

Search for Light Scalar Dark Matter with Quadratic Interactions

Da Liu

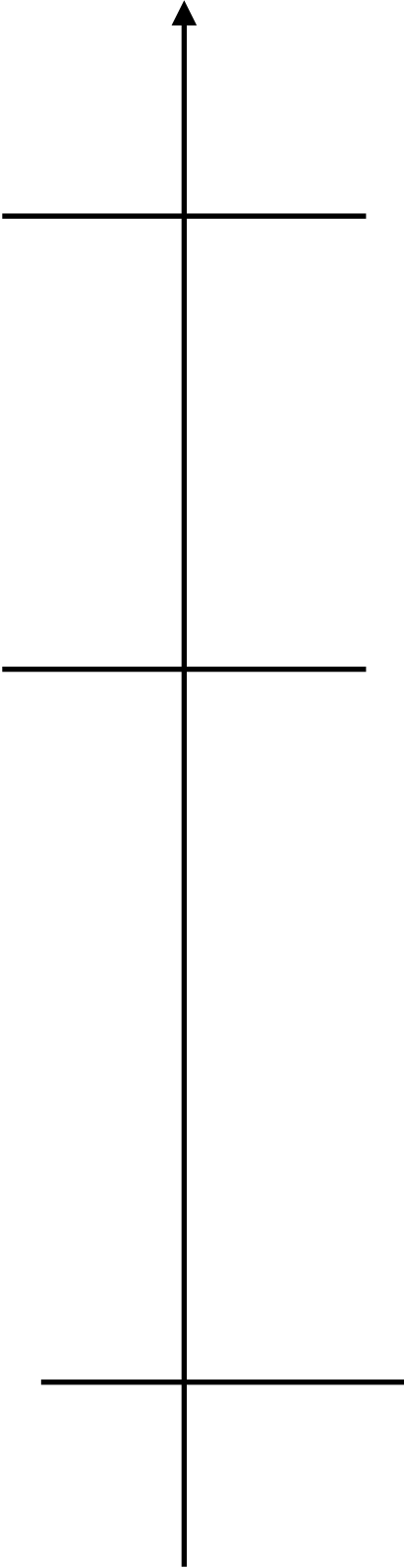
山东大学

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

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

Light Scalar Dark Matter Model

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



Ordinary Matter

$$\text{\AA} = 10^{-8}\text{cm}$$

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



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

Number density

Light Scalar Dark Matter Model

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



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



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

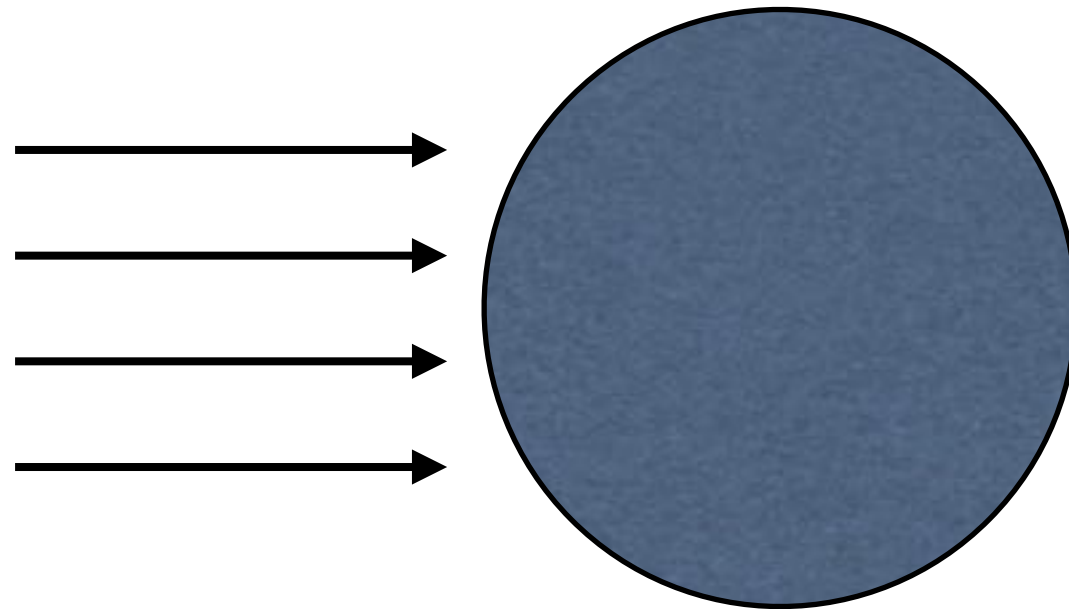
$$(\nabla^2 + E^2 - m^2 - \frac{n}{f})\psi(\vec{x}) = 0$$

Schrodinger equation with potential

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

Light Scalar Dark Matter Model

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

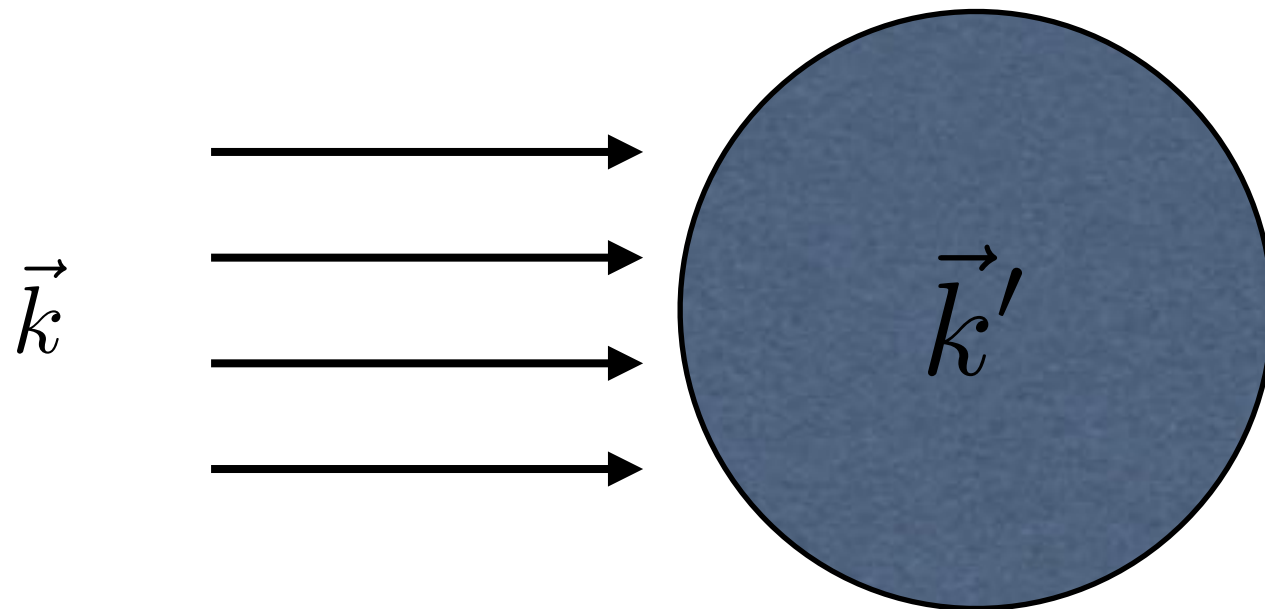


$$E^2 = \vec{k}^2 + m_\phi^2$$

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

Light Scalar Dark Matter Model

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



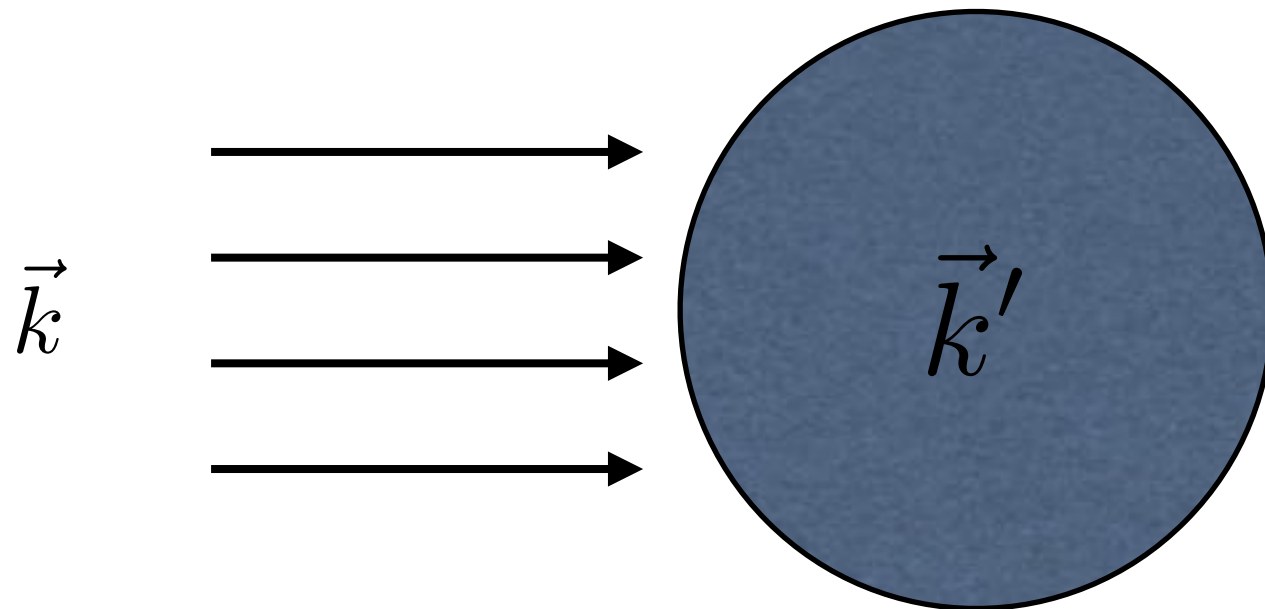
$$\vec{k}'^2 = \vec{k}^2 - \frac{n_N}{f}$$

Damping can occur when

$$\vec{k}^2 < \frac{n_N}{f}$$

Light Scalar Dark Matter Model

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

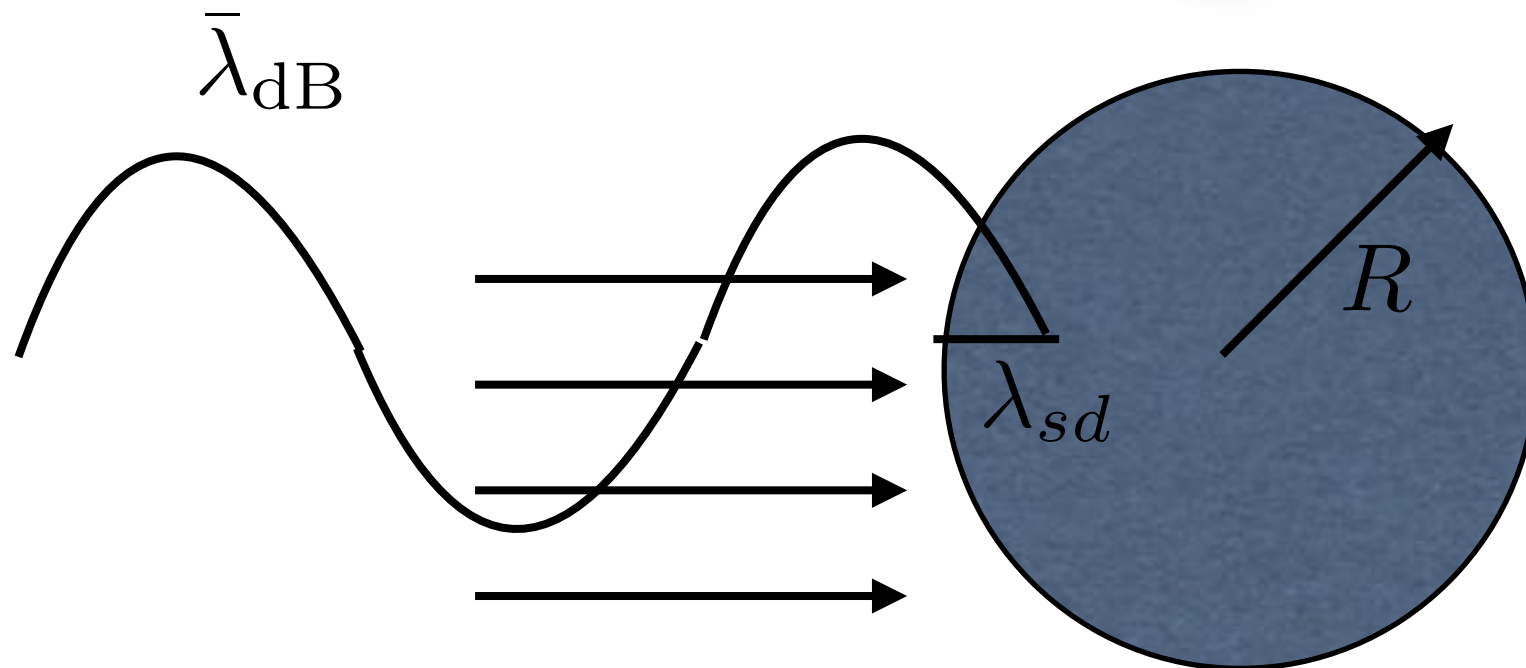


$$\lambda_{sd} = 1/\sqrt{\frac{n}{f}} \sim 5.6 \times 10^{-2} \text{cm} \times \sqrt{\frac{\frac{f}{10^8 \text{GeV}}}{\frac{\rho_{\text{matt}}}{2.7 \text{ g/cm}^3}}}$$

