Searching for a fifth fundamental force using precision trapped-ion spectroscopy

PSAS 2024

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Previously @ Vuletić group, MIT (Yb^+)

See J. C. Berengut et al, PRL **120** 091801 (2018)
J. C. Berengut et al, Phys Rev Research **2** 043444 (2020)

Φ could be a “relaxion”…

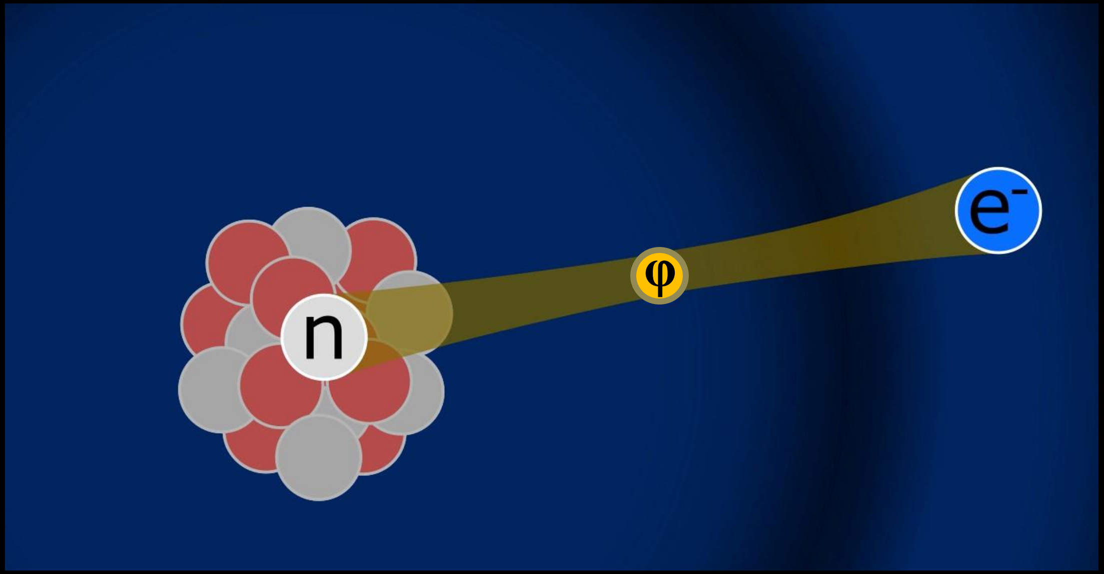
Graham, Kaplan, Rajendran, PRL **115**, 22180 (2015)

SM extensions that predict a neutron-electron force:
Debierre et al, Phys. Rev. A **106** 062801 (2022)

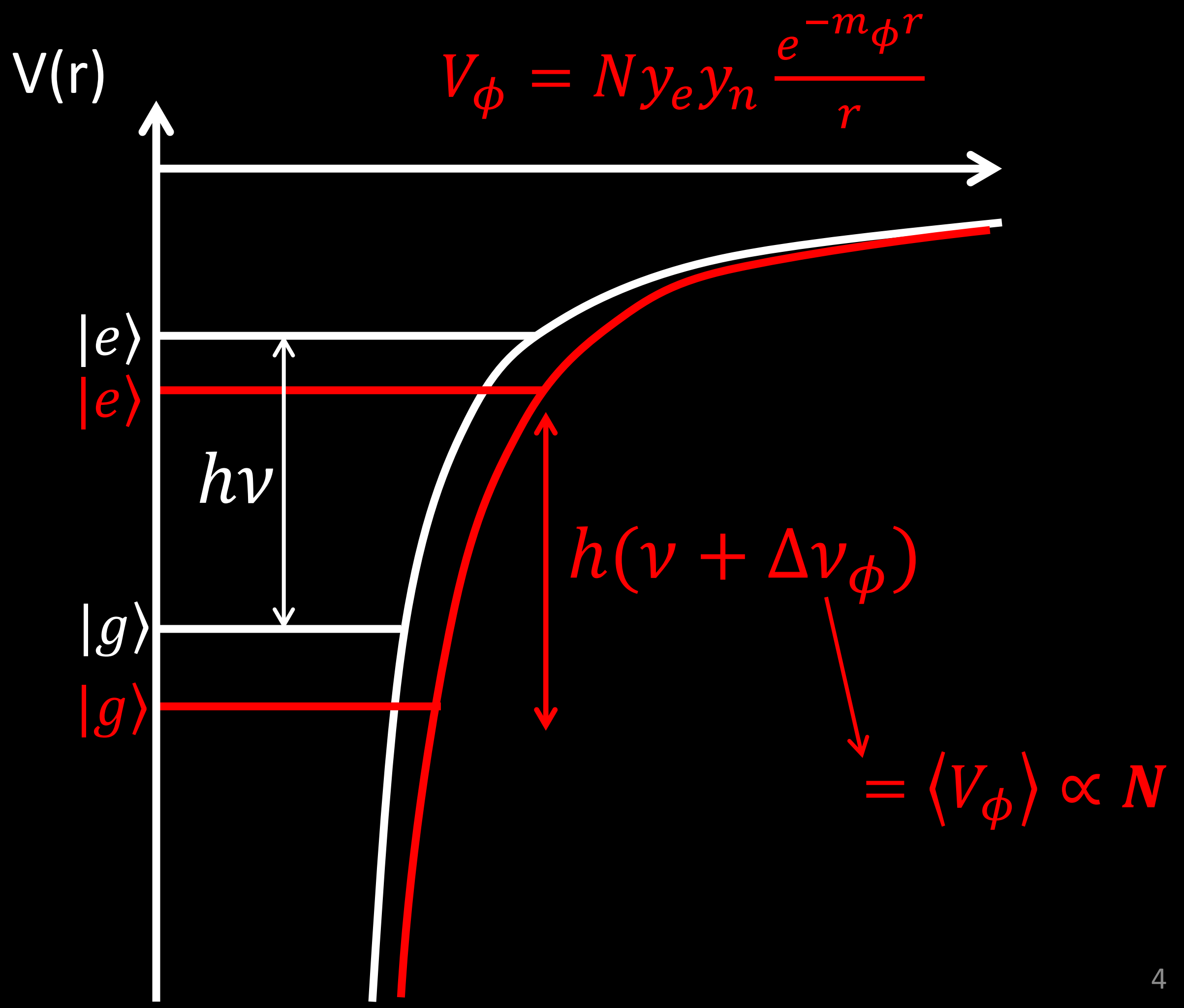
Animation from https://www.quantamagazine.org/higgs-boson-mass-explained-in-new-theory-20150527/

A hypothetical boson that mediates electron-neutron interaction

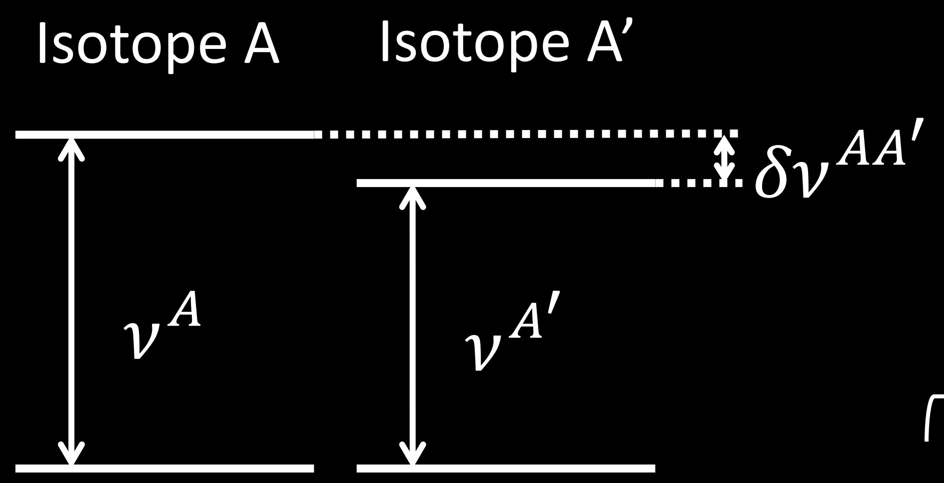
$$V_{coulomb} = -\frac{1}{4\pi\varepsilon_0}\frac{Ze \cdot e}{r}$$



Z protons
N neutrons



Probing the interaction by measuring isotope shifts



$\delta\nu^{AA'}$ = standard model shift + boson shift

field shift

Due to change in mass of the nucleus - changes center of mass of the atom

$= K \quad \delta\mu$

Average momentum squared of electrons

Change in reduced mass

Due to change in spatial distribution of the nuclear charge

$= F \cdot \langle \delta r^2 \rangle$

Electronic coefficient

Change in mean-squared nuclear charge radius

Probing the interaction by measuring isotope shifts

mass shift field shift

$$\delta\nu_1^{AA'} = K_1\,\delta\mu_{AA'} + F_1\,\langle\delta r^2\rangle_{AA'}$$

$$\delta\nu_2^{AA'} = K_2\,\delta\mu_{AA'} + F_2\,\langle\delta r^2\rangle_{AA'}$$

Probing the interaction by measuring isotope shifts

mass shift field shift

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$$\left(\frac{\delta\nu_2}{\delta\mu}\right)_{AA'} = \frac{F_2}{F_1}\left(\frac{\delta\nu_1}{\delta\mu}\right)_{AA'} + K_2 - \frac{F_2}{F_1}K_1$$

Probing the interaction by measuring isotope shifts

mass shift field shift

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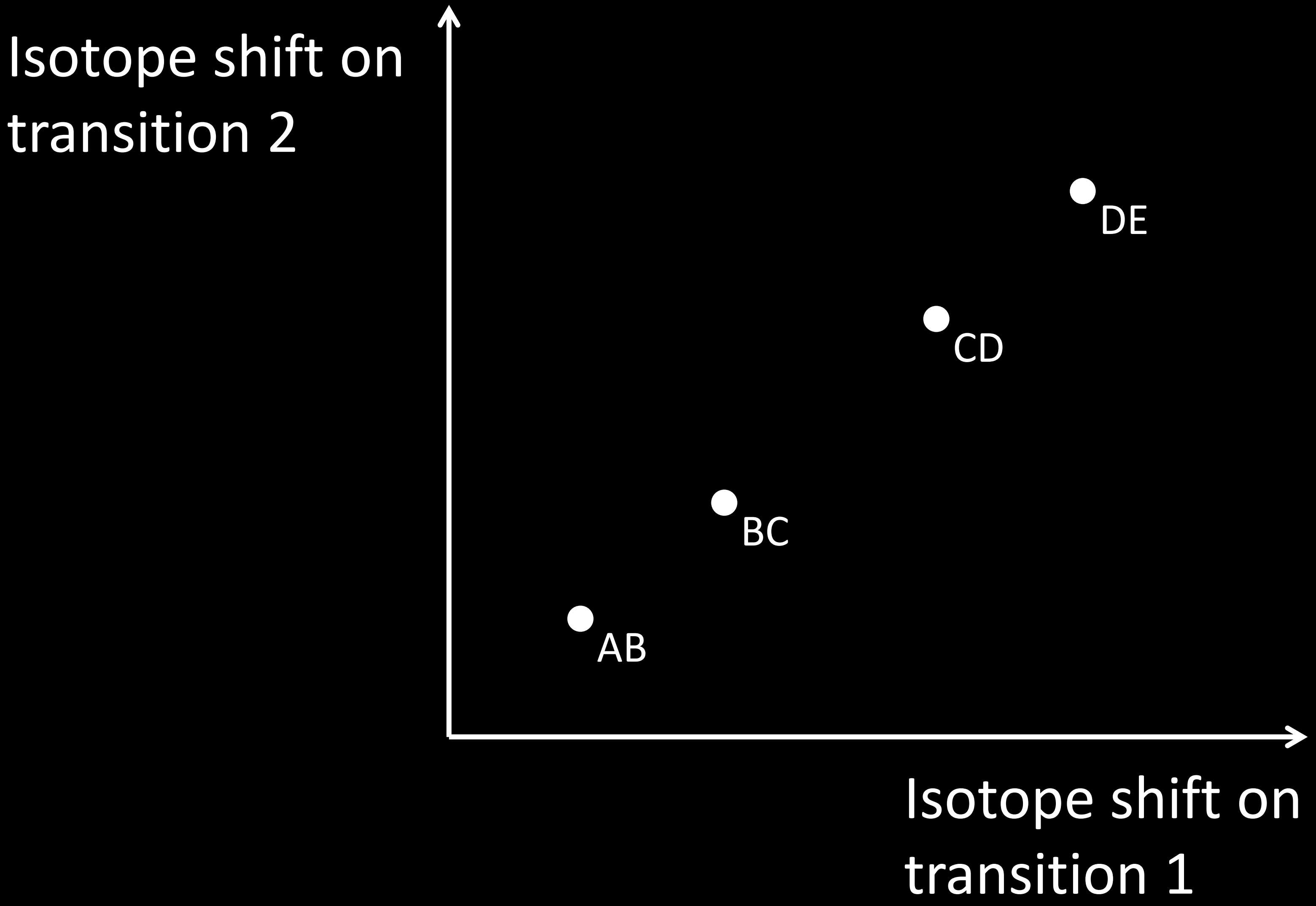
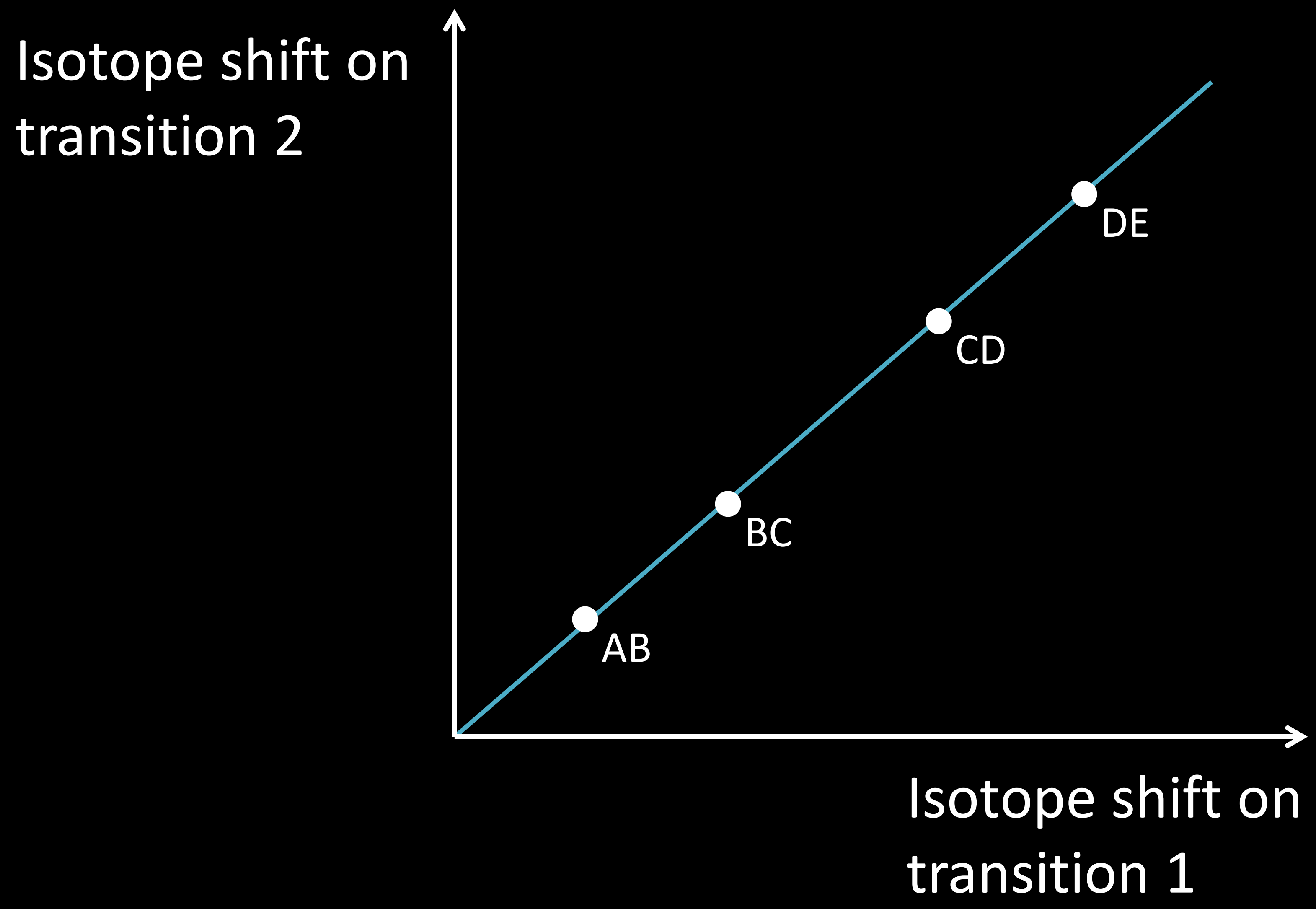
$$y = m\ x + c$$

King plot



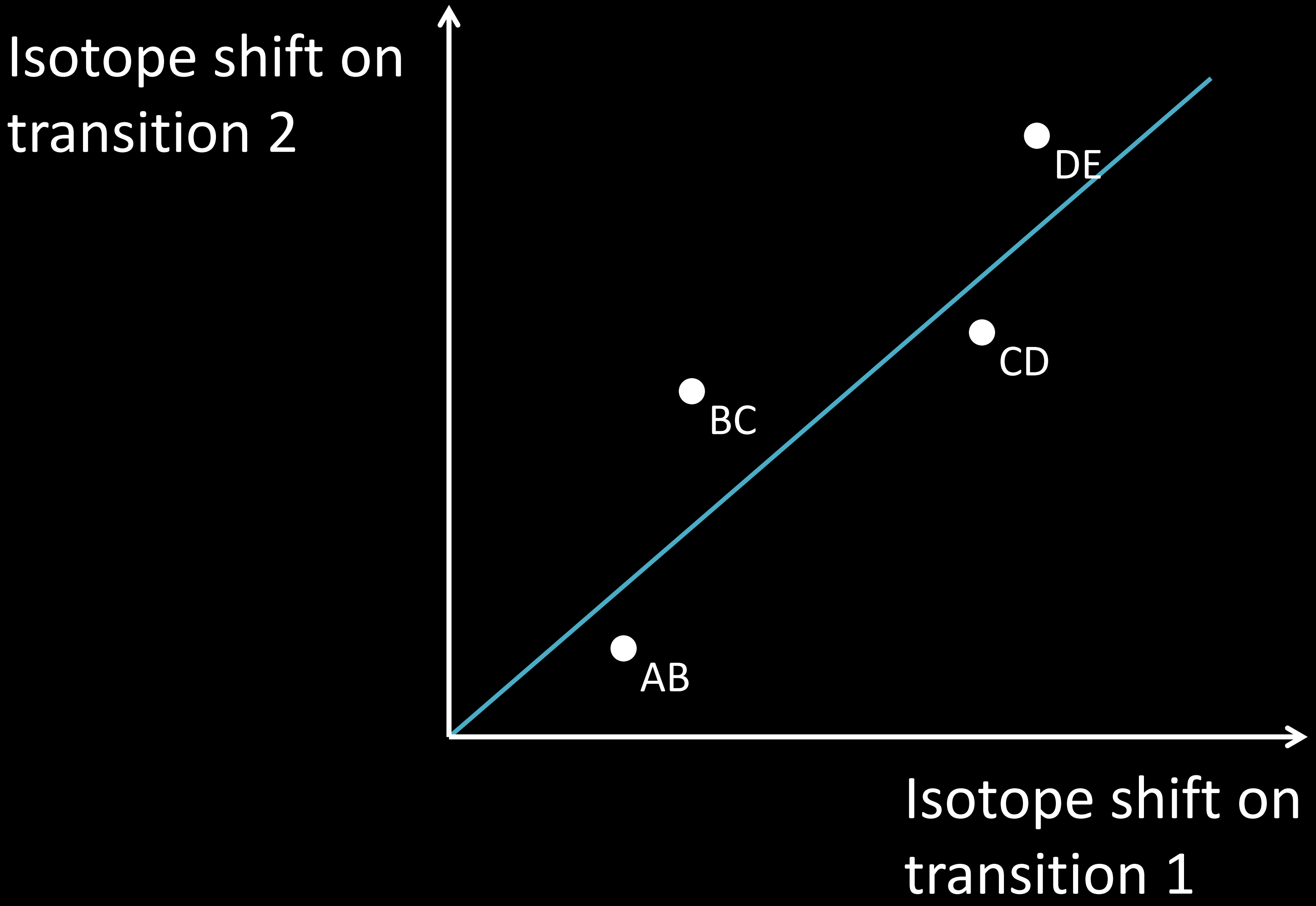
King Plot
W. H. King, JOSA 53, 638 (1963)

King plot



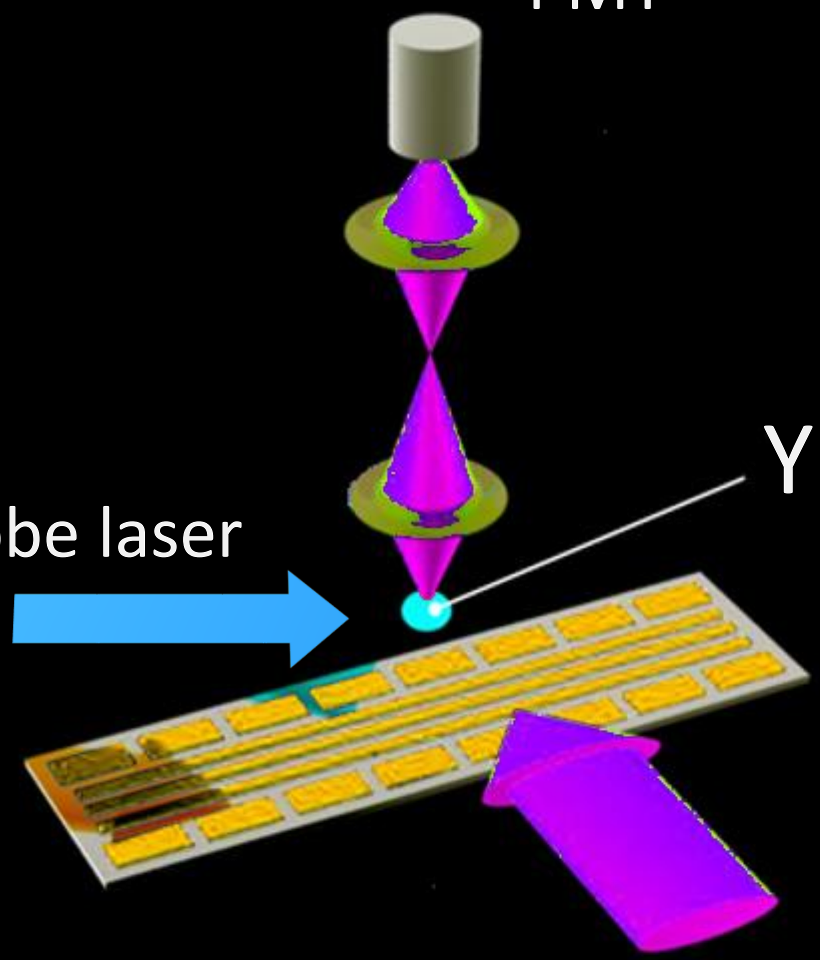
King Plot
W. H. King, JOSA 53, 638 (1963)

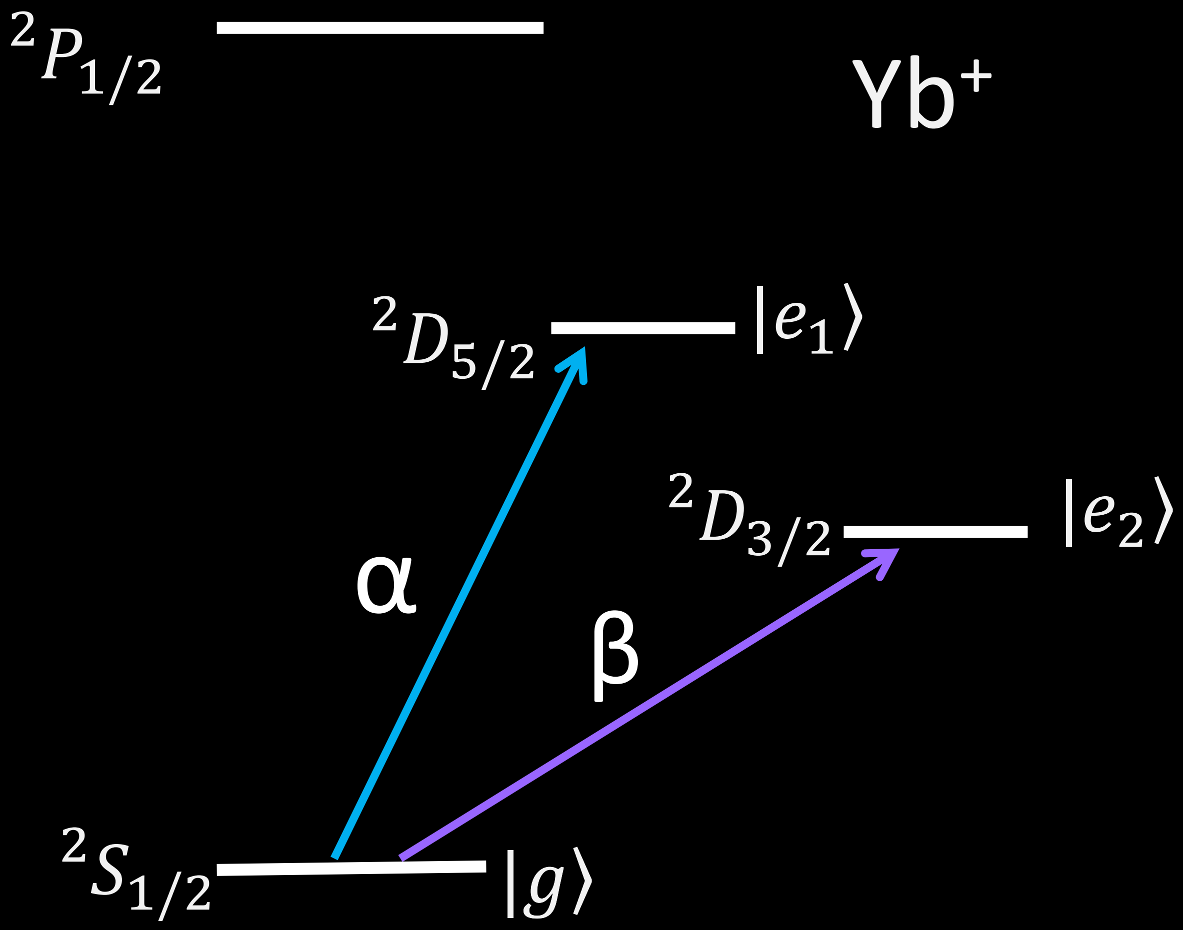
King plot



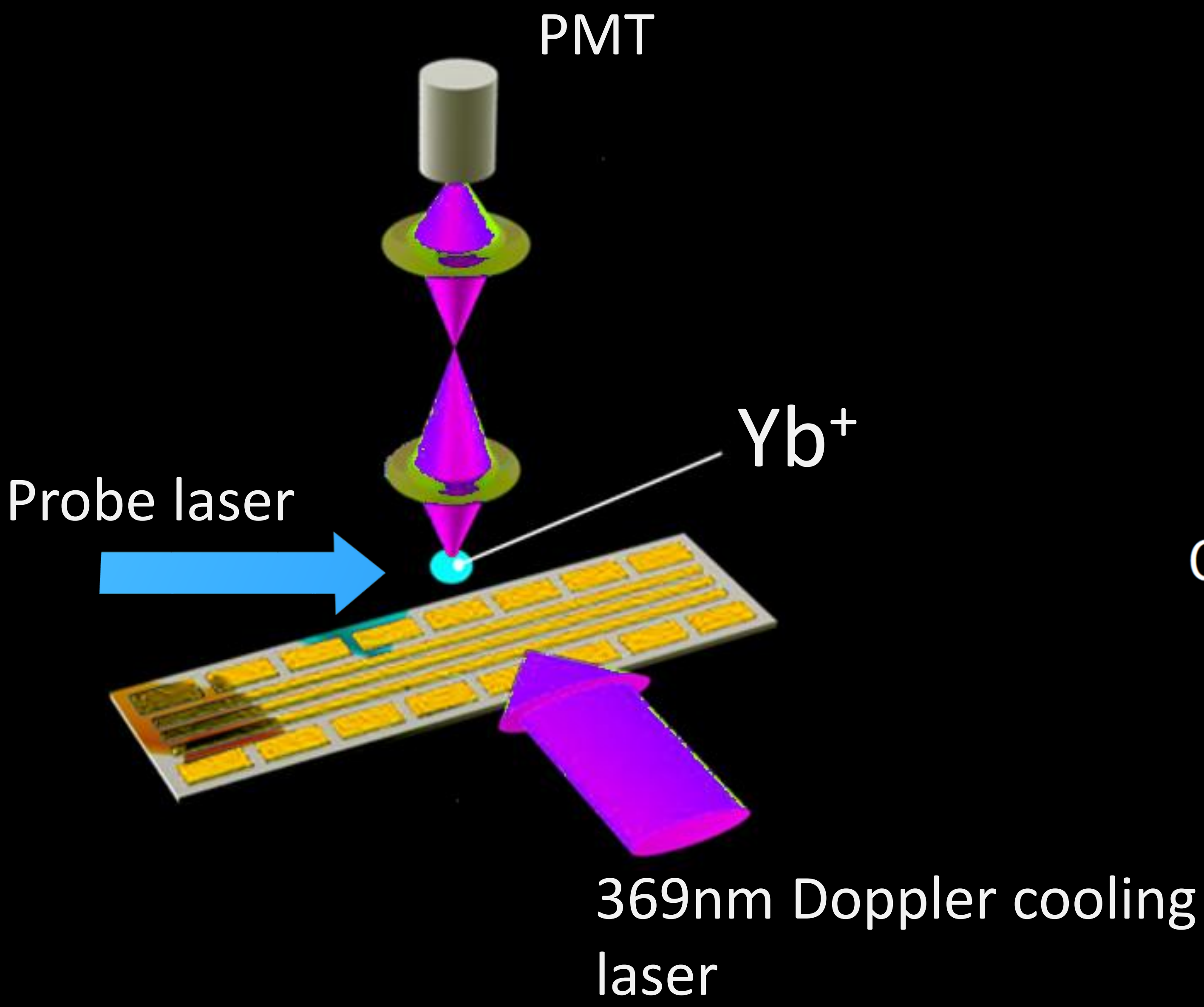
King Plot
W. H. King, JOSA 53, 638 (1963)

