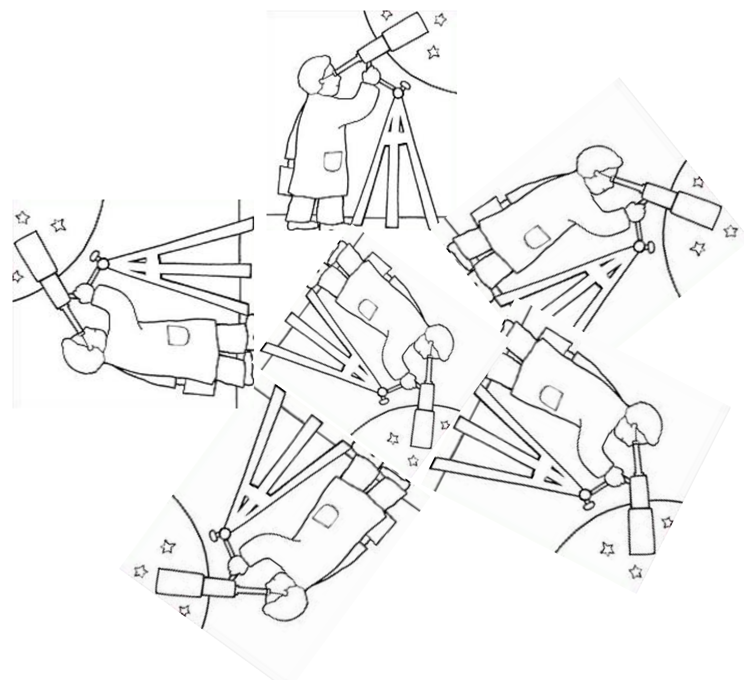
Searching for (Ultra-)light Dark Matter Using Mössbauer Spectroscopy



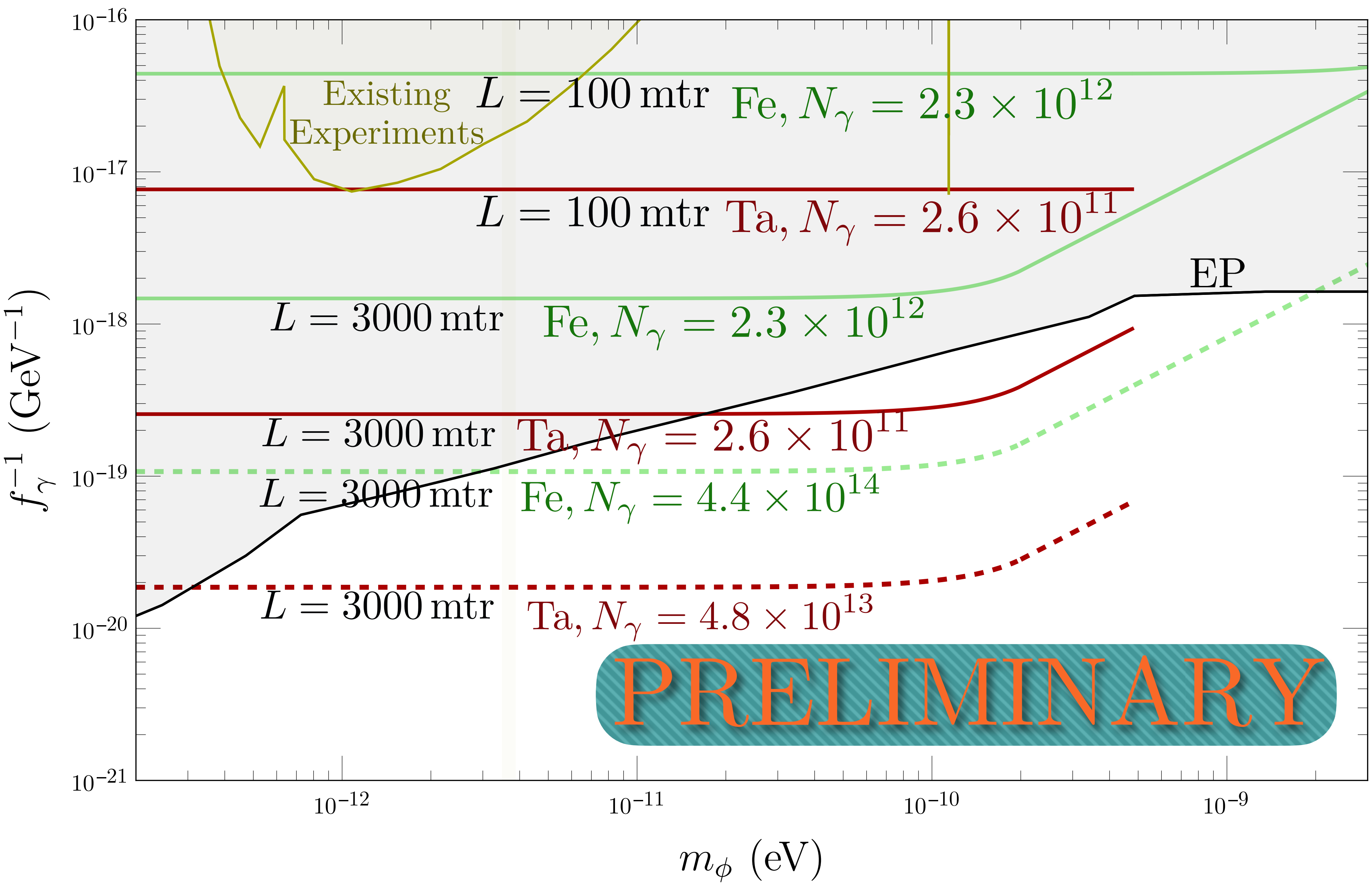
Abhishek Banerjee
University of Maryland

Fermilab, 2024

[AB, and Rajendran (to appear), '24]

Result

With the existing set-up, we are already probing interesting part of the parameter space, and a slight improvement would enable us to probe uncharted territory!



Plan

- What is Mössbauer Spectroscopy?
- How to use it for probing Dark Matter (DM)?
- Experimental considerations
- Difference between our method and existing searches
- Results

Introduction

We are interested in (sub-eV) dark matter (DM) which interacts with the SM CP even operators

$$\phi\,(t,\vec{x}) \simeq \phi_0 \cos\left[m_\phi(t+\vec{\beta}\cdot\vec{x})\right] \qquad \phi_0 \simeq \sqrt{2\rho_{\rm DM}}/m_\phi$$

Examples include

QCD axion DM $\quad \mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^{\mu\nu}\widetilde{G}_{\mu\nu}$

For a dilaton like scalar DM ⟶ through scale anomaly

For a Higgs portal type models ⟶ through Higgs mixing

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Examples include

QCD axion DM $\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^{\mu\nu}\widetilde{G}_{\mu\nu}$ (Quadratic order)

(Linear order)

For a dilaton like scalar DM ⟶ through scale anomaly

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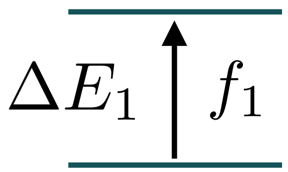
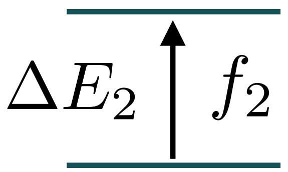
Leads to time dependence of (nuclear-) energy levels!

Probing oscillating DM using Precision Spectroscopy

General: find 2 systems with different dependence on the fundamental constants



$$\Delta E_{1,2} \equiv f_{1,2} = f_{1,2}\left(\alpha^{\xi_\alpha^{1,2}}, m_e^{\xi_{m_e}^{1,2}}, m_N^{\xi_{m_N}^{1,2}}\right)$$



[Safronova, Budker, DeMille, Kimball, Derevianko, Clark 18] [Antypas, Budker, Flambaum, Kozlov, Perez, Ye 20]

Fractional change of the frequency ratio: $\dfrac{\Delta(f_1/f_2)}{(f_1/f_2)} = \dfrac{\Delta f_1}{f_1} - \dfrac{\Delta f_2}{f_2} = (\xi_\alpha^1 - \xi_\alpha^2)\,\dfrac{\Delta\alpha}{\alpha}$

Classical ex: various clock comparisons, comparison clocks with cavity,...

