Physics
OSAKA UNIVERSITY

素粒子の新しい相互作用と原子スペクトルにおける同位体効果

田中 実（阪大）

共同研究者: 三上恭子、山本康裕(Yonsei U)

第一回琉球大学計算科学シンポジウム

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Introduction

Beyond the standard model (SM)

The SM of particle physics

- All particles are discovered.
  - gauge bosons, fermions, Higgs boson
- Gauge interactions are tested rather well.

Problems in the SM

- dark matter, dark energy, baryon # of universe
- Yukawa interactions, Higgs potential

→ Search for new physics

Frontiers in particle physics

Energy frontier

- Large Hadron Collider (LHC) & ATLAS, CMS
  - proton-proton collider @ 13 TeV
    - 27 km circumference ~ 大阪環状線
    - ~5000億円 (or more?)
  - discovery of Higgs boson in 2012
    - mass = 125 GeV
- International Linear Collider (ILC)
  - electron-positron collider @ 0.25~1 TeV
    - 30 km long, 5000億円~1兆円

Luminosity frontier

- copious production of particles
- SuperKEKB & Belle II ~300億円
  - electron-positron collider @ 10.6 GeV
    - physics run 2017~, ~10^{10} B mesons by 2025
- LHCb (bottom hadrons)
- KOTO (J-PARC, K meson), MEG II (PSI, muons)
- SHiP (CERN, dark photon search)

Cosmic frontier

- Cosmic microwave background
  - PLANCK ~700億円
- Gravitational wave
  - LIGO

Precision frontier, low energy frontier 安価

Neutrinoless ββ decay, Cosmic neutrinos

Dark matter search: WIMP, axion, …

Electric dipole moment search: atoms, molecules

Exotic force:

fifth force, short range gravity (extra dim.)…

Millicharge search: neutrality of atoms

Temporal variation of fundamental constants

α, m_e/m_p using atomic clock

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

Hunteman et al. (PTB) 2016

Isotope shift new neutron-electron interaction

^{8}Be anomaly and 17 MeV vector boson

Krasznahorkay et al. PRL116, 042501 (2016)

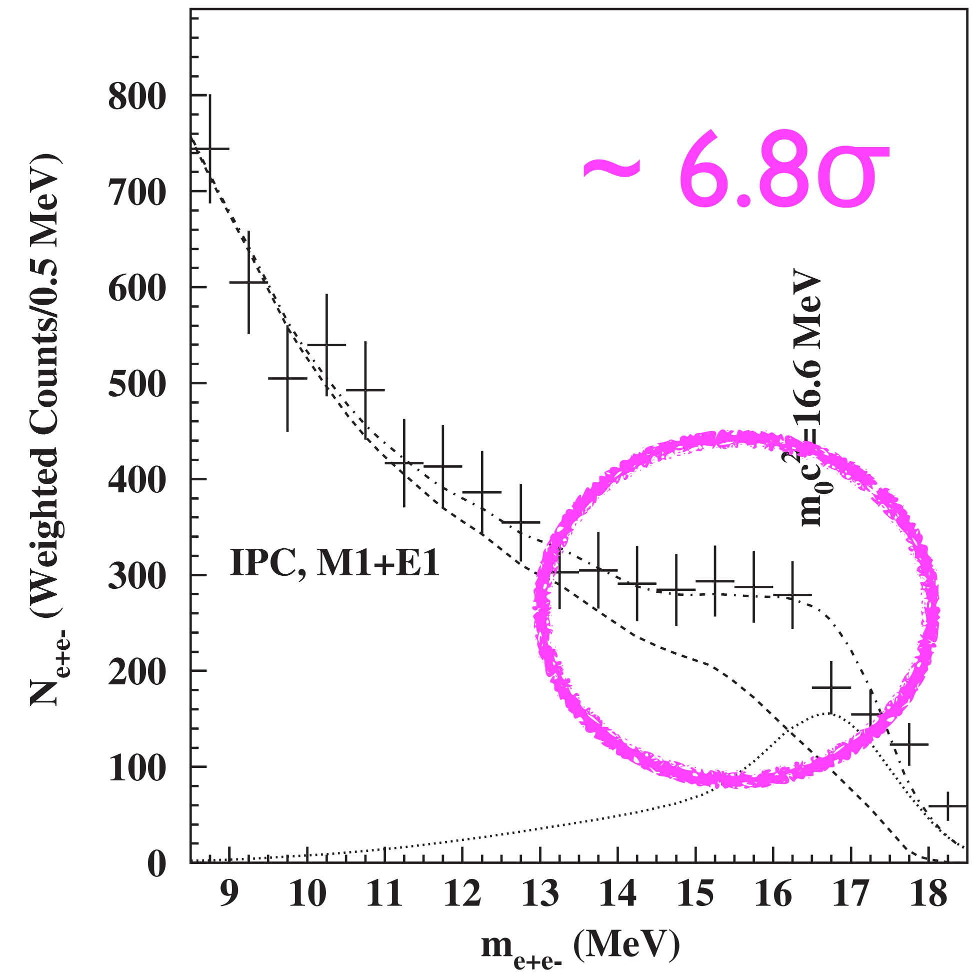
$$^{8}\mathrm{Be}^{*}(18.15\ \mathrm{MeV}) \to {}^{8}\mathrm{Be} + e^{+}e^{-}$$

