TECHNION
Israel Institute of Technology

October 13, 2026

New hadronic interactions with exotic atoms

NEW EXOTICA - 2026

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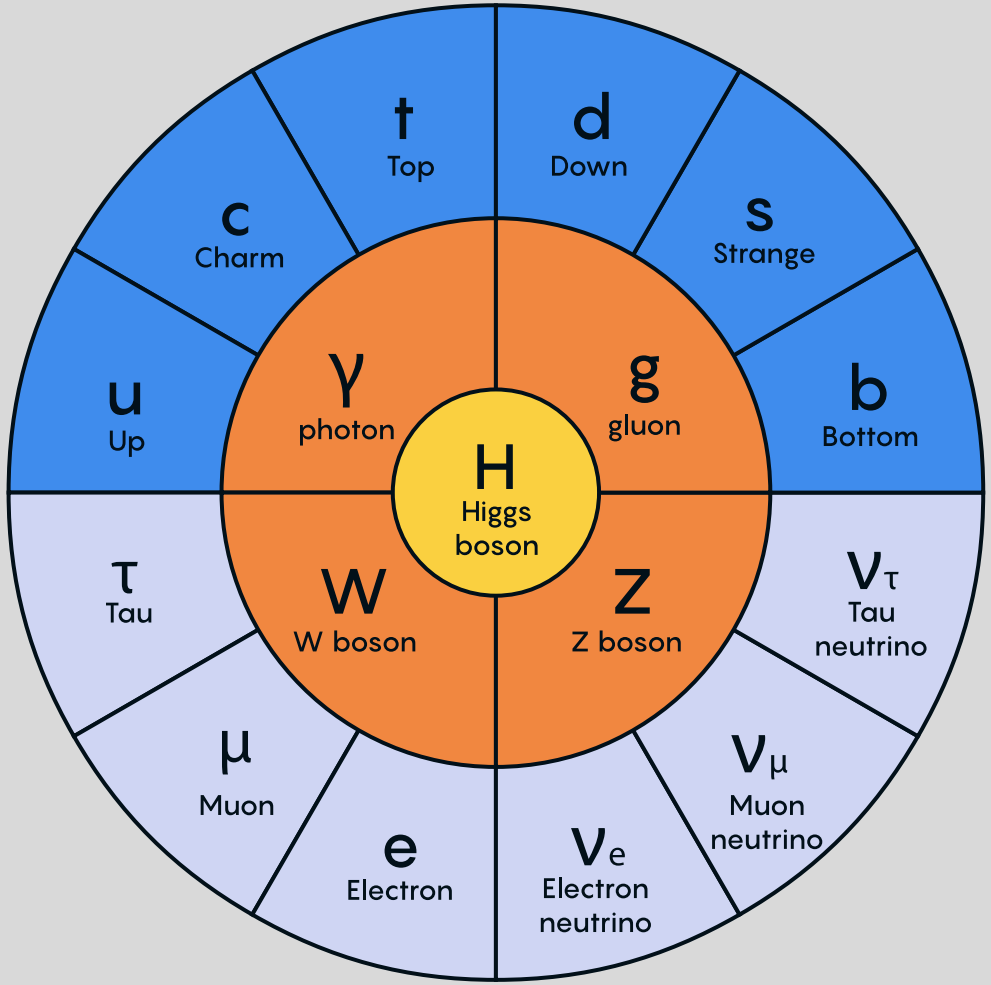
The particle physicist perspective





The particle physicist perspective

beyond the standard model (SM)



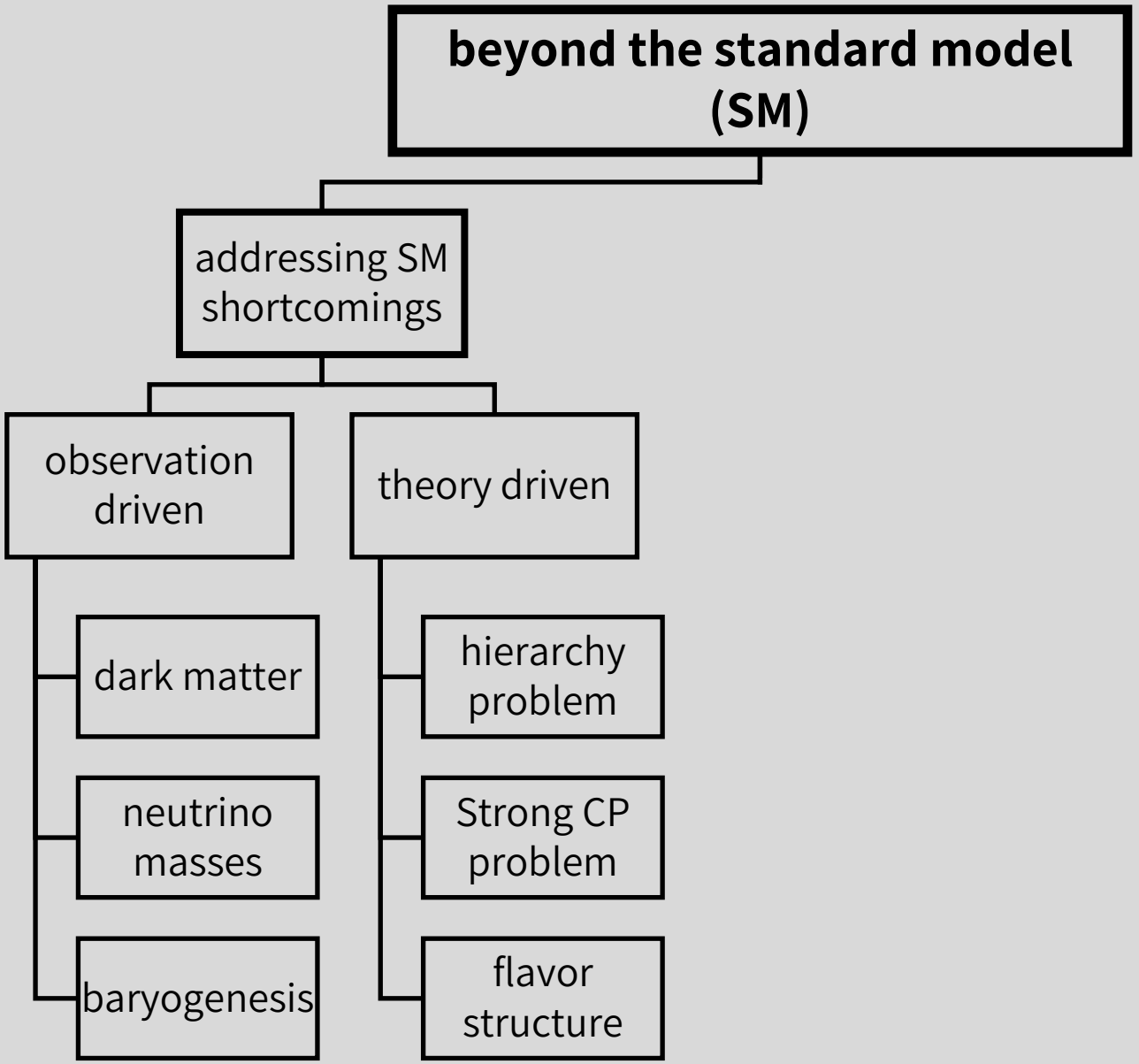
The particle physicist perspective

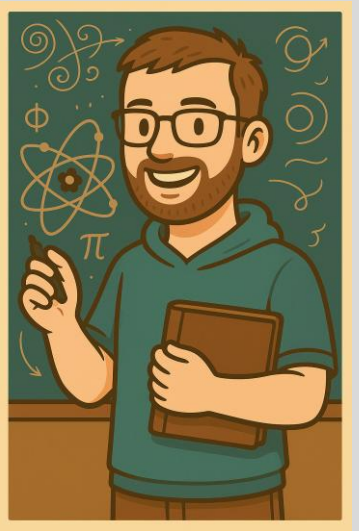
beyond the standard model (SM)

