Axion in Stockholm, July 3rd 2025

Detecting Ultralight Dark Matter with Matter Effect

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DESY, Hamburg

2504.11522

Collaborators:

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Quadratic Coupling

$$\frac{1}{\Lambda^2}\phi^2 \mathcal{O}_{\rm SM} \rightarrow F^2,\ G^2,\ m_f \bar{f} f$$

~~Shift Symmetry~~

$+$

$\mathbb{Z}_2: \ \phi \to -\phi$

Axion

Hook et al. 2017, Kim et al. 2023,
Beadle et al. 2023, …

Dilaton

Damour et al. 1992,
Sibiryakov et al. 2020, …

pNGB

Brzeminski et al. 2020,
Gan et al. 2023, …

Quadratic Coupling

$$\frac{1}{\Lambda^2}\phi^2\mathcal{O}_{\rm SM} \rightarrow F^2,\ G^2,\ m_f\bar{f}f$$

~~Shift Symmetry~~

+

$\mathbb{Z}_2:\ \phi \rightarrow -\phi$

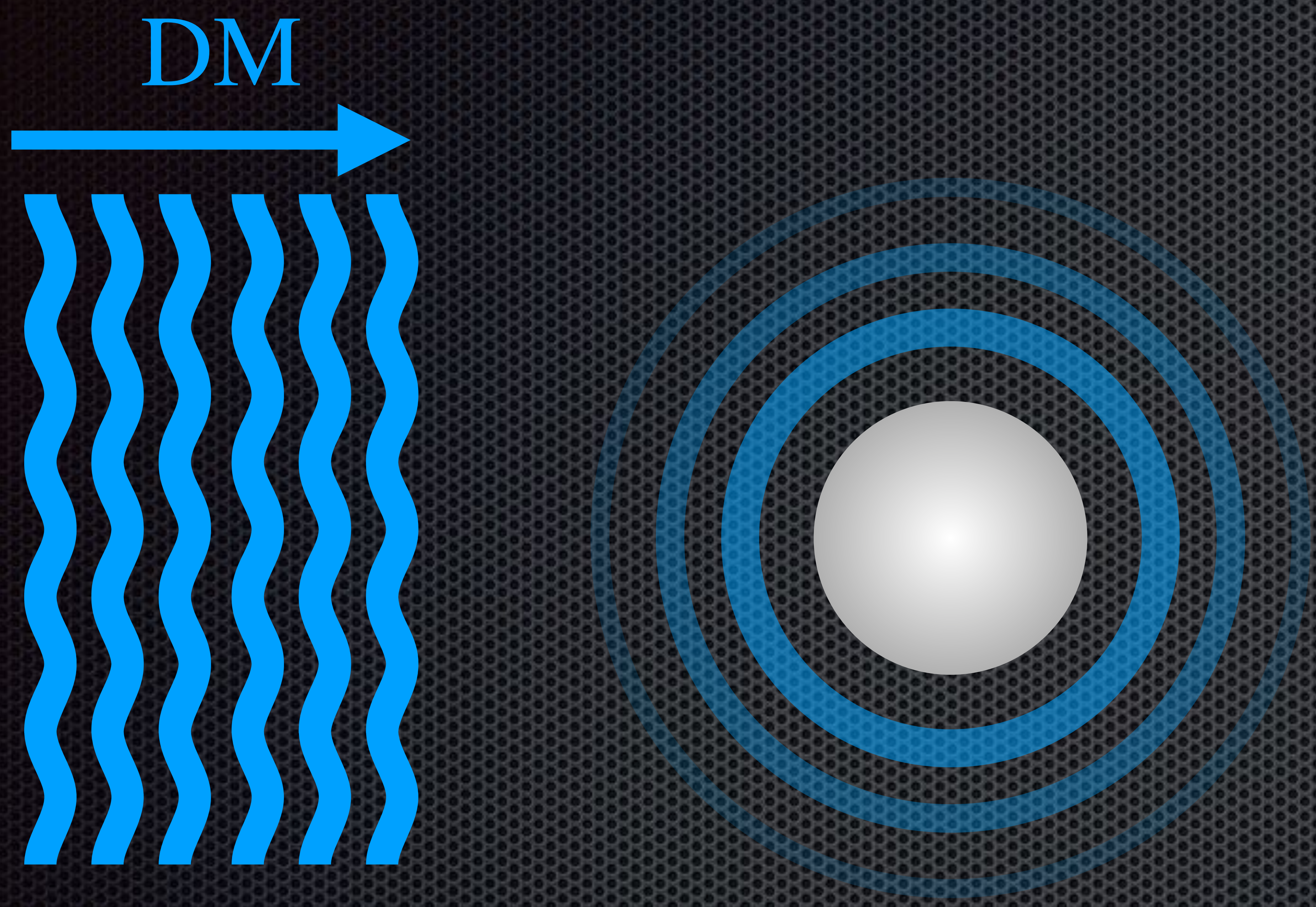
Ordinary Matter

$$\mathcal{O}_{\rm SM} \rightarrow \langle \mathcal{O}_{\rm SM} \rangle$$

Effective Mass

$$m_{\rm M}^2 \sim \frac{\langle \mathcal{O}_{\rm SM} \rangle}{\Lambda^2}$$

Matter Effect



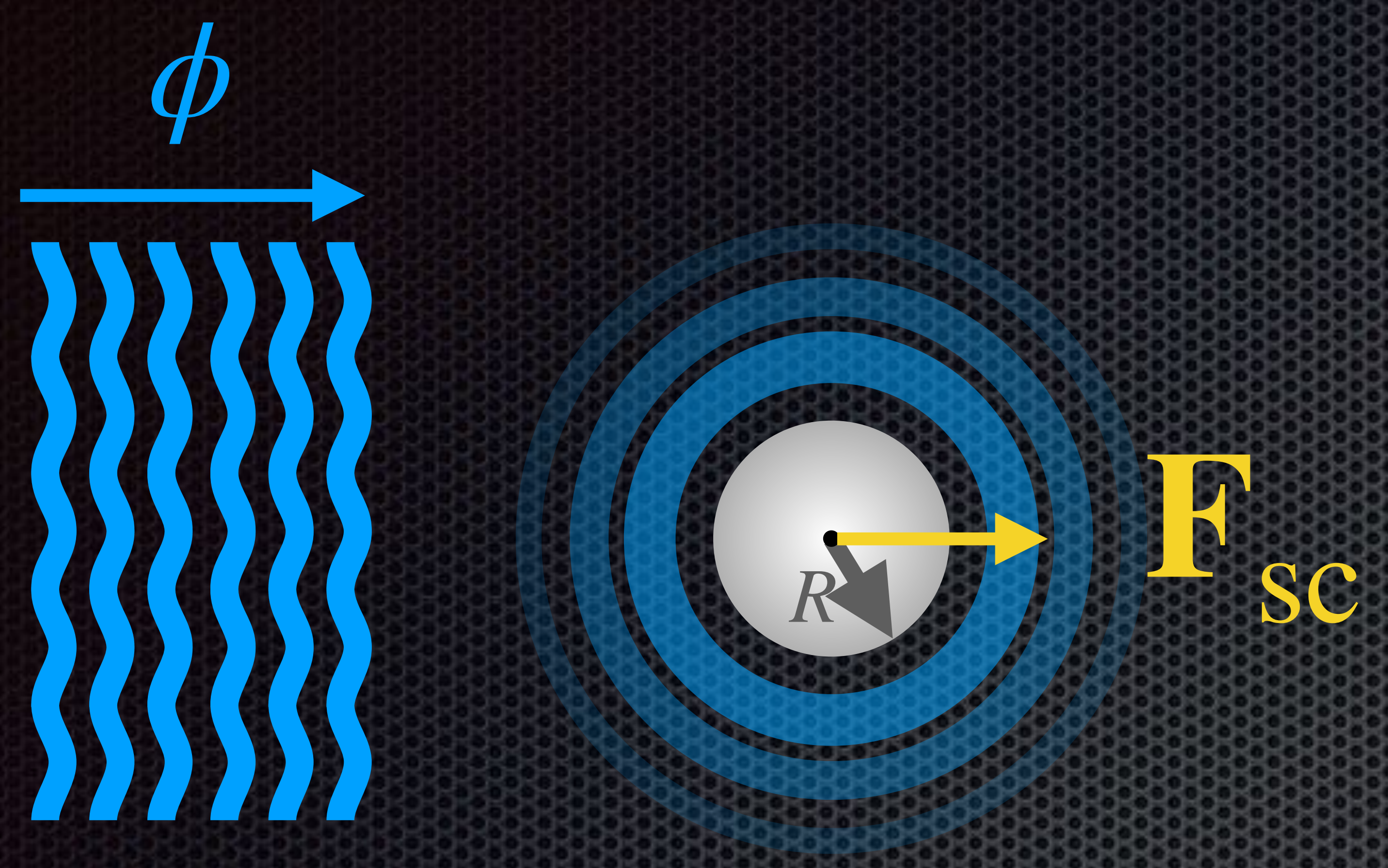
Ordinary Matter

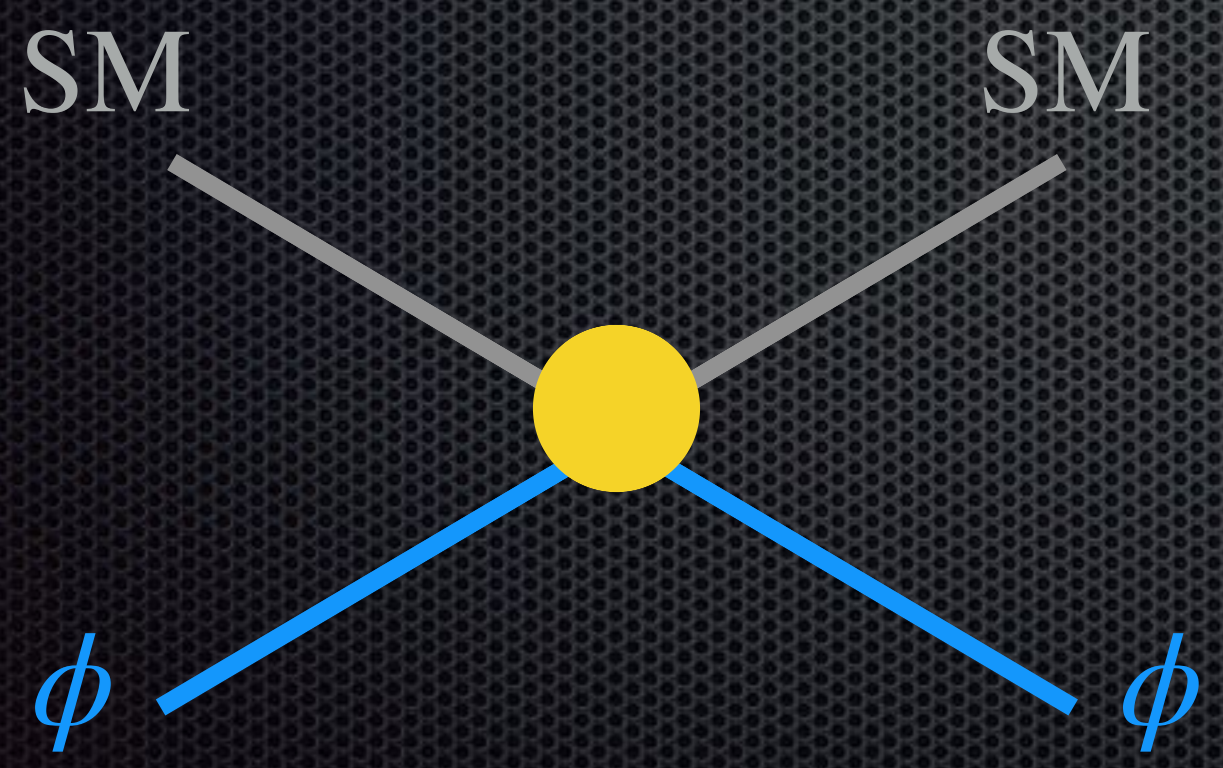
$$\mathcal{O}_{\rm SM} \to \langle \mathcal{O}_{\rm SM} \rangle$$

Effective Mass

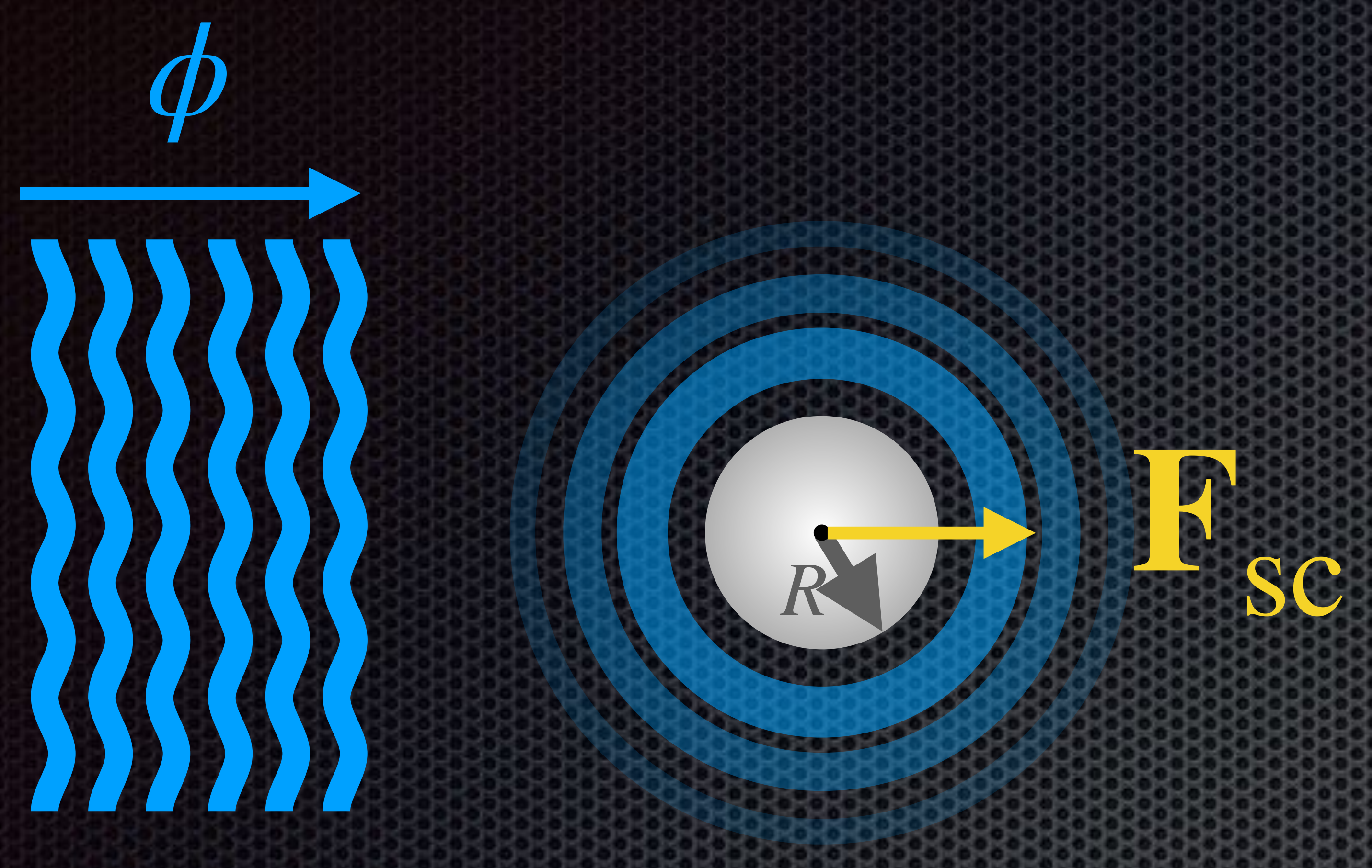
$$m_{\rm M}^2 \sim \frac{\langle \mathcal{O}_{\rm SM} \rangle}{\Lambda^2}$$

