同位体シフトを用いた
新物理探索における相対論効果

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Precision frontier in particle physics

g-2, EDM,…

Temporal variation of fundamental constants

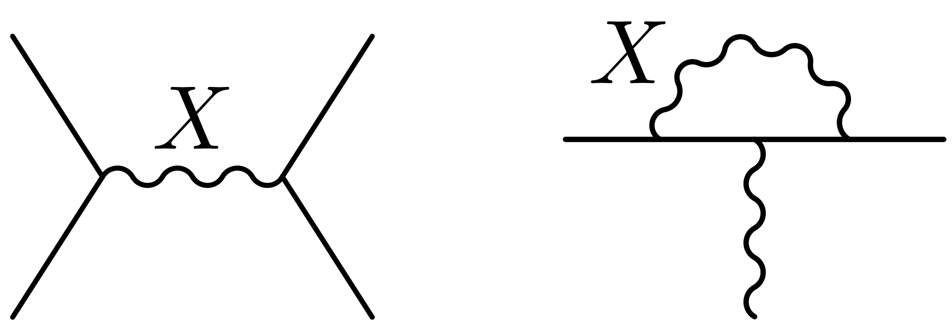
α, m_e/m_p using atomic clock

$$\mathrm{Yb}^+ :\ \delta\nu/\nu \sim 10^{-18},\ \delta\nu \sim \mathrm{sub\ Hz}$$

Huntemann et al. (PTB) 2016

Isotope shift new neutron-electron interaction

Implication on new light particle



$$\propto \frac{g^2}{m^2}$$

cf. weak interaction $\sim \frac{g_Z^2}{m_Z^2} \sim \frac{0.5}{(100\ \mathrm{GeV})^2} = \frac{0.5 \times 10^{-10}}{(1\ \mathrm{MeV})^2}$

Isotope shift (IS) and King's linearity

King, 1963

IS of two transitions: $t = 1, 2$

$$\nu^t_{A'A} = K_t\, \mu_{A'A} + F_t\, \langle r^2 \rangle_{A'A}$$

$$\mu_{A'A} = \mu_{A'} - \mu_A \qquad \langle r^2 \rangle_{A'A} = \langle r^2 \rangle_{A'} - \langle r^2 \rangle_A$$

mass shift — field shift (FS)

Modified IS: $\tilde{\nu}^t_{A'A} := \nu^t_{A'A} / \mu_{A'A}$

$$\tilde{\nu}^t_{A'A} = K_t + F_t \langle r^2 \rangle_{A'A} / \mu_{A'A}$$

K_t, F_t: electronic factors; $\langle r^2 \rangle_{A'A} / \mu_{A'A}$: nuclear factor

King's linearity — eliminating the nuclear factor

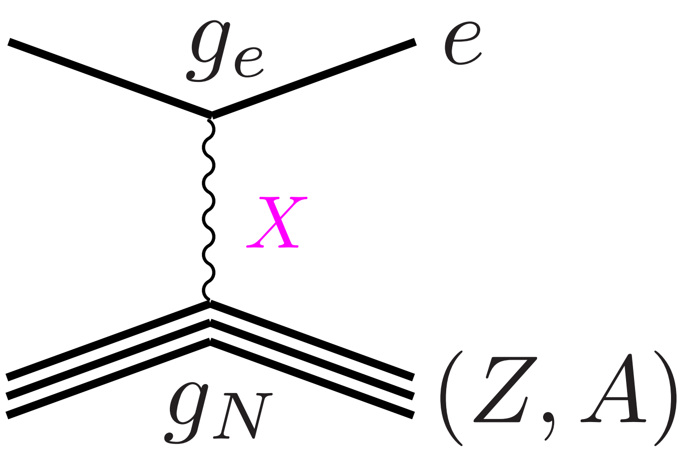
$$\tilde{\nu}^2_{A'A} = K_{21} + \frac{F_2}{F_1} \tilde{\nu}^1_{A'A}$$

$$K_{21} := K_2 - \frac{F_2}{F_1} K_1$$

→ $(\tilde{\nu}^1_{A'A}, \tilde{\nu}^2_{A'A})$ on a straight line, King's plot

Breakdown of the linearity

IS by new neutron-electron interaction



Delaunay et al. arXiv:1601.05087v2

$$\nu^t_{A'A} = K_t\,\mu_{A'A} + F_t\,\langle r^2\rangle_{A'A} + X_t(A' - A)$$

MS FS particle shift (PS)

