Physics
OSAKA UNIVERSITY

科研費
KAKENHI

原子遷移過程で探る素粒子物理

田中 実（阪大）

杜の都素粒子ワークショップ —Yasuhiro Okada Festa—, 2025/3/13-14

右から,
岡田さん
田中
Czarneckiさん
野村さん

“New Initiatives in Muon Lepton Flavor Violation and Neutrino Oscillation with High Intense Muon and Neutrino Sources"

University of Hawaii in Honolulu, Oct. 2-6, 2000

Introduction

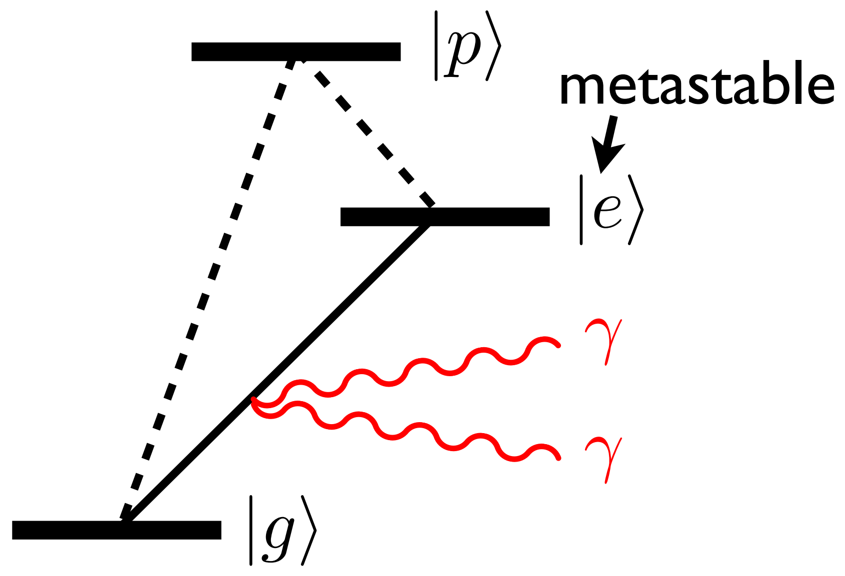
Precision frontier in fundamental physics

Development of precision spectroscopy / optical clock

Temporal variation of fundamental constants, α, m_e/m_p

$\mathrm{Yb}^+ : \ \delta\nu/\nu \sim 10^{-18}, \ \delta\nu \sim \mathrm{sub\ Hz}$ Huntemann et al. (PTB) 2016

Rate enhancement with quantum coherence



Paired Super-Radiance (PSR): $|e\rangle \to |g\rangle + \gamma + \gamma$

M. Yoshimura, N. Sasao, MT, PRA86, 013812 (2012)

macroscopic amplification by coherence ρ_{eg}

Para-hydrogen PSR experiment @Okayama U

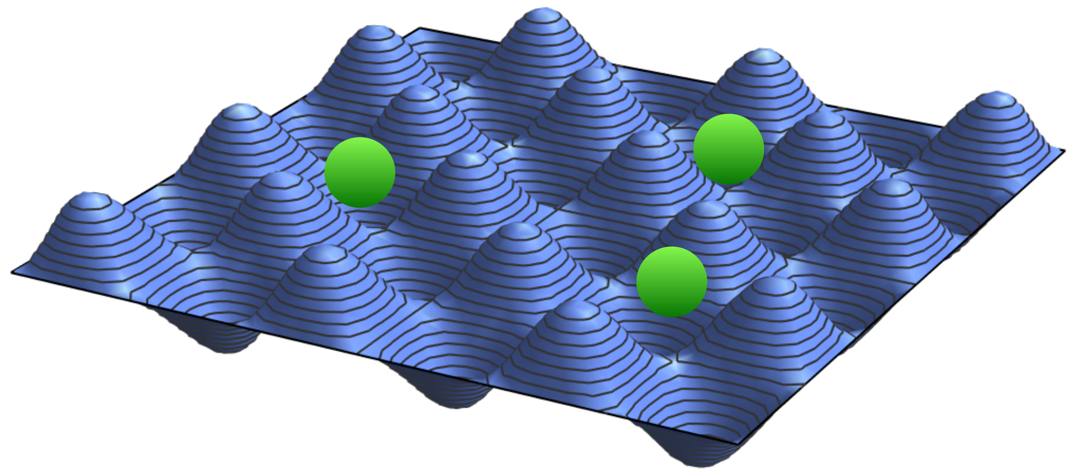
Y. Miyamoto et al. PTEP113C01(2014), PTEP081C01(2015)

10^{18} enhancement achieved

今，主にやっていること

Isotope shift with high precision spectroscopy

search for new neutron-electron interaction

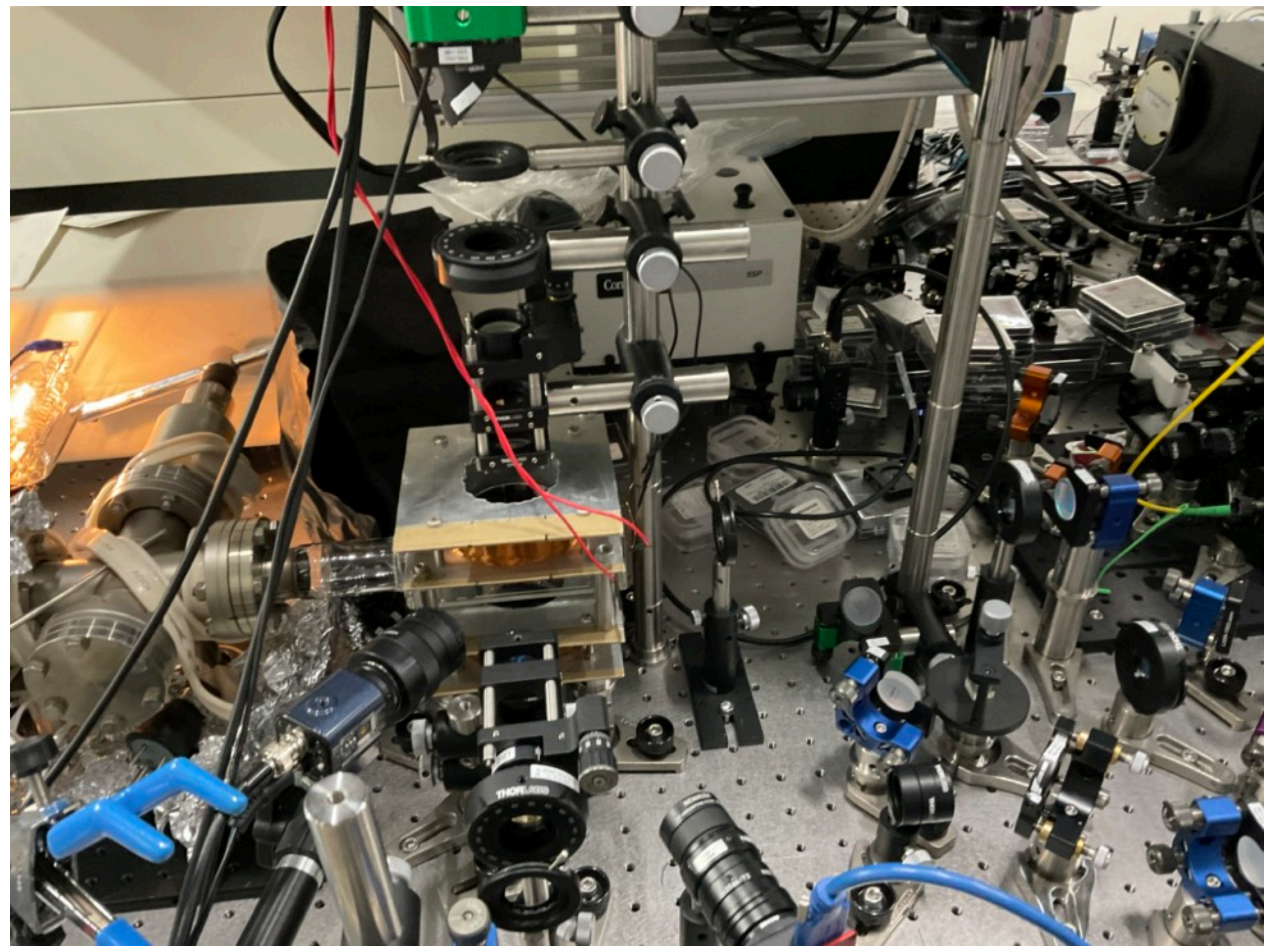


Yb atoms in an optical lattice

Takahashi group, Kyoto U

Dark matter search with macro-coherent amplification

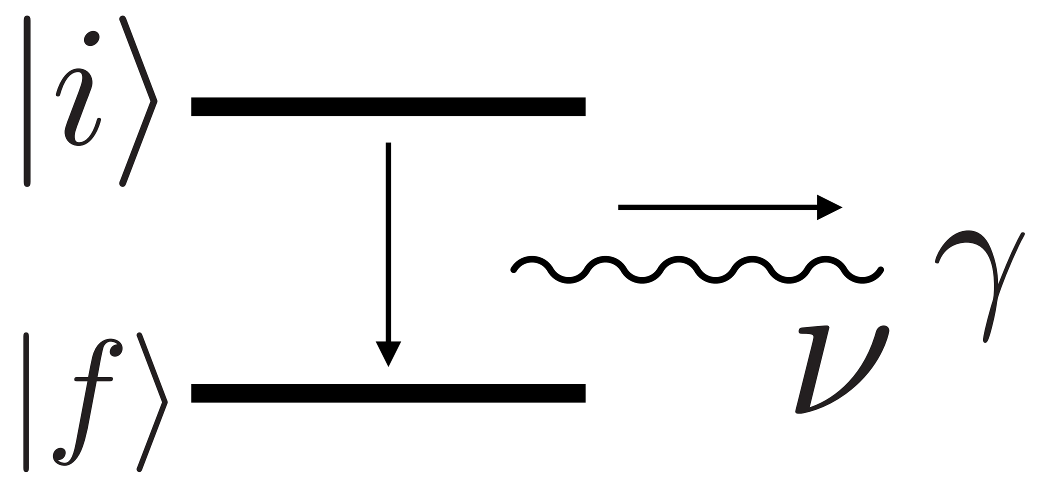
light halo dark matter,
e.g. axion, dark photon



