News from the dark 10

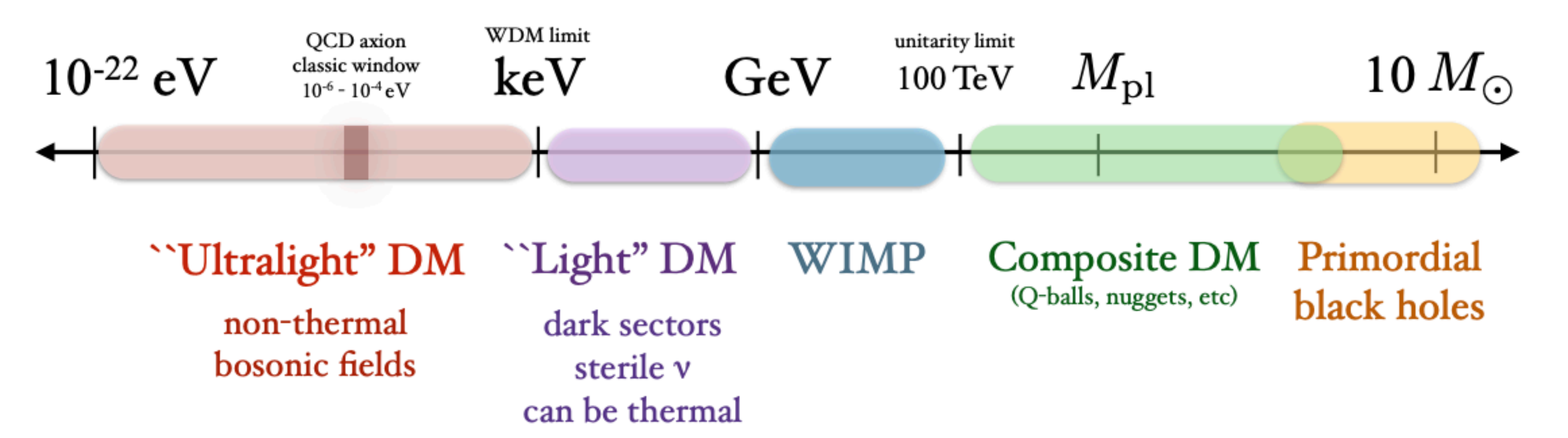
Detecting Ultralight Dark Matter with Matter Effect

Speaker: Xucheng Gan

DESY, Hamburg

2504.11522

Dark Matter Landscape



From Tongyan Lin, 2019 TASI Lecture

Ultralight Dark Matter

Large occupation number & Classical behavior

Quadratic Coupling

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

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

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

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

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

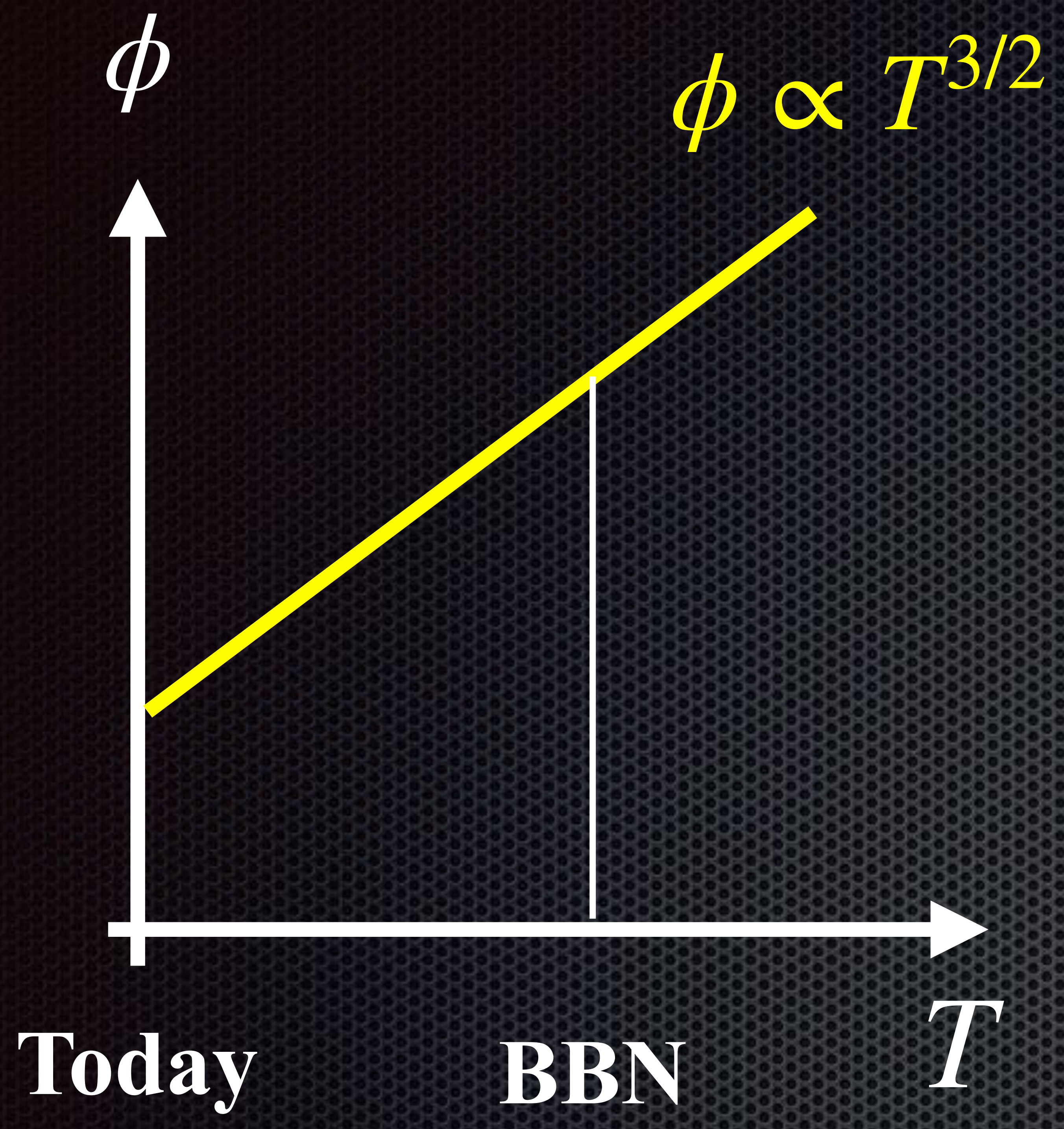
Ordinary Matter

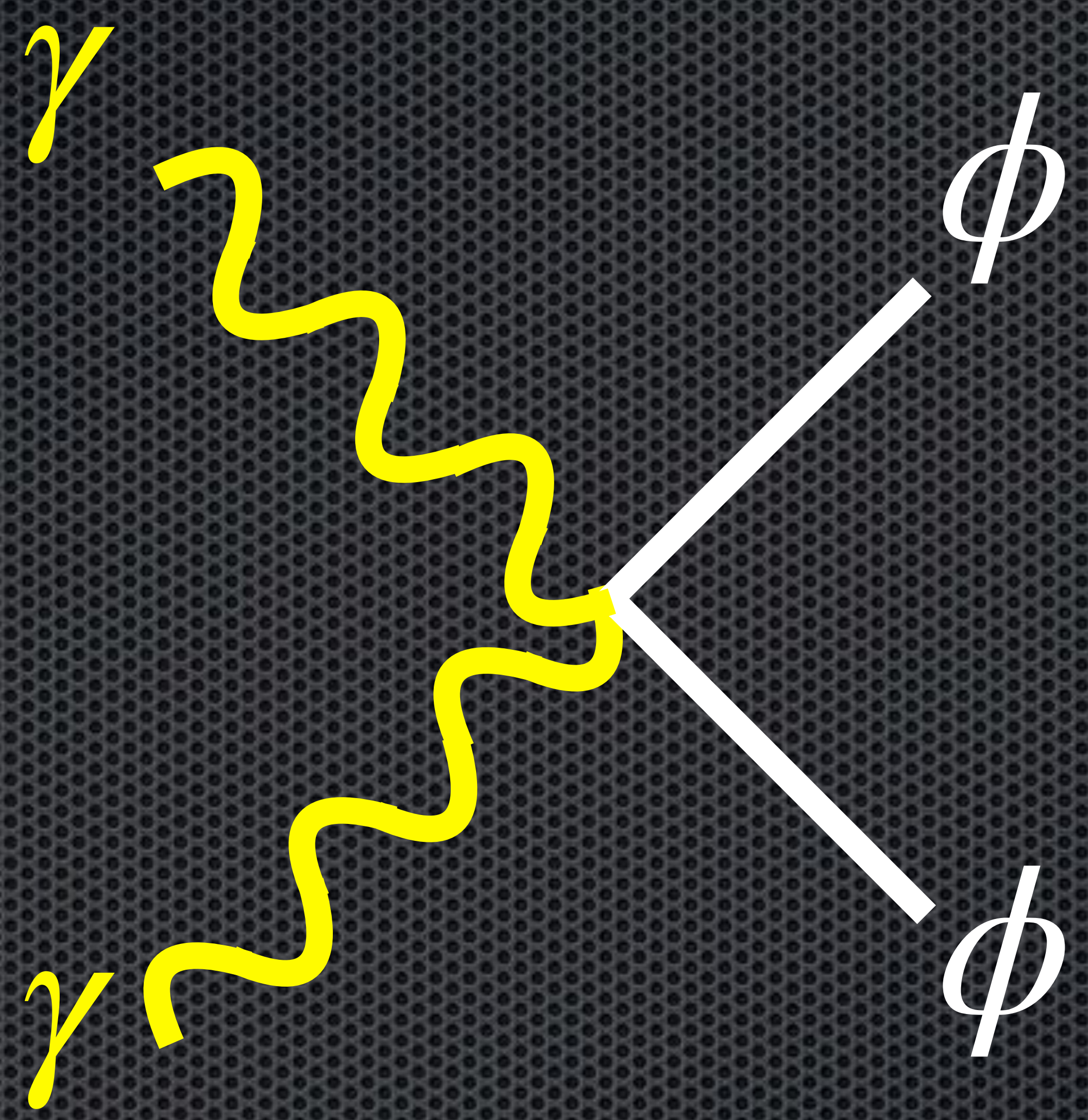
$$\mathcal{O}_{\rm SM} \to \langle \mathcal{O}_{\rm SM} \rangle$$