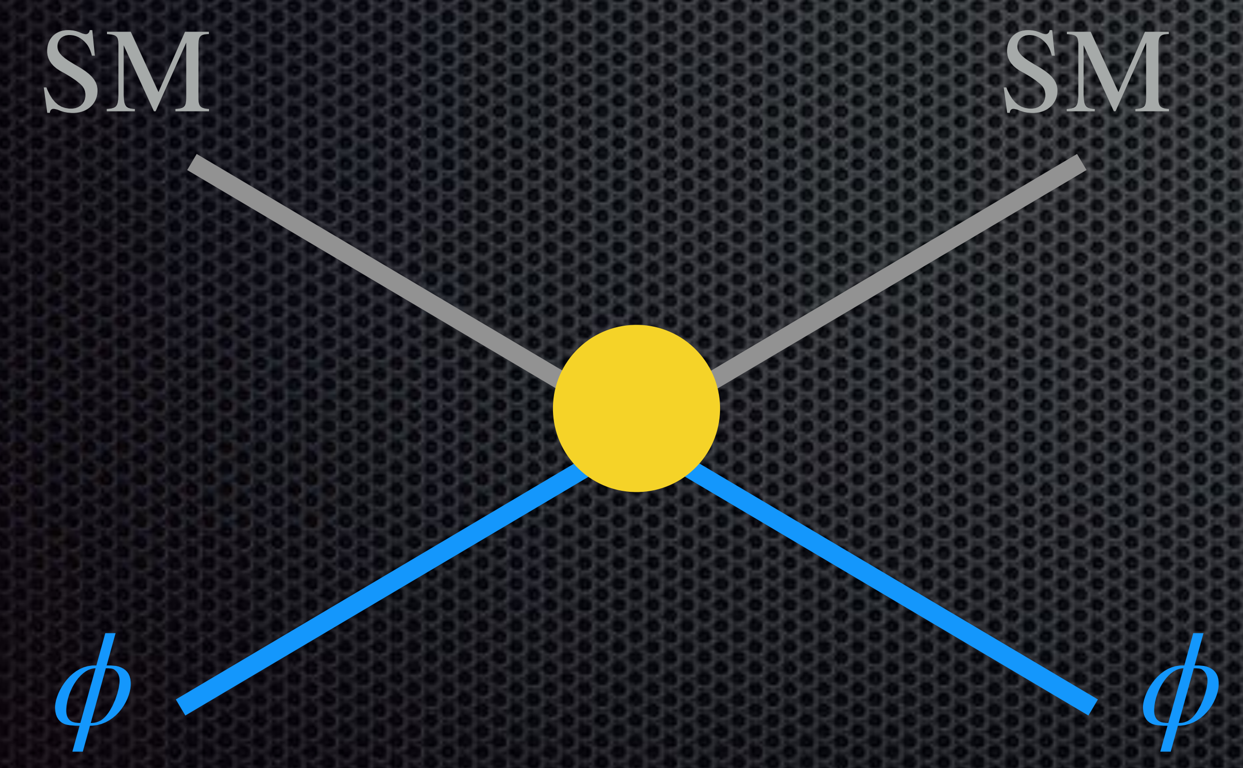
Scattering Force





Scattering Force





$$\sigma_{\rm T} \sim \frac{(m_{\rm M}^2 V_R)^2}{4\pi}$$

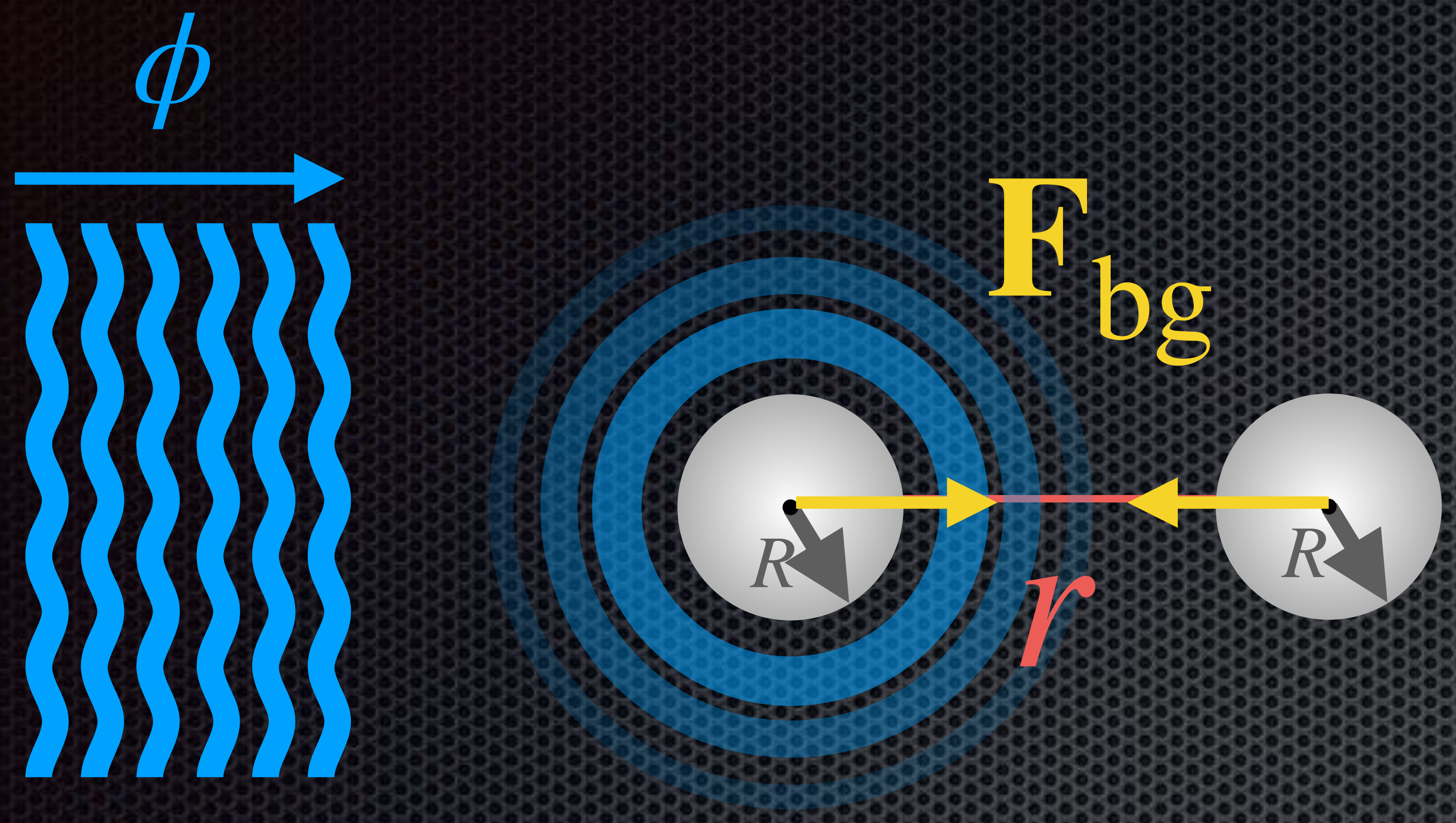
Coherent Scattering

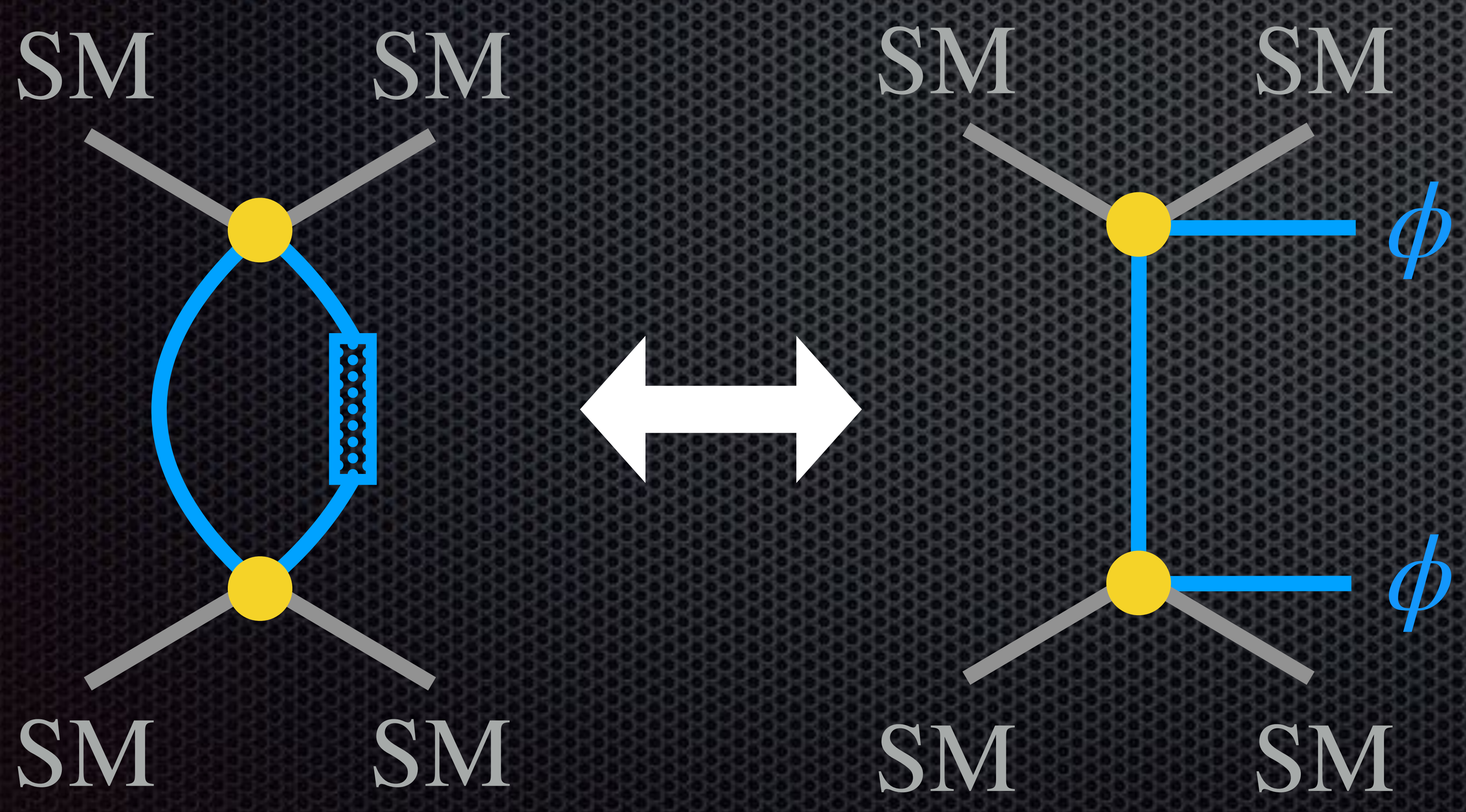
$$\mathbf{F}_{\rm sc} \sim \sigma_{\rm T} \times \rho_\phi v_\phi^2$$

$$a \sim 10^{-13}\,\mathrm{m/s^2} \times \left(\frac{1\mathrm{cm}}{R}\right) \times (m_{\rm M} R)^4$$

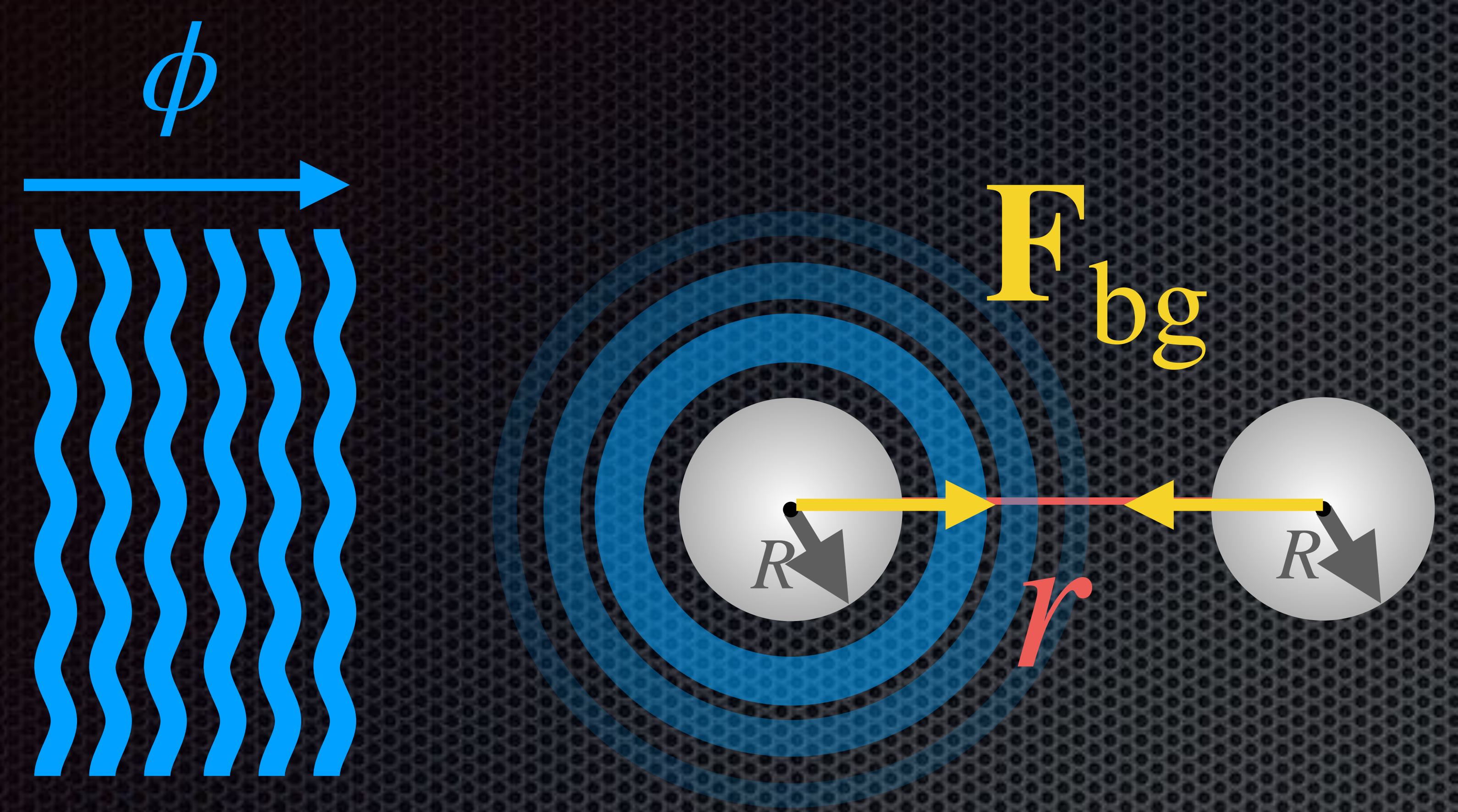
Fukuda, Shirai, 2021,
Day, Da, Luty et al. 2023, …

