Testing Fundamental Symmetries at the Atomic Scale

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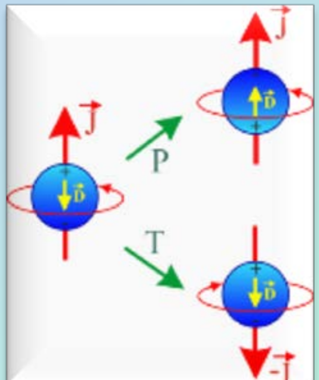

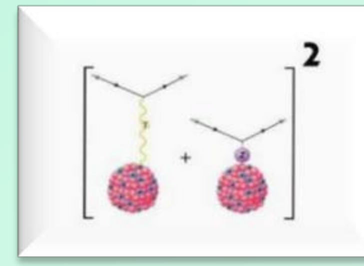

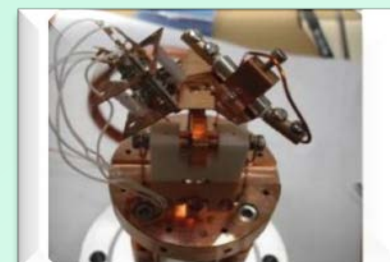

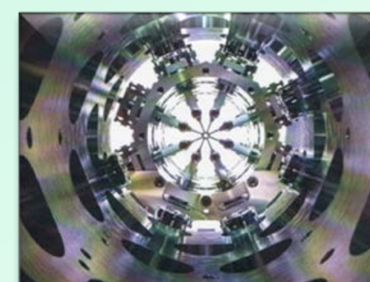

- ➢ **Selection of a Few Topics neccessary**
  → *Focus on Transformativity*
- ➢ **C, P, CP, CPT**
  → *Precision Test of Standard Model*
- ➢ **Hand in Hand with Applications**
  → *Atomic Parity Violation & Precision Clocks*
- ➢ **Search for permanent Electric Dipole Moments**
  → *Exploiting & Testing Symmetries*

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Van Swinderen Institute @RUG

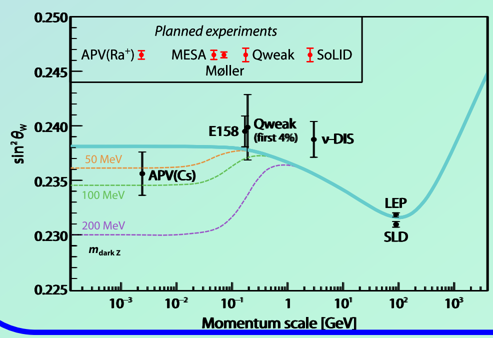
Low Energy Precision Physics

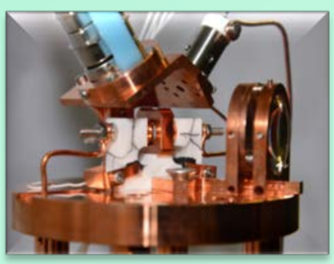
A. Borschevsky, S.Hoekstra, K. Jungmann, R.G.E. Timmermans, L. Willmann (H.W. Wilschut until 2016)

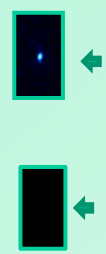
VSI has Three Research Lines *(with both Experiment & Theory)*:

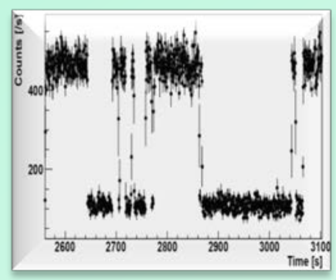
- **Cosmic Frontier** - *Early Universe & Gravitation*
- **High Energy Frontier** - *Standard Model Tests, LHCb*
- **Precision Frontier** - *Low Energy Precision Standard Model Tests*

Focus: Parity Violation in Ra/Ba towards measuring $\sin^2 \theta_W$ at low Q



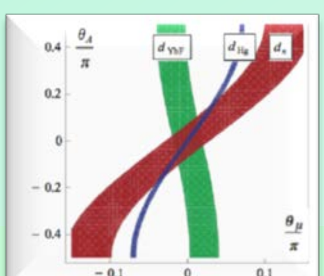


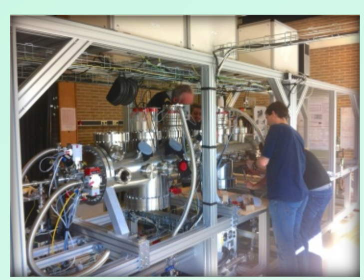




→
- single ion experiment
- sensitive to Z'
- sensitive to dark Z-boson
- many more

Focus: EDM in ^{129}Xe and in Cold Molecule BaF





→
- Xe experiment advanced (with U. Mainz & U. Heidelberg)
- BaF big enhancement (with VU Amsterdam)
- sensitive to New Physics
- Goal: Best Electron EDM

Standard Model Tests

- **Standard Model (SM) of particle physics is Best Theory we have !**
- **Still large number of open questions**
  e.g. particle masses, origin of parity violation, ...

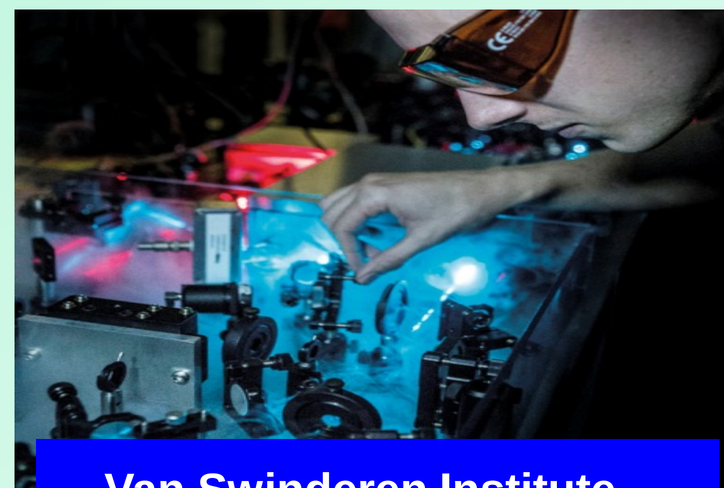
Direct:
Searches for New Particles

LHC @ CERN

e.g. Discovery of Higgs boson,..
also: Difference Matter-Antimatter …

Equivalent Approaches

Indirect:
High Precision Measurements



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e.g. Atomic Parity Violation (APV), EDM searches, …..

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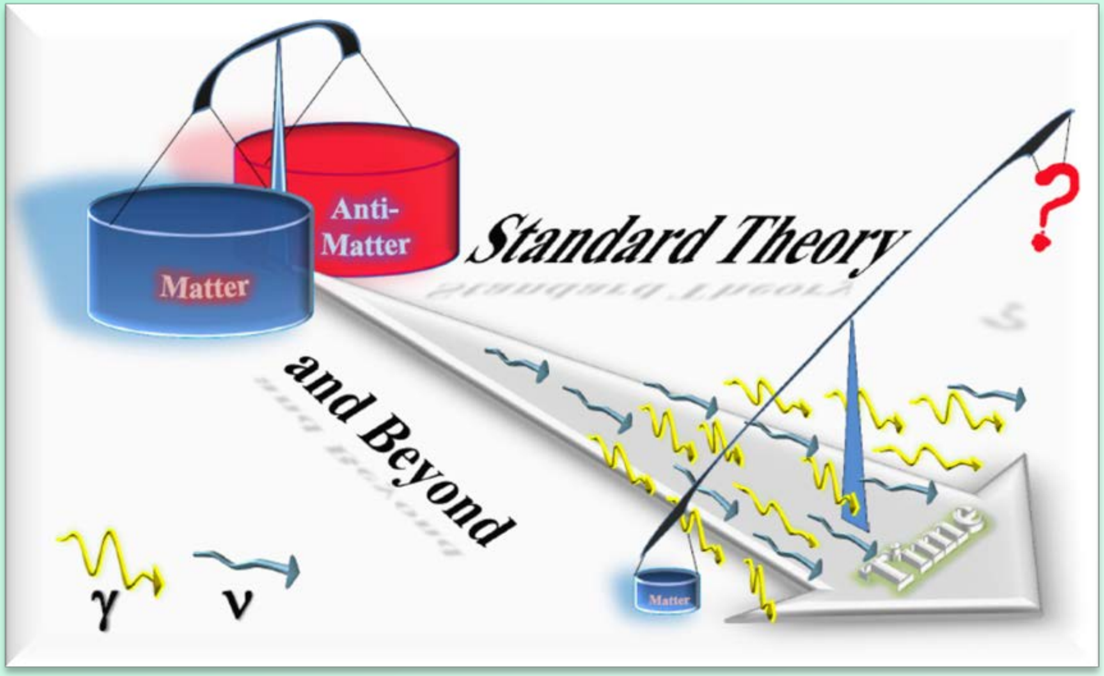
Discrete Symmetries C,P,T,CP,CPT



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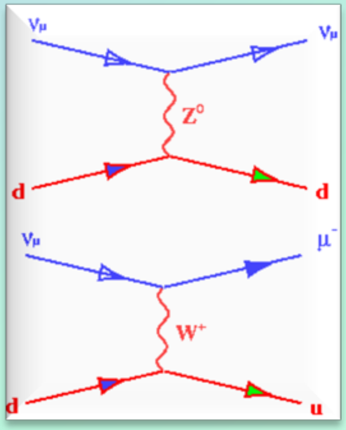
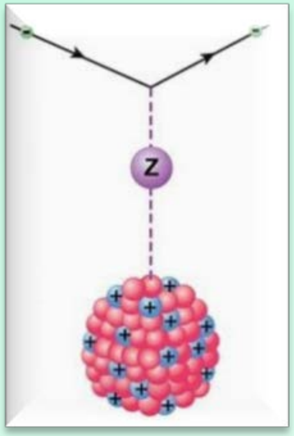
Parity





→ *relatively large effects* in some atoms and molecules

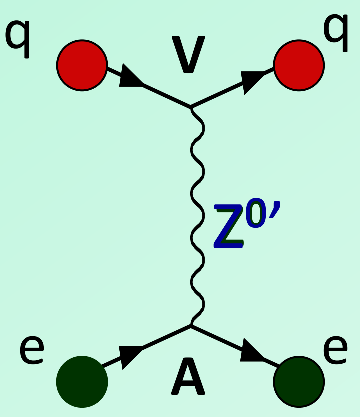
→ one valence electron atoms to extract precise constants

→ more complex systems to study e.g. anapole moments

Atomic Parity Violation (APV)

Physics beyond the SM

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



Extra Z' boson in SO(10) GUTs:

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

Londen en Rosner (1986)
Marciano en Rosner (1990)
Altarelli et al. (1991)

Bound on $M_{Z'}$ from cesium APV

(84% confidence level, ξ= 52° *Derevianko 2009*)

$M_{Z'} > 1.3$ TeV/c^2

(Tevatron $M_{Z'} > 0.82$ TeV/c^2)

Bound (possible) on $M_{Z'}$ from Ra^+ APV

$M_{Z'} > 5$ TeV/c^2

(full LHC $M_{Z'}$ ~4.5 TeV/c^2)

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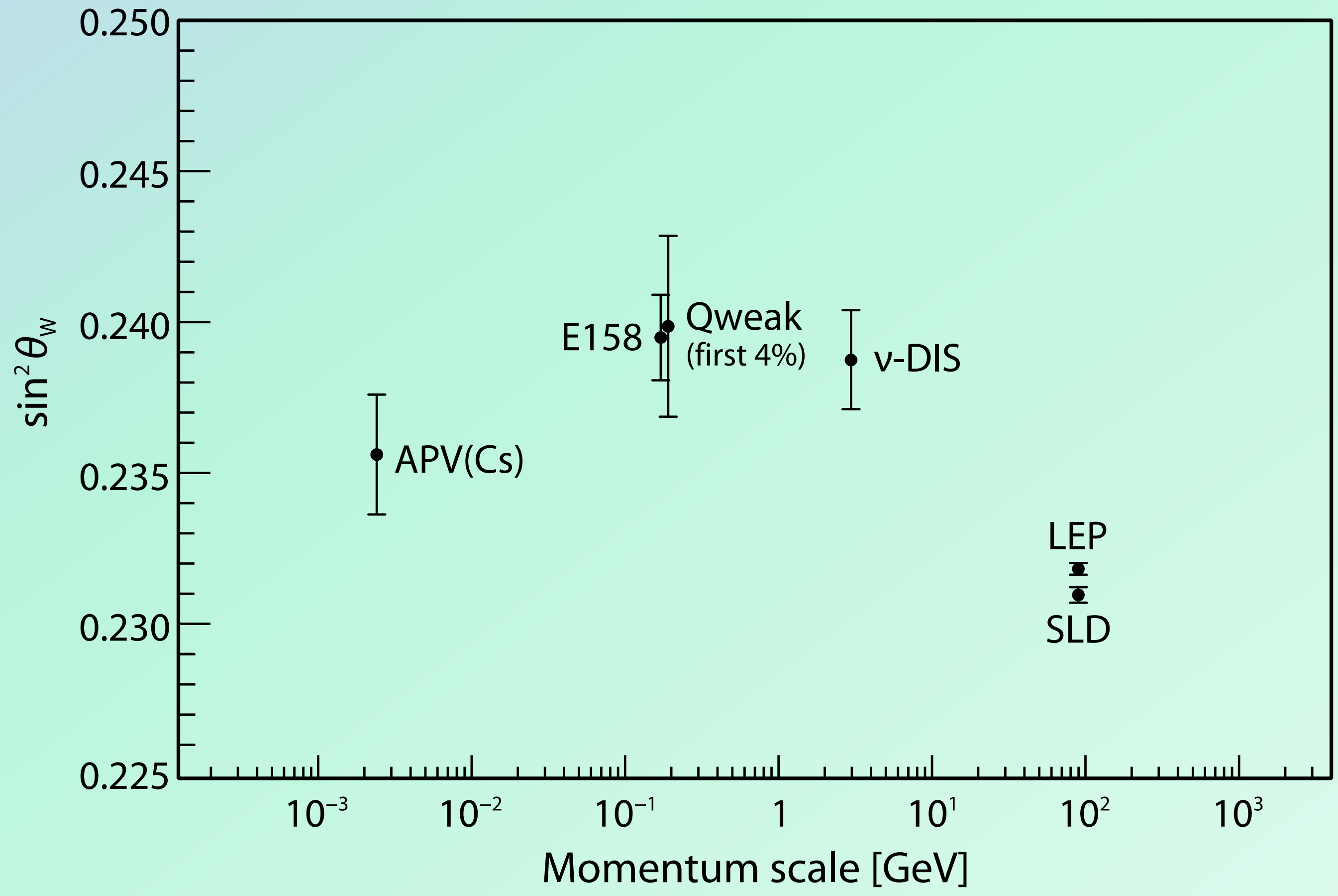
The way to go!

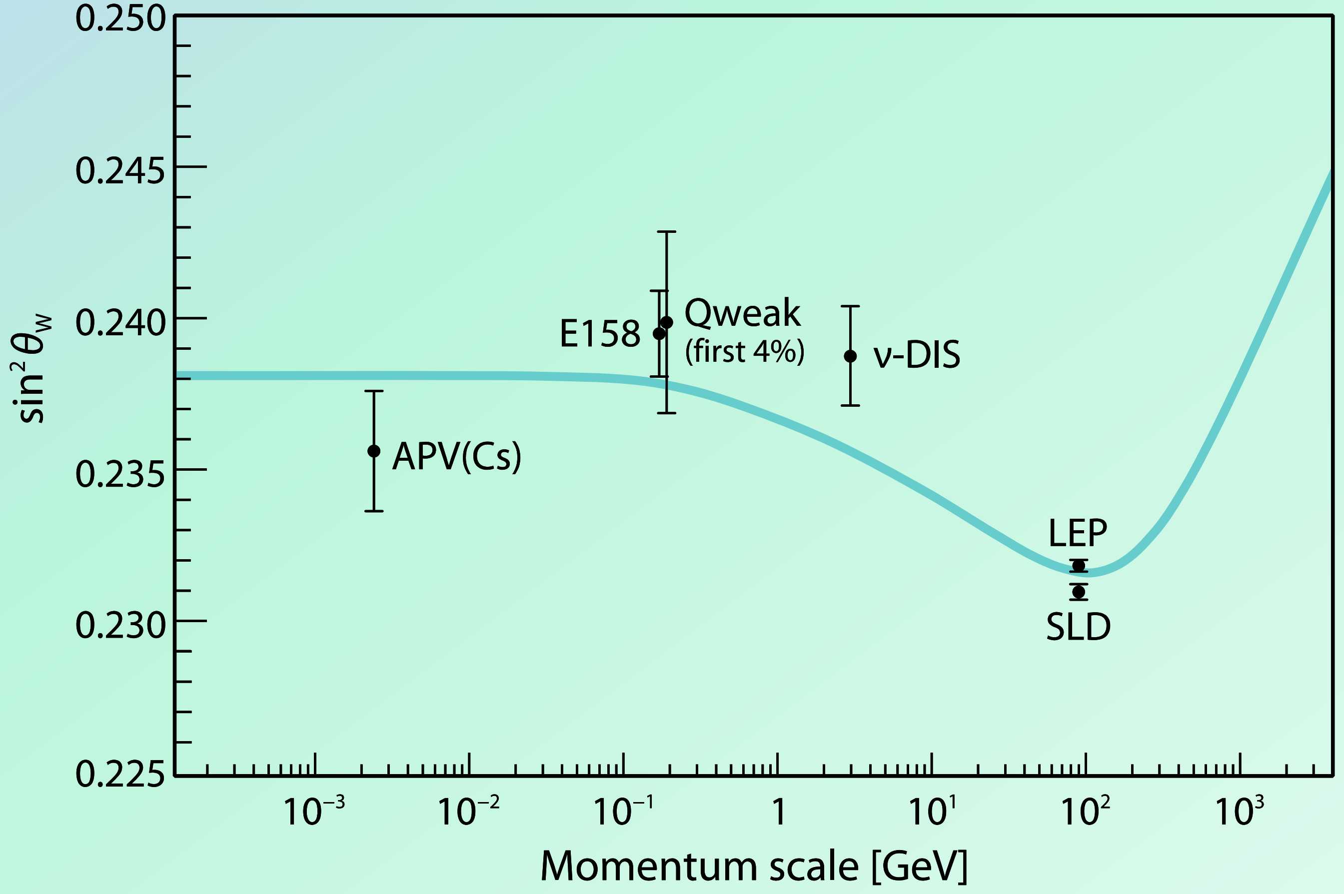
Test of Standard Model

Electroweak Interactions



Test of Standard Model

Electroweak Interactions



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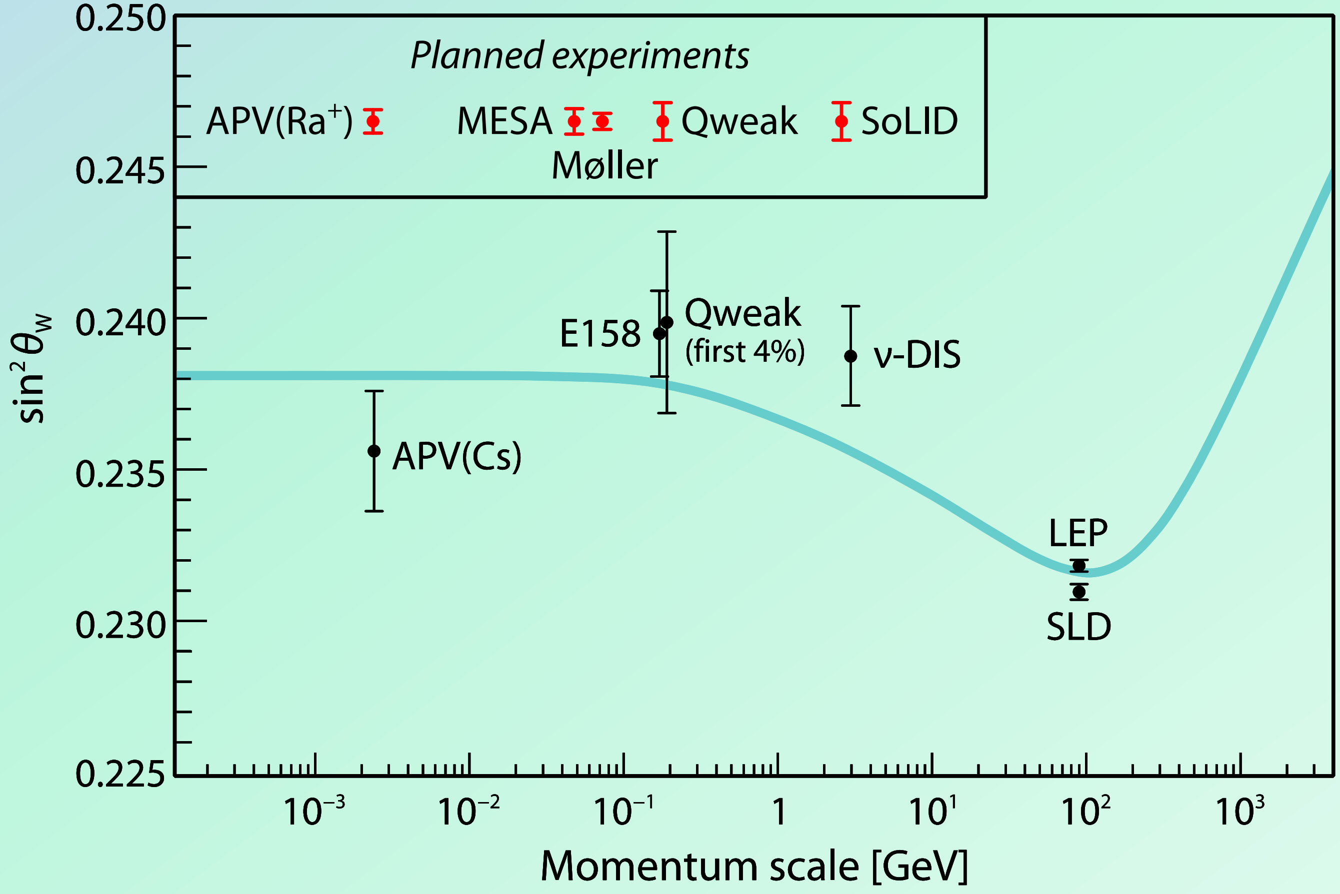
Test of Standard Model

Electroweak Interactions



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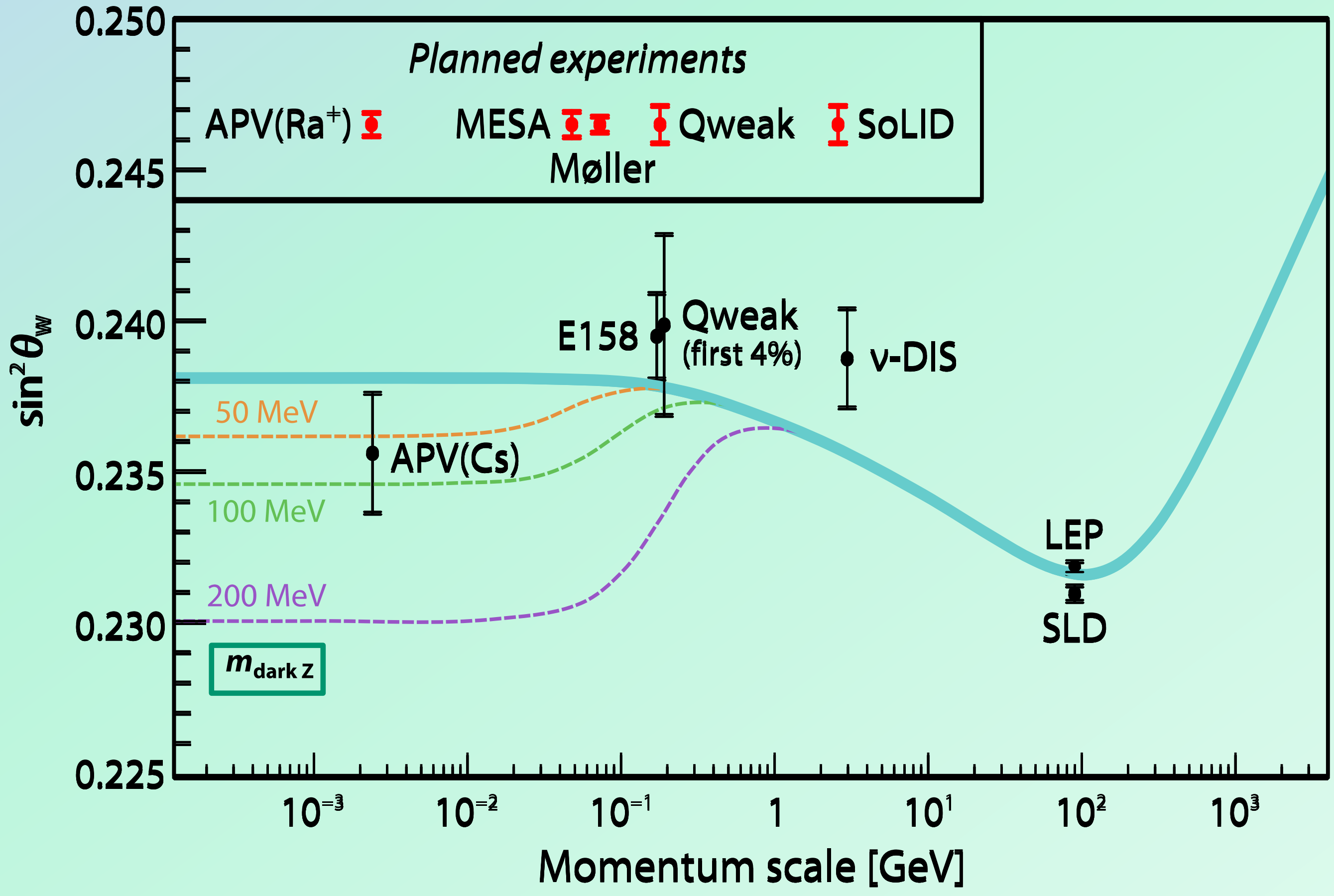
Test of Standard Model

Electroweak Interactions



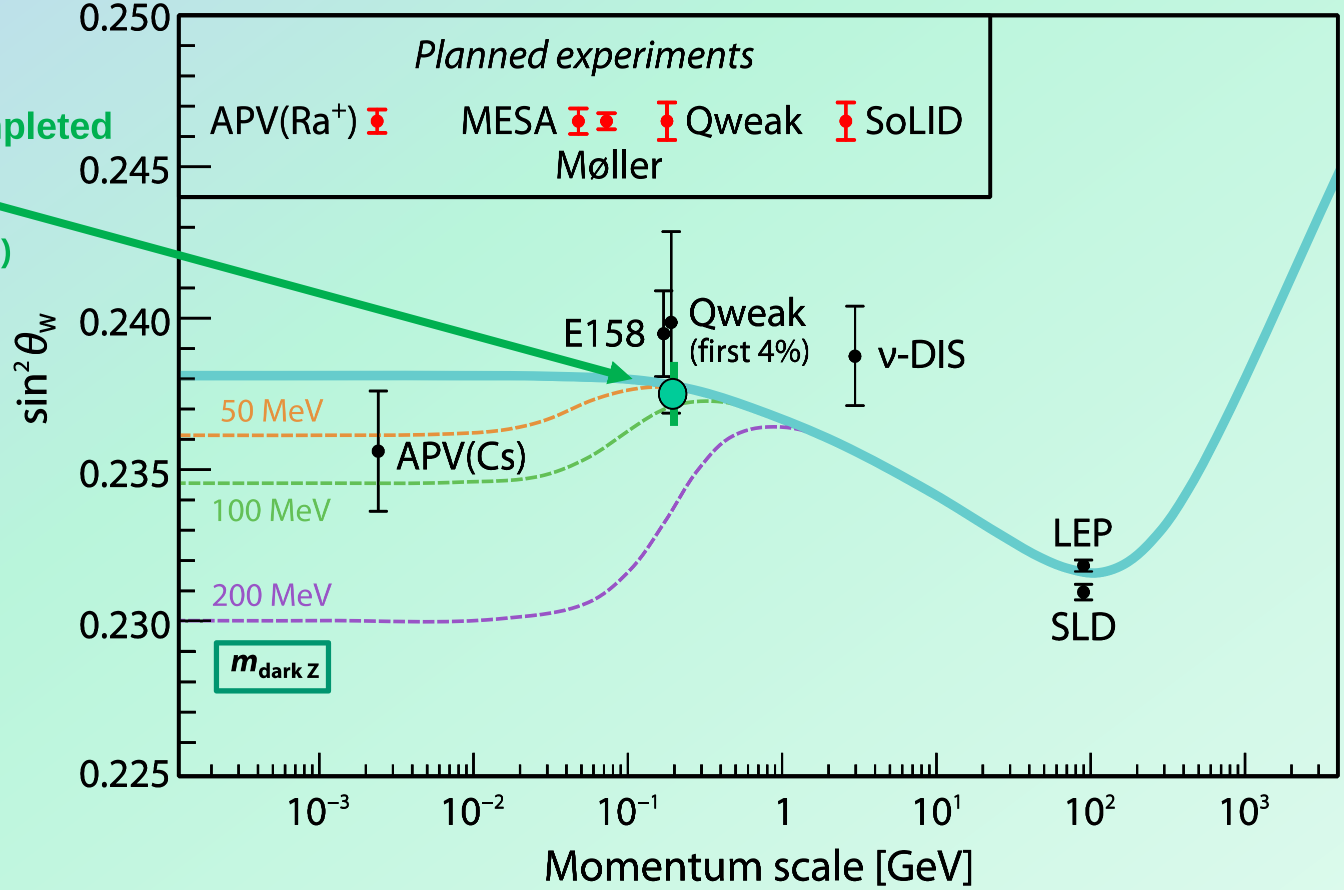
S. Kumar, W. Marciano, Annu. Rev. of Nucl. Part. Sci. **63,** 237 (2013)
H. Davoudiasl, Hye-Sung Lee, W. Marciano, arxiv. 1402.3620 (2014)

Test of Standard Model

Electroweak Interactions

work recently completed

Qweak collab.,
Nature 557, 207 (2018)



S. Kumar, W. Marciano, Annu. Rev. of Nucl. Part. Sci. **63,** 237 (2013)
H. Davoudiasl, Hye-Sung Lee, W. Marciano, arxiv. 1402.3620 (2014)

Test of Standard Model

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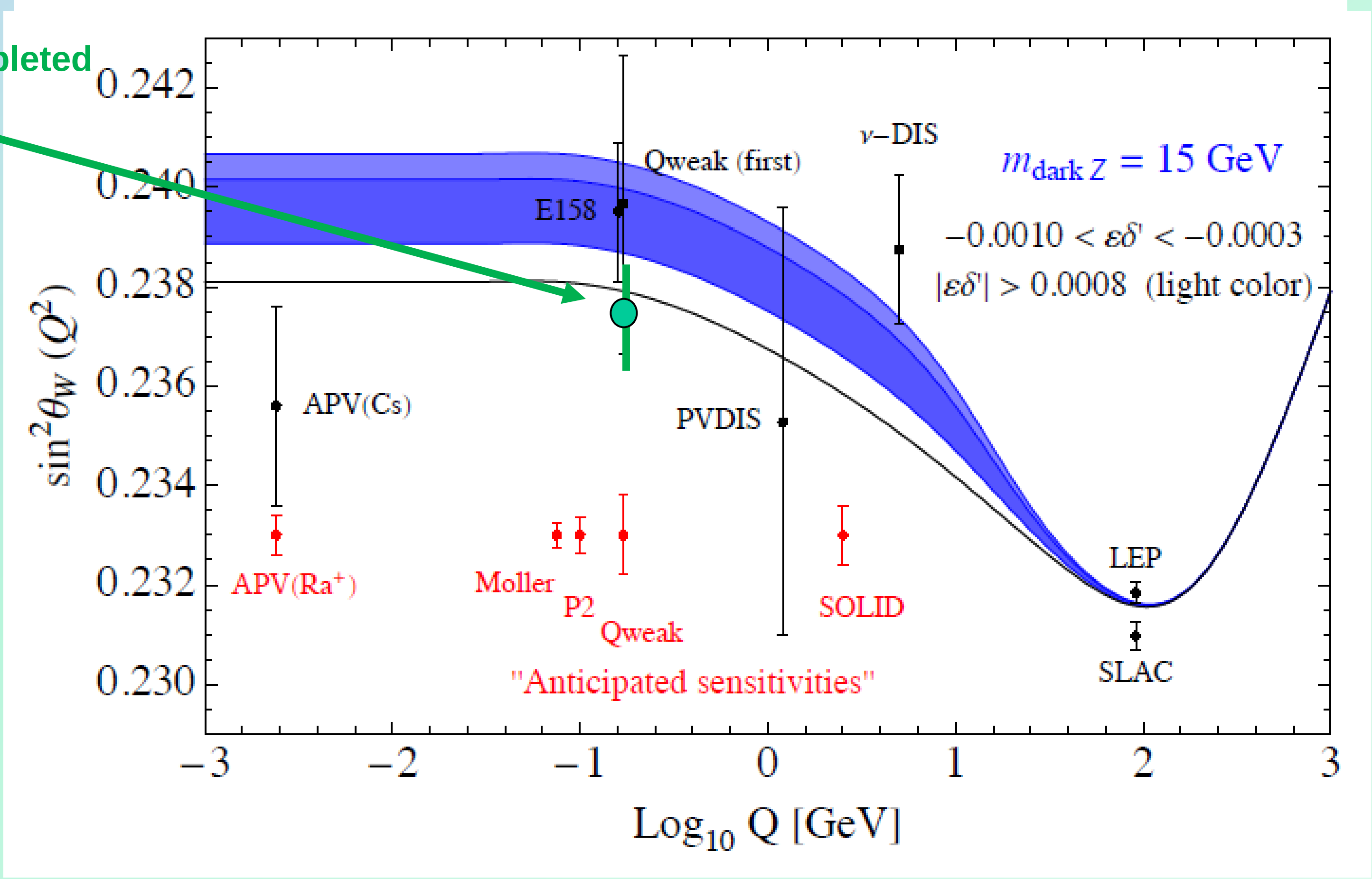
work recently completed

