同位体シフトによる新物理探索における新展開

田中 実 (阪大理)

共同研究者

山本康裕(NCBJ), 小野滉貴(京大理), 肥後本隼也(京大理), 斎藤優冴(京大理), 石山泰樹(京大理), 高須洋介(京大理), 高野哲至(日亜化学), 高橋義朗(京大理)

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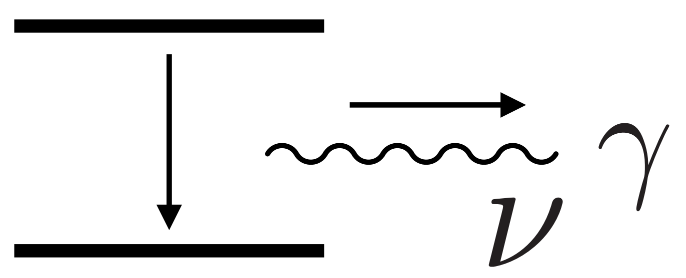
同位体シフト(IS)とキングの線形性 King, 1963



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

$$\nu^{(t)}_{A'A} = K_t \mu_{A'A} + F_t \langle r^2 \rangle_{A'A}$$

mass shift (MS) field shift (FS)

$$\mu_{A'A} := 1/m_{A'} - 1/m_A$$

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

Modified IS: $\tilde{\nu}^{(t)}_{A'A} := \nu^{(t)}_{A'A}/\mu_{A'A} = \boxed{K_t} + \boxed{F_t} \langle r^2 \rangle_{A'A}/\mu_{A'A}$

electronic factors nuclear factor

King's linearity: eliminating the nuclear factor

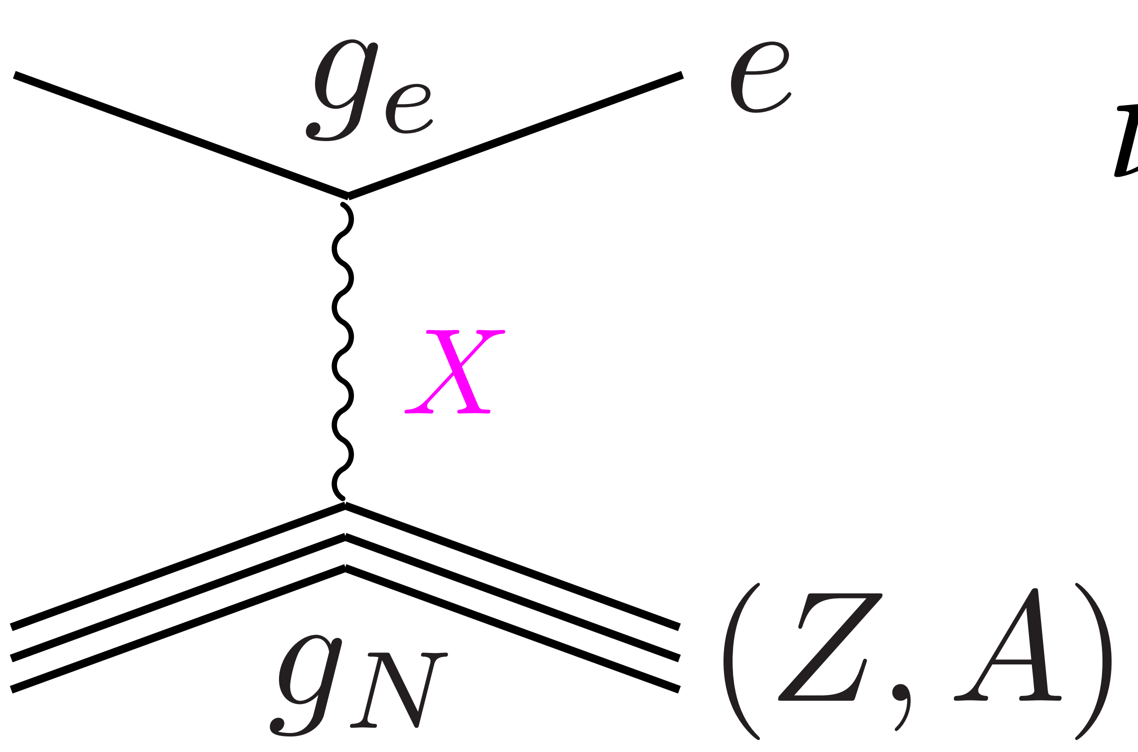
$$\tilde{\nu}^{(2)}_{A'A} = K_{21} + F_{21} \tilde{\nu}^{(1)}_{A'A}$$

