Background-Induced Forces from Quadratically Coupled Ultralight Dark Matter

arxiv: 2606.28481

Presenter: Hailin Xu

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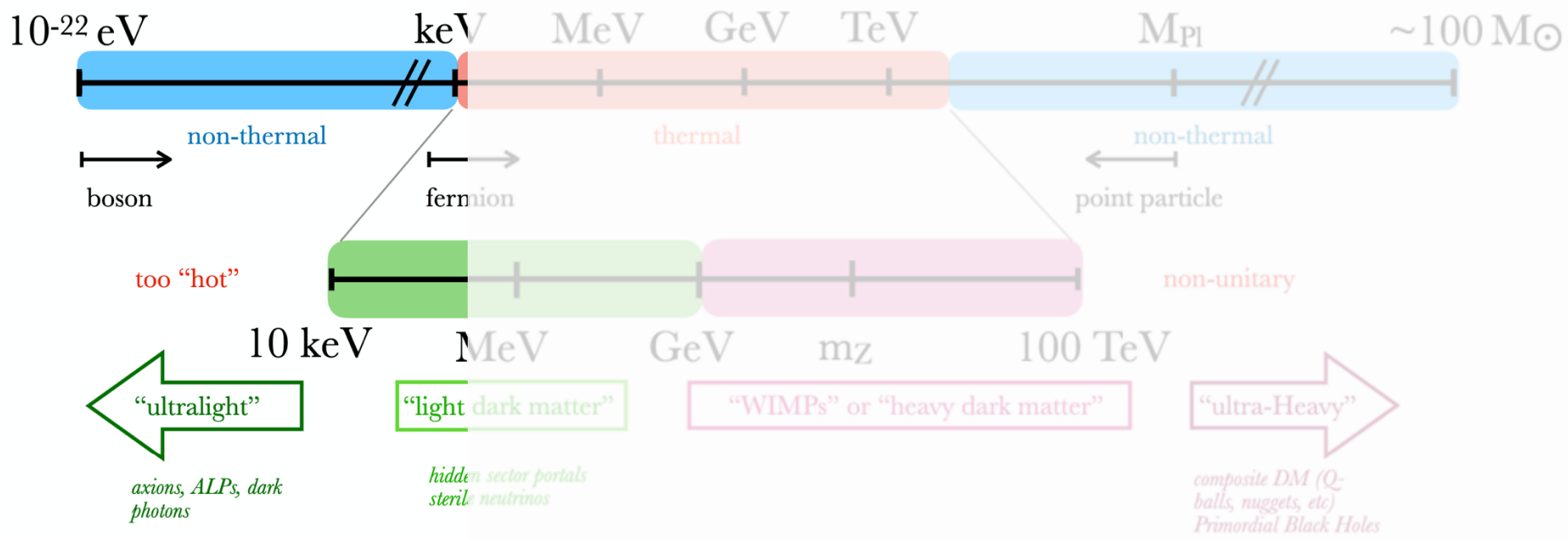
Ultralight Dark Matter



- Below keV: bosonic DM only
- We consider ultralight scalar DM, coupled to SM field constants that results in EP violation / fifth force phenos.

Quadratically Coupled ULDM

$$\mathcal{L}_{\rm int} \supset 2\pi \frac{\phi^2}{M_{\rm pl}^2}\left[\frac{d_e^{(2)}}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g^{(2)}\beta_s}{2g_s}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}^{(2)} m_e \bar{\psi}_e\psi_e - \sum_{q=u,d}\left(d_{m_q}^{(2)} + \gamma_{m_q} d_g^{(2)}\right) m_q\, \bar{\psi}_q\psi_q\right]$$

Implement $\mathbb{Z}_2$ symmetry (inv under $\phi \to -\phi$)

$$\frac{\Delta\alpha_{\rm em}}{\alpha_{\rm em}} = d_e^{(2)} \times 2\pi\frac{\phi^2}{M_{\rm pl}^2}\,, \qquad \frac{\Delta\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}} = d_g^{(2)} \times 2\pi\frac{\phi^2}{M_{\rm pl}^2}\,, \qquad \frac{\Delta m_e}{m_e} = d_{m_e}^{(2)} \times 2\pi\frac{\phi^2}{M_{\rm pl}^2}\,, \qquad \frac{\Delta m_q}{m_q} = d_{m_q}^{(2)} \times 2\pi\frac{\phi^2}{M_{\rm pl}^2}\,.$$

Fundamental constants varies, but different atoms (Z, A) have different binding energies, nuclear or electron compositions, so they respond differently to the scalar ϕ

EP violation!

Matter Effect for DM from macroscopic SM

$$L_{\rm int} = \frac{2\pi}{M_{\rm pl}^2}\phi^2 \times \text{SM}$$

$$V_{\phi\text{-from-}\mathcal{A}} = \frac{2\pi}{M_{\rm pl}^2}\alpha_{\mathcal{A}}^{(2)}\rho_{\mathcal{A}}\,\phi^2$$

$$V_{\mathcal{A}\text{-from-}\phi} = \frac{2\pi}{M_{\rm pl}^2}\alpha_{\mathcal{A}}^{(2)}M_{\mathcal{A}}\langle\phi^2\rangle$$

For DM ϕ:

$$m_{\mathrm{M},\mathcal{A}}^2(\mathbf{r}) = \alpha_{\mathcal{A}}^{(2)}\,\frac{4\pi\rho_{\mathcal{A}}(\mathbf{r})}{M_{\rm pl}^2}$$

matter-induced scalar mass, inside object A

ϕ^2 field re-distribution due to SM matter presence!

For macroscopic objects:

$$\mathbf{F}_{\mathrm{bg},\mathcal{A}} = -\frac{2\pi}{M_{\rm pl}^2}\alpha_{\mathcal{A}}^{(2)}M_{\mathcal{A}}\nabla\langle\phi^2\rangle$$

Background force due to ϕ^2 field's presence!

