Implication of precision atomic isotope shift measurements in particle physics

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Precision and low-energy frontiers

Neutrinoless $\beta\beta$ decay, Cosmic neutrinos

Dark matter search: WIMP, axion, …

Electric dipole moment search: atoms, molecules

Exotic force:

fifth force, short range gravity (extra dim.)…

Millicharge search: neutrality of atoms

Temporal variation of fundamental constants

α, m_e/m_p using atomic clock

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

Hunteman et al. (PTB) 2016

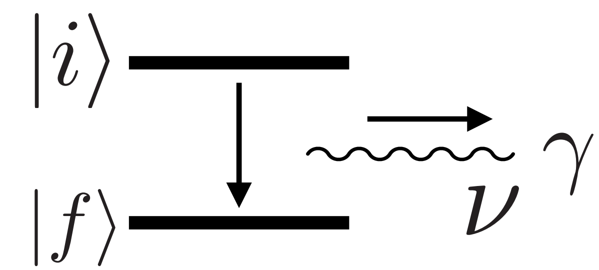
Isotope shift new neutron-electron interaction

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 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

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

King's 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's linearity eliminating the nuclear factor

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

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

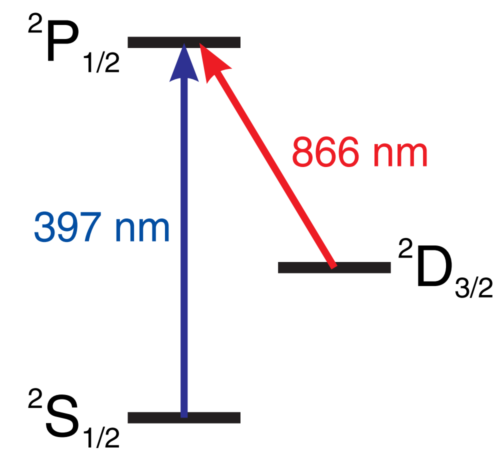
→ $(\tilde{\nu}^{1}_{A'A}, \tilde{\nu}^{2}_{A'A})$ on a straight line, King's plot

IS data of Ca^+

Gebert et al. PRL115, 053003 (2015)

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)