Cesium vapor
@Okayama U

Isotope Shift

Isotope shift (IS) and King linearity



Level-splitting difference between isotopes

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

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

electronic factors nuclear factor

King linearity: eliminating the nuclear factor King, 1963

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

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

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

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Ex. Yb⁺

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

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

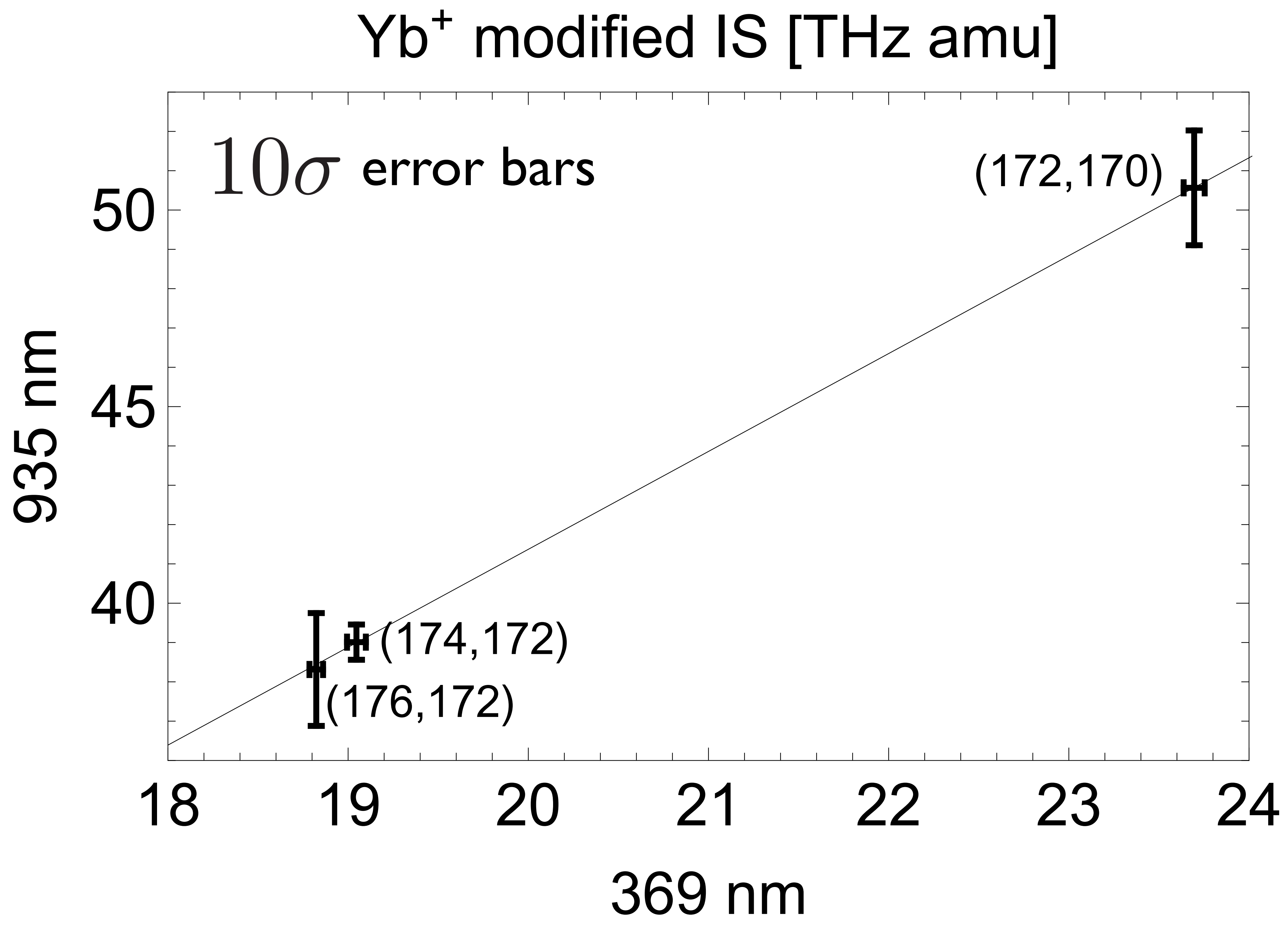
Sugiyama et al. CPEM2000

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

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

Isotope pairs

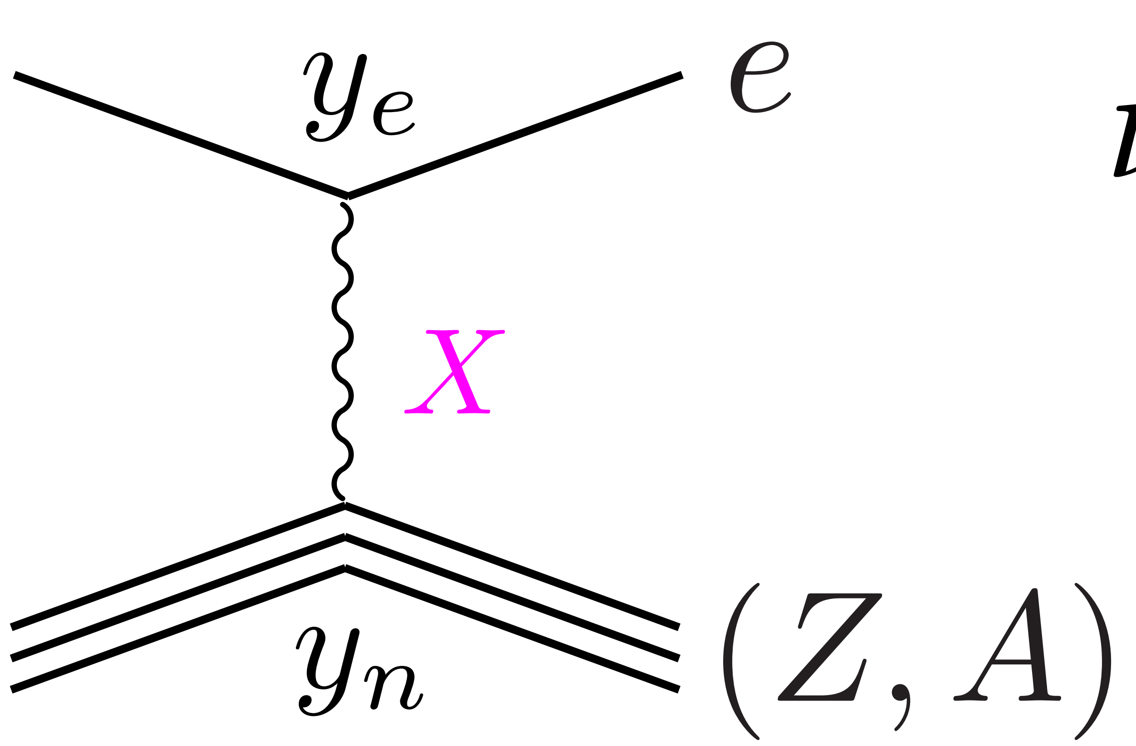
(172, 170), (174,172), (176,172)



