# Atomic Parity Violation in a single Ra ion

**5th International Symposium on Symmetries in Subatomic Physics (SSP2012)**

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# Test of Standard Model

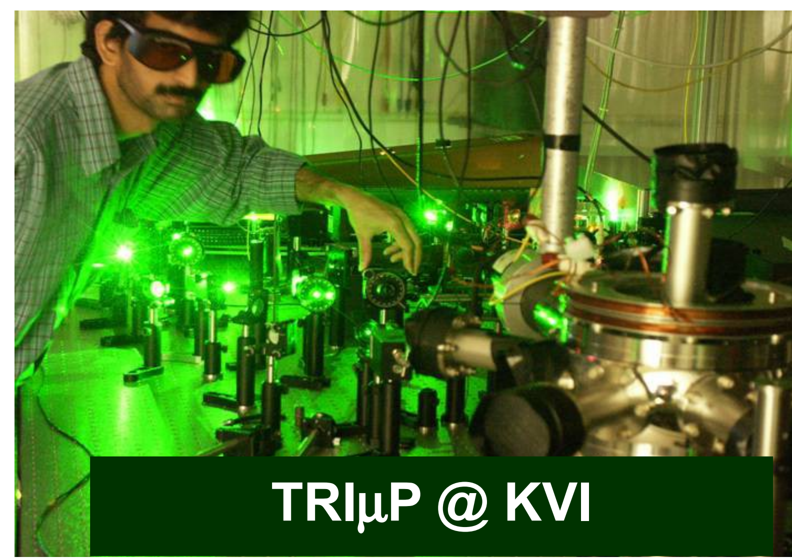
The Standard Model (SM) of particle physics is “incomplete” ⇒
searches for physics “beyond the SM” at two, complementary, fronts:

High energy collider experiments:
Direct observation of new particles


Search for a Higgs, SUSY, extra Z bosons

Complementary

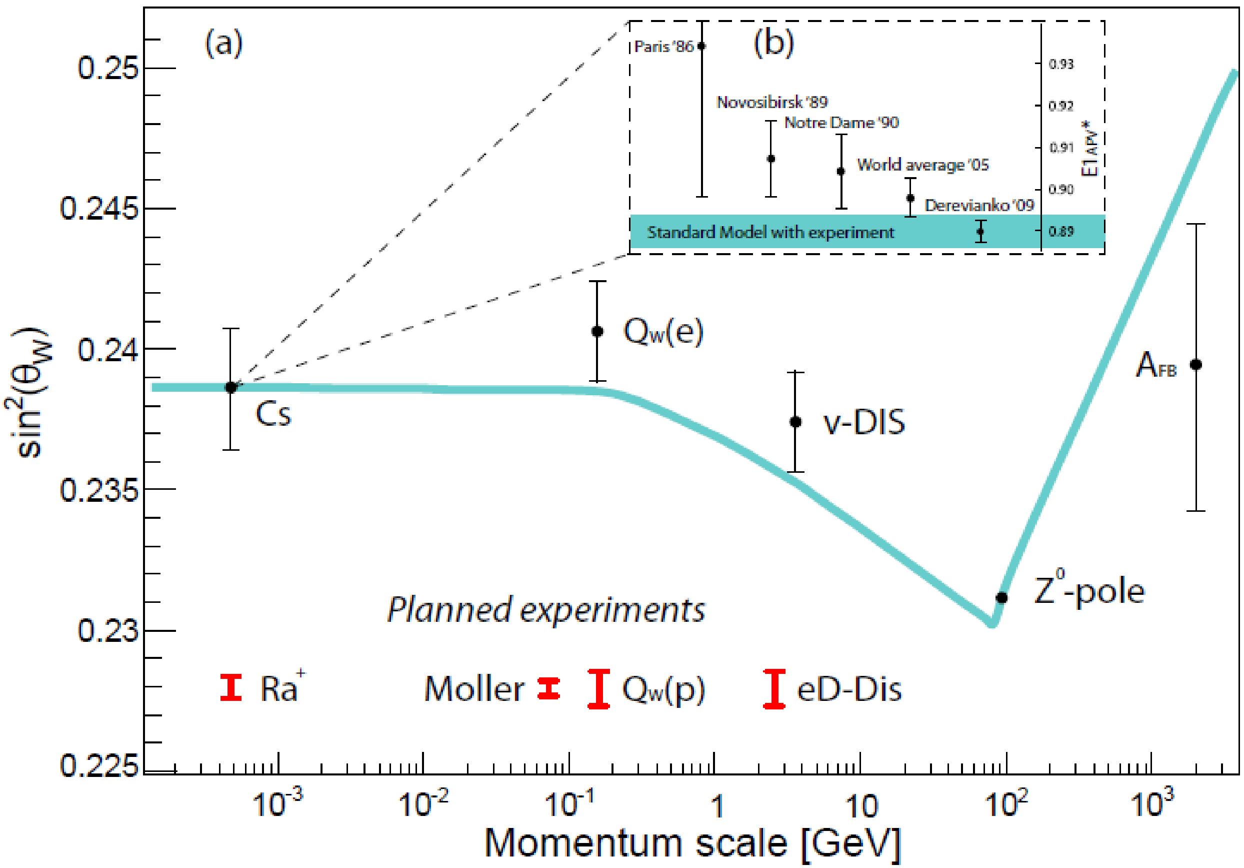
Low energy searches:
indirect, but with high precision




EDMs, unprecedent energy scale, Z' bosons

# Test of Standard Model

## Weak interaction

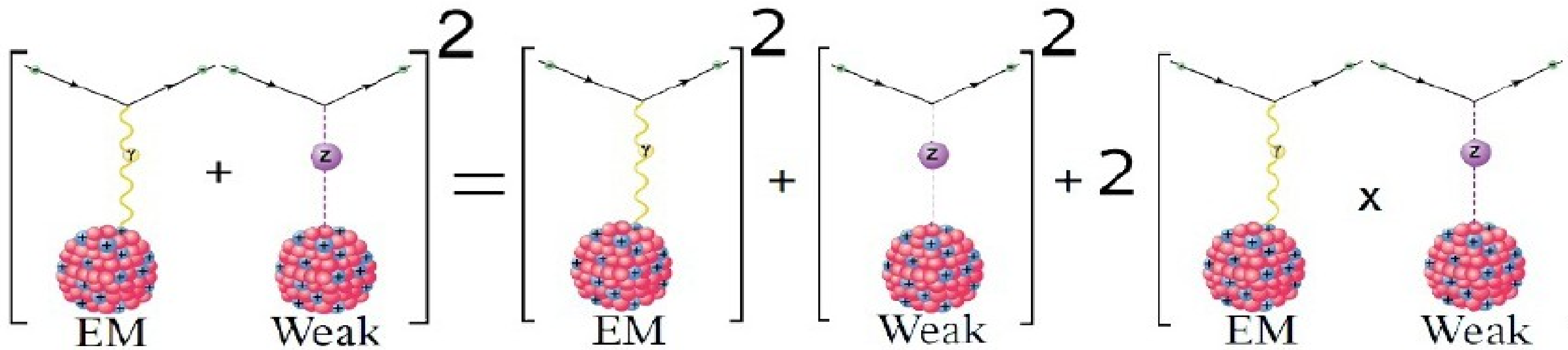



**$Q_W = -N + (1 - 4\sin^2\theta_W)Z$ + rad. corr. + "new physics"**

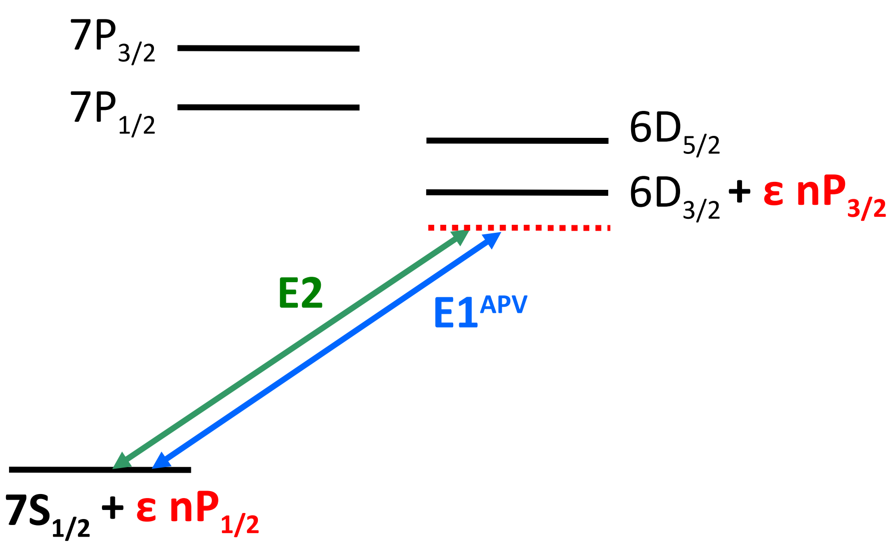
**Best limit on the mass of Z' from APV**

