Isotope shift as a probe of new physics

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Frontiers in particle physics

Energy frontier: LHC, ILC, FCC, …

Intensity frontier: B factory, K, muon, …

Cosmic frontier: CMB, GW, …

Precision / low energy frontier

$0\nu\beta\beta$, DM, EDM,…

Temporal variation of fundamental constants

α, m_e/m_p using atomic clock $\mathrm{Yb}^+ : \ \delta\nu/\nu \sim 10^{-18}, \ \delta\nu \sim \mathrm{sub\ Hz}$

Huntemann et al. (PTB) 2016

Isotope shift new neutron-electron interaction

Light new particle search

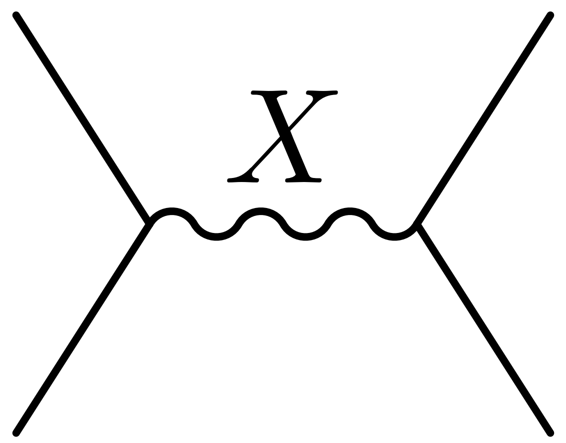
Direct search

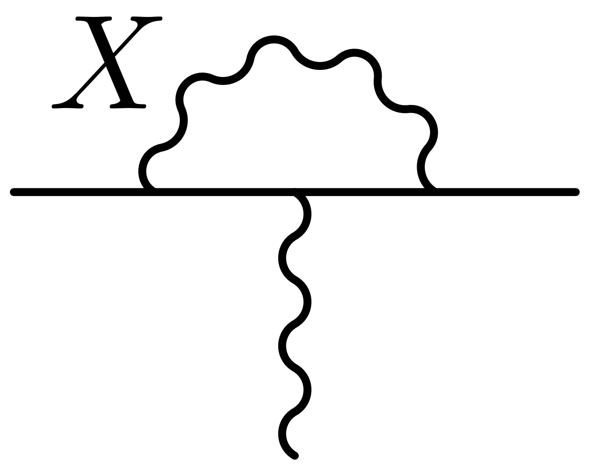
Visible decay, e.g. $X \to e^+e^-$: direct search

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

Stable: missing E/p, dark matter?

Indirect search





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

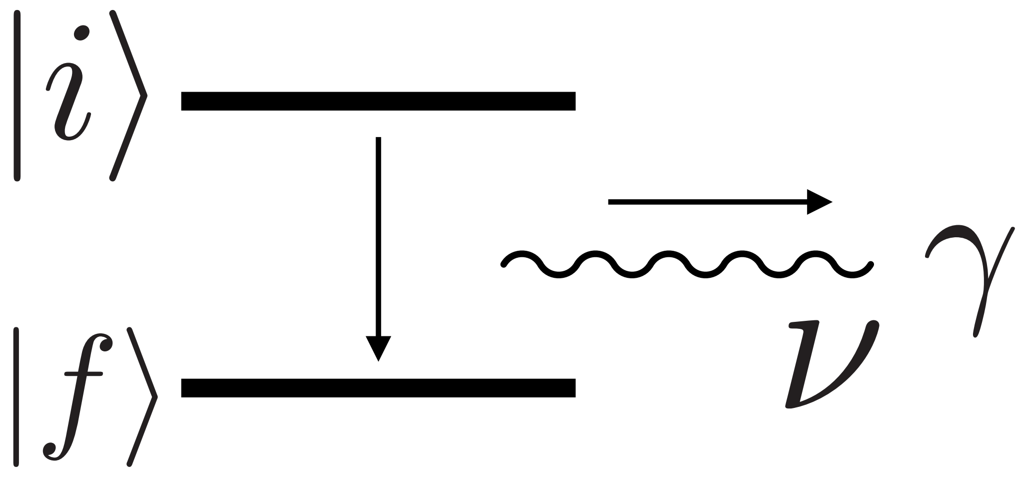
cf. weak interaction $\sim \frac{g_Z^2}{m_Z^2} \sim \frac{0.5}{(100\ \mathrm{GeV})^2} = \frac{0.5 \times 10^{-10}}{(1\ \mathrm{MeV})^2}$

