PASCOS 2025

Detecting Ultralight Dark Matter with Matter Effect

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DESY, Hamburg

2504.11522

Collaborators:

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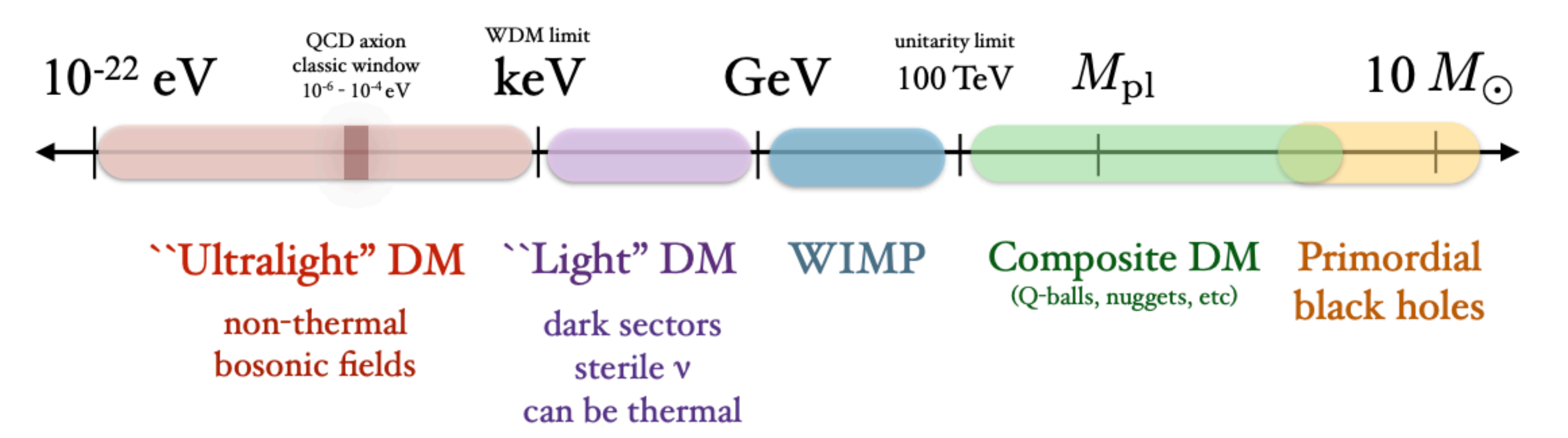
Dark Matter Landscape



From Tongyan Lin, 2019 TASI Lecture

Ultralight Dark Matter

Large occupation number & Classical behavior

Quadratic Coupling

$$\frac{1}{\Lambda^2}\phi^2\mathcal{O}_{\mathrm{SM}} \to \begin{cases} F^2 \\ G^2 \\ m_f\bar{f}f \end{cases}$$

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

Axion

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

Dilaton

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

Other Scalars

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

Quadratic Coupling

Benchmark Model

$$\frac{1}{\Lambda^2}\phi^2\mathcal{O}_{\rm SM} \to \begin{cases} \boxed{F^2} \\ G^2 \\ m_f\bar{f}f \end{cases}$$

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

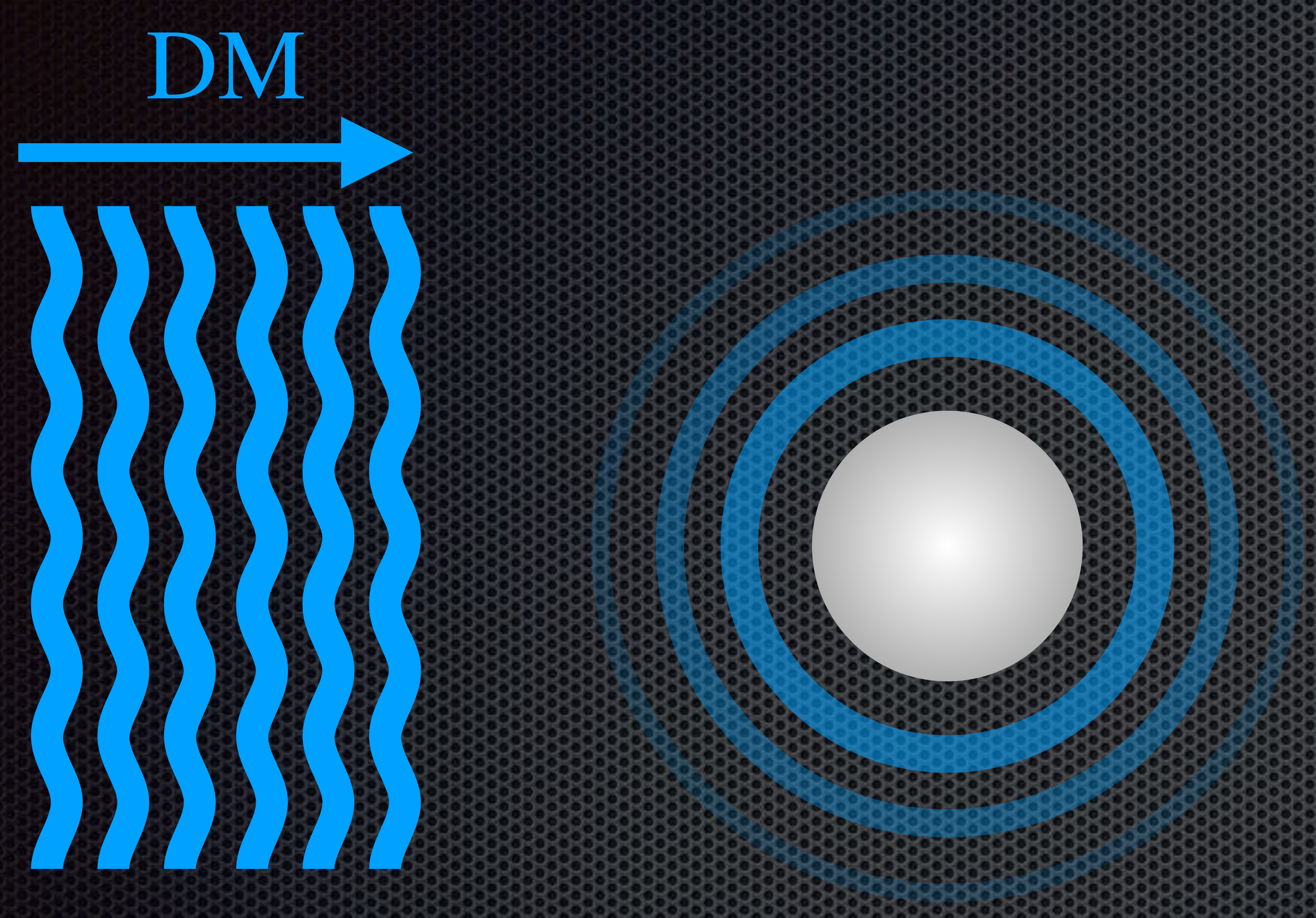
Ordinary Matter

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

Effective Mass

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

Matter Effect



Ordinary Matter

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

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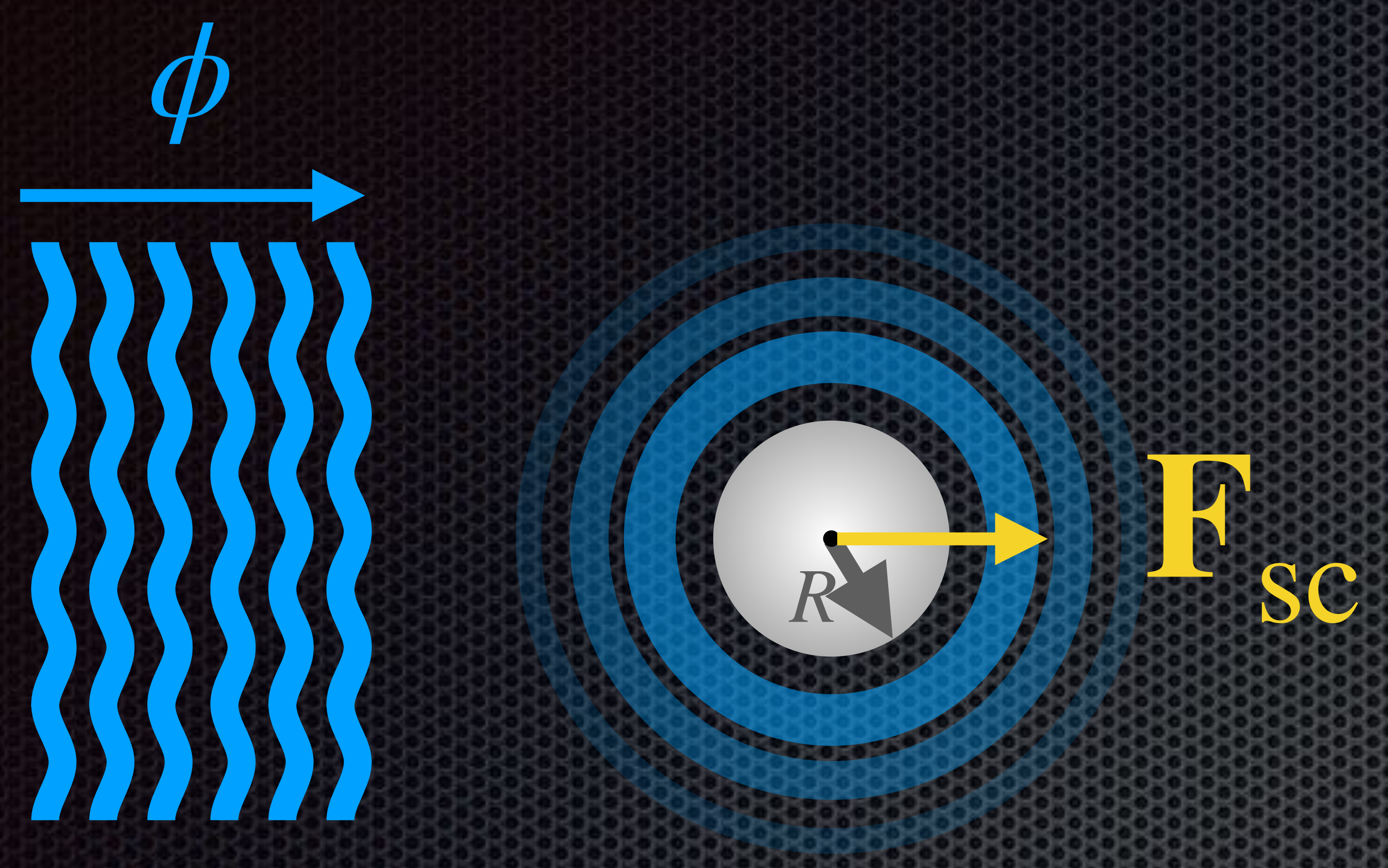
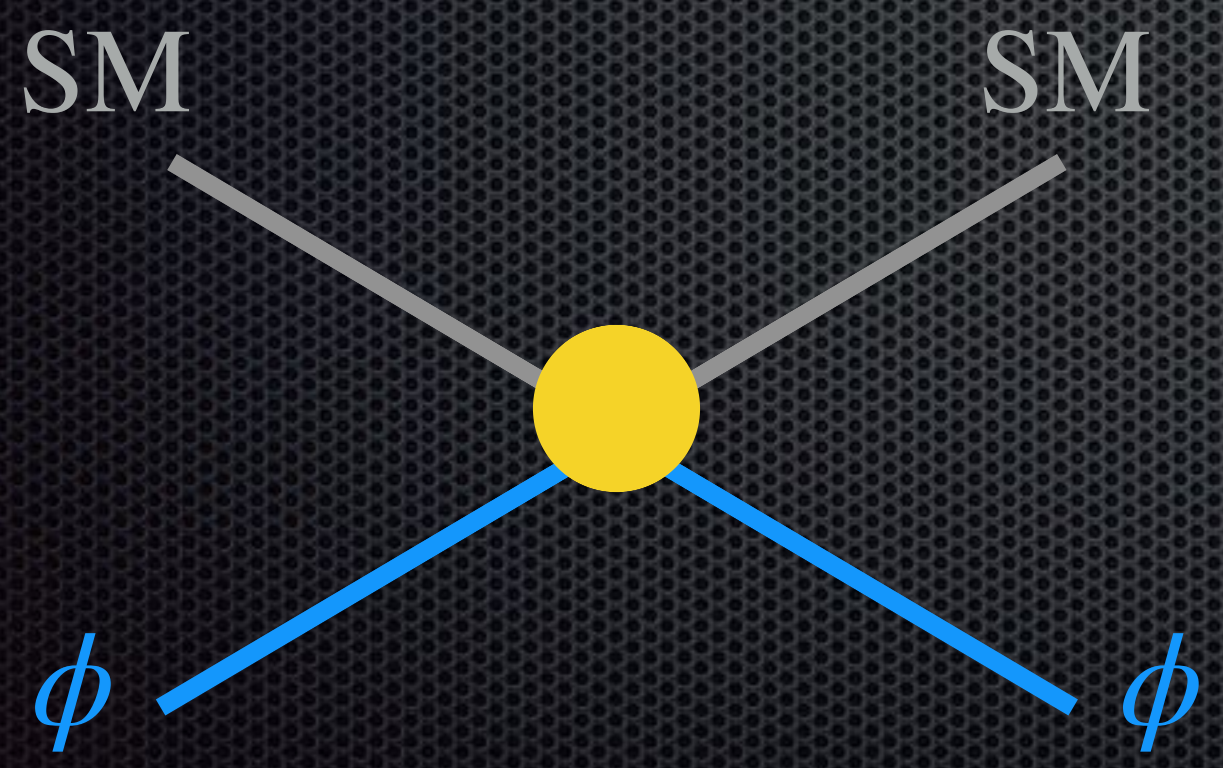
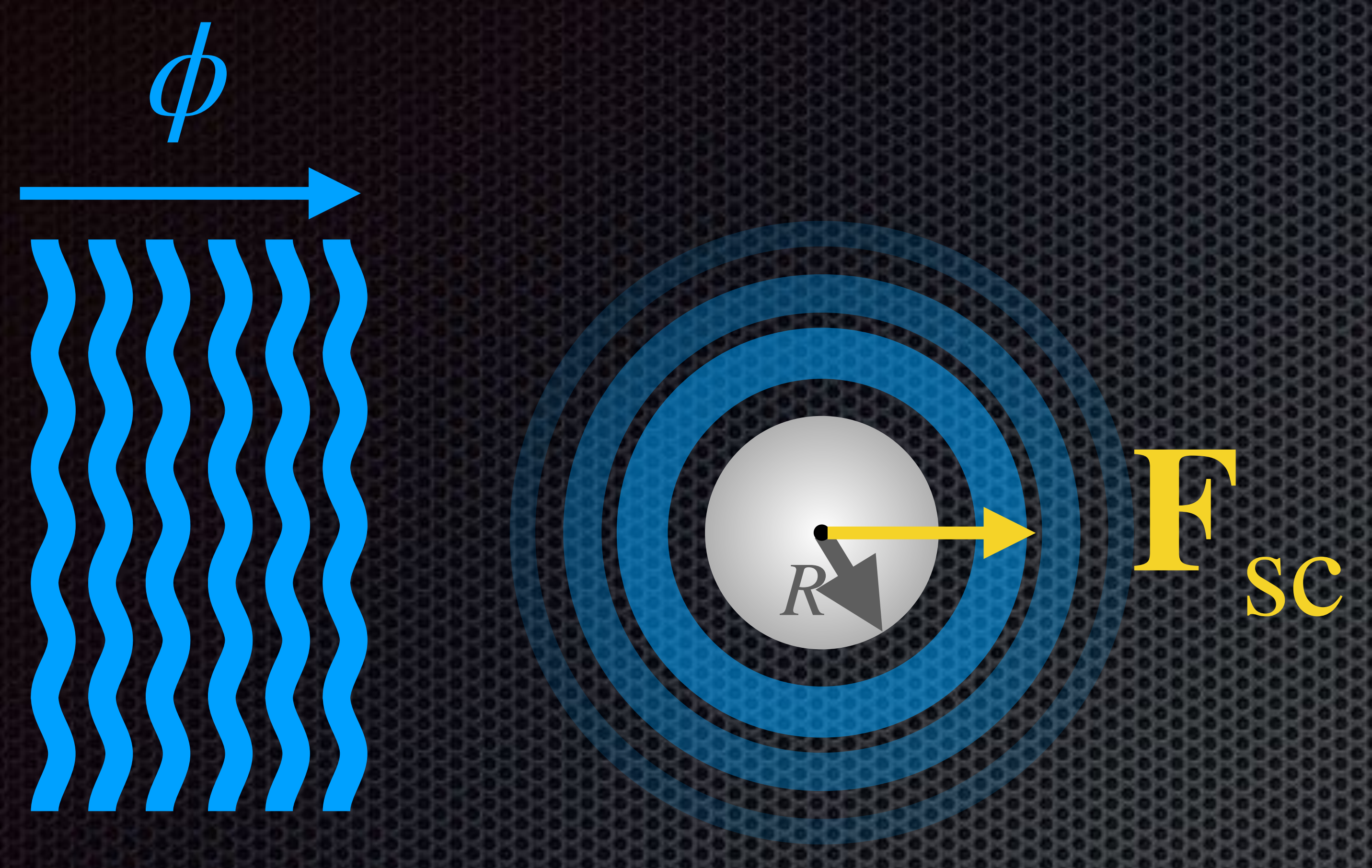
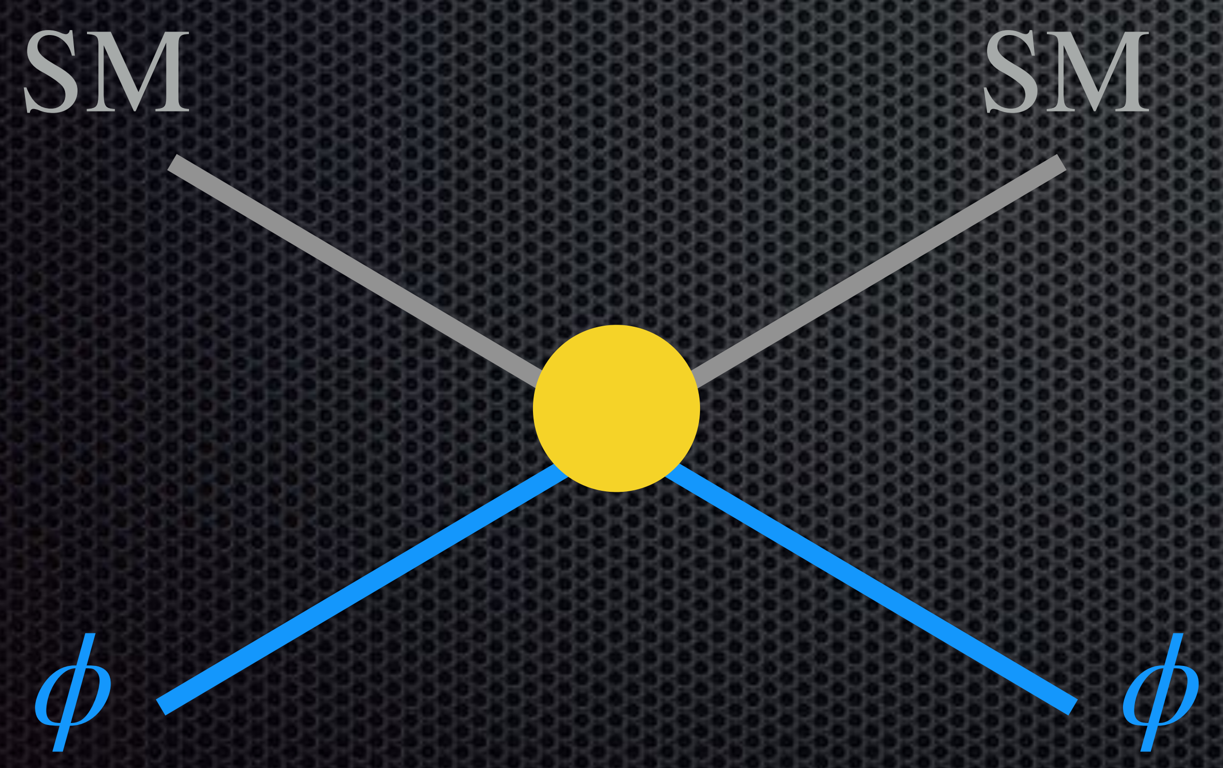
Scattering Force





Scattering Force





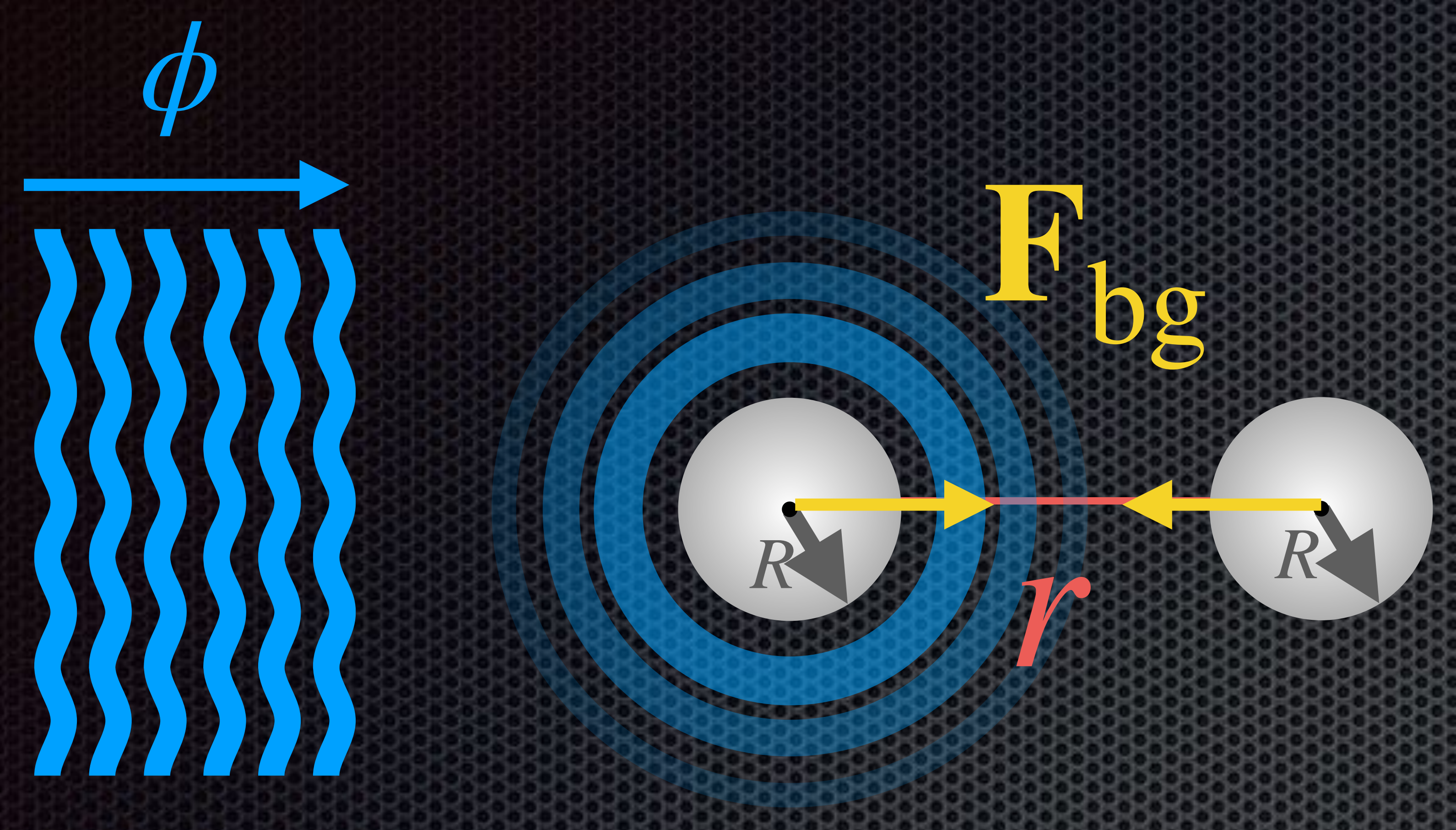
$$\sigma_{\mathrm{T}} \sim \frac{(m_{\mathrm{M}}^2 V_R)^2}{4\pi}$$