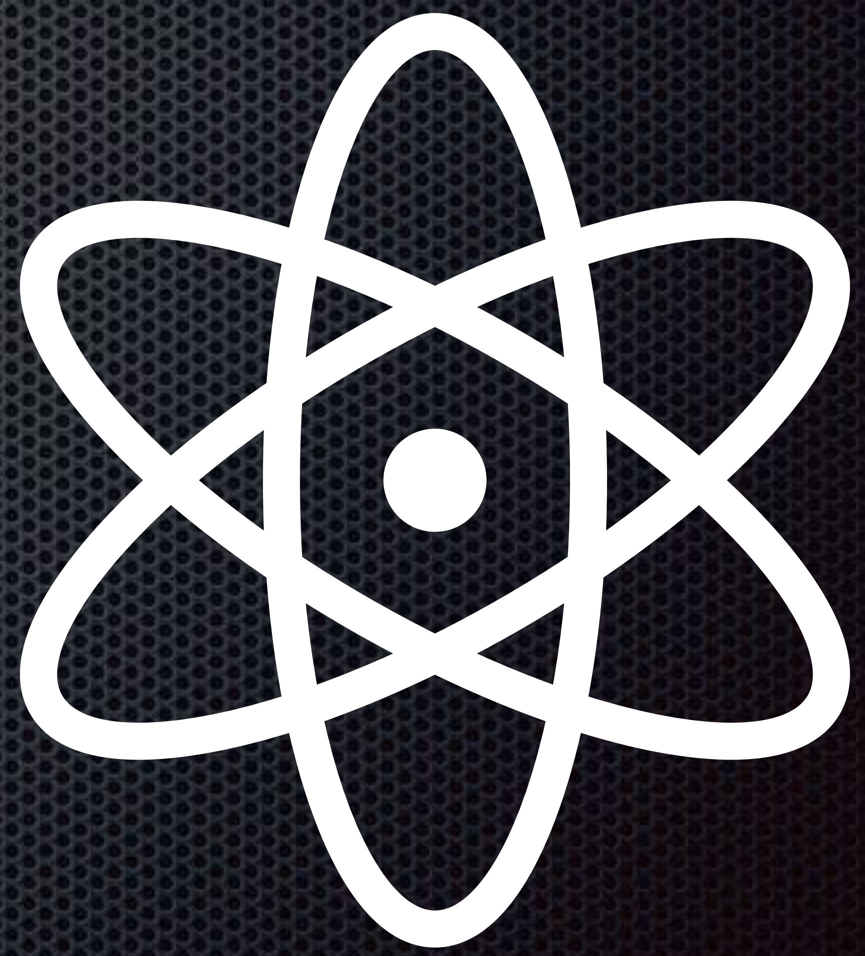
Effective Mass

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

Other Detections







Big Bang Nucleosynthesis

2006.04820, 2211.09826

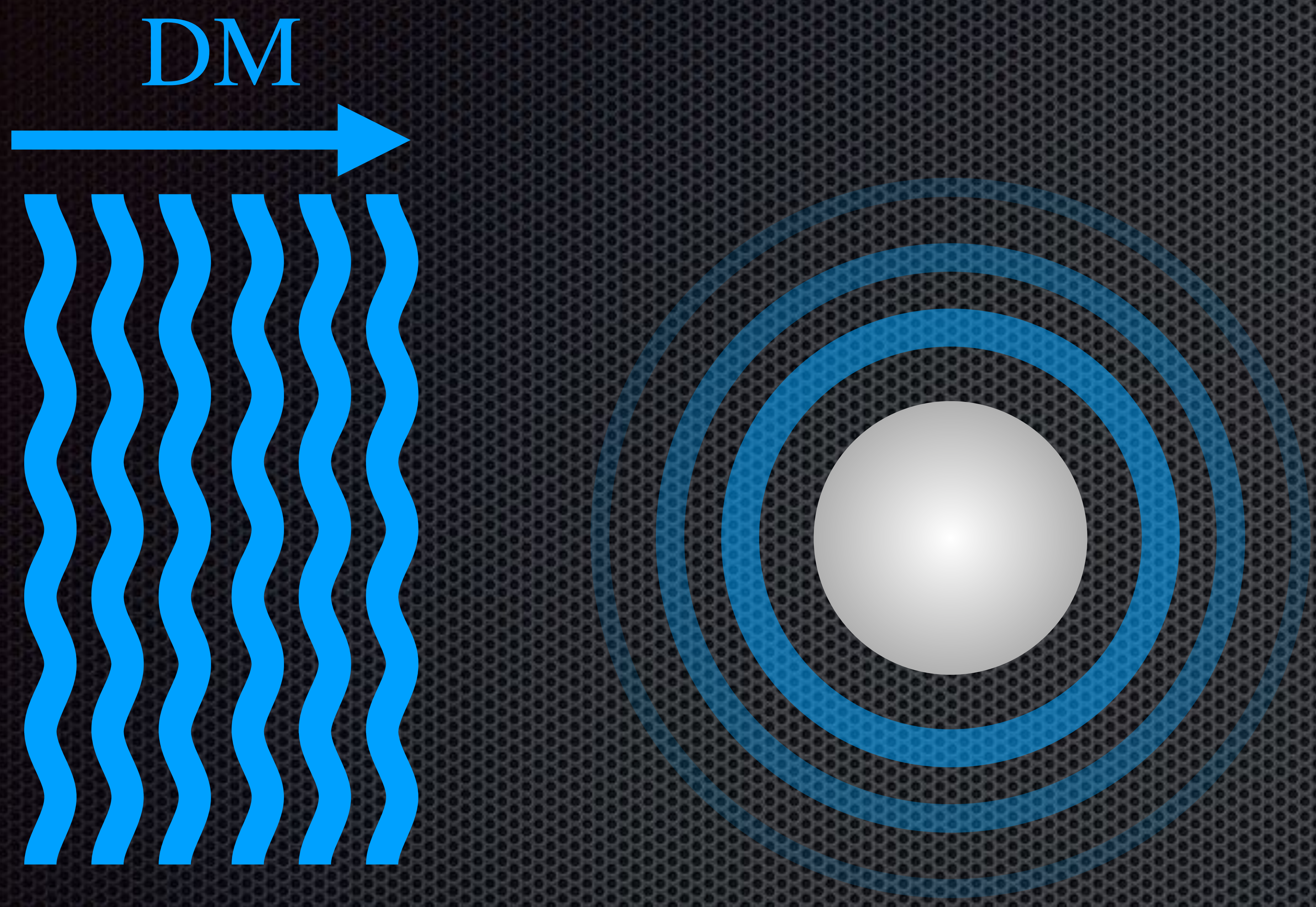
Supernova Cooling

0709.3825, 2412.17308

Atomic Clock

1405.2925, 1807.04512

Matter Effect



Ordinary Matter

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

Effective Mass

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

Matter Effect

Ordinary Matter

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

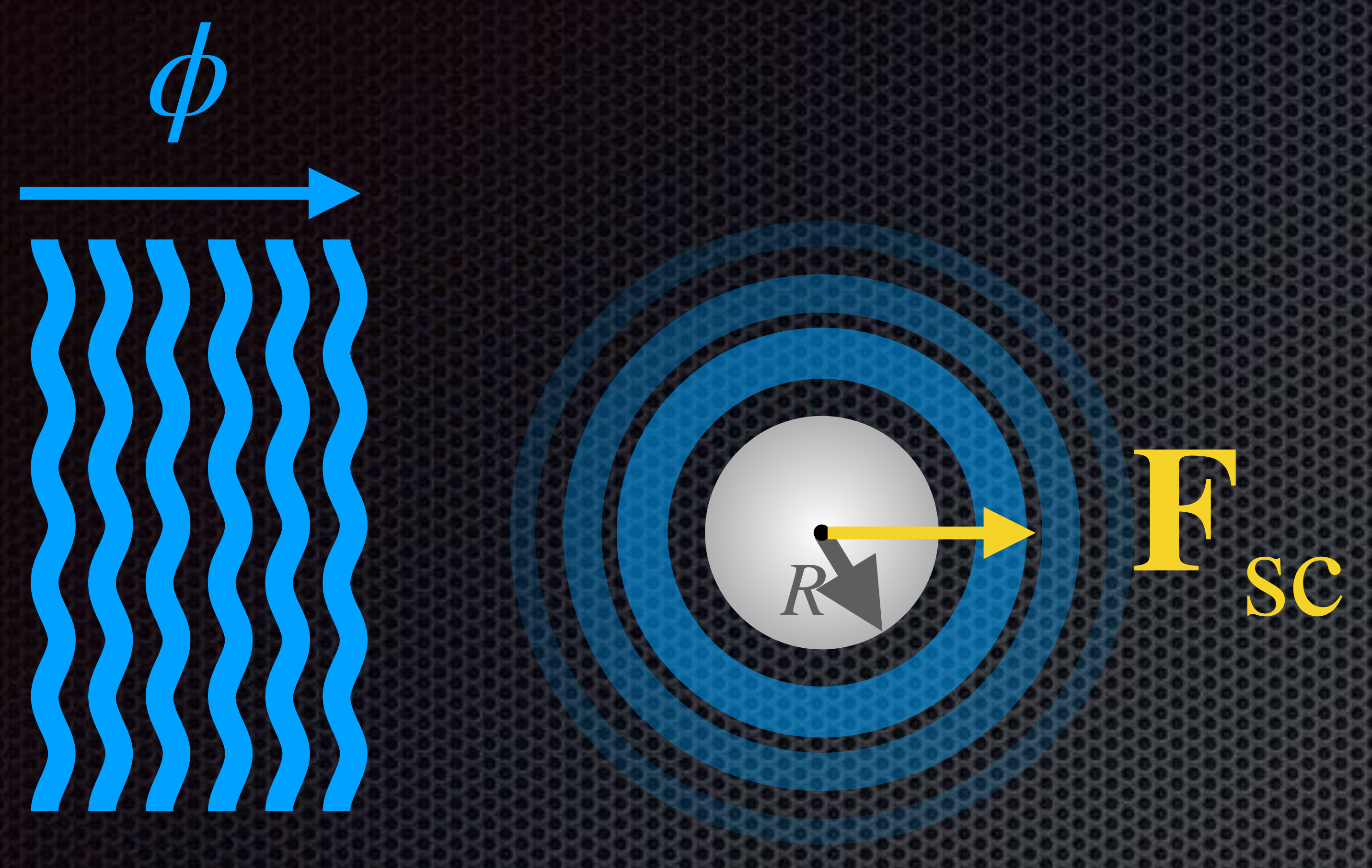
Scattering Force

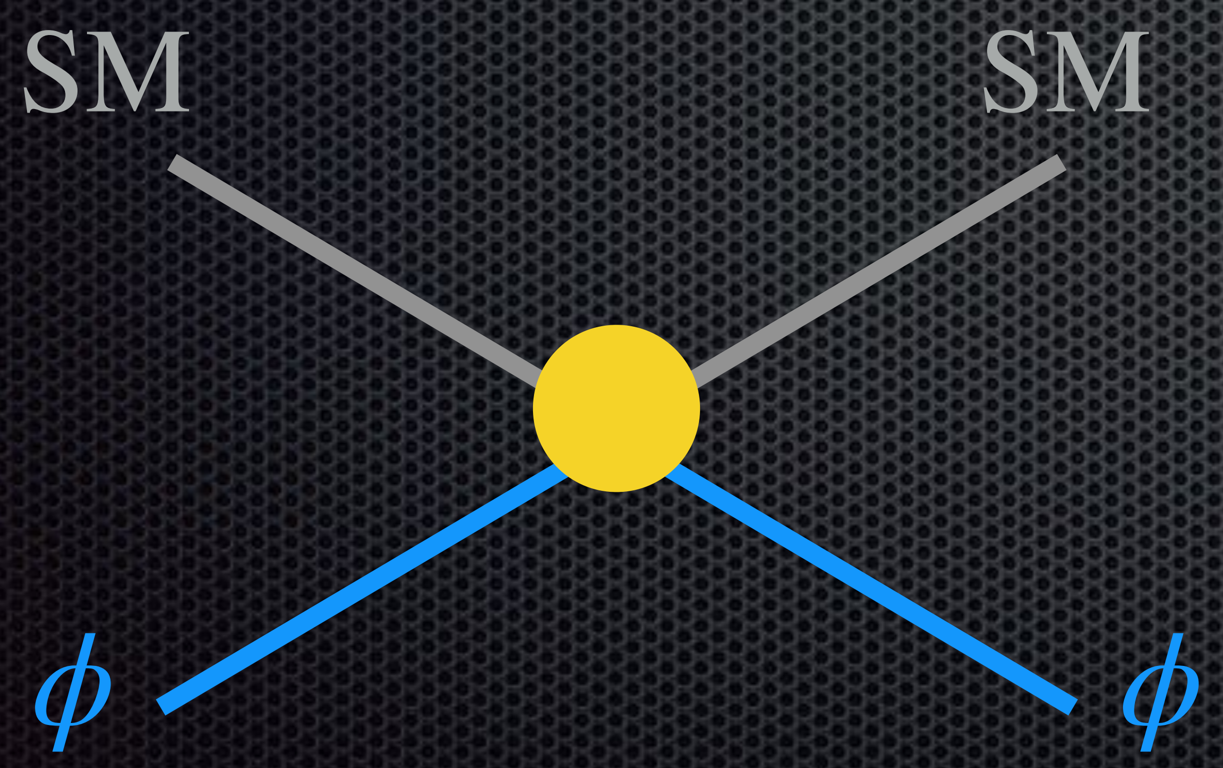
Background-Induced Force

Effective Mass

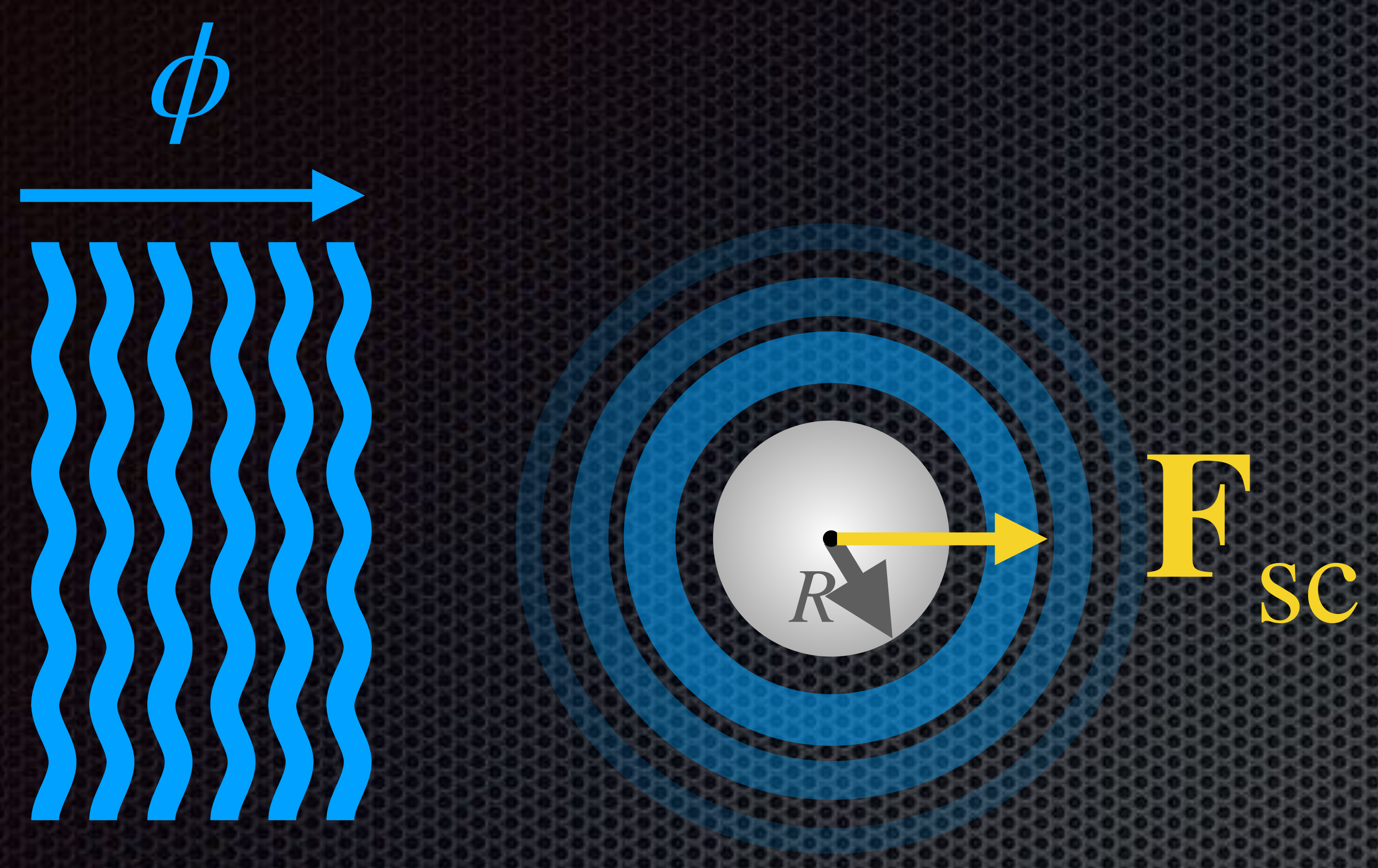
$$m_{\mathrm{M}}^2 \sim \frac{\langle \mathcal{O}_{\mathrm{SM}} \rangle}{\Lambda^2}$$

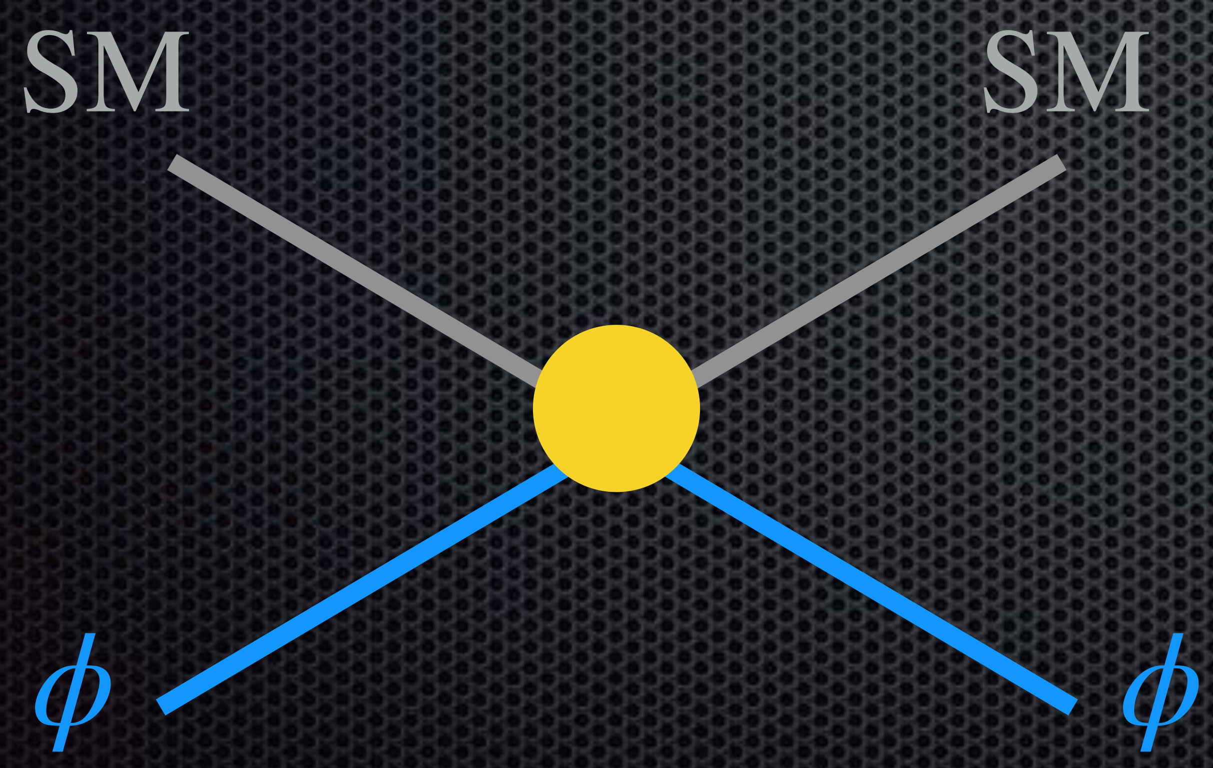
Scattering Force





Scattering Force





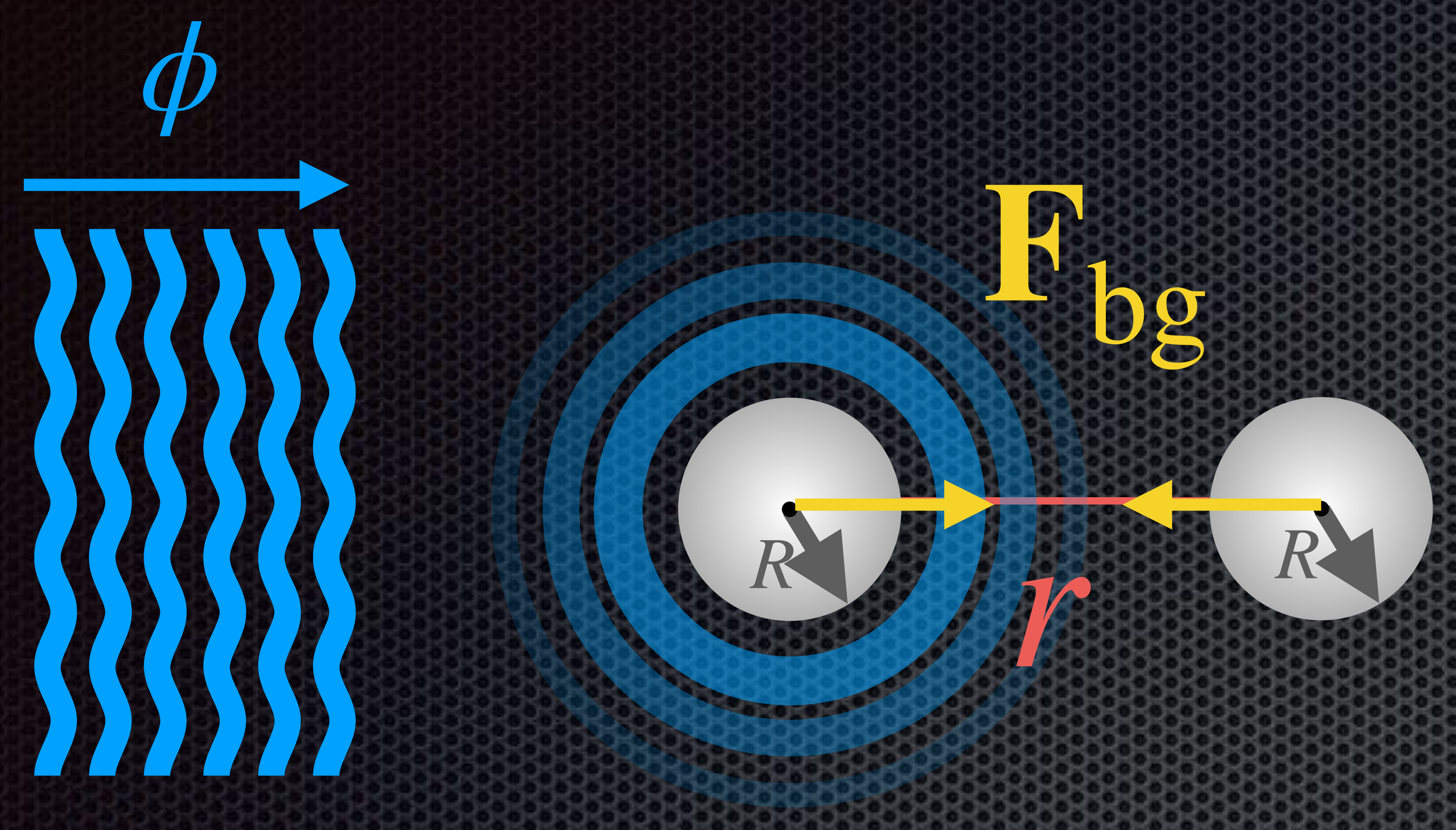
$$\sigma_{\rm T} \sim \frac{(m_{\rm M}^2 V_R)^2}{4\pi}$$ Coherent Scattering

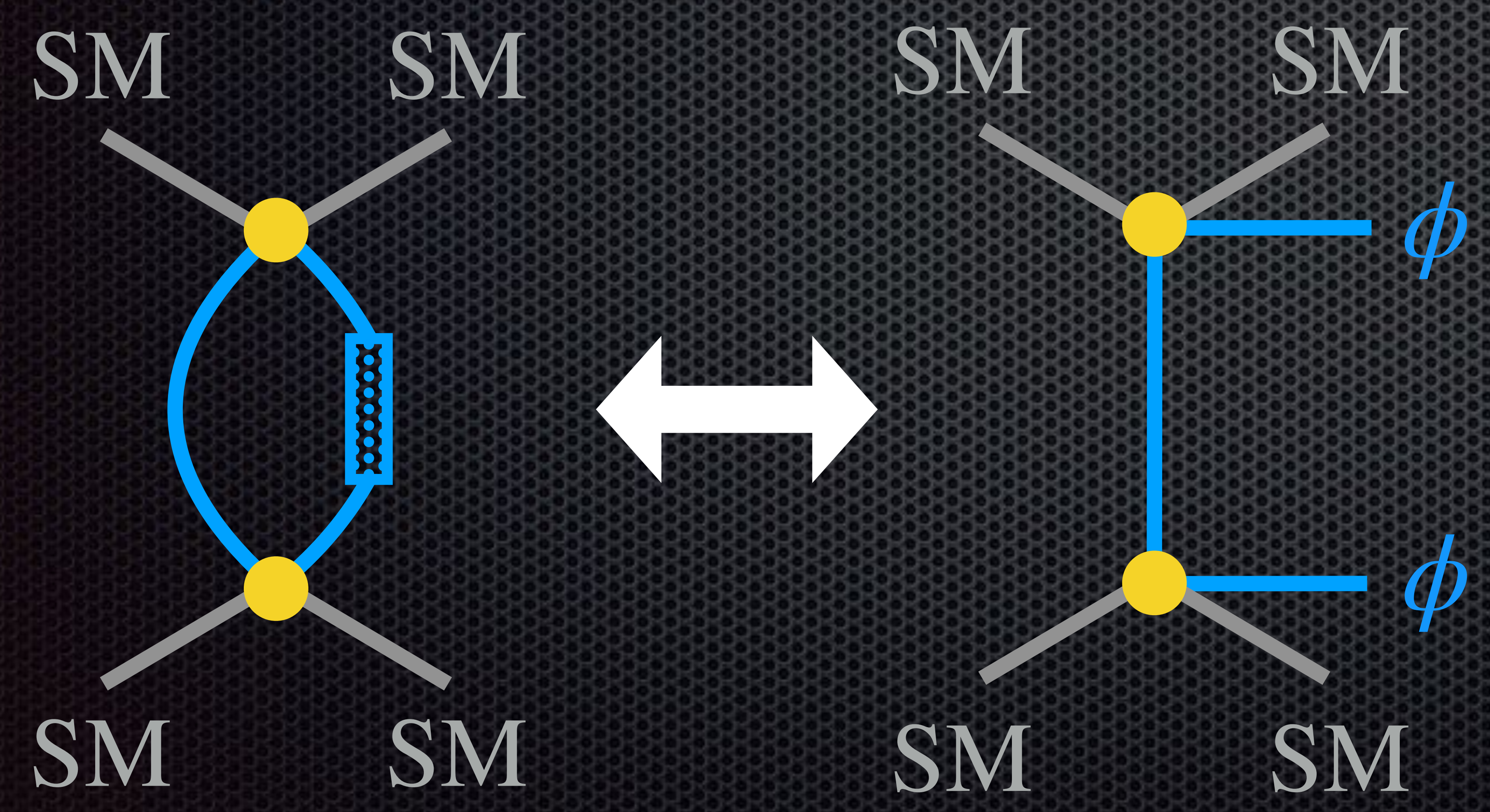
$$\mathbf{F}_{\rm sc} \sim \sigma_{\rm T} \times \rho_\phi v_\phi^2 \times \hat{k}$$

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

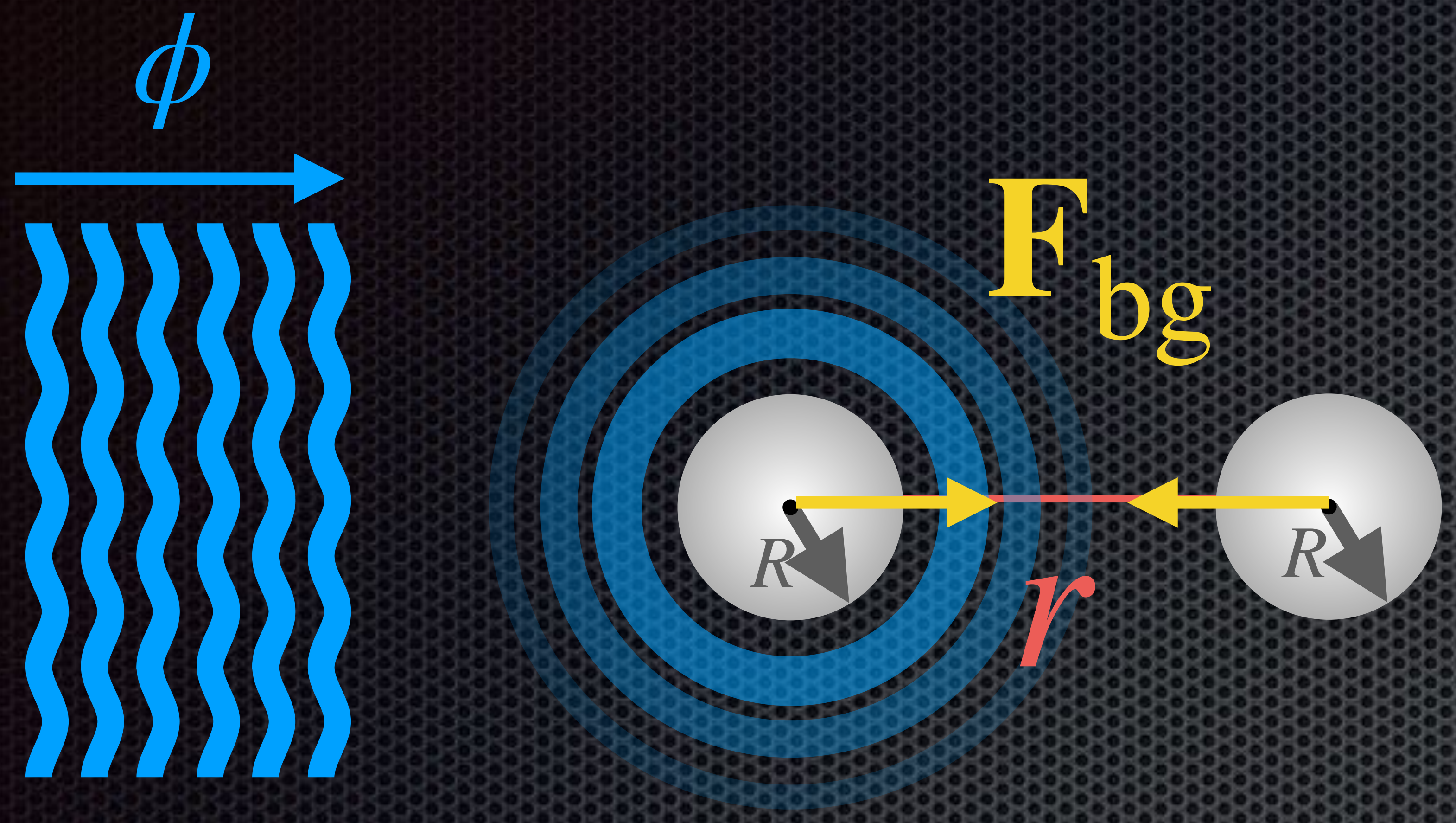
Also check Day, Liu, Luty, and Zhao 2023

