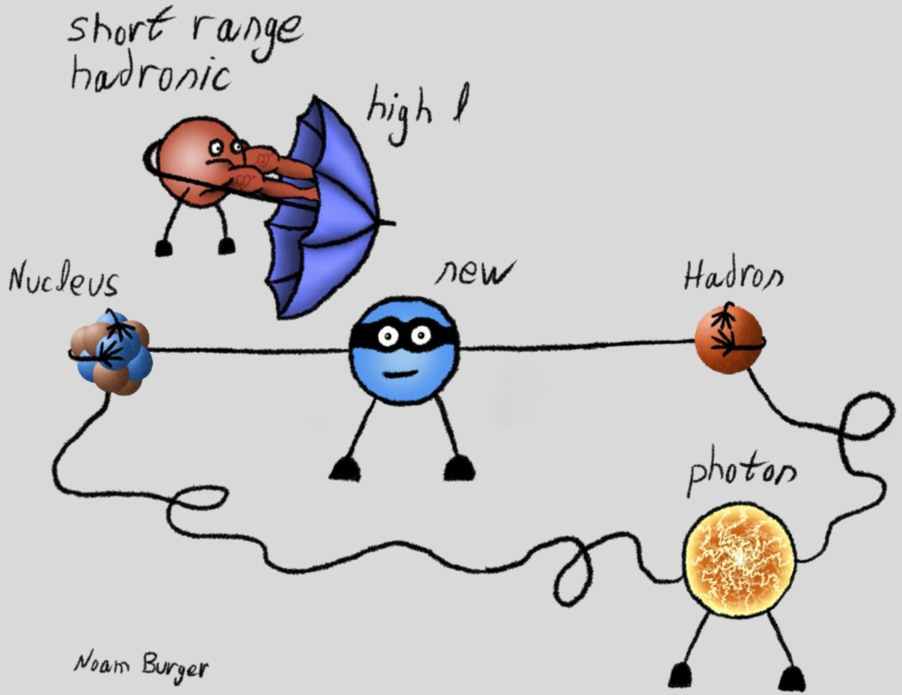
Technion
Israel Institute of Technology

Quantum Sensing for Fundamental Physics
November 18 – 21, 2024
https://indico.mitp.uni-mainz.de/event/424

Probing new hadronic interactions with exotic atoms

Omer Shtaif

Work in progress with Ben Ohayon, Hongkai Liu, Yotam Soreq



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New Physics from energy shifts

- Spectroscopy of simple atomic systems allows for a **precise** comparison between **theory** and **experiment**

$$E_n^{\mathrm{exp}} = E_n^{\mathrm{SM}} + E_n^{\mathrm{NP}}$$

approaching $\mathcal{O}(\mathrm{ppm})$ precision

equal or better precision than E_n^{exp}

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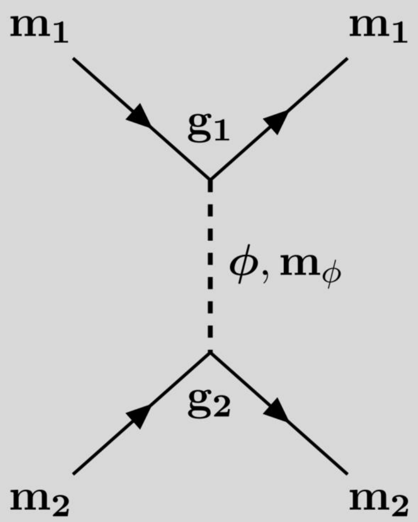
e.g. Fadeev et. al arXiv:1810.10364



$$V_{\mathrm{Yukawa}}(r) = -\mathrm{g}_1\mathrm{g}_2\frac{\mathrm{e}^{-m_\phi \mathrm{r}}}{4\pi\mathrm{r}} + \cdots$$

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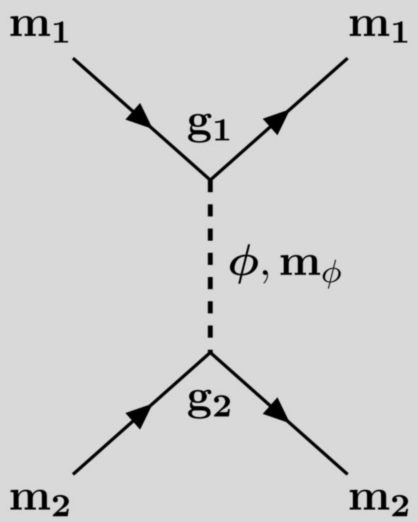

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heavier mediator = smaller range

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e.g. Zatroski, Patkóš, Pachucki arXiv:2207.14155 and N.Paul et.al arxiv:2011.09715

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- short-range hadronic interactions

The Atomic system

- The class of atomic systems we consider:

