Probing new intra-atomic force with isotope shifts

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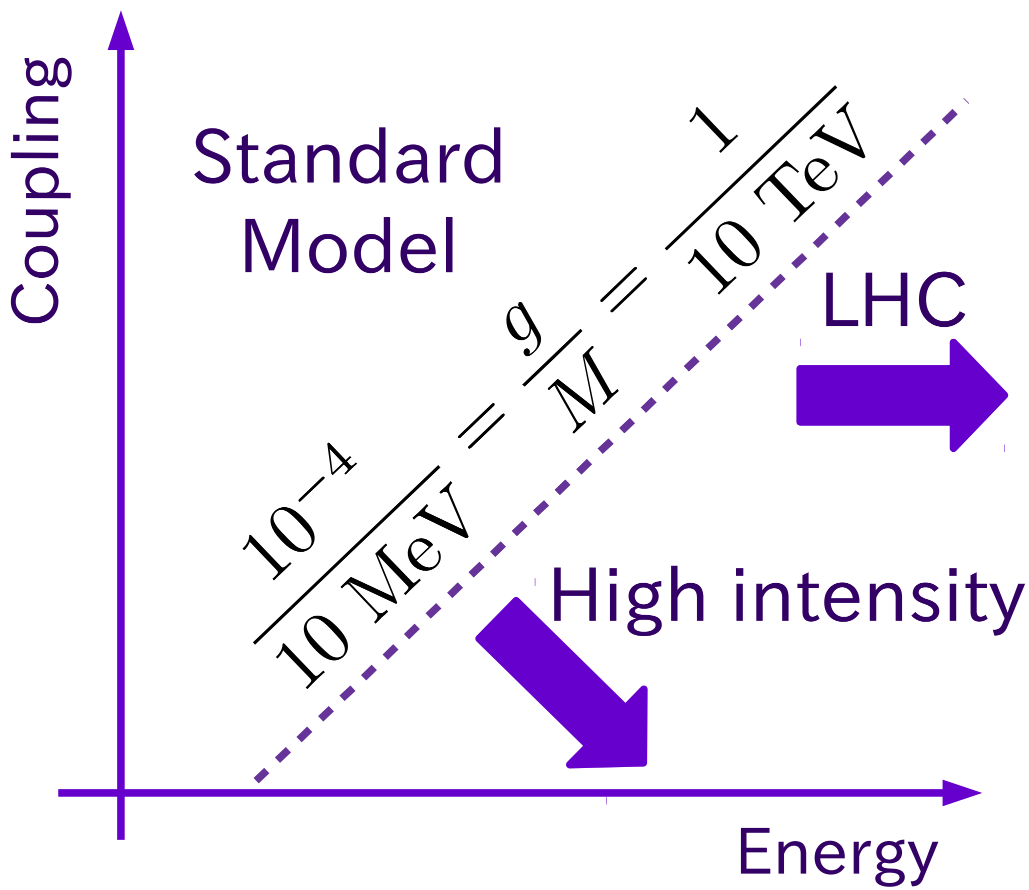
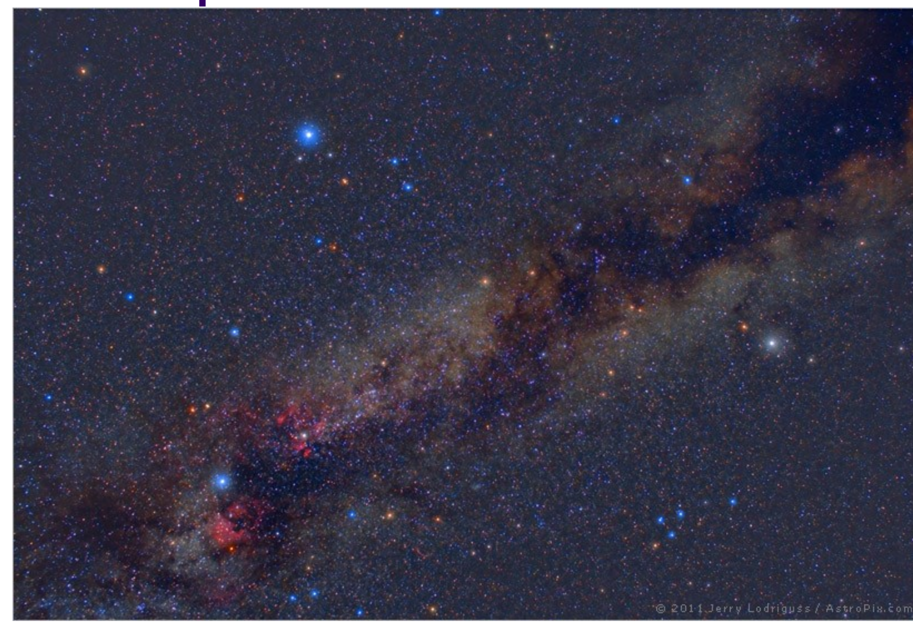
Based on 1710.11443
with K. Mikami & M. Tanaka (Osaka U)

