Exposing hidden sectors

Yotam Soreq

QU Colloquium, DESY, Nov 18, 2025

Status

LHC + intensity + precision + dark matter searches

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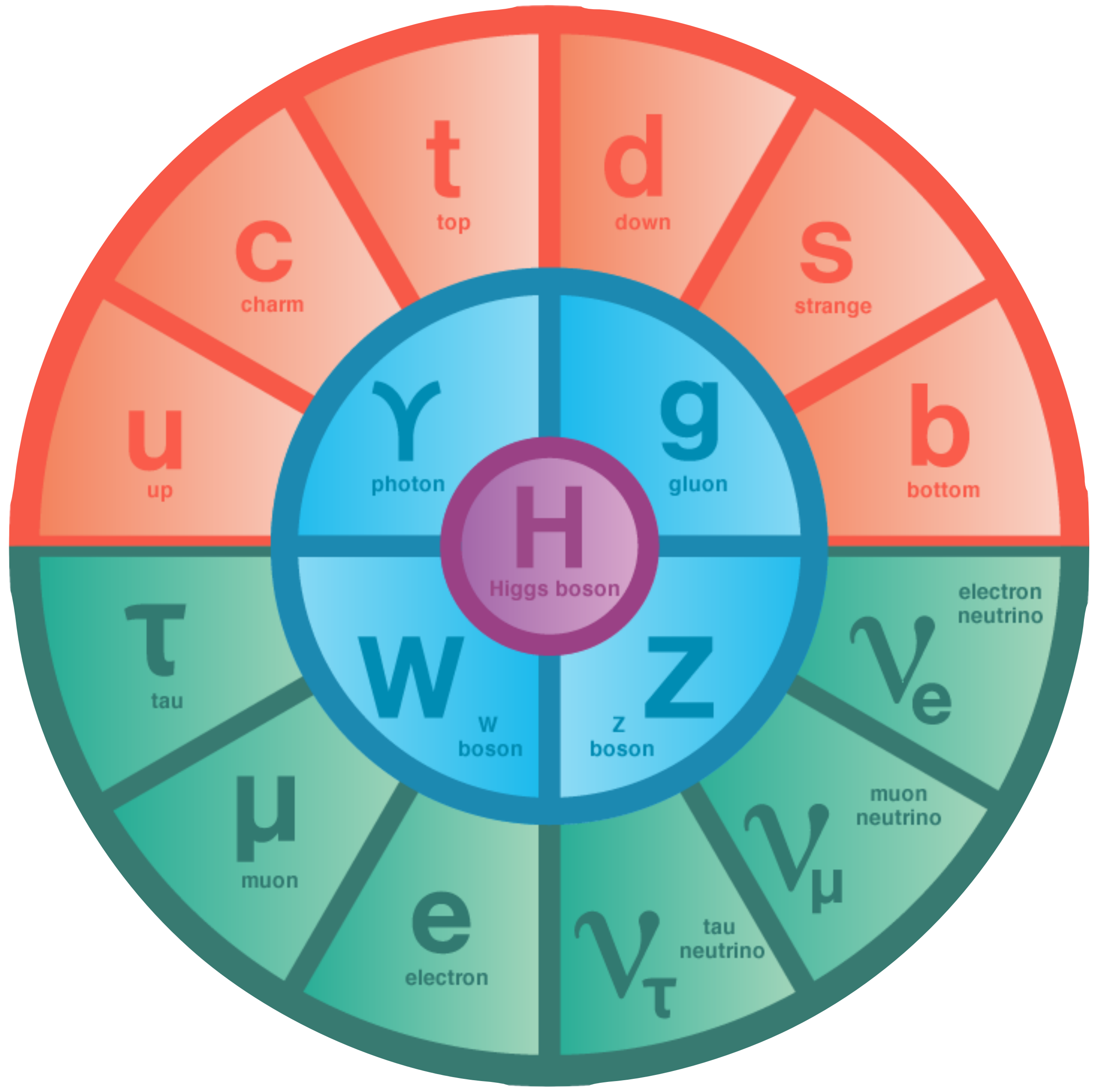

the Standard Model
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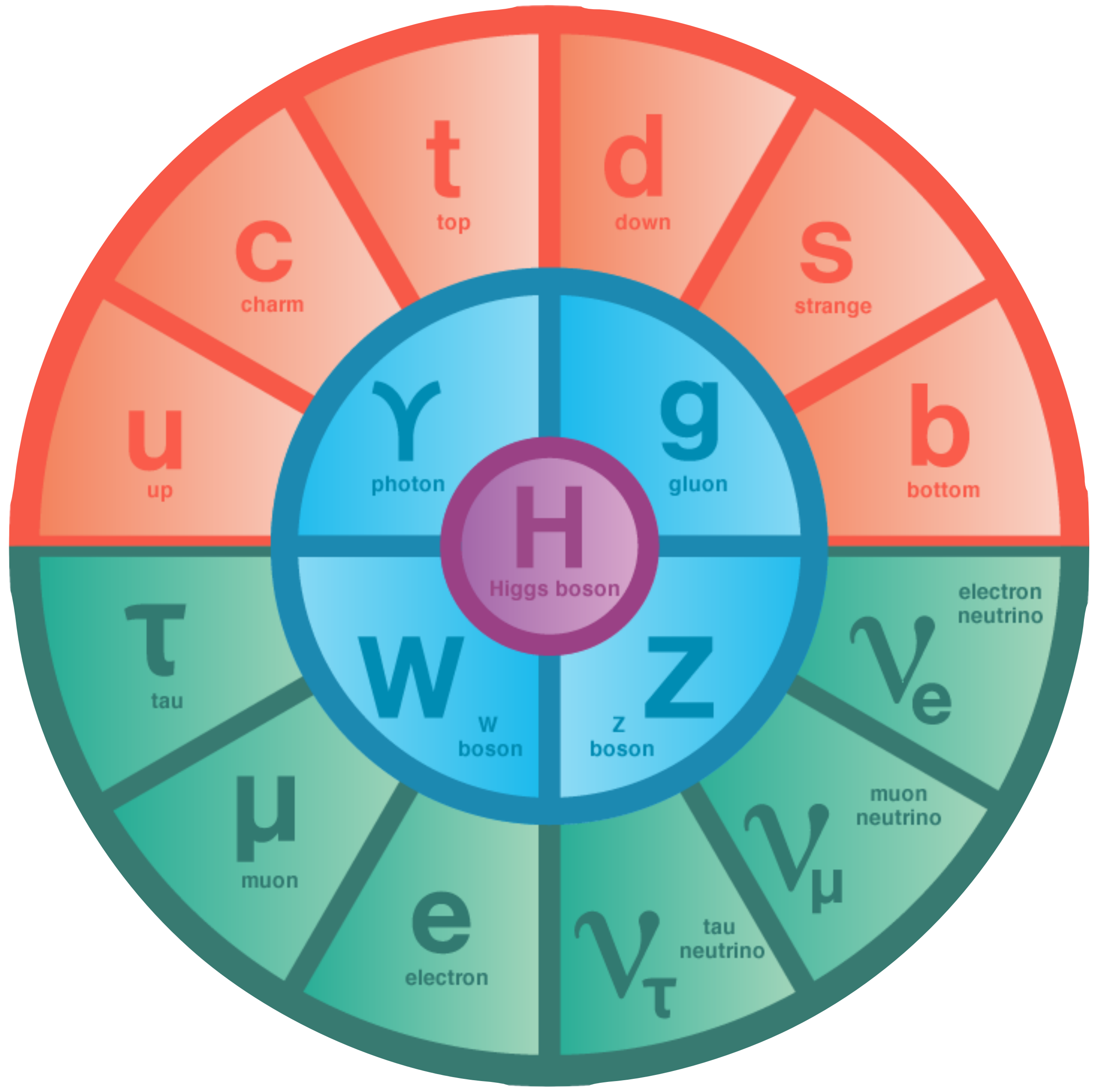

the Standard Model
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strong, electro-weak, Higgs …
thousands of independent
experimental confirmations

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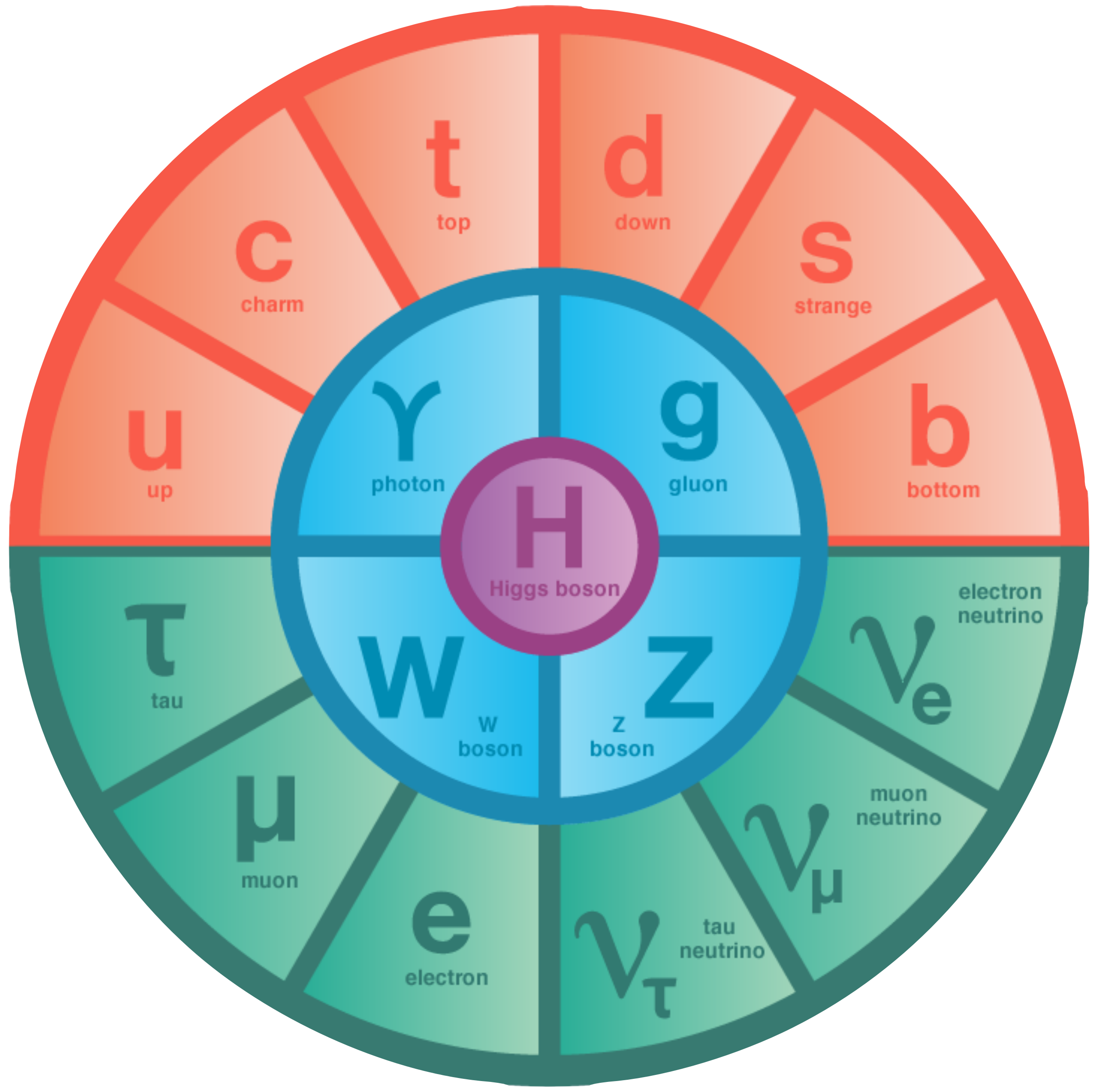

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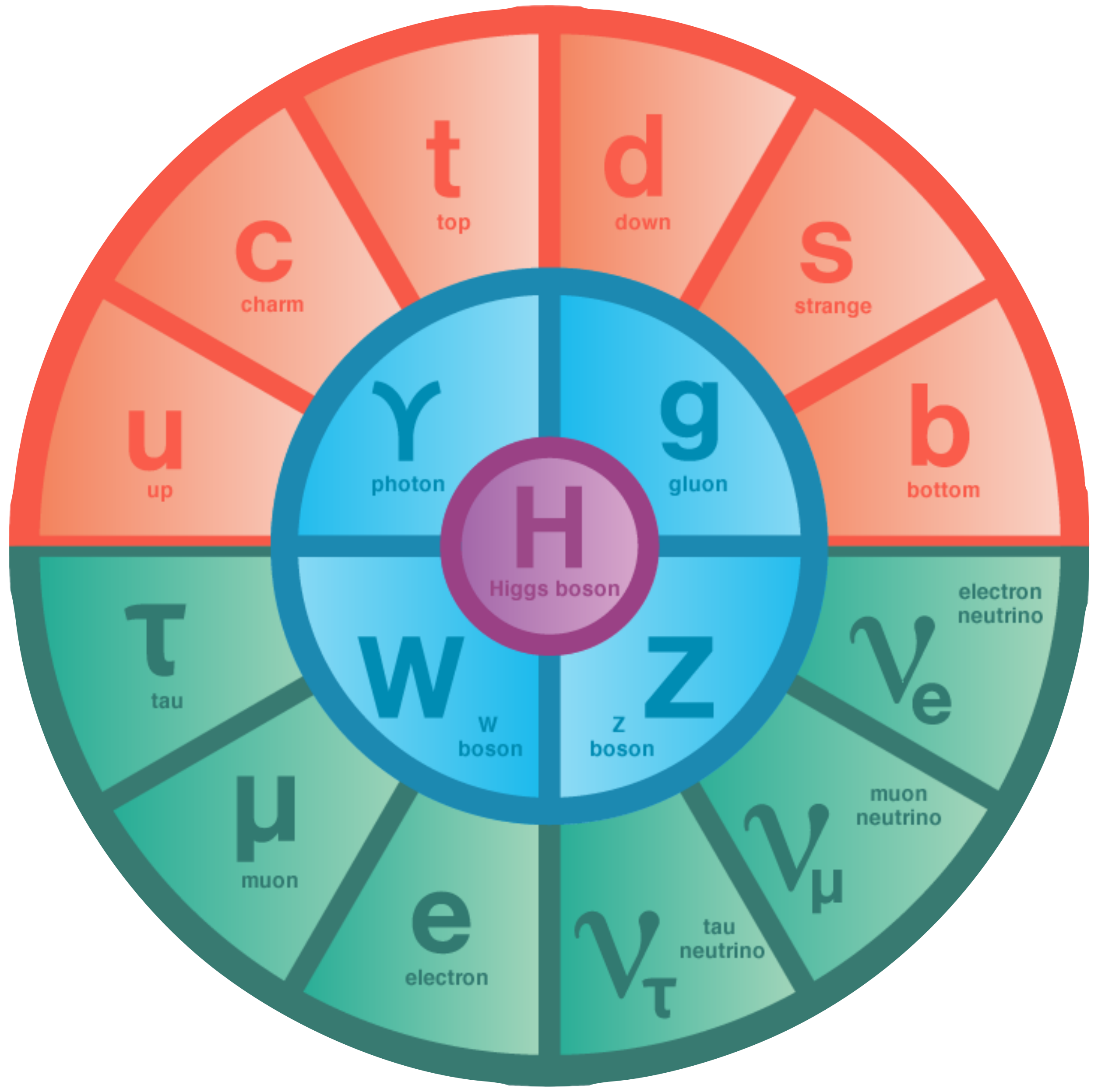

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neutrino oscillations, dark matter, Baryogenesis
weak scale stability, strong CP, flavor puzzle….

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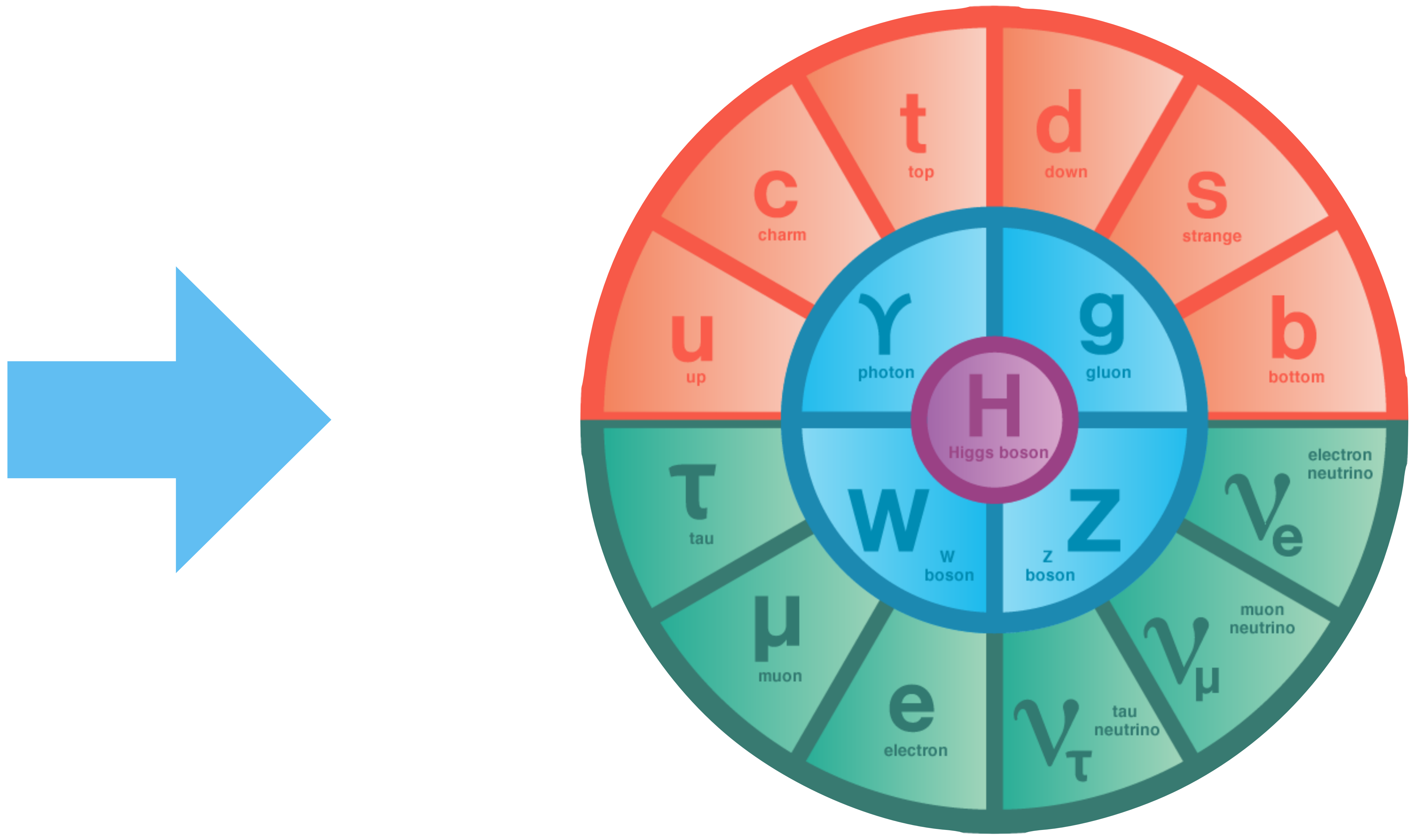

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the Standard Model is **incomplete**

How to extend the Standard Model?

motivations and what is allowed?

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from TeV scale focus ⇒ broader theory and searches

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leading signatures of new physics

The quest for hidden sectors and new particles

huge landscape for new physics, guidelines:

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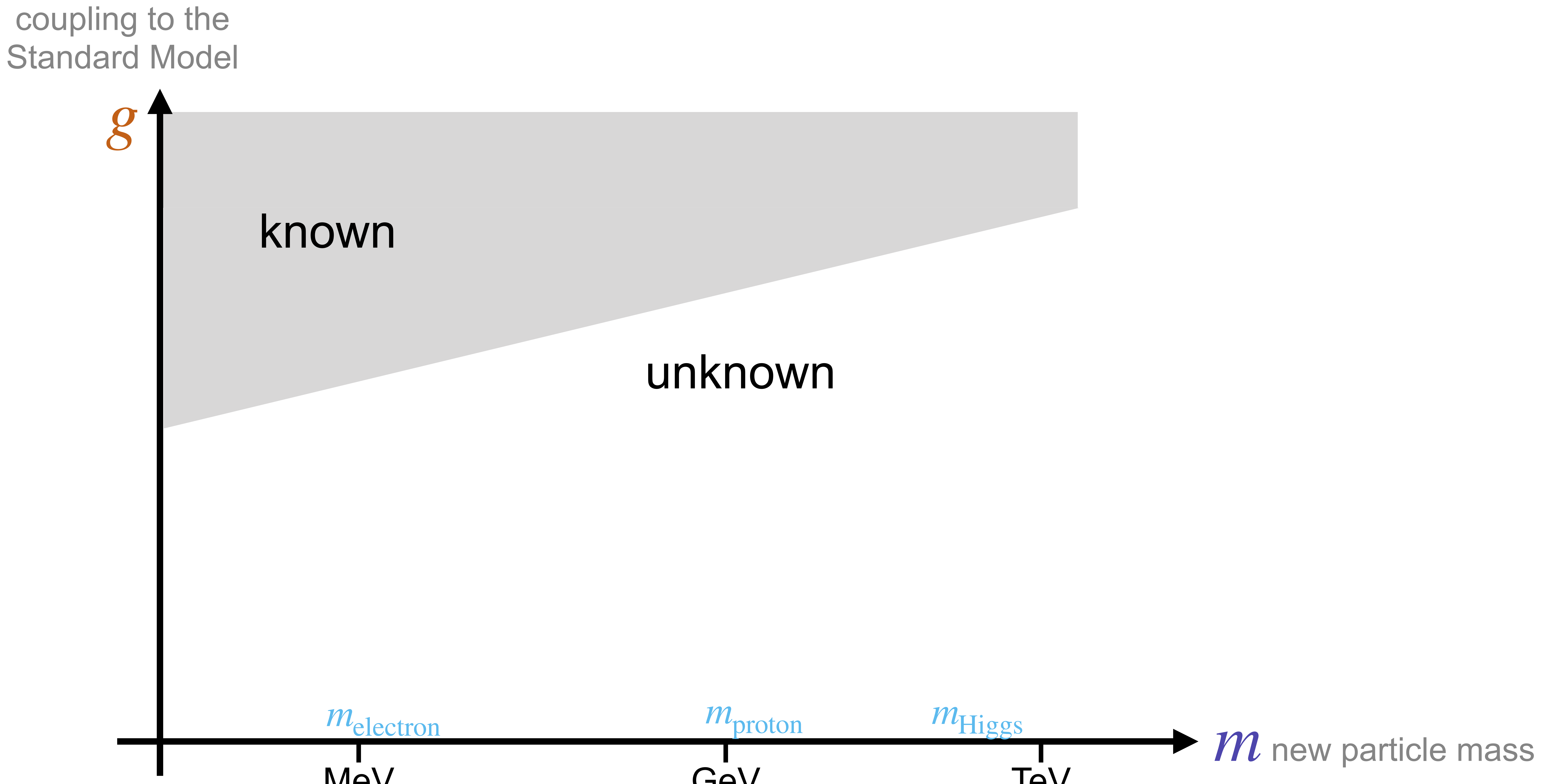
The quest for hidden sectors and new particles

huge landscape for new physics, guidelines:

- solution to the big problems
- model independent as possible (generic, effective field theory)
- develop new theoretical tools
- “anomalies” (disagreement of data with SM predictions)
- Standard Model rare phenomena as a probe for new physics

BSM at terrestrial experiments



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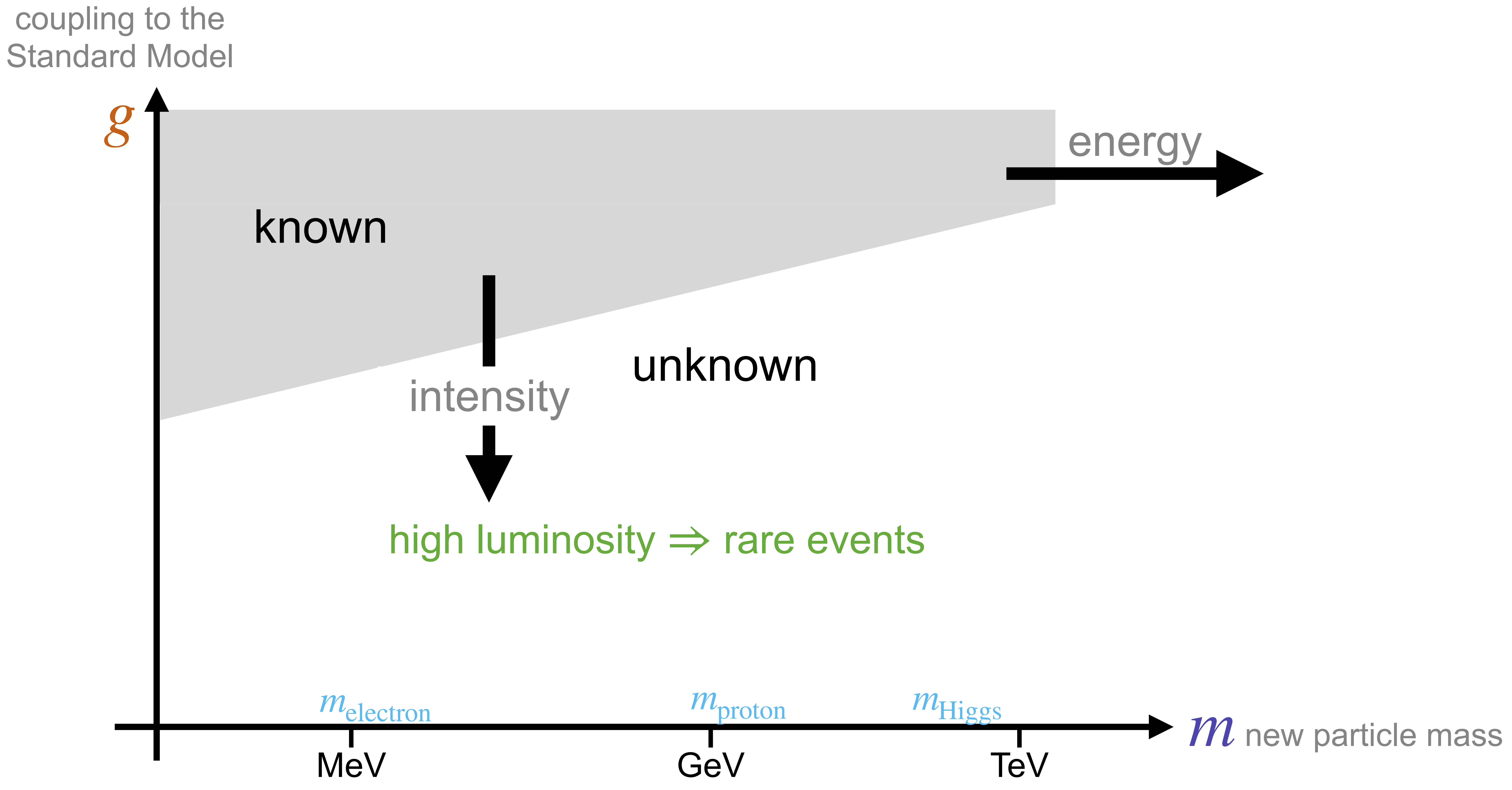

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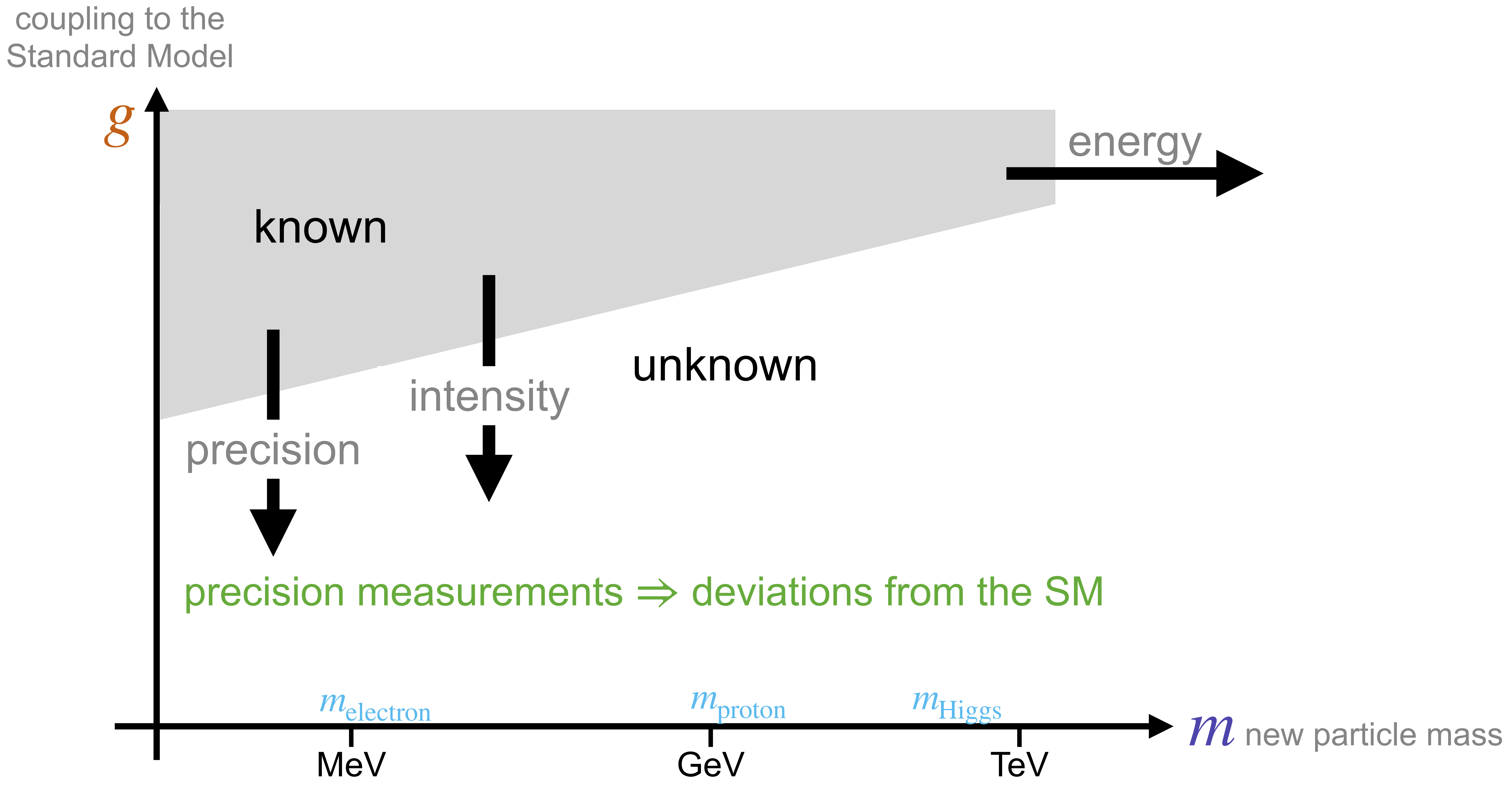

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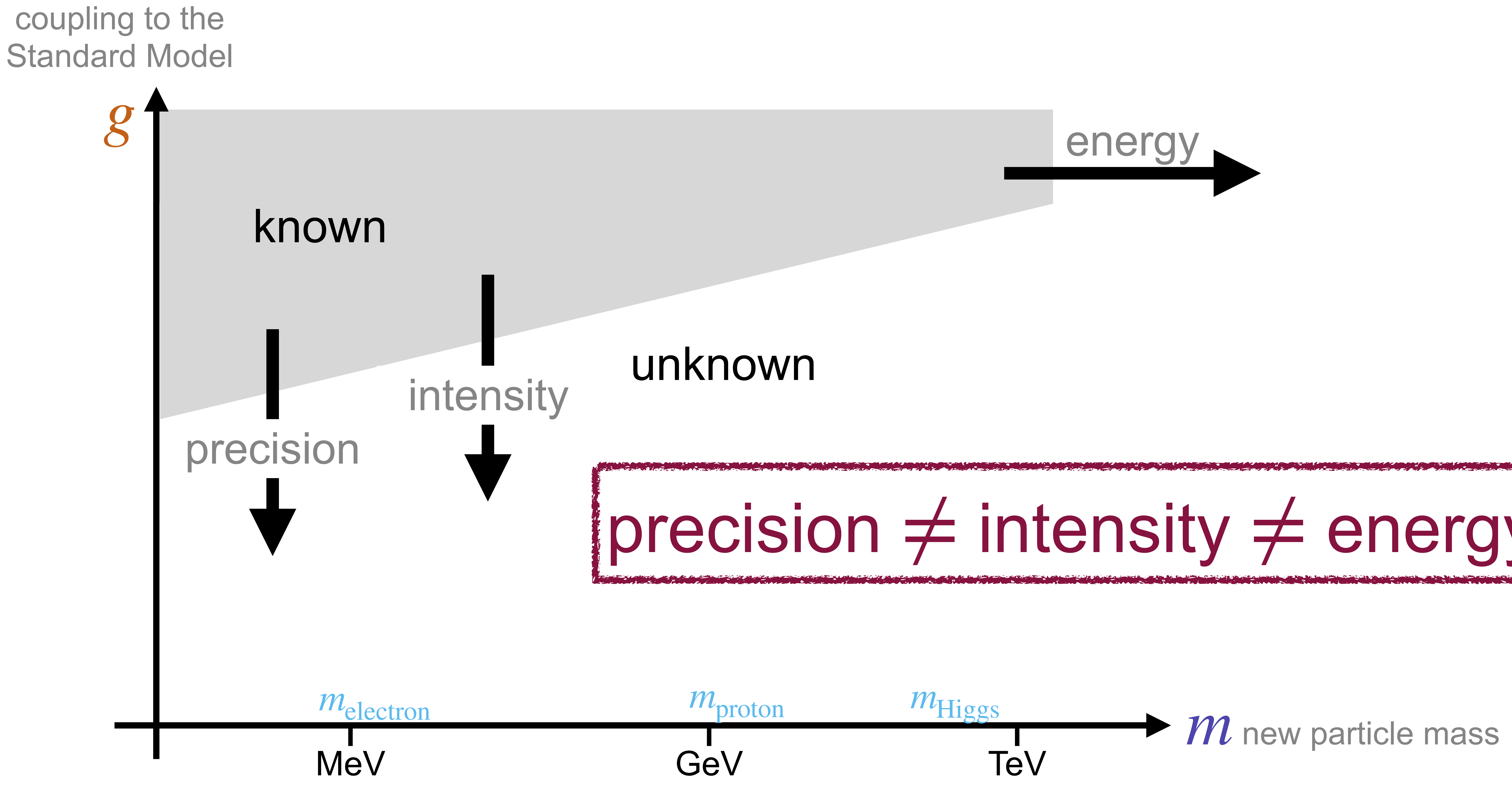

precision ≠ intensity ≠ energy

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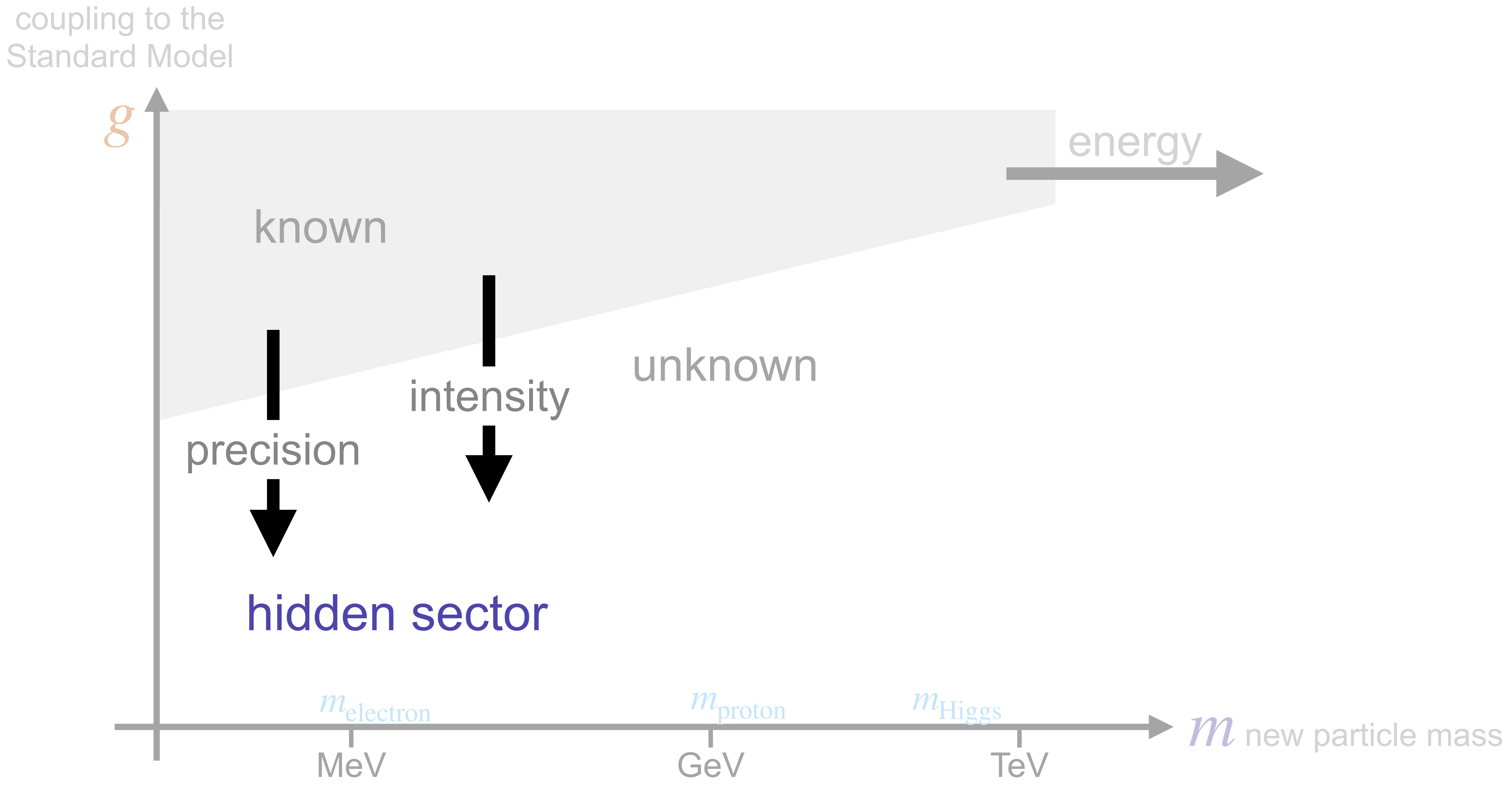

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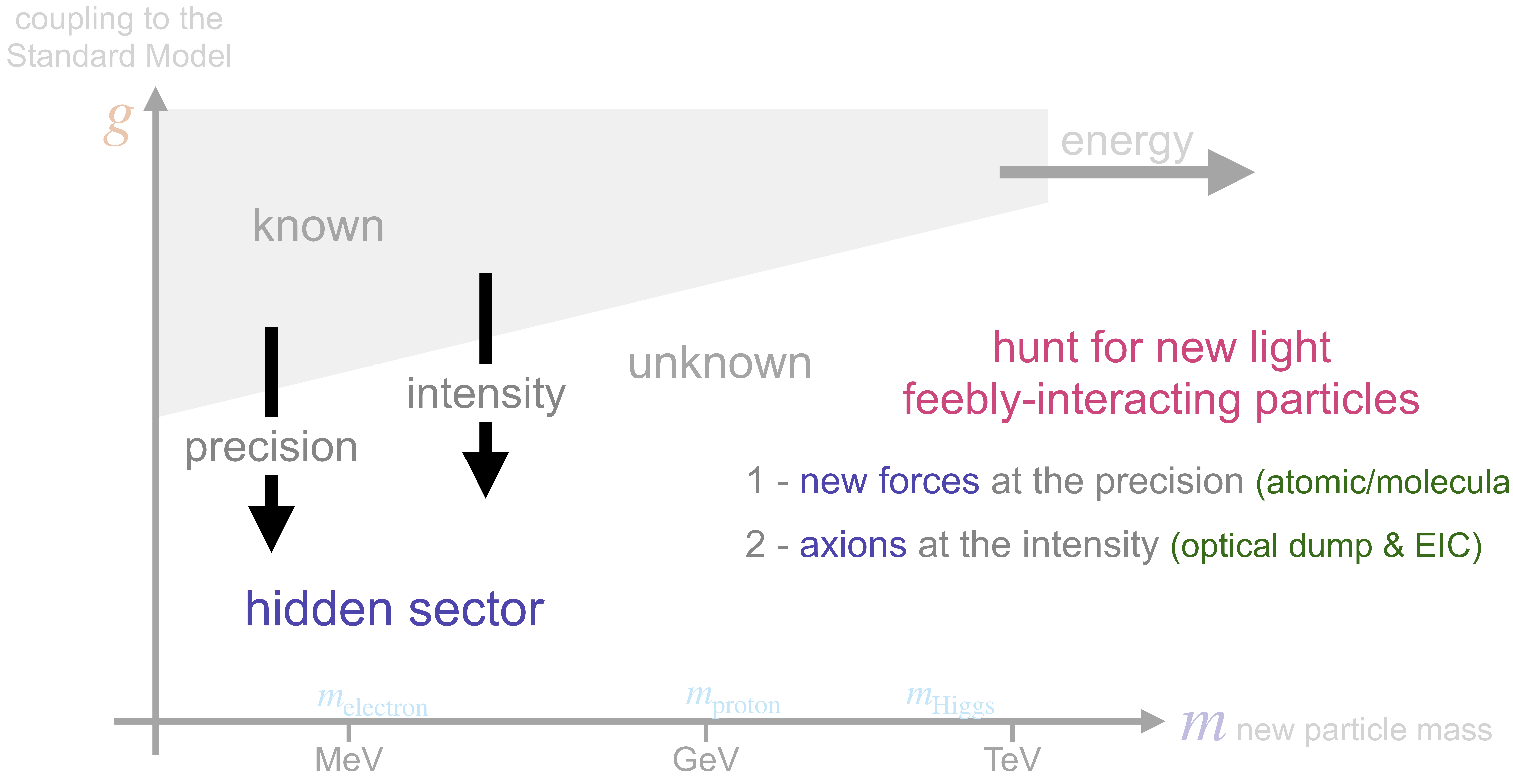

hunt for new light feebly-interacting particles

1 - new forces at the precision (atomic/molecular systems)

2 - axions at the intensity (optical dump & EIC)

standard model


standard model
feebly interacting spin 0
hidden sector

- naturally predicted in many extensions of the standard model

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- associated with solutions to fundamental problems:
  strong CP, dark matter, hierarchy problems

Peccei, Quinn 77; Weinberg 78; Wilczek 78
Preskill, Wise 83; Abbott, Sikivie 83; Dine, Fleischer 83
Graham, Kaplan, Rajendran 15
+ many many more

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Feebly interacting new spin-0

- limiting cases of the theory (flavor diagonal):
  - Higgs mixing (CP even)
  - pNGB: axion or axion-like particles (CP odd) or dilation (CP even)
  - general flavor aligned (CP even)

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Probing new physics in precision frontier

data vs Standard Model
predictions

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data vs Standard Model predictions

sensitive to theory error

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↓

sensitive to theory error

use special properties (symmetry, factorization)

Probing new physics in precision frontier

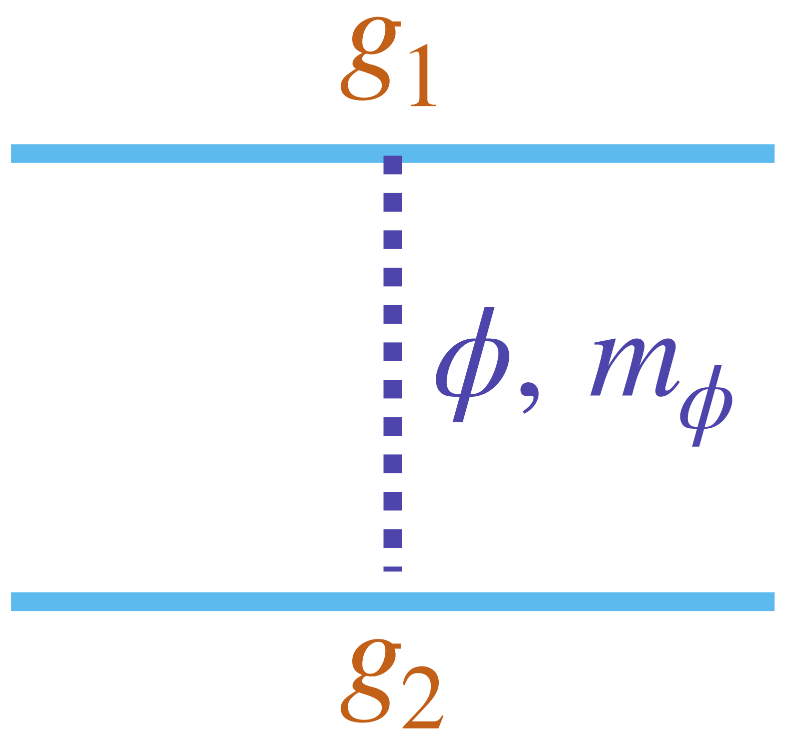
data vs Standard Model predictions

sensitive to theory error

use special properties (symmetry, factorization)

insensitive to theory error

CP even: spectroscopy



$$\propto g_1 g_2 \frac{e^{-m_\phi r}}{r}$$

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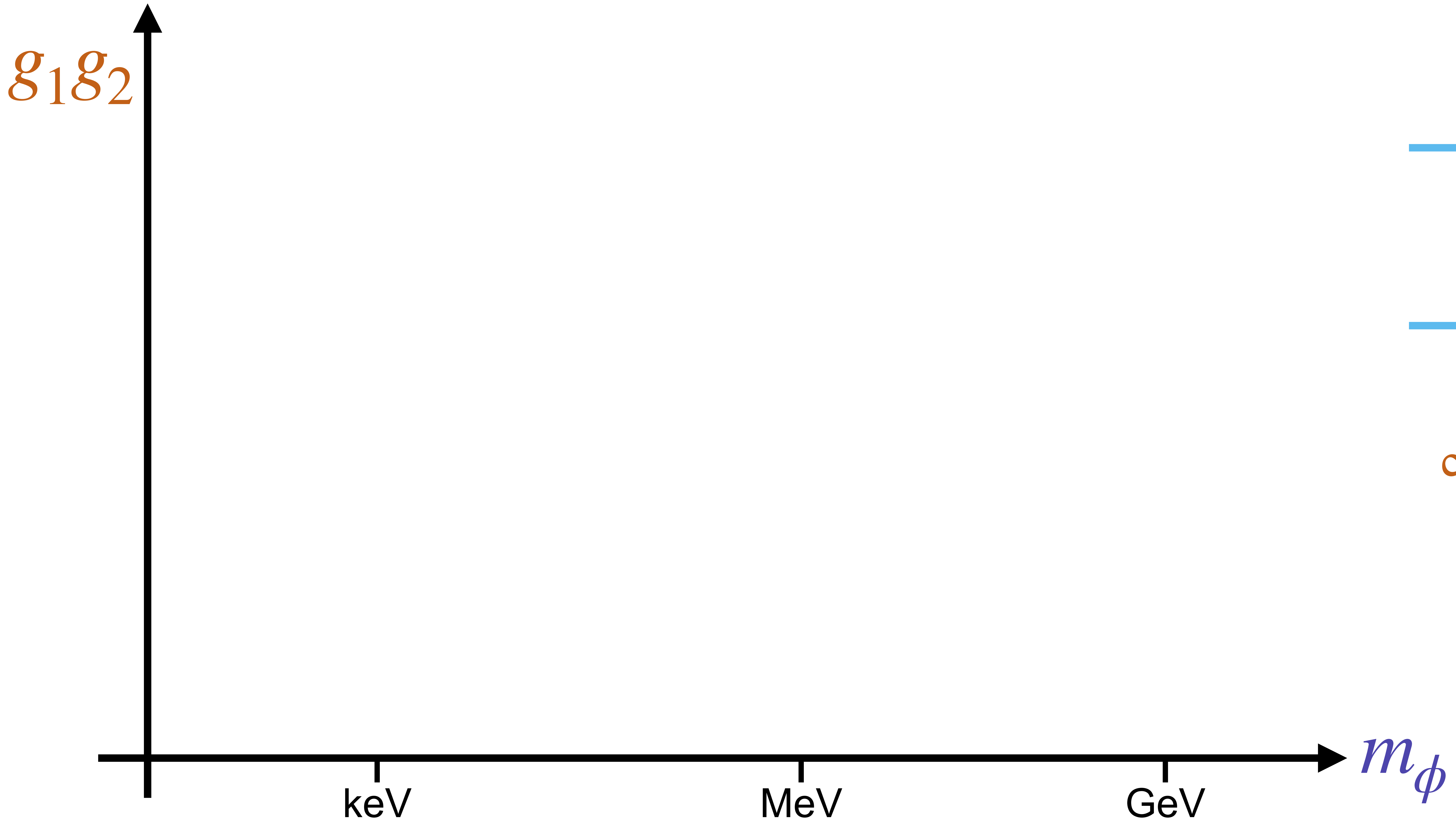

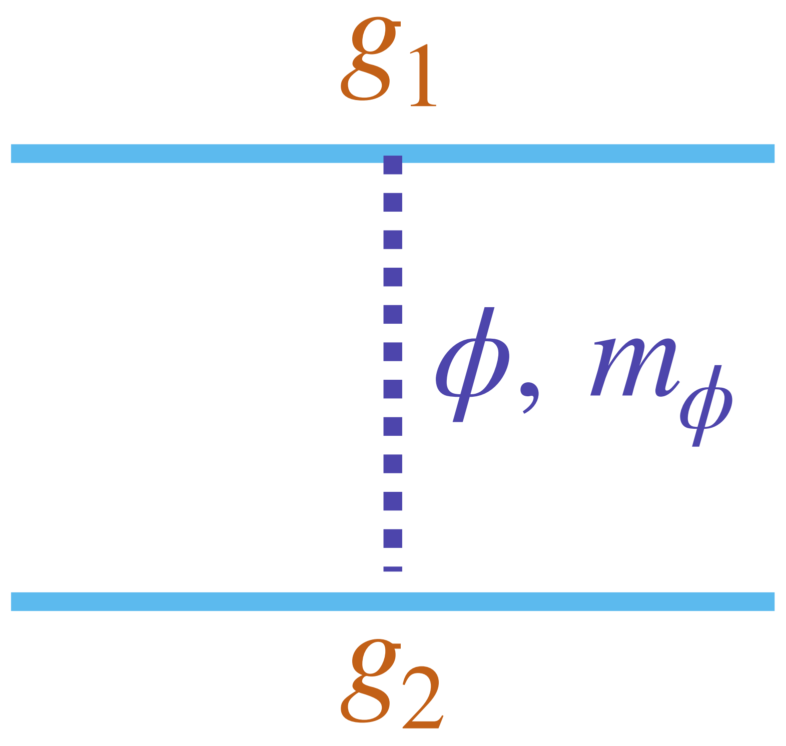

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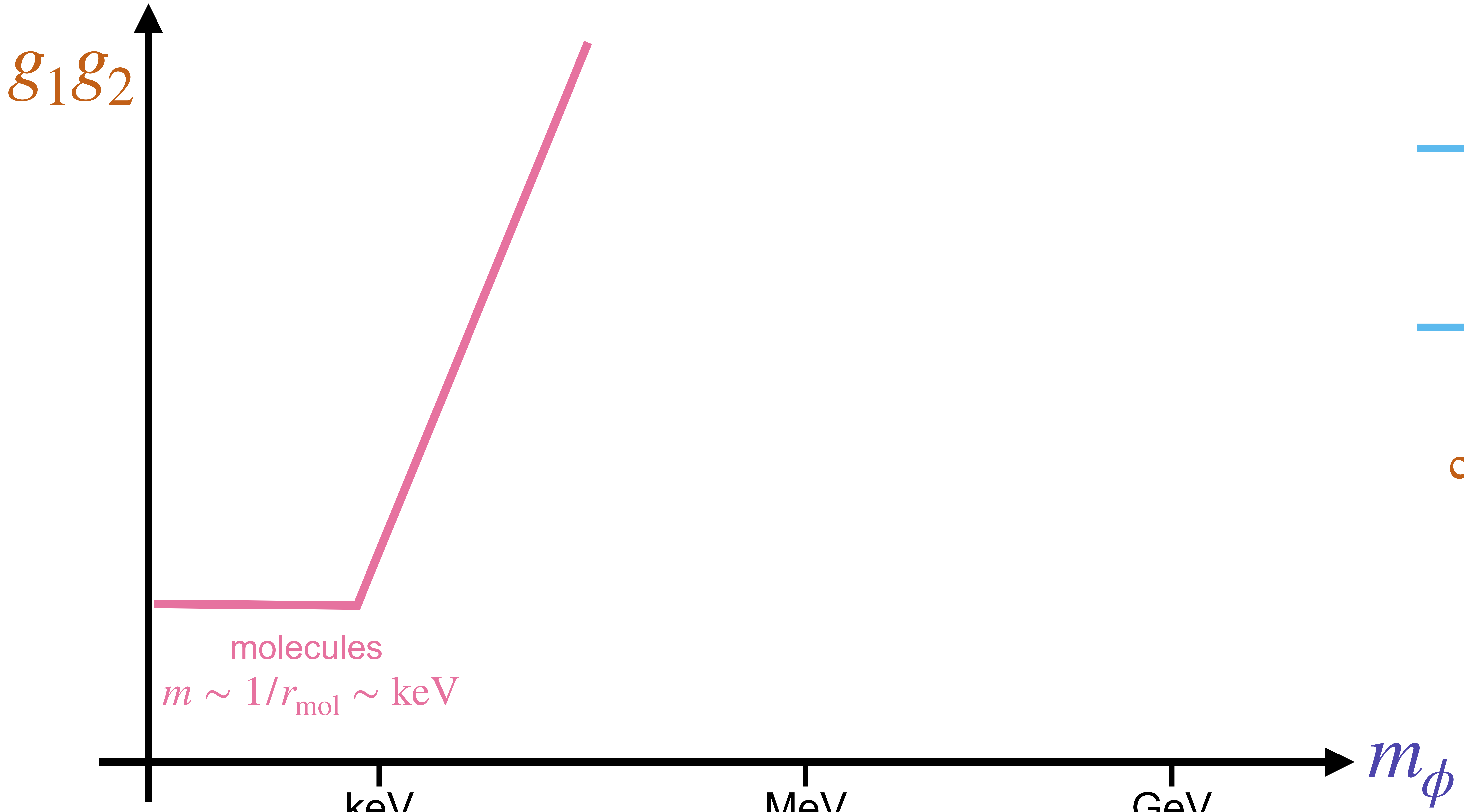

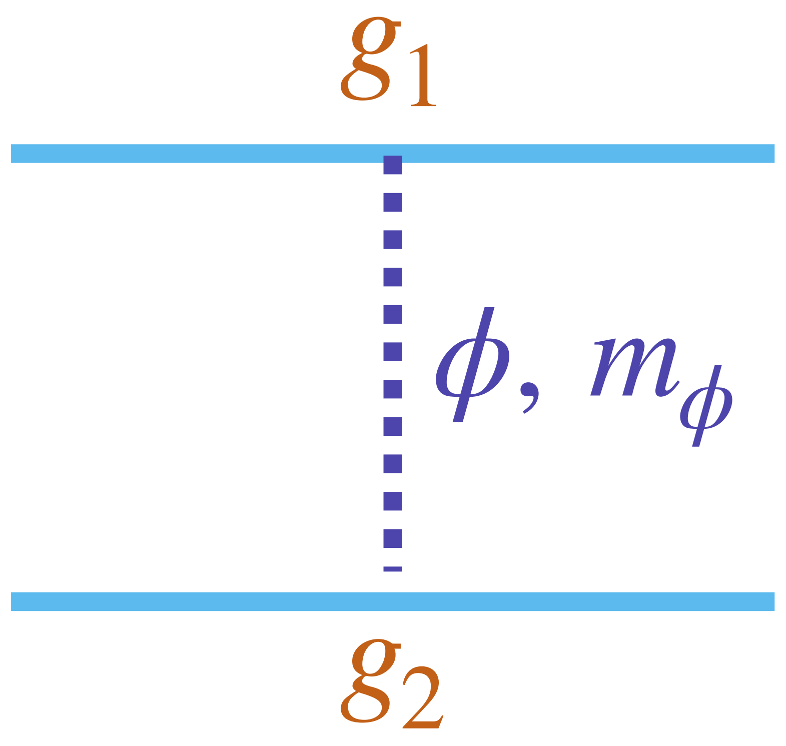

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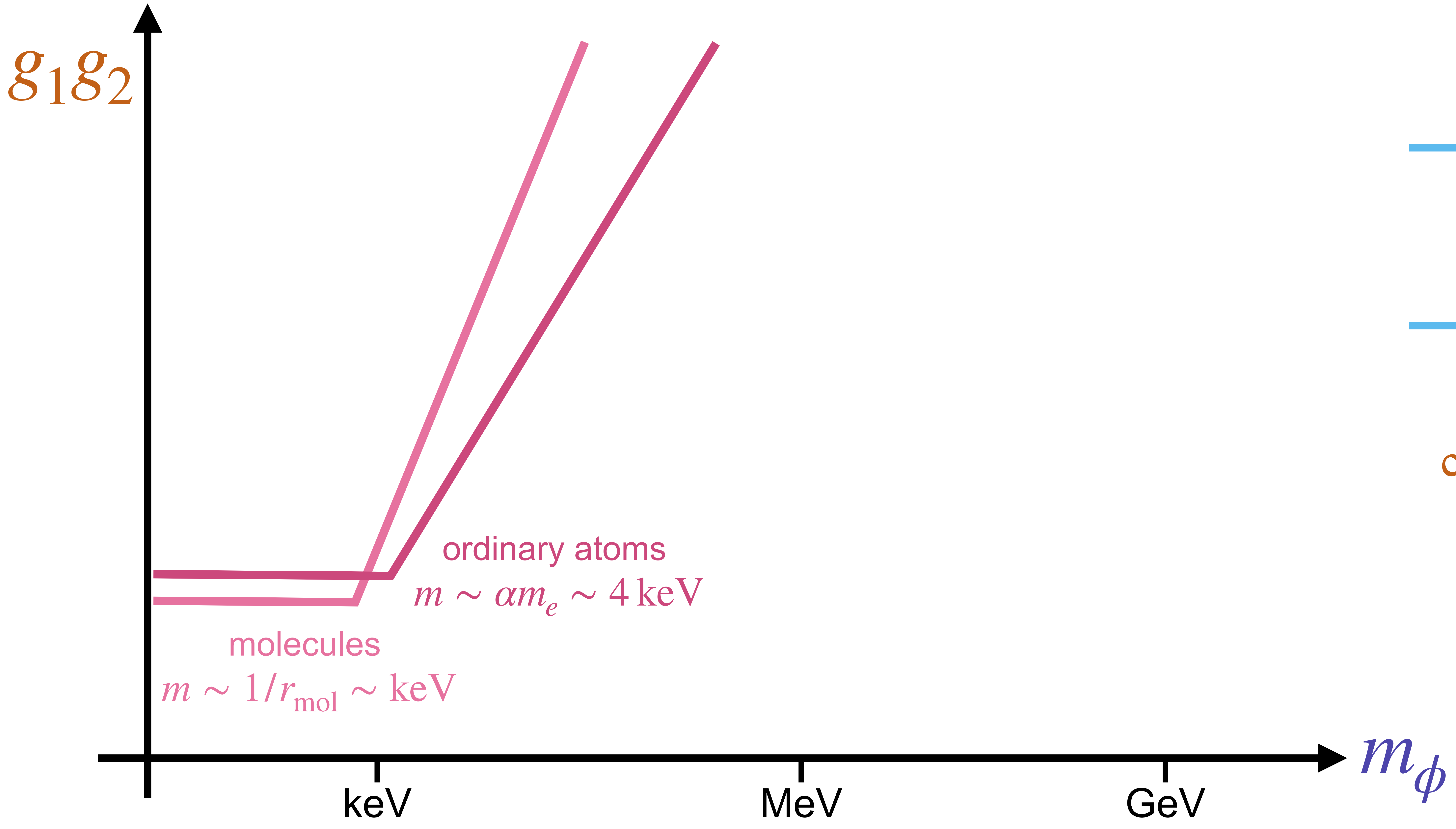

