

EDM with heavy nuclear probes

Lorenz Willmann, University of Groningen

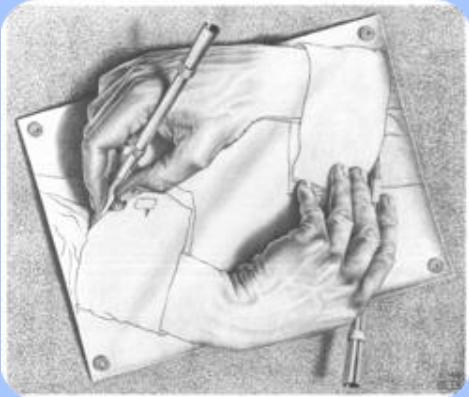
Isolde Workshop, 25-28 Nov. 2013

Low-energy precision tests

of fundamental symmetries and interactions

Complete control atoms, ions and molecules

Parity violation - weak interaction



Is the electron round?



Trapped ions and polar molecules

Mixing of Z^0 with 'dark' Z_d -boson?

Marciano et al, PRL **109**, 31802 (2012):

'Parity violation as the portal to Dark Matter'

Molecules give the

best eEDM limit

Nature **473**, 493 (2011)

arXiv:1310.7534 (2013)

**Symmetry violating effects increase faster than Z^3
in atoms and nuclei**

Questions



Where is the antimatter? What is Dark matter?

LHC @ CERN



New particles ~ TeV

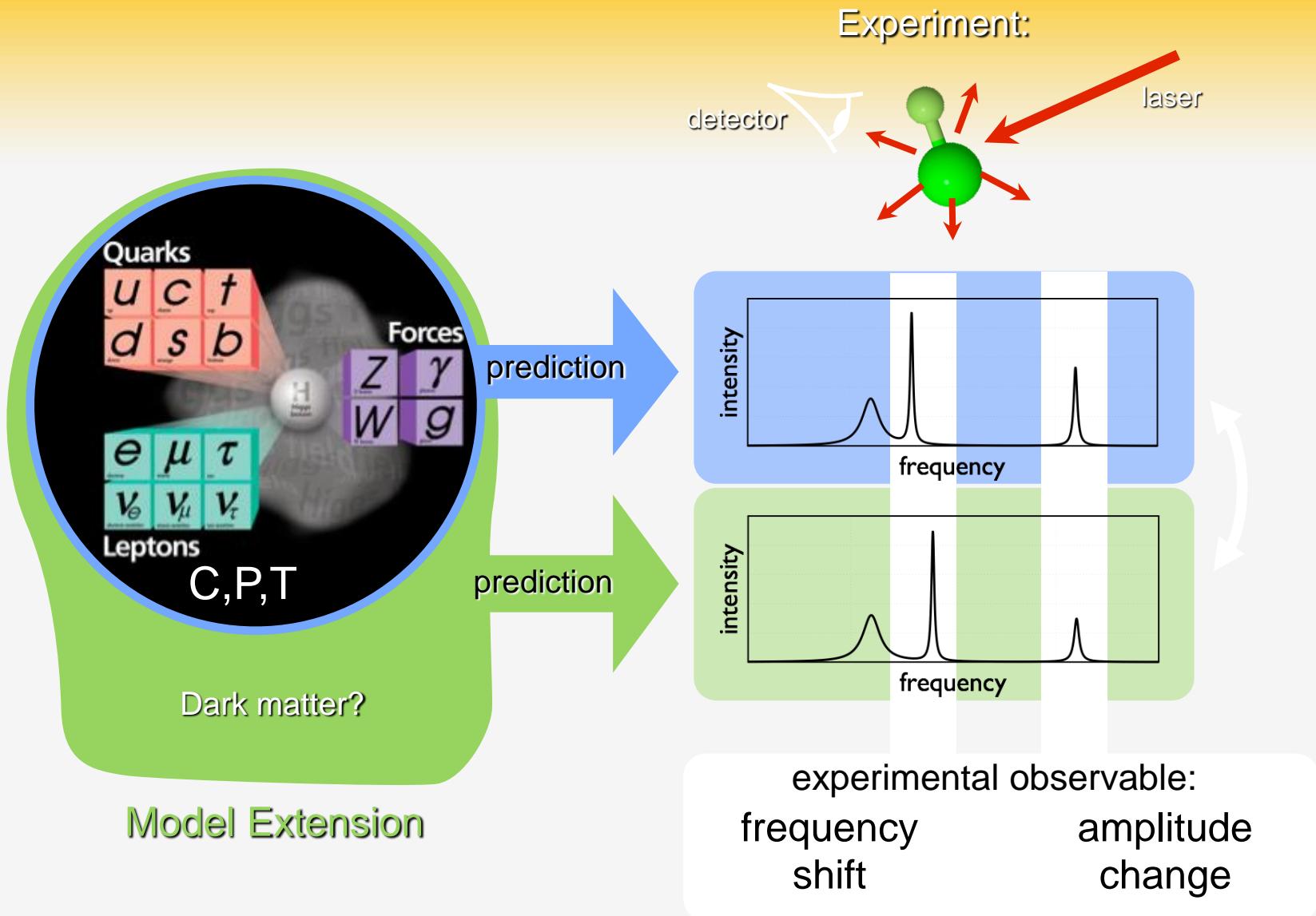
Achievable precision
Theoretically tractable
Sensitivity to physics

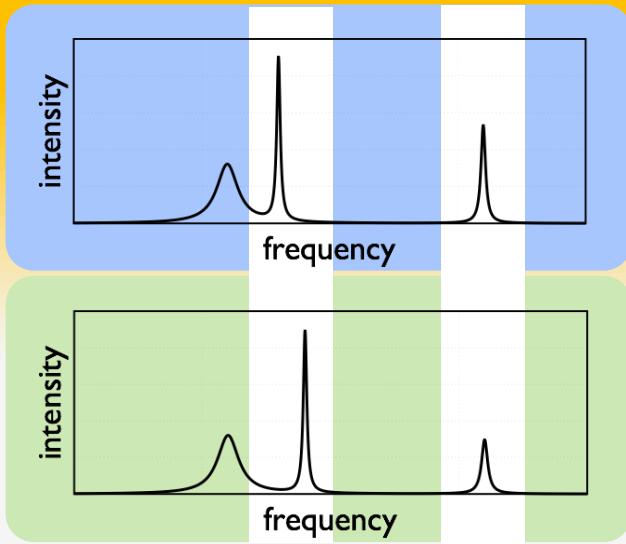
@ Groningen



Precision measurement ~ peV

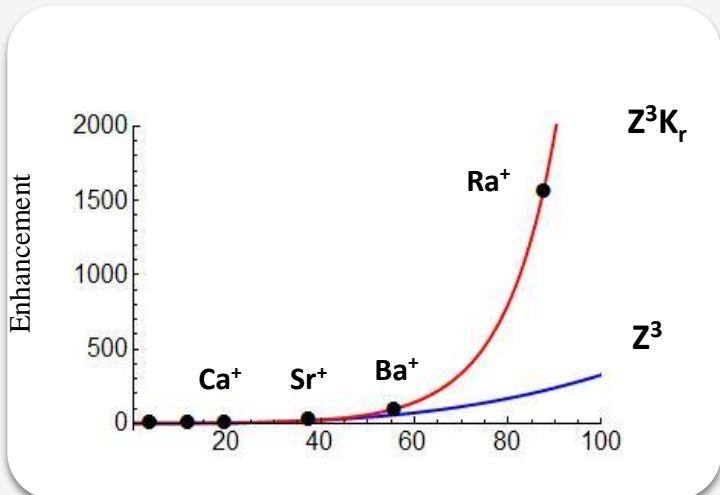
Precision measurement = test of (extension of) the Standard Model





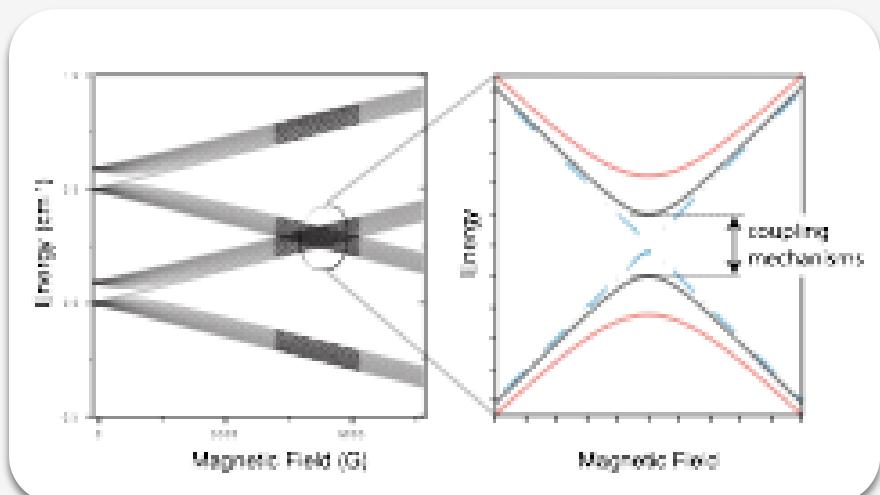
Selection of the system:

Radium ions



*Compared to Cs (Wieman)
50 x enhanced*

SrF molecules



*close-lying rotational levels:
10⁴ - 10⁵ enhancement*

Ultracold heavy diatomic molecules

Travelling-wave deceleration + lasercooling:

SrF for atomic parity violation (recent interest in RaF, Isaev, Berger *et al.*)





Lorentz Symmetry Breaking in weak decay

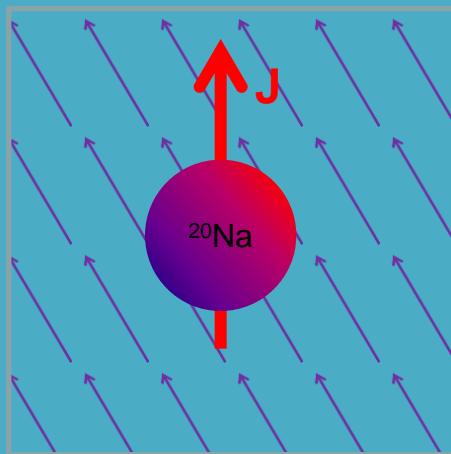
Theory

Lorentz-symmetry breaking in weak decay developed
+ applied to β decay.

J.P. Noordmans et al., Phys. Rev. C 87 055502 (2013)

Experiment at KVI β -decay of ^{20}Na ($T_{1/2} = 0.5$ s) obtained limit on LSB

S.E. Müller et al., Phys. Rev. D 88 071901(R) (2013)



Search for β -decay rate dependence on the orientation?