Physics of light new boson



Real production



Stellar cooling, dark matter, thermal history, Higgs decay, flavor physics, etc.

- The light bosons may appear in many observations.

Atomic clocks

- Atomic spectroscopy with an extreme precision.
  - ☺ 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)

c.f.) the electron g-2 is O(10^{-10}).

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

  - ☹ The calculation of the spectrum is too difficult.

▶ How to reduce the uncertainty.

▶ The new constraints on **the light new boson**.

Plan

- Introduction
- The linearity and its violation
- The field shift and its higher order
- The particle shift
- The constraint of a light new boson
- 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

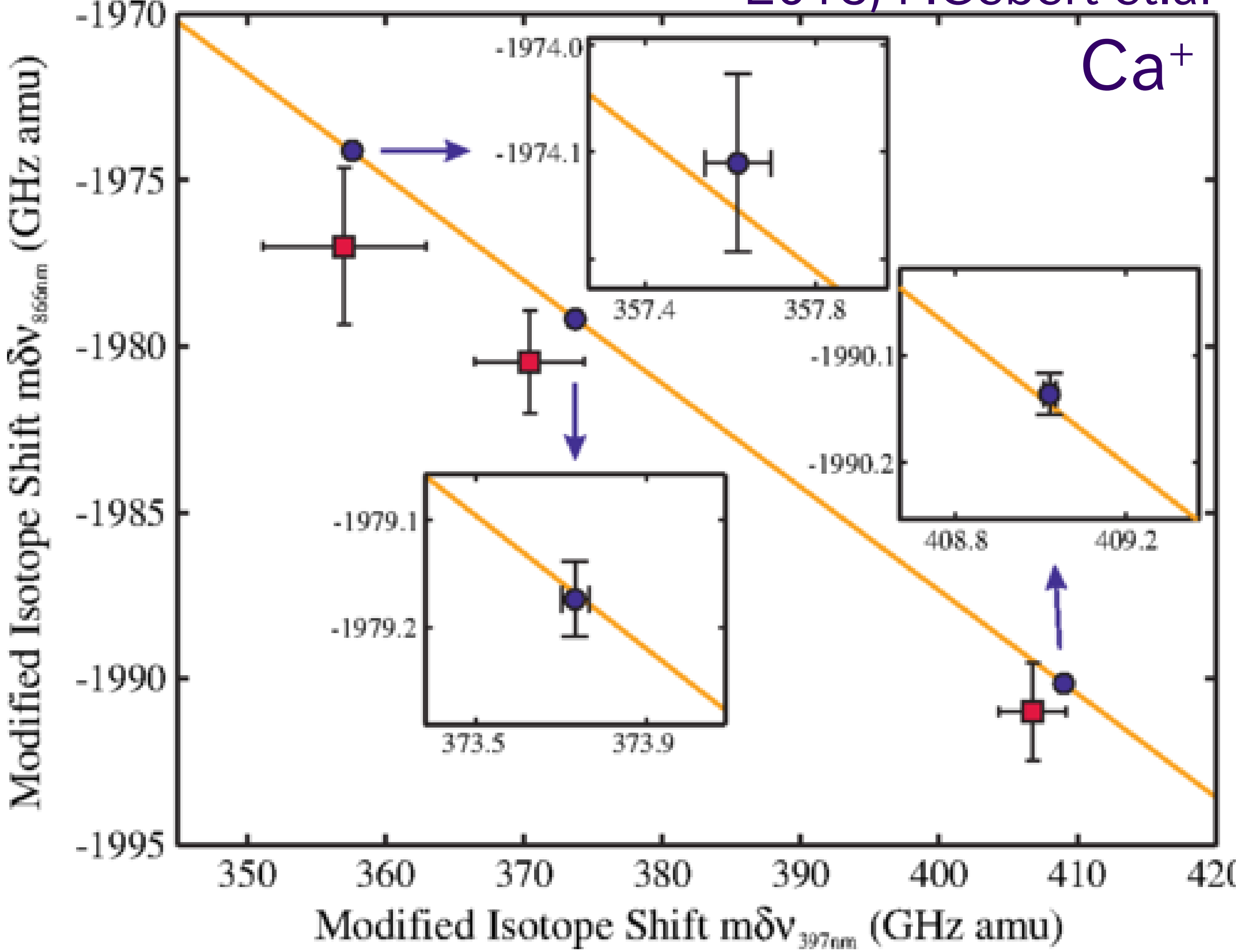
$$\frac{\delta\nu_2}{\delta\mu} = \frac{F_2}{F_1}\frac{\delta\nu_1}{\delta\mu} + \left(G_2 - \frac{F_2}{F_1}G_1\right)$$

