Physics
OSAKA UNIVERSITY

原子スペクトルにおける同位体効果の精密測定と素粒子の新しい相互作用

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科研費
KAKENHI

Precision and low-energy frontiers

Neutrinoless ββ decay, Dark matter search,
EDM search, Exotic force, Millicharge search, etc.

Temporal variation of fundamental constants

α, m_e/m_p using atomic clock

$\mathrm{Yb}^+\ {}^2\mathrm{S}_{1/2} \to {}^2\mathrm{F}_{7/2}(\mathrm{E3})$ Hunteman et al. (PTB) 2016

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

本講演のテーマ

Precision measurement of isotope shift

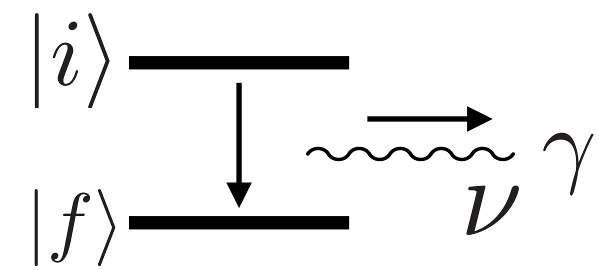
new neutron-electron interaction

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 small Z)

Field shift: finite size of nuclei

$\mathrm{FS} \propto r_{A'}^2 - r_A^2$ (dominant for large Z)

Theoretical calculation of IS: not easy

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

King linearity

King, 1963

IS of two transitions: $\ell = 1, 2$

$$\nu^{\ell}_{A'A} = K_{\ell}\,\mu_{A'A} + F_{\ell}\,r^2_{A'A}$$

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

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

$$\tilde{\nu}^{\ell}_{A'A} = K_{\ell} + F_{\ell}\, r^2_{A'A}/\mu_{A'A}$$

nuclear factor

electronic factors

King linearity eliminating the nuclear factor

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

$$K_{21} := K_2 - F_{21}K_1,\; F_{21} := F_2/F_1$$

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

King plot

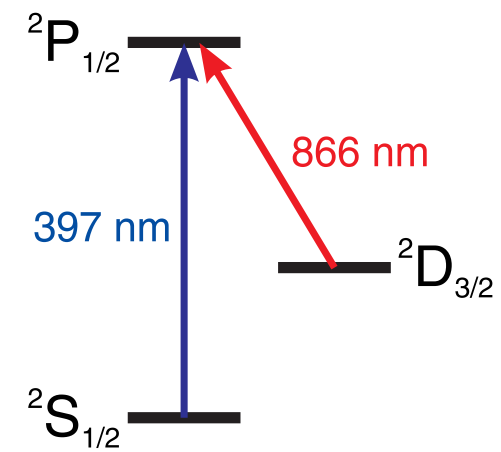
IS data of Ca^+

Gebert et al. PRL115, 053003 (2015)

Line 1: 397 nm $^2\mathrm{P}_{1/2}(4\mathrm{p}) - ^2\mathrm{S}_{1/2}(4\mathrm{s})$

Line 2: 866 nm $^2\mathrm{P}_{1/2}(4\mathrm{p}) - ^2\mathrm{D}_{3/2}(3\mathrm{d})$