# Atomic Parity Violation (APV)

**Weak interaction violates parity**




**Atomic states acquire tiny admixture of opposite-parity states**



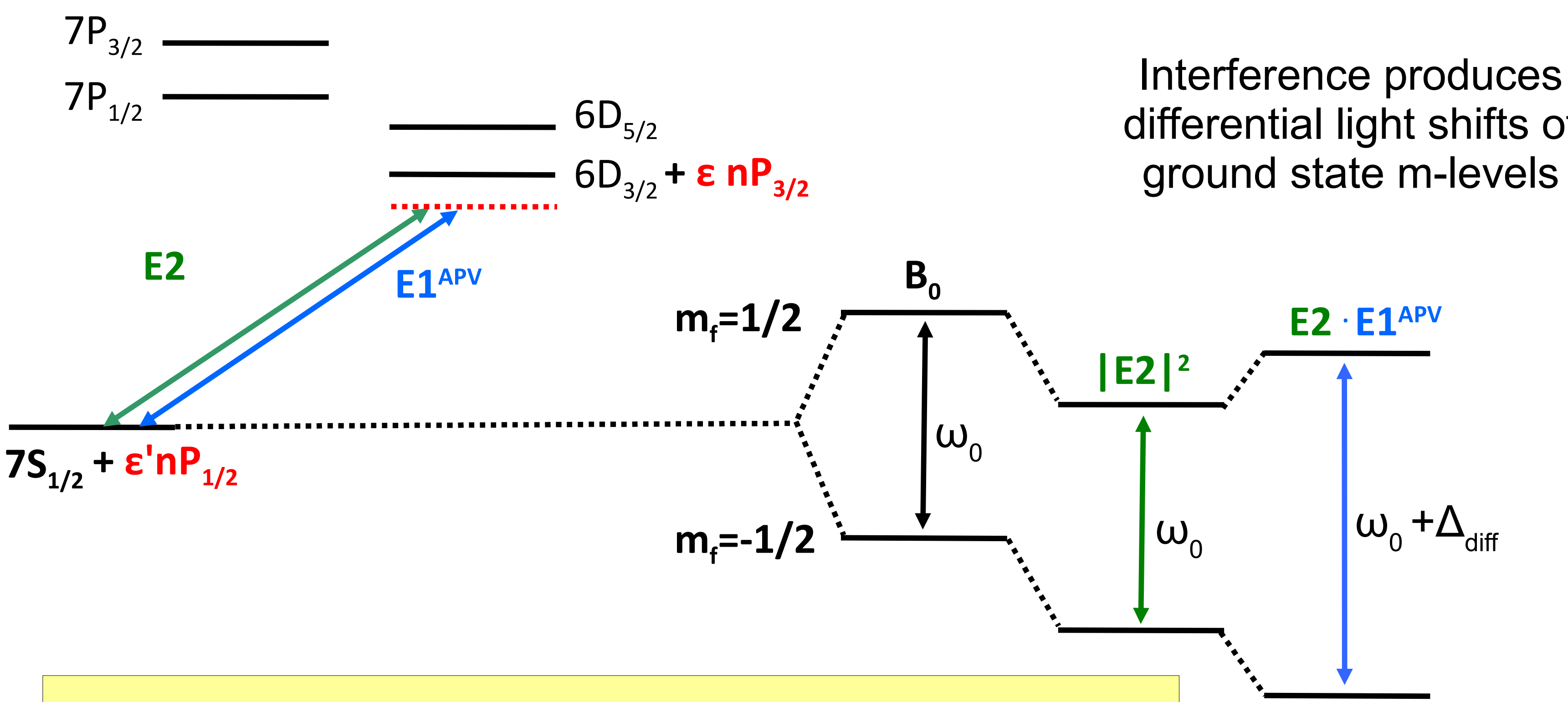

$$E1_{APV} = kQ_W$$

**Infer weak charge**

# Experiment principle

$$E1_{APV} = kQ_W$$

measure




**Localize single ion within one wavelength**
**Measure with RF spectroscopy and shelving**

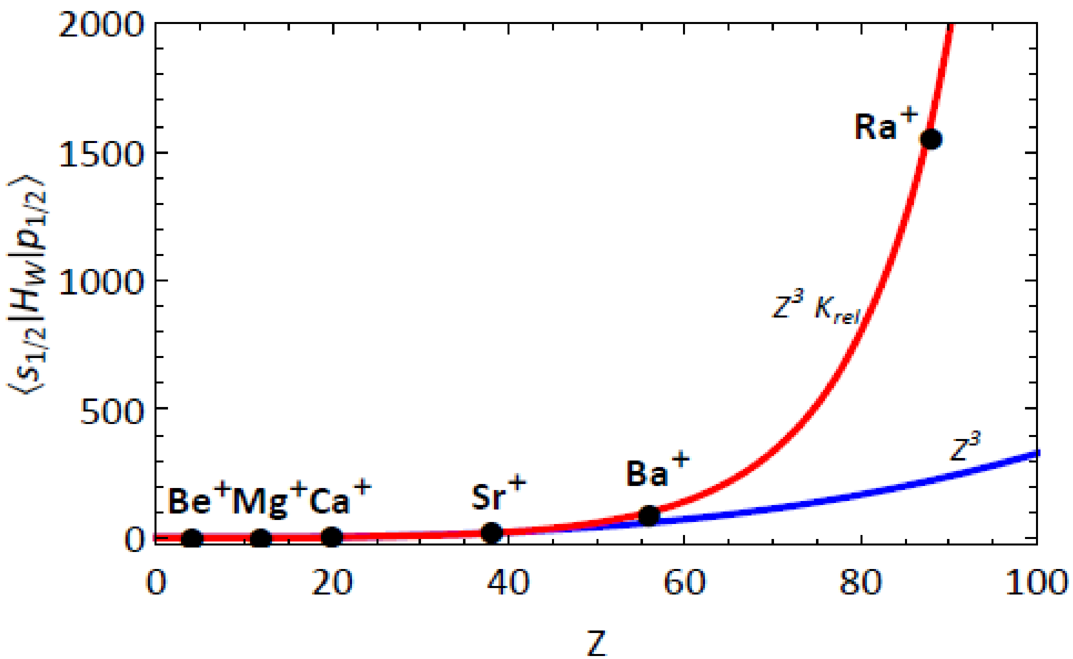
# Why Ra ions?

$$E1_{\text{APV}} = k\,Q_{\text{W}}$$

calculate atomic wavefunctions

| S-S | S-D |
|---|---|
| Cs | $Ba^{+}$ |
| 0.9 | 2.2 |
| Fr | **$Ra^{+}$** |
| 14.2 | **46.4** |

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




**$Ra^{+}$ is a superior APV candidate:**
In 1 day, a 5-fold improvement over Cs appears feasible!

$E1_{\text{APV}}$ effect in $Ra^{+}$ is 20 times larger than for $Ba^{+}$ and 50 times larger than for Cs!

Calculations:

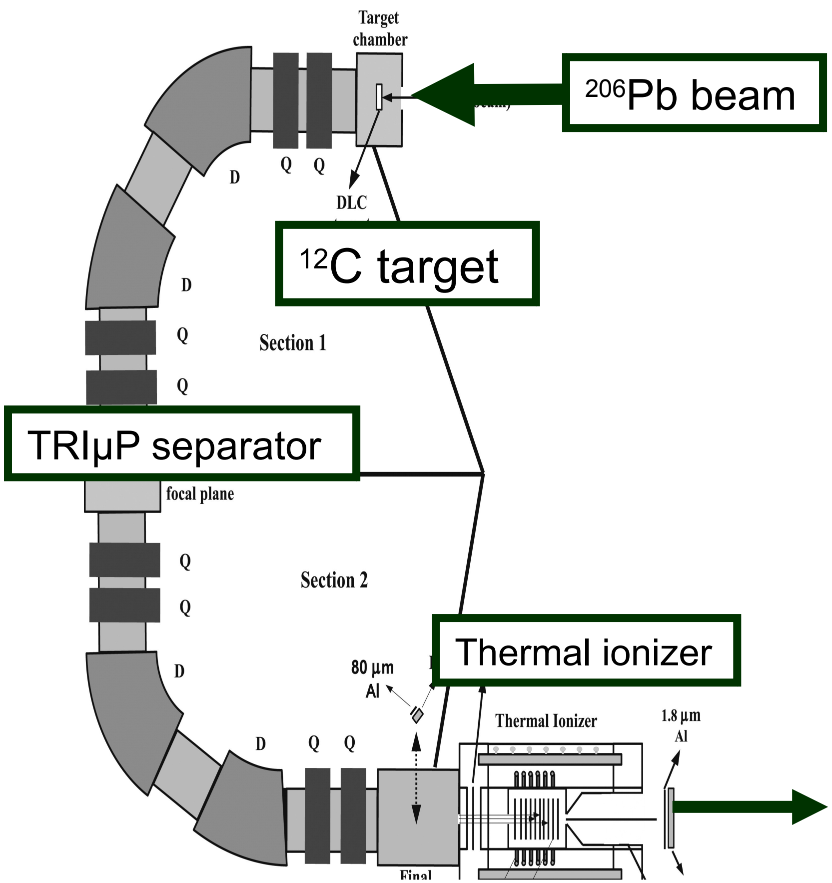
$k_{Ra}$ = 46.4(1.4) · $10^{-11}$ $iea_0/N$*

$k_{Cs}$ = 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)

# Ra ion Production: TRIμP Facility

$^{206}Pb + ^{12}C \rightarrow {}^{A}Ra + (218\text{-}A)\, n$




1m

To RFQ (Paul trap)
Rate after TI

$5\times10^{4}/s$

TRIμP@KVI (209–214)

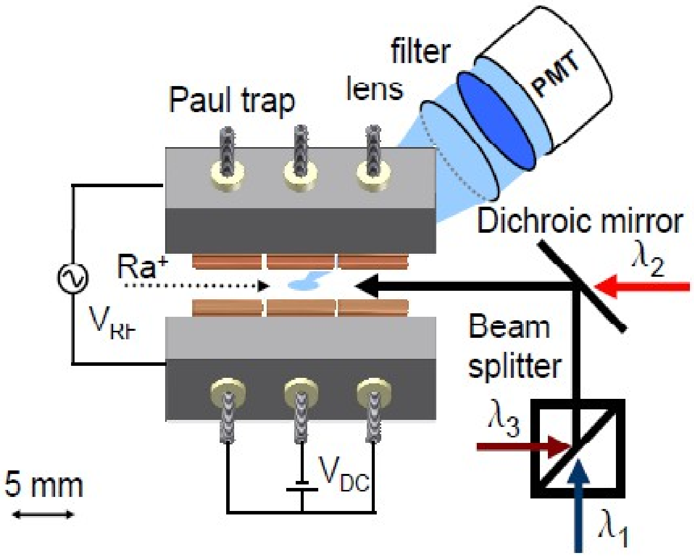
Sources or fragmentation (221–229)

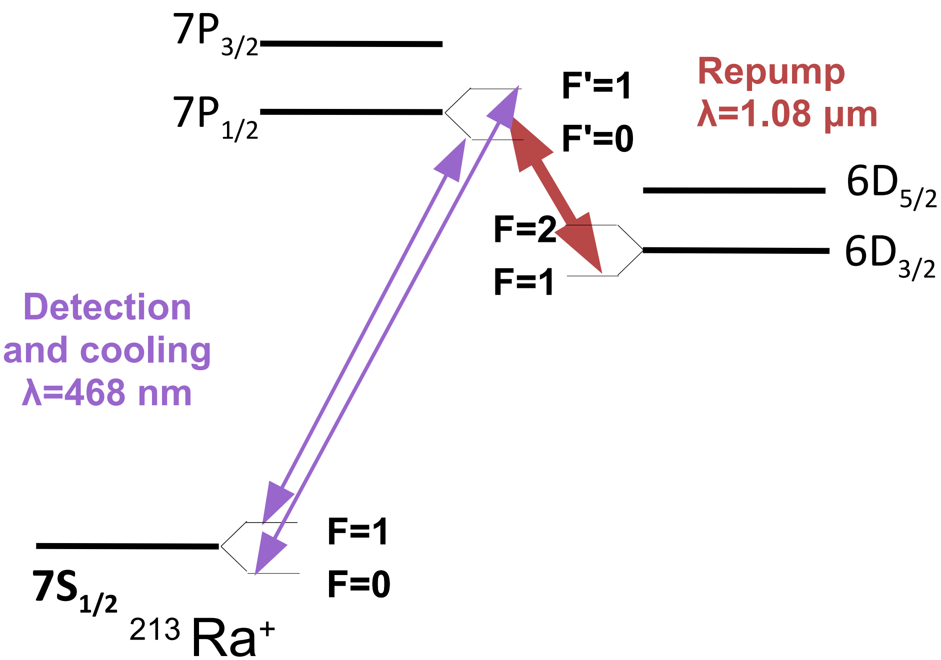
| | Lifetime | Spin |
|---|---|---|
| 209 | 4.6(2) s | 5/2 |
| 211 | 13(2) s | 1/2 |
| 212 | 13.0(2) s | |
| 213 | 2.74(6) m | 1/2 |
| 214 | 2.46(3) s | |
| 221 | 28.2 s | 5/2 |
| 223 | 11.43(5) d | 3/2 |
| 224 | 3.6319(23) d | |
| 225 | 14.9(2) d | 1/2 |
| 226 | 1600 y | |
| 227 | 42.2(5) m | 3/2 |
| 229 | 4.0(2) m | 5/2 |