Background-Induced Force



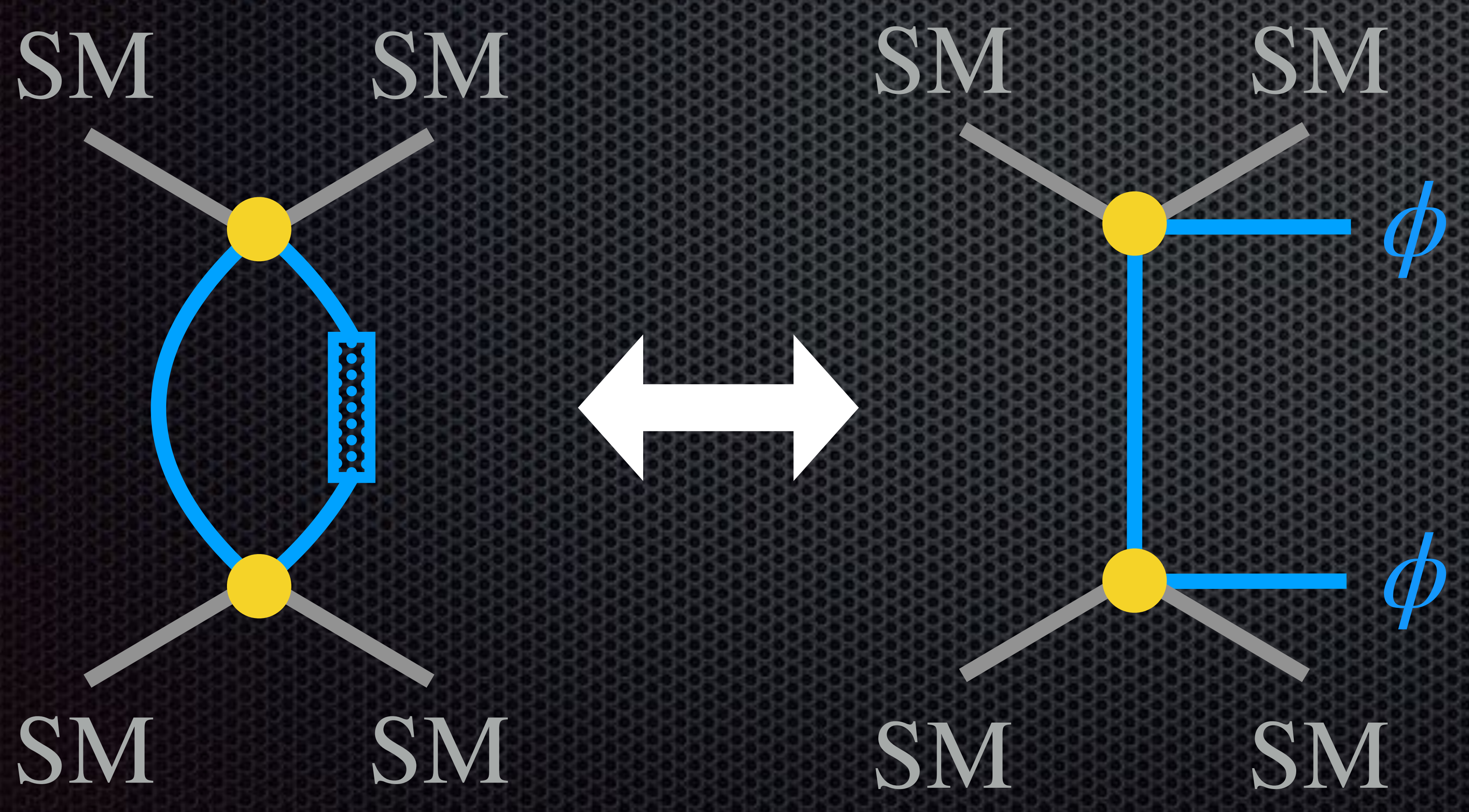


Background-Induced Force



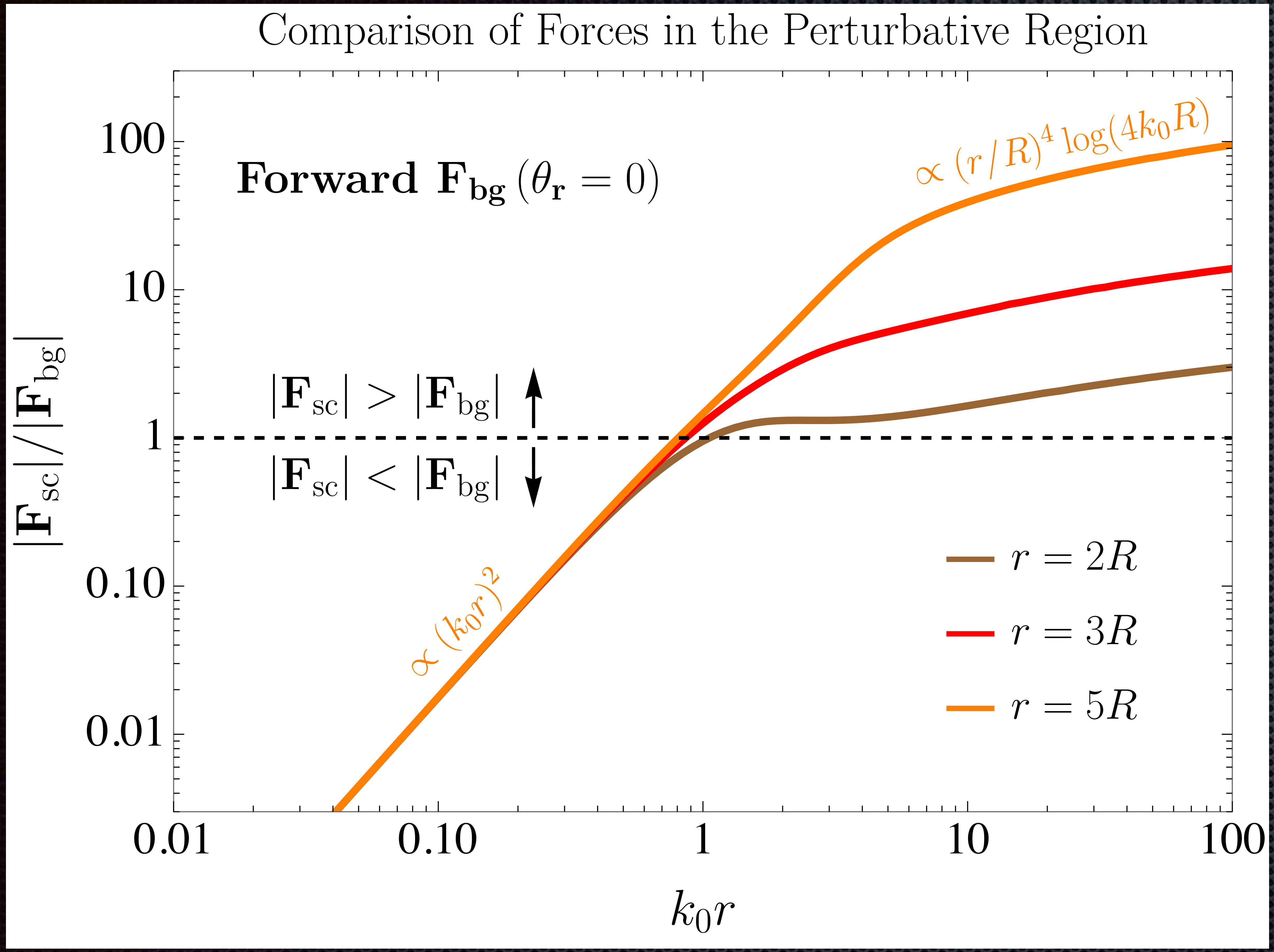
$$\mathbf{F}_{\mathrm{bg}} \sim \boxed{\frac{\rho_\phi}{m_\phi^2}}\ \boxed{(m^2_{\mathrm{M},\mathcal{S}} V_{R,\mathcal{S}})}\ \boxed{(m^2_{\mathrm{M},\mathcal{T}} V_{R,\mathcal{T}})}\ \boxed{\frac{1}{r^2}}$$

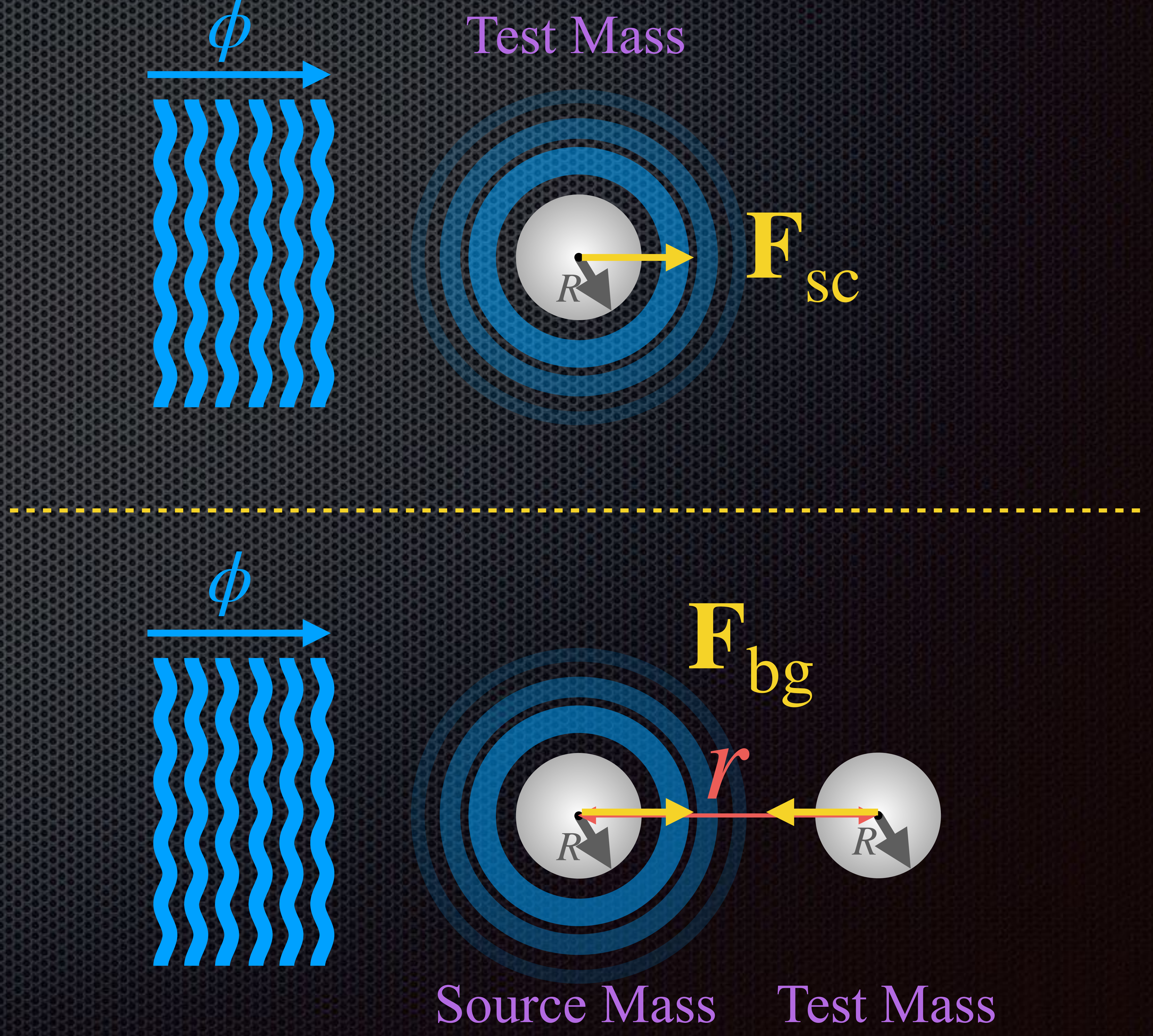
ϕ^2 | Source Mass Coherence | Test Mass Coherence | Inverse Square



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

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





Unified Treatment

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

$$\mathbf{F}_{\mathrm{bg}} \sim \frac{\rho_\phi}{m_\phi^2} (m_{\mathrm{M},\mathcal{S}}^2 V_{R,\mathcal{S}})(m_{\mathrm{M},\mathcal{T}}^2 V_{R,\mathcal{T}}) \frac{1}{r^2} \times \text{Form Factor}$$

Unified Treatment

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

$$\mathbf{F}_{\rm bg} \sim \frac{\rho_\phi}{m_\phi^2} (m_{{\rm M},\mathcal{S}}^2 V_{R,\mathcal{S}})(m_{{\rm M},\mathcal{T}}^2 V_{R,\mathcal{T}}) \frac{1}{r^2} \times \text{Form Factor}$$

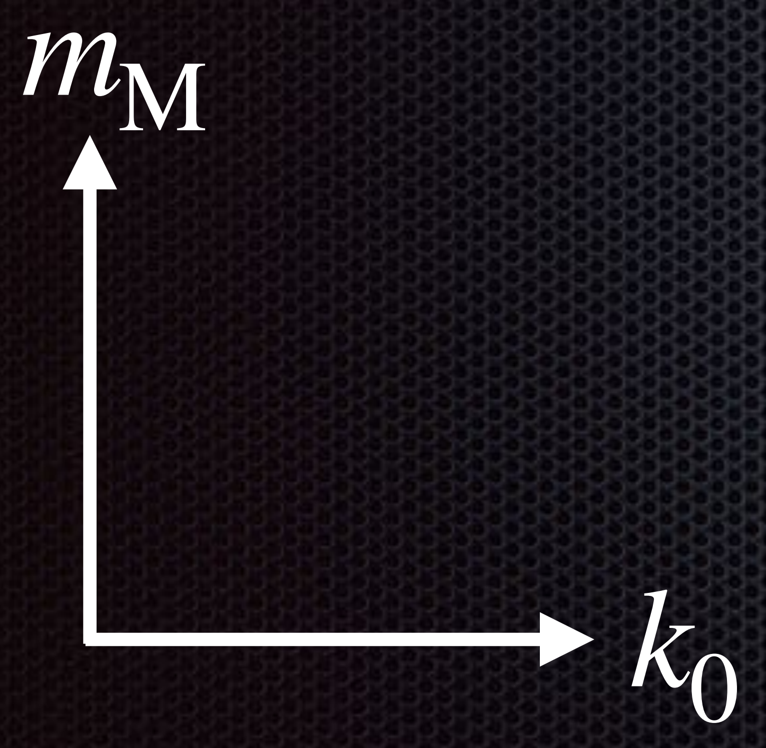
Field Oscillation+Finite Phase Space+Finite Geometry

Decoherence, Screening, Descreening

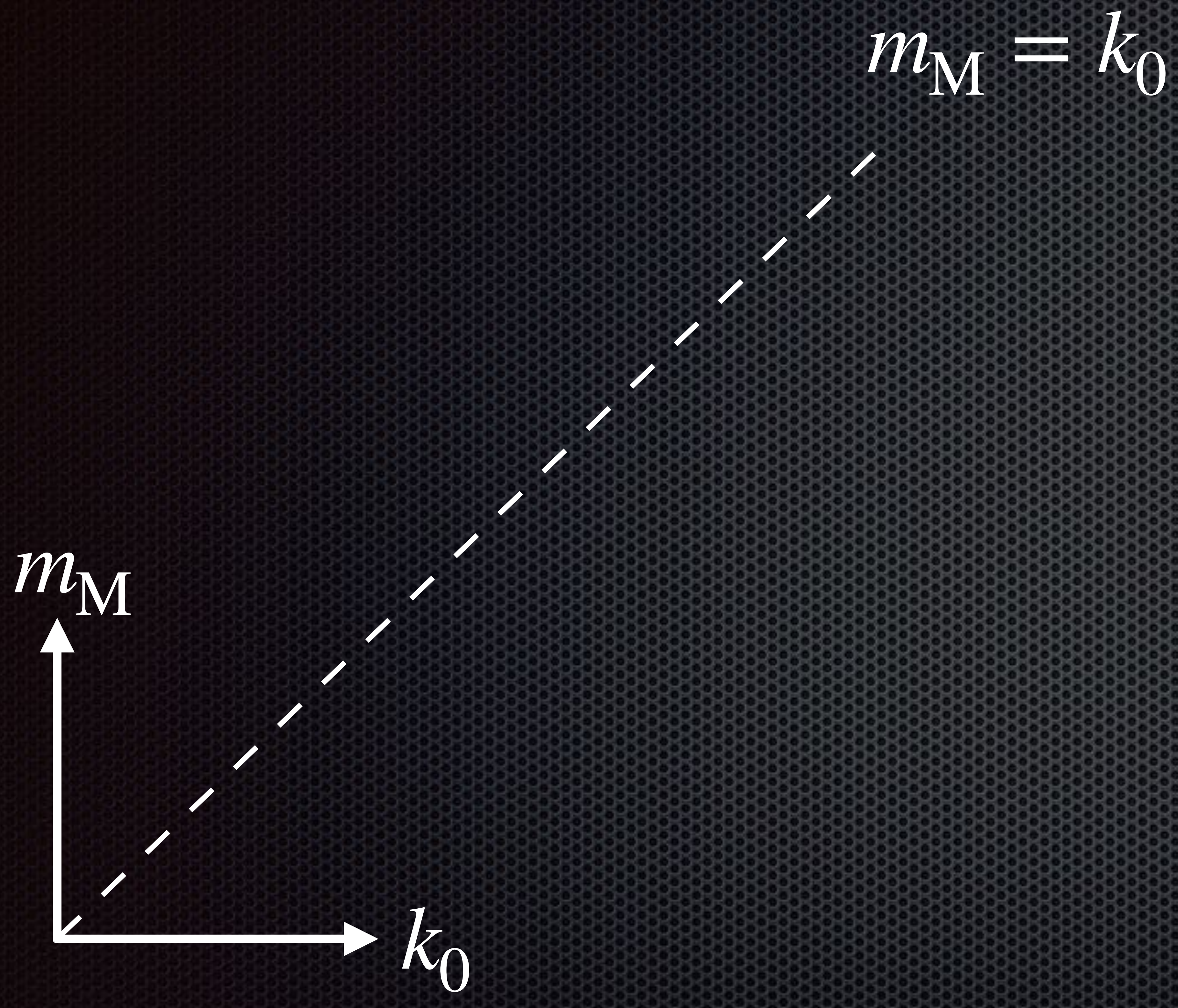
Classification

k_0: Incident Momentum

m_{M}: Effective Mass



Classification



k_0: Incident Momentum

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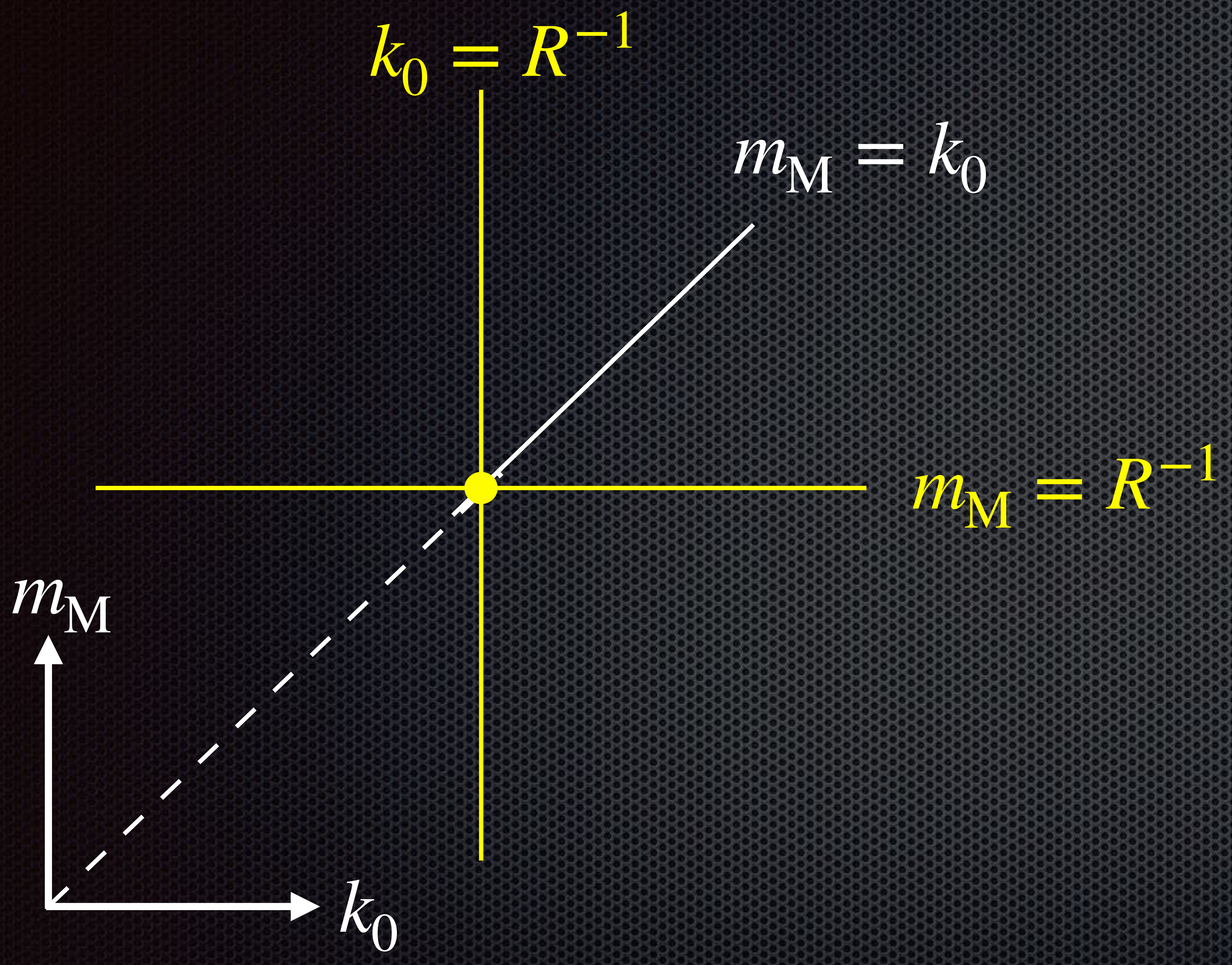
Classification

