



National Center for Theoretical Sciences
Physics Division 國家理論科學研究中心 物理組



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

田中 実 (阪大理)

共同研究者

山本康裕(NCTS), 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(京大理), 高橋義朗(京大理)

素粒子物理学の進展2022, 基研, 2022/08/30

Light new particle search

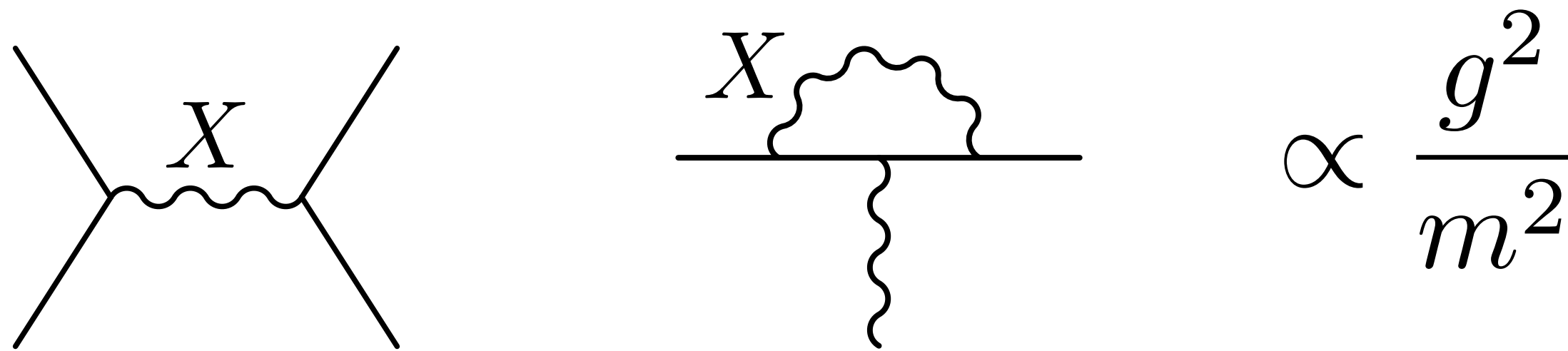
Direct search

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

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

Stable: missing E/p, dark matter?

Indirect search



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

Precision frontier

原子時計(“秒”の定義, 周波数標準)

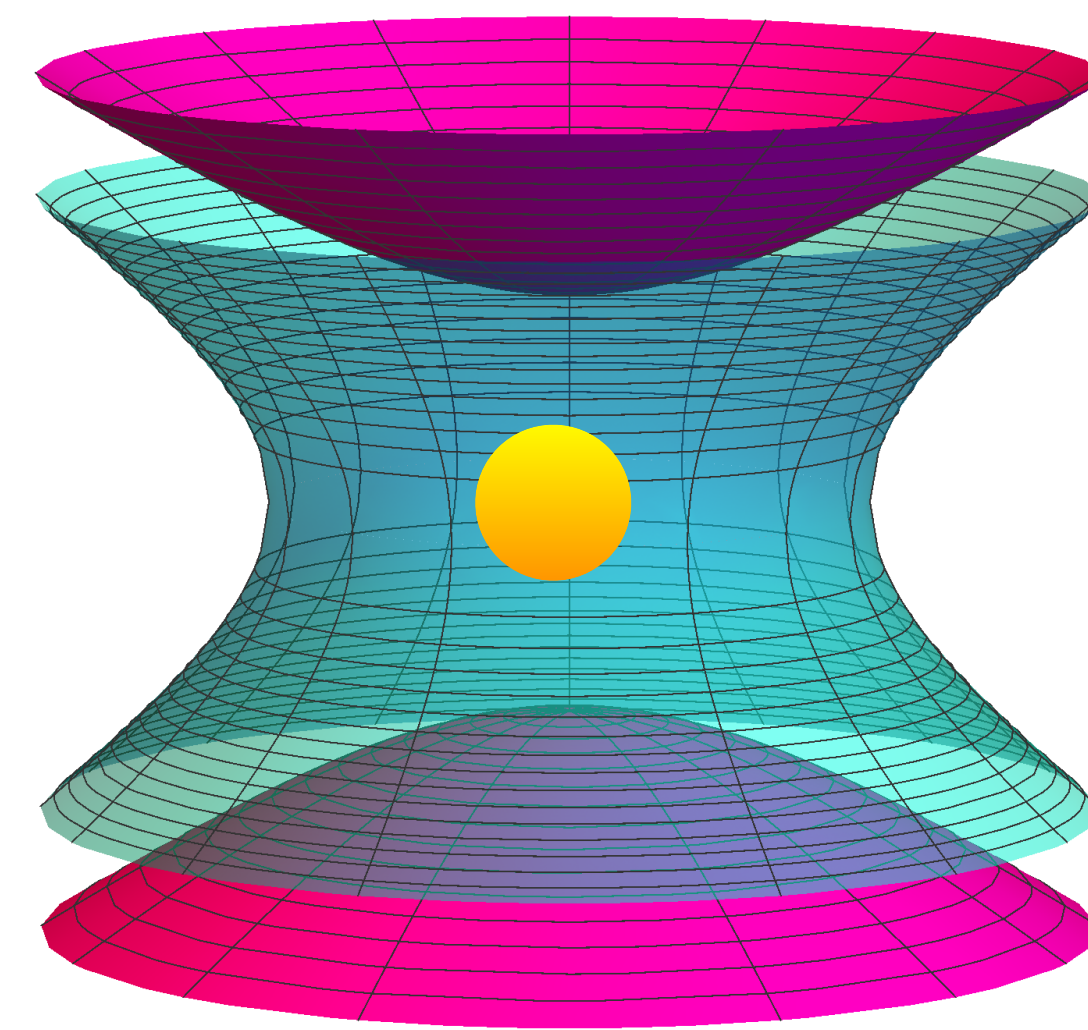
^{133}Cs ground state hyperfine splitting $\nu \sim 9 \text{ GHz}$, $\delta\nu/\nu \sim 10^{-15}$

光時計 $\nu \sim 10^{15} \text{ Hz}$

単一イオン光時計

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

Huntsman et al. PRL 116,063001 (2016)