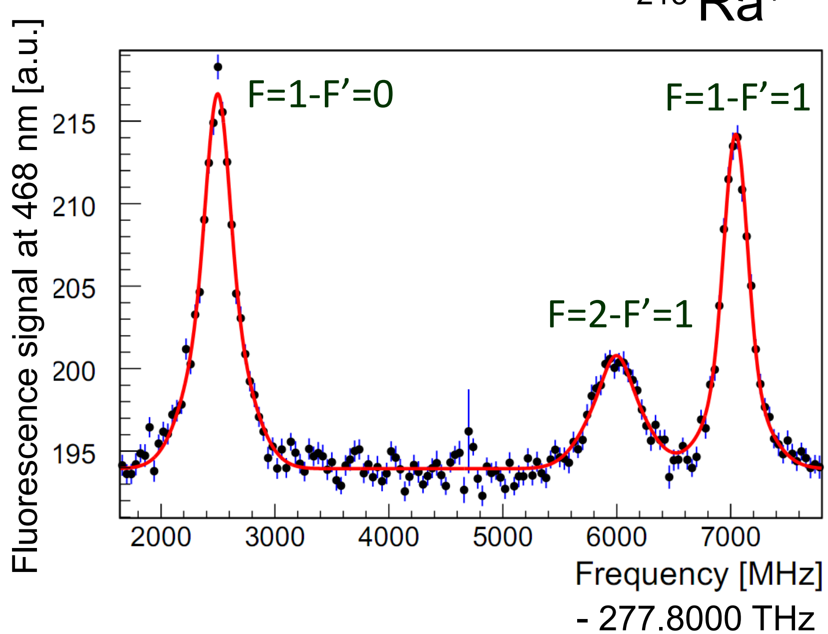
ΔN < 12 (213 ↔ 225)

# Laser Spectroscopy in Ra ions

## HFS measurement



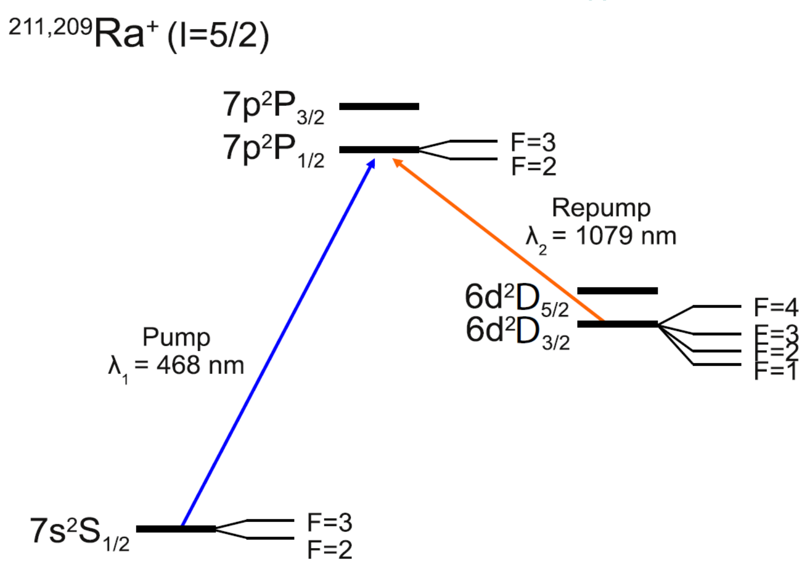



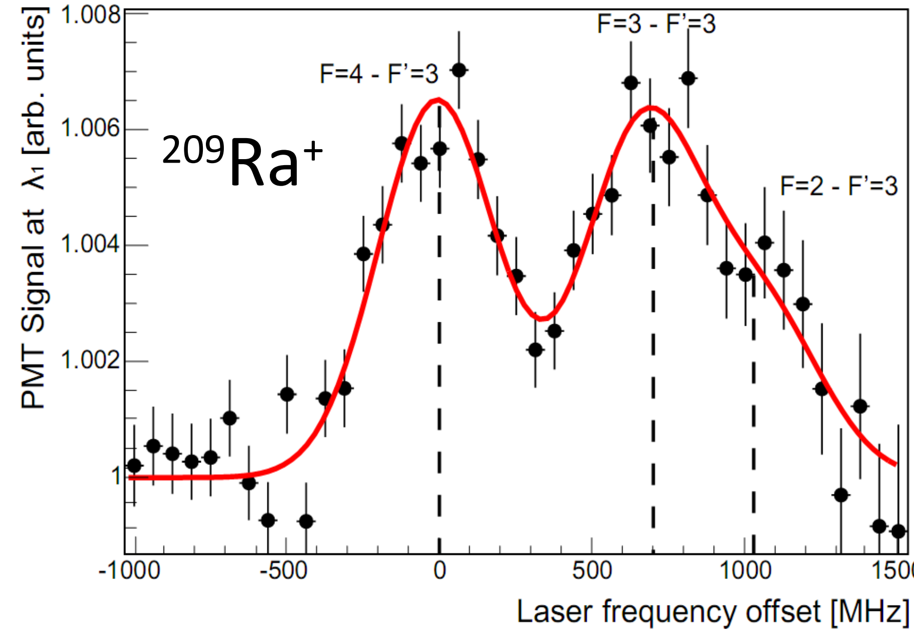



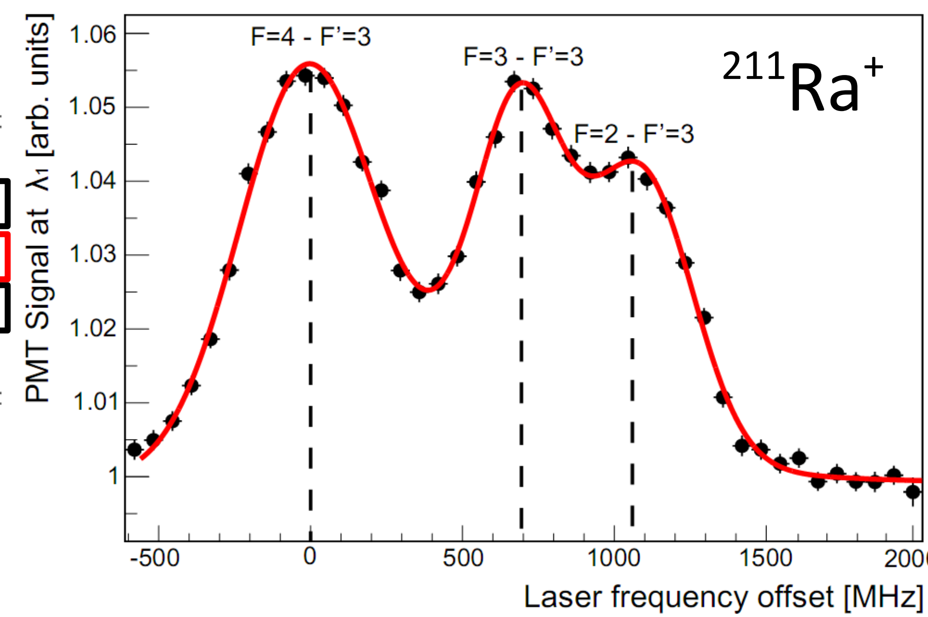

O.O. Versolato, G.S. Giri, et al., Phys. Rev. A **82**, 010501(R) (2010)

# Laser Spectroscopy in Ra ions

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



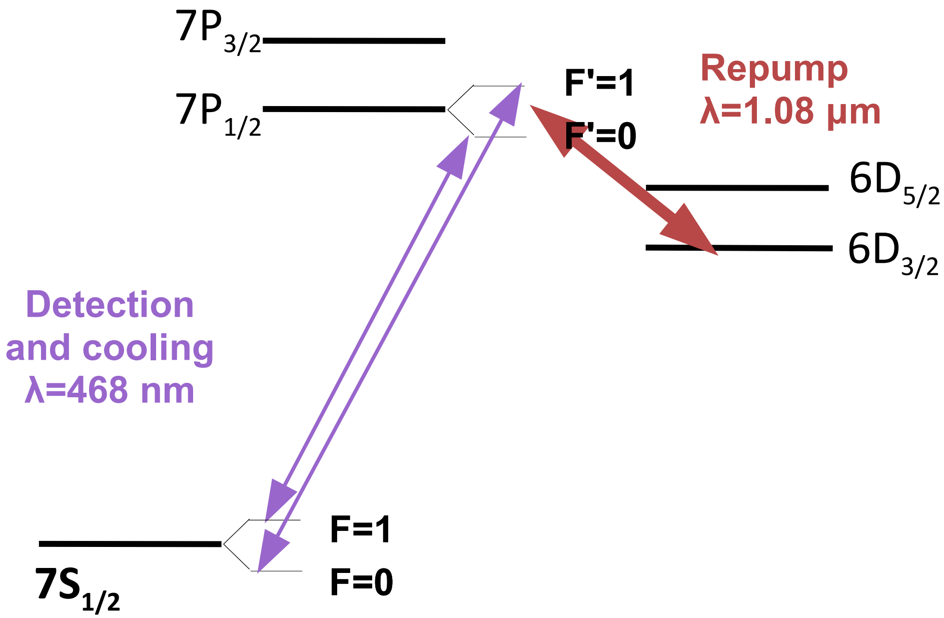



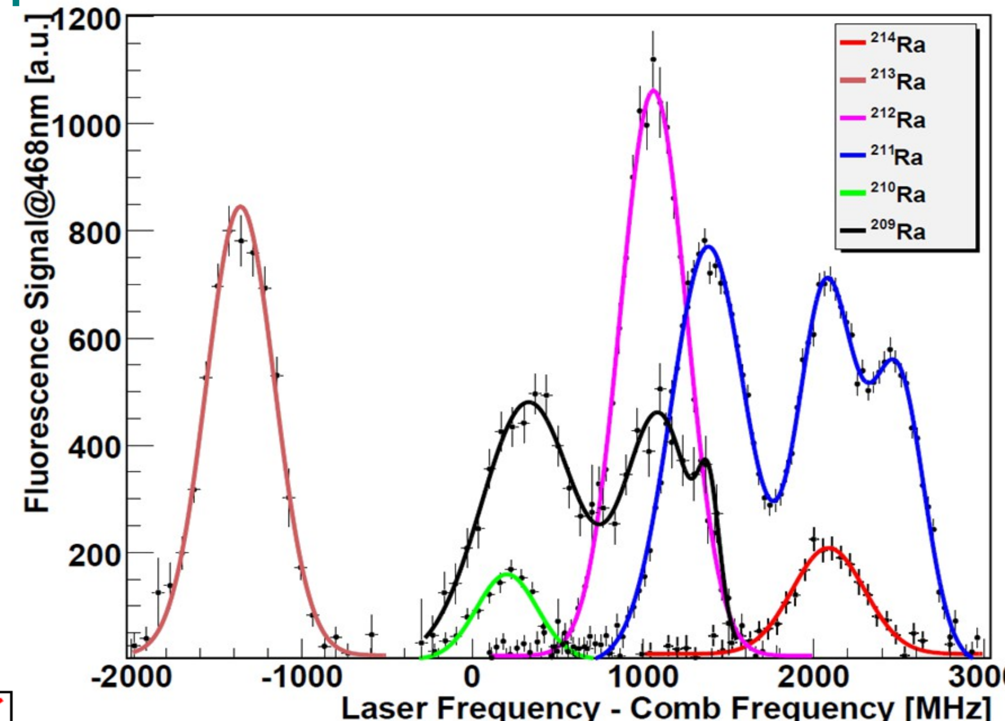

| | | This work | Theory |
|---|---|---|---|
| $^{211}Ra^+$ | A | 151(2) | 155* [4], 150* [10],155* [16] |
| | B | 103(6) | 147(12)** [10] |
| $^{209}Ra^+$ | A | 148(10) | 153* [4], 148* [10], 153* [16] |
| | B | 104(38) | 122(12)** [10] |