Constant for isotope pairs.

Isotope shift and the linearity

- Isotope shifts follow a linearity.

2015, F.Gebert et.al



lence.

H. King

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.

- Linearity for isotope pairs.

Non

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

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

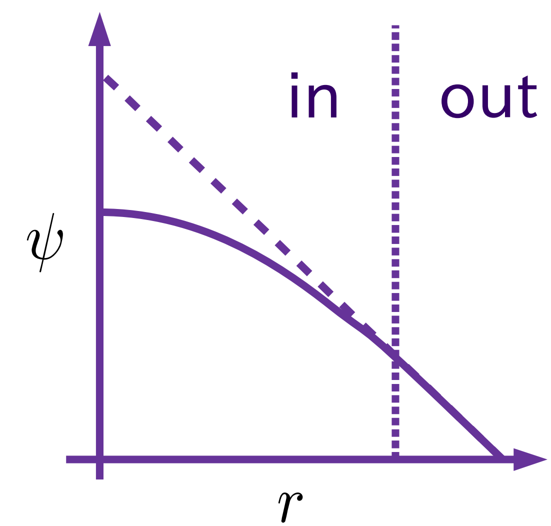
Expand

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

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

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

1969, E. C. Seltzer



- NLO field shift

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

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

Field shift

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

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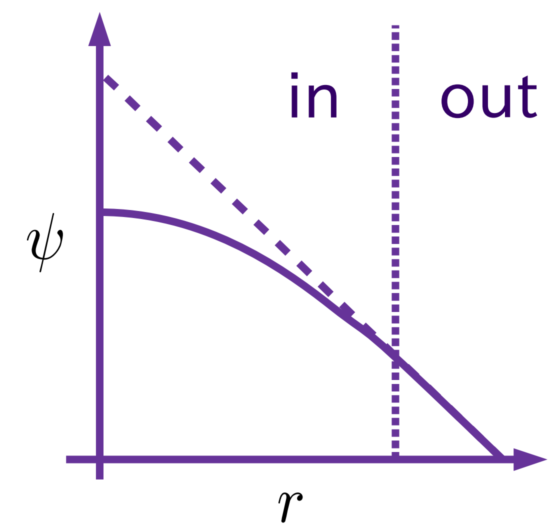

