Search for Ultralight Scalar Dark Matter with Quadratic Interactions

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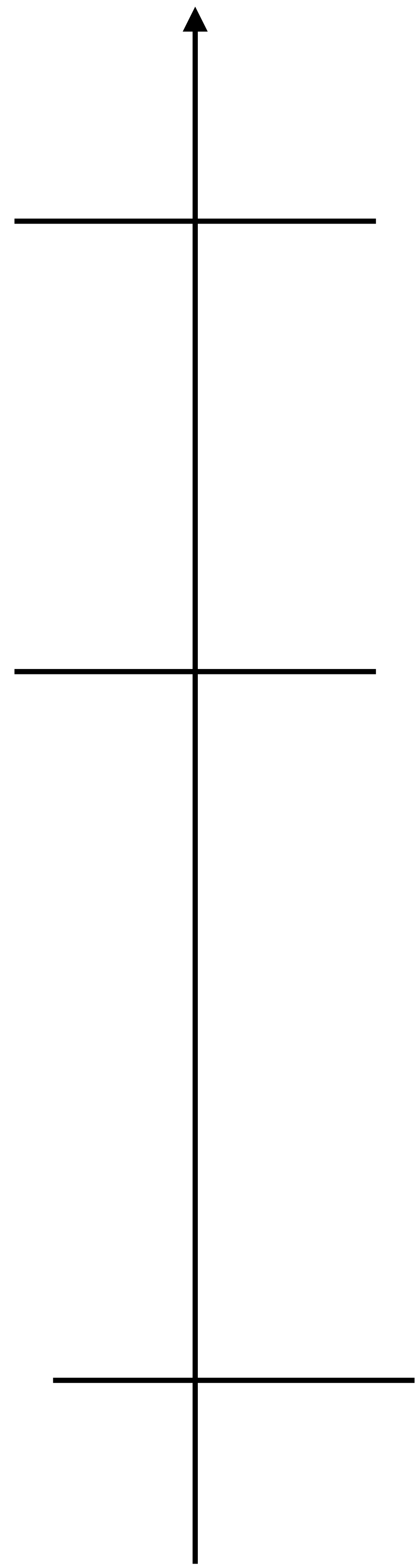
Based on work
X. Gan, D.L., D. Liu, X. Luo, B. Yu, JHEP 02 (2026) 043
H. D, D.L., M. Luty, Y. Zhao, JHEP 07 (2024) 136

Dark Matter: field-like or particle-like

eV



$$N = \frac{\rho_{\rm DM}}{m_\phi}(\lambda_{\rm dB})^3 \sim 10^6 \left(\frac{\rm eV}{m_\phi}\right)^4$$

Ultralight Scalar Dark Matter Model

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$

Ordinary Matter

$$\text{Å} = 10^{-8}\text{cm}$$

$$\bar{\lambda}_{dB} = \frac{1}{m_\phi v} \sim 2.0 \times 10^{-2}\text{cm}\frac{\text{eV}}{m_\phi}$$

$$\langle \bar{N}N \rangle = n_N$$

Number density

Ultralight Scalar Dark Matter Model

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$

$$(\Box + m^2 + \frac{n}{f})\phi = 0$$

$$\phi = \psi(\vec{x})e^{-iEt} + c.c.$$

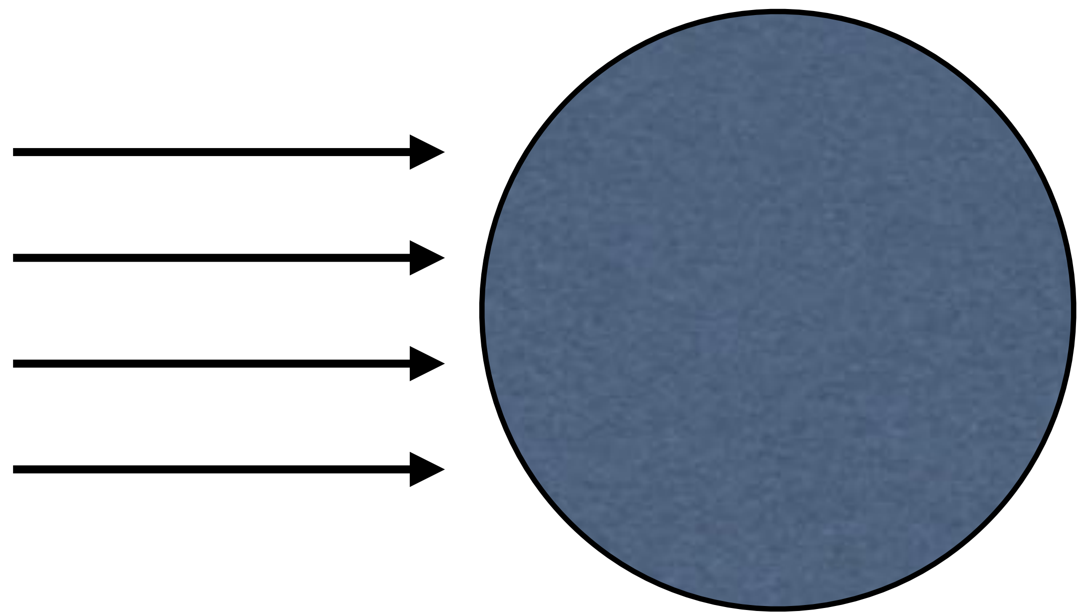
$$(\nabla + E^2 - m^2 - \frac{n}{f})\psi(\vec{x}) = 0$$

Schrodinger equation with potential

$$V = \frac{n}{2m_\phi f}$$

Ultralight Scalar Dark Matter Model

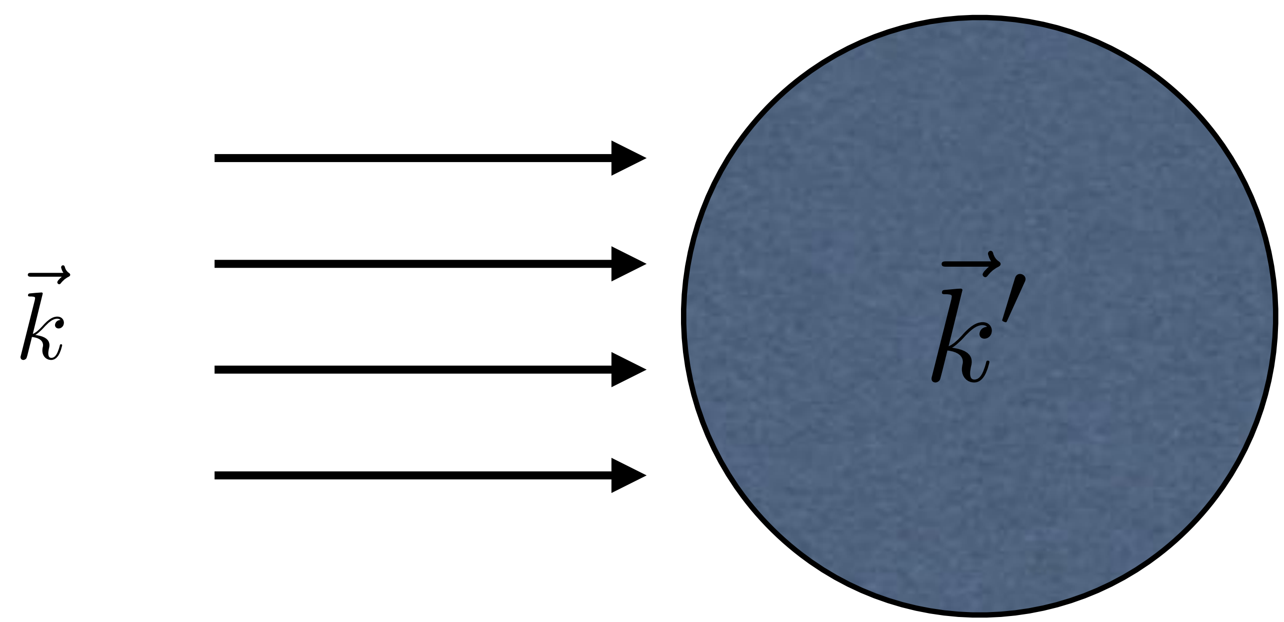
$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$



$$E^2 = \vec{k}^2 + m_\phi^2 \qquad E^2 = \vec{k}'^2 + m_\phi^2 + \frac{n_N}{f}$$

