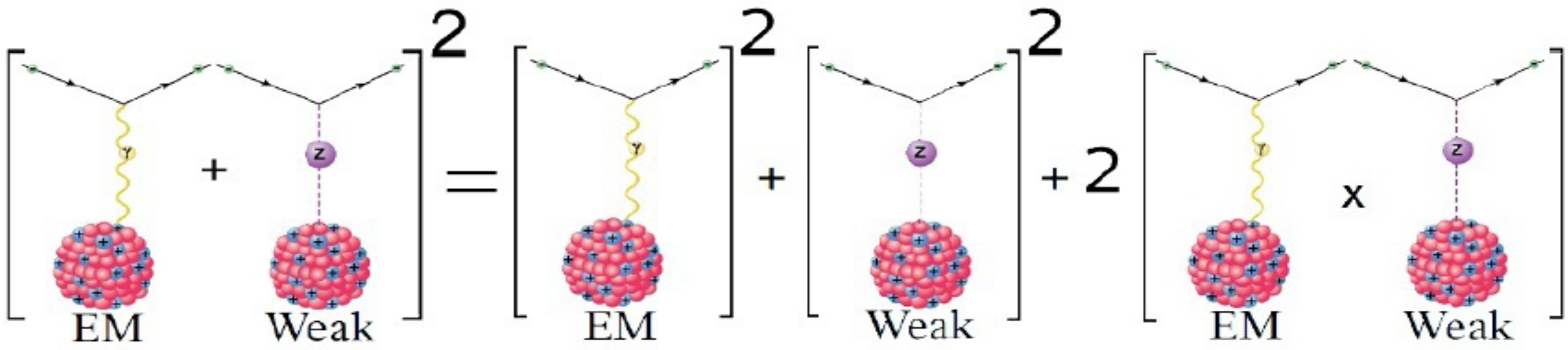
$Q_W = -N + (1 - 4\sin^2\theta_W)Z$ + rad. corr. + "new physics"

Best limit on the mass of Z' from APV

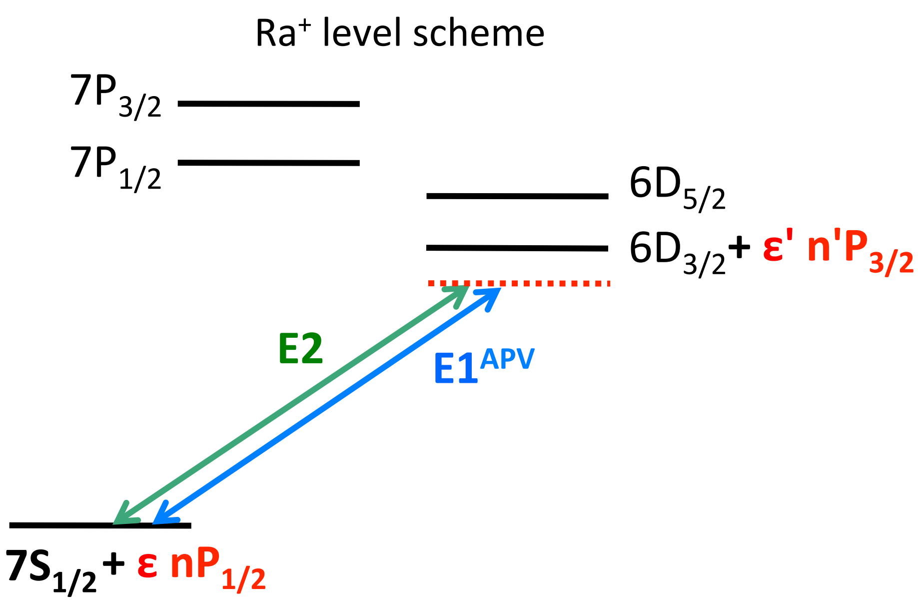
S. Kumar, W. Marciano, Annu. Rev. of Nucl. Part. Sci. **63**, 237 (2013)

Atomic Parity Violation (APV)

Weak interaction violates parity



Atomic states acquire tiny admixture of opposite-parity states



$$E1_{\mathrm{APV}} = kQ_{\mathrm{W}}$$

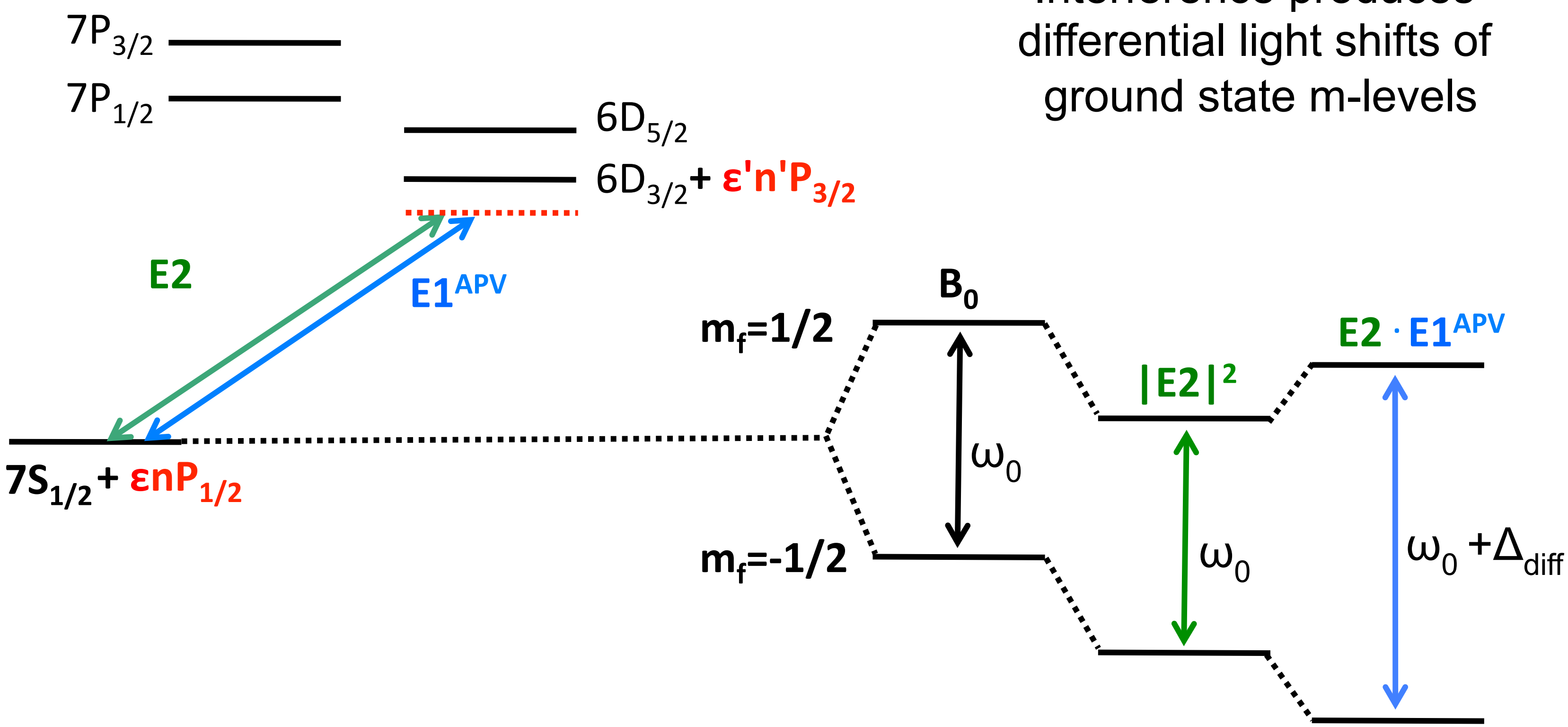
From atomic theory (→ k)

Infer weak charge (→ Q_{W})

Principle of Experiment

$$E1_{APV} = kQ_W$$

measure

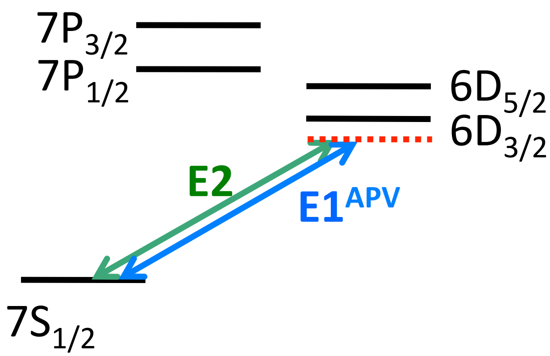


Interference produces differential light shifts of ground state m-levels

Localize single ion to better than one wavelength
Measure with RF spectroscopy and shelving

N. Fortson, Phys. Rev. Lett. **70**, 2383 (1993)

Why Ra^+ Ions?