Exotic atoms in circular and excited states with high-Z nuclei

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Exotic atoms in circular and excited states with high-Z nuclei

$$l = n - 1 \qquad\qquad n > 2$$

- $l \geq 1$ are unaffected by strong force contact terms
- Higher n states have smaller velocities $\langle v \rangle \propto \frac{Z}{n}$

e.g. Zatroski, Patkóš, Pachucki arXiv:2207.14155

The Atomic system

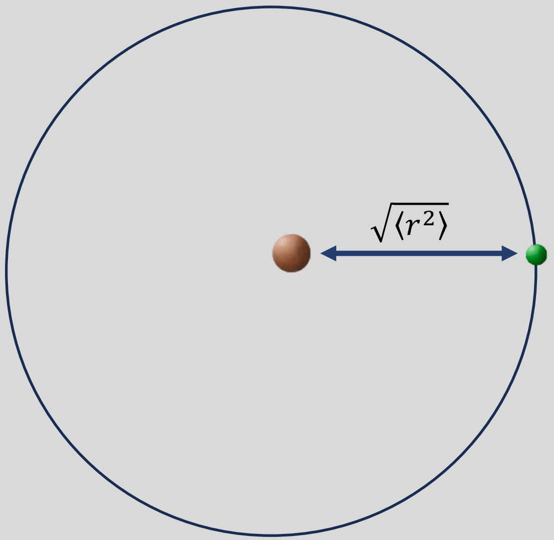
- The class of atomic systems we consider:

Exotic atoms in circular and excited states with high-Z nuclei

Either $\bar{p}$ or π^- as the orbiting particle

$7 < Z < 82$

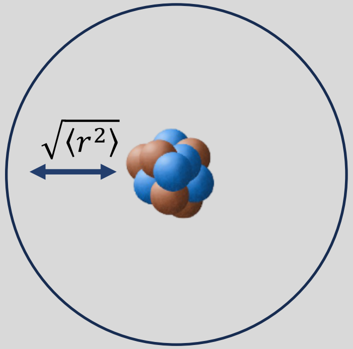
Hydrogen



$$\sqrt{\langle r^2 \rangle} \propto \frac{n^2}{\mu Z}$$

distance is still smaller!

Exotic atom



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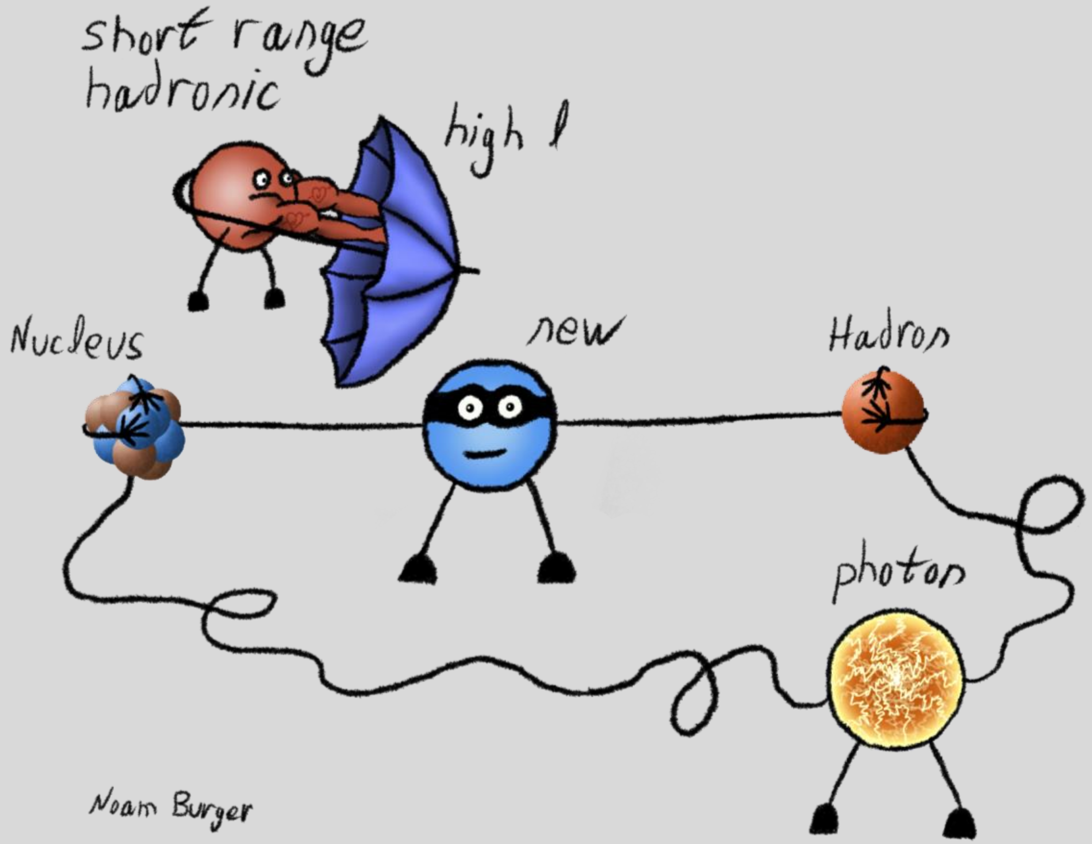

