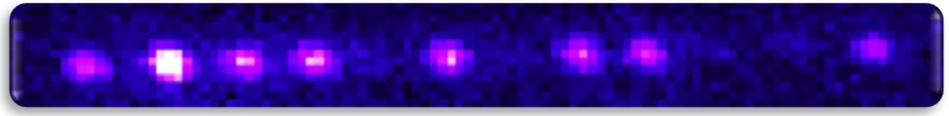
Probing new physics with precision isotope shift spectroscopy



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מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

ECT* Workshop on Discrete Symmetries in Particle, Nuclear and Atomic Physics and implications for our Universe

October 2018

AMO Precision Measurements

- Variation of fundamental constant
- eEDM measurements
- Atomic parity violation
- Test of local Lorentz invariance
- Testing general relativity with atom interferometry
- Probing\bounding new light force-mediators by isotope shift spectroscopy

C. Delaunay, R.Ozeri, G.Perez and Y. Soreq Phys. Rev. D 96, 093001 (2017)

Berengut J. C.; Budker D.; Delaunay C.; Flambaum V. V.; Frugiuele C.; Fuchs E.; Grojean C.; Harnik R.; RO; Perez G.; Soreq Phys. Rev. Lett. 120, 091801 (2018)

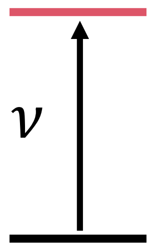
Isotope Shifts

hypothetical new force carriers

A boson that couples to electrons and neutrons

$$V_\phi(r) = \frac{-(-1)^s y_e y_n (A-Z)}{4\pi} \frac{e^{-m_\phi r}}{r}$$

Atomic transition



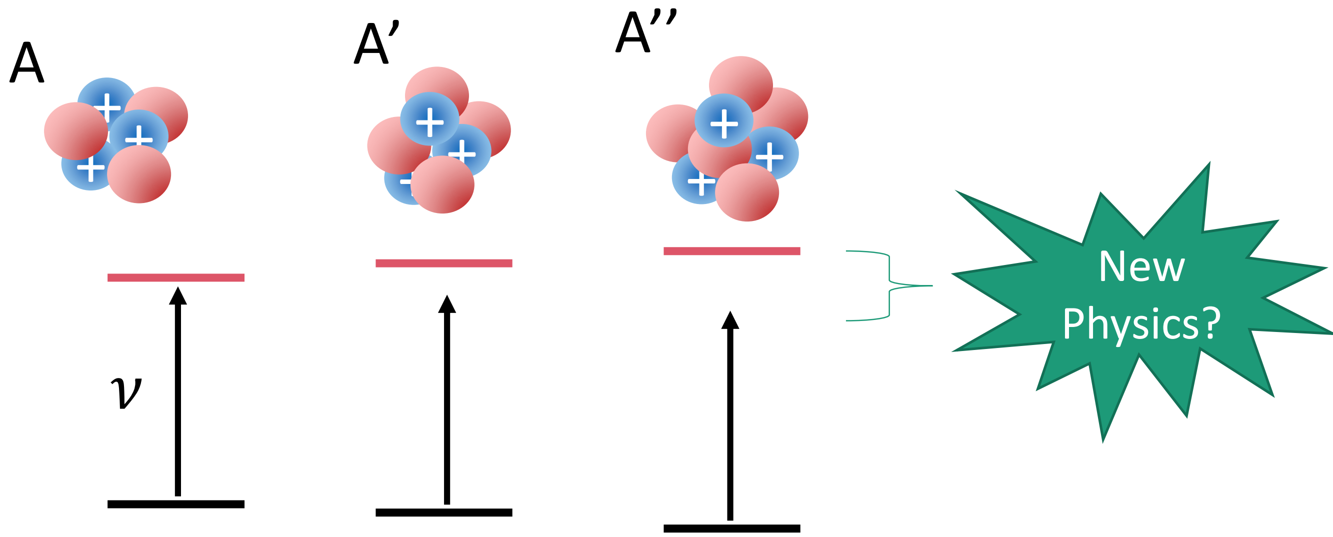
$\delta\nu/\nu = 10^{-18}$

An over simplified picture :

Measure different isotope

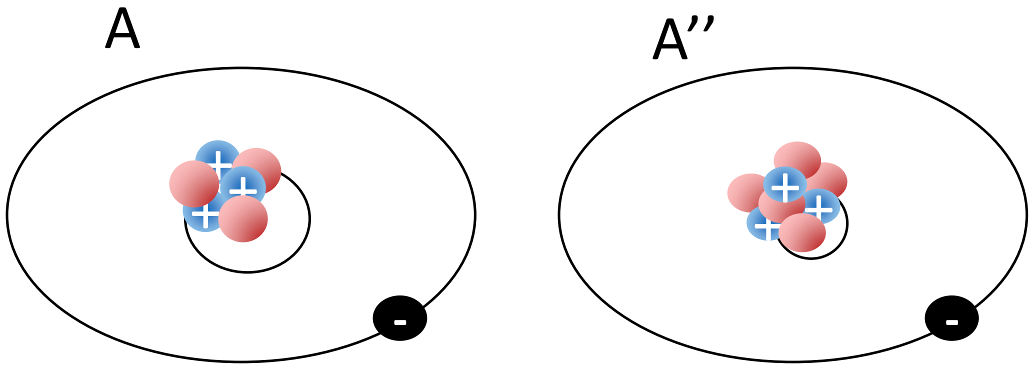
$\delta\nu_i^{AA'} \equiv \nu_i^{A}$ - $\nu_i^{A'}$

There are **normal** contributions :
Mass shift and **Field shift**



Isotope Mass Shift

Due to the kinetic energy of the nucleus



$$\frac{P_n^2}{2M_n} = \frac{(\sum p_e)^2}{2M_n} = \frac{\sum_i p_i^2 + \sum_{i \neq j} p_i p_j}{2M_n}$$

Normal Mass Shift
(Reduced mass)

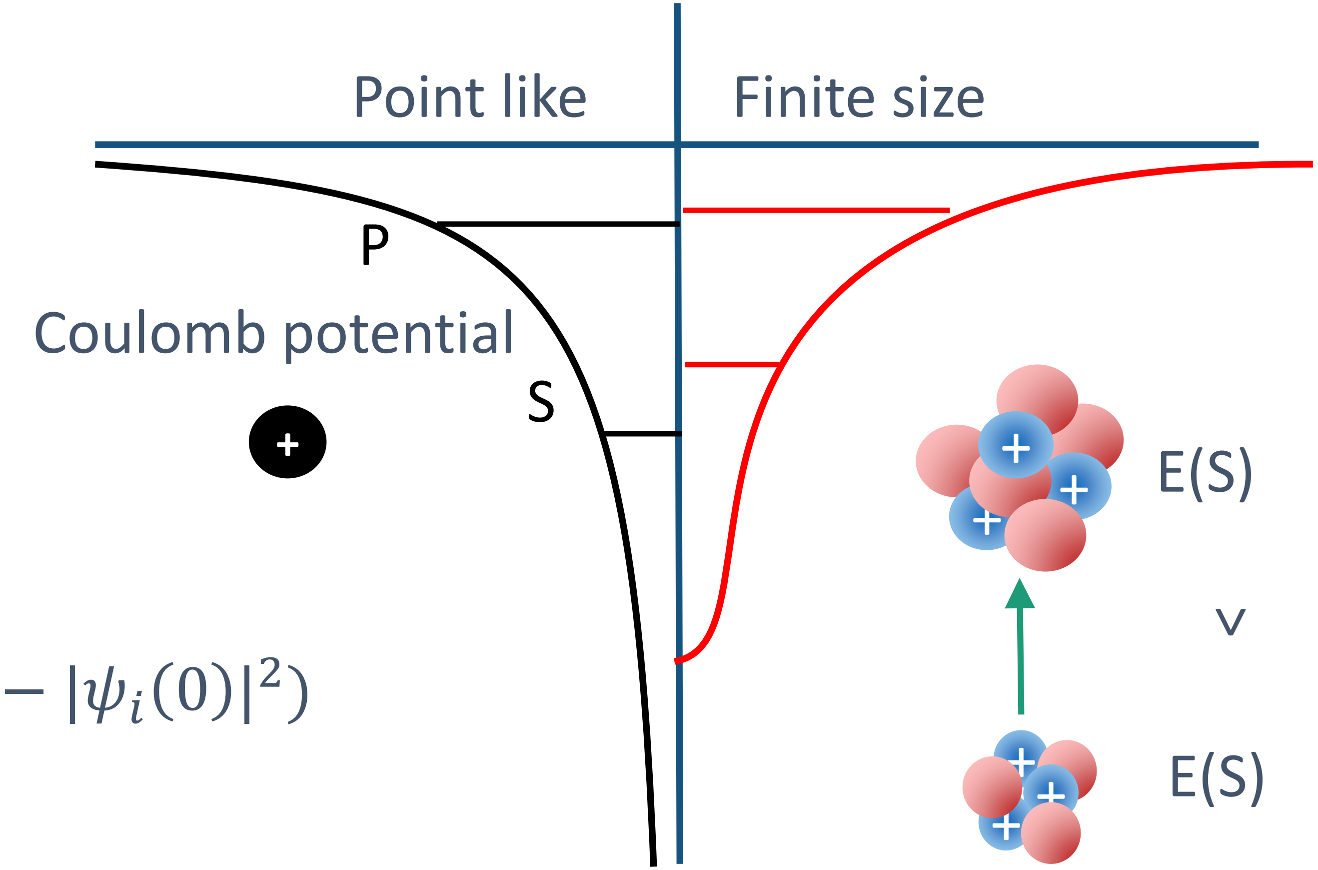
$$\delta \nu_{NMS}^{AA'} \sim \frac{1000}{A^2}\text{GHz}$$