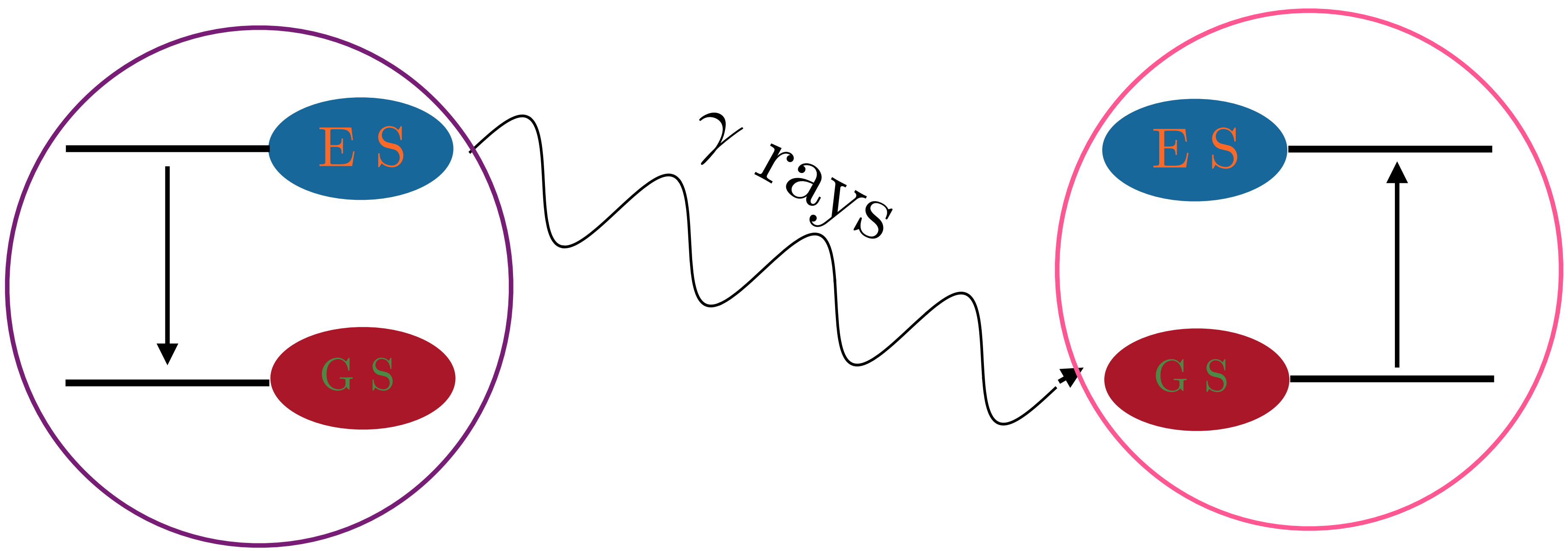
Reach of the experiments is limited by the stability of the clocks $t_{\rm avg} \gtrsim \mathcal{O}(\text{sec})$

Efficiently can only probe DM parameter space in the low mass region

We are proposing to use Mössbauer Spectroscopy to probe oscillating DM through the time dependence of nuclear energy levels

Mössbauer Spectroscopy

Mössbauer Spectroscopy relies on recoil free resonant re-absorption of gamma photons



Mössbauer emitter/source

Mössbauer receiver/absorber

These are nuclear transitions, and only possible to see in a lattice

Mössbauer Spectroscopy

Absorption cross-section

$$\sigma_{\rm res}(E_0, E_\gamma, \Gamma) \propto \frac{2\pi}{E_\gamma^2} \frac{(\Gamma/2)^2}{(E_0 - E_\gamma)^2 + (\Gamma/2)^2}$$

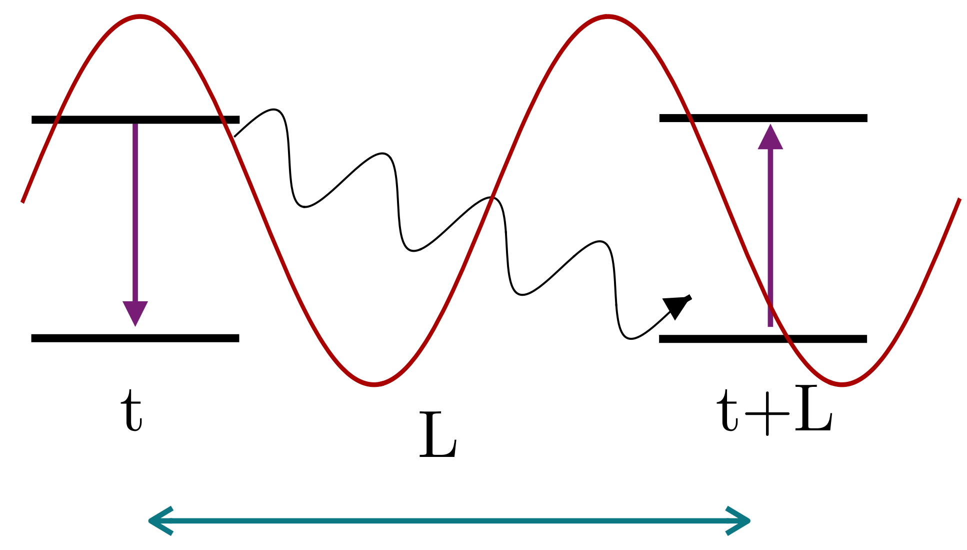
Cross section changes drastically while going from the "on resonance" to "off resonance" region, sometimes by several orders of magnitude

For a typical Mössbauer transition $E_\gamma \sim (6 - 100)\,\mathrm{keV}\,, \Gamma \sim (0.1 - 1000)\,\mathrm{neV}$

Amazing probe of new physics!

Probing DM

Oscillating DM background inducing time dependence to the energy levels



Change in the DM field

$$\Delta\phi \simeq \phi(t) - \phi(t+L) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi/2} \sin\left(\frac{m_\phi L}{2}\right) \simeq \sqrt{2\rho_{\rm DM}} L \times {\rm sinc}(m_\phi L/2)$$

To obtain the change in the energy levels, we need to specify DM-SM interaction!

For N_γ number of photons, the sensitivity of DM search

$$\Delta E = \frac{\Gamma}{\sqrt{N_\gamma}}$$

$$\sigma_{\rm res}(E_0, E_\gamma, \Gamma) \propto \frac{2\pi}{E_\gamma^2} \frac{(\Gamma/2)^2}{(E_0 - E_\gamma)^2 + (\Gamma/2)^2}$$

Probing DM

For a linearly coupled DM, change in the energy levels

$$\Delta E = E_{\rm tran}(t) - E_{\rm tran}(t+L) \propto \Delta\phi$$

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$${\rm sinc}(x) = \begin{cases} 1 \text{ for } x \lesssim 1 \\ 1/x \text{ for } x \gtrsim 1 \end{cases}$$

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$$\mathrm{sinc}(x) = \begin{cases} 1 \text{ for } x \lesssim 1 \\ 1/x \text{ for } x \gtrsim 1 \end{cases}$$

Maximum sensitivity is obtained for $m_\phi \sim 1/L \sim \mathrm{neV}\left(\frac{100\,\mathrm{mtr}}{L}\right)$

Enables us to probe higher(!) masses

Constraints on DM mass

DM better be coherent between the Mössbauer emitter and the absorber

$$m_\phi \lesssim 4 \times 10^{-4}\mathrm{eV}\left(\frac{3\,\mathrm{km}}{L}\right) \qquad \tau_{\mathrm{coh}} = \frac{2\pi}{m_\phi \beta^2}$$

The spread of both the emission, and the absorption lines in the time-domain should follow the oscillation

$$t_{\mathrm{osc}} = \frac{2\pi}{m_\phi} \gtrsim \tau_{\mathrm{dec}} = \frac{1}{\Gamma_{\mathrm{nat}}} \Rightarrow m_\phi \lesssim 2\pi\,\Gamma_{\mathrm{nat}}$$

For a given transition allowed mass range

$$m_\phi \lesssim 8.3 \times 10^{-5}\,\mathrm{eV} \times \mathrm{Min}\left[\frac{15\,\mathrm{km}}{L}, \frac{50\,\mathrm{ps}}{\tau_{\mathrm{dec}}}\right]$$

Challenges?