addressing SM shortcomings



The particle physicist perspective





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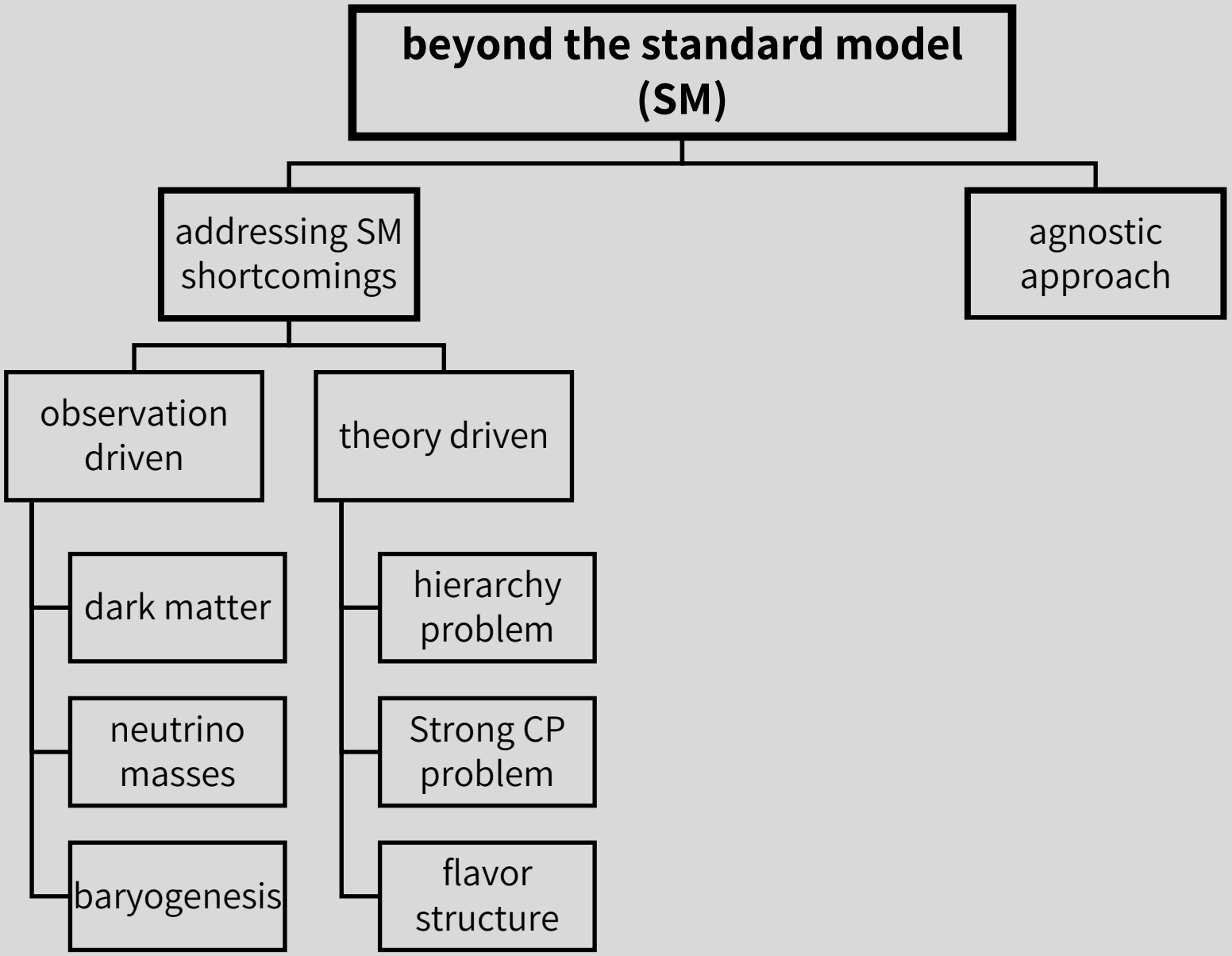



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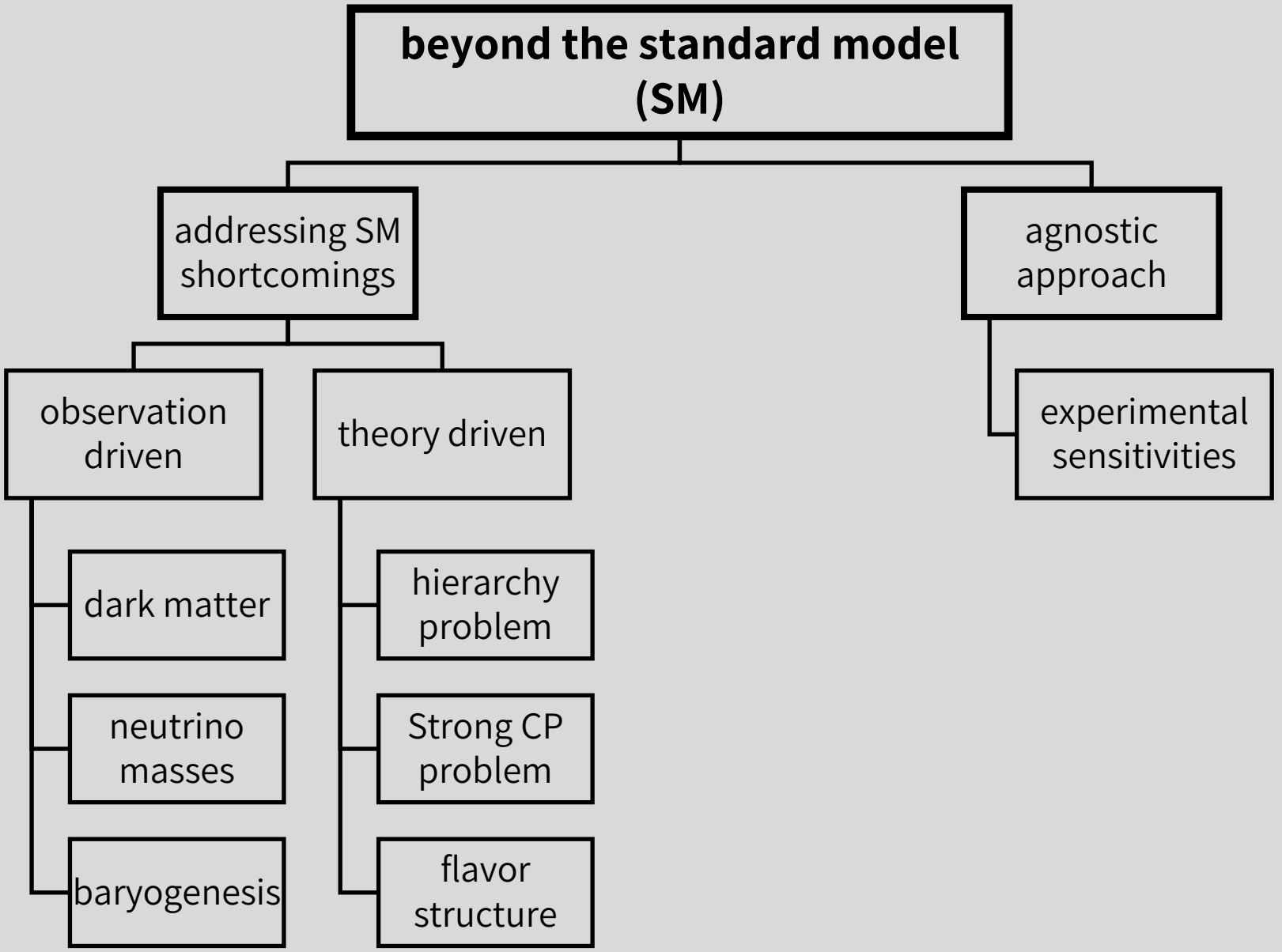
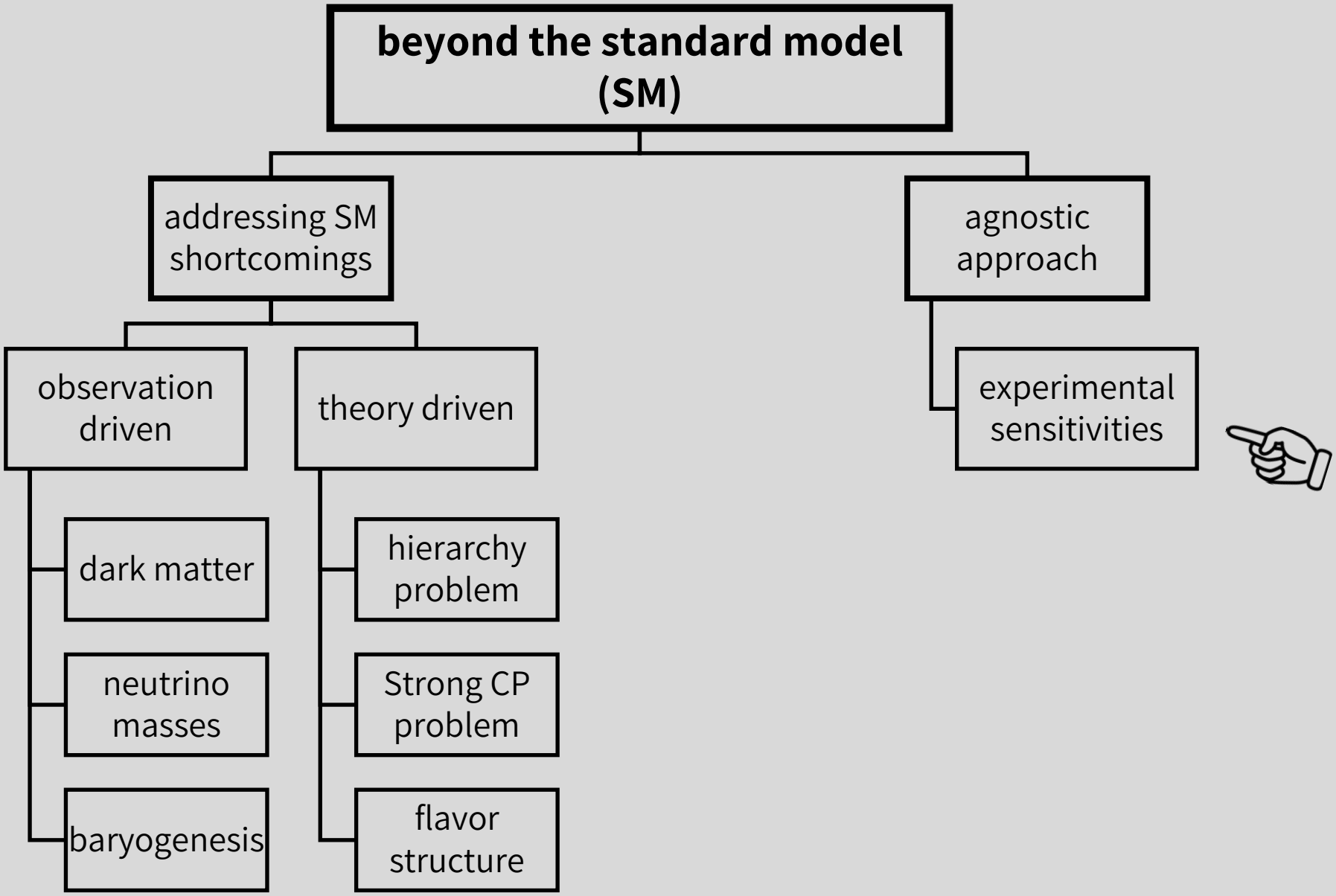