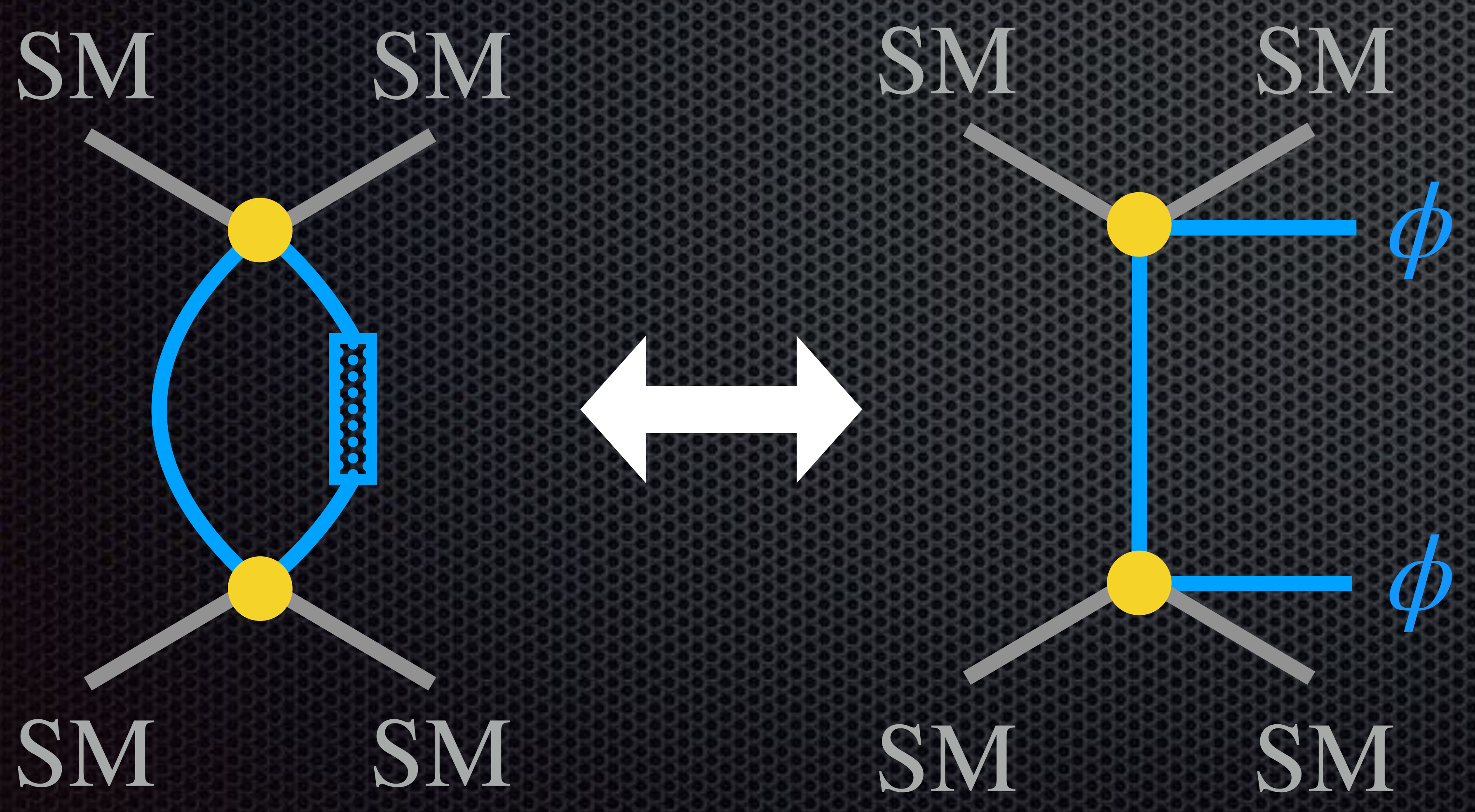
Background-Induced Force





Background-Induced Force





$$\mathbf{F}_{\rm bg} \sim \boxed{\frac{\rho_\phi}{m_\phi^2}} \, (m_{\rm M}^2 V_R)^2 \, \frac{1}{r^2}$$

$$\phi^2$$

$$a \sim 10^{-13}\,{\rm m/s^2} \times \left(\frac{1{\rm cm}}{R}\right) \times \frac{(m_{\rm M} R)^4}{(k_\phi r)^2}$$

Ferrer, Grifols, 2001,
Hees, et al, 2018,
Banerjee, et al., 2022,
Van Tilburg, 2024,
Barbosa, Fichet, 2024…

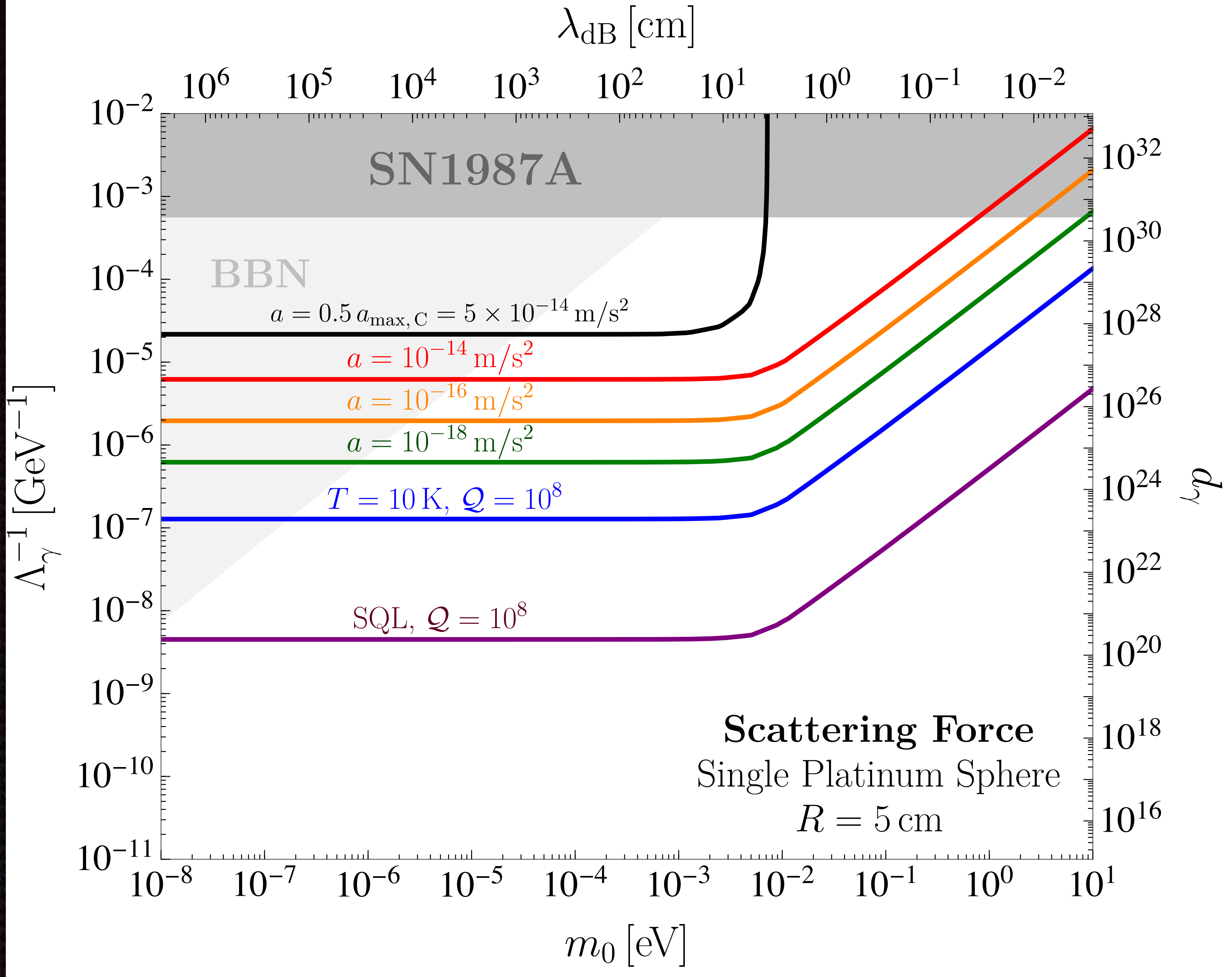
>20 Years

Experimental Sensitivity

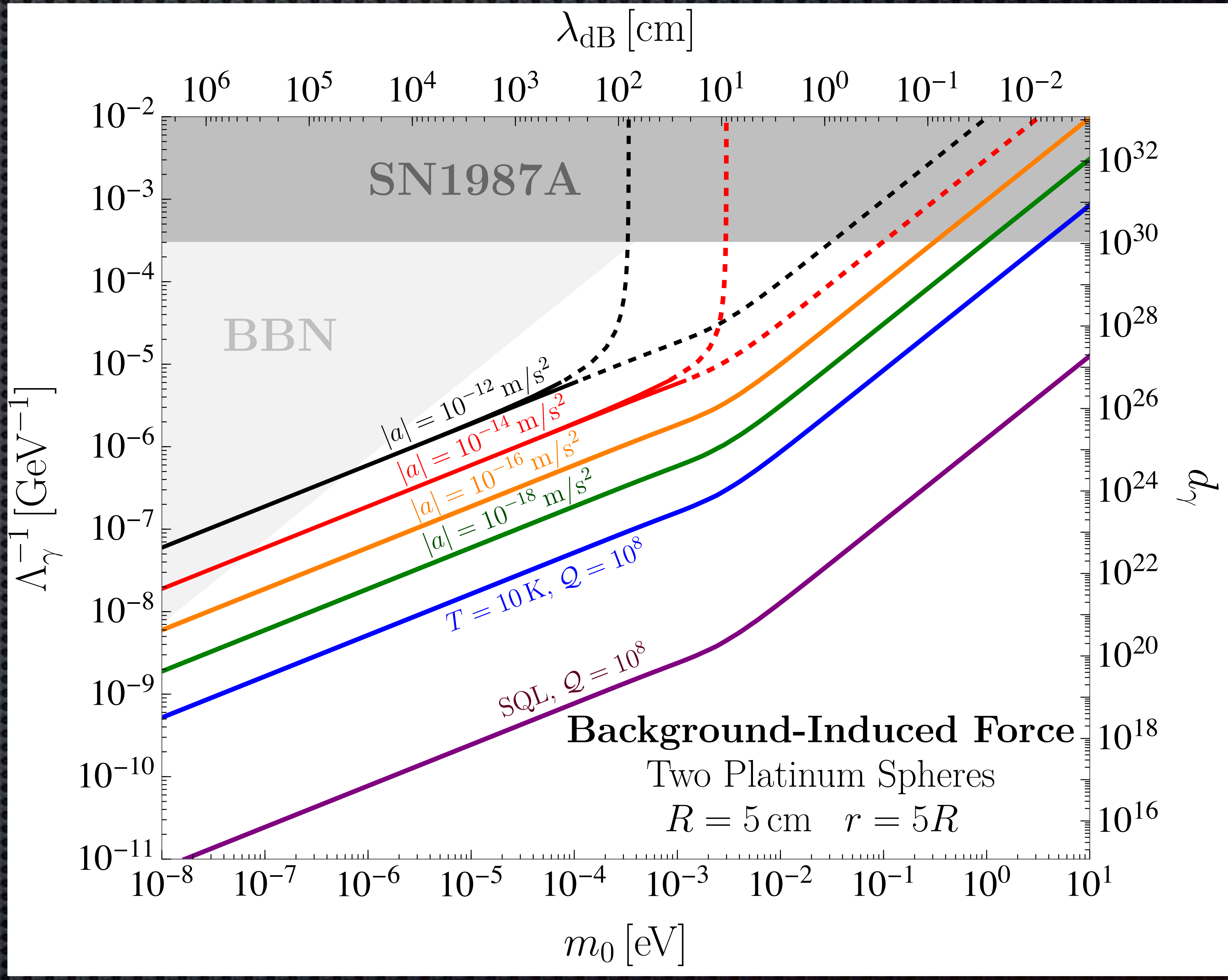
Experiments	Acceleration
MICROSCOPE	$\sim 10^{-14}\,\mathrm{m/s^2}$
Eot-Wash	$\sim 10^{-15}\,\mathrm{m/s^2}$
Galileo Galilei Satellite	$\sim 10^{-16}\,\mathrm{m/s^2}$
Deep Space Mission	$\sim 10^{-18}\,\mathrm{m/s^2}$

Test Mass : $R \sim 1\mathrm{cm} - 10\,\mathrm{cm}$

Experimental Sensitivity



Scattering Force



Background-Induced Force

End of Exploration?

We need unified treatment!

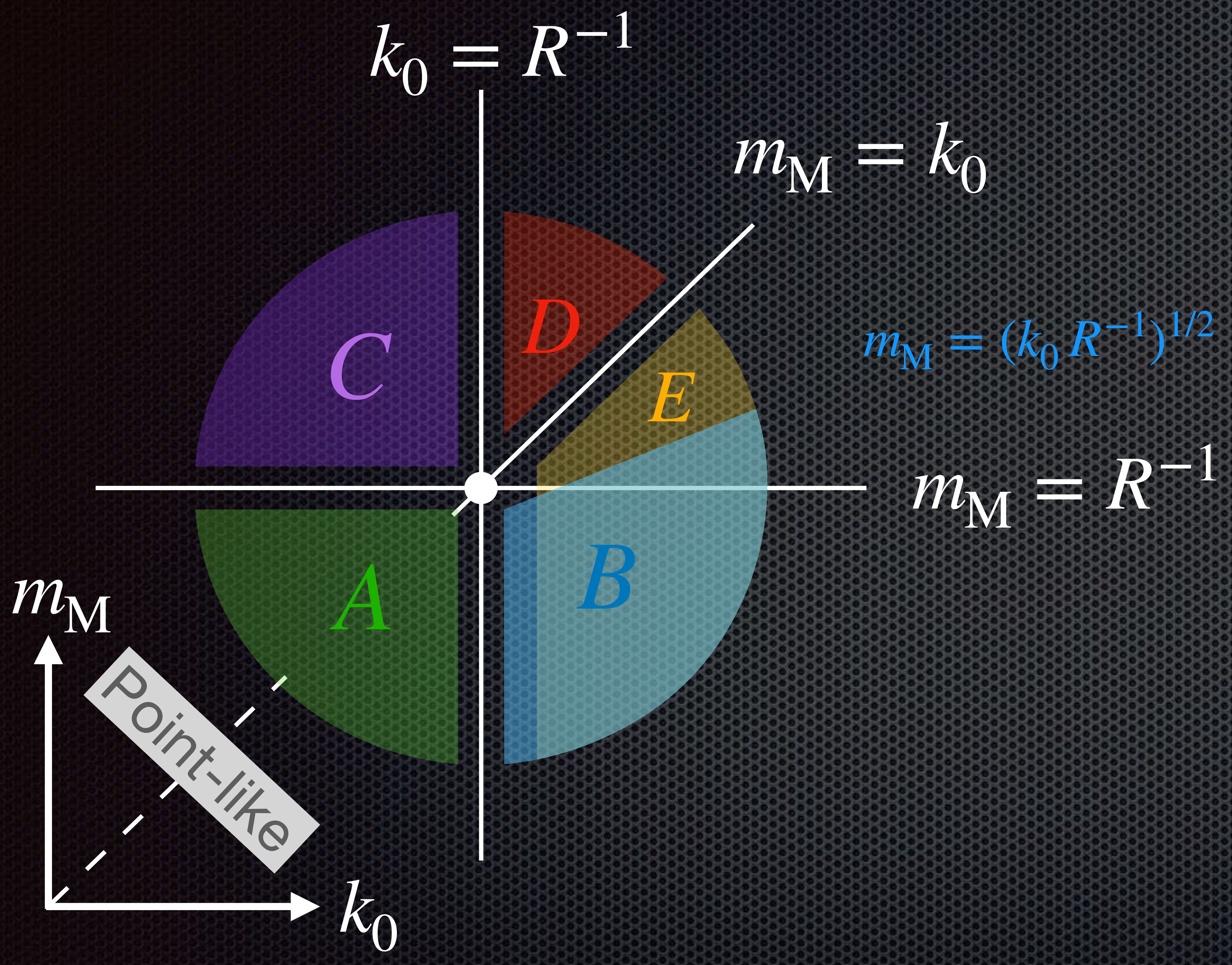
We need to include the non-perturbative behavior!