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

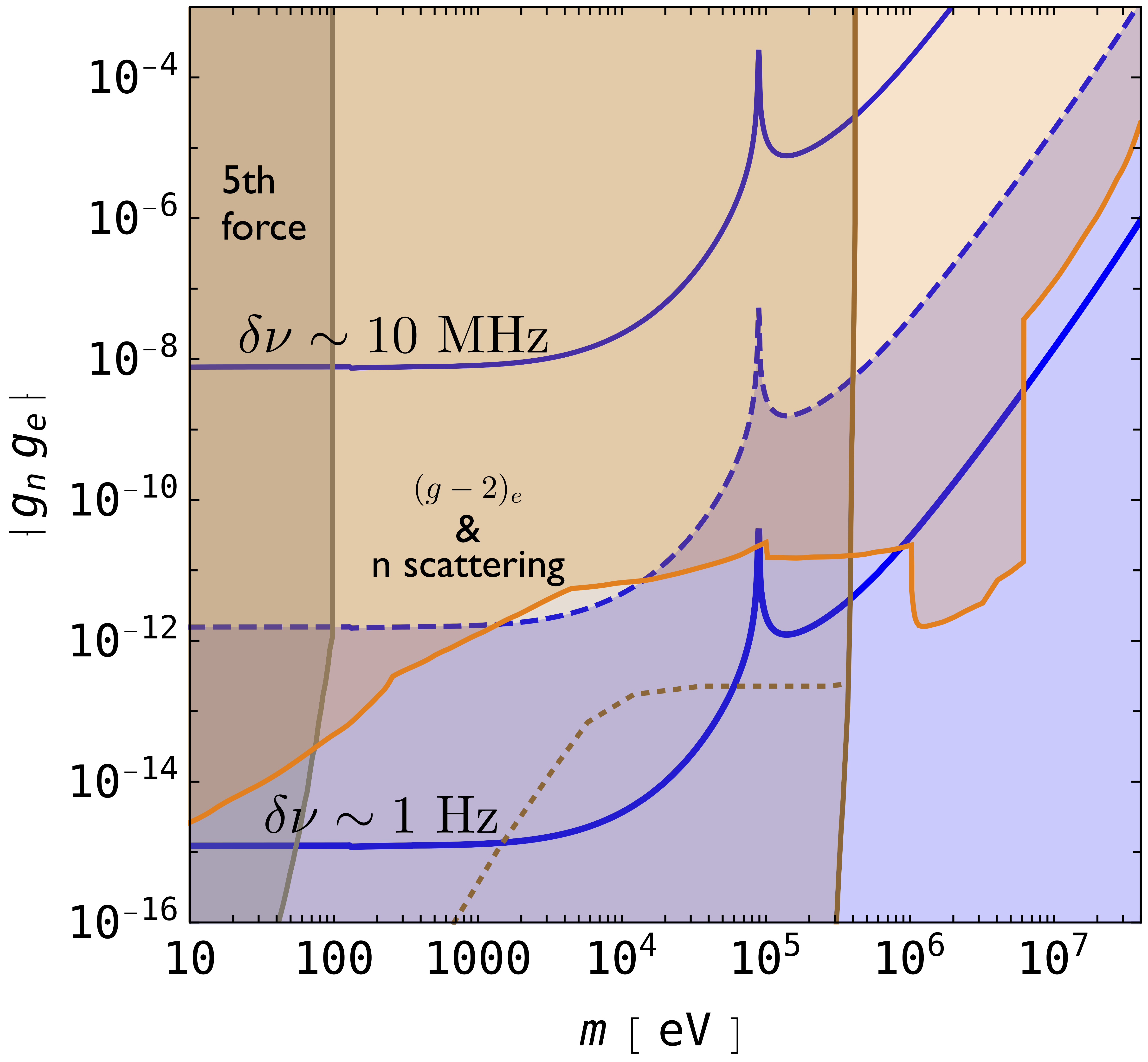
$$\mathrm{FS} = F_t \langle r^2 \rangle_{A'A} + F'_t [\langle r^2 \rangle_{A'A}]^2 + G_t \langle r^4 \rangle_{A'A} + \cdots$$

quadratic FS (FS_{22}) higher moment (FS_4)

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

Ex. Yb^+

MT, Y.Yamamoto PTEP 103B02 (2020)



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

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

Transition 2: 935 nm Sugiyama et al. CPEM2000

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

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

Yb^+ bounds

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

FSNL dominance:

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

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 FS$_{22}$ PS

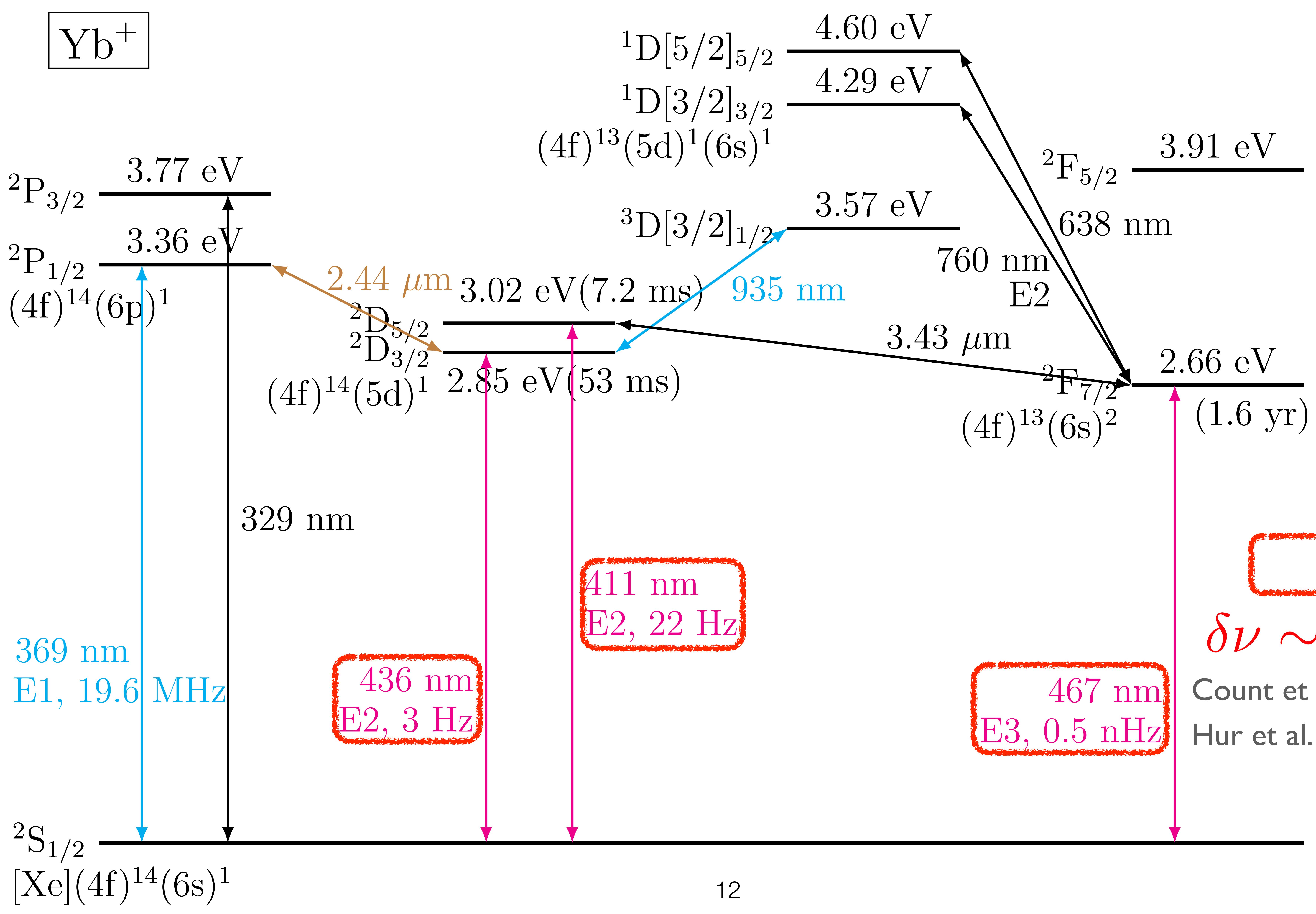
$$\begin{pmatrix} \nu^{(1)}_{A'A} - X_1(A'-A) \\ \nu^{(2)}_{A'A} - X_2(A'-A) \\ \nu^{(3)}_{A'A} - X_3(A'-A) \end{pmatrix} = \begin{pmatrix} K_1 & F_1 & F'_1 \\ K_2 & F_2 & F'_2 \\ K_3 & F_3 & F'_3 \end{pmatrix} \begin{pmatrix} \mu_{A'A} \\ \langle r^2 \rangle_{A'A} \\ [\langle r^2 \rangle_{A'A}]^2 \end{pmatrix}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

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

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

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

Data of Yb transitions



LS coupling

$^{2s+1}L_J$

MIT

$\delta\nu \sim 300 - 500$ Hz

Count et al. PRL 125, 123002 (2020)

Hur et al. PRL 128, 163201 (2022)