The particle physicist perspective





New physics from energy shifts

$$E_n^{exp} = E_n^{SM} + E_n^{BSM}$$

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



New physics from energy shifts

$$E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



New physics from energy shifts

$$E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



- The first Born approximation in QM

$$\int \frac{d^3q}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \frac{\mathcal{M}_{NR}(\boldsymbol{q})}{4m_1m_2} = V(\boldsymbol{r})$$

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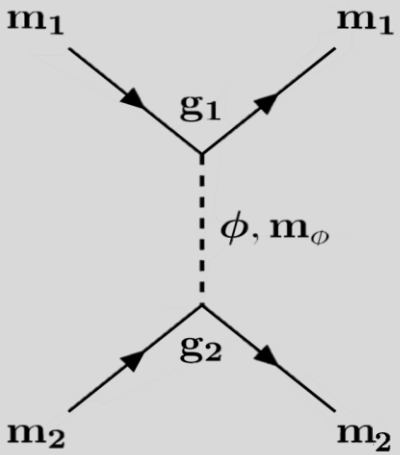
- In practice:



NR



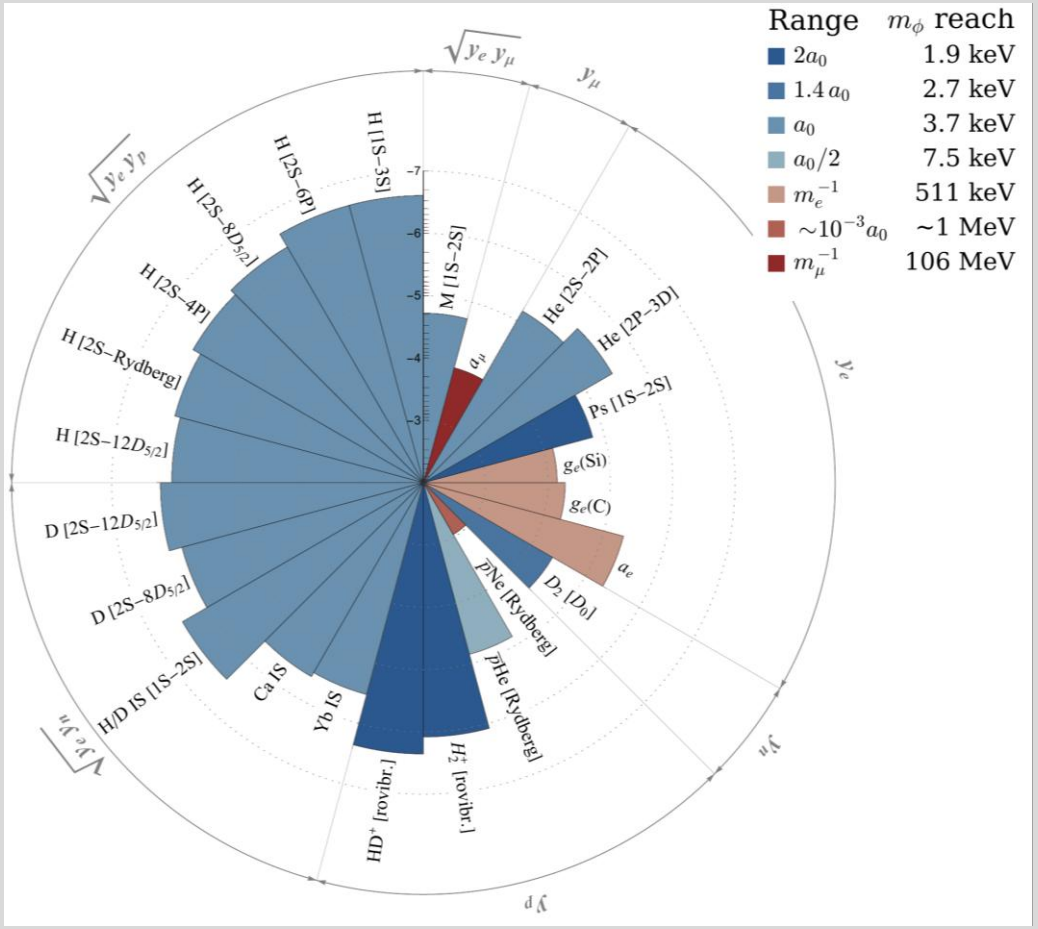
$$V(\boldsymbol{r}) = -(g_1 \times g_2)\frac{e^{-m_\phi r}}{4\pi r} + V_{NLO}\left(\boldsymbol{r}, \vec{\boldsymbol{S}}_1, \vec{\boldsymbol{S}}_2\right)$$

