Physics
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# 同位体シフトで探る素粒子の新しい相互作用


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and work in progress

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科研費 KAKENHI

# Frontiers in particle physics

Energy frontier: LHC, ILC,…

Intensity frontier: B factory, muon, K, …

Cosmic frontier: CMB,…

Precision / low energy frontier

$0\nu\beta\beta$, DM, EDM,…

Temporal variation of fundamental constants

$\alpha$, $m_e/m_p$ using atomic clock

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

Huntemann et al. (PTB) 2016

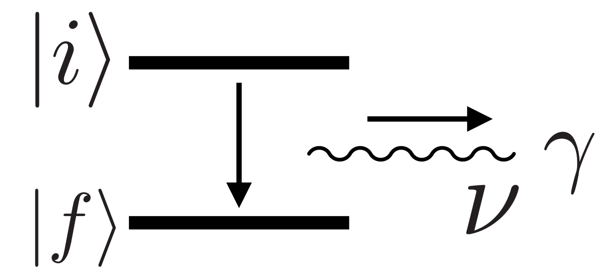
Isotope shift new neutron-electron interaction

# Isotope shift (IS)

Transition frequency difference between isotopes

$$h\nu_A = E_A^i - E_A^f$$

$$\mathrm{IS} = \nu_{A'A} := \nu_{A'} - \nu_A$$




No IS for infinitely heavy and point-like nuclei

$$\mathrm{IS} = \mathrm{MS} + \mathrm{FS}$$

Mass shift: finite mass of nuclei (reduced mass)

$\mathrm{MS} \propto \mu_{A'} - \mu_A$ (dominant for Z<20)

Field shift: finite size of nuclei

$\mathrm{FS} \propto \langle r^2 \rangle_{A'} - \langle r^2 \rangle_A$ (dominant for Z>40)

Theoretical calculation of IS: not easy

$$\mathrm{IS} \sim O(\mathrm{GHz}) \sim O(10\ \mu\mathrm{eV})$$

# King's linearity

King, 1963

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

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

$$\mu_{A'A} := \mu_{A'} - \mu_A$$

$$\langle r^2 \rangle_{A'A} := \langle r^2 \rangle_{A'} - \langle r^2 \rangle_A$$

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

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

nuclear factor

electronic factors

King's linearity eliminating the nuclear factor

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

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

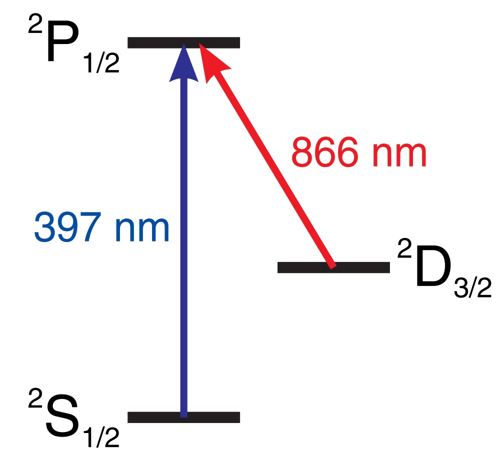
→ $(\tilde{\nu}^1_{A'A}, \tilde{\nu}^2_{A'A})$ on a straight line, King's plot

# IS data of $Ca^+$

Gebert et al. PRL115, 053003 (2015)

