Influence of Quadratic Axion-Matter Interaction on the Direct Detection of Dark Matter

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1. Introduction

- Axions and gluon-coupled ALPs present the coupling

$$\frac{\phi}{f_a}\frac{g_s^2}{32\pi^2}G^{\mu\nu}\tilde{G}^{\mu\nu}$$

- At low energies, this coupling produces a potential for ALPs that gets modified by **nucleon densities**

$$V(\phi) = -m_\pi^2 f_\pi^2\{(\epsilon - \frac{\sigma_N \rho}{m_\pi^2 f_\pi^2})|\cos(\frac{\phi}{2f_a})| + \mathcal{O}((\frac{\sigma_N \rho}{m_\pi^2 f_\pi^2})^2)\}$$

$\sigma_N = \sum_{q=u,d} m_q \frac{\partial m_N}{\partial m_q} \sim 59 \text{ MeV}$ [Hook, Huang 2017]

- For small values of the field ($f_a \gg \phi$) the effective Lagrangian for ALPs reads

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{2}\phi^2\rho \quad \begin{cases} m^2 = \frac{m_\pi^2 f_\pi^2 \epsilon}{4f_a^2} \\ \lambda = \frac{\sigma_N}{4f_a^2} \end{cases}$$

$$\boxed{\left(\Box + m^2 + \lambda\rho\right)\phi = 0}$$

[Hees et al. 2018,
Balkin et al. 2022,
Banerjee et al. 2023,
Bauer et al. 2024]

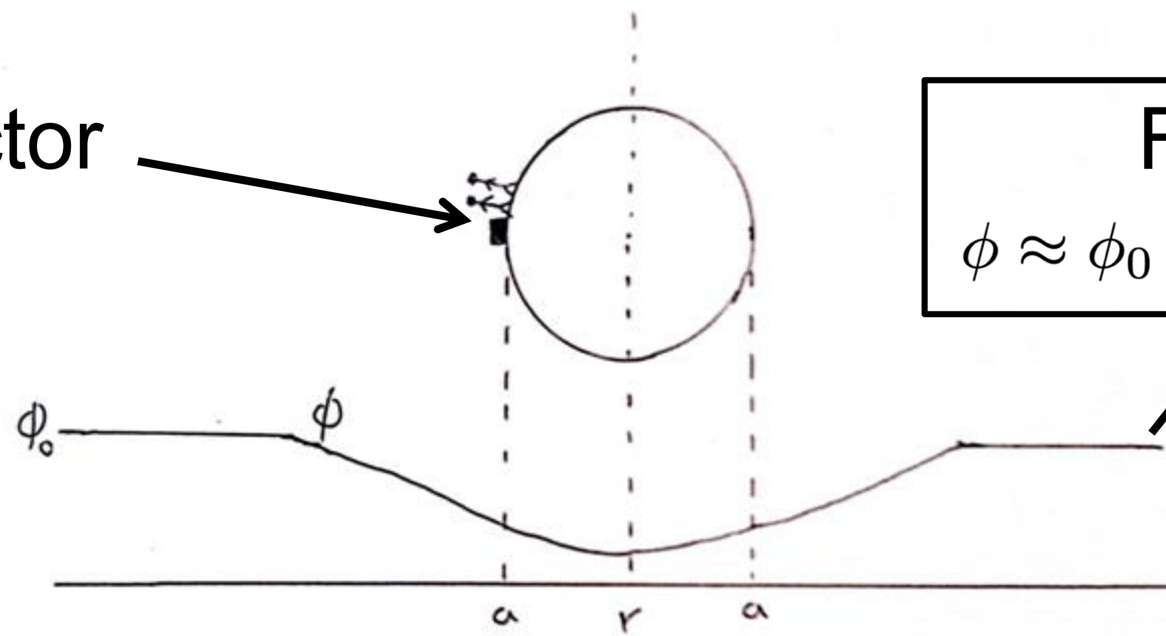
- Interesting phenomenology!
- Matter densities modify the ALP's field distribution.
- Can be generated through other portals.

2. Modification of direct detection sensitivities

- Some experiments aim for interactions that are **proportional to the field** (e.g. CASPEr-Electric ($g_d \phi \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$) or BREAD ($\frac{1}{4} g_{\phi\gamma\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$)).

- Sensitivity estimates with ϕ_0 too naive! ⇨ Earth affects! ⇨ Should be done with $\phi(a)$.