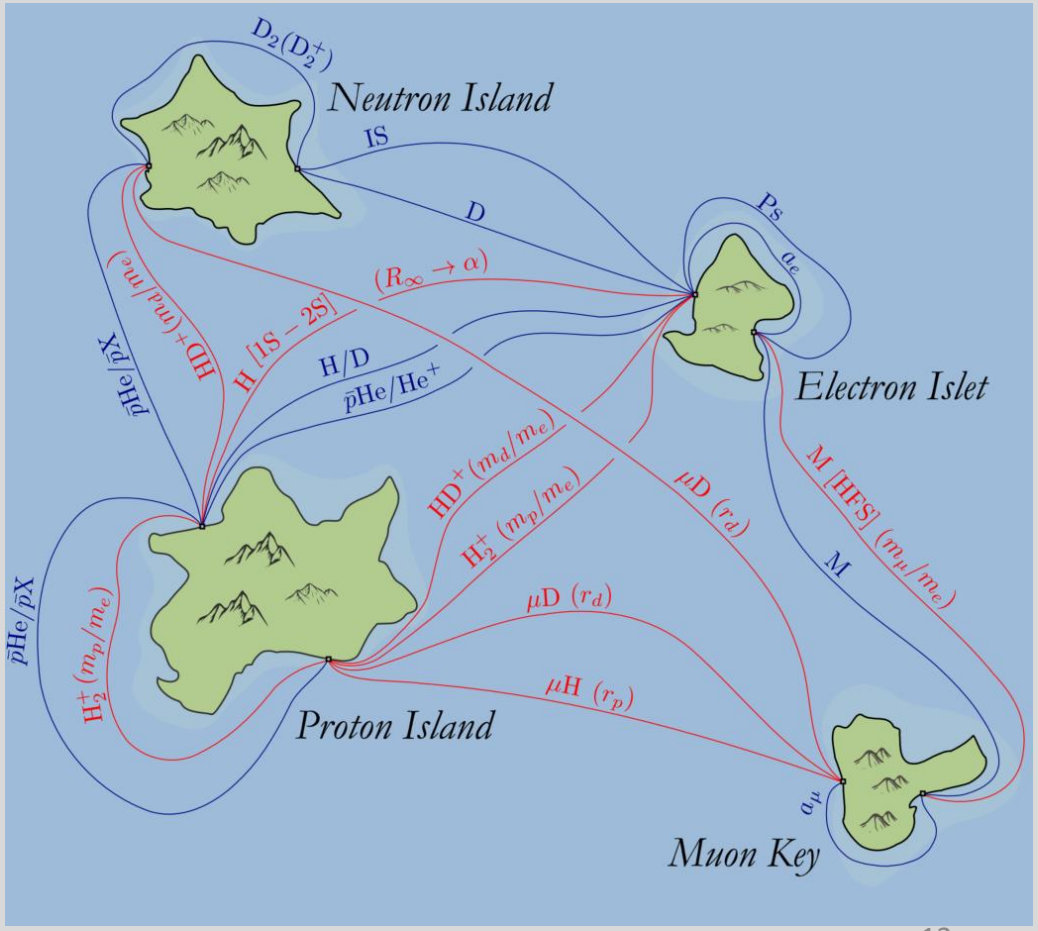
heavier mediator ⇔ smaller range

H. Yukawa (**1935**), Proc. Phys. Math. Soc. Jap. 17

New physics from energy shifts

$$V(\boldsymbol{r}) = -(\mathrm{g}_1 \times \mathrm{g}_2)\frac{\mathrm{e}^{-m_\phi \mathrm{r}}}{4\pi \mathrm{r}} + V_{NLO}\left(\boldsymbol{r}, \vec{\boldsymbol{S}}_1, \vec{\boldsymbol{S}}_2\right)$$





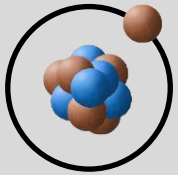
Delaunay, Karr, Soreq (2026), *Ann. Rev. Nuc. Part. Sci. 76*

New physics from energy shifts

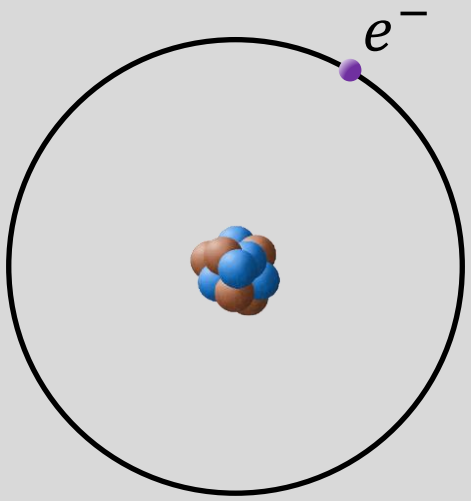
$$E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



Hadronic atoms

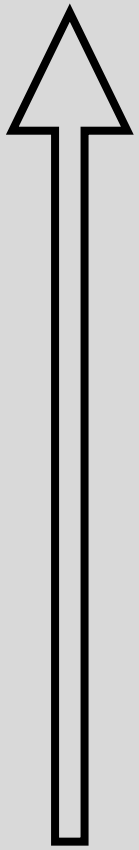


p^-, π^-, K^-



e^-

Range



$m_\phi = 0.1\sim10$ MeV

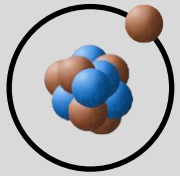
$m_\phi = 1\sim10$ KeV

Coupling type

Hadron-Hadron couplings

Electron-Hadron coupling

Hadronic atoms



p^-, π^-, K^-

Baptista et.al, (2025) Pos. Exa 085

PA ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

Sirghi el.al (2024), *JINST* 19

SIDDHARTA-2

Hashimoto et al (2019), JPS Conf. Proc 26

E62 j-PARC

Pure hadronic systems

New physics from energy shifts

PAX
ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

SIDDHARTA-2

E62
J-PARC

$$\Longleftarrow \quad E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



Theory components

- QED

New physics from energy shifts

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ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

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J-PARC

$$\Leftarrow \quad E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



Theory components

- QED 

Paul, Bian, Azuma, Okada, Indelicato (2021) Phys. Rev. Lett. 126,

Zatorski, Patkóš, Pachucki, (2022) Phys. Rev. A 106

New physics from energy shifts

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$$\Longleftarrow \quad E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



Theory components

- QED
- short-range hadronic interactions



The atomic system

- The class of atomic systems we consider:

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

The atomic system

- The class of atomic systems we consider:

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

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

- $l \geq 1$ are unaffected by strong force contact terms
- Higher n states have smaller velocities $v \sim \alpha Z/n$

The atomic system

➢ The class of atomic systems we consider:

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

orbiting particle $\bar{p}, K^-, \pi^-$

$7 < Z < 82$

$$\sqrt{\langle r^2 \rangle} \sim n^2/\alpha\mu Z$$

The atomic system

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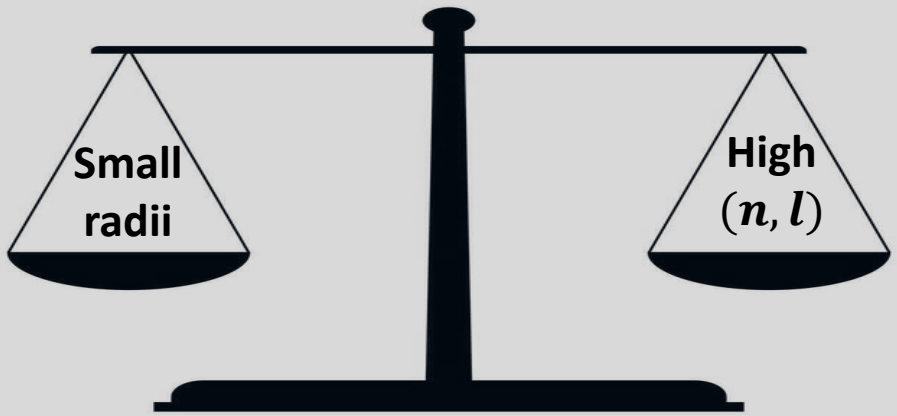

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Theory components

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New physics from energy shifts

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J-PARC

$$\Longleftarrow \quad E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



Theory components

- QED
- short-range hadronic interactions
- Nuclear polarization



Nuclear polarization

- The nucleus and orbiting particle polarize each other

nucleus polarizability

(anti)proton polarizability

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

poorly known!