Bump in the $e^{+}e^{-}$ inv. mass

$$\Rightarrow\ {}^{8}\mathrm{Be}^{*} \to {}^{8}\mathrm{Be} + X(\to e^{+}e^{-})$$

$$m_X \sim 17\ \mathrm{MeV}$$

vector $U(1)_B\,,\ U(1)_{B-L}$

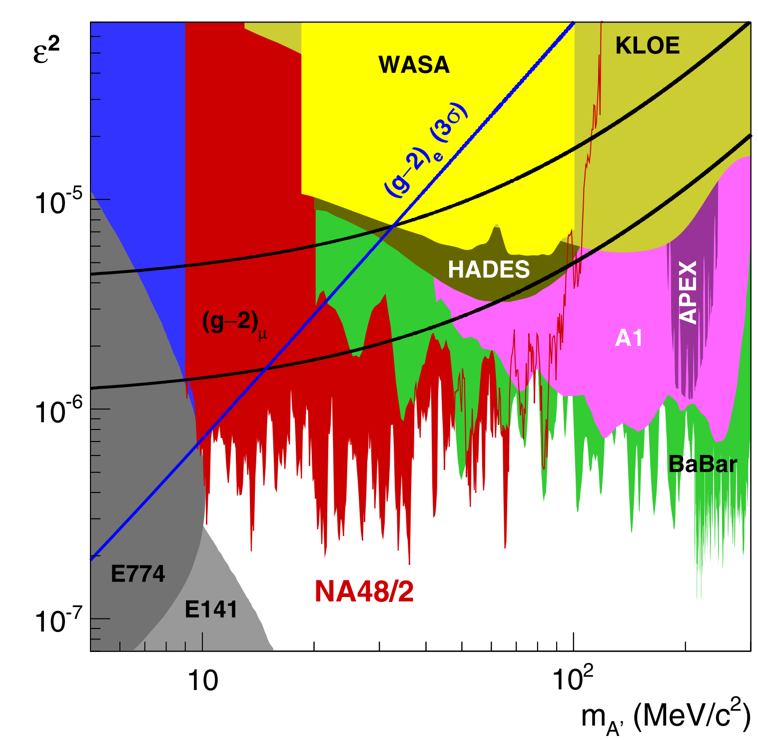


Constraint from dark photon search

Feng et al. PRL117, 071803 (2016)

NA48/2 $\quad \pi^{0} \to \gamma + A'(\to e^{+}e^{-})$

$\Rightarrow$ protophobic



Plan of talk

Introduction (5)

King linearity in isotope shift (4)

Particle shift nonlinearity (8)

Summary and outlook (1)

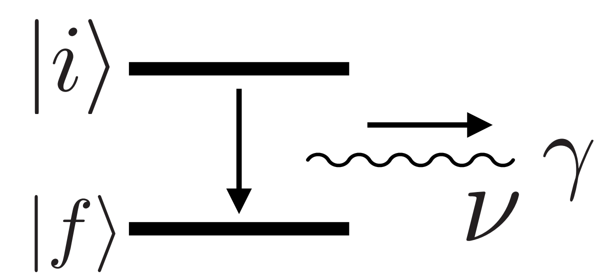
King linearity in isotope shift

Isotope shift (IS)

Transition frequency difference between isotopes

$$h\nu_A = E_A^i - E_A^f$$

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



No IS for infinitely heavy and point-like nuclei

$$\mathrm{IS} = \mathrm{MS} + \mathrm{FS}$$

Mass shift: finite mass of nuclei (reduced mass)

$\mathrm{MS} \propto \mu_{A'} - \mu_A$ (dominant for small Z)

Field shift: finite size of nuclei

$\mathrm{FS} \propto r_{A'}^2 - r_A^2$ (dominant for large Z)

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: $\ell = 1, 2$

$$\nu^{\ell}_{A'A} = K_{\ell}\,\mu_{A'A} + F_{\ell}\,r^2_{A'A}$$

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

Modified IS: $\tilde{\nu}^{\ell}_{A'A} := \nu^{\ell}_{A'A}/\mu_{A'A}$

$$\tilde{\nu}^{\ell}_{A'A} = \boxed{K_{\ell}} + \boxed{F_{\ell}}\,\boxed{r^2_{A'A}/\mu_{A'A}}$$ nuclear factor

electronic factors

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

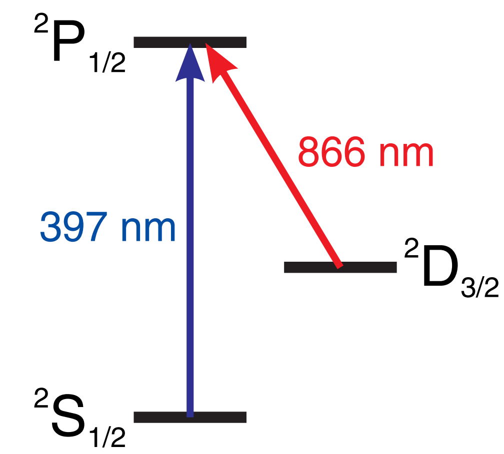
IS data of Ca^+

Gebert et al. PRL115, 053003 (2015)