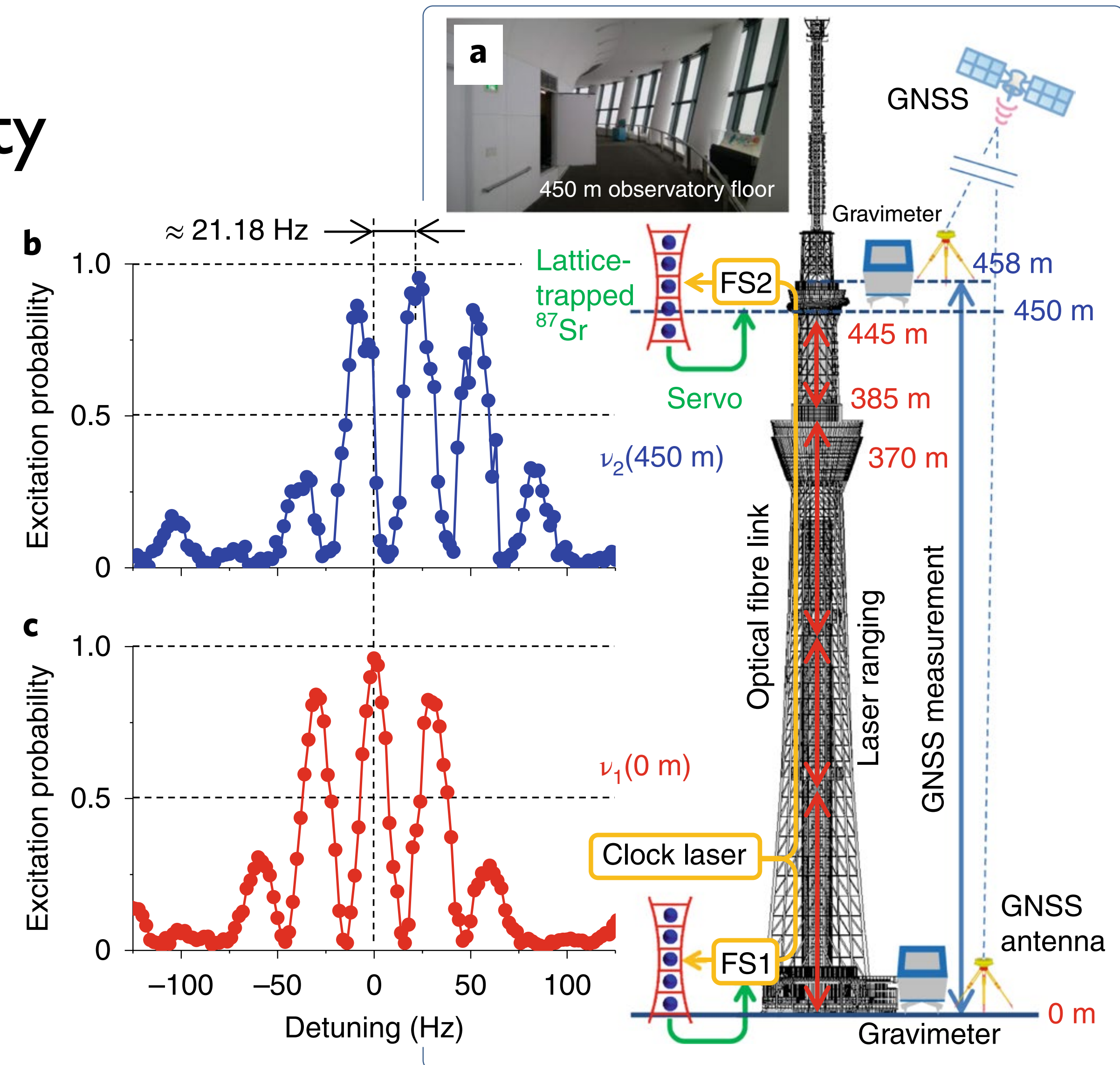
光格子時計

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

Ground test of General Relativity

$$\sim 10^{-5}$$

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

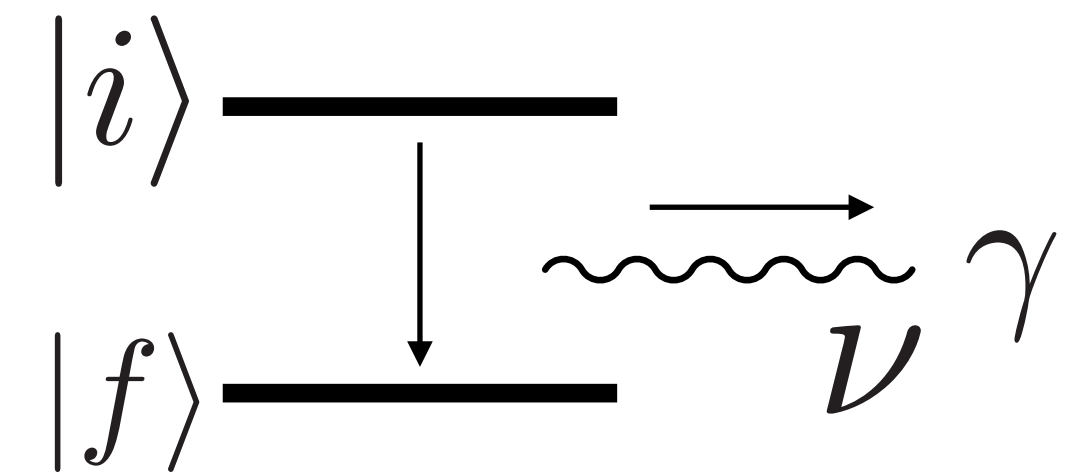


同位体シフト (Isotope shift, IS)

Level-splitting difference between isotopes

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

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



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

Mass shift: finite mass of nuclei (reduced mass)

$$\text{MS} \propto 1/m_{A'} - 1/m_A \quad (\text{dominant for } Z < 20)$$

Field shift: finite size of nuclei

$$\text{FS} \propto \langle r^2 \rangle_{A'} - \langle r^2 \rangle_A \quad (\text{dominant for } Z > 40)$$

Theoretical calculation of IS: Not easy $\text{IS} \sim O(\text{GHz}) \sim O(10 \mu\text{eV})$

キング線形性

King, 1963

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

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

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

electronic factors nuclear factor

King linearity: eliminating the nuclear factor

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

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

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

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)