Qweak collaboration, Nature 557, 207 (2018)



S. Kumar, W. Marciano, Annu. Rev. of Nucl. Part. Sci. **63,** 237 (2013)
H. Davoudiasl, Hye-Sung Lee, W. Marciano, arxiv. 1402.3620 (2014)
H. Davoudiasl, H. S. Lee and W. J. Marciano, Phys. Rev. **D 92**, 055005 (2015)

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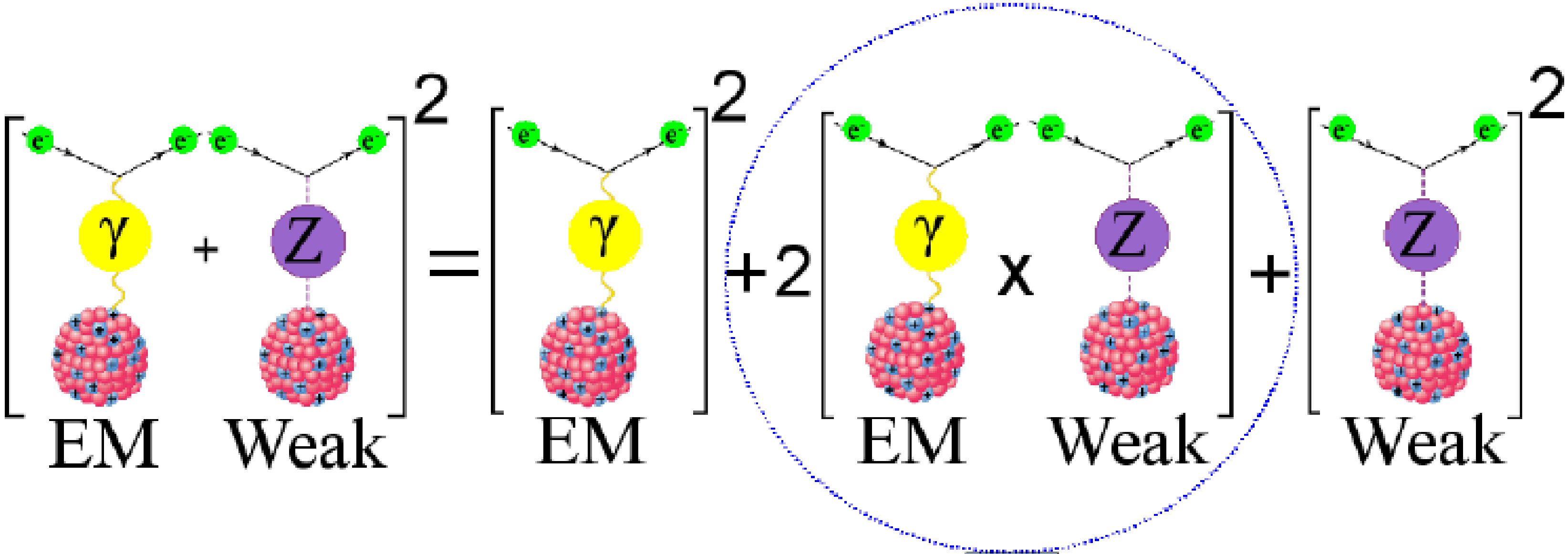
Atomic Parity Violation

basic concept



Sub-percent accuracy is essential

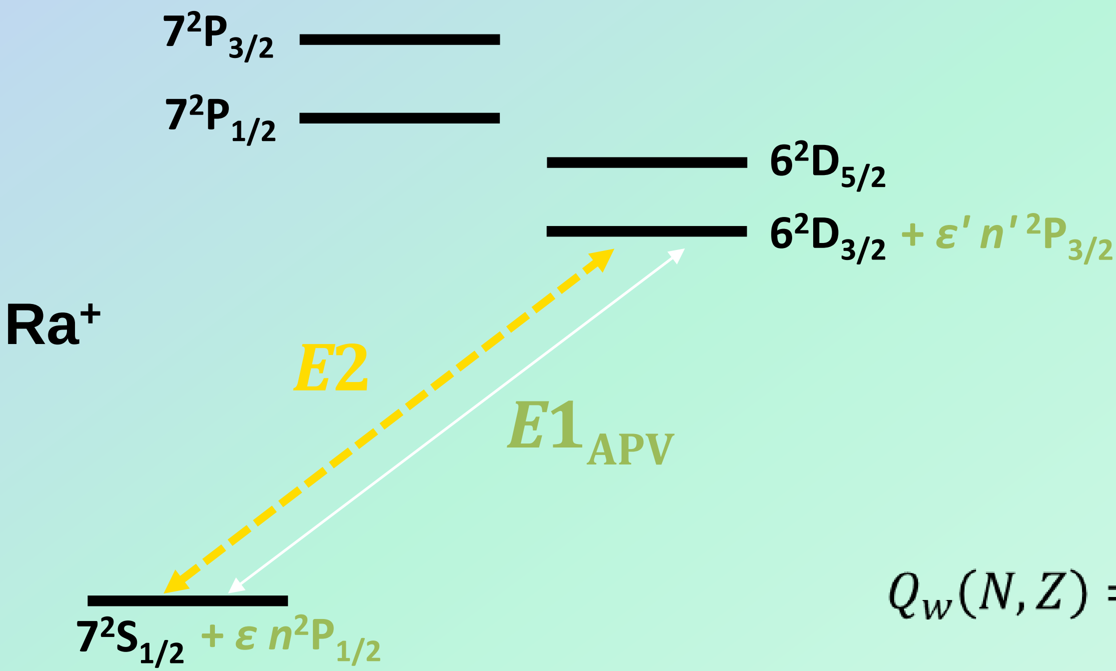
$Q_w = -N + (1-4\sin^2\theta_w)Z + QED +$ "New Physics"

$E1^{APV} = 46.4(1.4) \times 10^{-11}$ ie a_0 $(-Q_W/N)$ (for Ra^+)

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

Atomic Parity Violation

Extraction of Weinberg Angle



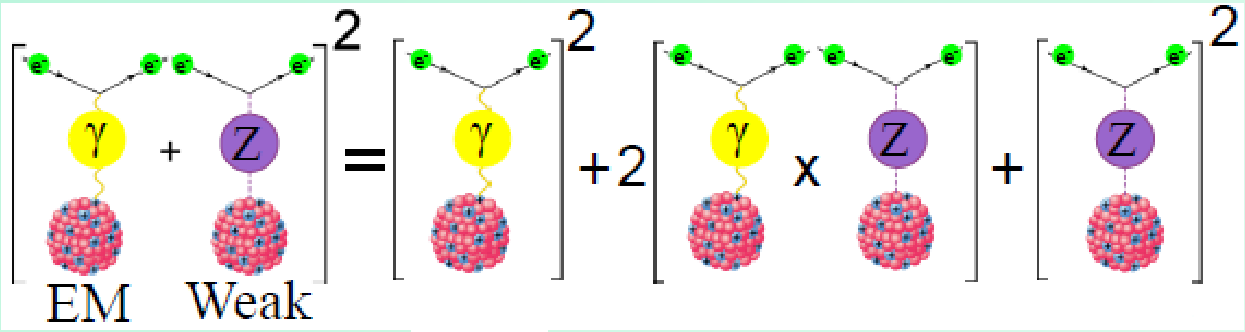
APV effect

$\Psi_e \Psi_n$ overlap

$$E1_{APV} = k \cdot Q_W$$

Weak charge

$$Q_W(N,Z) = -N + (1 - 4\sin^2\theta_W)Z + \text{rad. corr.}$$

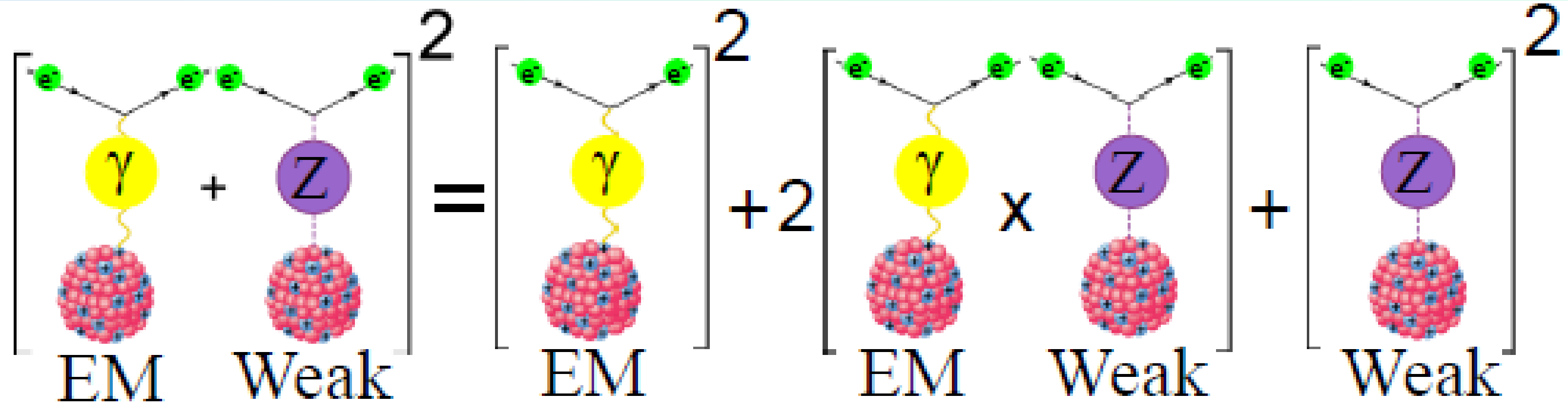


→ **Trapped single ion**

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

Atomic Parity Violation

Extraction of Weinberg Angle



$$Q_W = -N + (1-4\sin^2\theta_W)Z + \textit{rad. corr.}$$

Measured by light shifts

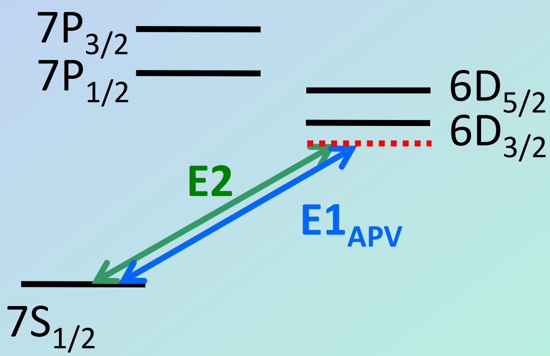
$$Q_W = \frac{E1_{APV}}{k}$$

Weak charge

Depends on atomic structure.

Atomic Parity Violation

Ba^+ and Ra^+

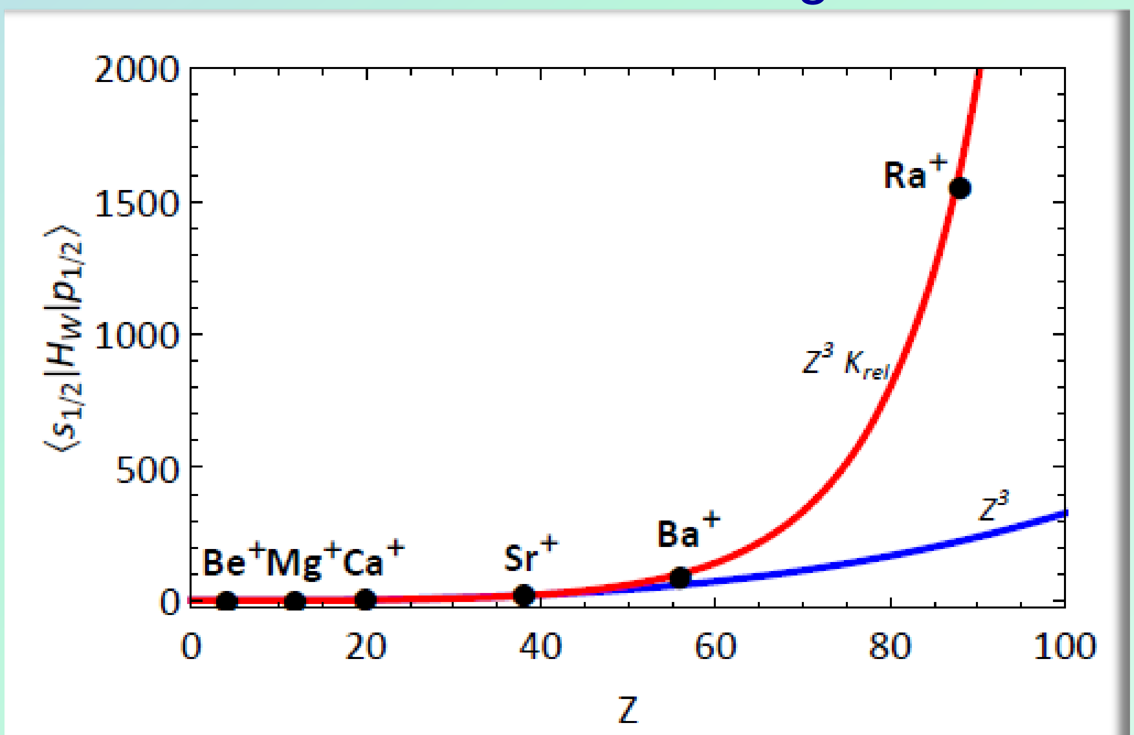


$$Q_W = \frac{E1_{APV}}{k}$$

Calculated from atomic wavefunctions

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

Detailed calculations → stronger than Z^3



Ra^+ superior to measure APV …

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

Theory Calculations:

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

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

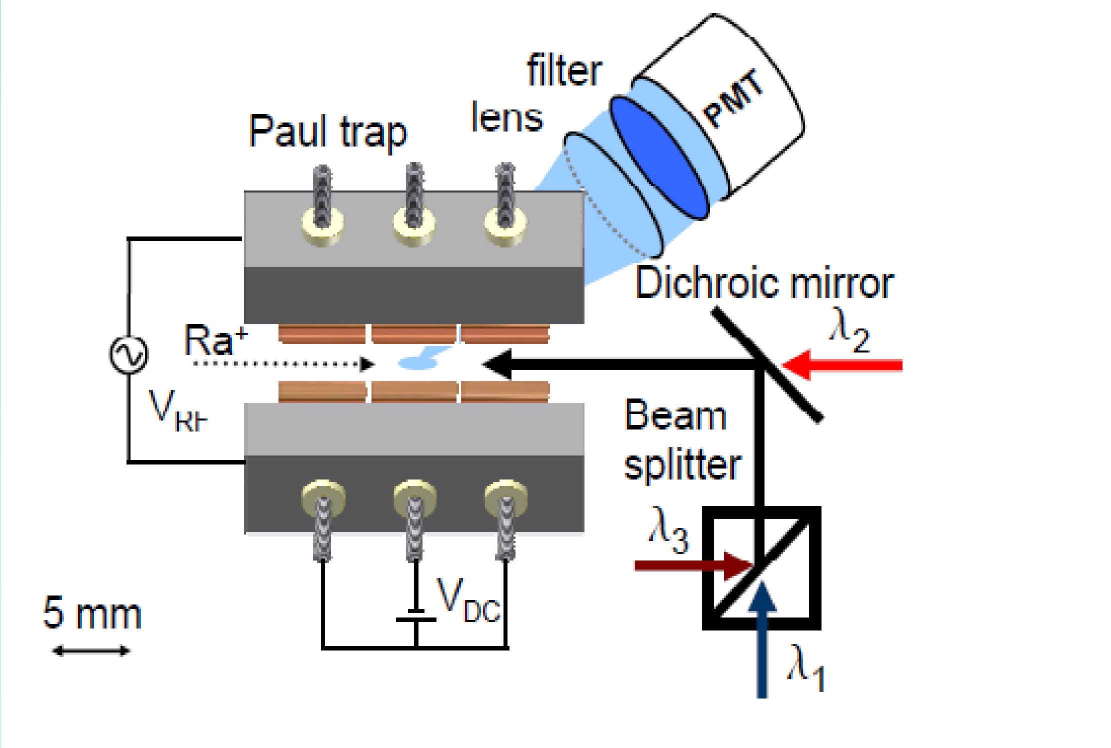
*L.W. Wansbeek *et al.*, Phys. Rev. A **78**, (2008)

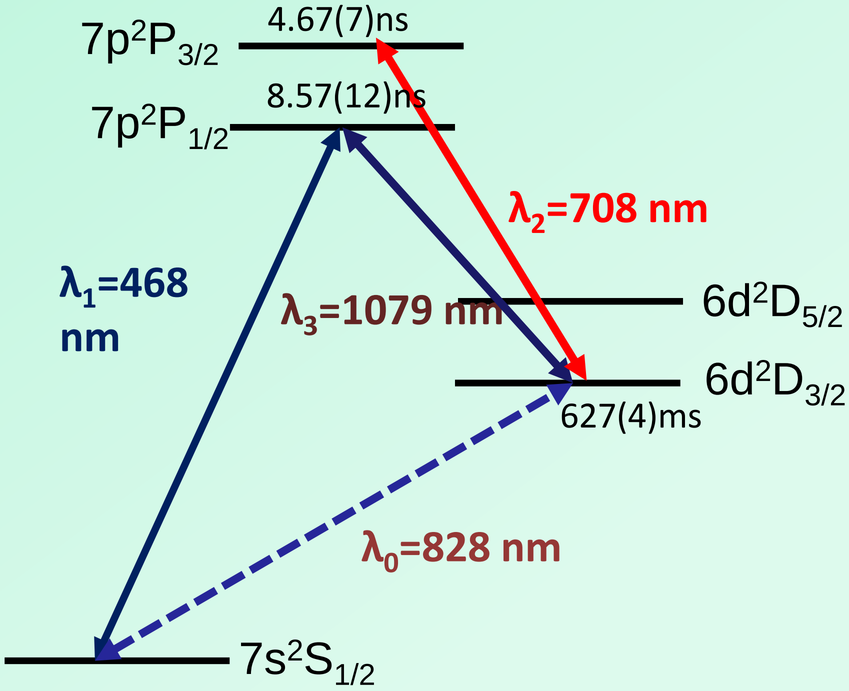
A. Derevianko *et al.*, Phys. Rev. A **79, 013404 (2009)

Laser Spectroscopy in Ra^+ ions

$$Q_W = \frac{E1_{APV}}{k}$$

Calculated from wavefunctions





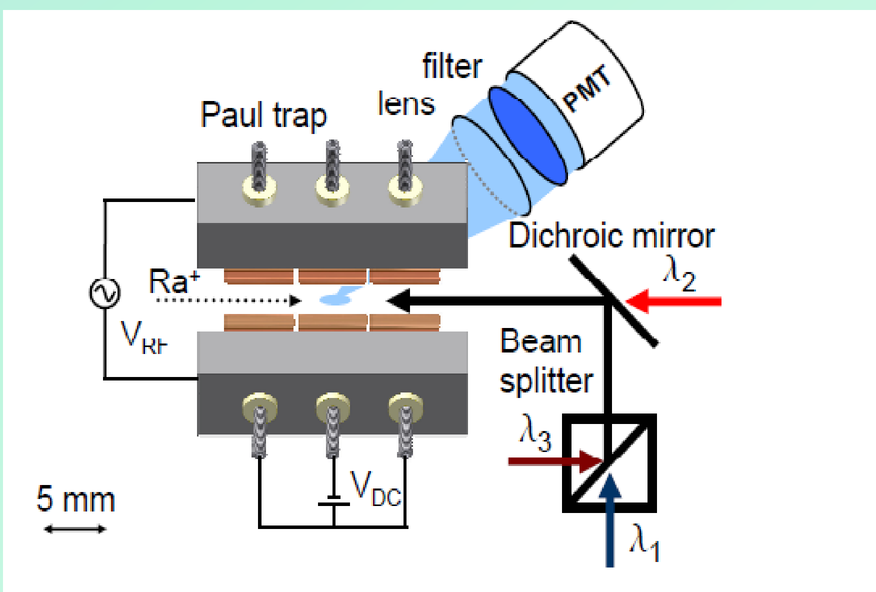
M. Nuñez Portela, et al., Appl. Phys. B, DOI:10.1007/s00340-013-5603-2 (2013)
O.O. Versolato, et al., Phys. Rev. A **82**, 010501(R) (2010)

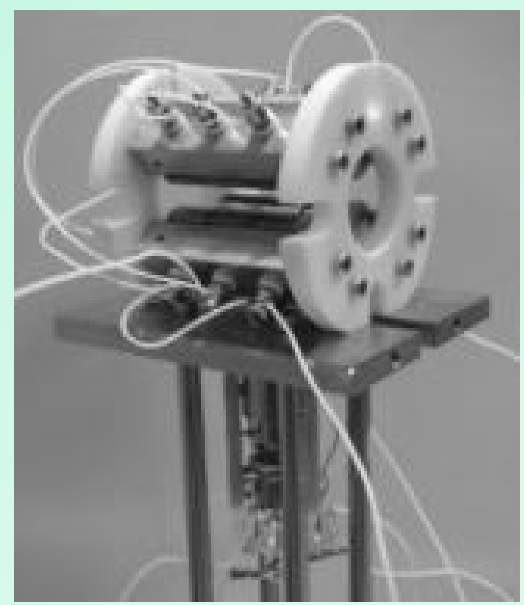
Online Ra^{+} Ion Production

$\Delta N > 10$

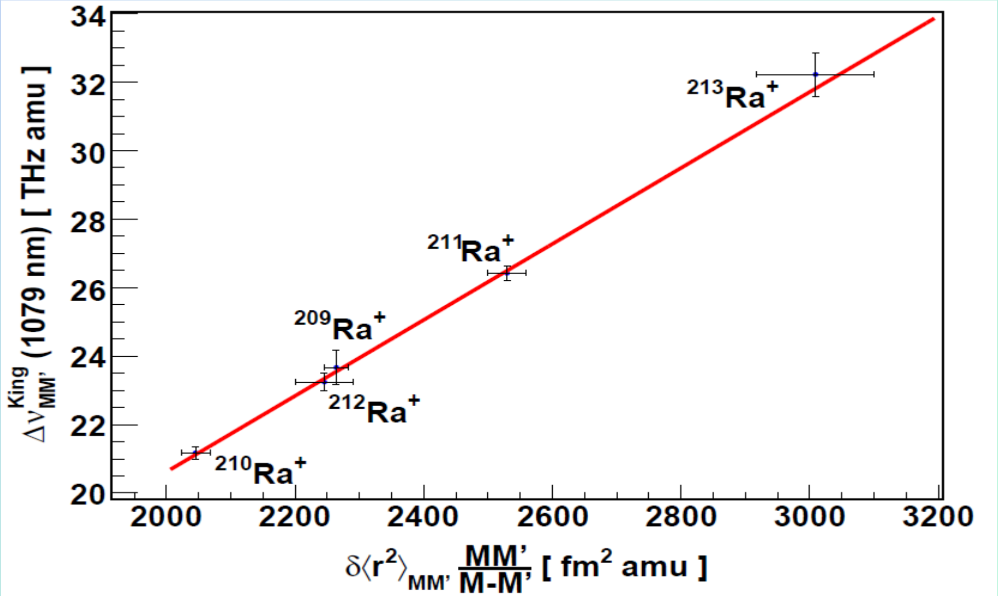
RIB

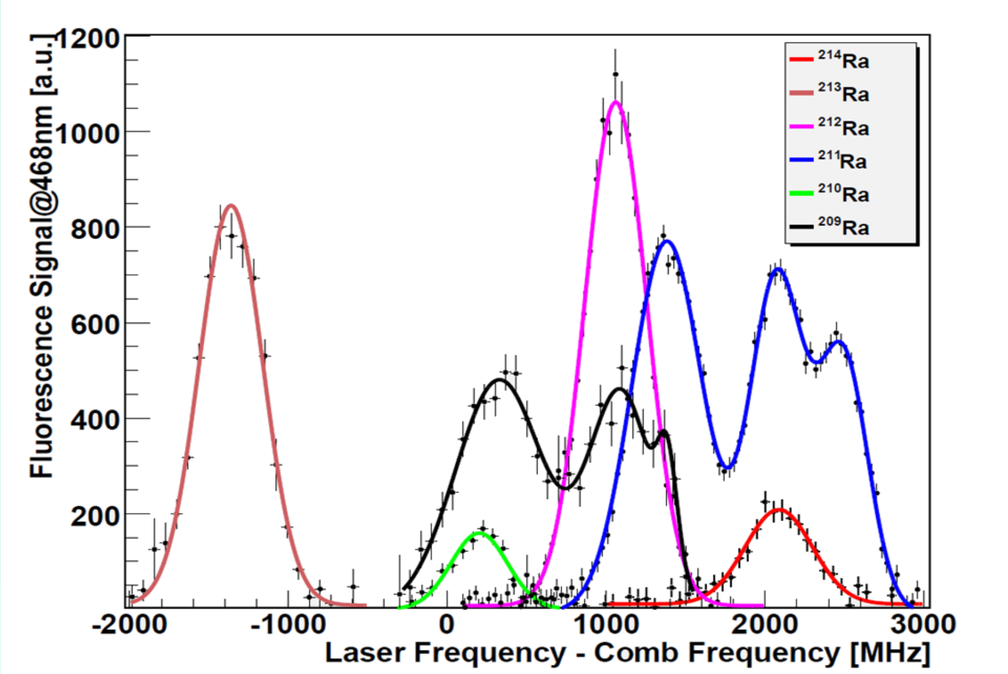
Isotope	I	$T_{1/2}$ [s]	Production Method	Production [ions/s]	Estimated No. trapped ions
^{209}Ra	5/2	4.6(1.5)	Facility	200	40
^{210}Ra	0	3.66(18)	Facility	500	75
^{211}Ra	5/2	12.61(5)	Facility	1 000	1 200
^{212}Ra	0	12.5(1.0)	Facility	800	1000
^{213}Ra	1/2	162.0(1.7)	Facility	2 600	10 000
^{214}Ra	0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





Laser Spectroscopy in Ra^+ Ions





Probe of atomic theory & size and shape of the nucleus

(nucleus starts to matter at sub% accuracy)

Probe of atomic wave functions at the origin

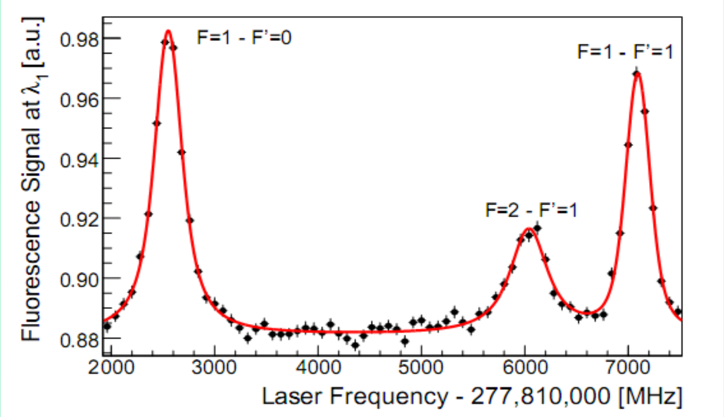
Good agreement with theory at few % level
Theory improvement is in pipeline.

O.O. Versolato et al., Phys. Lett. A 375, 3130 (2012)
O.O. Versolato et al., Phys. Rev. A 82, 010501(R) (2010)
G.S. Giri et al., Phys. Rev. A 84, 020503(R) (2011)

Ra+ Measurements @ AGOR

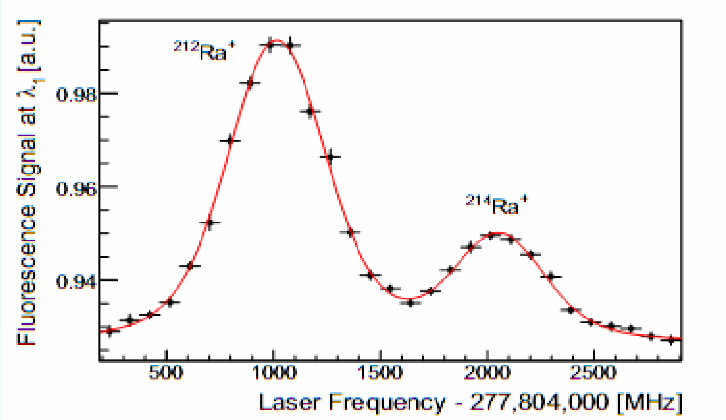
Hyperfine Structure:

Probe of atomic wave functions at the origin



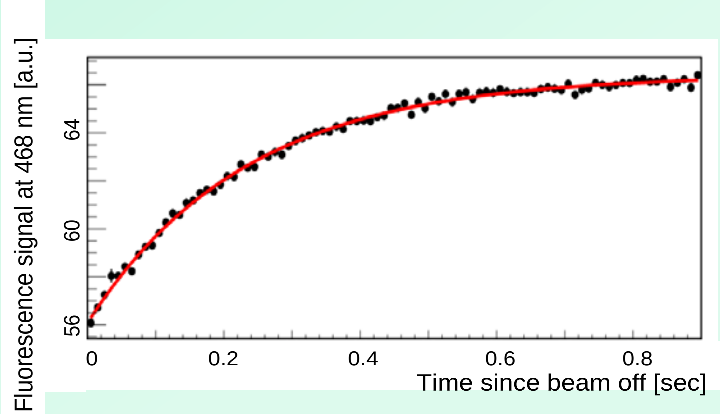
Isotope Shifts:

Probe of atomic theory & size and shape of the nucleus



Excited State Lifetimes:

Probe of S-D E2 matrix element



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

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Intermezzo:

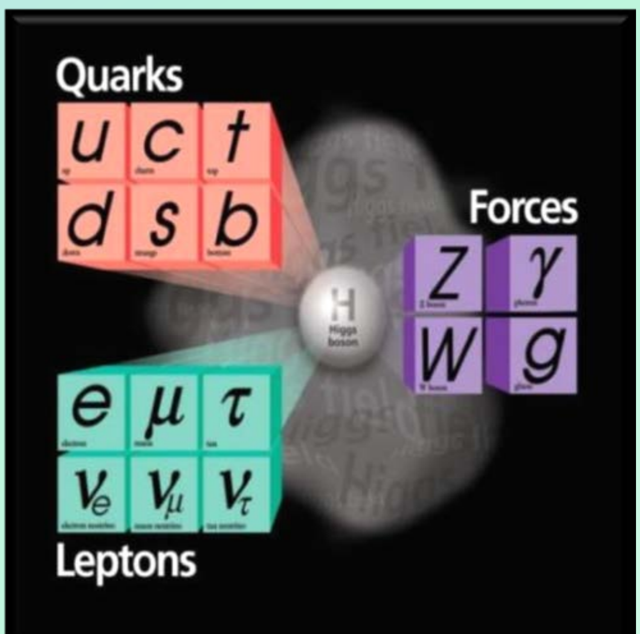
Fundamental Physics

Applied Physics

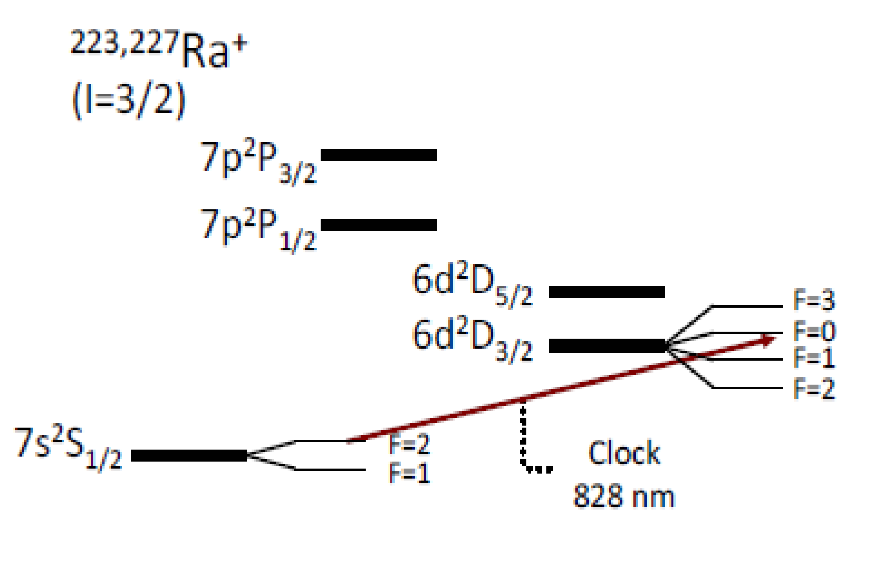
go hand in hand

Radium has a Great Potential for

- Fundamental Physics
- a Clock



Ra^+ Ion Atomic Clock



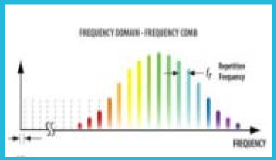
- Narrow Transition, Ultra Stable Lasers
- Low Sensitivity to external fields (for I=3/2)
- Time Variation of Fine Structure Constant
- Major Systematics: Quadrupole Shift

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

Note:

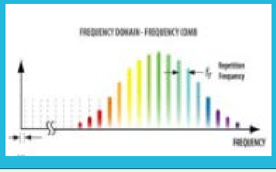
10^{-18} corresponds to 1 cm height differ

LaserLaB
VU Amsterdam
Al^+ Clock



2x280 km

KVI
Groningen University
Ra^+ Clock



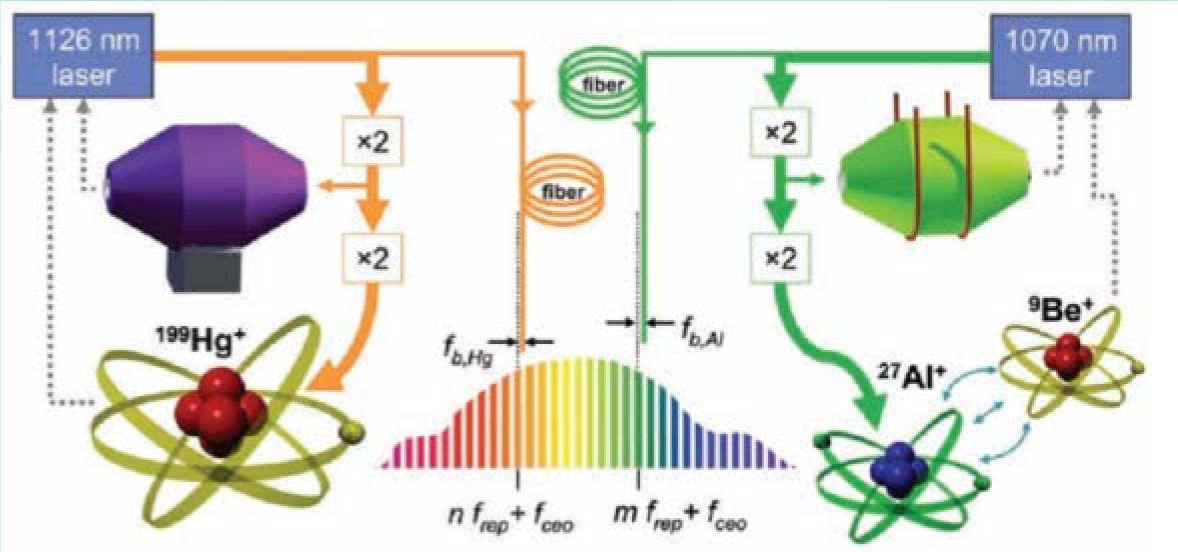
Koelemeij, Eikema, Ubachs et al.

