Probing new intra-atomic force with isotope shifts

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Fundamental Physics Using Atoms @ Nagoya U

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Based on 1710.11443
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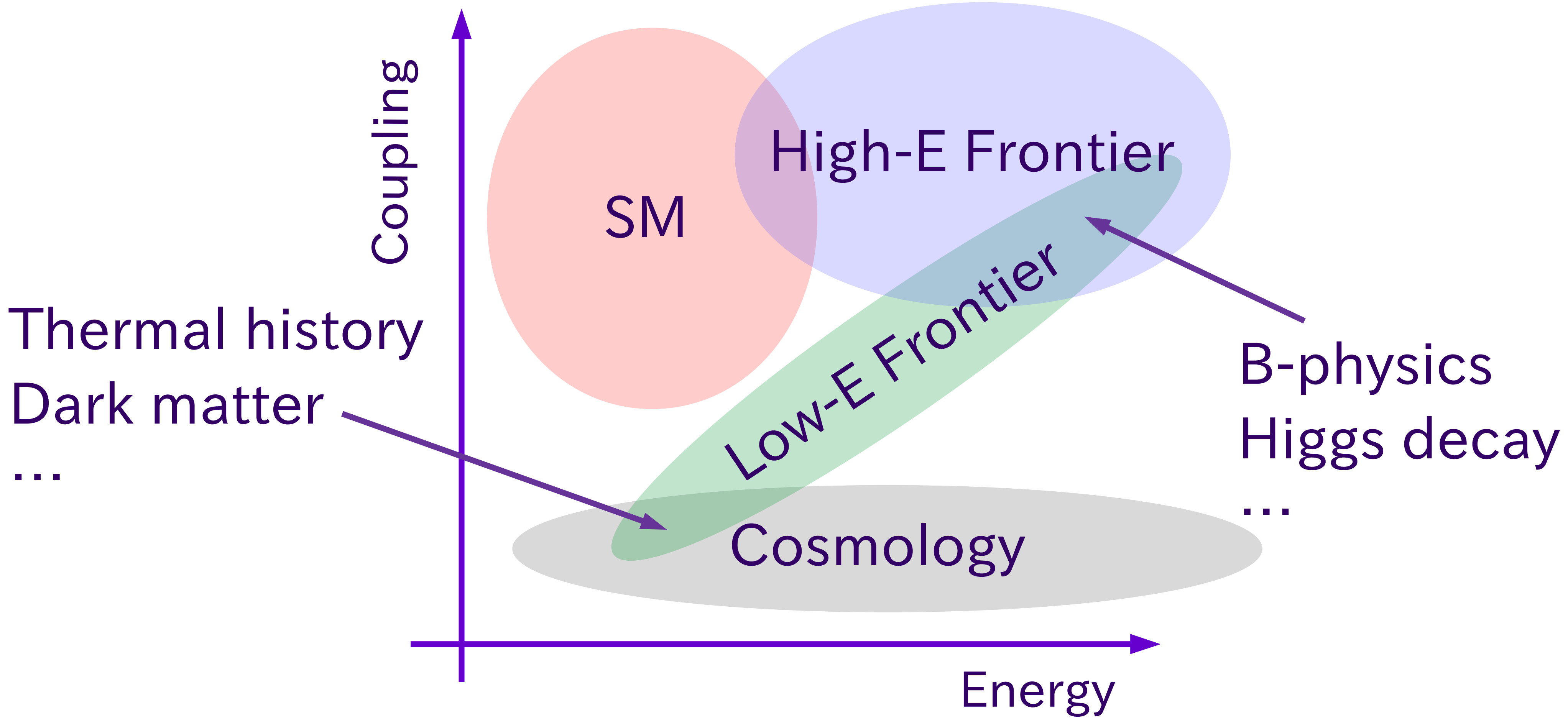
Physics of light new particles

- Interaction strength $\sim \frac{g}{M} : \frac{1}{1\ \mathrm{TeV}} = \frac{10^{-4}}{100\ \mathrm{MeV}}$



Precision measurements

- Error of the electron g-2 is $O(10^{-10})$.

$$\frac{g_e - 2}{2} = \begin{cases} -0.001\,159\,652\,180\,73(28)_{\mathrm{EX}} \\ -0.001\,159\,652\,181\,64(76)_{\mathrm{TH}} \end{cases}$$

- Error of the atomic clocks $O(10^{-15}$–$10^{-18})$.

$$^{87}\mathrm{Sr}: \;\; 429\;228\;004\;229\;873.4\ \mathrm{Hz}$$

(From Wikipedia:atomic clock)

  - The calculation of the spectrum is too difficult. (Even three body is disaster!)

