Search for Ultralight Scalar Dark Matter with Quadratic Interactions

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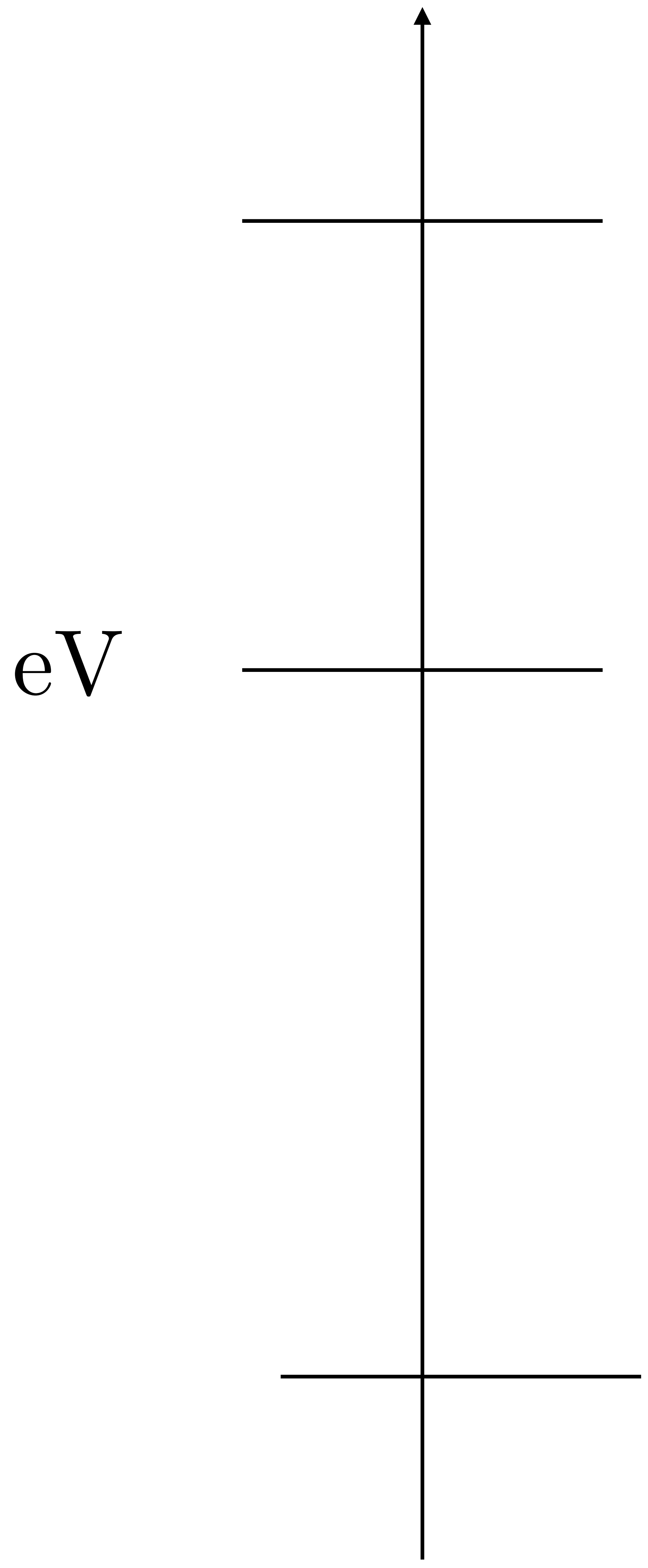
Based on work

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



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

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

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

$$\downarrow$$

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

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

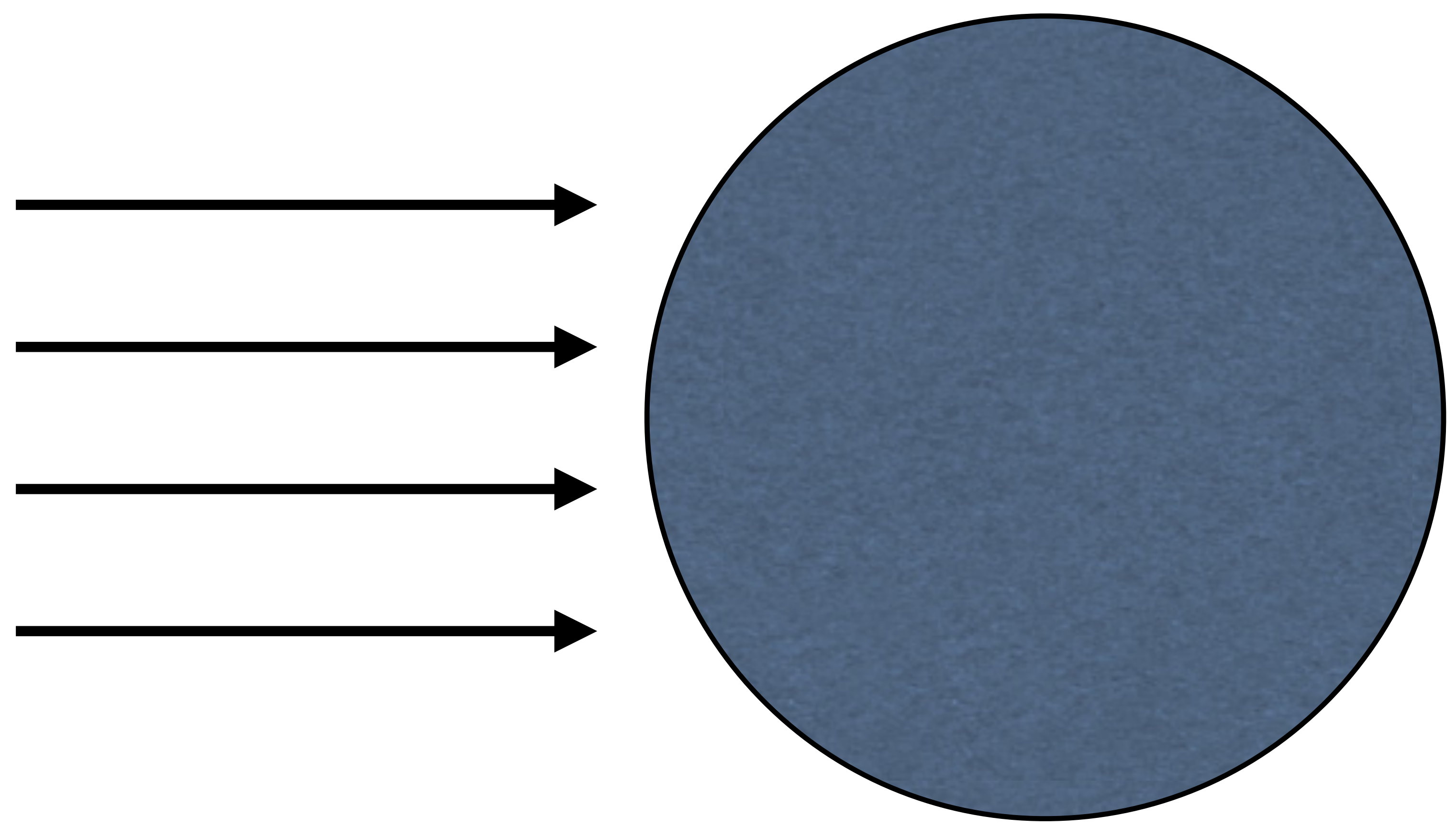
$$(\nabla + E^2 - m^2 - \frac{n}{f})\psi(\vec{x}) = 0$$

Schrodinger equation with potential

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

Ultralight Scalar Dark Matter Model

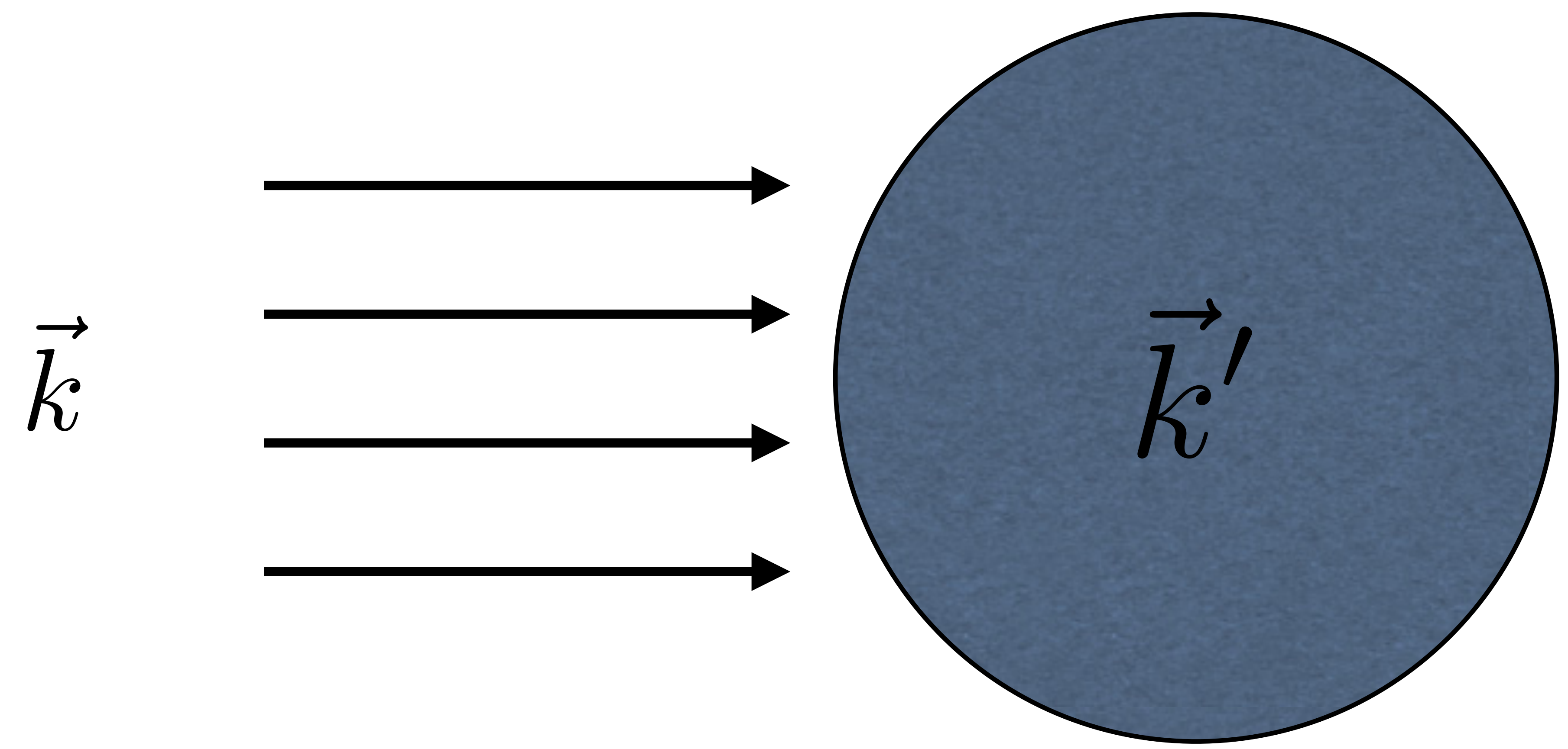
$$\Delta\mathcal{L} = -\frac{\phi^2}{2f}\bar{N}N$$