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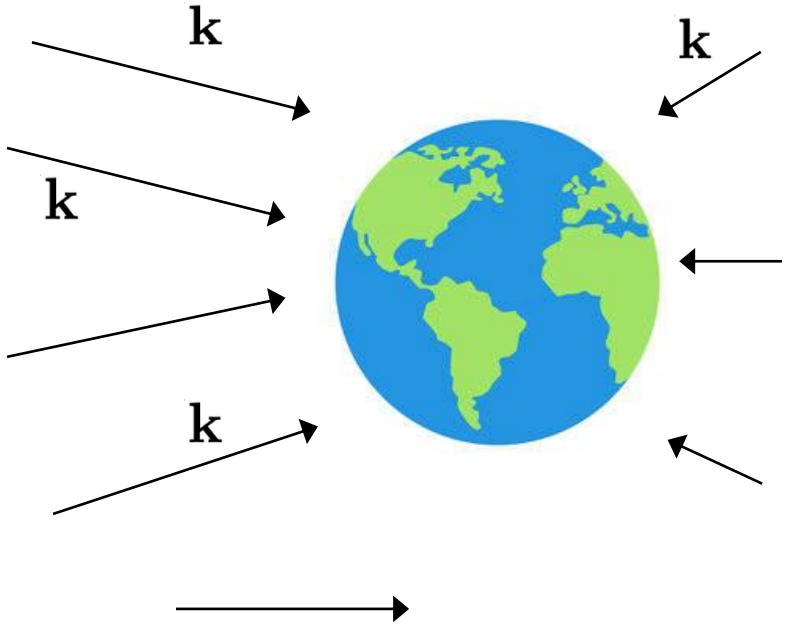
Blowin' In the (DM) Wind

Earth moving in the galaxy

$v_0 = 238$ km/s



$k_0 = m_\phi v_0$ DM wind 'average' momentum

In the Earth frame:

$$f_\phi(\mathbf{k}) = \frac{n_\phi}{\mathcal{N}(k_{\rm esc})} \left(\frac{2\pi}{\sigma_k^2}\right)^{3/2} \exp\left[-\frac{(\mathbf{k}-\mathbf{k}_0)^2}{2\sigma_k^2}\right] \Theta(k_{\rm esc} - |\mathbf{k}-\mathbf{k}_0|)$$

number density of DM w/ energy density of 0.3 GeV / cm^3

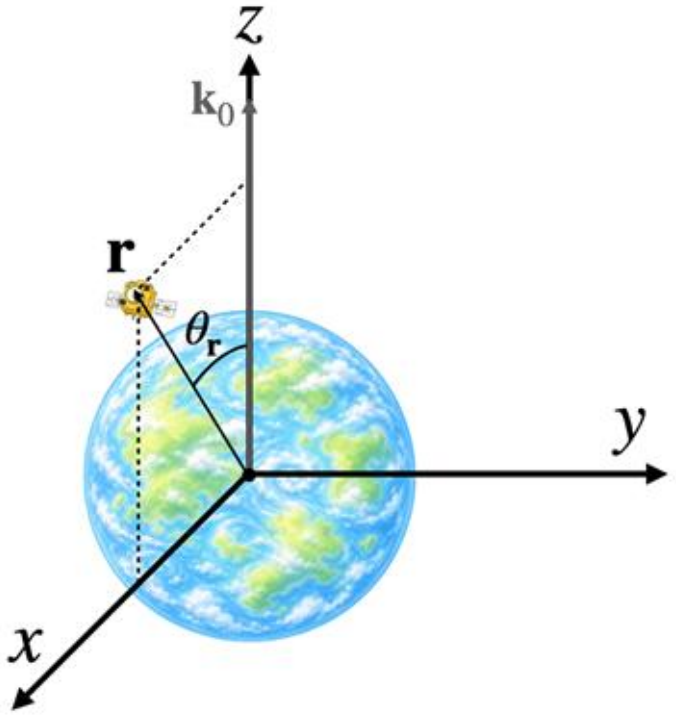
~ escape velocity of the galaxy

ULDM Scattered by the Earth ⊕

System is symmetric w/ $\mathbf{k}_0$ (direction of DM wind)

The field profile to be expanded:

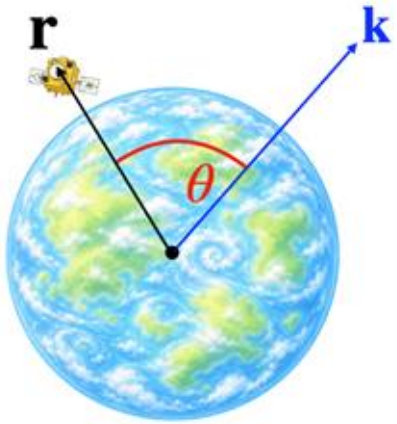
$$\langle \phi^2 \rangle = |\phi_0|^2 \sum_{L=0}^{\infty} a_L(r;\, k_0, m_{\mathrm{M},\oplus})\, P_L(\cos\theta_{\mathbf{r}})$$



ULDM Scattered by the Earth ⊕

Klein-Gordon equation:

$$\Box\phi + m^2_{\mathrm{eff},\oplus}(\mathbf{r})\,\phi = 0 \qquad m^2_{\mathrm{M},\oplus}(\mathbf{r}) = \alpha^{(2)}_{\oplus}\,\frac{4\pi\rho_{\oplus}(\mathbf{r})}{M^2_{\mathrm{pl}}}$$



For a mono-chromatic wave, in the NR limit:

$$\phi(\mathbf{r},t;\mathbf{k}) = \mathrm{Re}[e^{-i\omega(\mathbf{k})\,t}\psi(\mathbf{r};\mathbf{k})]$$

Schrödinger equation:

$$-\frac{1}{2m_0}\boldsymbol{\nabla}^2\psi + V_{\mathrm{eff}}(\mathbf{r})\psi = E_{\mathrm{eff}}(\mathbf{k})\psi$$

$$V_{\mathrm{eff},\oplus}(\mathbf{r}) = \frac{m^2_{\mathrm{M},\oplus}(\mathbf{r})}{2\,m_\phi}, \qquad E_{\mathrm{eff}}(\mathbf{k}) = \frac{\mathbf{k}^2}{2\,m_\phi}$$

partial-wave solution:

$$\psi(\mathbf{r};\mathbf{k}) = |\psi_0|\sum_{l=0}^{\infty}(2l+1)\,i^l\,\mathcal{R}_l(kr)\,P_l(\cos\theta)$$