- Can we reduce the theoretical uncertainty?

Plan

- Introduction
- The linearity and its violation
- The field shift and its higher order
- The particle shift
- Numerical results and other constraints
- Conclusion

Isotope shift and the linearity

- Isotope shifts follow a linearity.

$$\delta H_{A'A} = \delta K_{A'A} + \delta V_{A'A}$$

$$\delta\nu = G\,\delta\mu + F\,\delta\langle r^2\rangle$$

Isotope dependence.

Wave function dependence.

- Linearity for isotope pairs. 1963: W. H. King

$$\frac{\delta\nu_2}{\delta\mu} = \boxed{\frac{F_2}{F_1}}\frac{\delta\nu_1}{\delta\mu} + \boxed{G_2 - \frac{F_2}{F_1}G_1}$$

Constant for isotope pairs.

Isotope shift and the linearity

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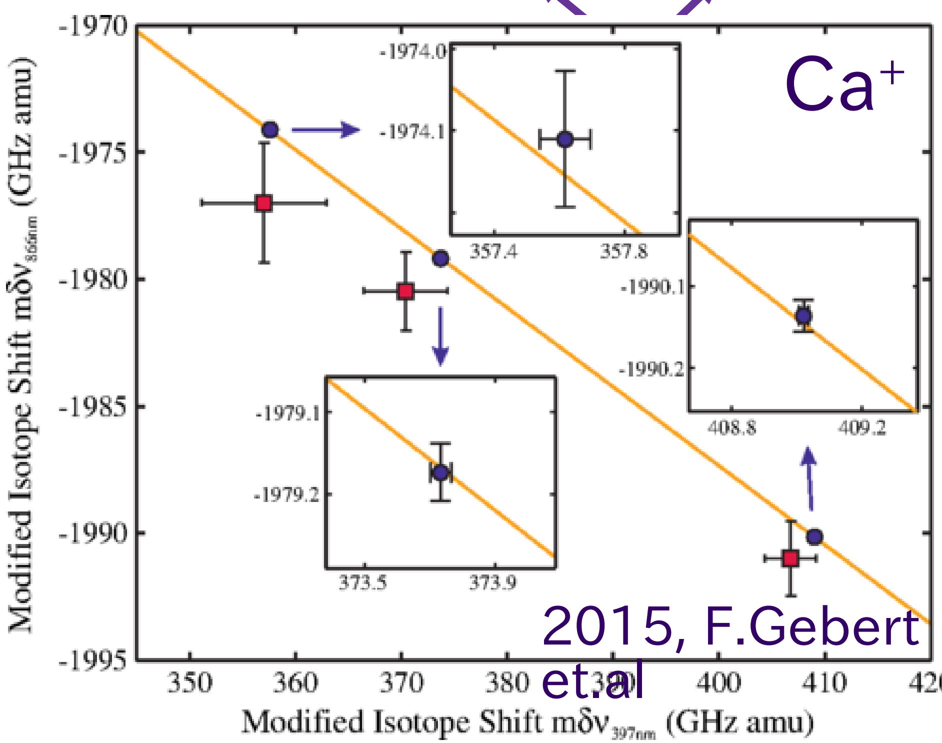
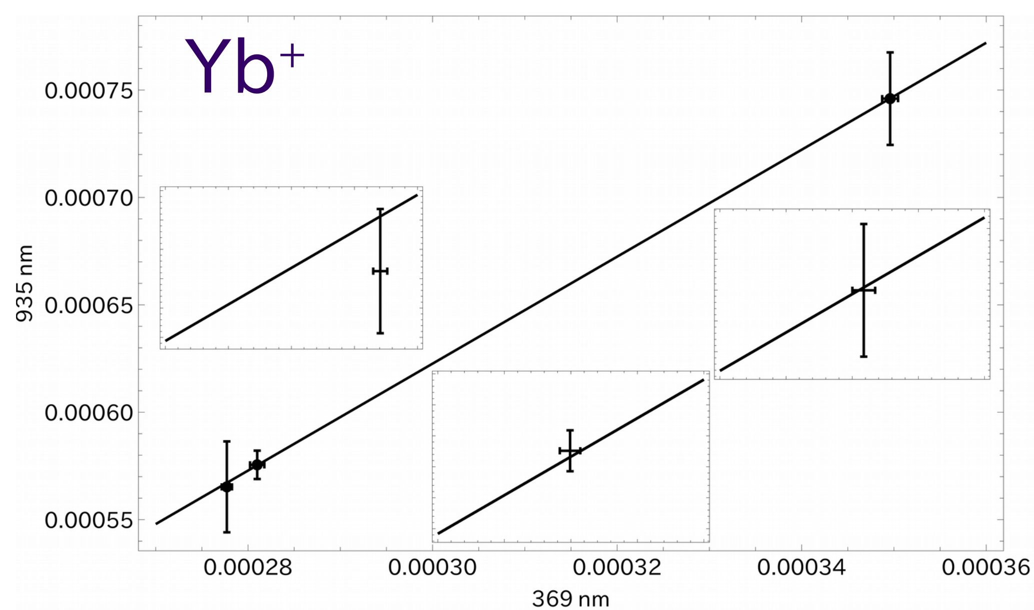
$$\delta H_{A'A} = \delta K_{A'A} + \delta V_{A'A}$$

