

# Searching for Ultralight Scalar Dark Matter with Clocks in Low Earth Orbit



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U.S. DEPARTMENT  
*of* ENERGY

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arXiv:2601.16259

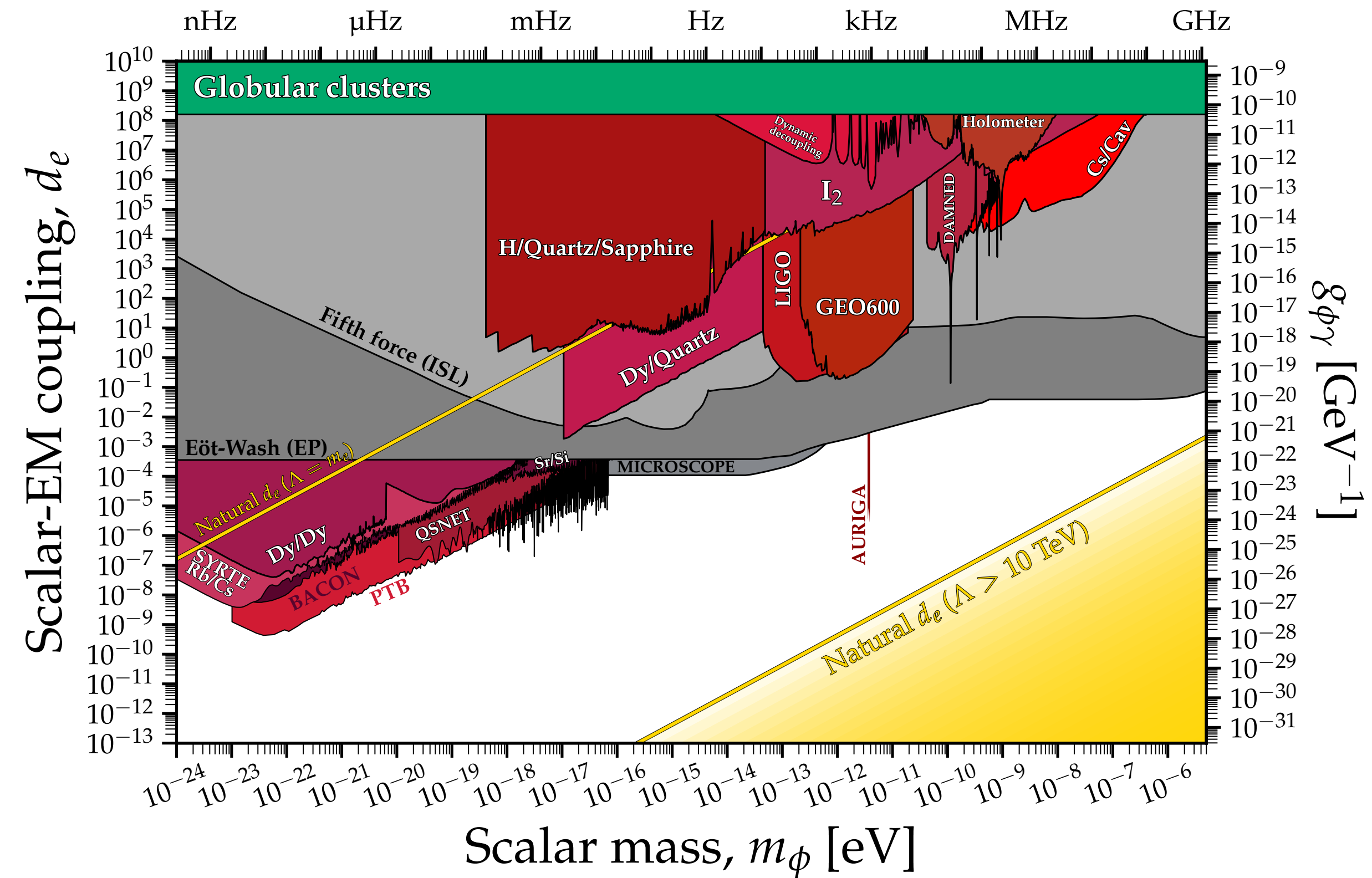
# Why this is interesting

Linear scalar couplings are already tightly constrained by WEP / fifth-force searches

