原子スペクトルの同位体シフトにおける一般化キング線形性を用いた新物理探索

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素粒子物理学の進展2022，基研，2022/08/30

Light new particle search

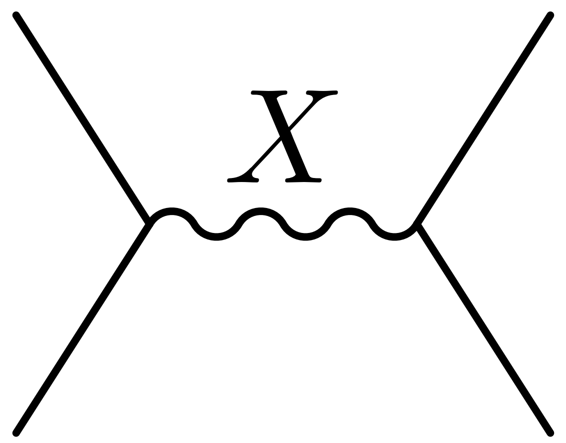
Direct search

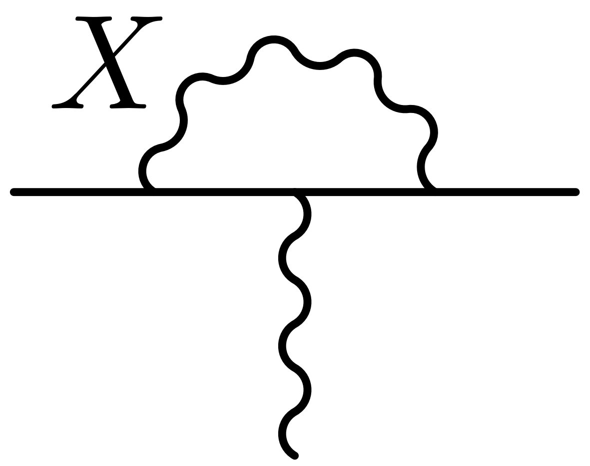
Visible decay, e.g. $X \to e^+e^-$: direct search

Invisible decay, e.g. $X \to \nu\bar{\nu}$: missing E/p

Stable: missing E/p, dark matter?

Indirect search





$$\propto \frac{g^2}{m^2}$$

cf. weak interaction $\sim \dfrac{g_Z^2}{m_Z^2} \sim \dfrac{0.5}{(100\ \mathrm{GeV})^2} = \dfrac{0.5 \times 10^{-10}}{(1\ \mathrm{MeV})^2}$

Precision frontier

原子時計(“秒”の定義，周波数標準)

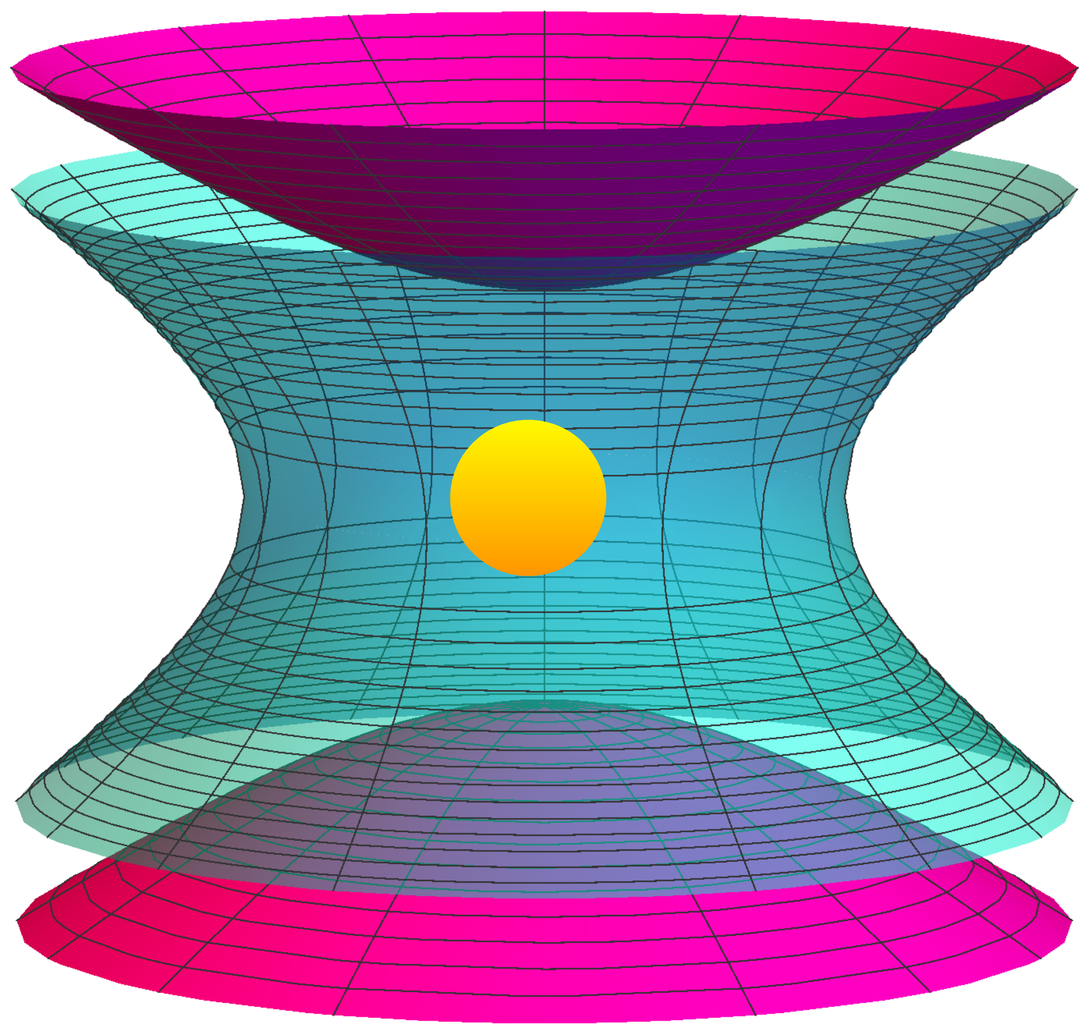
^{133}Cs ground state hyperfine splitting $\nu \sim 9\ \mathrm{GHz}\,,\ \delta\nu/\nu \sim 10^{-15}$

光時計　$\nu \sim 10^{15}\ \mathrm{Hz}$

単一イオン光時計

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

Huntsman et al. PRL116,063001 (2016)