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

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

線形性の破れ

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)

Nonlinearity due to subleading FS

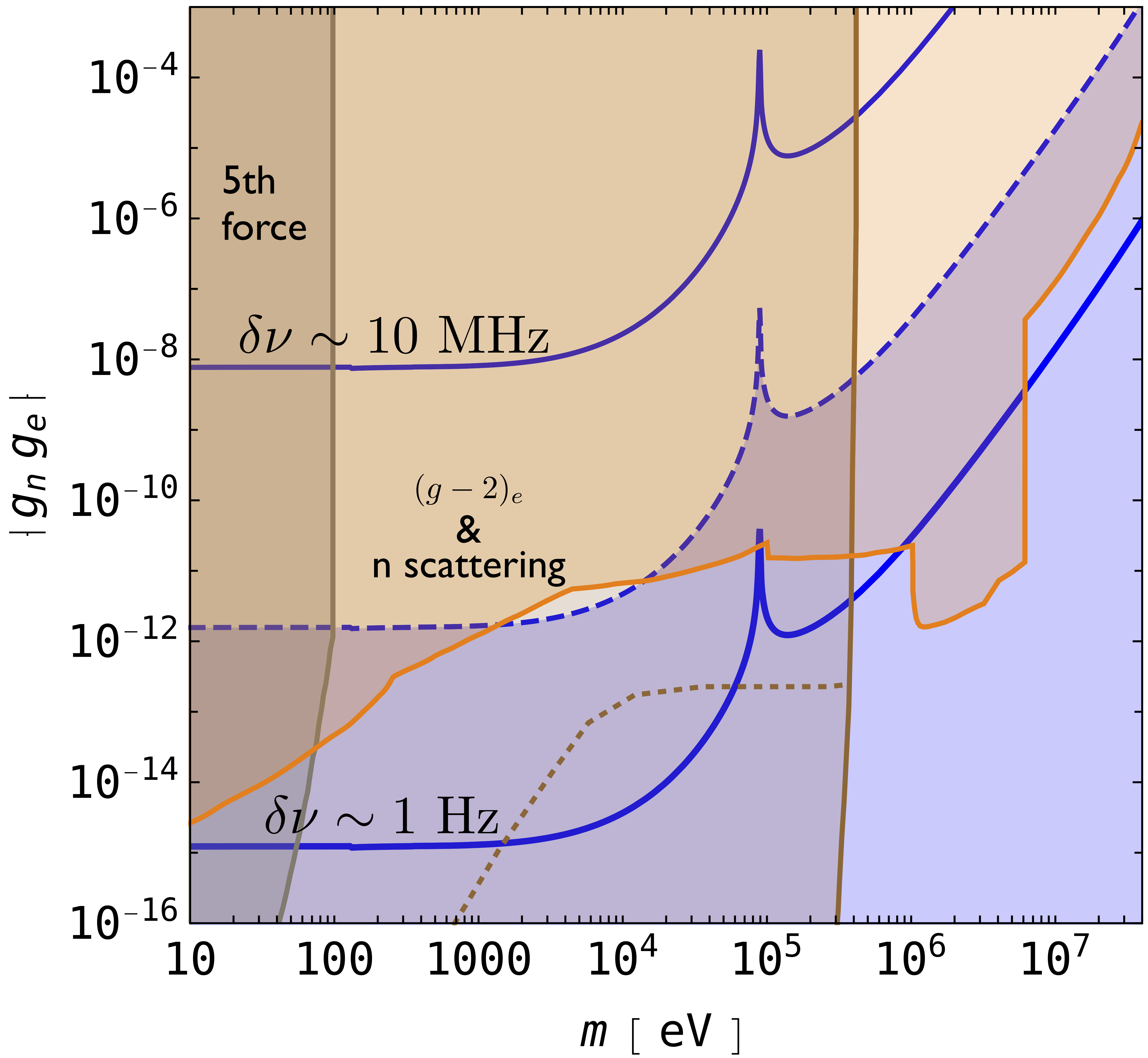
$$\mathrm{FS} = F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + G_t \langle r^4 \rangle_{A'A} + \cdots$$

