Searching for new physics with isotope-shift spectroscopy of trapped ions

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dacraik@mit.edu

Yb^+ experiment @ Vuletić group, MIT
(with J. Hur, I. Counts, E. Knyazev, L. Caldwell, S. Pandey, C. Leung, A. Kawasaki, H. Jeon, W. Jhe, V. Vuletić)
Ca^+ experiment @ Home group, ETHZ
(with R. Matt, J. Flannery, L. Huber, J. Home)
Theory collaborators: W. Nazarewicz, P. G. Reinhard, A. Geddes, J. Berengut

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

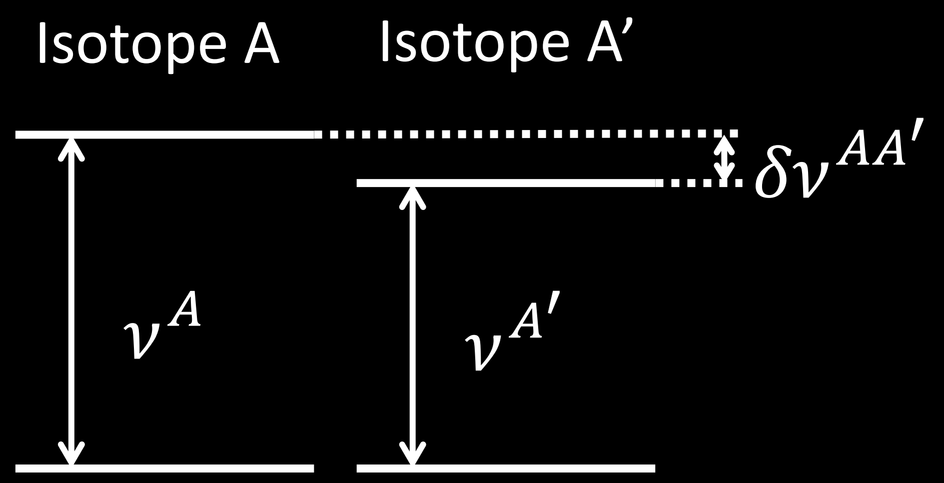
Φ could be a "relaxion"…

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

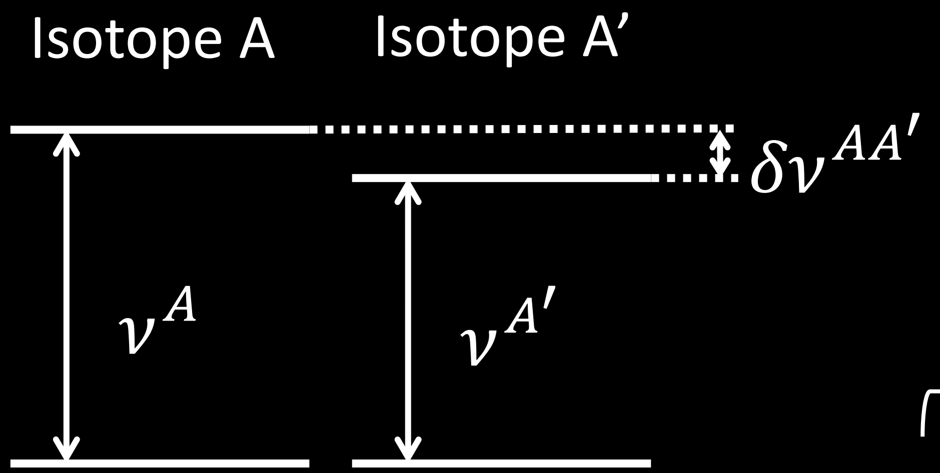
More SM extensions we can probe
Debierre et al, Phys. Rev. A **106** 062801 (2022)

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

Probing the interaction by measuring isotope shifts



Probing the interaction by measuring isotope shifts

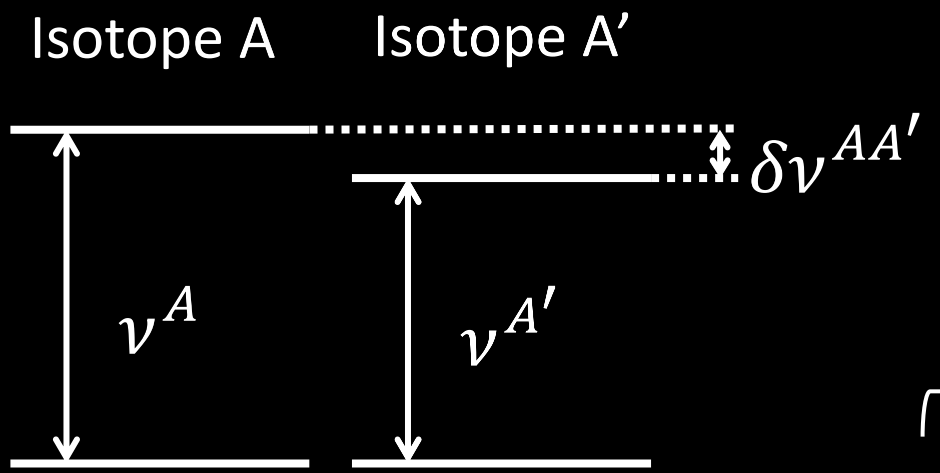


$\delta\nu^{AA'}$ = standard model shift + boson shift

field shift

Due to change in spatial distribution of the nuclear charge

Probing the interaction by measuring isotope shifts



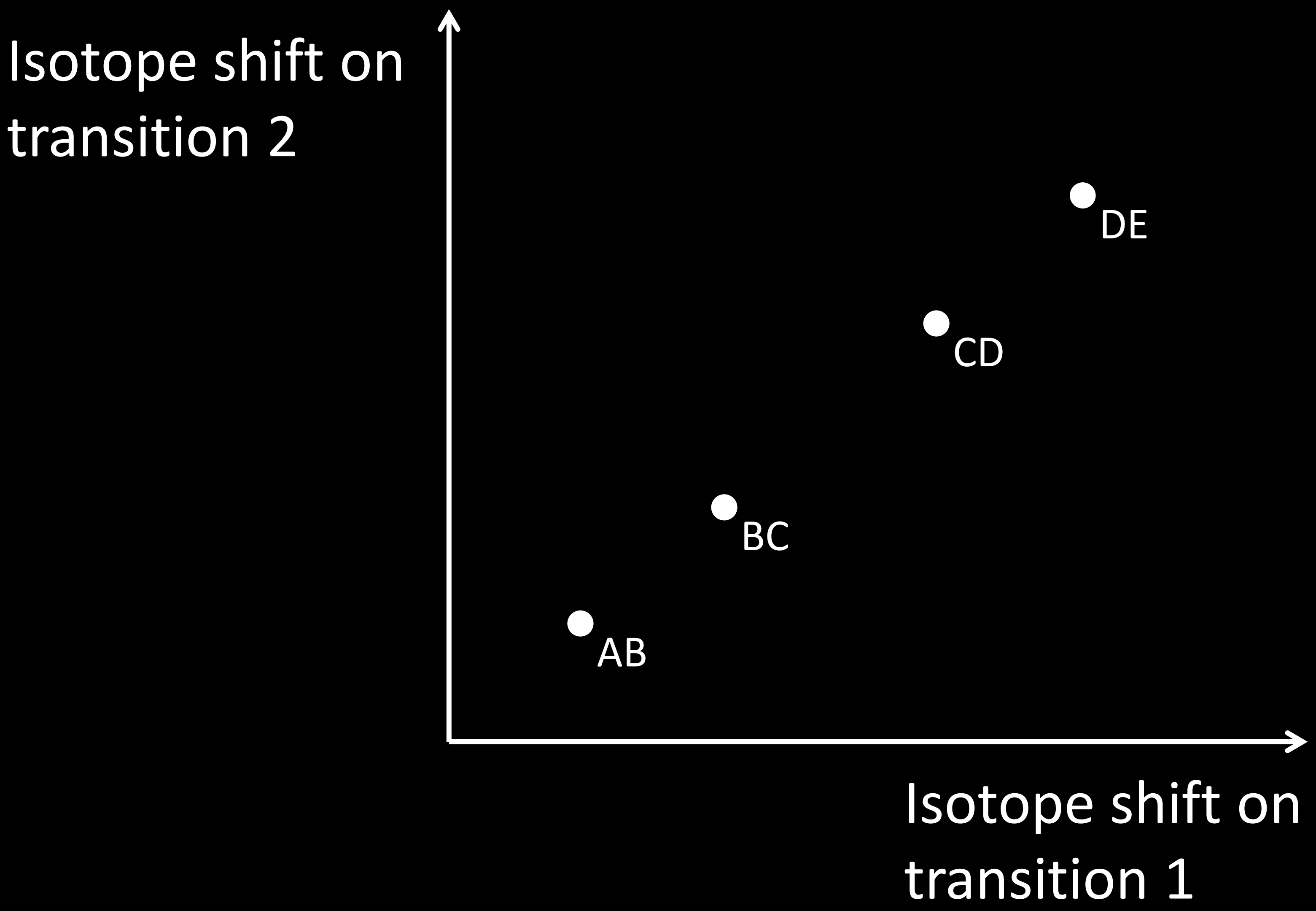
$$\delta\nu^{AA'} = \underbrace{\text{standard model shift}}_{\text{mass shift} \; + \; \text{field shift}} + \text{boson shift}$$

mass shift + field shift

mass shift: Due to change in kinetic energy, from change in nuclear mass

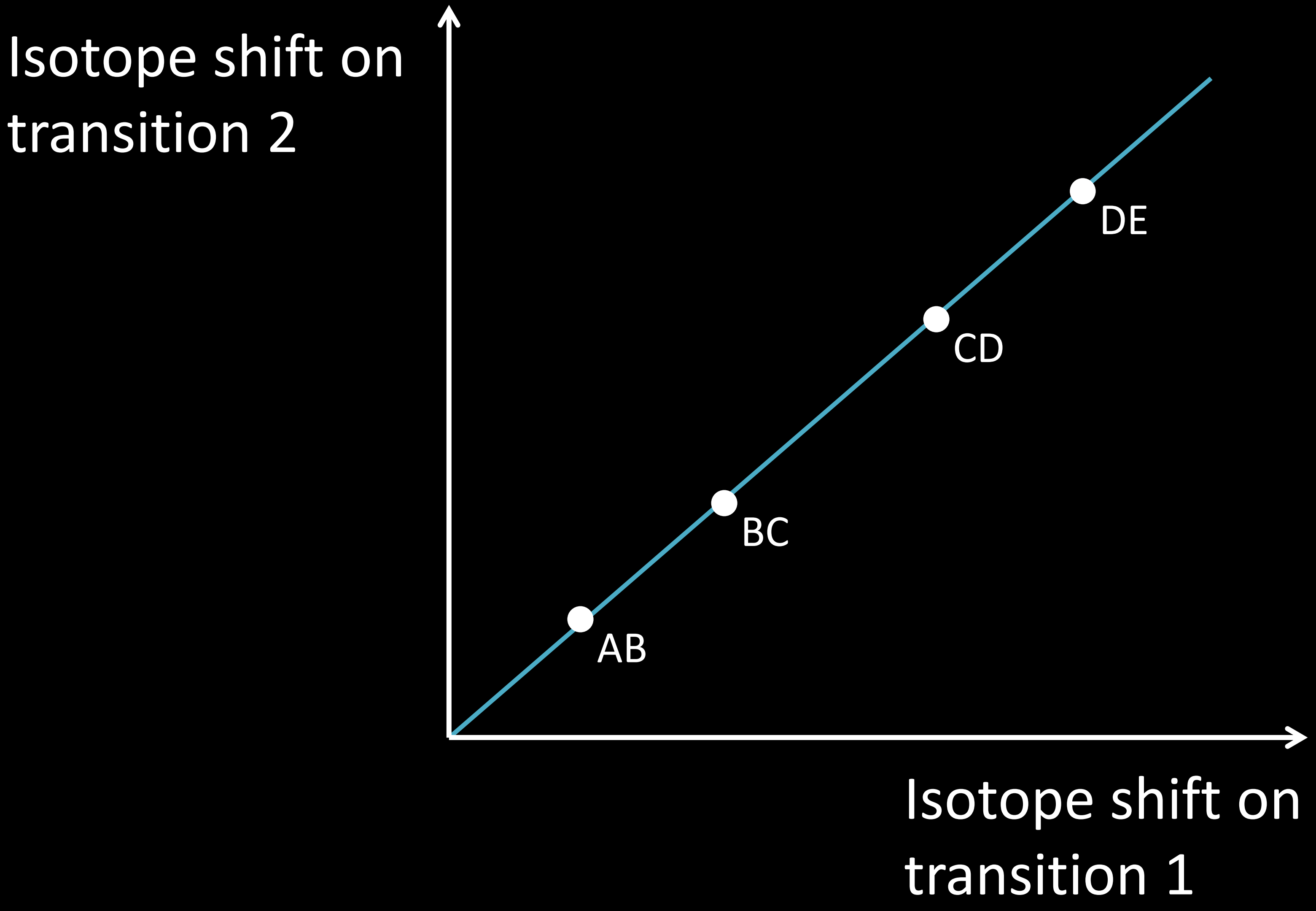
field shift: Due to change in spatial distribution of the nuclear charge

King plot



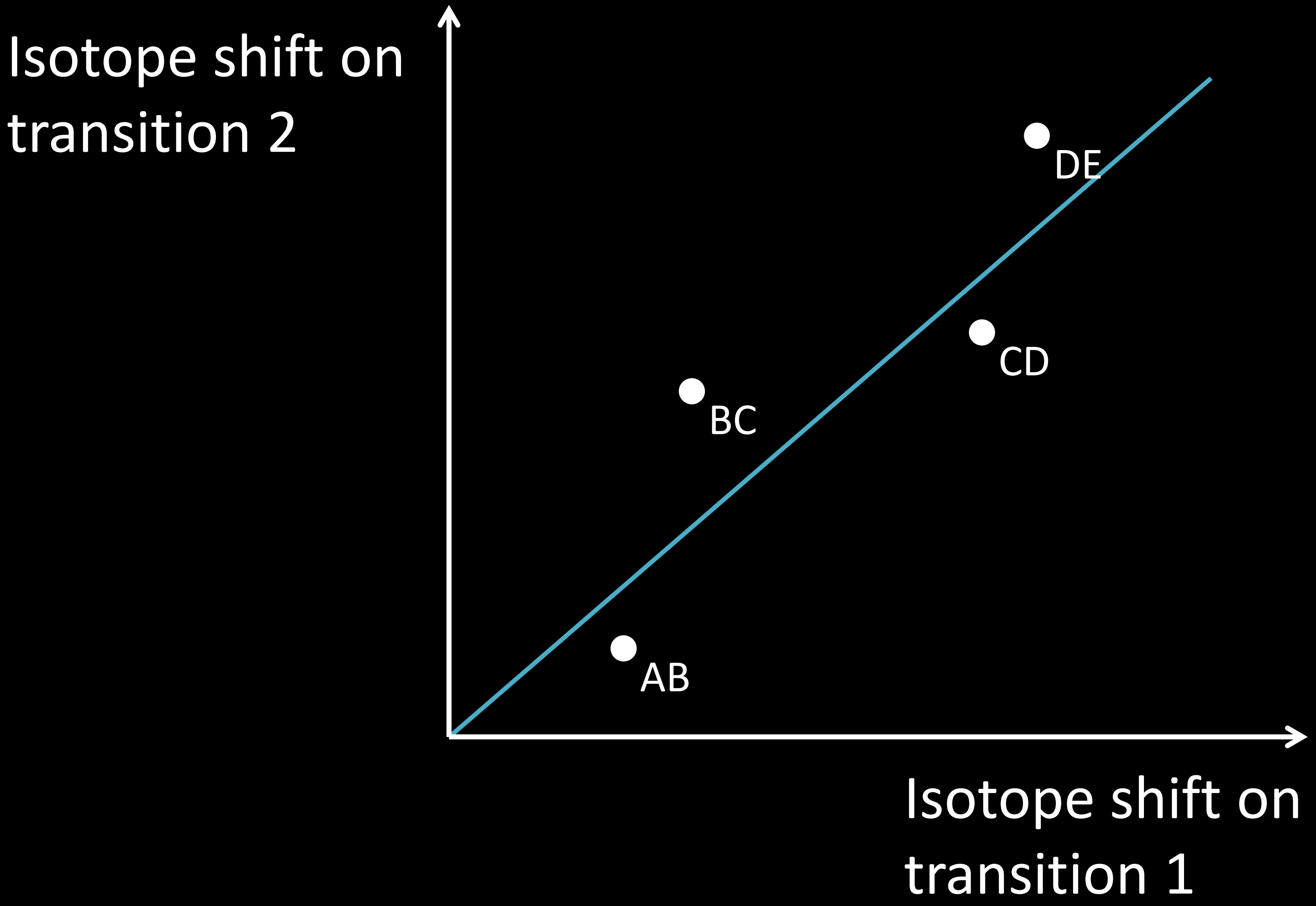
King Plot
W. H. King, JOSA 53, 638 (1963)

King plot



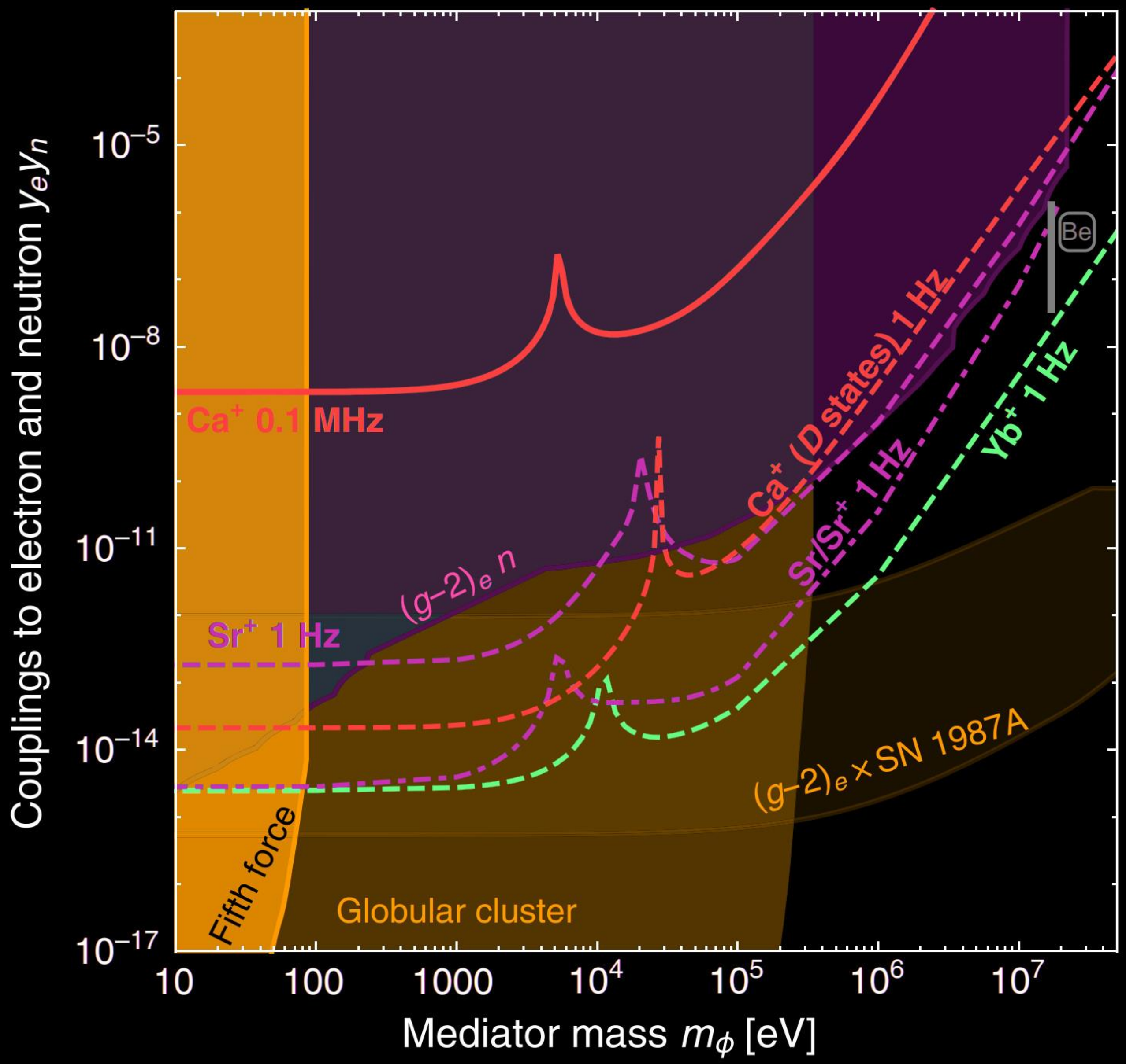
King Plot
W. H. King, JOSA 53, 638 (1963)

