Probing new intra-atomic force with isotope shifts

— Implication of precision spectroscopy of 10^{-18} accuracy —

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in collaboration with

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arXiv: 1710.11443

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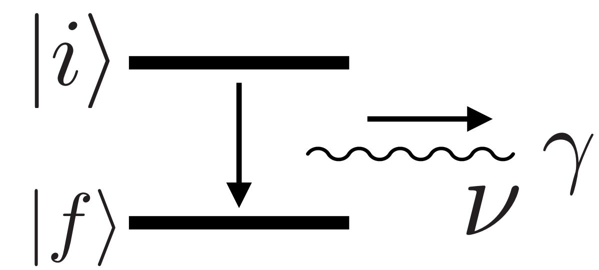
Isotope shift (IS)

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 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

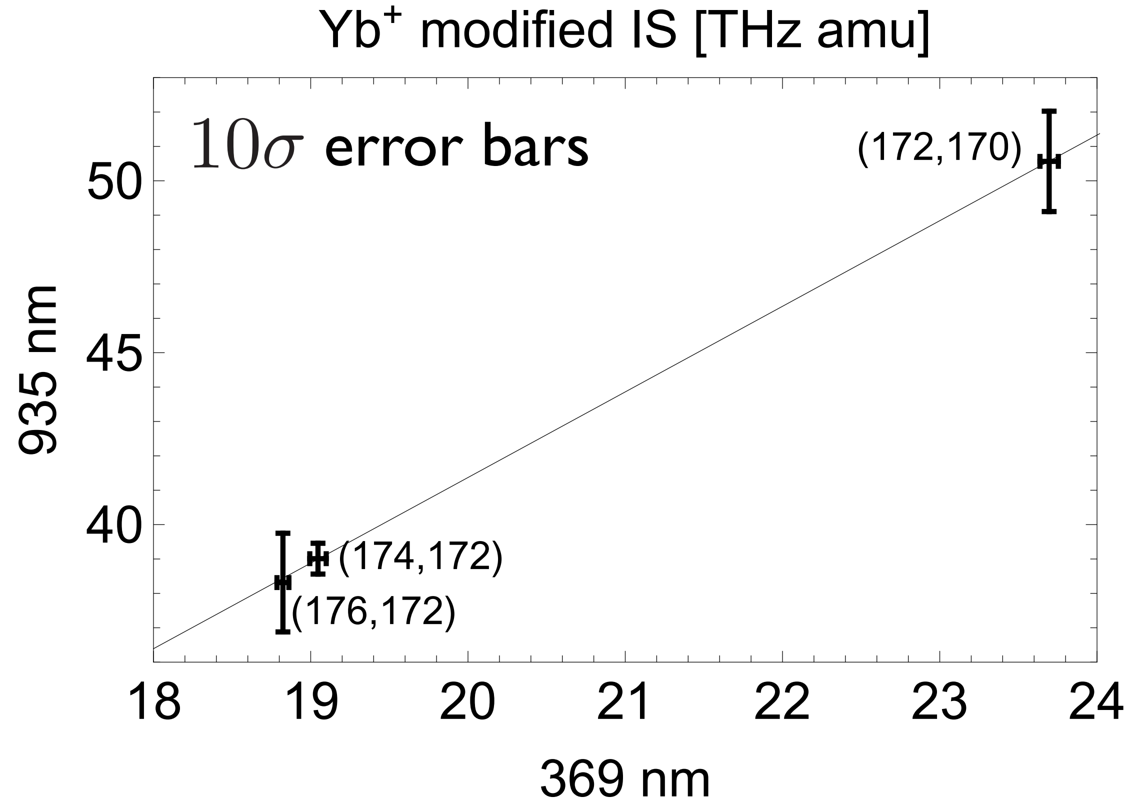
$$ {}^3\mathrm{D}[3/2]_{1/2}(4\mathrm{f})^{13}(5\mathrm{d})(6\mathrm{s}) - {}^2\mathrm{D}_{3/2}(4\mathrm{f})^{14}(5\mathrm{d}) $$