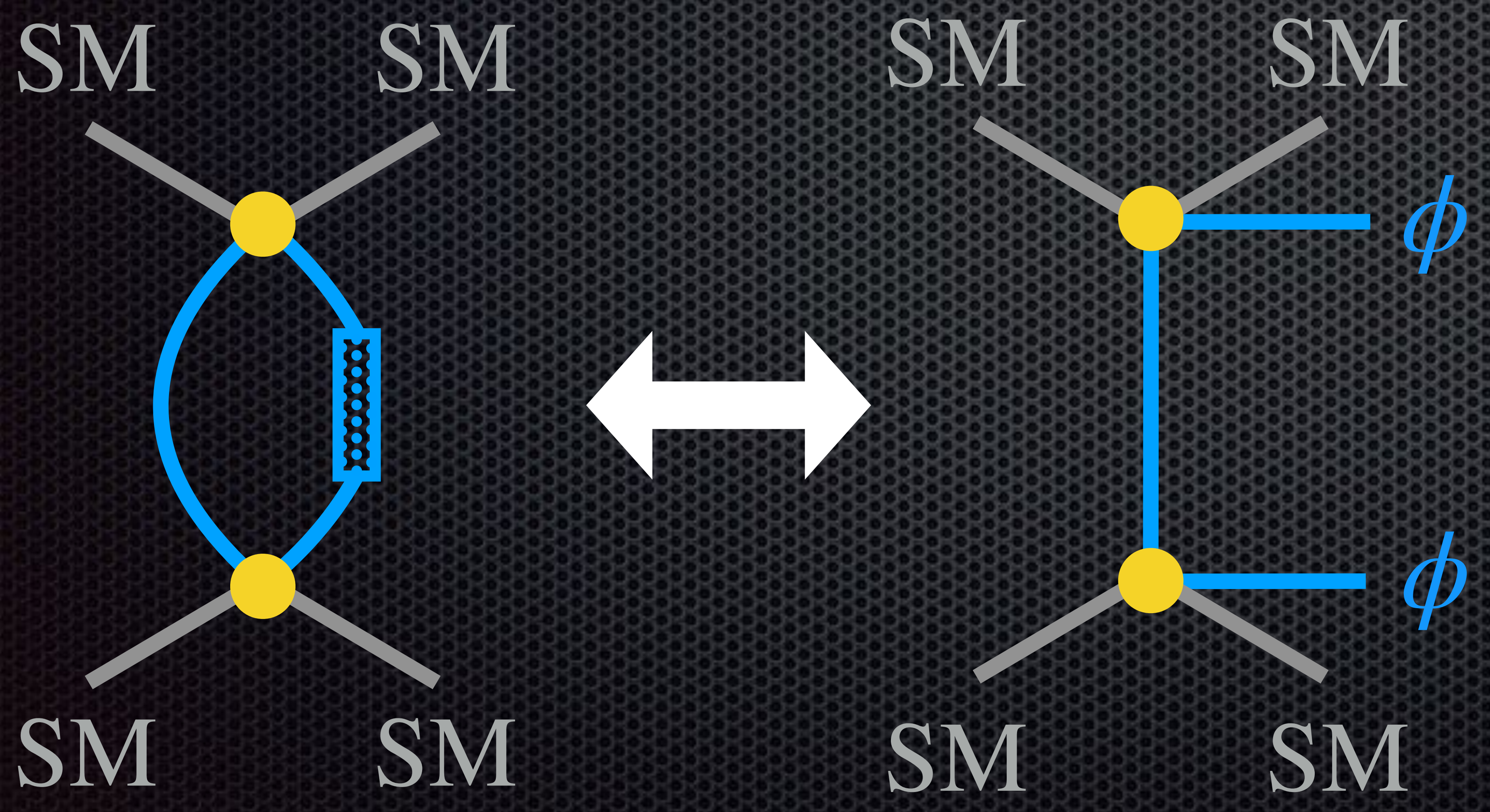
Coherent Scattering

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

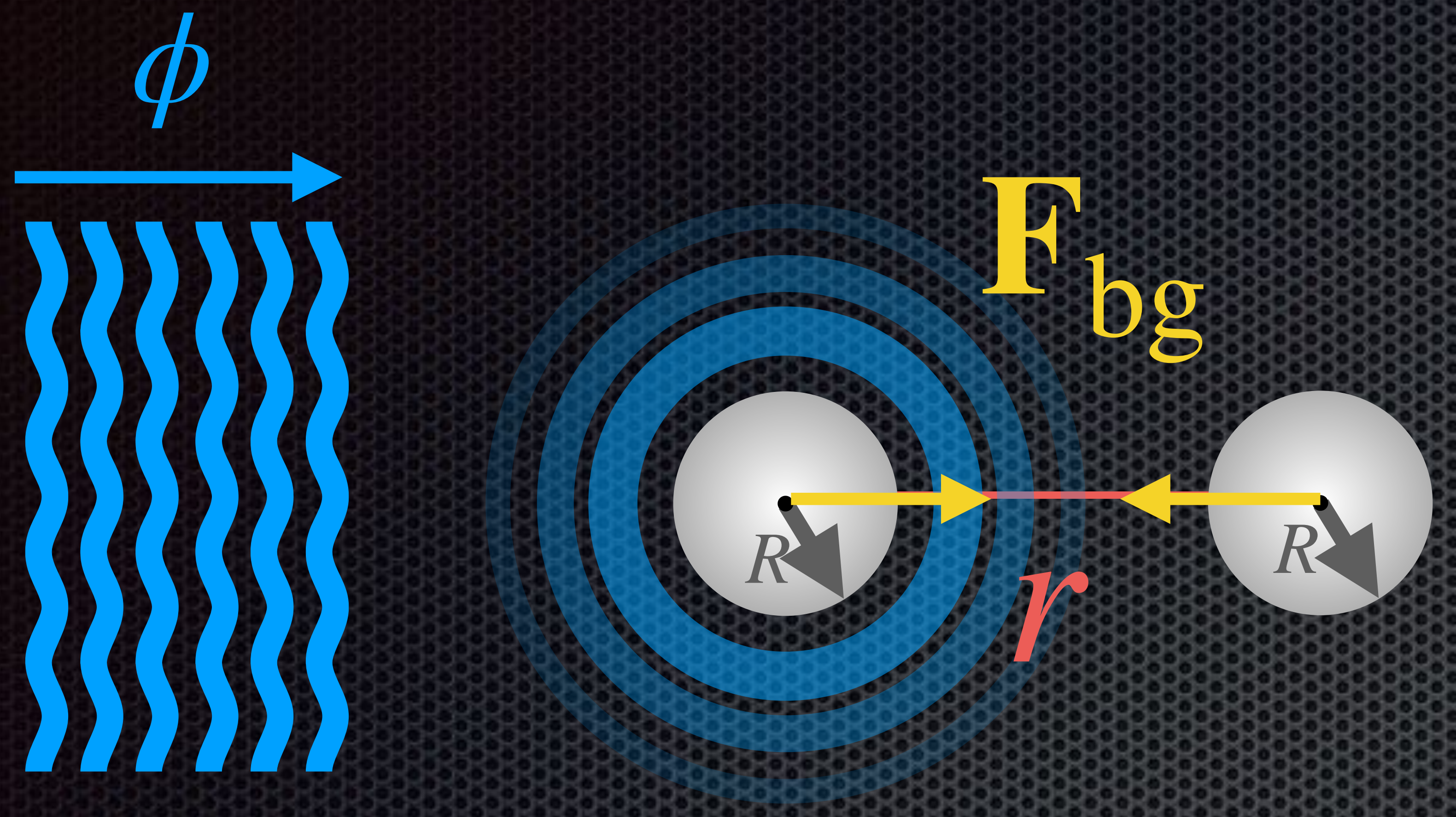
$$a \sim 10^{-13}\,\mathrm{m/s^2} \times \left(\frac{1\mathrm{cm}}{R}\right) \times (m_{\mathrm{M}} R)^4$$

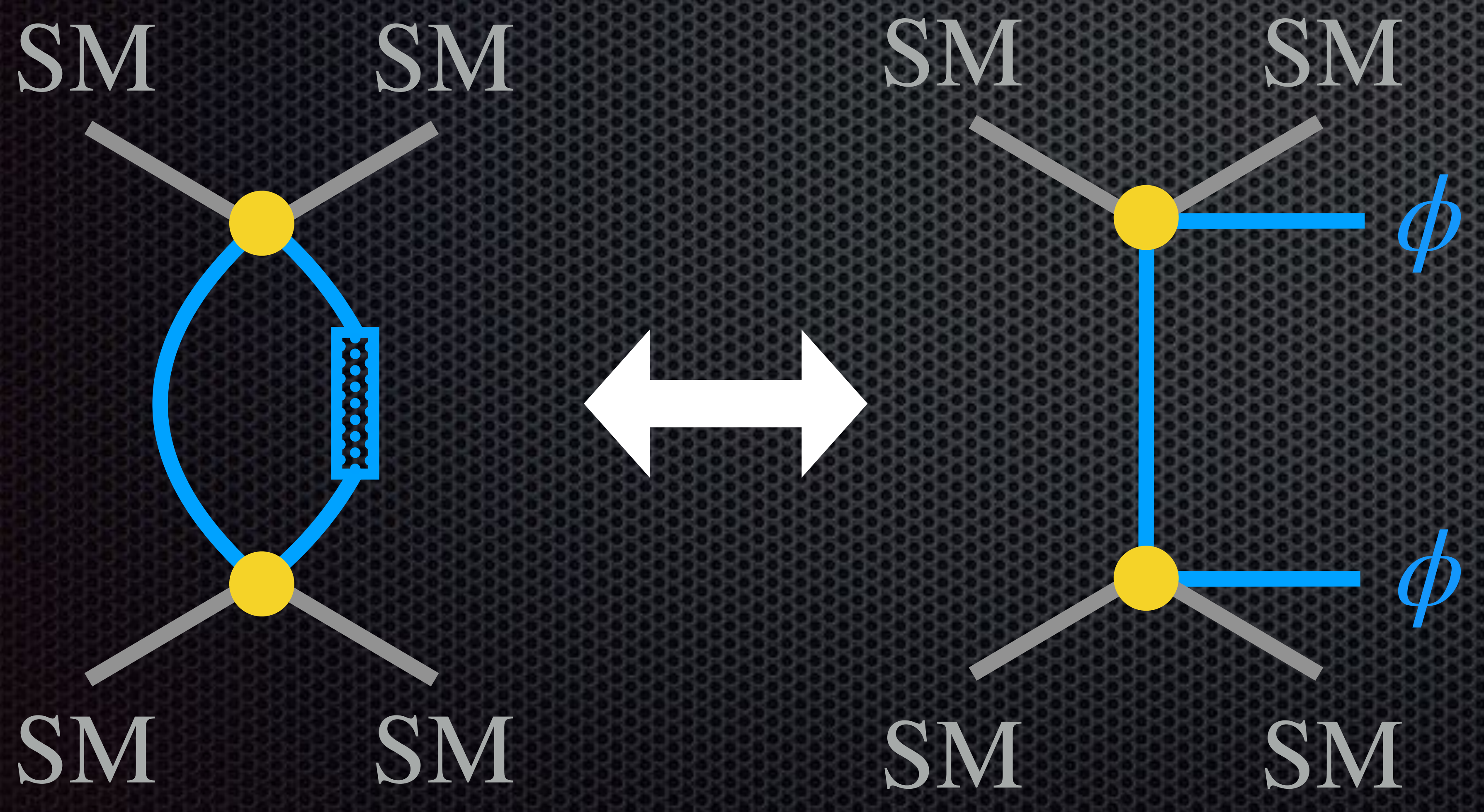
Background-Induced Force





Background-Induced Force

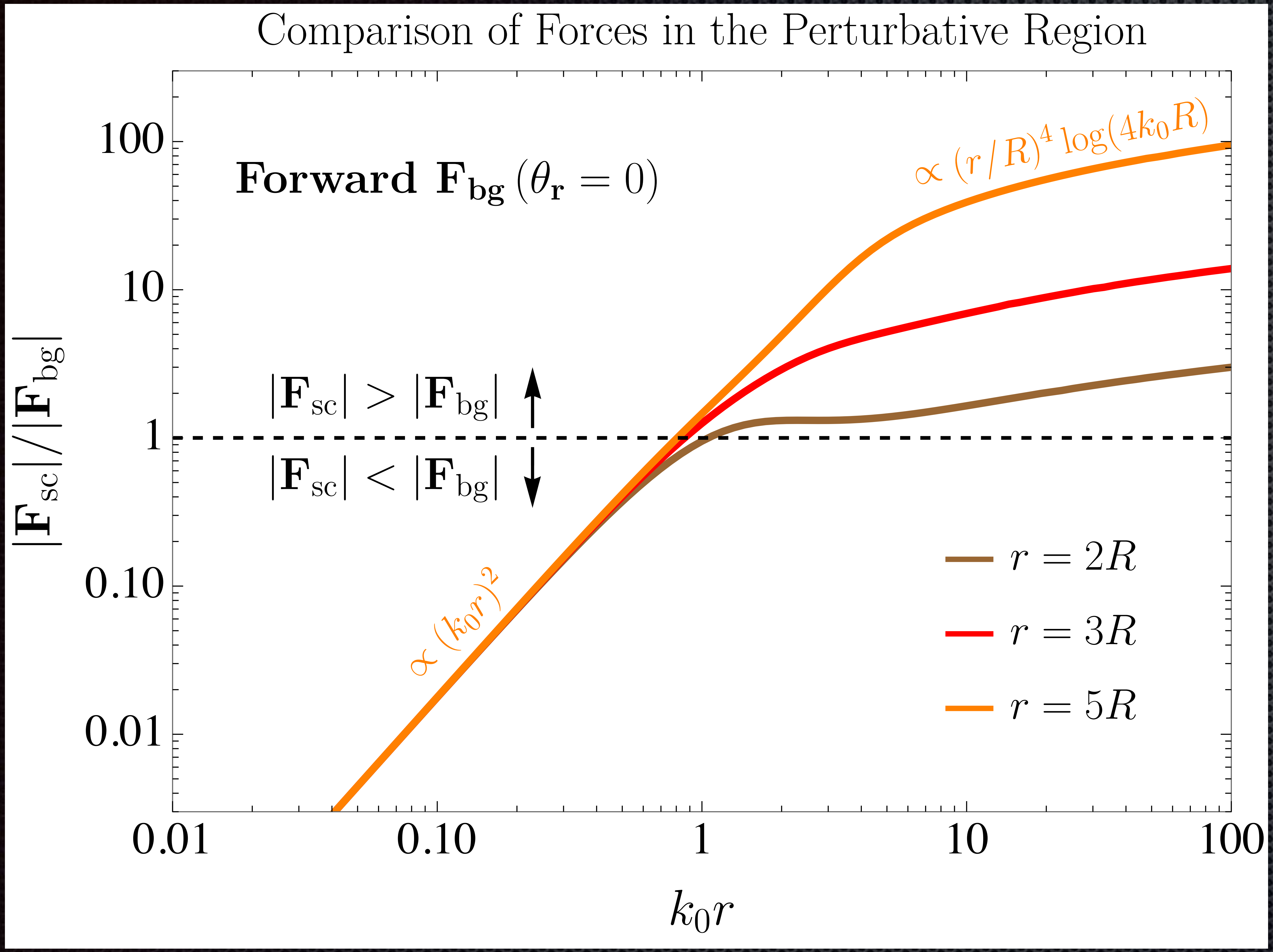


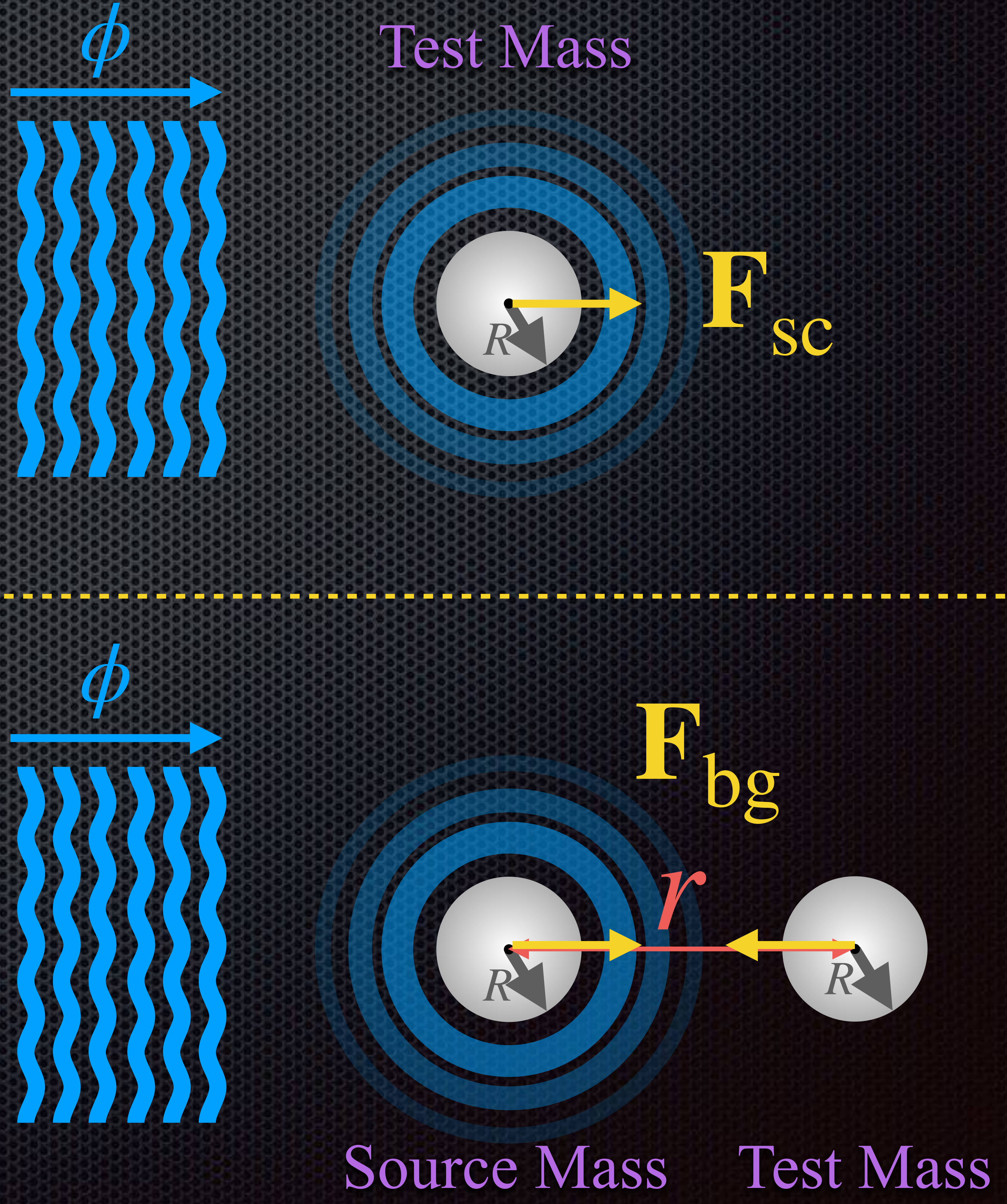


$$\mathbf{F}_{\text{bg}} \sim \underset{\phi^2}{\boxed{\frac{\rho_\phi}{m_\phi^2}}} \left(m_{\text{M}}^2 V_R\right)^2 \frac{1}{r^2}$$

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

$\mathbf{F}_{sc}$ vs $\mathbf{F}_{bg}$





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	$\sim 10^{-18}\,\mathrm{m/s^2}$