Detector



Far away

$$\phi \approx \phi_0 \cos(\omega t - \vec{k} \cdot \vec{x} + \delta)$$

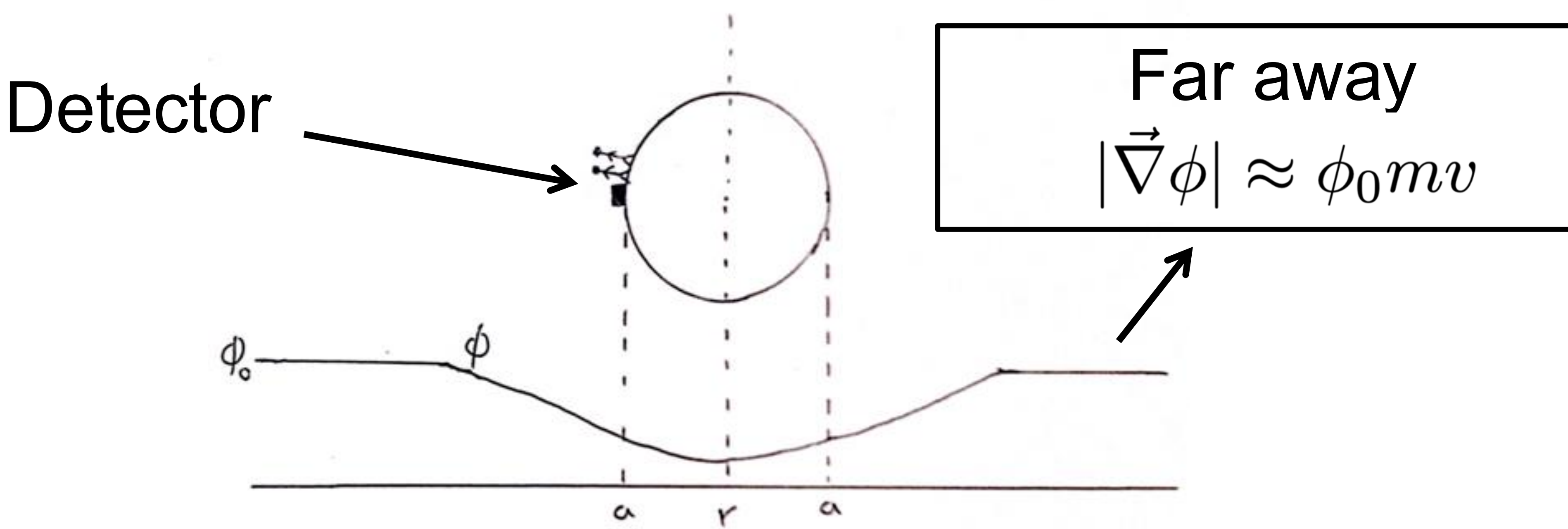
$$\omega \approx m$$

$$|k| = mv \approx m10^{-3}$$

$$\phi_0 = \frac{\sqrt{2\rho_{DM}}}{m}$$

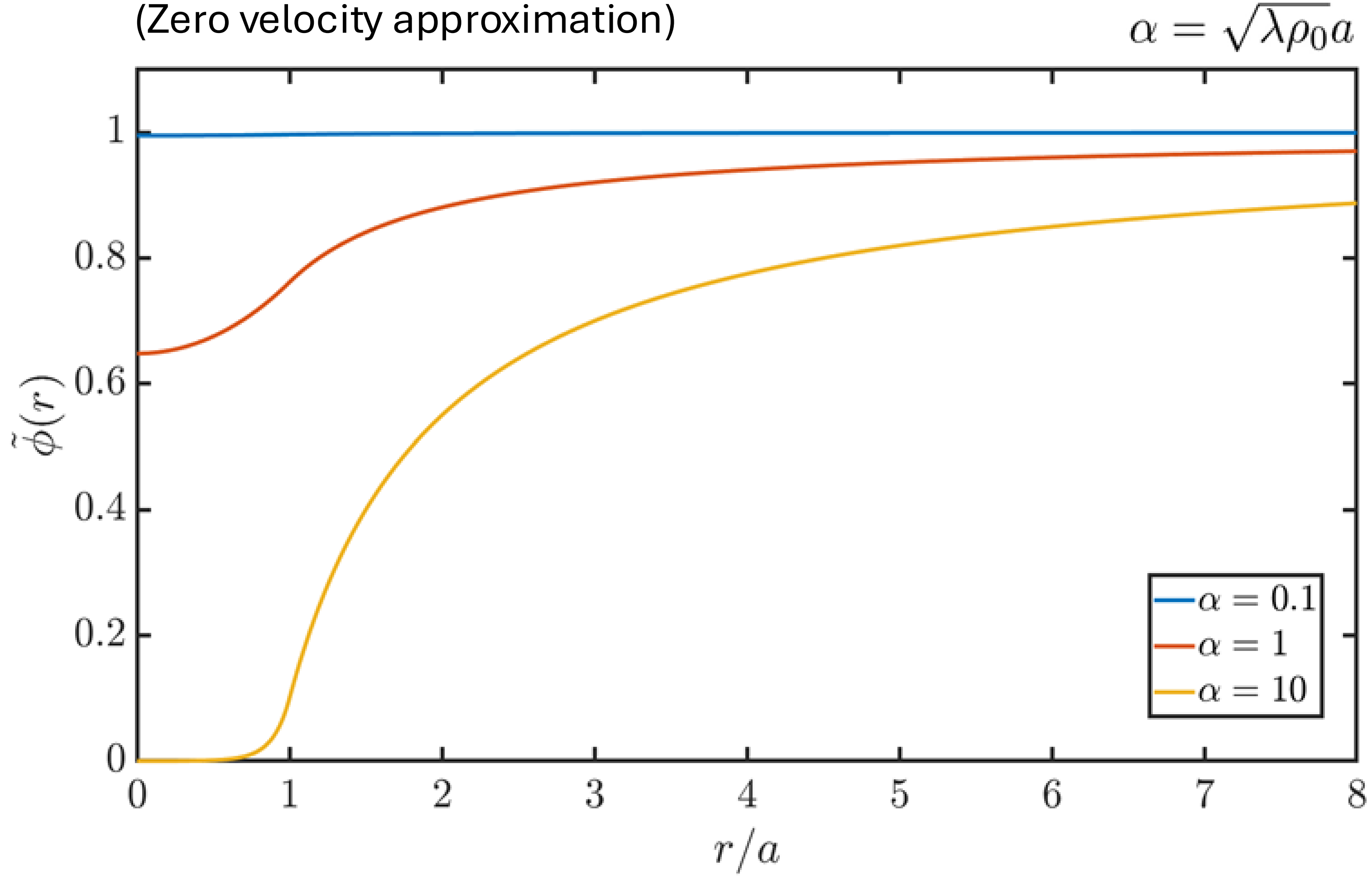
- Other experiments aim for interactions that are **proportional to the field's gradient** (e.g. CASPEr-Wind ($g_{\phi NN}\partial_\mu\phi\bar{N}\gamma^\mu\gamma_5 N$)).

- Sensitivity estimates with $|\vec{\nabla}\phi| \approx \phi_0 m v$ too naive! Earth affects! ⇨ Should be done with $|\vec{\nabla}\phi(a)|$.



3.1 Repulsive case (λ>0)

(Zero velocity approximation)