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

Ultralight Scalar Dark Matter Model

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

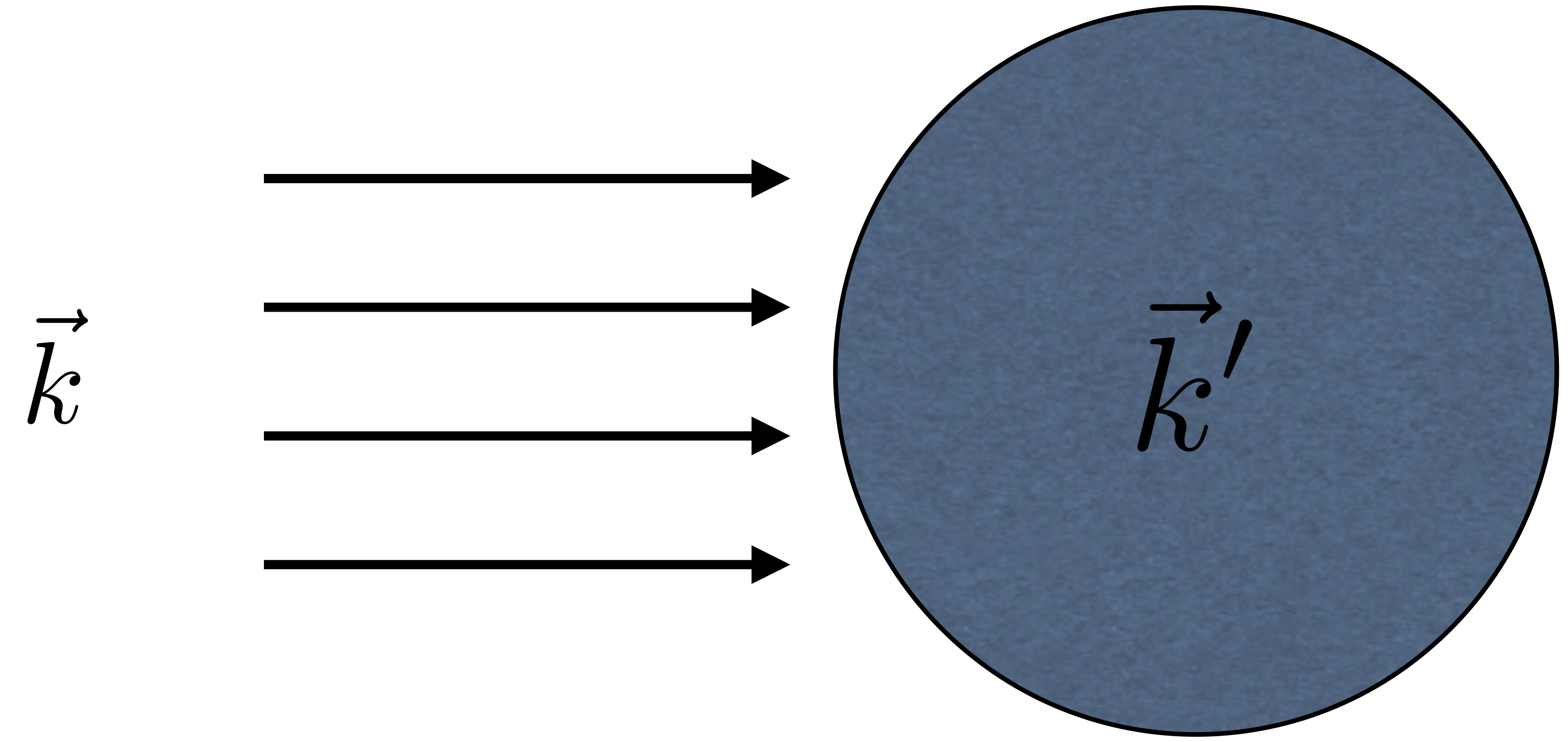


$$\vec{k}'^2 = \vec{k}^2 - \frac{n_N}{f}$$

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

Ultralight Scalar Dark Matter Model

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

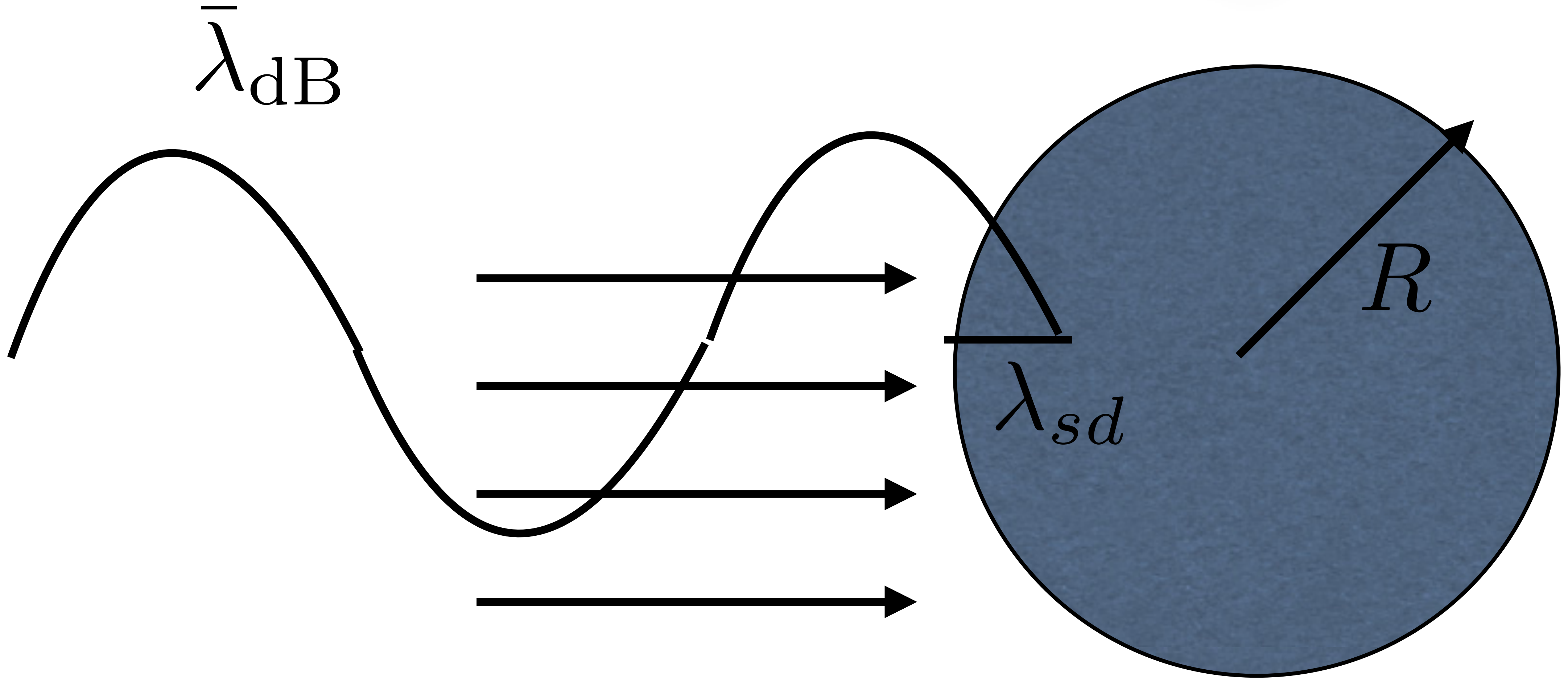


$$\lambda_{sd} = 1/\sqrt{\frac{n}{f}} \sim 5.6\times10^{-2}\mathrm{cm}\times\sqrt{\frac{\frac{f}{10^8\mathrm{GeV}}}{\frac{\rho_{\mathrm{matt}}}{2.7\ \mathrm{g/cm^3}}}}$$

$$\bar{\lambda}_{dB} = \frac{1}{m_\phi v} \sim 2.0\times10^{-2}\mathrm{cm}\frac{\mathrm{eV}}{m_\phi}$$