King plot



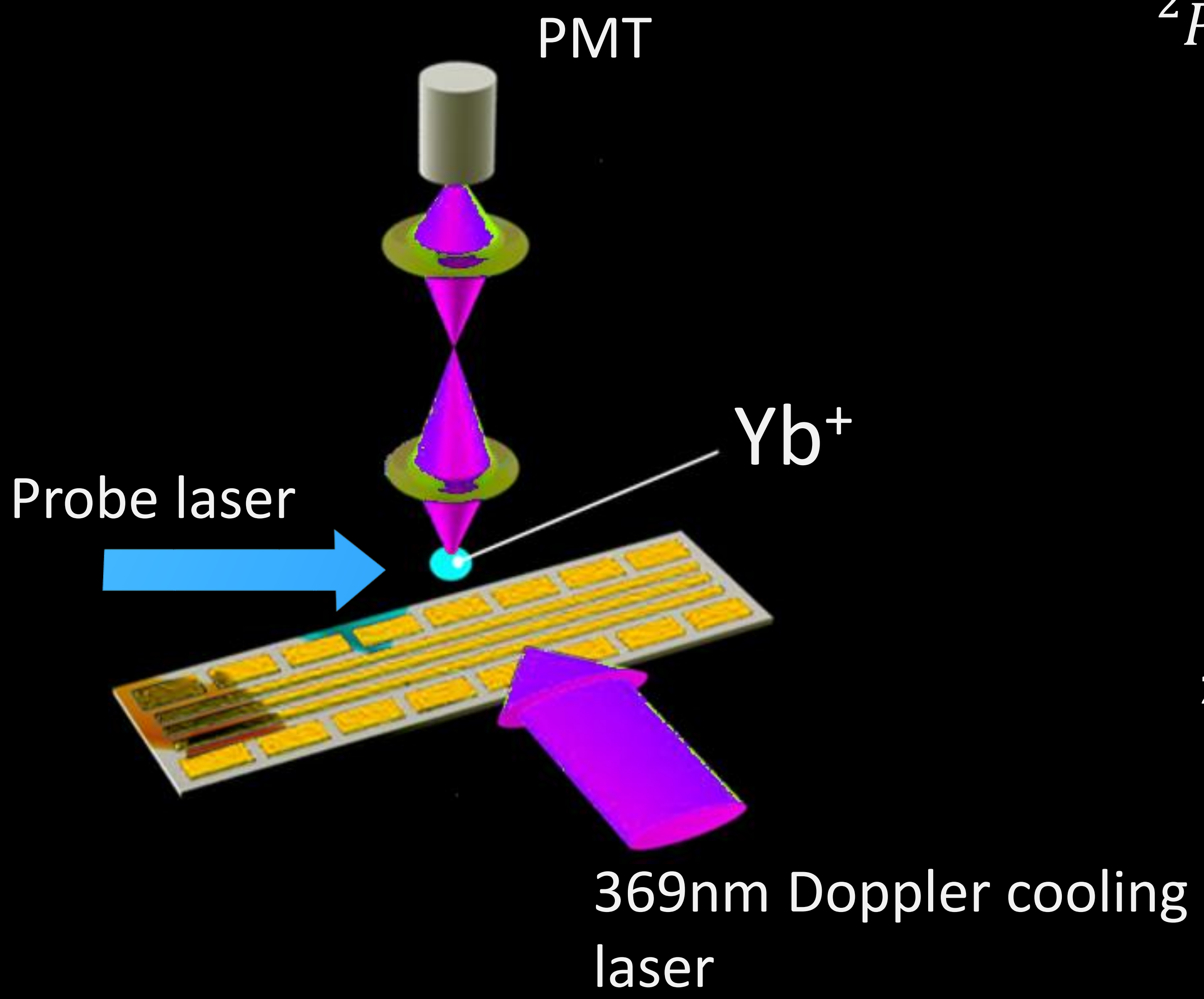
King Plot
W. H. King, JOSA 53, 638 (1963)

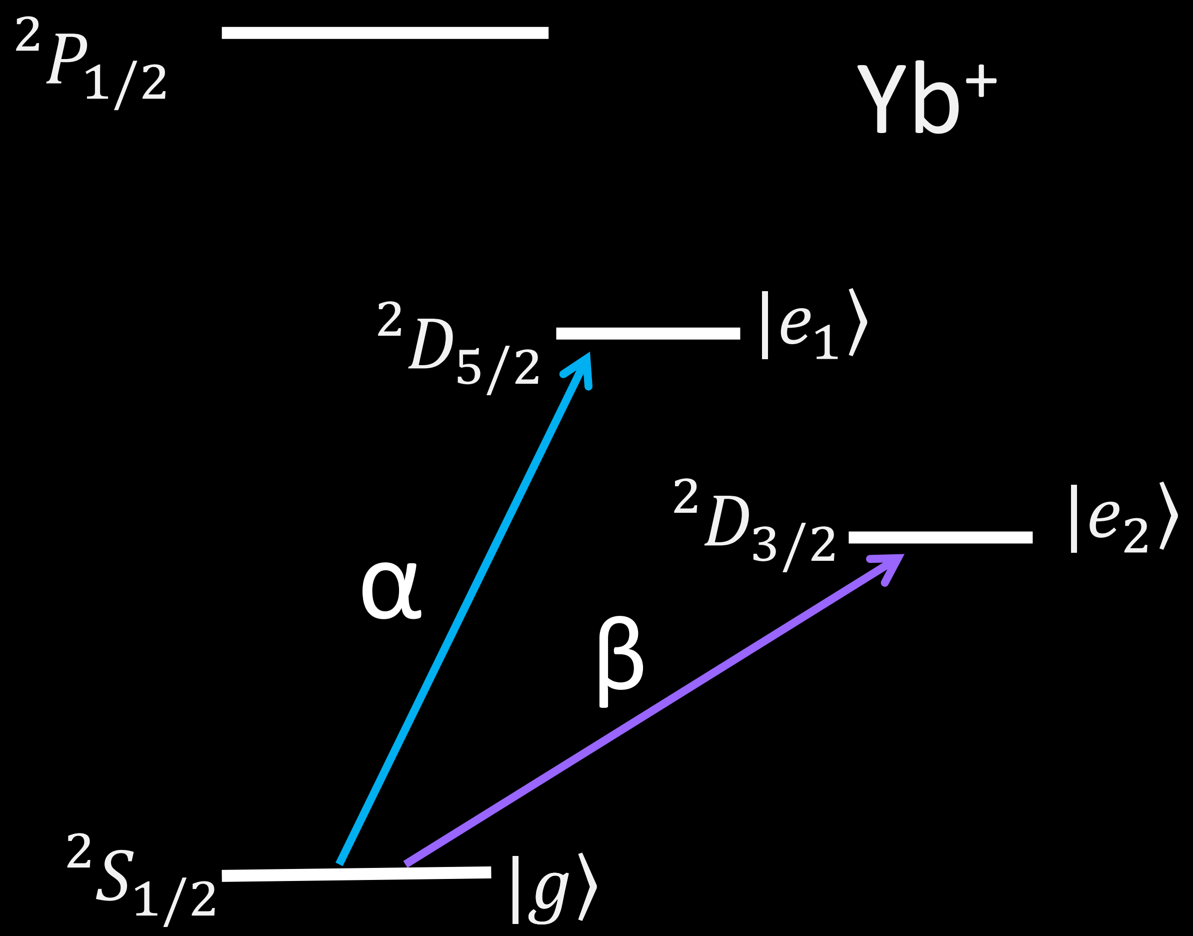
How sensitive is this method?



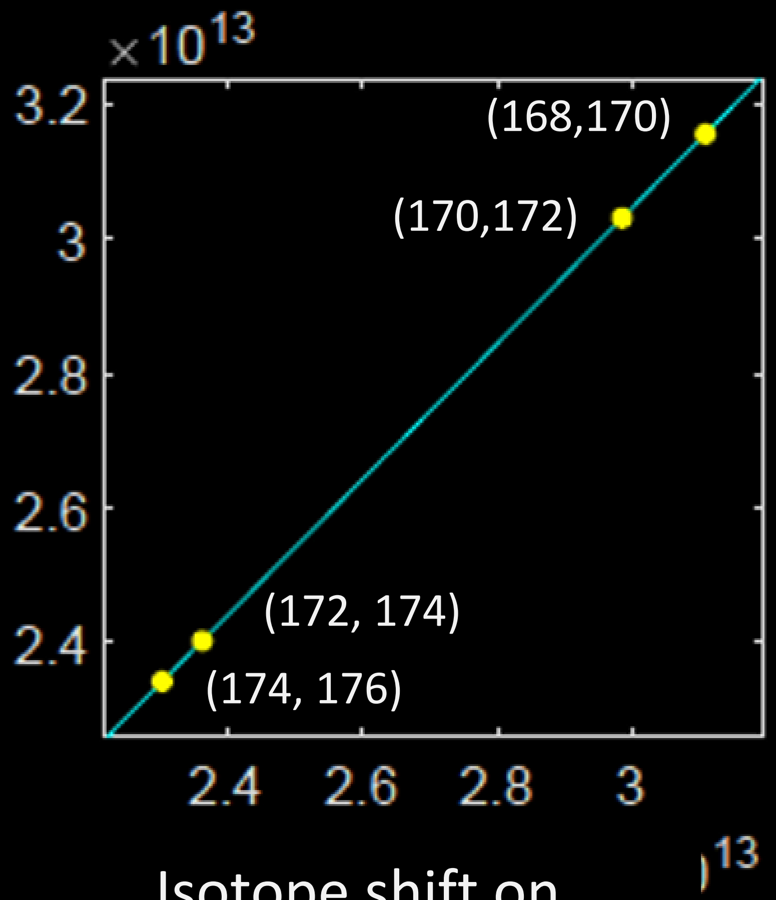
J. C. Berengut et al, PRL 120 (2018)

The measurement





King Plot



Isotope shift on transition β, $\delta\nu_{435}/\delta\mu$ (Hz · u)

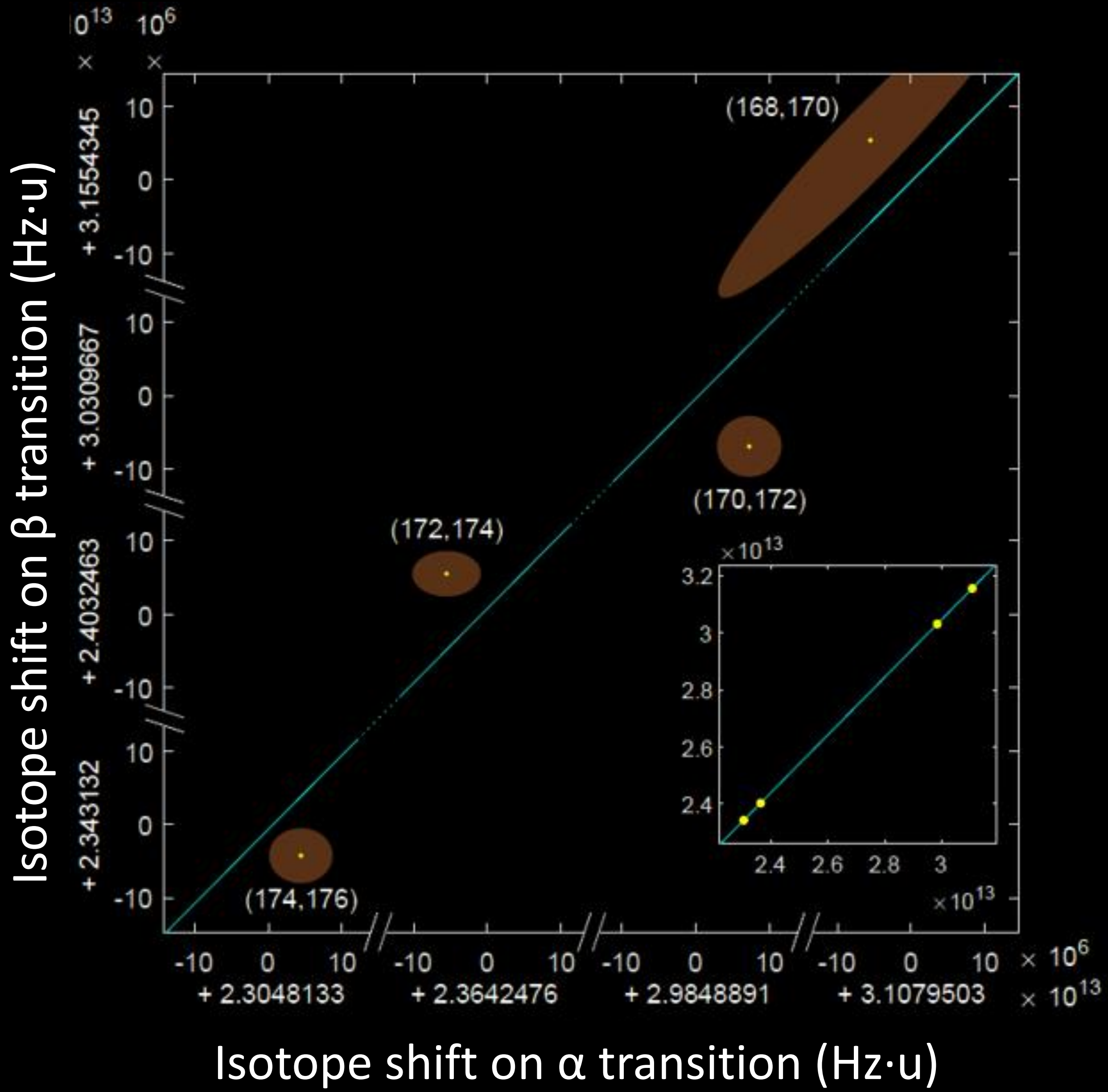
Isotope shift on transition α, $\delta\nu_{411}/\delta\mu$ (Hz · u)

King Plot

Zoom in by a factor of
1 million...

King Plot

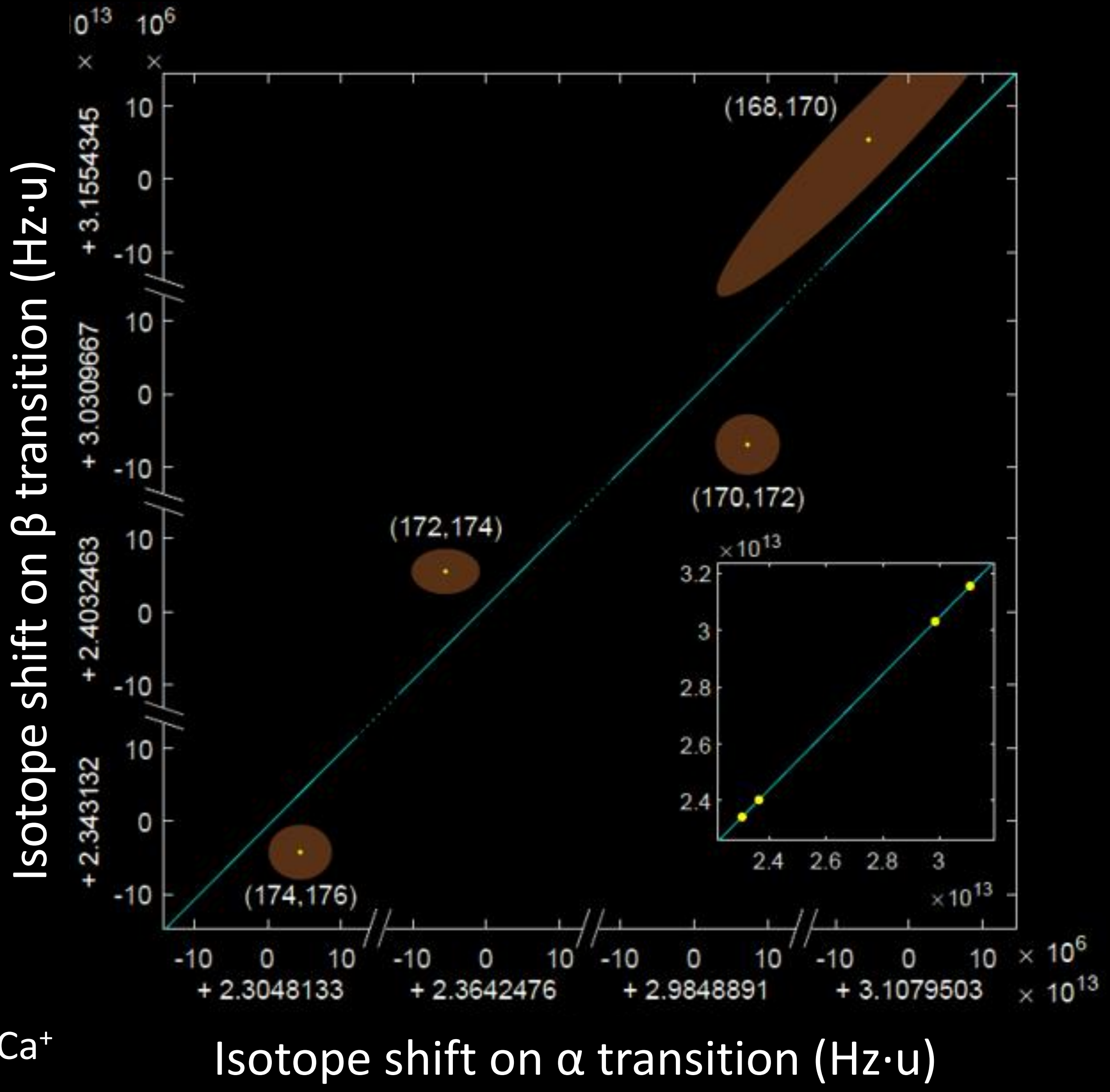
Zoom in by a factor of 1 million...



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^+

So, is this a new dark matter boson?!

So, is this a new dark matter boson?!

Not necessarily.

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

Mass shift | Field shift | Boson shift

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

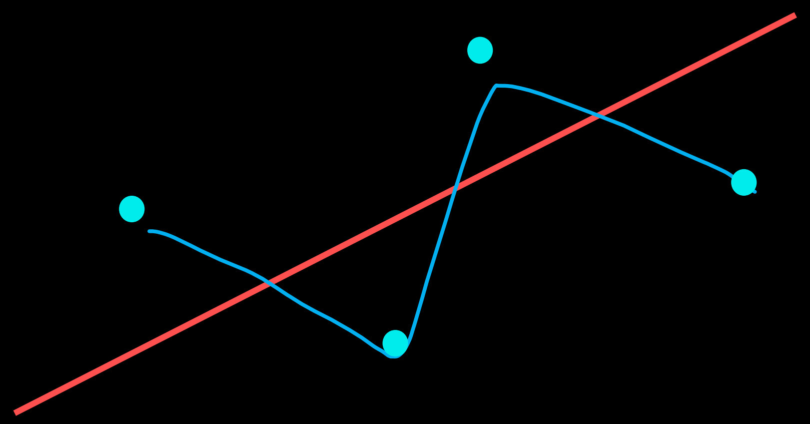
So, is this a new dark matter boson?!

Not necessarily.
There are higher-order standard model contributions that can also give rise to King-plot nonlinearity.

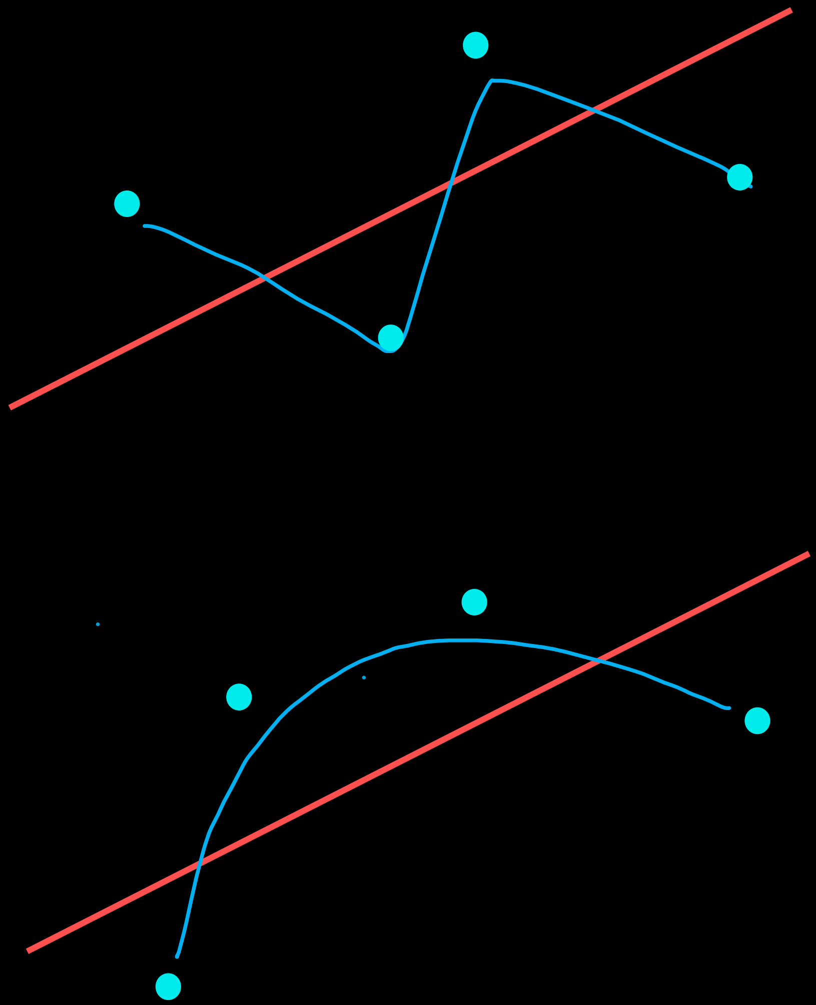
$$\delta v^{AA'} = \underbrace{K\delta\mu_{AA'}}_{\text{Mass shift}} + \underbrace{F\delta\langle r^2\rangle_{AA'}}_{\text{Field shift}} + \underbrace{\Phi_{AA'}}_{\text{Boson shift}}$$

$$\underbrace{+ F^{(2)}\delta\langle r^4\rangle_{AA'} + \frac{dF}{d\langle r^2\rangle}\delta\langle r^2\rangle^2_{AA'} + \frac{dK}{d\mu}\delta\mu^2_{AA'} + \cdots}_{\text{Higher-order SM terms}}$$