Transition	$\frac{\Delta E_n^{\mathrm{Pol}}}{\Delta E_n^{\mathrm{SM}}} \times \mathbf{10^{-6}}$
$\bar{p}\,{}^4\mathrm{He}\ (32,31) \rightarrow (31,30)$	$< 10^{-8}$
$\bar{p}\,{}^{nat}\mathrm{Pb}\ (11,10) \rightarrow (10,9)$	$\approx \mathbf{40 \pm 20}$

Ericson, Huefner (1972) Nuclear Physics B47

Orce, Ngwetsheni, Brown (2023) Phys. Rev. C 108

New physics from energy shifts

PAX
ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

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E62
J-PARC

$$\Longleftarrow \quad E_n^{exp} = E_n^{SM} + E_n^{BSM}$$



Theory components

- QED
- short-range hadronic interactions
- Nuclear polarization ?

New physics from energy shifts

$$E_n^{exp} = \left(E_n^{SM-Pol} + E_n^{Pol}\left(\alpha_{E_1}\right)\right) + E_n^{BSM}\left(\mathrm{g}_1 \times \mathrm{g}_2\right)$$

Is the polarization contribution under control?

New physics from energy shifts

$$E_n^{exp} = \left(E_n^{SM-Pol} + E_n^{Pol}(\alpha_{E_1})\right) + E_n^{BSM}(\mathrm{g}_1 \times \mathrm{g}_2)$$

Is the polarization contribution under control?

YES

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

NO

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

2 energy transitions

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

1st transition

$$E_n^{\mathrm{exp}} = \left(E_n^{\mathrm{SM-Pol}} + E_n^{\mathrm{Pol}}(\boldsymbol{\alpha_{E_1}})\right) + E_n^{\mathrm{BSM}}(\mathbf{g_1} \times \mathbf{g_2})$$

2nd transition

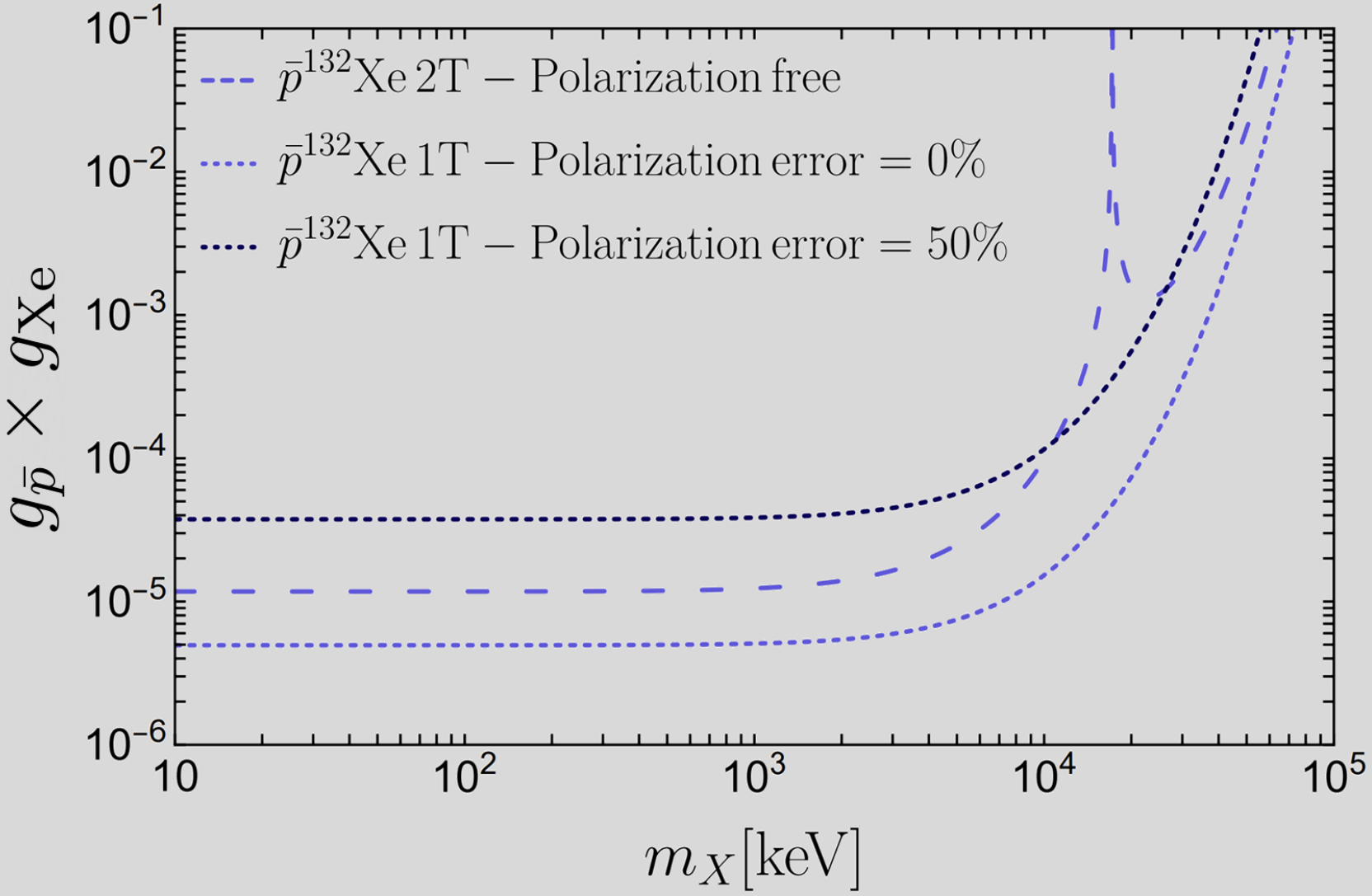
$$E_{n+1}^{\mathrm{exp}} = \left(E_{n+1}^{\mathrm{SM-Pol}} + E_{n+1}^{\mathrm{Pol}}(\boldsymbol{\alpha_{E_1}})\right) + E_{n+1}^{\mathrm{BSM}}(\mathbf{g_1} \times \mathbf{g_2})$$

$$E_{n+2}^{\mathrm{exp}} = \left(E_{n+2}^{\mathrm{SM-Pol}} + E_{n+2}^{\mathrm{Pol}}(\boldsymbol{\alpha_{E_1}})\right) + E_{n+2}^{\mathrm{BSM}}(\mathbf{g_1} \times \mathbf{g_2})$$

⇓

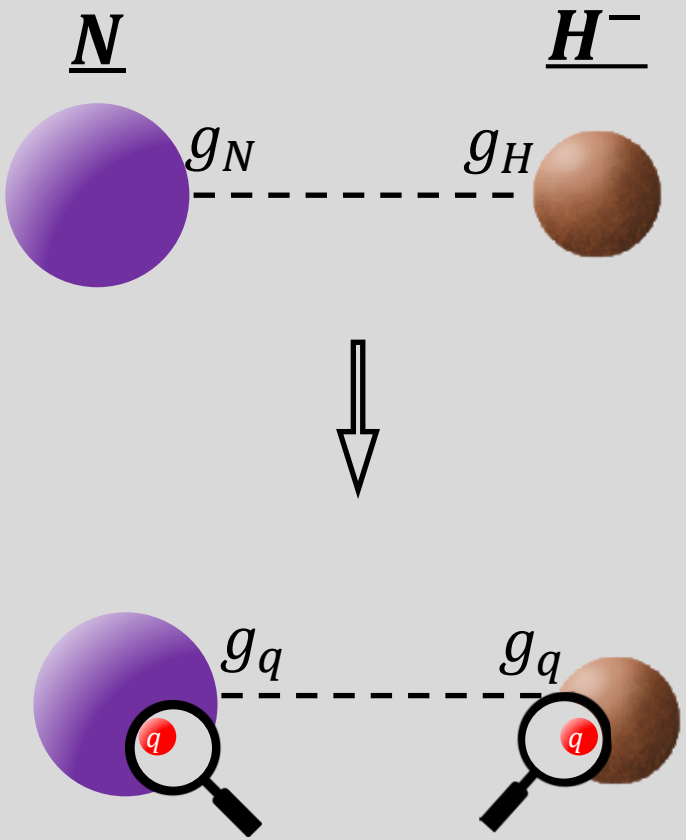
Simultaneous determination of $\mathrm{g}_1 \times \mathrm{g}_2$ and α_{E_1}

