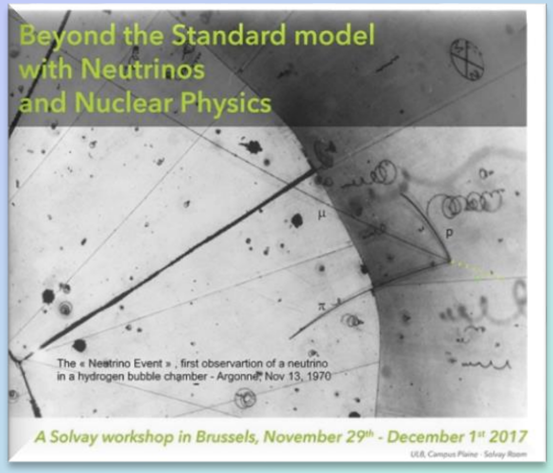

Beyond the Standard model
with Neutrinos
and Nuclear Physics

The « Neutrino Event » , first observartion of a neutrino
in a hydrogen bubble chamber - Argonne, Nov 13, 1970

A Solvay workshop in Brussels, November 29^{th} - December 1^{st} 2017
ULB, Campus Plaine - Solvay Room

SOLVAY WORKSHOP
"Beyond the Standard model with Neutrinos and Nuclear Physics"

Brussels, November 29th - December 1st, 2017

Instable Particles as Probes for New Physics –

Searches for APV and EDMs

Klaus Jungmann

Van Swinderen Institute, University of Groningen

university of groningen / VSI

Searches for Electric Dipole Moments/Parity Violation

- Testing the Standard Model with instable Molecules, Atoms and Particles

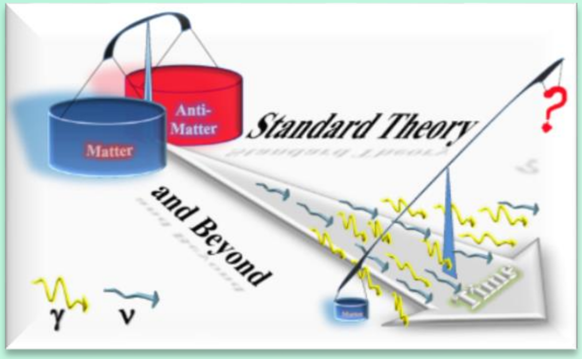
- Discrete Symmetries and their Conservation / Violation

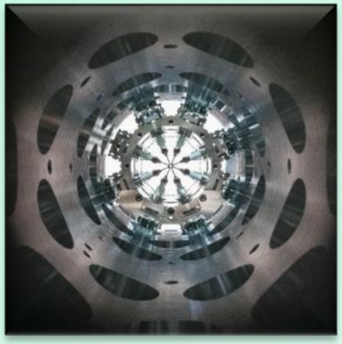
- In general :

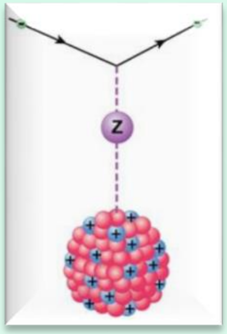
Few Valence Electron Systems	- Privileged
Heavy Atoms	- Advantageous
Radioactive Species	- Some Opportunities

- EDM Searches with Enhancement in Atoms, Molecules (& Some Nuclei)

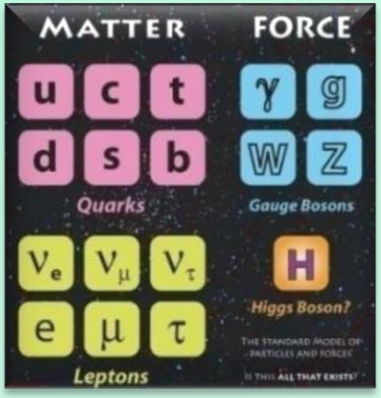
- Perspectives in the Period to Come Due to Technology Advances







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

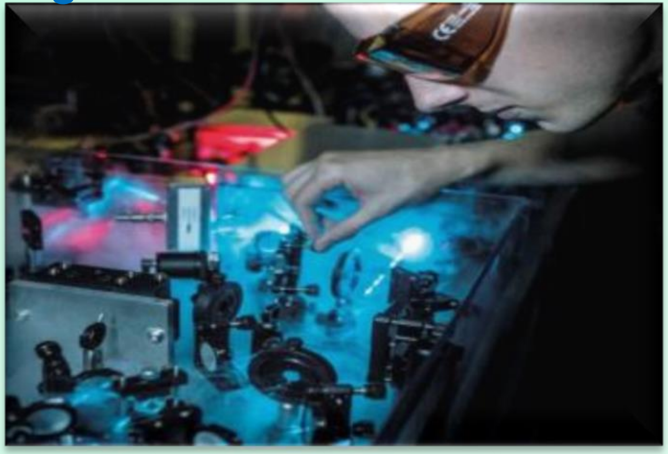
CERN e.g. LHC

e.g. Discovery of Higgs boson,..

also: Difference Matter-Antimatter …

Equivalent Approaches

Indirect:
High Precision Measurements

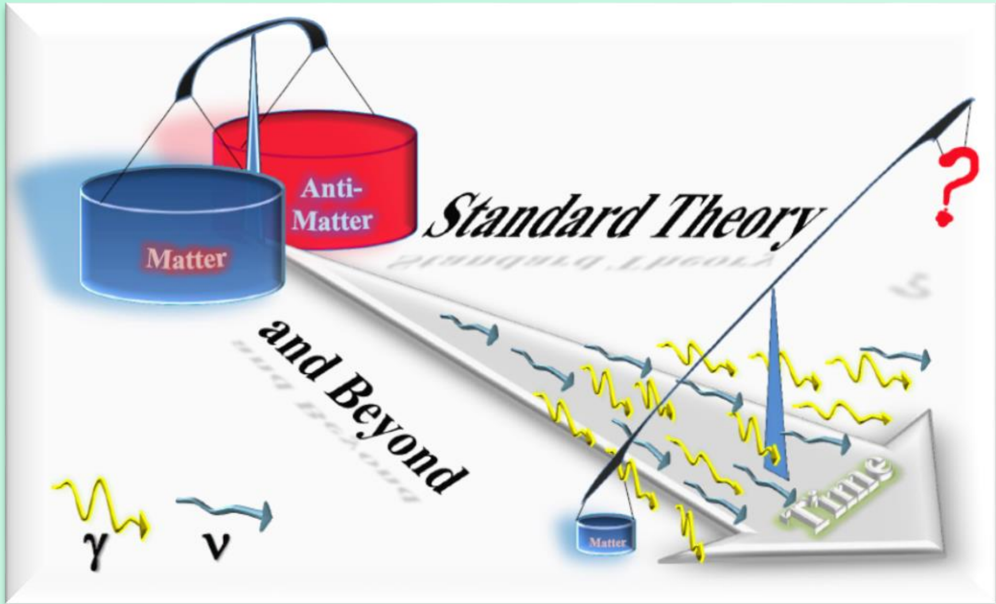


Small institutes e.g. VSI ..

e.g. Atomic Parity Violation, EDM searches, …..

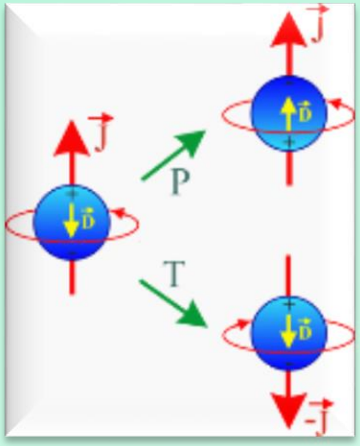
Discrete Symmetries

C,P,T,CP,CPT



An EDM

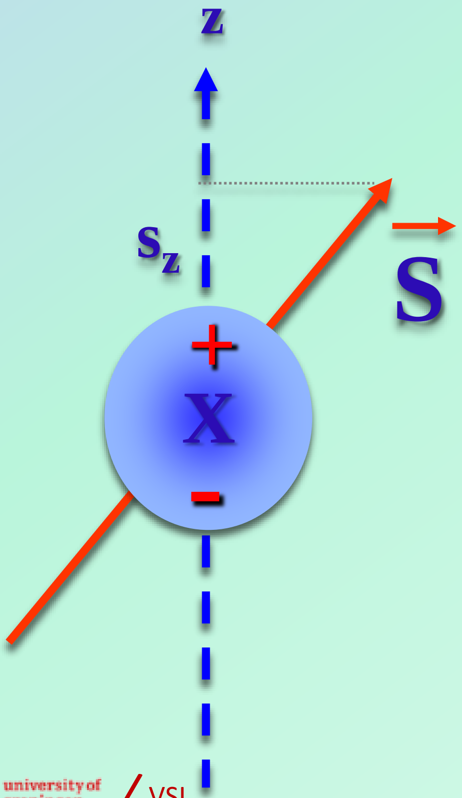
Violates P,T



and with CPT also CP

Permanent

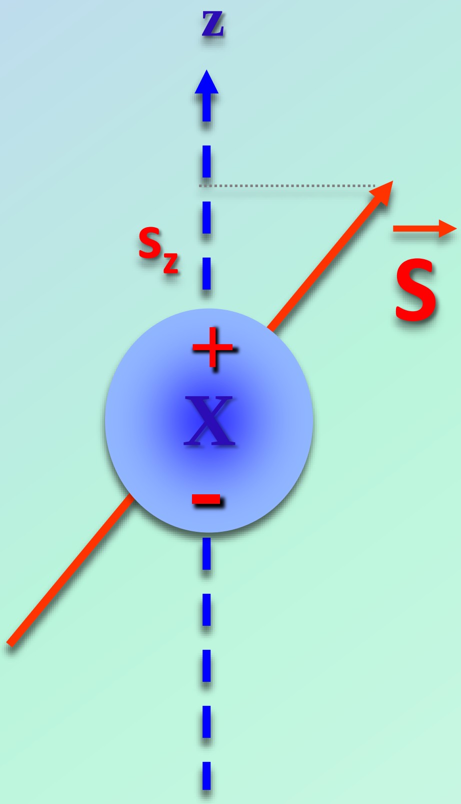
Electric Dipole MomentS



- → Electron: clean and ready for New Physics

- → Hadrons: depend on θ_{QCD} in Standard Model

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:

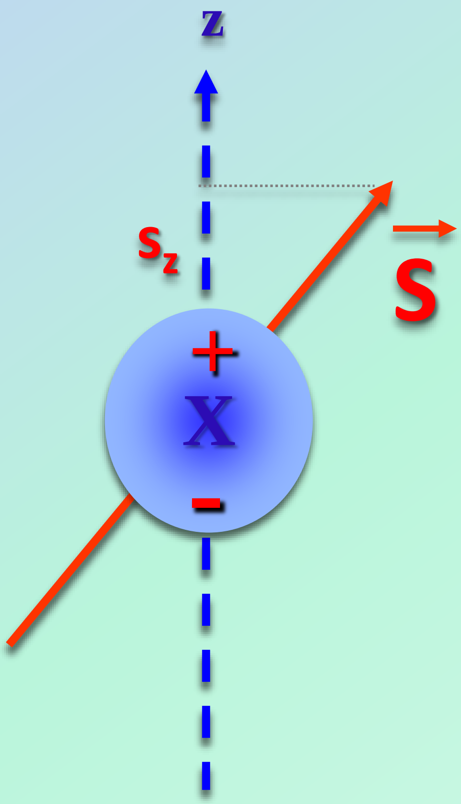
$$\vec{d}_x = \eta\,\mu_{0x}\,c^{-1}\,\vec{S}$$

magneton:

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

$$\mu_{0x}\,c^{-1}\,S = \begin{cases} 9.7\bullet10^{-12}\text{ e cm (electron)} \\ 4.6\bullet10^{-14}\text{ e cm (muon)} \\ 5.3\bullet10^{-15}\text{ e cm (nucleon)} \end{cases}$$

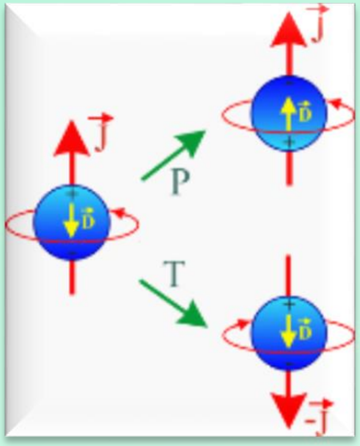
Instable Particle EDMs



- In principle EDM not forbidden in instable states
  → e.g. transition dipoles exist
- Heavy (therefore instable) atoms have general advantage
  → deformed nuclei
  → Z^x enhancement (x typically 2…3)
- Instable particles may have detection advantage
  → β – asymmetry
  → are there oscillations in EDMs ? (axions)

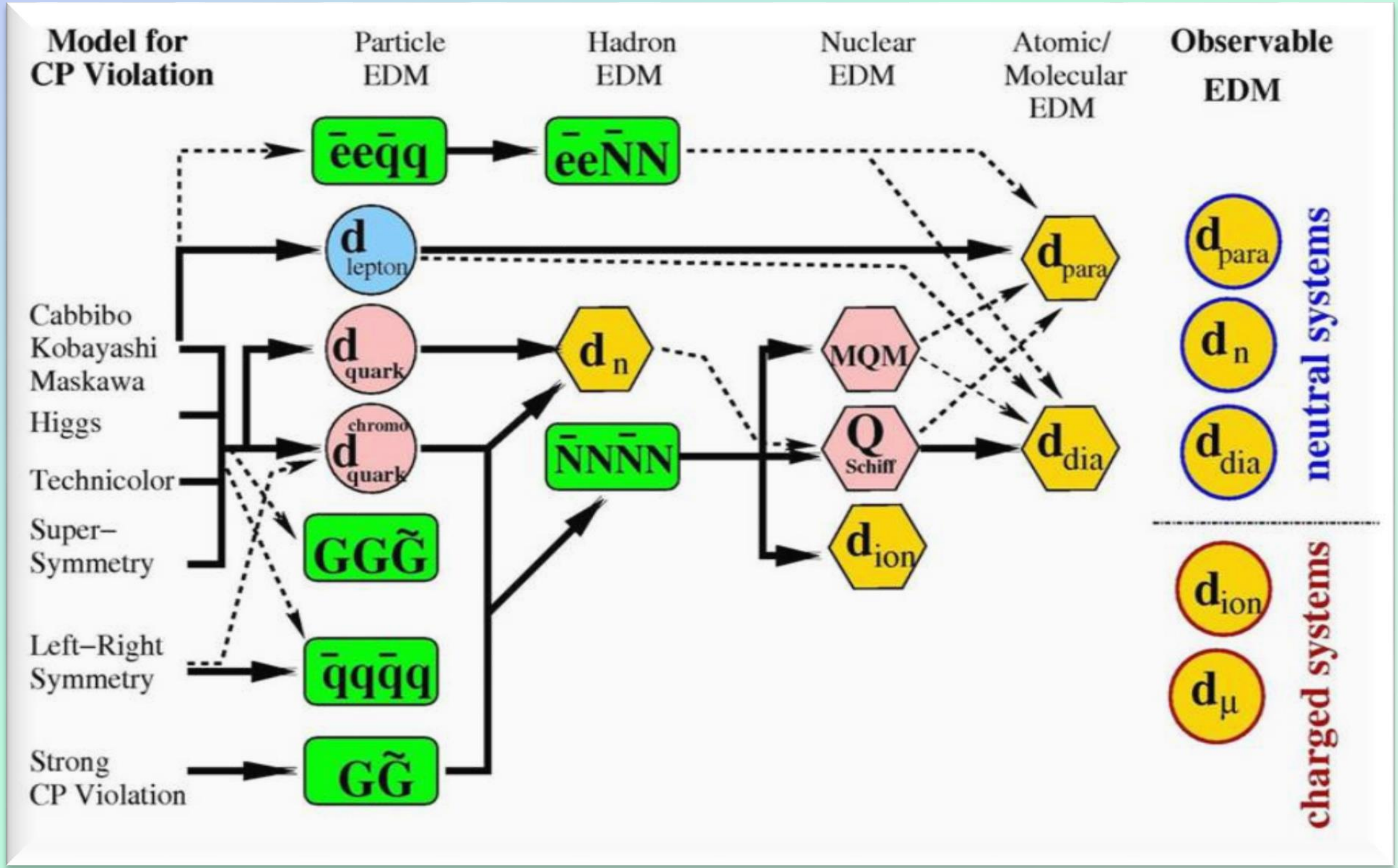
An EDM

Violates P,T



and with CPT also CP

Possible Sources of EDMs



The 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

ew source of $\cancel{CP}$

Molecules

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

- → ele
- →
- →
- → pectroscopic data

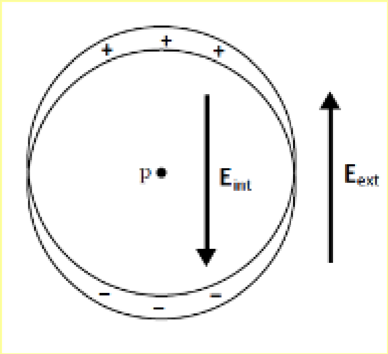
Condensed State

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

- → electron EDM
- → strong enhancements
- → systematics ??