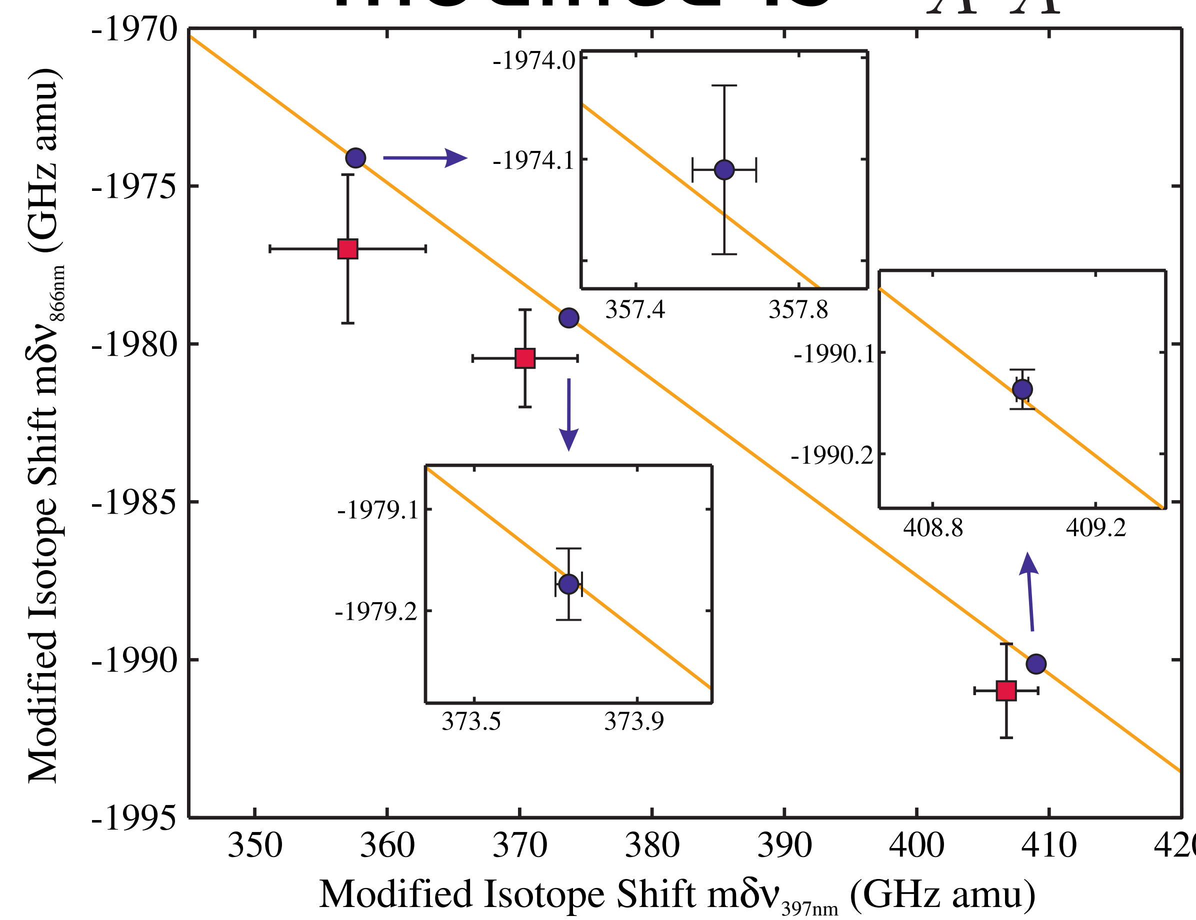
IS precision ~ O(100) kHz

King's plot

linear within errors

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

866 nm



397 nm

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

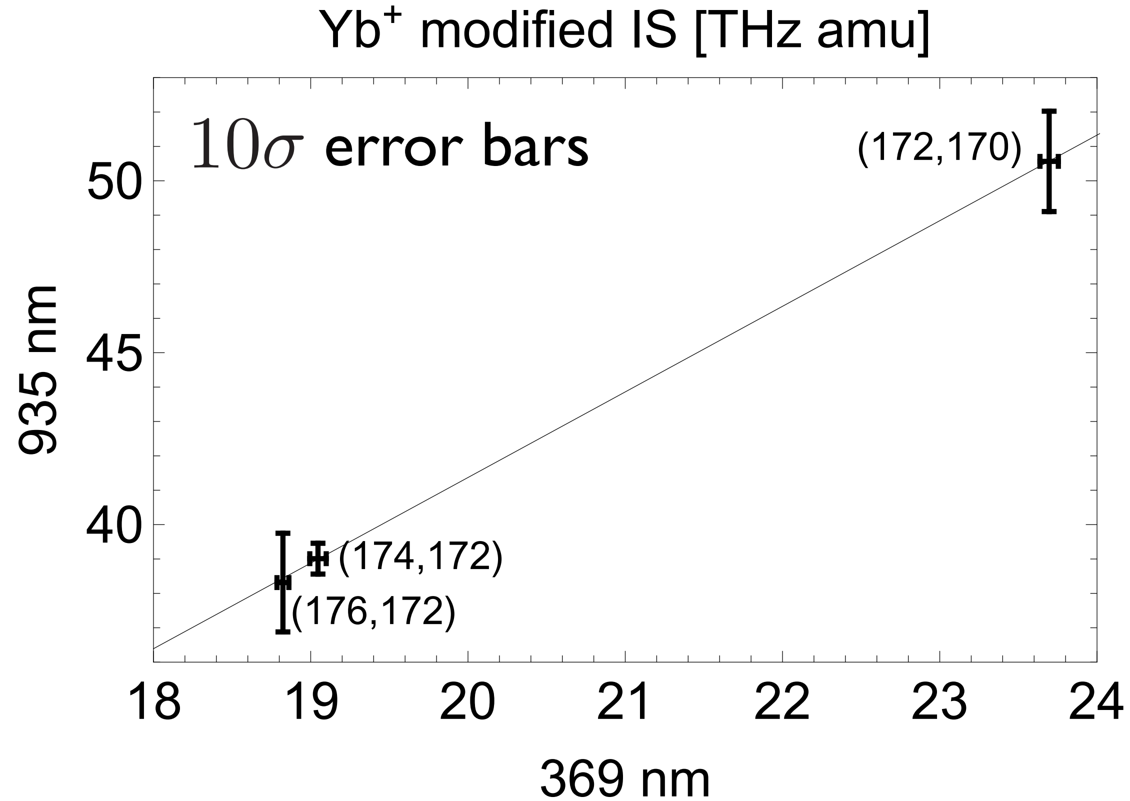
$$^3\mathrm{D}[3/2]_{1/2}(4\mathrm{f})^{13}(5\mathrm{d})(6\mathrm{s}) - {}^2\mathrm{D}_{3/2}(4\mathrm{f})^{14}(5\mathrm{d})$$

