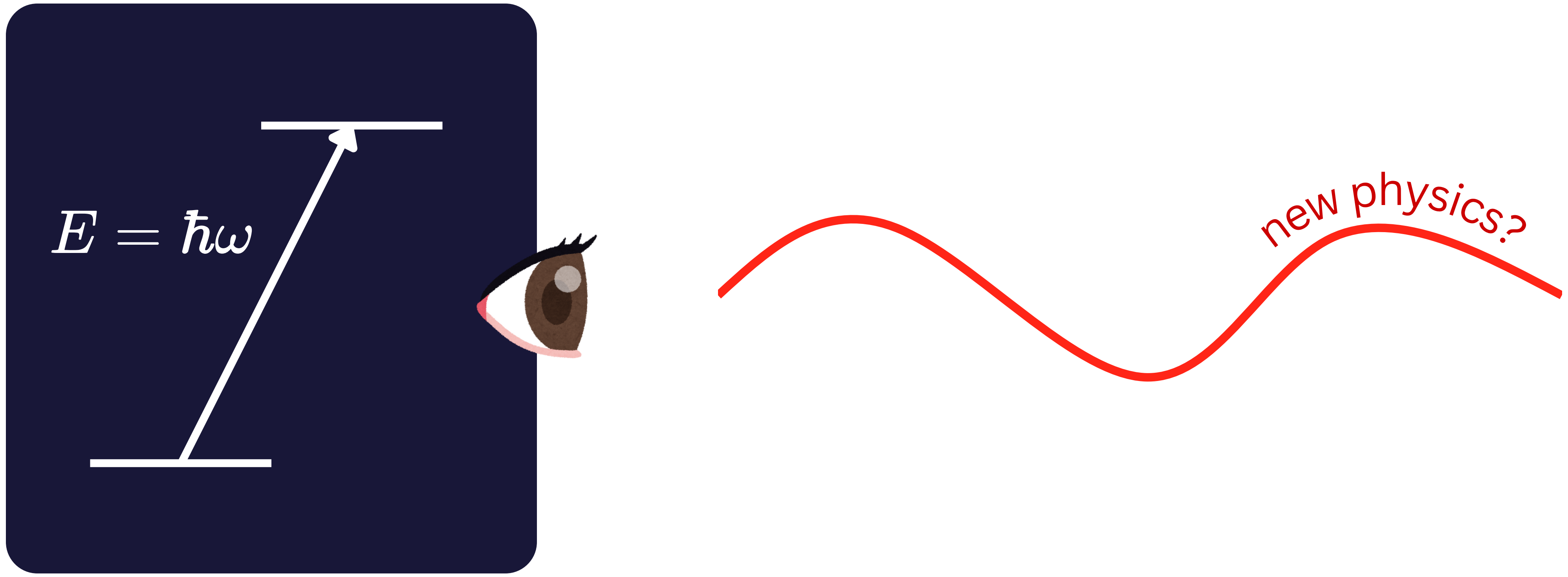
Novel methods for testing new physics with quantum sensors

Agnese Mariotti, ITP-LUH

Leibniz Universität Hannover



[1] Fuchs, Kirk, **Mariotti**, Richter, Robbiati
arXiv:2506.07303, PRA (acpt.)

[2] Wilzewski, **Mariotti** et al., PRL.134.233002

24-25 Nov 2025

Universität Hamburg
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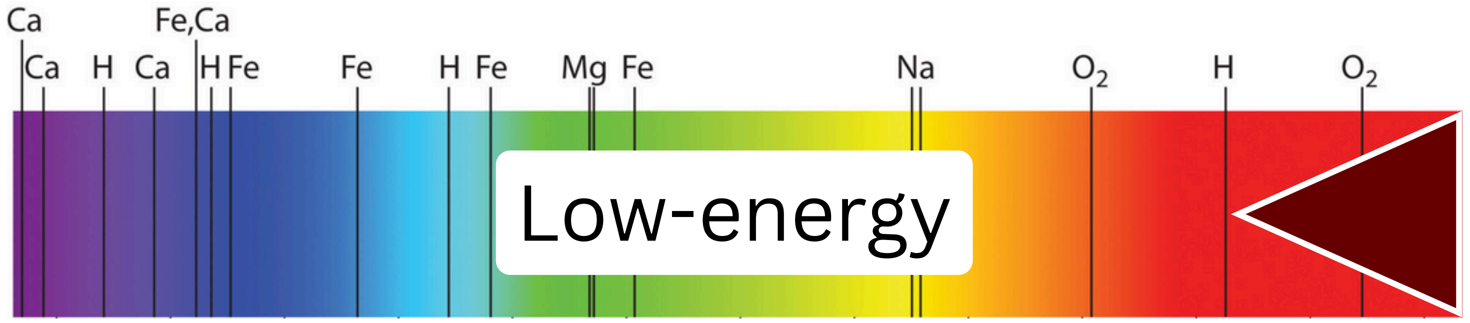
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

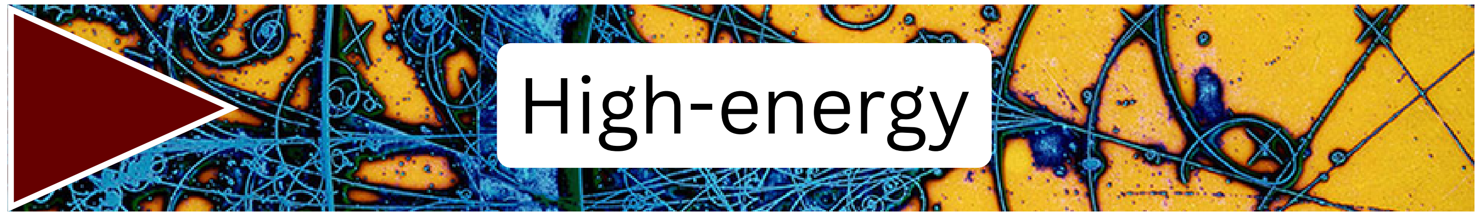
DESY.

Motivation

Shortcomings of the SM

Search for new physics





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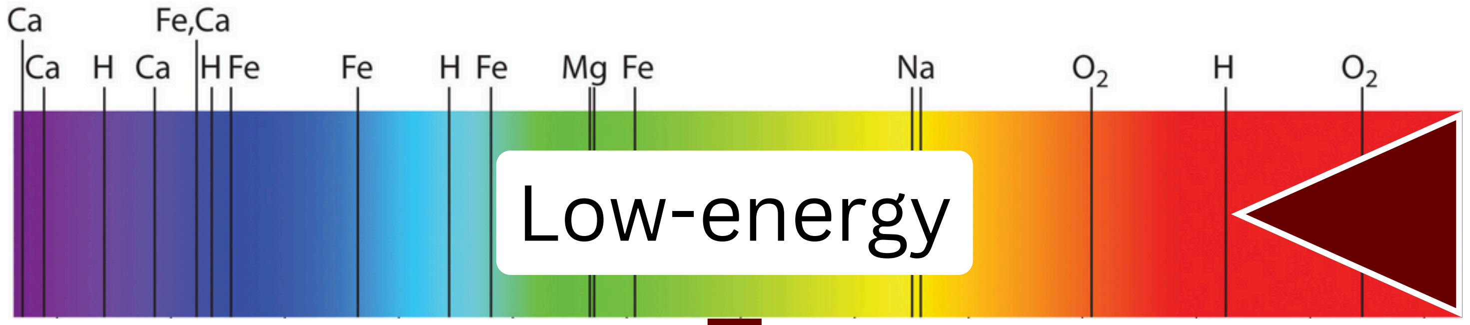
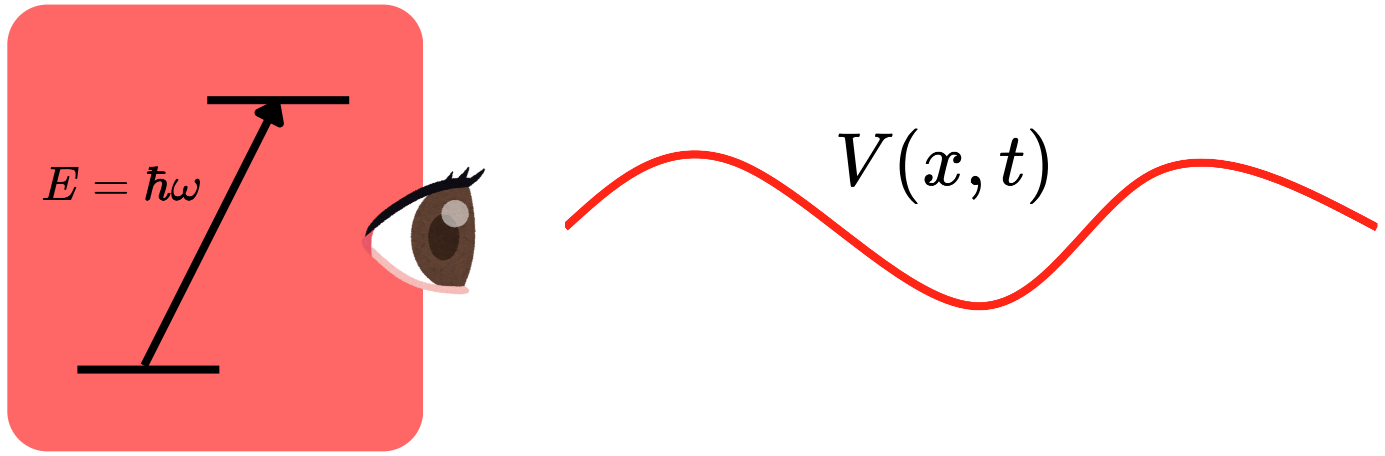
Shortcomings of the SM