Effective reach of the experiment $$\frac{\Gamma}{\sqrt{N_\gamma}} = \Delta E \propto \Delta\phi \propto \sqrt{\rho_{\rm DM}} L$$

For a Gaussian beam $$N_\gamma \propto 1/(L\theta)^2$$

Mitigating the apparent gain obtained by separating the emitter and the absorber

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Mitigating the apparent gain obtained by separating the emitter and the absorber

Flux at a distance L $$N_\gamma(L) \propto \frac{z_R^2}{L^2 + z_R^2}$$

$L \gg z_R$

the Rayleigh range — qualitatively, a beam remains "parallel" over this distance $$z_R = \frac{\pi w_0^2}{\lambda} \sim \frac{\lambda}{\Omega}$$

We want a lot of well collimated emitted photons!

Challenges?

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Synchrotron based Mössbauer Spectroscopy (SMS)

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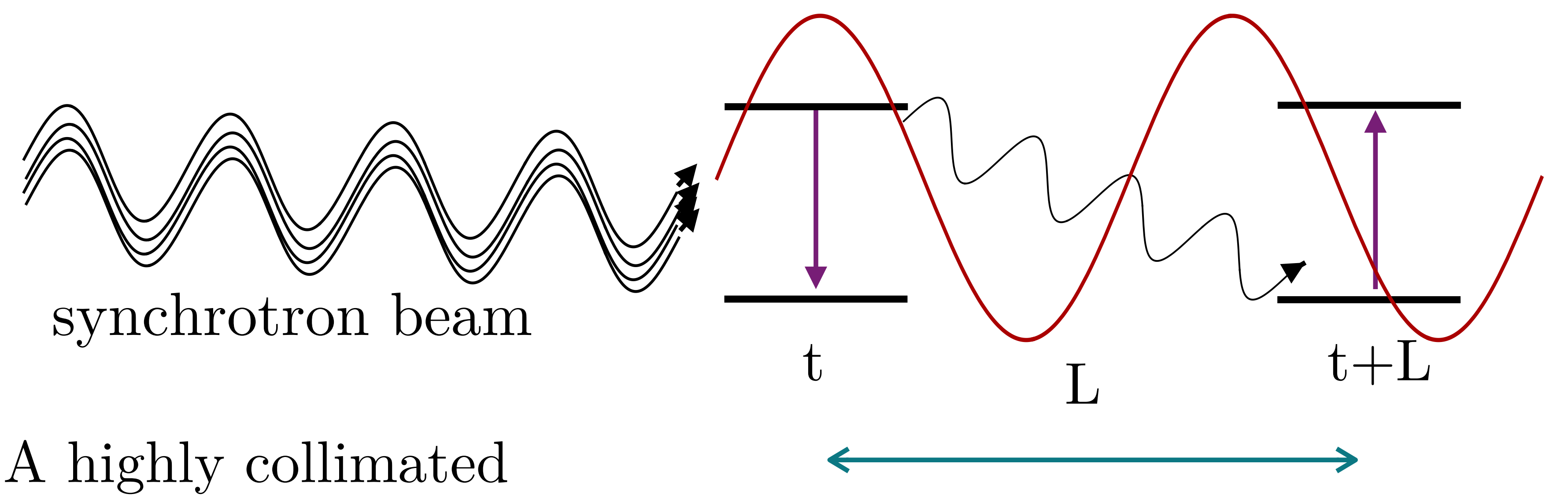
A sample is directly excited through the absorption of an x-ray photon



A highly collimated

high intensity beam

In the case of SMS, the emitted radiation after the synchrotron light excitation is coherent

Leads to an enhanced collimated x-ray photons, which happens from the whole source

The flux is equal to the number of source excited source nuclei

Synchrotron based Mössbauer Spectroscopy (SMS)

Number of excited source nuclei?

The resolution of the synchrotron source $(\Delta E)_{\rm SR} \gg \Gamma$

Only a fraction of the nuclei can be excited

Effective flux at the Mössbauer source $\quad (N_\gamma)_{\rm MS} = (N_\gamma)_{\rm SR} \dfrac{\Gamma}{(\Delta E)_{\rm SR}}$

DM search translates to find a suitable synchrotron source!

$$\Delta E = \frac{\Gamma}{\sqrt{N_\gamma}} = \sqrt{\frac{\Gamma\,(\Delta E)_{\rm SR}}{(N_\gamma)_{\rm SR}}}$$

How to even improve the set-up?

Synchrotron based Mössbauer Spectroscopy (SMS)

How to achieve a higher Rayleigh range? $z_R = \frac{\pi w_0^2}{\lambda}$

For that purpose, we want to refocus the radiation by using a lens

The effective radius of curvature $R = (n-1)f$ (Lensmaker's equation)

For x-ray energies, the resonant nuclear contribution to the refractive index

$$n - 1 \simeq \frac{2 n_{\rm nuc}}{E_\gamma^3}$$

$n_{\rm nuc}$ → nucleon number density in a material

$\sim (\text{keV})^3$

Rayleigh range $z_R \sim 3.2\,\text{km}\left(\frac{20\,\text{keV}}{E_\gamma}\right)^5\left(\frac{f}{1\,\text{m}}\right)^2$

Go to larger distances without losing flux!

Synchrotron Sources

SMS can done with various transitions with different width

Available synchrotron sources: APS in USA, ESRF in Europe, and SPring-8 in Japan...

Different transitions => various DM mass $m_\phi \lesssim 8.3 \times 10^{-5}\,\mathrm{eV} \times \mathrm{Min}\left[\frac{15\,\mathrm{km}}{L}, \frac{50\,\mathrm{ps}}{\tau_{\mathrm{dec}}}\right]$

Different transitions => different sensitivity $\Delta E = \frac{\Gamma}{\sqrt{N_\gamma}} = \sqrt{\frac{\Gamma\,(\Delta E)_{\mathrm{SR}}}{(N_\gamma)_{\mathrm{SR}}}}$

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Transition List					Beam	
Transition	E_0 (keV)	Γ_{exp} (eV)	τ_{dec}	N_γ (γ/month)	$(\Delta E)_{\text{SR}}$	$(N_\gamma)_{\text{SR}}$ γ/s
$^{181}_{73}$Ta [58]	6.2	5.5×10^{-10}	8.7 μs	2.6×10^{11}	35.7 meV	6.3×10^{12}
$^{57}_{26}$Fe [59]	14.4	5×10^{-9}	141.8 ns	2.3×10^{12}	35.7 meV	6.3×10^{12}
$^{187}_{76}$Os [60, 61]	9.8	1.9×10^{-7}	3.4 ns	8.8×10^{13}	35.7 meV	6.3×10^{12}
$^{187}_{76}$Os [61, 62]	74.4	1.2×10^{-5}	0.0534 ns	4.6×10^{13}	70 eV	1×10^{14}

BLXU09 at SPring-8

20-ID-D at APS

Improvement: effective flux can be improved by a factor of 100

3-ID beam line at the APS

Reach on DM parameter space

DM-SM Interaction

$$\mathcal{L} \supset \sum_{\psi=u,d} -\frac{m_\psi}{f_\psi}\phi\,\bar{\psi}\psi - \frac{\alpha\,\phi}{4\,f_\gamma}F^2 - \frac{\beta(g_s)}{2g_s}\frac{\phi}{f_g}G^2$$

Alpha module: $\alpha \to \alpha - \frac{\alpha^2\phi}{f_\gamma} \Rightarrow \frac{\Delta\alpha}{\alpha(0)} = \frac{\alpha(\phi)-\alpha(0)}{\alpha(0)} \simeq -\frac{\alpha\,\phi}{f_\gamma}$

Yukawa module: $\hat{m} \to \hat{m} - \frac{\hat{m}\,\phi}{f_{\hat{m}}} \Rightarrow \frac{\Delta\hat{m}}{\hat{m}} = \frac{\hat{m}(\phi)-\hat{m}(0)}{\hat{m}(0)} = \frac{\phi}{f_{\hat{m}}}$ $\quad \hat{m} = \frac{m_u+m_d}{2}$ and $\frac{2\hat{m}}{f_{\hat{m}}} = \frac{m_u}{f_u} + \frac{m_d}{f_d}$

Gluon module: $\frac{\Delta\alpha_s}{\alpha_s(0)} = \frac{\alpha_s(\phi)-\alpha_s(0)}{\alpha_s(0)} \simeq -\frac{2\beta(g_s)}{g_s}\frac{\phi}{f_g} \Rightarrow \frac{\partial\ln\Lambda_{\rm IR}}{\partial\phi} \simeq -\frac{\alpha_s}{\beta(\alpha_s)} = \frac{1}{f_g}$