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

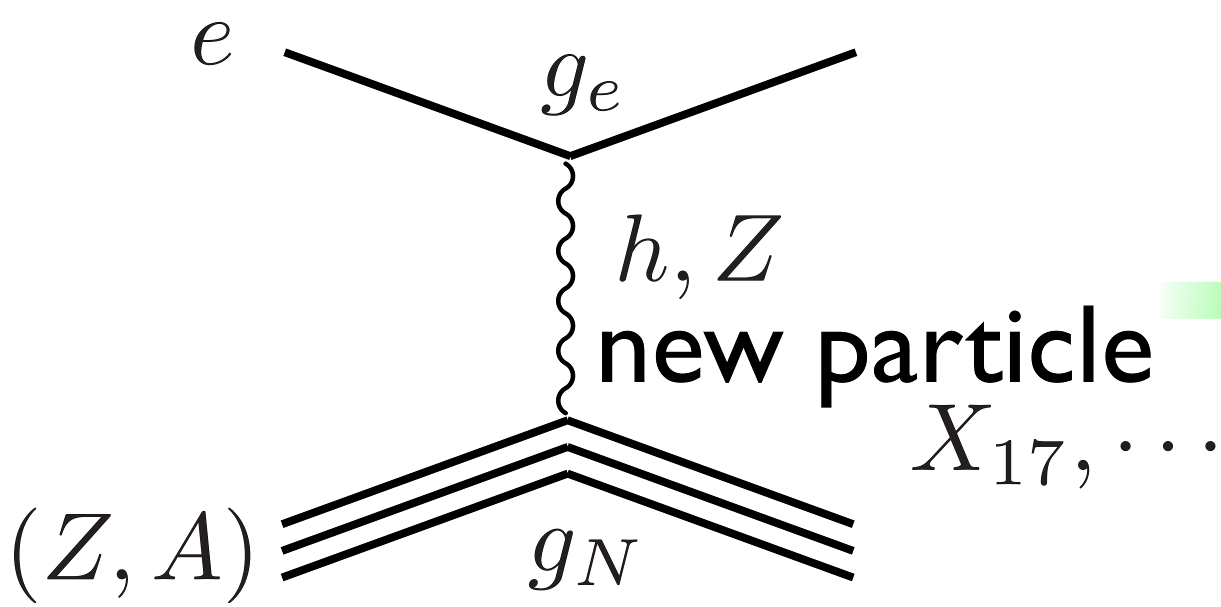
Isotope pairs: (172, 170), (174,172), (176,172)

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

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

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.