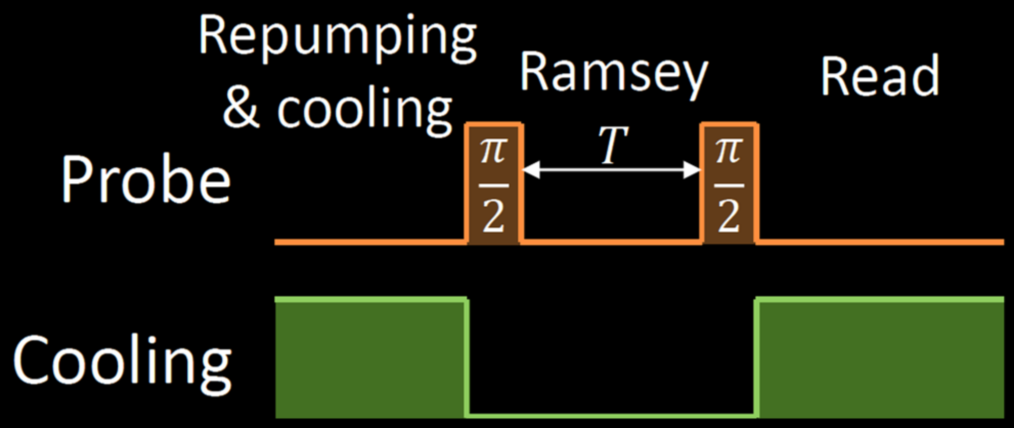
The measurement



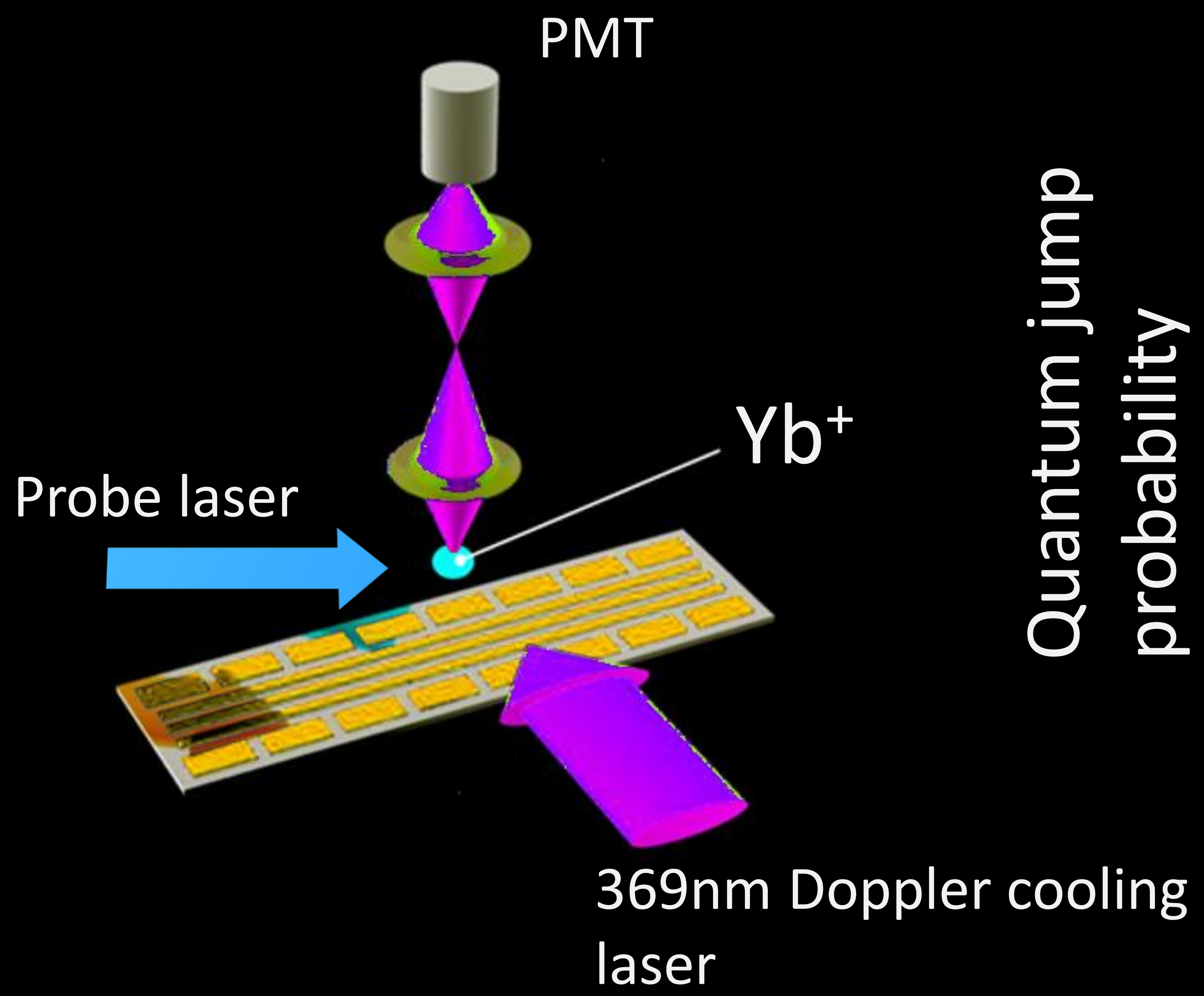


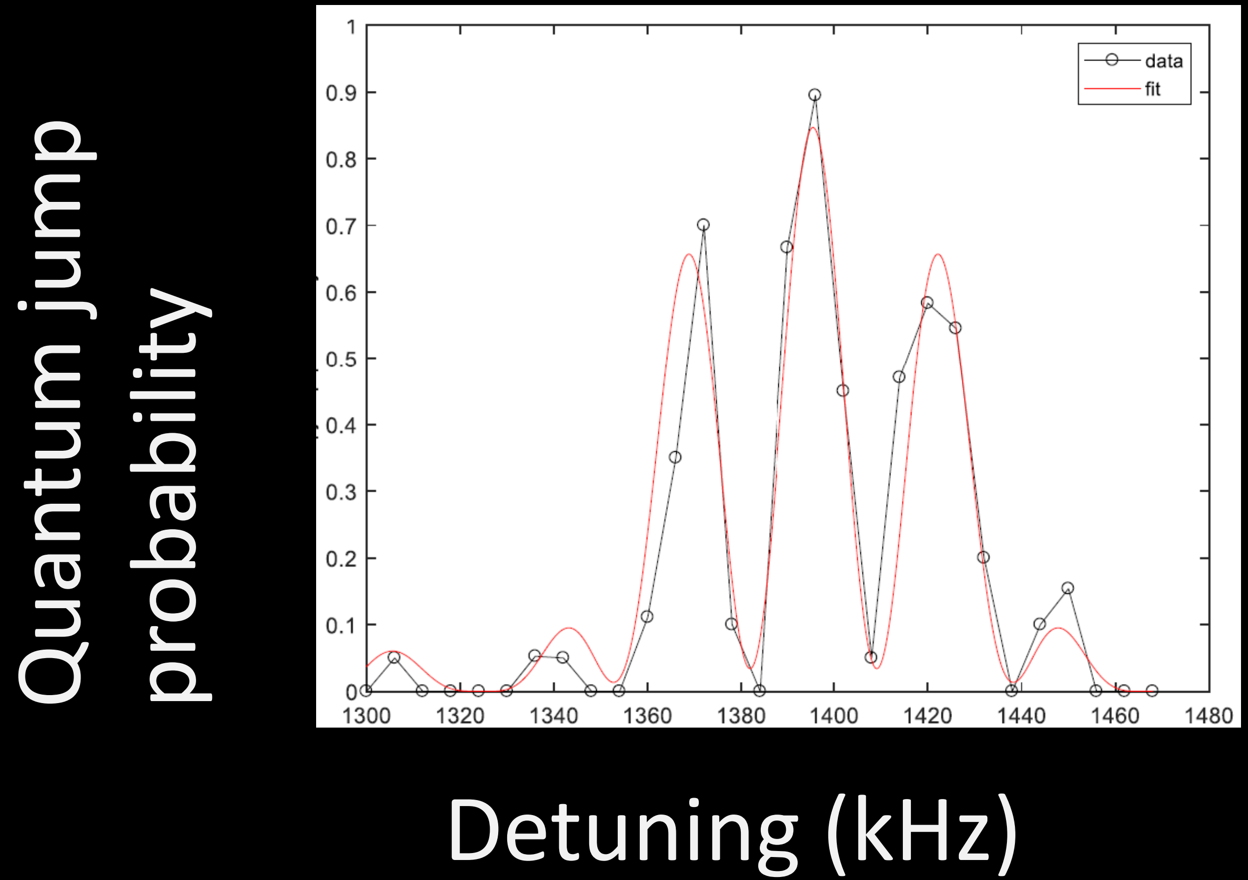
The measurement



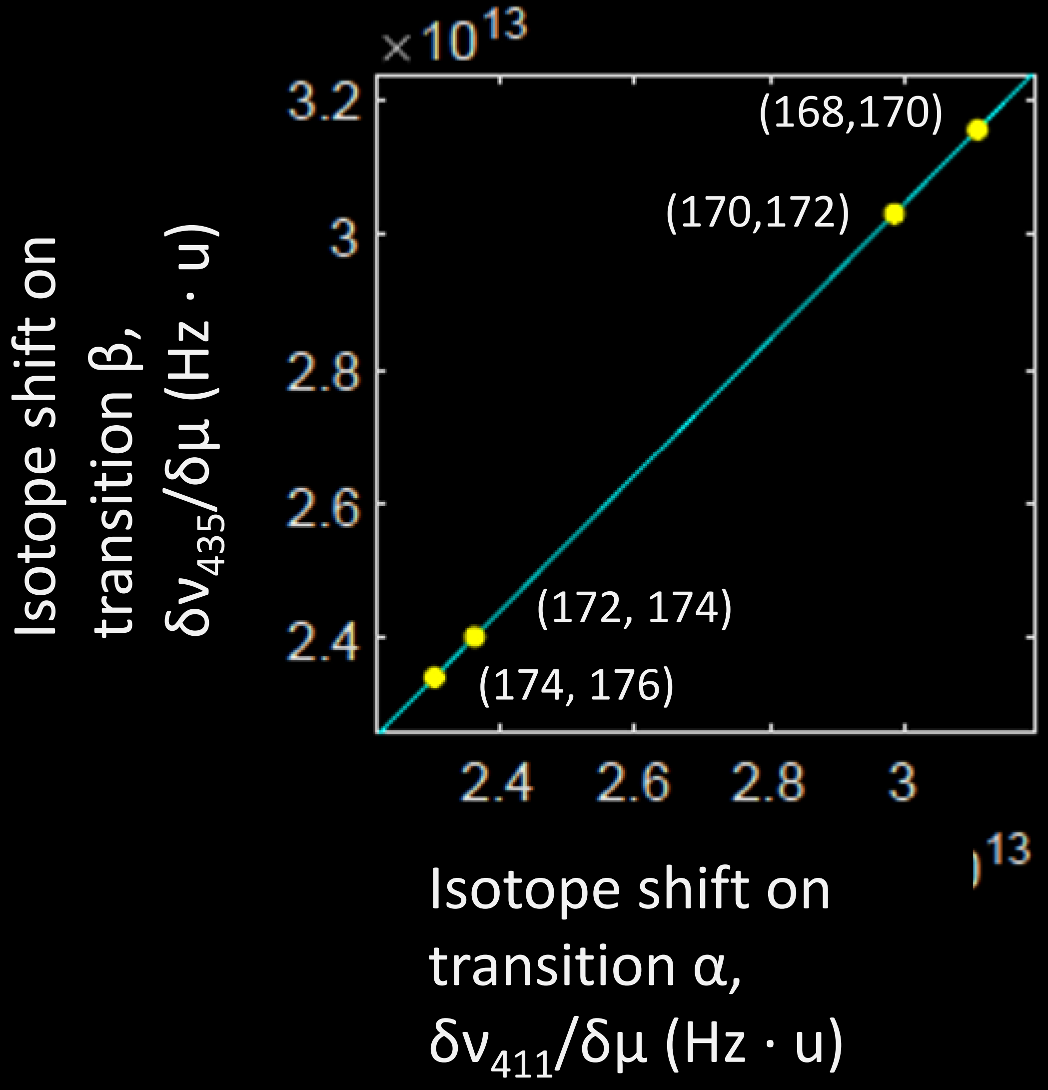


The measurement





King Plot



×10^13
3.2
3
2.8
2.6
2.4
(168,170)
(170,172)
(172, 174)
(174, 176)
2.4
2.6
2.8
3
13
Isotope shift on transition β, $\delta\nu_{435}/\delta\mu$ (Hz · u)
Isotope shift on transition α, $\delta\nu_{411}/\delta\mu$ (Hz · u)

King Plot

Zoom in by a factor of
1 million...

King Plot

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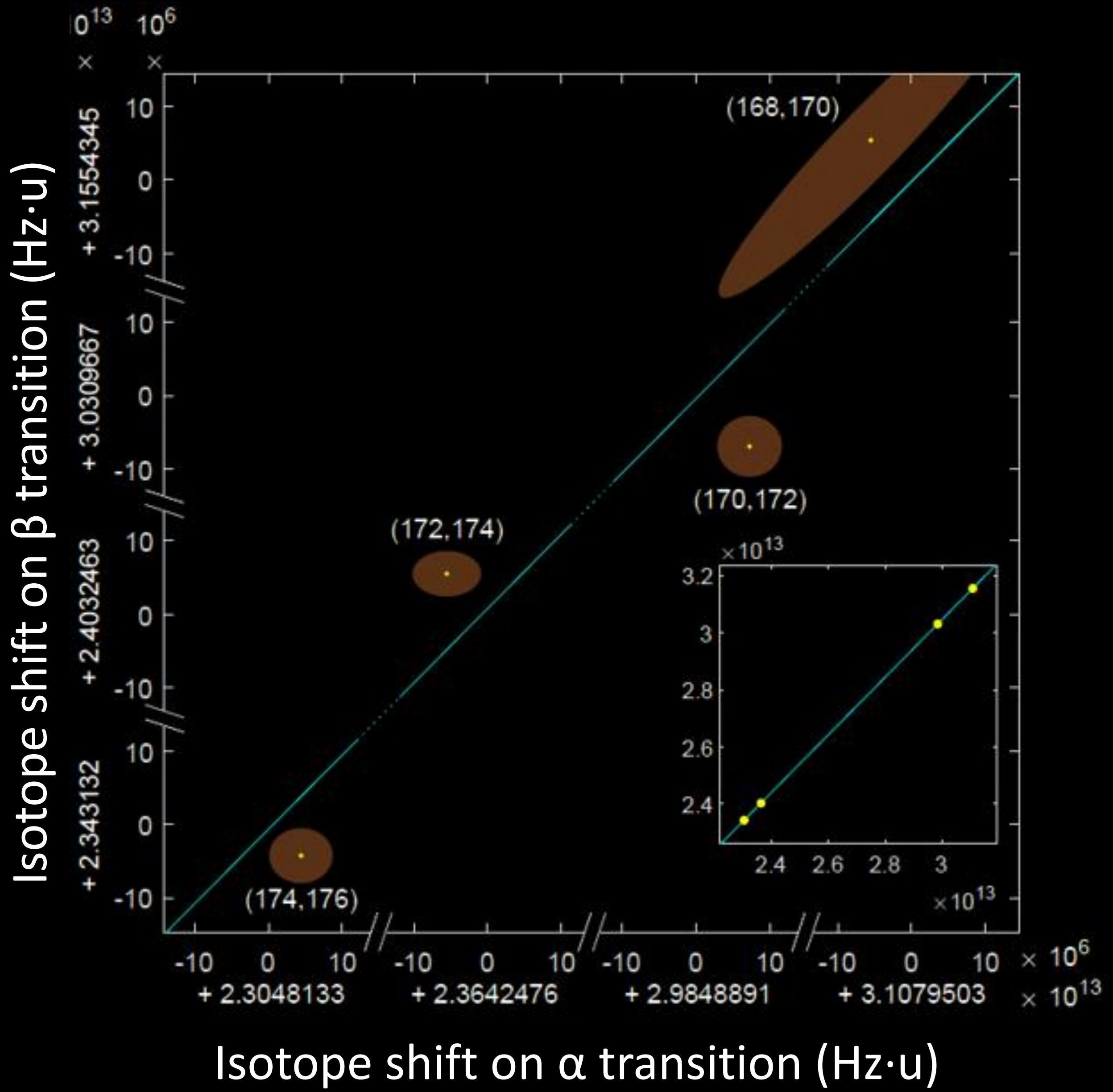
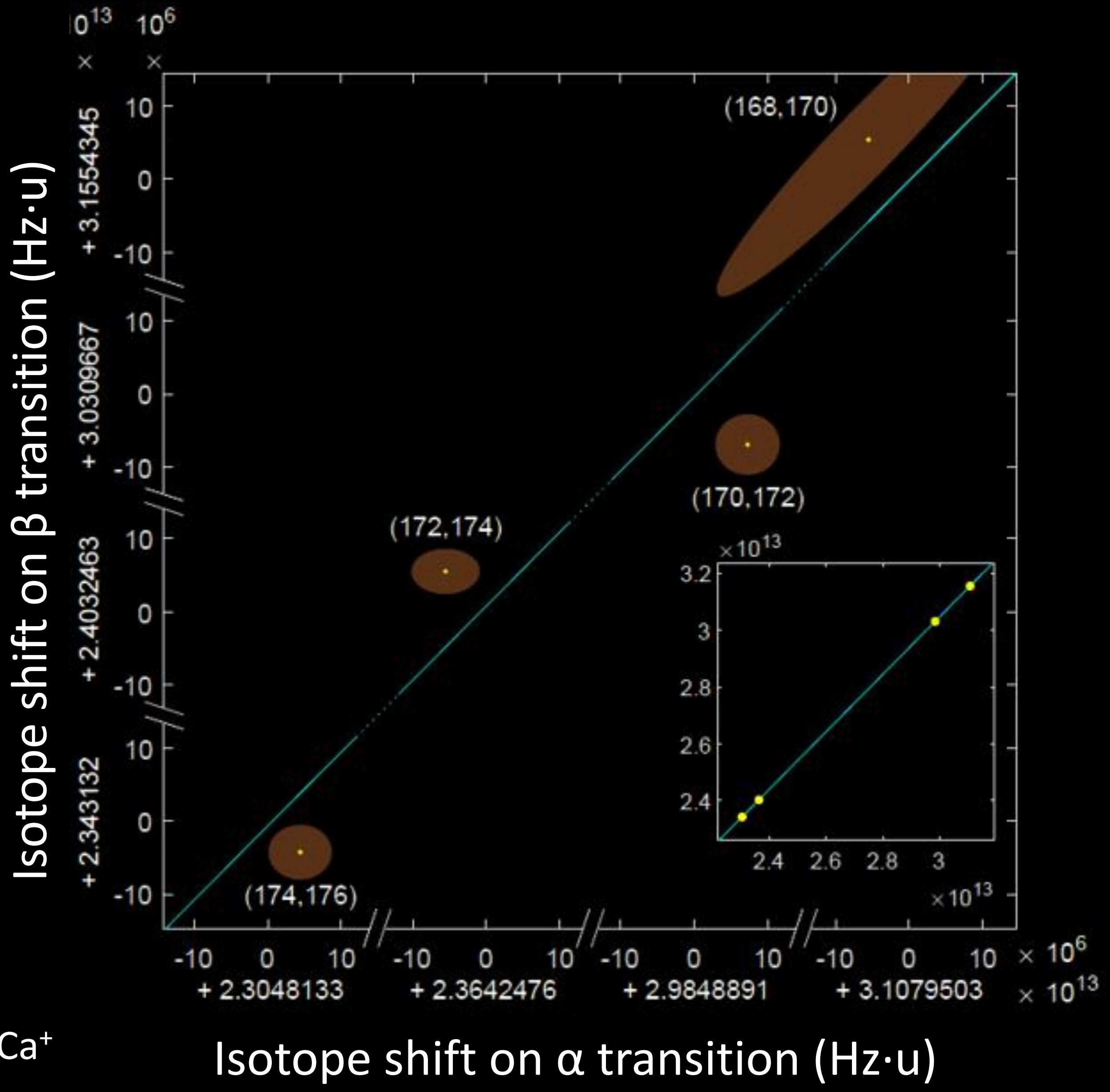


King Plot

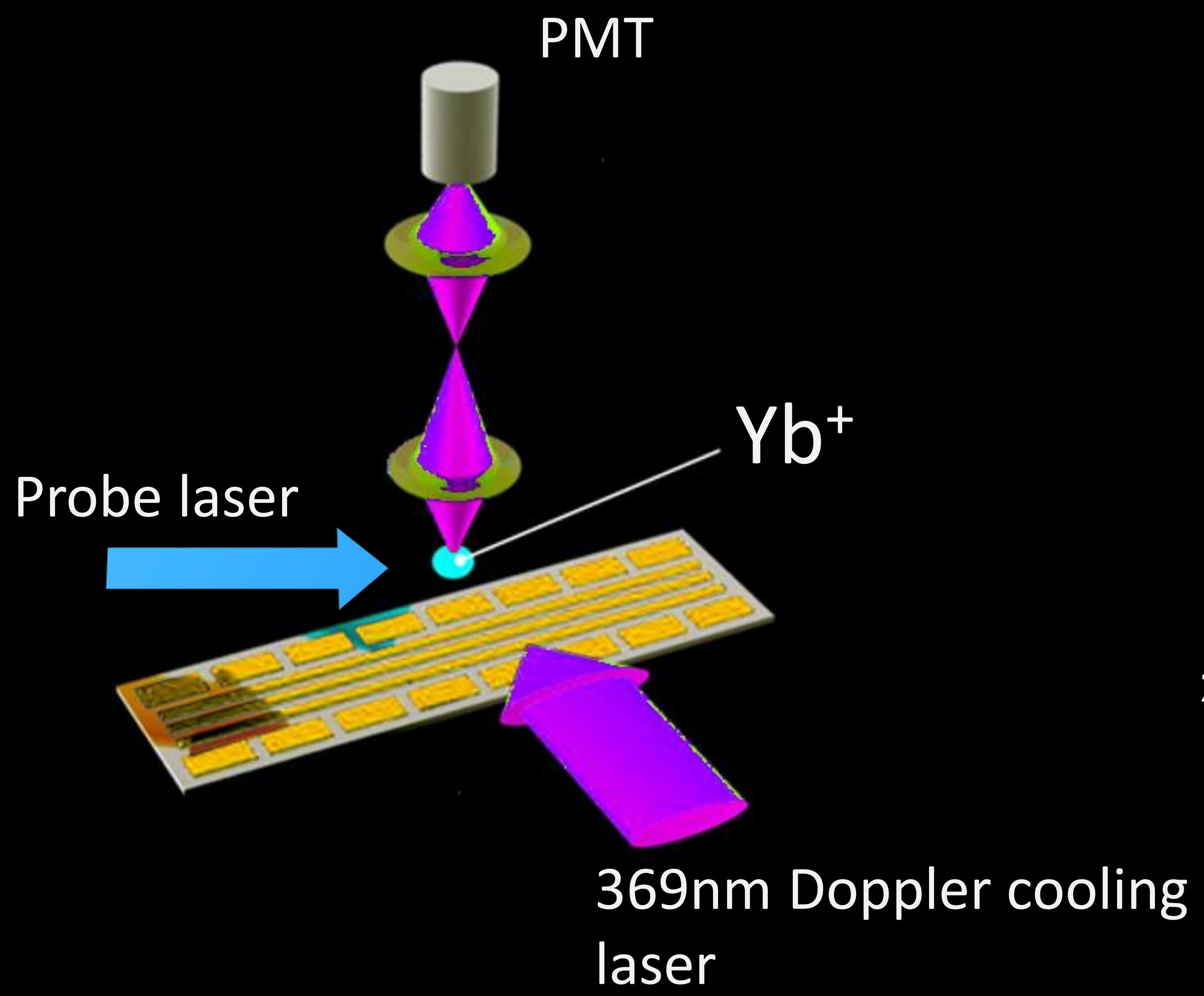
Zoom in by a factor of 1 million...