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

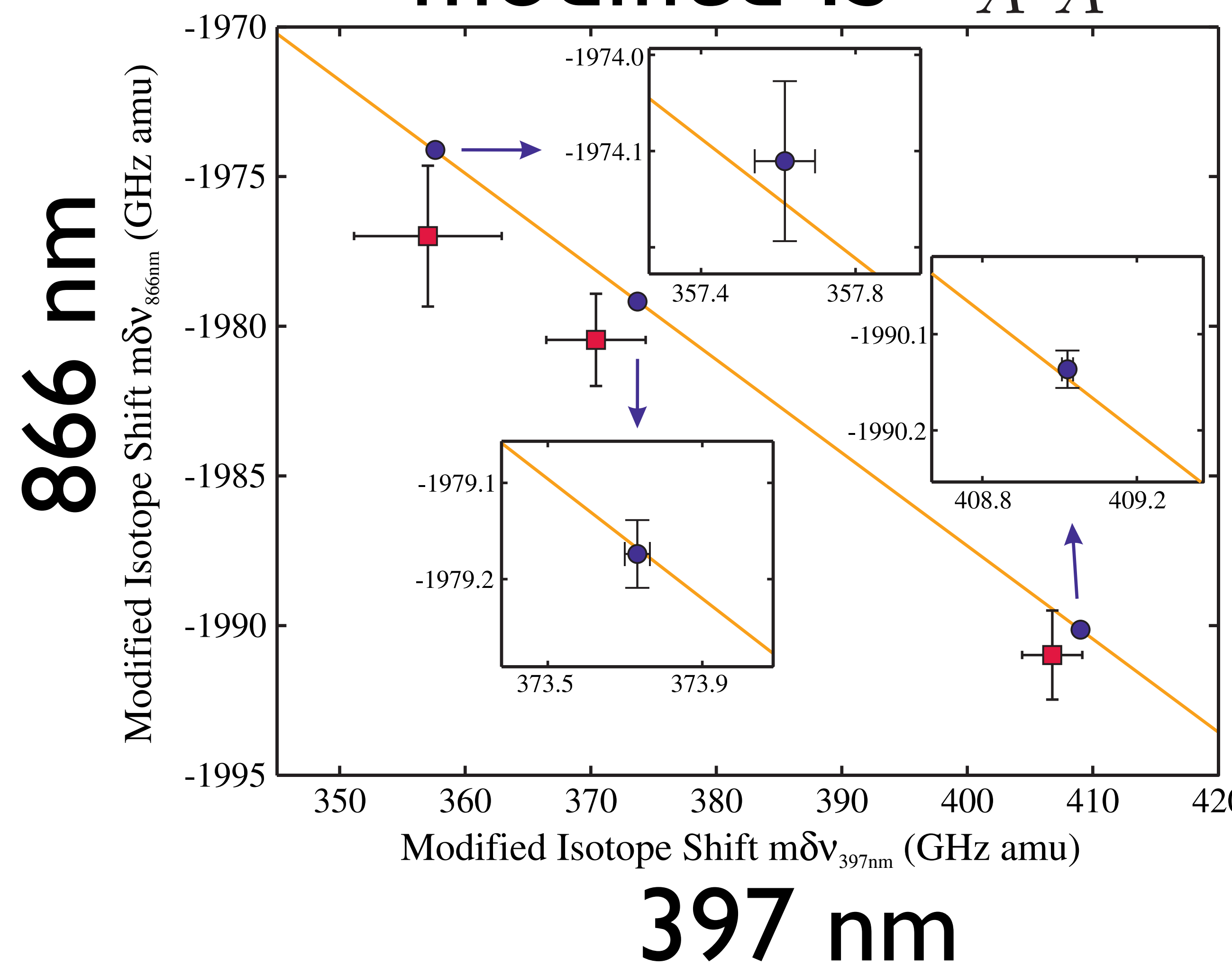


IS precision ~ O(100) kHz

King plot

linear within errors

modified IS $\tilde{\nu}^{\ell}_{A'A}$



IS data of Yb^+

Line 1: 369 nm

Martensson-Pendrill et al. PRA49, 3351 (1994)