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

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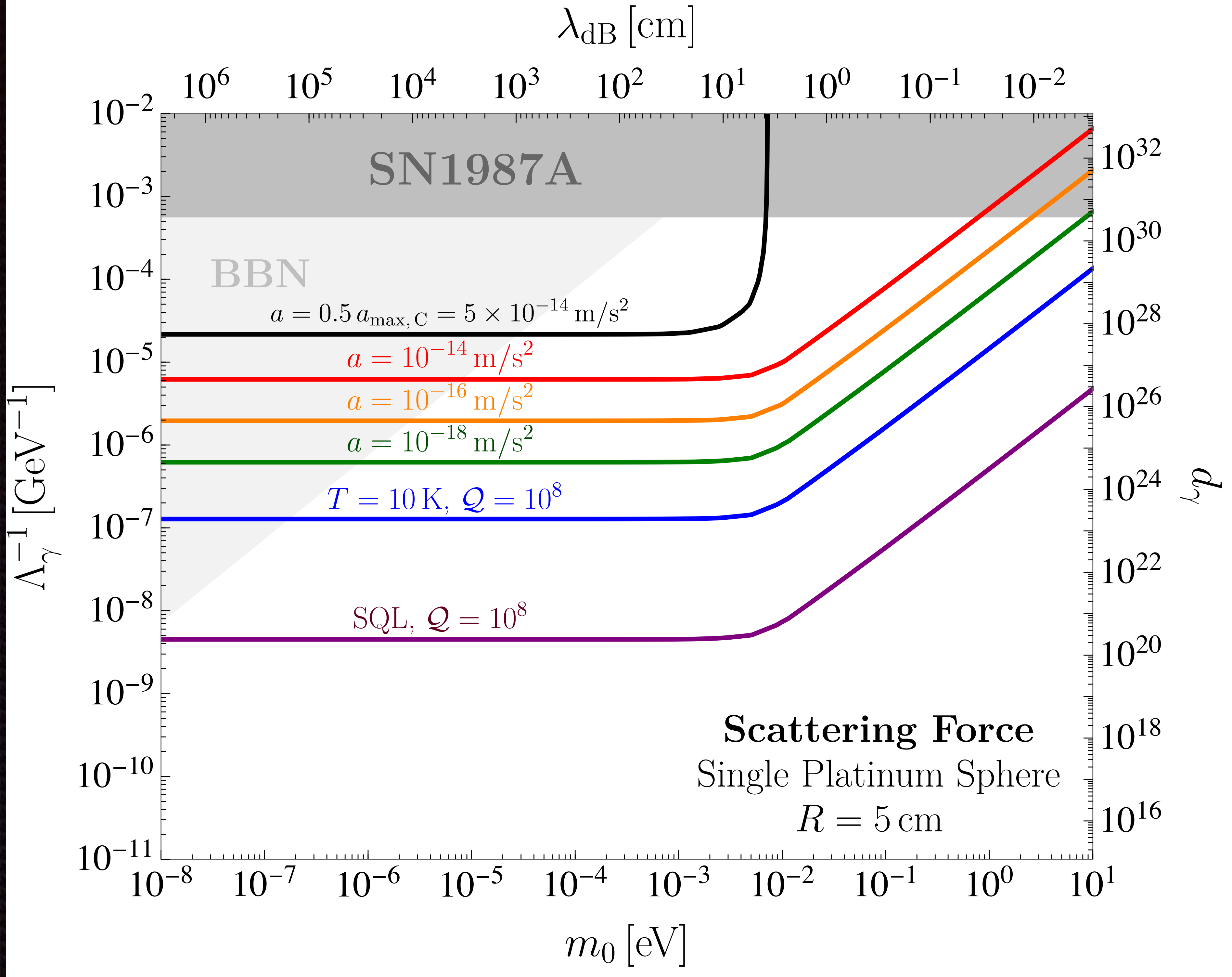
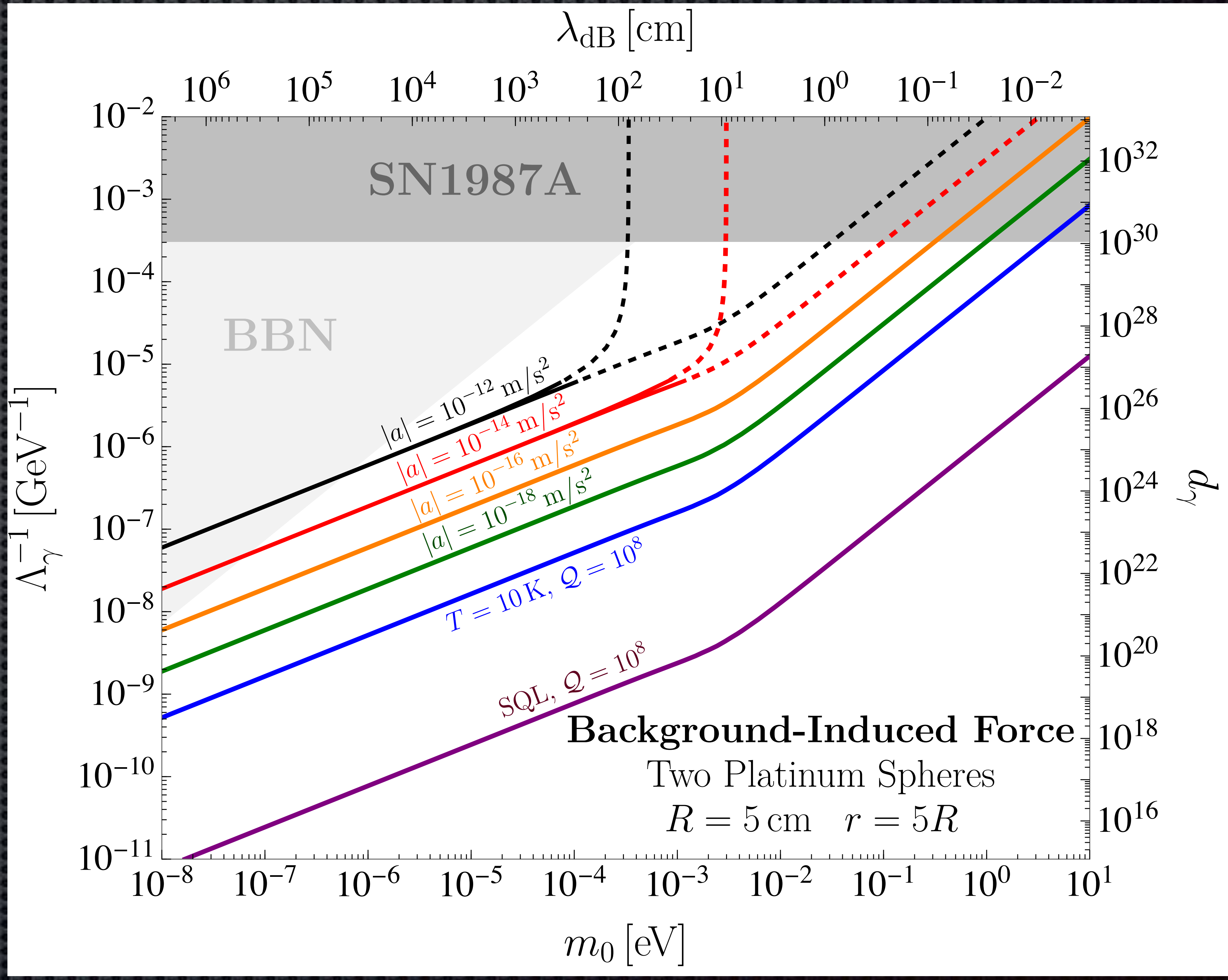
$f_{\mathrm{osc}} \sim 1\,\mathrm{mHz}$	$T \sim 10\,\mathrm{K}, \quad Q \sim 10^8$	$\sim 10^{-20}\,\mathrm{m/s^2}$
$t_{\mathrm{int}} \sim 3\,\mathrm{years}$	$\mathrm{SQL}, \quad Q \sim 10^8$	$\sim 10^{-27}\,\mathrm{m/s^2}$

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

Experimental Sensitivity





Scattering Force

Background-Induced Force

Unified Treatment

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

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

Unified Treatment

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

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

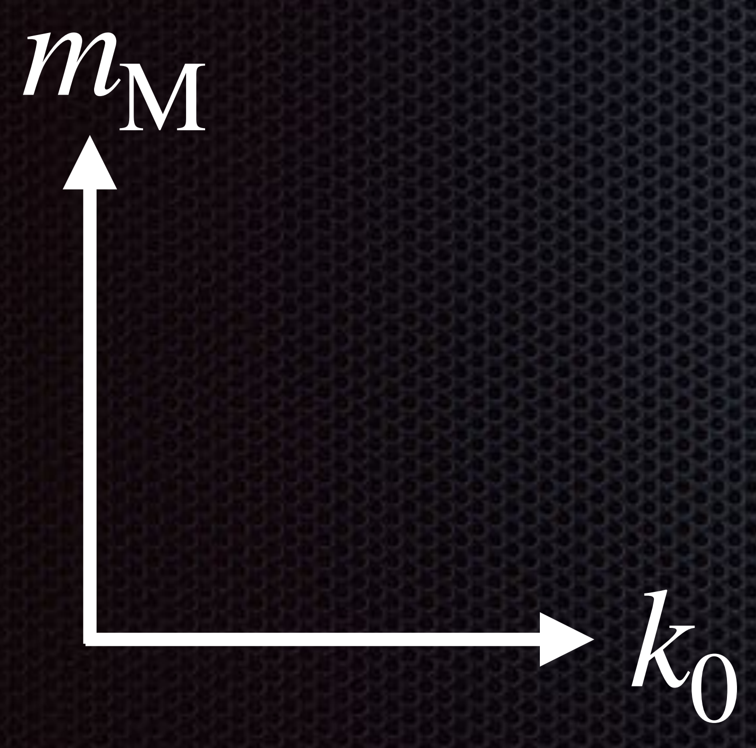
Field Oscillation+Finite Phase Space+Finite Geometry

Decoherence, Screening, Descreening

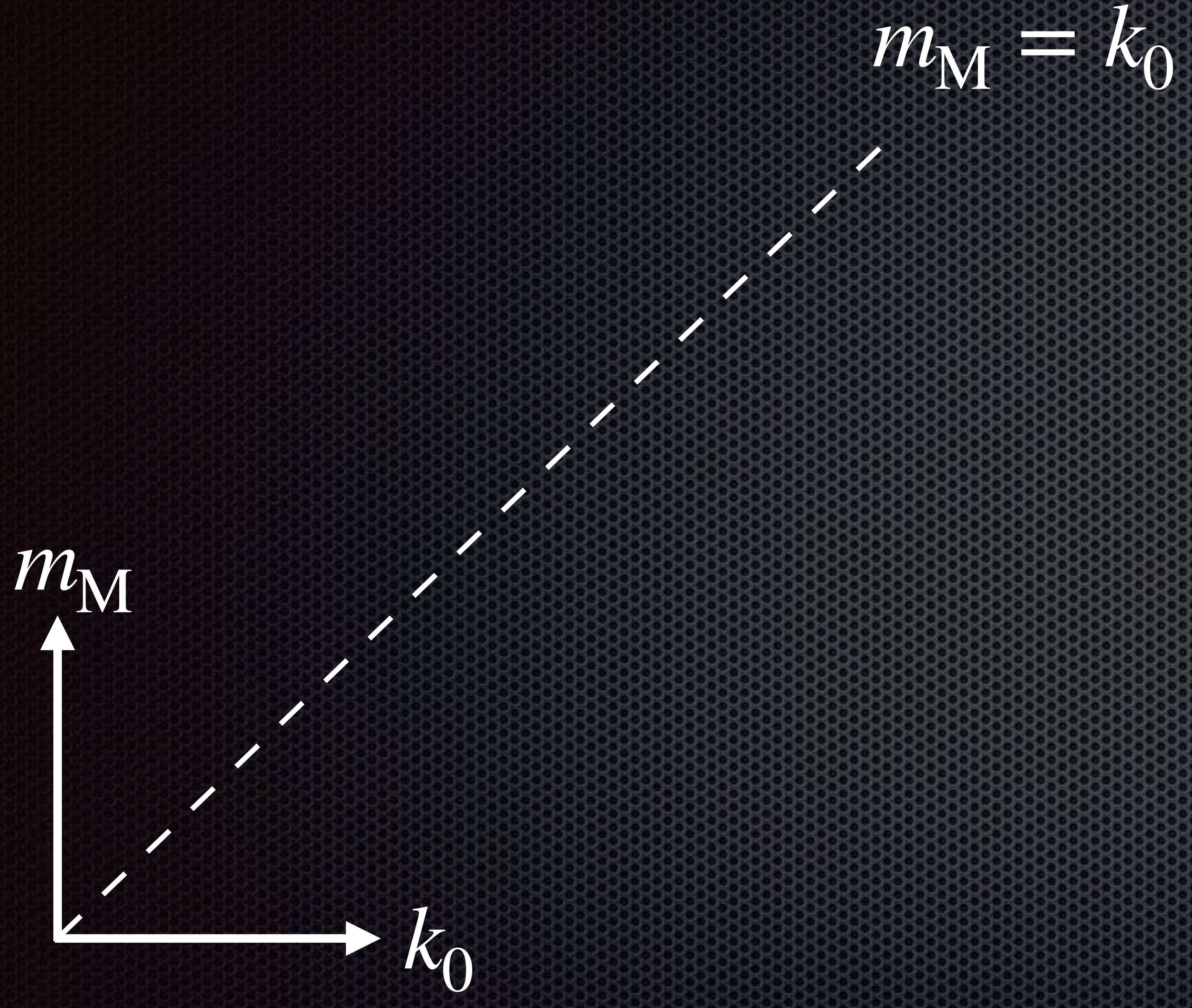
Classification

k_0: Incident Momentum

m_{M}: Effective Mass



Classification



k_0: Incident Momentum

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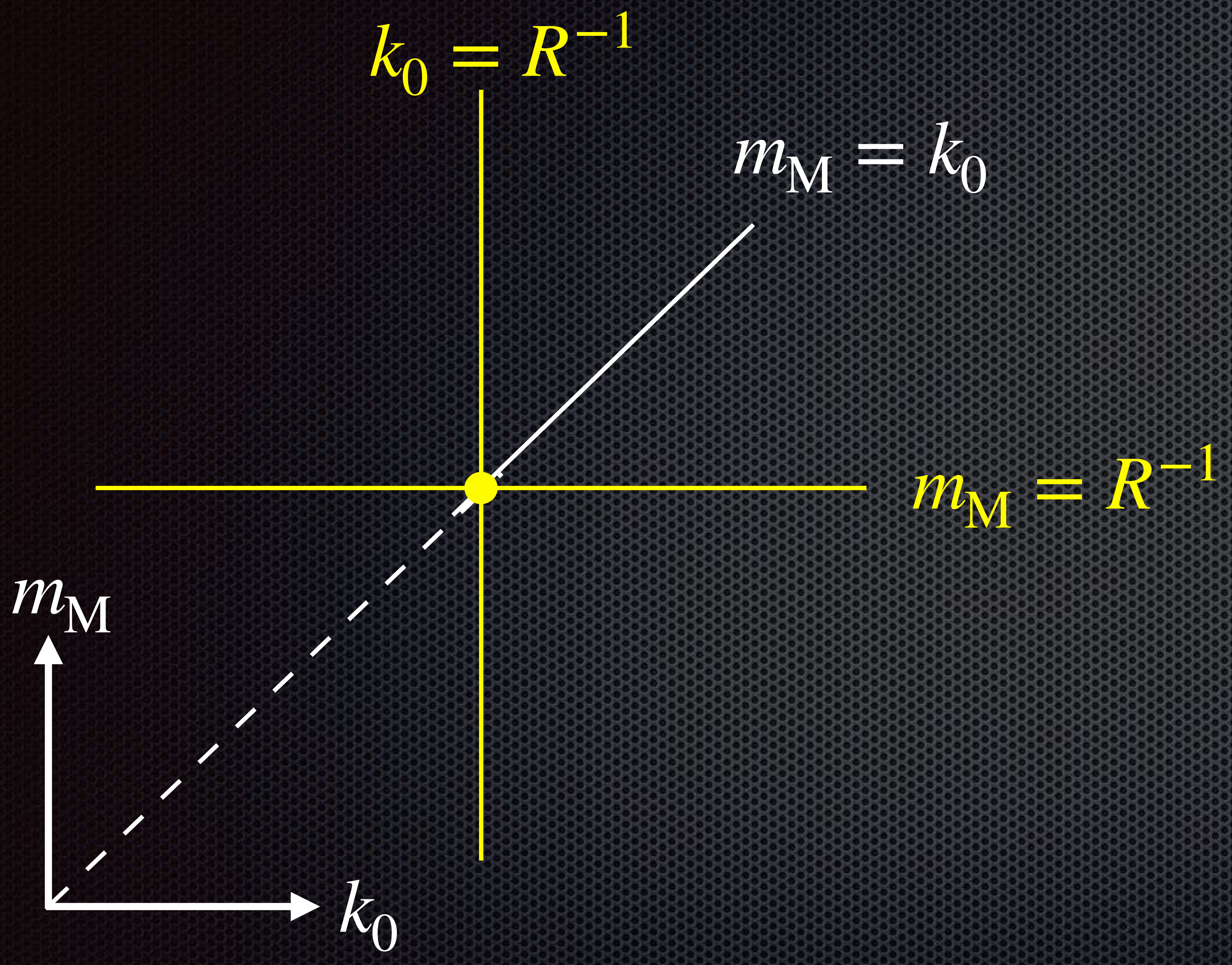
Classification