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

King linearity

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

Ex. Yb^+

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

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

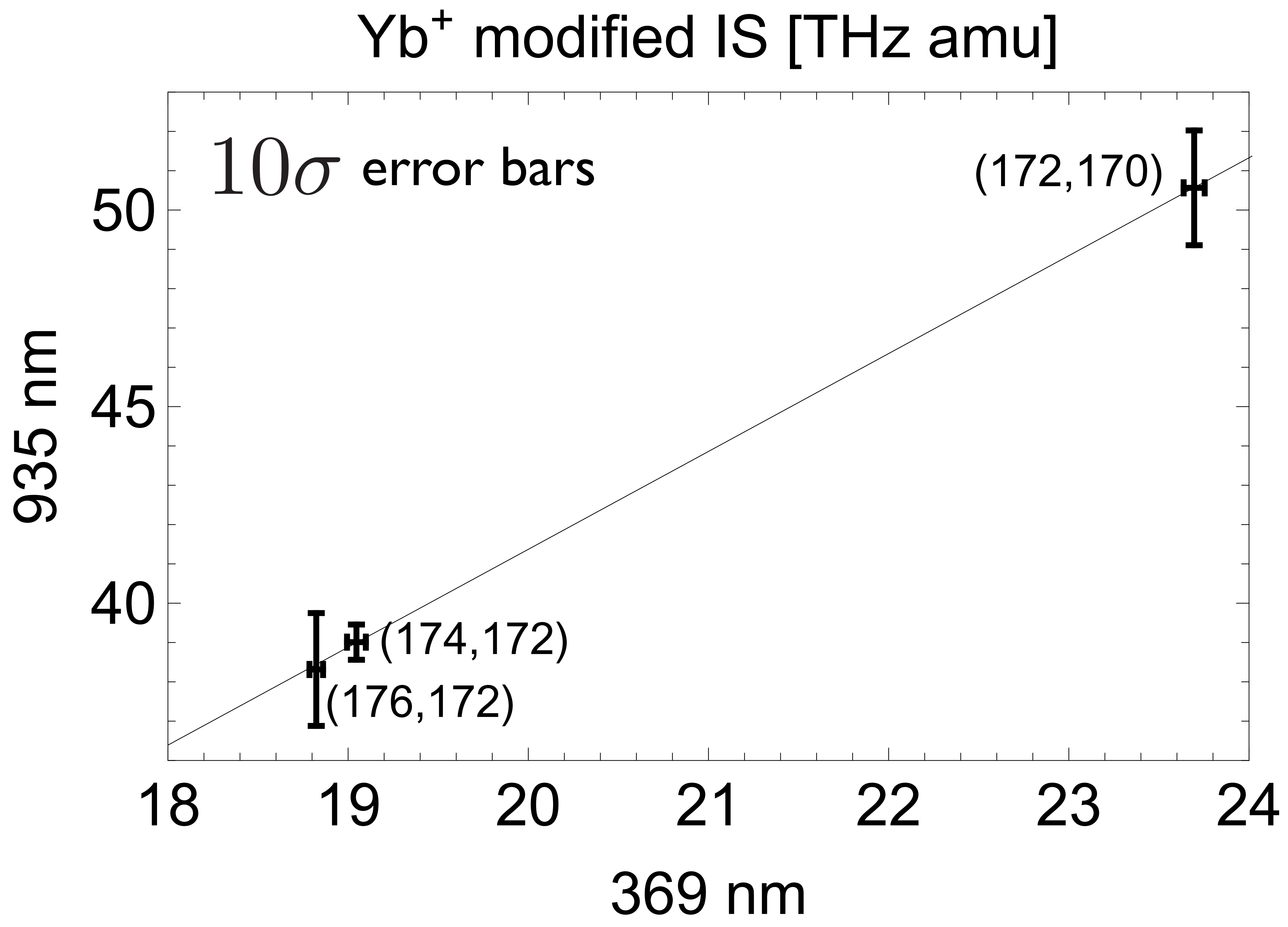
Sugiyama et al. CPEM2000

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

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

Isotope pairs

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



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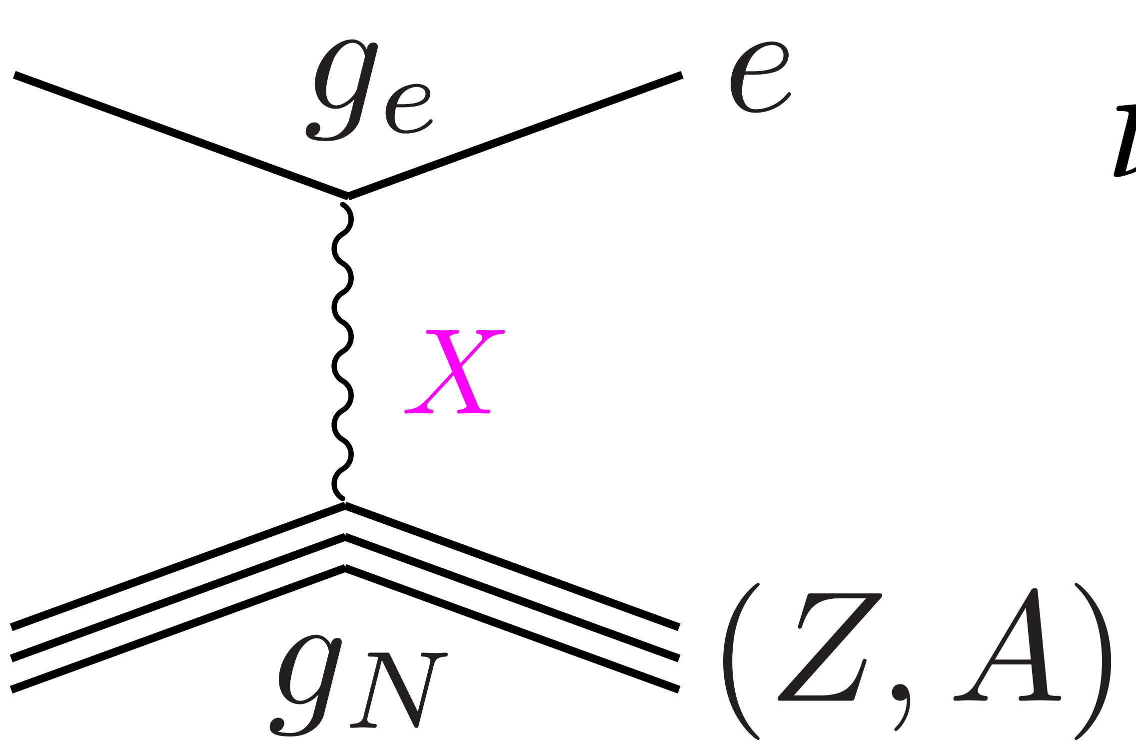
Nonlinearity

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

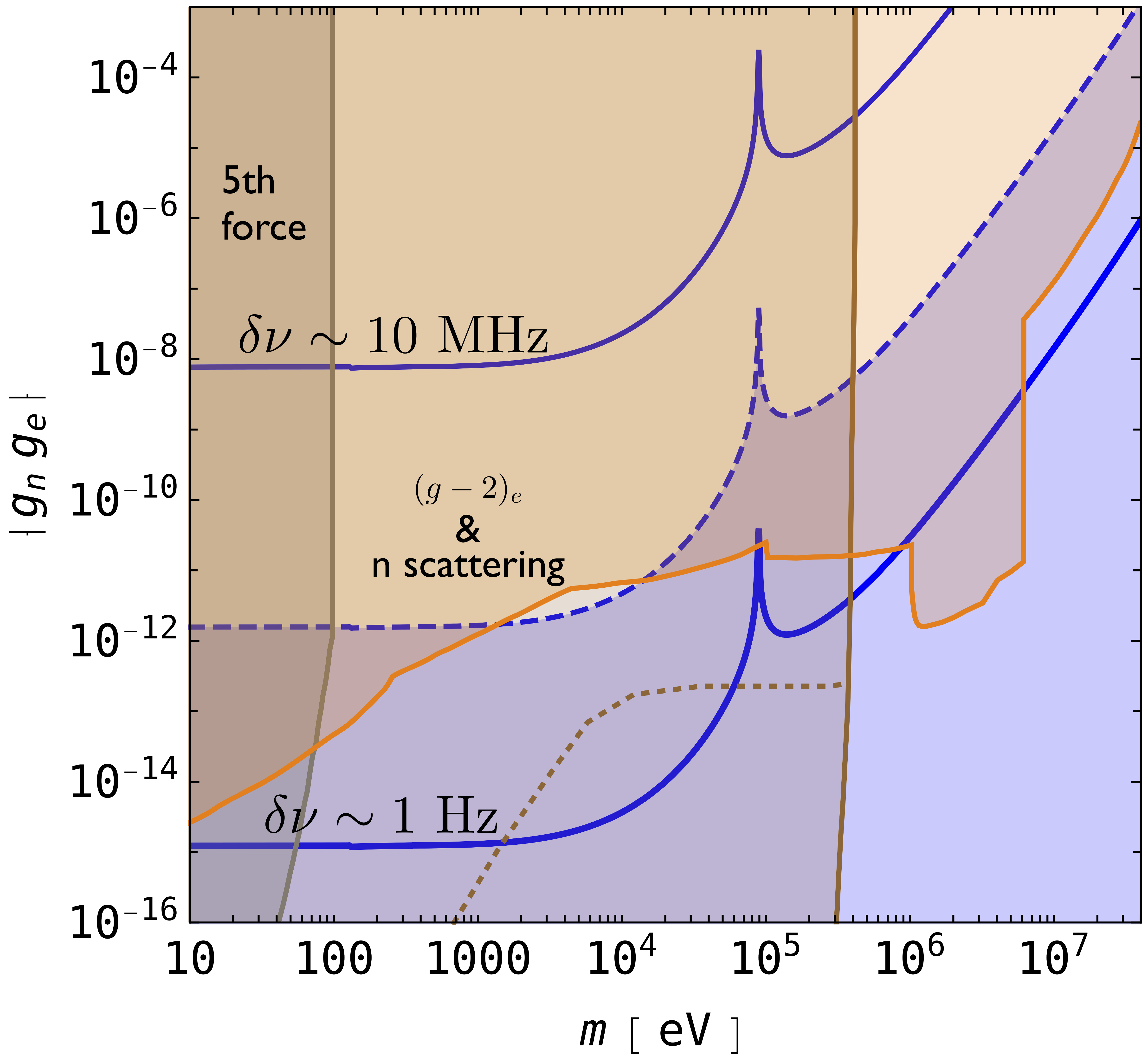
$$\mathrm{FS} = F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + G_t \langle r^4 \rangle_{A'A} + \cdots$$

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)

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

Transition 2: 935 nm   Sugiyama et al. CPEM2000

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

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

Yb^+ bounds

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

FSNL dominance:

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

What about SM nonlinearity?