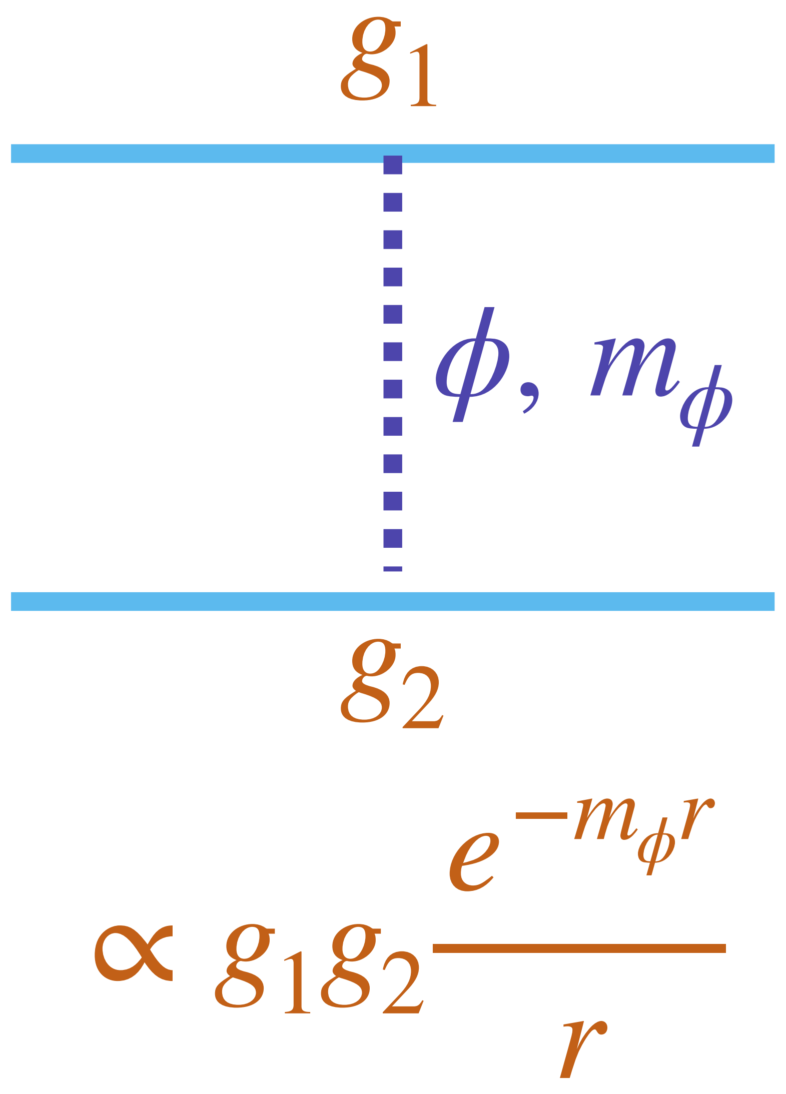

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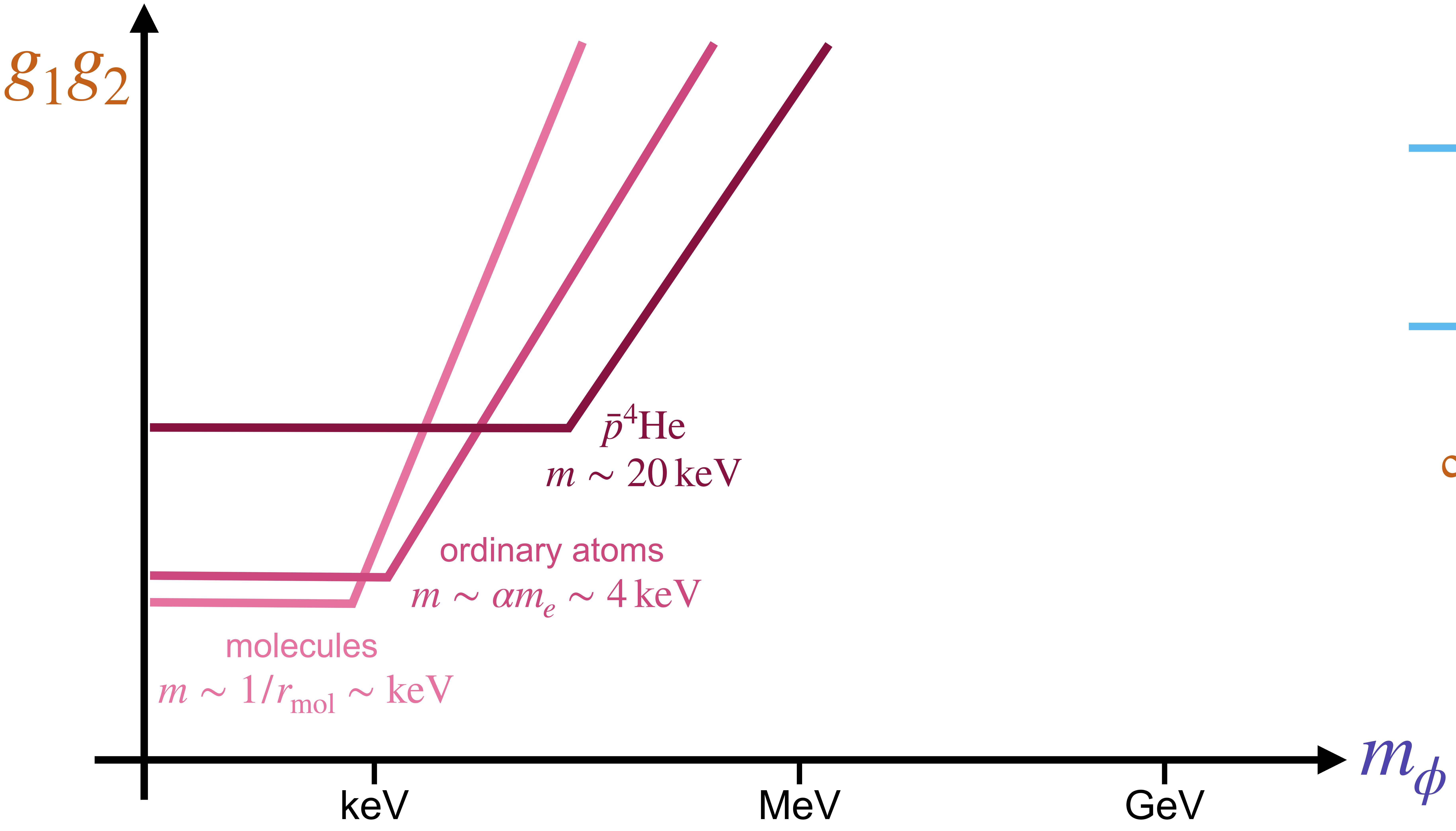

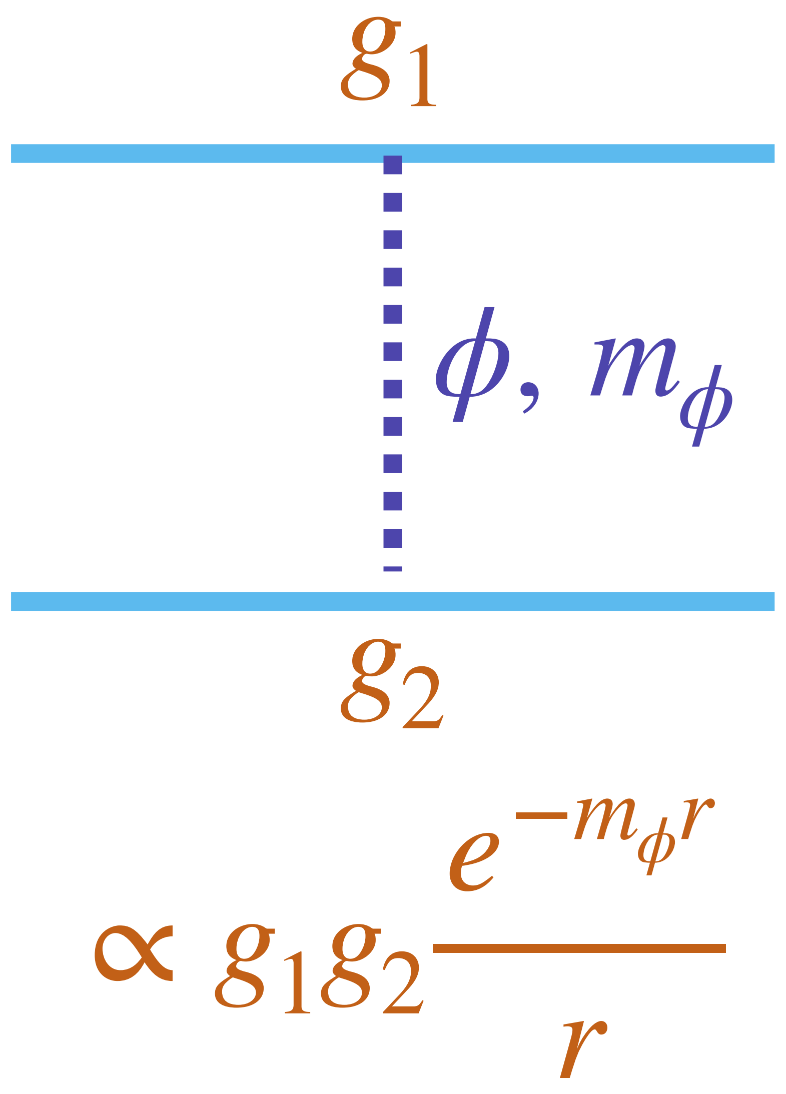

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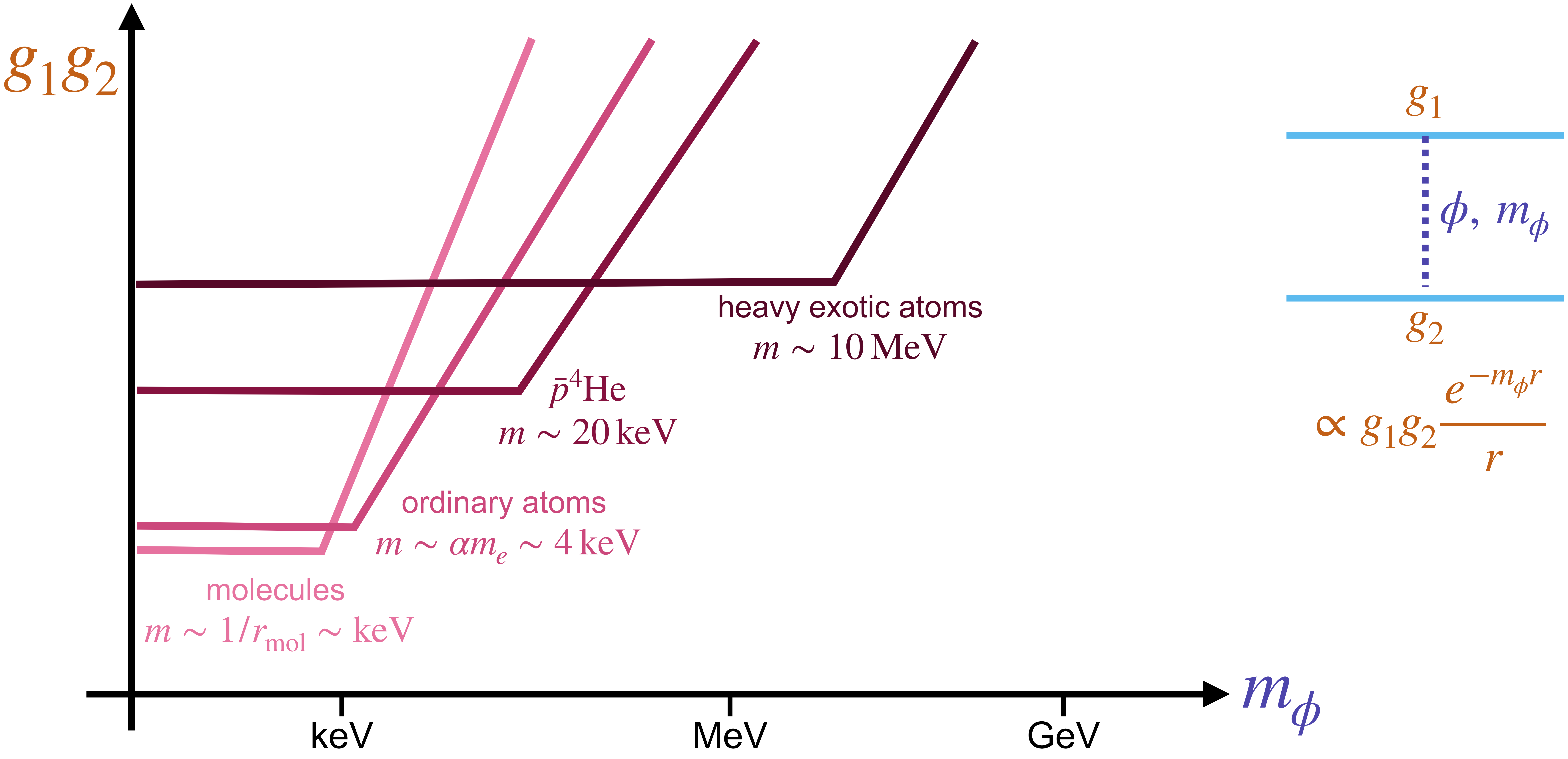

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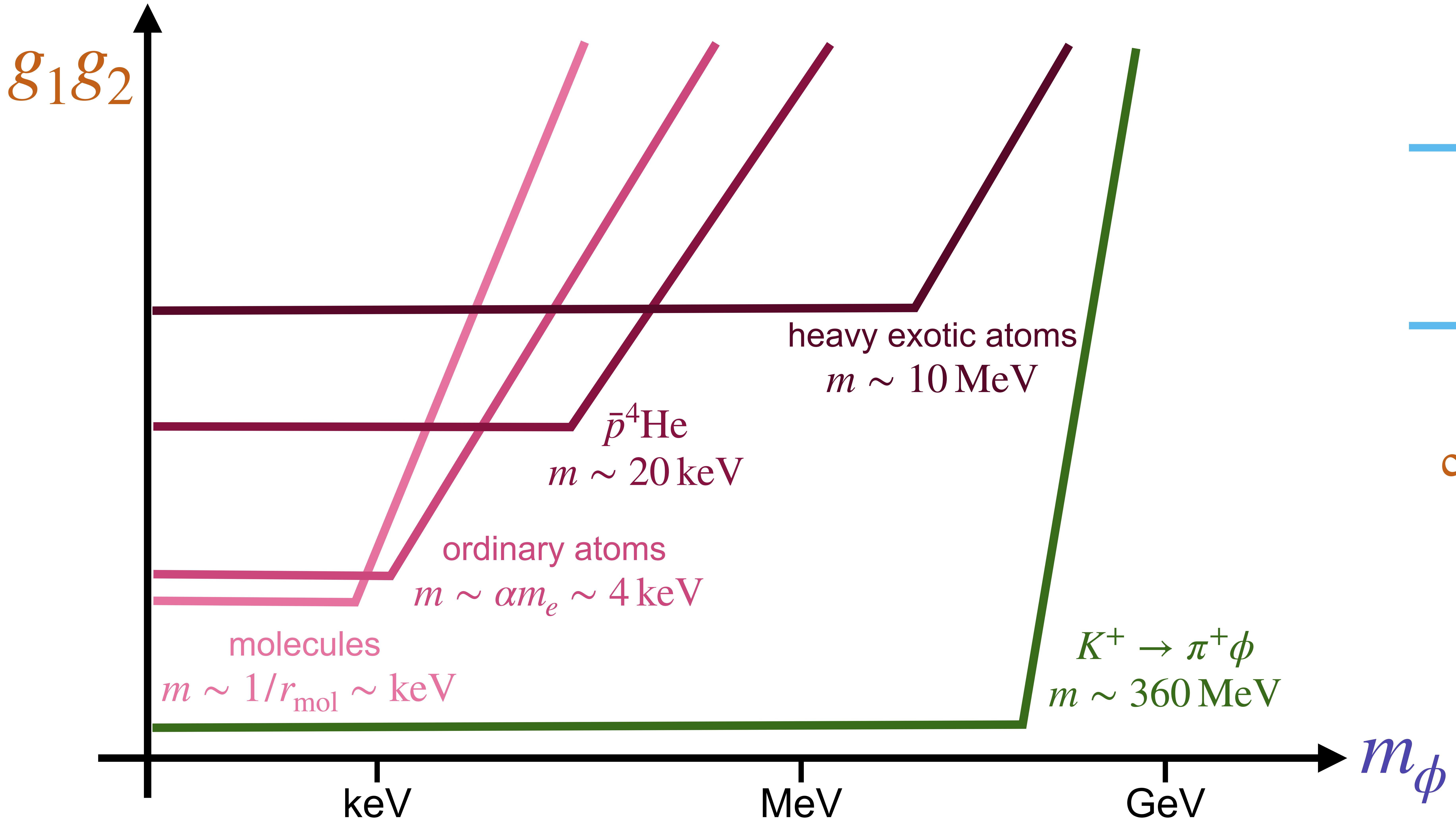

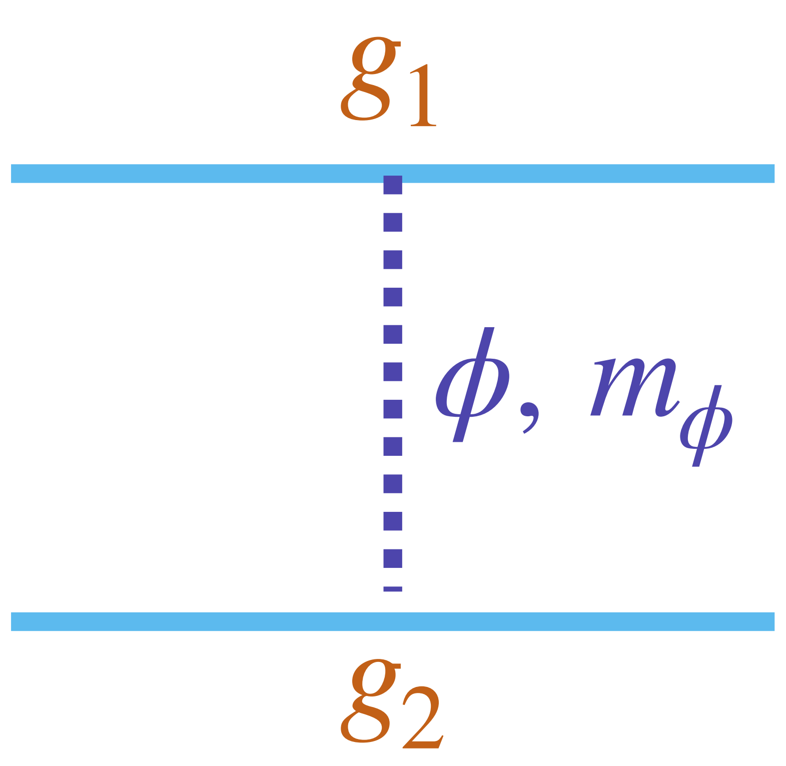

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Self-consistent extraction of spectroscopic bounds on light new physics

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Fundamental constants

fundamental constants cannot be

- predicted by the current theory, e.g. α, m_e
- reliably calculated e.g. r_p, m_p

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precision measurements used to

- determine the fundamental constants, e.g. CODATA
- probe new physics (NP) - new particles

Fundamental constants: extraction

$$\mathcal{O} = \mathcal{O}_{\rm SM}(g_{\rm SM}) + \mathcal{O}_{\rm NP}(g_{\rm SM}, \alpha_\phi, m_\phi) + \delta\mathcal{O}_{\rm th}$$

observable

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

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Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

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➡ new physics affect the fundamental constants extraction

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Beyond Standard model and CODATA

the aim

a self-consistent determination of fundamental constants in the presence of new physics

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

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→ mutual fit of new physics and fundamental constants

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Beyond Standard model and CODATA

the aim

a self-consistent determination of fundamental constants in the presence of new physics

⇒ mutual fit of new physics and fundamental constants

⇒ generically, reduce sensitivity to new physics
larger errors on fundamental constants

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Light new physics - dark photon

$m_\phi \ll \alpha m_e \approx 4\,\mathrm{keV}$ ➡ long range force

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

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$m_\phi \to 0$, spin-1, couplings aligned to QED

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need to calculate new physics at the same order as the standard model, not practical

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Light new physics

capture the alignment effect by redefine the potential as

$$V_{\mathrm{NP}}^{ij} = \alpha_\phi \frac{Q_i Q_j}{r} + \tilde{V}_{\mathrm{NP}}^{ij}$$

QED part

$$\tilde{V}_{\mathrm{NP}}^{ij} = \alpha_\phi \frac{q_i q_j e^{-m_\phi r} - Q_i Q_j}{r}$$

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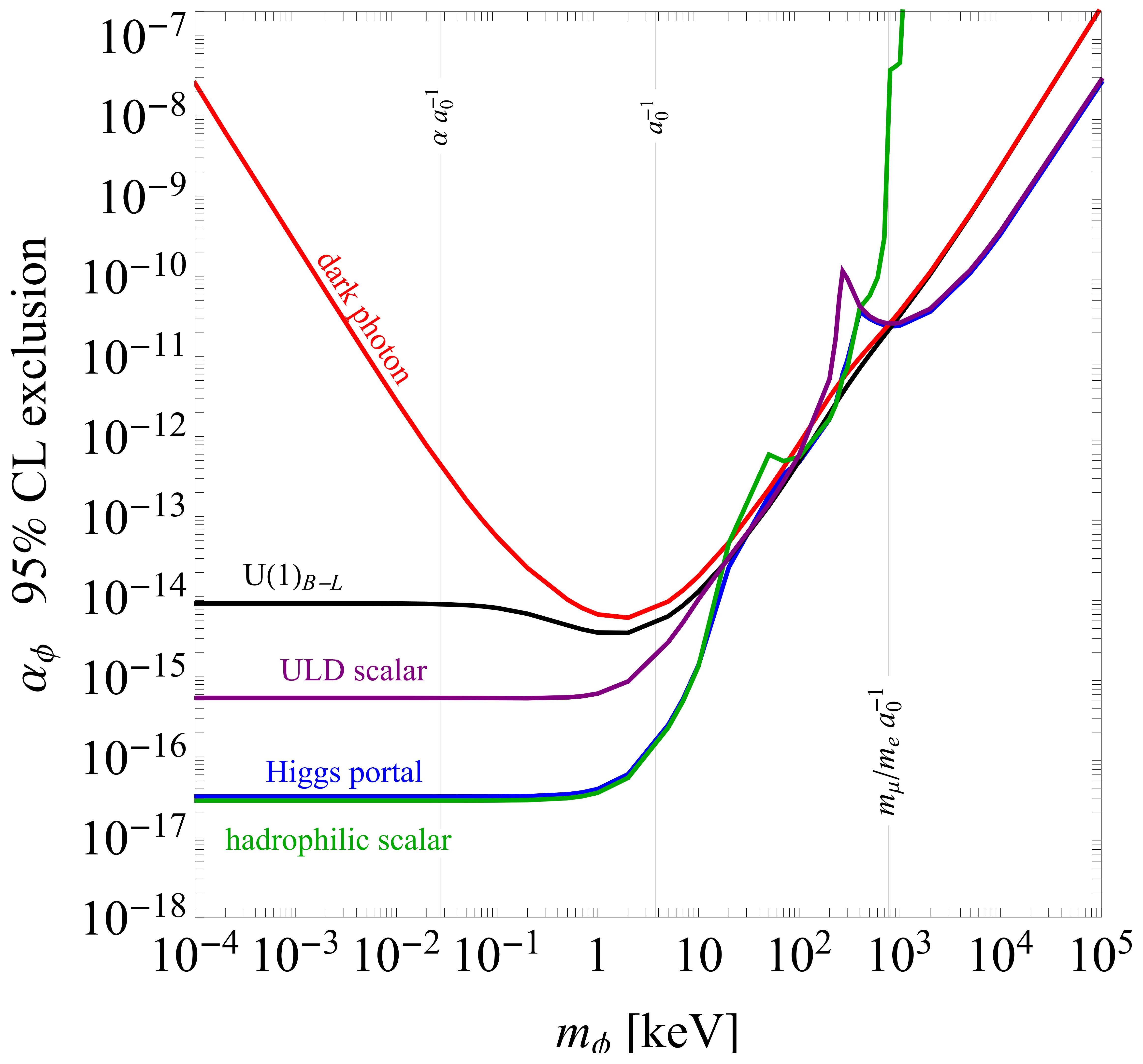
QED part

$$\mathcal{O} = \mathcal{O}_{\mathrm{SM}}(\alpha + \alpha_\phi) + \tilde{\mathcal{O}}_{\mathrm{NP}}(\alpha + \alpha_\phi, \alpha_\phi, m_\phi) + \delta\mathcal{O}_{\mathrm{th}}$$

state-of-the-art leading order

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Results

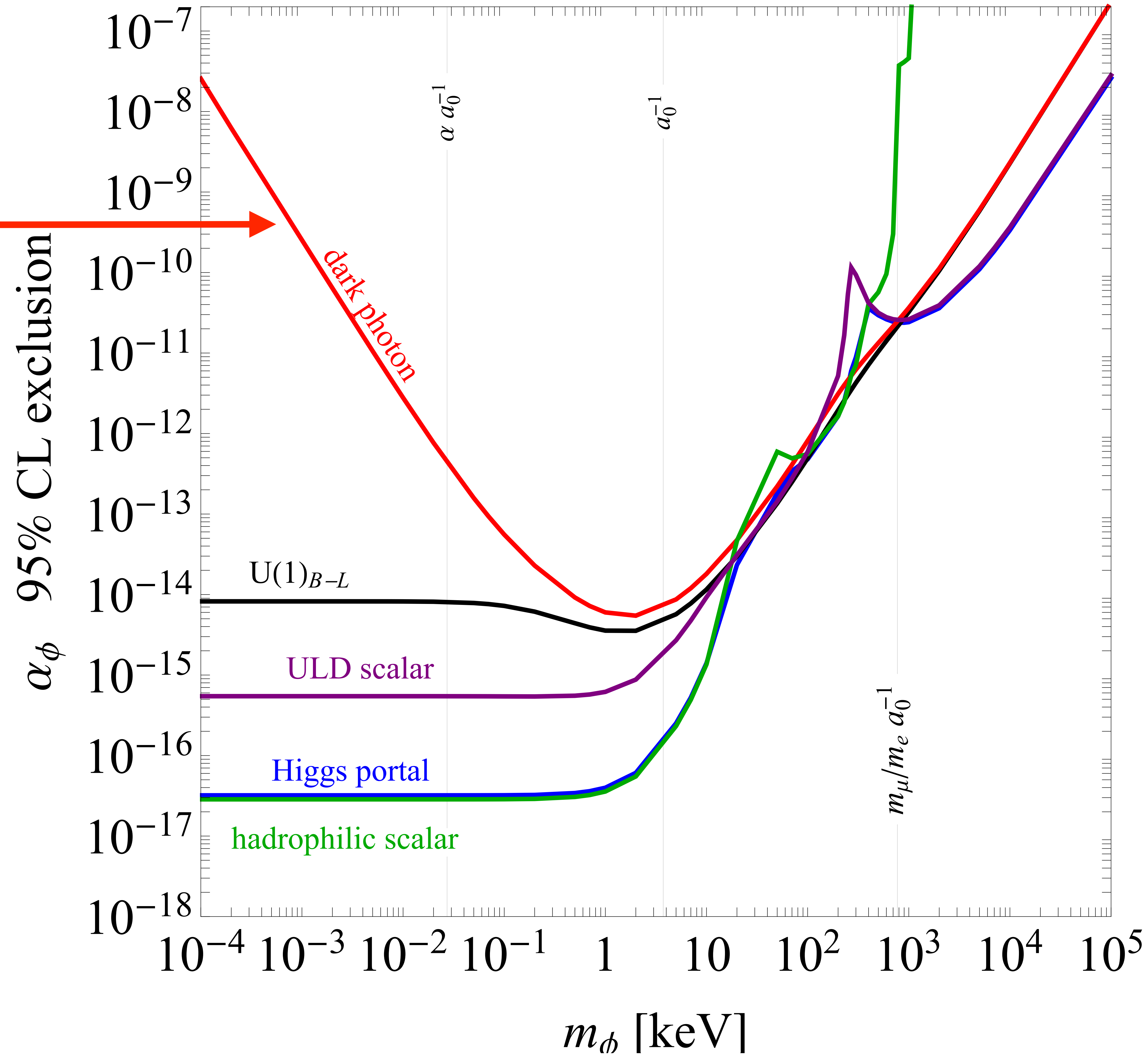


DATA22
CODATA18 + improvements
H, HD^+, $\bar{p}$He, μHe, $(g-2)_e$,
masses

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Results

$\propto m_\phi^{-2}$ aligned with QED



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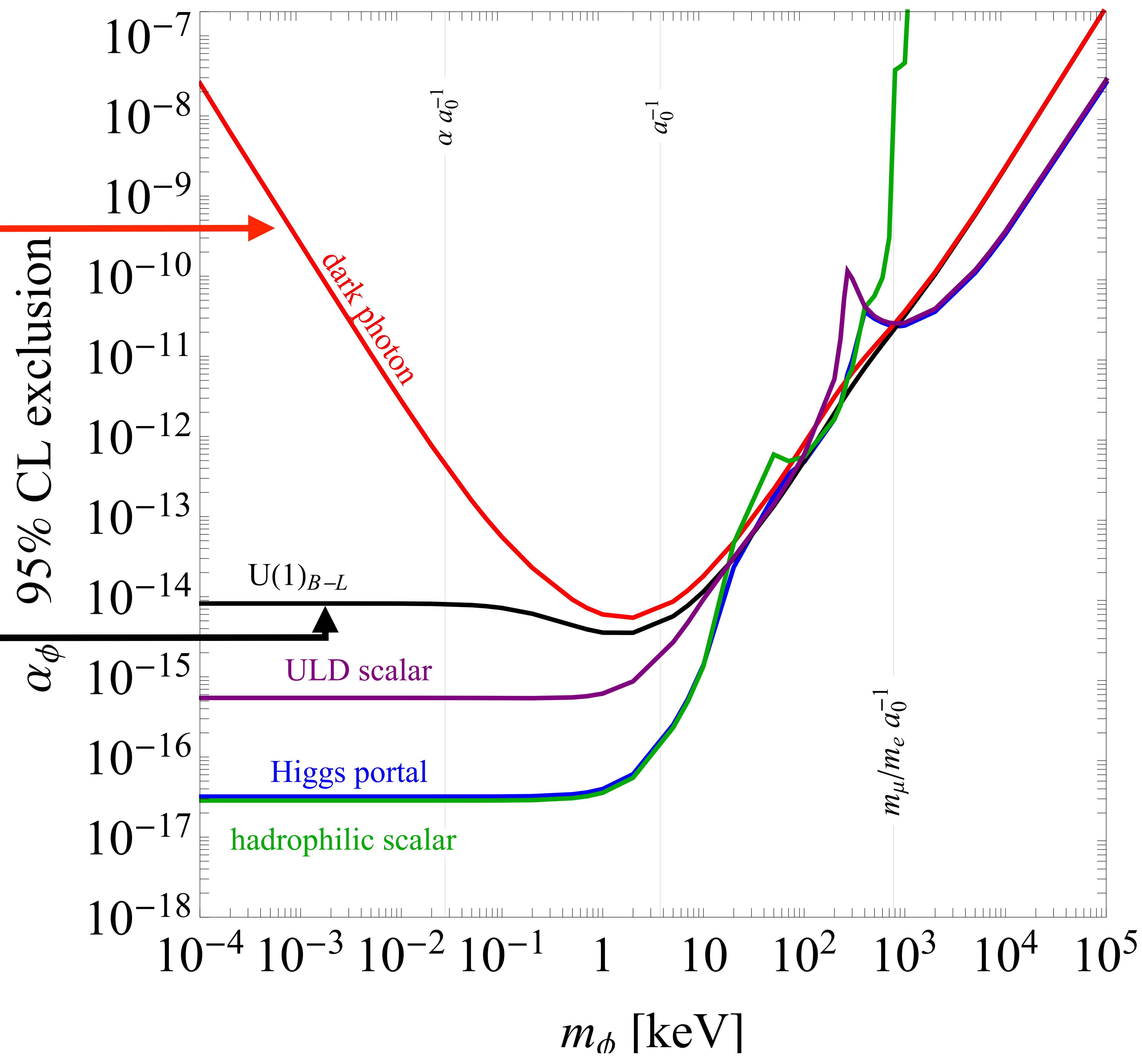
$\propto m_\phi^{0}$ due to deuterium



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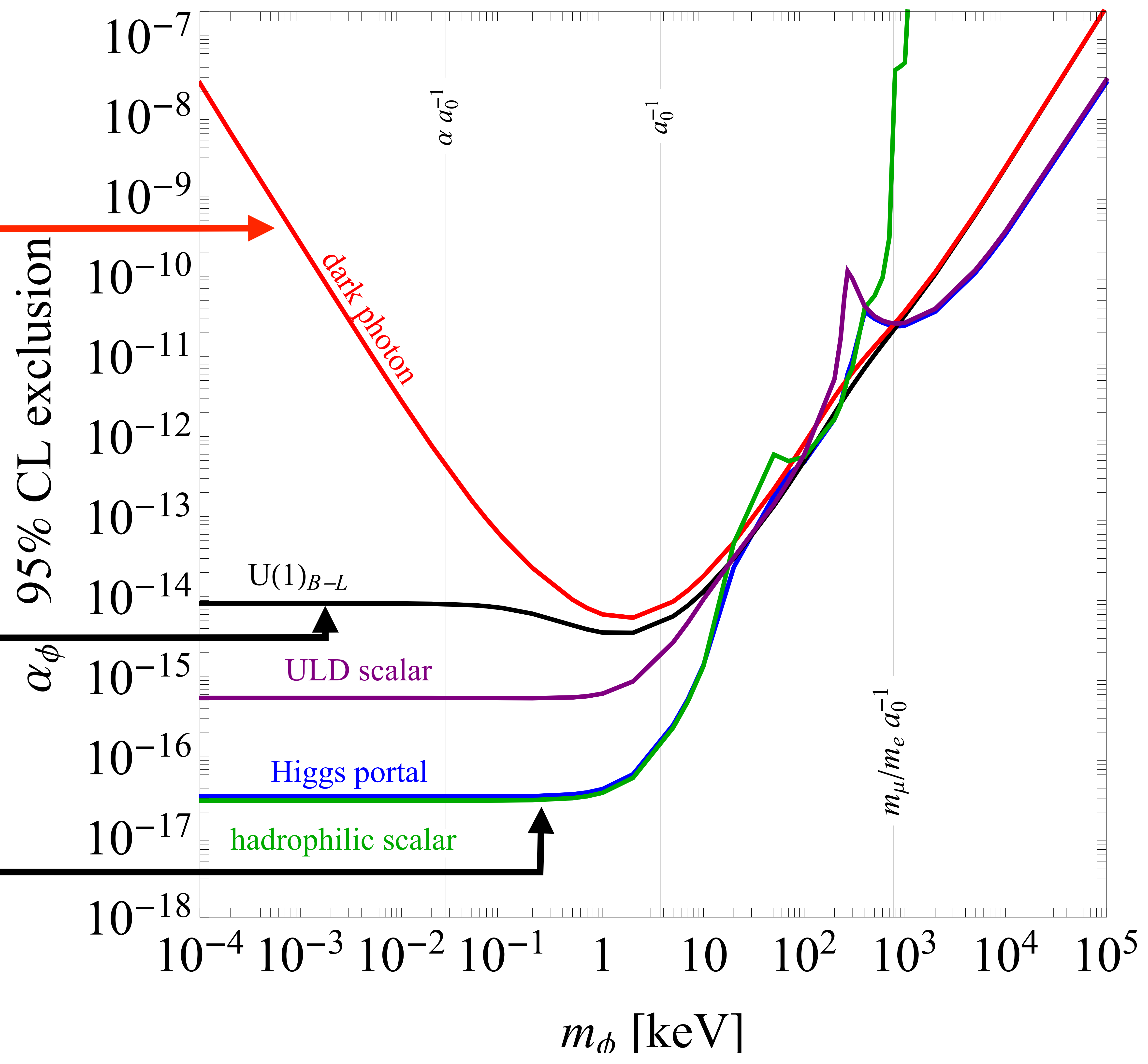

$\propto m_\phi^0$ due to deuterium

stronger sensitivity due to molecules

$q_N/q_e \sim m_N/m_e \sim 10^3$

DATA22

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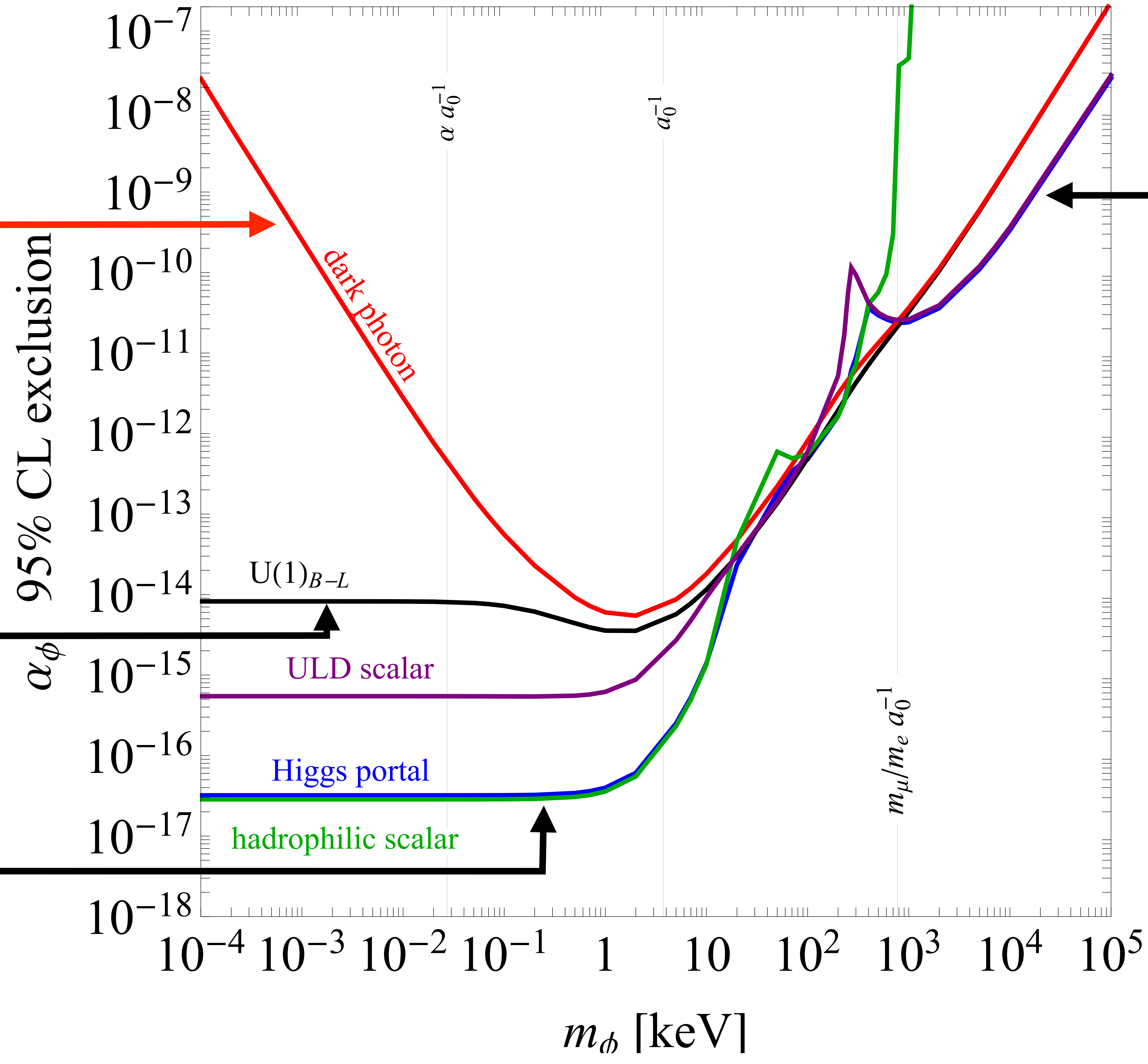

stronger sensitivity due to muonic atoms

$q_\mu/q_e \sim m_\mu/m_e \sim 200$

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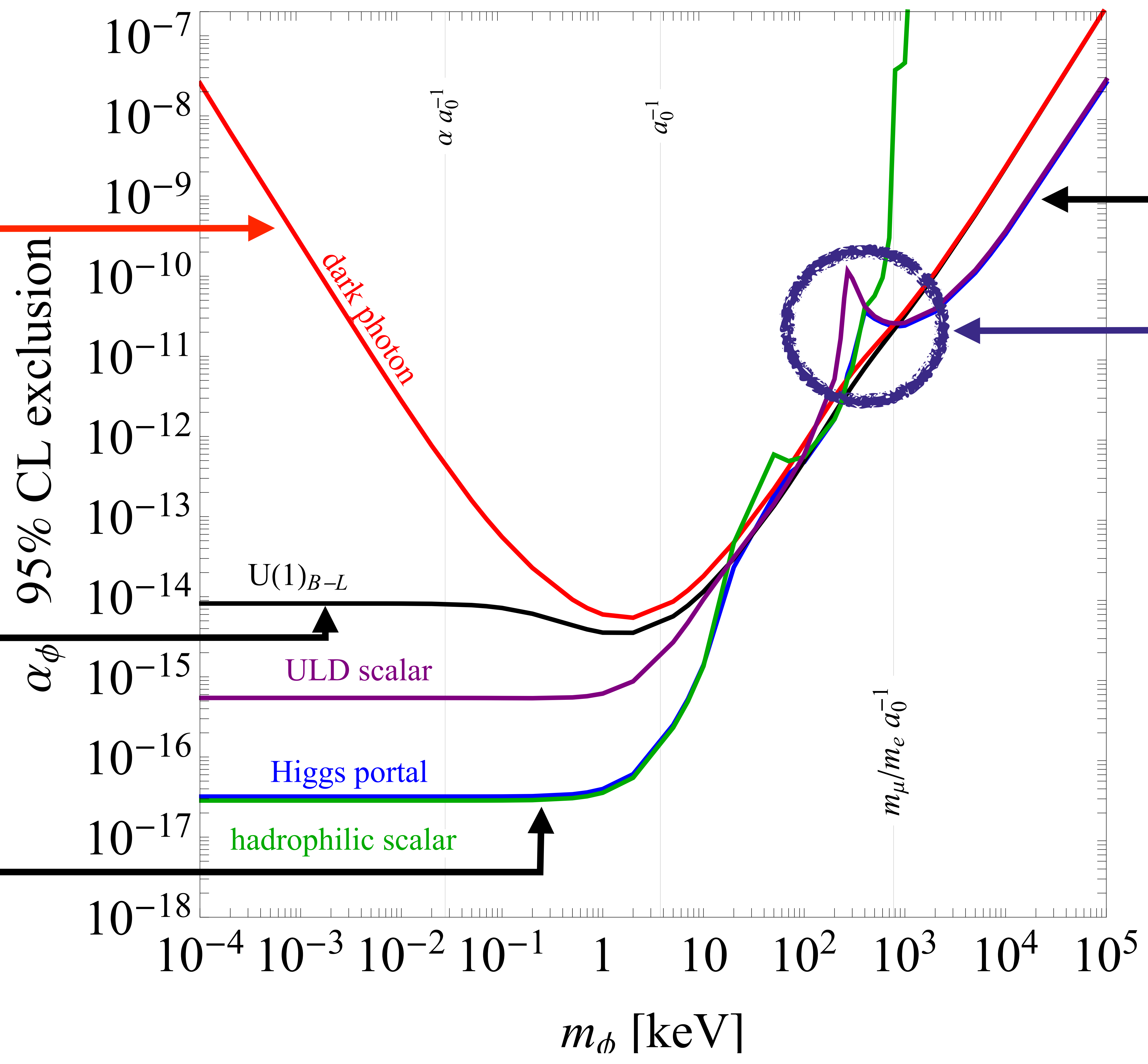

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data favors $\alpha_\phi \neq 0$ for Higgs portal and ULD

DATA22

CODATA18 + improvements

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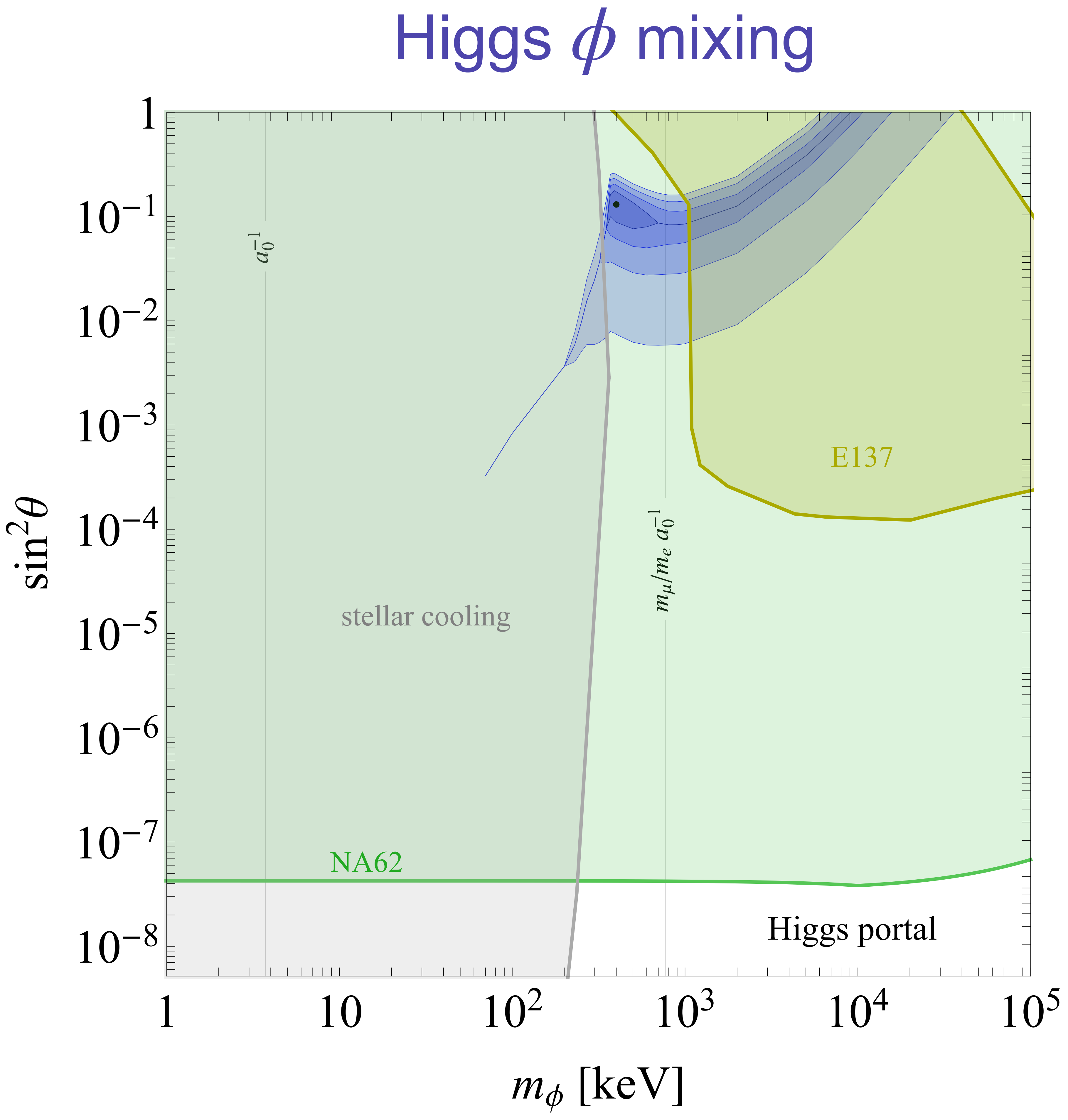
Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

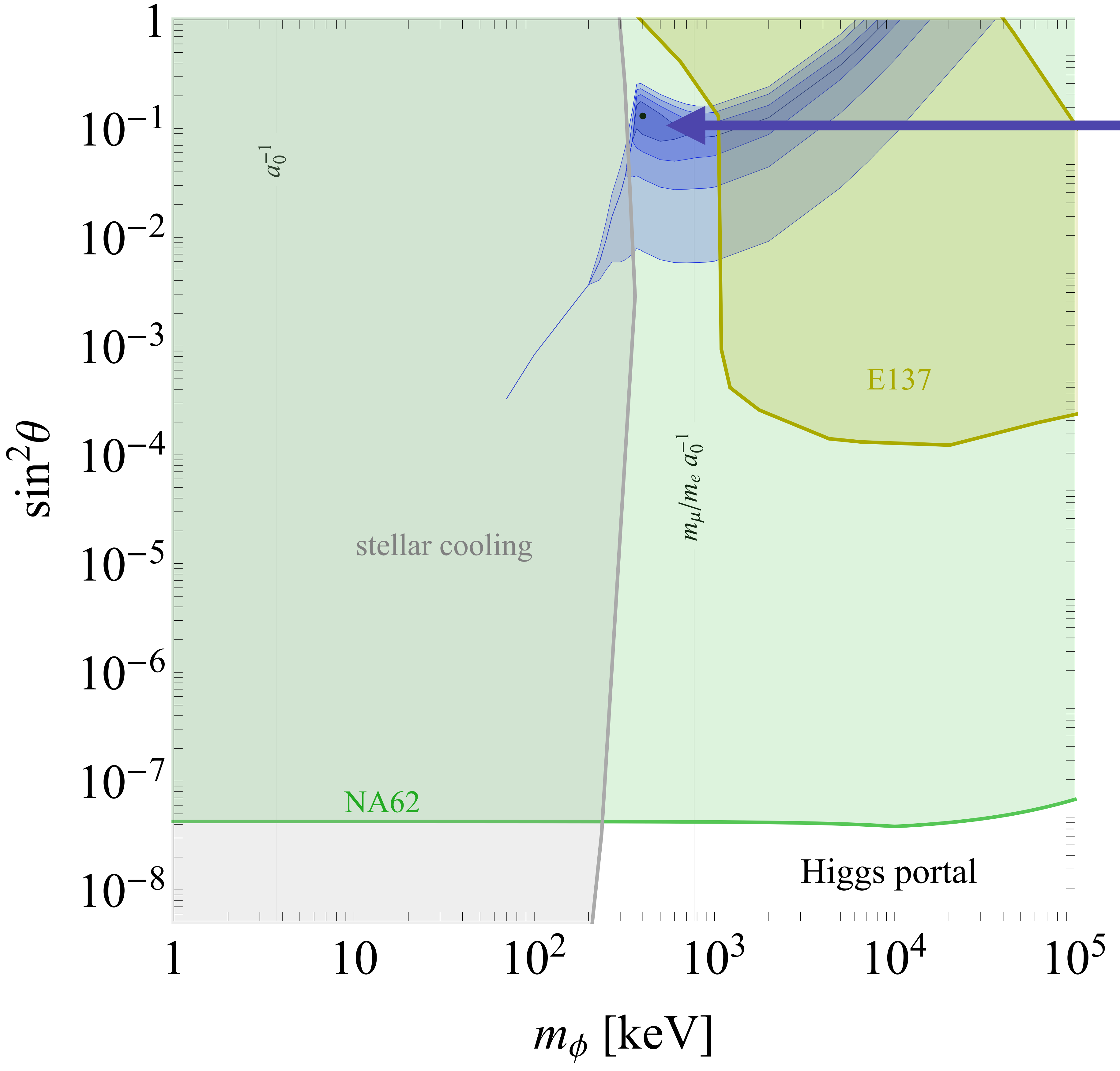
2022 Spectroscopy data



Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

2022 Spectroscopy data

Higgs ϕ mixing



excess in spectroscopy data

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

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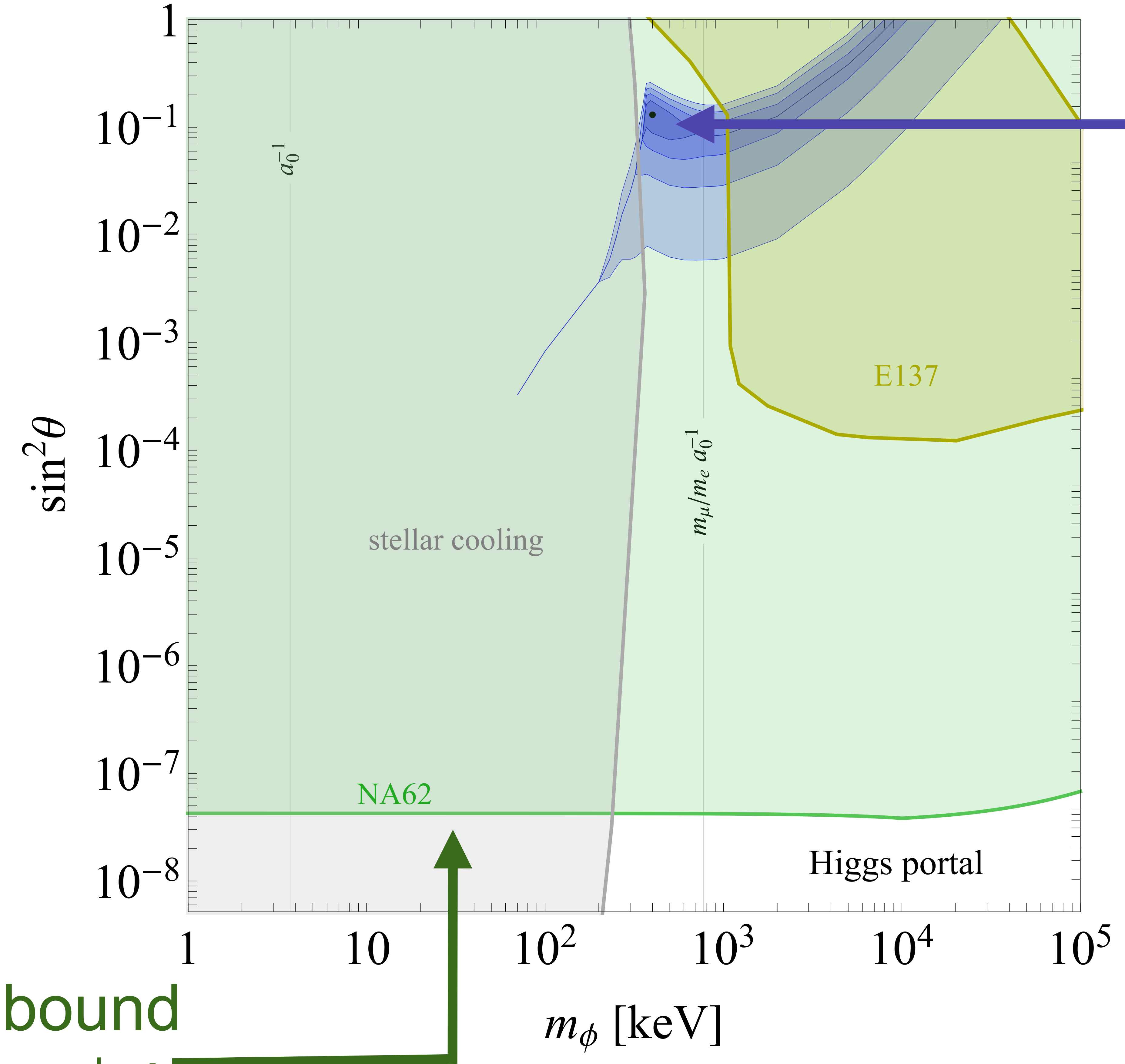


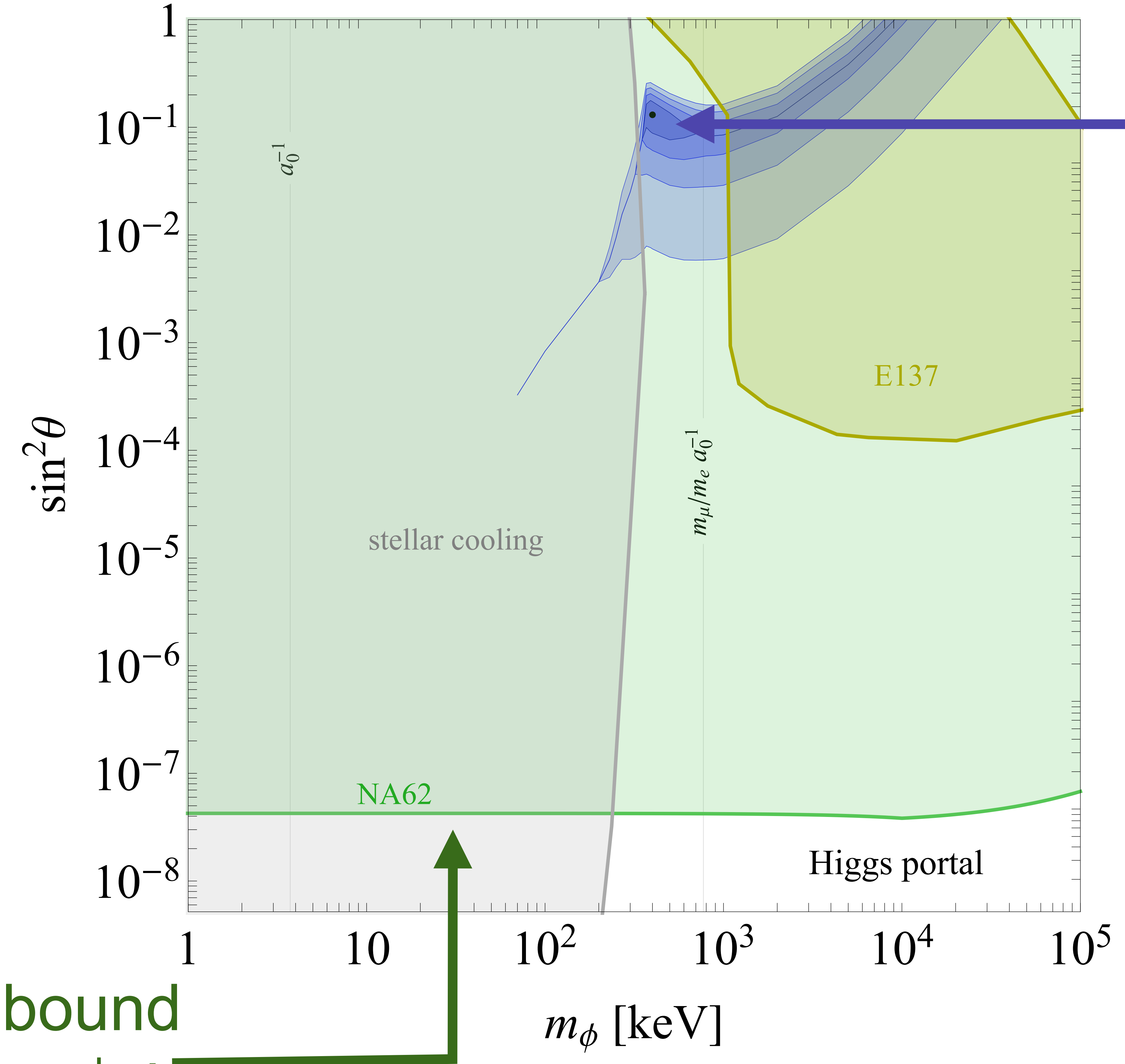
excess in spectroscopy data

very strong bound from $K^+ \to \pi^+\phi$

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

2022 Spectroscopy data

Higgs ϕ mixing



excess in spectroscopy data

very strong bound from $K^+ \to \pi^+\phi$

1. How robust is the Kaon bound? i.e. how to avoid it?

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

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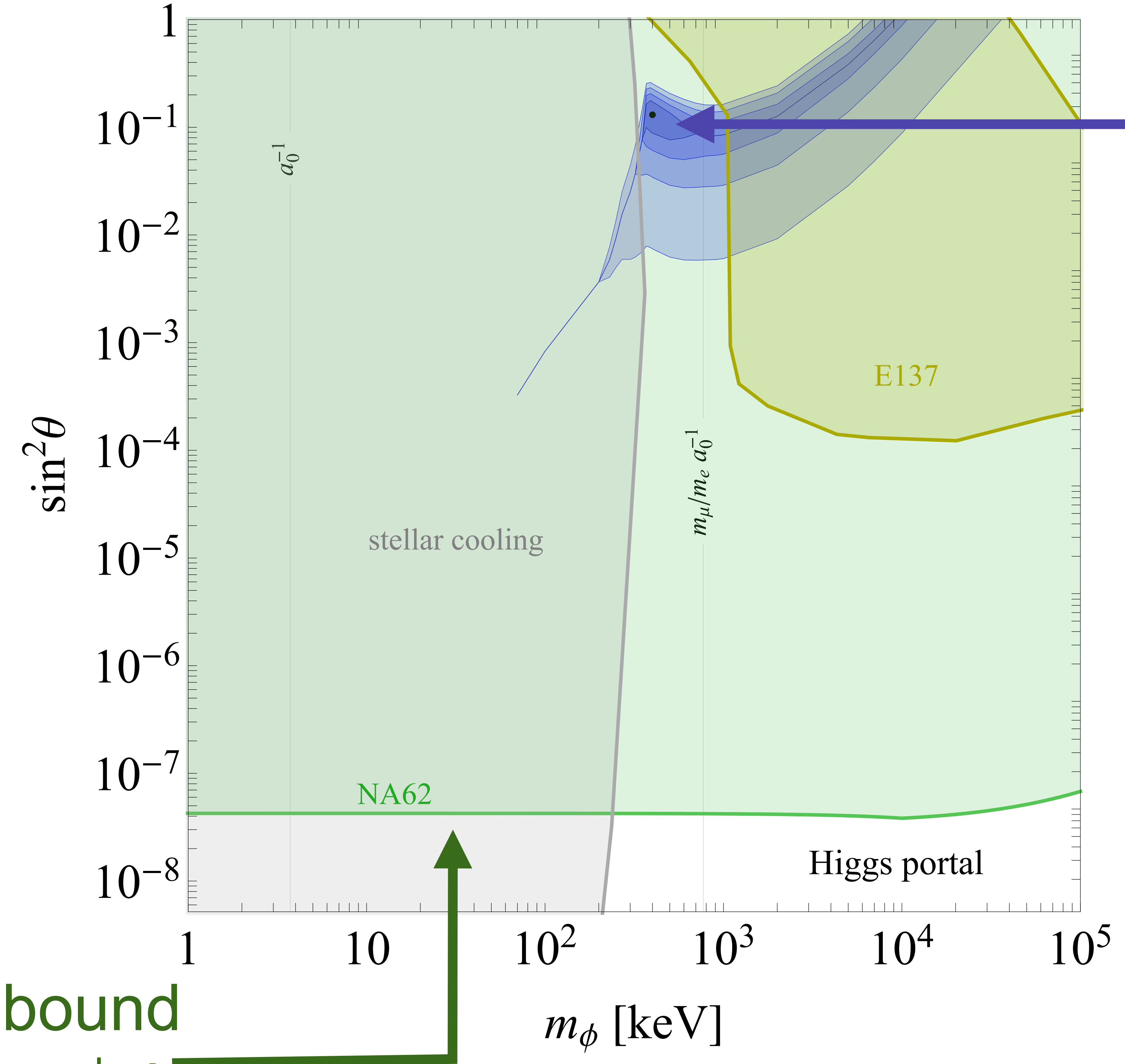

excess in spectroscopy data

very strong bound from $K^+ \to \pi^+\phi$

1. How robust is the Kaon bound? i.e. how to avoid it?
2. How can we go beyond it ?

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Can we avoid Kaon decay bounds?