$$\delta\nu = G\,\delta\mu + F\,\delta\langle r^2\rangle$$

Isotope dependence.



2015, F.Gebert et.al



Isotope shift and the linearity

non

does not

- Isotope shifts follow a linearity.

$$\delta H_{A'A} = \delta K_{A'A} + \delta V_{A'A}$$

▼

Isotope dependence.

$$\delta\nu = G\,\delta\mu + F\,\delta\langle r^2\rangle + X$$

NLO corrections
Yukawa potential

Wave function dependence.

Non

- Linearity for isotope pairs.

2016, C. Delaunay et. al

$$\frac{\delta\nu_2}{\delta\mu} = \frac{F_2}{F_1}\frac{\delta\nu_1}{\delta\mu} + G_2 - \frac{F_2}{F_1}G_1 + \left(X_2 - \frac{F_2}{F_1}X_1\right)/\delta\mu$$

Constant for isotope pairs.

Field shift

Def: $$\int d\vec{r}\,\left(|\psi_j(\vec{r})|^2 - |\psi_i(\vec{r})|^2\right)\delta V(\vec{r})$$

$$-Z\alpha \int d\vec{r'}\,\frac{\delta\rho(\vec{r'})}{|\vec{r}-\vec{r'}|}$$

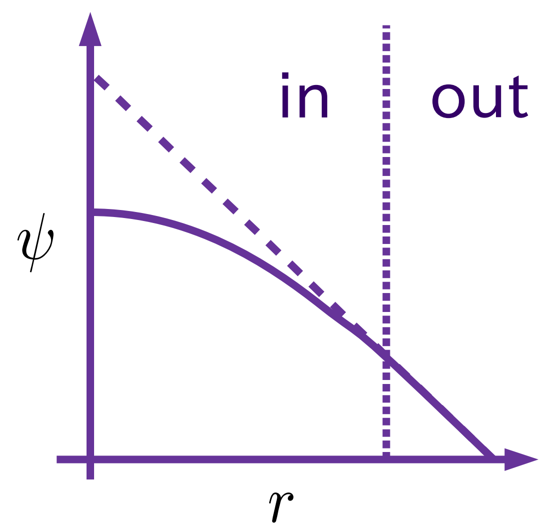
Expand

$$\propto \int_0^\infty dr' \int_0^{r'} dr\, r^2 \sum_k \xi_k r^k \left(r' - \frac{r'^2}{r}\right)\delta\rho(r')$$

$$\delta\langle r^k\rangle = \int d\vec{r}\, r^k \delta\rho(r)$$

$$= Z\alpha \sum_k \frac{\xi_k}{(k+3)(k+2)}\delta\langle r^{k+2}\rangle$$

1969, E. C. Seltzer



- NLO field shift

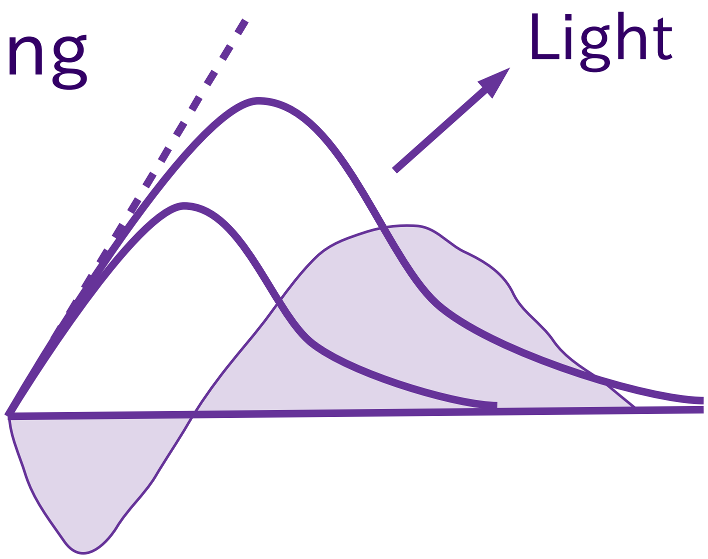
$$\delta\nu = G\delta\mu + F\delta\langle r^2\rangle + \tilde{F}\delta\langle r^4\rangle + \cdots$$

$$\psi \sim \chi_0 + \chi_2 r^2 + \cdots$$

Particle shift

Def: $$\int d\vec{r}\,\left(|\psi_j(\vec{r})|^2 - |\psi_i(\vec{r})|^2\right)(A' - A)\frac{g_n g_e}{4\pi}\frac{e^{-mr}}{r}$$