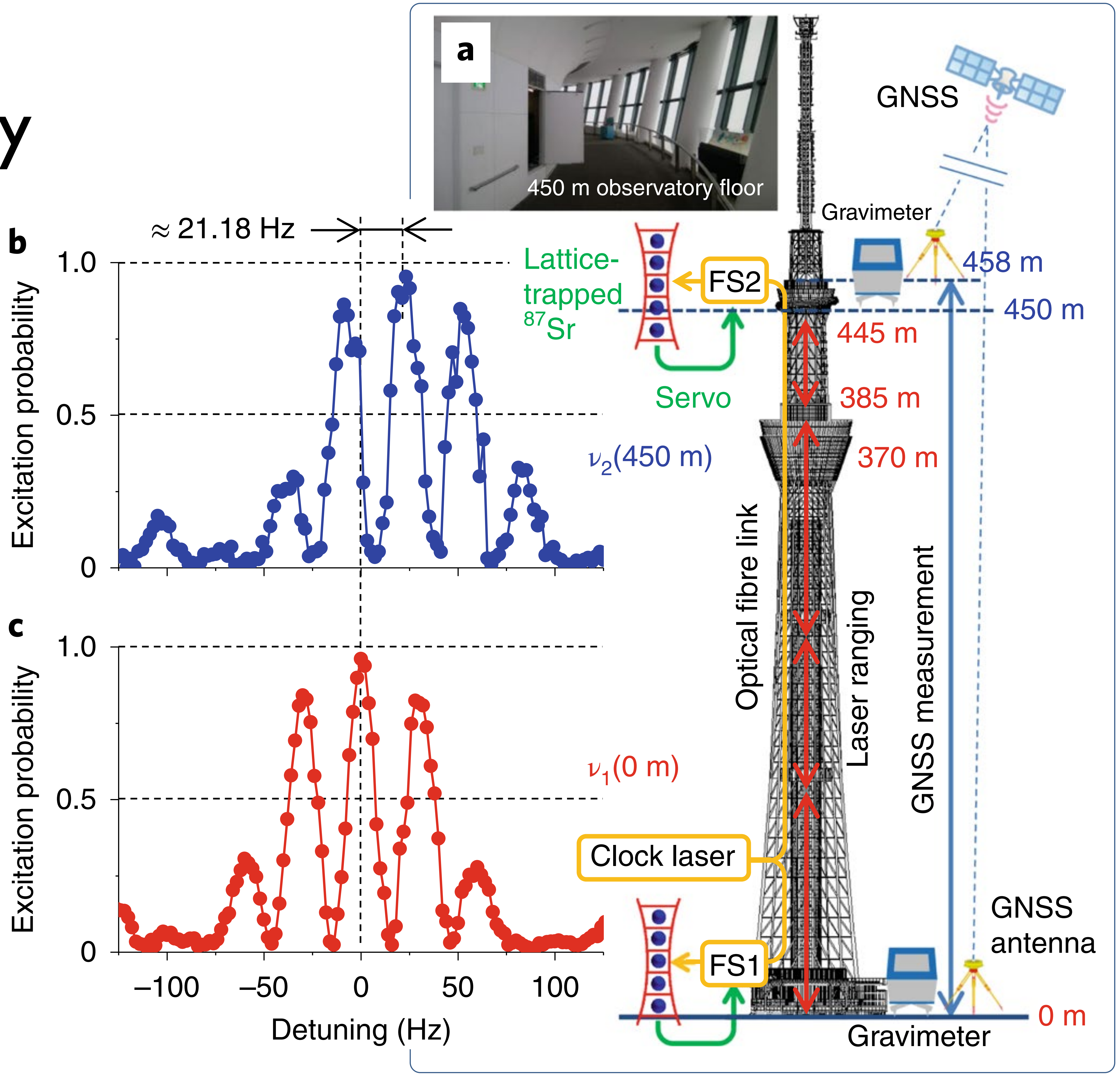
光格子時計

$\mathrm{Sr}: \ \delta\nu/\nu \sim 10^{-18}$

Ground test of General Relativity

$\sim 10^{-5}$

Takamoto et al., Nat. Photon. 14, 411 (2020)

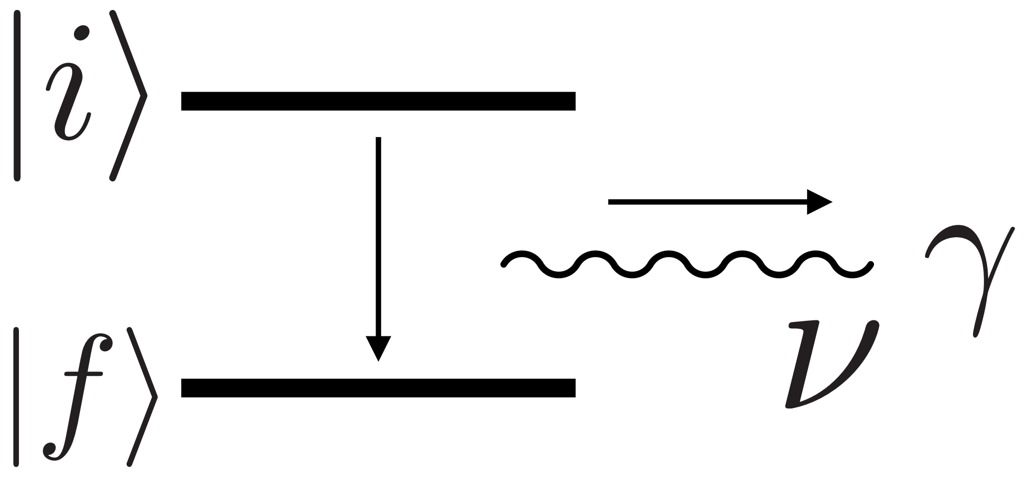


同位体シフト(Isotope shift, IS)

Level-splitting difference between isotopes

$$h\nu_A = E_A^i - E_A^f\,,\;\; h\nu_{A'} = E_{A'}^i - E_{A'}^f$$

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



No IS for infinitely heavy and point-like nuclei → $\mathrm{IS} = \mathrm{MS} + \mathrm{FS}$

Mass shift: finite mass of nuclei (reduced mass)

$\mathrm{MS} \propto 1/m_{A'} - 1/m_A$ (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 $\mathrm{IS} \sim O(\mathrm{GHz}) \sim O(10\ \mu\mathrm{eV})$

キング線形性

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 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

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Ex. Yb^+

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

(Z=70, A=168,170,171,172,173,174,176)

Transition 1: 369 nm

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

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

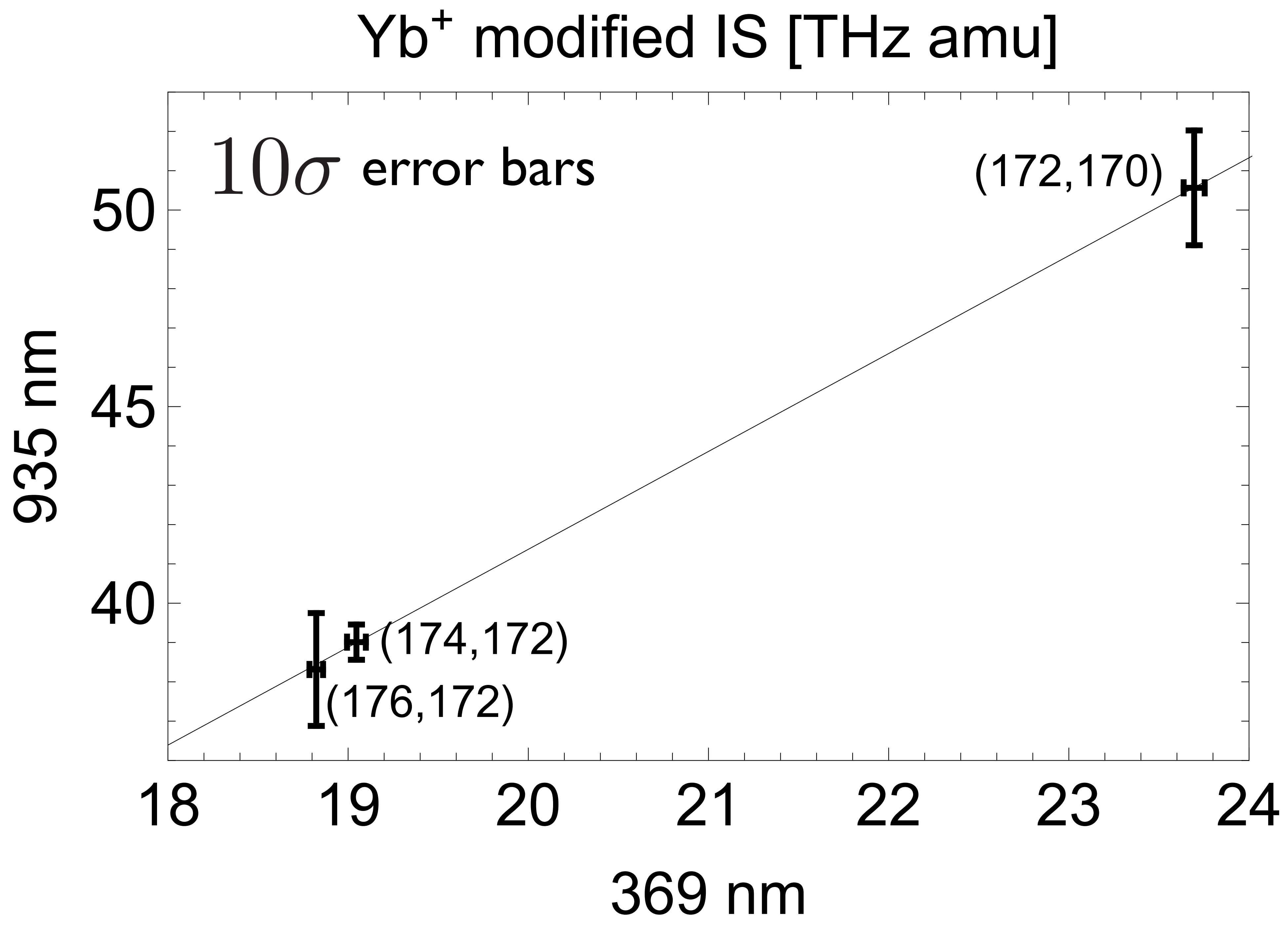
Transition 2: 935 nm

Sugiyama et al. CPEM2000

$$^3\mathrm{D}[3/2]_{1/2}(4\mathrm{f})^{13}(5\mathrm{d})(6\mathrm{s}) - ^2\mathrm{D}_{3/2}(4\mathrm{f})^{14}(5\mathrm{d}) \quad \delta\nu^2_{A'A} \sim O(10)\ \mathrm{MHz}$$