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- nuclear polarization

Nuclear Polarization

- The nucleus and orbiting particle are polarized

nucleus polarizability

proton polarizability

$$\Delta E_n^{\mathrm{Pol}} = -\frac{1}{2} e^4 \left(\boldsymbol{\alpha}_{\boldsymbol{E_1}}^{\boldsymbol{N}} + Z^2 \alpha_{E_1}^{\bar{p}} \right) \langle r^{-4} \rangle_n$$

Ericson, Hüfner, Nuclear Physics B47

poorly measured!

e.g. J.N.Orce et.al PHYSICAL REVIEW C 108, 044309 (2023)

Transition	$\frac{\Delta E_n^{\mathrm{Pol}}}{\Delta E_n^{\mathrm{SM}}} \times \mathbf{10^{-6}}$
$\bar{p}\,^4\mathrm{He}\,(32,31) \to (31,30)$	$(6 \pm 1) \times 10^{-8}$
$\bar{p}\,^{208}\mathrm{Pb}(11,10) \to (10,9)$	$70 \pm \mathbf{15}$

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- nuclear polarization ?

One vs Two energy transitions

$$E_n^{\text{exp}} = \overbrace{\left(E_n^{\text{SM-Pol}} + E_n^{\text{Pol}}(\boldsymbol{\alpha}_{\boldsymbol{E_1}})\right)}^{\text{SM}} + E_n^{\text{NP}}(\boldsymbol{g}_{\boldsymbol{new}})$$

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Is the polarizability contribution under control?

One vs Two energy transitions

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Is the polarizability contribution under control?

YES

Solve g_{new} using **one** transition

NO

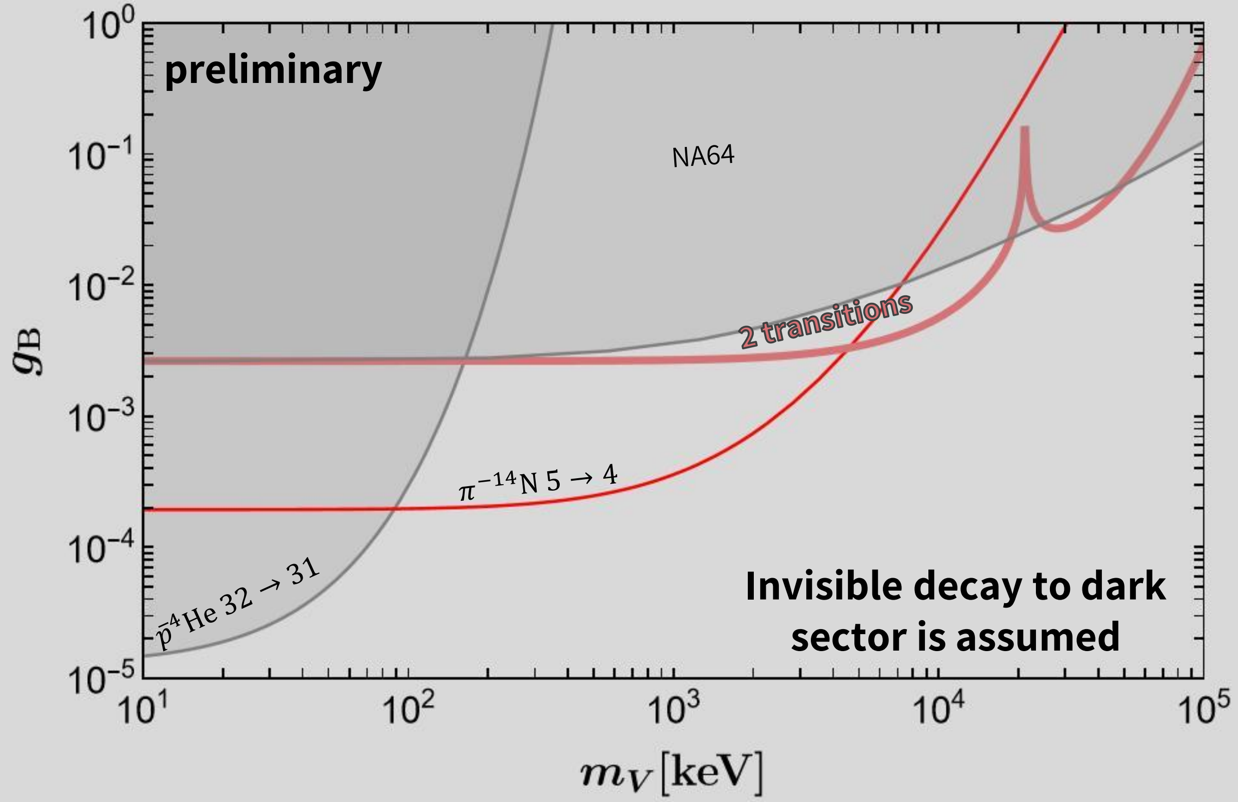
Solve g_{new} and α_{E_1} using **two** transitions