Generalized King's relation w/ nonlinearity

$$\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A} + \varepsilon_{\rm PS}\; A'A$$

Nonlinearity due to subleading FS

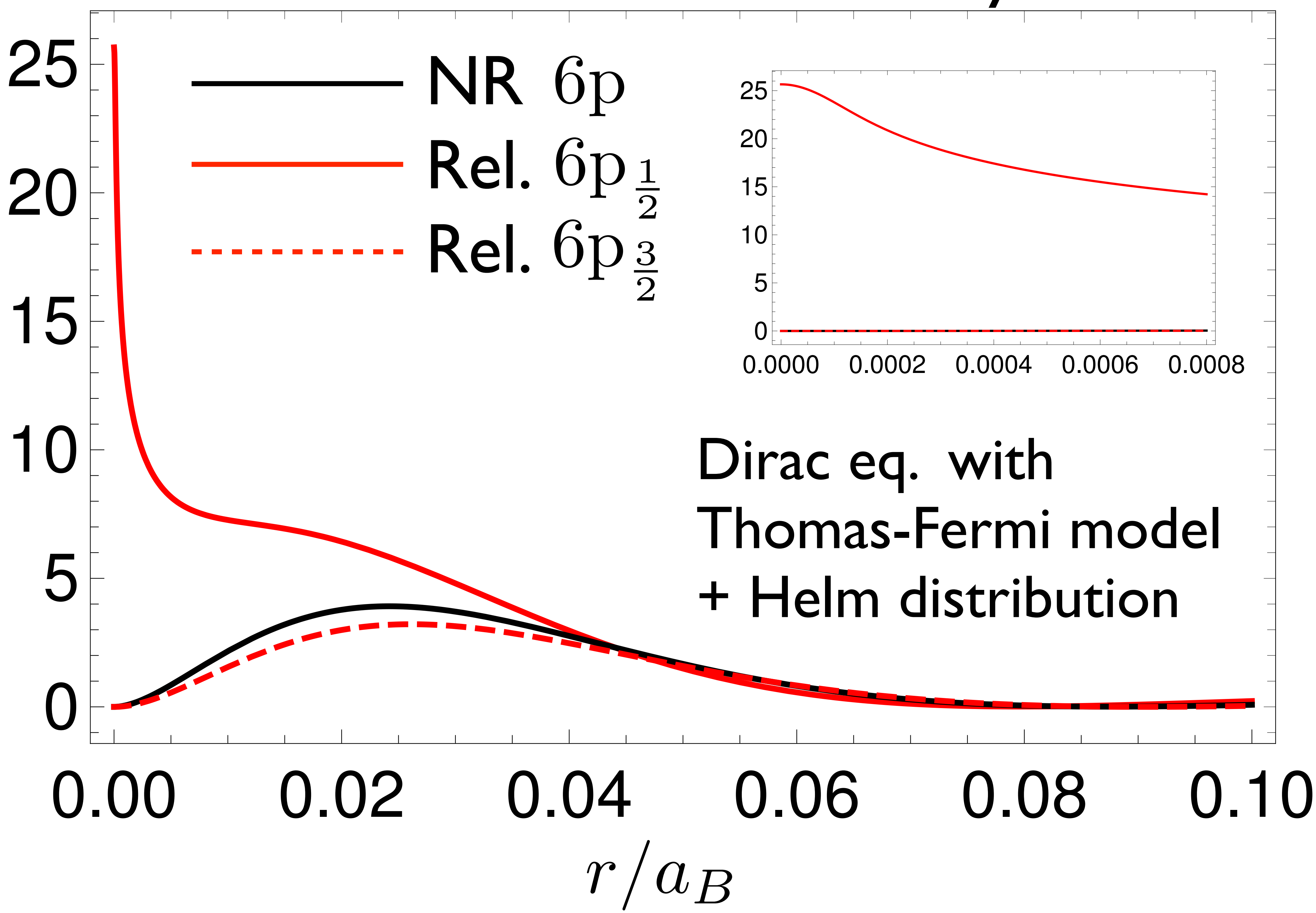
$$\mathrm{FS} = F_t\,\langle r^2\rangle_{A'A} + G_t\,\langle r^4\rangle_{A'A} + \cdots$$