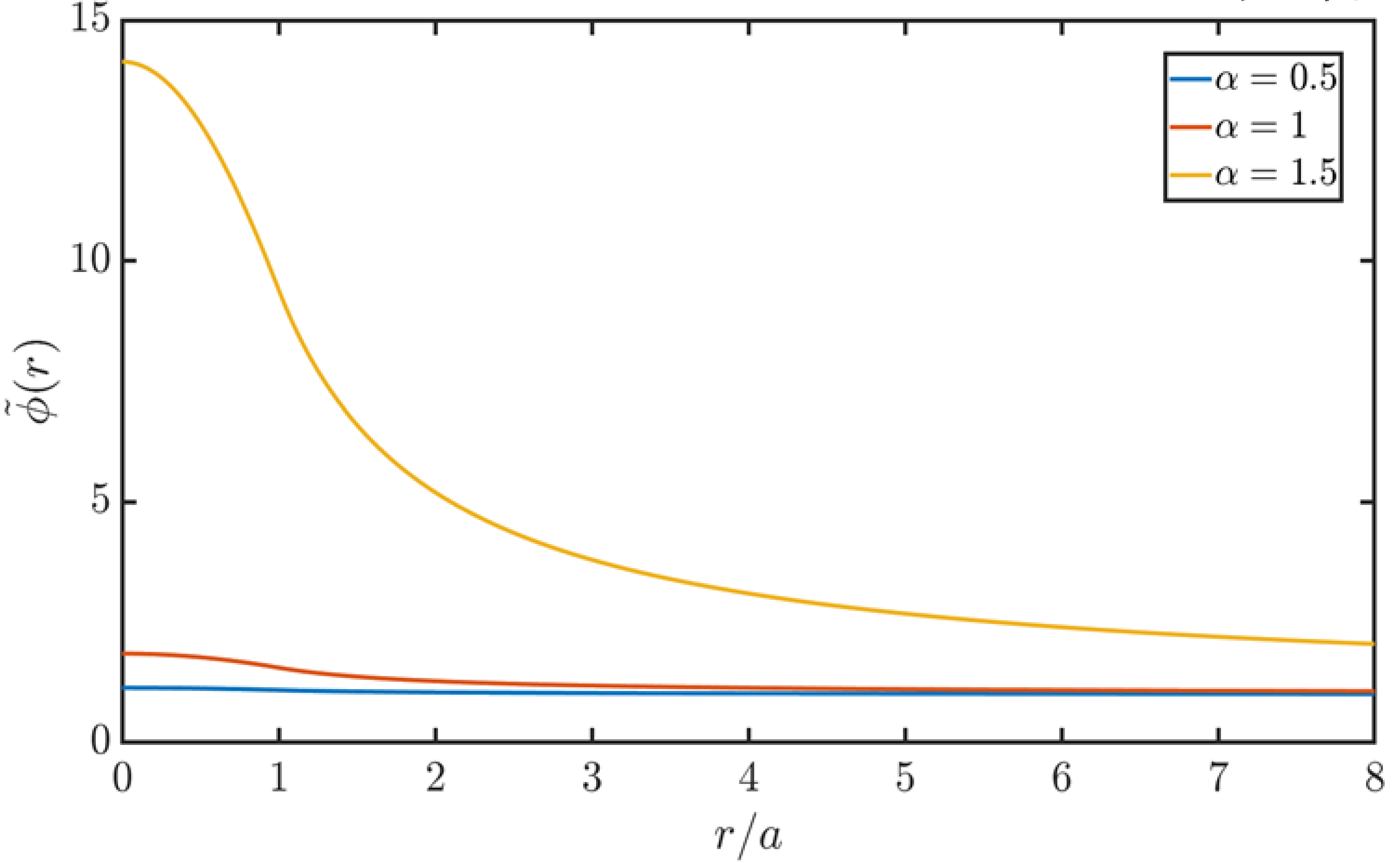
- Suppressed amplitude
- **Enhanced gradient**

[Hees et al. 2018]

3.2 Attractive case (λ<0)

(Zero velocity approximation)

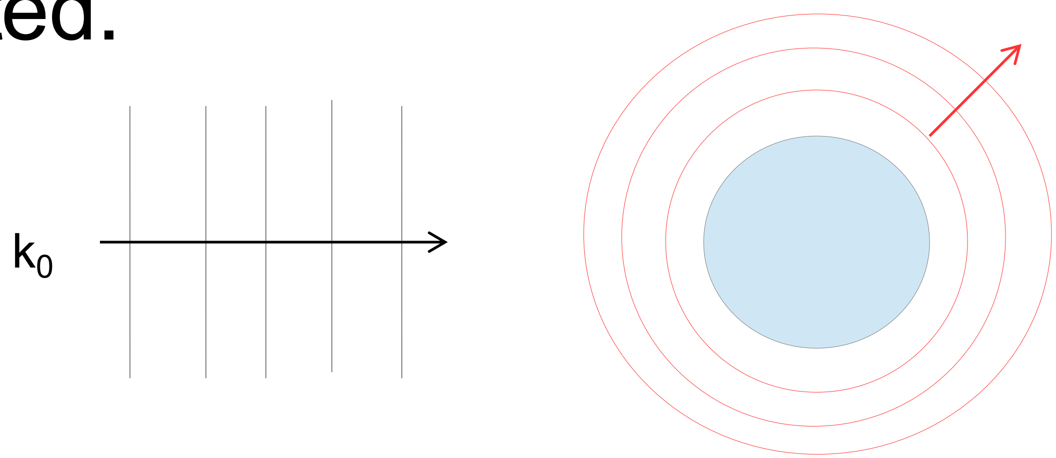
$\alpha = \sqrt{-\lambda\rho_0}a$



- Enhanced amplitude
- **Enhanced gradient**

4. Incident wave approach

- The Solar System moves as a whole towards Cygnus ~200km/s. A flux of dark matter is expected.