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

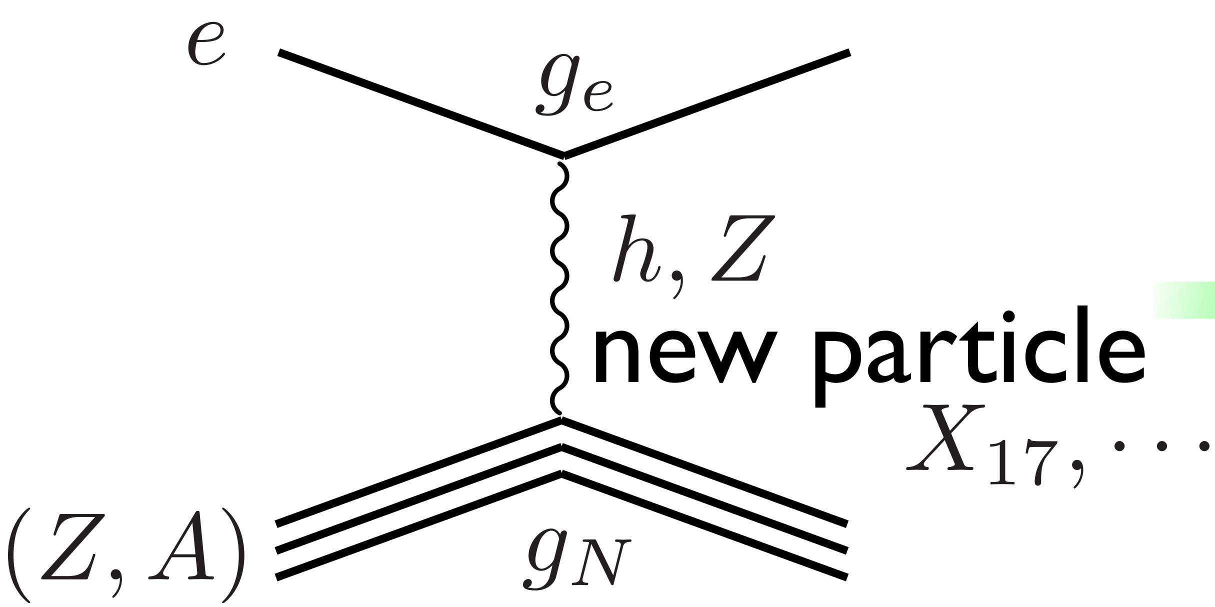
Isotope pairs: (172, 170), (174,172), (176,172)

King'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.)

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

<< 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

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

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

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

Heavy particle limit

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

$$F_\ell, X_\ell \propto |\psi_{i_\ell}(0)|^2 - |\psi_{f_\ell}(0)|^2 \longrightarrow \lim_{m\to\infty}\left(\frac{X_2}{X_1} - \frac{F_2}{F_1}\right) = 0$$

Asymptotic behavior of PS

$$\int d^3r |\psi(r)|^2 \frac{e^{-mr}}{r} = \frac{1}{m^2}\sum_{k=0}(2+2l+k)!\frac{\xi_k^l}{m^{2l+k}} + \cdots$$

$$l = \text{angular momentum}$$

$\xi_1^0 = 0$ for nucl. charge distribution without cusp

$$\frac{X_2}{X_1} - \frac{F_2}{F_1} \sim O\left(\frac{1}{m^2}\right) \longrightarrow \varepsilon_{\rm PS} \sim O\left(\frac{1}{m^4}\right)$$

less sensitive to heavier particles

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

Field shift nonlinearity

One of the sources of nonlinearity in QED

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

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

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

Wavefunction inside the nucleus is relevant.