Precise calculation difficult

Generalized linearity

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

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

3 transitions: t=1, 2, 3 QFS PS

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

→

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

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

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

Recent experiments: Yb+ ion

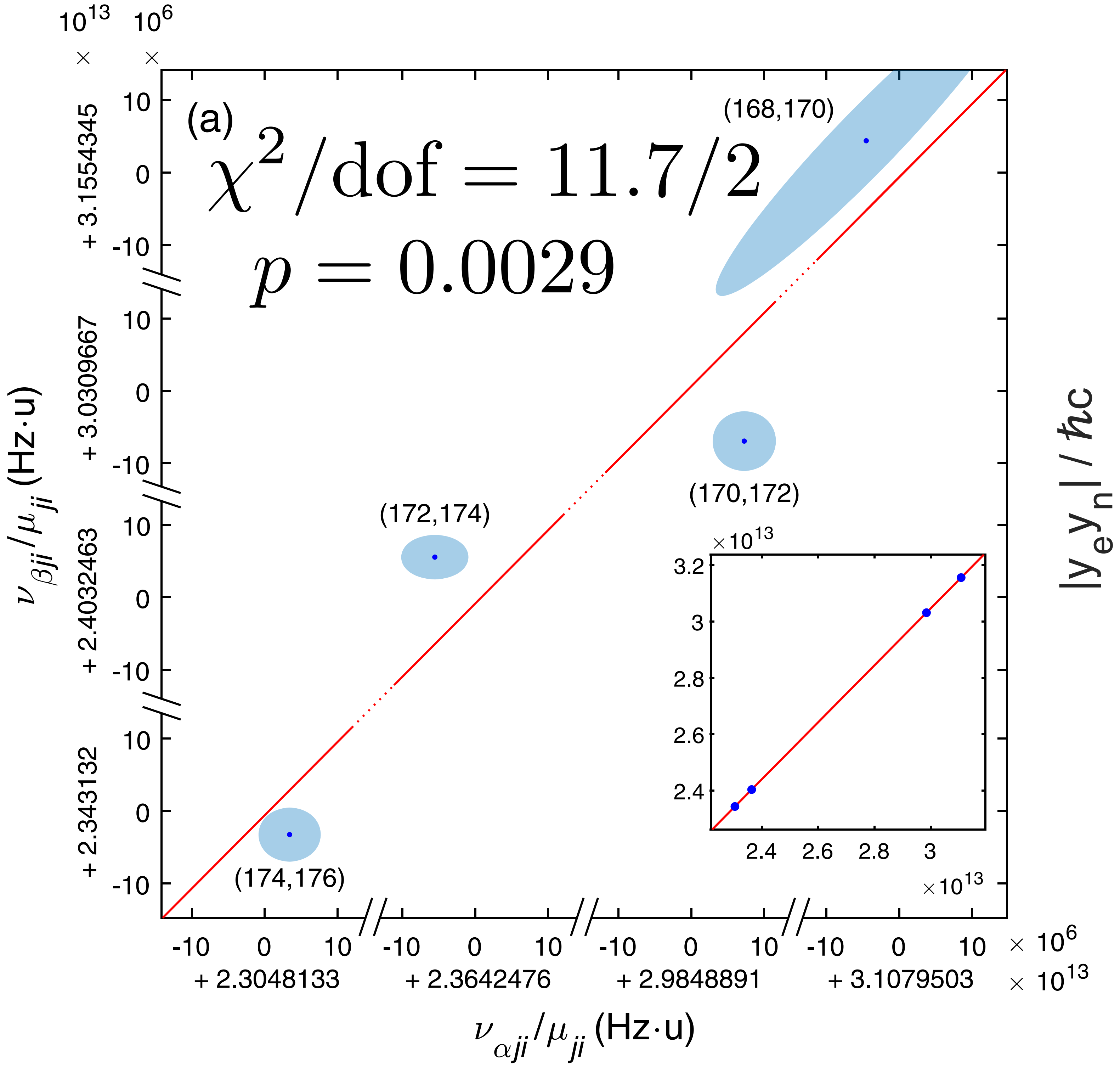
Count et al. PRL 125, 123002 (2020)

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

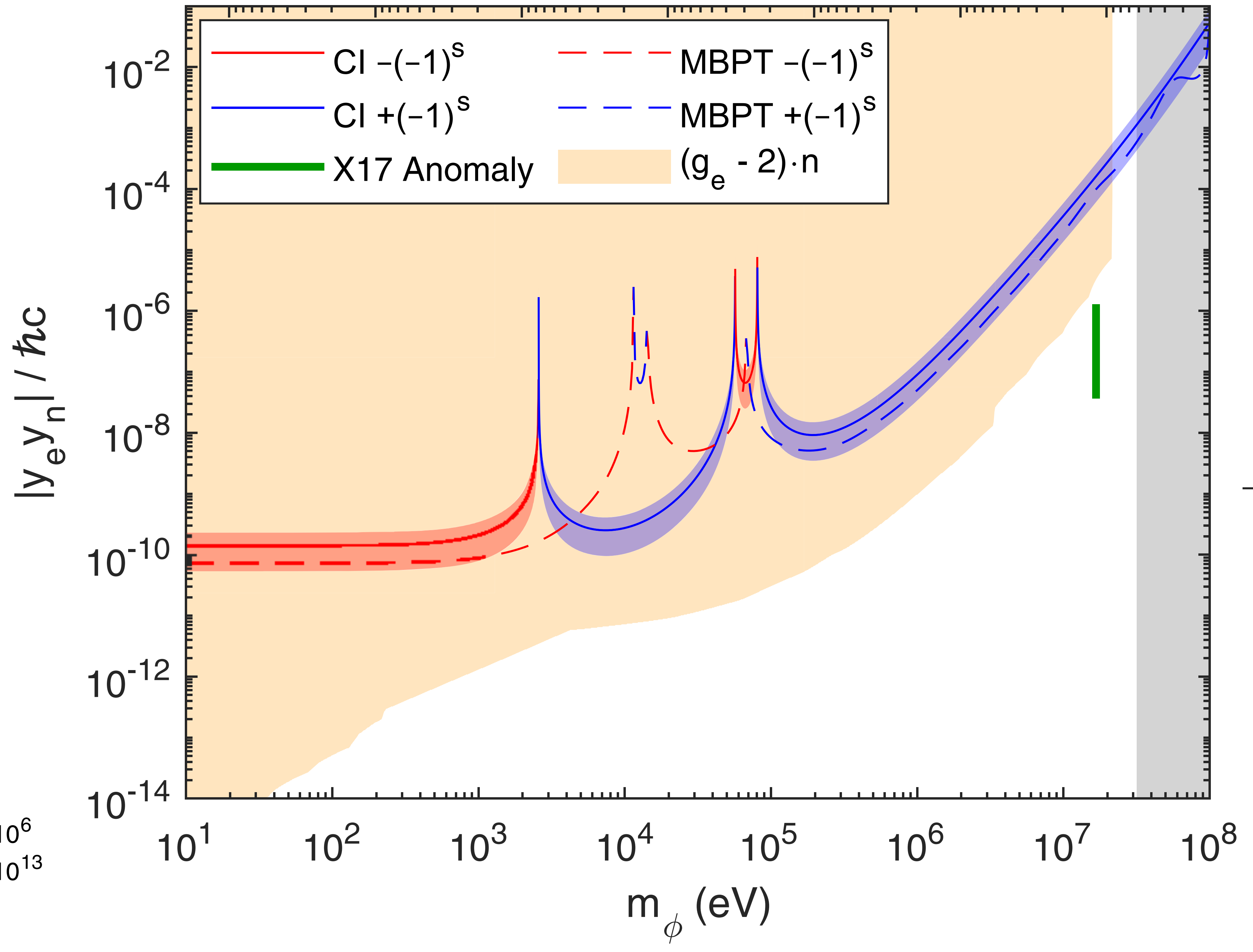
Transition 2: 436 nm
$^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{3/2}(5d)$