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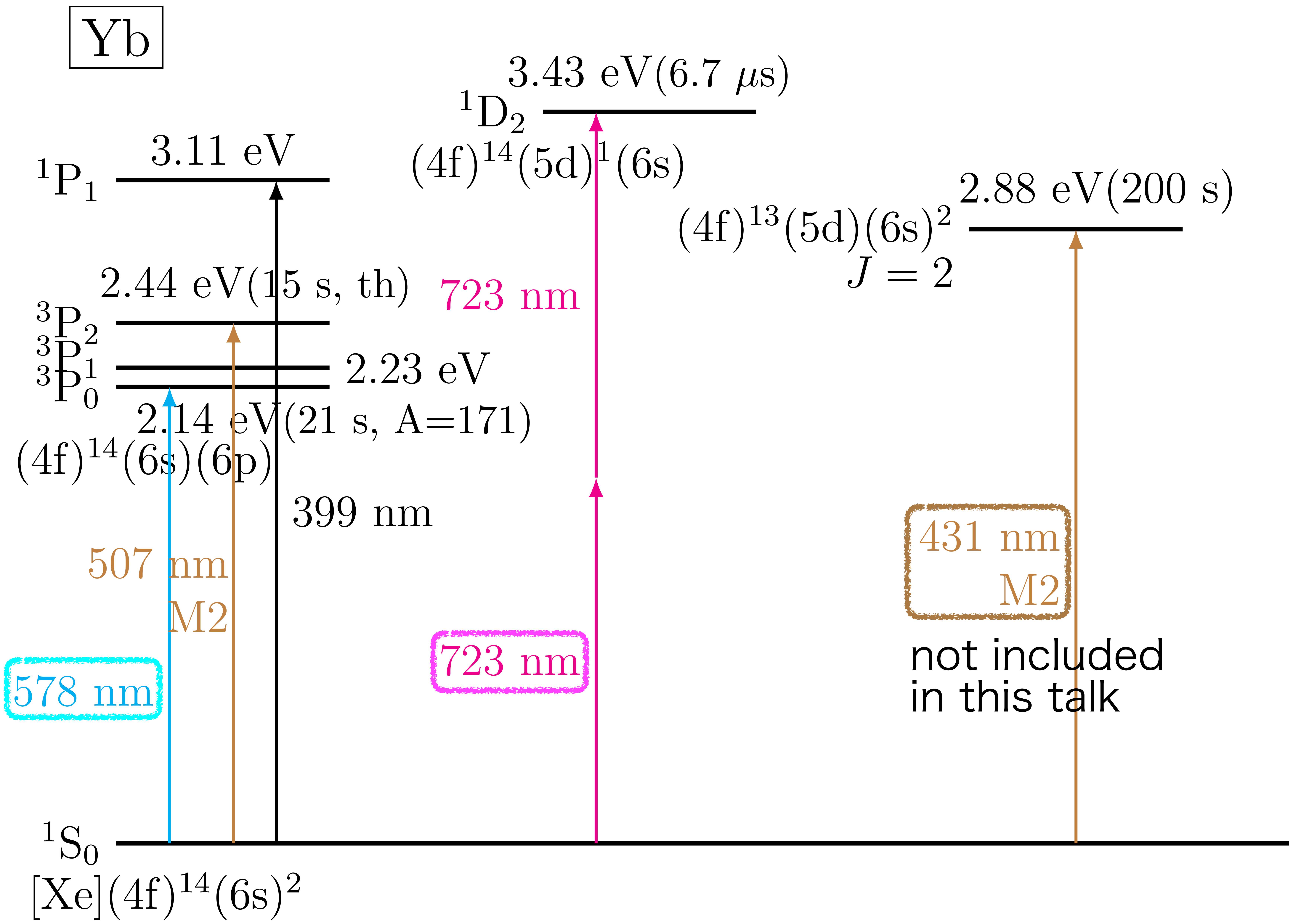
LS coupling

$^{2s+1}L_J$



Kyoto

$\delta\nu \sim$ a few Hz

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

Mainz

Figueroa et al. PRL 128, 073001 (2022)

$\delta\nu \sim O(100)$ Hz

Kyoto

T. Ishiyama et al. PRL 130, 153402 (2023)

NMIJ,AIST

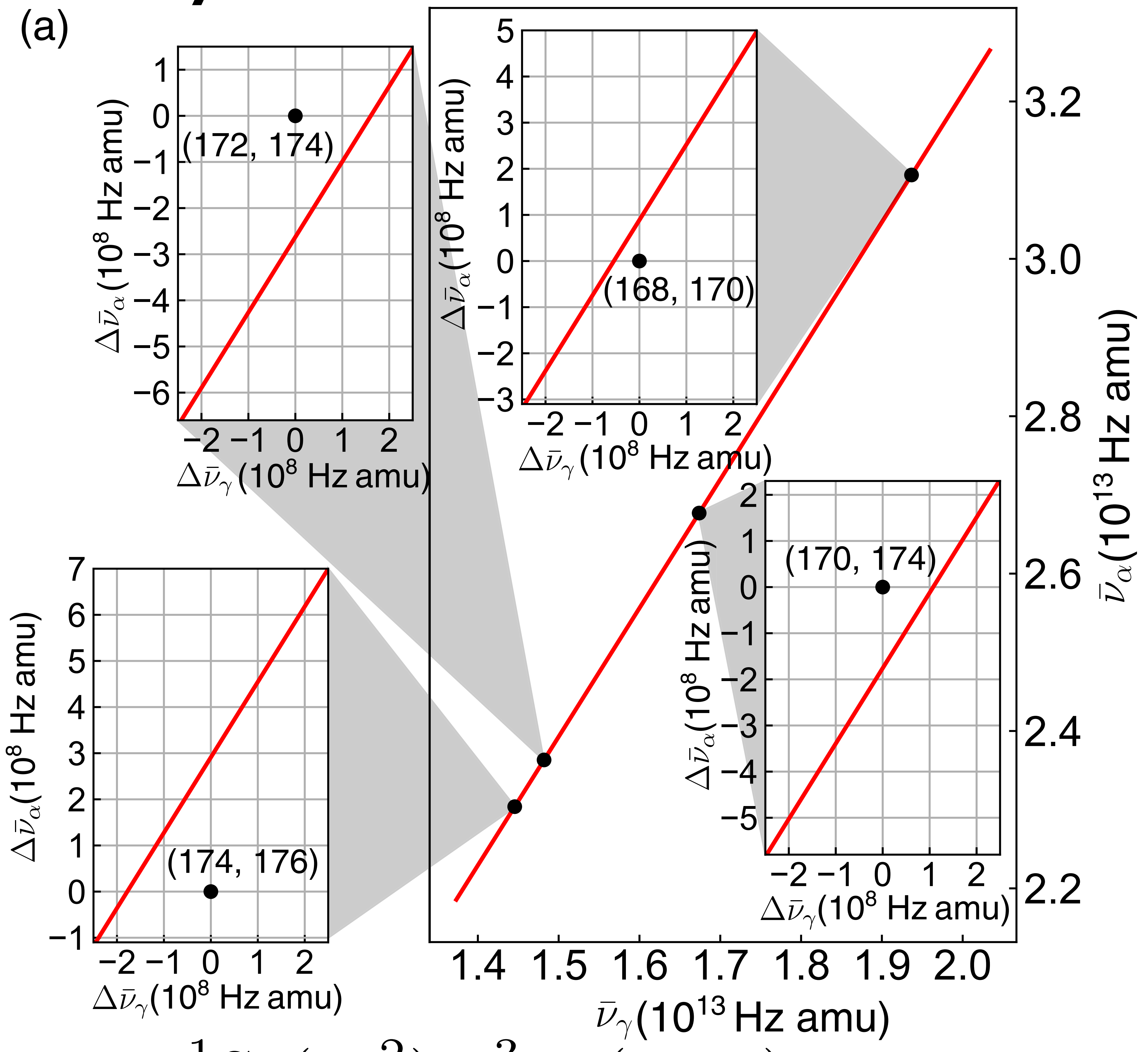
A. Kawasaki et al. PRA 109, 062806 (2024)

MIT+Kyoto

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

2D analysis

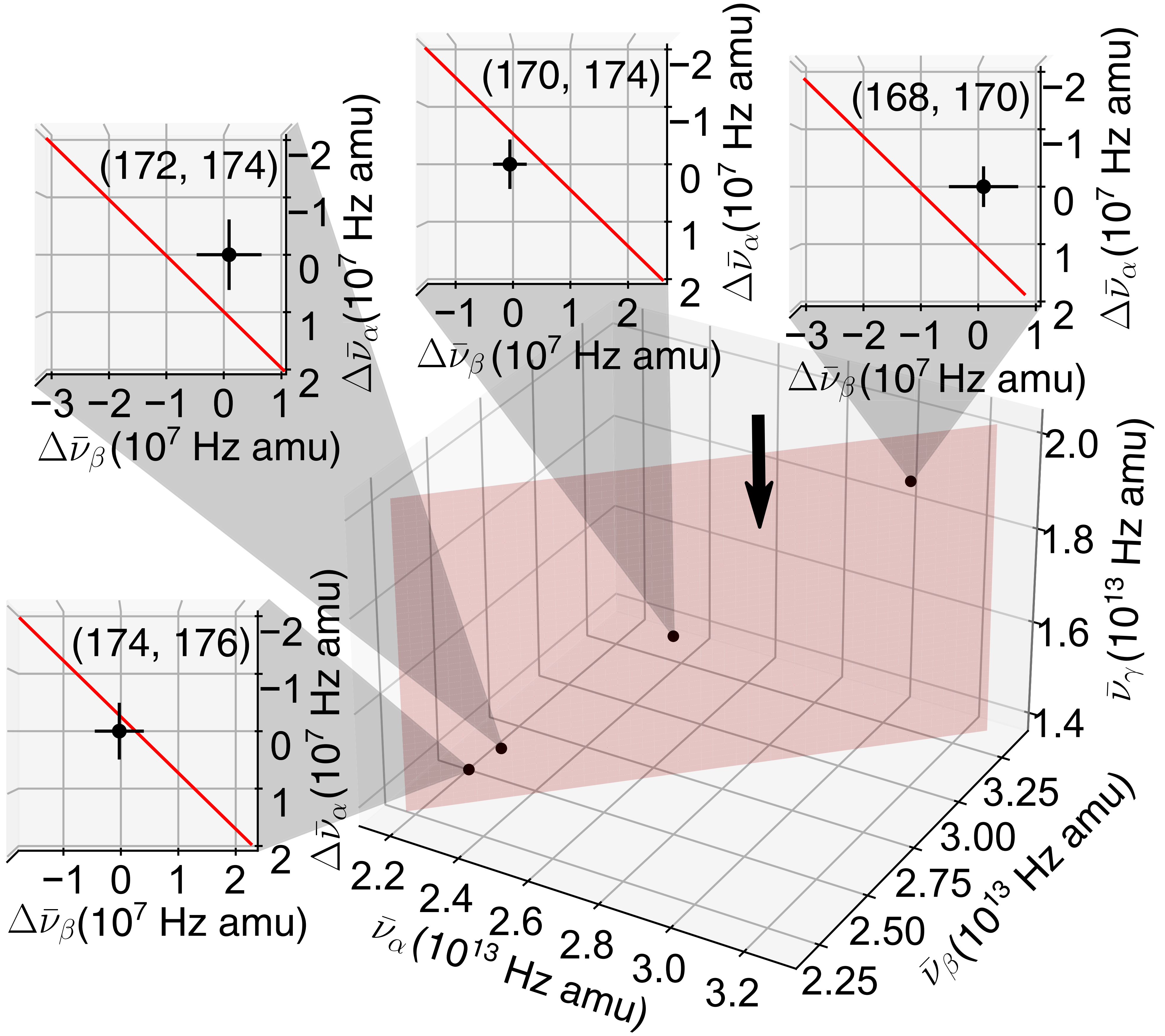
$^2\mathrm{S}_{1/2}(6s) - {}^2\mathrm{D}_{5/2}(5d)$