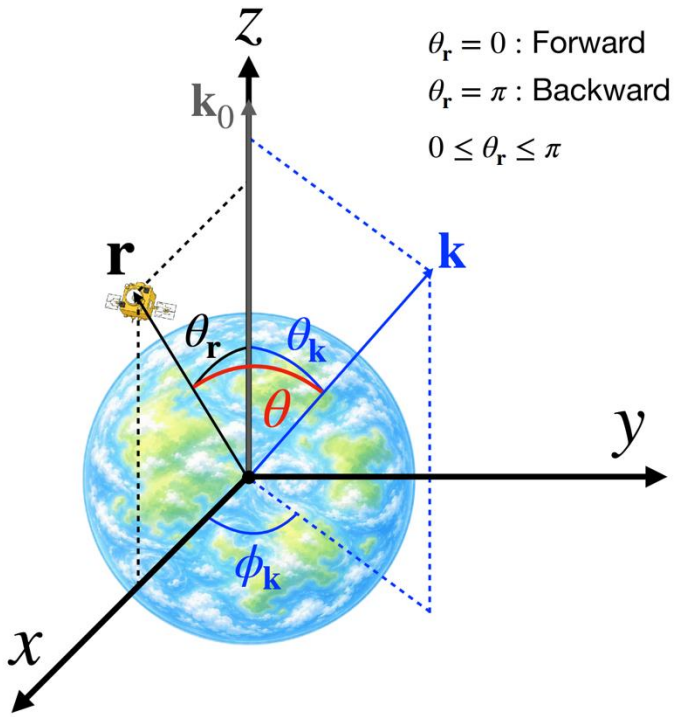
Phase Space Average

average over time and phase-space distribution:

$$\langle \phi^2 \rangle = \frac{1}{2}\langle |\psi|^2 \rangle = \frac{1}{2n_\phi} \int \bar{d}^3\mathbf{k}\, f_\phi(\mathbf{k})\, |\psi(\mathbf{x};\mathbf{k})|^2$$

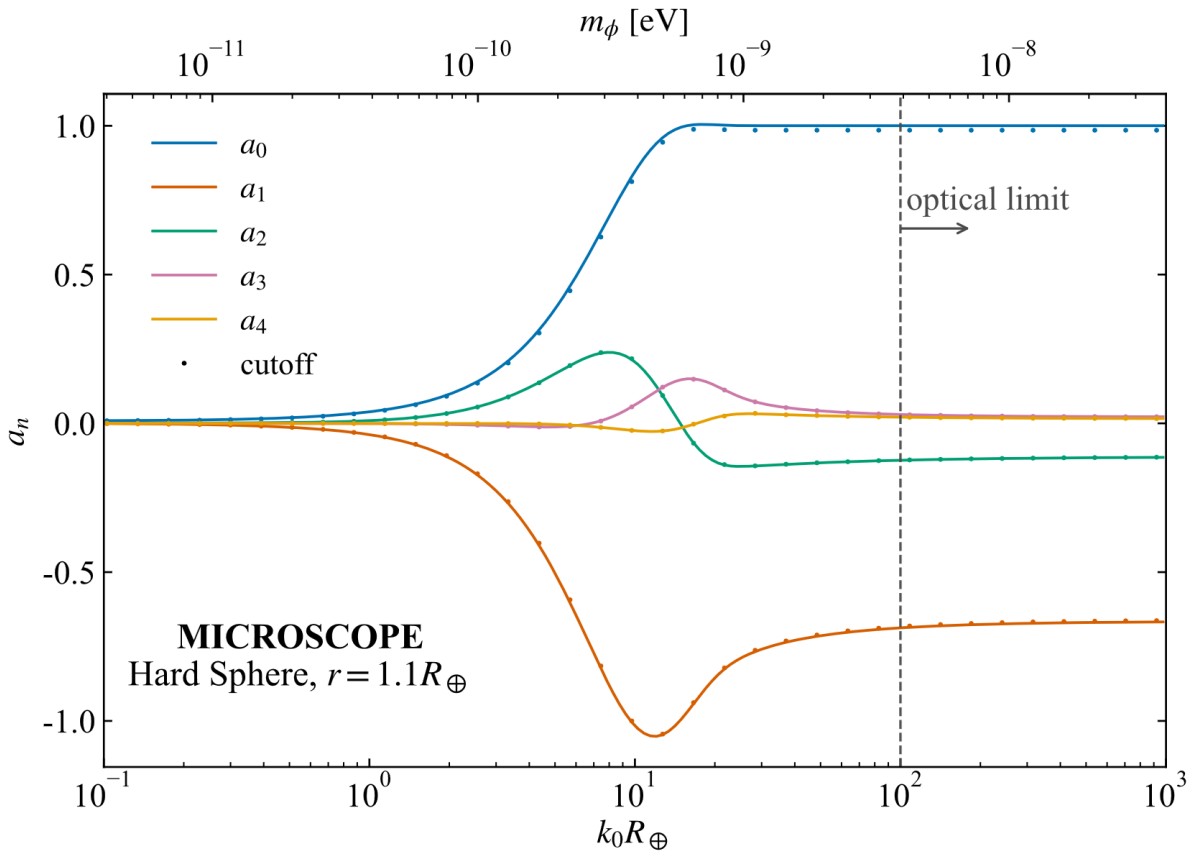
with:

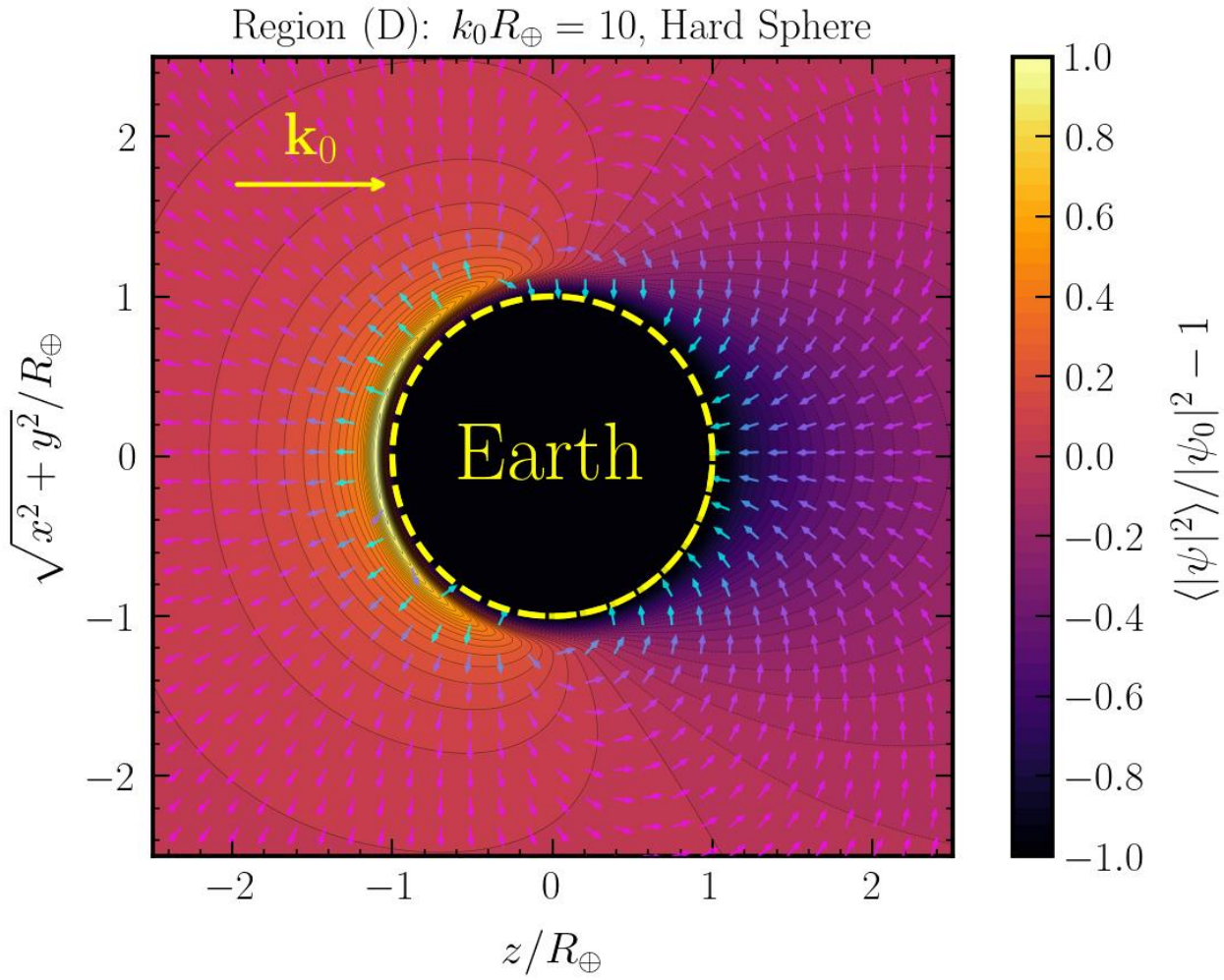
$$f_\phi(\mathbf{k}) = \frac{n_\phi}{\mathcal{N}(k_{\rm esc})} \left(\frac{2\pi}{\sigma_k^2}\right)^{3/2} \exp\left[-\frac{(\mathbf{k}-\mathbf{k}_0)^2}{2\sigma_k^2}\right] \Theta(k_{\rm esc} - |\mathbf{k}-\mathbf{k}_0|)$$



$$\langle |\psi|^2 \rangle = |\psi_0|^2 \sum_{L=0}^{+\infty} a_L(r;\, k_0, m_{\rm M,\oplus})\, P_L(\cos\theta_{\mathbf{r}})$$

Multipole Expansion





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Background force due to ϕ^2 field's presence!

Background Force

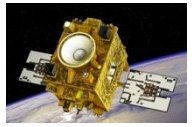
From scalar-induced potential, its gradient introduces background force/acceleration on macroscopic objects.

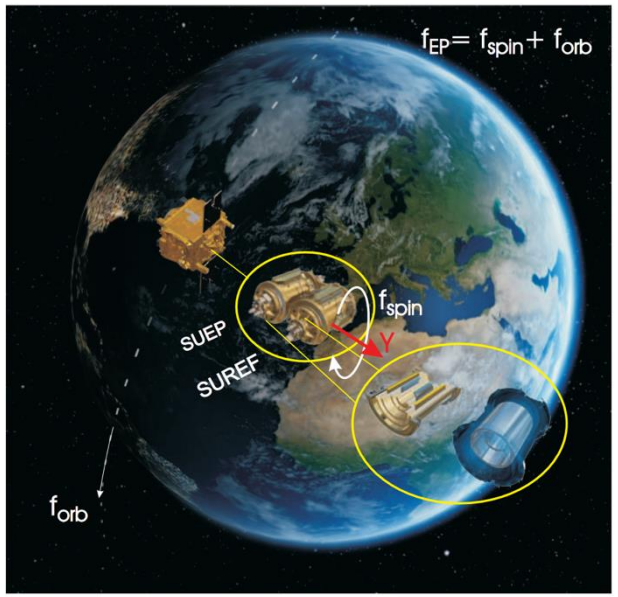
$$\boldsymbol{a}_{\mathrm{bg},\mathcal{A}} = -\frac{2\pi}{M_{\mathrm{pl}}^2}\alpha_{\mathcal{A}}^{(2)}\nabla\left\langle\phi^2\right\rangle = -\frac{\pi}{M_{\mathrm{pl}}^2}\alpha_{\mathcal{A}}^{(2)}\nabla\langle|\psi|^2\rangle$$

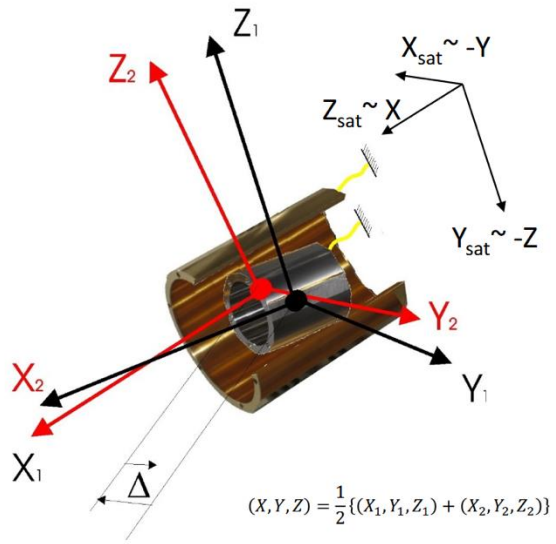
decomposition to radial and tangential:

$$\nabla\frac{\langle|\psi|^2\rangle}{|\psi_0|^2} = \underbrace{\hat{\mathbf{r}}\sum_L^{\infty}\frac{\mathrm{d}a_L}{\mathrm{d}r}P_L(\cos\theta_{\mathbf{r}})}_{\text{Radial derivative}} - \underbrace{\frac{1}{r}(\sin\theta_{\mathbf{r}}\,\hat{\boldsymbol{\theta}}_{\mathbf{r}})\sum_{L=0}^{\infty}a_L(r)P_L'(\cos\theta_{\mathbf{r}})}_{\text{Angular derivative}}$$