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

Line 2: 935nm

Sugiyama et al. CPEM2000

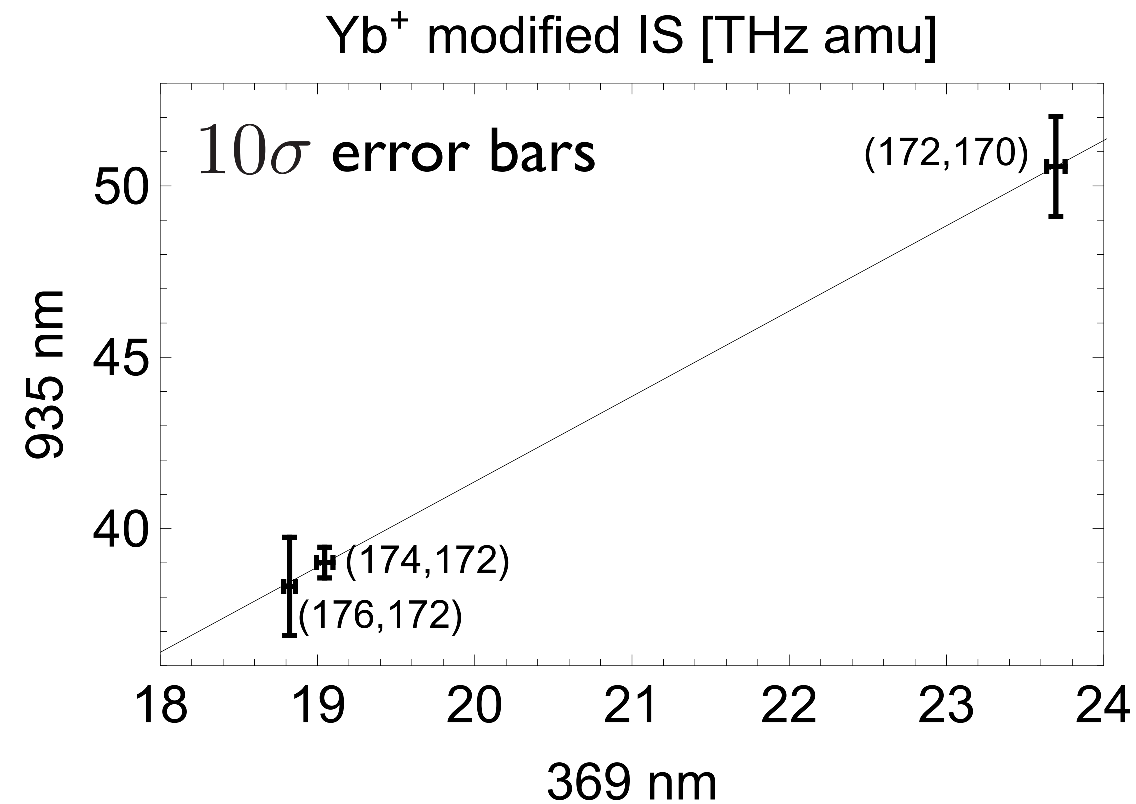
$$^3\mathrm{D}[3/2]_{1/2}(4\mathrm{f})^{13}(5\mathrm{d})(6\mathrm{s