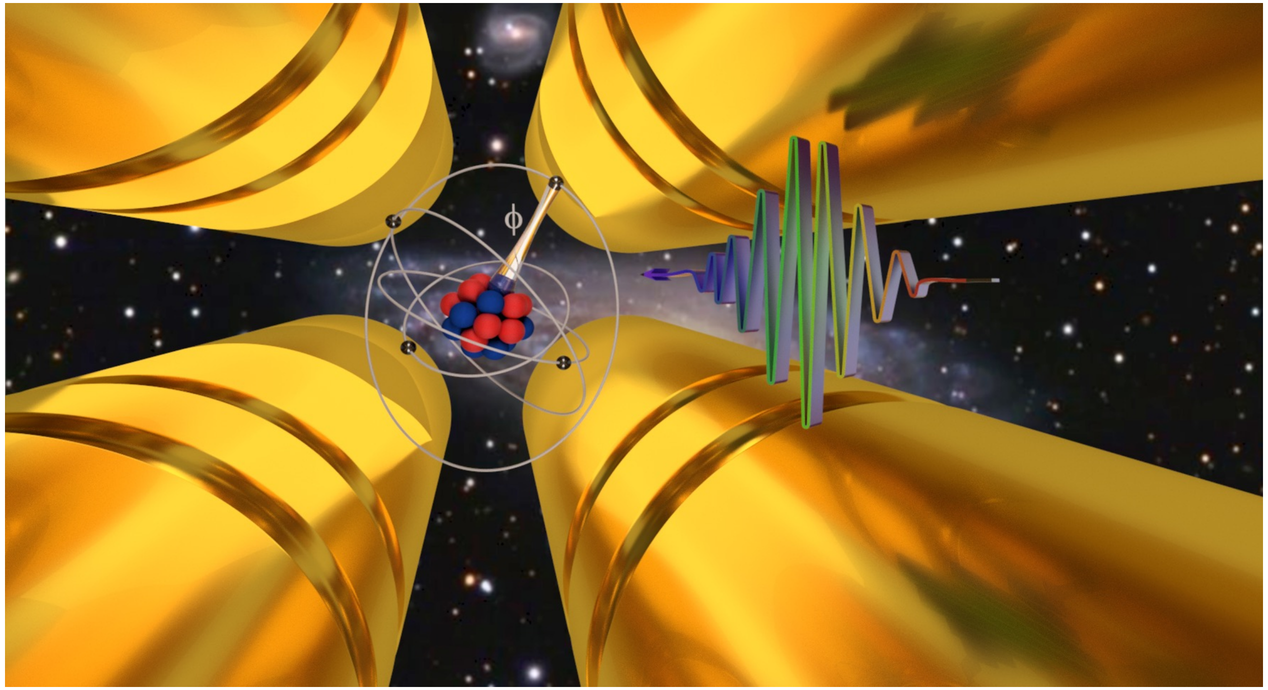
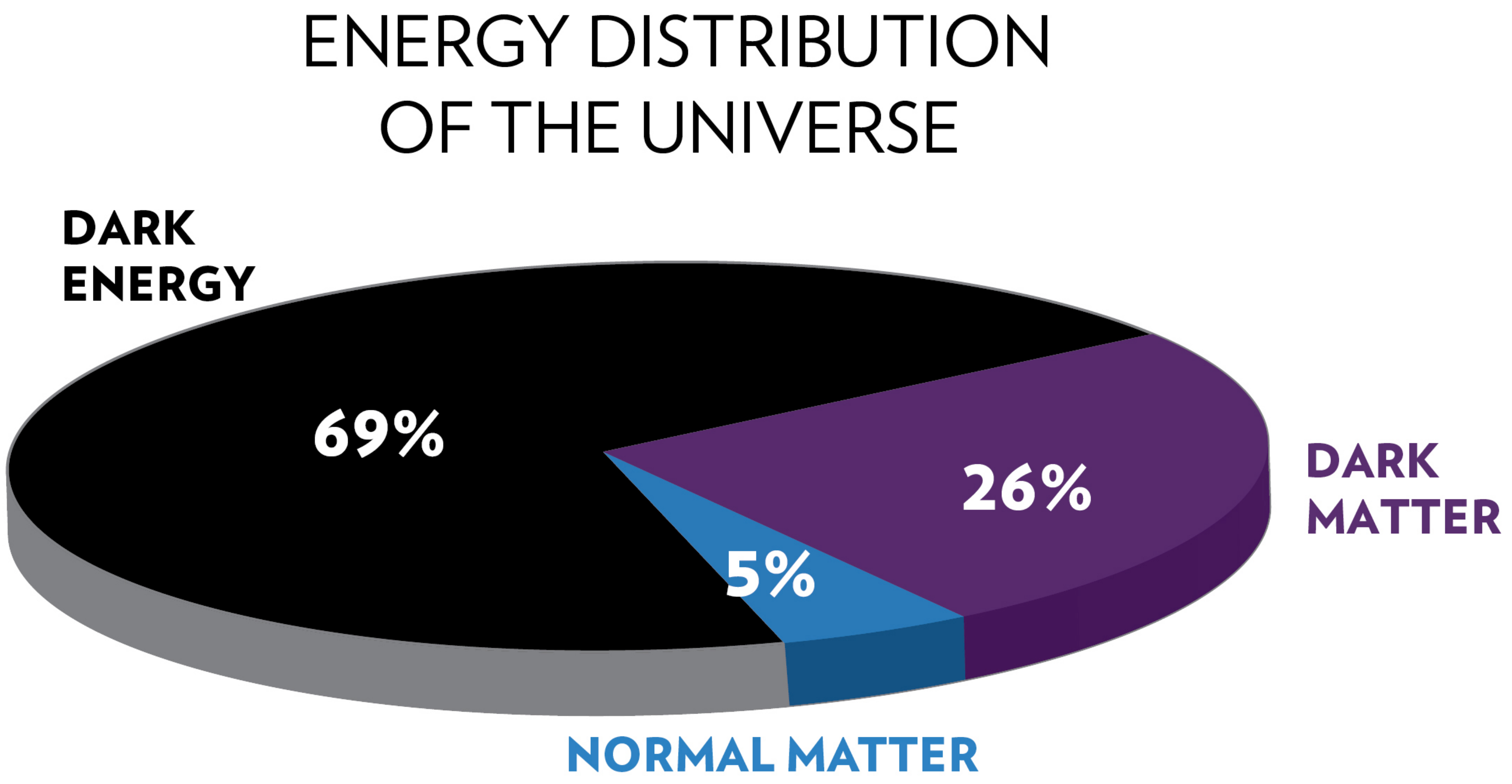
Search for bosons beyond the Standard Model with atoms through precise isotope shift measurements in Ca^+



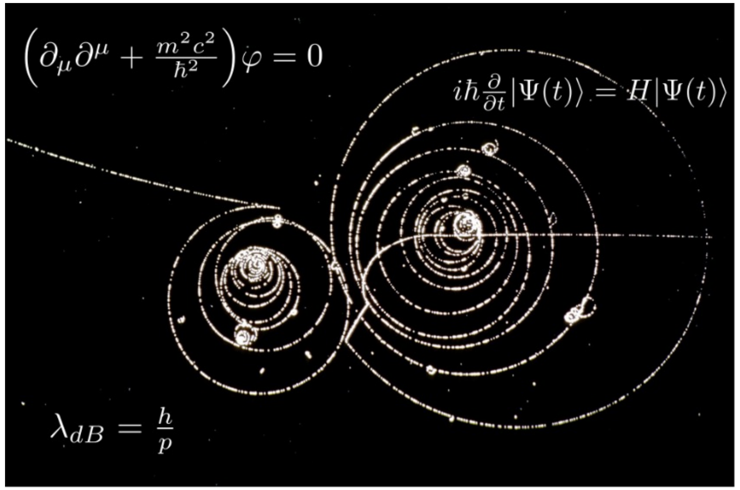
Michael Drewsen
The Ion Trap Group – Center for Complex Quantum Systems
Department of Physics and Astronomy
Aarhus University

International Symposium on Stored Ions for Precision Measurements
Fudan University, Shanghai, China, November 23, 2023

Our understanding of the universe at present

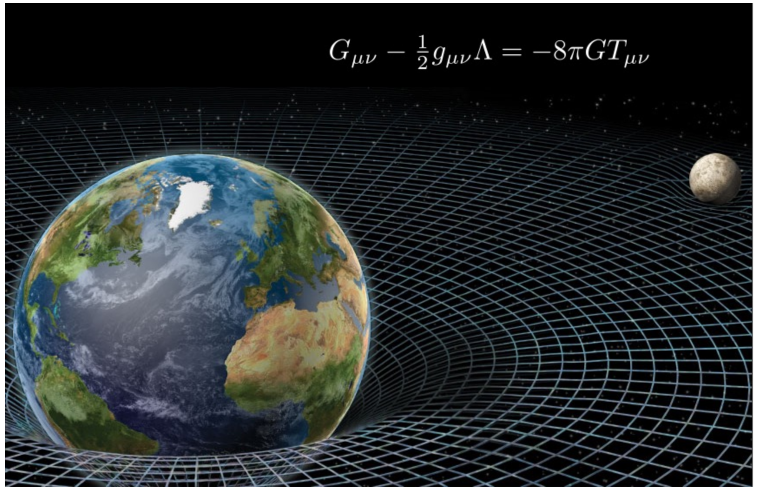


Our understanding of the universe at present



Standard Model of particle physics
Electromagnetic, Weak, Strong interaction
(photons, bosons Z^0&$W^\pm$, gluons)

Currently incompatible

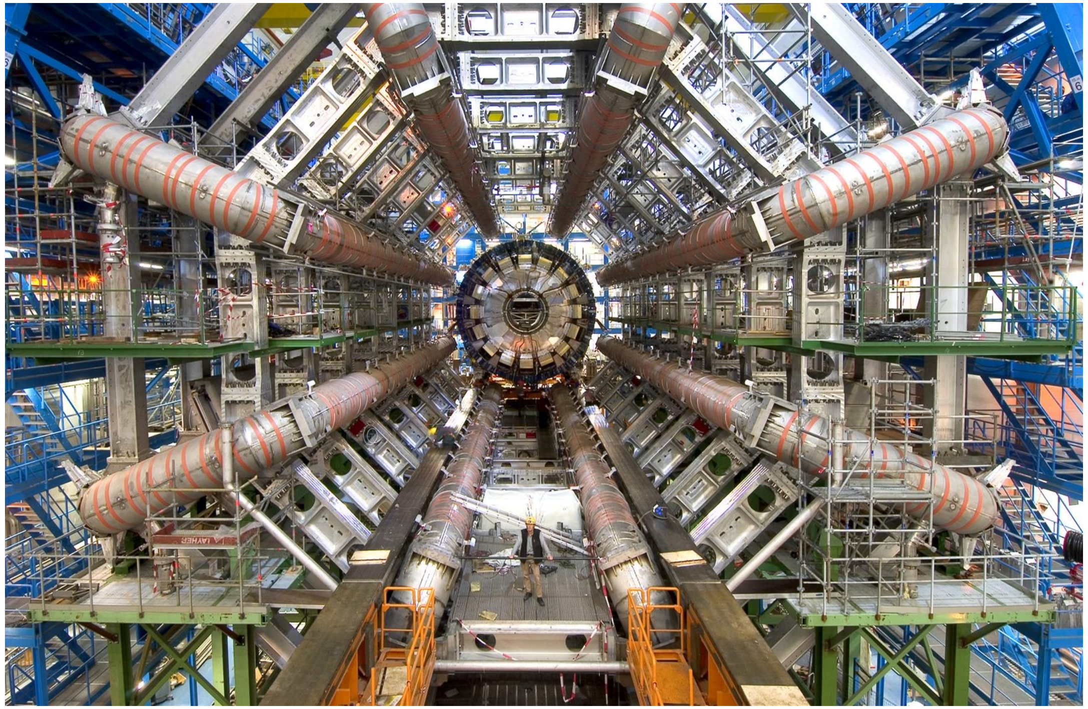


General Relativity
Gravitational interaction

Unifying theories => new particles responsible for so far unknown interactions

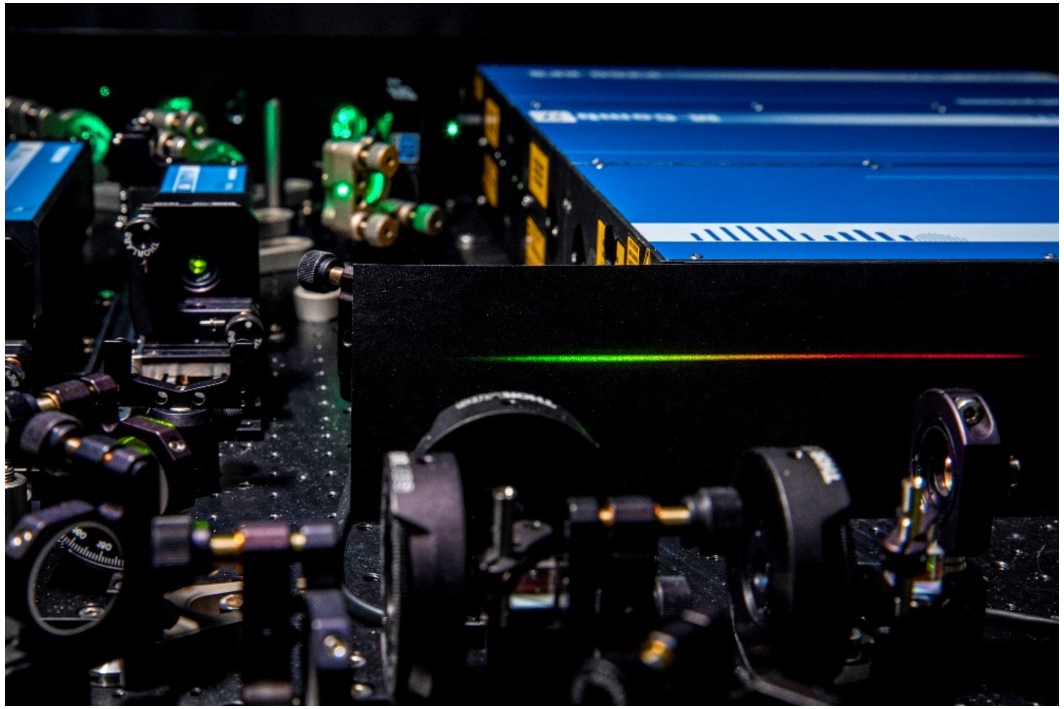
Searching for new physics

Particle accelerators: high energy collisions (GeV – TeV)



The ATLAS experiment at CERN. (Image: Maximilien Brice/CERN)

Table-top experiments: high precision measurements at low energies (< 10 MeV)



Optical Frequency comb used for our high-resolution spectroscopy of Ca^+

Complementary approaches

Searching for new physics

PHYSICAL REVIEW LETTERS **120,** 091801 (2018)

Probing New Long-Range Interactions by Isotope Shift Spectroscopy

Julian C. Berengut,[1,*] Dmitry Budker,[2,3,4,†] Cédric Delaunay,[5,‡] Victor V. Flambaum,[1,§] Claudia Frugiuele,[6,∥] Elina Fuchs,[6,¶] Christophe Grojean,[7,8,**] Roni Harnik,[9,††] Roee Ozeri,[10,‡‡] Gilad Perez,[6,§§] and Yotam Soreq[11,∥∥]

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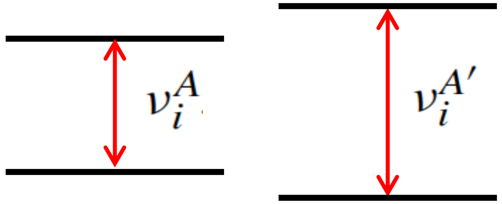
(Received 22 May 2017; revised manuscript received 20 September 2017; published 26 February 2018)

We explore a method to probe new long- and intermediate-range interactions using precision atomic isotope shift spectroscopy. We develop a formalism to interpret linear King plots as bounds on new physics with minimal theory inputs. We focus only on bounding the new physics contributions that can be calculated independently of the standard model nuclear effects. We apply our method to existing Ca^+ data and project its sensitivity to conjectured new bosons with spin-independent couplings to the electron and the neutron using narrow transitions in other atoms and ions, specifically, Sr and Yb. Future measurements are expected to improve the relative precision by 5 orders of magnitude, and they can potentially lead to an unprecedented sensitivity for bosons within the 0.3 to 10 MeV mass range.