End of Exploration?

$$\mathbf{F}_{\rm sc} \sim \frac{(m_{\rm M}^2 V_R)^2}{4\pi} \times \rho_\phi v_\phi^2 \times \text{Form Factor}$$

$$\mathbf{F}_{\rm bg} \sim \frac{\rho_\phi}{m_\phi^2} (m_{\rm M}^2 V_R)^2 \frac{1}{r^2} \times \text{Form Factor}$$

Classification



★ Region: A

Ferrer, Grifols, 2001,
Barbosa, Fichet, 2024…

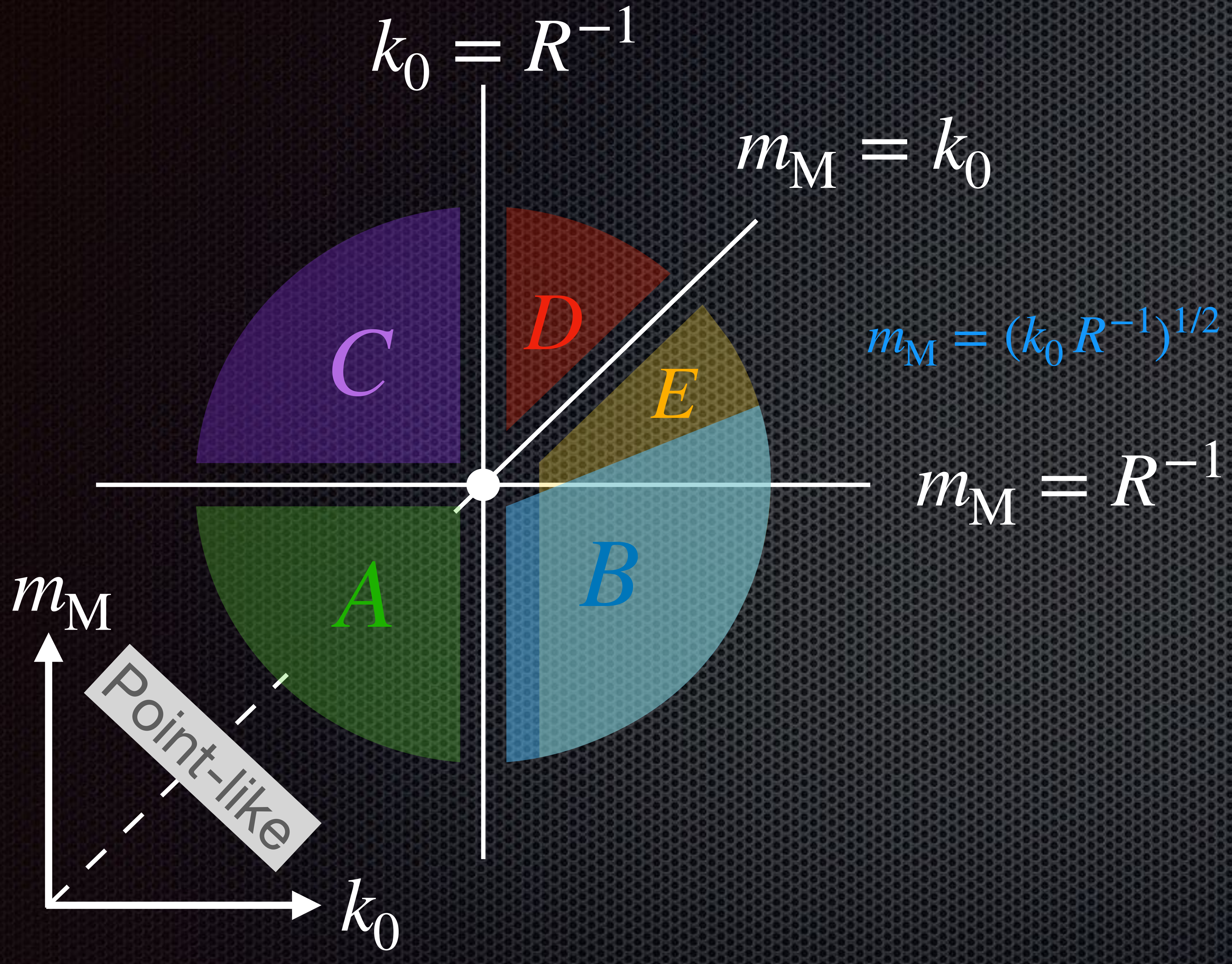
★ Regions: A+B

Van Tilburg, 2024

★ Regions: A+C

Hees, et al, 2018,
Banerjee, et al., 2022

Classification



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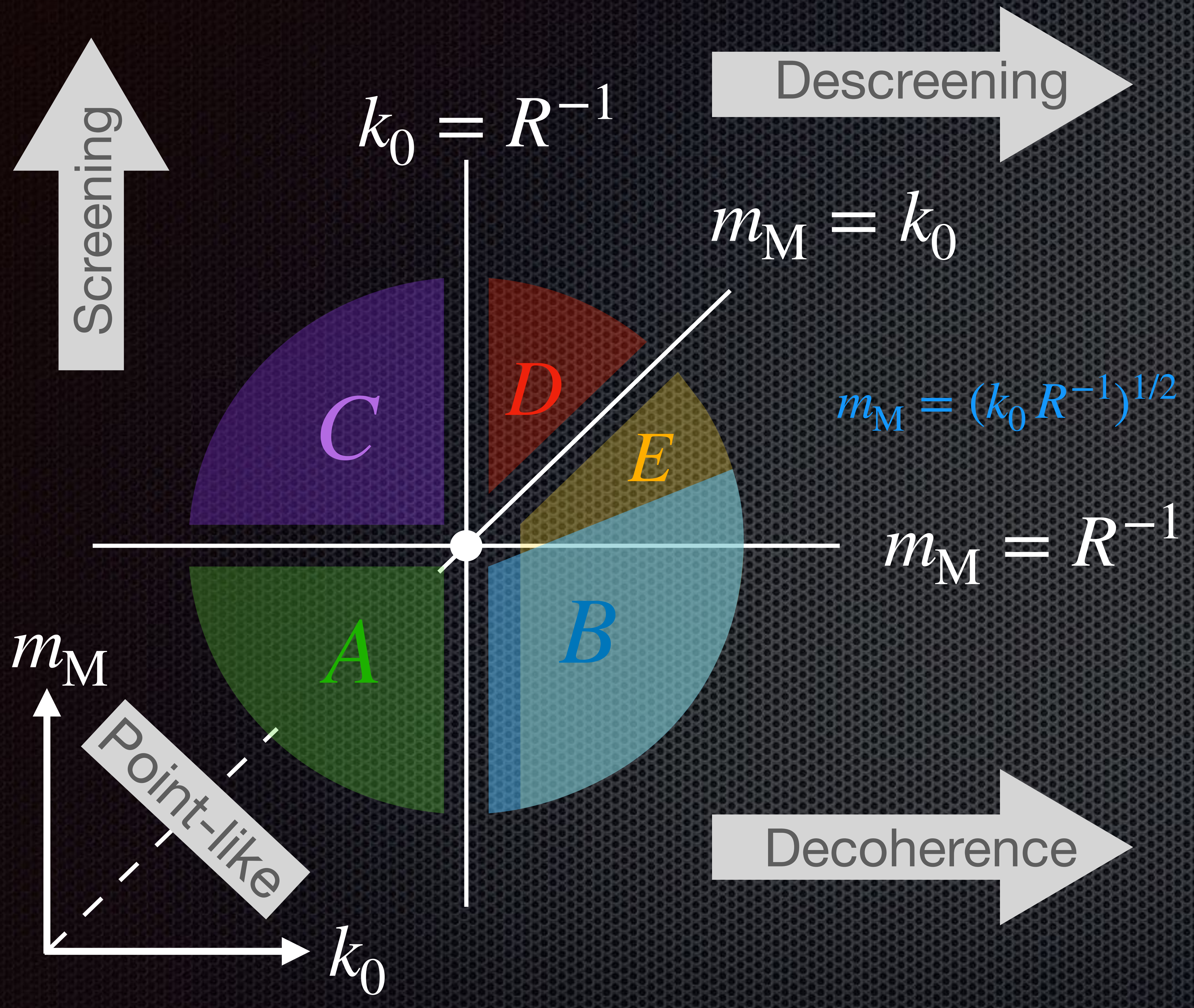
Banerjee, et al., 2022

Our work

A+B+C
+D+E

Classification



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Hees, et al, 2018,
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Our work

A+B+C
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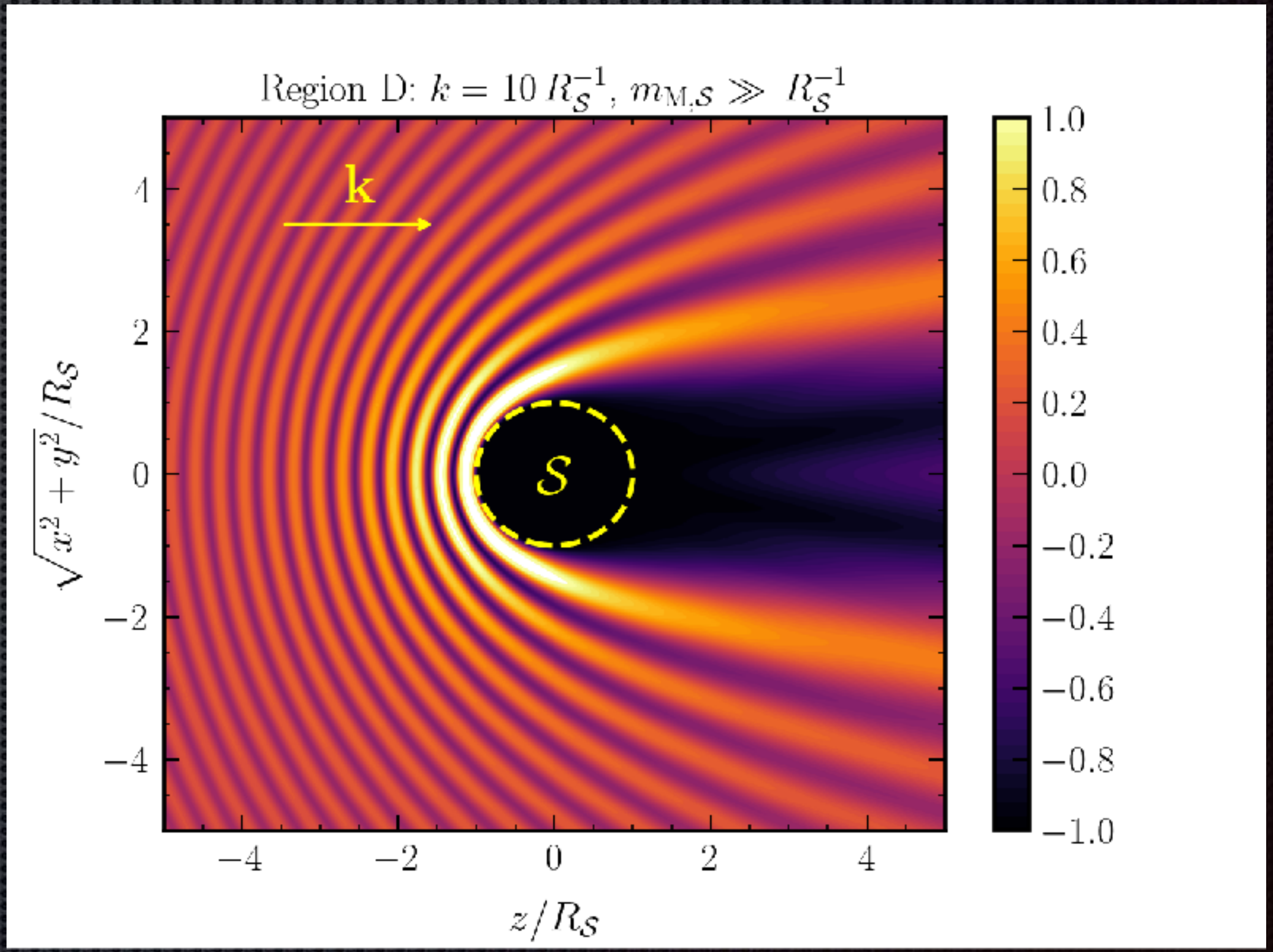
Partial Wave + Phase Space

$$\psi_{\rm tot} = \psi_{\rm in} + \psi_{\rm sc}$$

$$\begin{cases} \psi_{\rm in} = |\phi_0| e^{i\mathbf{k}\cdot\mathbf{r}} \\ \psi_{\rm sc} = \sum_{l=1}^{l_{\rm max}} \psi_{{\rm sc},l} \end{cases}$$