If symmetry suppresses the linear term, quadratic couplings become the leading observable effect

## Key complication

Quadratic couplings make the local field environment-dependent



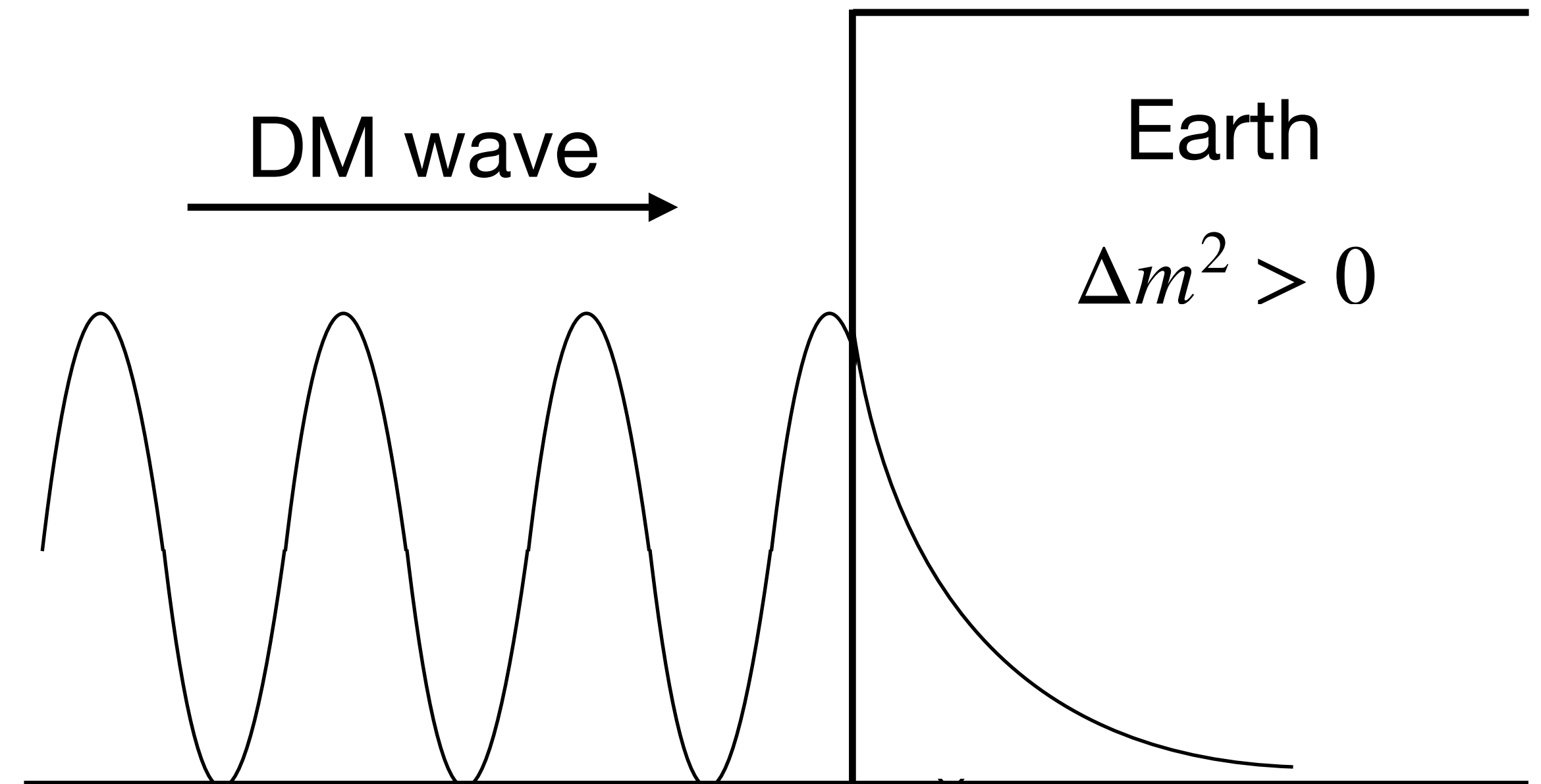
Credit: Ciaran O'Hare

# Quadratically coupled scalars

## Earth backreaction matters

$$\mathcal{L} \supset \frac{\phi^2}{2\Lambda^2} \left( \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \dots \right)$$

$$m_{\text{eff}}^2(\vec{x}) = m_{\text{DM}}^2 + \Delta m^2(\vec{x})$$



### Key point

Setting experimental limits requires understanding field profile **near** Earth. Location of the experiment **matters**.