Search for new physics



Quantum sensing

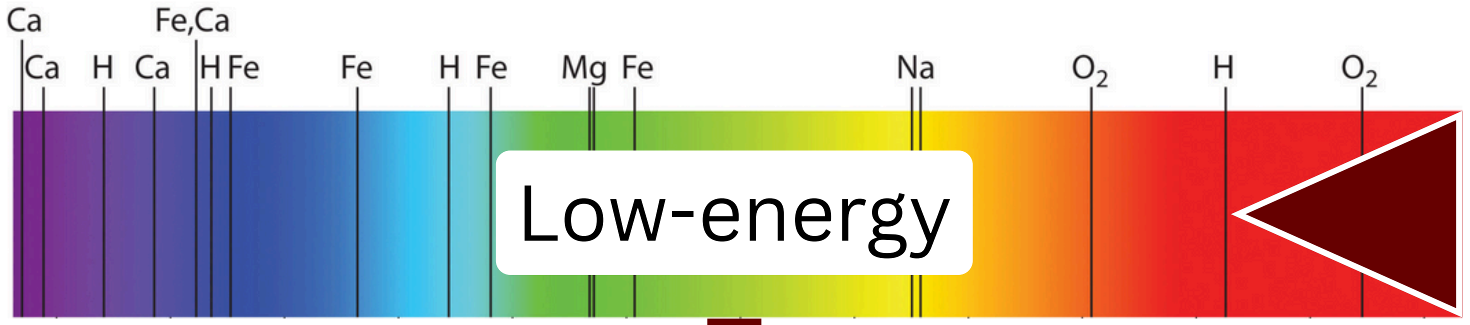
- Trapped ions
- Rydberg atoms
- Atomic clocks
- Superconducting circuits
- ...



[Degen, Friedemann, Cappellaro. "Quantum sensing." Reviews of modern physics 89.3 (2017): 035002.]

Motivation

Shortcomings of the SM



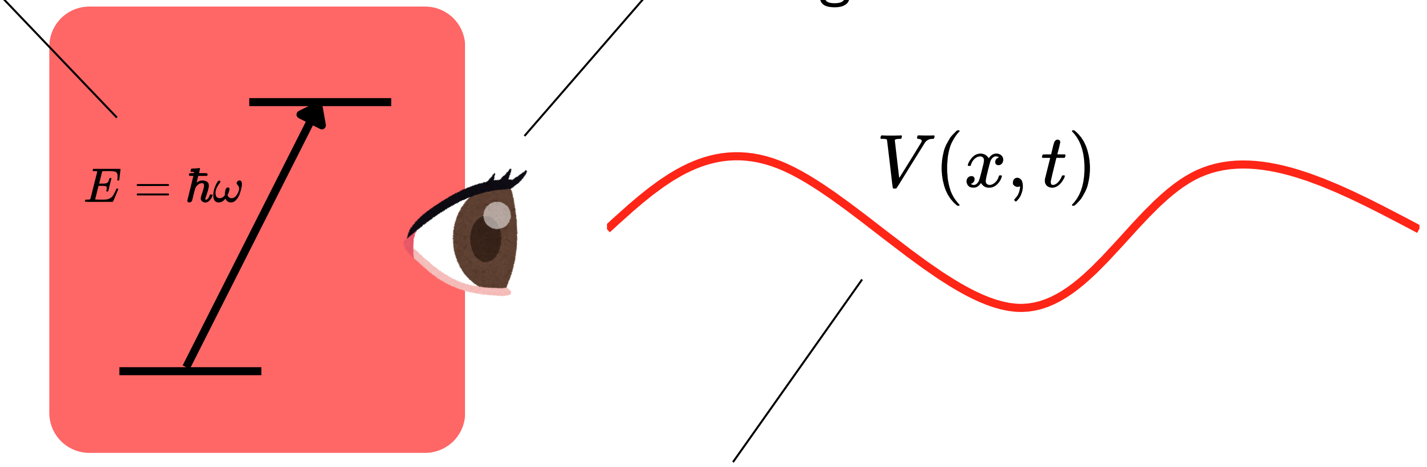
Search for new physics

Quantum sensing

- Trapped ions
- Rydberg atoms
- Atomic clocks
- Superconducting circuits
- ...

High precision < 10^{-18}

Sensitive to interaction range ~ atomic radius



New particle coupling electrons to neutrons → Shift in transition energies:

$E_{tot} = E_{SM} + E_{NP}$

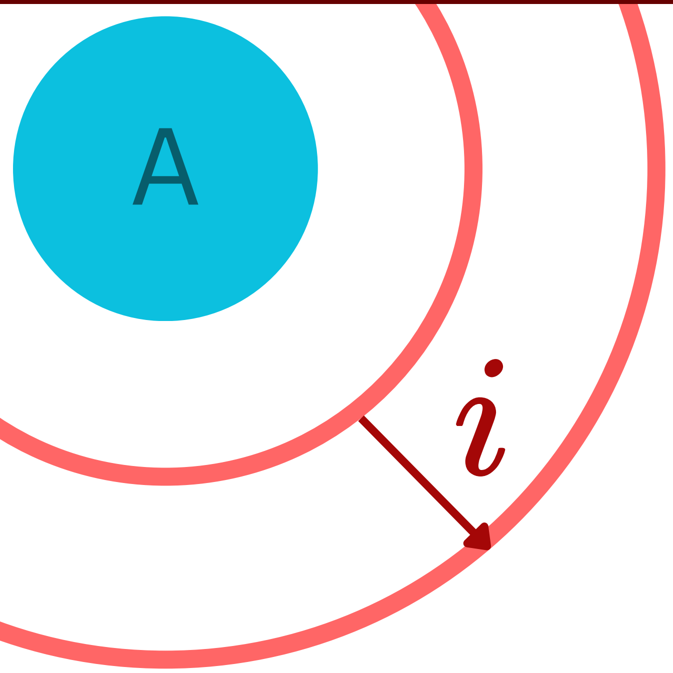
[Degen, Friedemann, Cappellaro. "Quantum sensing." Reviews of modern physics 89.3 (2017): 035002.]

Shift in transition energies:

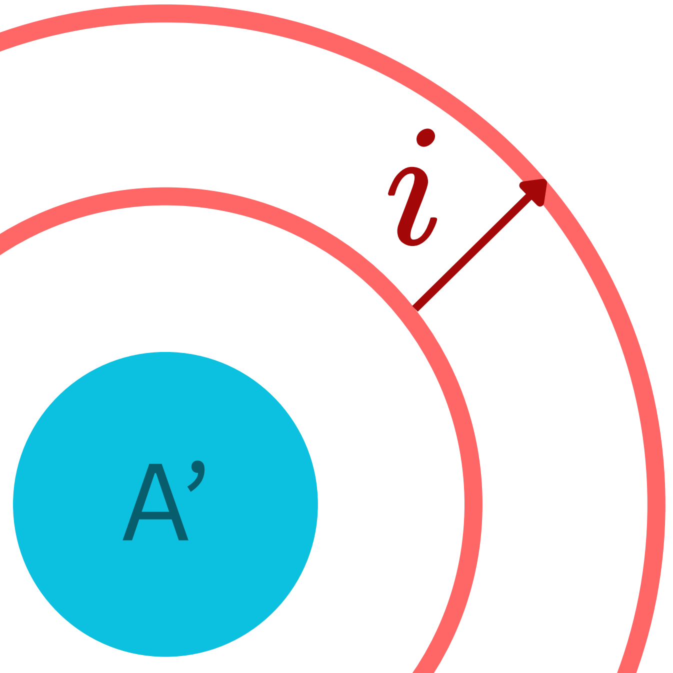
$$E_{tot} = E_{SM} + E_{NP}$$

Shift in transition energies:

$E_{tot} = E_{SM} + E_{NP}$ → Isotope shifts



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



Shift in transition energies:

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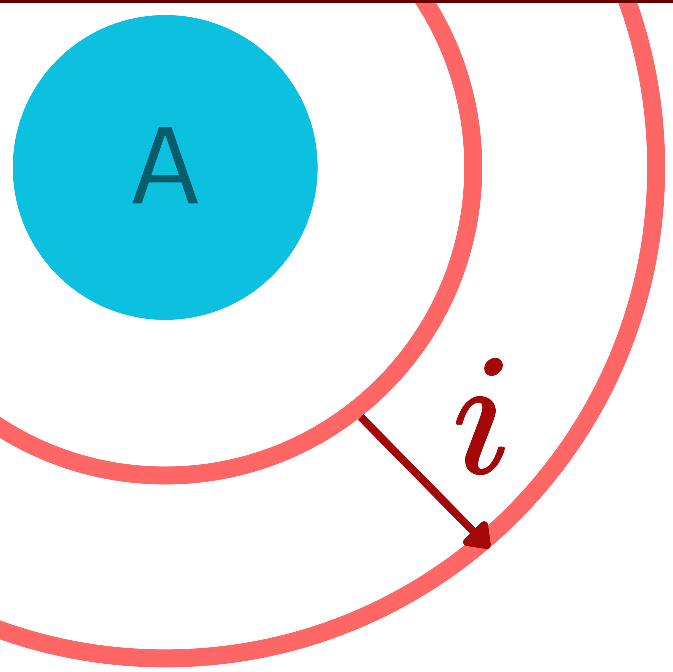
Isotope shifts and King plots