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

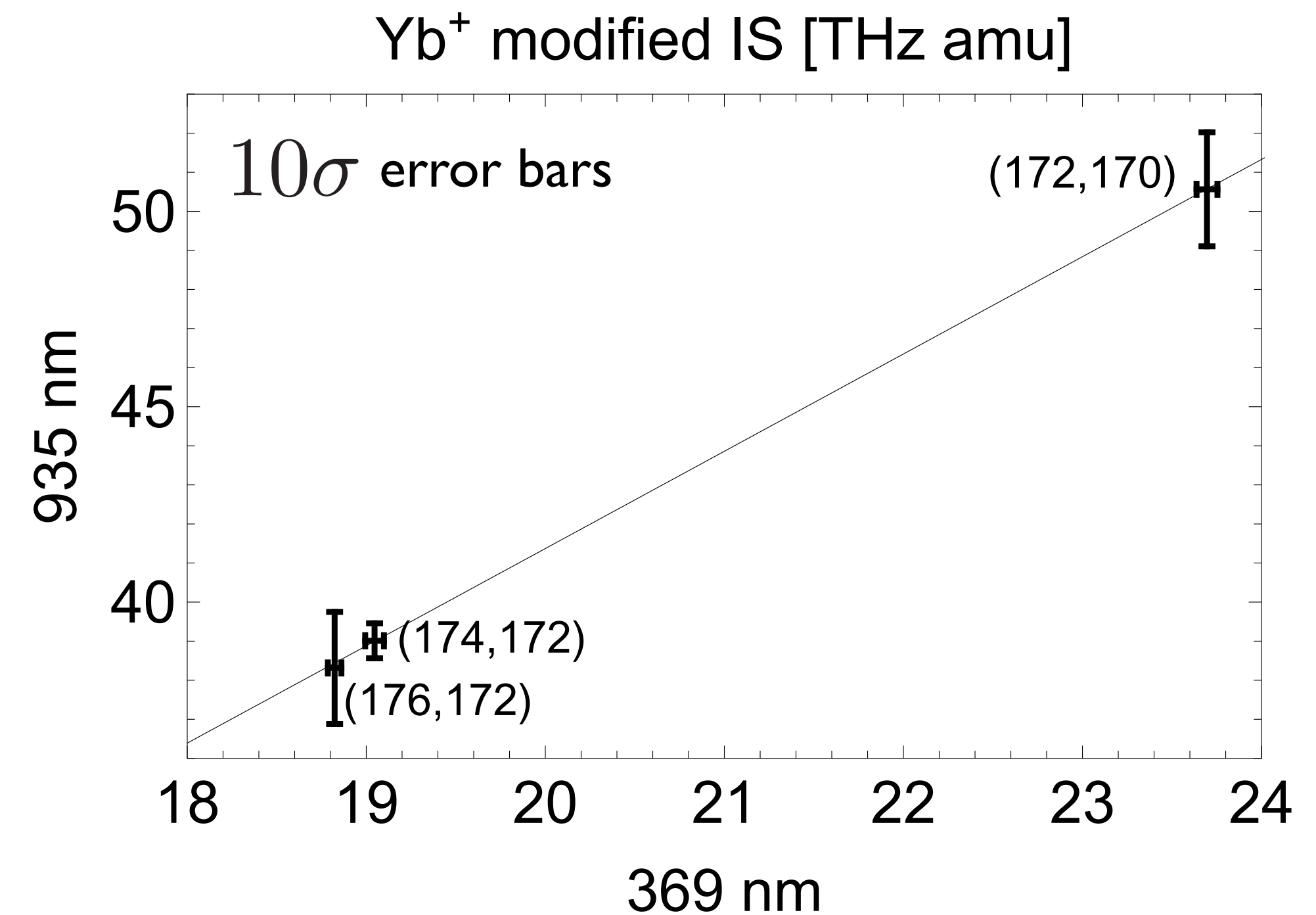
Transition 2: 935 nm

Sugiyama et al. CPEM2000

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

Isotope pairs

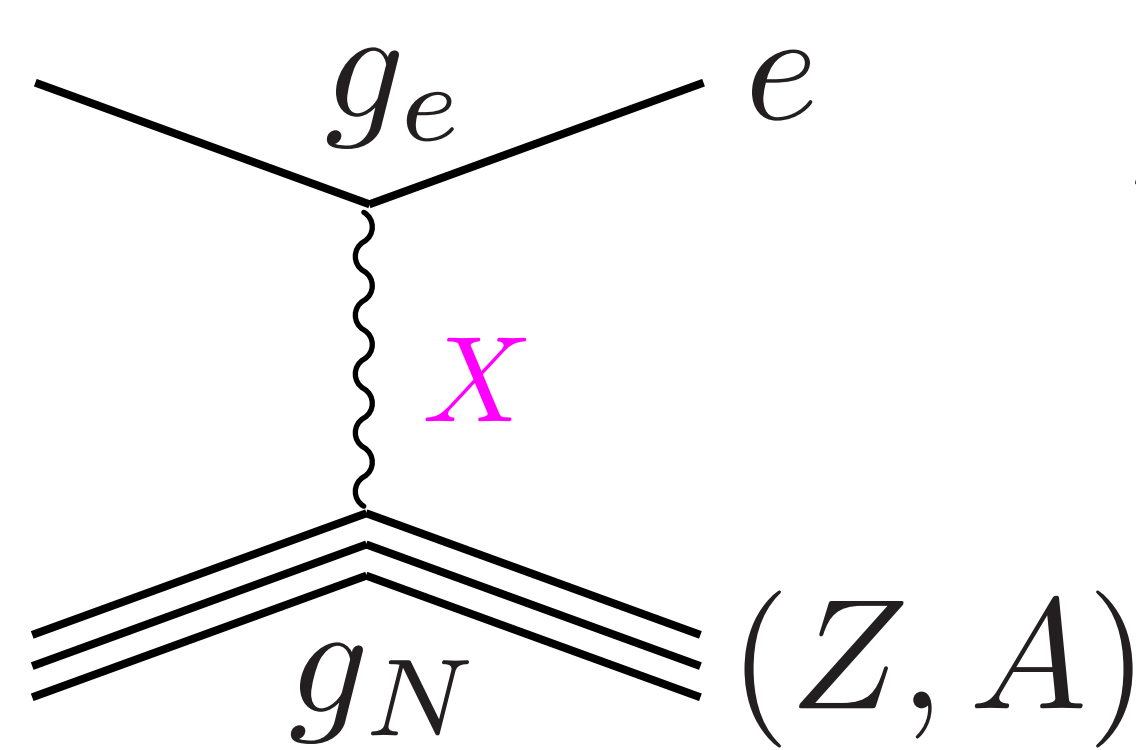
(172, 170), (174, 172), (176, 172)



線形性の破れ

IS by new **neutron-electron interaction**

Delaunay et al. arXiv:1601.05087v2



$$\nu_{A'A}^{(t)} = K_t \mu_{A'A} + F_t \langle r^2 \rangle_{A'A} + X_t (A' - A)$$

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**

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

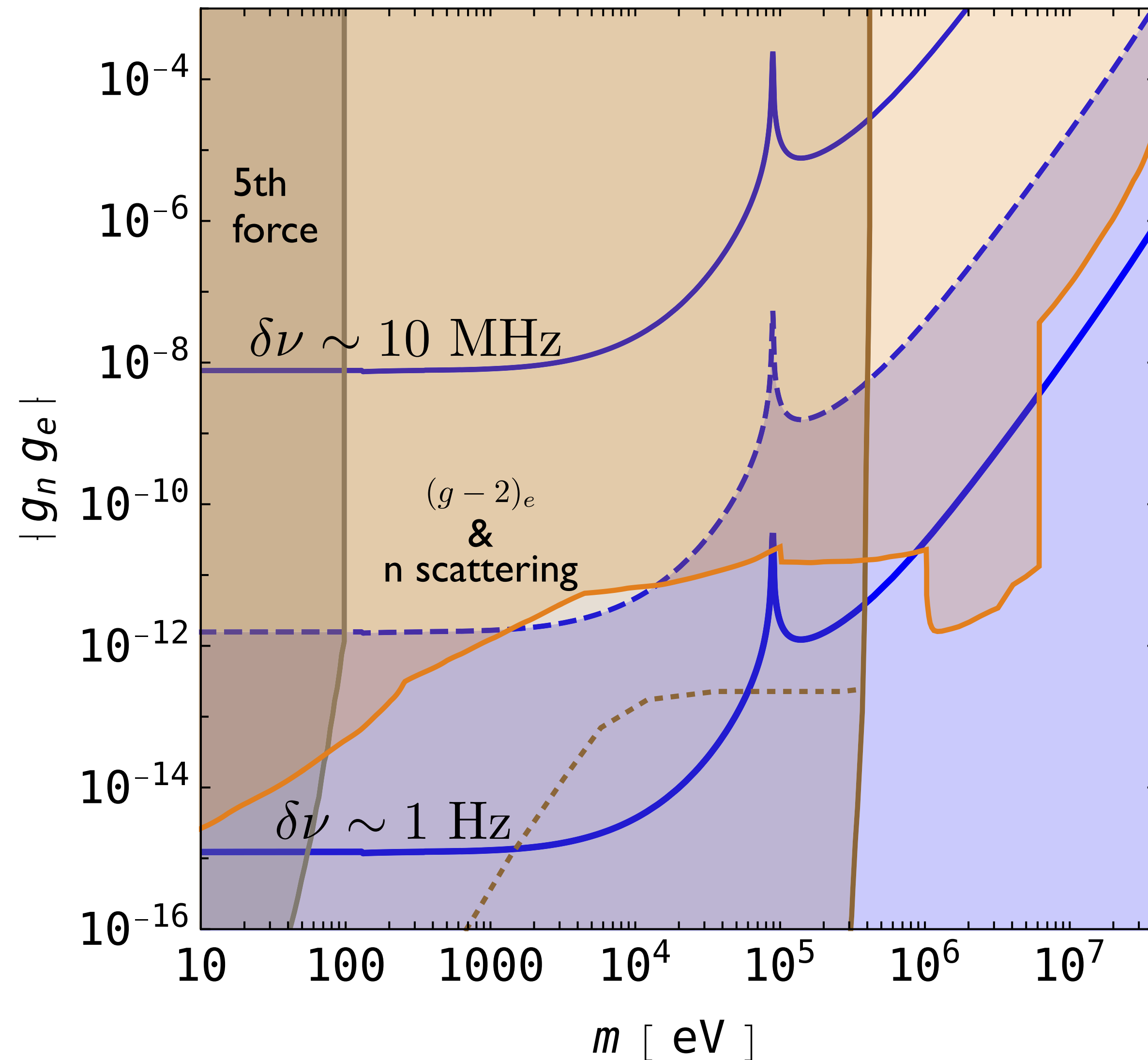
quadratic FS

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 I03B02 (2020)



Transition 1: 369 nm Martensson-Pendrill et al. PRA49, 3351 (1994)
 $^2P_{1/2}(4f)^{14}(6p) - ^2S_{1/2}(4f)^{14}(6s)$ $\delta\nu_{A'A}^1 \sim O(1)$ MHz

Transition 2: 935 nm Sugiyama et al. CPEM2000
 $^3D[3/2]_{1/2}(4f)^{13}(5d)(6s) - ^2D_{3/2}(4f)^{14}(5d)$
 $\delta\nu_{A'A}^2 \sim O(10)$ 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)

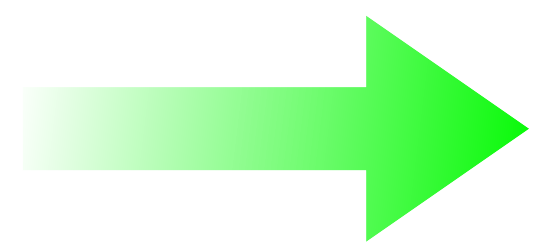
$$\nu_{A'A}^{(t)} = K_t \mu_{A'A} + F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + X_t (A' - A)$$

3 transitions: t=1, 2, 3

QFS

PS

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



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

$$(\nu_{A'A}^{(1)}, \nu_{A'A}^{(2)}, \nu_{A'A}^{(3)}) / \mu_{A'A}$$

on a plane if $X_t = 0$

n transitions and n+1 IS pairs \rightarrow 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
 $^2S_{1/2}(6s) - ^2D_{5/2}(5d)$