# Earth's response depends on the dark matter wavelength

## Long wavelength ( $\lambda_{\text{dB}} \gg R_{\oplus}$ )

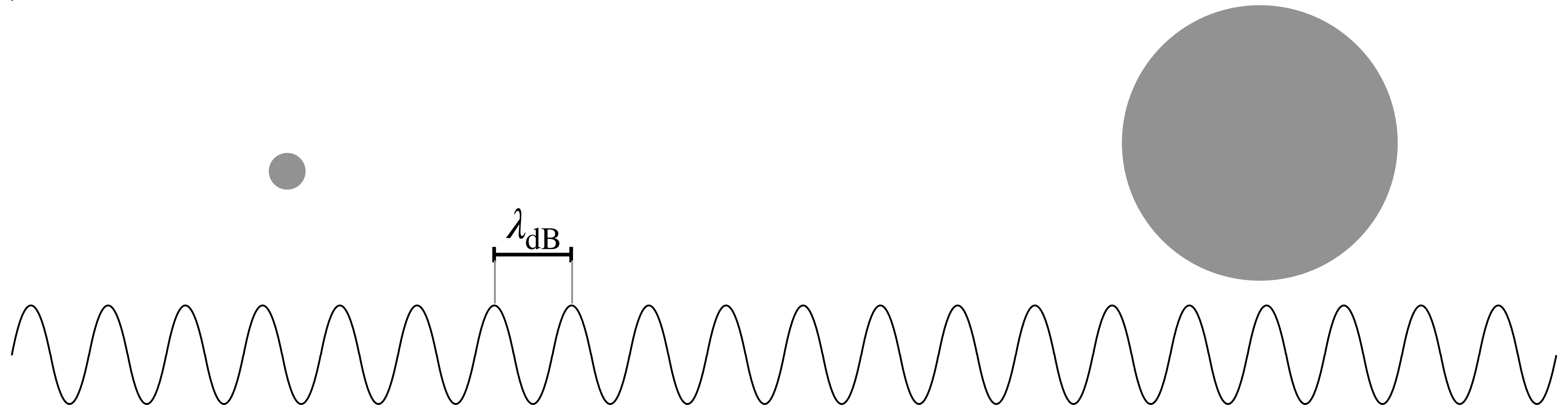
1. Earth is effectively point-like: isotropic response
2. Spherical approximation works
3. Need High Earth Orbit to restore the signal