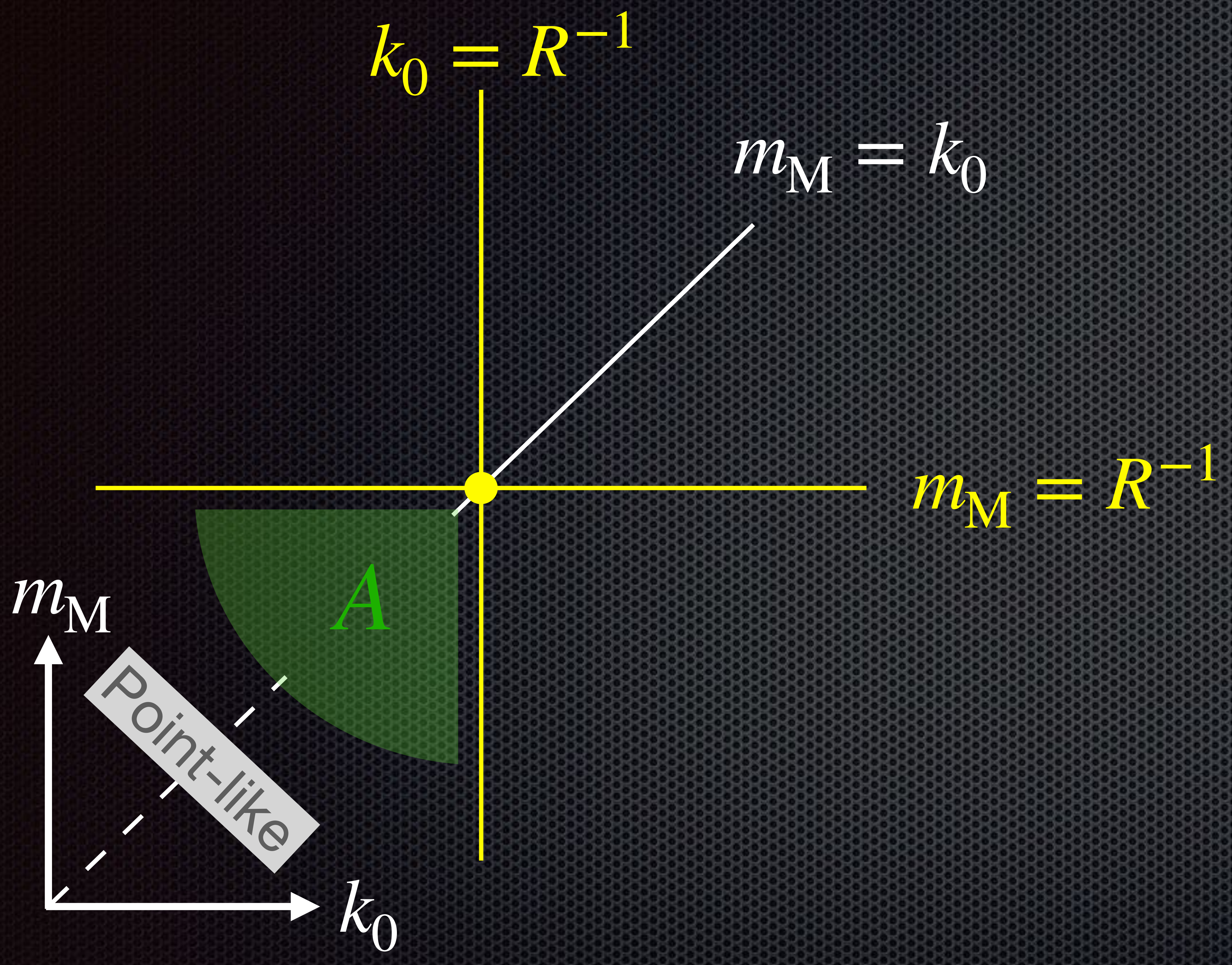


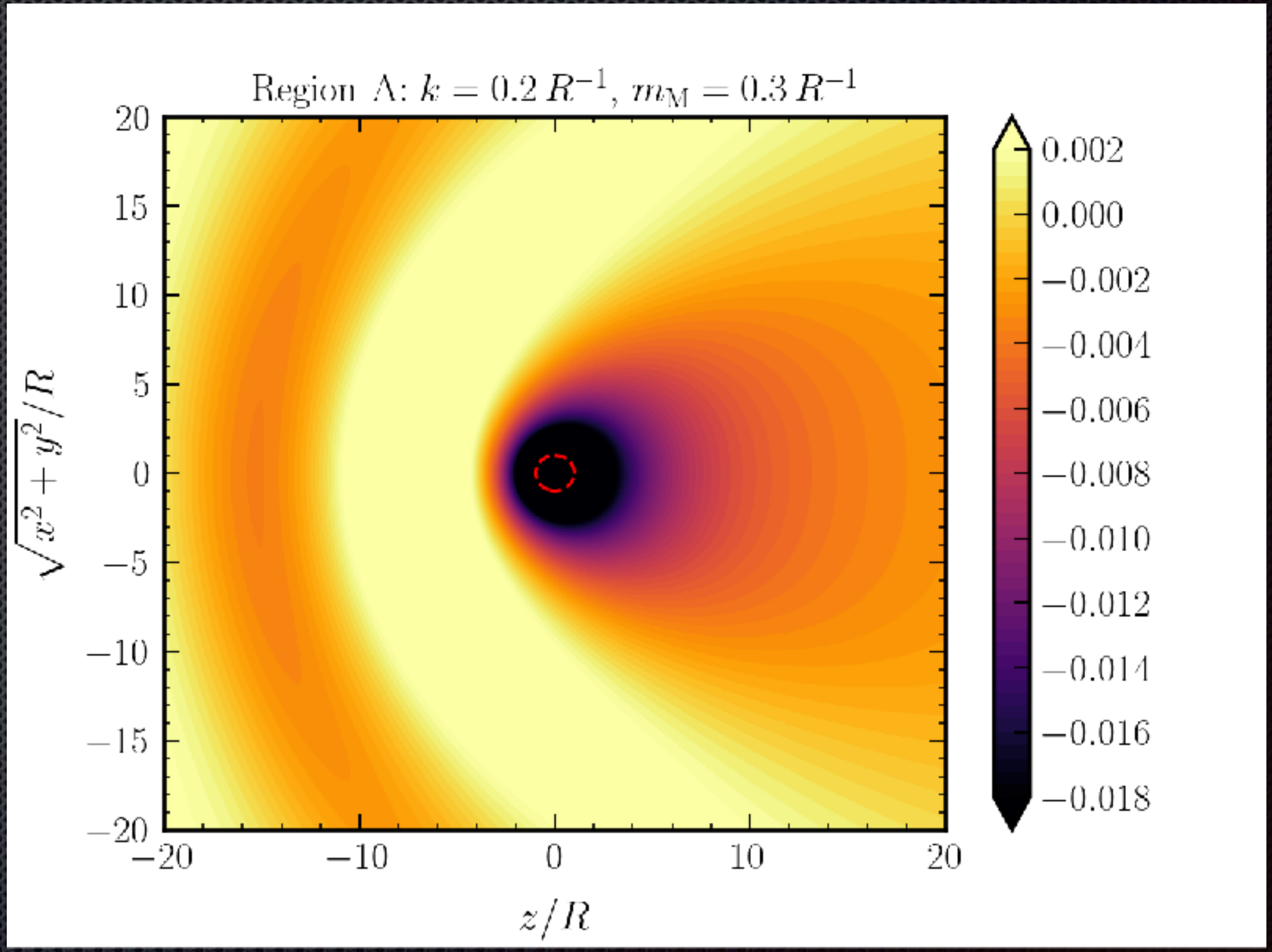
k_0: Incident Momentum

m_M: Effective Mass

R: Radius of Scattered Sphere

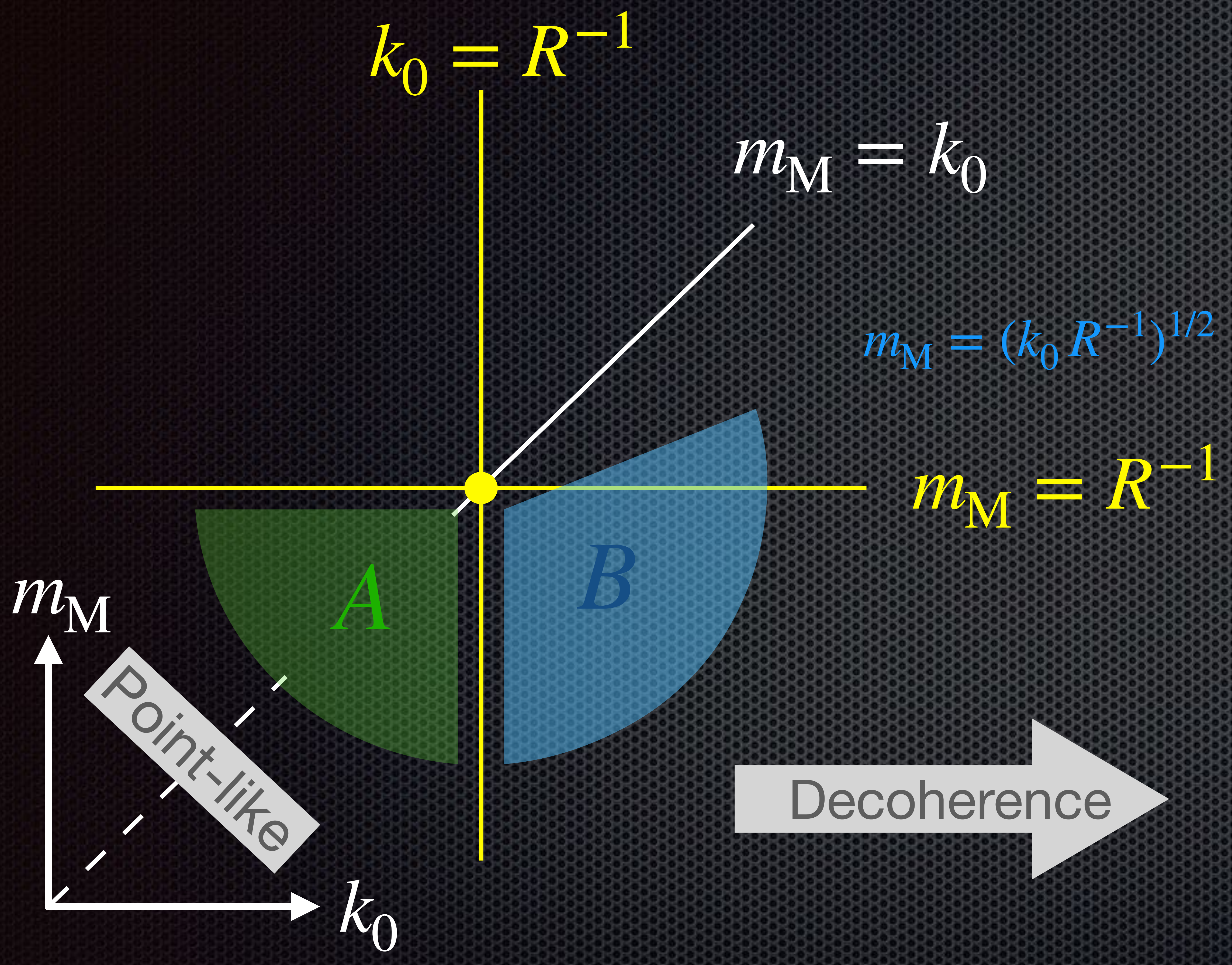
Classification

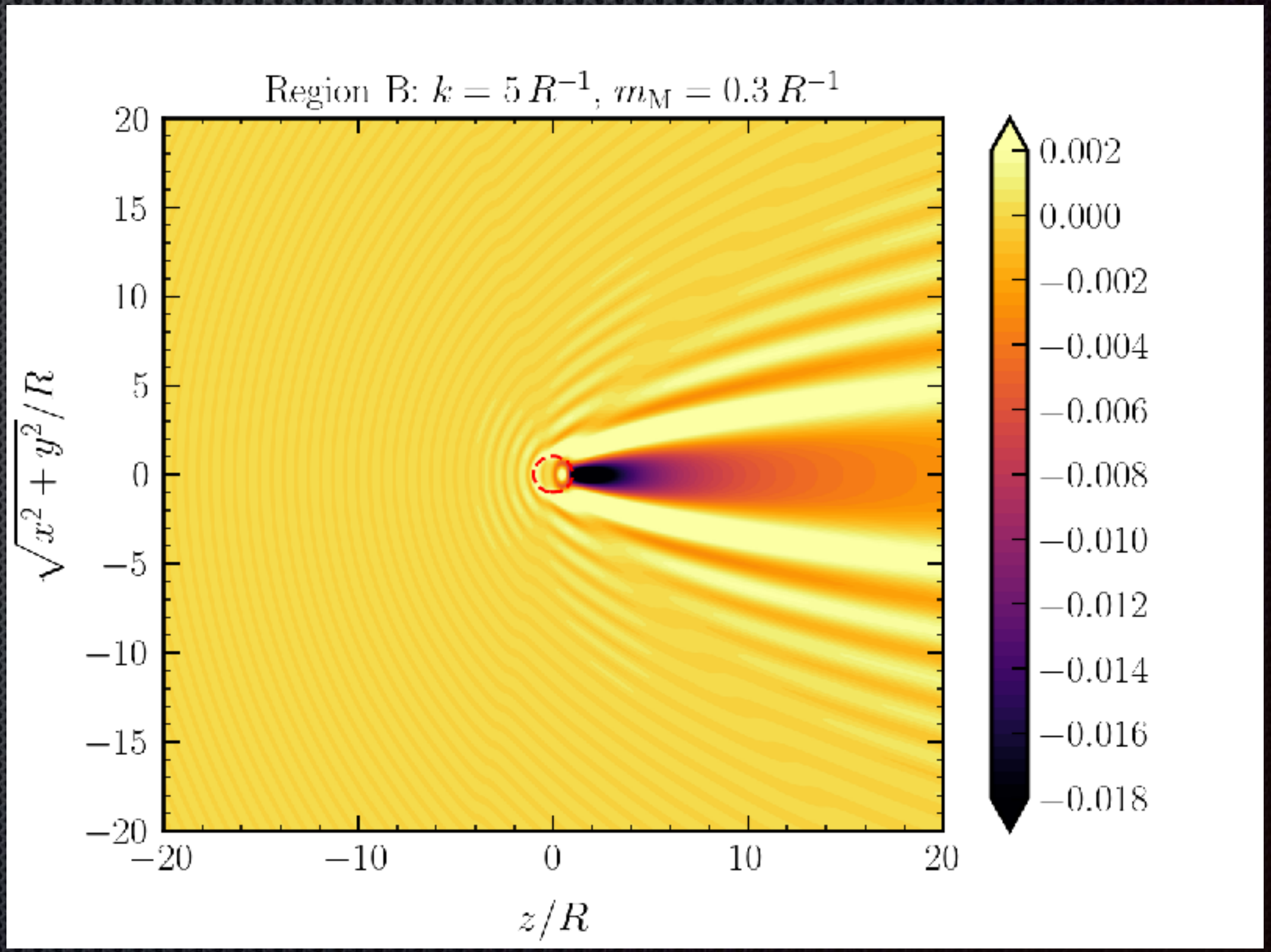




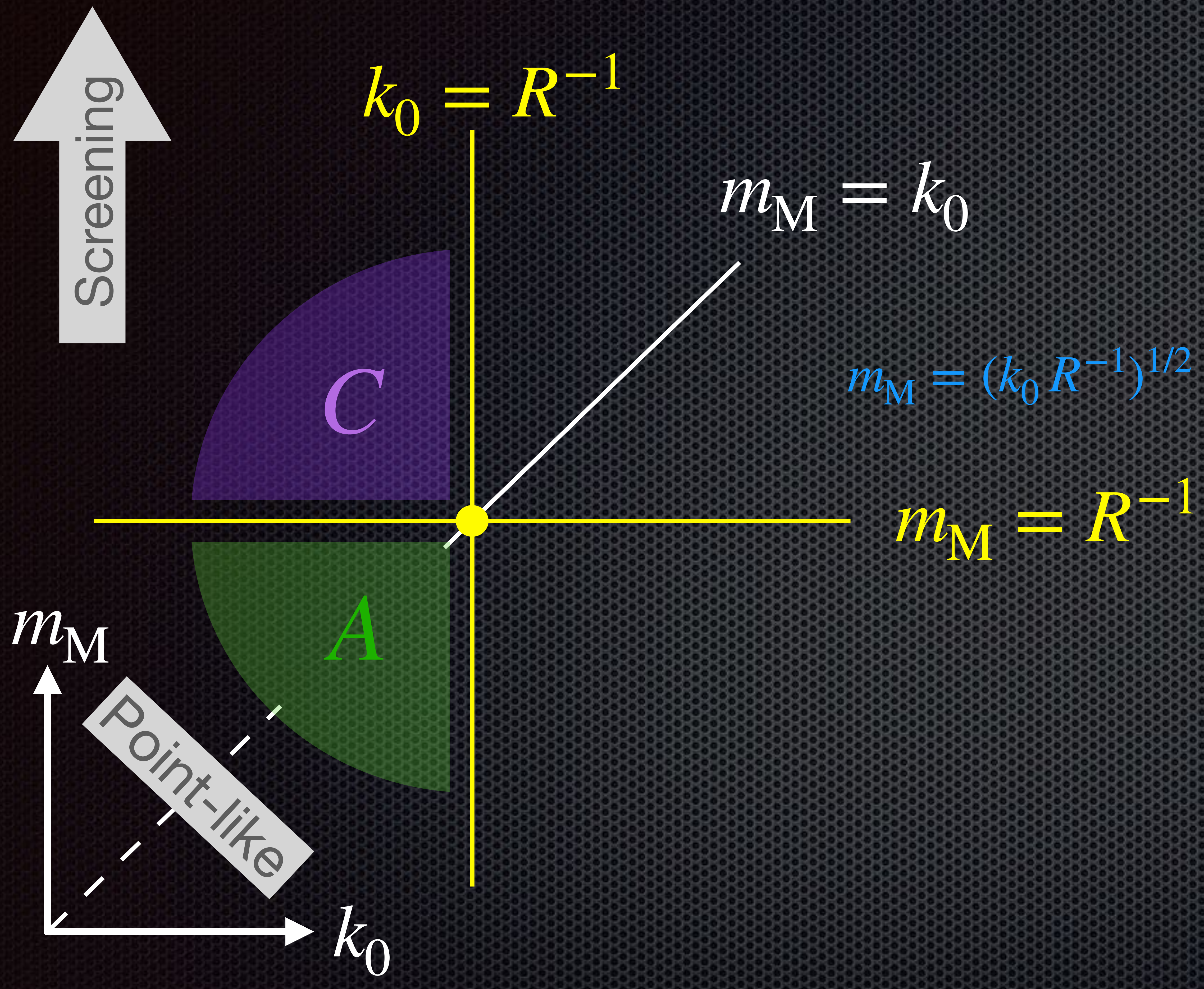
s-wave: oscillatory when $kr > 1$

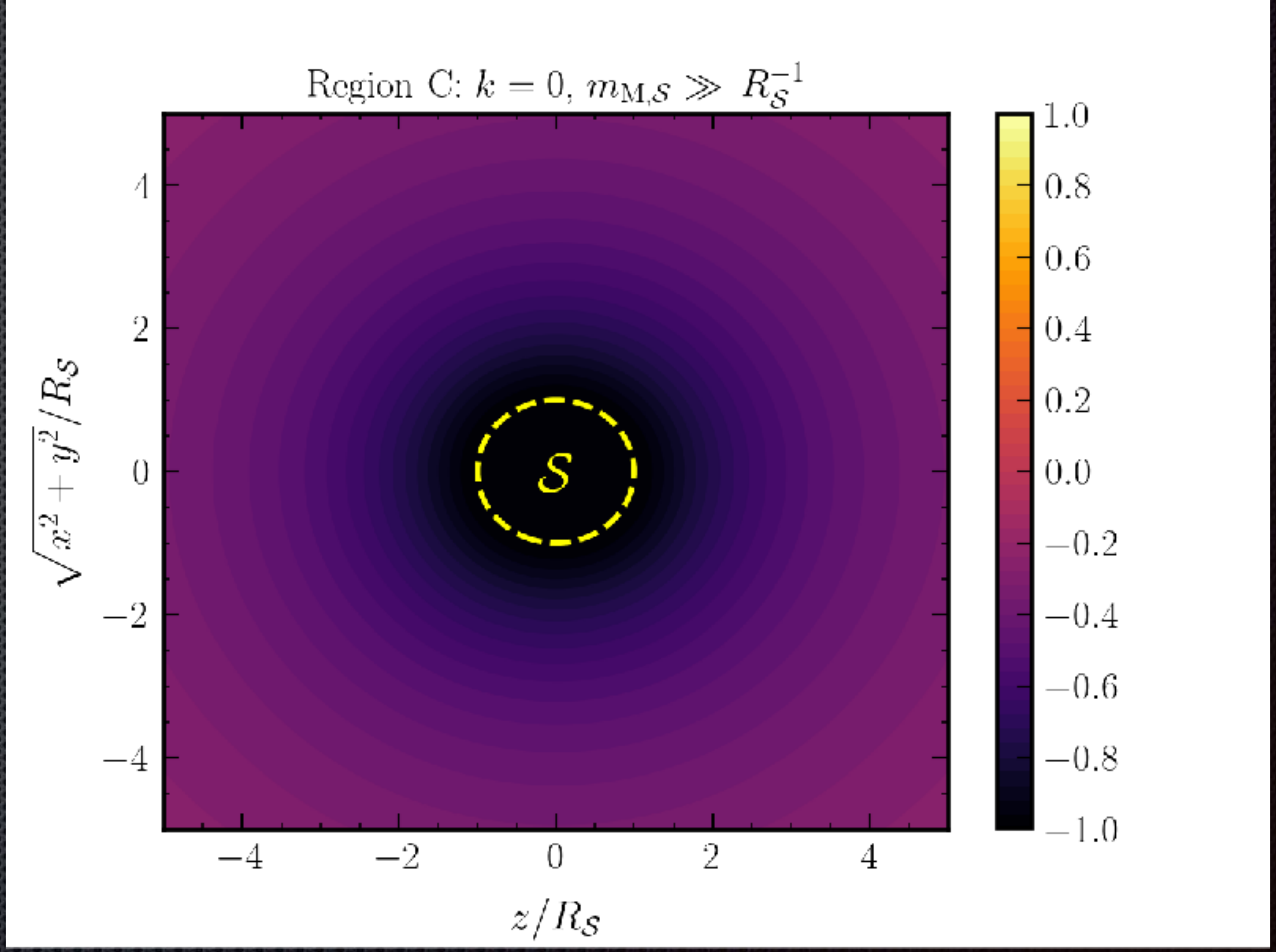
Classification





Classification





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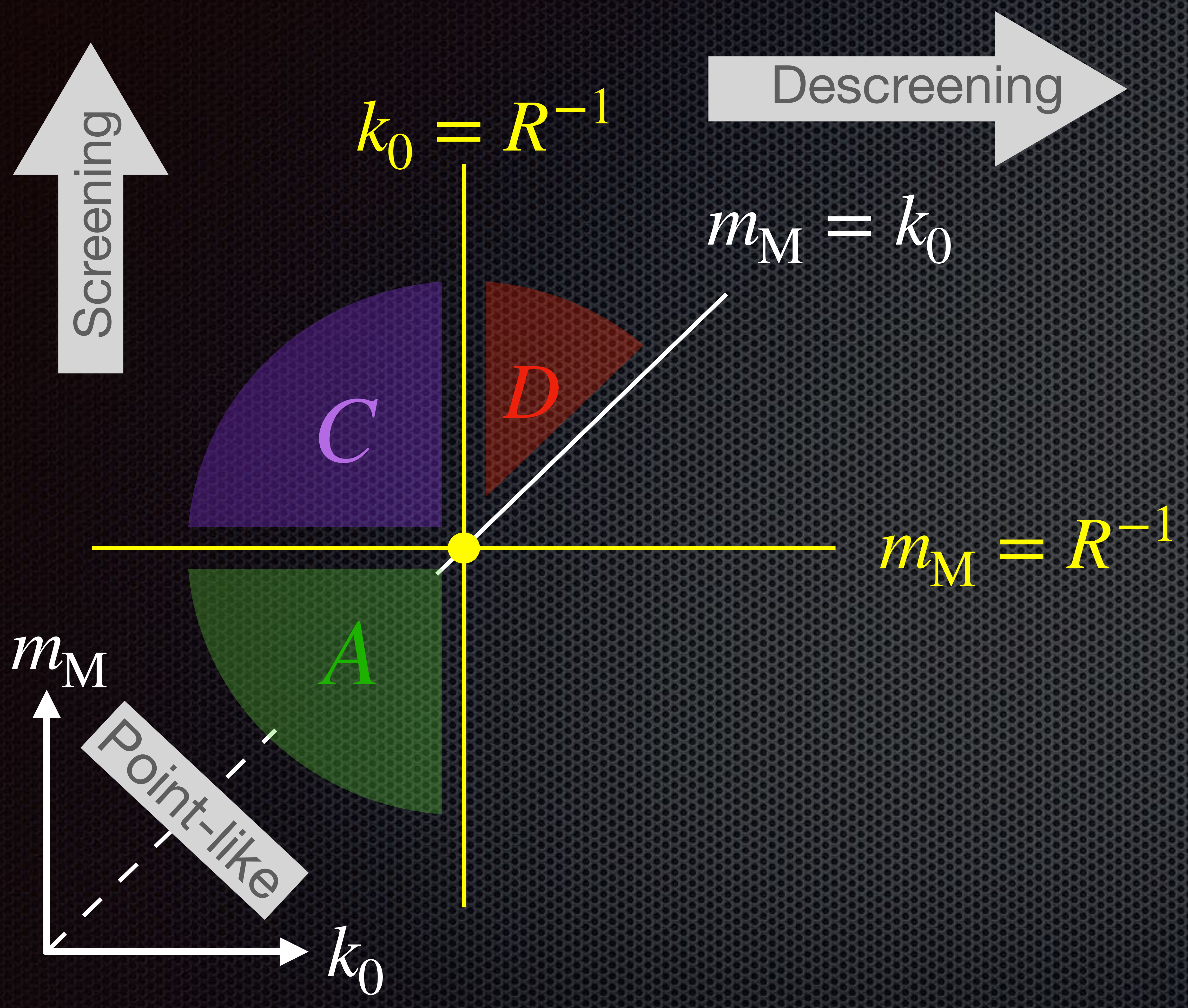