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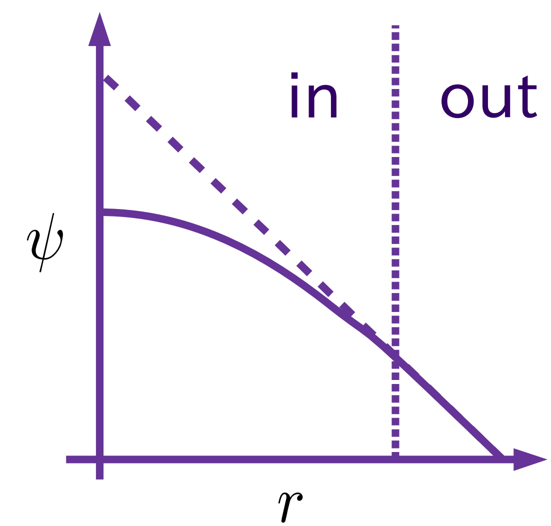
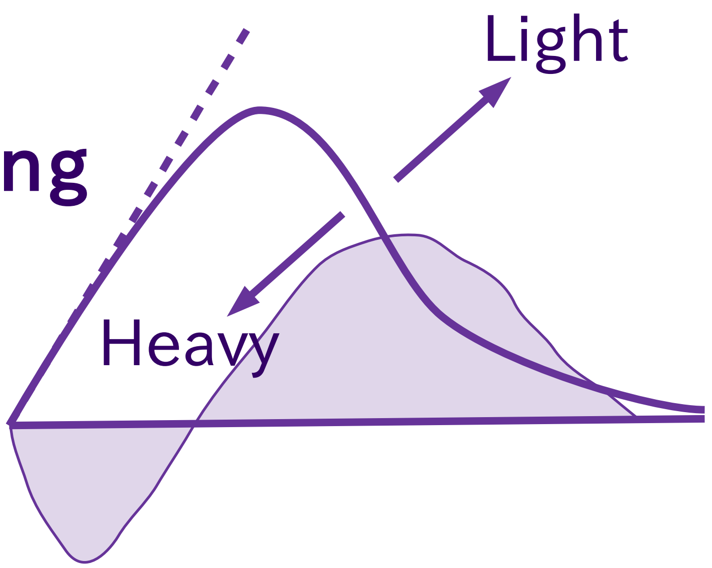


Particle shift

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

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



◆ For heavier particle

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

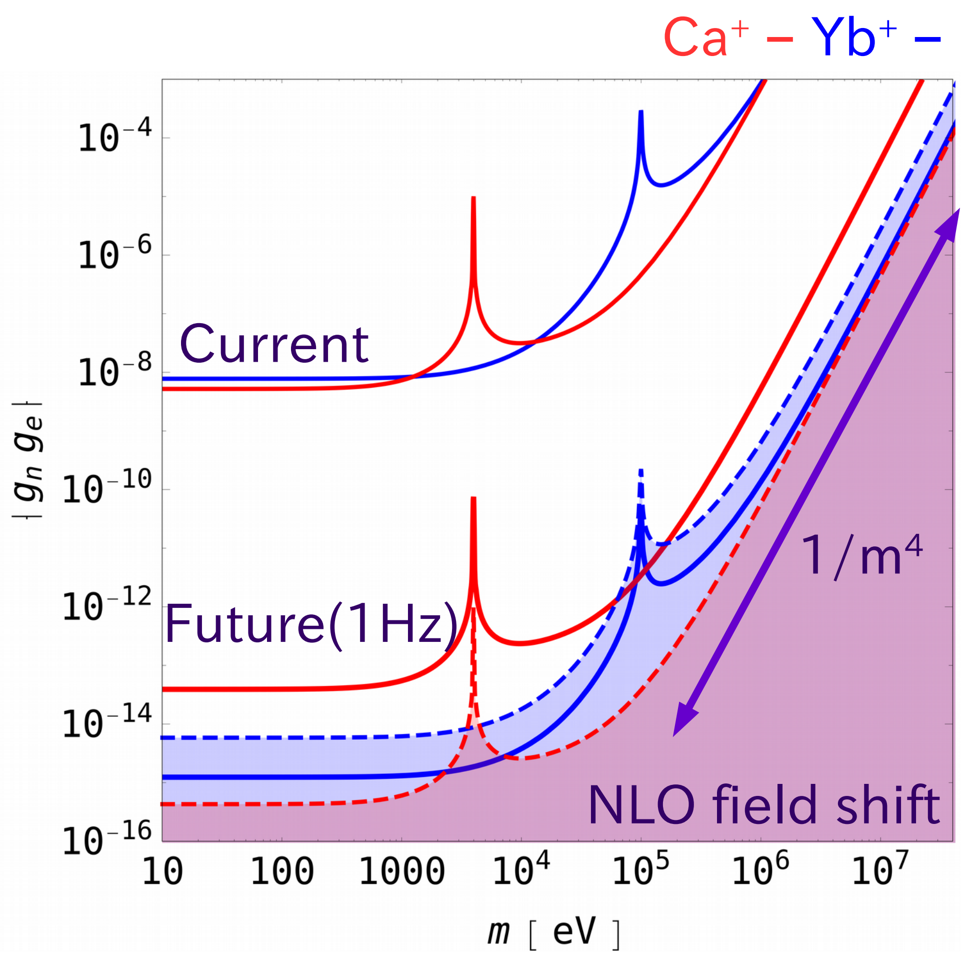
- $\delta\nu = G\delta\mu + F\left(\delta\langle r^2\rangle + c_0/m^2\right)$