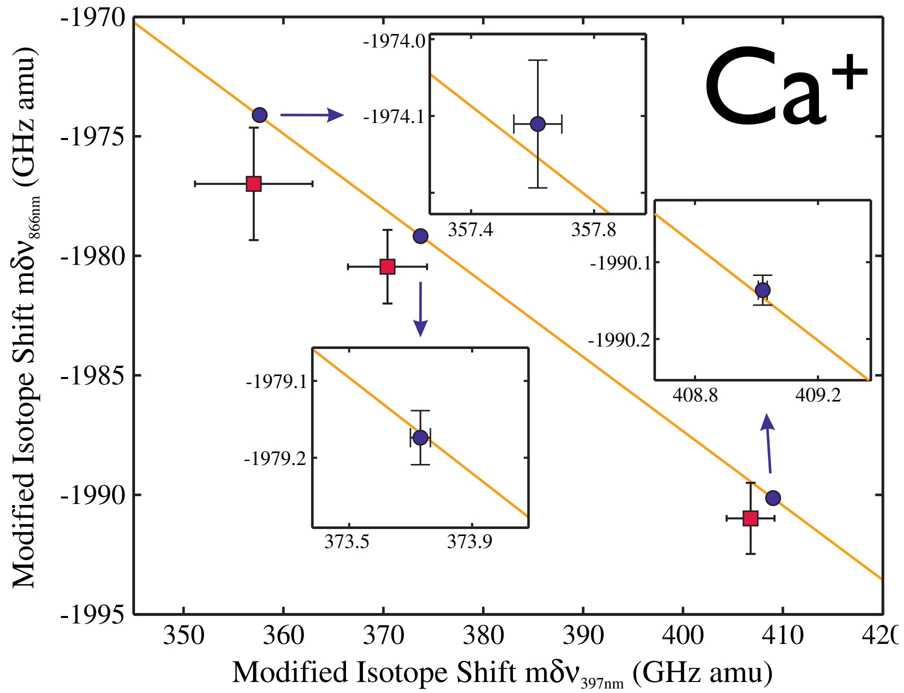
p state dominant: Ca^{+} 4p, Yb^{+} 6p

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

↑ nuclear Helm distribution

Present constraint and future prospect

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