Specific mass shift

- correlation in the electrons many body wave function.
- Very hard to calculate -> Unknown

Isotope Field Shift

Due to the finite size of the nucleus
and Charge distribution



Leading order :

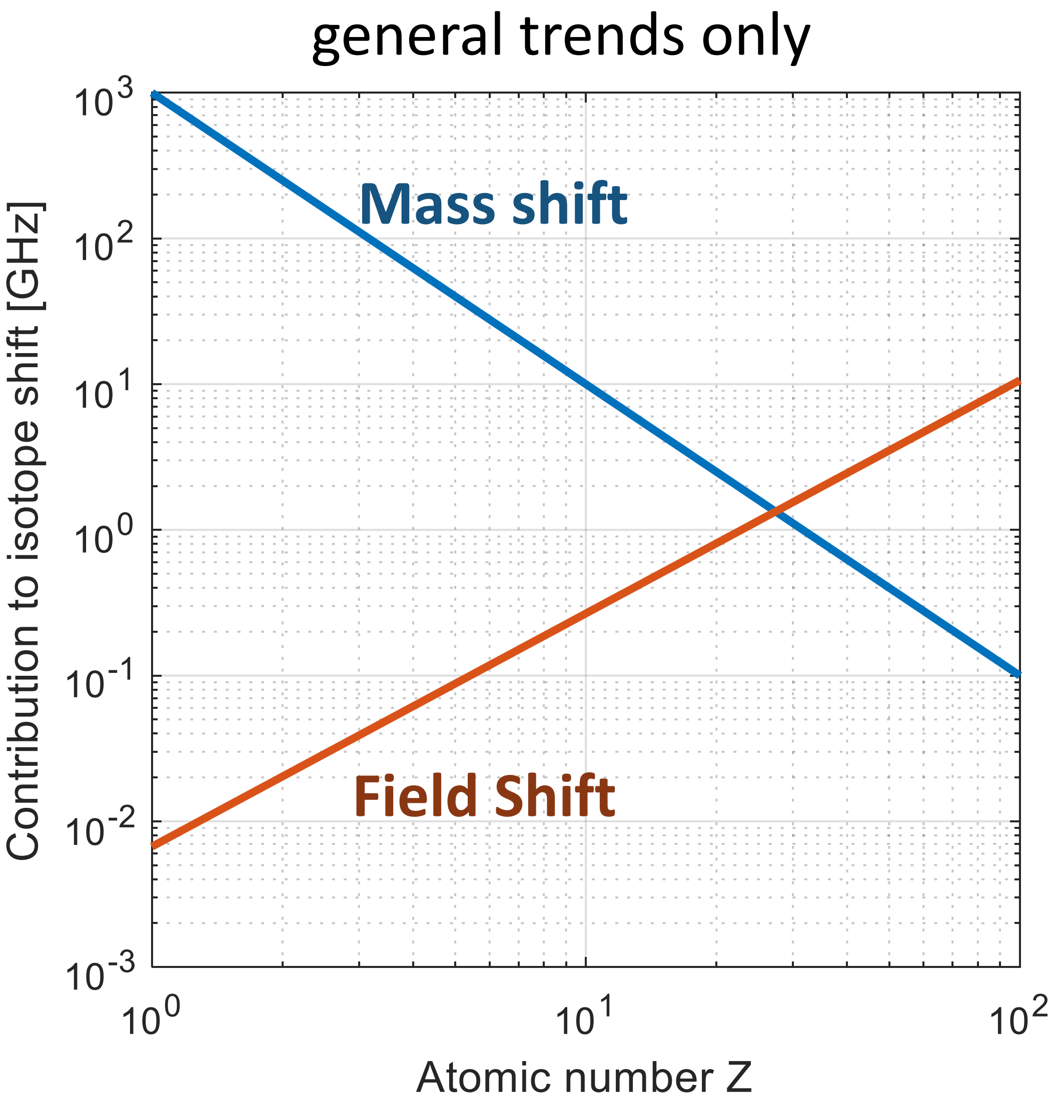
$$\delta\nu_{FS}^{AA'} \propto \delta < r_c^2 >^{AA'} (|\psi_f(0)|^2 - |\psi_i(0)|^2)$$

$$\delta\nu_{FS}^{AA'} \sim A^{5/3}$$

Mass shifts and Field Shift

$$\delta\nu^{AA'} = \delta\nu^{AA'}_{MS} + \delta\nu^{AA'}_{FS}$$

- Mass shift dominates in light atoms
- Field shift dominates in heavy atoms
- IS on the order of GHz for A>10
- **Theoretical uncertainty is still poor**



King plot comparison (to the rescue…)

$$\delta\nu^{AA'} = \delta\nu^{AA'}_{MS} + \delta\nu^{AA'}_{FS}$$

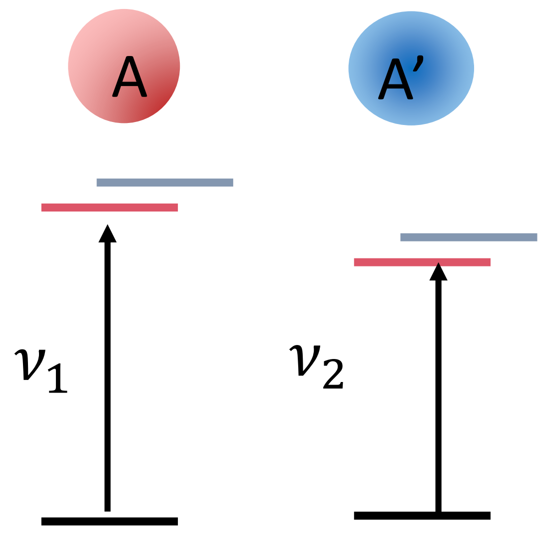
Following King's factorization :

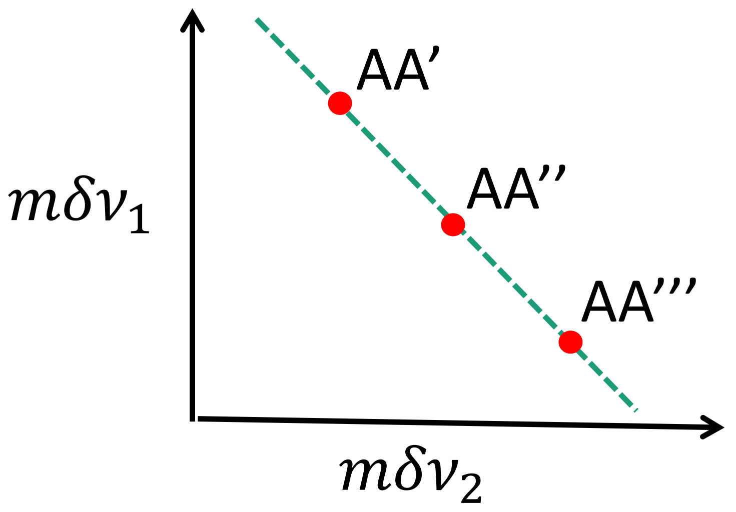
$$\delta\nu_i^{AA'} = K_i\mu + F_i\delta\langle r^2\rangle^{AA'} + X_i\gamma_{AA'}$$

For two transitions $\delta\nu_1^{AA'}$ and $\delta\nu_2^{AA'}$:

$$m\delta\nu_2^{AA'} = K_{21} + F_{21}m\delta\nu_1^{AA'}$$

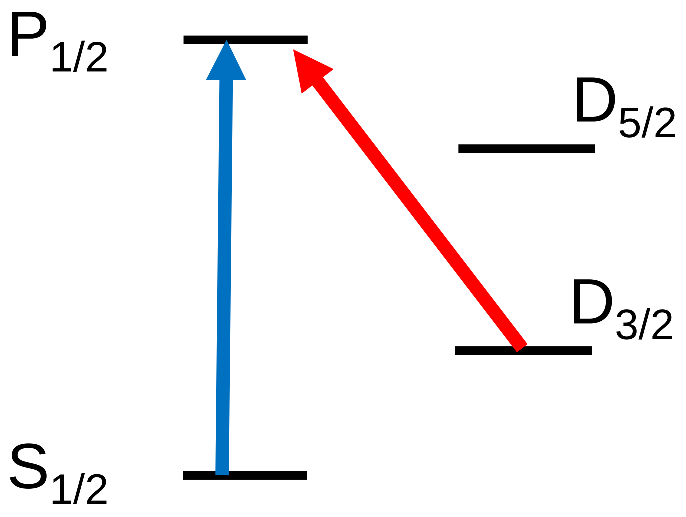
with $m \equiv \frac{M^A M^{A'}}{M^A - M^{A'}}$; $F_{21} \equiv \frac{F_2}{F_1}$; $K_{21} \equiv K_2 - F_{21}K_1$