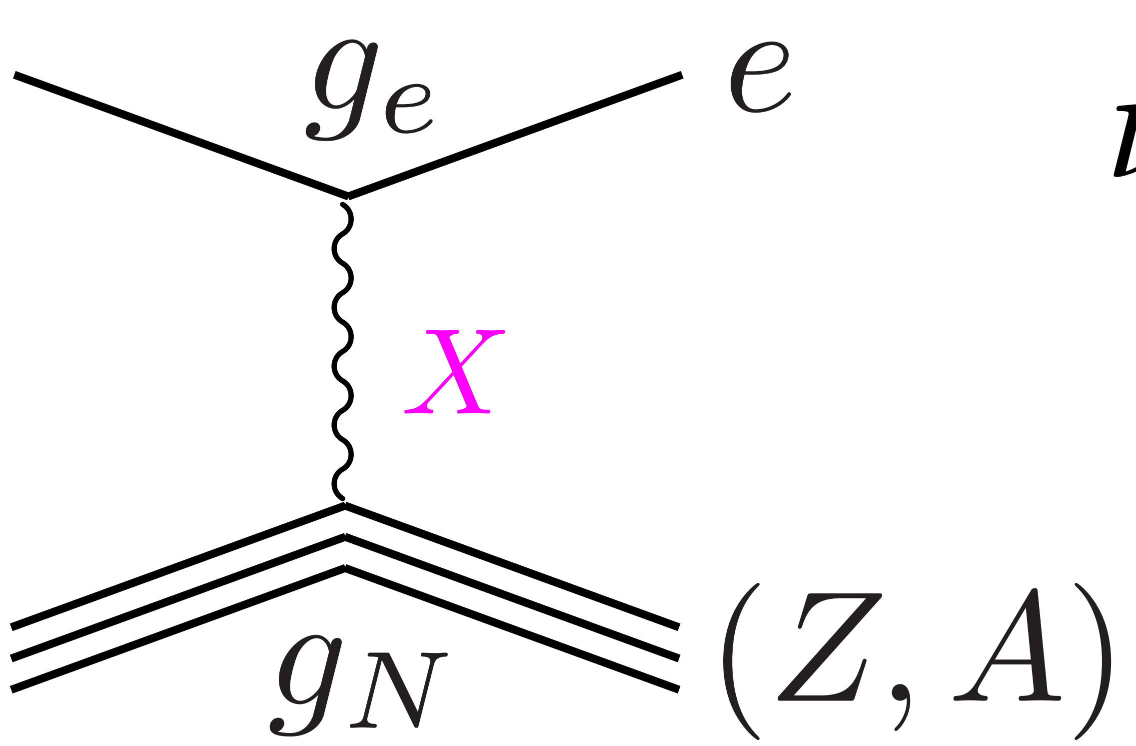
Isotope pairs

(172, 170), (174,172), (176,172)



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)

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

Nonlinearity due to subleading FS

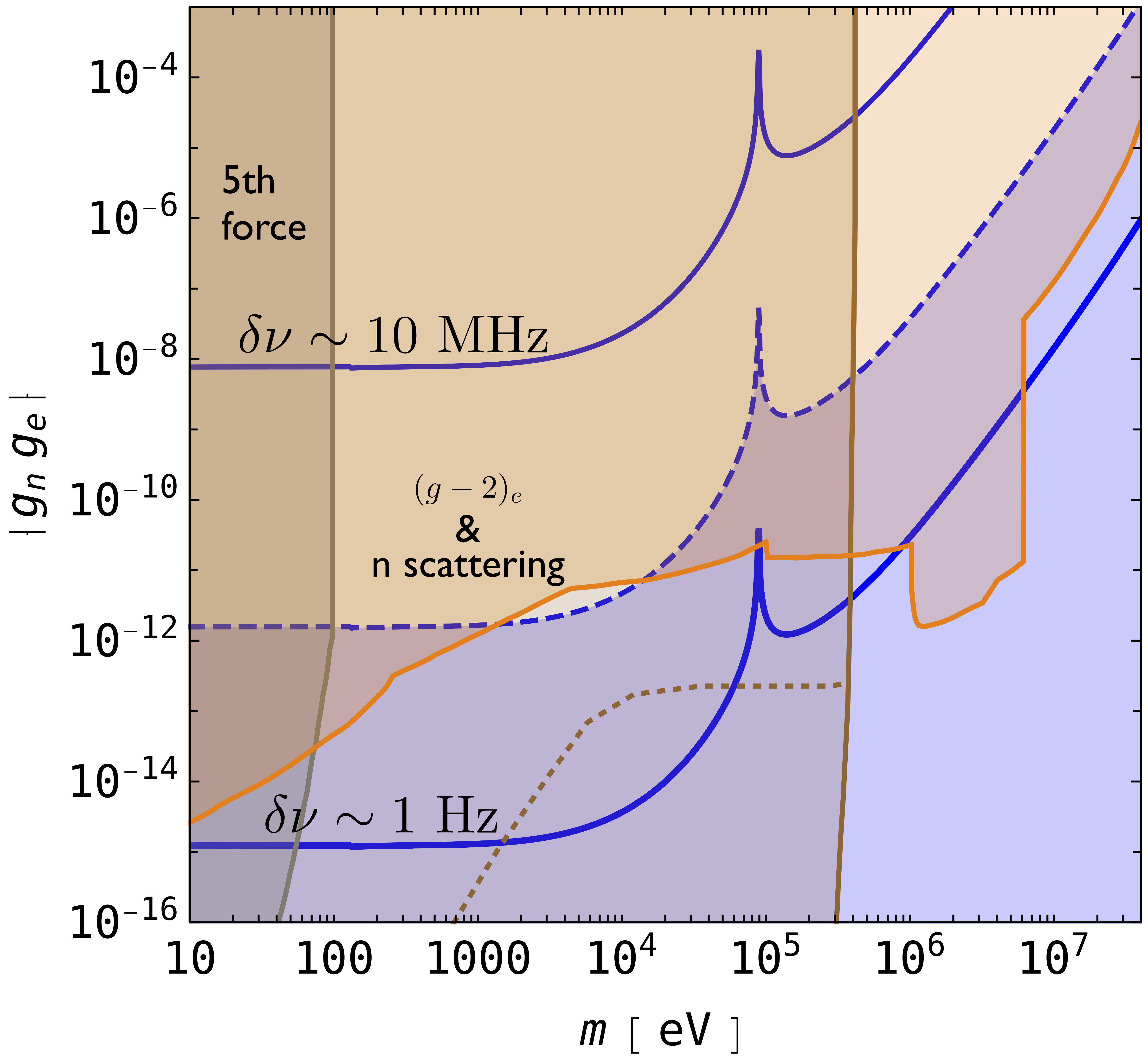
$$\mathrm{FS} = F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + G_t \langle r^4 \rangle_{A'A} + \cdots$$

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)

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

Transition 2: 935 nm Sugiyama et al. CPEM2000

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

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

Yb^+ bounds

$\langle r^4 \rangle$ FS nonlinearity (SM BG)