Willmann, Dijck, Jungmann et a

→ TJ Pinkert et al., Applied Optics 54, 728 (2015)
e.g. clock signal exchange significantly better than GPS

Sensitivity to $\dot{\alpha}$

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

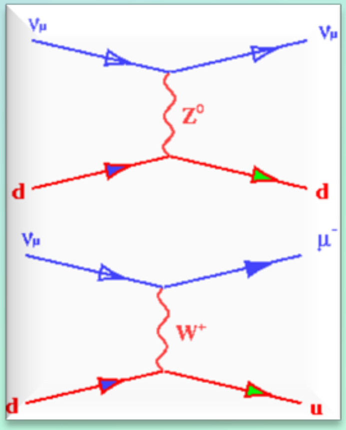


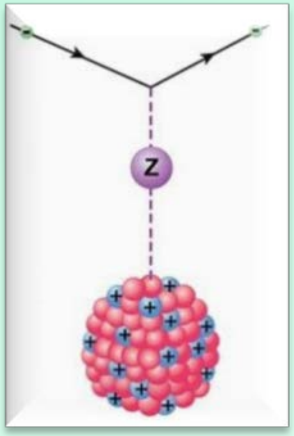
Ion	A		Transition
Sr+	0.43		$^2S_{1/2}$-$^2D_{5/2}$
Hg+	−2.94		$^2S_{1/2}$-$^2D_{5/2}$
In+	0.18		S_0-P_0
Al+	0.008		S_0-P_0
Ba+	2.52		$6^2S_{1/2}$-$5^2D_{3/2}$
Ba+	2.44		$6^2S_{1/2}$-$5^2D_{5/2}$
Ra+	3.00		$7^2S_{1/2}$-$6^2D_{3/2}$
Ra+	2.77		$7^2S_{1/2}$-$6^2D_{5/2}$

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

back to

Parity

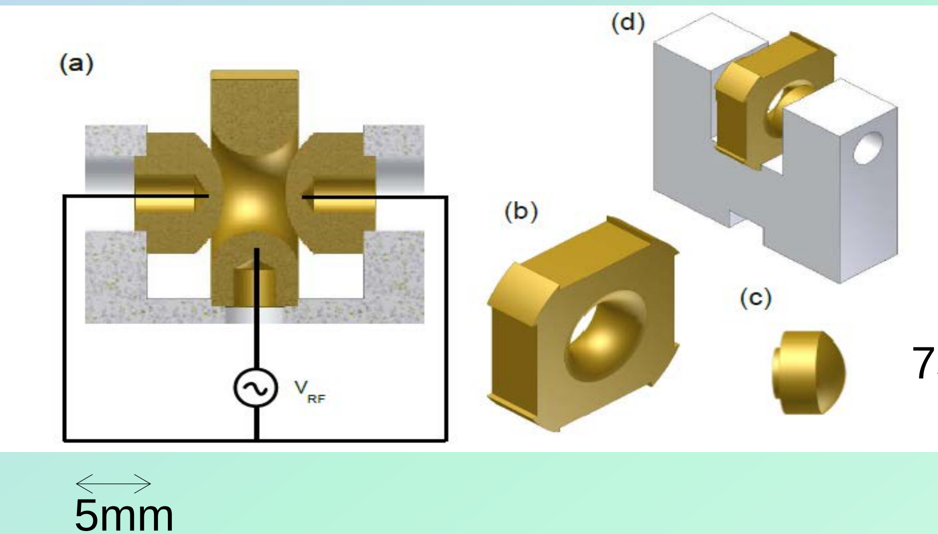




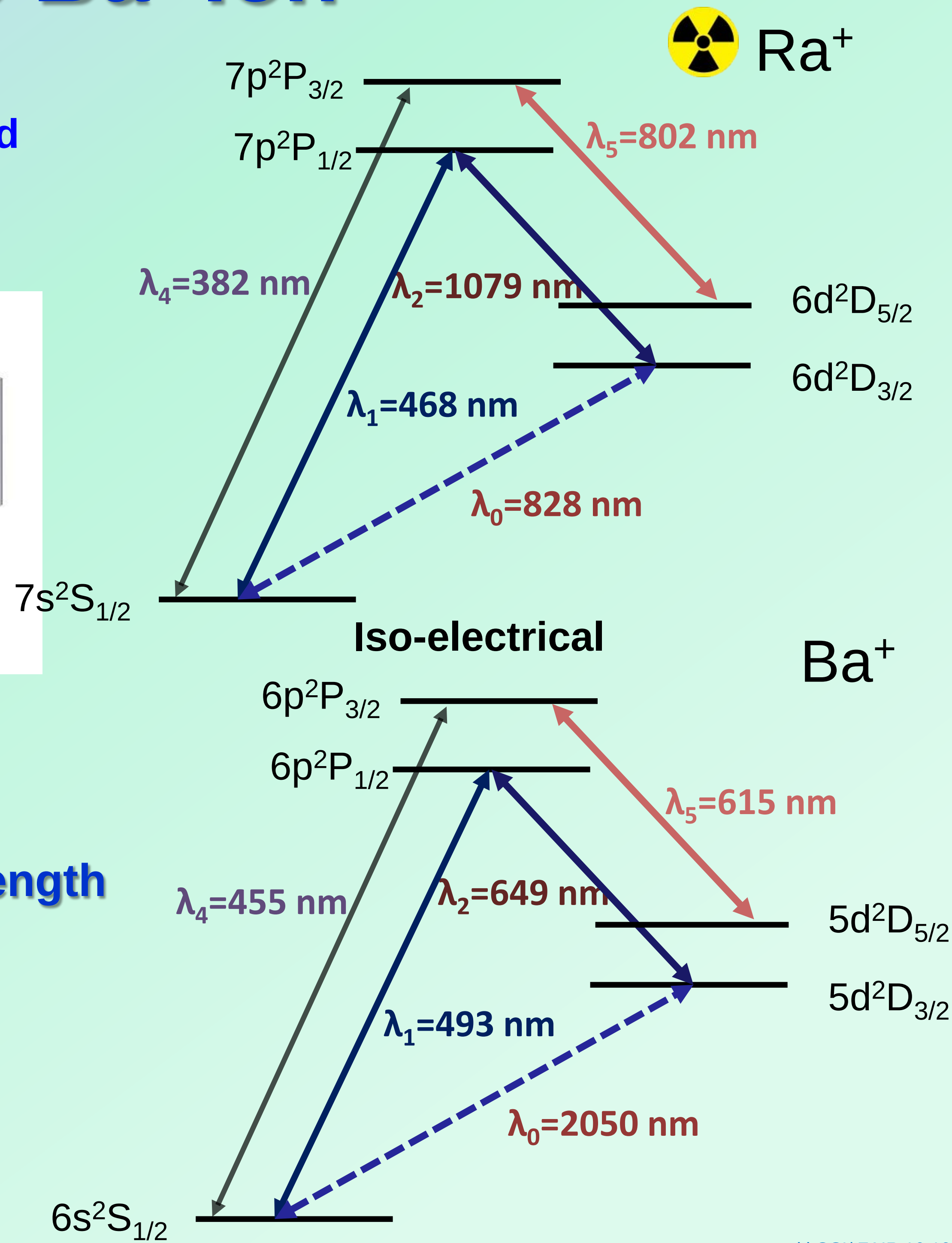
Ba^+ almost as good as Ra^+

Single Ba^+ Ion

$$Q_W = \frac{E1_{APV}}{k}$$ ← **To be measured**

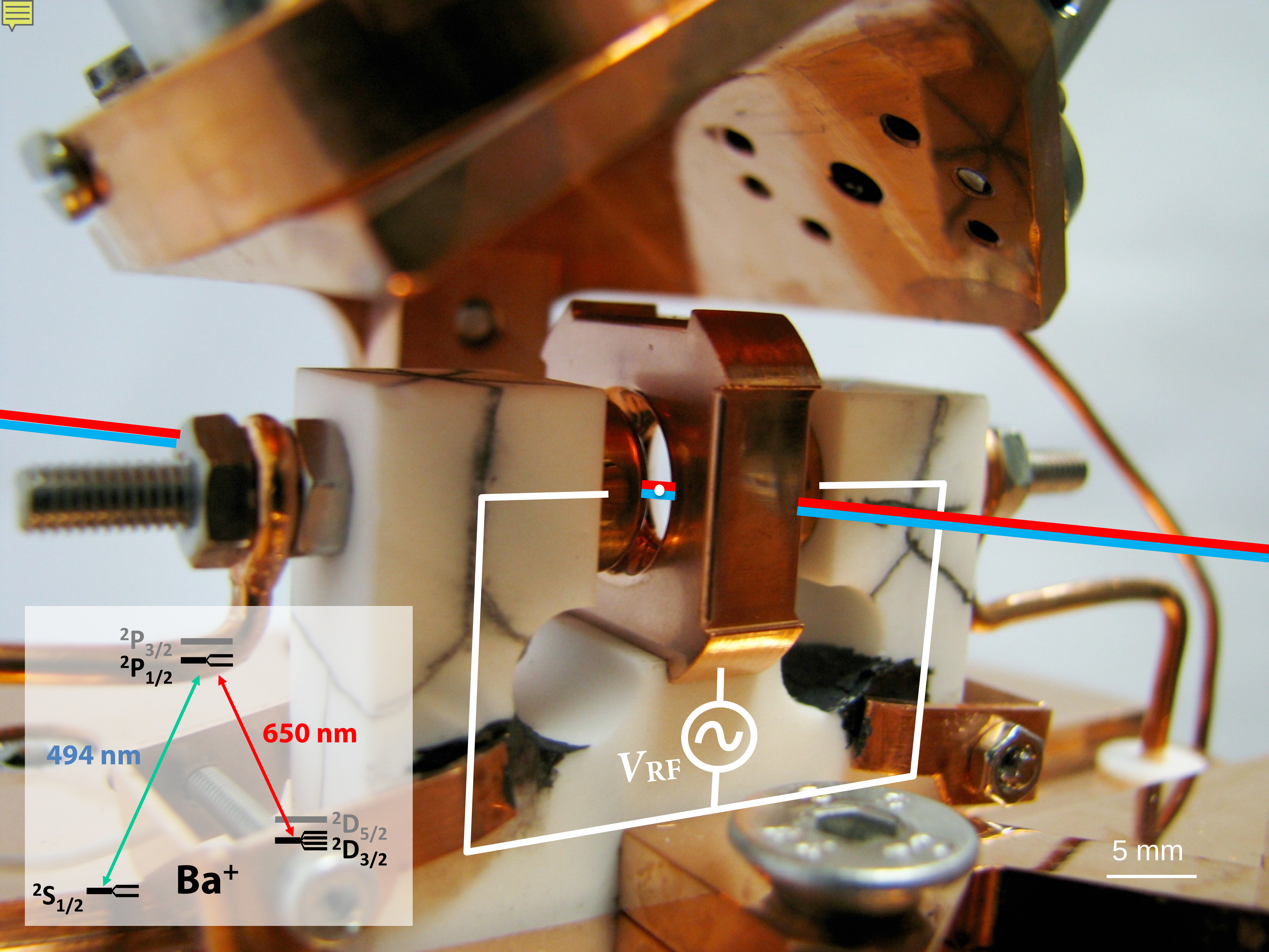


Hyperbolic Paul Trap



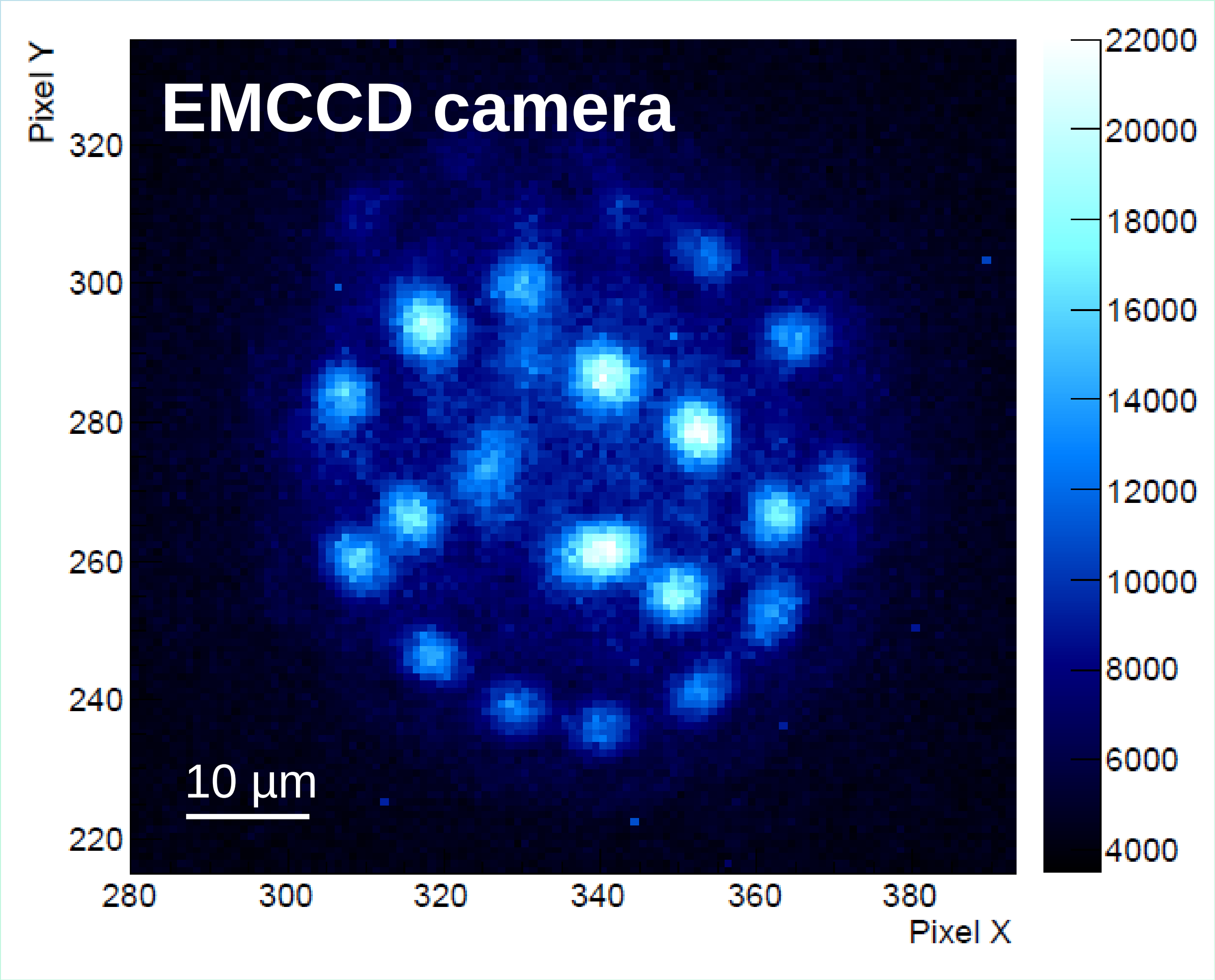
- **localize one ion within one wavelength**
- **electron shelving**
- **large volume**

Ba^+ : Precursor to Ra^+



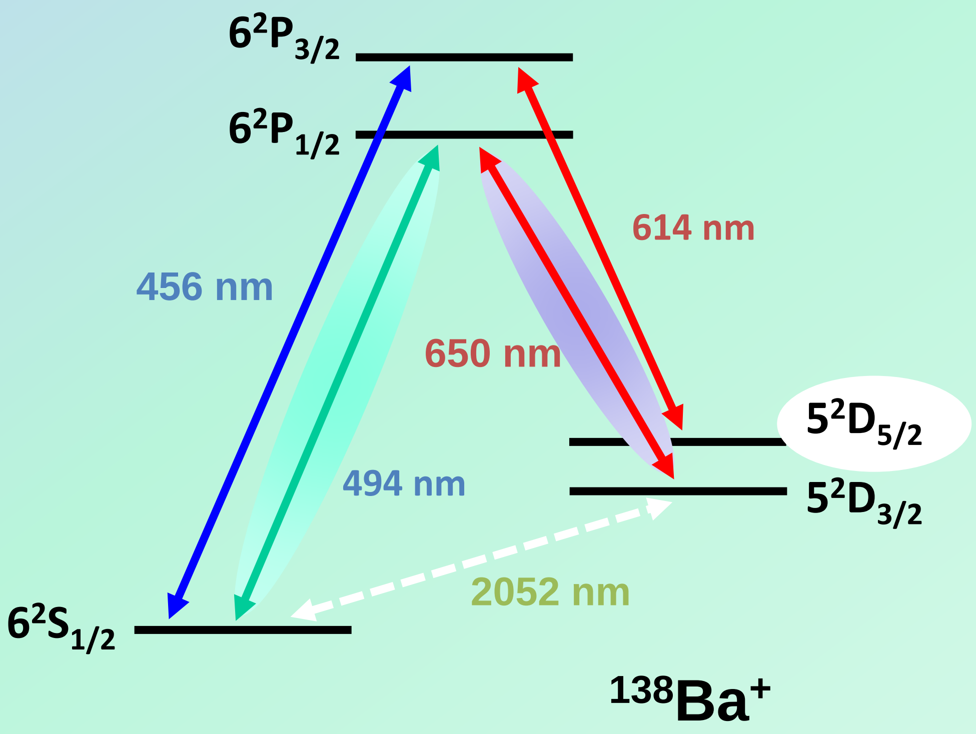
$^2P_{3/2}$
$^2P_{1/2}$
494 nm
650 nm
$^2D_{5/2}$
$^2D_{3/2}$
$^2S_{1/2}$
Ba^+
V_{RF}
5 mm

Detection Methods



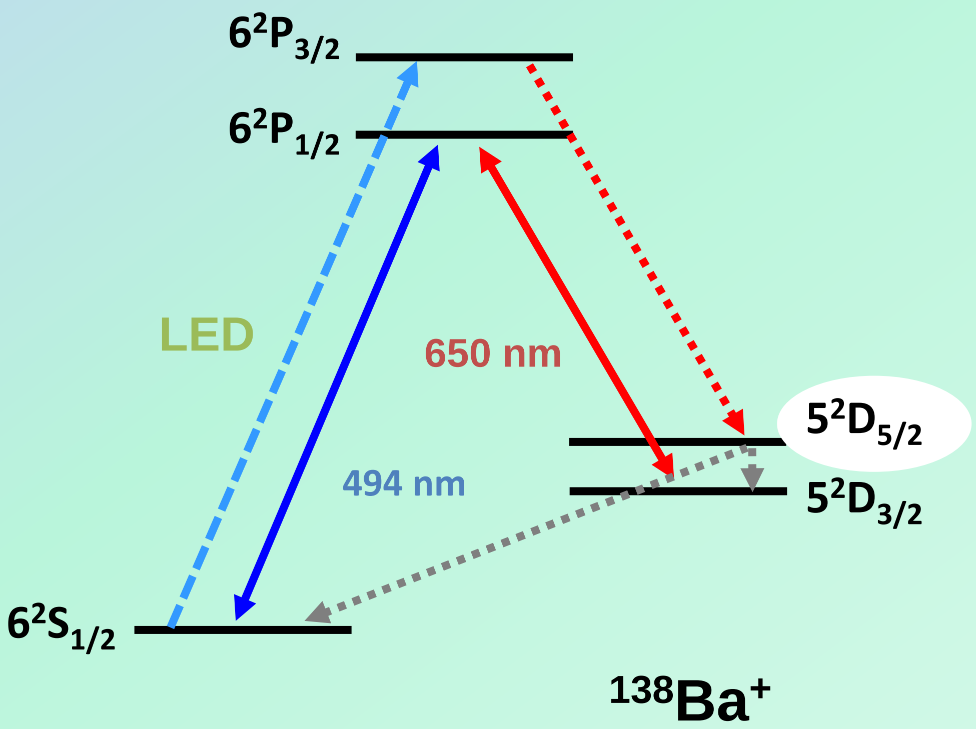
& PMT

Ba^+ spectroscopy



- **$^2D_{5/2}$ level lifetime**
  Electron shelving
- **Transition frequencies**
  Line shape analysis

Ba^+ spectroscopy

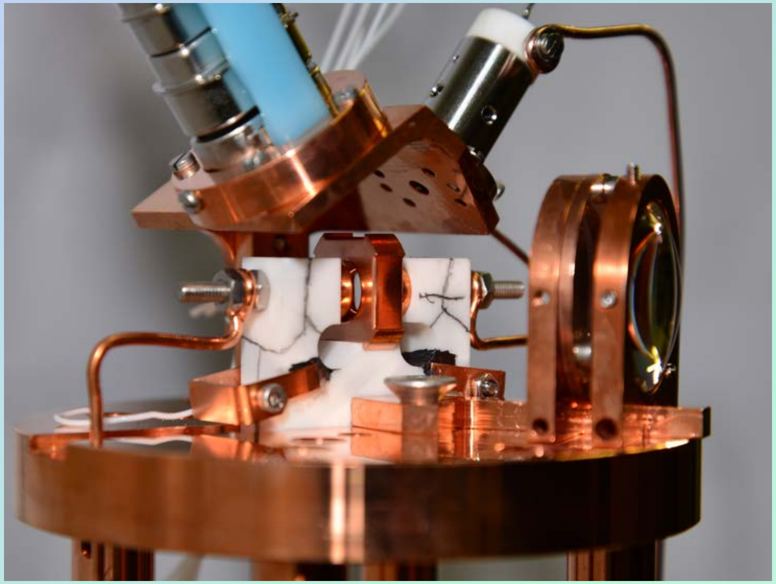


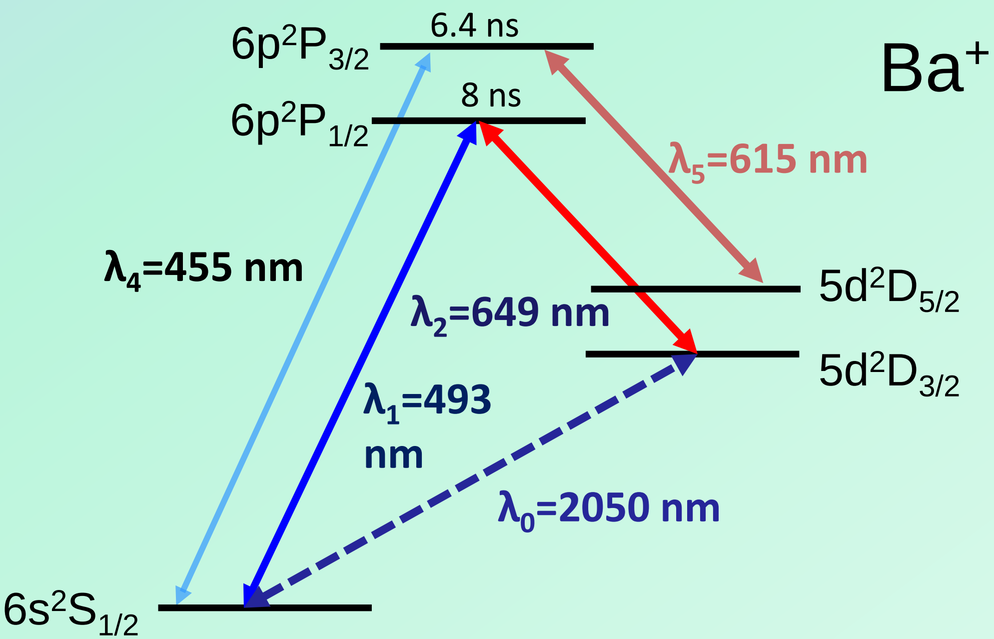
- **$^2D_{5/2}$ level lifetime**
  Electron shelving

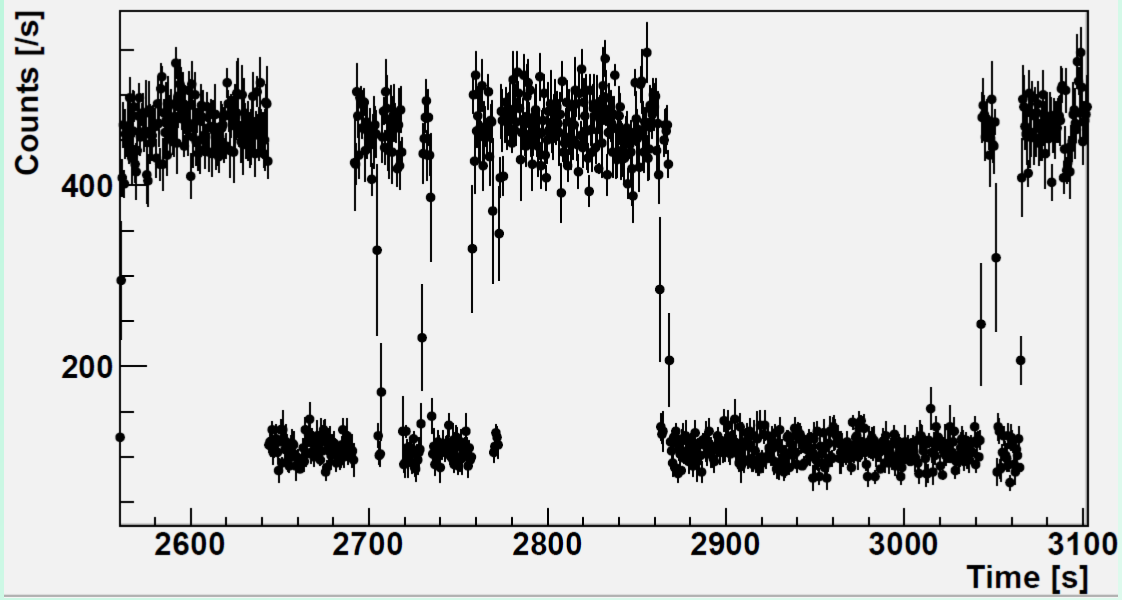
- **Transition frequencies**
  Line shape analysis