King plot & isotope shifts within the Standard Model



Isotope Shift

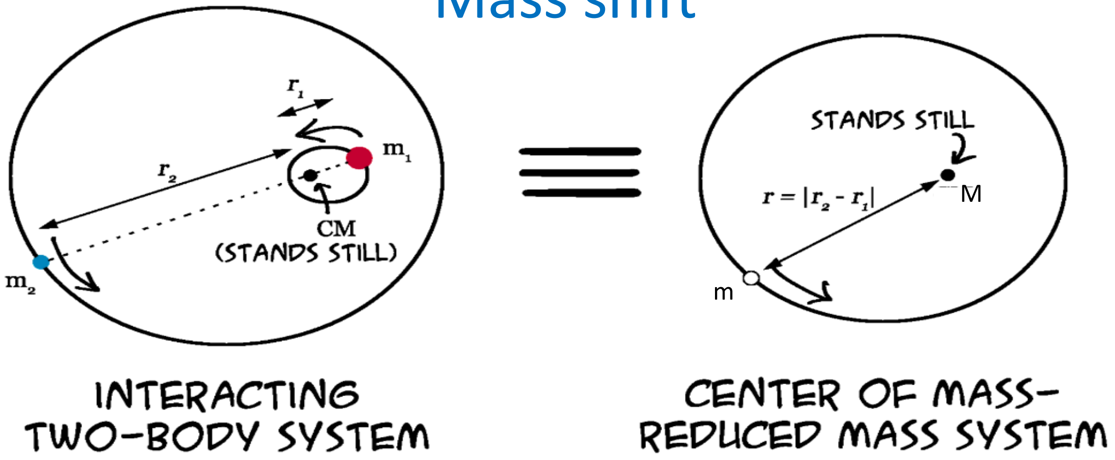
$$\delta\nu_i^{A,A'} = \nu_i^{A'} - \nu_i^{A}$$

$$\delta\nu_i^{A,A'} = K_i \frac{m_{A'} - m_A}{m_A \cdot m_{A'}} + F_i\, \delta\langle r_c^2 \rangle^{A,A'}$$

$1/\mu$ — Relative mass change

Mean charge radius

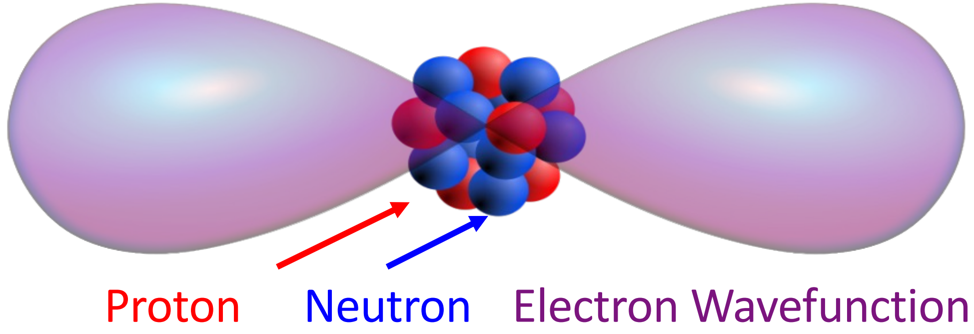
Mass shift



King plot: use two transitions i and j

$$\mu\delta\nu_i^{AA'} = K_i - \frac{F_i}{F_j} K_j + \frac{F_i}{F_j}\, \mu\delta\nu_j^{AA'}$$

Field shift



Leading order prediction !

King Plot and the search for new physics

PHYSICAL REVIEW LETTERS **120,** 091801 (2018)

Probing New Long-Range Interactions by Isotope Shift Spectroscopy

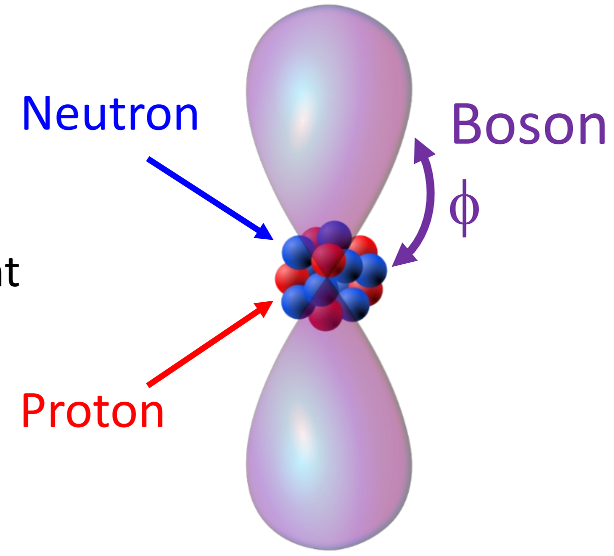
Julian C. Berengut,[1,*] Dmitry Budker,[2,3,4,†] Cédric Delaunay,[5,‡] Victor V. Flambaum,[1,§] Claudia Frugiuele,[6,∥] Elina Fuchs,[6,¶] Christophe Grojean,[7,8,**] Roni Harnik,[9,††] Roee Ozeri,[10,‡‡] Gilad Perez,[6,§§] and Yotam Soreq[11,∥∥]

New Physics Coupling constant — Transition dependent — Isotope dependent

$$\delta\nu_i^{A,A'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + \alpha_{\rm NP} X_i\,\gamma_{AA'}$$

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

=> Non-linear King plot



Electron Wavefunction

King plot and the search for new physics

What species to use?

$$\delta\nu_i^{A,A'} = \boxed{K_i\,\mu_{AA'}} + \boxed{F_i\,\delta\langle r^2\rangle_{AA'}} + \boxed{\alpha_{\rm NP} X_i\,\gamma_{AA'}}$$

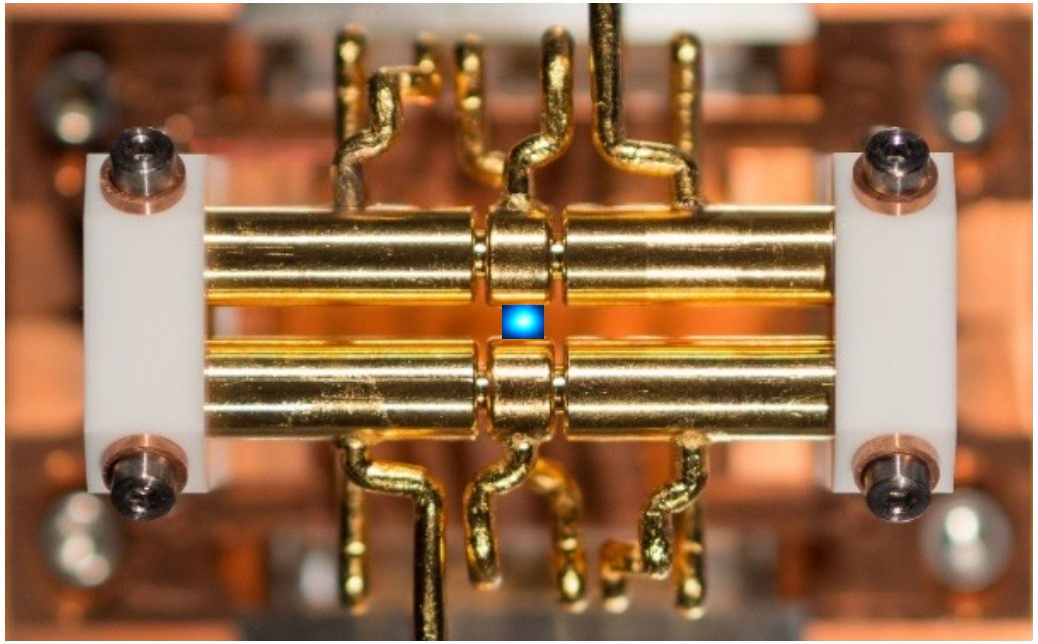
Single atomic ions:
- Long interrogation times
- Good shielding from environment

Candidate-elements
- Many stable isotopes (at least four)
- Preferably no hyperfine structure
- Narrow transitions

~~$^{9}Be^{+}$~~ ~~$^{24,26}Mg^{+}$~~ ~~$^{84,86,88}Sr^{+}$~~

$^{40,42,44,46,48}Ca^{+}$ ~~$^{106,108,110,112,114,116}Cd^{+}$~~

$^{130,132,134,136,138}Ba^{+}$ $^{168,170,172,174,176}Yb^{+}$

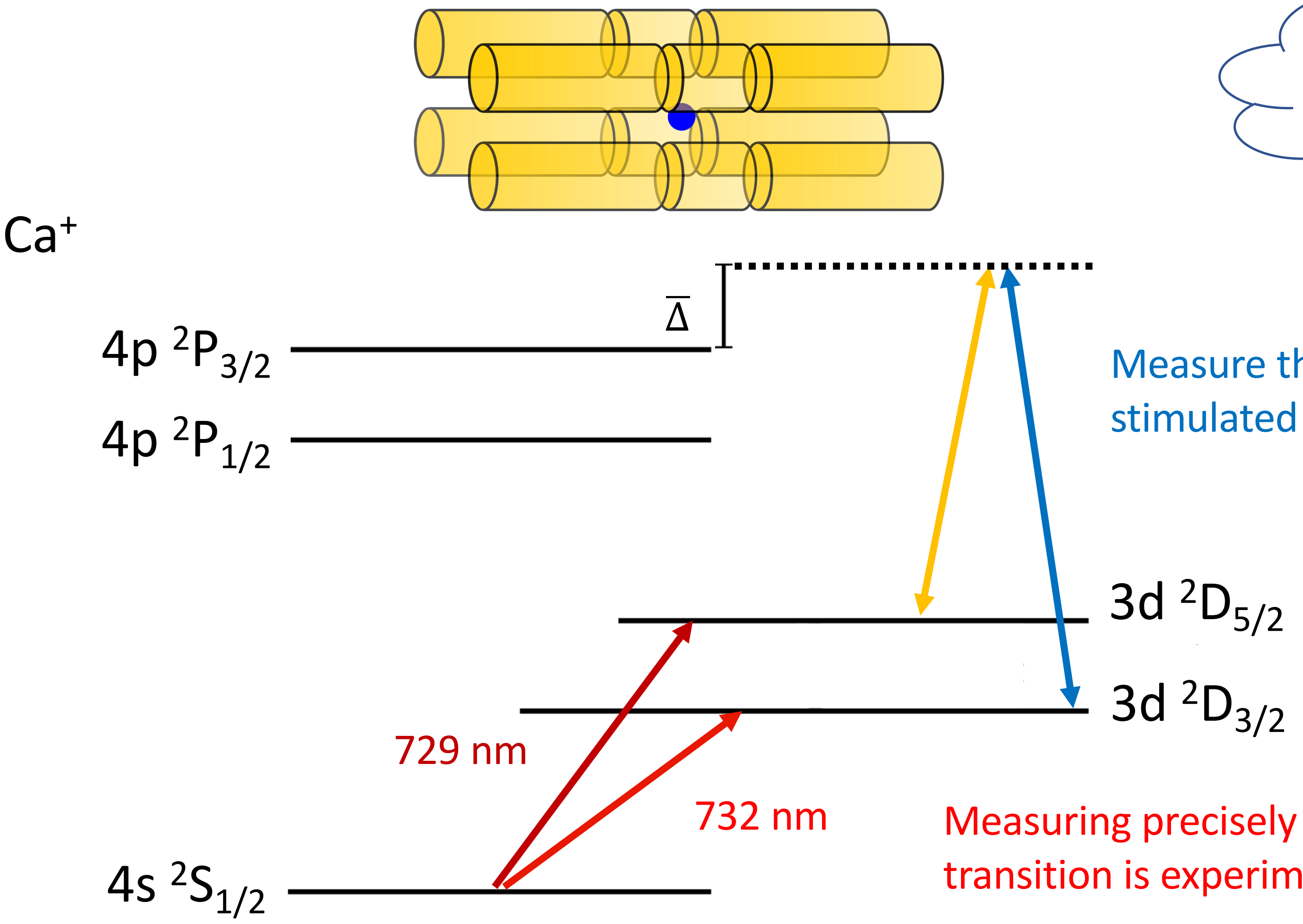


Linear Paul traps @ Aarhus University

Vuletic Group, MIT: PRL **125**, 123002 (2020);PRL **128**, 163201 (2022)

Relevant electronic levels and transitions of Ca^+

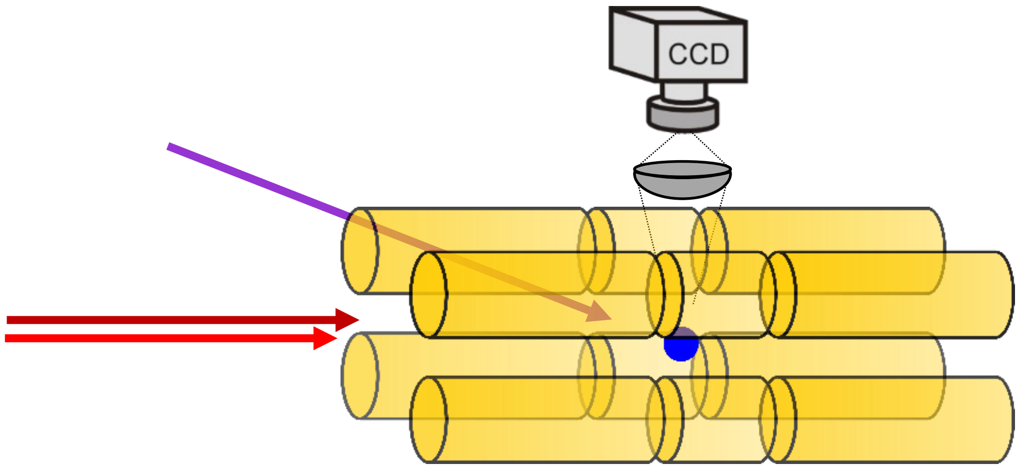
$$\mu\delta\nu_i^{AA'} = K_i - \frac{F_i}{F_j}K_j + \frac{F_i}{F_j}\mu\,\delta\nu_j^{AA'}$$