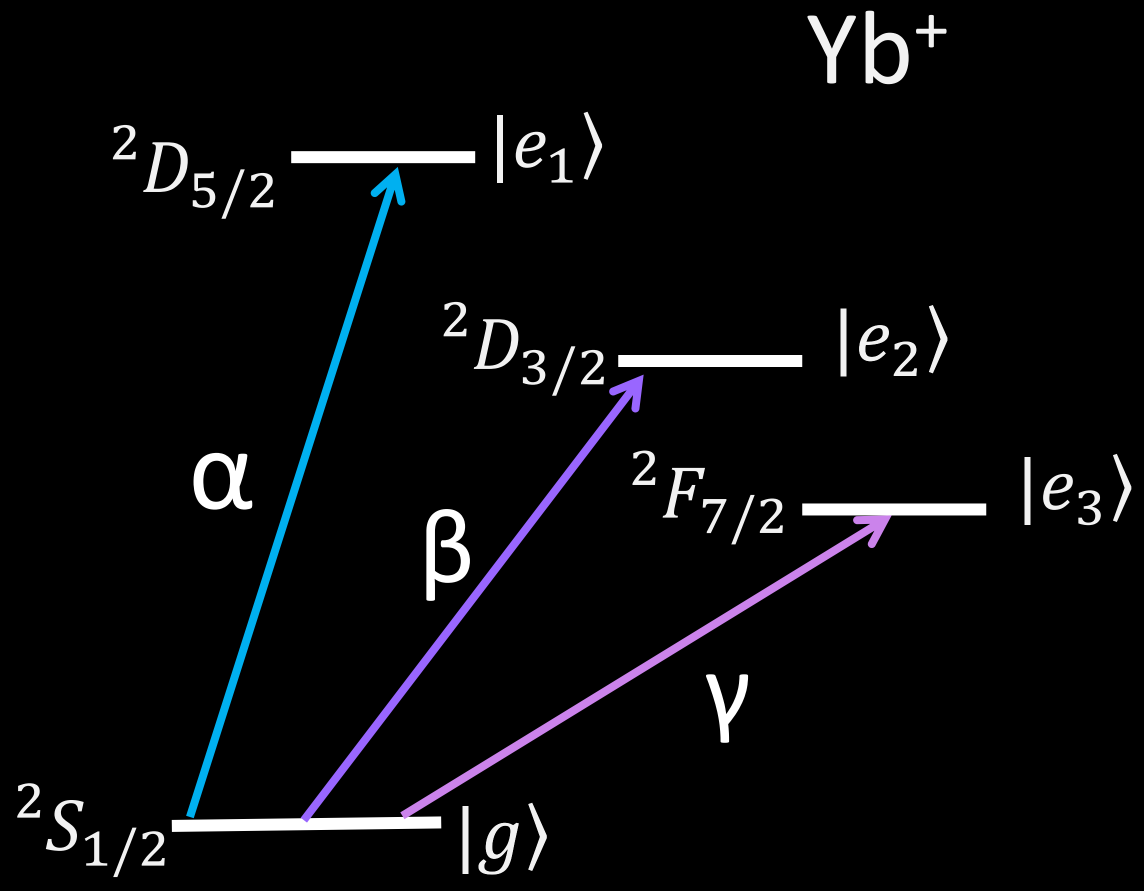
Deviation from linearity with 3σ confidence



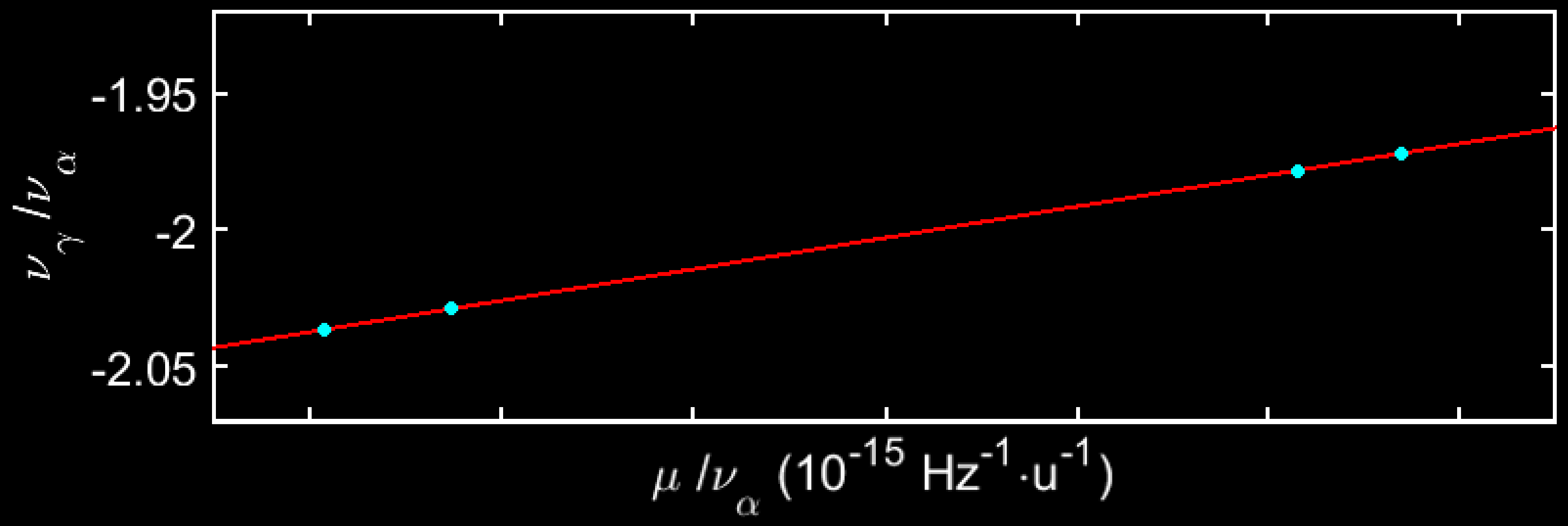
This work: Counts et al, PRL **125** 123002 (2020)
See also: Solaro et al, PRL **125** 123003 (2020) - Ca^+

The measurement

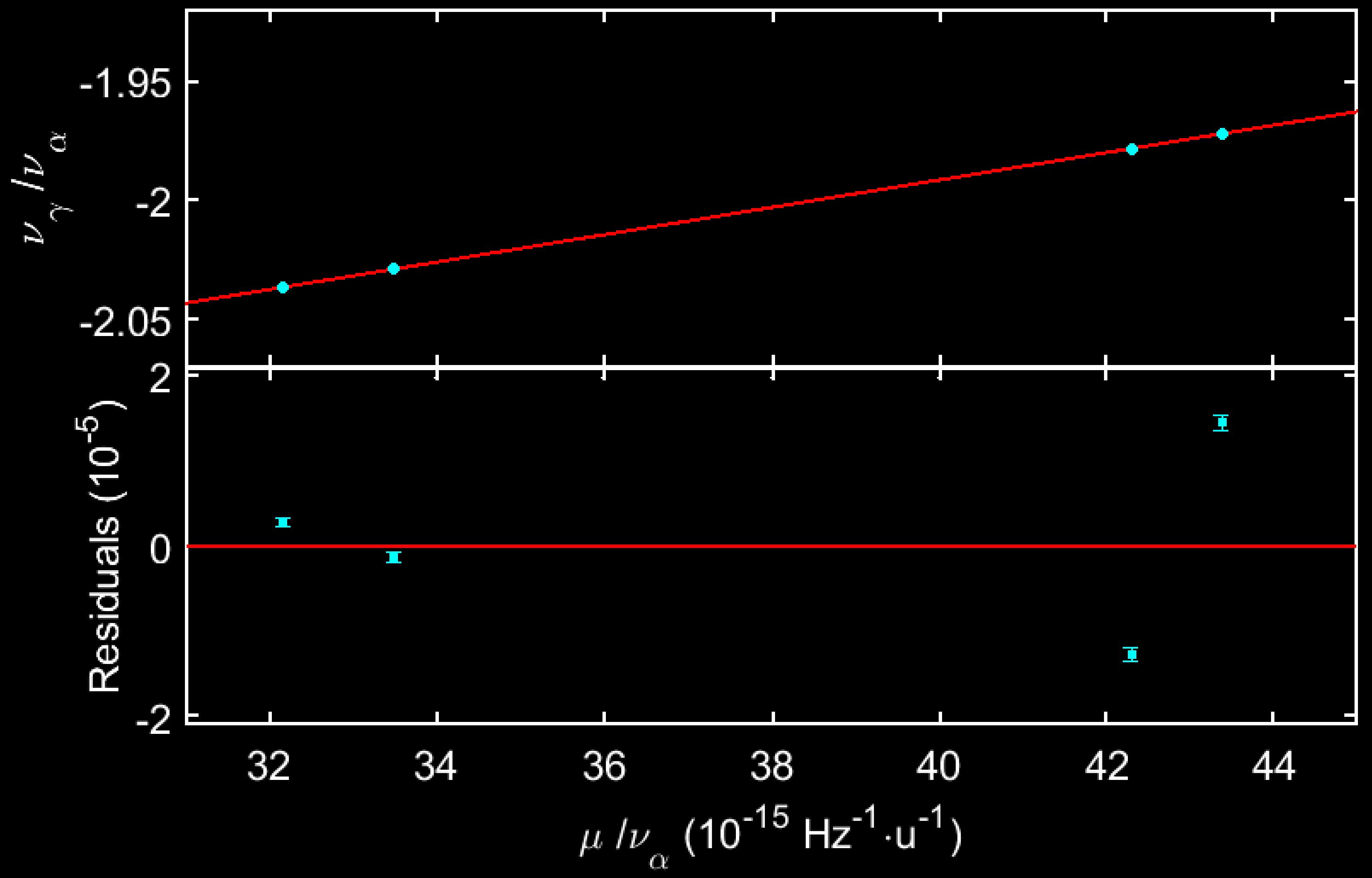




467-411 King Plot

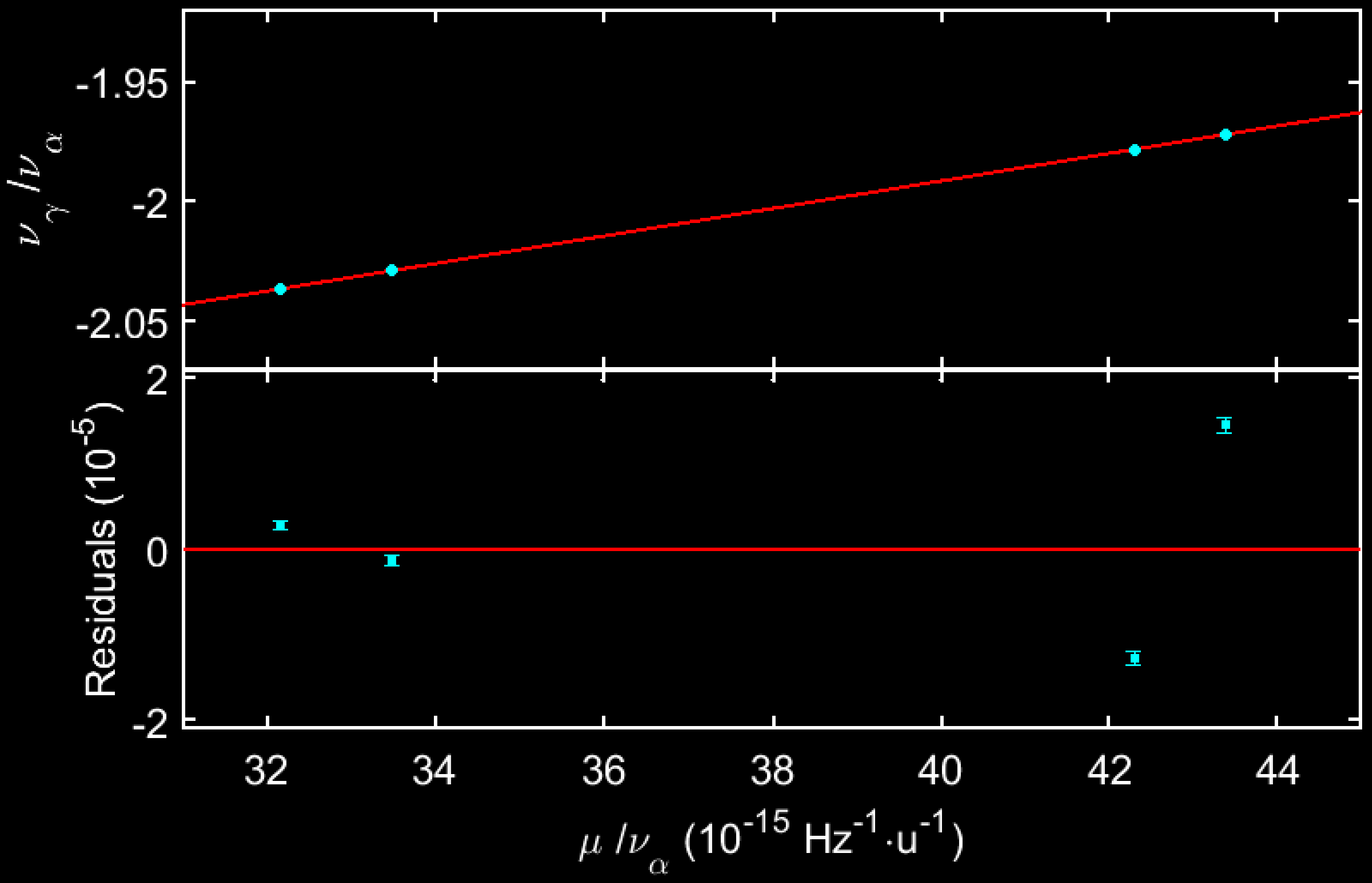


467-411 King Plot



See Hur, Aude Craik*, Counts* et al, PRL **128**, 163201 (2022)*

467-411 King Plot



41σ nonlinearity!

See Hur, Aude Craik*, Counts* et al, PRL **128**, 163201 (2022)*

So, is this a new dark matter boson?!

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Not necessarily.

There are higher-order standard model contributions that can also give rise to King-plot nonlinearity.

Mass shift | Field shift | Boson shift

$$\delta v^{AA'} = K\delta\mu_{AA'} + F\delta\langle r^2\rangle_{AA'} + \Phi_{AA'}$$

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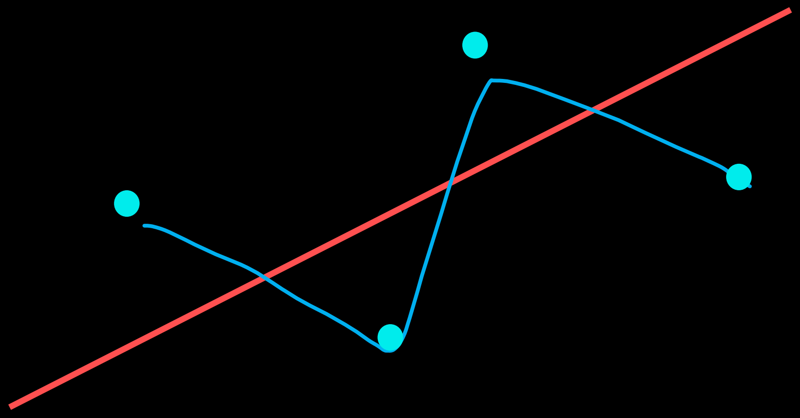
Mass shift | Field shift | Boson shift

$$\delta v^{AA'} = K\delta\mu_{AA'} + F\delta\langle r^2\rangle_{AA'} + \Phi_{AA'}$$

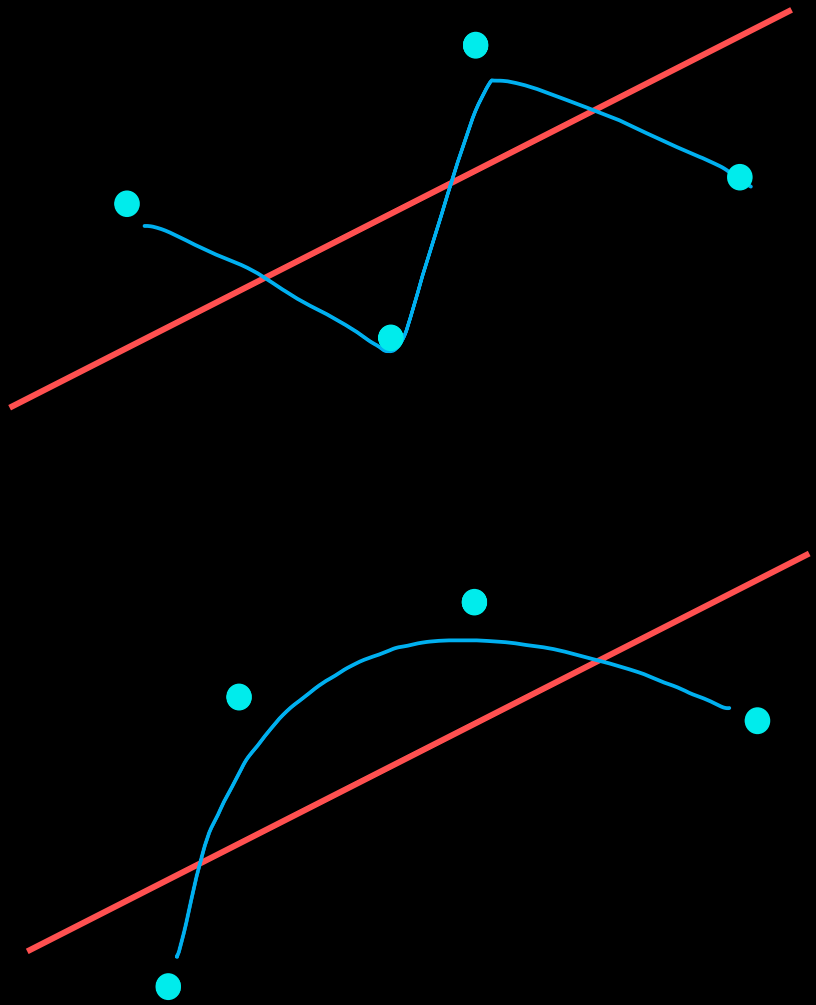
$$+ F^{(2)}\delta\langle r^4\rangle_{AA'} + \frac{dF}{d\langle r^2\rangle}\delta\langle r^2\rangle^2_{AA'} + \frac{dK}{d\mu}\delta\mu^2_{AA'} + \cdots$$

Higher-order SM terms

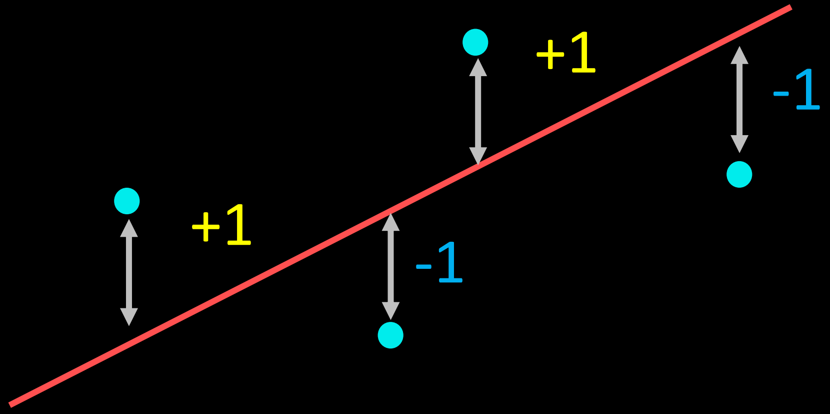
Origin of the nonlinearity



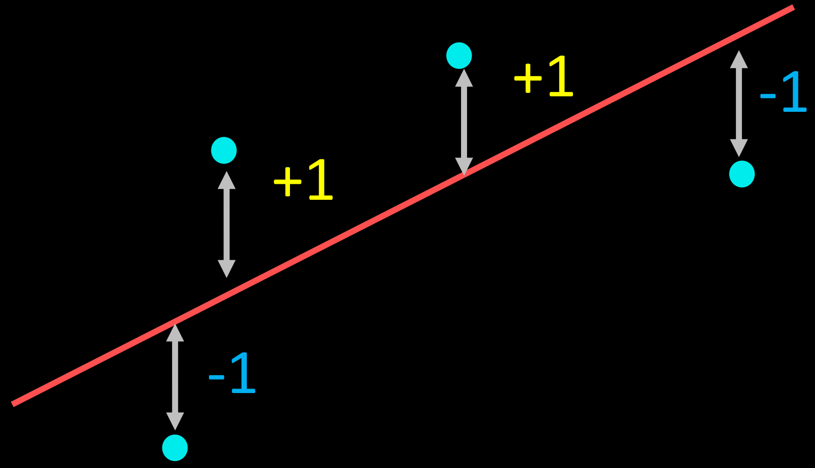
Origin of the nonlinearity



Shape of the nonlinearity



$$\vec{d}_{zig} \equiv \begin{pmatrix} +1 \\ -1 \\ +1 \\ -1 \end{pmatrix}$$



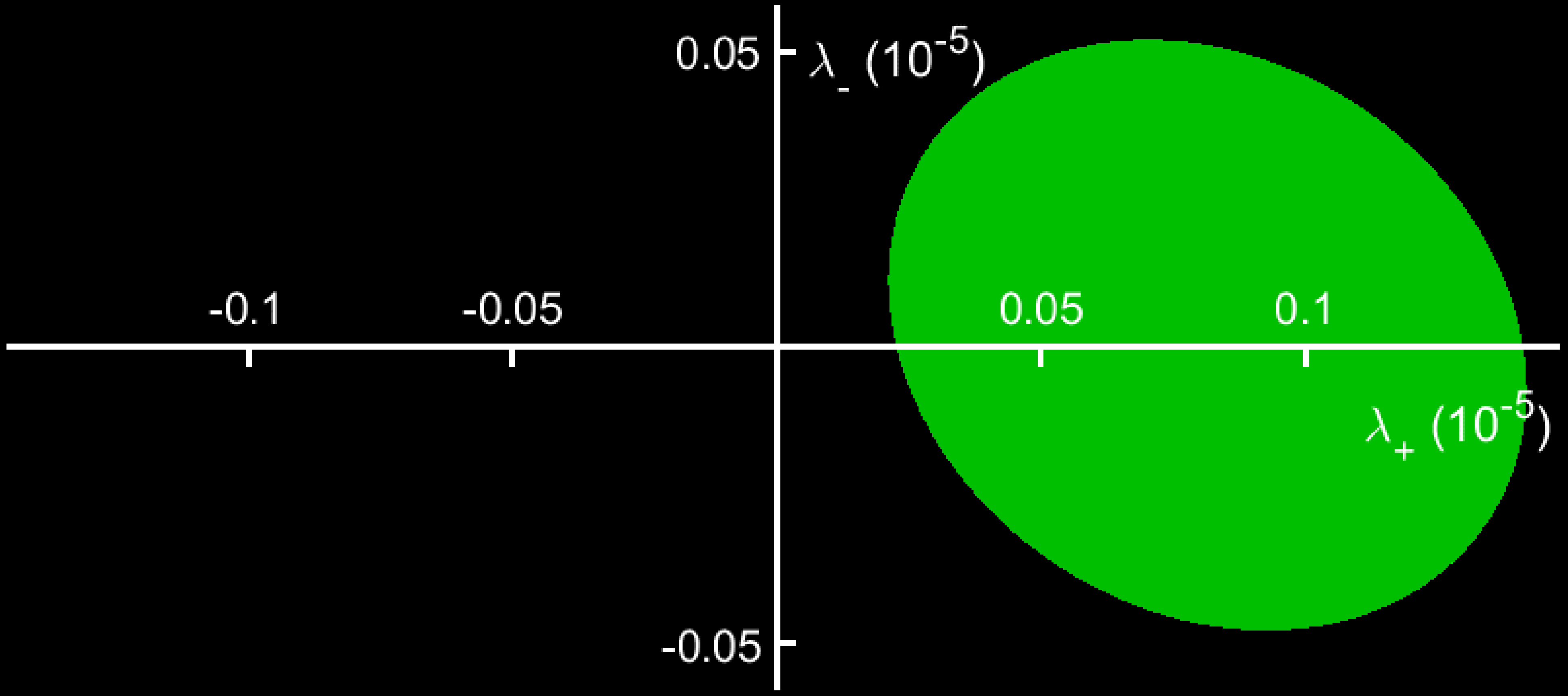
$$\vec{d}_{curv} \equiv \begin{pmatrix} -1 \\ +1 \\ +1 \\ -1 \end{pmatrix}$$

Shape of the nonlinearity

$$\vec{\boldsymbol{d}} = \lambda_+ \begin{pmatrix} +1 \\ -1 \\ +1 \\ -1 \end{pmatrix} + \lambda_- \begin{pmatrix} -1 \\ +1 \\ +1 \\ -1 \end{pmatrix} = \lambda_+ \vec{\boldsymbol{d}}_{\boldsymbol{zig}} + \lambda_- \vec{\boldsymbol{d}}_{\boldsymbol{curve}}$$

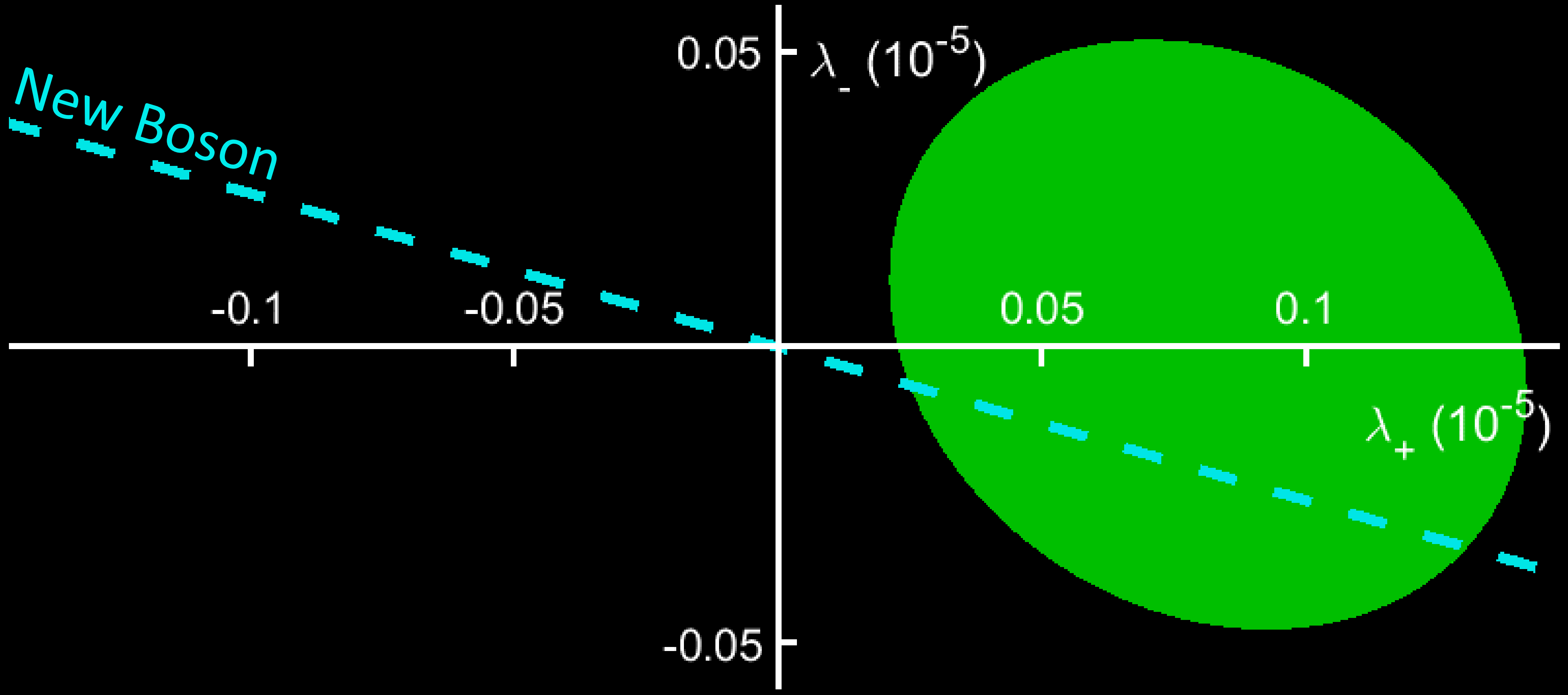
Origin of the non-linearity

$$\vec{d} = \lambda_+ \vec{d}_{zig} + \lambda_- \vec{d}_{curve}$$



Origin of the non-linearity

$$\vec{d} = \lambda_+ \vec{d}_{zig} + \lambda_- \vec{d}_{curve}$$



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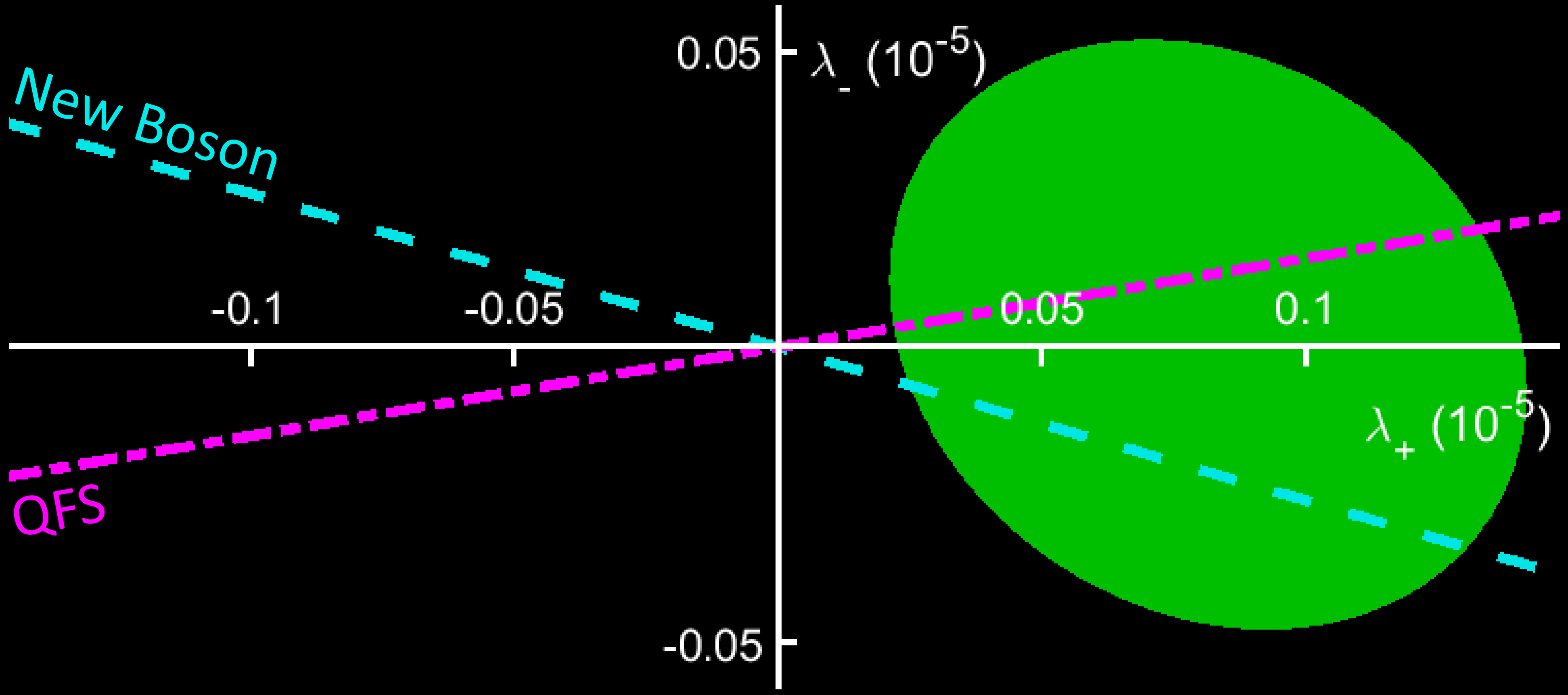