Origin of the nonlinearity

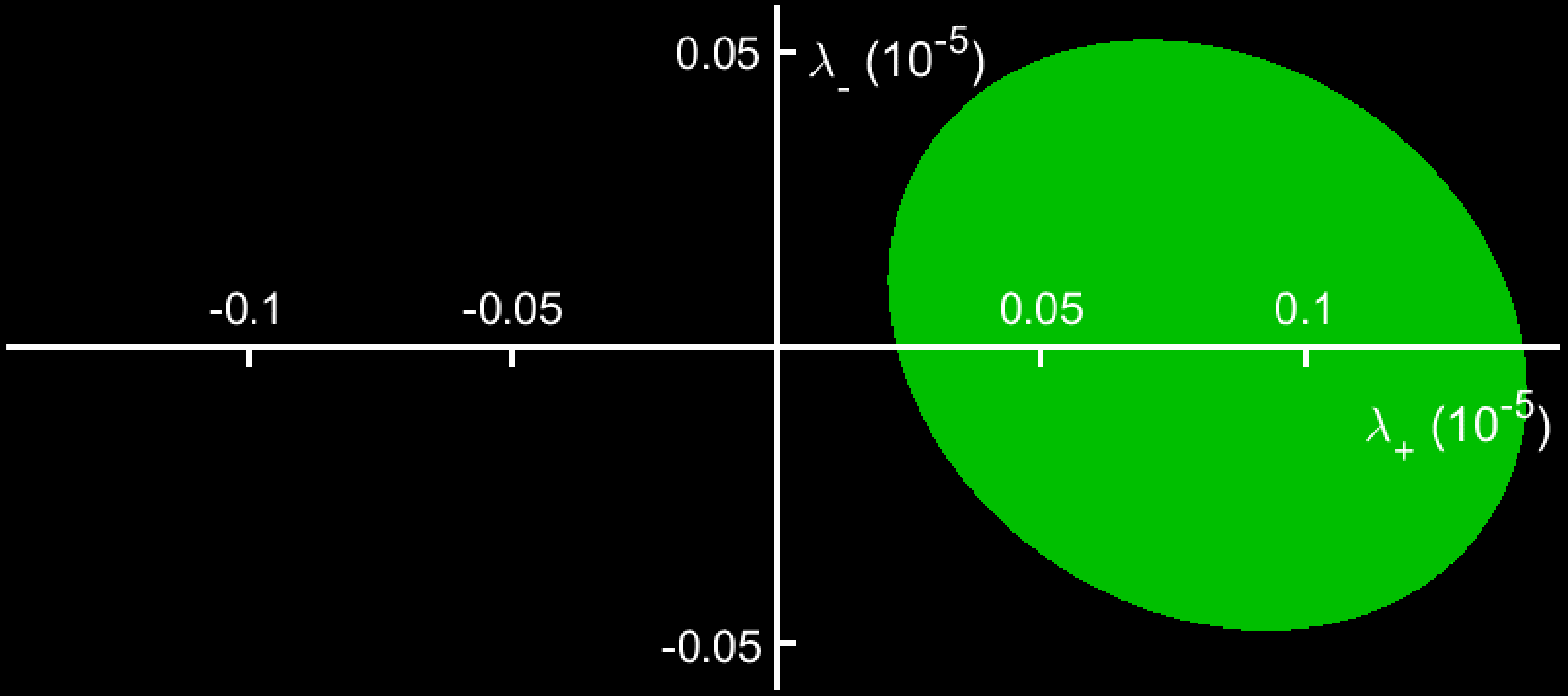


Origin of the nonlinearity



Origin of the non-linearity

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



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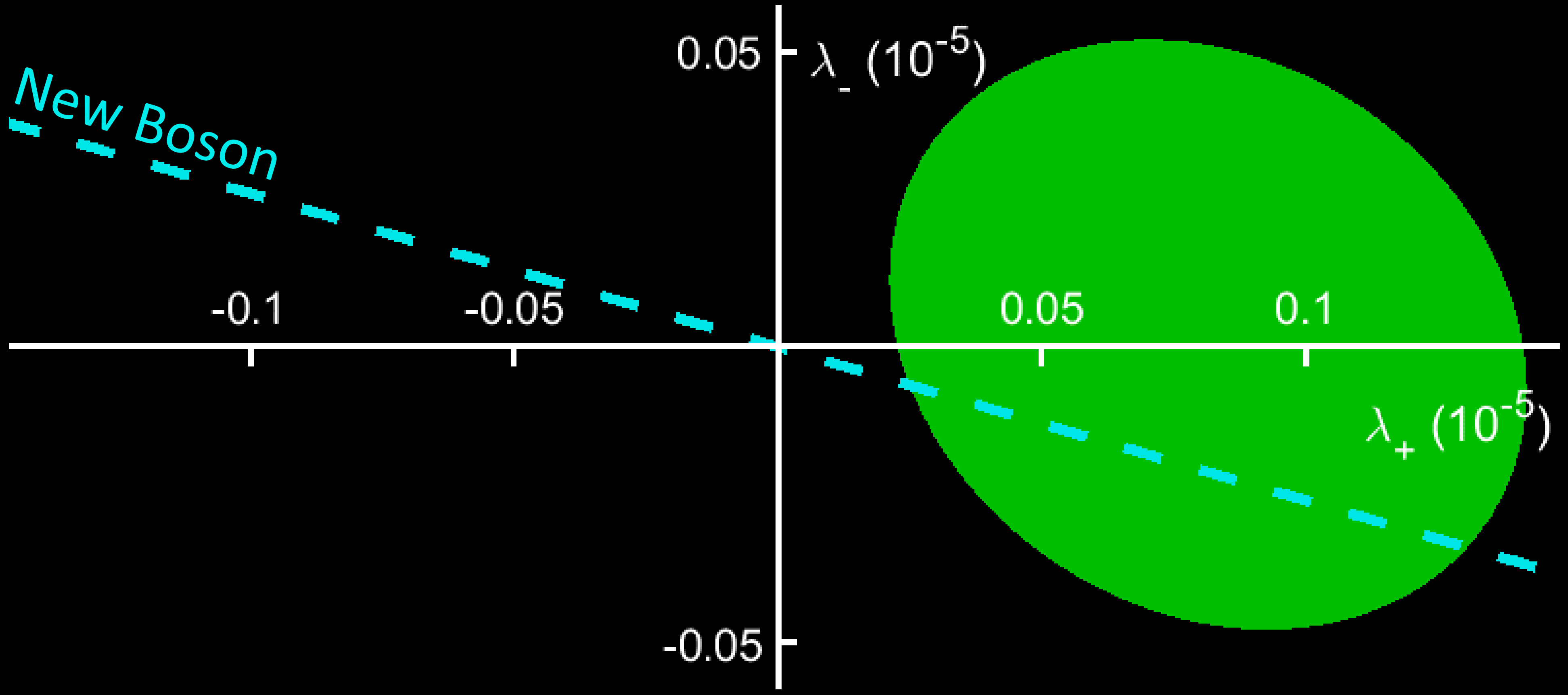

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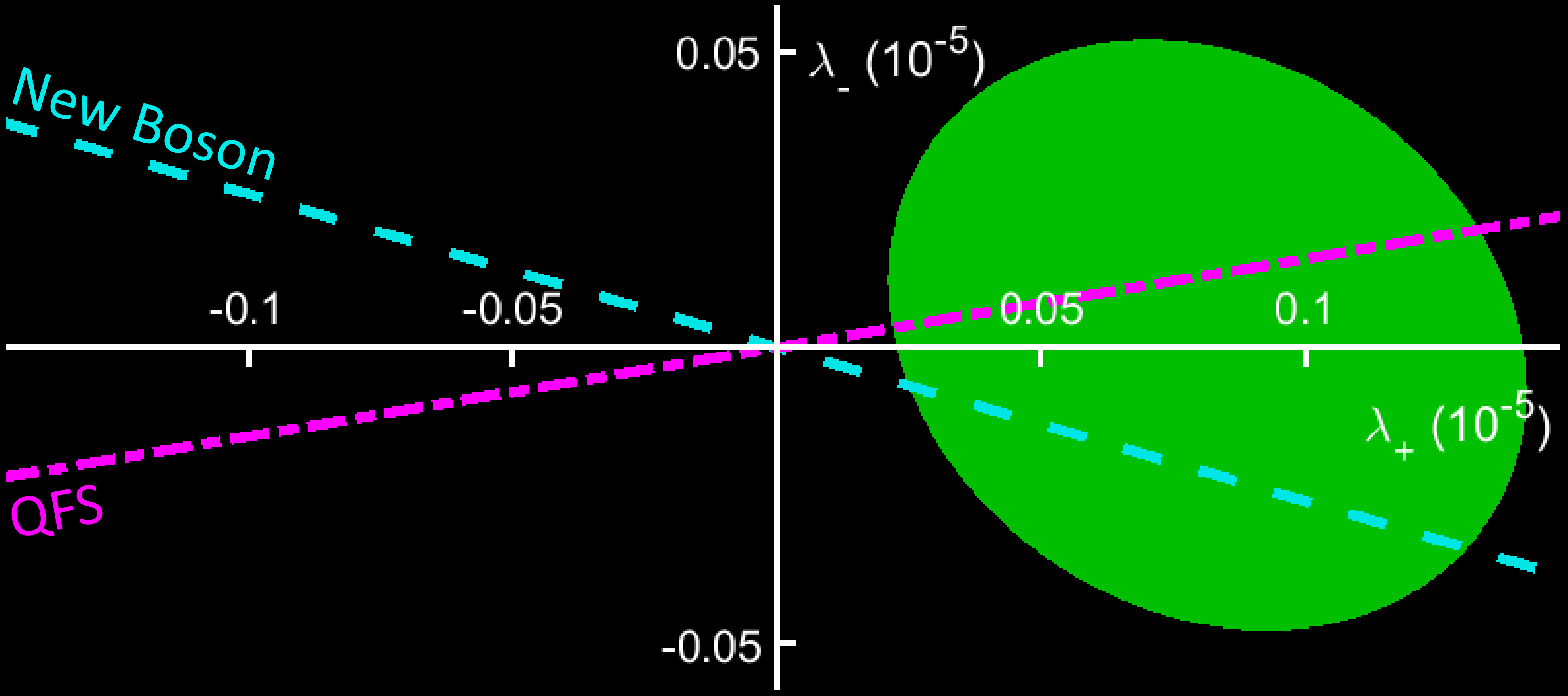
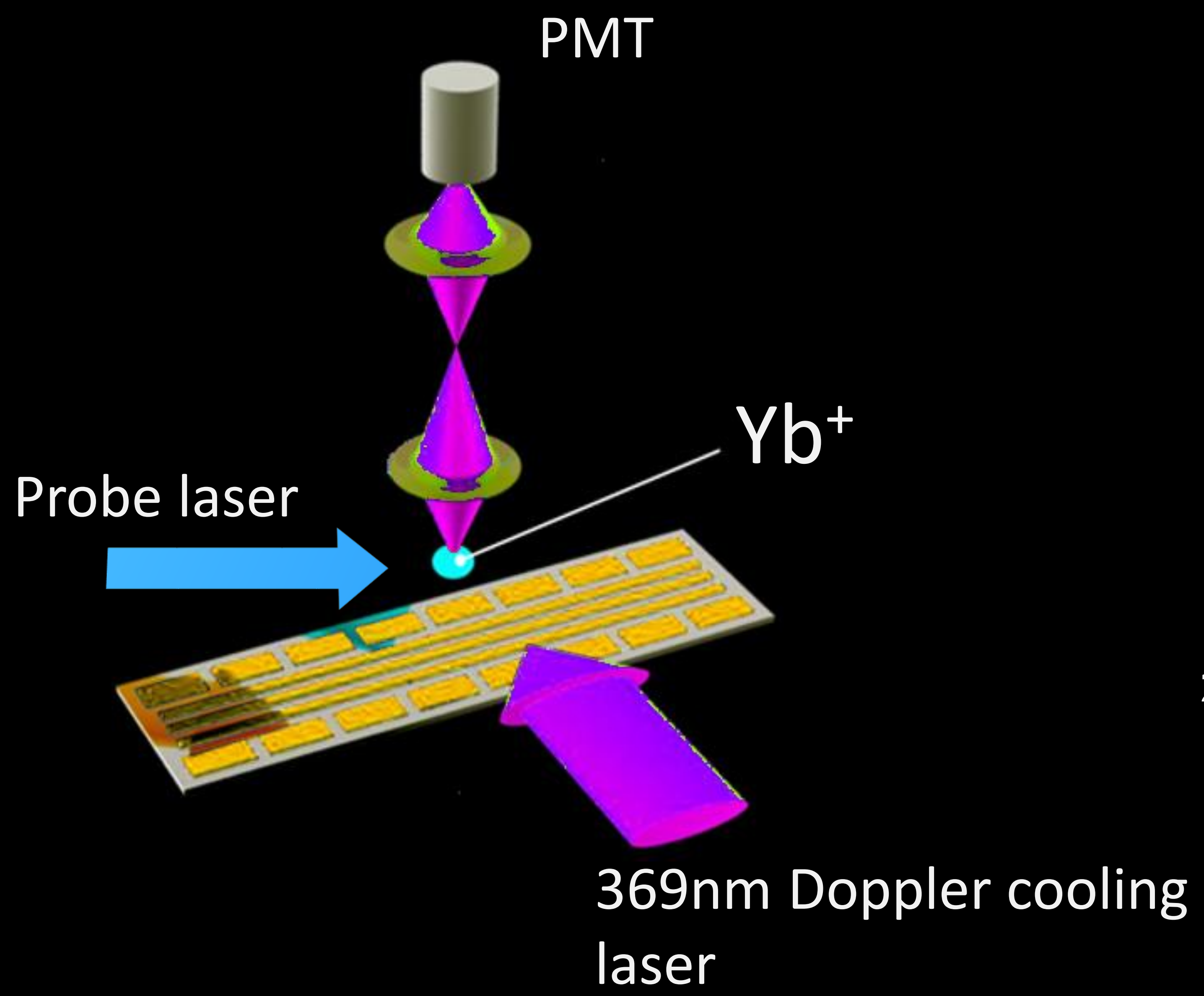
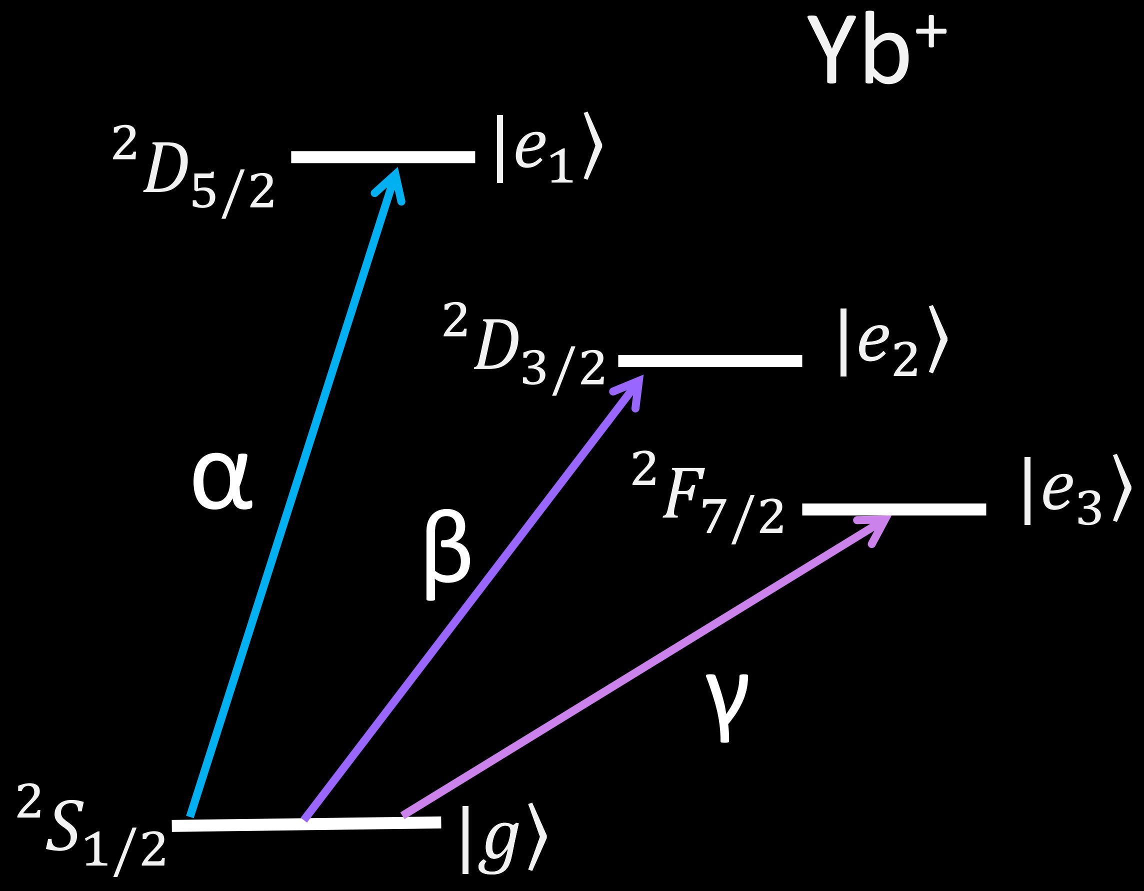
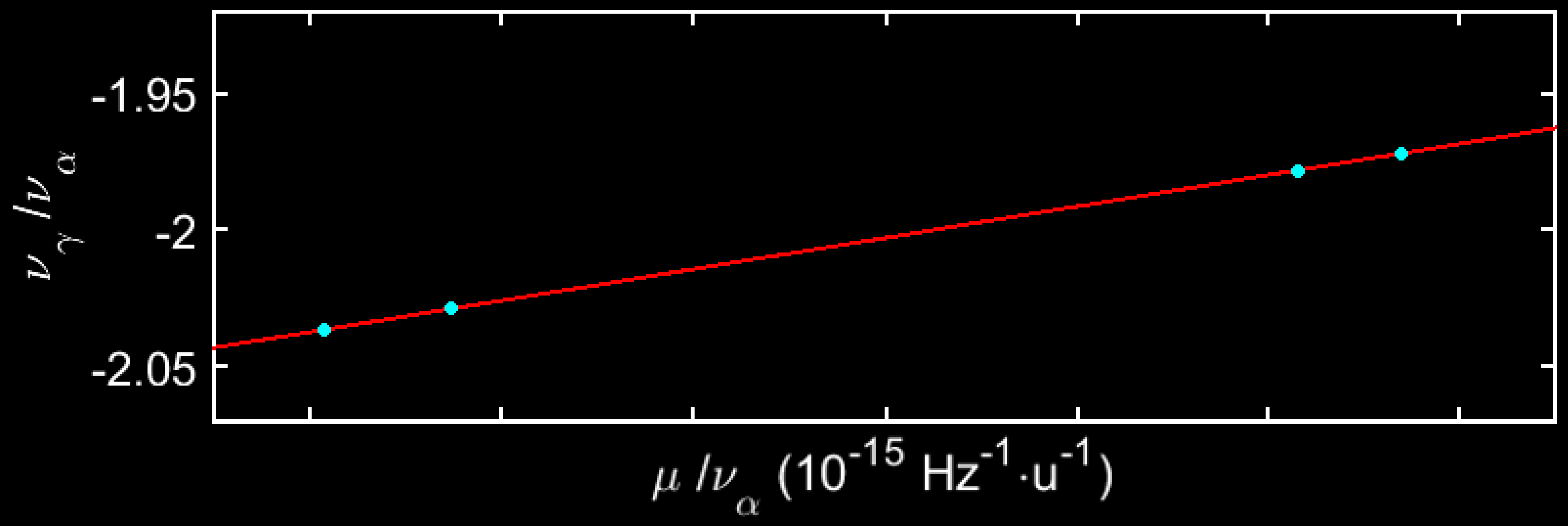