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

Two conditions for the maximal force

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



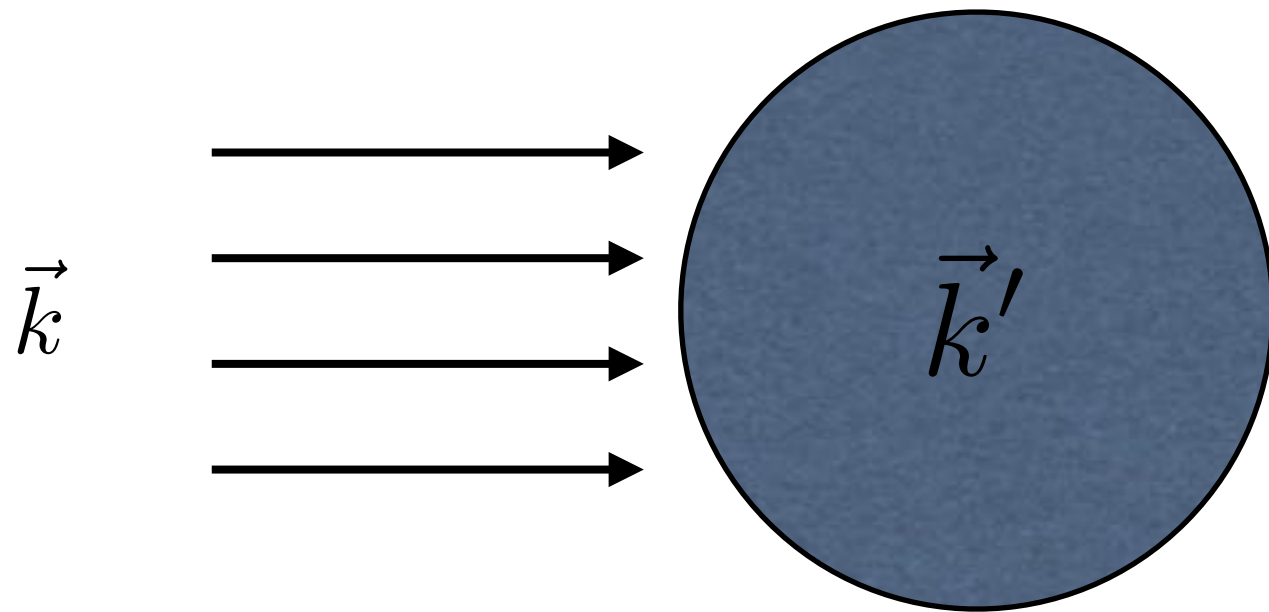
– Strong Potential

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

– Small skin depth

$$\lambda_{sd} \ll R$$

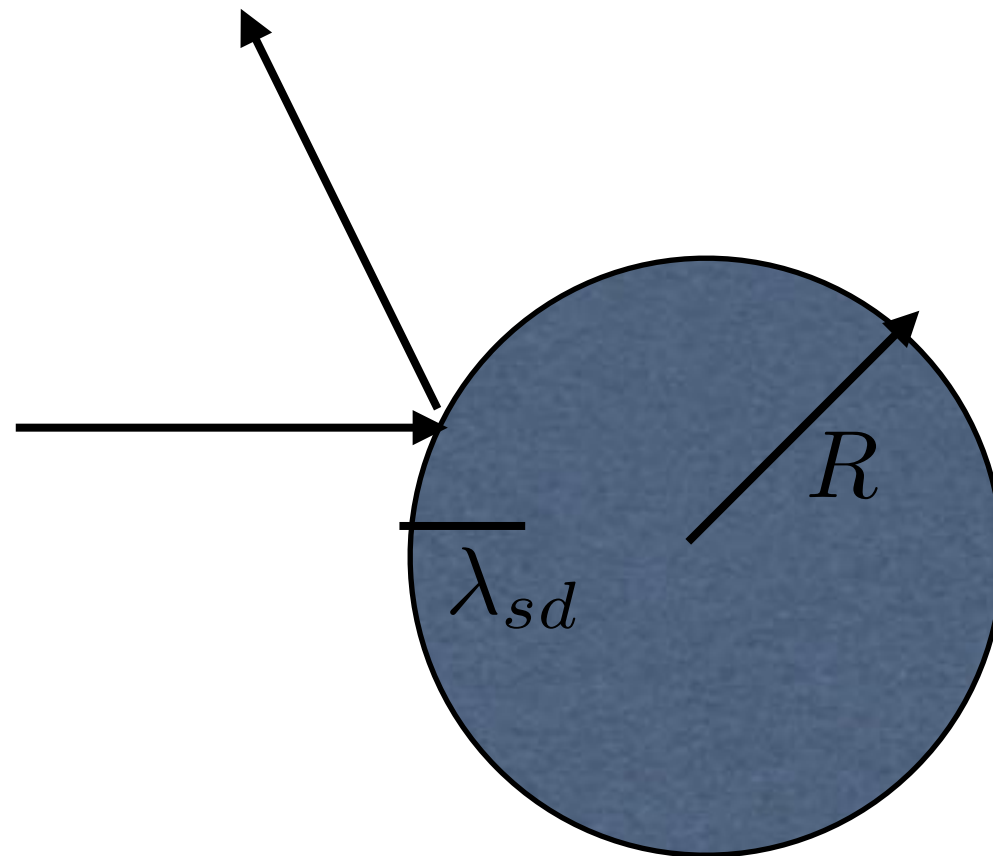
Acceleration induced by DM wind



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

Geometric Limit

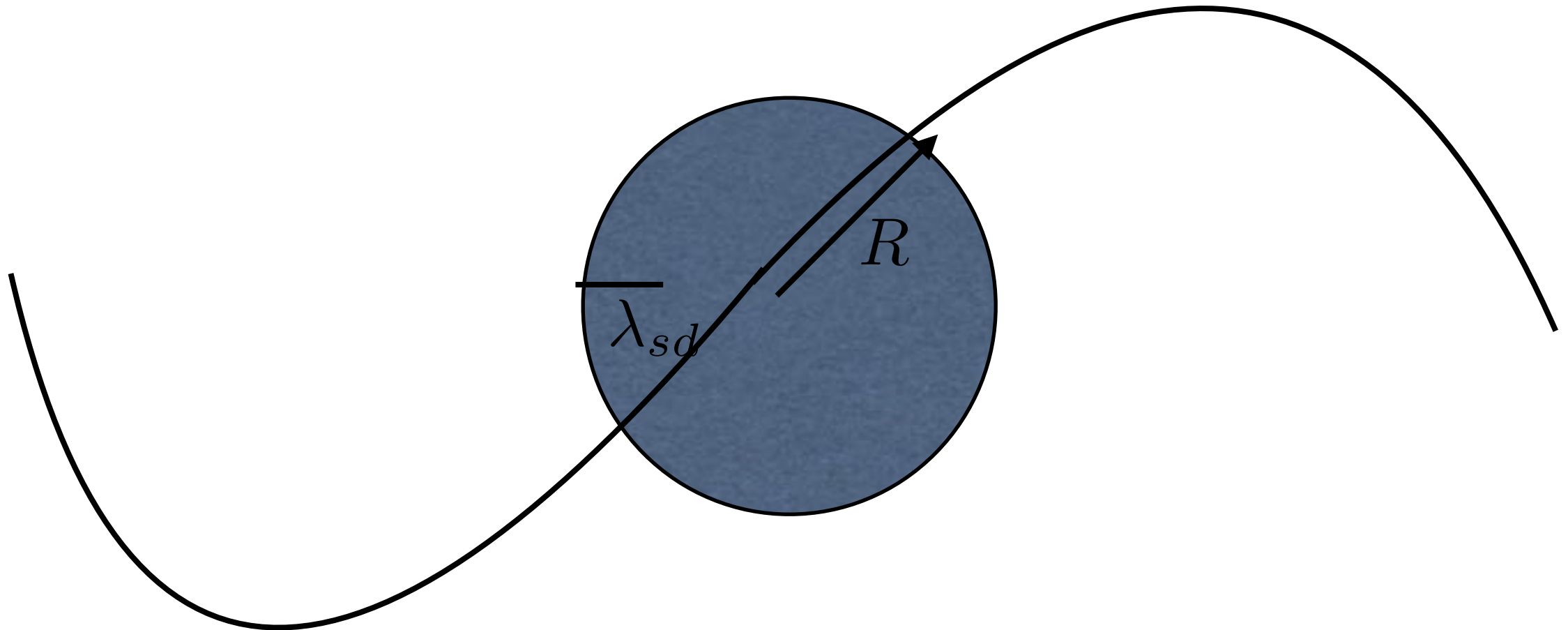
$$\lambda_{sd} \ll \bar{\lambda}_{\text{dB}} \ll R$$