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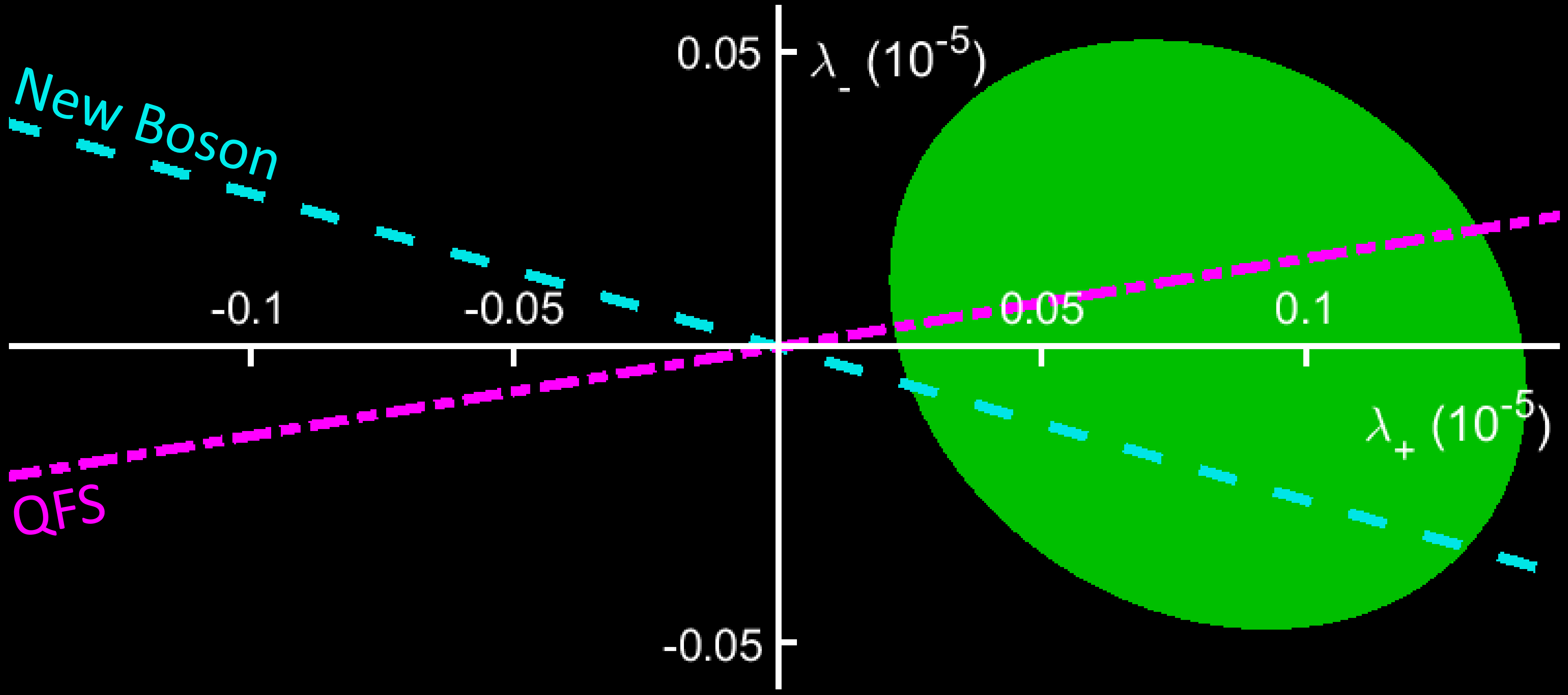

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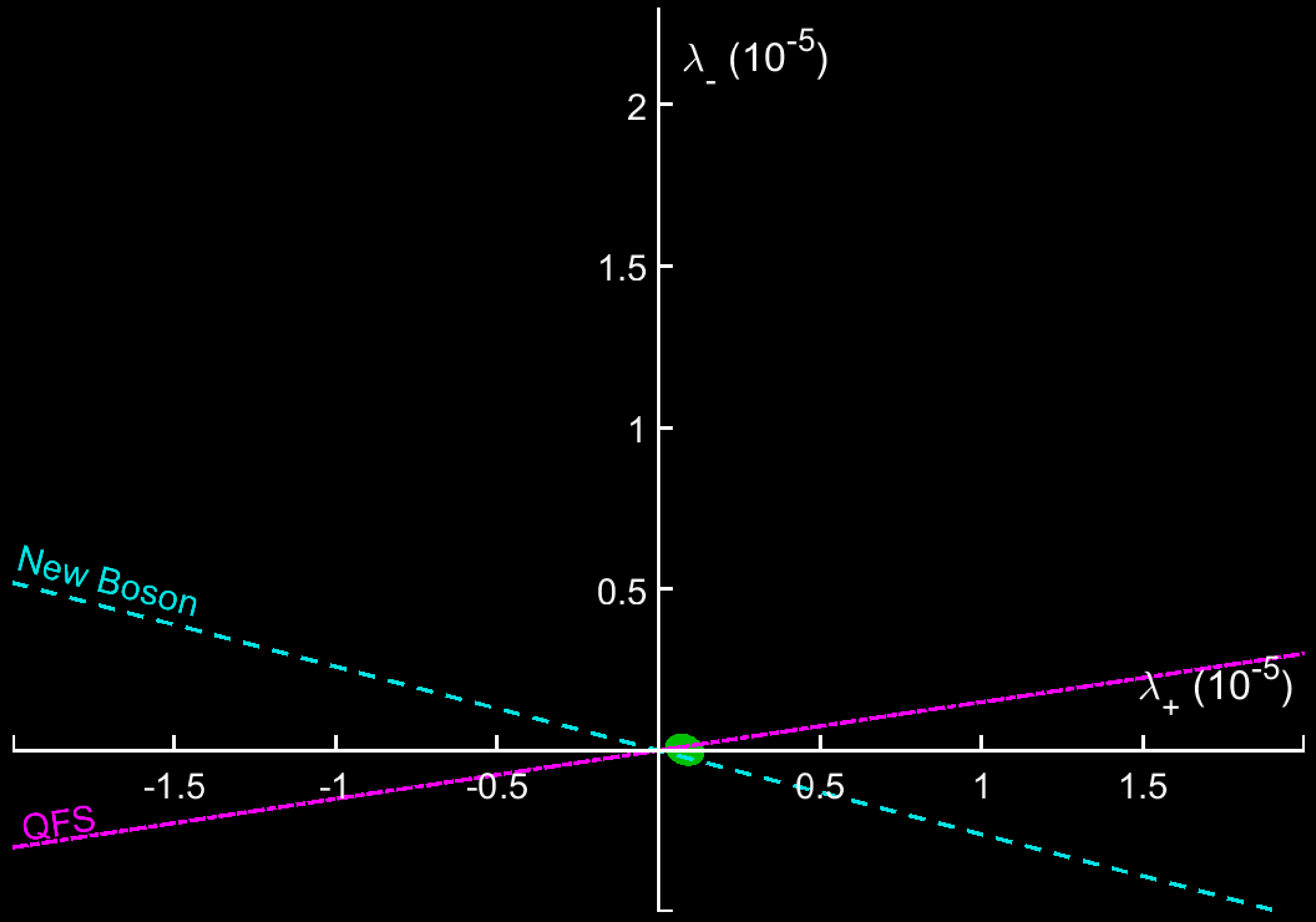

See Hur, <u>Aude Craik</u>*, Counts* et al, PRL **128**, 163201 (2022)*

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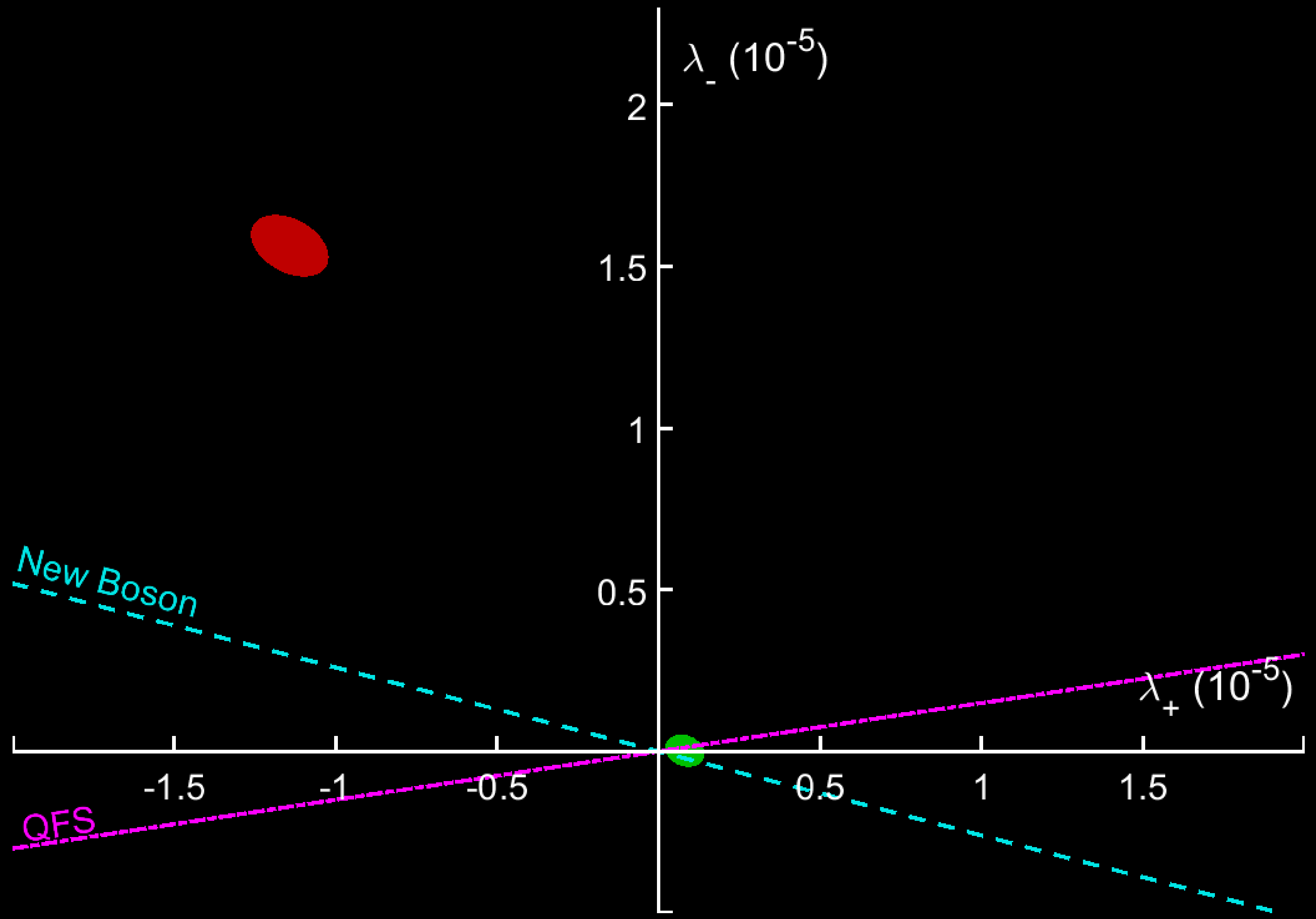


See Hur, Aude Craik*, Counts* et al, PRL **128**, 163201 (2022)*

Higher order SM contributions

4th order nuclear charge moment

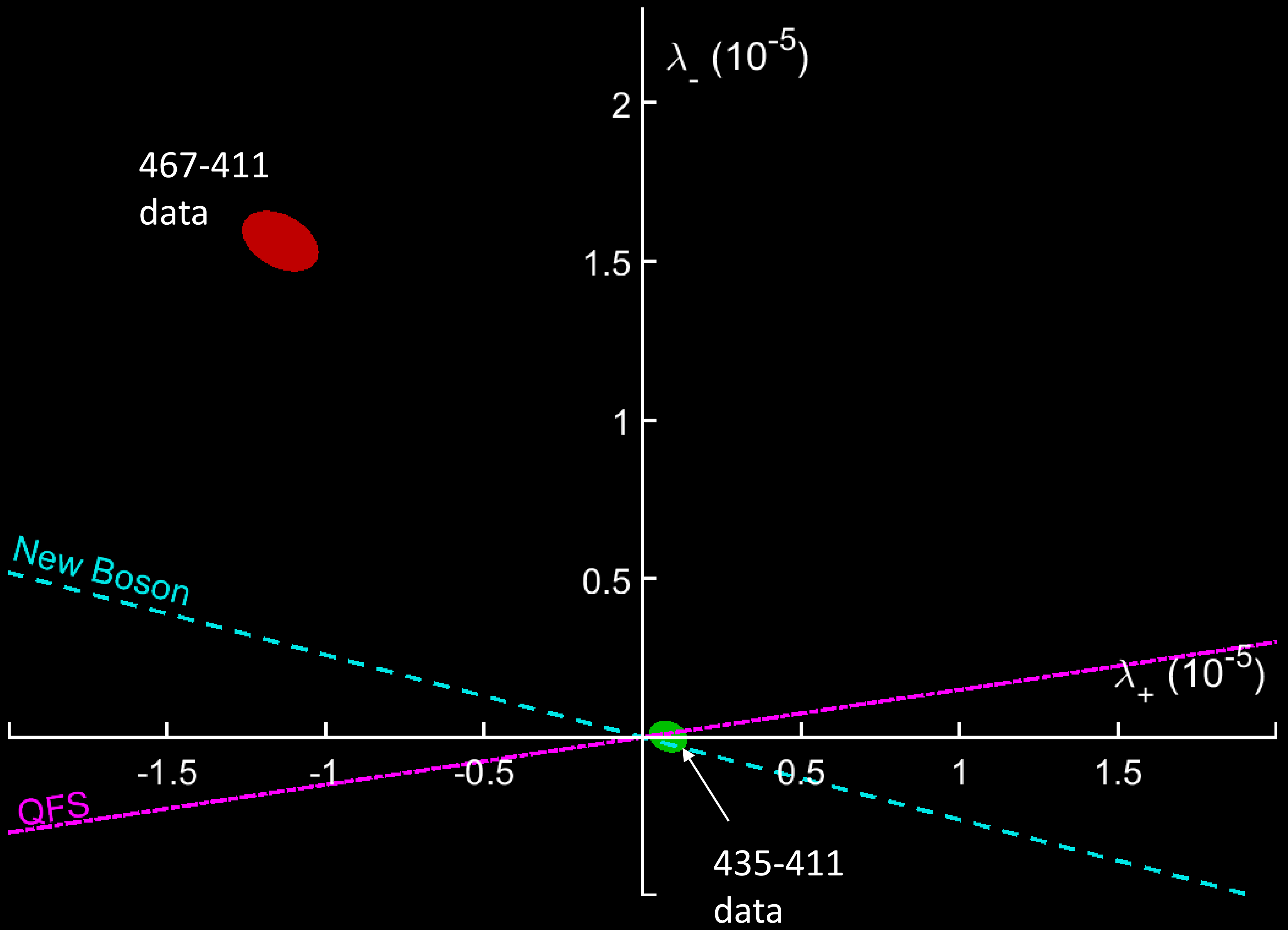
QFS

Second order mass shift – O (10Hz)

$$+ F^{(2)}\delta\langle r^4\rangle_{AA'} + \frac{dF}{d\langle r^2\rangle}\delta\langle r^2\rangle^2_{AA'} + \cancel{\frac{dK}{d\mu}\delta\mu^2_{AA'}} + \cdots$$

Higher-order SM terms

Origin of the non-linearity



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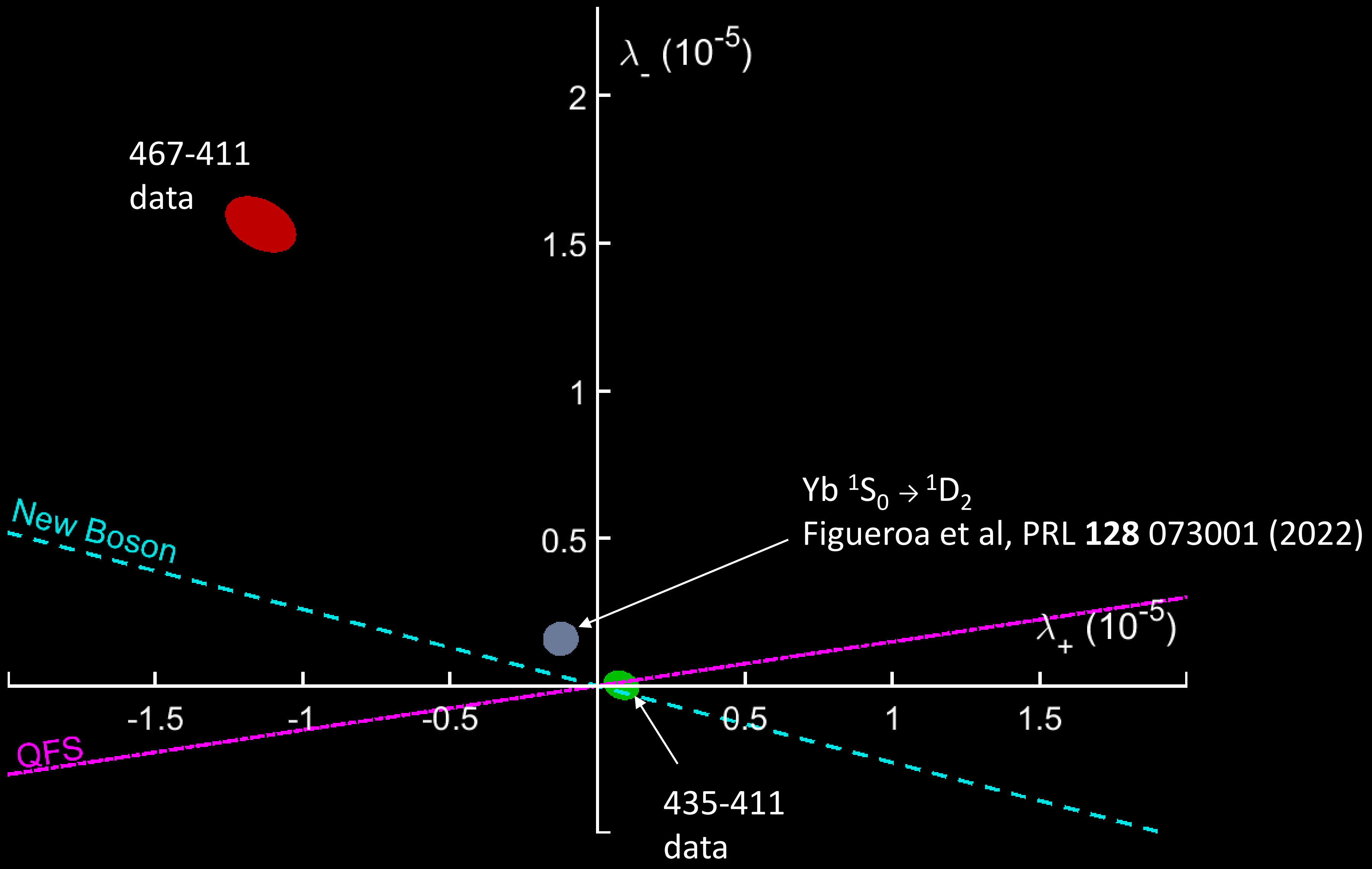
Origin of the non-linearity



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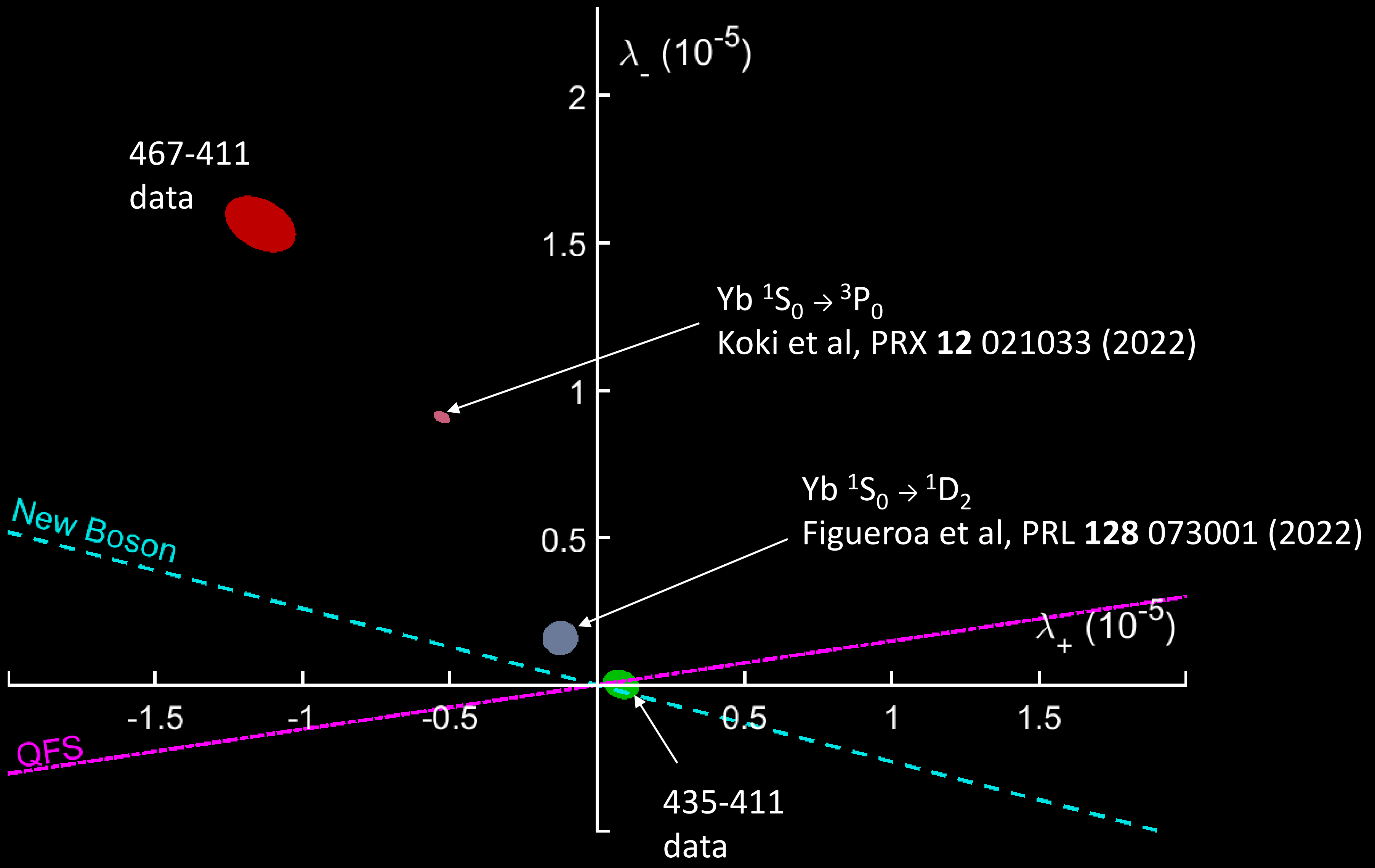

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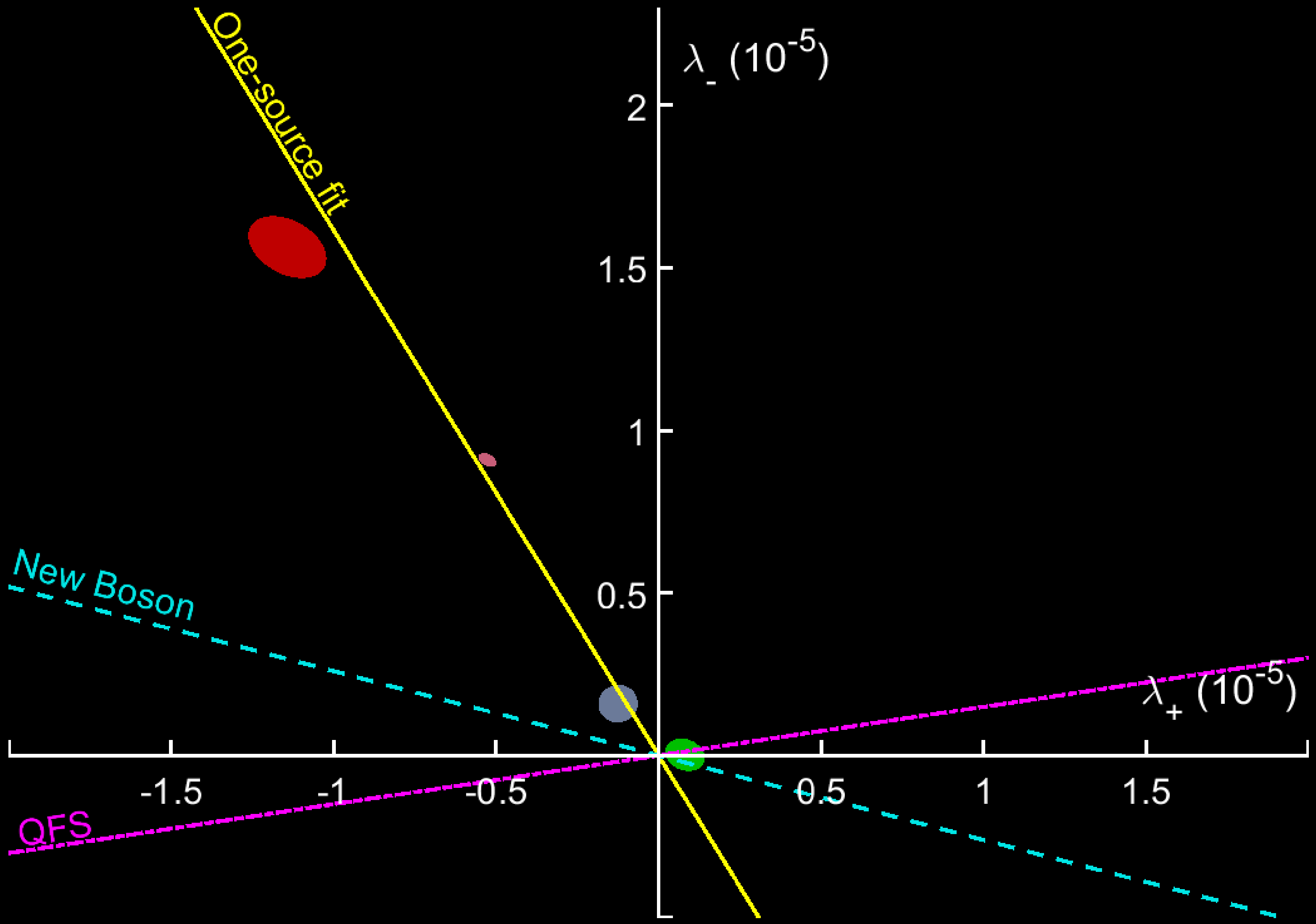