- Sensitive to the e-n coupling
- Similar to the field shift.



◆ For heavy mediator

$$= (A' - A)\frac{g_n g_e}{4\pi}\sum_k \frac{k!}{m^{k+2}}\xi_k$$

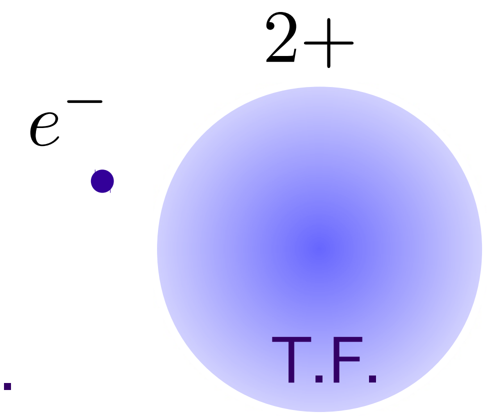
- $$\delta\nu = G\delta\mu + F\left(\delta\langle r^2\rangle + c_0/m^2\right) + \tilde{F}\left(\delta\langle r^4\rangle + c_2/m^4\right) + \cdots$$

Keep the linearity

Non-linearity

Wave functions of ions

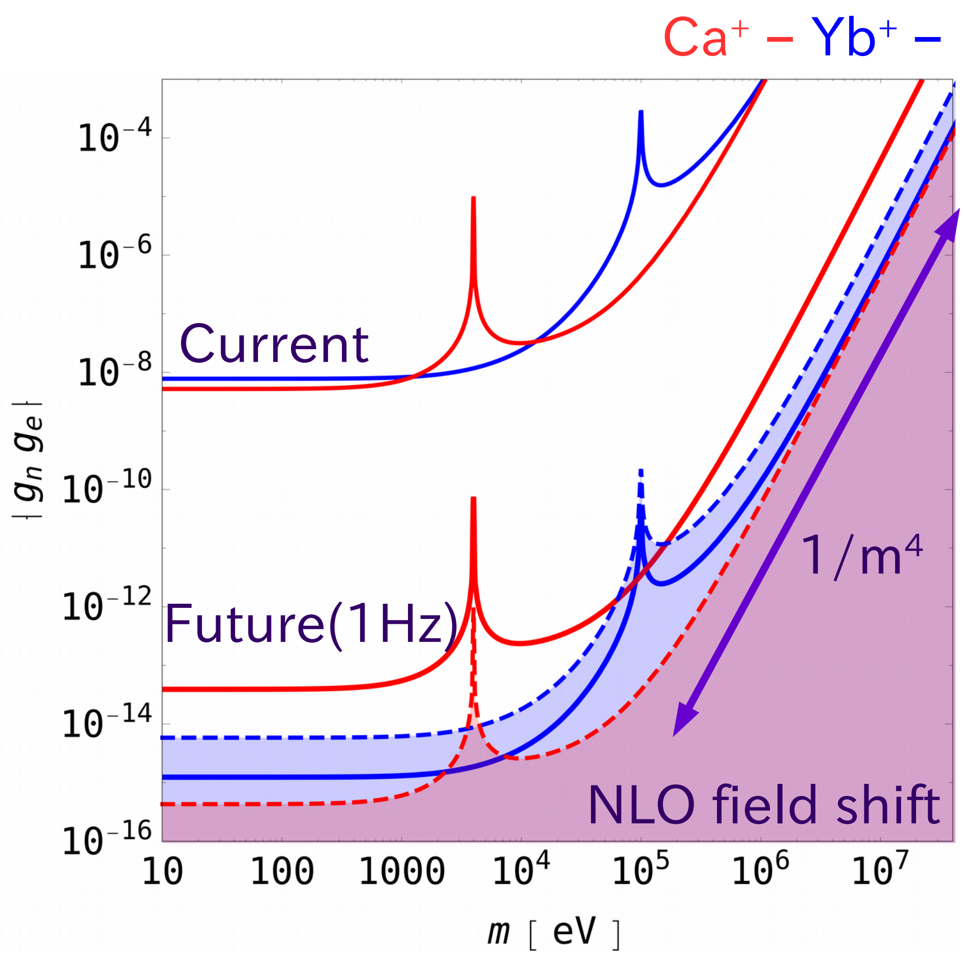
- Single electron
  +
  The Thomas-Fermi potential
  Semi-classical free electron gas.