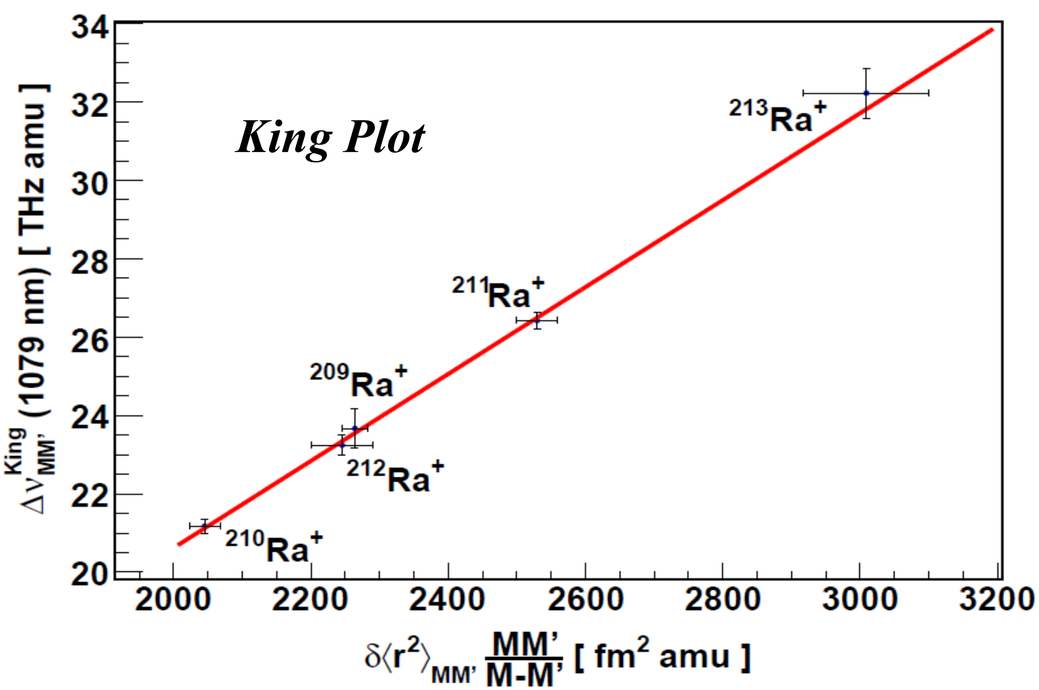
**~ 3,5 σ**


O. O Versolatao et. al., Phys. Lett. A375 (2011) 3130-3133
G. S. Giri et al. Phys. Rev. A 84, 020503(R) (2011)
[10] B.K. Sahoo *et al.* Phys. Rev. A, 76 (2007)

# Laser Spectroscopy in Ra ions:
## Isotope Shift



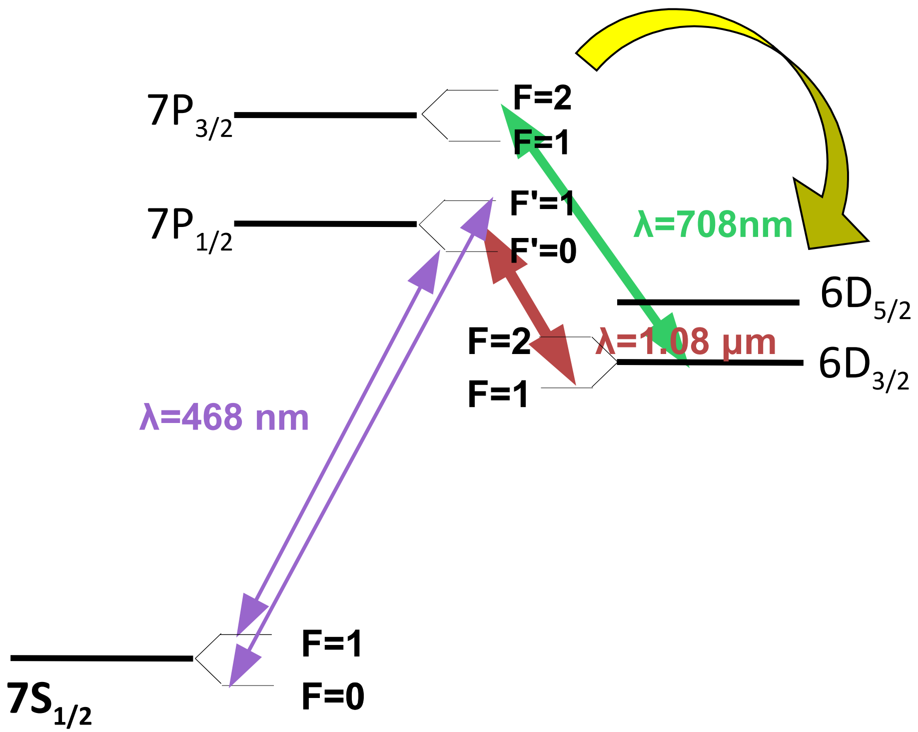

*Comparison of different transitions*

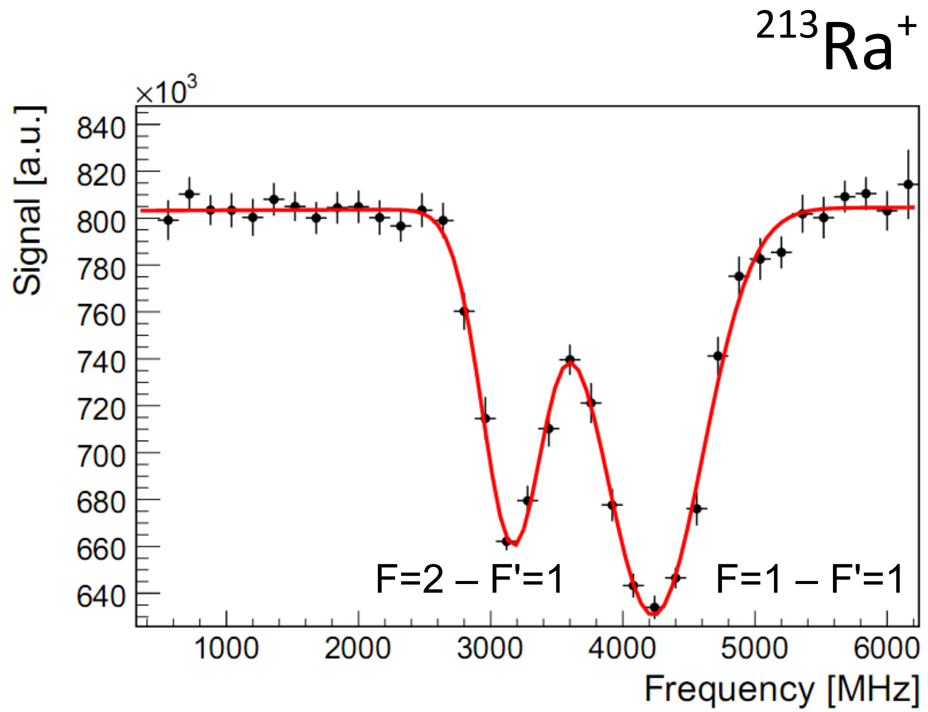
*⇒ Good agreement with atomic theory on few % level*

*⇒ Atomic theory understood rather well at present level of accuracy*

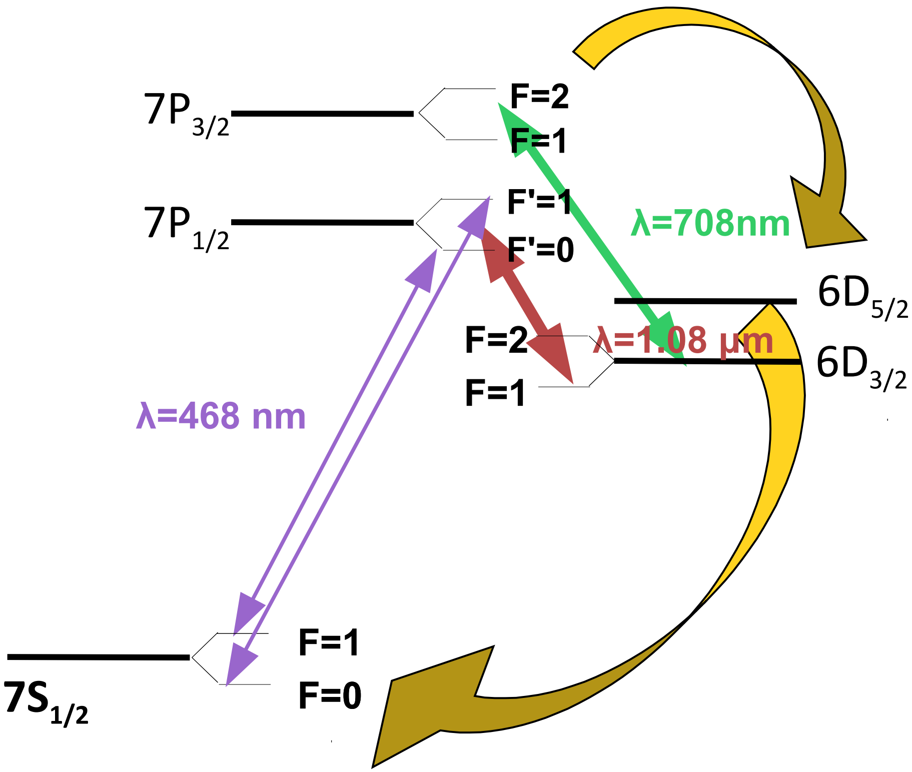
O. O Versolatao et. al., Phys. Lett. A375 (2011) 3130–3133
G. S. Giri et al. Phys. Rev. A 84, 020503(R) (2011)

