Influence of the axion-nucleon interaction on the direct detection of dark matter

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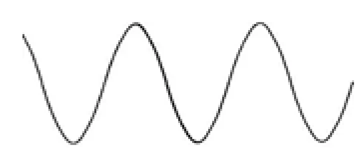
1. Introduction

- Various astrophysical observations can not be explained without the presence of a non-detected form of matter (dark matter).

- Axions and Axion-Like Particles (ALPs) are well-motivated candidates for dark matter.

- Features
  - Pseudo-scalars
  - Light mass $10^{-20}\mathrm{eV} \lesssim m \lesssim \mathrm{eV}$
  - Wave-like classical field 

- 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**

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

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

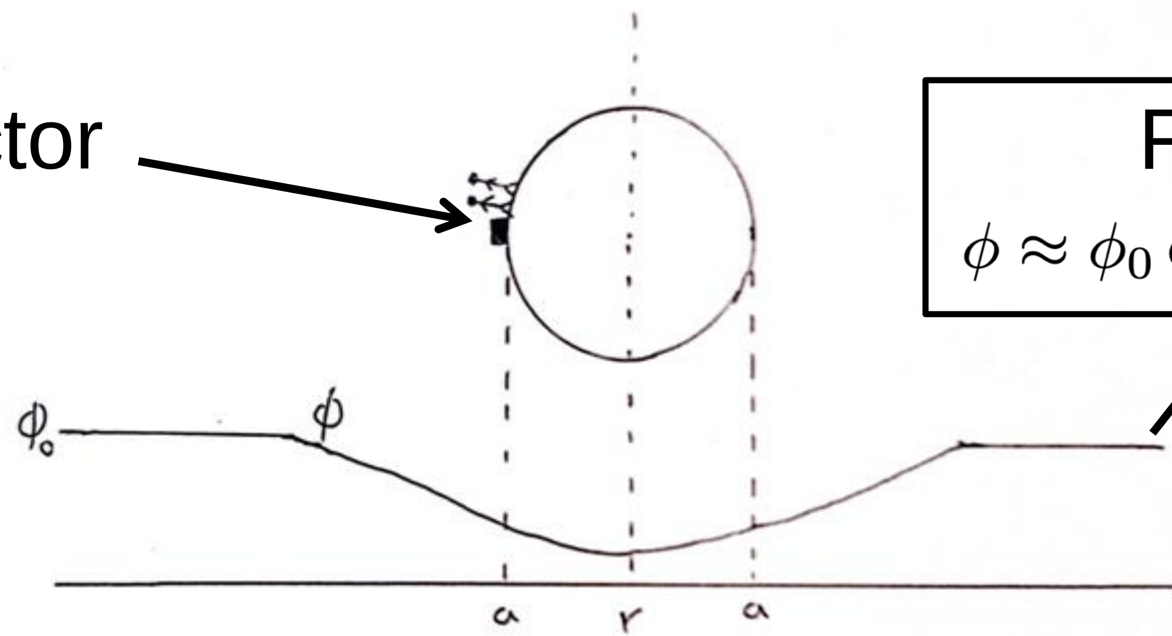
Interesting phenomenology!
Nucleon densities modify the ALP's field distribution.