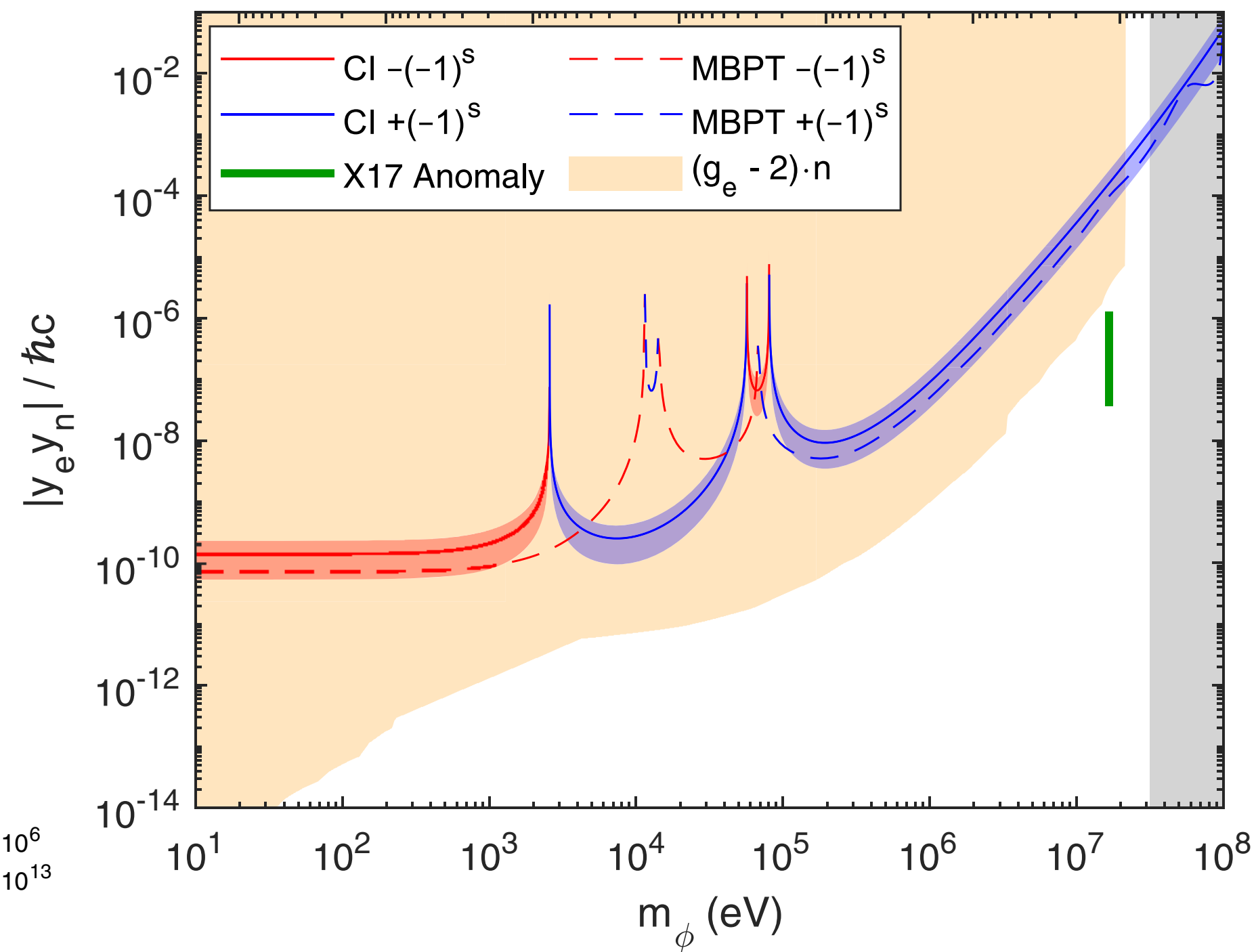
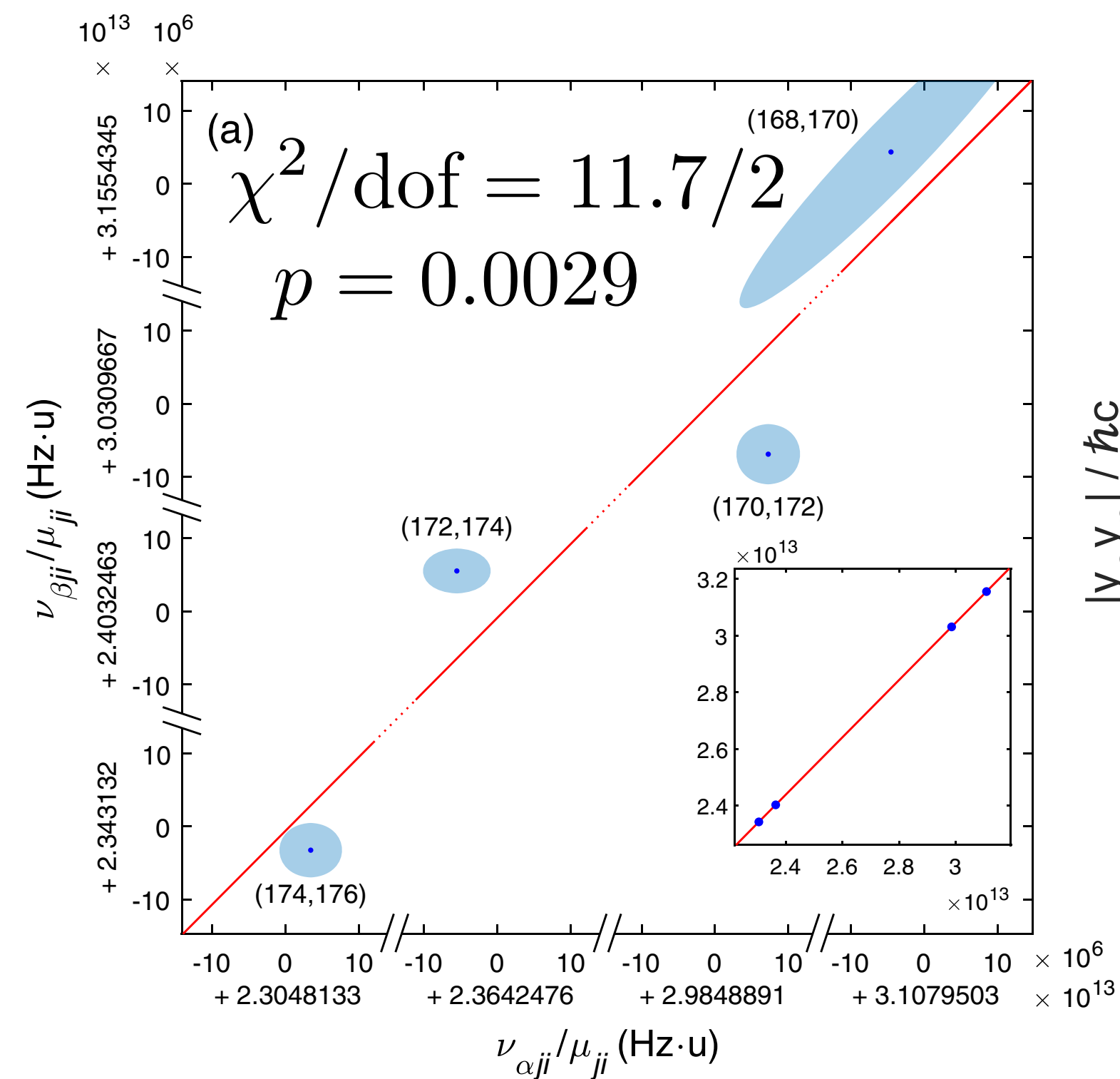
Transition 2: 436 nm
 $^2S_{1/2}(6s) - ^2D_{3/2}(5d)$