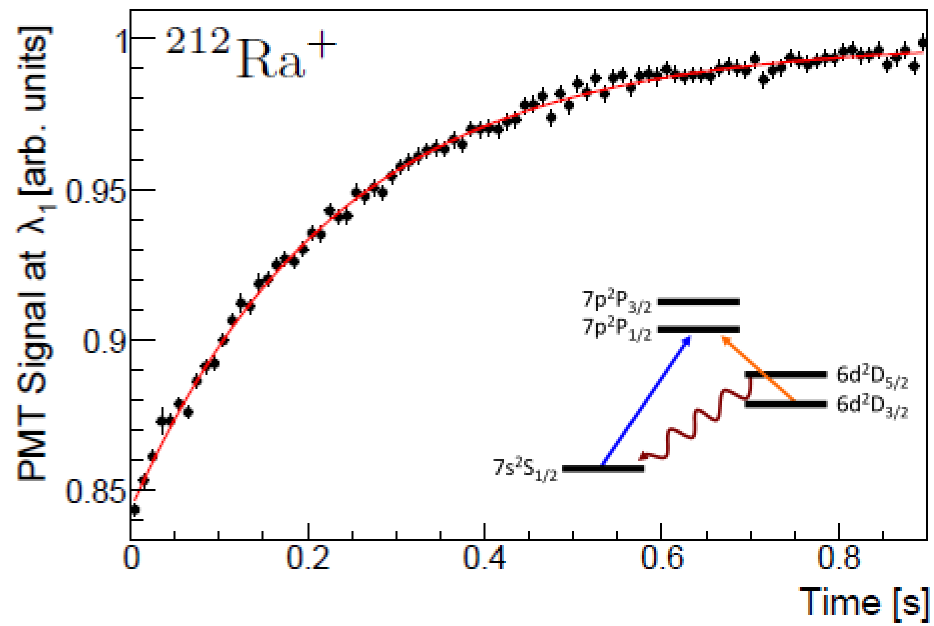
# Laser Spectroscopy in Ra ions:
## Shelving



# Laser Spectroscopy in Ra ions:
## Lifetime of the $6^2D_{5/2}$ state

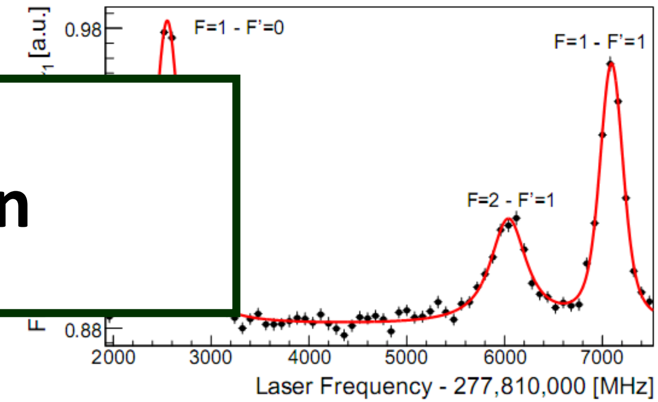


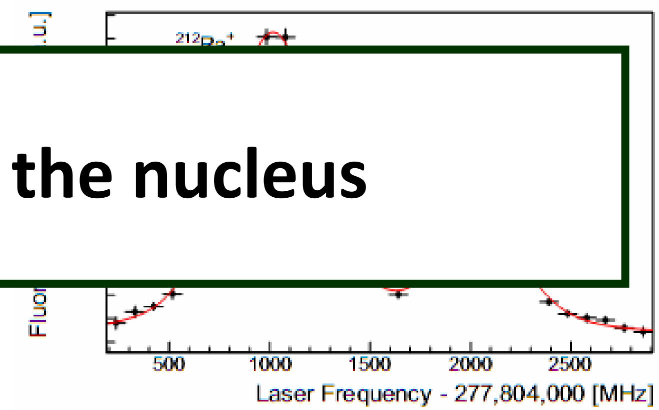

| Experiment1 | **Lower limit**[1] | Theory[2] | Theory[3] |
|---|---|---|---|
| | **232(4) s** | 297(4) s | 303(4)s |


1. O.O. Versolato et al., Phys. Rev A, (2010)
2. B. K. Sahoo et al., Phys. Rev. A 76, 040504(R) (2007).
3. R. Pal et al., Phys. Rev. A 79, 062505 (2009).

# $Ra^+$ Measurements




**Probe of atomic wave functions at the origin**



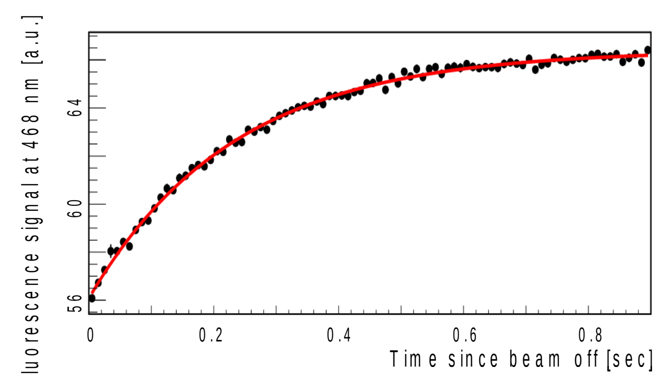

**Probe of atomic theory & size and shape of the nucleus**

– $6^2D_{3/2}$ - $7^2P_{1/2}$ and

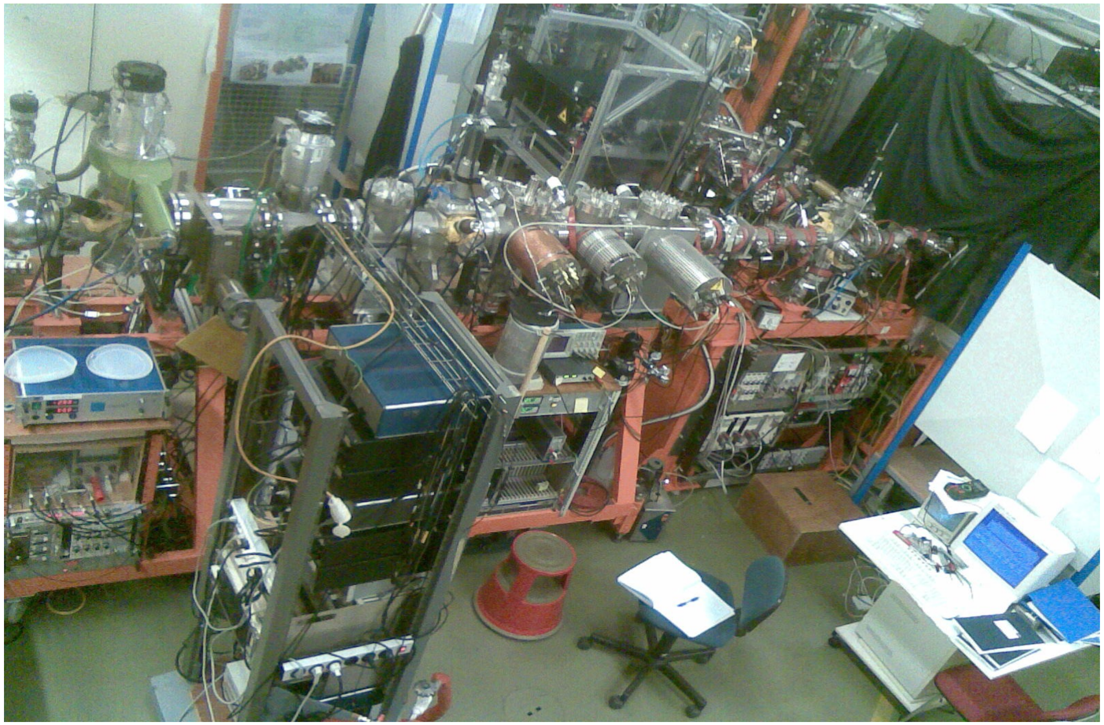
– $6^2D_{3/2}$ - $7^2P_{3/2}$ transitions in $^{212, 213, 214}Ra^+$