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

Enhancements of particle EDMs



$$\frac{d_{atom}}{d_e} \propto Z^3 \alpha^2 \chi$$

P. Sandars, 1968

$$d_{atom} = \sum_{n'} \frac{< n, l| - d_e(\beta - 1)\vec{\sigma} \cdot \vec{E}|n', l \pm 1 >< n', l \pm 1| - e\vec{r}|n, l >}{E_{n,l} - E_{n',l\pm 1}} + h.c.$$

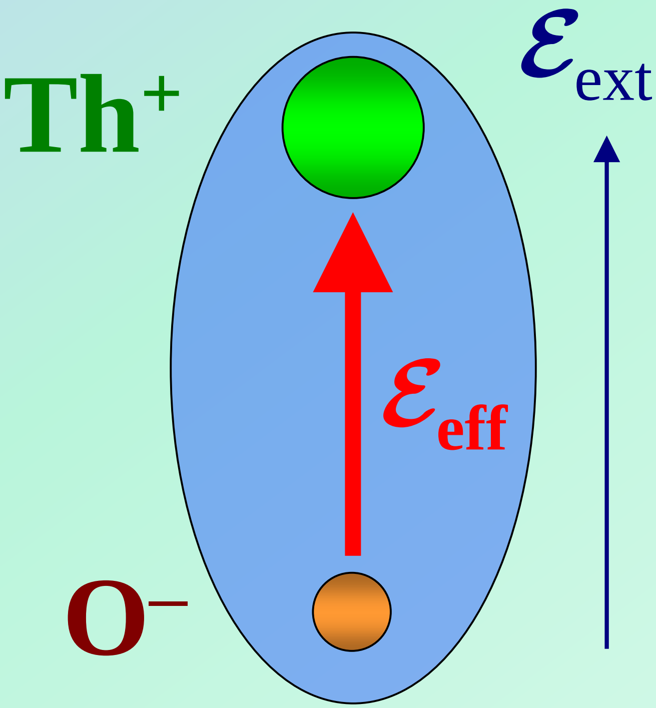
$\Rightarrow$ go for heavy systems, where Z>>1, e.g. Hg, Xe

$\Rightarrow$ take advantage of enhancements, e.g. Ra, Rn

$\Rightarrow$ consider molecules such as YbF, RaF, …

Highlight: ThO electron EDM experiment

Jan 2014



$\mathcal{E}_{\mathrm{eff}} \sim \mathcal{P}\,\alpha^2 Z^3 e/a_0^{\,2}$

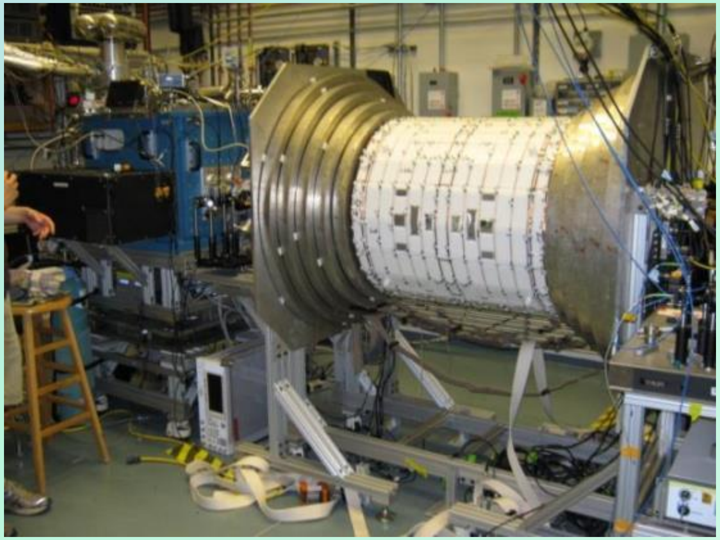
due to relativity

(P.G.H. Sandars)

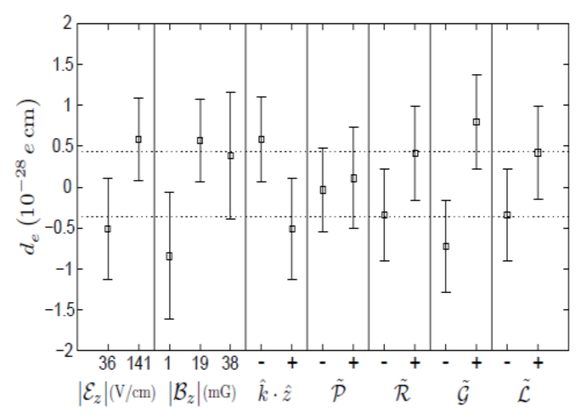
$\mathcal{E}_{\mathrm{eff}} \cong$ 80 GV/cm

(depending on theorist)

$\mathcal{E}_{\mathrm{ext}}$ ~ 1 V/cm enough for ThO



Doyle, Gabrielse , DeMille



New limit for e-

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

(90% c.l.)

Experiment presently taking further data

Atomic/Molecular Enhancement Factors

for Electron EDM

Particle		Rb	Cs	Tl	Fr	Ra
Enhancement		24	125	585	1 150	40 000

Flambaum, Dzuba, 2012

Particle		ThO	BaF	YbF	PbO
Enhancement		10^9	5×10^5	1.6×10^6	6×10^4

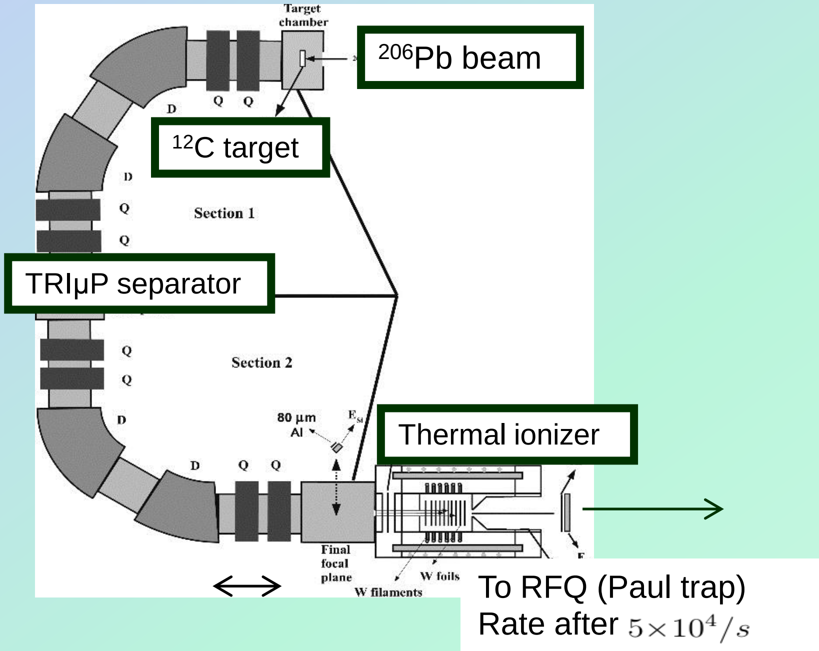
watch out:

Saturation

→ different theorists agree, typically at 30% level

Radium Isotopes

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



To RFQ (Paul trap)
Rate after $5\times10^4/s$

^{225}Ra

- **extraction from ^{229}Th source (ANL)**
- **Long lived ^{229}Th source in an oven (VSI)**

Other Isotopes

- **Online production at accelerator facilities e.g.**
- **TRIμP@KVI (flux ~ 10^5/s) (until 2013)**
- **ISOLDE , CERN (flux ~ 10^9/s)**
- **FRIB**

TRIμP@KVI

	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	

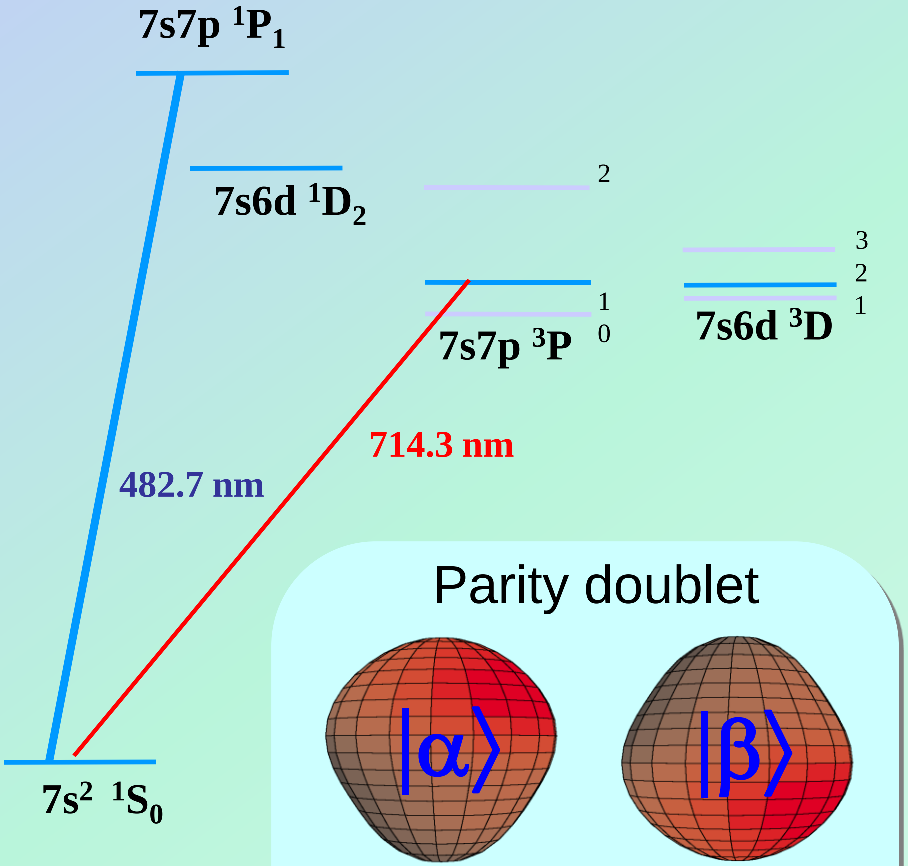
Sources or fragmentation

	Lifetime	Spin
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

$\Delta N < 14$

Radium EDMs

Atomic energy level diagram of Ra

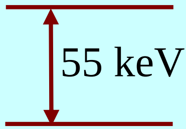


- **Nearly degenerate opposite parity $^3P_1$ and $^3D_2$** *enhancement >5000 e EDM*

$$d = \frac{< {}^3D_1 | -er | {}^3P_1 >< {}^3P_1 | H_{EDM} | {}^3D_1 >}{\boxed{E({}^3D_1) - E({}^3P_1)}}$$

V. A. Dzuba et al. Phys. Rev. A, 61, 062509 (2000)

Parity doublet



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

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

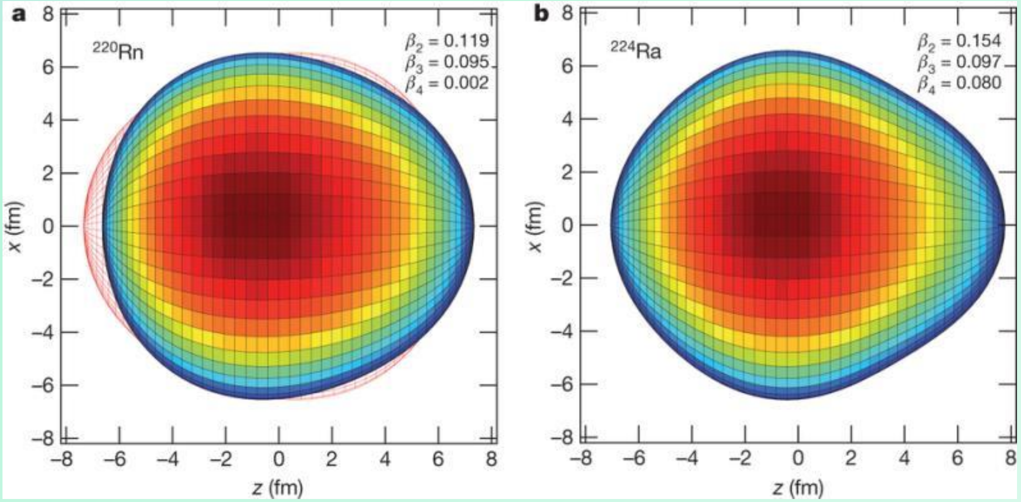
Density distribution of nuclear charge has mixed octupole and quadrupole deformation

- **Deformed charge distribution in some isotopes (^{225}Ra)**
- **Nucleon EDM enhances ≈ 10^2**

Dobczewski, Engel, PRL (2005) & Phys. Rev. C (2010)

EDM Enhancement by Nuclear Deformation

L. P. Gaffney et al, **Nature 497 ,157 (2013)**

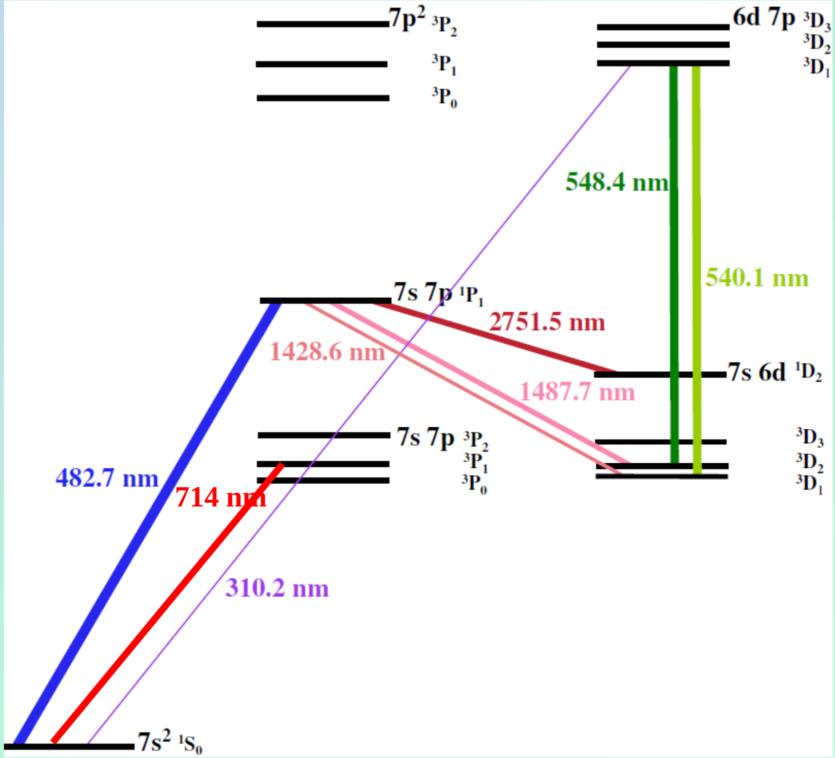


- ➢ **If that were true also for odd spin isotopes there'd be a nucleon EDM enhancement by factor of some 200**
- ➢ **Need measurements for odd isotopes now !!**

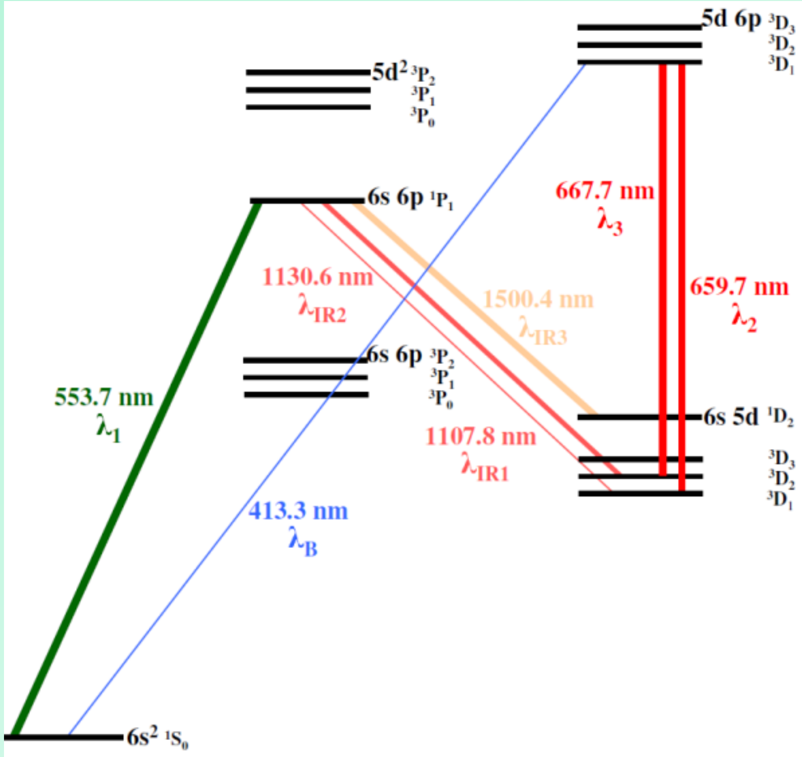
(see e.g. Y.K. Khriplovich)

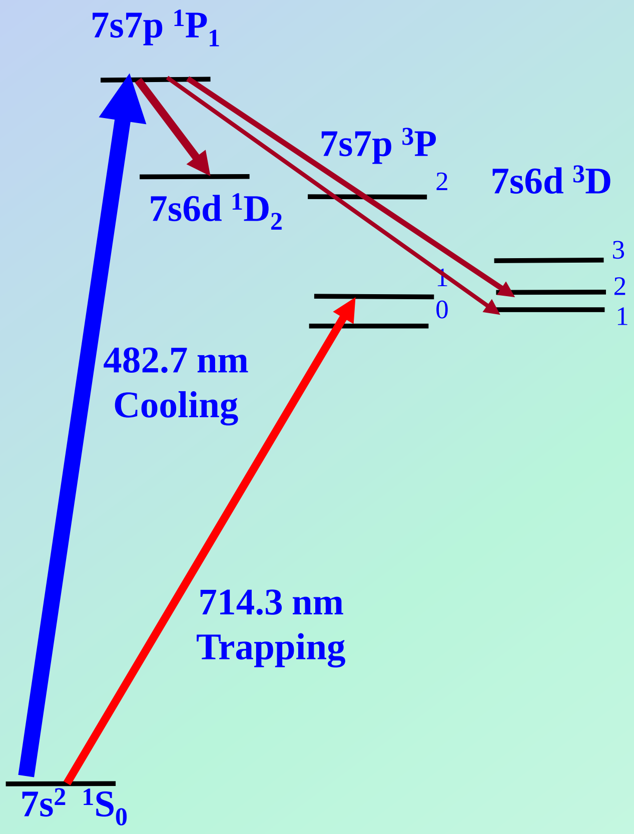
Radium and Barium

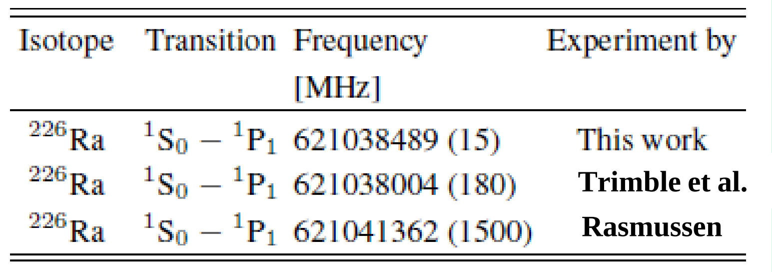
Radium



Barium







Isotope	Transition	Frequency [MHz]	Experiment by
^{226}Ra	$^1S_0 - {^1P_1}$	621038489 (15)	This work
^{226}Ra	$^1S_0 - {^1P_1}$	621038004 (180)	**Trimble et al.**
^{226}Ra	$^1S_0 - {^1P_1}$	621041362 (1500)	**Rasmussen**