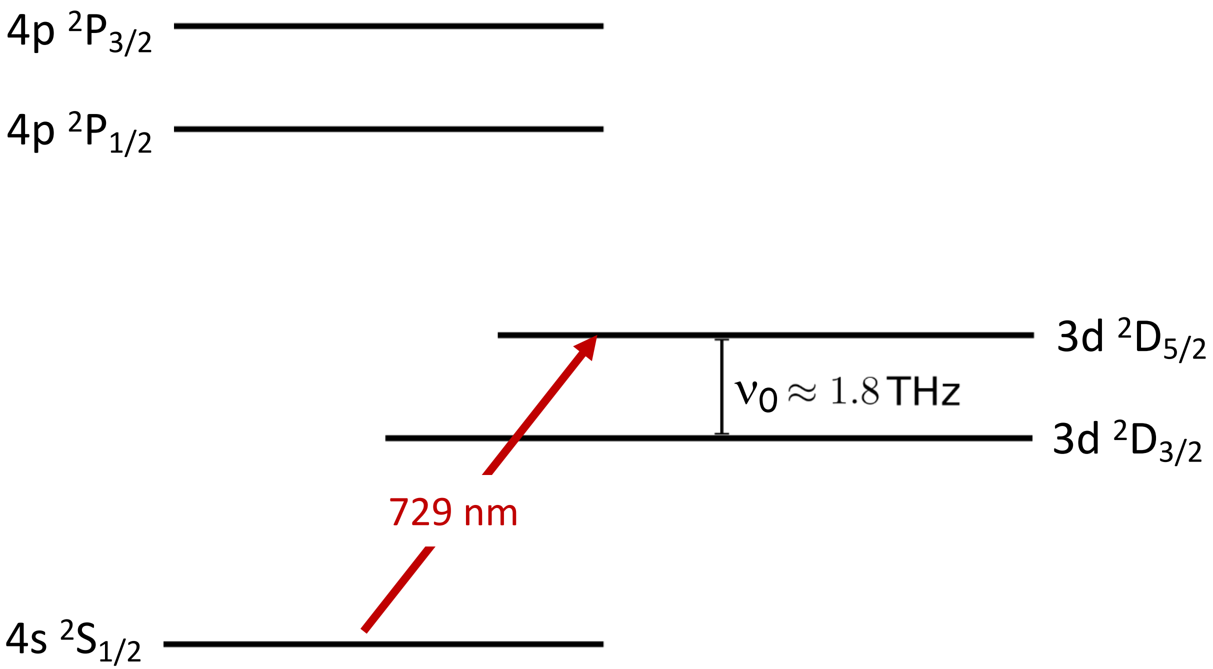
Measure the D-fine splitting with stimulated Raman spectroscopy

Measuring precisely the 732 nm transition is experimentally difficult.

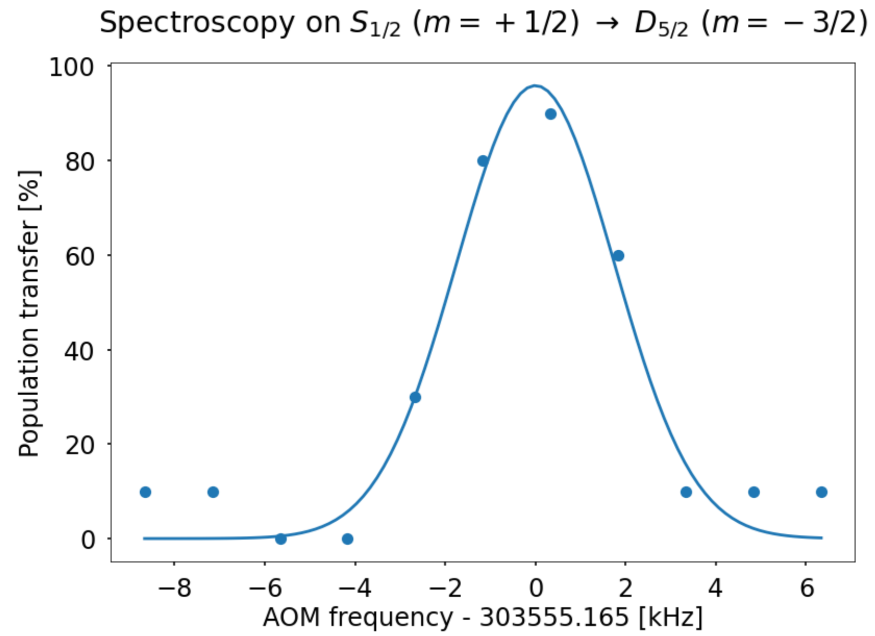
Measurement of the 729 nm transition



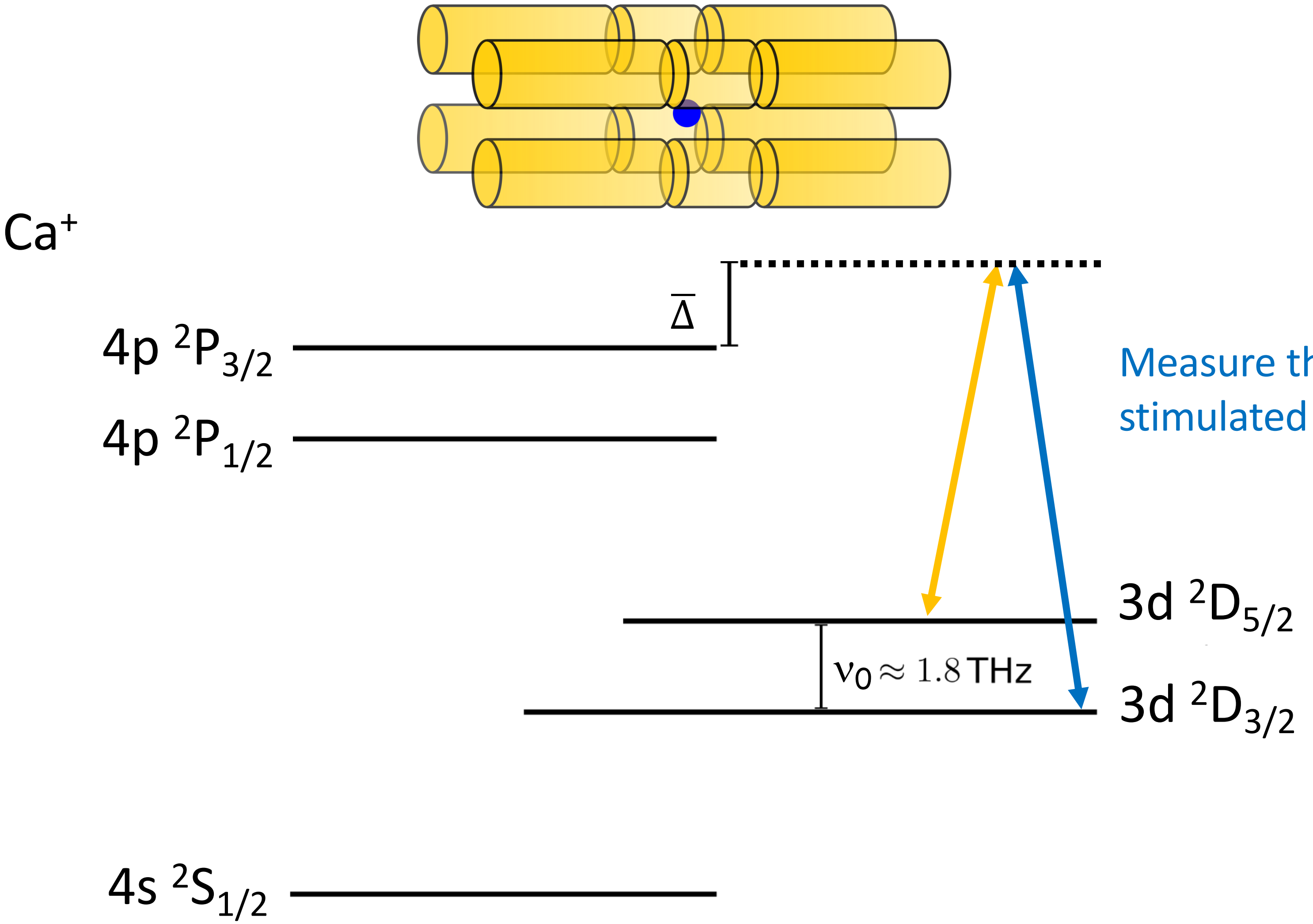
Ca$^+$



Accuracy:
~1 kHz



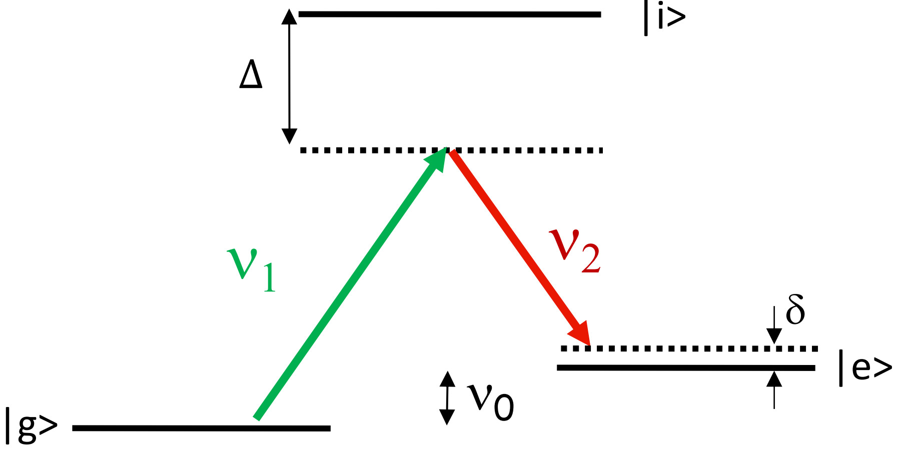
Measurement of the D-fine splitting



Measure the D-fine splitting with stimulated Raman spectroscopy

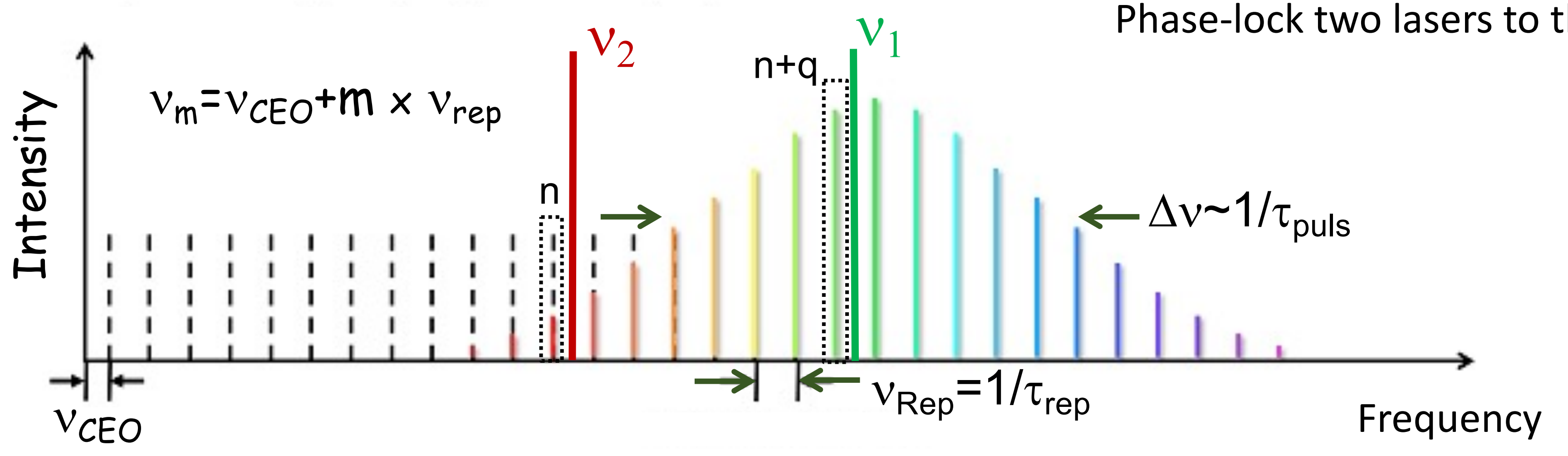
Optical frequency comb for Raman spectroscopy

Raman transition:



$$\nu_1 - \nu_2$$
$$= q \times \nu_{Rep}$$
$$+ (\nu_1 - \nu_{n+q})$$
$$- (\nu_2 - \nu_n)$$

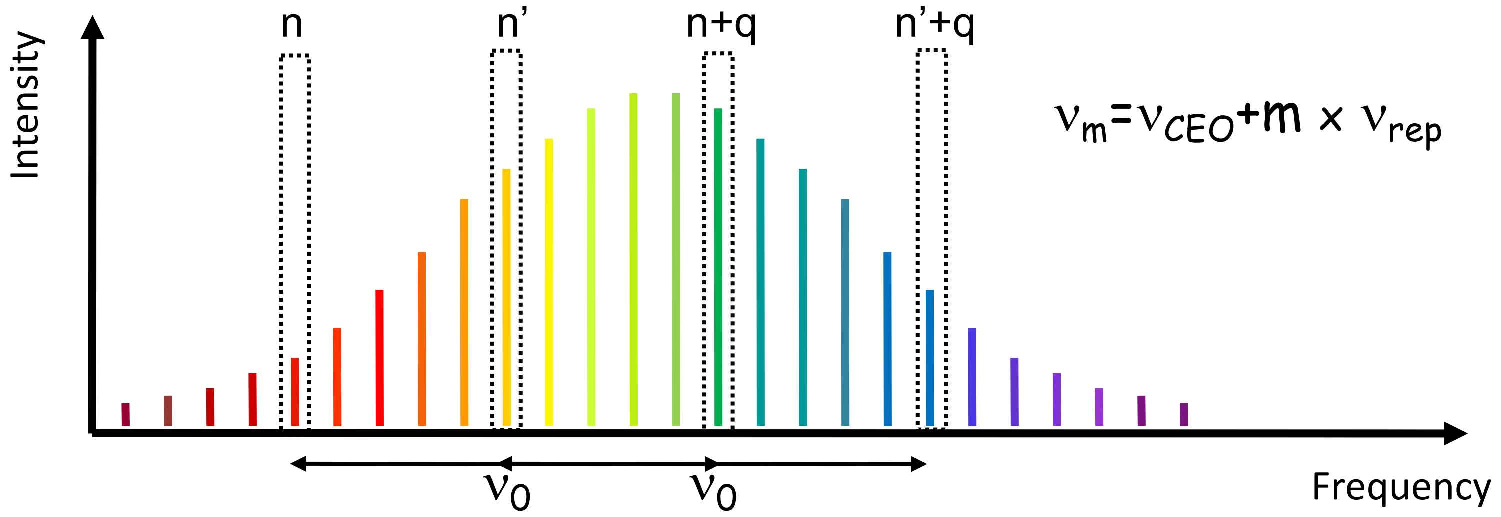
Optical Frequency comb:



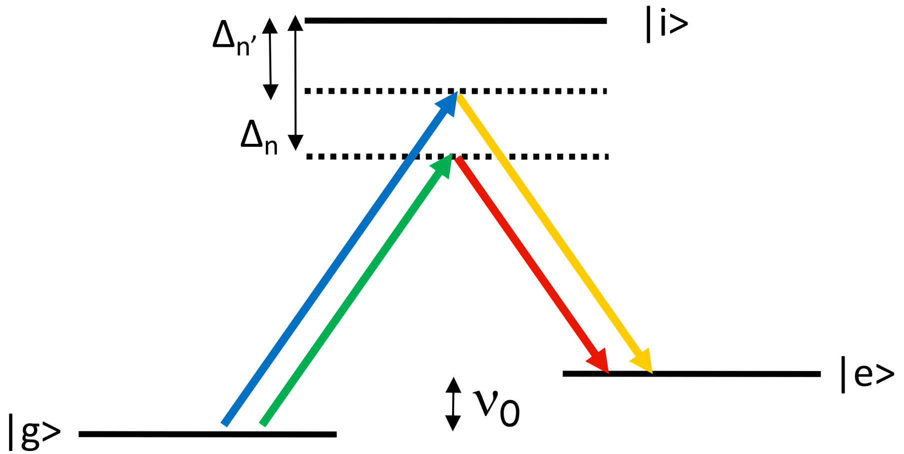
<u>Traditionally:</u>

Phase-lock two lasers to the comb

Direct frequency comb driven Raman transitions



If $\nu_0=q \times \nu_{rep}$:



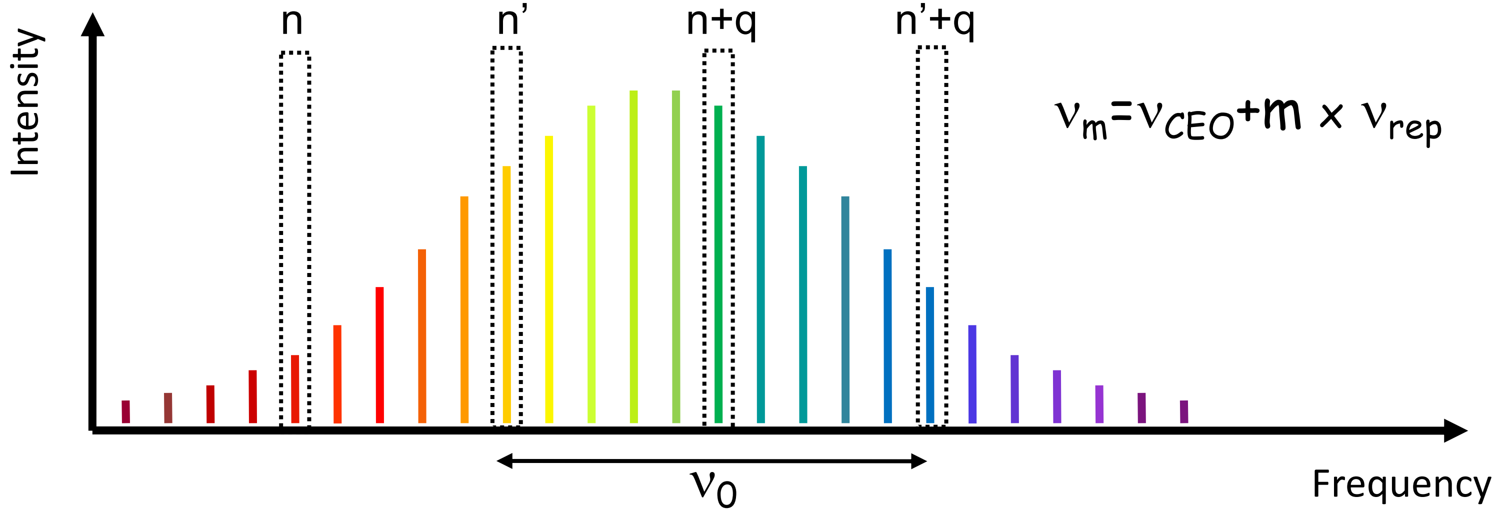
I) *No* dependence on ν_{CEO}

II) *All* pairs separated by *q* are resonant

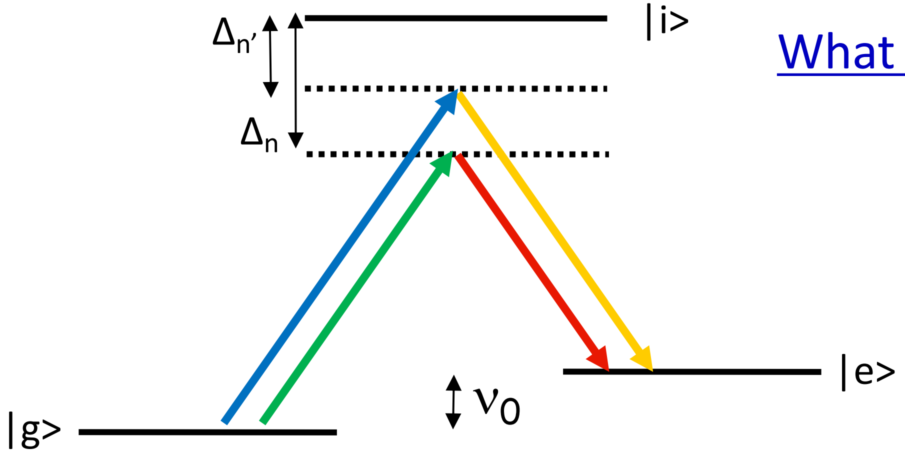
III) *All* Raman transitions from ν_{rep} to ~10 THz possible

Previously demonstrated in the *10GHz* range with a *picosecond* frequency comb by Chris Monroe's group: PRL **104**, 140501 (2010).

Direct frequency comb driven Raman transitions



If $\nu_0 = q \times \nu_{rep}$:



What is the Raman Rabi frequency?

$$\Omega_{Raman} = \sum_m \frac{\Omega_m \Omega_{m-q}}{\Delta_m} e^{i\varphi_{m,m-q}}$$

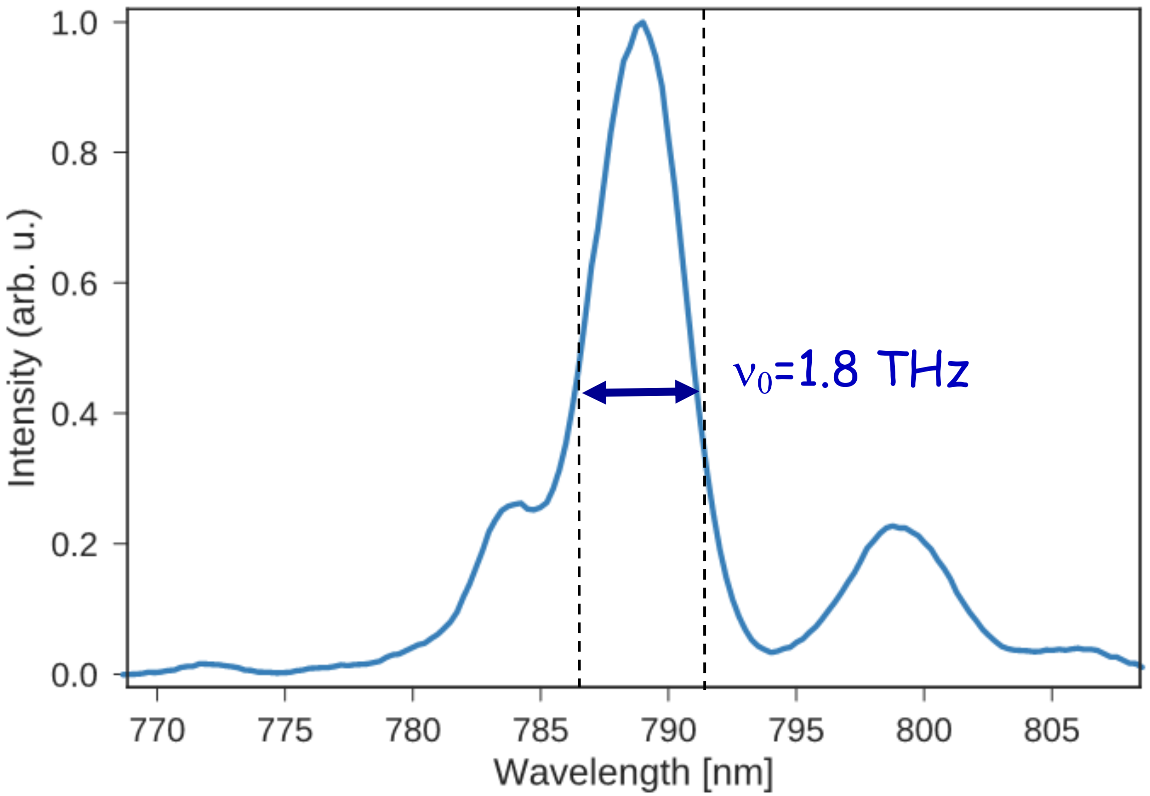
Optimal when constant !!

Measurement of the D-fine splitting

Frequency comb spectrum

Menlo-comb

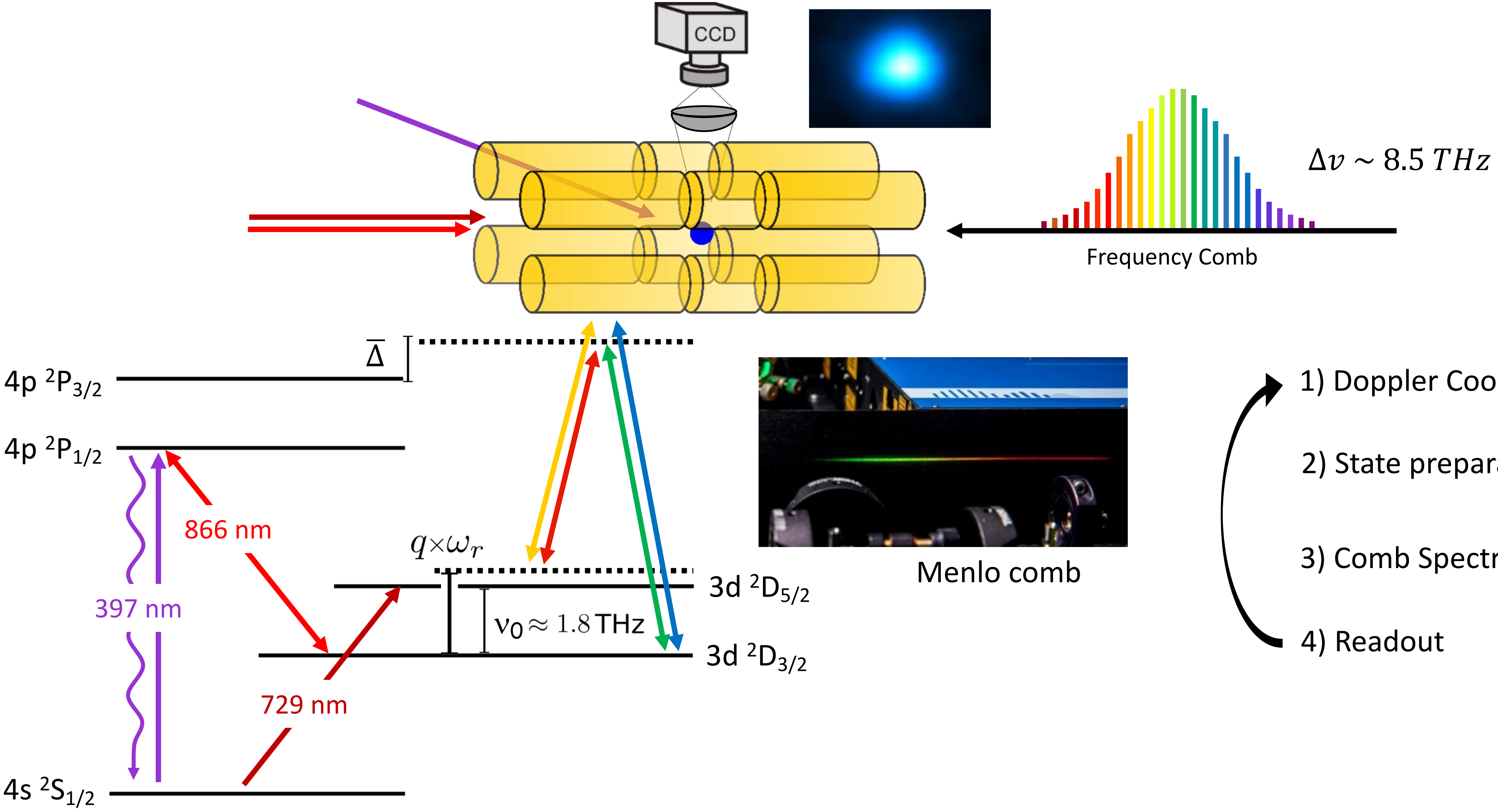
ν_{rep}=250 MHz



ν_0=1.8 THz

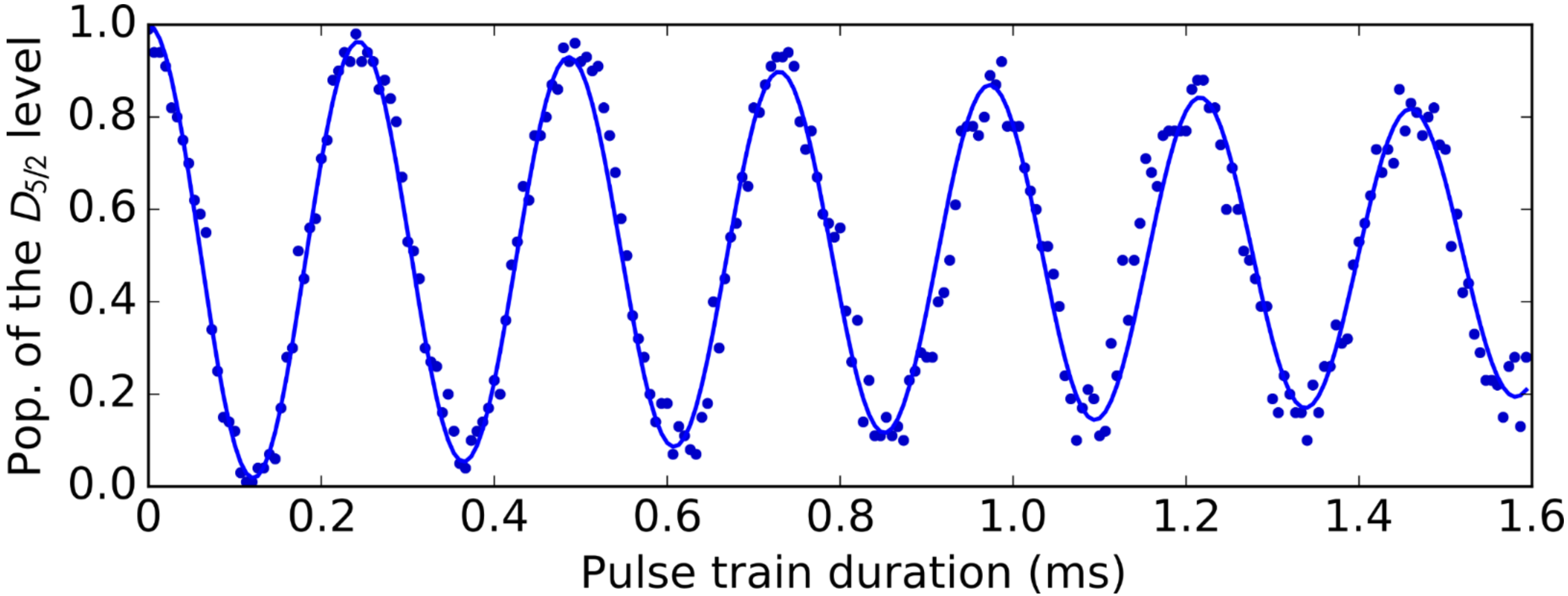
Far from a "perfect" spectrum !