FSNL dominance:

$$\delta\nu \lesssim 1 \text{ kHz}$$

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

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

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

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

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

実験の進展: Yb+イオン

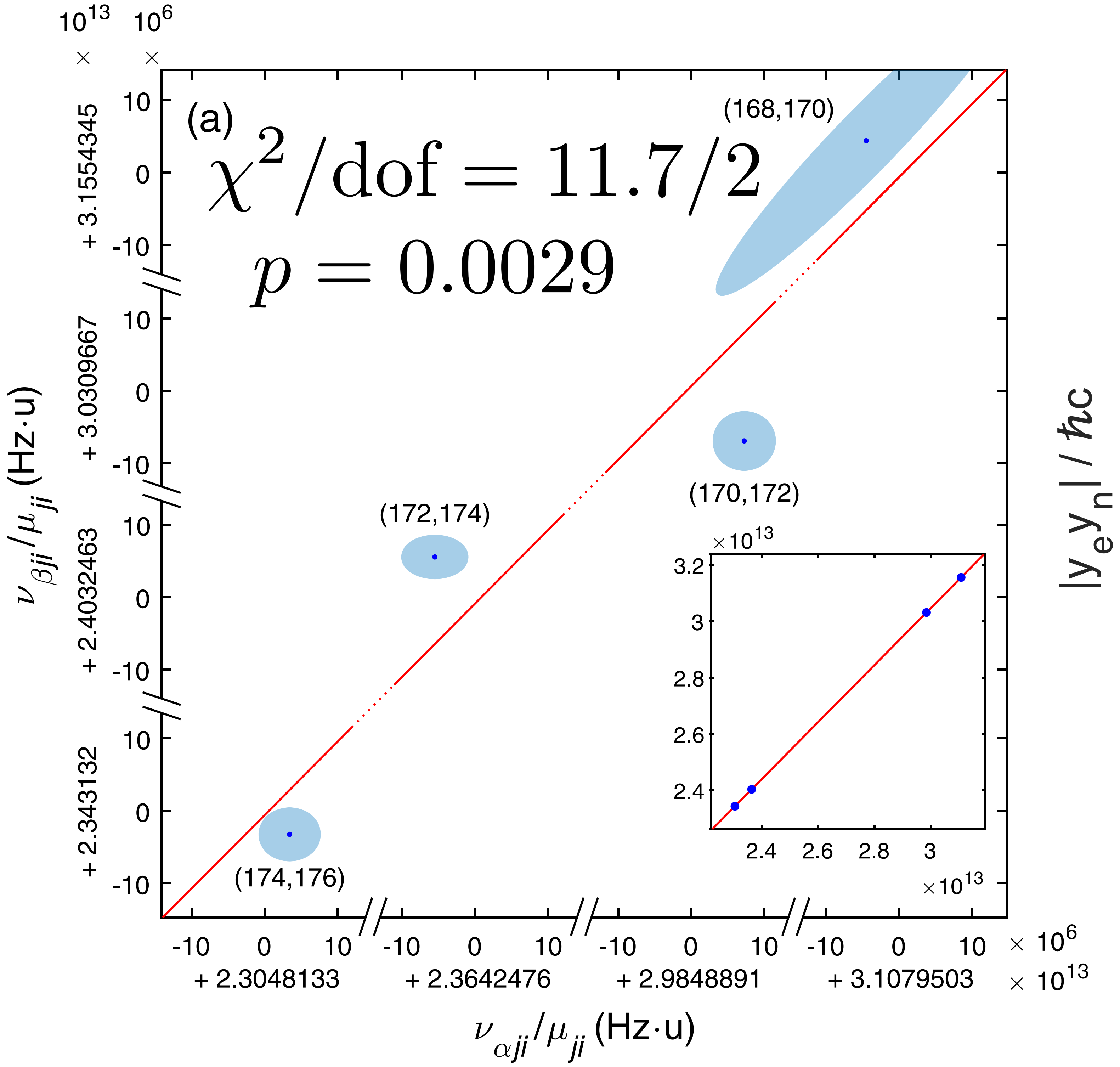
Count et al. PRL 125, 123002 (2020)

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

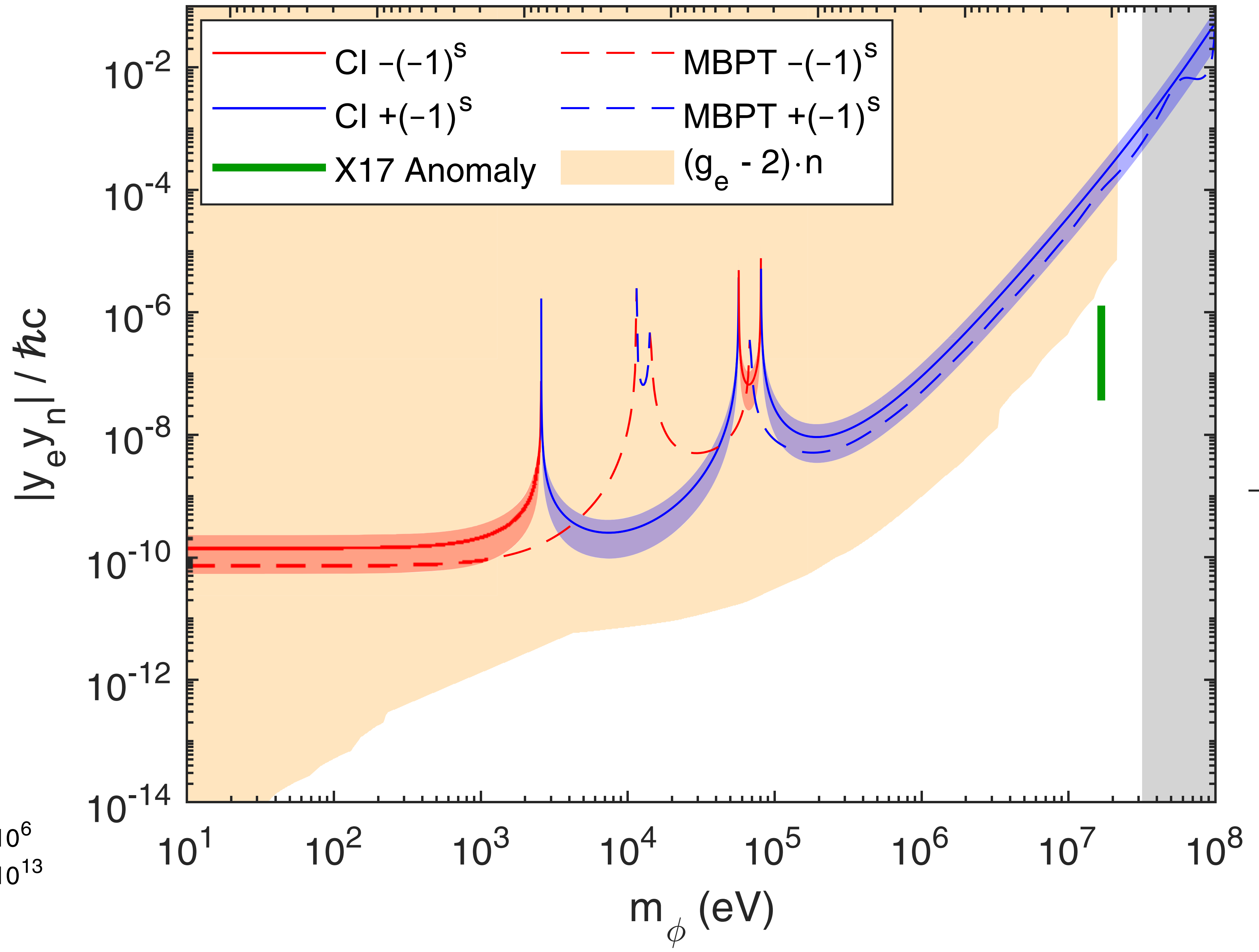
Transition 2: 436 nm
$^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{3/2}(5d)$