Energy Level change

$$\mathcal{L} \supset \sum_{\psi=u,d} -\frac{m_\psi}{f_\psi}\phi\,\bar{\psi}\psi - \frac{\alpha\,\phi}{4\,f_\gamma}F^2 - \frac{\beta(g_s)}{2g_s}\frac{\phi}{f_g}G^2$$

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The dominant electromagnetic effect is encoded in the α dependence of the nuclear binding energy

$$\Delta E_{\rm bind} \simeq \frac{Z^2\Delta\alpha}{A^{1/3}r} = \frac{Z^2\alpha}{A^{1/3}r}\frac{\Delta\alpha}{\alpha}$$

The energy shift of a highly deformed nucleus due to one nucleon transition

$$\Delta E \simeq \frac{Z\Delta\alpha}{r_{\rm nuc}} \simeq \frac{Z\alpha}{A^{1/3}r_0}\frac{\Delta\alpha}{\alpha} \simeq -\frac{Z\alpha^2}{A^{1/3}r_0}\frac{\Delta\phi}{f_\gamma}$$

Reach of the Proposed Method

SMS can done with various transitions with different width

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Different transitions => various DM mass

$$m_\phi \lesssim 8.3 \times 10^{-5}\,\text{eV} \times \text{Min}\left[\frac{15\,\text{km}}{L}, \frac{50\,\text{ps}}{\tau_{\rm dec}}\right]$$

Different transitions => different sensitivity

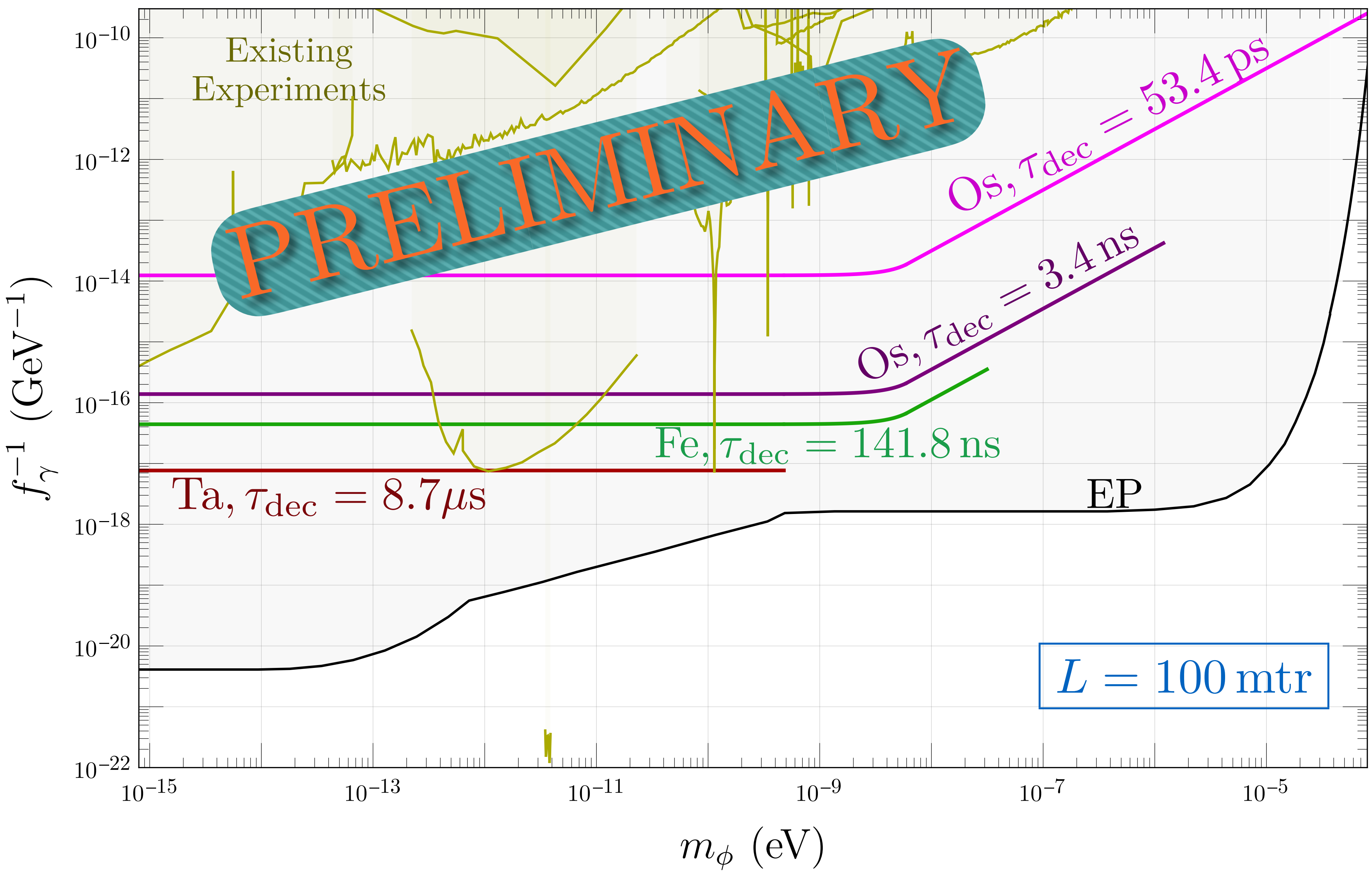
$$\Delta E = \frac{\Gamma}{\sqrt{N_\gamma}} = \sqrt{\frac{\Gamma\,(\Delta E)_{\rm SR}}{(N_\gamma)_{\rm SR}}}$$

DM => Changing alpha => changing binding energy

$$\Delta E \simeq \frac{Z\Delta\alpha}{r_{\rm nuc}} \simeq -\frac{Z\alpha^2}{A^{1/3} r_0}\frac{\Delta\phi}{f_\gamma}$$

$$\Delta\phi \simeq \sqrt{2\rho_{\rm DM}}L \times \text{sinc}(m_\phi L/2)$$

Results



Existing
Experiments
PRELIMINARY
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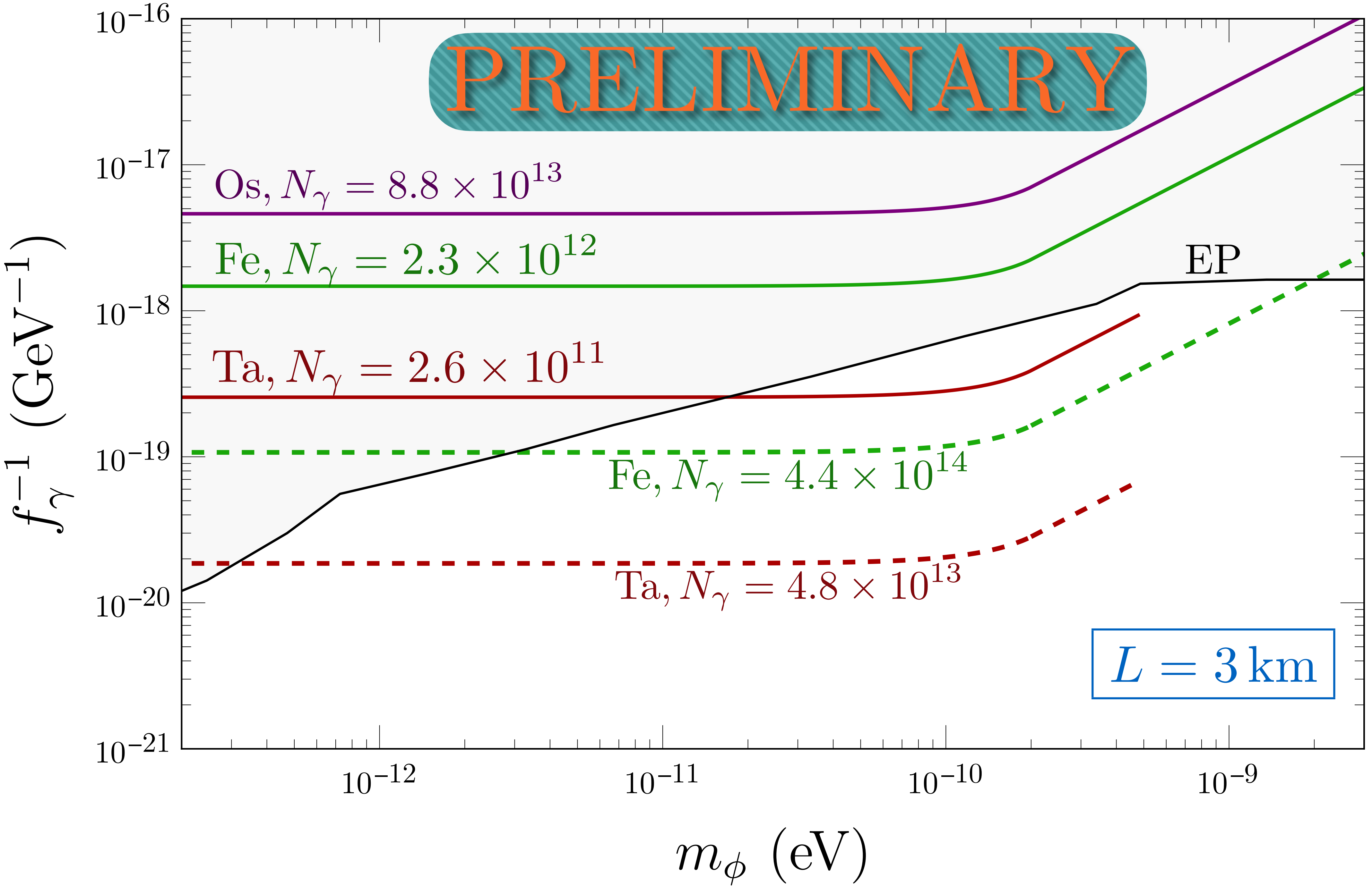
EP
$L = 100\,{\rm mtr}$
f_γ^{-1} (GeV^{-1})
m_ϕ (eV)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}