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

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

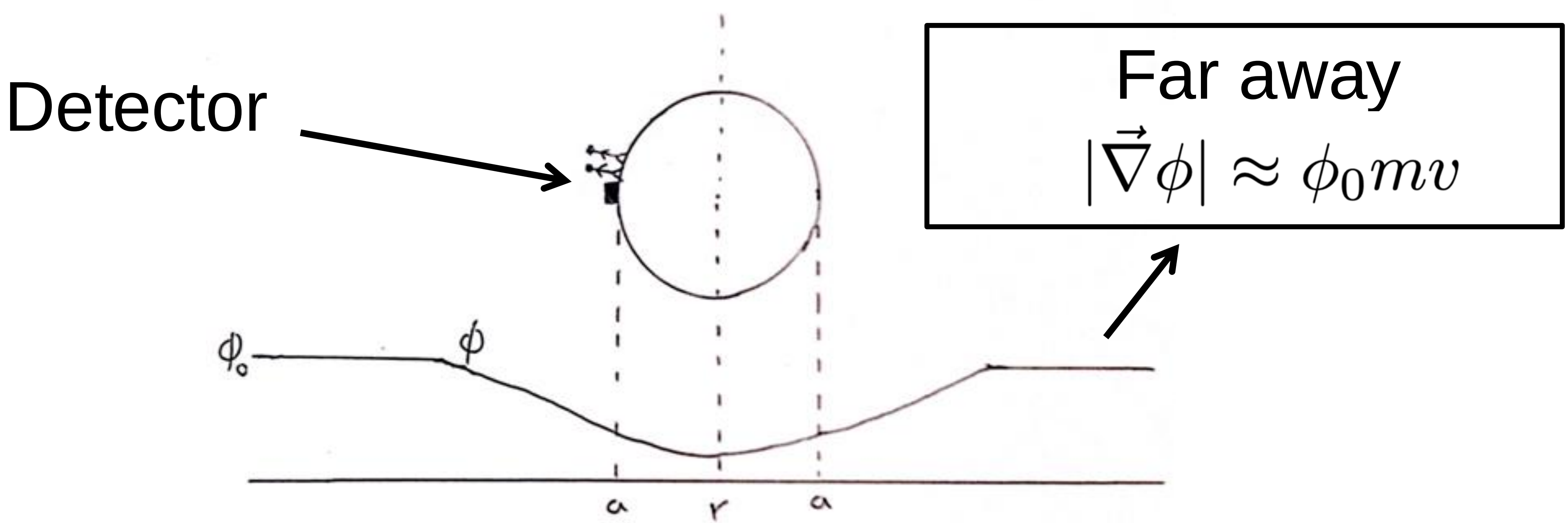
$$\omega \approx m$$

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

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

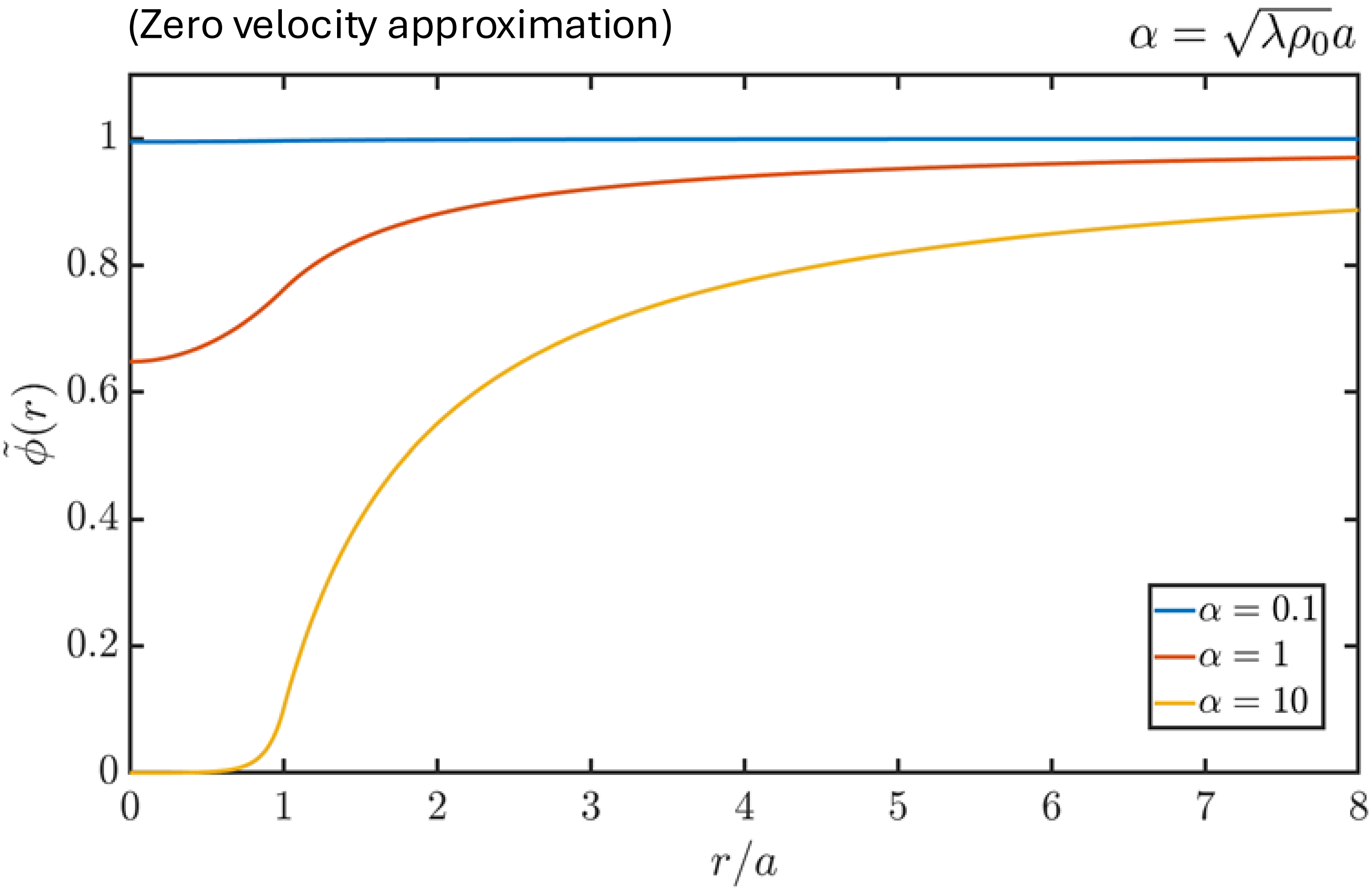
- Other experiments aim for interactions that are **proportional to the field's gradient** (e.g. CASPEr-Wind ($g_{\phi NN}\partial_\mu\phi\bar{N}\gamma^\mu\gamma_5 N$)).

- 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)

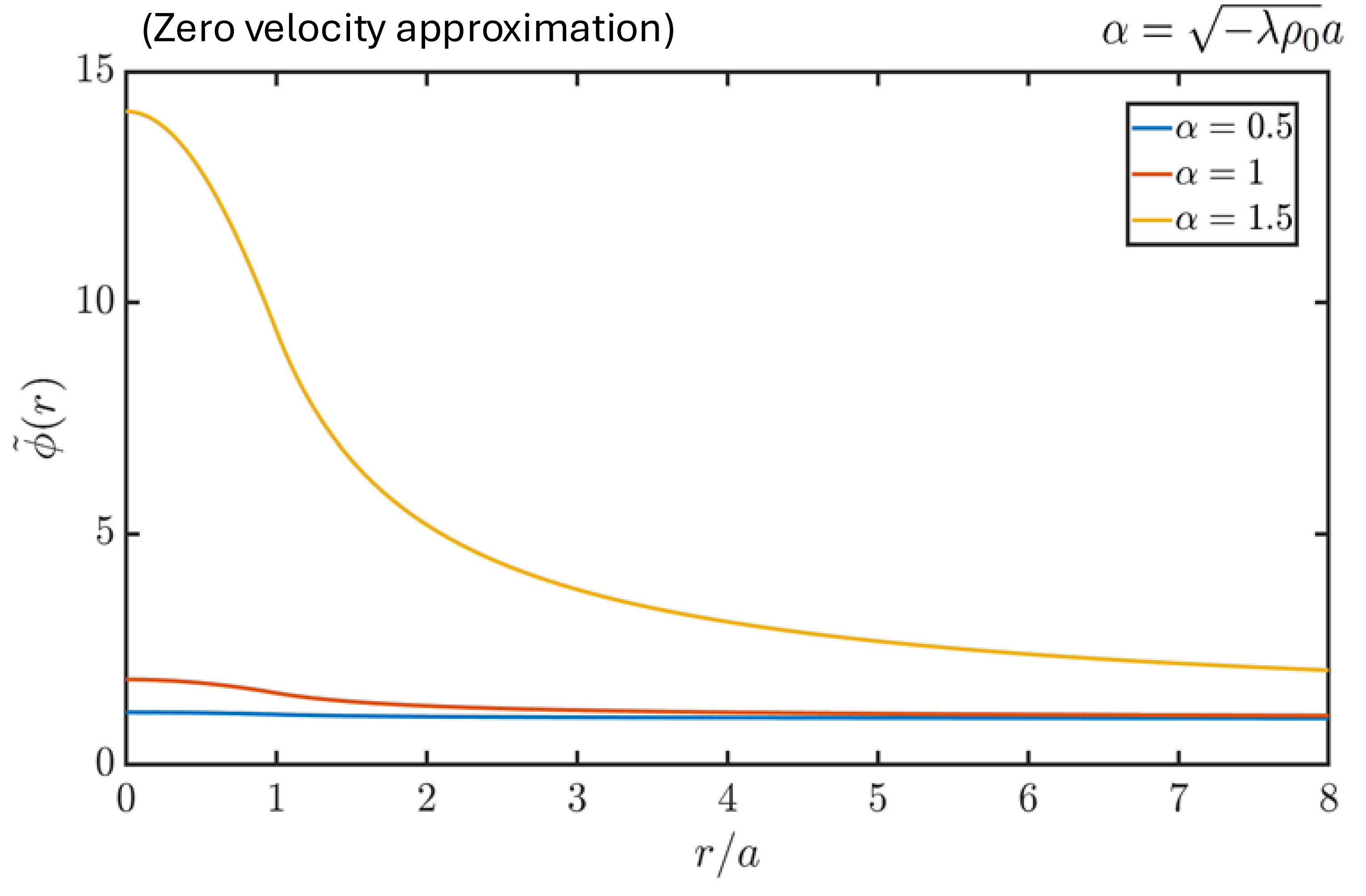
(Zero velocity approximation)