Answer:

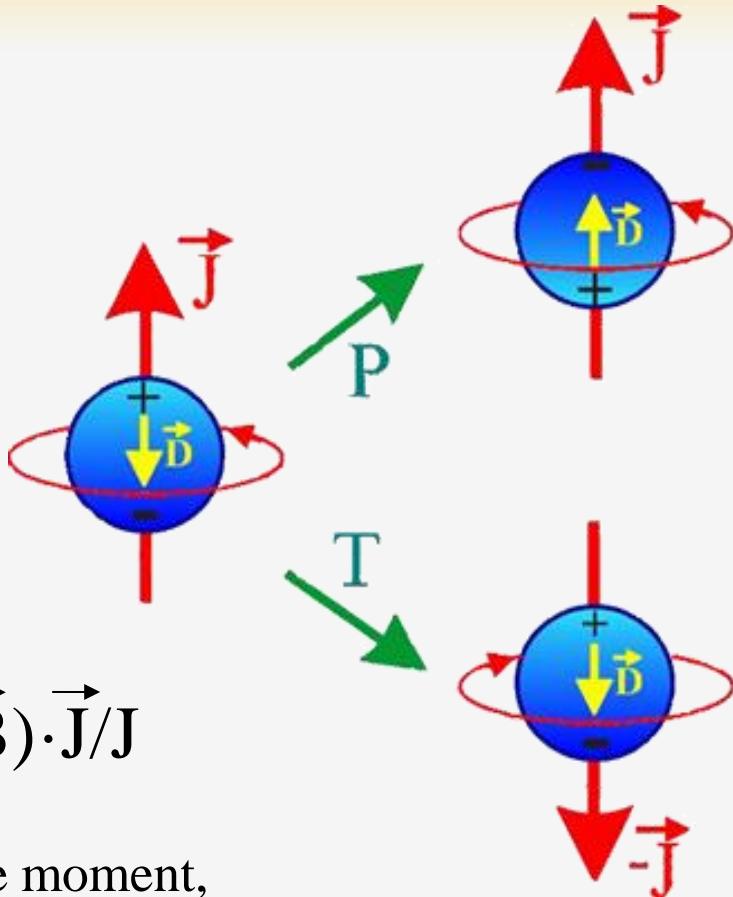
$$\frac{\tau^{\uparrow} - \tau^{\downarrow}}{\tau^{\uparrow} + \tau^{\downarrow}} < 3 \times 10^{-4}$$

(Further order of magnitude
in full data set)

Theory + Experiment ('70s) "Forbidden" β decays, reanalyzed, complementary
LSB bounds derived

J.P. Noordmans et al., Phys. Rev. Lett. 111, 171601 (2013)

Electric Dipole Moments



$$H = -(d \vec{E} + \mu \vec{B}) \cdot \vec{J} / J$$

d - EDM,

μ - magnetic dipole moment,

J - Spin

EDMs violate
- Parity
- Time Reversal

Many Possibilities

Model for
CP Violation

Particle
EDM

Hadron
EDM

Nuclear
EDM

Atomic/
Molecular
EDM

Observable
EDM

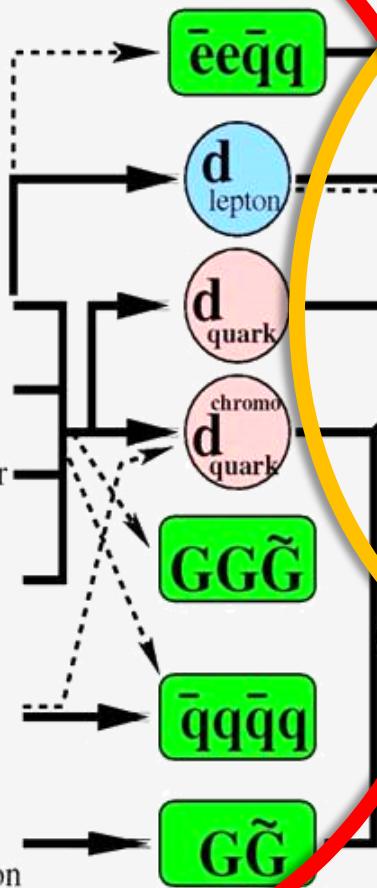
Cabbibo
Kobayashi
Maskawa

Higgs

Technicolor
Super-
Symmetry

Left-Right
Symmetry

Strong
CP Violation



Interactions

Atomic, nuclear properties

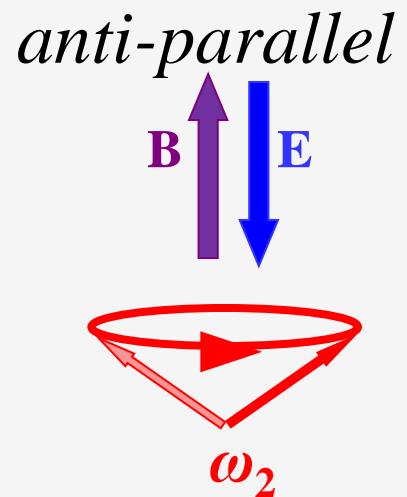
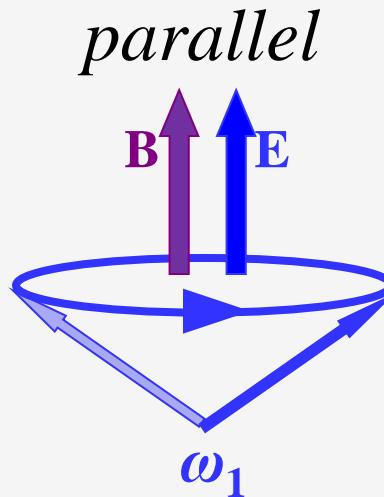
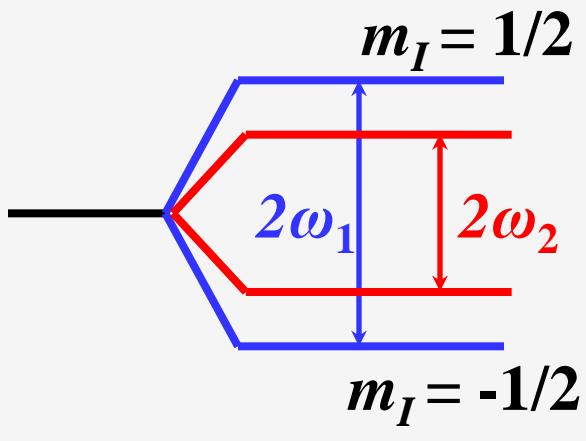
...

Fundamental EDM

Observable Dipole Moment

Measure EDM ($I=1/2$)

$$H = -(d \mathbf{E} + \mu \mathbf{B}) \cdot \mathbf{I}/I$$



Difference Frequency

$$\omega = 2\omega_1 - 2\omega_2 = 4 d \mathbf{E} / \hbar$$

$$d = 10^{-26} \text{ e cm}, E = 100 \text{ kV/cm},$$
$$\Rightarrow \omega = 15 * 10^6 \text{ rad/s}$$

Sensitivity of EDM Experiments

ε *Efficiency*

T *Measurement Time*

τ *Spin Coherence Time*

E *Electric Field*

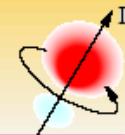
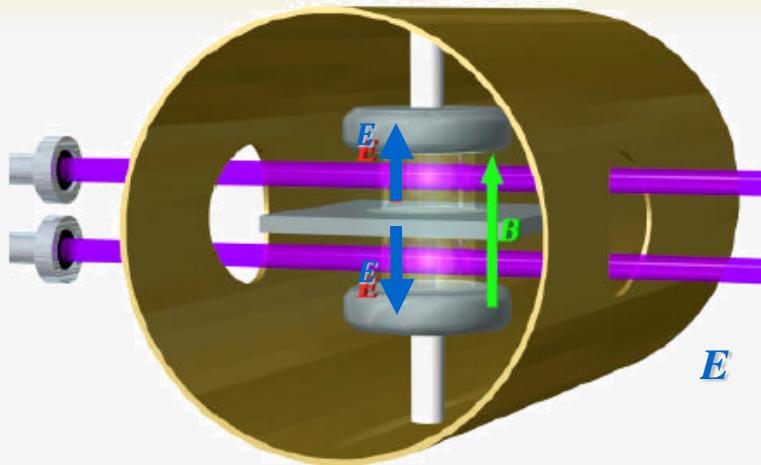
F *Incoming Flux*

$$\Delta d = \frac{\hbar}{E \varepsilon \sqrt{F T} \tau}$$

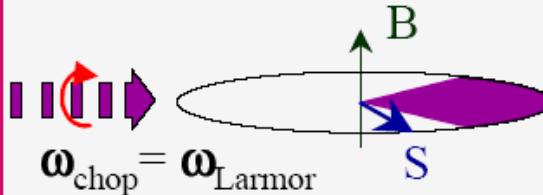
**Parameters to be optimized
are different for all EDM searches**

Nuclear EDM

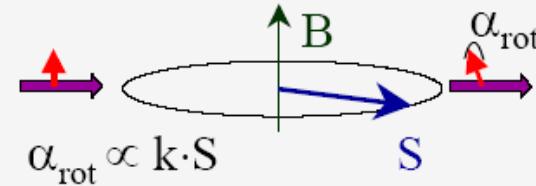
^{199}Hg EDM Experiment



Synchronous Optical Pumping



Monitoring Spin Precession



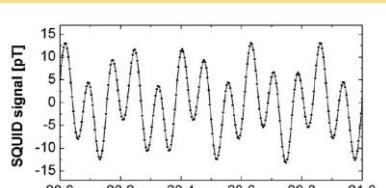
$$d_{\text{Hg}} < 3.1 \times 10^{-29} \text{ e cm (95% c.l.)}$$

Griffith et al., PRL 102, 101601 (2009)

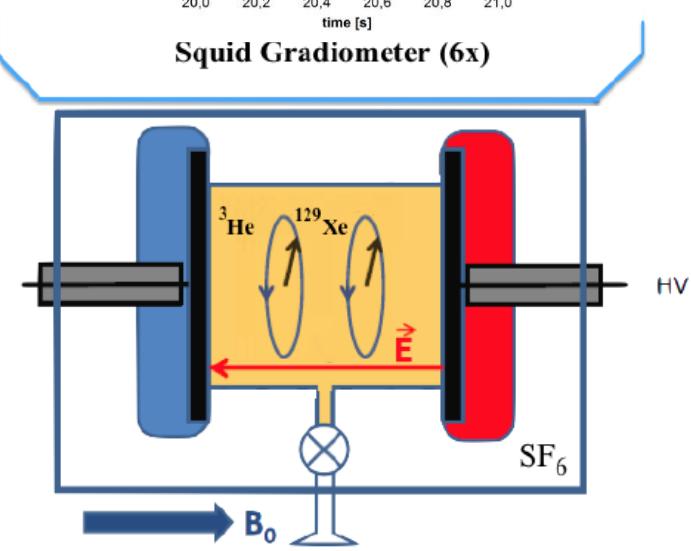
- Long coherence time
- Large number of particles
- Suppression of systematics

Expect improved result in next decade

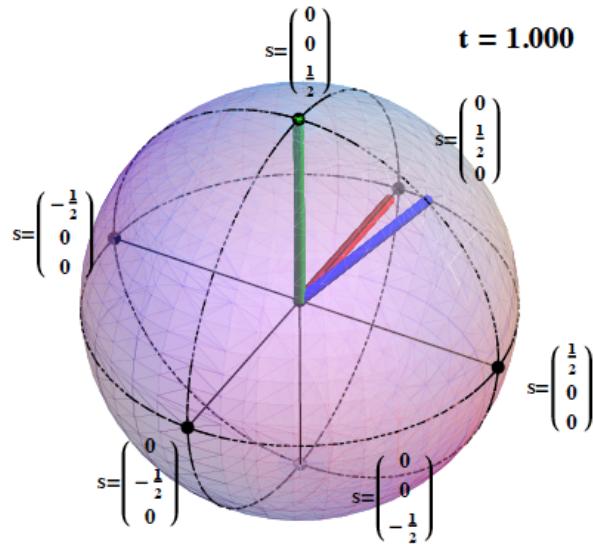
Search for the Permanent Electric Dipole Moment of ^{129}Xe



Aim at $\mathcal{O}(10^4)$ Xe EDM limit improvement



$^{129}\text{Xe}/^3\text{He}$ spin clock



Spins of ^{129}Xe , after 1s rotation:
(static holding field, additional rotating field)

- * Very precise spin clock, crucial to understand spin clock systematics (Xe, Ra, Hg...)
- * Search for P&T violation; search for Physics Beyond the Standard Model.
- * Simulations to understand systematic phase shifts.
- * Collaboration: Mainz, Heidelberg , Groningen (DPG Hannover 2013, AMO Lunteren 2013)