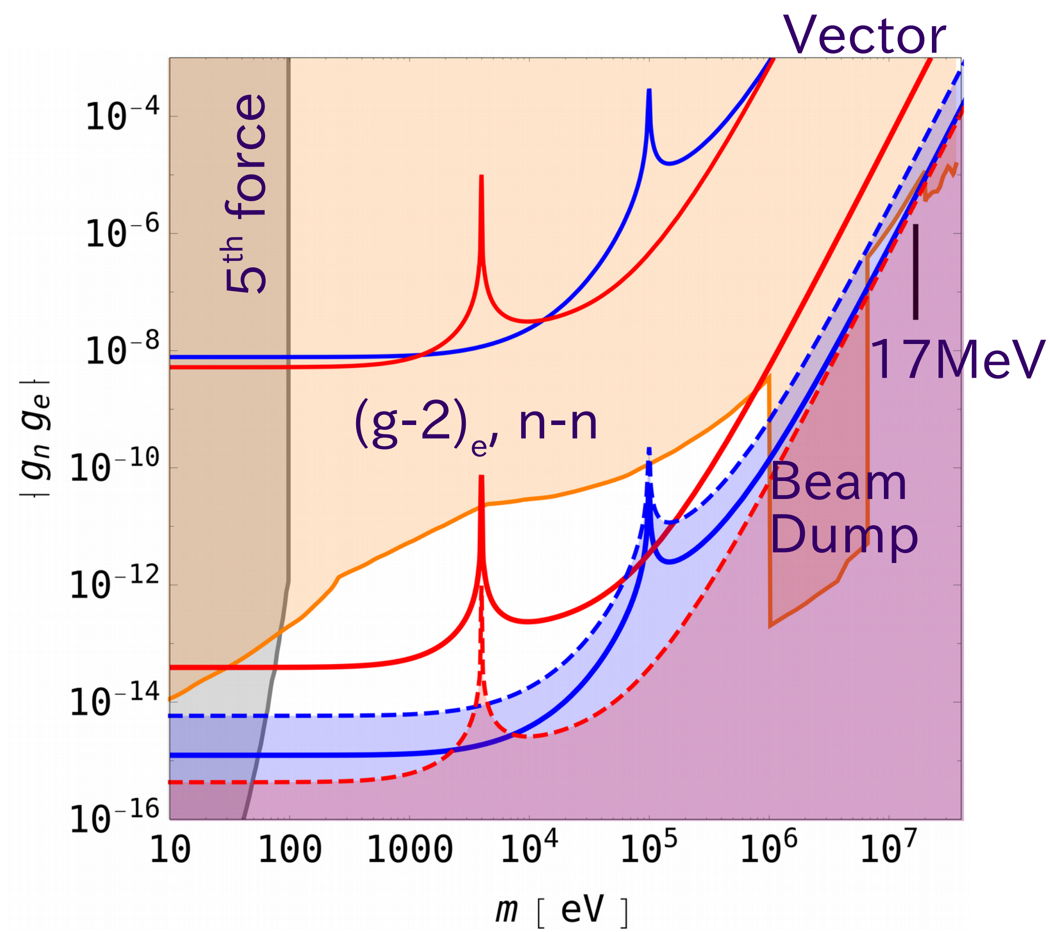
$$+\tilde{F}\left(\delta\langle r^4\rangle + c_2/m^4\right) + \cdots$$