Spherical treatments: 1807.04512, 2211.05174

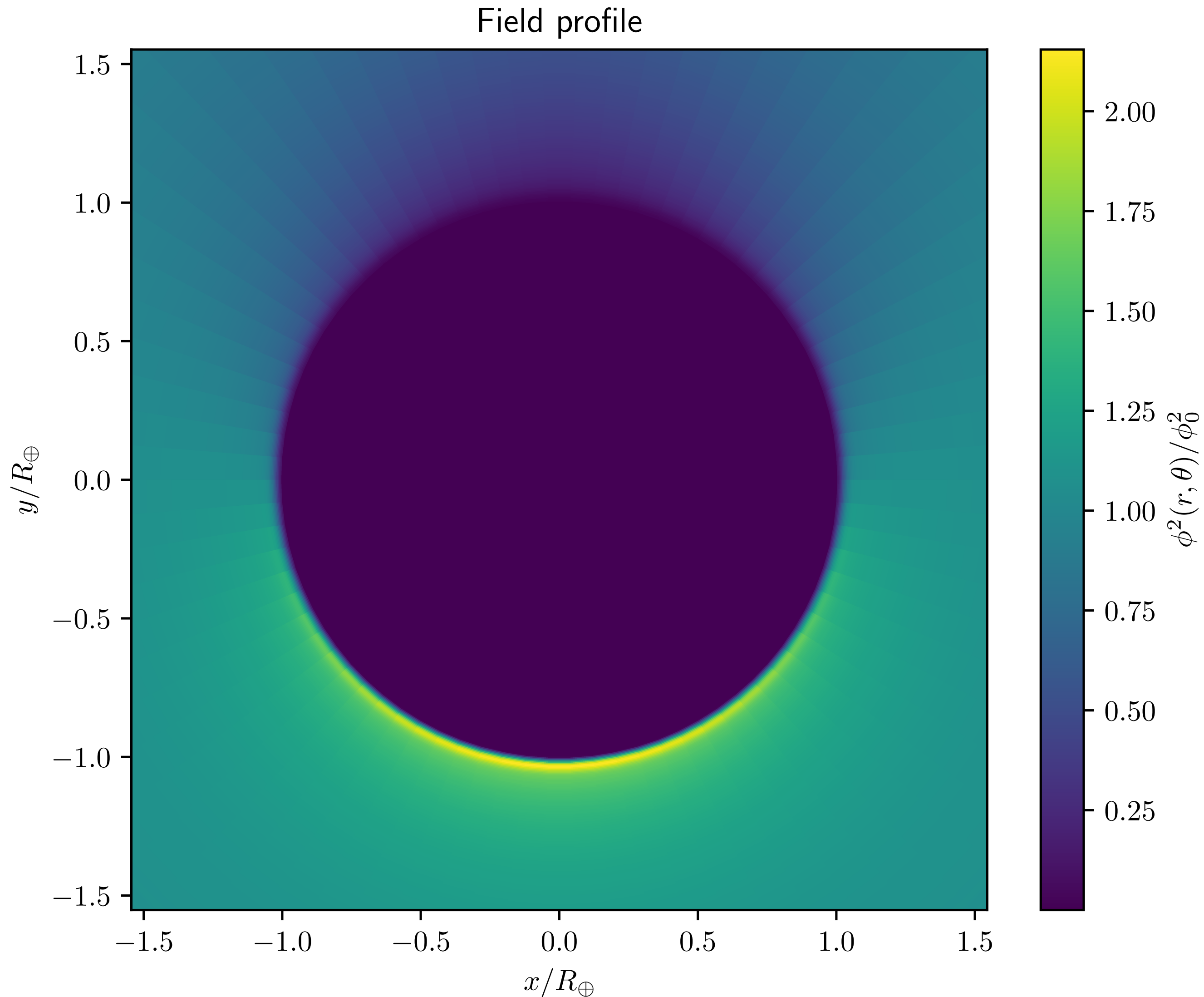
## Short wavelength ( $\lambda_{\text{dB}} \ll R_{\oplus}$ )

1. Earth resolves the galactic DM wind: direction-dependent profile
2. Spherical approximation fails
3. Need High Earth Orbit to restore the signal?