4 indep. IS pairs
A=168,170,172,174,176
$\delta\nu \sim 300$ Hz

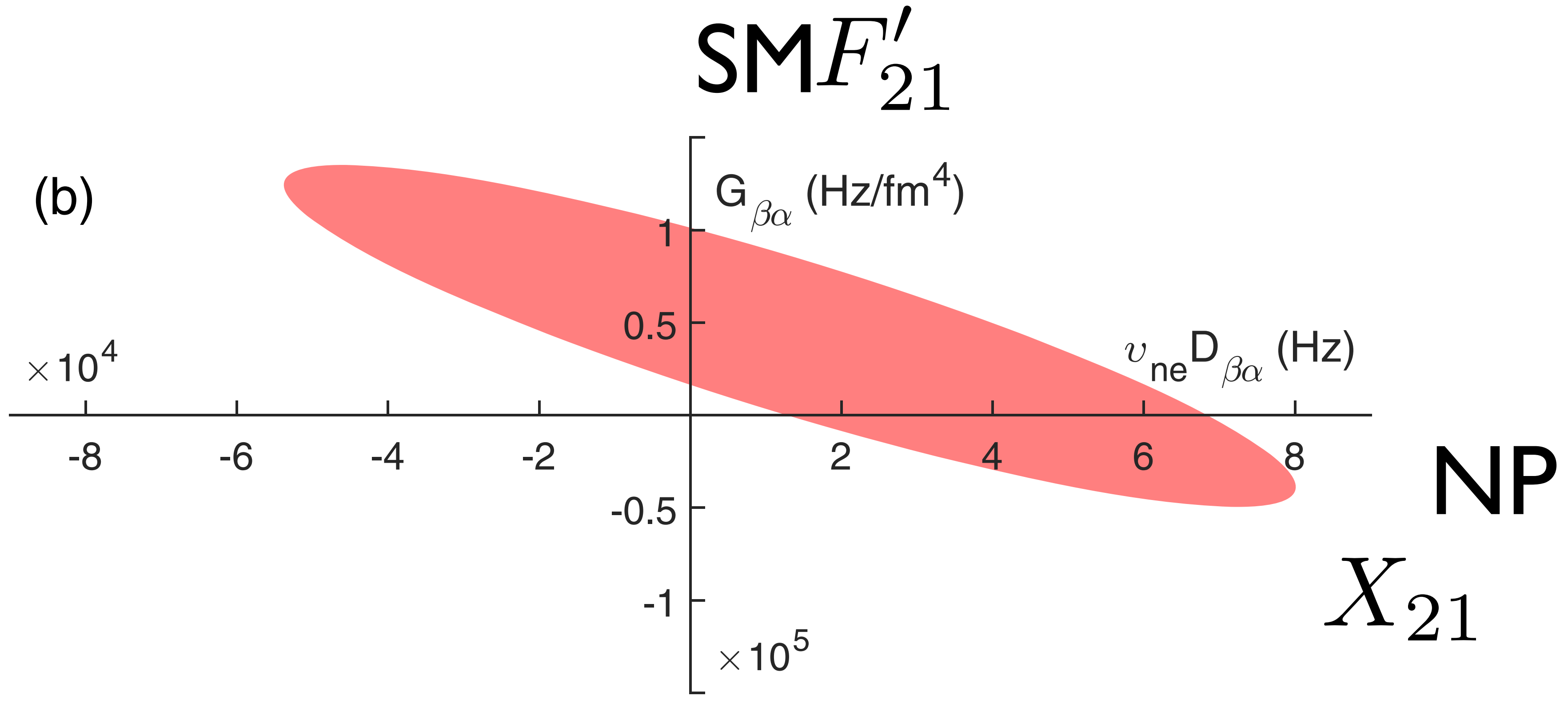
evidence for nonlinearity



new physics?



SM vs NP nonlinerities



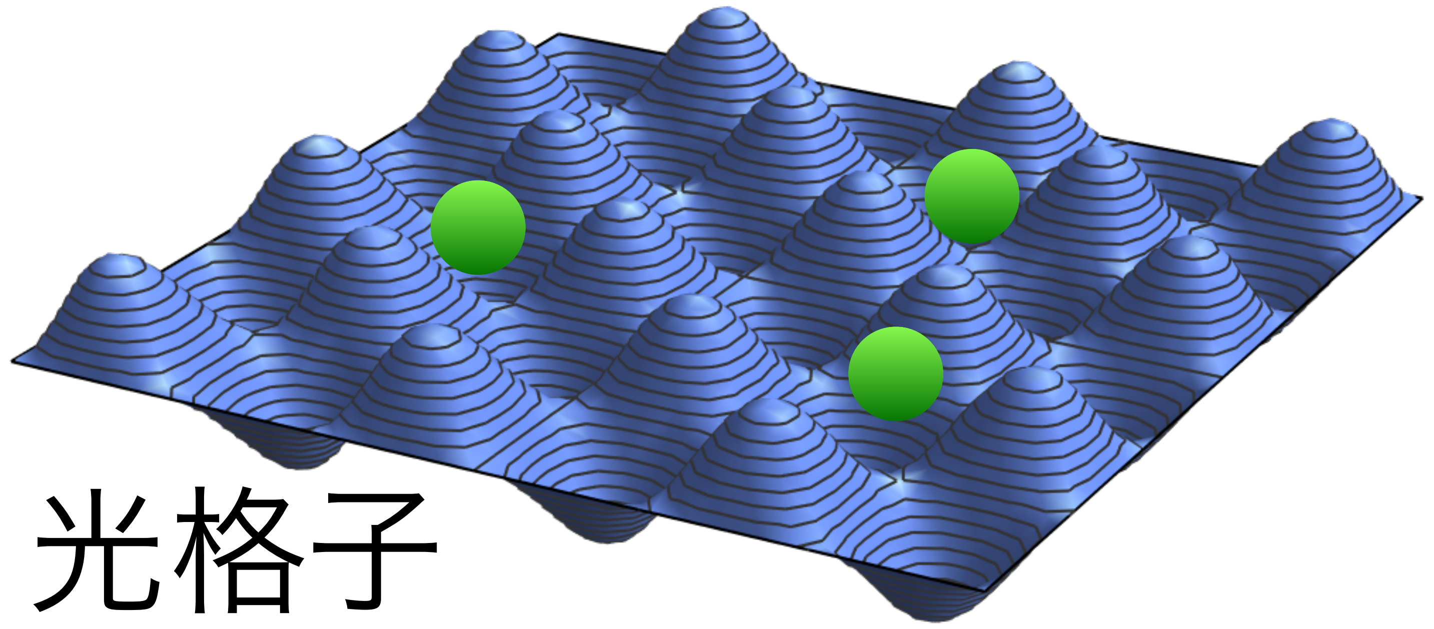
実験の進展: 中性Yb原子

K. Ono, MT et al. PRX 12, 021033 (2022)

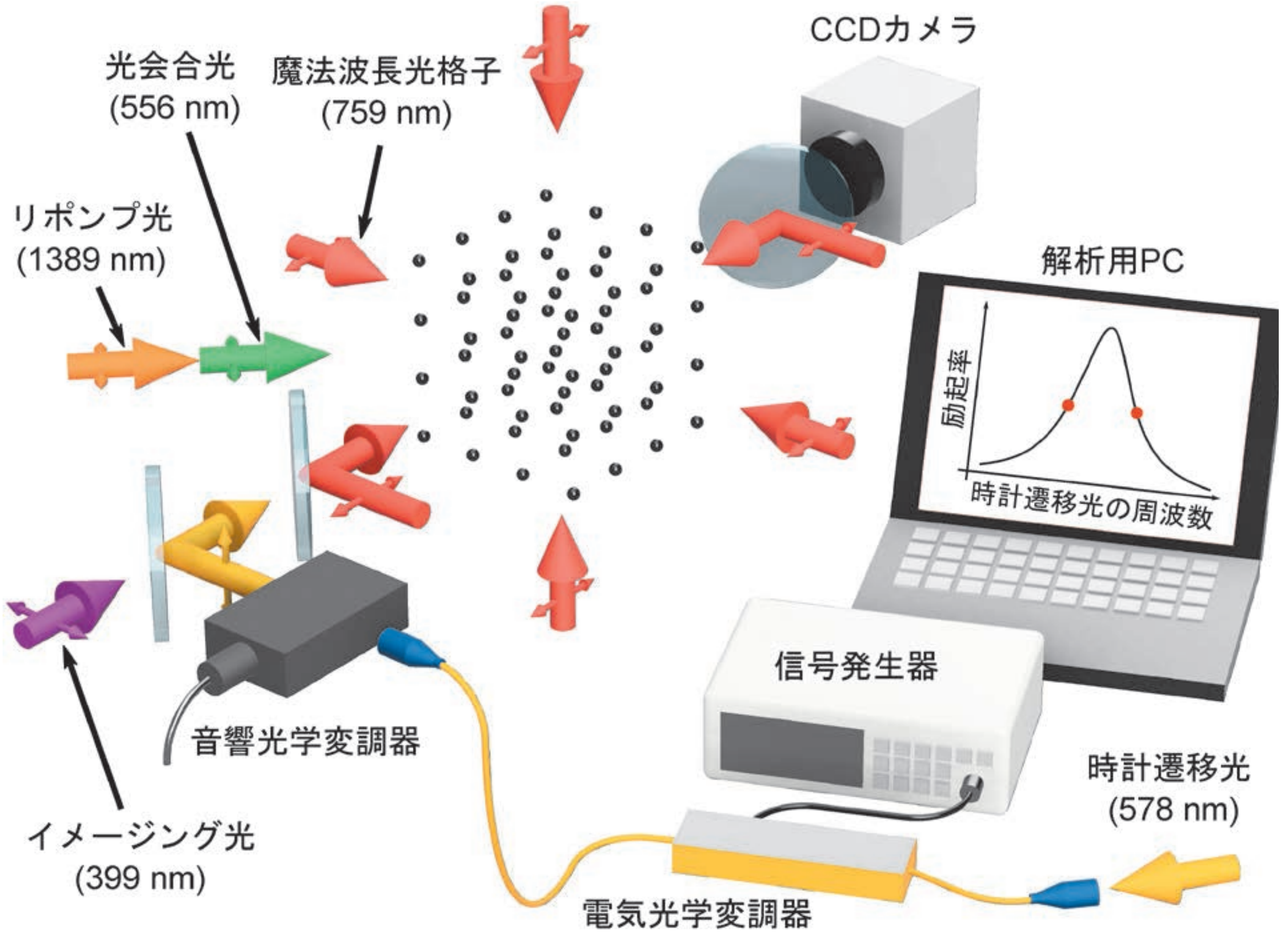
Yb $^1\mathrm{S}_0(6s^2) - {}^3\mathrm{P}_0(6s6p)$