4 indep. IS pairs
A=168,170,172,174,176

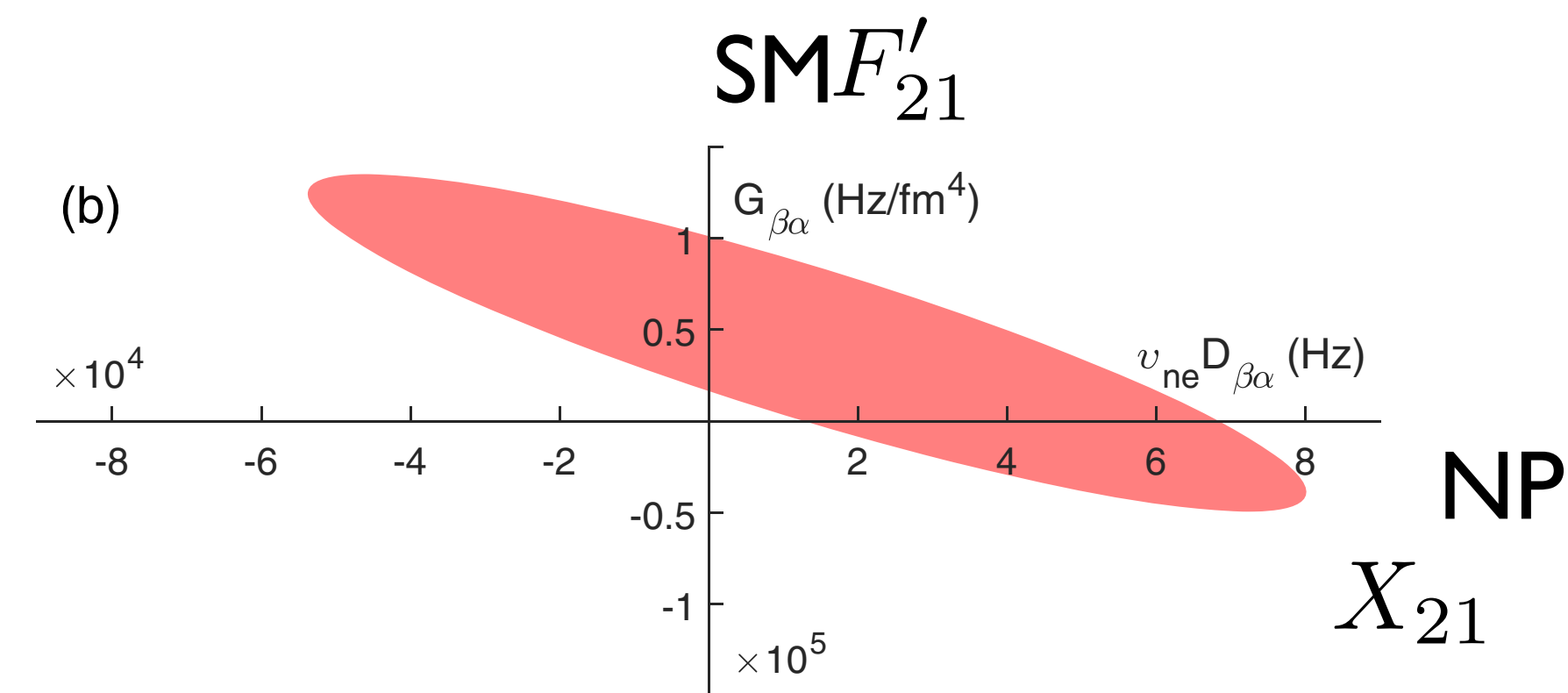
$\delta\nu \sim 300$ Hz

evidence for nonlinearity

new physics?

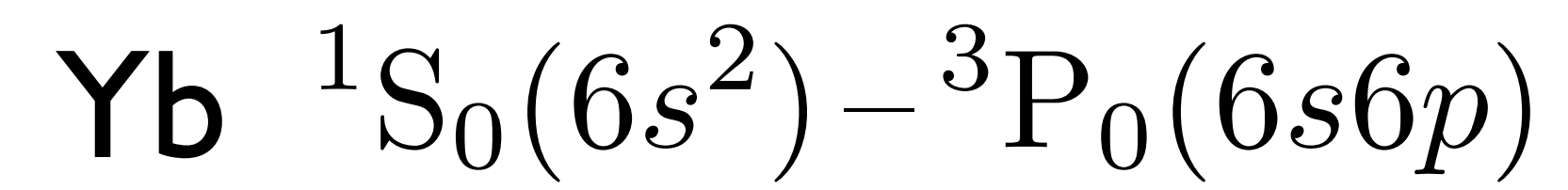


SM vs NP nonlinearities



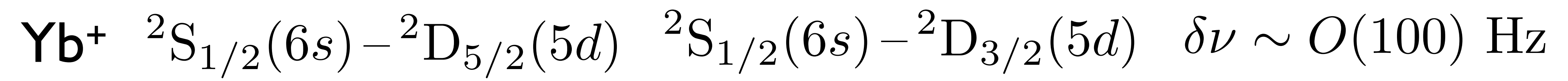
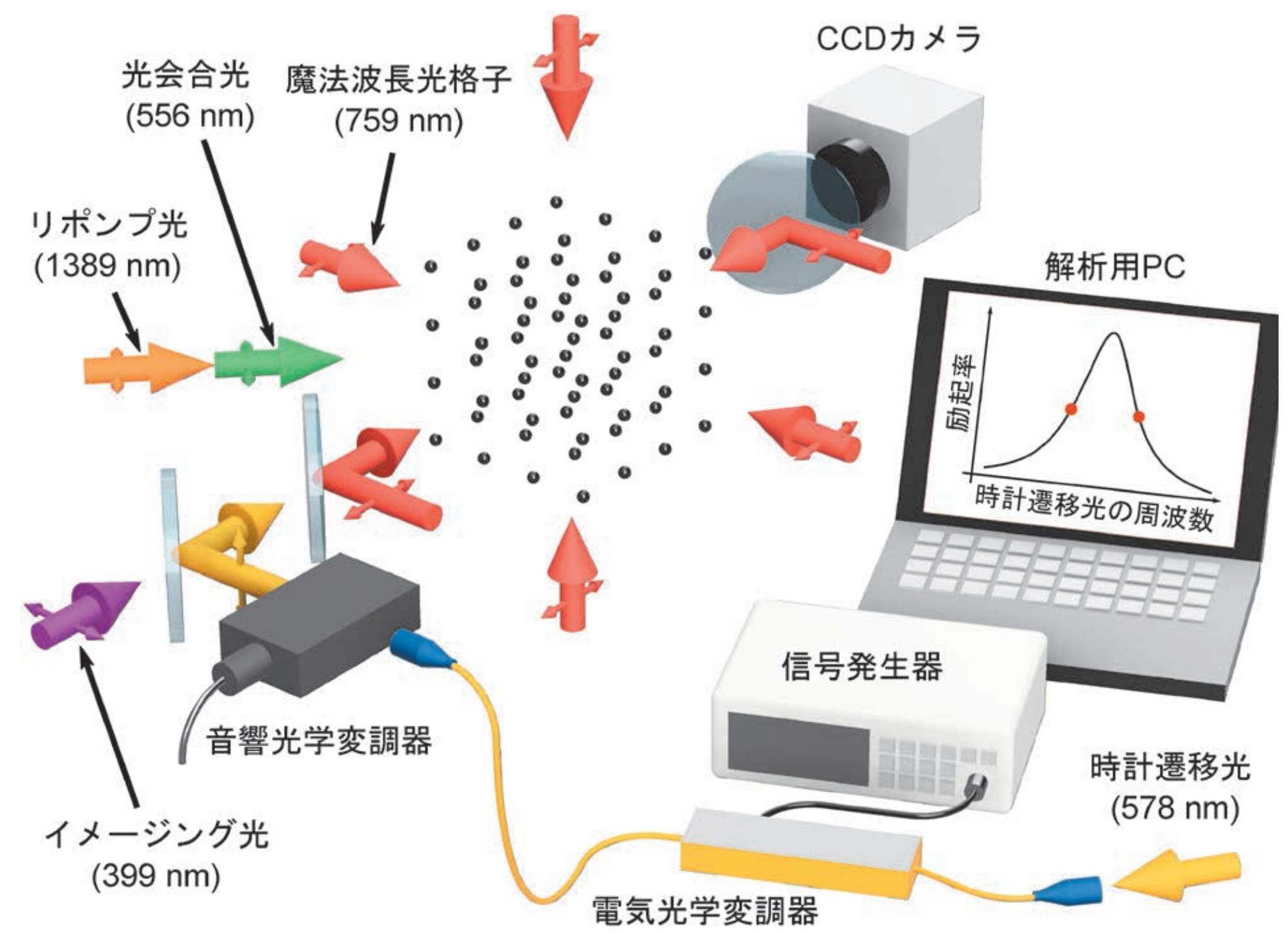
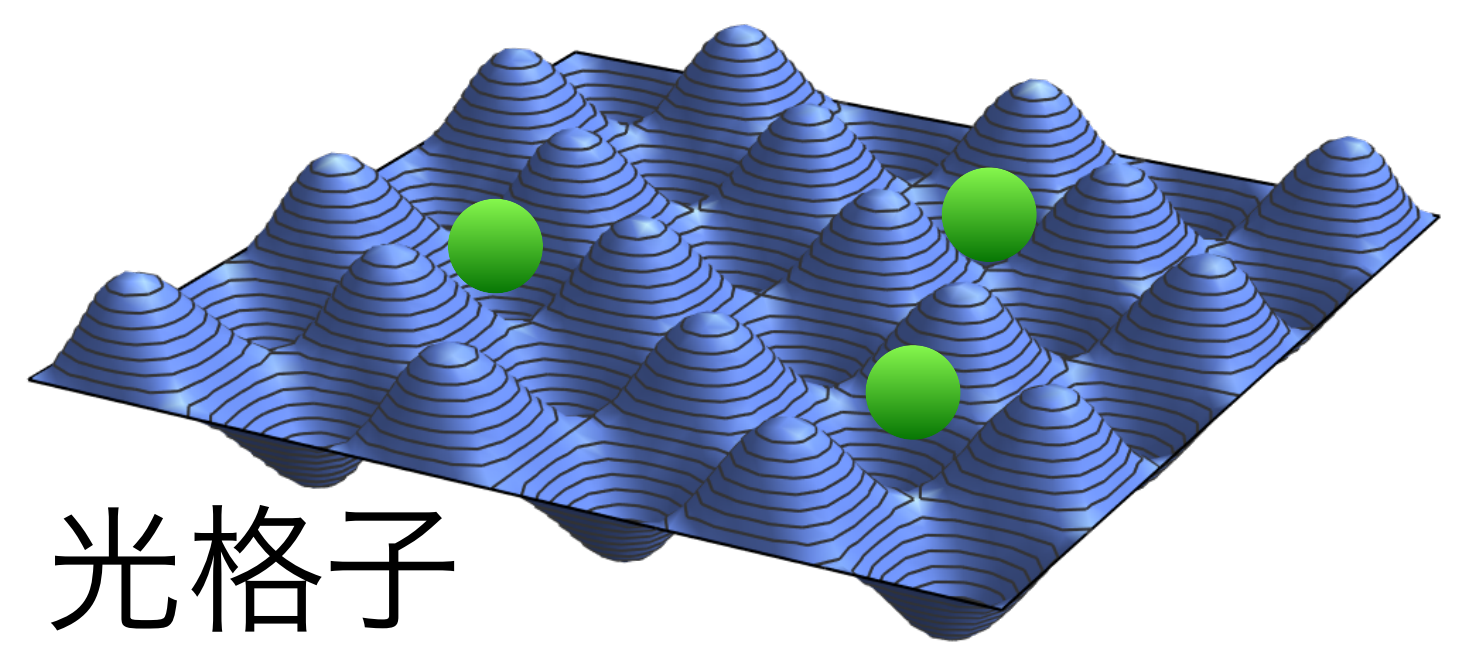
実験の進展: 中性Yb原子