Directional-force context: 2504.11522



# In the short-wavelength regime the field is directional, not spherical



## Short wavelength regime:

Earth resolves the DM wind  $\rightarrow$  shadow + enhancement

## Our contribution:

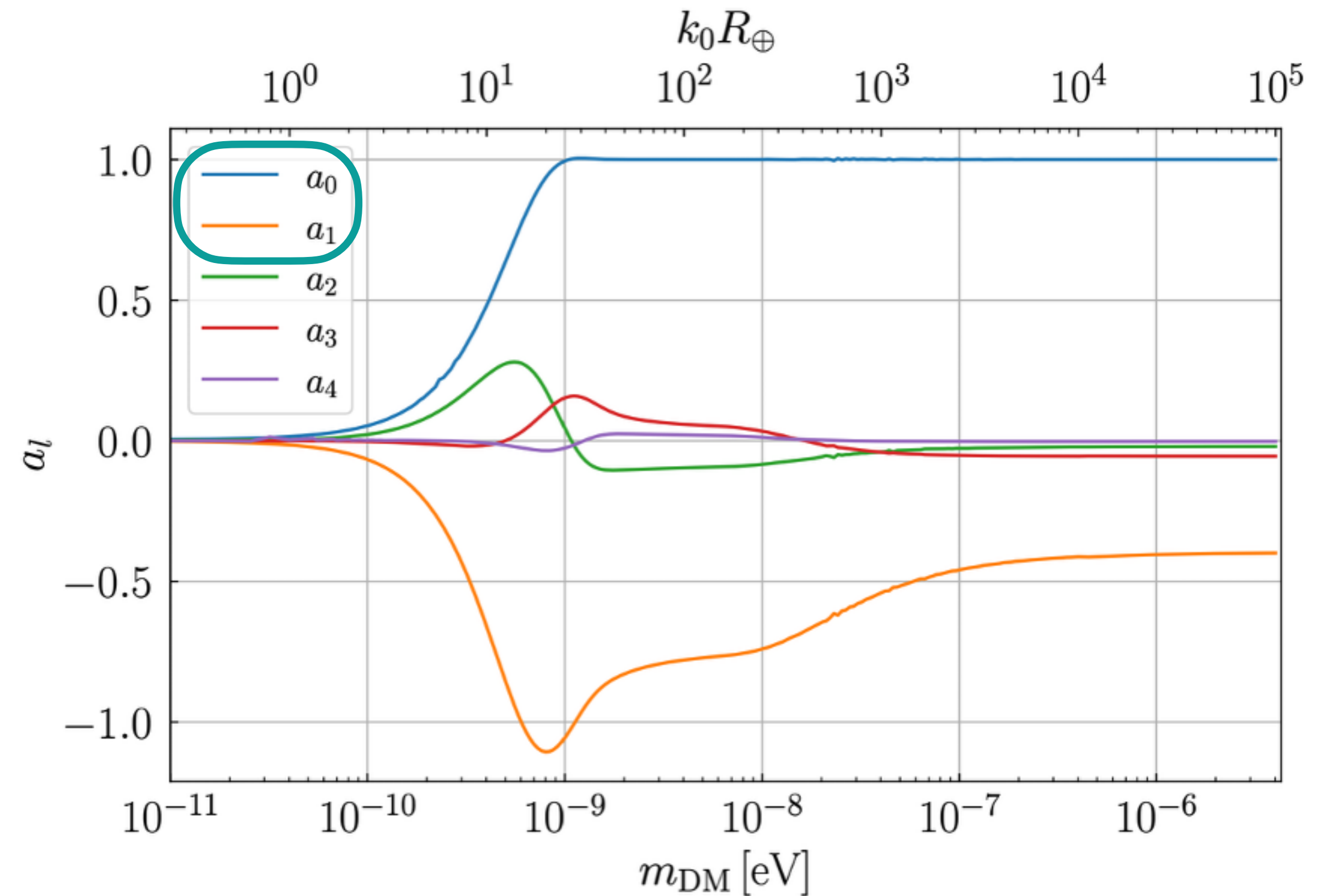
Full angular profile, organized by multipoles