	$K \to \pi\phi$	spectroscopy (nucleon coupling)
Higgs mixing		
uds: $\kappa_{u,d,s} = 1$		

$$\mathscr{L}_{\rm int}^{\phi} \supset \frac{\phi}{f}\left(\frac{9\alpha_s}{8\pi}K_{\Theta}G^a_{\mu\nu}G^{a\mu\nu} - 2\kappa_W \mathscr{L}_{4q}^{\Delta S=1} + \kappa_{sd}m_s\bar{d}_L s_R + \kappa_{ds}m_d\bar{d}_R s_L - \sum_{\phi}\kappa_\psi m_\psi \bar{\psi}\psi\right)$$

Delaunay, Kitahara, YS, Zupan, 2501.16477

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Higgs mixing		
uds: $\kappa_{u,d,s} = 1$	0	$\propto m_n^2$

only u, d, s couplings $\propto m_{u,d,s}$

$\Rightarrow$ avoid strong Kaon bounds

$\Rightarrow$ have spectroscopy signature

$$\mathscr{L}^{\phi}_{\text{int}} \supset \frac{\phi}{f}\left(\frac{9\alpha_s}{8\pi}K_\Theta G^a_{\mu\nu}G^{a\mu\nu} - 2\kappa_W \mathscr{L}^{\Delta S=1}_{4q} + \kappa_{sd} m_s \bar{d}_L s_R + \kappa_{ds} m_d \bar{d}_R s_L - \sum_{\phi} \kappa_\psi m_\psi \bar{\psi}\psi\right)$$

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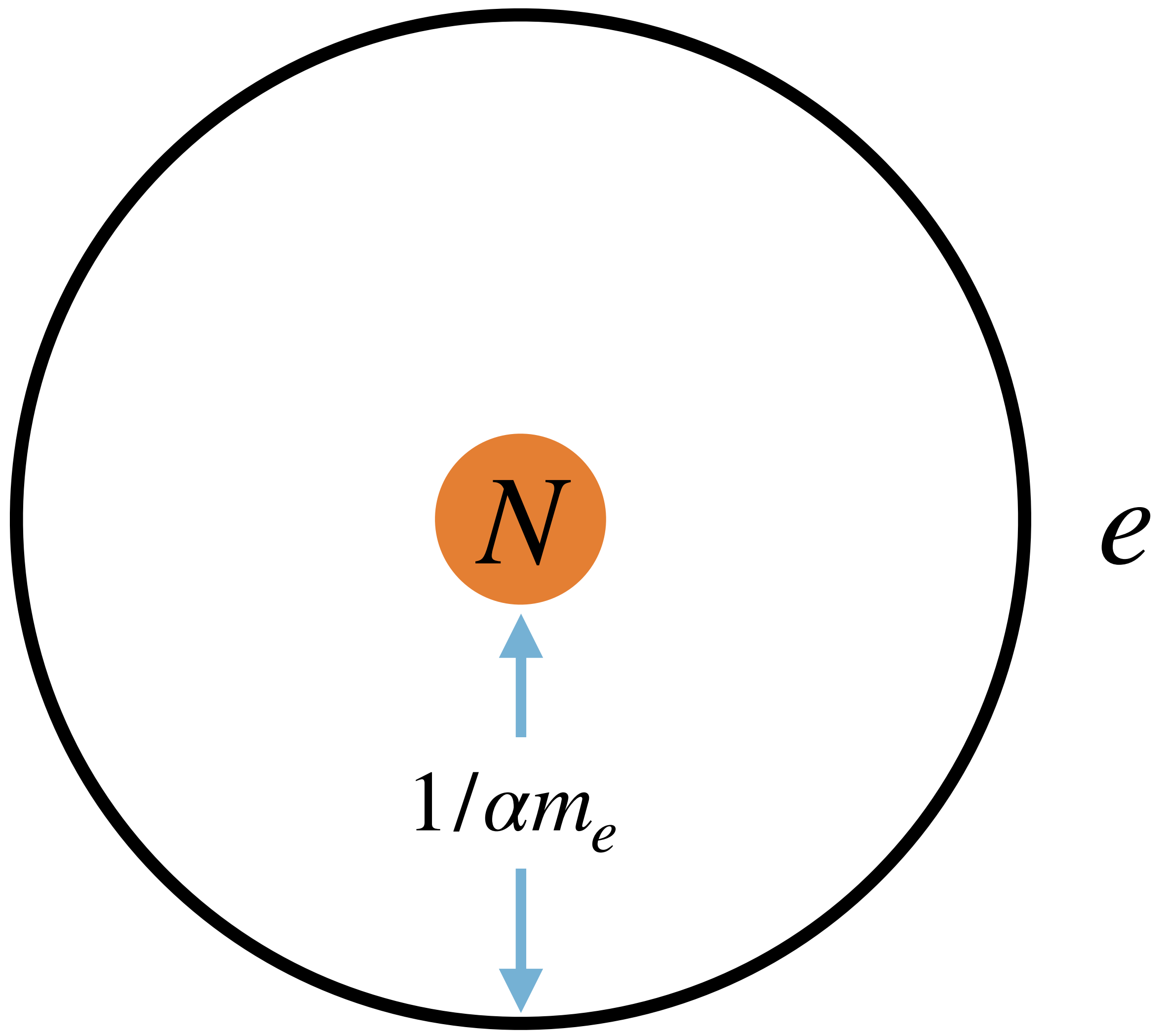
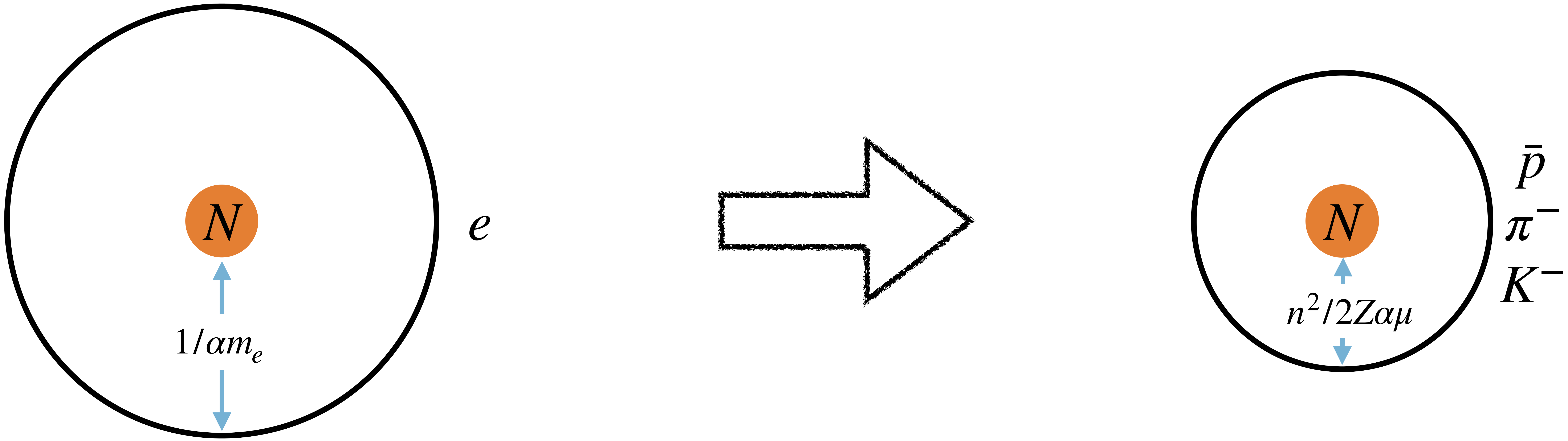
Probing new hadronic forces with heavy exotic atoms

Liu, Ohayon, Shtaif, YS, 2502.03537

Exotic atoms for BSM



Exotic atoms for BSM



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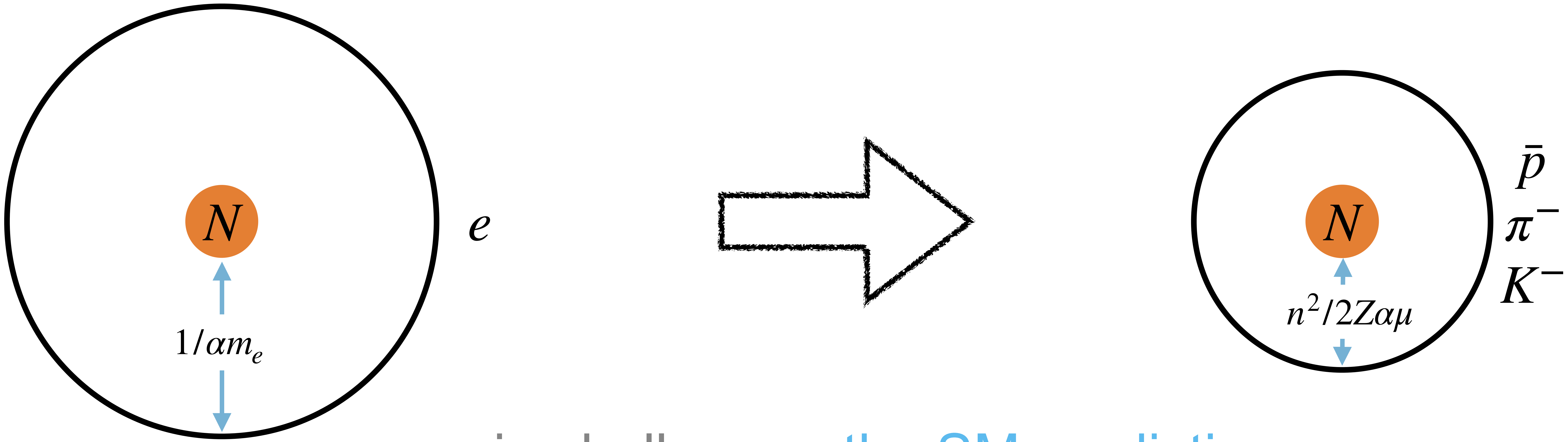

main challenge - the SM prediction
(hadronic interactions)

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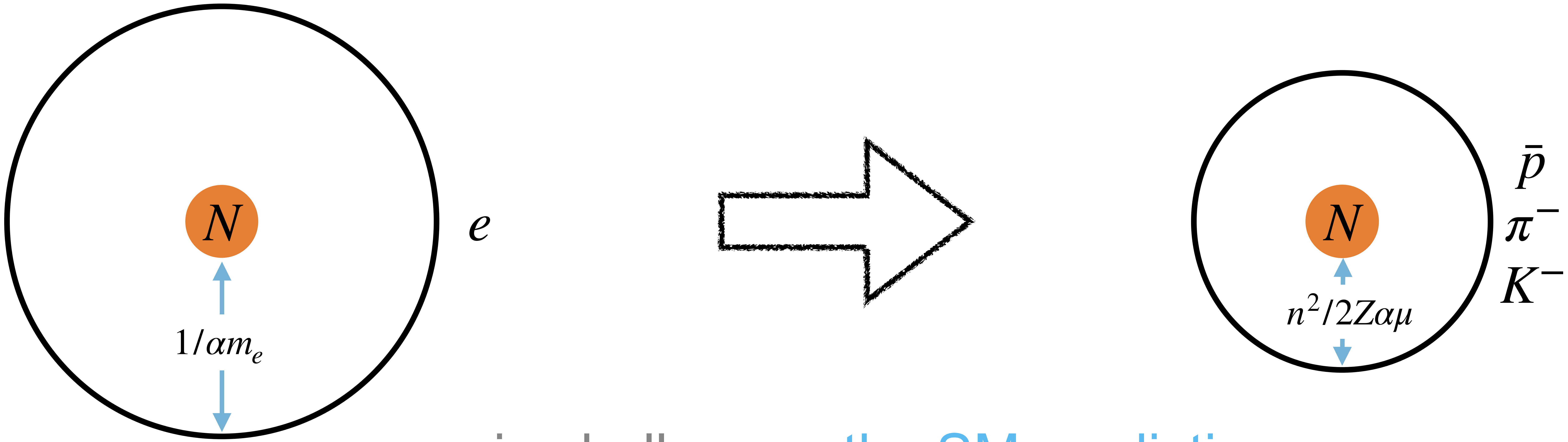

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circular states $(n \gg 1,\ l = n - 1)$ insensitive to local hadronic interactions
$\Rightarrow$ can be predicted (up to nuclear polarizability)

Paul et al PRL 21
Zatorski, Patkos, Pachucki PRA 22

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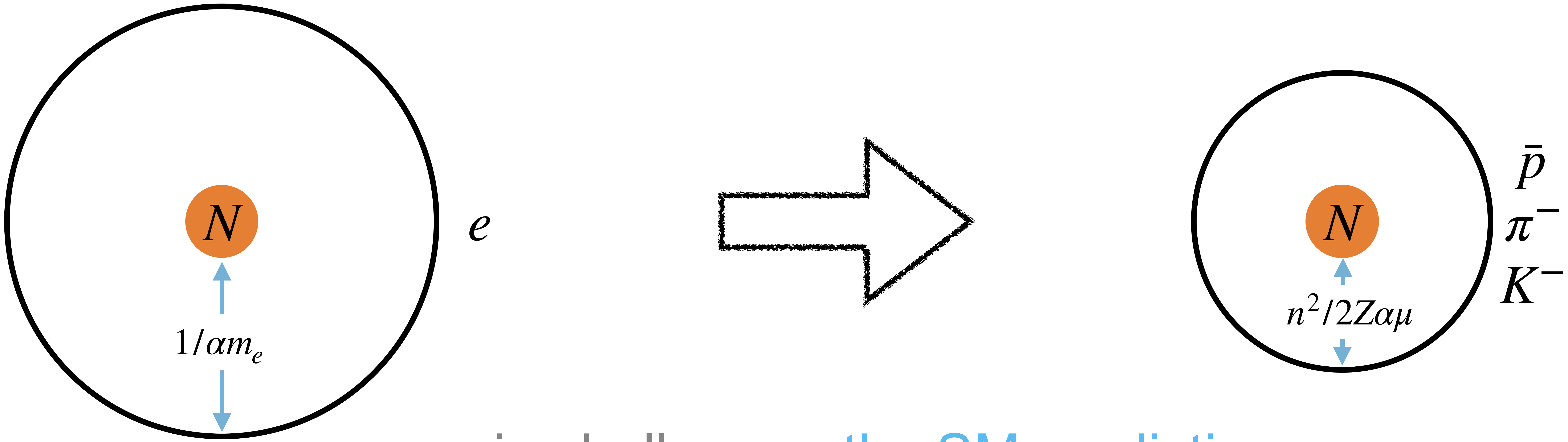

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new physics sensitivity

$g_N \times g_e\,,\, m_\phi \lesssim 4\,\mathrm{keV}$

$g_N \times g_H,\, m_\phi \lesssim 10\,\mathrm{MeV}$

Exotic atoms for BSM

$$E_n^{\mathrm{th}} = \overbrace{E_n^{\mathrm{SM-NPol}} + E_n^{\mathrm{NPol}}}^{E_n^{\mathrm{SM}}} + E_n^{X}$$

Liu, Ohayon, Shtaif, YS, 2502.03537

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$\mathcal{O}(10^{-5})$ → $E_n^{\rm NPol}$

$\propto \alpha_E^{\rm tot} \langle r^{-4} \rangle$

can be extracted from data
by using 2 transitions (2T)

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$$E_n^{\text{th}} = \overbrace{E_n^{\text{SM-NPol}} + E_n^{\text{NPol}}}^{E_n^{\text{SM}}} + E_n^X \longleftarrow \text{new physics } \frac{g_N^X g_H^X}{4\pi}\frac{e^{-m_X r}}{r}$$

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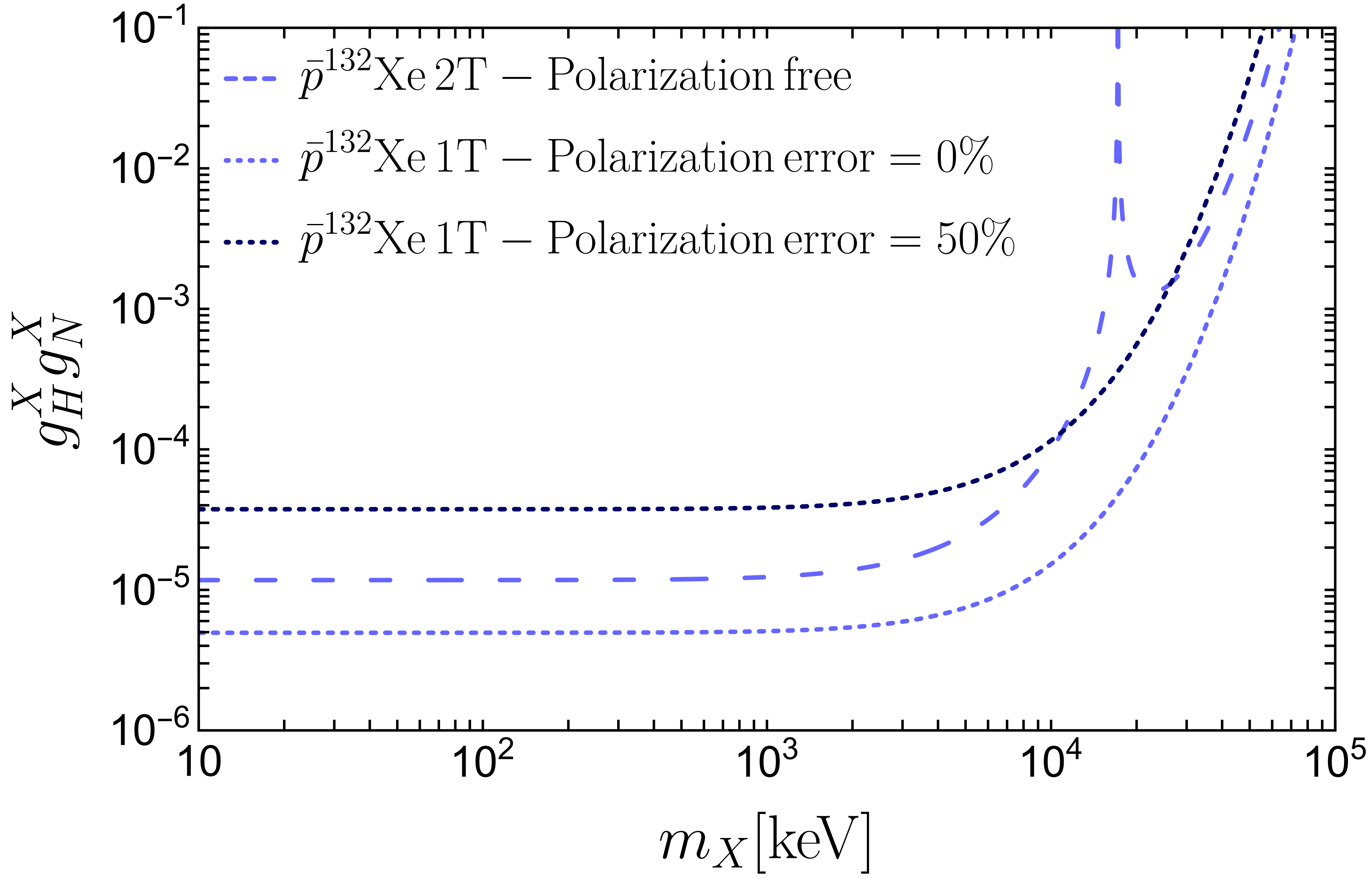
the nuclear polarizability effect



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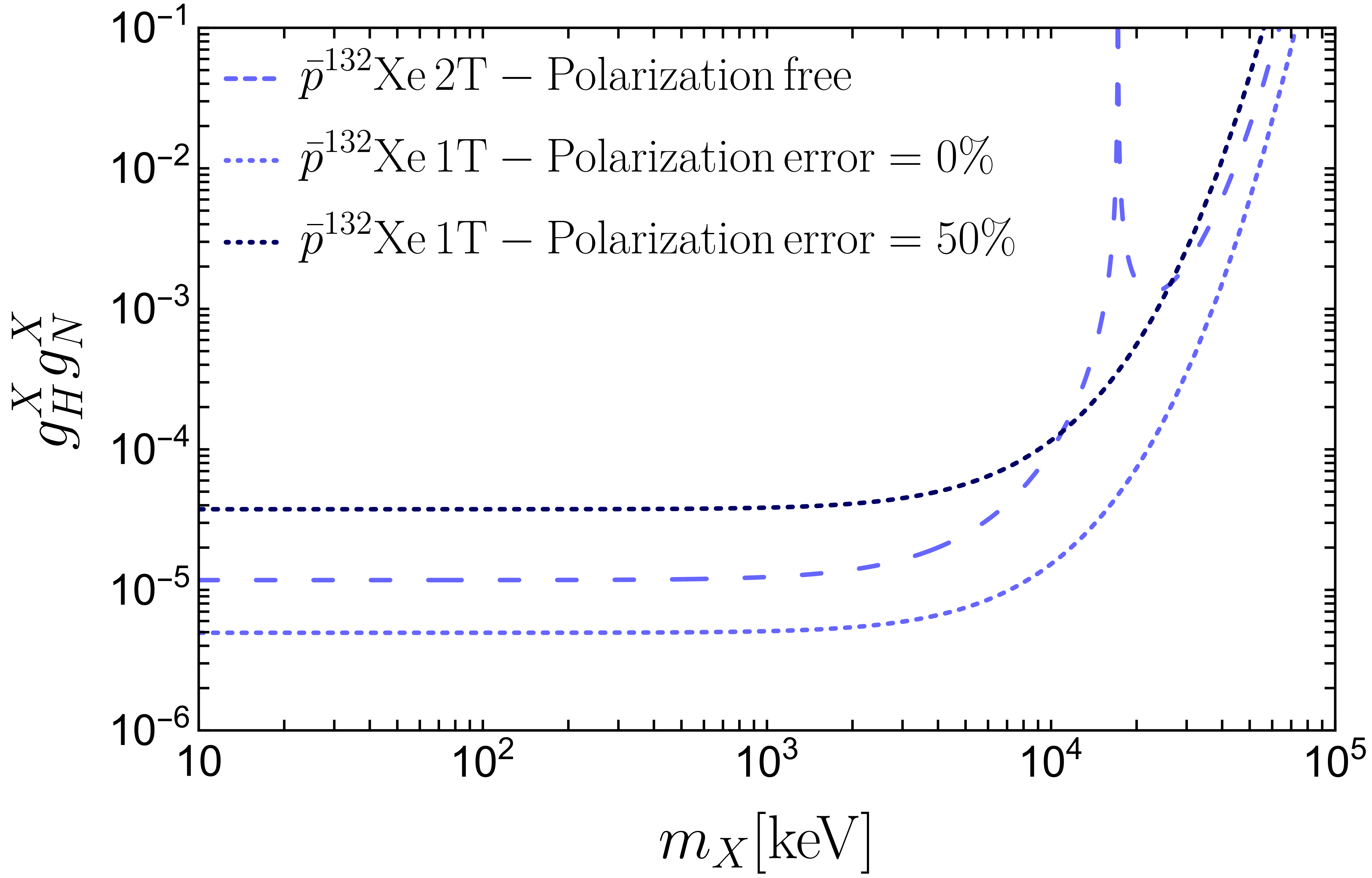
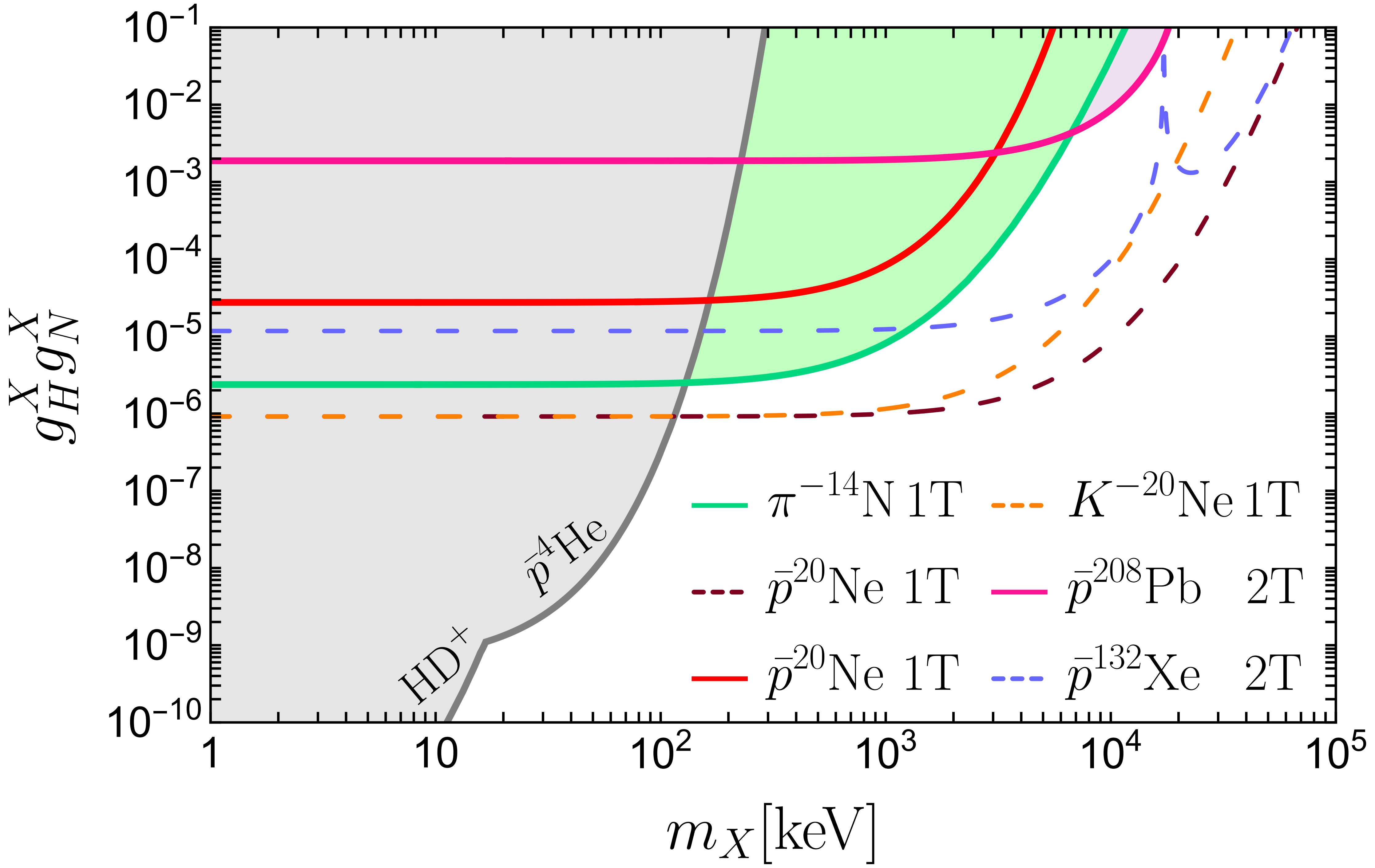


current and future bounds



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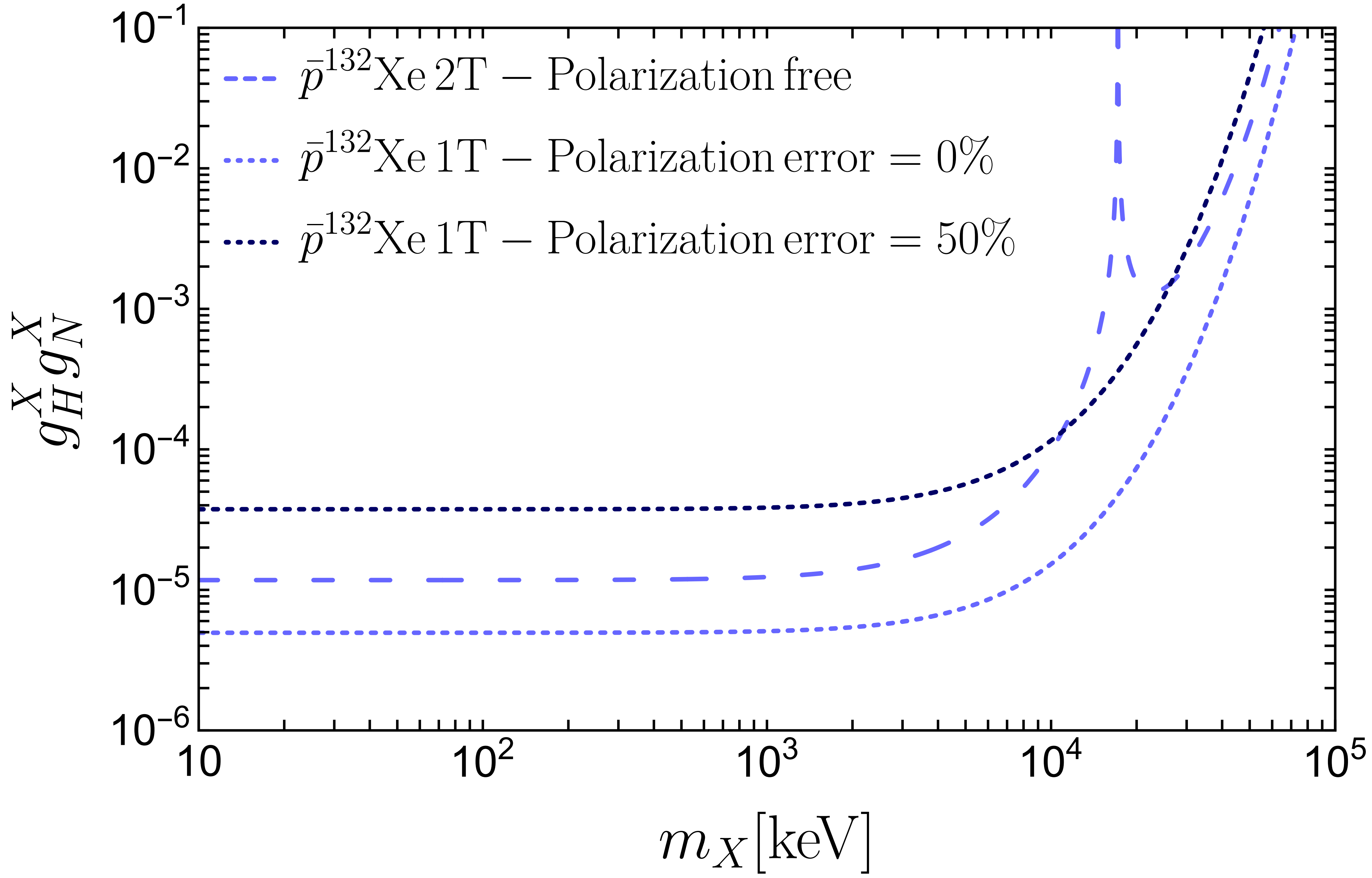

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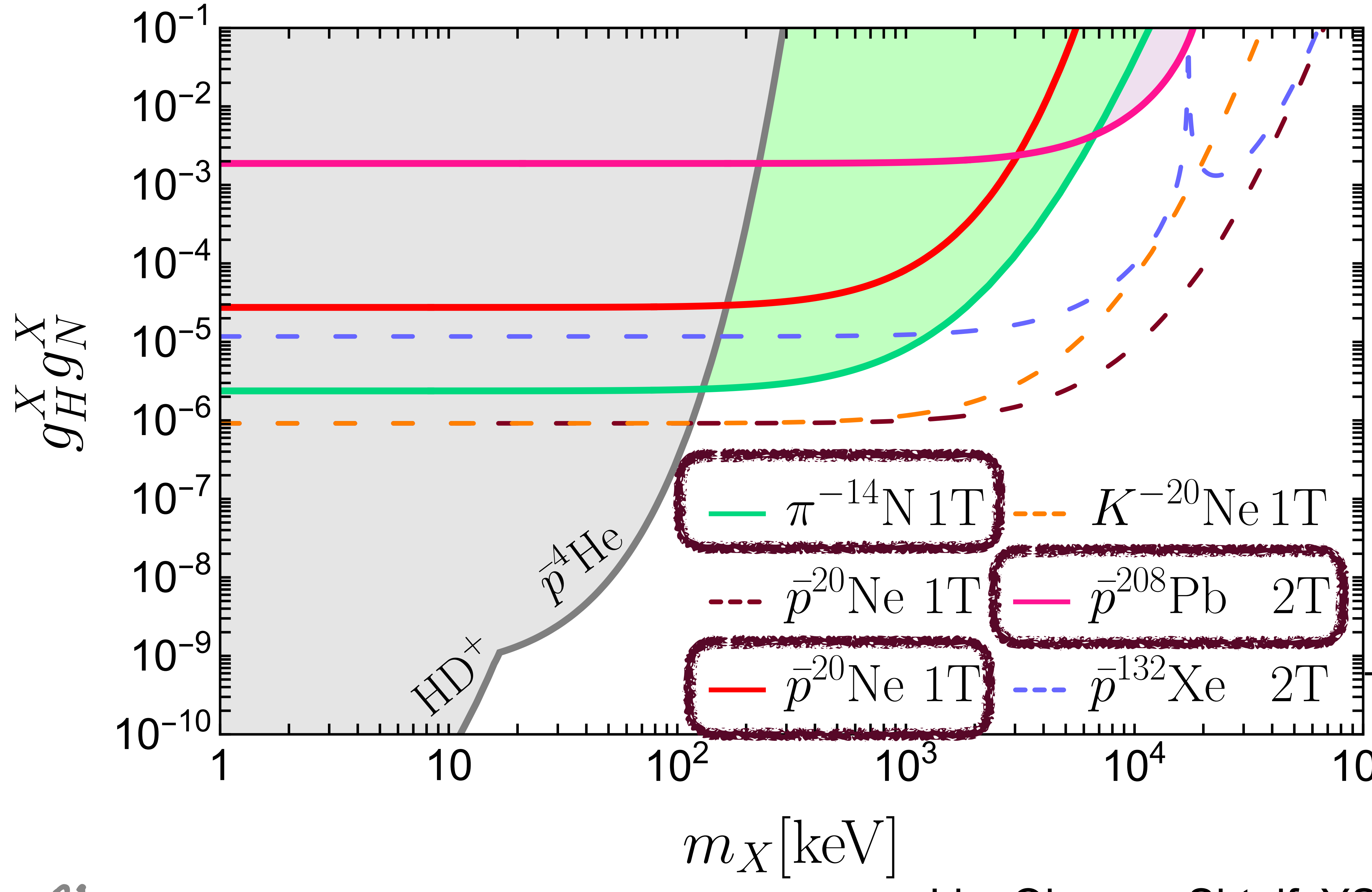

data

Hu et al NPA, 75
Borie, PRA 83
Trassinelli PLB 16

Liu, Ohayon, Shtaif, YS, 2502.03537

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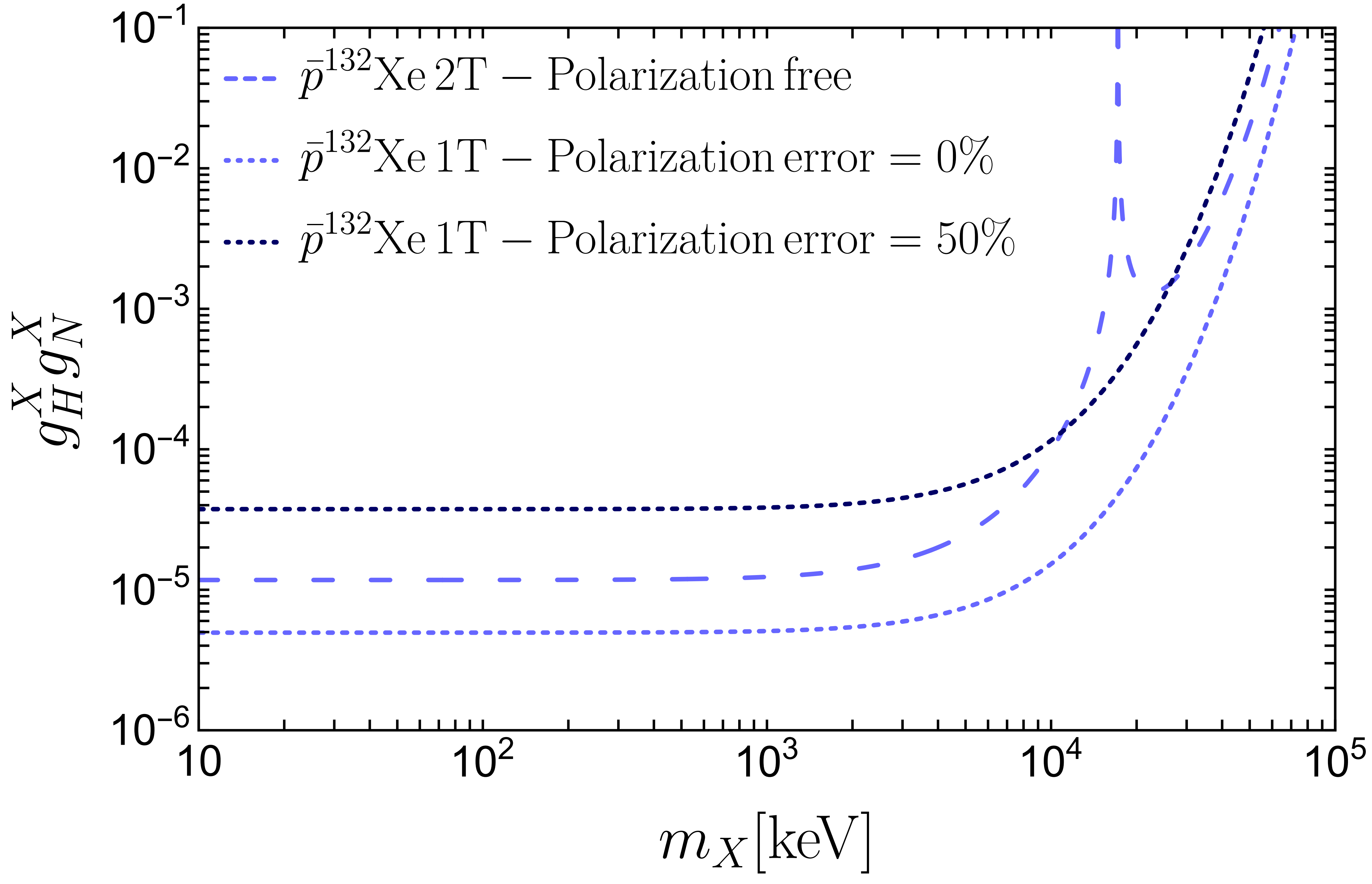

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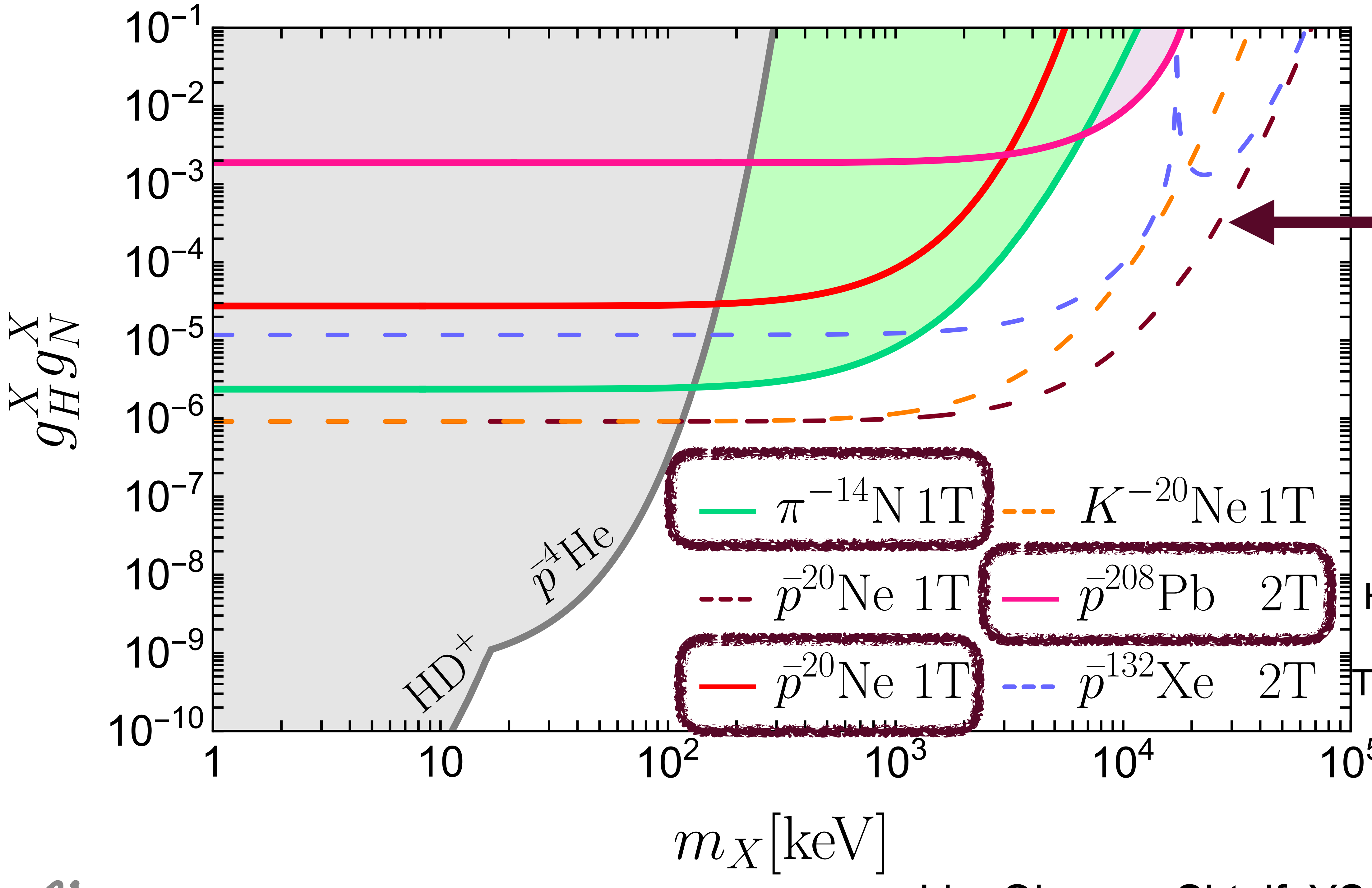
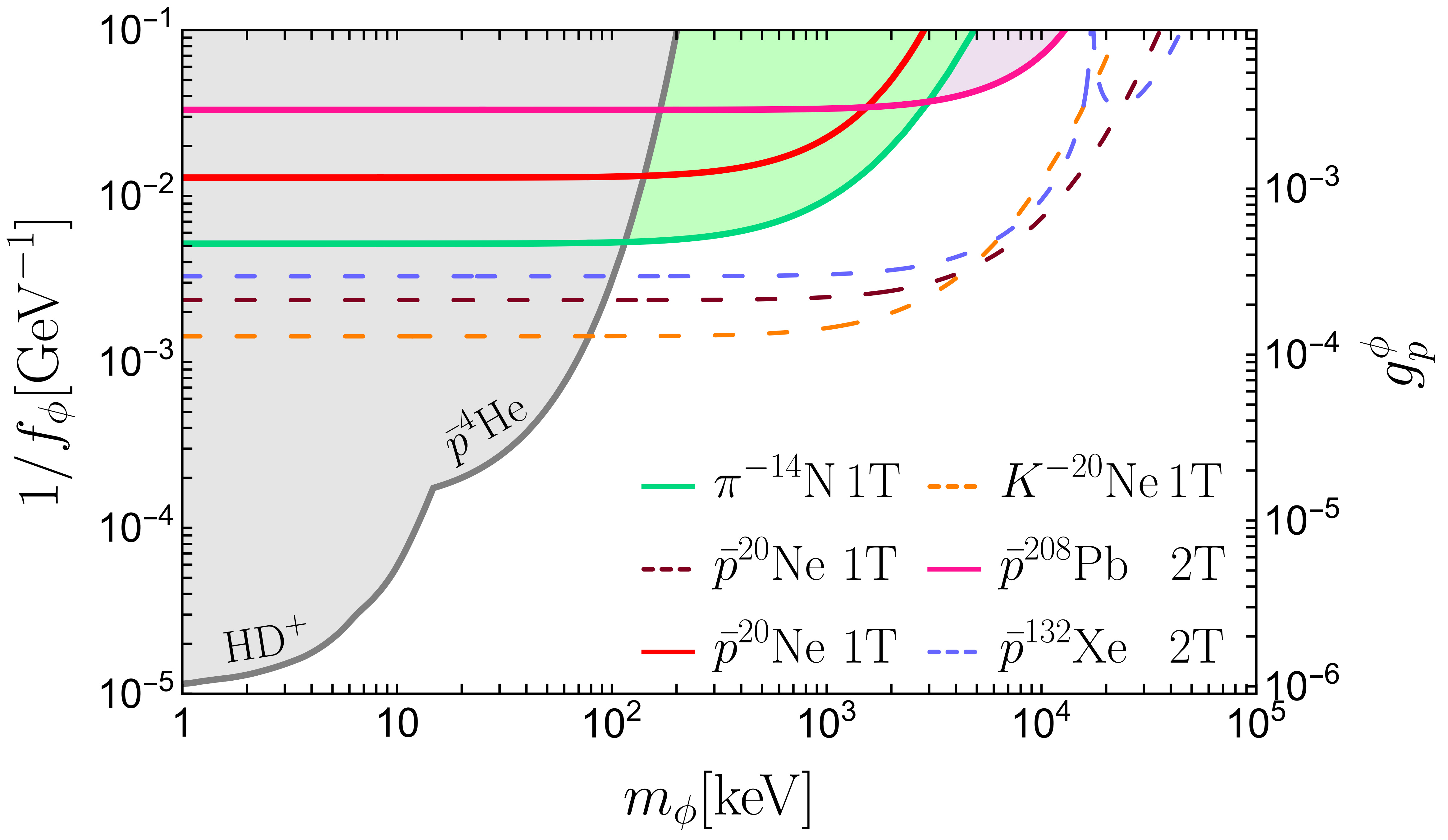


Liu, Ohayon, Shtaif, YS, 2502.03537

Exotic atoms for BSM

$$\frac{\phi}{f_\phi}\sum_{q=u,d,s} m_q \bar{q} q$$

uds-model



no kaon bounds, but spectroscopy signature

Liu, Ohayon, Shtaif, YS, 2502.03537

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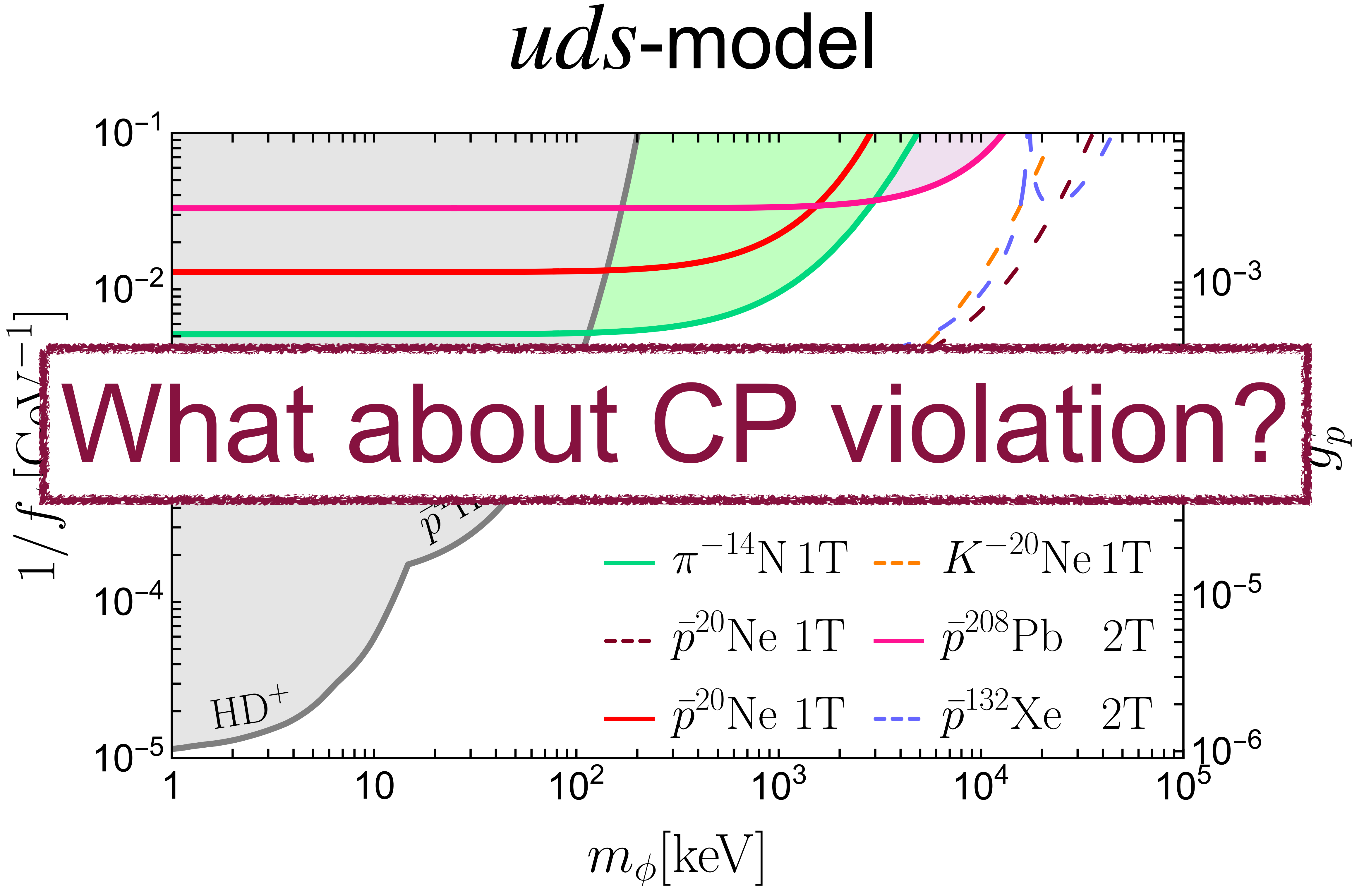

What about CP violation?

no kaon bounds, but spectroscopy signature

Liu, Ohayon, Shtaif, YS, 2502.03537

CP violation

$$\phi(g_S^\psi \bar{\psi}\psi + i g_P^\psi \bar{\psi}\gamma_5\psi)$$

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electric dipole moment (EDM) $\Rightarrow$ CP violation in low energy systems

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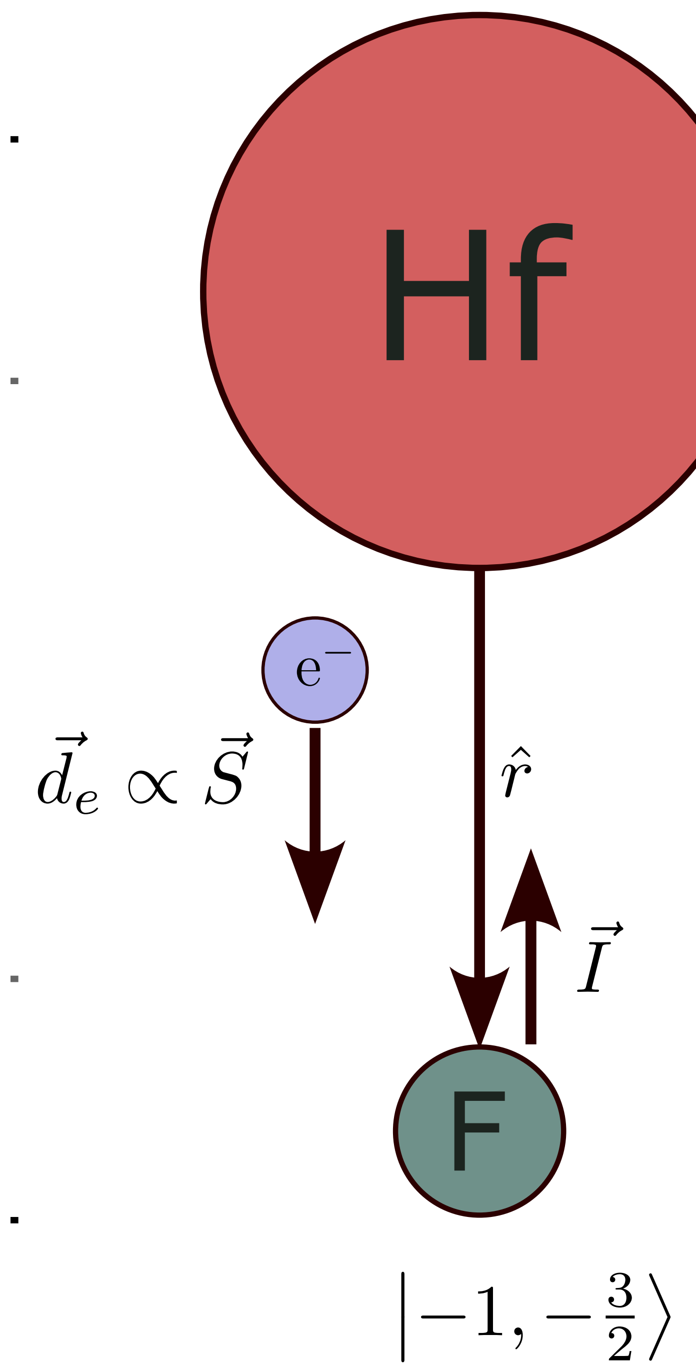
What we can learn from the electron EDM about CPV long range hadronic interactions?