$$l_{\rm max} \sim kR \leq 10^4$$

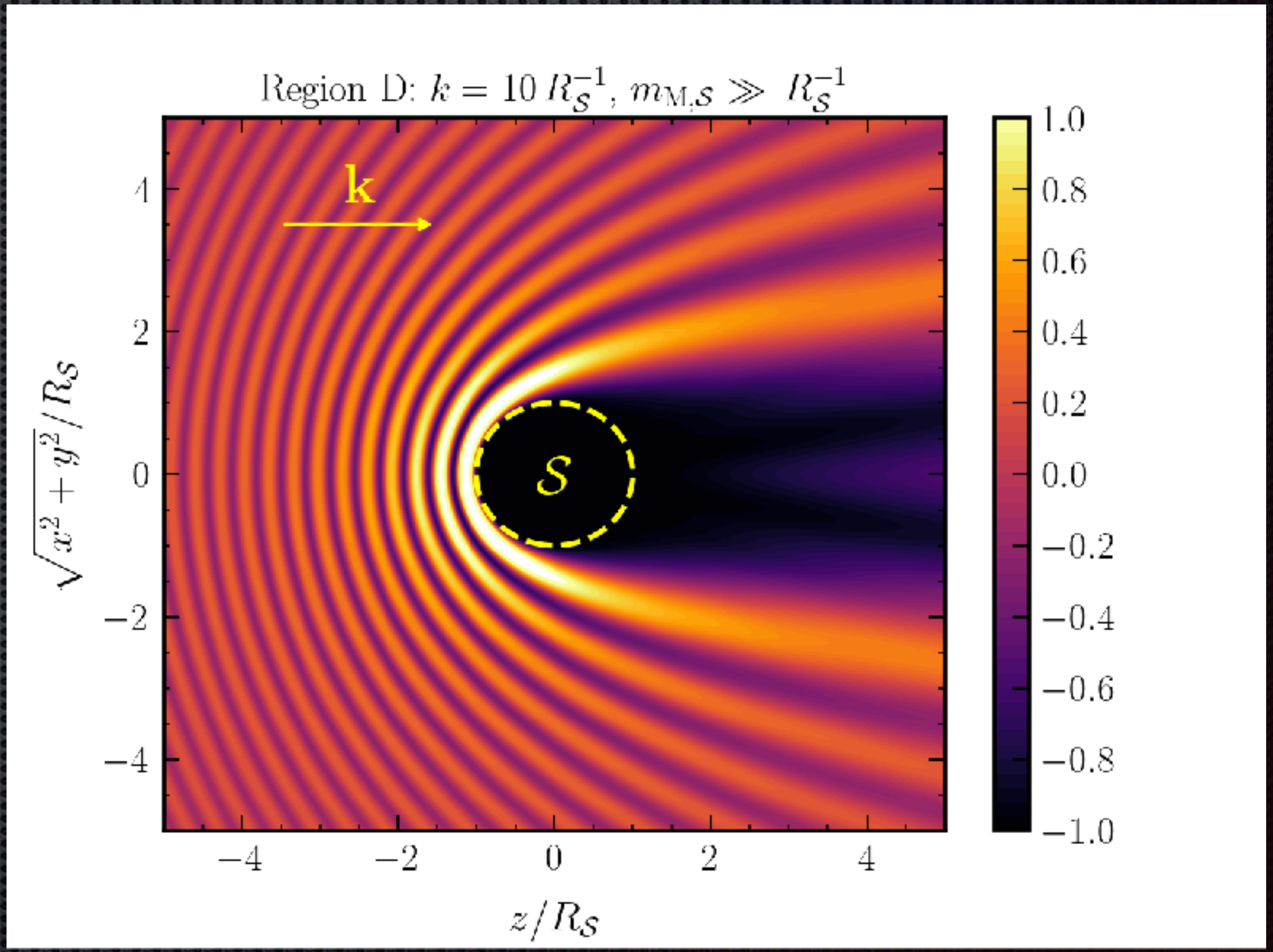


Partial Wave + Phase Space

$$V_{\rm bg}(\mathbf{k}) \propto |\psi_{\rm tot}(\mathbf{k})|^2$$

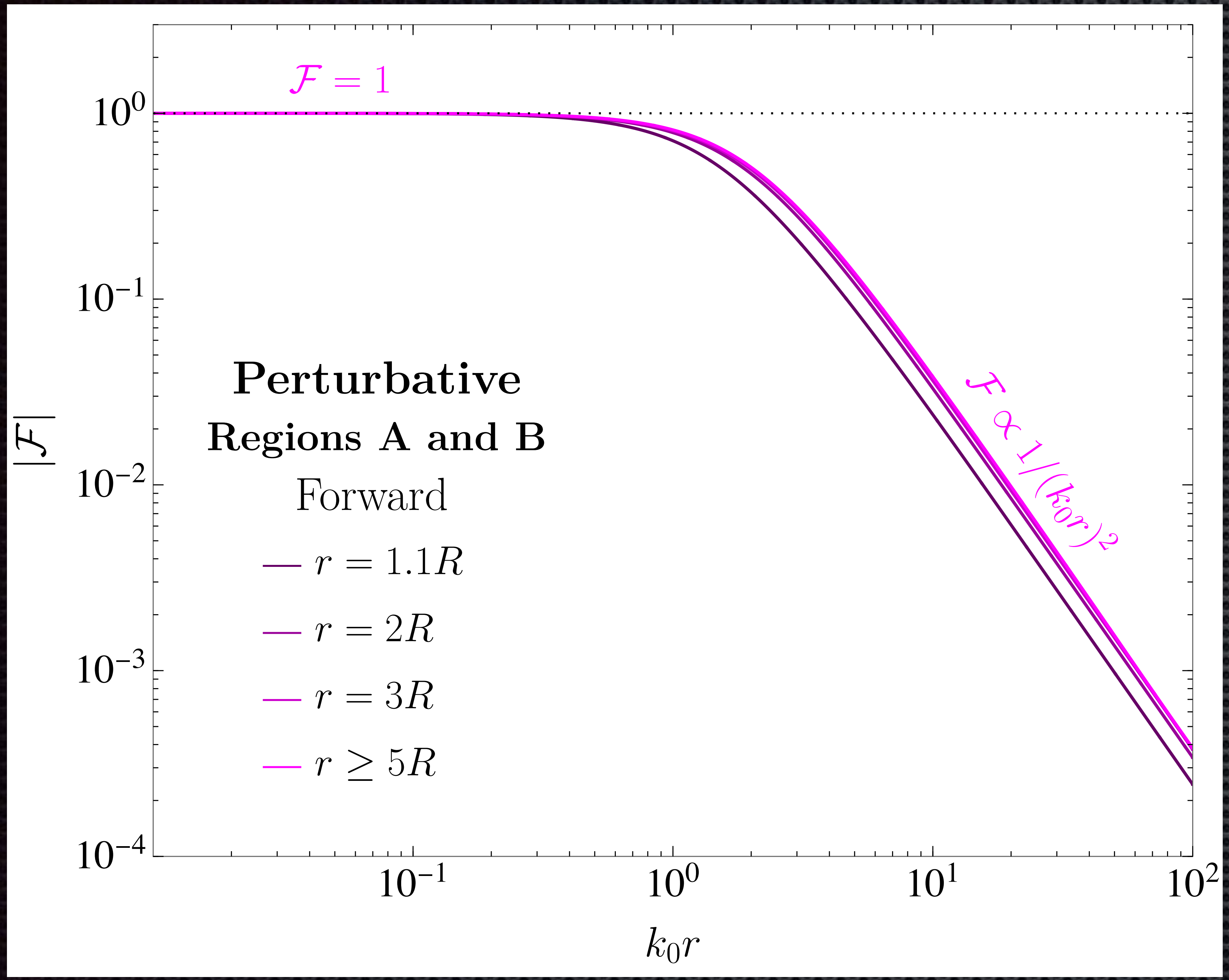
$$\langle V_{\rm bg}\rangle_{\mathbf{k}} = \frac{1}{n_\phi}\int_{\mathbf{k}} f_\phi(\mathbf{k}) V_{\rm bg}(\mathbf{k})$$

$$f_\phi(\mathbf{k}) = n_\phi \left(\frac{2\pi}{\sigma_k^2}\right)^{3/2} \exp\left[-\frac{(\mathbf{k}-\mathbf{k}_0)^2}{2\sigma_k^2}\right]$$

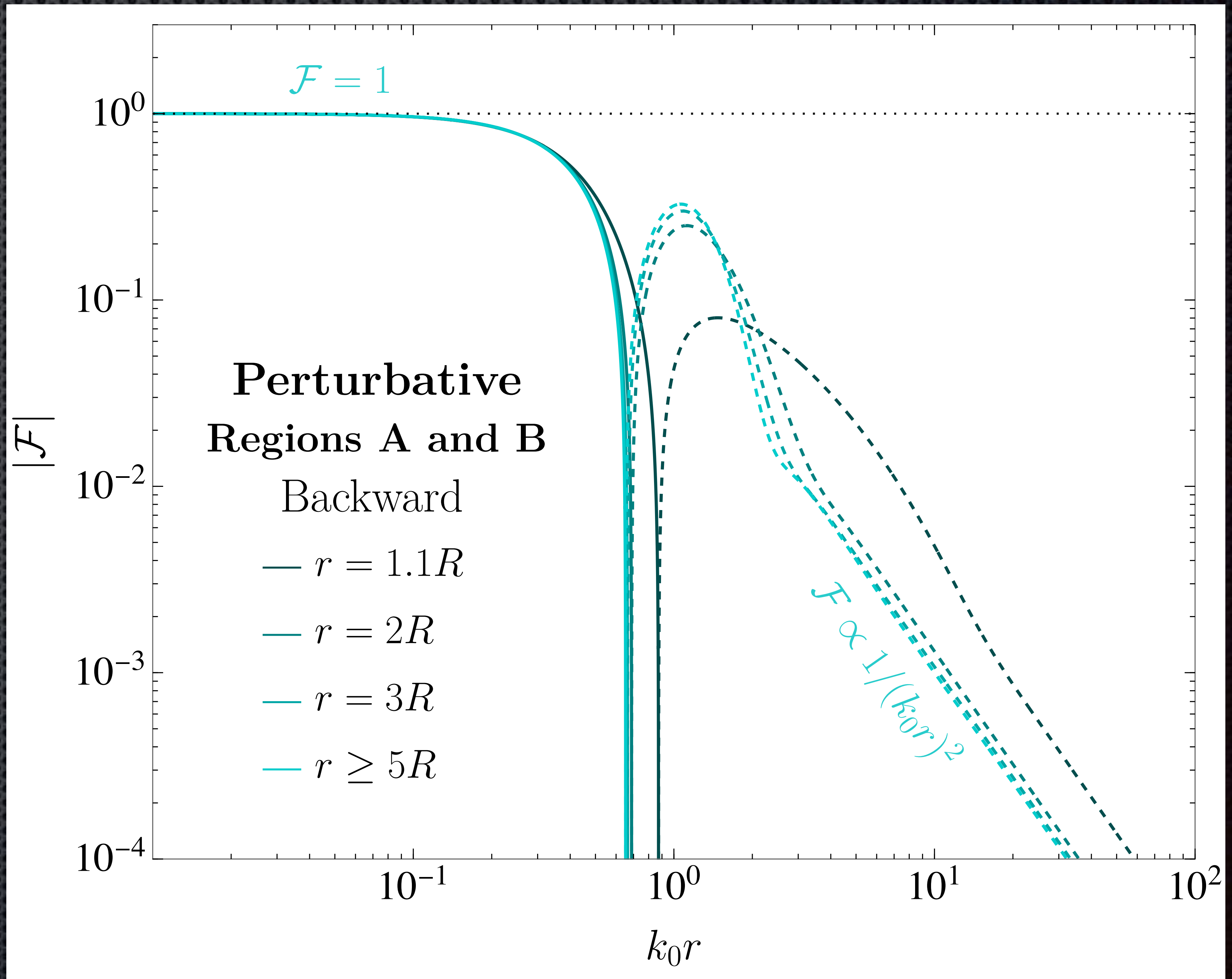


Perturbative Form Factor

$$V_{\rm bg} \sim \frac{\rho_\phi}{m_\phi^2}\,(m_{\rm M}^2 V_R)^2\,\frac{1}{r} \times \mathscr{F}$$