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

Slow scattering limit

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

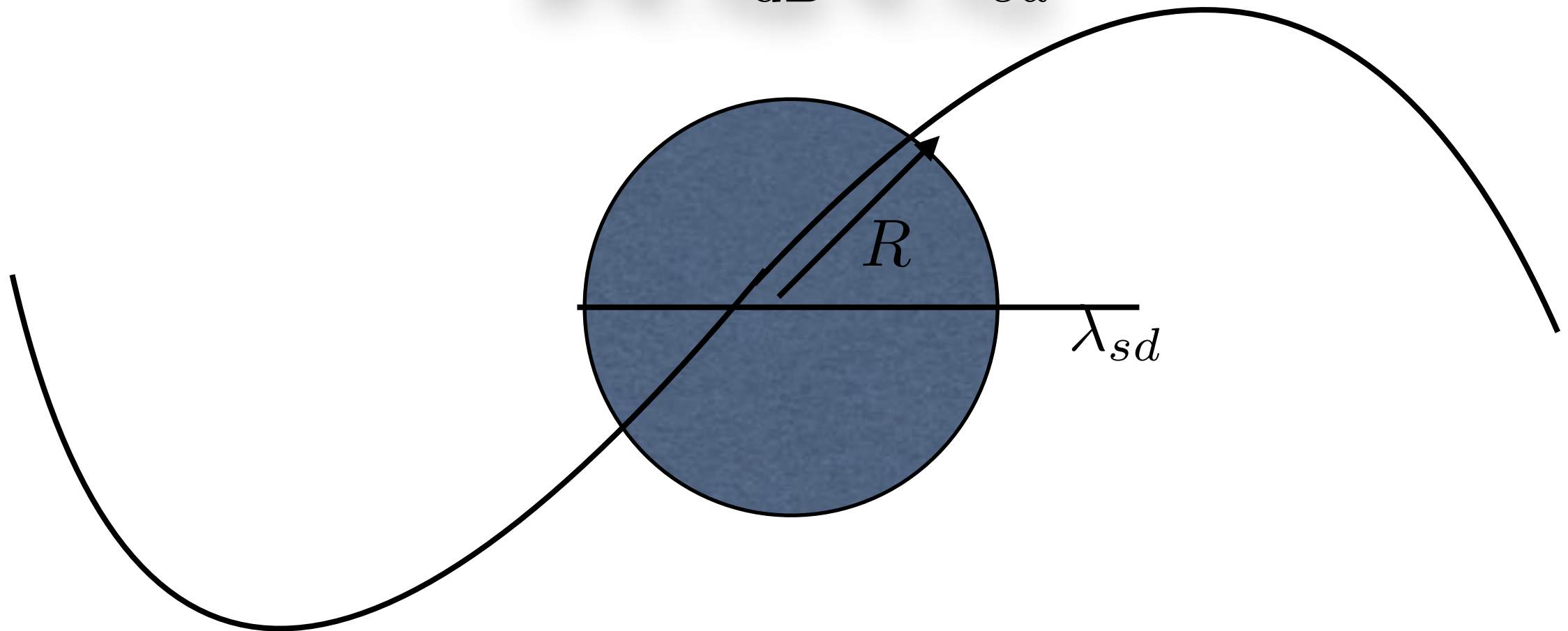


$$F_z = 4\rho_{\text{DM}}v^2\pi R^2$$

Slow scattering limit: large skin depth

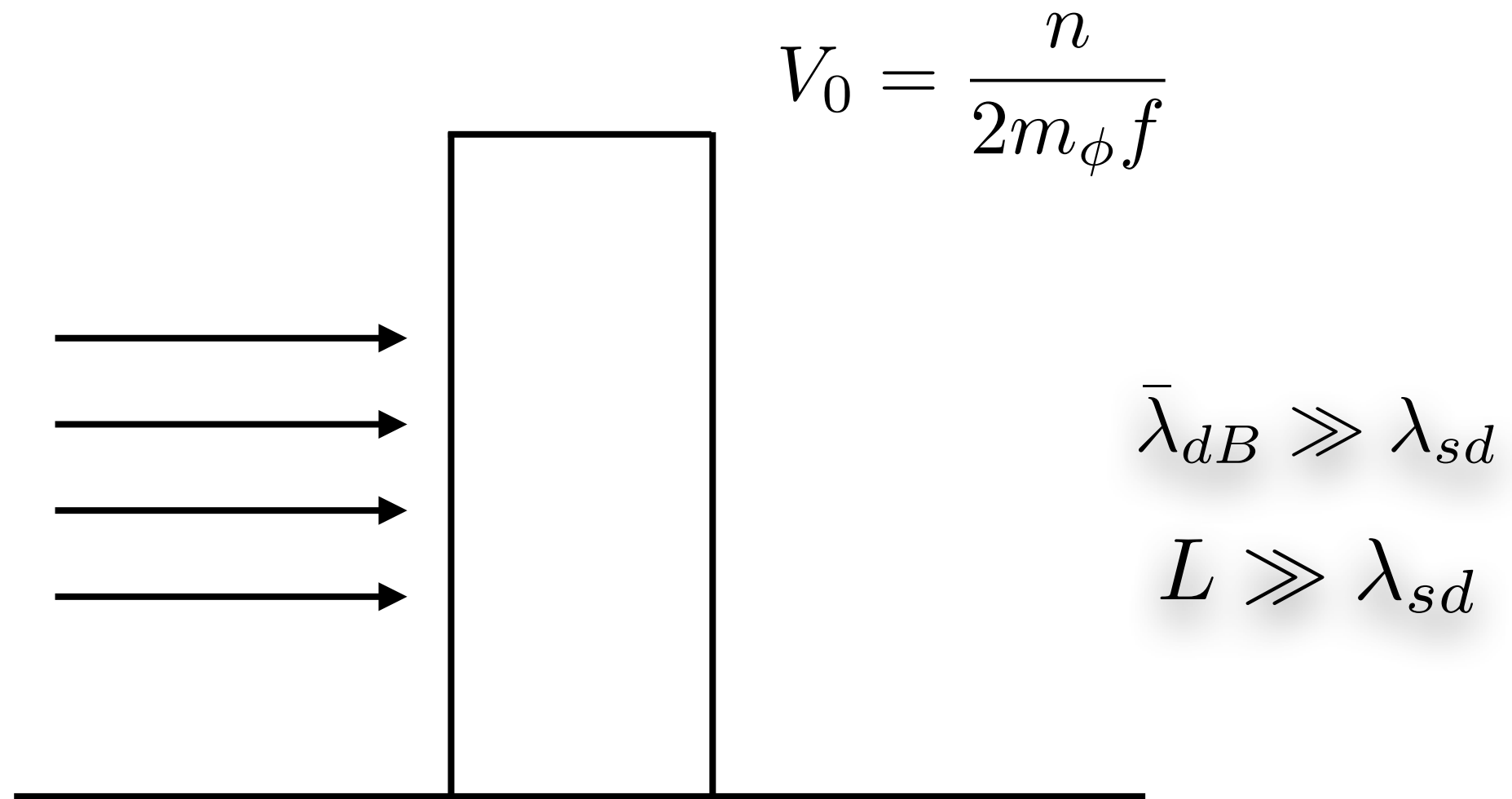
$$R \ll \lambda_{sd} \ll \bar{\lambda}_{\text{dB}}$$

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



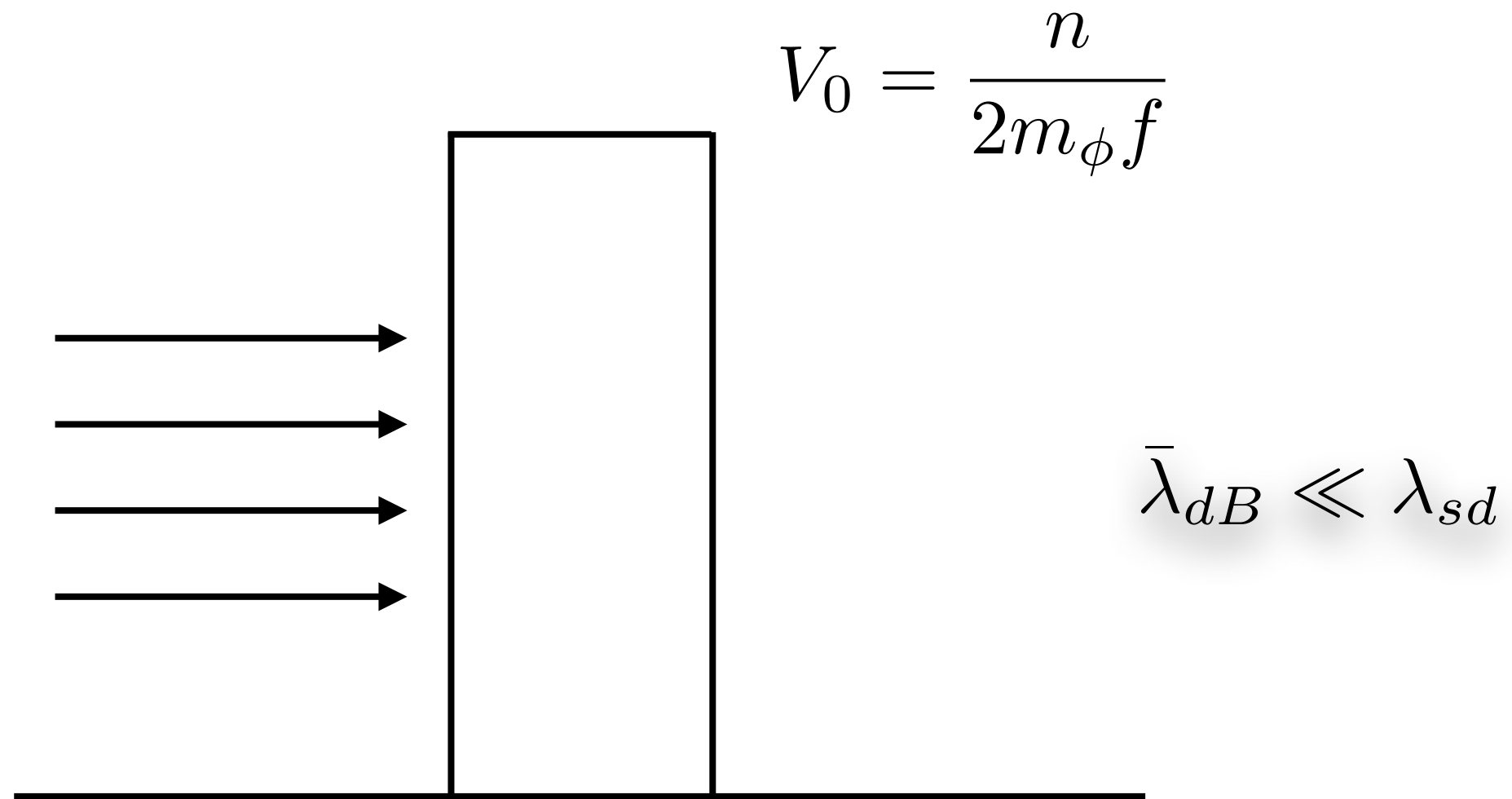
$$\frac{F_z}{\rho_{\text{DM}} v^2 \pi R^2} \sim \frac{4}{9} \frac{R^4}{\lambda_{sd}^4}$$

Shielding effect: potential barrier



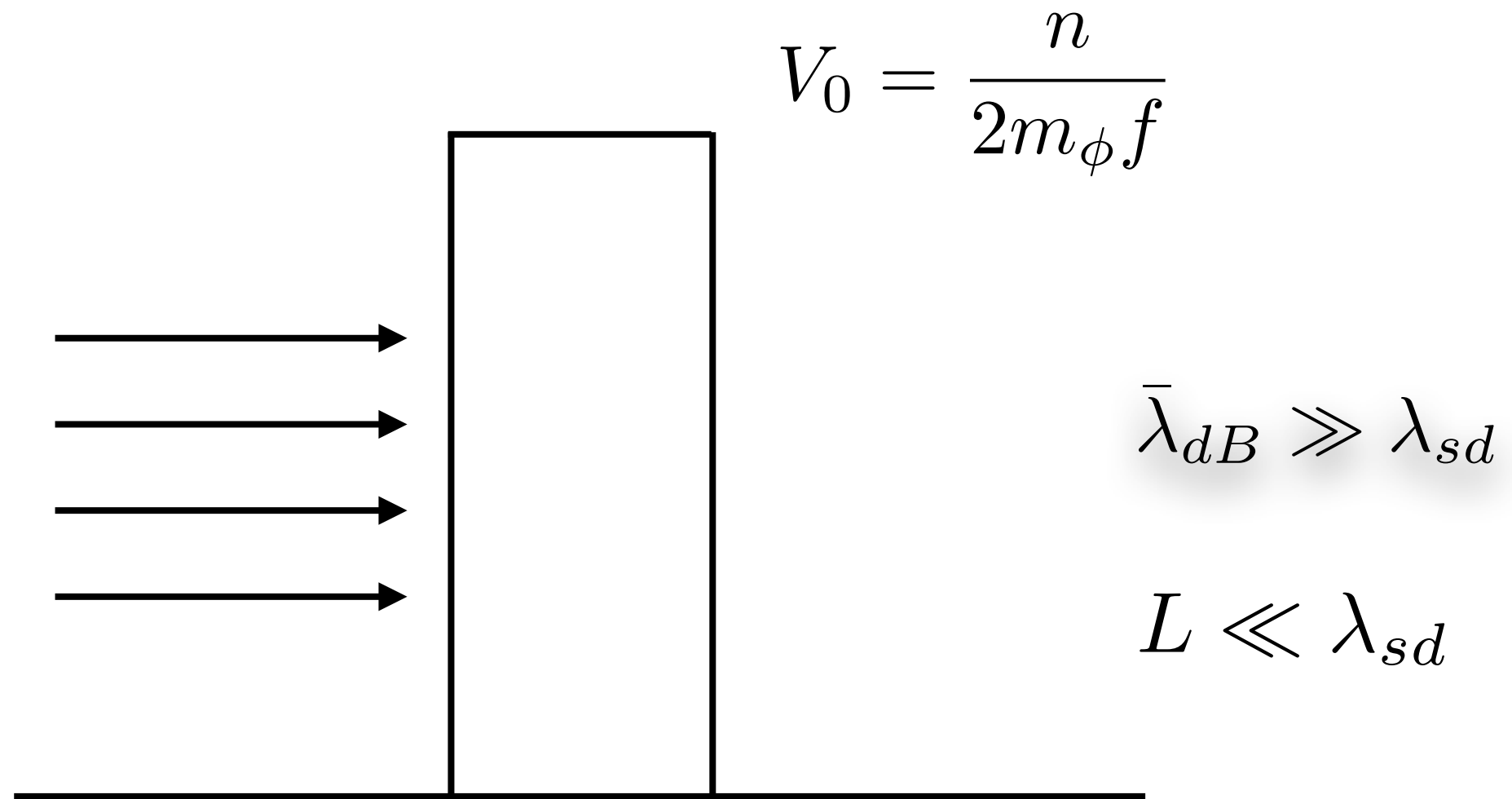
$$T \sim 16 \frac{\lambda_{sd}^2}{\bar{\lambda}_{dB}^2} e^{-2L/\lambda_{sd}}$$

Shielding effect: potential barrier



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

Shielding effect: potential barrier



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

Questions?