- Suppressed amplitude
- **Enhanced gradient**

[Hees et al. 2018]

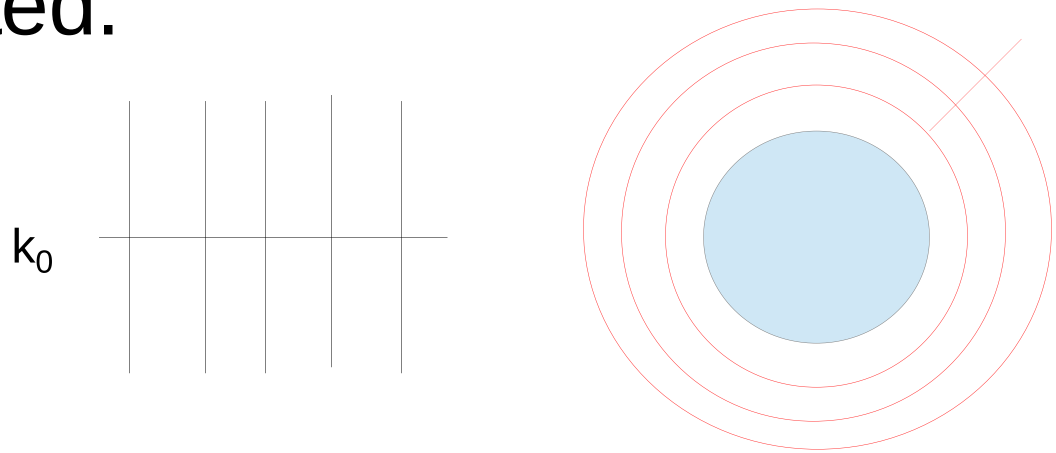
3.2 Attractive case (λ<0)



- 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

$$\lim_{r\to\infty}\phi(\vec{r},t)=\phi_0\left(e^{-i\omega t+i\vec{k}_0\vec{r}}+f(\theta)\frac{e^{-i\omega t+ik_0 r}}{r}\right)$$

5. Power spectrum

- Proper treatment of ALP as stochastic classical field.

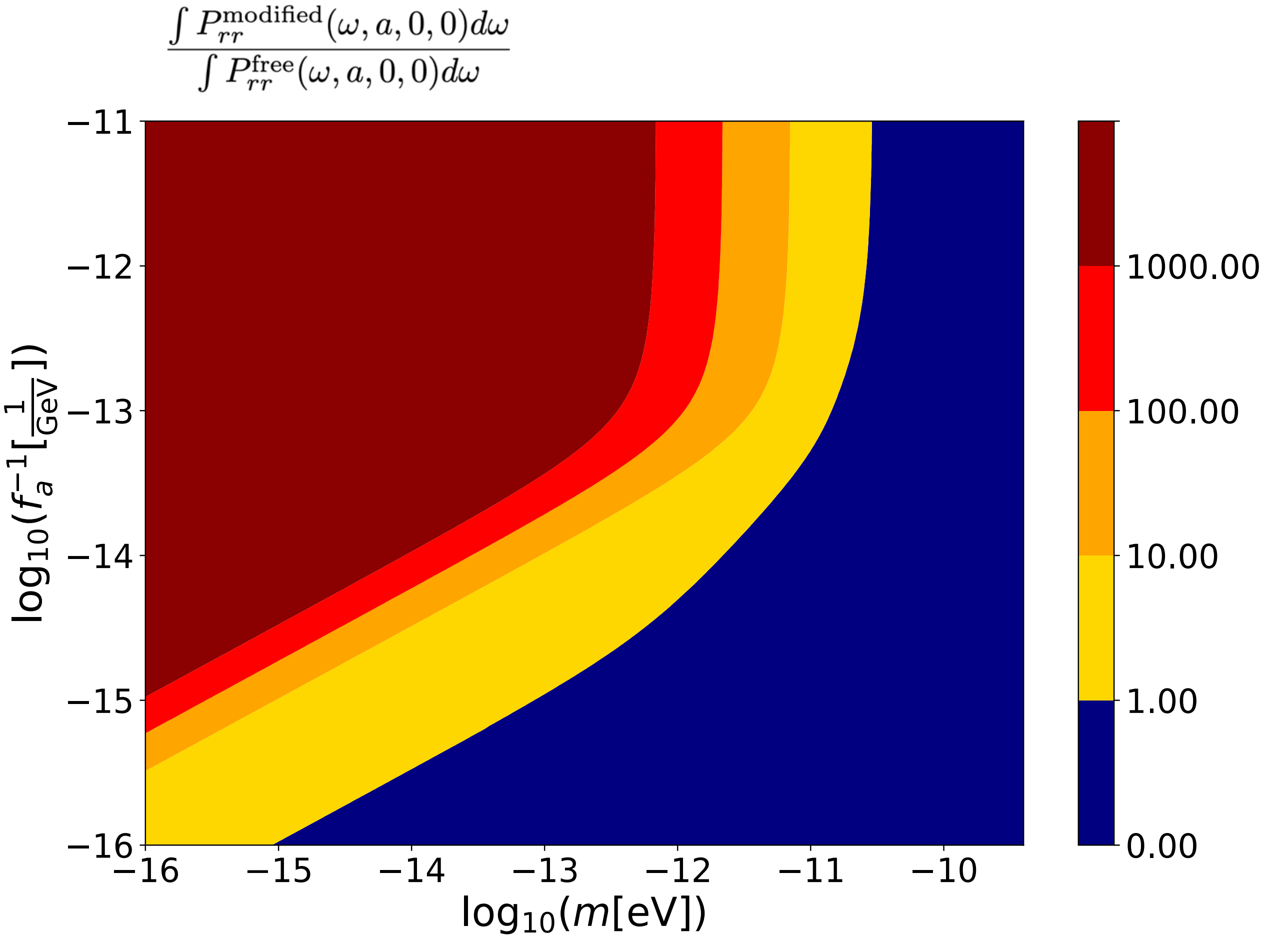
- Non-monochromatic (dark matter velocity distribution $|\tilde{\phi}(\vec{k})|^2 \propto e^{-\frac{(\vec{k}-\vec{k}_0)^2}{2\sigma^2}}$).