- Realistic boundary condition

[Banerjee et al. 2025]

$$\lim_{r\to\infty} \phi(\vec{r}, t) = \phi_0 \left(e^{-i\omega t + i\vec{k}_0 \vec{r}} + f(\theta) \frac{e^{-i\omega t + i k_0 r}}{r} \right)$$

5. Power spectrum

- Proper treatment of ALP as stochastic classical field.

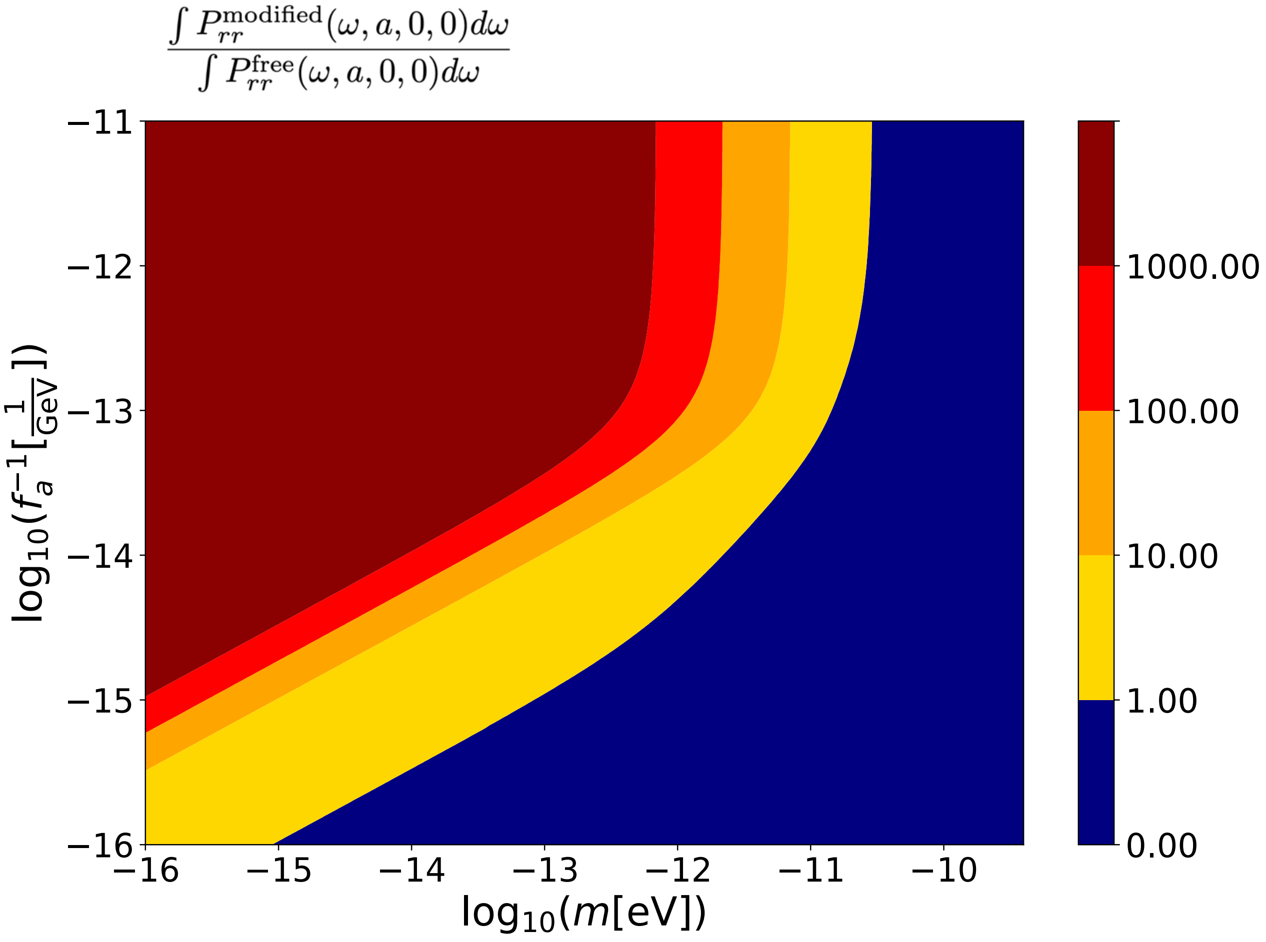
- Non-monochromatic (dark matter velocity distribution $|\tilde{\phi}(\vec{k})|^2 \propto e^{-\frac{(\vec{k}-\vec{k}_0)^2}{2\sigma^2}}$).