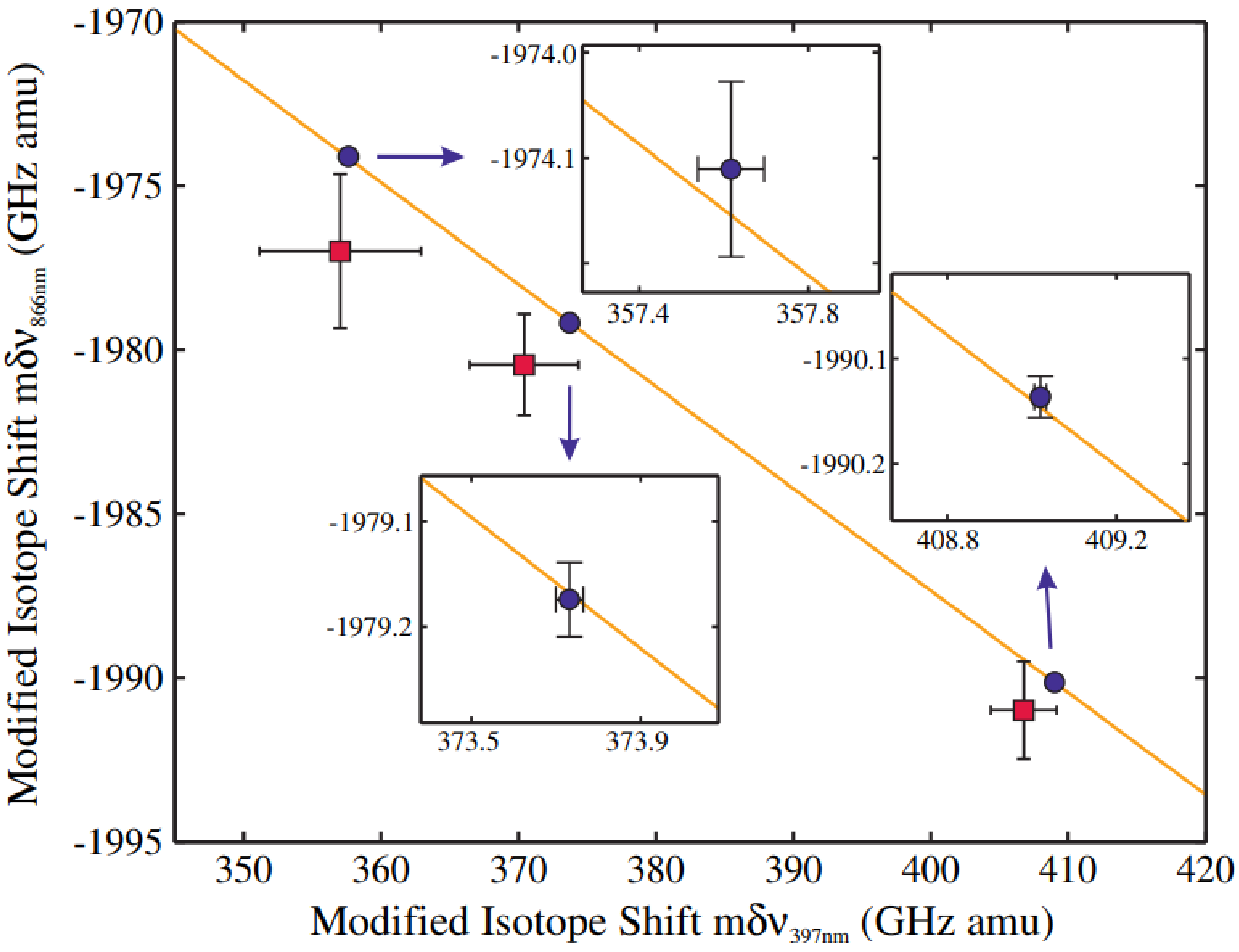
W. H. King "Isotope Shifts in Atomic Spectra" Springer (1984)

King's plot for **dipole** transitions in Ca^+



Linear at the level of 100 kHz

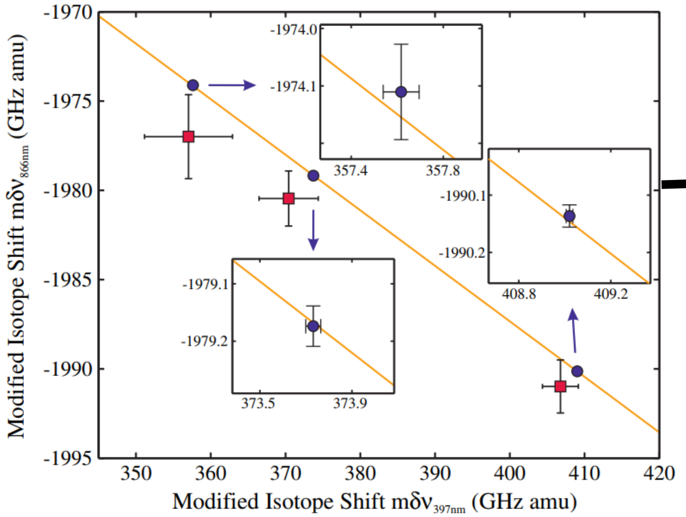
Gebert at al PRL 115, 053003 (2015)

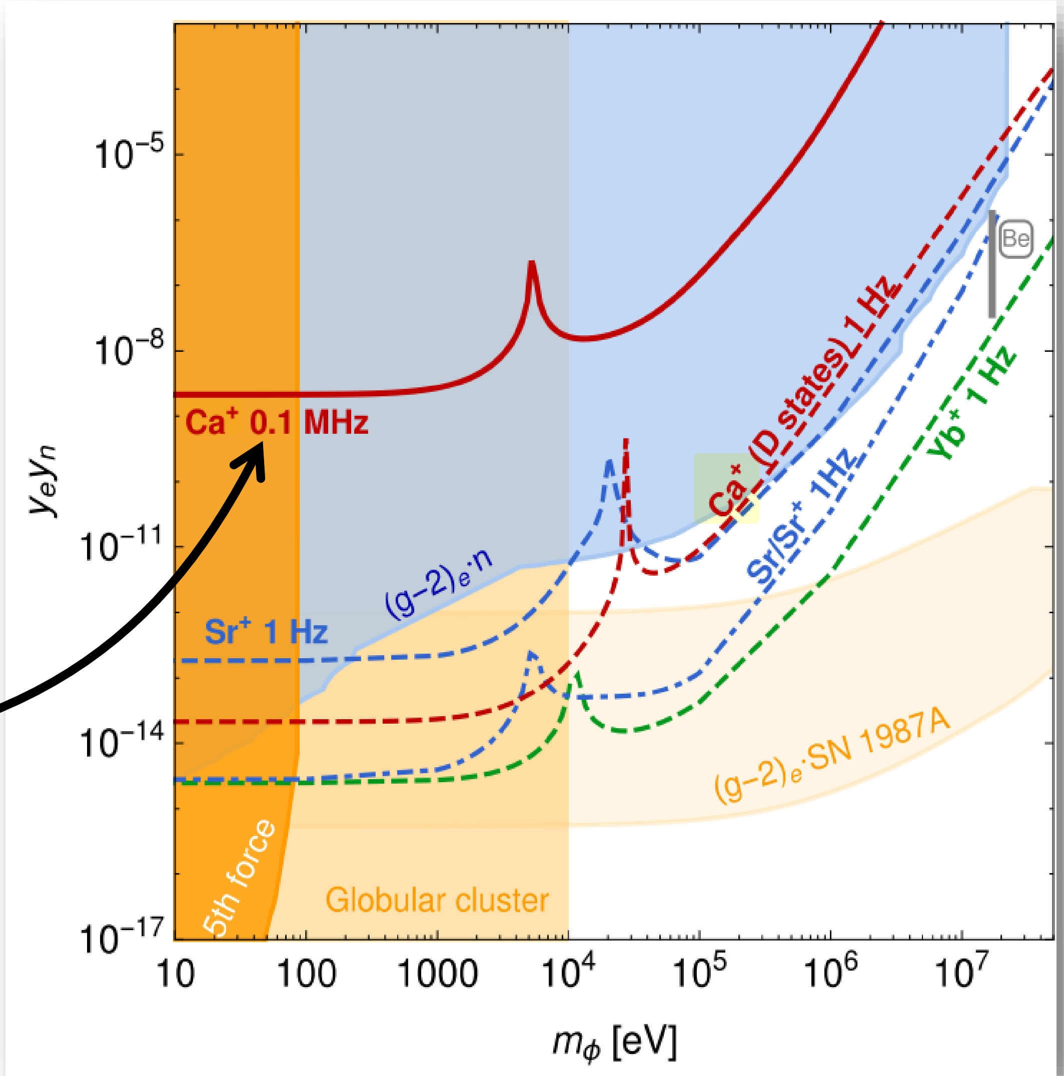


Bounds on new force-mediators

For hypothetical new force carriers of spin s = 0, 1 or 2 and mass m_ϕ :

$$V_\phi(r) = \frac{-(-1)^s y_e y_n}{4\pi} \frac{e^{-m_\phi r}}{r}$$





Berengut et al. *Phys. Rev. Lett.* 120.9 (2018): 091801.