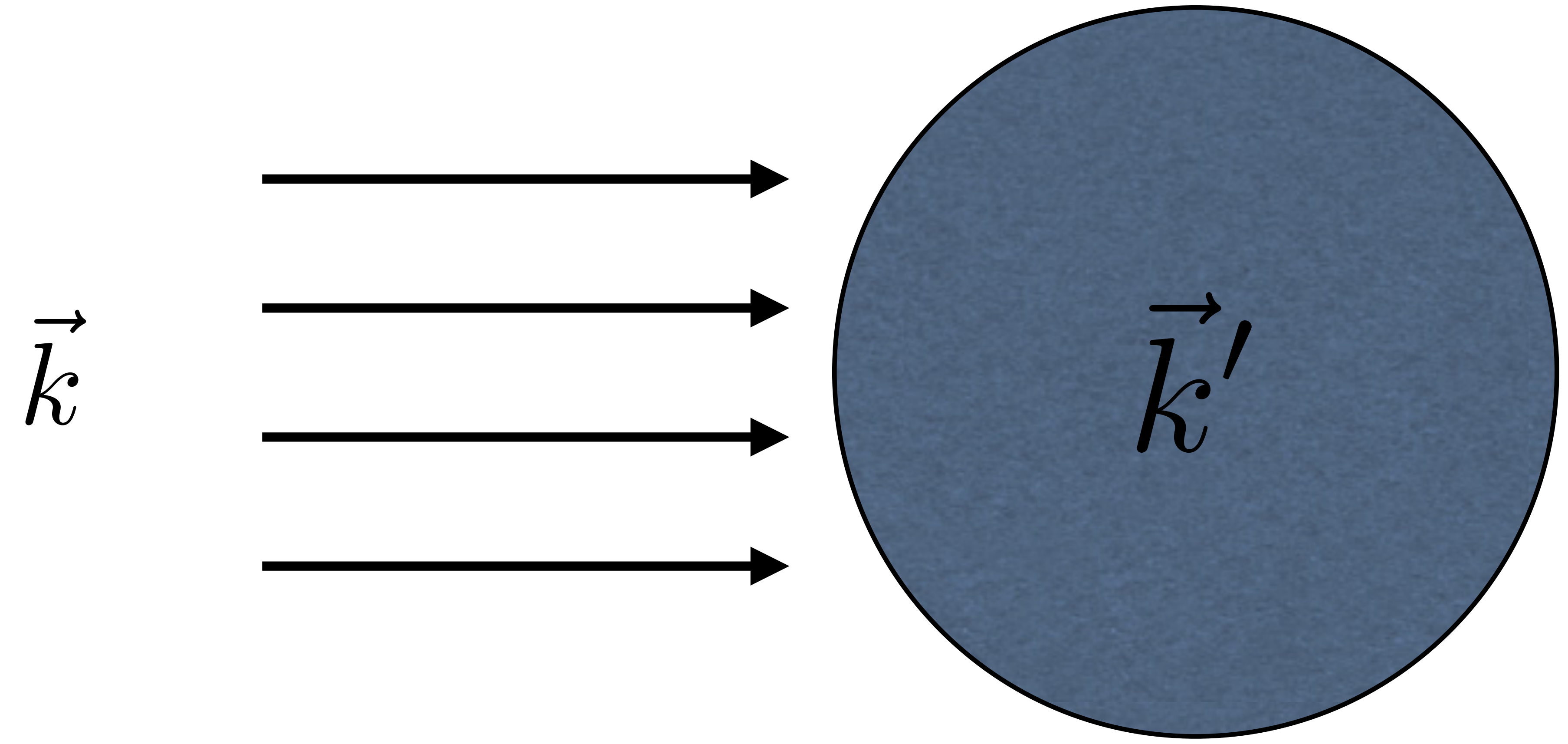
Two conditions for the maximal force

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



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

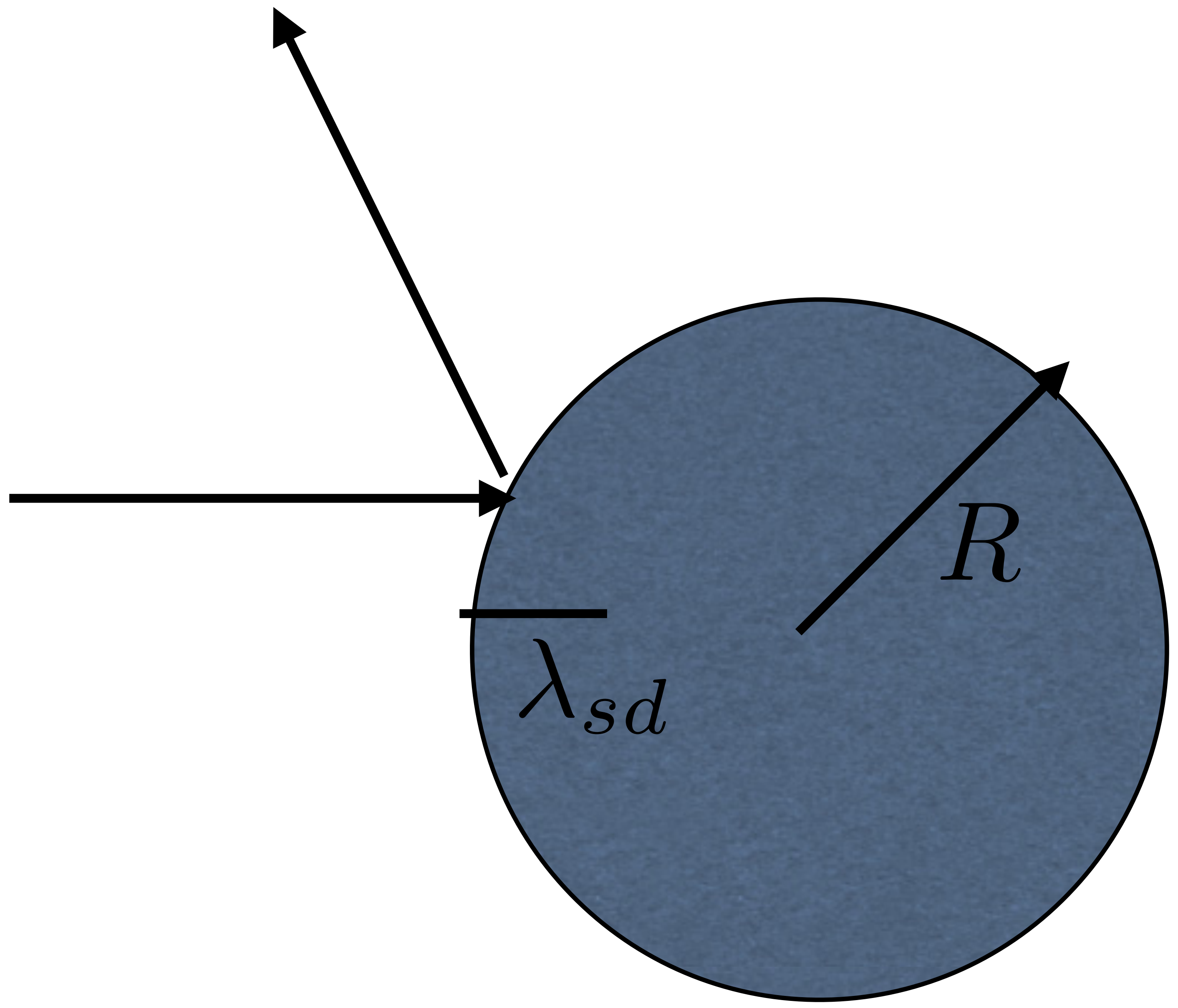
Acceleration induced by DM wind



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

Geometric Limit

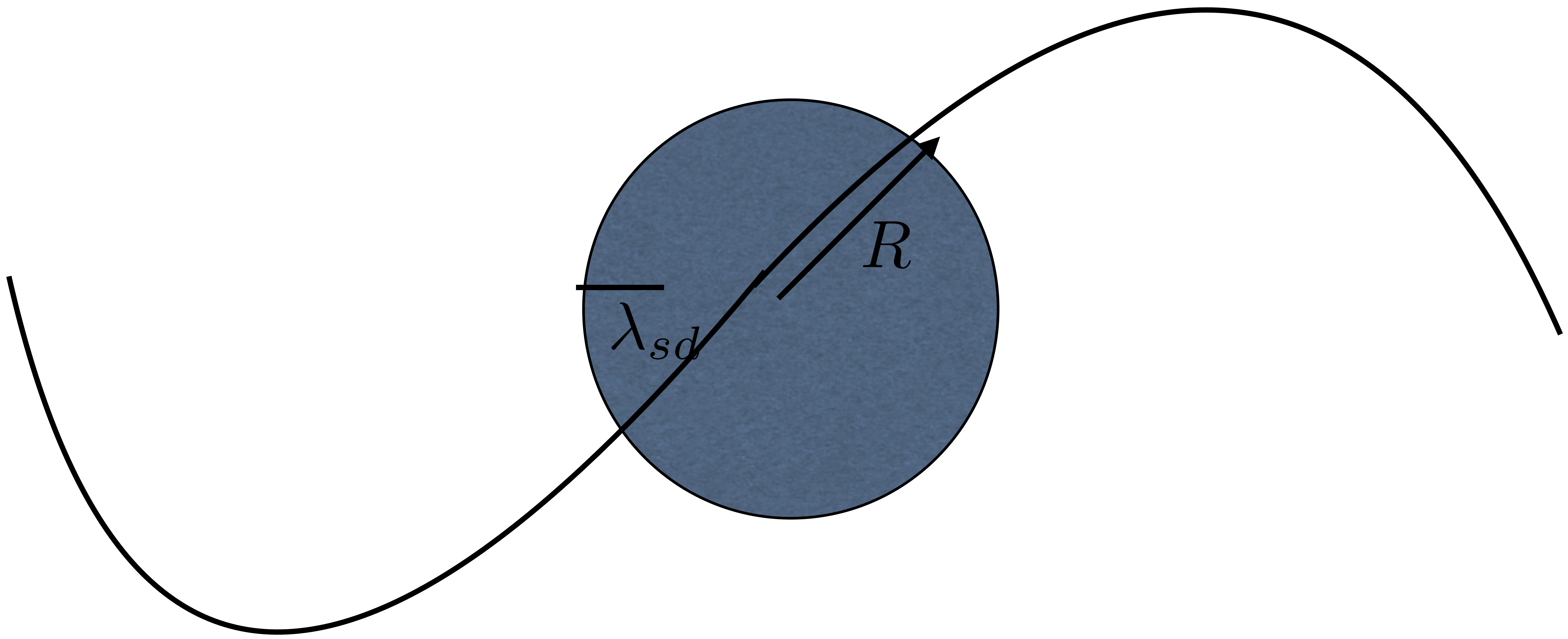
$$\lambda_{sd} \ll \bar{\lambda}_{\mathrm{dB}} \ll R$$



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

Slow scattering limit

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

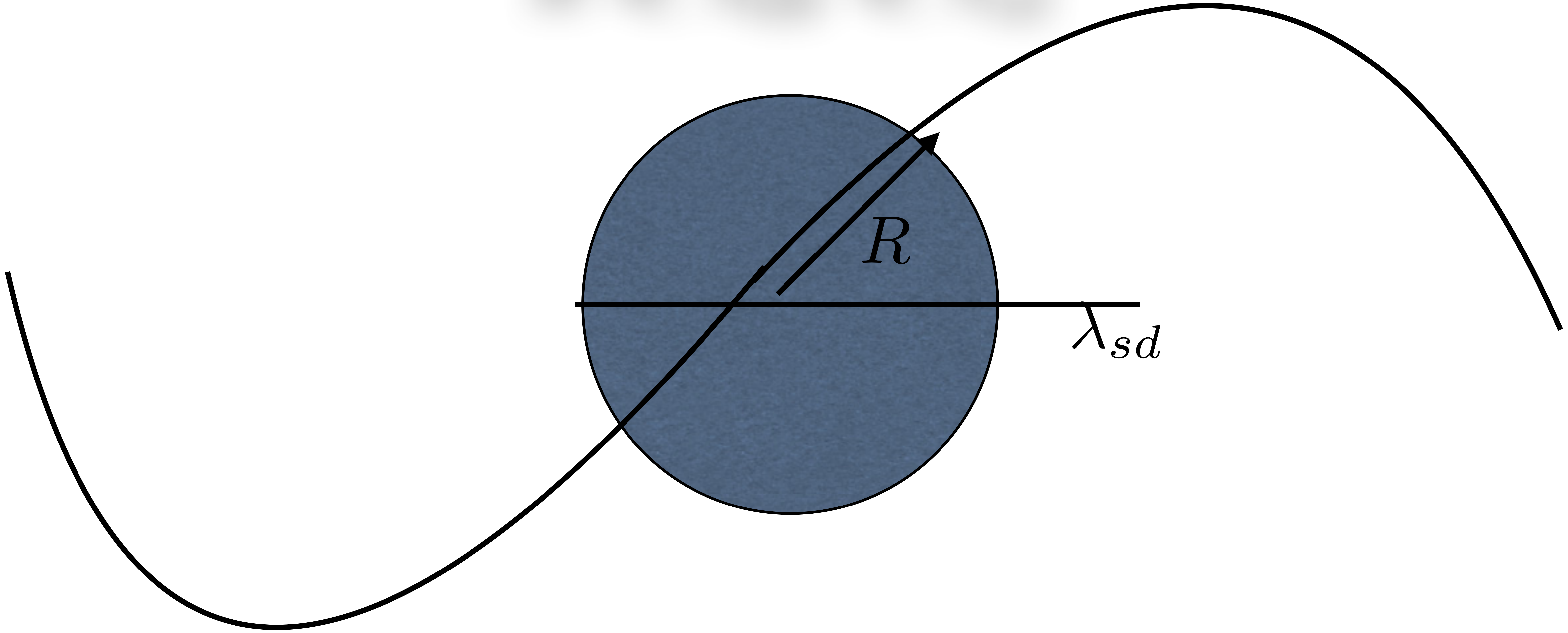


$$F_z = 4\rho_{\mathrm{DM}} v^2 \pi R^2$$

Slow scattering limit: large skin depth

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

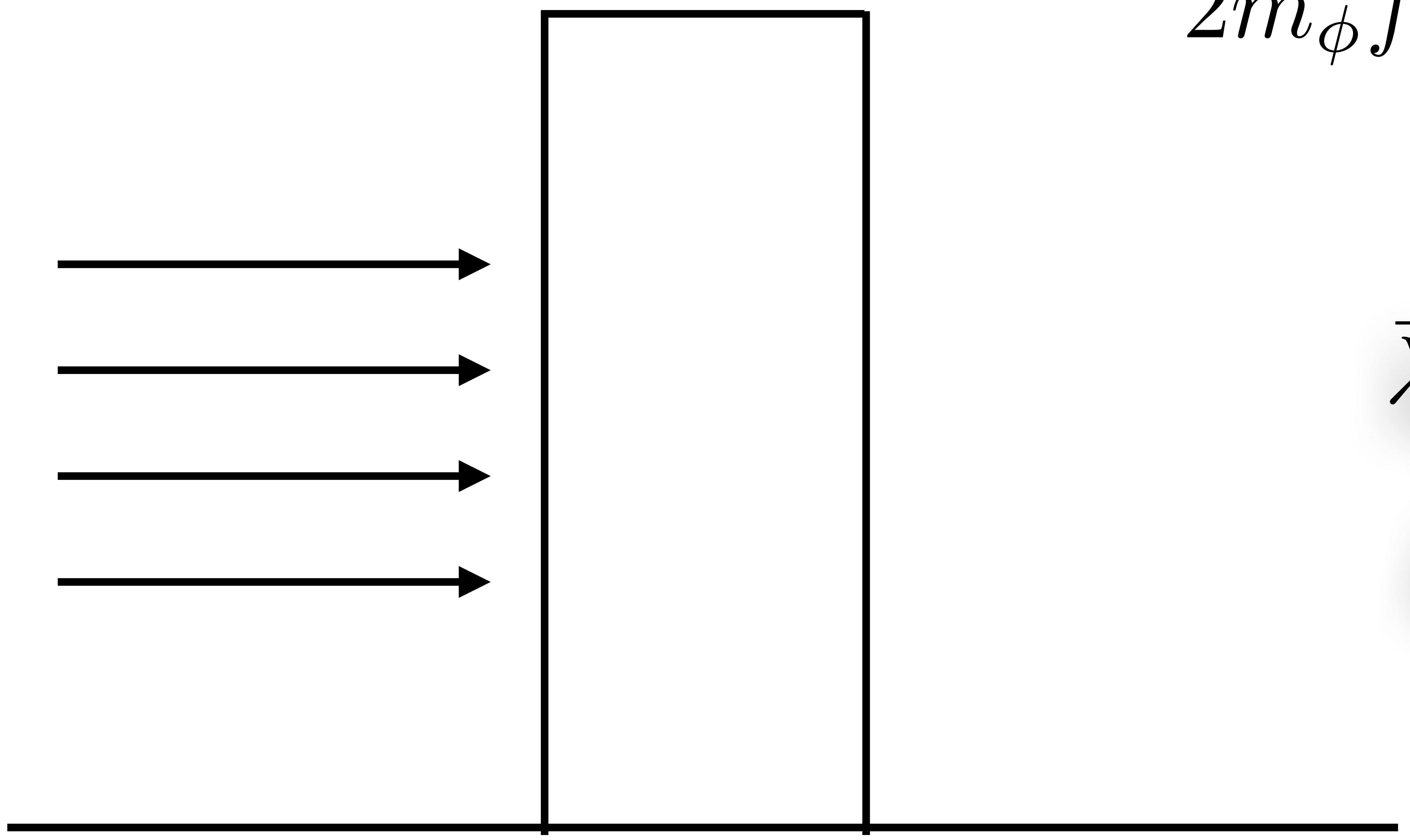
$$R \ll \bar{\lambda}_{\rm dB} \ll \lambda_{sd}$$