$$\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A} + (\varepsilon_{\rm PS} + \varepsilon_{\rm FS})\; A'A$$

Wave function inside the nucleus is relevant.

$$\text{support of } \phi_{A'}(r) - \phi_A(r) :\; r \lesssim r_A$$

Yb^+ electron density

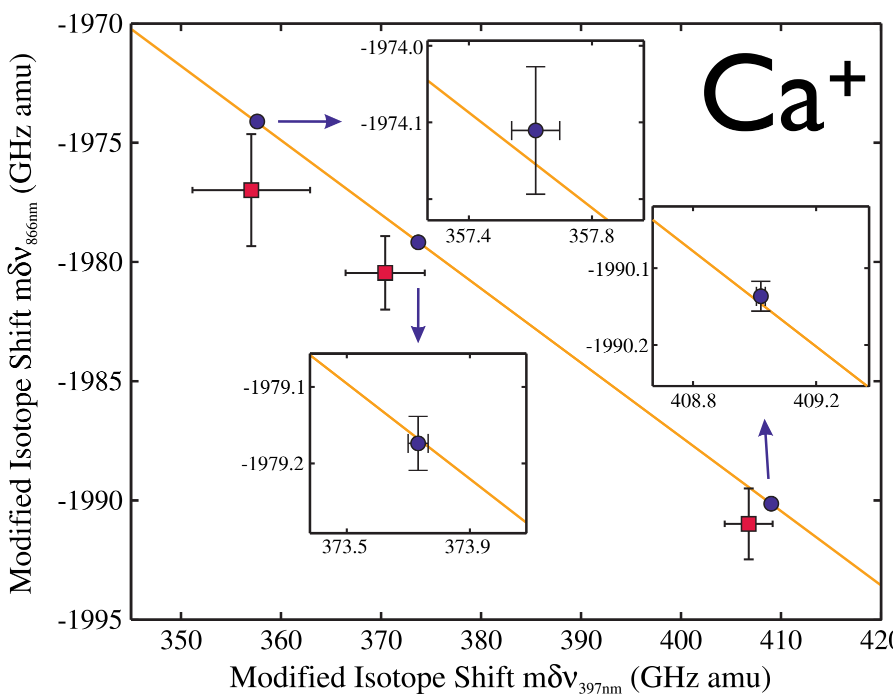


$\mathrm{p}_{\frac{1}{2}}$ gives larger FS nonlinearity than NR.

Present constraint and future prospect

Data fitting with $\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A} + \varepsilon\, A'A$