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

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

3D analysis

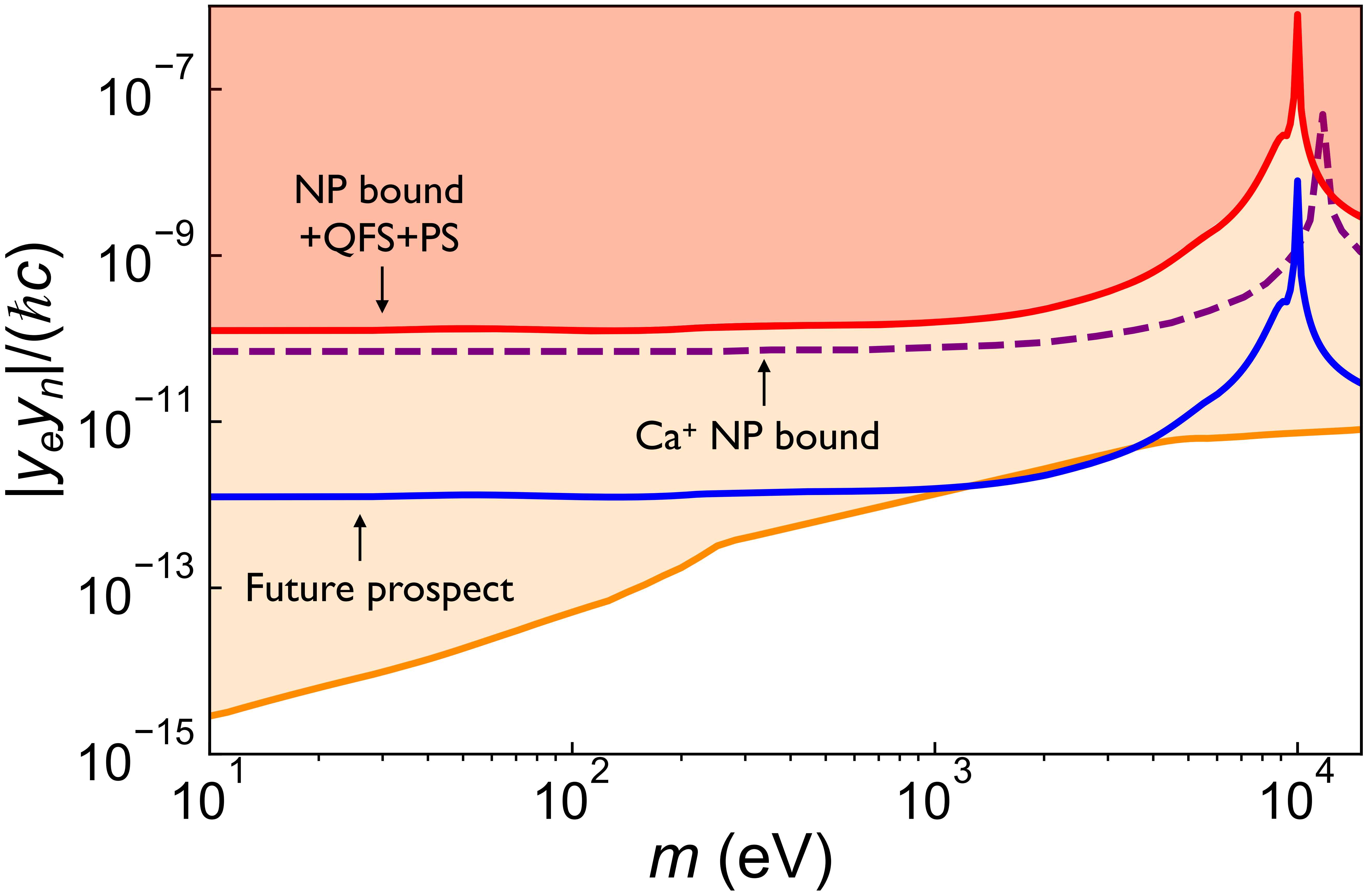


$$\chi^2/\mathrm{dof} = 15/3$$

two or more NL sources

+QFS+PS → New physics bound

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



Simultaneous analysis of plural linearities

Yb: 4 independent IS pairs

3D linearity is nontrivial, while 5 transitions available.

→ Combined fit of 3 independent 3D relations

$$\nu_3 = k_3\mu + f_{31}\nu_1 + f_{32}\nu_2\,,\;\; \nu_4 = k_4\mu + f_{41}\nu_1 + f_{42}\nu_2\,,\;\; \nu_5 = k_5\mu + f_{51}\nu_1 + f_{52}\nu_2$$

($A'A$ omitted)

$\delta\chi^2/\mathrm{dof} = 35.1/3$

Assigning this nonlinearity to PS,

→ $\delta\chi^2/\mathrm{dof} = 9.98/1$

PS alone cannot explain the observed 3D nonlinearity.

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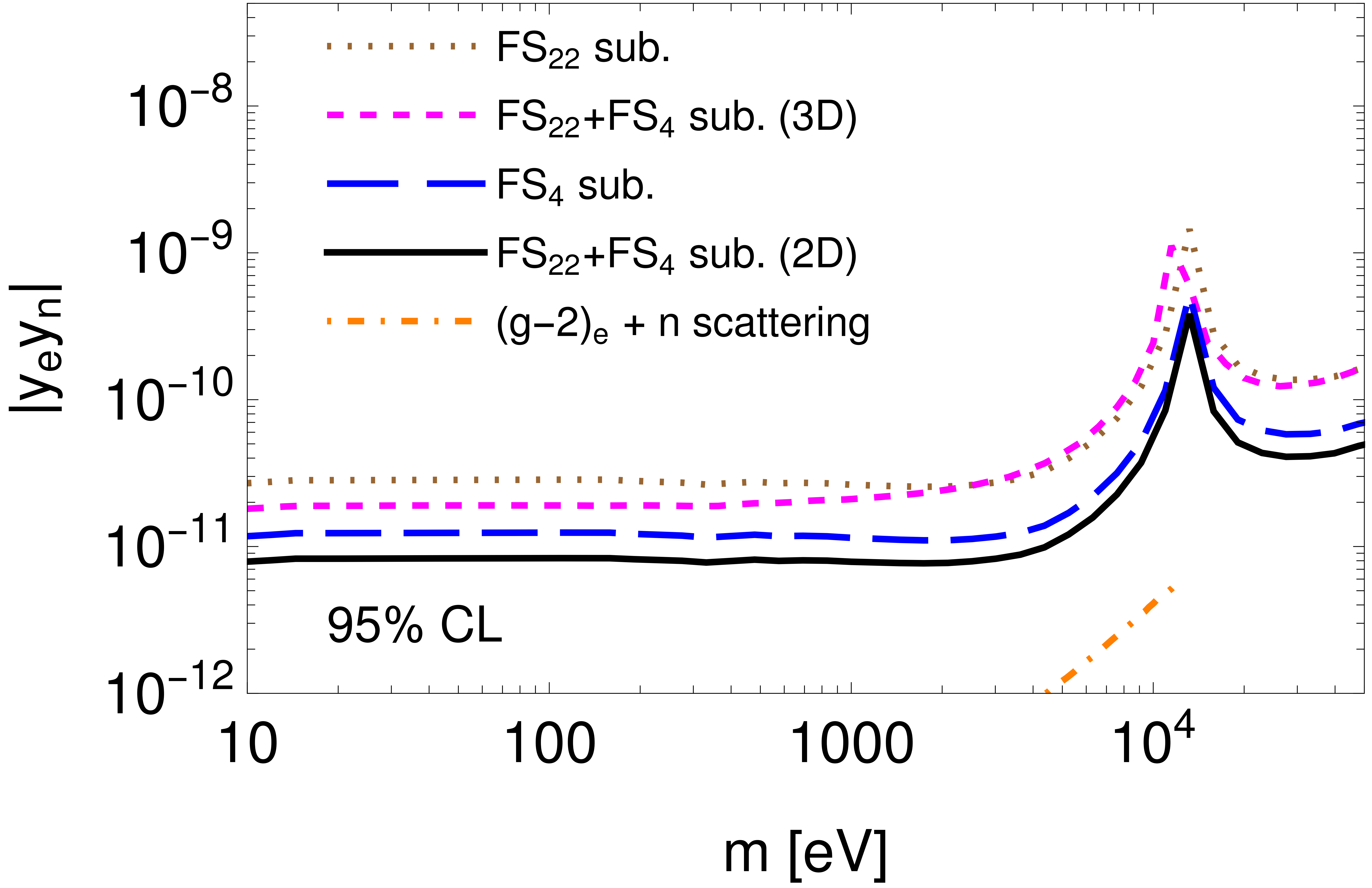
Five transitions combined