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

evidence for nonlinearity

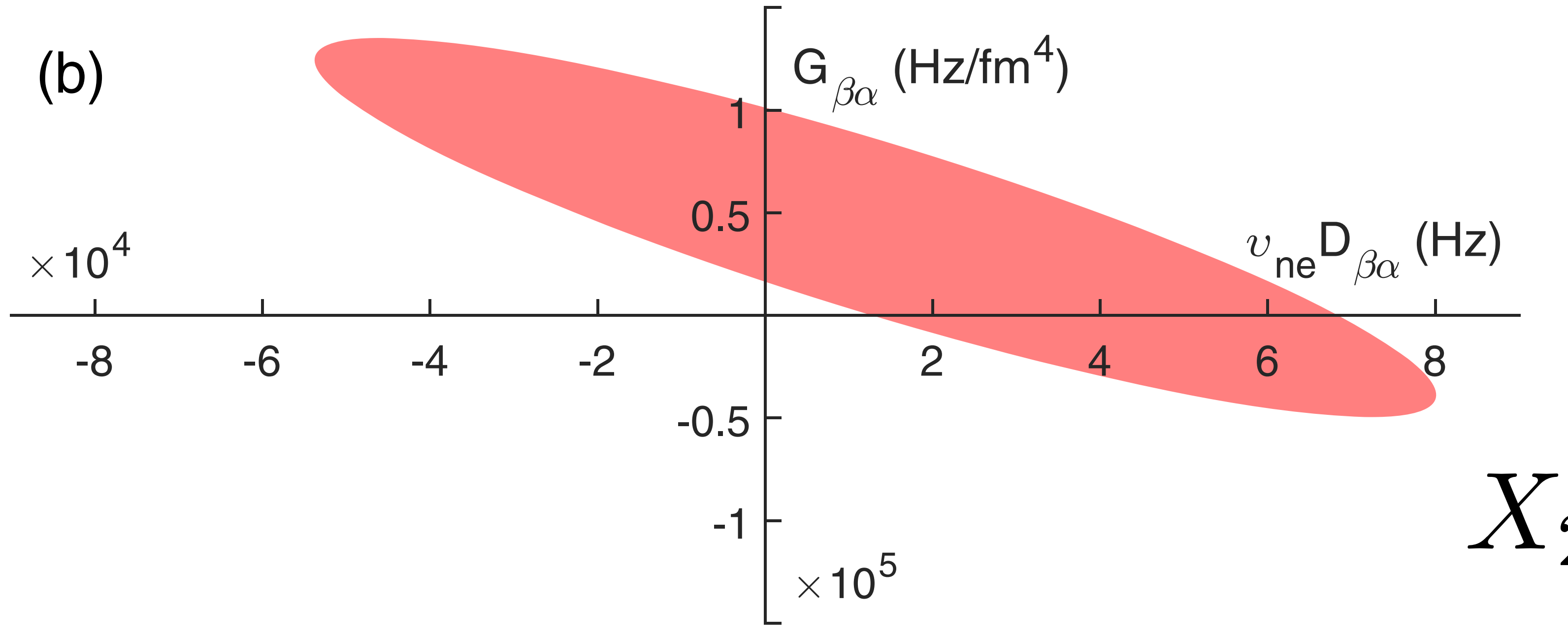


new physics?