}) -{}^2\mathrm{D}_{3/2}(4\mathrm{f})^{14}(5\mathrm{d})$$

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

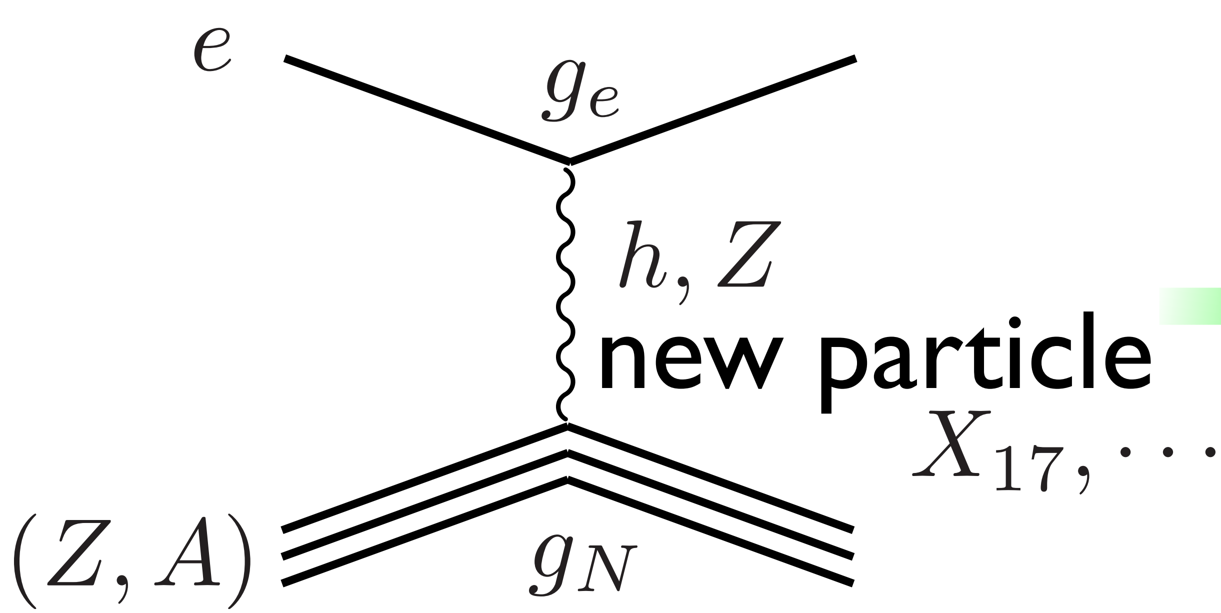
Isotope pairs: (172, 170), (174,172), (176,172)