$\tau_{^2D_{5/2}} \approx 30$ s

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

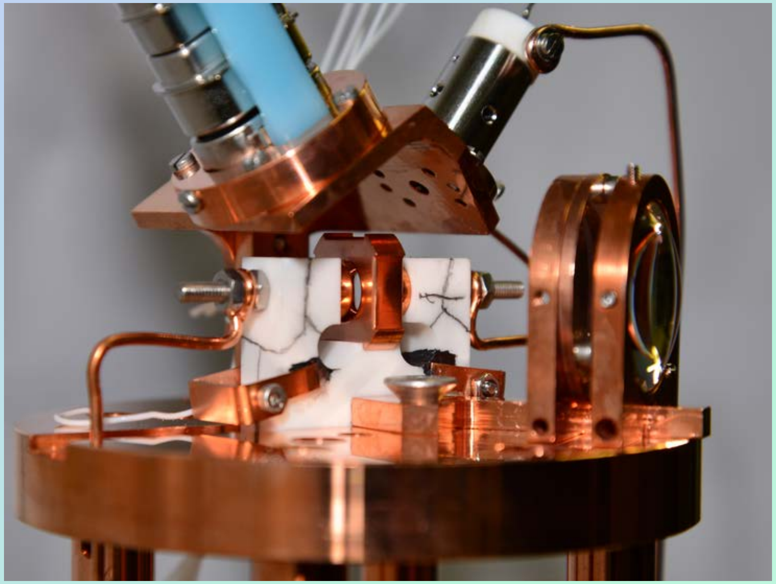


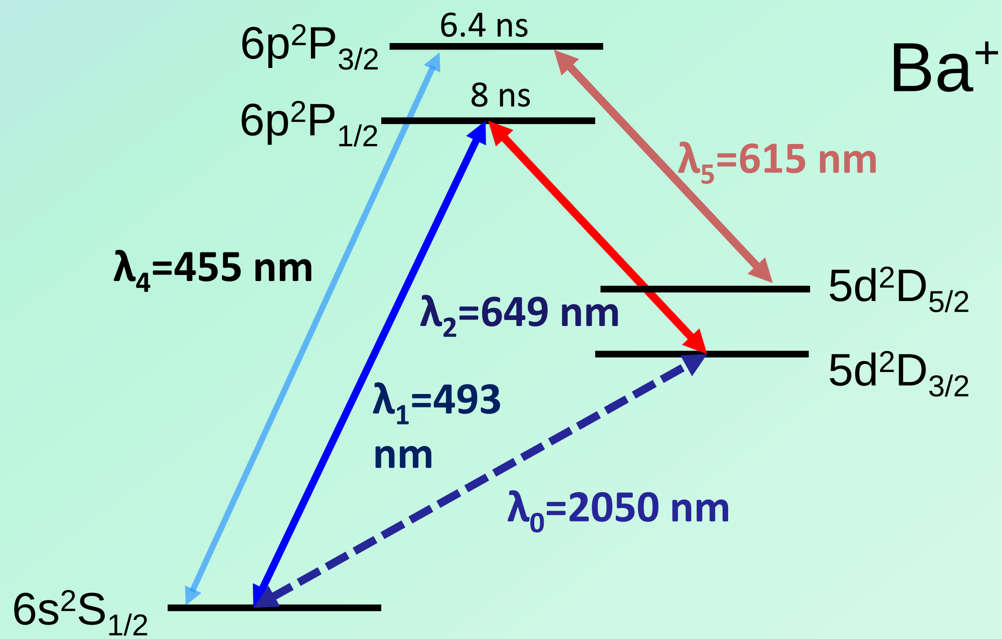


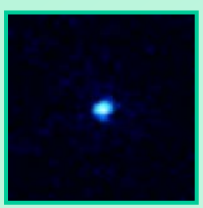


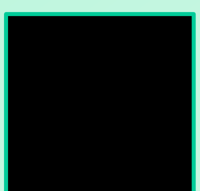
university of groningen / VSI

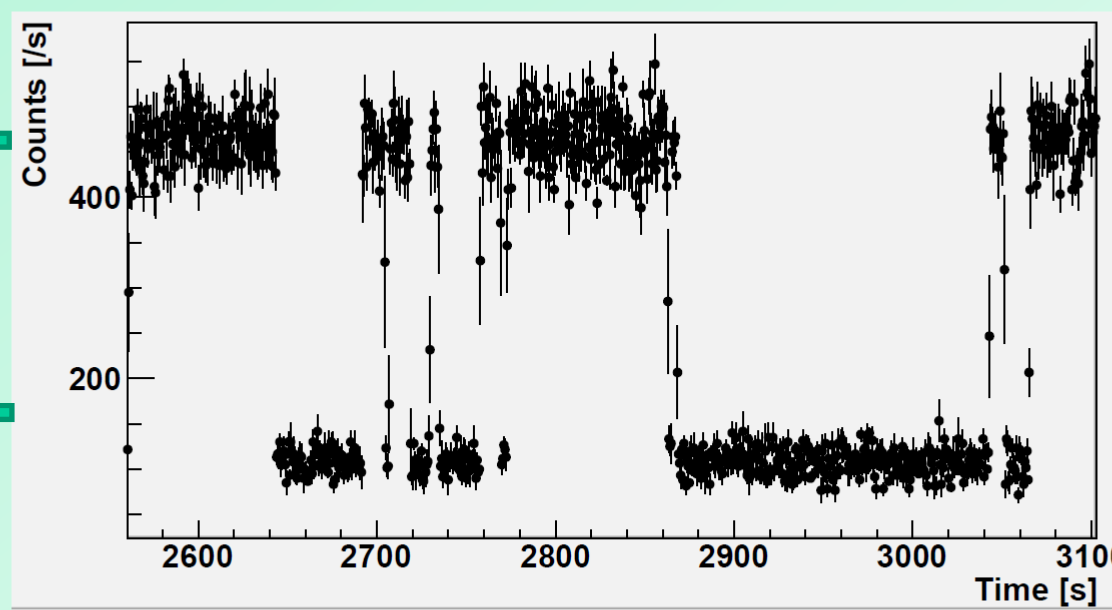
Ba^+ Experiment : Lifetime $D_{5/2}$



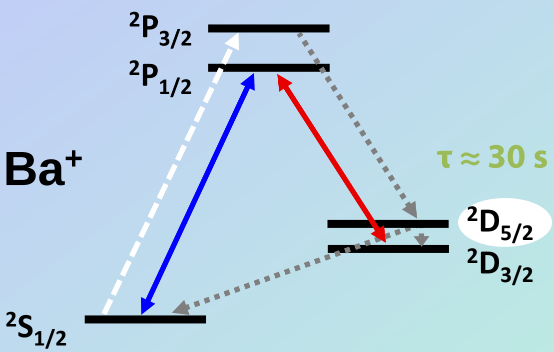


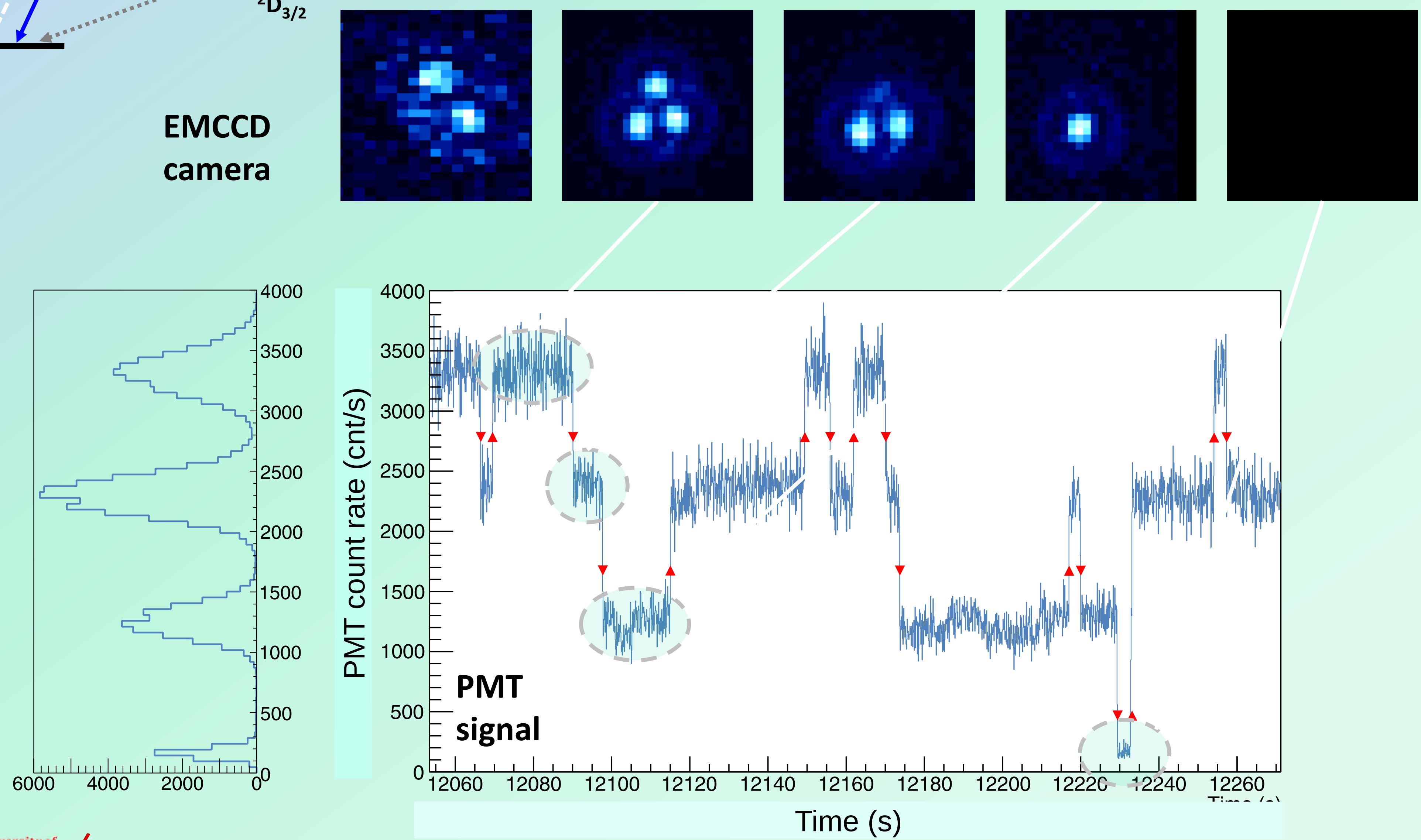




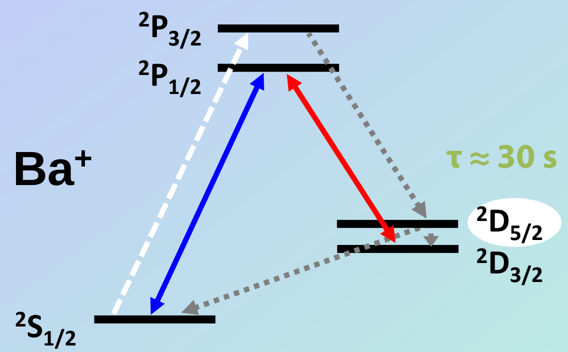


Ba^+ 5 $^2D_{5/2}$ Level Lifetime

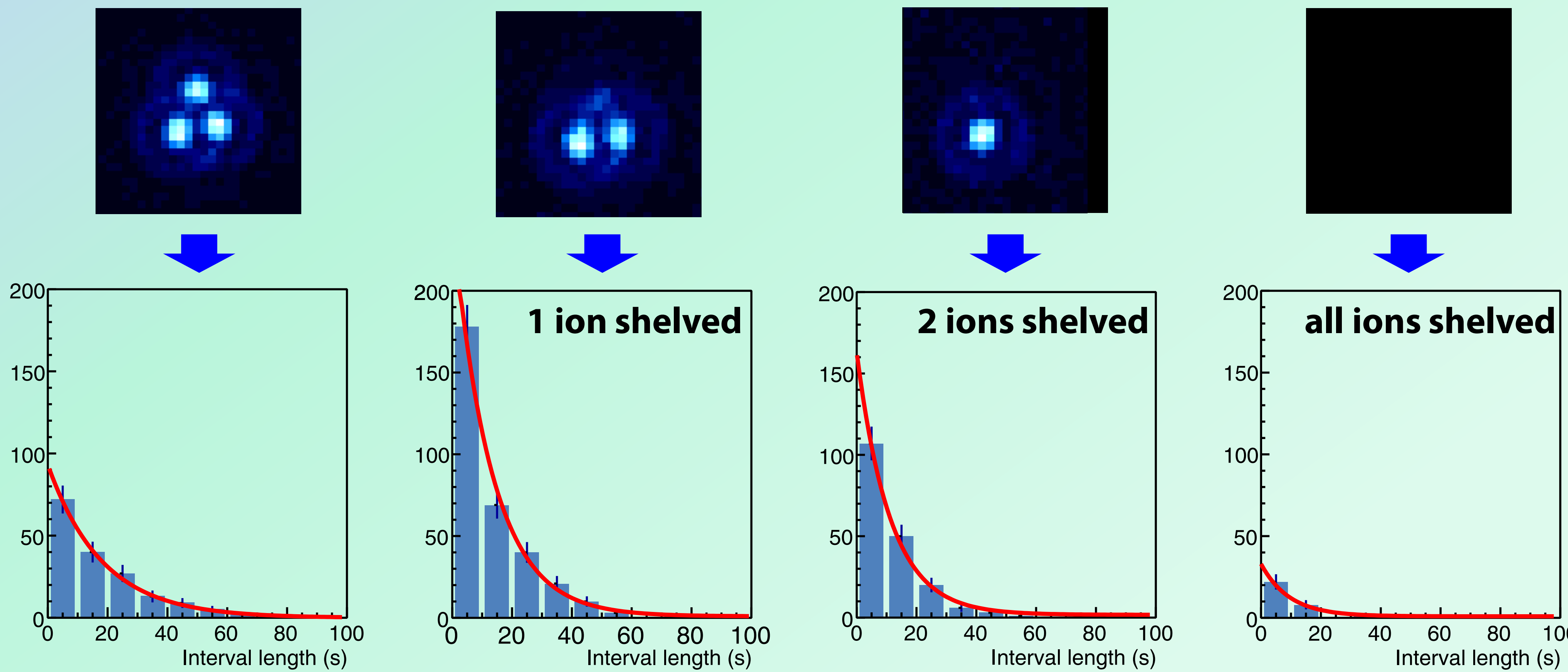




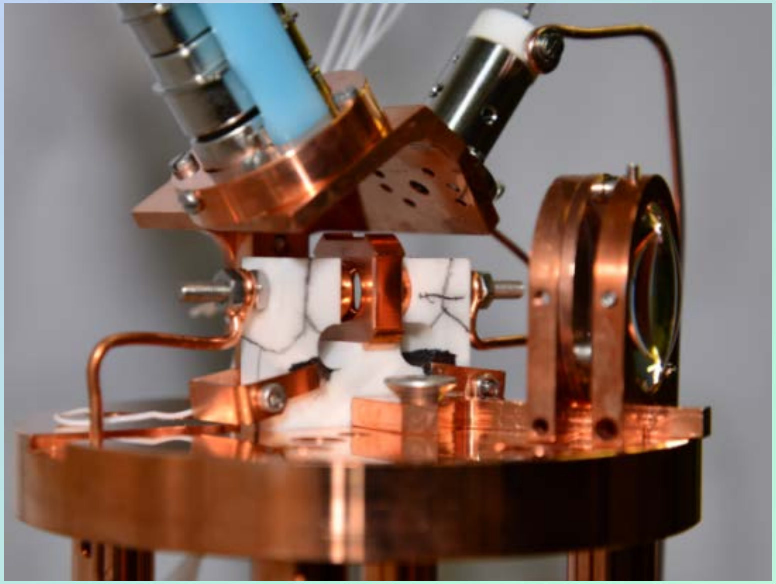
Ba$^+$ 5 $^2D_{5/2}$ Level Lifetime

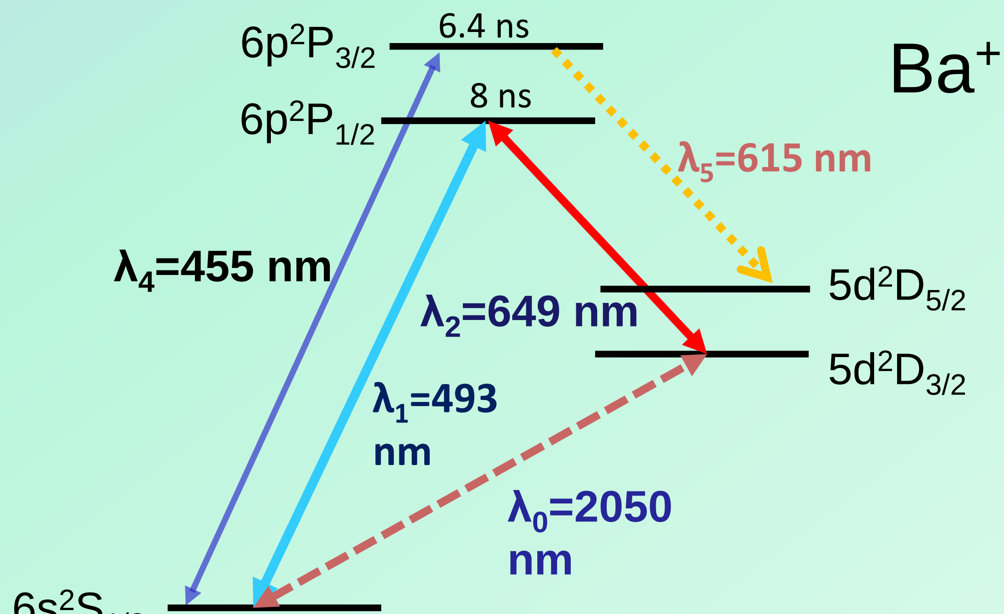


- **Fitted $^2D_{5/2}$ level lifetime and shelving rate**
- **No prominent difference with single ion runs**
- **Excellent to Investigate systematics**

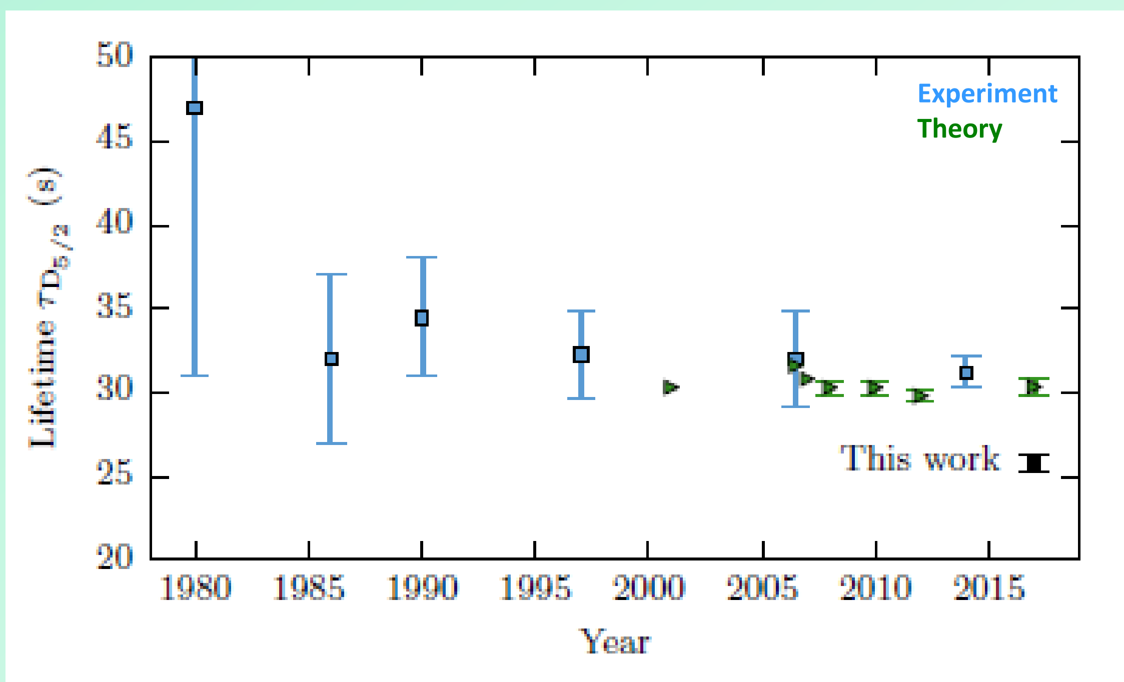


Ba^+ Experiment : Lifetime $D_{5/2}$





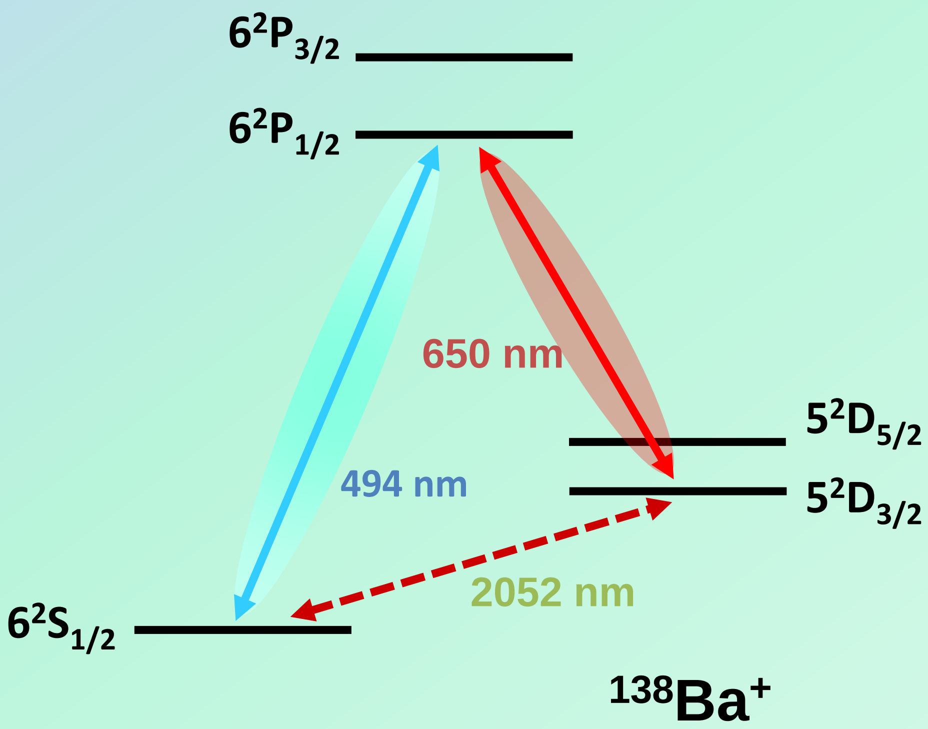
Ba^+ $D_{5/2}$ state lifetime



$\tau_{D5/2}$ = 25.6(5) s

E.A. Dijck et al.
PRA 97, 032508 (2018)

Ba^+ spectroscopy



- **$^2D_{5/2}$ level lifetime**
  Electron shelving

- **Transition frequencies**
  Line shape analysis

Modeling of Line Shape

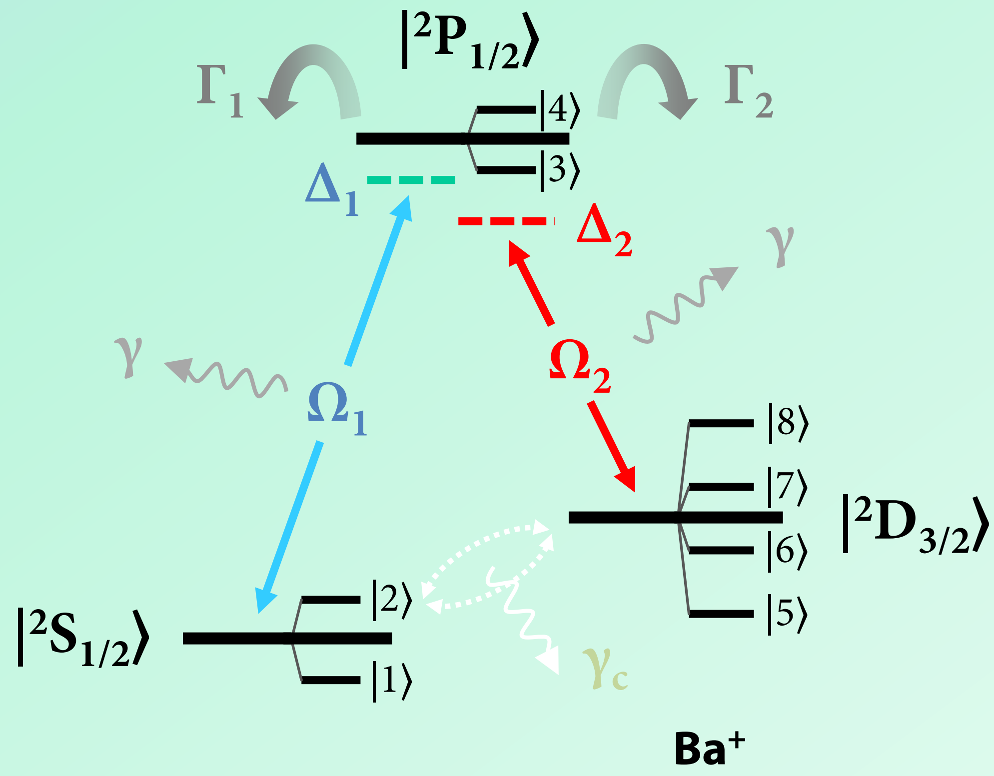
- **Optical Bloch equation**

  3 level example

$$\frac{d}{dt}\rho_{ij} = \frac{i}{\hbar}\left[H, \rho\right] + R(\rho)$$

$$H = \hbar \begin{pmatrix} \Delta_1 - \omega_B & 0 & -\frac{2}{\sqrt{3}}\Omega_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Delta_1 + \omega_B & 0 & \frac{2}{\sqrt{3}}\Omega_1 & 0 & 0 & 0 & 0 \\ -\frac{2}{\sqrt{3}}\Omega_1 & 0 & -\frac{1}{3}\omega_B & 0 & \frac{1}{\sqrt{2}}\Omega_2 & \frac{2}{\sqrt{6}}\Omega_2 & -\frac{1}{\sqrt{6}}\Omega_2 & 0 \\ 0 & \frac{2}{\sqrt{3}}\Omega_1 & 0 & \frac{1}{3}\omega_B & 0 & \frac{1}{\sqrt{6}}\Omega_2 & \frac{2}{\sqrt{6}}\Omega_2 & -\frac{1}{\sqrt{2}}\Omega_2 \\ 0 & 0 & -\frac{1}{\sqrt{2}}\Omega_2 & 0 & \Delta_2 - \frac{6}{5}\omega_B & 0 & 0 & 0 \\ 0 & 0 & \frac{2}{\sqrt{6}}\Omega_2 & -\frac{1}{\sqrt{6}}\Omega_2 & 0 & \Delta_2 - \frac{2}{5}\omega_B & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{6}}\Omega_2 & \frac{2}{\sqrt{6}}\Omega_2 & 0 & 0 & \Delta_2 + \frac{2}{5}\omega_B & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}}\Omega_2 & 0 & 0 & 0 & \Delta_2 + \frac{6}{5}\omega_B \end{pmatrix}$$

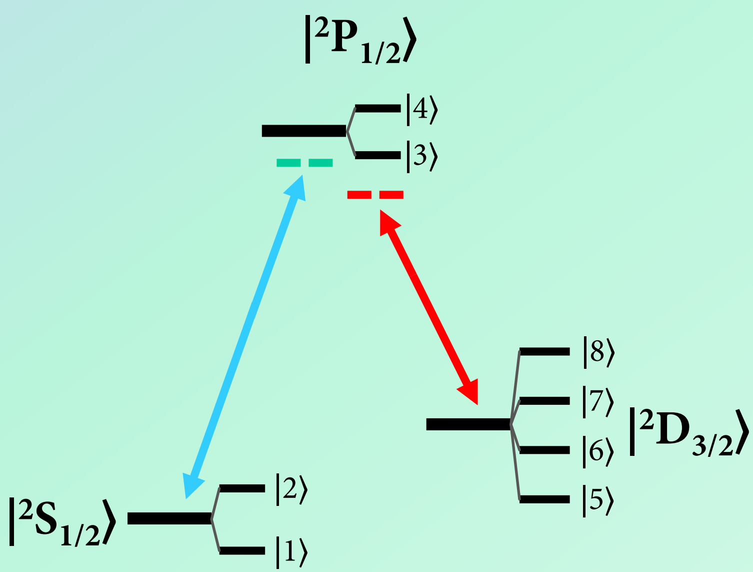
$$R(\rho) = \begin{pmatrix} \Gamma_1(\frac{1}{3}\rho_{33} + \frac{2}{3}\rho_{44}) & -\Gamma_1\frac{1}{3}\rho_{34} & -\gamma'\rho_{13} & -\gamma'\rho_{14} & -\gamma_2\rho_{15} & -\gamma_2\rho_{16} & -\gamma_2\rho_{17} & -\gamma_2\rho_{18} \\ -\Gamma_1\frac{1}{3}\rho_{43} & \Gamma_1(\frac{2}{3}\rho_{33} + \frac{1}{3}\rho_{44}) & -\gamma'\rho_{23} & -\gamma'\rho_{24} & -\gamma_2\rho_{25} & -\gamma_2\rho_{26} & -\gamma_2\rho_{27} & -\gamma_2\rho_{28} \\ -\gamma'\rho_{31} & -\gamma'\rho_{32} & -\Gamma\rho_{33} & -\Gamma\rho_{34} & -\gamma'\rho_{35} & -\gamma'\rho_{36} & -\gamma'\rho_{37} & -\gamma'\rho_{38} \\ -\gamma'\rho_{41} & -\gamma'\rho_{42} & -\Gamma\rho_{43} & -\Gamma\rho_{44} & -\gamma'\rho_{45} & -\gamma'\rho_{46} & -\gamma'\rho_{47} & -\gamma'\rho_{48} \\ -\gamma_2\rho_{51} & -\gamma_2\rho_{52} & -\gamma'\rho_{53} & -\gamma'\rho_{54} & \Gamma_2\frac{1}{2}\rho_{33} & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{34} & 0 & 0 \\ -\gamma_2\rho_{61} & -\gamma_2\rho_{62} & -\gamma'\rho_{63} & -\gamma'\rho_{64} & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{43} & \Gamma_2(\frac{1}{3}\rho_{33} + \frac{1}{6}\rho_{44}) & \Gamma_2\frac{1}{3}\rho_{34} & 0 \\ -\gamma_2\rho_{71} & -\gamma_2\rho_{72} & -\gamma'\rho_{73} & -\gamma'\rho_{74} & 0 & \Gamma_2\frac{1}{3}\rho_{43} & \Gamma_2(\frac{1}{6}\rho_{33} + \frac{1}{3}\rho_{44}) & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{34} \\ -\gamma_2\rho_{81} & -\gamma_2\rho_{82} & -\gamma'\rho_{83} & -\gamma'\rho_{84} & 0 & 0 & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{43} & \Gamma_2\frac{1}{2}\rho_{44} \end{pmatrix}$$

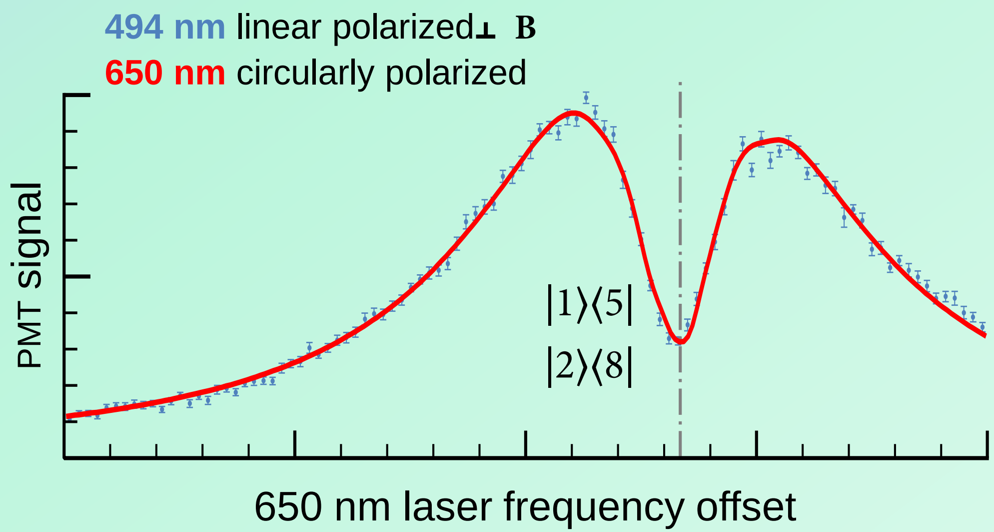


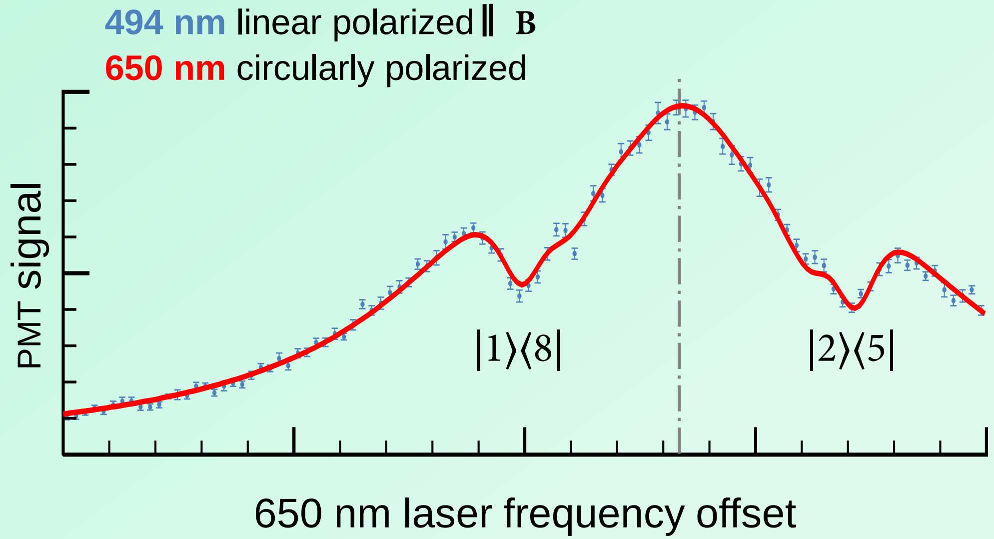
Ω_1, Ω_2	Rabi frequencies (laser power)	$\Gamma = \Gamma_1 + \Gamma_2$	relaxation rate
		$\gamma = \Gamma/2$	decoherence rate
Δ_1, Δ_2	laser detunings	γ_c	laser linewidth

Line Shapes and Polarization

- **Zeeman sublevels:** 8 level system
  Magnetic field **B**
  Laser polarization

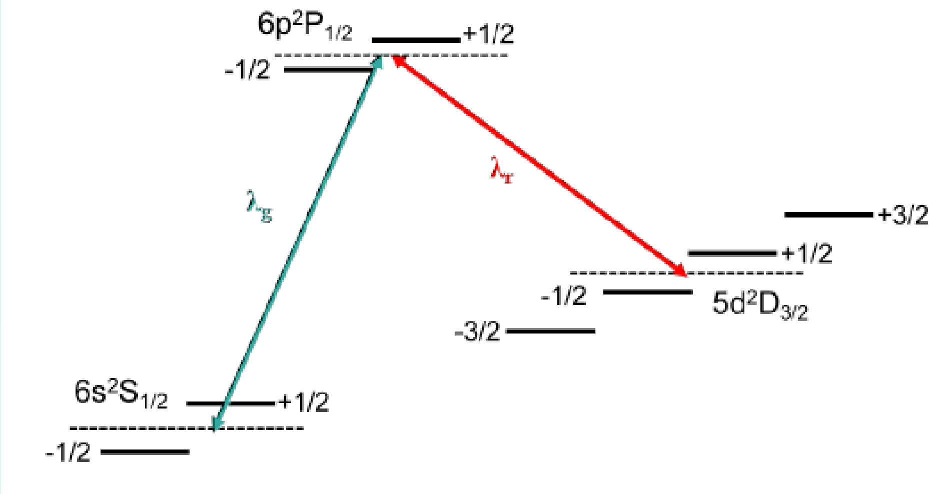




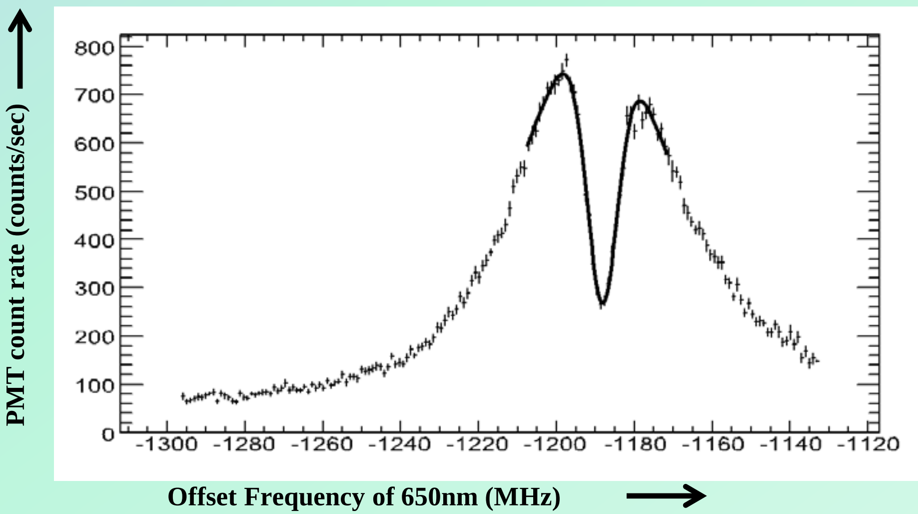


Two-photonTransitions in single Ba^+

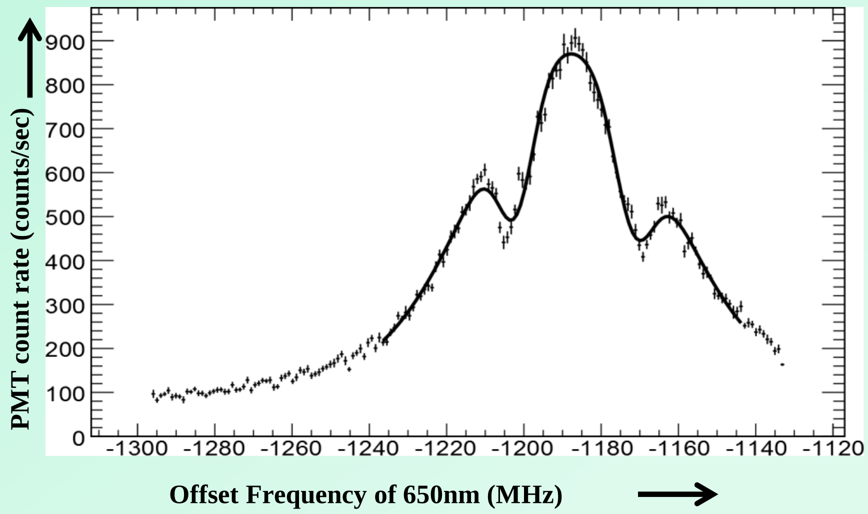
- Ba+ level scheme : 8 Zeeman sublevels.
- Two photon transition : Raman resonance (δ_R)
- Strongly dependent on:
  - Mangetic field strength and direction
  - Laser light polarization