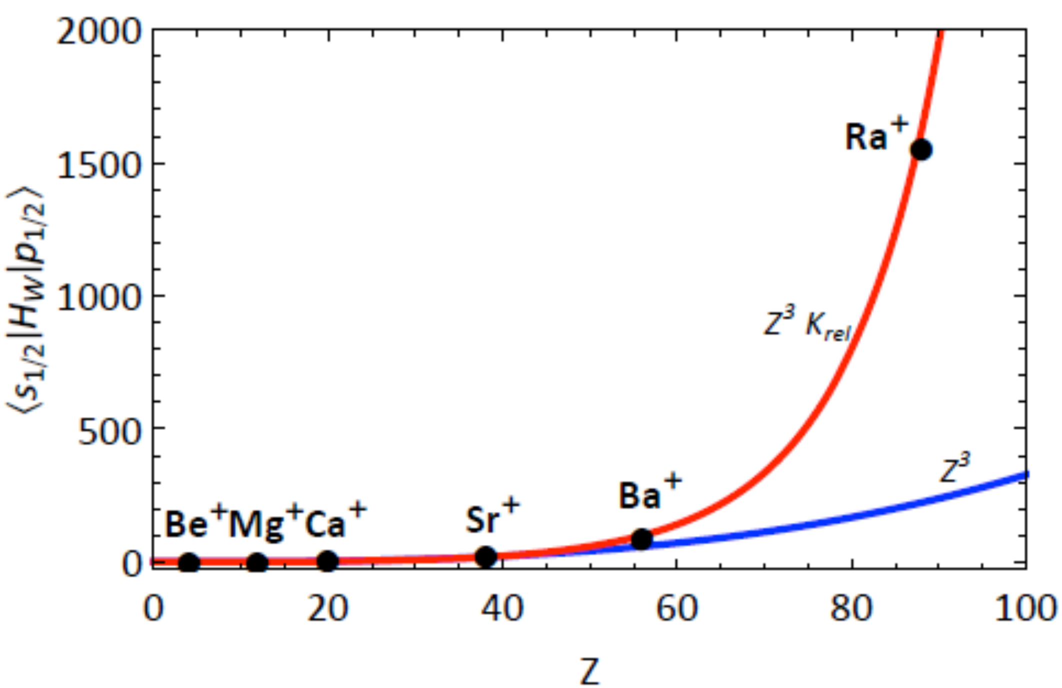


$$E1_{APV} = k Q_W$$

calculate atomic wavefunctions

S-S	S-D
Cs	Ba^+
0.9	2.2
Fr	Ra^+
14.2	46.4

Bouchiat & Bouchiat (1974): “stronger than Z^3-law”



Ra^+ is a superior APV candidate

50x more sensitive to APV than current best measurement in Cs

The effect in Ra^+ is 20 times larger than for Ba^+, and 50 times larger than for Cs

Calculations:

k_{Ra} = 46.4(1.4) · 10^{-11} iea_0 /N*

k_{Cs} = 0.8906(26) · 10^{-11} iea_0 /N**

*L.W. Wansbeek *et al.*, Phys. Rev. A **78**, (2008)
A. Derevianko *et al.*, Phys. Rev. A **79, 013404 (2009)

APV Experiment in Ra^+ Ions

$$E1_{\mathrm{APV}} = k Q_{\mathrm{W}}$$

measure

Infer weak charge

calculate atomic wavefunctions

Radium Spectroscopy and Theory:

✔ Ra Ions production

✔ Laser spectroscopy of Ra Ions

✔ Atomic wavefunctions calculations

Theses:
O. O Versolato
G. S. Giri
L. W. Wansbeek

$E1_{APV}$ measurement:

✔ Trapped and laser cooled ions

✔ Single ion detection and spectroscopy

✔ Localize ions

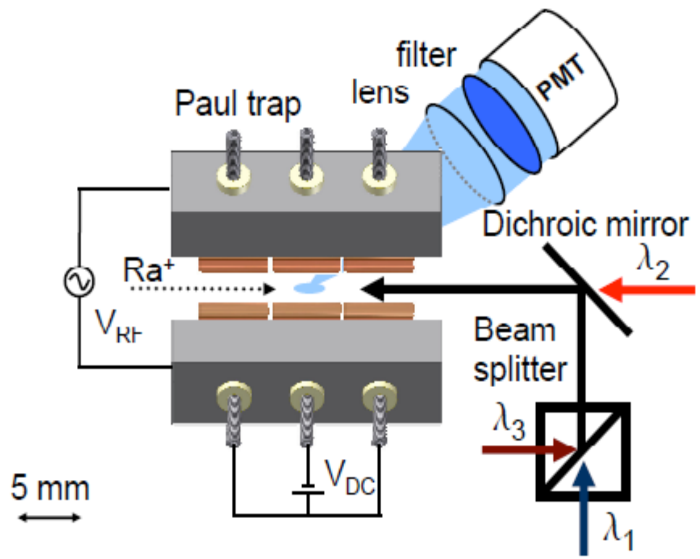
→ Parity violation measurement

✔ done
✔ work in progress

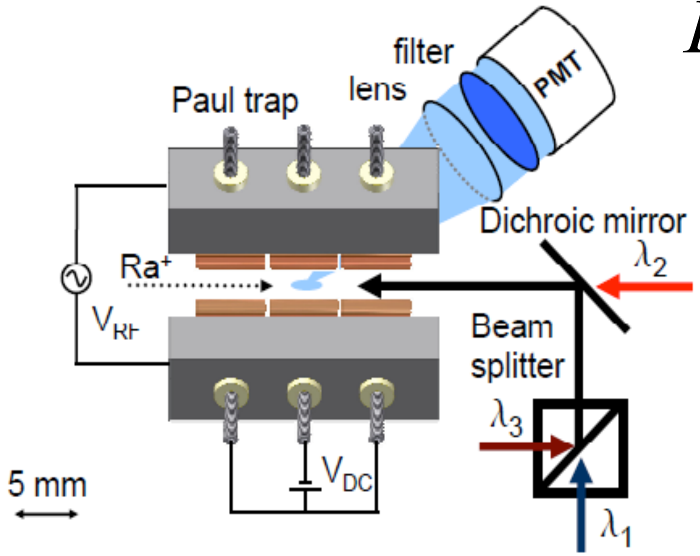
Ra Ion Source

Isotope	I	$T_{1/2}$ [s]	Production Method	Production [ions/s]	Estimated No. trapped ions
^{209}Ra	5/2	4.6(1.5)	Triμp Facility	200	40
^{210}Ra	0	3.66(18)	Triμp Facility	500	75
^{211}Ra	5/2	12.61(5)	Triμp Facility	1 000	1 200
^{212}Ra	0	12.5(1.0)	Triμp Facility	800	1000
^{213}Ra	1/2	162.0(1.7)	Triμp Facility	2 600	10 000
^{214}Ra	0	2.42(14)	Triμp Facility	1 000	100
^{225}Ra	1/2	14.9(2)d	off line source		few
^{226}Ra	0	1 600(7)y	off line source		few

ΔN > 10 (^{210}Ra – ^{214}Ra)