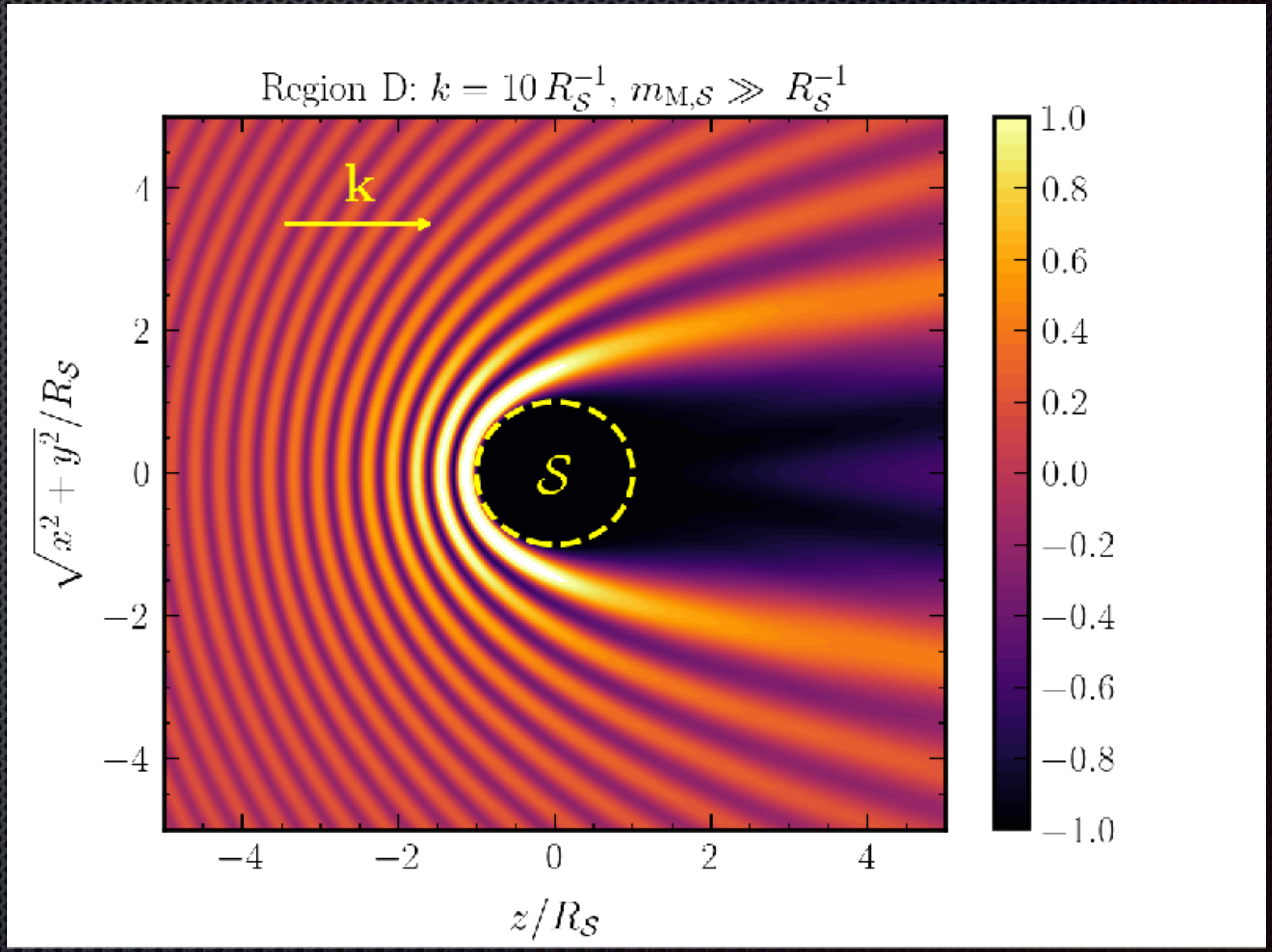

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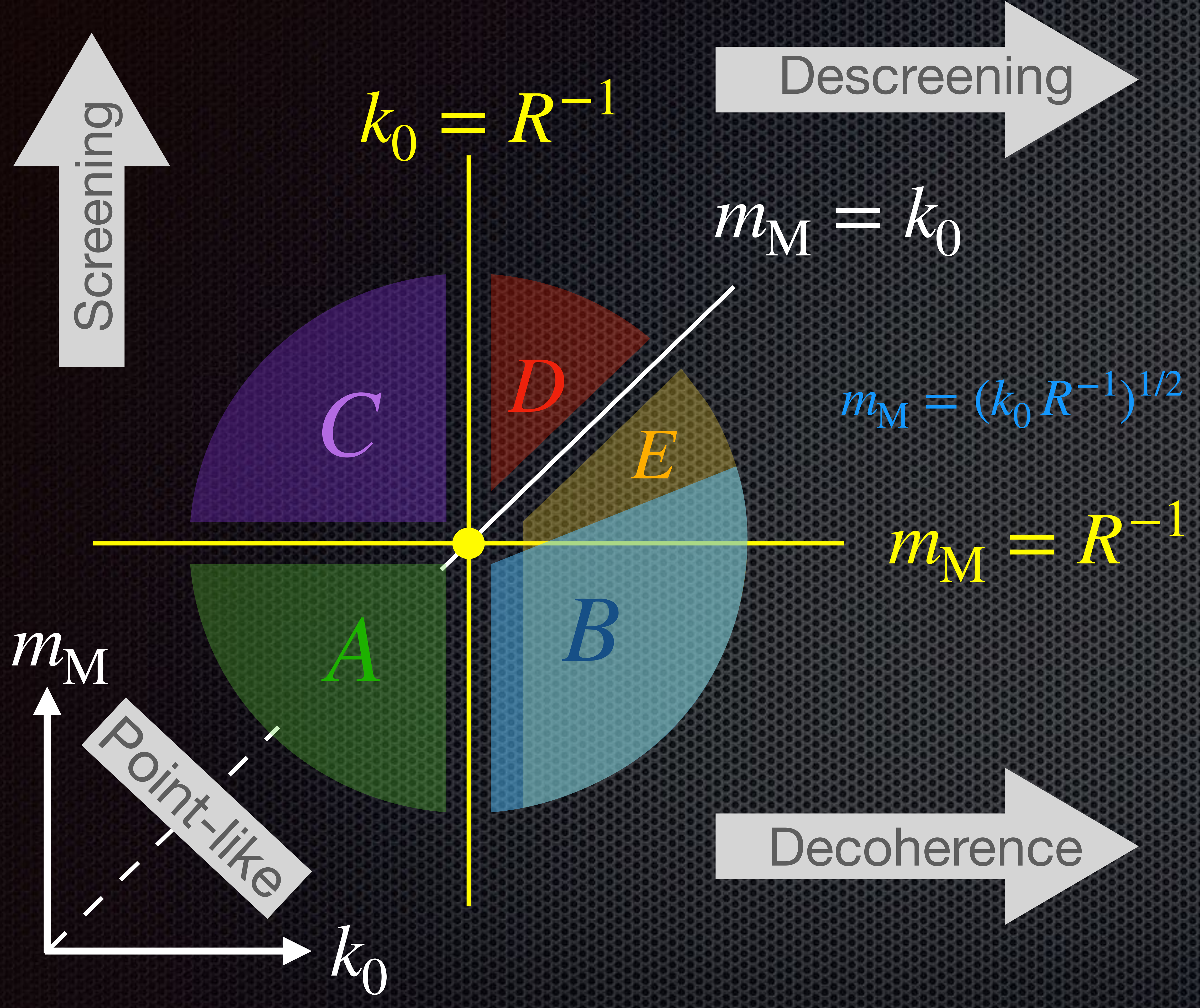
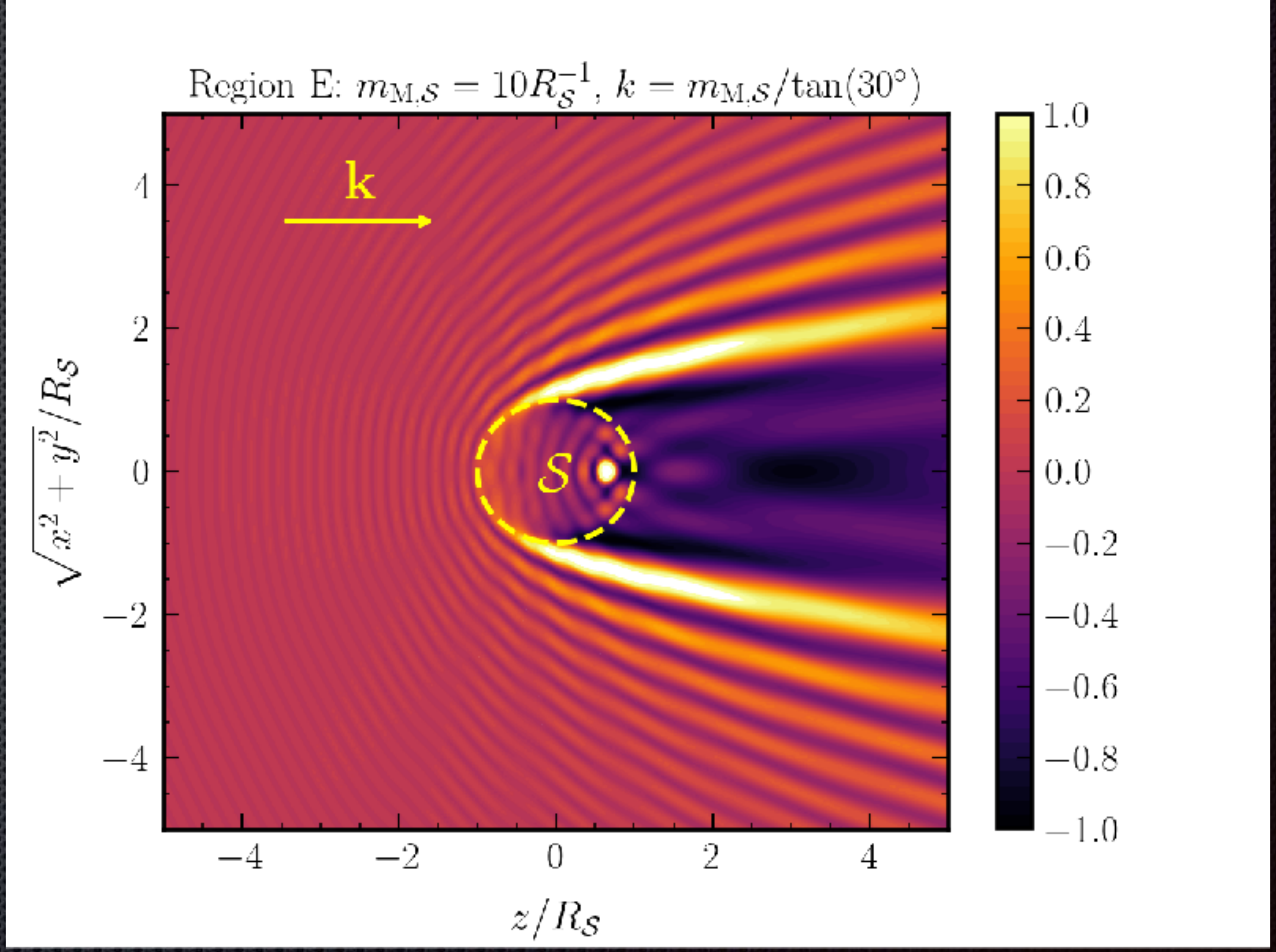
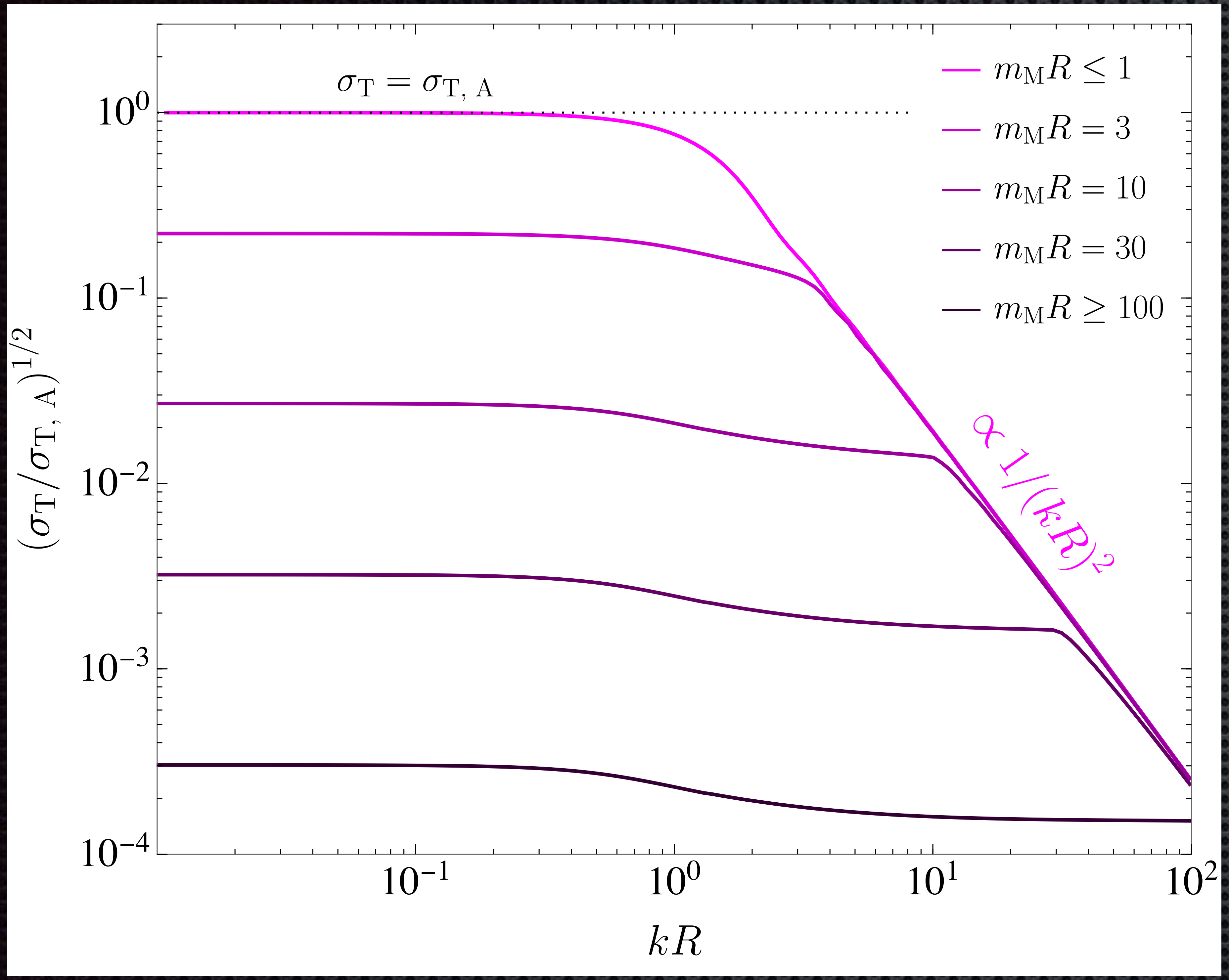


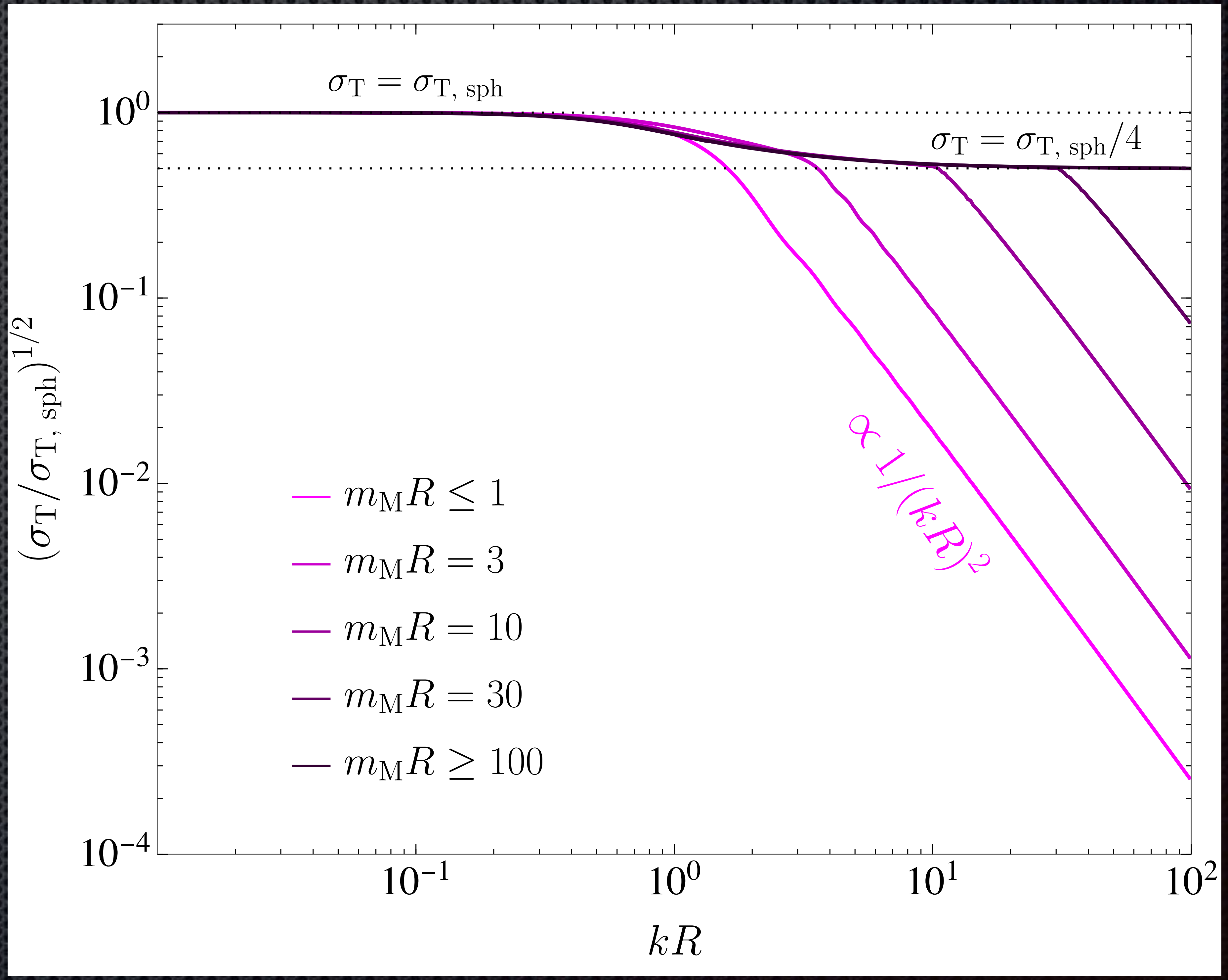


Scattering Force

$$F_{\rm sc} \sim \frac{(m_{\rm M}^2 V_R)^2}{4\pi}\, \rho_\phi v_\phi^2 \times \boxed{\mathscr{F}_{sc}}$$



$\mathscr{F}_{\rm sc}$



$\mathscr{F}_{\rm sc}/\mathscr{F}_{\rm sph}$

Scattering Force

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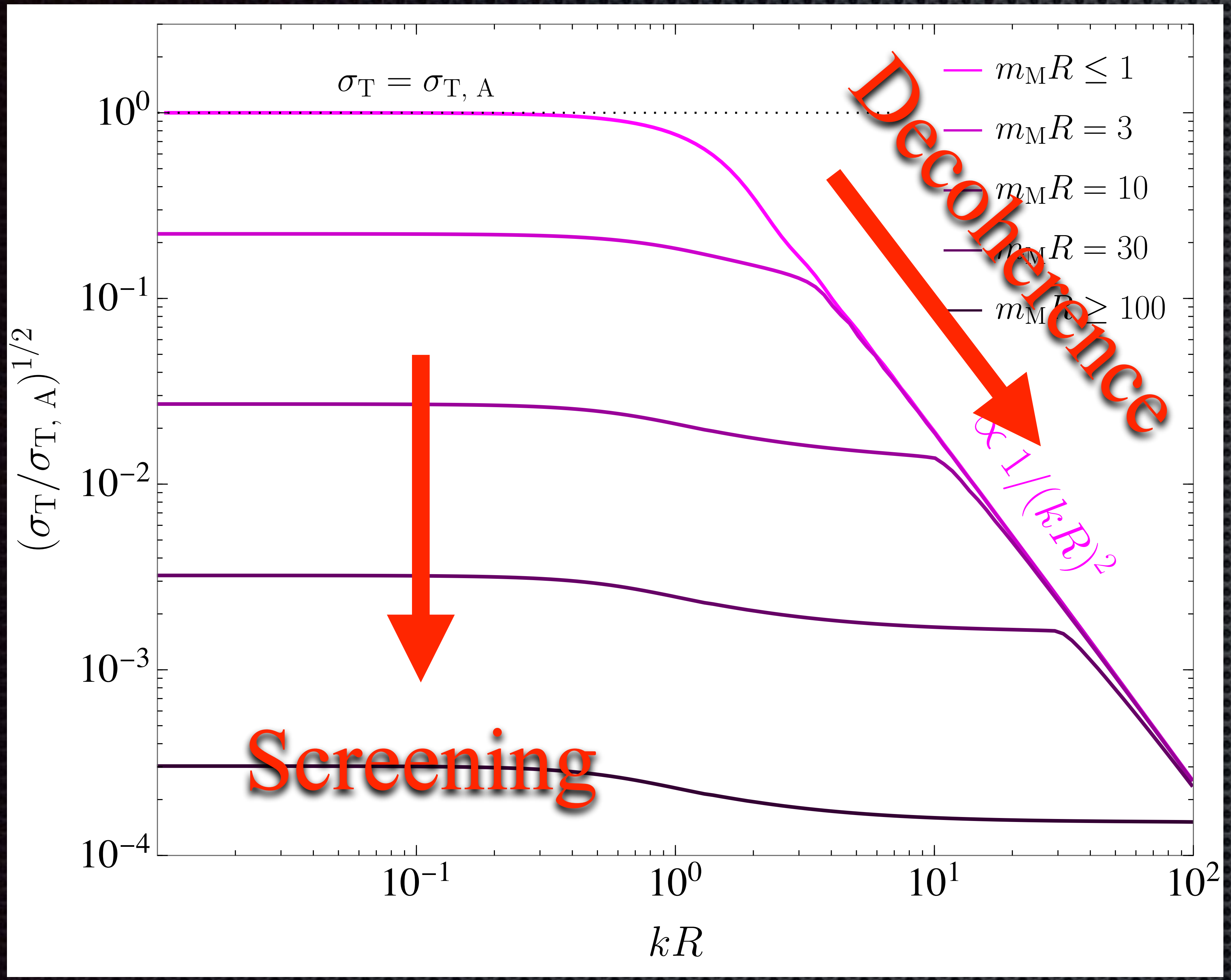
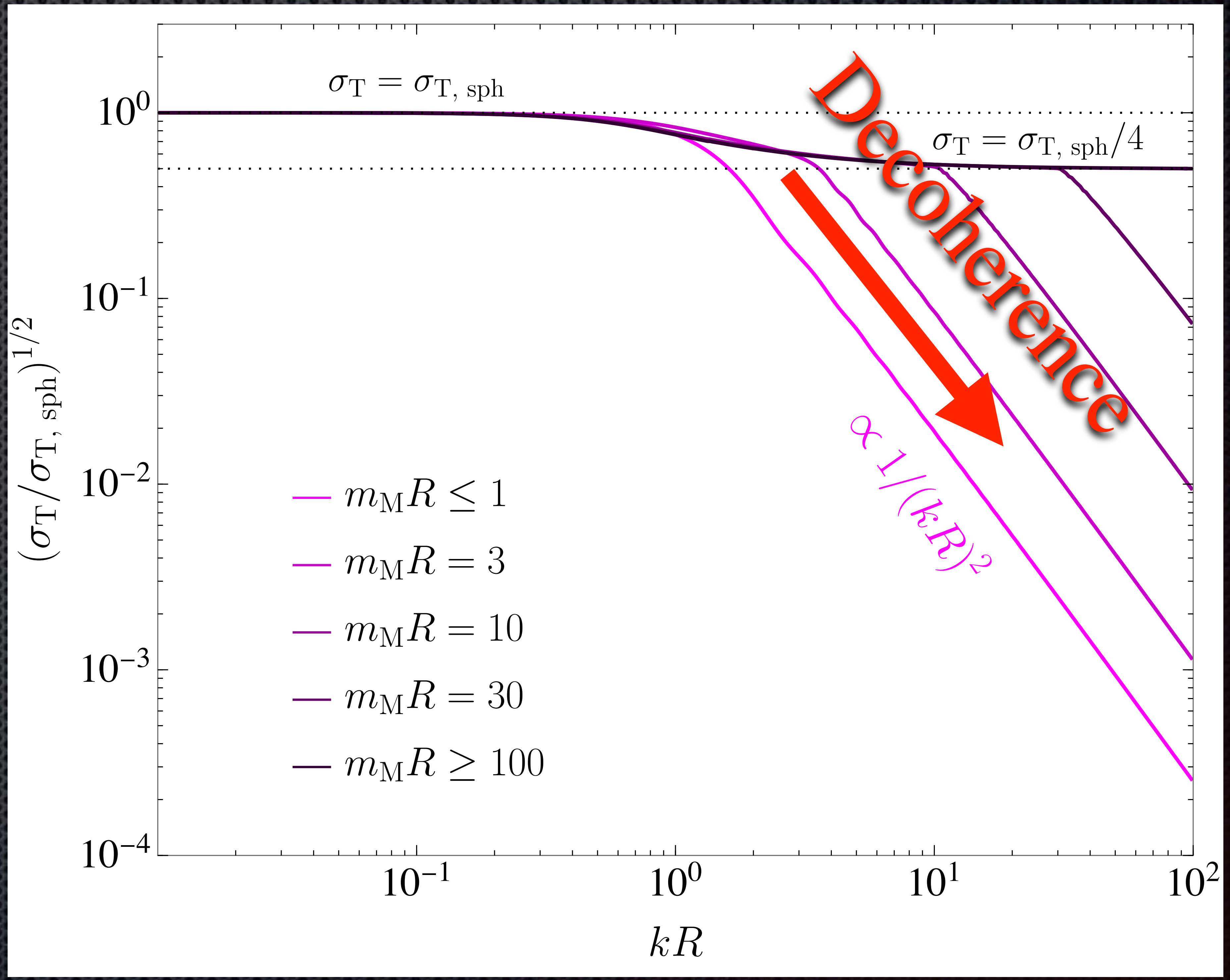