Results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10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
f_γ^{-1} (GeV^{-1})
10^{-12}
10^{-11}
10^{-10}
10^{-9}
m_ϕ (eV)

Probing QCD axion DM

$$\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^{\mu\nu}\widetilde{G}_{\mu\nu}$$

$$m_\pi^2(\theta_{\rm eff}) = B\sqrt{m_u^2 + m_d^2 + 2m_u m_d\cos(\theta_{\rm eff})} \text{ where } \theta_{\rm eff} = \bar{\theta} + a/f_a\,,\ B = -\langle \bar{q}q\rangle_0 / f_\pi^2$$

The oscillating QCD axion DM induces an oscillating component to pion mass

$$\frac{\Delta m_\pi^2}{m_\pi^2} = \frac{m_\pi^2(\theta_{\rm eff}) - m_\pi^2(0)}{m_\pi^2(0)} \simeq -\frac{m_u m_d\,\theta_{\rm eff}^2(t)}{2(m_u+m_d)^2} \qquad \theta_{\rm eff}(t) = \frac{(a - \langle a\rangle)}{f_a} = \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a}\cos(m_a t)$$

The nucleon mass also depends on the pion mass

$$m_N(\theta_{\rm eff}) = m_0 - 4c_1 m_\pi^2(\theta_{\rm eff}) - \frac{3g_A^2 m_\pi^3(\theta_{\rm eff})}{32\pi f_\pi^2} \qquad \frac{\partial \ln m_N}{\partial \ln m_\pi^2} \simeq 0.06$$

The QCD axion DM => oscillating pion mass and nucleon mass

[Kim, Perez 22]

Probing QCD axion DM

How does pion mass and nucleon mass affect nuclear transition energy?

We estimate it using one pion exchange potential

$$V_{\rm OPE}(r) = -\frac{g_{\pi NN}^2}{4\pi}\,\frac{m_\pi^2}{4\,m_N^2}\,\frac{e^{-m_\pi r}}{r}$$

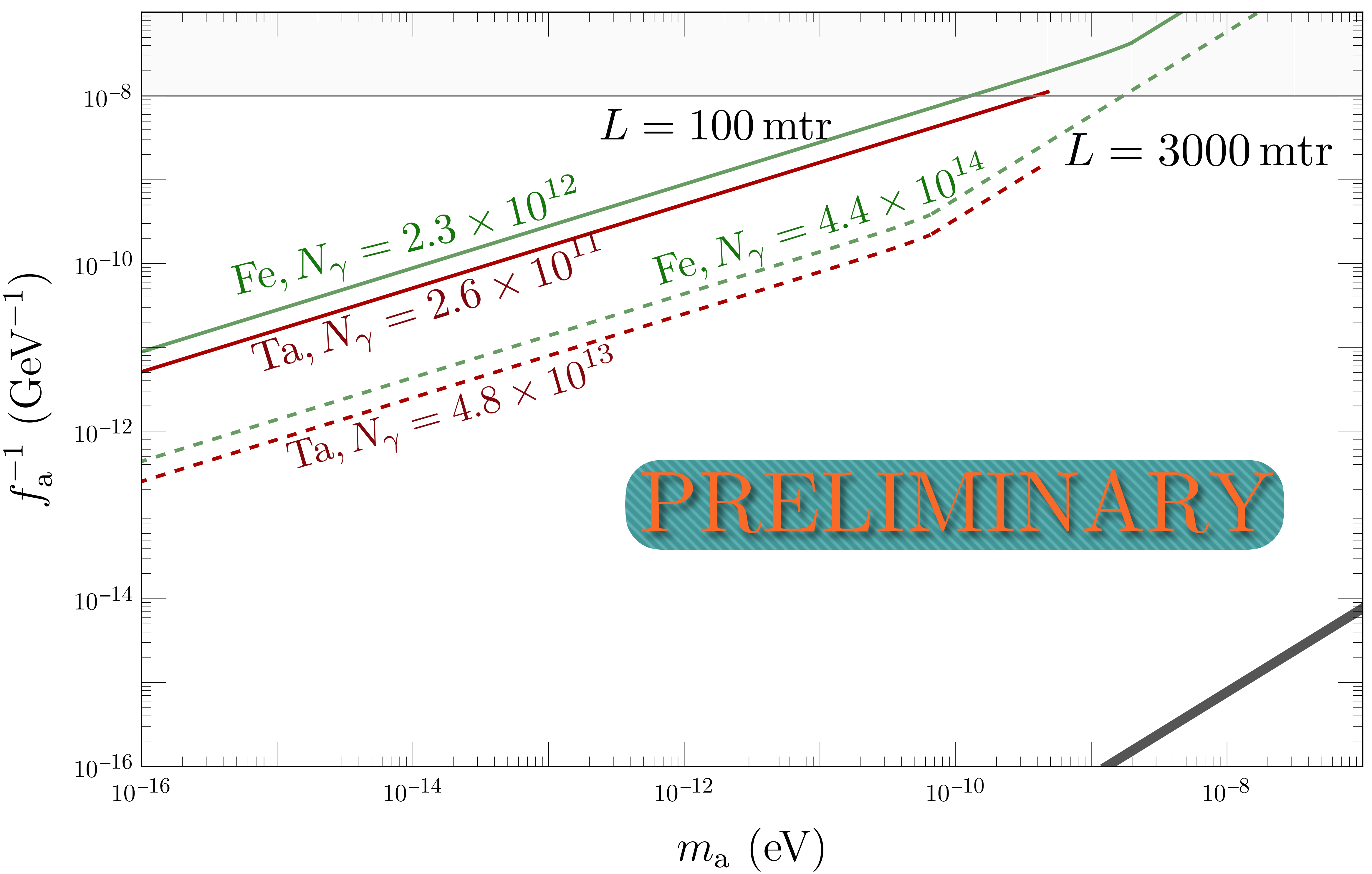
The energy shift due to changing pion and nucleon mass

$$\Delta E \simeq \frac{g_{\pi NN}^2}{(4\pi)\,4\,r}\left[\frac{\partial(m_\pi^2/m_N^2)}{\partial \ln m_\pi^2}\right]\frac{\Delta m_\pi^2}{m_\pi^2}$$

$$\frac{\Delta m_\pi^2}{m_\pi^2} = \frac{m_\pi^2(\theta_{\rm eff}) - m_\pi^2(0)}{m_\pi^2(0)} \simeq -\frac{m_u m_d\,\theta_{\rm eff}^2(t)}{2(m_u+m_d)^2}$$

$$\theta_{\rm eff}(t) = \frac{(a - \langle a\rangle)}{f_a} = \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a}\cos(m_a t)$$