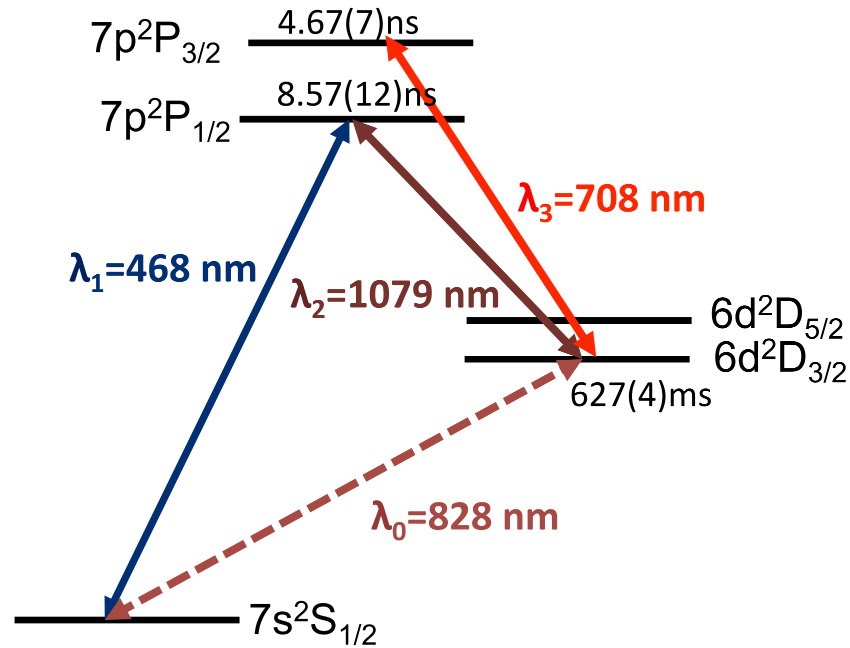


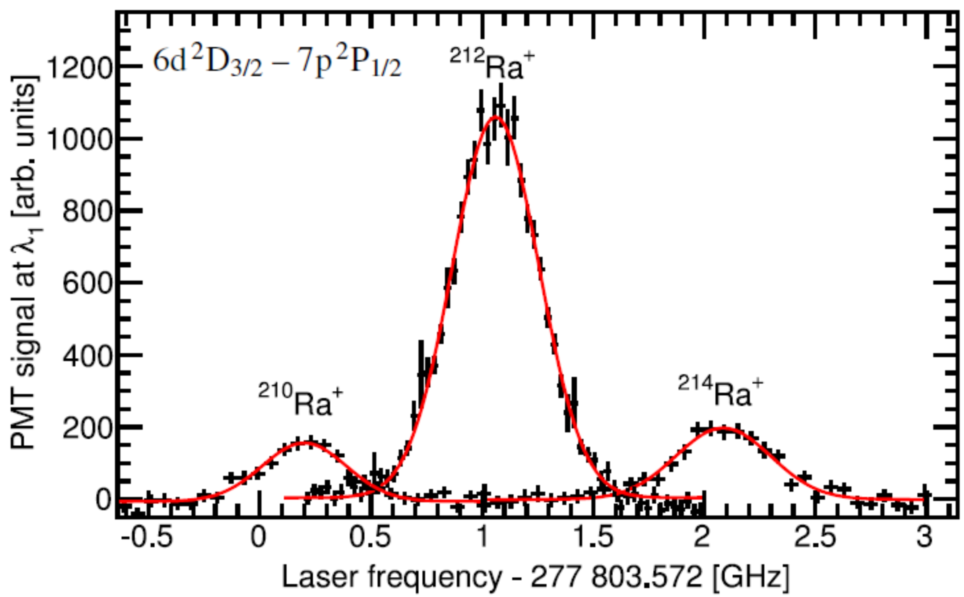
Laser Spectroscopy in Ra^+ ions

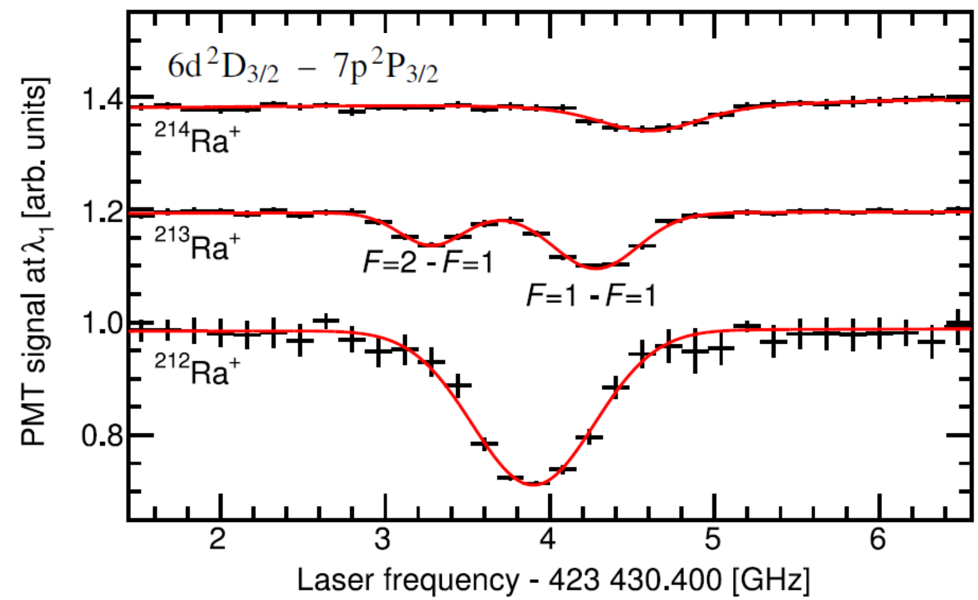


$$E1_{APV} = kQ_W$$

calculate atomic wavefunctions



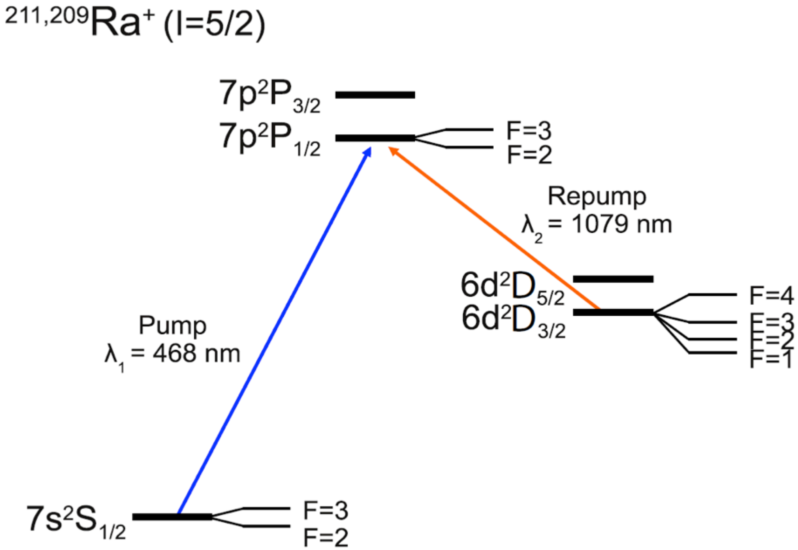


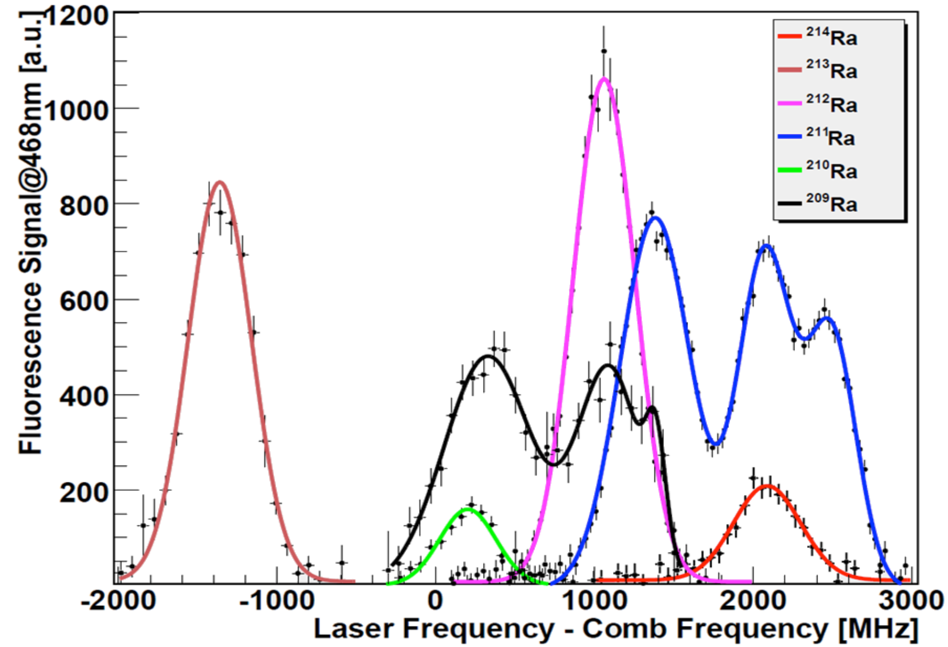


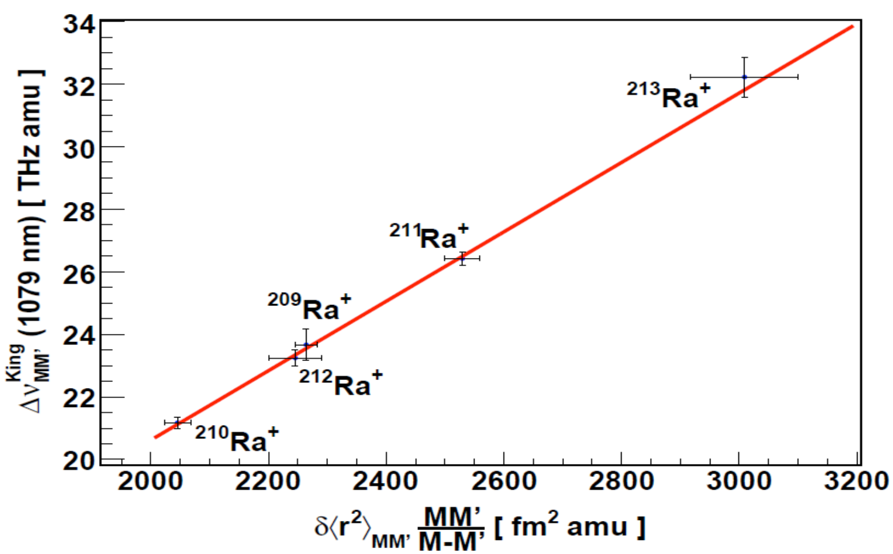
M. Nuñez Portela, et al., Appl. Phys. B, DOI:10.1007/s00340-013-5603-2 (2013)
O.O. Versolato, et al., Phys. Rev. A **82**, 010501(R) (2010)