# Monopole + dipole capture the physics

We organize the angular profile via a multipole expansion

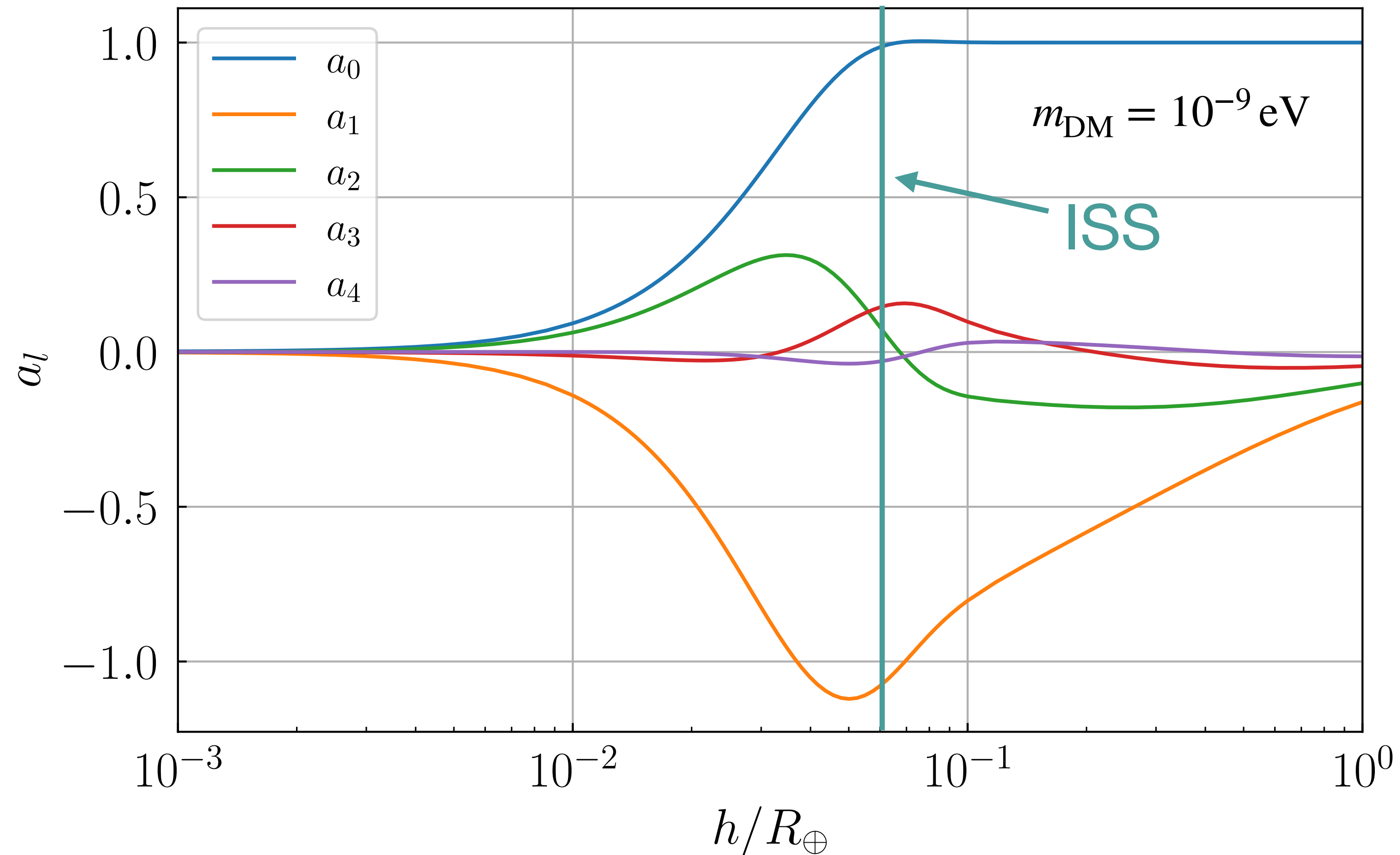
$$\phi^2(\vec{x}) \propto a_0(h, m_{\text{DM}}) P_0(\cos \theta) + a_1(h, m_{\text{DM}}) P_1(\cos \theta) + \dots$$

- $a_0$ : orbit-averaged field value
- $a_1$ : directional modulation from the DM wind
- Higher multipoles are subleading for the clocks signal shown here



# LEO is the sweet spot

restored signal + strong modulation



1.  $a_0$  **restored**: average field near halo value
2.  $a_1$  **large**: directional modulation survives
3. **Higher orbit**: no monopole gain, weaker dipole

# What clocks can actually measure?

$$\frac{\Delta f}{f} = K_X \frac{\Delta X}{X} \quad \frac{\Delta X}{X} \propto \langle \phi^2 \rangle$$

## Clocks vs. fifth force experiments

Clocks probe  $\langle \phi^2 \rangle$ . Force experiments probe  $\nabla \langle \phi^2 \rangle$ .