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

Shielding effect: potential barrier

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



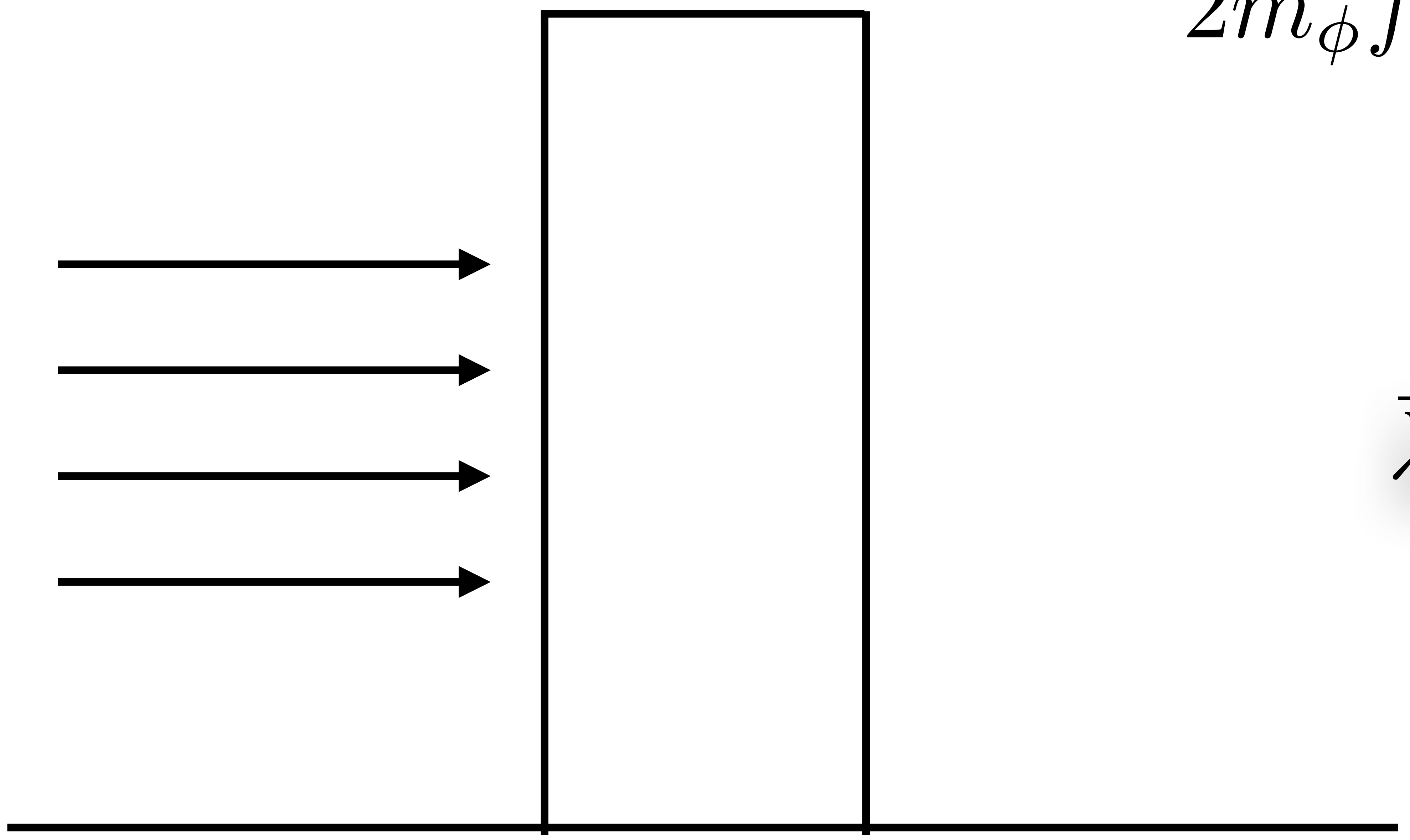
$$\bar{\lambda}_{dB} \gg \lambda_{sd}$$

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

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

Shielding effect: potential barrier

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

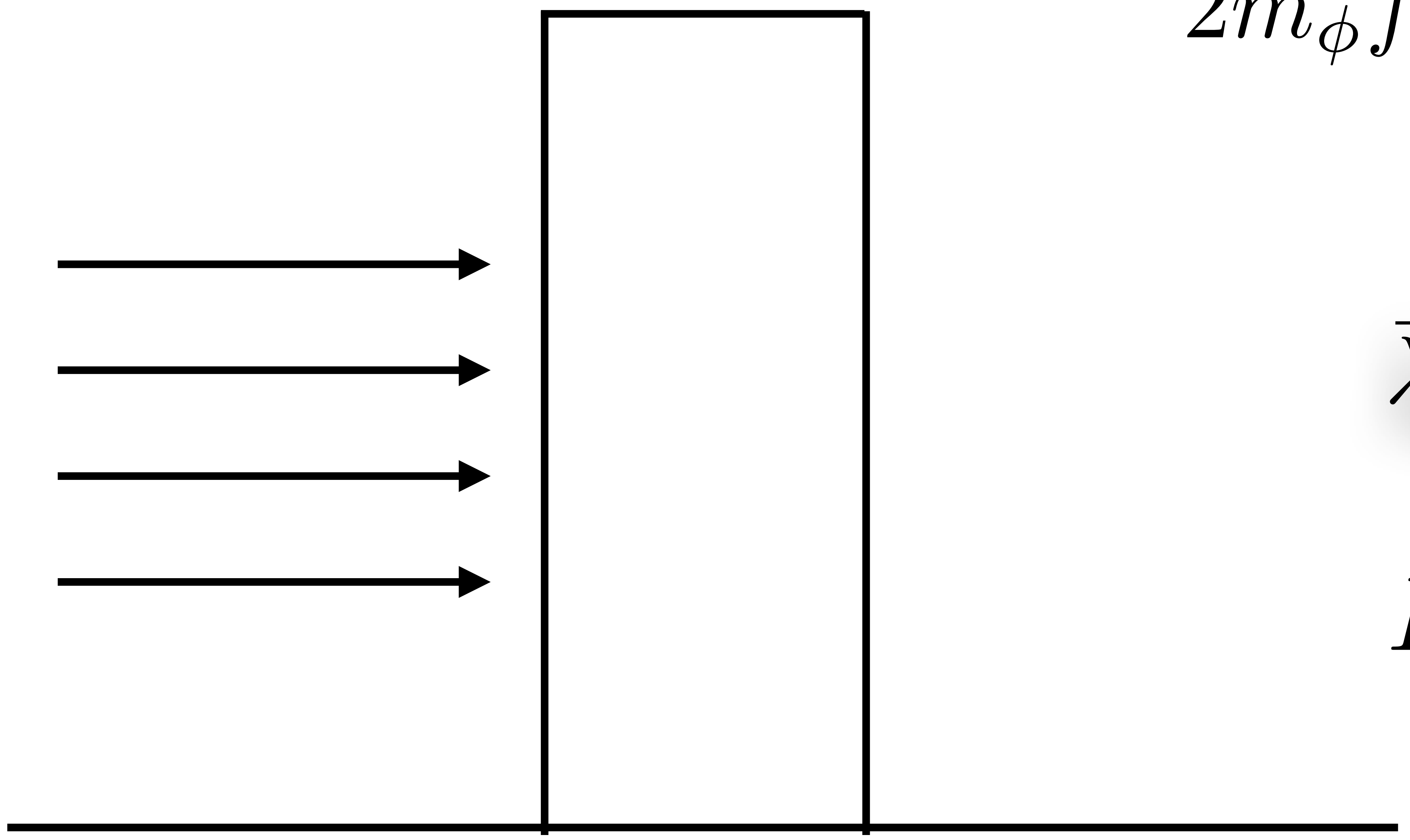


$$\bar{\lambda}_{dB} \ll \lambda_{sd}$$

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

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

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

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

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

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

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

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

Primordial Curvature Perturbation

$$\ln(10^{10}\Delta^2_{\mathcal{R}})|_{k_0 = 0.05 \mathrm{Mpc}^{-1}}$$
$$= 3.044 \pm 0.014$$
$$n_s = 0.965 \pm 0.004$$