The measurement

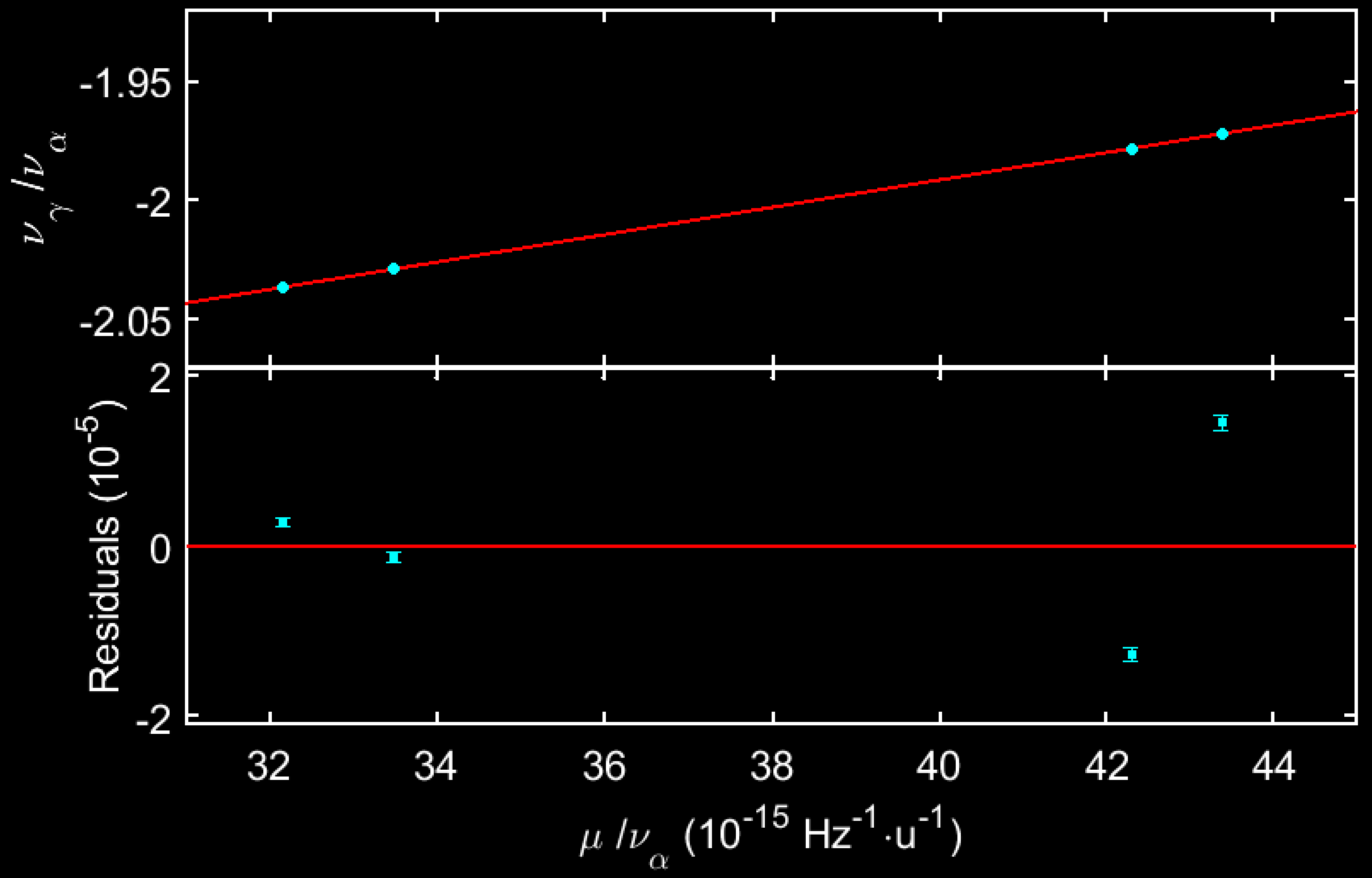




467-411 King Plot

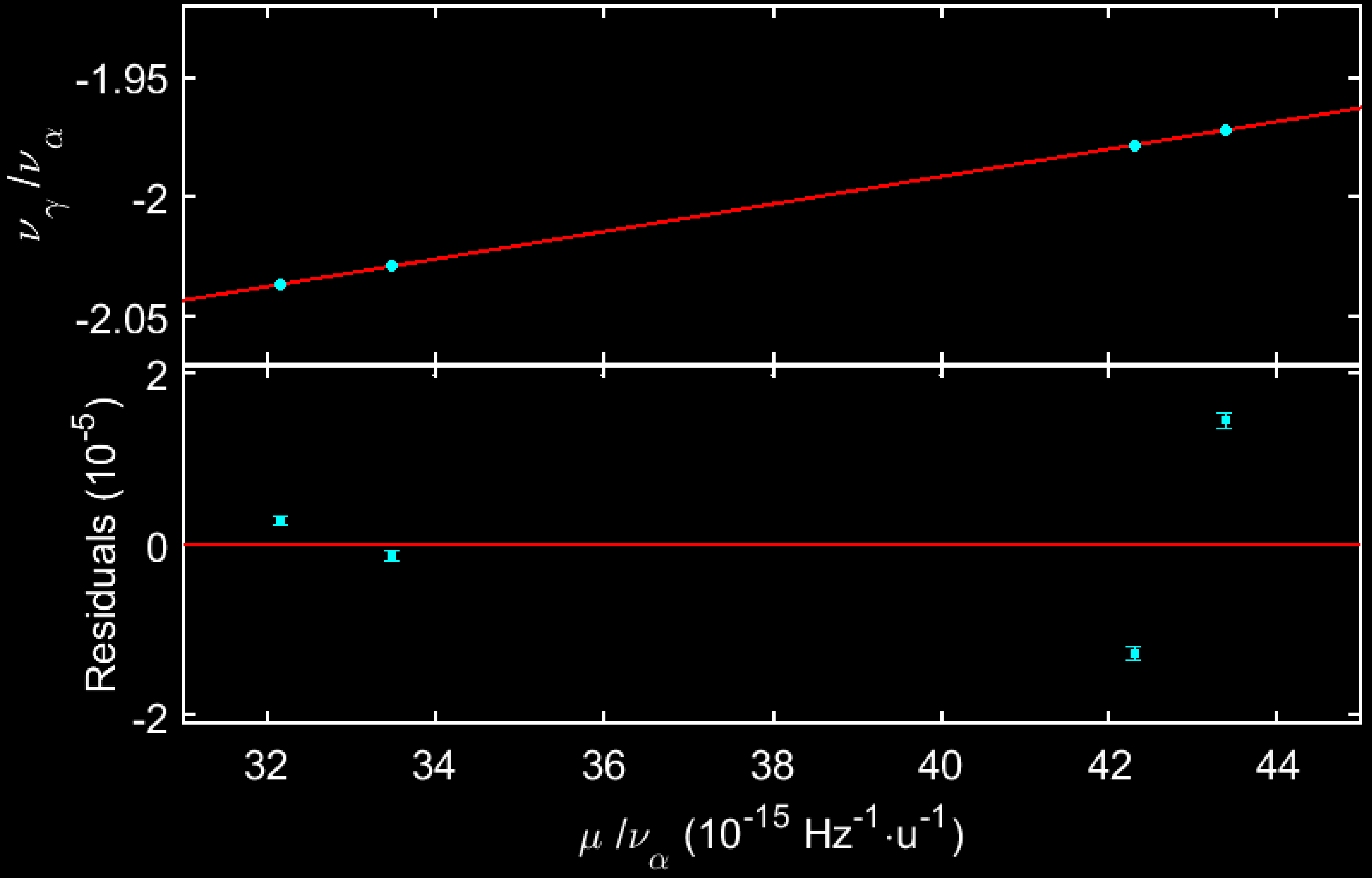


467-411 King Plot



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

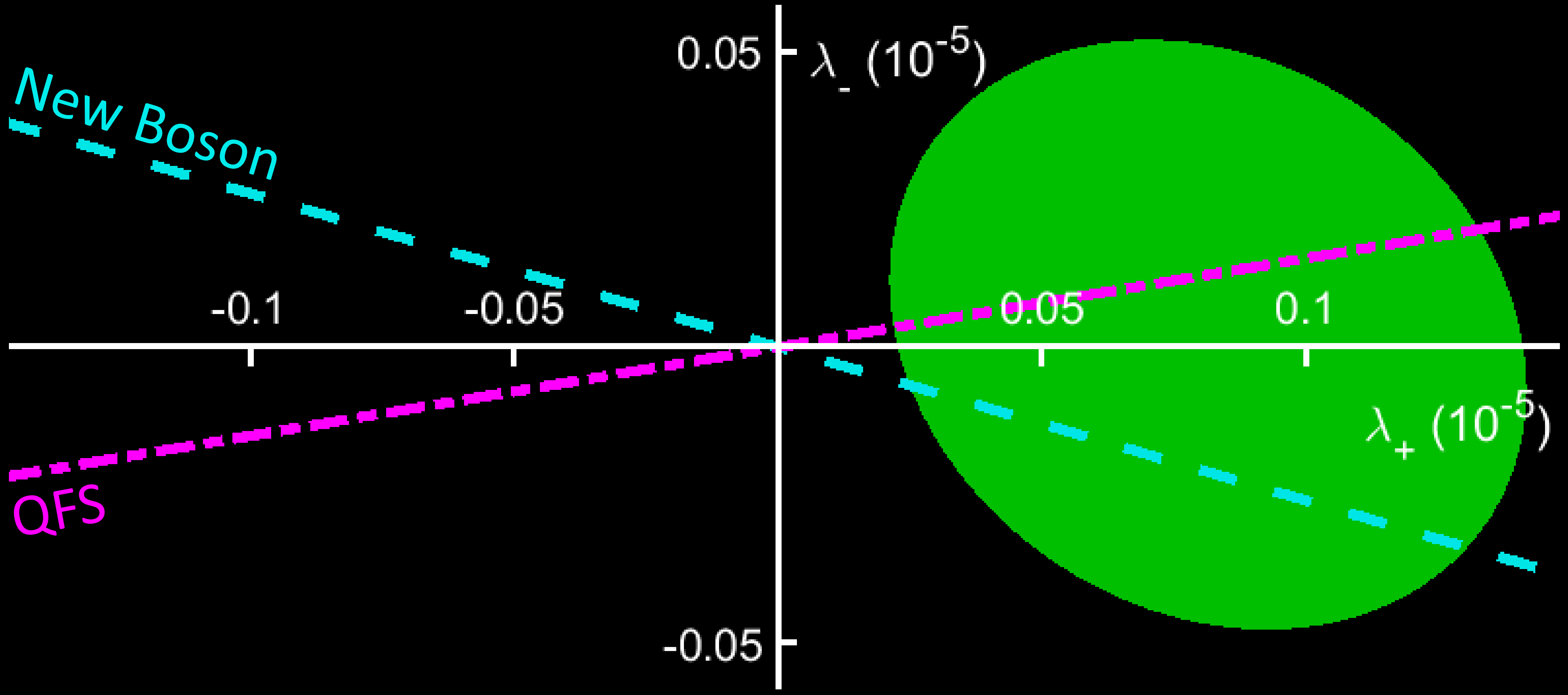
467-411 King Plot



41σ nonlinearity!

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

Origin of the non-linearity



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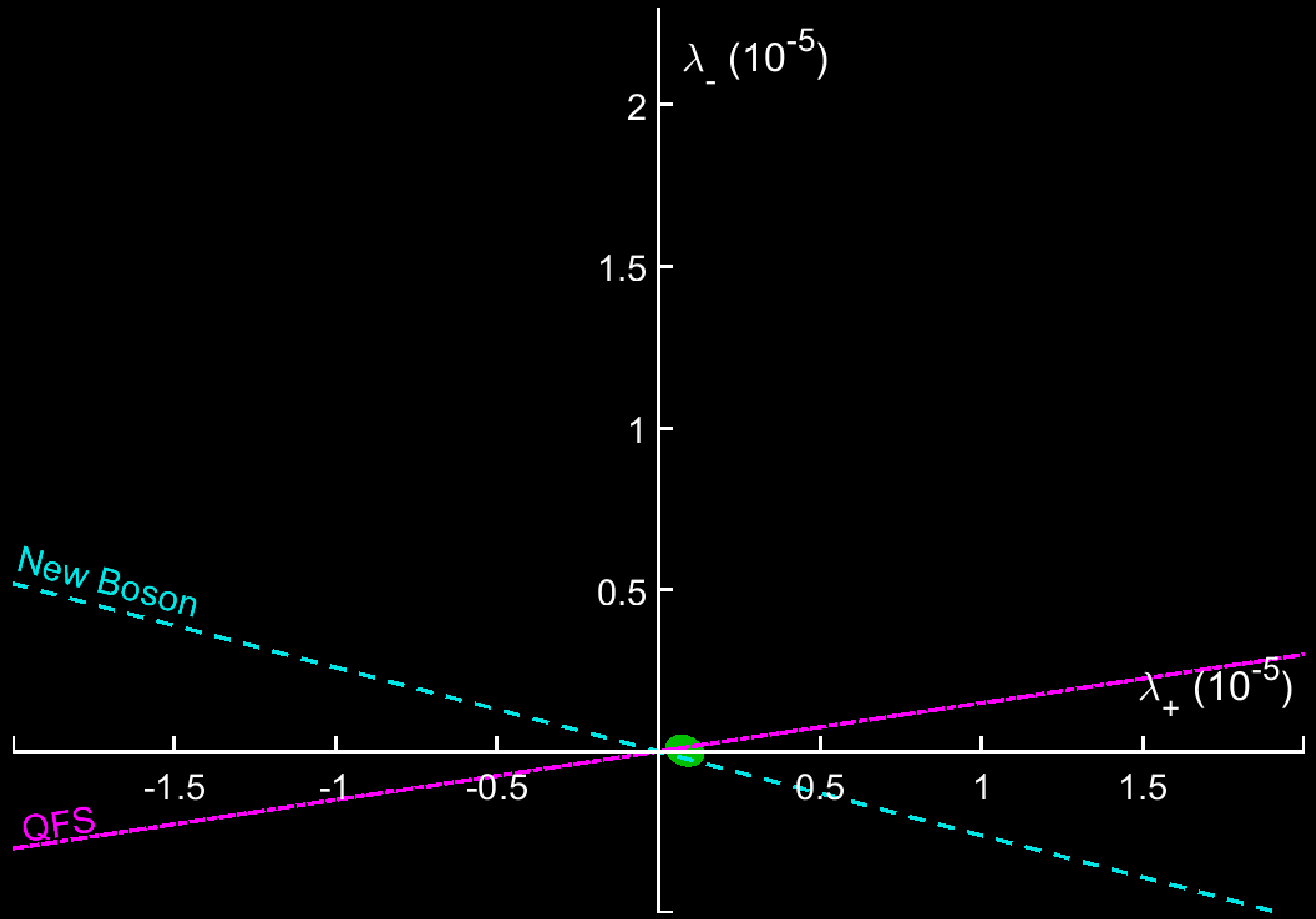

See Hur, Aude Craik*, Counts* et al, PRL **128**, 163201 (2022)*

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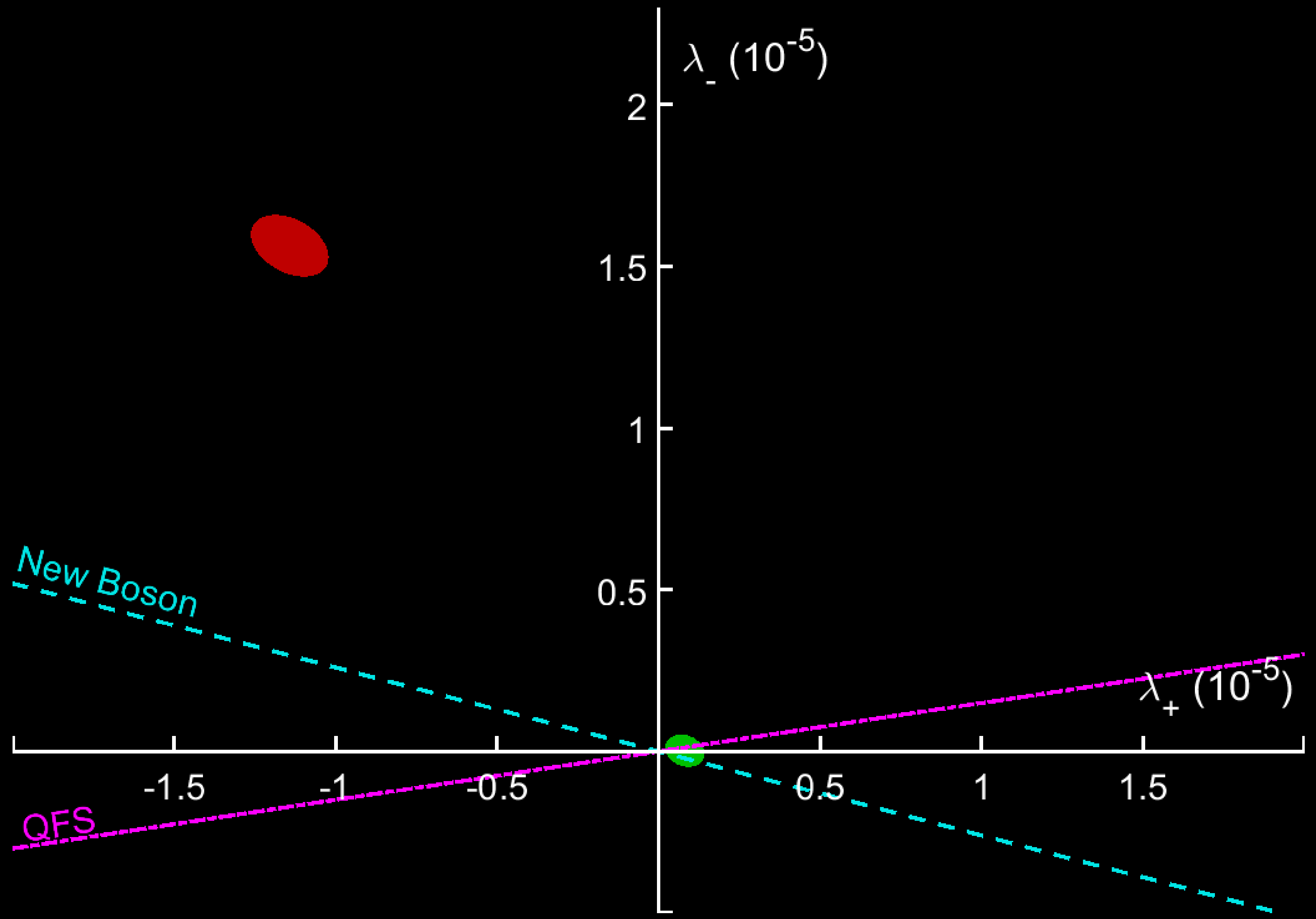


See Hur, Aude Craik*, Counts* et al, PRL **128**, 163201 (2022)*

Higher order SM contributions

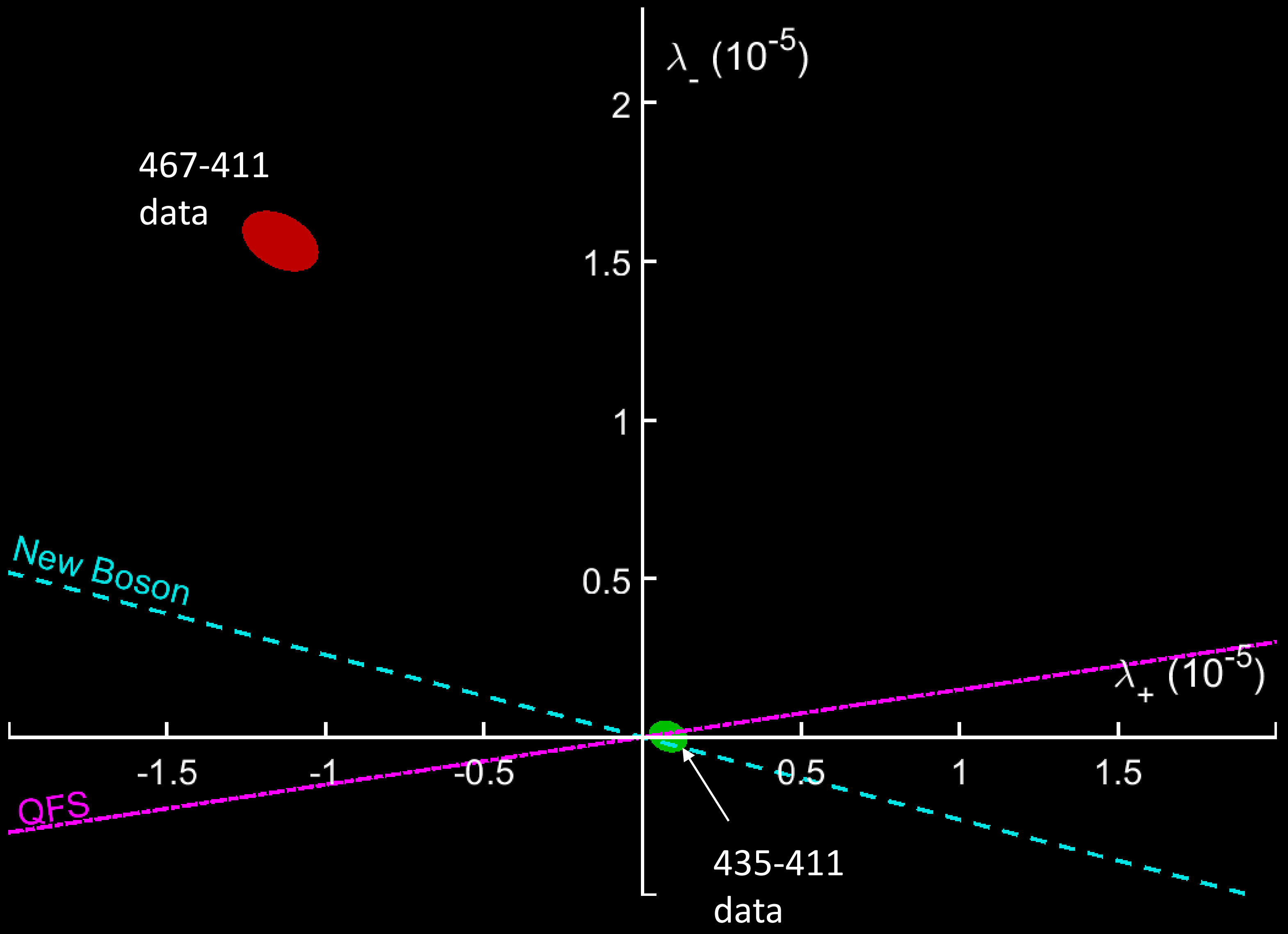
4th order nuclear charge moment

QFS

Second order mass shift – O (10Hz)

$$\underbrace{+\,F^{(2)}\delta\langle r^4\rangle_{AA'} + \frac{dF}{d\langle r^2\rangle}\delta\langle r^2\rangle^2_{AA'} + \cancel{\frac{dK}{d\mu}\delta\mu^2_{AA'}} + \cdots}_{\text{Higher-order SM terms}}$$