Results QCD axion plot

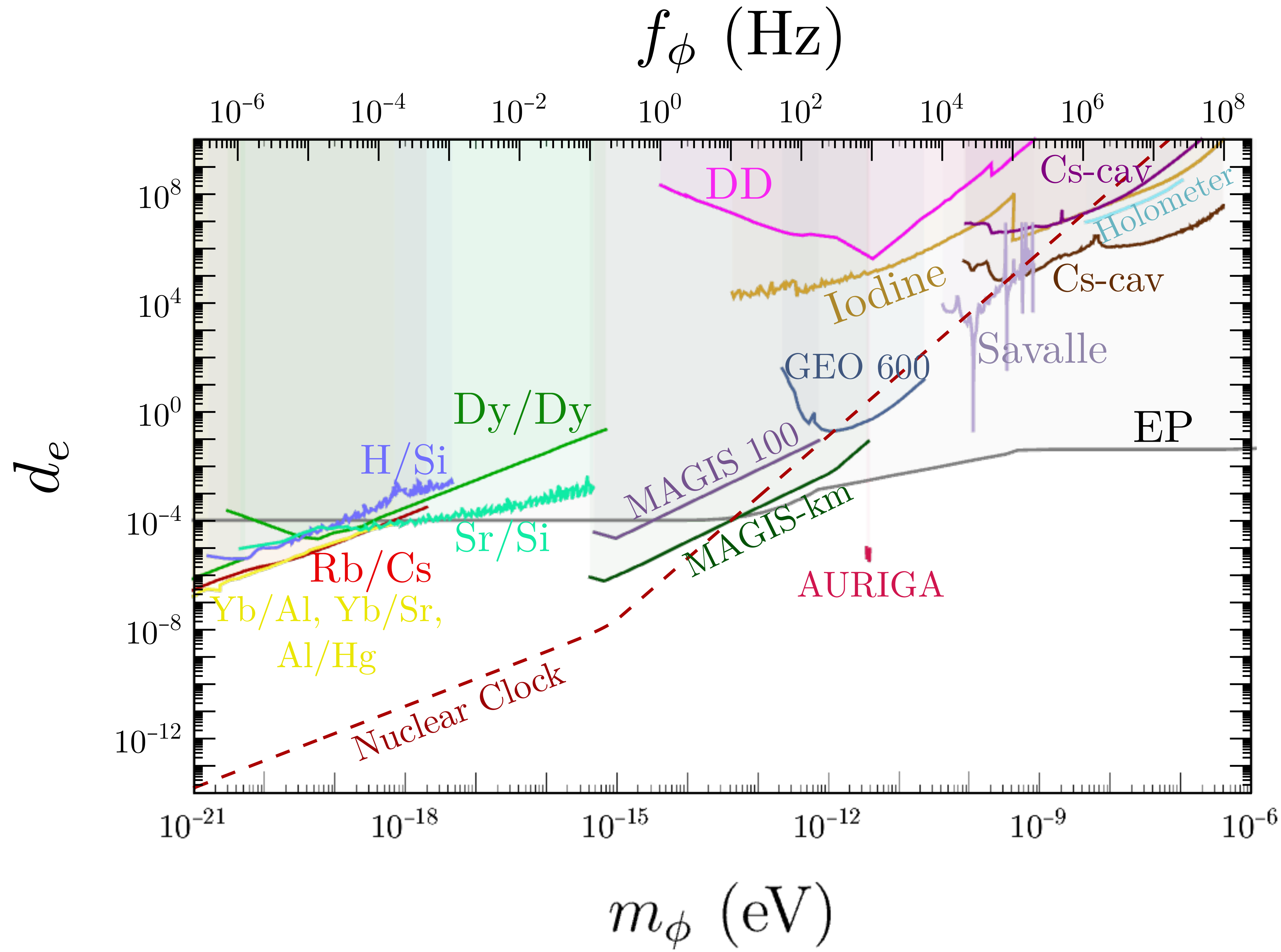


CONCLUSION

Mössbauer Spectroscopy can be used to look for New Physics and especially DM

We show the bounds from our suggested method are at a similar level compared to the most stringent current limits, and future investigations promise significant improvements

Existing Experiments plot



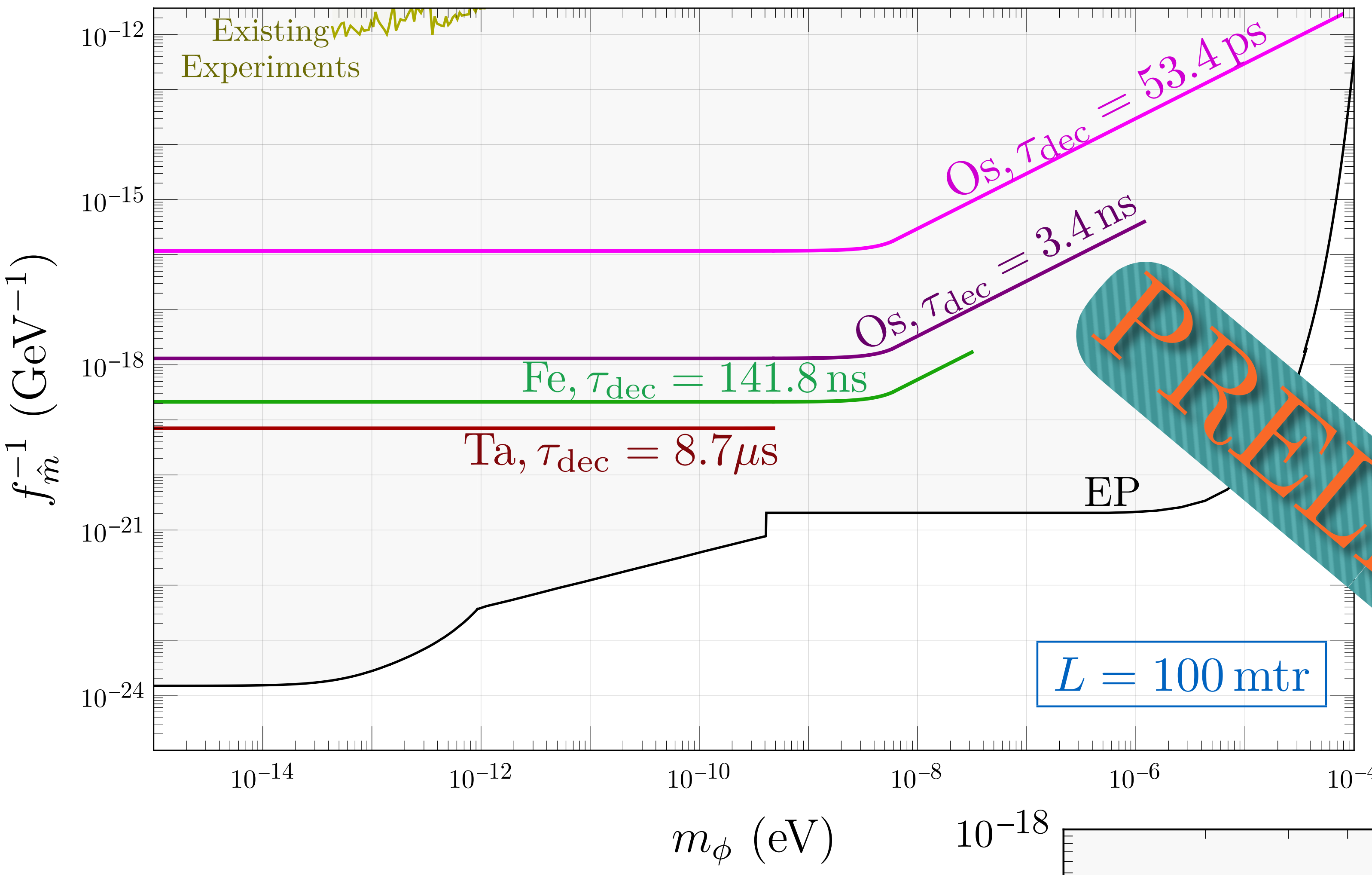
[Snowmass, 2203.14915]