1 VS 2 energy transitions



Liu, Ohayon, **Shtaif**, Soreq, (2025), *Phys.Rev.Lett.* 135

Applying to specific models



Exclusion plots for new physics models

UDS model

$$\mathcal{L}_{\mathrm{UDS}}^{\mathrm{int}} = \frac{\phi}{f_\phi} \sum_{q=u,d,s} m_q \bar{q} q$$

By construction

- ☒ Leading order chiral expansion Kaon decay
- ☑ Sub leading order chiral expansion Kaon decay

Delaunay, Kitahara, Soreq, Zupan (2025), JHEP 222

Exclusion plots for new physics models

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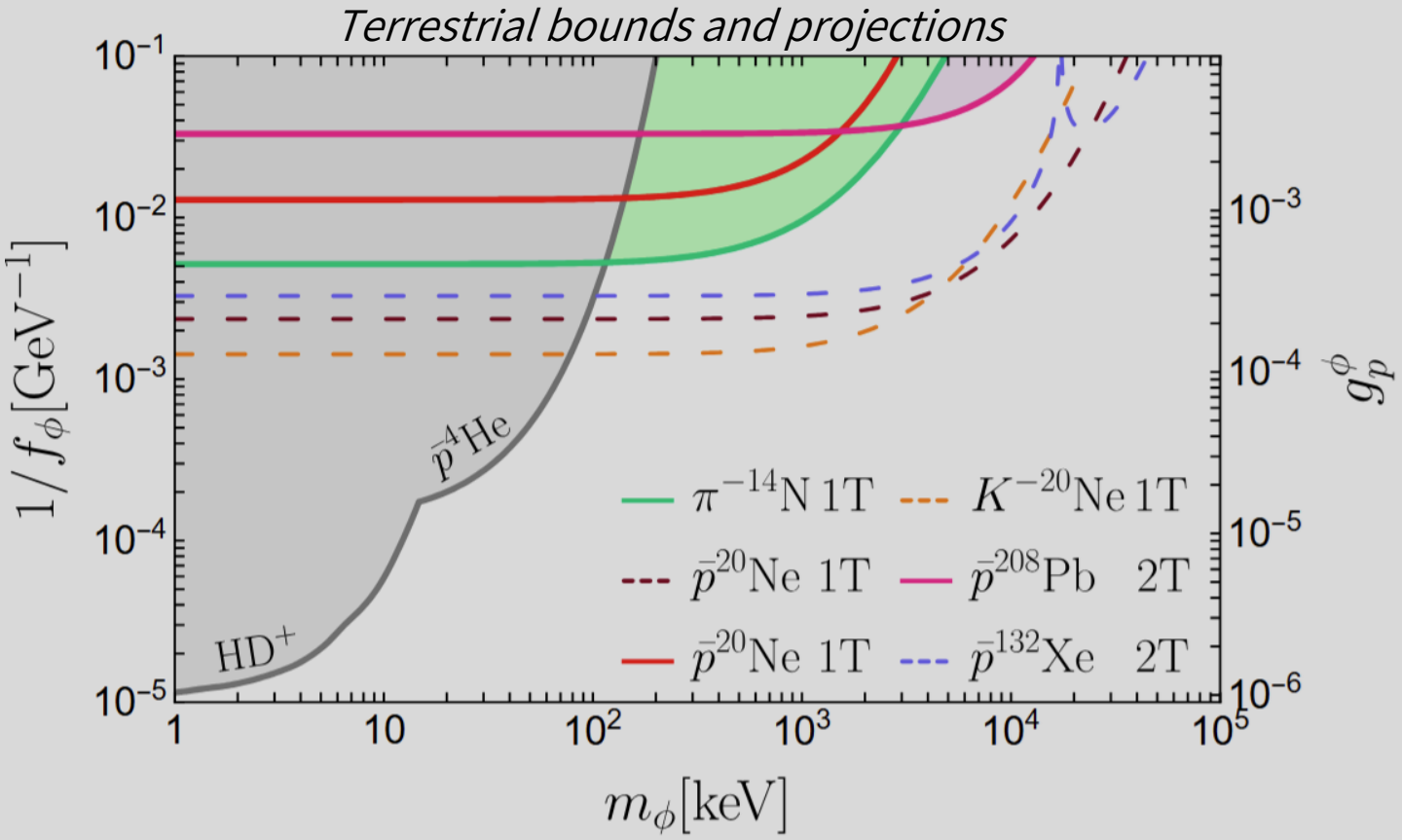


Delaunay, Kitahara, Soreq, Zupan (2025), JHEP 222

Liu, Ohayon, Shtaif, Soreq, (2025), *Phys.Rev.Lett.* 135

Exclusion plots for new physics models

Baryon-number model

$$\mathcal{L}_{\mathrm{B}}^{\mathrm{int}} = \frac{g_B}{3} B^\mu \sum_q \bar{q}\gamma_\mu q - \frac{g_B e^2}{48\pi^2} B^\mu \sum_l \bar{l}\gamma_\mu l$$

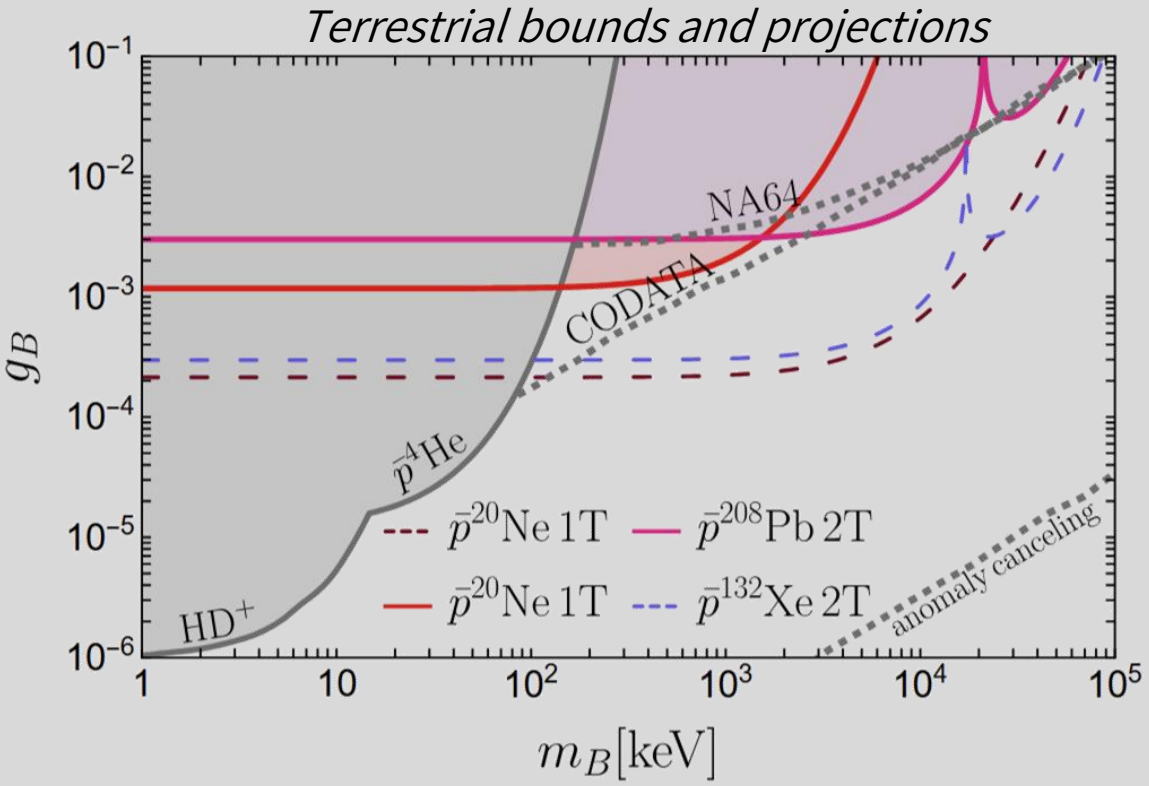
$\mathrm{BR}(B \to \mathrm{inv.}) \approx 1$ ☒ Beam dumps, colliders, fixed target experiments