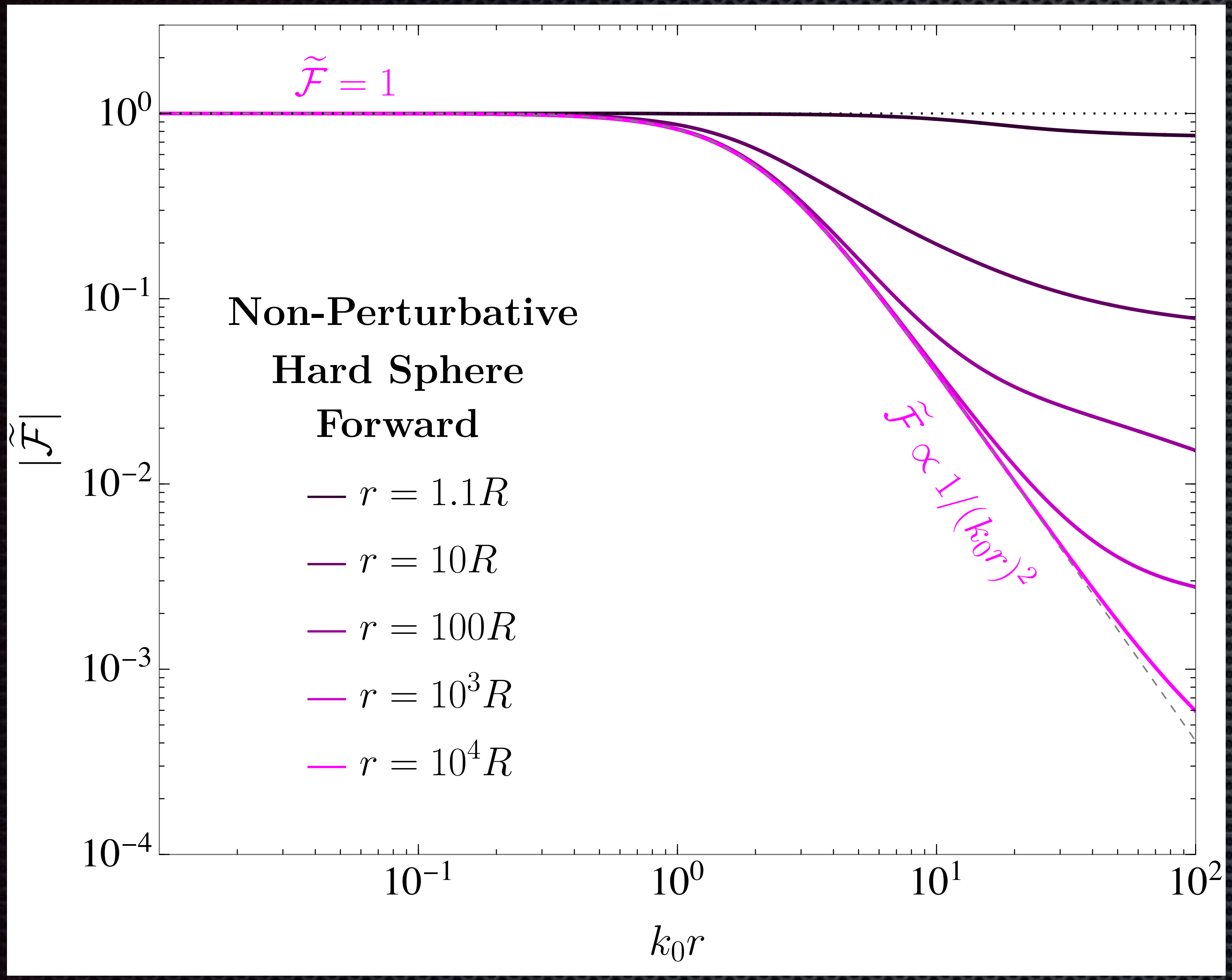
Forward Direction



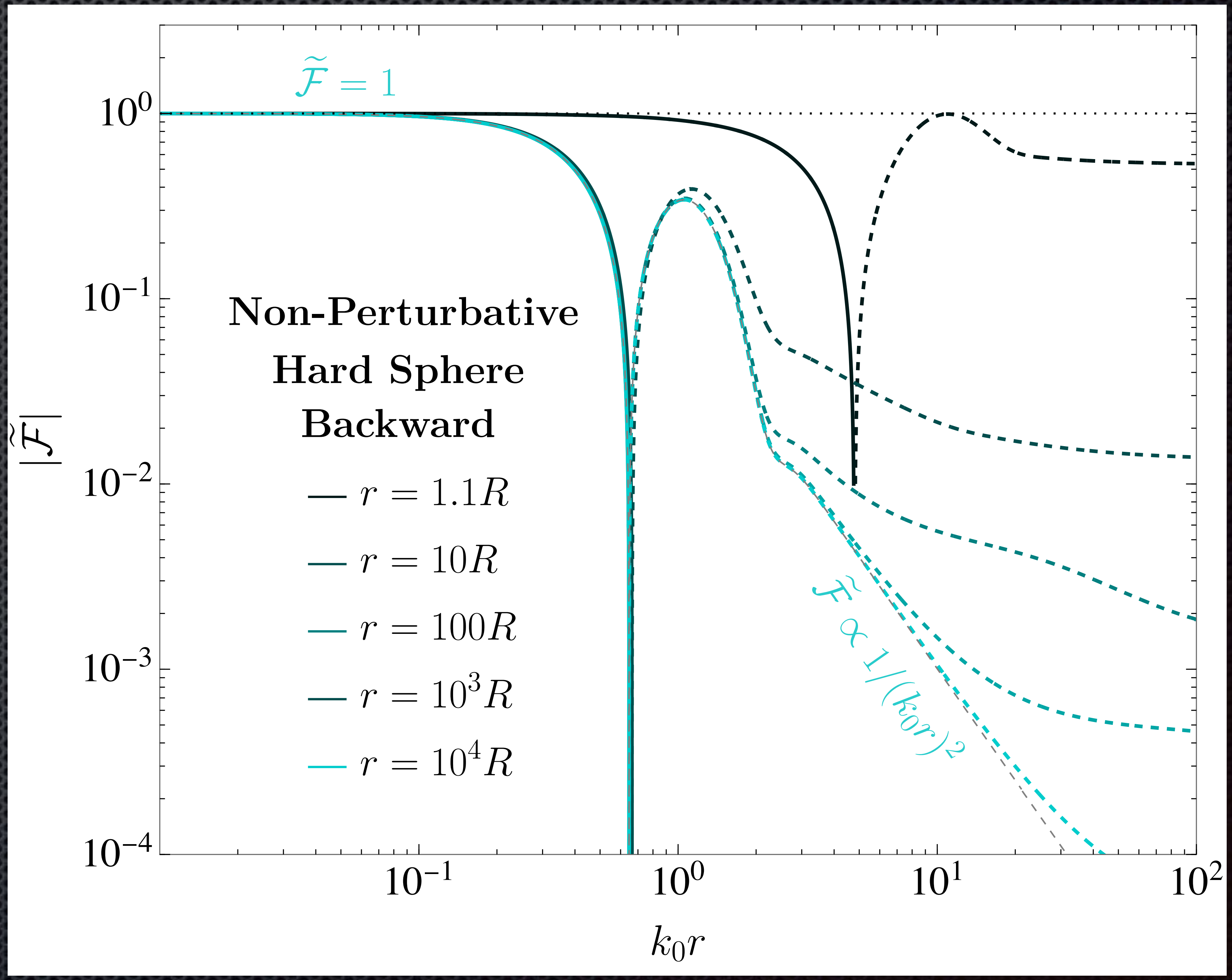
Backward Direction

Non-Perturbative Form Factor

$$V_{\rm bg} \sim \frac{\rho_\phi}{m_\phi^2}\,(m_{\rm M}^2 V_R)^2\,\frac{1}{r} \times \mathscr{F}_{\rm sph} \times \widetilde{\mathscr{F}}$$