4He mass fraction

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

Sound horizon

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

Reinonization optical depth

$$\tau = 0.054 \pm 0.007$$

Cosmic Evolution

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

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

$$H \sim m_\phi$$

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

BBN in a Nutshell

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

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

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

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

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

$$X_n/X_p \sim e^{-m_{np}/T_{\rm W}} \sim \frac{1}{6}$$

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

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

$$X_n/X_p \sim \frac{1}{7} \longrightarrow Y_p \sim \frac{1}{4}$$

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

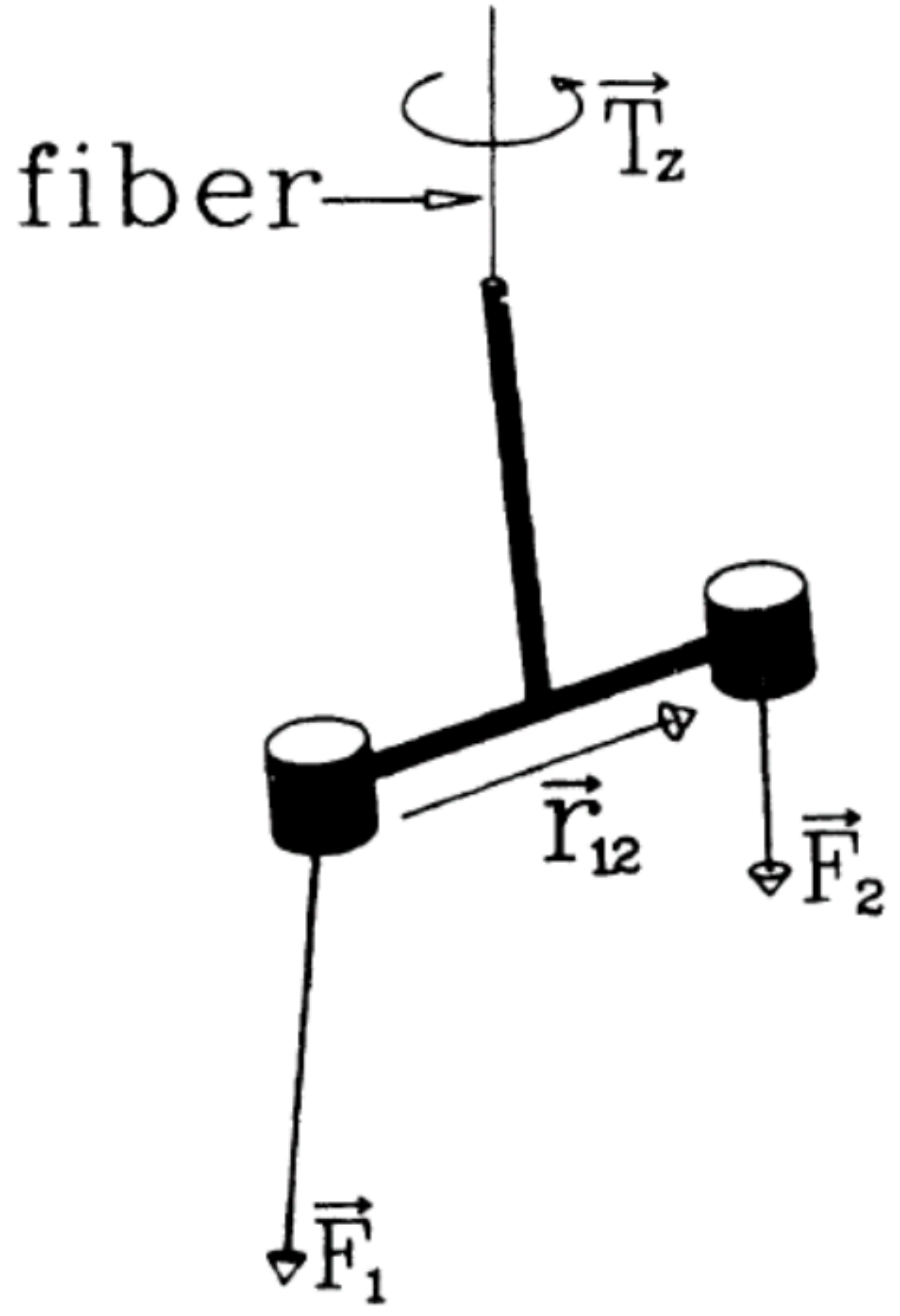
BBN Bounds

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

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

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

Possible experiments: Torsion Balance

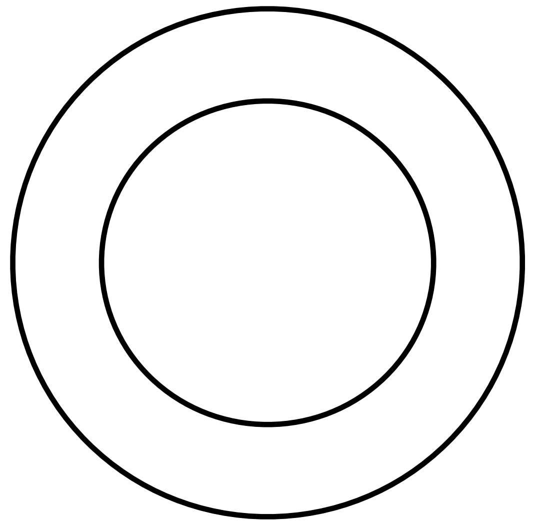


$$T_z = (\boldsymbol{F}_1 \times \boldsymbol{F}_2 \cdot \boldsymbol{r}_{12})/|\boldsymbol{F}_1 + \boldsymbol{F}_2|.$$