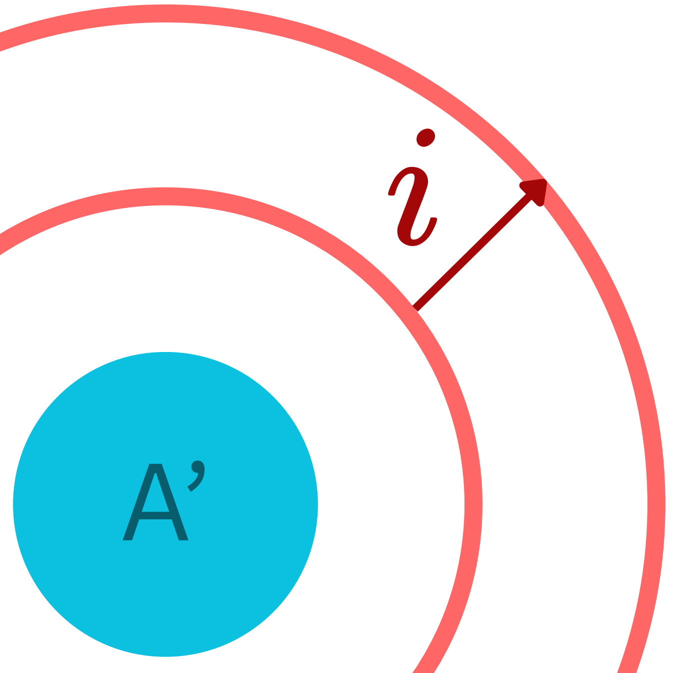


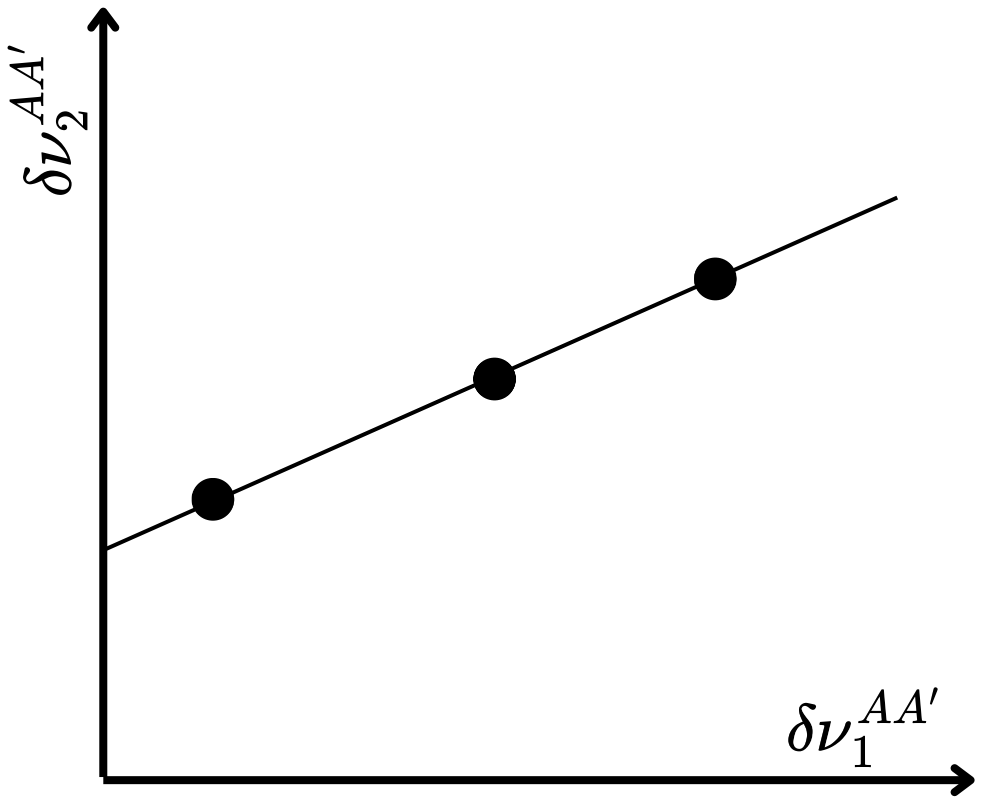
$$\delta\nu_i^{AA'} \equiv \nu_i^A - \nu_i^{A'}$$

= leading-order SM

$$\delta\nu_2^{AA'} = K + F\,\delta\nu_1^{AA'}$$

[W. H. King, “Comments on the article “Peculiarities of the isotope shift in the samarium spectrum”,” J. Opt. Soc. Am. 53, 638 (1963)]





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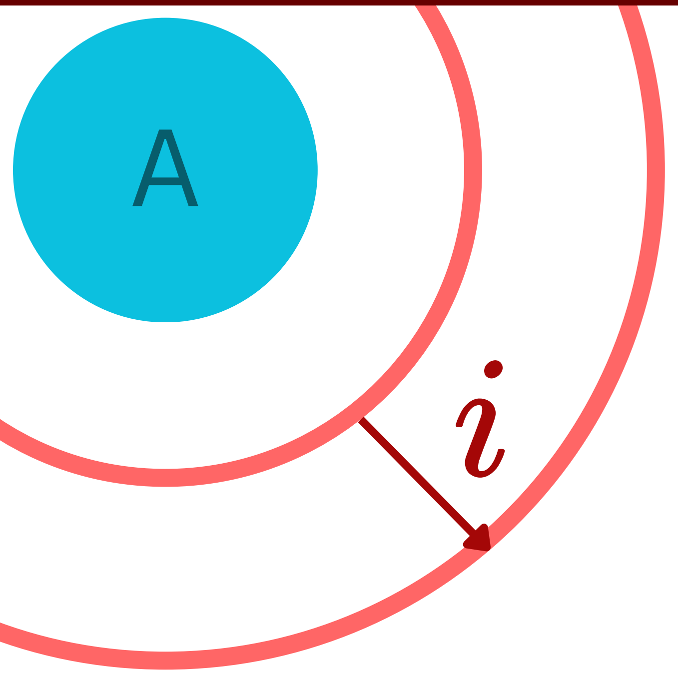
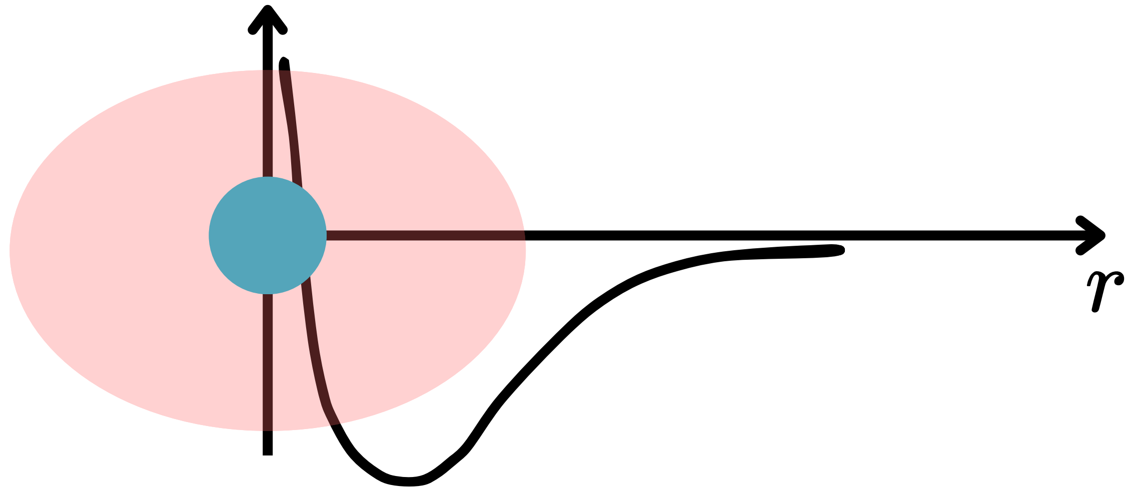


$$\delta\nu_i^{AA'} \equiv \nu_i^{A} - \nu_i^{A'}$$

= leading-order SM + new physics

$$\delta\nu_2^{AA'} = K + F\,\delta\nu_1^{AA'} + X\,\alpha_{\rm NP}$$

$$V_\phi(r;m_\phi) \propto \alpha_{\rm NP}\frac{e^{-m_\phi r}}{r}$$



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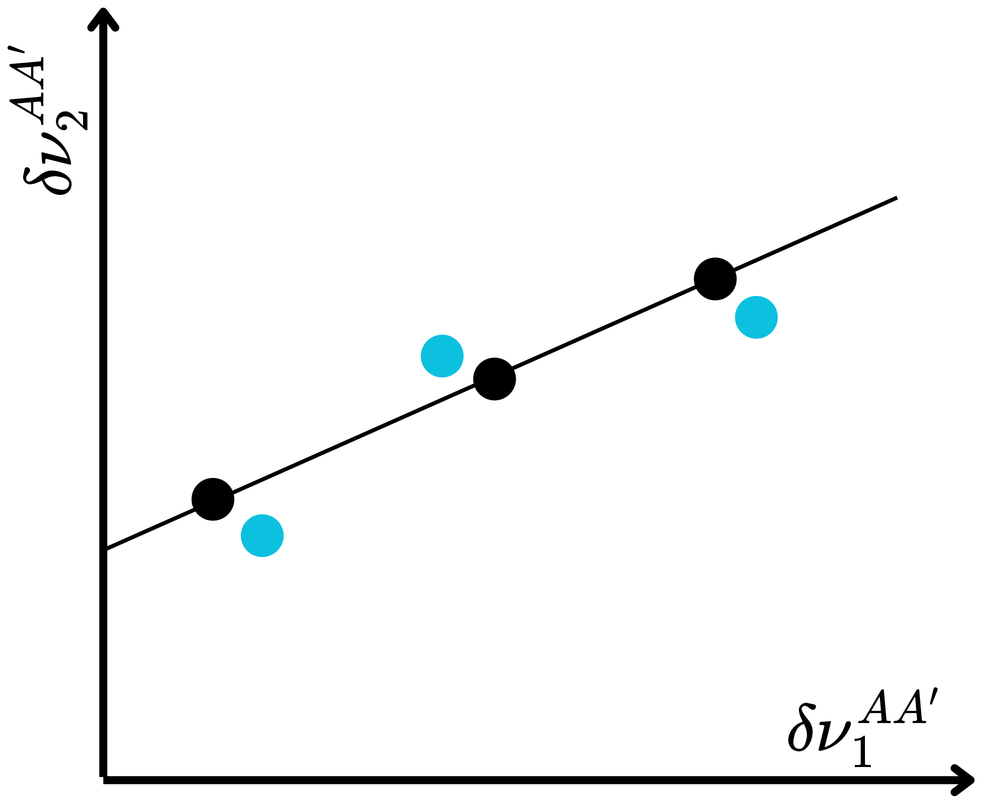