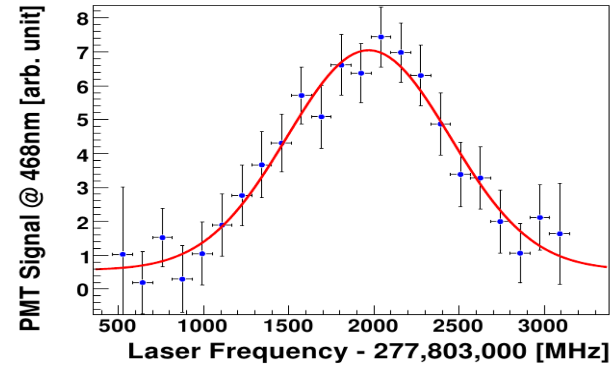
**Probe of S-D E2 matrix element**

of the $6^2D_{5/2}$ state

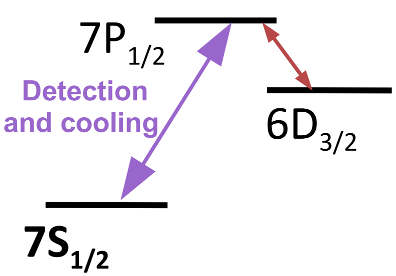


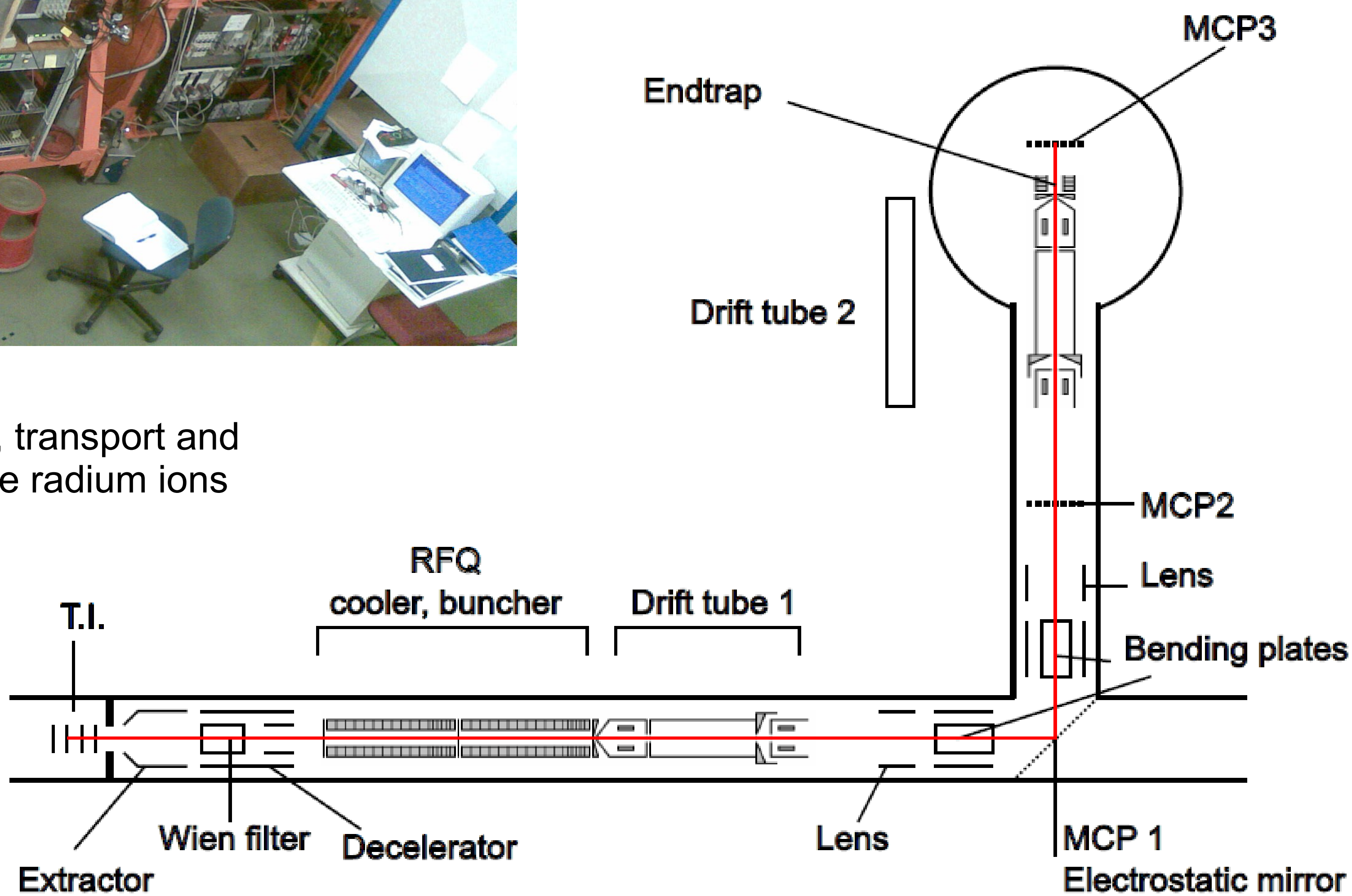
# Single $Ra^+$ :online experiments



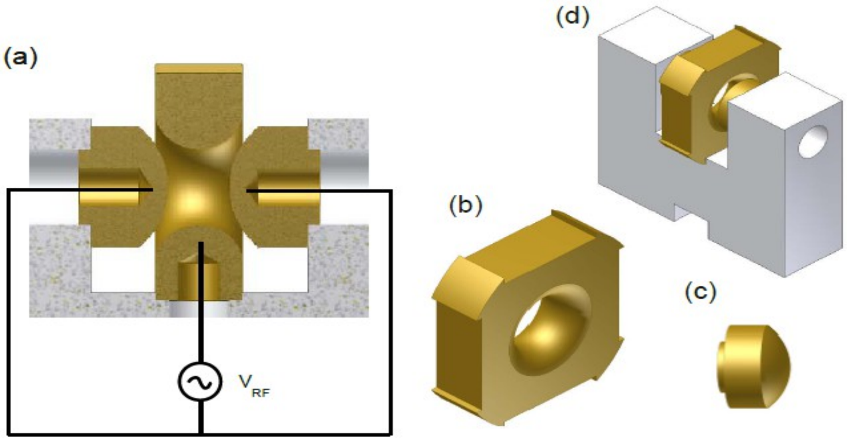



deceleration, transport and
capture of the radium ions



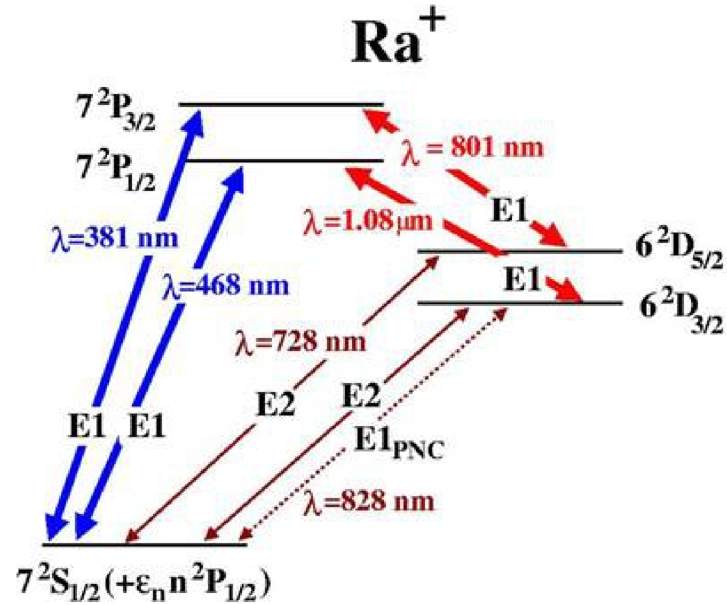



# Single $Ra^+$ : off line experiments

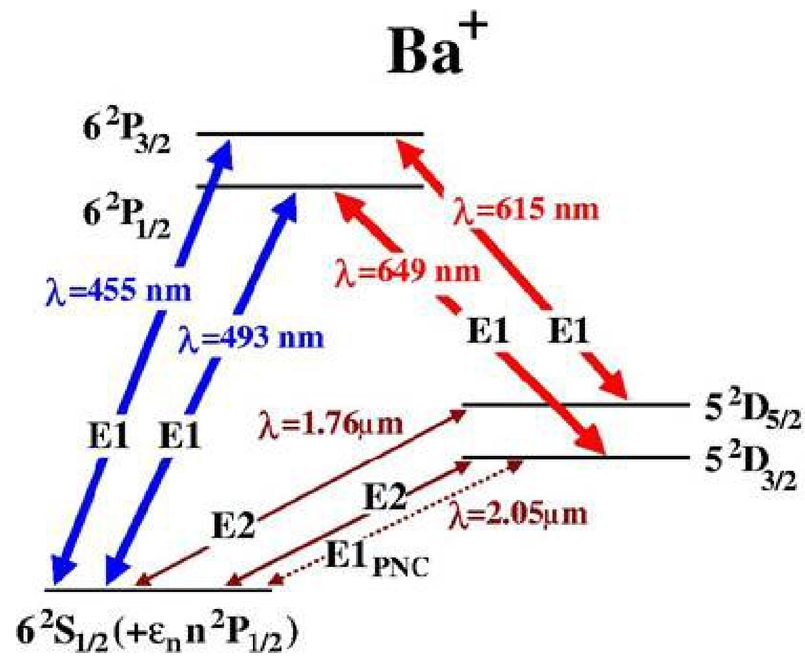



Hyperbolic Paul Trap

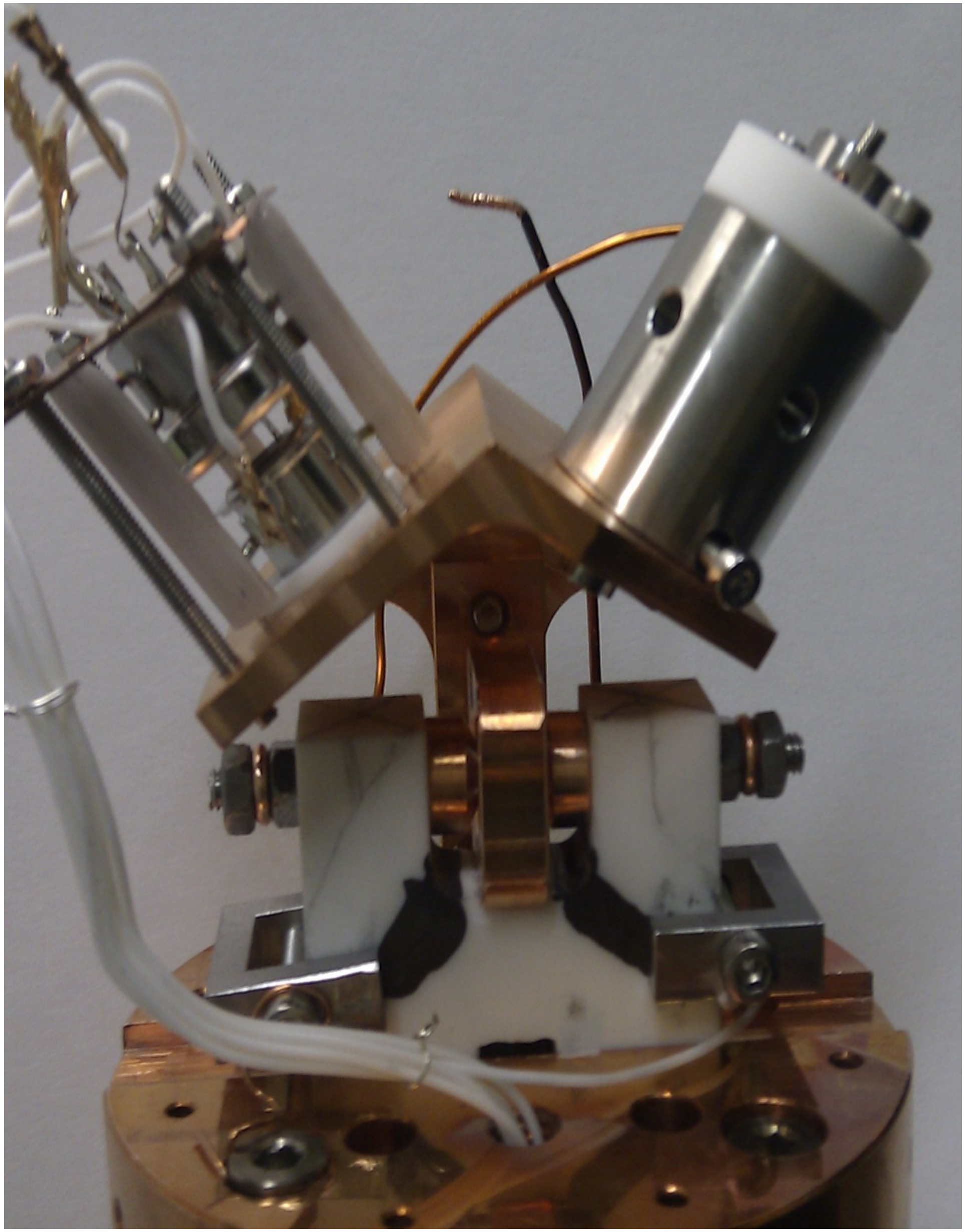
- **localize one ion within one wavelength**
- **RF spectroscopy**
- **electron shelving**
- **large volume**
- **hyperbolic shape**
- **capture $Ra^+$ is THE issue**
- **proved IBM desing**