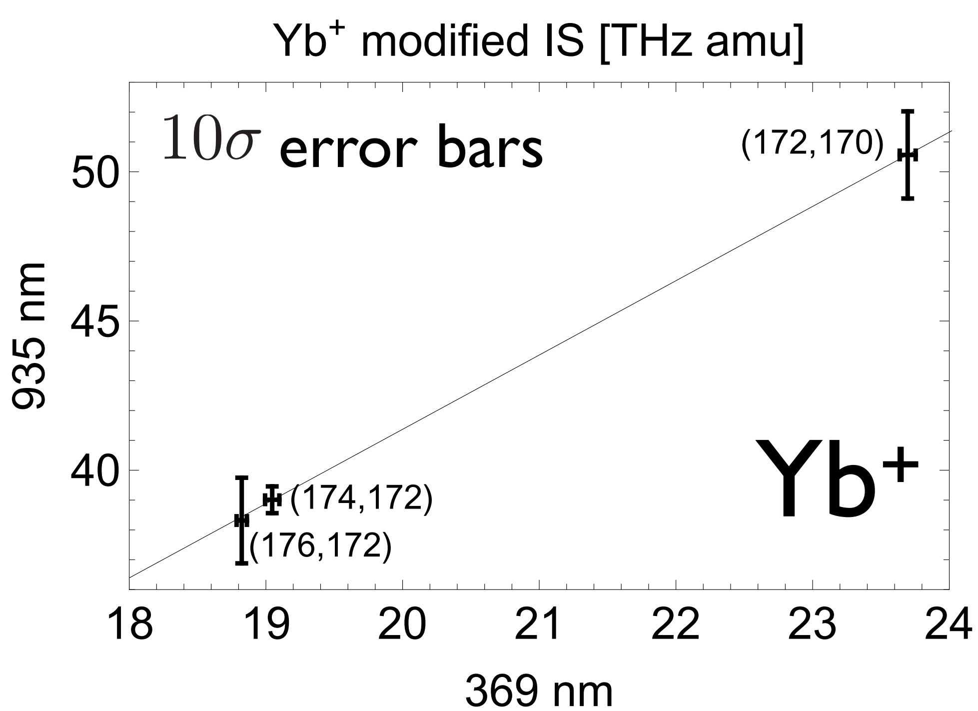


$$\varepsilon = (-2.45 \pm 4.05) \cdot 10^{-6}$$

au

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

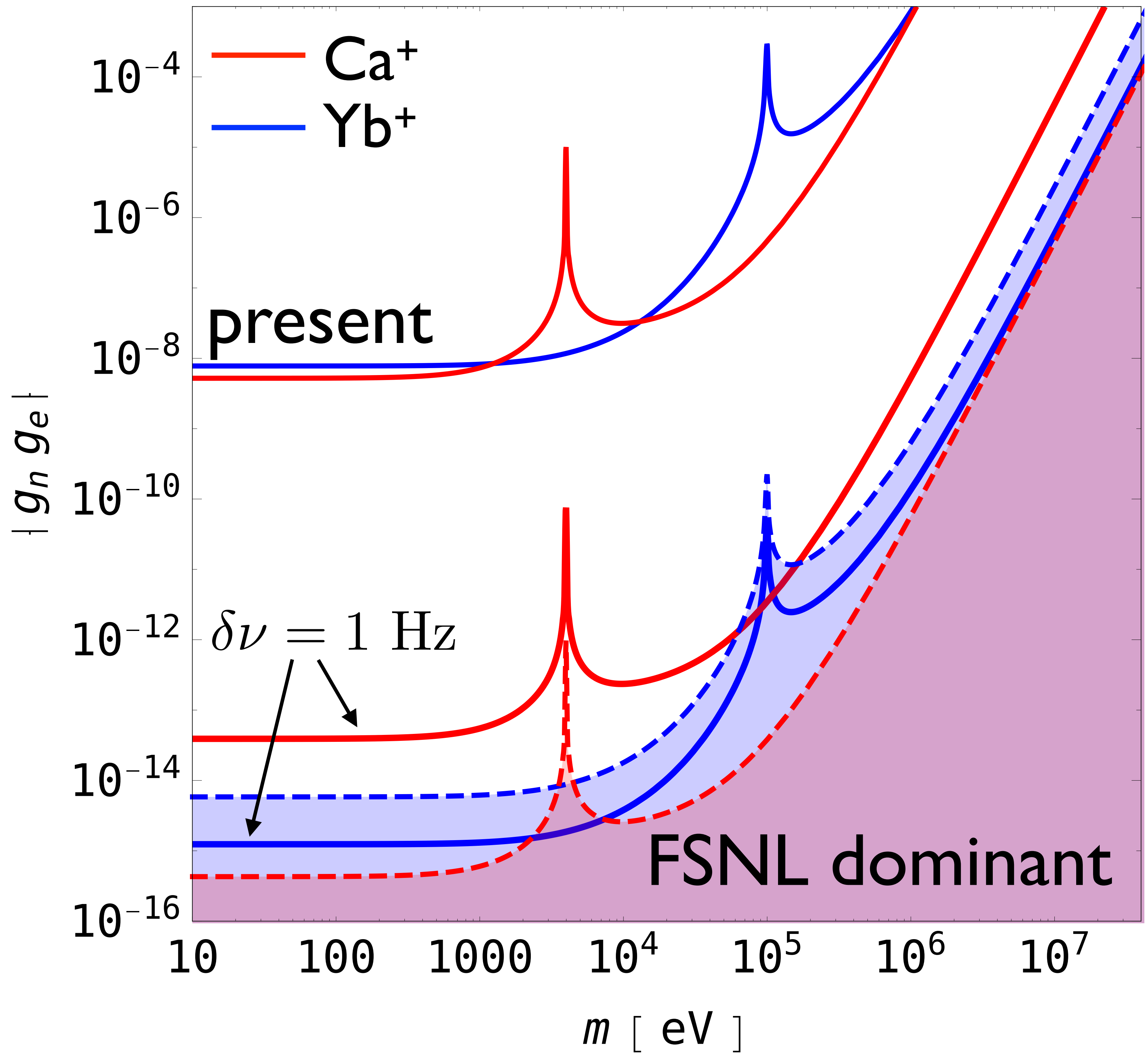
$$|\varepsilon| < 4.5 \cdot 10^{-11}$$