Requirements

- At least four different even isotopes (without hyperfine)
- Two narrow optical transitions (could be neutral and ions)
- Transitions between as different states as possible
- Possible candidates :
  - Ion and neutral : Ca, Yb (Sr)
  - E2 transitions in ions :

    Ca+, Sr+,Ba+, Yb+
  - E2 and E3 in Yb+
- **Small Standard Model nonlinearity**

Nonlinearity in King plots

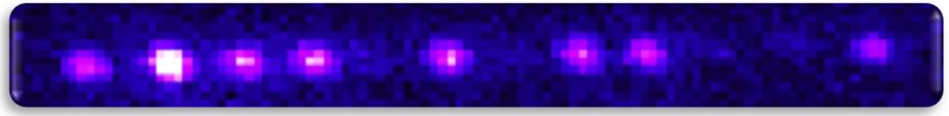
PHYSICAL REVIEW A **97**, 032510 (2018)

Isotope shift, nonlinearity of King plots, and the search for new particles

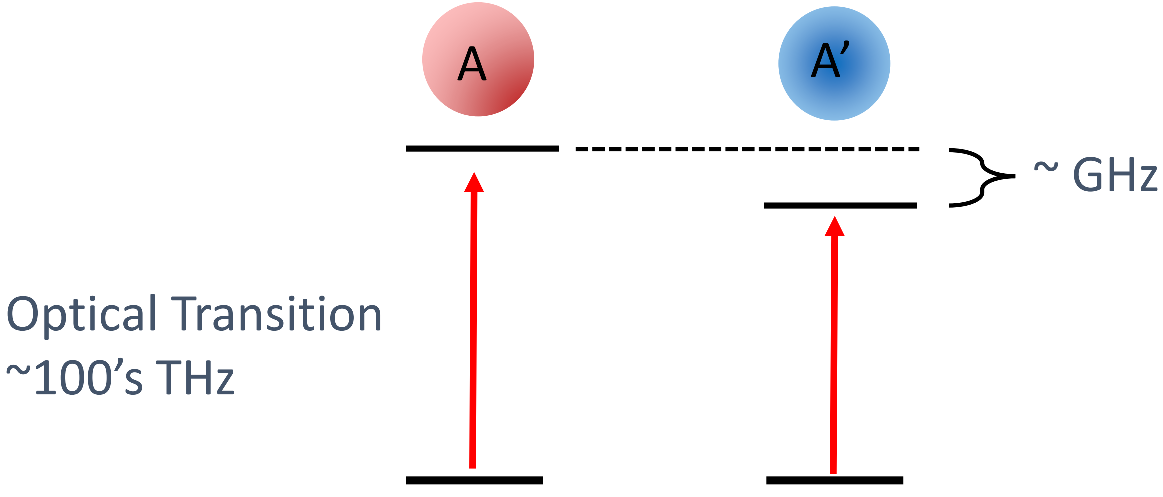
V. V. Flambaum,[1,2] A. J. Geddes,[1] and A. V. Viatkina[2]

Ion	Z	A	A_1	A_2	A_3	Pair of transitions	Nonlinearity (Hz) Method 4	Method 5	Quadratic term inc. MB Without α_p	With α_p	QMS
Ca^+	20	40	42	44	48	$3p^6 4s\ ^2S_{1/2} \rightarrow 3p^6 3d\ ^2D_{3/2}$ $3p^6 4s\ ^2S_{1/2} \rightarrow 3p^6 3d\ ^2D_{5/2}$	3.0×10^{-4}	-6.6×10^{-2}	$\pm 2.9 \times 10^{-3}$	$\pm 2.7 \times 10^{-3}$	± 3.0
Sr^+	38	84	86	88	90	$4p^6 5s\ ^2S_{1/2} \rightarrow 4p^6 4d\ ^2D_{3/2}$ $4p^6 5s\ ^2S_{1/2} \rightarrow 4p^6 4d\ ^2D_{5/2}$	1.1×10^{-2}	-2.6	± 0.23	± 0.25	± 9.0
Ba^+	56	132	134	136	138	$5p^6 6s^1\ ^2S_{1/2} \rightarrow 5p^6 5d\ ^2D_{3/2}$ $5p^6 6s^1\ ^2S_{1/2} \rightarrow 5p^6 5d\ ^2D_{5/2}$	-3.9×10^{-2}	7.4	∓ 2.0	∓ 1.9	∓ 1.8
Yb^+	70	168	170	172	176	$4f^{14} 6s\ ^2S_{1/2} \rightarrow 4f^{13} 6s^2\ ^2F^o_{7/2}$ $4f^{14} 6s\ ^2S_{1/2} \rightarrow 4f^{14} 5d\ ^2D_{3/2}$	-3.1	39	± 12260	± 12130	± 28
						$4f^{14} 6s\ ^2S_{1/2} \rightarrow 4f^{14} 5d\ ^2D_{3/2}$ $4f^{14} 6s\ ^2S_{1/2} \rightarrow 4f^{14} 5d\ ^2D_{5/2}$	3.1	-18	± 392	± 386	± 1.1
Hg^+	80	196	198	200	204	$5d^{10} 6s\ ^2S_{1/2} \rightarrow 5d^9 6s^2\ ^2D_{3/2}$ $5d^{10} 6s\ ^2S_{1/2} \rightarrow 5d^9 6s^2\ ^2D_{5/2}$	3.0	-13	± 2406	± 2382	± 0.38

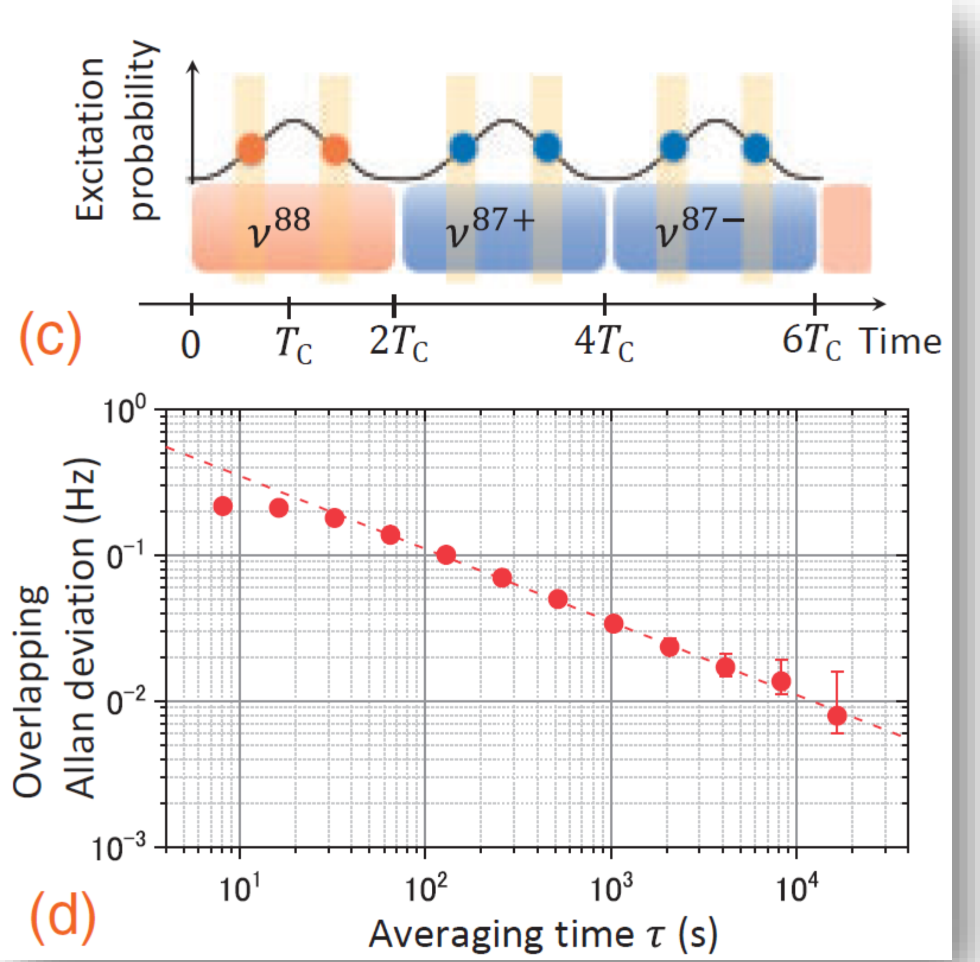
Precision isotope shift spectroscopy in trapped ions



Isotope Shift Spectroscopy



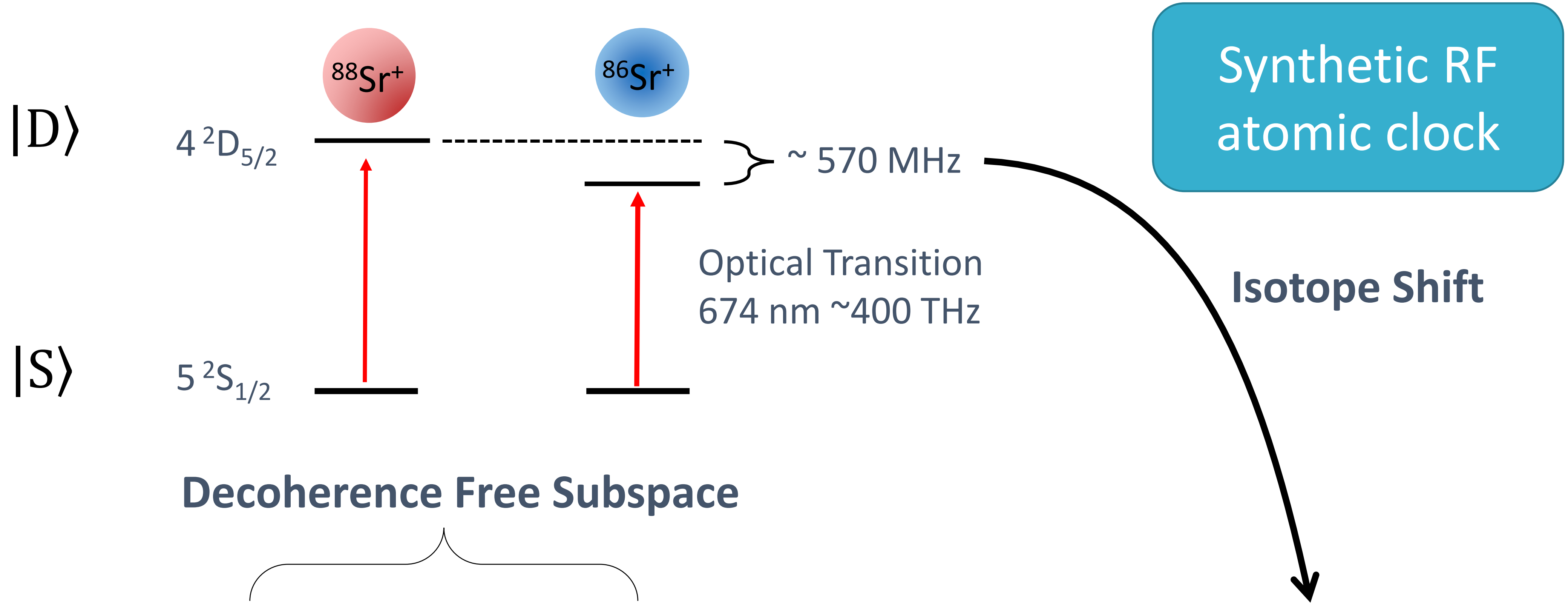
$$\Delta\nu^{88,87}_{S_0,P_0} = 62{,}188{,}134.004(10)\ \mathrm{Hz}$$