Permanent electric dipole moments

EDM violates P and T symmetry

Non-zero EDM requires physics beyond Standard Model

Limit on EDM test models

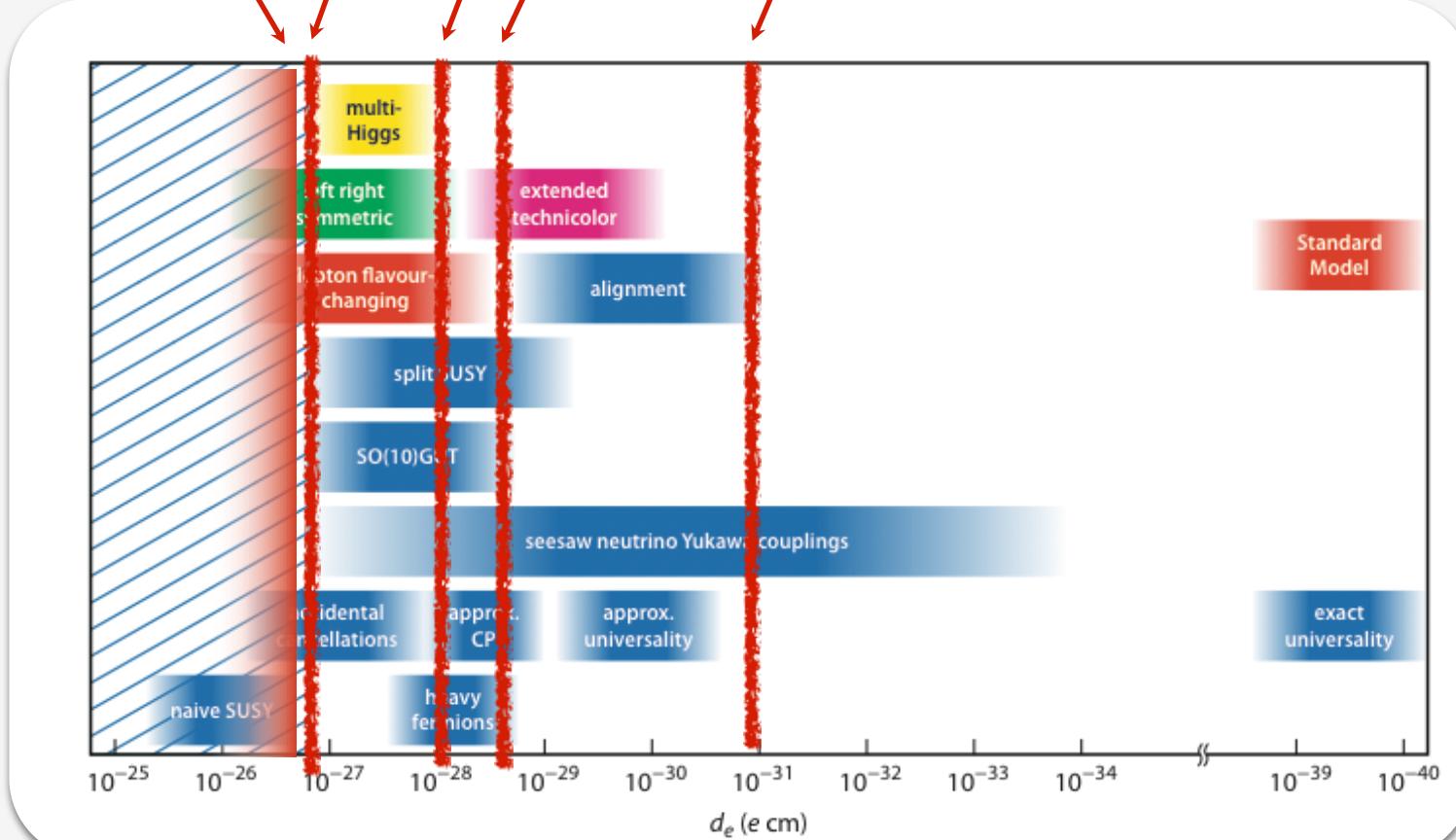
2011: e-EDM YbF molecule result (Hinds et al, London)

2013: e-EDM ThO molecule (DeMille, Gabrielse, Doyle, Yale/Harvard)

2002: e-EDM Tl atoms,
(Commins, Berkeley)

2009: EDM Hg (Fortson et al, Seattle)

Next-generation using cold molecules, Xe, Ra



EDM of ^{225}Ra Enhancement

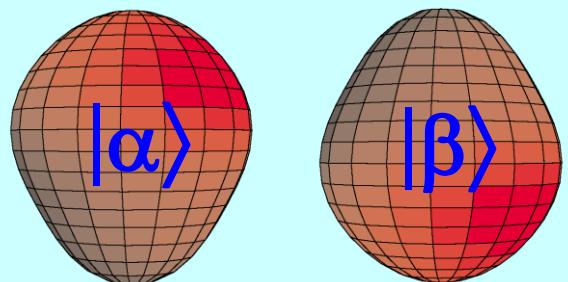
^{225}Ra :

$I = \frac{1}{2}$

$t_{1/2} = 15 \text{ d}$

- Closely spaced parity doublet – Haxton & Henley (1983)
- Large intrinsic Schiff moment due to octupole deformation
 - Auerbach, Flambaum & Spevak (1996)
- Relativistic atomic structure ($^{225}\text{Ra} / ^{199}\text{Hg} \sim 3$)
 - Dzuba, Flambaum, Ginges, Kozlov (2002)

Parity doublet



$$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$
$$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

$$S \equiv \langle \psi_0 | \hat{S}_z | \psi_0 \rangle = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + \text{c.c.}$$

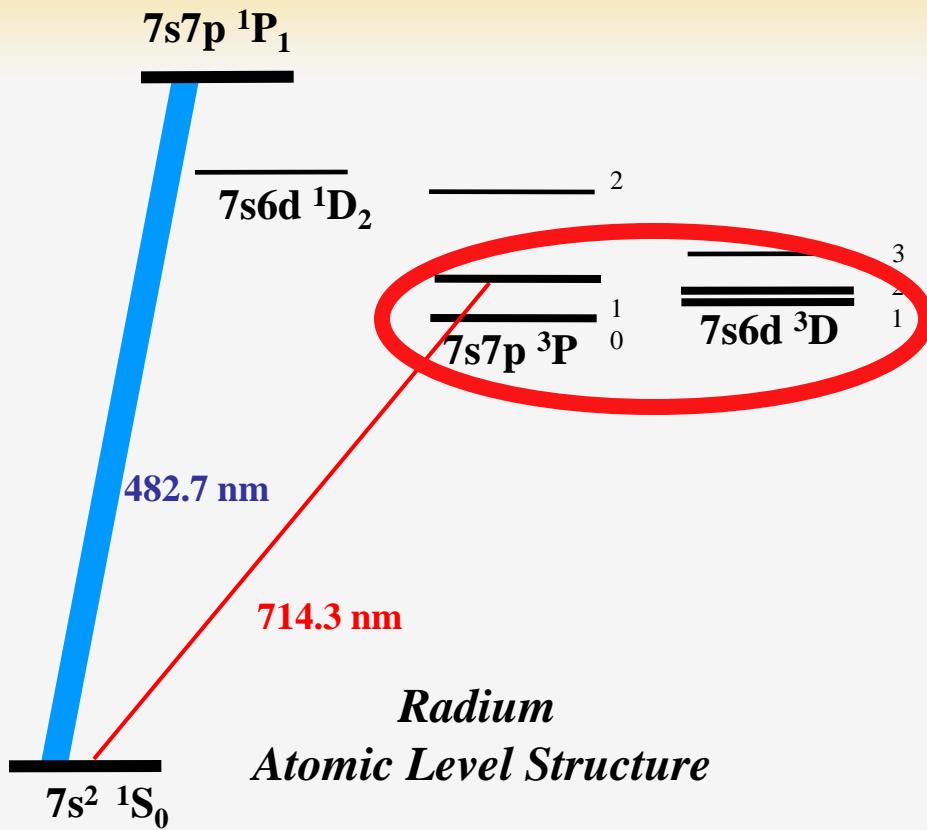
Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra , Dobaczewski, Engel (2005)

Schiff moment of ^{199}Hg , Ban, Dobaczewski, Engel, Shukla (2010)

Enhancement in Radium



EDM Enhancement

Atomic Structure:

$$d = \frac{\langle ^3D_2 | -er | ^3P_1 \rangle \langle ^3P_1 | H_{EDM} | ^3D_2 \rangle}{E(^3D_2) - E(^3P_1)}$$

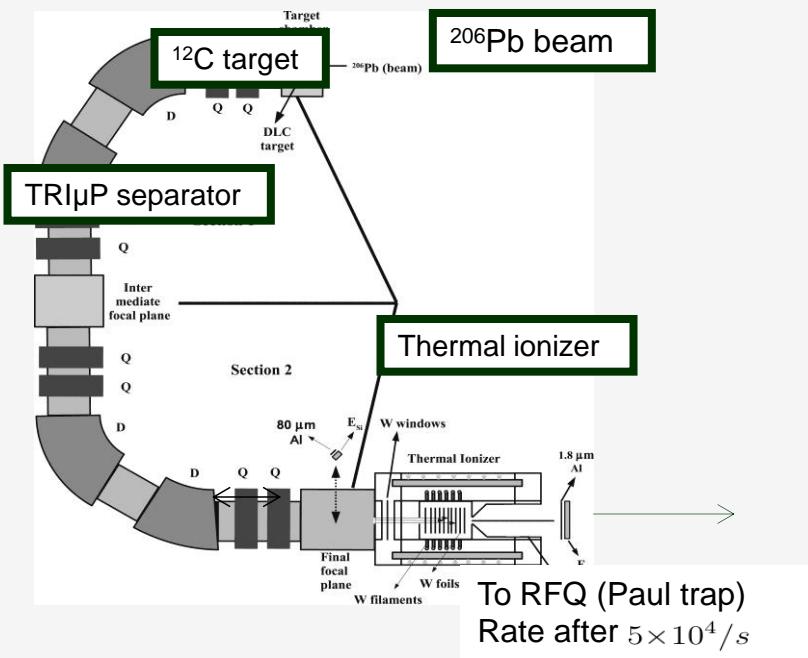
Nuclear EDM in ³D₂ state
40000

Electron EDM in ³D₁ state
5000

Dzuba, Flambaum, Bieron

In addition: Schiff moment due to octupole as discussed by P. Butler

Radium Isotopes



${}^{225}\text{Ra}$

Electrochemical extraction from ${}^{229}\text{Th}$ source ([ANL](#))

Long lived ${}^{229}\text{Th}$ source in an oven ([TRI \$\mu\$ P@KVI](#))

Other Isotopes

Online production at accelerator facilities

[TRI \$\mu\$ P@KVI](#) (flux $\sim 10^5/\text{s}$)

[ISOLDE, CERN](#) (flux $\sim 10^9/\text{s}$)

Sources or fragmentation

	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

N > 10

Sources & Isotopes

$^{225}\text{Radium}$ (from sources)

Long lived ^{229}Th source in crucible (TRIMP@KVI)

**Electrochemical extraction from ^{229}Th source (ANL)
regular filling required**



filled with
 ^{229}Th 10 μCi

Experiment seems feasible with modest
(< 10 mCi) ^{225}Ra sources.



Special thanks to our health physicists Paul Niquette and Lee Sprouse.

Argonne
National Lab

Isotope Production Facilities

ISOLDE, CERN (flux $\sim 10^9/\text{s}$)
FRIB, MI, USA (flux $\sim 10^9/\text{s}$)
ISOL@MIRRHA even higher

Isotope	Half life ($\tau_{1/2}$)	Nuclear spin (I)
^{225}Ra	14.9 days	1/2
^{223}Ra	11.4 days	3/2
^{213}Ra	2.74 min	1/2