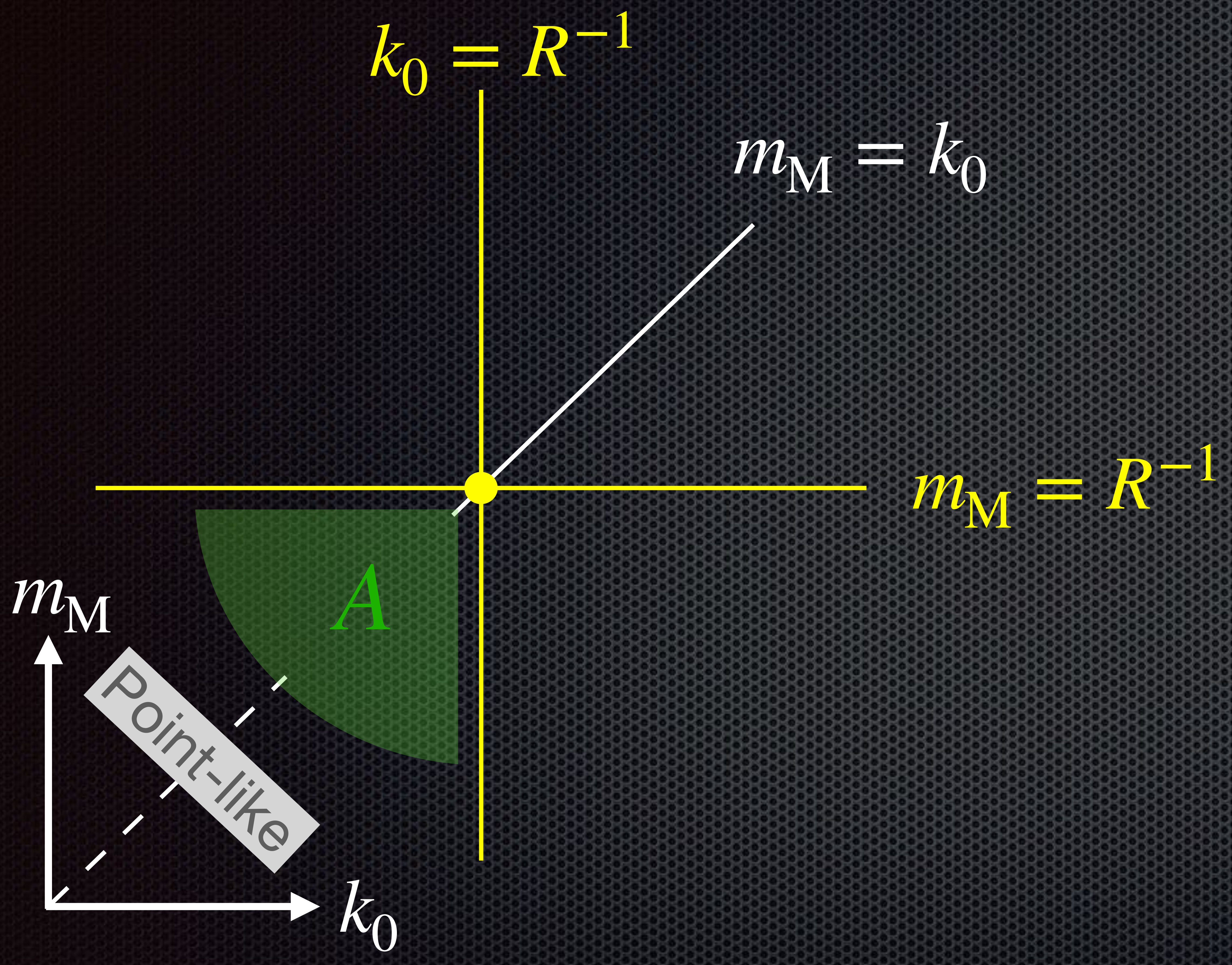


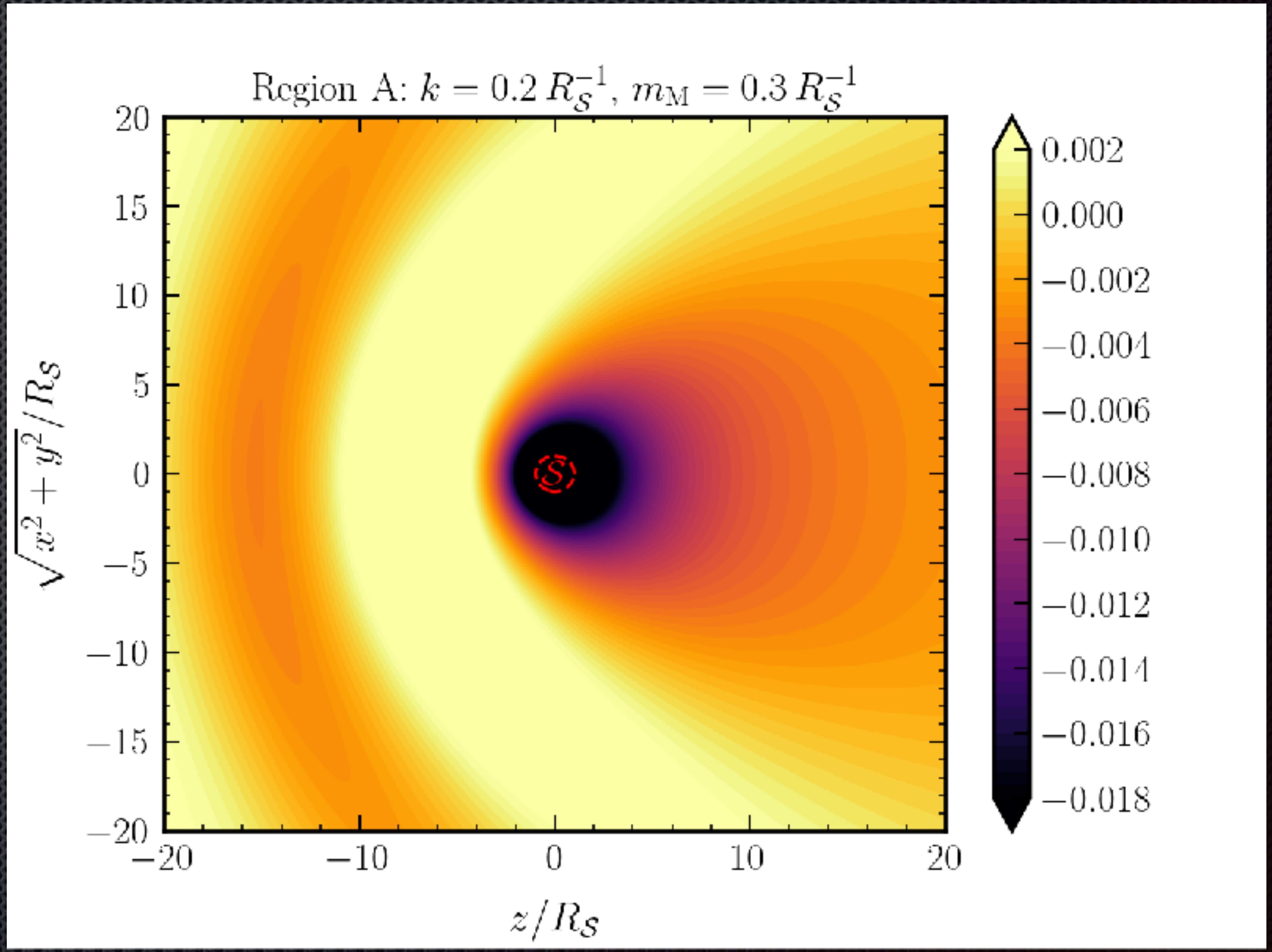
k_0: Incident Momentum

m_M: Effective Mass

R: Radius of Scattered Sphere

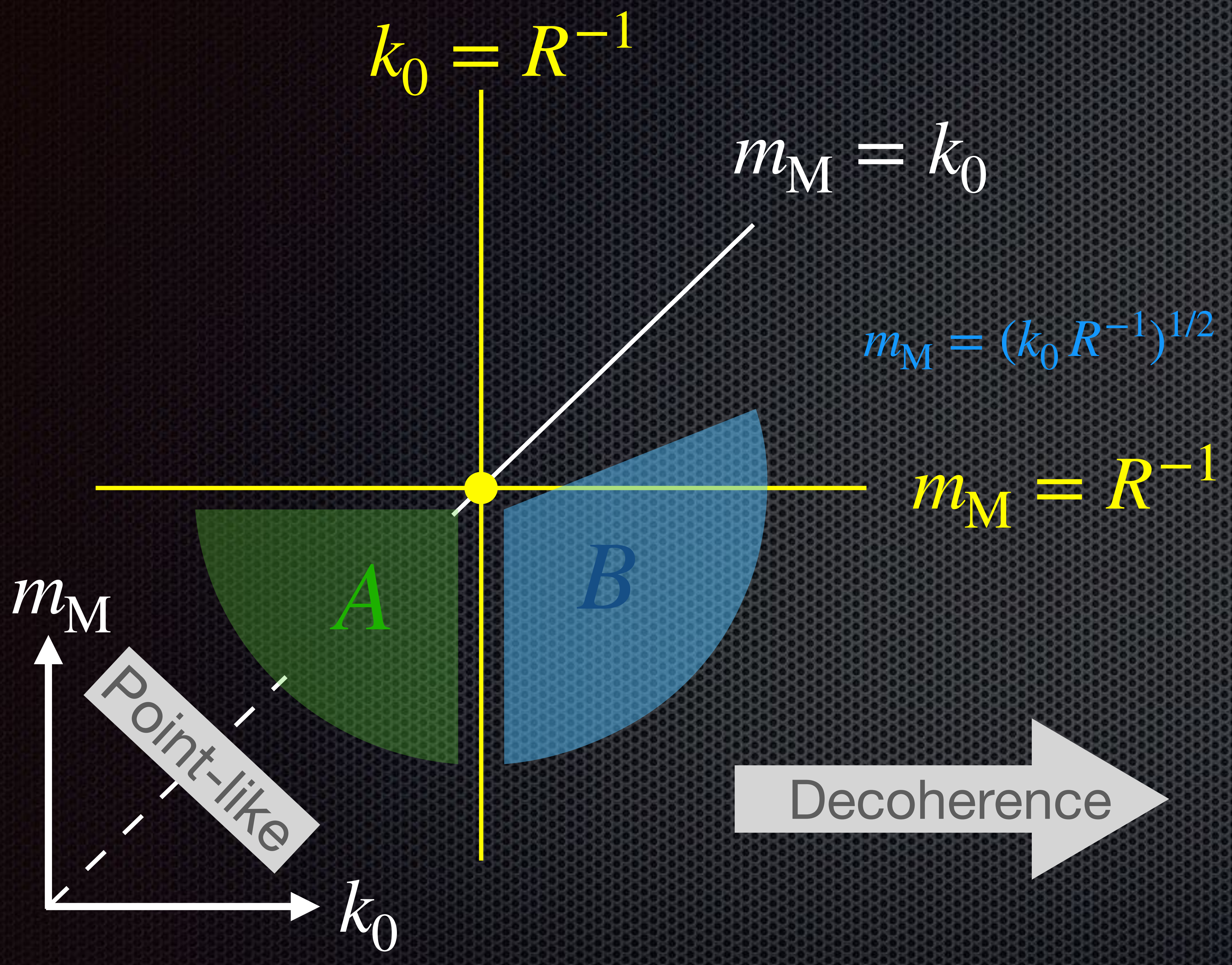
Classification

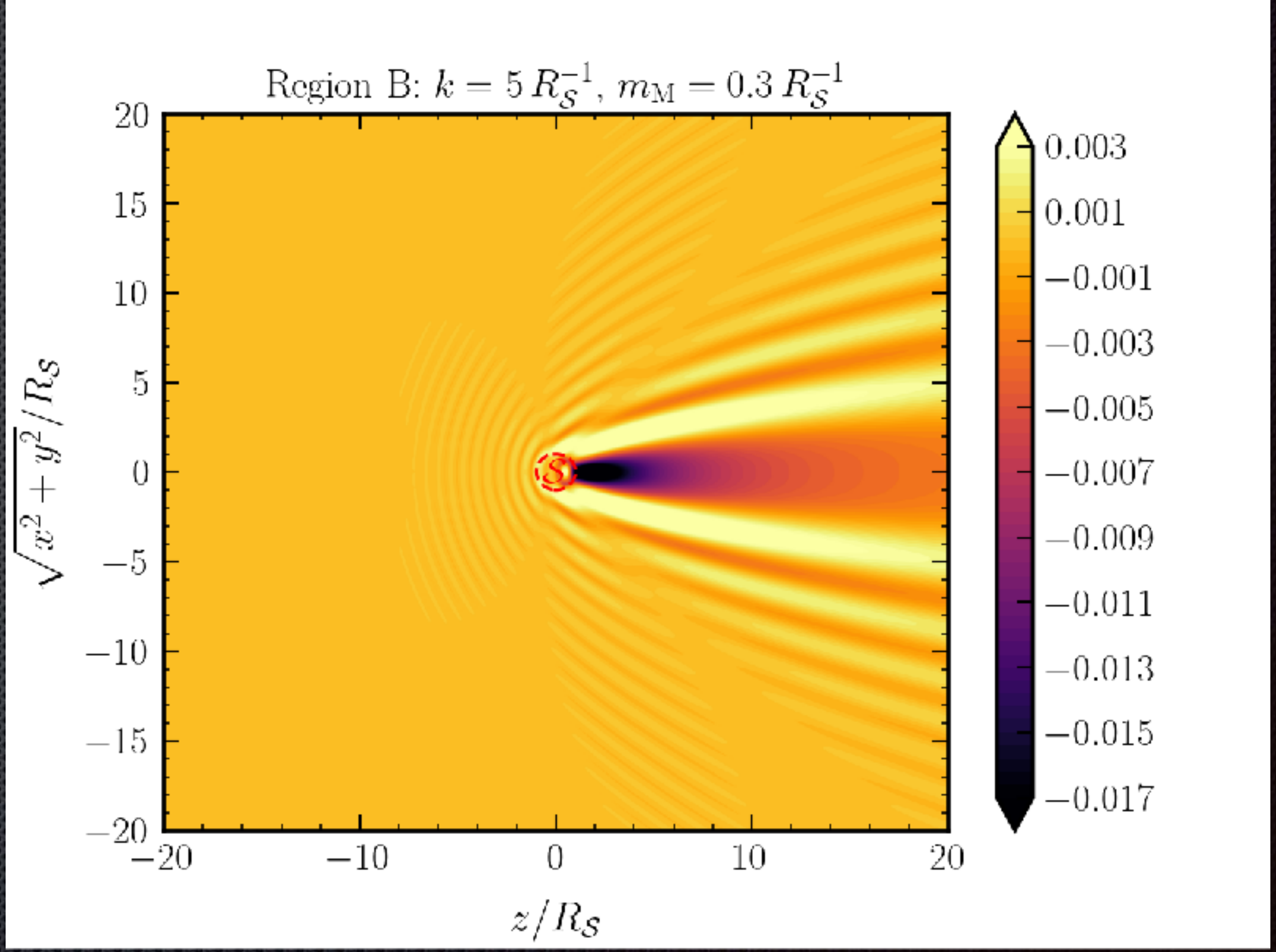




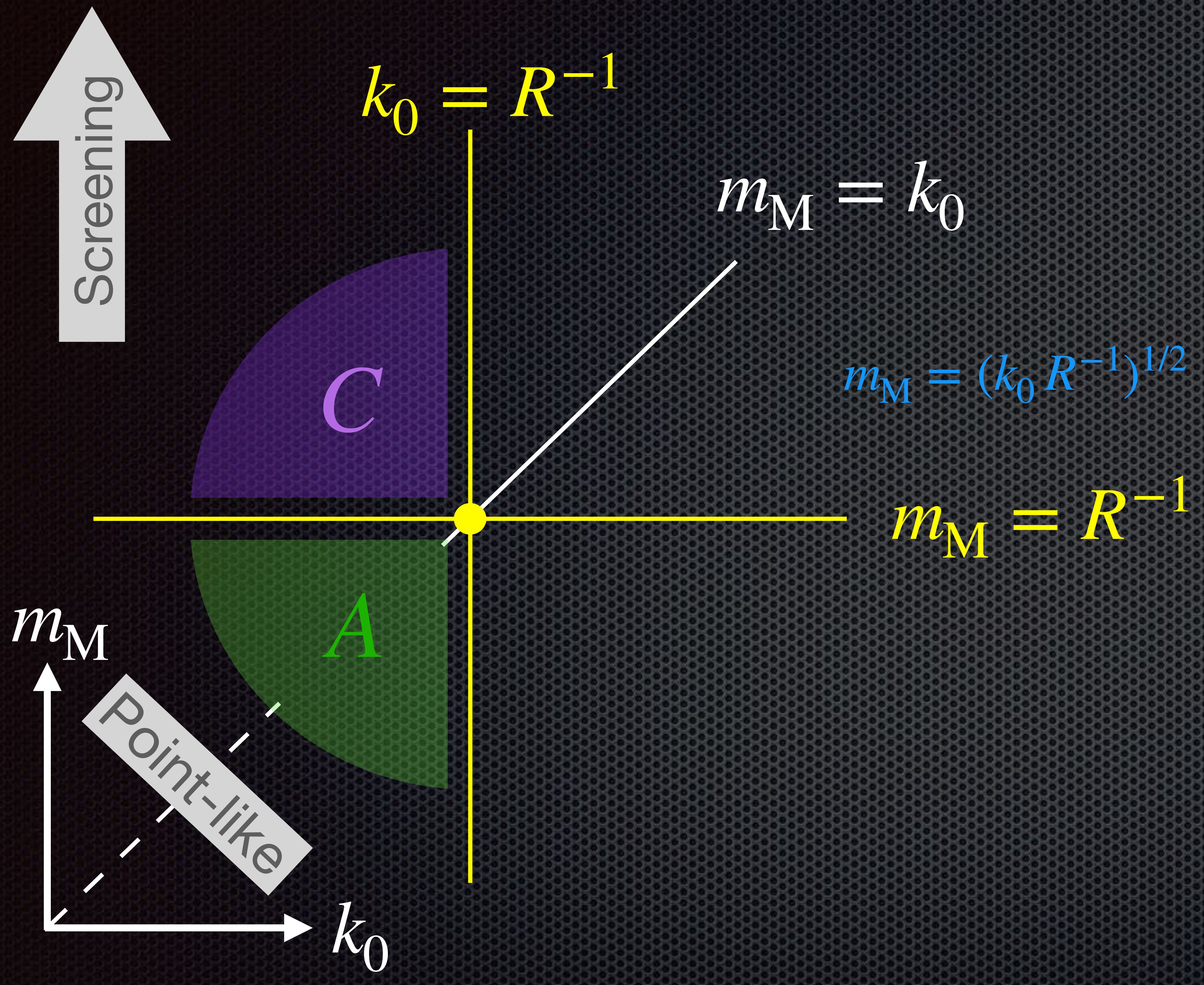
s-wave: oscillatory when $kr > 1$

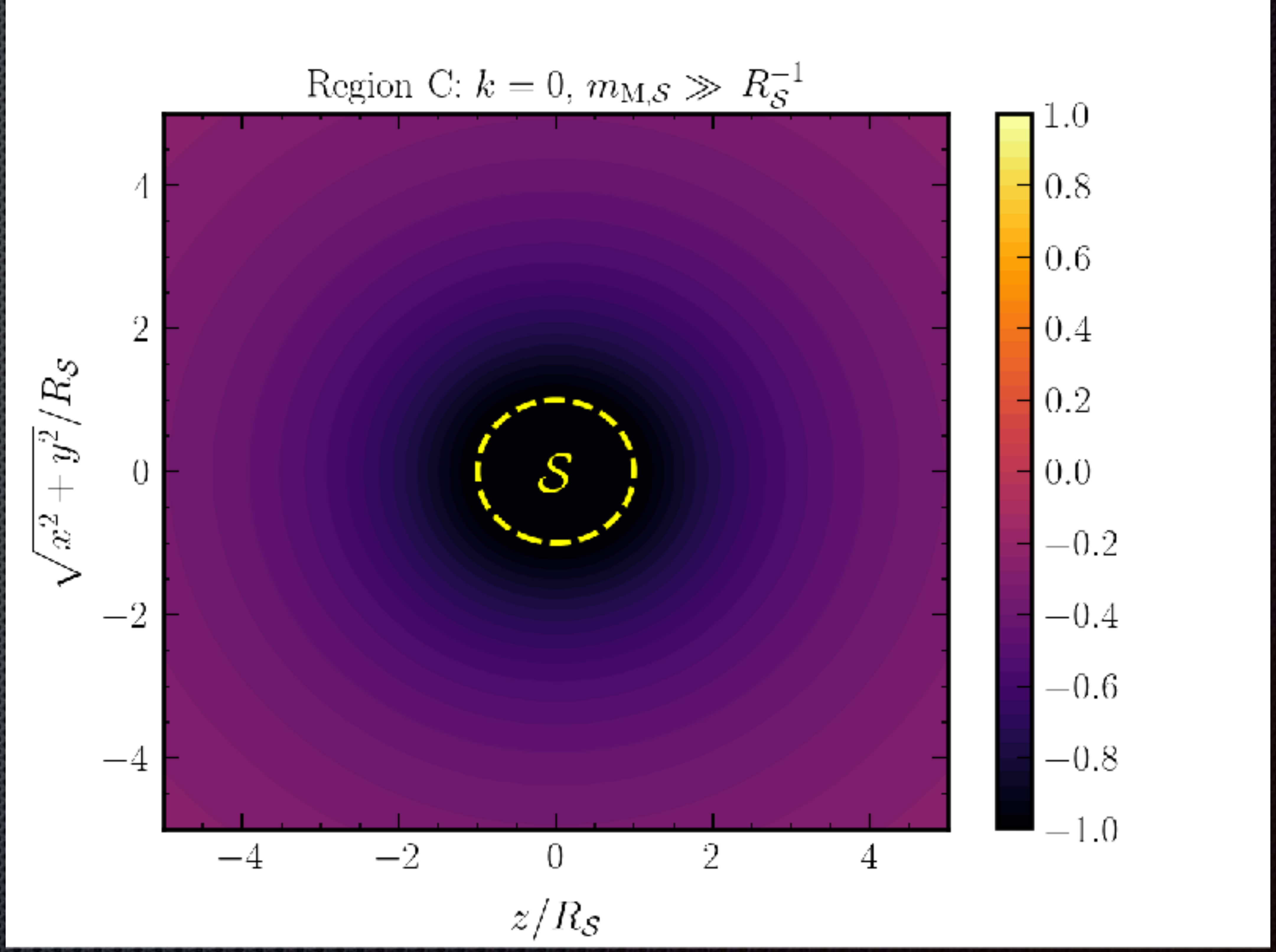
Classification



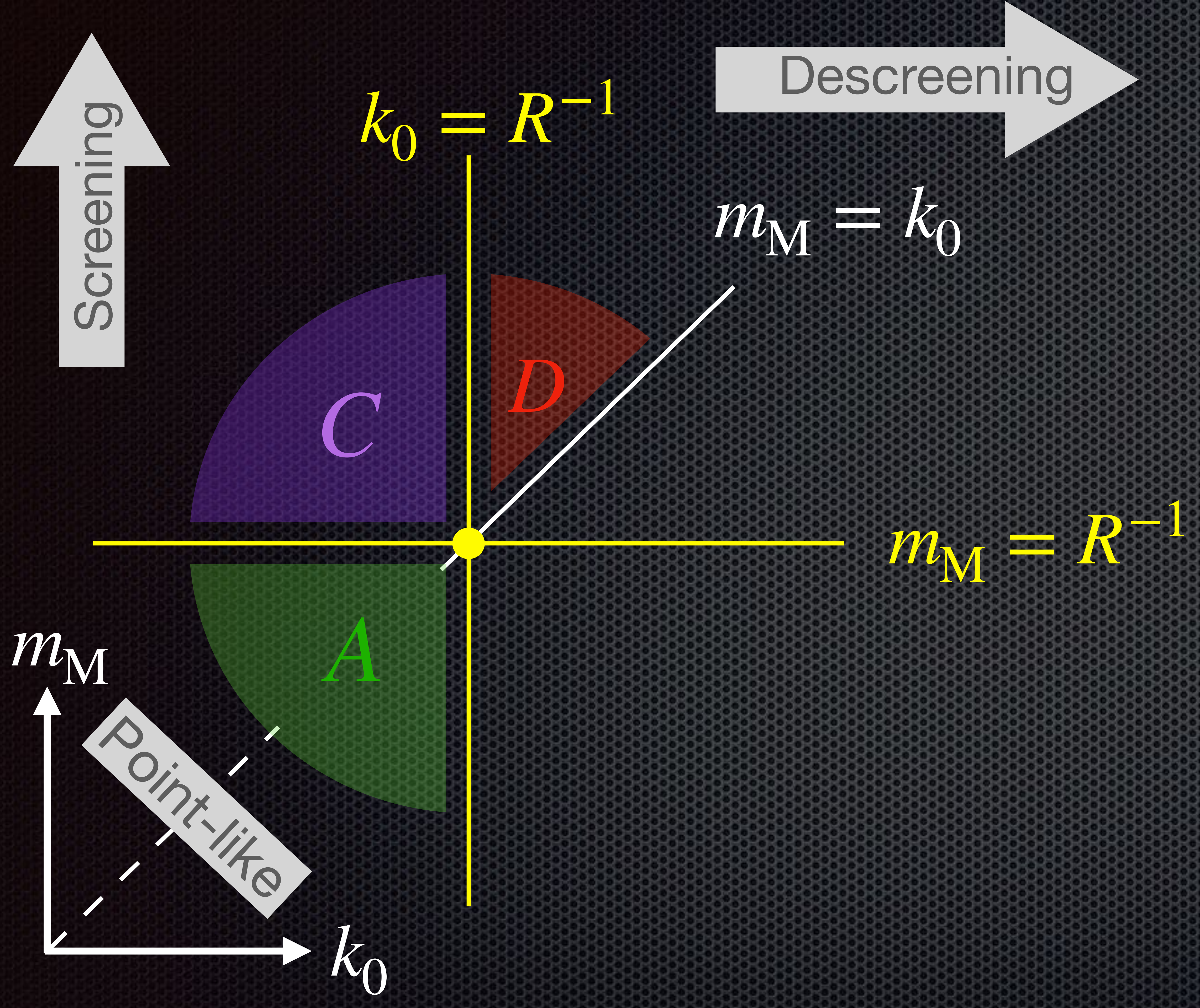


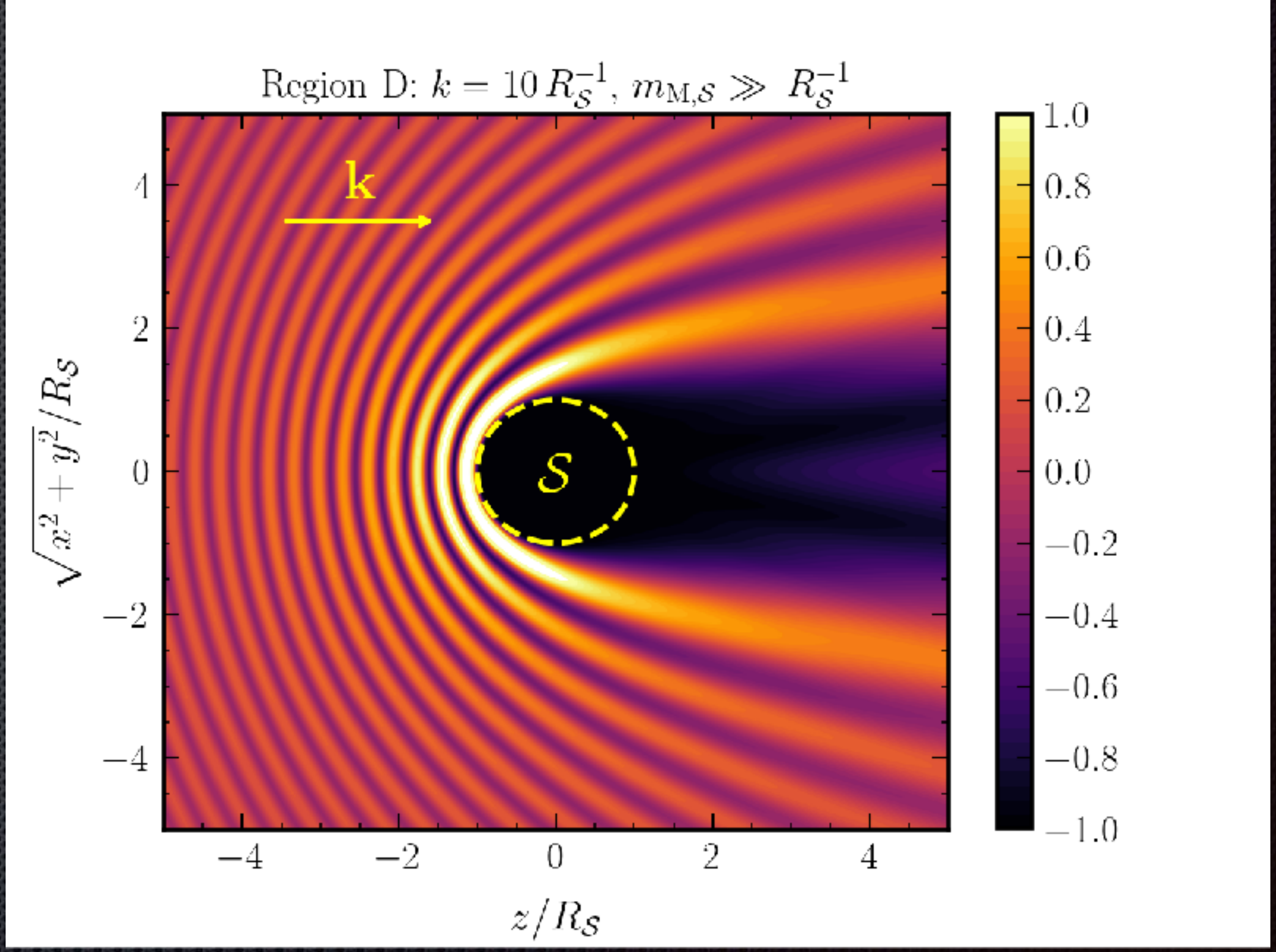
Classification



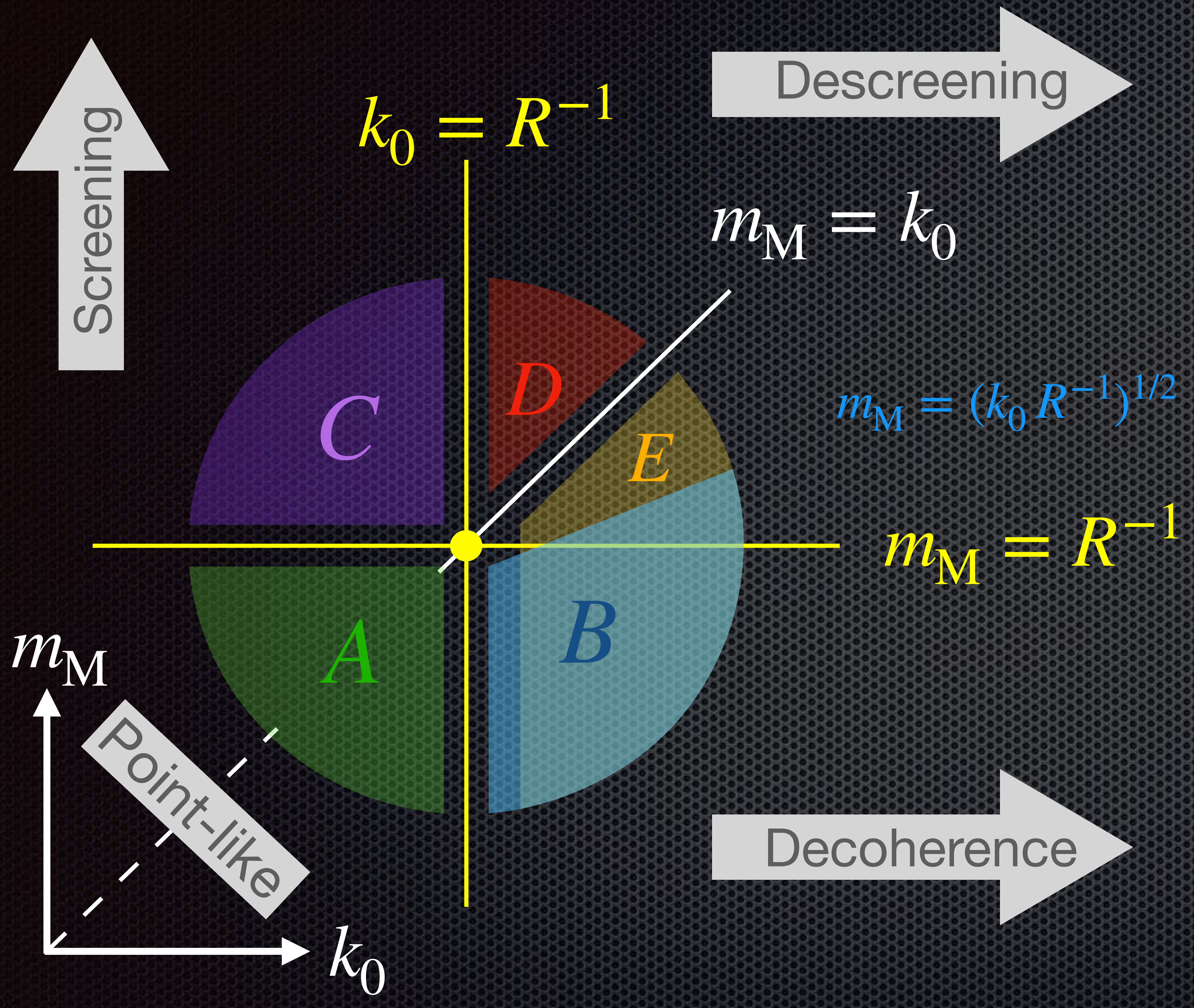


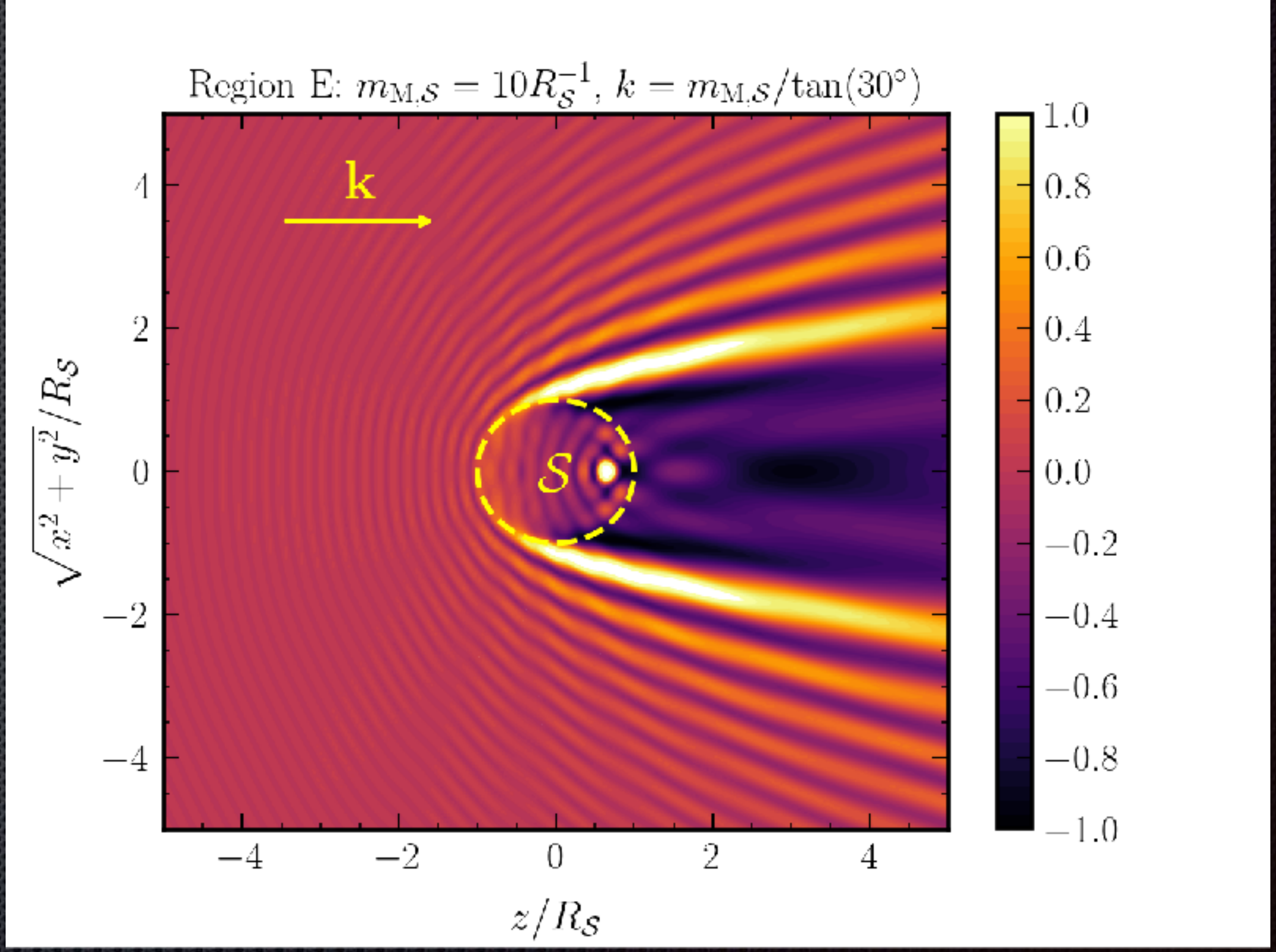
Classification





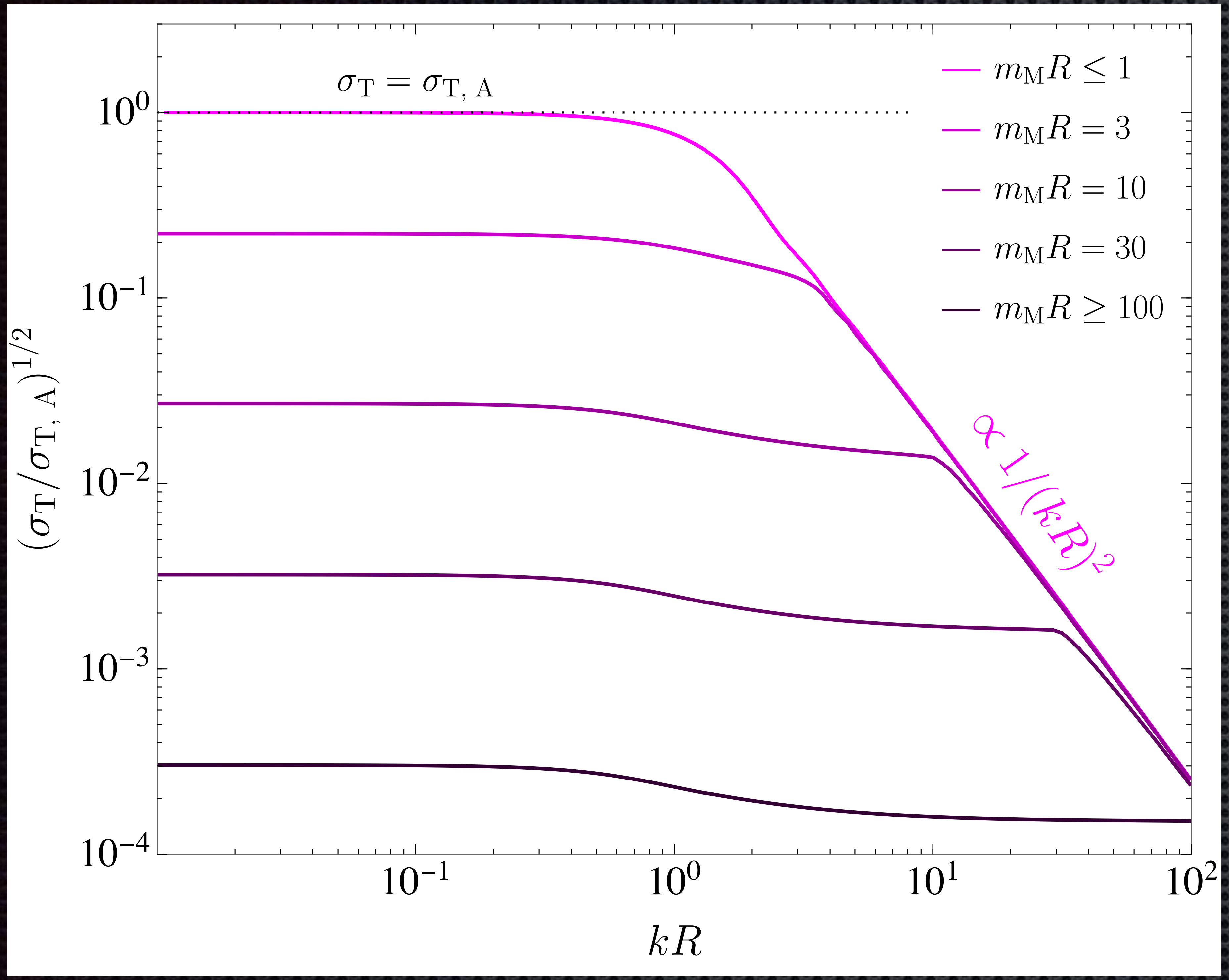
Classification



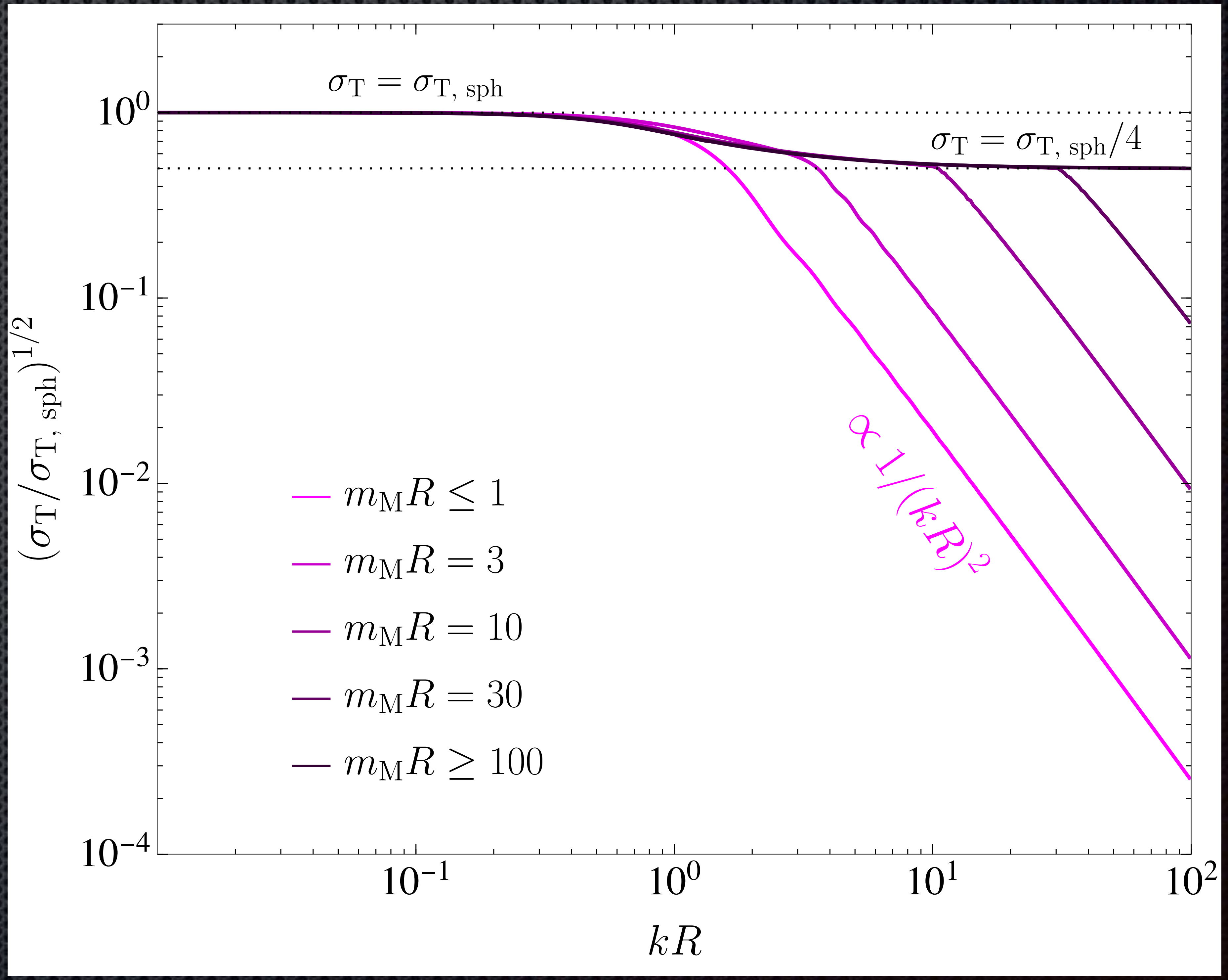


Scattering Force

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