$\vec{B} \perp \vec{E}$



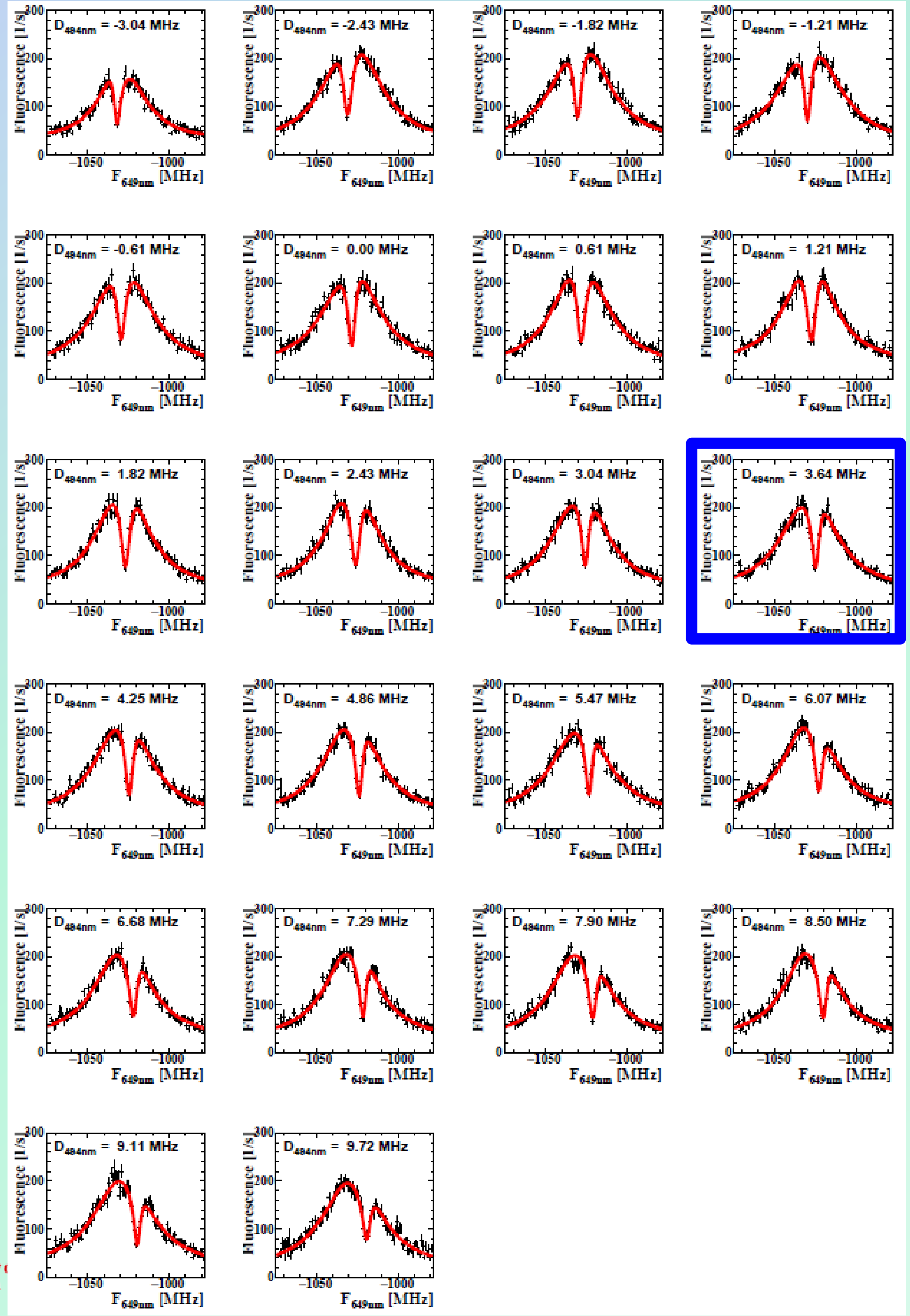
$\vec{B} \parallel \vec{E}$

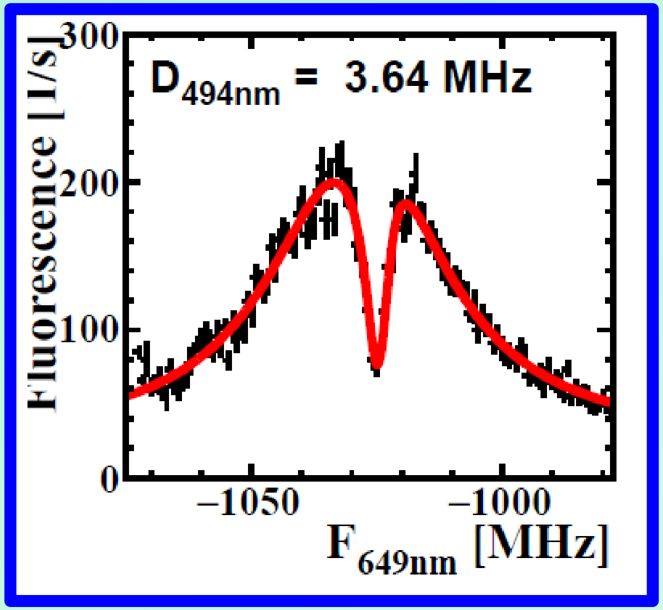


→ **Signals also with blue detuning!**

→ **Due to rapid cooling laser frequency switching**

Systematic Checks of all Parameters: Here, e.g., Blue Laser Detuning





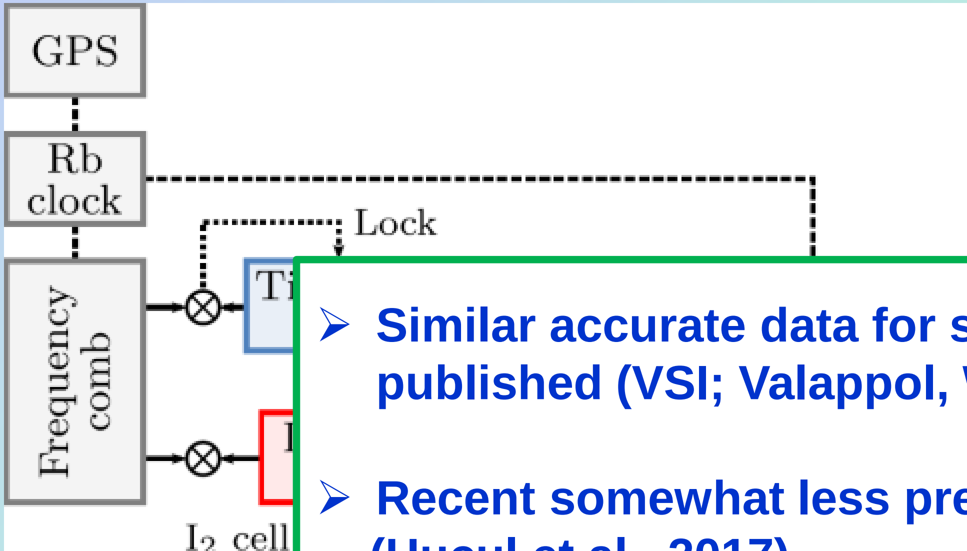
- ➢ **Eliminate Light Shifts**
- ➢ **Determine Transition Frequencies**
- ➢ **Check Atomic Calculations**
- ➢ **Exploit knowledge from Fano resonances**

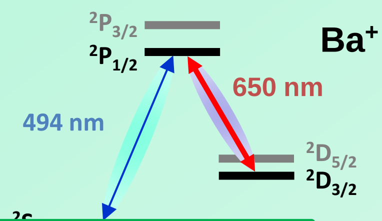
⇒ **Theses:**

Nivedya Valappol & Elwin Dijck (2019)

university of groningen

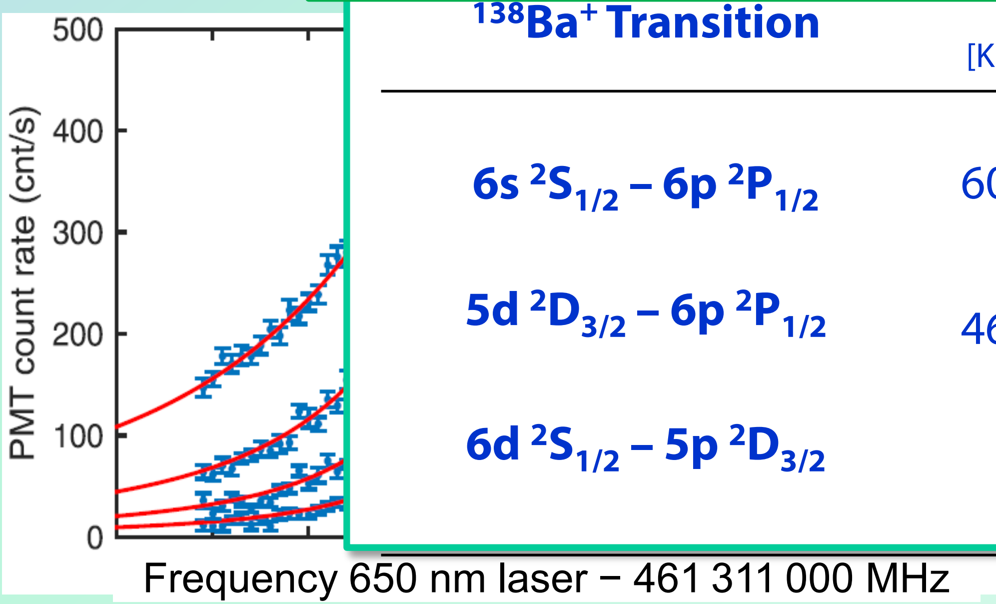
Transition frequencies

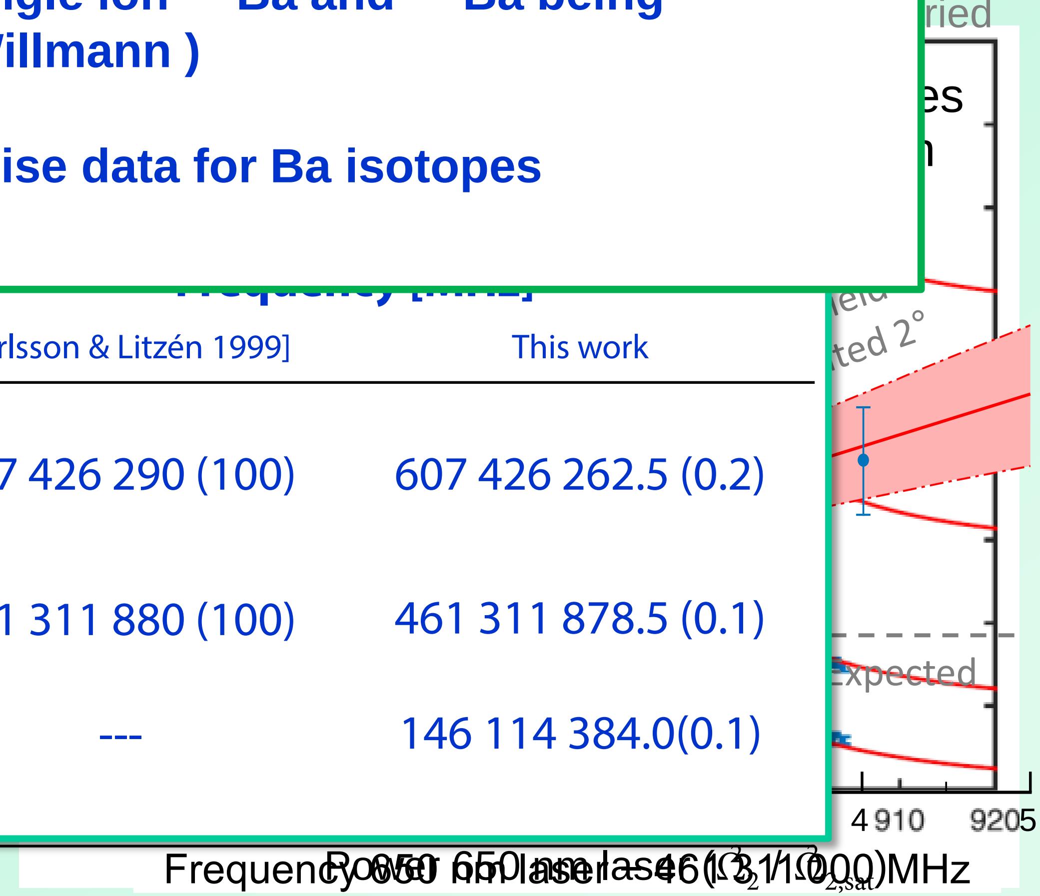




- Similar accurate data for single ion ^{136}Ba and ^{134}Ba being published (VSI; Valappol, Willmann)
- Recent somewhat less precise data for Ba isotopes (Hucul et al., 2017)

$^{138}Ba^+$ Transition	Frequency [MHz] [Karlsson & Litzén 1999]	This work
6s $^2S_{1/2}$ – 6p $^2P_{1/2}$	607 426 290 (100)	607 426 262.5 (0.2)
5d $^2D_{3/2}$ – 6p $^2P_{1/2}$	461 311 880 (100)	461 311 878.5 (0.1)
6d $^2S_{1/2}$ – 5p $^2D_{3/2}$	---	146 114 384.0(0.1)



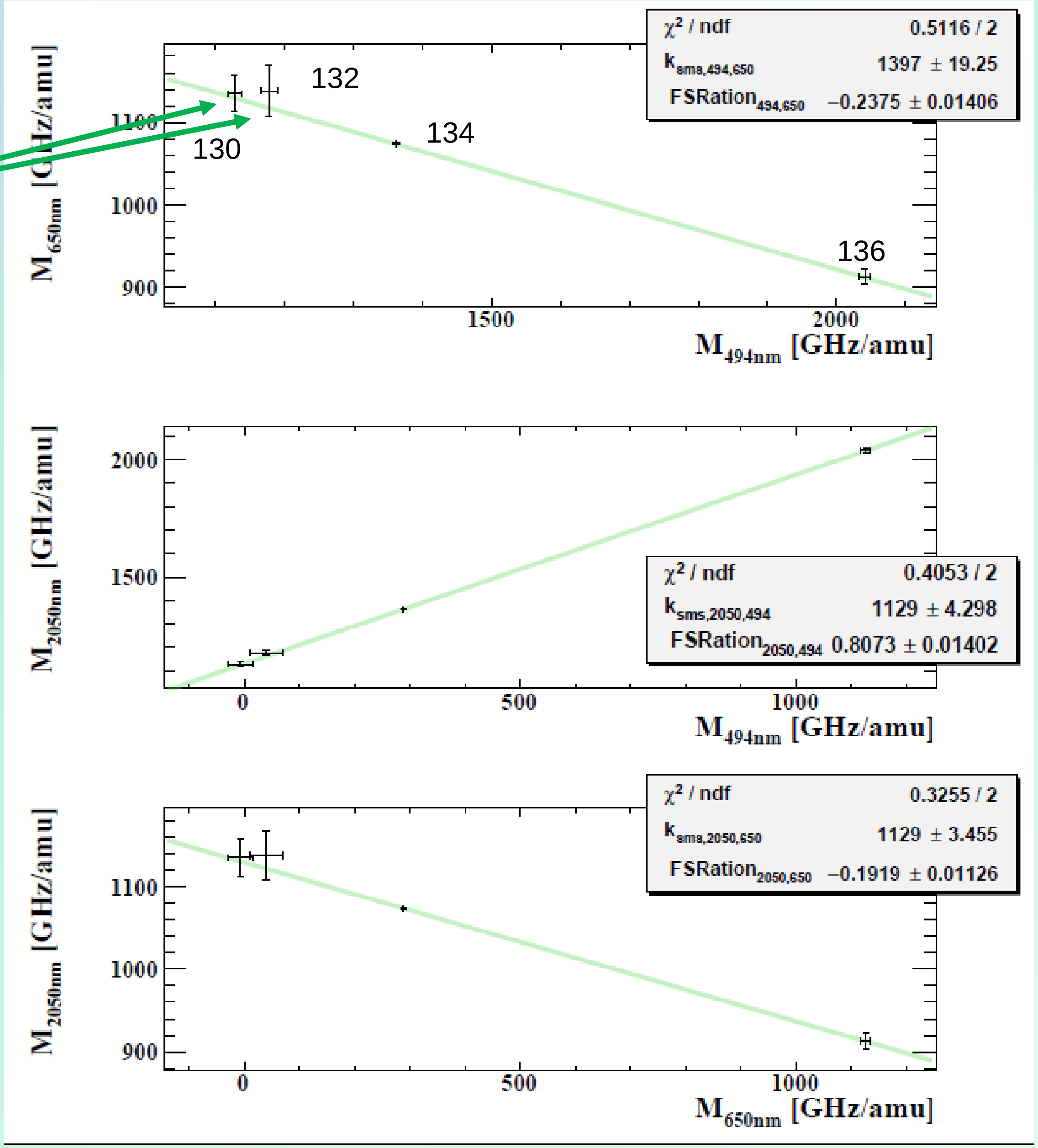


- Data fit to optical Bloch equation model
- Extract transition frequencies with 100 kHz accuracy

Dijck et al., Phys. Rev. A **91**, 060501(R) (2015)

Ba$^+$ Transitions - King Plot

D. Hucul et al, PRL 119, 100501 (2017)

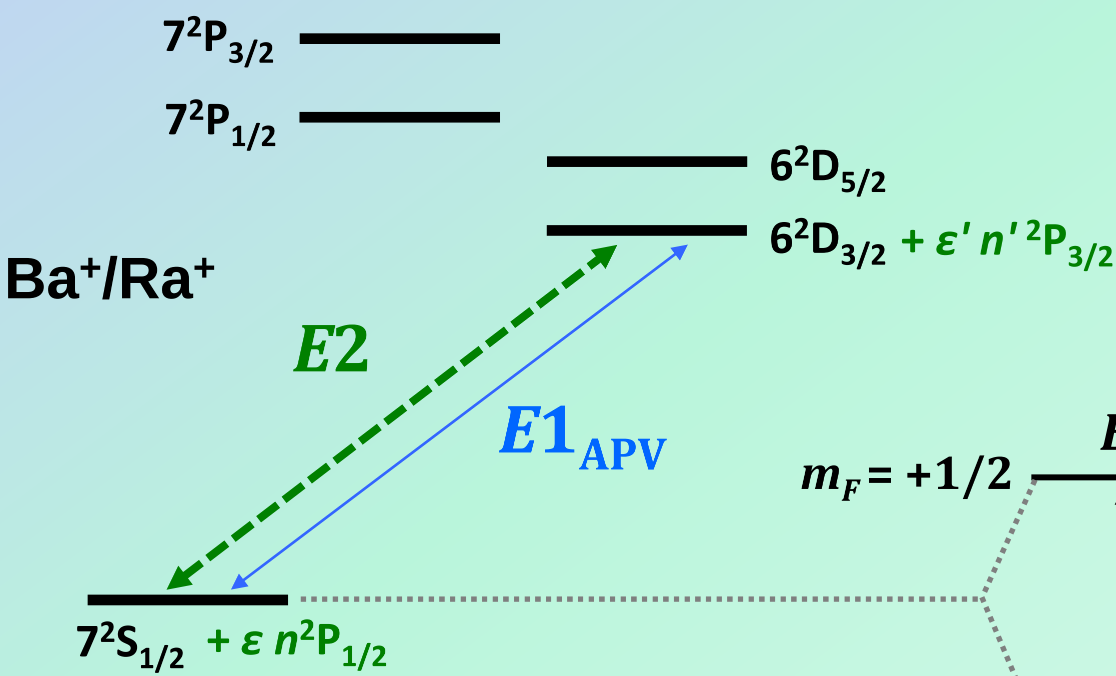


looks o.k.

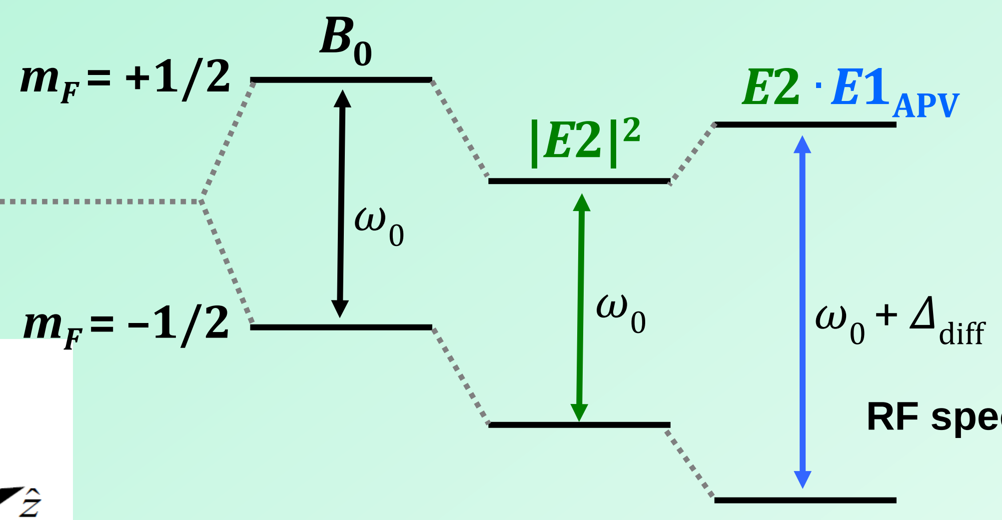
N. Valappol, thesis RUG 2019

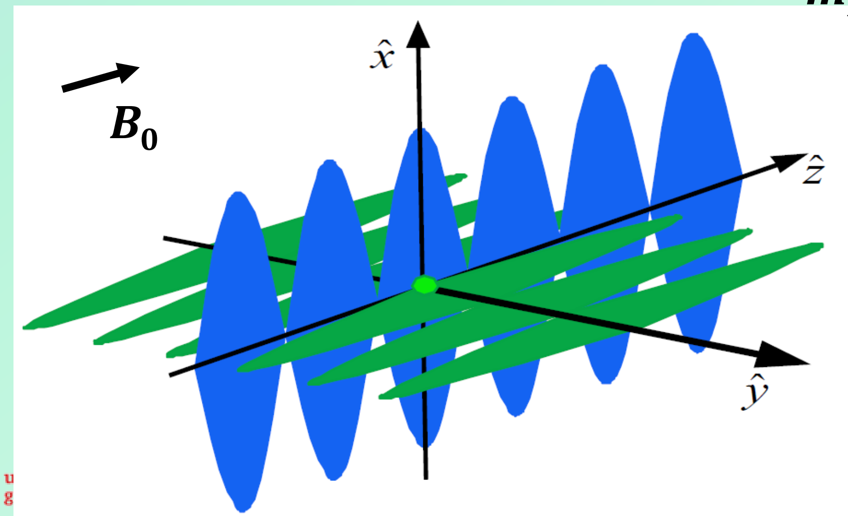
Atomic parity violation

$$E1_{APV} = k \cdot Q_W$$



Interference: differential light shift



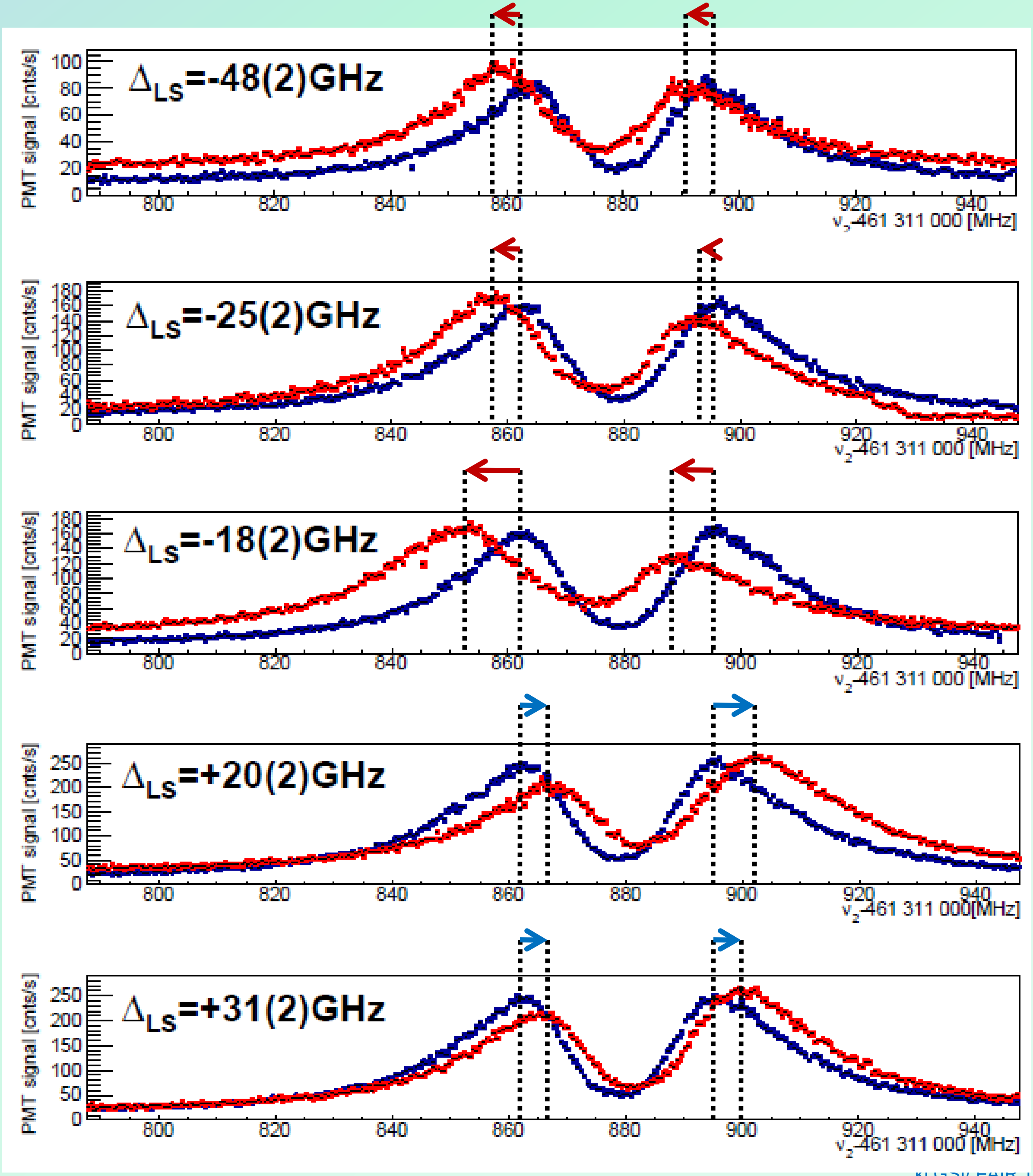


- $^2D_{5/2}$ lifetime → matrix elements
- Bloch equations → light shift

N. Fortson, Phys. Rev. Lett. **70**, 2383 (1993)
J. A. Sherman arXiv:0907.0459v1 (2009)

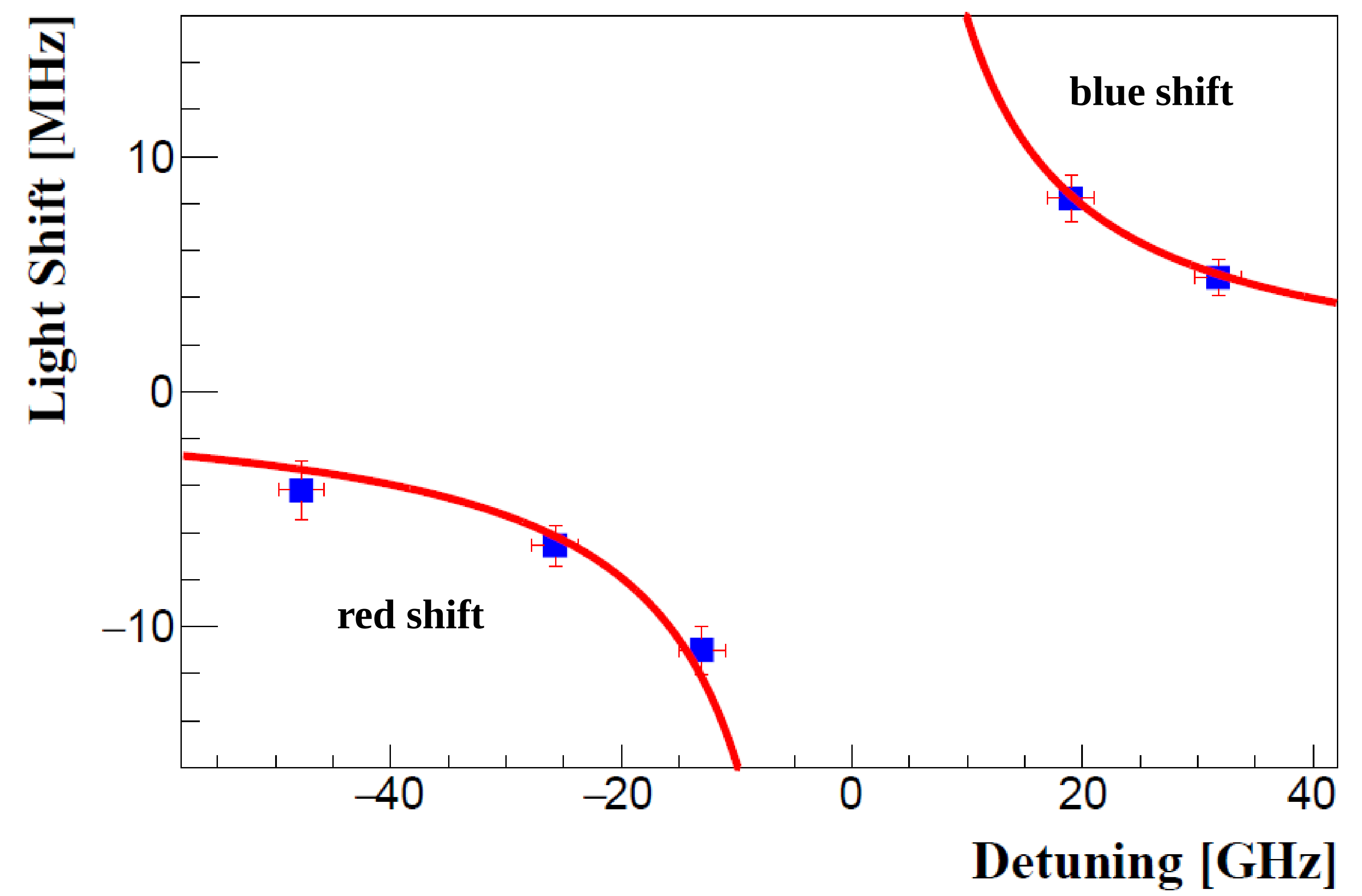
Light Shifts measured in Ba^+ ion

- Measured Raman dip spectrum for the $5d^2D_{3/2}$ - $6p^2P_{1/2}$ transition
- 494nm light linearly polarised in vertical direction along z-axis
- 650nm light circularly polarised
- light shift laser polarised in the horizontal direction
- magnetic field of 510μT along B_z-direction
- Detunings were large compared to the power broadened linewidth



Light Shifts measured in Ba^+ ion

- Scaling of light shift with the detunings of light shifting light
- $\Delta\ v_{LS} = 0.16(3) GHz^2 . 1/\Delta_{LS}$, Δ_{LS} is detuning of light shifting light
- Polarisation with respect to quantization axes i.e. magnetic field are important