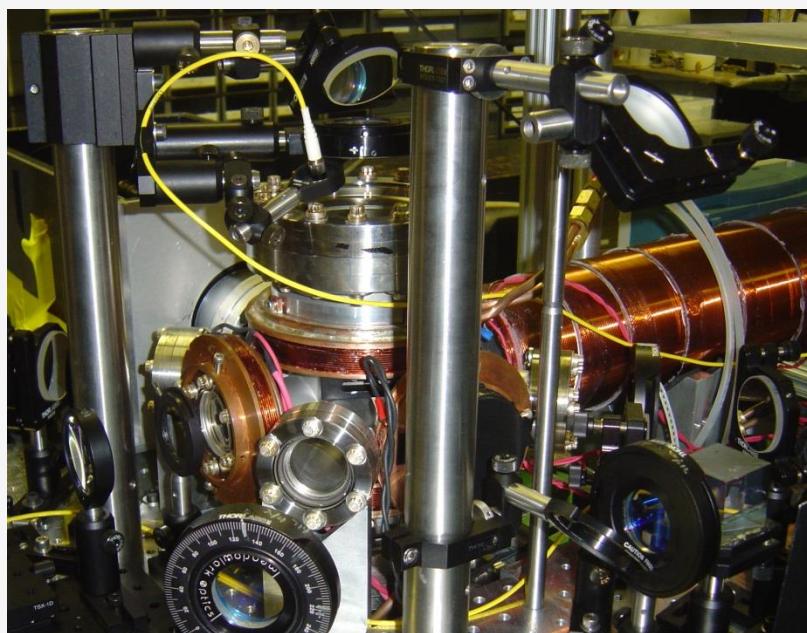
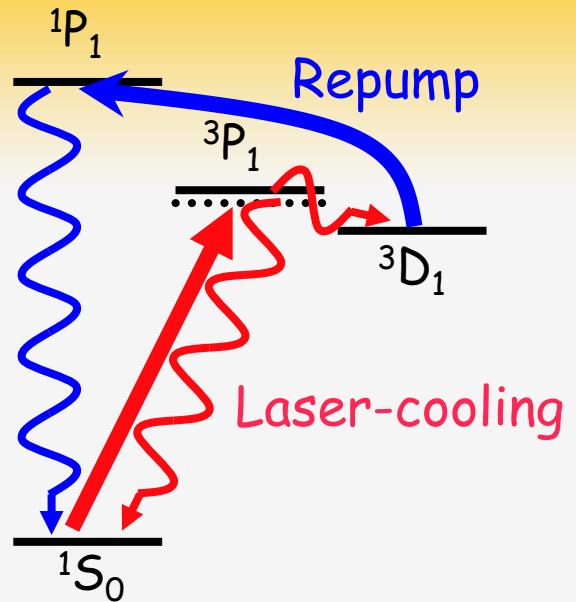
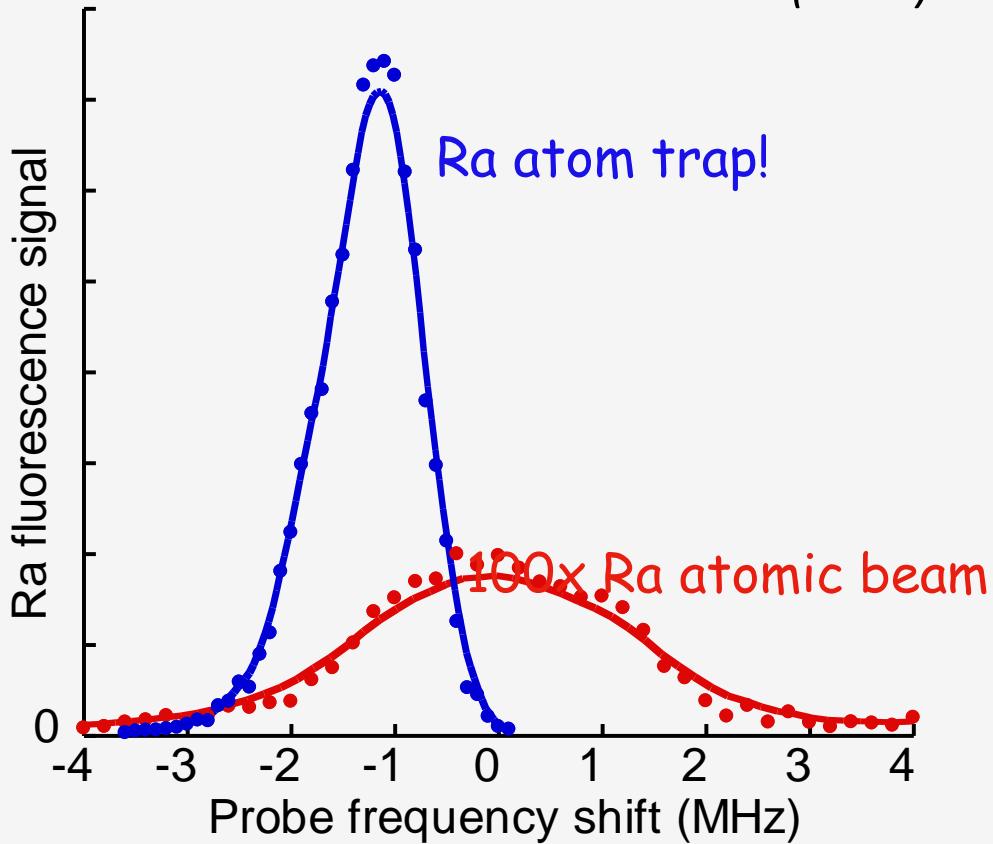
Trapping of ^{225}Ra and ^{226}Ra Atoms

- Key ^{225}Ra frequencies, lifetimes measured

Scielzo et al. PRA (2006)

- ^{225}Ra laser cooled and trapped!

Guest et al. PRL (2007)



Radium cooling

Parameter	483 nm	714 nm
Maximum deceleration (a)	$330 \times 10^3 \text{ m/s}^2$	$3 \times 10^3 \text{ m/s}^2$
Distance to stop 300 m/s (d)	0.14 m	15 m
Doppler cooling limit (T_D)	700 μK	9 μK
Recoil limit (T_R)	180 nK	83 nK

- transition leak rate 1:350
- indispensable repumping
- 0.1 m slowing section
60 % of all atoms

- transition leak rate 1:25000
- 1 m slowing section
0.06% of all atoms
- 0.6% with repumping

Heavy alkaline earth: Ba

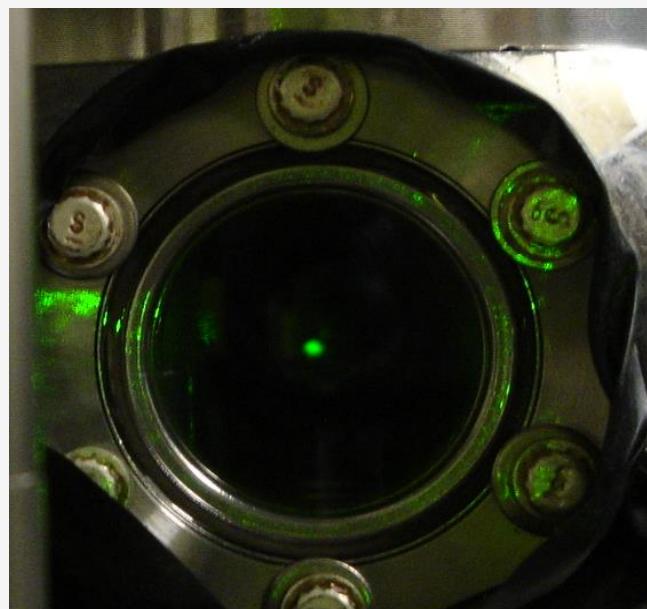
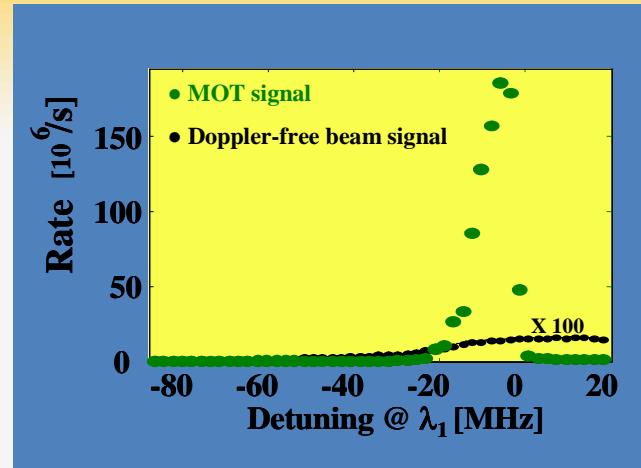
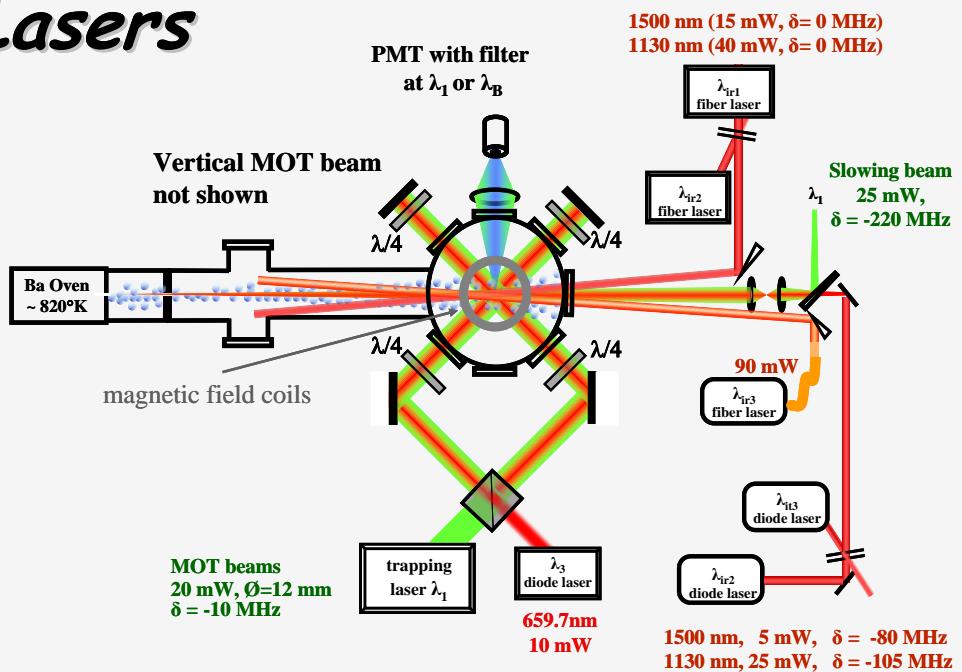
Efficient capture from atomic beam: >1%
multi-color, multi level laser cooling

S. De et al. PRA 041402 (2009)

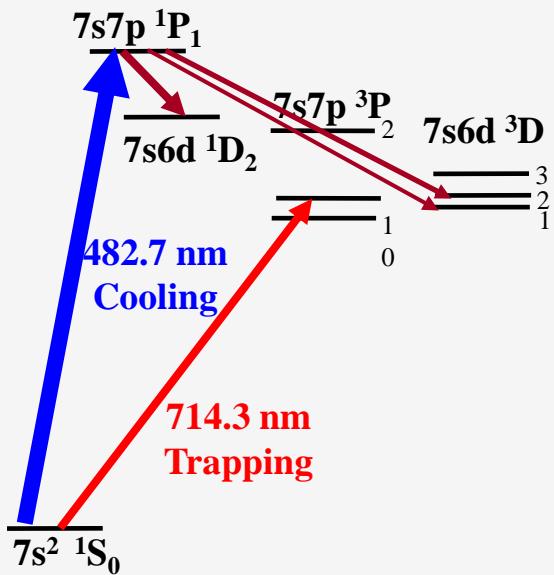
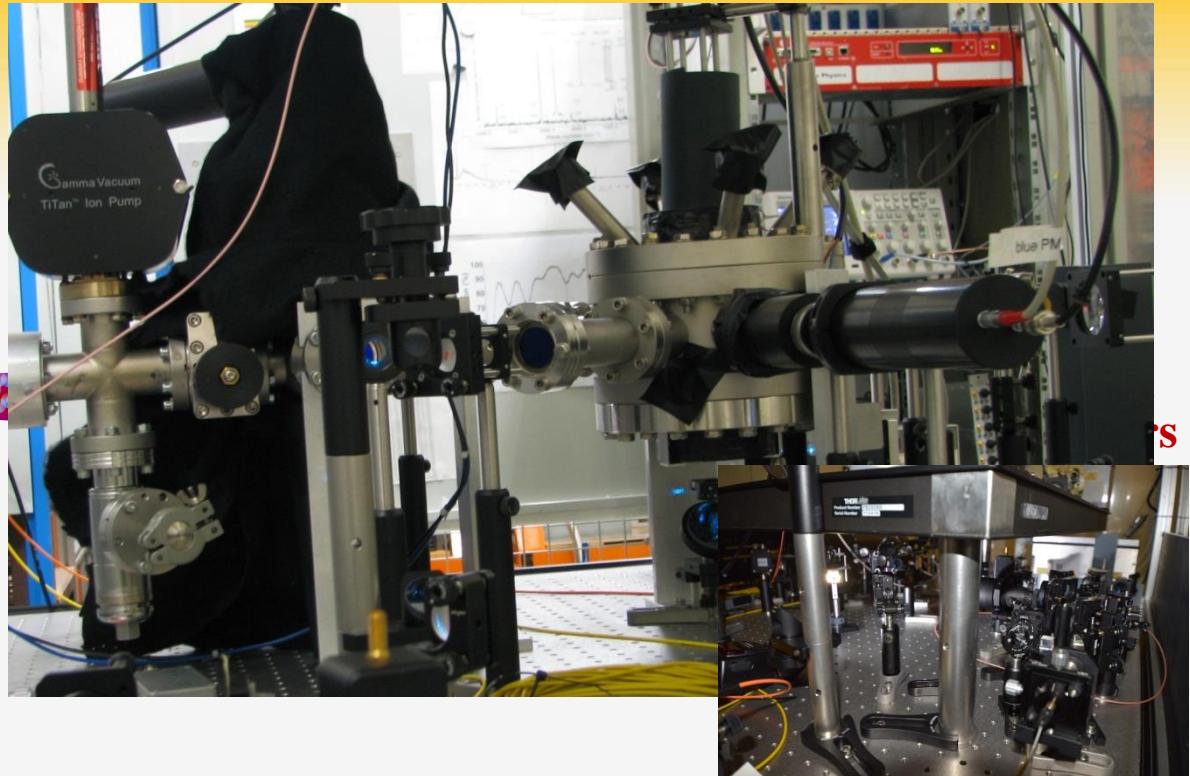
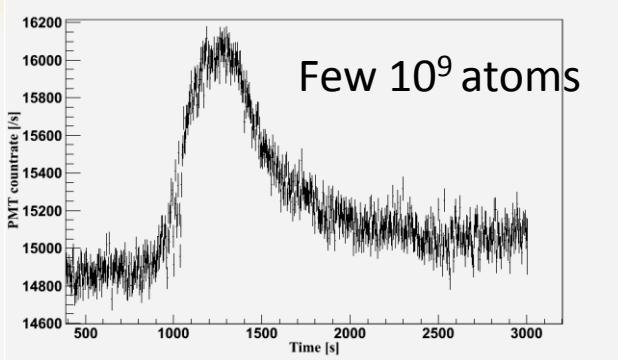
Alternate way pursued at ANL (Ra): $< 10^{-6}$
single color, two-level laser cooling