Transition 1: 397 nm $^2P_{1/2}(4p) - ^2S_{1/2}(4s)$

Transition 2: 866 nm $^2P_{1/2}(4p) - ^2D_{3/2}(3d)$



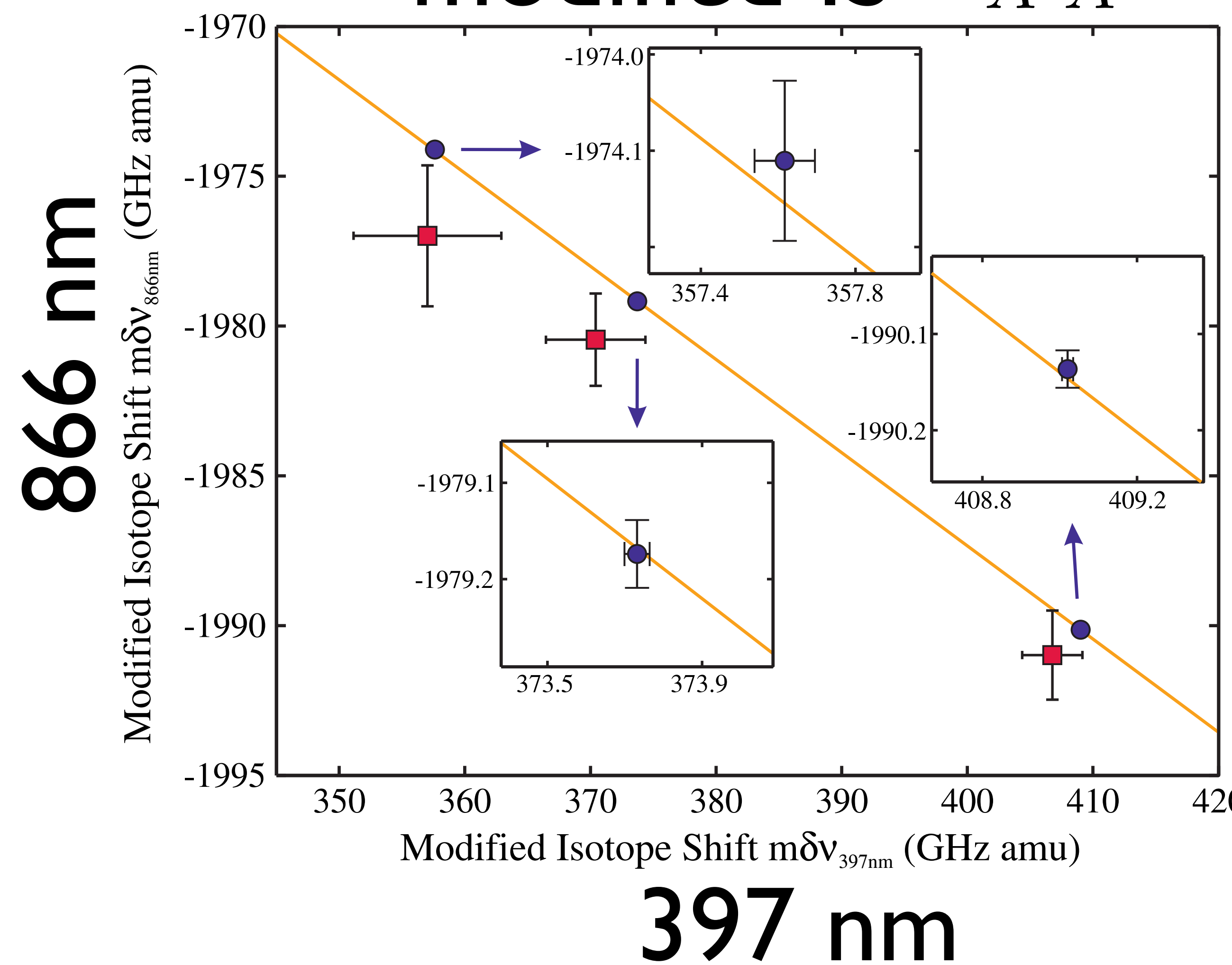

Isotope pairs: (42, 40), (44,40), (48,40)

IS precision ~ O(100) kHz

King's plot

linear within errors

modified IS $\tilde{\nu}^t_{A'A}$



# IS data of Yb$^+$

**Transition 1: 369 nm** Martensson-Pendrill et al. PRA49, 3351 (1994)

$${}^2\mathrm{P}_{1/2}(4\mathrm{f})^{14}(6\mathrm{p}) - {}^2\mathrm{S}_{1/2}(4\mathrm{f})^{14}(6\mathrm{s}) \quad \delta\nu^1_{A'A} \sim O(1)\ \mathrm{MHz}$$