Laser Spectroscopy in Ra^+ ions

$6d^2D_{3/2}$ HFS measurement







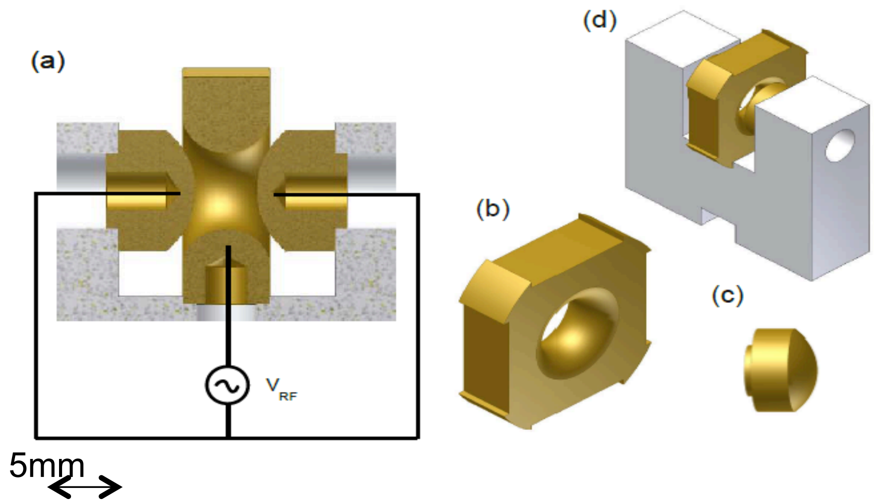
Probe of atomic wave functions at the origin

		This work (MHz)	Theory (MHz)
$^{211}Ra^+$	A	151(2)	155*, 150**
	B	103(6)	147(12)**
$^{209}Ra^+$	A	148(10)	153*, 148**
	B	104(38)	122(12)**

Probe of atomic theory & size and shape of the nucleus

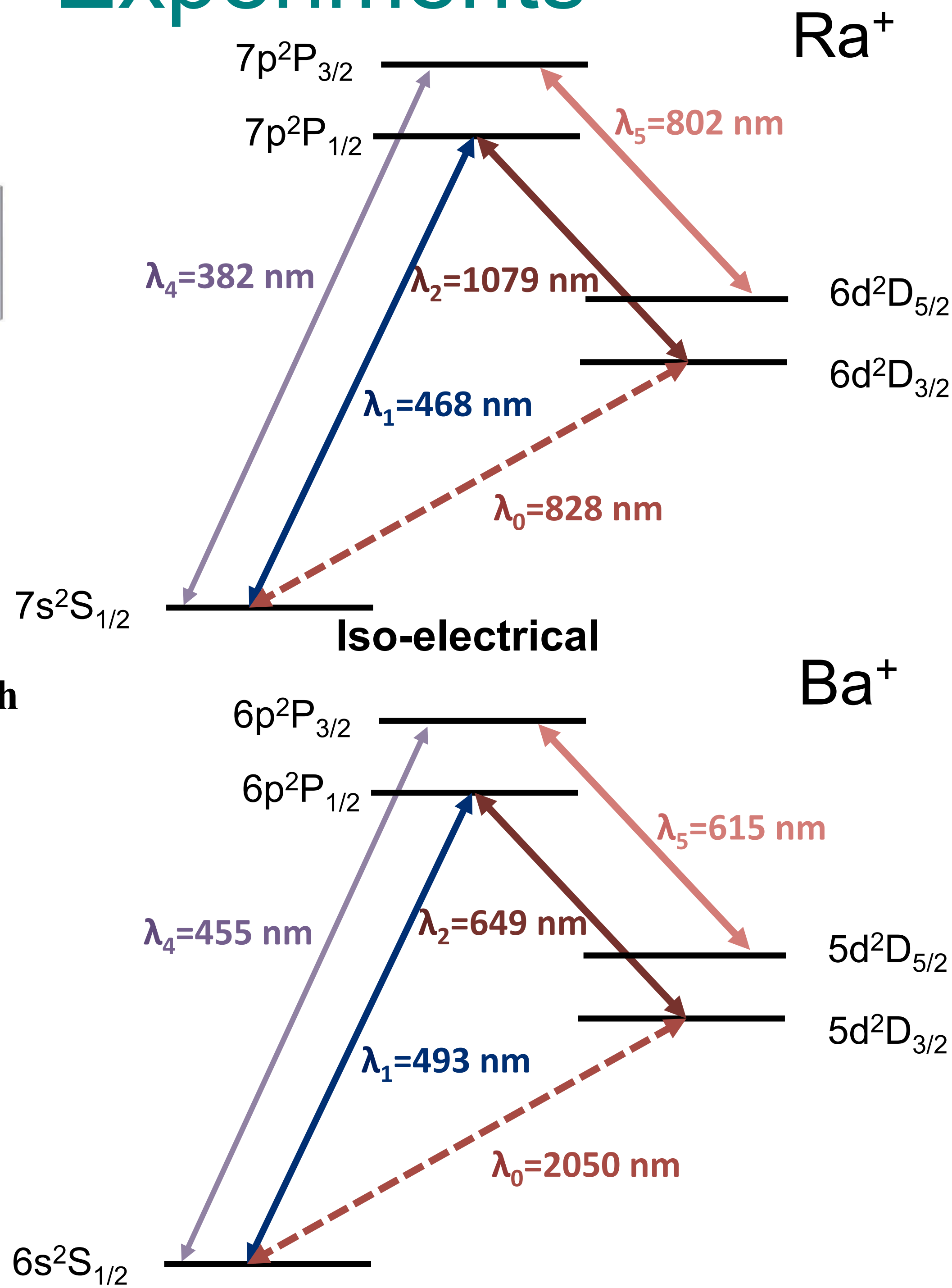
O. O Versolatao *et. al.*, Phys. Lett. A **375** (2011) 3130-3133
G. S. Giri *et al*. Phys. Rev. A **84**, 020503(R) (2011)
*L. W. Wansbeek, *et al.*, Phys. Rev. A **78**, 050501(R) (2008)
B.K. Sahoo *et al.* Phys. Rev. A, **76 (2007)

Single Ra^+ Experiments

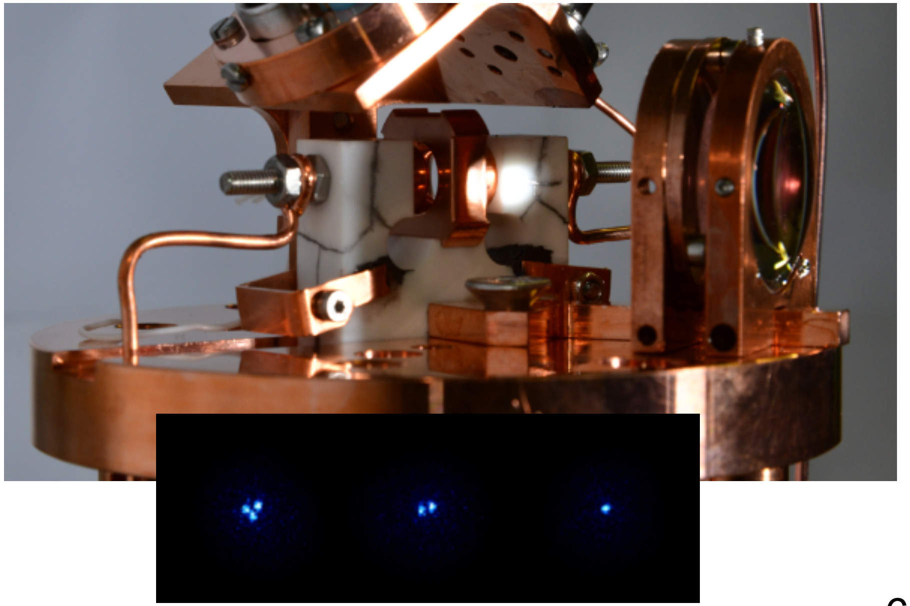


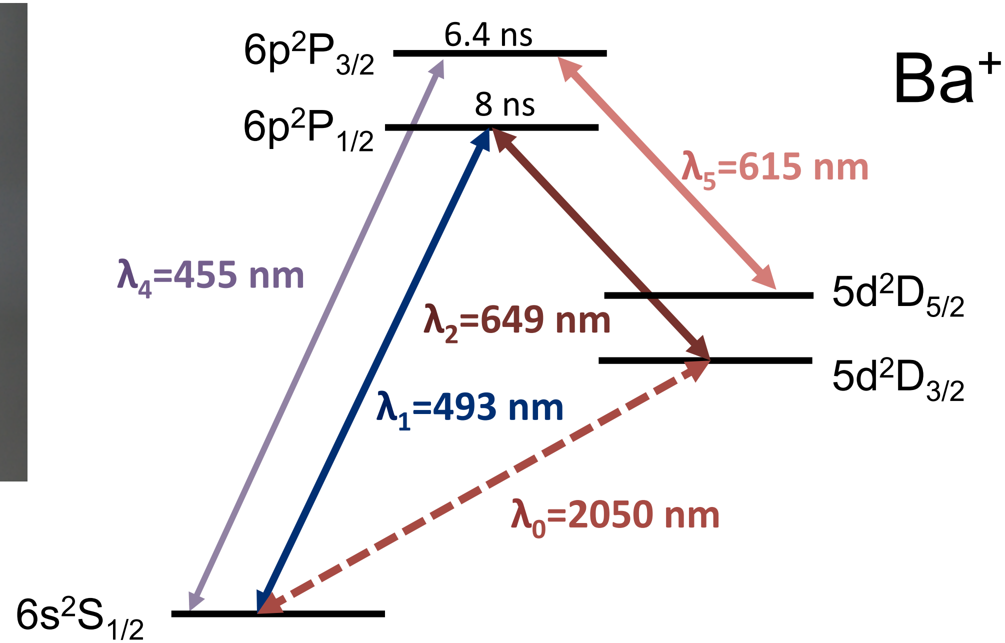
Hyperbolic Paul Trap

- localize one ion within one wavelength
- large volume
- hyperbolic shape
- localization major issue
- Ra^+ trapping
- All diode lasers