CP violation in diatomic molecules

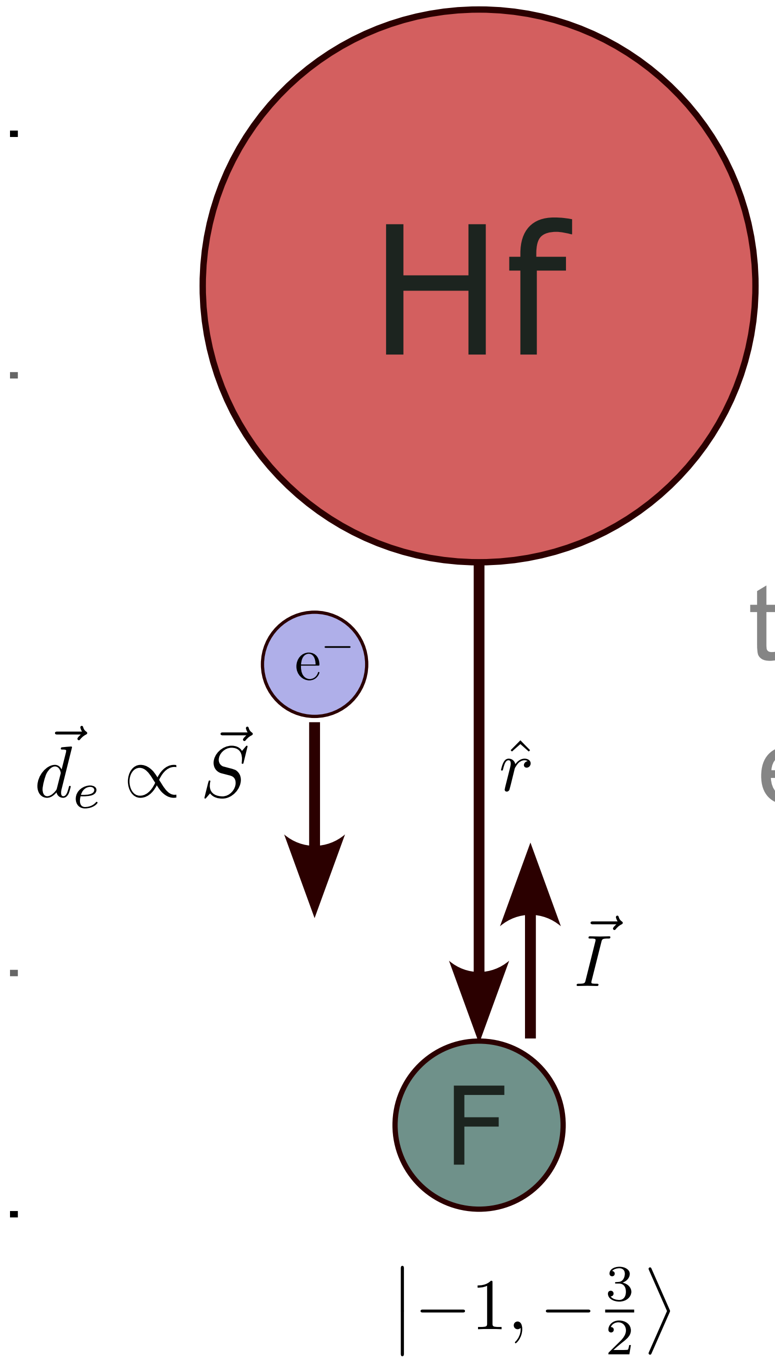


typical use for the electron electric dipole moment, d_e

Baruch, Changala, Shagam, YS, PRL 24

CP violation in diatomic molecules

$$E_{\Omega,m_F} = E_0 + E_S + E_Z + E_{CPV}$$



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$|\Omega, m_F\rangle$ - the quantum states
Ω - projection of electronic angular momentum on $\hat{r}$
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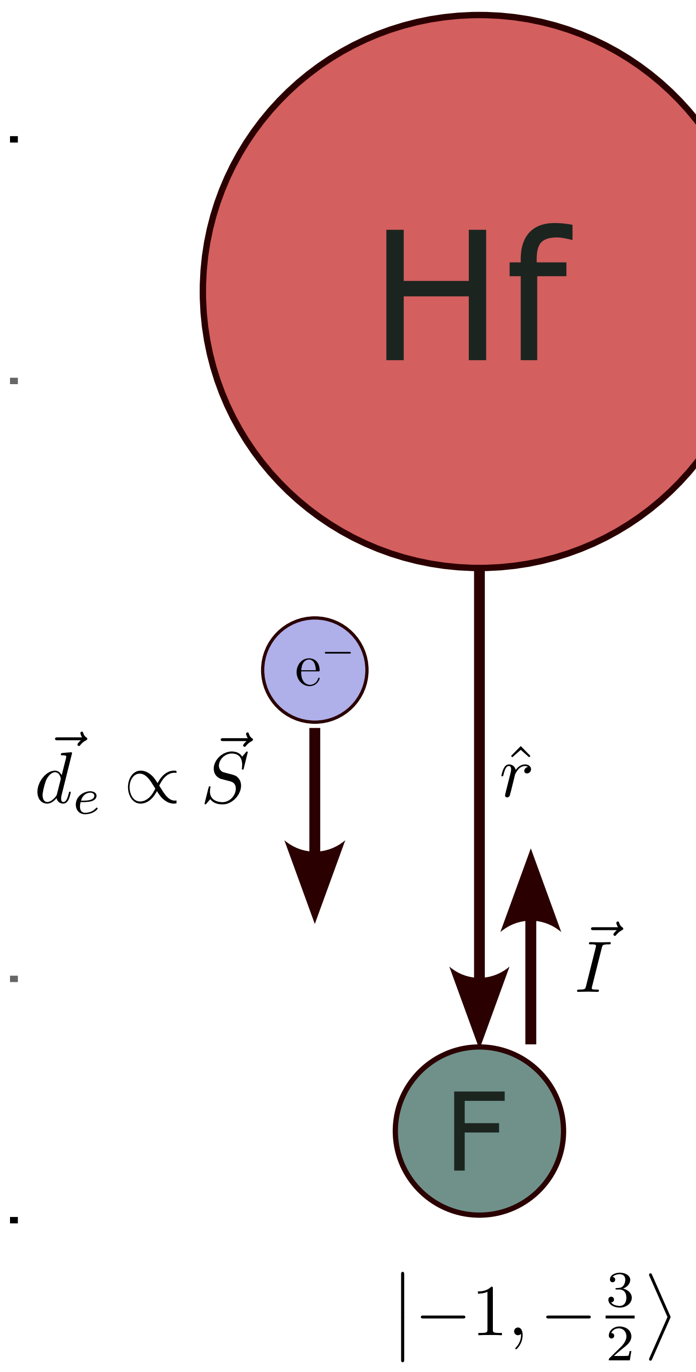

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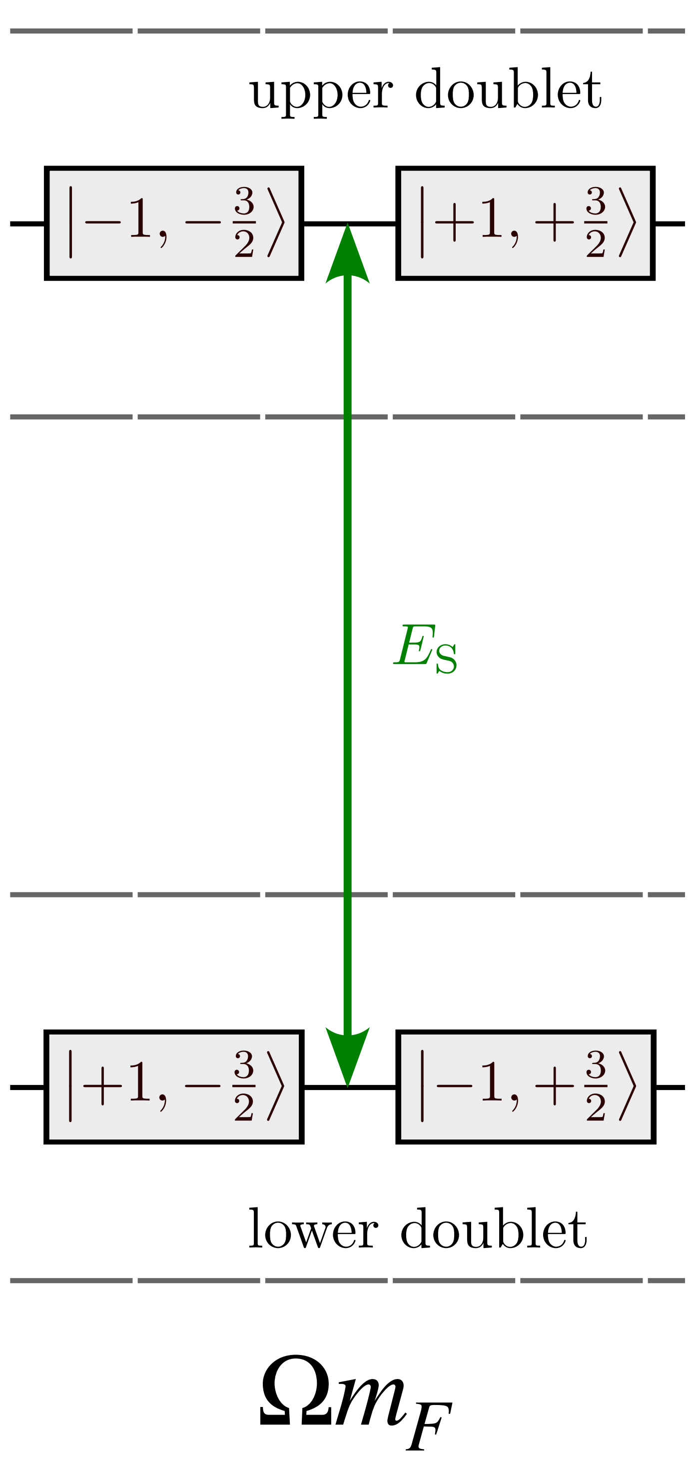

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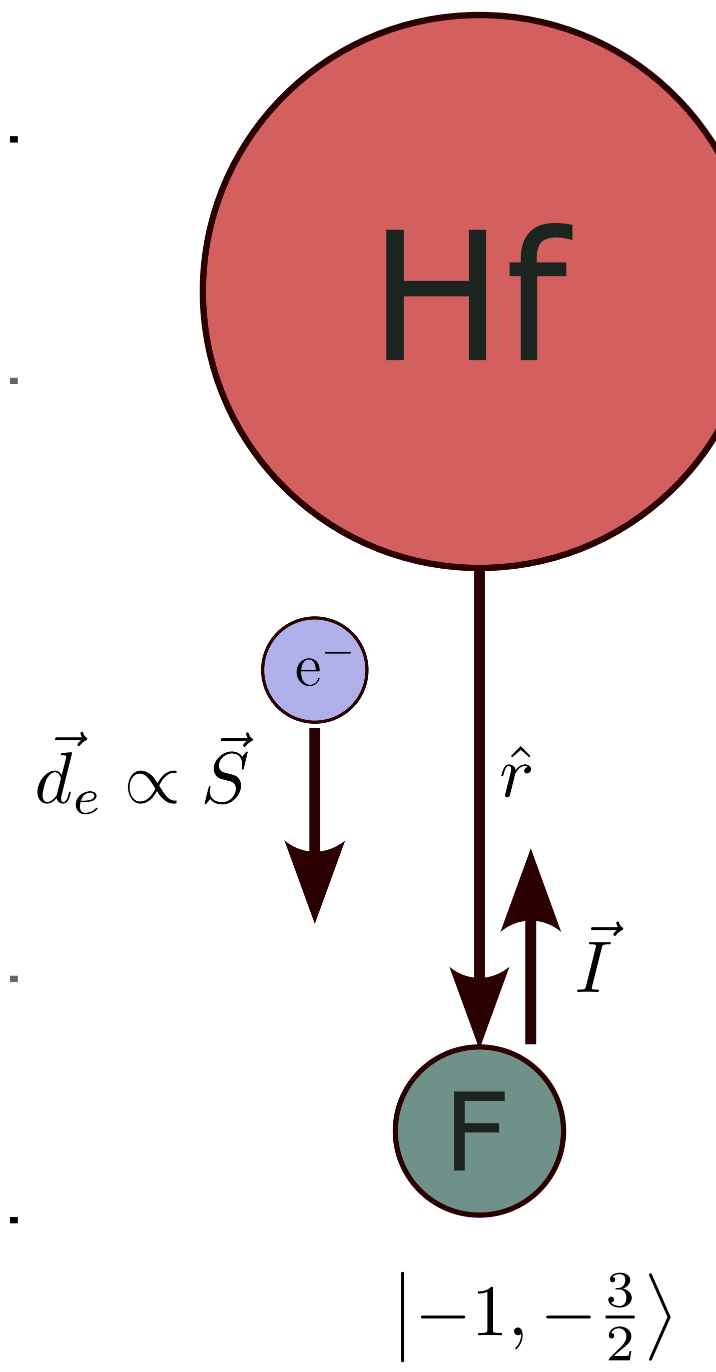

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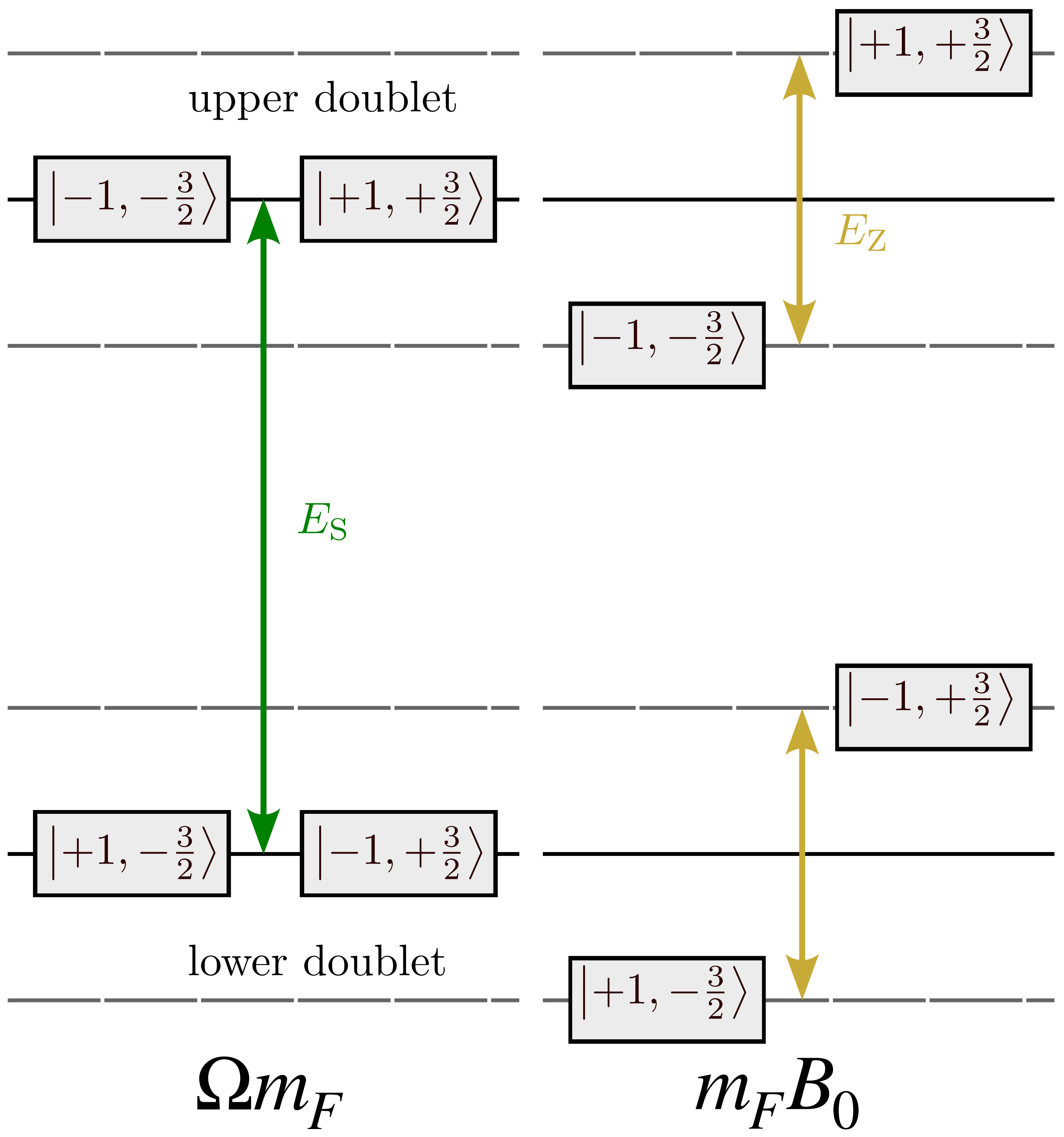

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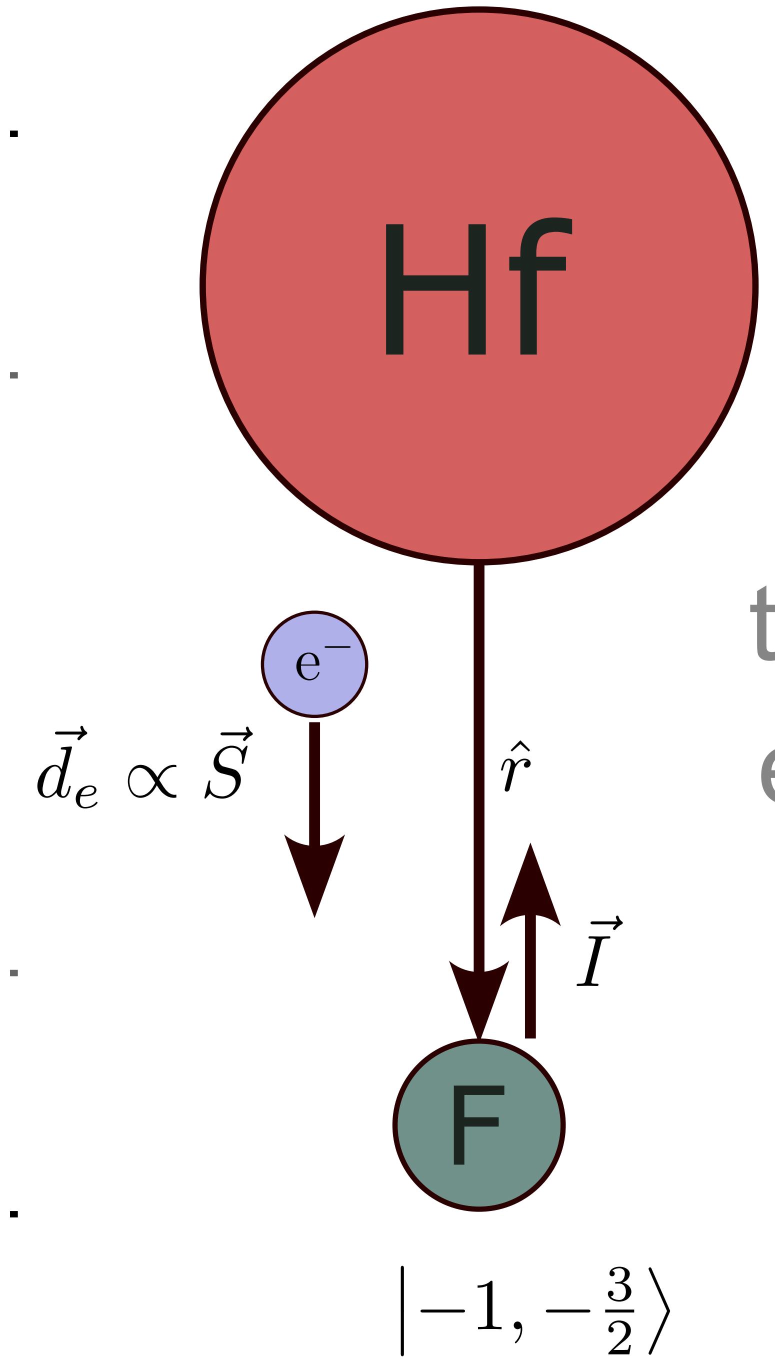

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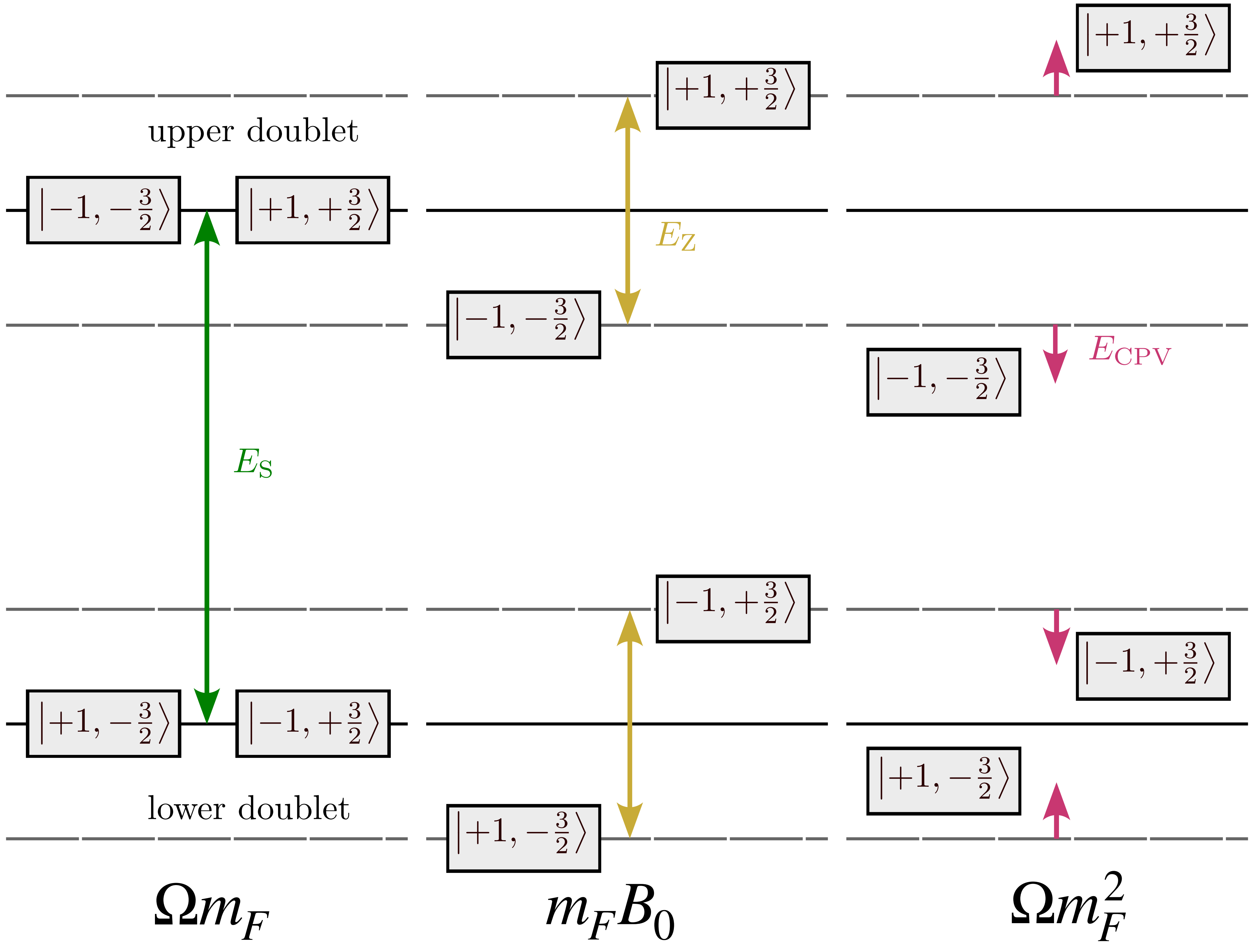

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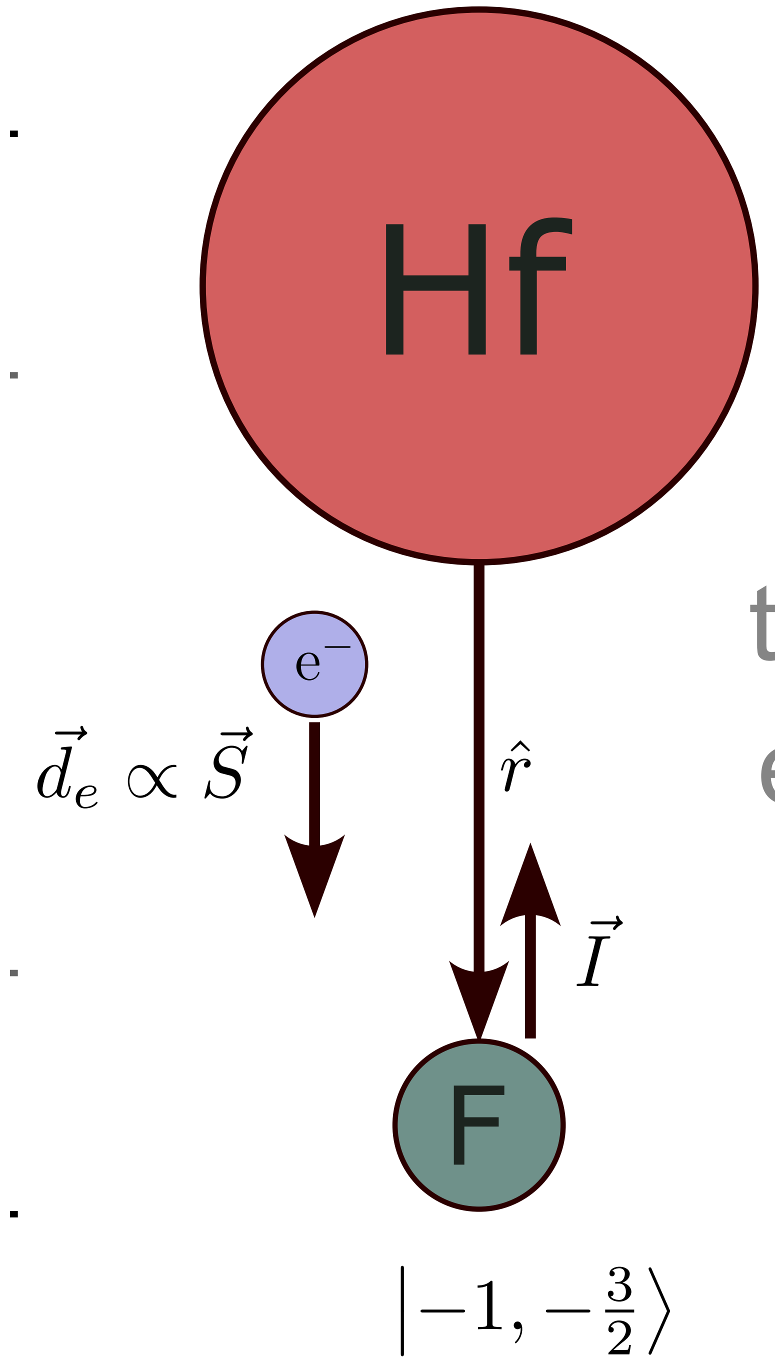

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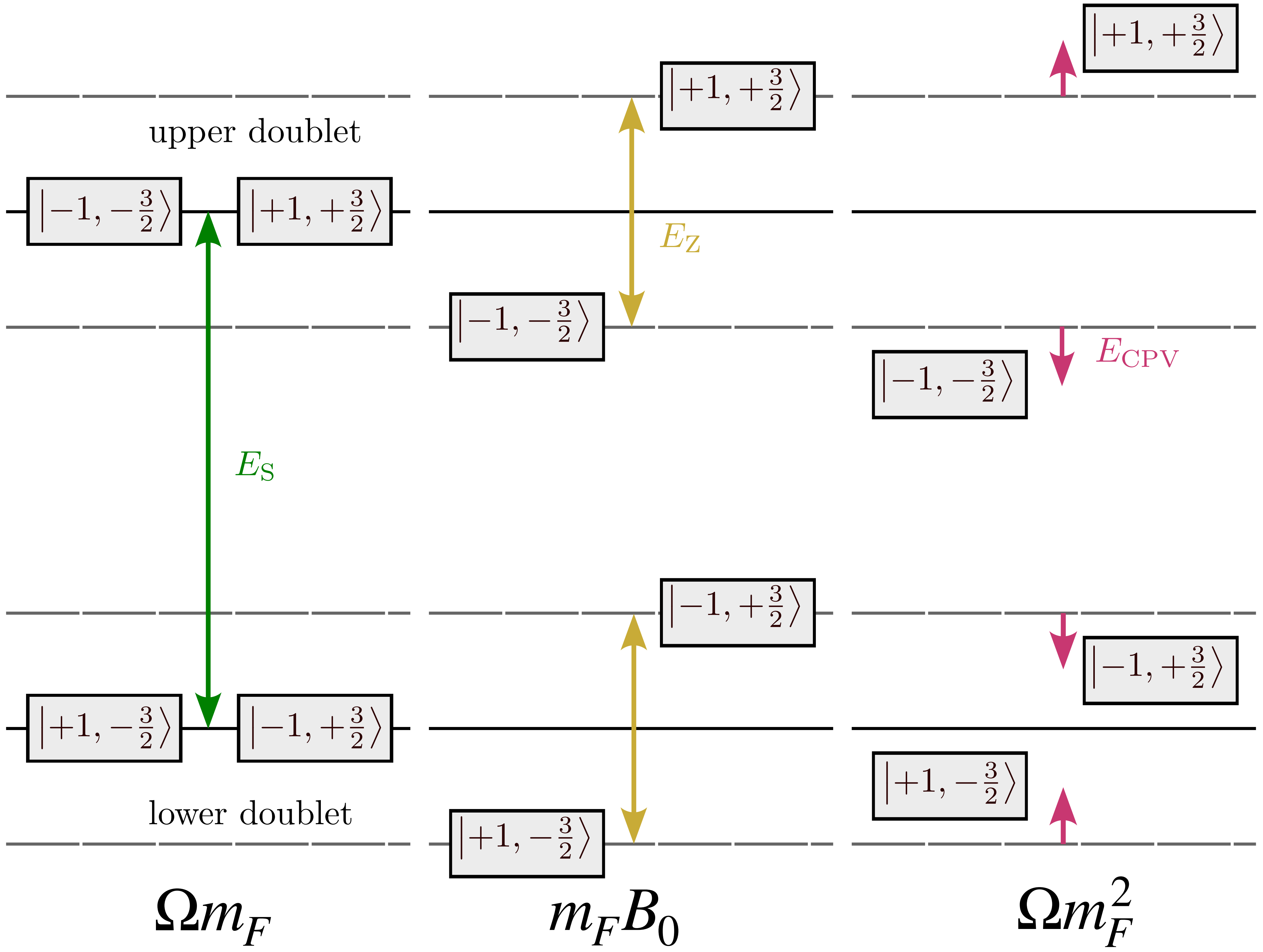

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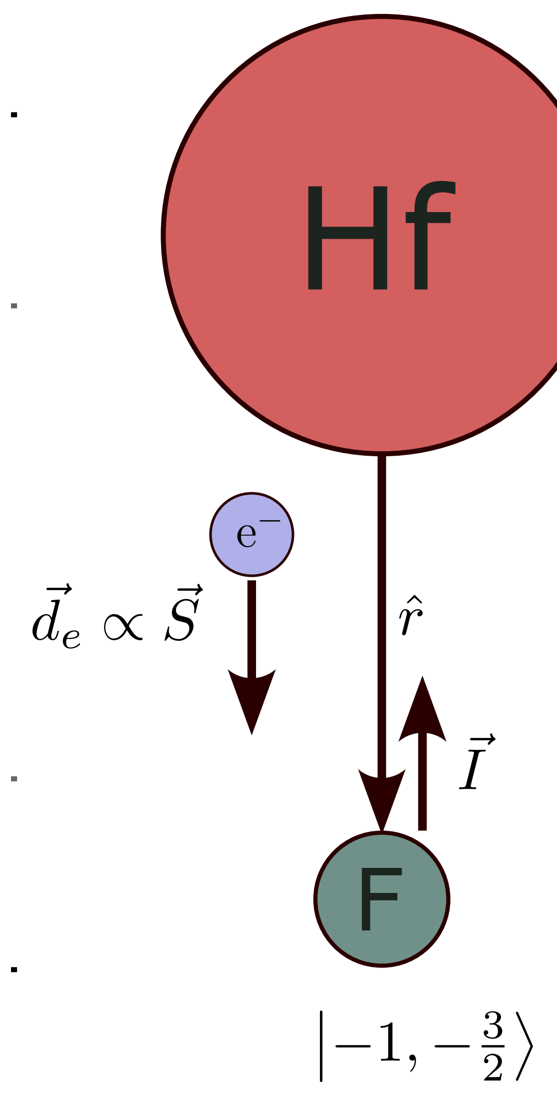
$$E_{CPV} = \frac{\left(E_{+1,+\frac{2}{3}} - E_{-1,-\frac{2}{3}}\right) - \left(E_{-1,+\frac{2}{3}} - E_{+1,-\frac{2}{3}}\right)}{4} = \mathscr{E}_{\text{eff}} d_e + V_{SP} + \ldots$$

Baruch, Changala, Shagam, YS, PRL 24

CP violation in diatomic molecules



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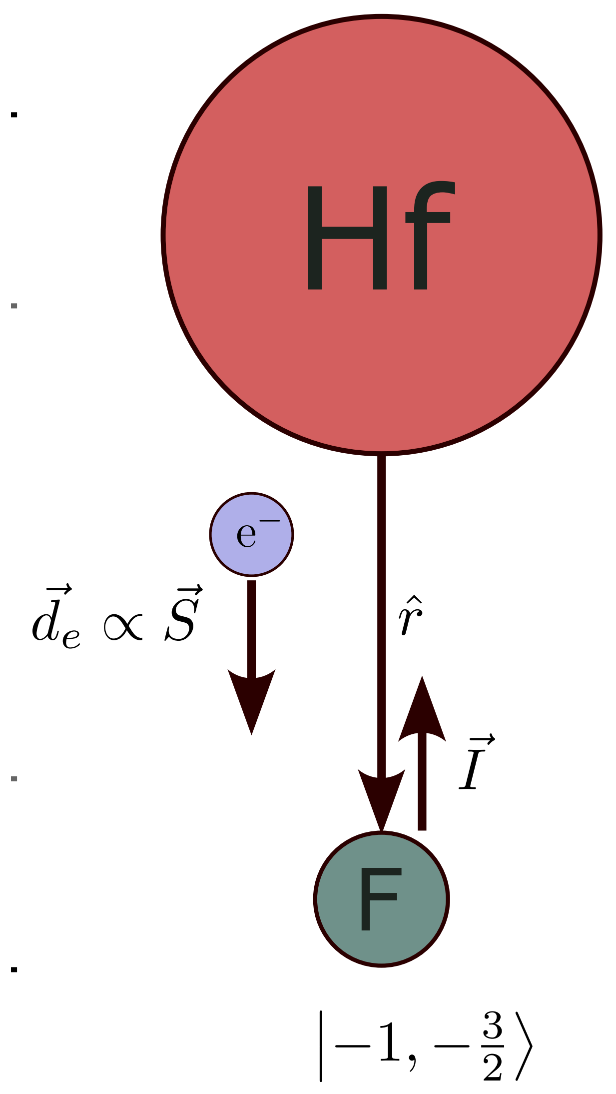

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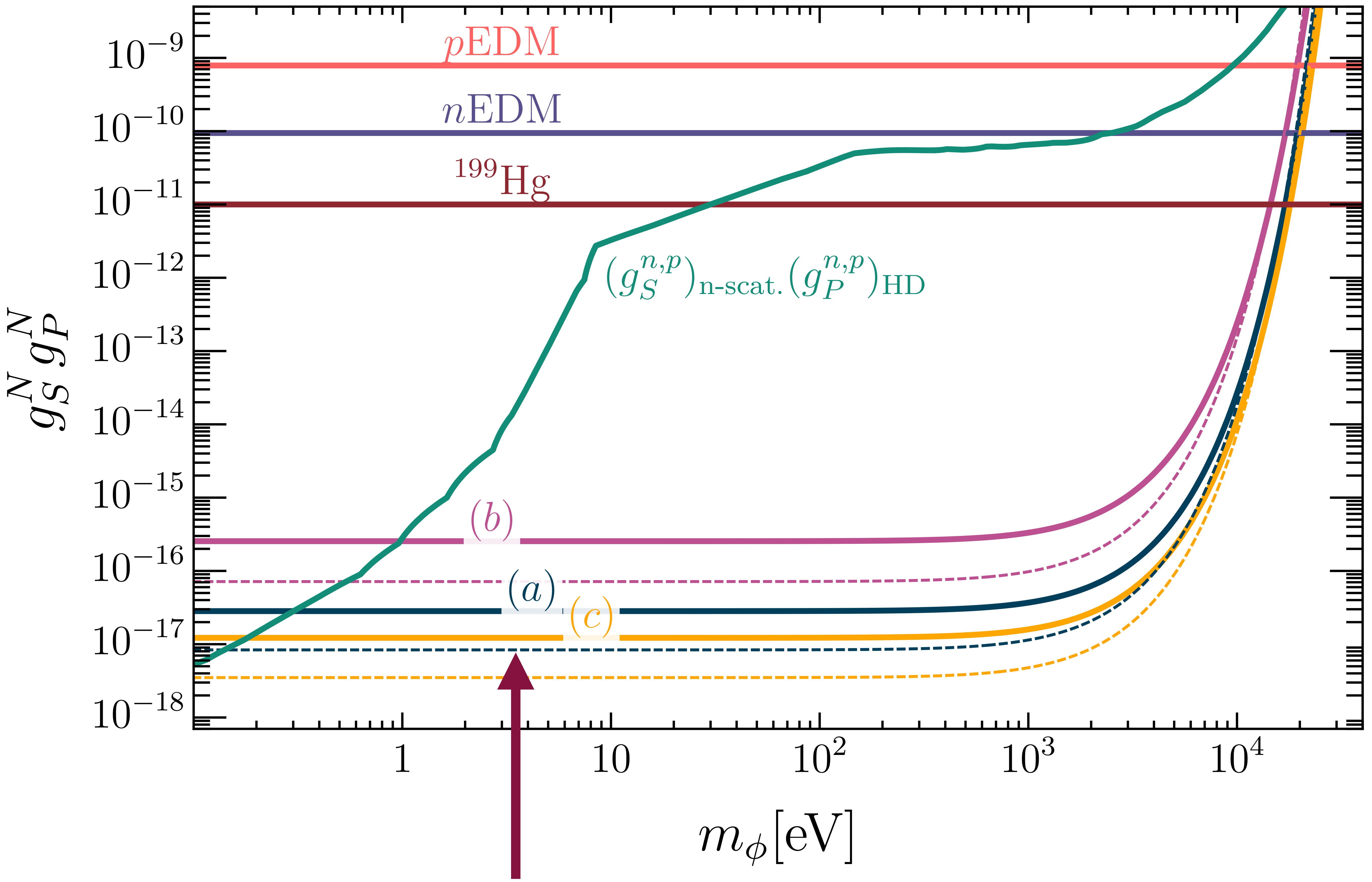

Molecules are the best terrestrial probe of long range hadronic CPV force

Baruch, Changala, Shagam, YS, PRL 24

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$$\vec{x} \overset{P}{\longleftrightarrow} -\vec{x}$$

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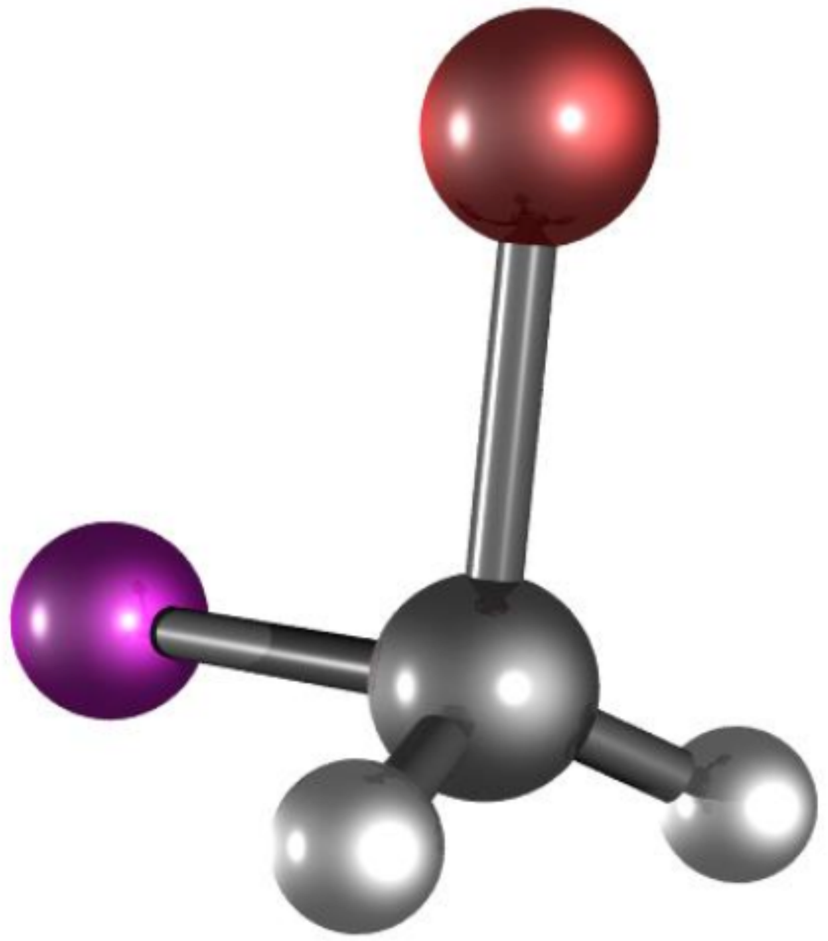
P violation $\Rightarrow$ left $\neq$ right

the SM weak interaction breaks P (by construction)

PV new force: $X^{\mu}(g_V^X \bar{\psi}\gamma_\mu \psi + g_A^X \bar{\psi}\gamma_\mu\gamma_5\psi)$

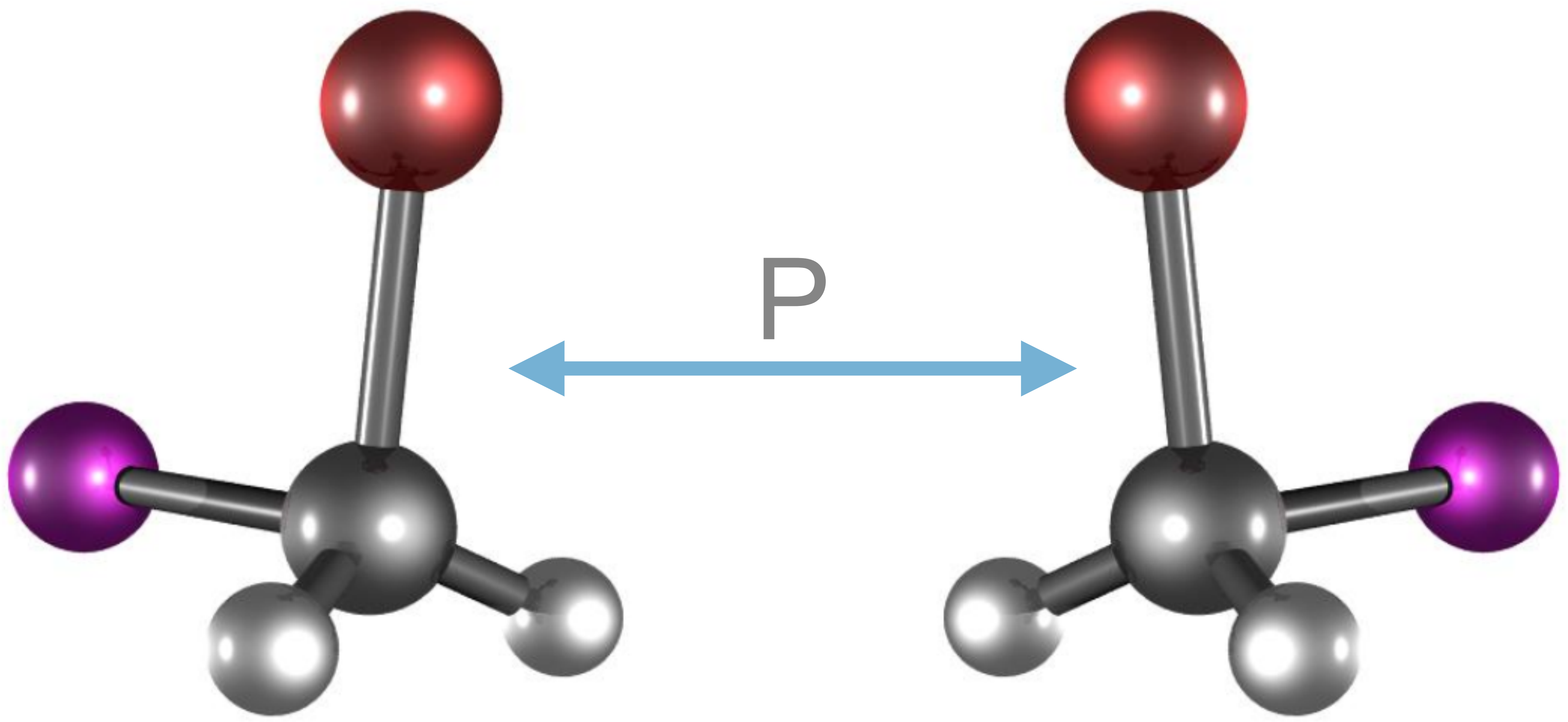
$$V_{\text{SP}} \propto g_V g_A \frac{(\vec{\sigma}_{\psi_1} \times \vec{\sigma}_{\psi_2}) \cdot \hat{r}}{2m_N} \left(\frac{1}{r} + m_\phi\right) \frac{e^{-m_\phi r}}{r}$$

P violation in chiral molecules



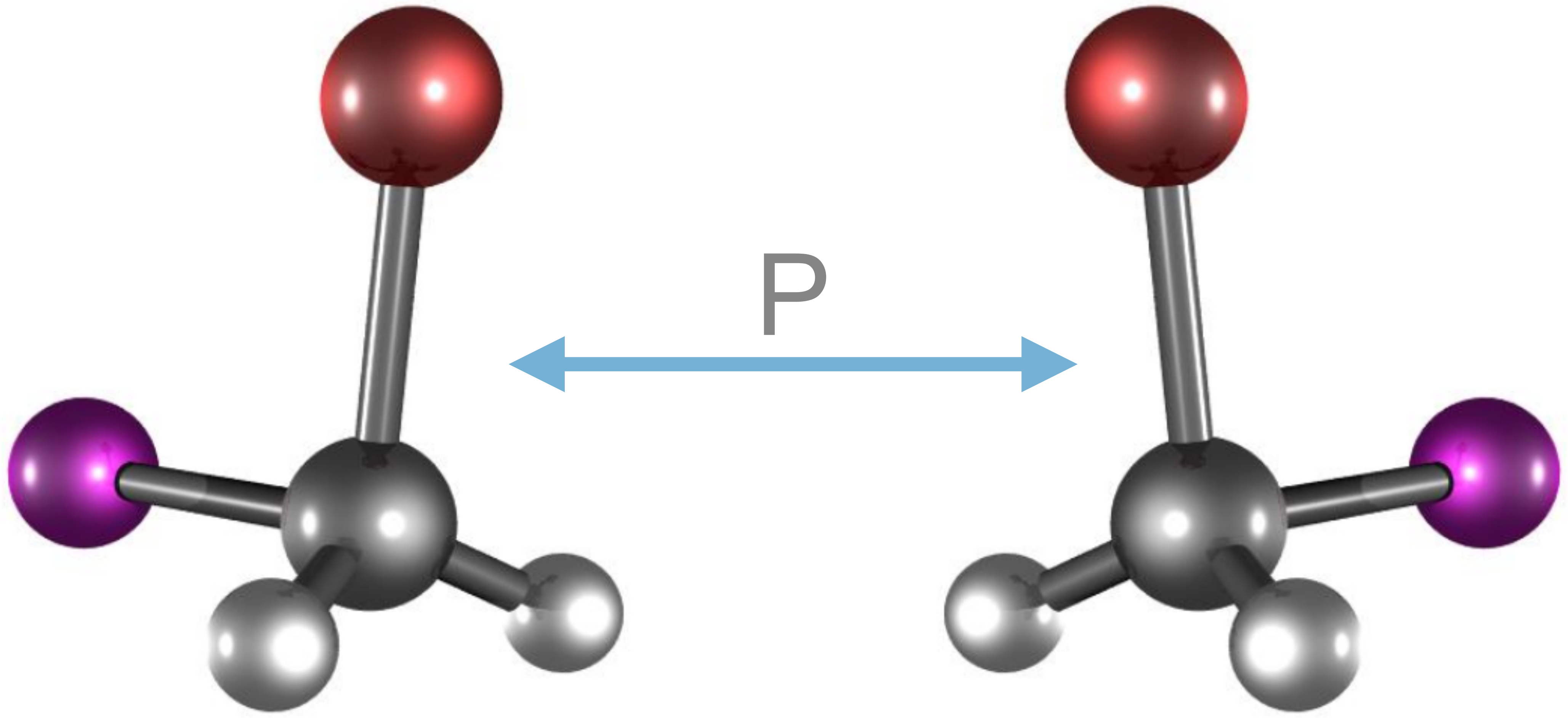
Baruch, Changala, Shagam, YS, PRR 24

P violation in chiral molecules



Baruch, Changala, Shagam, YS, PRR 24

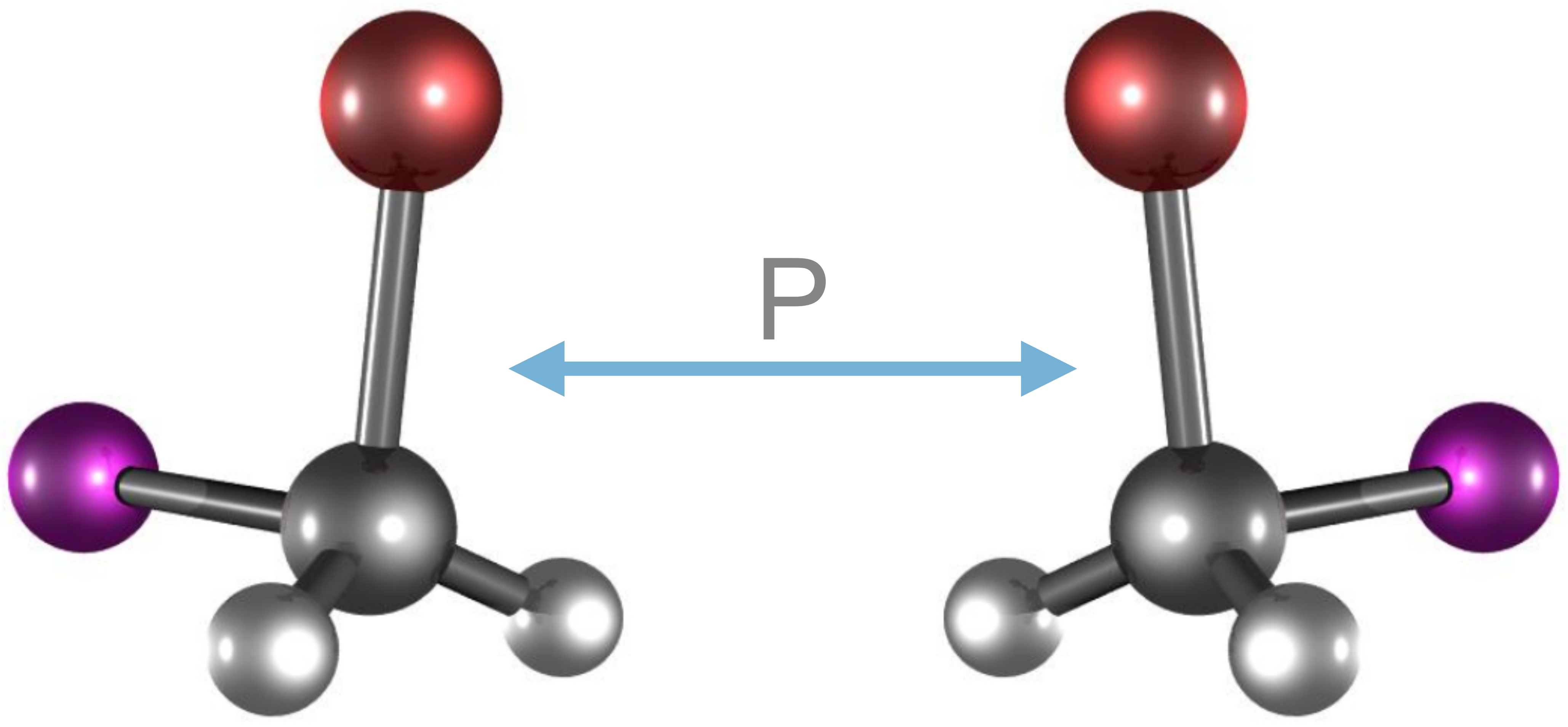
P violation in chiral molecules



$E_L \neq E_R \Rightarrow$ parity violation

Baruch, Changala, Shagam, YS, PRR 24

P violation in chiral molecules



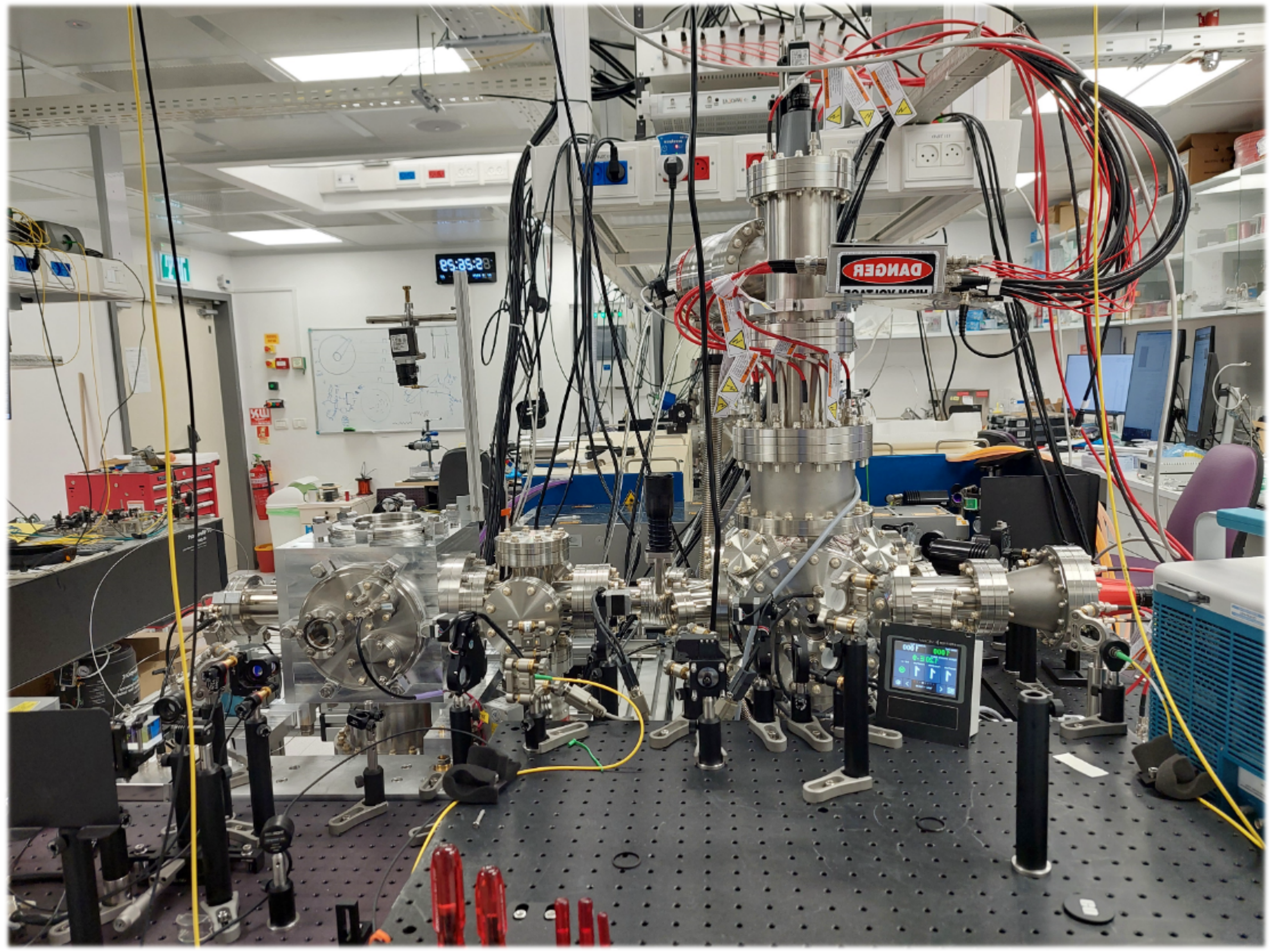
$E_L \neq E_R \Rightarrow$ parity violation

within the SM tiny effect (weak interaction)

Baruch, Changala, Shagam, YS, PRR 24

P violation in chiral molecules

comparing the hyperfine structure of L and R



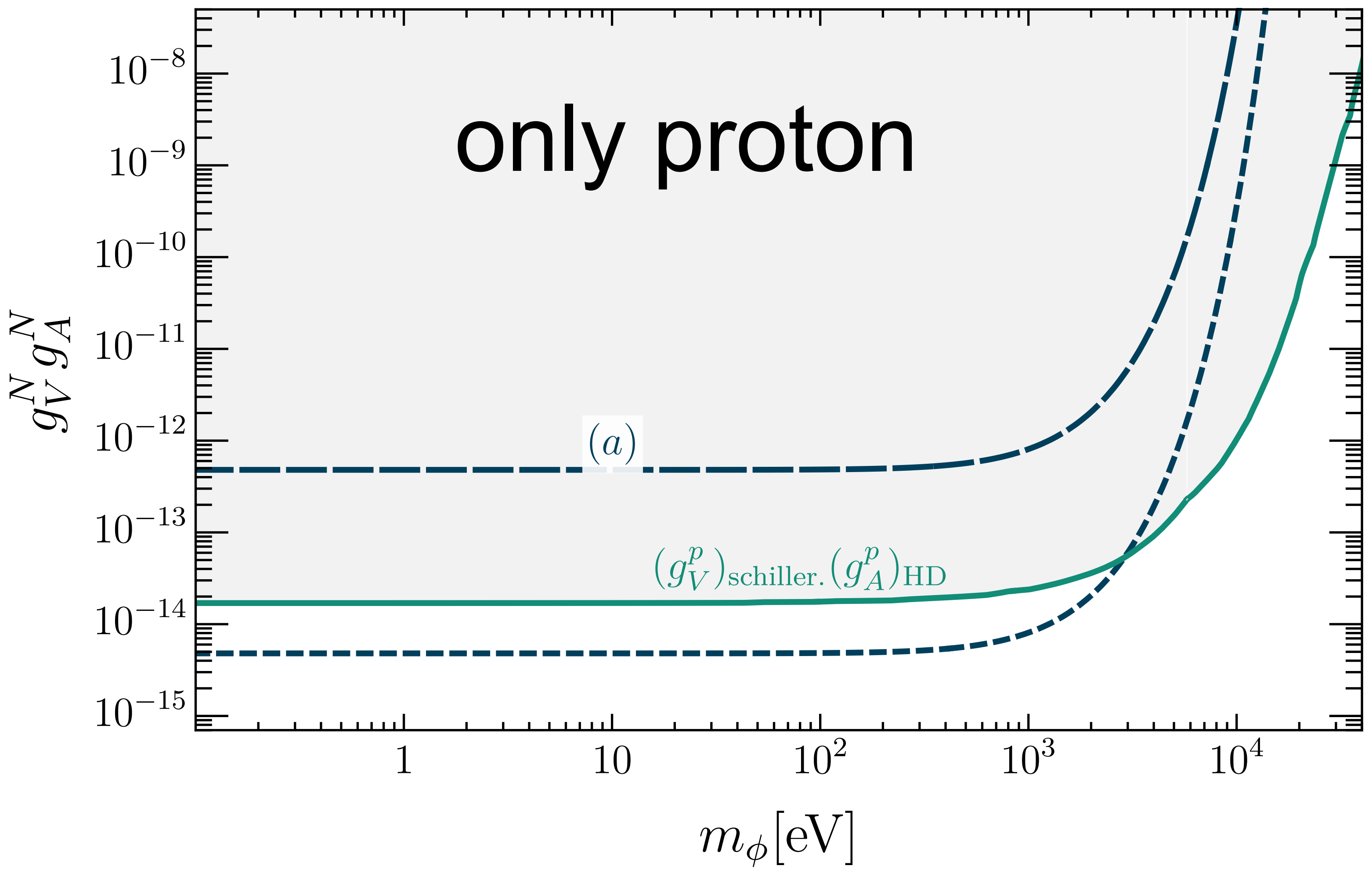
CHDBrI⁺ (Shagam lab)

			state 1		state 2	
	(i,j)	$E_{1\to 2}$ [GHz]	$\langle N, K_a, K_c, J, F_1, F_2, F_3, F \vert$	$\langle \sigma_i \times \sigma_j \rangle \cdot \hat{r}_{\mathrm{eq}}^{ij}$	$\vert N, K_a, K_c, J, F_1, F_2, F_3, F \rangle$	$\langle \sigma_i \times \sigma_j \rangle \cdot \hat{r}_{\mathrm{eq}}^{ij}$
(a),(b),(c)	(D, I)	3.34	$\langle 1, 1, 0, \frac{3}{2}, 1, 1, \frac{5}{2}, 0 \vert$	0.49	$\vert 1, 0, 1, \frac{1}{2}, 1, 2, \frac{7}{2}, 1 \rangle$	0.12
(d)	(H, I)	3.99	$\langle 2, 2, 0, \frac{5}{2}, 3, 3, \frac{5}{2}, 0 \vert$	0.23	$\vert 1, 0, 1, \frac{3}{2}, 1, 2, \frac{3}{2}, 1 \rangle$	0

Baruch, Changala, Shagam, YS, PRR 24

P violation in chiral molecules

comparing the hyperfine structure of L and R



CHDBrI⁺ (Shagam lab)

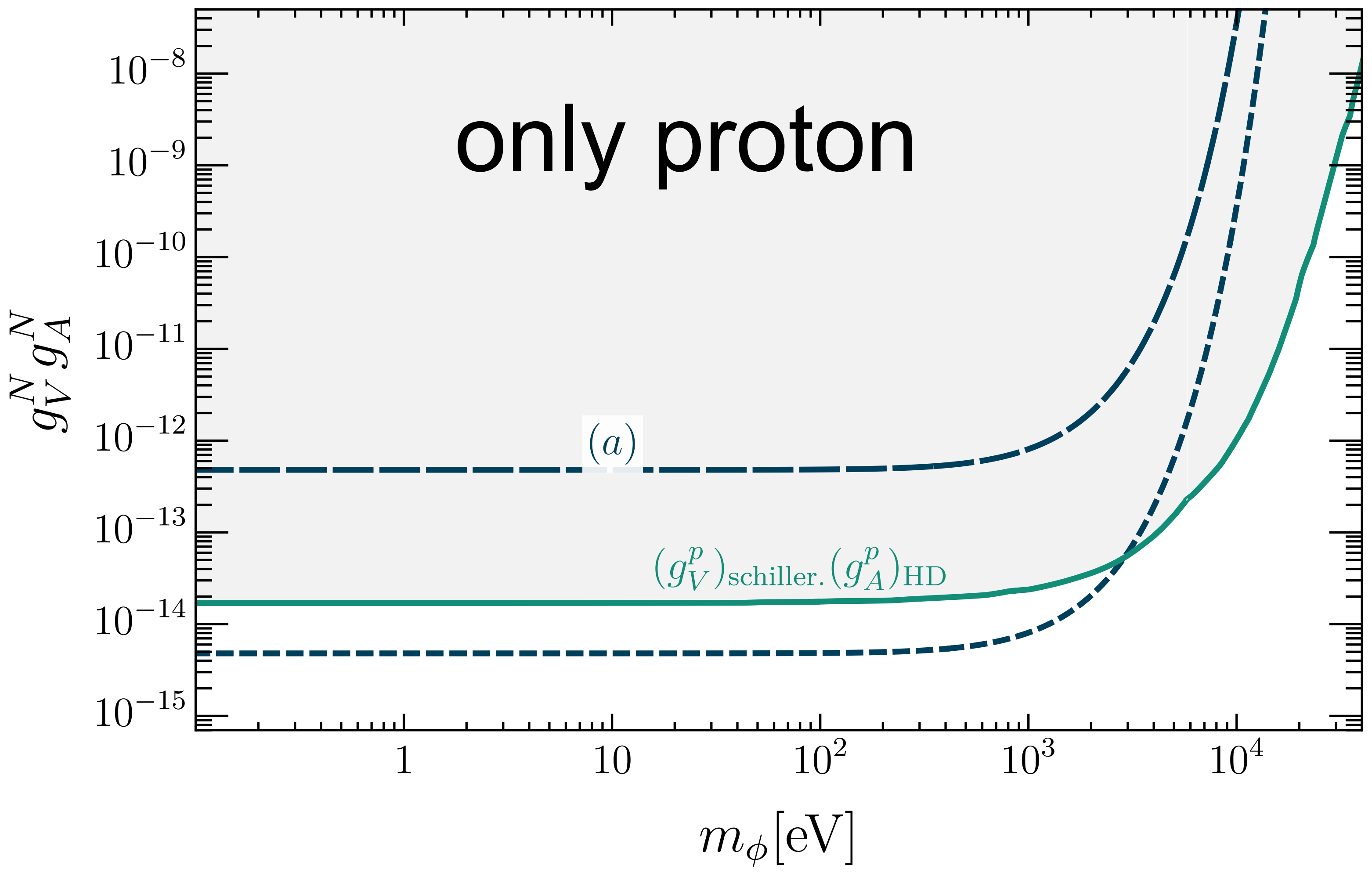
	(i,j)	$E_{1\to2}$ [GHz]	state 1 $\langle N,K_a,K_c,J,F_1,F_2,F_3,F\vert$	$\langle\sigma_i\times\sigma_j\rangle\cdot\hat{r}^{ij}_{\text{eq}}$	state 2 $\vert N,K_a,K_c,J,F_1,F_2,F_3,F\rangle$	$\langle\sigma_i\times\sigma_j\rangle\cdot\hat{r}^{ij}_{\text{eq}}$
(a),(b),(c)	(D, I)	3.34	$\langle 1,1,0,\frac{3}{2},1,1,\frac{5}{2},0\vert$	0.49	$\vert 1,0,1,\frac{1}{2},1,2,\frac{7}{2},1\rangle$	0.12
(d)	(H, I)	3.99	$\langle 2,2,0,\frac{5}{2},3,3,\frac{5}{2},0\vert$	0.23	$\vert 1,0,1,\frac{3}{2},1,2,\frac{3}{2},1\rangle$	0