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

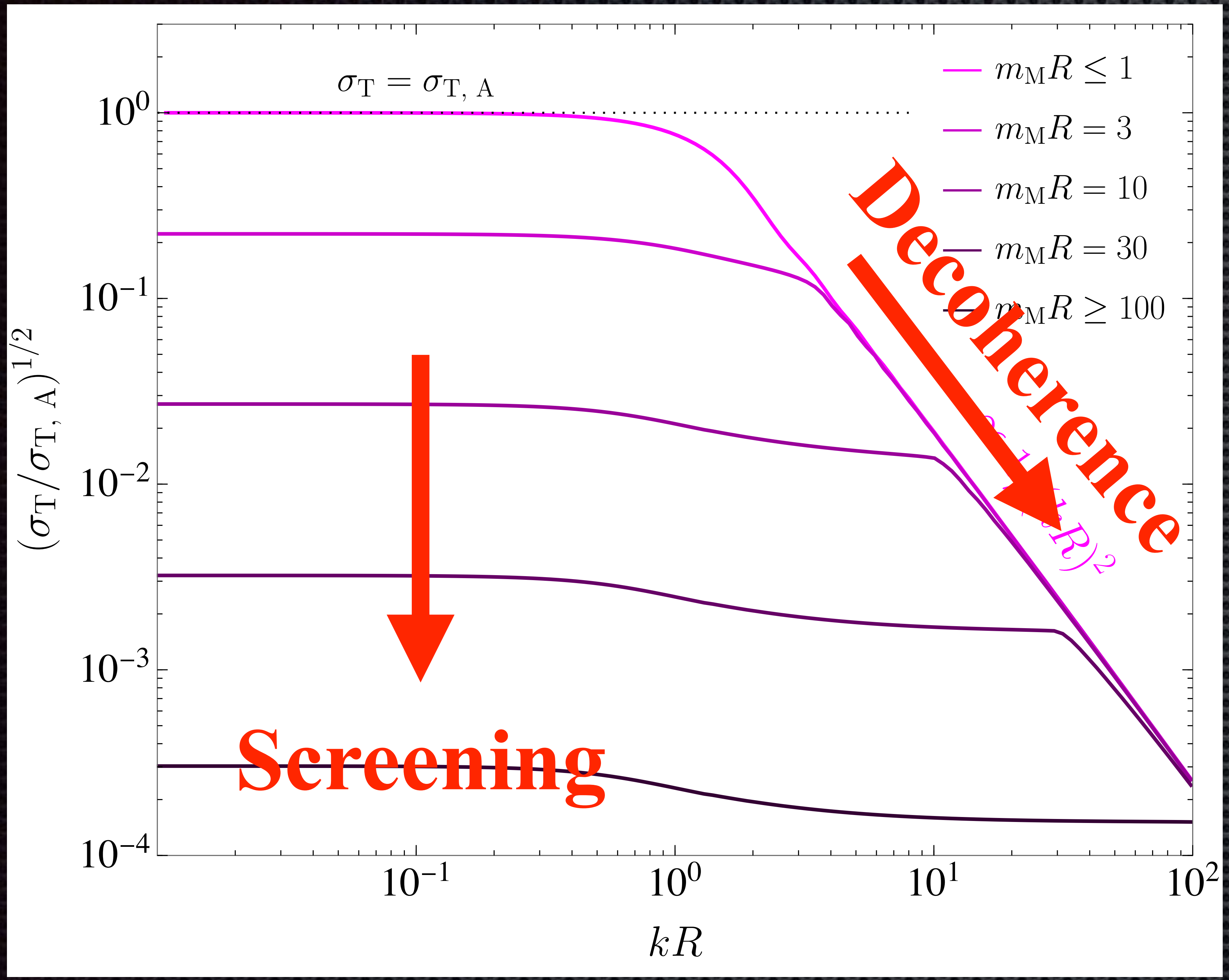


$\mathcal{F}_{\rm sc}/\mathcal{F}_{\rm sph}$

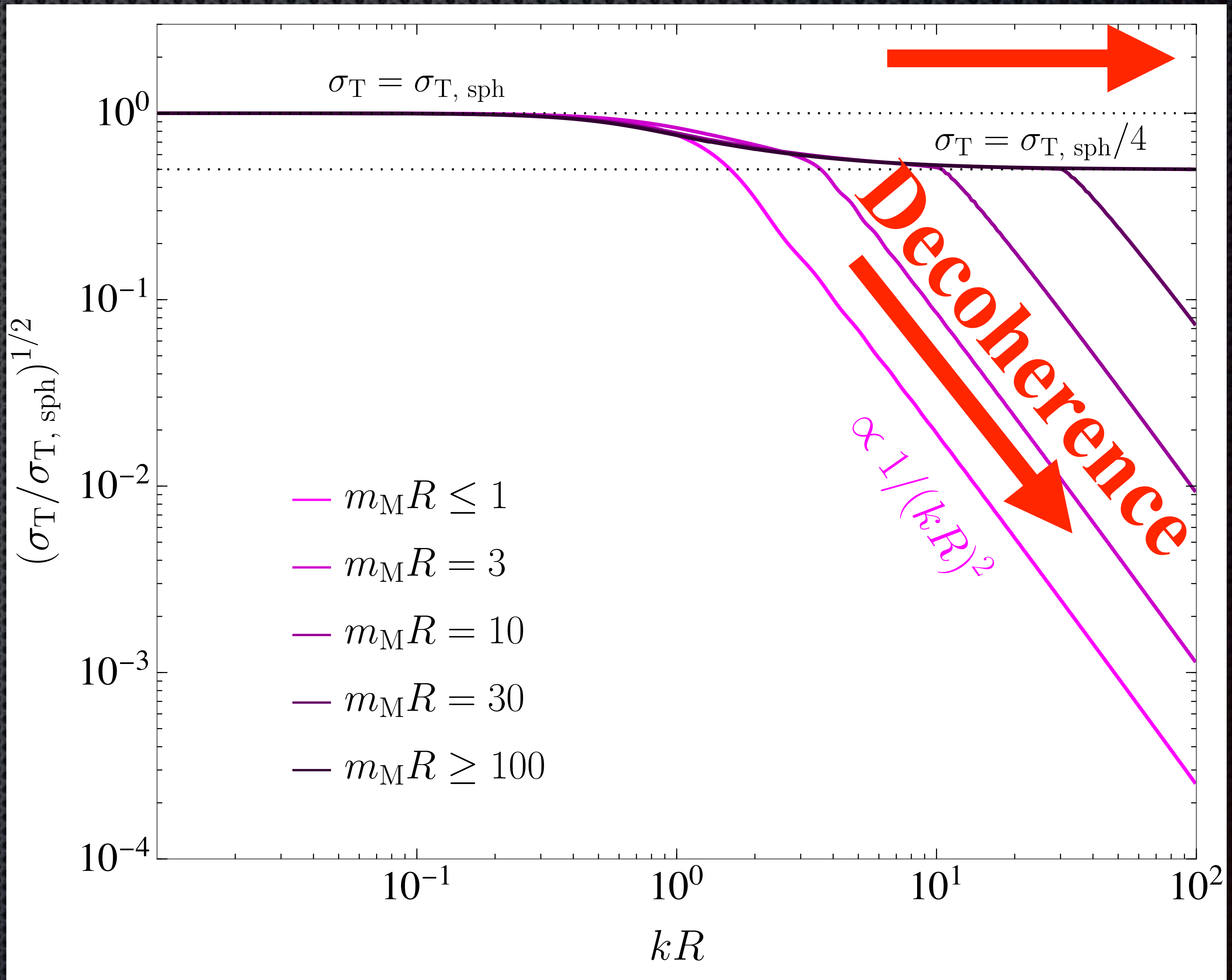
Scattering Force

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

Descreening vs Decoherence



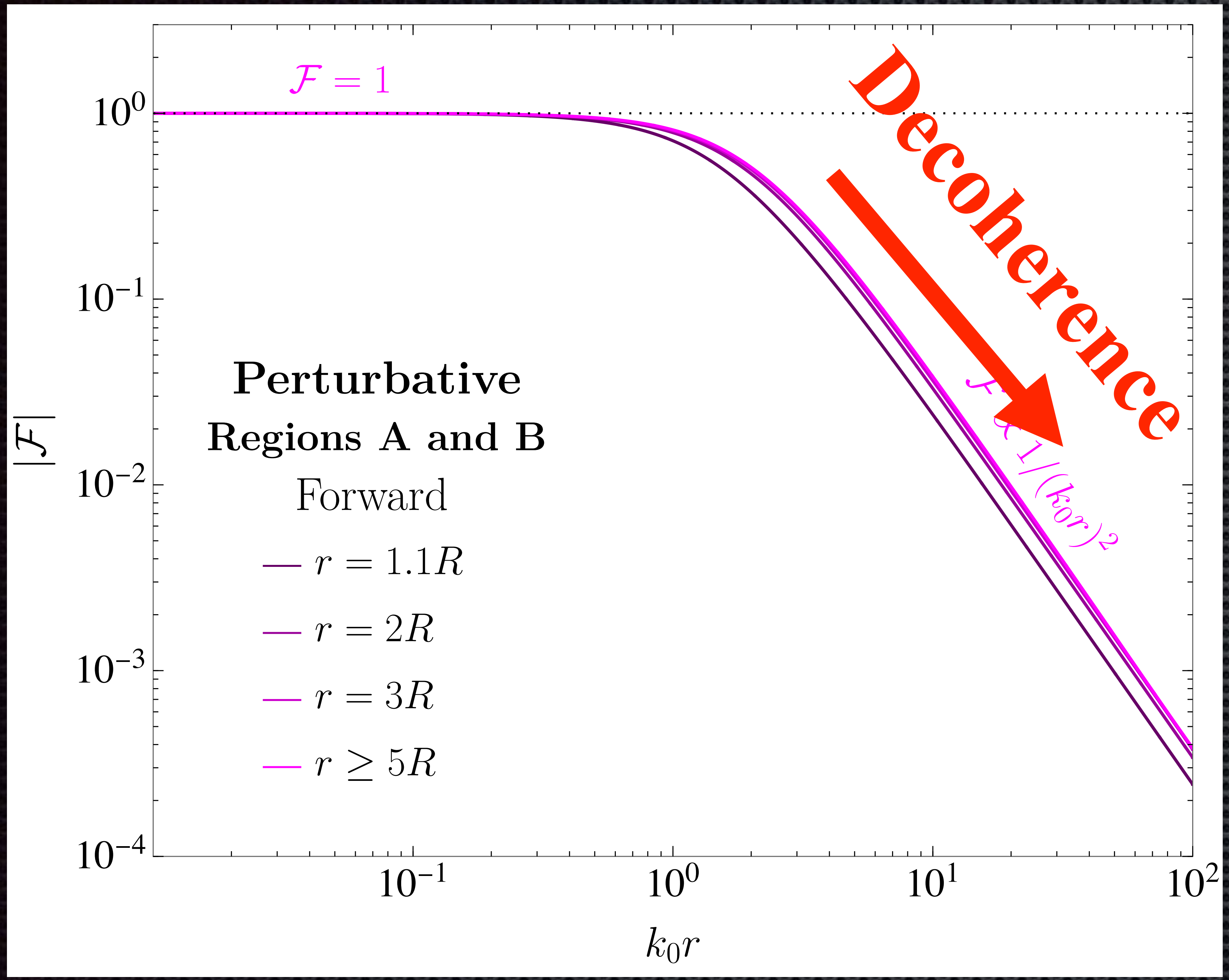
$\mathscr{F}_{sc}$



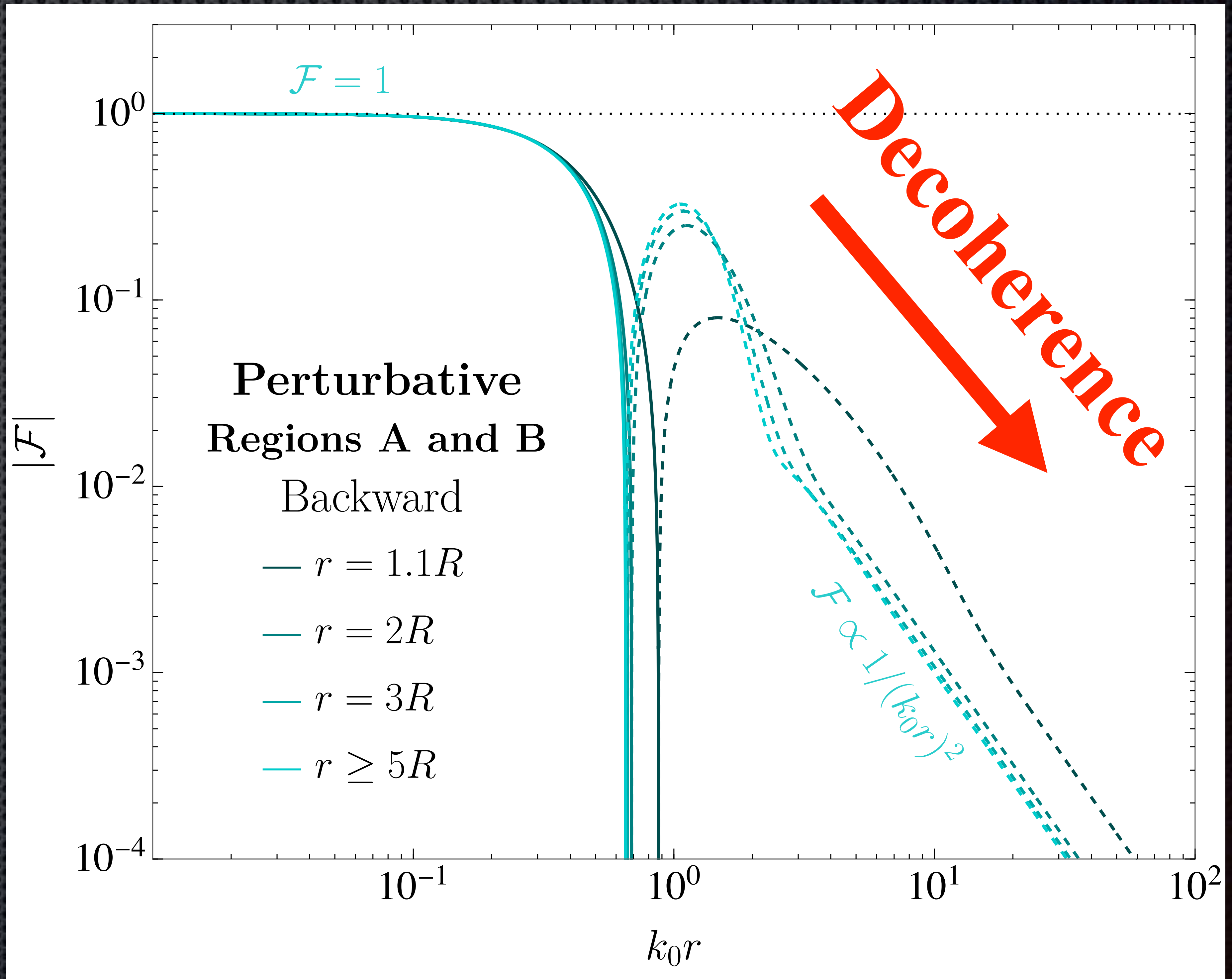
$\mathscr{F}_{sc}/\mathscr{F}_{sph}$

Background-Induced Force: Perturbative

$$V_{\rm bg} \sim \frac{\rho_\phi}{m_\phi^2}\,(m^2_{\mathrm{M},\mathscr{S}} V_{R,\mathscr{S}})(m^2_{\mathrm{M},\mathscr{T}} V_{R,\mathscr{T}})\,\frac{1}{r} \times \boxed{\mathscr{F}}$$



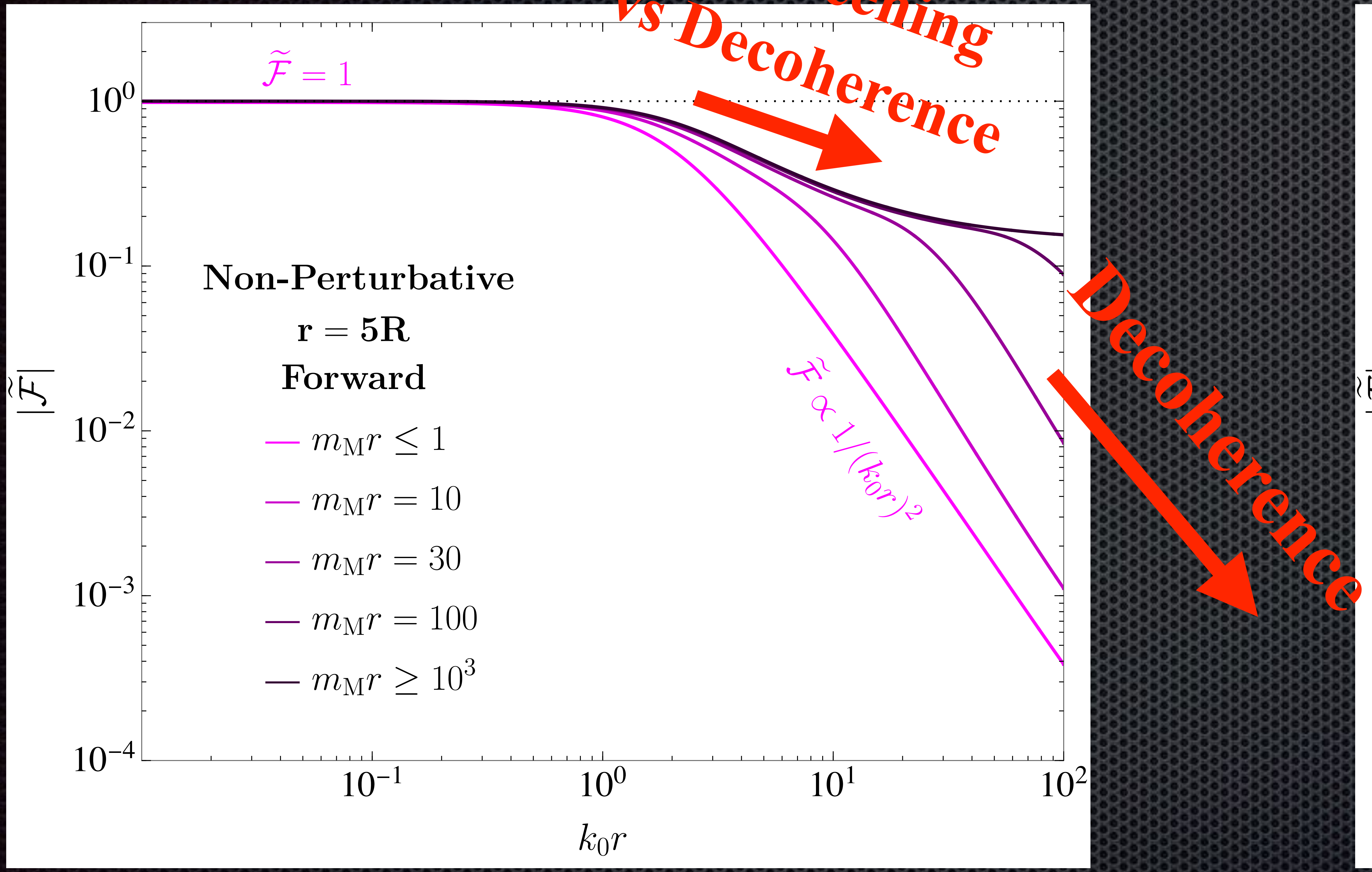
Forward Direction



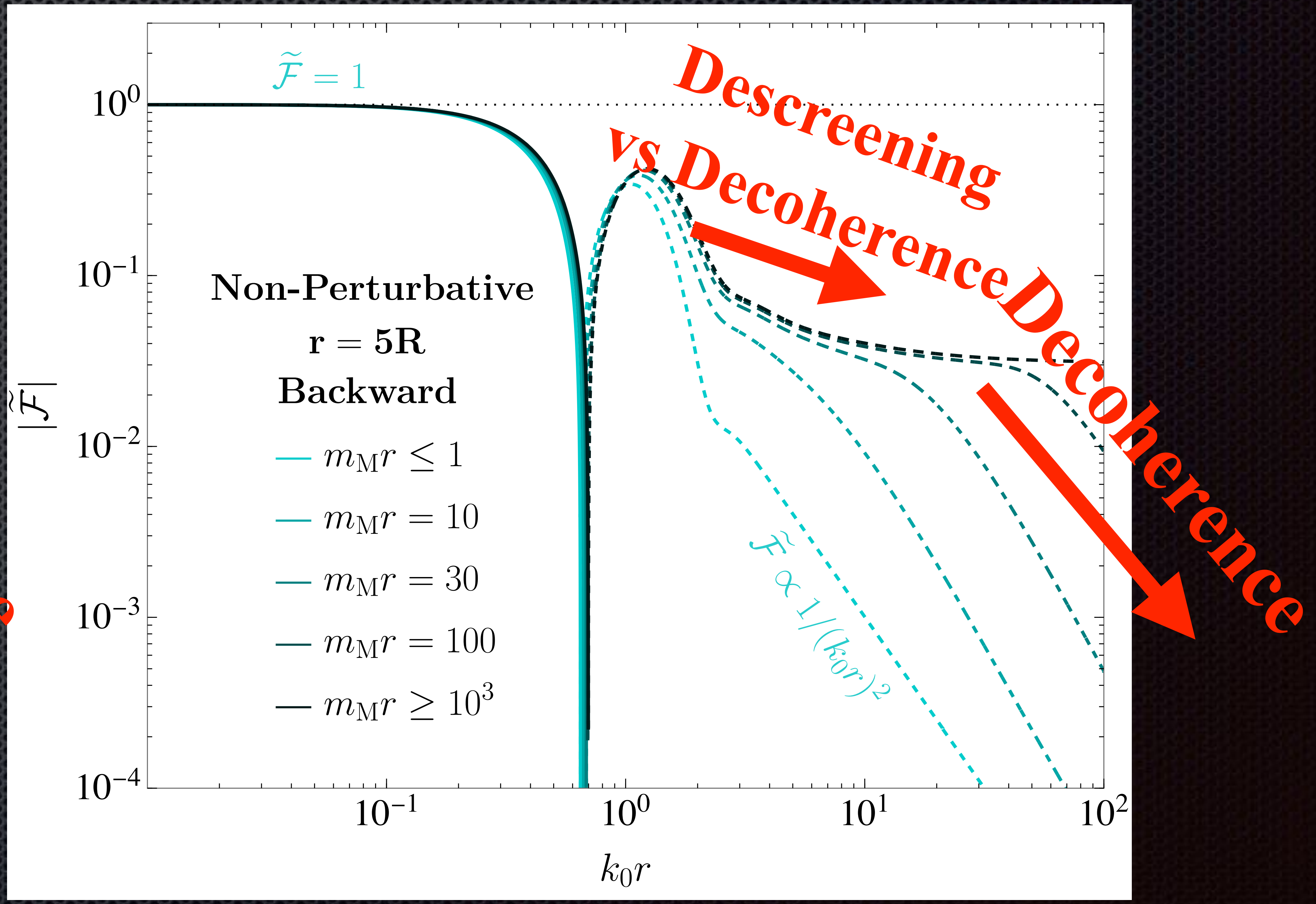
Backward Direction