King plot

linear within errors



Particle shift (PS)



Yukawa potential

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

(atomic units)

Frequency shifts by particle exchange (Yb⁺)

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

<< theoretical uncertainties

Breakdown of the linearity by PS

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

Delaunay et al. arXiv:1601.05087v2

PS by new neutron-electron interaction

$$\nu^{\ell}_{A'A} = K_\ell \, \mu_{A'A} + F_\ell \, r^2_{A'A} + X_\ell (A' - A)$$

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 $\varepsilon_{\mathrm{PS}} = X_1 (X_{21} - F_{21})$ $X_{21} := X_2 / X_1$

Heavy particle limit: $m a_B \gg \alpha$

Berengut et al. arXiv:1704.05068

$F_\ell, X_\ell \propto |\psi_{i_\ell}(0)|^2 - |\psi_{f_\ell}(0)|^2$ → $X_{21} - F_{21} \sim O(1/m)$

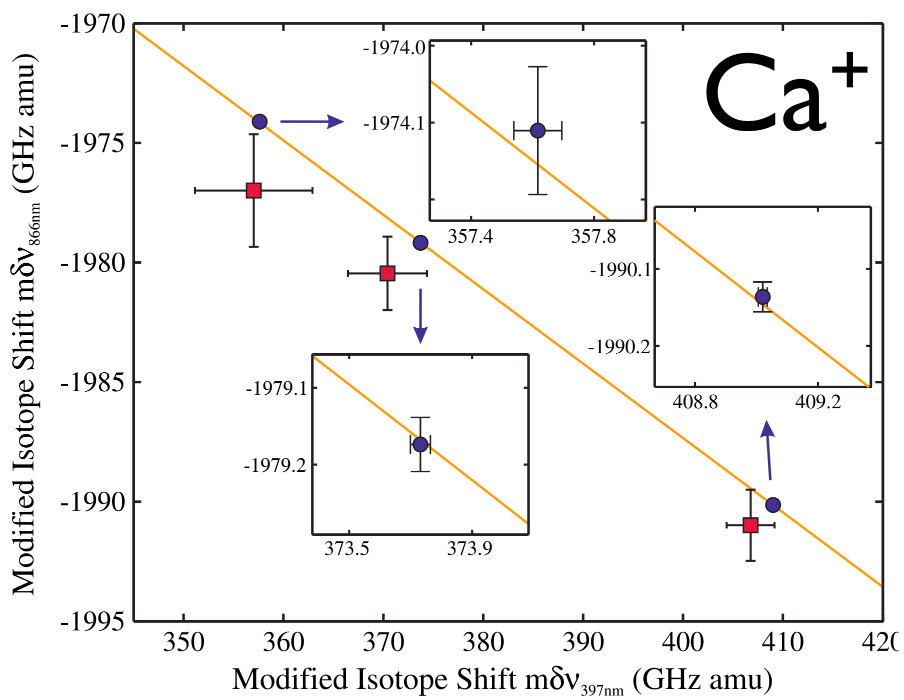
$X_\ell \sim O(1/m^2)$

→ $\varepsilon_{\mathrm{PS}} \sim O(1/m^3)$

less sensitive to heavier particles

Present constraint and future prospect

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



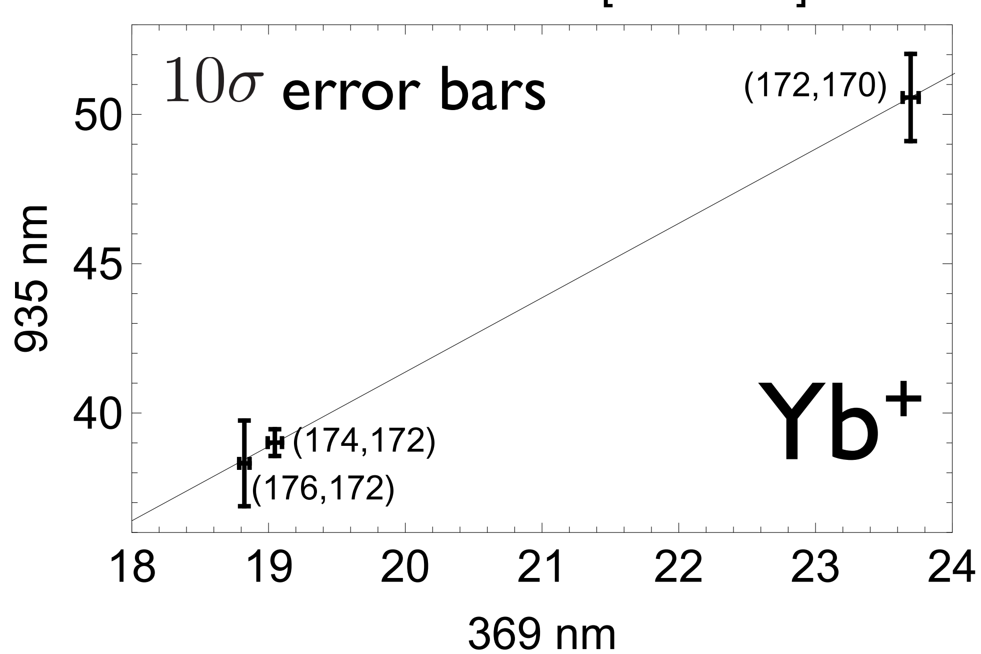
$$\varepsilon = (-2.45 \pm 4.05) \cdot 10^{-6}$$