Line 1: 397 nm $^2\mathrm{P}_{1/2}(4\mathrm{p}) - ^2\mathrm{S}_{1/2}(4\mathrm{s})$

Line 2: 866 nm $^2\mathrm{P}_{1/2}(4\mathrm{p}) - ^2\mathrm{D}_{3/2}(3\mathrm{d})$

Isotope pairs: (42, 40), (44,40), (48,40)



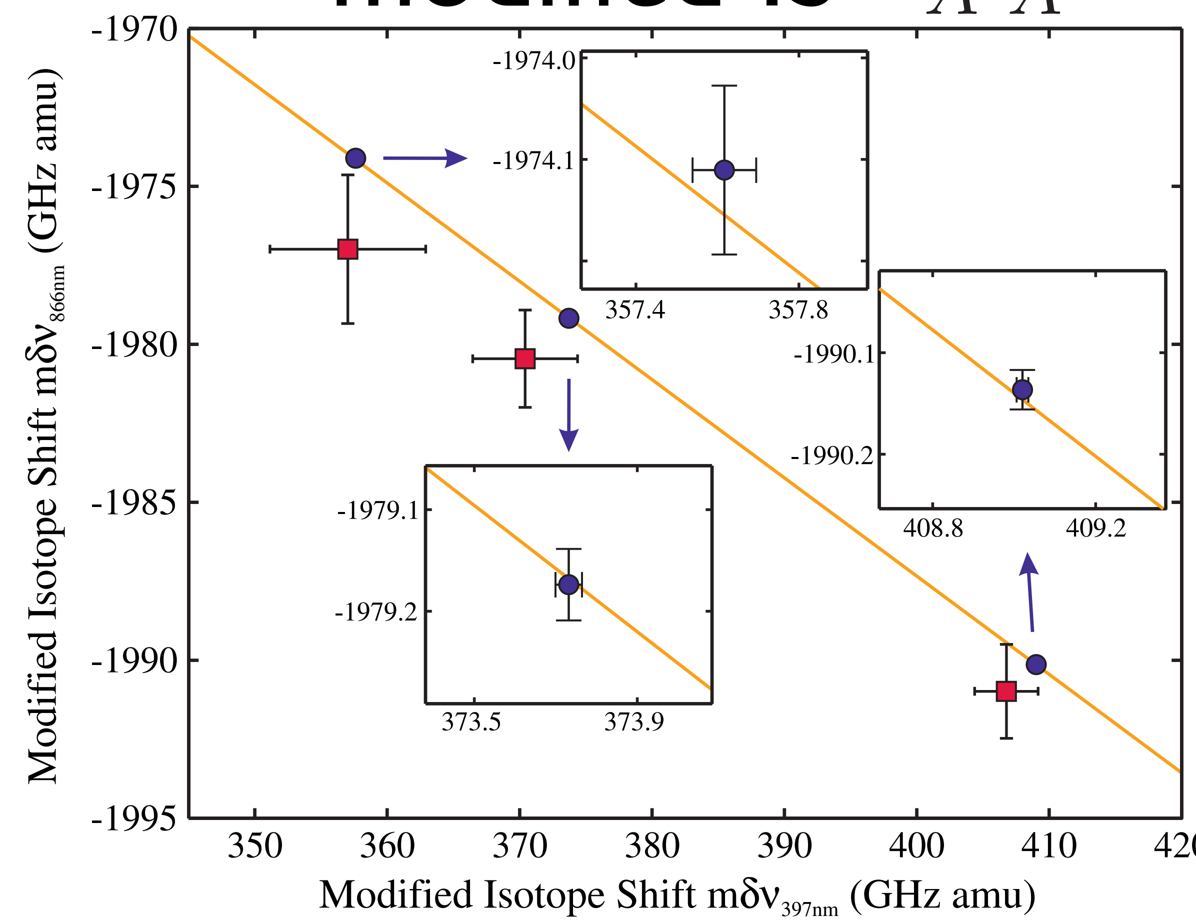
IS precision ~ O(100) kHz

King plot

linear within errors

modified IS $\tilde{\nu}^{\ell}_{A'A}$

866 nm



397 nm

IS data of Yb^+

Line 1: 369 nm

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

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

Line 2: 935nm

Sugiyama et al. CPEM2000

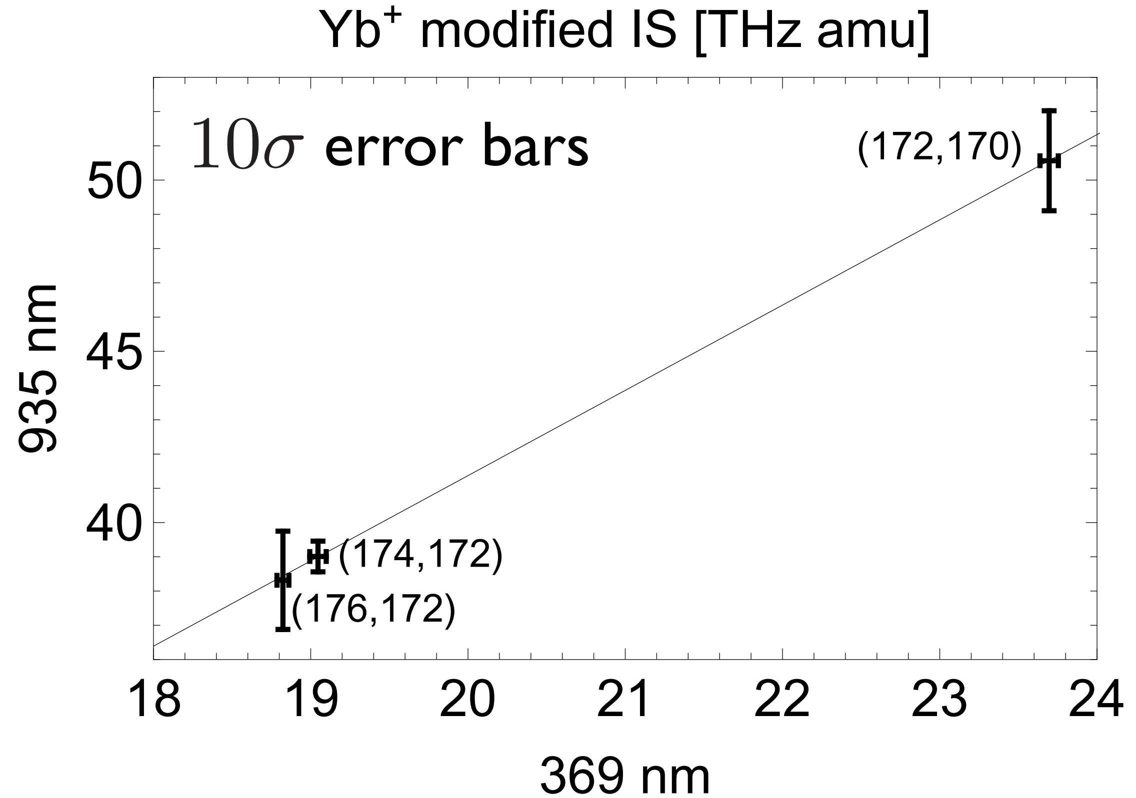