MT, Y. Yamamoto @JPS meeting, Mar. 2024



Dark Matter Search

Light dark matter candidates

Axion (and axion-like particles)

Proposed solution of the strong CP problem

$$\mathcal{L}_{\rm int} \supset g_{a\gamma\gamma}\, aF^{\mu\nu}\tilde{F}_{\mu\nu} \propto a\boldsymbol{E}\cdot\boldsymbol{B}$$

2 parameters : $m_a,\ g_{a\gamma\gamma}$

Dark photon

Minimal extension of the SM gauge sector $U_X(1)$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \boxed{\frac{\chi}{2}F_{\mu\nu}X^{\mu\nu}} + \frac{1}{2}m_X^2 X_\mu X^\mu - j^\mu_{\rm em}A_\mu$$

2 parameters : $m_X,\ \chi$

kinetic mixing

Standard model + inflation + dark photon

Graham, Mardon, Rajendran, PRD93, 103520 (2016)

→ Dark photon dark matter

$$\Omega_X = \Omega_{\rm CDM} \left(\frac{m_X}{6\times 10^{-6}\ {\rm eV}} \right)^{1/2} \left(\frac{H_I}{10^{14}\ {\rm GeV}} \right)^2$$

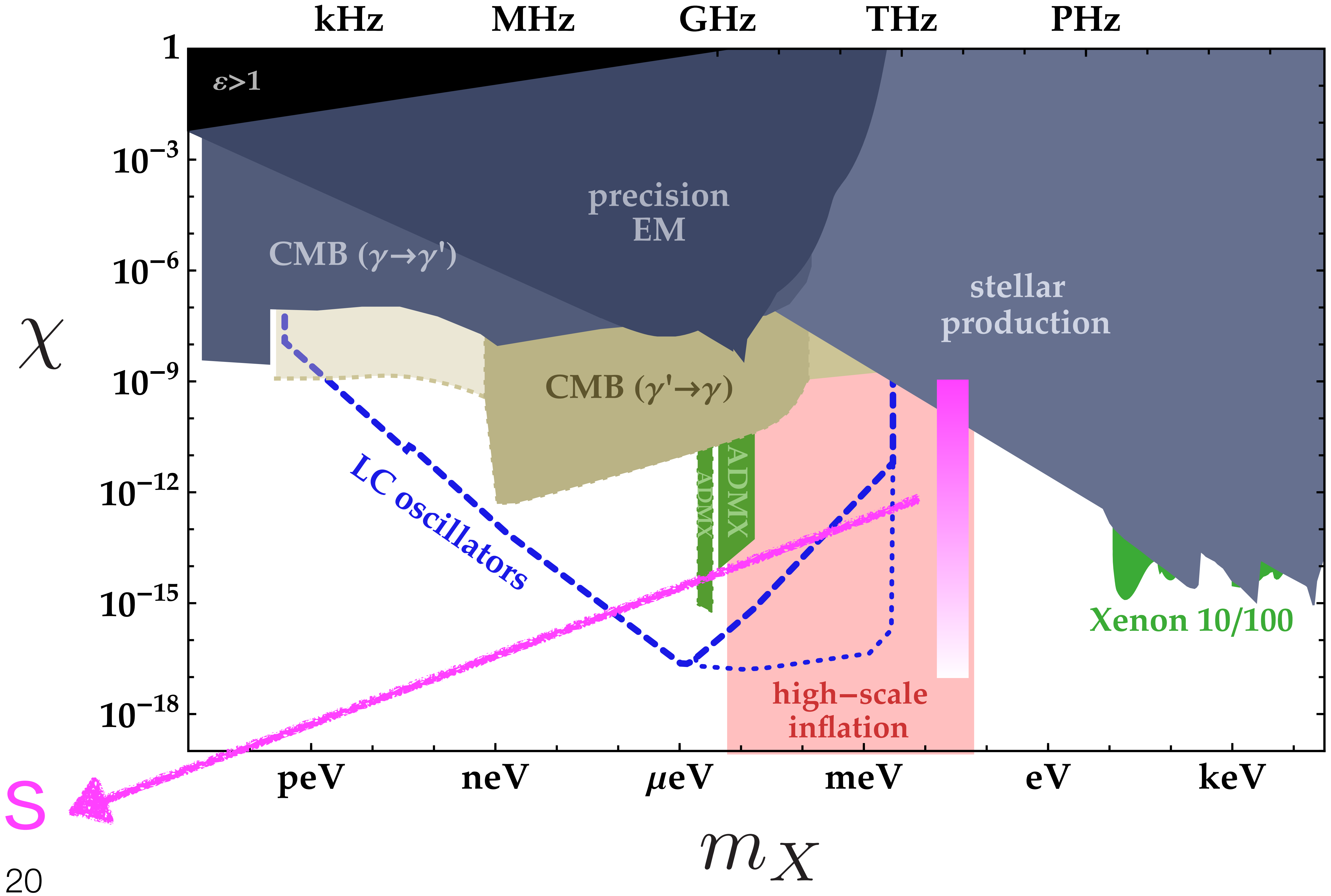
H_I : Hubble scale of inflation

$$H_I \lesssim 10^{14}\ {\rm GeV}$$

$$\longrightarrow \quad m \gtrsim 10^{-5}\ {\rm eV}$$

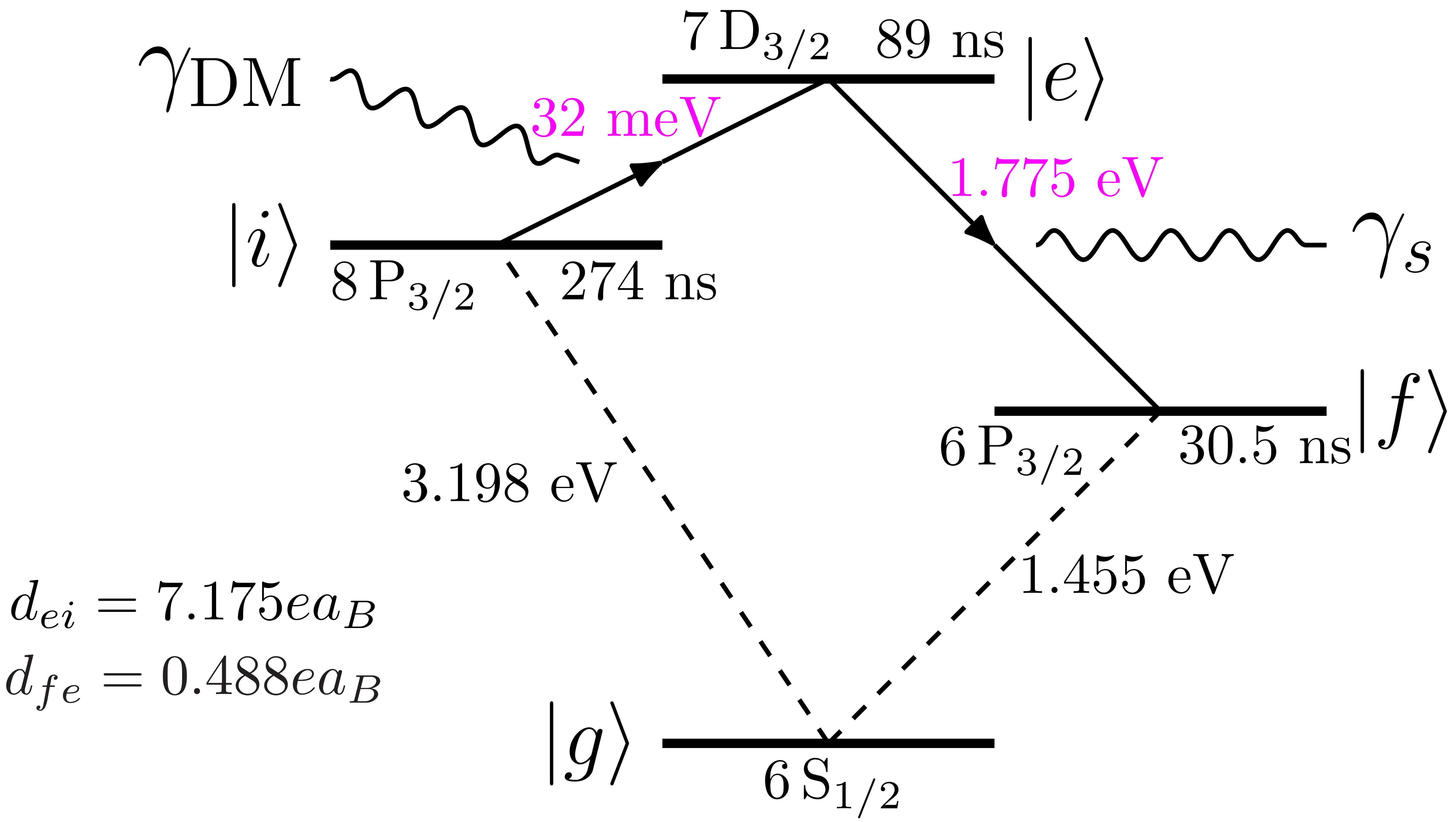
coherently oscillating

$$X^\mu \propto e^{i m_X t}$$



Search with atomic process

Cs pilot experiment @Okayama U



target spec.