SM vs NP nonlinerities

SM F'_{21}



NP X_{21}

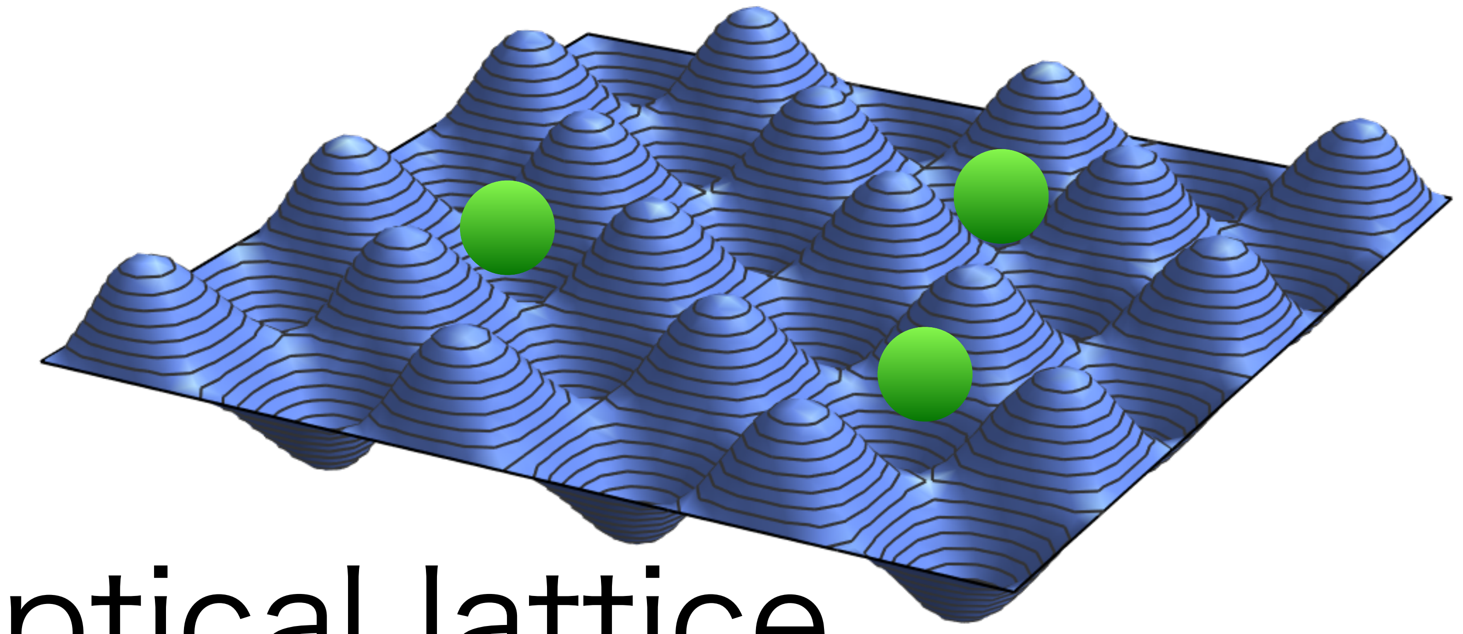
Recent experiments: Yb atom

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

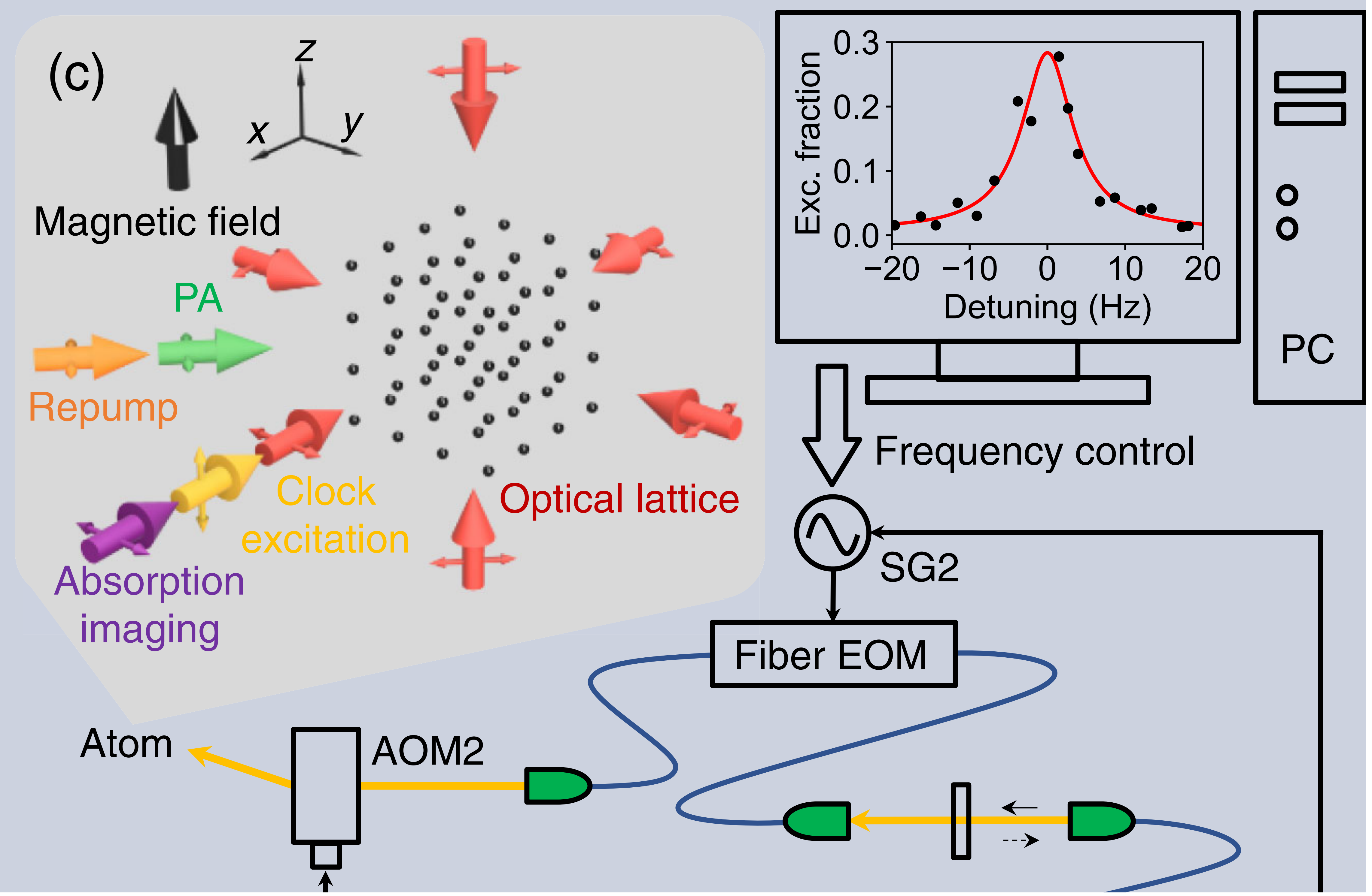
Yb $^1\mathrm{S}_0(6s^2) - {}^3\mathrm{P}_0(6s6p)$