$${}^3\mathrm{D}[3/2]_{1/2}(4\mathrm{f})^{13}(5\mathrm{d})(6\mathrm{s}) - {}^2\mathrm{D}_{3/2}(4\mathrm{f})^{14}(5\mathrm{d})$$

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

Isotope pairs: (172, 170), (174,172), (176,172)

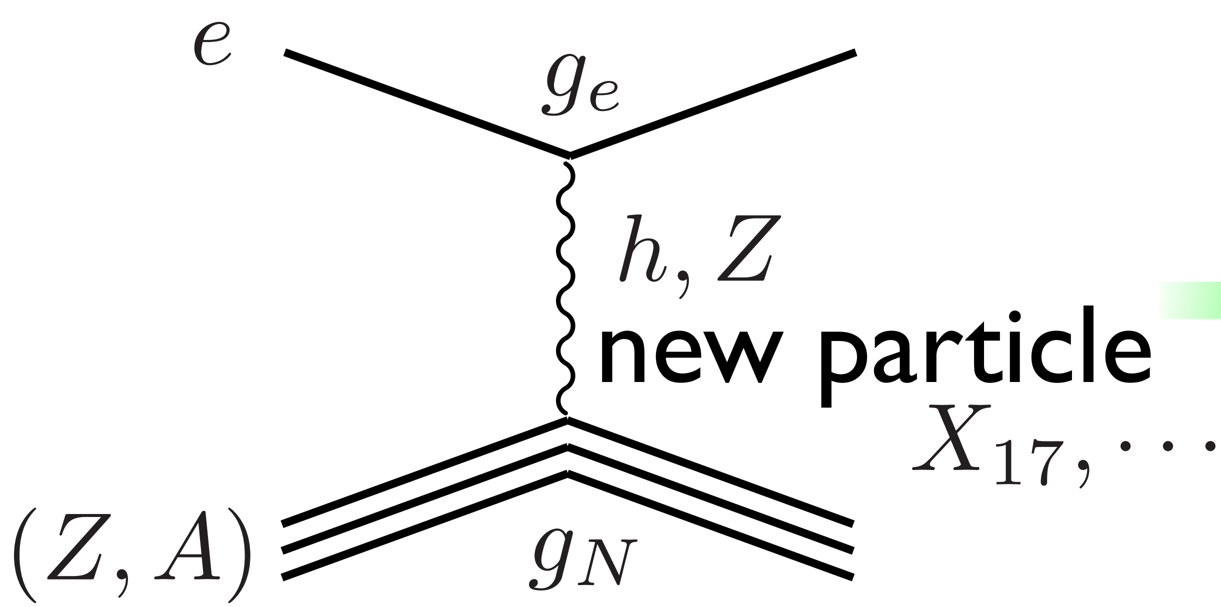
King plot

linear within errors



Particle shift nonlinearity

Particle shift (PS)



Yukawa potential

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

(atomic units)

Frequency shifts by particle exchange (Yb^+)

$$|\Delta\nu| \sim \begin{cases} 10^{-4}\ \text{Hz} & \text{Higgs (SM)} \\ 400\ \text{Hz} & \text{Higgs (LHC bound)} \\ 800\ \text{Hz} & Z \\ 10\ \text{MHz} & X_{17}\ \text{17 MeV vector boson} \end{cases}$$