Takano et al. Applied Physics Express 10, 089201 (2017)
Origlia et. al. arXiv:1803.03157 (2018)

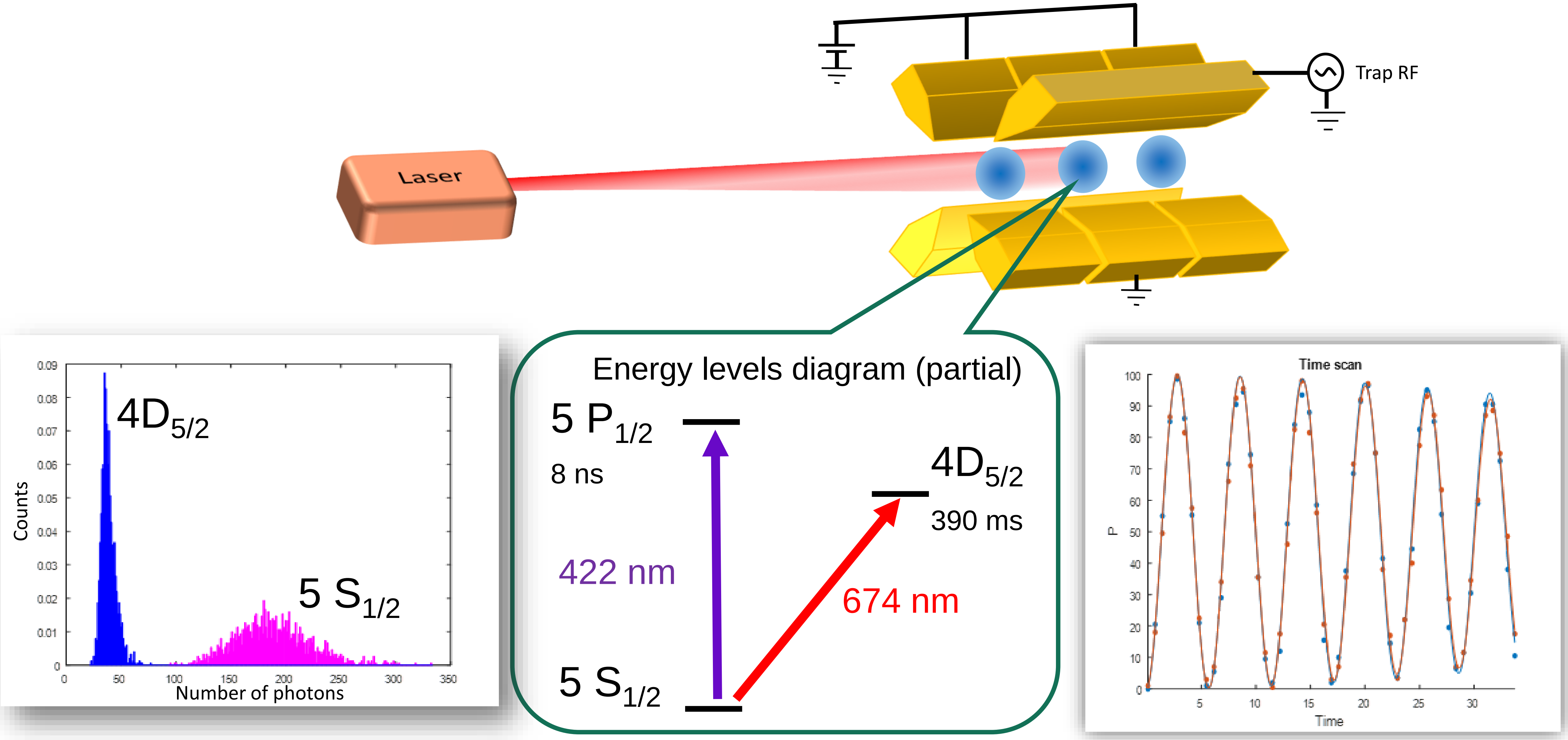
Isotope Shift Spectroscopy In DFS

The Quadruple transition in Sr+ ion

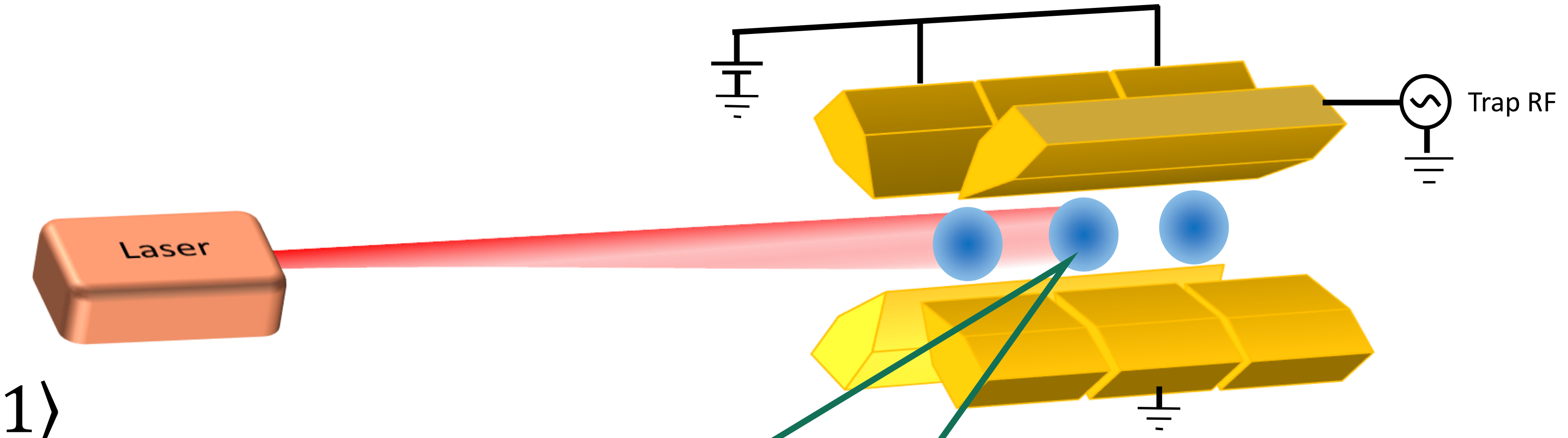


$$\psi_{init} = |S\rangle|D'\rangle + |D\rangle|S'\rangle \rightarrow \psi\ (T) = |S\rangle|D'\rangle + e^{i2\pi\delta\nu T}|D\rangle|S'\rangle$$