Measurement of the D-fine splitting



1) Doppler Cooling
2) State preparation
3) Comb Spectroscopy
4) Readout

Raman Rabi oscillations



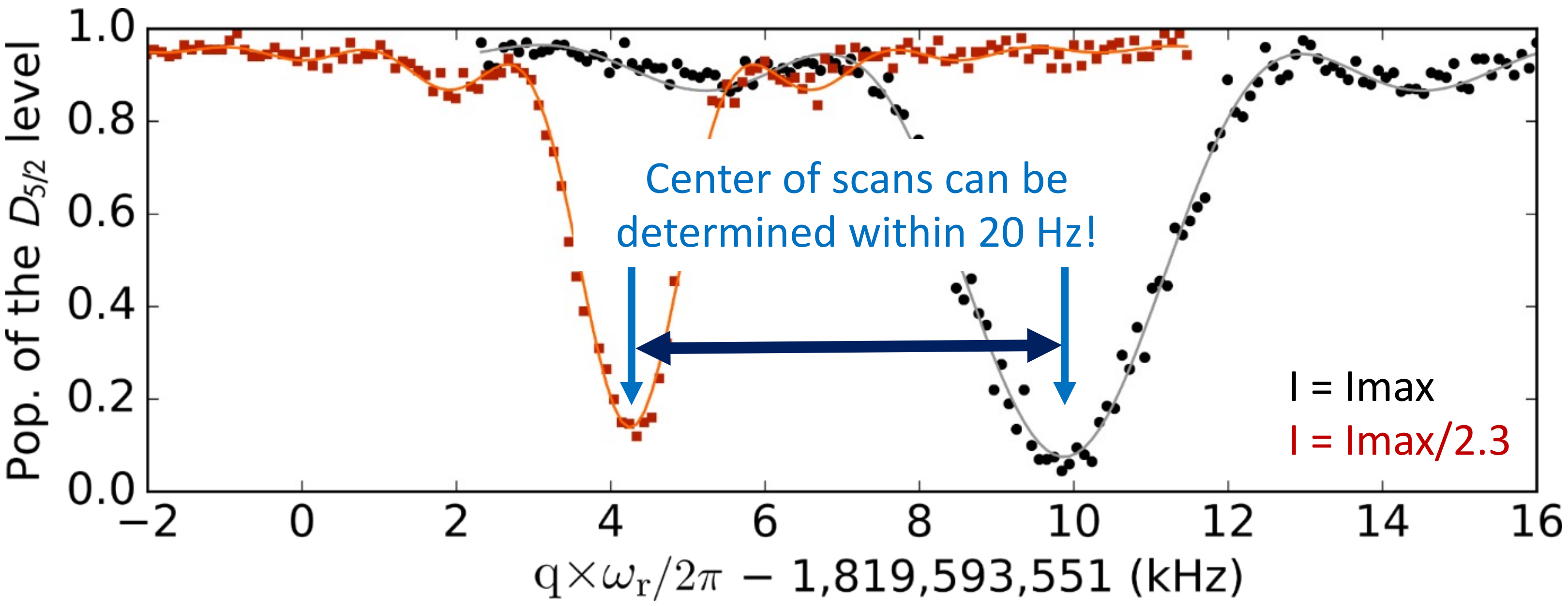
99% transfer efficiency! ☺

Coherence over ms timescale! ☺

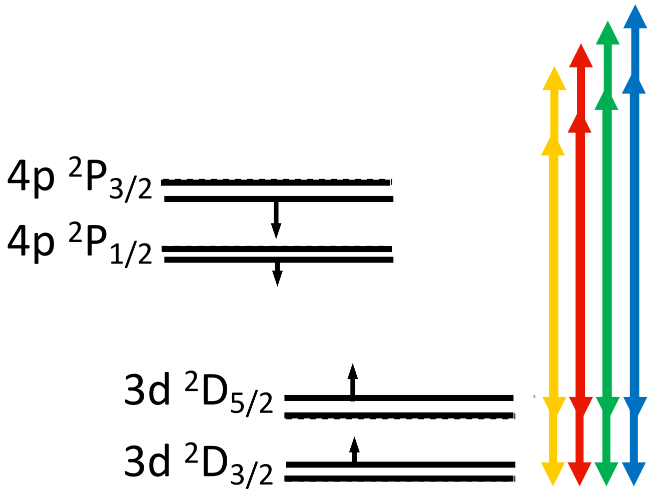
Relatively low Raman Rabi frequency (4 kHz) ☺ For spectroscopy

$$\Omega_{Raman} = \sum_m \frac{\Omega_m \Omega_{m-q}}{\Delta_m} e^{i\varphi_{m,m-q}}$$

Raman Spectroscopy



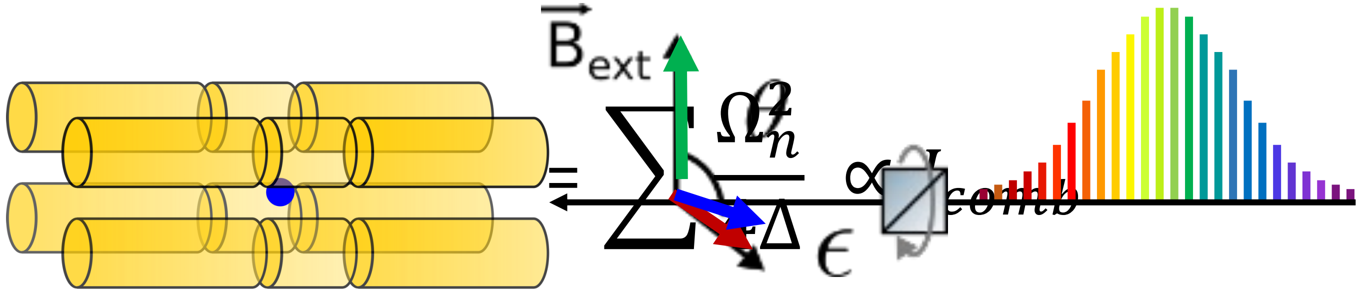
AC-Stark shifts of the P and D states due to the off-resonant comb light:



Systematic errors

$$\delta\nu_{AC} = \sum \frac{\Omega_n^2}{4\Delta} \propto I_{comb}$$

Magic polarization



Solution:

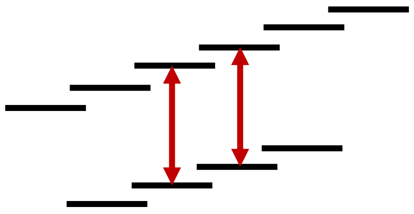
Vary the frequency comb's intensity to extrapolate to zero laser intensity

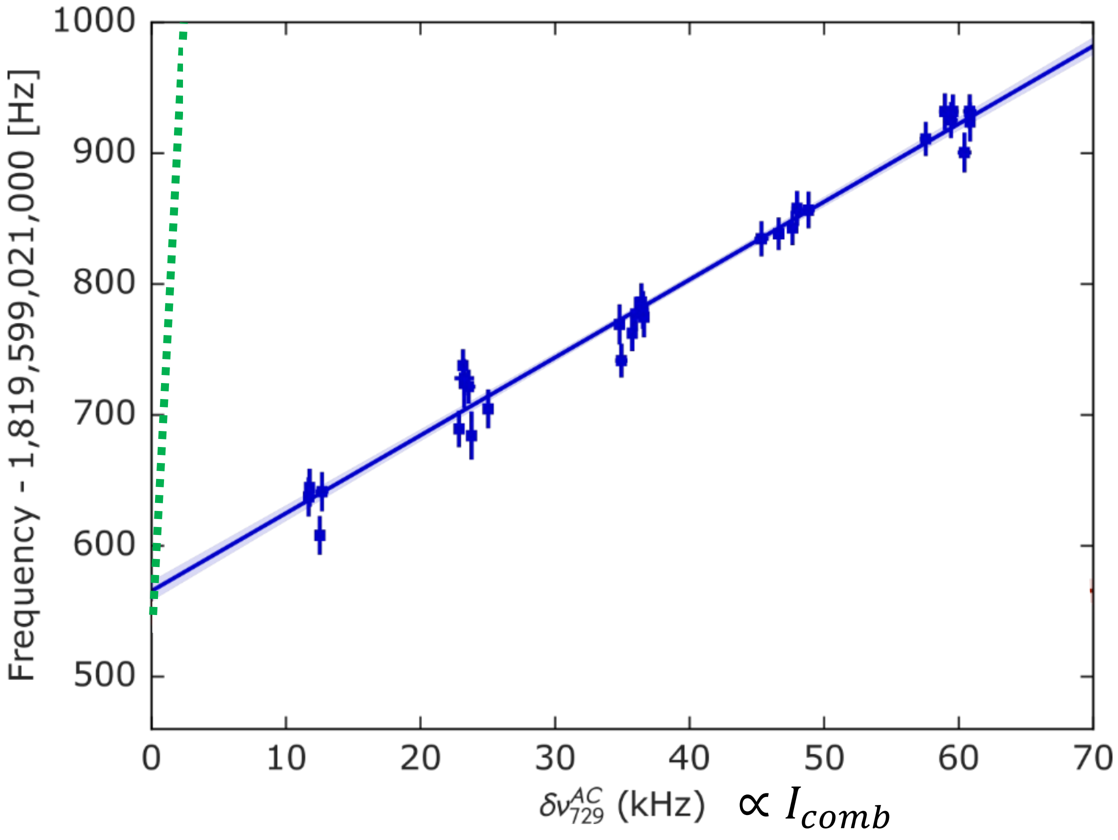
Important:

For some transitions, there exist a "magic" polarization for which the differential AC-Stark shift becomes zero!

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

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





5.5 x 10^{-12} statistical uncertainty limited by our clock inaccuracy

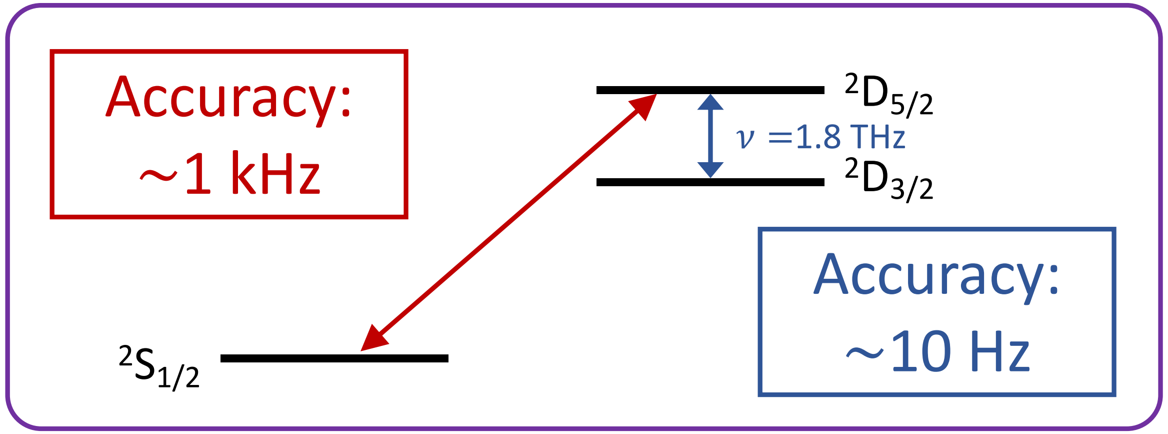
$^{40}Ca^+$: 1,819,599,021,534 (8) Hz

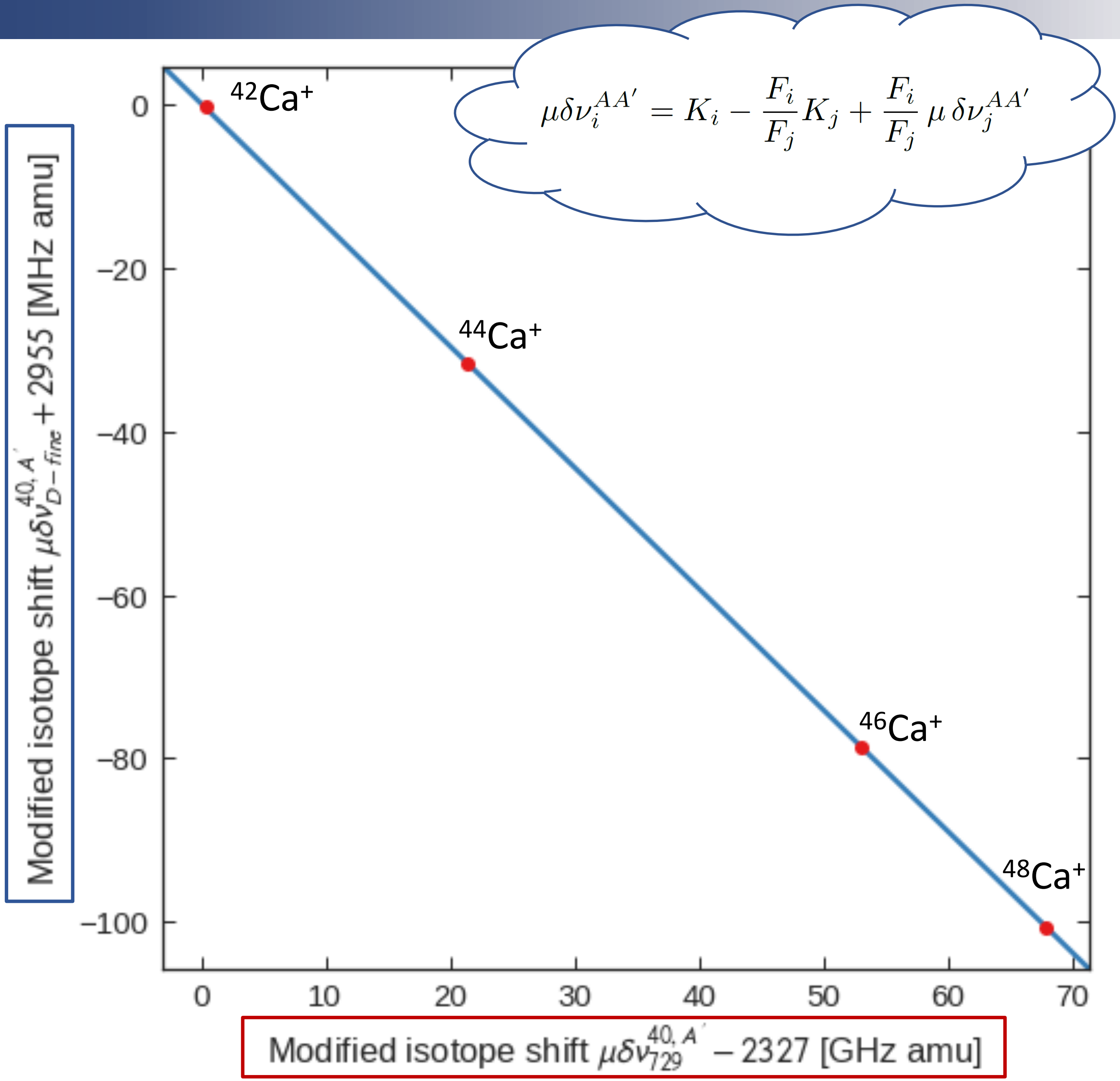
1,819,599,021,504 (37) Hz

Yamazaki *et al*. PRA **77**, 012508 (2008)

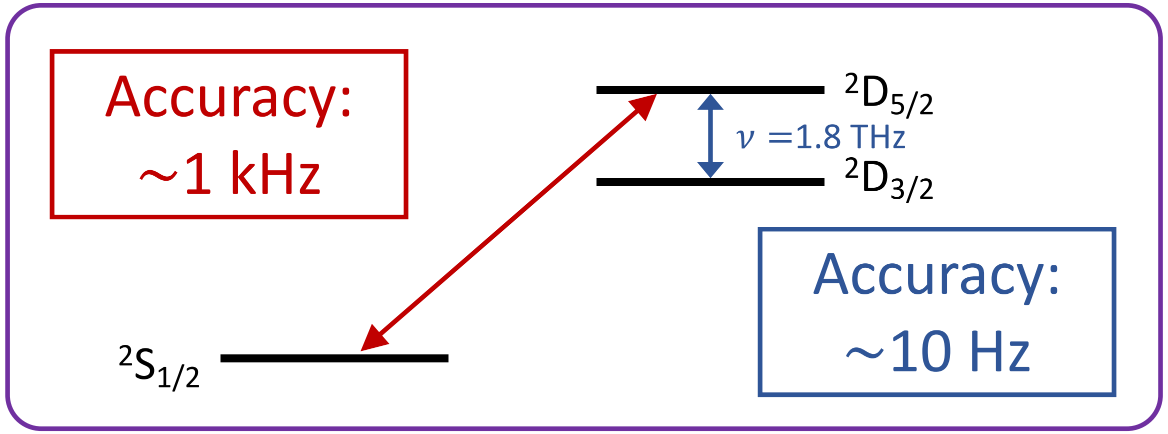
C. Solaro *et al*. PRL **120**, 253601, (2018)

Is the King Plot non-linear?