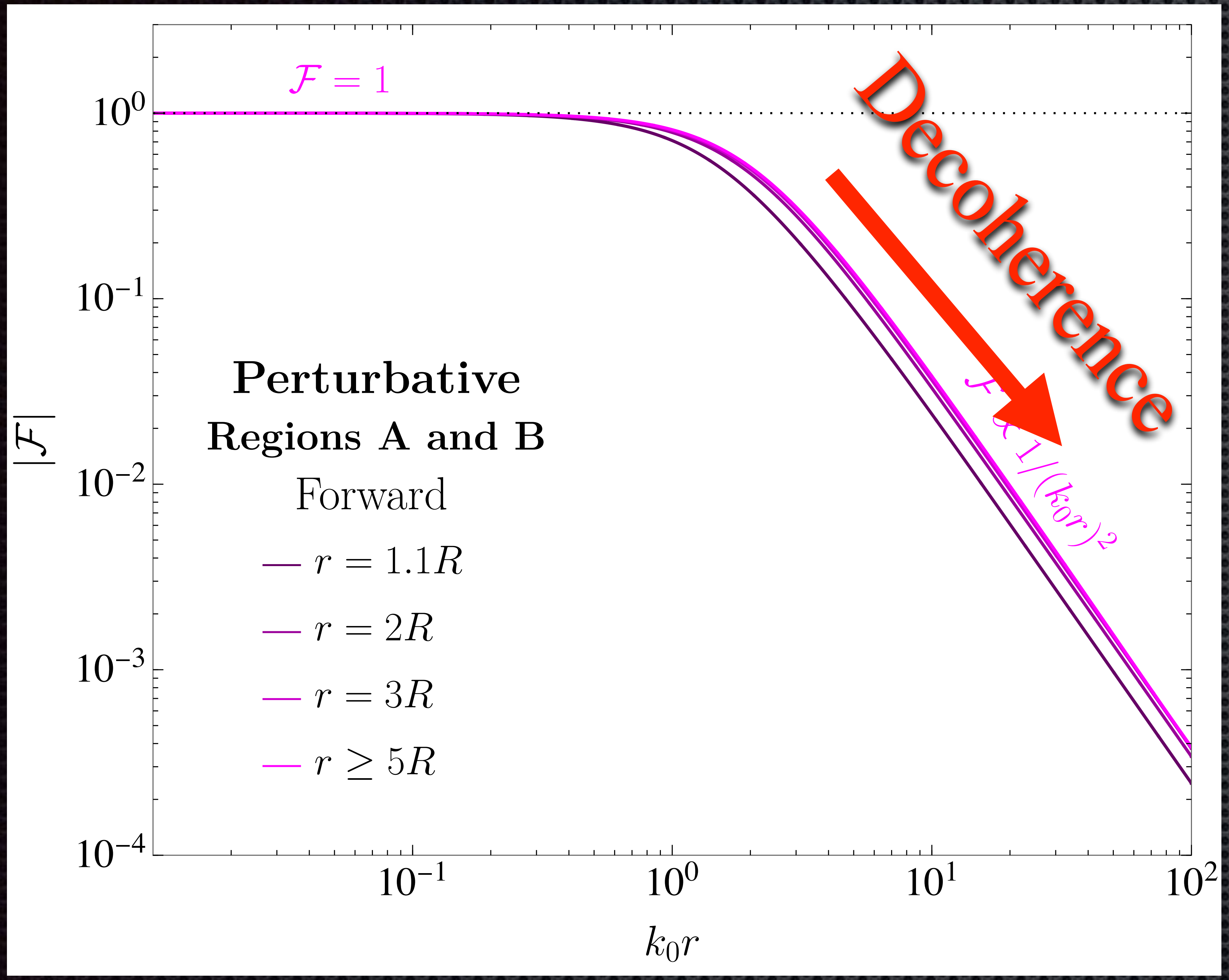
$\mathscr{F}_{\rm sc}$



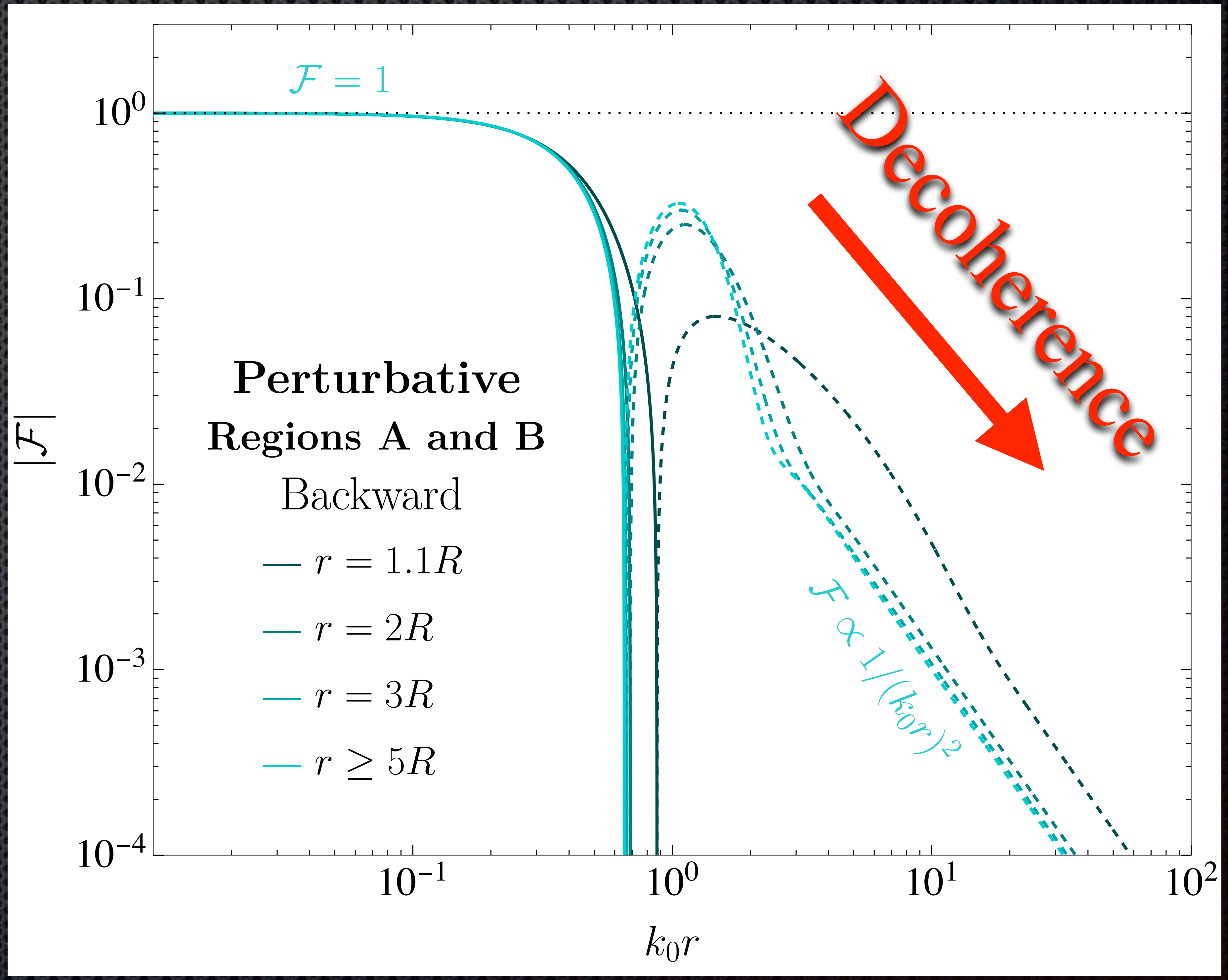
$\mathscr{F}_{\rm sc}/\mathscr{F}_{\rm sph}$

Background-Induced Force: Perturbative

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



Forward Direction

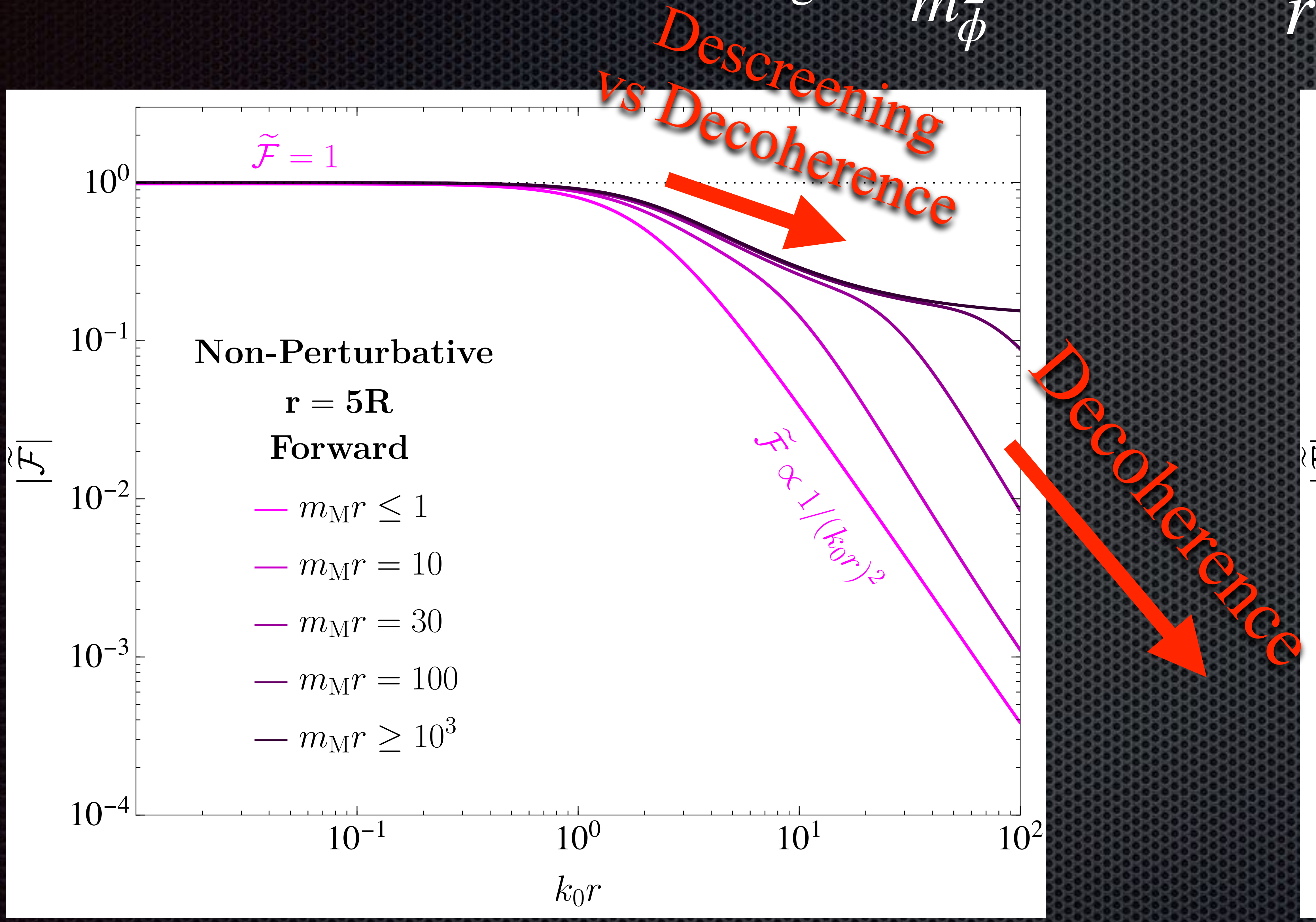


Backward Direction

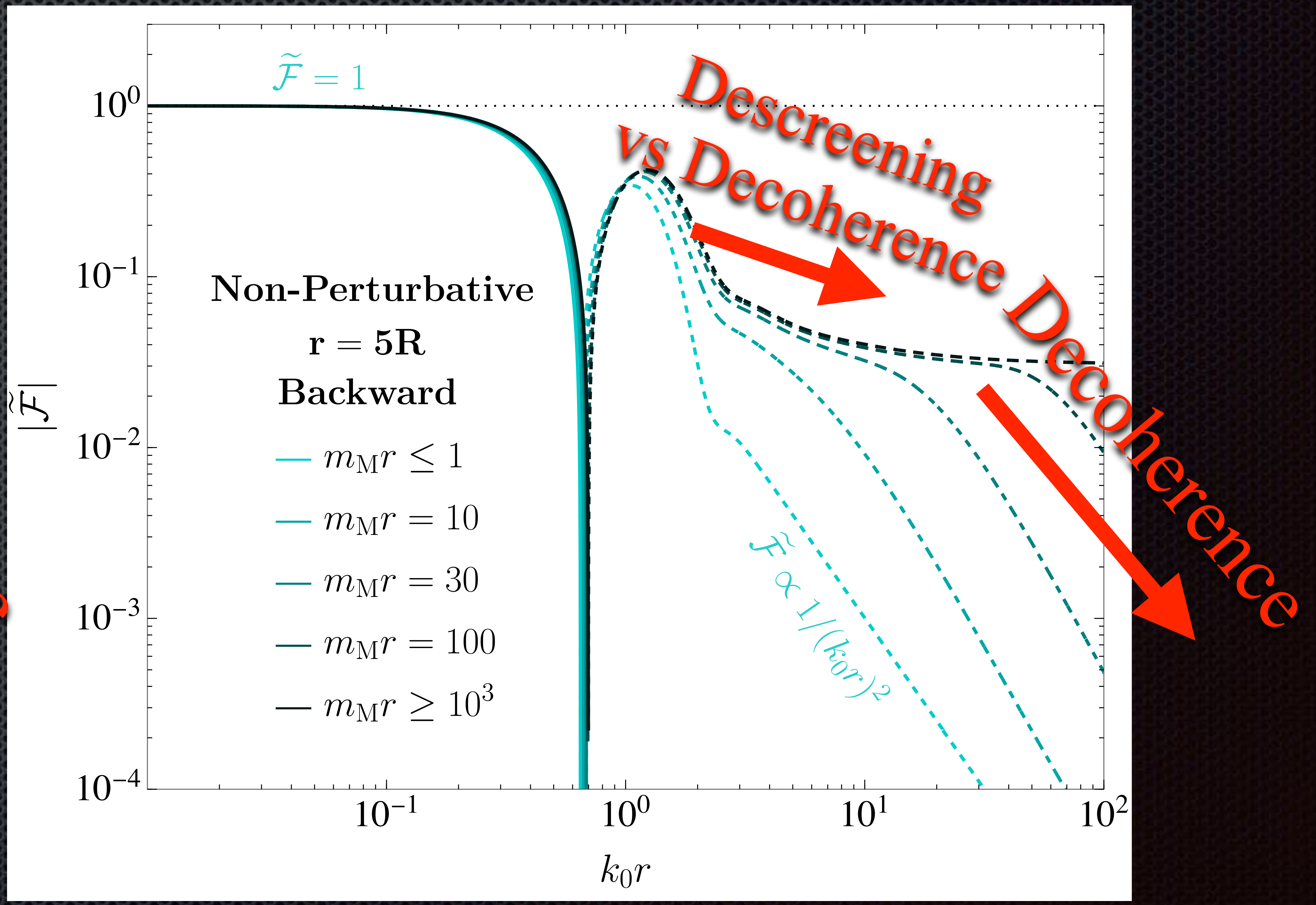
Background-Induced Force: Finite Barrier