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

Possible experiments: Torsion Balance

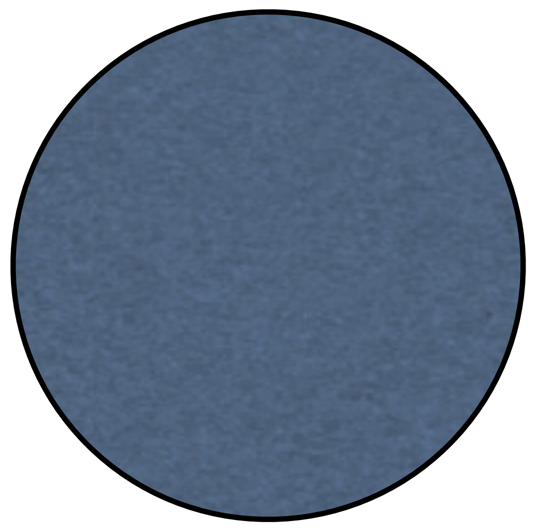
Ti



$R_1 \sim 0.71\text{cm}$

$R_2 \sim 0.85\text{cm}$

Be

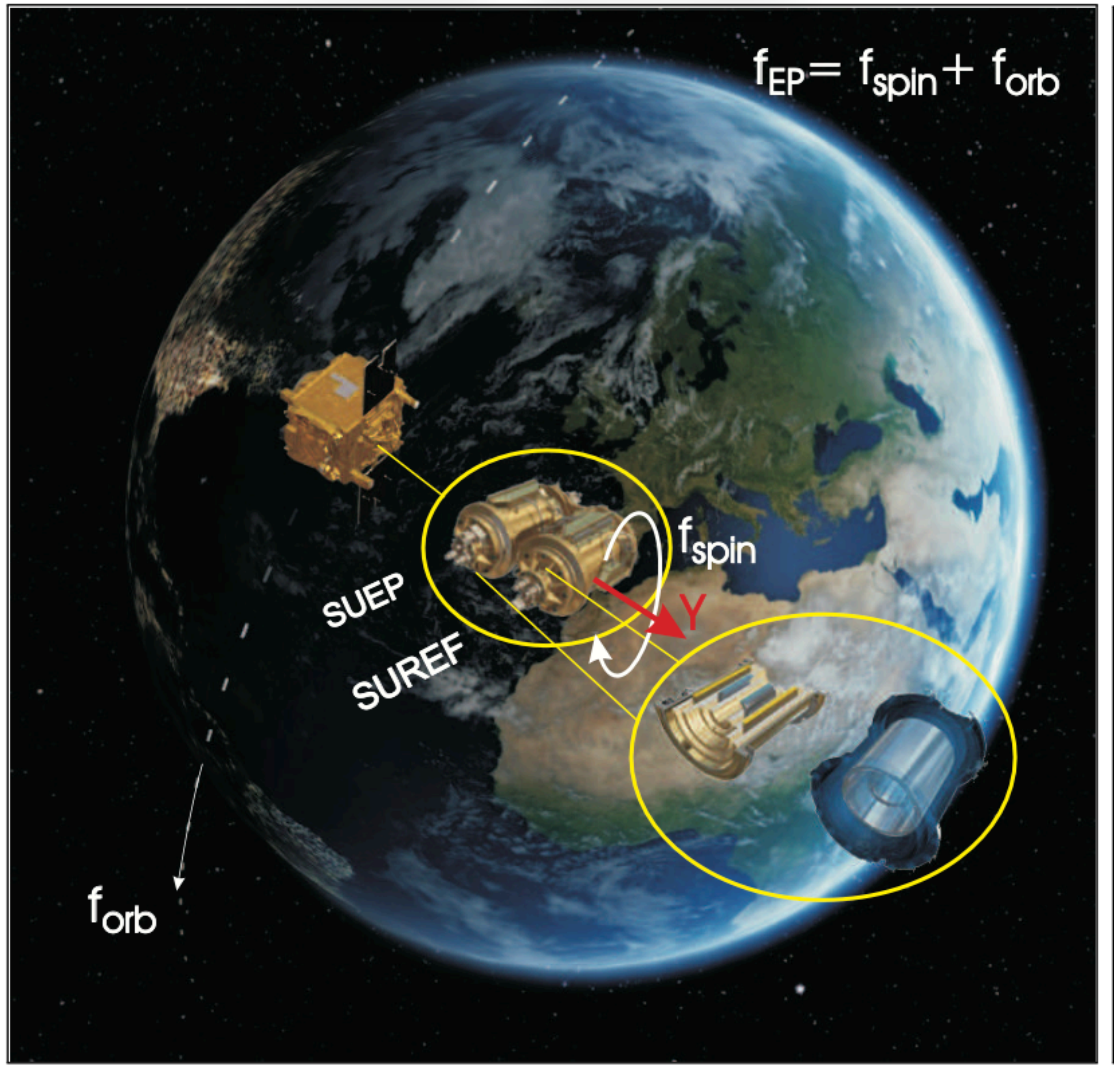


$R \sim 0.85\text{cm}$

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

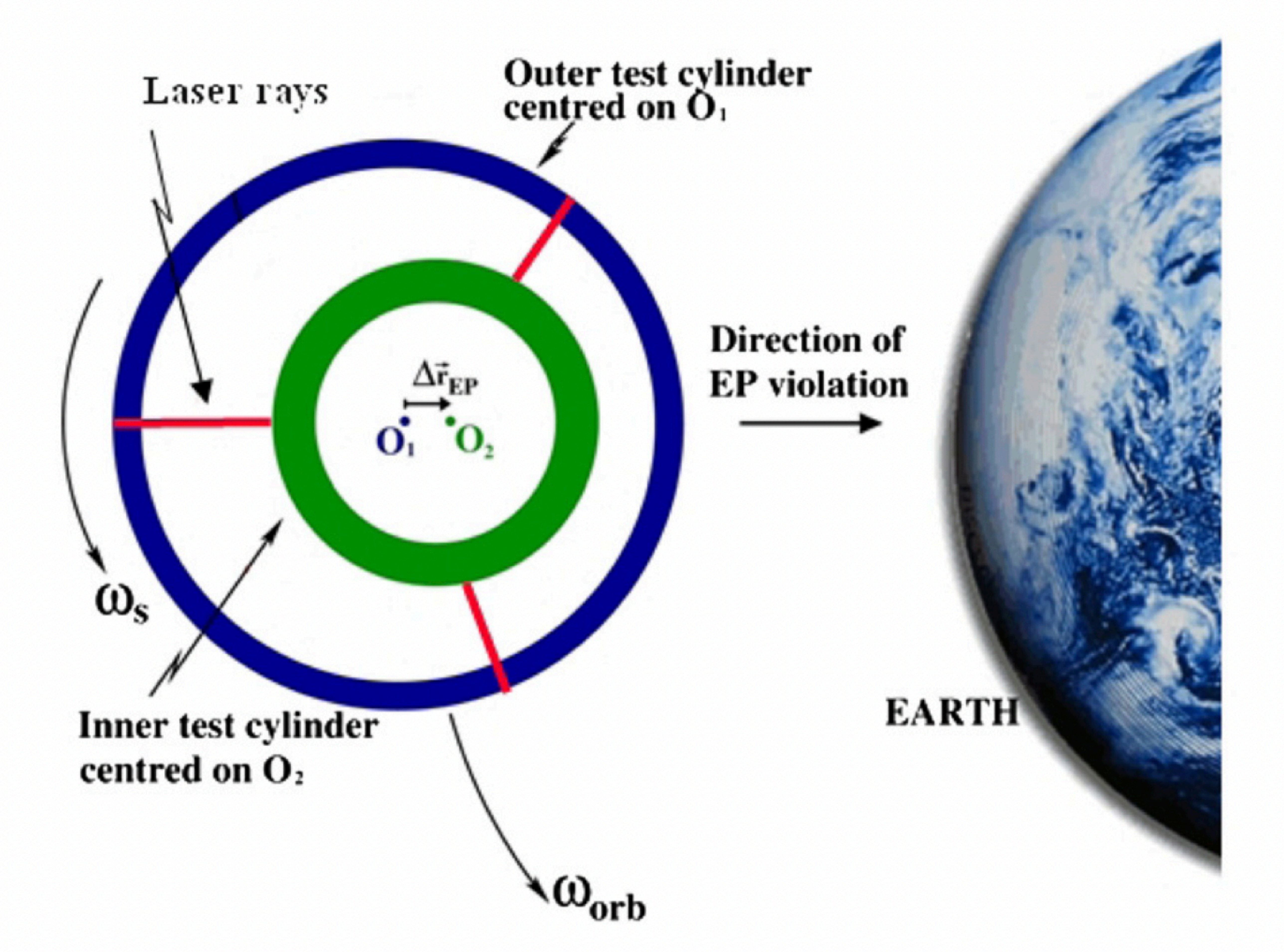
Possible experiments: Microscope

710km altitude



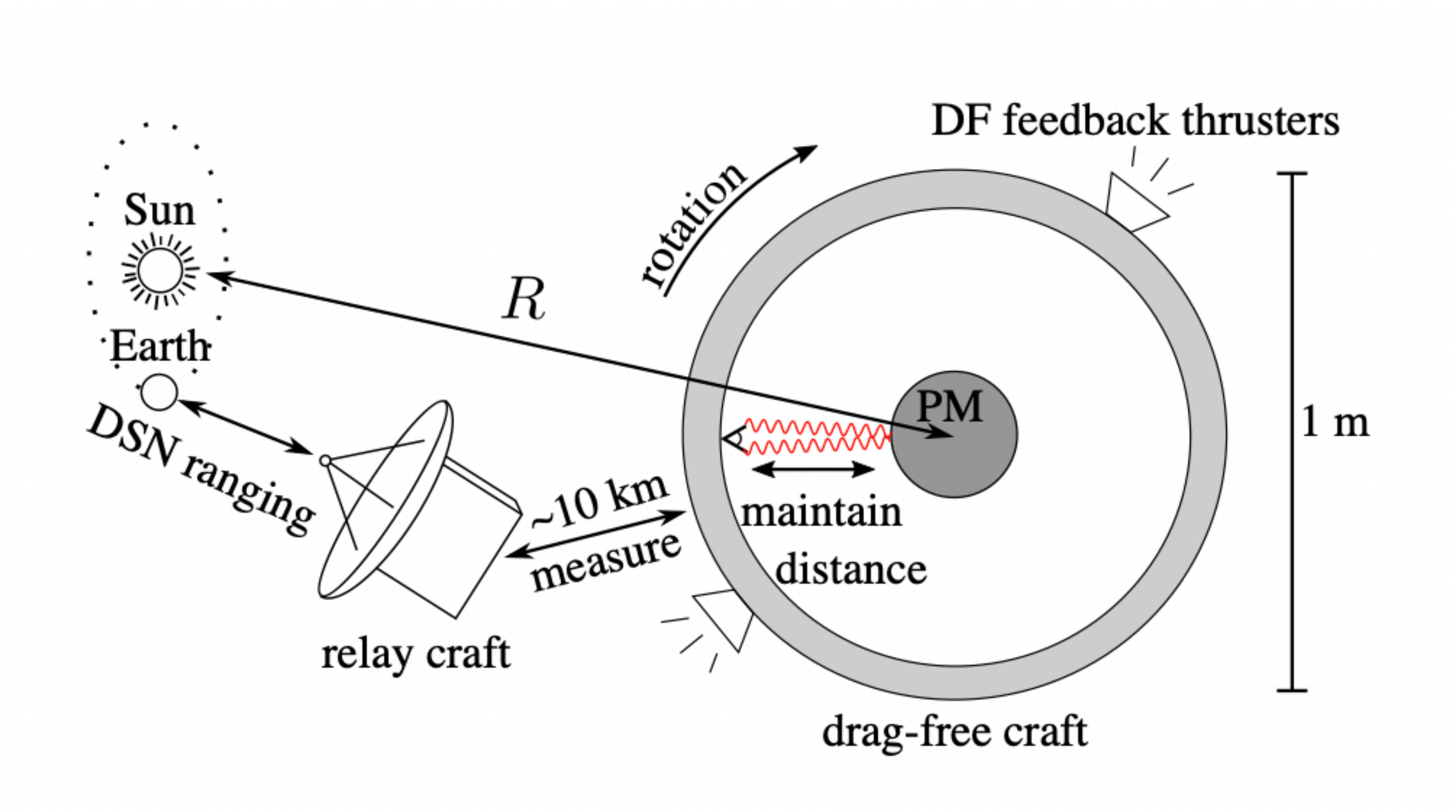
$$\Delta a = -1.2 \pm 2.2 \times 10^{-14} \mathrm{m/s^2}$$