Ultralight Scalar Dark Matter Model

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$

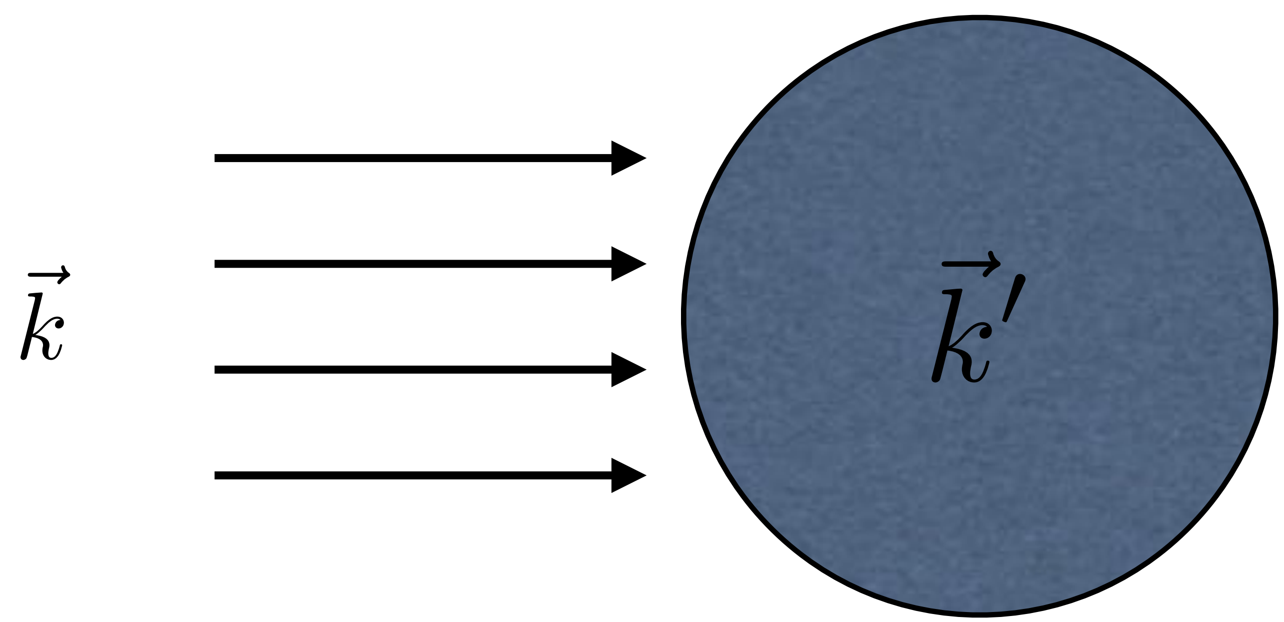


$$\vec{k}'^2 = \vec{k}^2 - \frac{n_N}{f}$$

Damping can occur when $\vec{k}^2 < \frac{n_N}{f}$

Ultralight Scalar Dark Matter Model

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$

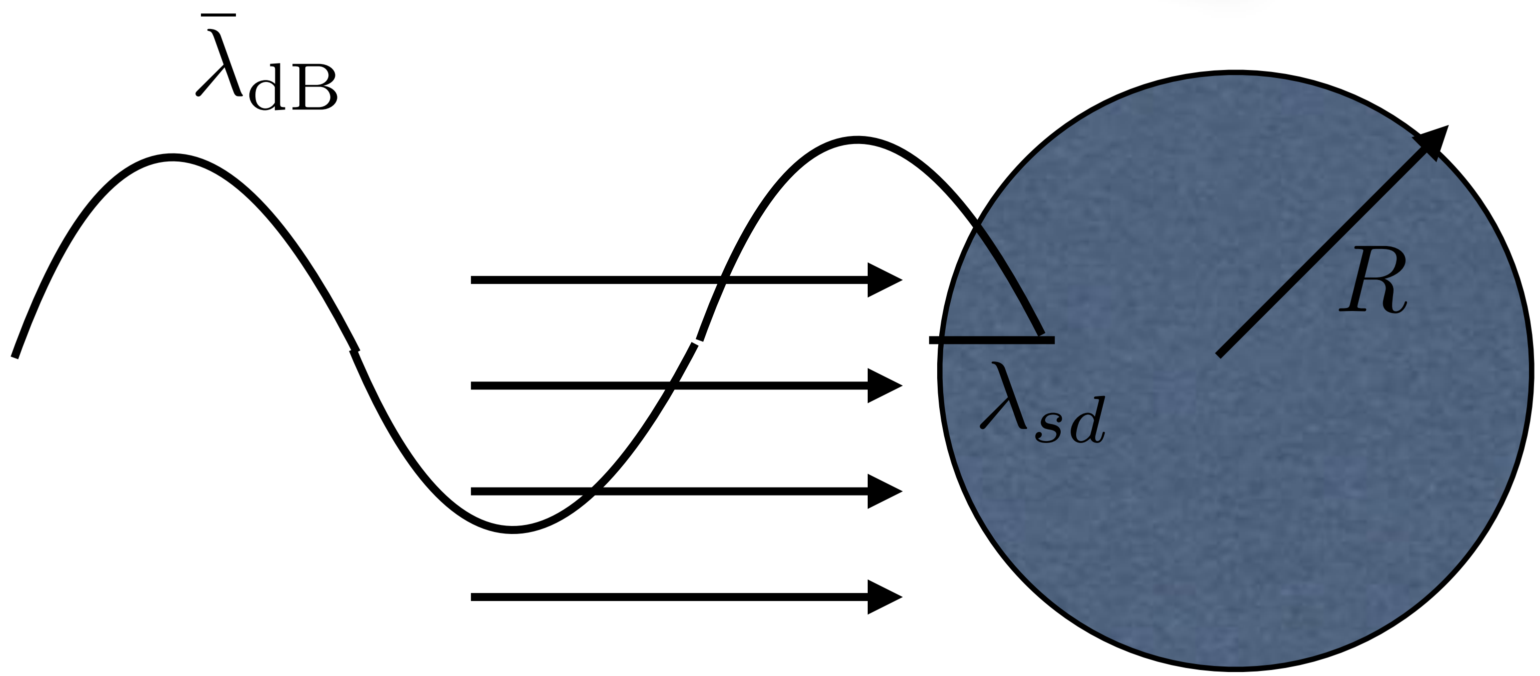


$$\lambda_{sd} = 1/\sqrt{\frac{n}{f}} \sim 5.6 \times 10^{-2}\mathrm{cm} \times \sqrt{\frac{\frac{f}{10^8\mathrm{GeV}}}{\frac{\rho_{\mathrm{matt}}}{2.7\ \mathrm{g/cm^3}}}}$$

$$\bar{\lambda}_{dB} = \frac{1}{m_\phi v} \sim 2.0 \times 10^{-2}\mathrm{cm}\frac{\mathrm{eV}}{m_\phi}$$

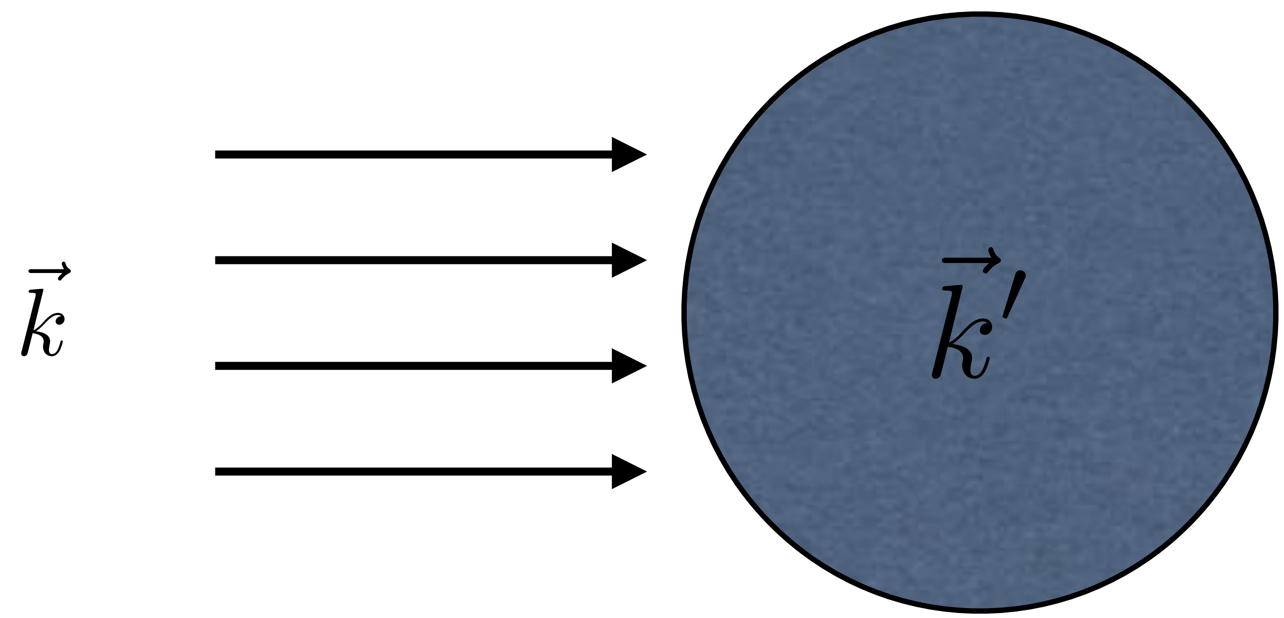
Two conditions for the maximal force

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$



- Strong Potential $\lambda_{sd} \ll \bar{\lambda}_{\mathrm{dB}}$
- Small skin depth $\lambda_{sd} \ll R$

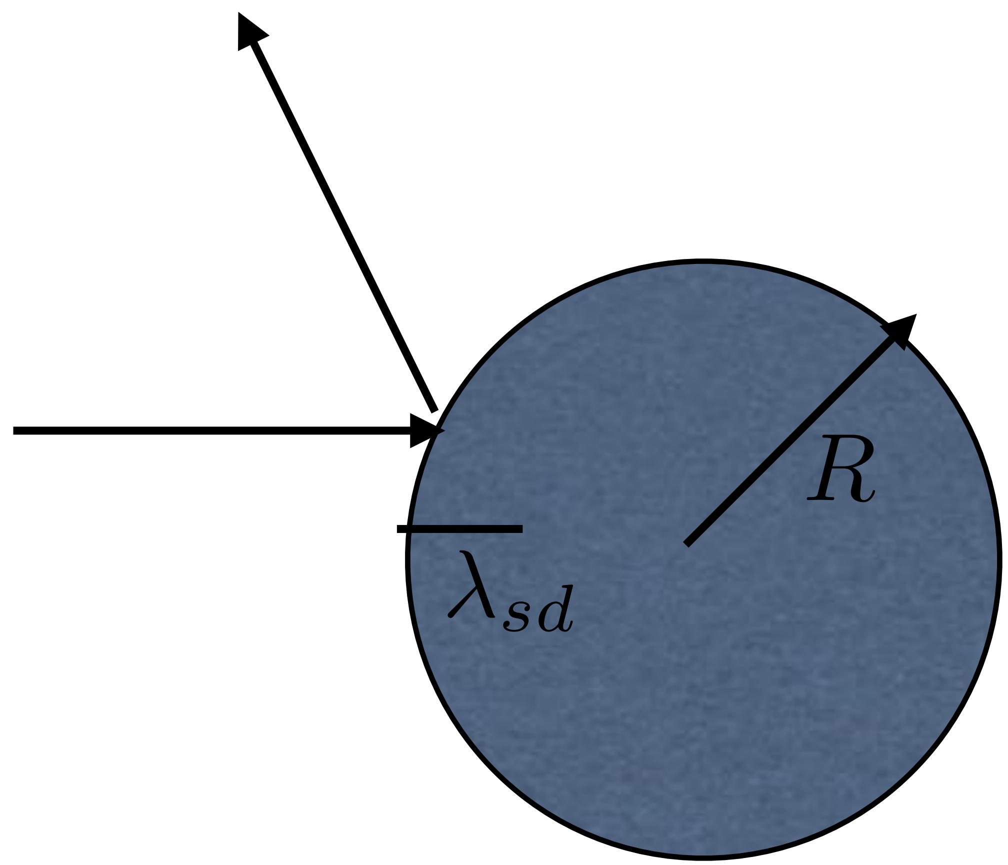
Acceleration induced by DM wind



$$a = \frac{F}{M} = \frac{3}{4}\frac{\rho_{\rm DM} v_D^2}{\rho_m R} \sim 1.3\times 10^{-12} m/s^2 \frac{2.7{\rm g/cm^3}}{\rho_m}\frac{\rm cm}{R}$$

Geometric Limit

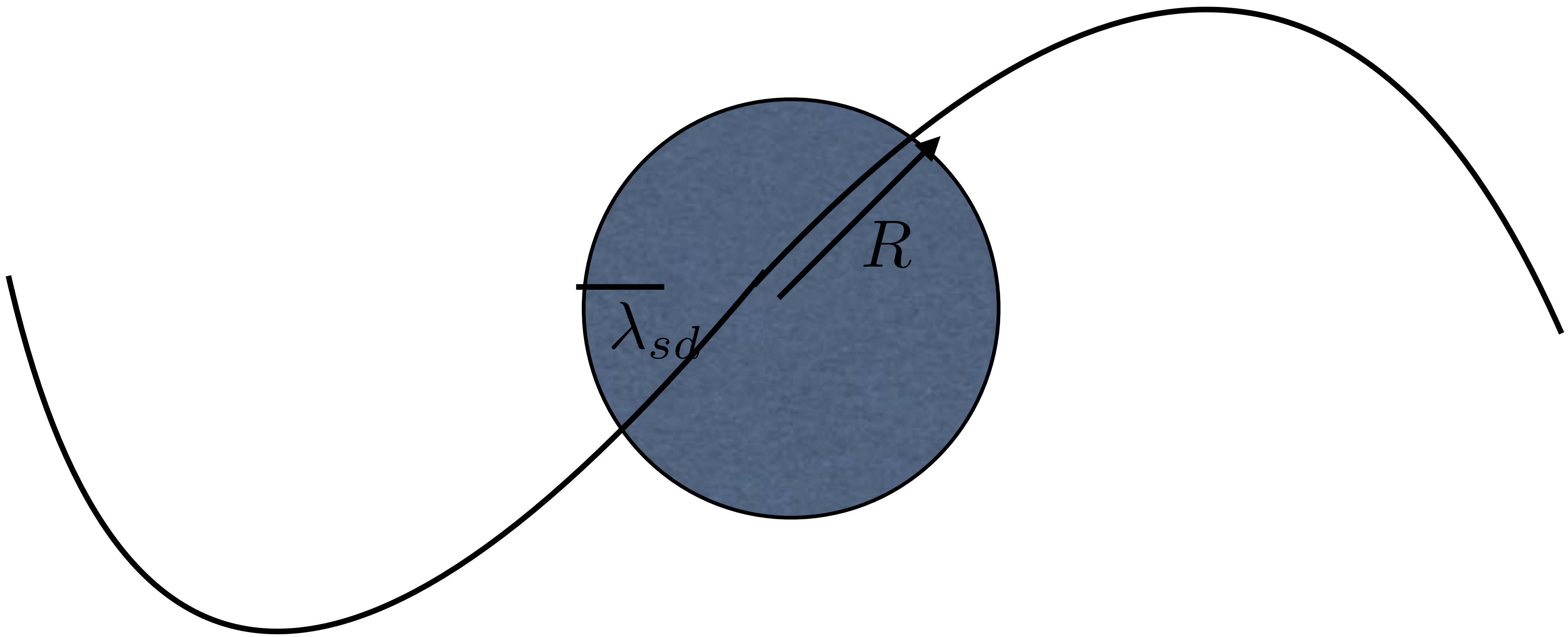
$$\lambda_{sd} \ll \bar{\lambda}_{\mathrm{dB}} \ll R$$