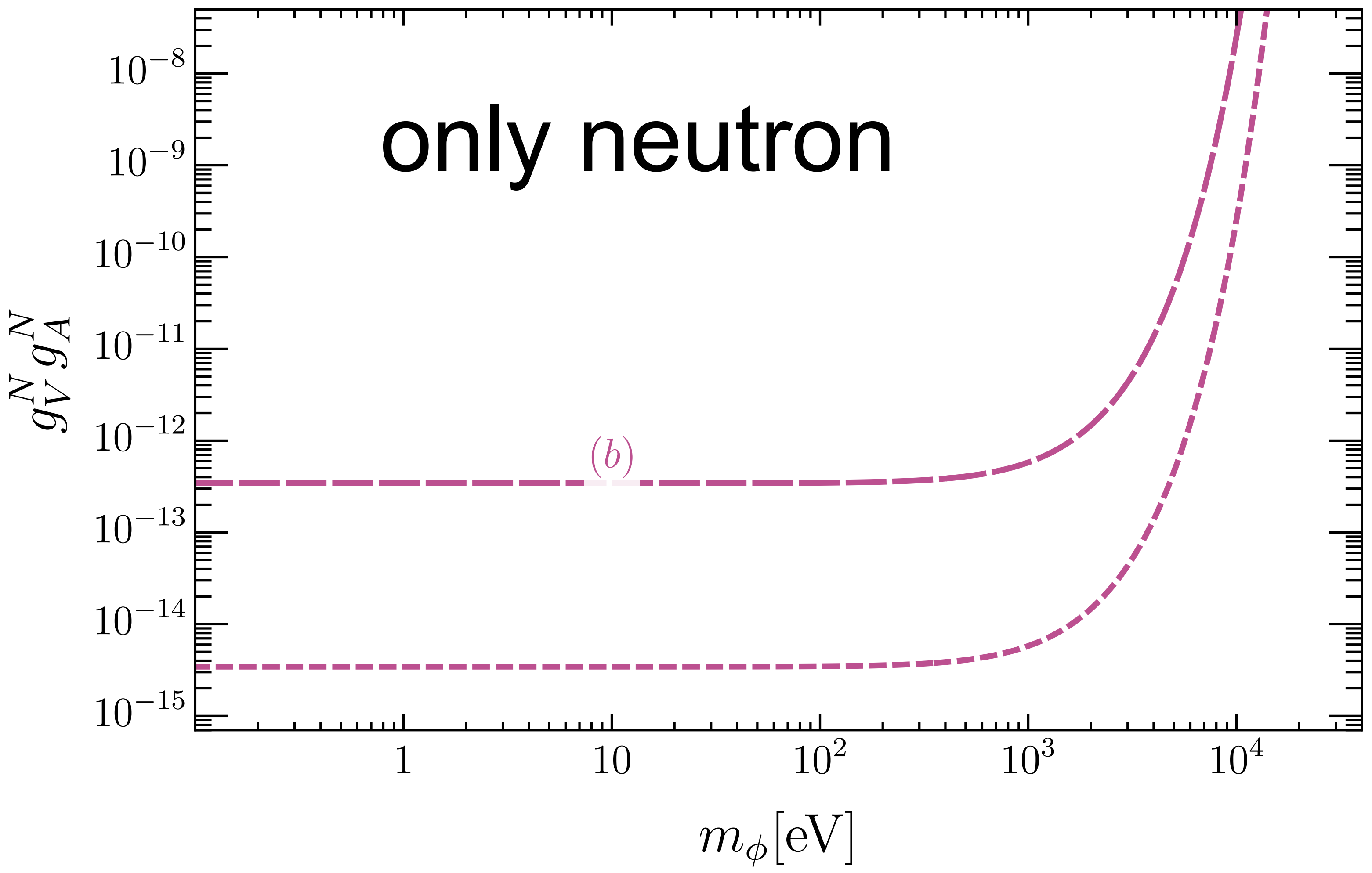
dashed - 0.1 Hz , dotted 1mHz

Baruch, Changala, Shagam, YS, PRR 24

P violation in chiral molecules

comparing the hyperfine structure of L and R





$CHDBrI^+$ (Shagam lab)

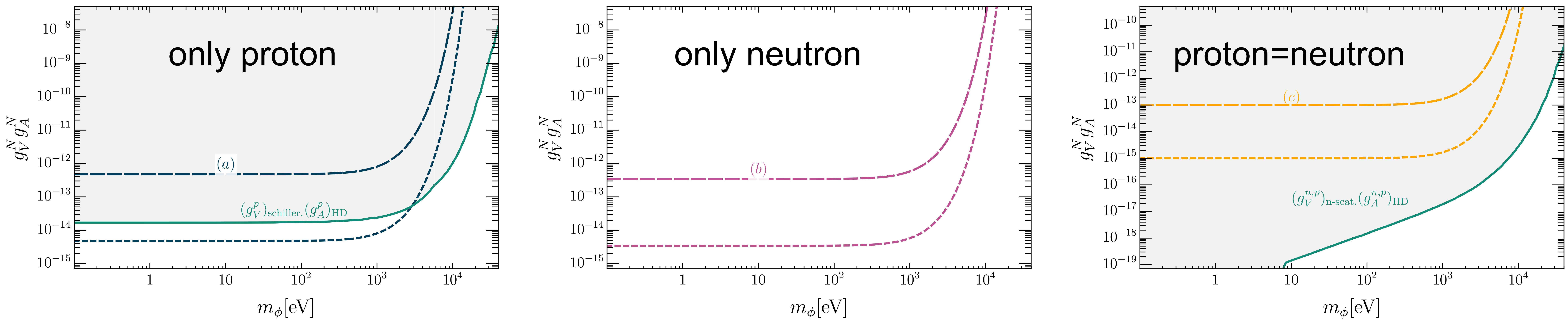
	(i,j)	$E_{1\to 2}$ [GHz]	state 1 $\langle N, K_a, K_c, J, F_1, F_2, F_3, F\|$	$\langle \sigma_i \times \sigma_j \rangle \cdot \hat{r}_{\rm eq}^{ij}$	state 2 $\|N, K_a, K_c, J, F_1, F_2, F_3, F\rangle$	$\langle \sigma_i \times \sigma_j \rangle \cdot \hat{r}_{\rm eq}^{ij}$
(a),(b),(c)	(D, I)	3.34	$\langle 1, 1, 0, \frac{3}{2}, 1, 1, \frac{5}{2}, 0\|$	0.49	$\|1, 0, 1, \frac{1}{2}, 1, 2, \frac{7}{2}, 1\rangle$	0.12
(d)	(H, I)	3.99	$\langle 2, 2, 0, \frac{5}{2}, 3, 3, \frac{5}{2}, 0\|$	0.23	$\|1, 0, 1, \frac{3}{2}, 1, 2, \frac{3}{2}, 1\rangle$	0

dashed - 0.1 Hz , dotted 1mHz

Baruch, Changala, Shagam, YS, PRR 24

P violation in chiral molecules

comparing the hyperfine structure of L and R



CHDBrI⁺ (Shagam lab)

	(i,j)	$E_{1\to 2}$ [GHz]	state 1 $\langle N, K_a, K_c, J, F_1, F_2, F_3, F\vert$	state 1 $\langle \sigma_i \times \sigma_j \rangle \cdot \hat{r}^{ij}_{\rm eq}$	state 2 $\vert N, K_a, K_c, J, F_1, F_2, F_3, F\rangle$	state 2 $\langle \sigma_i \times \sigma_j \rangle \cdot \hat{r}^{ij}_{\rm eq}$
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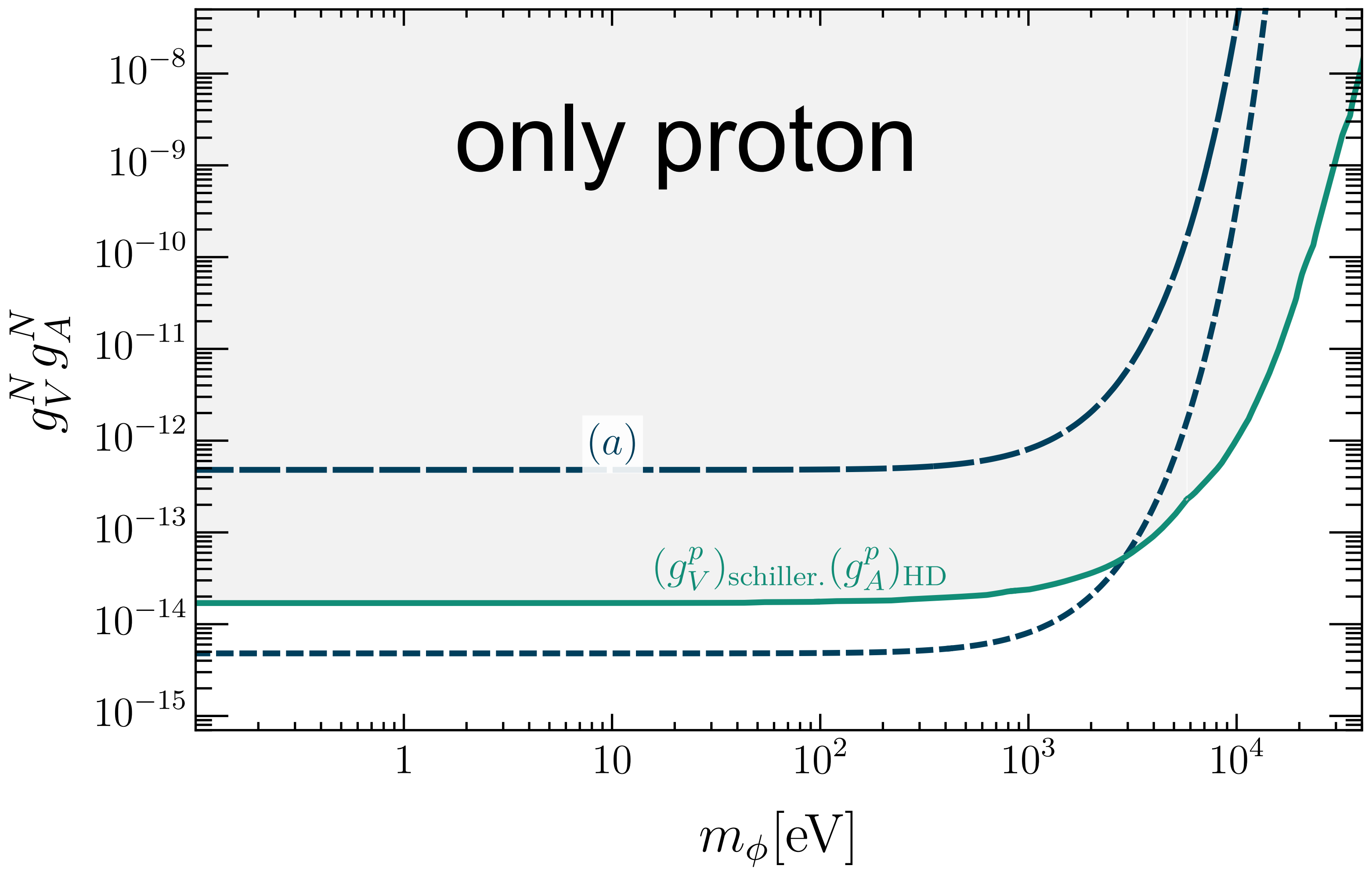
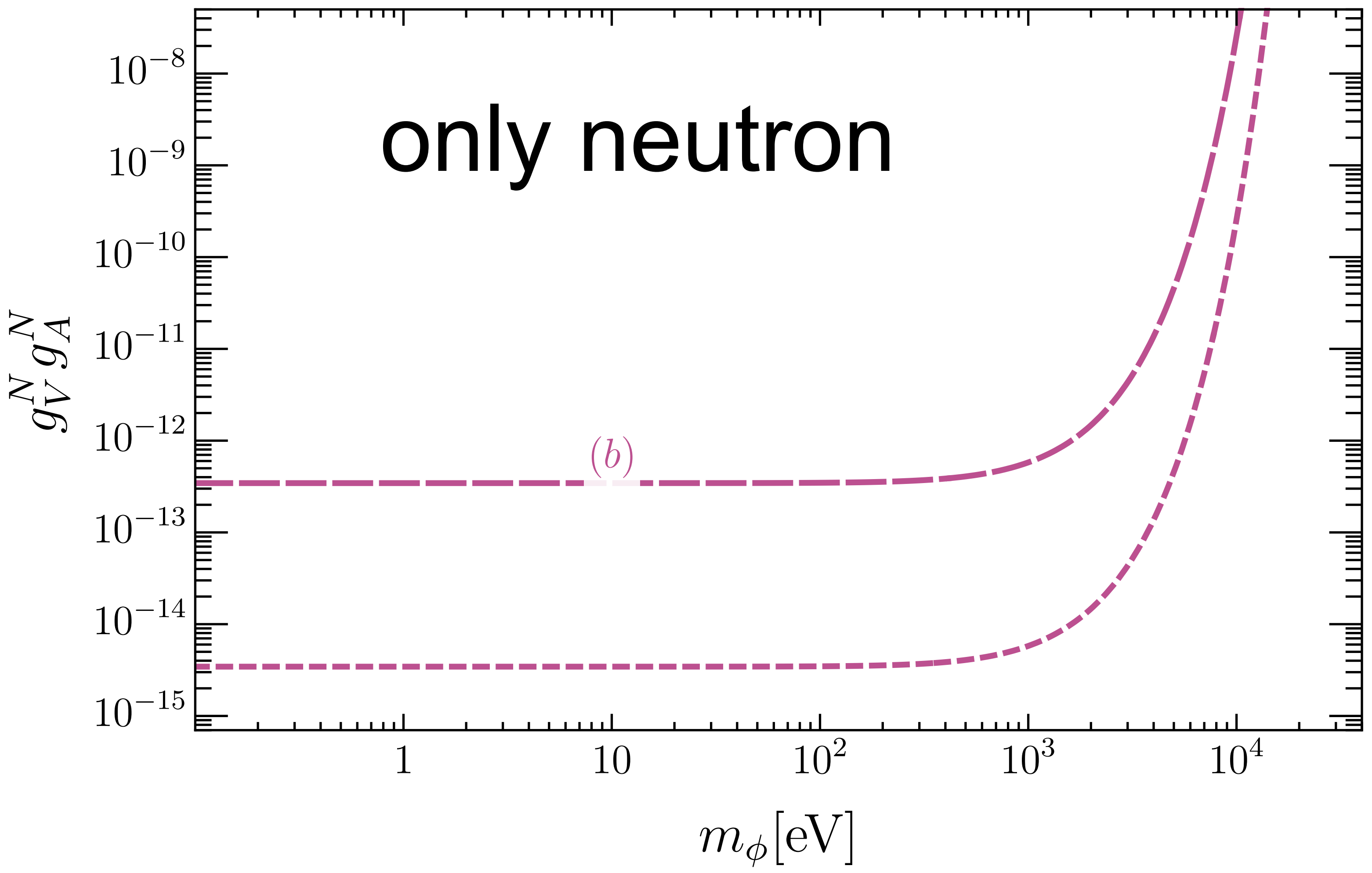
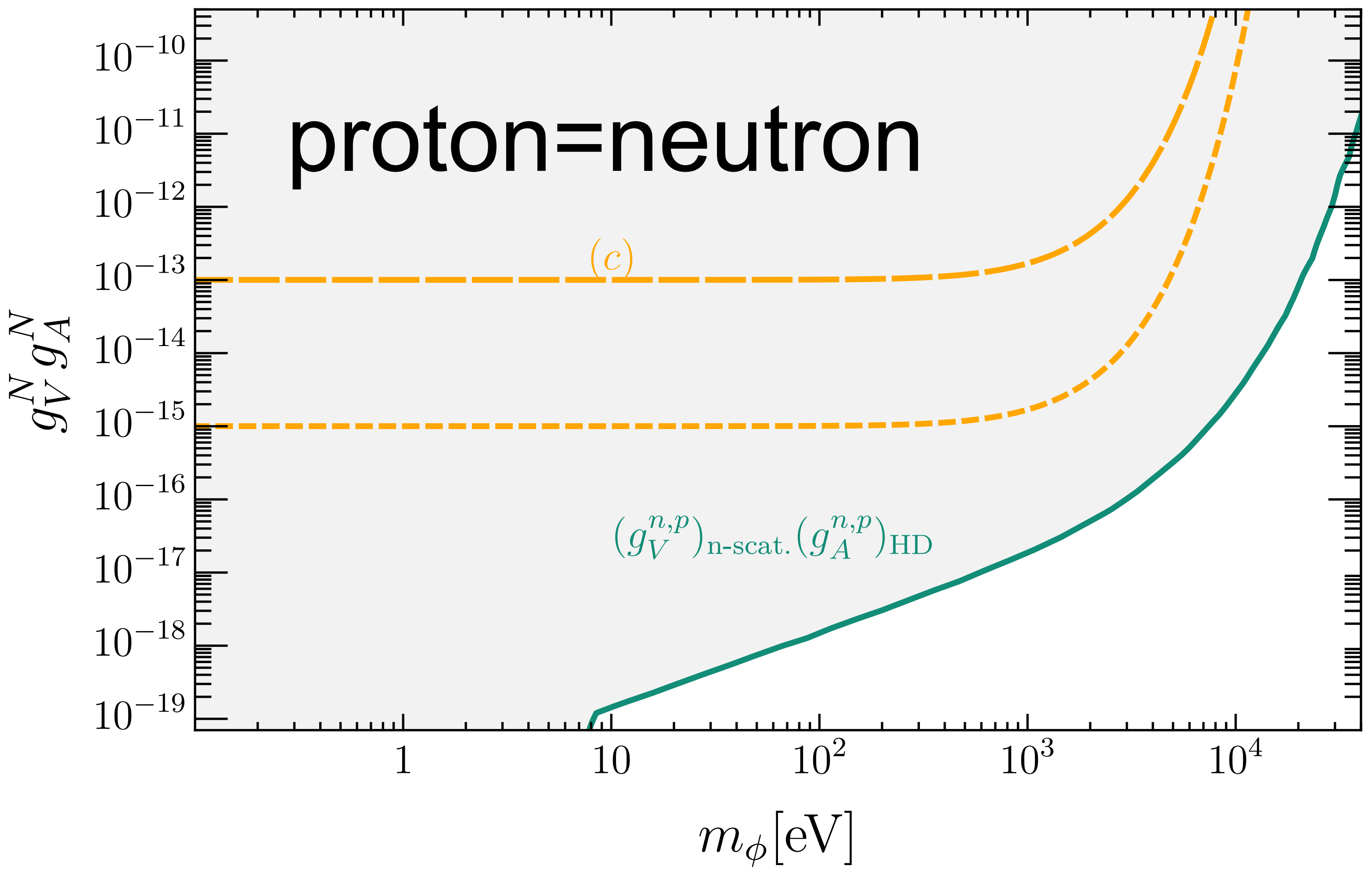
Baruch, Changala, Shagam, YS, PRR 24

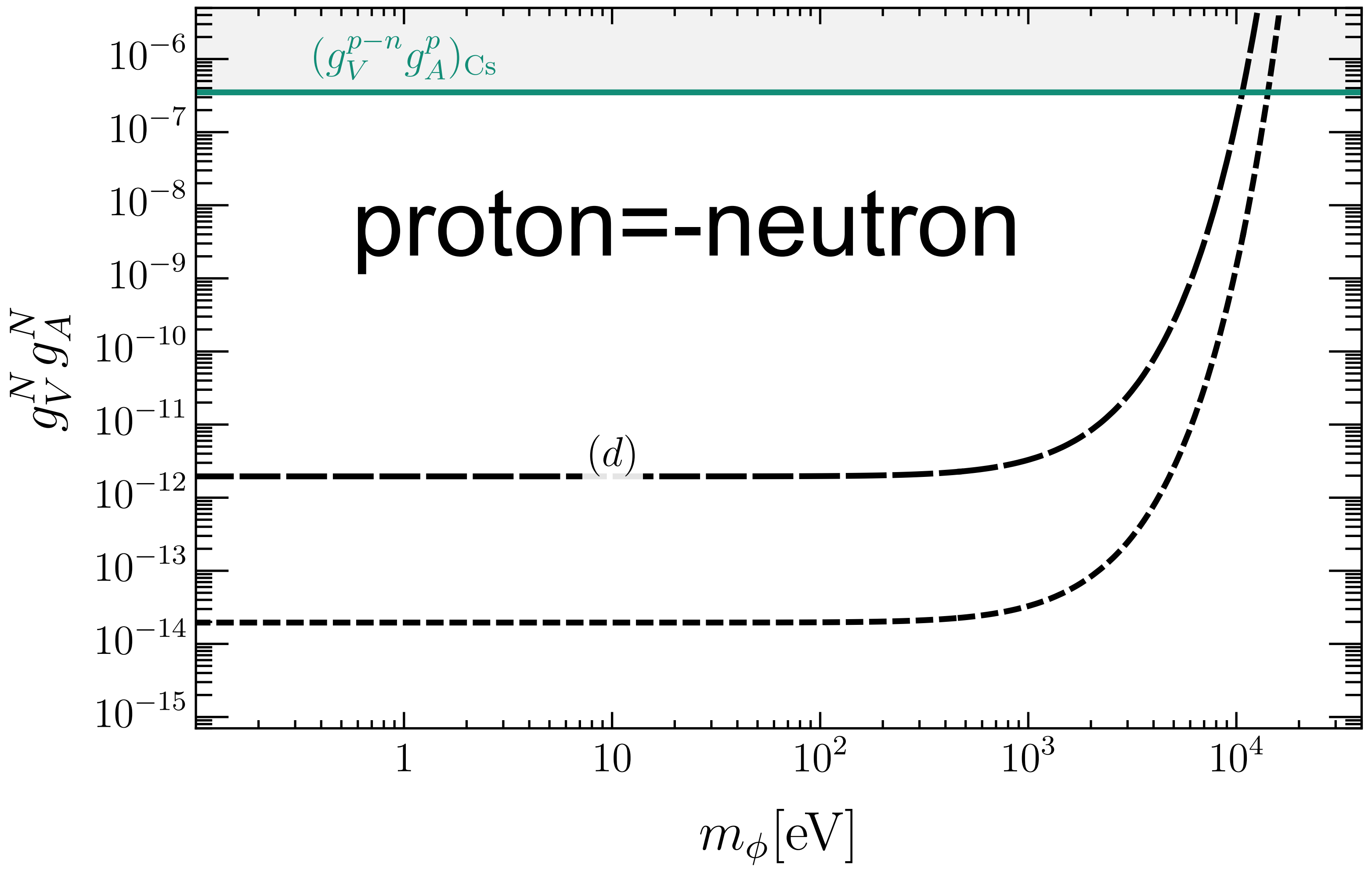
P violation in chiral molecules

comparing the hyperfine structure of L and R









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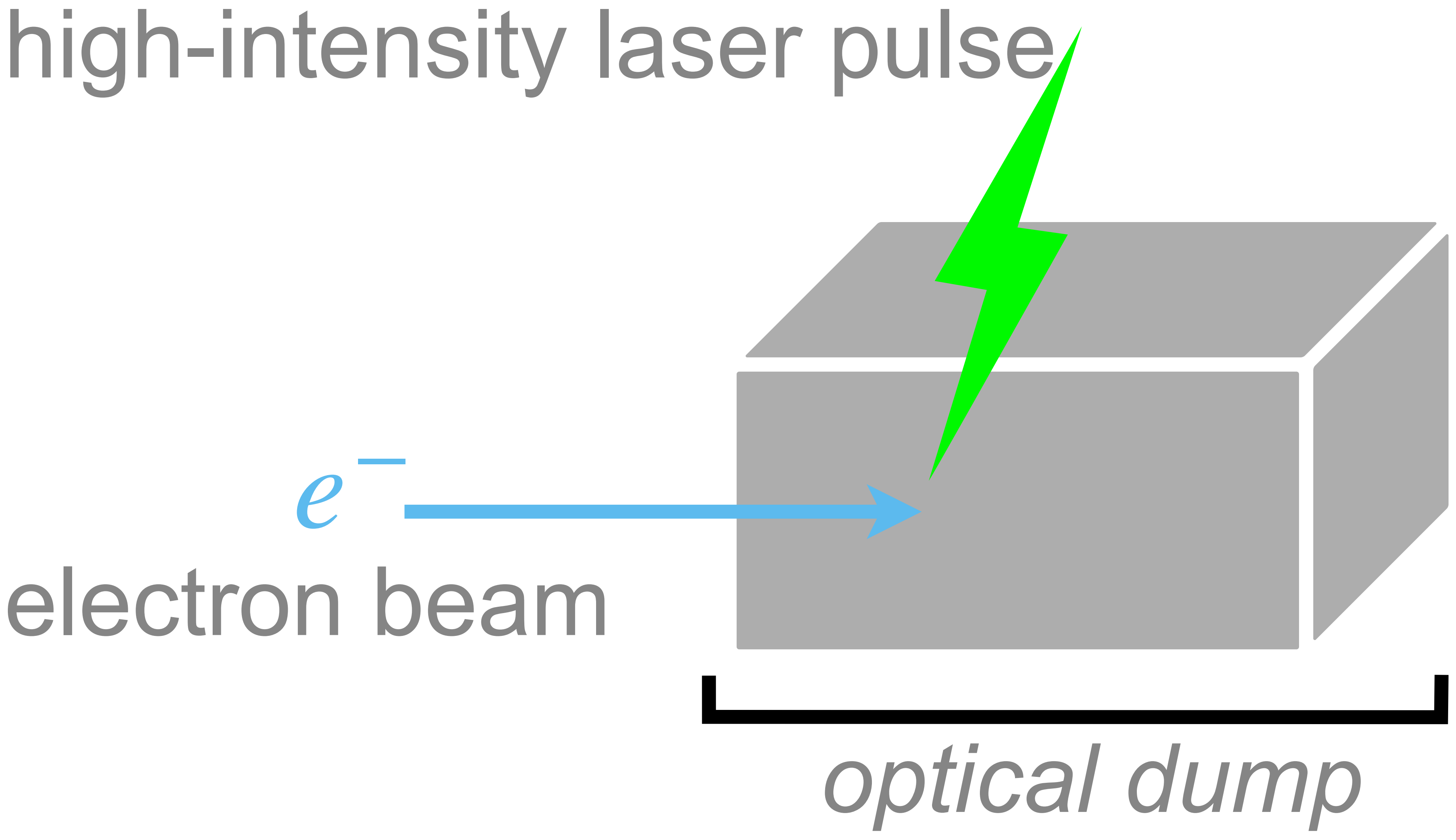
dashed - 0.1 Hz , dotted 1mHz

Baruch, Changala, Shagam, YS, PRR 24

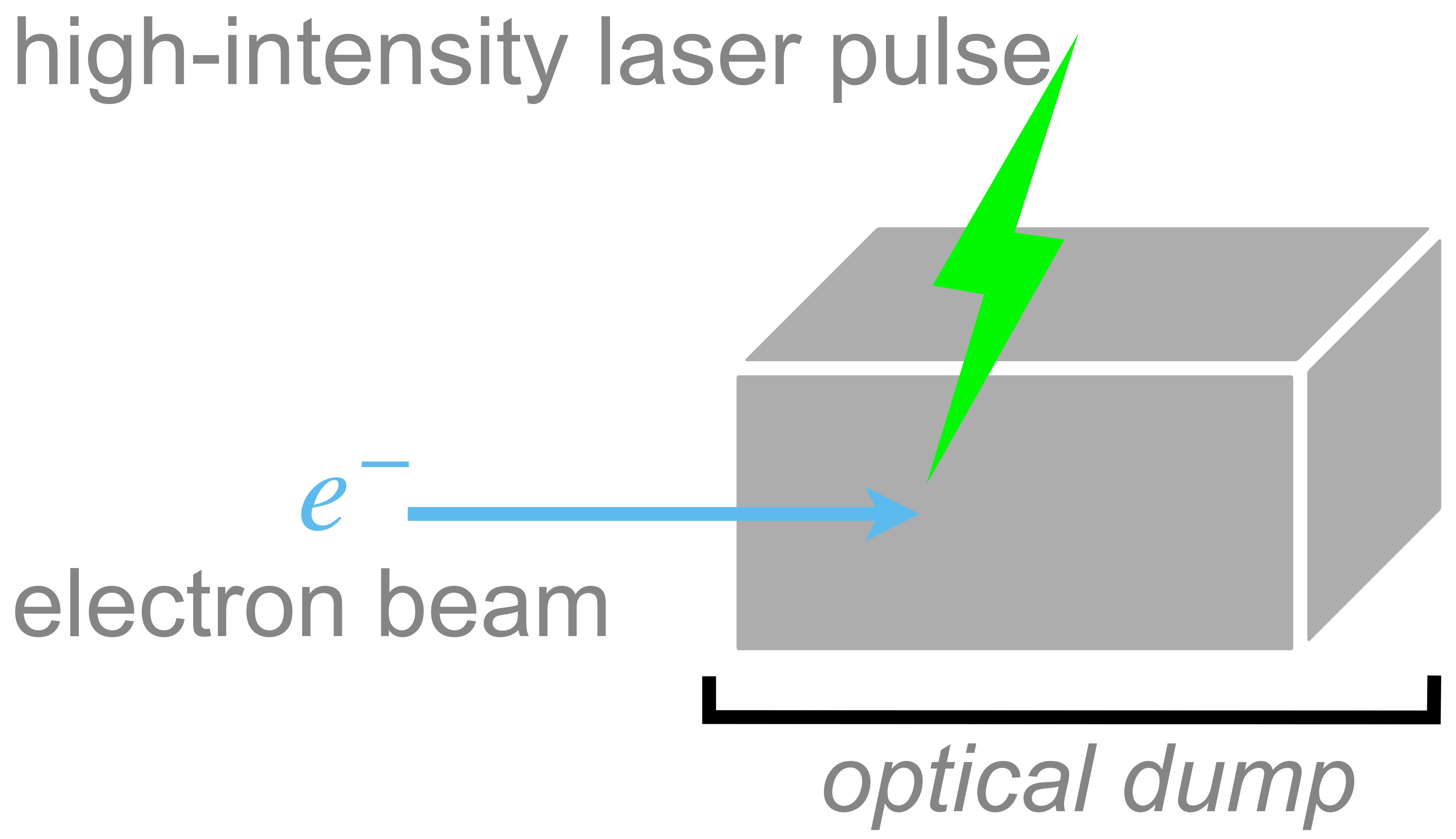
Future probes of scalars and axions at the intensity frontier Optical Dump and EIC

An optical dump



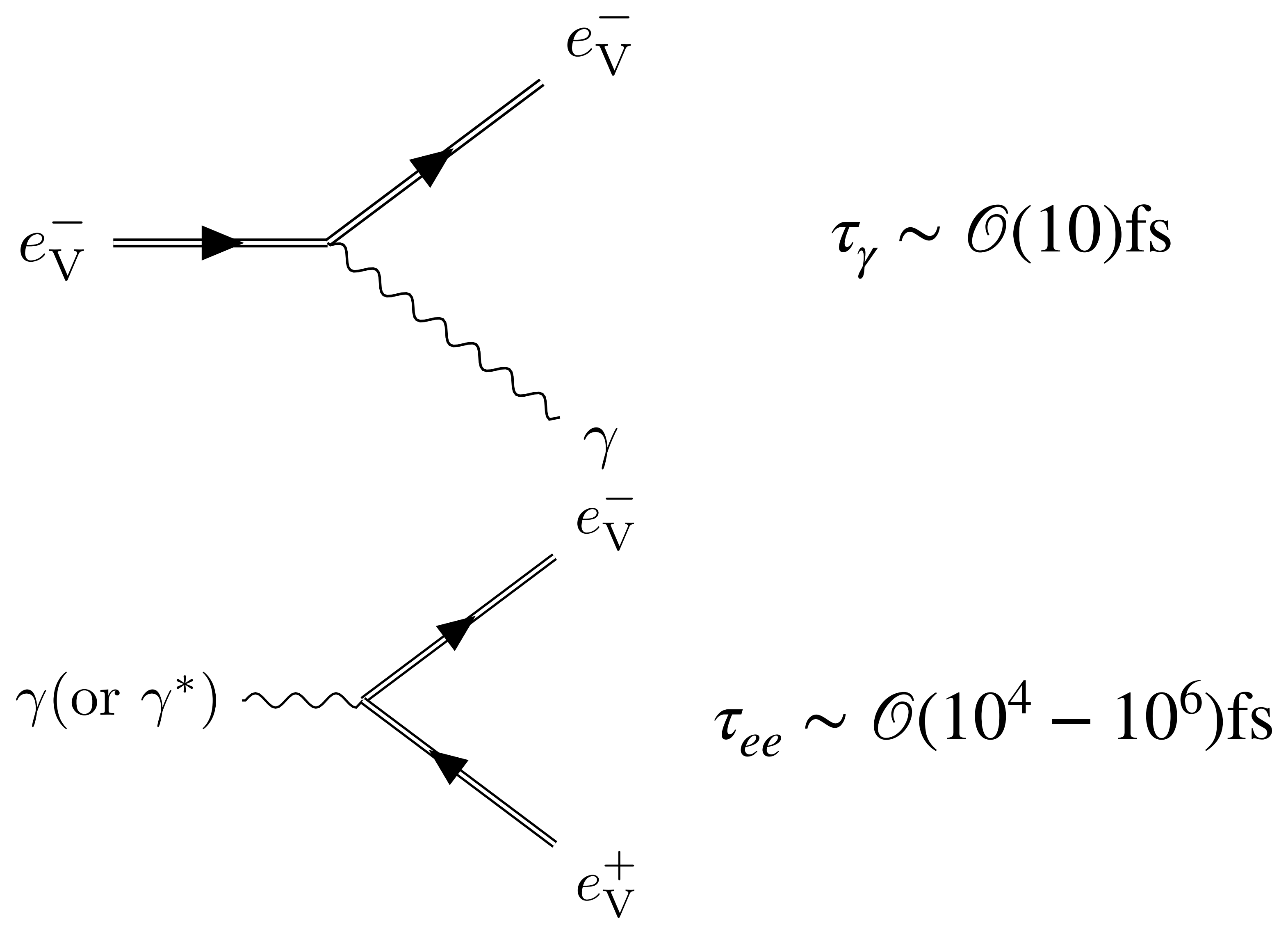
LOI 1909.00860 ,CDR 2102.02032

An optical dump



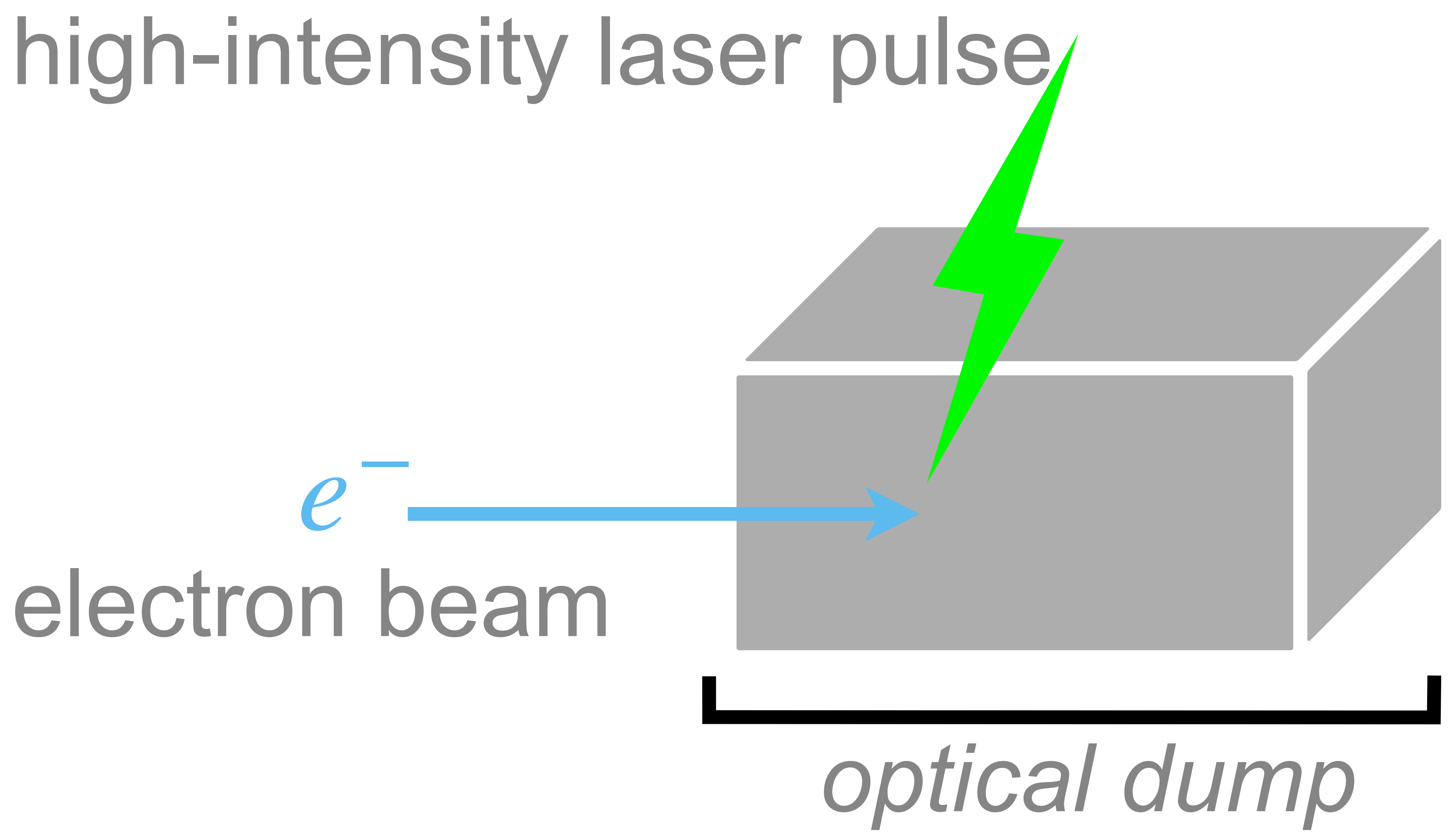
$$E_e \approx 16.5\,\text{GeV},\ \omega_L \approx 1.5\,\text{eV} \sim 1/(0.4\,\text{fs}),\ \ t_L \sim \mathcal{O}(10-100)\,\text{fs}$$

LUXE

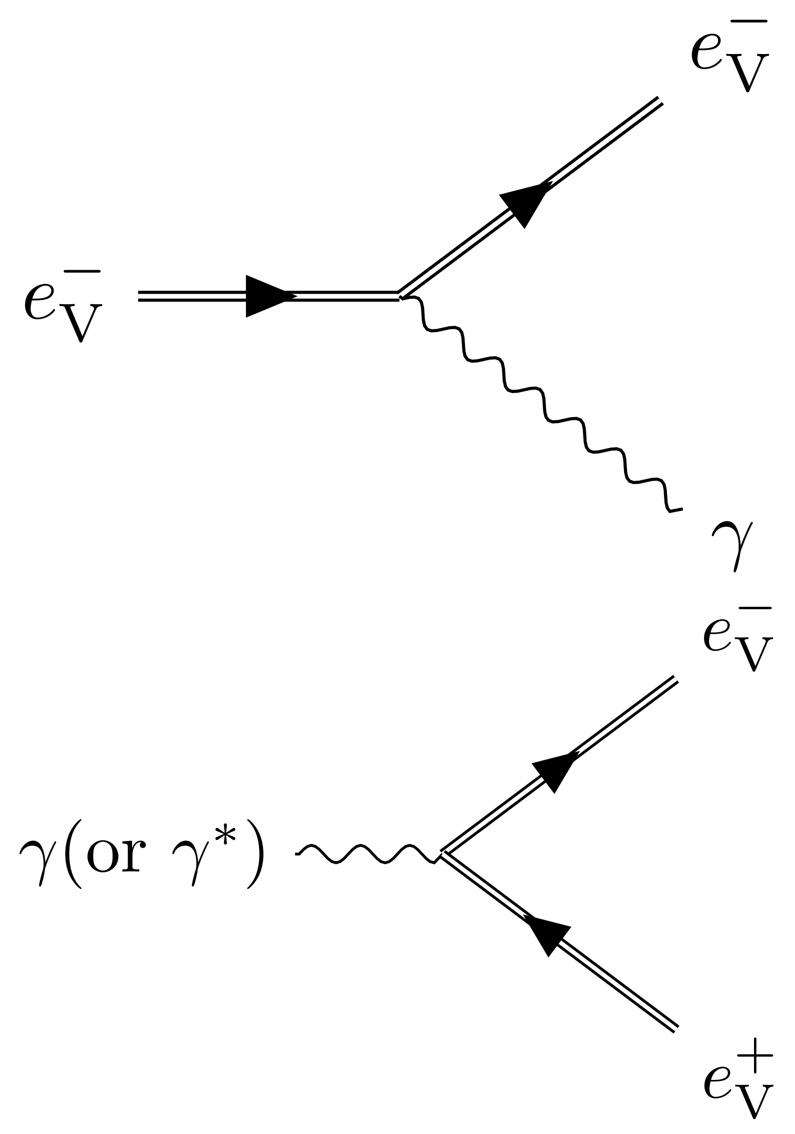


Schwinger like pair production
the main physics goal

An optical dump



$E_e \approx 16.5\,\mathrm{GeV},\ \omega_\mathrm{L} \approx 1.5\,\mathrm{eV} \sim 1/(0.4\,\mathrm{fs}),\ \ t_\mathrm{L} \sim \mathcal{O}(10 - 100)\,\mathrm{fs}$



$\tau_\gamma \sim \mathcal{O}(10)\mathrm{fs}$

$1/\omega_\mathrm{L} \ll \tau_\gamma \lesssim t_\mathrm{L} \ll \tau_{ee}$

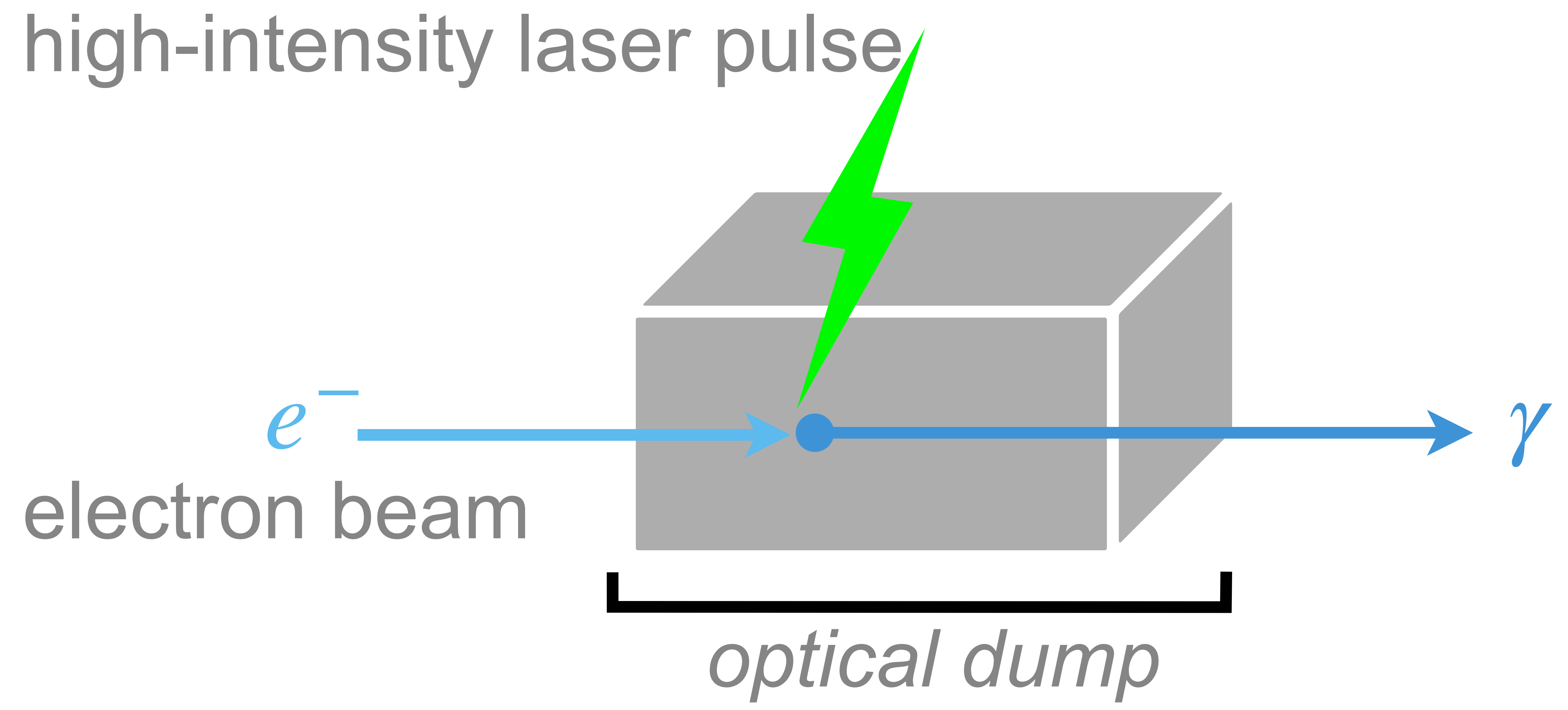
$\tau_{ee} \sim \mathcal{O}(10^4 - 10^6)\mathrm{fs}$

Schwinger like pair production
the main physics goal

in ordinary material $\tau_\gamma \sim \tau_{ee}$

LOI 1909.00860 ,CDR 2102.02032

An optical dump

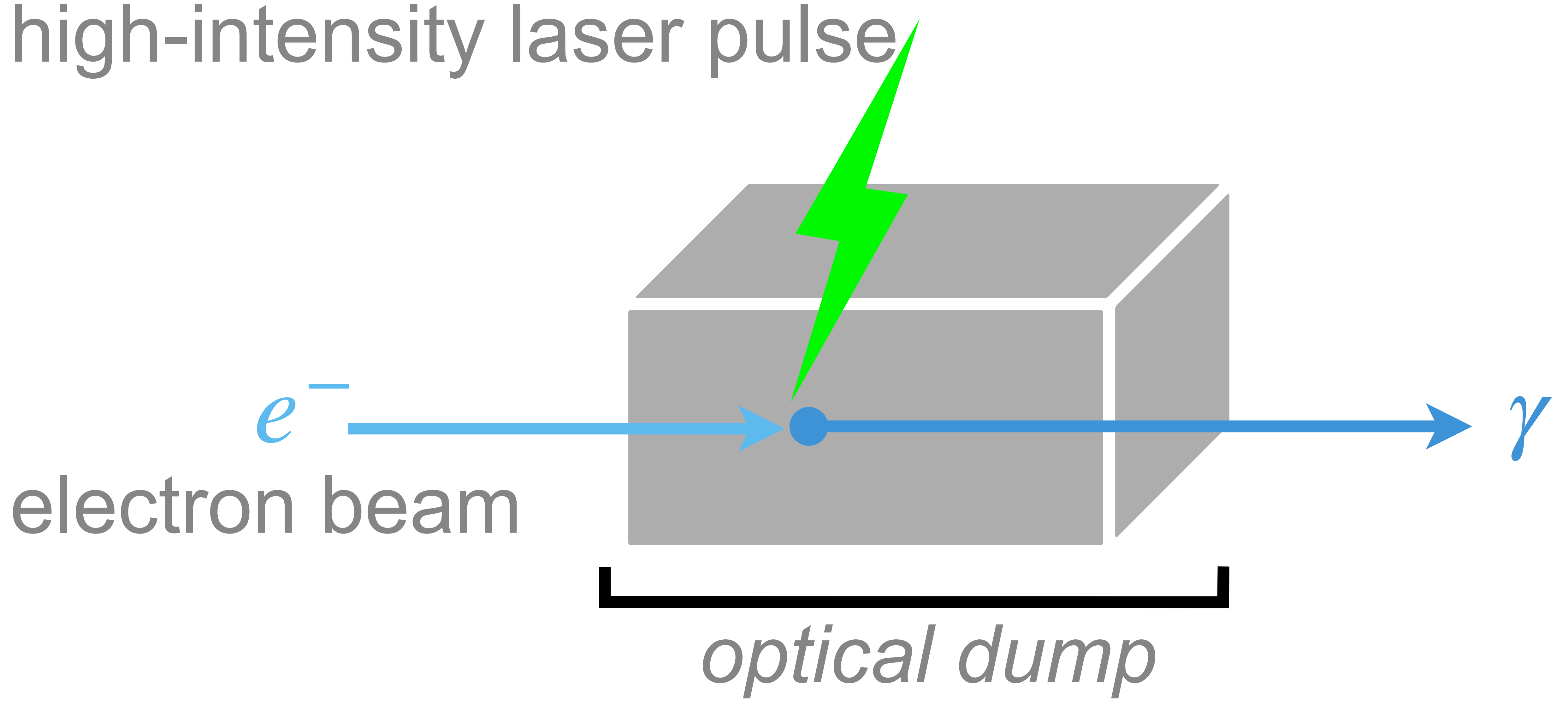


photon emission, frequent process
several outgoing photons per electron

LUXE

LOI 1909.00860 ,CDR 2102.02032

An optical dump



photon emission, frequent process
several outgoing photons per electron

LUXE = high intensity and high energy collimated photon source

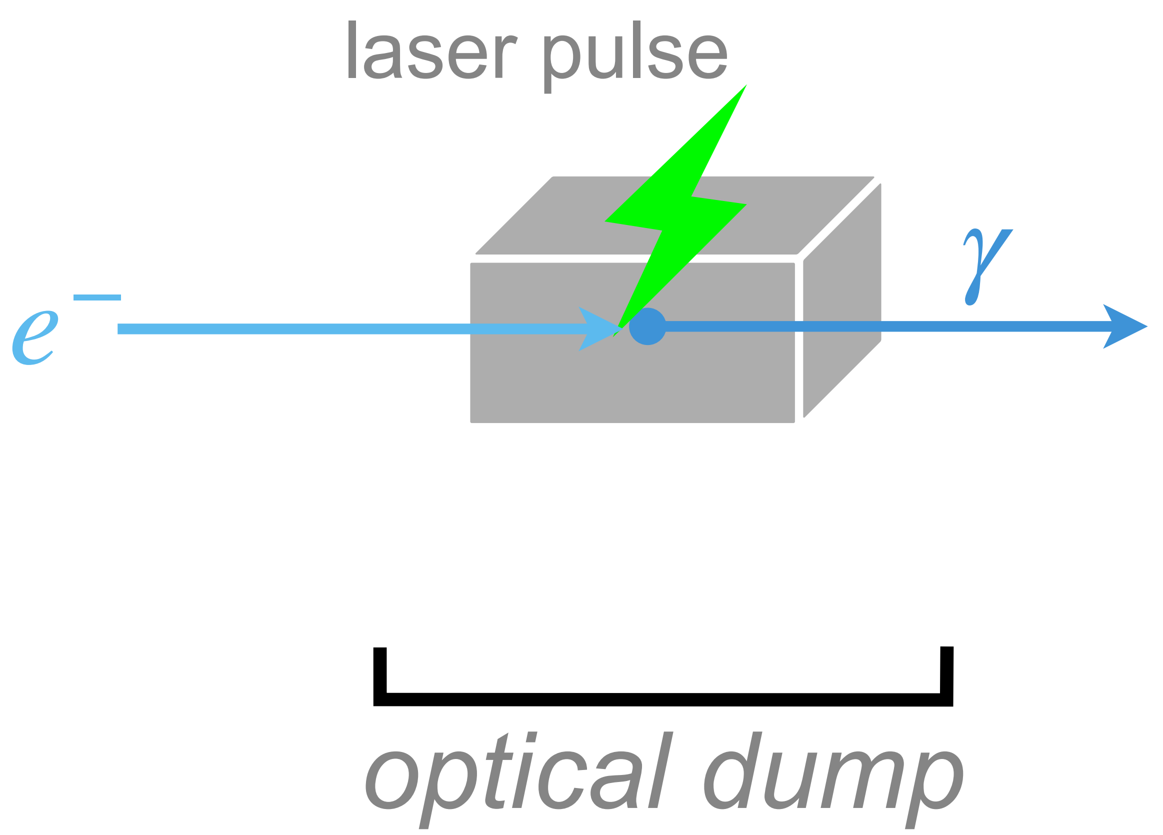
$10^{10}\,\gamma/\mathrm{sec},\ E_\gamma \sim \mathcal{O}(m_p)$

LOI 1909.00860 ,CDR 2102.02032

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, YS, Tal Hod PRD 22

Axions at an optical dump

LUXE-NPOD
(new physics at optical dump)



Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, YS, Tal Hod PRD 22
Soto et al 2507.17716

Axions at an optical dump

LUXE-NPOD
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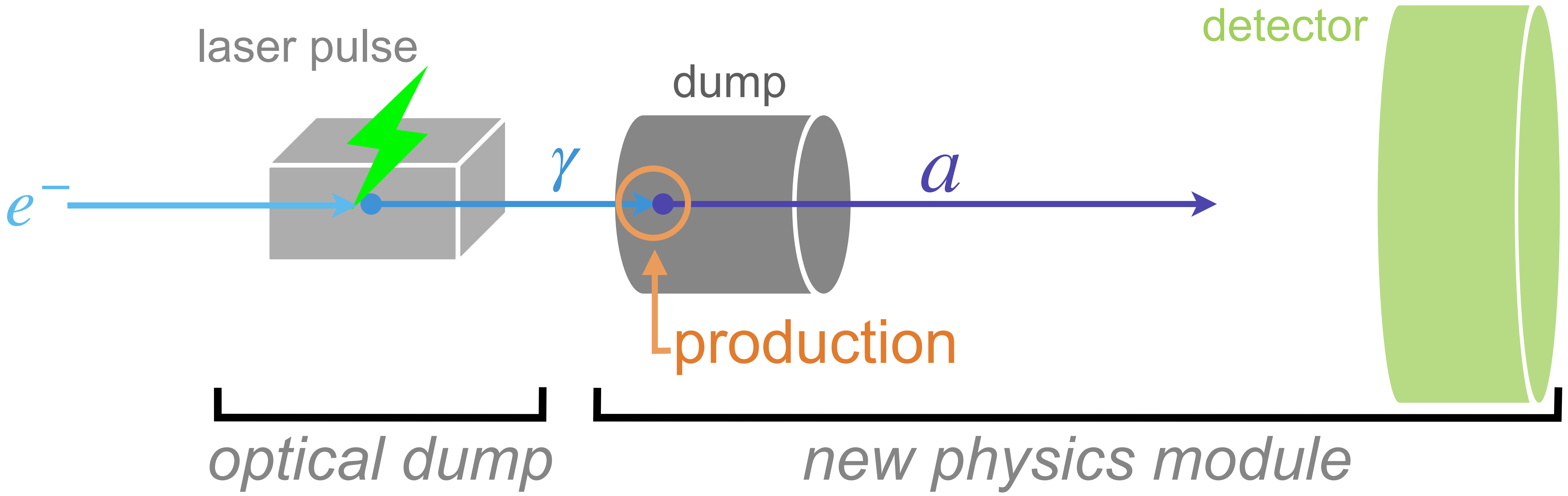

adopted by the
LUXE collaboration

$$\frac{g_a}{4}\, aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Bai, Blackburn, Borysov, Davidi, Hartin,
Heinemann, Ma, Perez, YS, Tal Hod PRD 22
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Axions at an optical dump

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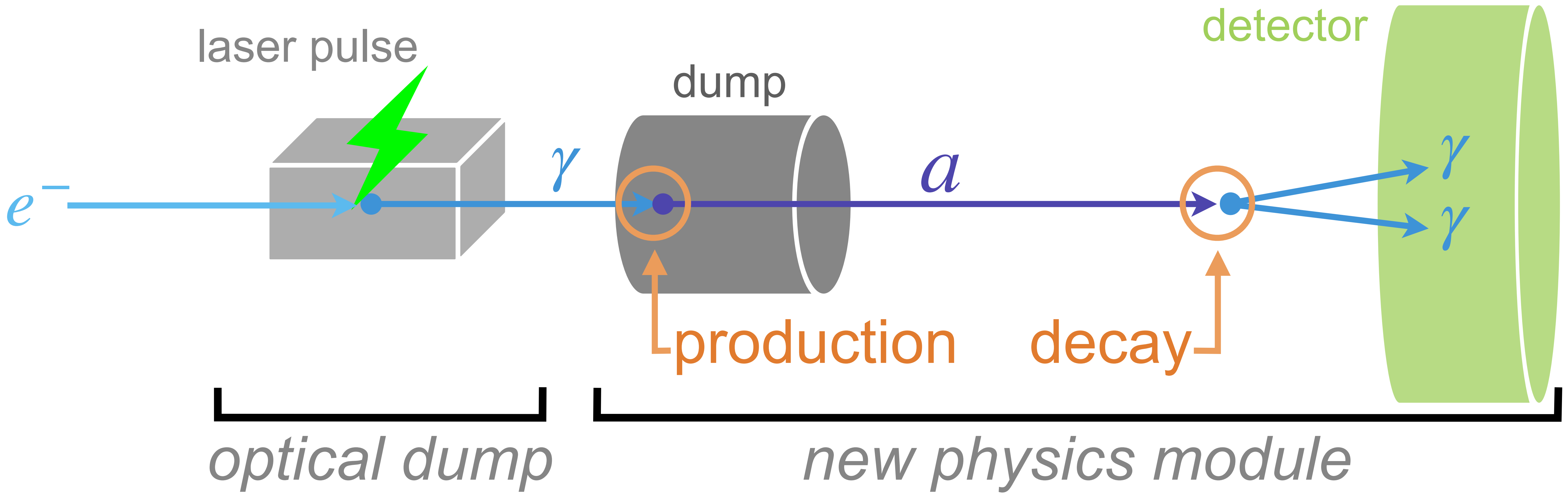

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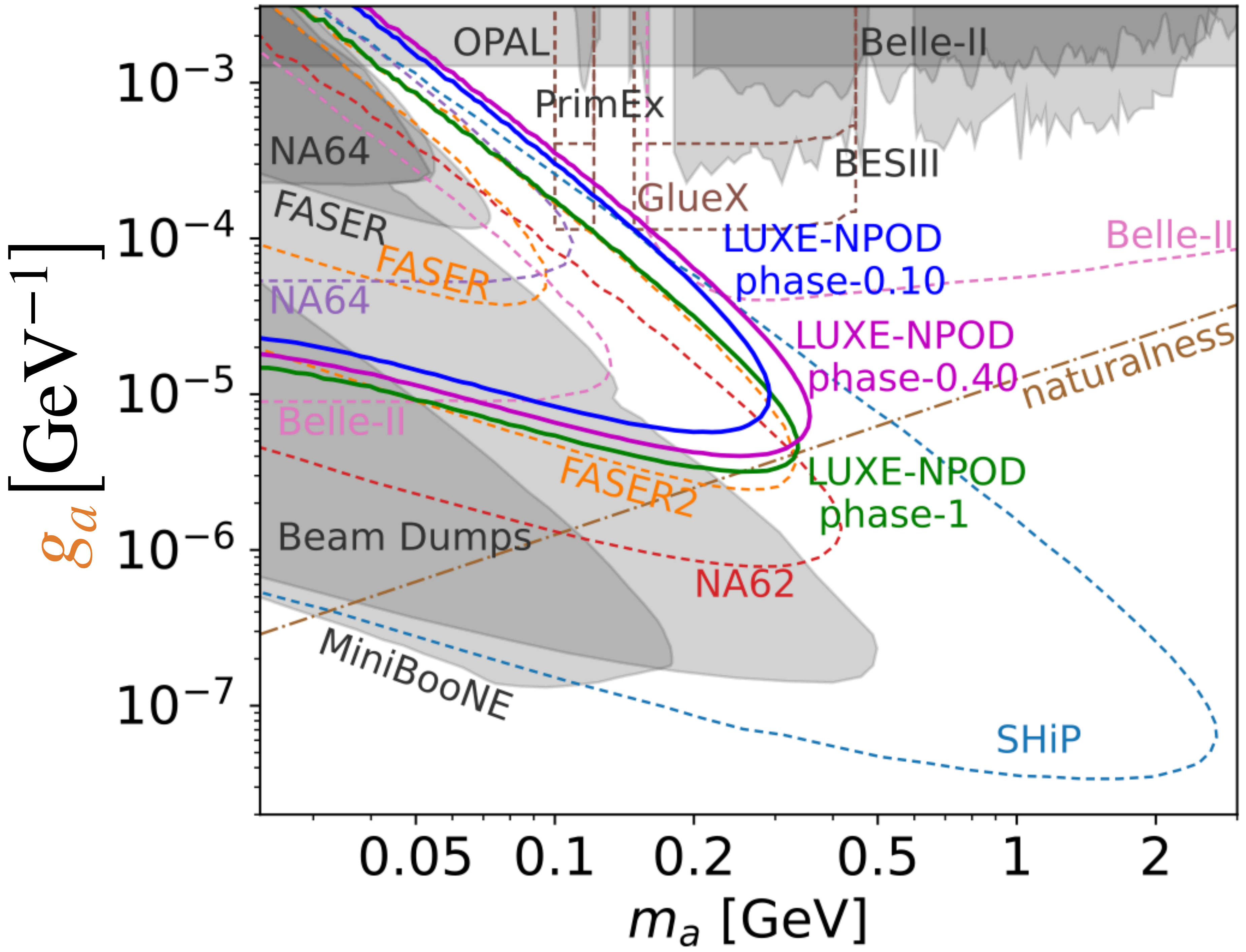
$$\frac{g_a}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



very low background rate

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, YS, Tal Hod PRD 22
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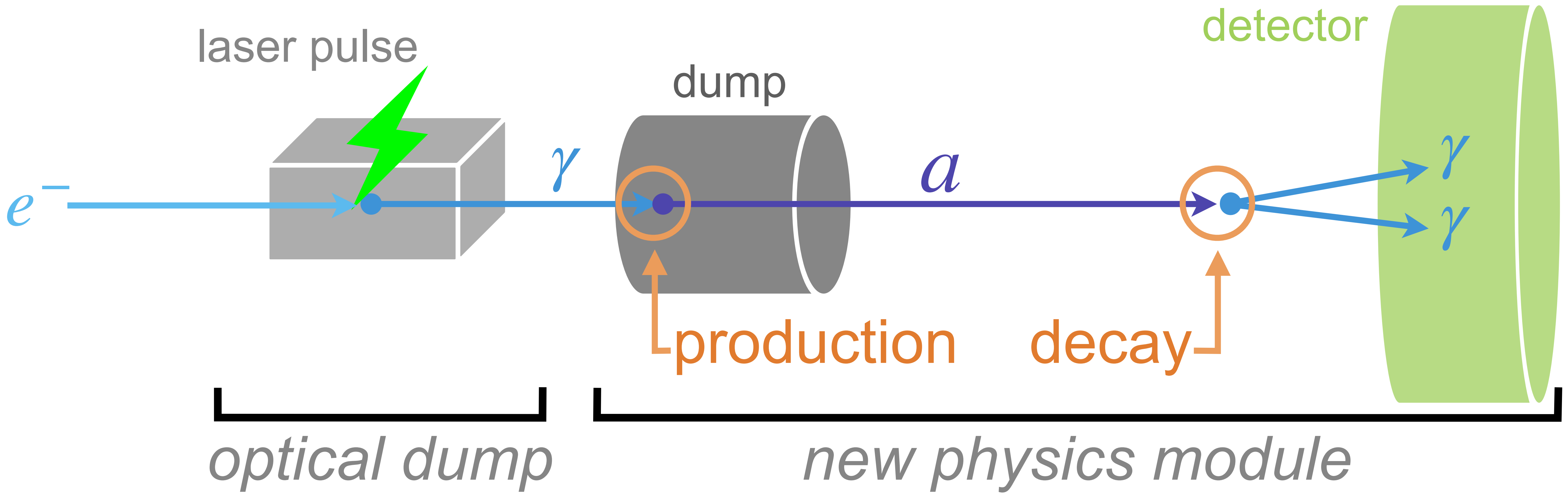

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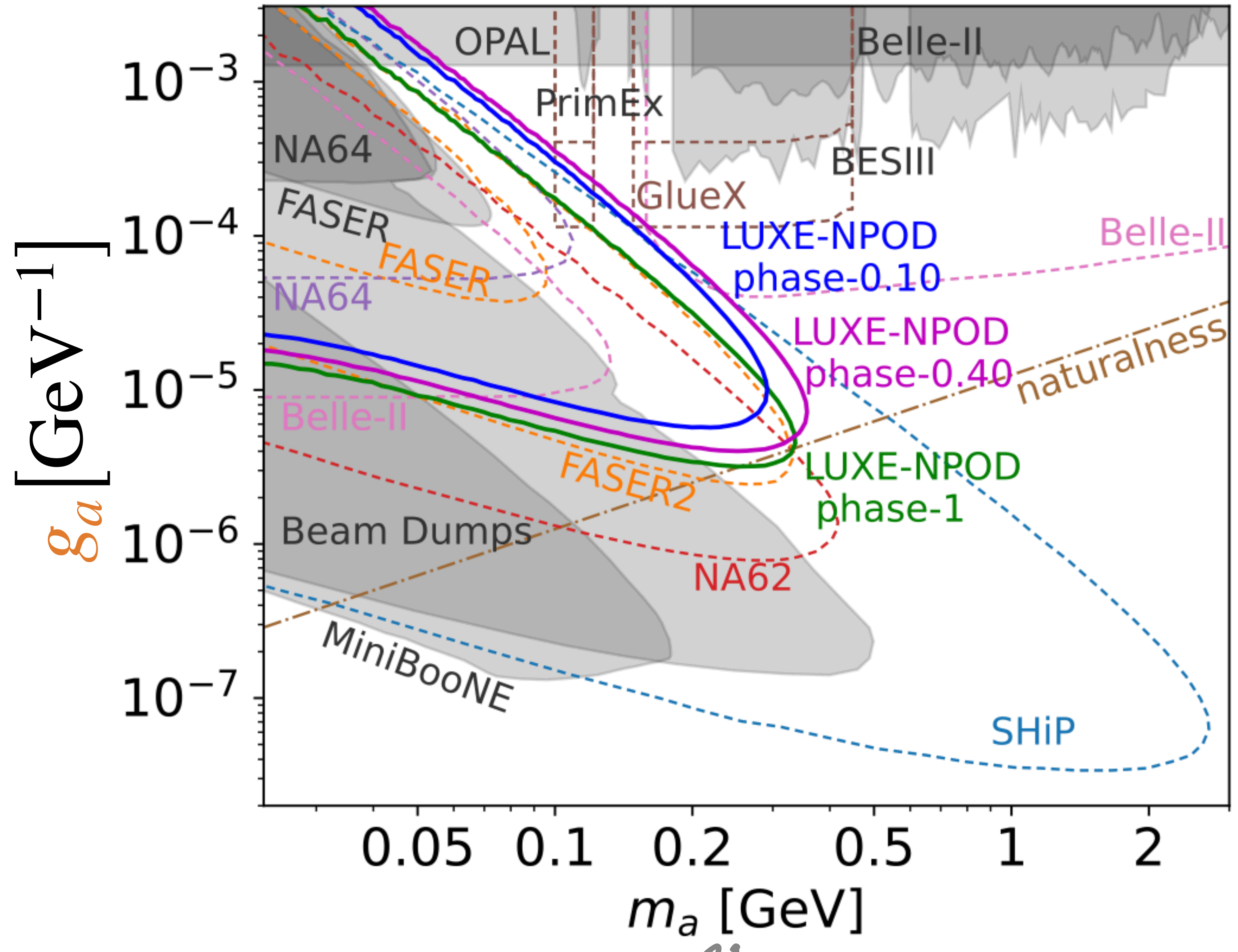


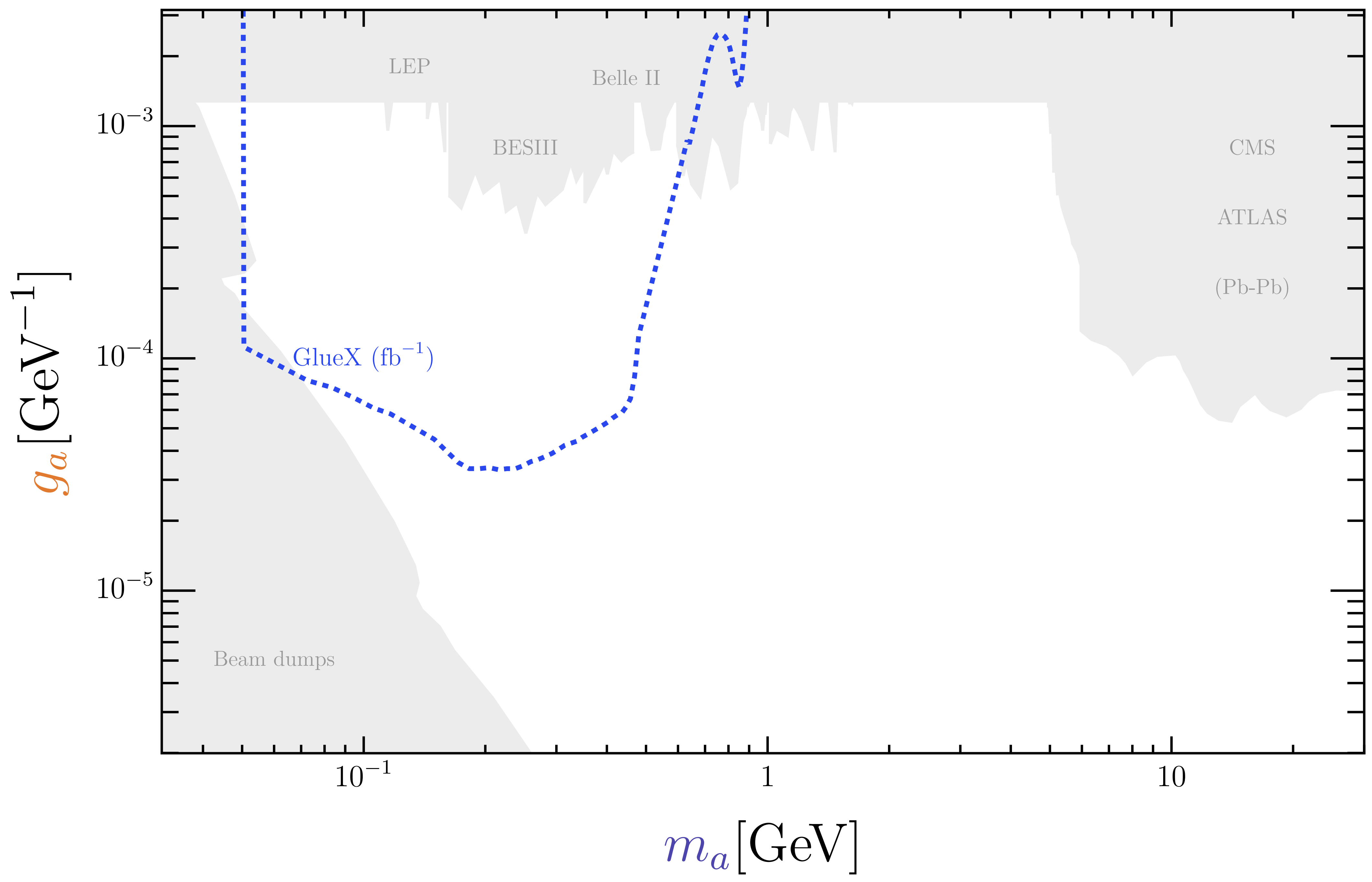
very low background rate

applicable to:
SLAC, LBNL, ILC….