Is the King Plot non-linear?



F_{DSIS}/F_{729} = -1,48305(20)x10^{-3}

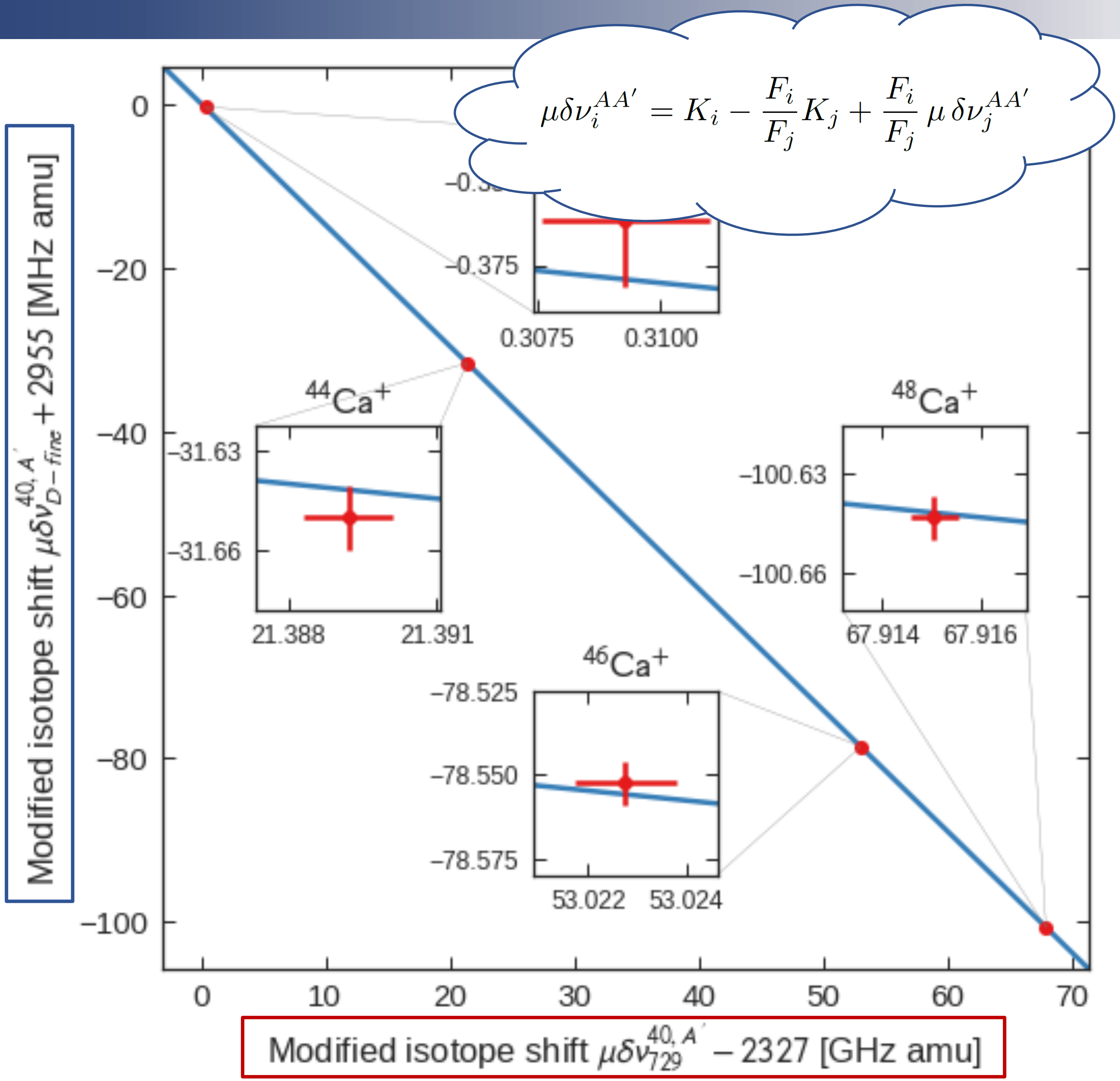
F_{732}/F_{729} = 1- F_{DSIS}/F_{729}

F_{732}/F_{729} = 1,00148305(20)

Very accurate field shift ratio!

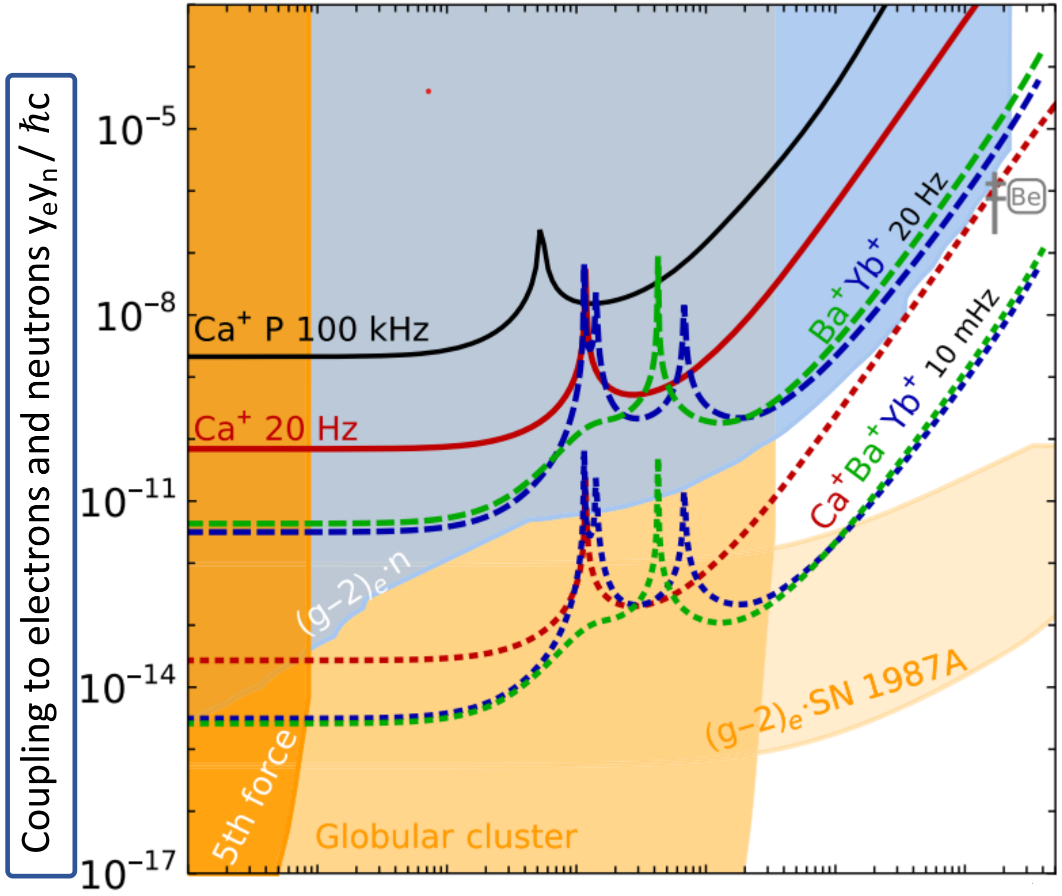
No new particles discovered

But …



Is the King Plot non-linear?

… bounds on potential couplings:



Massless limit
Long range (> 200 Å)

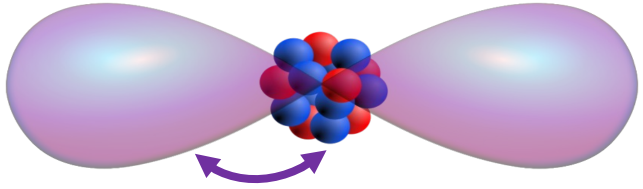
Nuclear radius (about 10^{-4} Å)

- Our results: PRL **125**, 123003 (2020)
- F. Gebert *et al*. PRL **115**, 053003 (2015)
- Results by other methods
- Predictions by improved isotope shift measurements

$$\delta\nu_i^{A,A'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'} + \alpha_{\mathrm{NP}} X_i\,\gamma_{AA'}$$

$$\alpha_{\mathrm{NP}} = (-1)^s y_e y_n / 4\pi$$

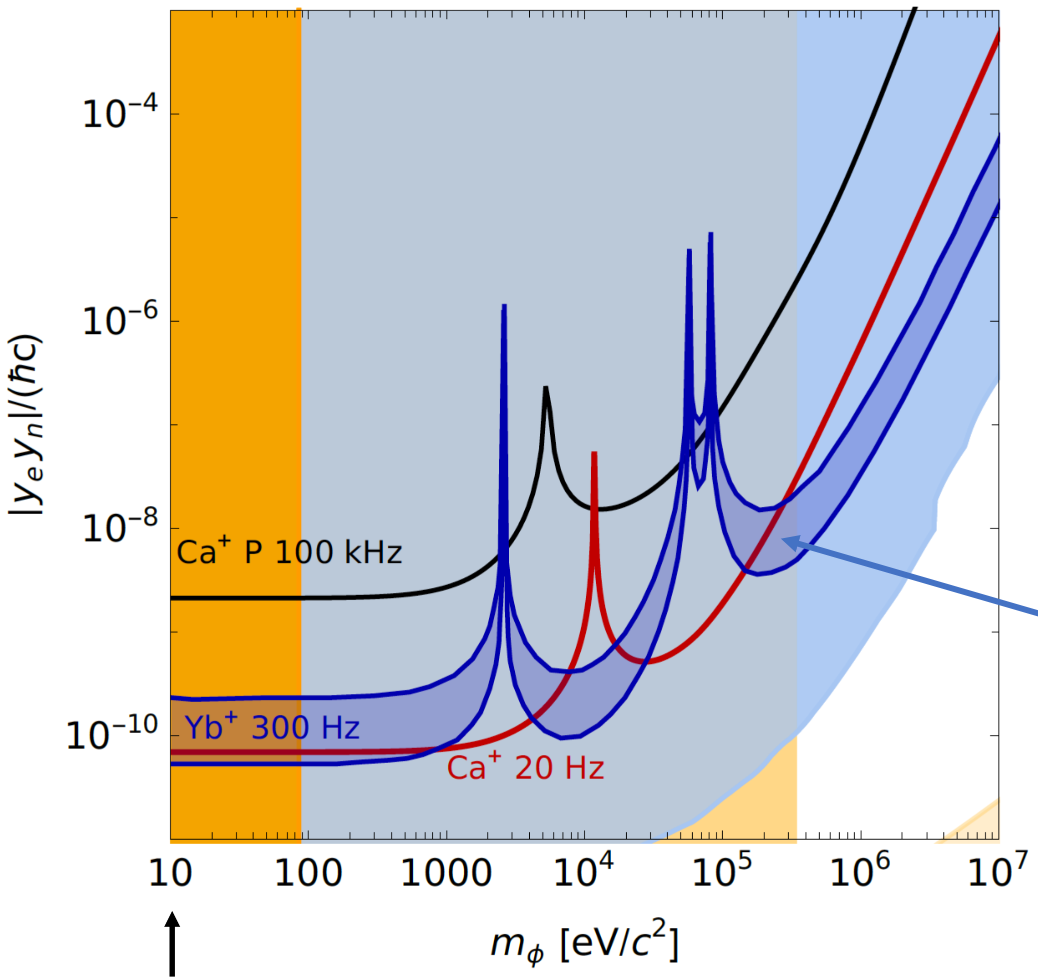
$$V_\phi(r) = -\alpha_{\mathrm{NP}}(A-Z)e^{-m_\phi r}/r$$



ϕ Boson

New bounds on new physics

Comparison of isotope shift measurements in 2020



Massless limit
Long range (> 200 Å)

- F. Gebert *et al.*, PRL **115**, 053003 (2015)
- C. Solaro *et al.*, PRL **125**, 123003 (2020)
- I. Counts *et al.*, PRL **125**, 123002 (2020)

Assuming observed non-linearity being a mixture of Quadrupole Field Shifts (QFS) and New Physics

Possible future improvements

PRL **116,** 013001 (2016) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2016

Frequency Comparison of Two $^{40}Ca^{+}$ Optical Clocks with an Uncertainty at the 10^{-17} Level

Y. Huang,[1,2] H. Guan,[1,2,*] P. Liu,[1,2] W. Bian,[1,2] L. Ma,[3] K. Liang,[4] T. Li,[4] and K. Gao[1,2,5,†]

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(Received 13 June 2015; published 6 January 2016)

$S_{1/2} – D_{5/2}$ transition

+

Better reference for our frequency comb for more precise measurement of the $D_{3/2} – D_{5/2}$ transition

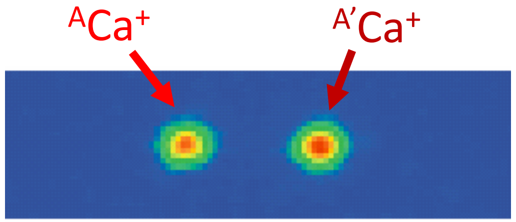
Possible future improvements

PHYSICAL REVIEW LETTERS **123,** 203001 (2019)

Precision Measurement of Atomic Isotope Shifts Using a Two-Isotope Entangled State

Tom Manovitz,* Ravid Shaniv, Yotam Shapira, Roee Ozeri, and Nitzan Akerman
Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

$^{86,88}Sr^+$: $\delta\nu^{S,D}_{88,86} = 570\,264\,063.435(9)(5)(8)$ Hz



Use decoherent-free sub-spaces:

$S_{1/2} – D_{5/2}$ transition: $|S_{1/2},m_S\rangle_A |D_{5/2},m_D\rangle_{A'} + e^{i\phi(\tau)} |D_{5/2},m_D\rangle_A |S_{1/2},m_S\rangle_{A'}$ $\phi = \phi_{init} + \Delta\omega_{isotope}\tau + \delta\omega_{Zeeman}\tau$

$D_{3/2} – D_{5/2}$ transition: $|D_{3/2},m_D\rangle_A |D_{5/2},m_D{}^*\rangle_{A'} + e^{i\phi(\tau)} |D_{5/2},m_D{}^*\rangle_A |D_{3/2},m_D\rangle_{A'}$