Ba^+ Experiment I: Lifetime $D_{5/2}$





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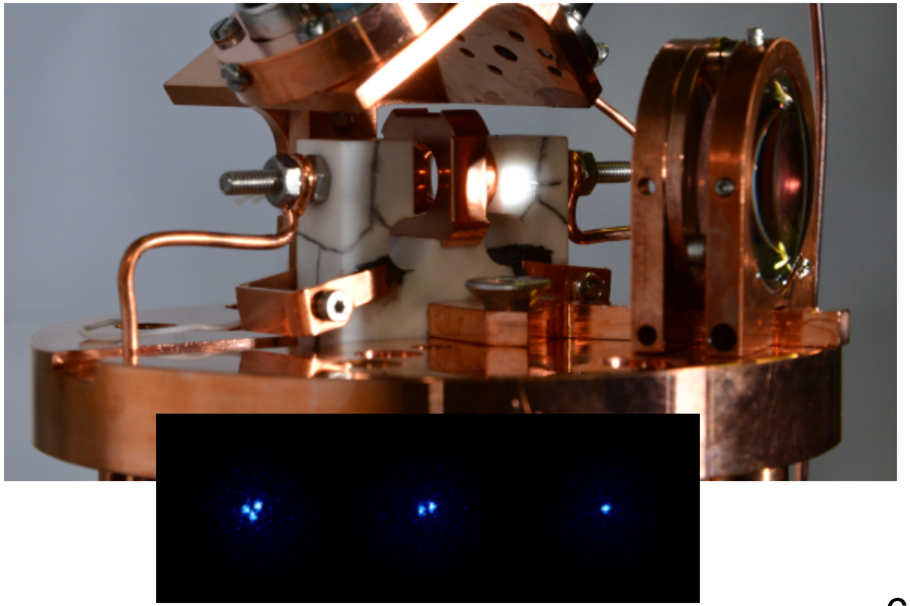