578 nm, 4 IS pairs

$\delta\nu \sim$ a few Hz



optical lattice



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

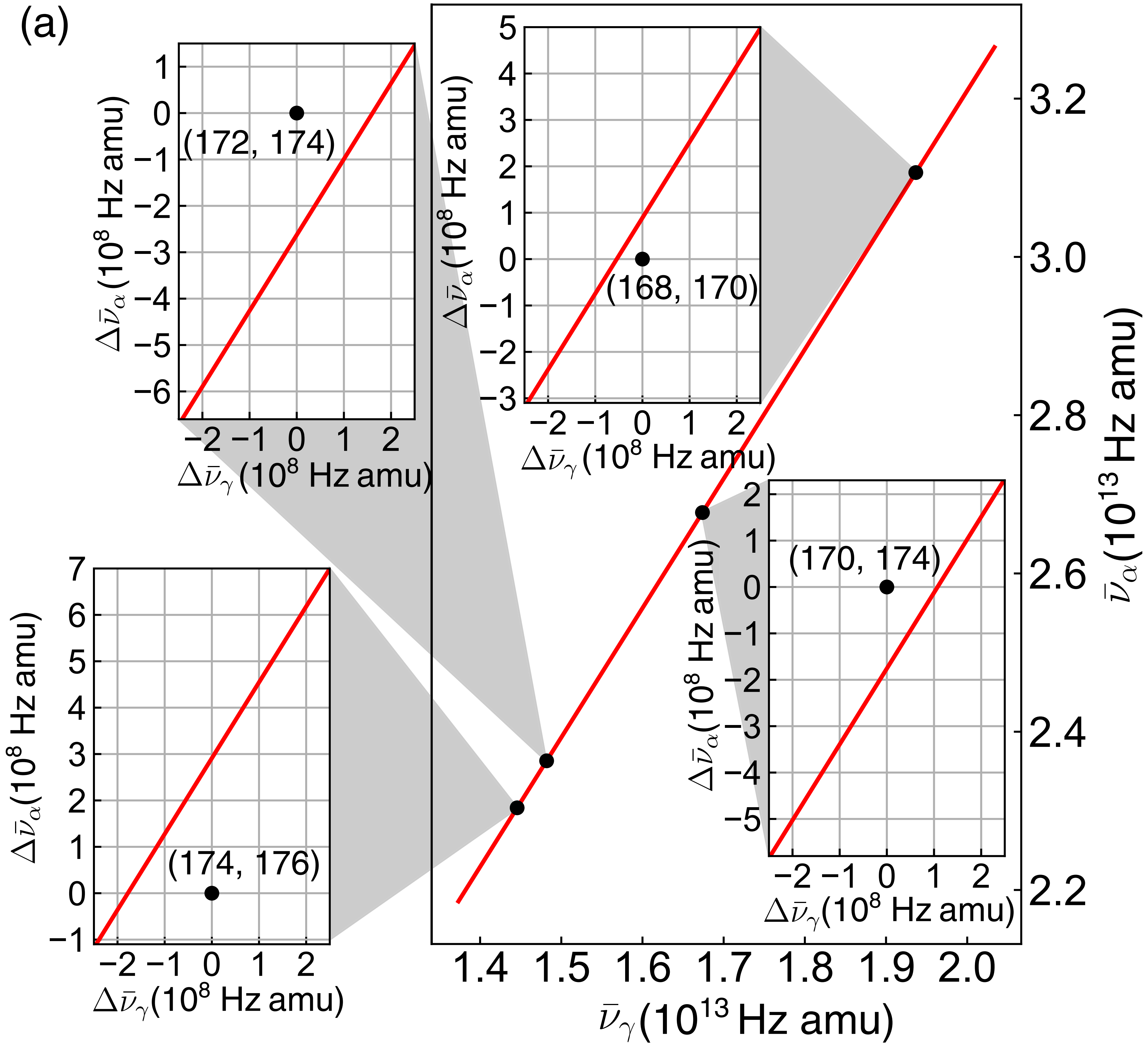
3 transitions, 4 IS pairs

→ First new physics search with the generalized linearity

2D analysis

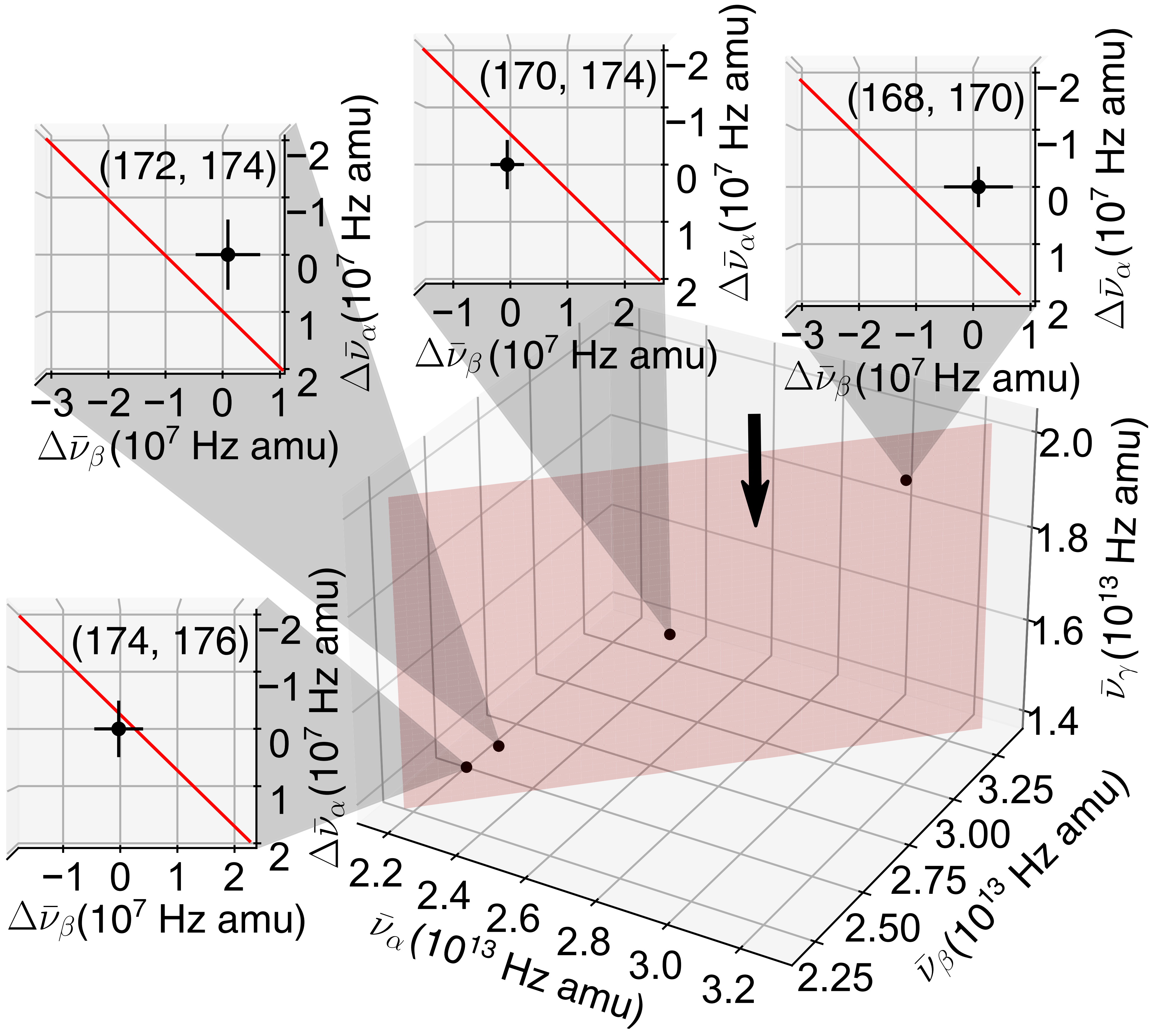
3D analysis

$^2S_{1/2}(6s) - {}^2D_{5/2}(5d)$



$^1S_0(6s^2) - {}^3P_0(6s6p)$

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