$n = 1 \times 10^{12}\ \mathrm{cm}^{-3}$

$V = 0.1 \times 0.1 \times 1\ \mathrm{cm}^3$

$\Gamma_{\rm eff} \simeq 2.2 \times 10^{-5}\ \mathrm{eV}$

(>> natural width)

$$\Gamma = 1.6 \times 10^3 \left(\frac{\chi}{10^{-9}}\right)^2 \left(\frac{n}{10^{12}\ \mathrm{cm}^3}\right)^2 \left(\frac{\rho_{fi}}{0.25}\right)^2\ \mathrm{Hz}$$

cf. single atom rate: $\Gamma_0 = 3.7 \times 10^{-9} \left(\frac{\chi}{10^{-9}}\right)^2\ \mathrm{Hz}$

Coherence generation

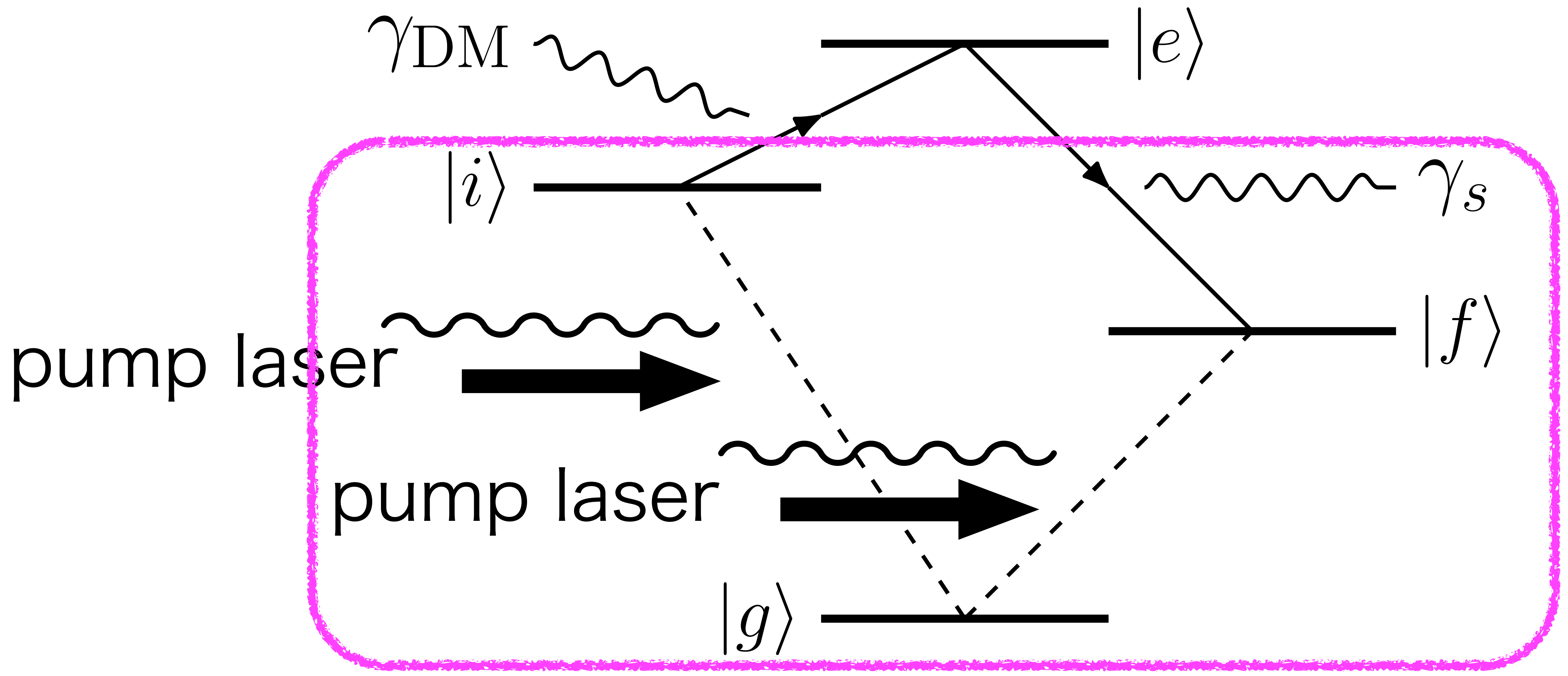
Liouville - von Neumann equation with relaxation

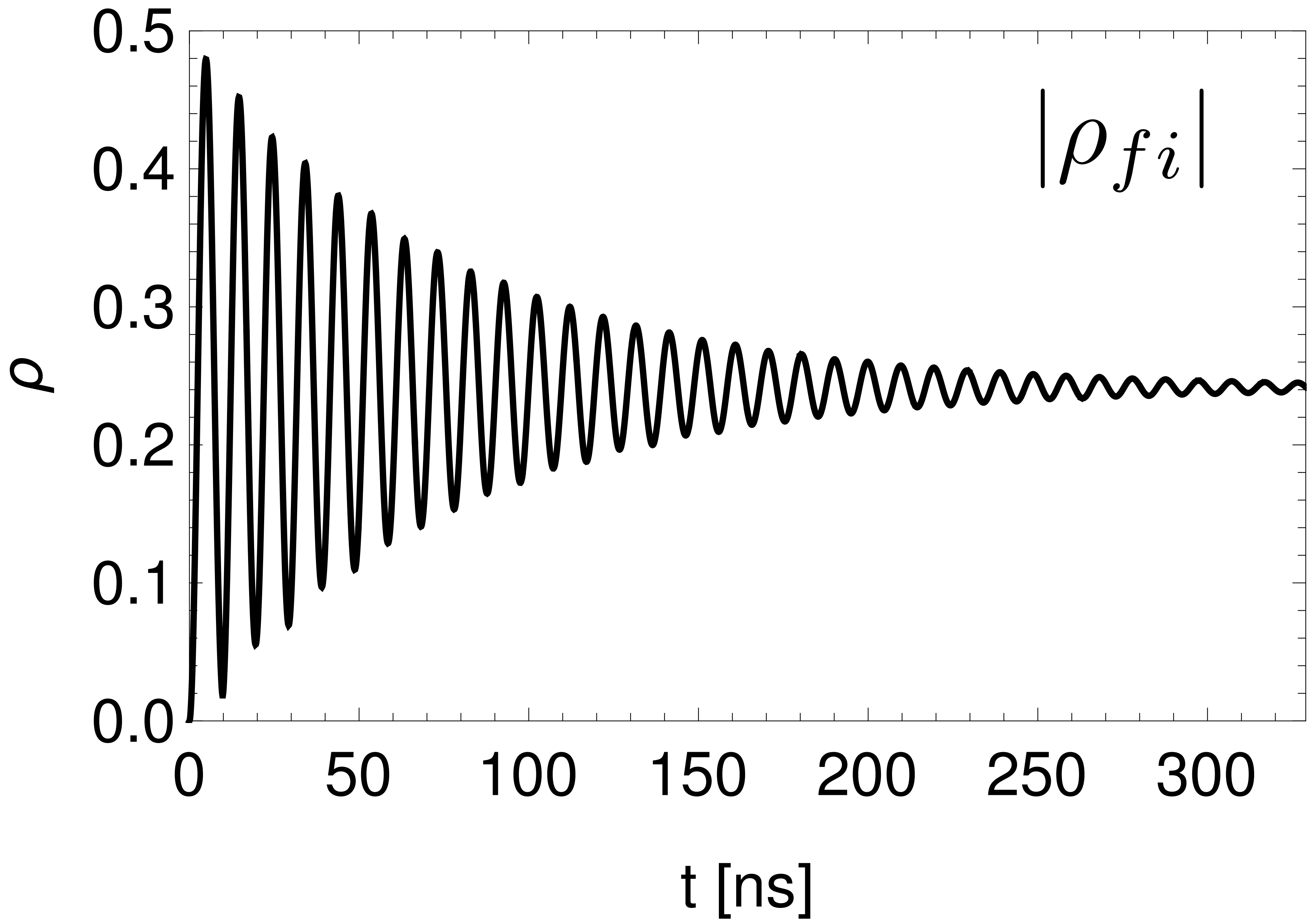
$$\partial_t \rho_{ij}(t) = -i[H(t), \rho(t)]_{ij} - \sum_{m,n} \Gamma_{ij,mn}\rho_{mn}$$