B. Santra et al, PRA (R) (2014)

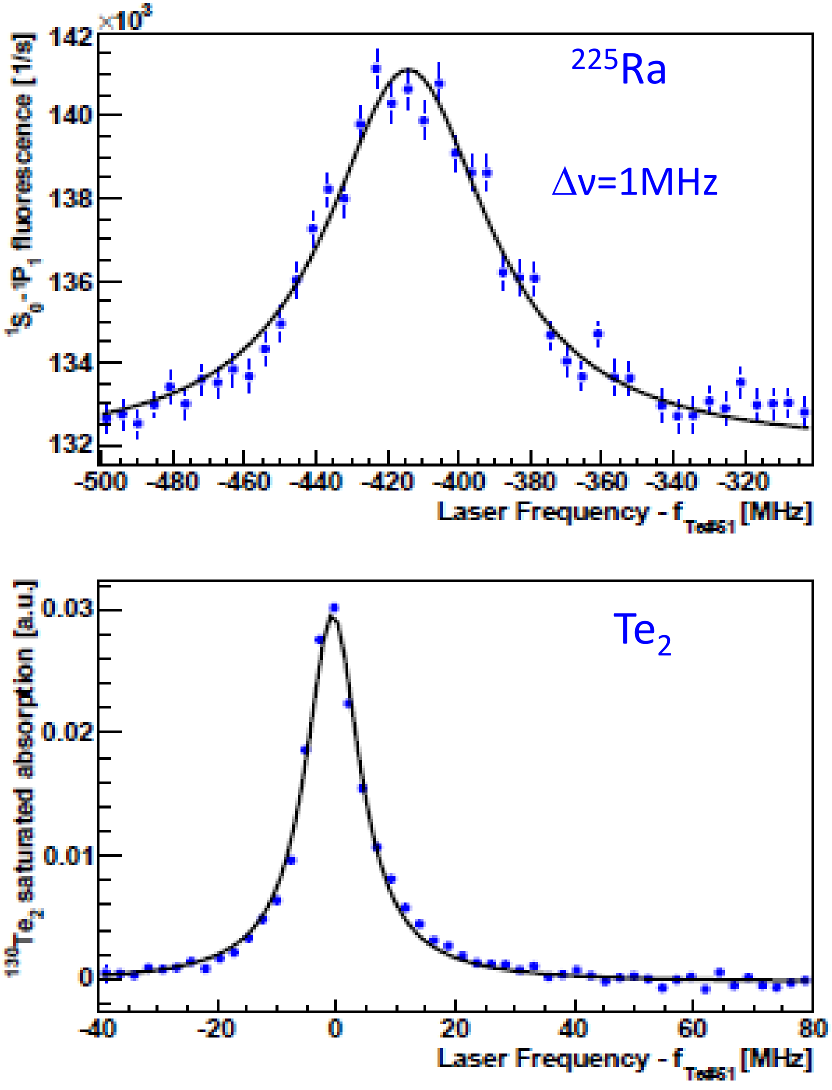
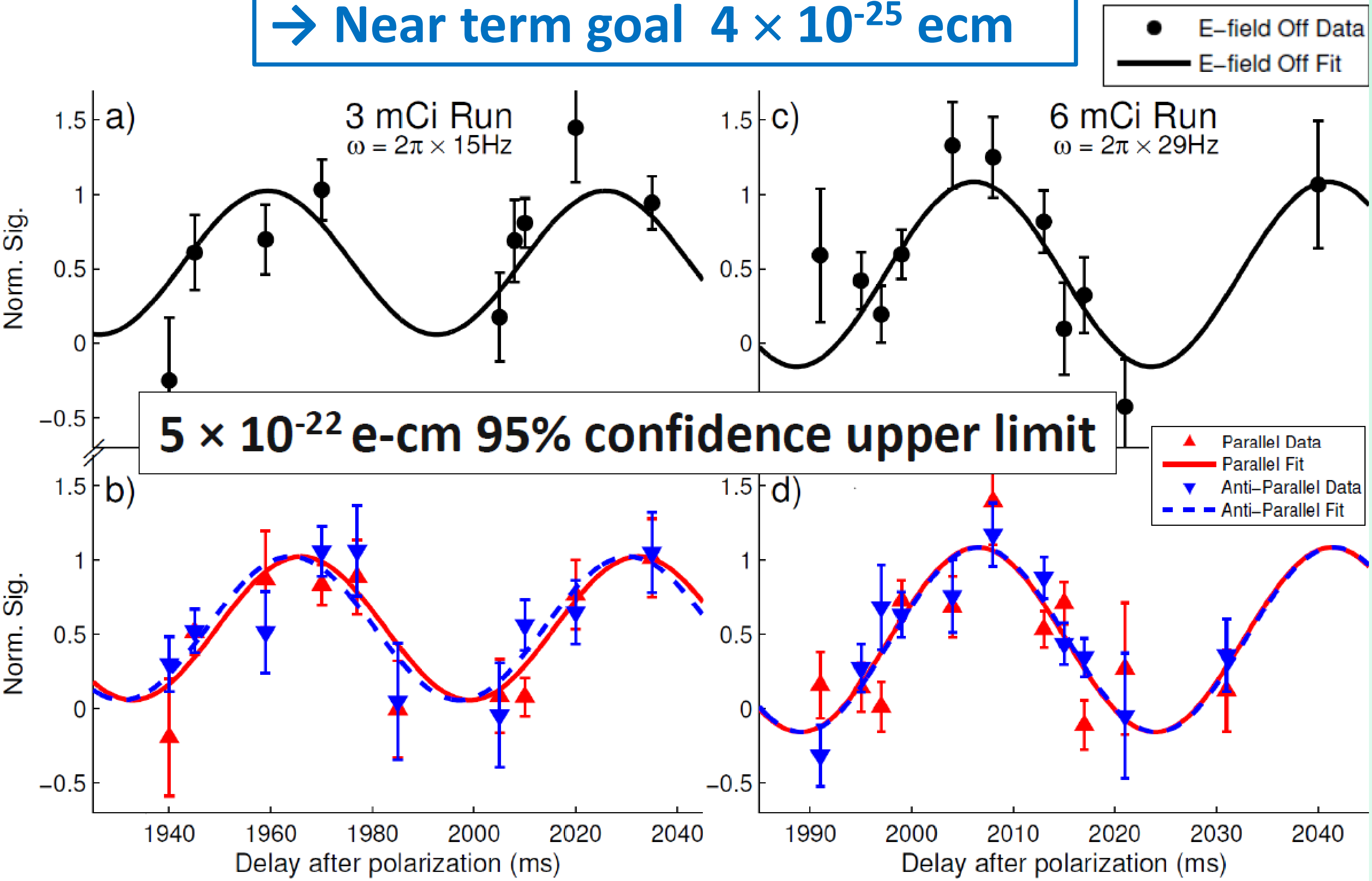


FIG. 6.6: (Top) Fluorescence from the $^1S_0(F=1/2)$-$^1P_1(F=3/2)$ transition in ^{225}Ra. (Bottom) Saturated absorption line no.51 in $^{130}Te_2$. The frequency of the transition in radium is 418(1) MHz lower than the reference line #51 (Sec-

Argonne ^{225}Ra Experiment

→ Near term goal 4 × 10^{-25} ecm



5 × 10^{-22} e-cm 95% confidence upper limit

R.H. Parker, *Phys*. *Rev*. *Lett*. 114, 233002 (2015)

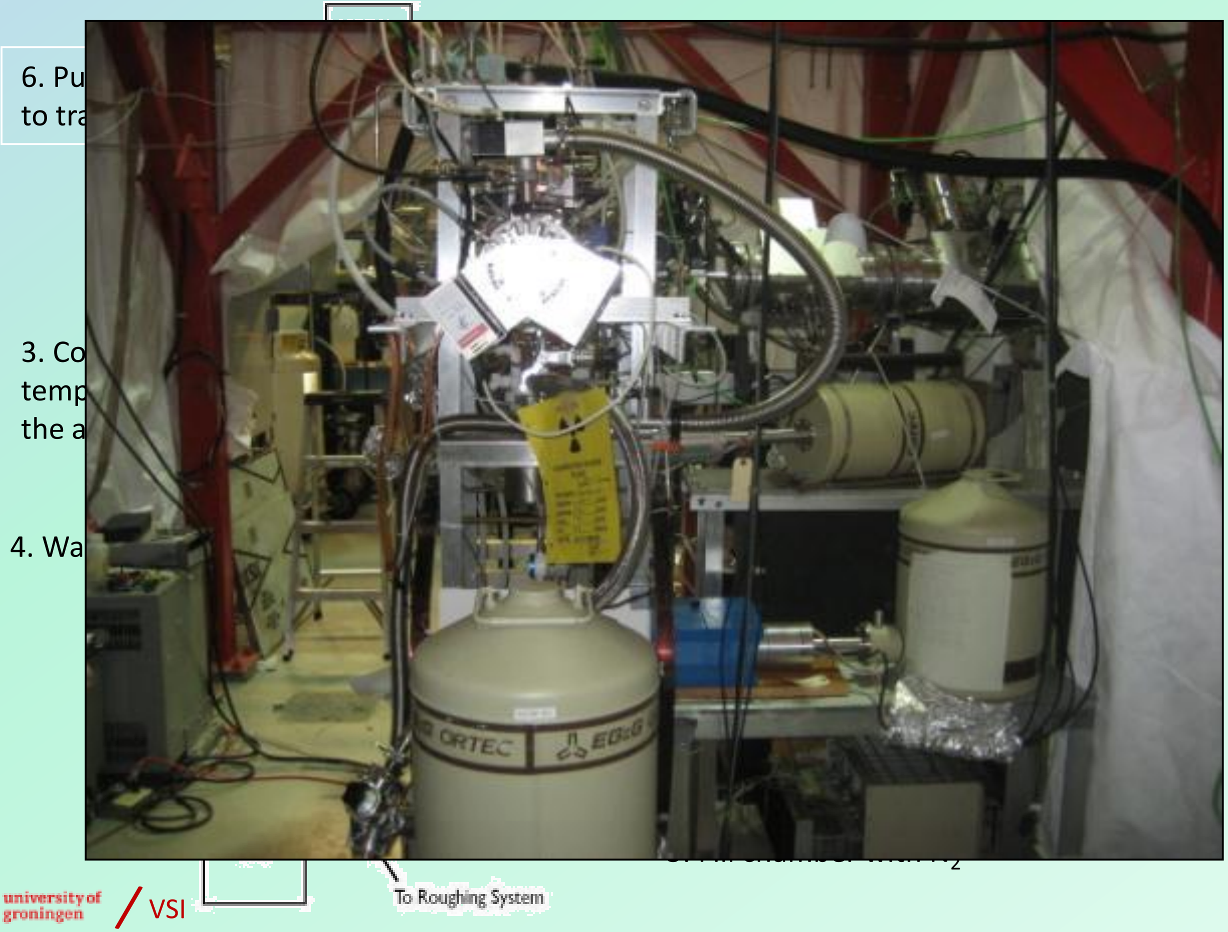
from M. Bishop, Argonne National Laboratory

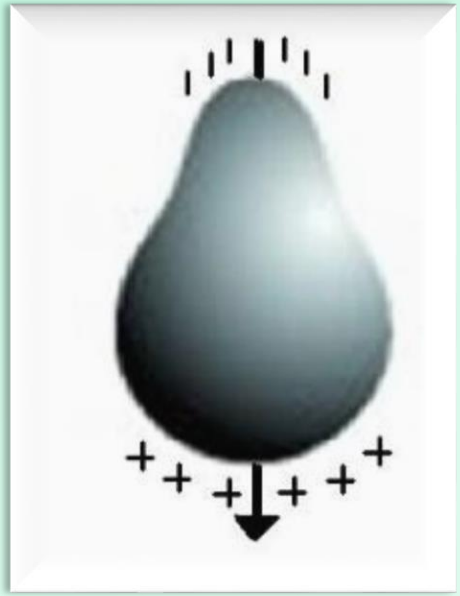
Towards a Rn EDM Experiment at TRIUMF

T. Chupp and C. Svensson

- Magnitude of EDM ~ Z^3
- Radon isotopes possibly octupole deformed

- Rn is predicted to be ~ 600 times more sensitive than ^{199}Hg



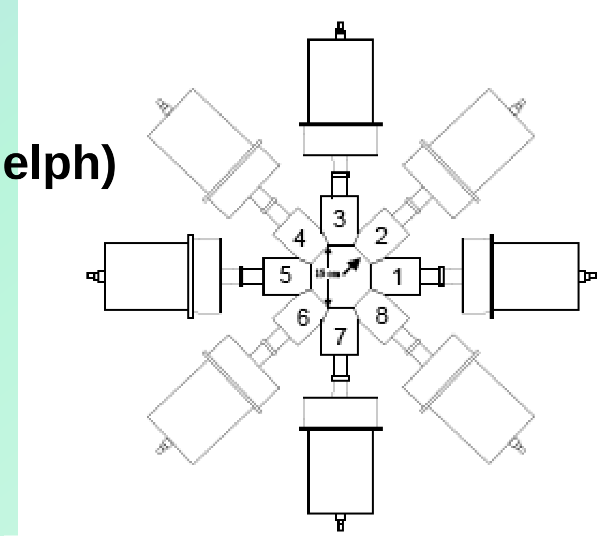


Radon-EDM Experiment

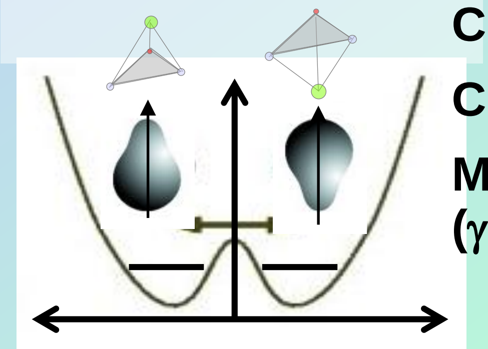
TRIUMF E929

T. Chupp (Michigan) & C. Svensson (Guelph)

Funding: NSF, DOE, NRC, NSERC



TRIUMF



β_3

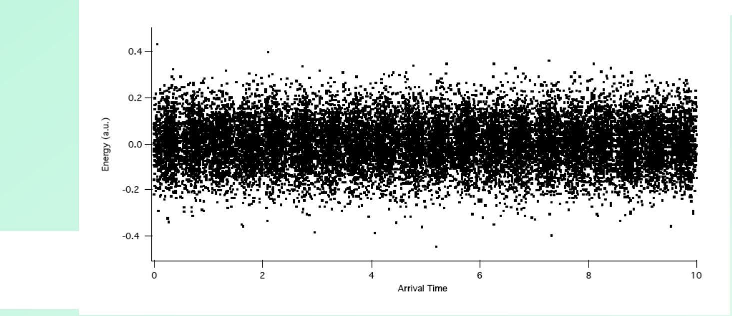
Produce rare ion radon beam

Collect in cell

Comagnetometer

Measure free precesion
(γ anisotropy/β asymmetry)

$$\sigma_d \approx \frac{\hbar}{AET_2\sqrt{N}}$$



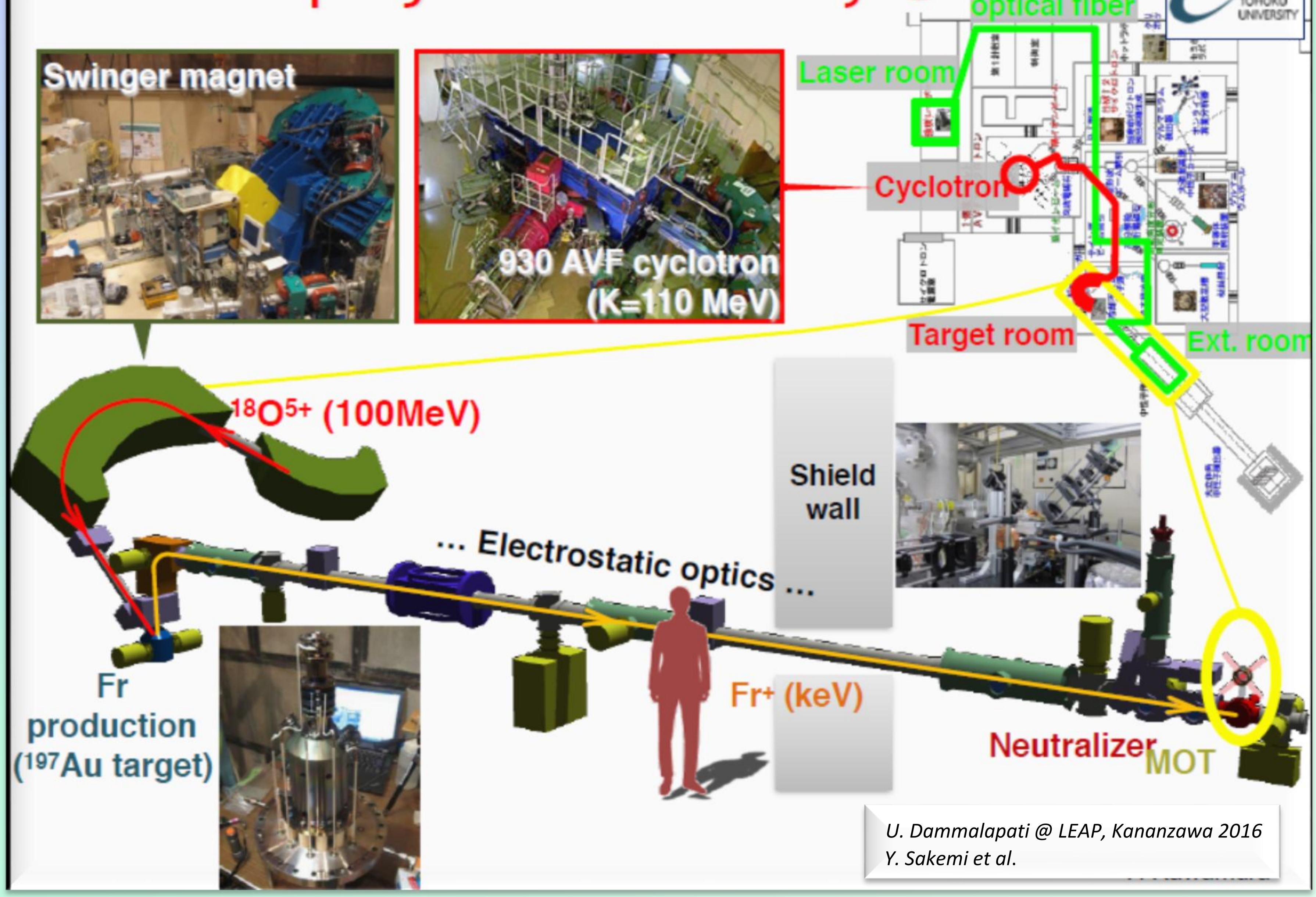
$^{221/223}$Rn EDM projected sensitivity