Ultralight DM

The number of particle in a coherent volume

$$N = n \times V_{\text{coh}} = \frac{\rho_{\text{DM}}}{m_\phi} \frac{1}{(m_\phi \beta)^3}$$

$$N = 10^3 \left(\frac{\text{eV}}{m} \right)^4 \gg 1$$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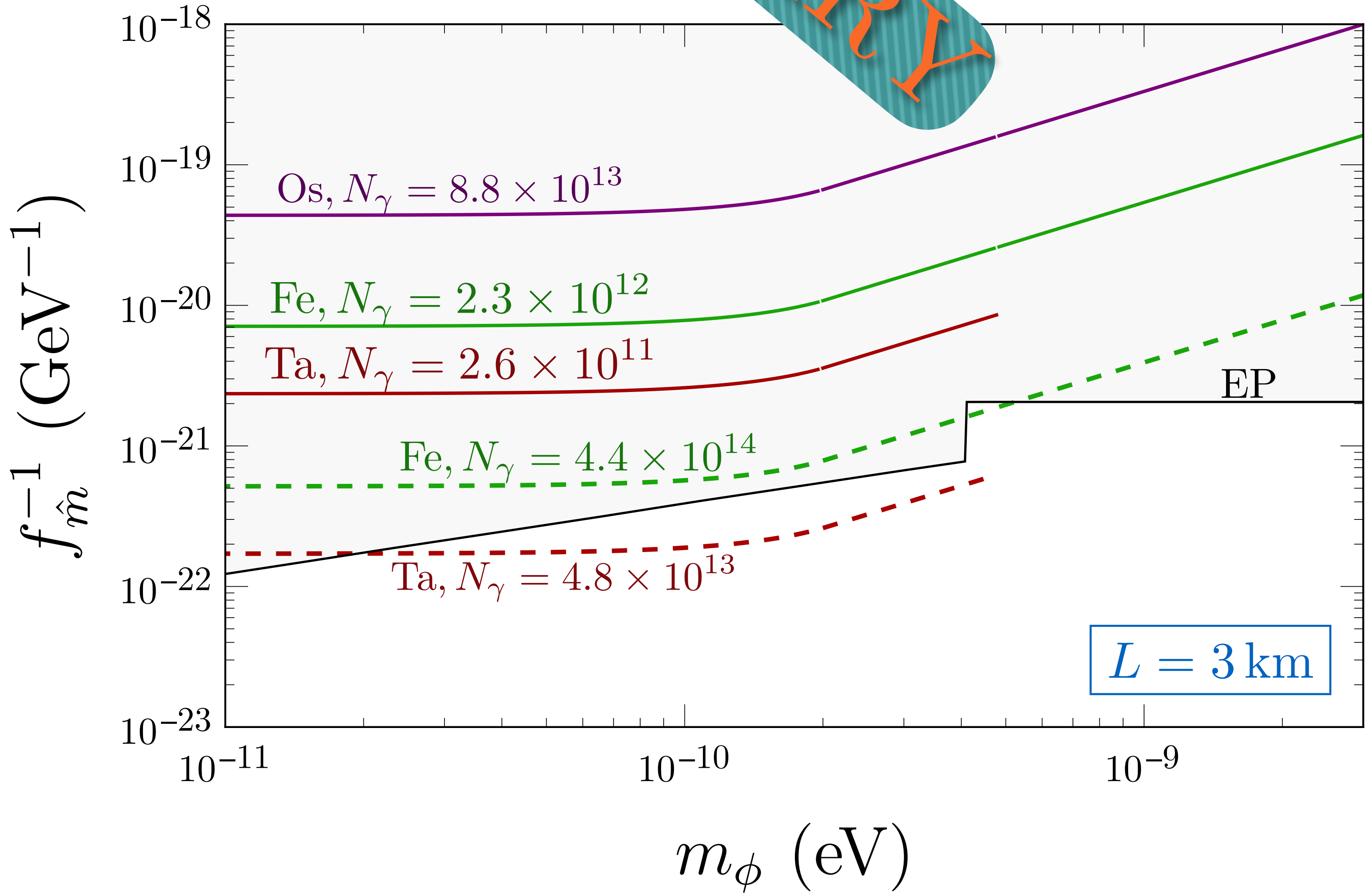
PRELIMINARY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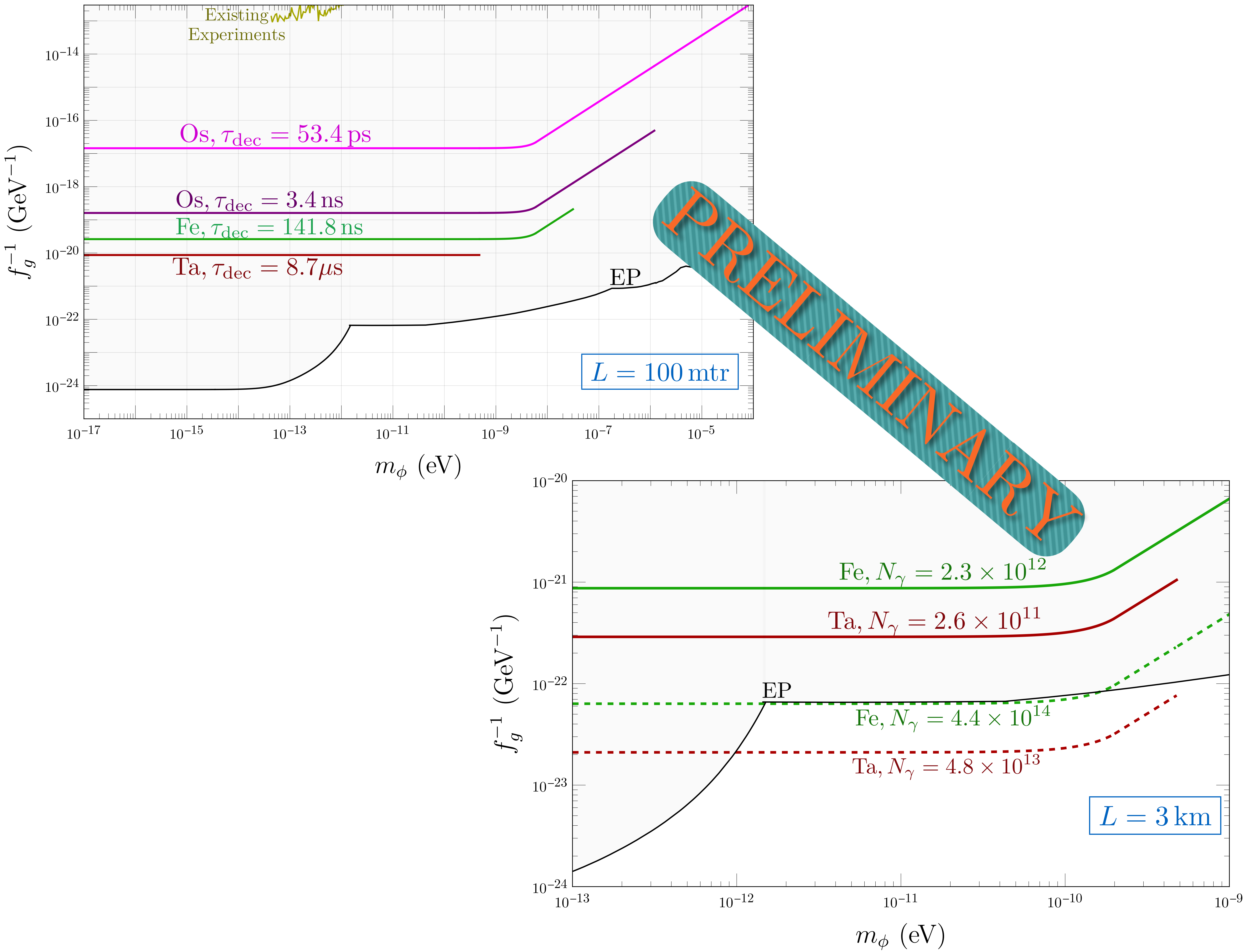