Keep the linearity

Non-linearity

Sensitivity and constraints





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

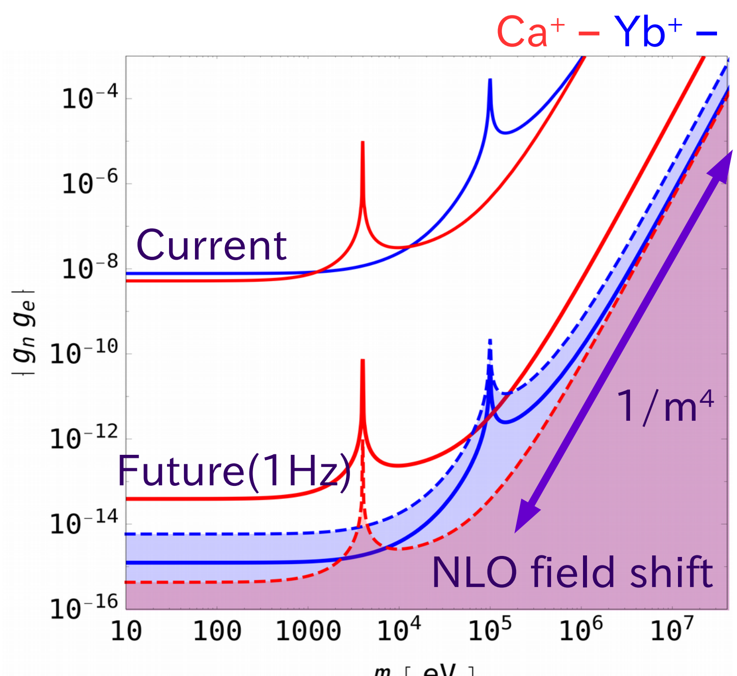
Conclusion

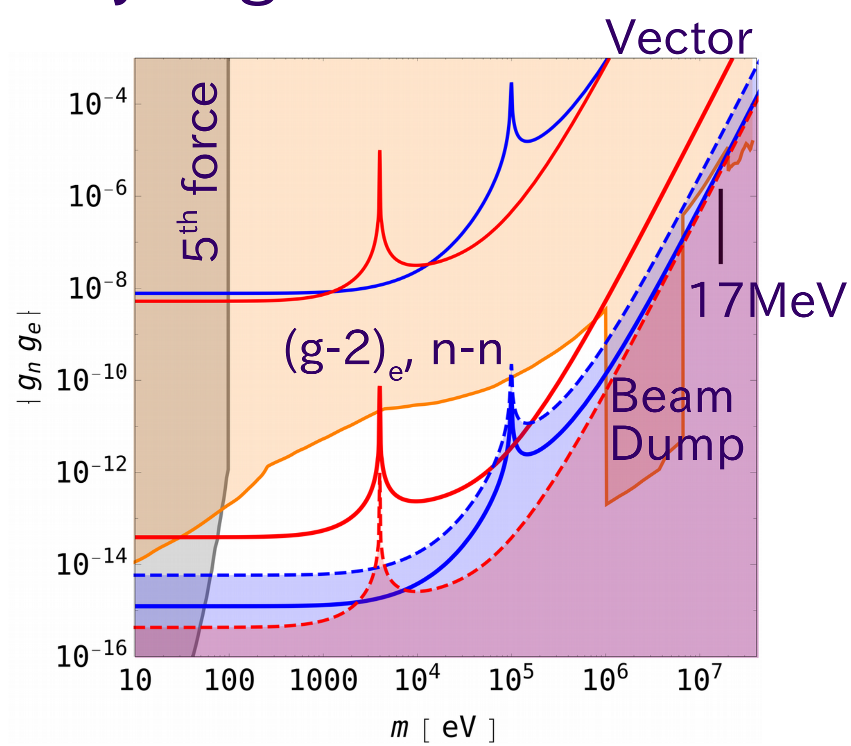
Precision spectroscopy + Linearity of isotopes