Background-Induced Force: Finite Barrier

$$V_{\rm bg} \sim \frac{\rho_\phi}{m_\phi^2}\,(m^2_{\mathrm{M},\mathcal{S}} V_{R,\mathcal{S}})(m^2_{\mathrm{M},\mathcal{T}} V_{R,\mathcal{T}})\,\frac{1}{r} \times \mathcal{F}_{\rm sph} \times \boxed{\tilde{\mathcal{F}}} \qquad \mathcal{F}_{\rm sph} \simeq \frac{3}{(m_{\rm M} R)^2}$$



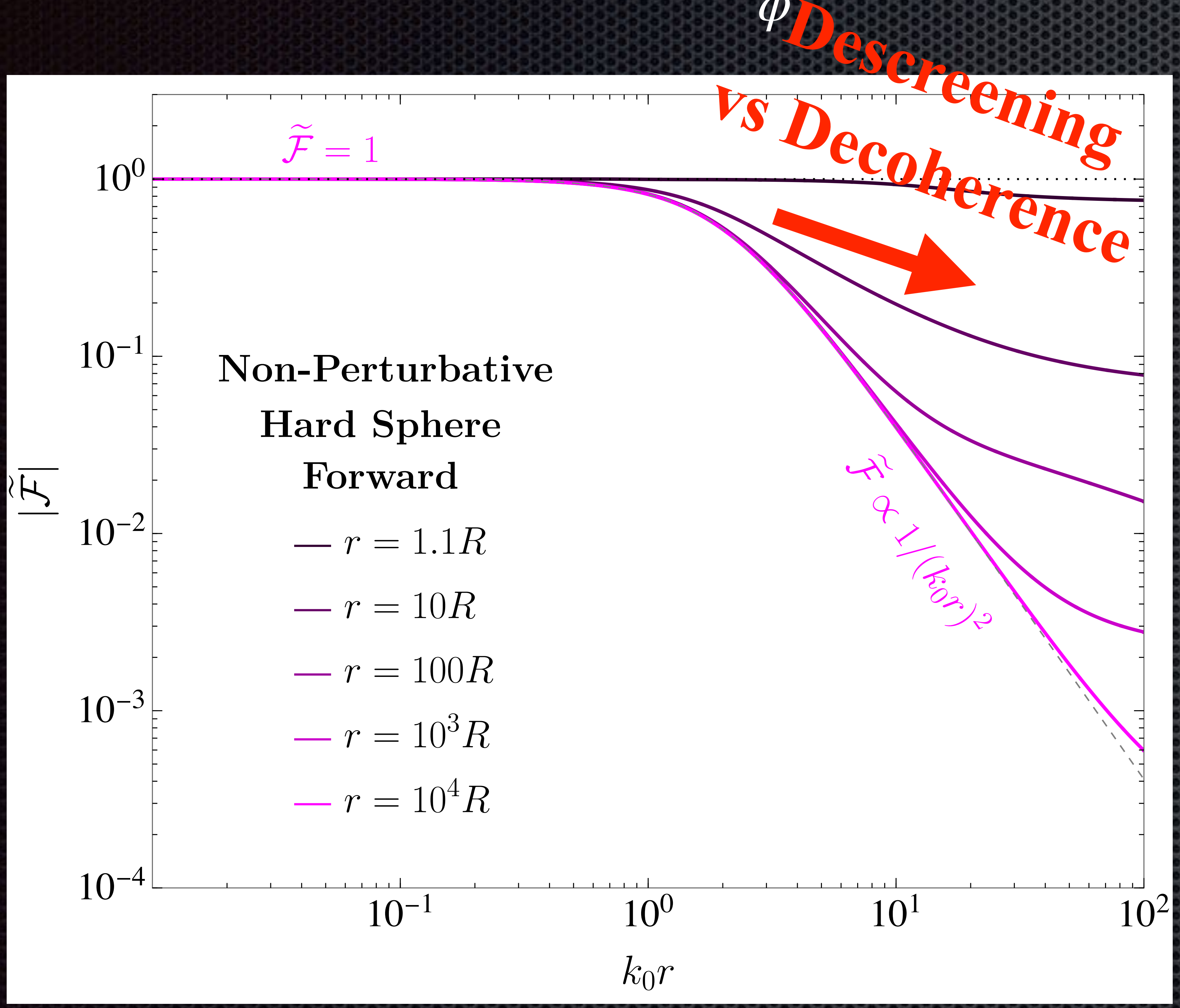
Forward Direction



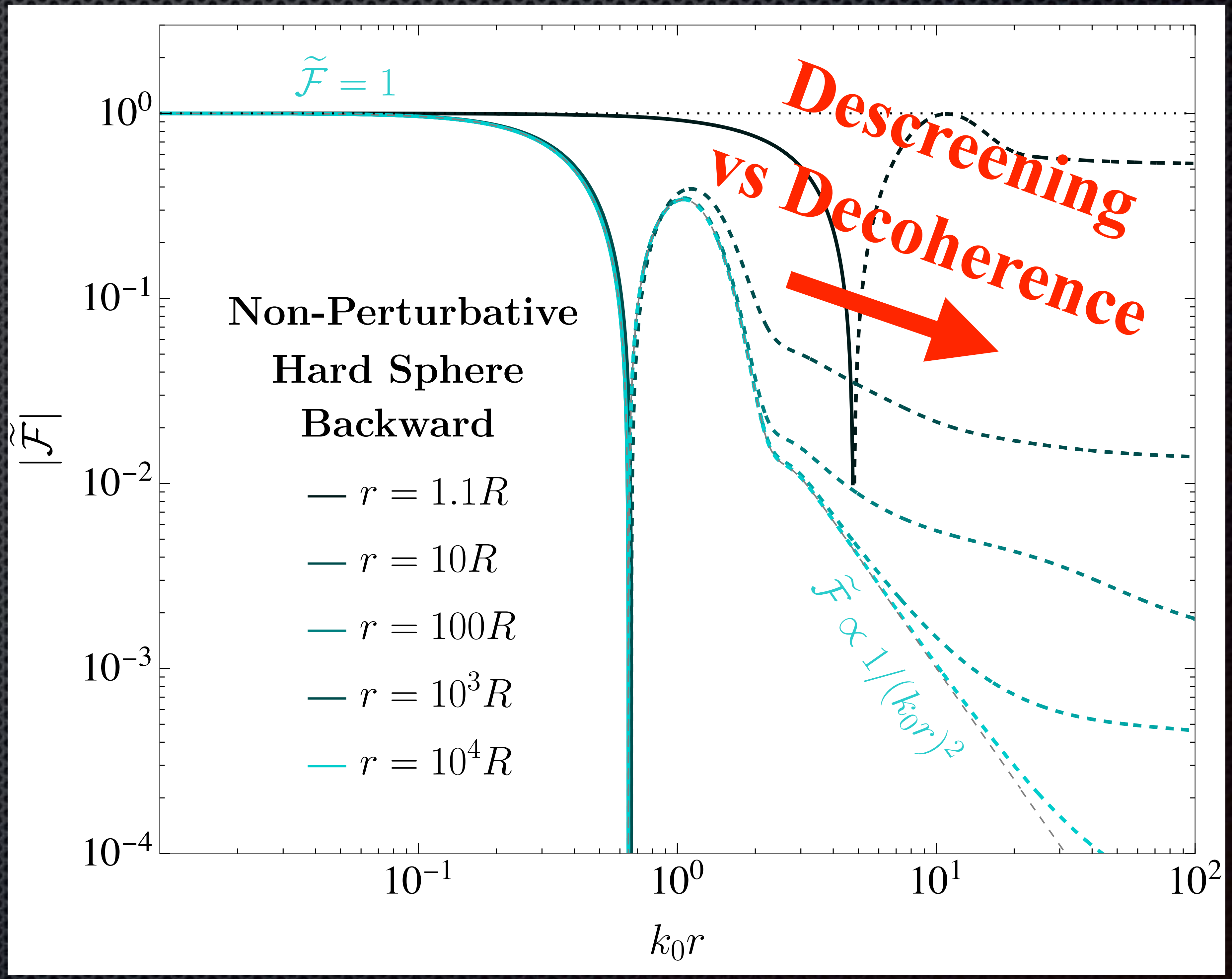
Backward Direction

Background-Induced Force: Hard Sphere

$$V_{\rm bg} \sim \frac{\rho_\phi}{m_\phi^2}\,(m^2_{{\rm M},\mathscr{S}} V_{R,\mathscr{S}})(m^2_{{\rm M},\mathscr{T}} V_{R,\mathscr{T}})\frac{1}{r} \times \mathscr{F}_{\rm sph} \times \boxed{\widetilde{\mathscr{F}}} \qquad \mathscr{F}_{\rm sph} \simeq \frac{3}{(m_{\rm M} R)^2}$$