quadratic FS　higher moment

$$[\langle r^2 \rangle_{A'A}]^2 := (\langle r^2 \rangle_{A'A_0})^2 - (\langle r^2 \rangle_{AA_0})^2$$

Ex. Yb^+

MT, Y. Yamamoto PTEP 103B02 (2020)



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

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

Transition 2: 935 nm Sugiyama et al. CPEM2000

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

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

Yb^+ bounds

$\langle r^4 \rangle$ FSNL (SM BG)

FSNL dominance:

$\delta\nu \lesssim 1$ kHz

SMの非線形性をどうする？

高精度計算は難しい.

一般化線形性

K. Mikami, MT, Y. Yamamoto EPJC77:896 (2017)

$$\nu^{(t)}_{A'A} = K_t \mu_{A'A} + F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + X_t (A' - A)$$

QFS PS

3 transitions: t=1, 2, 3

$$\begin{pmatrix} \nu^{(1)}_{A'A} - X_1(A'-A) \\ \nu^{(2)}_{A'A} - X_2(A'-A) \\ \nu^{(3)}_{A'A} - X_3(A'-A) \end{pmatrix} = \begin{pmatrix} K_1 & F_1 & F'_1 \\ K_2 & F_2 & F'_2 \\ K_3 & F_3 & F'_3 \end{pmatrix} \begin{pmatrix} \mu_{A'A} \\ \langle r^2 \rangle_{A'A} \\ [\langle r^2 \rangle_{A'A}]^2 \end{pmatrix} =: M \begin{pmatrix} \mu_{A'A} \\ \langle r^2 \rangle_{A'A} \\ [\langle r^2 \rangle_{A'A}]^2 \end{pmatrix}$$

➡

$$(M^{-1})_{11} \nu^{(1)}_{A'A} + (M^{-1})_{12} \nu^{(2)}_{A'A} + (M^{-1})_{13} \nu^{(3)}_{A'A}$$
$$- \{(M^{-1})_{11} X_1 + (M^{-1})_{12} X_2 + (M^{-1})_{13} X_3\}(A'-A) = \mu_{A'A}$$

$(\nu^{(1)}_{A'A}, \nu^{(2)}_{A'A}, \nu^{(3)}_{A'A})/\mu_{A'A}$ on a plane if $X_t = 0$