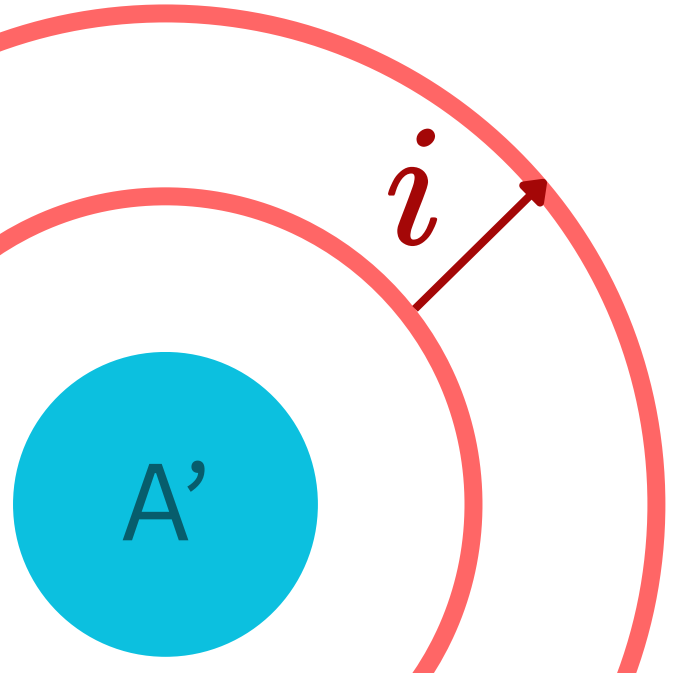

[Delaunay, Ozeri, Perez, Soreq, "Probing Atomic Higgs-like Forces at the Precision Frontier," Phys. Rev. D 96, 093001 (2017)]

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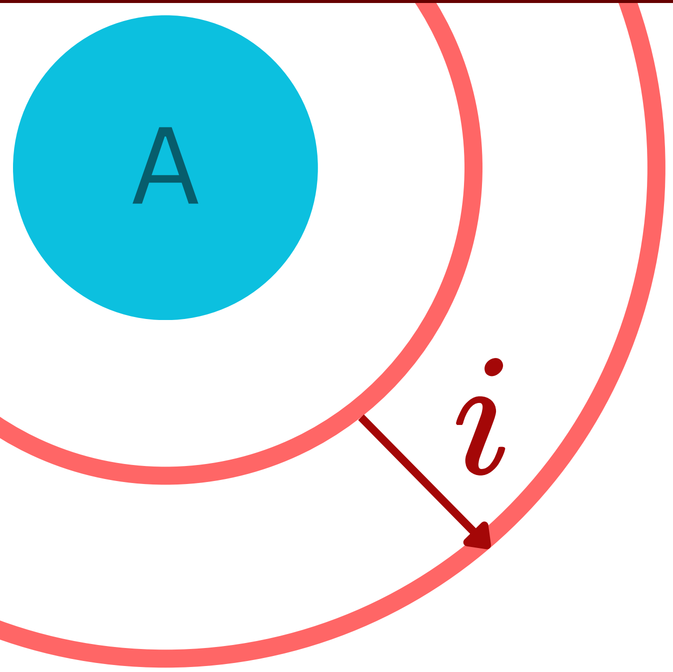
Isotope shifts and King plots



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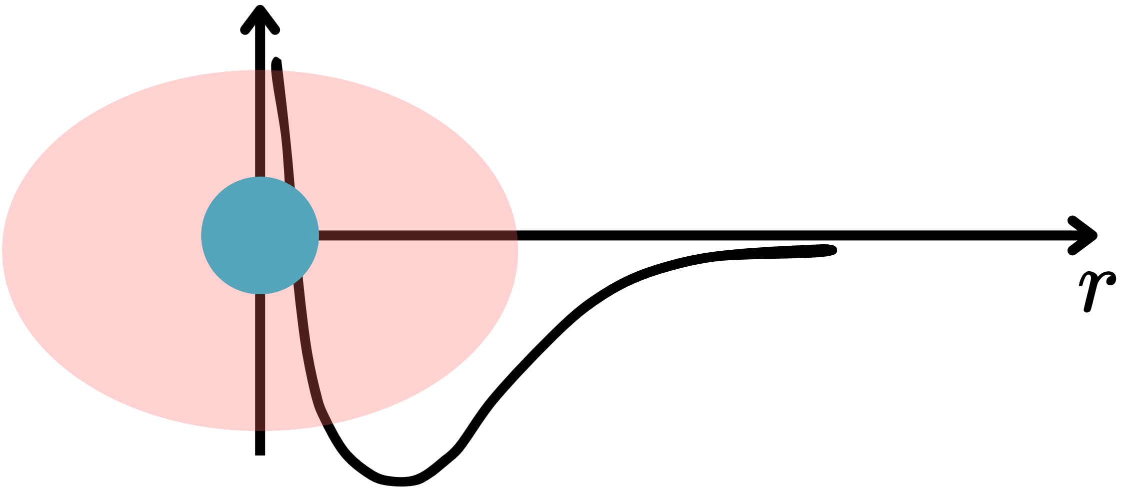

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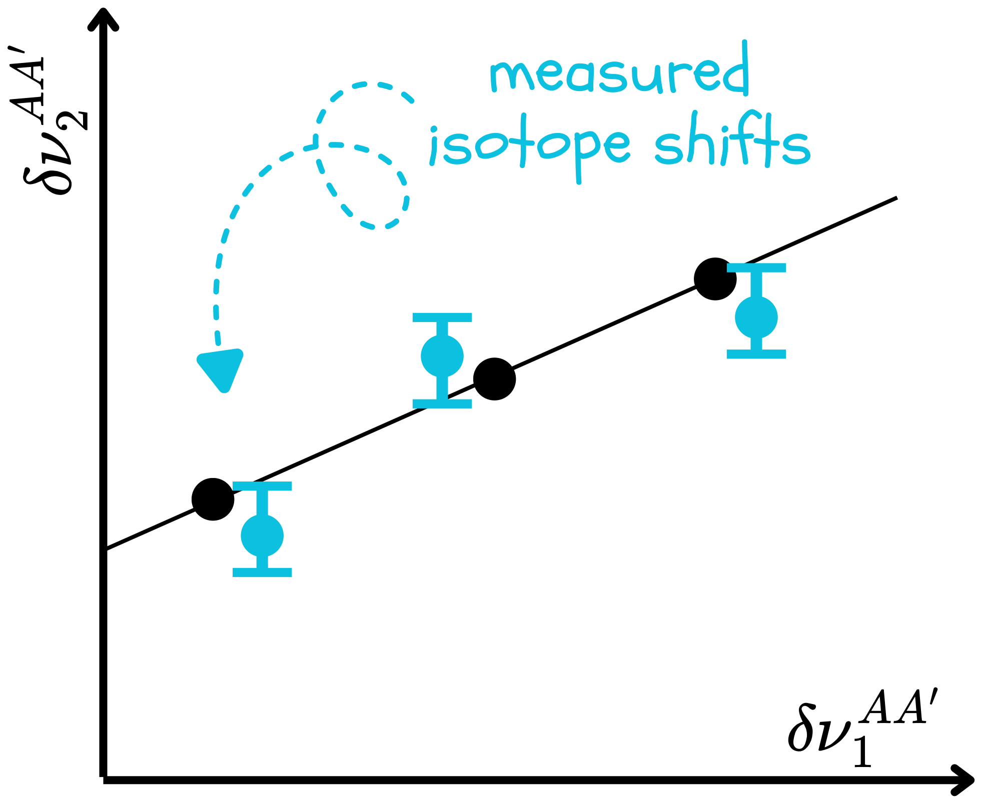
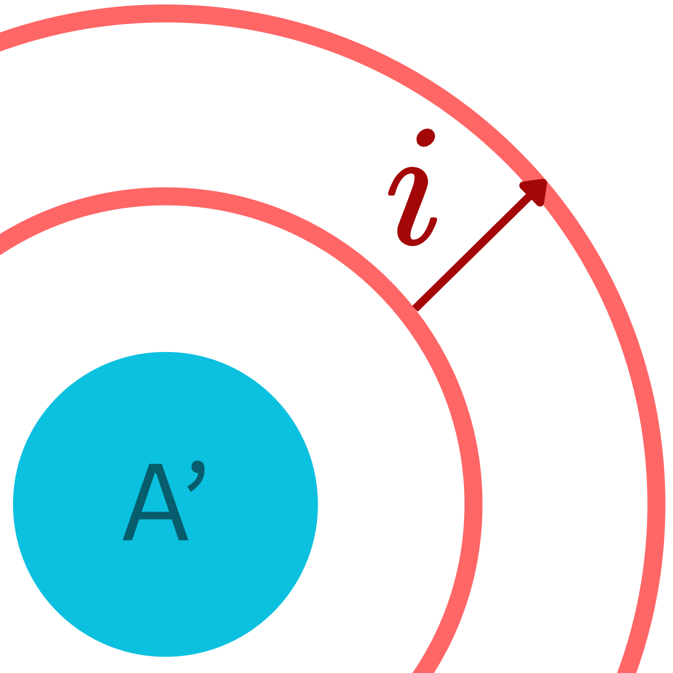


How do we define isotope shifts to be linear?