Origin of the non-linearity



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

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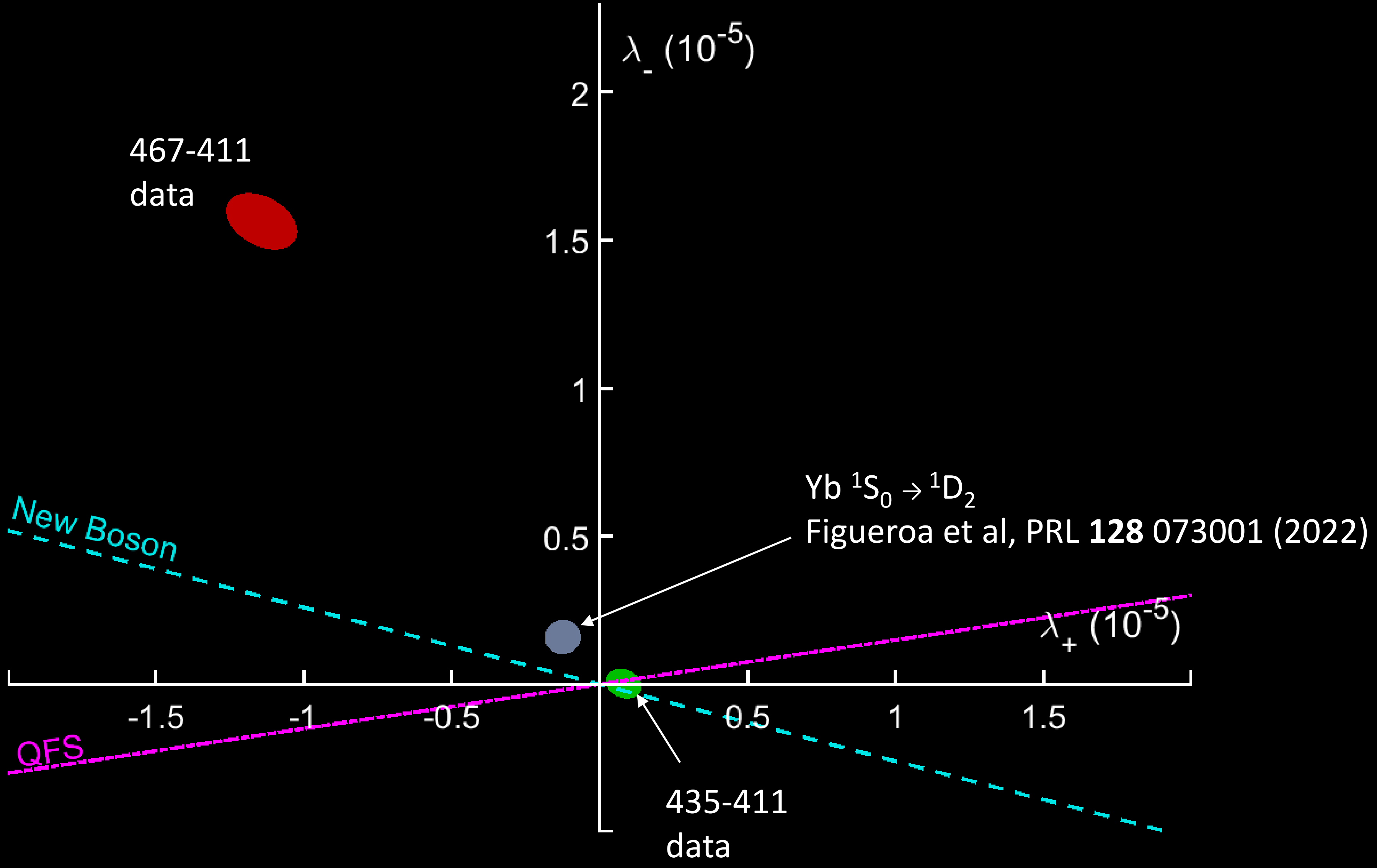

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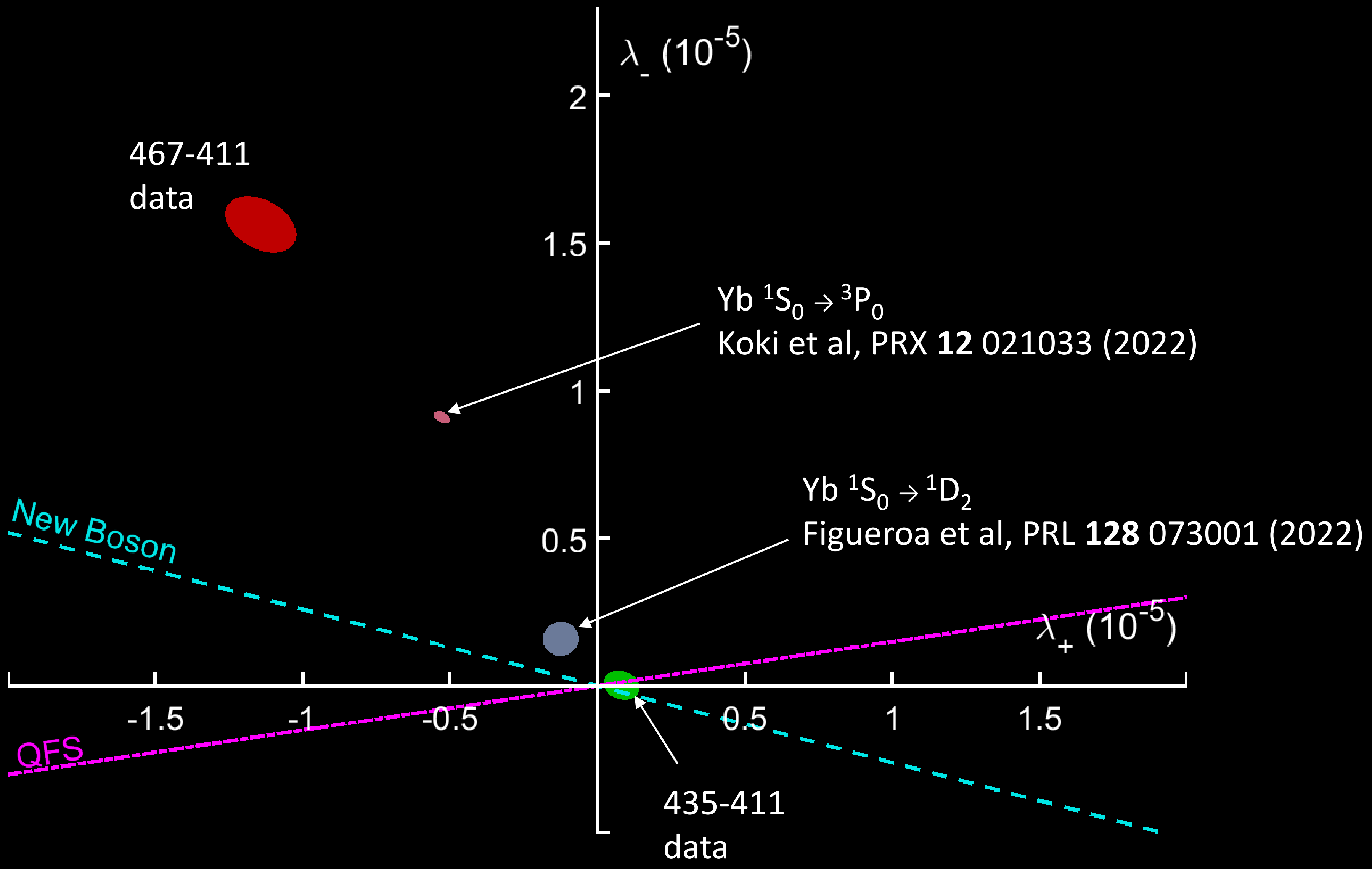

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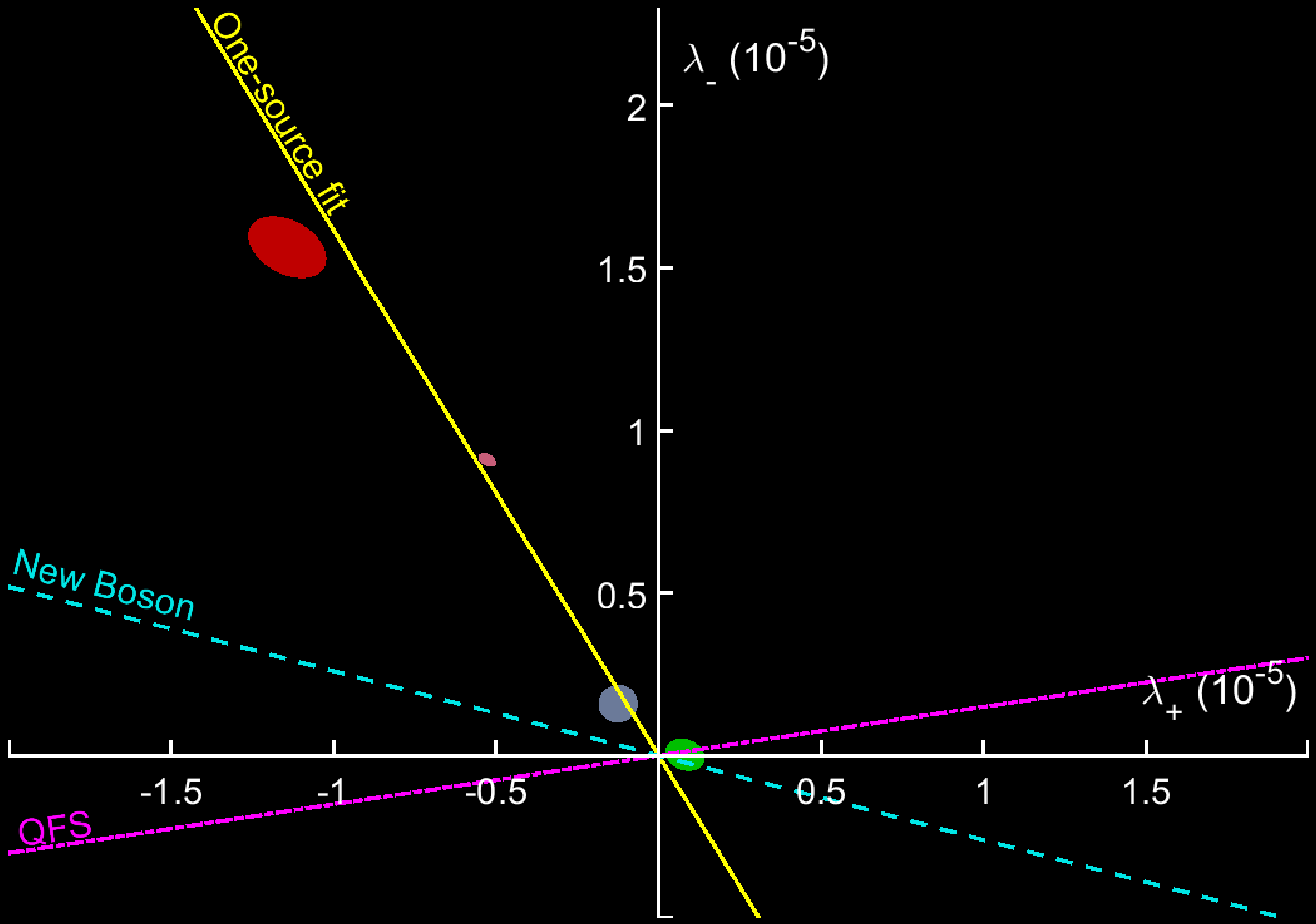

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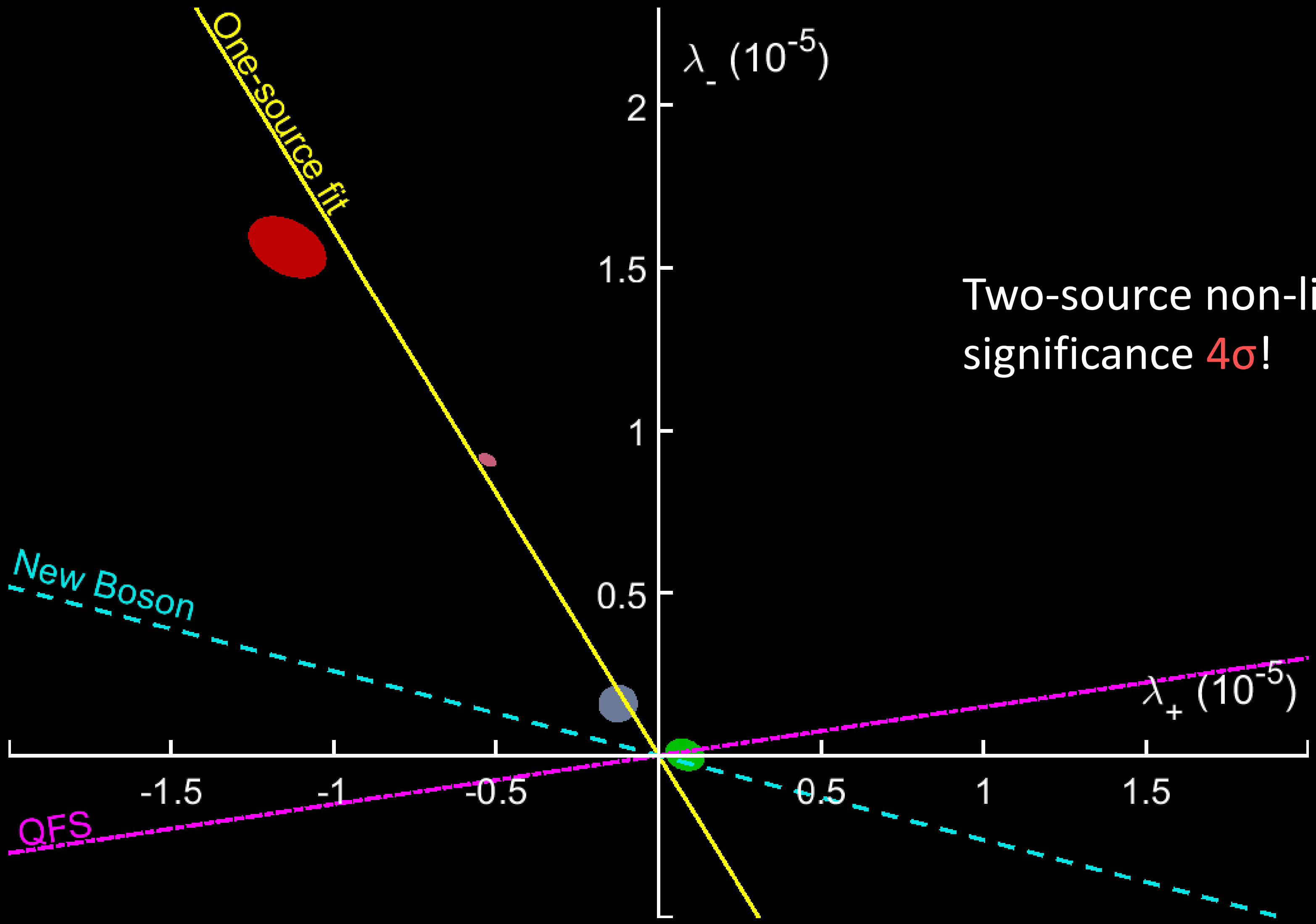
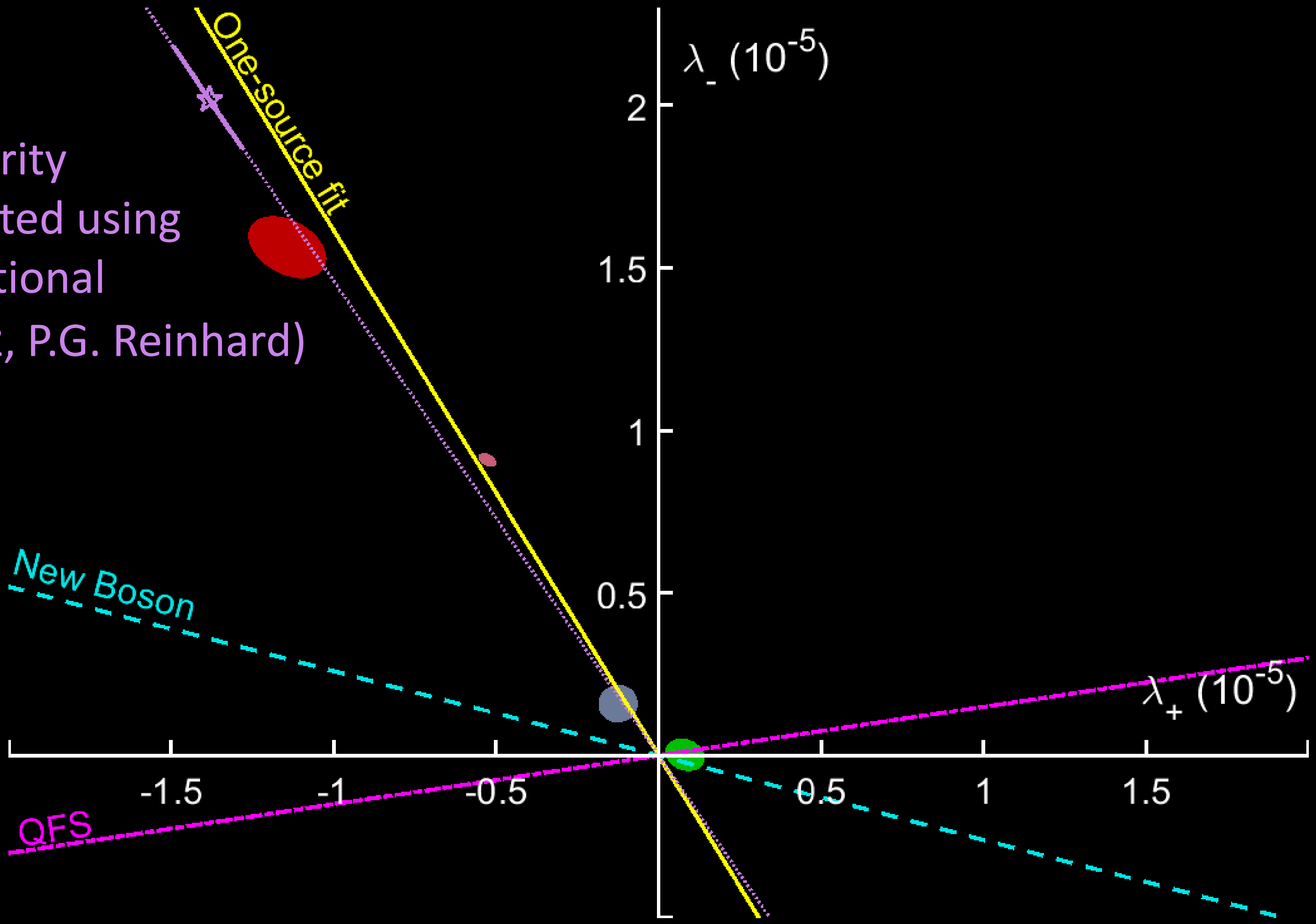


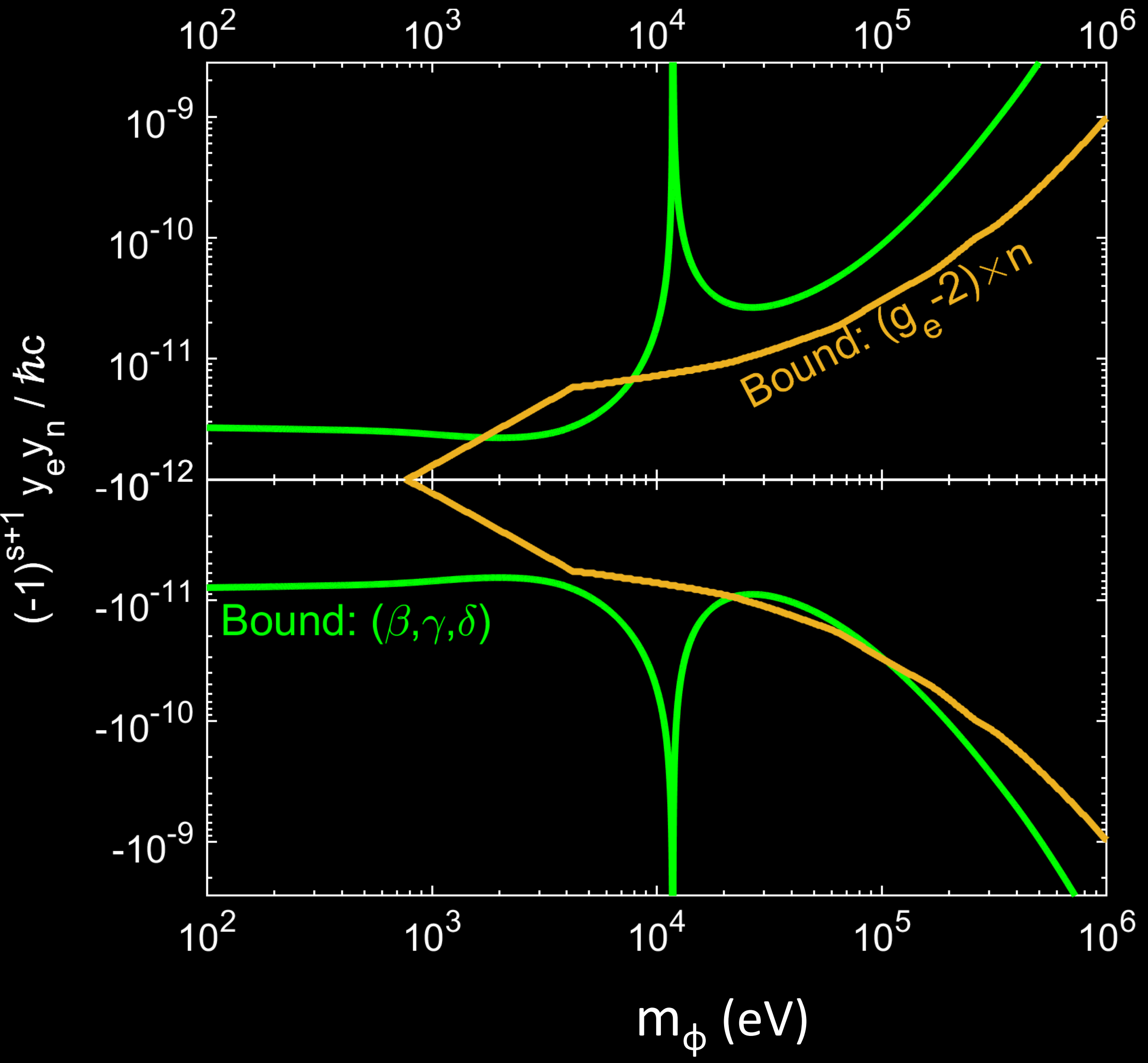
Two-source non-linearity significance 4σ!