Possible experiments: Galileo Galilei



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

Possible experiments: Space Mission

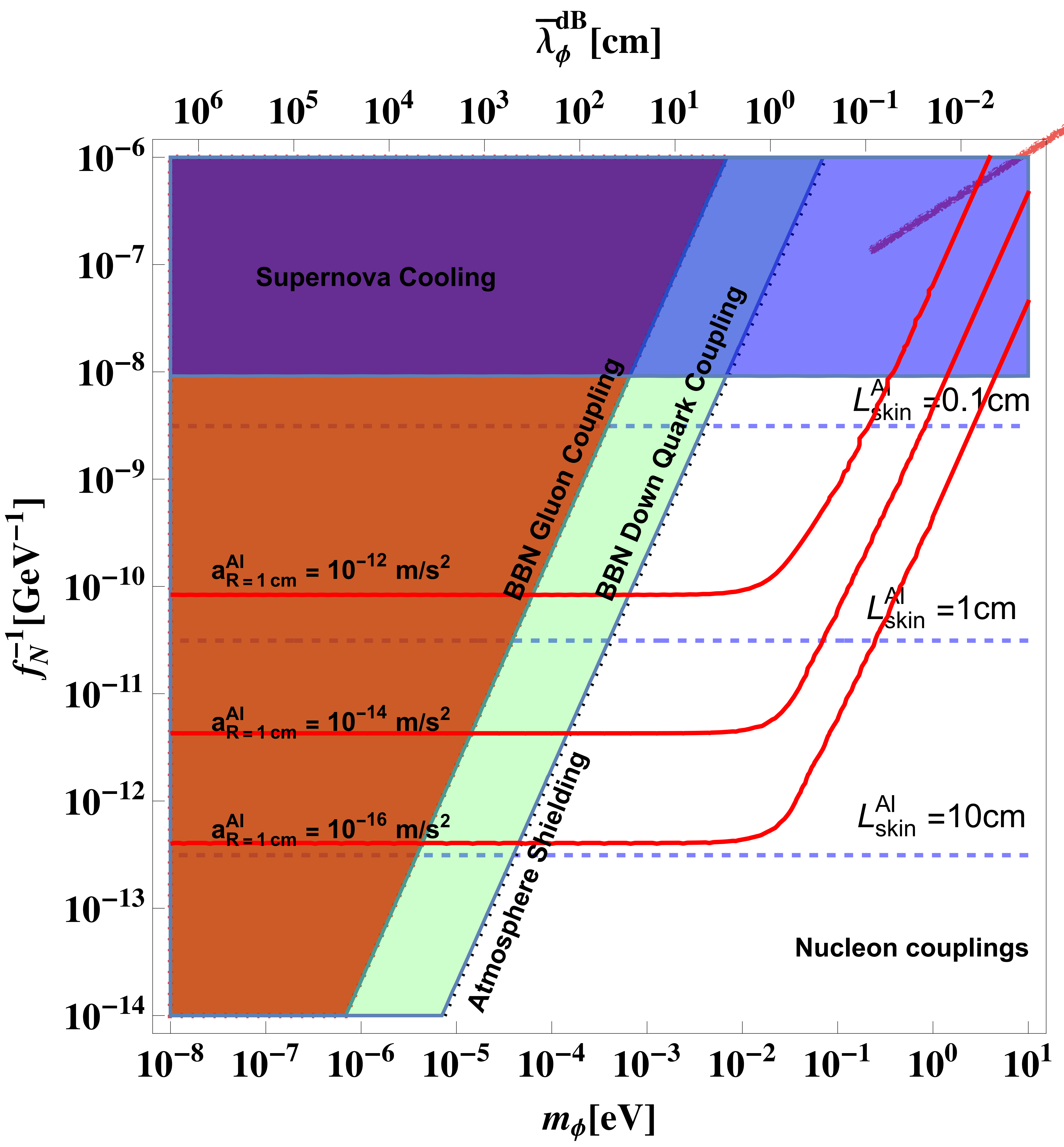


$$\delta a \sim 4.1 \times 10^{-17} \mathrm{m/s^2}$$

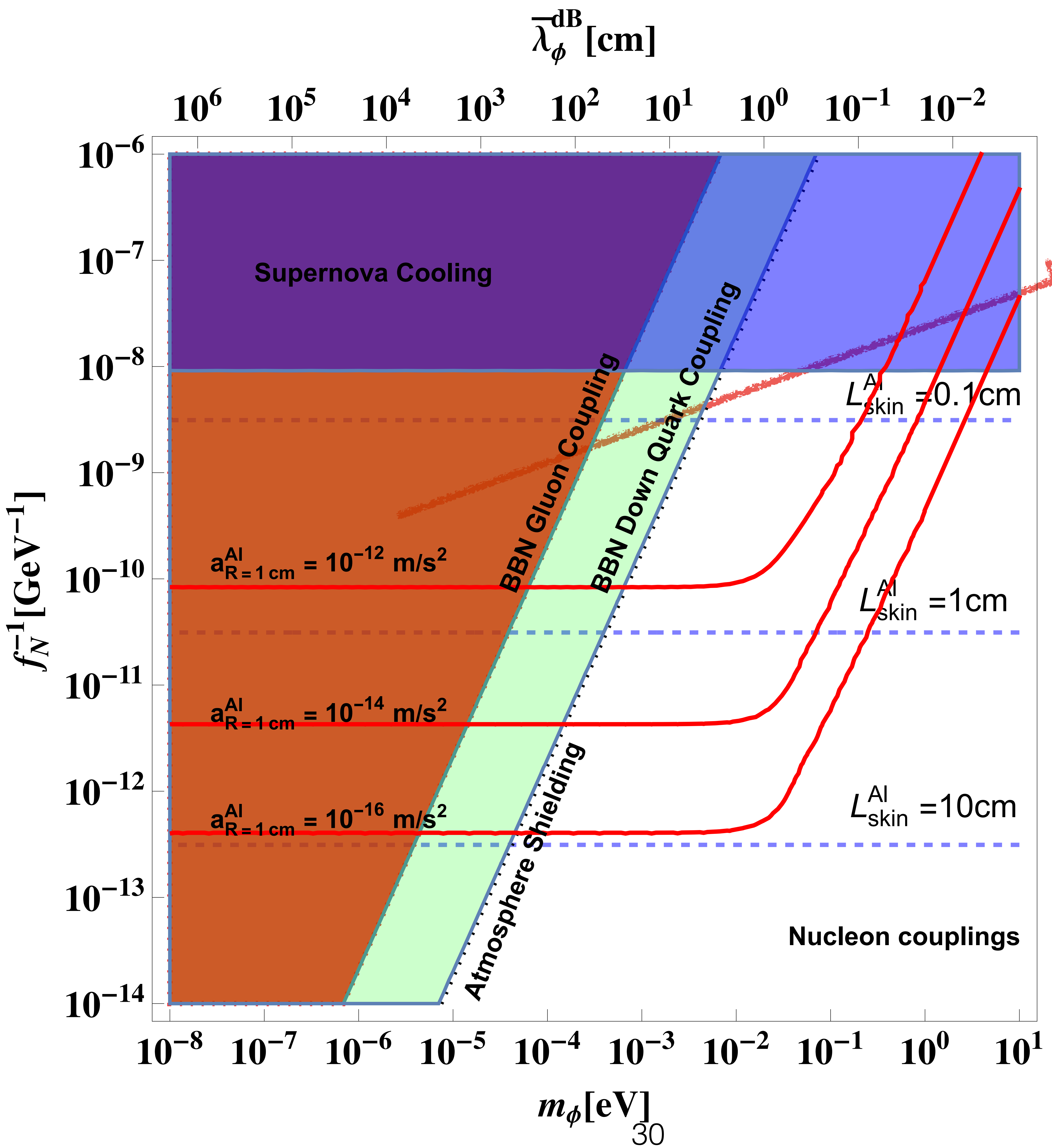
1 meter ranging over 7 years

Summary in One Plot

Supernova Cooling

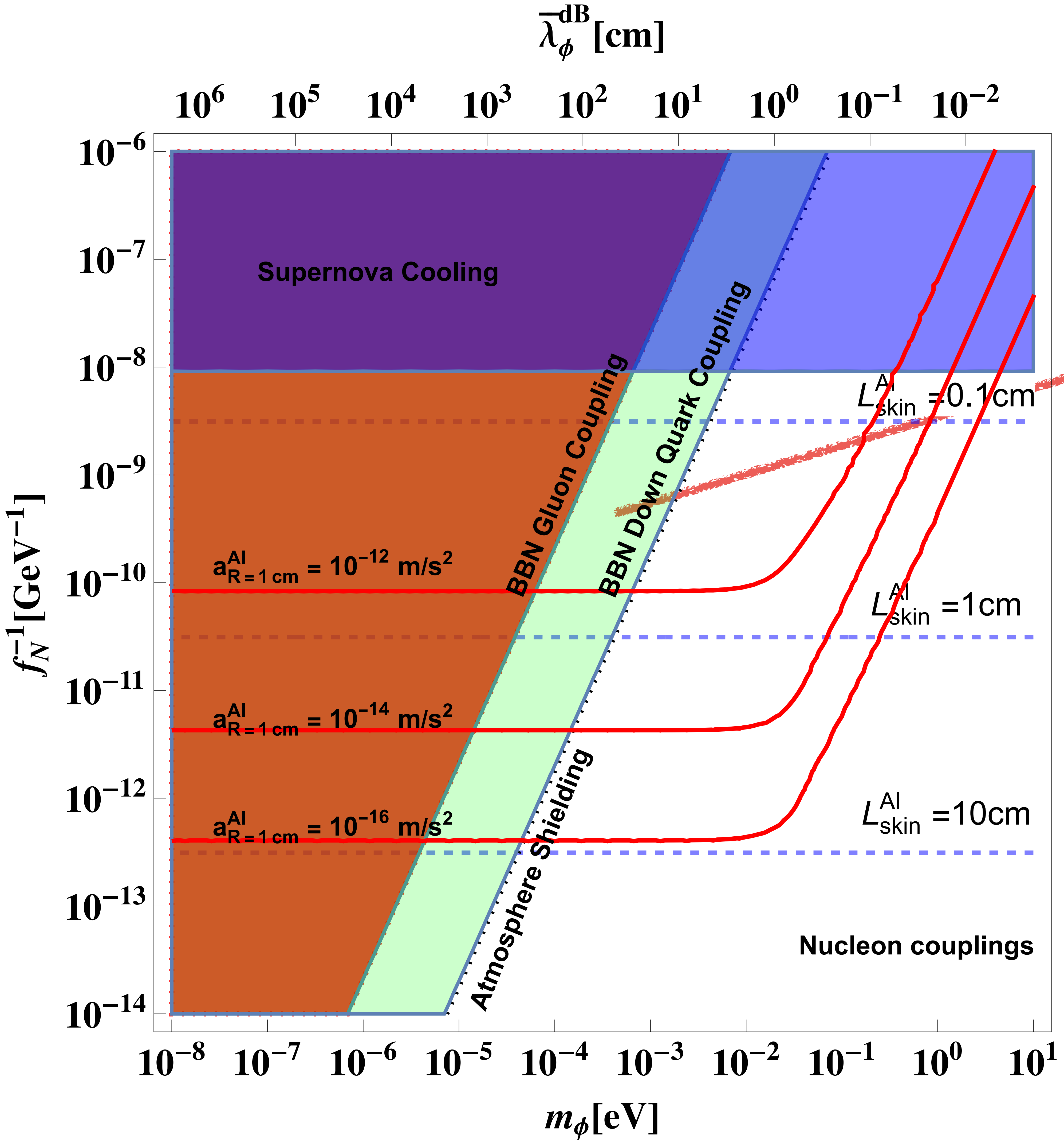


Summary in One Plot



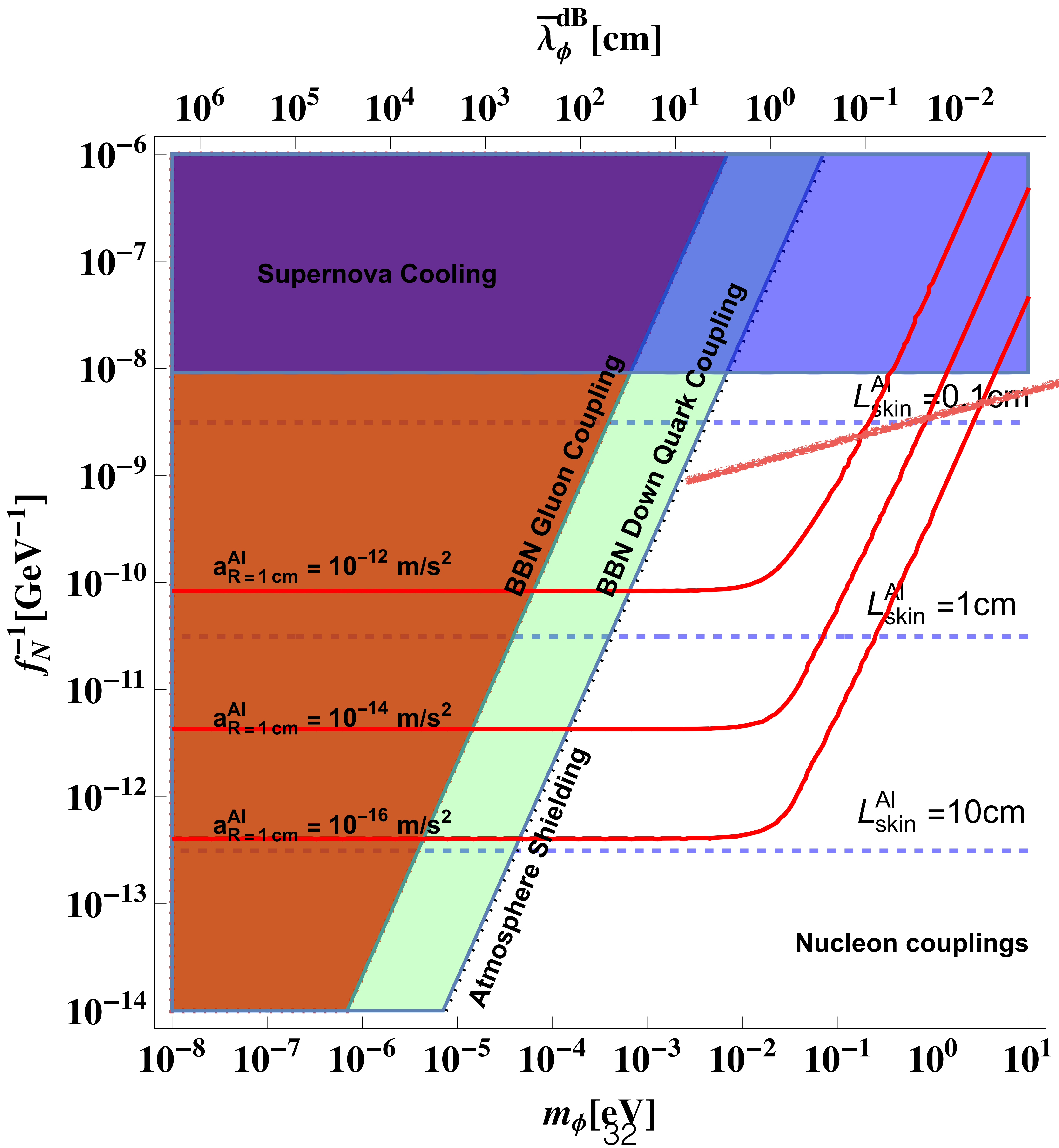
BBN Gluon coupling

Summary in One Plot



BBN Light Quark Coupling

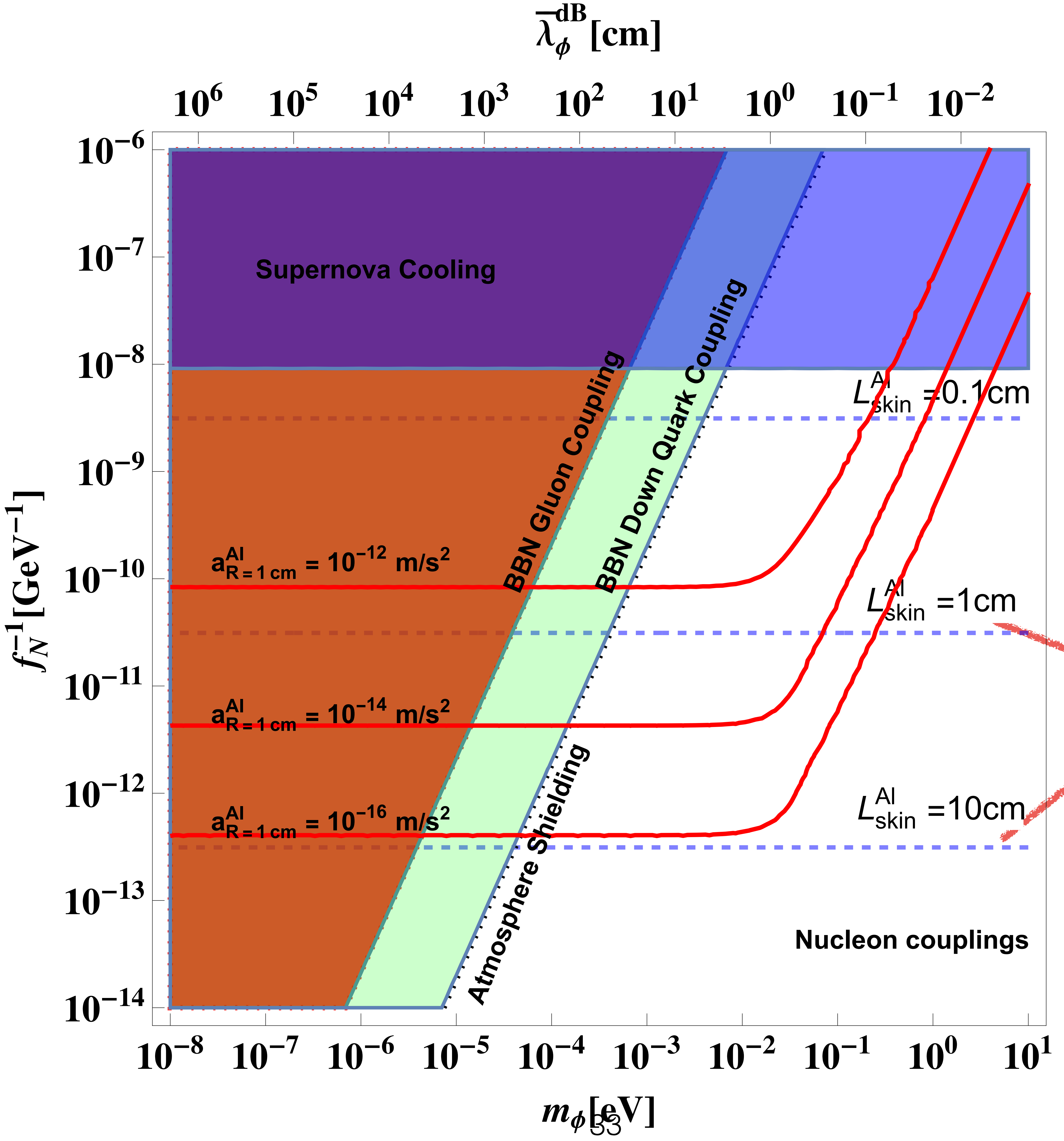
Summary in One Plot



Atmosphere