MICROSCOPE







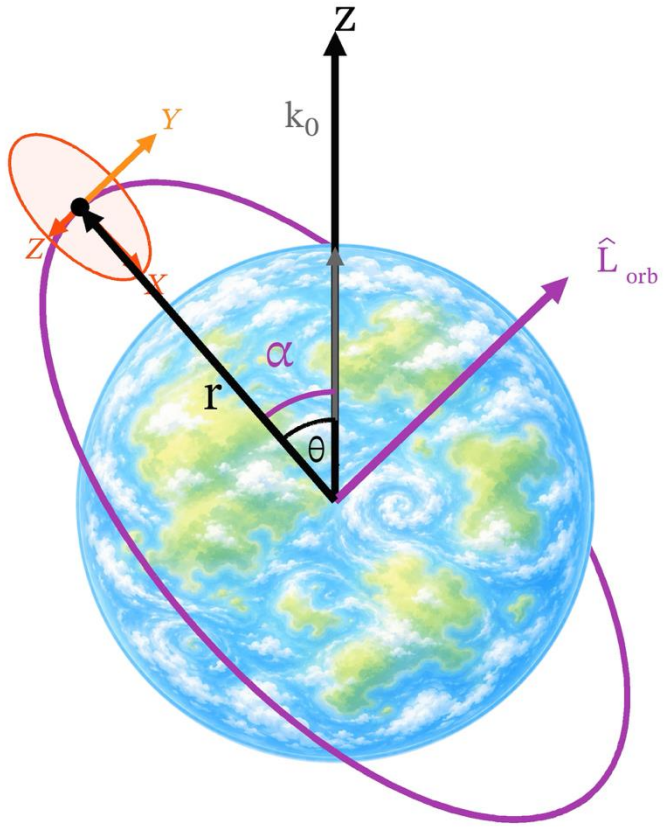
EP-test from April 25, 2016 to October 16, 2018

- Motion: $\begin{cases} \text{orbit around Earth} \\ \text{spin} \qquad \text{by itself} \end{cases}$
- Pair of test masses – coaxial cylinders of Ti (outer) and Pt (inner) alloys.
- Observable: Δa along X-axis, at the EP frequency

$$\eta = 2\frac{a_{\mathrm{Ti}} - a_{\mathrm{Pt}}}{a_{\mathrm{Ti}} + a_{\mathrm{Pt}}}$$

$$= [-1.5 \pm 2.3\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})] \times 10^{-15}$$

Along X-axis, at the EP Frequency?



α: < $\mathbf{k_0}$, orbital plane >
$\theta_\mathbf{r}$: < $\mathbf{k_0}$, $\mathbf{r}$>

V2 ωspin = 9/2 ωorb Torb = 5946 s t/Torb = 0.00 spin turns = 0.0

$\hat{\mathbf{X}}$, $\hat{\mathbf{Y}}$, $\hat{\mathbf{Z}}$: instrument axis.
The measurement focuses on $\hat{\mathbf{X}}$

MICROSCOPE used instrument axis $\hat{\mathbf{X}}$ to measure the centripetal acceleration difference $\Delta a_\mathbf{r}\hat{\mathbf{r}}$ between test masses.

If $\Delta a_\mathbf{r}$ does not vary during the orbit trajectory, then the measurement peaks at EP frequency:

$$\Delta a_\mathbf{r}\,\hat{\mathbf{r}}\cdot\hat{\mathbf{X}} = \Delta a_\mathbf{r}\,\cos(\Theta_{\mathrm{EP}})$$

$$\Theta_{\mathrm{orb}} = \omega_{\mathrm{orb}}\,t + \mathrm{init.}$$

$$\Theta_{\mathrm{spin}} = \omega_{\mathrm{spin}}\,t + \mathrm{init.}$$

$$\Theta_{\mathrm{EP}} = \Theta_{\mathrm{spin}} + \Theta_{\mathrm{orb}} = \underbrace{(\omega_{\mathrm{orb}} + \omega_{\mathrm{spin}})}_{\text{EP frequency}}\,t + \mathrm{init.}$$

Along X-axis, All Frequencies

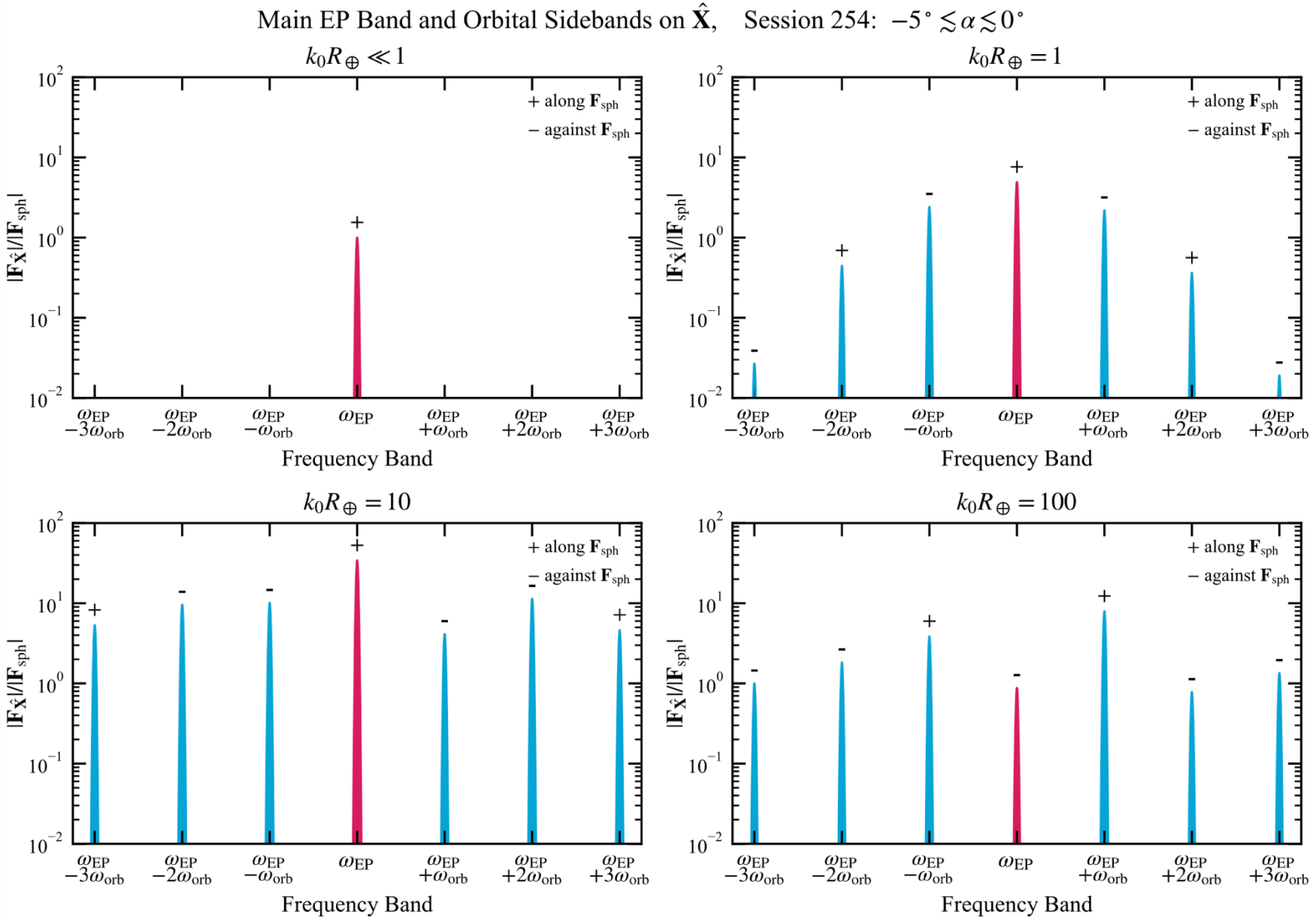
$$\boldsymbol{a}_{\mathrm{bg,Ti}} - \boldsymbol{a}_{\mathrm{bg,Pt}} = -\frac{\pi}{M_{\mathrm{pl}}^2}\left(\alpha_{\mathrm{Ti}}^{(2)} - \alpha_{\mathrm{Pt}}^{(2)}\right)\nabla\langle|\psi|^2\rangle$$