K. Mikami, MT, Y. Yamamoto, Eur. Phys. J. C (2017) 77:896

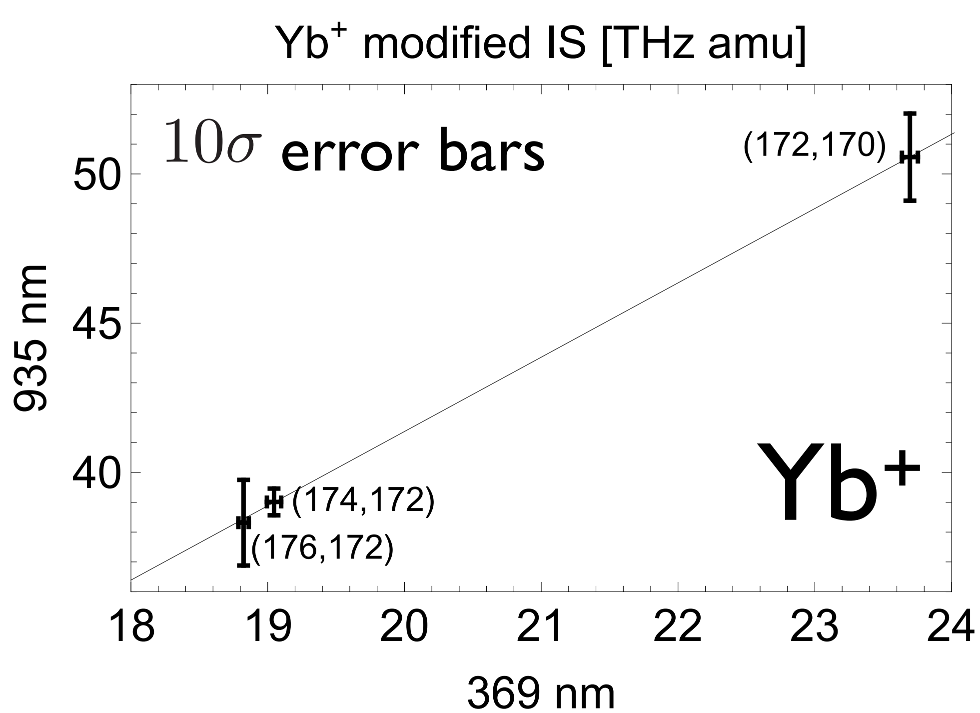


$\varepsilon = (-2.45 \pm 4.05)\cdot 10^{-6}$ au

$\delta\nu \sim O(100)$ kHz