Origin of the non-linearity

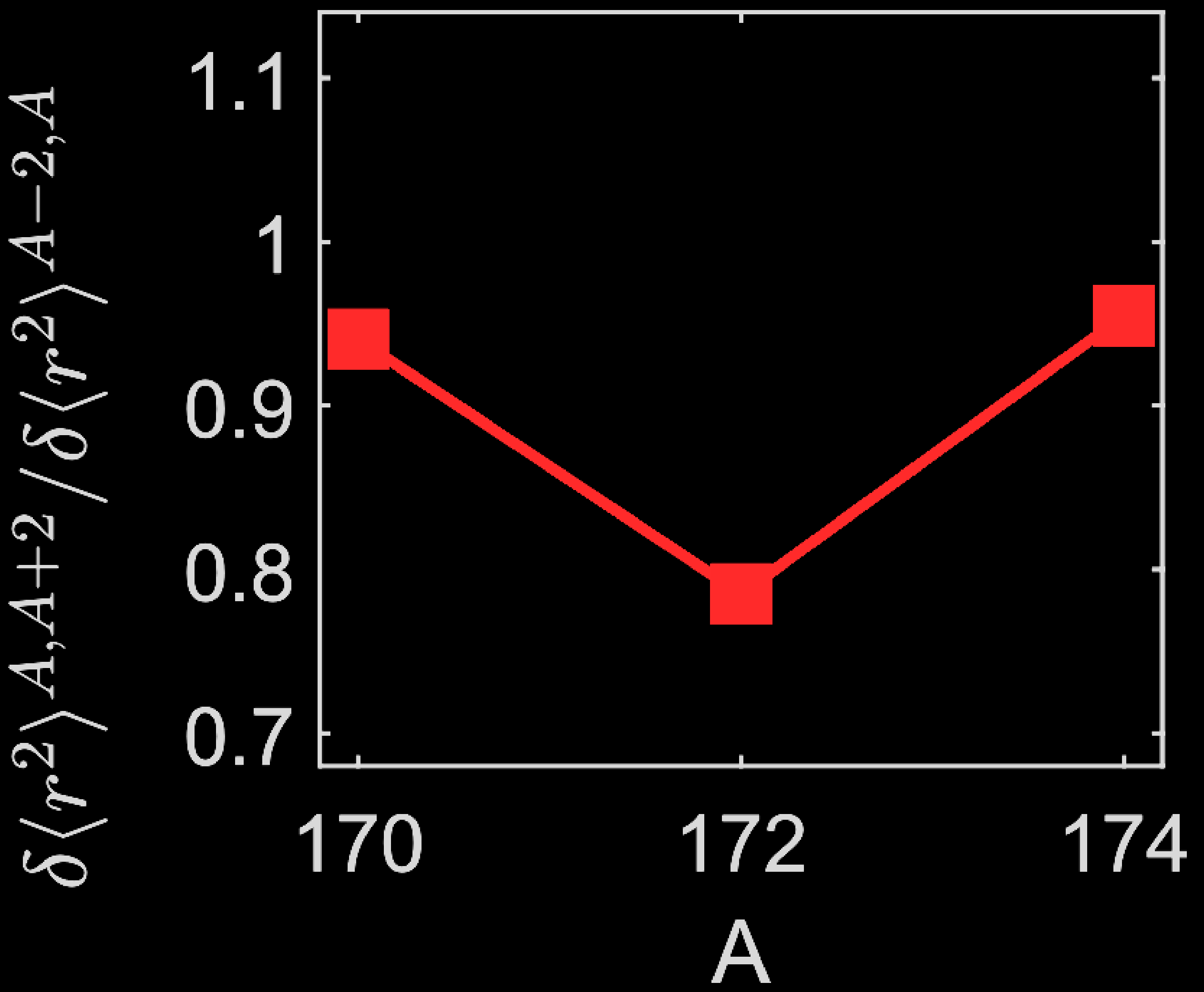
$\delta\langle r^4\rangle$ nonlinearity
Direction predicted using
the Fayans functional
(W. Nazarewicz, P.G. Reinhard)