Supernova Cooling Bound: Raffelt criterion

$$N\bar{N} \rightarrow N\bar{N}\phi\phi$$

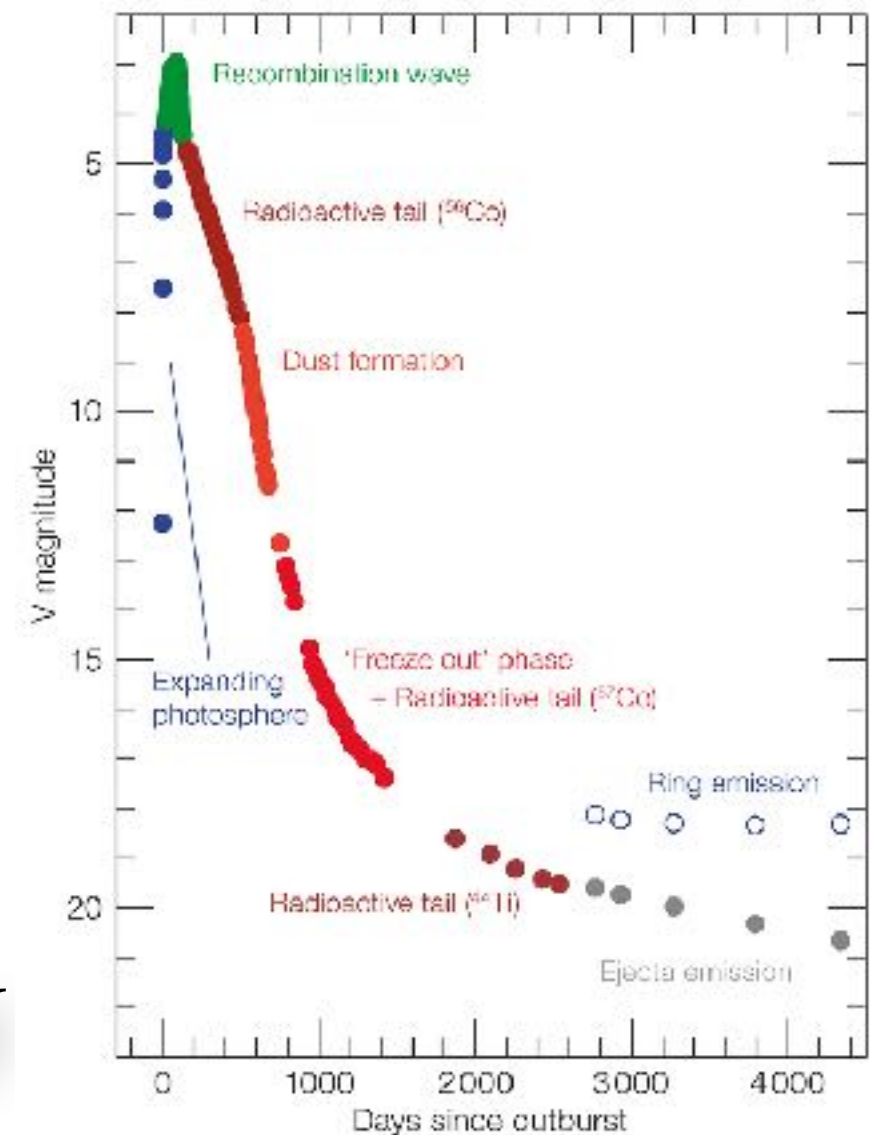
Neutrino Luminosity

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

$$10^{-14} \text{ MeV}^5$$



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



Credit: ESO

Cosmology in a Nutshell

Temperature

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

$$T_W \simeq 0.8\text{MeV}$$

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

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

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

Primordial Curvature Perturbation

$$\begin{aligned} \ln(10^{10} \Delta_{\mathcal{R}}^2)|_{k_0=0.05\text{Mpc}^{-1}} \\ = 3.044 \pm 0.014 \\ n_s = 0.965 \pm 0.004 \end{aligned}$$

4He mass fraction

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

Sound horizon

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

Reionization optical depth

$$\tau = 0.054 \pm 0.007$$

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

Cosmic Evolution

$$\Omega_x \equiv \rho_x / \rho_{\text{crit}}$$

$$\rho_{\text{crit}} = 3H_0^2 / 8\pi G$$

Energy Content Determines the Cosmic Evolution

$$z_* \sim 1100$$

Photon Last Scattering Surface

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_\Lambda + \Omega_k (1+z)^2}$$

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{c_s(z) dz}{H(z)}$$

$$D_A(z_*) = \frac{1}{(1+z_*)} \int_0^{z_*} \frac{dz}{H(z)}$$

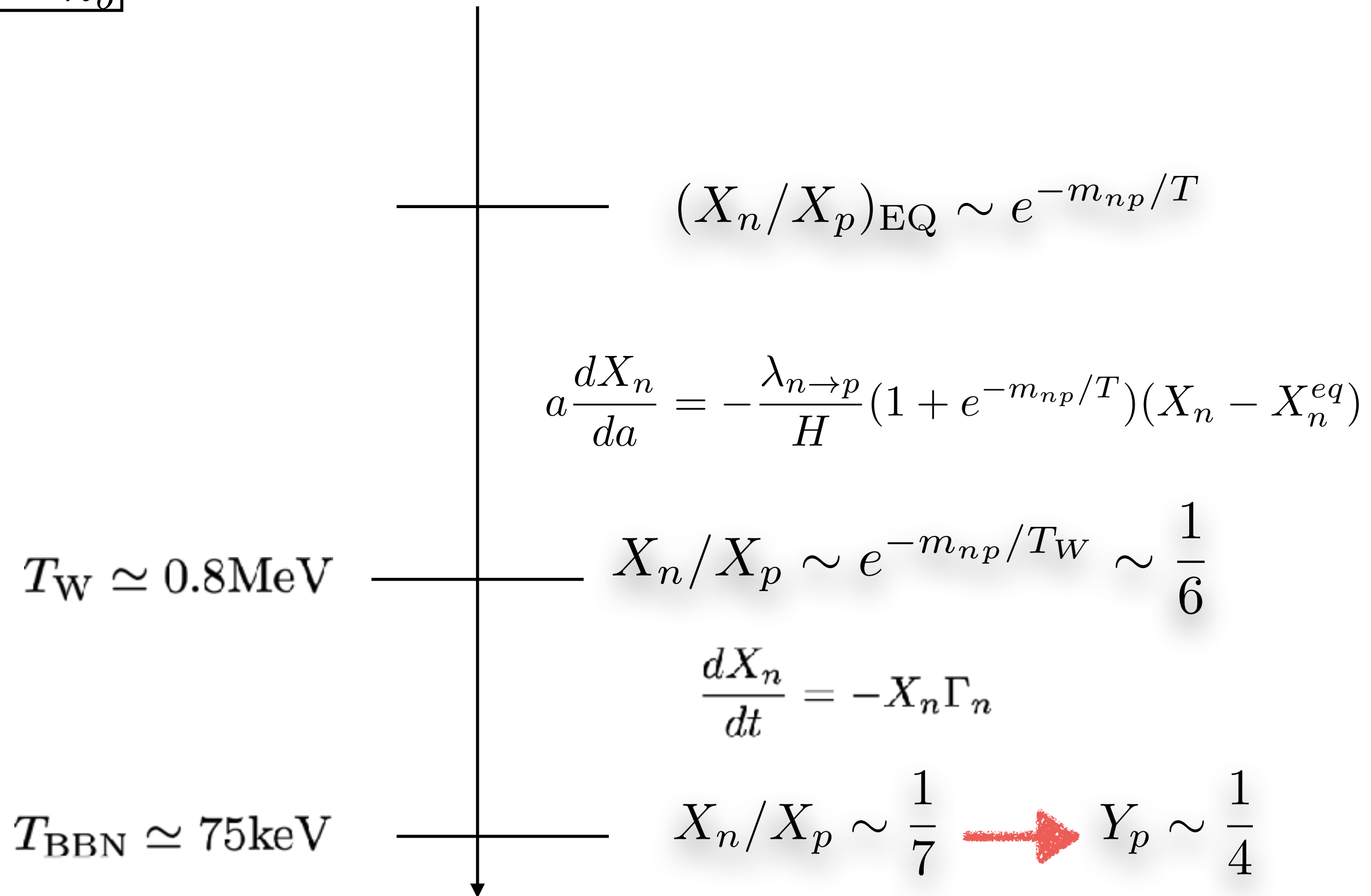
$$\theta_s = \frac{r_s(z_*)}{D_A(z_*)}$$

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

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

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

BBN in a Nutshell



4He mass fraction

$$Y_p^{\text{ex}} = 0.245 \pm 0.003 \quad \sim 10^{-2}$$

BBN: Helium-4

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

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

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

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

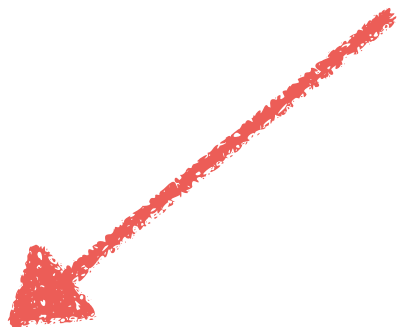
$$\frac{\Delta m_{np}}{m_{np}} \sim 18 \frac{\phi^2}{f_p m_p}$$

BBN: Helium-4

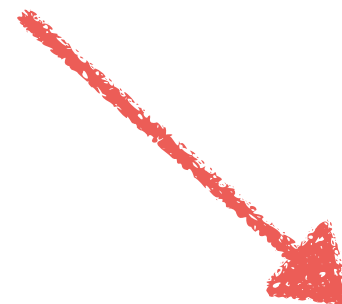
$$-\frac{\phi^2}{\Lambda^2} \left(\frac{\beta_3}{2g_3} G_{\mu\nu}^A G^{A\mu\nu} + \sum_i \gamma_{m_i} m_i \bar{\psi}_i \psi_i \right)$$



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



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



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

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

The modification is suppressed for the same f

BBN Bounds

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

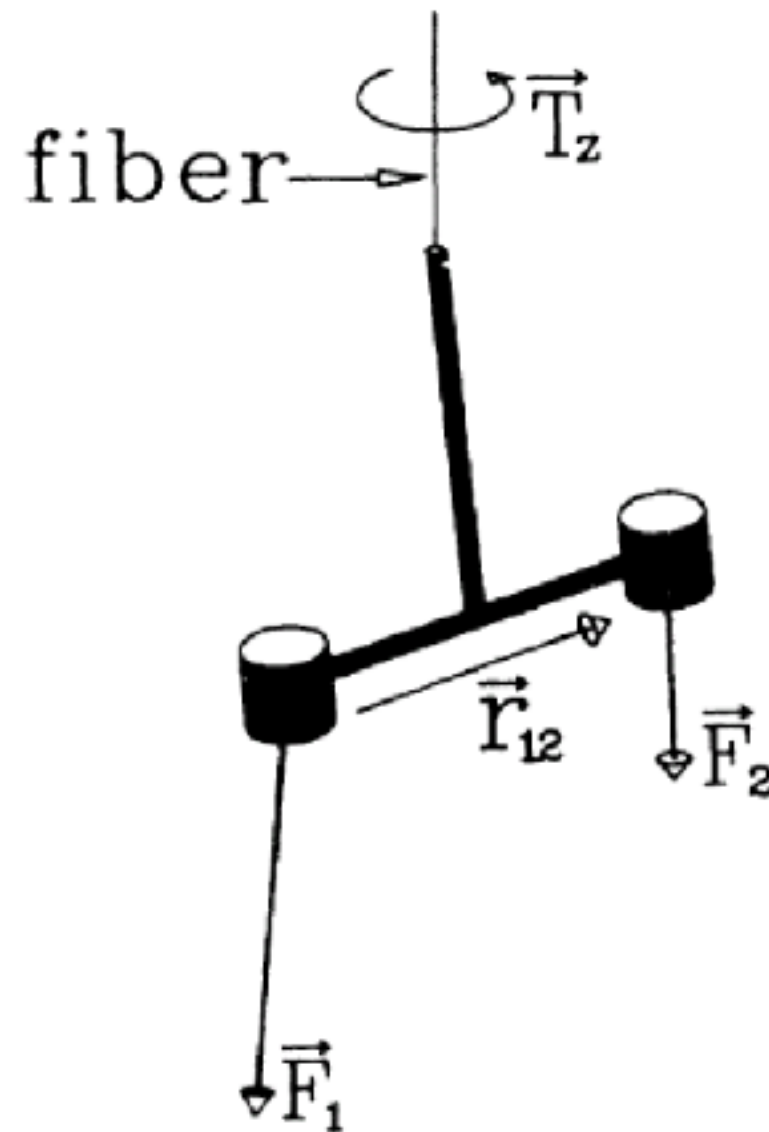
$$\boxed{\frac{\phi_0^2}{\Lambda^2} \sim \frac{2\rho_{\text{DM}}}{m_\phi^2\Lambda^2}}$$



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

$$\frac{1}{f_p} < 1.9 \times 10^{-2} \text{ GeV}^{-1} \left(\frac{m_\phi}{\text{eV}}\right)^2$$

Possible experiments: Torsion Balance

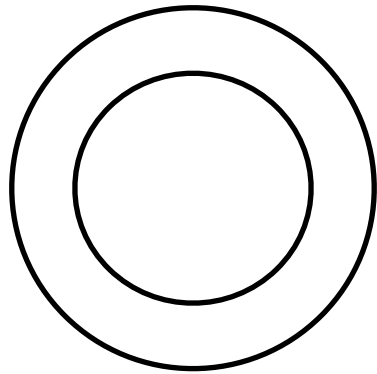


$$T_z = (\mathbf{F}_1 \times \mathbf{F}_2 \cdot \mathbf{r}_{12}) / |\mathbf{F}_1 + \mathbf{F}_2|.$$