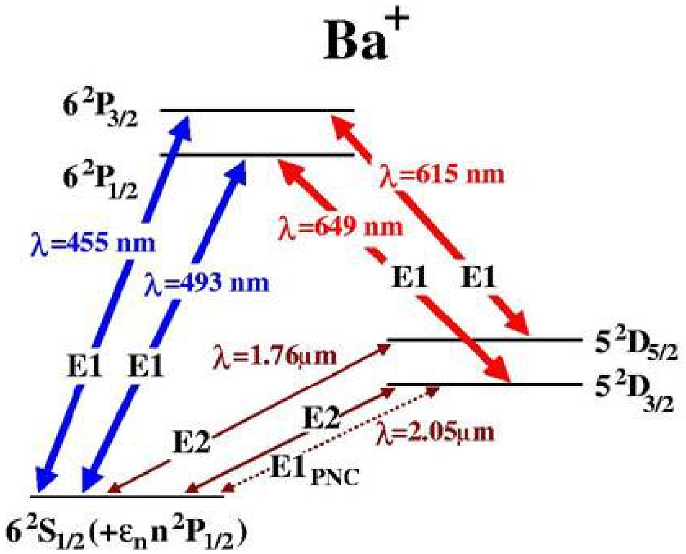


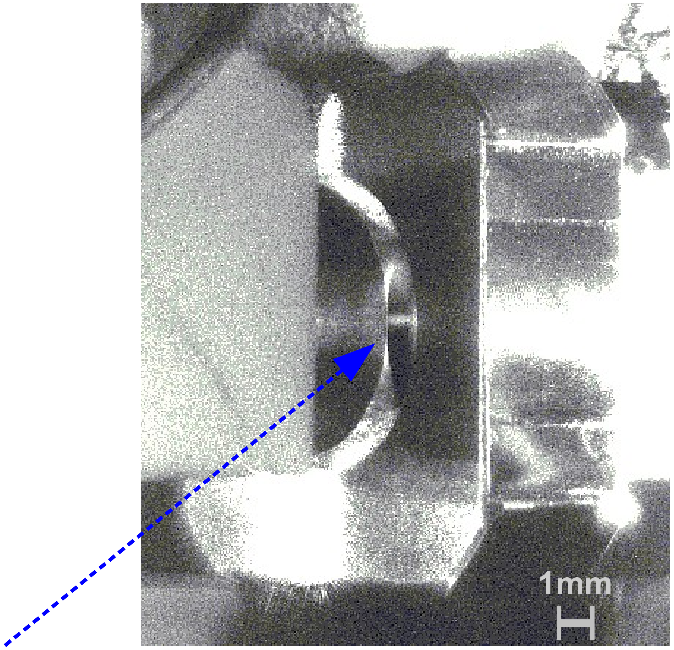

**Iso-electrical**



# Ba$^+$ Experiment






**Ion Cloud → Laser cooling in progress**

# Conclusions

Many Ions

- Production and capture of $Ra^+$ Isotopes ✓
- Laser Spectroscopy different $Ra^+$ Isotopes (209-214) ✓
- Transitions frequencies as test of theory ✓
- Life times of excited states ✓
- Several theory groups actively working ✓

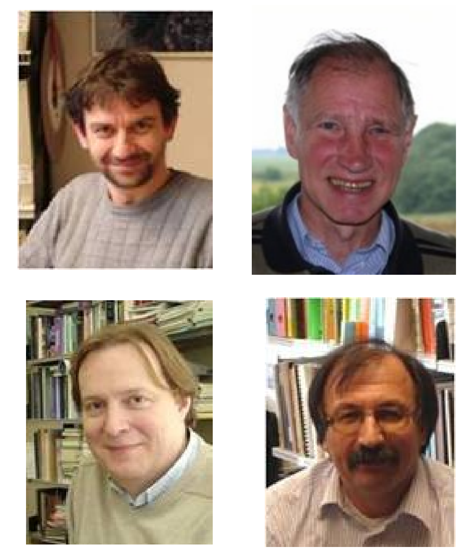
Single Ion

- Trap being characterized with $Ba^+$ ✓
- Laser cooling of trapped ions ✓
- Single ion detection and spectroscopy to come next

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

# The crew & acknowledgments

- Experiment
  - **Mayerlin Nuñez Portela**
  - **Amita Mohanti**
  - **Hendrik Bekker**
  - Gouri Giri
  - Oscar Versolato
  - **Lorenz Willmann**
  - **Klaus Jungmann**
- **Theory**
  - Lotje Wansbeek
  - **Sophie Schlesser**
  - Lex Dieperink
  - **Rob Timmermans**
- **International collaborators**
  - B. P. Das (India)
  - N. E. Fortson (USA)



- Funding
  - FOM open competition
  - NWO Toptalent grant
  - NWO Veni fellowship

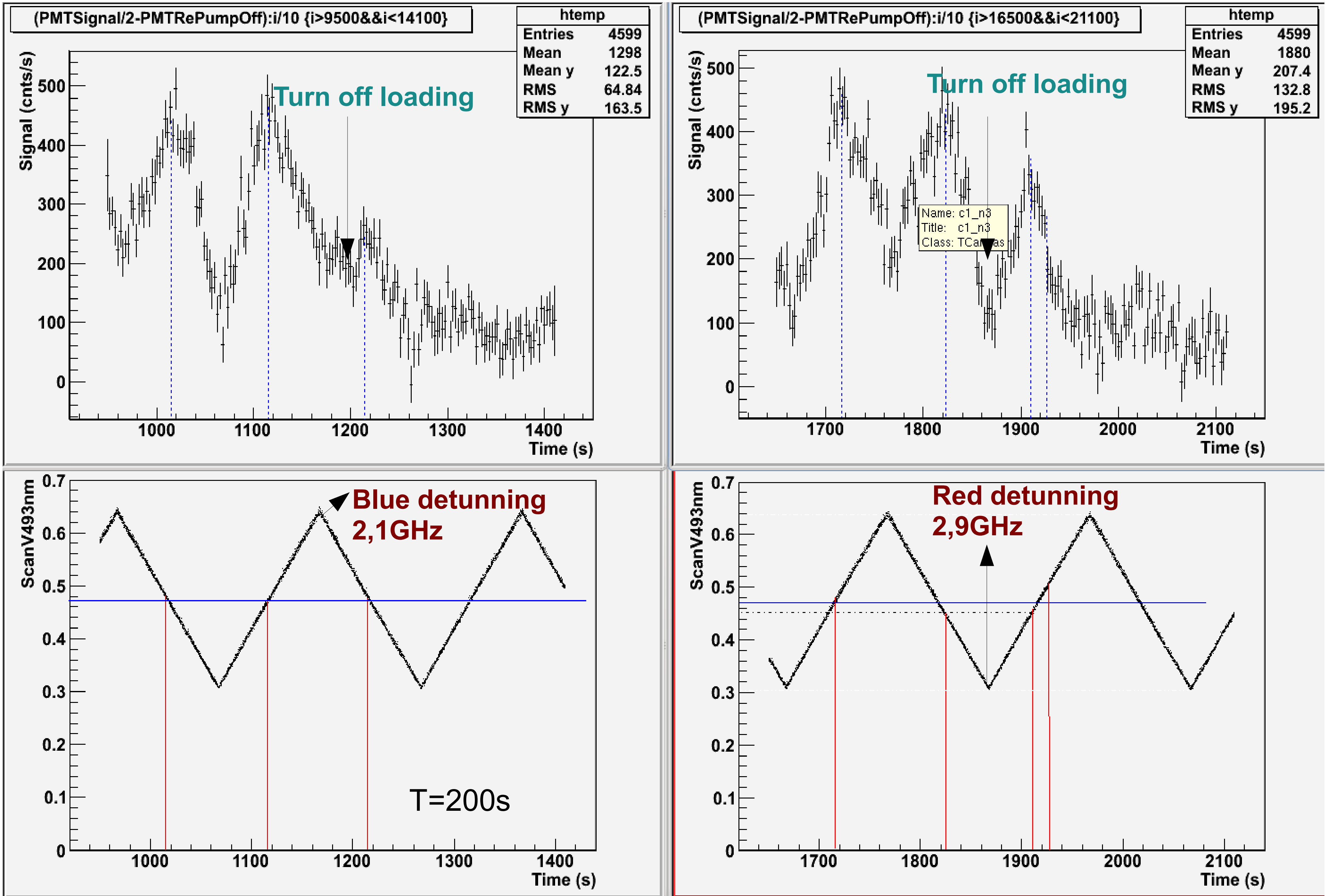
FOM

university of groningen

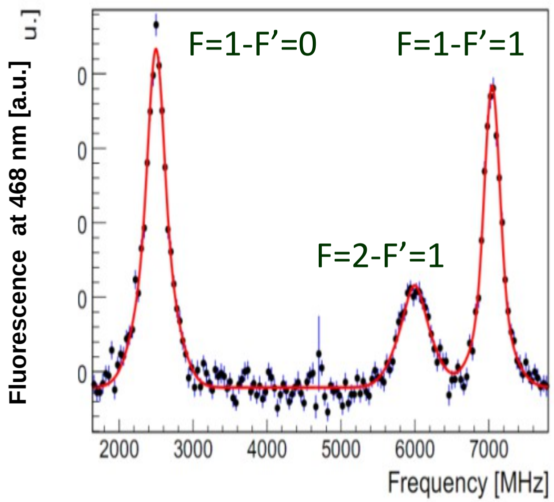
NWO Netherlands Organisation for Scientific Research