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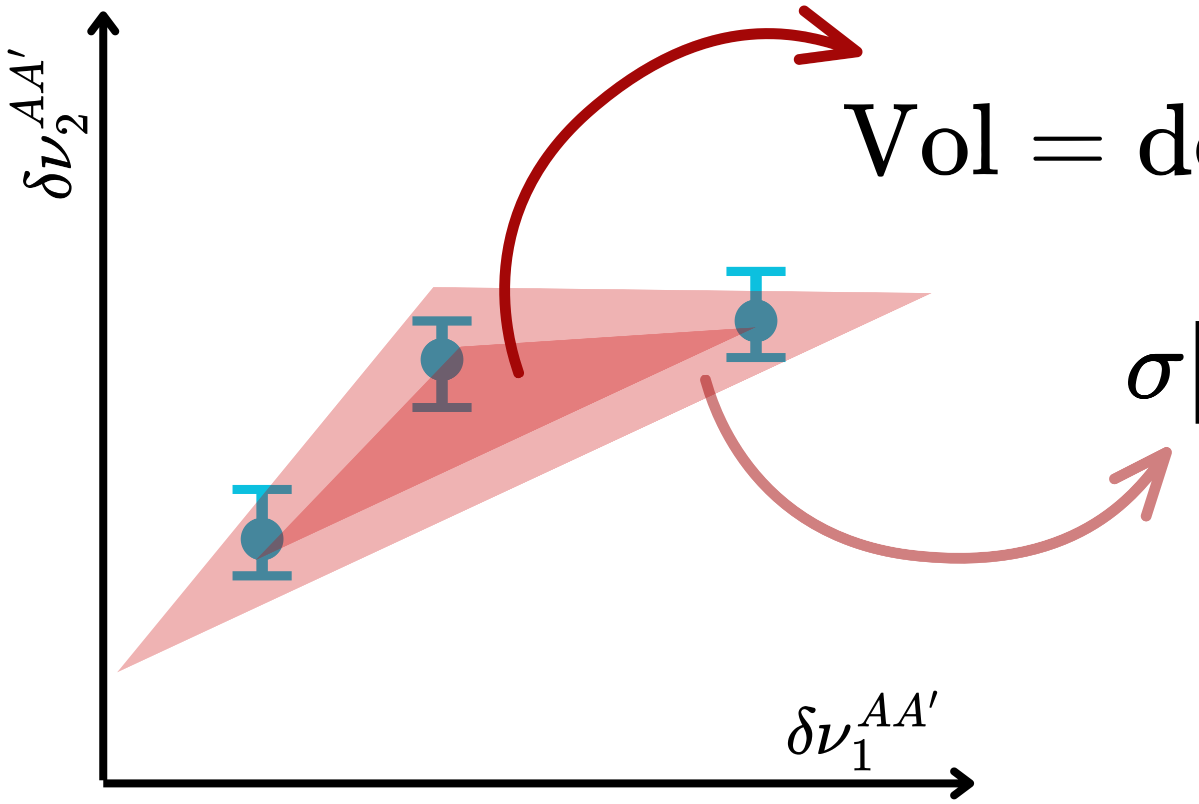
Linear King plot



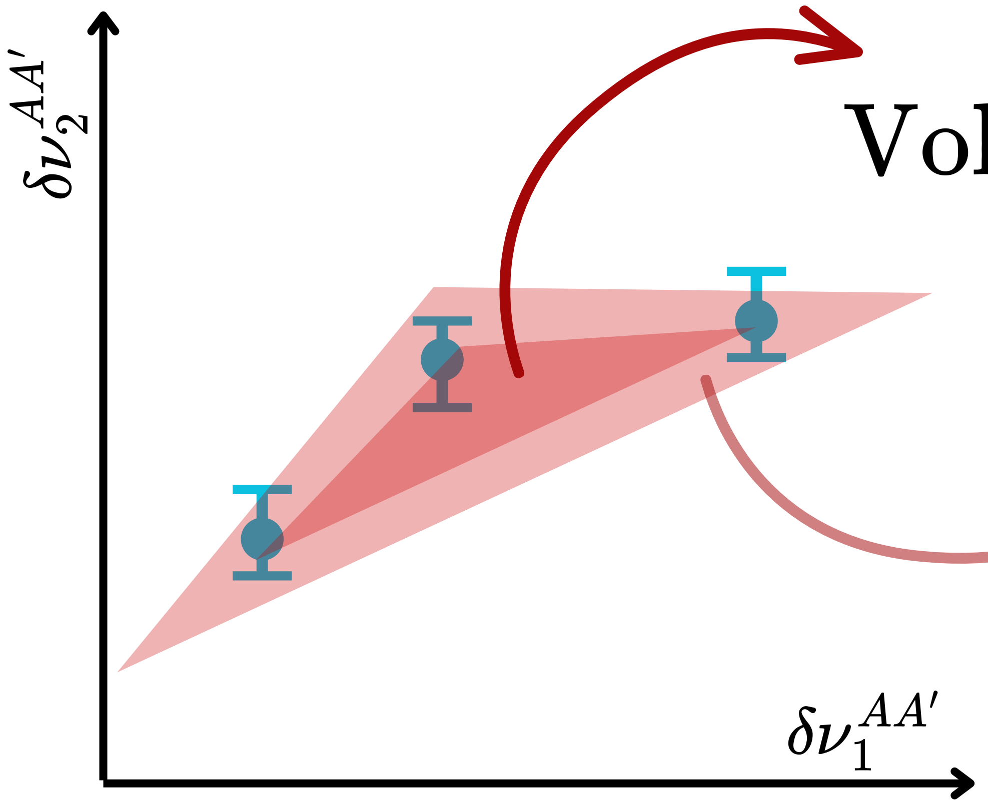
$$\mathrm{Vol} = \det(\delta\nu_1, \delta\nu_2, 1)$$

$$\sigma[\mathrm{Vol}]$$

Linear if $\dfrac{\mathrm{Vol}}{\sigma[\mathrm{Vol}]} < 2$ → Limits on new physics coupling strength

- Limited by number n of data points
- Ambiguous definition if n>3
- One element at a time

Linear King plot



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"Towards a Global Search for New Physics with Isotope Shifts"

[1] Fuchs, Kirk, Mariotti, Richter, Robbiati

Isotope shifts from <u>different elements</u> (Ca, Yb, ...)

KIFiT

- Orthogonal distance regression (fit to a line)
- Log-Likelihood minimization
  → confidence interval for α_{NP}

GLOBAL limits on new physics coupling strength

Nonlinear King plot

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

= leading-order SM + new physics

+ higher-order SM

Must be taken into account!

$$\delta\nu_2^{AA'} = K + F\,\delta\nu_1^{AA'} + X\,\alpha_{\mathrm{NP}}$$

+ other terms → nonlinearities

Issues:

- Cannot resolve new physics on top of these terms
- Require computation → might introduce big uncertainties

Nonlinear King plot

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

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"Nonlinear Calcium King Plot Constrains New Bosons and Nuclear Properties"

[2] Wilzewski, Mariotti et al.

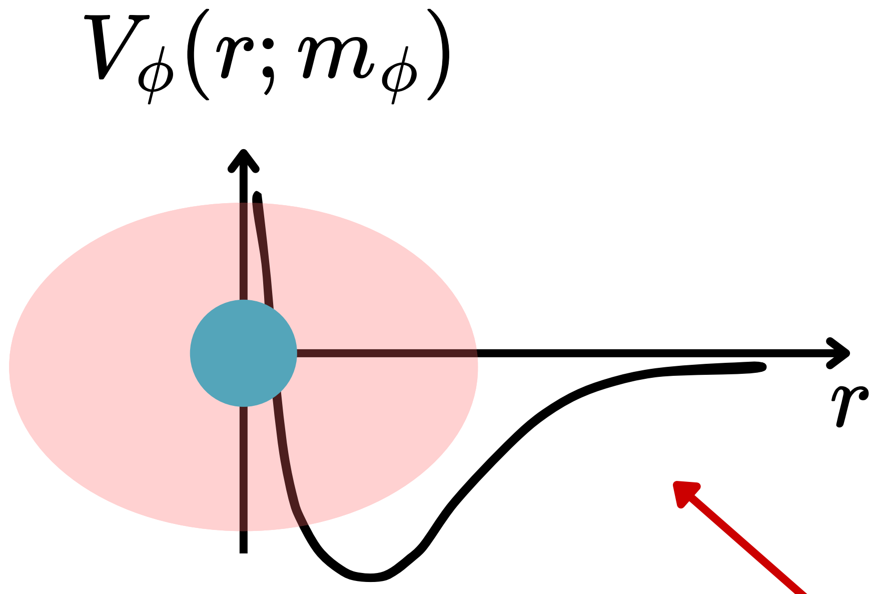
Max-Planck-Institut für Kernphysik · Leibniz Universität Hannover · PTB · UNSW · ETH zürich

1. Measured nonlinearity
2. Identified and computed dominant higher-order term
3. Subtracted from data → back to linear King plot!