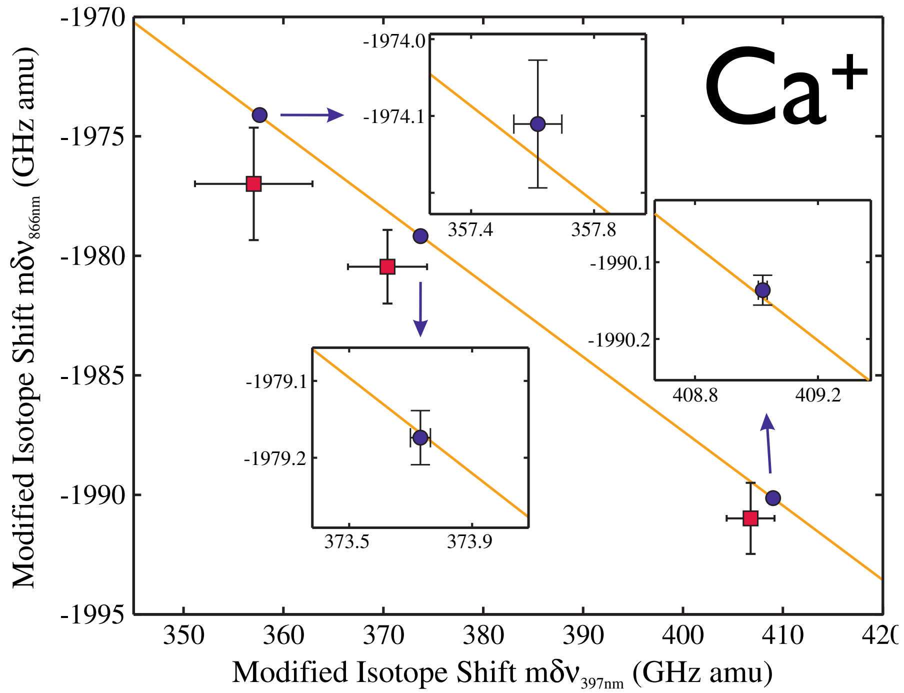
p state dominant: Ca^+ 4p, Yb^+ 6p

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

↑ nuclear Helm distribution

Present constraint and future prospect

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

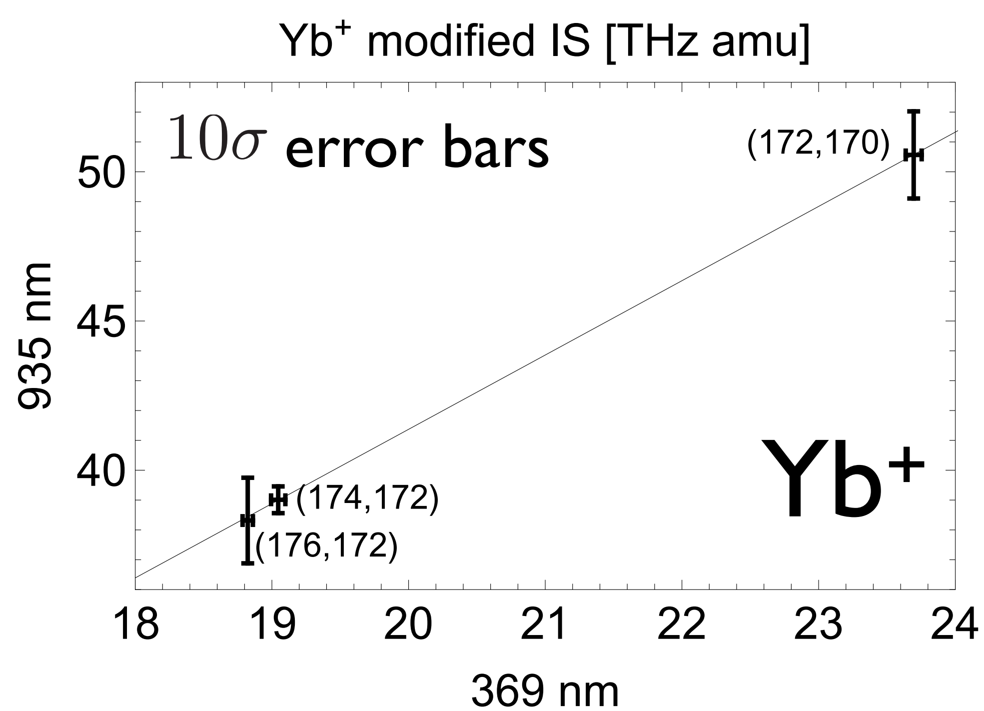


$$\varepsilon = (-2.45 \pm 4.05)\cdot 10^{-6}$$

au

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

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

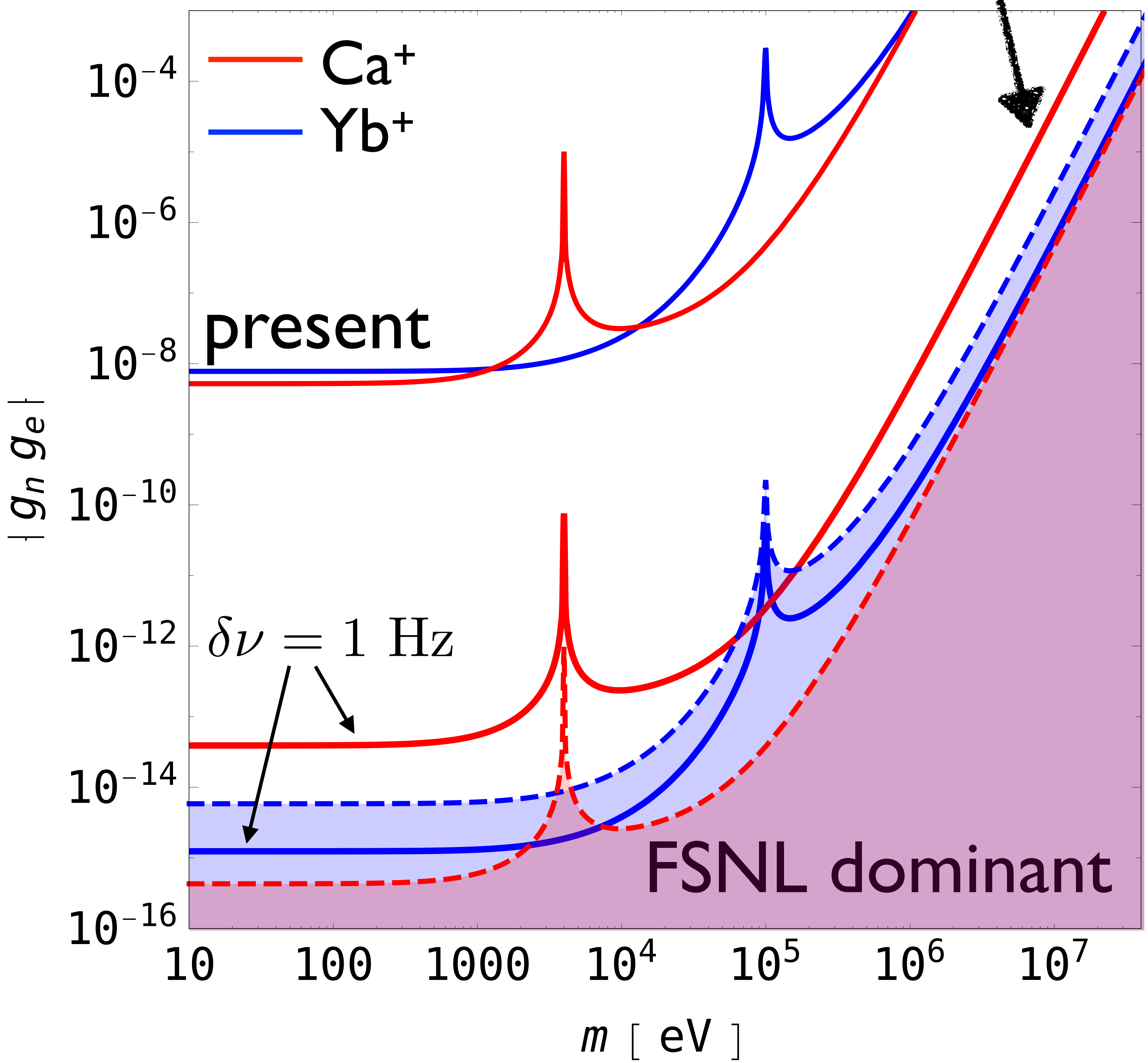