Guest et al. PRL 98 093001 (2007)

Lasers



^{225}Ra beam

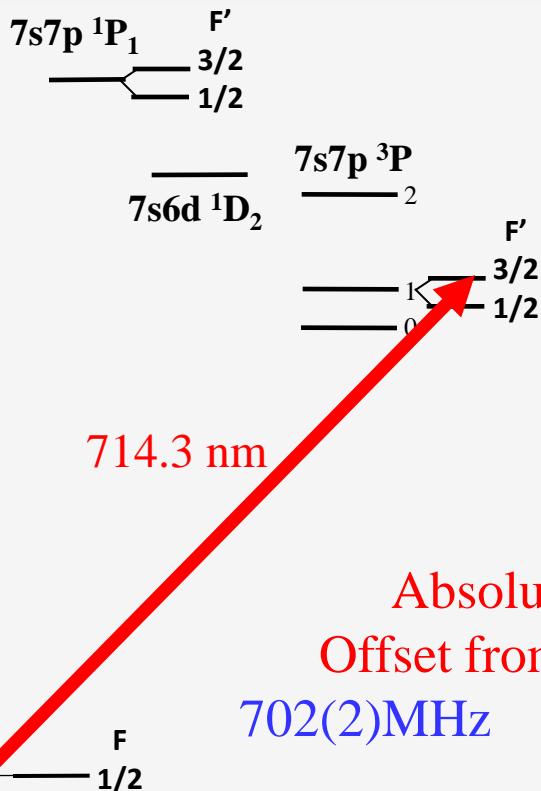


✓ Ti: Sapphire laser @ **966 nm**
Second harmonic generation (KNbO_3) ->**483 nm**

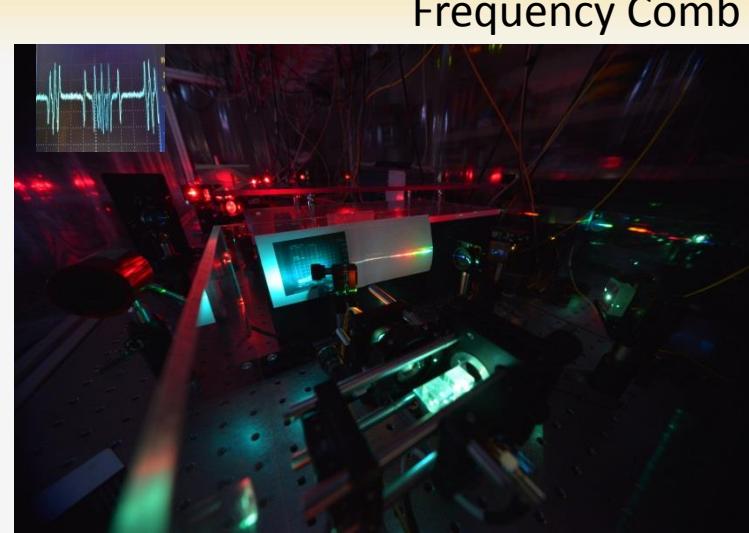
- ✓ Semi-conductor Diode lasers @
- ✓ **714 nm, 50mW, stabilized to frequency comb**
- ✓ Repump lasers, 1428nm, 1488nm

Example: ^{225}Ra Spectroscopy

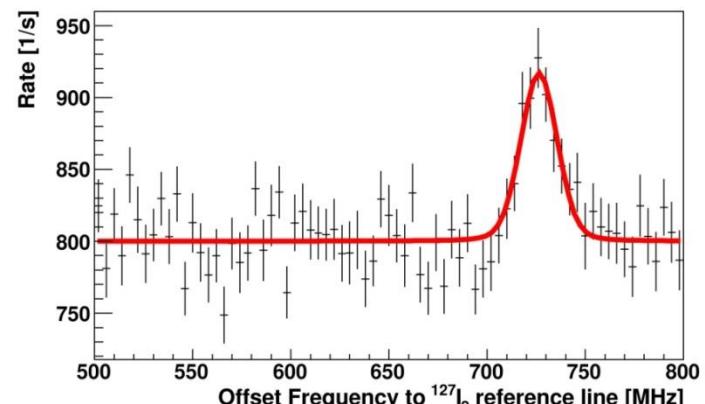
$7\text{s}^2 \text{1S}_0 - 7\text{s}7\text{p } ^3\text{P}_1$: Weak transition, trapping



Calibration by I_2 transition and frequency comb



$F=1/2 - F'=3/2$



#Ra comparable to 1s beam at ISOLDE

Sensitivity of EDM Experiments

ε	<i>Efficiency</i>	~ 1
T	<i>Measurement Time</i>	$= 10^5 \text{ s}$
τ	<i>Spin Coherence Time</i>	$= 10 \text{ s}$
E	<i>Electric Field</i>	$= 10^5 \text{ V/cm}$
F	$N/\Delta t$	
N	<i>Average Trap population</i>	$= 10^6$
Δt	<i>measurement cycle time</i>	$\sim \tau$

**Sensitivity for nuclear and electron EDM
in one day of measurement time possible
(requires Ra rates as available at ISOLDE)**