Difference of acceleration along instrument X-axis

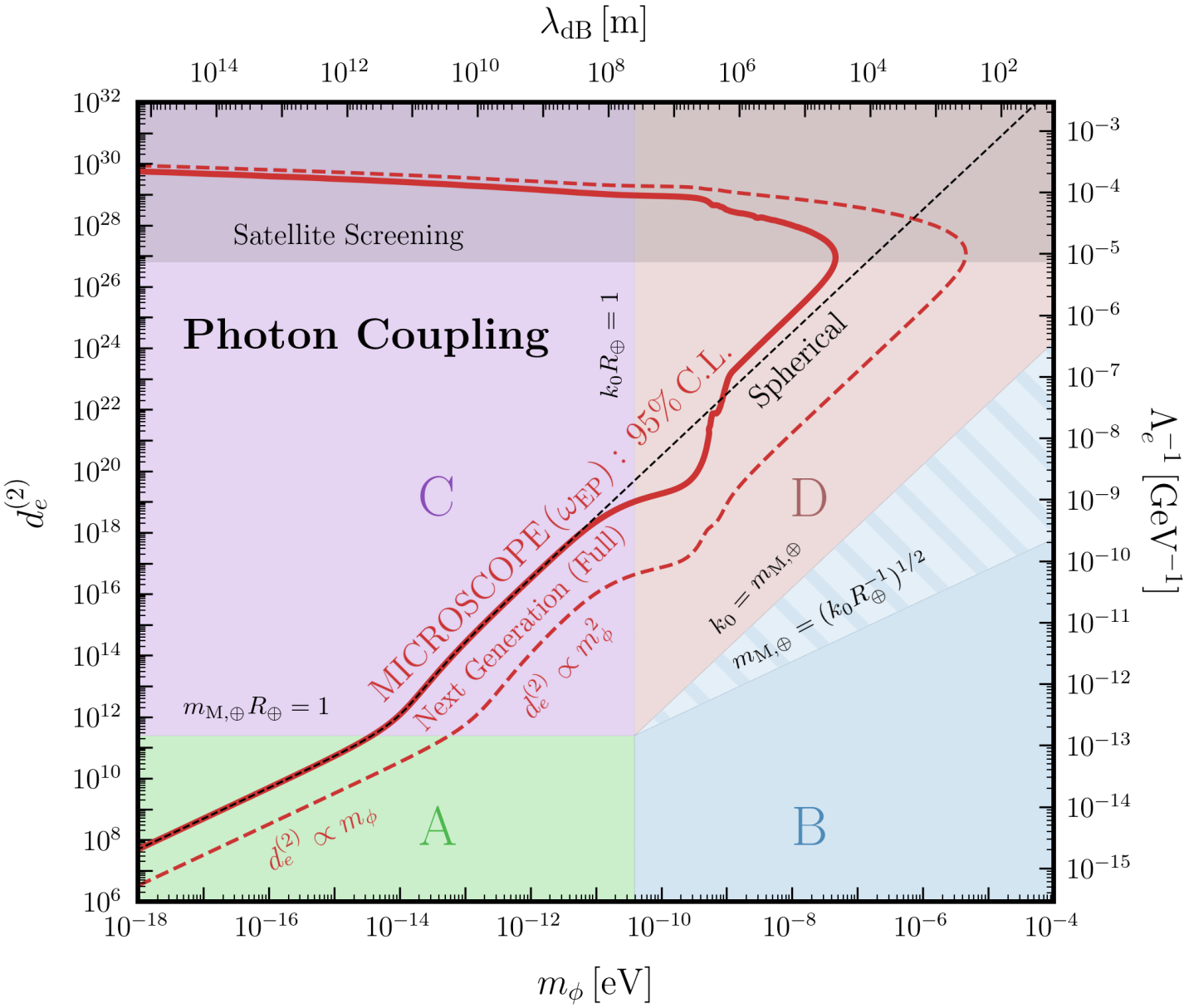
$$\hat{\mathbf{X}}\cdot(\boldsymbol{a}_{\mathrm{bg,Ti}} - \boldsymbol{a}_{\mathrm{bg,Pt}}) = -\frac{\pi}{M_{\mathrm{pl}}^2}\left(\alpha_{\mathrm{Ti}}^{(2)} - \alpha_{\mathrm{Pt}}^{(2)}\right)|\phi_0|^2 \times\left[\cos\Theta_{\mathrm{EP}}\sum_{L=0}^{\infty}\frac{\mathrm{d}a_L}{\mathrm{d}r}P_L(\cos\theta_{\mathbf{r}}) + \cos\alpha\,\cos\Theta_{\mathrm{orb}}\sin\Theta_{\mathrm{EP}}\sum_{L=0}^{\infty}\frac{a_L(r)}{r}P_L'(\cos\theta_{\mathbf{r}})\right]$$

- The monopole term of a_0 gives the signal with exactly ω_{EP} in the frequency space,
- while higher poles (L) gives sideband structures.