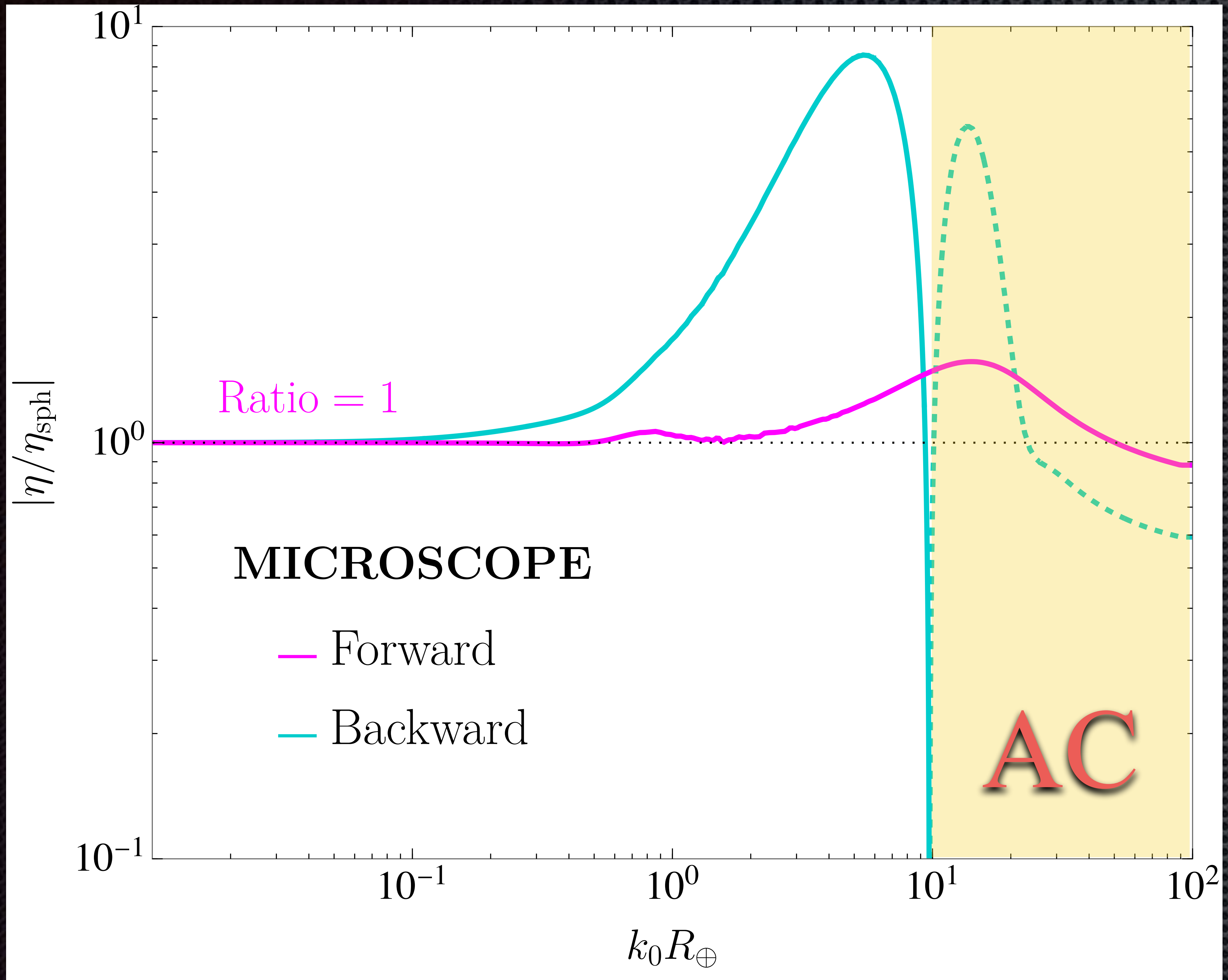


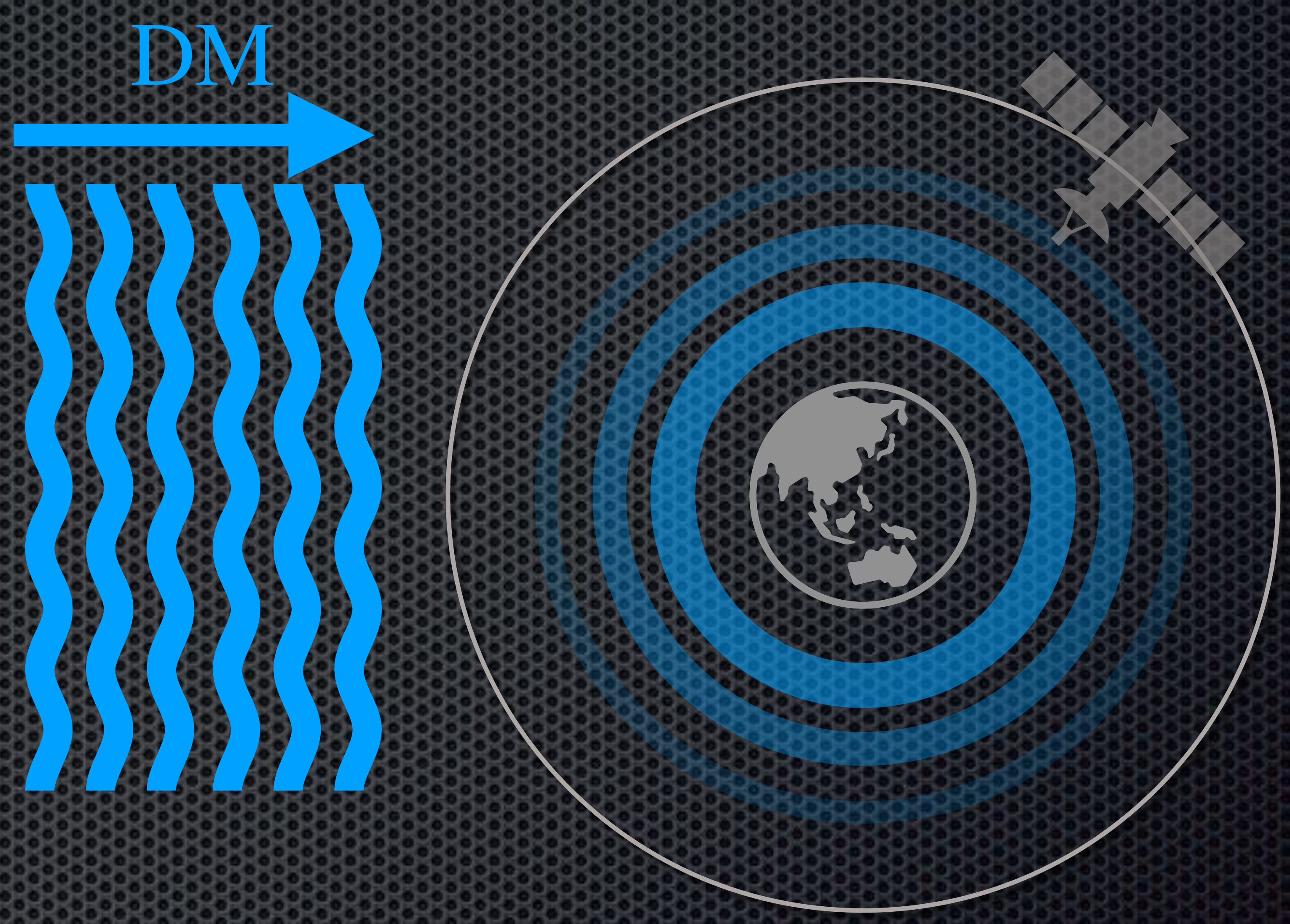
Forward Direction



Backward Direction

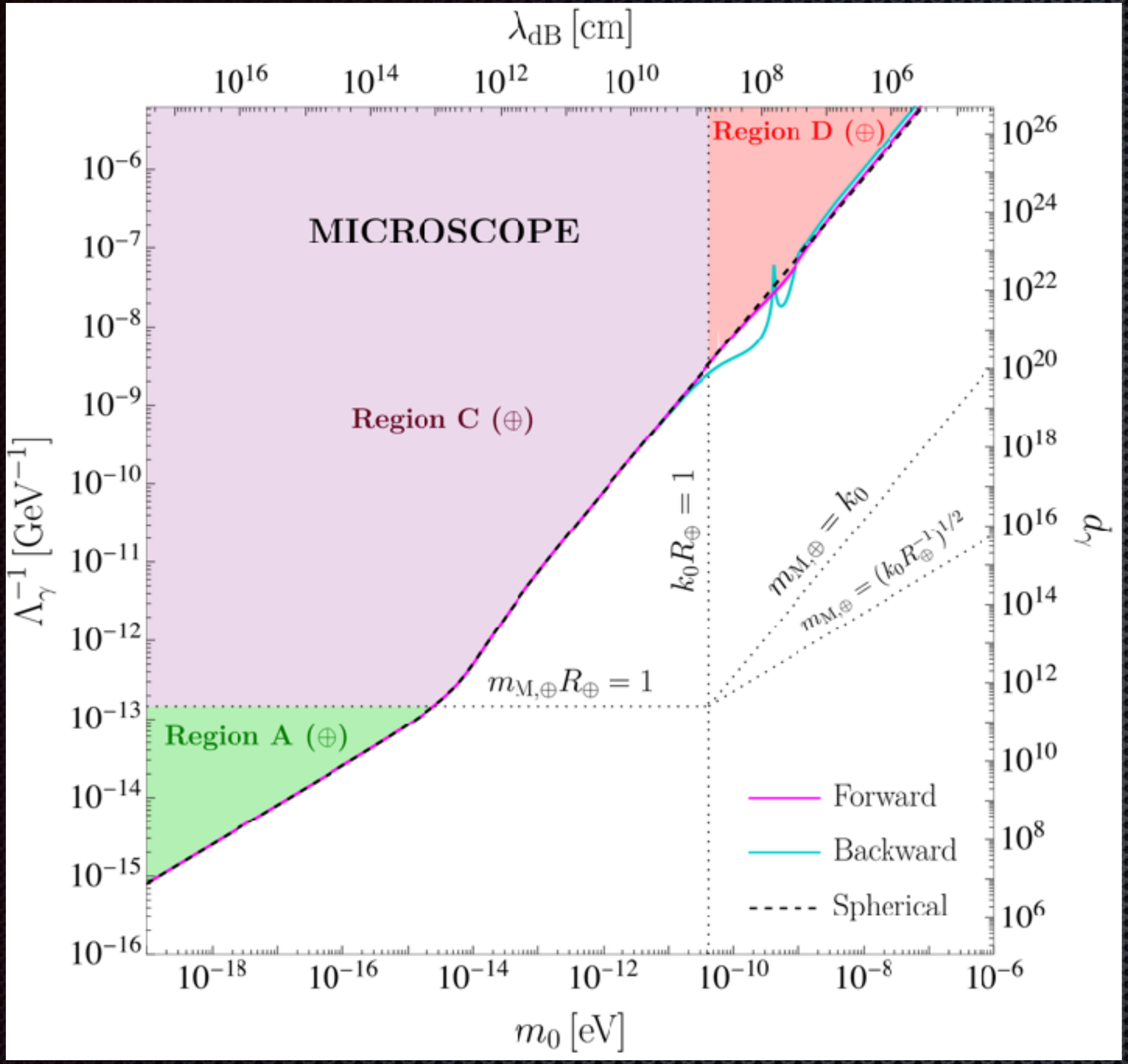
MICROSCOPE Satellite

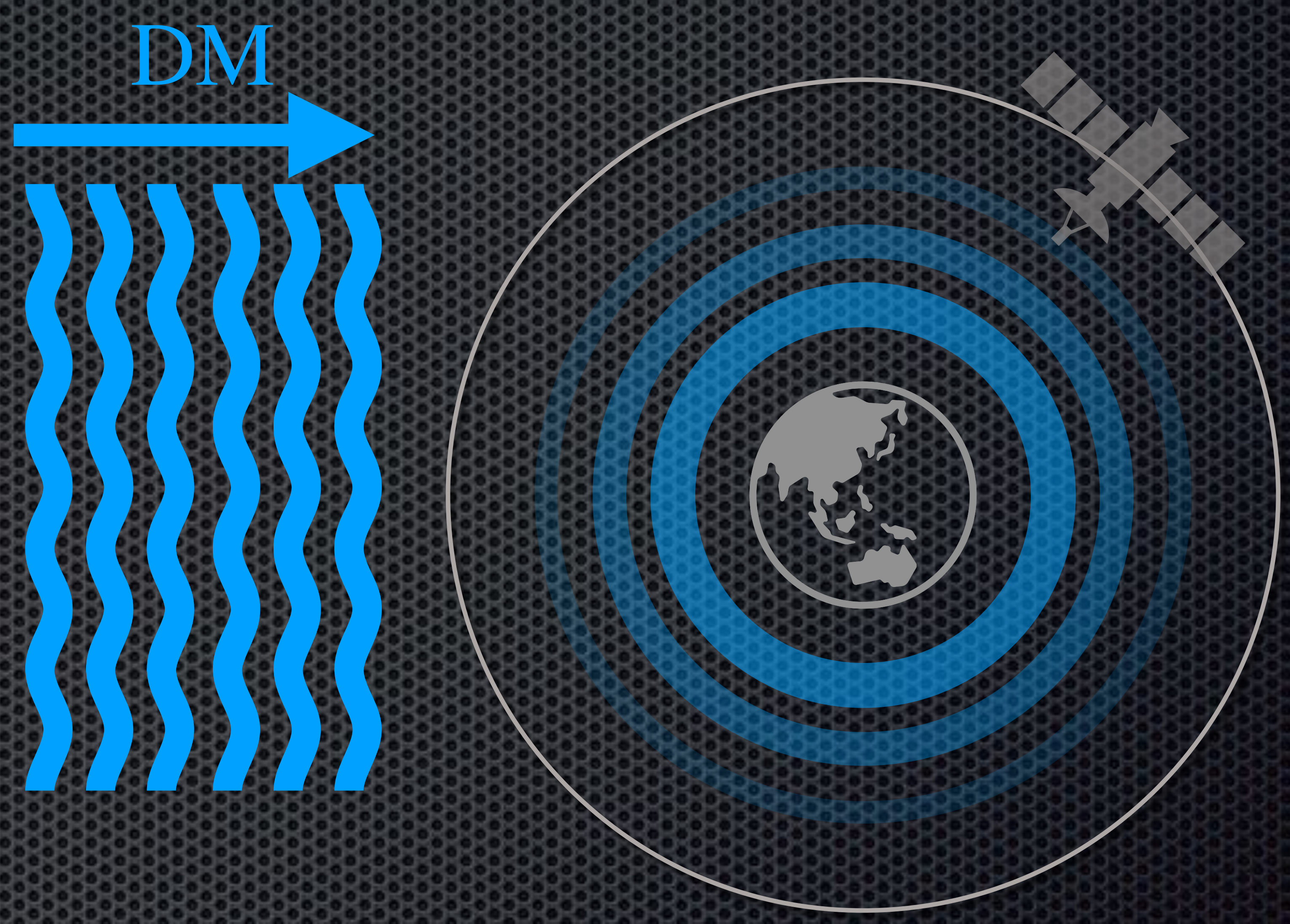




1. $\mathcal{O}(1) - \mathcal{O}(10)$ Difference
2. $m > 10^{-8}$eV, AC Force (1.6 hour)

MICROSCOPE Satellite





$$\eta = \frac{|\mathbf{a}_A - \mathbf{a}_B|}{|\mathbf{a}_A + \mathbf{a}_B|} \sim 10^{-14}$$

Conclusions

1. The quadratic coupling arise in axion, dilaton, and pNGB models.

2. Quadratic couplings can be probed via matter effects, which manifest as a scattering force and a background-induced force. Both forces produce accelerations of test masses that can be measured using precision accelerometers.

3. Previous studies were limited to specific regions of the parameter space. By employing partial wave analysis, we develop a unified framework that covers the entire parameter space, including both perturbative and non-perturbative regimes.

4. We revisited the MICROSCOPE equivalence principle test and updated the constraints in the high-momentum regime. Additionally, we identified the AC component of the background-induced force acting on the test mass.

Appendix

Experimental Sensitivity

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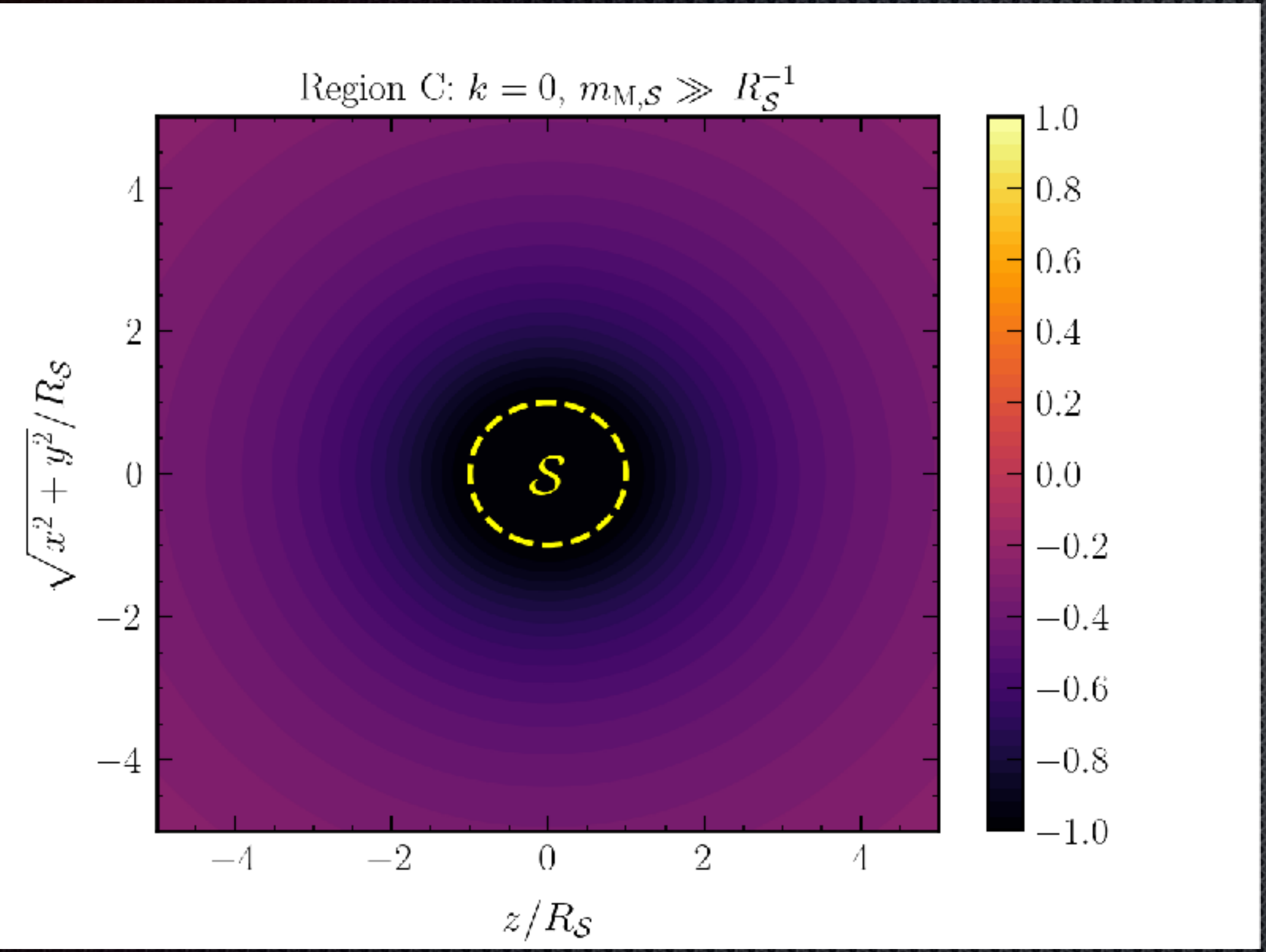
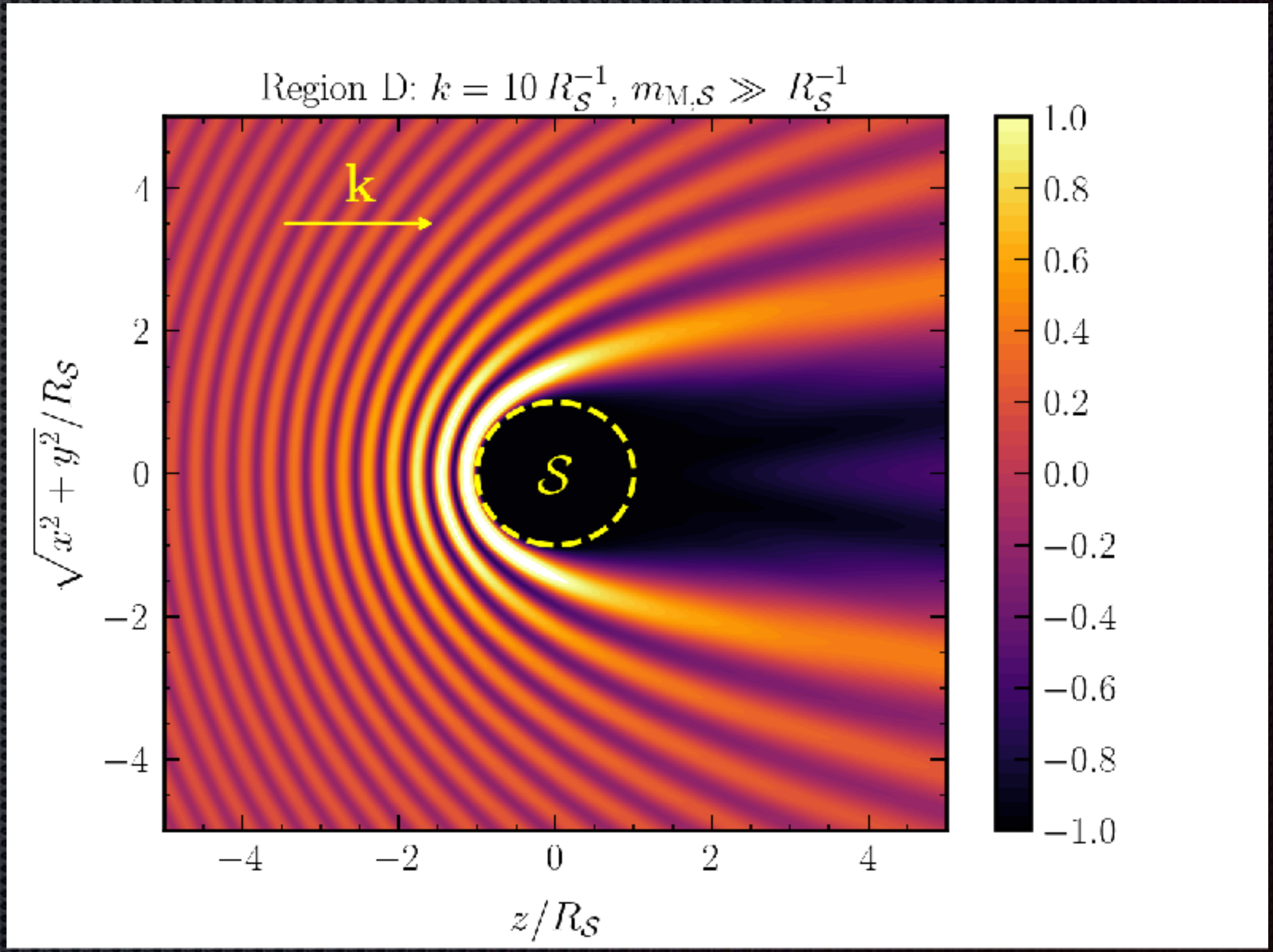
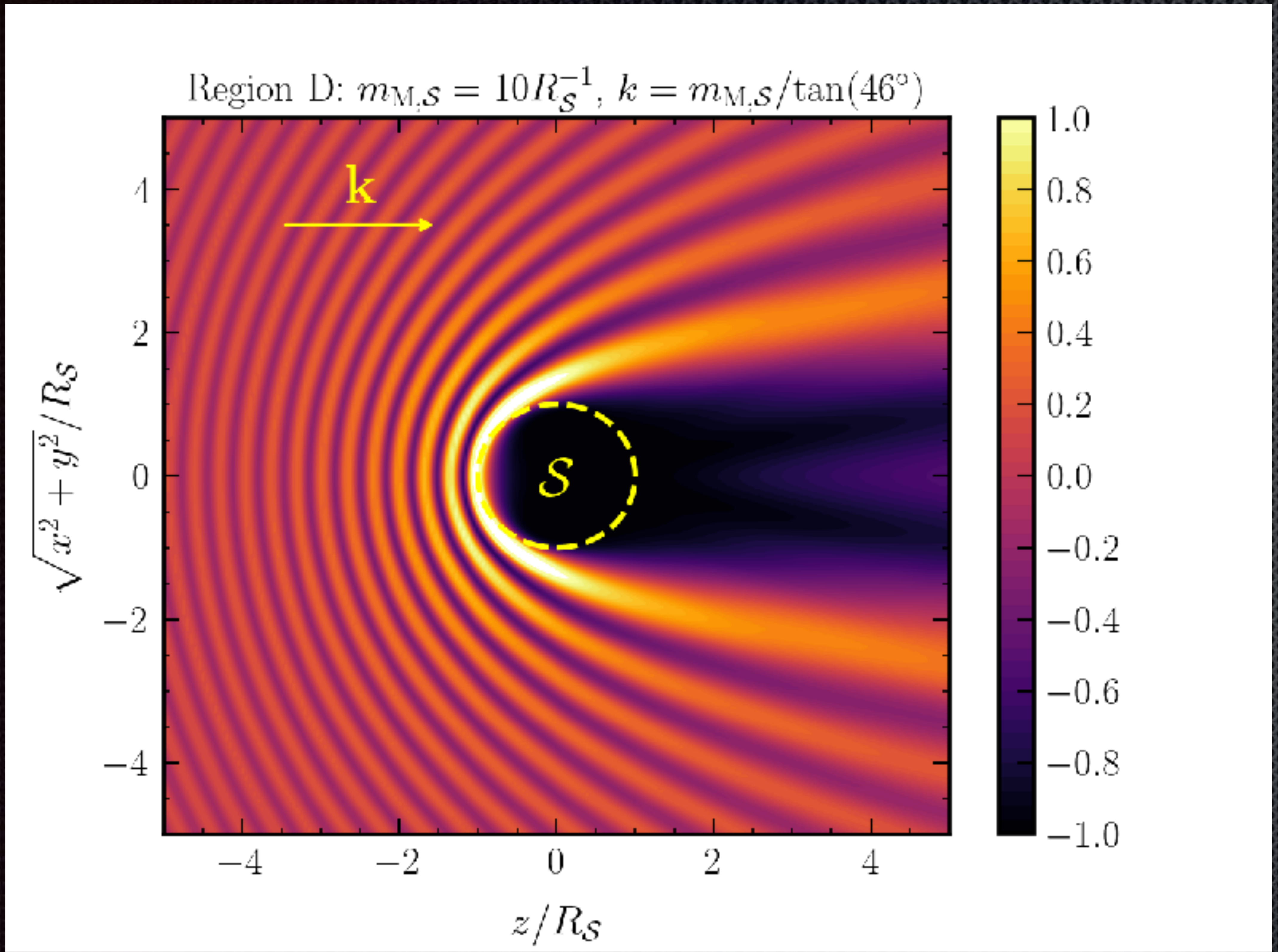
Galileo Galilei Satellite	$\sim 10^{-16}\,\mathrm{m/s^2}$
Deep Space Mission	$\sim 10^{-18}\,\mathrm{m/s^2}$
$T \sim 10\,\mathrm{K}, \quad Q \sim 10^8$	$\sim 10^{-20}\,\mathrm{m/s^2}$
$\mathrm{SQL}, \quad Q \sim 10^8$	$\sim 10^{-27}\,\mathrm{m/s^2}$