au

future prospect $\delta\nu = 1\ \mathrm{Hz}$

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

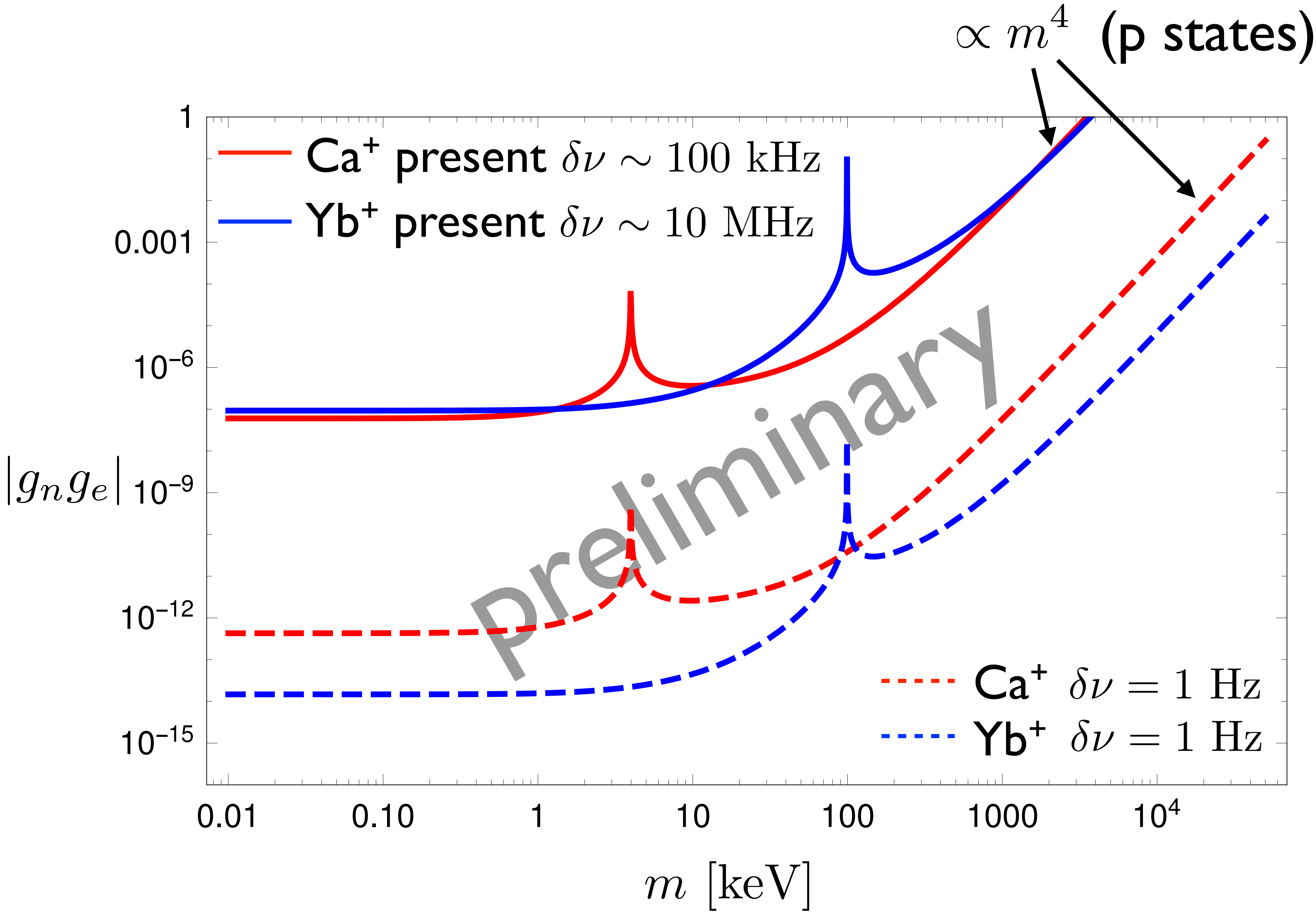
Yb$^+$ modified IS [THz amu]



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

future prospect $\delta\nu = 1\ \mathrm{Hz}$

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


$\propto m^4$ (p states)
Ca^+ present $\delta\nu \sim 100$ kHz
Yb^+ present $\delta\nu \sim 10$ MHz
Ca^+ $\delta\nu = 1$ Hz
Yb^+ $\delta\nu = 1$ Hz
preliminary
$|g_n g_e|$
1
0.001
10^{-6}
10^{-9}
10^{-12}
10^{-15}
0.01
0.10
1
10
100
1000
10^4
m [keV]