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



578 nm, 4 IS pairs

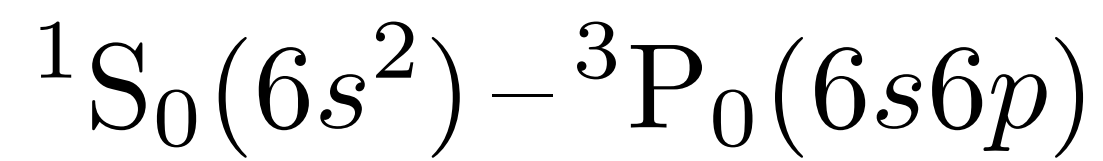
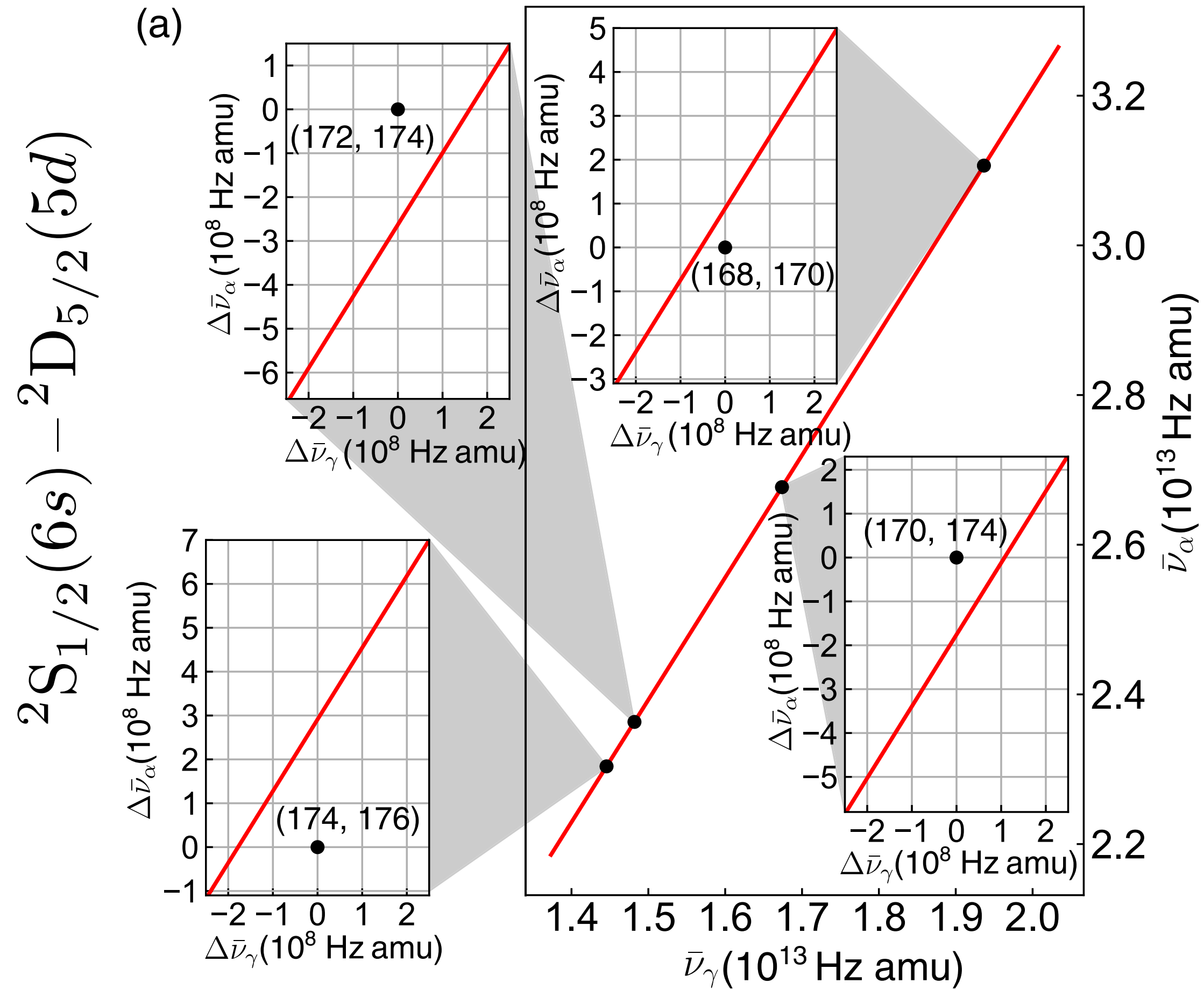
$\delta\nu \sim$ a few Hz



3 transitions, 4 IS pairs

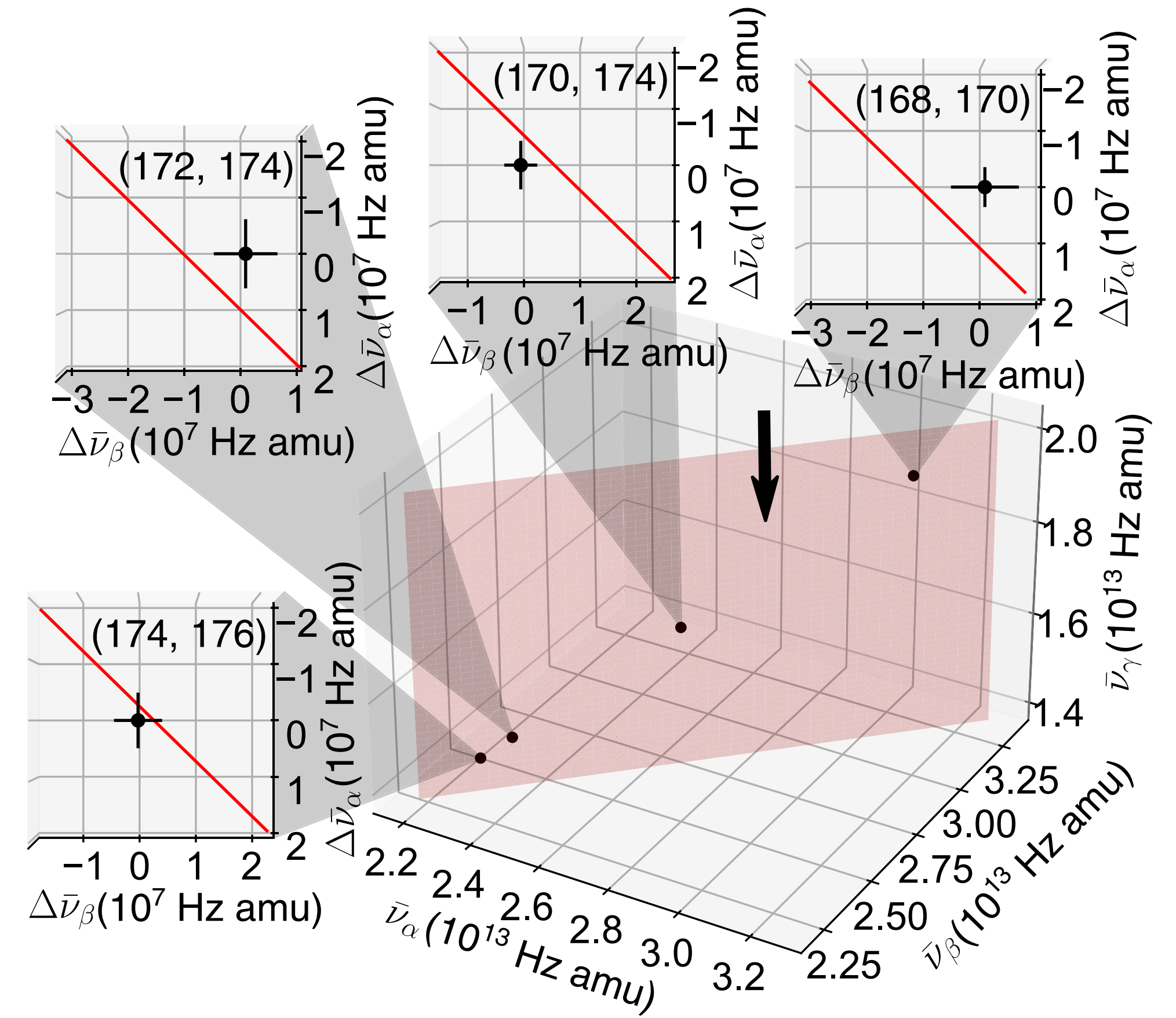
→ 一般化線形性を用いた新物理探索(世界初)