$$F_z = \rho_{\mathrm{DM}} v^2 \pi R^2$$

Slow scattering limit

$$\lambda_{sd} \ll R \ll \bar{\lambda}_{\rm dB}$$

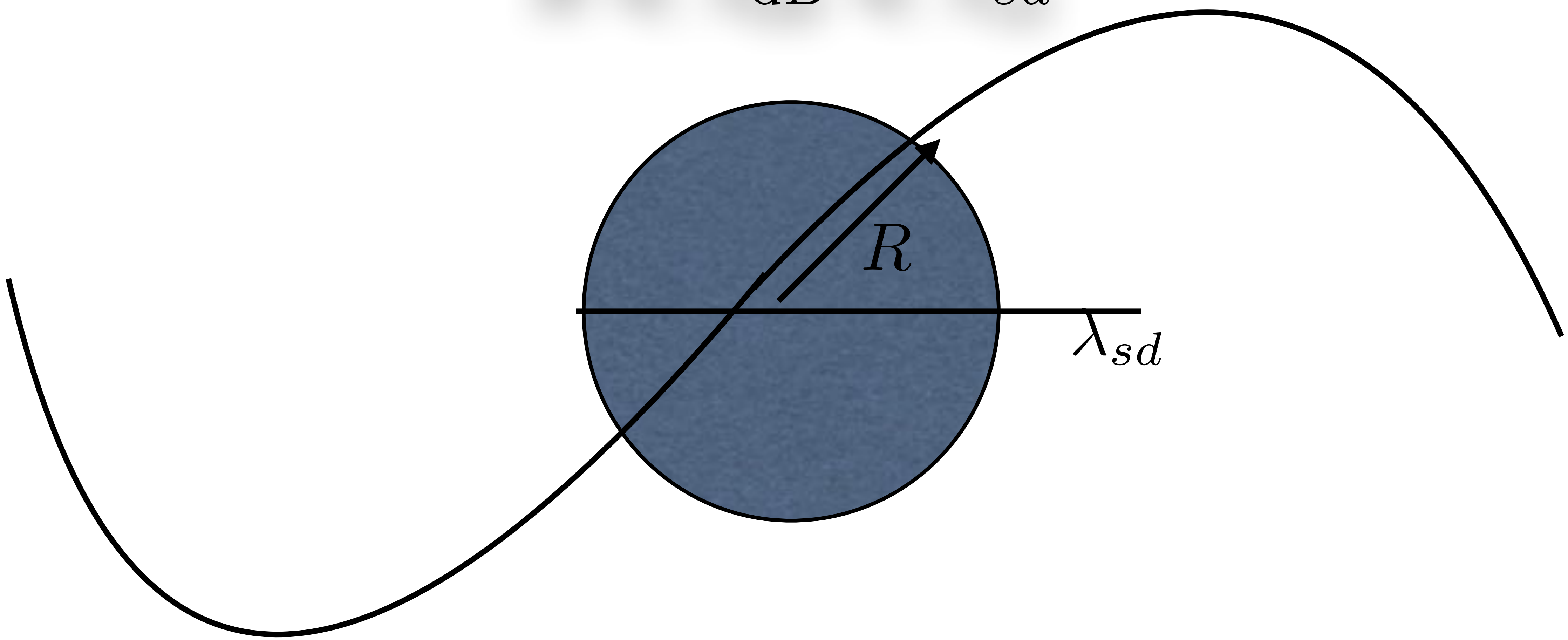


$$F_z = 4\rho_{\rm DM} v^2 \pi R^2$$

Slow scattering limit: large skin depth

$$R \ll \lambda_{sd} \ll \bar{\lambda}_{\rm dB}$$

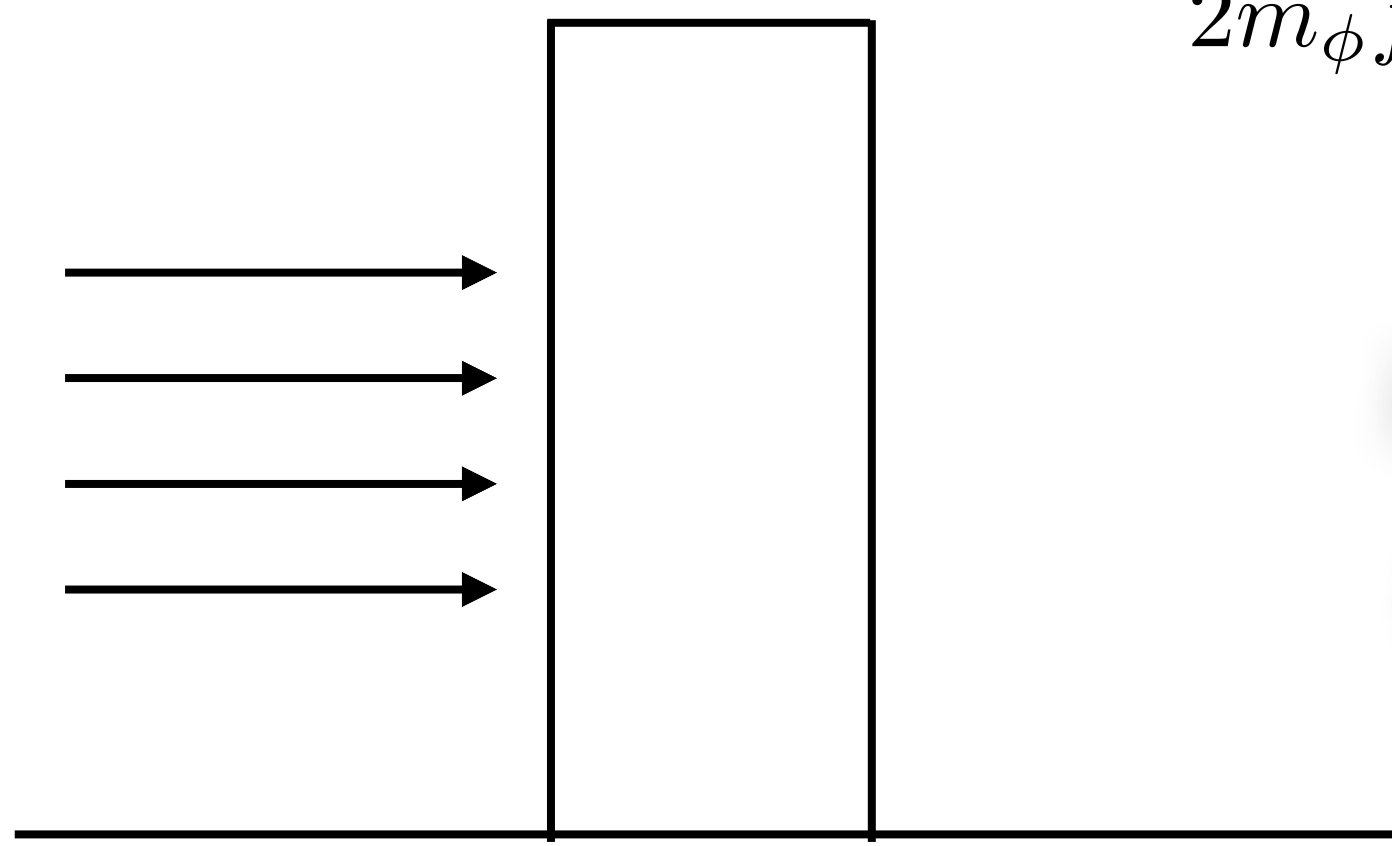
$$R \ll \bar{\lambda}_{\rm dB} \ll \lambda_{sd}$$



$$\frac{F_z}{\rho_{\rm DM} v^2 \pi R^2} \sim \frac{4}{9}\frac{R^4}{\lambda_{sd}^4}$$

Shielding effect: potential barrier

$$V_0 = \frac{n}{2 m_\phi f}$$



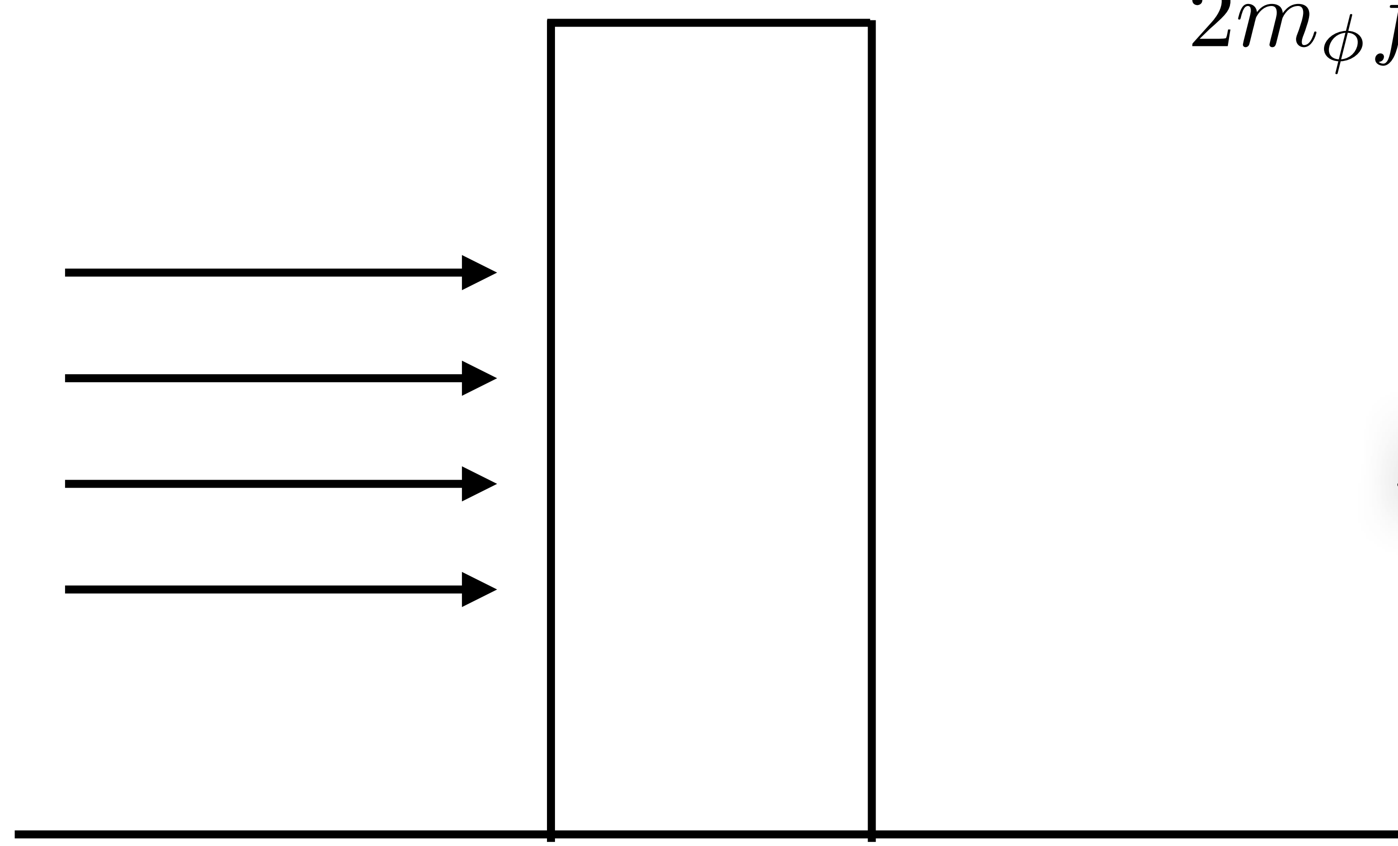
$$\bar{\lambda}_{dB} \gg \lambda_{sd}$$

$$L \gg \lambda_{sd}$$

$$T \sim 16 \frac{\lambda_{sd}^2}{\bar{\lambda}_{\rm dB}^2} e^{-2L/\lambda_{sd}}$$