Field shift nonlinearity

One of the sources of nonlinearity in QED

$$\mathrm{FS} = F_\ell \, r^2_{A'A} + G_\ell \, r^4_{A'A}$$

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

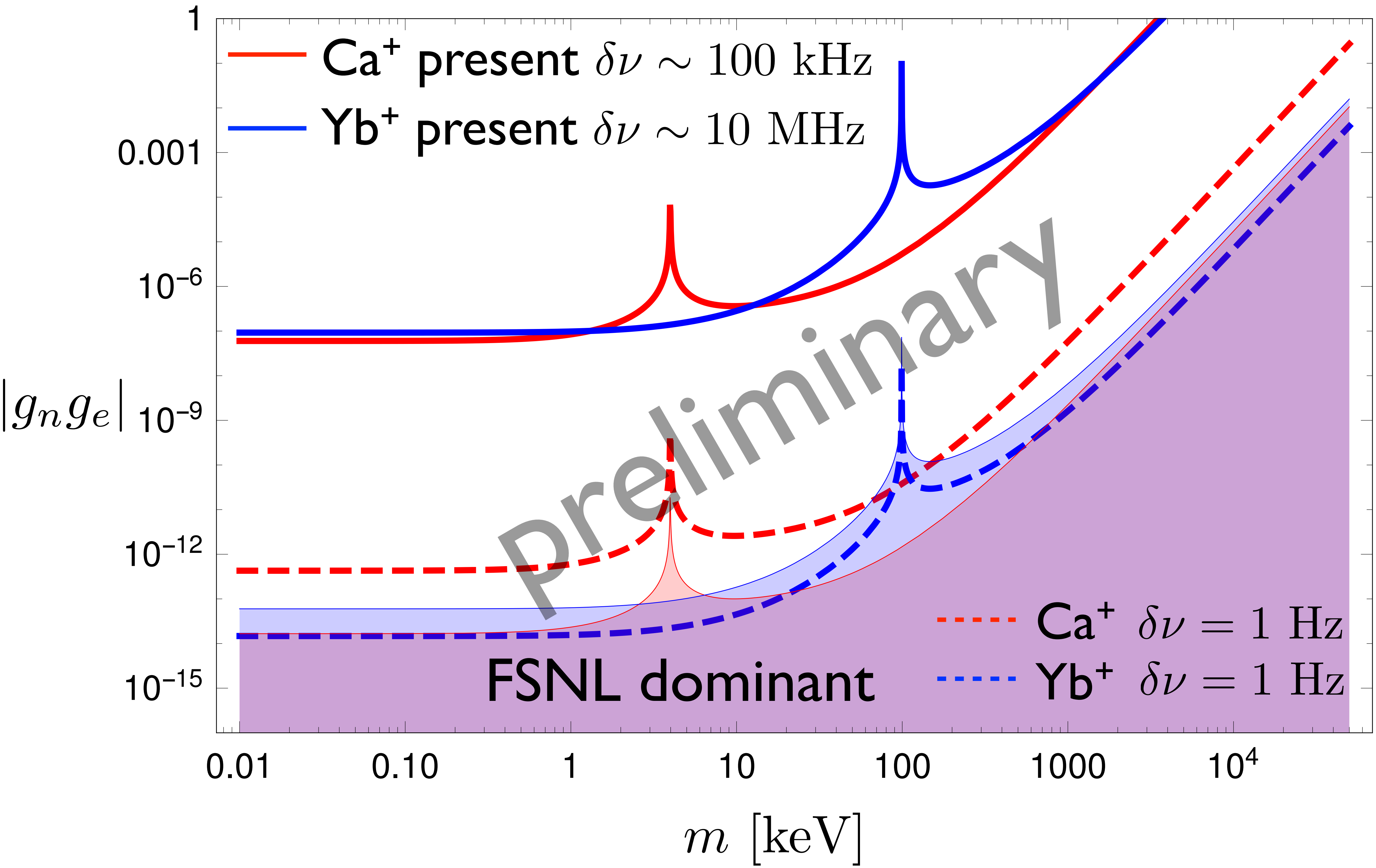
$$\Rightarrow \quad \varepsilon = \varepsilon_{\mathrm{PS}} + \varepsilon_{\mathrm{FS}} + \cdots$$

Wavefunction inside the nucleus is relevant.