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

→ two or more NL sources

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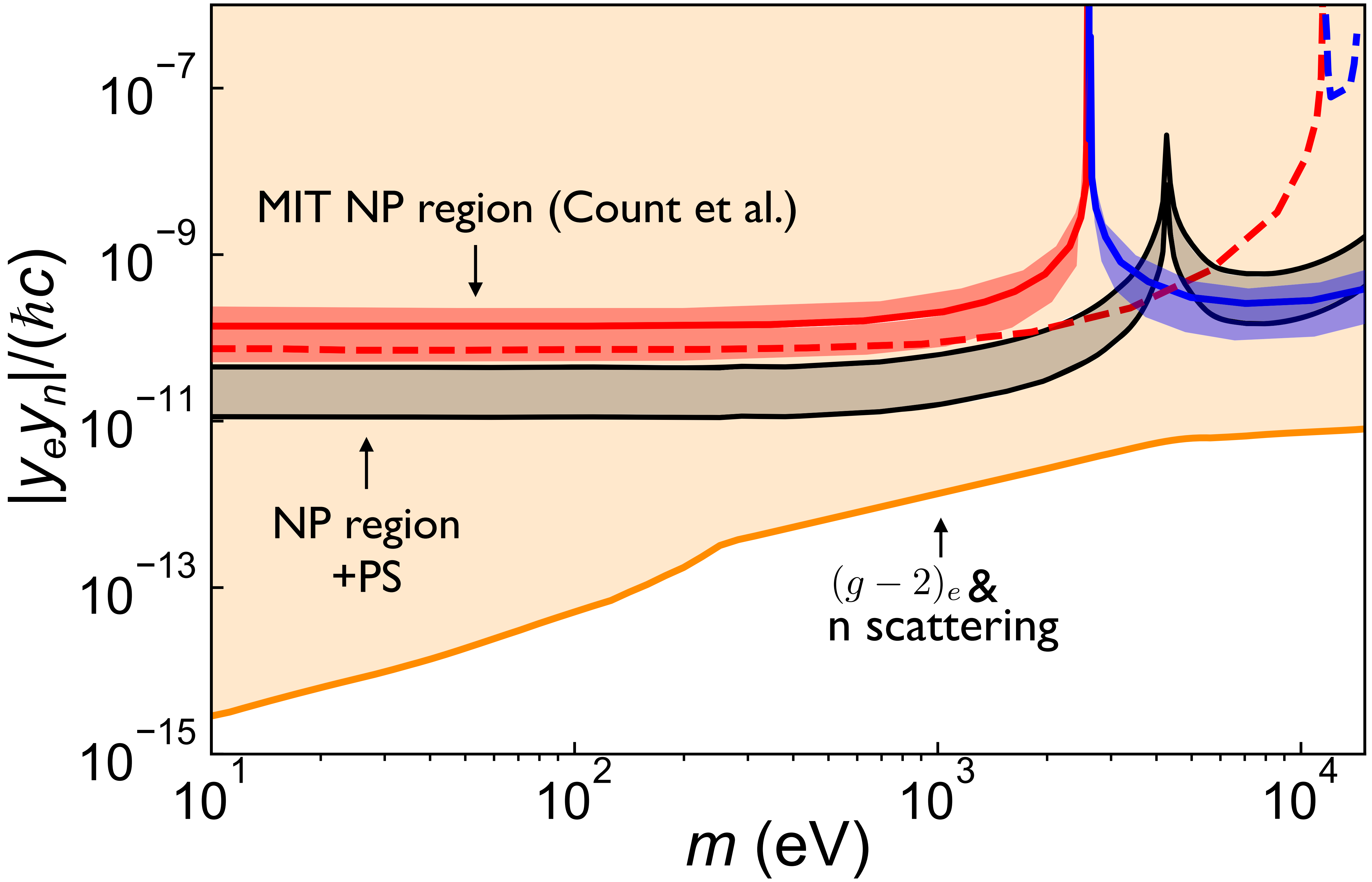
Nonlinearity sources and new physics bound

One of NL sources is eliminated in 3D analysis.

+PS: Inconsistent with the existing constraints of PS



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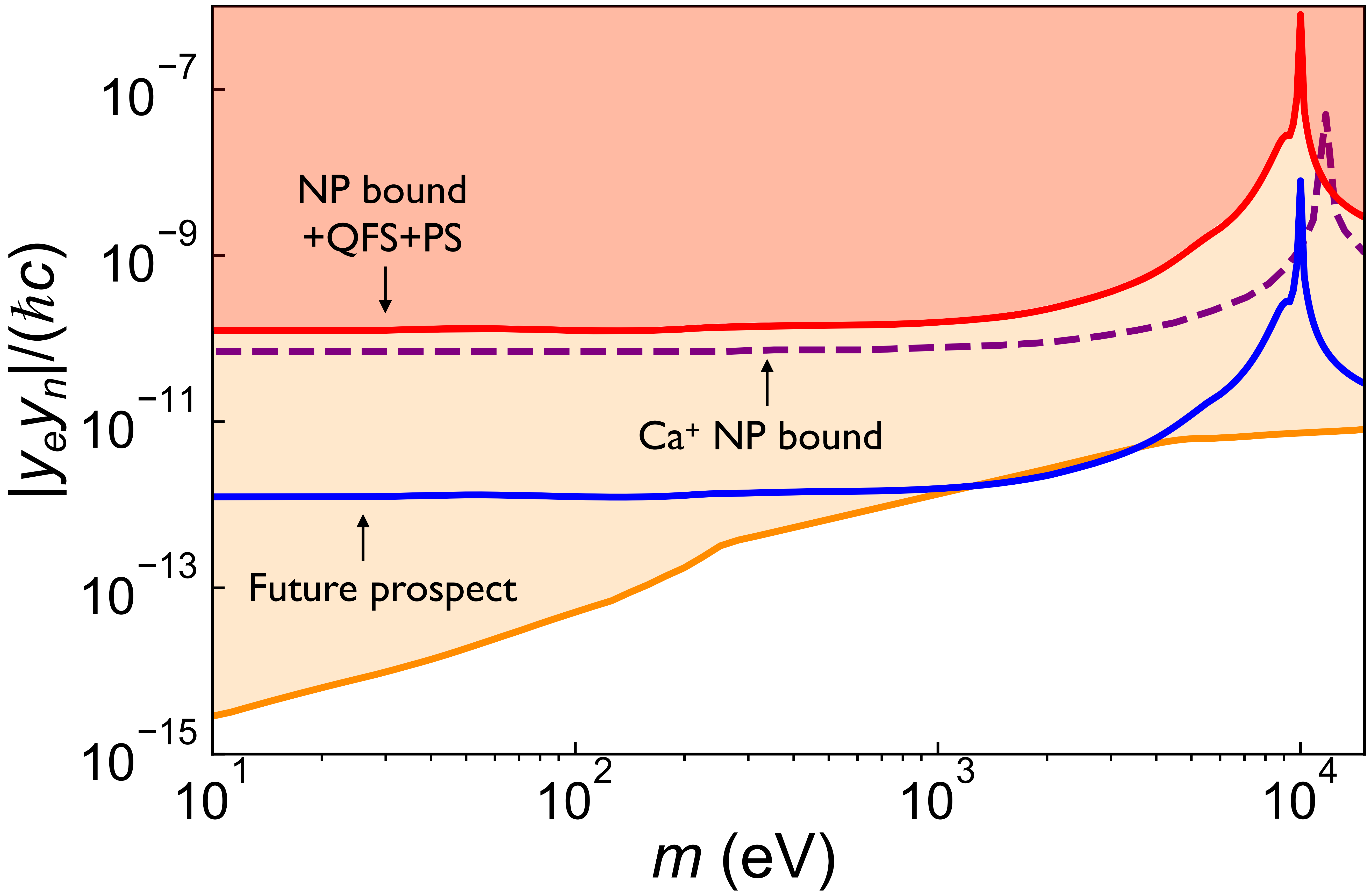
+QFS+PS → New physics bound