n transitions and n+1 IS pairs → NP search with n-2 FSNL's removed

実験の進展

Yb⁺イオン

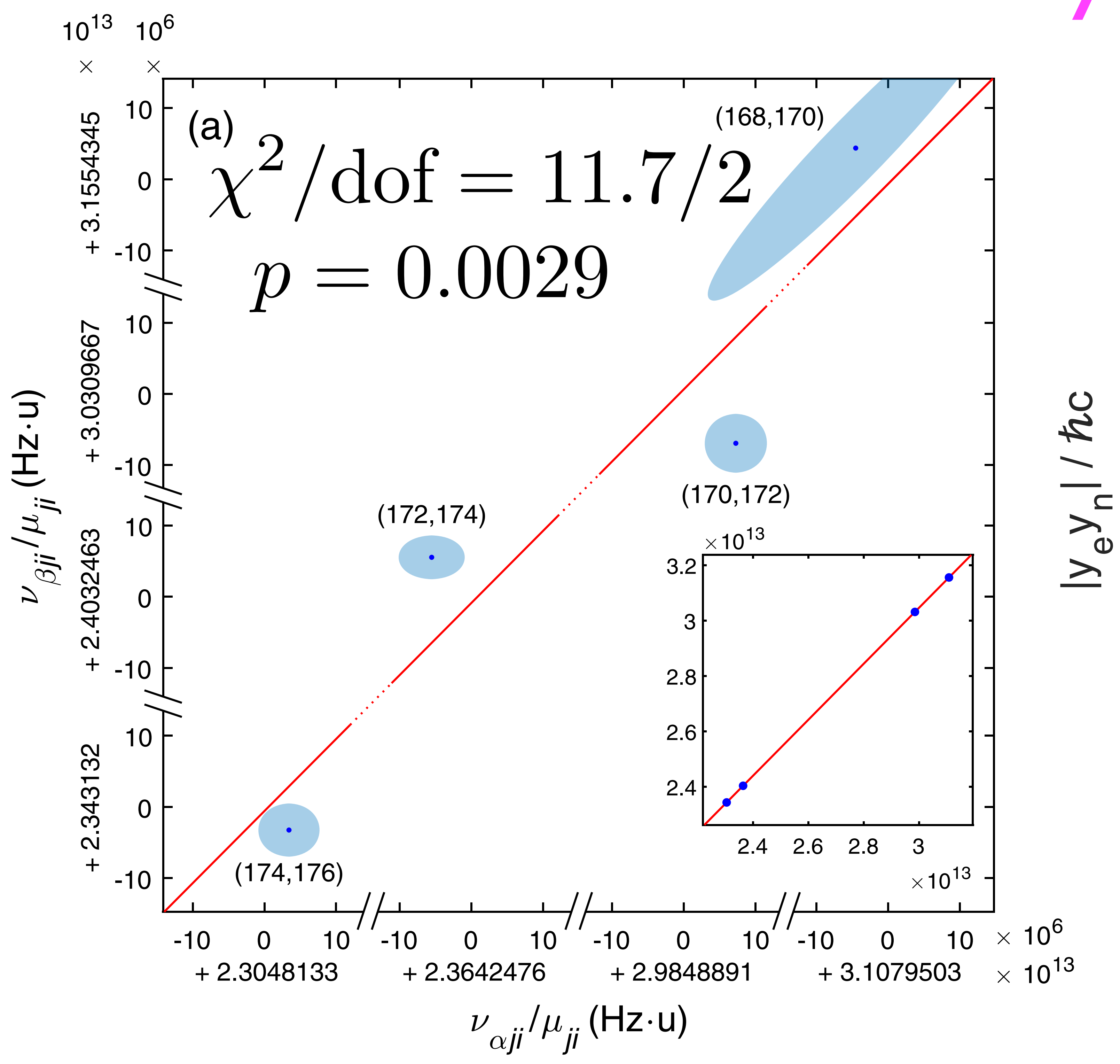
Count et al. PRL 125, 123002 (2020)

Transition 1: 411 nm $^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{5/2}(5d)$