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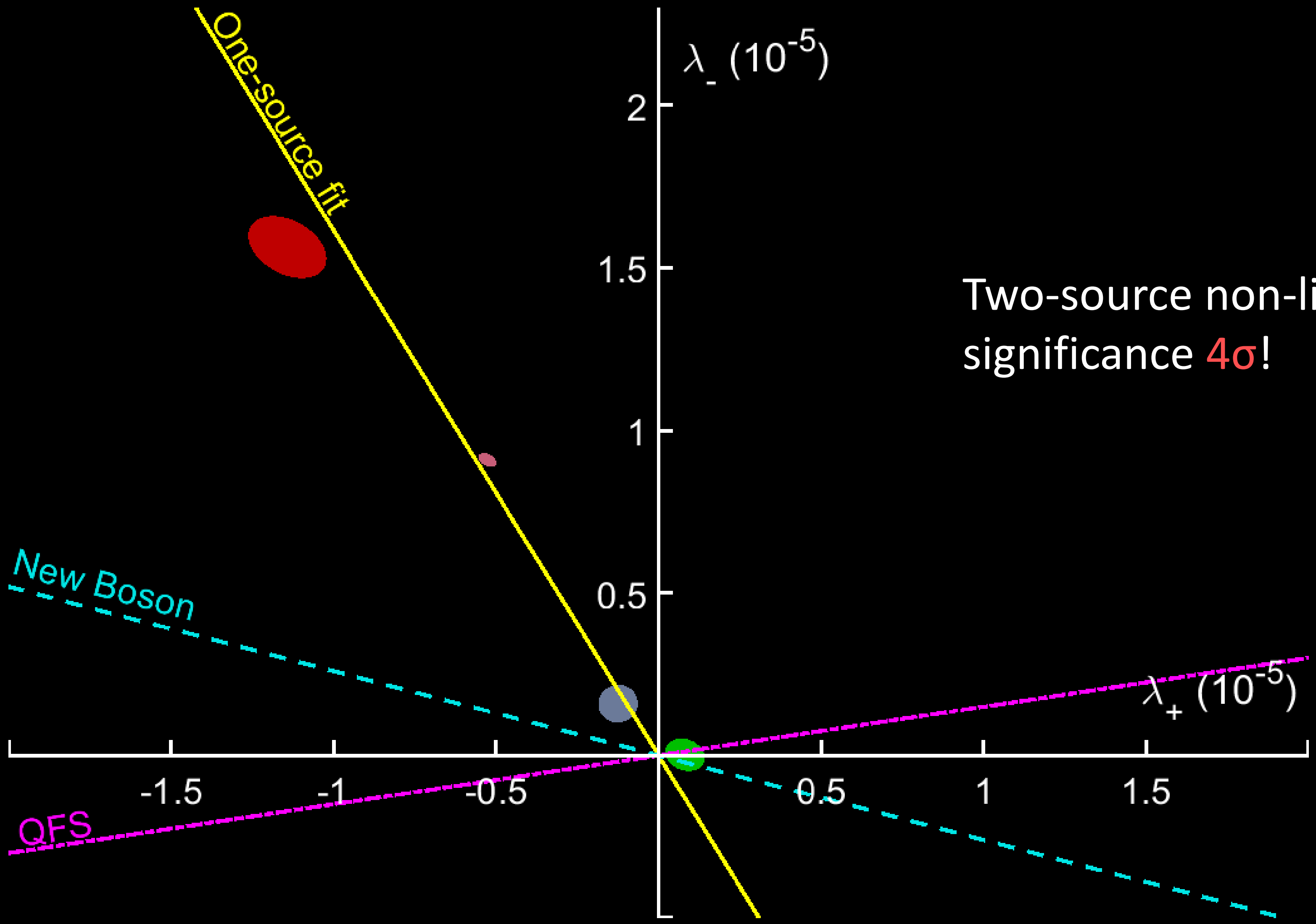
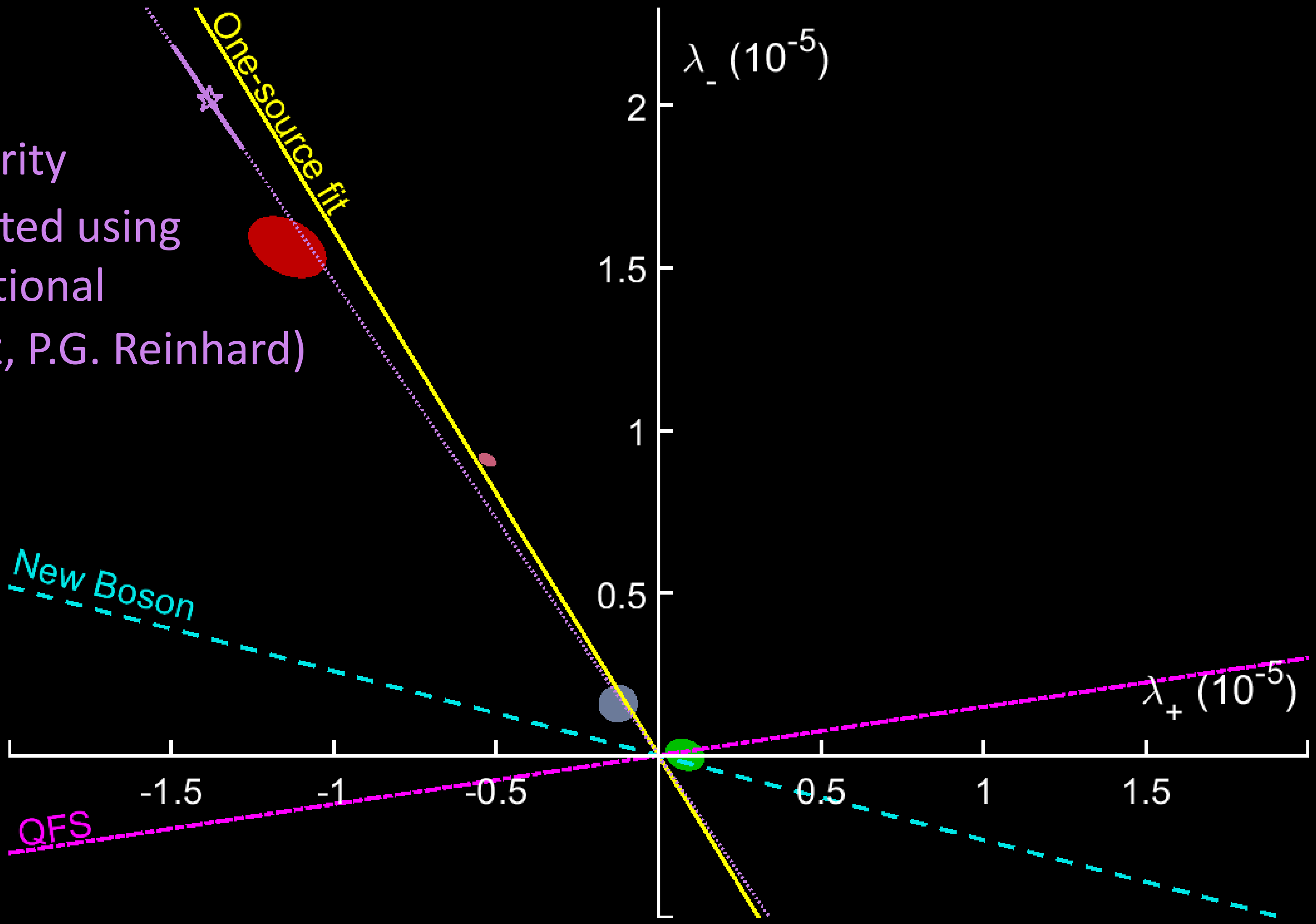


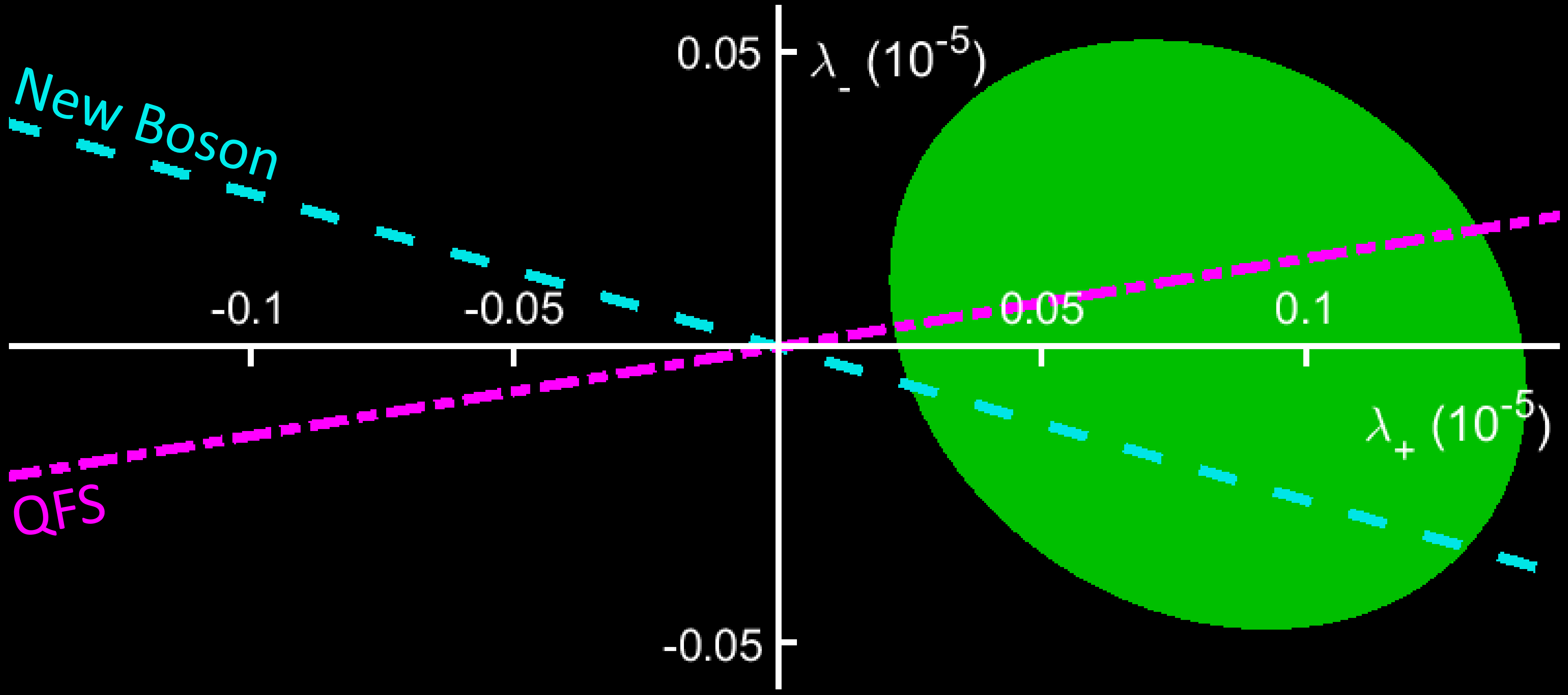
Two-source non-linearity significance 4σ!

Origin of the non-linearity

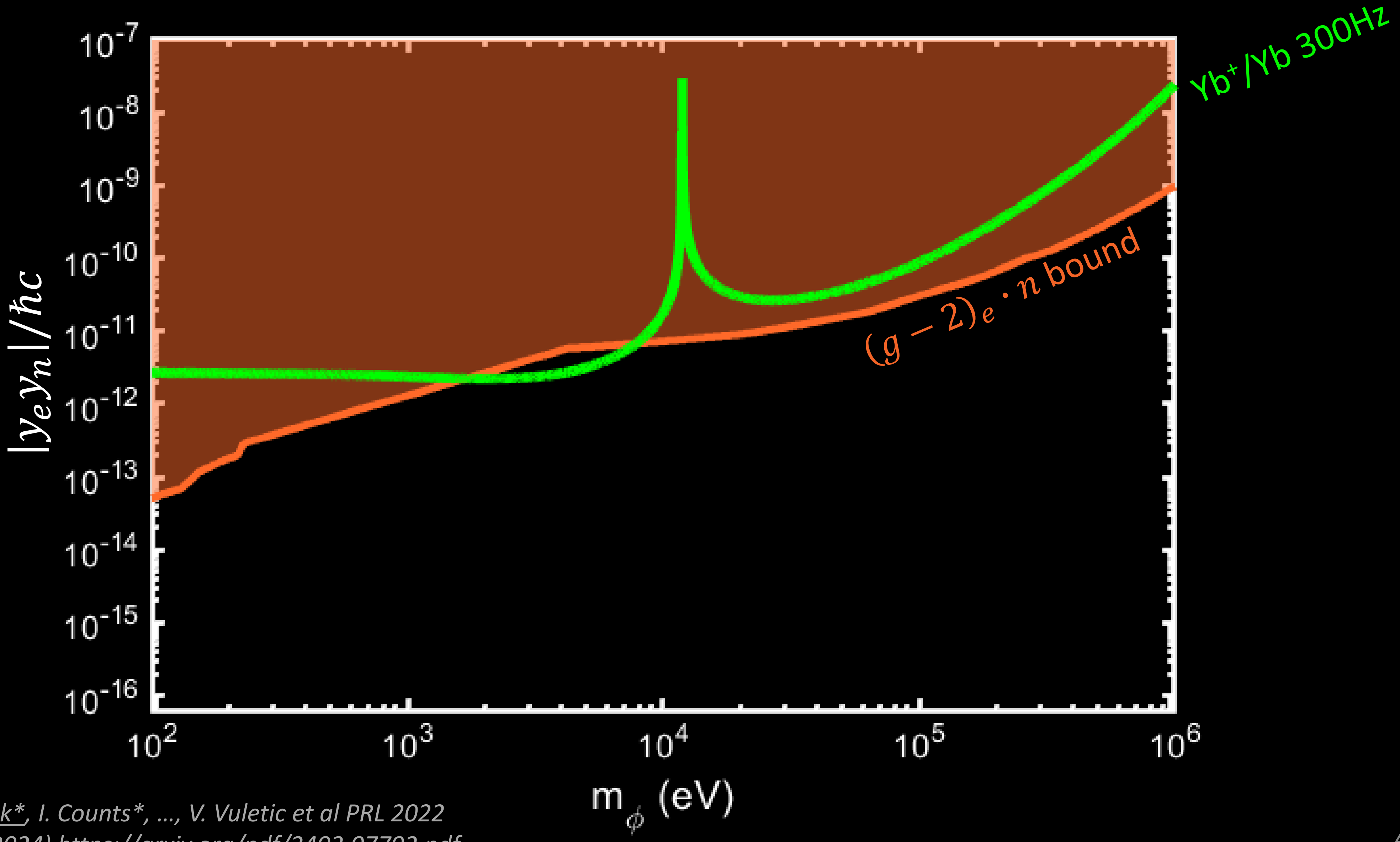
$\delta\langle r^4 \rangle$ nonlinearity
Direction predicted using the Fayans functional
(W. Nazarewicz, P.G. Reinhard)



Origin of the non-linearity

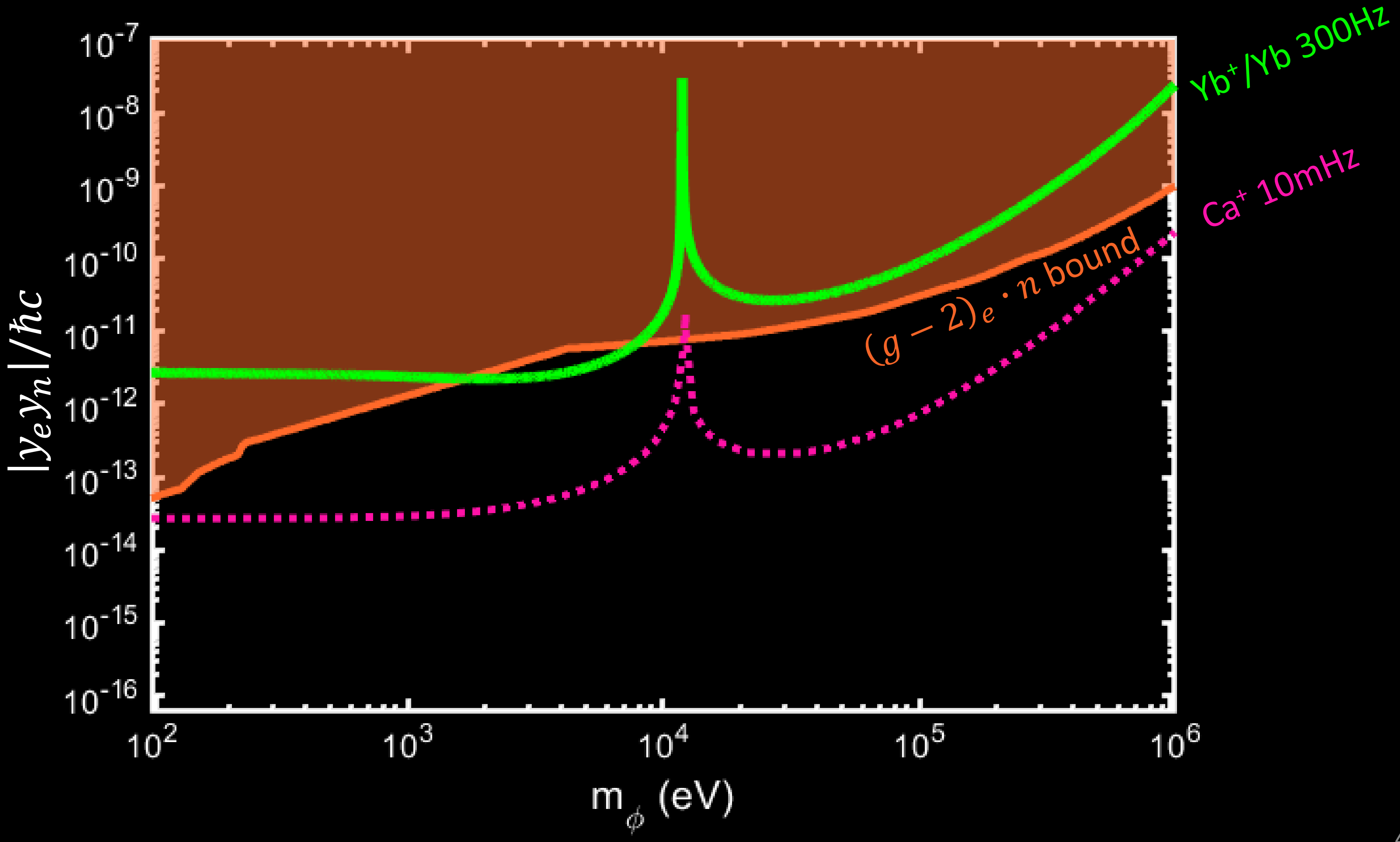


Bounds on new physics



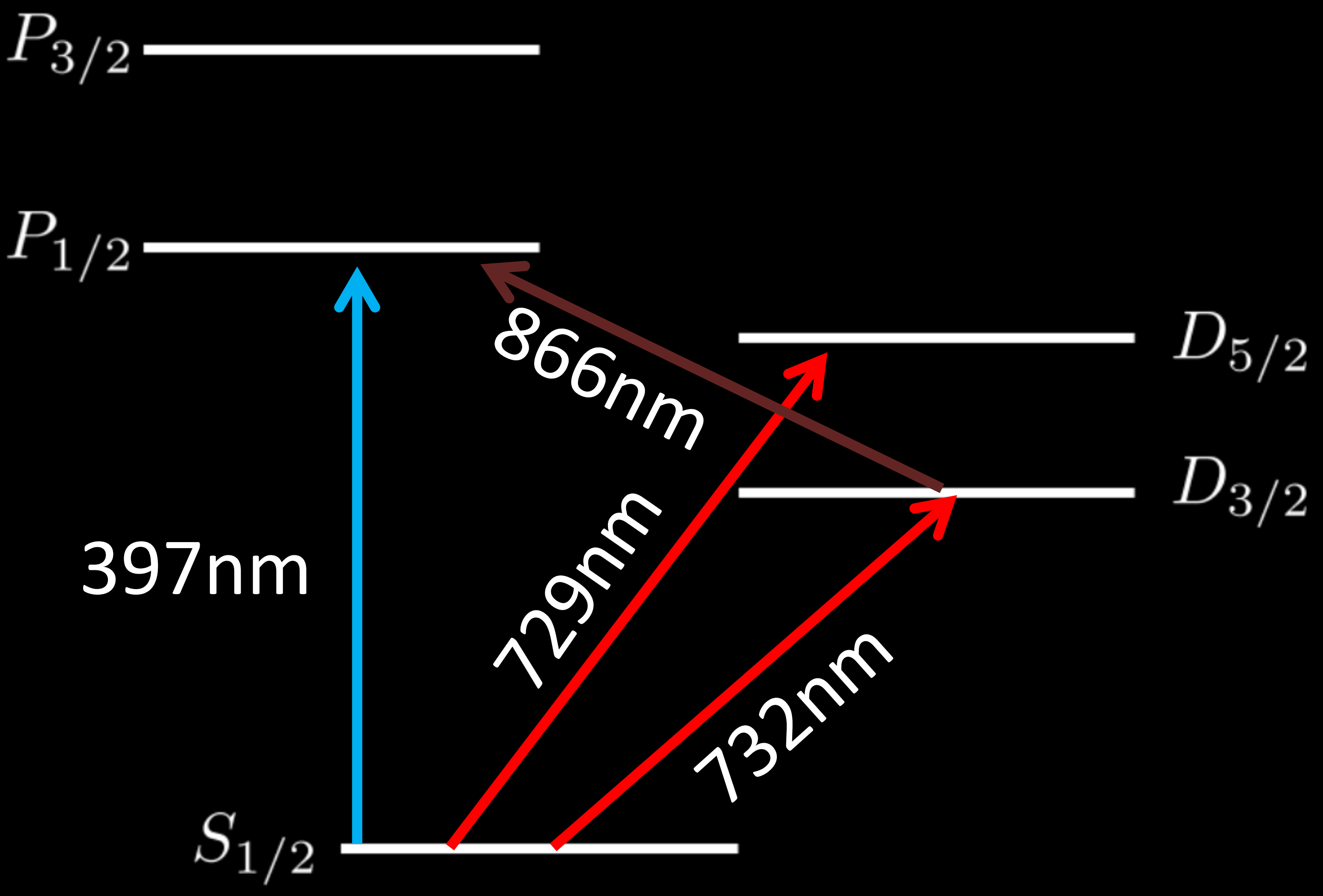
J. Hur, D. P. L. Aude Craik*, I. Counts*, …, V. Vuletic et al PRL 2022*
See also: M. Door et al (2024) https://arxiv.org/pdf/2403.07792.pdf

Bounds on new physics

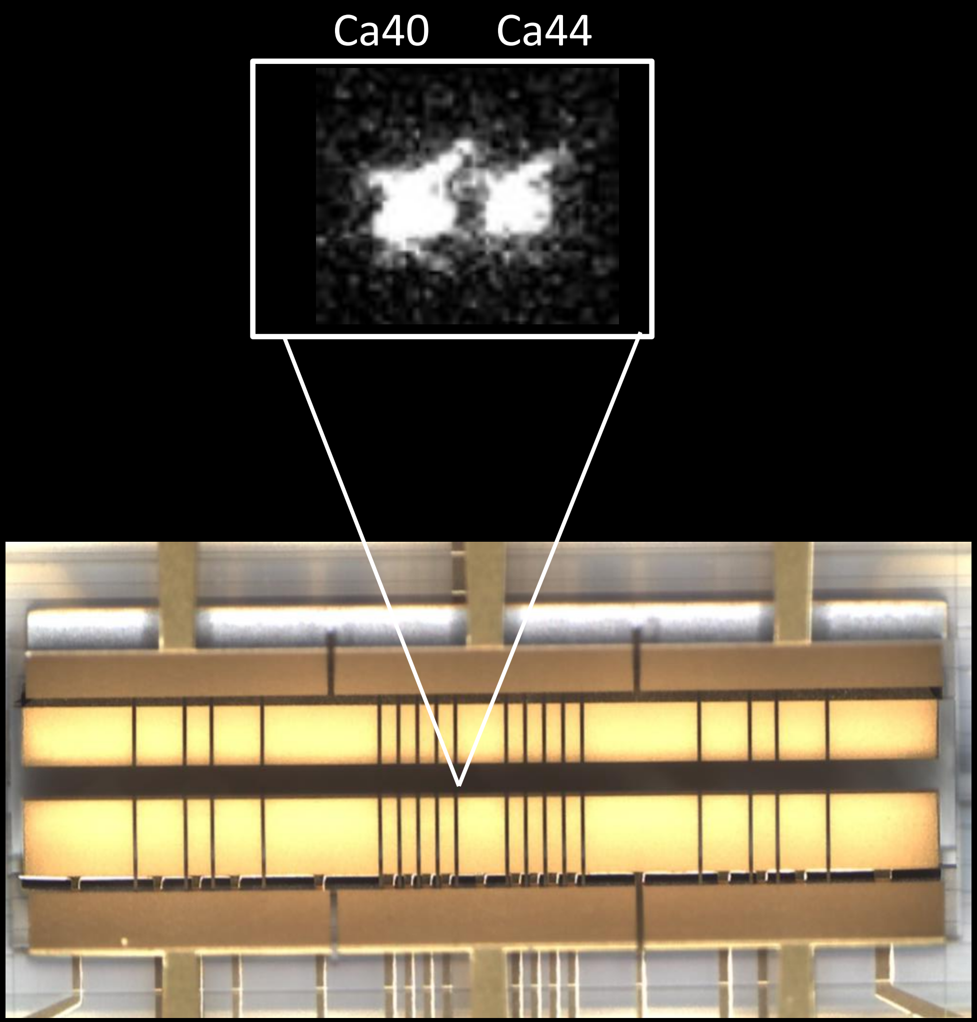


IS spectroscopy at ETHZ - Calcium

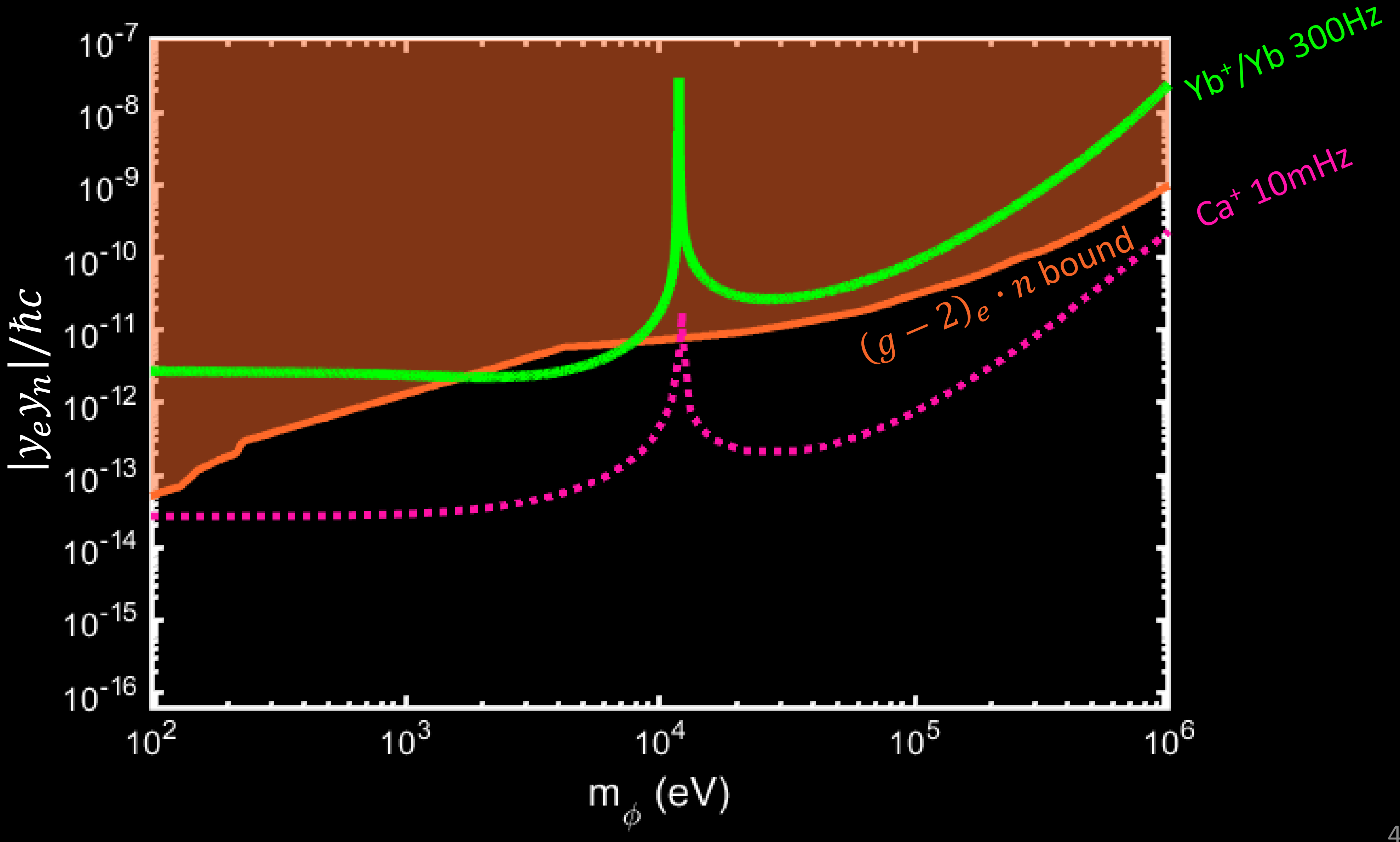
Ca^+



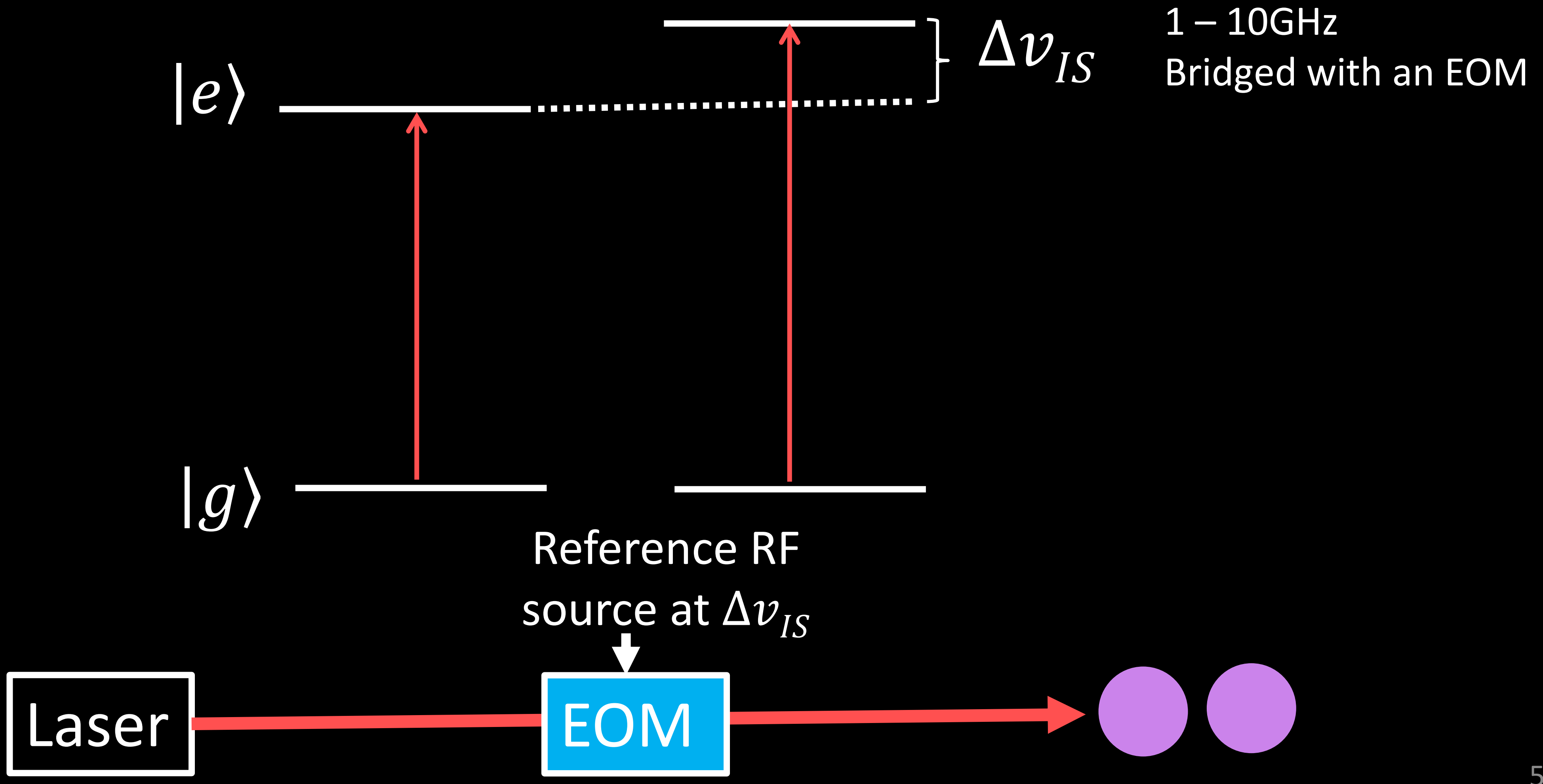
Isotope shift spectroscopy in Calcium @ ETH