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

- Gradient's power spectrum

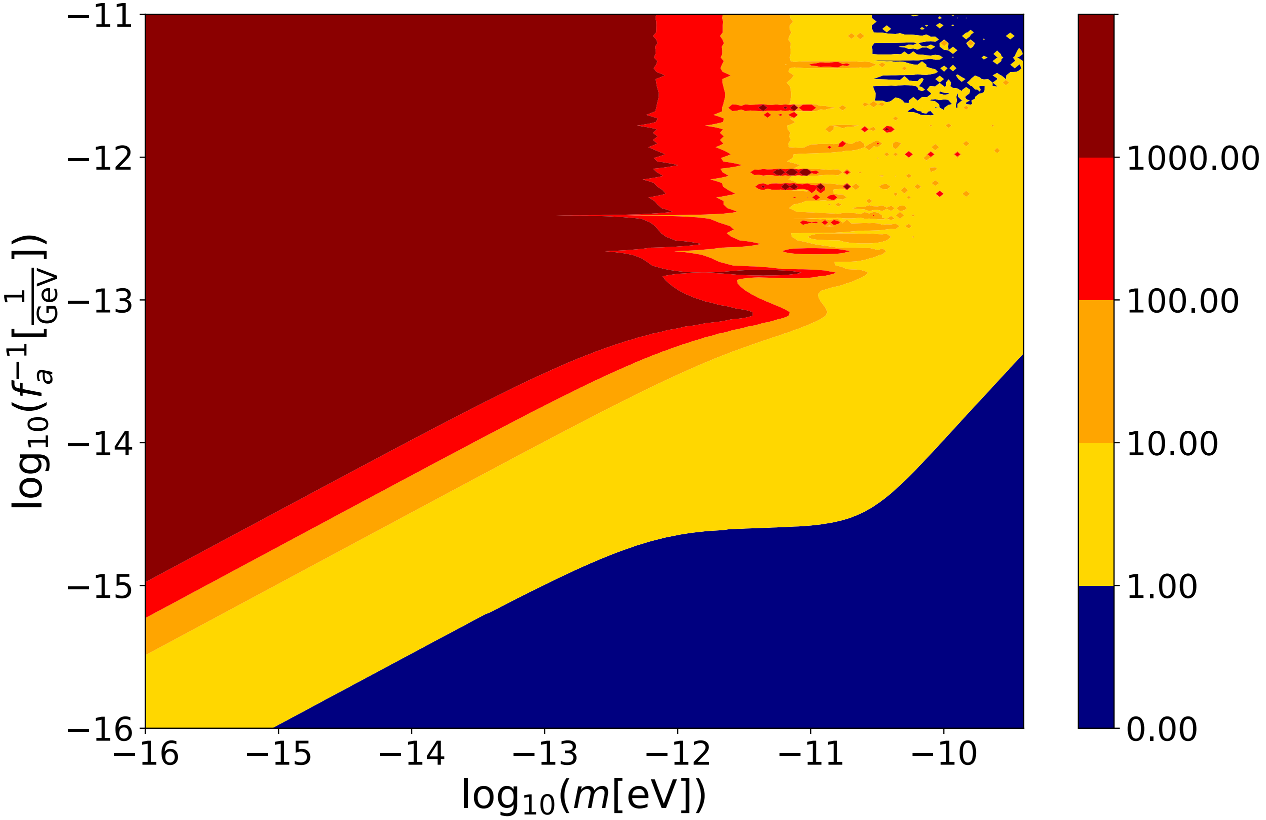
$$P_{ij}(\omega,\vec{x})d\omega = \mathcal{F}_\omega \left\{ \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} dt \, \langle \partial_i \phi(t+\tau,\vec{x}) \partial_j \phi(t,\vec{x}) \rangle \right\}$$