New bounds on the B-model

- New baryonic interaction with invisible decay to a dark sector:

$$\mathcal{L}_{\text{SM+B model}} \subset -\frac{1}{3} g_B V^{\mu}\left(\bar{u}\gamma_{\mu}u + \bar{d}\gamma_{\mu}d\right) + \text{dark sector}$$

*see also J.A. Dror et. Al arXiv:1705.06726



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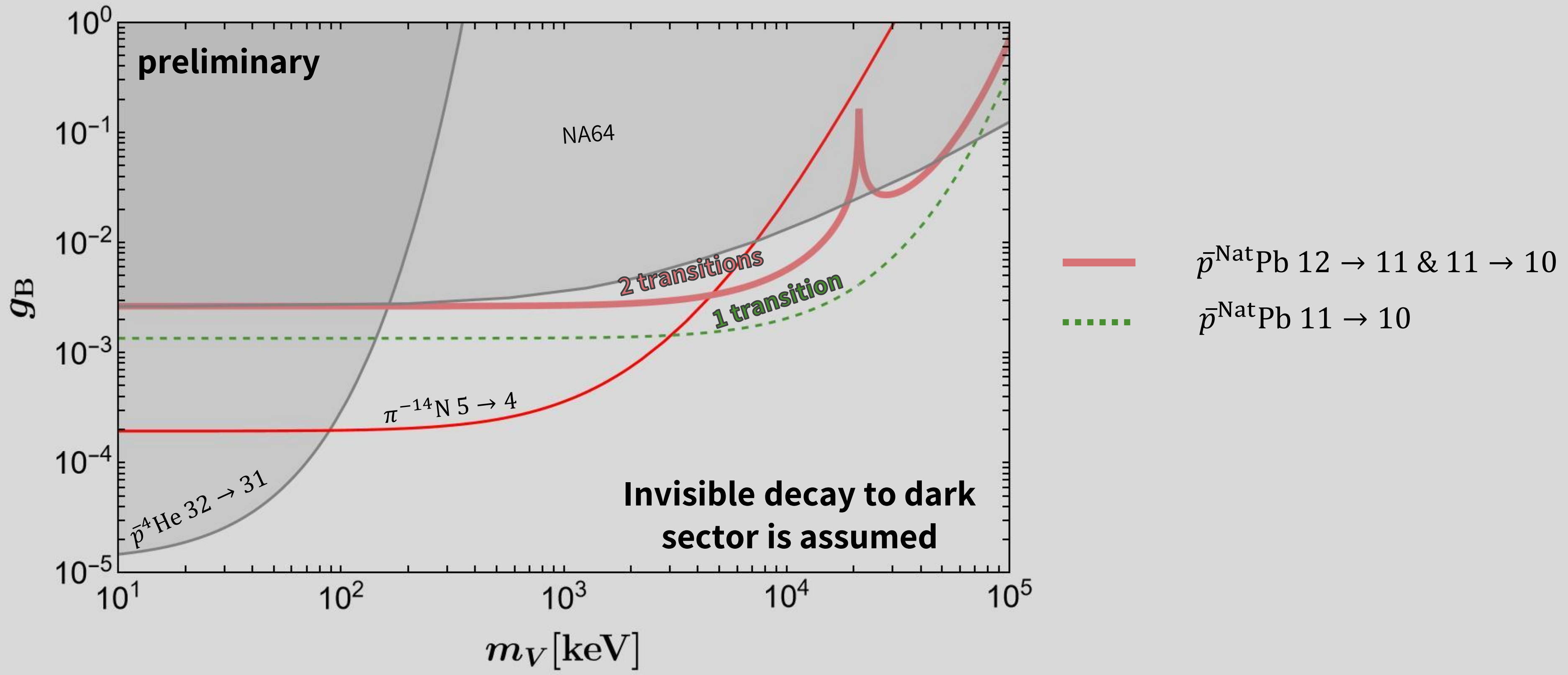