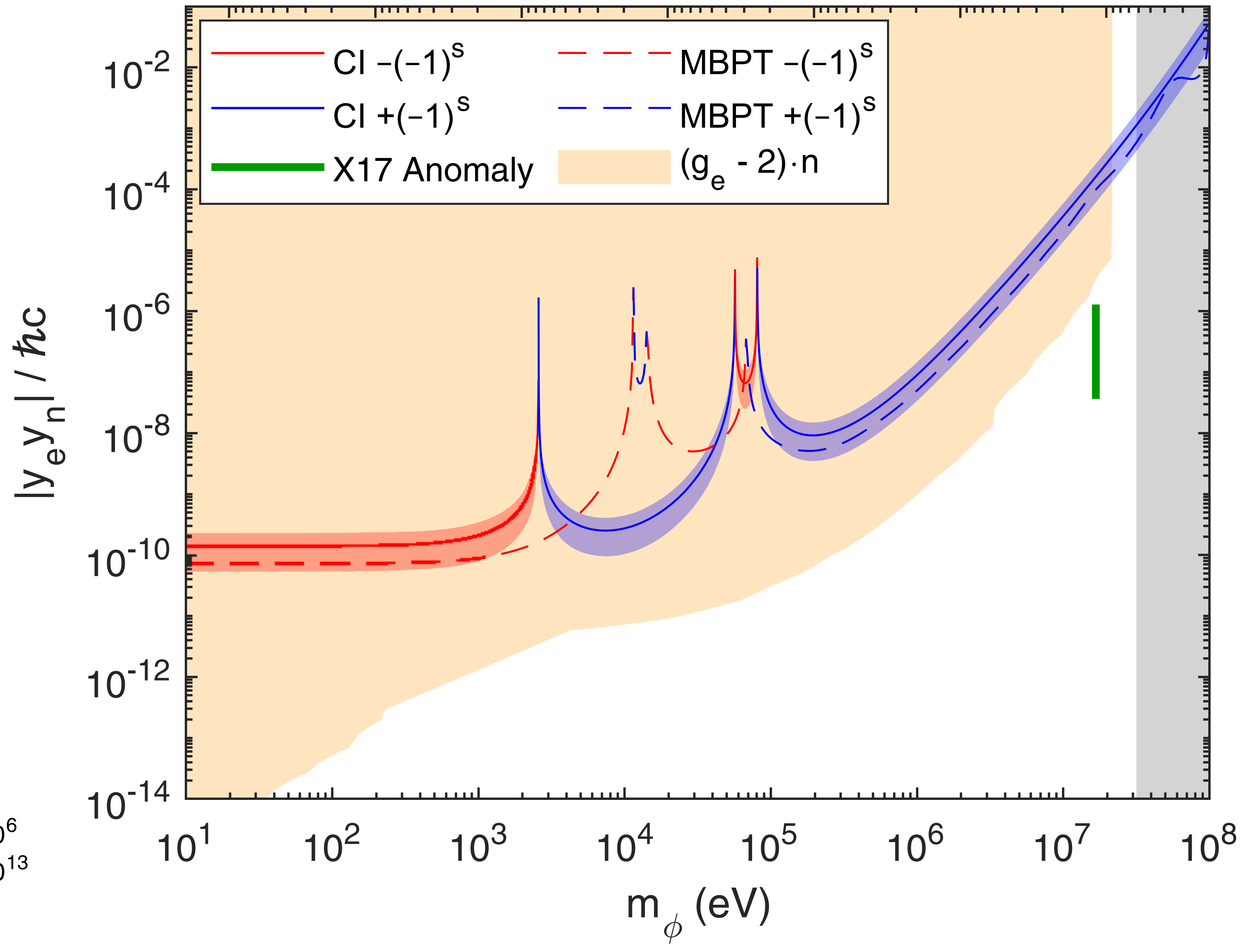
Transition 2: 436 nm $^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{3/2}(5d)$