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

$$\mathscr{F}_{\rm sph} \simeq \frac{3}{(m_{\rm M}R)^2}$$



Forward Direction

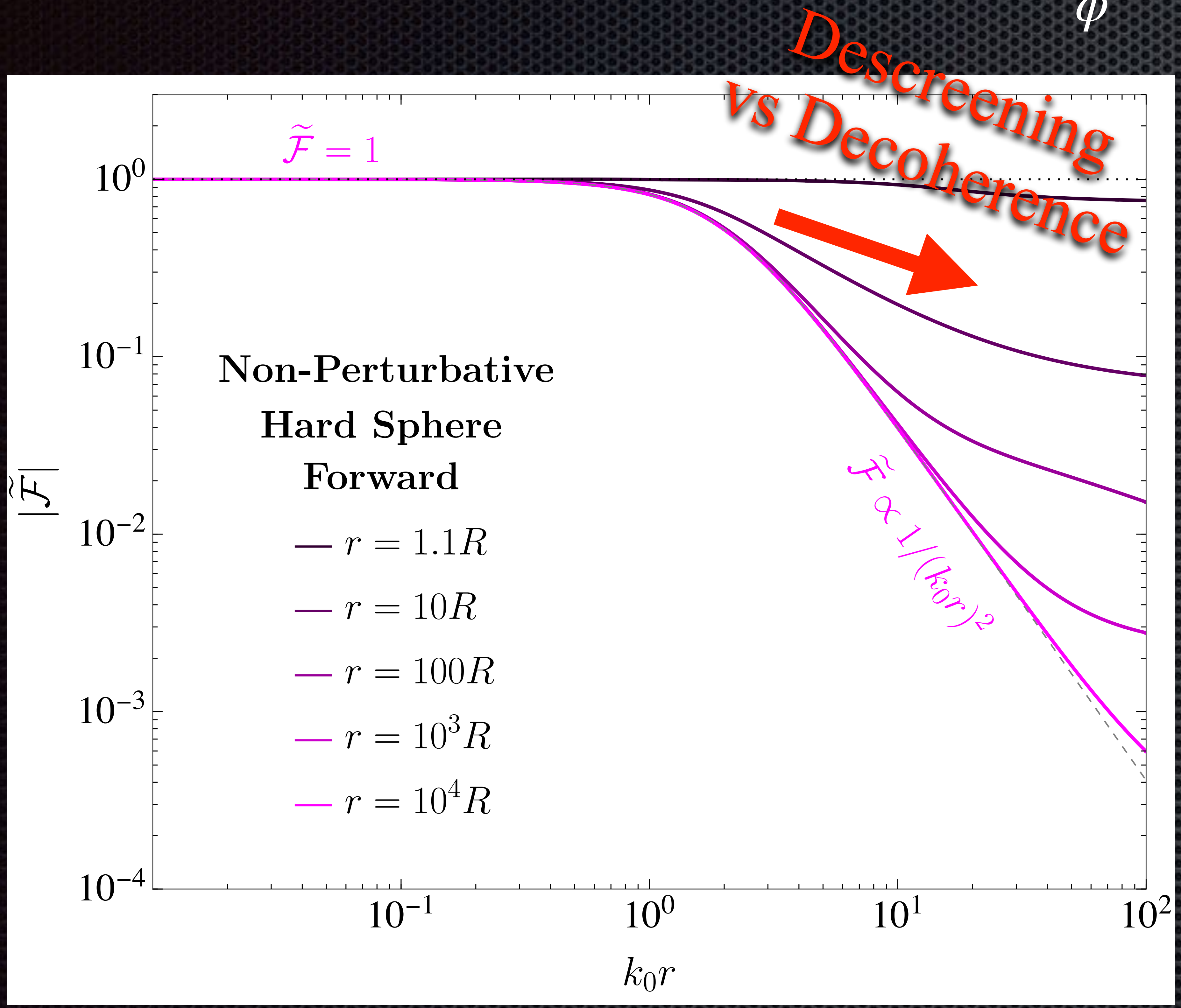


Backward Direction

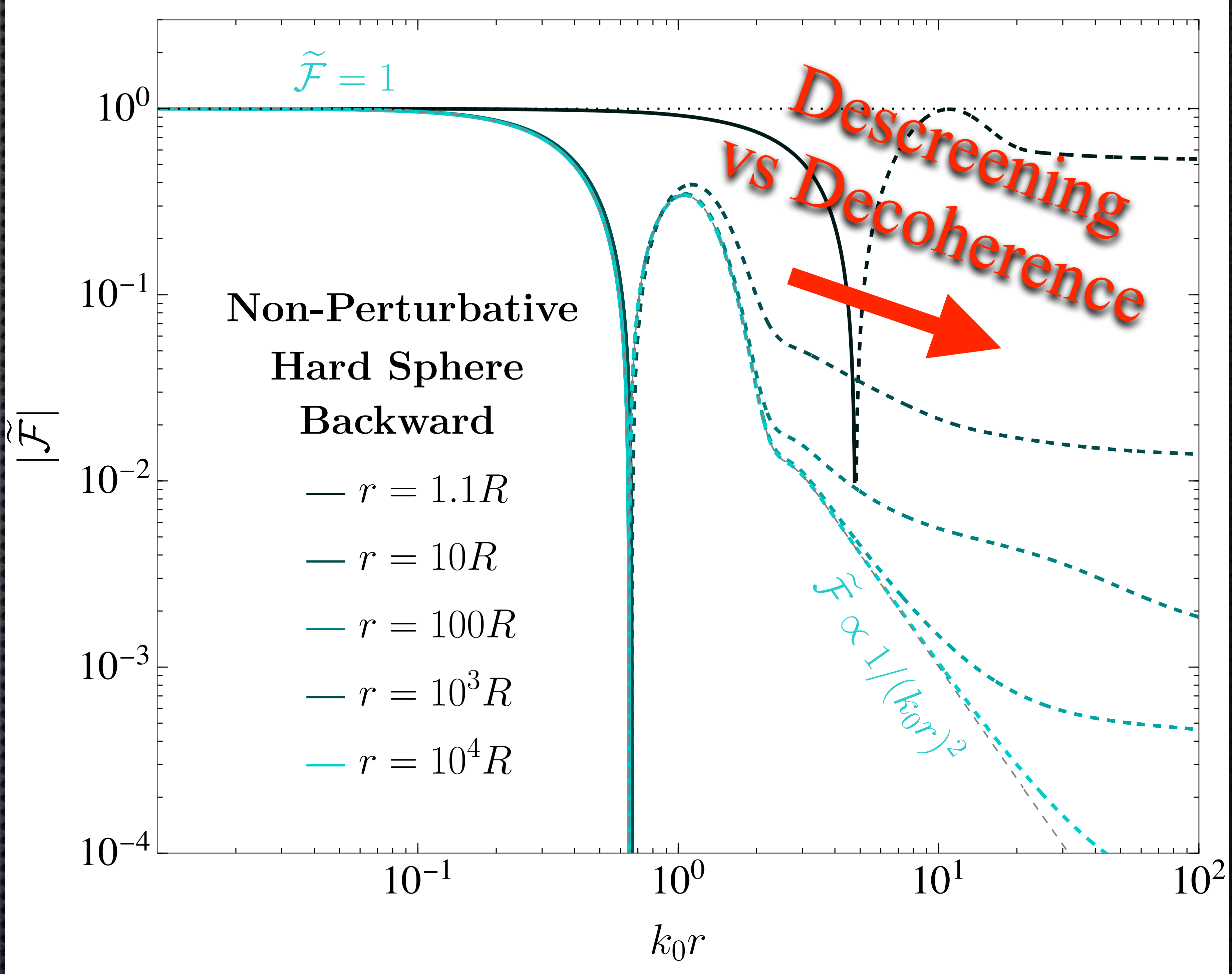
Background-Induced Force: Hard Sphere

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

$$\mathcal{F}_{\mathrm{sph}} \simeq \frac{3}{(m_{\mathrm{M}} R)^2}$$

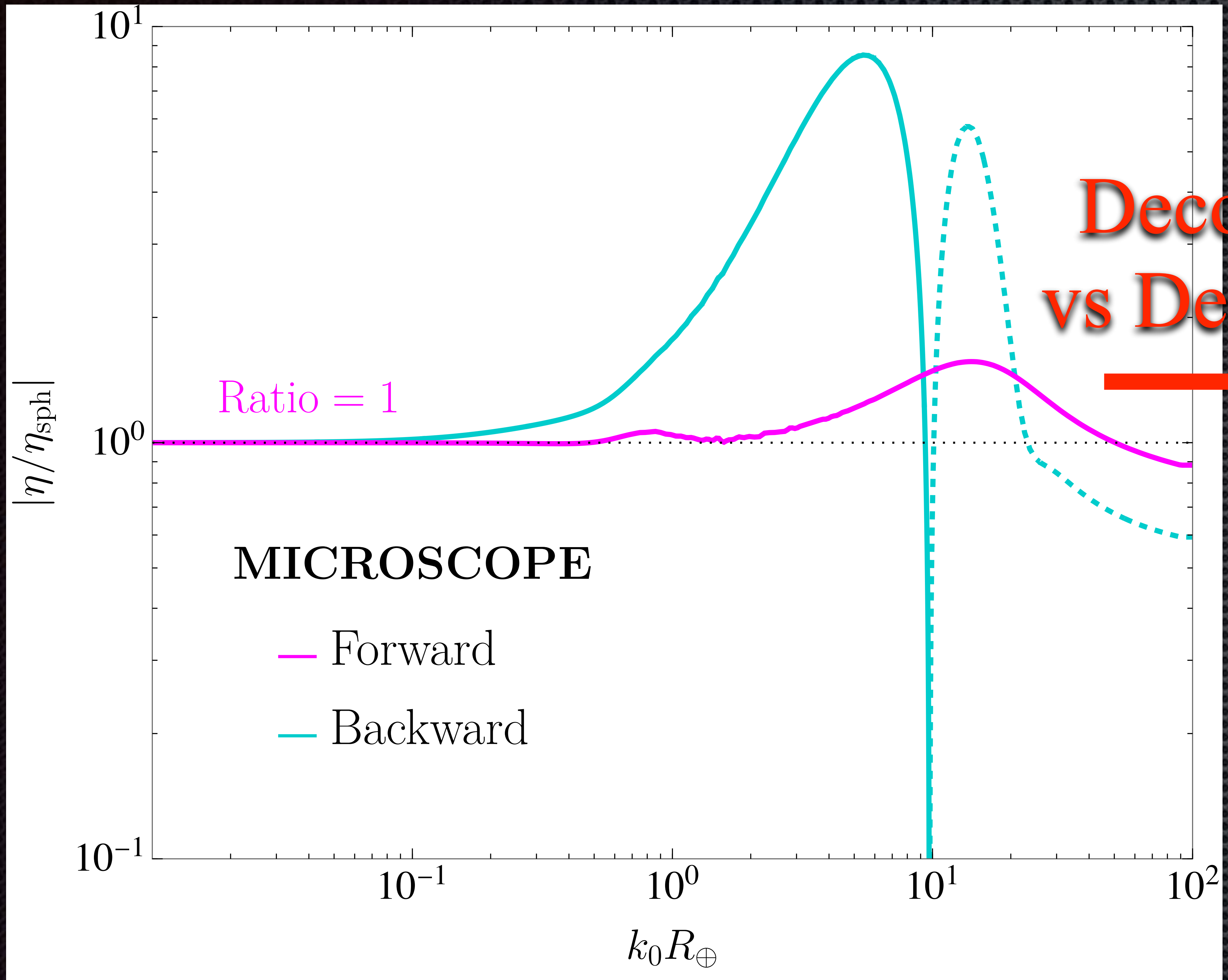


Forward Direction

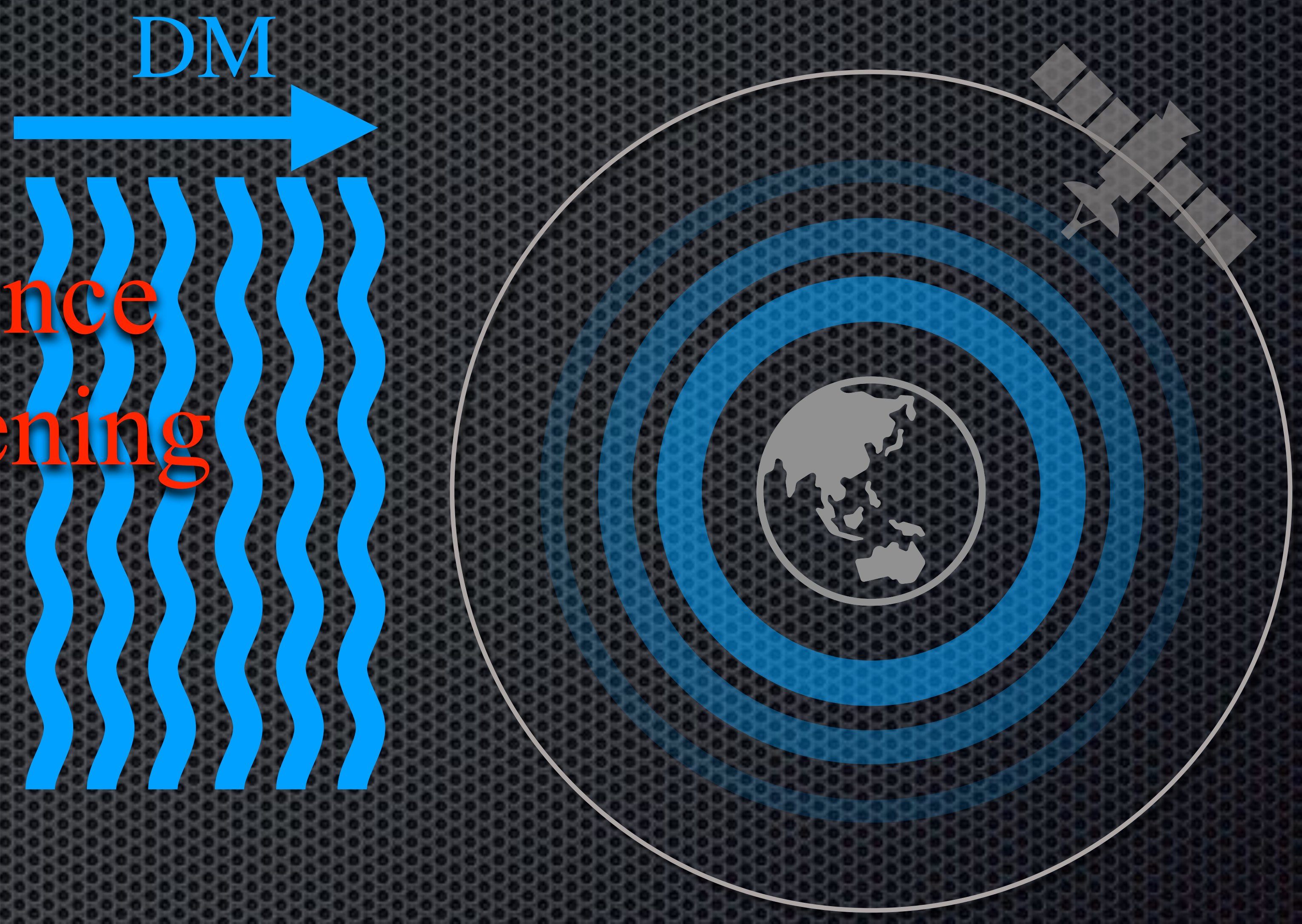


Backward Direction

MICROSCOPE Satellite

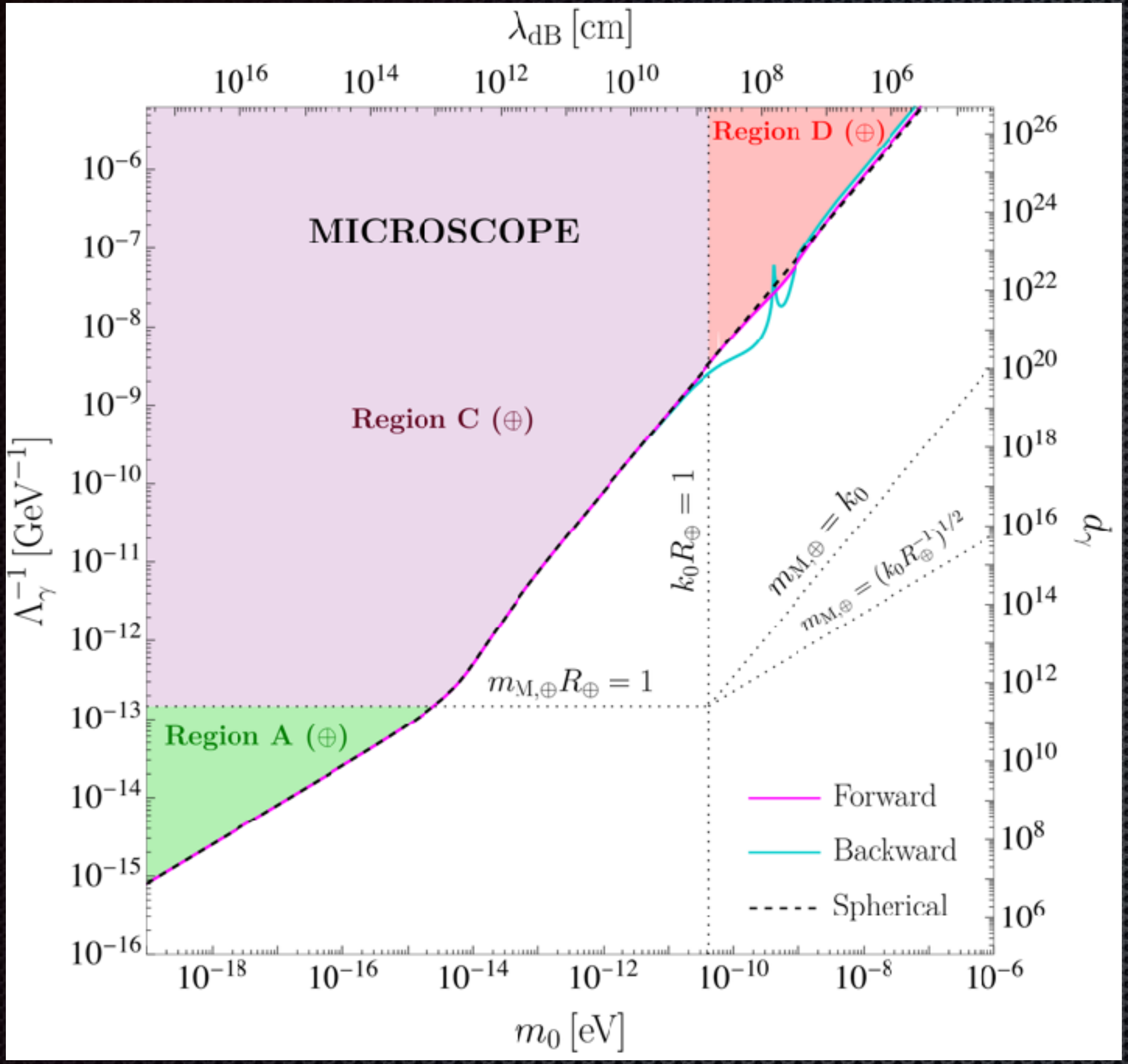


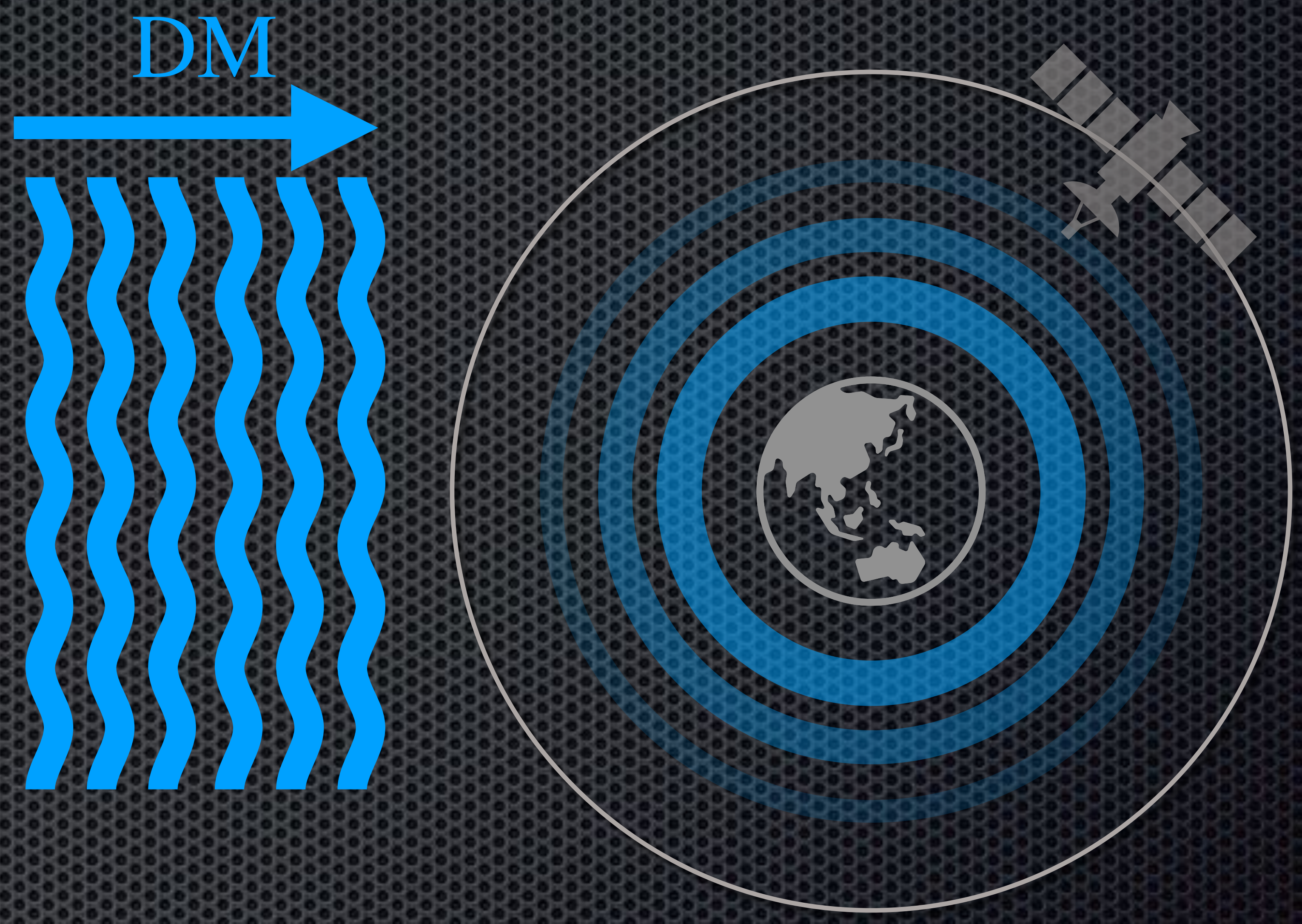
Decoherence vs Descreening



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 arises in dilaton, axion, and other scalar 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. We highlight three effects: the decoherence effect, the screening effect, and the descreening effect.

4. We revisited the MICROSCOPE equivalence principle test and updated the constraints in the high-momentum regime $kR_\oplus \gg 1$. Additionally, we identified the AC component of the background-induced force acting on the test mass.