$$\varepsilon = (-1.26 \pm 1.35)\cdot 10^{-4}$$

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

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

$O(m^4)$ due to p states

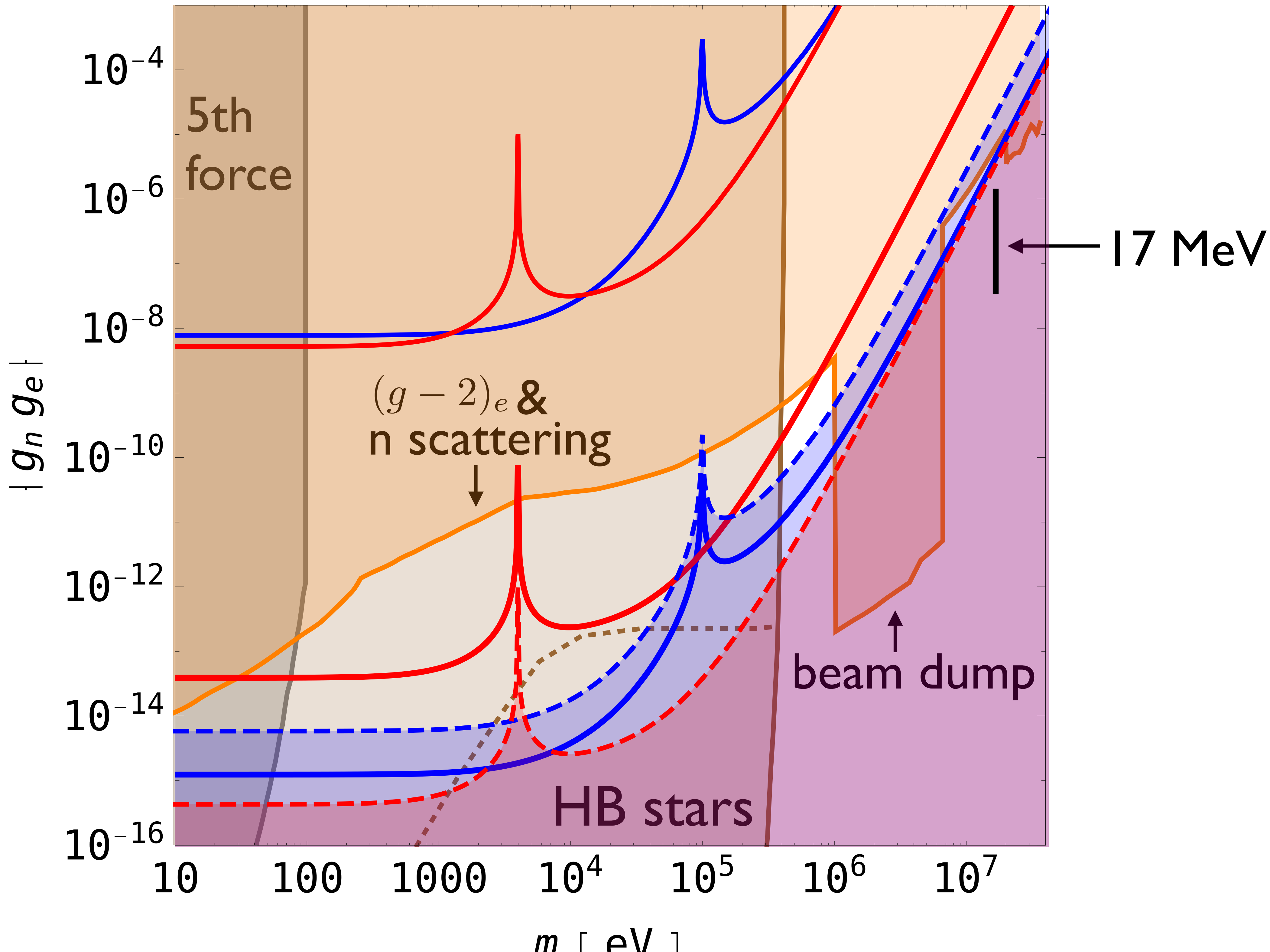


FSNL dominance:

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

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

Comparison to other constraints: vector



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)

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

  possible with proved technique

Backup

Frontiers in particle physics

Energy frontier: LHC, ILC,…

Intensity frontier: B factory, muon,…

Cosmic frontier: CMB,…

Precision / low energy frontier

$0\nu\beta\beta$, DM, EDM,…

Temporal variation of fundamental constants

α, m_e/m_p using atomic clock

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

Hunteman et al. (PTB) 2016

Isotope shift new neutron-electron interaction

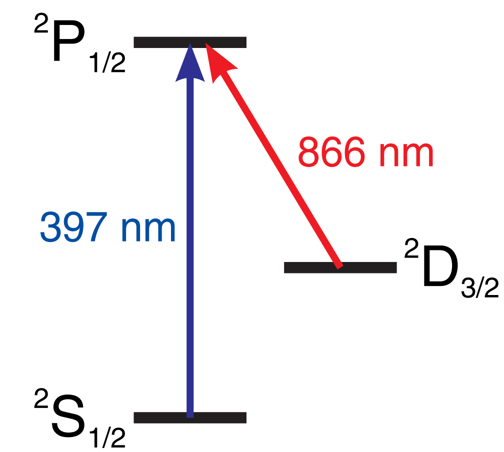
IS data of Ca⁺

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)