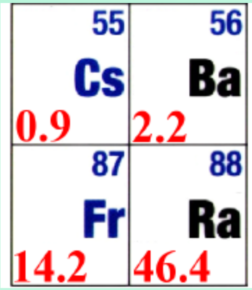
Radium for APV

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

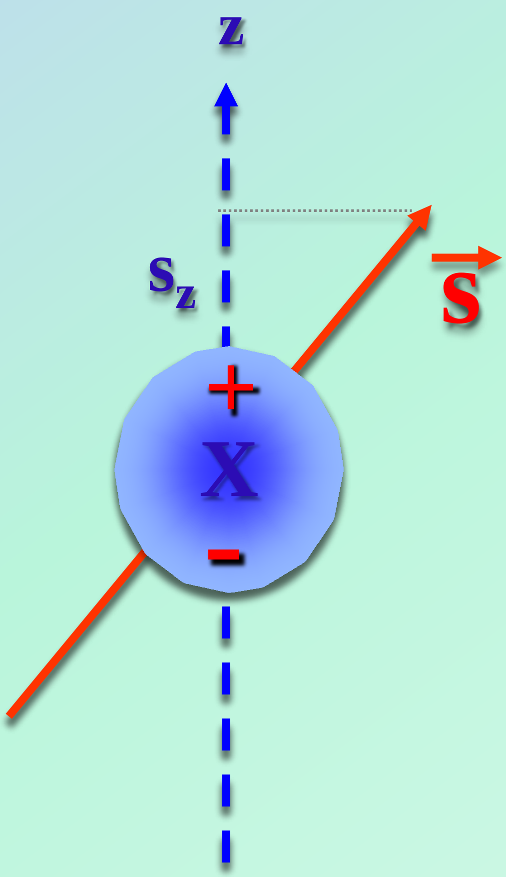
	Coherence Time	Projected Accuracy	Measurement Time
Ba^+	80 sec	0.2%	1.1 day
Ra^+	0.6 sec	0.2%	1.4 day



→ 10 days for 5 fold improvement over Cs

Permanent

Electric Dipole Moments



→ Quantum Mechanics ⇒ perm. EDM $\vec{d} \parallel \vec{s}$
(no such constraints on time varying EDM)

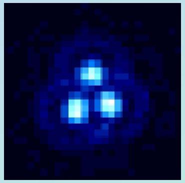
→ Leptons: clean and ready for New Physics

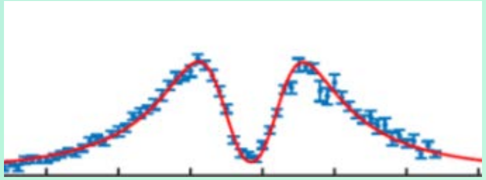
→ Baryons: depend on θ_{QCD} in Standard Model

→ Limit on θ_{QCD} : extracted from EDM searches

Status Atomic Parity Violation in Ba^+/Ra^+

- **Developing Ba^+/Ra^+ single ion trapping setup & techniques**





- **Calculations tested**

- **Response Λ-system to two lasers described by optical Bloch Model**

  Improved measurement of transition frequencies

  Light shift measurements started

- ***Driving Force: Determination $\sin^2\Theta_W$ at low Q***

Ion Trappers

Van Swinderen Institute, University of Groningen

university of groningen

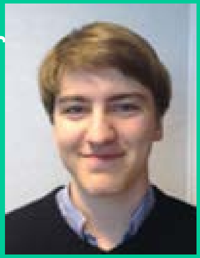
FOM

Elwin Dijck

Amita Mohanty

Nivedya Valappol

Olivier Grasdijk



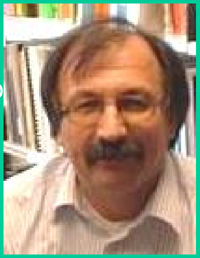
Oliver Böll

Andrew Grier

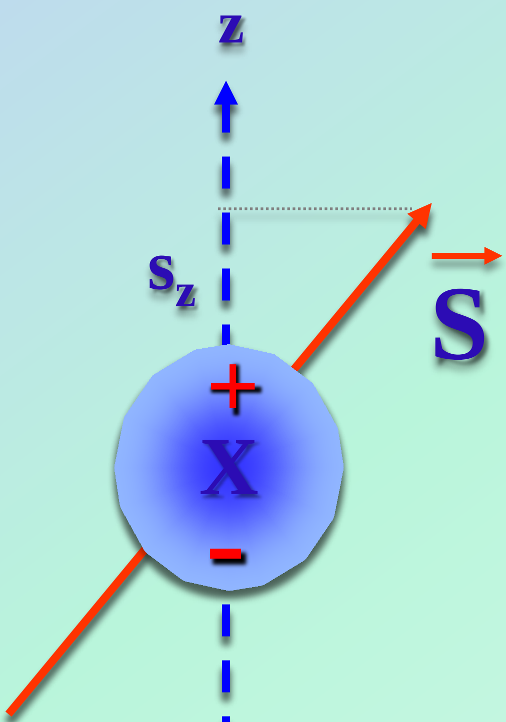
Mayerlin Nuñez Portela

Lorenz Willmann

Klaus Jungmann



Spin of Fundamental Particles



$\vec{S}$ is the only vector characterizing a non-degenerate quantum state

magnetic moment:

$$\vec{\mu}_x = 2(1+a_x)\ \mu_{0x}\ c^{-1}\ \vec{S}$$

electric dipole moment:

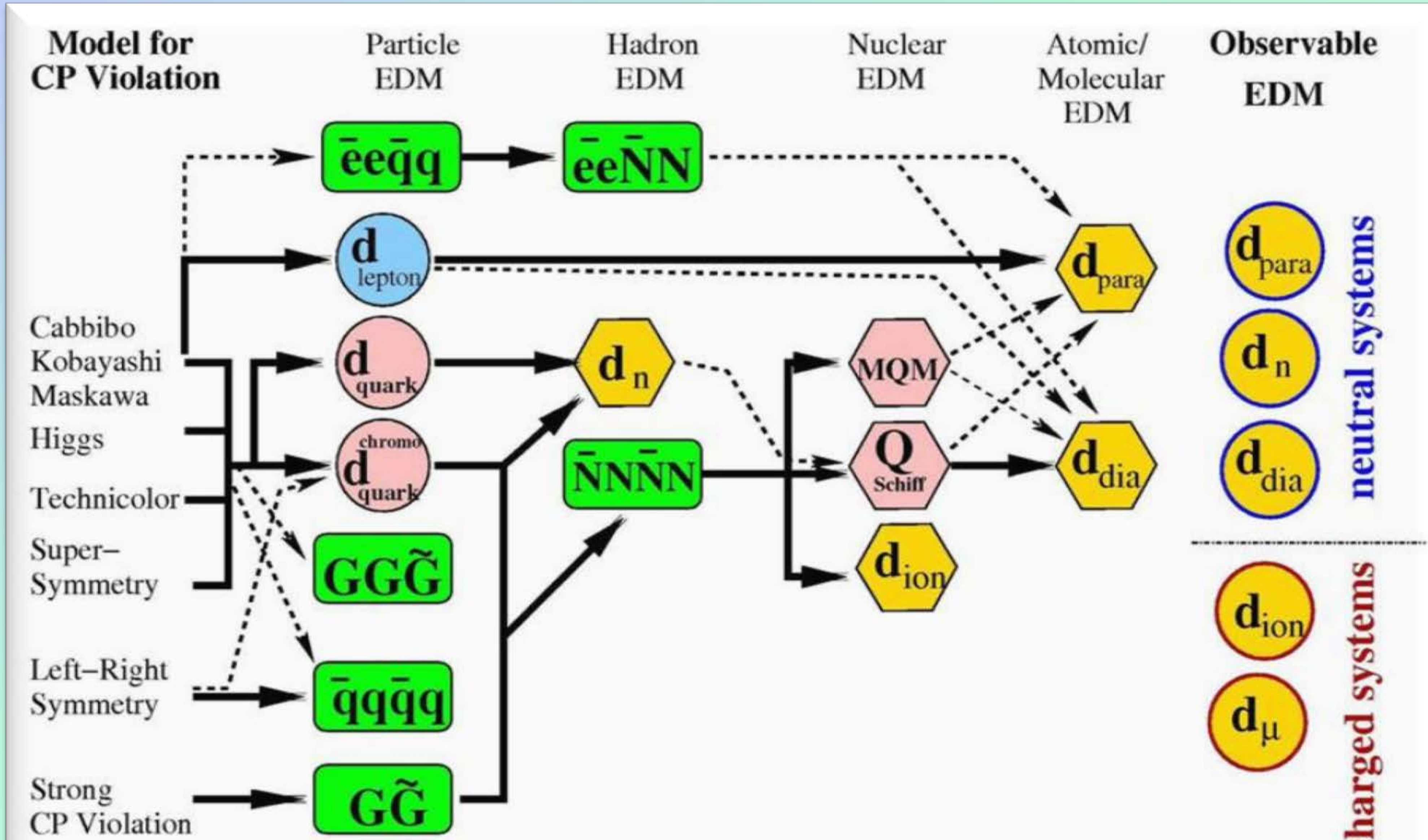
$$\vec{d}_x = \eta\ \mu_{0x}\ c^{-1}\ \vec{S}$$

magneton:

$$\mu_{0x} = e\hbar\ /\ (2m_x)$$

$$\mu_{0x}\ c^{-1}\ S = \begin{cases} 9.7 \cdot 10^{-12}\ \text{e cm} & \text{(electron)} \\ 4.6 \cdot 10^{-14}\ \text{e cm} & \text{(muon)} \\ 5.3 \cdot 10^{-15}\ \text{e cm} & \text{(nucleon)} \end{cases}$$

Possible Sources of EDMs



Numerically best experiment until now: ^{199}Hg @Seattle

⇒ Leaves somewhat restricted room for SUSY …

Lines of attack towards an EDM

Free Particles

neutron
muon
deuteron
bare nuclei ?
…

→ particle EDM
→ unique information
→ new insights
→ new techniques
→ challenging technology

Atoms

Hg Xe
Tl
Cs Rb
Ra Rn
Fr …

→ electron ED
→ n
…ology

Electric
Dip…

…w source of CP

Molecules

→ ele
→ …pectroscopic data

BaF , YbF
PbO ,WC
PbF ,ThO
HfF^+,ThF^+
…

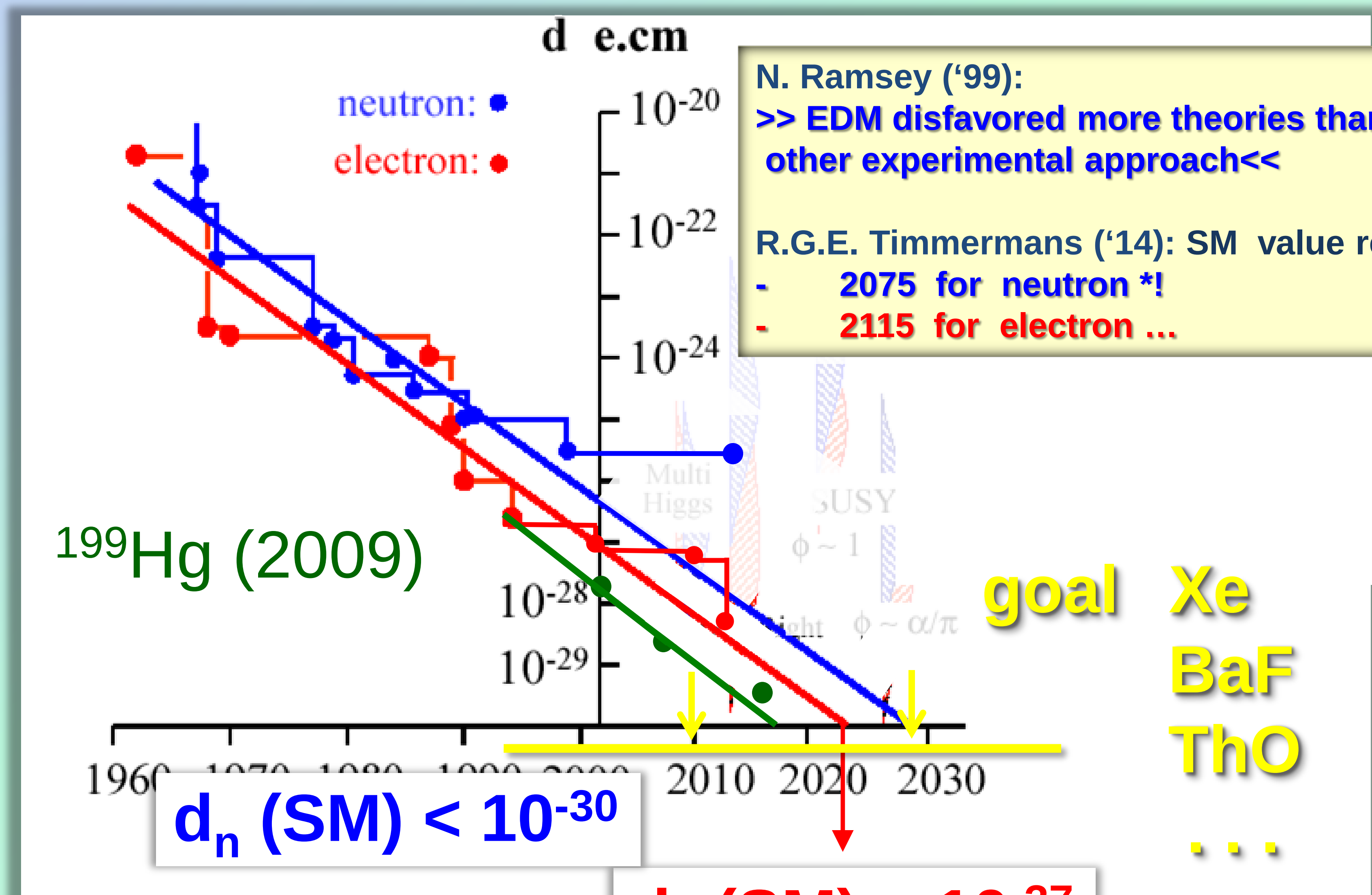
Condensed State

→ electron EDM
→ strong enhancements
→ systematics ??

garnets
($Gd_3Ga_5O_{12}$)
($Gd_3Fe_2Fe_3O_{12}$)
solid He ?
liquid Xe

* Since θ_{QCD} limited by hadronic EDMs
→ only leptons have direct transformative potential

Limit on EDM vs Time



N. Ramsey ('99):
>> EDM disfavored more theories than any other experimental approach<<

R.G.E. Timmermans ('14): SM value reached
- 2075 for neutron *!
- 2115 for electron …

goal Xe
BaF
ThO
. . .

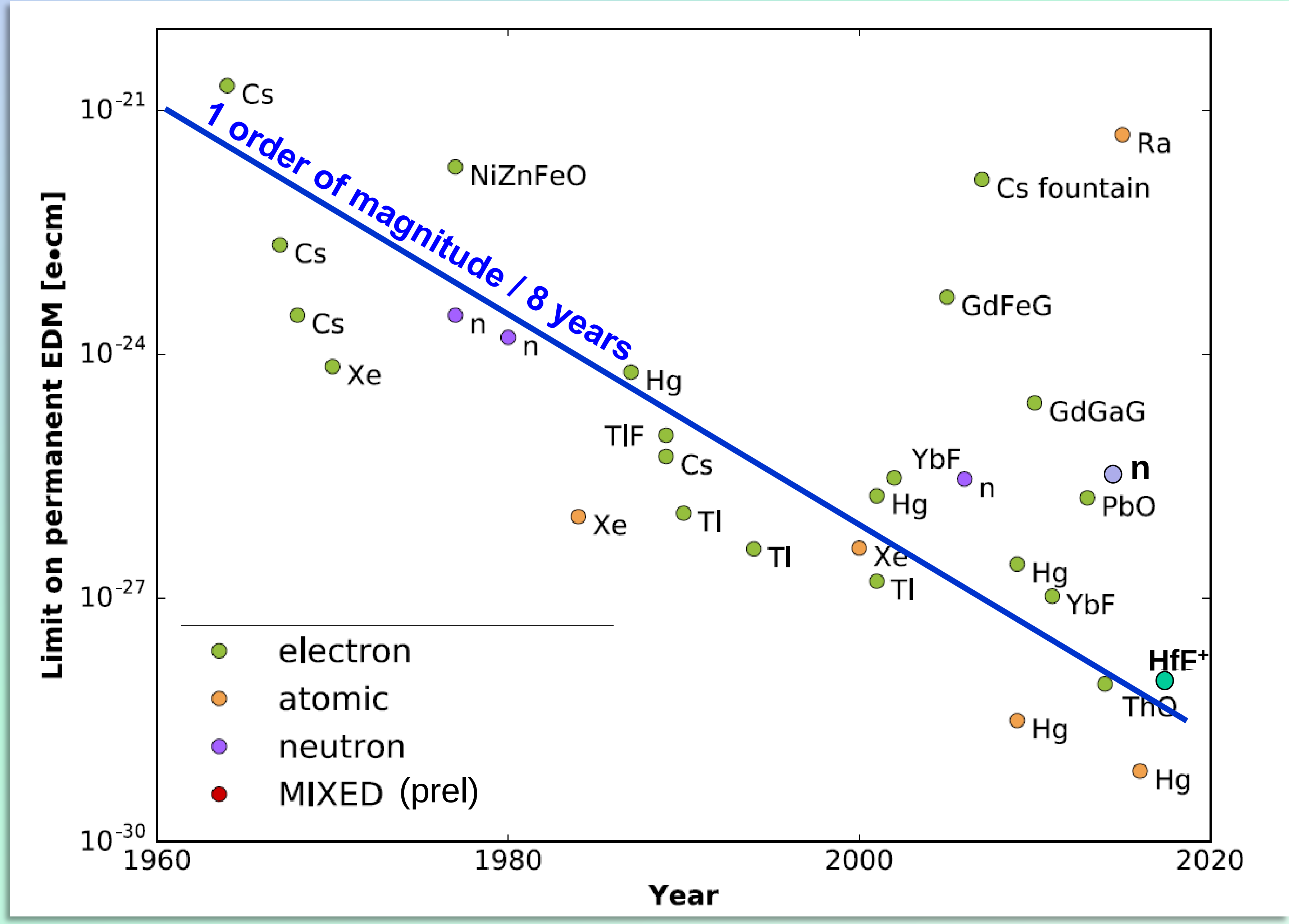
d_n (SM) < 10^{-30}

d_e (SM) < 10^{-37}

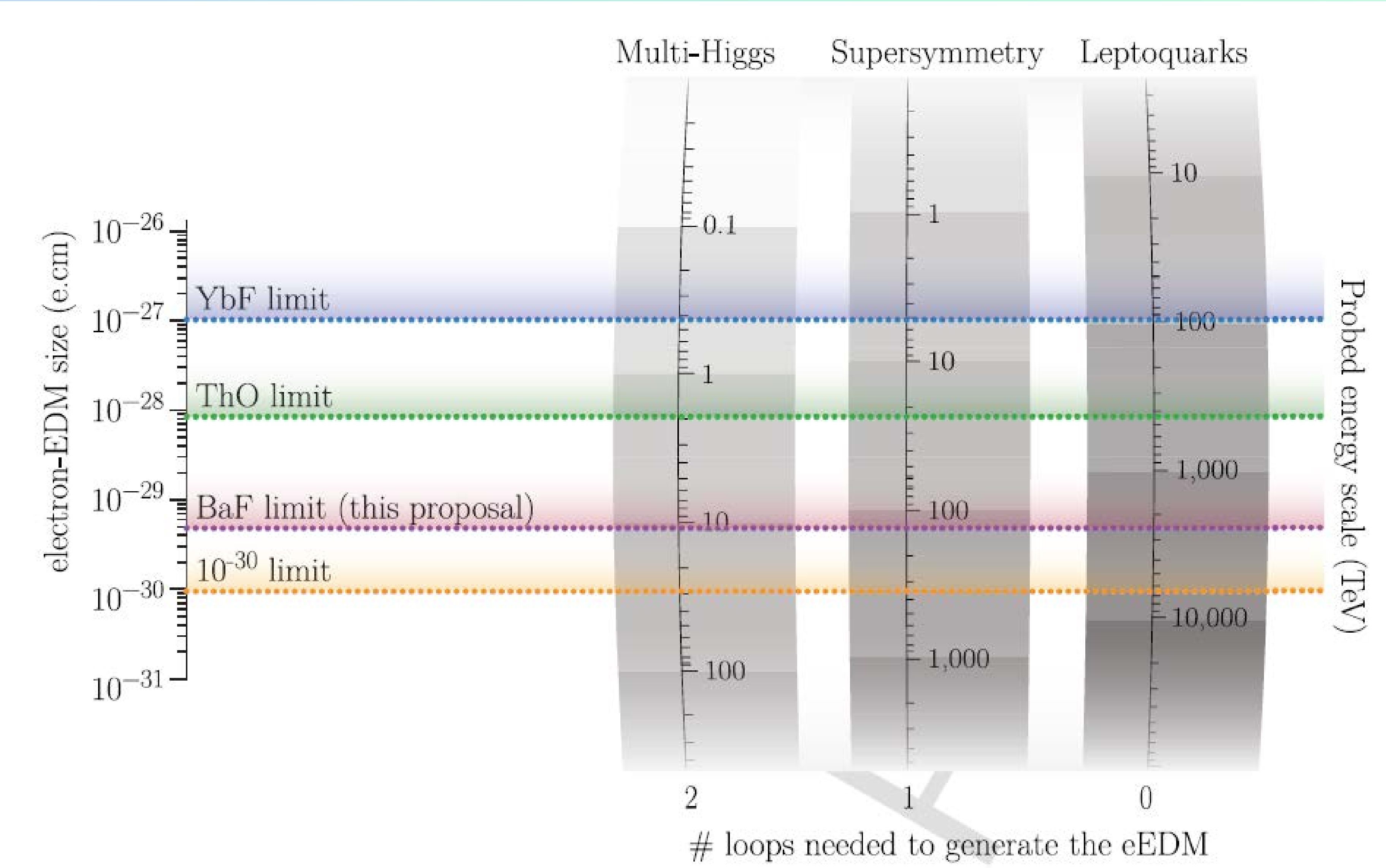
Hg: B.Graner *et al., Phys. Rev. Lett. 116, 161601 (2016) [Seattle]*

e^- : J. Baron *et al., Science 343, 269 (2014) [Harward, Yale]*

EDM Experiments vs. Time



EDM Sensitivity to Different Models



P. Aggarwal et al. Eur. Phys. J. D, in print (2018)

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Some EDM Limits (in e cm)

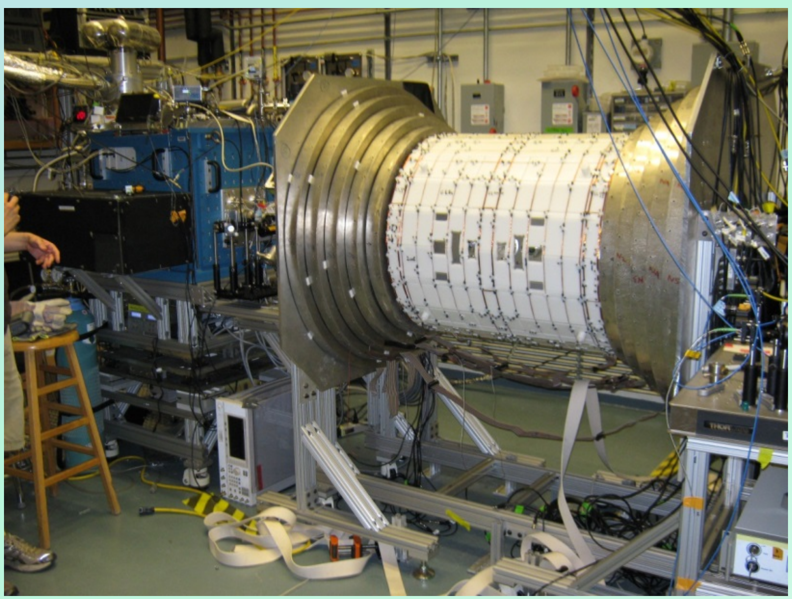
e	^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
	ThO	Harvard-Yale	8.7×10^{-29}	90	$-2.1(3.7)(2.5) \times 10^{-29}$	2014
	$Eu_{0.5}Ba_{0.5}TiO_3$	Yale	6.05×10^{-25}	90	$-1.07(3.06)(1.74) \times 10^{-25}$	2012
	PbO	Yale	1.7×10^{-26}	90	$-4.4(9.5)(1.8) \times 10^{-27}$	2013
	ThO	ACME	8.7×10^{-29}	90	$-2.1(3.7)(2.5) \times 10^{-29}$	2014
n	*n*	Sussex-RAL-ILL	2.9×10^{-26}	90	$0.2(1.5)(0.7) \times 10^{-26}$	2006
atom	^{129}Xe	UMich	6.6×10^{-27}	95	$0.7(3.3)(0.1) \times 10^{-27}$	2001
	^{199}Hg	UWash	7.4×10^{-30}	95	$2.2(2.8)(1.5) \times 10^{-30}$	2016
μ	muon	E821 BNL *g*–2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

EDM limits probe TeV scale physics ↔ about LHC

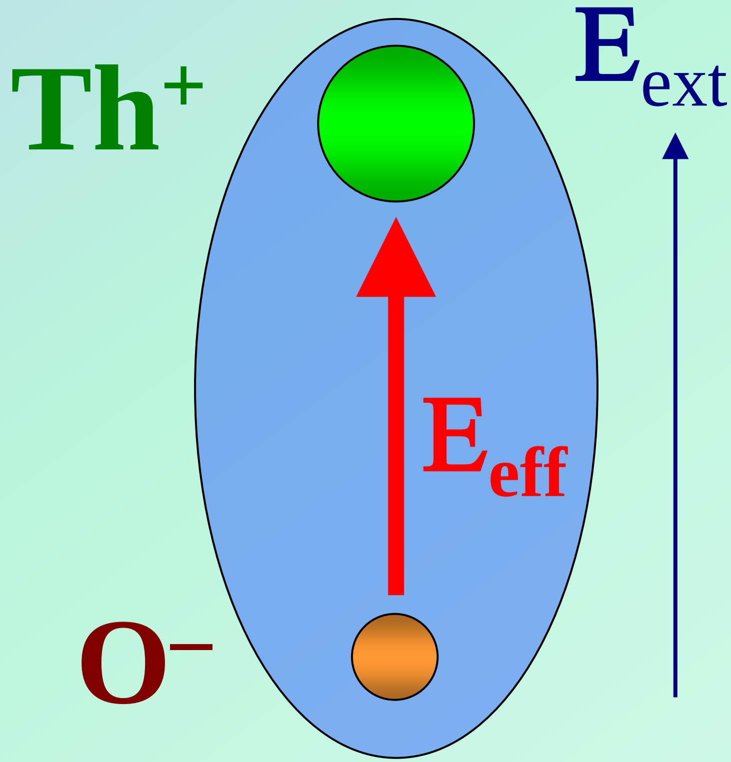
next generation → beyond LHC

Highlight: ThO electorn EDM experiment

Jan 2014



Doyle, Gabrielse , DeMille



E_{ext} ~ 1 V/cm enough for ThO

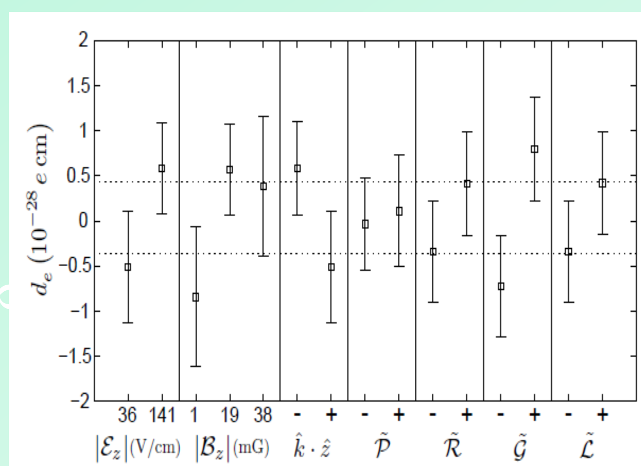
$E_{eff} \sim \Pi\, \alpha^2 Z^3 e/a_0^2$

due to relativity

(P.G.H. Sandars)

$E_{eff} \cong$ 80 GV/cm

(depending on theorist)



New limit for e-

$d_e < 8.7 * 10^{-29}$ e cm

(90% c.l.)

Generic EDM Sensitivity

EDM limit possible

$$\delta d = \frac{\hbar}{E P \varepsilon \sqrt{\tau T N}}$$

electric field

polarization

efficiency

coherence time

total measurment time

particles in experiment

→ quantum limit

Bastian Yip, Master thesis RUG, 2015

Preferred Composed Systems

$$\delta d = \frac{\hbar}{EP\varepsilon\sqrt{\tau T N}} \ / \ \text{enh}$$

T measurement time
P polarization
enh enhancement

Particle	Number Particles N	Coherence Time τ [s]	Efficiency ε	Electric Field E [kV/cm]	Figure of Merrit
^{199}Hg	10^{14}	$2x10^{2}$	$8x10^{-3}$	10	$5x10^{13}$
^{129}Xe	10^{22}	10^{4}	$9x10^{-9}$	3.6	$1x10^{14}$
^{225}Ra	10^{3}	$4x10^{1}$	$7x10^{-5}$	67	$3x10^{6}$
ThO	10^{11}	$1.1x10^{-3}$	$2x10^{-2}$	<0.1	$2x10^{13}$
BaF	10^{11}	10^{-1}	10^{-2}	10	$5x10^{13}$
p/d	10^{8}	10^{3}	10^{-2}	80	$7x10^{13}$

MIXed

Measurement and Investigation of the Xenon-129 electric dipole moment

university of groningen

J.O. Grasdijk

K. Jungmann

L. Willmann

RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

F. Allmendinger

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

M. Doll

W. Heil

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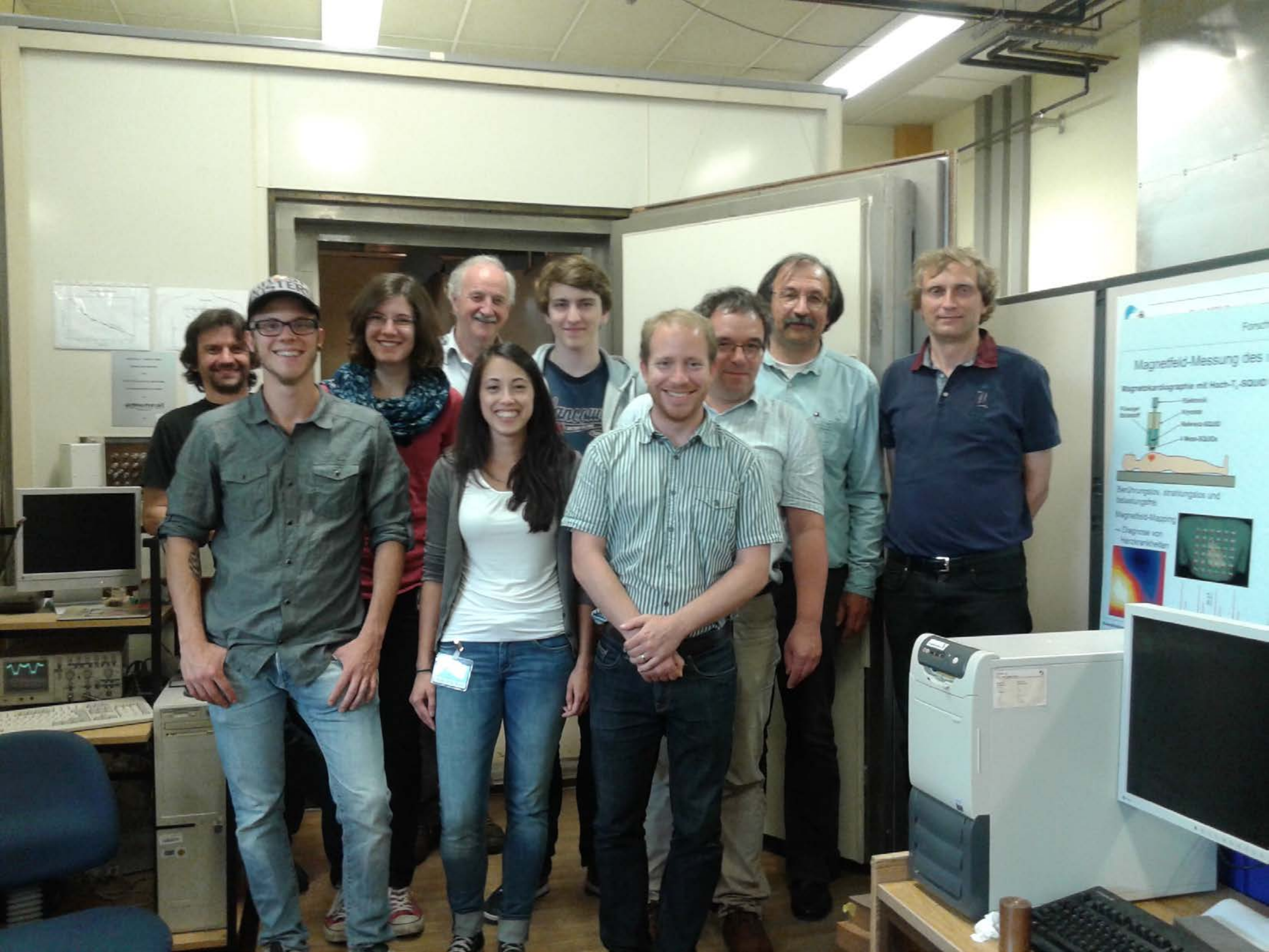
S. Zimmer