4 indep. IS pairs $\delta\nu \sim O(100)$ Hz

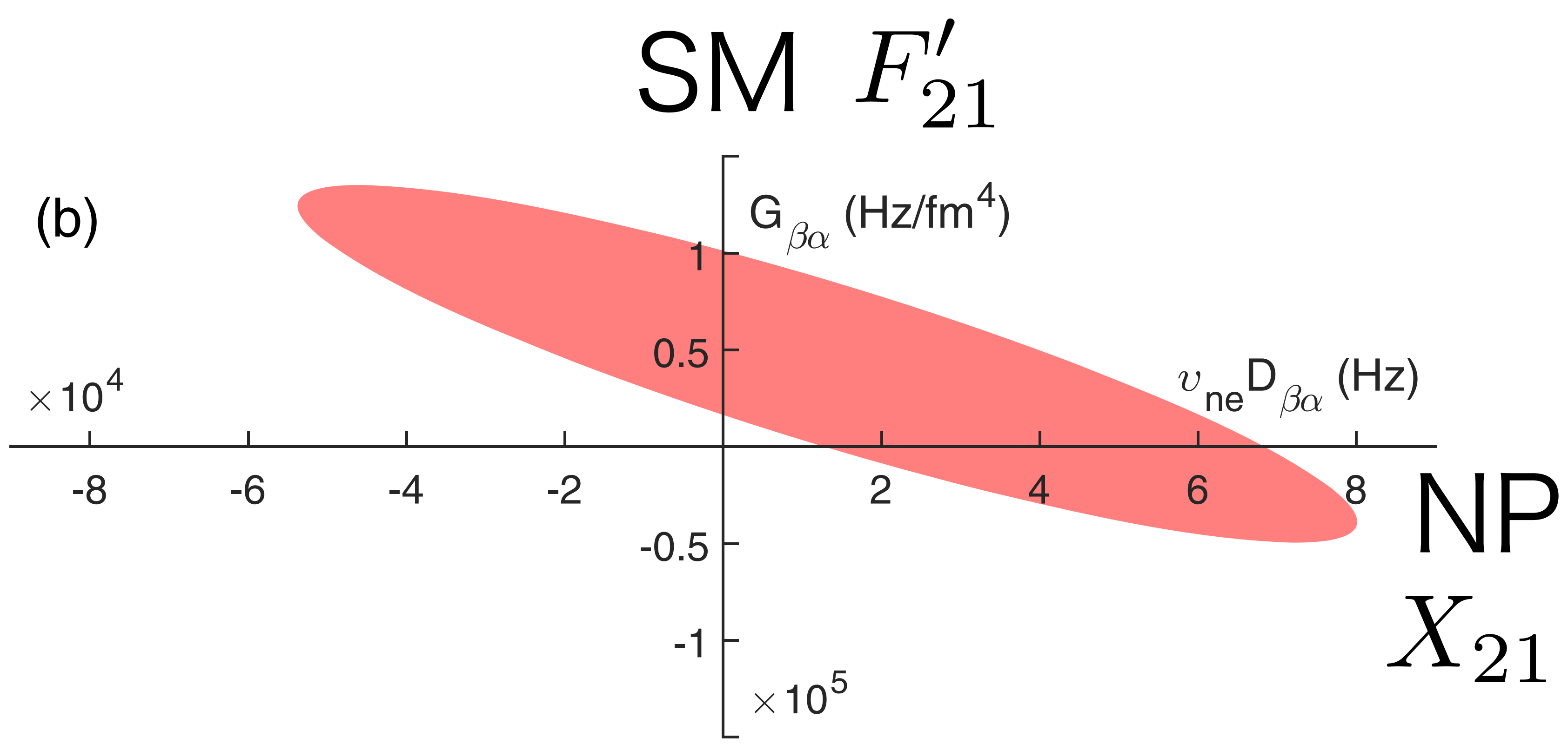
evidence for nonlinearity



new physics?