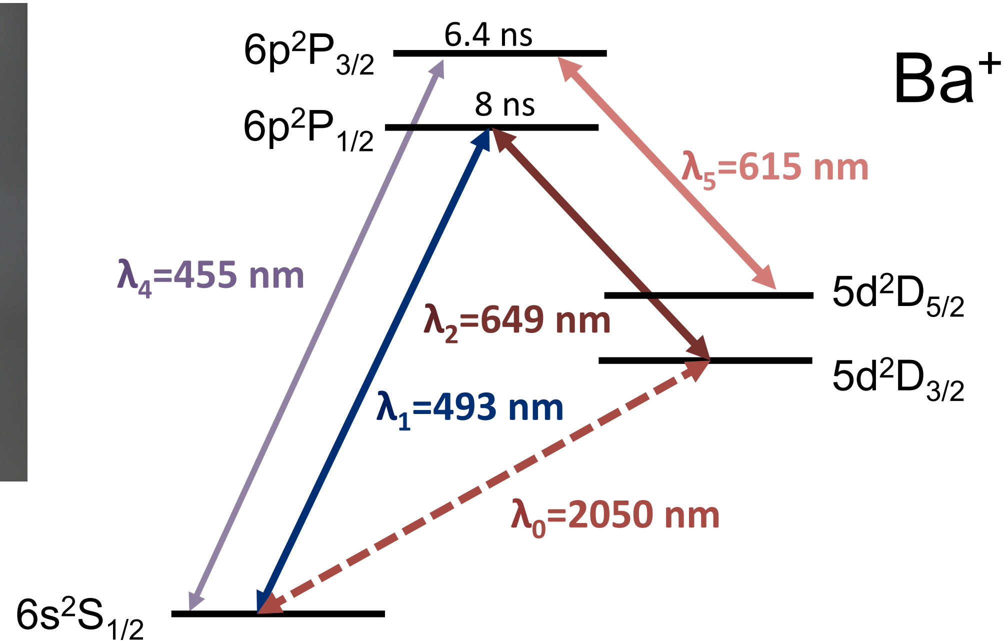

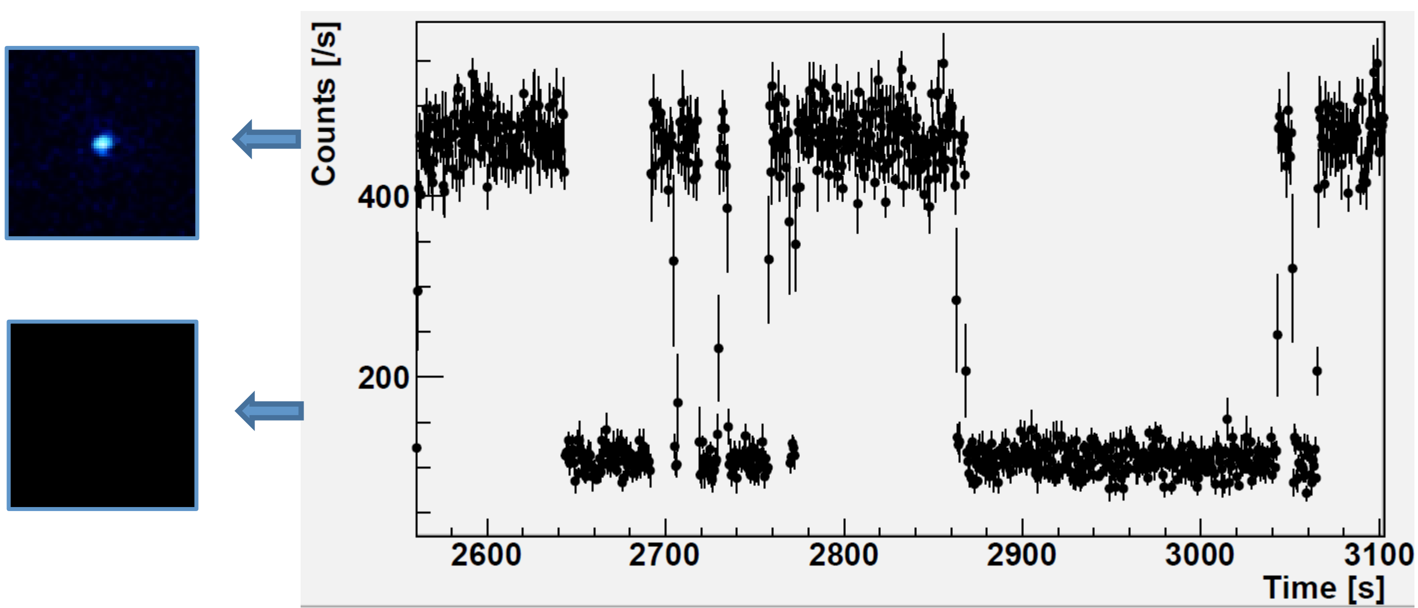

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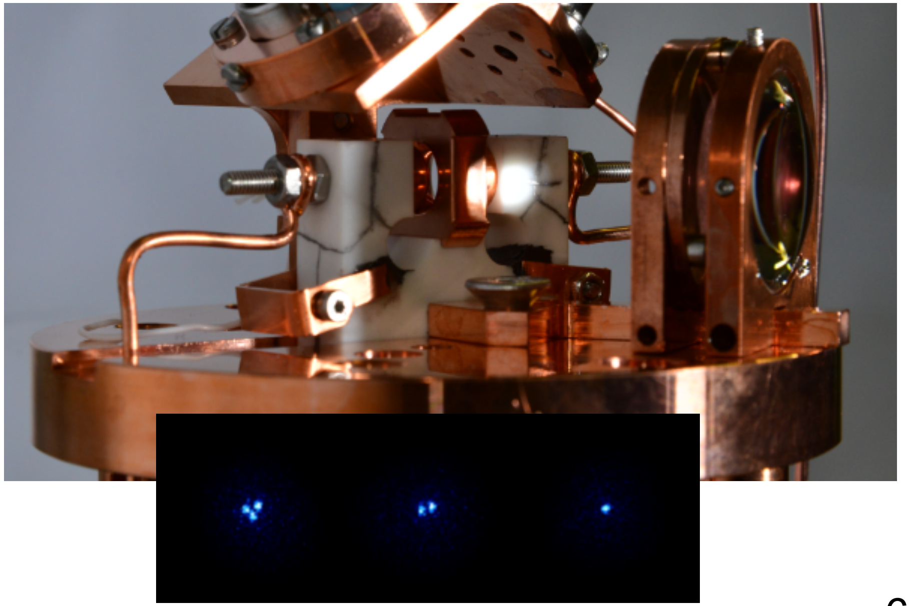
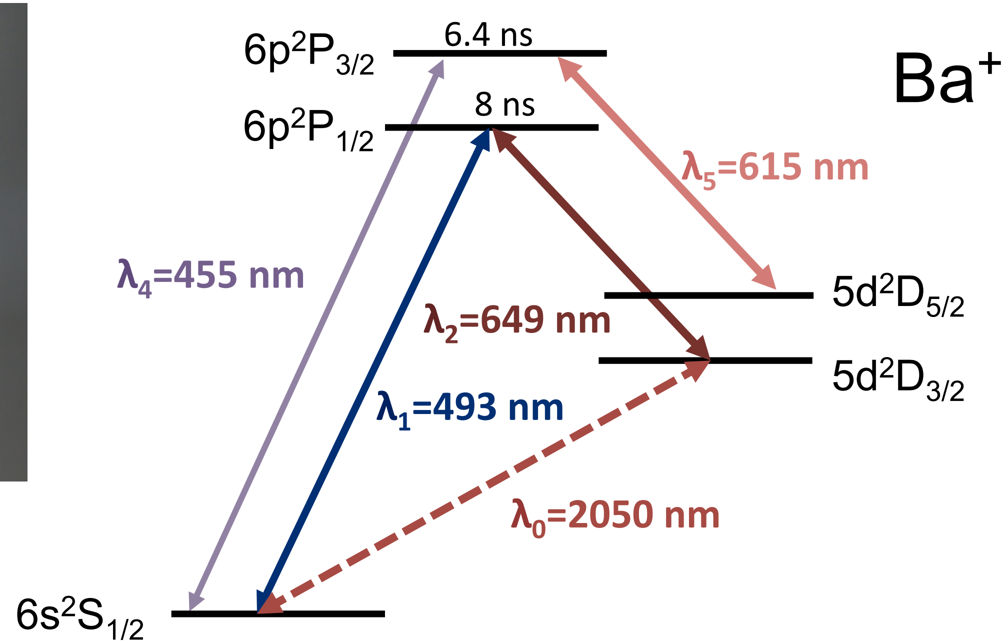
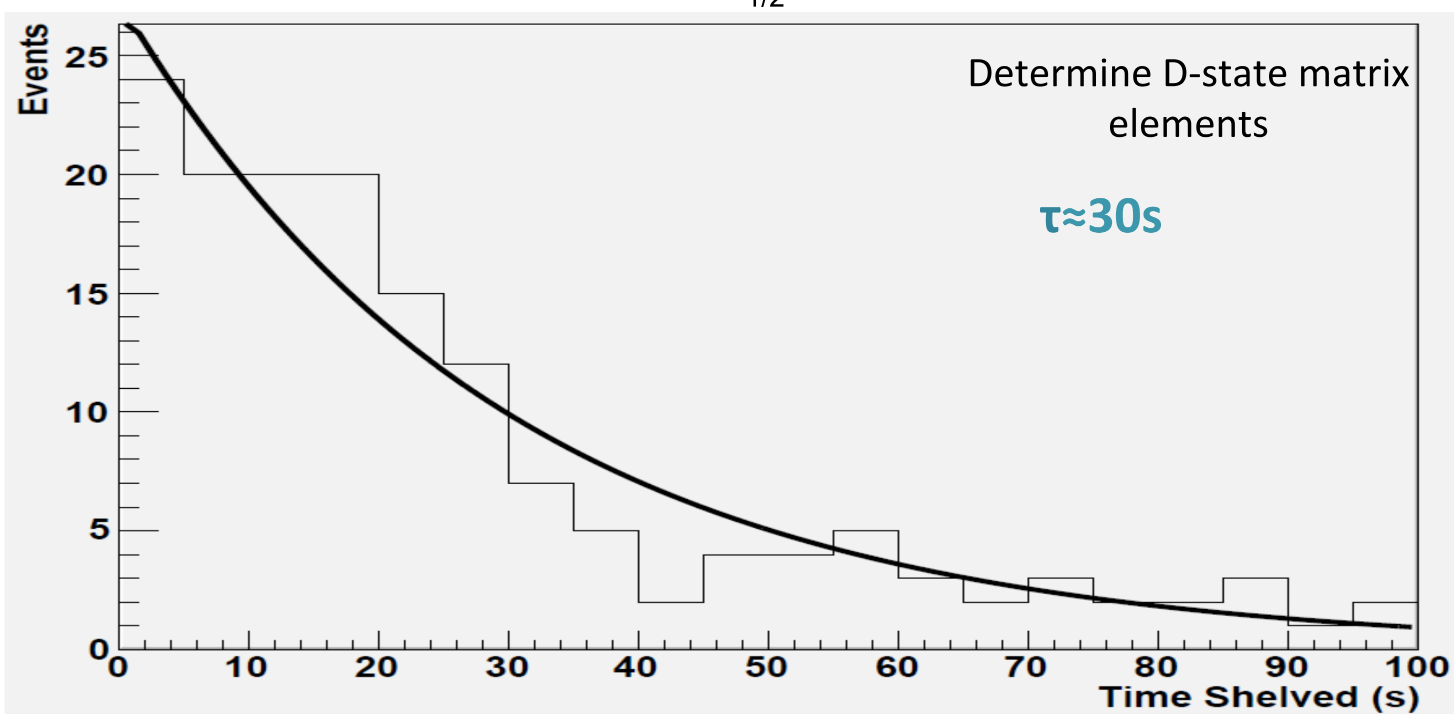