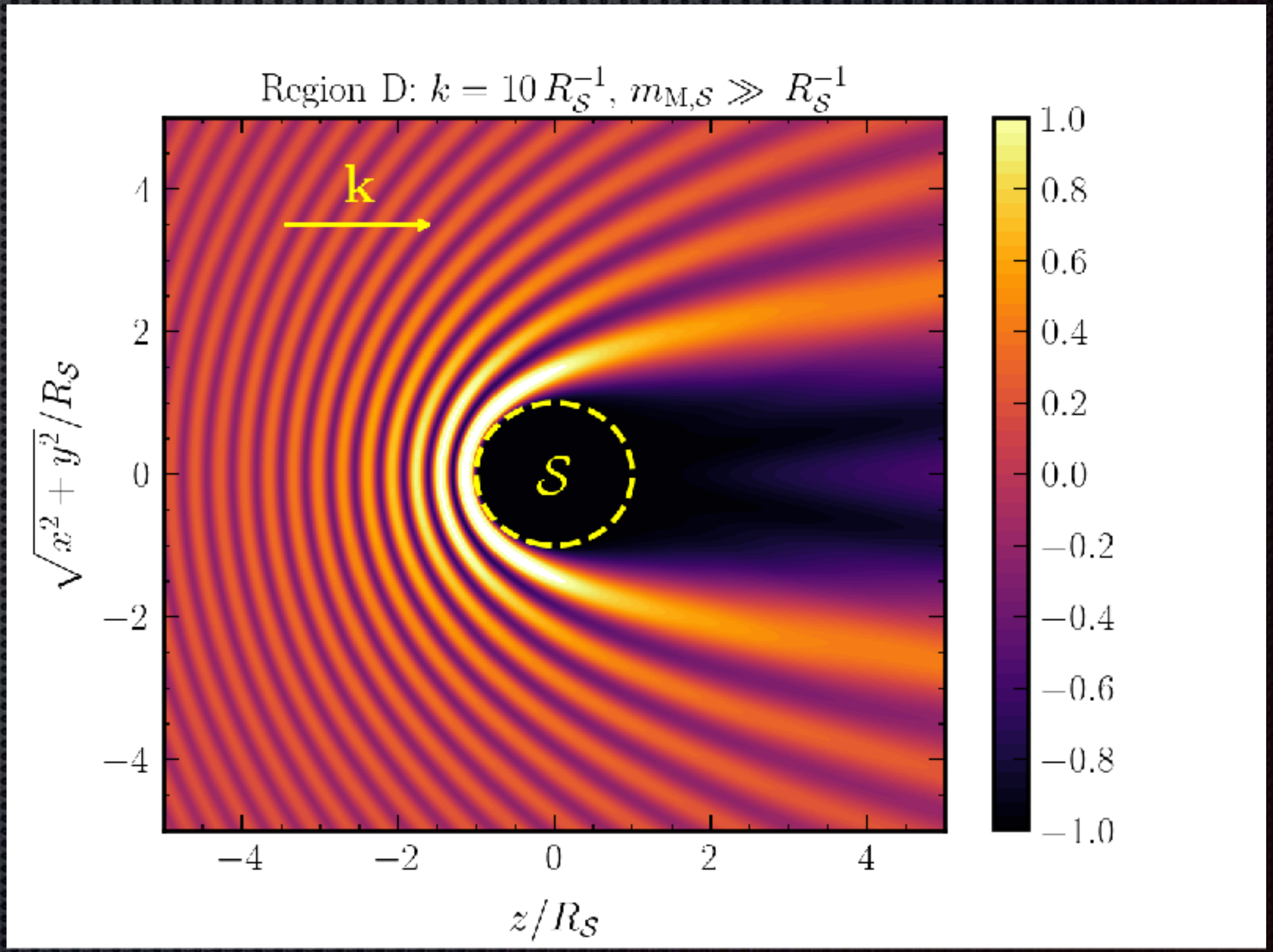
Appendix

Partial Wave + Phase Space

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

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

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

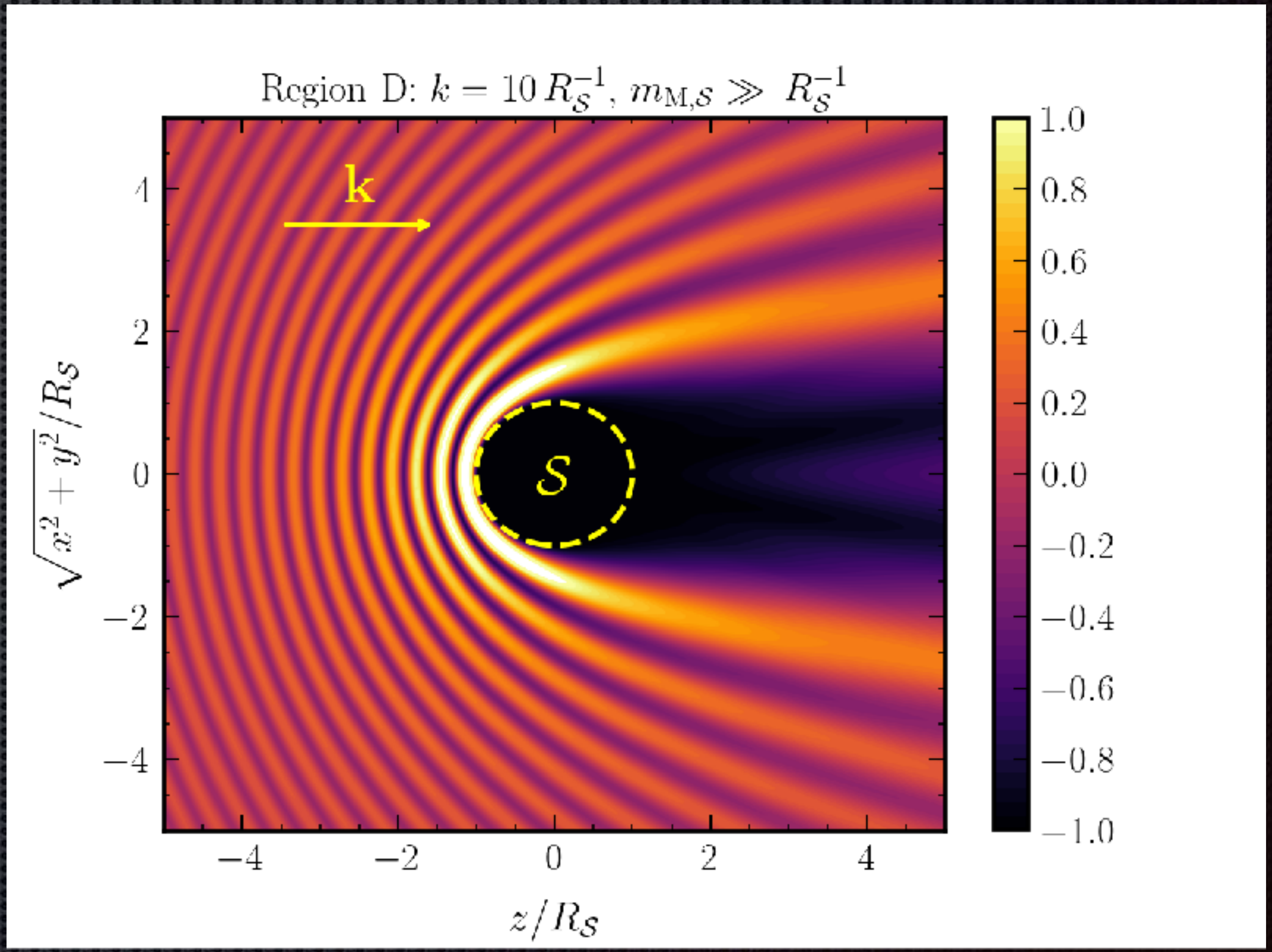


Partial Wave + Phase Space

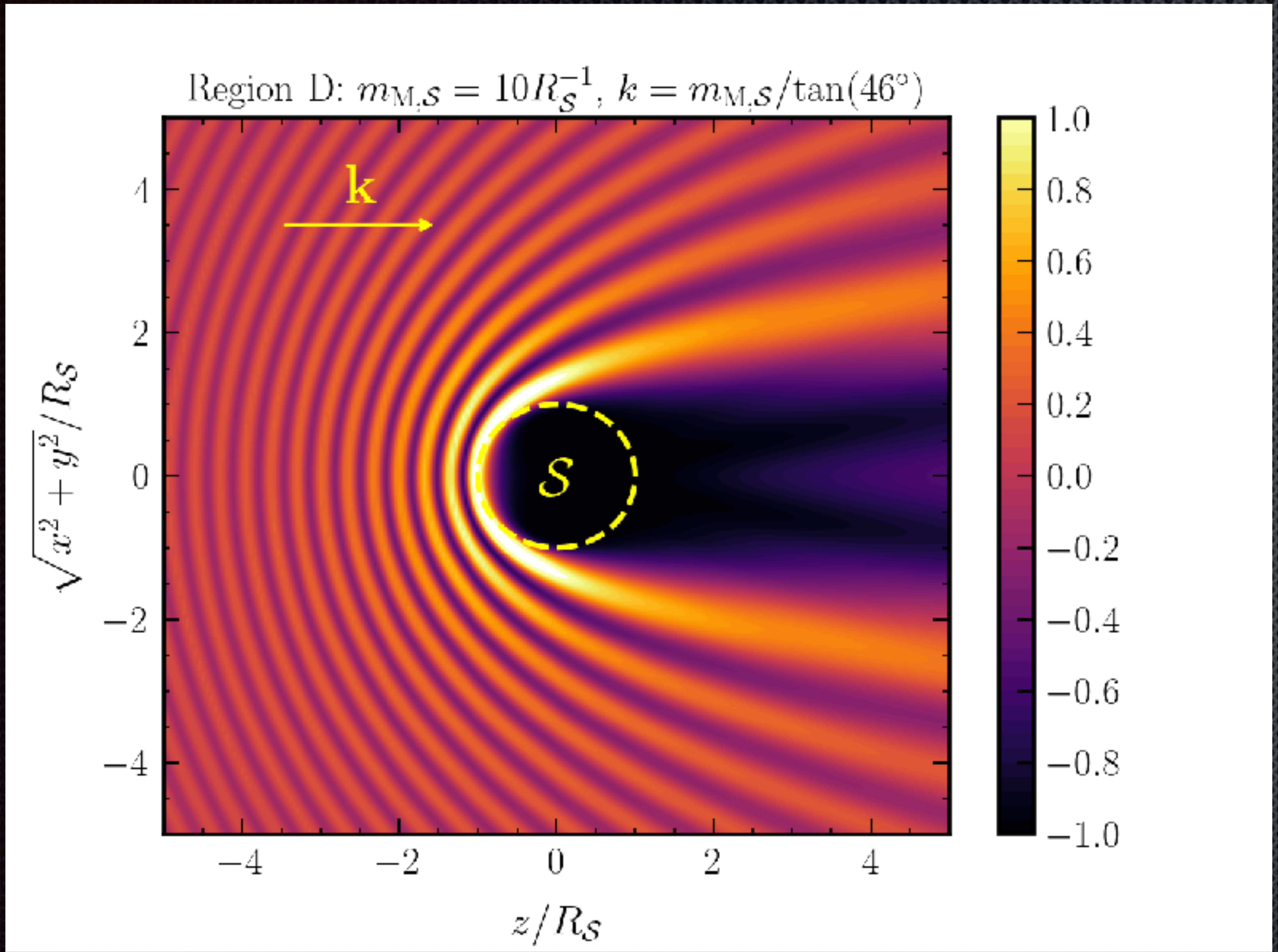
$$V_{\rm bg}(\mathbf{k}) \propto |\psi_{\rm tot}(\mathbf{k})|^2$$

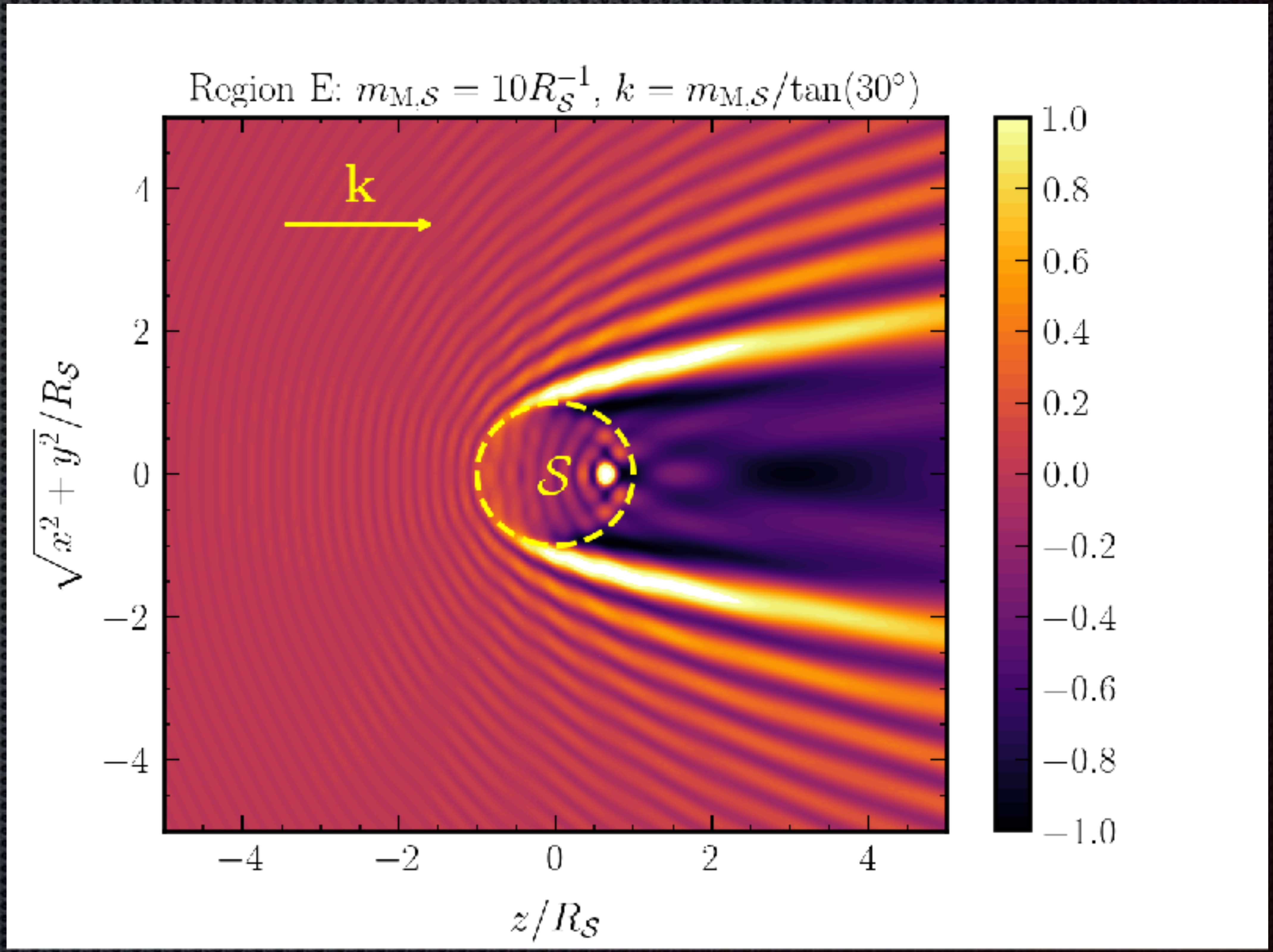
$$\langle V_{\rm bg}\rangle_{\mathbf{k}} = \frac{1}{n_\phi}\int_{\mathbf{k}} f_\phi(\mathbf{k}) V_{\rm bg}(\mathbf{k})$$

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



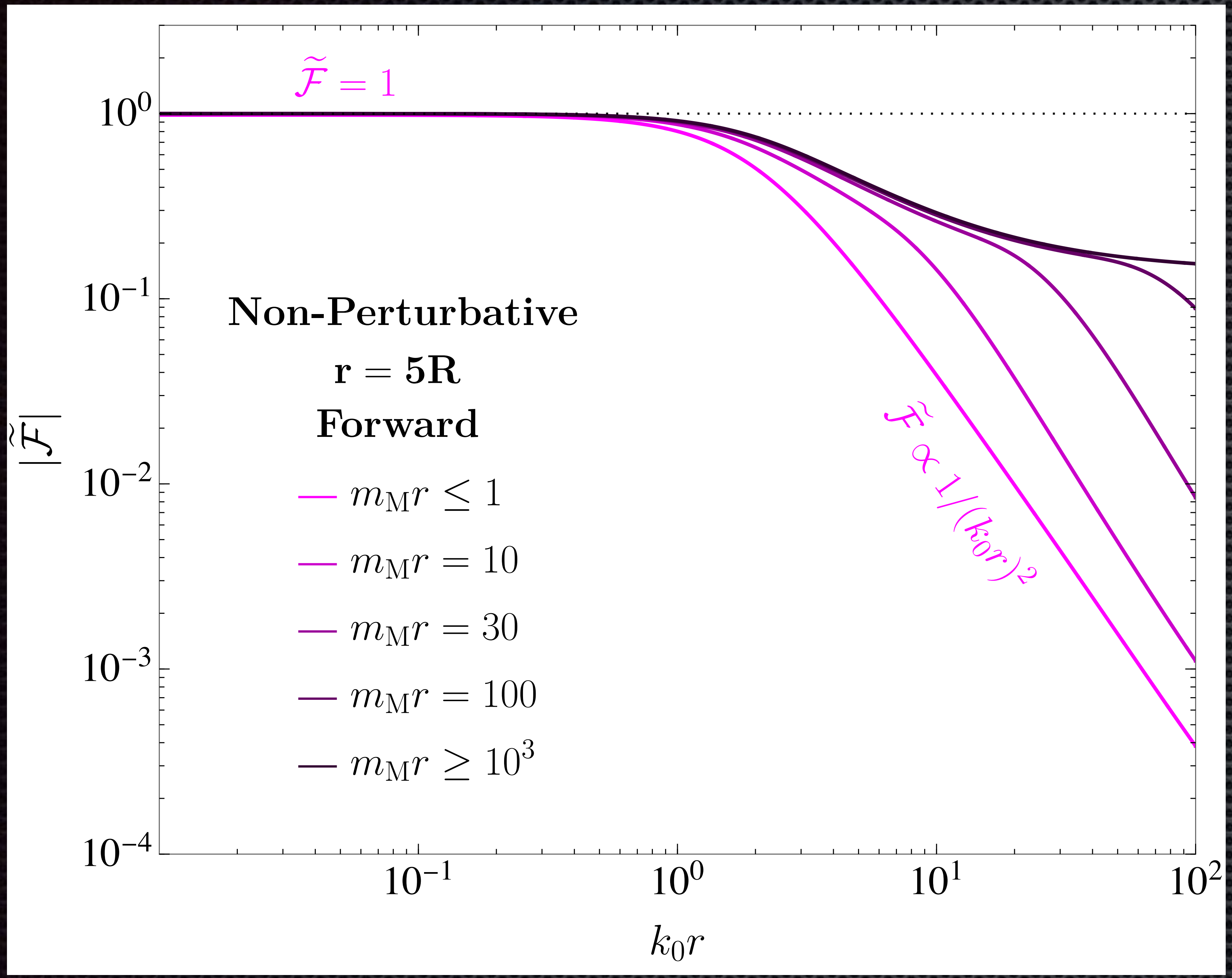
Descreening Effect



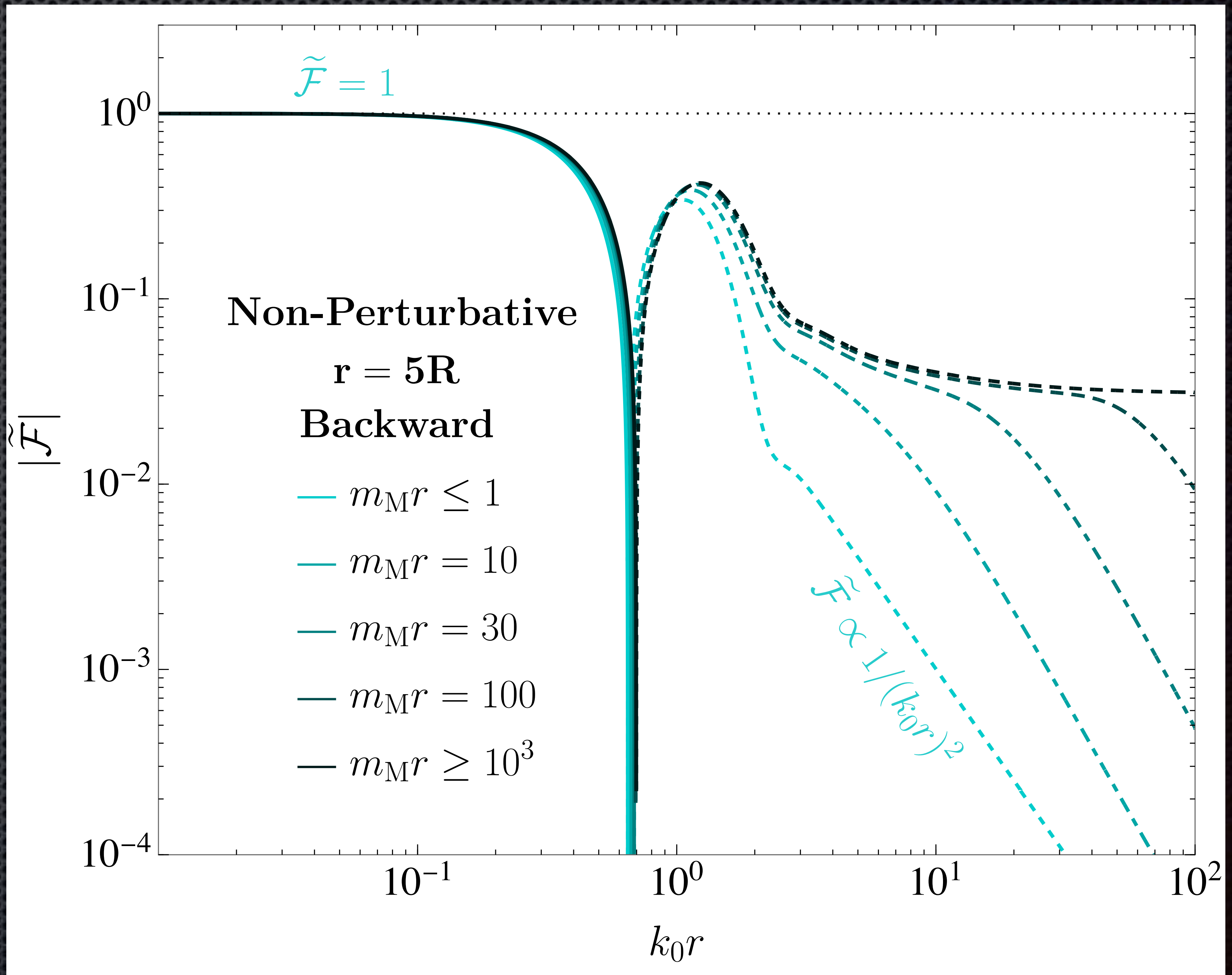


Descreening Effect

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



Forward Direction



Backward Direction

Spherical Symmetric Ansatz

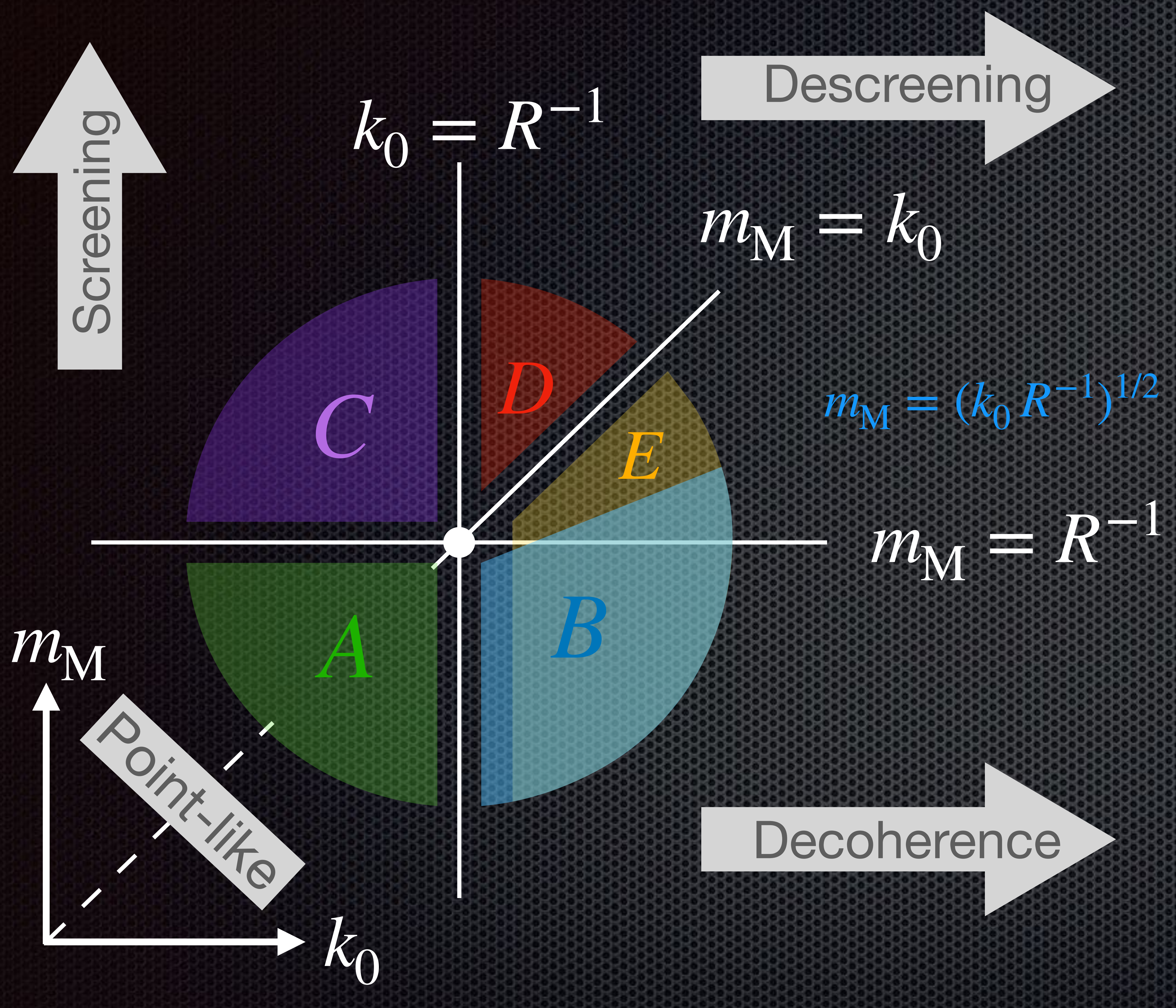
$$\nabla^2 \psi_{\text{sph}} = m_{\text{M}}^2 \, \theta(R - r) \, \psi_{\text{sph}}$$

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

Screening Effect

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

Classification of $\mathbf{F}_{\rm bg}$



★ 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

Our work

A+B+C

+D+E