$$\Delta d = 6 \cdot 10^{-27} \text{ e cm (in 1 day)}$$

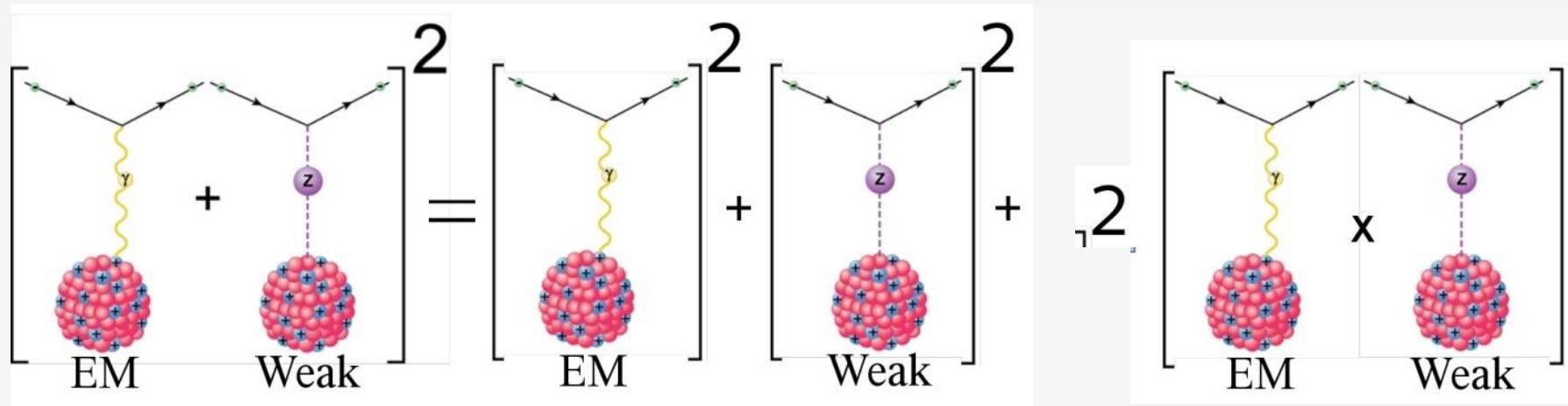
$$d_x = d_{Ra} / \text{Enhancement}$$

same physics sensitivity as ^{199}Hg

Atomic Parity Violation in Ra^+

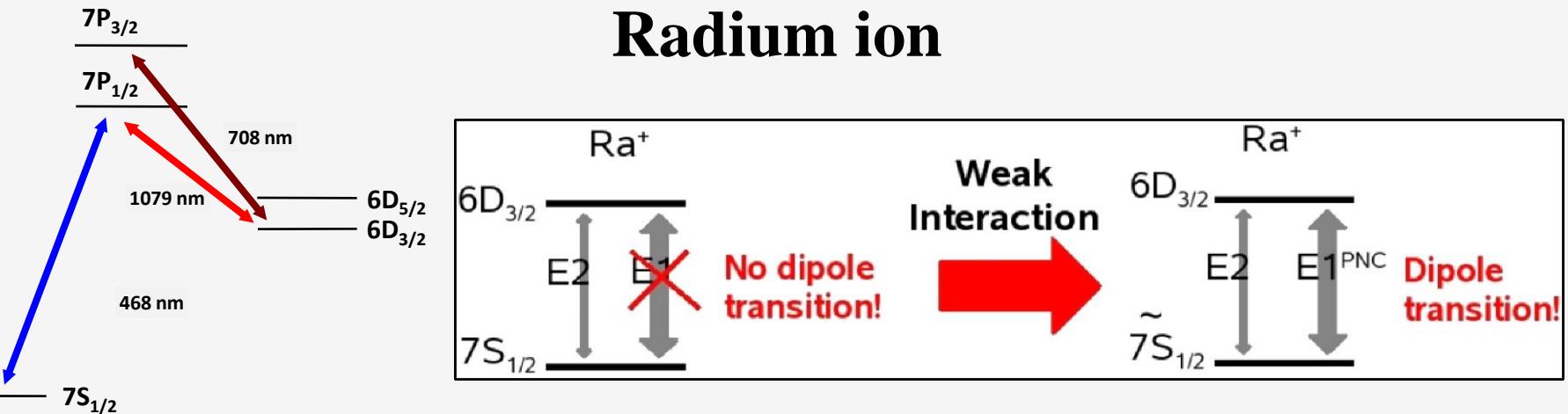
Weak Interaction in Atoms

Interference of EM and Weak interactions



Weak Interaction in Atoms

Interference of EM and Weak interactions



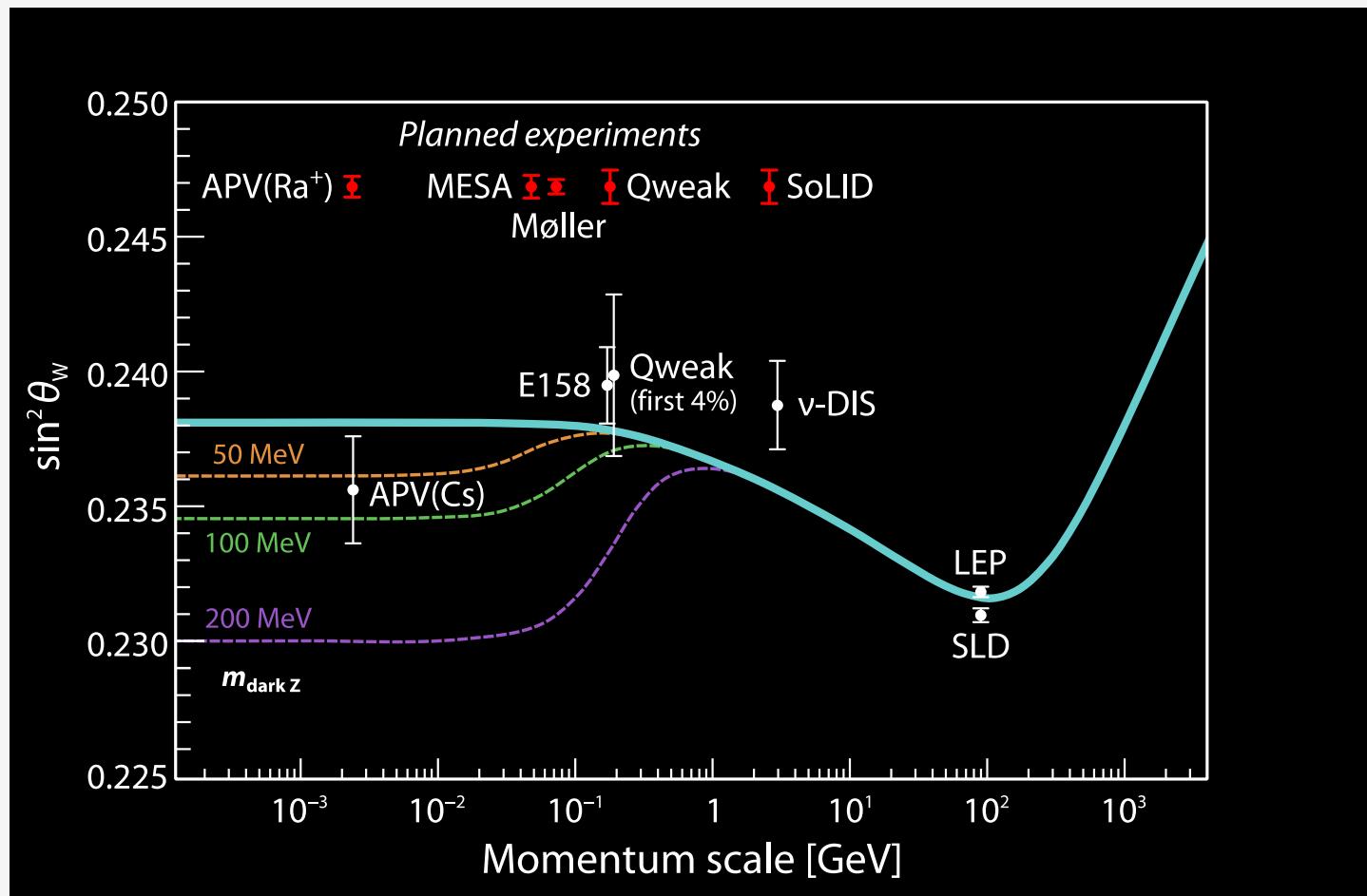
$$E1_{PNC} = K_r Z^3 Q_w = K_r Z^3 (-N + Z (1 - 4 \sin^2 \theta_w))$$

↑ ↙

$\text{Ra}^+@\text{TRI}\mu\text{P}$ 3% accuracy: Theory@KVI

Weinberg Angle θ_W

$$\sin^2(\theta_W) = \underbrace{(1 - (M_W/M_Z)^2) + \text{rad. corrections}}_{\text{Standard Model}} + \text{New Physics}$$



Physics Beyond the SM

Extra Z' boson in SO(10) GUTs:

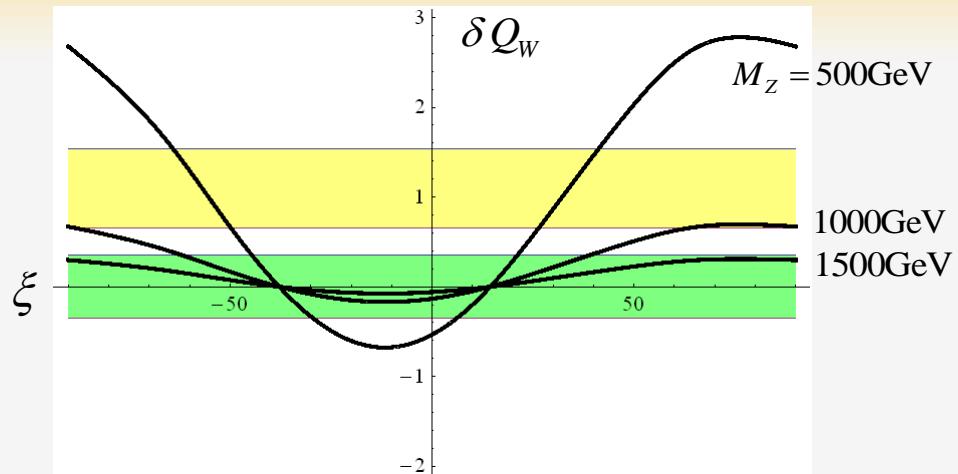
- Additional U(1)' gauge symmetry
- Does not affect ordinary Z and W physics
- Assume no Z - Z' mixing

$$\delta Q_W \cong (2N + Z) a_e'(\xi) v_d'(\xi) \left[\frac{M_Z^2}{M_{Z'}^2} \right]$$

London en Rosner (1986)

Marciano en Rosner (1990)

Altarelli et al. (1991)



Bounds on $M_{Z'}$ from APV (68% confidence level, $\xi = 52^\circ$)

- With current Cs result
 $M_{Z'} > 1.2 \text{ TeV}/c^2$ (Wansbeek et al.. PRA (2010))
- Range for Ra⁺ (5-fold improvent)
 $> 6 \text{ TeV}/c^2$

From High Energy Experiments
Tevatron

$$M_{Z'} > 0.9 \text{ TeV}/c^2$$

Expected Range LHC

$$M_{Z'} \sim 4.5 \text{ TeV}/c^2$$

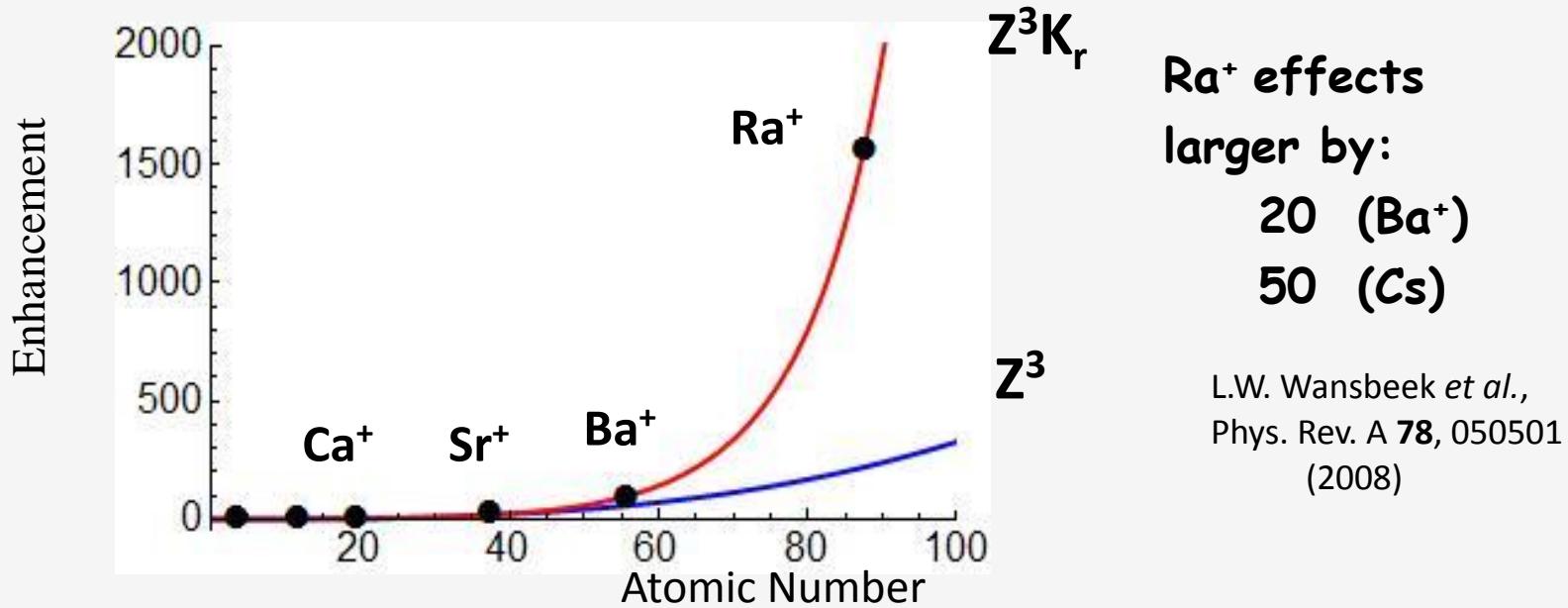
Scaling of the APV

increase faster than Z^3

(Bouchiat & Bouchiat, 1974)

$$\langle nS_{1/2} | H_W | nP_{1/2} \rangle \propto K_r Z^3$$

K_r relativistic enhancement factor



$Z^3 K_r$
 Ra^+ effects
larger by:
20 (Ba^+)
50 (Cs)

L.W. Wansbeek *et al.*,
Phys. Rev. A **78**, 050501
(2008)

→ 5-fold improvement over Cs feasible in 1 day

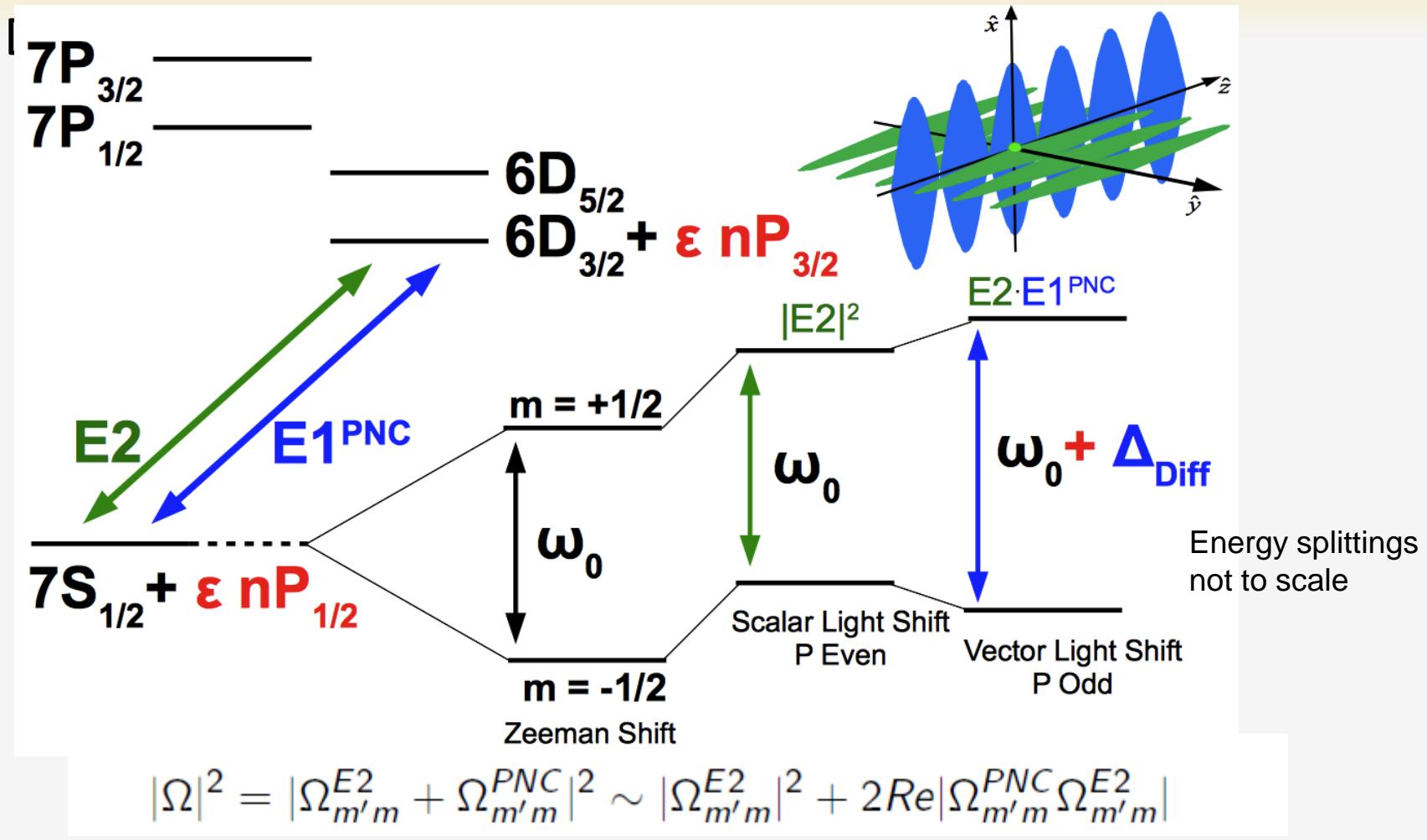
Relativistic coupled-cluster (CC) calculation of $E1_{\text{APV}}$ in Ra^+

$$E1_{\text{APV}} = 46.4(1.4) \cdot 10^{-11} \text{ iea}_0(-Q_w/N) \quad (3\% \text{ accuracy})$$