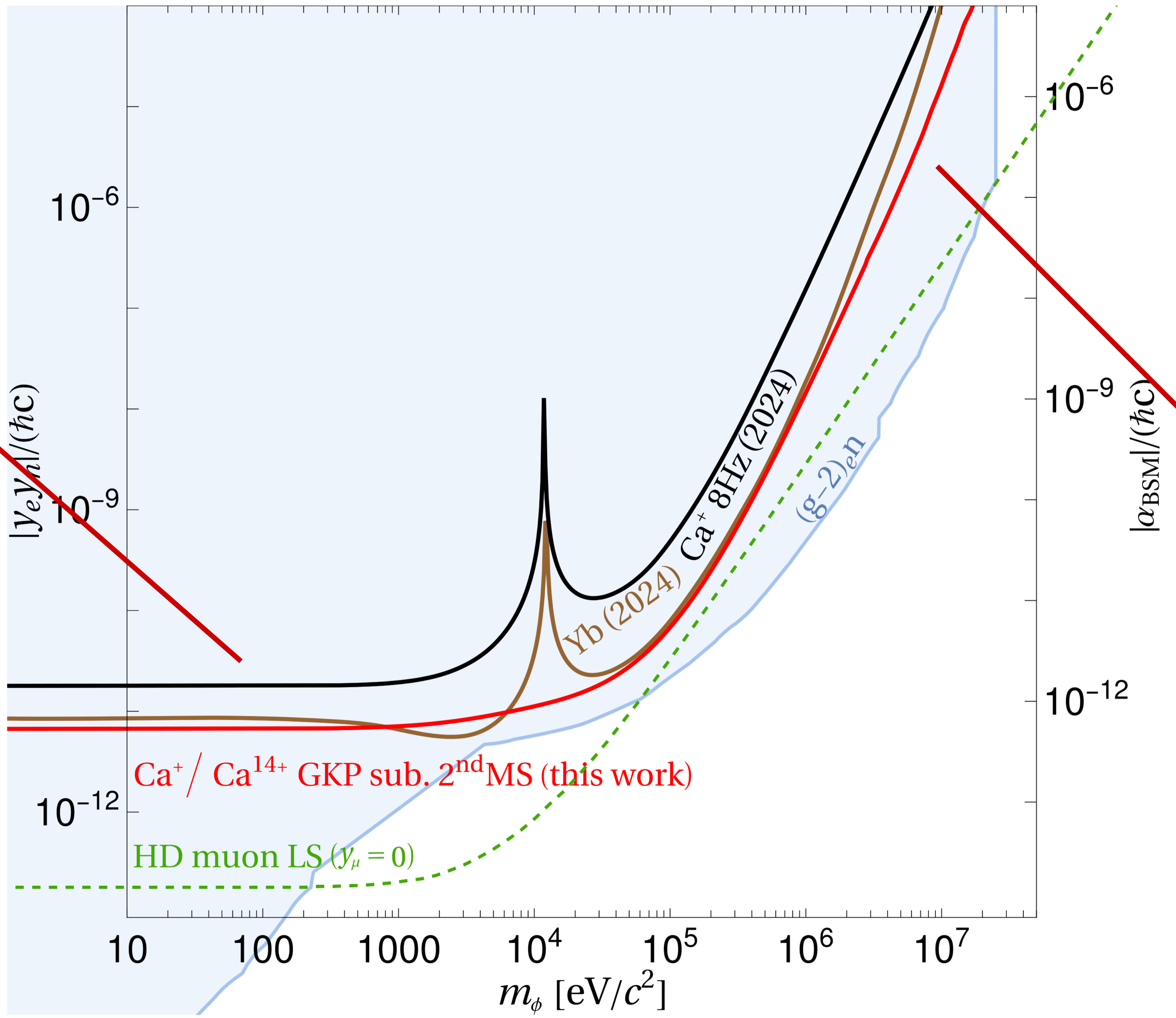
$\delta\nu_{\mathrm{meas.}} - \delta\nu_{\mathrm{HO}}$ → Limits on new physics coupling

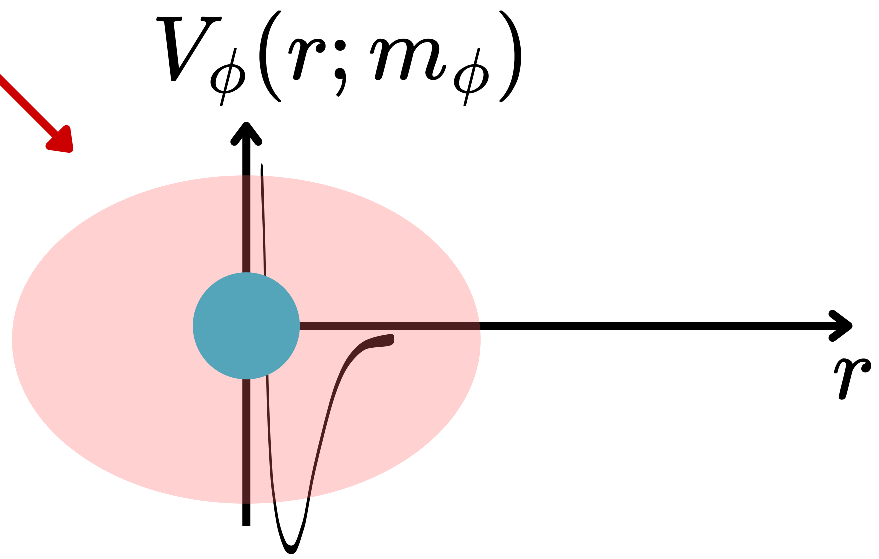
Limits on new physics coupling

[2] Wilzewski, Mariotti et al.