5.1 Repulsive coupling (λ>0)



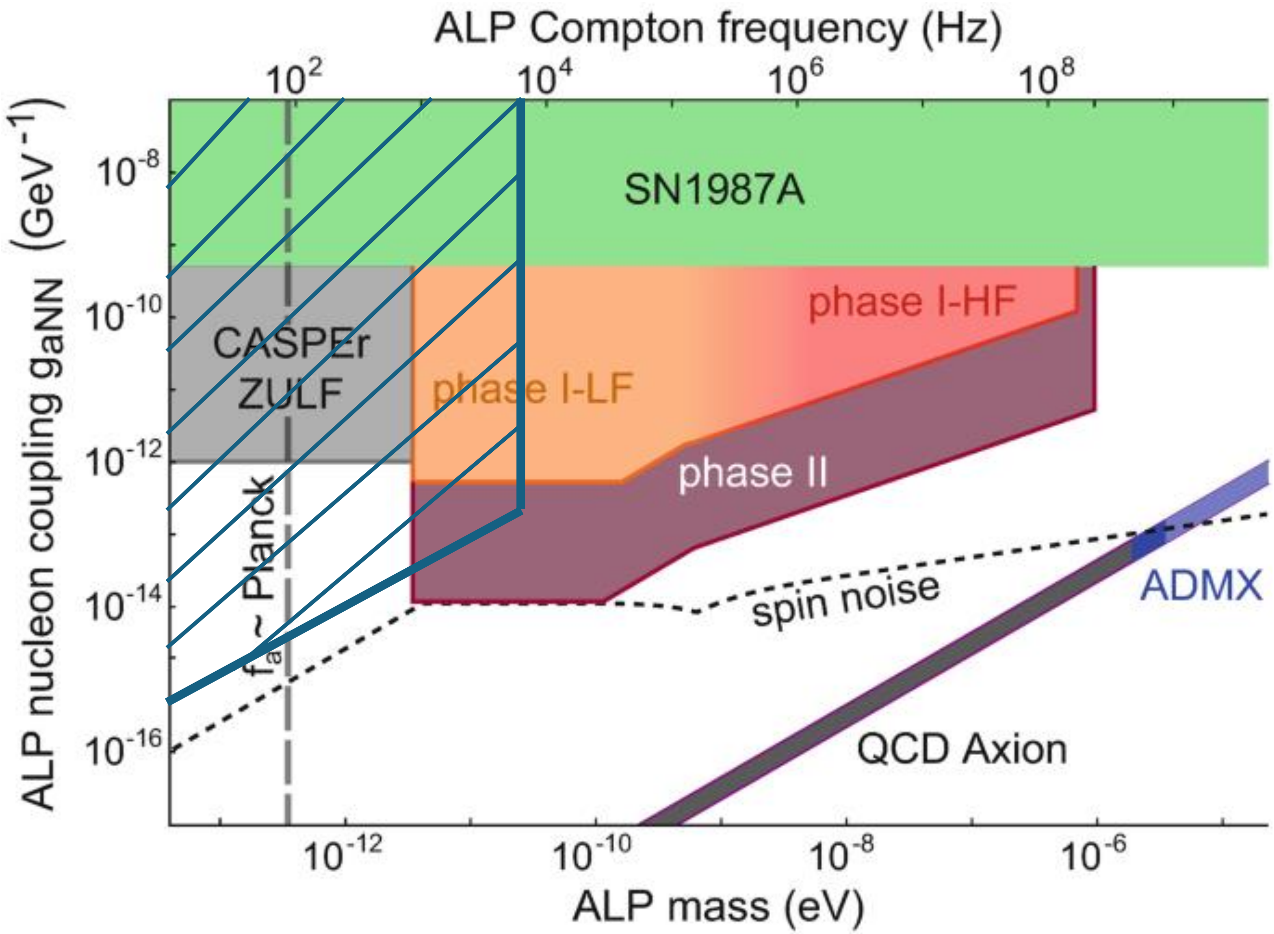
Enhanced sensitivity

5.2 Attractive coupling (λ<0)



Interesting profile due to bound states

5.3 Enhanced sensitivity region in CASPEr-wind



6. Validity of the stationary solutions

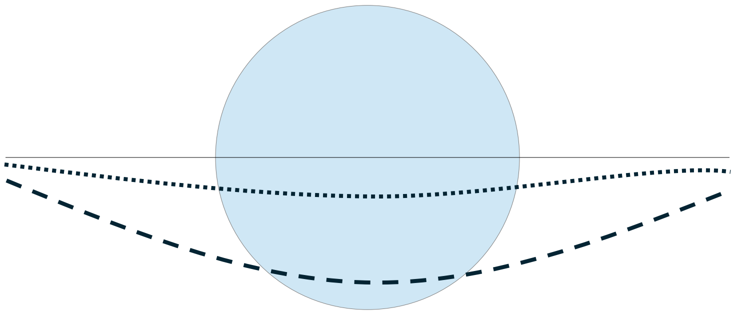
- We have considered stationary solutions, but the Earth is in an accelerated movement around the Sun.

- Understand in which time scales these solutions are a good approximation.

Study simple physical situations that capture the relevant time scales.

6.1. Appearing source

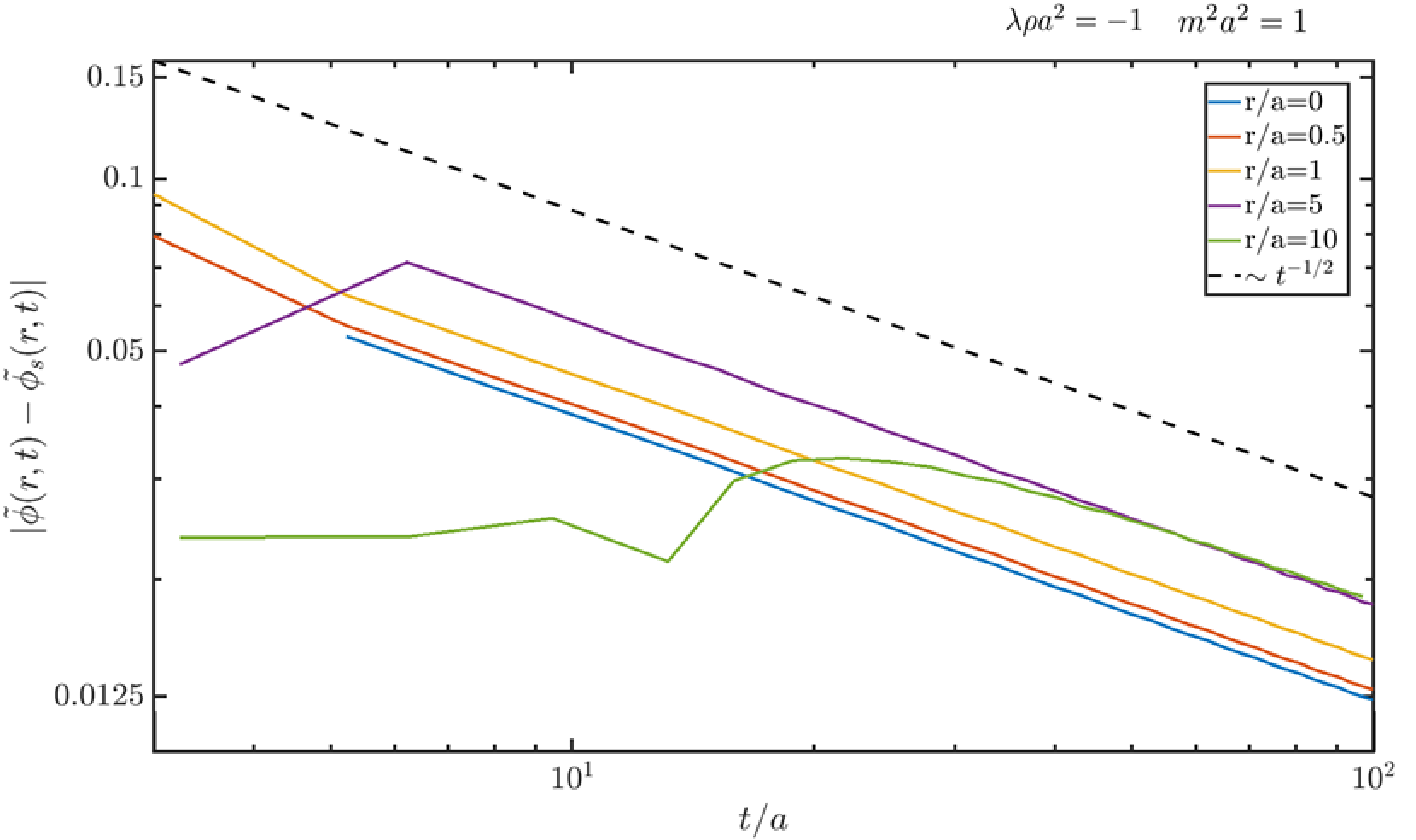
- Why is it interesting?