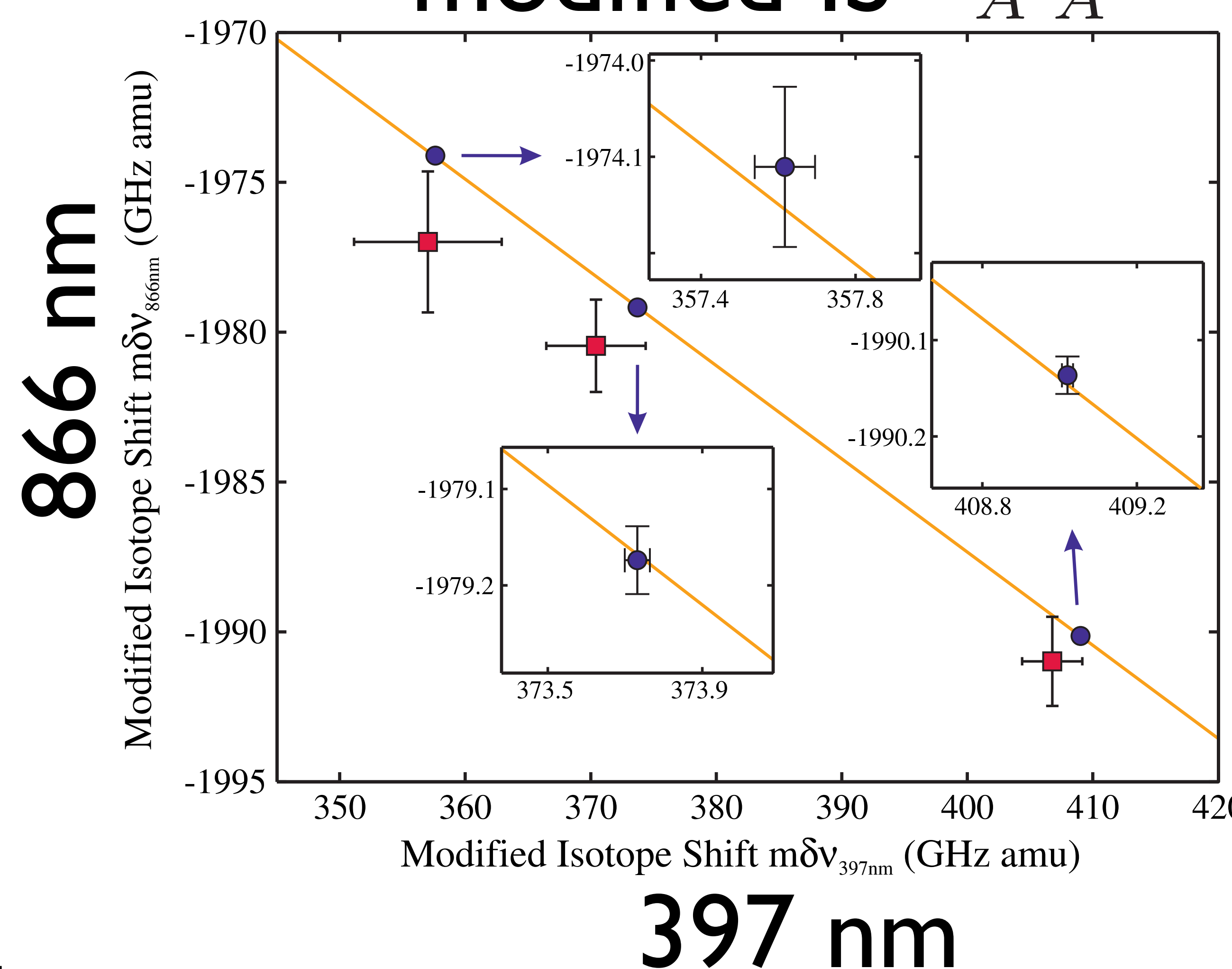


IS precision ~ O(100) kHz

King's plot

linear within errors

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



Heavy particle limit

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

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

Asymptotic behavior of PS

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