Signals: Frequency Band Structures

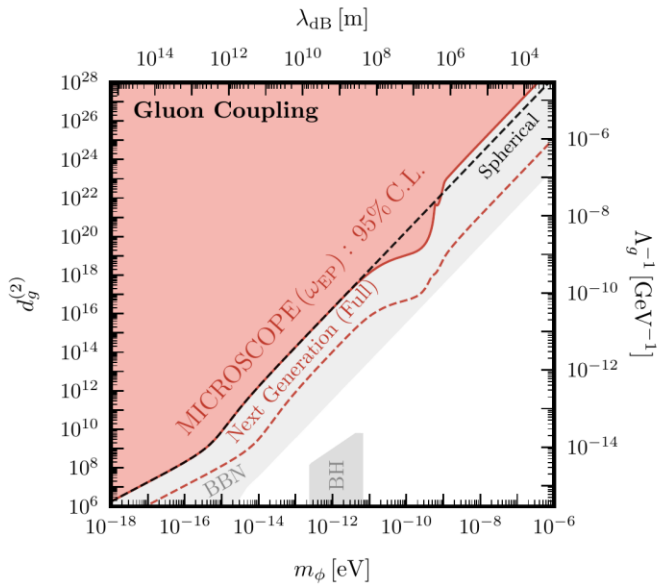


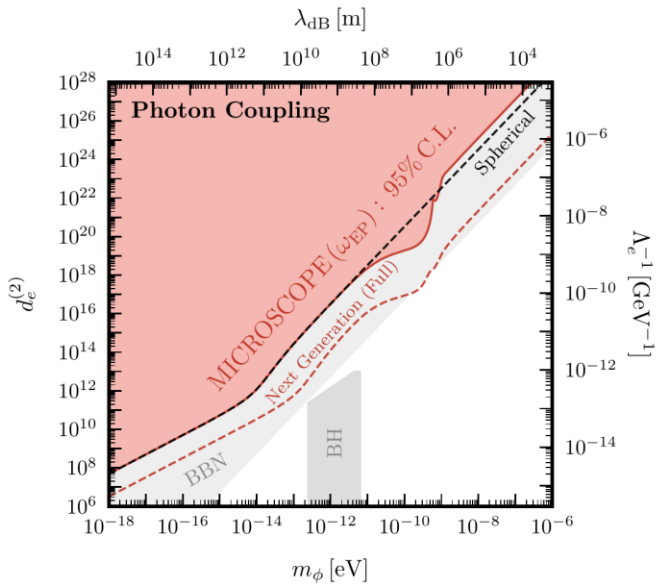
Constraints and Projections

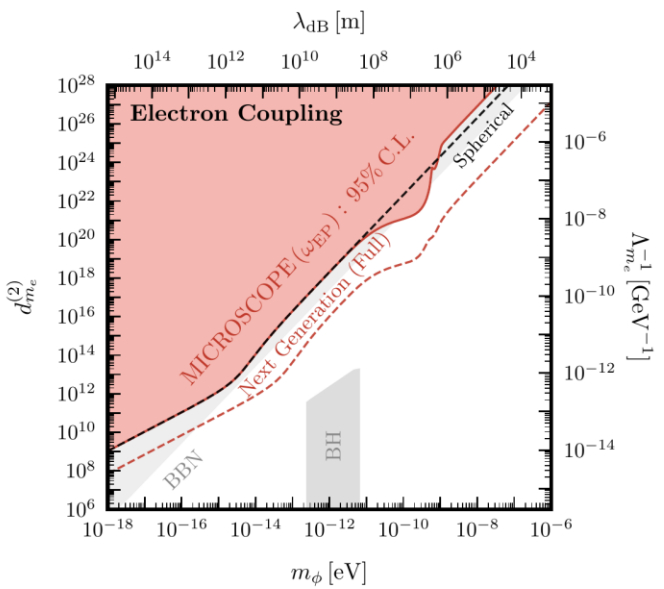


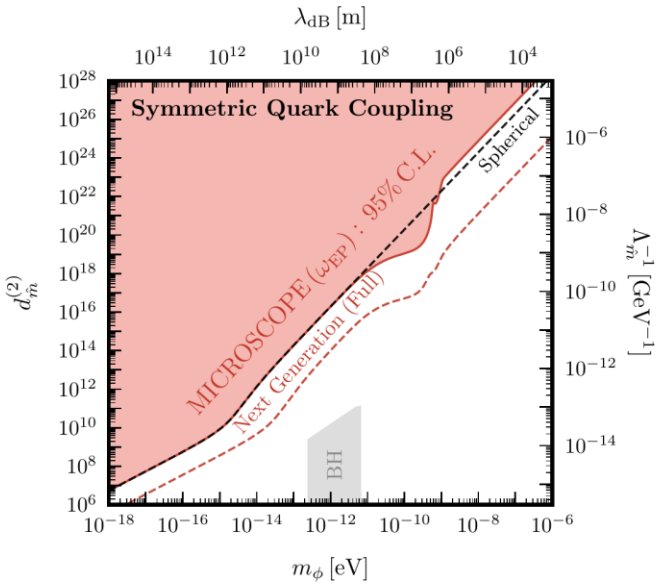
- 95% C.L. bound from χ^2 analysis of 19 segments of observation.
- Upper limit of the bound is from satellite screening.