Sensitive to the angle
between the two forces

Possible experiments: Torsion Balance

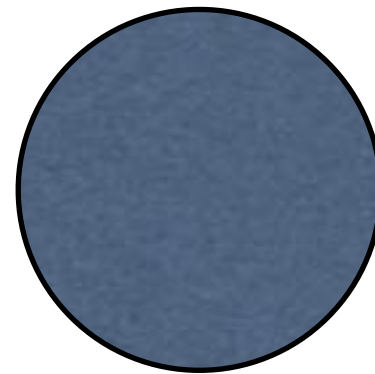
Ti



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

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

Be



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

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

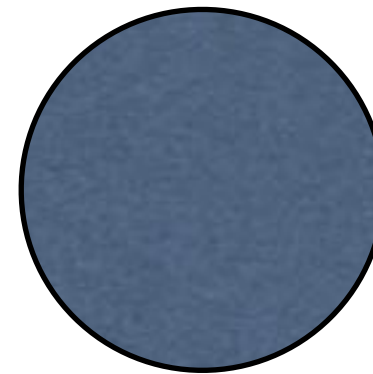
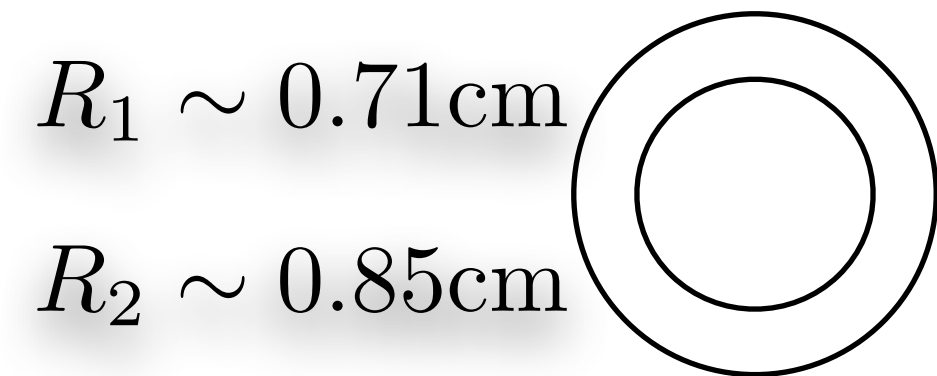
Torsion Balance: Dark Matter

$$4.51\text{g/cm}^3$$

$$1.85\text{g/cm}^3$$

Ti

Be



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

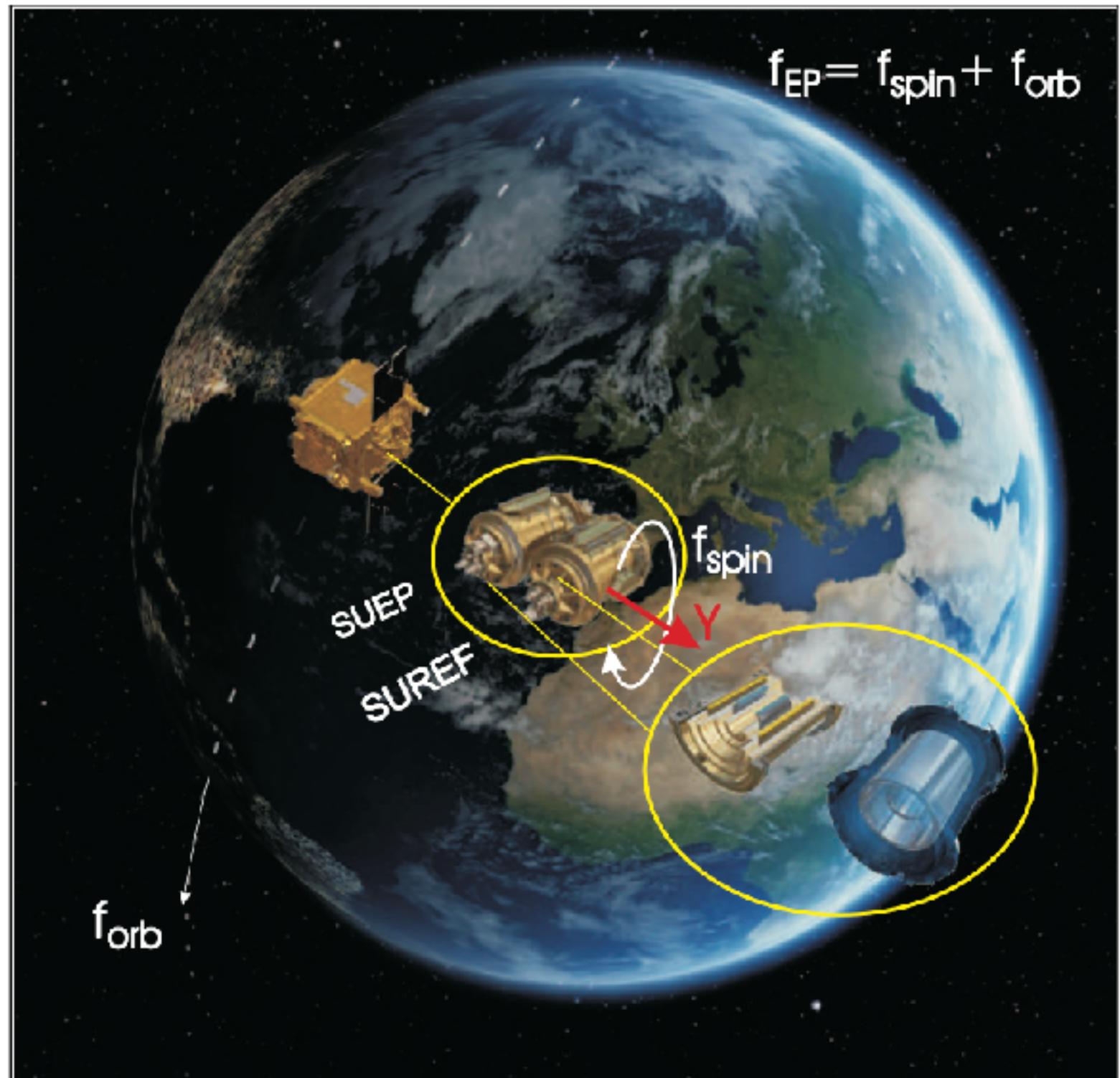
$$\lambda_{sd}^{\text{Ti}} > 0.14\text{cm}$$

$$\lambda_{sd}^{\text{Be}} < 0.85\text{cm}$$

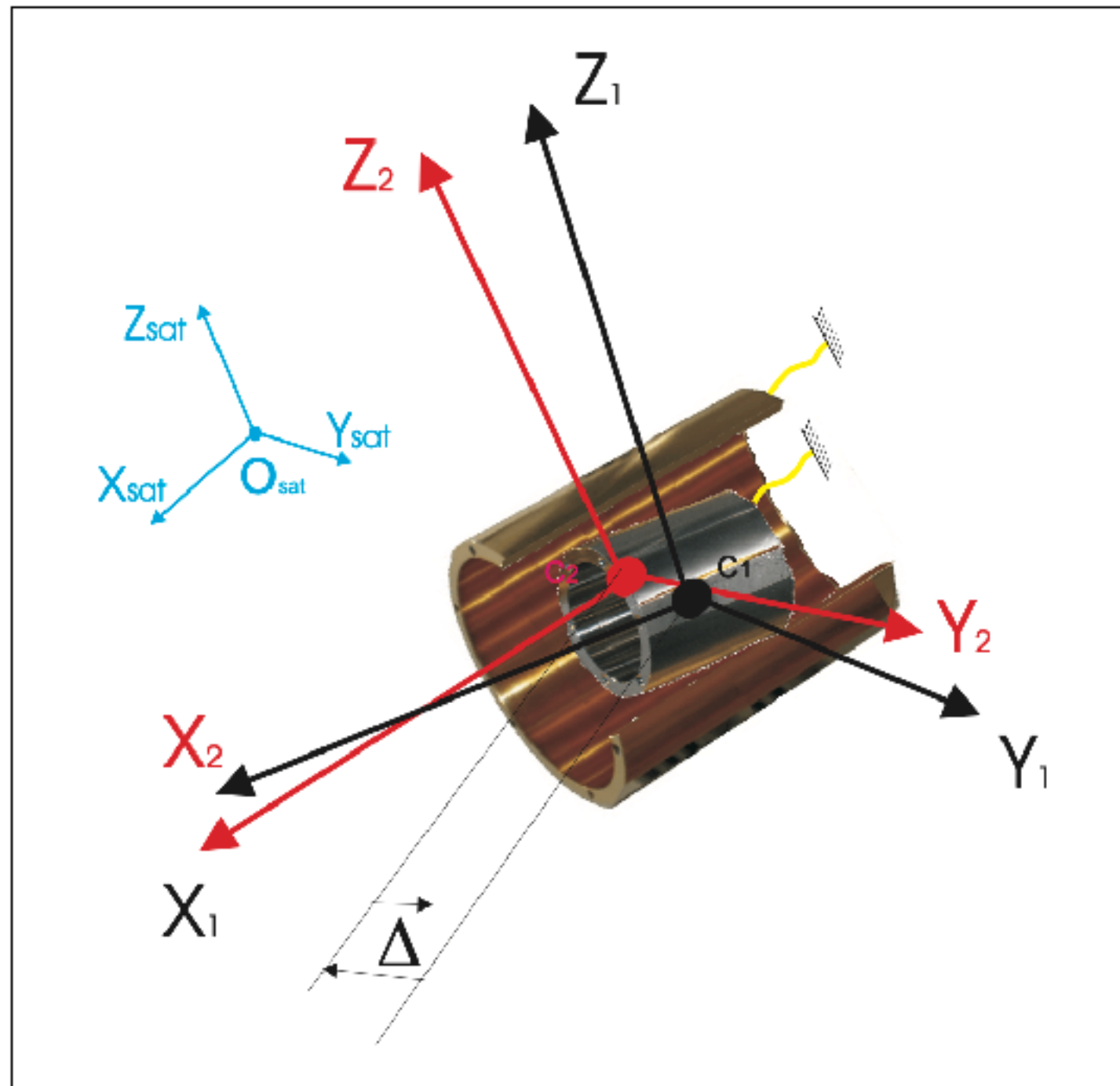
$$1.1 \times 10^9 \text{GeV} < f < 1.6 \times 10^{10} \text{GeV}$$