<<theoretical uncertainties

Breakdown of the linearity by PS

$\mathrm{IS} = \mathrm{MS} + \mathrm{FS} + \mathrm{PS}$

Delaunay et al. arXiv:1601.05087v2

PS by new neutron-electron interaction

$$\nu^{\ell}_{A'A} = K_{\ell}\,\mu_{A'A} + F_{\ell}\,r^2_{A'A} + X_{\ell}(A' - A)$$

Generalized King's relation

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

nonlinearity

probe into new physics

PS nonlinearity $\varepsilon_{\mathrm{PS}} = X_1(X_{21} - F_{21})$ $\quad X_{21} := X_2/X_1$

Heavy particle limit: $m a_B \gg \alpha$

Berengut et al. arXiv:1704.05068

$F_{\ell}, X_{\ell} \propto |\psi_{i_\ell}(0)|^2 - |\psi_{f_\ell}(0)|^2 \rightarrow X_{21} - F_{21} \sim O(1/m)$

$X_{\ell} \sim O(1/m^2)$

$\rightarrow \varepsilon_{\mathrm{PS}} \sim O(1/m^3)$

less sensitive to heavier particles

Evaluation of PS nonlinearity

Single electron approximation

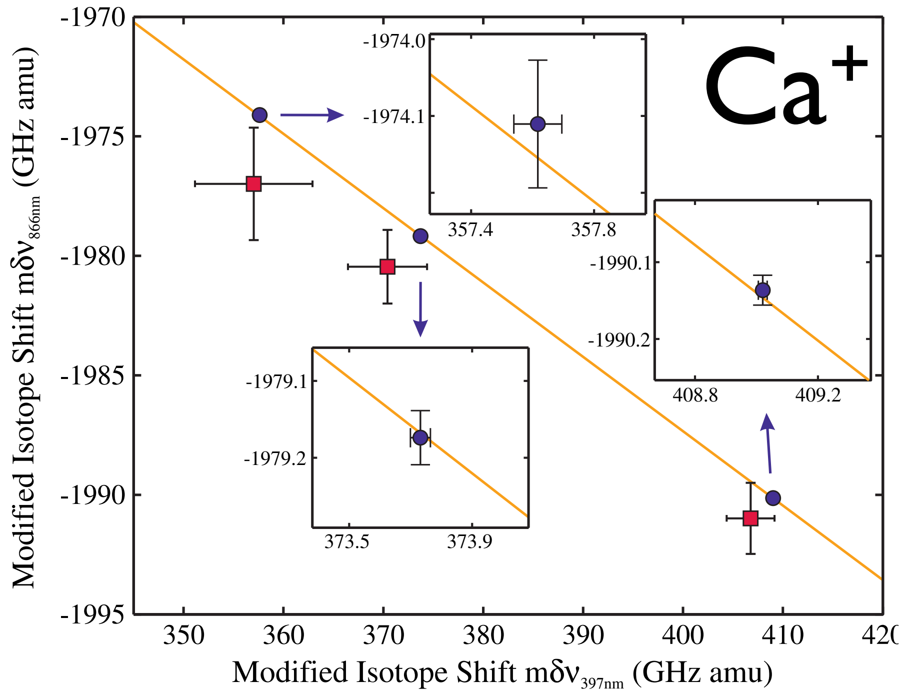
$$X_\ell = g_n g_e \int r^2 dr \frac{e^{-mr/\alpha}}{r} \left[R_{i_\ell}^2(r) - R_{f_\ell}^2(r) \right]$$

Wavefunction

- non relativistic (not bad for m<<100 MeV)
- Thomas-Fermi model
  - semiclassical, statistical, selfconsistent field
  - exact in large Z limit

Present constraint and future prospect

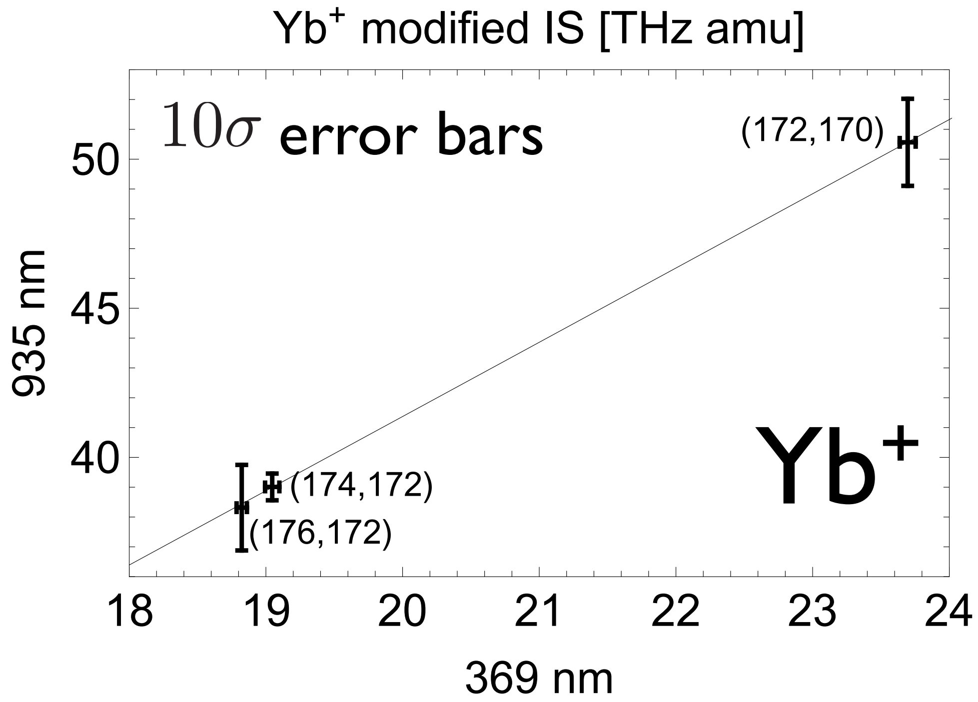
Data fitting with $\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A} + \varepsilon\, A'A$