Bounds on new physics

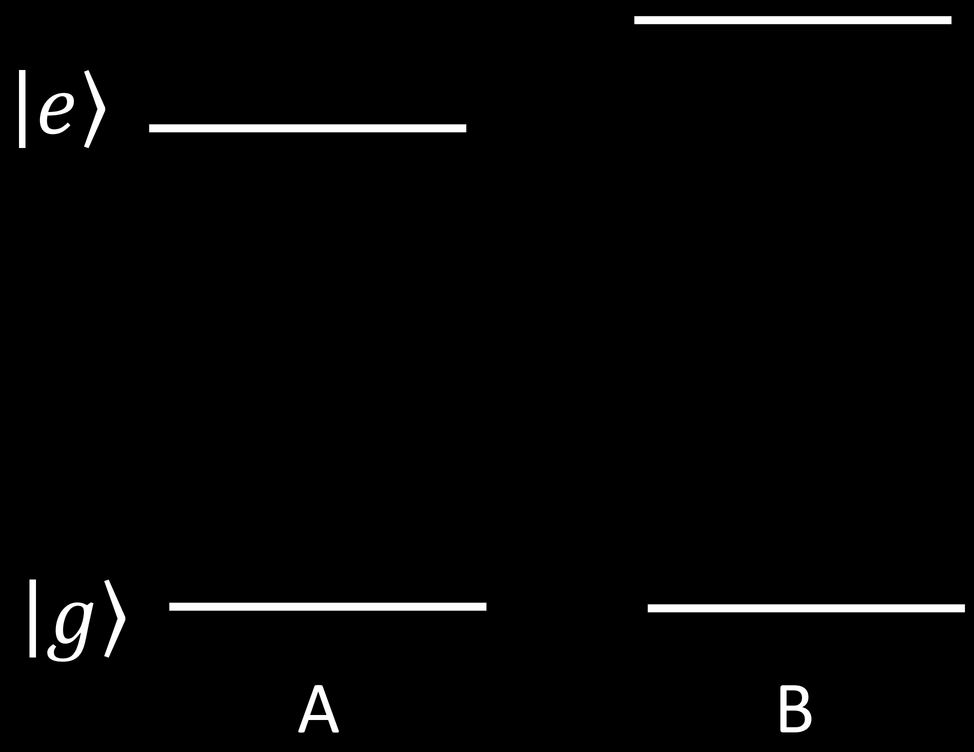


IS spectroscopy on co-trapped Ca⁺ isotopes



Decoherence-free subspace

See Manovitz *et al*, *PRL 123, 203001* (2019)
And C. F. Roos *et al, Nature 443* (2006)



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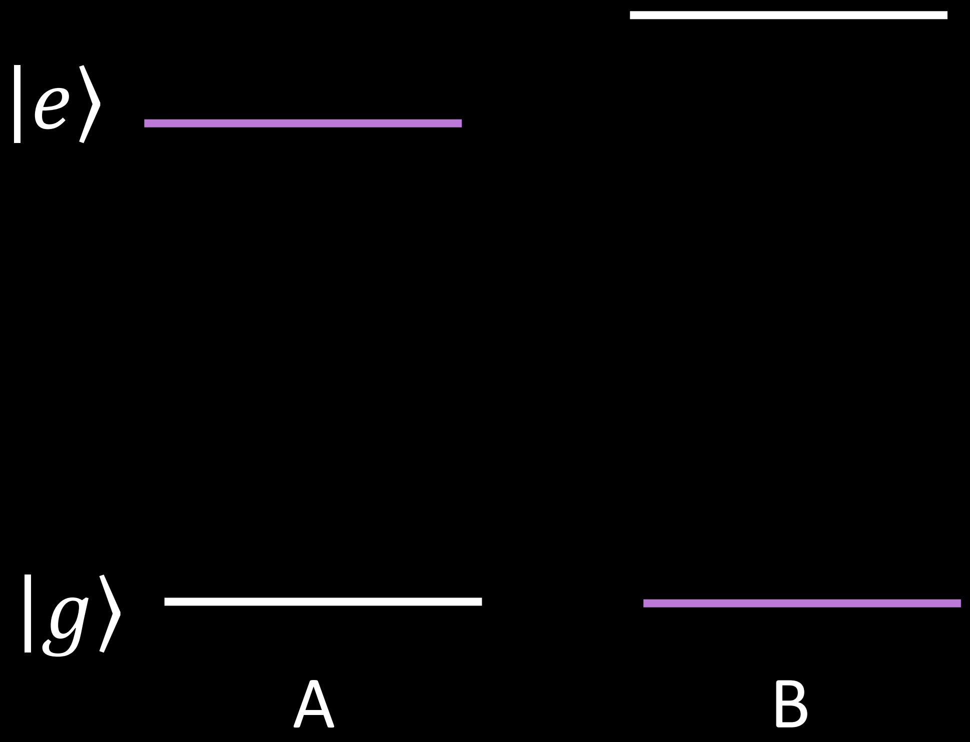

$|e_A g_B\rangle$

Decoherence-free subspace

See Manovitz *et al*, *PRL 123, 203001* (2019)
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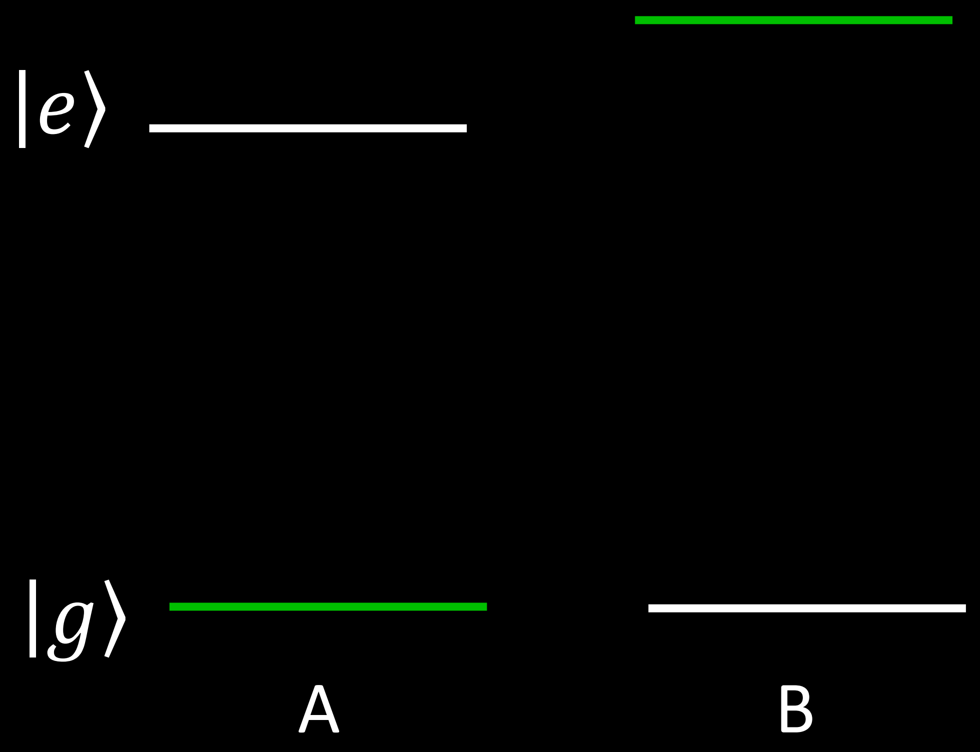
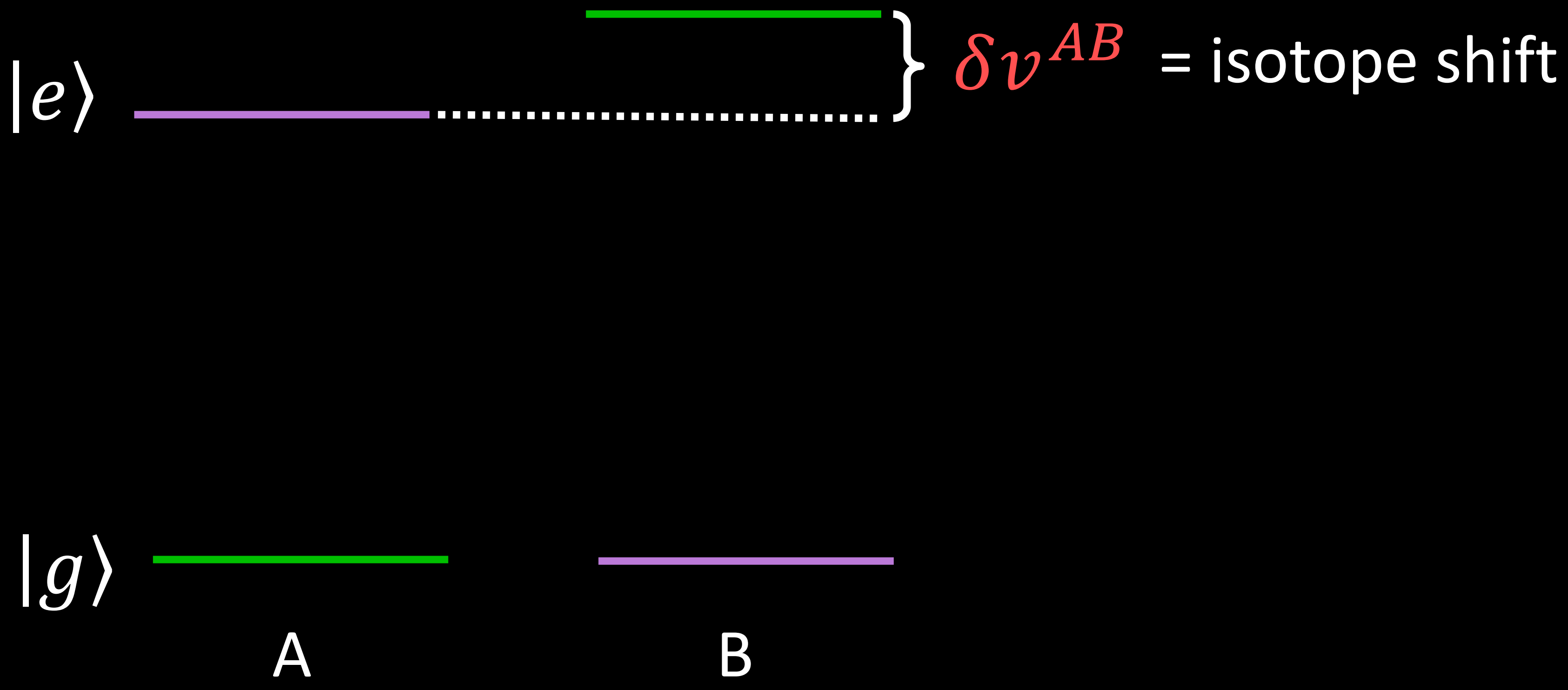


$$|e_A g_B\rangle + |g_A e_B\rangle$$

Decoherence-free subspace

See Manovitz *et al*, *PRL 123, 203001* (2019)
And C. F. Roos *et al, Nature 443* (2006)



$$|e_A g_B\rangle + e^{i\delta v^{AB} t}|g_A e_B\rangle$$

Decoherence-free subspace

See Manovitz *et al*, *PRL 123, 203001* (2019)
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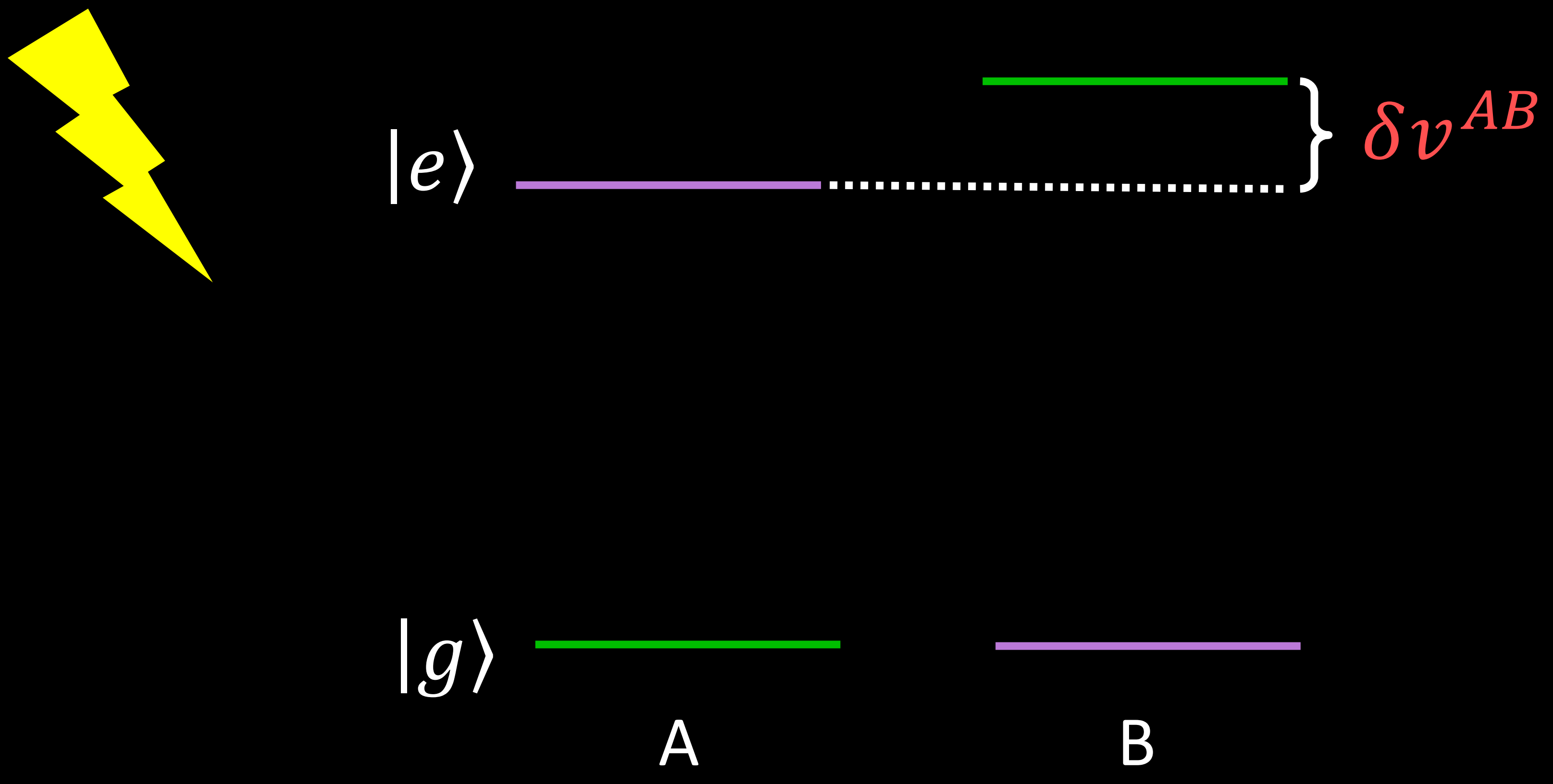

Phase protected from noise!

$$|e_A g_B\rangle \quad + e^{i\delta\nu^{AB}t}|g_A e_B\rangle$$

Spectroscopy in a decoherence free subspace

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(|e_a g_b\rangle + e^{i\delta v^{AB} t} |g_a e_b\rangle \right)$$

When $\delta v^{AB} t = \pi$: $$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(|e_a g_b\rangle - |g_a e_b\rangle \right) \equiv |\Psi_-\rangle$$

When $\delta v^{AB} t = 2\pi$: $$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(|e_a g_b\rangle + |g_a e_b\rangle \right) \equiv |\Psi_+\rangle$$

Spectroscopy in a decoherence free subspace

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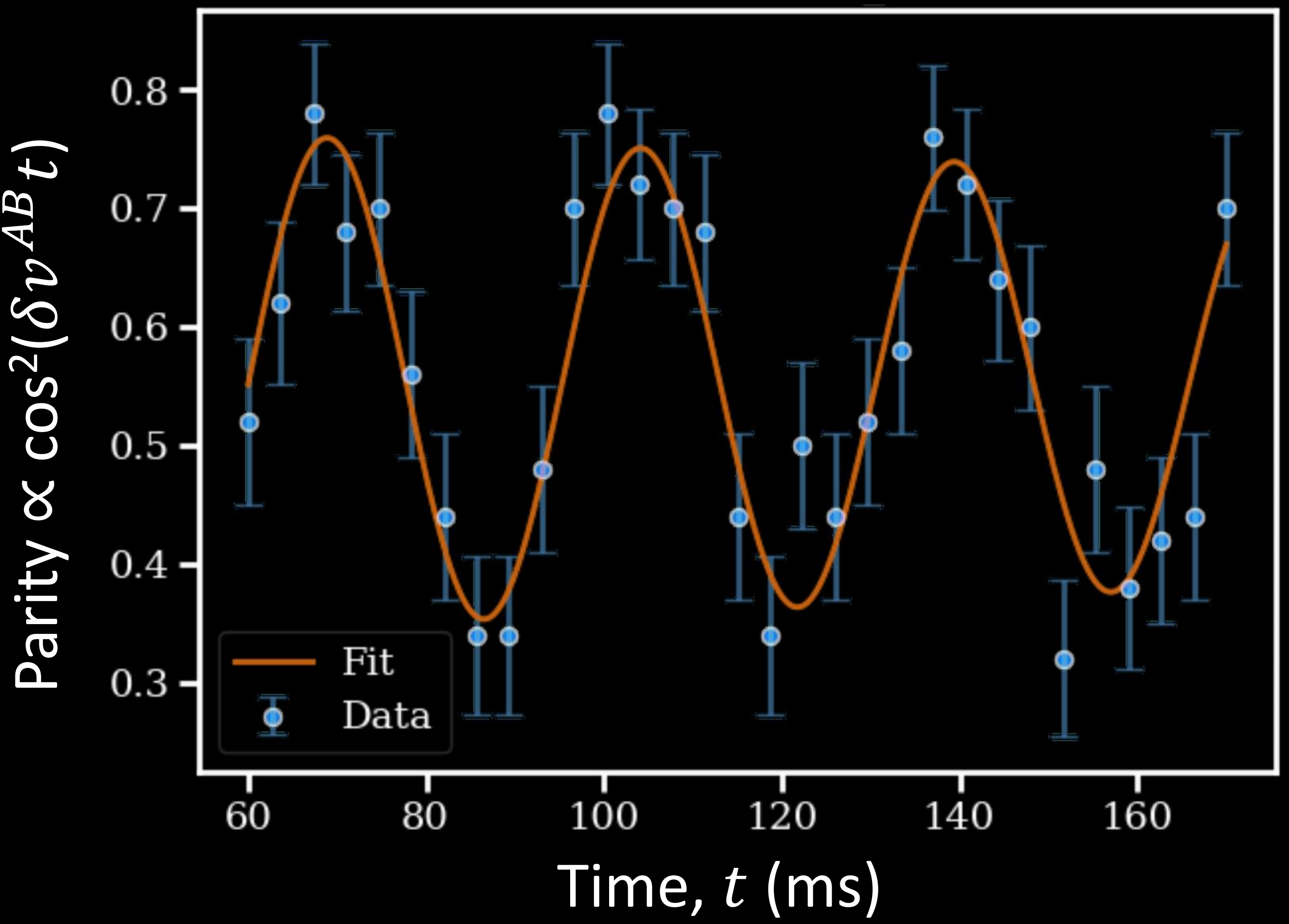
When $\delta v^{AB}t = 2\pi$: $$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(|e_a g_b\rangle + |g_a e_b\rangle\right) \equiv |\Psi_+\rangle$$

Global $\frac{\pi}{2}$ pulse: $|\psi_-\rangle \rightarrow |\psi_-\rangle$ $\quad |\psi_+\rangle \rightarrow -i|\phi_+\rangle \equiv -\frac{i}{\sqrt{2}}\left(|g_a g_b\rangle + |e_a e_b\rangle\right)$

Extracting the isotope shift



Oscillates @ detuning from isotope shift frequency, $(\omega_{laser} - \delta\nu^{AB})$!

Systematics

- Zeeman shifts, BBR, quadrupole shifts, 2nd order Doppler shifts - cancelled up to gradients.
- We swap the ion positions to account for any gradients
  – but the swap can be imperfect if we have stray radial or axial fields.

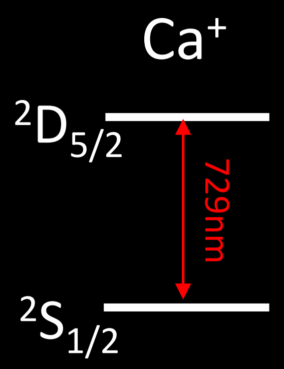
$$\delta \mathbf{r} = \frac{e\mathbf{E}_r}{M\omega_r^2}$$

Systematics (preliminary)

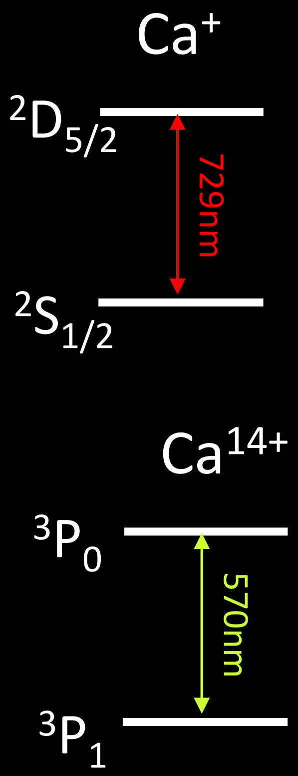
Isotope pair	$^{40}Ca^{+}$-$^{48}Ca^{+}$	
Type of shift	$\delta\nu_{40-48}$ (mHz)	$\sigma_{\delta\nu_{40-48}}$ (mHz)
Clock uncertainty	0	39.7
Magnetic field gradient fluctuations	0	12
AC Stark shift during Ramsey pulses	0	4.5
Excess micromotion	24.1	29.9
Intrinsic micromotion	0.3	3.3
AC Stark shift due to light-leakage	< 1	< 1
Magnetic field drift	$\ll 1$	$\ll 1$
Electric quadrupole shift	$\ll 1$	$\ll 1$
Second-order Zeeman	$\ll 1$	$\ll 1$
Black-body radiation	$\ll 1$	$\ll 1$
Total	24.4	50.0

For a detailed discussion: L. I. Huber et al (in preparation for submission to PRA)

Calcium King Plot (preliminary)



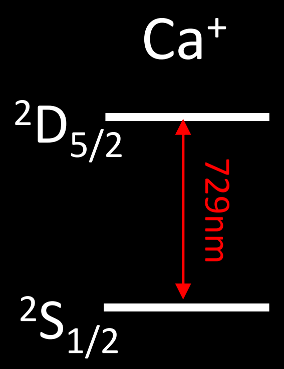
Calcium King Plot (preliminary)

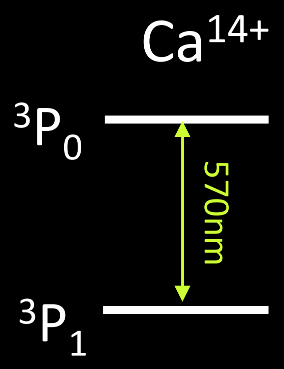


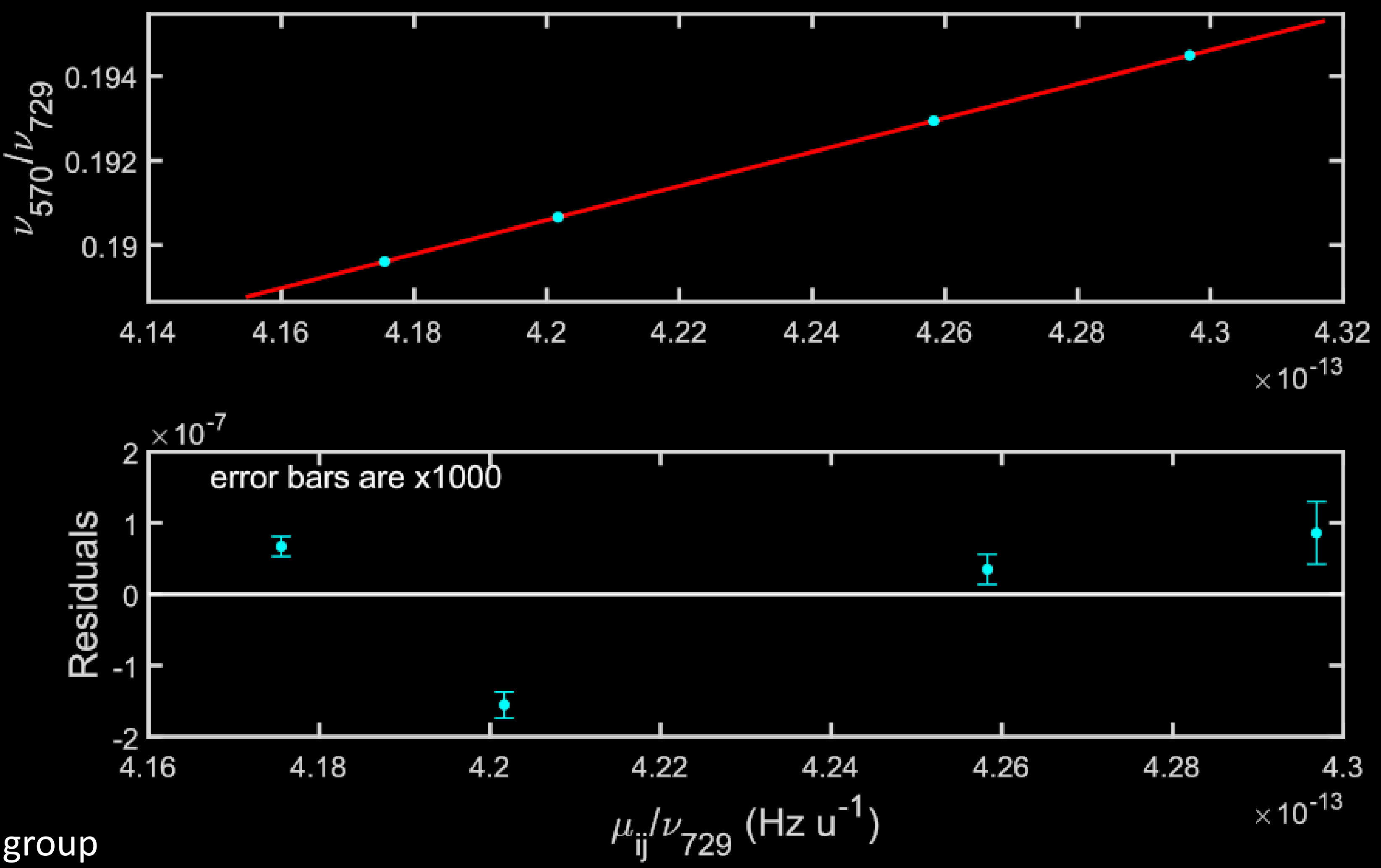
Ca^{14+} data : P. Schmidt's group

Improved nuclear masses: K. Blaum's group

Calcium King Plot (preliminary)