Facility	Detection	S_d (100 d)
ISAC	γ anisotropy	2 x 10^{-26} e-cm
ISAC	β asymmetry	1 x 10^{-27} e-cm
FRIB	β asymmetry	2 x 10^{-28} e-cm

→ ~ 5x10^{-30} for ^{199}Hg

Courtesy of Tim Chupp

Francium project and facility @ CYRIC



U. Dammalapati @ LEAP, Kananzawa 2016
Y. Sakemi et al.

Experiment is on the move to U Tokyo / RIKEN

Generic EDM Figure of Merit

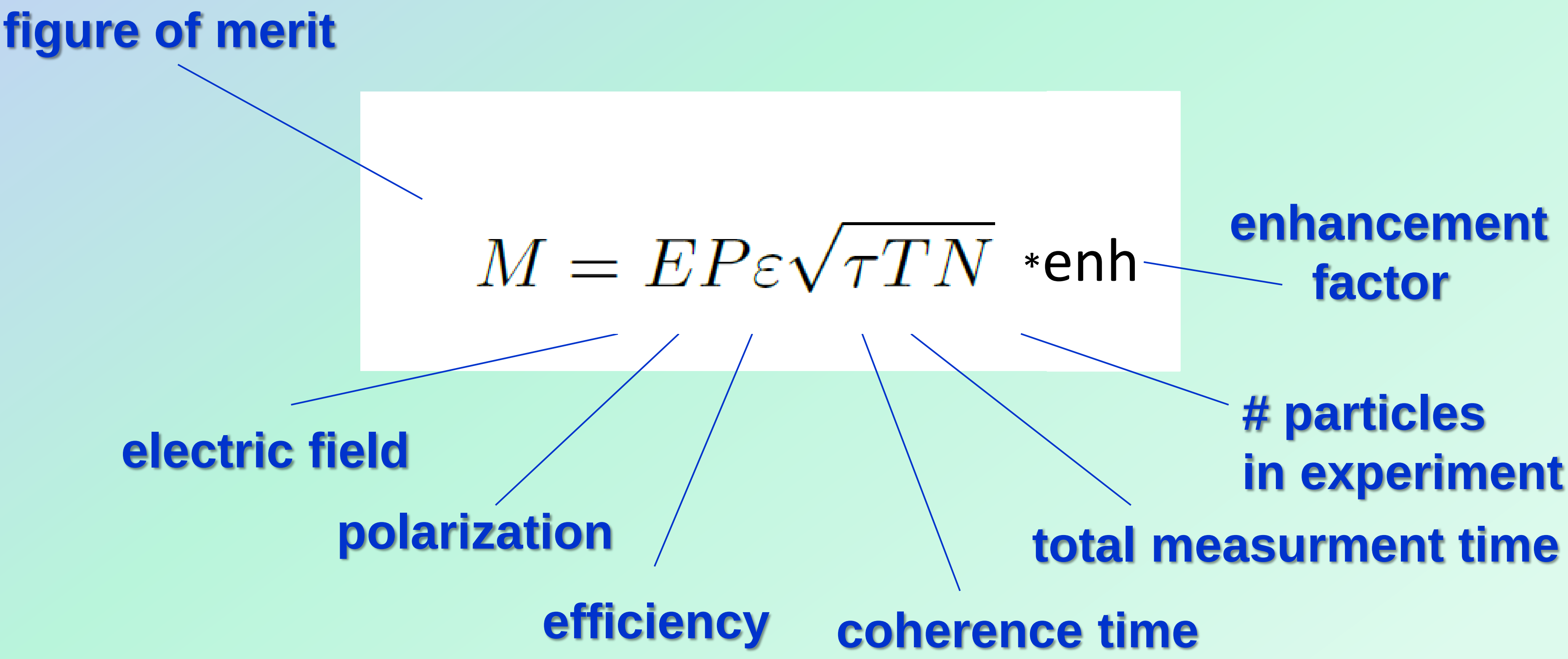


figure of merit

$$M = EP\varepsilon\sqrt{\tau T N} \;{}^{*}\mathrm{enh}$$

enhancement factor

electric field

polarization

efficiency

coherence time

total measurment time

particles in experiment

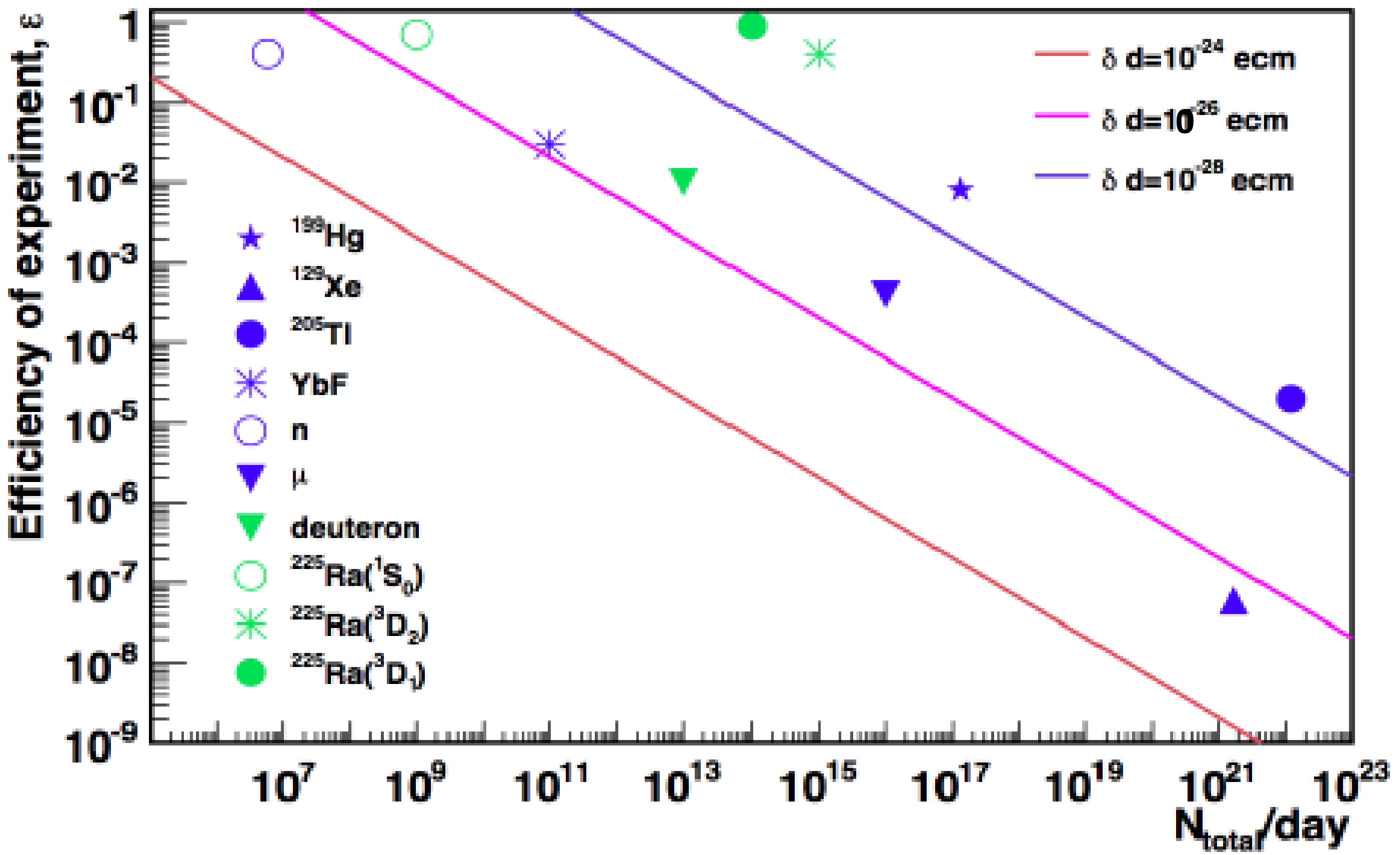
Preferred Systems

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

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}	$2\text{x}10^{2}$	$8\text{x}10^{-3}$	10	$5\text{x}10^{13}$
^{129}Xe	10^{22}	10^{4}	$9\text{x}10^{-9}$	3.6	$1\text{x}10^{14}$
ThO	10^{11}	$1.1\text{x}10^{-3}$	$2\text{x}10^{-2}$	<0.1	$2\text{x}10^{13}$
YbF	10^{5}	$1.5\text{x}10^{-3}$	$3\text{x}10^{-2}$	10	$1\text{x}10^{12}$
BaF	10^{11}	10^{-1}	10^{-2}	10	$5\text{x}10^{13}$
^{225}Ra	10^{3}	$4\text{x}10^{1}$	$7\text{x}10^{-5}$	67	$3\text{x}10^{6}$

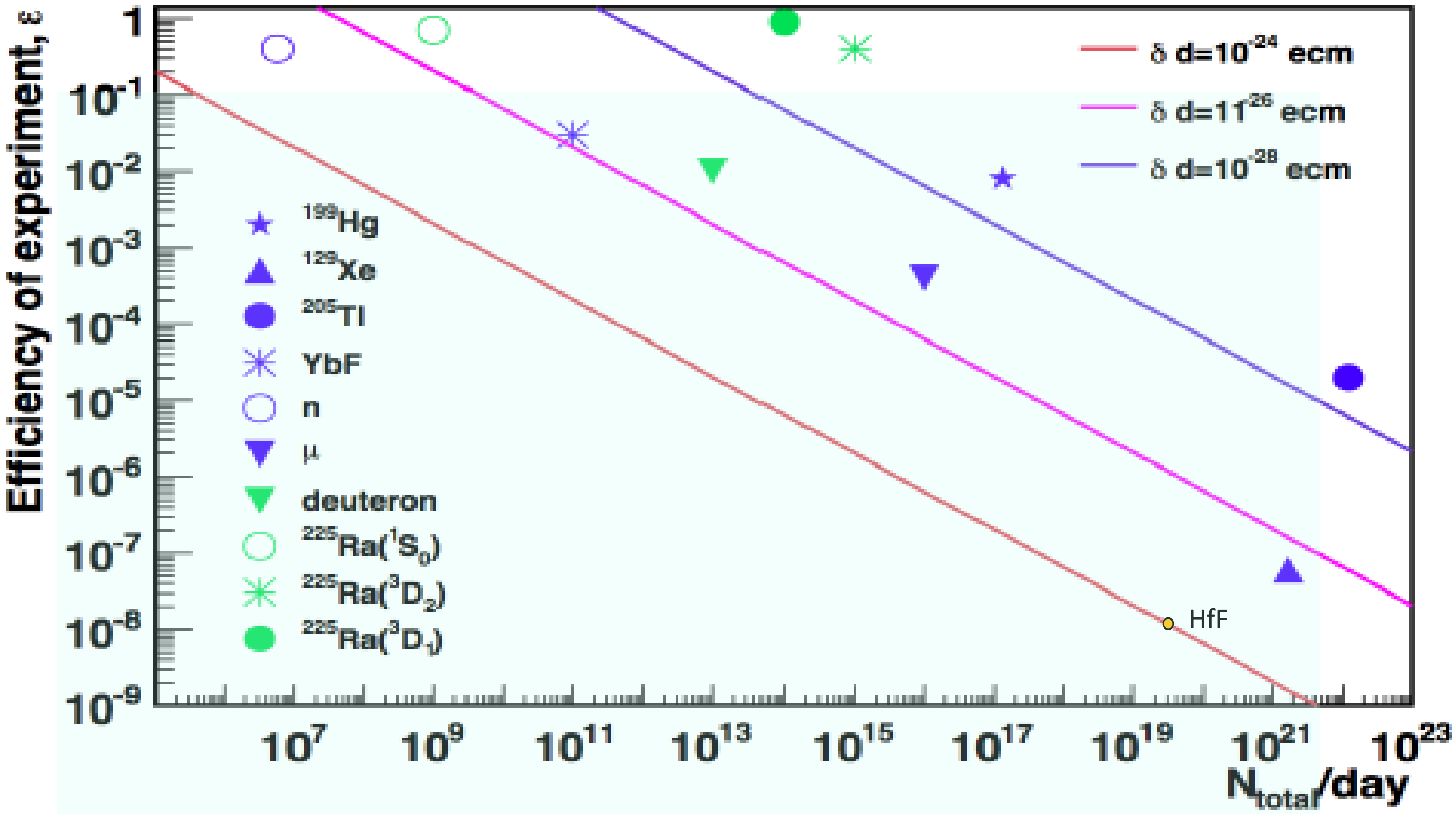
EDM Experiments: Efficiency



- realized
- future

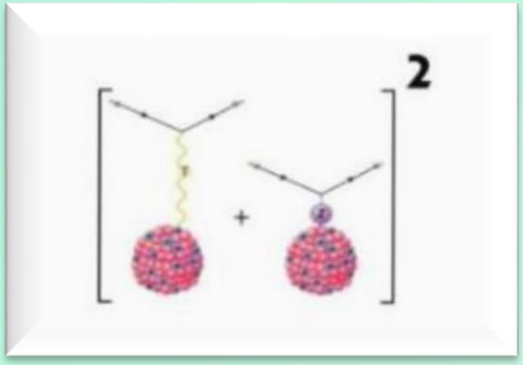
$$\delta d = \frac{\hbar|\vec{I}| \text{ / enh}}{EP\epsilon\tau\sqrt{N_{total}}}$$

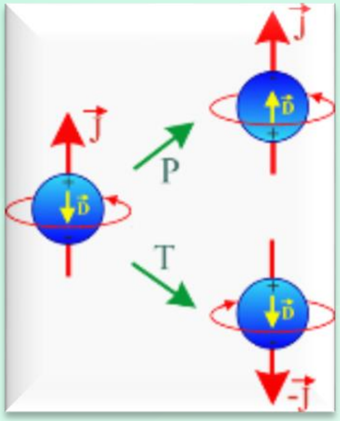
B. Santra, L. Willmann (2013)



$$\delta d = \frac{\hbar |I| \;/\; enh}{E P \epsilon \tau \sqrt{N_{total}}}$$

Cold Molecules for EDMs & Parity

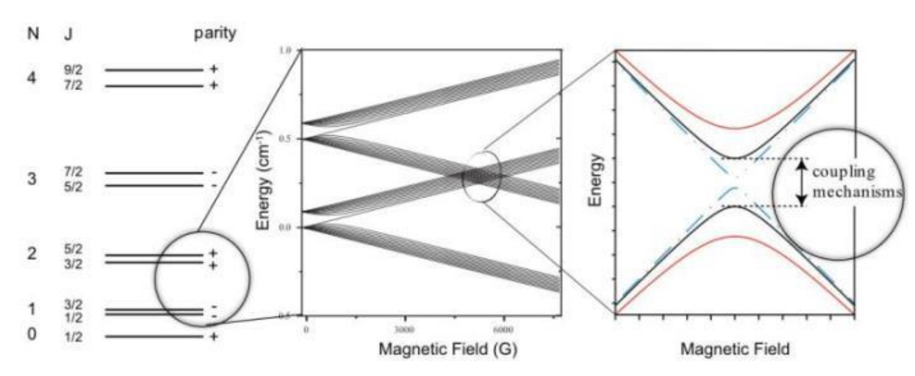




SrF **BaF** **RaF**

Precision Measurements with Molecules

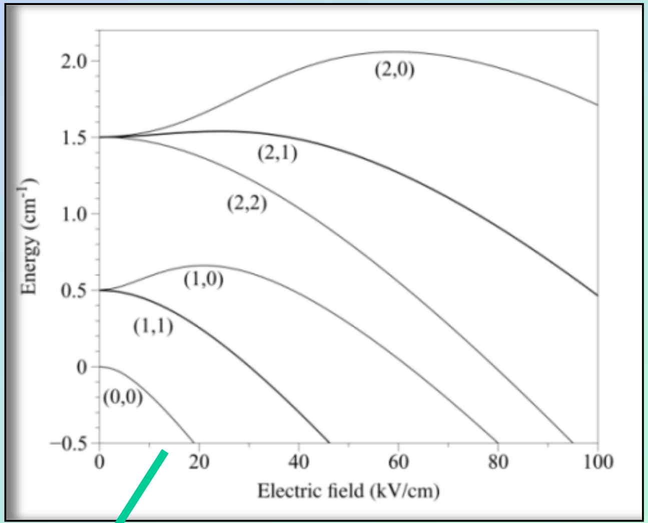
- Heavy diatomic molecules (*SrF, RaF,..*) are suited for precision measurements (parity violation, eEDM)
- Large enhancement due to almost degenerate rotational levels

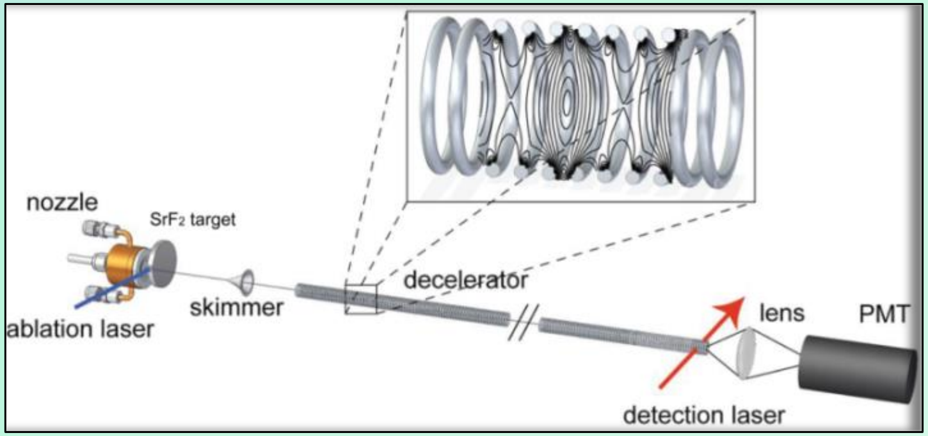


- Ultracold molecules by a traveling wave decelerator and laser cooling
- Benefit from the long interaction time provided by a cold, trapped sample