▼

New physics as the non-linearity

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





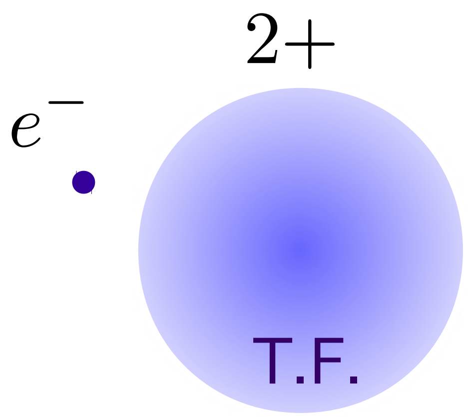
Other issues

- **Relativistic effects** on wave function and potential.
  - The inner behavior can be modified.
  - Possibly important for light elements.
- **Isotope shift corrections** to wave functions.
  - Can be large for heavy elements.
- **Details of nuclear density** distributions.
  - Angular distributions.

And others...

- **Suggest appropriate atoms to experiments.**

Wave functions of ions



Single electron

$+$

The **Thomas-Fermi** potential

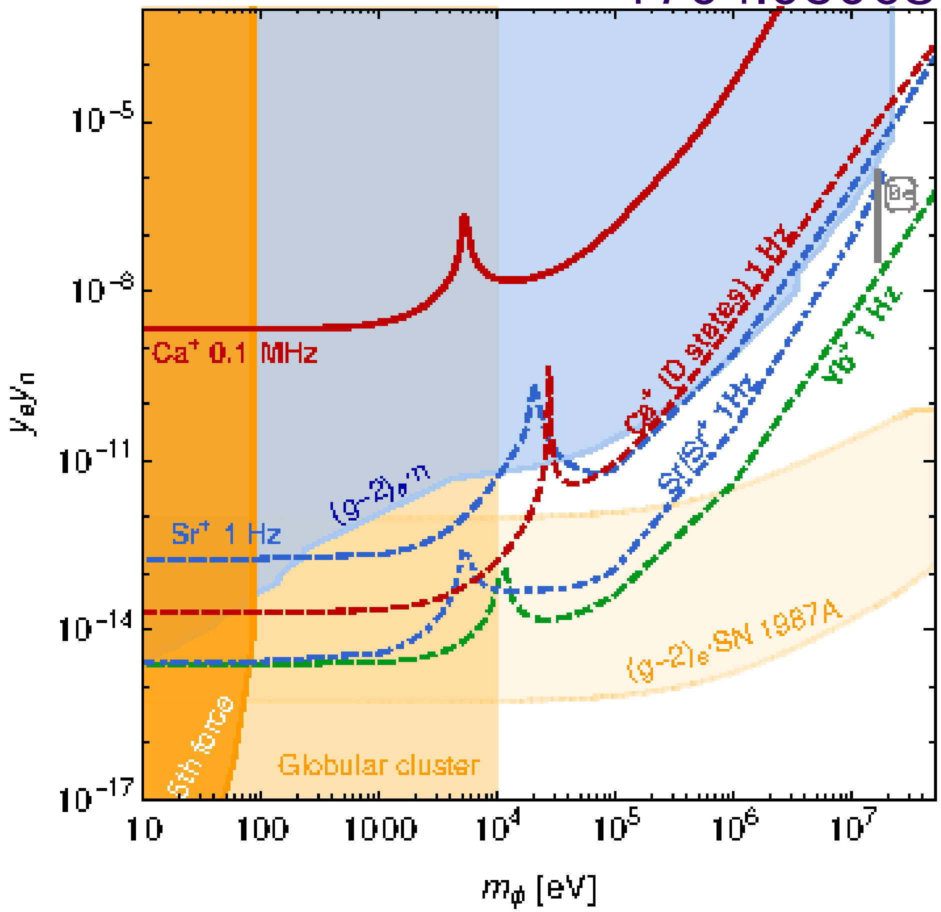
(Semi-classical free electron gas.)