2D analysis



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

3D analysis



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

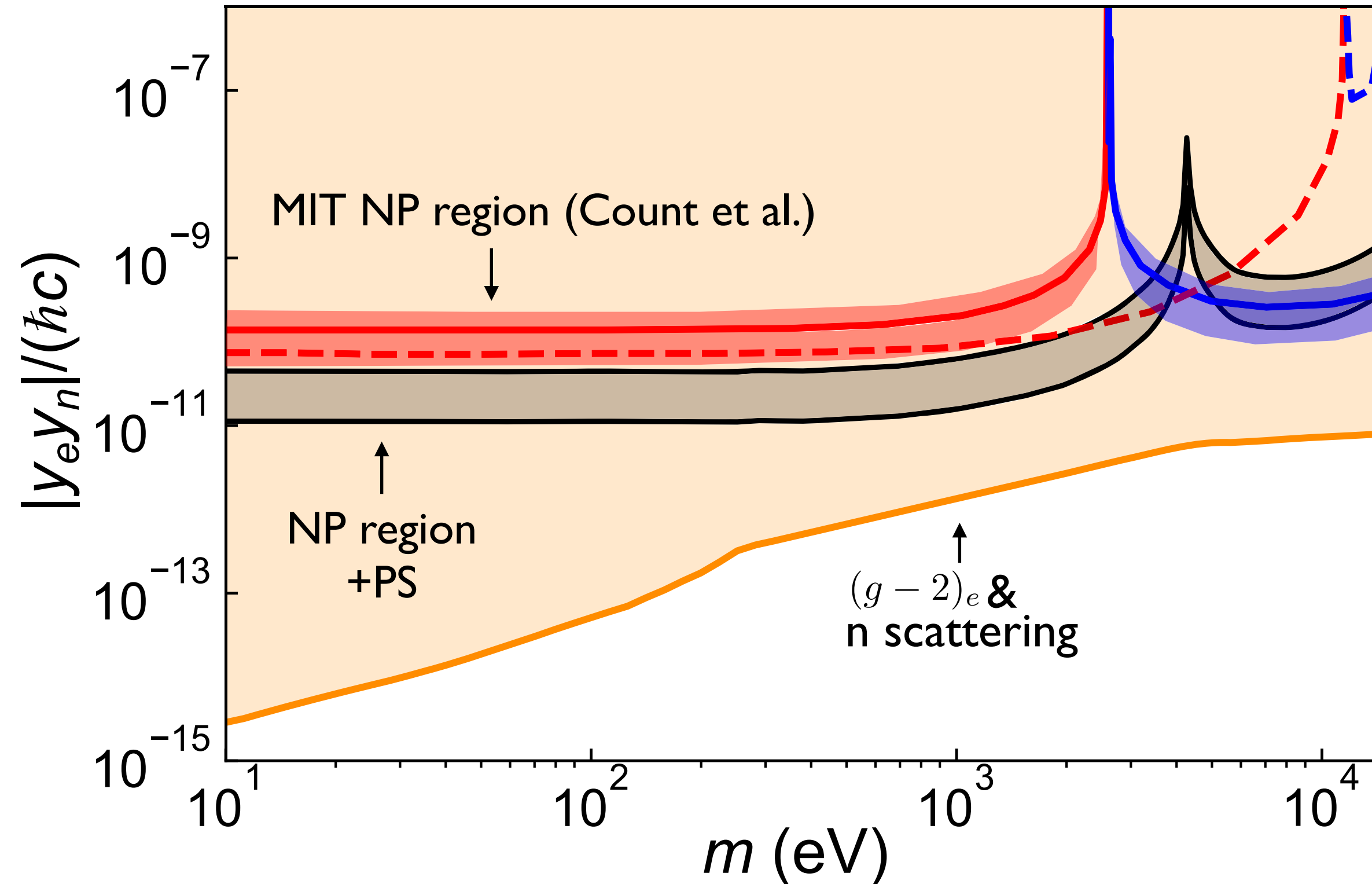


two or more NL sources

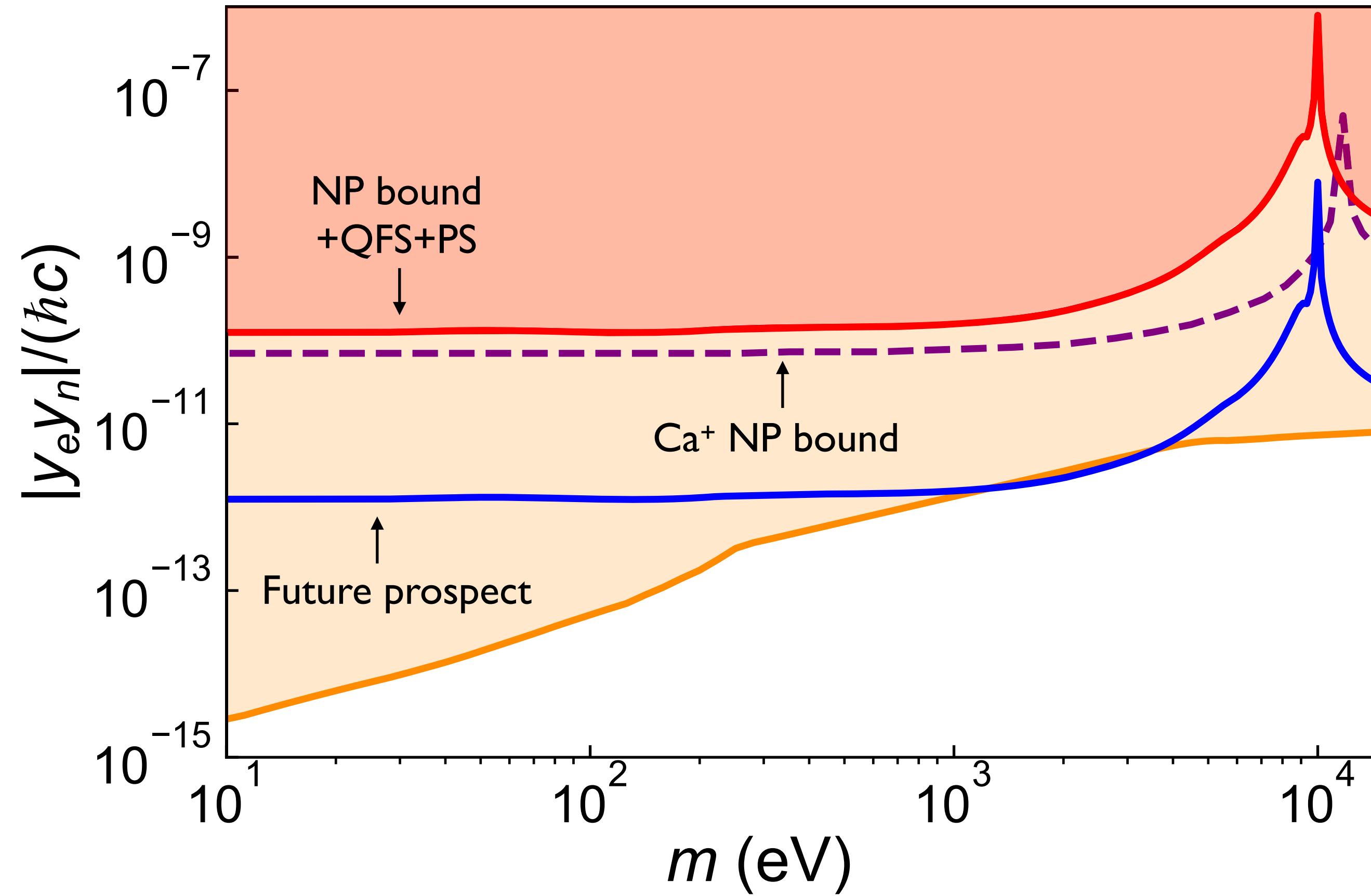
Nonlinearity sources and new physics bound

One of NL sources is eliminated in 3D analysis.