Forward Direction



Backward Direction

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

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

Experimental Sensitivity

	Experiments	Acceleration
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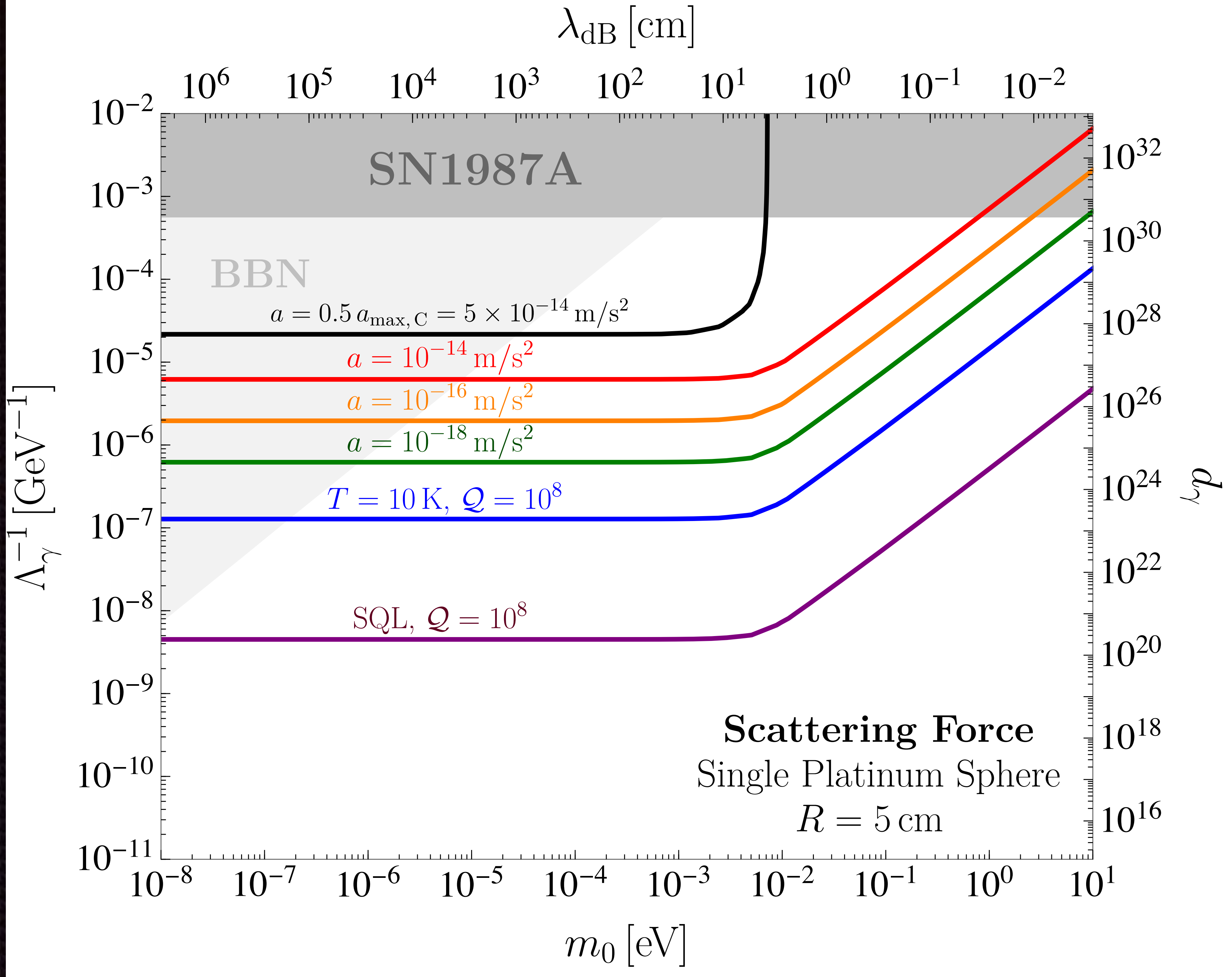
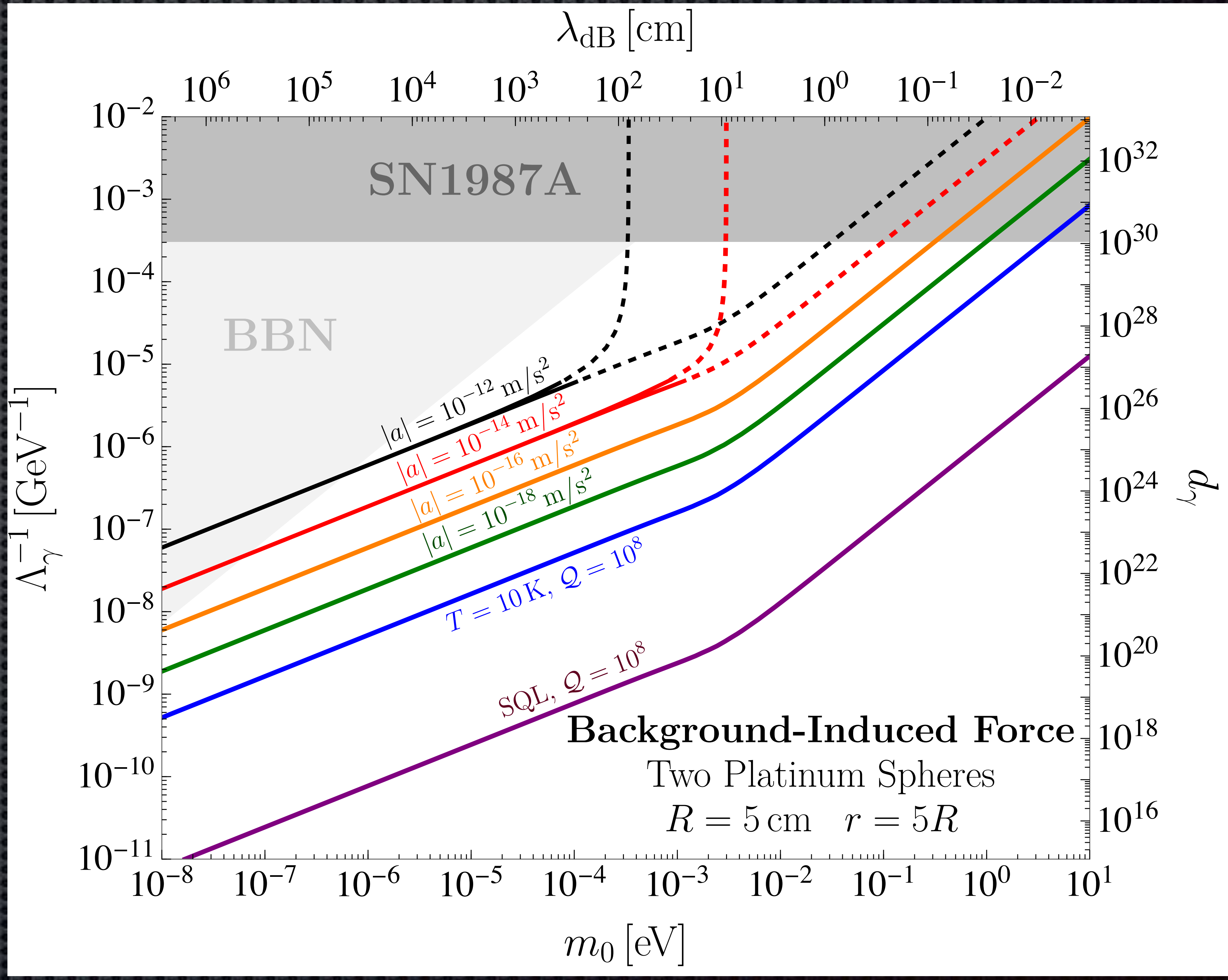
	Galileo Galilei Satellite	$\sim 10^{-16}\,\mathrm{m/s^2}$
	Deep Space Mission	$\sim 10^{-18}\,\mathrm{m/s^2}$
$f_{\mathrm{osc}} \sim 1\,\mathrm{mHz}$	$T \sim 10\,\mathrm{K}, \quad Q \sim 10^8$	$\sim 10^{-20}\,\mathrm{m/s^2}$
$t_{\mathrm{int}} \sim 3\,\mathrm{years}$	$\mathrm{SQL}, \quad Q \sim 10^8$	$\sim 10^{-27}\,\mathrm{m/s^2}$

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

Experimental Sensitivity

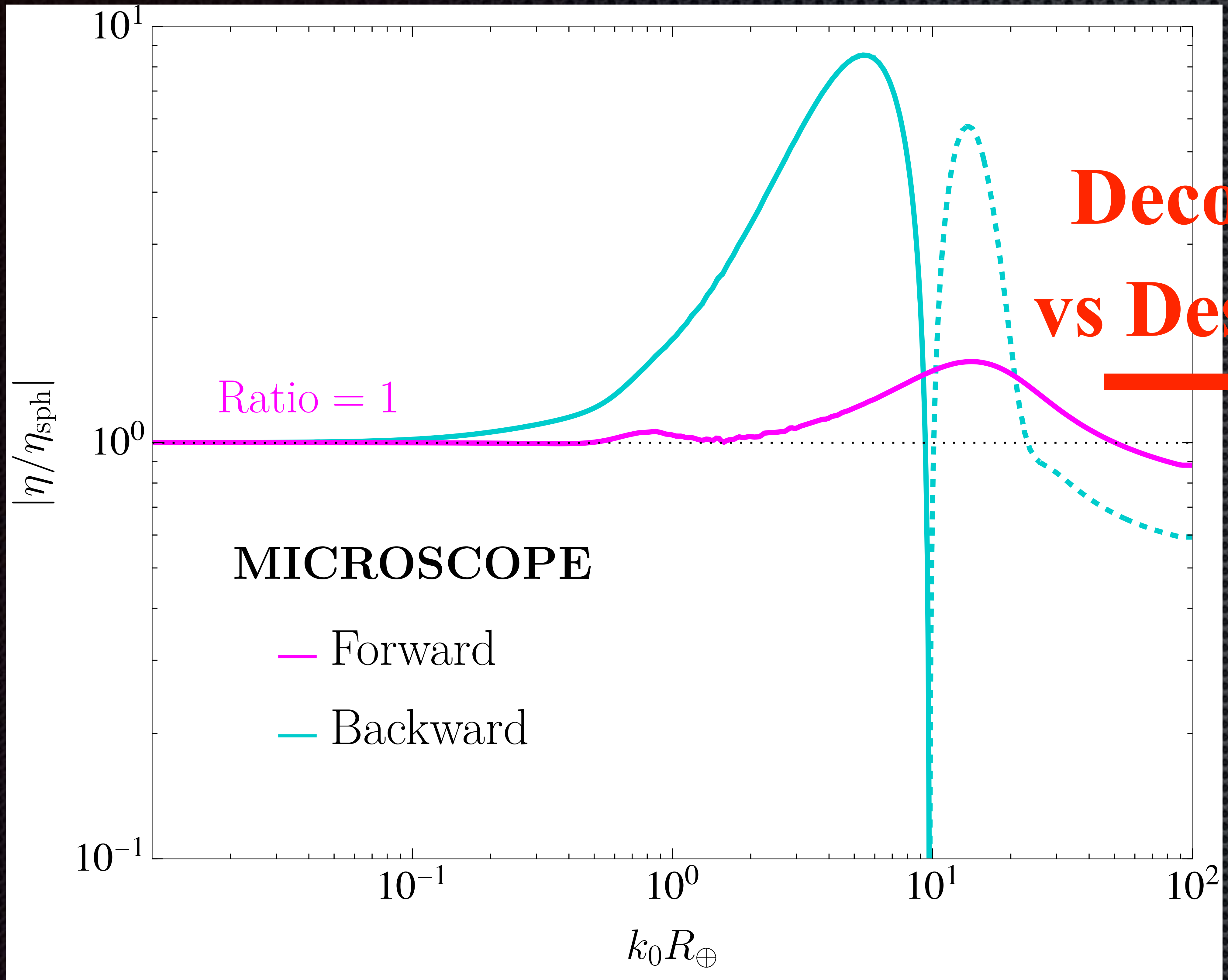


Scattering Force

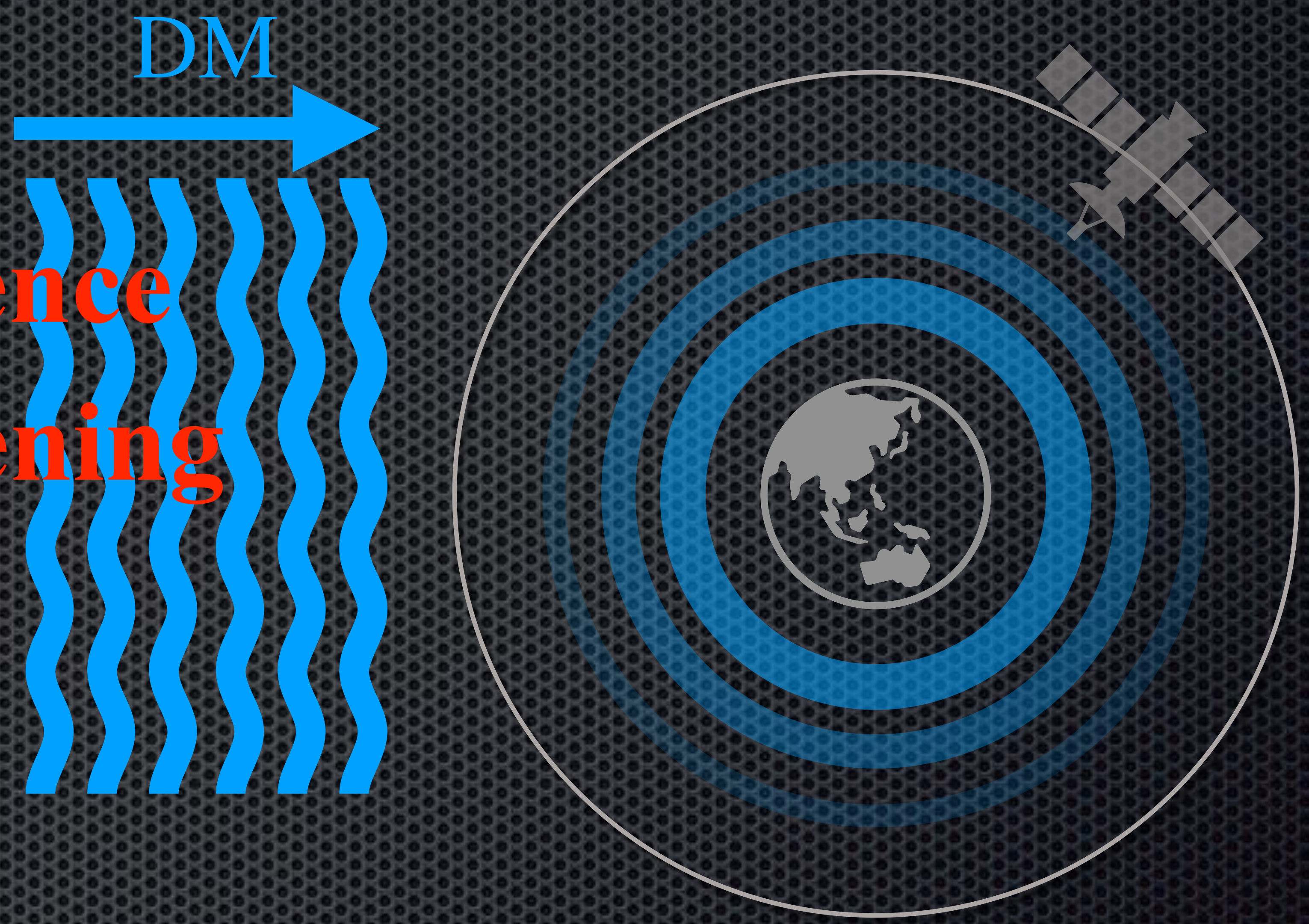


Background-Induced Force

MICROSCOPE Satellite



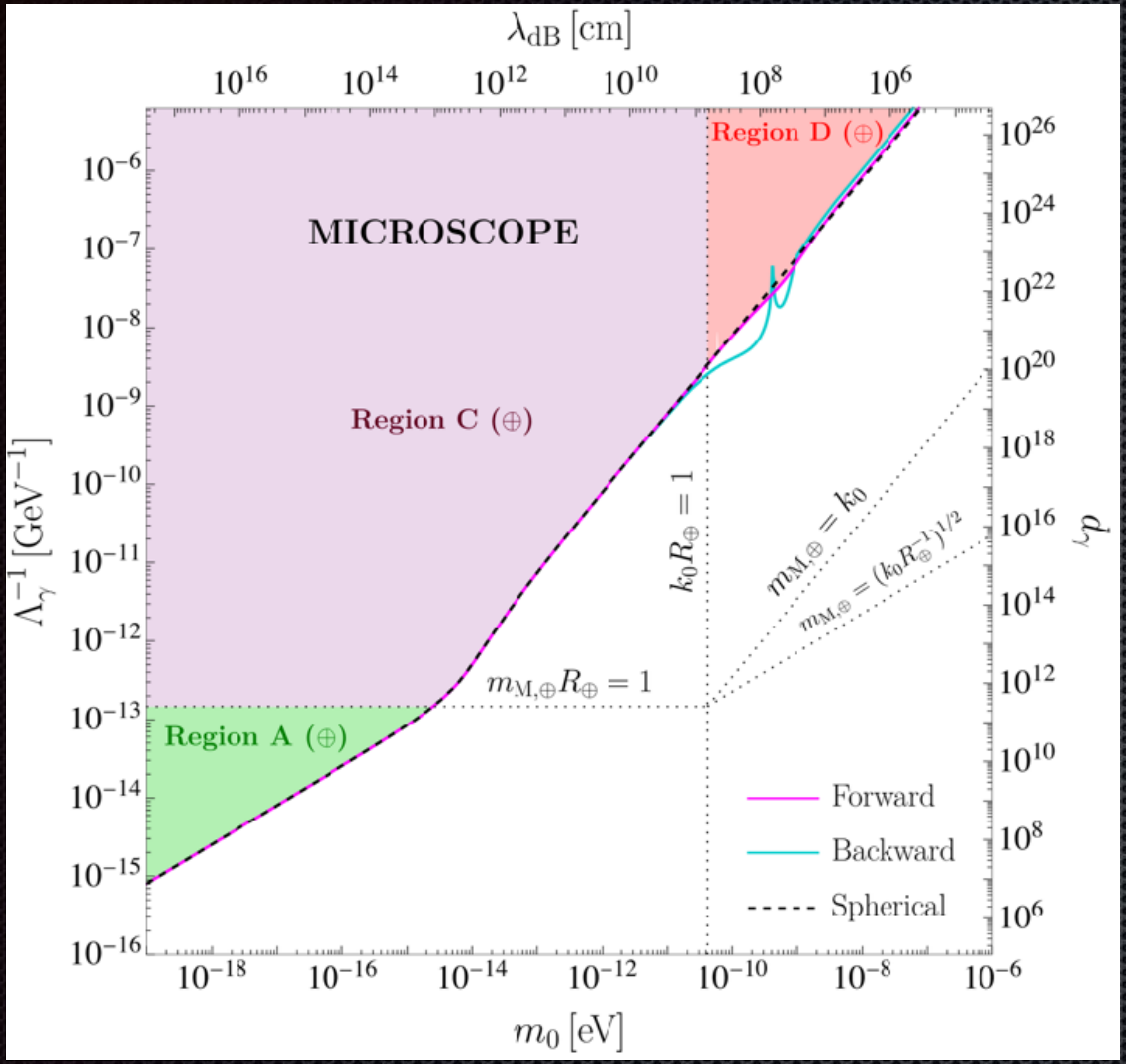
Decoherence vs Descreening

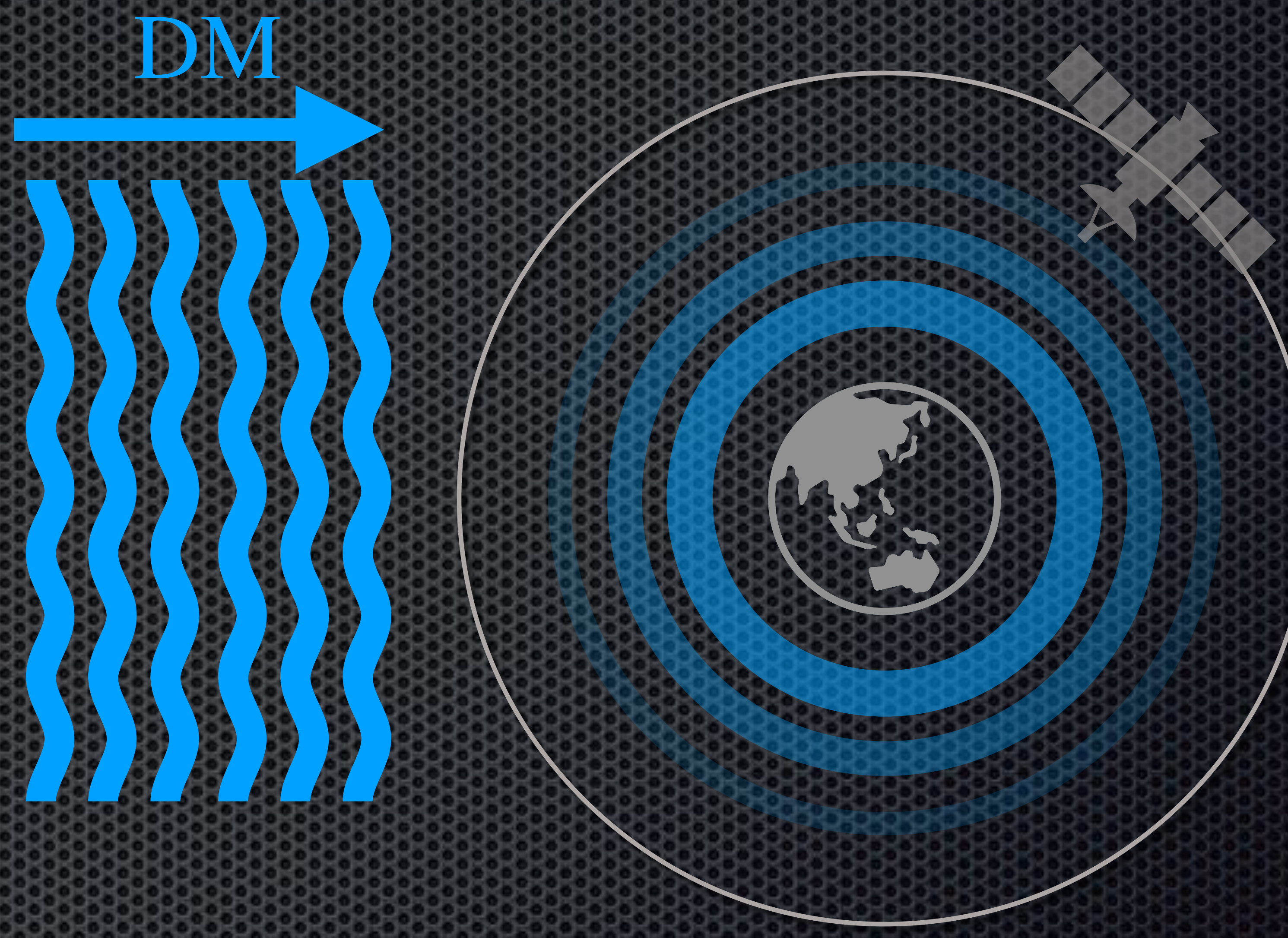


1. $\mathcal{O}(10)$ Difference
2. $m > 10^{-8}$eV,

Non-centripetal Force (1.6 hour)