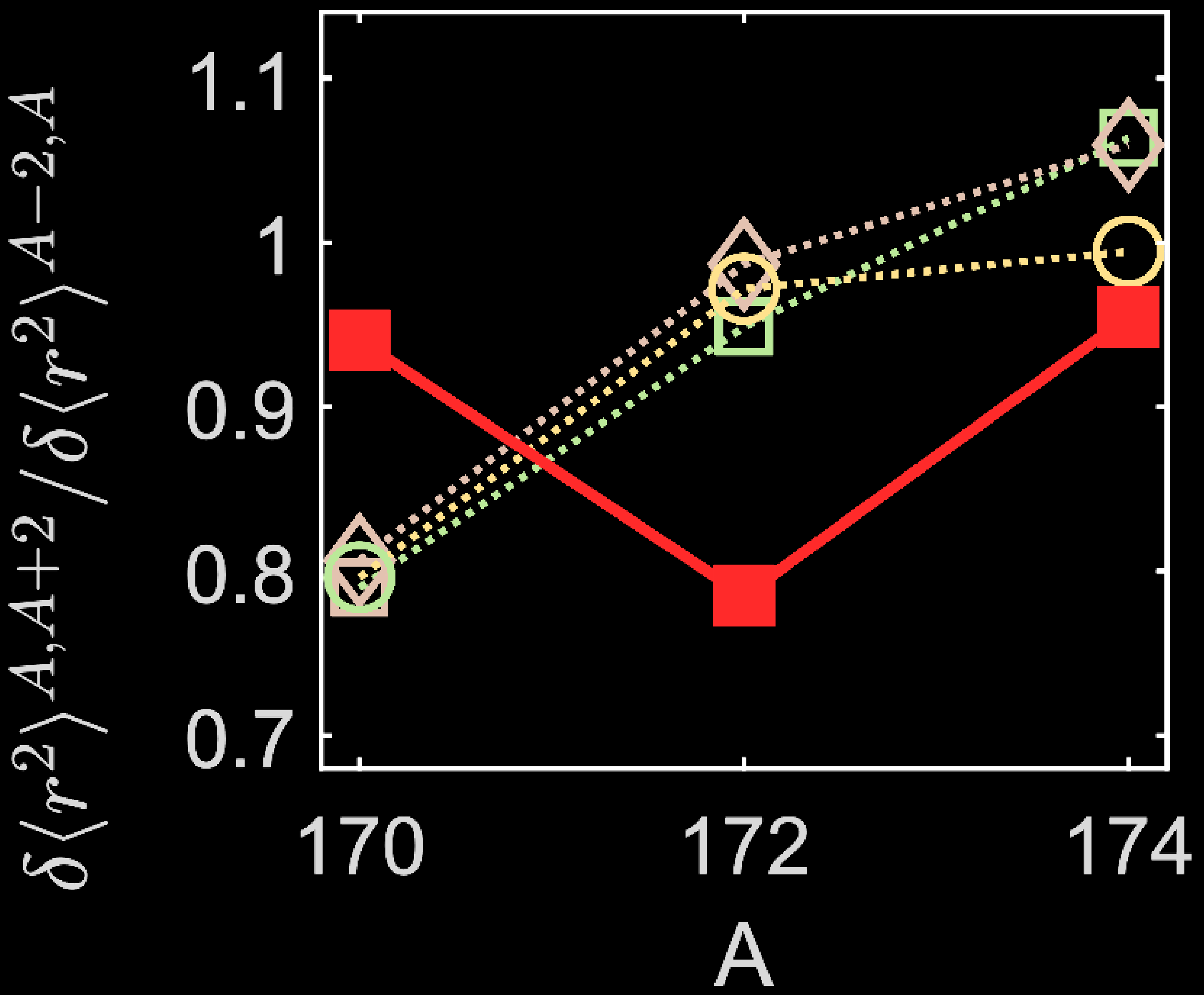
Bounds on new physics



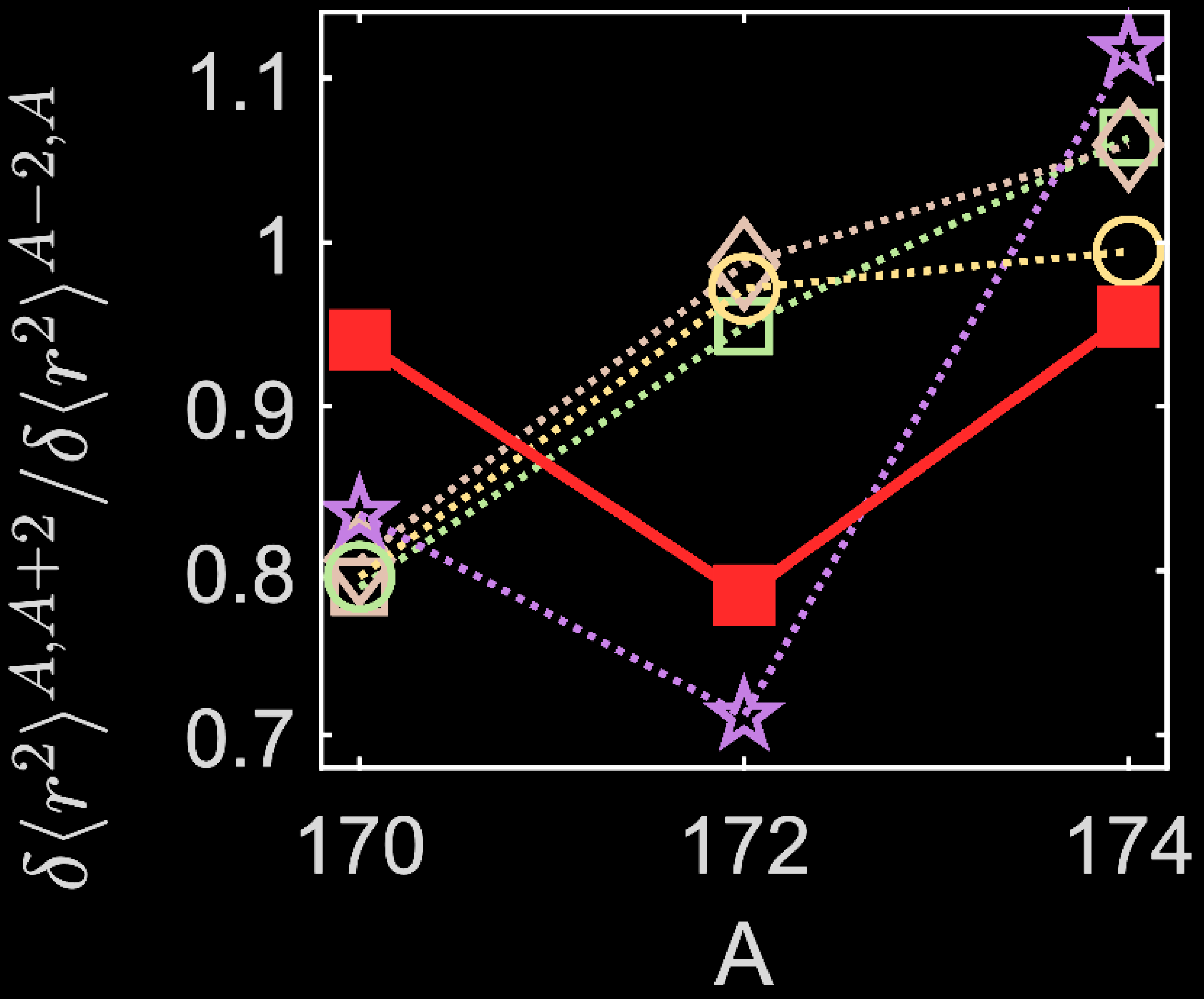
Nuclear physics insights



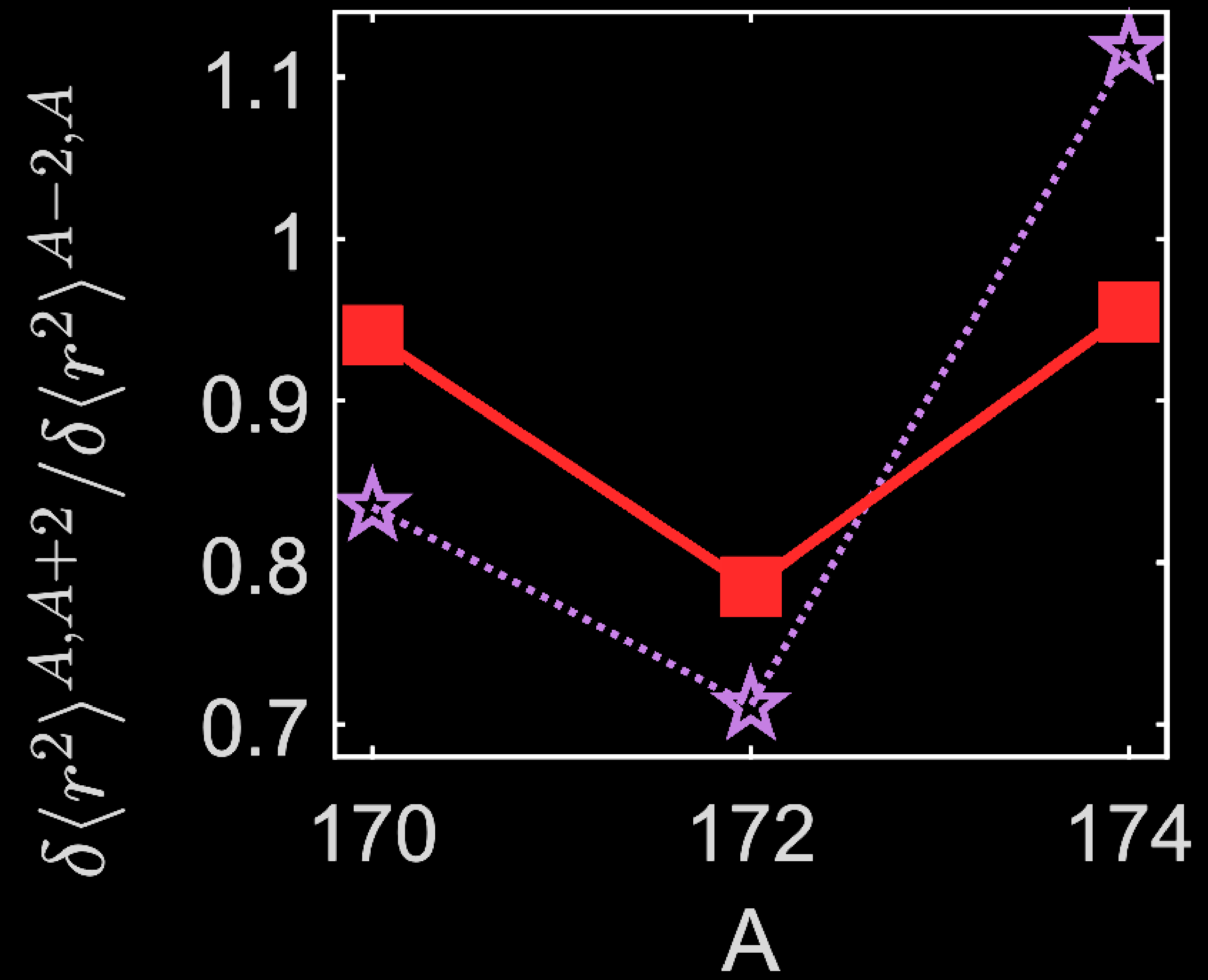
Nuclear physics insights



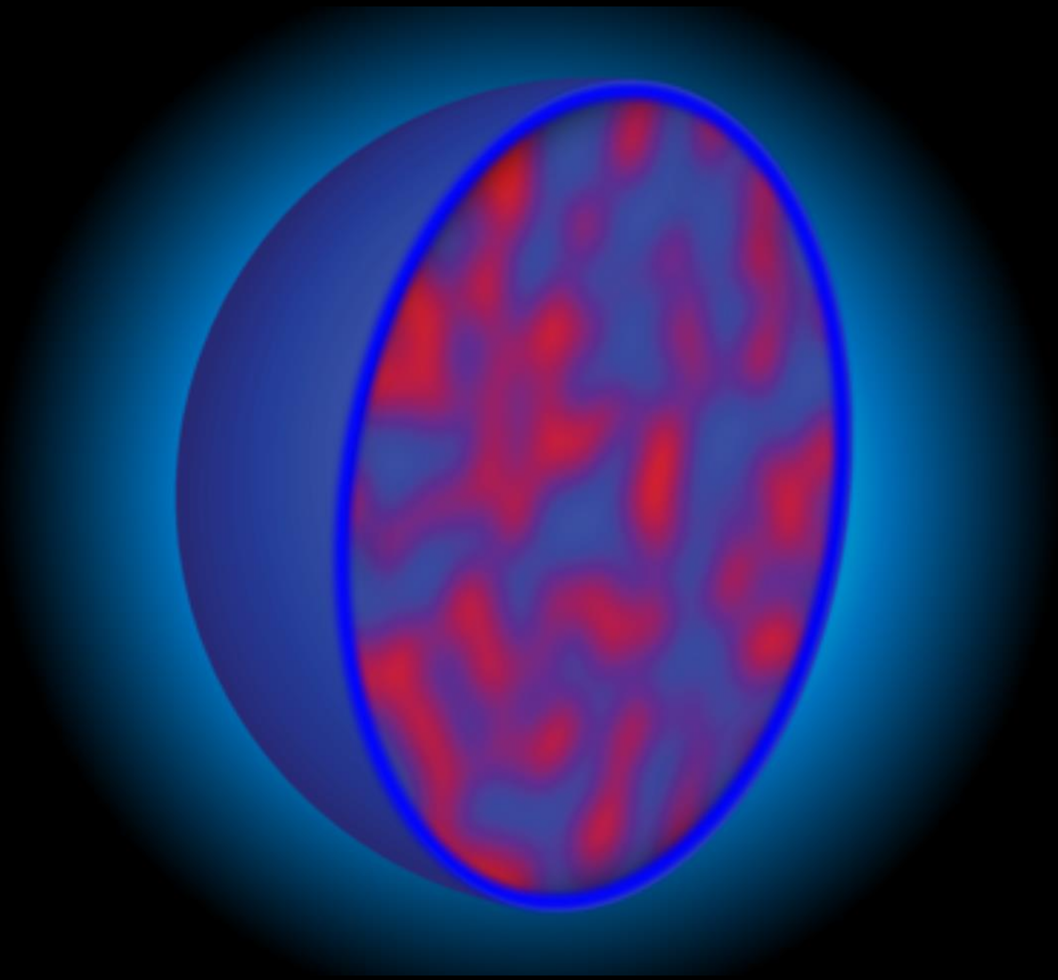
Nuclear physics insights

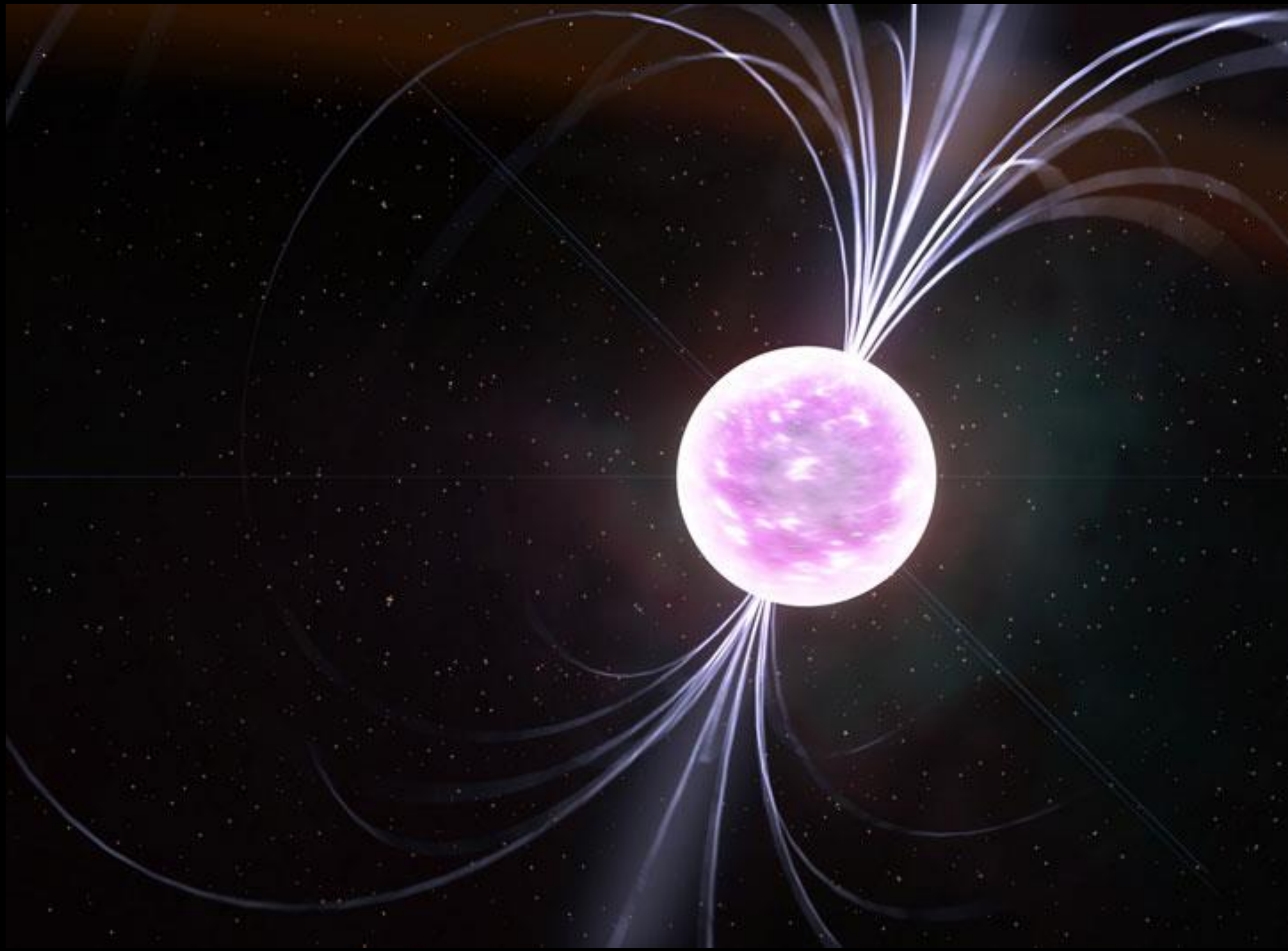


Nuclear physics insights



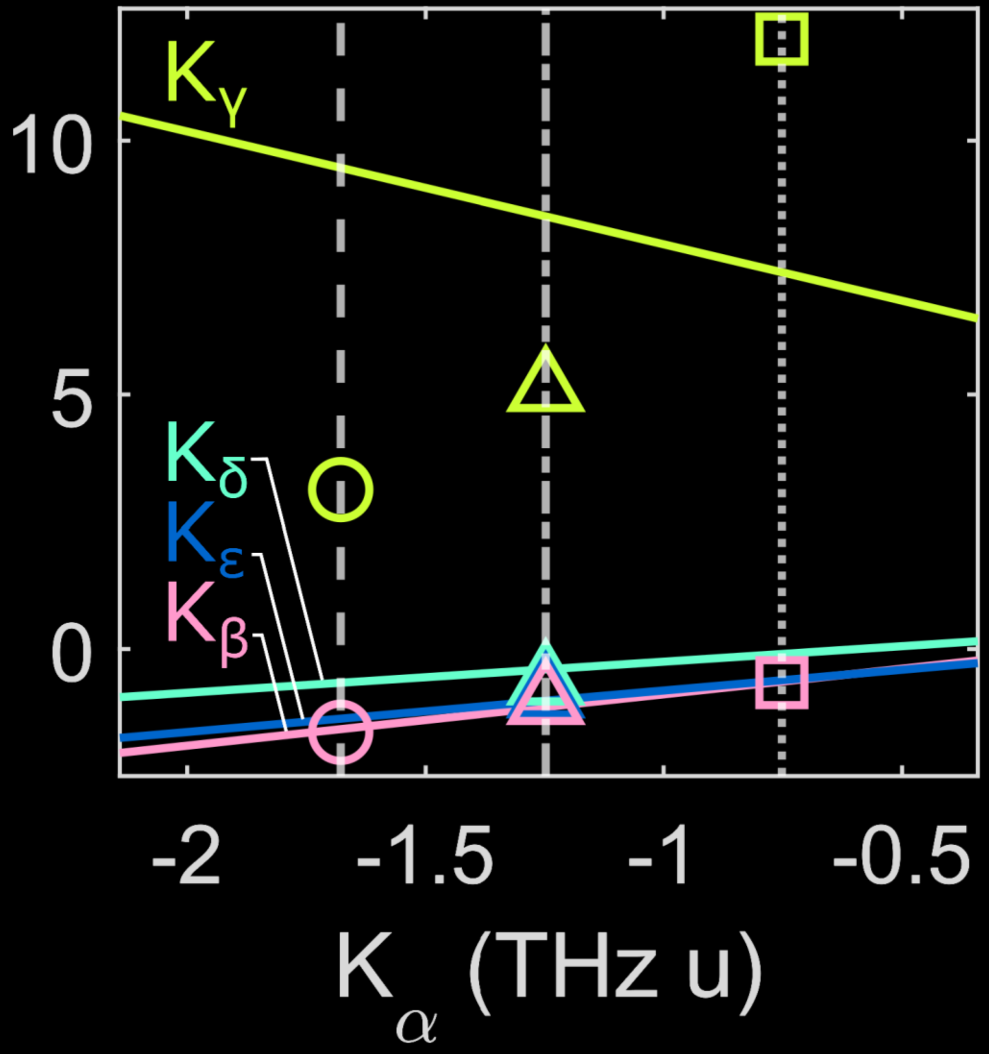
Isotope shift spectroscopy as a very precise nuclear physics probe



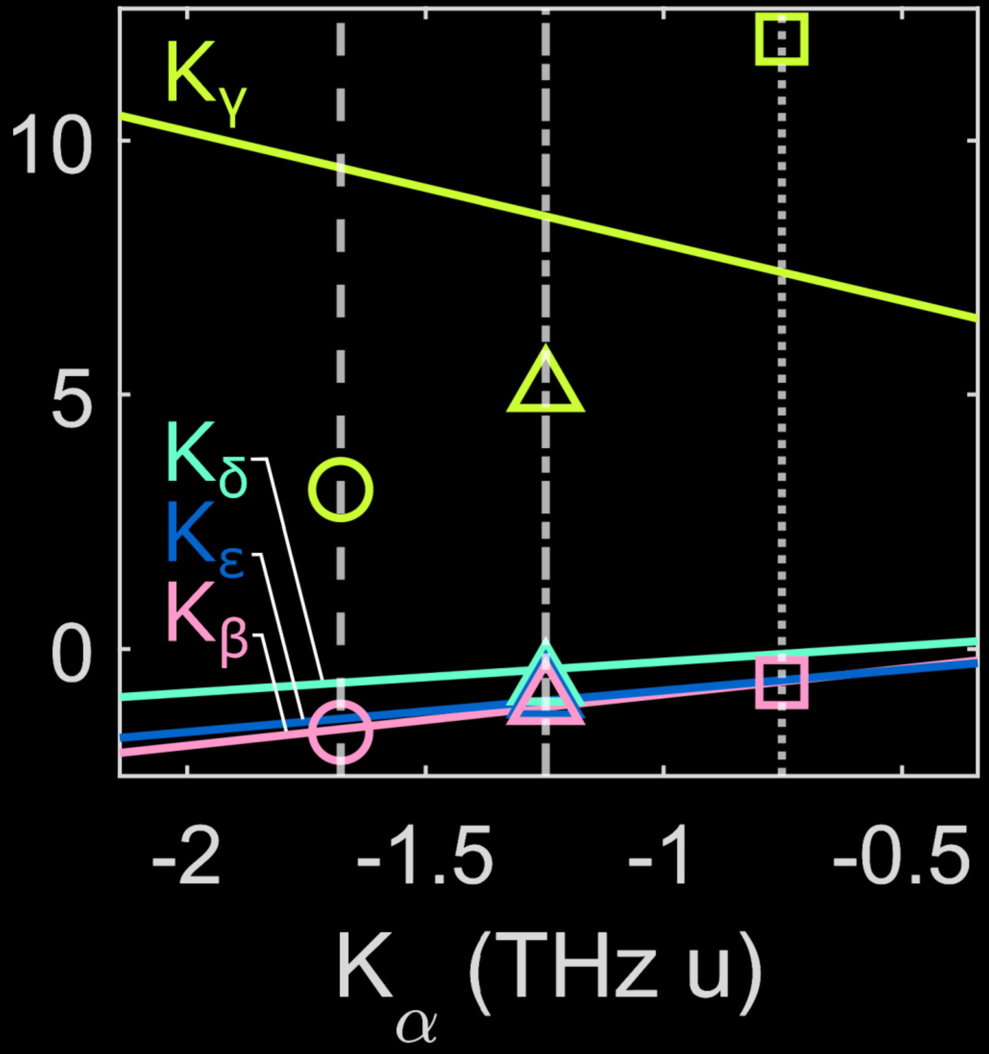


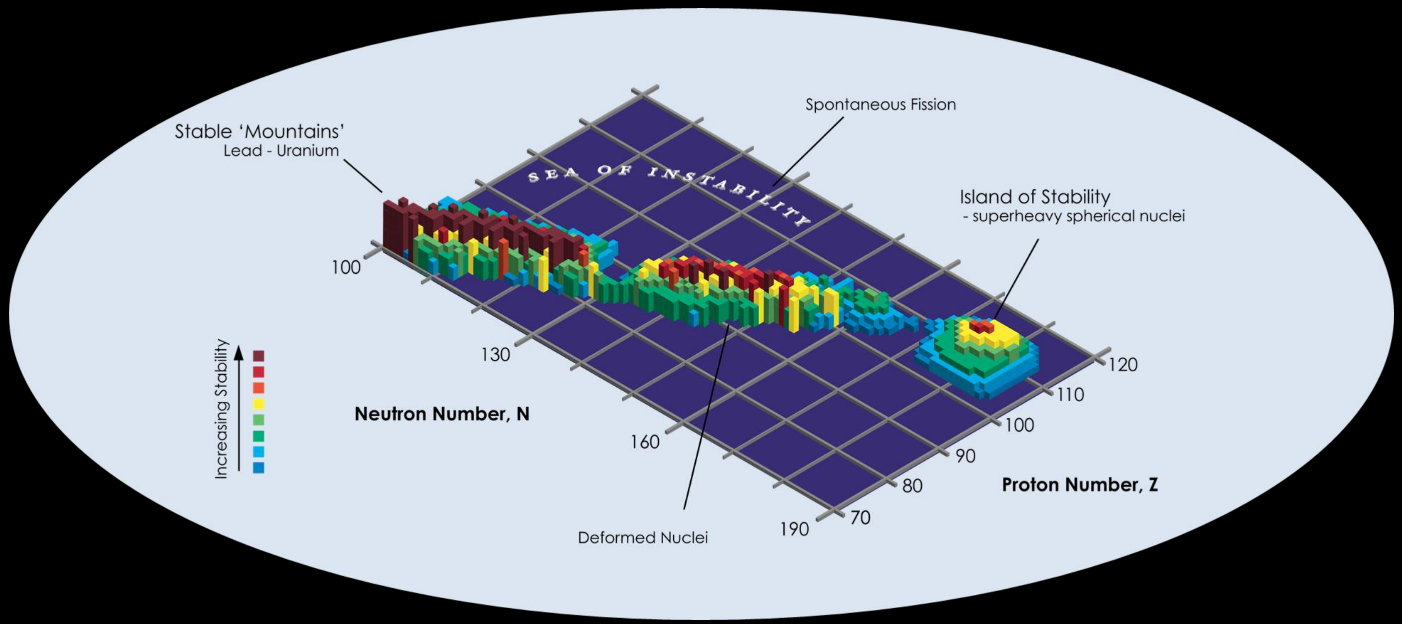
Right figure from https://physics.aps.org/articles/v14/58
Left figure from https://www.insidescience.org/news/tiny-neutron-skins-secrets-neutron-stars

Nuclear and astrophysics directions



Nuclear and astrophysics directions





See V. Dzuba et al, Phys. Rev. A **95**, 062515 (2017)

Figure by InvaderXan - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=20003611

Vuletić Ion Lab, MIT (Yb$^+$ work)

Eugene Knyazev

Joonseok Hur

Diana P L Aude Craik

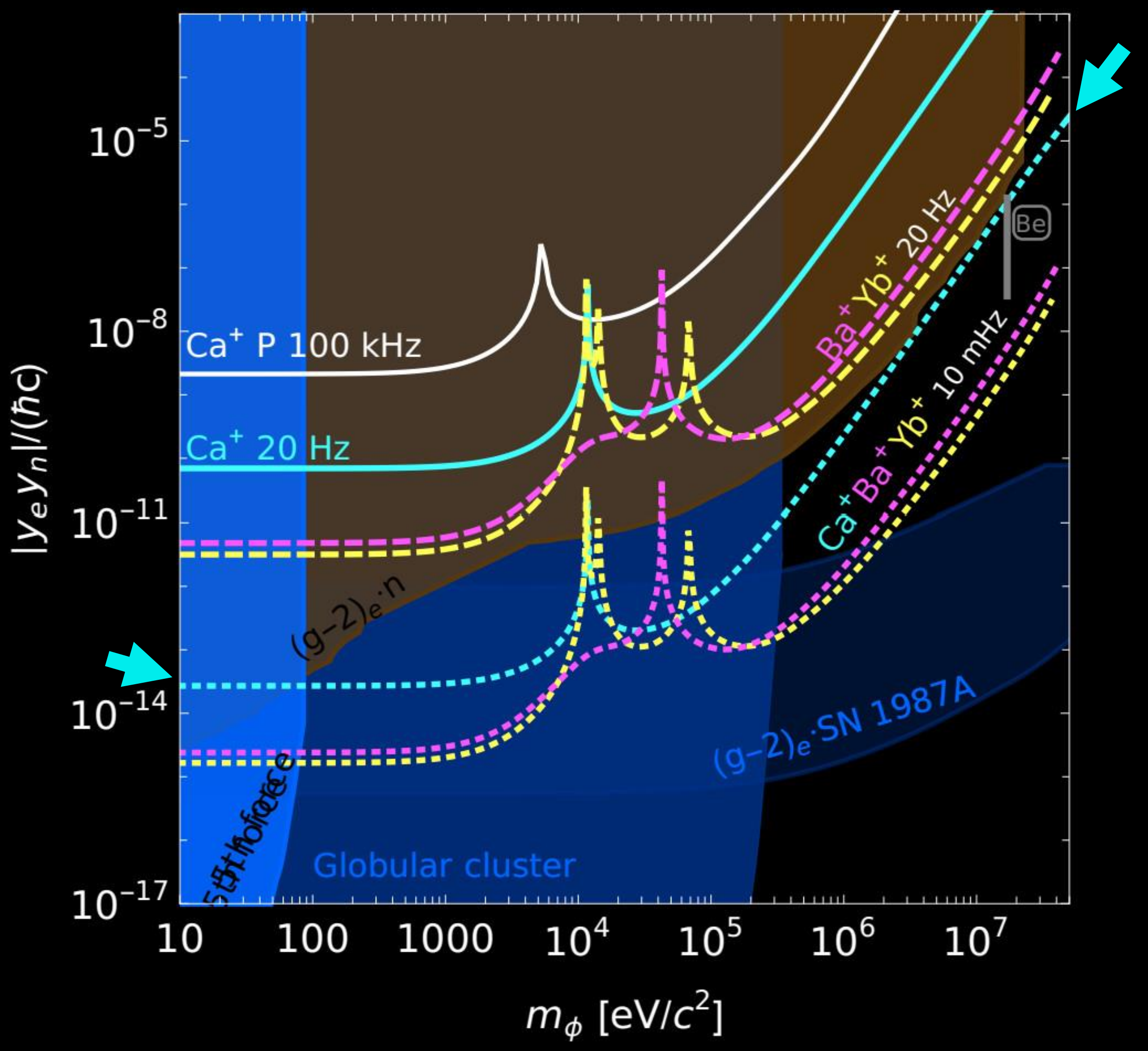
Vladan Vuletić

Alumni:
Ian Counts
Honggi Jeon
Calvin Leung
Swadha Pandey
Luke Caldwell

Collaborators:
Witold Nazarewicz
Paul-Gerhard Reinhard
Julian Berengut
Amy Geddes
Akio Kawasaki
Wonho Jhe

IS spectroscopy at ETHZ – Ca^+

- Low SM backgound. No nonlinearity up to 20Hz precision (Solaro et al, PRL 125, 2020)
- Can push bounds 1-2 orders of magnitude in intermediate mass range by measuring at 10mHz (Manovitz et al, PRL 123, 203001, 2019).



Nuclear physics puzzles

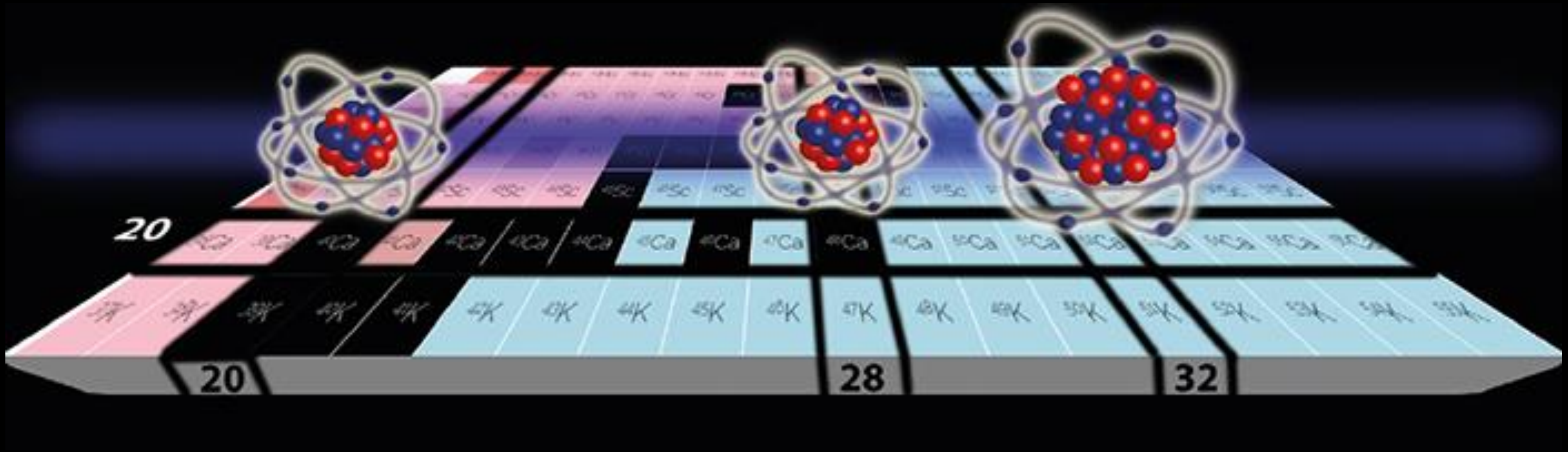
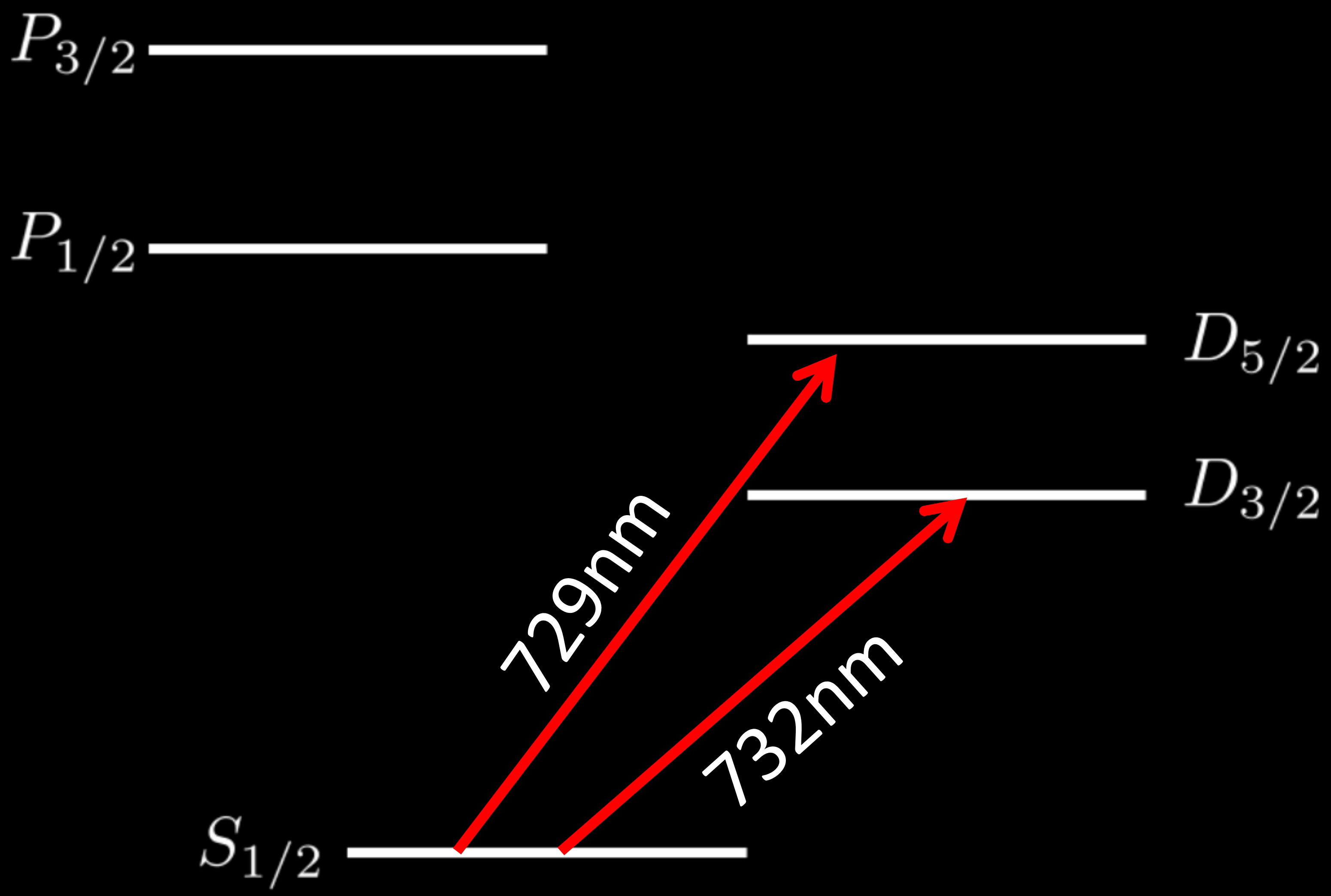