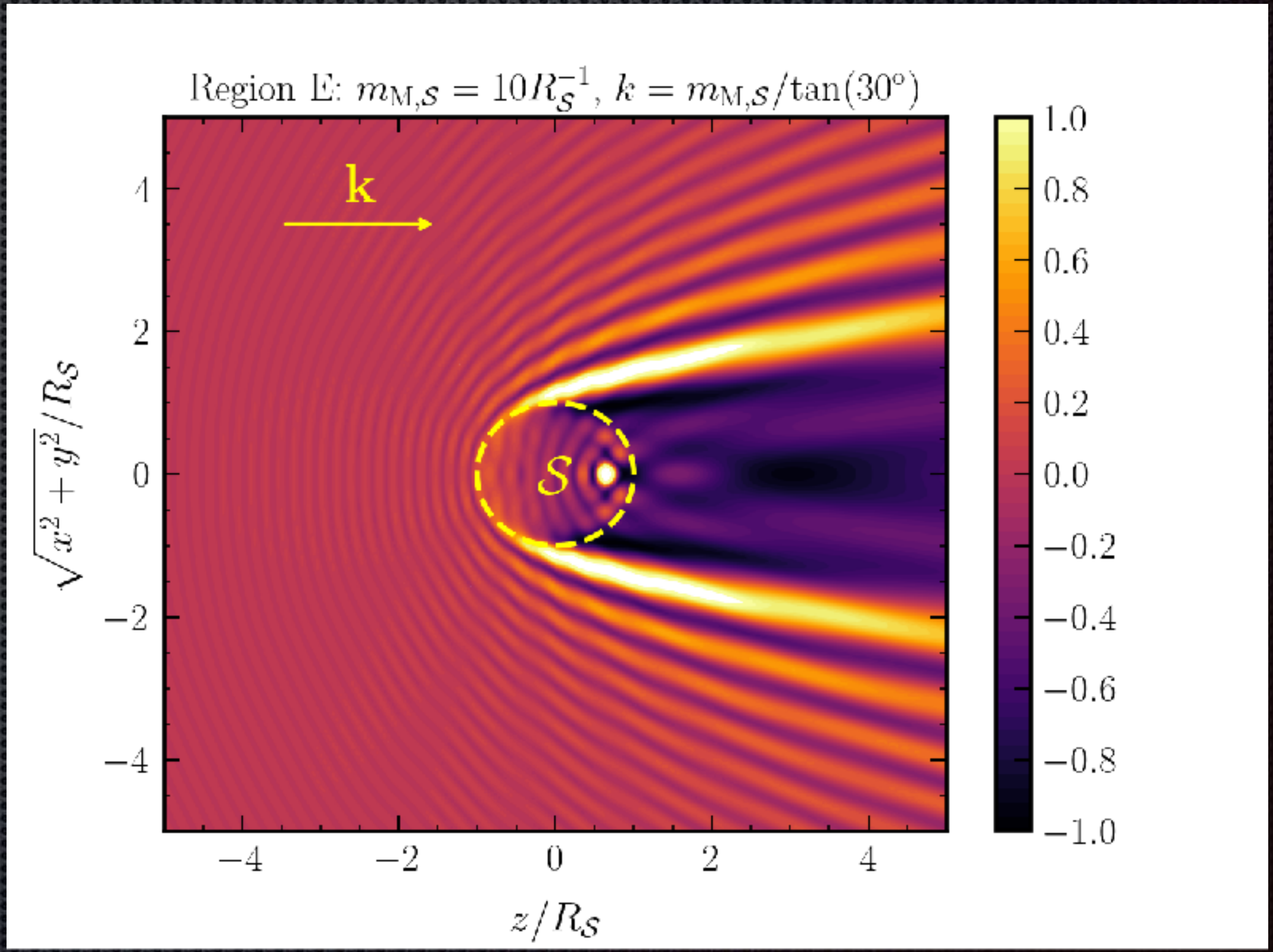
Screening Effect





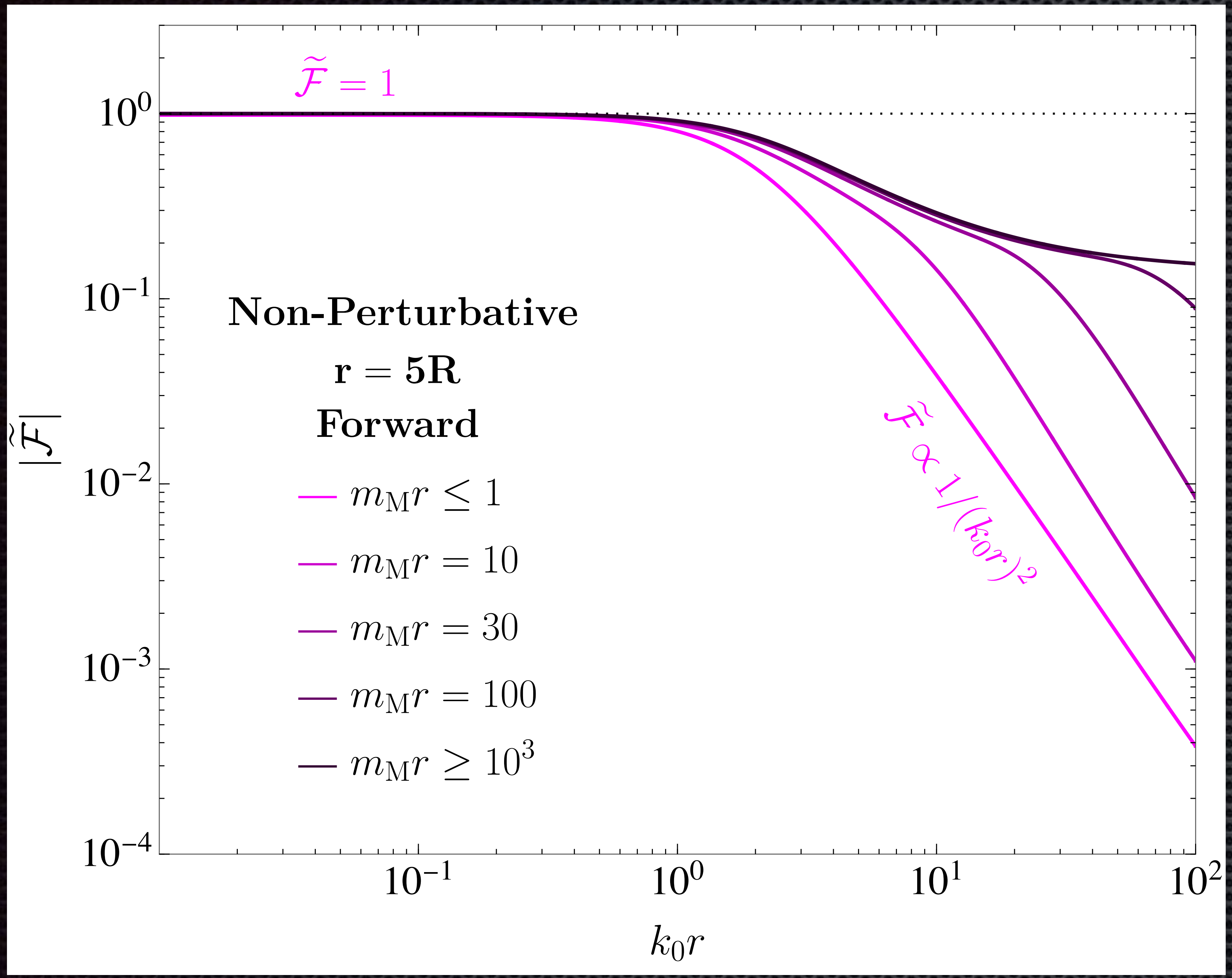
Descreening Effect



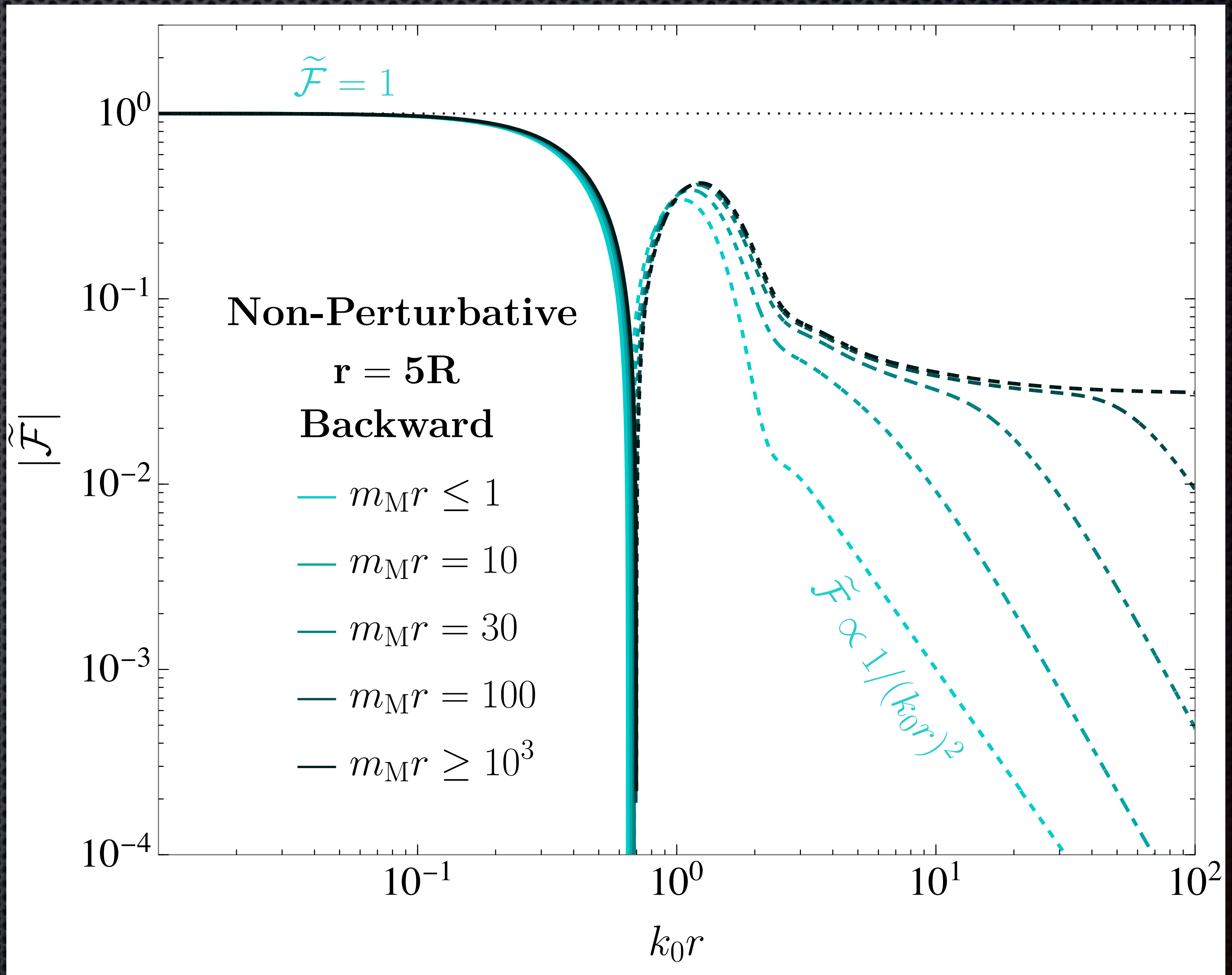


Descreening Effect

$$V_{\text{bg}} \sim \frac{\rho_\phi}{m_\phi^2} \, (m_{\text{M}}^2 V_R)^2 \frac{1}{r} \times \mathscr{F}$$



Forward Direction



Backward Direction

Spherical Symmetric Ansatz

$$\nabla^2 \psi_{\rm sph} = m_{\rm M}^2\, \theta(R-r)\, \psi_{\rm sph}$$

$$\psi_{\rm sph} = |\phi_0| \left[1 - \frac{m_{\rm M} R - \tanh(m_{\rm M} R)}{m_{\rm M}}\right] \simeq \min\left[1, \frac{3}{(m_{\rm M} R)^2}\right]$$

Screening Effect

Hees, et al, 2018,
Banerjee, et al., 2022

UV Models: Scalar-Photon

Heavy Fermion

$$\mathscr{L} \supset -\frac{y\alpha_{\rm em} Q_F^2 \cos(c)}{6\sqrt{2}\pi M_F f_\phi}\phi^2 F_{\mu\nu}F^{\mu\nu}$$

Heavy Scalar

$$\mathscr{L} \supset -\frac{\lambda\alpha_{\rm em} Q_S^2}{48\pi M_S^2}\phi^2 F_{\mu\nu}F^{\mu\nu}$$

Dark QCD Axion

$$\mathscr{L} \supset -\frac{\epsilon^2\alpha'}{192\pi f_a^2}a^2 F_{\mu\nu}F^{\mu\nu} + \delta_{\rm iso}\frac{\epsilon\alpha'}{4\pi f_a}\left(a\, F_{\mu\nu}\tilde{F}'^{\mu\nu} + \epsilon\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$