$\varepsilon = (-2.45 \pm 4.05)\cdot 10^{-6}$ au

future prospect $\delta\nu = 1\ \mathrm{Hz}$

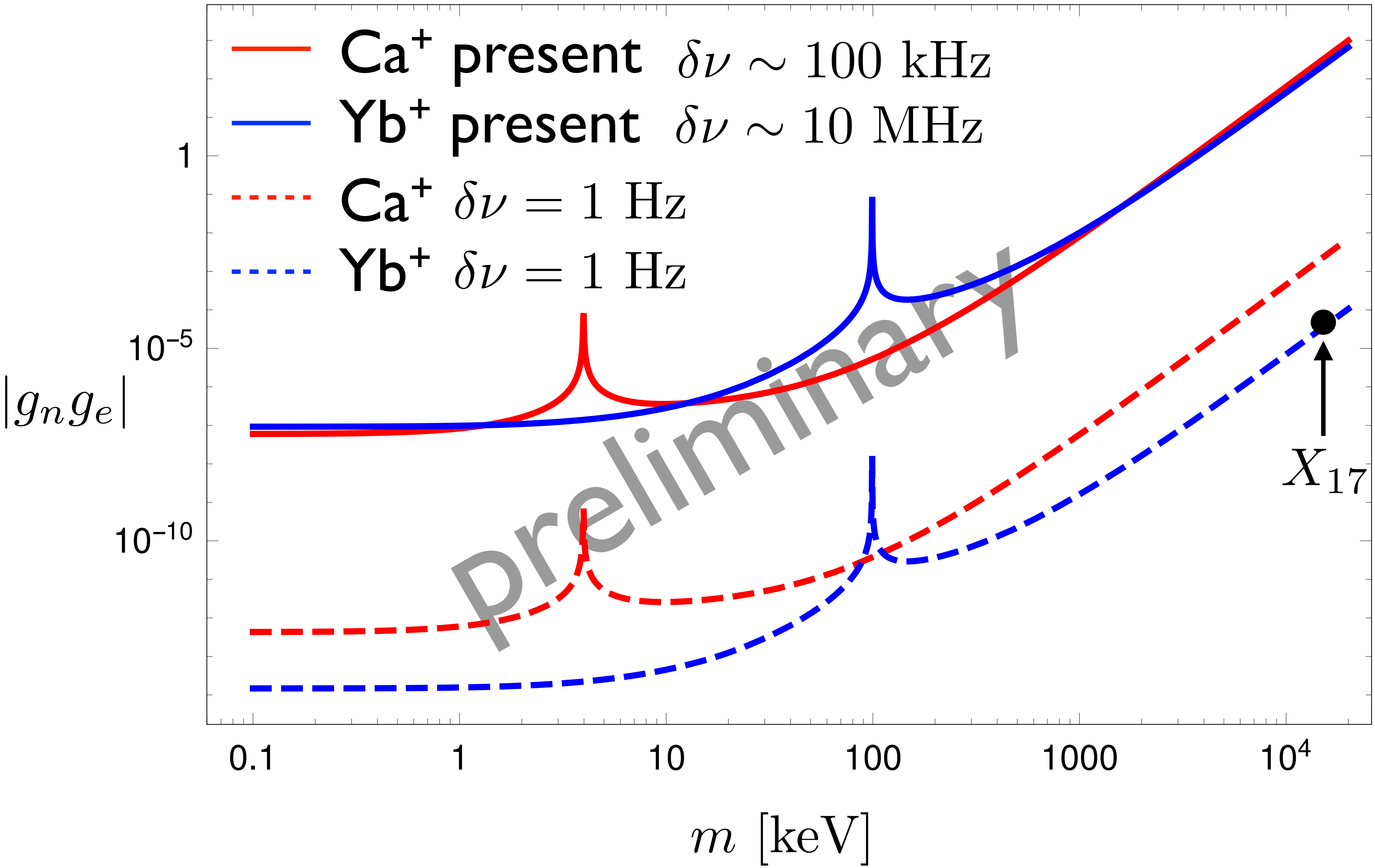
$|\varepsilon| < 4.5 \cdot 10^{-11}$



$\varepsilon = (-1.26 \pm 1.35)\cdot 10^{-4}$

future prospect $\delta\nu = 1\ \mathrm{Hz}$

$|\varepsilon| < 4.2 \cdot 10^{-11}$



Ca^+ present $\delta\nu \sim 100$ kHz
Yb^+ present $\delta\nu \sim 10$ MHz
Ca^+ $\delta\nu = 1$ Hz
Yb^+ $\delta\nu = 1$ Hz
preliminary
$|g_n g_e|$
1
10^{-5}
10^{-10}
X_{17}
0.1
1
10
100
1000
10^4
m [keV]