Fermion in a dark sector ☒ Anomaly canceling fermions

☑ $eN \to eN + B$ Bremsstrahlung

Ilten, Soreq, Williams, Xue (2018), JHEP 4

Exclusion plots for new physics models



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Delauny, et .al (2023) Phys. Rev. Lett. 130

Liu, Ohayon, Shtaif, Soreq, (2025), *Phys.Rev.Lett.* 135

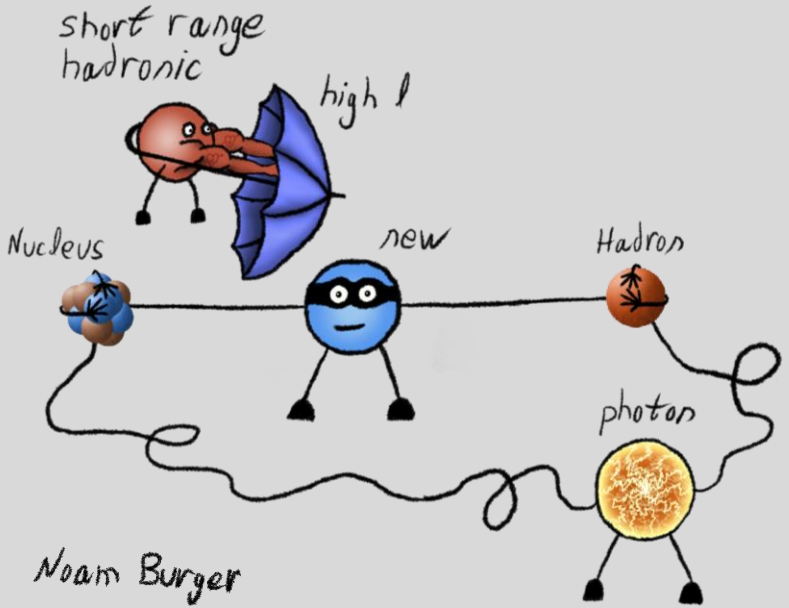
NA64 Collaboration (2022), Phys.Rev.Lett. 129

Takeaway

1. Spectroscopy of Hadronic atoms is a competitive probe for new physics in the MeV scale

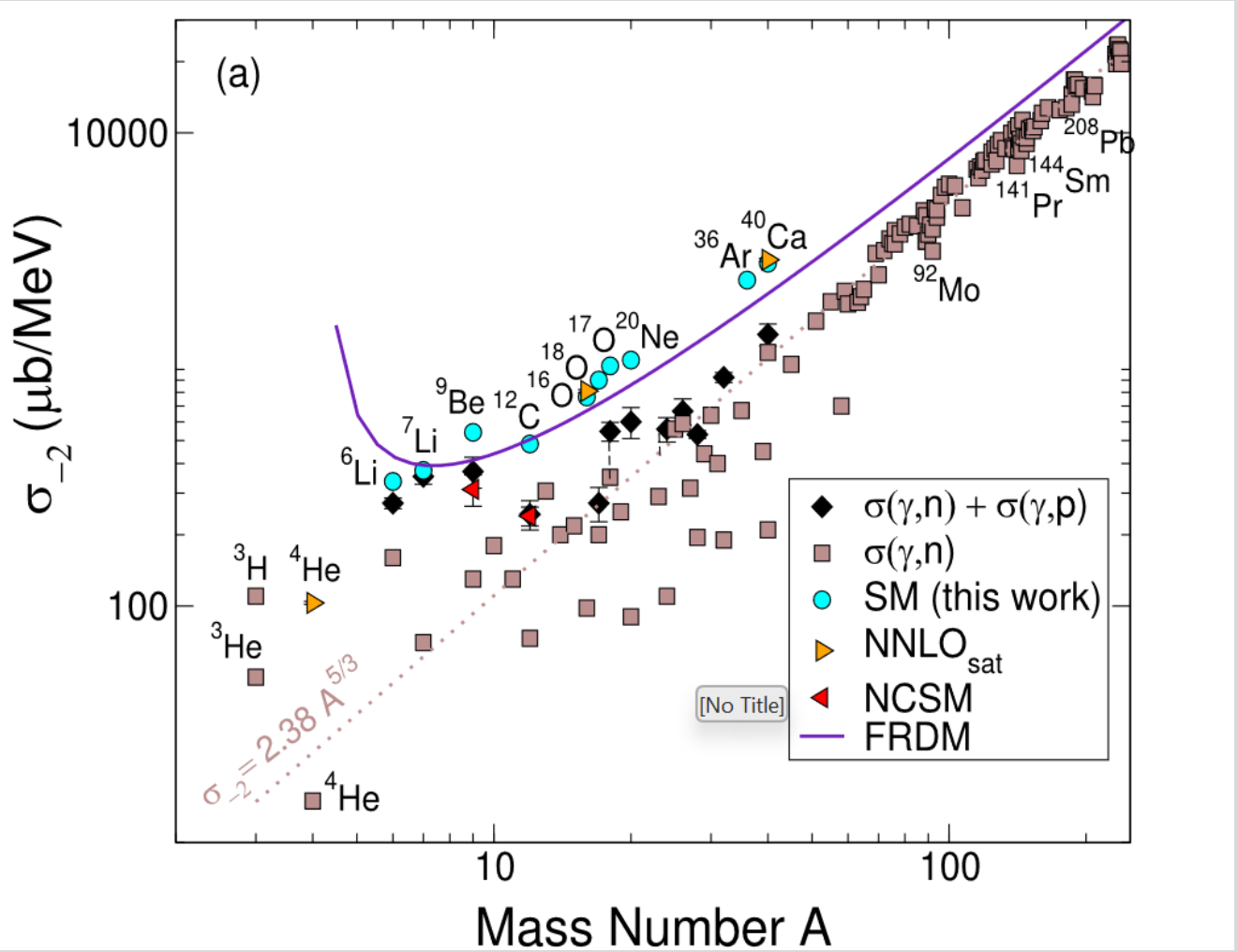
2. Hadronic atoms provide complementary sensitivity to the new force coupling manifold.

Thanks!