Shielding effect: potential barrier

$$V_0 = \frac{n}{2m_\phi f}$$

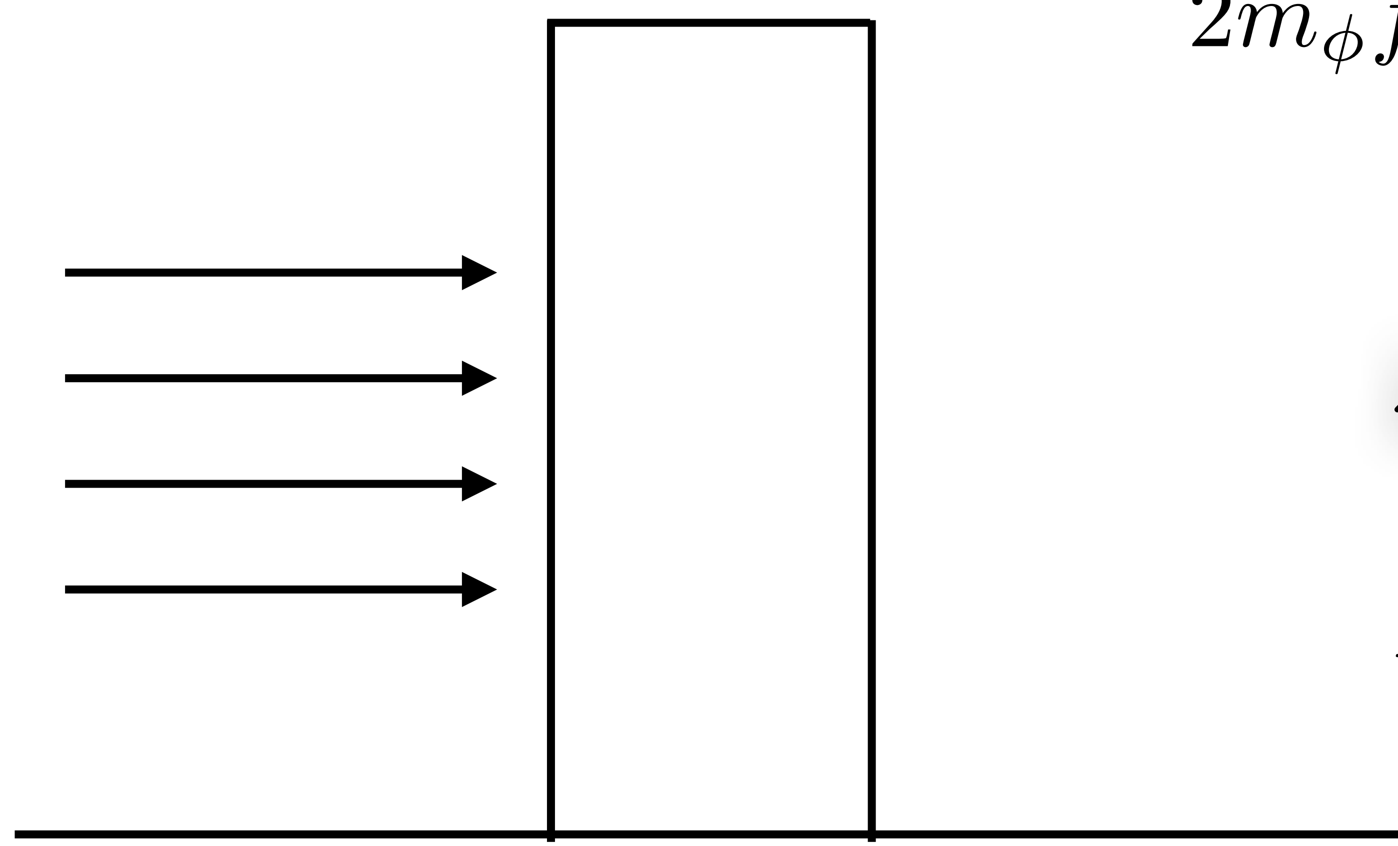


$$\bar{\lambda}_{dB} \ll \lambda_{sd}$$

$$T \sim 1 - \frac{1}{4}\frac{\bar{\lambda}_{\rm dB}^4}{\lambda_{sd}^4}\sin^2(L/\bar{\lambda}_{\rm dB})$$

Shielding effect: potential barrier

$$V_0 = \frac{n}{2m_\phi f}$$



$$\bar{\lambda}_{dB} \gg \lambda_{sd}$$

$$L \ll \lambda_{sd}$$

$$T \sim \frac{1}{1 + \frac{1}{4}\frac{L^2 \bar{\lambda}_{\mathrm{dB}}^2}{\lambda_{sd}^4}}$$

Bounds and Projections

Supernova Cooling Bound: Raffelt criterion

$$N\bar{N} \to N\bar{N}\phi\phi$$

Neutrino Luminosity

$$\Gamma \sim \sigma_{nn} \times \frac{\rho_c^2 T_c^{7/2}}{48\pi^4 m_n^{5/2} f^2} \lesssim 10^{-14}\ \mathrm{MeV}^5$$

$$f \gtrsim 1.1 * 10^8\,\mathrm{GeV}$$

Cosmology in a Nutshell

Temperature | **Primordial Curvature Perturbation**

$$T(z) = T_0(1+z)$$

$$\ln(10^{10}\Delta_{\mathcal{R}}^2)|_{k_0=0.05\mathrm{Mpc}^{-1}} = 3.044 \pm 0.014$$

$$n_s = 0.965 \pm 0.004$$

$$T_{\mathrm{W}} \simeq 0.8\mathrm{MeV}$$

4He mass fraction

$$T_{\mathrm{BBN}} \simeq 75\mathrm{keV}$$

$$Y_p^{\mathrm{ex}} = 0.245 \pm 0.003$$

Sound horizon

$$T_{\mathrm{rec}} \sim 0.3\mathrm{eV}$$

$$100\theta_{\mathrm{MC}} = 1.04 \pm 0.00031$$

$$T_0 = 2.34 \times 10^{-4}\mathrm{eV}$$

Reinonization optical depth

$$\tau = 0.054 \pm 0.007$$

$$t \sim H^{-1}$$

Cosmic Evolution

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi^2 = 0$$

$$\phi \sim \phi_{\rm in}$$

$$H \sim m_\phi$$

$$\phi \sim \frac{\phi_{\rm in}}{a^{3/2}}$$

BBN in a Nutshell

$$\boxed{X_n = \frac{n_n}{n_b}}$$

$$z_{\rm BBN} \sim 10^8$$

$$(X_n/X_p)_{\rm EQ} \sim e^{-m_{np}/T}$$

$$a\frac{dX_n}{da} = -\frac{\lambda_{n\to p}}{H}(1+e^{-m_{np}/T})(X_n - X_n^{eq})$$

$$T_{\rm W} \simeq 0.8{\rm MeV} \qquad X_n/X_p \sim e^{-m_{np}/T_W} \sim \frac{1}{6}$$

$$\frac{dX_n}{dt} = -X_n\Gamma_n$$

$$T_{\rm BBN} \simeq 75{\rm keV} \qquad X_n/X_p \sim \frac{1}{7} \longrightarrow Y_p \sim \frac{1}{4}$$

4He mass fraction

$$Y_p^{\rm ex} = 0.245 \pm 0.003 \qquad \sim 10^{-2}$$

BBN: Helium-4

$$-\frac{\phi^2}{\Lambda^2}(m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d)$$

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$

$$\frac{1}{f_p} \sim 0.09\frac{m_p}{\Lambda^2}$$

$$\frac{\Delta m_{np}}{m_{np}} \sim 1.6\frac{\phi^2}{\Lambda^2}$$

$$\frac{\Delta m_{np}}{m_{np}} \sim 18\frac{\phi^2}{f_p m_p}$$

BBN: Helium-4

$$-\frac{\phi^2}{\Lambda^2}\left(\frac{\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu}+\sum_i \gamma_{m_i} m_i \bar{\psi}_i\psi_i\right)$$

$$\frac{\Delta\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}}=\frac{\phi^2}{\Lambda^2}$$

$$\frac{1}{f_p}\sim 1.8\frac{m_p}{\Lambda^2}$$

$$\frac{\Delta m_{np}}{m_{np}}\sim -0.6\frac{\phi^2}{\Lambda^2}$$

$$\frac{\Delta m_{np}}{m_{np}}\sim -0.33\frac{\phi^2}{f_p m_p}$$

The modification is suppressed for the same f

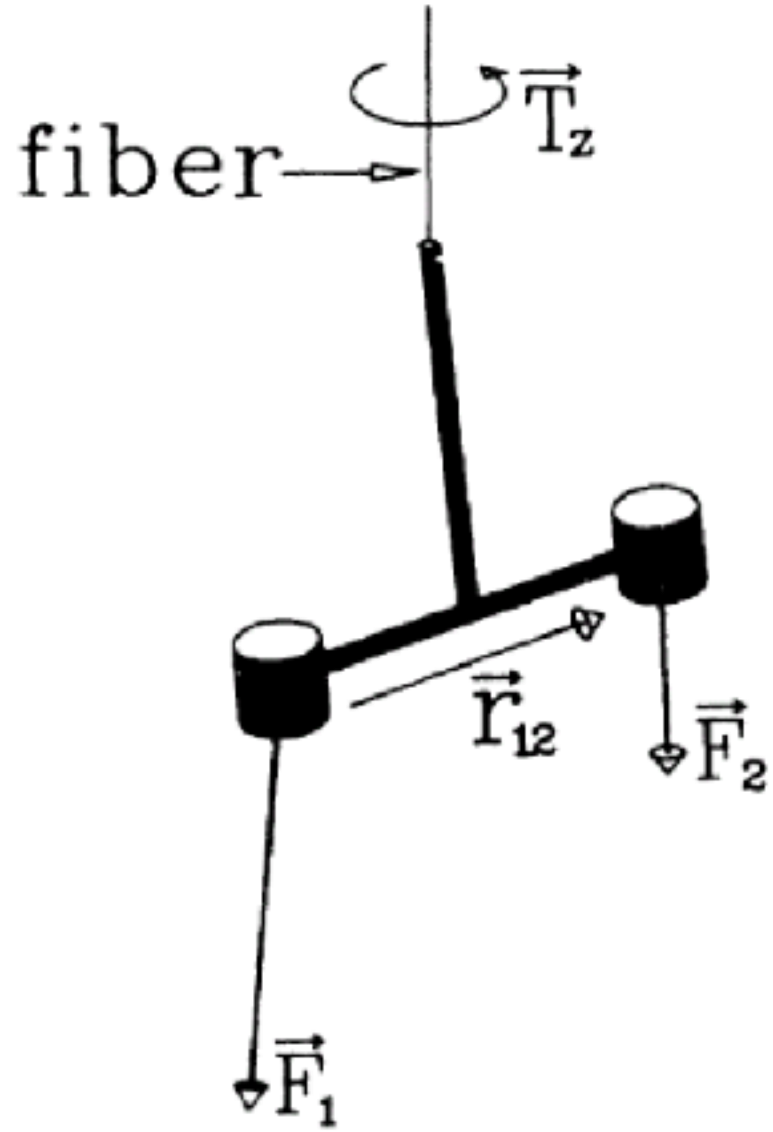
BBN Bounds

$$-\frac{\phi^2}{\Lambda^2}(m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d) \quad -\frac{\phi^2}{\Lambda^2}\left(\frac{\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} + \sum_i \gamma_{m_i} m_i\bar{\psi}_i\psi_i\right)$$

$$\boxed{\frac{\phi_0^2}{\Lambda^2} \sim \frac{2\rho_{\mathrm{DM}}}{m_\phi^2\Lambda^2}}$$

$$\frac{1}{f_p} < 3.7\times 10^{-4}\,\mathrm{GeV}^{-1}\left(\frac{m_\phi}{\mathrm{eV}}\right)^2 \qquad \frac{1}{f_p} < 1.9\times 10^{-2}\,\mathrm{GeV}^{-1}\left(\frac{m_\phi}{\mathrm{eV}}\right)^2$$

Possible experiments: Torsion Balance

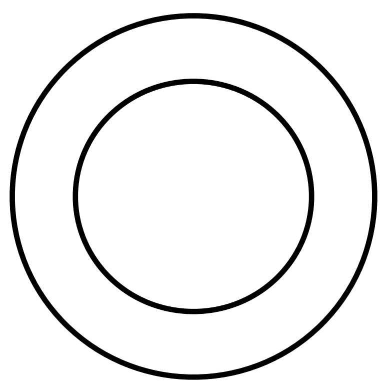


$$T_z = (\boldsymbol{F}_1 \times \boldsymbol{F}_2 \cdot \boldsymbol{r}_{12})/|\boldsymbol{F}_1 + \boldsymbol{F}_2|.$$

Sensitive to the angle between the two forces

Possible experiments: Torsion Balance

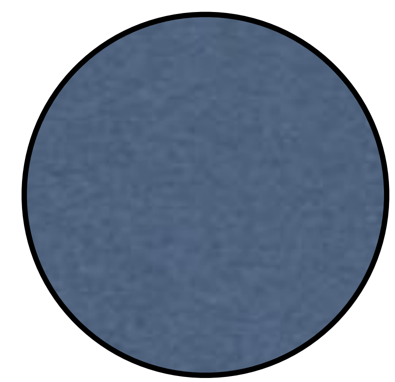
Ti



$$R_1 \sim 0.71\text{cm}$$

$$R_2 \sim 0.85\text{cm}$$

Be



$$R \sim 0.85\text{cm}$$

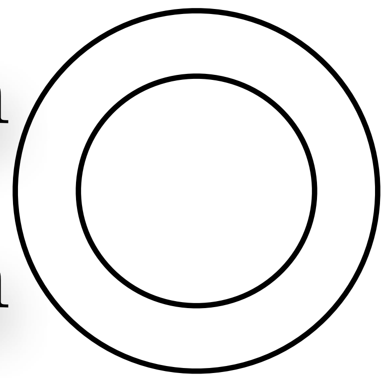
$$\Delta a = (0.6 \pm 3.1) \times 10^{-15}\text{m/s}^2$$