Field shift nonlinearity

One of the sources of nonlinearity in QED

$$\mathrm{FS} = F_\ell \, r^2_{A'A} + G_\ell \, r^4_{A'A}$$

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

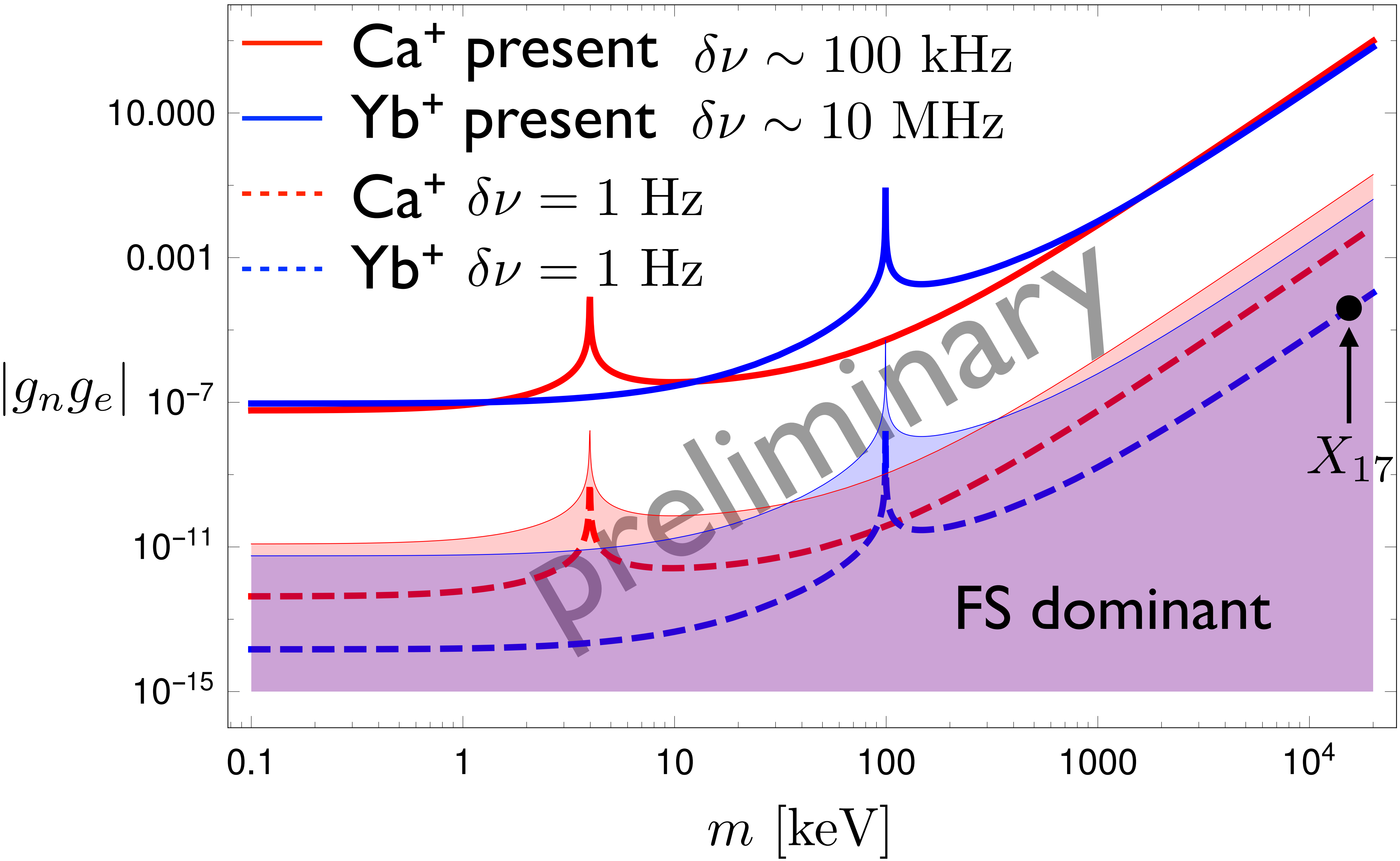
→ $\varepsilon = \varepsilon_{\mathrm{PS}} + \varepsilon_{\mathrm{FS}}$

An order estimation for nS state

$$\varepsilon_{\mathrm{FS}} \sim \frac{16}{35}\xi \left(\frac{Z\alpha}{n}\right)^3 \left(\frac{m_e}{m_0}\right)^3$$