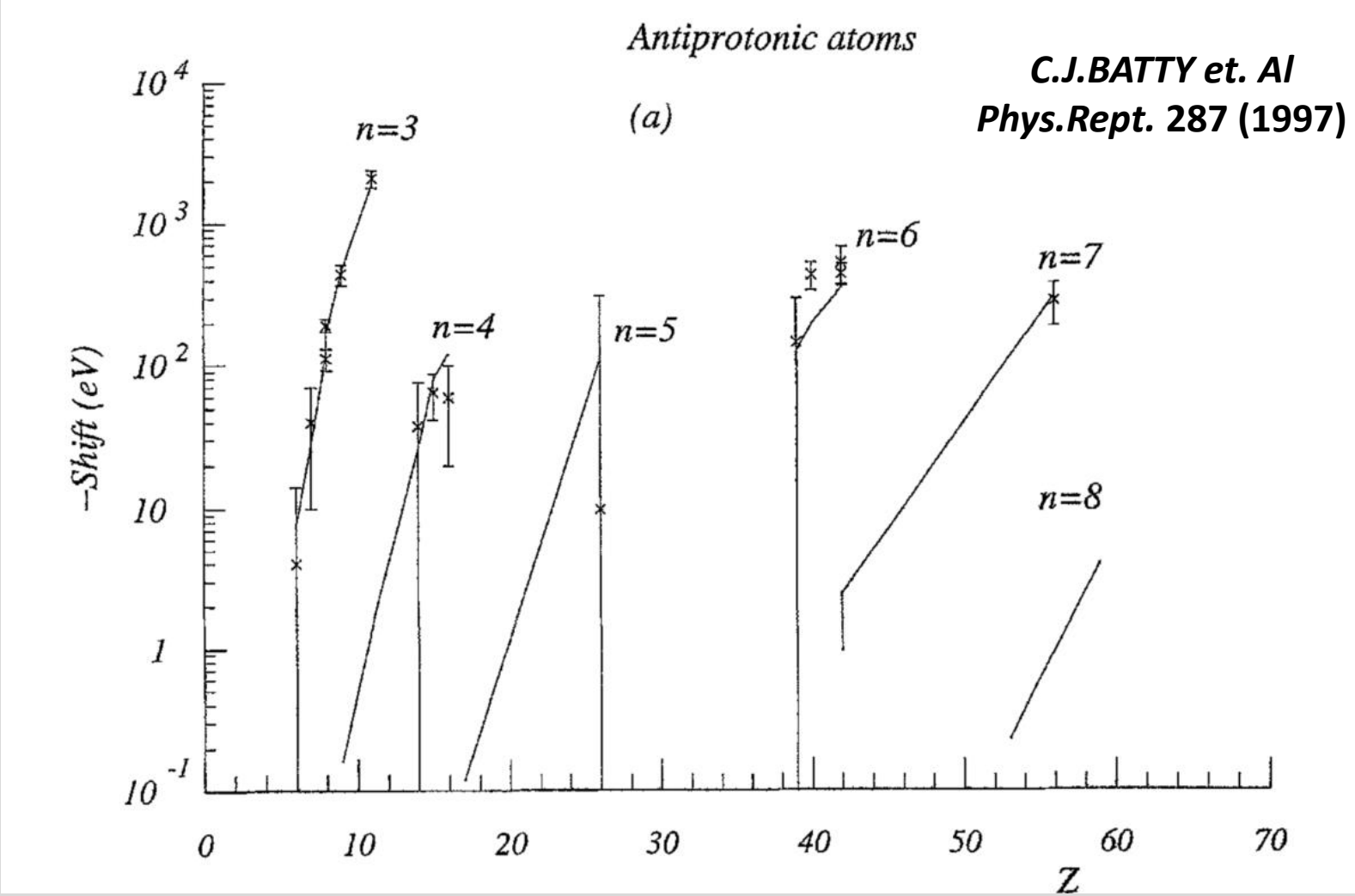
Backup 1

Backup: polarizability semi empirical equation



J.N.Orce et.al
2309.08810

Backup: short-range hadronic interactions



The atomic system

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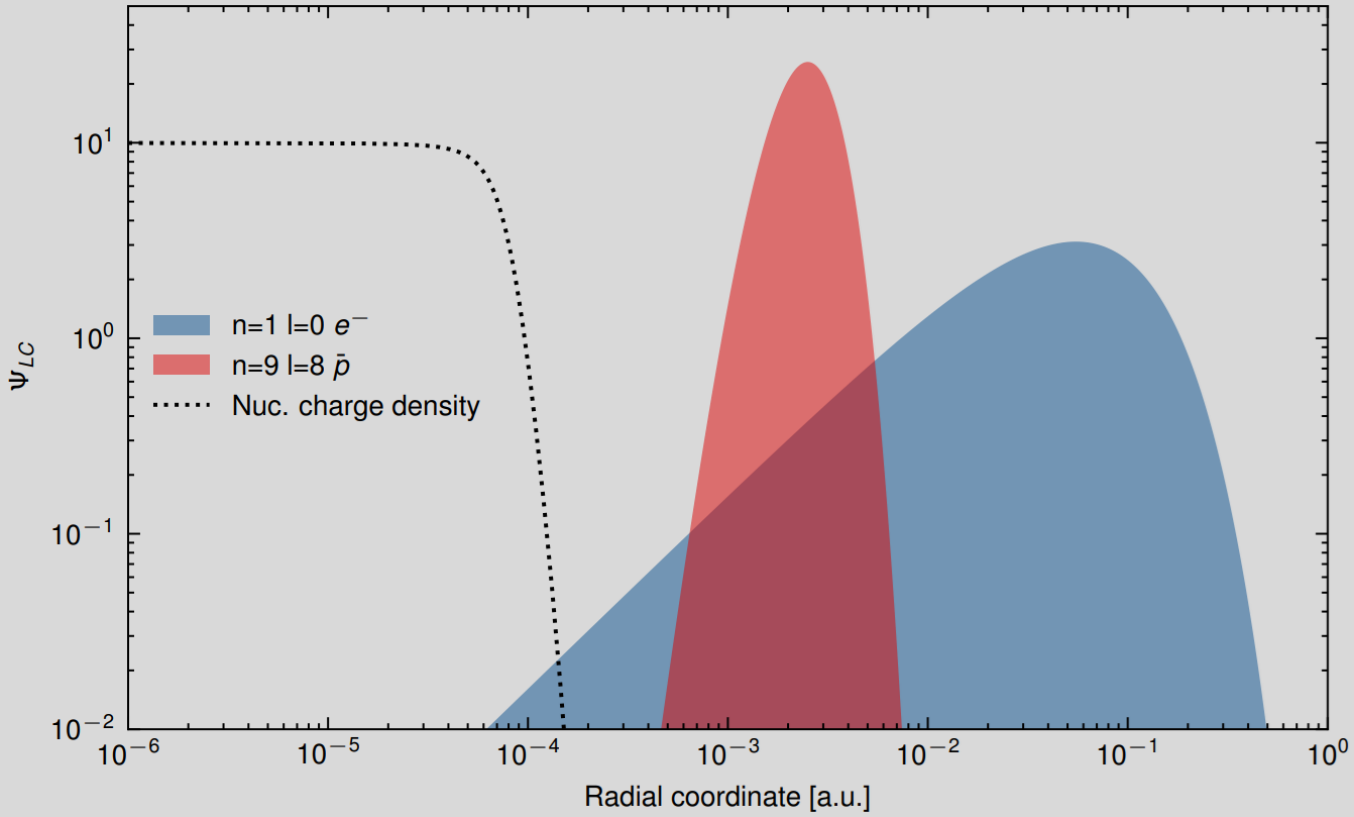
Exotic atoms in circular and excited states with high-Z nuclei



G. Baptista, etl.al. 2501.08893 (2025)

Backup: atomic transitions

Bound-state	(n_i, l_i)	(n_f, l_f)	$E^{\mathrm{SM,LO}}_{n,n-1}$ [keV]	$\Delta_{n,n-1}/E^{\mathrm{SM,LO}}_{n,n-1}$ [ppm]	$1/r_{n_f}$ [MeV]	$E^{\mathrm{NPol}}_{n,n-1}/E^{\mathrm{SM,LO}}_{n,n-1}$ [ppm]
$\pi^-\ ^{14}$N	(5,4)	(4,3)	4.05	3.9 ± 1.7 [47]	0.44	0.005
$K^-\ ^{20}$Ne	(6,5)	(5,4)	15.6	± 1	1.4	< 0.5
$\bar{p}\ ^4$He	(32,31)	(31,30)	5.11×10^{-3}	$(2.2 \pm 2.3) \times 10^{-3}$ [73]	0.011	10^{-8}
$\bar{p}\ ^{20}$Ne	(13,12)	(12,11)	2.44	14 ± 23 [39]	0.45	0.005
$\bar{p}$ Pb	(12,11)	(11,10)	221	109 ± 77 [65, 66]	4.6	20
$\bar{p}$ Pb	(11,10)	(10,9)	290	114 ± 72 [65, 66]	5.5	40
$\bar{p}\ ^{20}$Ne	(6,5)	(5,4)	29.0	± 1	2.6	1
$\bar{p}\ ^{132}$Xe	(11,10)	(10,9)	125	± 1	3.7	8
$\bar{p}\ ^{132}$Xe	(10,9)	(9,8)	170	± 1	4.5	20

Backup: atomic transitions