Possible experiments: Microscope

710km altitude

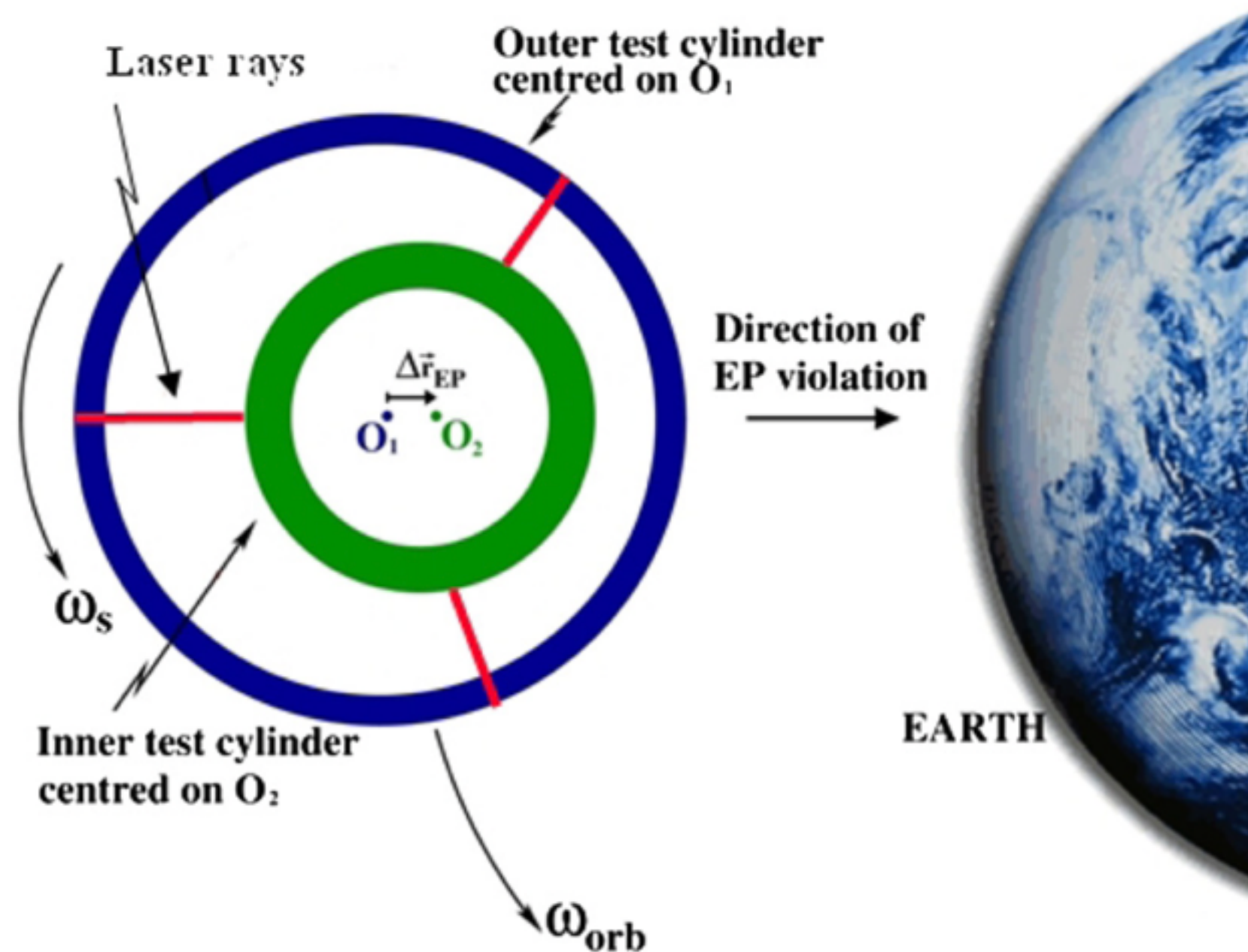


Possible experiments: Microscope



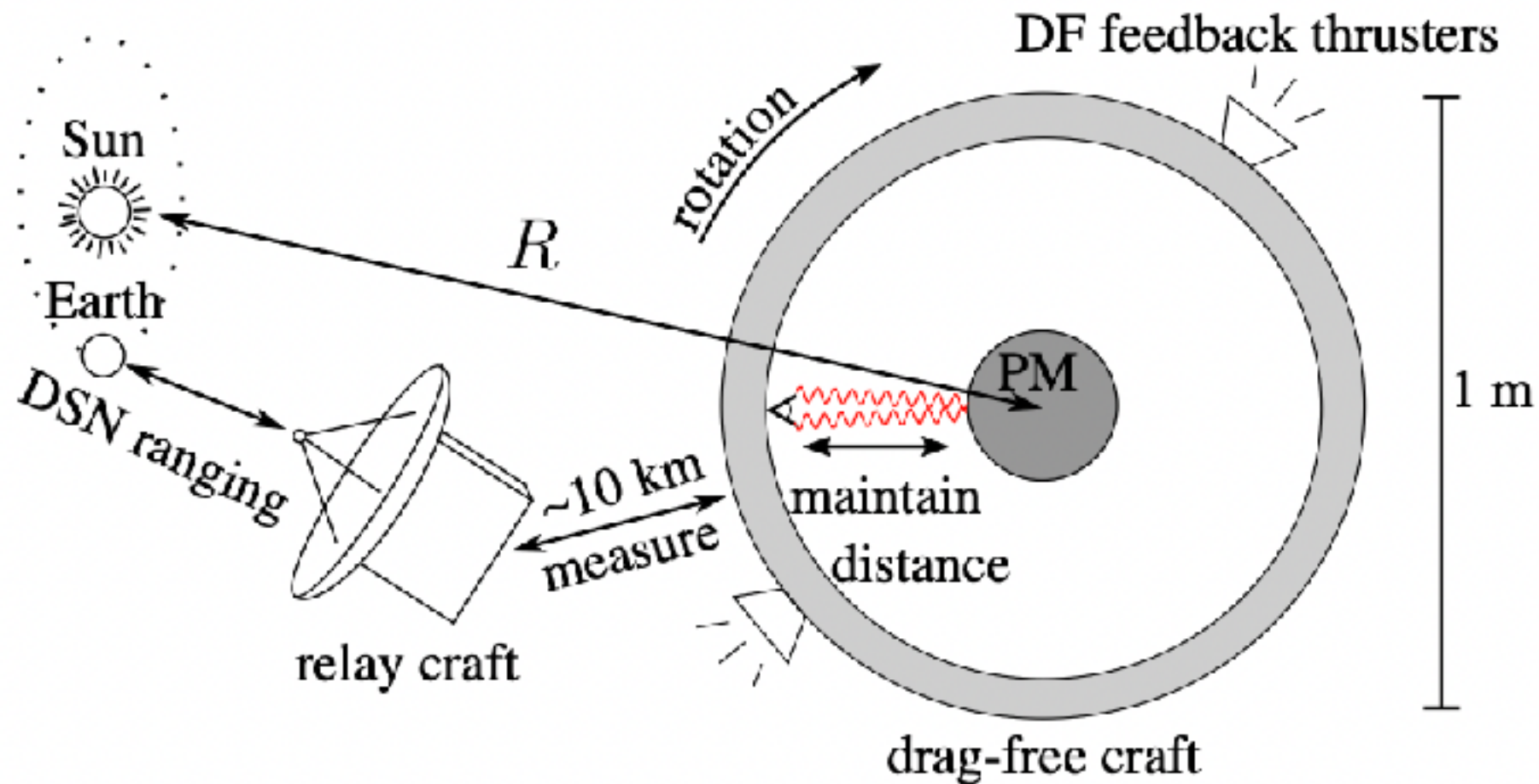
$$\Delta a = -1.2 \pm 2.2 \times 10^{-14} \text{ m/s}^2$$