$l = \text{angular momentum}$

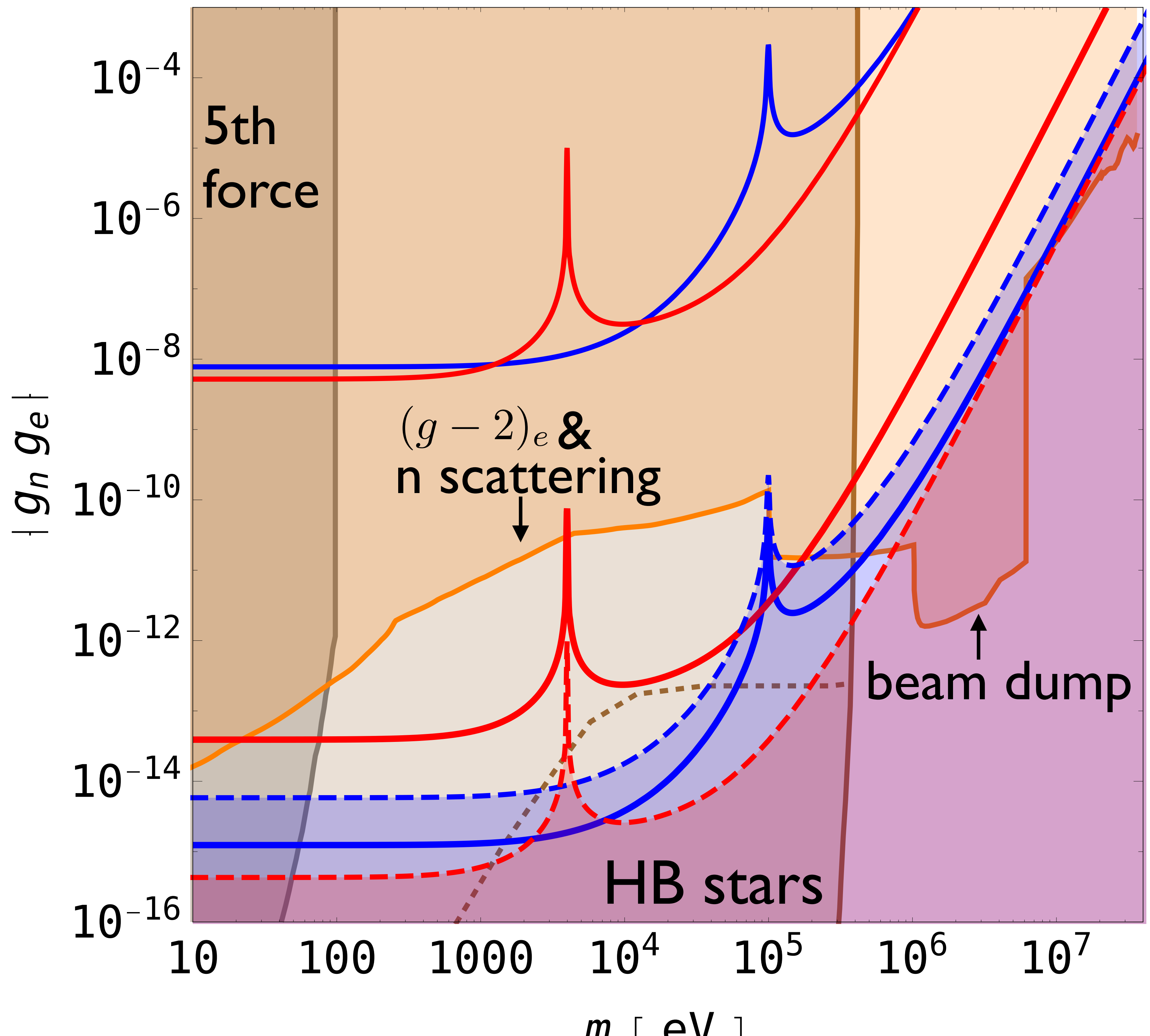
$\xi_1^0 = 0$ for nucl. charge distribution without cusp

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

less sensitive to heavier particles

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

Comparison to other constraints: scalar



^{8}Be anomaly and 17 MeV vector boson

Krasznahorkay et al. PRL116, 042501 (2016)