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

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

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

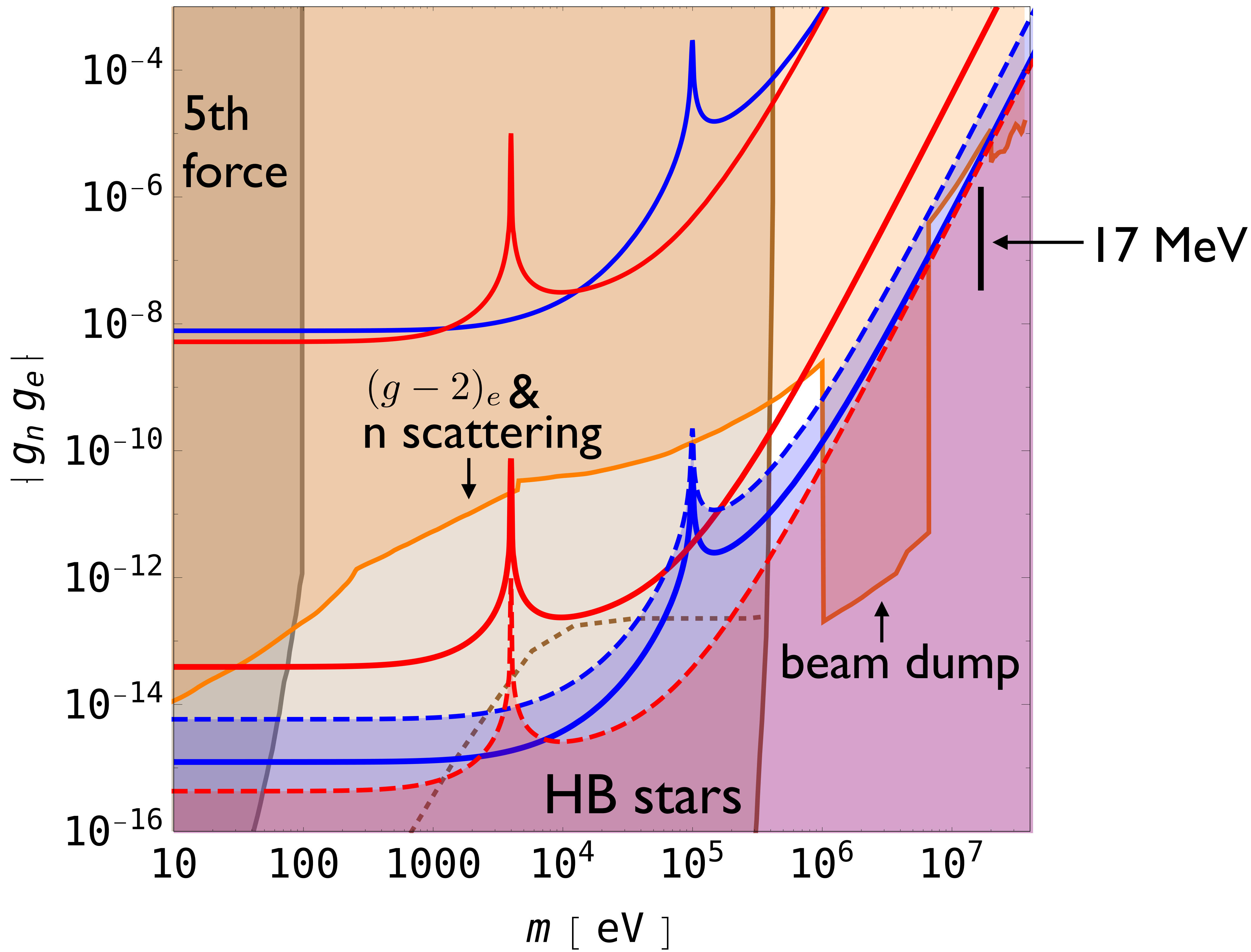


FSNL dominance:

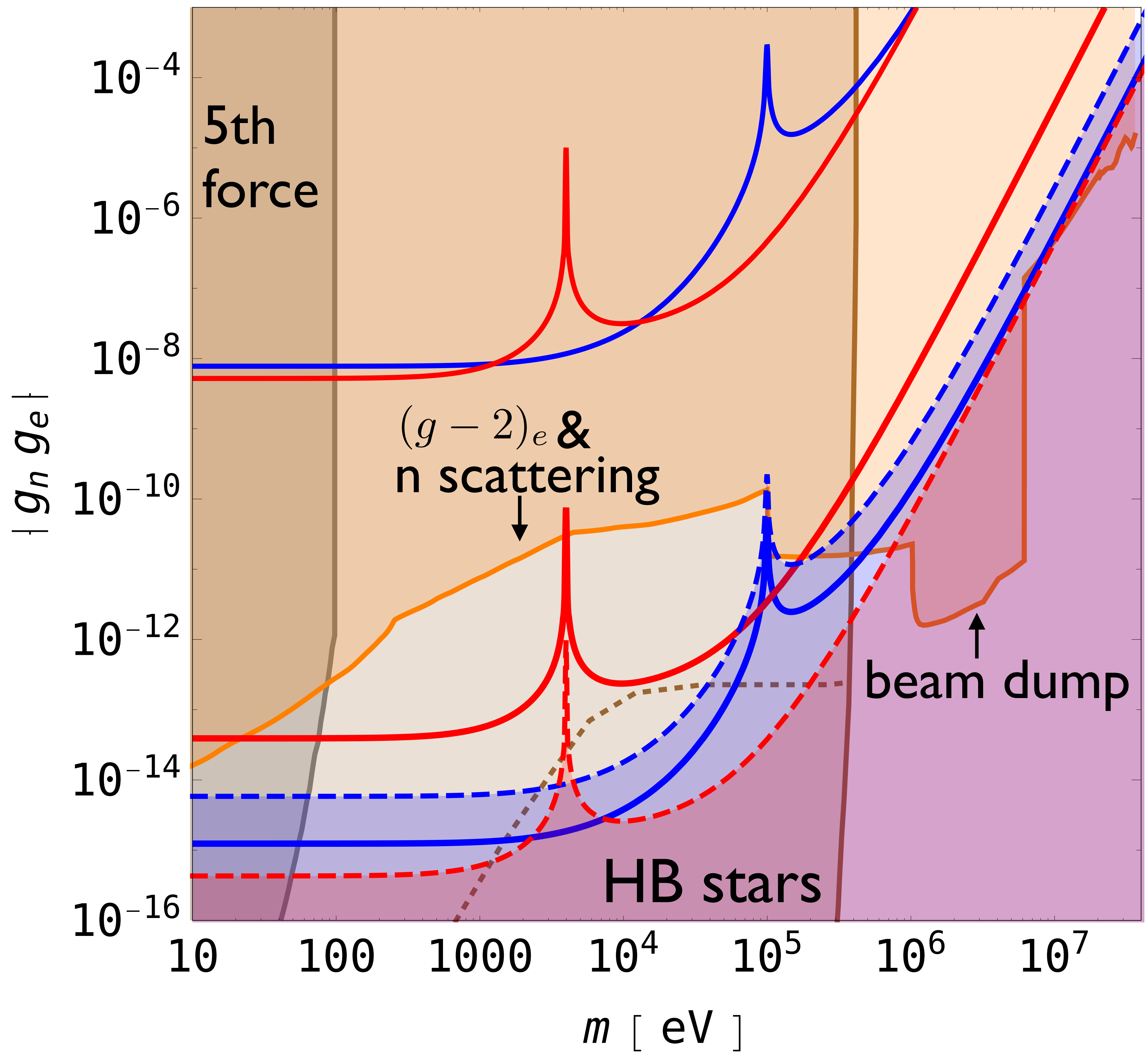
Ca^+ $\delta\nu \lesssim 0.01$ Hz

Yb^+ $\delta\nu \lesssim 4.7$ Hz

Comparison to other constraints: vector



Comparison to other constraints: scalar



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, $m \ll 100\ \rm MeV$

  Other nonlinearities: more study needed

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

  $\delta\nu < 1\ \rm kHz$ with in a few years

Backup

^{8}Be anomaly and 17 MeV vector boson

Krasznahorkay et al. PRL116, 042501 (2016)