Possible experiments: Galileo Galilei



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

Possible experiments: Space Mission

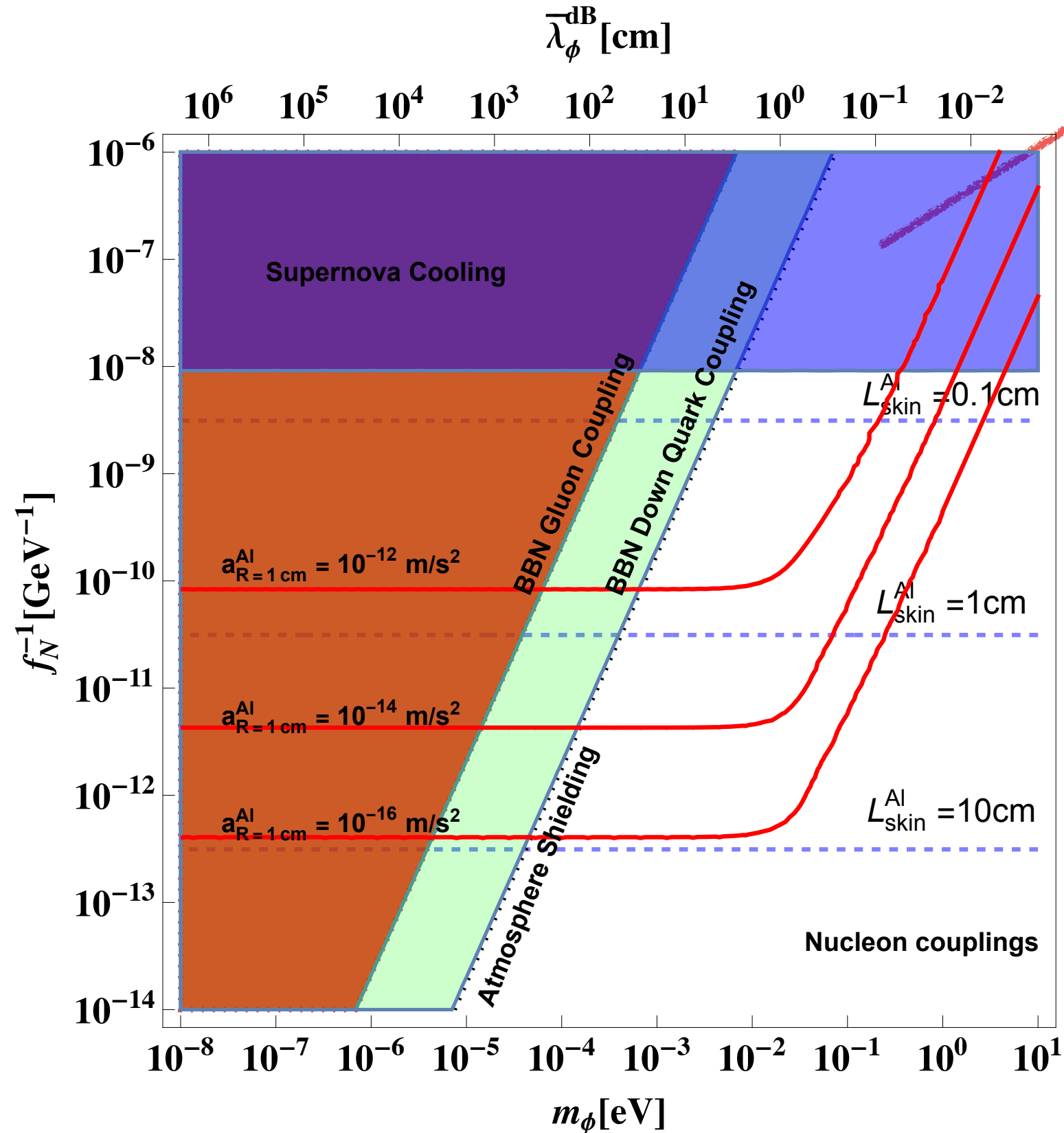


$$\delta a \sim 4.1 \times 10^{-17} \text{ m/s}^2$$

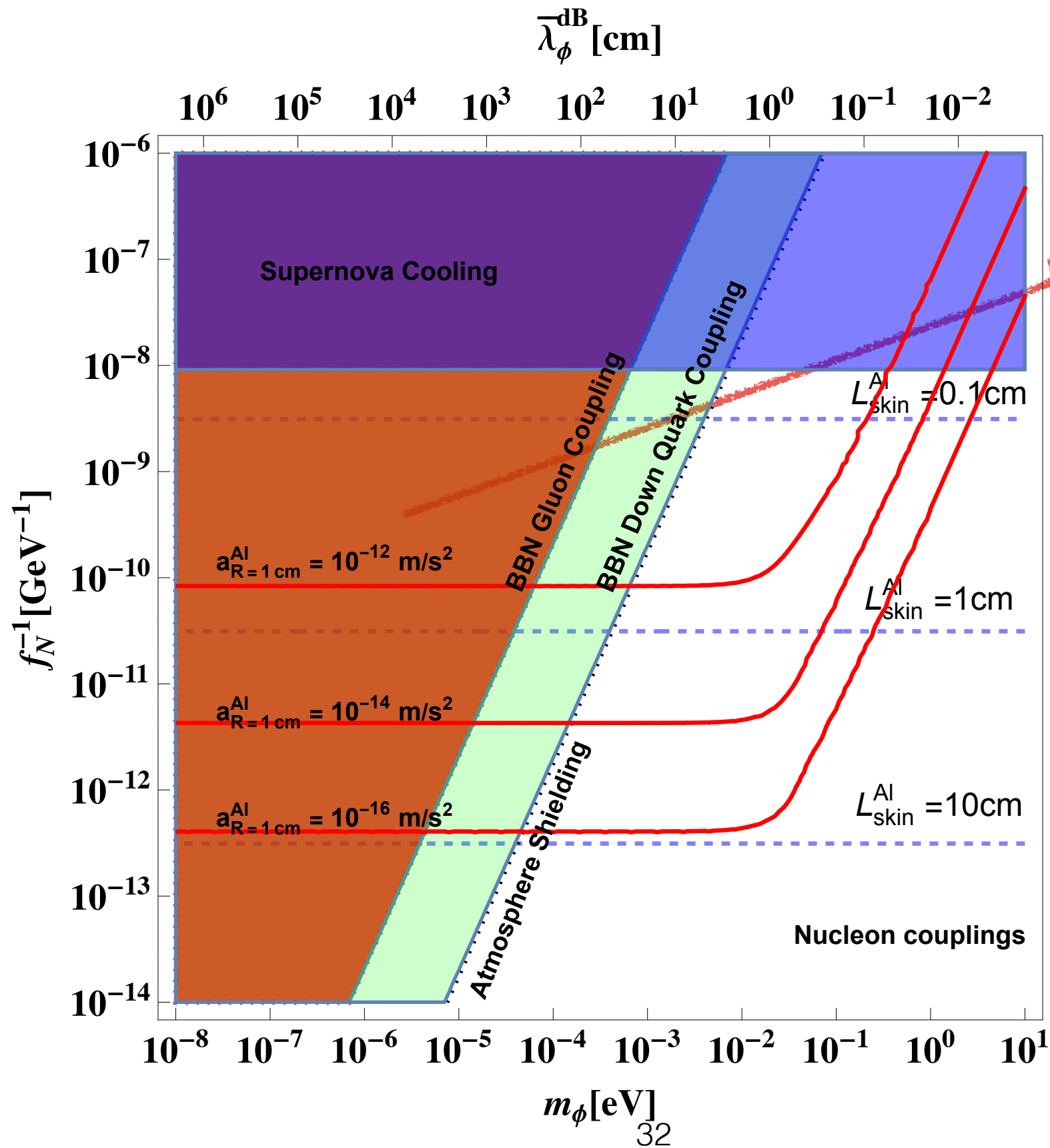
1 meter ranging over 7 years

Summary in One Plot

Supernova Cooling

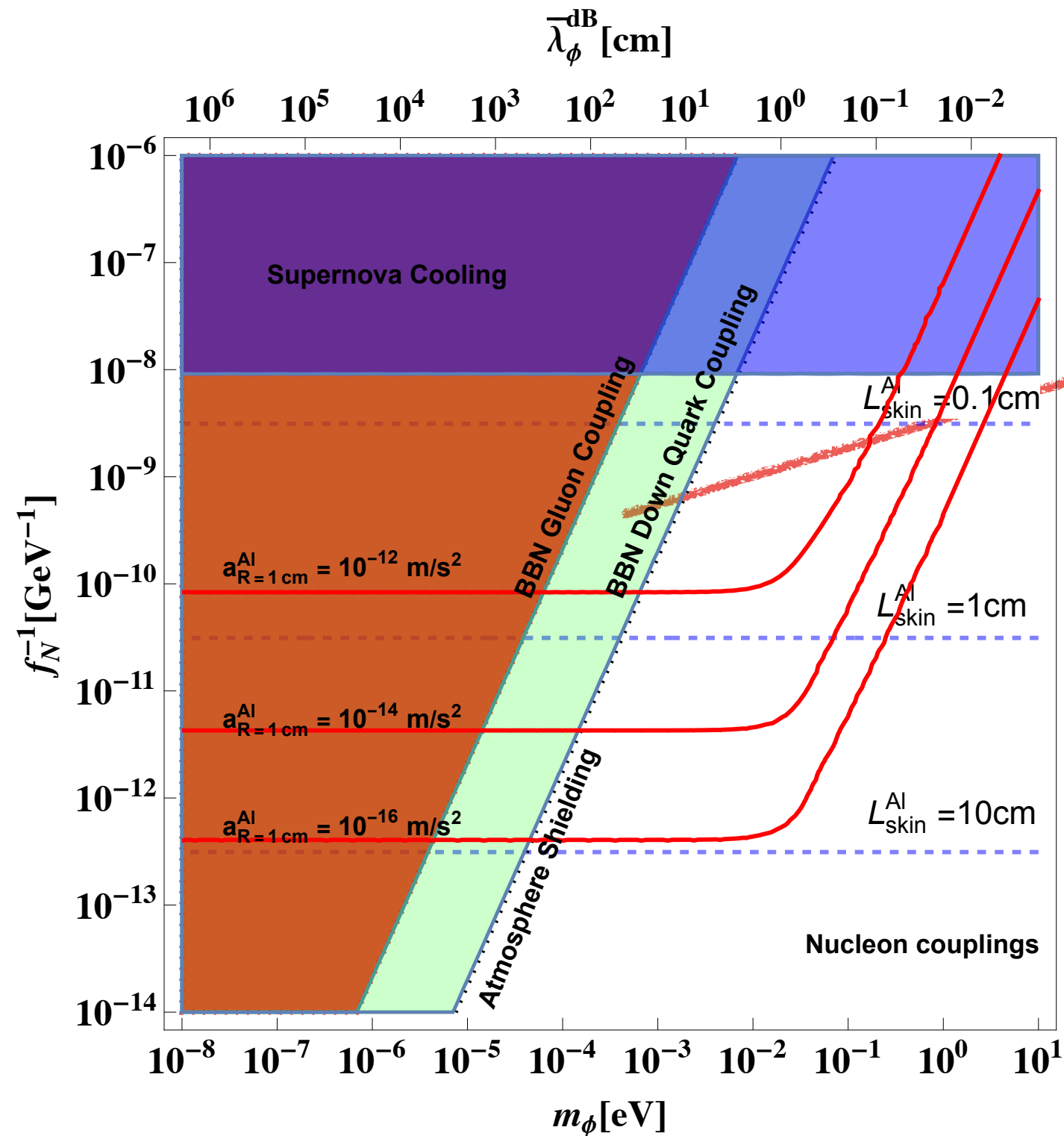


Summary in One Plot

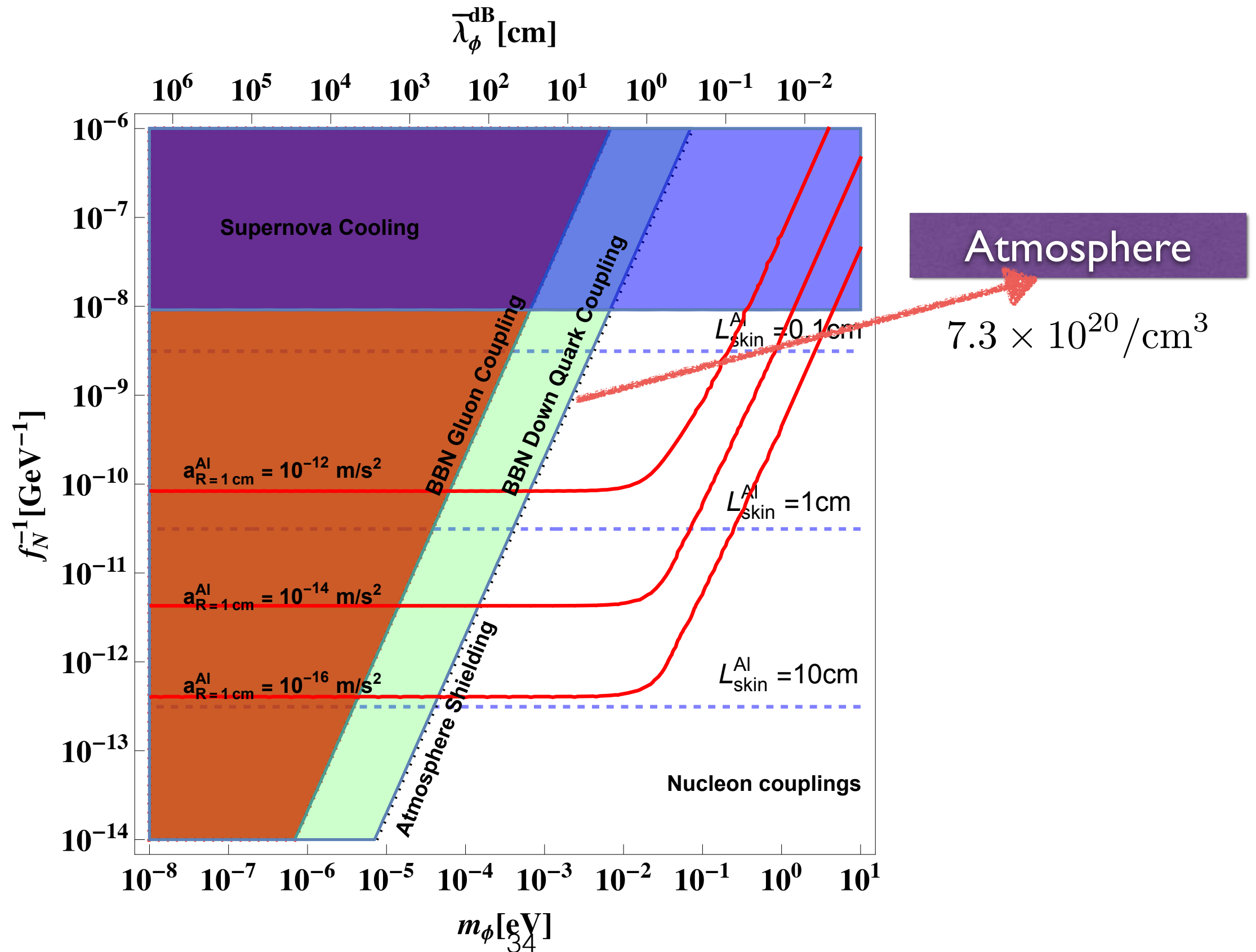


BBN Gluon coupling

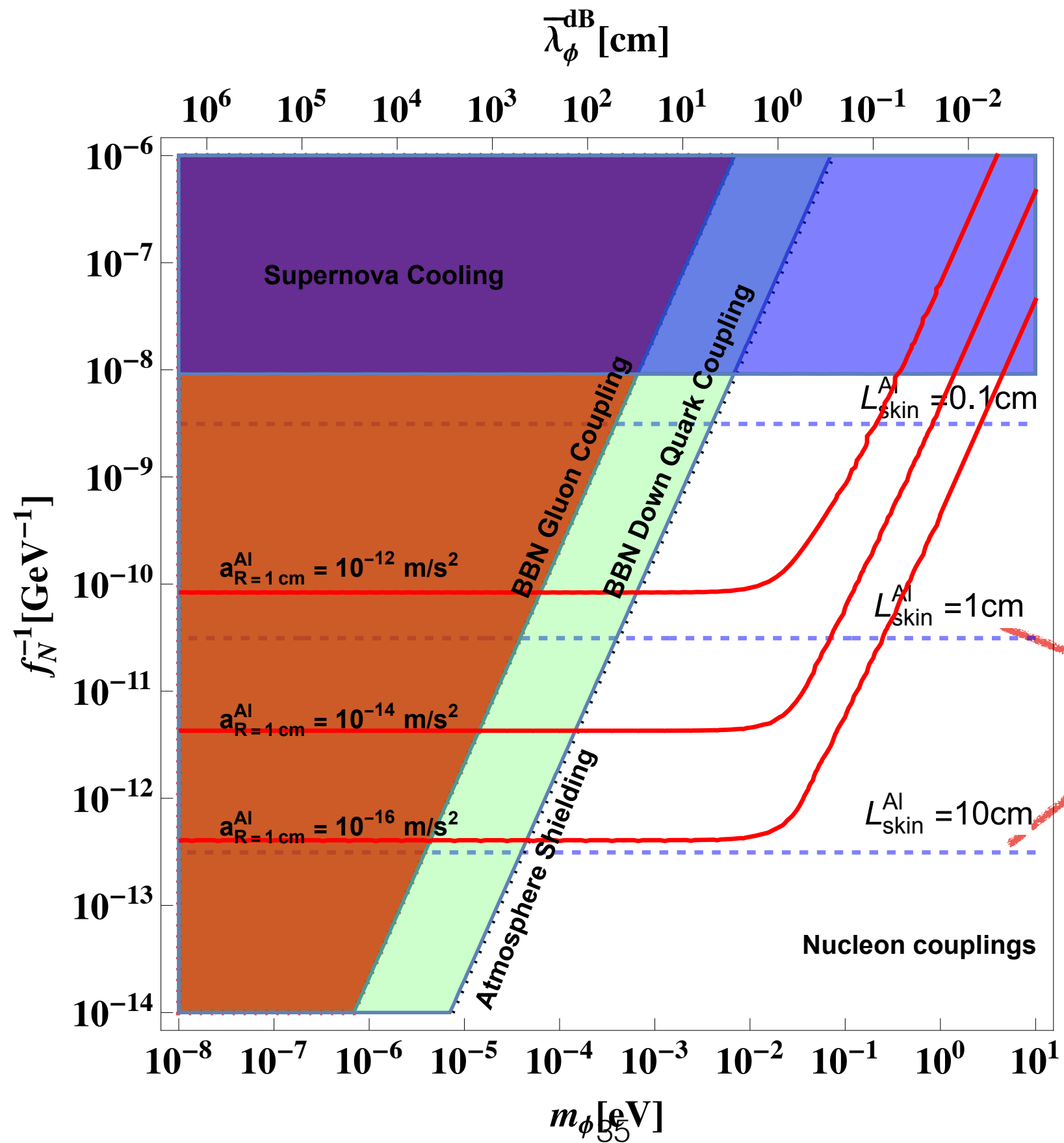