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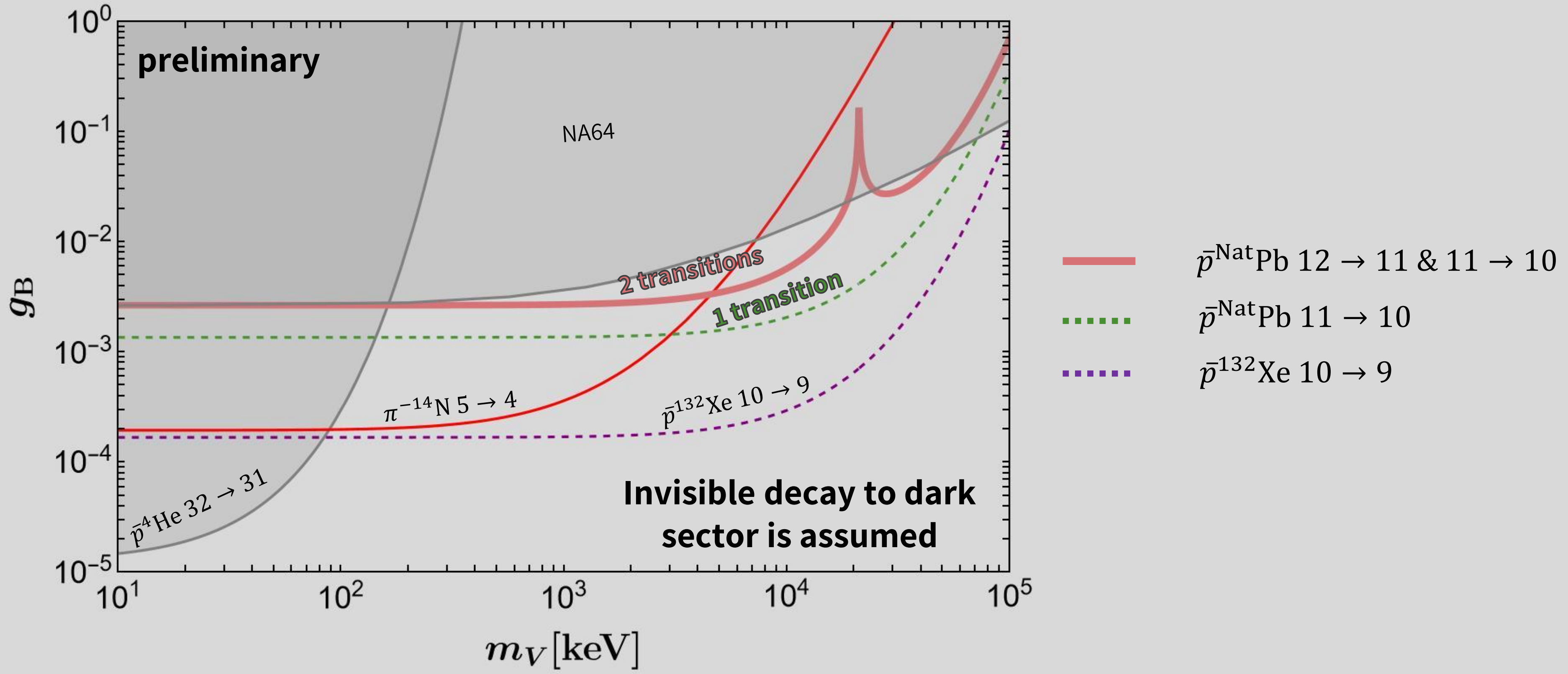

Conclusions

- Spectroscopy of simple atomic systems is a competitive probe for new physics in the keV-MeV scale

- Smart selection of atomic systems can avoid challenging SM contributions

- Further investigation of nuclear polarizabilities can advance new physics searches

- Ideal application for next-generation experiments with antiprotonic atoms!