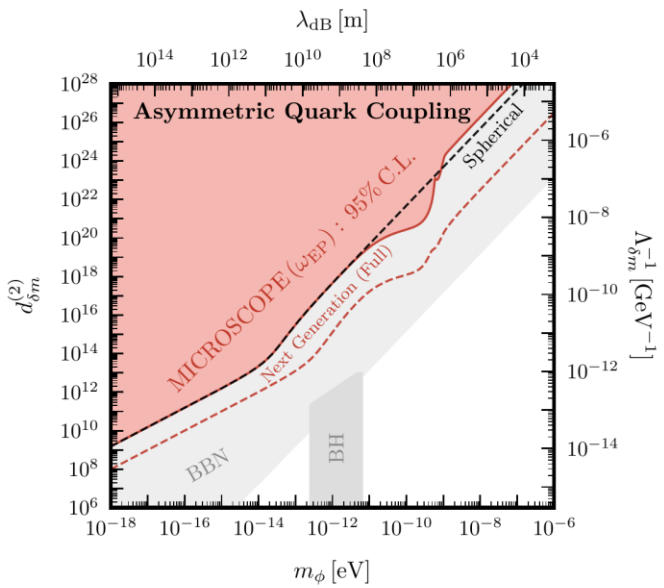
Other Couplings

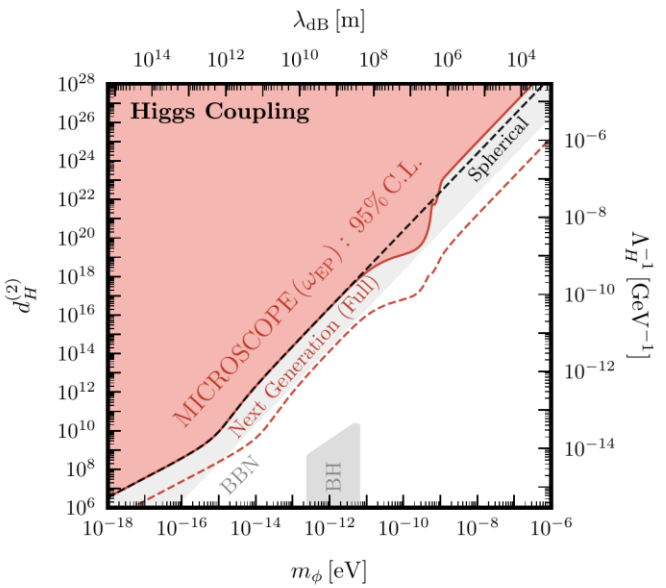






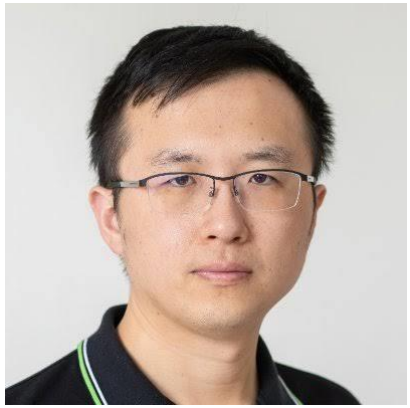






Thank you!

Hailin Xu
Adirondack Park, NY



Xucheng Gan
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Tien-Tien Yu
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Thomas Bouley
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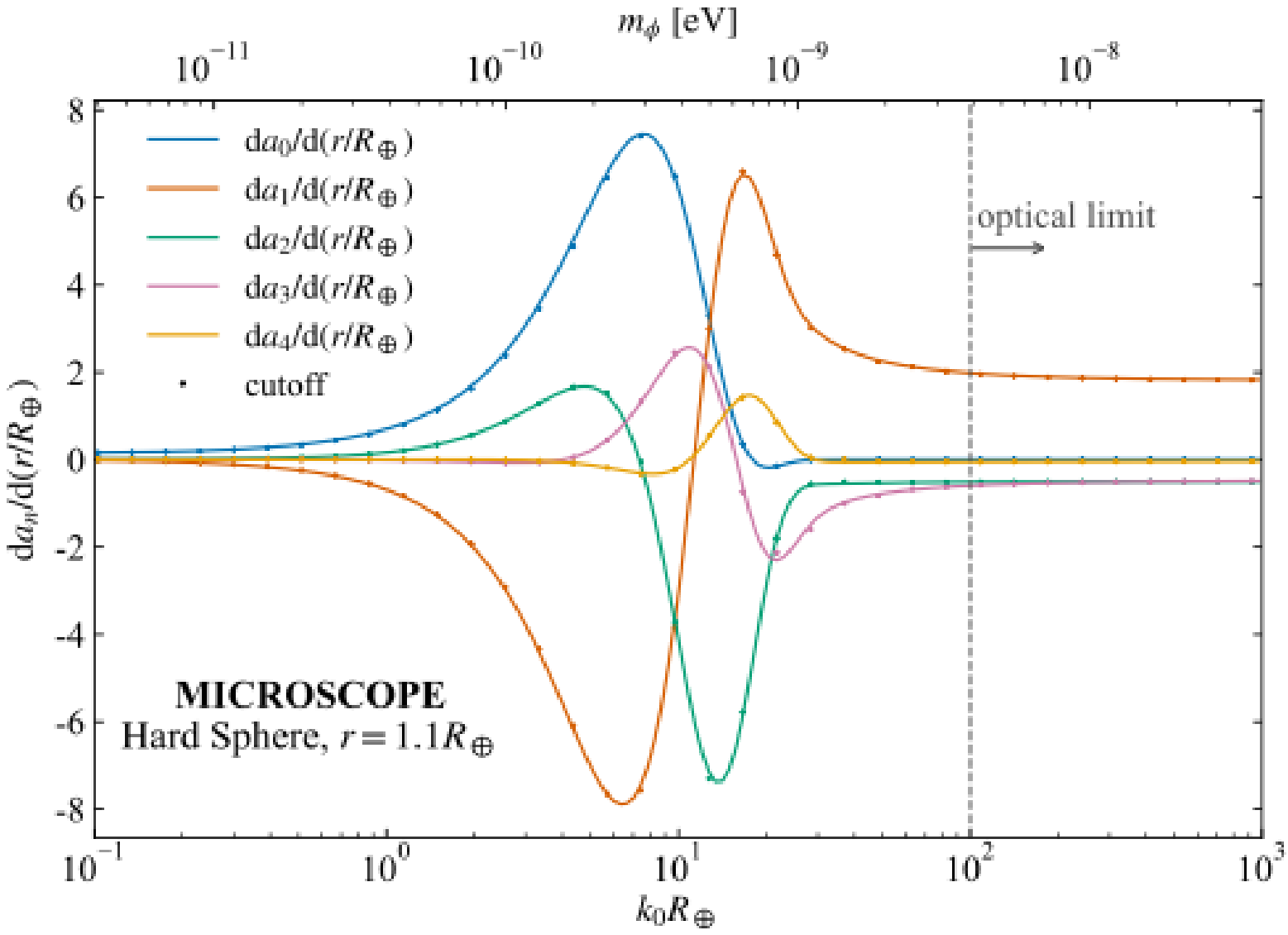
m_ϕ [eV]
10^{-11}
10^{-10}
10^{-9}
10^{-8}
$da_0/d(r/R_\oplus)$
$da_1/d(r/R_\oplus)$
$da_2/d(r/R_\oplus)$
$da_3/d(r/R_\oplus)$
$da_4/d(r/R_\oplus)$
cutoff
optical limit
MICROSCOPE
Hard Sphere, $r = 1.1R_\oplus$
$da_n/d(r/R_\oplus)$
8
6
4
2
0
-2
-4
-6
-8
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$k_0 R_\oplus$