+

Ramsey spectroscopy using the *same* laser sources to drive the relevant transitions in the two isotopes

Possible future improvements

Improved mass measurements

King relation: $$\mu\delta\nu_i^{AA'} = K_i - \frac{F_i}{F_j}K_j + \frac{F_i}{F_j}\mu\delta\nu_j^{AA'}$$

$$\mu \equiv \frac{m_A m_{A'}}{m_A - m_{A'}}$$

PHYSICAL REVIEW LETTERS **124,** 113001 (2020)

Editors' Suggestion

Mass-Difference Measurements on Heavy Nuclides with an eV/c^2 Accuracy in the PENTATRAP Spectrometer

A. Rischka,[1,*] H. Cakir,[1] M. Door,[1] P. Filianin,[1] Z. Harman,[1] W. J. Huang,[1] P. Indelicato,[2] C. H. Keitel,[1] C. M. König,[3] K. Kromer,[1] M. Müller,[3] Y. N. Novikov,[4,5] R. X. Schüssler,[1] Ch. Schweiger,[1] S. Eliseev,[1] and K. Blaum[1]

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[2]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France, Paris 75005, France*
[3]*Ruprecht-Karls-Universität Heidelberg, 69117 Heidelberg, Germany*
[4]*Department of Physics, St. Petersburg State University, St. Petersburg 198504, Russia*
[5]*Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia*

Ion pair	Frequency ratio	Mass difference / u (this Letter)	Mass difference / u (AME2016 [13])	Improvement of accuracy
$^{134}Xe^{17+}/^{132}Xe^{17+}$	1.015 172 982 205(19)(8)	2.001 237 945 4(25)(11)	2.001 237 947(12)	4
$^{132}Xe^{17+}/^{131}Xe^{17+}$	1.007 632 569 193(13)(6)	0.999 070 956 6(17)(8)	0.999 070 951(11)	6
$^{131}Xe^{17+}/^{129}Xe^{17+}$	1.015 518 803 388(9)(8)	2.000 303 273 5(12)(10)	2.000 303 277(11)	7
$^{129}Xe^{17+}/^{128}Xe^{17+}$	1.007 828 736 895(10)(6)	1.001 250 105 6(13)(8)	1.001 249 9(11)	740
$^{128}Xe^{17+}/^{126}Xe^{17+}$	1.015 880 167 834(18)(8)	1.999 233 328 2(23)(10)	1.999 234(4)	1700

Accuracy:

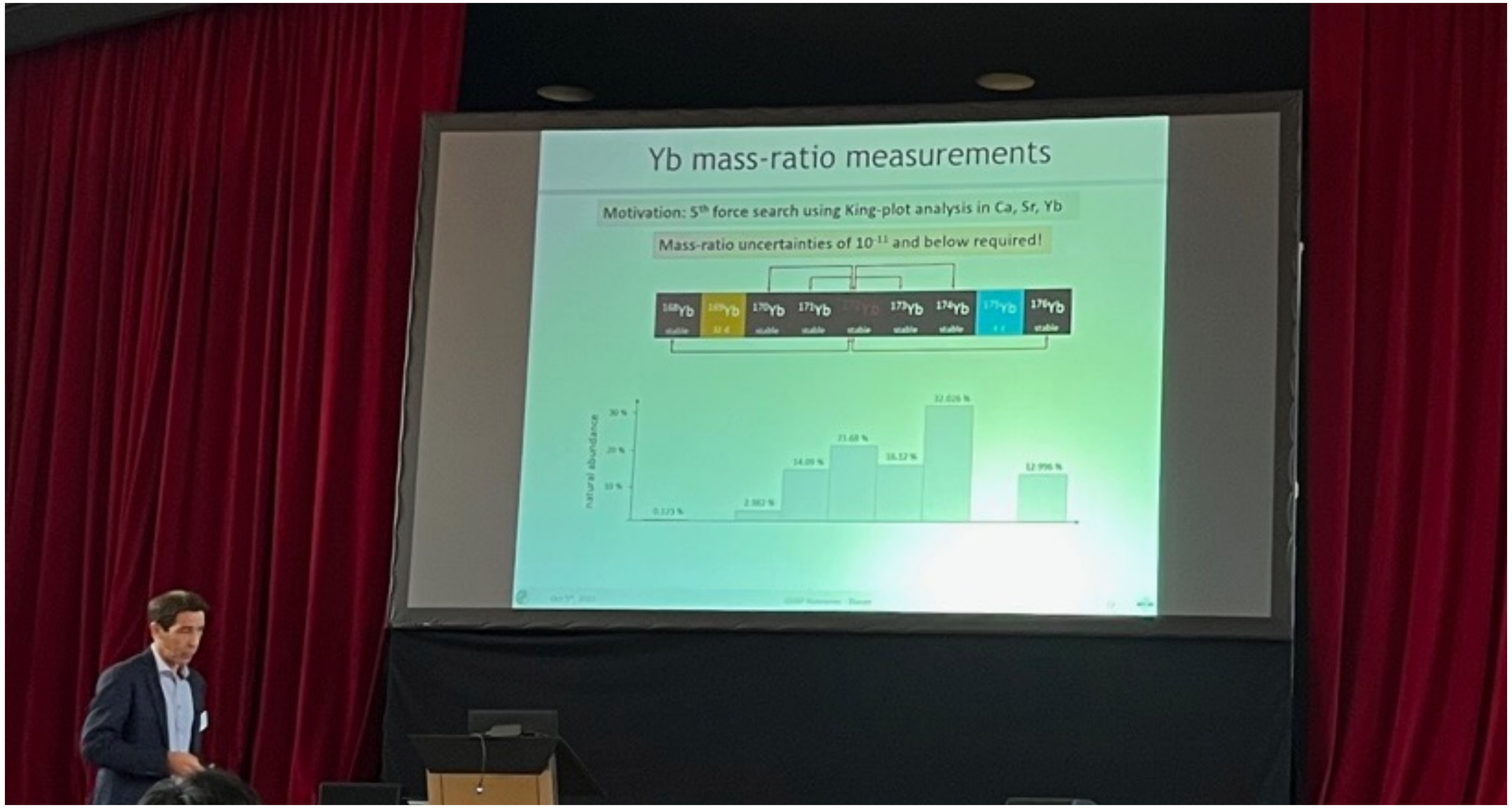
$\Delta m/m \sim 10^{-11}$

Possible future improvements

Improved mass measurements

King relation: $\mu\delta\nu_i^{AA'} = K_i - \frac{F_i}{F_j}K_j + \frac{F_i}{F_j}\mu\delta\nu_j^{AA'}$

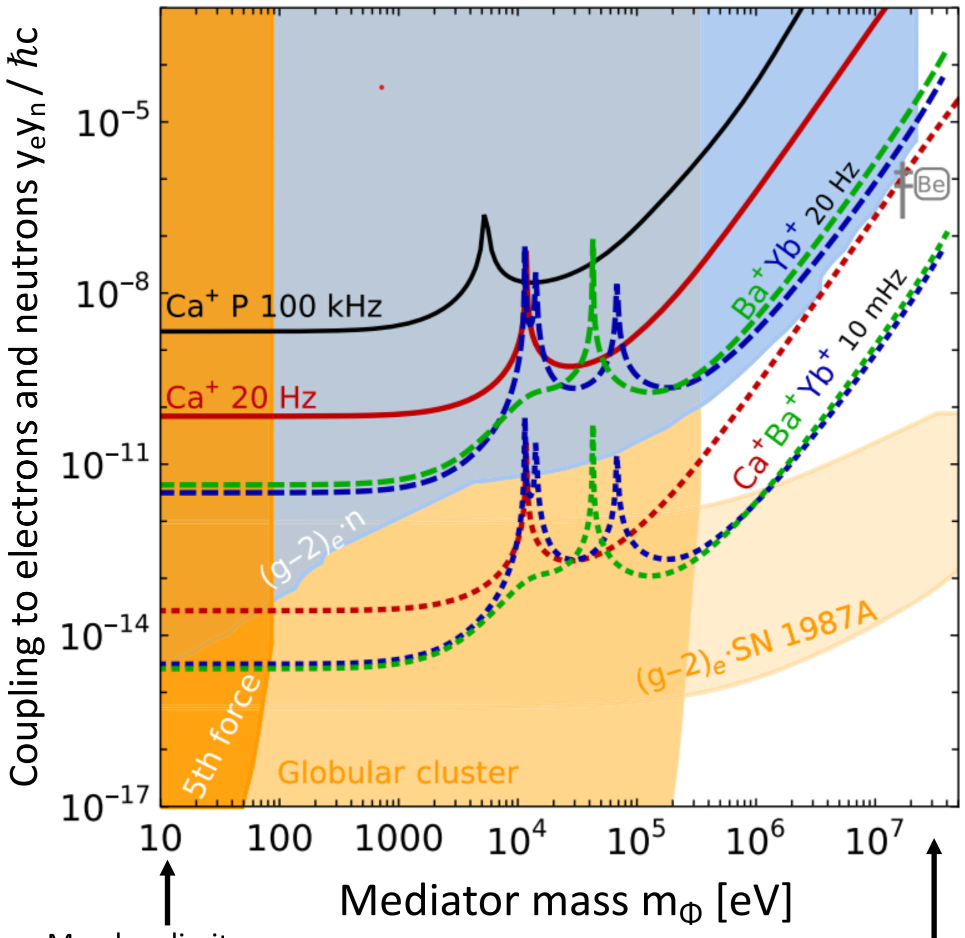
$$\mu \equiv \frac{m_A m_{A'}}{m_A - m_{A'}}$$



Klaus Blaum (MPIK), Hannover meeting, Oct. 2022

Possible future improvements

Carving into interesting regimes by isotope shift measurements seems possible!



Massless limit
Long range (> 200 Å)

Nuclear radius (about 10^{-4} Å)

However,…

Possible future improvements

Standard Model nonlinearities

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]

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[2]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*

							Standard Model nonlinearities (Hz)				
									Quadratic term inc. MB		
Ion	Z	A	A_1	A_2	A_3	Pair of transitions	Method 4	Method 5	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

Possible future improvements

Standard Model nonlinearities

PHYSICAL REVIEW A **108**, 022802 (2023)

Calculation of isotope shifts and King-plot nonlinearities in Ca^+

A. V. Viatkina,[1,2] V. A. Yerokhin,[3] and A. Surzhykov[1,2]
[1] *Technische Universität Braunschweig, 38106 Braunschweig, Germany*
[2] *Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*
[3] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

Hence, for the $(3d_{3/2}, 3d_{5/2} \rightarrow 4s)$ pair only an upper limit of NL can be obtained: we conclude that the standard-model NLs for this transition pair in Ca^+ might be observed when the experimental accuracy is below 200 Hz. As a matter of fact, such accuracy is already achievable in modern experiments with Ca^+ [16,18], although no confirmed NLs have been reported so far.

This analysis includes 1st + 2nd order mass and field shifts, nuclear polarization correction and the cross term between field and mass shifts.

[16] F. W. Knollmann *et al.*,, Phys. Rev. A **100**, 022514 (2019); [18] C. Solaro *et al.*, Phys. Rev. Lett. 125, 123003 (2020)

Possible future improvements

Make generalized King plots

PHYSICAL REVIEW RESEARCH **2**, 043444 (2020)

Generalized King linearity and new physics searches with isotope shifts

Julian C. Berengut [1,*] Cédric Delaunay,[2,†] Amy Geddes,[1,‡] and Yotam Soreq [3,§]
[1] *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*
[2] *Laboratoire d'Annecy-le-Vieux de Physique Théorique LAPTh, CNRS – Université Savoie Mont Blanc, BP 110, F-74941 Annecy-le-Vieux, France*
[3] *Physics Department, Technion—Israel Institute of Technology, Haifa 3200003, Israel*

Generalized formula for isotope shifts
including higher order terms (SM):

$$\nu_i^a = K_i \mu_a + F_i \delta \langle r^2 \rangle_a + \sum_{l=2}^{m-1} F_{il} \lambda_{l,a}$$

All the terms upto *m*-1 can be determined
if *m* "clock"-transitions are available,
AND
m+1 isotope-pairs can be measured