$$\phi(\vec{r},t) = \int \tilde{\phi}(\vec{k}) e^{-i\omega(k)t + i\vec{k}\vec{x} + i\alpha(\vec{k})} \frac{dk^3}{(2\pi)^3}$$

- Gradient's power spectrum

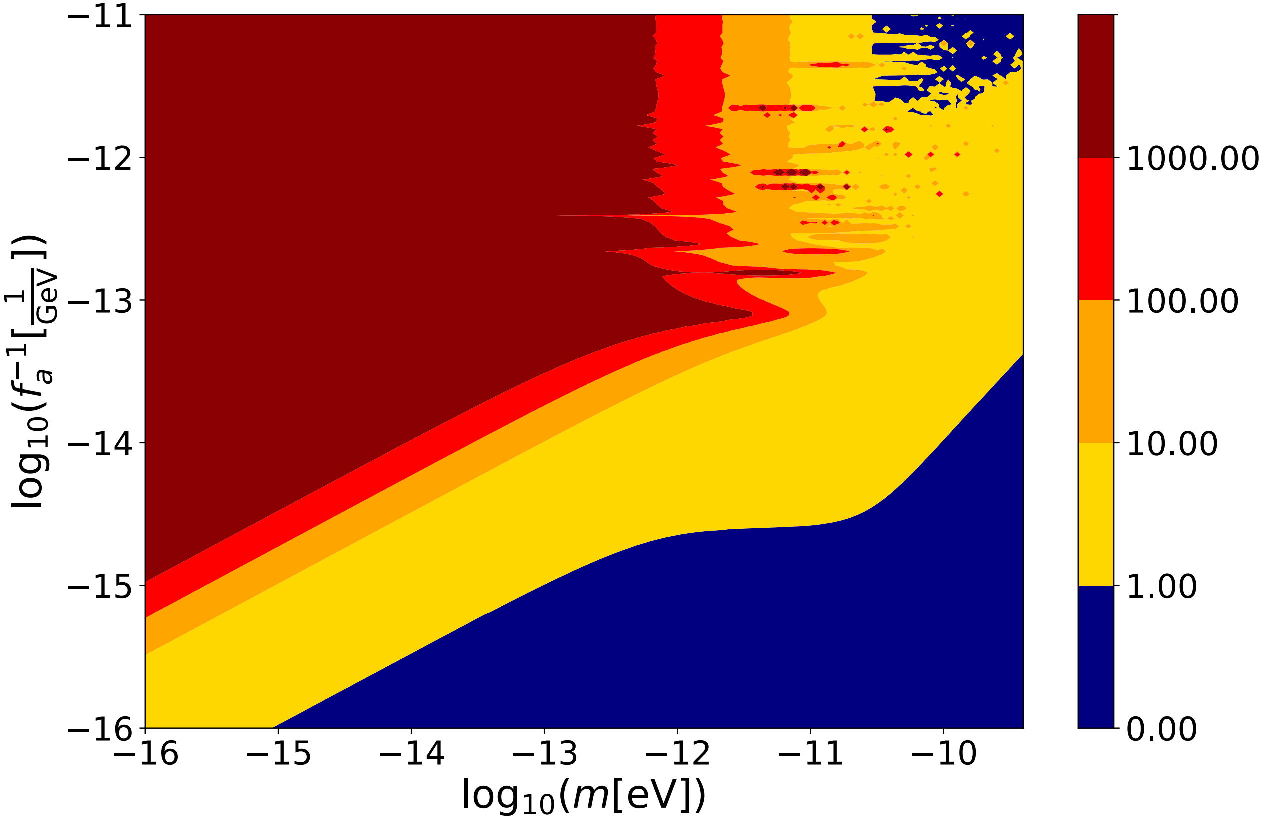
$$P_{ij}(\omega,\vec{x})d\omega = \mathcal{F}_\omega \left\{ \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} dt \, \langle \partial_i \phi(t+\tau,\vec{x}) \partial_j \phi(t,\vec{x}) \rangle \right\}$$