- Non-trivial time dependence.
- Related to the accelerating source situation.

- How? → Semi-analytical method (Eigenfunctions).

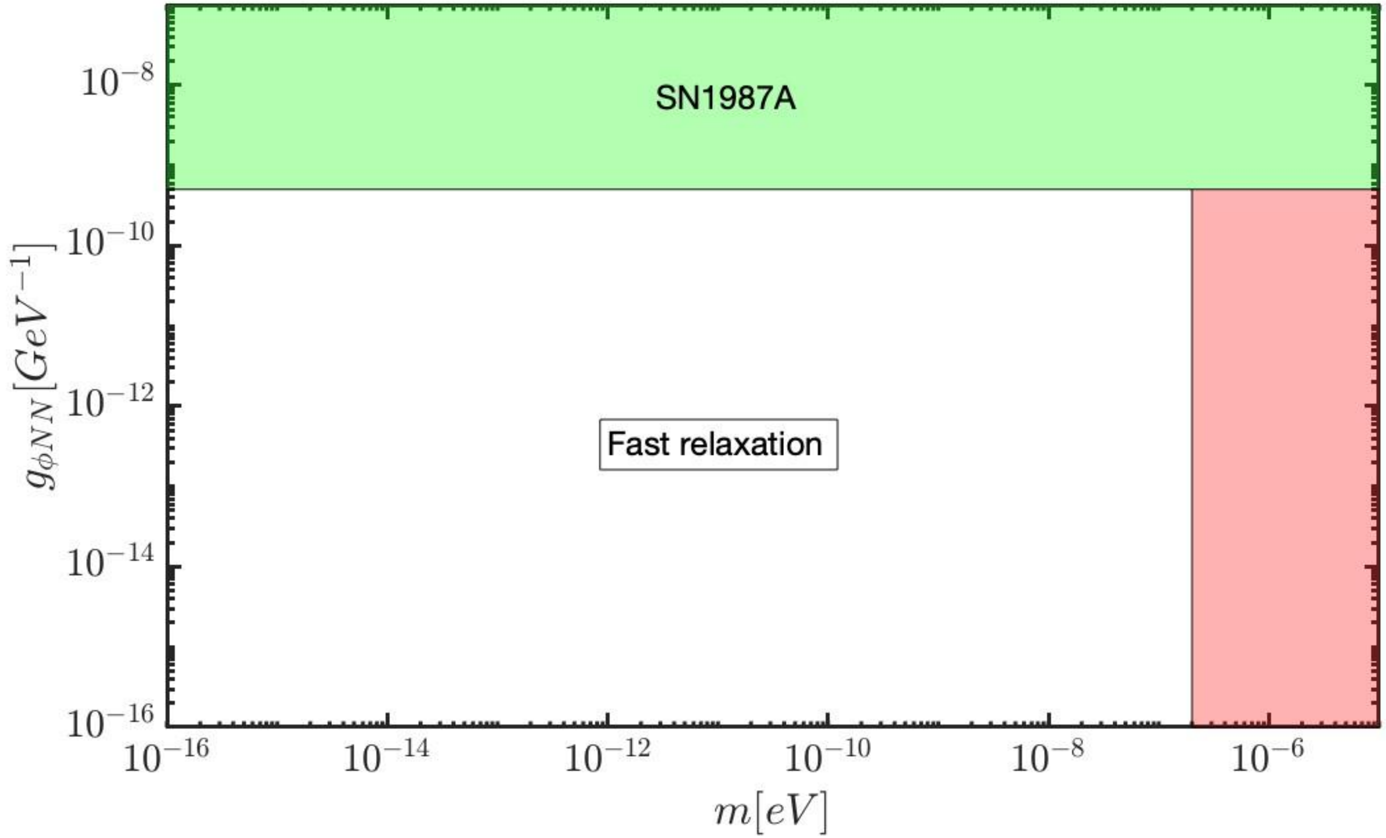
6.1.1 Time scaling of the approach to the stationary configuration



$$\phi_0(\vec{r},t) \approx \phi_s(\vec{r})\cos(mt) + \phi_s(\vec{r})\cos(mt)\left(\frac{\alpha a - \tanh(\alpha a)}{\alpha}\right)\sqrt{\frac{2m}{\pi t}}$$

6.2 Validity of stationary solutions

- Comparing relaxation times with Earth's deviation from a straight path.



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.

- For most of the mass range of interest, stationary solutions at the Earth’s vicinity are a good approximation.

Thank you for listening!

Questions?

Back up slides

- At low energies this coupling produces a potential for ALPs

$$V(\phi) = -m_\pi^2 f_\pi^2 \epsilon \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2(\frac{\phi}{2 f_a})}$$

[3]

- Nucleon densities modify the potential

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

$\sigma_N = \sum_{q=u,d} m_q \frac{\partial m_N}{\partial m_q} \sim 59 \text{ MeV}$ [1,2]

References

[1] G. Grilli di Cortona, E. Hardy, J. Pardo Vega, and G. Villadoro, The QCD axion, precisely,

JHEP 01 (2016) 034, [arXiv:1511.02867].

[2] Anson Hook and Junwu Huang. “Probing axions with neutron star inspirals and other stellar processes”. In: JHEP 06 (2018), p. 036. doi: 10.1007/JHEP06(2018)036. arXiv: 1708.08464 [hep-ph].

[3] J. M. Alarcon, J. Martin Camalich, and J. A. Oller, The chiral representation of the πN scattering amplitude and the pion-nucleon sigma term, Phys. Rev. D85 (2012) 051503.