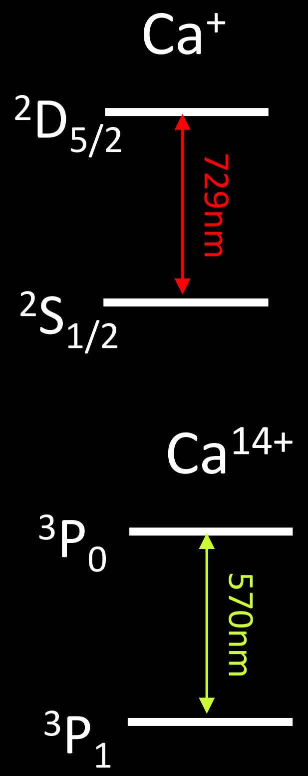


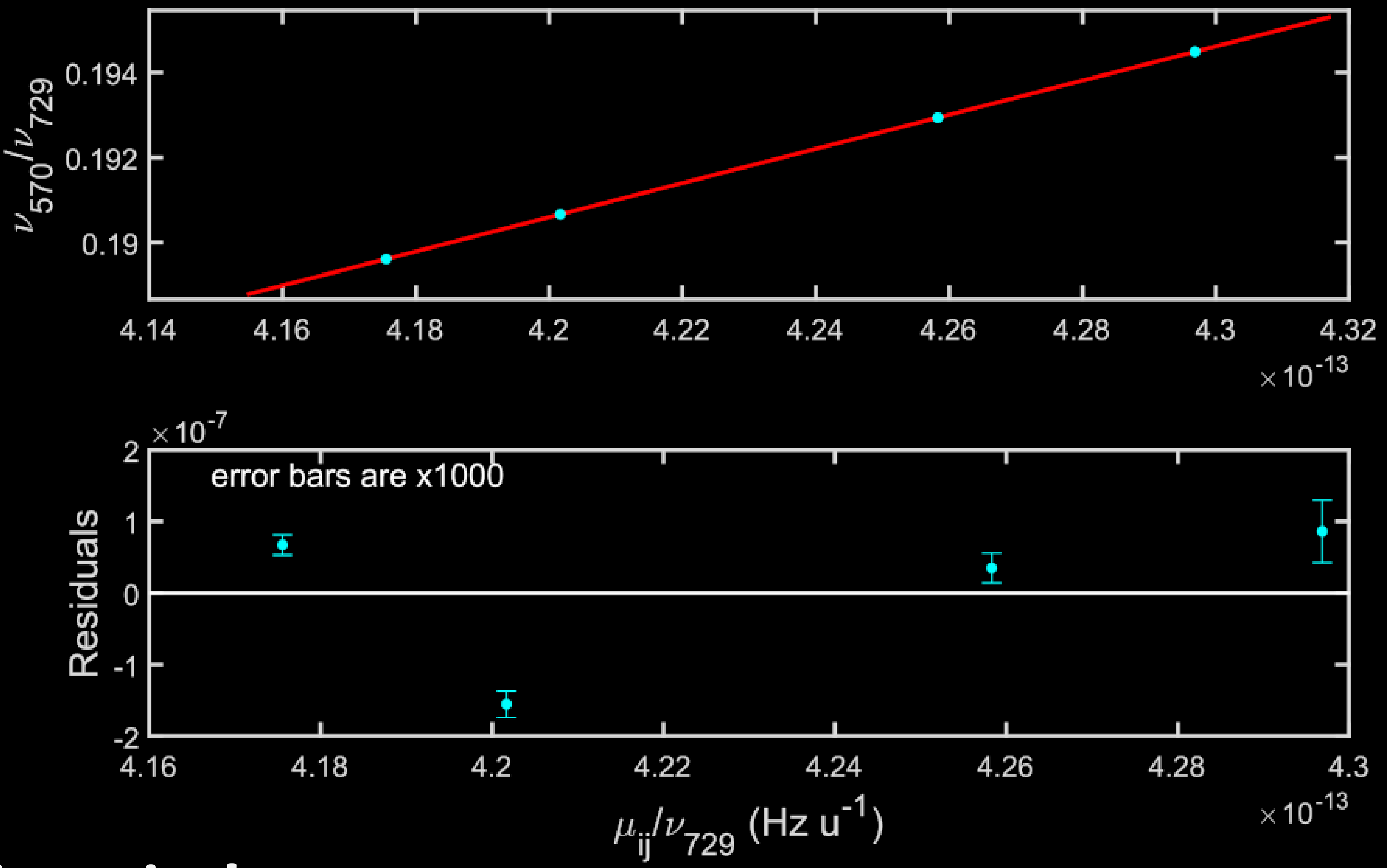


Ca^{14+} data : P. Schmidt's group

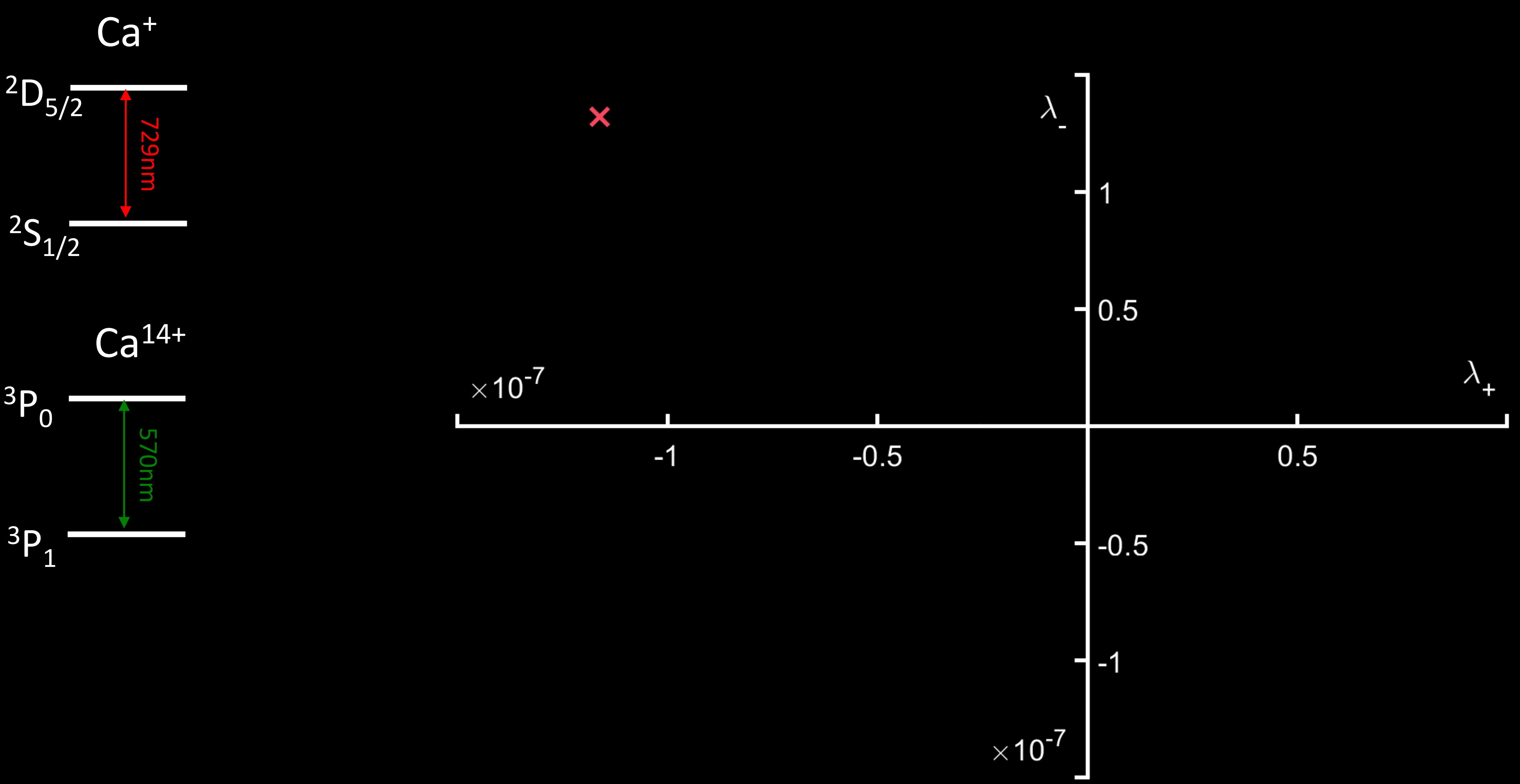
Improved nuclear masses: K. Blaum's group

Calcium King Plot (preliminary)

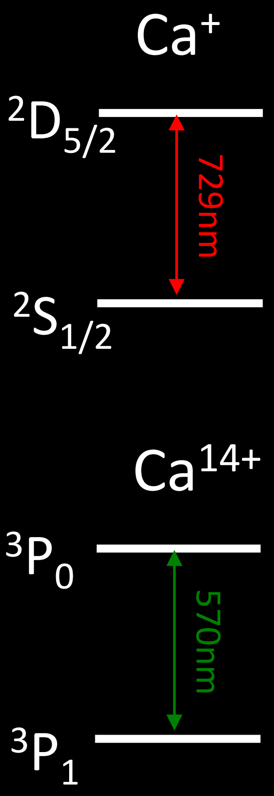


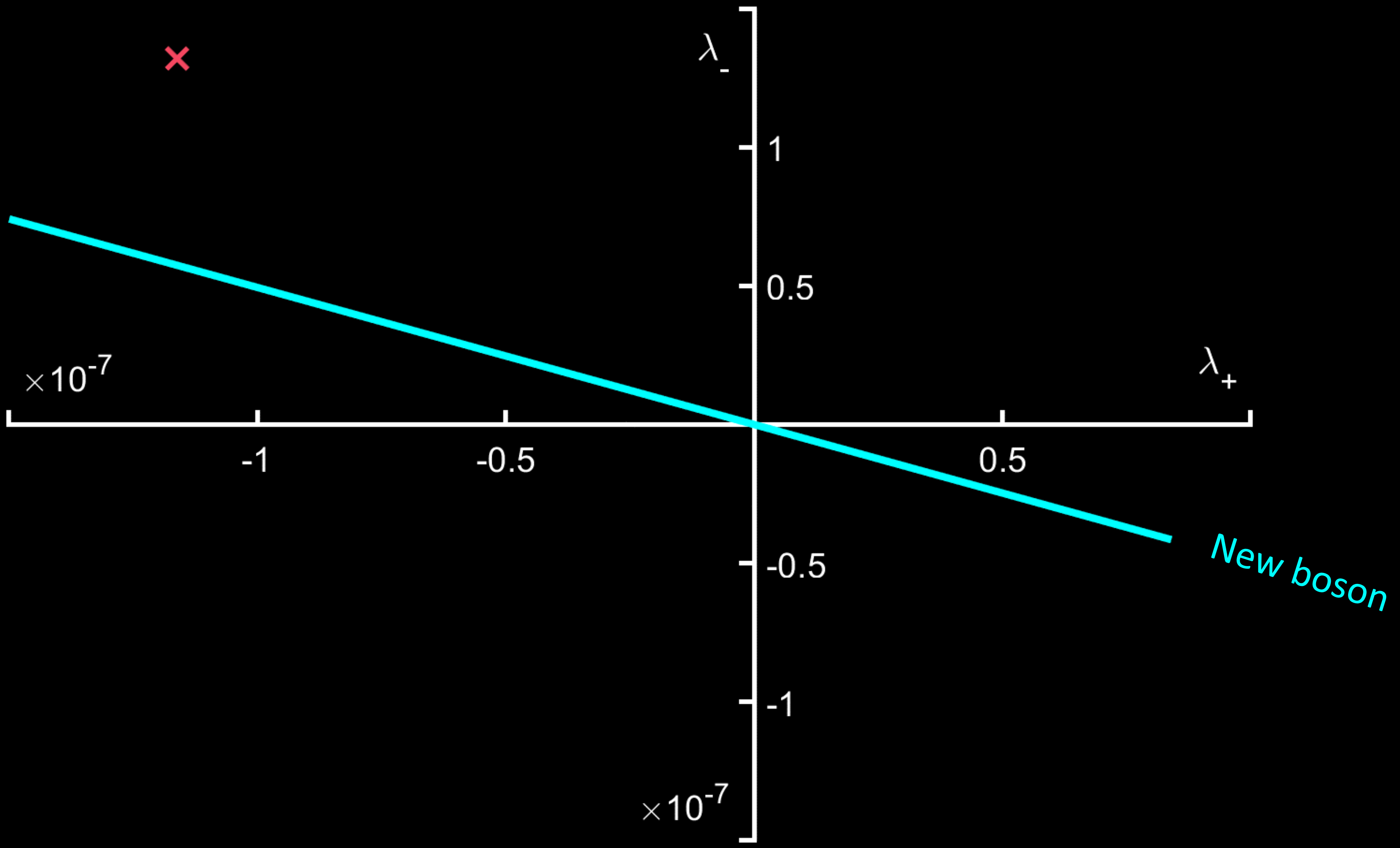


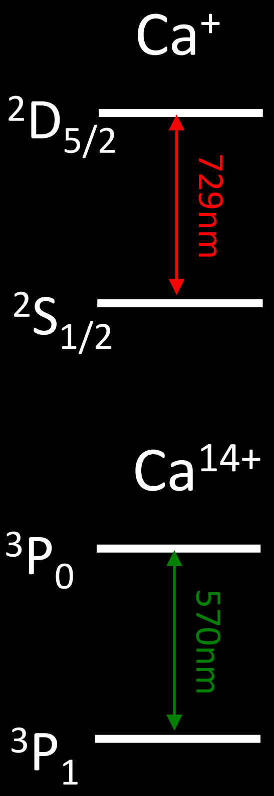
1000σ nonlinearity!



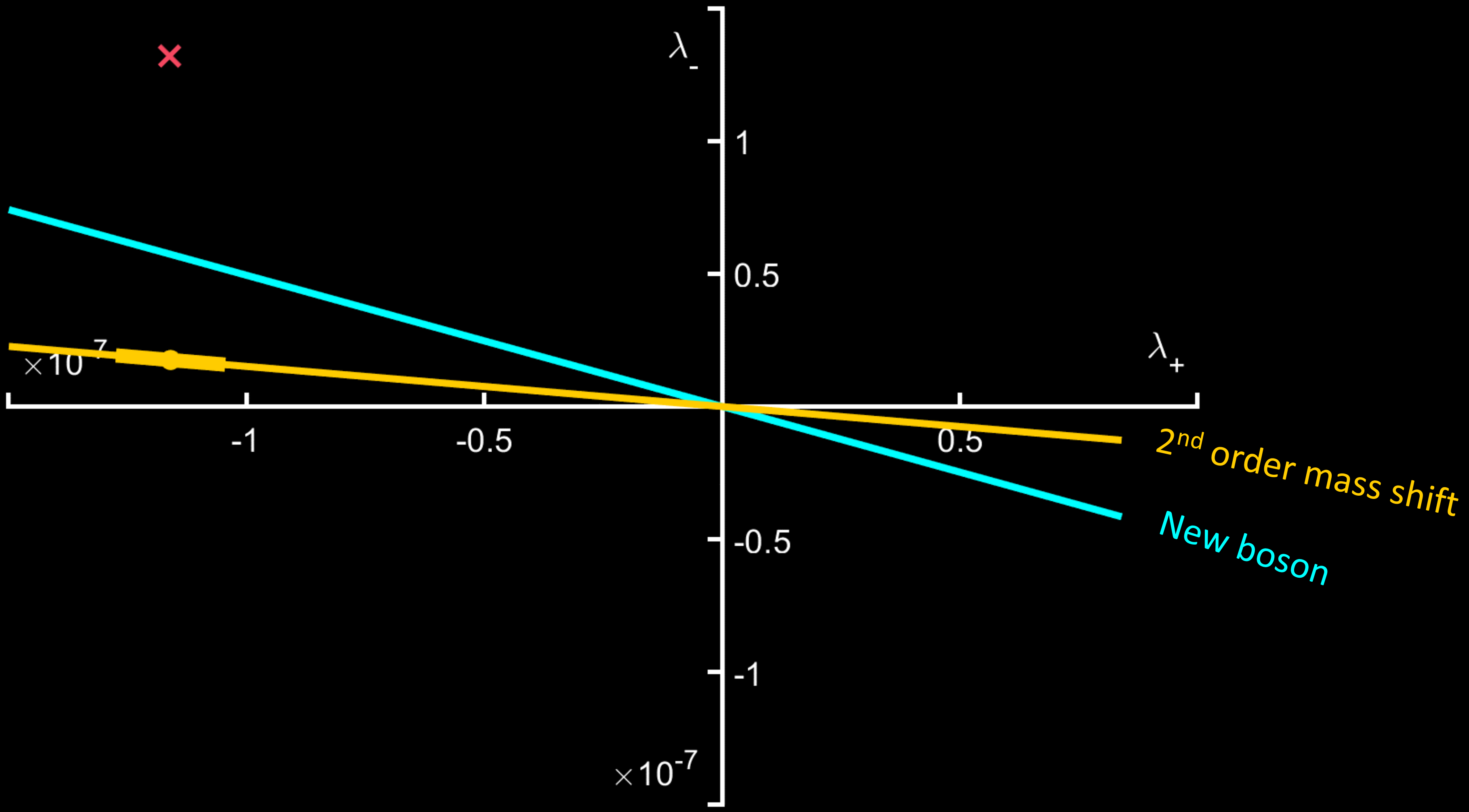
Ca+
2D5/2
729nm
2S1/2
Ca14+
3P0
570nm
3P1
λ-
1
0.5
-0.5
-1
×10-7
λ+
×10-7
-1
-0.5
0.5


Ca$^+$
$^2D_{5/2}$
729nm
$^2S_{1/2}$
Ca^{14+}
$^3P_0$
570nm
$^3P_1$

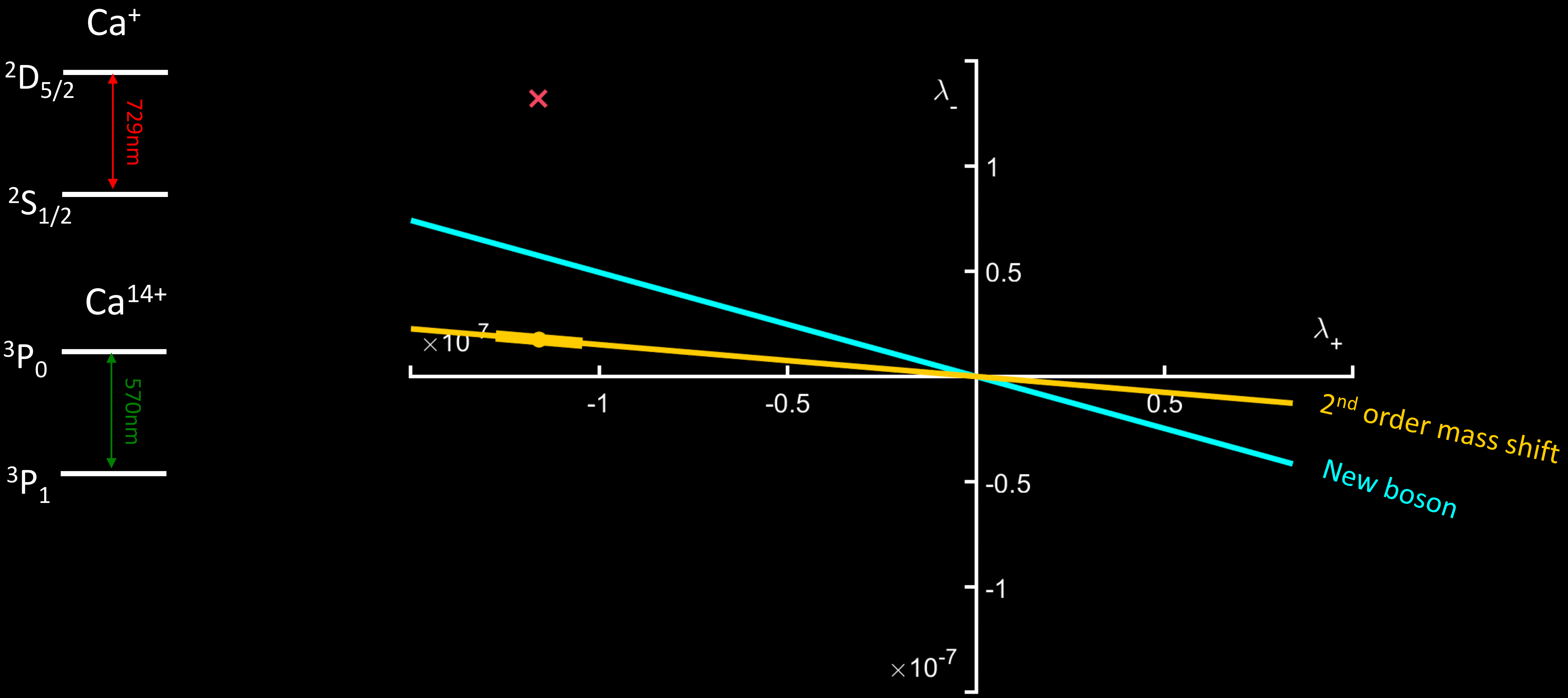

λ_-
1
0.5
-0.5
-1
$\times 10^{-7}$
λ_+
-1
-0.5
0.5
$\times 10^{-7}$
New boson



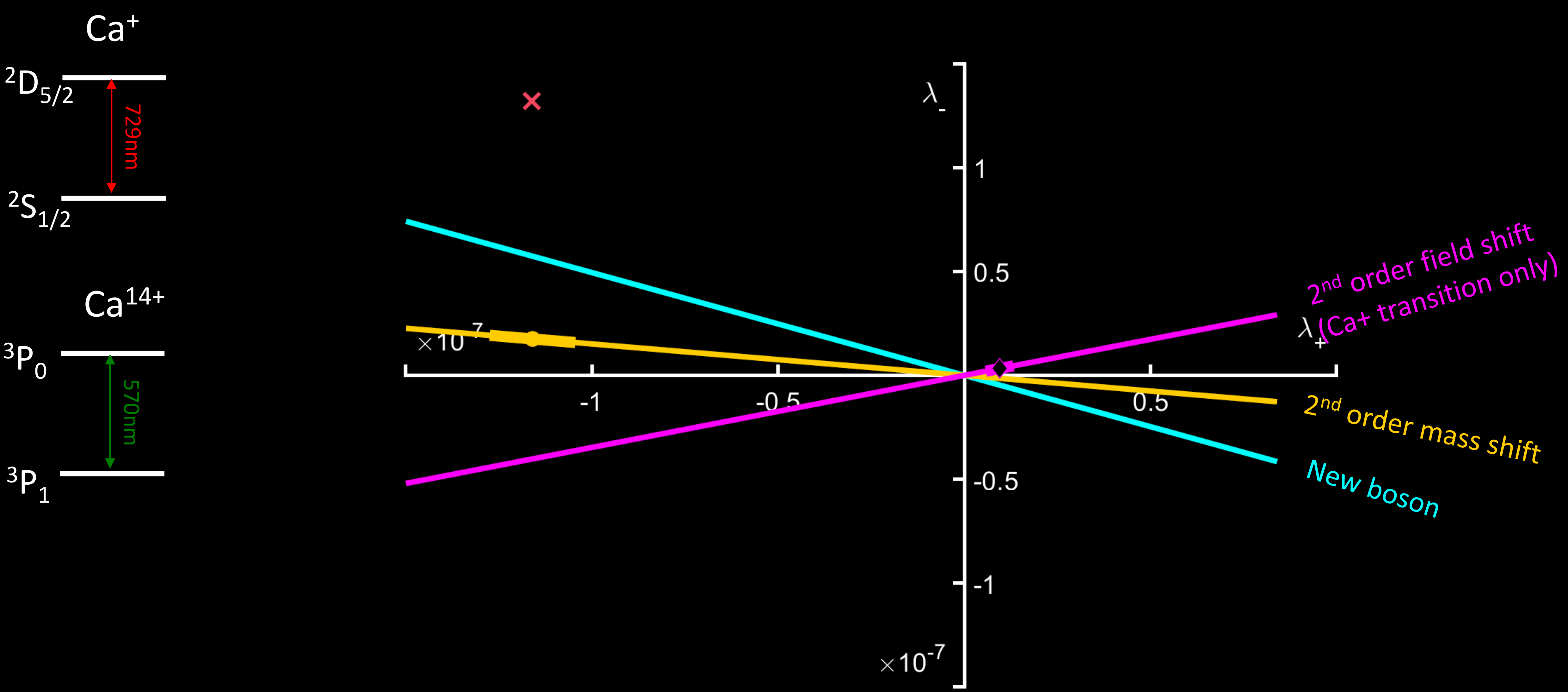
Ca+
2D5/2
729nm
2S1/2
Ca14+
3P0
570nm
3P1



λ-
λ+
1
0.5
-0.5
-1
×10-7
-1
-0.5
0.5
×10-7
2nd order mass shift
New boson

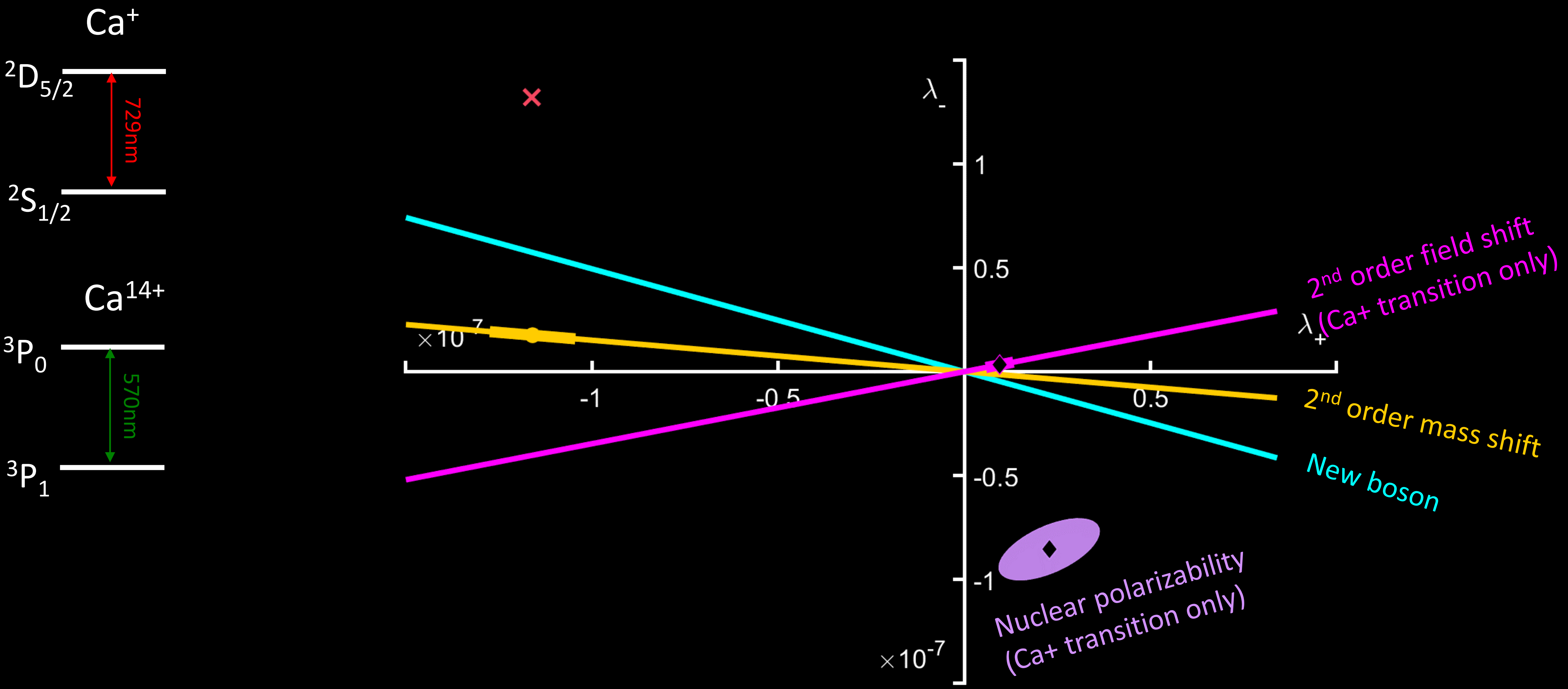


Calculation of 2nd order mass shift electronic coefficient for Ca14+ by Andrey Surzhykov, Anna Viatkina