Other results:

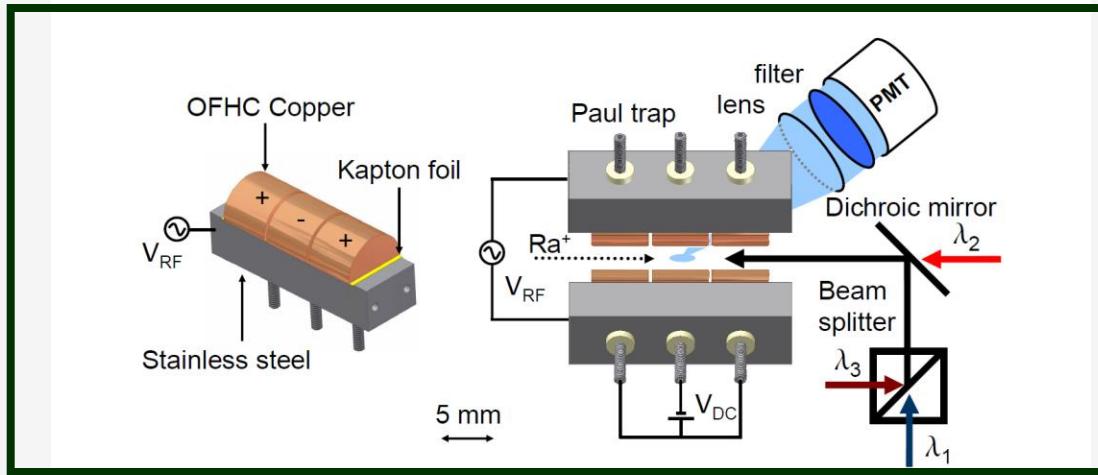
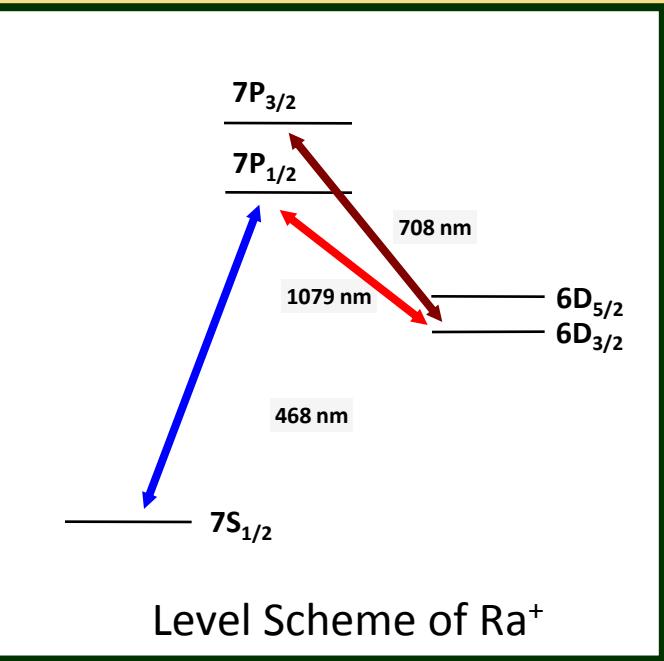
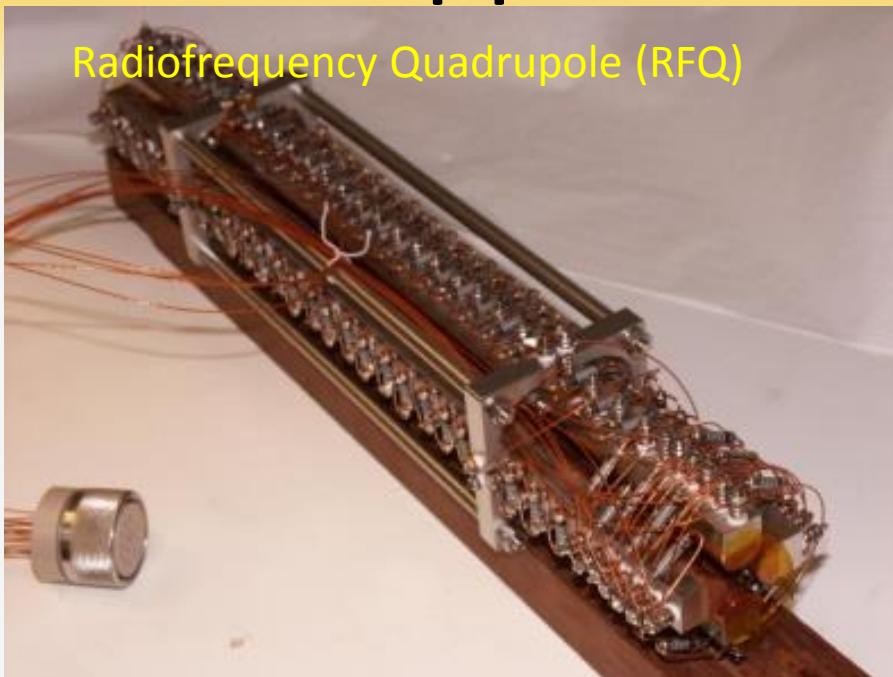
$$45.9 \cdot 10^{-11} \text{ iea}_0(-Q_w/N) \quad (\text{R. Pal } \textit{et al.}, \text{ Phys. Rev. A } \mathbf{79}, 062505 \text{ (2009)}, \text{ Dzuba } \textit{et al.}, \text{ Phys. Rev. A } \mathbf{63}, 062101 \text{ (2001)})$$

Experimental Method



Trapped Ra⁺ Spectroscopy

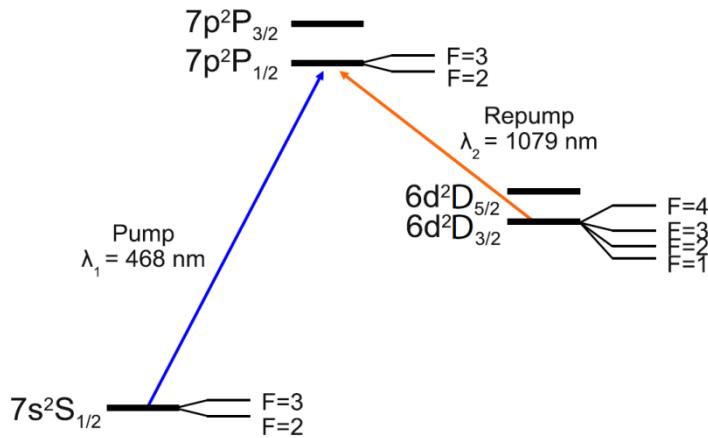
Radiofrequency Quadrupole (RFQ)



Laser Spectroscopy in Ra^+

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

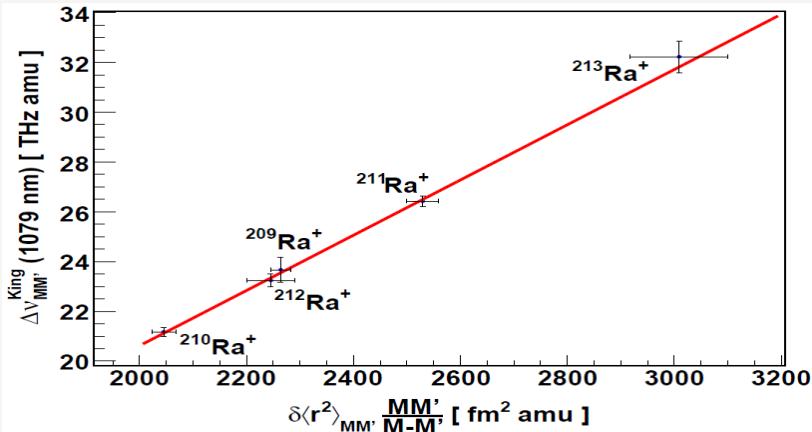
$^{211,209}\text{Ra}^+ (I=5/2)$



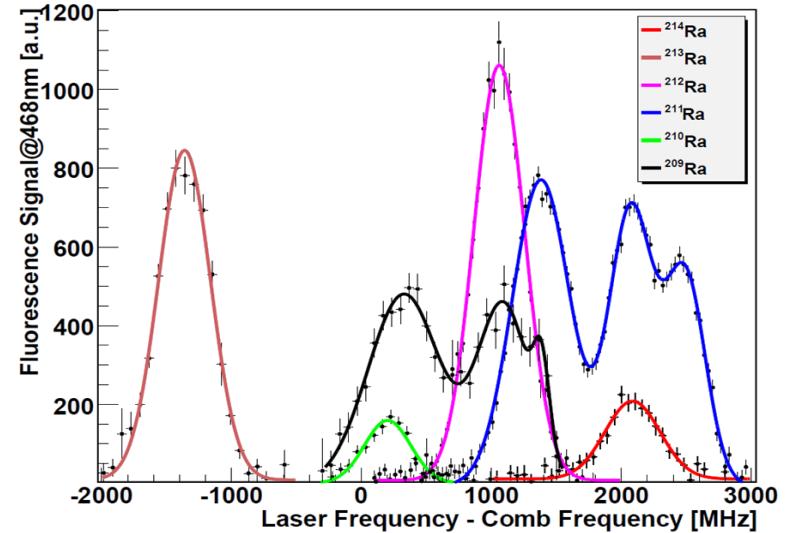
		This work	Theory
$^{211}\text{Ra}^+$	A	151(2)	155* [4], 150* [10], 155* [16]
	B	103(6)	147(12)** [10]
$^{209}\text{Ra}^+$	A	148(10)	153* [4], 148* [10], 153* [16]
	B	104(38)	122(12)** [10]

$\sim 3,5 \sigma$

Probe of atomic wave functions at the origin



Probe of atomic theory & size and shape of the nucleus



O. O Versolatao et. al., Phys. Lett. A375 (2011) 3130-3133

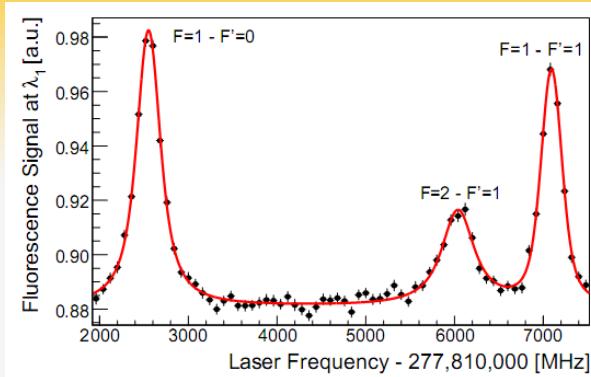
G. S. Giri et al. Phys. Rev. A 84, 020503(R) (2011)

[10] B.K. Sahoo et al. Phys. Rev. A, 76 (2007)

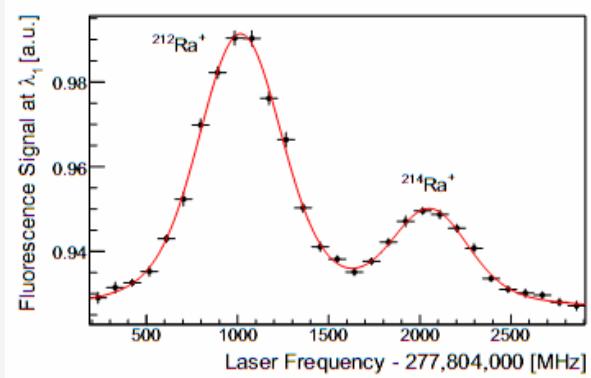
B.K. Sahoo et al. Phys. Rev. A, 79, 052512 (2009)

Ra^+ measurements

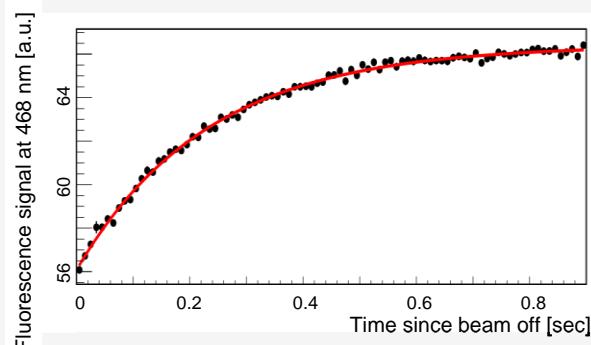
Hyperfine Structure:
Atomic wave functions at the origin