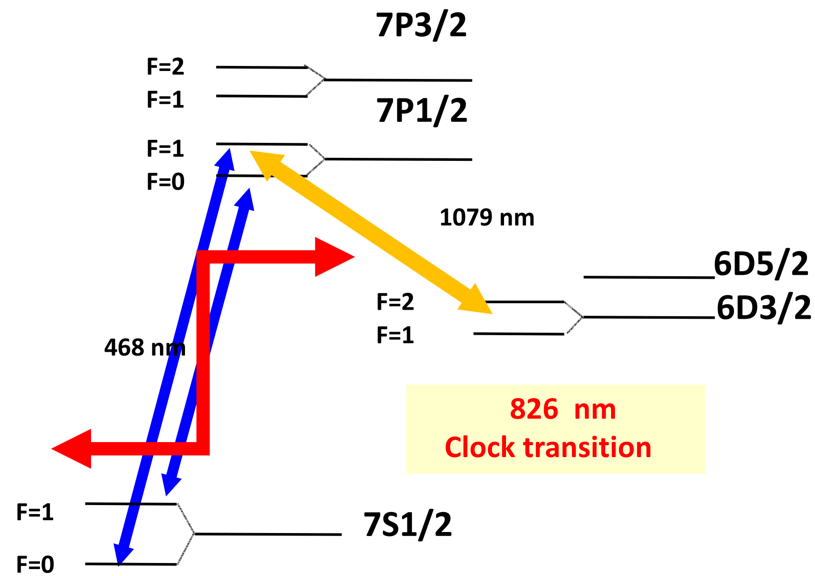
KVI

# Laser cooling: Ba ions



# Ra ion Atomic Clock

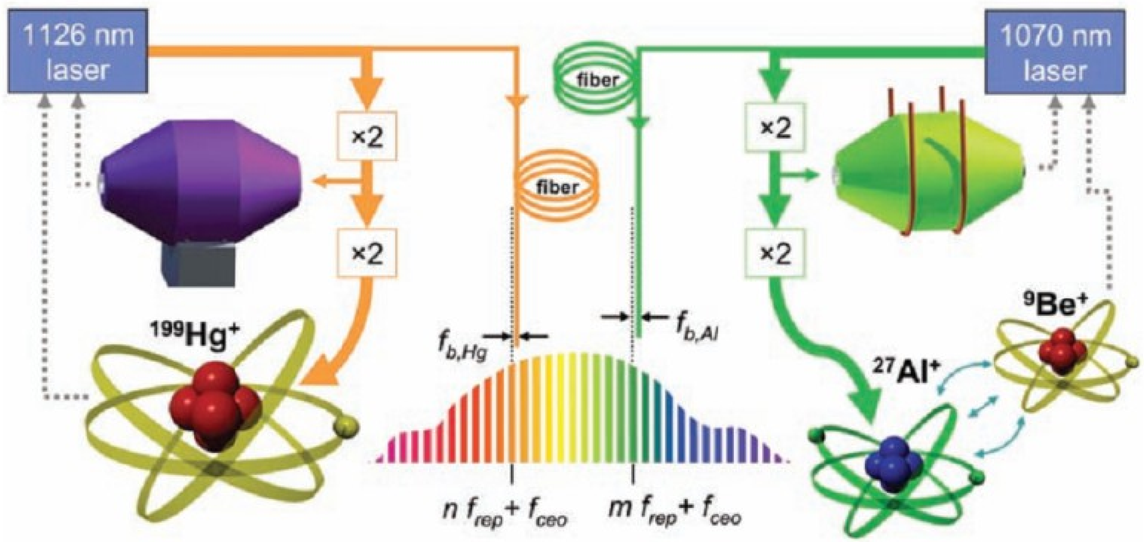



| | Major systematics: Quadrupole shift | dα/dt relative strength | Atomic Parity Violation | Laser wavelength |
|---|---|---|---|---|
| $^{27}$Al | $< 10^{-17}$ *[Itano]* | 1 *[Dzuba, Flambaum]* | Z small | deep UV |
| $^{199}$Hg | $10^{-17}$ *[Itano]* | - 400 *[Dzuba, Flambaum]* | atomic theory difficult to treat | deep UV |
| $^{223}$Ra | $< 10^{-18}$ *[Sahoo]* | + 450 *[Versolato et. al]* | relativististic effects structure calculable | Visible/IR diode lasers |

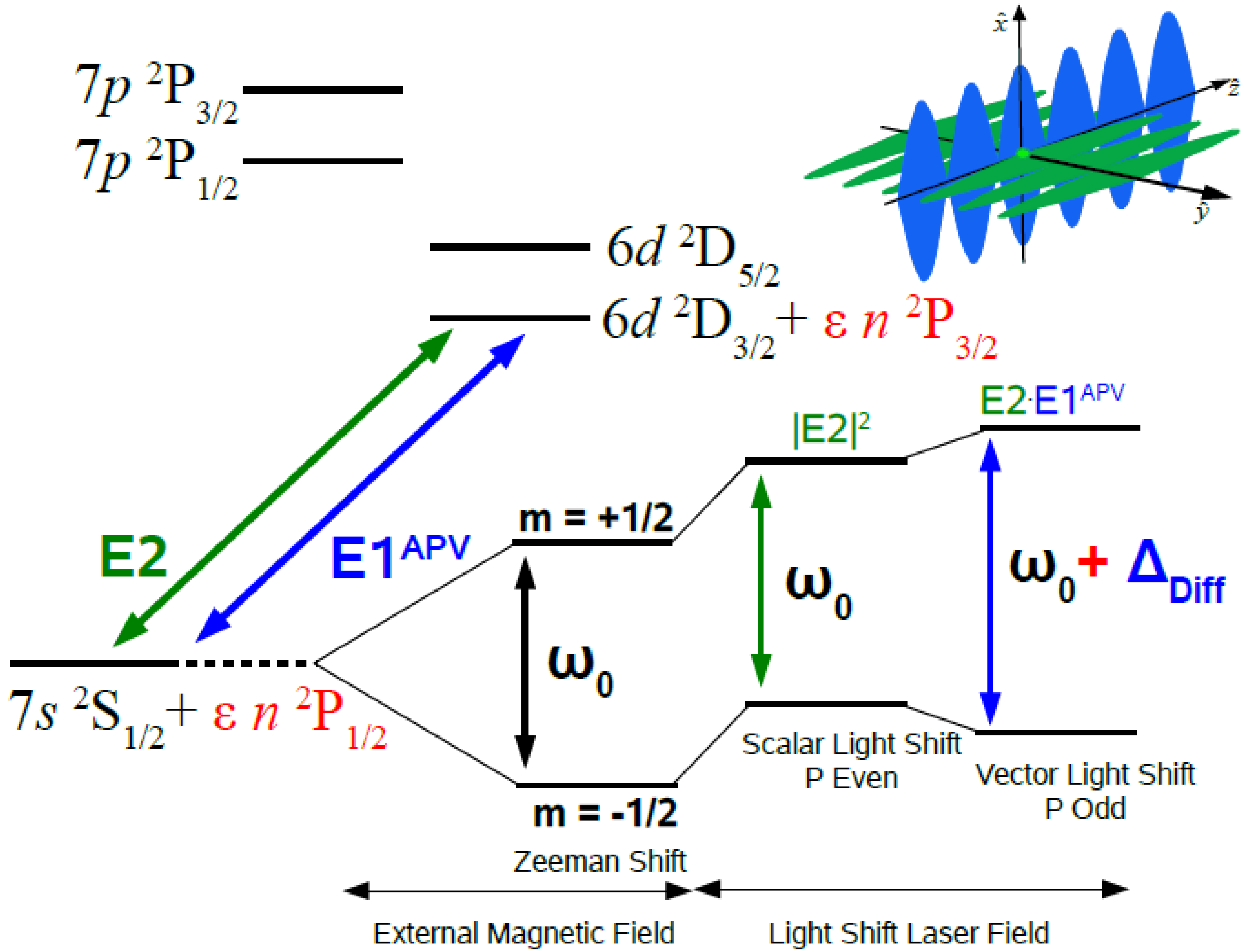
# Sensitivity to ά

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

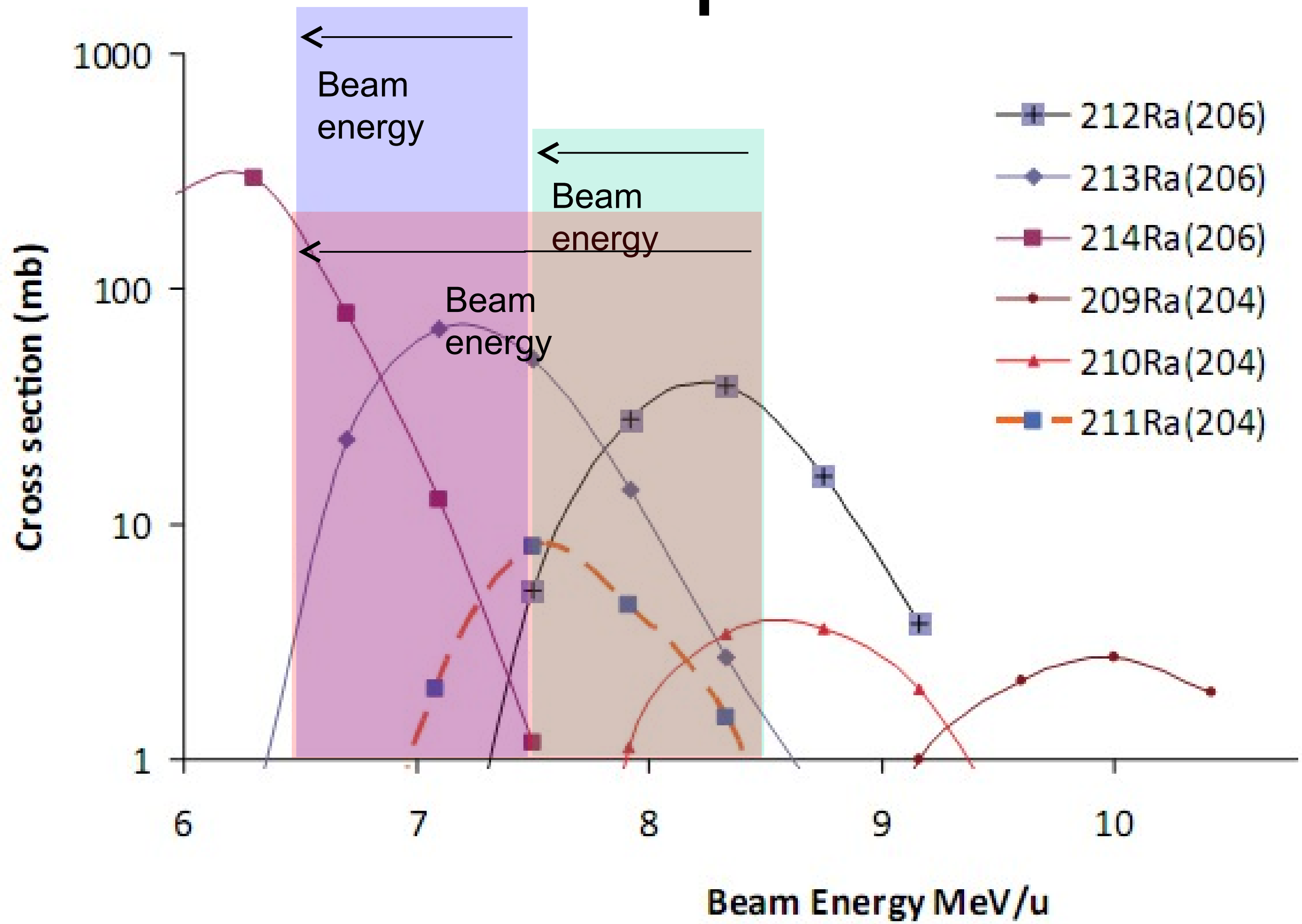



| Ion | A | Ref. | Transition |
|---|---|---|---|
| Sr+ | 0.43 | [15] | $^2S_{1/2}$-$^2D_{5/2}$ |
| Hg+ | −2.94 | [15] | $^2S_{1/2}$-$^2D_{5/2}$ |
| In+ | 0.18 | [18] | $S_0$-$P_0$ |
| Al+ | 0.008 | [18] | $S_0$-$P_0$ |
| Ba+ | 2.52 | [15] | $6^2S_{1/2}$-$5^2D_{3/2}$ |
| Ba+ | 2.44 | [15] | $6^2S_{1/2}$-$5^2D_{5/2}$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

Differential Light Shift : Interference of E2 and $E1^{APV}$



# Ra Ion production



# Lifetime vs. Buffer gas pressure