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, YS, Tal Hod PRD 22
Soto et al 2507.17716

Axions at electron-ion collider (EIC)

How can we go further?

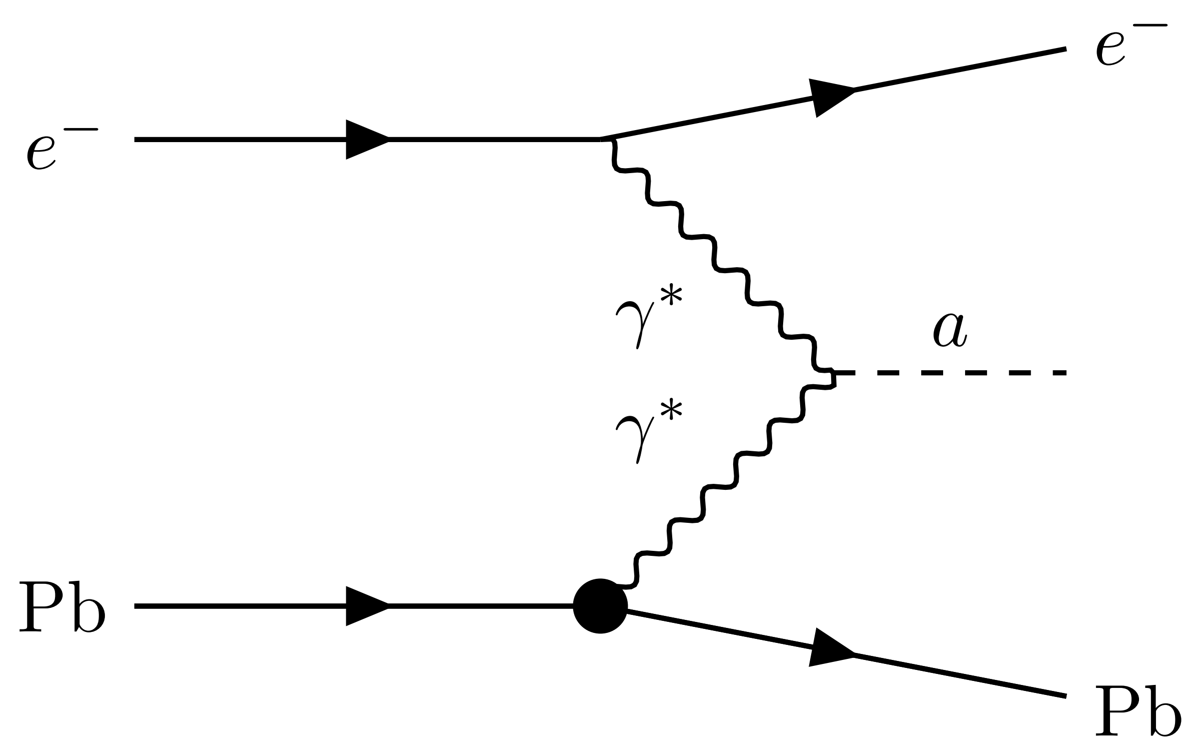


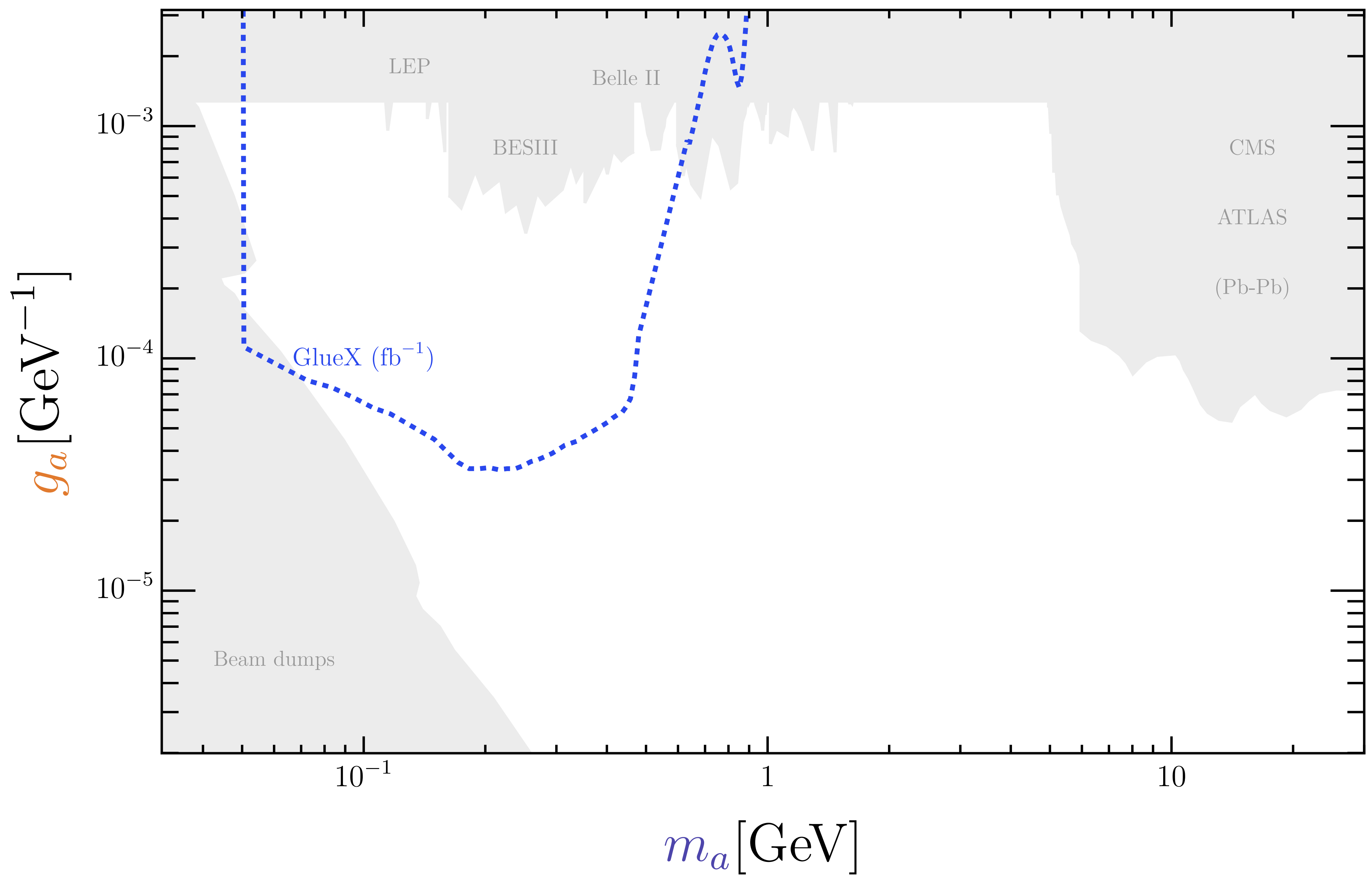
Balkin, Hen, Li, Liu, Ma, YS, Williams JHEP 24

Axions at electron-ion collider (EIC)

$E_e = 18\,\mathrm{GeV}$

$E_{\mathrm{Pb}} = 20\,\mathrm{TeV}$





Balkin, Hen, Li, Liu, Ma, YS, Williams JHEP 24

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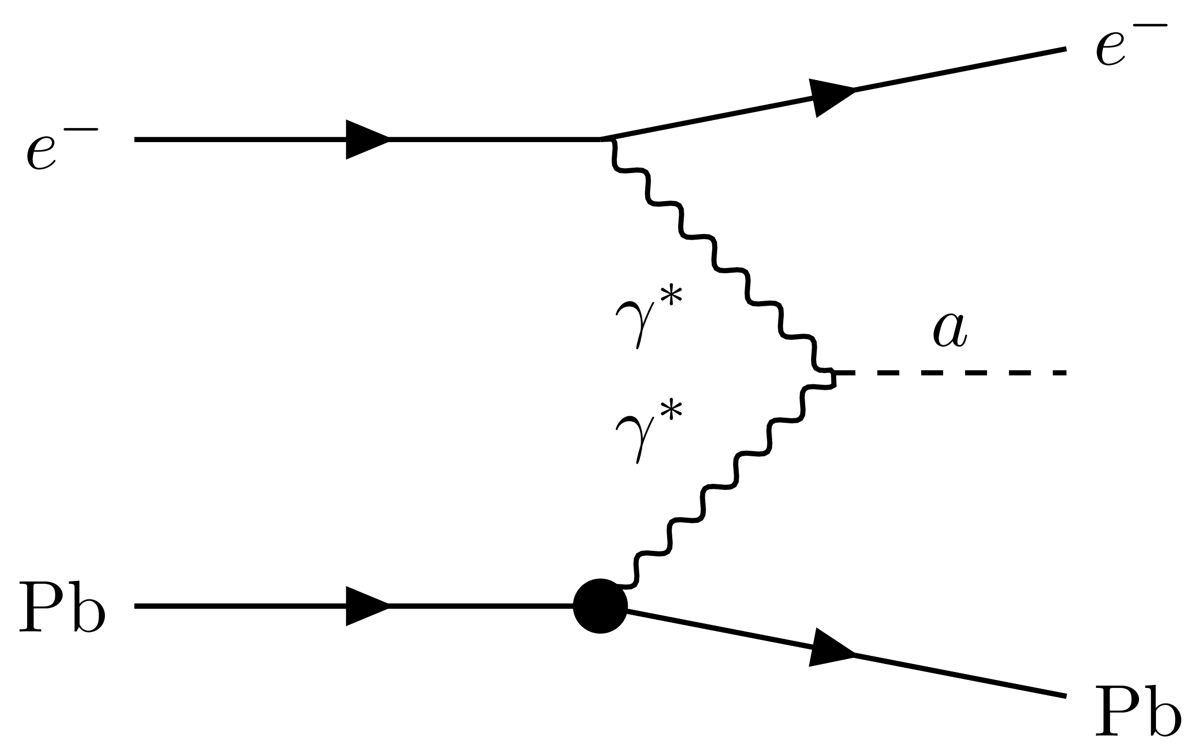
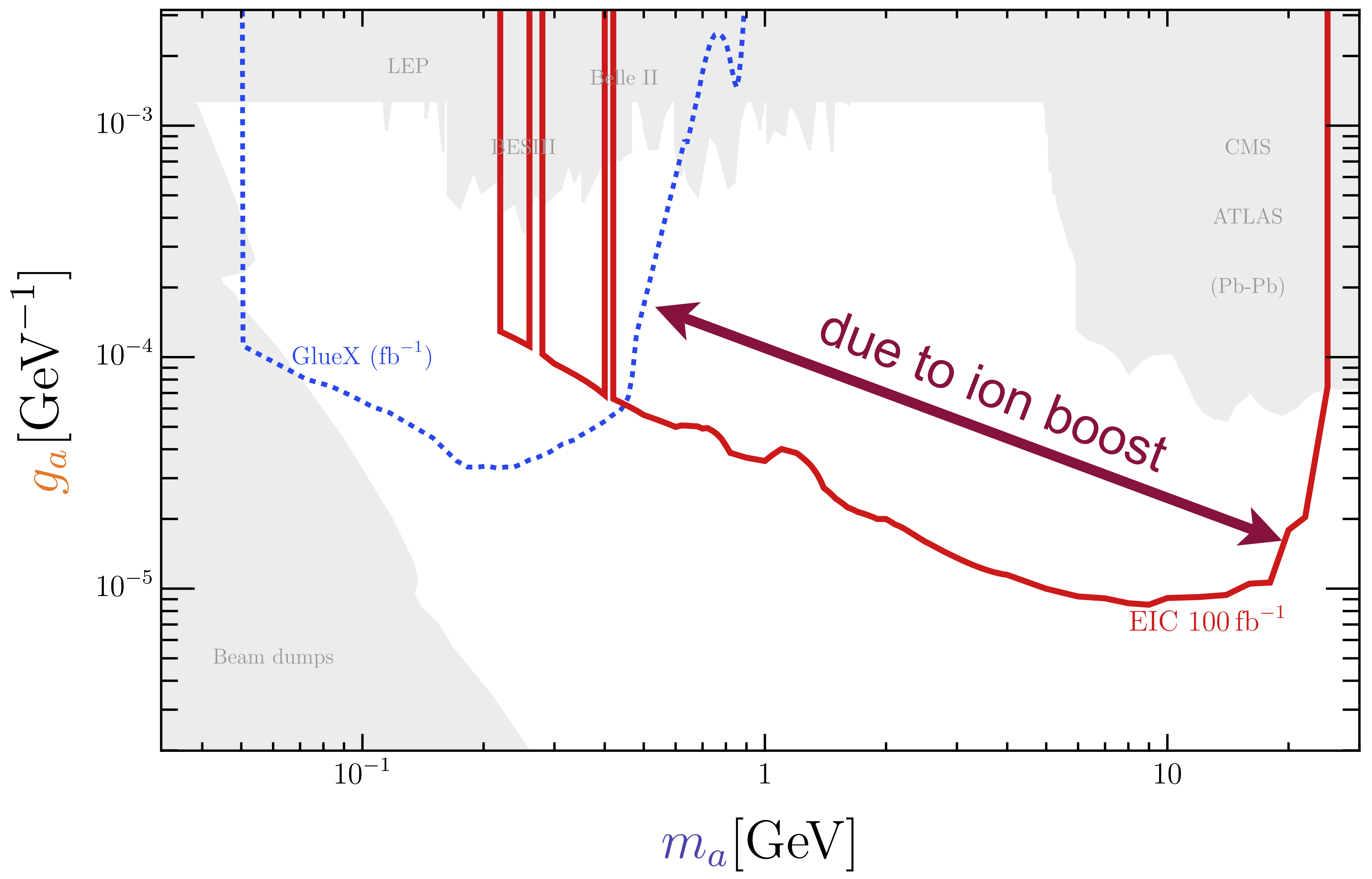


coherent production of new particles up to $m_a \sim 20\,\mathrm{GeV}$

prompt



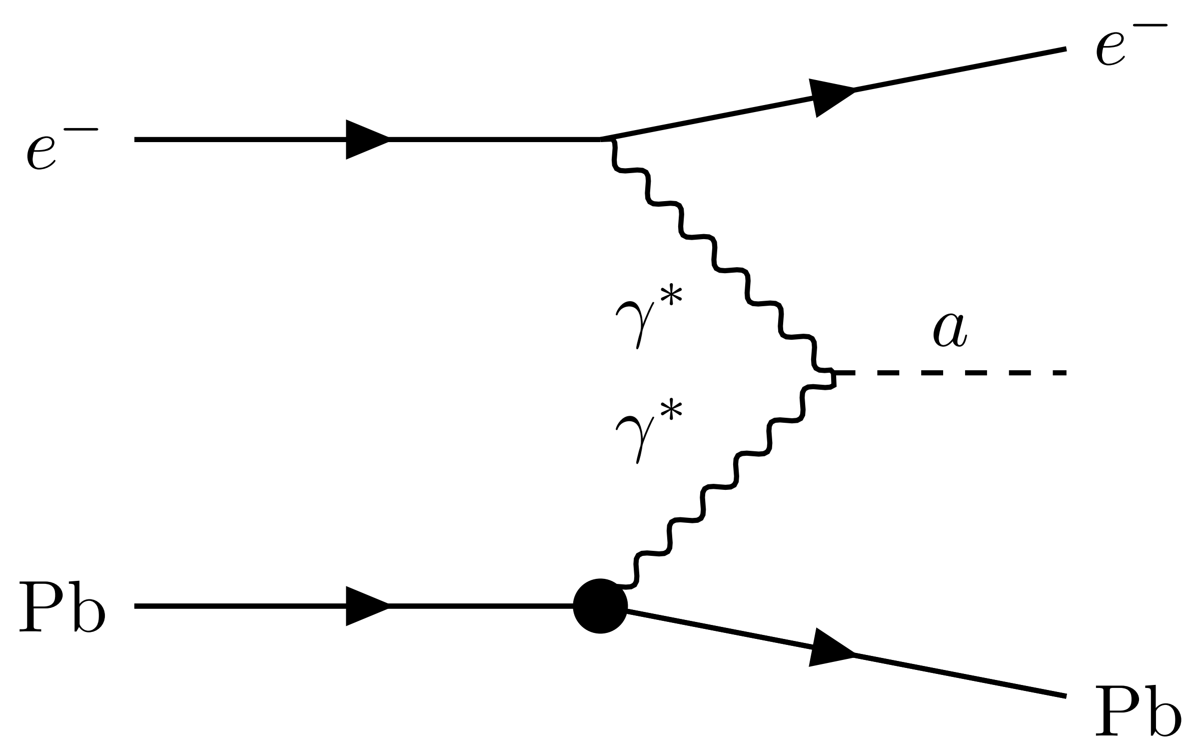
axion is produced and promptly decays to photons

Balkin, Hen, Li, Liu, Ma, YS, Williams JHEP 24

Axions at electron-ion collider (EIC)

$E_e = 18\,\text{GeV}$

$E_{Pb} = 20\,\text{TeV}$



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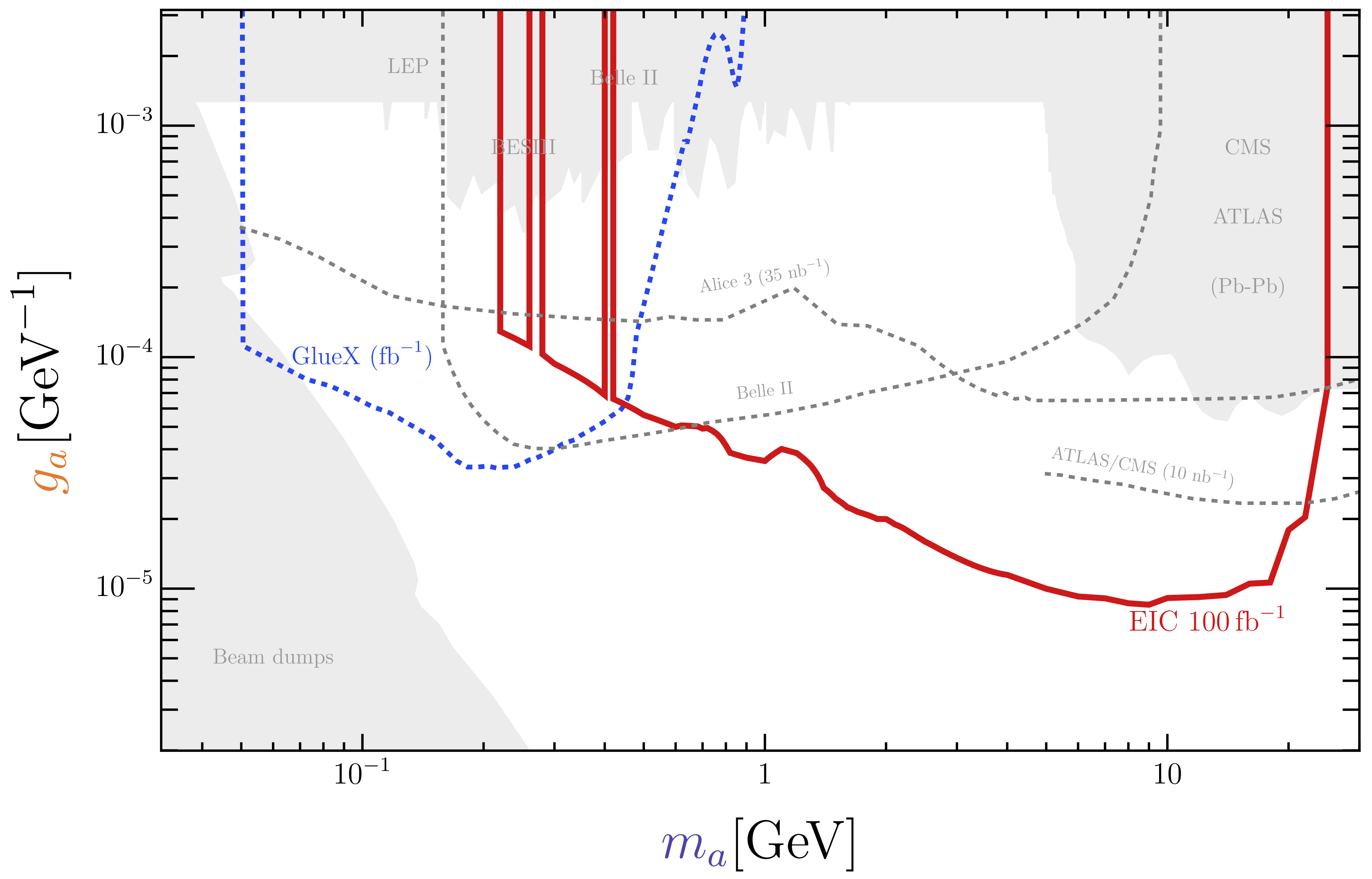

axion is produced and promptly decays to photons

Balkin, Hen, Li, Liu, Ma, YS, Williams JHEP 24

Axions at electron-ion collider (EIC)

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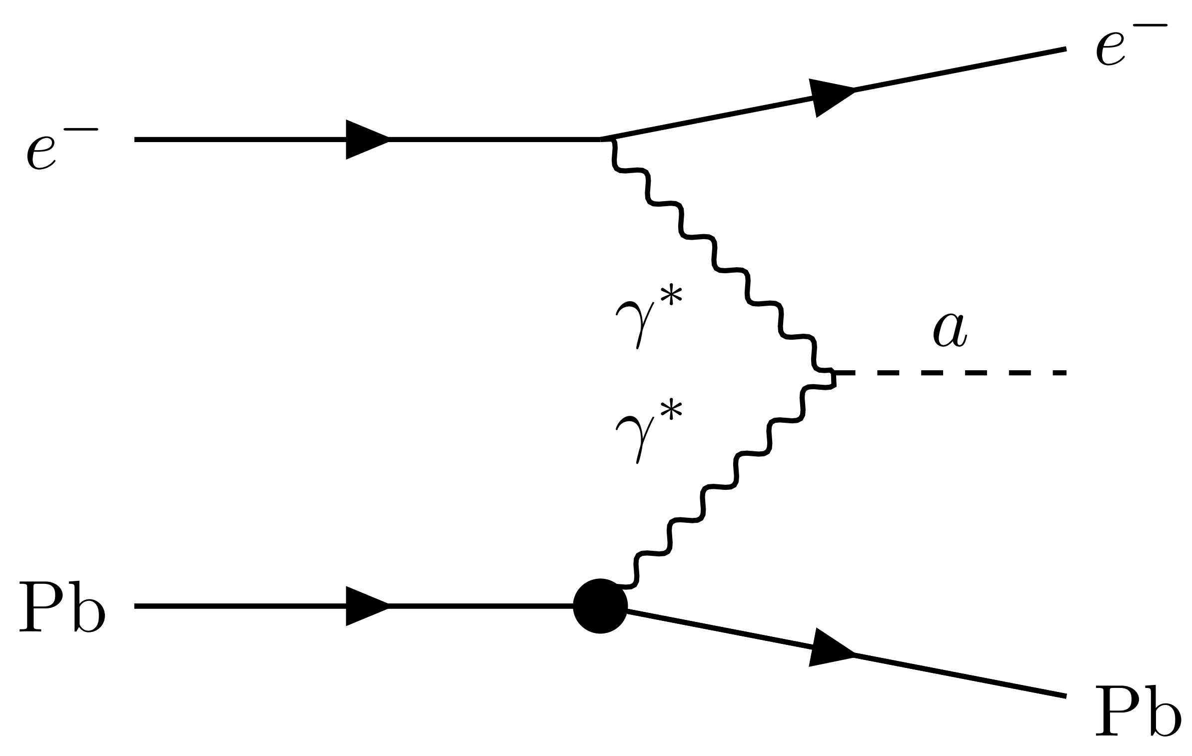
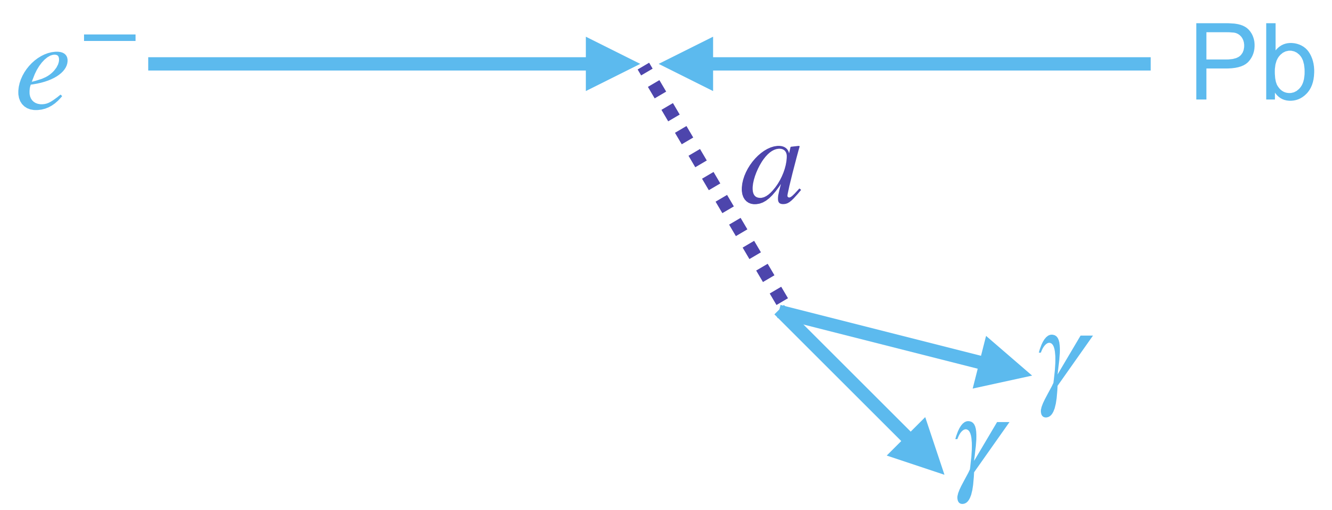
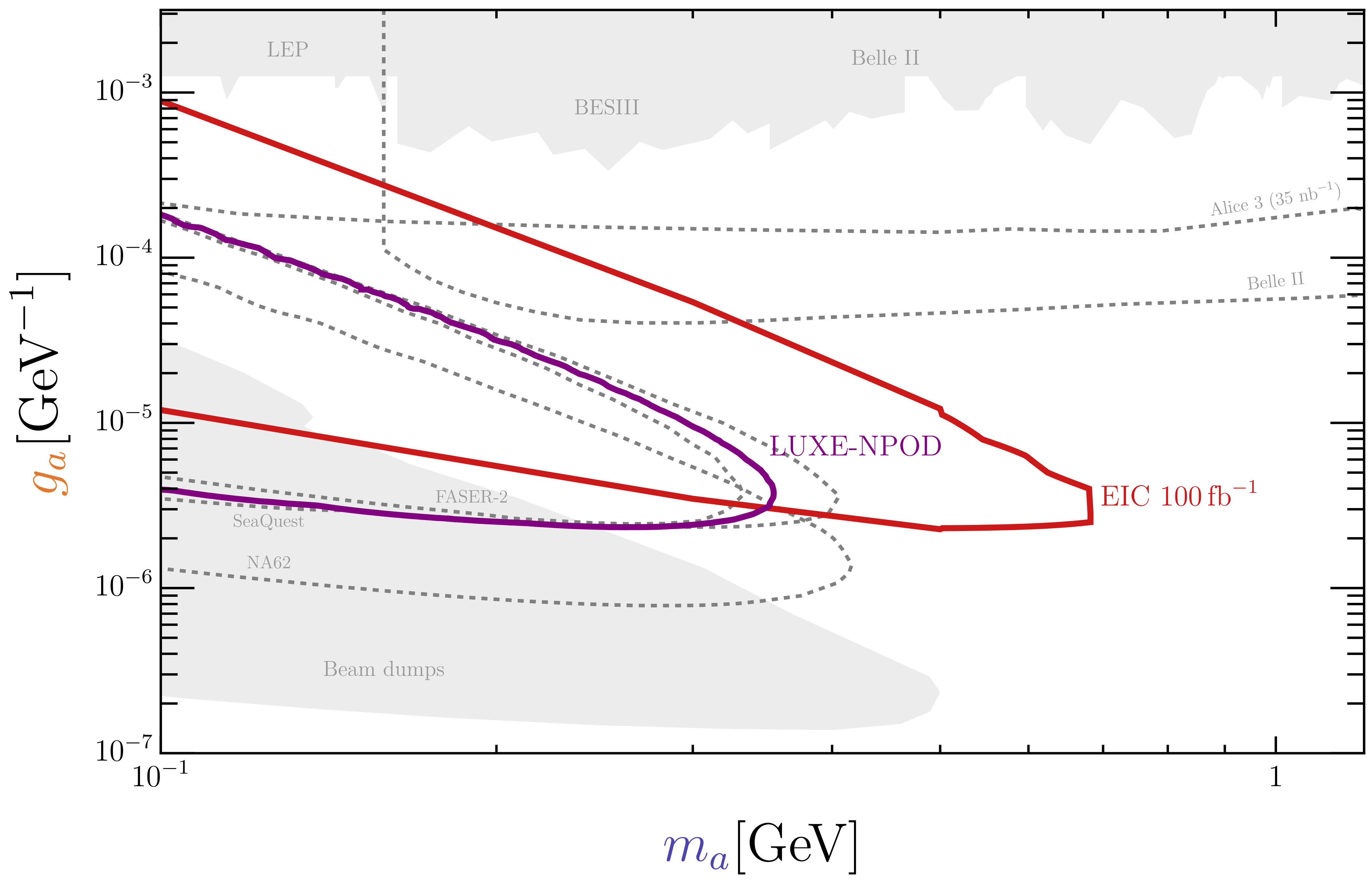


coherent production of new particles up to $m_a \sim 20\,\mathrm{GeV}$

axion is produced, travels a finite distance and decays to photons



displaced

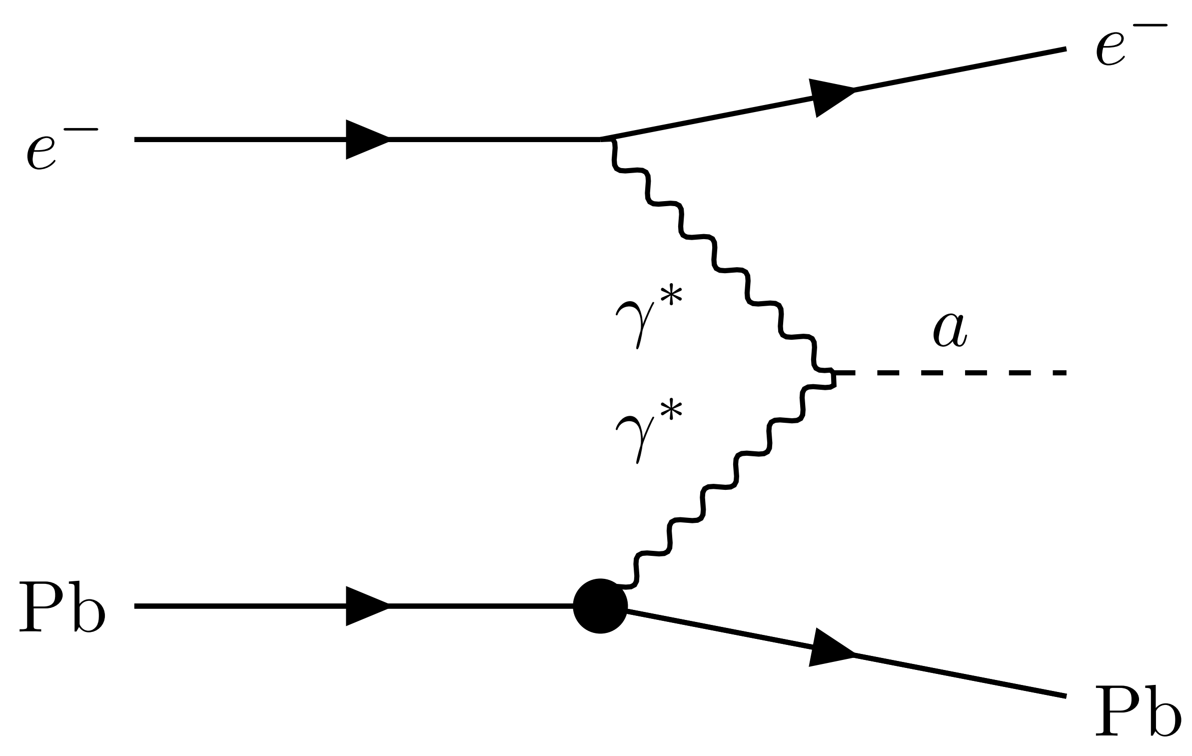


Balkin, Hen, Li, Liu, Ma, YS, Williams JHEP 24

Axions at electron-ion collider (EIC)

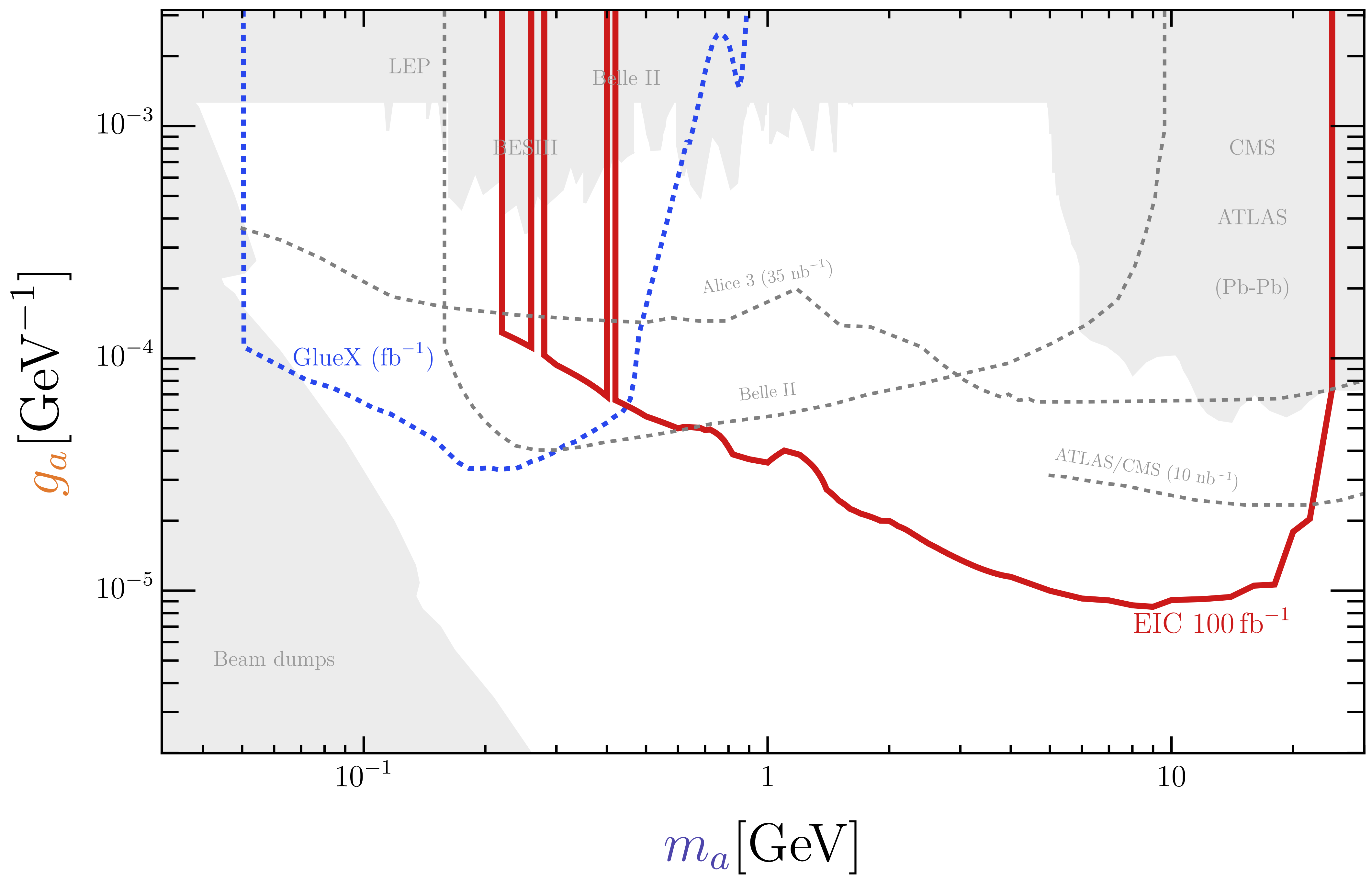
$E_e = 18\,\mathrm{GeV}$

$E_{\mathrm{Pb}} = 20\,\mathrm{TeV}$

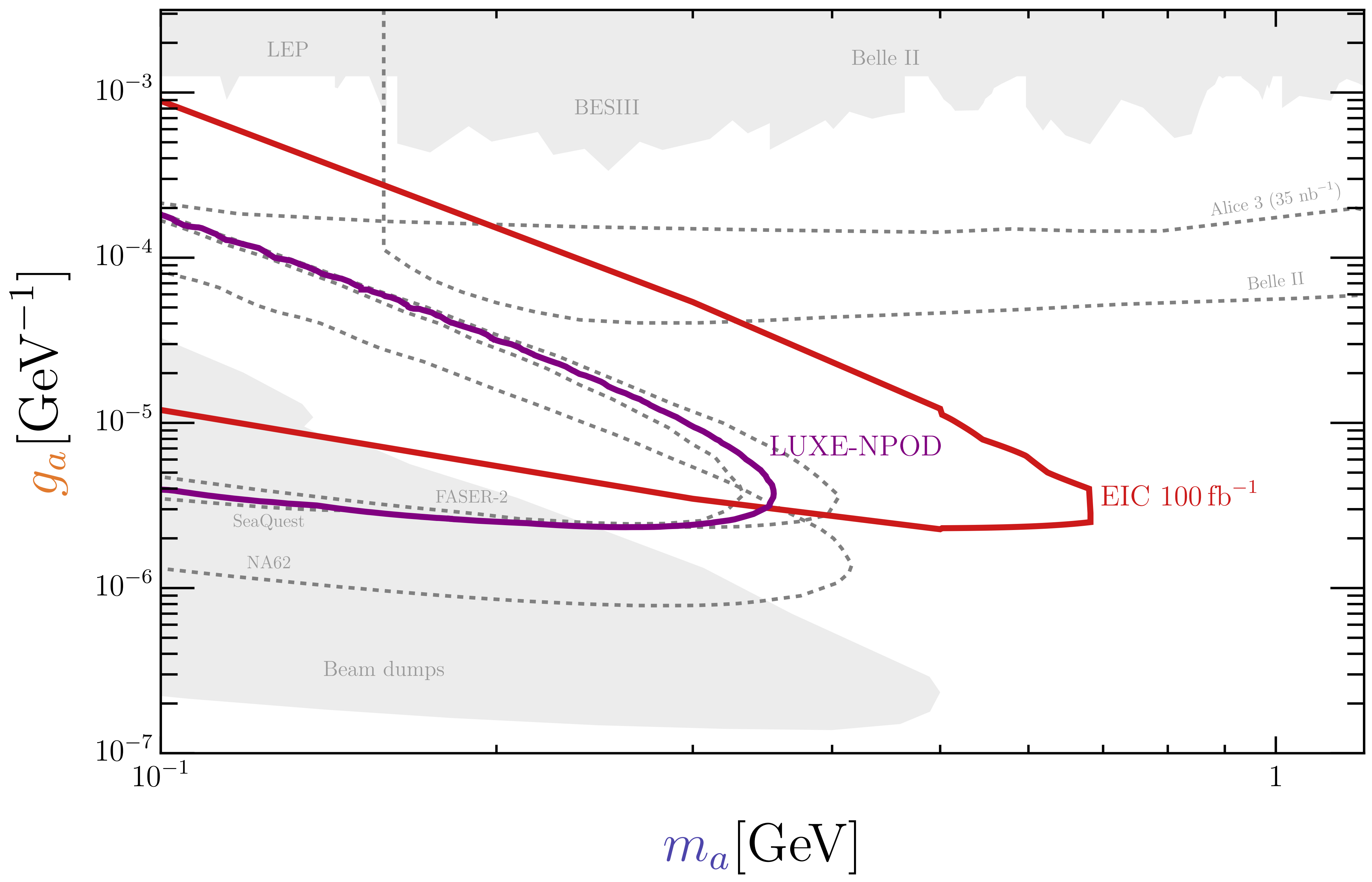


coherent production of new particles up to $m_a \sim 20\,\mathrm{GeV}$

prompt



displaced



Balkin, Hen, Li, Liu, Ma, YS, Williams JHEP 24

Axions at electron-ion collider (EIC)

axion with gluon couplings + invisible decay

$$\frac{a}{f_a}\frac{\alpha_s}{4\pi}G^{\mu\nu}\tilde{G}_{\mu\nu} + ig_{\chi a}a\bar{\chi}\gamma_5\chi$$

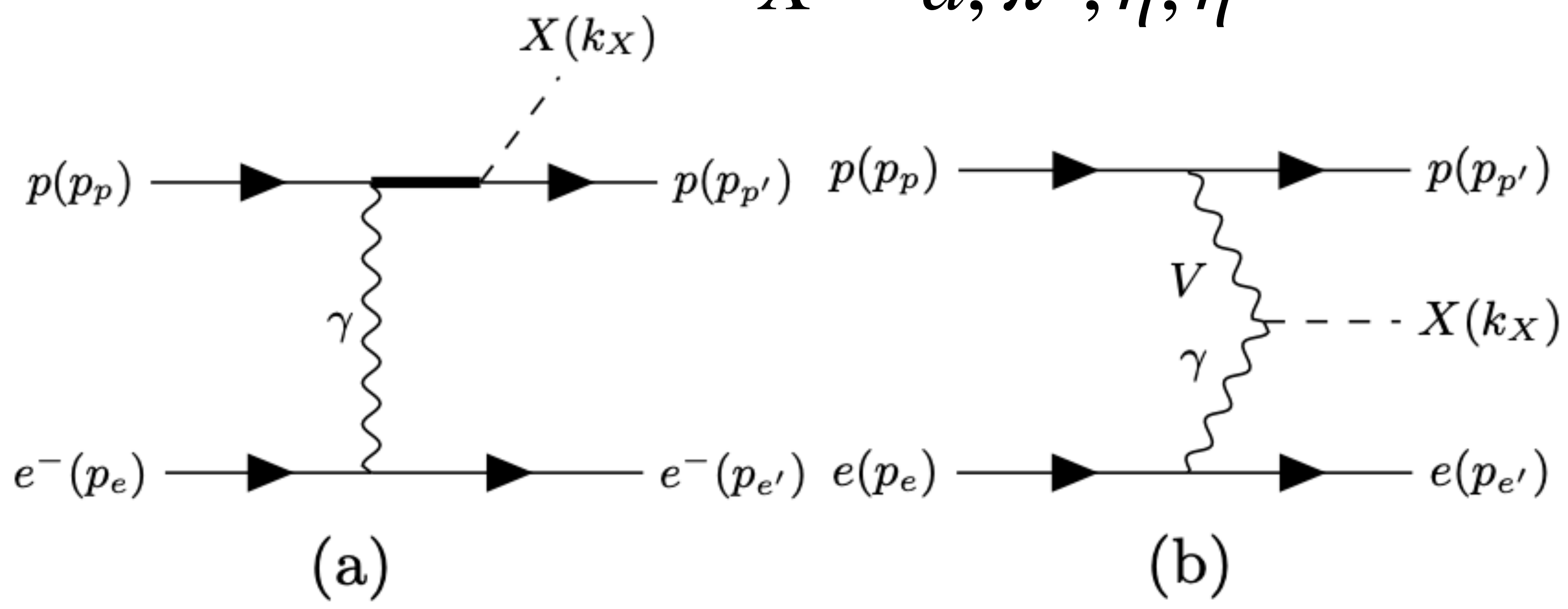
Balkin, Coren, Jentsch, Liu, Ovchynnikov, YS, Trifinopoulos
in progress

Axions at electron-ion collider (EIC)

axion with gluon couplings + invisible decay

$$\frac{a}{f_a}\frac{\alpha_s}{4\pi}G^{\mu\nu}\tilde{G}_{\mu\nu} + ig_{\chi a}a\bar{\chi}\gamma_5\chi$$

$$X = a, \pi^0, \eta, \eta'$$



$E_{p'} < E_p$ - large proton energy loss

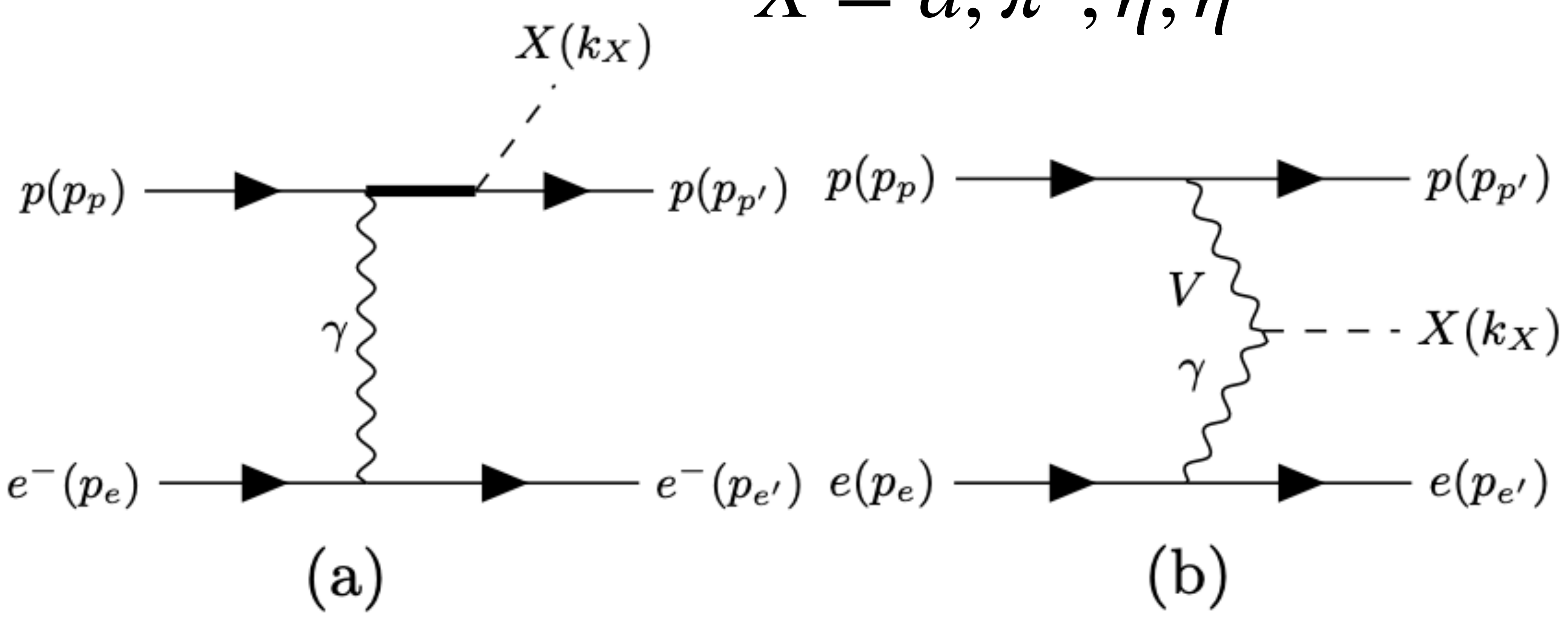
Balkin, Coren, Jentsch, Liu, Ovchynnikov, YS, Trifinopoulos
in progress

Axions at electron-ion collider (EIC)

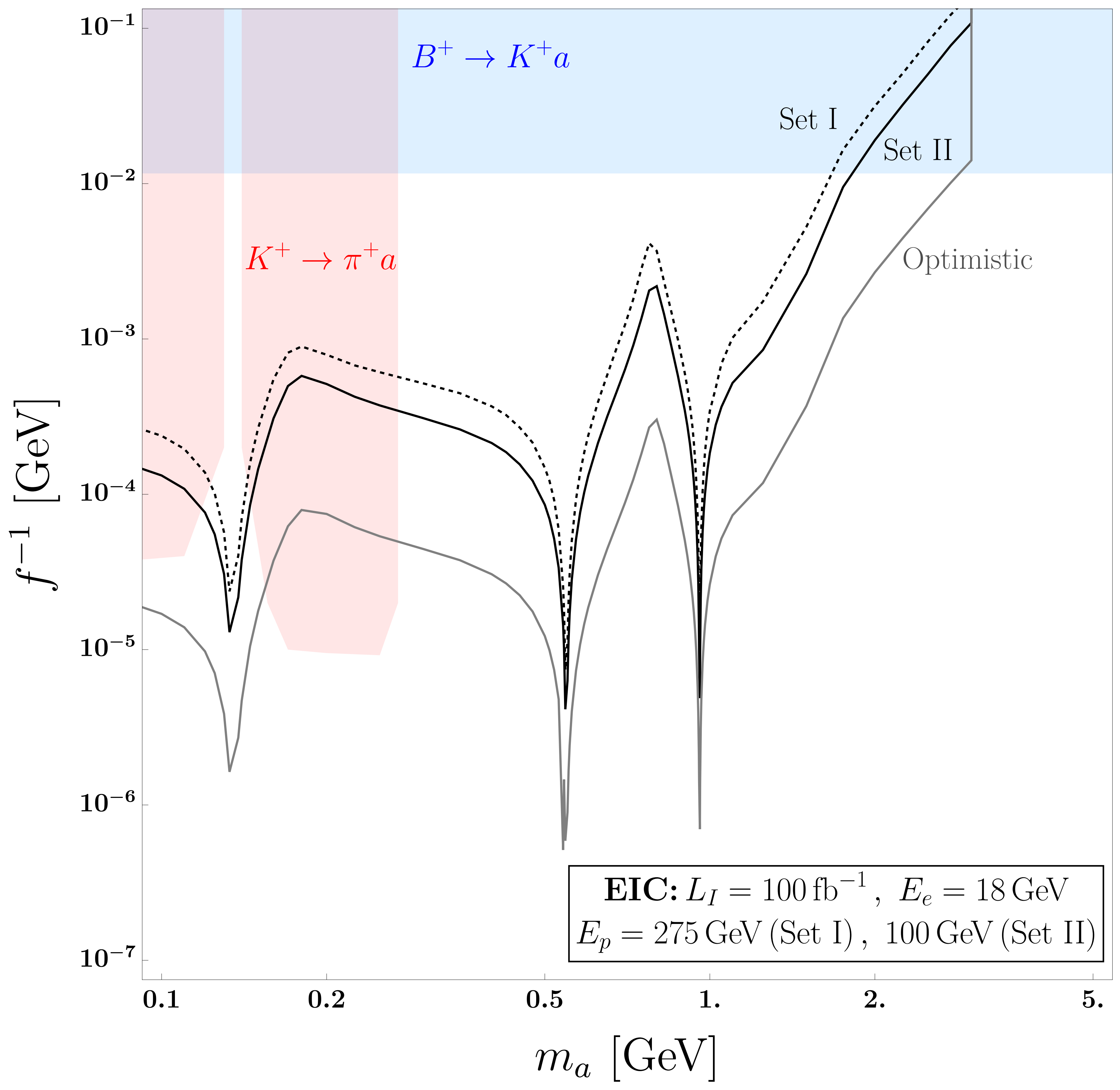
axion with gluon couplings + invisible decay

$$\frac{a}{f_a}\frac{\alpha_s}{4\pi}G^{\mu\nu}\tilde{G}_{\mu\nu} + i g_{\chi a} a \bar{\chi}\gamma_5\chi$$

$$X = a, \pi^0, \eta, \eta'$$



$E_{p'} < E_p$ - large proton energy loss



excellent sensitivity to: $\pi^0, \eta, \eta' \to \mathrm{inv}$

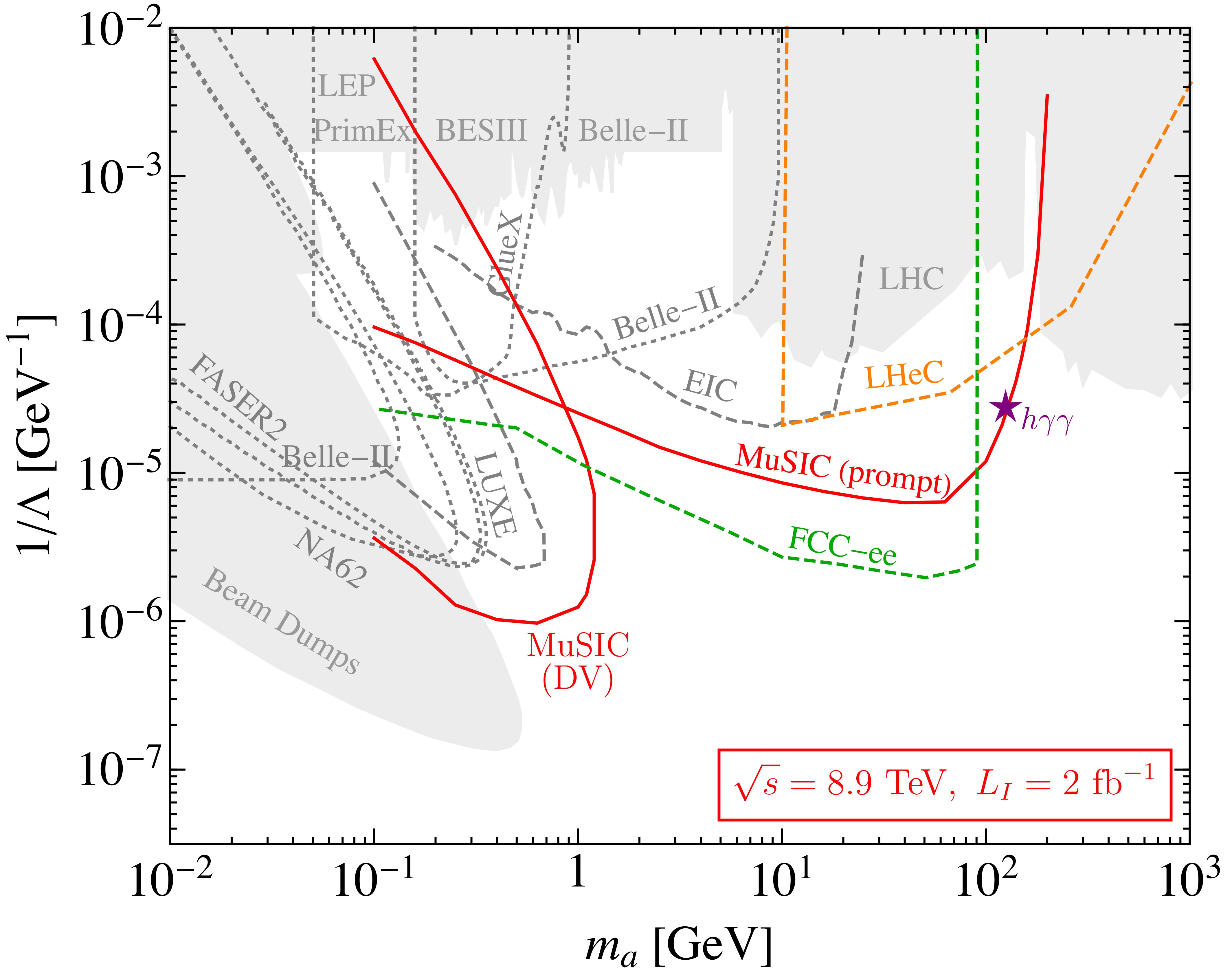
Balkin, Coren, Jentsch, Liu, Ovchynnikov, YS, Trifinopoulos
in progress