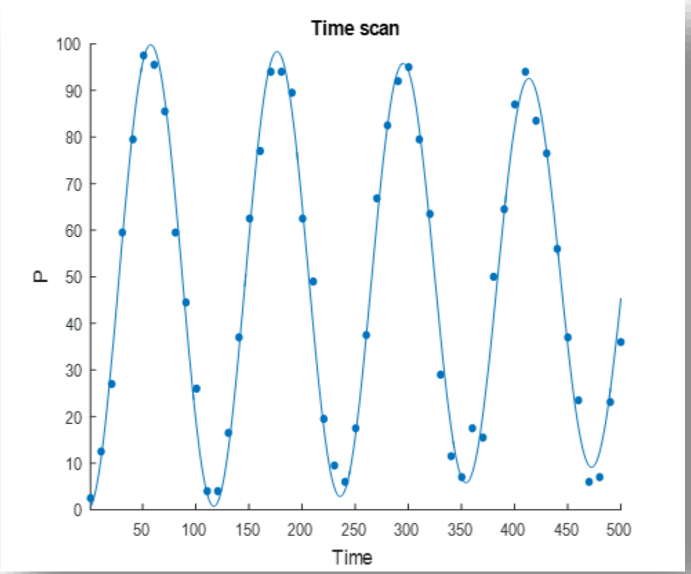
Trapped Ions

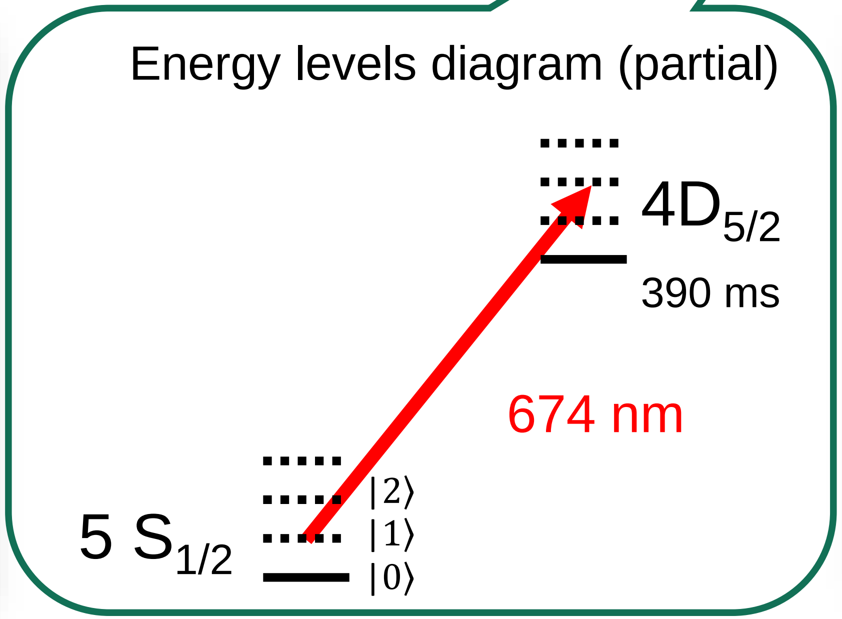


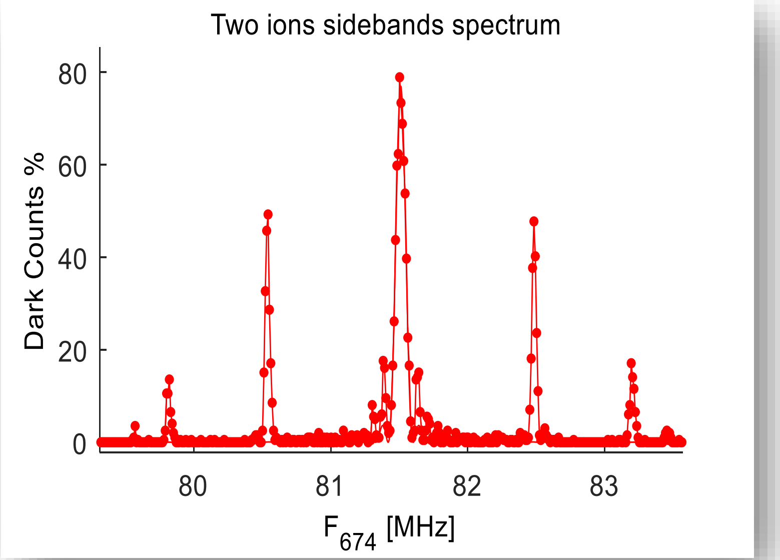
Trapped Ions



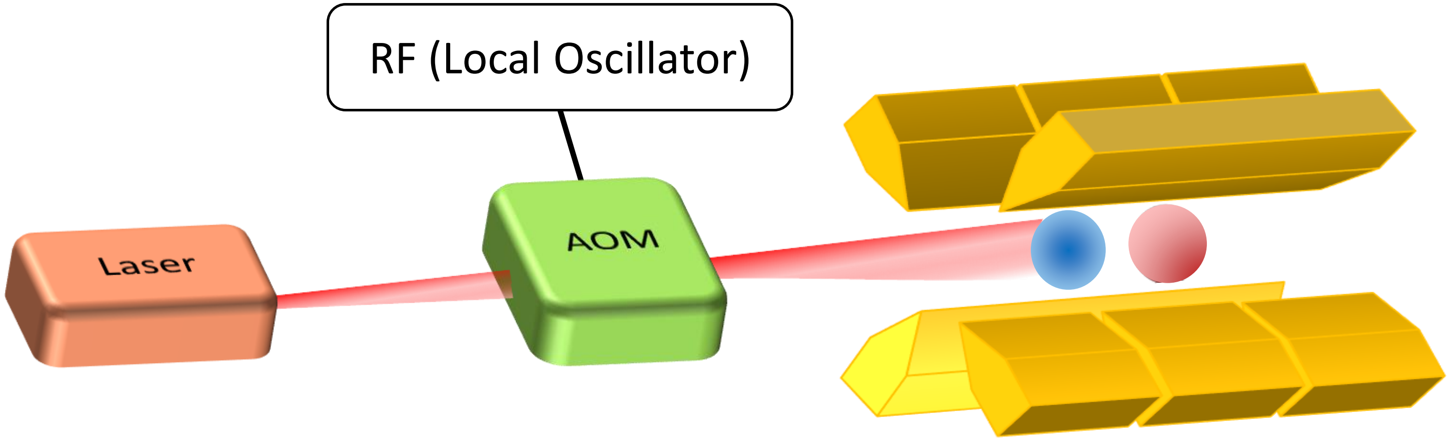
$|S\rangle|0\rangle \leftrightarrow |D\rangle|1\rangle$

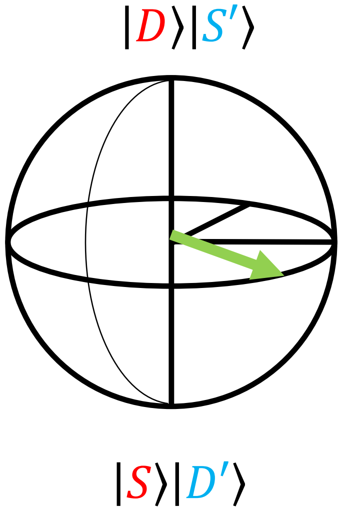






Isotope Shift Spectroscopy In DFS

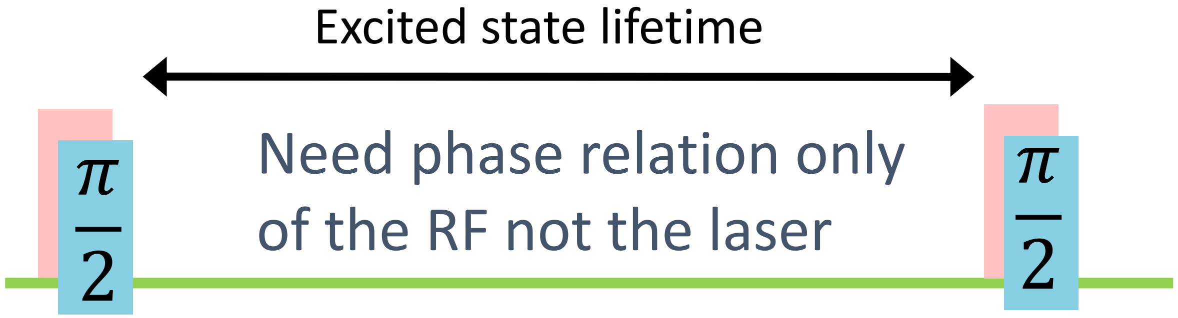




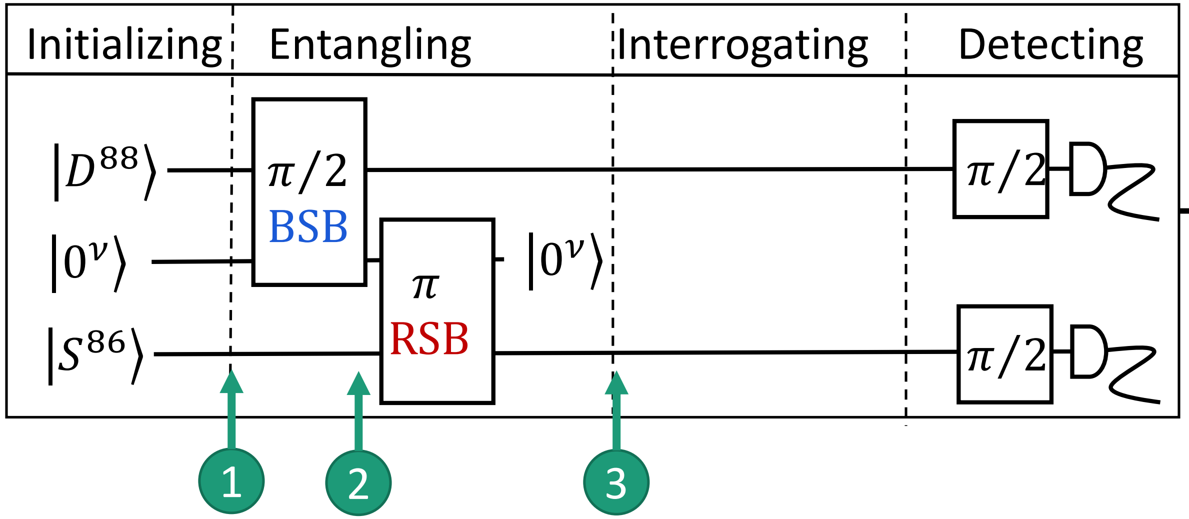
Measuring the Isotope shift in decoherence free subspace

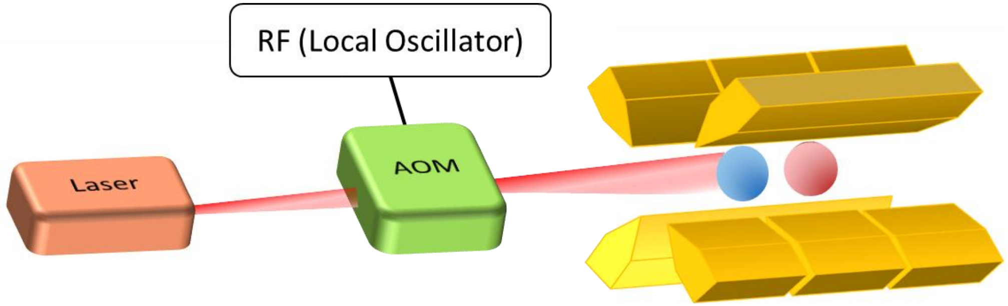
$$\psi\,(T) = |S\rangle|D'\rangle + e^{i2\pi\delta\nu T}|D\rangle|S'\rangle$$

Ramsey sequence:

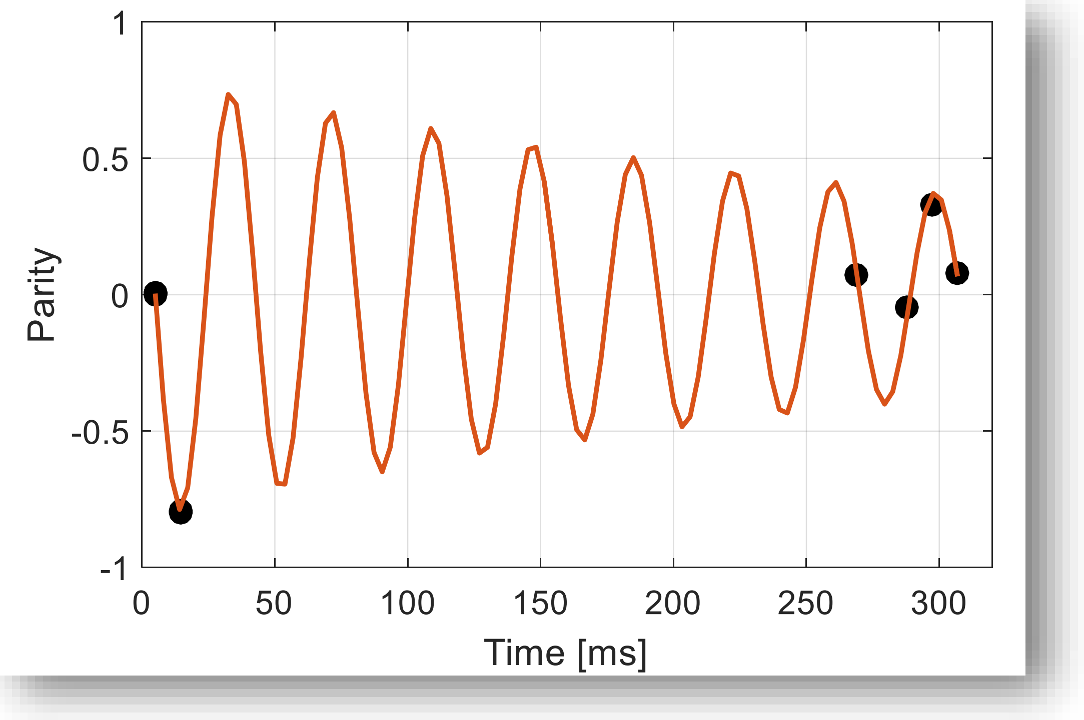


The Experiment Sequence - Entangled





$$Parity = P_{SS} + P_{DD} - (P_{DS} + P_{SD})$$

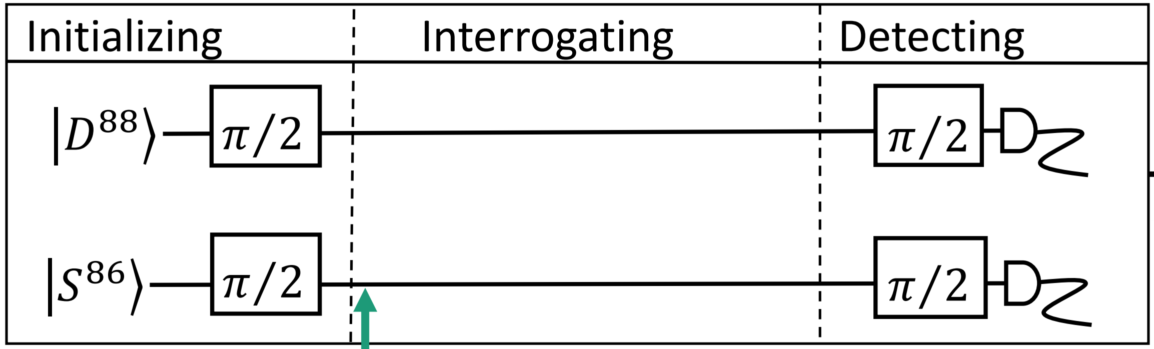


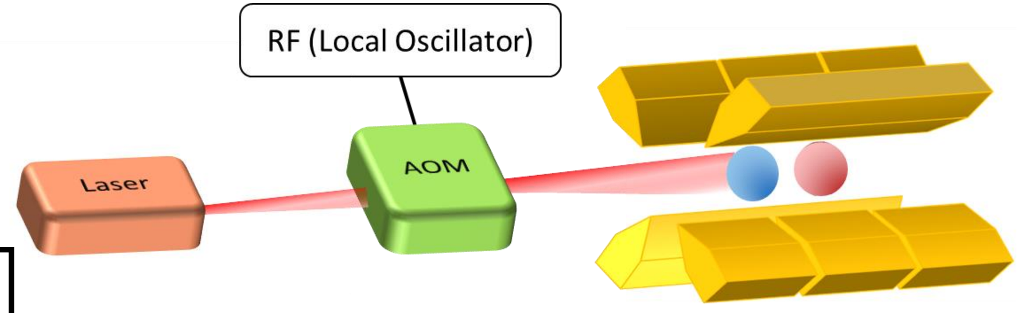
1 $\psi(T) = (|S^{88}\rangle|D^{86}\rangle|0\rangle$

2 $\psi(T) = 1/\sqrt{2}(|S^{88}\rangle|0\rangle + |D^{88}\rangle|1\rangle)\ |S^{86}\rangle$

3 $\psi(T) = 1/\sqrt{2}(|S^{88}\rangle|D^{86}\rangle + e^{i2\pi\delta\nu T}|D^{88}\rangle|S^{86}\rangle)$

The Experimental Sequence - Separable



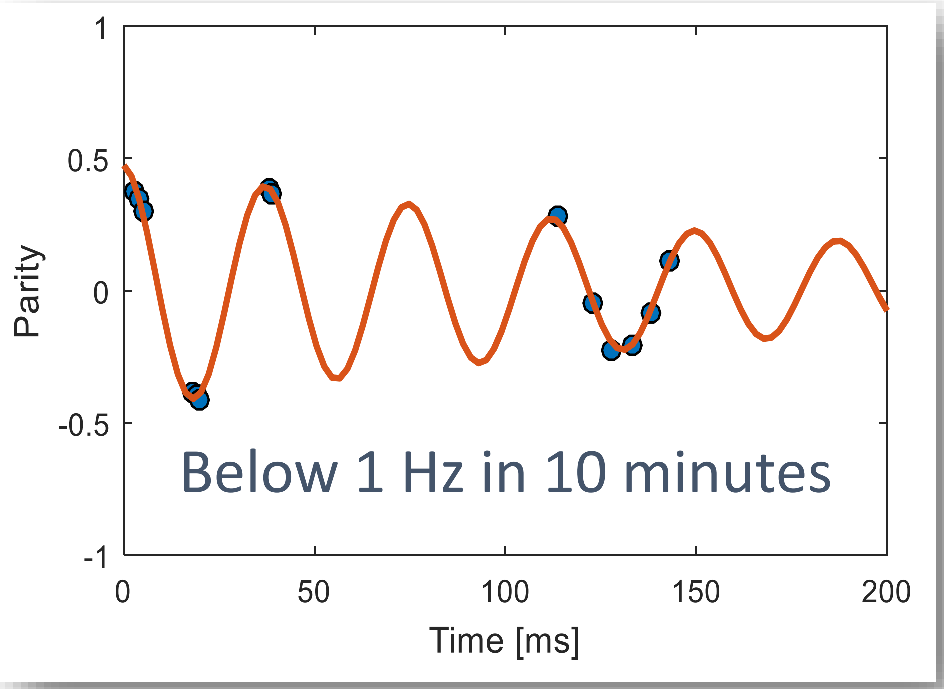


$$Parity = P_{SS} + P_{DD} - (P_{DS} + P_{SD})$$

$$\psi(T) = 1/2\,(|S^{88}\rangle|D^{86}\rangle + e^{i2\pi\delta\nu T}|D^{88}\rangle|S^{86}\rangle$$

$$+e^{-i\phi(T)}\,|S^{88}\rangle|S^{86}\rangle + e^{i\phi(T)}|D^{88}\rangle|D^{86}\rangle)$$

Average to zero in the Parity signal



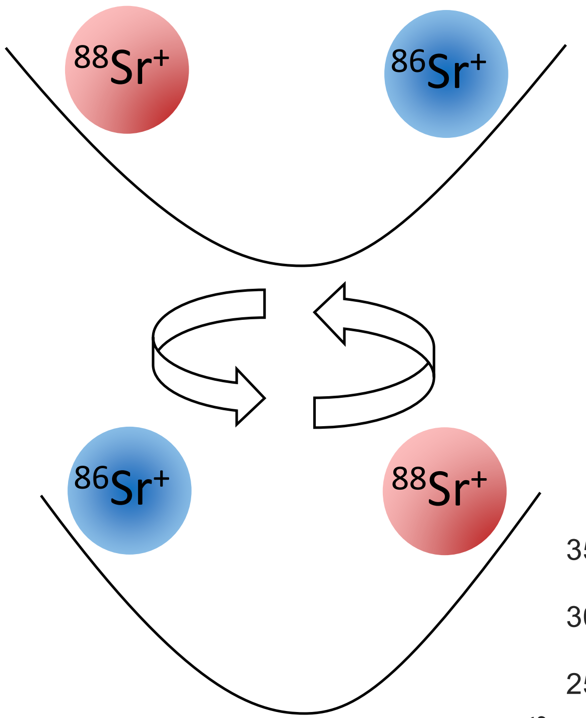
Chwalla et al. Applied Physics B 89,4 (2007)
Pruttivarasin et al. Nature 517, 592-595 (2015)