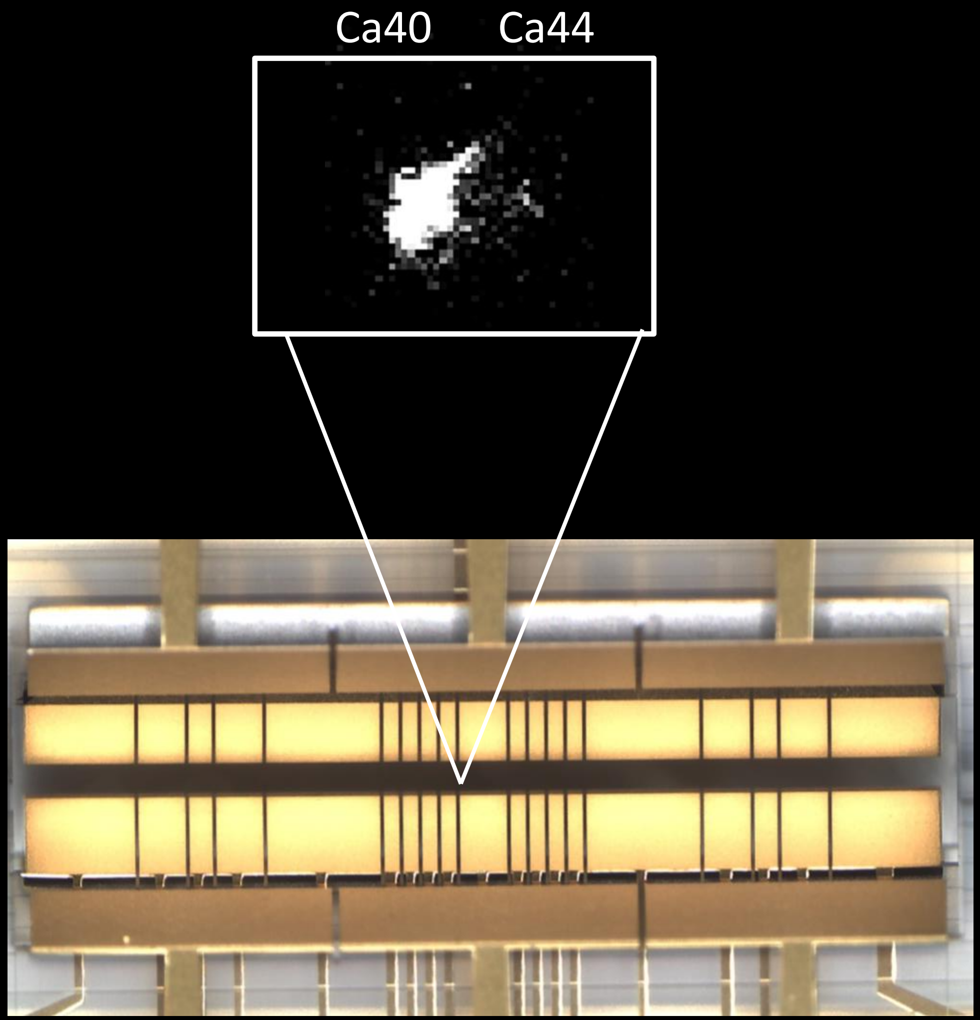
Figure credit: Ronald Fernando Garcia Ruiz

IS spectroscopy at ETHZ - Calcium

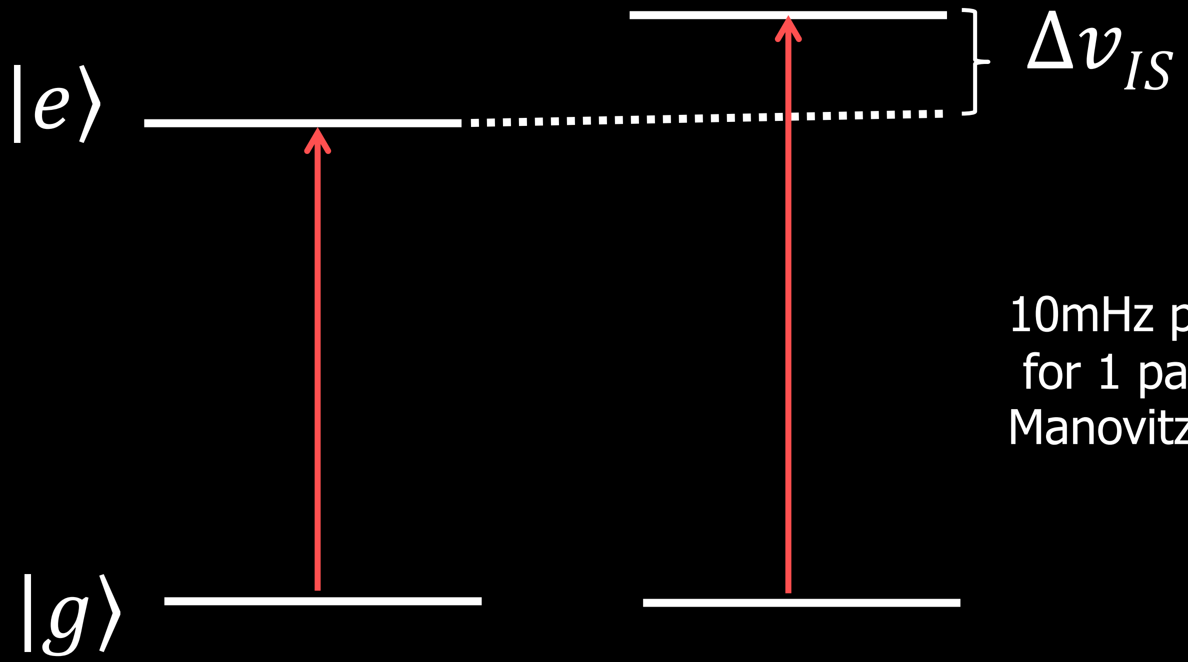
Ca^+



Encoded **Qu**bit **Al**ive (EQuAl) setup at TIQI ETHZ



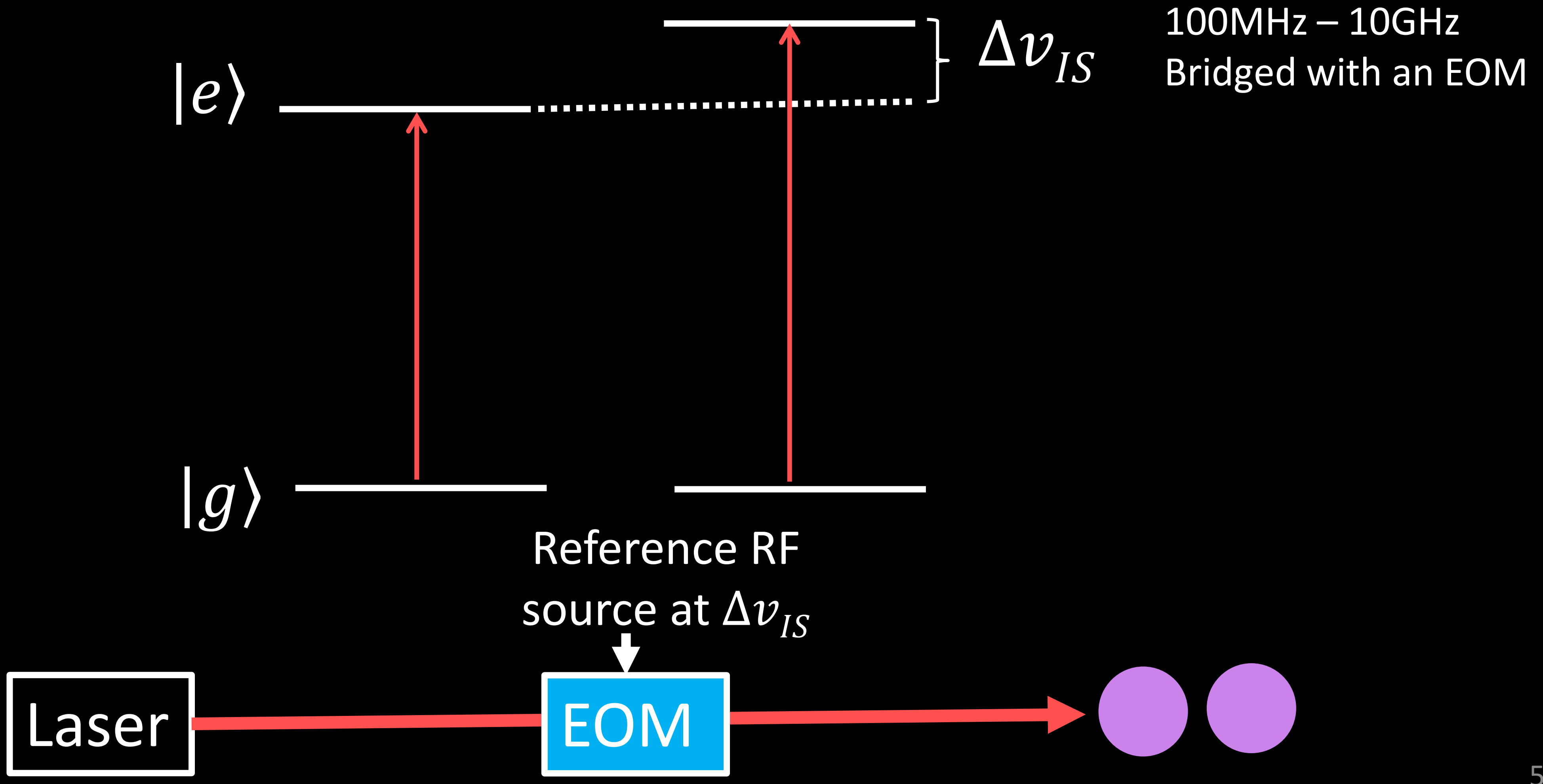
IS spectroscopy on co-trapped Ca^+ isotopes



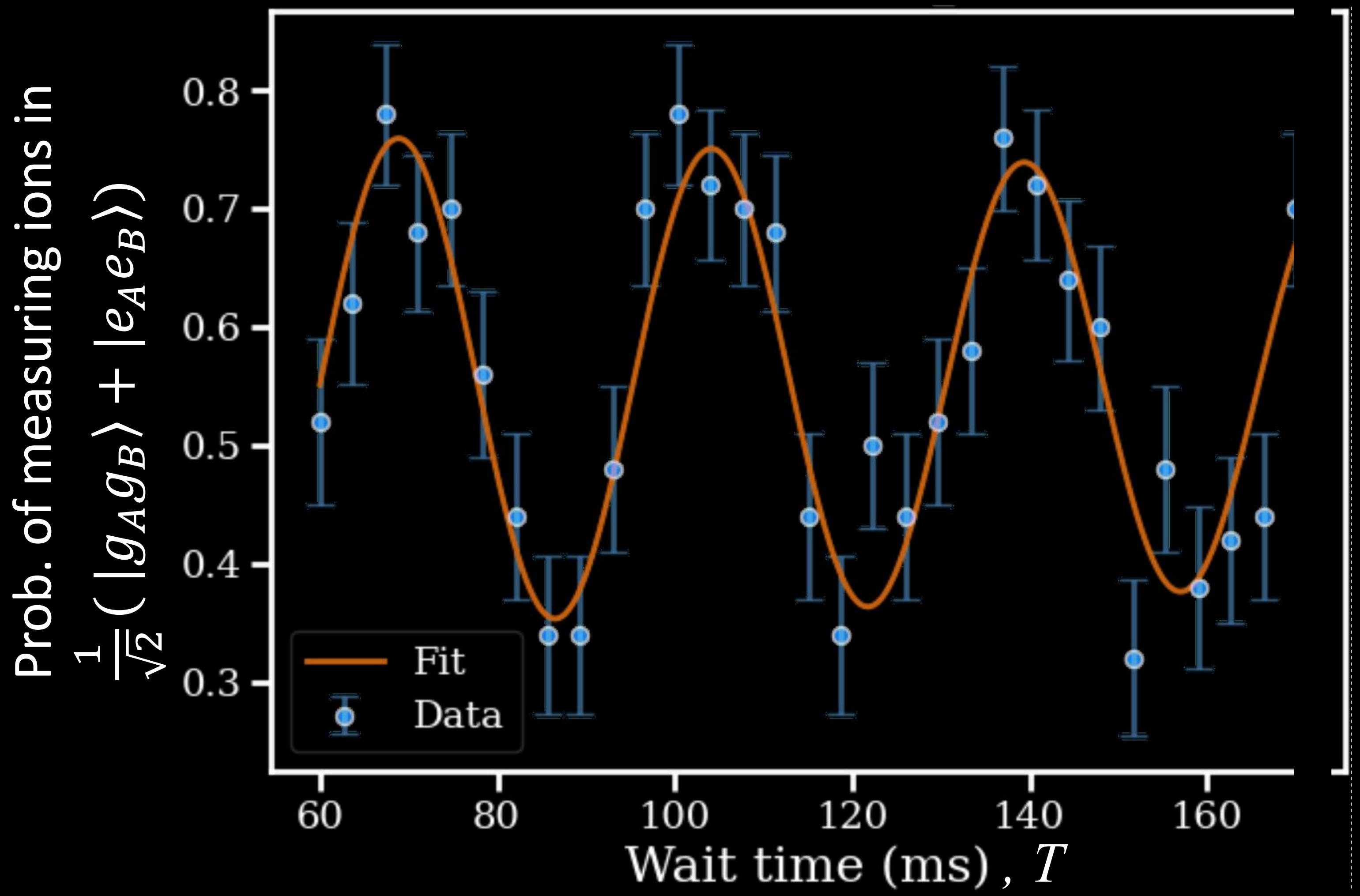
10mHz precision demonstrated
for 1 pair of Sr^+ isotopes
Manovitz et al, PRL **123**, 203001, 2019

$$\psi(T) = \frac{1}{\sqrt{2}}\left(|e_A g_B\rangle + e^{i2\pi\Delta v_{IS}T}|g_A e_B\rangle\right)$$

IS spectroscopy on co-trapped Ca^+ isotopes

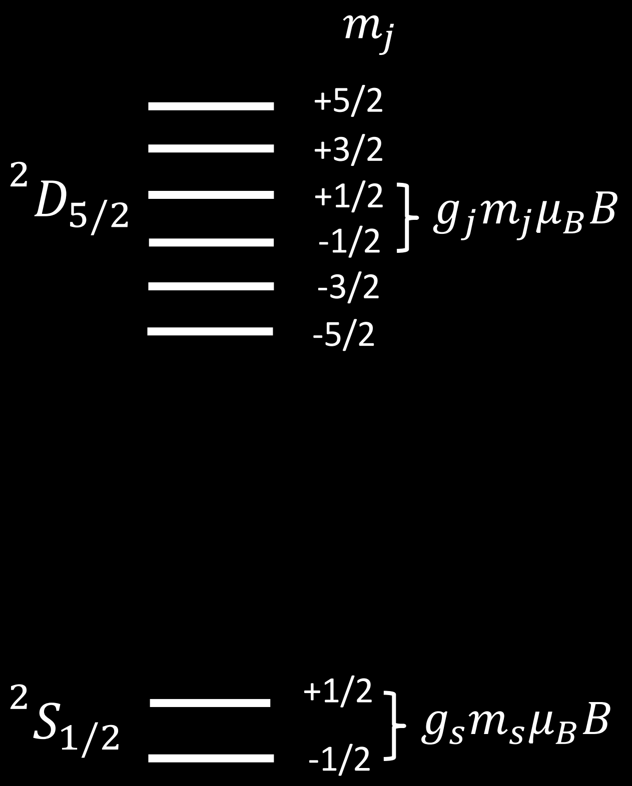


Measuring the Ca40-44 IS



$$\psi\,(T) = \frac{1}{\sqrt{2}}(|e_A g_B\rangle + e^{i2\pi\Delta v_{IS}T}|g_A e_B\rangle)$$

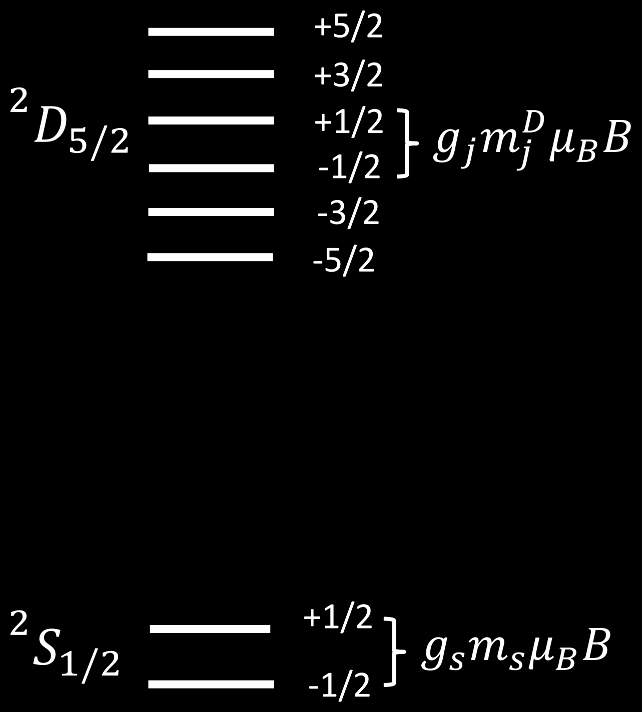
Measuring Ca40-Ca44 IS

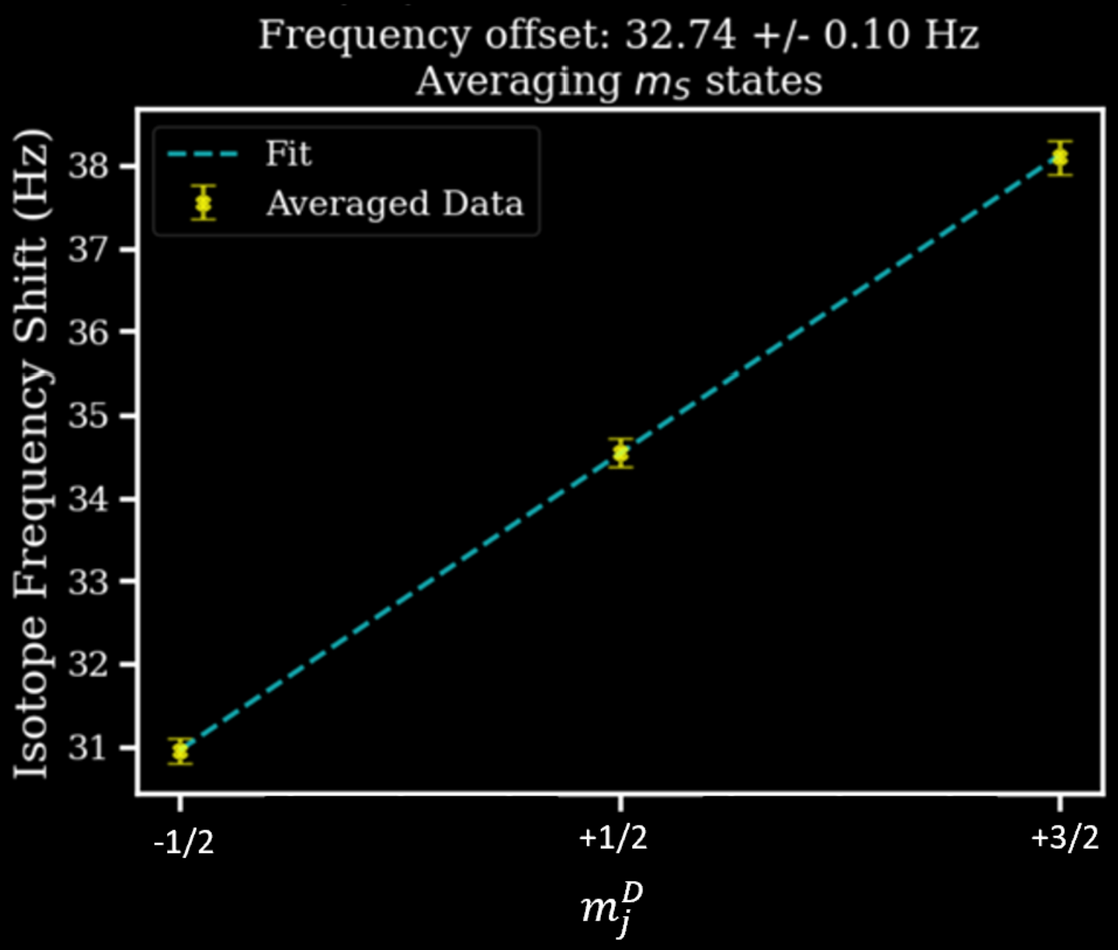


Measuring Ca40-Ca44 IS

Isotope pair:Ca40-Ca44,
Synth detuning:[redacted]

PRELIMINARY





EQuAl team - TIQI group, ETH Zürich


Luca Huber


Gillen Beck


Roland Matt


Jeremy Flannery


Diana P L Aude Craik


Jonathan Home


TIQI group retreat 2022, Bettmeralp

Questions?