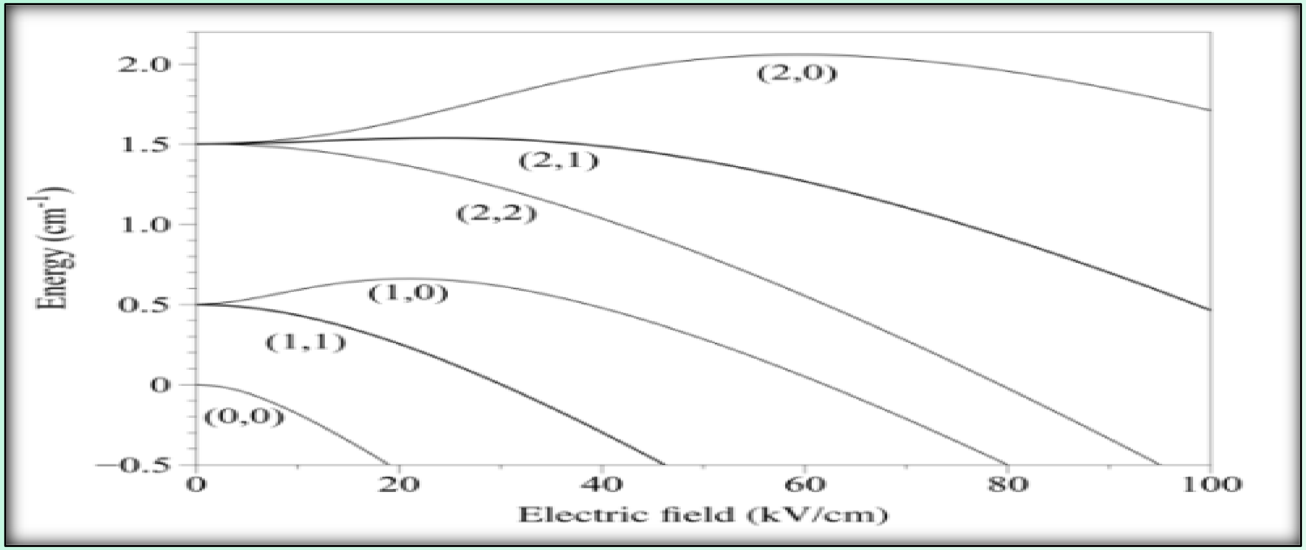
C. Meinema, J. v/d Berg, S. Hoekstra

Traveling wave decelerator



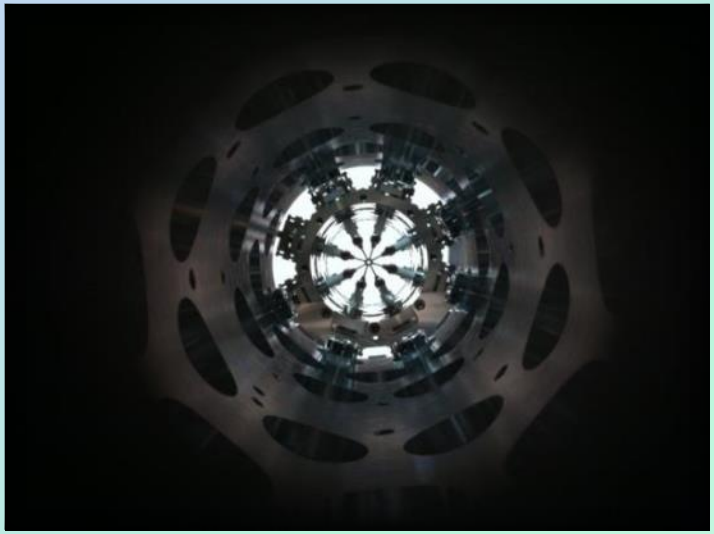


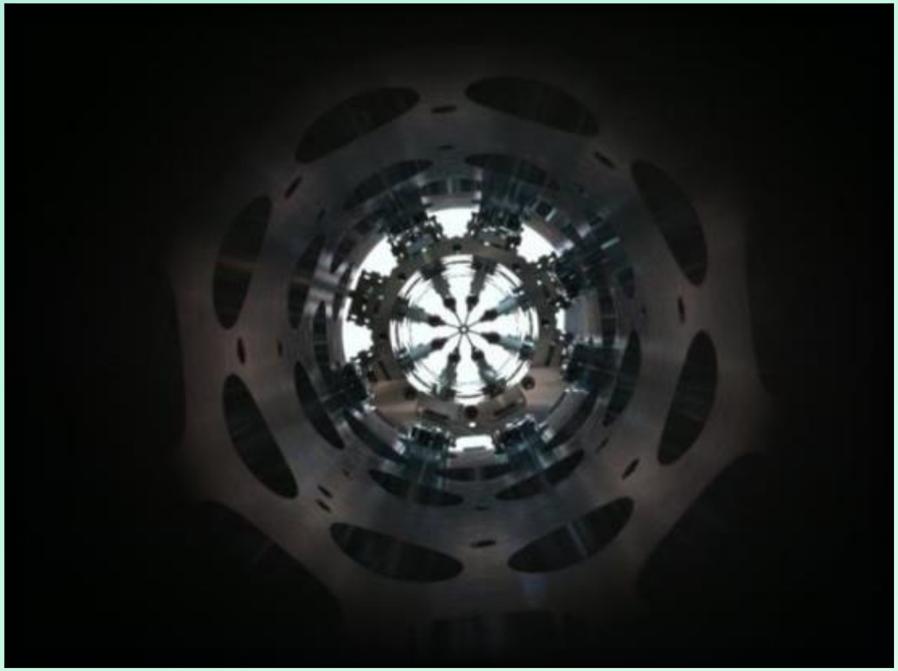
SrF

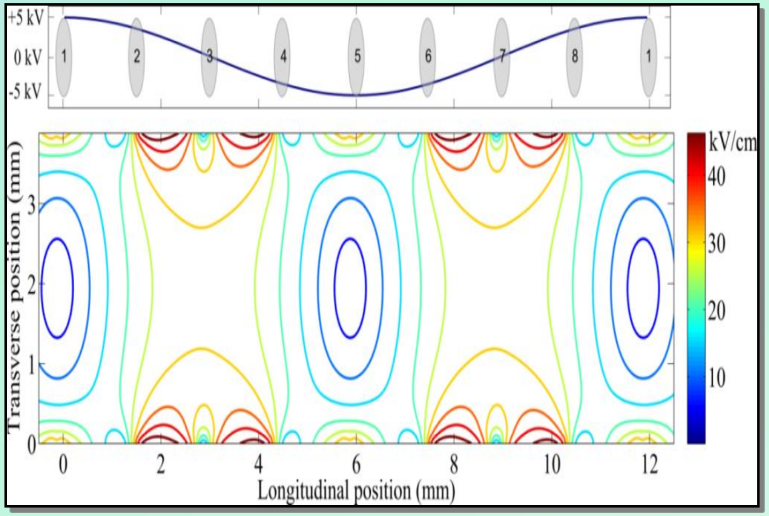


C. Meinema, J. v/d Berg, S. Hoekstra

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

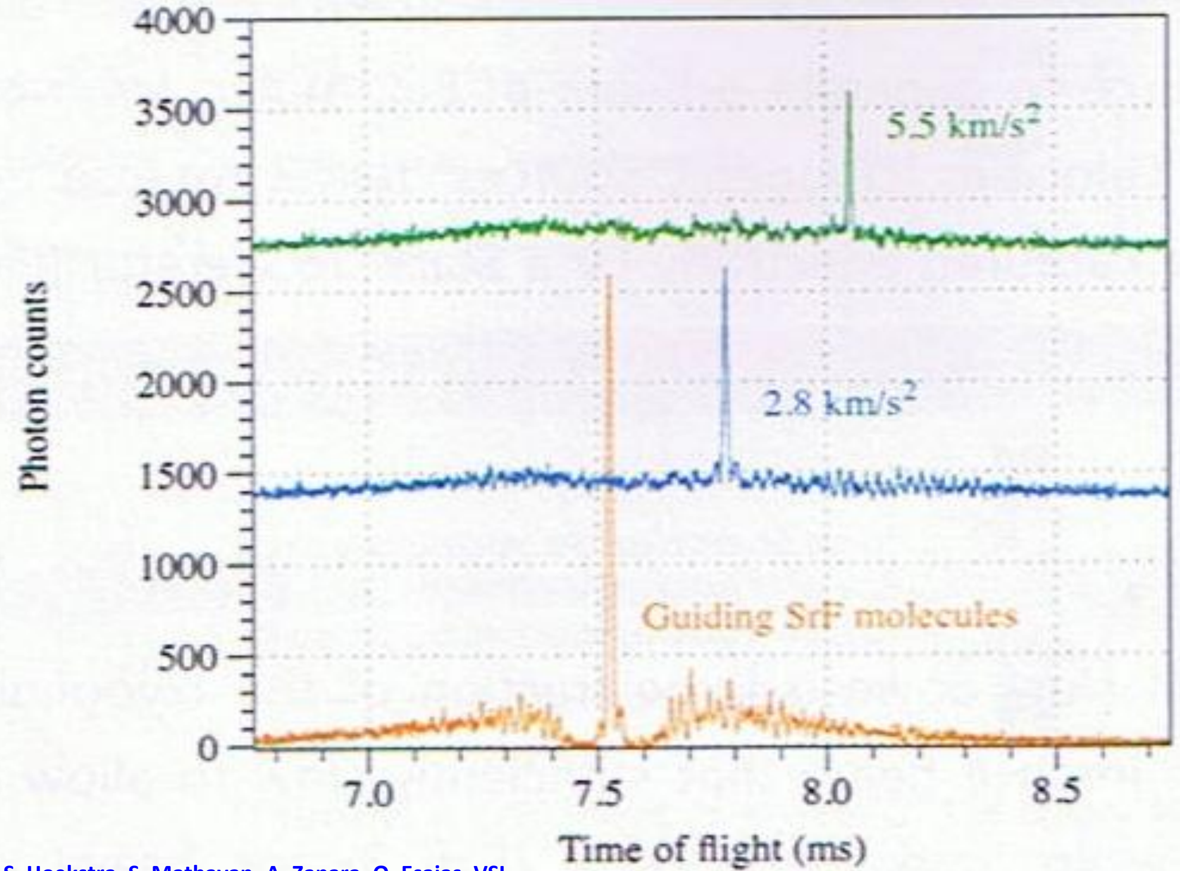
Signal and Simulations

- 4 of 8 amplifiers
- 2 m machine

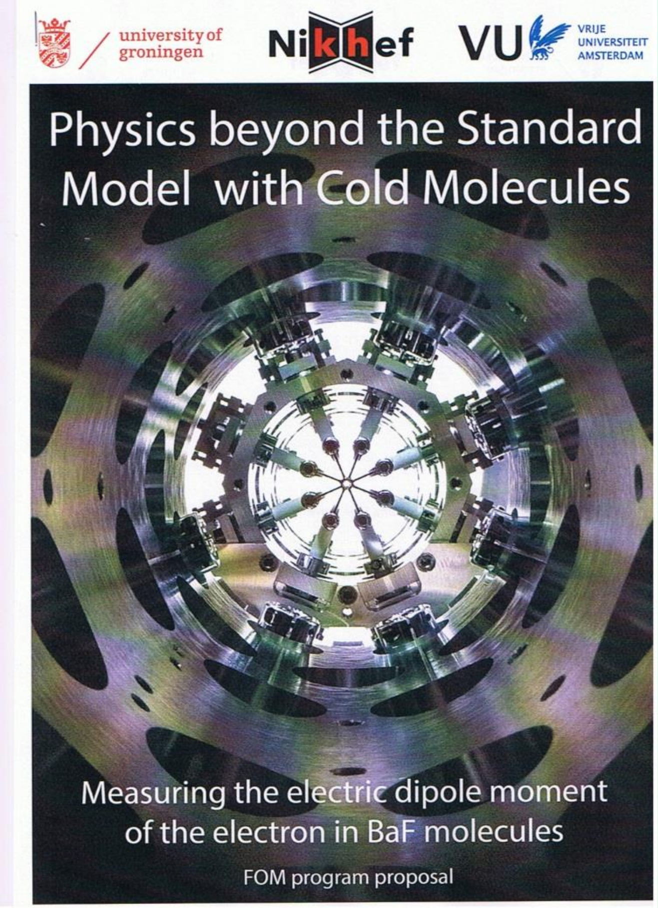
C. Meinema, J. v/d Berg, S. Hoekstra

SrF Slowed Down and Guided

- 8 of 8 amplifiers
- 4 m machine



S. Hoekstra, S. Mathavan, A. Zapara, Q. Esajas, VSI


university of groningen

Nikhef

VU VRIJE UNIVERSITEIT AMSTERDAM

Physics beyond the Standard Model with Cold Molecules

Measuring the electric dipole moment of the electron in BaF molecules

FOM program proposal

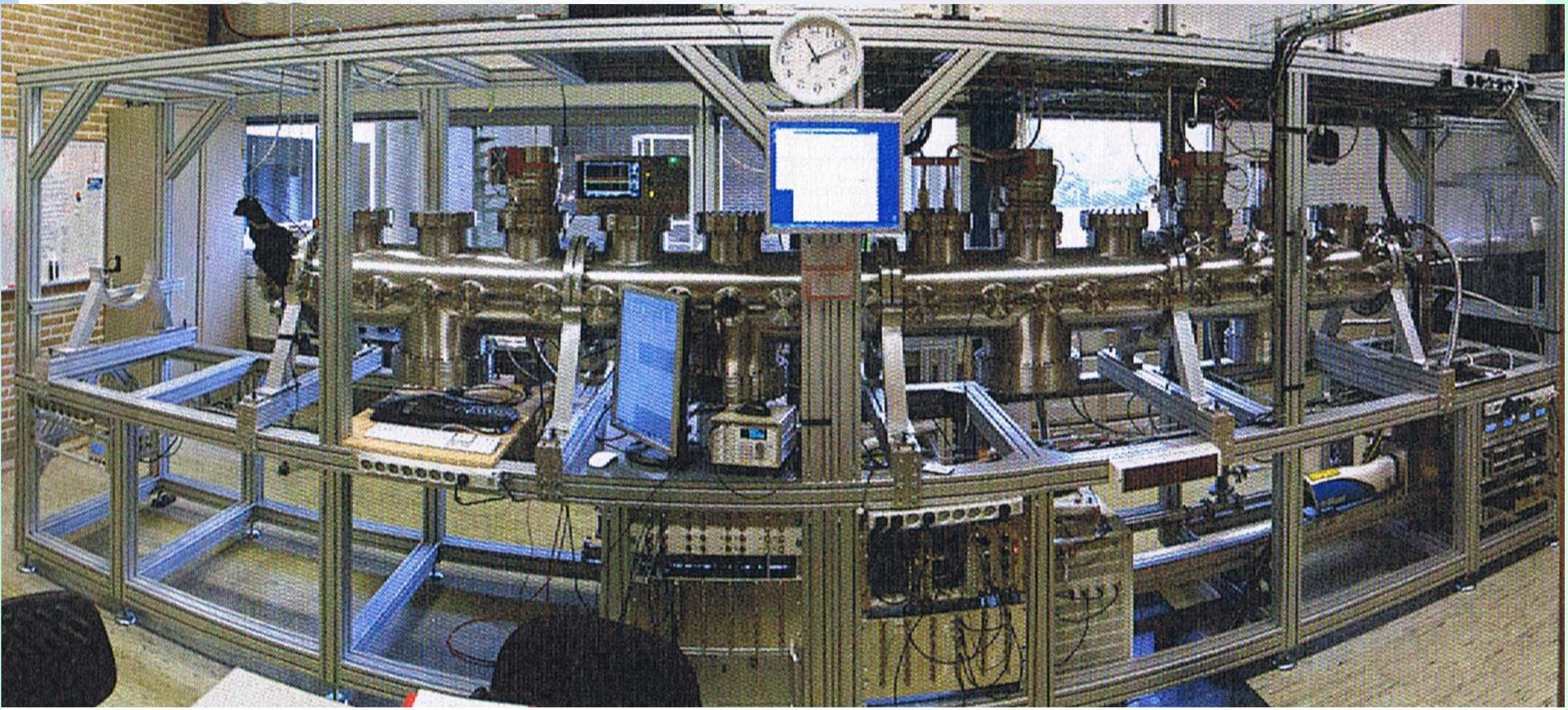
S. Hoekstra et al.