future prospect $\delta\nu = 1$ Hz

$|\varepsilon| < 4.5 \cdot 10^{-11}$



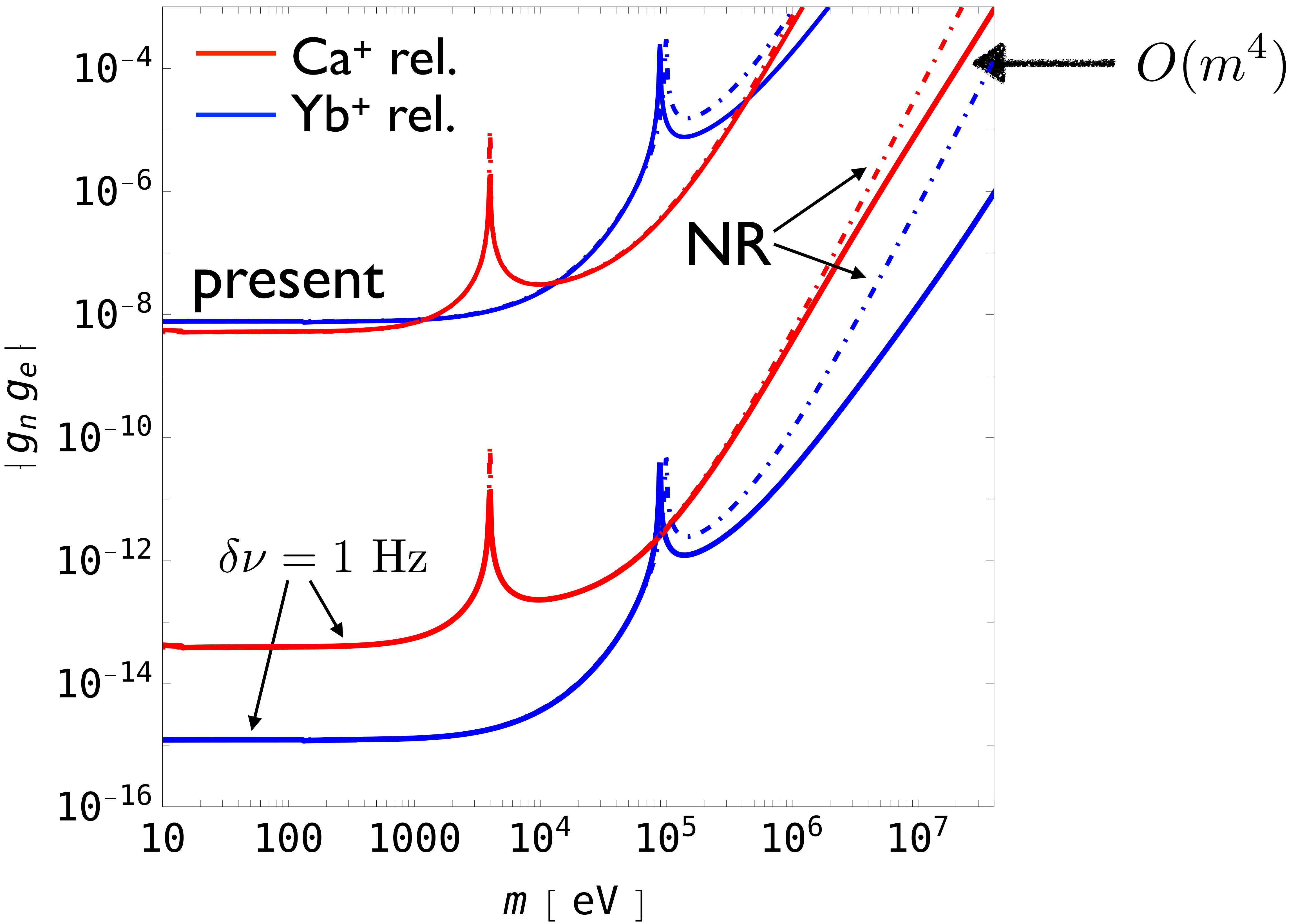
$\varepsilon = (-1.26 \pm 1.35)\cdot 10^{-4}$