JÜLICH FORSCHUNGSZENTRUM

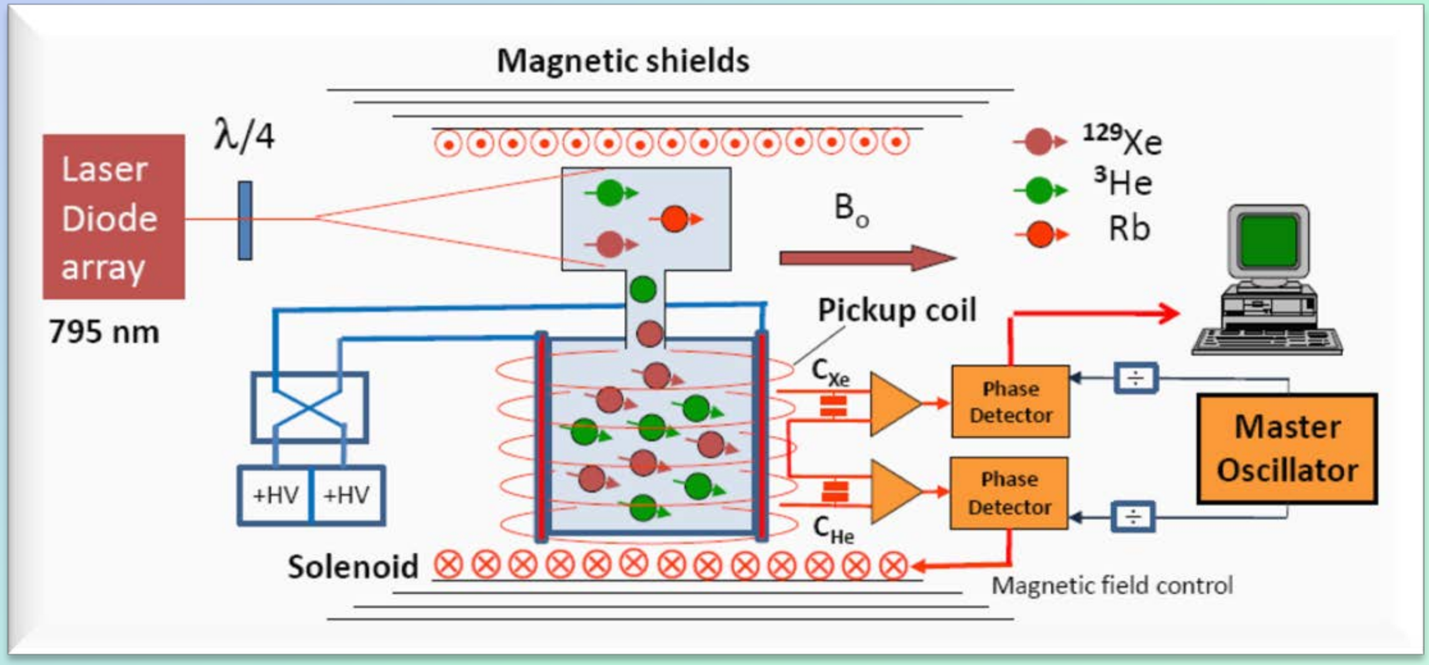
H.-J. Krause

A. Offenhäusser

FOM DFG PRiSMA

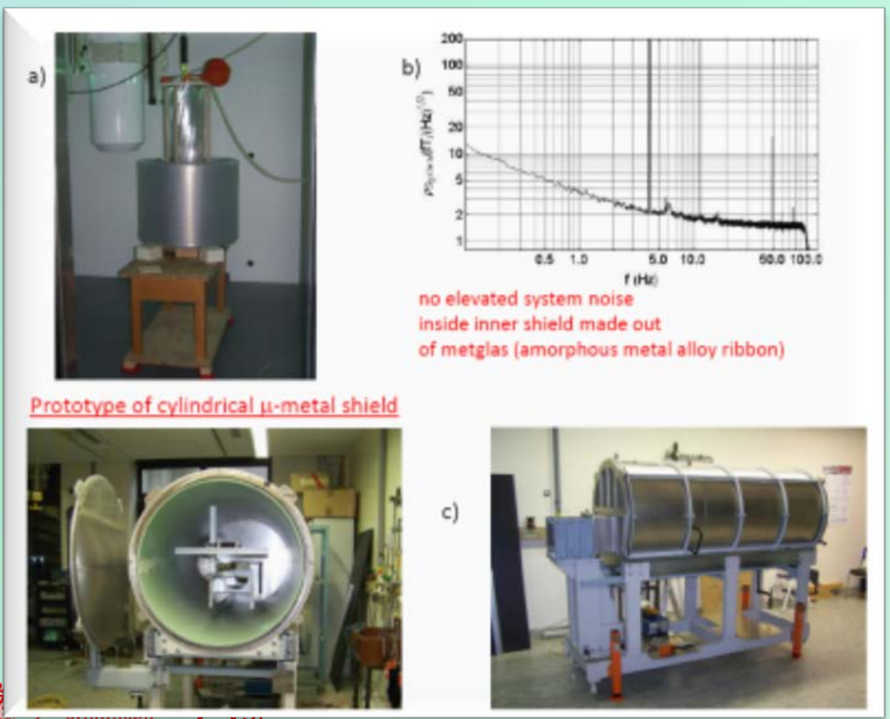

Magnetfeld-Messung des

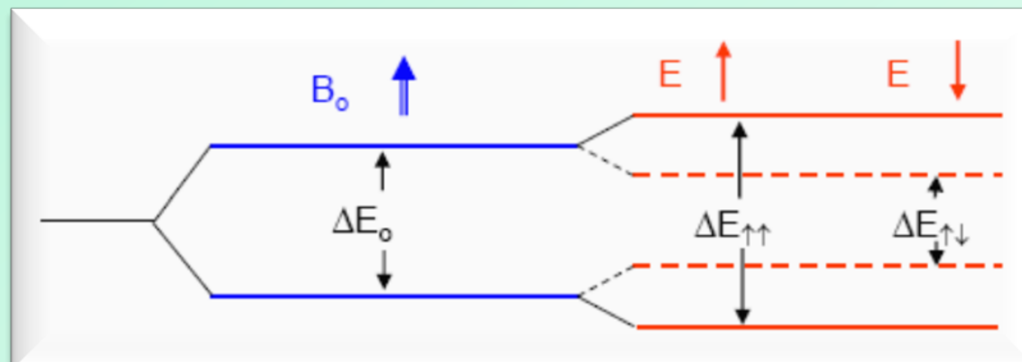
EDM Search from ^{3}He/^{129}Xe Clock Comparison



^{3}He: $T_2^* = (60.2 \pm 0.1)h$

^{129}Xe: $4h < T_2^* < 6h$



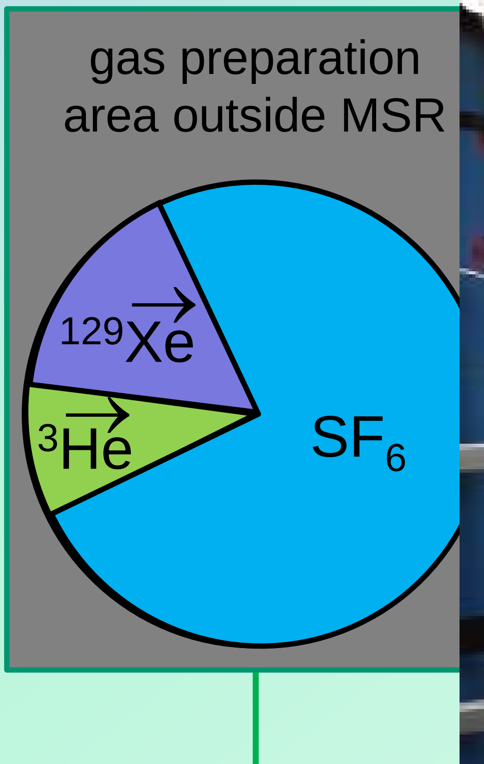


- **present limit** d_{Xe} $< 3\times10^{-27}$ **ecm**
- **potential** **gain > 3-4 orders o.m.**
- **note** d_{Hg} $< 7\times10^{-30}$ **ecm (recent)**

W.Heil, U. Schimdt, L. Willmann et al.

Sketch of experimental setup

typically:
4 mbar He
8 mbar Xe
40 mbar SF_6



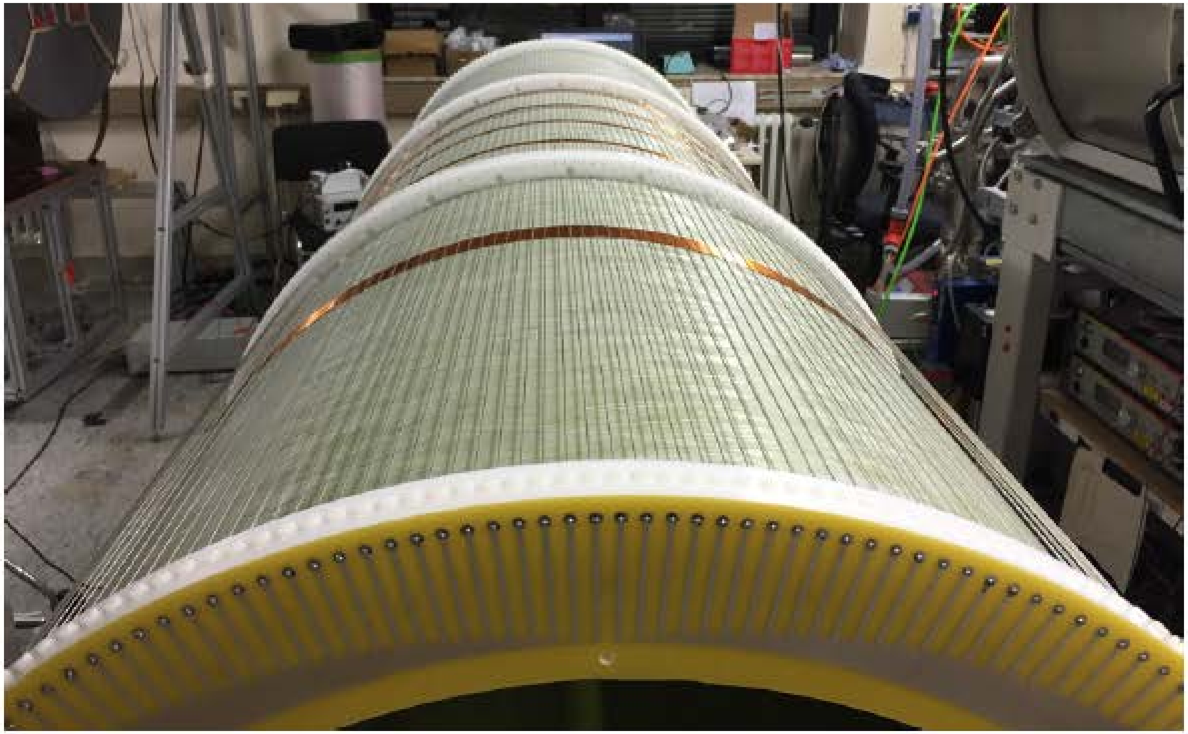
cylinder

nforced plastic

ump

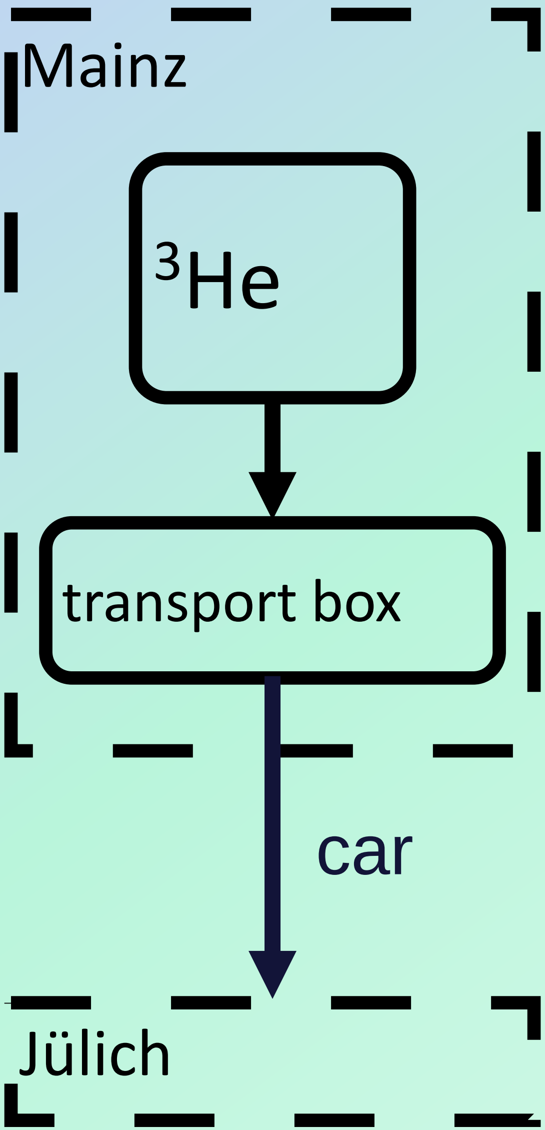
trans

Coil Setup



- cosine coil (400nT)
- solenoid
- gradients coils

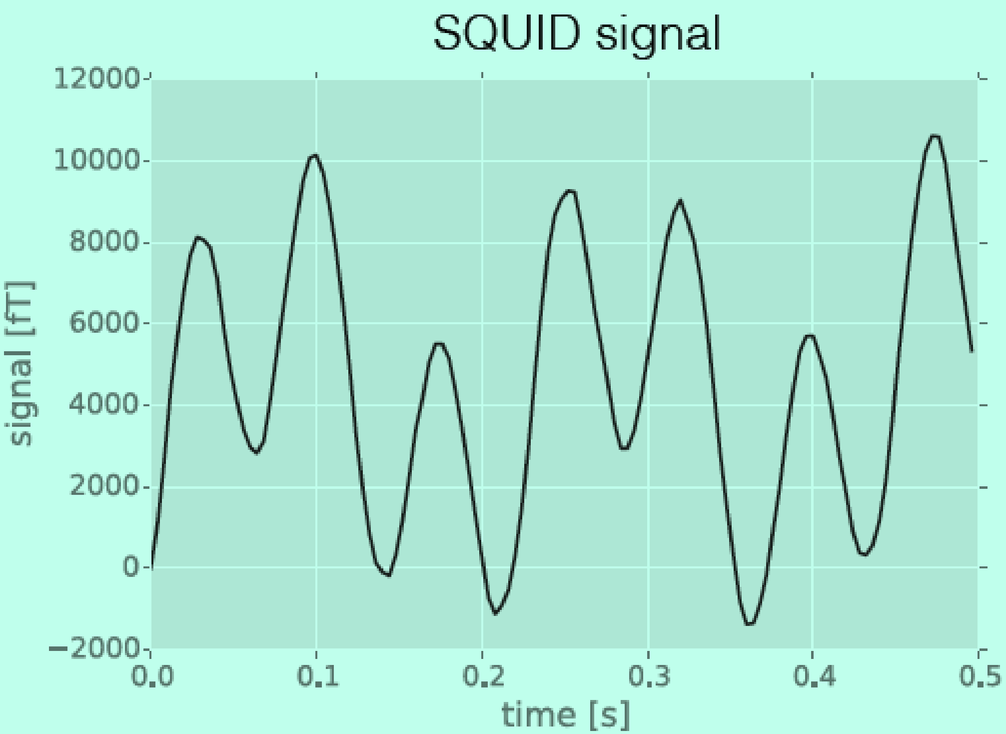
Polarized Helium

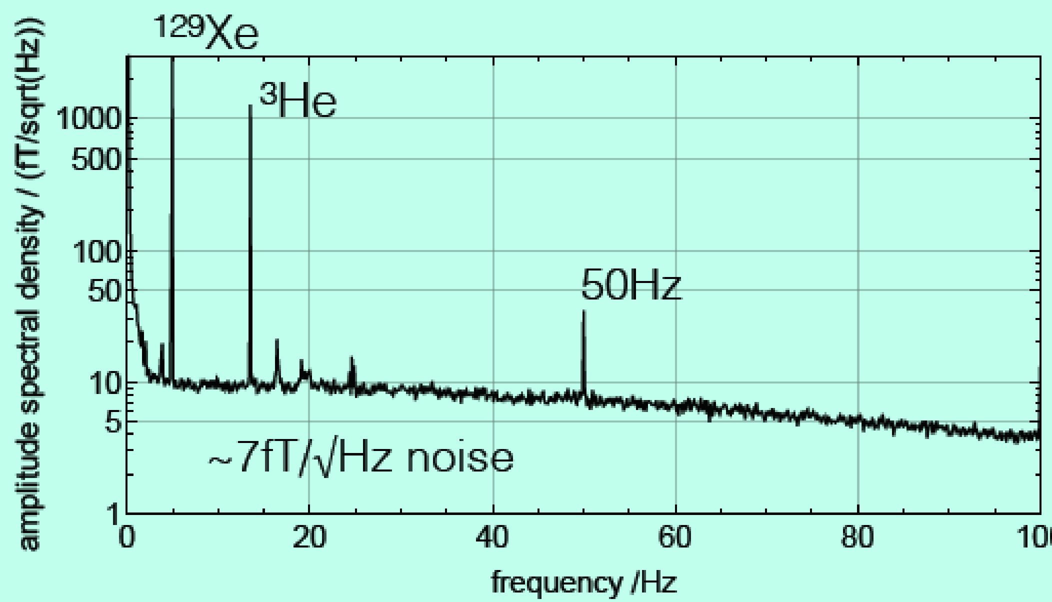


219 km

$^{3}He/^{129}Xe$ Measurement

October 2015





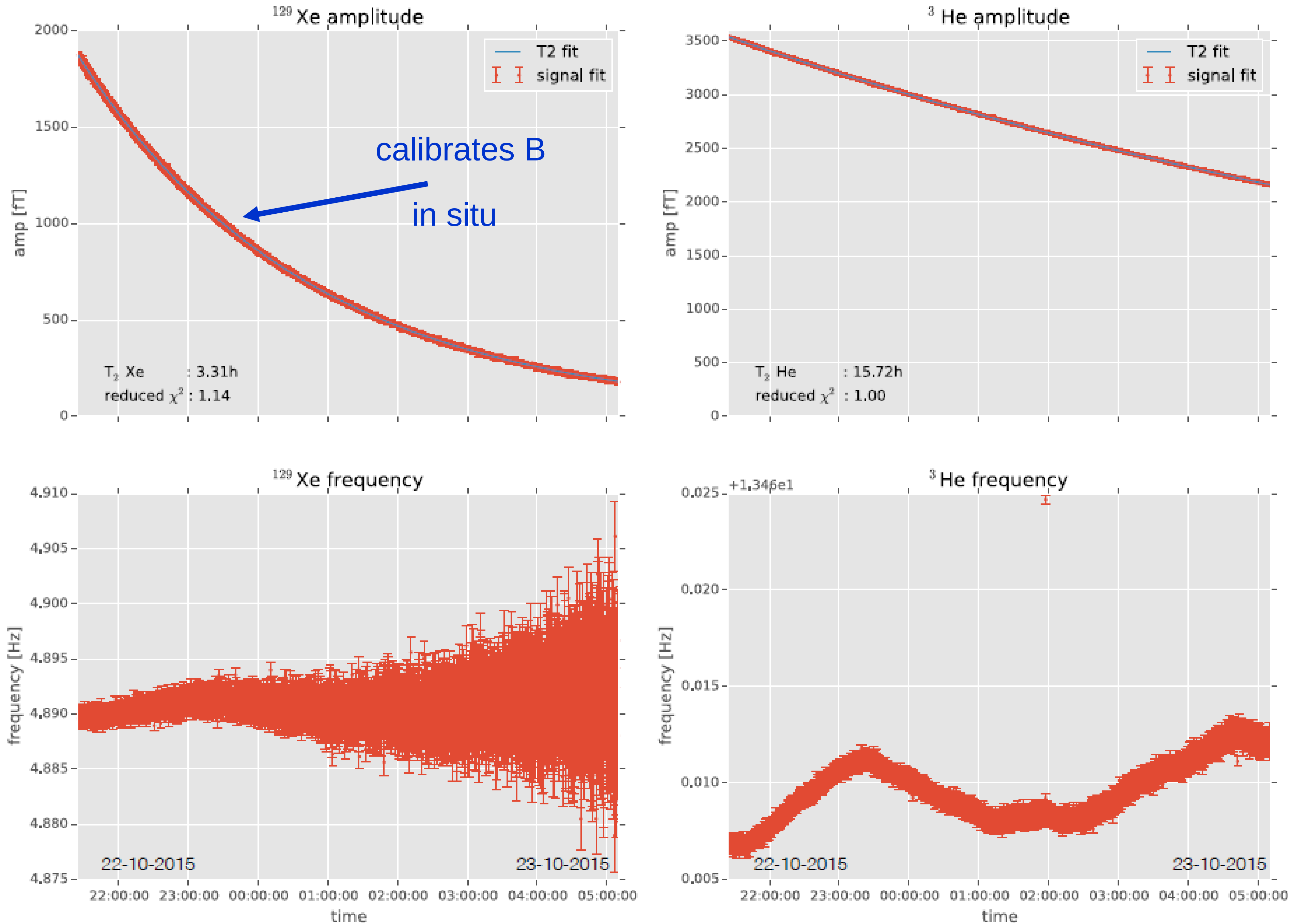
- polarized ^{3}He and ^{129}Xe transported from Mainz by car

- T_1 (^{129}Xe) transport cell ~7h

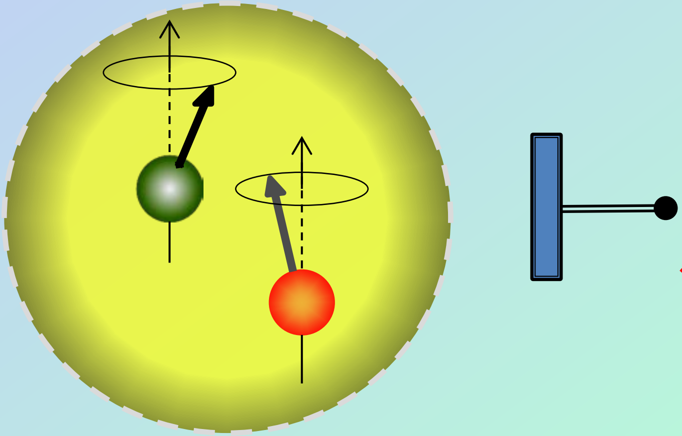
M. Repetto et al, J Mag. Reson. 252, 163(2015)

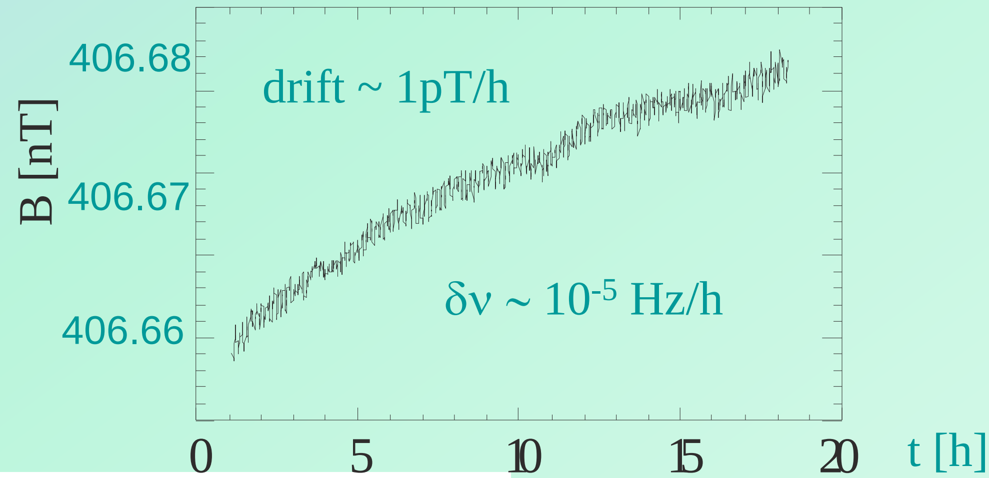
$^3He/^{129}Xe$ Measurement

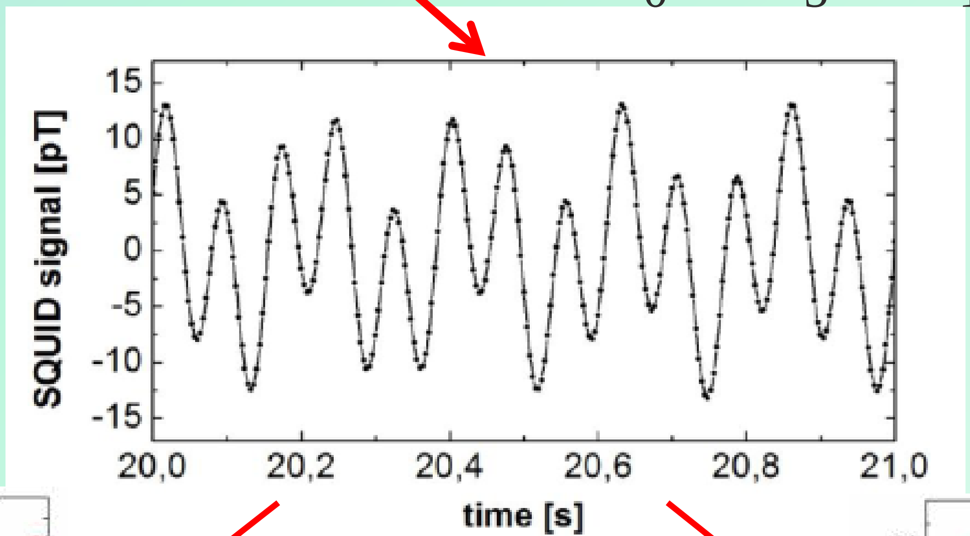
October 2015



^{3}He / ^{129}Xe clock comparison to get rid of magnetic field drifts

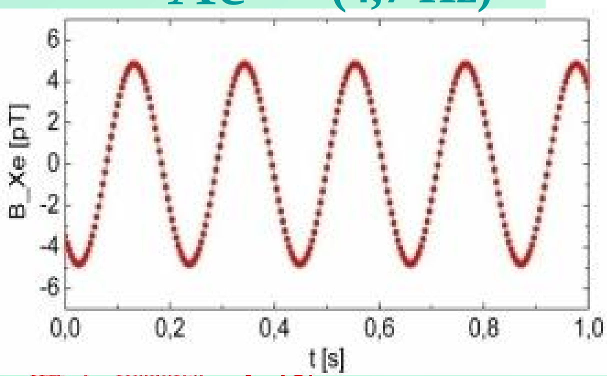






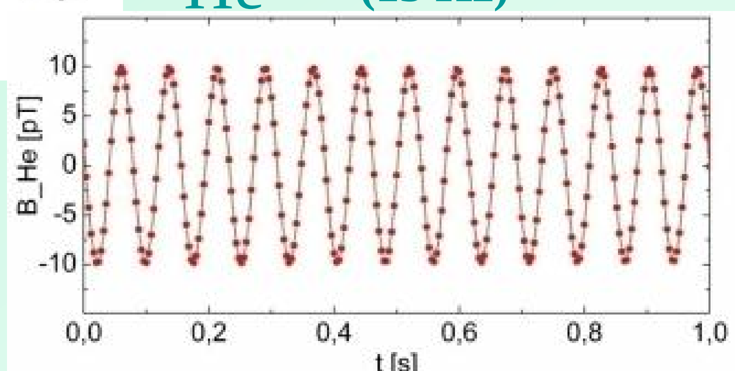
$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

^{129}Xe **(4,7 Hz)**



$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} \overset{!}{=} const.$$

^{3}He **(13 Hz)**

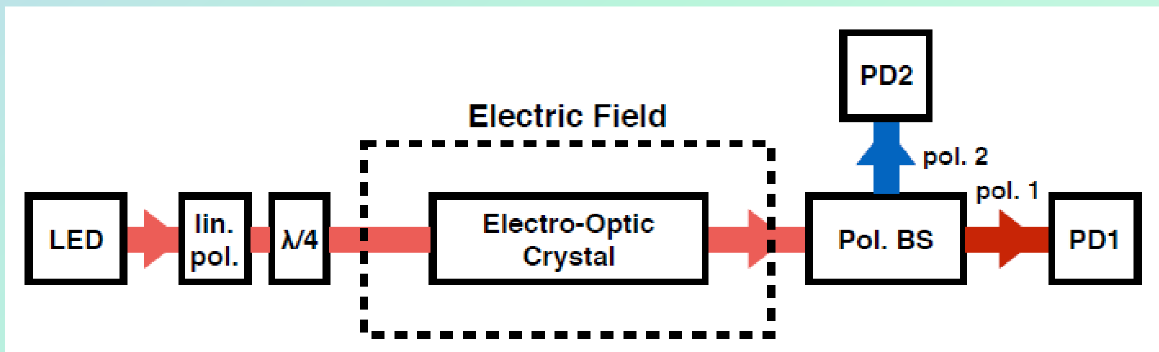


slide from W. Heil

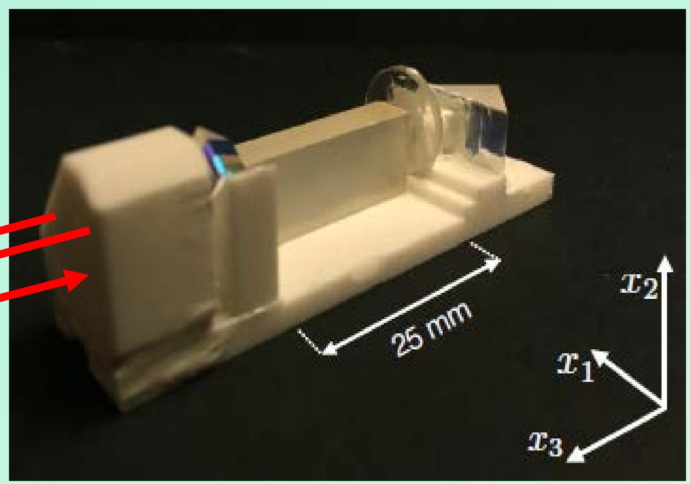
Main Issue: Systematics
e.g. Electric Field

How to measure static Electric Field inside glass bulb (no electrodes)?

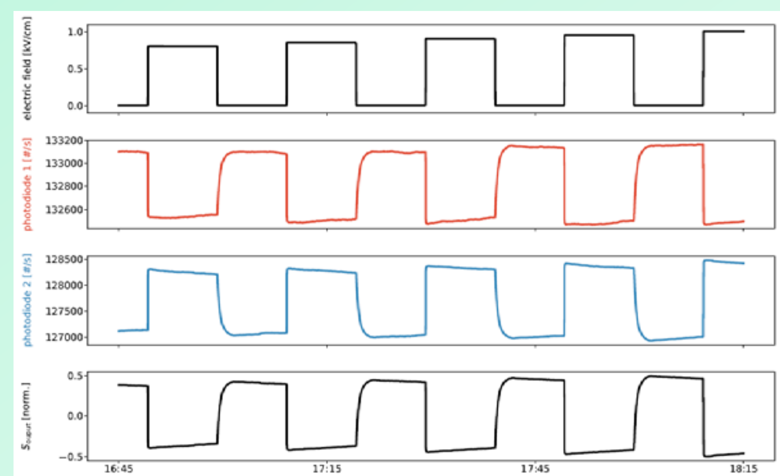
Sensor Concept:



Realization:



optical fibers



J.O. Grasdijk, PhD thesis, Groningen (2018)

⇒ We can follow dc field > 20h !