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

BaF eEDM

machine in statu nascendi

S.Hoekstra, A. Borschevsky, K. Jungmann, R.G.E. Timmermans, L. Willmann,
H. Bethlem, W. Ubachs et al. (FOM/NWO programme 2016-2022)



→ eEDM Collaboration Goal: Best EDM Limit on Electron

Time of flight (ms)

S. Hoekstra, S. Mathavan, A. Zapara, Q. Esajas, VSI

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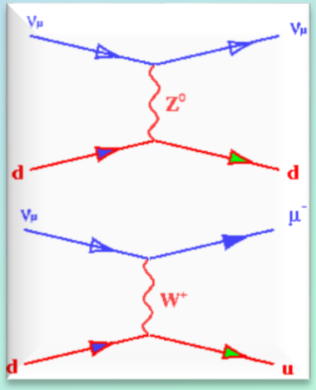
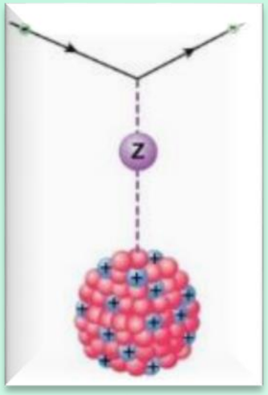
Parity





→ *relatively large effects* in some atoms and molecules scaling with Z^3 or even stronger

→ 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

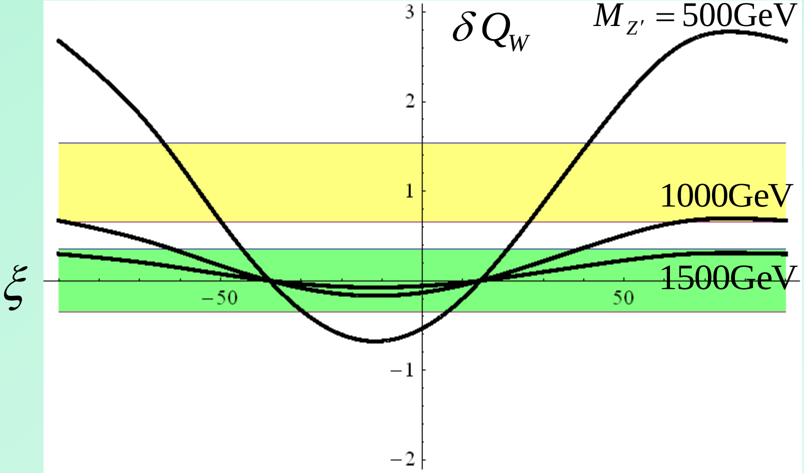
$Q_W = -N + (1-4\sin^2\theta_W)Z$ + rad. corr. + "new physics"

Extra Z' boson in SO(10) GUTs:

- Additional U(1)' gauge symmetry
- Known Z and W unaffected
- No Z-Z' mixing

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

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



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

(68% confidence level, ξ= 52°) Wansbeek et al.. PRA,(2010)

$M_{Z'} > 1.2$ TeV/c^2

(Tevatron $M_{Z'} > 0.9$ TeV/c^2)

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

$M_{Z'} > 6$ TeV/c^2

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

The way to go!

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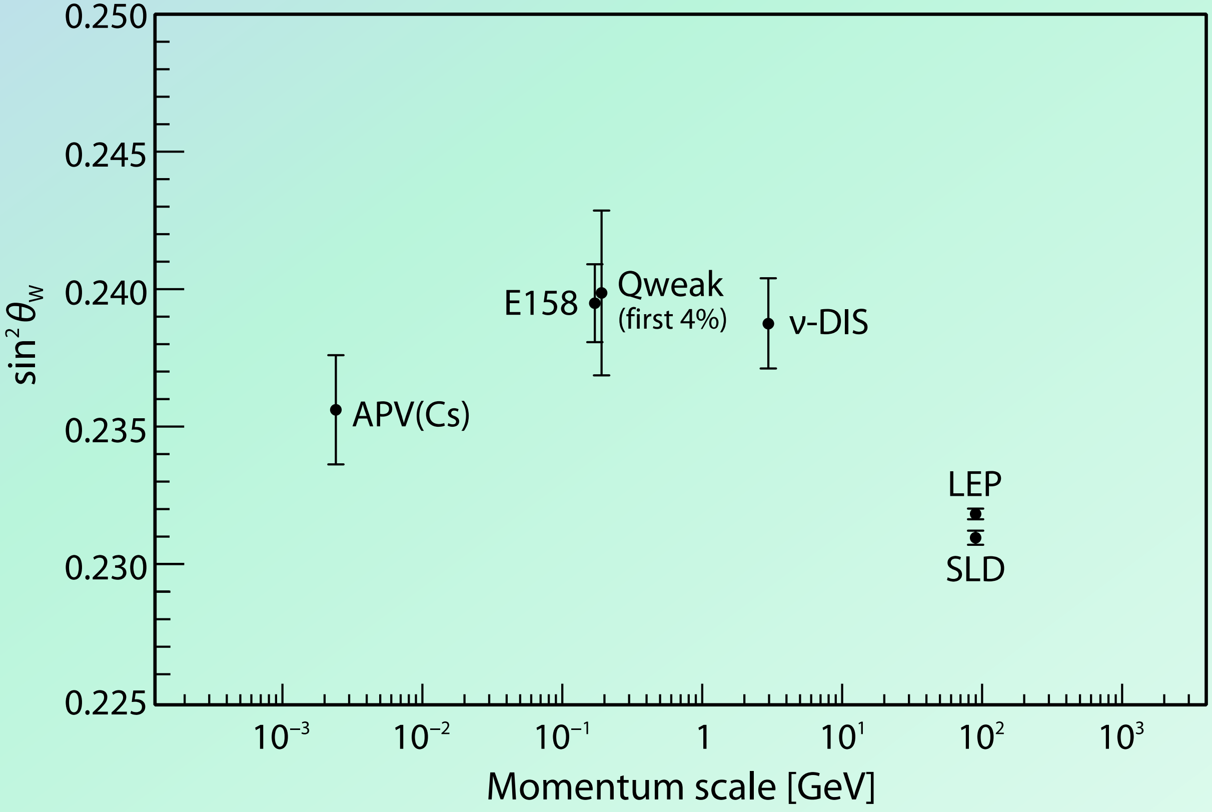
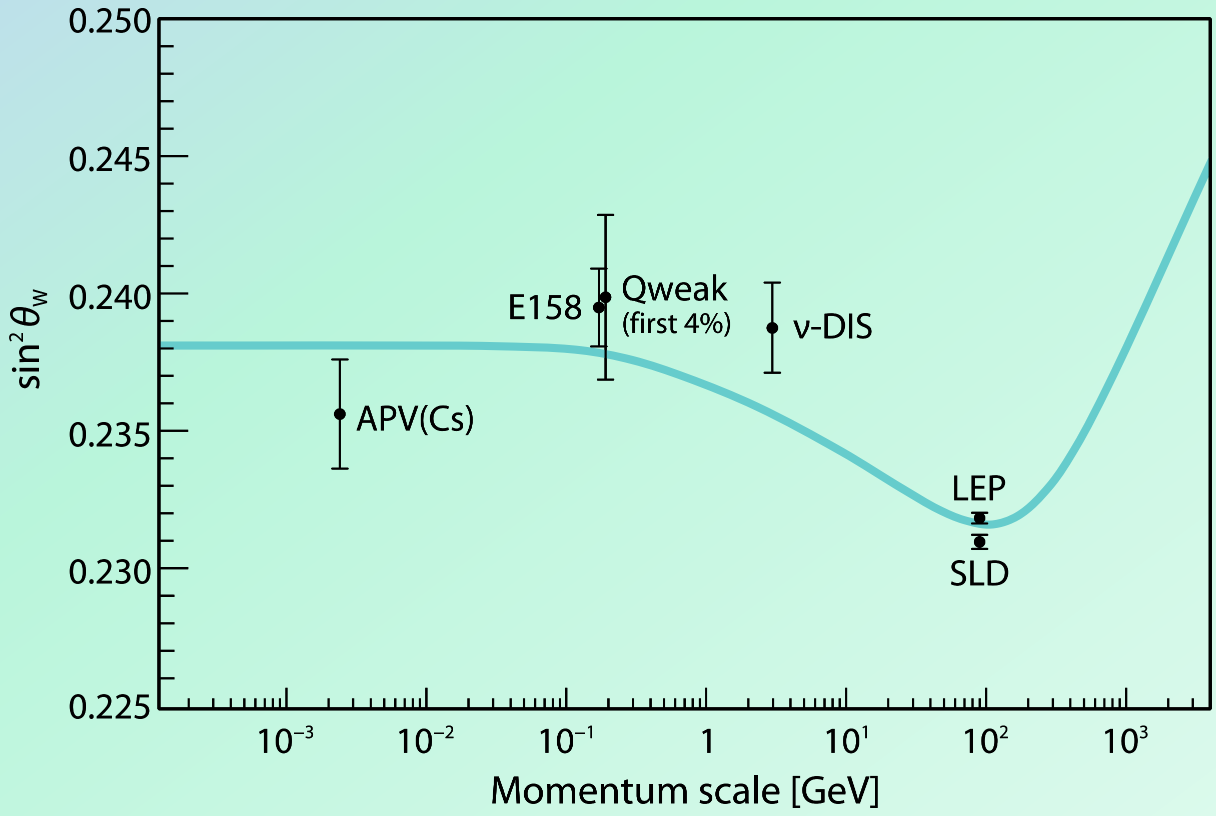
Test of Standard Model

Electroweak Interaction



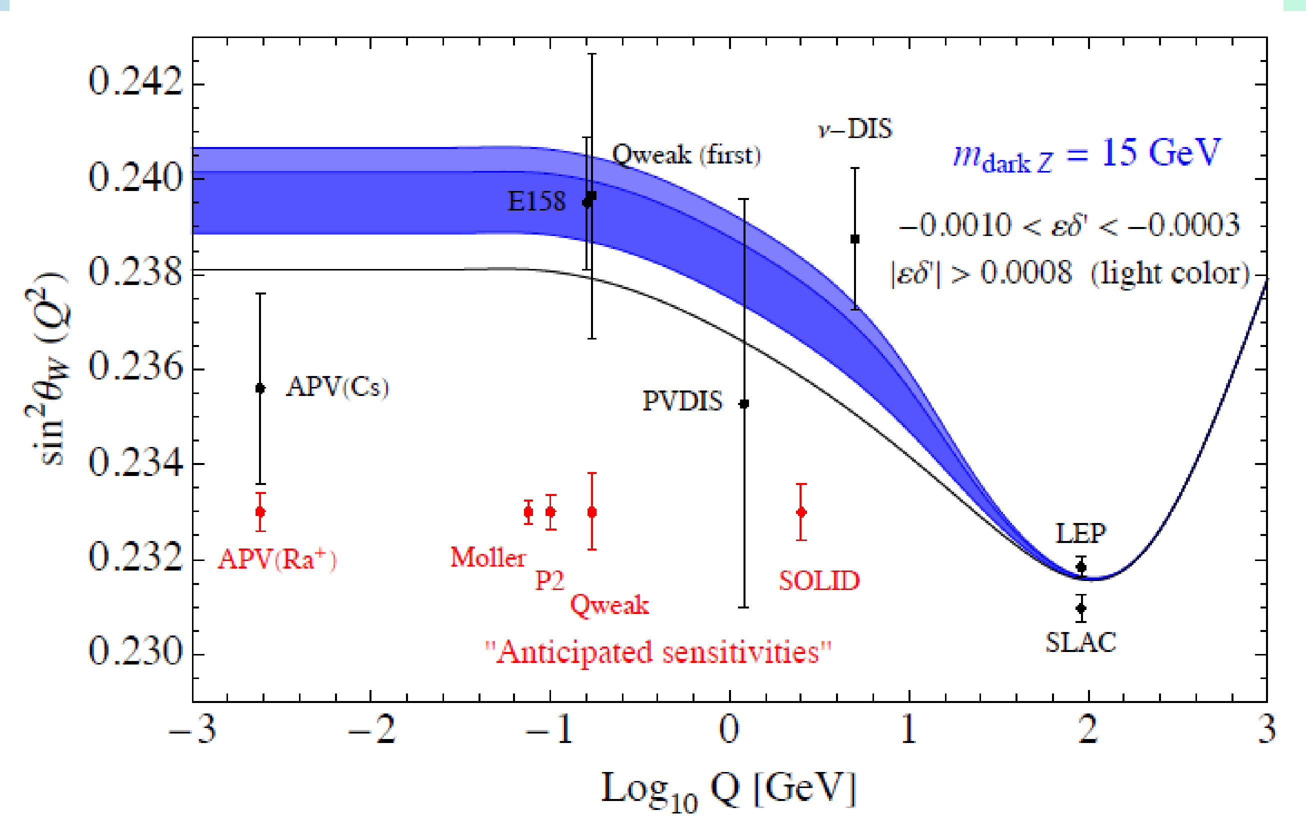
Test of Standard Model

Electroweak Interaction



Test of Standard Model

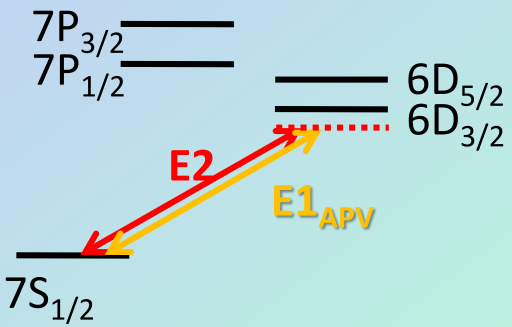
Electroweak Interaction



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)

Atomic Parity Violation

Ba^+ and Ra^+

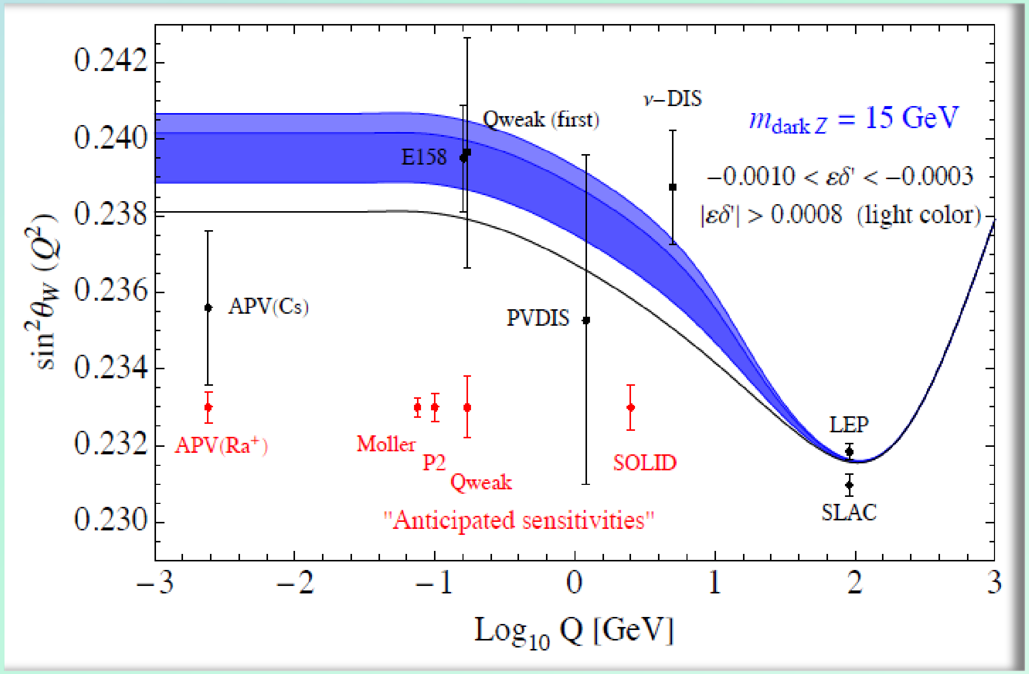


$$Q_W = \frac{E1_{APV}}{\enclose{circle}{k}}$$

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

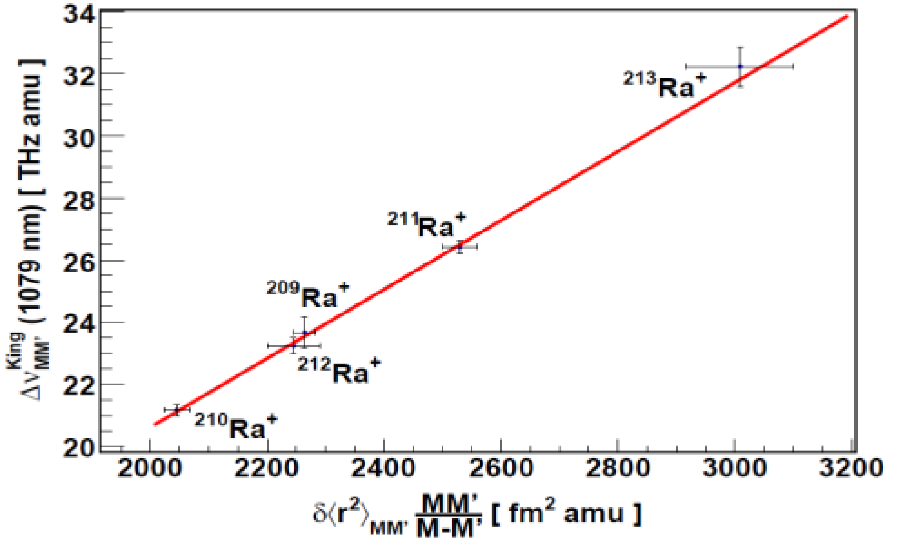
Theory Calculations:

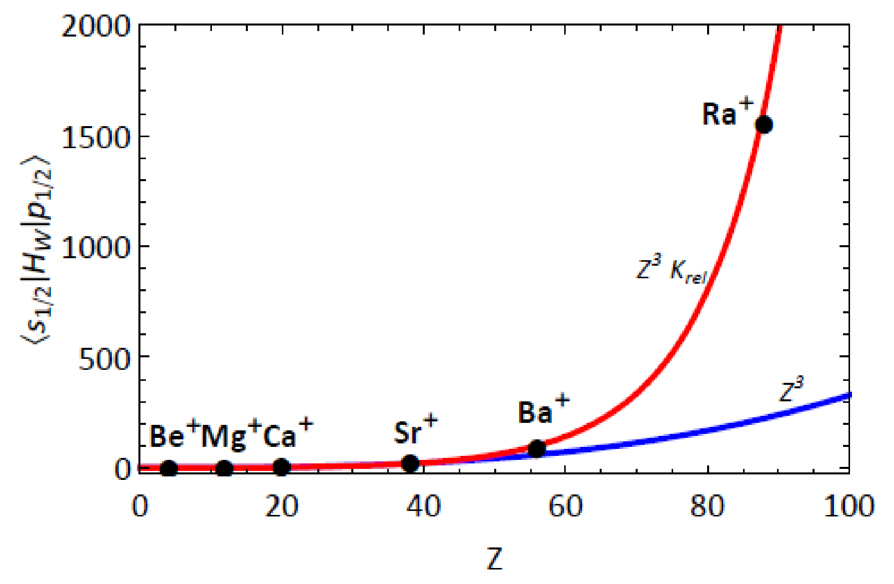
$k_{Ra} = 46.4(1.4) \cdot 10^{-11}\, iea_0 /N$ *

$k_{Cs} = 0.8906(26) \cdot 10^{-11}\, iea_0 /N$ **

*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





Probe of atomic theory & size and shape of the nucleus

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)

TABLE VI. The radial differences $\delta\langle r^2\rangle = \langle r^2\rangle_i - \langle r^2\rangle_0$ in fm^2 extracted using the database of Table II, and corrected for nuclear deformation (column 8), compared with the values listed in the Atomic Data and Nuclear Data Tables [20] (column 9, originally from ISOLDE [25]; the square brackets indicate that the 10% error needs to be taken towards higher absolute values). The factor B^i of Eq. (4) is given in MHz in column 2. Column 3 gives the corresponding results of Sec. III for the sharp cutoff nucleus using coupled-cluster (CC) theory for the field shift and specific mass shift for the reference transition. Columns 4, 5, and 6 give the results of Sec. IV needed to correct for nuclear deformation, with a sharp cutoff and Fermi nucleus using the Dirac-Fock (DF) approach. "Δ" in column 7 gives the relative difference in % between the sharp cutoff model in column 4 and the Fermi model with deformation in column 6. We use Δ to correct the value of column 3, which gives column 8. Because for $A = 209$ and 232 the reference transition at 468 nm in Ra$^+$ is not available, the effect of the deformation could not be calculated; for these two isotopes, the results for Δ (in italics) are estimated by extrapolation of the results of the neighboring isotopes.