Isotope Shifts:
Atomic theory & size and shape of the nucleus



State lifetime:
Probe of S-D E2 matrix element



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

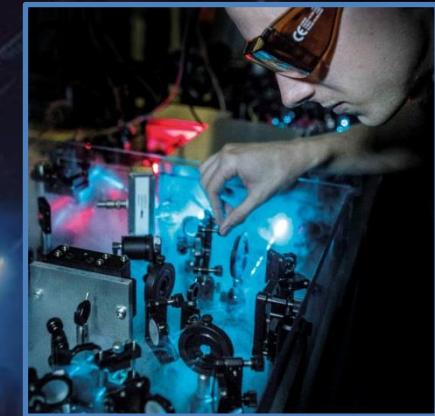
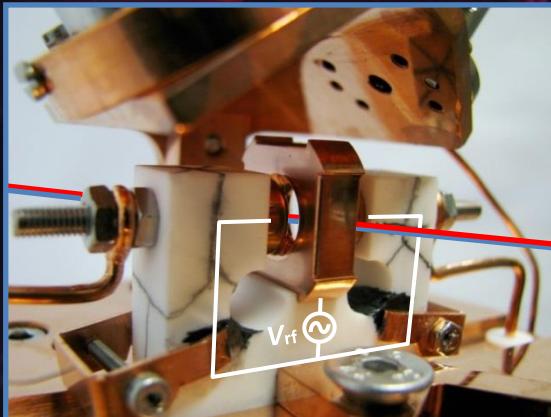


Single trapped Ba⁺ ion

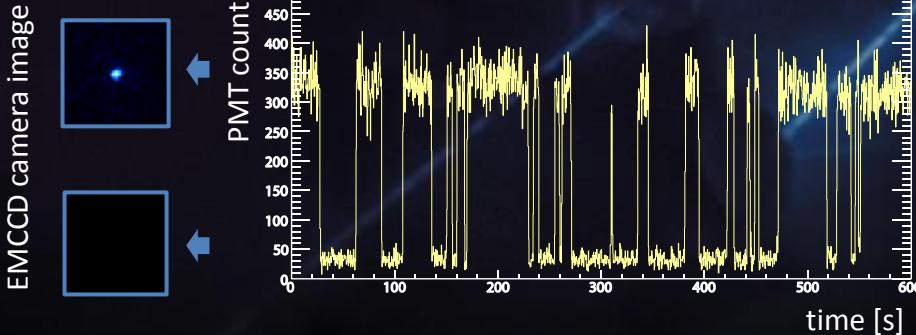
- Iso-electronic to radium
- Develop apparatus & techniques

Featured in Universiteitskrant (Oct 2013)

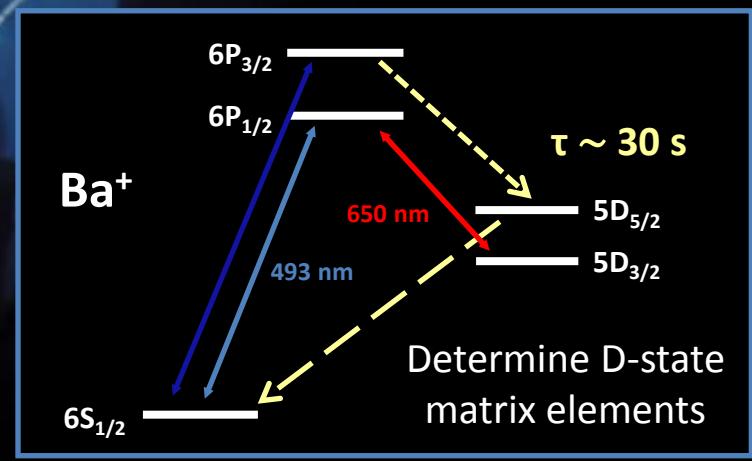
Photo: Pepijn van den Broeke



- 5D_{5/2} state lifetime measurement
- Single ion quantum jump spectroscopy

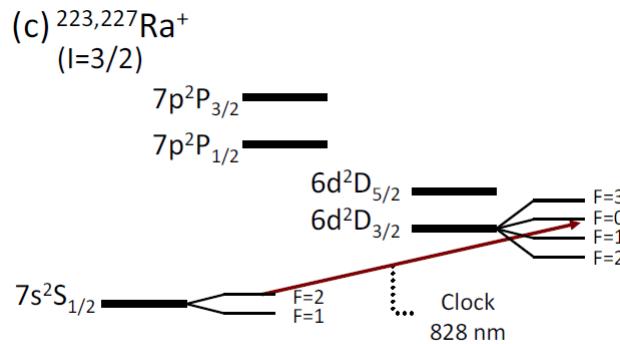
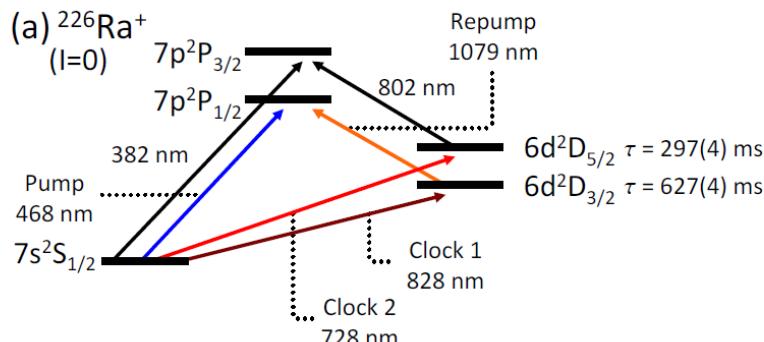


- Measure lifetime and transition freqs



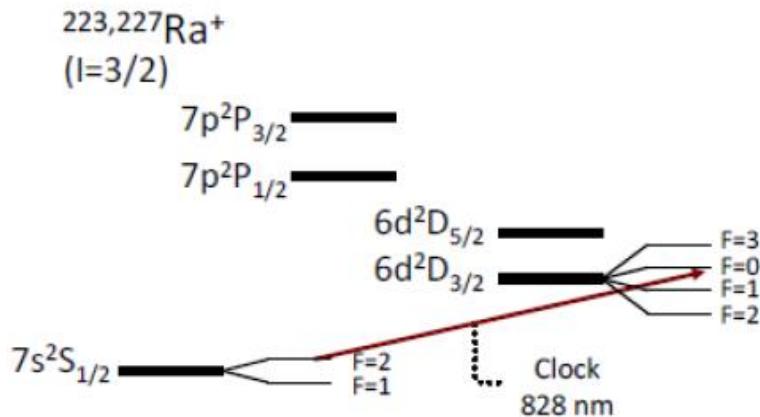
Ra⁺ Clock

- Narrow transition, ultra stable lasers
- Low sensitivity to external fields for some transitions ($I=3/2$)



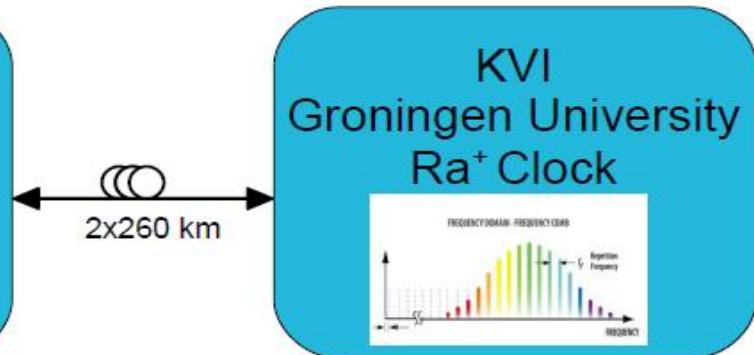
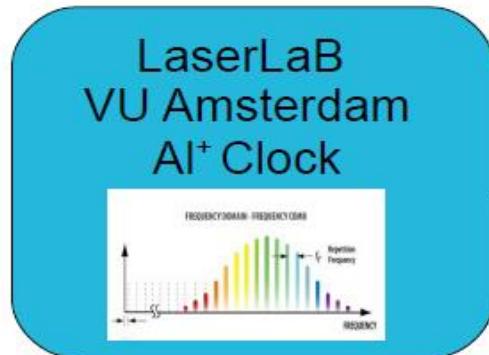
	Major systematics: Quadrupole shift	da/dt relative strength	Atomic Parity Violation	Laser wavelength
^{27}Al	$< 10^{-17}$ [Itano]	1 [Dzuba, Flambaum]	Z small	deep uv
^{199}Hg	10^{-17} [Itano]	-400 [Dzuba, Flambaum]	atomic theory difficult to treat	deep uv
^{213}Ra	$< 10^{-17}$ [Sahoo]	400 [Versolato et al.]	relativistic effects structure calculable	diode lasers

Ra^+ 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

$<10^{-18}$ $^{223}\text{Ra}^+$ Atomic Clock

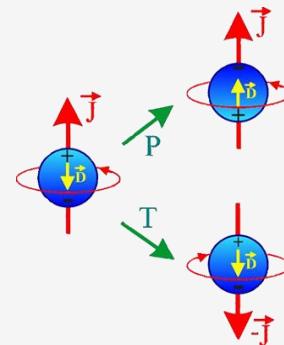
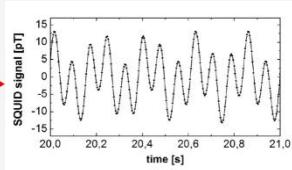
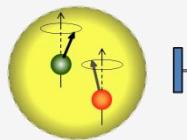


Symmetry violation Tests with nuclear Probes

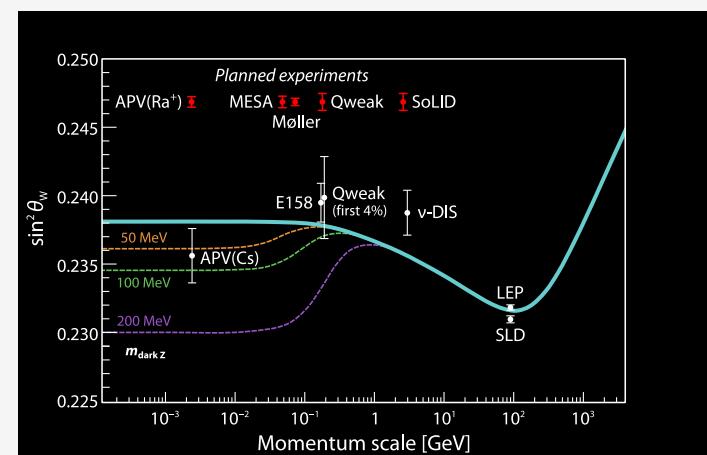
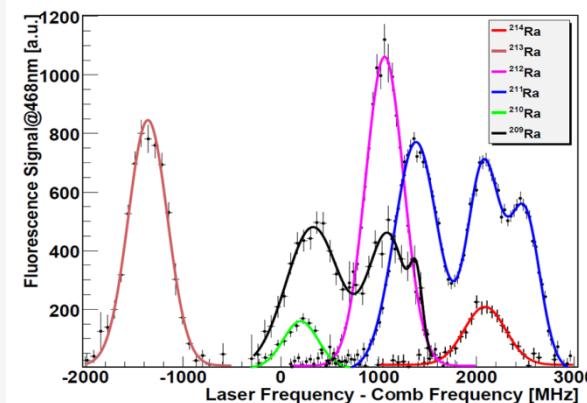
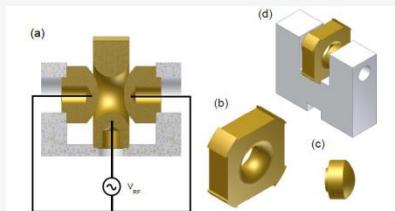
Unique possibilities to test Standard Models

Requires access to isotopes (available at facilities)

EDM in Radium and ^{129}Xe



Atomic Parity Violation in a single Ra^+



The Crew & Acknowledgments

Experiment

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

Theory

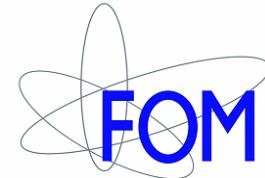
- Lotje Wansbeek
- Sophie Schlessler
- Bijaya Sahoo
- Lex Dieperink
- Rob Timmermans

International collaborators

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

Funding

- FOM open competition
- FOM program TRI μ P
- NWO Toptalent grant
- NWO Veni fellowship



Program 2011-2017

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Broken Mirrors and Drifting Constants



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groningen

Mainz



Netherlands Organisation for Scientific Research