578 nm, 4 IS pairs

$\delta\nu \sim \mathrm{a\ few\ Hz}$



光格子

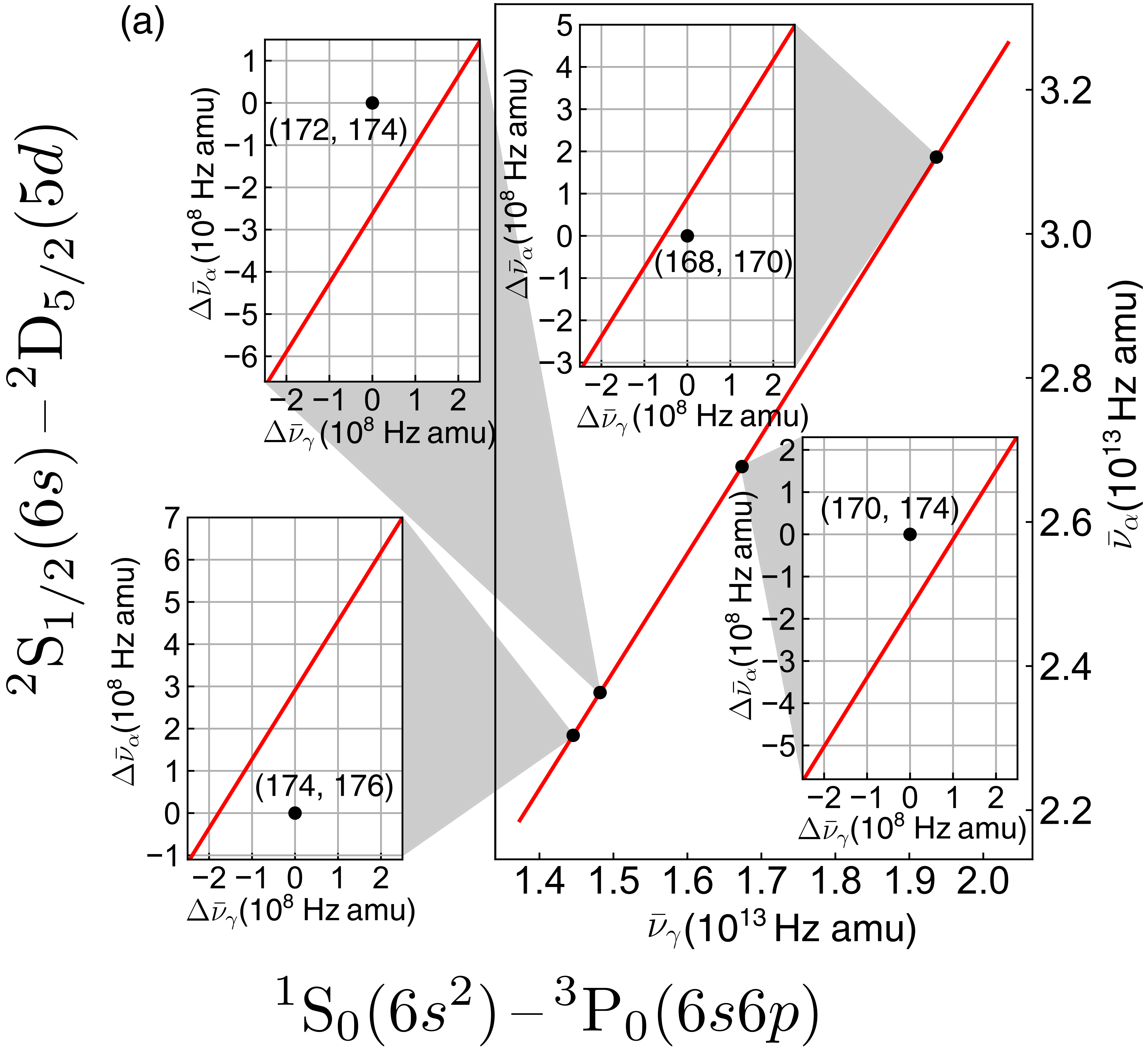


Yb+ $^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{5/2}(5d)$ $^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{3/2}(5d)$ $\delta\nu \sim O(100)\ \mathrm{Hz}$

3 transitions, 4 IS pairs

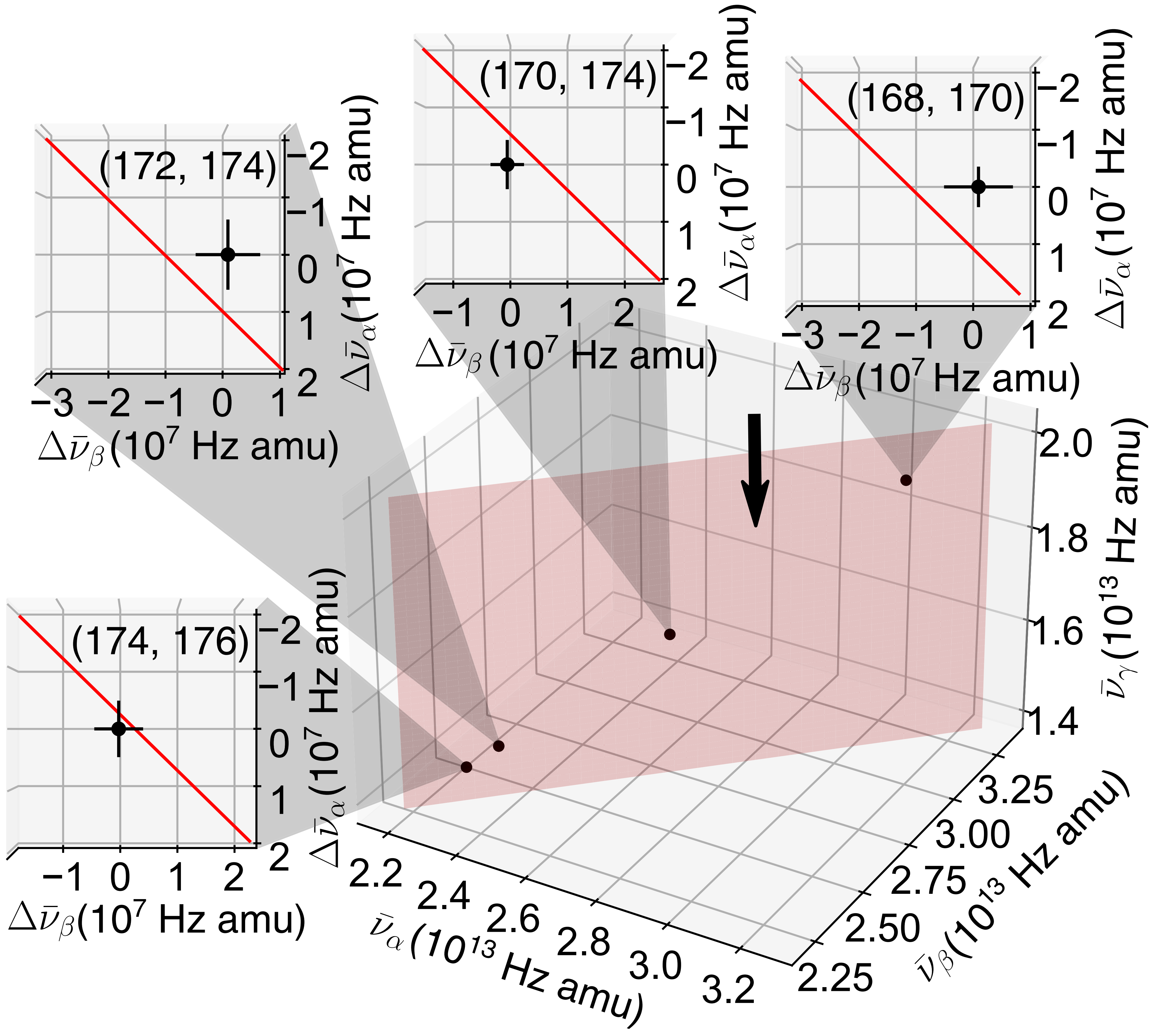
→ 一般化線形性を用いた新物理探索(世界初)