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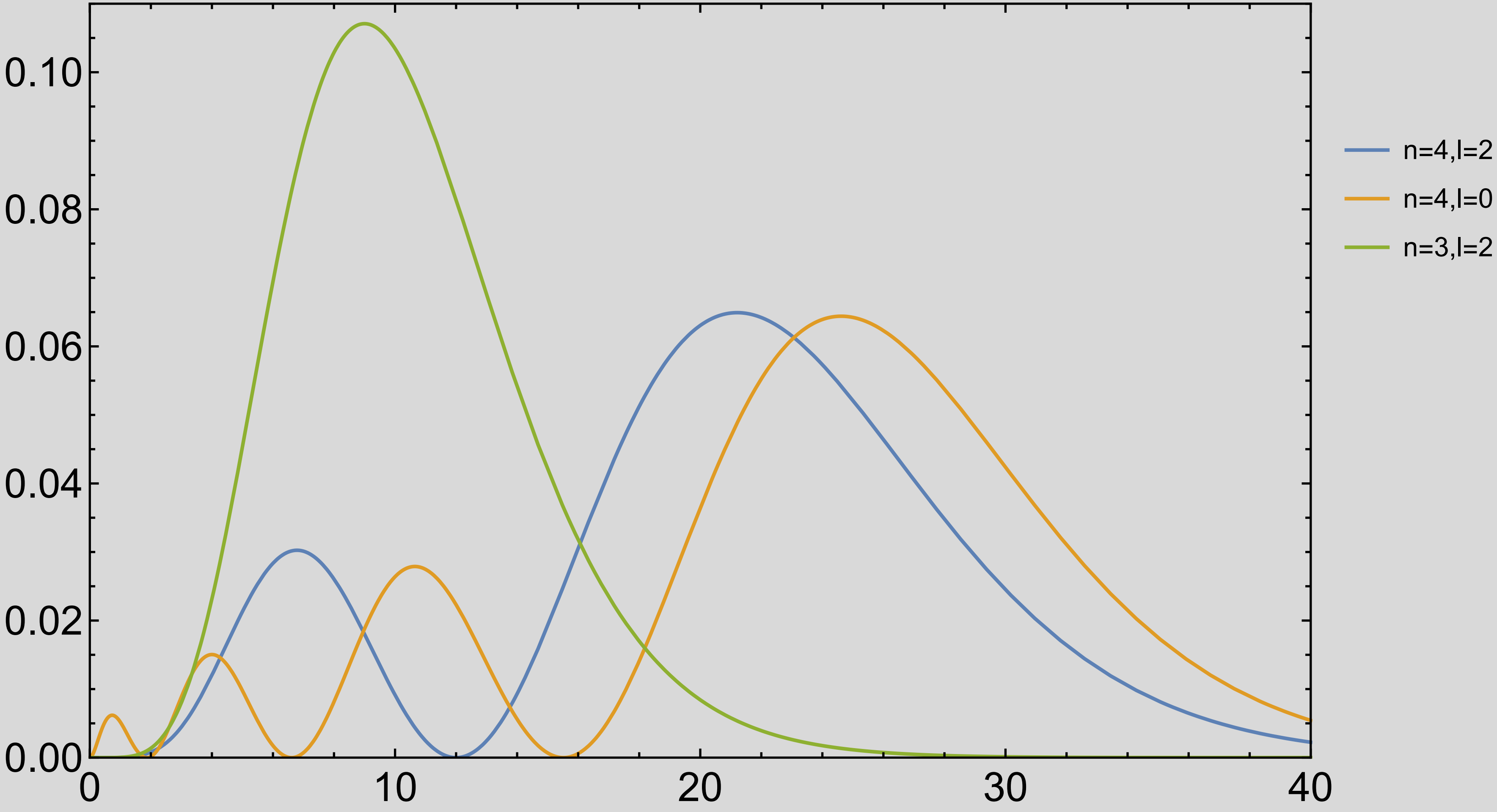
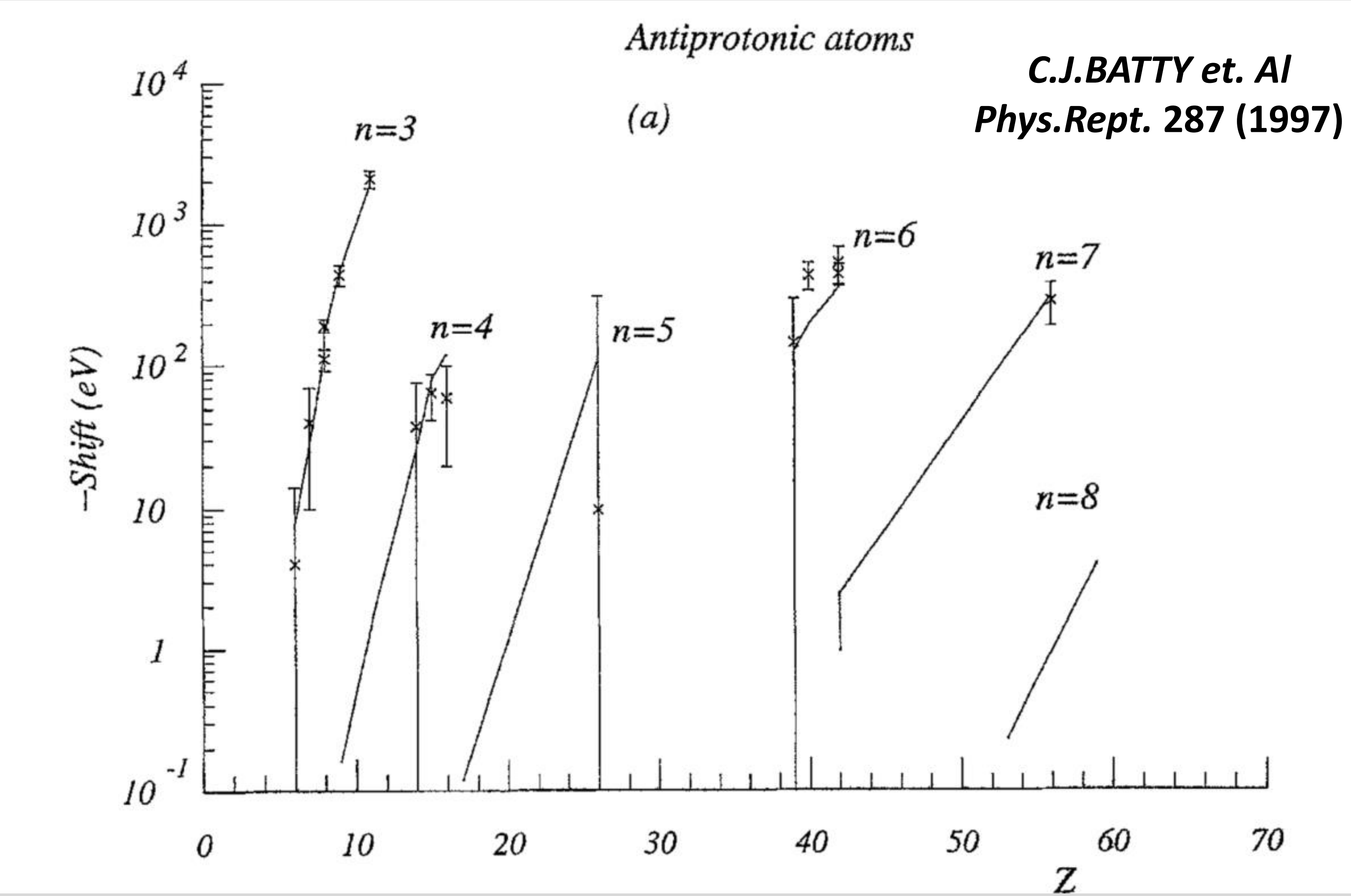
Thanks for listening!