		$\delta\langle r^2\rangle$ in fm^2					$\delta\langle r^2\rangle$ in fm^2	
A	B^i in MHz	Sharp (CC)	Sharp (DF)	Fermi	Fermi (def.)	Δ in %	This work	ISOLDE
208	11 860(15)	−0.298(15)	−0.357	−0.361	−0.362	1.3	−0.302(16)	−0.256[27]
209	11 630(15)	−0.292(15)	–	–	–	*1.3*	*−0.296(15)*	−0.253[25]
210	8393(11)	−0.211(11)	−0.252	−0.255	−0.256	1.3	−0.214(11)	−0.182[19]
211	7728.9(70)	−0.1941(98)	−0.2320	−0.2347	−0.2			
212	4554.9(44)	−0.1144(58)	−0.1369	−0.1386	−0.1			
213	3035.3(41)	−0.0762(39)	−0.0911	−0.0922	−0.0			
214	0	0	0	0	0			
220	−30 731(18)	0.772(39)	0.920	0.946	0.9			
221	−36 402(19)	0.914(47)	1.090	1.127	1.1			
222	−40 444(21)	1.016(52)	1.211	1.269	1.2			
223	−45 533(23)	1.144(58)	1.364	1.414	1.3			
224	−49 274(24)	1.238(63)	1.476	1.535	1.5			
225	−54 560(27)	1.370(69)	1.634	1.701	1.6			
226	−57 692(29)	1.449(73)	1.728	1.805	1.771	2.5	1.486(75)	1.277[129]
227	−61 638(32)	1.548(78)	1.846	1.929	1.892	2.5	1.587(80)	1.365[138]
228	−65864(34)	1.654(84)	1.973	2.068	2.023	2.6	1.697(86)	1.459[148]
229	−70235(37)	1.764(89)	2.103	2.208	2.158	2.6	1.810(92)	1.556[158]
230	−75243(39)	1.890(95)	2.253	2.391	2.317	2.8	1.943(98)	1.667[169]
232	−83590(47)	2.10(11)	–	–	–	*2.8*	*2.16(11)*	1.854[188]

available $\delta(r^2)$ values:

1.486(75) fm^2

vs.

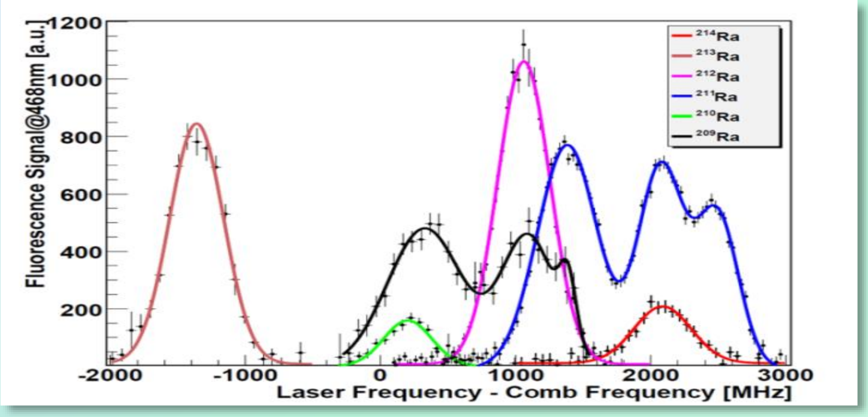
1.277(129) fm^2

L.W. Wansbeek et al, Phys. Rev. C 86, 015503 (2012)

Single Ra^+ and Ba^+ Ions

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

← To be measured

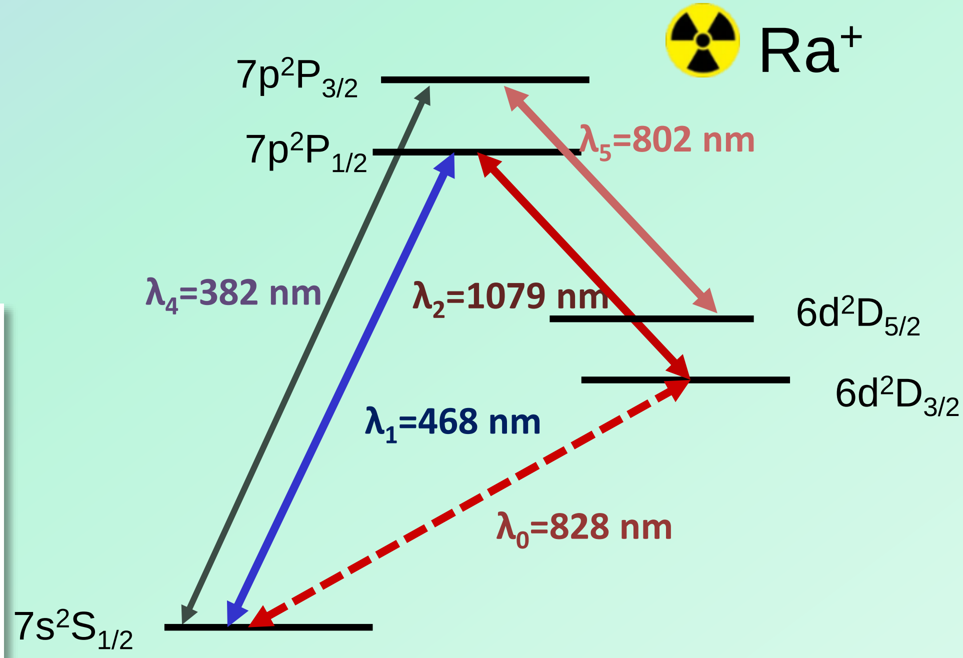


↔
5mm

Hyperbolic Paul Trap

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

Ba^+ : Precursor to Ra^+



Ra^+

$7p^2P_{3/2}$

$7p^2P_{1/2}$

λ_5=802 nm

λ_4=382 nm

λ_2=1079 nm

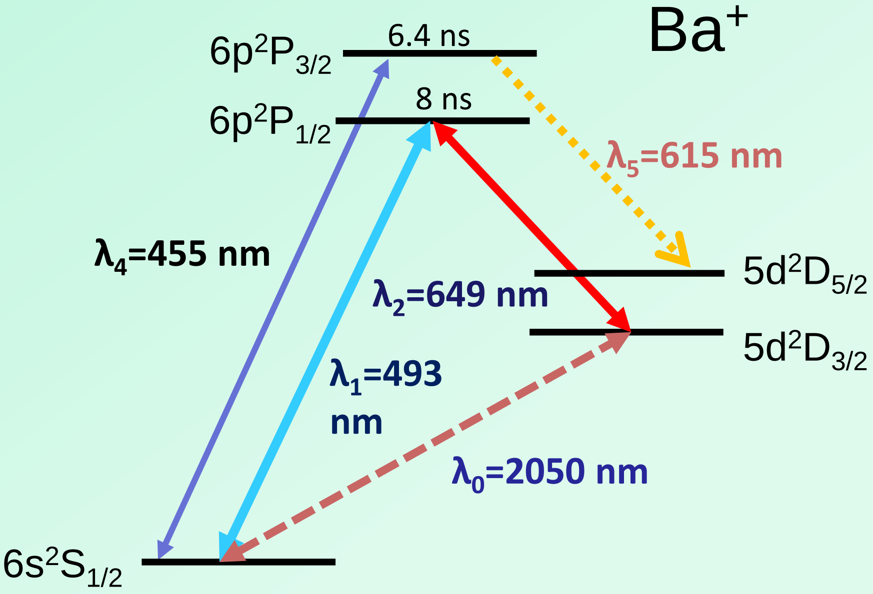
$6d^2D_{5/2}$

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

λ_1=468 nm

λ_0=828 nm

$7s^2S_{1/2}$



Ba^+

$6p^2P_{3/2}$ 6.4 ns

$6p^2P_{1/2}$ 8 ns

λ_5=615 nm

λ_4=455 nm

$5d^2D_{5/2}$

λ_2=649 nm

$5d^2D_{3/2}$

λ_1=493 nm

λ_0=2050 nm

$6s^2S_{1/2}$

Modeling of Line Shape

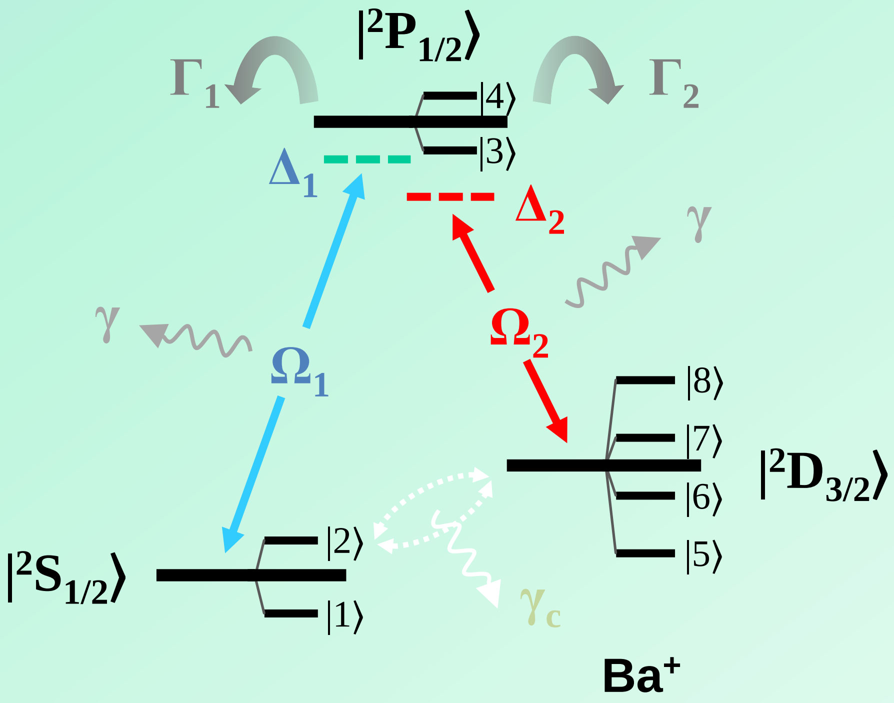
- **Optical Bloch equation**

  3 level example

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

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

$$R(\rho) = \begin{pmatrix}
\Gamma_1(\frac{1}{3}\rho_{33}+\frac{2}{3}\rho_{44}) & -\Gamma_1\frac{1}{3}\rho_{34} & -\gamma'\rho_{13} & -\gamma'\rho_{14} & -\gamma_0\rho_{15} & -\gamma_0\rho_{16} & -\gamma_0\rho_{17} & -\gamma_0\rho_{18}\\
-\Gamma_1\frac{1}{3}\rho_{43} & \Gamma_1(\frac{2}{3}\rho_{33}+\frac{1}{3}\rho_{44}) & -\gamma'\rho_{23} & -\gamma'\rho_{24} & -\gamma_0\rho_{25} & -\gamma_0\rho_{26} & -\gamma_0\rho_{27} & -\gamma_0\rho_{28}\\
-\gamma'\rho_{31} & -\gamma'\rho_{32} & -\Gamma\rho_{33} & -\Gamma\rho_{34} & -\gamma'\rho_{35} & -\gamma'\rho_{36} & -\gamma'\rho_{37} & -\gamma'\rho_{38}\\
-\gamma'\rho_{41} & -\gamma'\rho_{42} & -\Gamma\rho_{43} & -\Gamma\rho_{44} & -\gamma'\rho_{45} & -\gamma'\rho_{46} & -\gamma'\rho_{47} & -\gamma'\rho_{48}\\
-\gamma_0\rho_{51} & -\gamma_0\rho_{52} & -\gamma'\rho_{53} & -\gamma'\rho_{54} & \Gamma_2\frac{1}{2}\rho_{33} & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{34} & 0 & 0\\
-\gamma_0\rho_{61} & -\gamma_0\rho_{62} & -\gamma'\rho_{63} & -\gamma'\rho_{64} & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{43} & \Gamma_2(\frac{1}{3}\rho_{33}+\frac{1}{6}\rho_{44}) & \Gamma_2\frac{1}{3}\rho_{34} & 0\\
-\gamma_0\rho_{71} & -\gamma_0\rho_{72} & -\gamma'\rho_{73} & -\gamma'\rho_{74} & 0 & \Gamma_2\frac{1}{3}\rho_{43} & \Gamma_2(\frac{1}{6}\rho_{33}+\frac{1}{3}\rho_{44}) & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{34}\\
-\gamma_0\rho_{81} & -\gamma_0\rho_{82} & -\gamma'\rho_{83} & -\gamma'\rho_{84} & 0 & 0 & \Gamma_2\frac{1}{2\sqrt{3}}\rho_{43} & \Gamma_2\frac{1}{2}\rho_{44}
\end{pmatrix}$$



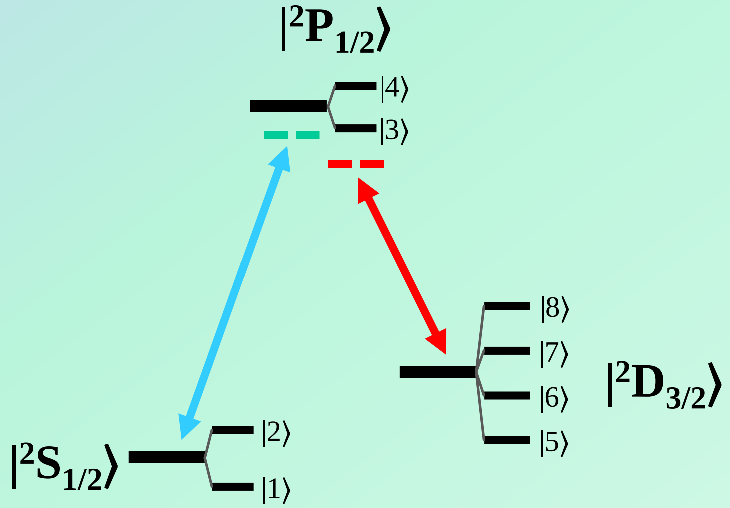
Ω_1, Ω_2	Rabi frequencies (laser power)	$\Gamma = \Gamma_1 + \Gamma_2$	relaxation rate
		$\gamma = \Gamma/2$	decoherence rate
Δ_1, Δ_2	laser detunings	γ_c	laser linewidth

Line Shapes and Polarization

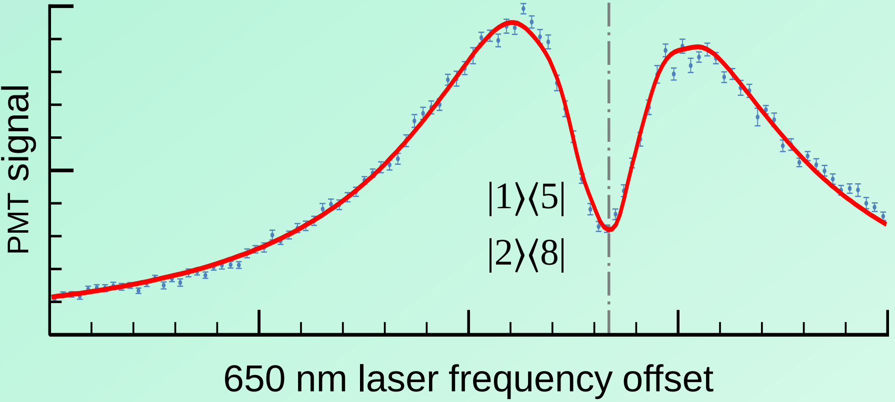
- **Zeeman sublevels:** 8 level system

  Magnetic field **B**

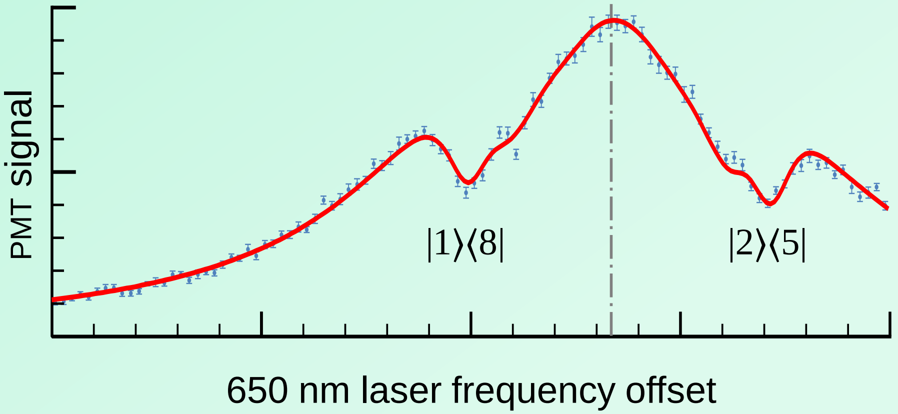
  Laser polarization



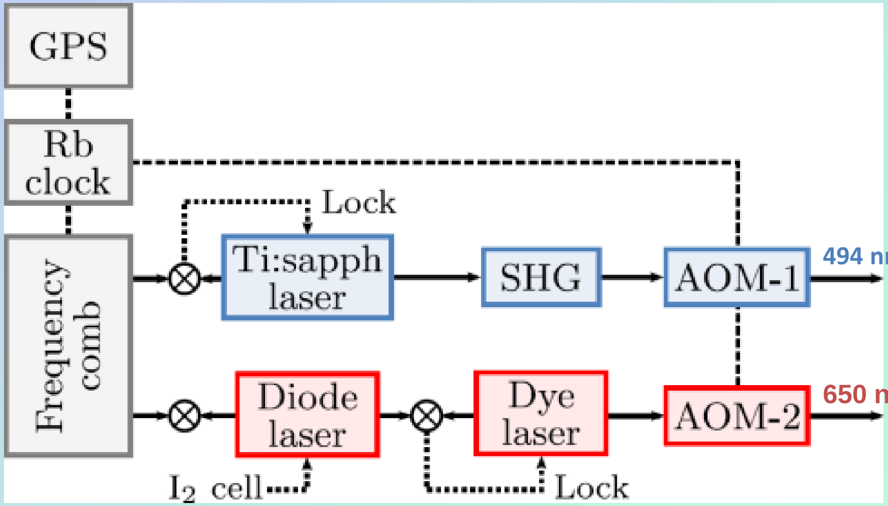
494 nm linear polarized ⊥ **B**
650 nm circularly polarized