**Transition 2: 935 nm** Sugiyama et al. CPEM2000

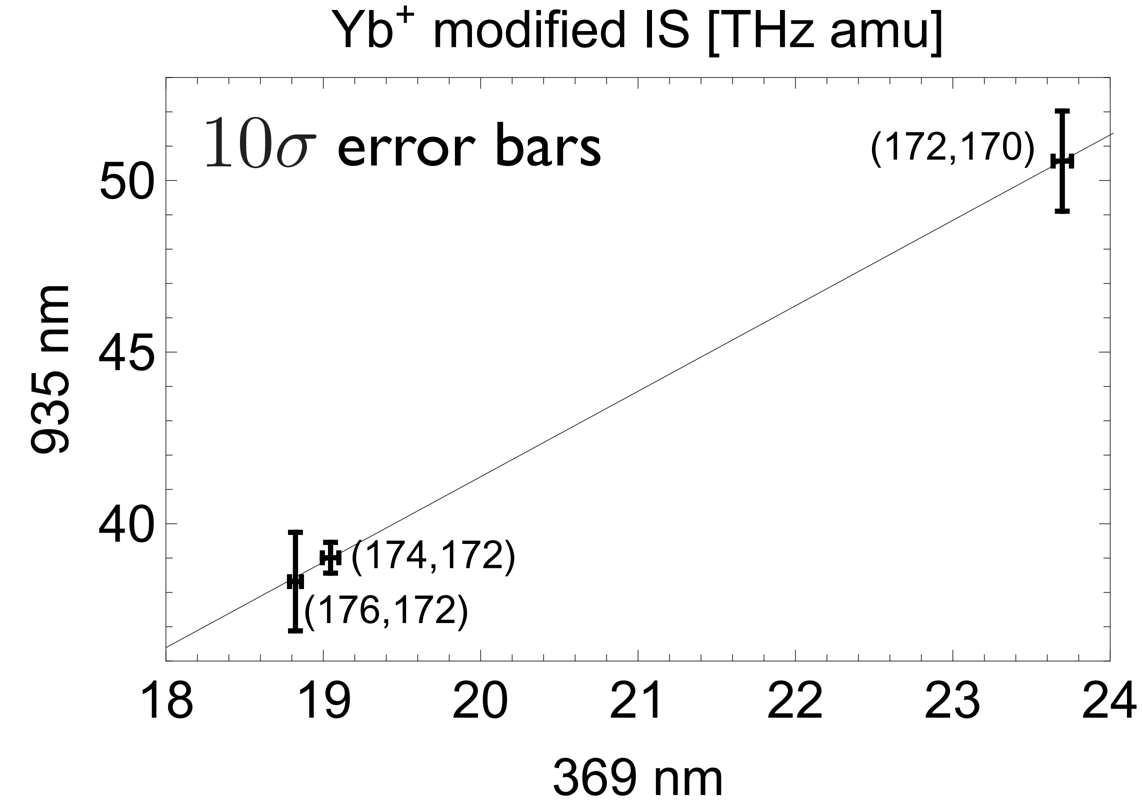
$${}^3\mathrm{D}[3/2]_{1/2}(4\mathrm{f})^{13}(5\mathrm{d})(6\mathrm{s}) - {}^2\mathrm{D}_{3/2}(4\mathrm{f})^{14}(5\mathrm{d})$$

$$\delta\nu^2_{A'A} \sim O(10)\ \mathrm{MHz}$$

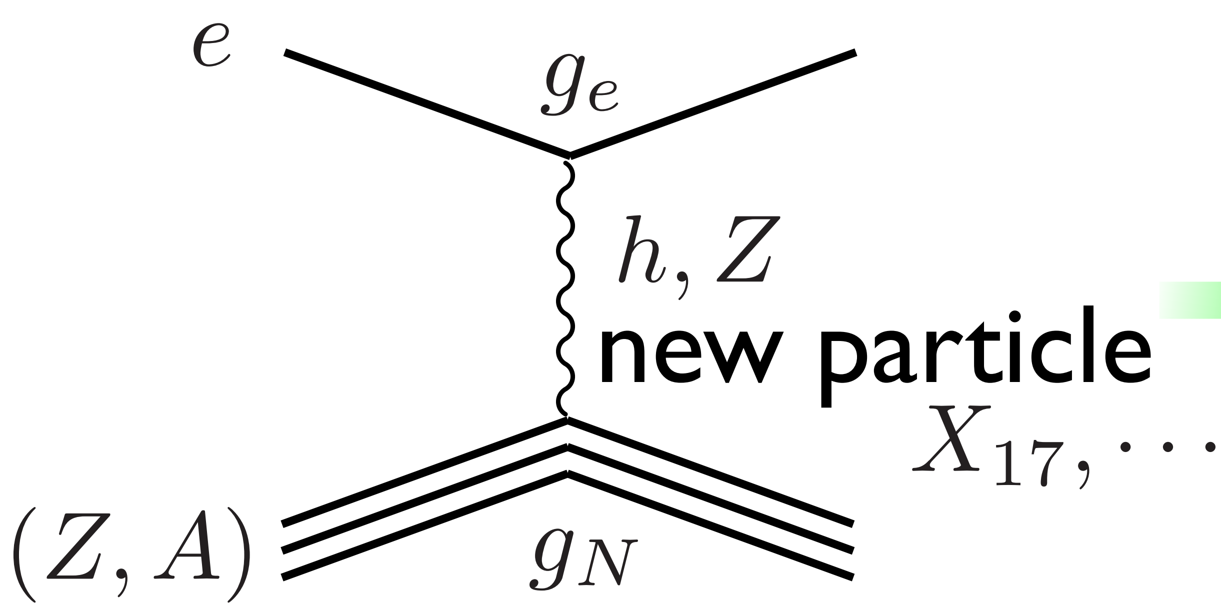
**Isotope pairs: (172, 170), (174,172), (176,172)**