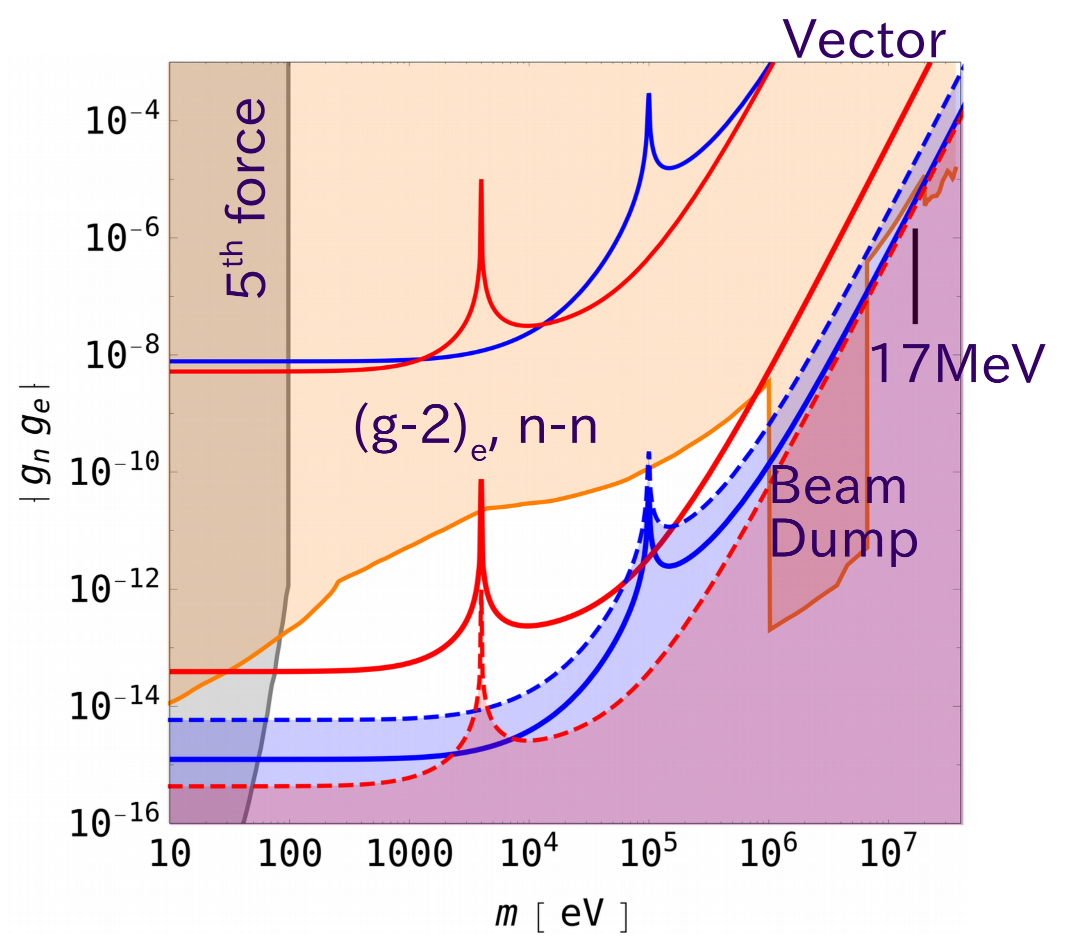


Ca^+	$^2S_{1/2} \rightarrow {}^2P_{1/2}$ (397nm) 4s → 4p (475nm)	$^2D_{3/2} \rightarrow {}^2P_{1/2}$ (866nm) 3d → 4p (-1610nm)
Yb^+	$^2S_{1/2} \rightarrow {}^2P_{1/2}$ (370nm) 6s → 6p (380nm)	$^2D_{3/2} \rightarrow {}^2D[3/2]_{1/2}$ (935nm) 4f → 6s (48.6nm)

- s- & p-states are , d- & f-states are .
- Numerically, good agreement with other results.

Sensitivity and constraints





- NLO field shift limits the future sensitivity.
- 100 eV – 1 MeV is the main target.

Conclusion

Precision spectroscopy + King's linearity

▼

New physics as the non-linearity

- SM background of NLO field shift.
- The scaling law at the heavy region.