Torsion Balance: Dark Matter

$4.51\mathrm{g/cm^3}$ $1.85\mathrm{g/cm^3}$

Ti Be

$R_1 \sim 0.71\mathrm{cm}$



$R_2 \sim 0.85\mathrm{cm}$

$R \sim 0.85\mathrm{cm}$

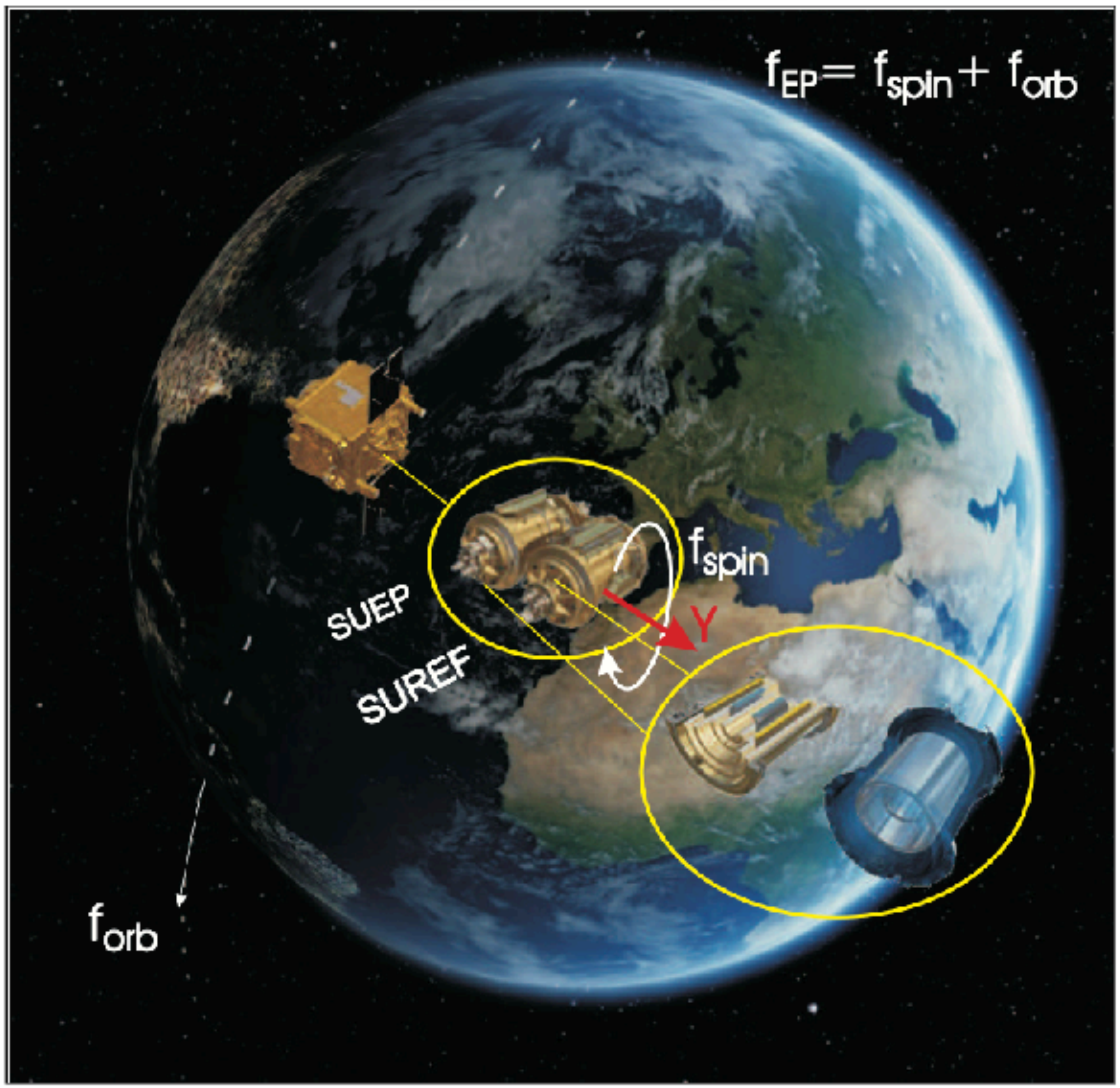
$$F_1^{\mathrm{DM}} \neq F_2^{\mathrm{DM}}$$

$$\lambda_{sd}^{\mathrm{Ti}} > 0.14\mathrm{cm} \qquad \lambda_{sd}^{\mathrm{Be}} < 0.85\mathrm{cm}$$

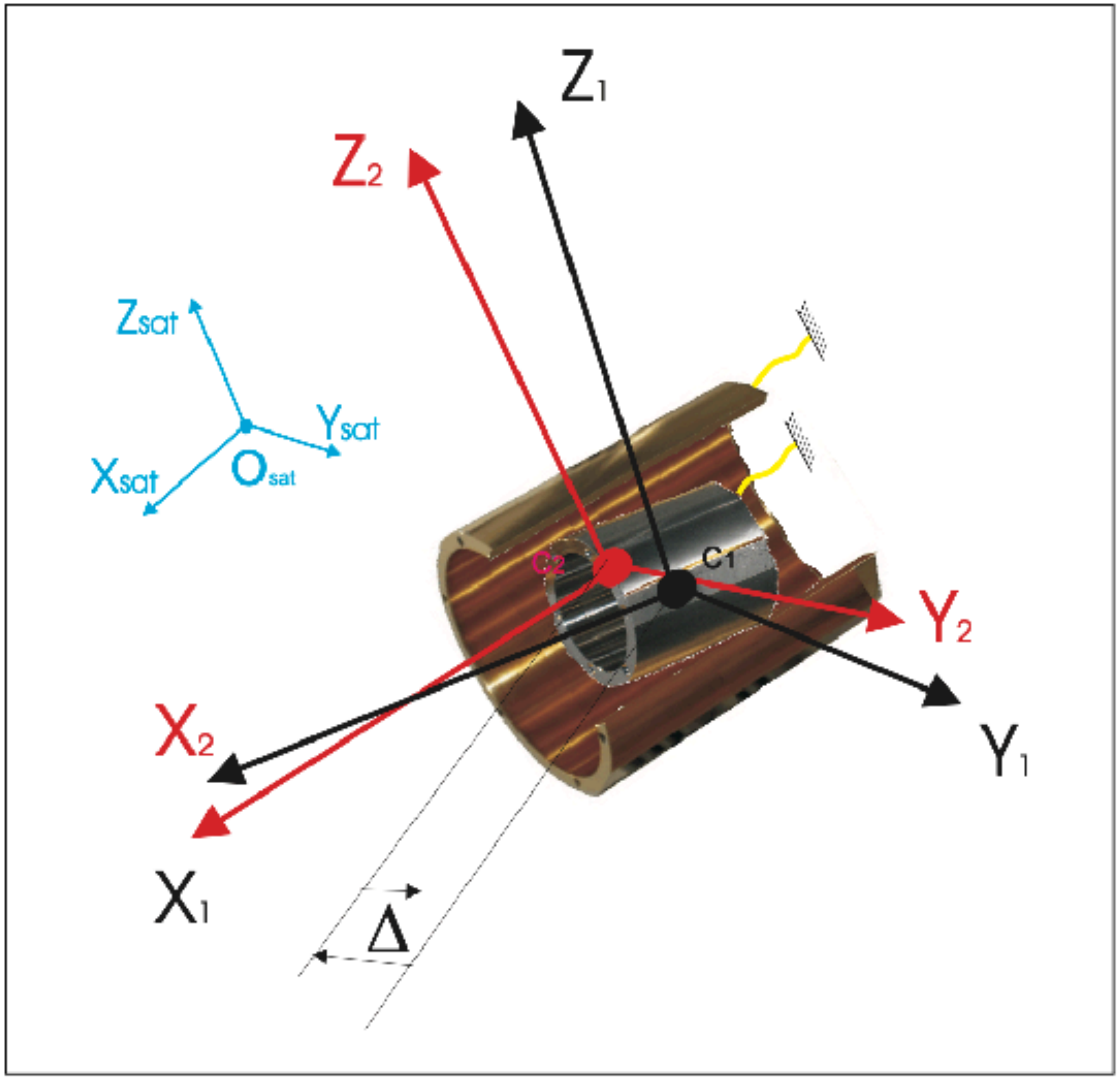
$$1.1 \times 10^9 \mathrm{GeV} < f < 1.6 \times 10^{10} \mathrm{GeV}$$