**King's plot**

linear within errors



# Particle shift (PS)




## Yukawa potential

$$V(r) = (-1)^{s+1} \frac{g_N g_e}{4\pi} \frac{e^{-mr}}{r}$$

## Frequency shifts by particle exchange ($Yb^+$ g.s.)

$$|\Delta\nu| \sim \begin{cases} 10^{-4}\ \mathrm{Hz} & \text{Higgs (SM)} \\ 400\ \mathrm{Hz} & \text{Higgs (LHC bound)} \\ 800\ \mathrm{Hz} & Z \\ 10\ \mathrm{MHz} & X_{17}\ \text{17 MeV vector boson} \end{cases}$$ (Atomki)

<< theoretical uncertainties

# Breakdown of the linearity by PS

Delaunay et al. arXiv:1601.05087v2

$$\mathrm{IS} = \mathrm{MS} + \mathrm{FS} + \mathrm{PS}$$

PS by new neutron-electron interaction

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

Generalized King's relation

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

nonlinearity

probe into new physics

PS nonlinearity

$$\varepsilon_{\mathrm{PS}} = X_1 \left( \frac{X_2}{X_1} - \frac{F_2}{F_1} \right) \qquad X_t \propto \frac{g_n g_e}{m^2} \text{ as } m \to \infty$$

# Heavy particle limit

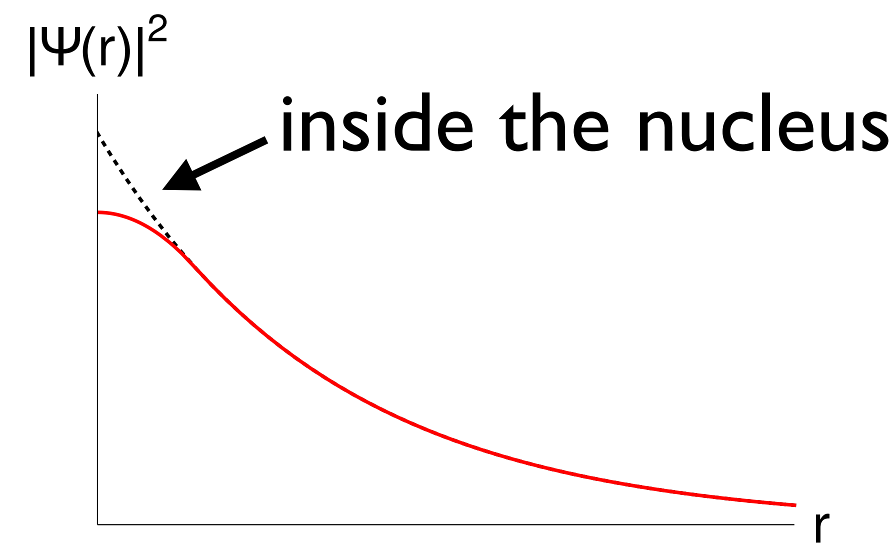
$$ma_B \gg Z\,, \;\; a_B = \text{Bohr radius} \sim (4\ \text{keV})^{-1}$$

$$F_t, X_t \propto |\psi_{i_t}(0)|^2 - |\psi_{f_t}(0)|^2 \longrightarrow \lim_{m\to\infty}\left(\frac{X_2}{X_1} - \frac{F_2}{F_1}\right) = 0$$

## Asymptotic behavior of PS

$$X_t \propto \frac{1}{m^2}\sum_{k=0}(2j+k)!\,\frac{\xi_k^j}{m^{2j+k-1}}$$

$$j = 1/2, 3/2, \cdots$$




$\xi_1^{1/2} = 0$ for nucl. charge distribution without cusp

$$\varepsilon_{\rm PS} = X_1\left(\frac{X_2}{X_1} - \frac{F_2}{F_1}\right) \sim O\left(\frac{1}{m^4}\right)$$