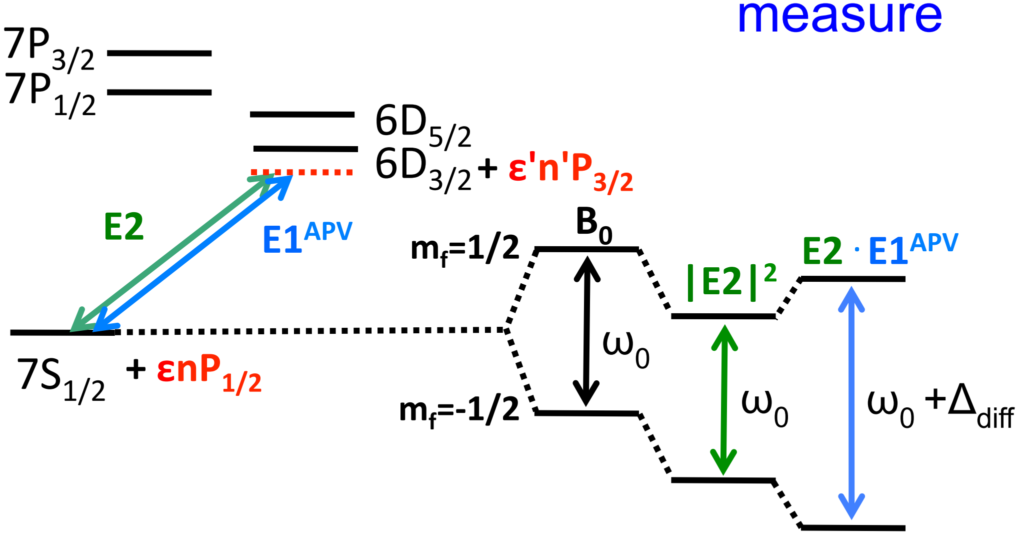


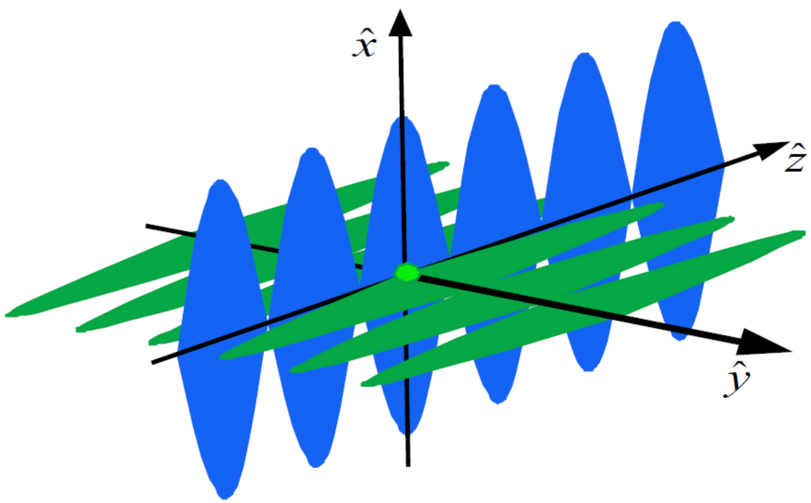


Ba+ Experiment II:Light Shift

$$E1_{APV} = kQ_W$$

measure

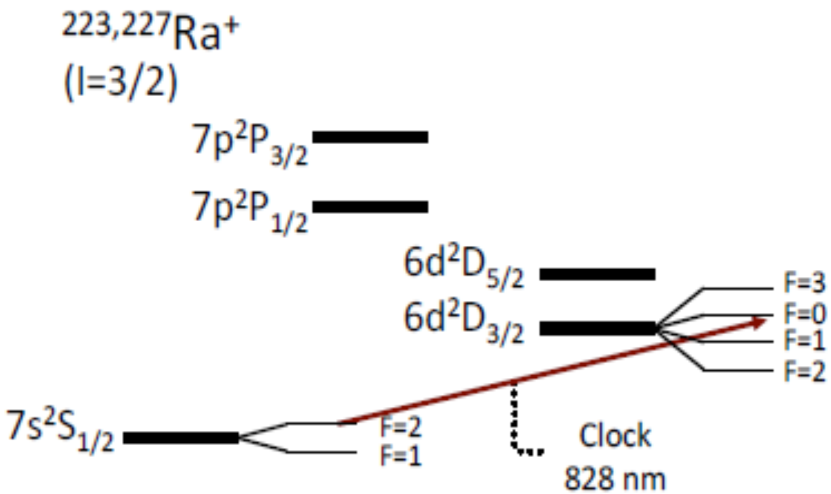




- Single ion localization < λ
- Cavity in vacuum
- Laser system: high power laser
- Work in progress with barium

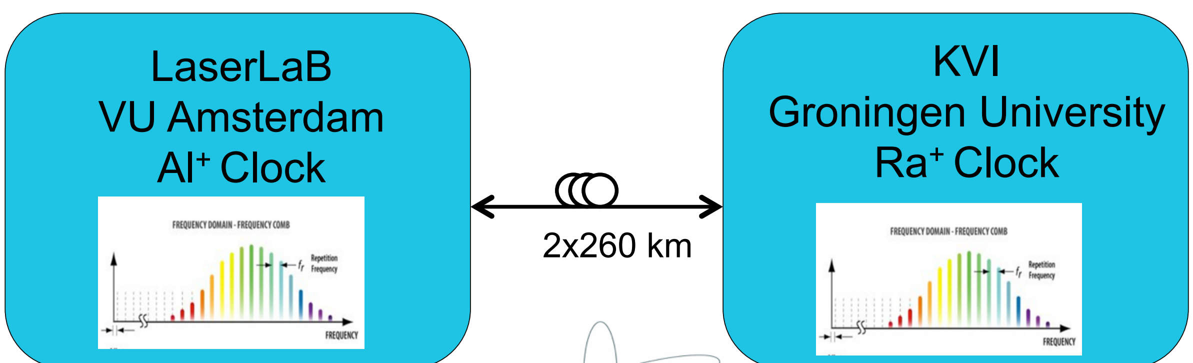
J. A. Sherman arXiv:0907.0459v1 (2009)

Ra^+ Ion Atomic Clock



- Narrow transition, ultra stable lasers
- Low sensitivity to external fields (for I=3/2)
- Time variation of fine structure constant
- Major systematics: Quadrupole shift

$\Delta\upsilon / \upsilon < 10^{-18}$
$^{223}Ra^+$ Atomic Clock



Program 2011-2017

Broken Mirrors and Drifting Constants

O. O. Versolato, et, al, Phys. Rev. A **83**, 043829 (2011)

Conclusions

$$E1_{\mathrm{APV}} = k Q_{\mathrm{W}}$$

measure

Infer weak charge

calculate atomic wavefunctions

✔ Ra Ions production
✔ laser spectrocopy of Ra Ions
✔ trap ions
✔ laser cooling of trapped ions
✔ single ion detection and spectroscopy
✔ localize ions
✔ parity violation measurement

In 1 day, a 5-fold improvement over Cs appears feasible!

The Crew & Acknowledgments

Experiment

- **Mayerlin Nuñez Portela**
- **Amita Mohanti**
- **Elwin Dijck**
- **Nivedya Valappol**
- **Andrew Grier**
- Hendrik Bekker
- Gouri Giri
- Oscar Versolato
- Joost van den Berg
- **Lorenz Willmann**
- **Klaus Jungmann**

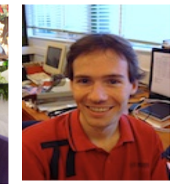












Theory

- Lotje Wansbeek
- **Sophie Schlesser**
- Lex Dieperink
- **Bijaya Sahoo**
- **Rob Timmermans**

Technicians


Professors




International collaborators

- B. P. Das (India)
- N. E. Fortson (USA)

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- FOM Programes 114, 125
- FOM open competition
- NWO Toptalent grant
- NWO Veni fellowship

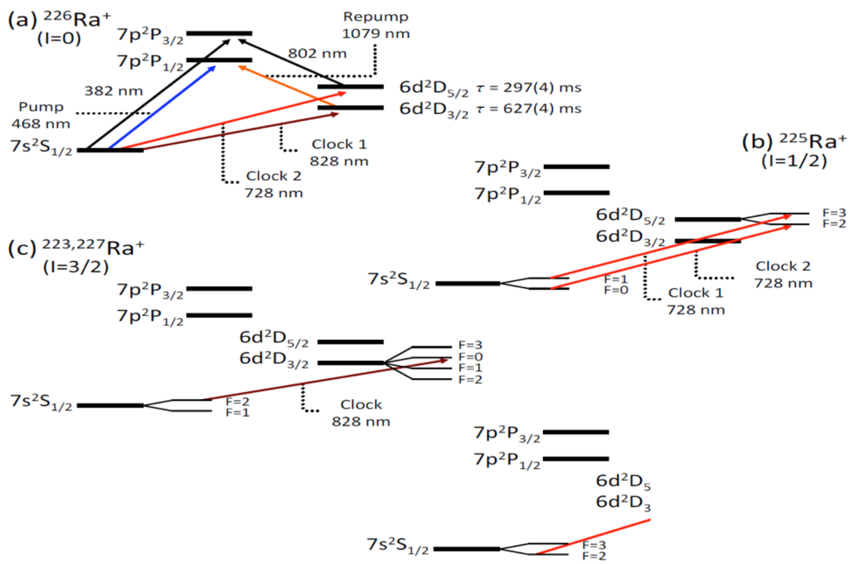
NWO Netherlands Organisation for Scientific Research

university of groningen

FOM

THANK YOU

Ra+ ion Atomic Clock

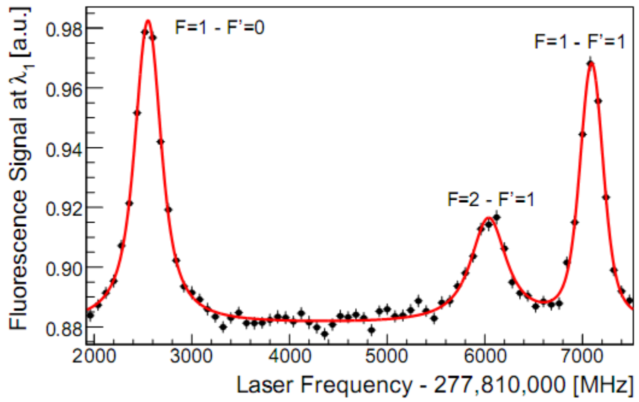


- Narrow transition, ultra stable lasers
- Low sensitivity to external fields (for I=3/2)
- Time variation of fine structure constant

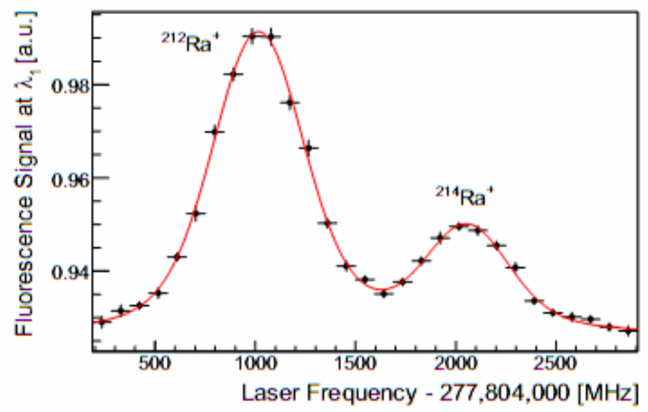
	Major systematics: Quadrupole shift	**dα/dt relative strength**	**Atomic Parity Violation**	**Laser wavelength**
^{27}Al	$< 10^{-17}$ *[Itano]*	1 *[Dzuba, Flambaum]*	Z small	deep UV
^{199}Hg	10^{-17} *[Itano]*	- 400 *[Dzuba, Flambaum]*	atomic theory difficult to treat	deep UV
^{213}Ra	$< 10^{-18}$ *[Sahoo]*	+ 450 *[Dzuba]*	relativististic effects structure calculable	Visible/IR diode lasers