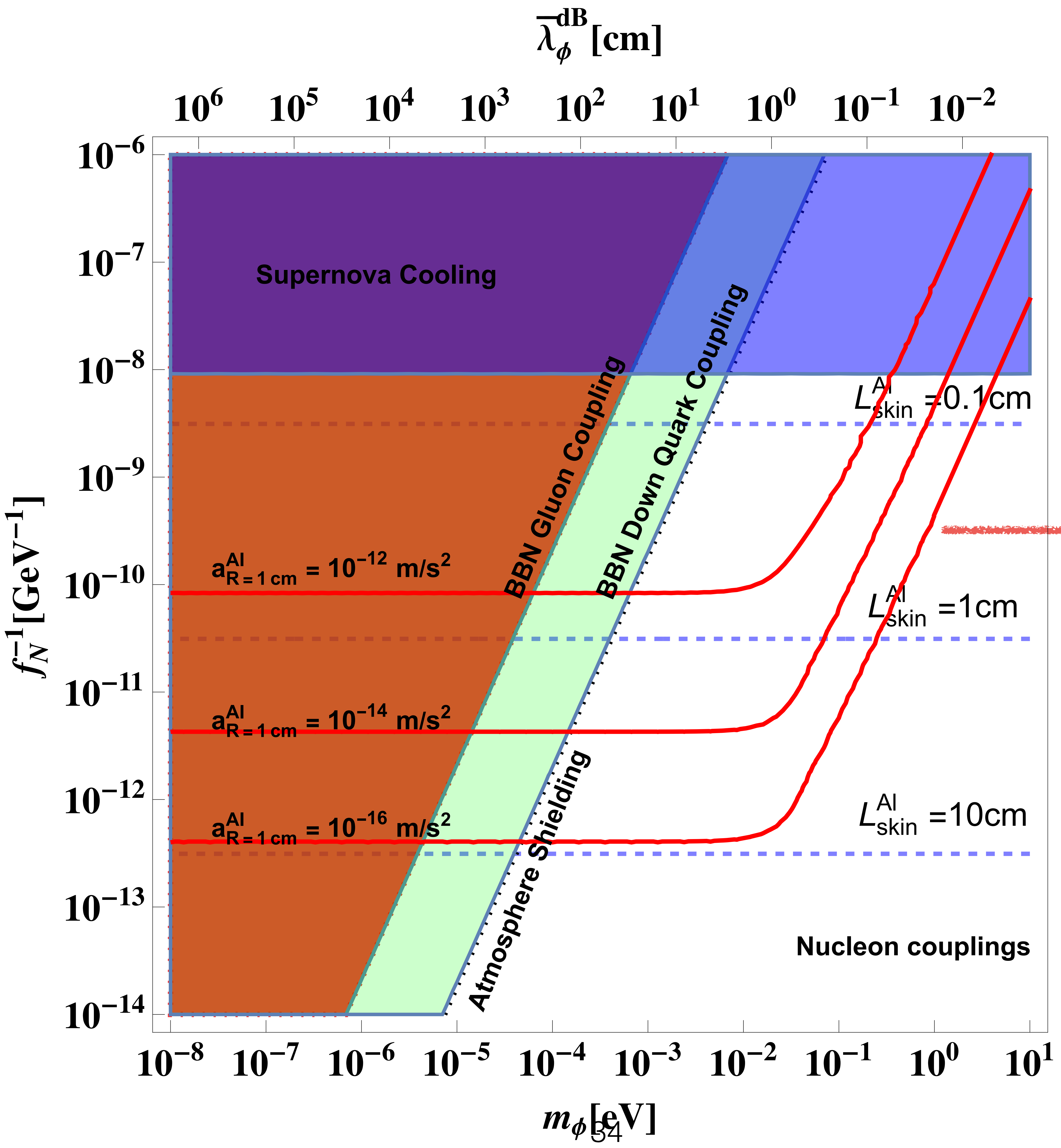
$7.3 \times 10^{20}/\text{cm}^3$

Summary in One Plot



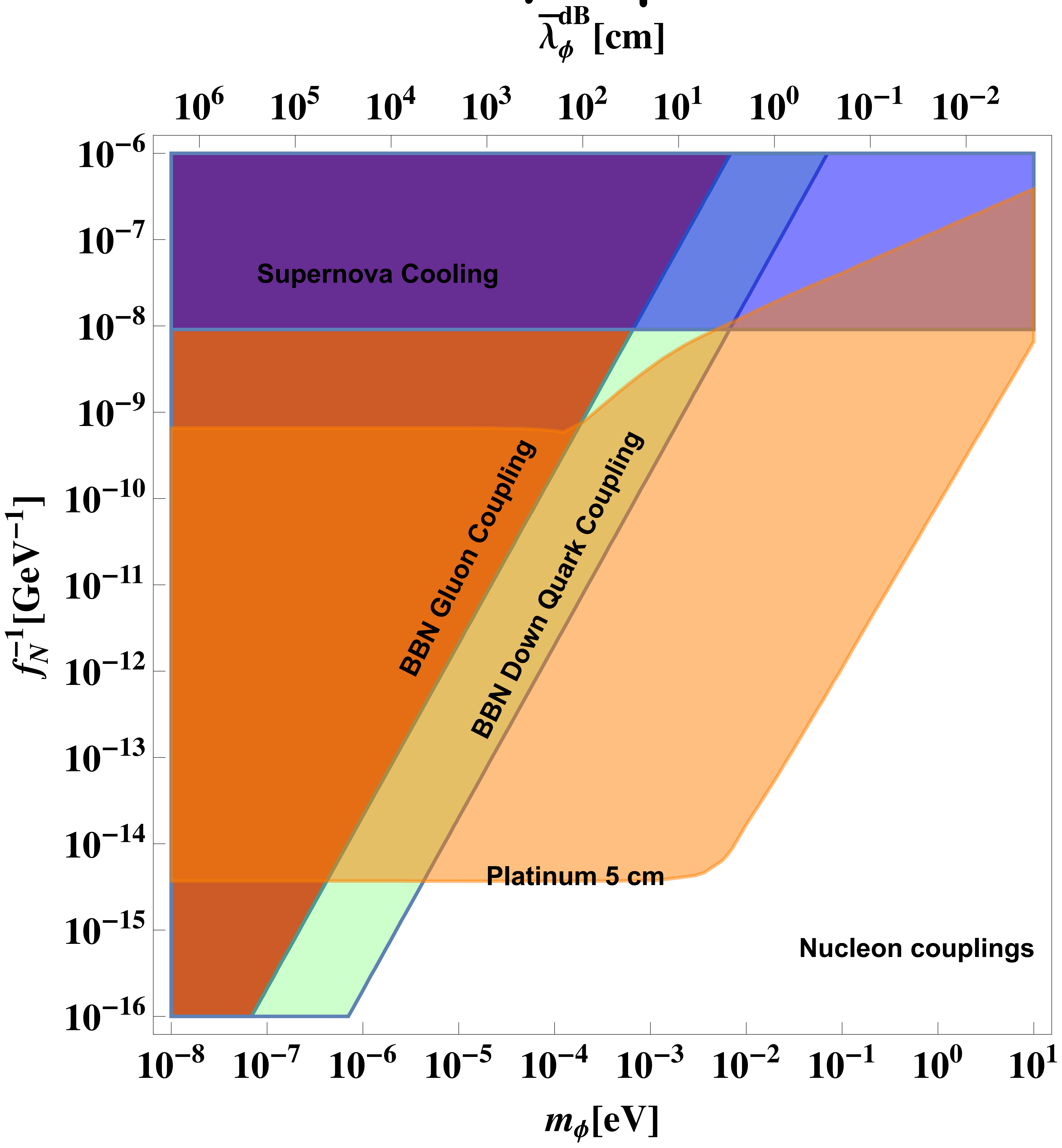
Aluminum skin depth

Summary in One Plot



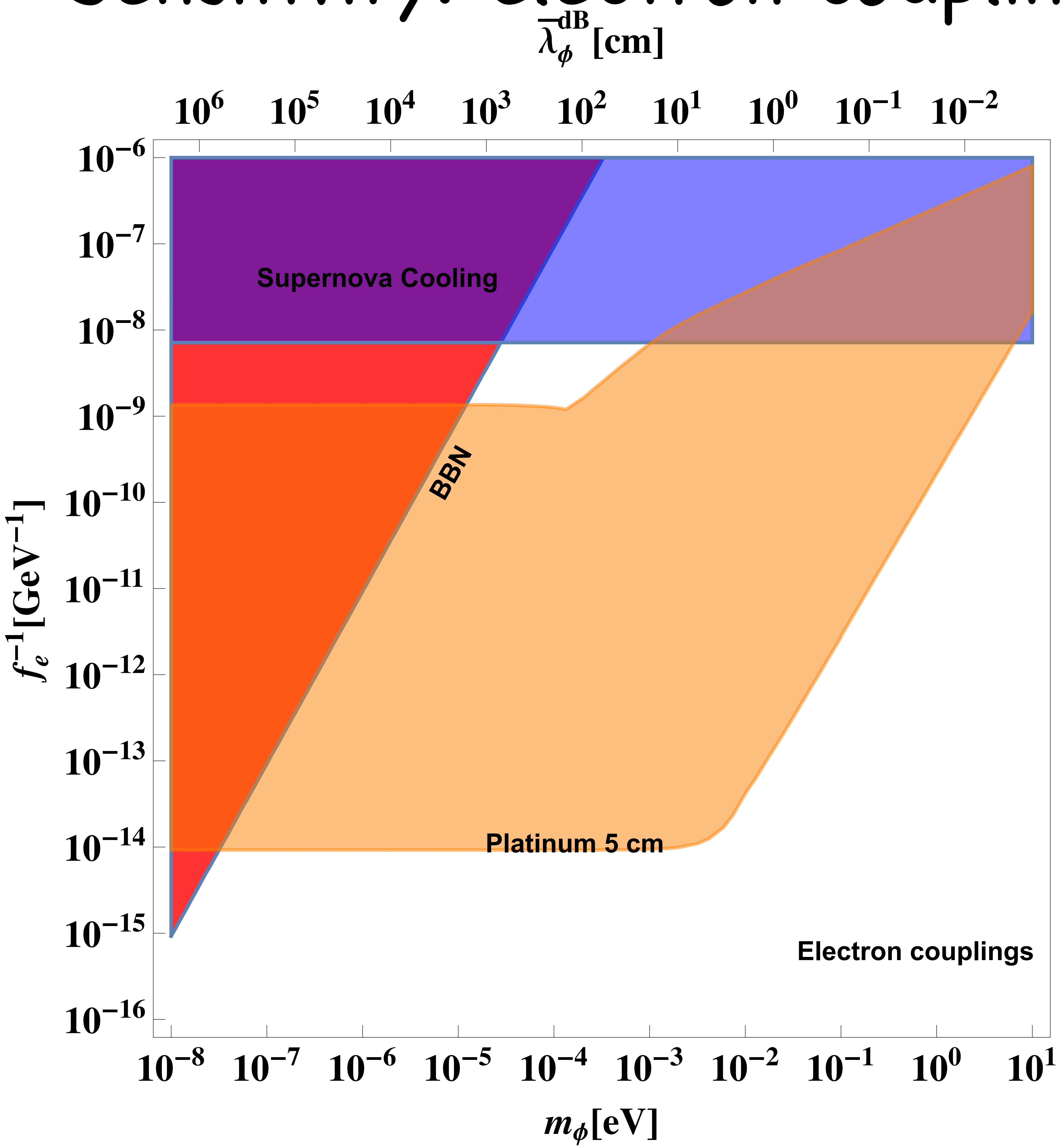
Constant Acceleration

Sensitivity:Space Mission



1mm Aluminum shell with radius 1m

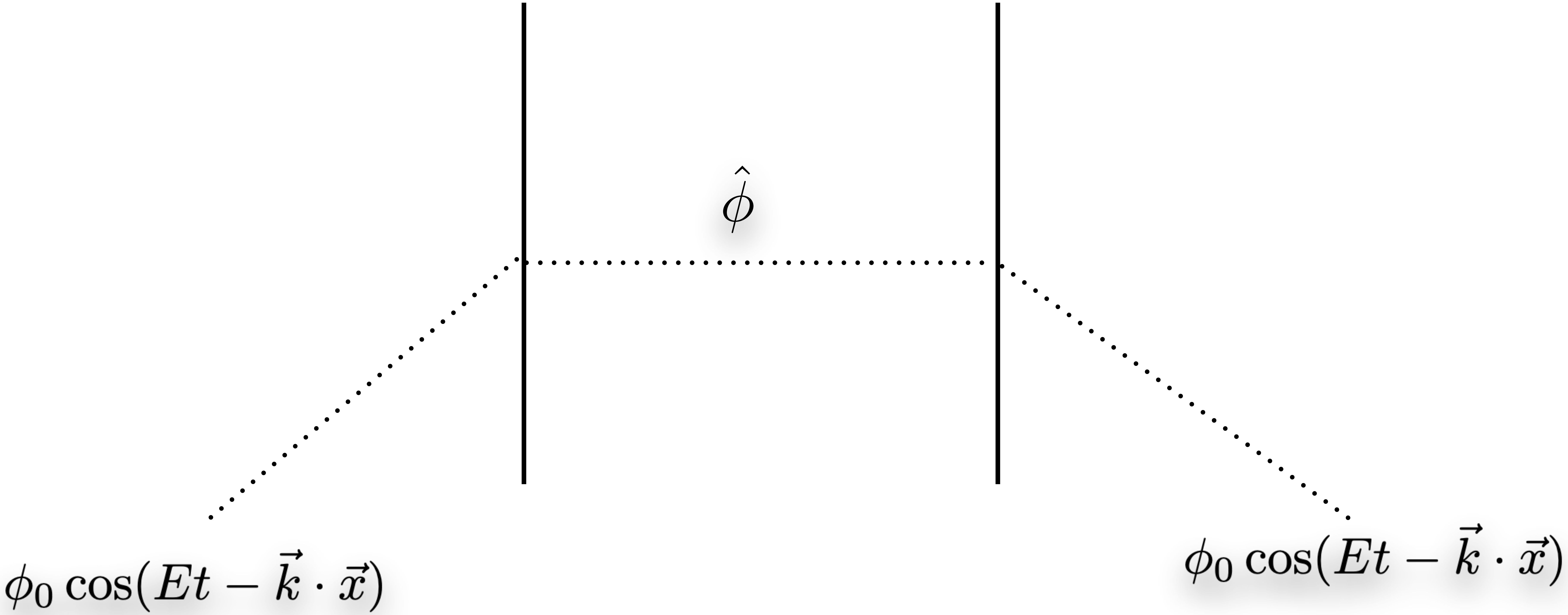
Sensitivity: electron coupling



1mm Aluminum shell with radius 1m

Wake Force

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



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

By Ken Van Tilburg, 2024

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