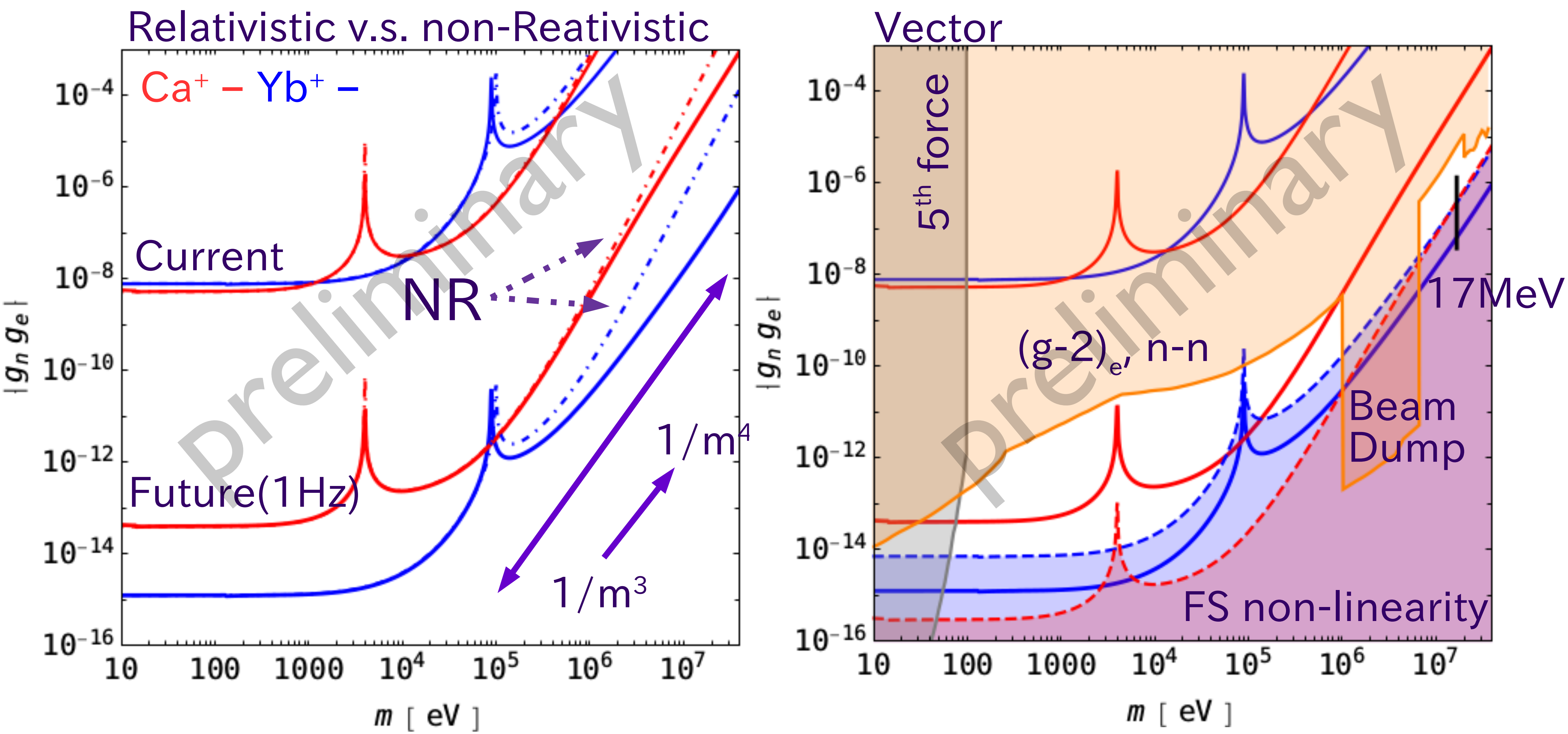
less sensitive to heavier particles

cf. Berengut et al. arXiv:1704.05068 $\varepsilon_{\rm PS} \propto 1/m^3$

# Present constraint and future prospect

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

## Relativistic wavefunc. employed (preliminary)



# Summary and outlook

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

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

  Particle shift nonlinearity: $\varepsilon_{\rm PS} \sim O(1/m^4)$

  sensitive for lighter particles, $m \ll 100\ {\rm MeV}$

- $Yb^+$ ion trap project by Sugiyama et al. (Kyoto)

  $\delta\nu < 1\ {\rm Hz} \sim 100\ {\rm kHz}$

  $^{168}{\rm Yb}^+$ trapped successfully last month