$\delta\nu \sim O(10)$ MHz

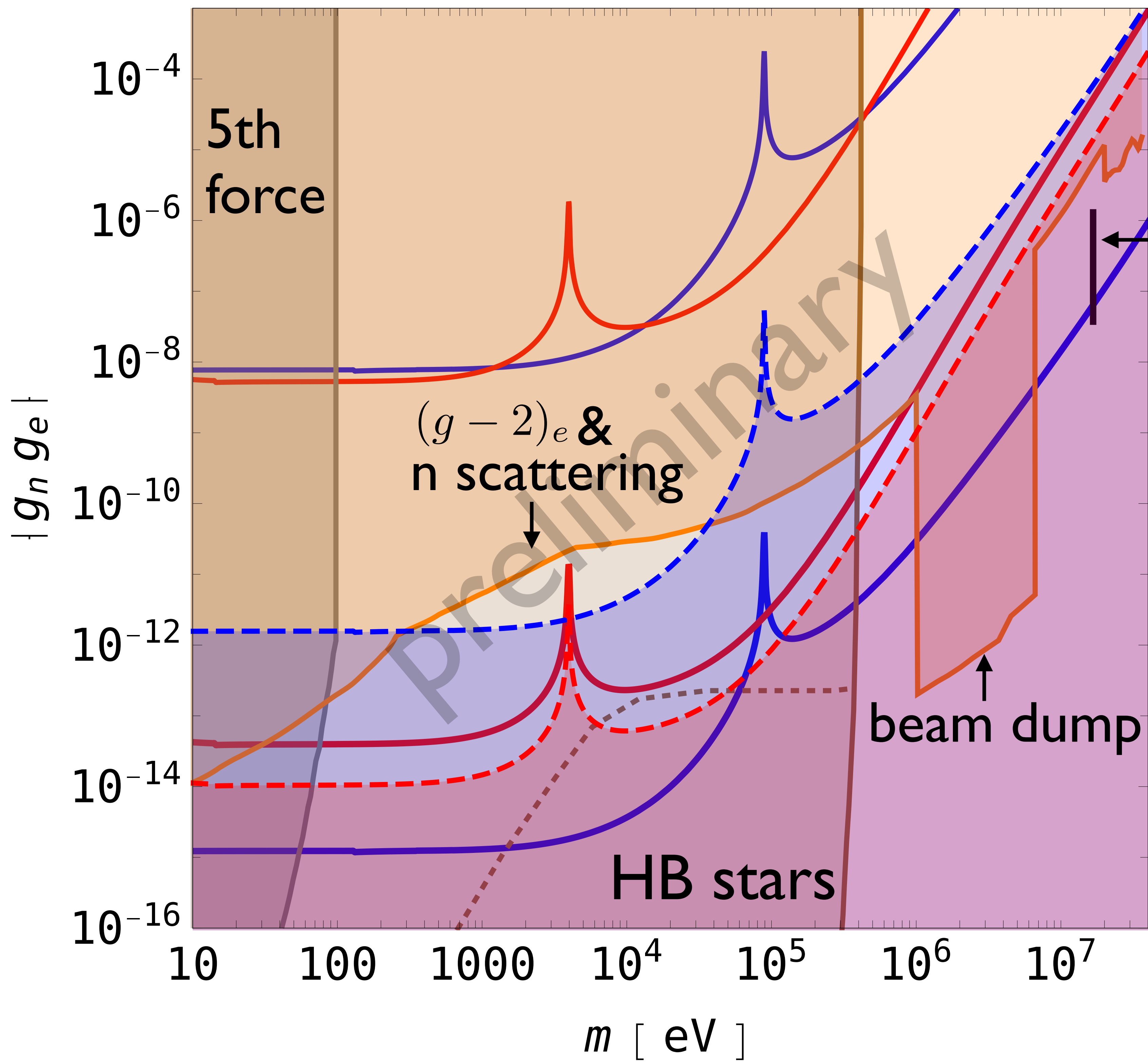
future prospect $\delta\nu = 1$ Hz

$|\varepsilon| < 4.2 \cdot 10^{-11}$

$$\mathcal{L}_{\rm int} = -g_f \bar{f}\gamma^\mu f V_\mu$$



Comparison to other constraints: vector



FSNL

FSNL dominance:

Ca⁺ $\delta\nu \lesssim 0.3$ Hz

Yb⁺ $\delta\nu \lesssim 1$ kHz

Suppression of FS nonlinearity using $P_{3/2}$

	Ca^+	Yb^+
$\varepsilon_{\mathrm{exp}}(\mathrm{present})$	$< 6.5 \cdot 10^{-6}$	$< 2.6 \cdot 10^{-4}$
$\varepsilon_{\mathrm{exp}}(1\ \mathrm{Hz})$	$4.5 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$
$\varepsilon_{\mathrm{FS}}(\mathrm{NR})$	$5 \cdot 10^{-13}$	$2 \cdot 10^{-10}$
$\varepsilon_{\mathrm{FS}}(\mathrm{p}_{\frac{1}{2}})$	$1 \cdot 10^{-11}$	$5 \cdot 10^{-8}$
$\varepsilon_{\mathrm{FS}}(\mathrm{p}_{\frac{3}{2}})$	$5 \cdot 10^{-13}$	$5 \cdot 10^{-10}$
$\varepsilon_{\mathrm{PS}}$	$8 \cdot 10^{-11}$	$3 \cdot 10^{-9}$

$$m = 1\ \mathrm{keV},\ \ |g_n g_e| = 1 \times 10^{-13}$$

Summary

- Isotope shift and King's linearity

  IS=MS+FS, $\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A}$

  Linear relation of modified IS of two lines

- Nonlinearity $\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A} + \varepsilon\, A'A$

  $\varepsilon = \varepsilon_{\mathrm{PS}} + \varepsilon_{\mathrm{FS}}$

- Relativistic effects

  Signal enhancement for m>1 MeV

  But, FS nonlinearity also enhanced

- Suppression of FS nonlinearity

  avoid $\mathrm{p}_{\frac{1}{2}}$, use e.g. $\mathrm{p}_{\frac{3}{2}}$