Ca^+	$^2S_{1/2} \rightarrow {}^2P_{1/2}$ (323meV) $4s \rightarrow 4p$ (386meV)	$^2D_{3/2} \rightarrow {}^2P_{1/2}$ (704meV) $3d \rightarrow 4p$ (-1309meV)
Yb^+	$^2S_{1/2} \rightarrow {}^2P_{1/2}$ (301meV) $6s \rightarrow 6p$ (309meV)	$^2D_{3/2} \rightarrow {}^2D[3/2]_{1/2}$ (760meV) $4f \rightarrow 6s$ (39.5meV)

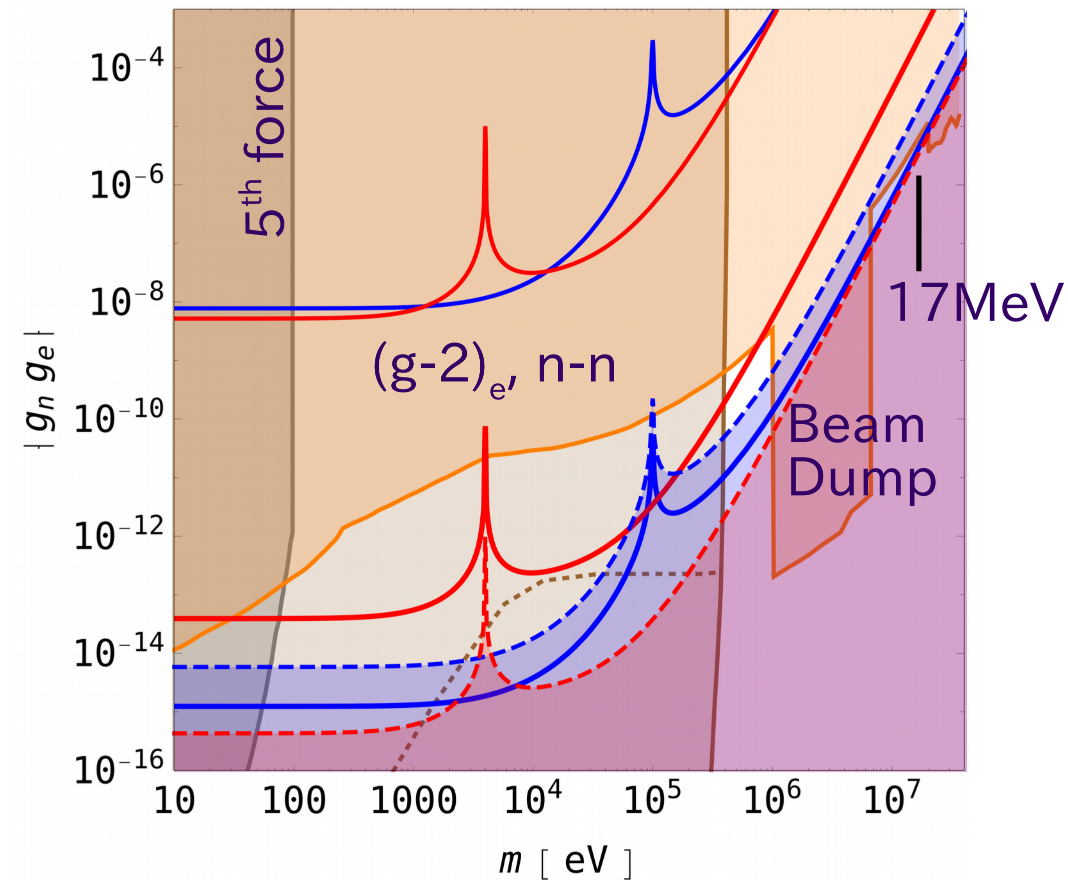
- s- & p-states are , d- & f-states are .
- Numerically, good agreement with other results.

Some comments

1704.05068



Vector



- The stellar cooling has large uncertainty.
- Our result is smooth because of the analytic study.