Bound states

- Bound states exist for certain values of the coupling and cause divergences.
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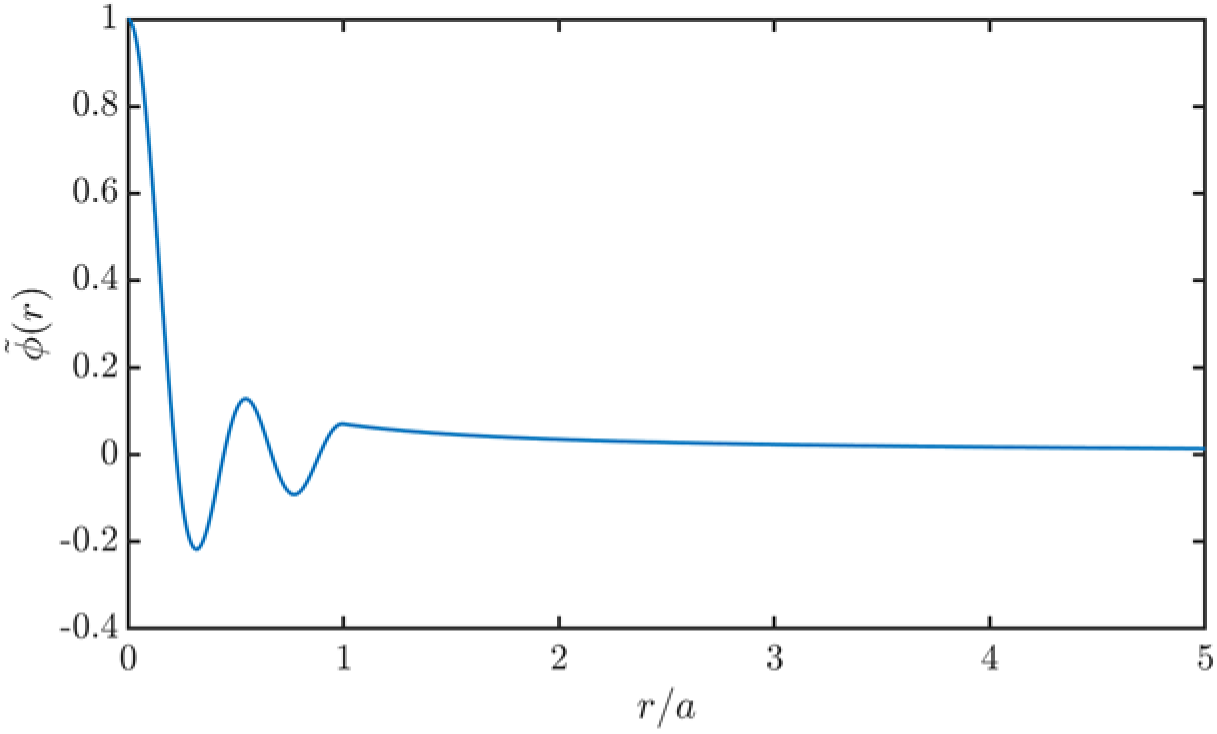
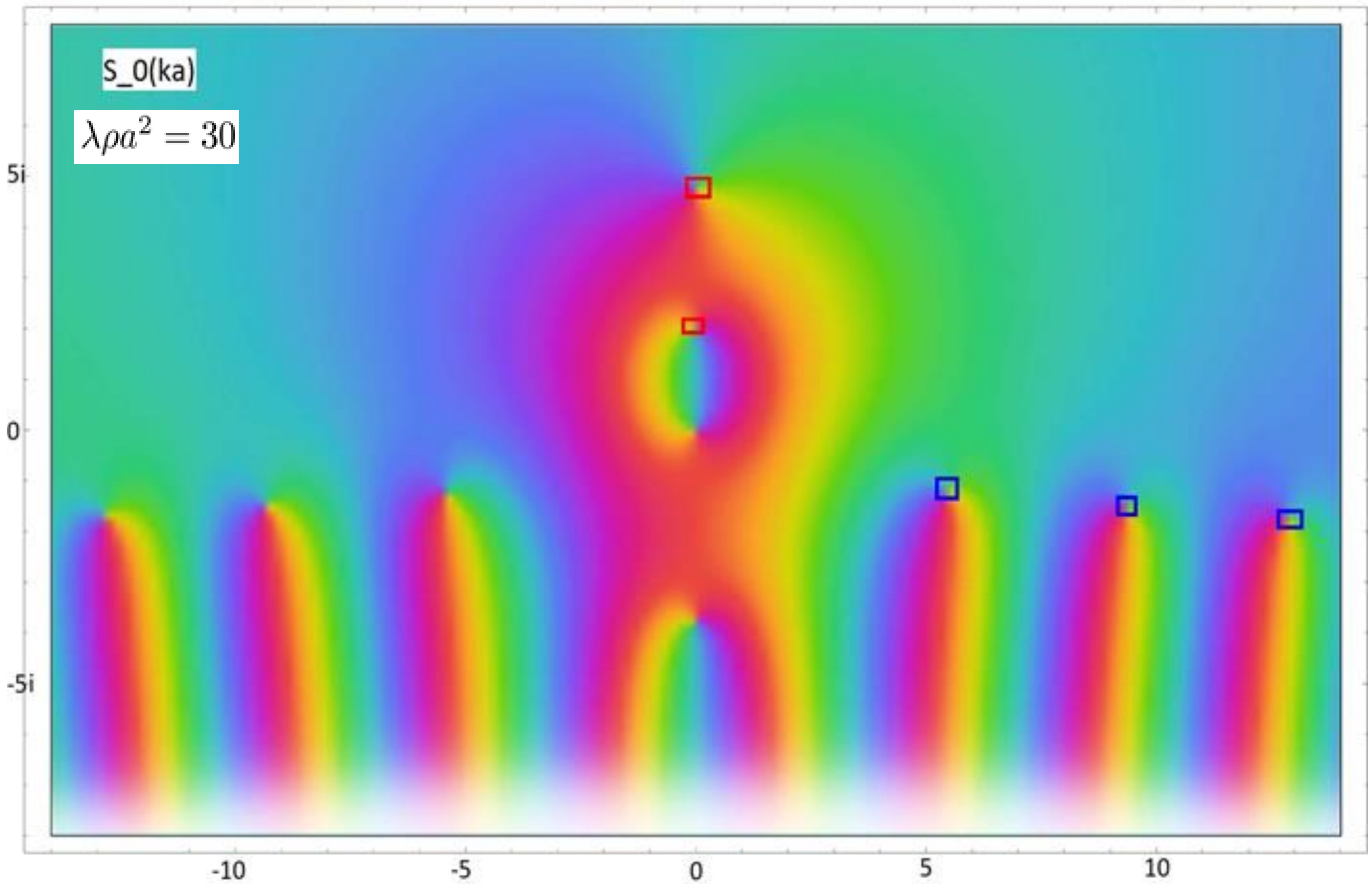
$a\sqrt{\lambda\rho_0} = \frac{9}{2}\pi$



$$a\sqrt{\lambda\rho_0} = \frac{(2n+1)\pi}{2} \text{ with } n = 0, 1, 2, \ldots$$