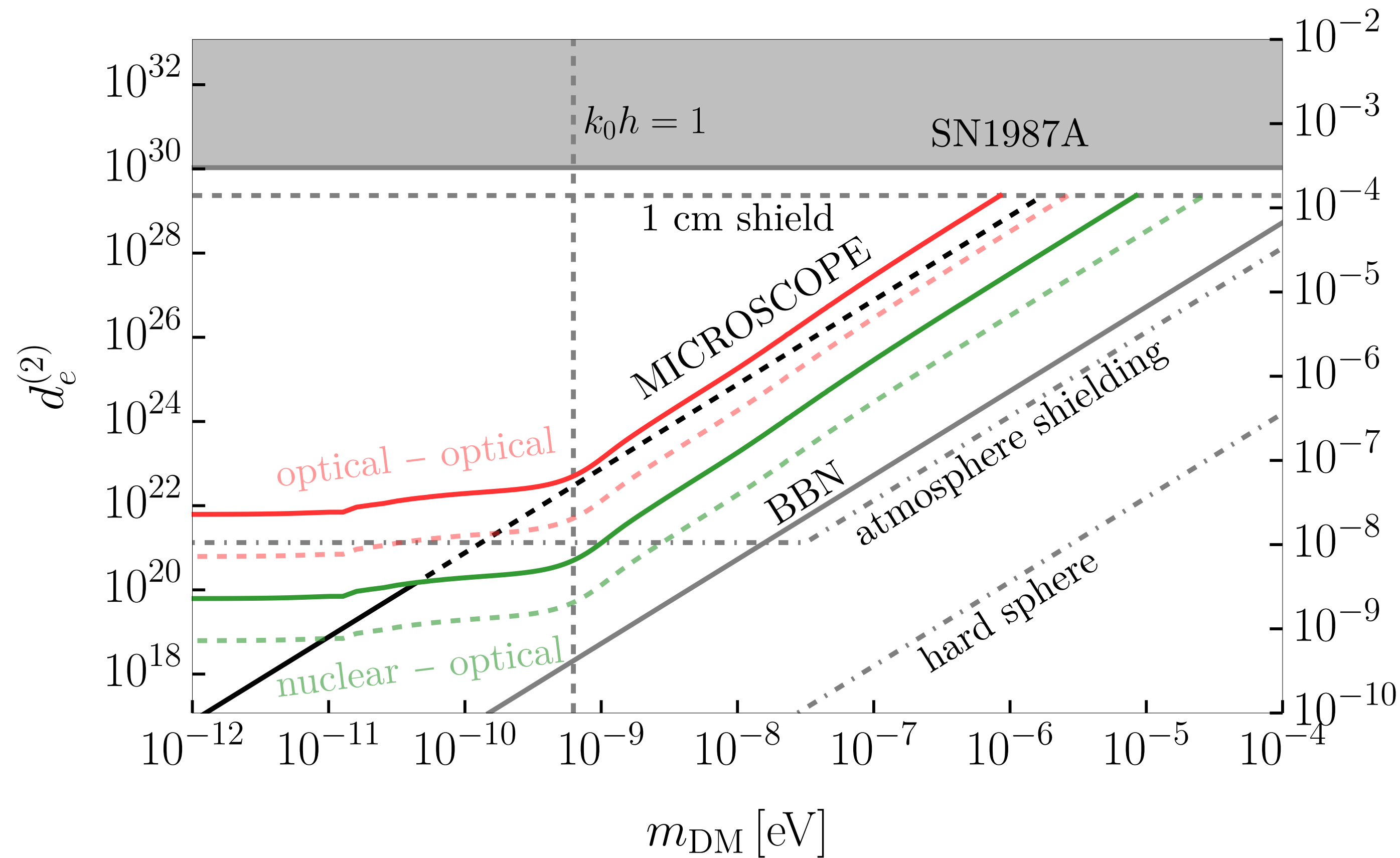
## Space-to-ground

- Space clock vs. **screened** ground clock
- Measures **offset** between space and ground clock
- Probes monopole and dipole

## Co-located space clocks

- Two space clocks with **different**  $K_X$
- Measures **same** field through different sensitivities
- Probes dipole modulation

# Directional modulation enables co-located clock searches



**Signal source**  
Orbital sampling of the dipole  $a_1$

**Observable**  
Modulated frequency ratio of two clocks

**Reach**  
Nuclear-optical pairs can extend beyond MICROSCOPE

# Conclusions

## Main results

- Quadratically coupled scalar DM near Earth is a scattering problem
- At short wavelength, the field is directional rather than spherical
- LEO clocks can exploit both restored signal strength and dipole modulation

## Outlook

- The same profile implies strongly directional forces at high mass
- This motivates refined MICROSCOPE reinterpretation