Backup: different wave functions comparison



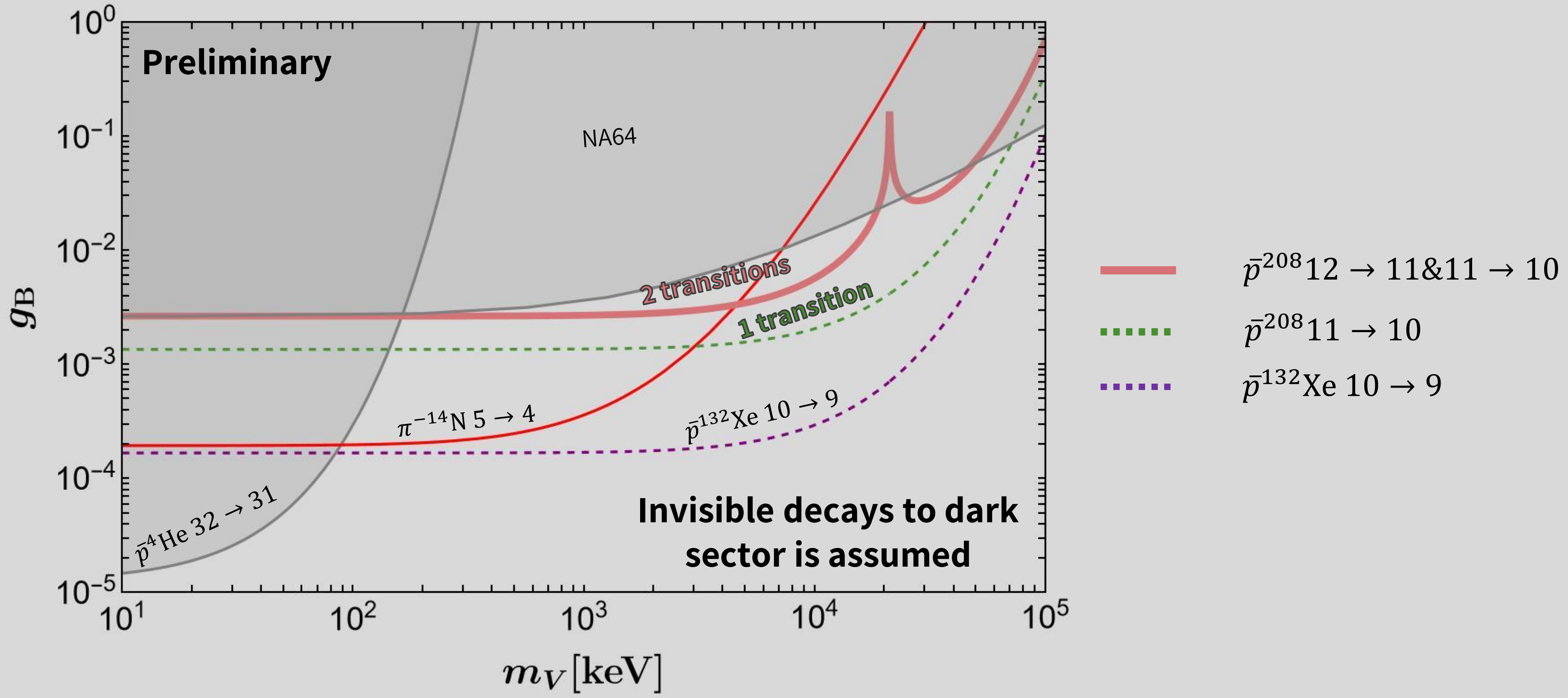
Backup: short-range hadronic interactions