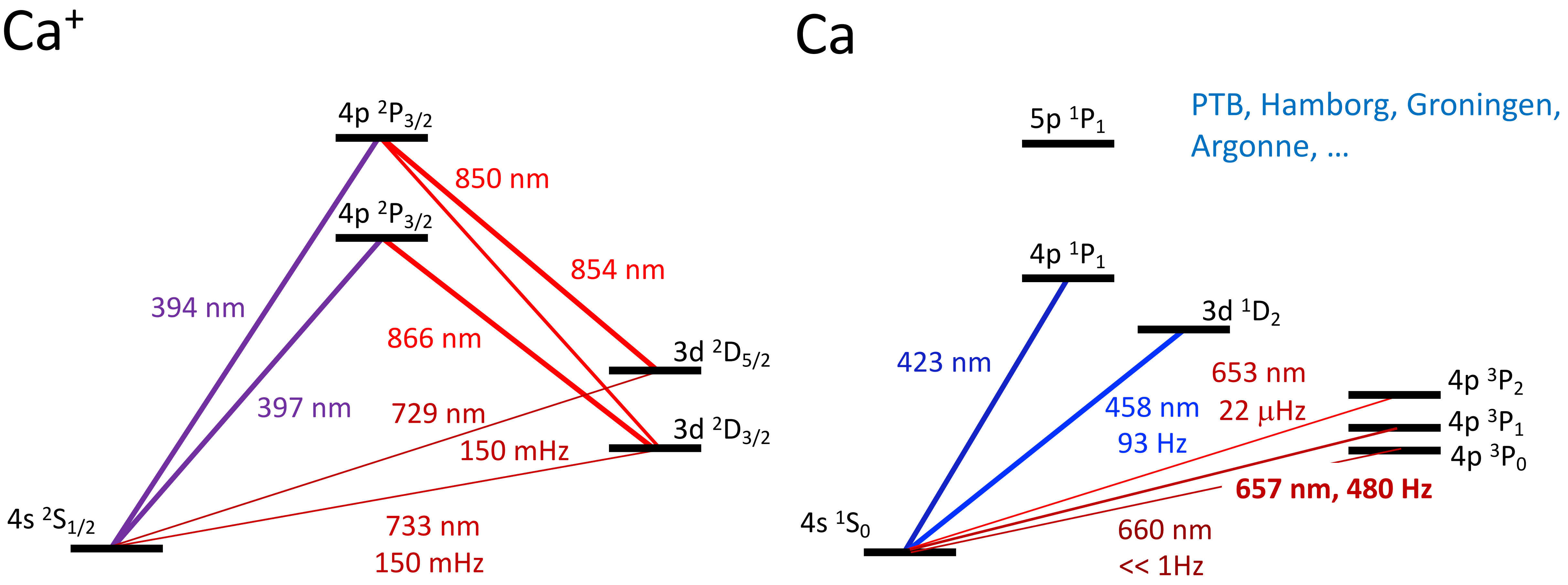
$^{40,42,44,46,48}Ca^+$

$^{168,170,172,174,176}Yb^+$

=> *m*=3

Possible future improvements

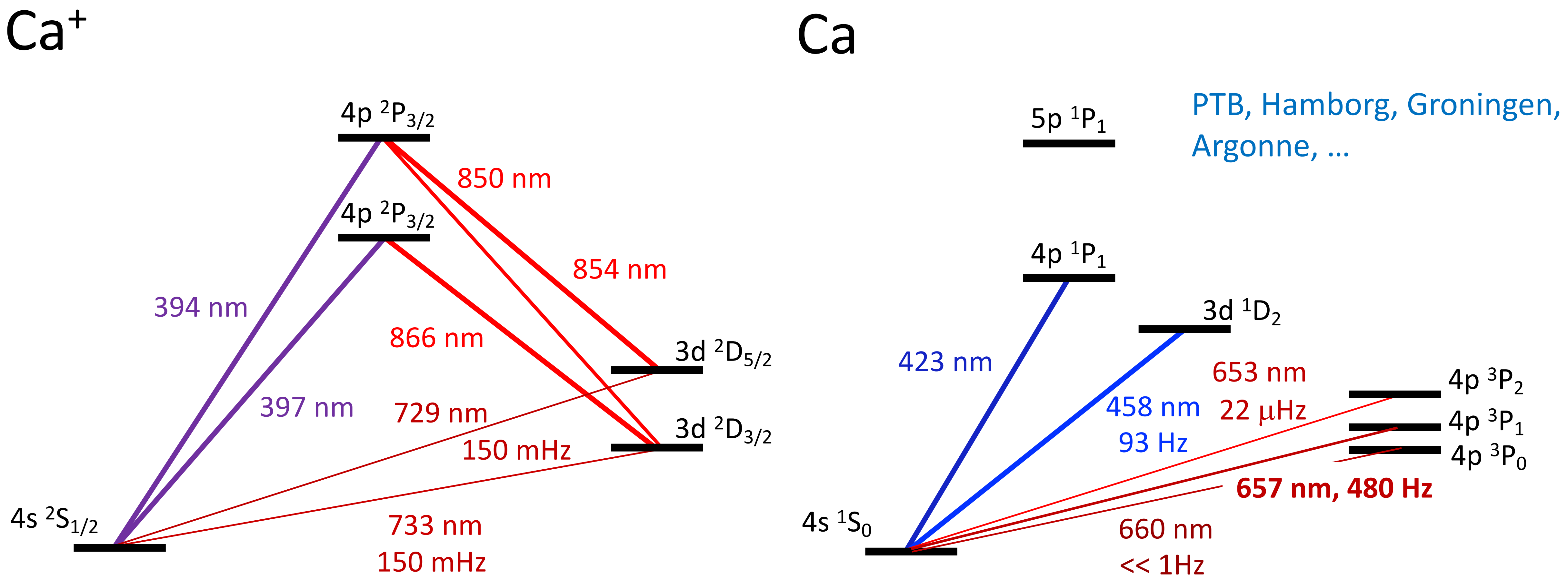
Make generalized King plots



3 transitions of Ca^+/Ca transitions should makes it possible to correct for 1 SM nonlinearity

Possible future improvements

Make generalized King plots



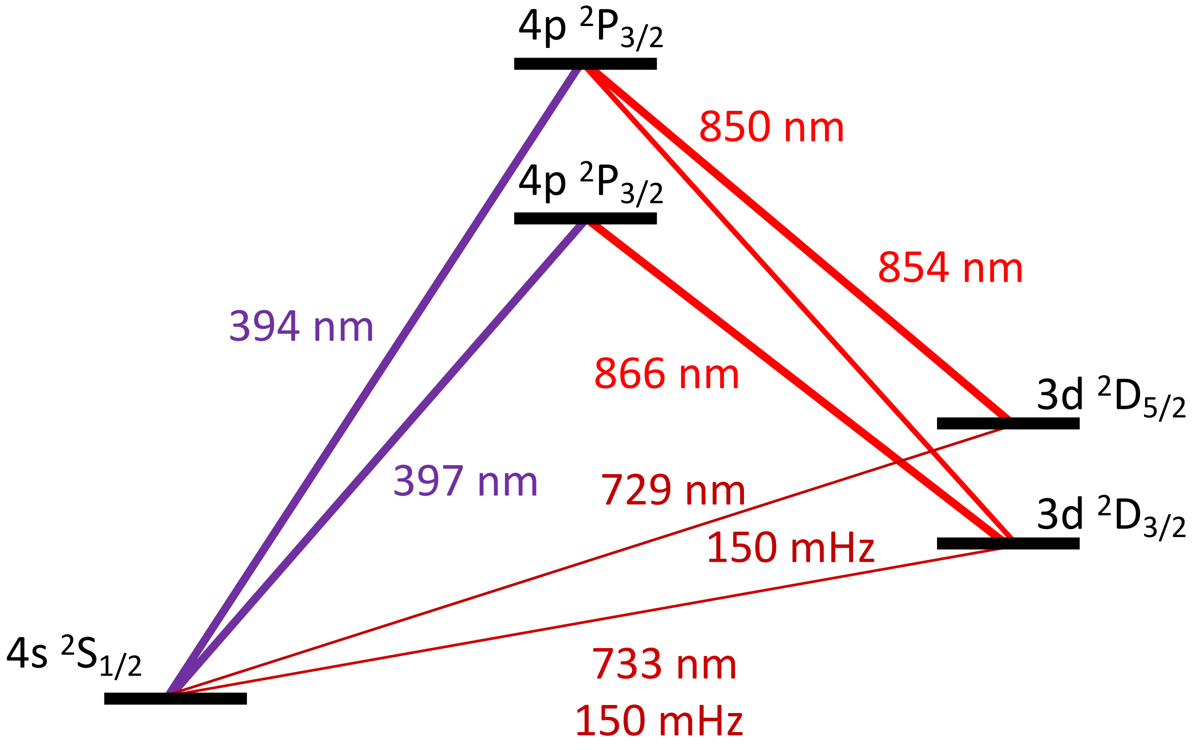
$^{40,\mathbf{41},42,\mathbf{43},44,46,48}Ca^+$ => m=5

5 transitions of Ca^+/Ca transitions should makes it possible to correct for 3 SM nonlinearities

Possible future improvements

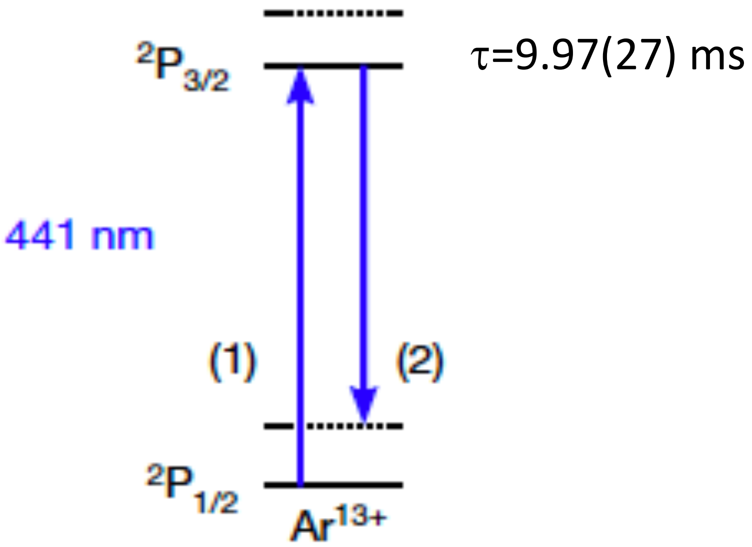
Make generalized King plots

Ca^+



Ca^{N+} finestructure transitions

Example from Ar^{13+}



Piet Schmidt's group: Nature **578**, 60 (2020)

40,**41**,42,**43**,44,46,48Ca^+ => m=5

5 transitions of Ca^+/Ca transitions should makes it possible to correct for 3 SM nonlinearities

Possible future improvements

Generalized 3-dimensional King Plots I

3 transitions in Yb^+ : $^2S_{1/2}$– $^2D_{5/2}$, $^2S_{1/2}$– $^2D_{3/2}$, and $^2S_{1/2}$– $^2F_{7/2}$

PHYSICAL REVIEW LETTERS **128,** 163201 (2022)

Featured in Physics

Evidence of Two-Source King Plot Nonlinearity in Spectroscopic Search for New Boson

Joonseok Hur,[1,*] Diana P. L. Aude Craik,[1,*] Ian Counts,[1,*] Eugene Knyazev,[1] Luke Caldwell,[2] Calvin Leung,[1] Swadha Pandey,[1] Julian C. Berengut,[3] Amy Geddes,[3] Witold Nazarewicz,[4] Paul-Gerhard Reinhard,[5] Akio Kawasaki,[6] Honggi Jeon,[7] Wonho Jhe,[7] and Vladan Vuletić[1,†]

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[6]*National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan*

[7]*Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea*

Possible future improvements

Generalized 3-dimensional King Plot II

2 transitions in Yb^+: $^2S_{1/2}$– $^2D_{5/2}$ and $^2S_{1/2}$– $^2D_{3/2}$ (Vuletic-group) + 1 transition in Yb: $^1S_0$ -$^3P_0$

PHYSICAL REVIEW X **12**, 021033 (2022)

Observation of Nonlinearity of Generalized King Plot in the Search for New Boson

Koki Ono,[1,*] Yugo Saito,[1] Taiki Ishiyama,[1] Toshiya Higomoto,[1] Tetsushi Takano,[2] Yosuke Takasu,[1]
Yasuhiro Yamamoto,[3,4] Minoru Tanaka,[5] and Yoshiro Takahashi[1]
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[2]*NICHIA Corporation, 3-13-19, Moriya-Cho, Kanagawa-Ku, Yokohama, Kanagawa 221-0022, Japan*
[3]*National Centre for Nuclear Research, Pasteura 7, Warsaw 02-093, Poland*
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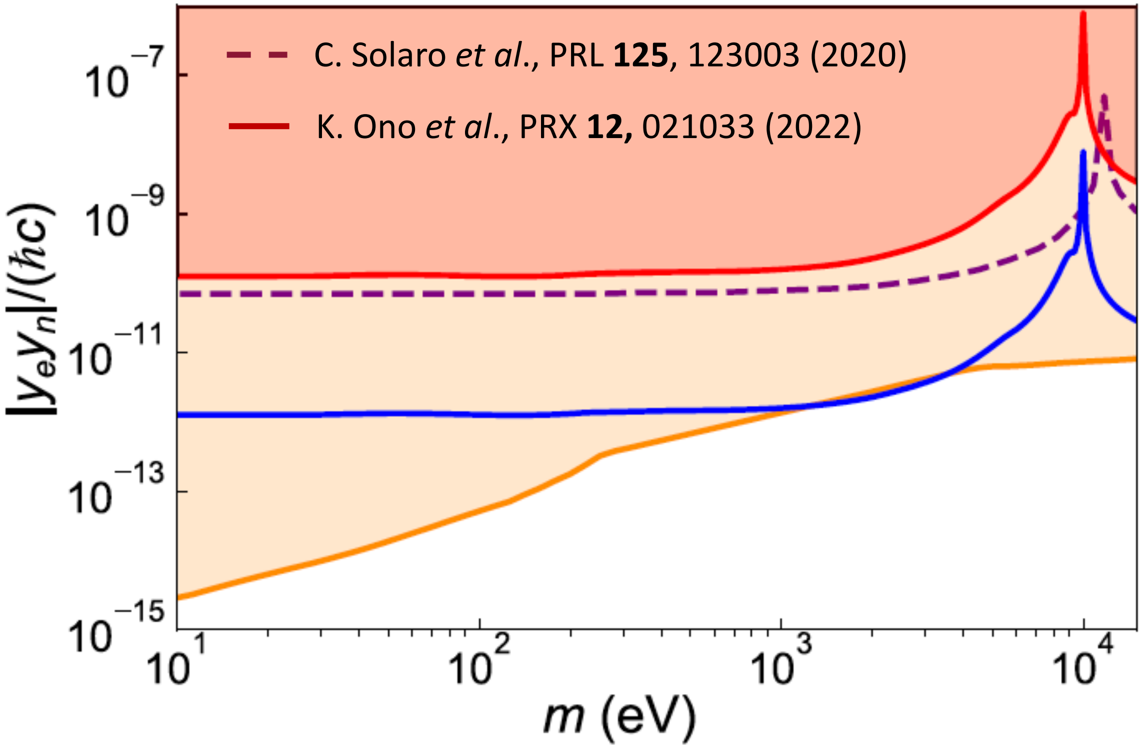
(Received 18 October 2021; accepted 16 March 2022; published 10 May 2022)

Possible future improvements

Generalized 3-dimensional King Plot II

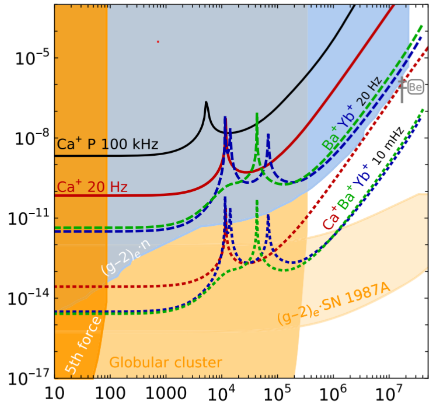
2 transitions in Yb^+: $^2S_{1/2}$– $^2D_{5/2}$ and $^2S_{1/2}$– $^2D_{3/2}$ (Vuletic-group) + 1 transition in Yb: $^1S_0$ -$^3P_0$



The 3-dimensional King Plot did not improve our Ca^+ results, however,
it showed the original analysis in [PRL 125, 123002 (2020)] was a bit too naïve !

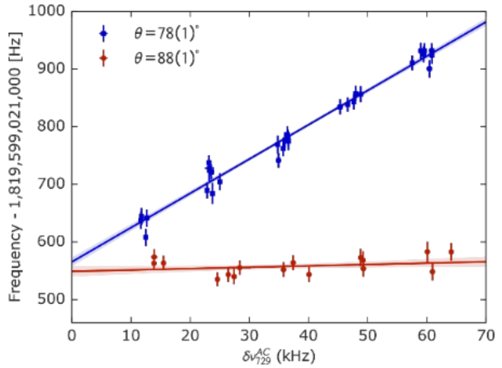
Conclusion

- Improved bounds on new gauge bosons coupling to neutrons and electrons based on isotope shift measurements.
- Demonstrated high-resolution direct frequency-comb Raman spectroscopy, of the 1.8 THz D-splitting in Ca^{+} with 10 Hz accuracy.
- Demonstrated >99% transfer efficiency and ms timescale coherence.



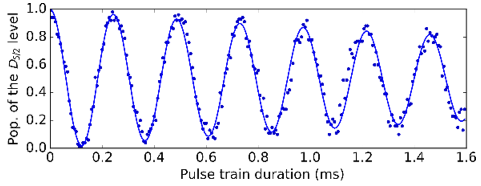
C. Solaro *et al.*, PRL **125**, 123003 (2020)

Other applications of Direct Frequency-Comb driven Raman transitions in the THz range:



C. Solaro *et al.*, PRL **120**, 253601, (2018)

- Qubit manipulation (Monroe [PRL **104**, 140501 (2010)] and Ospelkaus [PRL **122**, 123606 (2019)] groups).
- Spectroscopy of pure rotational lines in molecules. (Us, NIST [Science **367**, 1458 (2020); arXiv:2207.10215], NUS,…)
- Spectroscopy of hyperfine transitions in highly charged ions.



Thank you for your attention !

Elina Fuchs

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PTB

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Qubiz

MI

MARIE CURIE ACTIONS

TEQ

Sapere Aude

CCQ