Ra^{+} measurements

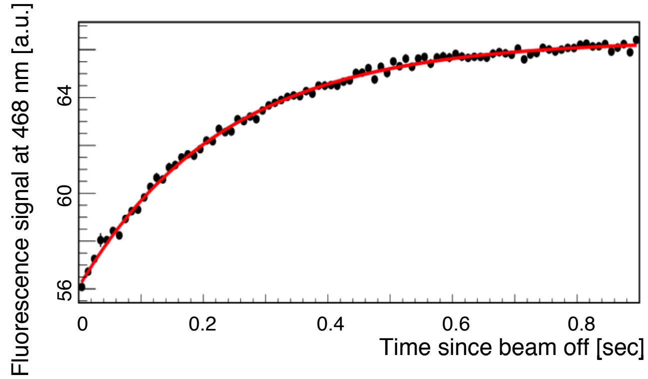
Probe of atomic wave functions at the origin



Probe of atomic theory & size and shape of the nucleus



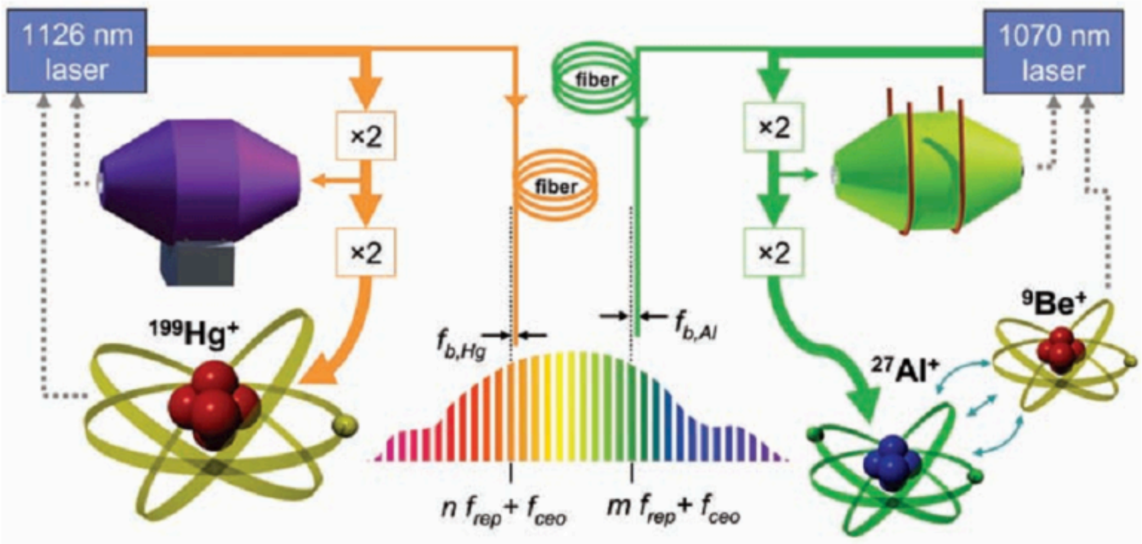
Probe of S-D E2 matrix element



agreement with theory at % level (Safronova, Sahoo Timmermans et al.)

Sensitivity to ά

$$\frac{\dot{\nu}}{\nu} = A\frac{\dot{\alpha}}{\alpha}$$



Ion	A	Ref.	Transition
Sr+	0.43	[15]	$^2S_{1/2}$-$^2D_{5/2}$
Hg+	−2.94	[15]	$^2S_{1/2}$-$^2D_{5/2}$
In+	0.18	[18]	S_0-P_0
Al+	0.008	[18]	S_0-P_0
Ba+	2.52	[15]	$6^2S_{1/2}$-$5^2D_{3/2}$
Ba+	2.44	[15]	$6^2S_{1/2}$-$5^2D_{5/2}$
Ra+	3.00	[15]	$7^2S_{1/2}$-$6^2D_{3/2}$
Ra+	2.77	[15]	$7^2S_{1/2}$-$6^2D_{5/2}$

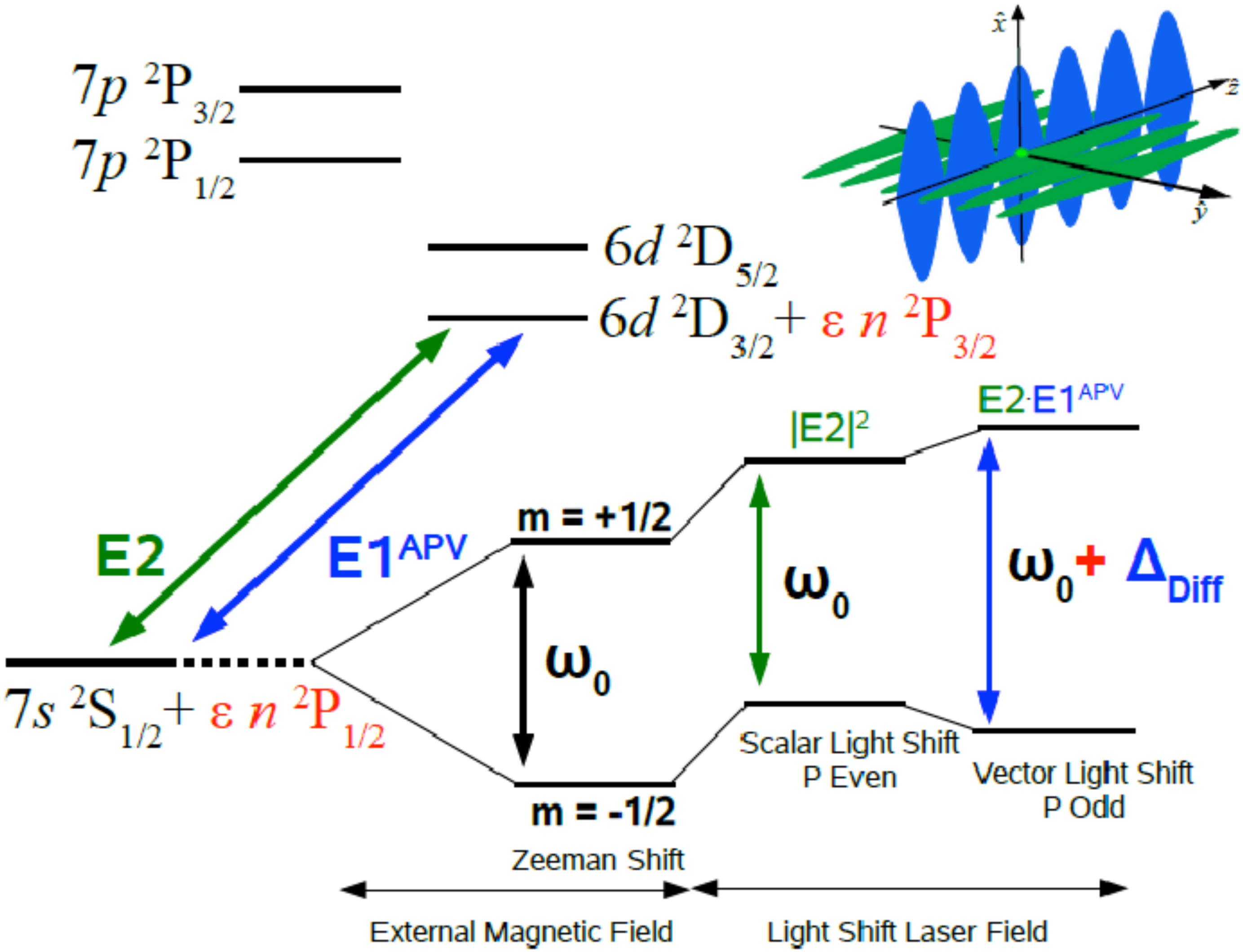
Accuracy of single ion Experiment

$$\frac{\mathcal{E}^{\mathrm{PNC}}}{\delta\mathcal{E}^{\mathrm{PNC}}} \cong \frac{\mathcal{E}^{\mathrm{PNC}} E_0}{\hbar} f \sqrt{N \tau t}$$

E_0 = Light electric field amplitude, τ = Coherence time
N = Number of ions = 1, t = Time of observation

	Coherence Time	Projected Accuracy	Measurement Time
Ba^+	80 sec	0.2%	1.1 day
Ra^+	0.6 sec	0.2%	1.4 day

→ 10 days for 5 fold improvement over Cs



$7p\ ^2P_{3/2}$
$7p\ ^2P_{1/2}$
$6d\ ^2D_{5/2}$
$6d\ ^2D_{3/2} + \varepsilon\, n\ ^2P_{3/2}$
$\hat{x}$
$\hat{y}$
$\hat{z}$
E2
$E1^{APV}$
$7s\ ^2S_{1/2} + \varepsilon\, n\ ^2P_{1/2}$
m = +1/2
m = -1/2
ω_0
$|E2|^2$
ω_0
$E2 \cdot E1^{APV}$
$\omega_0 + \Delta_{Diff}$
Zeeman Shift
Scalar Light Shift
P Even
Vector Light Shift
P Odd
External Magnetic Field
Light Shift Laser Field