Summary in One Plot



Summary in One Plot

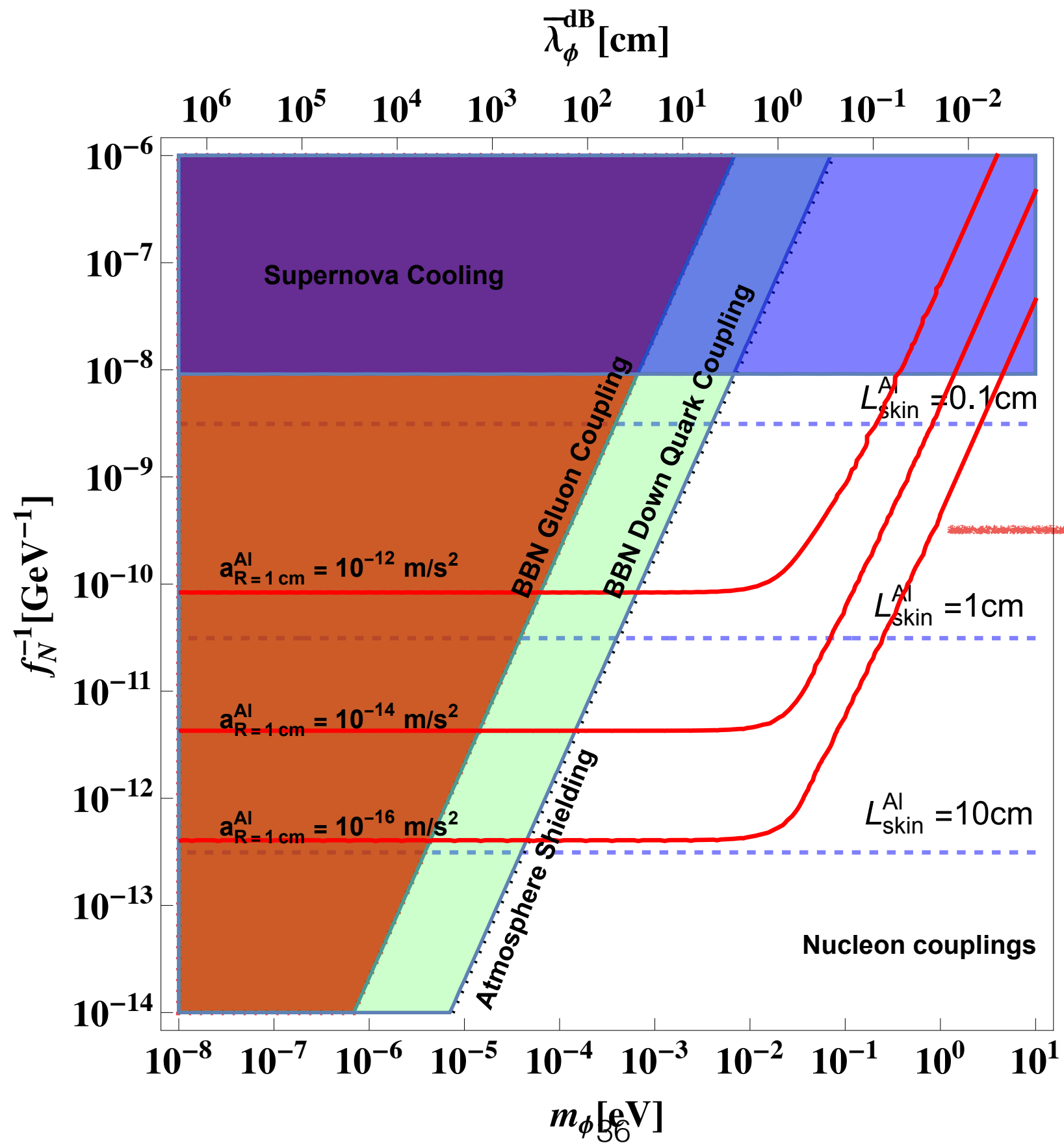


Summary in One Plot



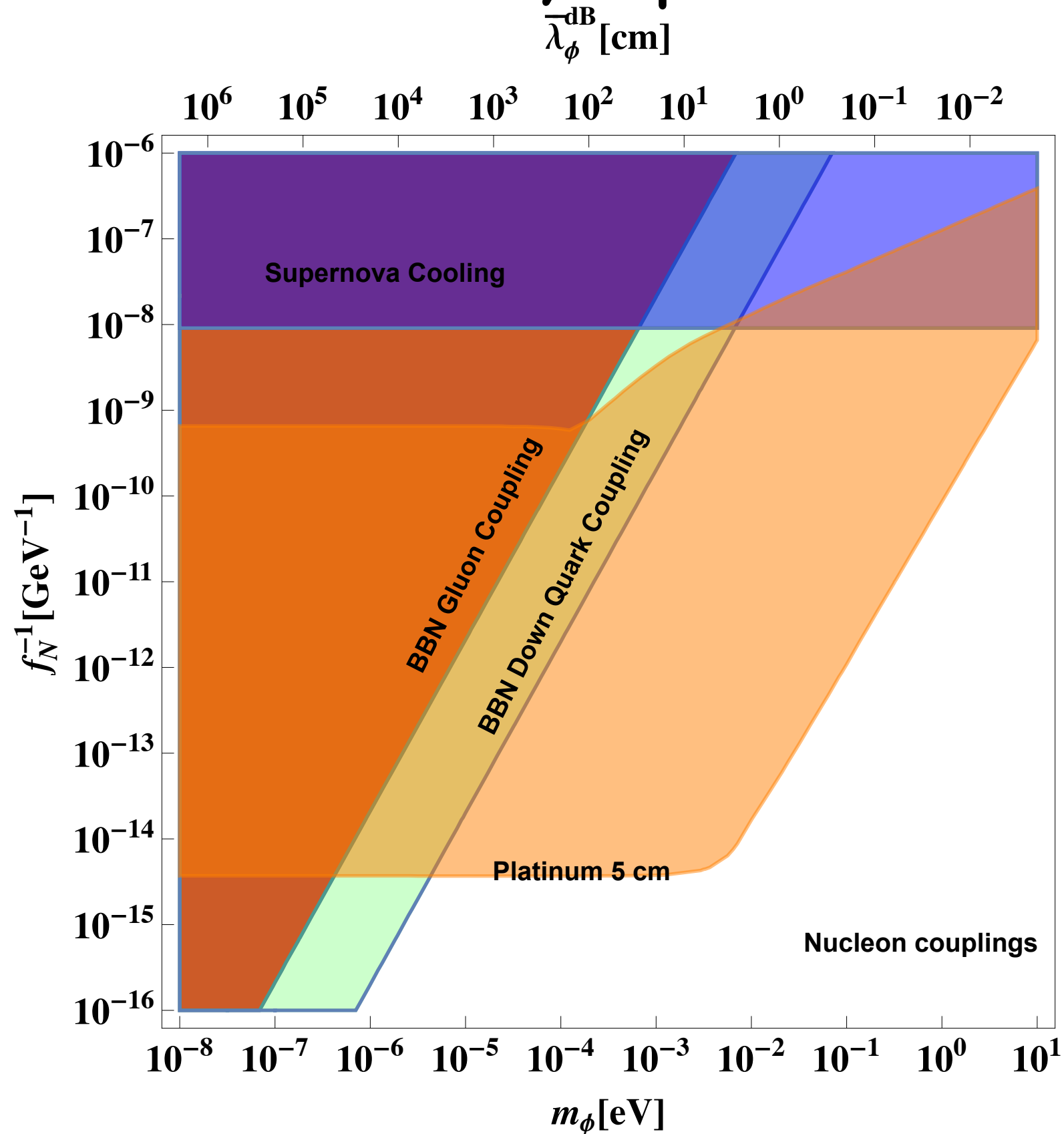
Aluminum
skin depth

Summary in One Plot



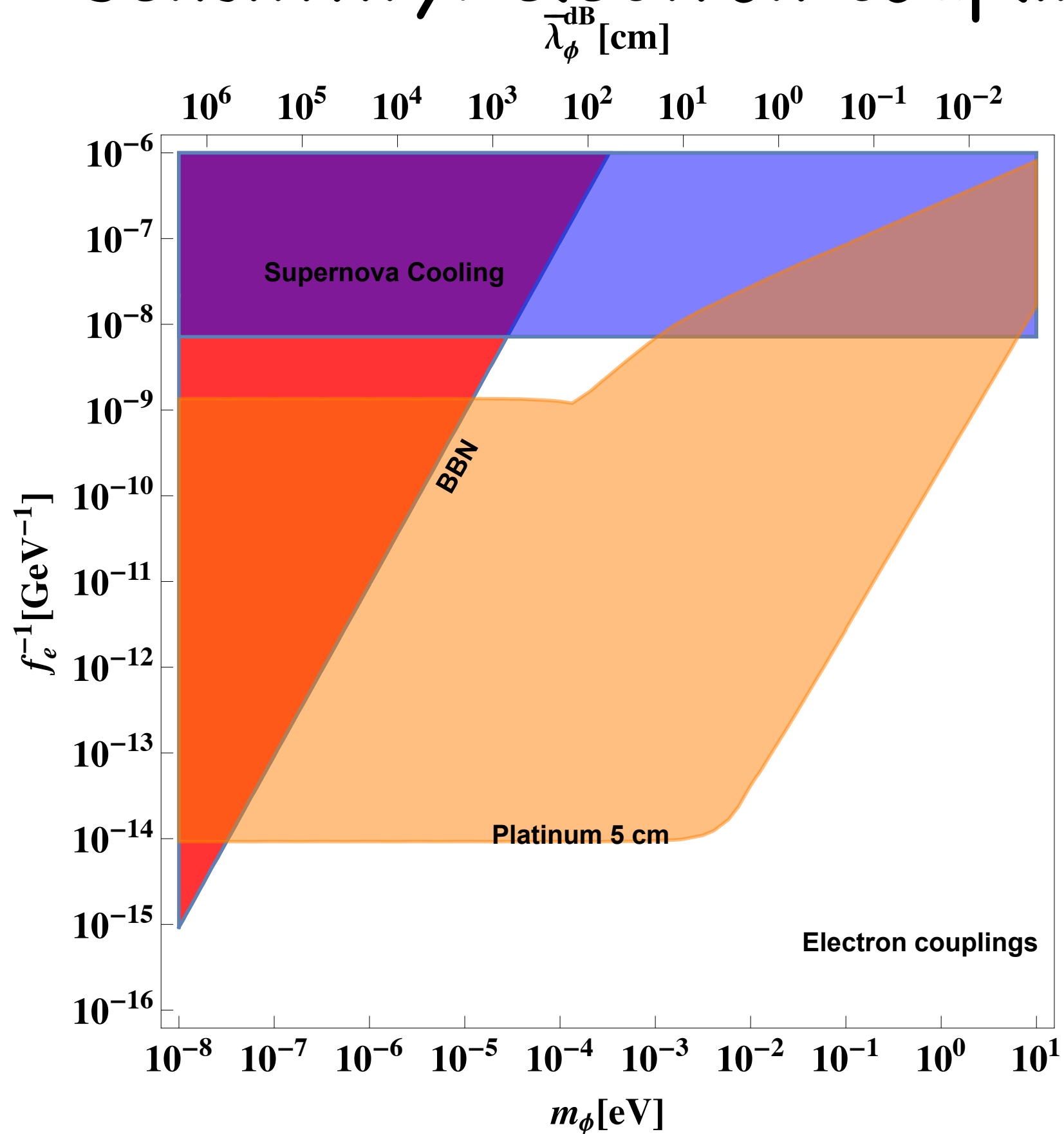
Constant
Acceleration

Sensitivity: Space Mission



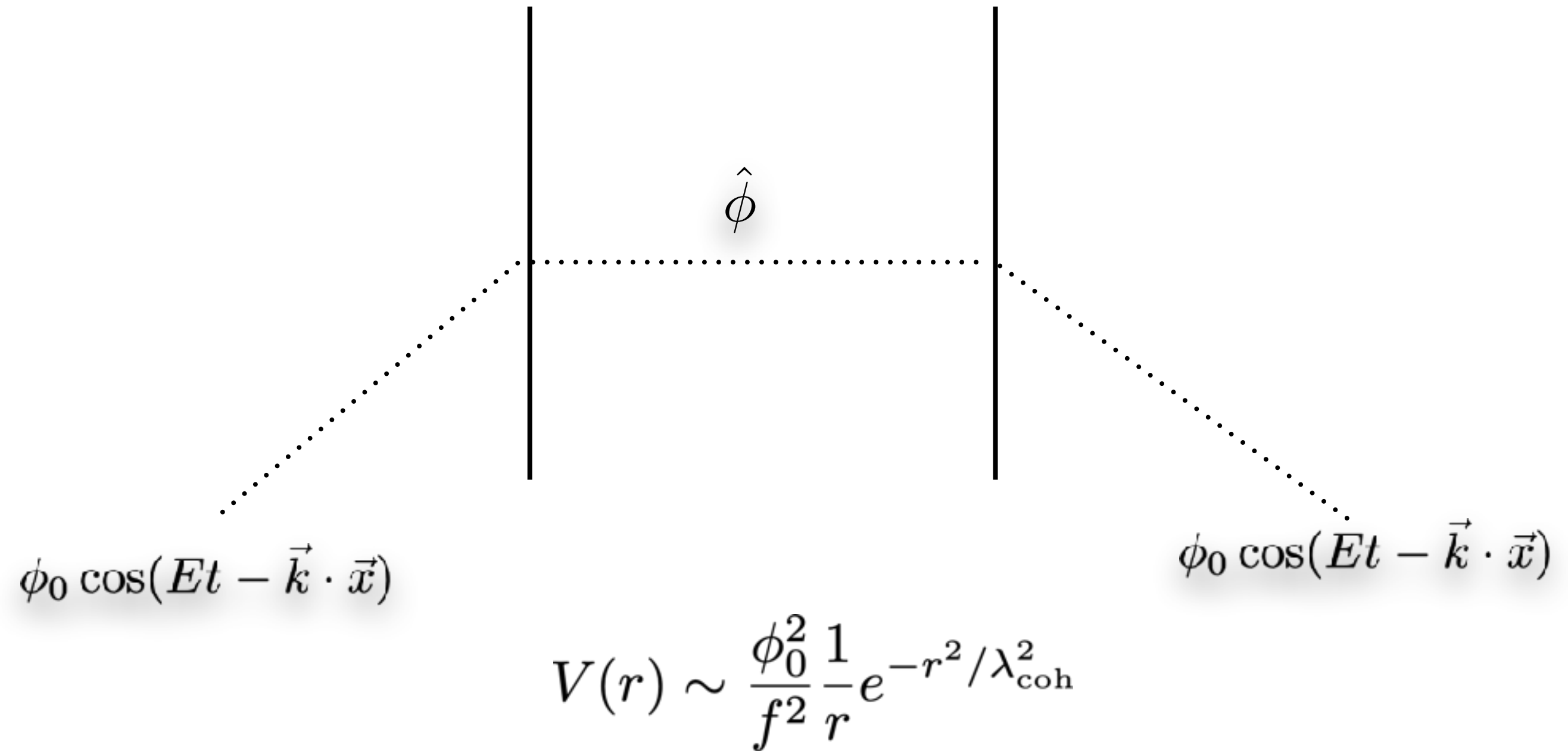
1mm Aluminum shell with radius 1m

Sensitivity: electron coupling



Wake Force

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



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