Main Issue: Systematics just some possibilities

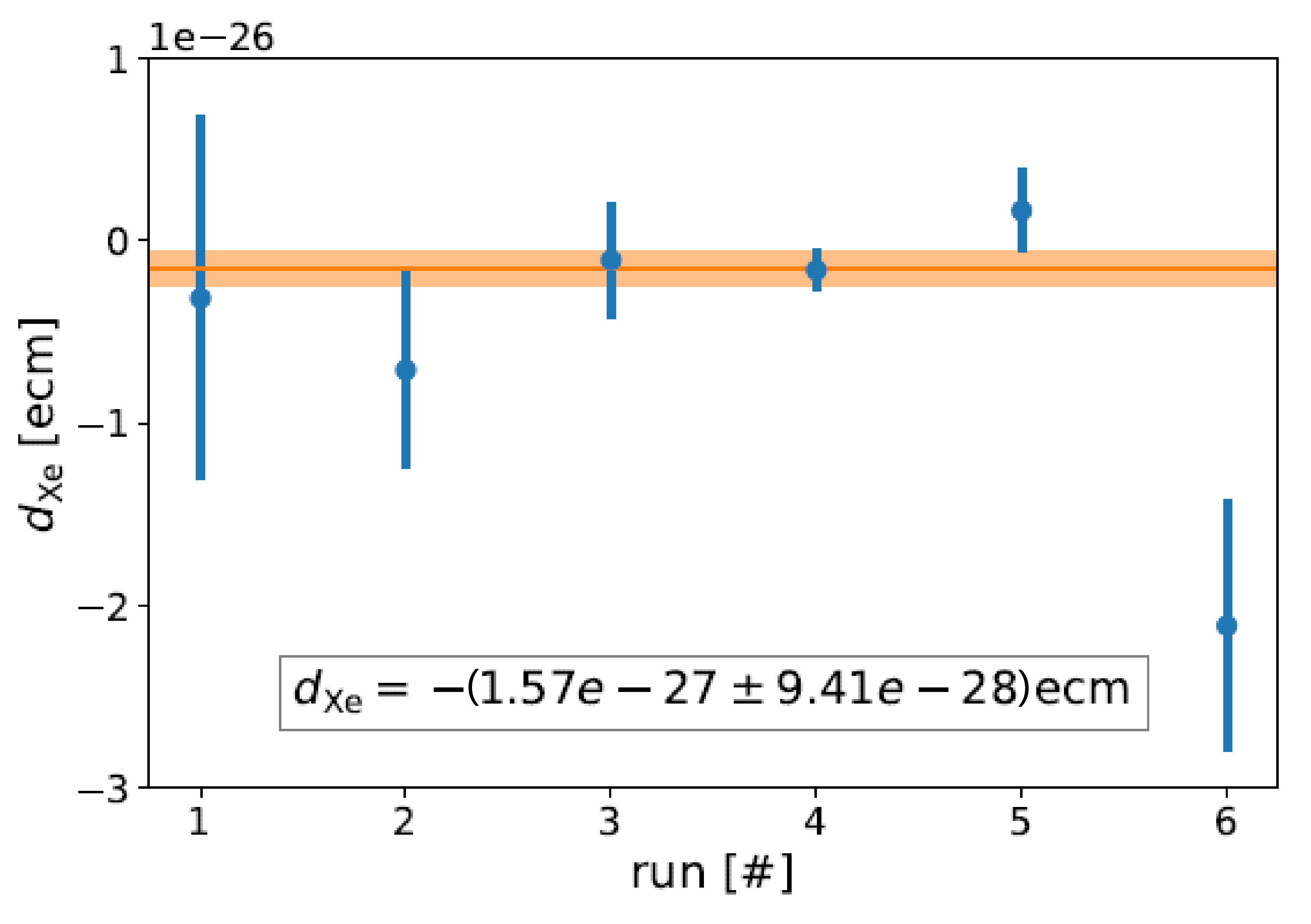
	Frequency Shift	Co-Magnetometry	Flipping	Fitting Routine	Max. False EDM at 800 V/cm
Earth Rotation [Sec. 5.4.3]	2.9×10^{-5} rad/s	No	Yes	Yes	*) 1.2×10^{-23} ecm
Center of Mass [Sec. 5.1.2]	-5.5×10^{-8} rad/s	No	Yes	Yes	-2.3×10^{-26} ecm
Bloch-Siegert Shift [Sec. 5.4.1]	$< 1 \times 10^{-10}$ rad/s	No	No	Yes	$< 8 \times 10^{-30}$ ecm
Chemical Shift [Sec. 5.4.4]	$< 1 \times 10^{-10}$ rad/s	No	Yes	Yes	$< 8 \times 10^{-30}$ ecm
Geometric Phaseshift [Sec. 5.4.2]	9.4×10^{-13} rad/s	No	No	No	3.8×10^{-31} ecm
Leakage Current (10 pA) [Sec. 5.3.1]	1.5×10^{-14} rad/s	No	No	No	**) 6×10^{-33} ecm
Motional Magnetic Field [Sec. 5.1.3]	2.3×10^{-16} rad/s	No	No	No	9.3×10^{-35} ecm
Magnetic Gradient Shift [Sec. 5.1.4]	1.0×10^{-16} rad/s	No	Yes	Yes	4.2×10^{-35} ecm

J.O. Grasdijk, PhD thesis, Groningen (2018)

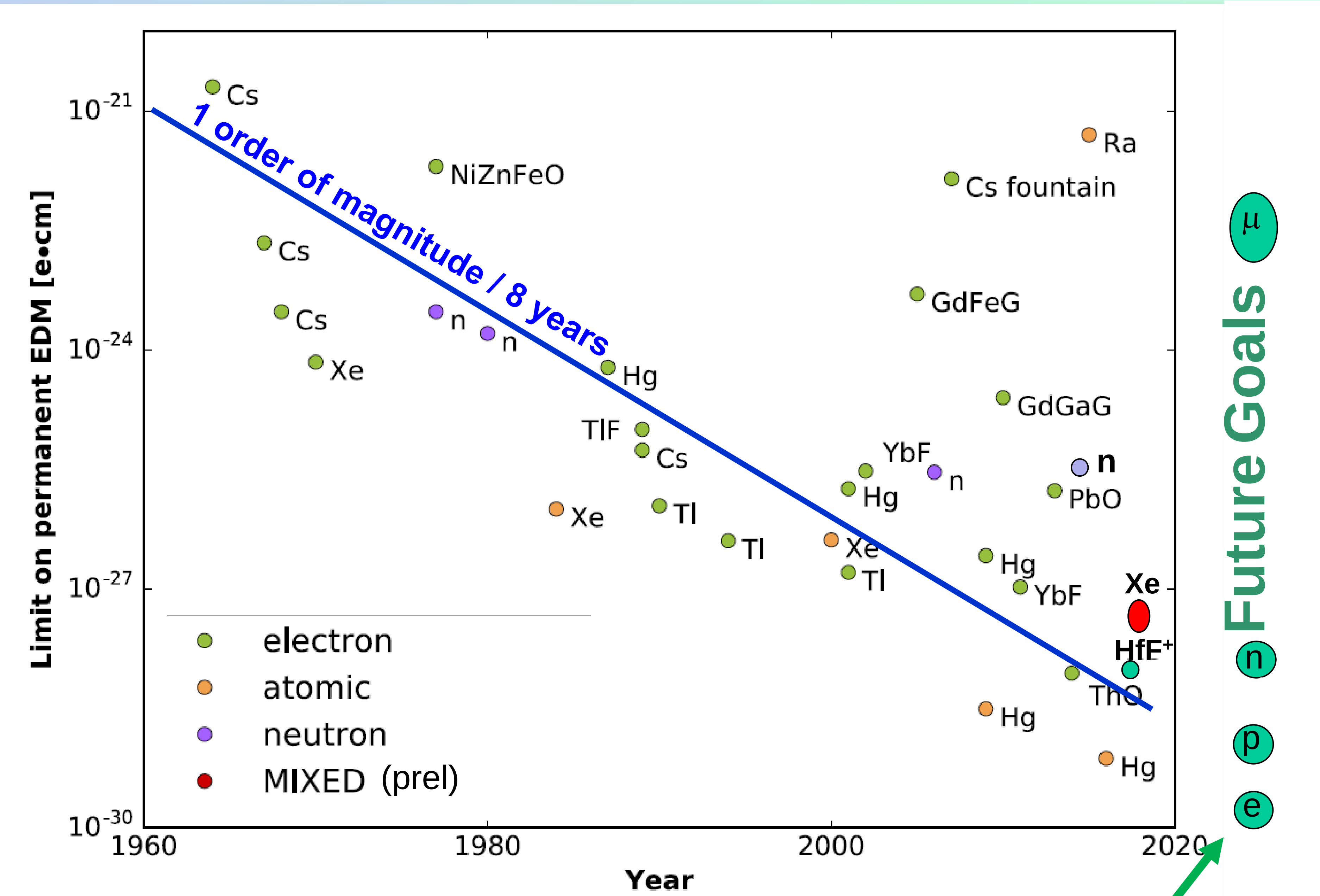
*) effect $\mu\ \vec{B} \times \vec{w}$ $\Rightarrow$ "can be treated"

**) effects worrisome $\Rightarrow$ "can be treated"

Results First Phase EDM Search on ^{129}Xe



EDM Experiments vs. Time



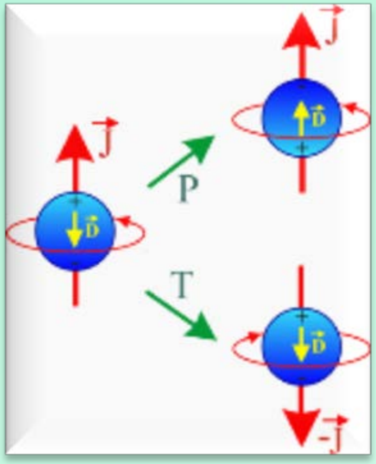
molecules

university of groningen / VSI

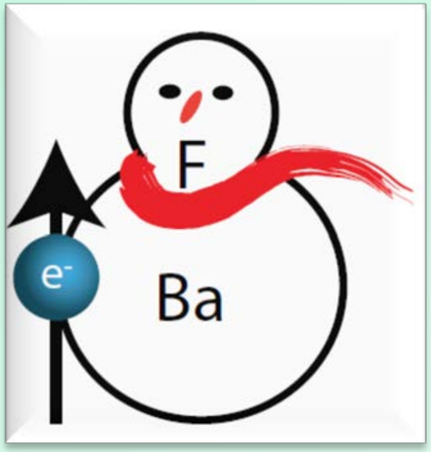
Cold Molecules

for

EDMs

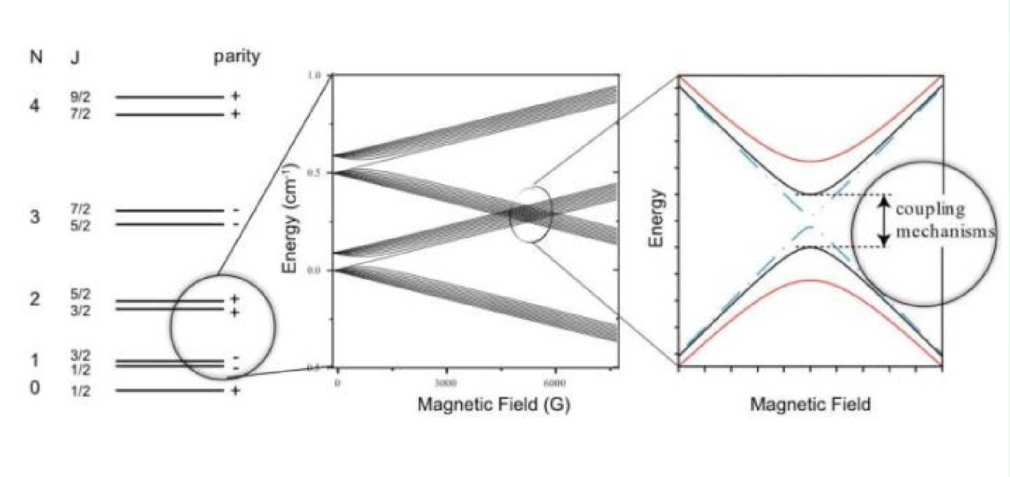


BaF



Precision Measurements with Molecules

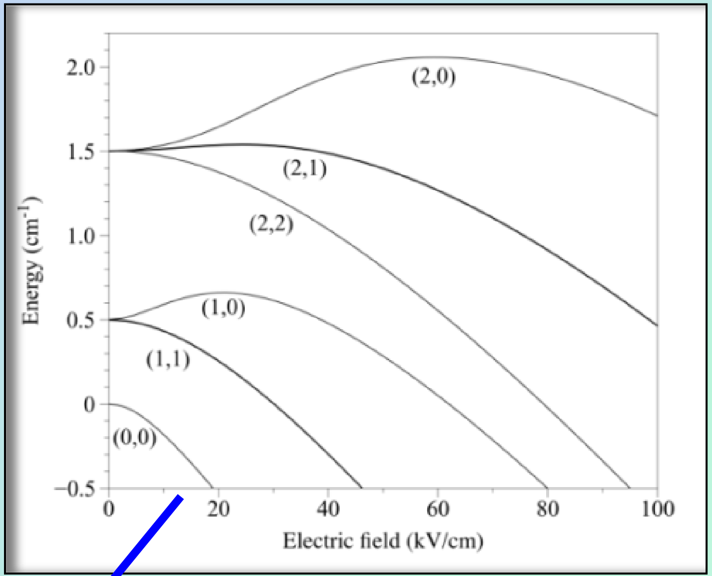
- Heavy diatomic molecules (*SrF, RaF, BaF, ...*) are suited for precision measurements (parity violation, eEDM, ..)
- Large enhancement due to almost degenerate rotational levels



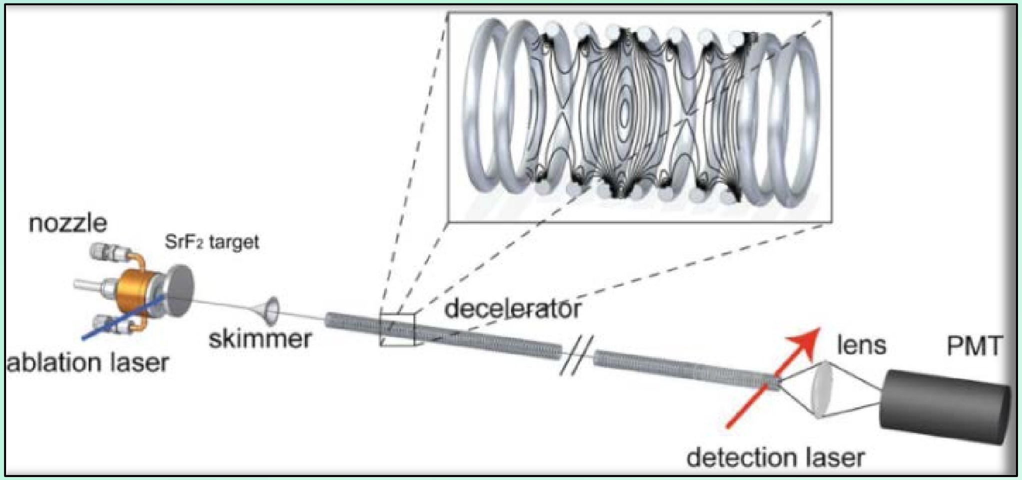
- Ultracold molecules by a traveling wave decelerator and laser cooling
- Benefit from the long interaction time provided by a cold, trapped sample

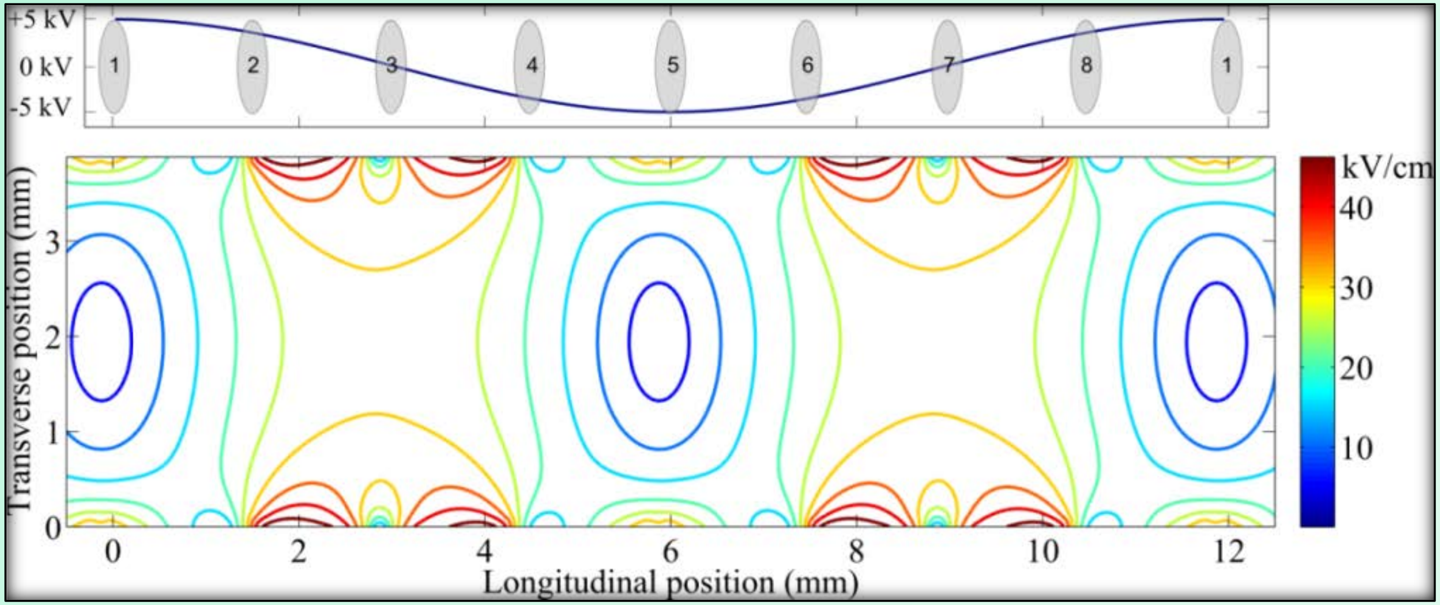
C. Meinema, J. v/d Berg, S. Hoekstra

Traveling wave decelerator



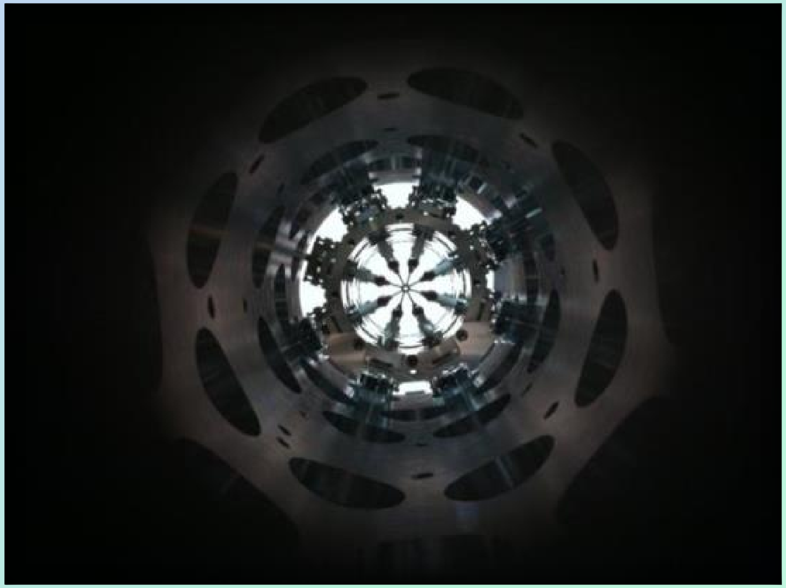
SrF (BaF)

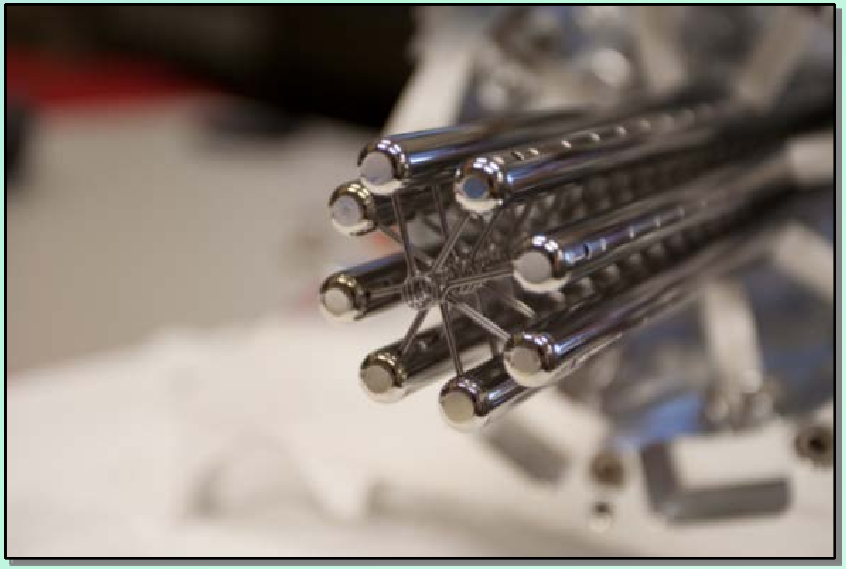




C. Meinema, J. v/d Berg, S. Hoekstra

Traveling wave decelerator



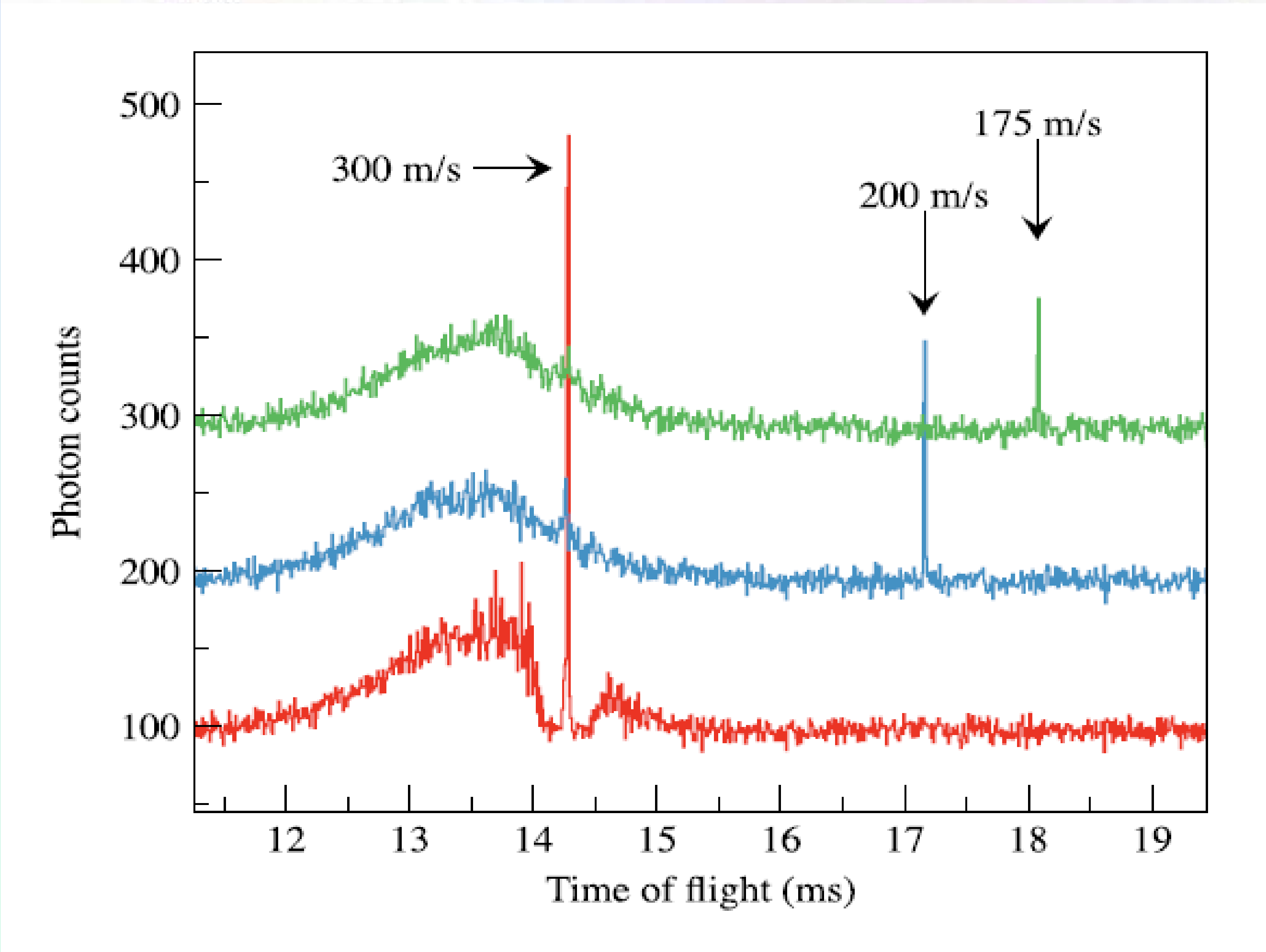


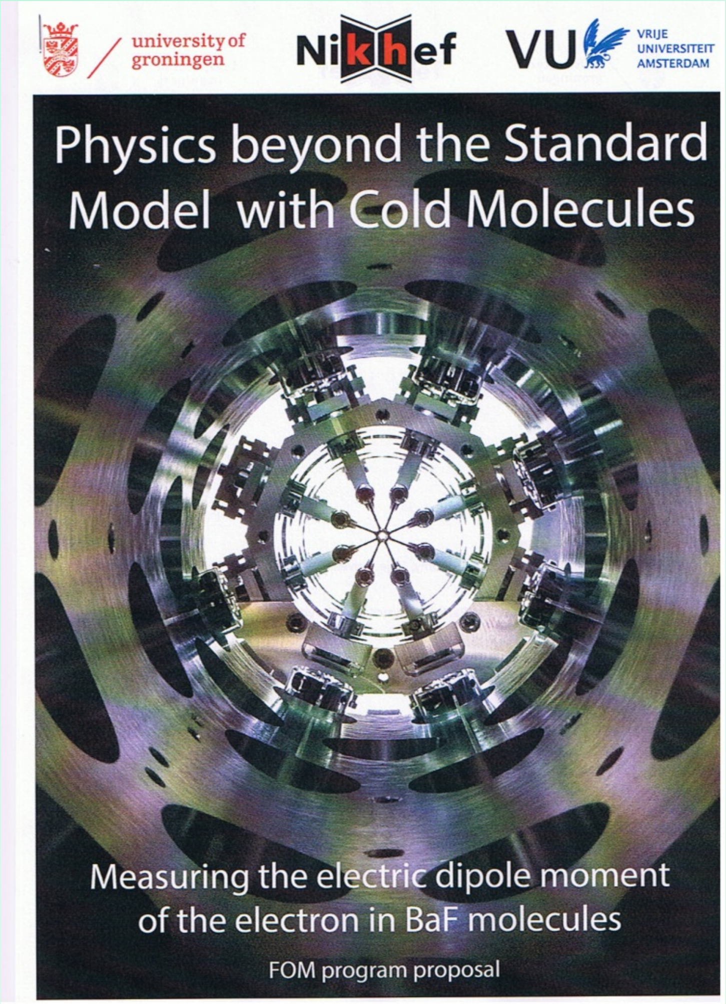
5 m of decelerator
10 modules of 50 cm
3360 ring electrodes
diameter electrode: 4 mm

C. Meinema, J. v/d Berg, S. Hoekstra

SrF Slowed Down and Guided

- 8 of 8 amplifiers
- 4 m machine





J. E. vd Berg at al, J. Mol. Spec. 300, 22 (2014)
S.C. Mathavan et al., Chem.Phys.Chem. 17,3709 (2016)

S. Hoekstra et al.

The way to go for eEDM below 10^{-29} ecm

university of groningen / VSI

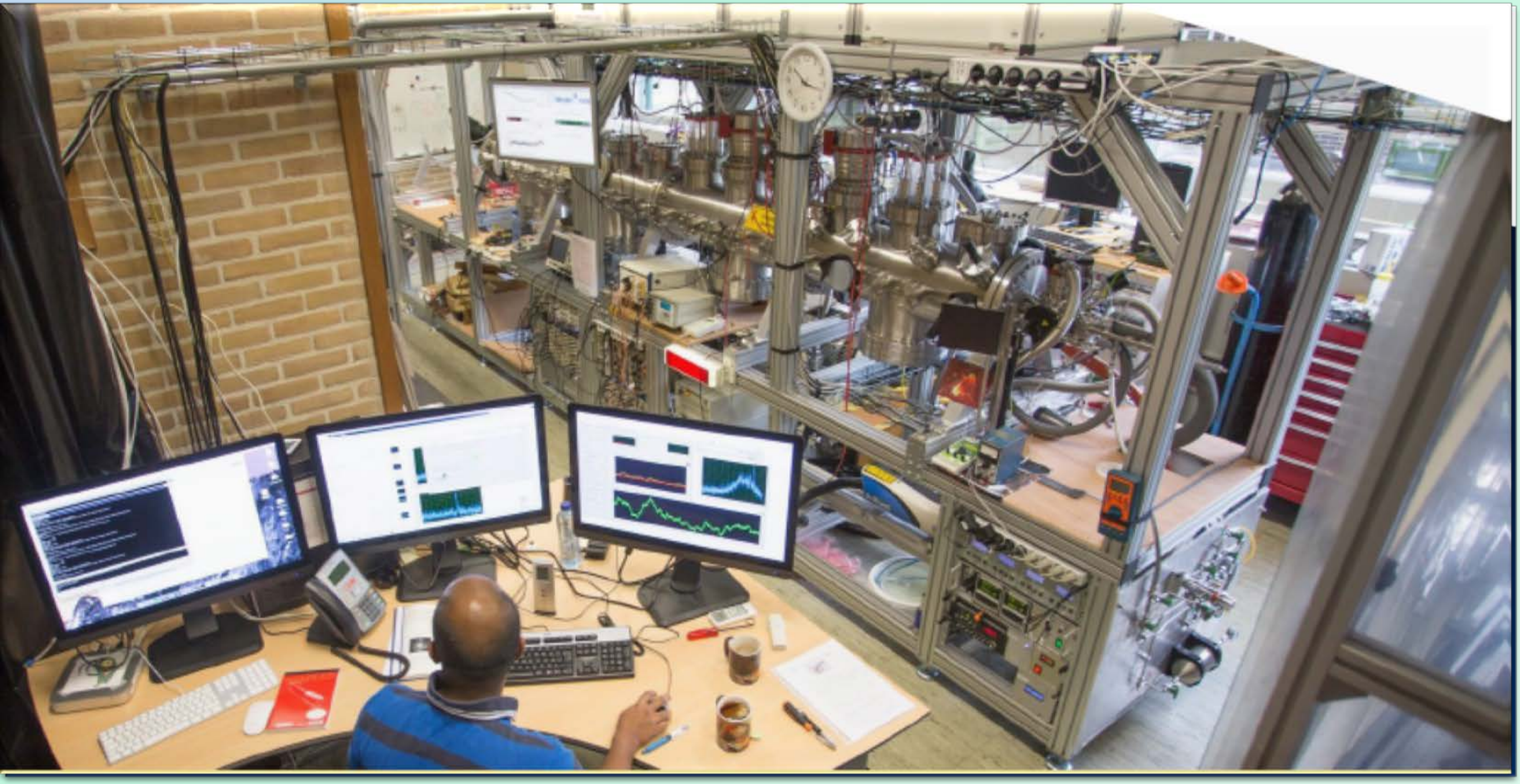
NL-2EDM

university of groningen | Nikhef | VU VRIJE UNIVERSITEIT AMSTERDAM

NL-2EDM

NWO programme - S. Hoekstra, H. Bethlem, A, Borschevsky, K. Jungmann,
(2017-2022) R. Timmermans, W. Ubachs, L. Willmann

Goal: limit $< 10^{-29}$ e cm on electron EDM



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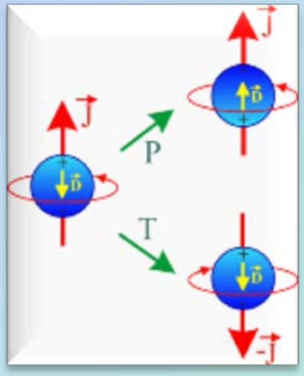
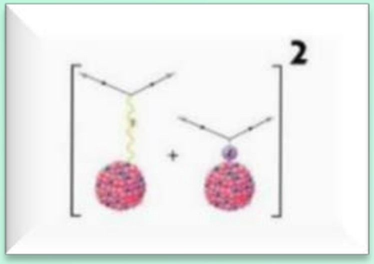
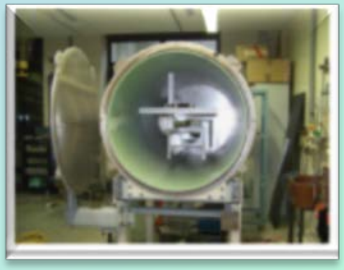
SUMMARY

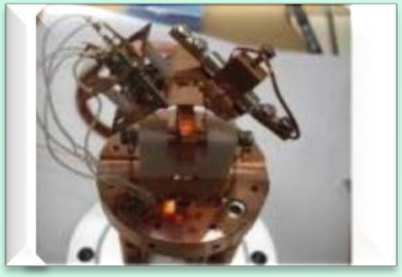
Testing Fundamental Symmetries at the Atomic Scale

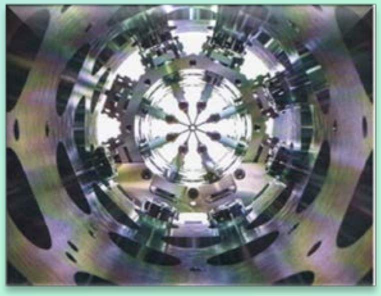


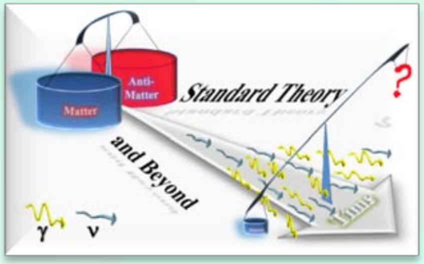


- A few selected Topics
  - → Focus on Transformativity
- C, P, CP, CPT
  - → Precision Test of Standard Model
- Hand in Hand with Applications
  - → Atomic Parity violation & Precision Clocks
- Search for permanent Electric Dipole Moments
  - → Exploiting & Testing Symmetries
  - → Challenge New Physics Models









THANKS to ALL Members of the collaborations !

THANK YOU !