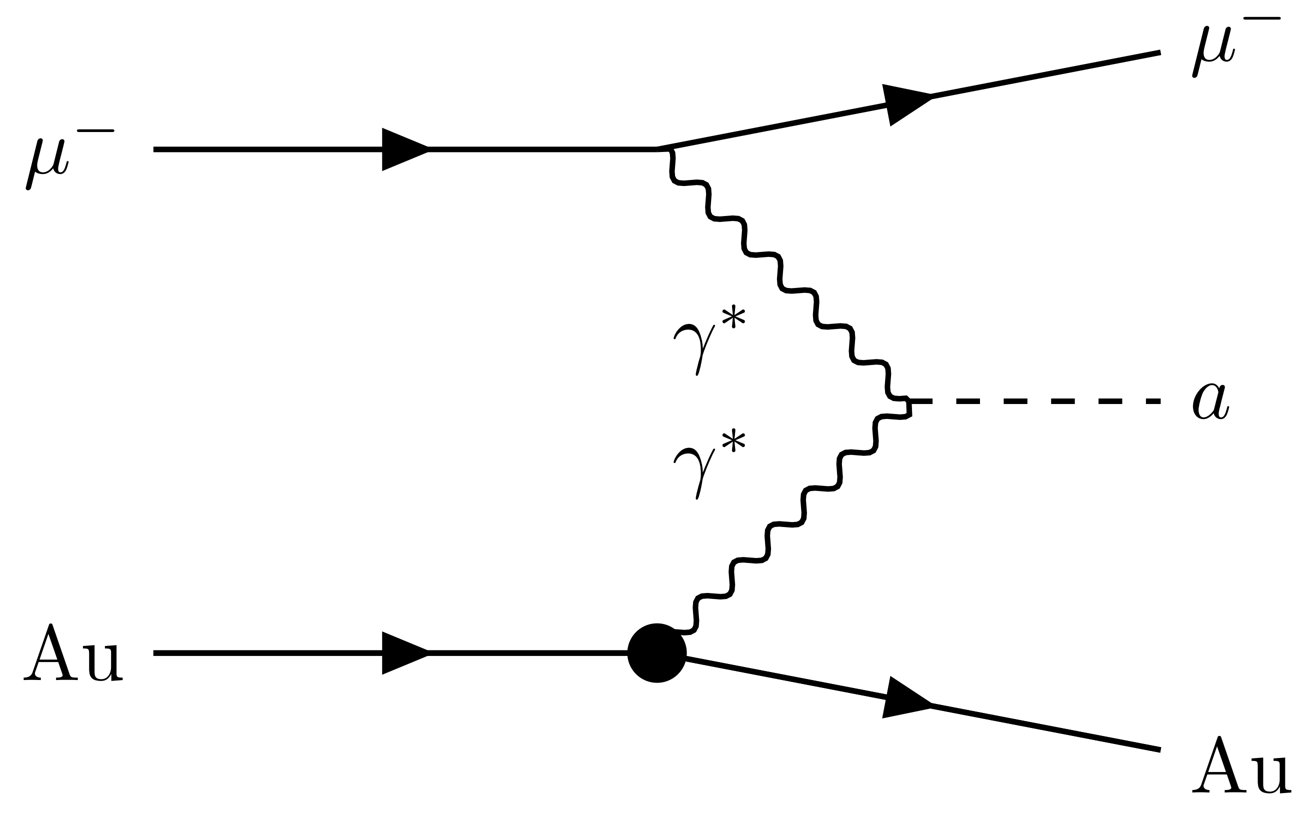
Axions at muon-ion collider (MuSIC)

How can we go more further (next decades)?
muon-ion collider

Davoudiasl, Liu, Marcarelli, YS, Trifinopoilos 2412.13289

Axions at muon-ion collider (MuSIC)



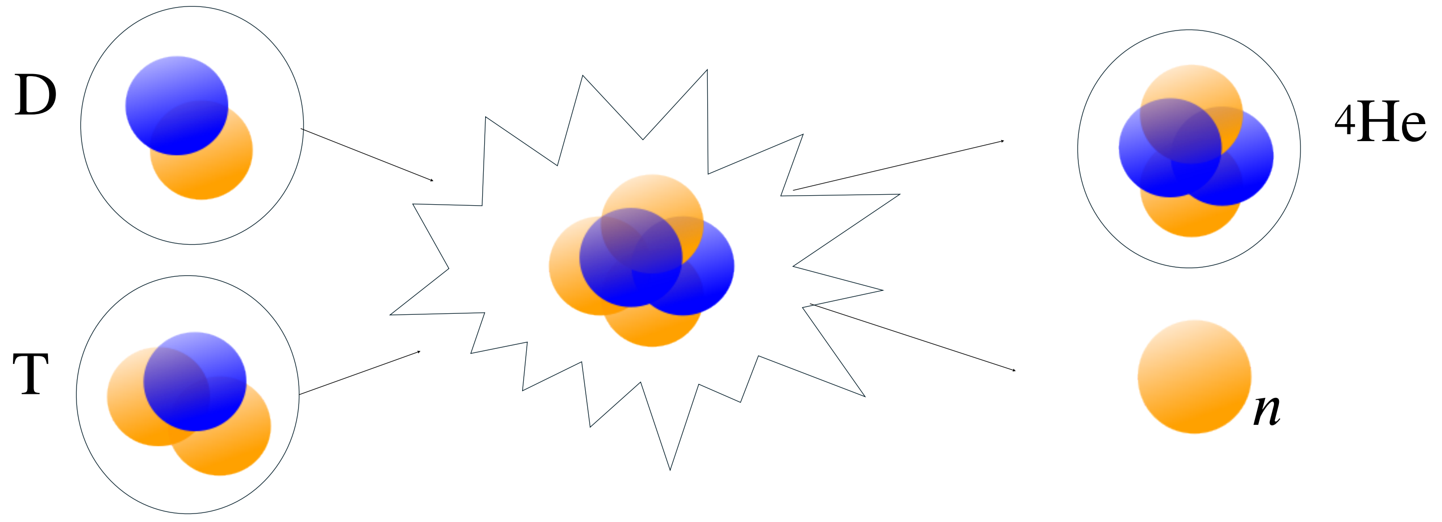


coherent production of new particles up to $m_a \sim 200\,\mathrm{GeV}$

$E_\mu \approx 1\,\mathrm{TeV}, E_{\mathrm{Au}} \approx 20\,\mathrm{TeV}$

Davoudiasl, Liu, Marcarelli, YS, Trifinopoilos 2412.13289

BSM at Fusion reactors



utilize the huge neutron flux

$$\Phi_n^{\text{total}} \sim 10^{15} \text{cm}^{-2}\text{sec}^{-1}$$

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

BSM at Fusion reactors

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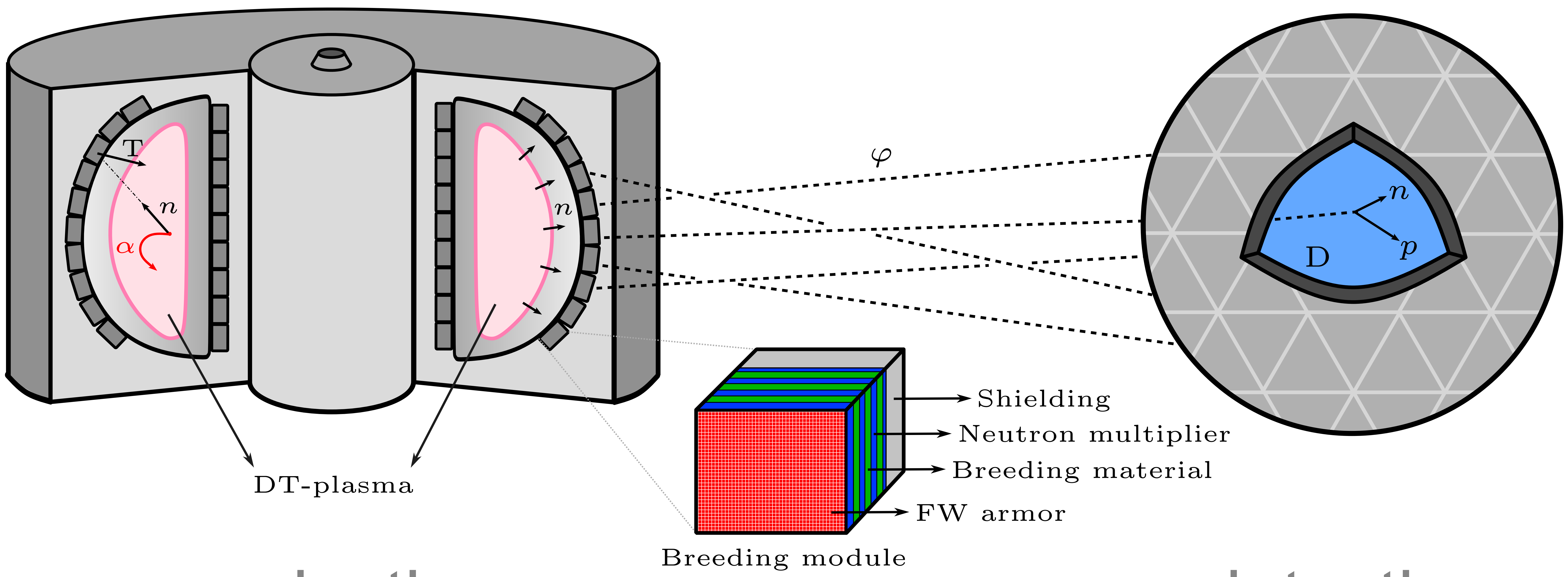

production

detection

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

New physics production

utilize the huge neutron flux
+ blanket as a target

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

New physics production

utilize the huge neutron flux
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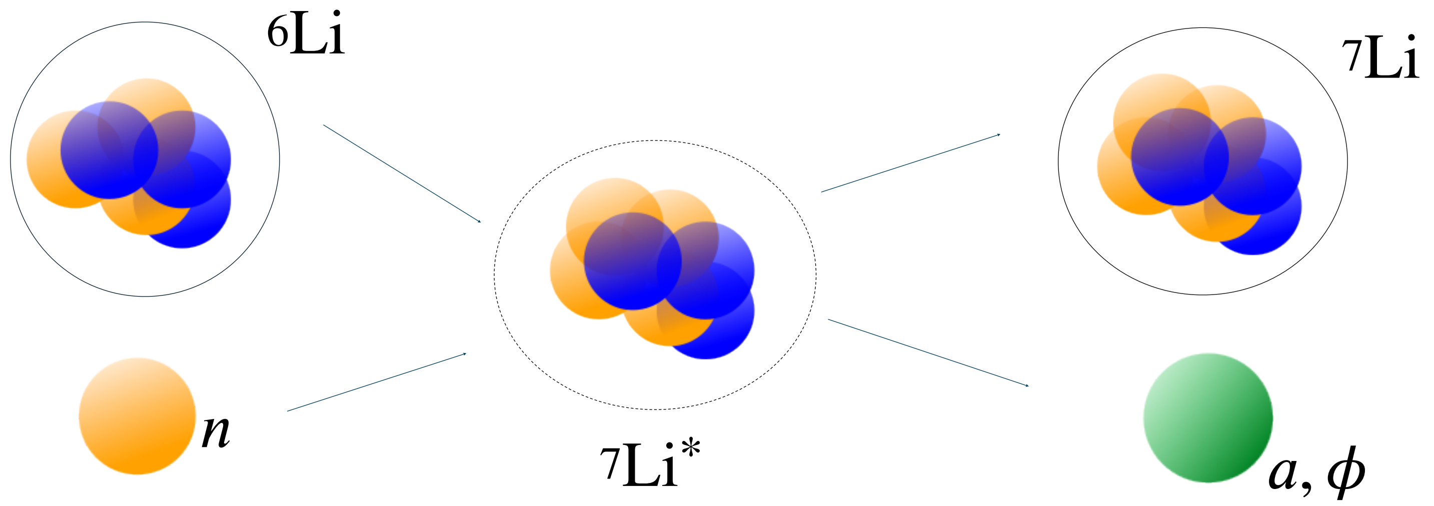

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

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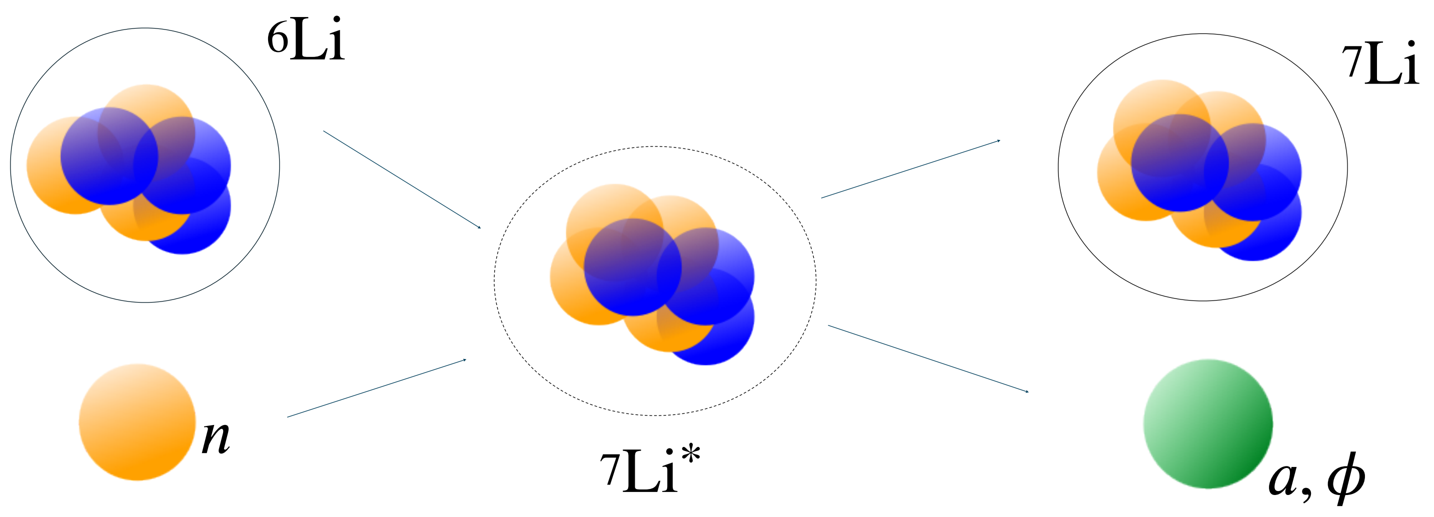

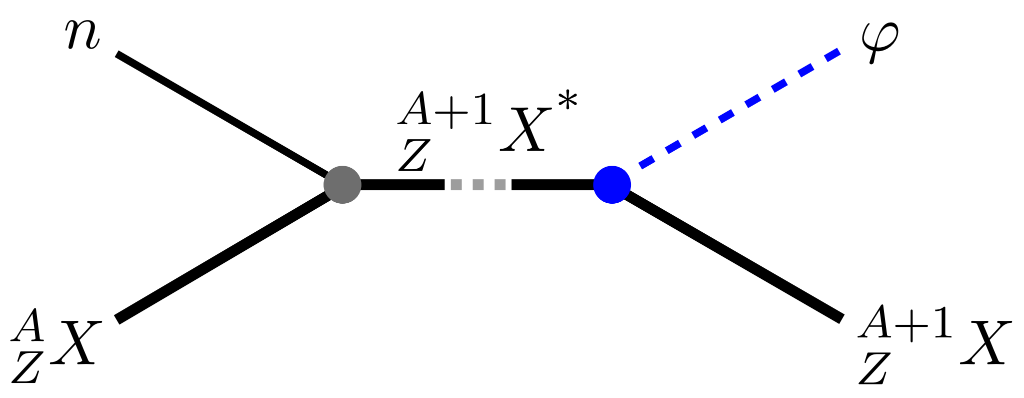

$$n + {}^A_Z X \to {}^{A+1}_{Z}X^* \to {}^{A+1}_{Z}X + \varphi$$

$$\frac{\sigma_{a;\mathrm{M1}}}{\sigma_{\gamma;\mathrm{M1}}} \propto \left(\frac{p_a}{E_\gamma}\right)^3 \frac{g_{ap}^2}{2\pi\alpha}, \quad \frac{\sigma_{\phi;\mathrm{M1}}}{\sigma_{\gamma;\mathrm{M1}}} \propto \frac{p_\phi}{E_\gamma}\frac{g_{\phi p}^2}{2\pi\alpha}$$

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

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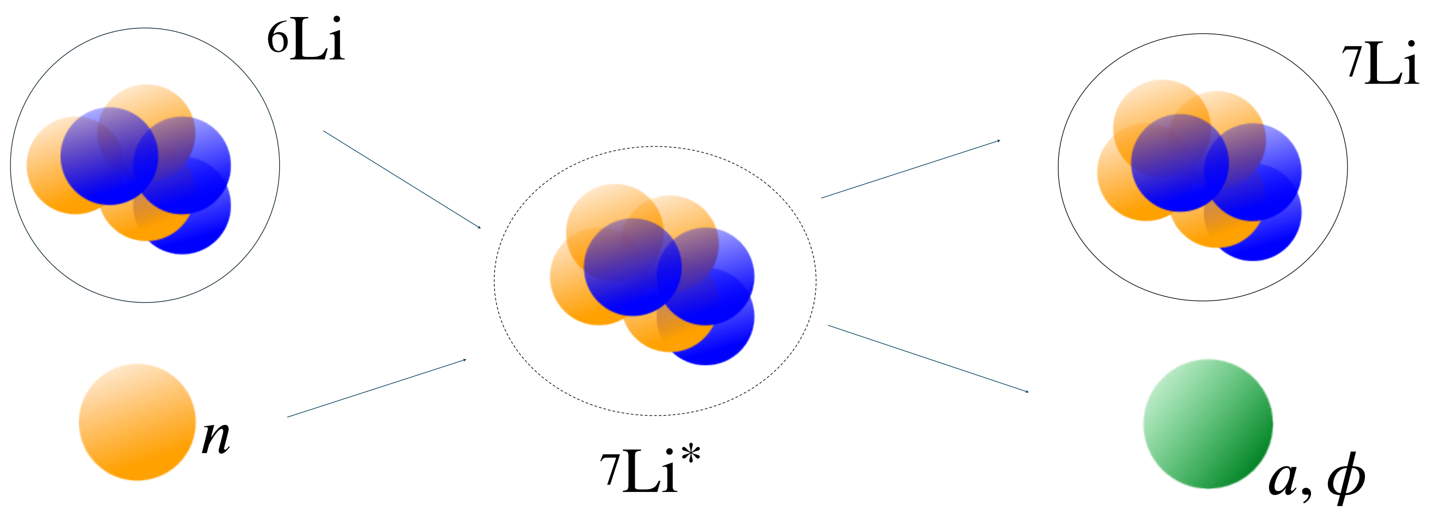

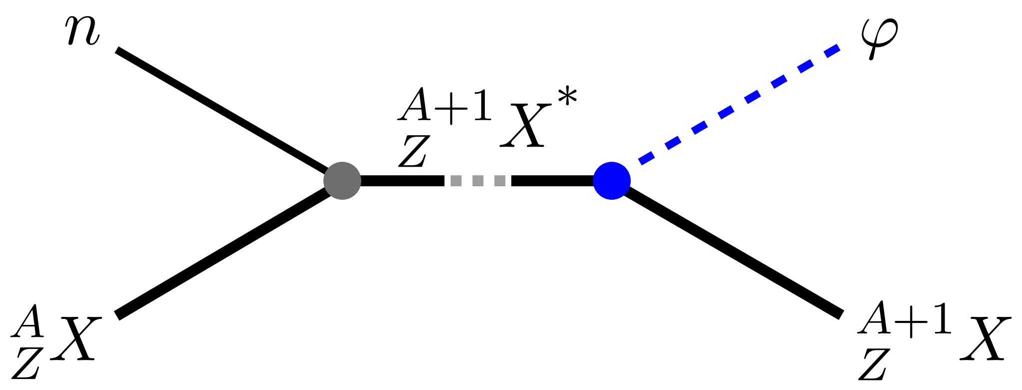

Resonant capture + de-excitation

$$n + {}^{A}_{Z}X \to {}^{A+1}_{Z}X^* \to {}^{A+1}_{Z}X + \varphi$$

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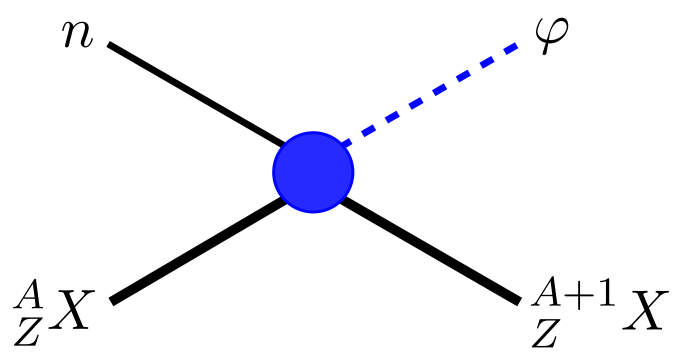


Non-resonant capture + de-excitation

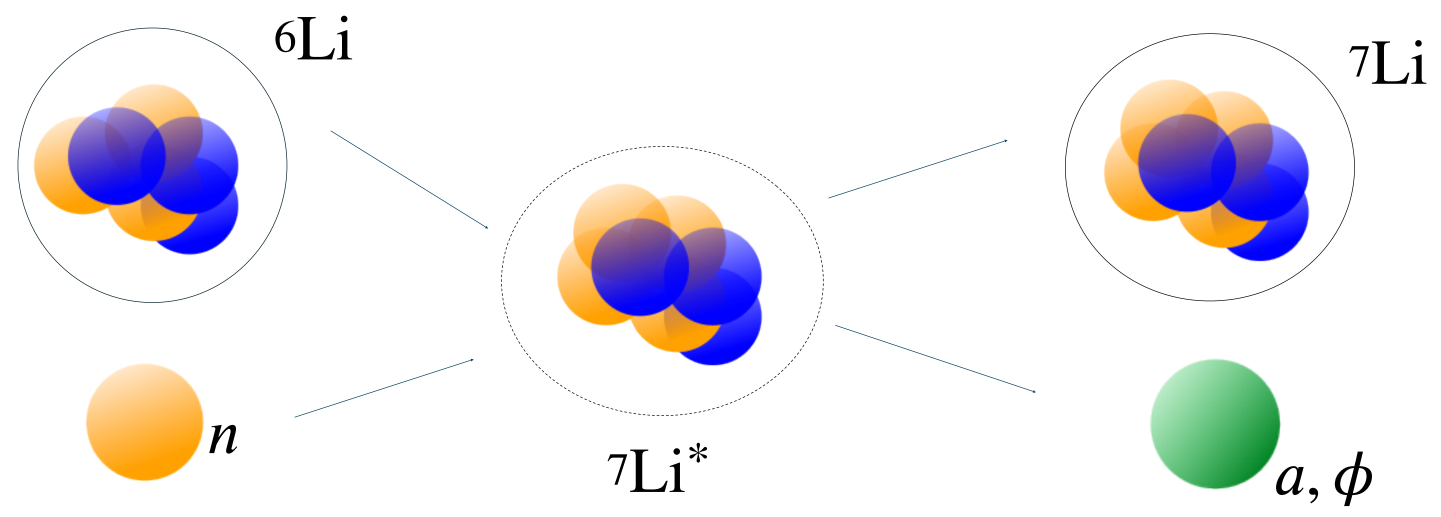
$$n + {}^{A}_{Z}X \to {}^{A+1}_{Z}X + \varphi$$

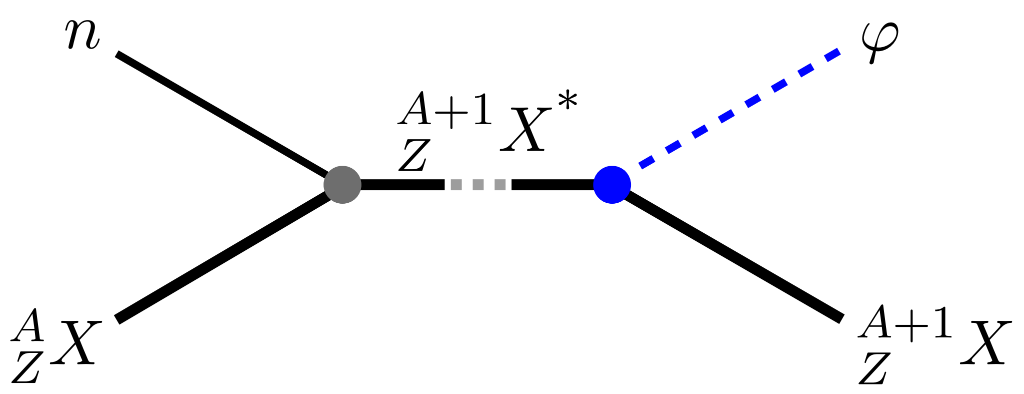
$$\frac{\sigma_{\phi}^{\mathrm{non-res}}}{\sigma_{\gamma;\mathrm{E1}}^{\mathrm{non-res}}} \sim \frac{g_{\phi p}^2}{e^2}\frac{Q^2}{E_\gamma^2}\frac{p_\phi}{E_\gamma}$$

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

New physics production

utilize the huge neutron flux
+ blanket as a target





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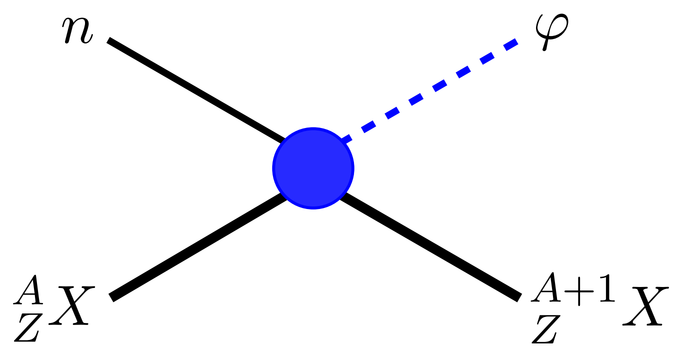

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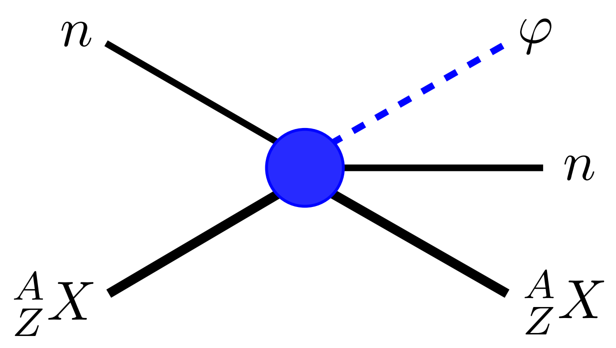


Coherent scattering

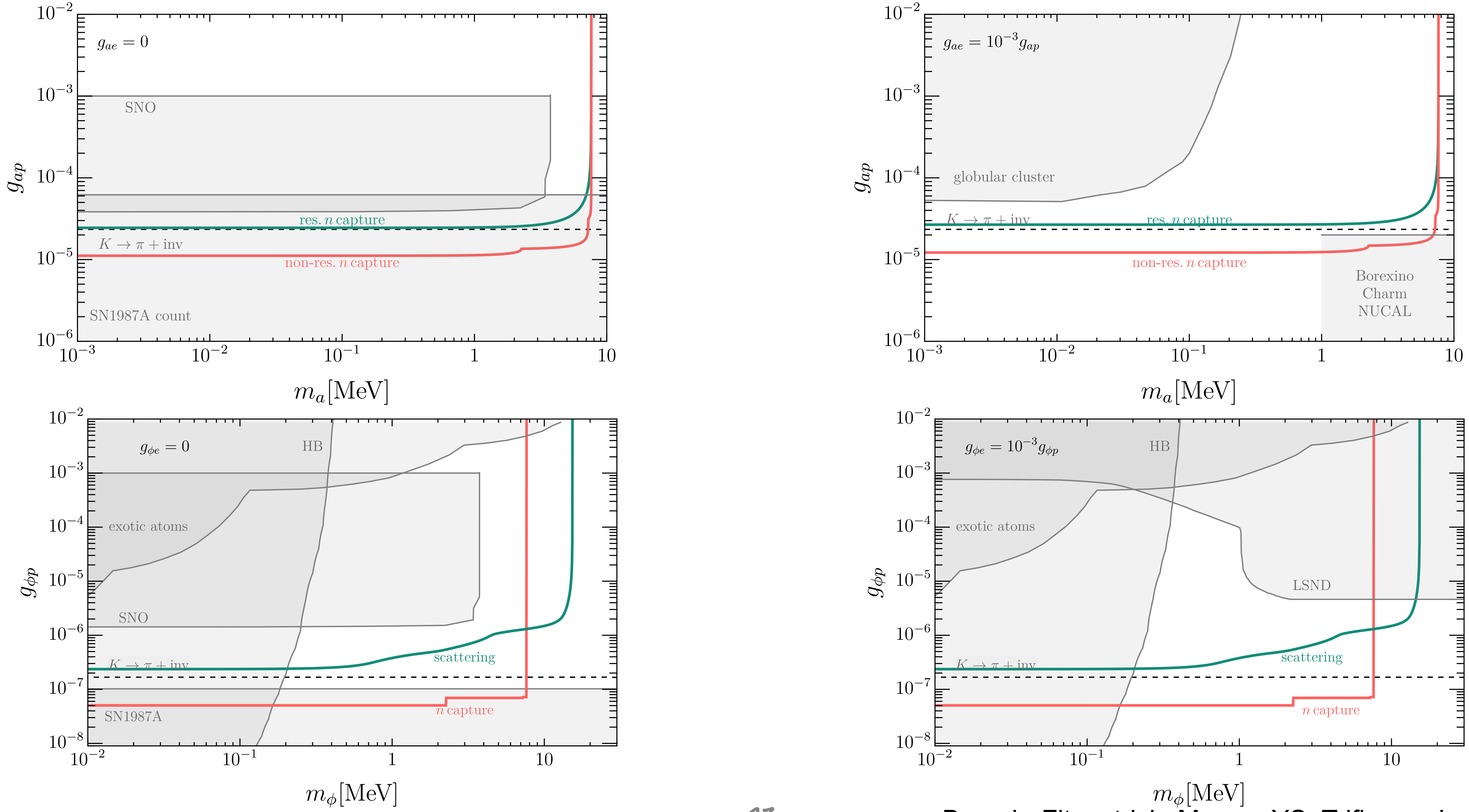
$$n + {}^A_Z X \to {}^A_Z X + n + \varphi$$

$$\frac{\sigma_\phi}{\sigma_{\mathrm{SM}}} \sim \frac{Z^2 g_{\phi p}^2}{16\pi^2 E_\phi^3} \left(E_\phi^2 - m_\phi^2\right)^{3/2}$$

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

BSM at Fusion reactors

only proton coupling | proton + small electron couplings



Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

True muonium

True muonium at LHCb

true muonium ($\mathscr{TM}$) = $\mu^+\mu^-$ bound state

Never observed!

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

true muonium ($\mathcal{TM}$) = $\mu^+\mu^-$ bound state

Never observed!

the 1^3S_1 state (spin-1) is a “dark photon” like state

$$m_{\mathcal{TM}} = 2m_\mu - B_E \approx 211\,\mathrm{MeV}$$

$$\varepsilon_{\mathcal{TM}} = \alpha^2/2 \approx 2.7 \times 10^{-5}$$

$$\mathcal{L} \supset \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

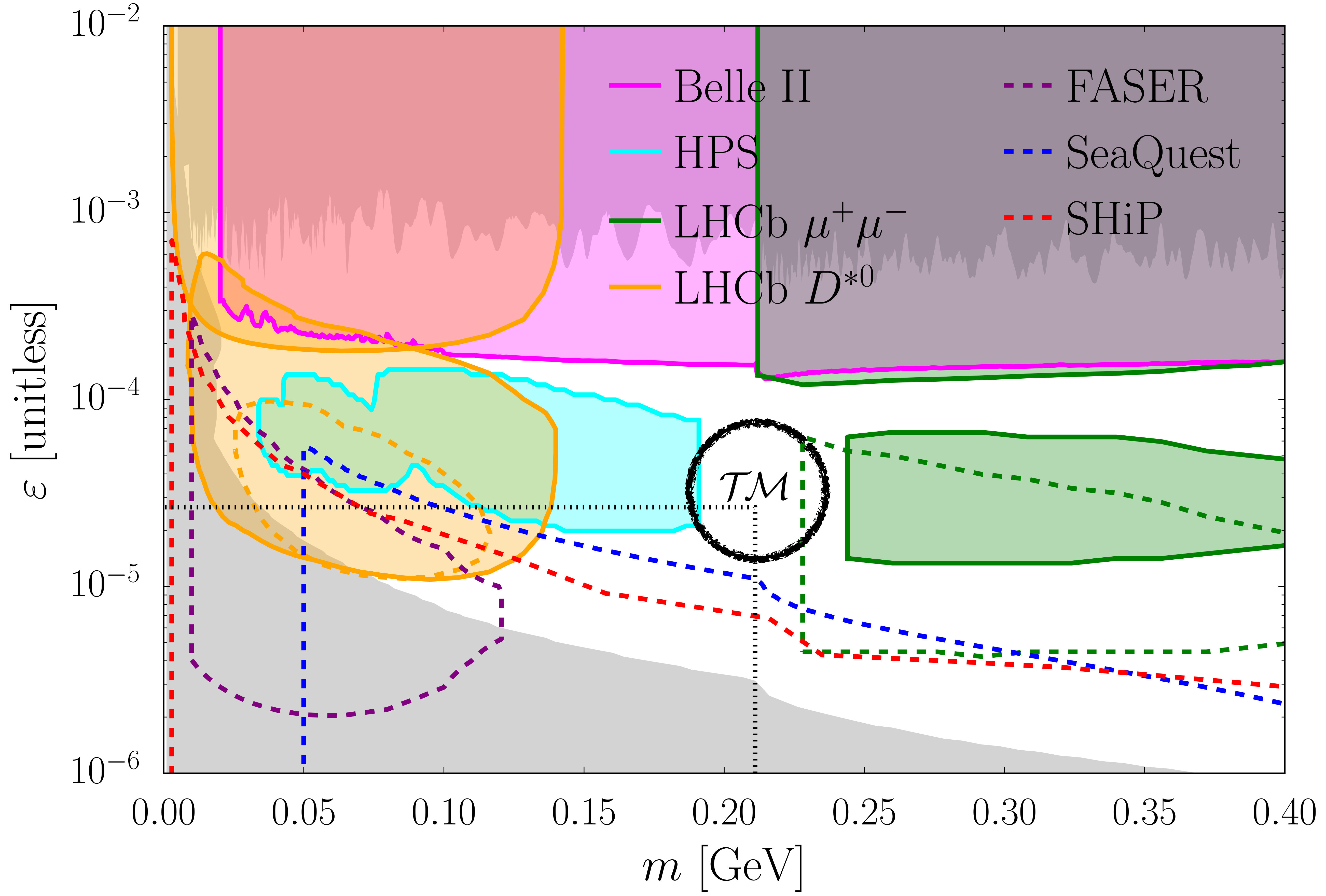
but it is dissociated due to muons detector material interaction

→ similar search strategy as dark photon

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

true muonium ($\mathscr{TM}$) = $\mu^+\mu^-$ bound state



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Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

dominant production

$$\eta \to \gamma\, \mathscr{T}\mathscr{M} \to \gamma\, e^+ e^-$$

$$c\tau_{\mathscr{T}\mathscr{M}} \approx 0.53\,\mathrm{mm}\,,\ \sigma_{m_{ee}} \approx 20\,\mathrm{MeV}$$

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

True muonium at LHCb

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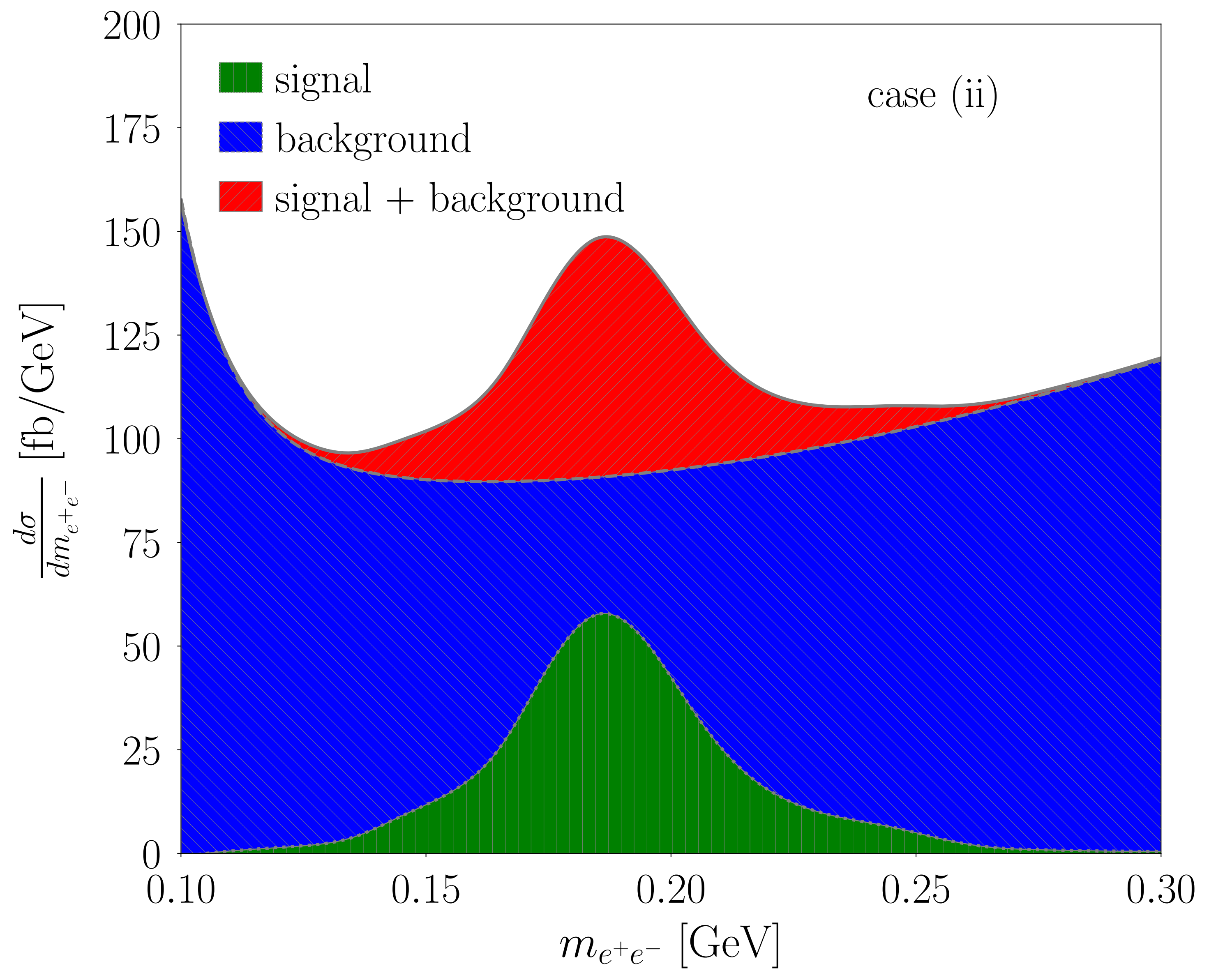
$$\eta \to \gamma\, \mathcal{TM} \to \gamma\, e^+e^-$$

$$c\tau_{\mathcal{TM}} \approx 0.53\,\mathrm{mm}\,,\ \sigma_{m_{ee}} \approx 20\,\mathrm{MeV}$$

displaced e^+e^- resonance

reconstruct: $e^+e^-\gamma$



expect $5\sigma_{\rm stat}$ (discovery) within next LHCb run ($15\,\mathrm{fb}^{-1}$)

Cid Vidal, Ilten, Plews, Shuve, YS, PRD 19

Summary

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* Kaon decay can be disentangled from spectroscopy.

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* Precision spectroscopy is a powerful probe of new hadronic interactions.

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* Kaon decay can be disentangled from spectroscopy.
* Precision spectroscopy is a powerful probe of new hadronic interactions.
* In the next coming years new options will be open for ALPs physics (LUXE, EIC).

backups

Kaon decays: $K \to \pi\phi$

$$\mathcal{M}(K^+ \to \pi^+\phi) = \frac{1}{f}\Bigg\{ \frac{1}{2}(\kappa_W - K_\Theta)\Big[\gamma_1\big(m_K^2 - m_\phi^2 + m_\pi^2\big) - 2\gamma_2\big(m_K^2 + m_\pi^2\delta_I\big)\Big] + \frac{1}{4}\kappa_{sd}^{\phi*}\left[2m_K^2 - m_\pi^2(1-\delta_I)\right] + \frac{m_\pi^2}{4}\kappa_{ds}^{\phi*}(1+\delta_I)$$
$$-\frac{m_\pi^2}{4}\left(\kappa_u^\phi - \frac{\kappa_{s+d}^\phi}{2}\right)\gamma_1(1-\delta_I) + \frac{m_\pi^2\kappa_{s-d}^\phi}{8(m_K^2 - m_\pi^2)}\Big(m_K^2\big[(3+\delta_I)\gamma_1 - 4(1+\delta_I)\gamma_2\big] - m_\pi^2\big[(1-\delta_I)\gamma_1 - 2\gamma_2\big]\Big)\Bigg\}$$

$$\mathcal{M}(K_L \to \pi^0\phi) = -\frac{1}{f}\Bigg\{ \frac{1}{2}(\kappa_W - K_\Theta)\Big[\gamma_1\big(m_K^2 - m_\phi^2 + m_\pi^2\big) - 2\gamma_2 m_K^2\Big] + \frac{1}{4}\mathrm{Re}\,\kappa_{sd}^\phi\left[2m_K^2 - m_\pi^2(1+\delta_I)\right]$$
$$+\frac{m_\pi^2}{4}\mathrm{Re}\,\kappa_{ds}^\phi(1+\delta_I) + \frac{\kappa_{s-d}^\phi m_\pi^2}{4(m_K^2 - m_\pi^2)}(\gamma_1 - \gamma_2)\left[2m_K^2(1+\tilde{\delta}_I) - m_\pi^2\right]\Bigg\}$$

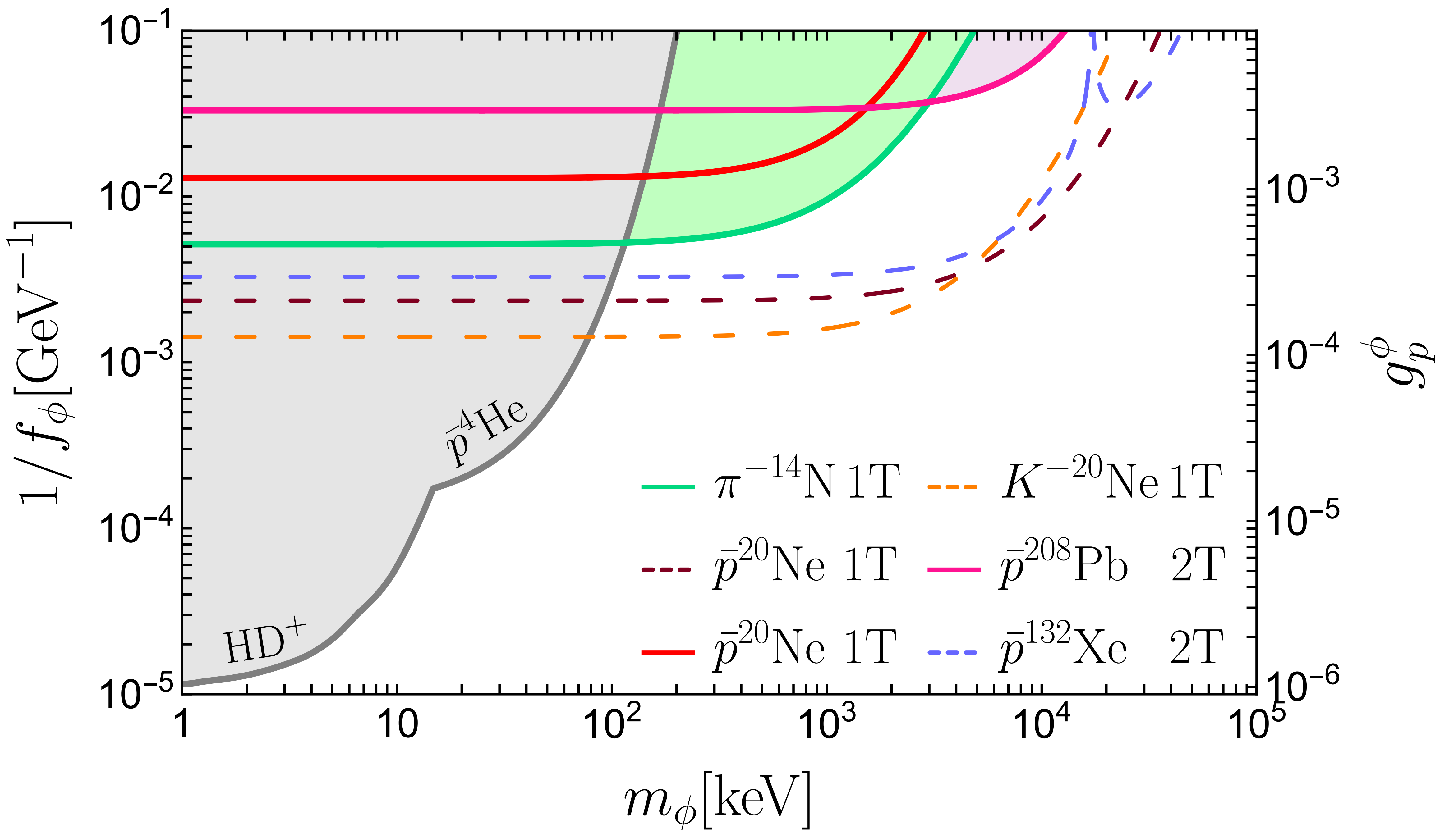
$$\mathcal{M}(K_S \to \pi^0_{\mathrm{int}}\phi) = \frac{1}{4f}\Bigg\{ \mathrm{Im}\,\kappa_{sd}^\phi\left[2m_K^2 - m_\pi^2(1+\delta_I)\right] + \mathrm{Im}\,\kappa_{ds}^\phi m_\pi^2(1+\delta_I)\Bigg\}$$

$$\mathcal{M}(K^+ \to \pi^+\phi) + \mathcal{M}(K_L \to \pi^0\phi) + i\mathcal{M}(K_S \to \pi^0\phi) = 0$$

Delaunay, Kitahara, YS, Zupan, 2501.16477

Exotic atoms for BSM

uds-model

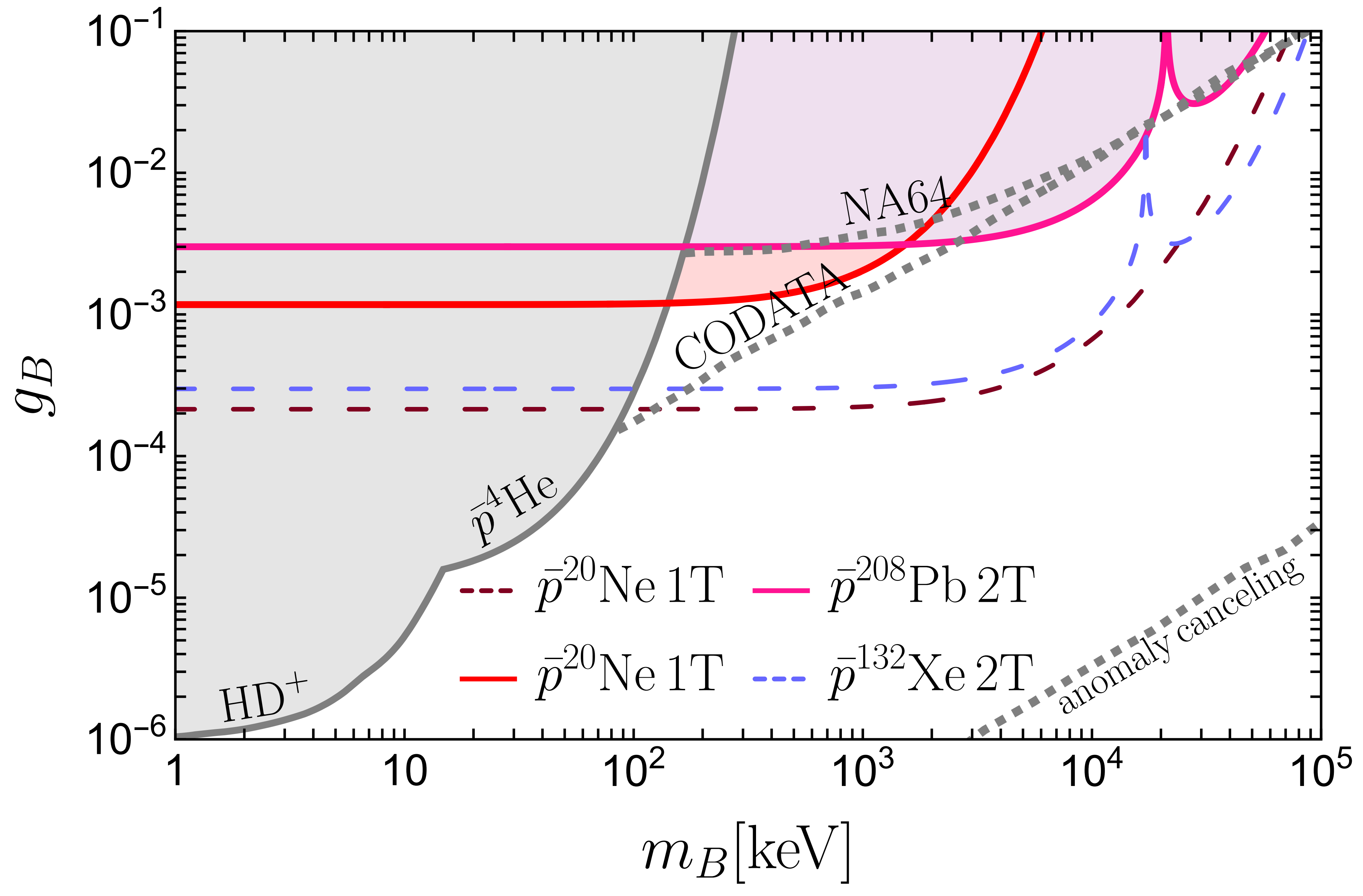


$$\frac{\phi}{f_\phi} \sum_{q=u,d,s} m_q \bar{q} q$$

avoid bounds from $K \to \pi + \mathrm{inv}$

Delaunay, Kitahara, YS, Zupan, 2501.16477

B-number + invisible



$$\frac{g_B}{3} B^\mu \sum_q \bar{q}\gamma_\mu q - \frac{g_B e^2}{48\pi^2} B^\mu \sum_\ell \bar{\ell}\gamma_\mu \ell$$

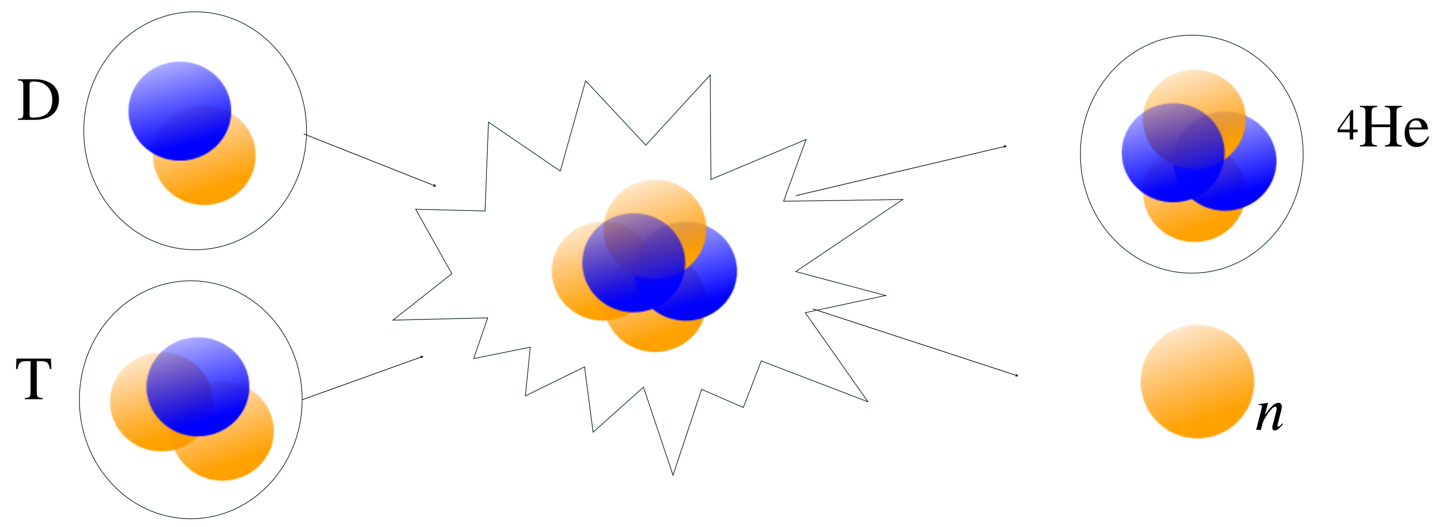
Liu, Ohayon, Shtaif, YS, 2502.03537

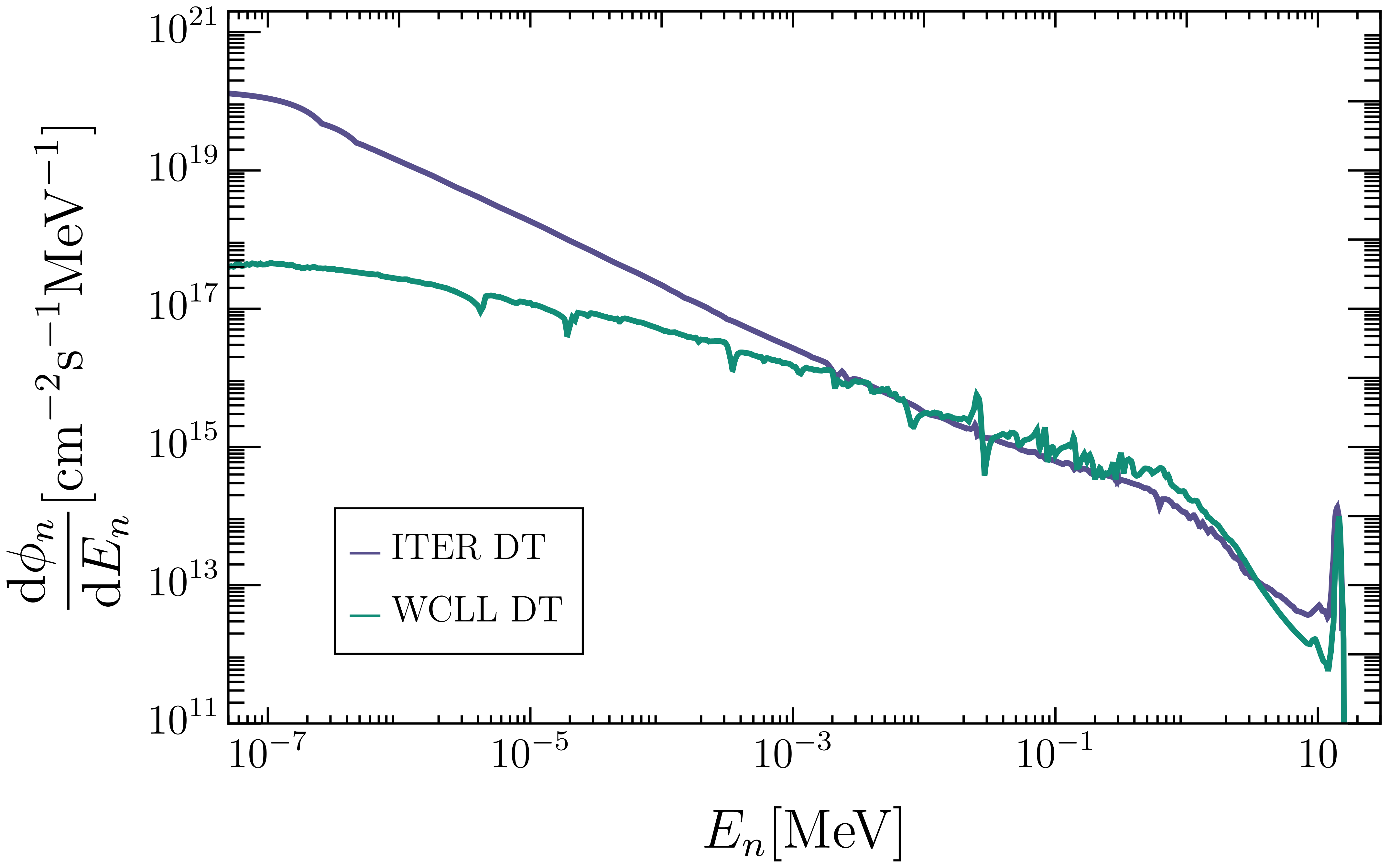
BSM at Fusion reactors

$$^2_1\mathrm{D} + ^3_1\mathrm{T} \to ^4_2\mathrm{He} + n + 17.6\,\mathrm{MeV}$$

utilize the huge neutron flux
$\Phi_n^{\mathrm{total}} \sim 10^{15}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

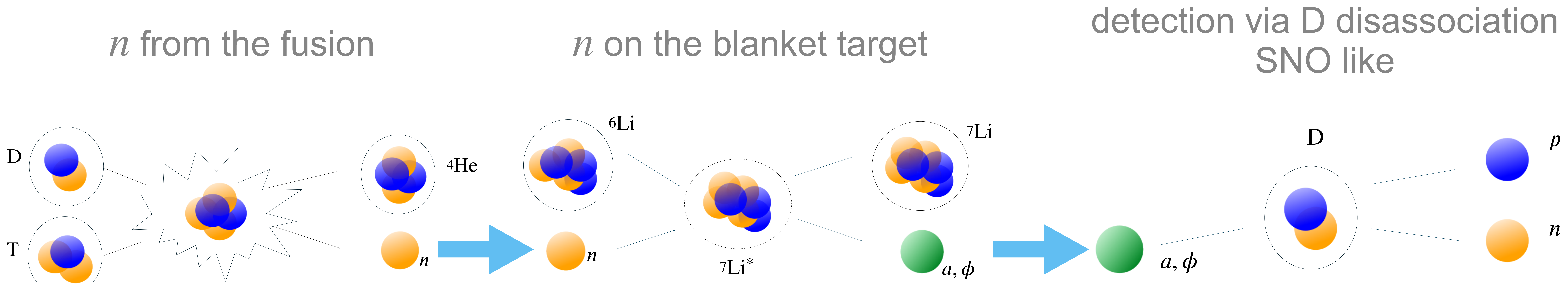
energy excess to new particle
$^2_1\mathrm{D} + ^3_1\mathrm{T} \to ^4_2\mathrm{He} + n + \varphi$





Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

New physics chain



$E_\varphi > 2.2$ MeV

number of detected events: $N_\varphi = TN_D \int dE_n dE_\varphi \frac{d\Phi_\varphi}{dE_n} \sigma_{\varphi \mathrm{D} \to np} \propto g_{\varphi p}^4$

operation time (T)