p state dominant: Ca^+ 4p, Yb^+ 6p

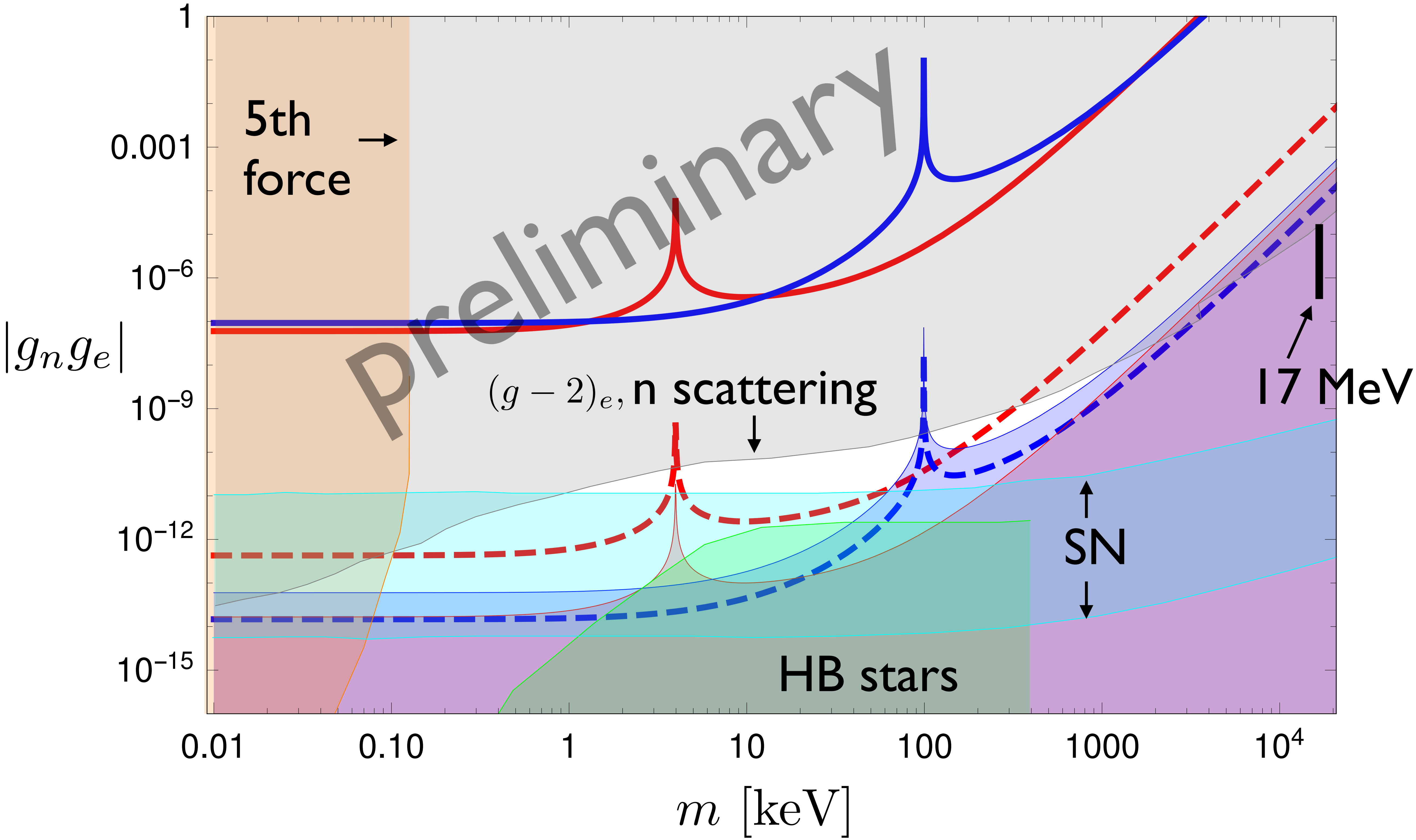
$$\varepsilon_{\mathrm{FS}} \propto Z |\psi'_{np}(0)|^2 \frac{d}{dA} \langle r^4 \rangle_A$$

↖ nuclear Helm distribution



FSNL dominant: Ca^+ $\delta\nu \lesssim 0.04$ Hz Yb^+ $\delta\nu \lesssim 4$ Hz

Comparison to other constraints



Summary and outlook

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

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

  Particle shift nonlinearity: $\varepsilon_{\mathrm{PS}} \sim O(1/m^{3,4})$

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

  Other nonlinearities: more study needed

  selecting better candidates

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

  $\delta\nu < 1\ \mathrm{kHz}$ with in a few years