SM vs NP nonlinerities



中性Yb原子　K. Ono et al. to apper

$^1\mathrm{S}_0(6s^2) - {}^3\mathrm{P}_0(6s6p)$ **579 nm, 4 IS pairs**

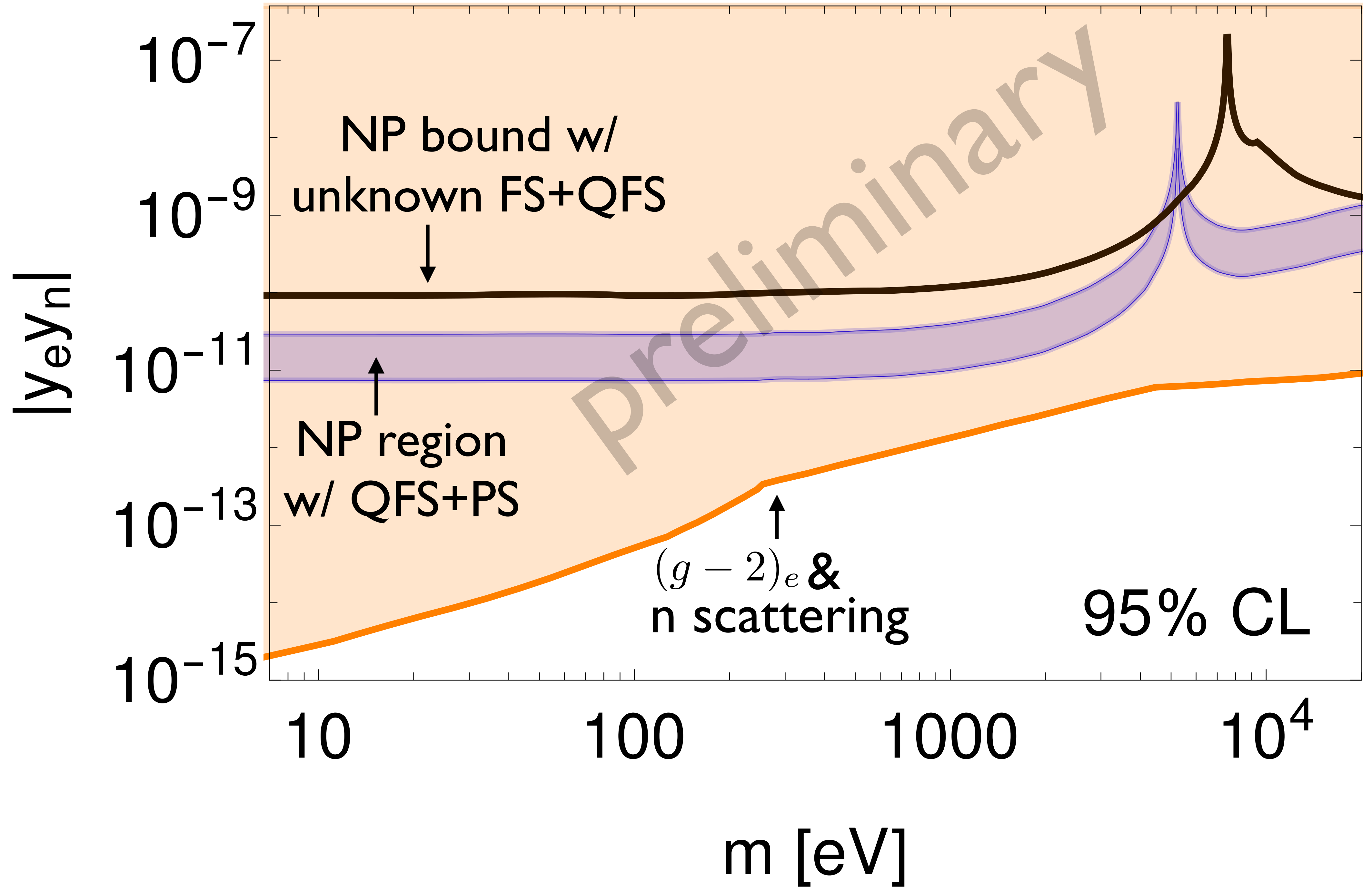
$\delta\nu \sim O(1)\ \mathrm{Hz}$

Yb⁺イオン

$^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{5/2}(5d)$

$^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{3/2}(5d)$

$\delta\nu \sim O(100)\ \mathrm{Hz}$



3 transitions, 4 IS pairs

→ 一般化線形性を用いた新物理探索

詳細は，小野さんの講演 22pA1-6で.

まとめ

- Isotope shift and King's linearity $\tilde{\nu}^{(2)}_{A'A} = K_{21} + F_{21}\tilde{\nu}^{(1)}_{A'A}$
  IS=MS+FS, linear relation of mIS of two transitions
- Nonlinearities : New physics and/or SM higher order
- 一般化線形性 (generalized linearity)
  SM nonlinearity removed, improved sensitivity to new physics
- 高精度Yb IS測定実験
  Yb^+イオン O(100) Hz,　Yb原子 O(1) Hz
  Ybで複数のO(1) Hzも近い将来可能

関連講演: 小野さん 22pA1-6 (領域1)