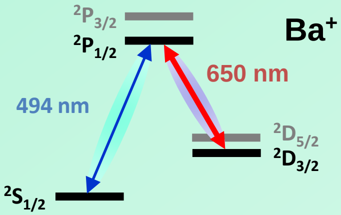


494 nm linear polarized ∥ **B**
650 nm circularly polarized



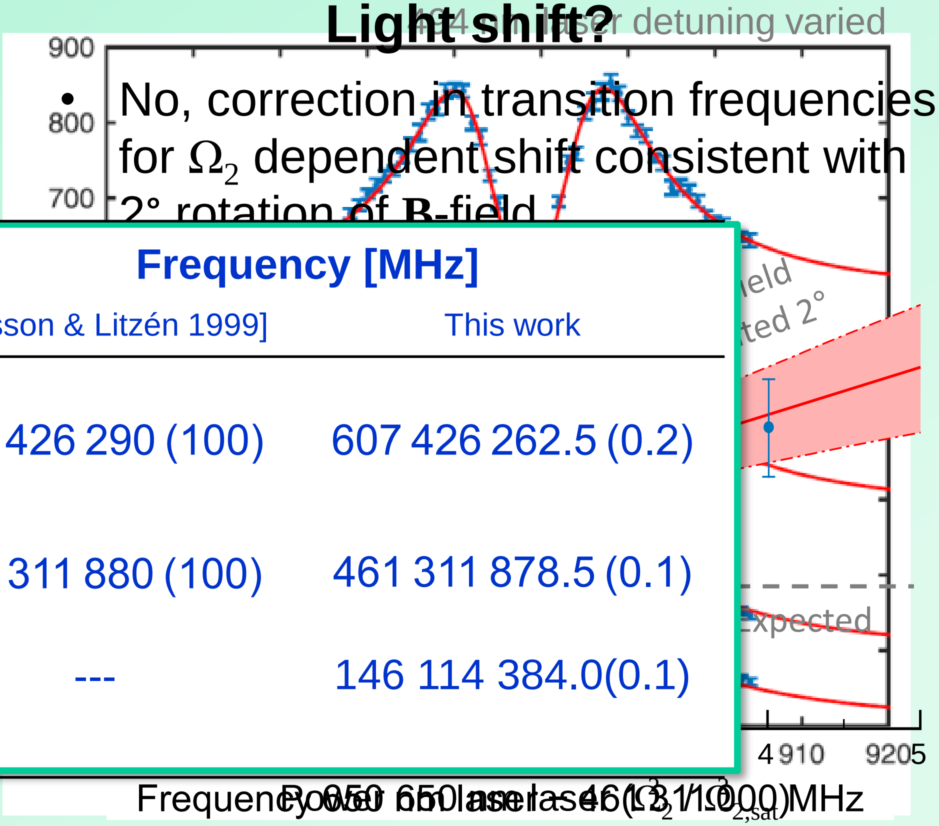
Transition Frequencies

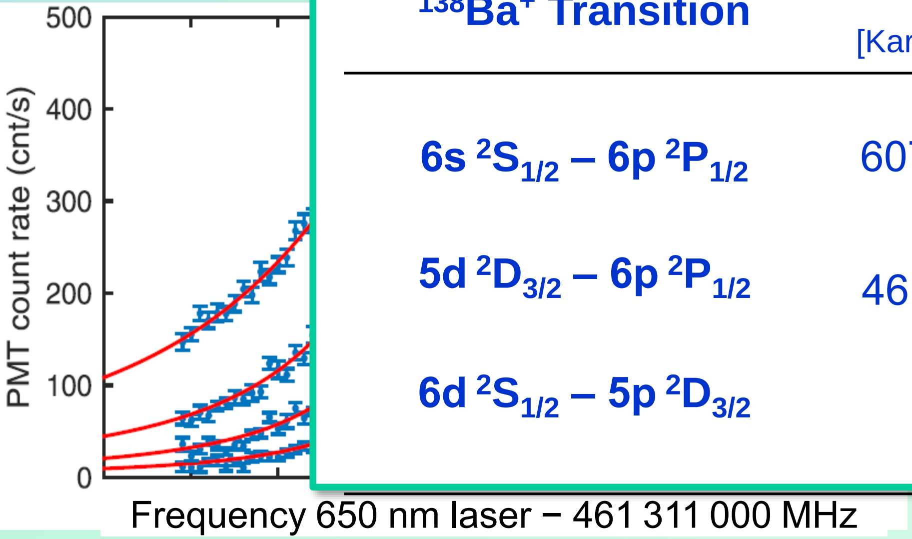




Light shift?

- No, correction in transition frequencies for Ω_2 dependent shift consistent with 2° rotation of **B**-field



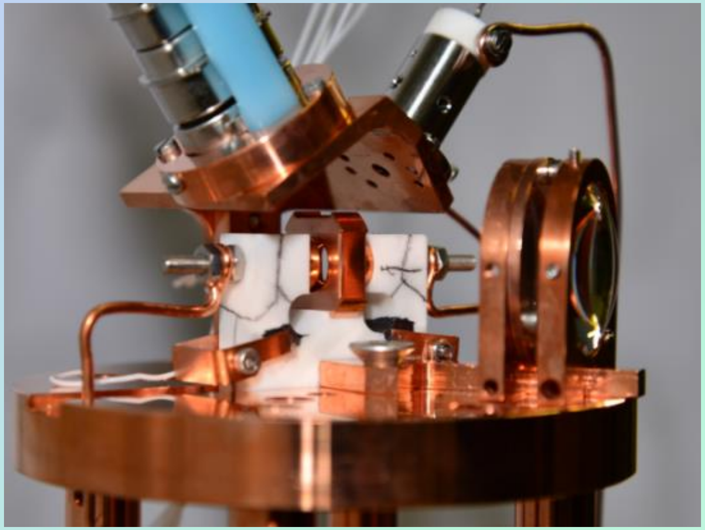


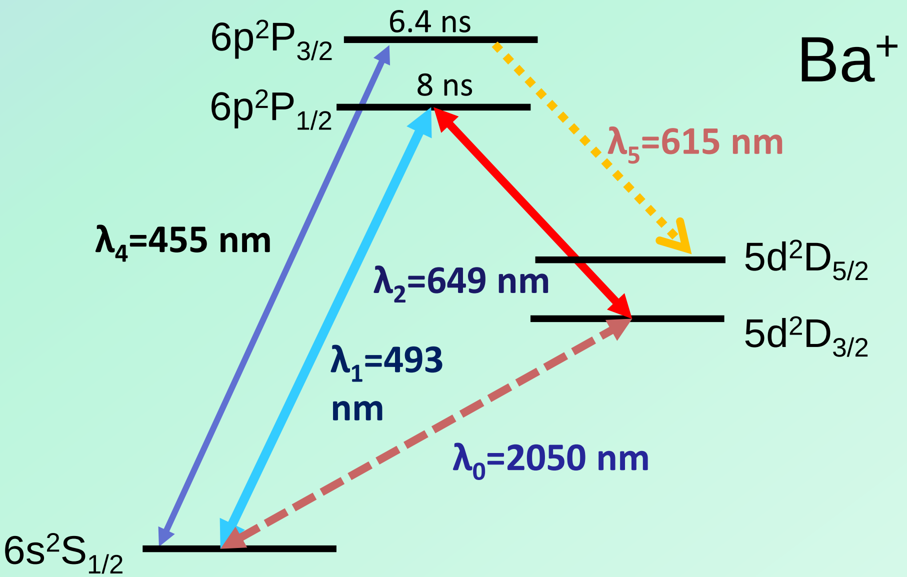
^{138}Ba$^+$ Transition	Frequency [MHz]	
	[Karlsson & Litzén 1999]	This work
6s $^2S_{1/2}$ – 6p $^2P_{1/2}$	607 426 290 (100)	607 426 262.5 (0.2)
5d $^2D_{3/2}$ – 6p $^2P_{1/2}$	461 311 880 (100)	461 311 878.5 (0.1)
6d $^2S_{1/2}$ – 5p $^2D_{3/2}$	---	146 114 384.0(0.1)

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

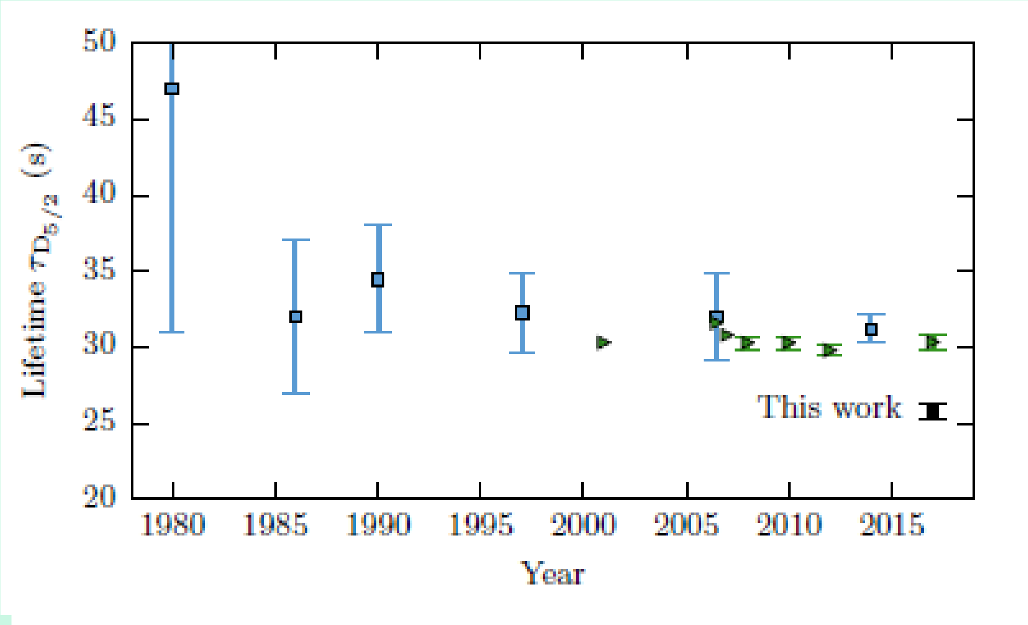
Dijck et al., Phys. Rev. A **91**, 060501(R) (2015)

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





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



$\tau_{D5/2} = 25.8(5)$ s

E.A. Dijck et al, submitted (2017)

Radium for APV

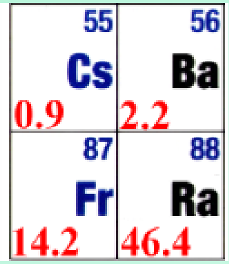
Accuracy of single ion Experiment

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

E_0 = Light electric field amplitude, τ = Coherence time

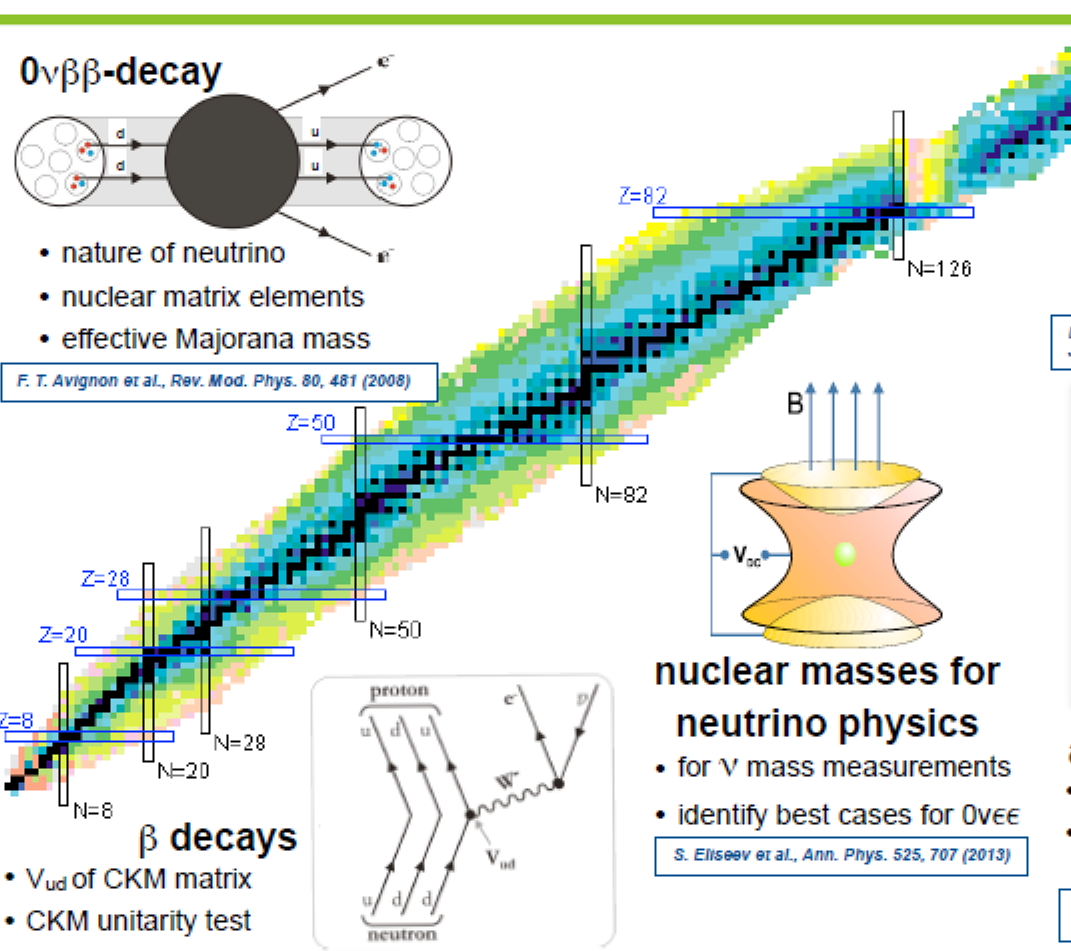
N = Number of ions = 1, t = Time of observation

	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

weak interaction studies in radionuclides



0νββ-decay

- nature of neutrino
- nuclear matrix elements
- effective Majorana mass

F. T. Avignon et al., Rev. Mod. Phys. 80, 481 (2008)

β decays

- V_{ud} of CKM matrix
- CKM unitarity test
- limits on scalar & tensor currents
- …

J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)
N. Severijns and O. Naviliat-Cuncic, Phys. Scr. T152, 014018 (2013)
V. Cirigliano et al., Prog. Part. Nucl. Phys. 71, 93 (2013)
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. 525, 600 (2013)
K. K. Vos et al., Rev. Mod. Phys. 87, 1483 (2015)

nuclear masses for neutrino physics

- for ν mass measurements
- identify best cases for 0νεε

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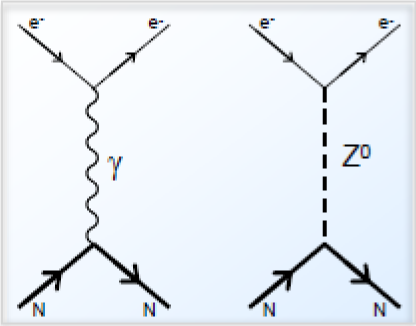
Octupole enhanced atomic EDMs

- in 'pear shaped' nuclei

L. P. Gaffney, Nature 497, 199–204 (2013)
J. Dobaczewski and J. Engel, PRL 94, 232502 (2005)



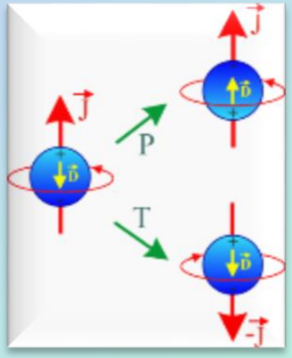
atomic parity violation

- access $\sin^2(\Theta_W)$ at low energy
- strong enhancement in (radioactive) Fr or Ra⁺

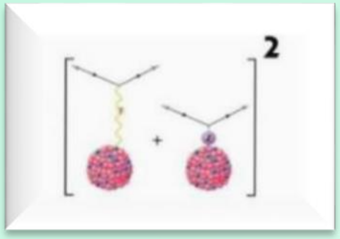
S. Aubin et al., Hyp. Int. 214, 163 (2013),
L. Willmann et al., CERN-INTC-2017-069 / INTC-I-196

SUMMARY

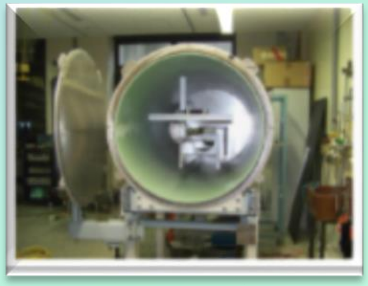
Precision Tests of Discrete Symmetries at Low Energies



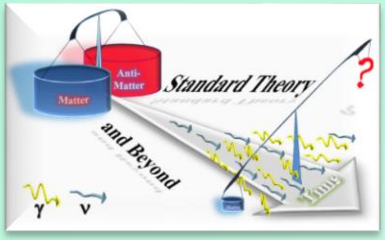
- A few Selected Experiments
  - → Focus on Transformativity



- C, P, CP, CPT Tests
  - → Precision Test of Standard Model
- Experiment & Theory Hand in Hand
  - → Atomic Parity Violation and EDM to search for New Physics



- Search for permanent Electric Dipole Moments
  - → Atoms & Molecules with Enhancement
  - → Electron and Nucleon EDMs
  - → Some Radioactive Species may have Advantages
  - → No particular advantage from Radioactivity per se
  - → Central Goal: Challenge New Physics Models



THANK YOU !

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