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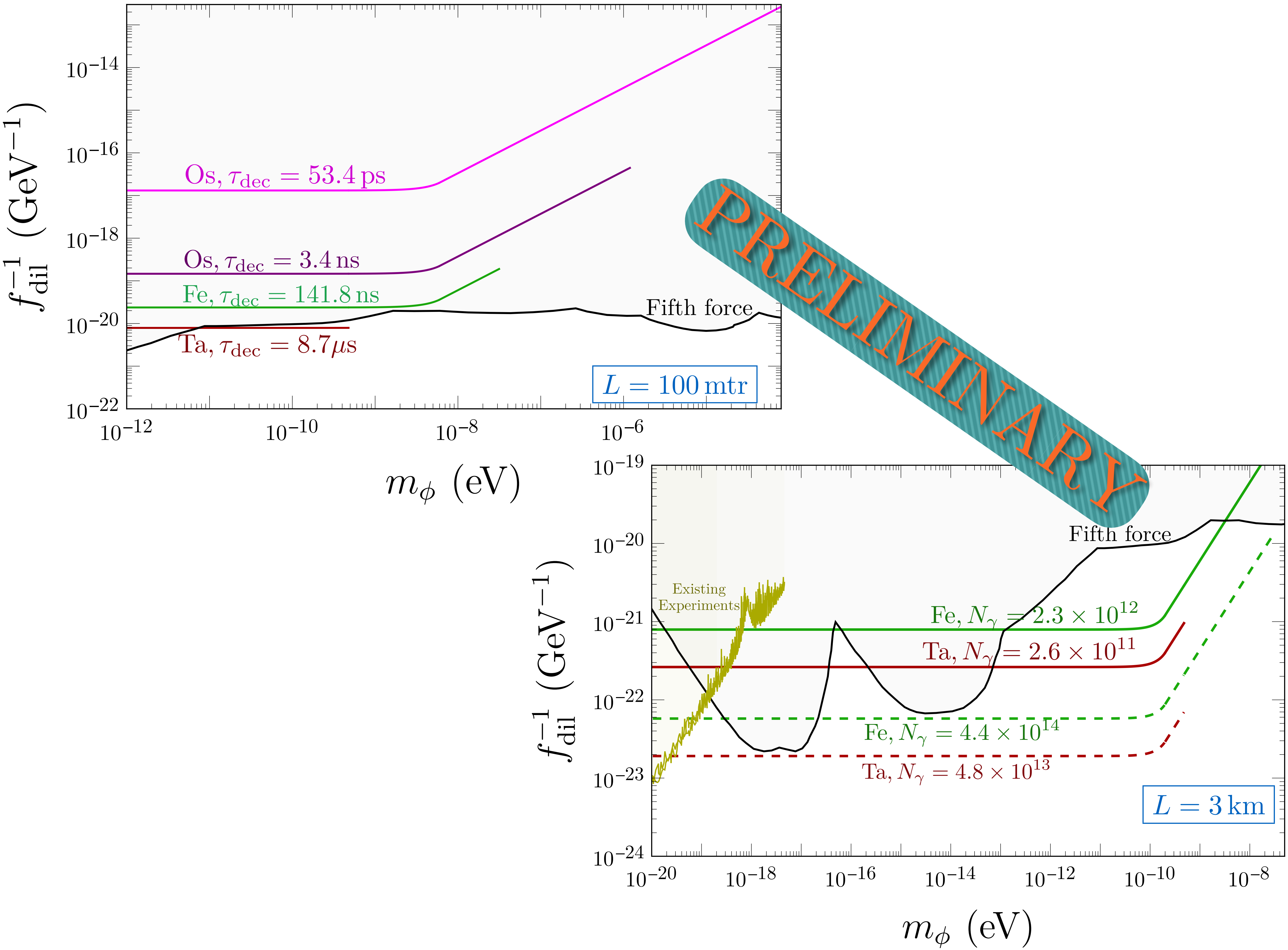
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Os, $\tau_{\rm dec} = 3.4\,$ns
Fe, $\tau_{\rm dec} = 141.8\,$ns
Ta, $\tau_{\rm dec} = 8.7\mu$s
Fifth force
$L = 100\,$mtr
10^{-12}
10^{-10}
10^{-8}
10^{-6}
m_ϕ (eV)
PRELIMINARY
$f_{\rm dil}^{-1}$ (GeV^{-1})
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Fifth force
Existing
Experiments
Fe, $N_\gamma = 2.3 \times 10^{12}$
Ta, $N_\gamma = 2.6 \times 10^{11}$
Fe, $N_\gamma = 4.4 \times 10^{14}$
Ta, $N_\gamma = 4.8 \times 10^{13}$
$L = 3\,$km
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
m_ϕ (eV)

QCD axion DM at the quadratic order

$$\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^{\mu\nu}\widetilde{G}_{\mu\nu}$$

$$m_\pi^2(\theta_{\rm eff}) = B\sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos(\theta_{\rm eff})} \text{ where } \theta_{\rm eff} = \bar{\theta} + a/f_a\,,\ B = -\langle \bar{q}q\rangle_0 / f_\pi^2$$

The oscillating QCD axion DM induces an oscillating component to pion mass

$$\frac{\Delta m_\pi^2}{m_\pi^2} = \frac{m_\pi^2(\theta_{\rm eff}) - m_\pi^2(0)}{m_\pi^2(0)} \simeq -\frac{m_u m_d\,\theta_{\rm eff}^2(t)}{2(m_u+m_d)^2} \qquad \theta_{\rm eff}(t) = \frac{(a - \langle a\rangle)}{f_a} = \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a}\cos(m_a t)$$

The nucleon mass also depends on the pion mass

$$m_N(\theta_{\rm eff}) = m_0 - 4c_1 m_\pi^2(\theta_{\rm eff}) - \frac{3g_A^2 m_\pi^3(\theta_{\rm eff})}{32\pi f_\pi^2} \qquad \frac{\partial \ln m_N}{\partial \ln m_\pi^2} \simeq 0.06$$

The QCD axion DM => oscillating pion mass and nucleon mass

[Kim, Perez 22]

Scalar DM interacting with the QCD Parameters

$$\mathcal{L} \supset -\frac{\phi}{\sqrt{2}M_{\rm pl}}\left[\sum_{q=u,d} d_{m_q}\, m_q\, \bar{q}q + \frac{d_g\,\beta(g_s)}{2g_s} G^{\mu\nu}G_{\mu\nu}\right]$$

Oscillating DM background $\phi\,(t) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}\cos(m_\phi t)$

leads to time oscillation of the QCD parameters as

$$\alpha_s(t) = \alpha_s(0)\left(1 - 2d_g\frac{\beta(g_s)\phi(t)}{g_s\sqrt{2}M_{\rm pl}}\right),\ \frac{\partial \ln \Lambda_{\rm QCD}}{\partial\phi} = \frac{d_g}{\sqrt{2}M_{\rm pl}} \qquad \hat{m} = (m_u + m_d)/2$$

$$\hat{m}(t) = \hat{m}(0)\left(1 + d_{\hat{m}}\frac{\phi(t)}{\sqrt{2}M_{\rm pl}}\right),\ \frac{\partial \ln \hat{m}}{\partial\phi} = \frac{d_{\hat{m}}}{\sqrt{2}M_{\rm pl}} \qquad d_{\hat{m}} = \frac{m_u d_{m_u} + m_d d_{m_d}}{m_u + m_d}$$

$$m_\pi^2 \propto \Lambda_{\rm QCD}\hat{m} \Rightarrow \frac{\Delta m_\pi^2}{m_\pi^2} = (d_g + d_{\hat{m}})\,\frac{\phi(t)}{\sqrt{2}M_{\rm pl}}$$

scalar DM interacting with QCD parameter => oscillating pion mass and nucleon mass

How to probe time oscillation of hadron masses ?

Let us estimate the amplitude of such oscillations are for nucleon mass

For the QCD axion $\frac{\Delta m_\pi^2}{m_\pi^2} = \frac{m_\pi^2(\theta_{\rm eff}) - m_\pi^2(0)}{m_\pi^2(0)} \simeq -\frac{m_u m_d\, \theta_{\rm eff}^2(t)}{2(m_u+m_d)^2}$ $\quad \theta_{\rm eff}(t) = \frac{(a - \langle a \rangle)}{f_a} = \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a}\cos(m_a t)$

$$\frac{\Delta m_N}{m_N} \simeq 0.06\, \frac{\Delta m_\pi^2}{m_\pi^2} \sim 10^{-16} \cos(2\, m_a t) \left(\frac{10^{-15}\,\mathrm{eV}}{m_a}\right)^2 \left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)^2$$

For the scalar DM $\alpha_s(t) = \alpha_s(0)\left(1 - 2d_g \frac{\beta(g_s)\phi(t)}{g_s\sqrt{2}M_{\rm pl}}\right),\ \frac{\partial \ln \Lambda_{\rm QCD}}{\partial \phi} = \frac{d_g}{\sqrt{2}M_{\rm pl}}$ $\quad \phi\,(t) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}\cos(m_\phi t)$

$$\frac{\Delta m_N}{m_N} \simeq \frac{\Delta \Lambda_{\rm QCD}}{\Lambda_{\rm QCD}} \sim 10^{-16} \cos(m_\phi t) \left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right) \left(\frac{d_g}{10^{-1}}\right)$$

Is it possible to probe such small oscillation? Yes!