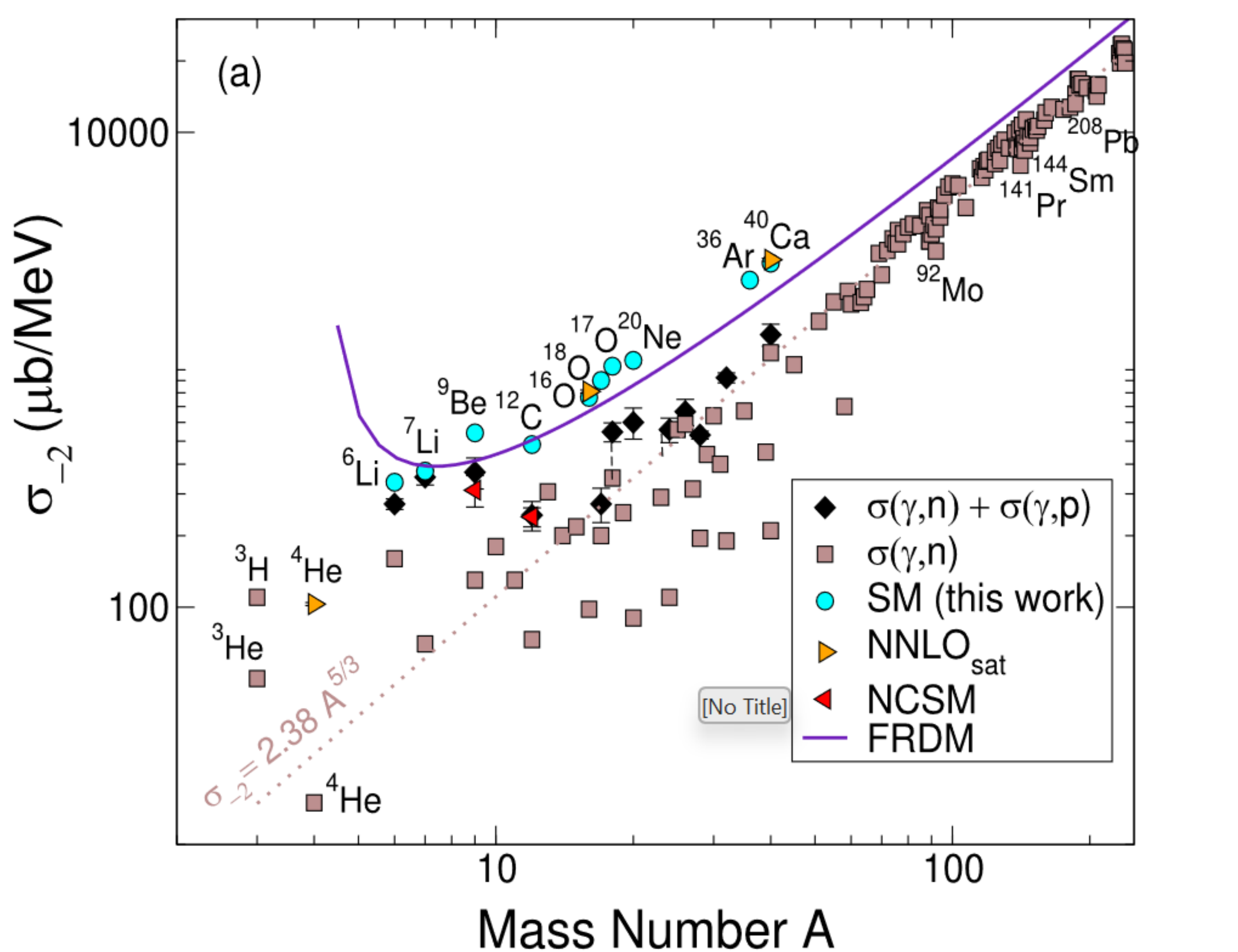
Backup: mass reach of different atoms

$$\Delta E_n^X = \frac{g_{\bar{p}}^X g_N^X}{4\pi}\frac{Z\alpha\mu}{n^2}\left(1+\frac{\boldsymbol{n}}{\boldsymbol{2Z\alpha\mu}}m_X\right)^{-2n}$$

$$\frac{Z_{\mathrm{Pb}}n_{\mathrm{He}}}{Z_{\mathrm{He}}n_{\mathrm{Pb}}} = \frac{82\cdot 31}{2\cdot 10} \approx 10^2$$



Backup: polarizability semi empirical equation



Backup: Capture of $\bar{p}$ and cascade