Possible experiments: Microscope

710km altitude

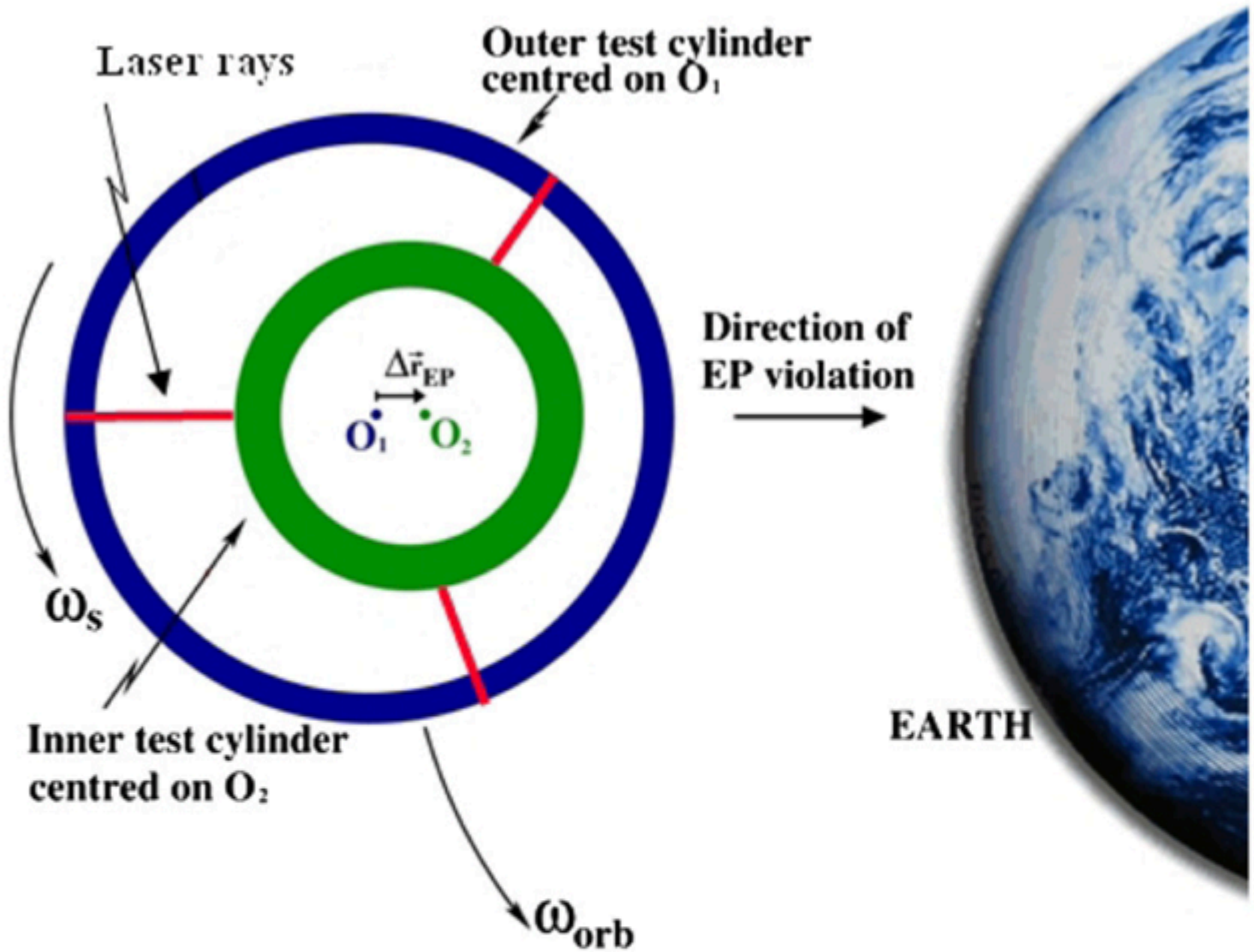


Possible experiments: Microscope



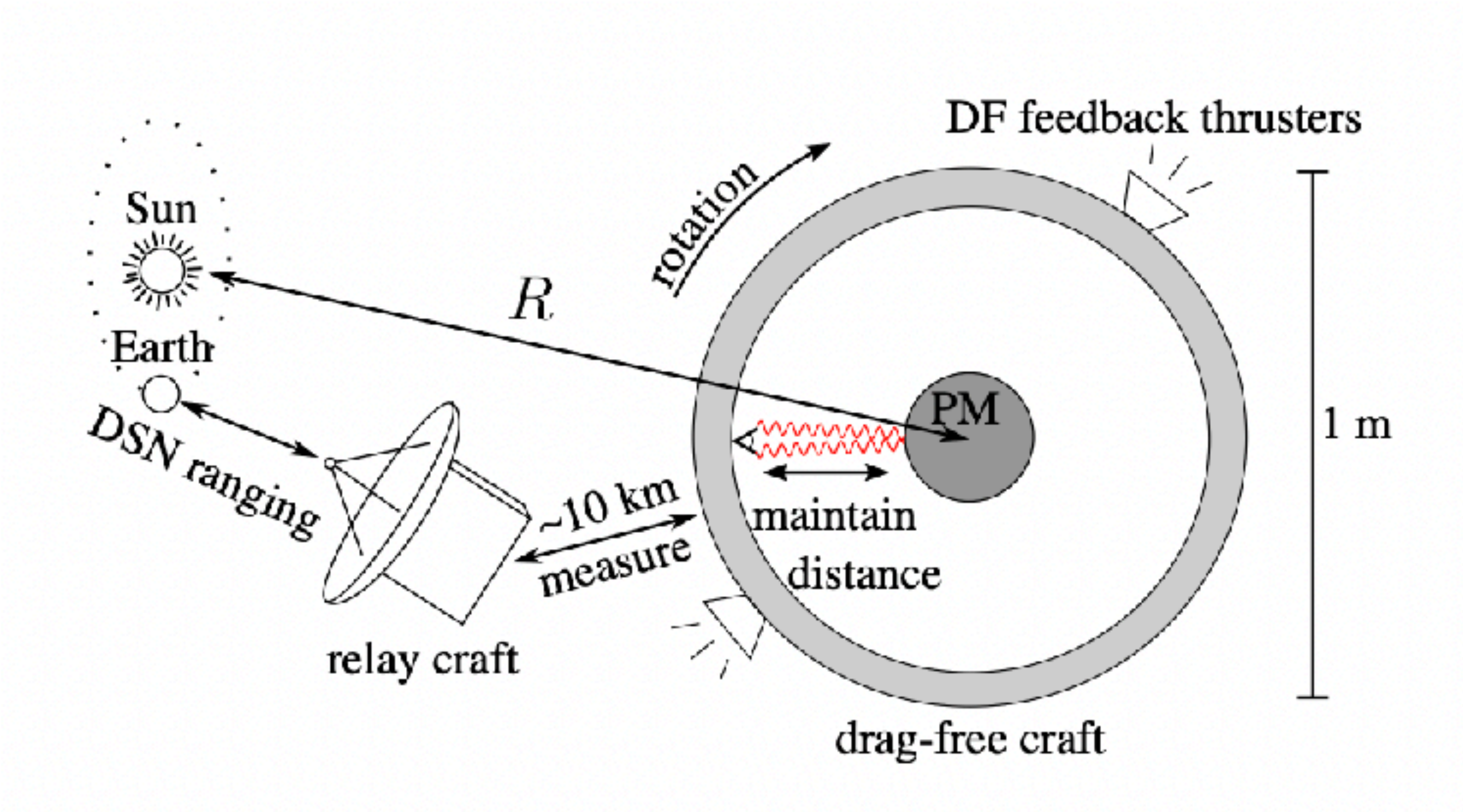
$$\Delta a = -1.2 \pm 2.2 \times 10^{-14} \mathrm{m/s}^2$$

Possible experiments: Galileo Galilei



$$\Delta a \sim 8 \times 10^{-17} \mathrm{m/s^2}$$

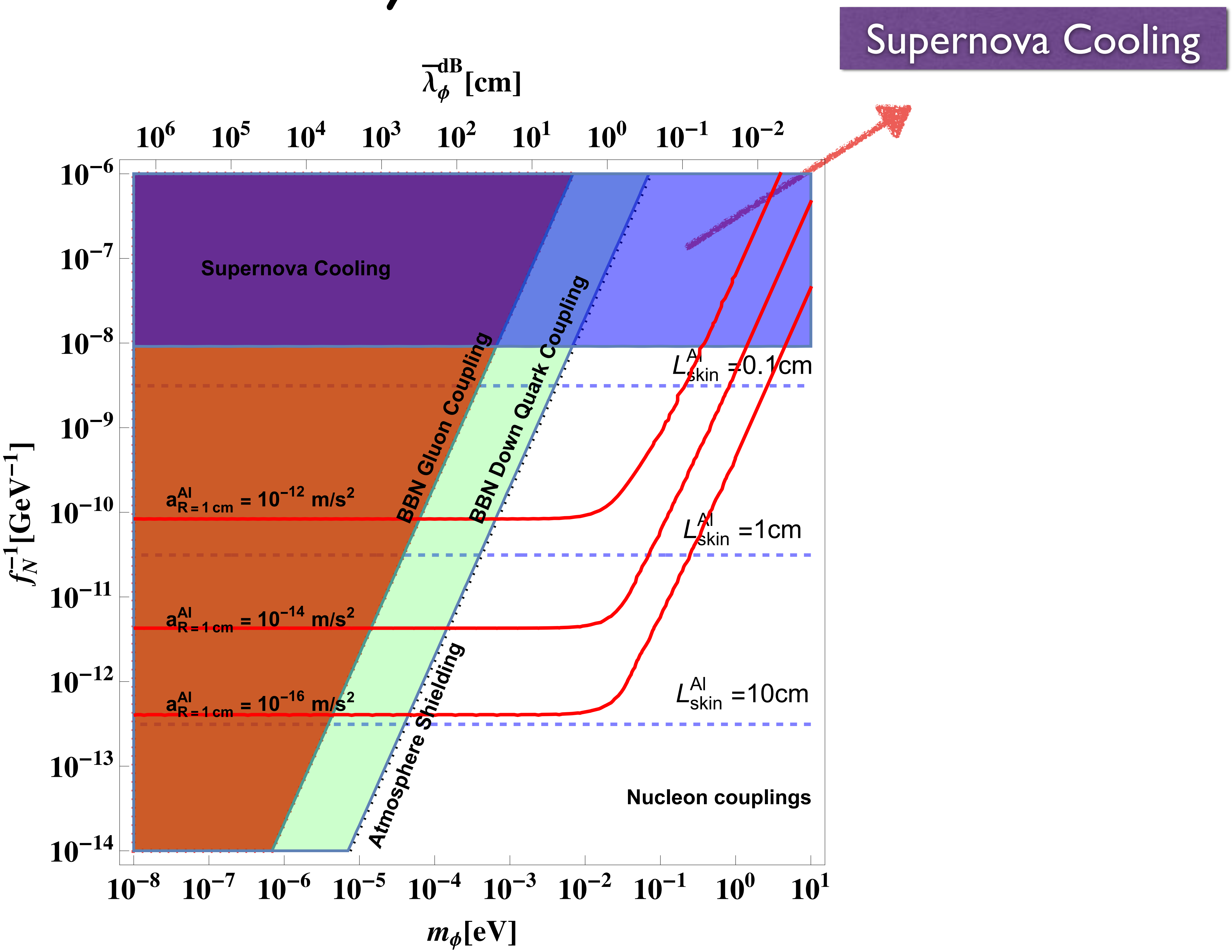
Possible experiments: Space Mission



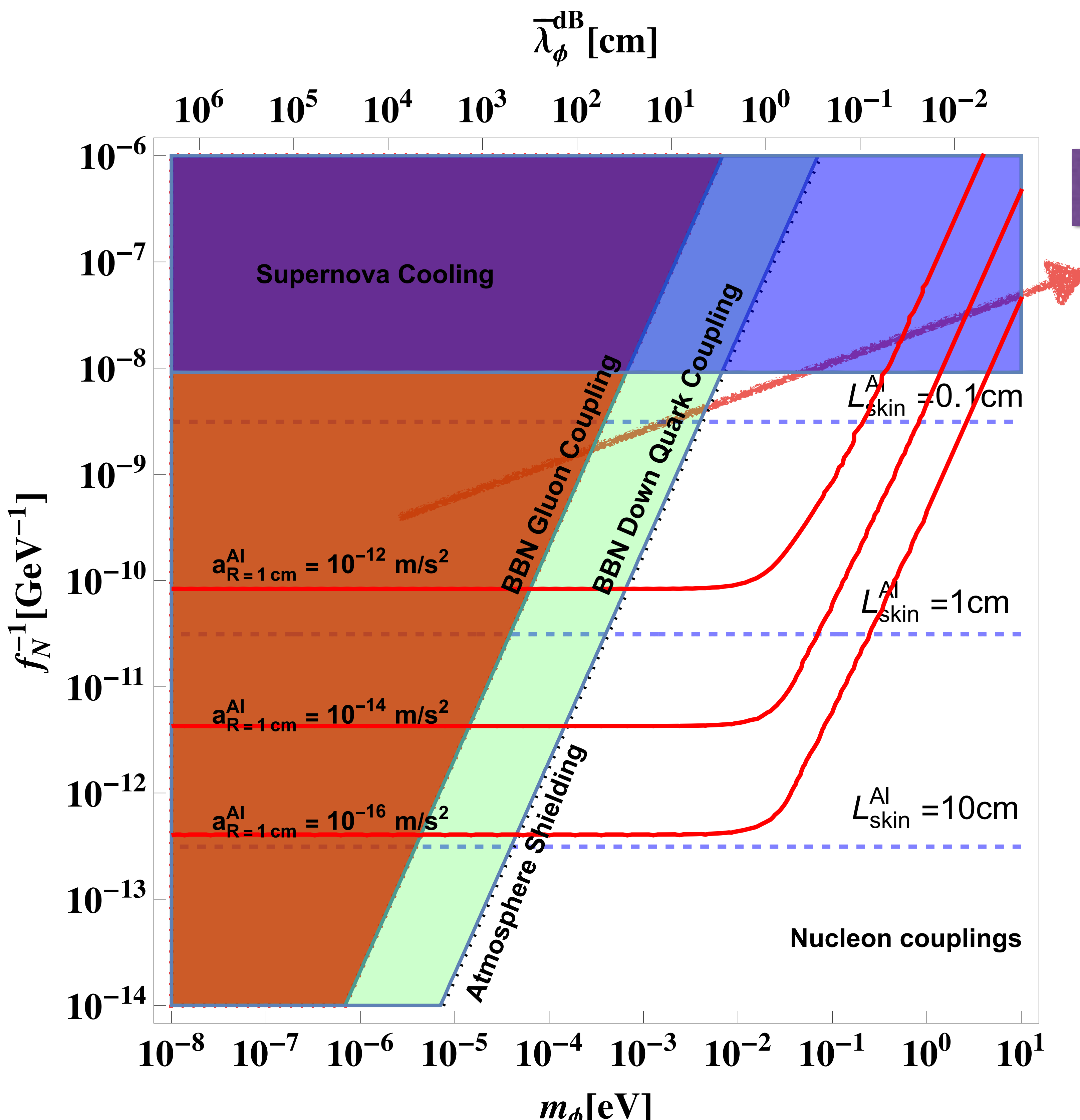
$$\delta a \sim 4.1 \times 10^{-17} \mathrm{m/s}^2$$