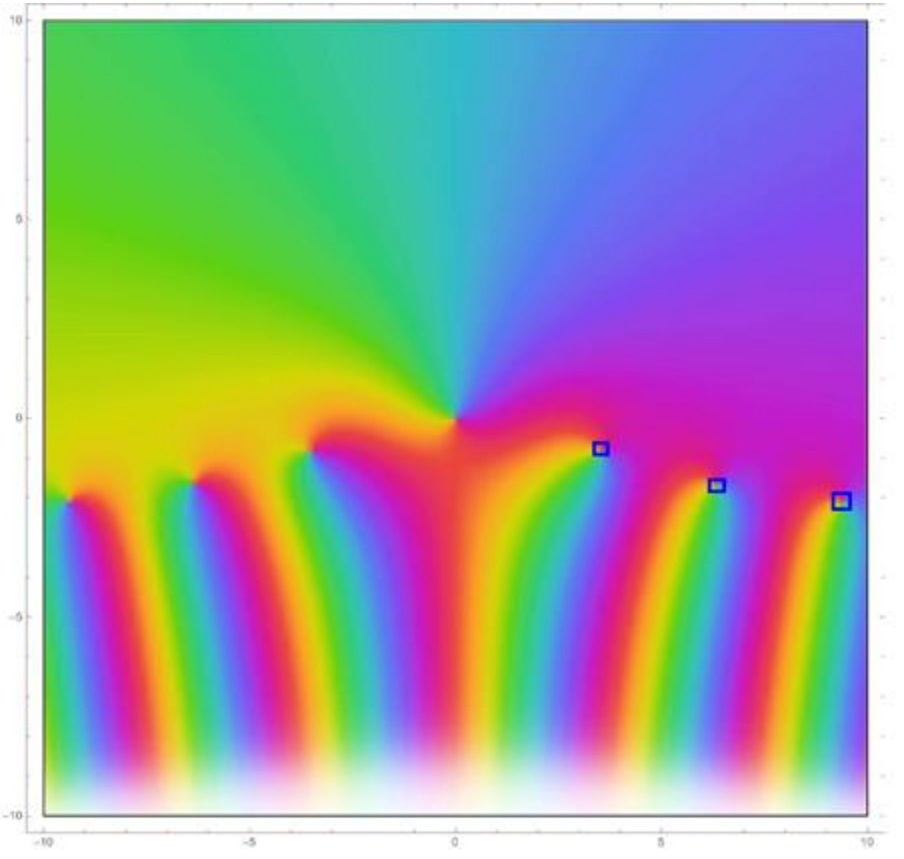
Resonances and bound states in the k complex plane



As long as k non 0 there are no divergences!

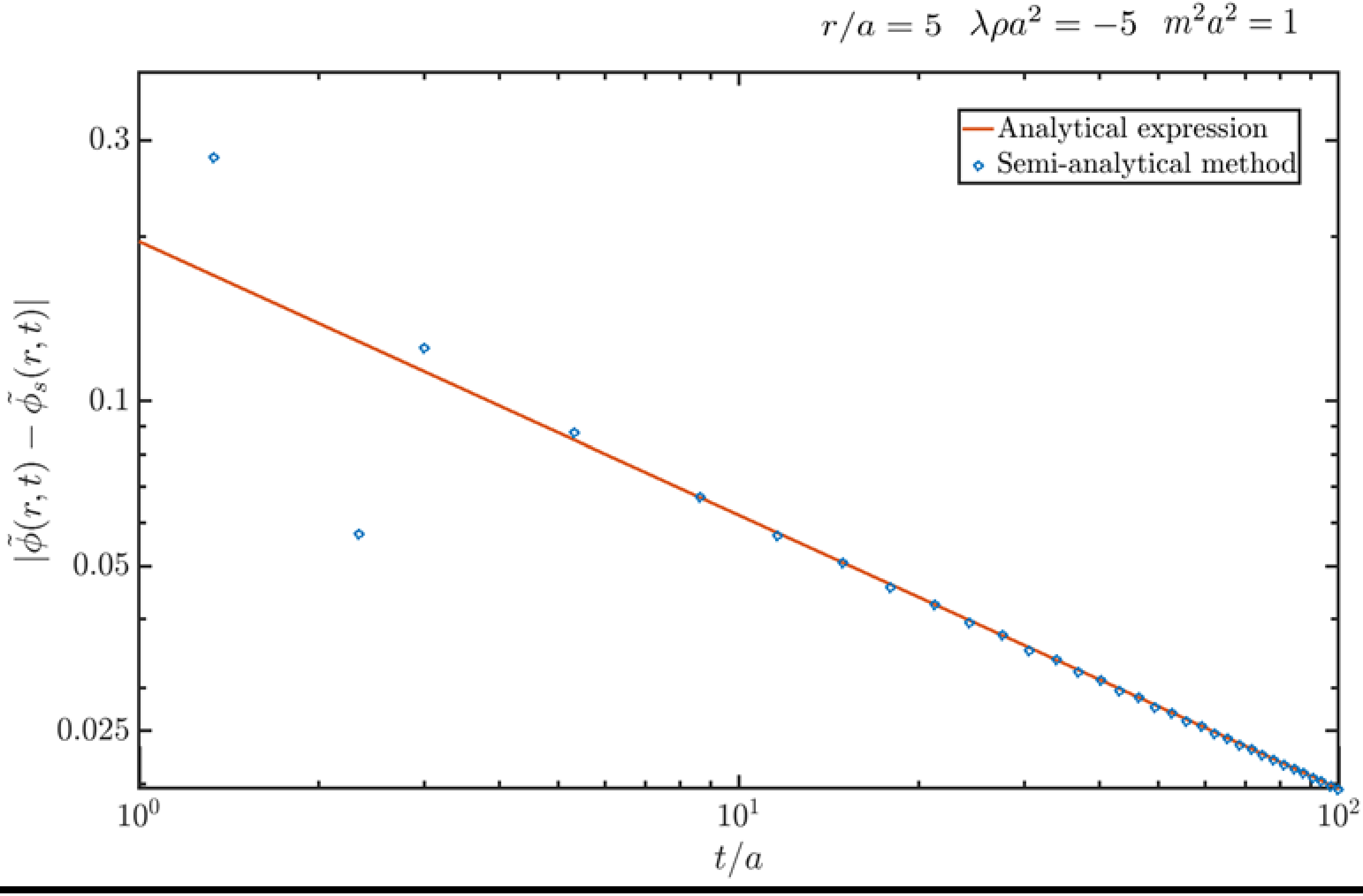
Poles S matrix repulsive case

$$\boxed{S_l = 1 + 2ia_l}$$



$\lambda\rho a^2 = -5$

Analytical expression for the scaling



$$\phi_0(\vec{r},t) \approx \phi_s(\vec{r})\cos(mt) + \phi_s(\vec{r})\cos(mt)\left(\frac{\alpha a - \tanh(\alpha a)}{\alpha}\right)\sqrt{\frac{2m}{\pi t}}$$