5.1 Repulsive coupling (λ>0)



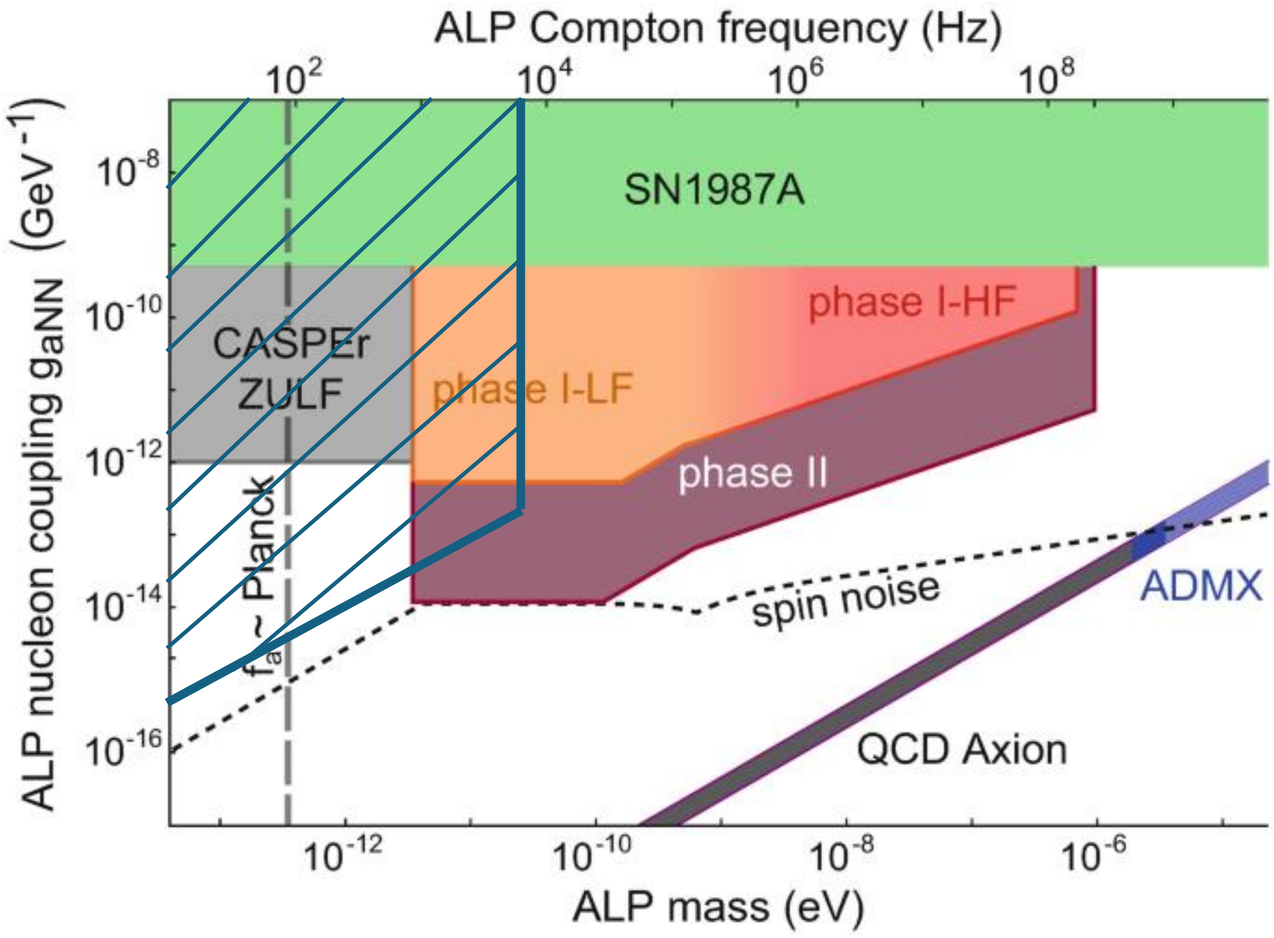
Enhanced sensitivity

5.2 Attractive coupling (λ<0)



Interesting profile due to bound states

6. Enhanced sensitivity region in CASPEr-wind



7. Conclusions

- The presence of the Earth can affect sensitivities of direct detection.

- Enhanced sensitivities for experiments that aim for a gradient coupling, e.g. CASPEr-wind.

Thank you for listening!