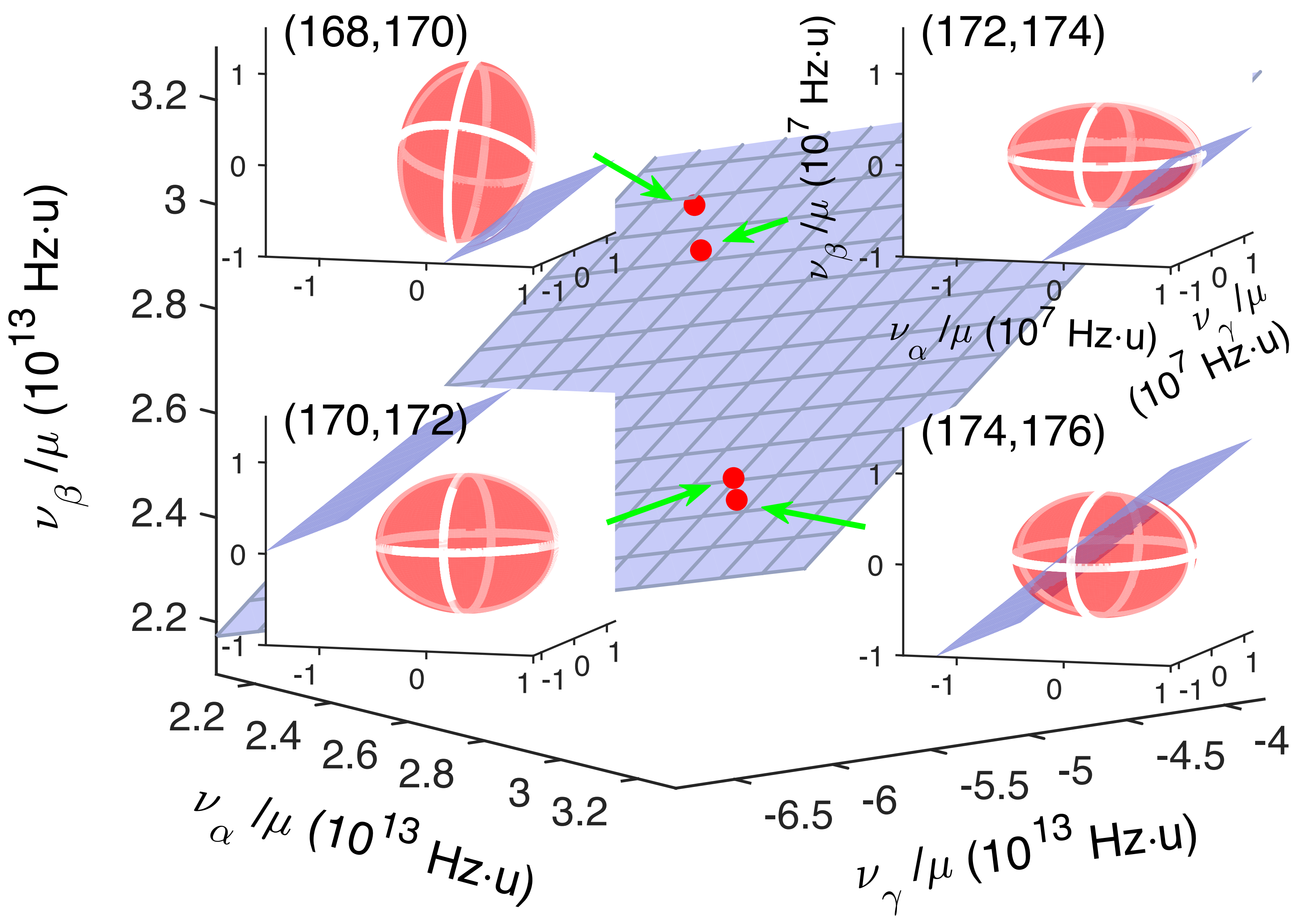
Recent experiments (cont'd)

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 $3.2\ \sigma$

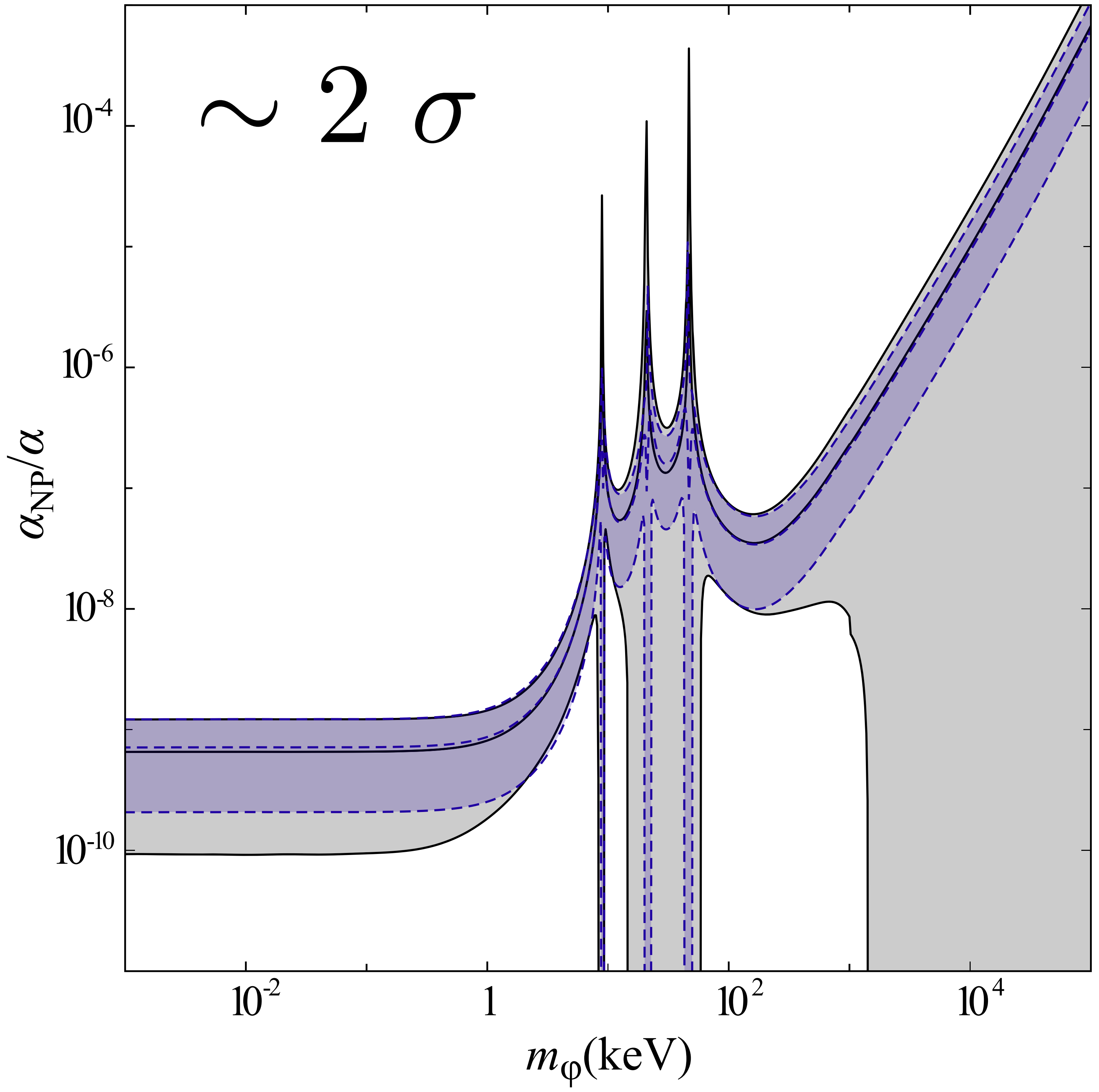


Consistent with our result

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



Summary and outlook

- 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
- Generalized linearity

  SM nonlinearity removed, improved sensitivity to new physics
- Precise Yb IS measurements

  Yb^+ ion O(100) Hz, Yb atom O(1) Hz

  New Yb O(1) Hz data expected
- Data analysis

  Unifying the 5 transitions of Yb, Yb^+ (ongoing)