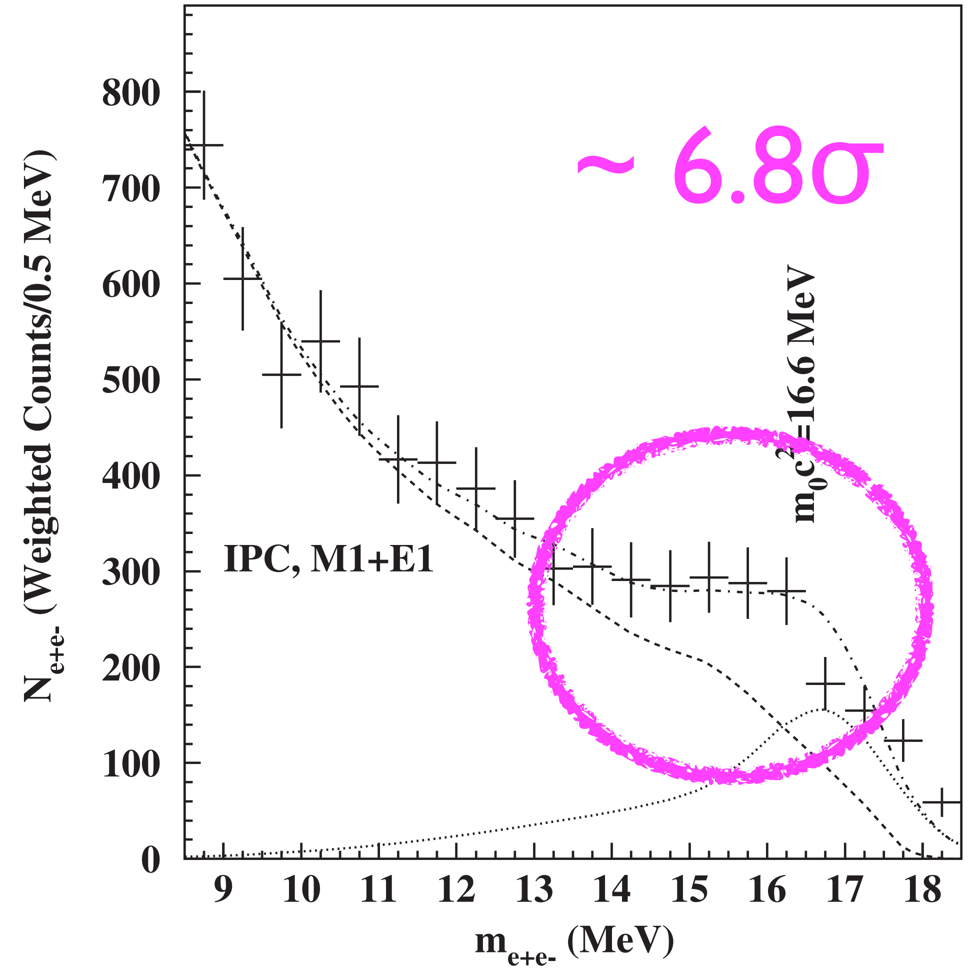
$$^8\text{Be}^*(18.15\ \text{MeV}) \to {}^8\text{Be} + e^+e^-$$

Bump in the e^+e^- inv. mass

$$\to\ {}^8\text{Be}^* \to {}^8\text{Be} + X(\to e^+e^-)$$

$$m_X \sim 17\ \text{MeV}$$

vector $U(1)_B\,,\ U(1)_{B-L}$

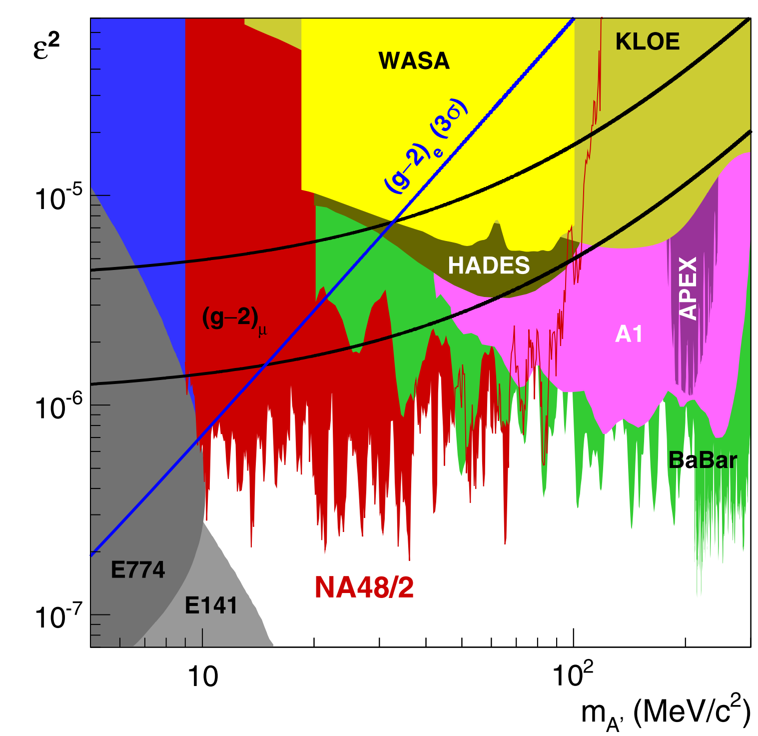


Constraint from dark photon search

Feng et al. PRL117, 071803 (2016)

NA48/2 $\quad \pi^0 \to \gamma + A'(\to e^+e^-)$

$\to$ protophobic



Evaluation of PS nonlinearity

Single electron approximation

$$X_\ell = \frac{g_n g_e}{4\pi} \int r^2 dr \frac{e^{-mr}}{r} \left[R^2_{i_\ell}(r) - R^2_{f_\ell}(r) \right]$$

Wavefunction

- non relativistic (not bad for m<<100 MeV)
- Thomas-Fermi model
  - semiclassical, statistical, selfconsistent field
  - exact in large Z limit