$m_0 \simeq 168 \ \mathrm{MeV}$
nuclear scale

$\xi = O(1)$
wavefunction

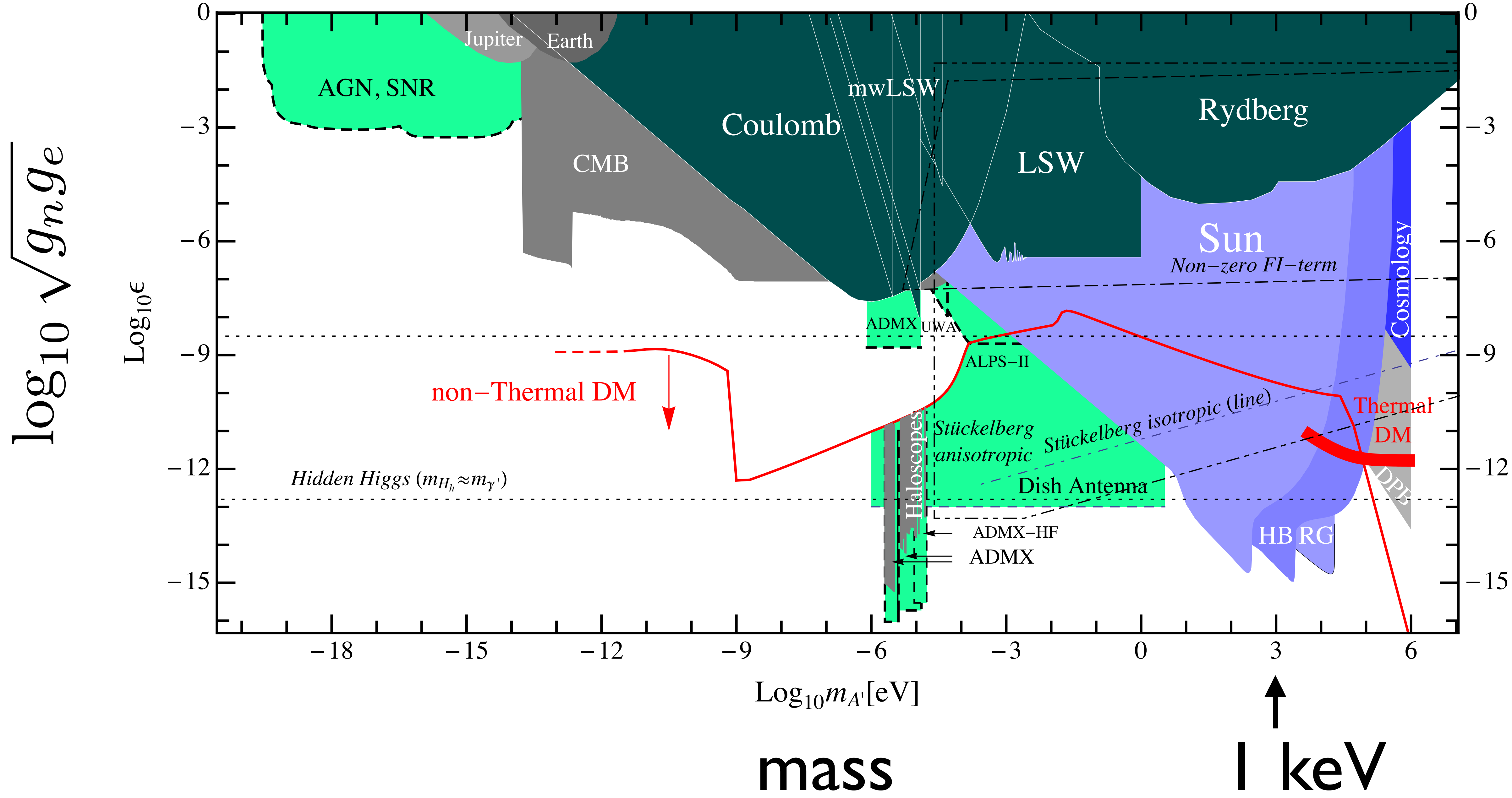


Ca$^+$ present $\delta\nu \sim 100$ kHz
Yb$^+$ present $\delta\nu \sim 10$ MHz
Ca$^+$ $\delta\nu = 1$ Hz
Yb$^+$ $\delta\nu = 1$ Hz
10.000
0.001
$|g_n g_e|$
10^{-7}
10^{-11}
10^{-15}
preliminary
FS dominant
X_{17}
0.1
1
10
100
1000
10^4
m [keV]

Comparison to other constraints

Dark photon search

Essig et al. arXiv:1311.0029v2



Minoru TANAKA

Summary and outlook

- New physics search at precision frontier
  - Lots of projects on going or proposed
- Isotope shift and King linearity
  - IS=MS+FS, $\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A}$
  - Linear relation of modified IS of two lines
- Nonlinearity $\tilde{\nu}^2_{A'A} = K_{21} + F_{21}\tilde{\nu}^1_{A'A} + \varepsilon\, A'A$
  - $\varepsilon = \varepsilon_{\rm PS} + \varepsilon_{\rm FS}$
  - Particle shift nonlinearity: $\varepsilon_{\rm PS} \sim O(1/m^3)$
    - sensitive for lighter particles, $m \ll 100\ {\rm MeV}$
  - Field shift nonlinearity $\varepsilon_{\rm FS}$: more study needed
- Yb^+ ion trap project by Sugiyama et al. (Kyoto)
  - $\delta\nu < 1\ {\rm kHz}$ with in a few years