2D analysis



$$\chi^2/\mathrm{dof} = 1.1 \times 10^4/3$$

3D analysis



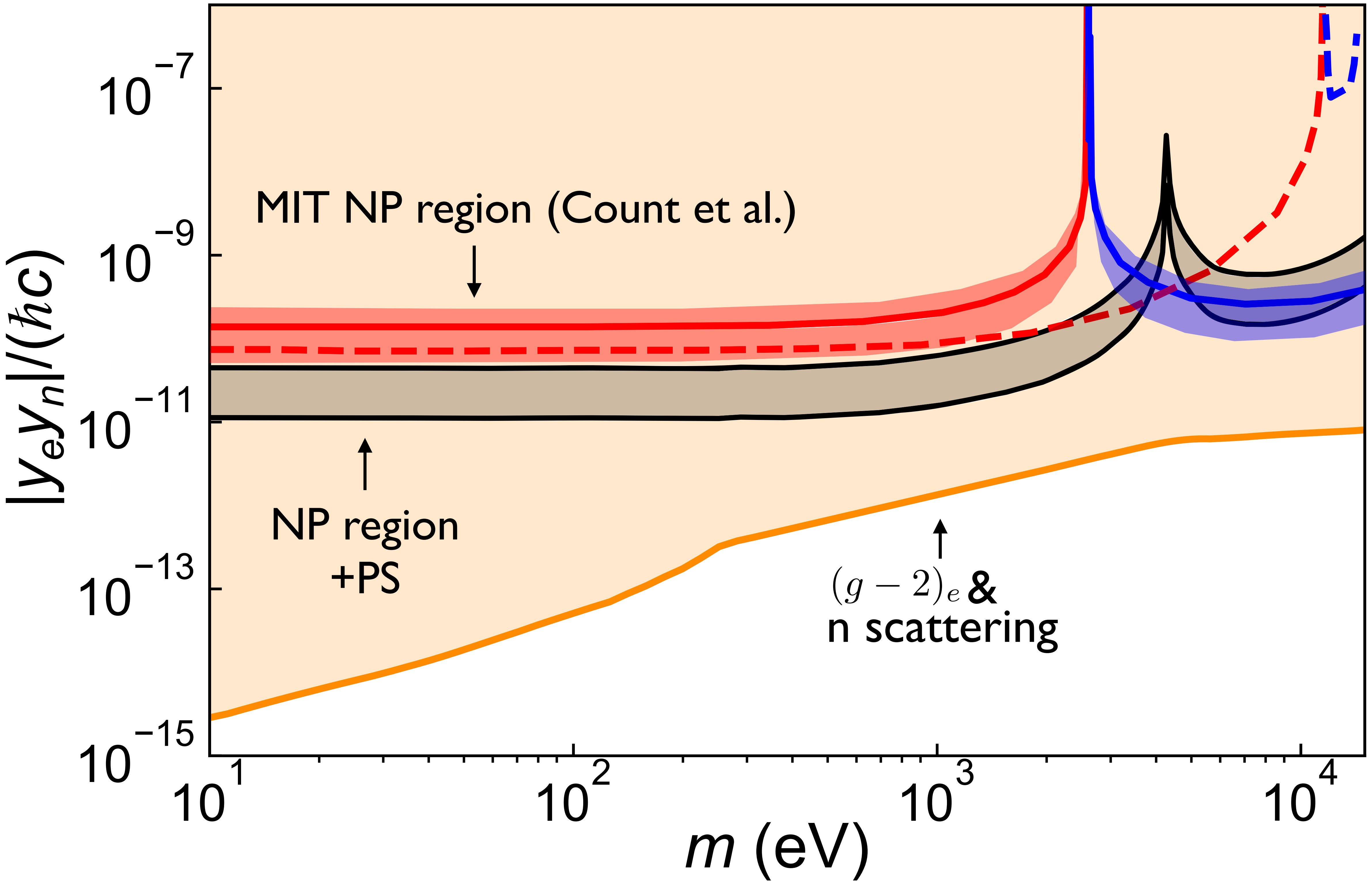
$$\chi^2/\mathrm{dof} = 15/3$$

→ two or more NL sources

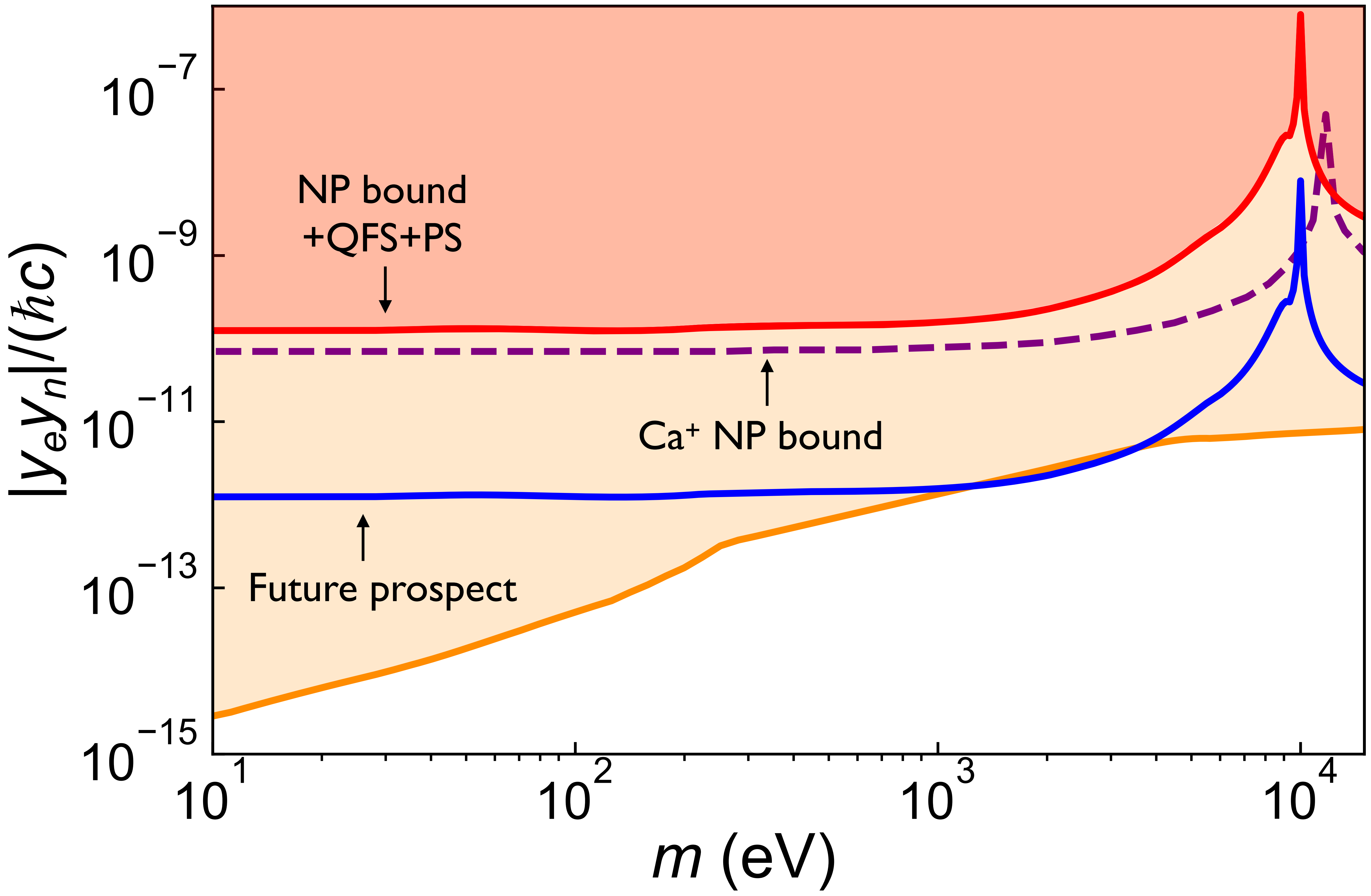
Nonlinearity sources and new physics bound

One of NL sources is eliminated in 3D analysis.