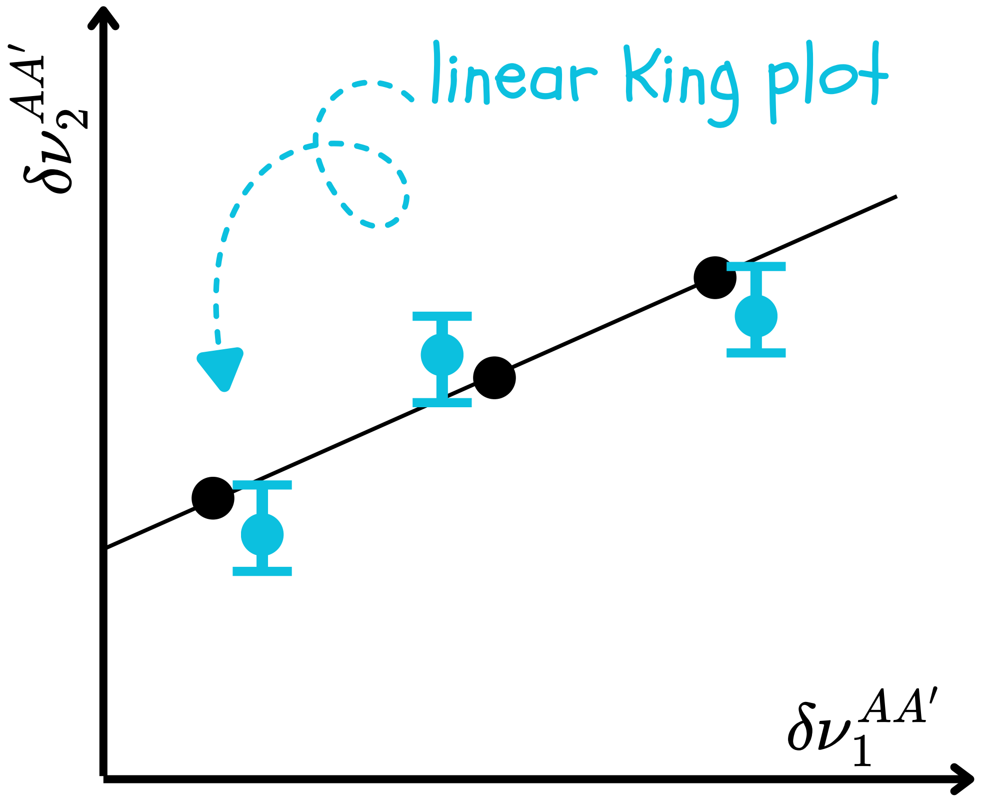
Low mass → max overlap



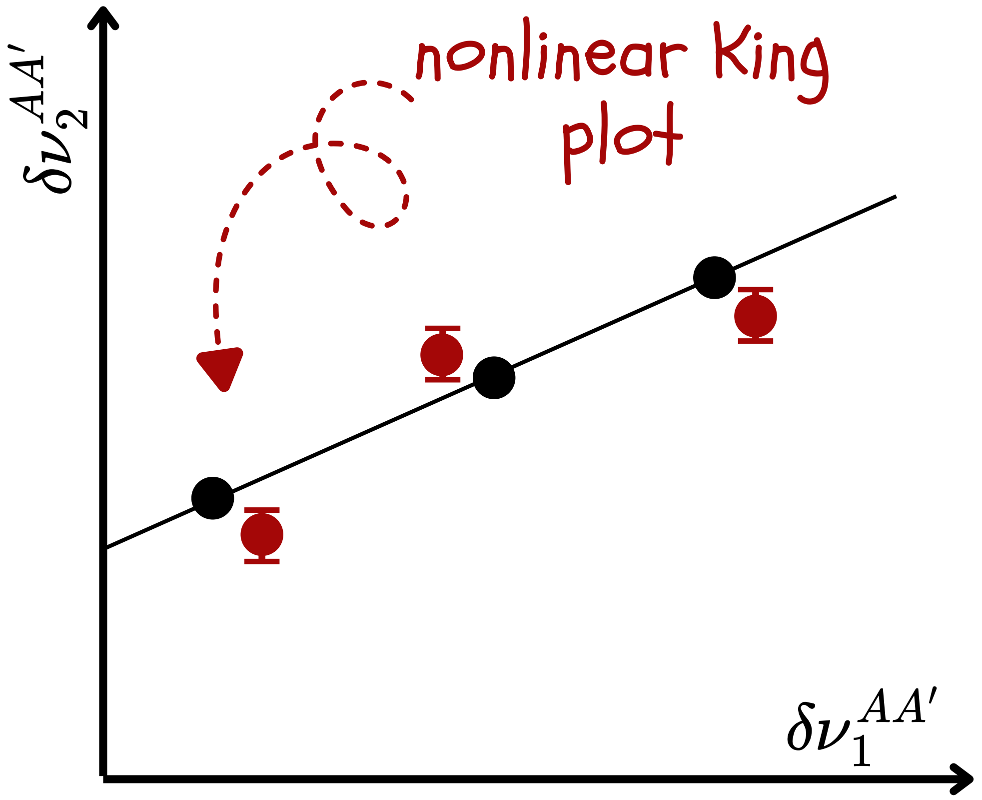


High mass → no overlap

Conclusions



Limits on new physics coupling strength



Need careful assessment of higher-order contributions

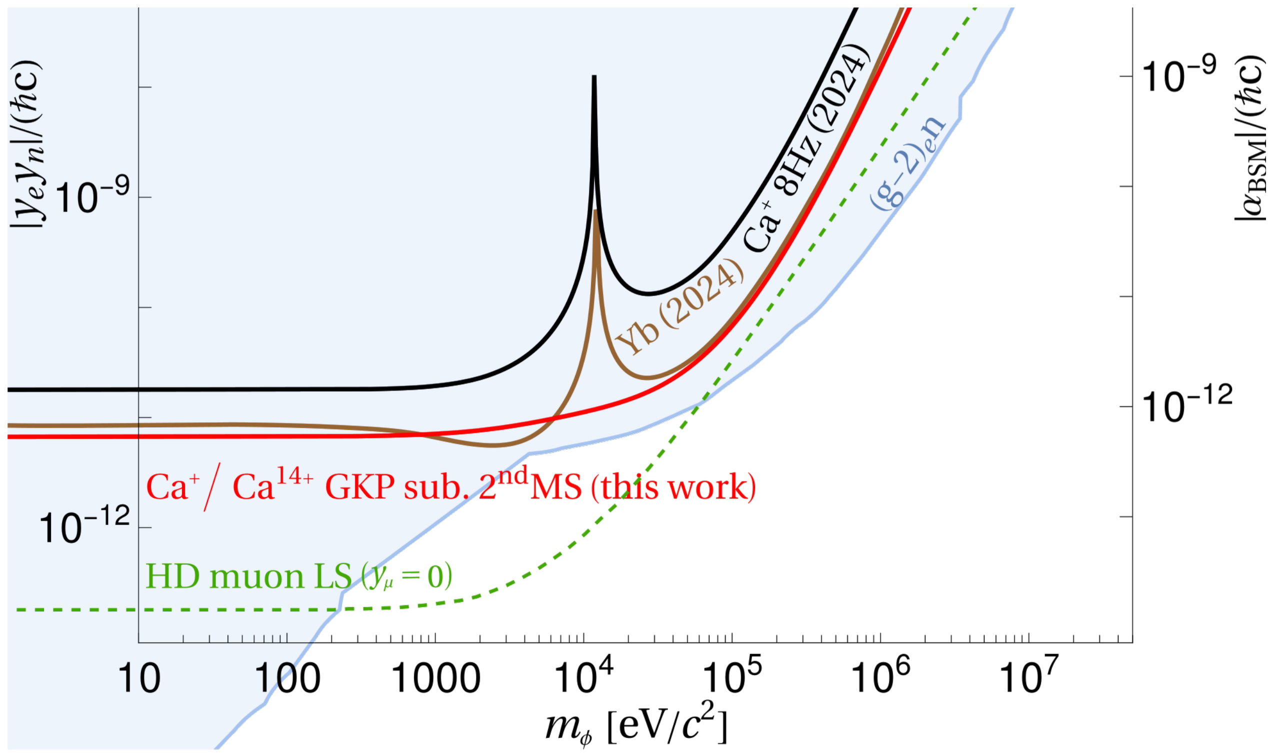
[1] Fuchs, Kirk, **Mariotti**, Richter, Robbiati arXiv:2506.07303

KIFIT

Relevant and timely!

Isotope shifts from <u>different elements</u> → GLOBAL limits on coupling strength

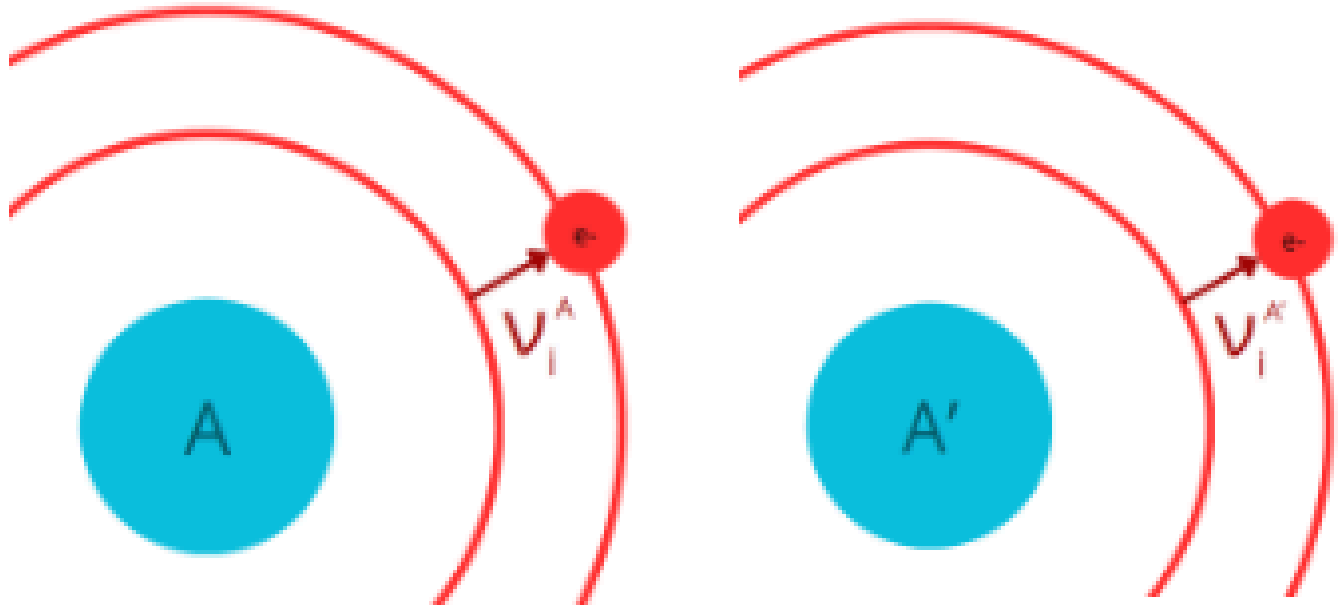
$\delta\nu_{\text{meas.}} - \delta\nu_{\text{HO}}$ →



[2] Wilzewski, **Mariotti** et al., PRL.134.233002

Backups

Isotope shifts and King plots



$$\delta\nu_i^{AA'} = \nu_i^{A} - \nu_i^{A'}$$ [W. King, J.Opt.Soc.Am. 53 (1963)]

$$\overset{\text{LO}}{\equiv} K_i \mu^{AA'} + F_i \delta\langle r^2\rangle^{AA'}$$