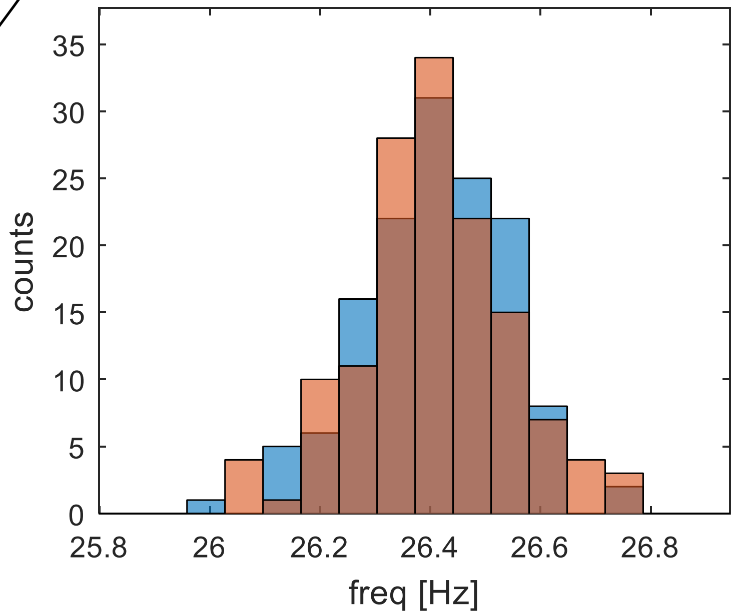
Systematic Uncertainties

- ➢ Common mode rejection:
  - Common Magnetic field noise
  - Quadruple shift (for only two ions)
  - Blackbody radiation

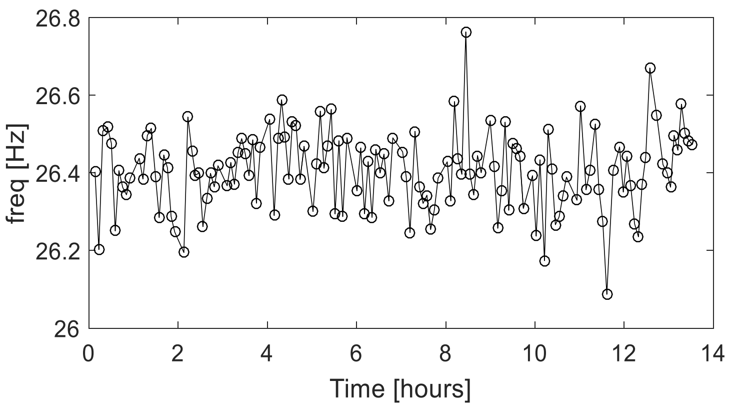
- ➢ Spatial Inhomogeneity :
  - Magnetic field gradient
  - Micromotion :
    - Second order Doppler
    - ac stark shift

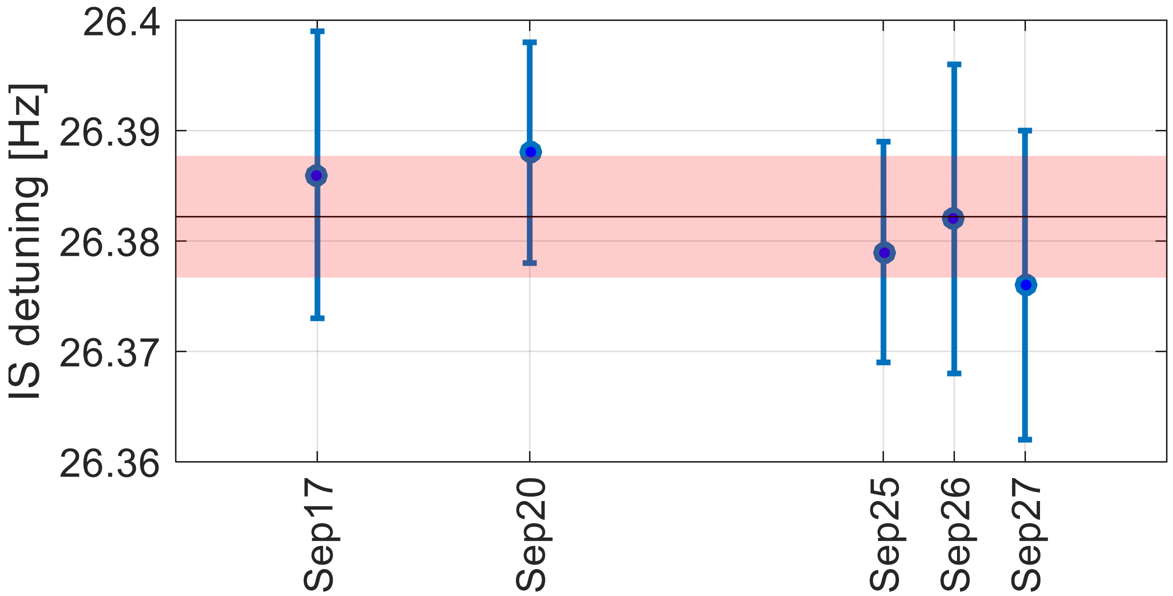
- ➢ Light shift (laser light leakage)
- ➢ g-factor ?

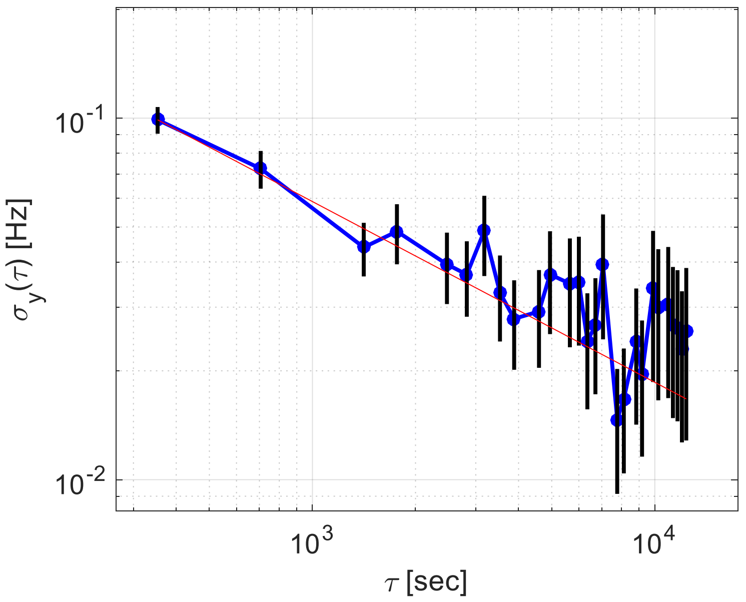




Preliminary Result





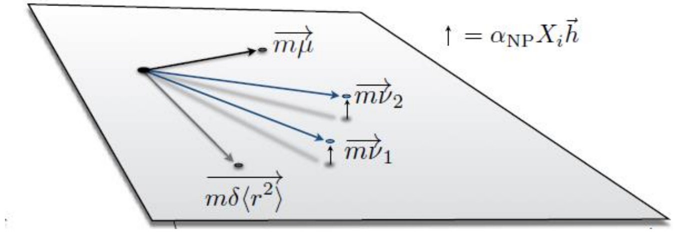


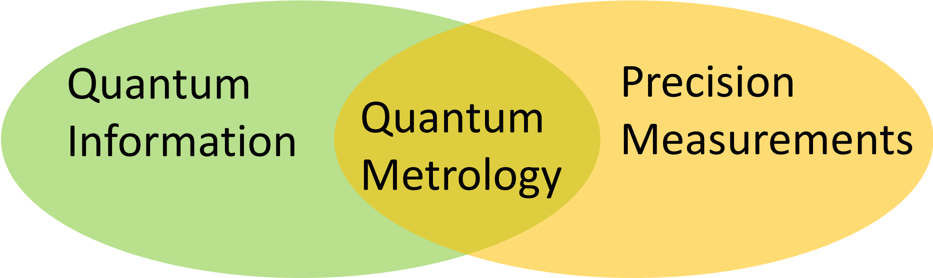
$$\Delta\nu^{88,86}_{S_{1/2},D_{5/2}} = \mathit{570{,}264{,}116.382}\ (\pm 0.005\ \text{stat.})\ [\text{Hz}]$$

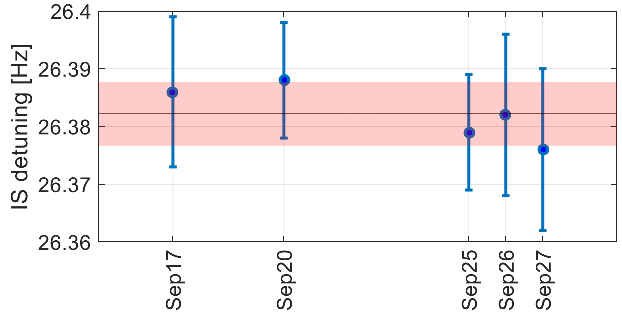
systematic ?

Summary

- King plot linearity has the potential to bound new physics
- Isotope shift can be measured with very high precision (relatively easy in trapped ions)







- Future plans:
  - Measuring King plot for the two E2 transitions is Yb^+ (Ca+)
  - For Strontium we need the fourth isotope ^{90}Sr
  - Measuring the isotope g-factor

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Precision mass measurements: 10^{-10}

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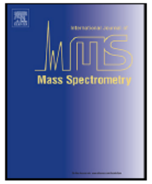

The most precise atomic mass measurements in Penning traps

Edmund G. Myers*

Florida State University, Department of Physics, Tallahassee, FL 32306-4350, USA

Table 10
Atomic masses of the most abundant isotopes of strontium and ytterbium measured at FSU [109].

Atom	FSU mass (u)	σ_m/m (ppt)
^{86}Sr	85.909 260 730 9(91)	105
^{87}Sr	86.908 877 497 0(91)	105
^{88}Sr	87.905 612 257 1(97)	110
^{170}Yb	169.934 767 241(18)	105
^{171}Yb	170.936 331 514(19)	110
^{172}Yb	171.936 386 655(18)	105
^{173}Yb	172.938 216 213(18)	105
^{174}Yb	173.938 867 539(18)	105
^{176}Yb	175.942 574 702(22)	125