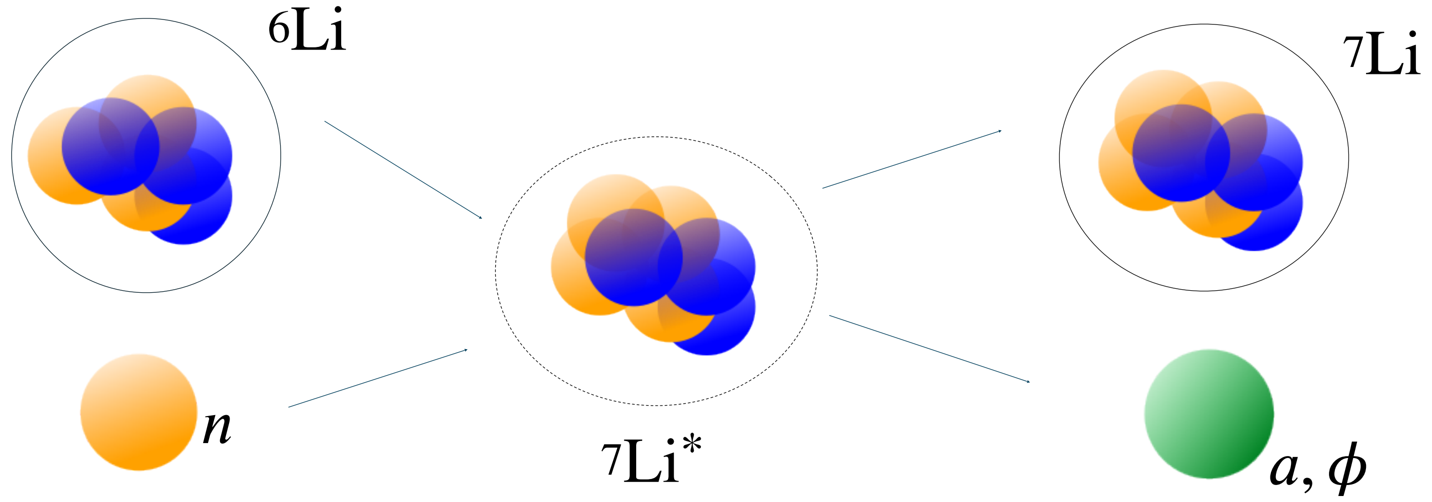
# of deuterium targets (N_D)

detection cross section ($\sigma_{\varphi \mathrm{D} \to np}$)

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

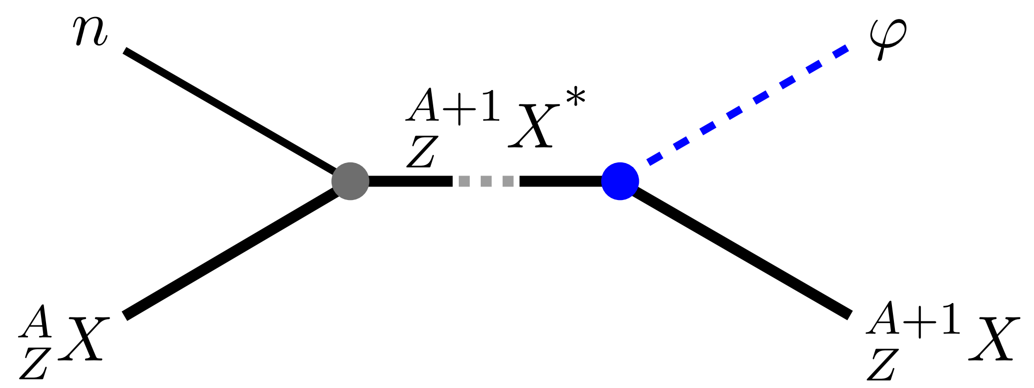
New physics production

utilize the huge neutron flux
+ blanket as a target

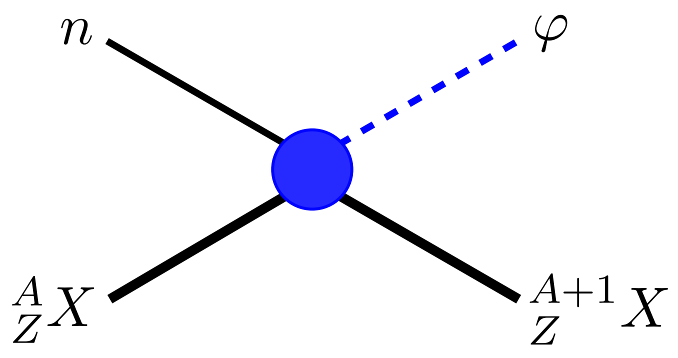


new physics flux

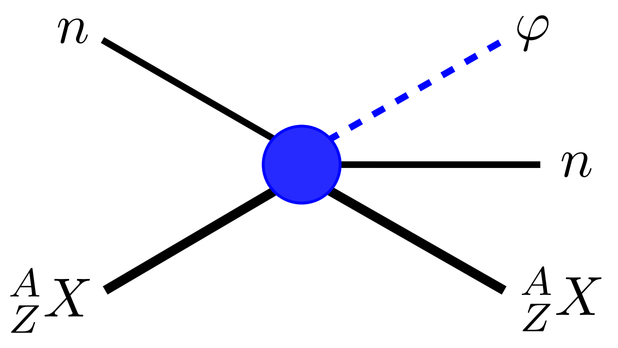
$$\frac{d\Phi_\varphi}{dE_n} = \frac{1}{4\pi L^2}\sum_{i,X} N_X \frac{d\Phi_n}{dE_n}\sigma_\varphi^{i,X}$$



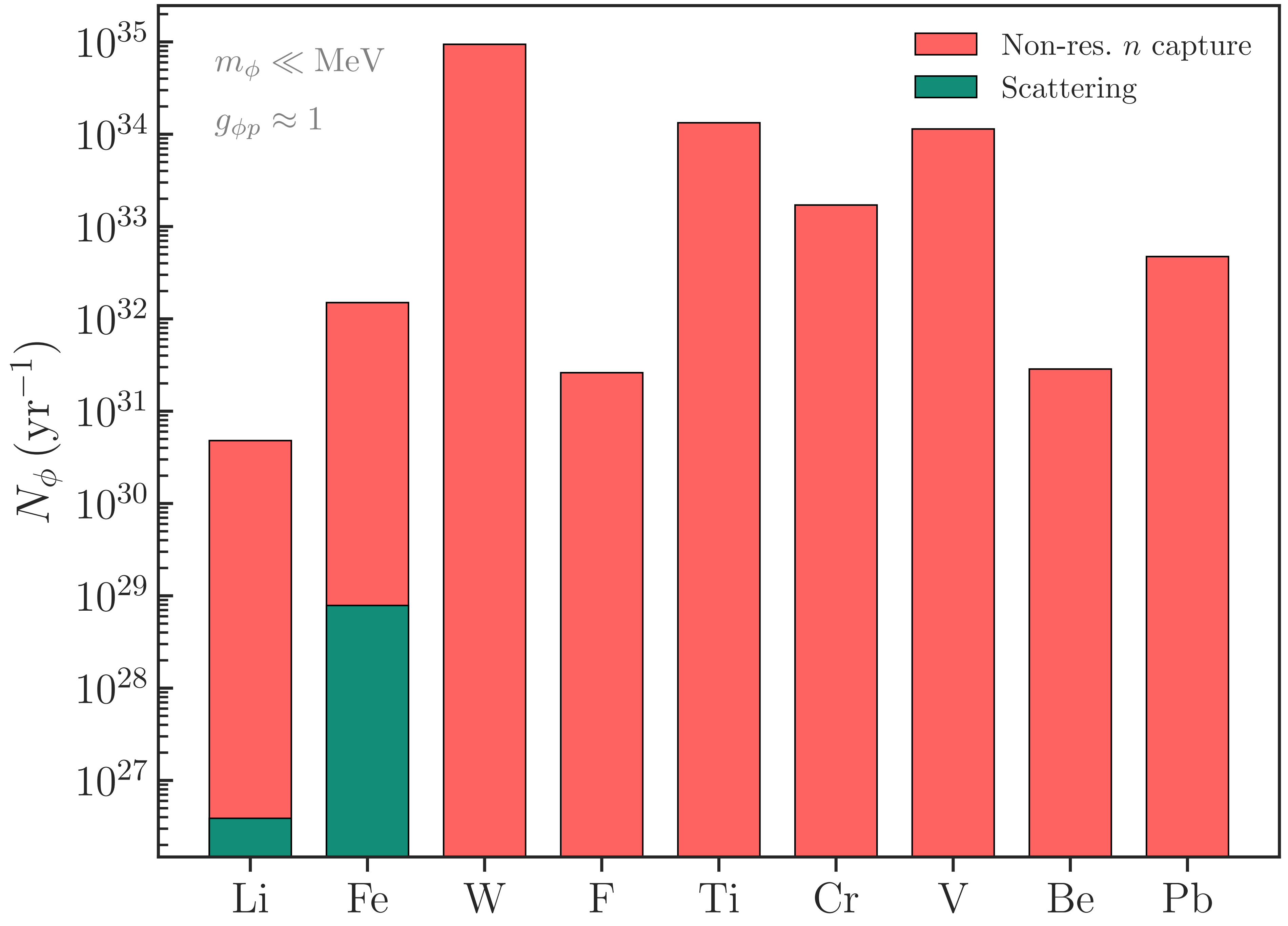
Resonant capture + de-excitation

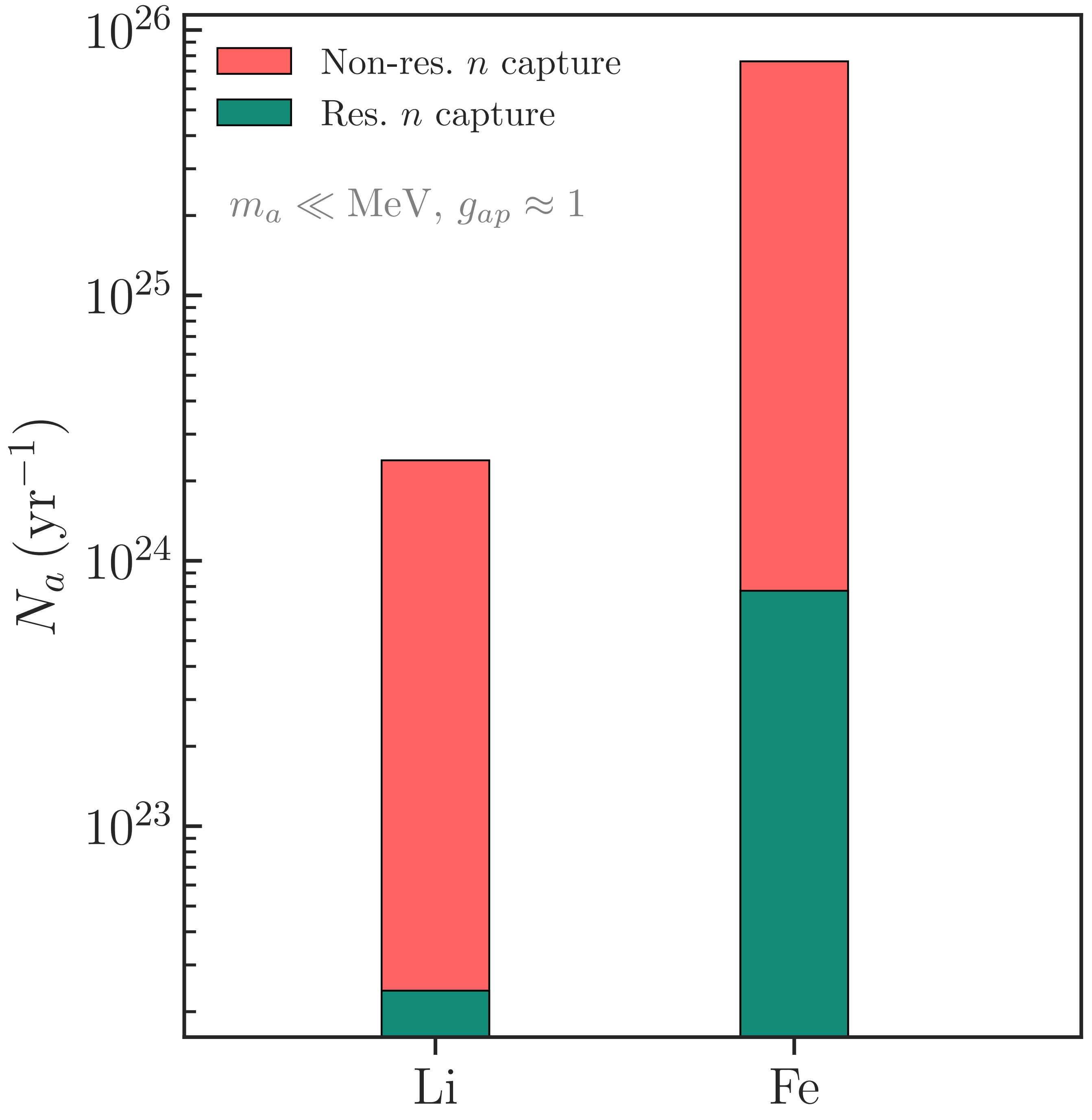


Non-resonant capture + de-excitation



Coherent scattering



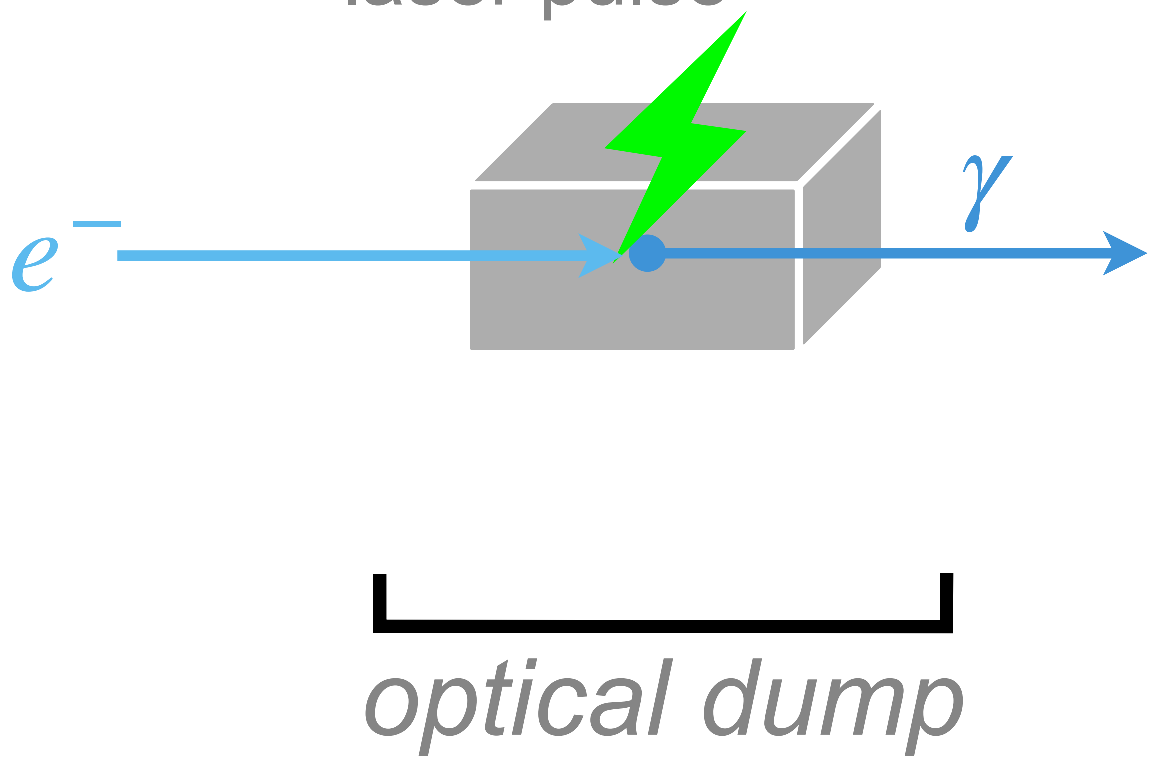


$N_X = 10^{29}$ target nuclei, ITER with 2000W

Baruch, Fitzpatrick, Menzo, YS, Trifinopoulos, Zupan, 2502.12314

Axions at an optical dump

LUXE-NPOD
(new physics at optical dump)



Bai, Blackburn, Borysov, Davidi, Hartin,
Heinemann, Ma, Perez, YS, Tal Hod PRD 22

Axions at an optical dump

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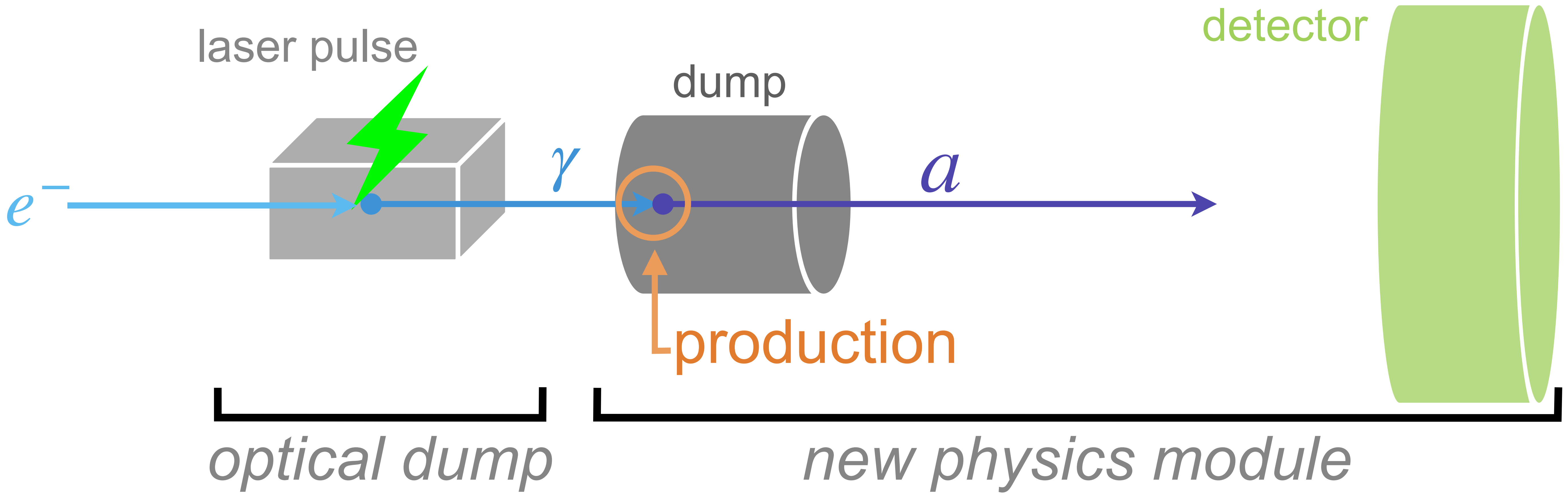

adopted by the LUXE collaboration

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, YS, Tal Hod PRD 22

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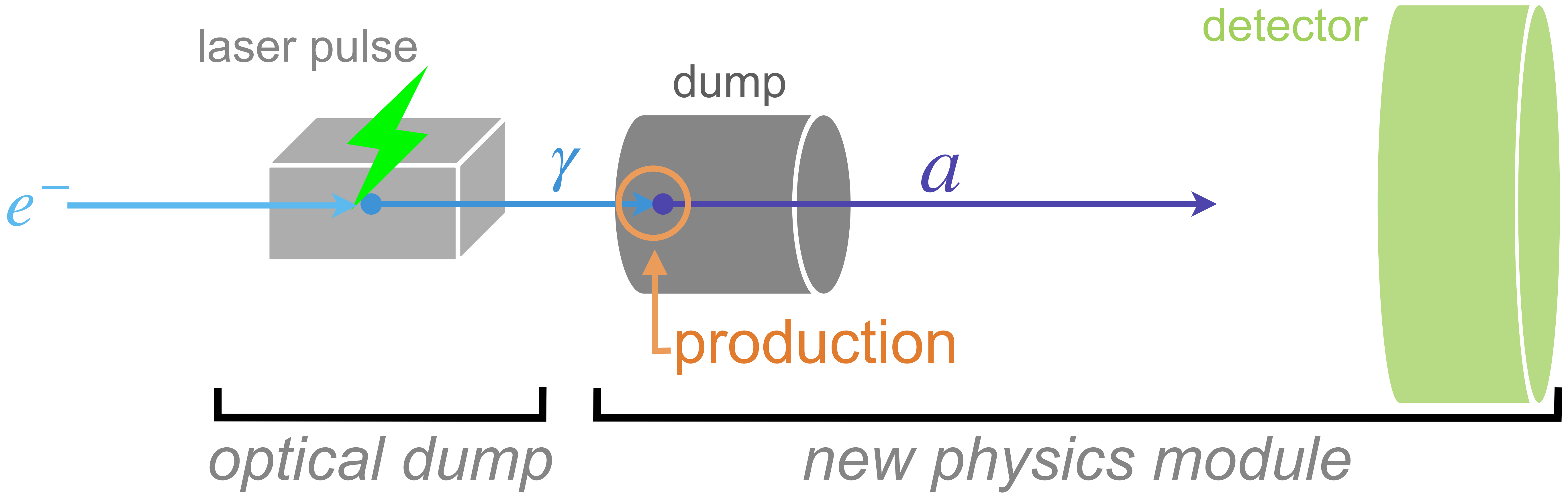
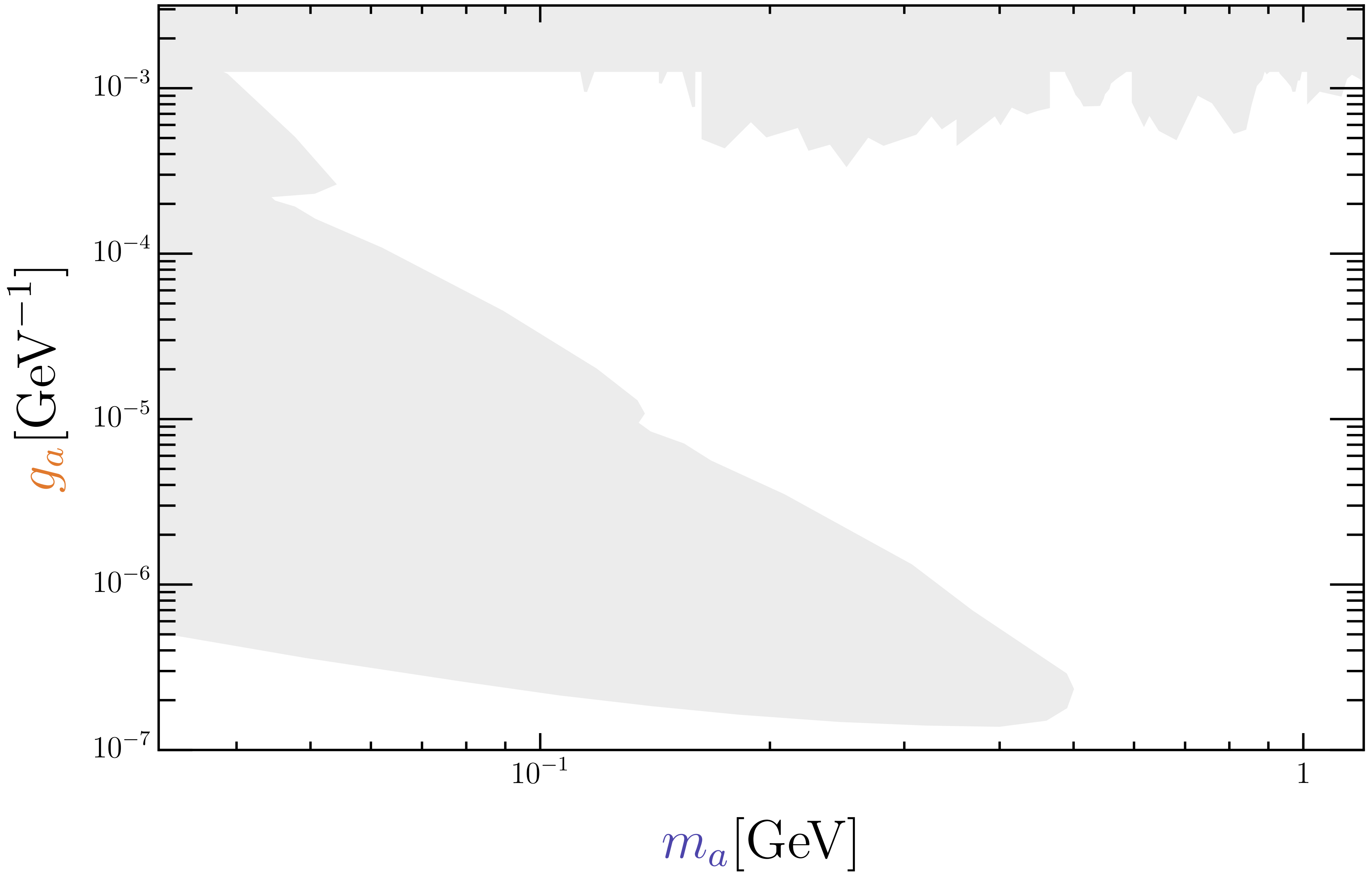


adopted by the
LUXE collaboration

$$\frac{g_a}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Bai, Blackburn, Borysov, Davidi, Hartin,
Heinemann, Ma, Perez, YS, Tal Hod PRD 22

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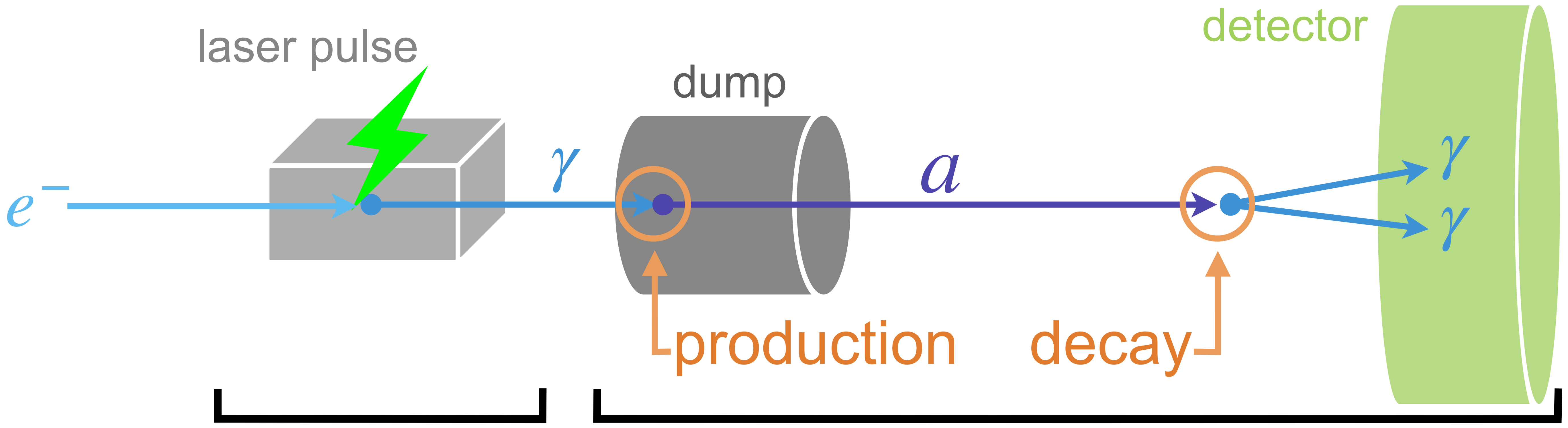
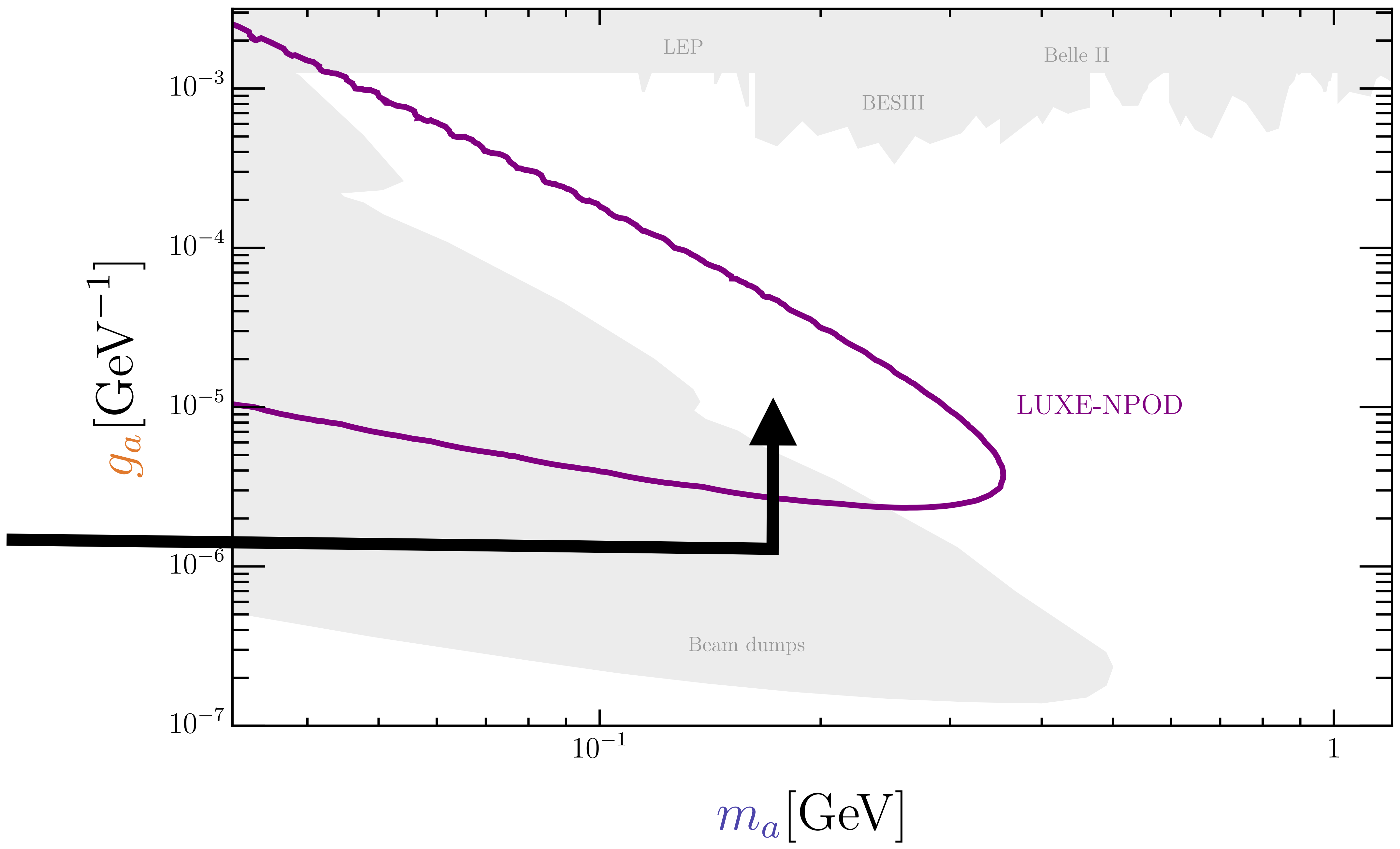


adopted by the LUXE collaboration

$$\frac{g_a}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

probe uncharted territory



very low background rate

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, YS, Tal Hod PRD 22

Axions at an optical dump

LUXE-NPOD
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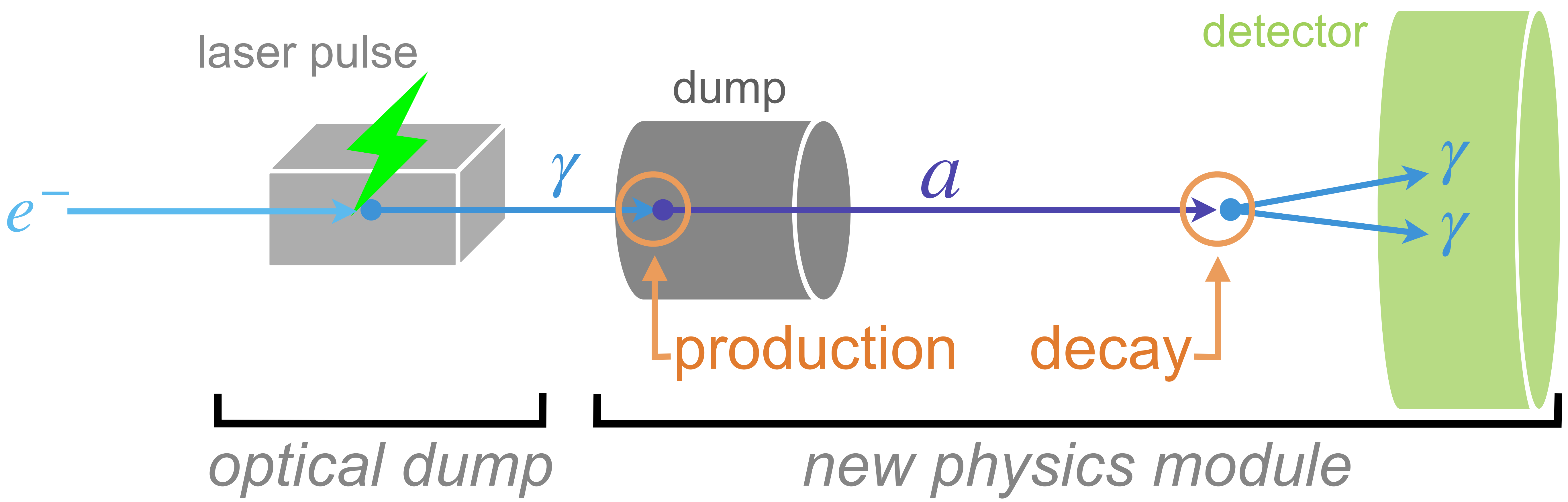
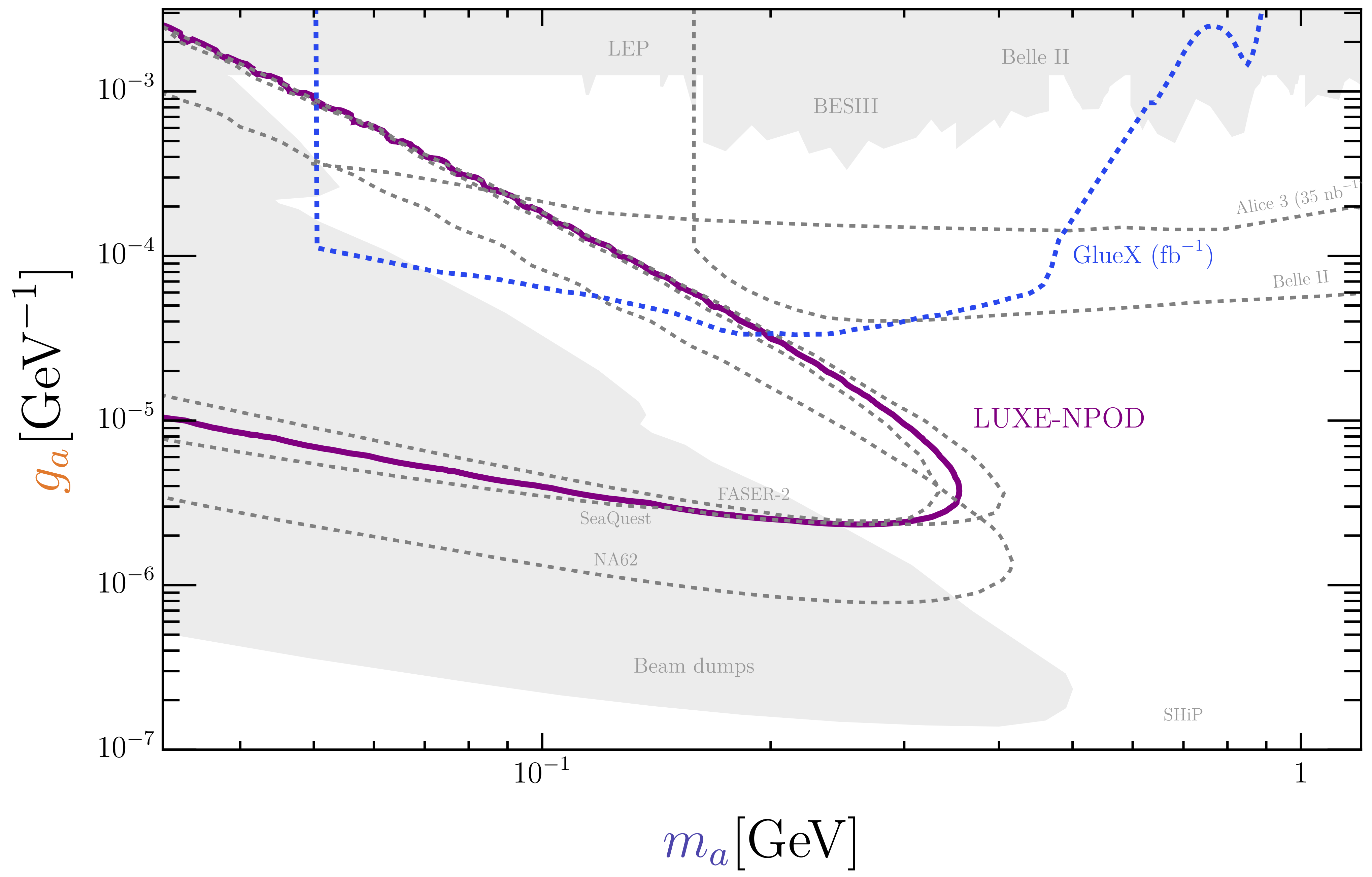


adopted by the LUXE collaboration

$$\frac{g_a}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



very low background rate

applicable to:
SLAC, LBNL, ILC….

GlueX: Aloni, Fanelli, YS, Williams, PRL 2019

Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, Perez, YS, Tal Hod PRD 22

Datasets

CODATA18 - for validation

reproduced CODATA with excellent agreement, $\lesssim 0.2\sigma$

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Datasets

CODATA18 - for validation

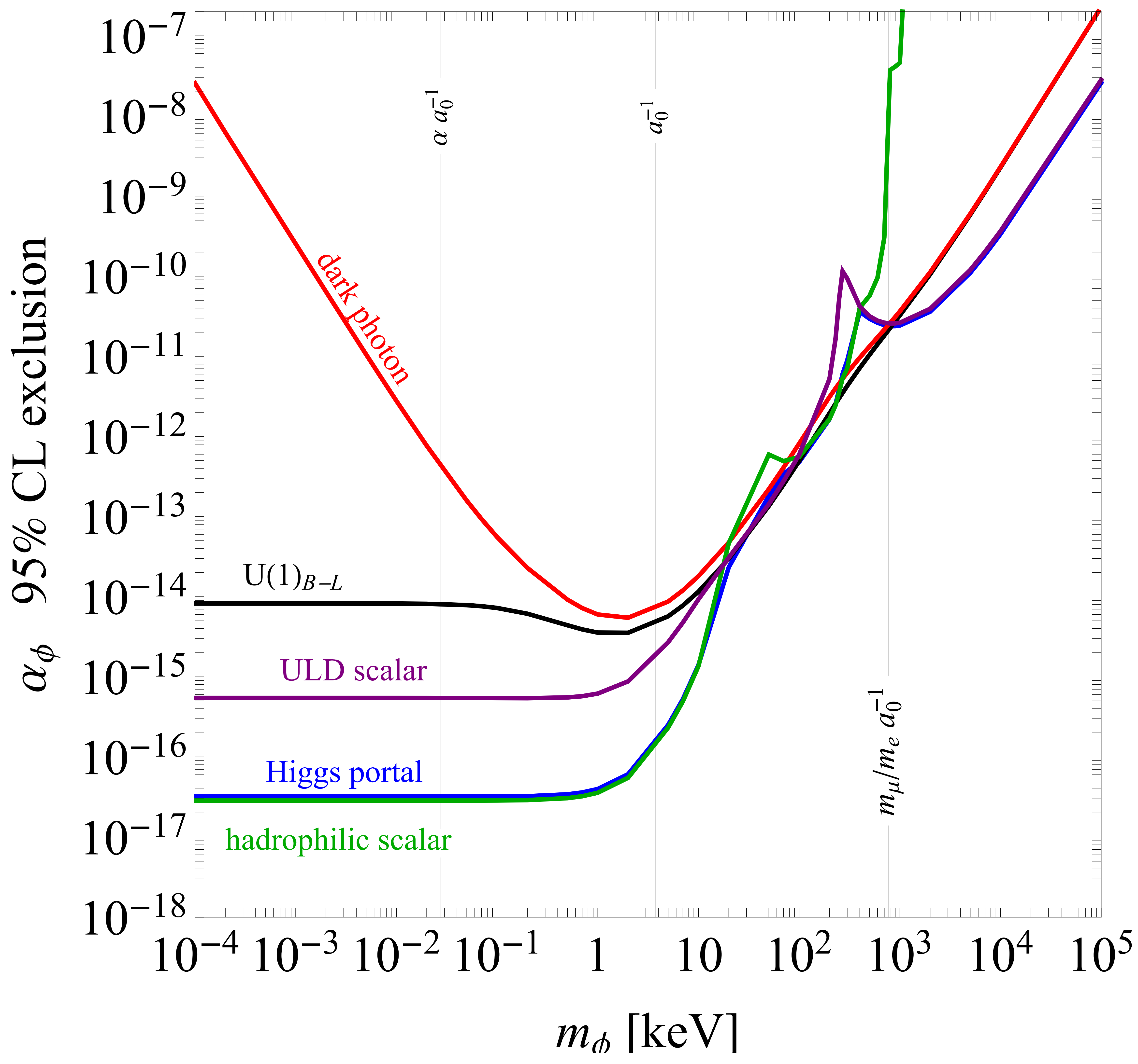
reproduced CODATA with excellent agreement, $\lesssim 0.2\sigma$

DATA22 - for new physics analysis

CODATA18 + improvements from Hydrogen, HD^+, $\bar{p}$He, μHe, $(g-2)_e$, masses

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

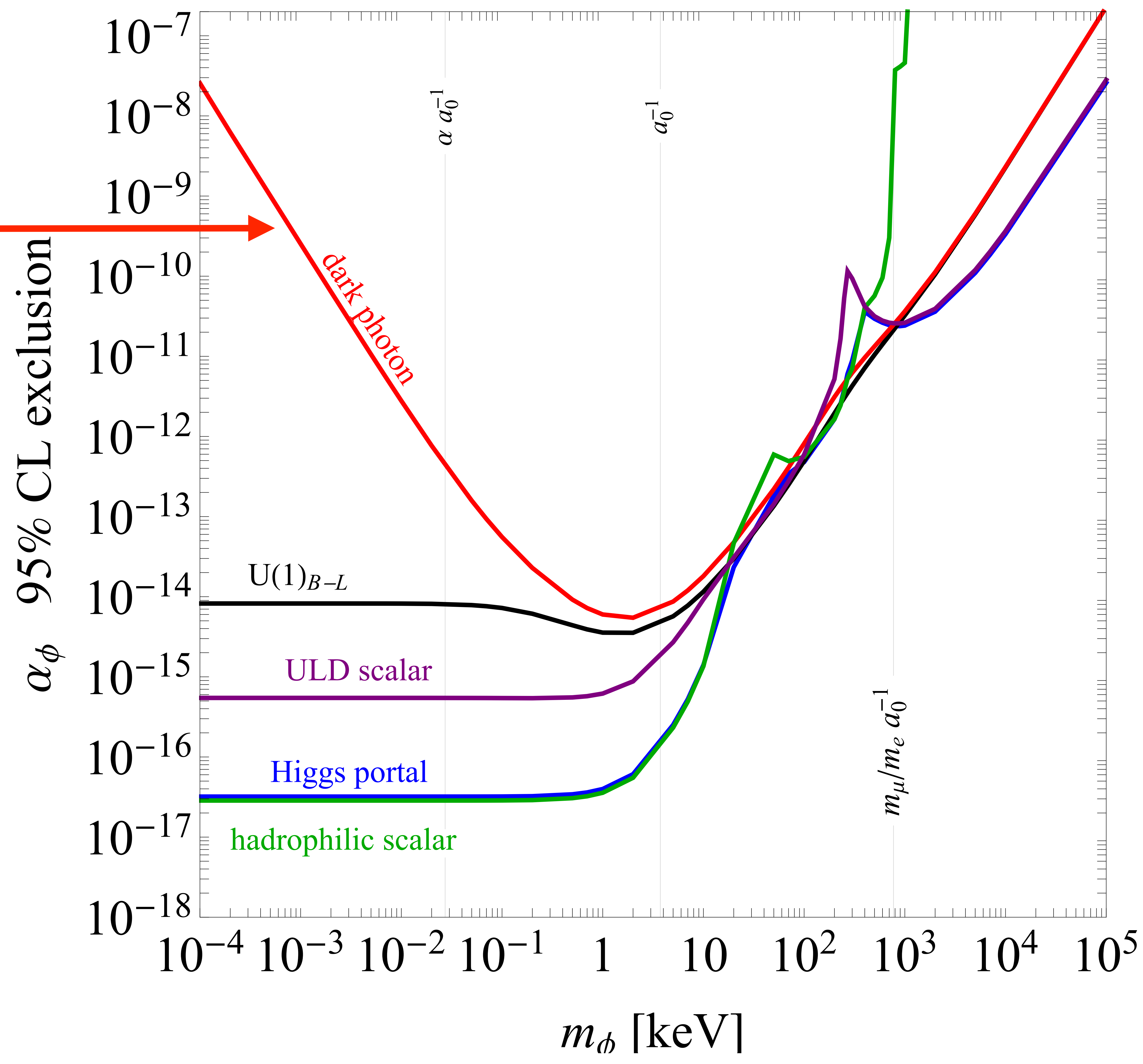
Results



Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

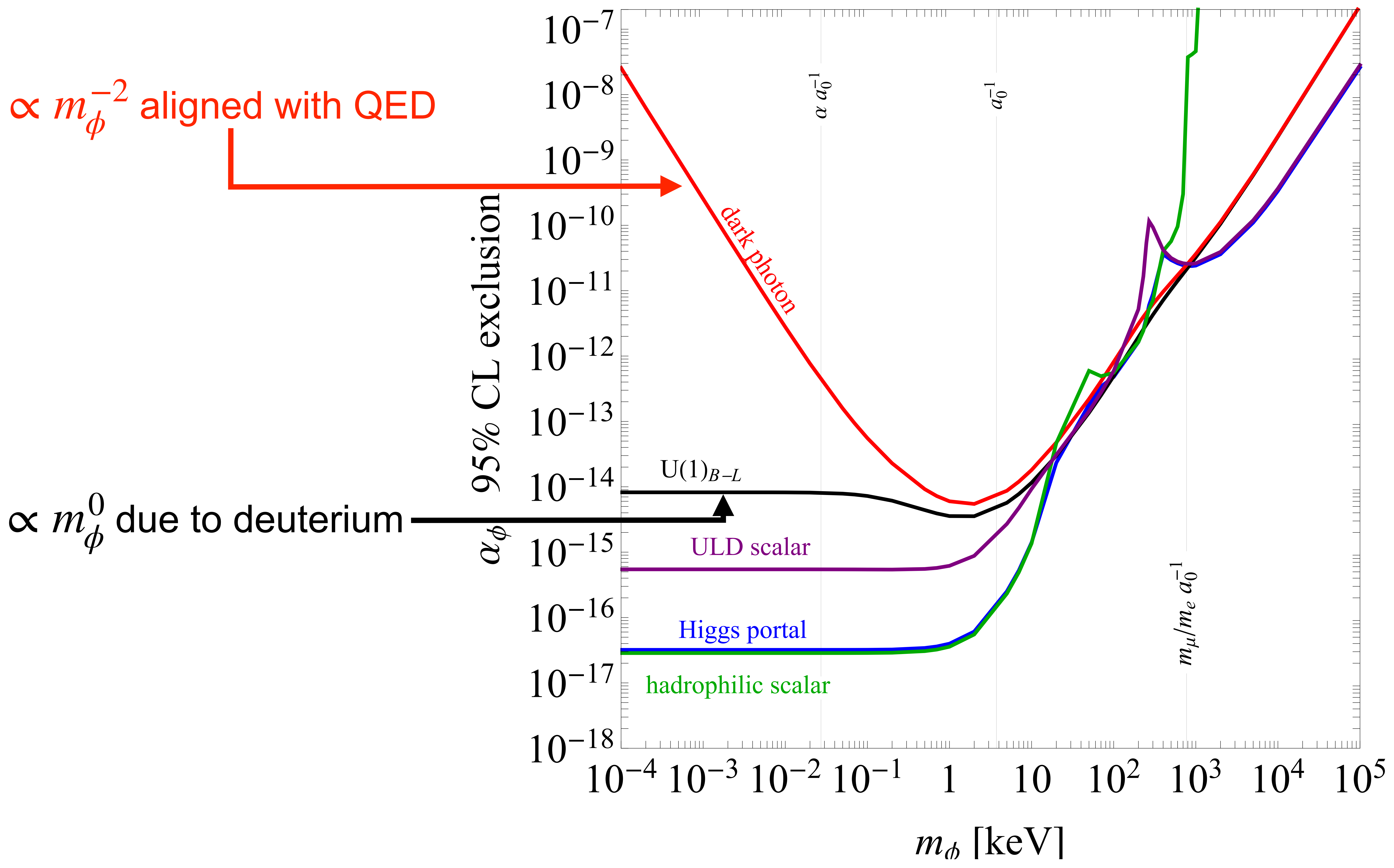
Results

$\propto m_\phi^{-2}$ aligned with QED



Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Results



Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

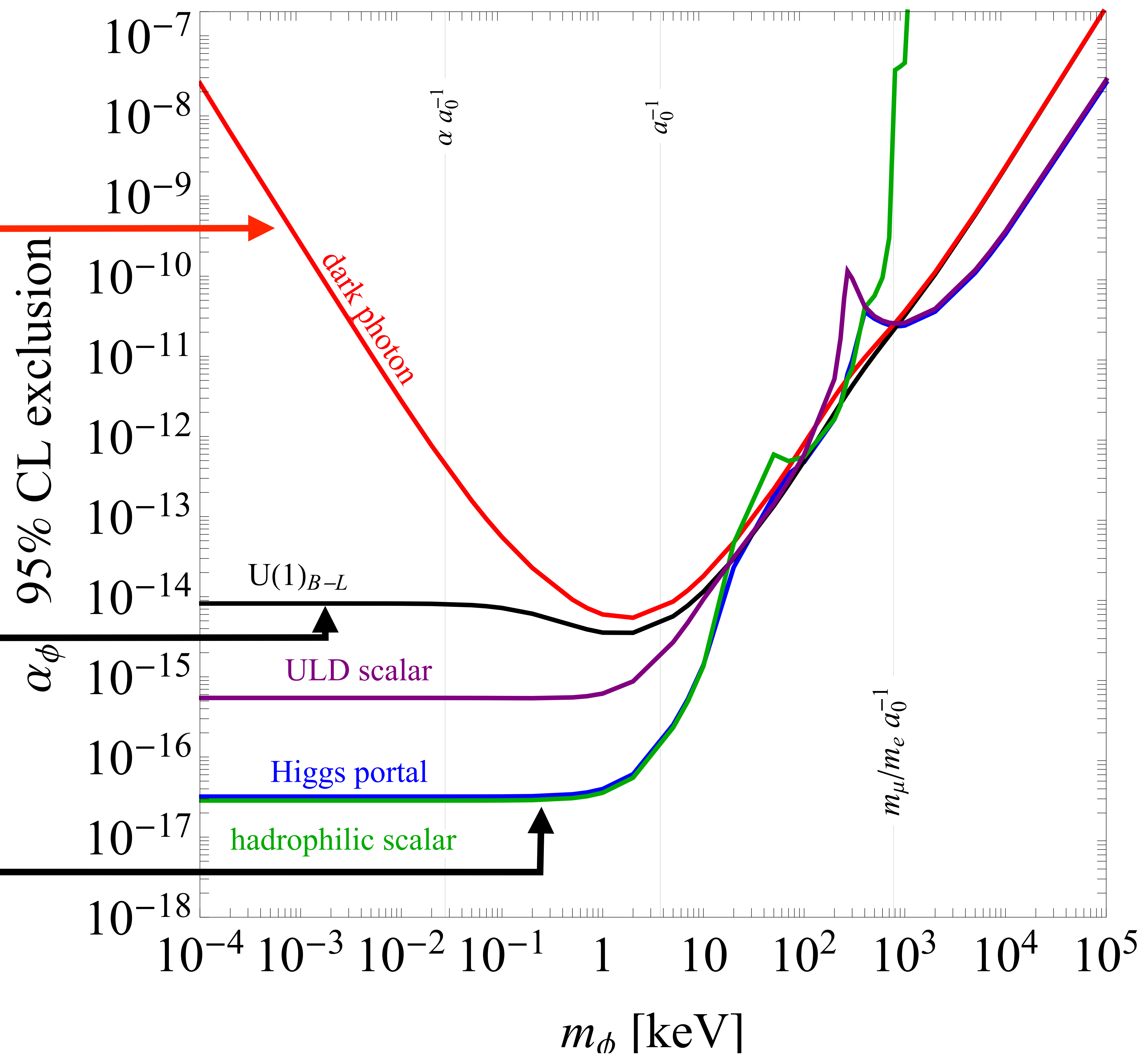
Results

$\propto m_\phi^{-2}$ aligned with QED

$\propto m_\phi^{0}$ due to deuterium

stronger sensitivity due to molecules

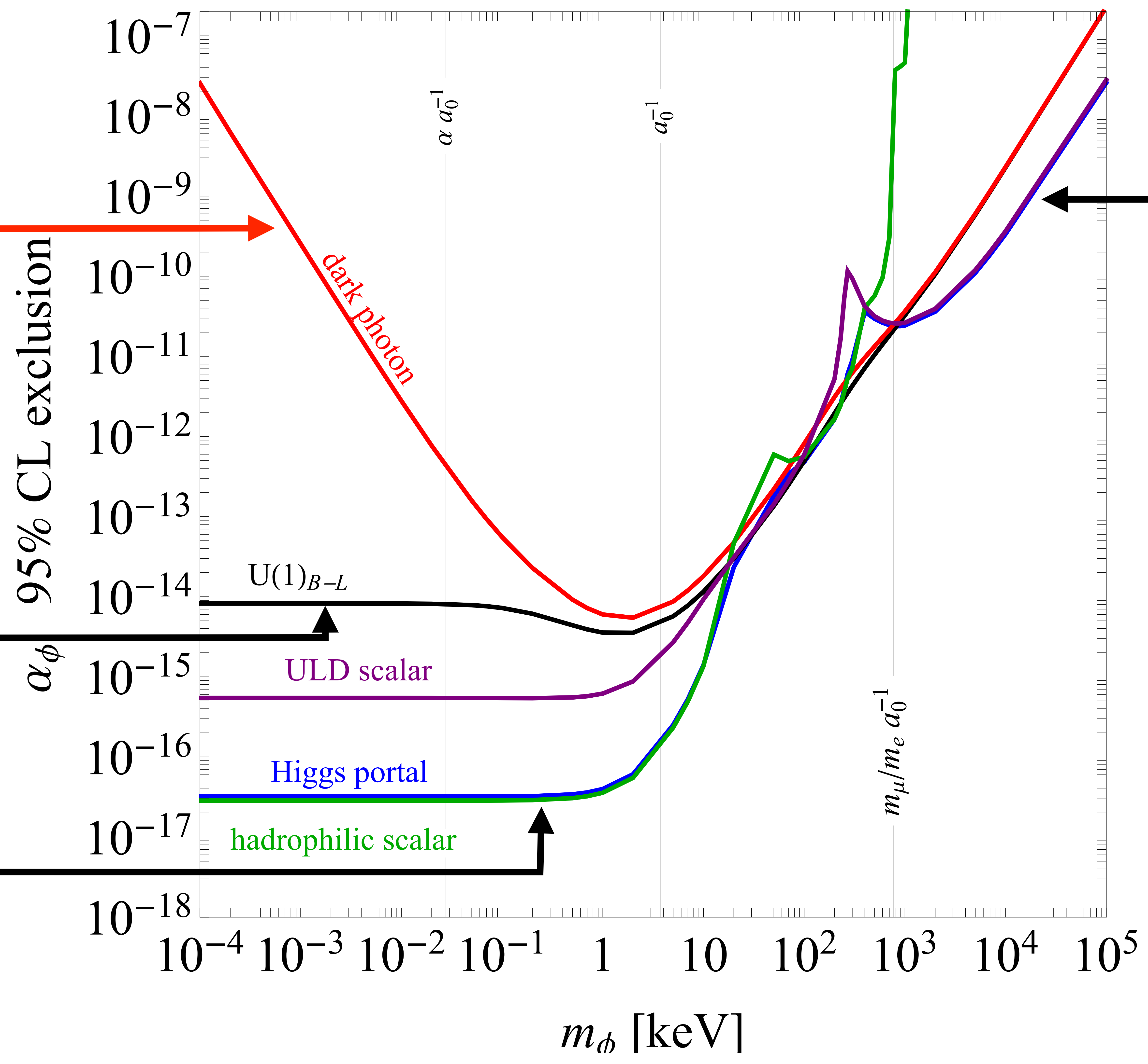
$q_N/q_e \sim m_N/m_e \sim 10^3$



Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Results

$\propto m_\phi^{-2}$ aligned with QED



stronger sensitivity due to muonic atoms
$q_\mu/q_e \sim m_\mu/m_e \sim 200$

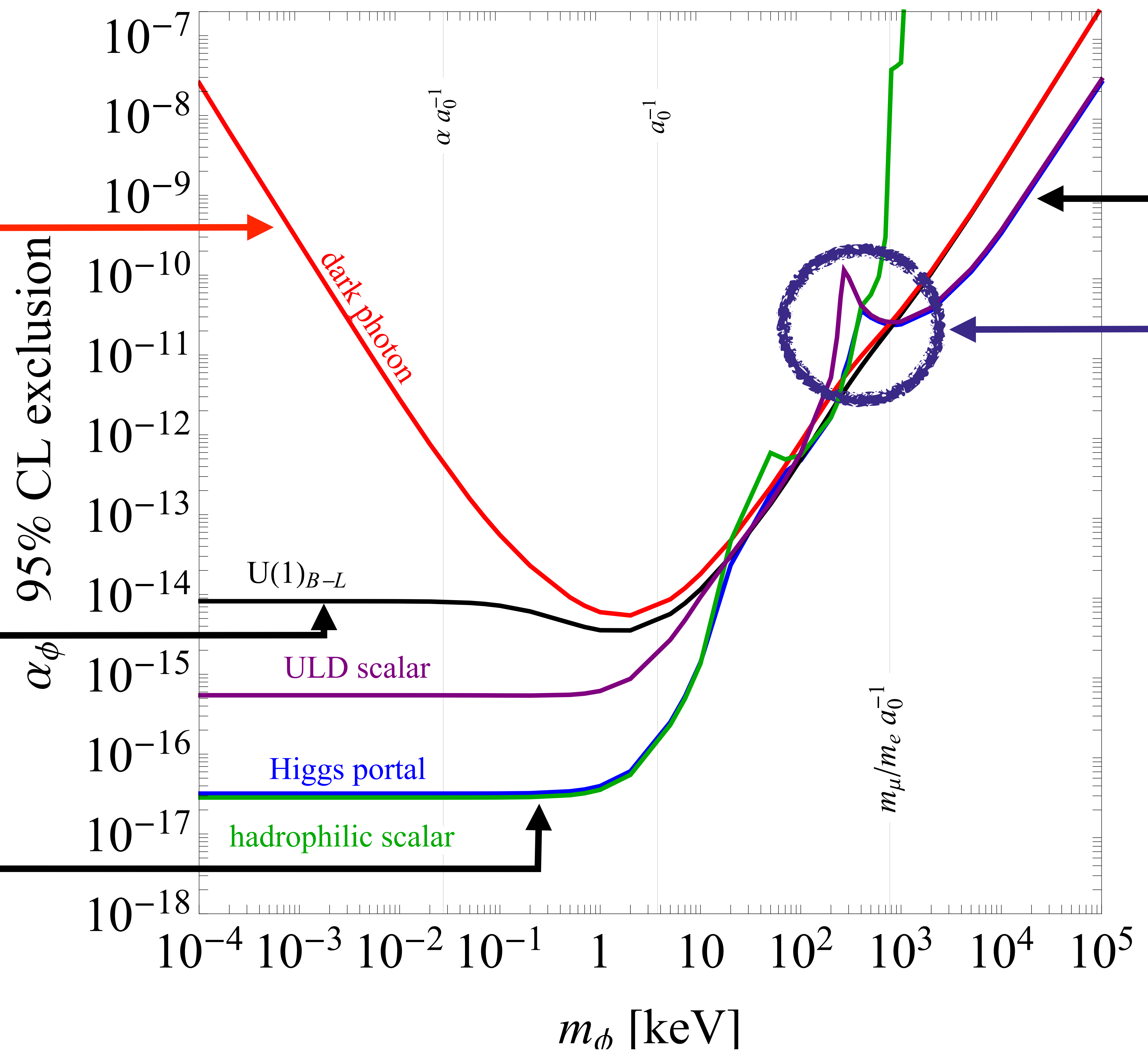
$\propto m_\phi^0$ due to deuterium

stronger sensitivity due to molecules
$q_N/q_e \sim m_N/m_e \sim 10^3$

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23

Results

$\propto m_\phi^{-2}$ aligned with QED



stronger sensitivity due to muonic atoms $q_\mu/q_e \sim m_\mu/m_e \sim 200$

data favors $\alpha_\phi \neq 0$ for Higgs portal and ULD

$\propto m_\phi^0$ due to deuterium

stronger sensitivity due to molecules $q_N/q_e \sim m_N/m_e \sim 10^3$

Delaunay, Karr, Kitahara, Koelemeij, YS, Zupan, PRL 23