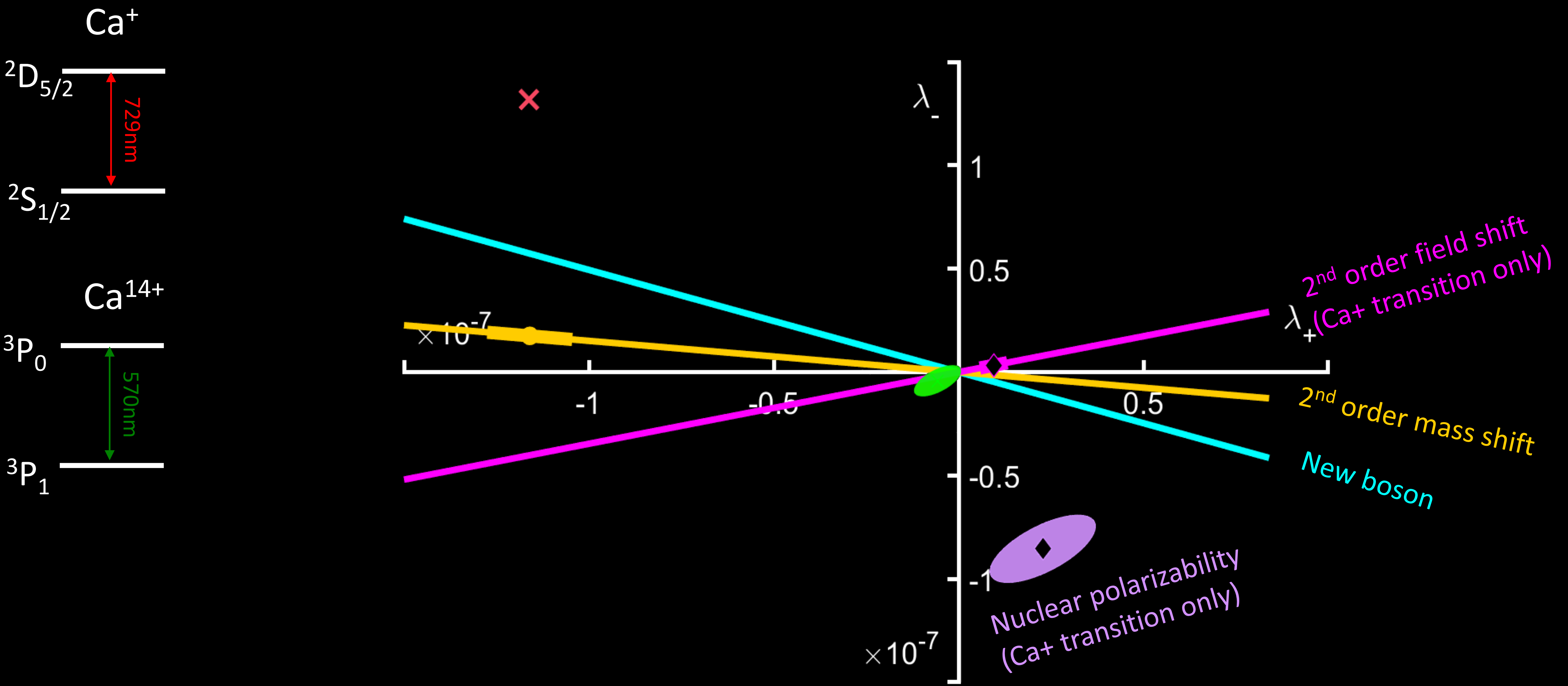


Calculation of 2nd order mass shift electronic coefficient for Ca14+ by Andrey Surzhykov, Anna Viatkina

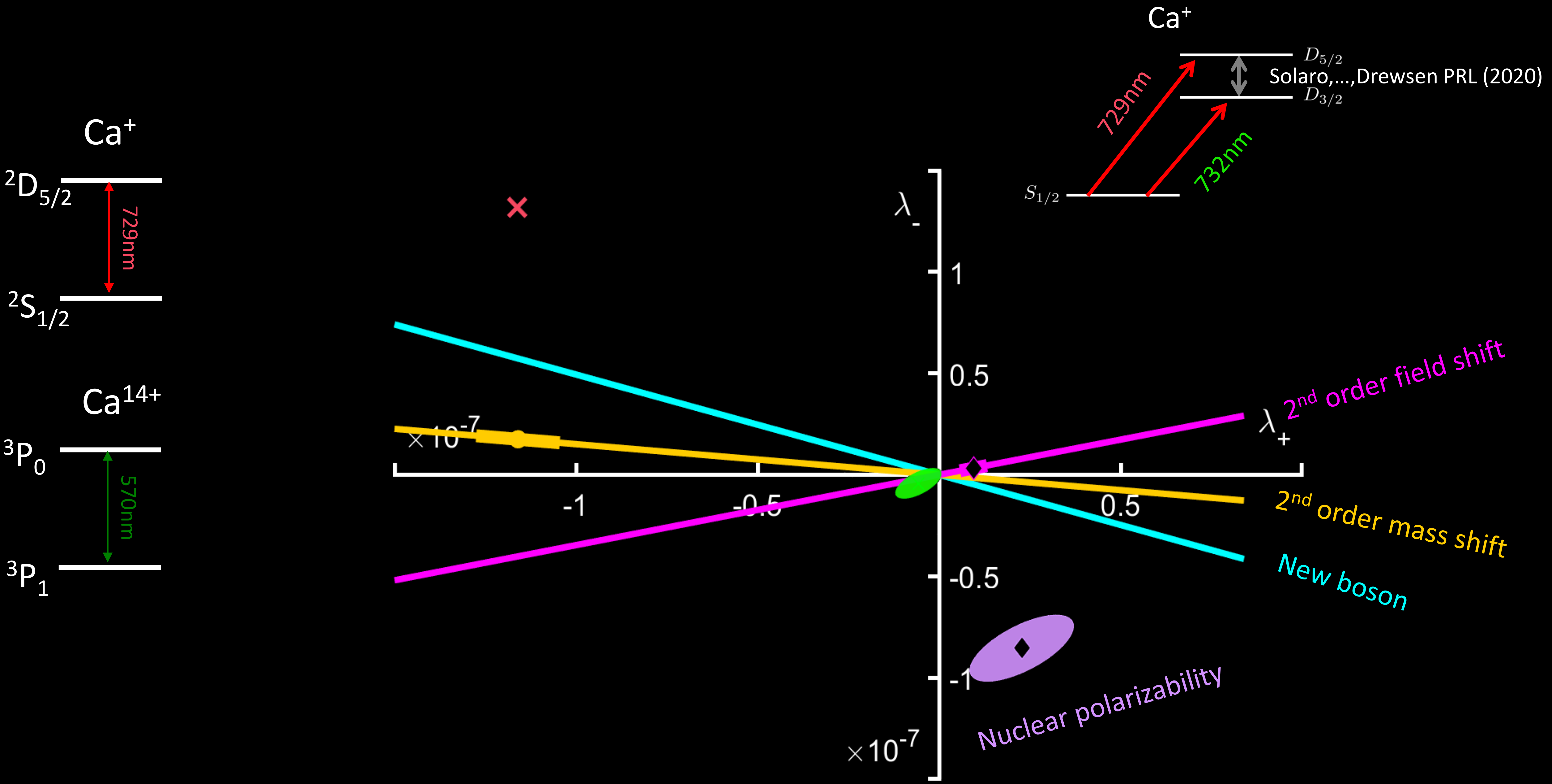
For Ca+ electronic coefficients: Viatkina, Yerokhin, Surzhykov, PRA (2023)



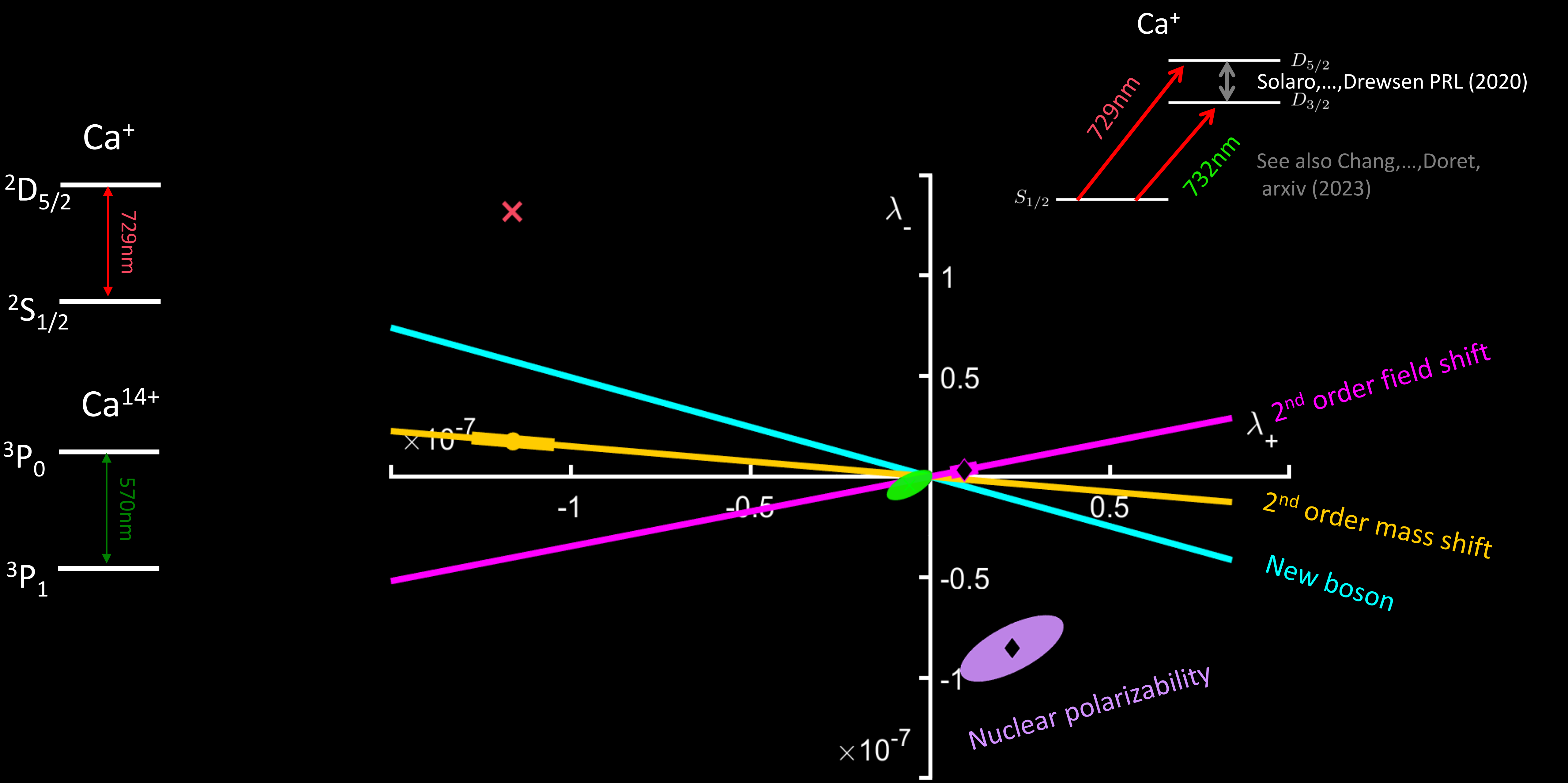
Calculation of 2nd order mass shift electronic coefficient for Ca14+ by Andrey Surzhykov, Anna Viatkina
For Ca+ electronic coefficients: Viatkina, Yerokhin, Surzhykov, PRA (2023)



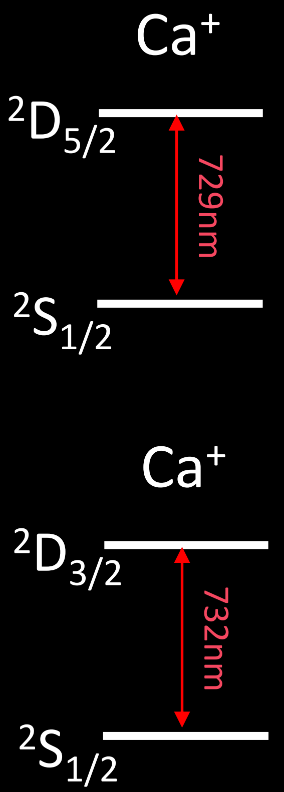
Ca+
$^2D_{5/2}$
729nm
$^2S_{1/2}$
Ca14+
$^3P_0$
570nm
$^3P_1$
λ_-
1
0.5
-0.5
-1
$\times 10^{-7}$
λ_+
-1
-0.5
0.5
$\times 10^{-7}$
2nd order field shift (Ca+ transition only)
2nd order mass shift
New boson
Nuclear polarizability (Ca+ transition only)

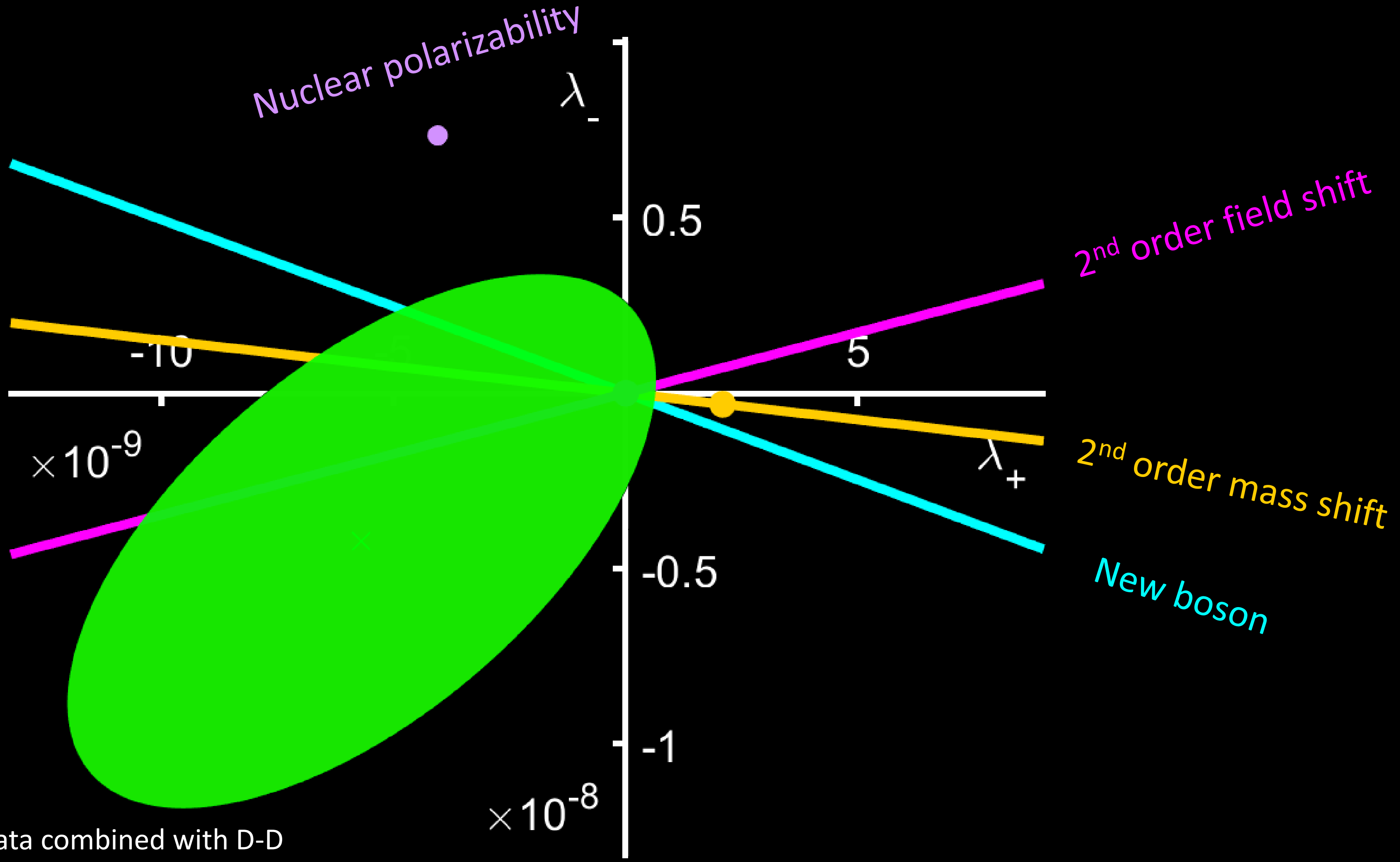


Ca+
$^2D_{5/2}$
$^2S_{1/2}$
729nm
Ca14+
$^3P_0$
$^3P_1$
570nm
Ca+
$D_{5/2}$
$D_{3/2}$
$S_{1/2}$
729nm
732nm
Solaro,...,Drewsen PRL (2020)
λ_-
λ_+
1
0.5
-0.5
-1
$\times 10^{-7}$
$\times 10^{-7}$
-1
-0.5
0.5
2nd order field shift
2nd order mass shift
New boson
Nuclear polarizability

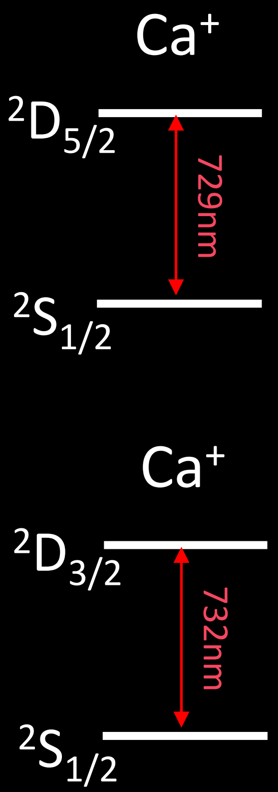


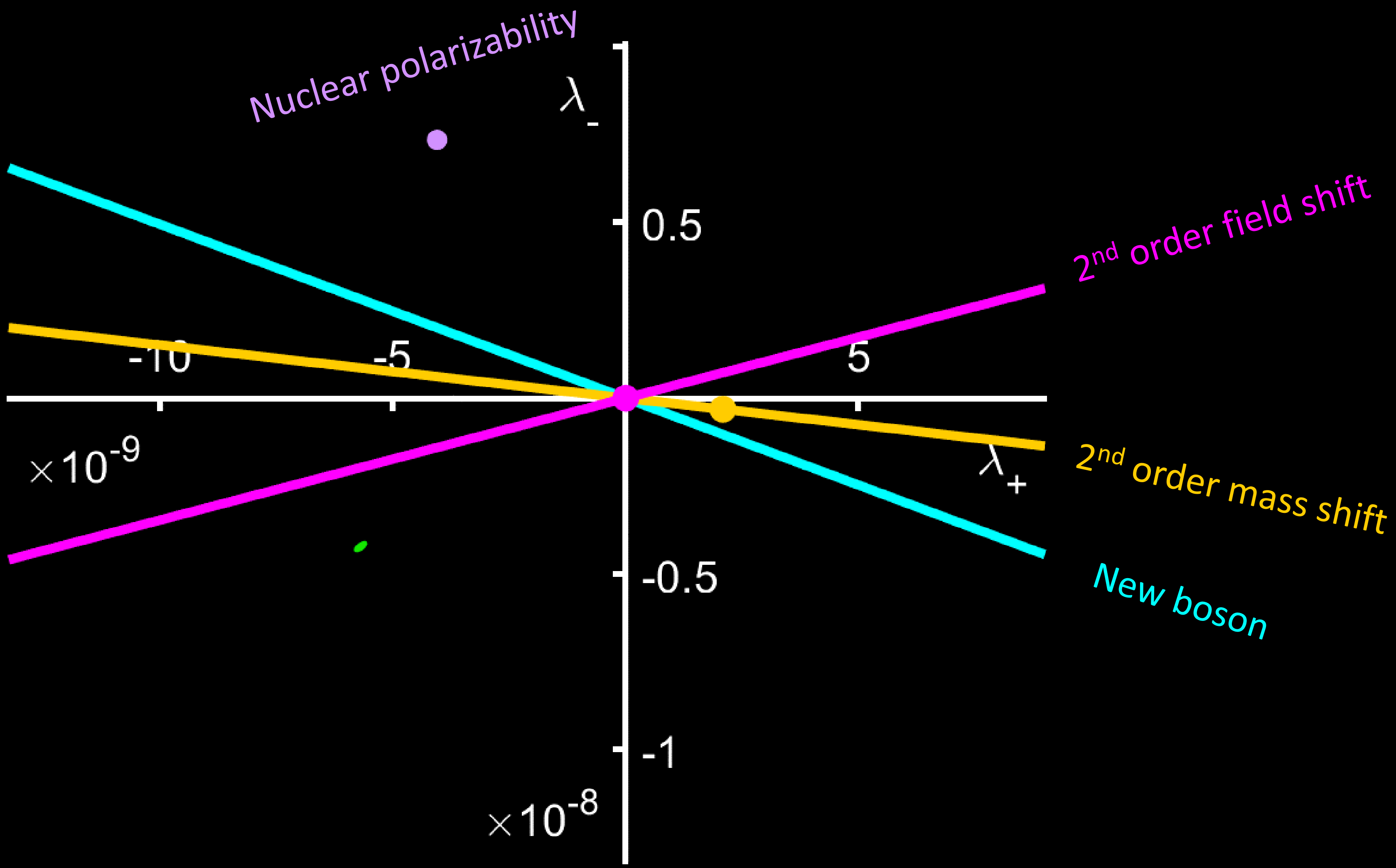
Ca+
2D5/2
2S1/2
729nm
Ca14+
3P0
3P1
570nm
Ca+
D5/2
D3/2
S1/2
729nm
732nm
Solaro,...,Drewsen PRL (2020)
See also Chang,...,Doret, arxiv (2023)
λ-
λ+
1
0.5
-0.5
-1
×10-7
-1
-0.5
0.5
×10-7
2nd order field shift
2nd order mass shift
New boson
Nuclear polarizability





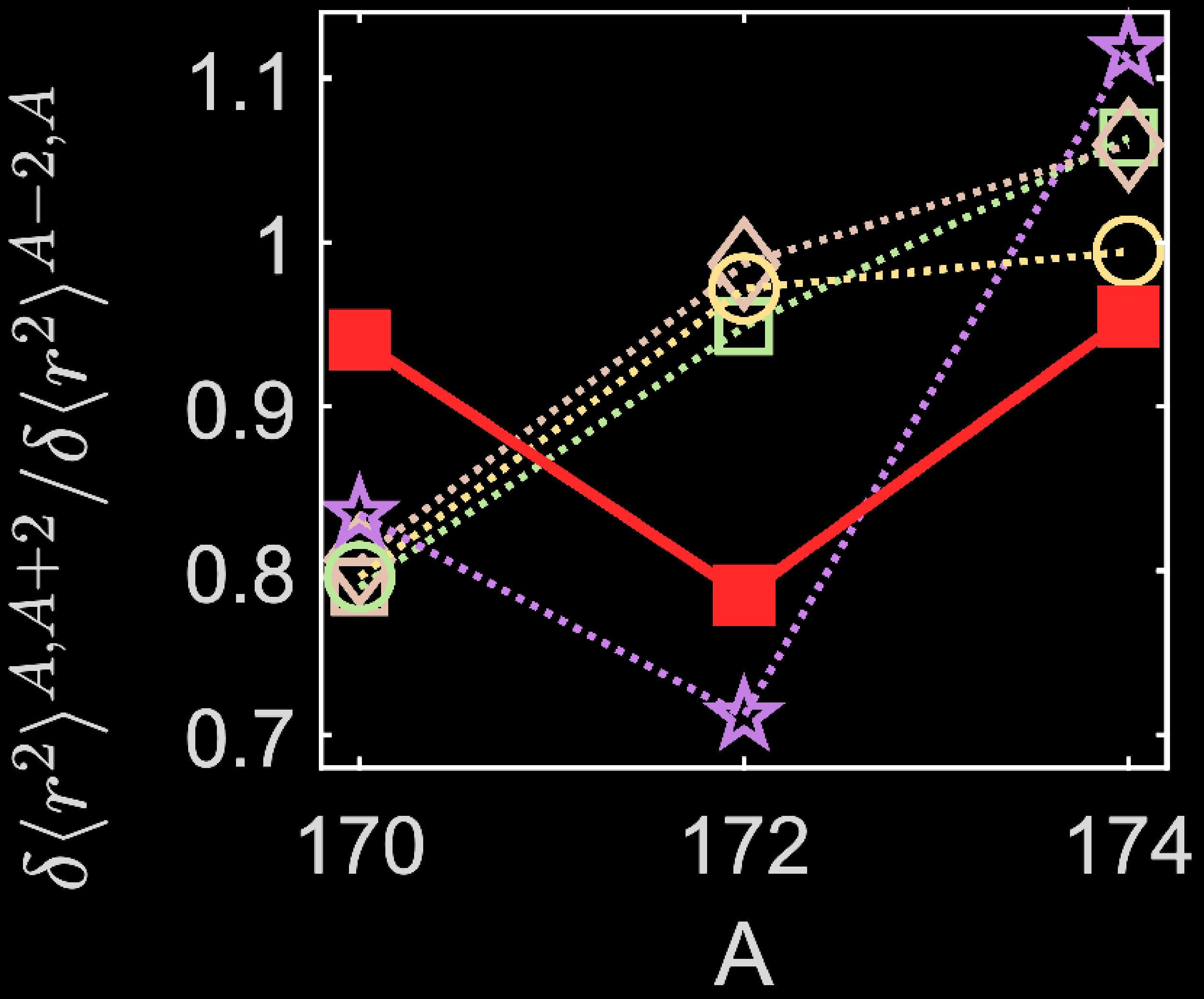
Our data combined with D-D measurement (20Hz) by Solaro,…,Drewsen PRL (2020)



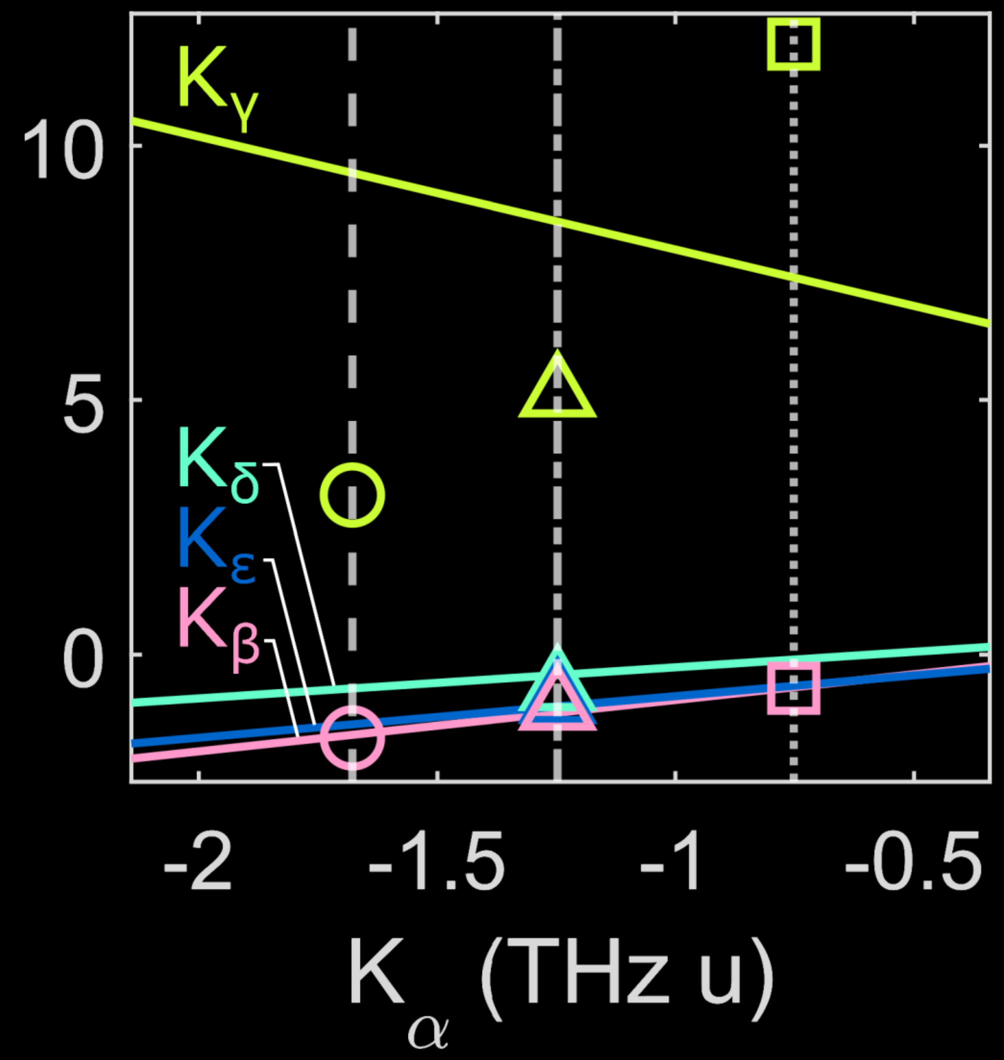


Now measuring 732nm transition – aim <500mHz uncertainty

Nuclear physics insights (Yb+)



Benchmarking atomic calculations (Yb+)



TIQI group, ETH Zürich (Ca^+)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Roland Matt


Jeremy Flannery


Diana P L Aude Craik


Jonathan Home

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Wonho Jhe

Questions?