Cs parameters with radiation damping only

CW laser power: 1W(g-i), 1mW(g-f)
Laser cross section: 1mm^2

$|\rho_{fi}| \simeq 1/4$ possible





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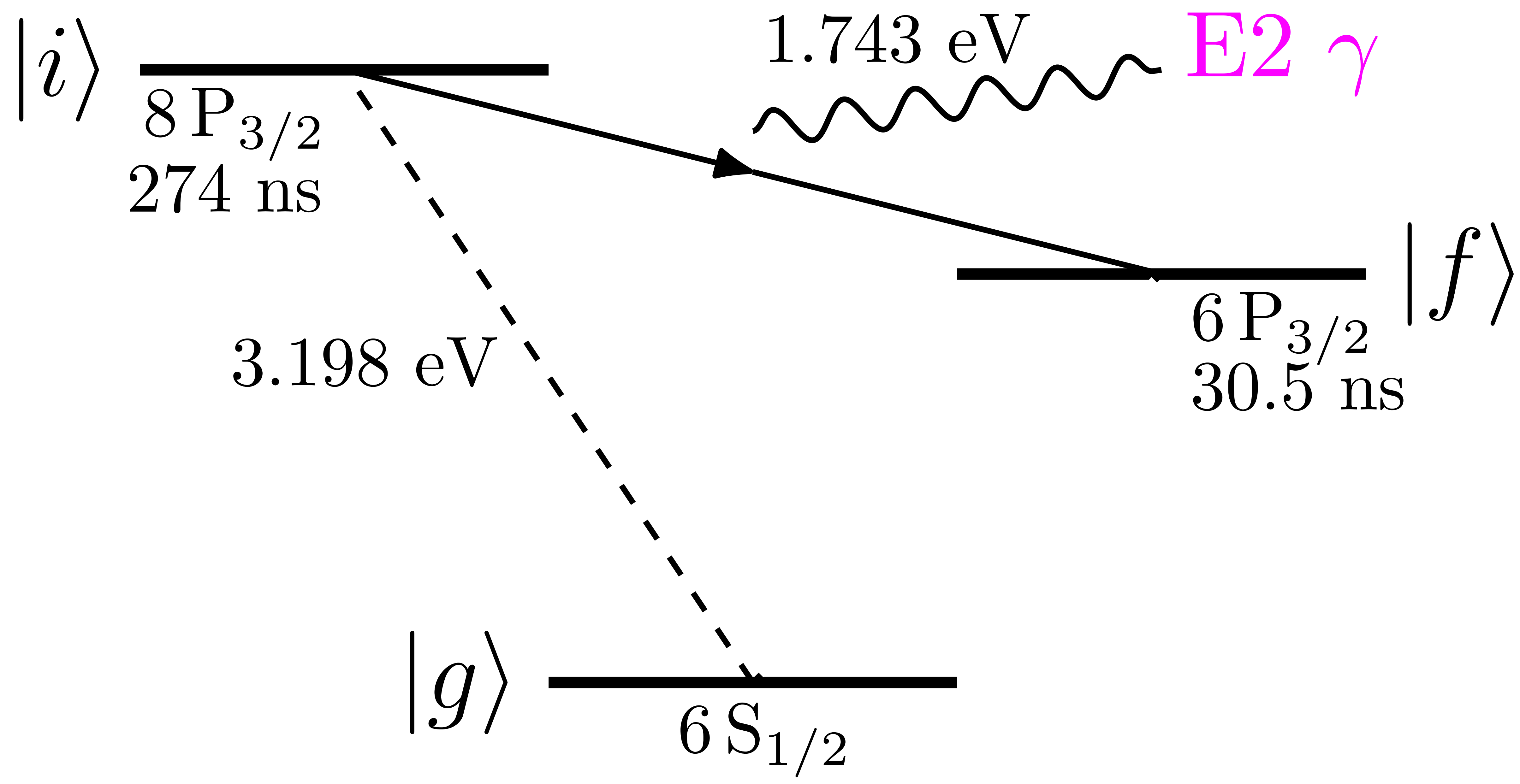
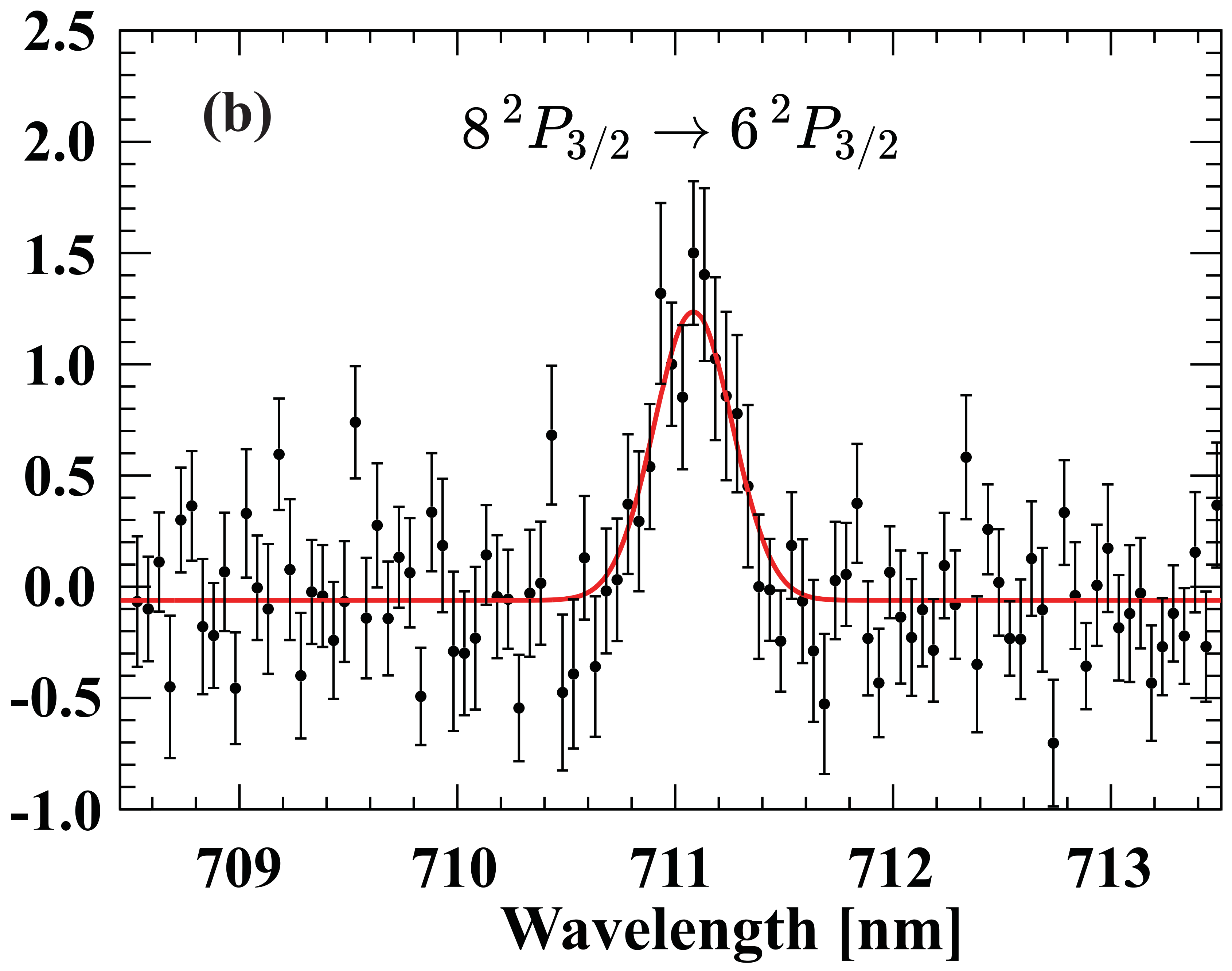
Coherence measurement



J.Wang, MT et al. PRA 110, 012804 (2024)



E2 transition

$\Gamma(i \to f) \sim$ a few Hz

Observed w/o coherence

Rate measurement with coherence → ρ_{fi}

applying the second pump laser, ongoing

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Summary

Isotope shift

- 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

  Two or more SM higher order contributions revealed

  One SM higher order + PS, excluded by our combined analysis
- New precise Yb IS data

  Yb^+ ion O(10) Hz, MPI-PTB Door et al., PRL 134 063002 (2025)

  improvement of MIT data and Yb masses

  Yb atom <O(10) Hz, Kyoto

  $^1\mathrm{S}_0(6s)^2 - (4f)^{13}(5d)(6p)^2\ (J=2)\ 431\ \mathrm{nm}\,,\ ^1\mathrm{S}_0(6s)^2 - {}^3\mathrm{P}_2(6s)(6p)\ 507\ \mathrm{nm}$

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Dark matter search

- Rate amplification by coherence in ensemble of atoms

  macrocoherence and momentum conservation

  significance of ρ_{fi}

- Halo dark photon/axion search experiment

  Cs pilot experiment at Okayama U

  coherence generation and ρ_{fi} measurement ongoing

- Theoretical issues

  more realistic simulation of signal and background