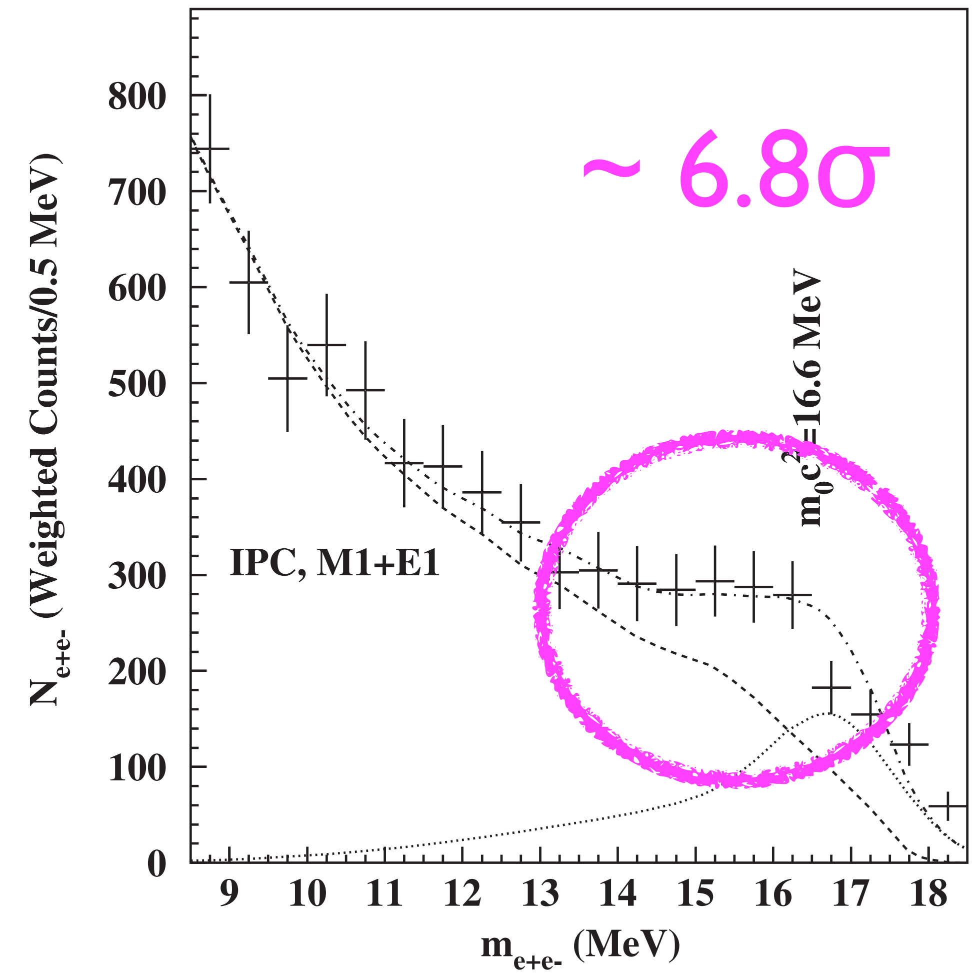
$$^8\mathrm{Be}^*(18.15\ \mathrm{MeV}) \to {}^8\mathrm{Be} + e^+e^-$$

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

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

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

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

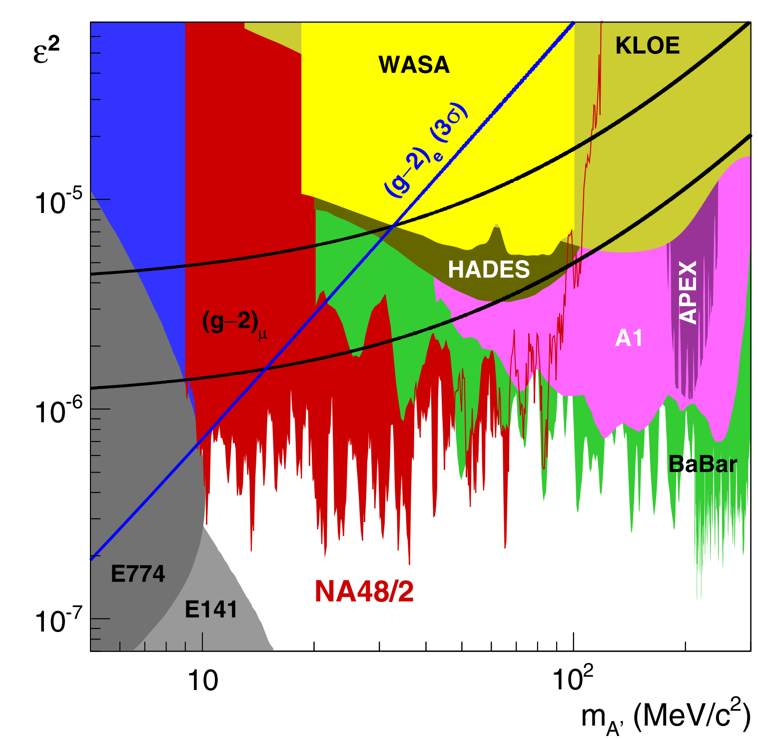


Constraint from dark photon search

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

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

Wavefunction

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