+PS: Inconsistent with the existing constraints of PS



+QFS+PS \longrightarrow New physics bound



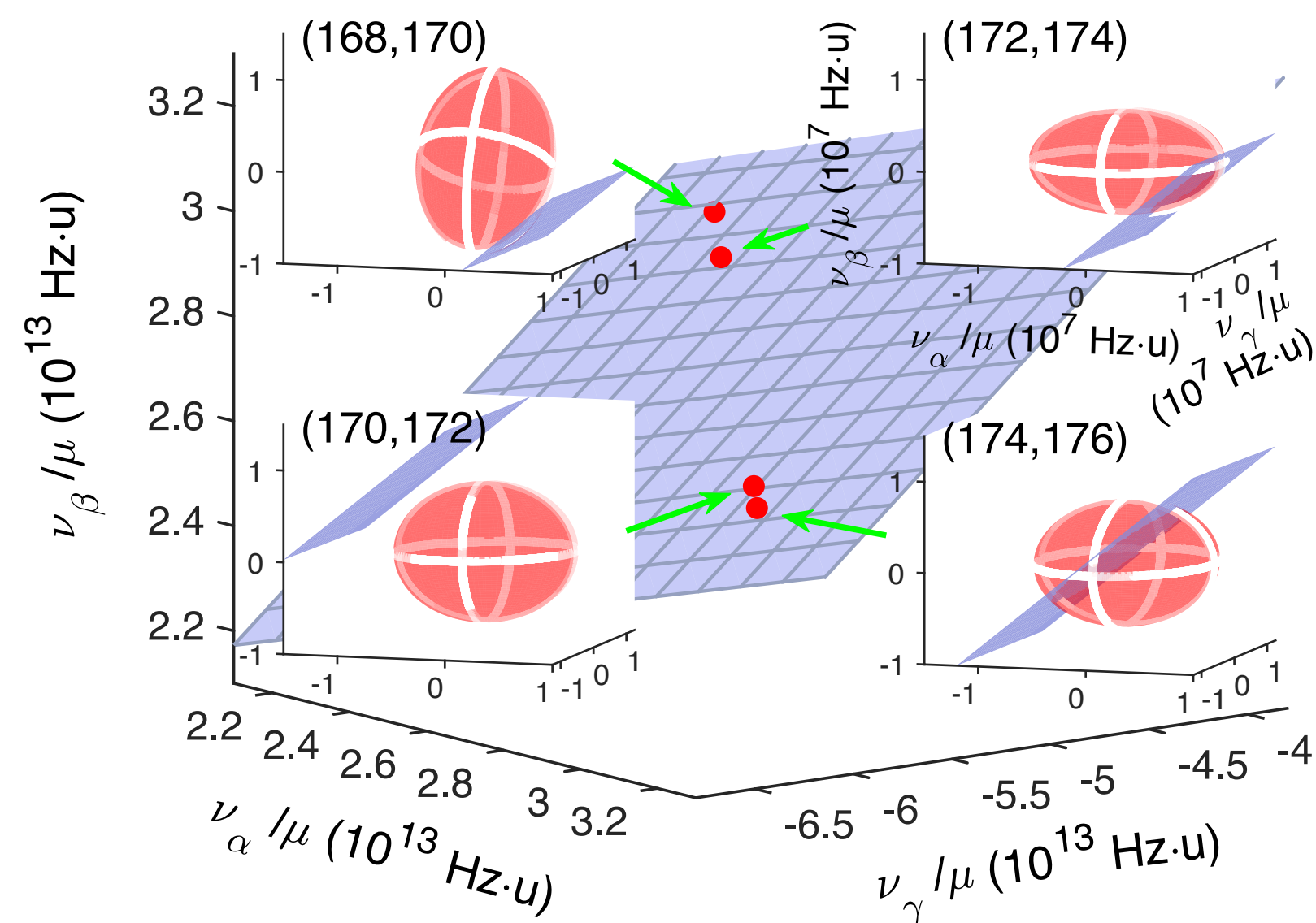
実験の進展(続き)

Yb⁺ Hur et al. PRL 128, 163201 (2022)

$$^2S_{1/2}(4f)^{14}(6s) - ^2F_{7/2}(4f)^{13}(6s)^2$$

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

3D analysis 3.2σ

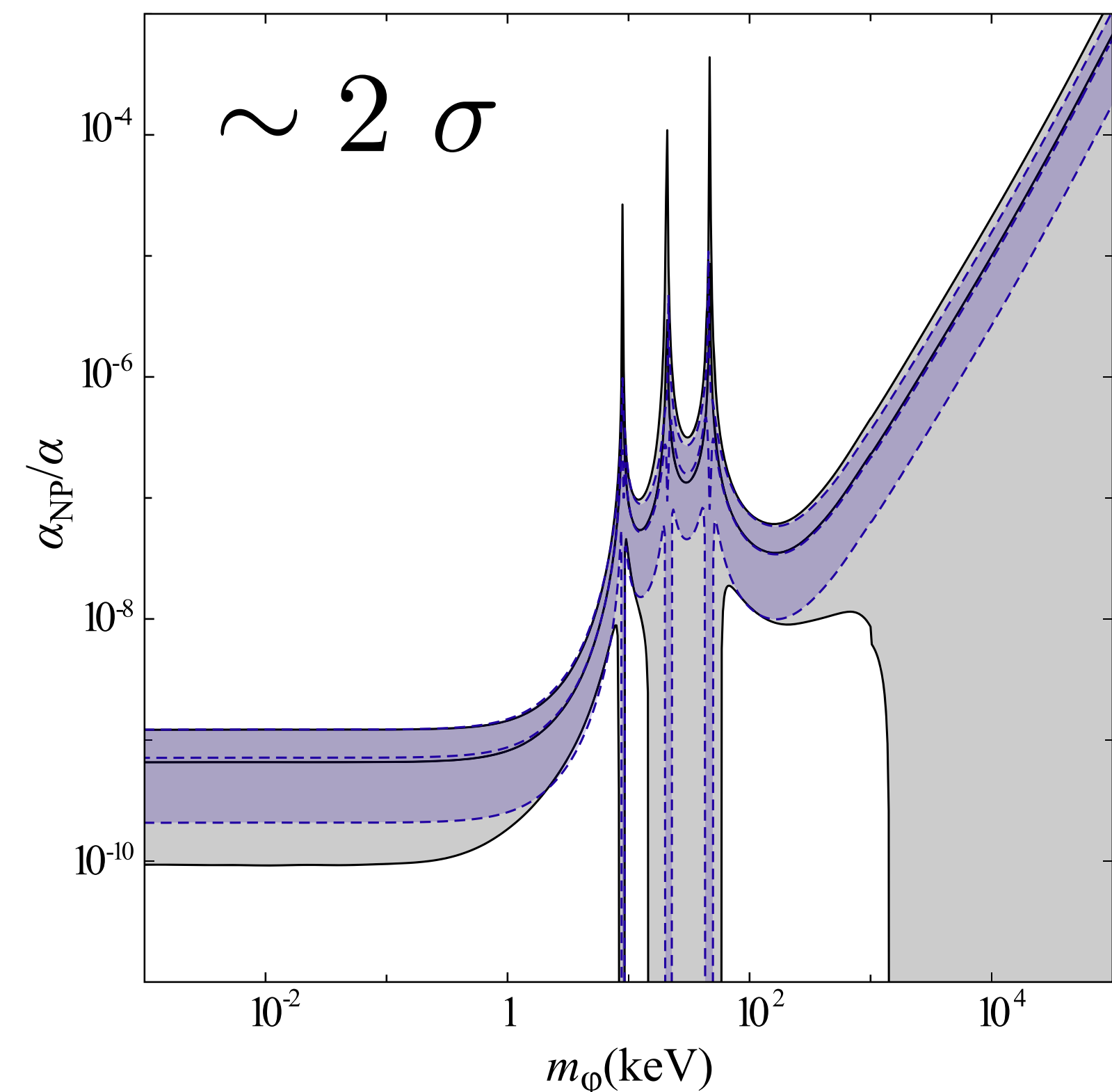


Consistent with our result

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

$$^1S_0(6s)^2 - ^1D_2(6s5d) \quad \delta\nu \sim O(100) \text{ Hz}$$

3D analysis: reduced significance



まとめと展望

- **Isotope shift and King linearity** $\tilde{\nu}_{A'A}^{(2)} = K_{21} + F_{21}\tilde{\nu}_{A'A}^{(1)}$
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