+PS: Inconsistent with the existing constraints of PS



+QFS+PS ⟶ New physics bound



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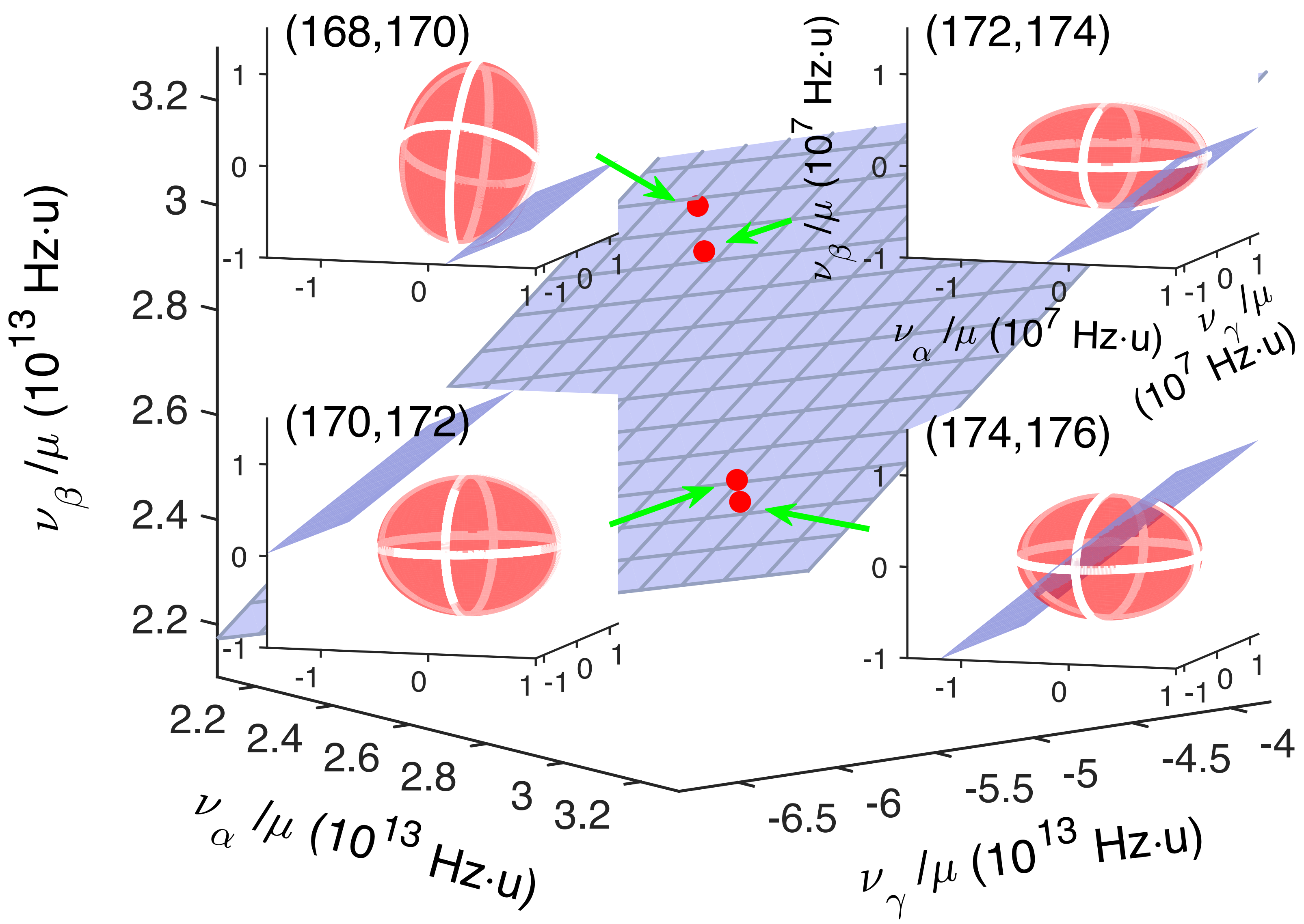
実験の進展(続き)

Yb⁺ Hur et al. PRL 128, 163201 (2022)

$$^2\mathrm{S}_{1/2}(4f)^{14}(6s) - {}^2\mathrm{F}_{7/2}(4f)^{13}(6s)^2$$

$$\delta\nu \sim 500\ \mathrm{Hz}$$

3D analysis $3.2\ \sigma$

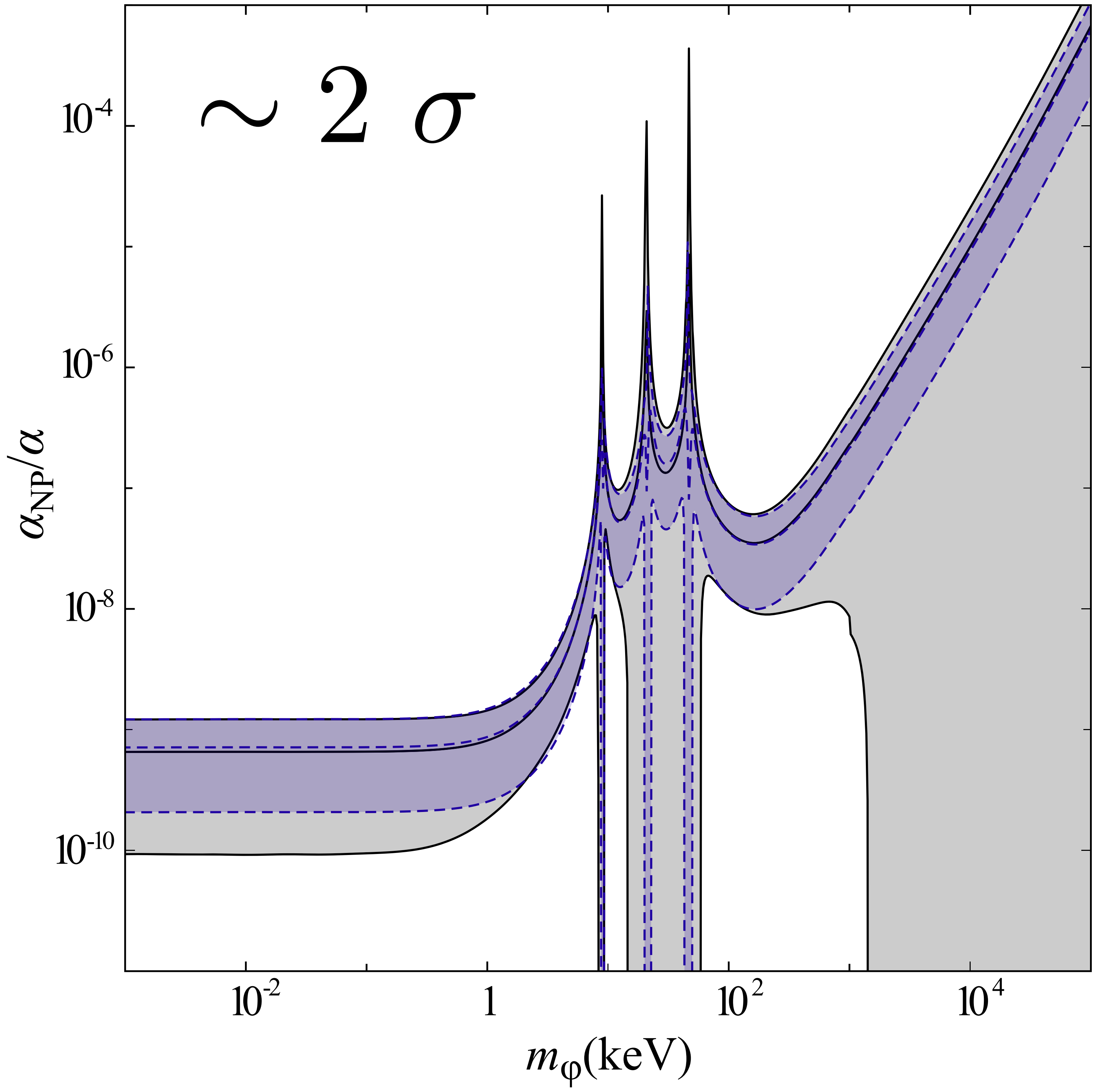


Consistent with our result

Yb Figueroa et al. PRL 128, 073001 (2022)

$$^1\mathrm{S}_0(6s)^2 - {}^1\mathrm{D}_2(6s5d) \quad \delta\nu \sim O(100)\ \mathrm{Hz}$$

3D analysis: reduced significance



まとめと展望

- Isotope shift and King 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
- データ解析

  Yb, Yb^+イオンで5つの遷移データを総合(準備中)

参考文献: 日本物理学会誌 vol. 77, No. 6, 355