1 meter ranging over 7 years

Summary in One Plot

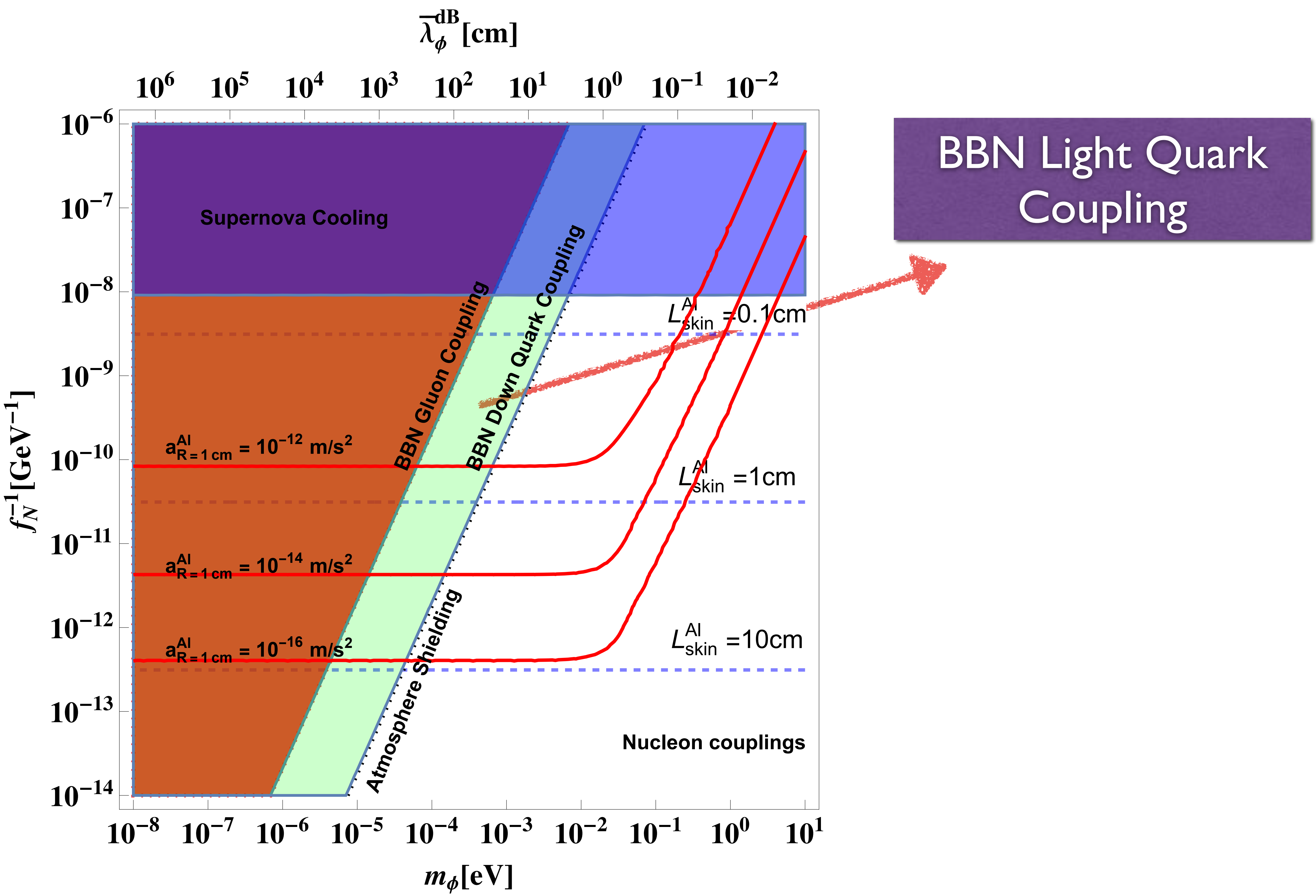


Summary in One Plot

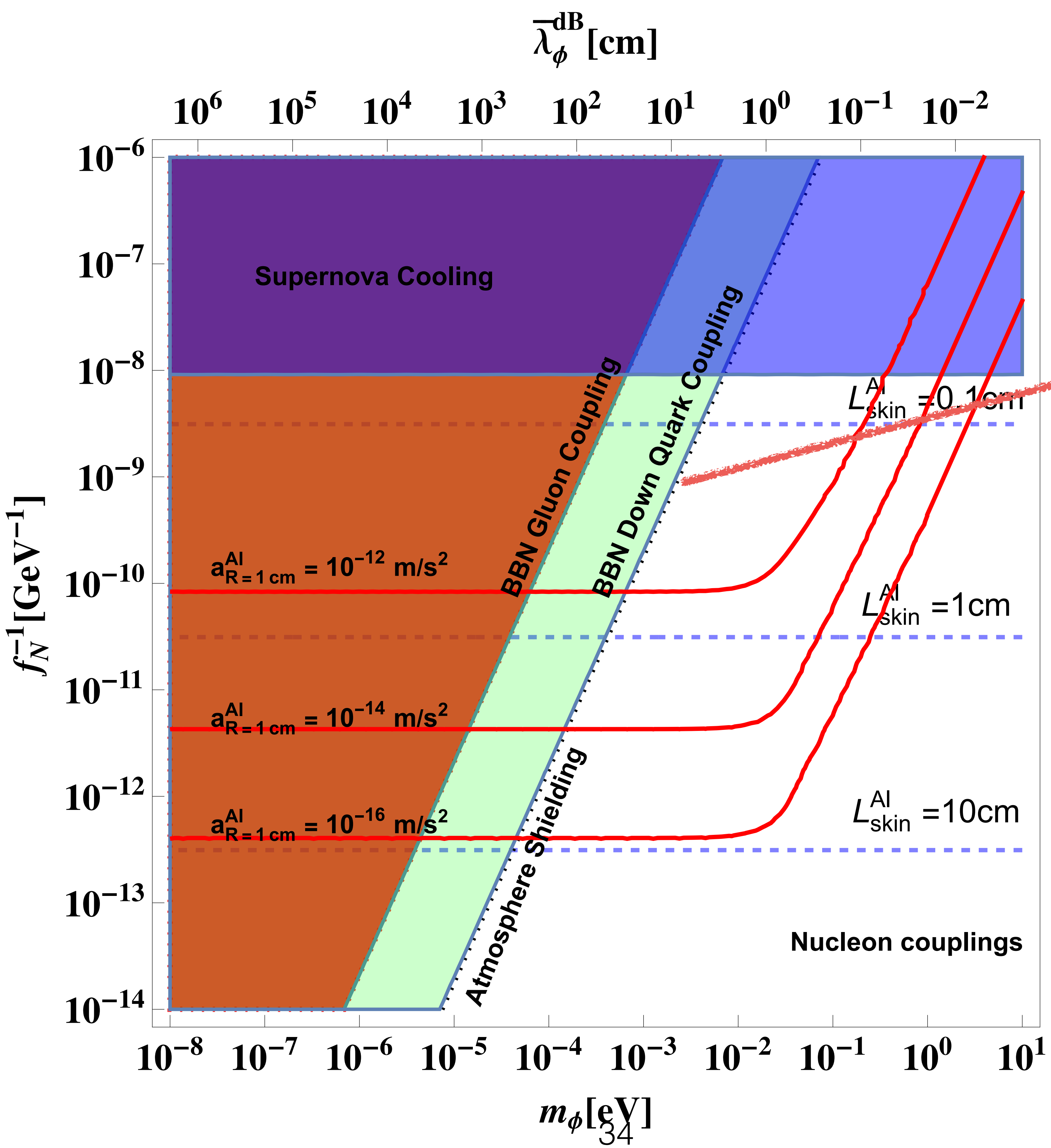


BBN Gluon coupling

Summary in One Plot



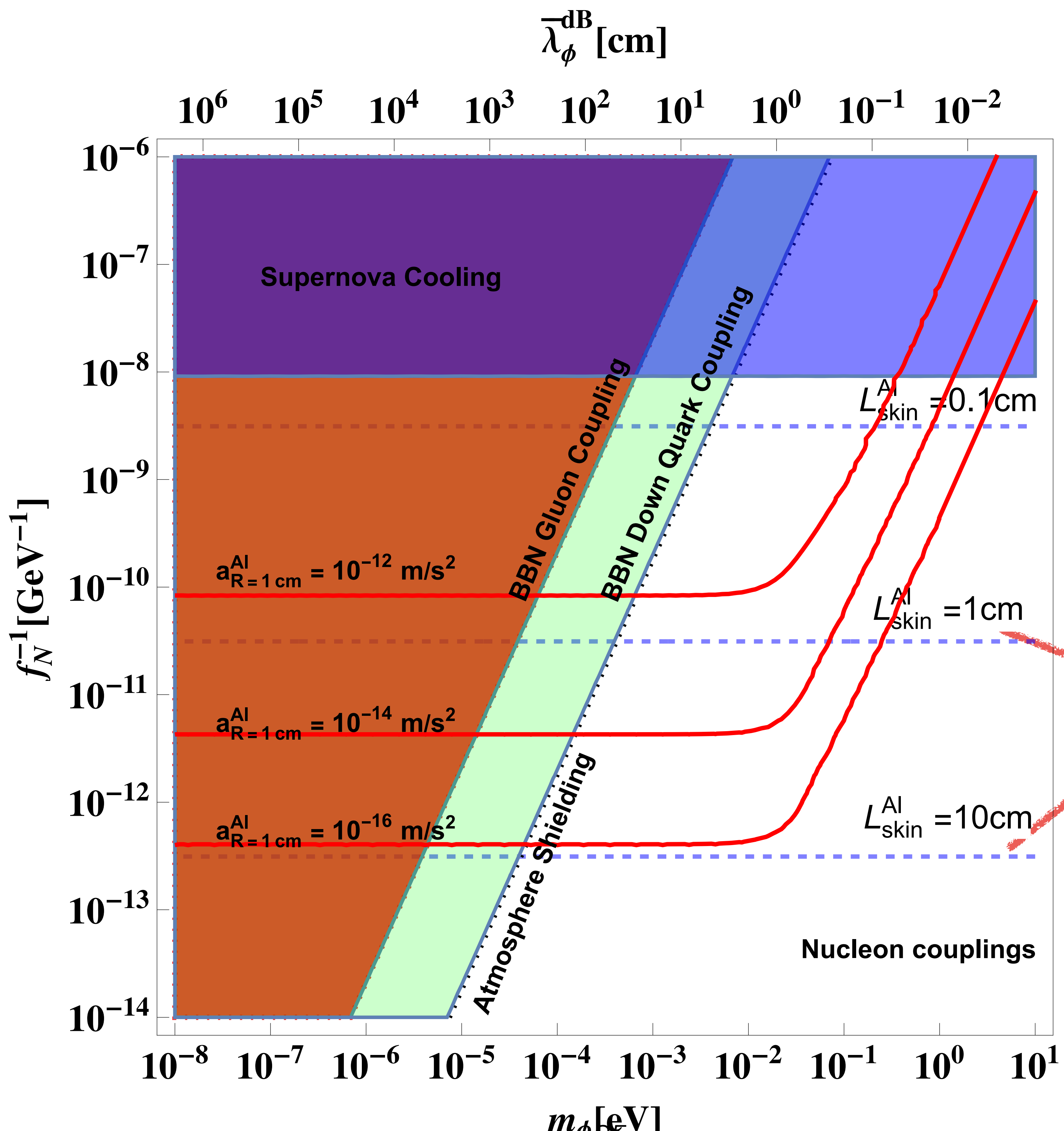
Summary in One Plot



Atmosphere

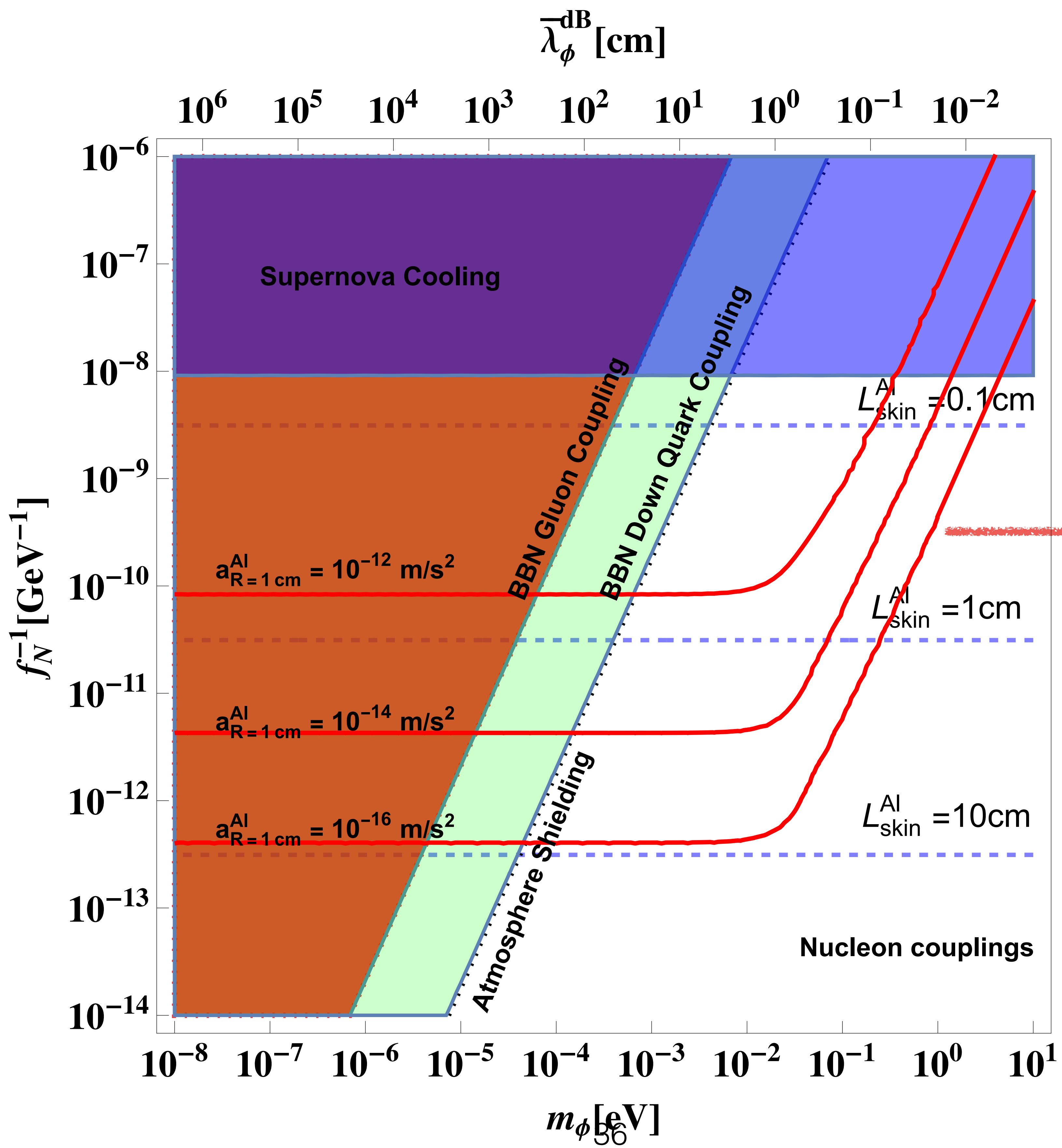
$7.3 \times 10^{20}/\mathrm{cm}^3$

Summary in One Plot



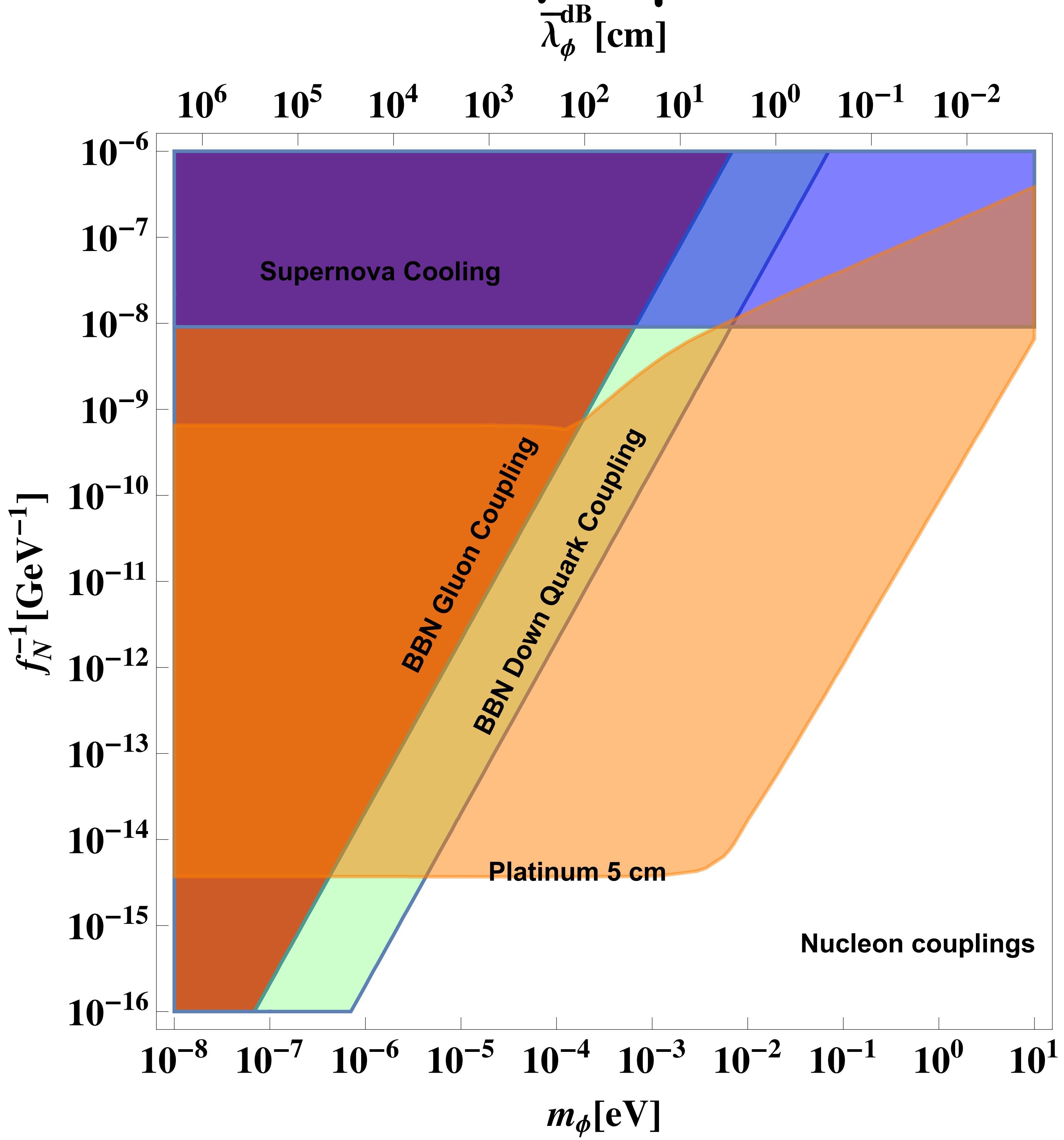
Aluminum skin depth

Summary in One Plot



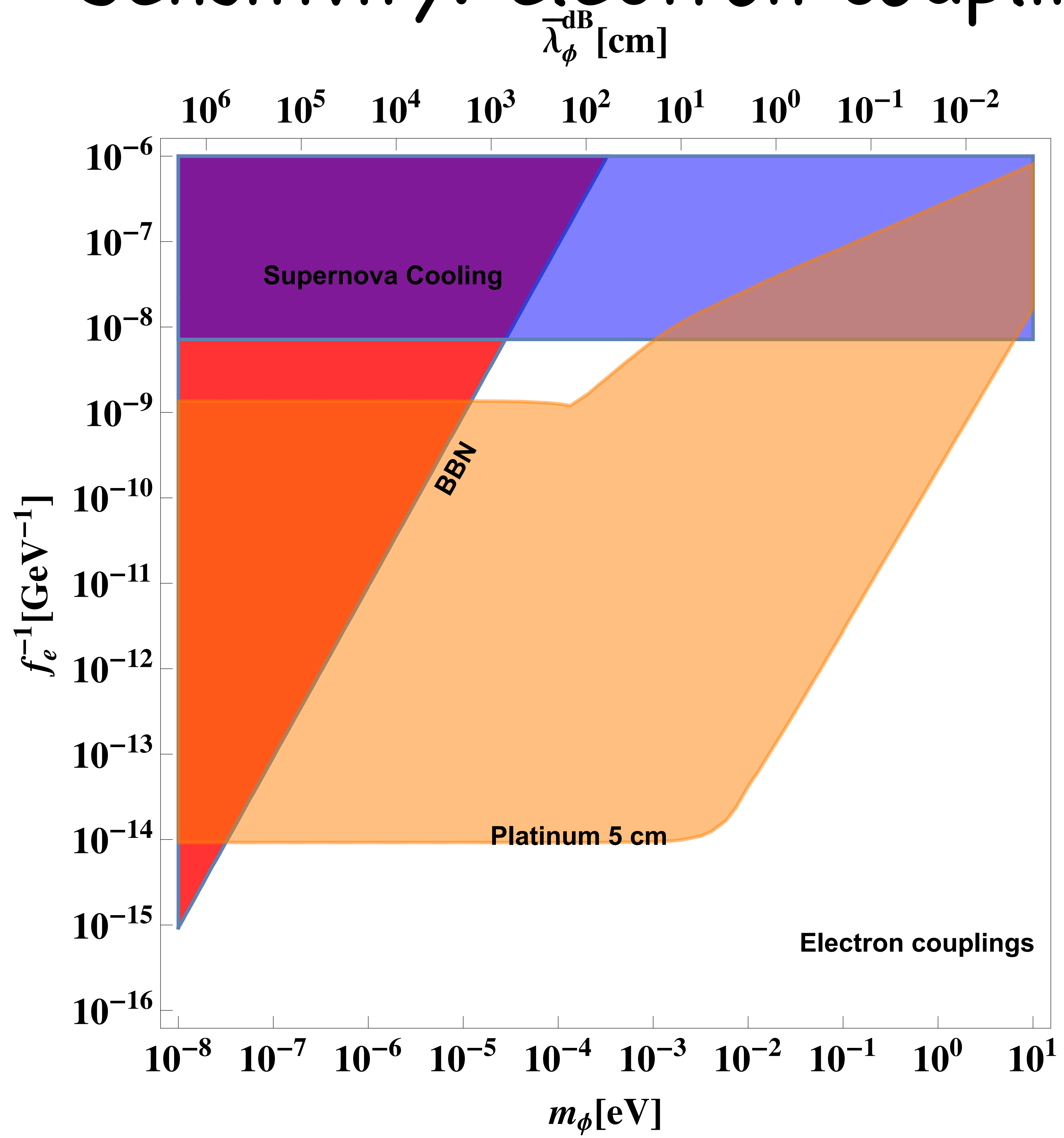
Constant Acceleration

Sensitivity:Space Mission



1mm Aluminum shell with radius 1m

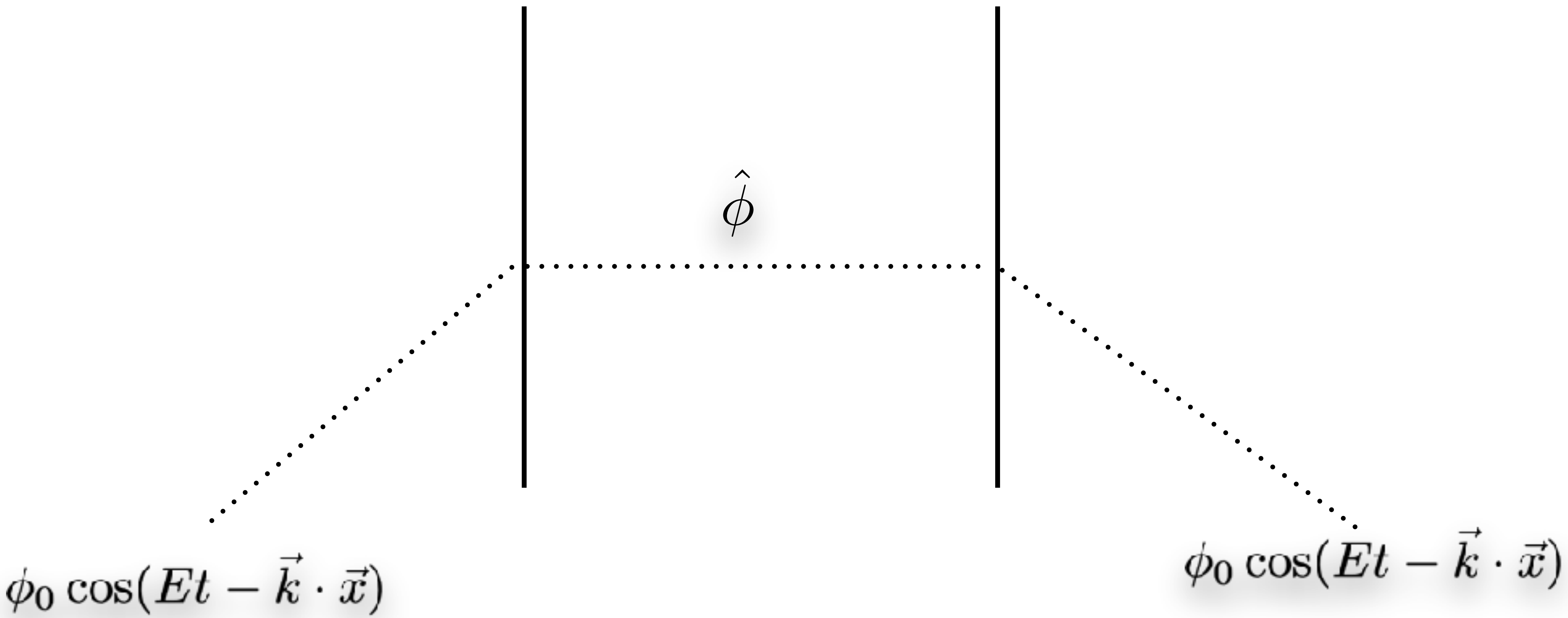
Sensitivity: electron coupling



1mm Aluminum shell with radius 1m

Wake Force

$$\phi = \phi_0 \cos(Et - \vec{k} \cdot \vec{x}) + \hat{\phi}$$



$$V(r) \sim \frac{\phi_0^2}{f^2} \frac{1}{r} e^{-r^2/\lambda_{\text{coh}}^2}$$

By Ken Van Tilburg, 2024

Future directions

- Wake force by taking into account the screening effect
  B. Batell, A. Bhoonah, A. Ghalsasi, D. Liu and M. Luty, work in progress

Conclusion

- We discover a novel effect for light scalar dark matter with quadratic interactions.

- The drag force can be probed by the possible future test of the weak equivalence principle

Back-up slides

Possible experiments: Microscope

TABLE I. Main test-mass physical properties measured in the laboratory before integration in the instrument.

Measured parameters at 20 ^{o}C	SUREF Inner mass Pt/Rh	SUREF Outer mass Pt/Rh	SUEP Inner mass Pt/Rh	SUEP Outer mass Ti/Al
Mass in kg	0.401533	1.359813	0.401706	0.300939
Density in $\mathrm{g\,cm^{-3}}$	19.967	19.980	19.972	4.420