Electronic factor
x
Nuclear factor

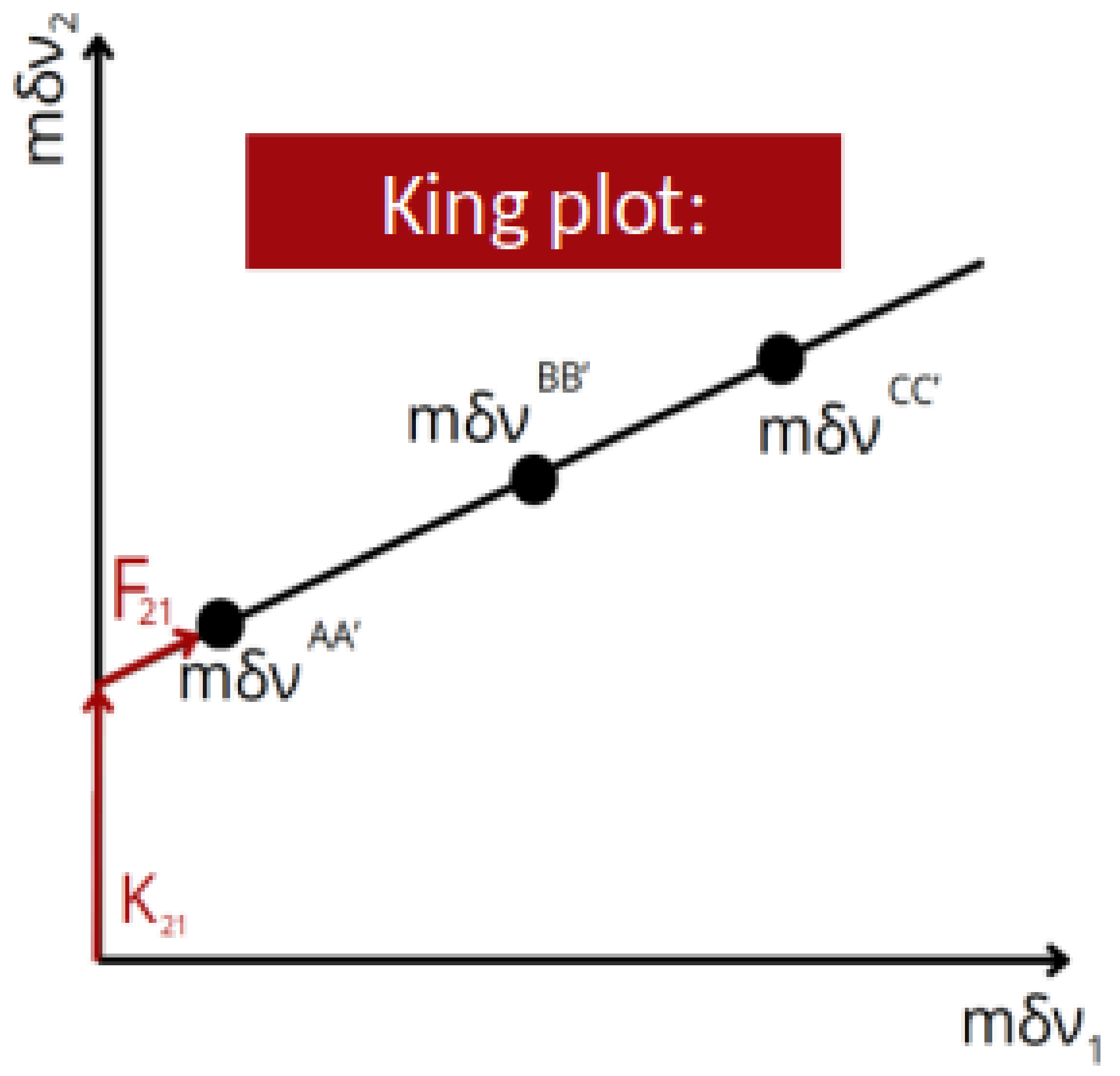
2 transitions

$$\begin{cases} \delta\nu_1^{AA'} = K_1\mu^{AA'} + F_1\delta\langle r^2\rangle^{AA'} \\ \delta\nu_2^{AA'} = K_2\mu^{AA'} + F_2\delta\langle r^2\rangle^{AA'} \end{cases}$$

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

$$\left[K_{21} \equiv K_2 - \frac{F_2}{F_1}K_1\,, \quad F_{21} = \frac{F_2}{F_1}\right]$$

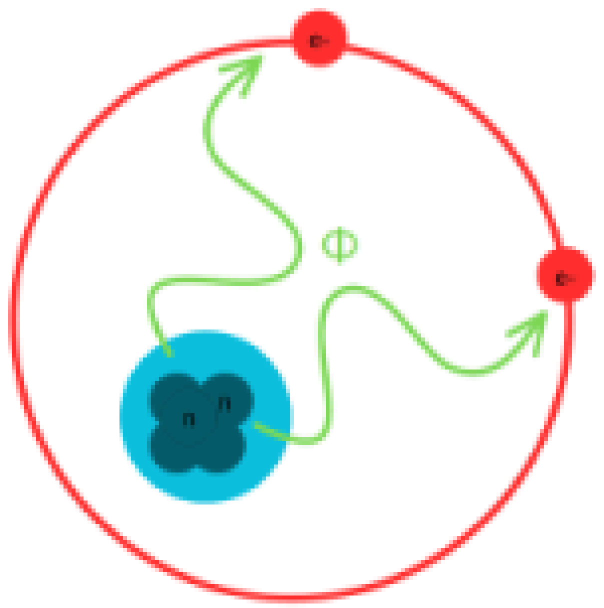
≥ 2 isotope pairs



Linear King plots for new physics: determinant method

Idea: new light boson coupling to electrons and neutrons

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



Isotope-dependent shift

$\gamma^{AA'} = A\text{-}A'$

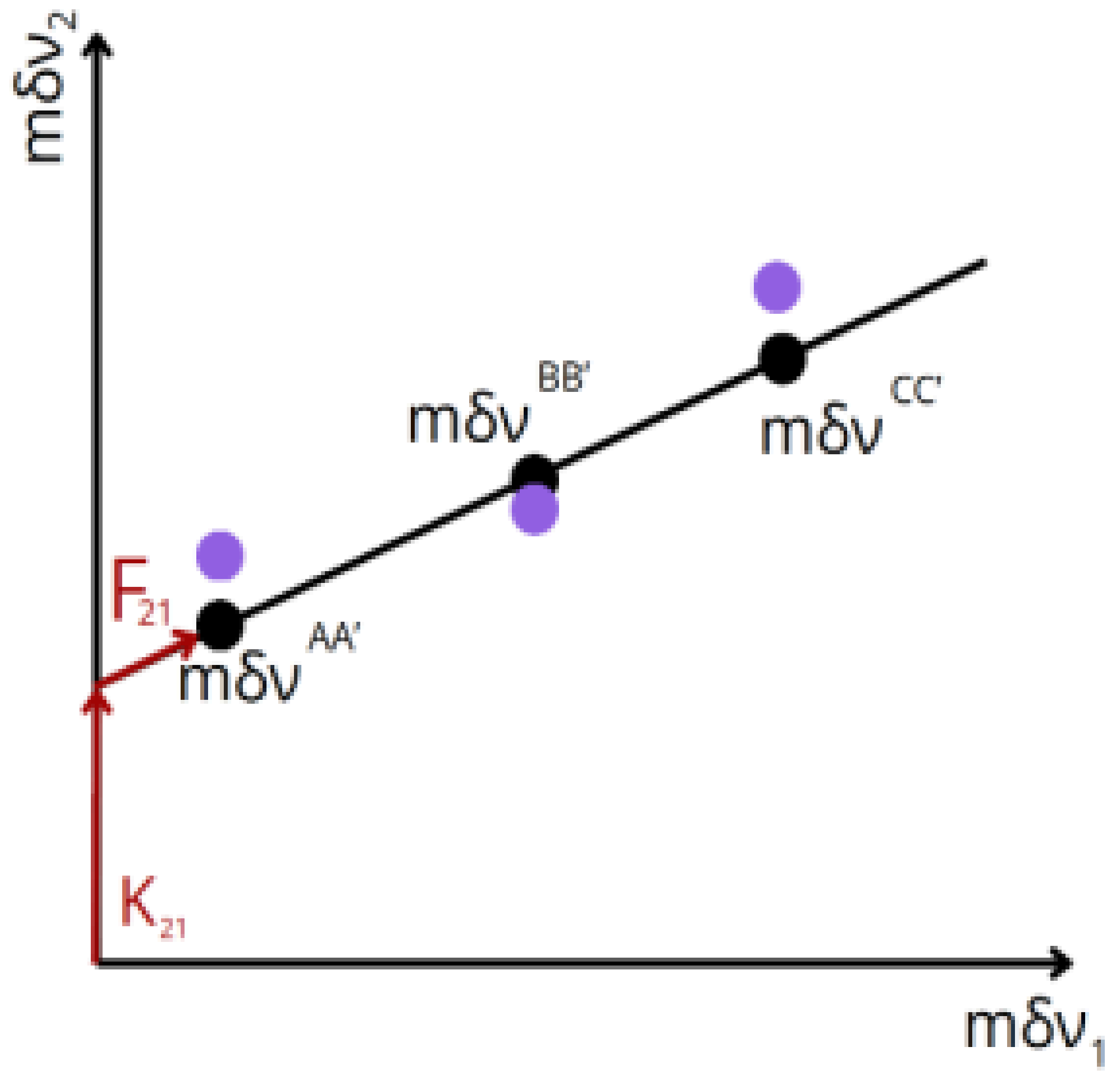
$$\delta\nu_i^{AA'} = K_i\mu^{AA'} + F_i\delta\langle r^2\rangle^{AA'} + \alpha_{\mathrm{NP}}X_i\gamma^{AA'}$$

3 isotope pairs

$$\alpha_{\mathrm{NP}} = \frac{\det\left(m\vec{\delta}\nu_1, m\vec{\delta}\nu_2, \vec{\mathbb{I}}\right)}{\det\left(X_1 m\vec{\delta}\nu_2 - X_2 m\vec{\delta}\nu_2, \vec{\mathbb{I}}, m\vec{\gamma}\right)}$$

Th. input: overlap of electronic wave-function with potential

[Berengut et al. PRL 120 (2018)]



Spikes

$$\alpha_{\mathrm{NP}} = \frac{\det\left(m\vec{\delta}\nu_1, m\vec{\delta}\nu_2, \vec{\mathbb{I}}\right)}{\det\left(X_1 m\vec{\delta}\nu_2 - X_2 m\vec{\delta}\nu_2, \vec{\mathbb{I}}, m\vec{\gamma}\right)}$$

↓ Th. input

$$\alpha \mathrm{NP} = \frac{\det\left(m\vec{\delta}\nu_1, m\vec{\delta}\nu_2, \vec{\mathbb{I}}\right)}{(F_1 X_2 - F_2 X_1)\det(\delta\langle\vec{r^2}\rangle, m\vec{\gamma}, \vec{\mathbb{I}})}$$

Spikes occur when

$$X_2/X_1 = F_2/F_1$$

This also explains reduced sensitivity at high masses, where

$$X_2/X_1 \to F_2/F_1$$

X coefficients

$$X_i(m_\phi) = \int V_{\mathrm{NP}}(r, m_\phi) \left[|\Psi_{fin}(r)|^2 - |\Psi_{in}(r)|^2 dr \right]$$

Computed using
CI+MBPT in AMBiT
[Berengut]