MICROSCOPE Satellite





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

Pulsar Timing Array

Field Decomposition

$$\phi \sim \sum_{\mathbf{k}} \left(a_{\mathbf{k}} e^{-i\omega t + i\mathbf{k}\cdot\mathbf{x}} + a^*_{\mathbf{k}} e^{i\omega t - i\mathbf{k}\cdot\mathbf{x}} \right)$$

Quadratic Behaviors

$$\phi^2 \sim \sum_{\mathbf{k},\mathbf{k}'} \left(a_{\mathbf{k}} a_{\mathbf{k}'} e^{i(\mathbf{k}+\mathbf{k}')\cdot\mathbf{x}} \times e^{-i\,(2m_0)\,t} \right) \Bigg\} \quad \text{Fast Mode}$$

$$+ \sum_{\mathbf{k},\mathbf{k}'} \left(a_{\mathbf{k}} a^*_{\mathbf{k}'} e^{i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{x}} \times e^{-i\,m_0\,(v^2 - v'^2)\,t/2} \right) \Bigg\} \quad \text{Slow Mode}$$

Pulsar Timing Array

Field Decomp

$\phi \sim \sum_{\mathbf{k}} \Big(a_{\mathbf{k}} e$

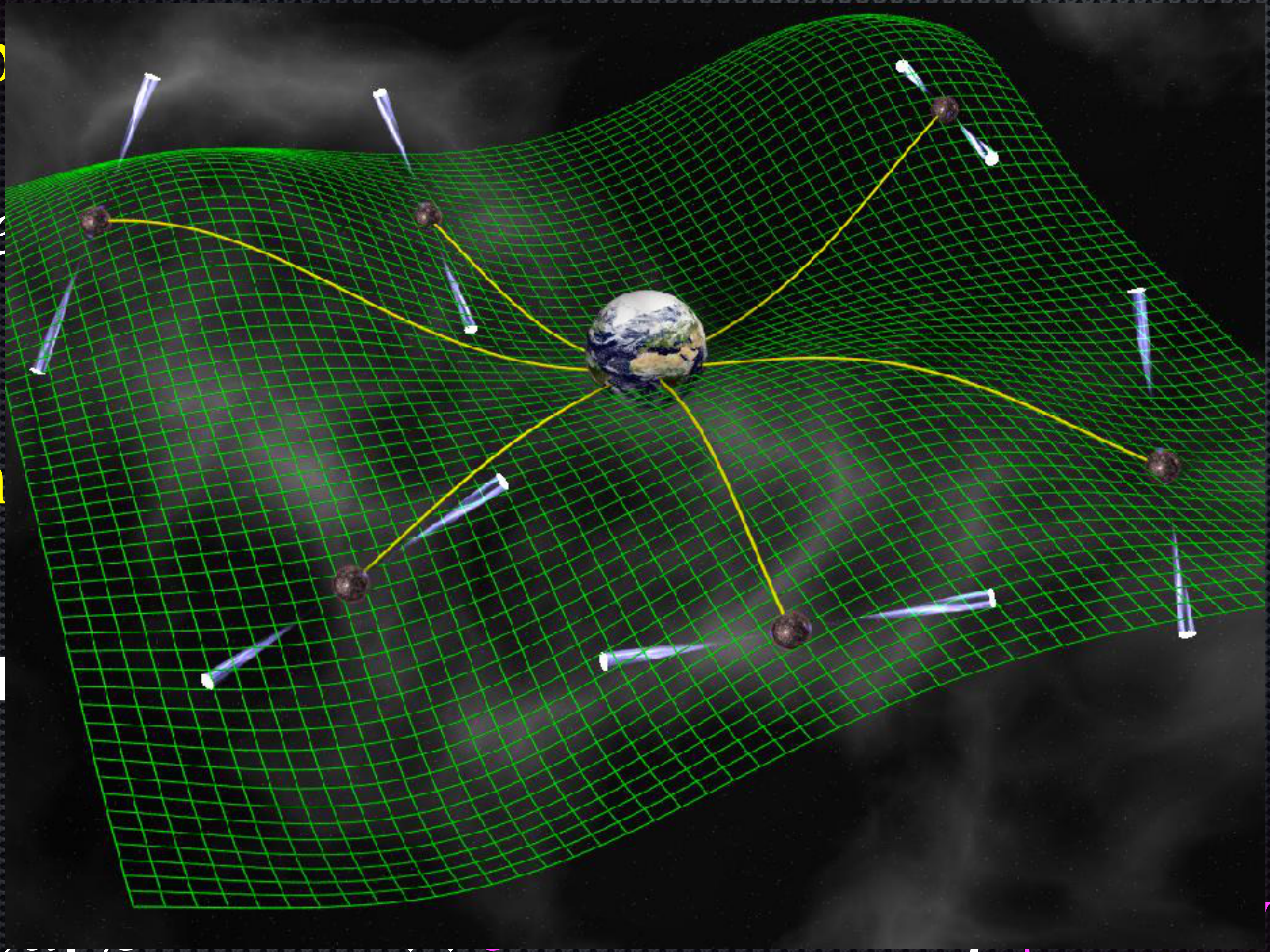
Quadratic Beh

$\phi^2 \sim \sum_{\mathbf{k},\mathbf{k}'} (a$

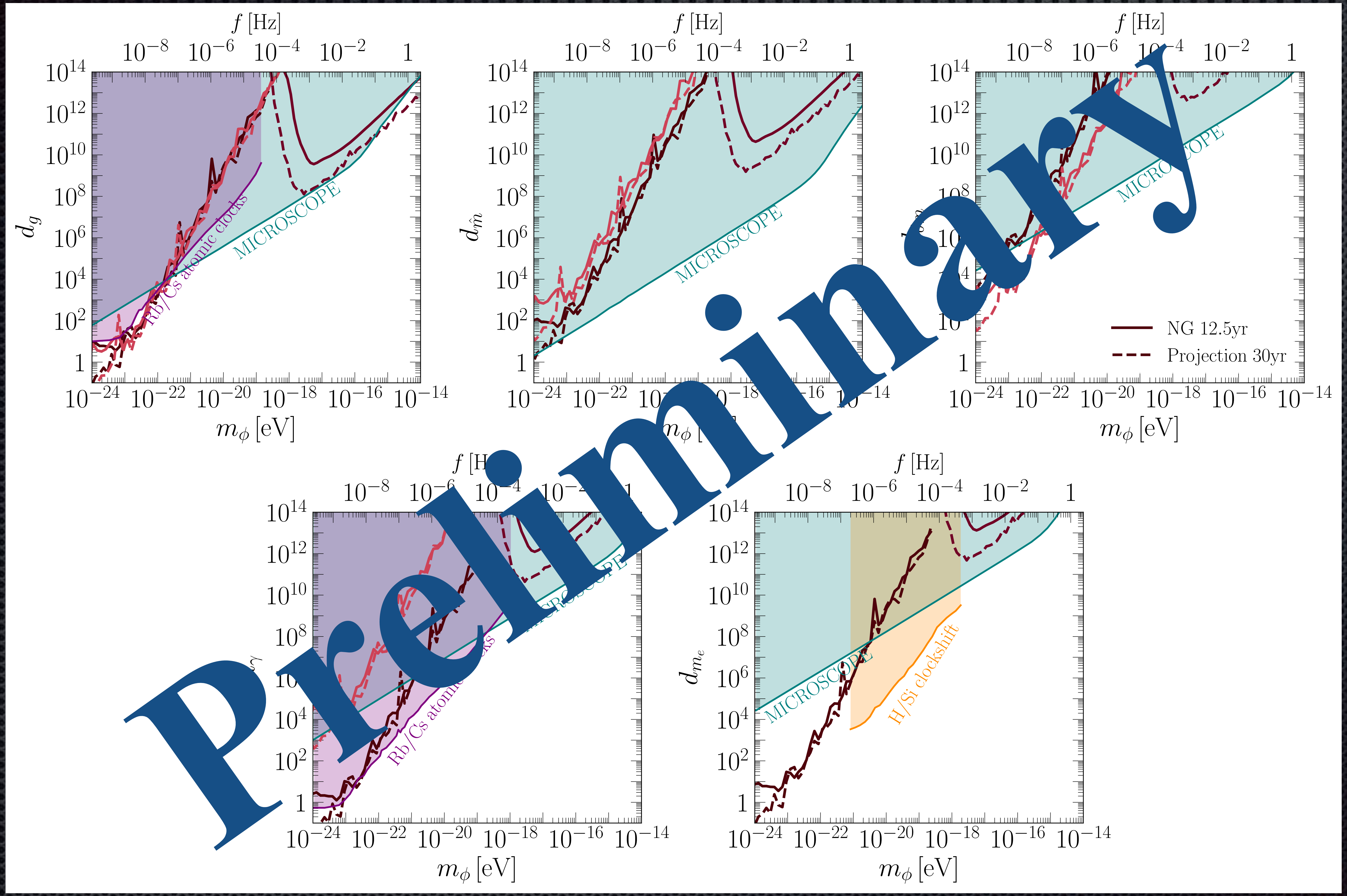
Mode

$+ \sum_{\mathbf{k},\mathbf{k}'} \Big(a_{\mathbf{k}} a_{\mathbf{k}'}$

Mode



Pulsar Timing Array



XG, Kim, Mitridate, XXXX.XXXXX

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 discuss the sensitivities for the accelerometer experiments, which detects the acceleration induced by the scattering force and background-induced force.
5. We also revisited the MICROSCOPE equivalence principle test and extend the constraints to the high-momentum regime $kR_\oplus \gg 1$.
6. We also introduce the detection of the quadratic coupling using PTA observations.

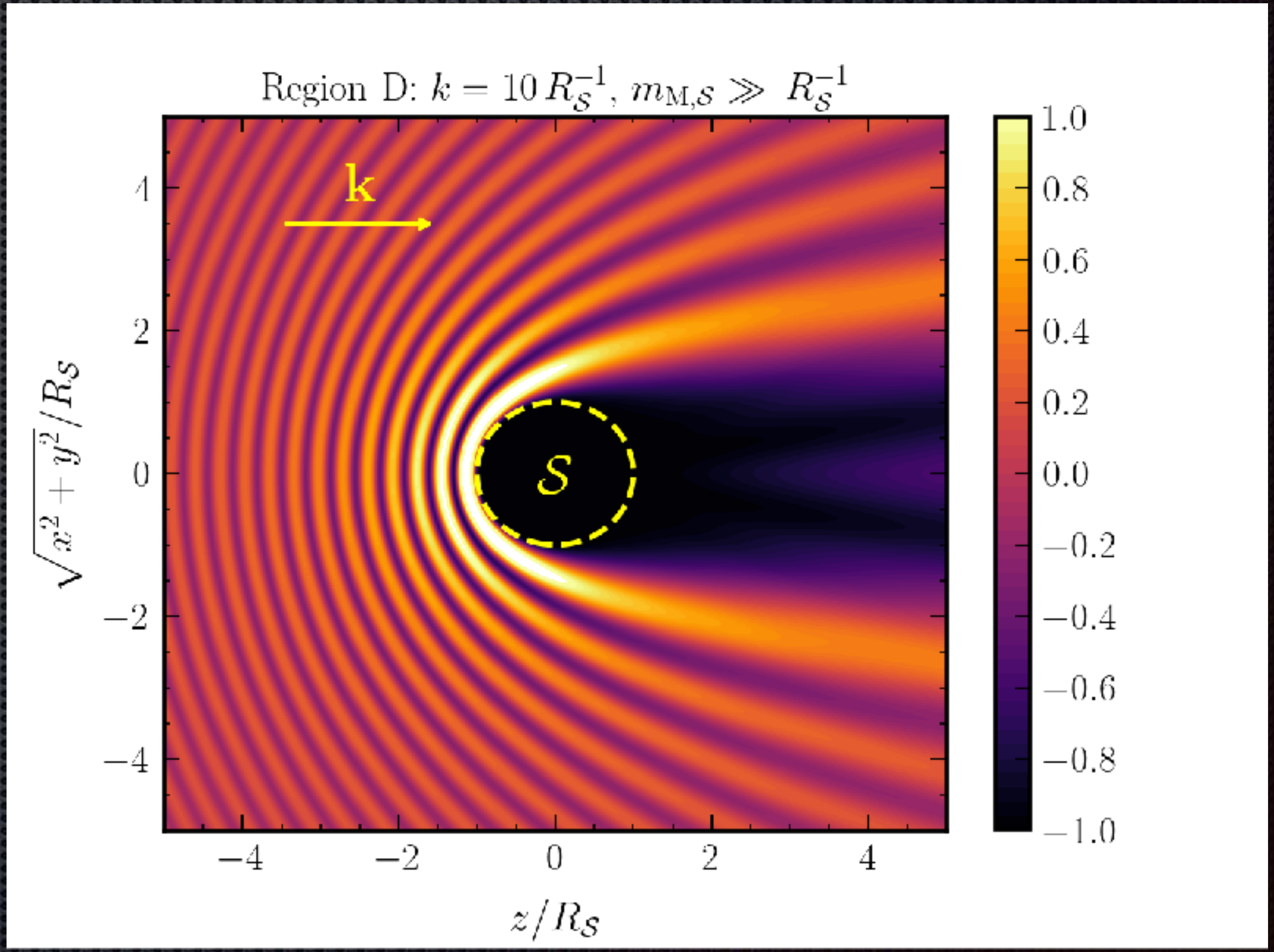
Appendix

Partial Wave + Phase Space

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

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

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

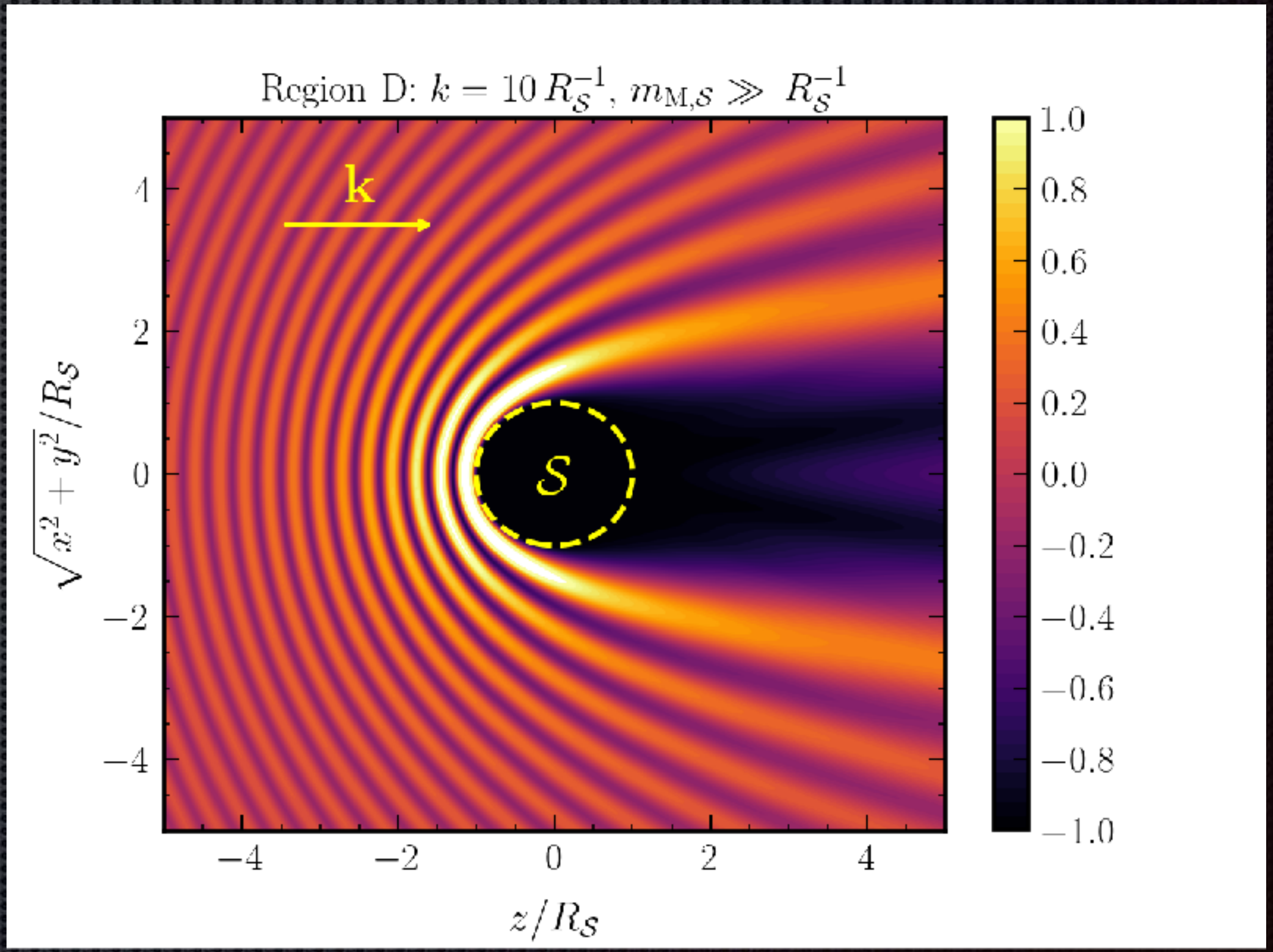


Partial Wave + Phase Space

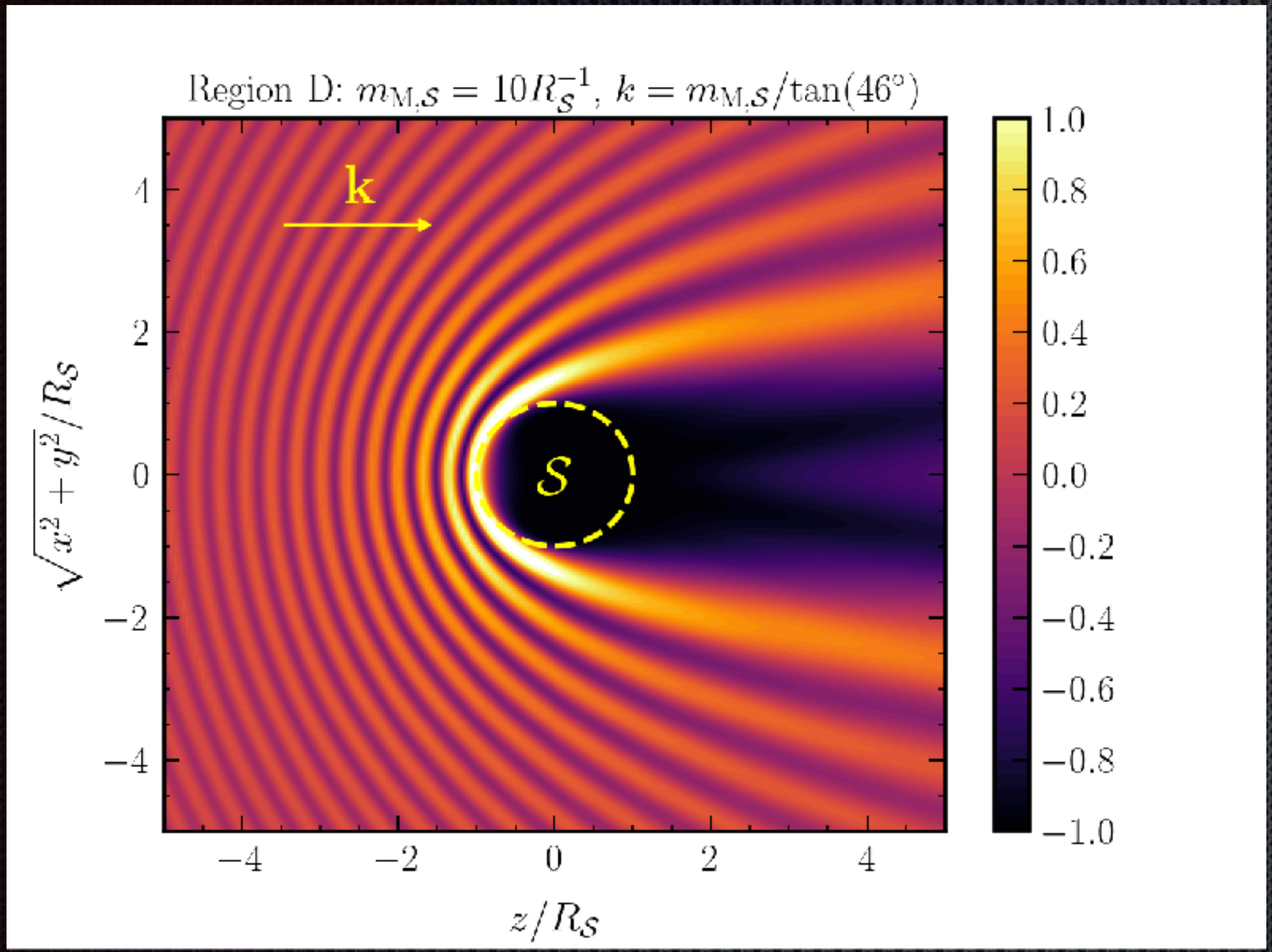
$$V_{\rm bg}(\mathbf{k}) \propto |\psi_{\rm tot}(\mathbf{k})|^2$$

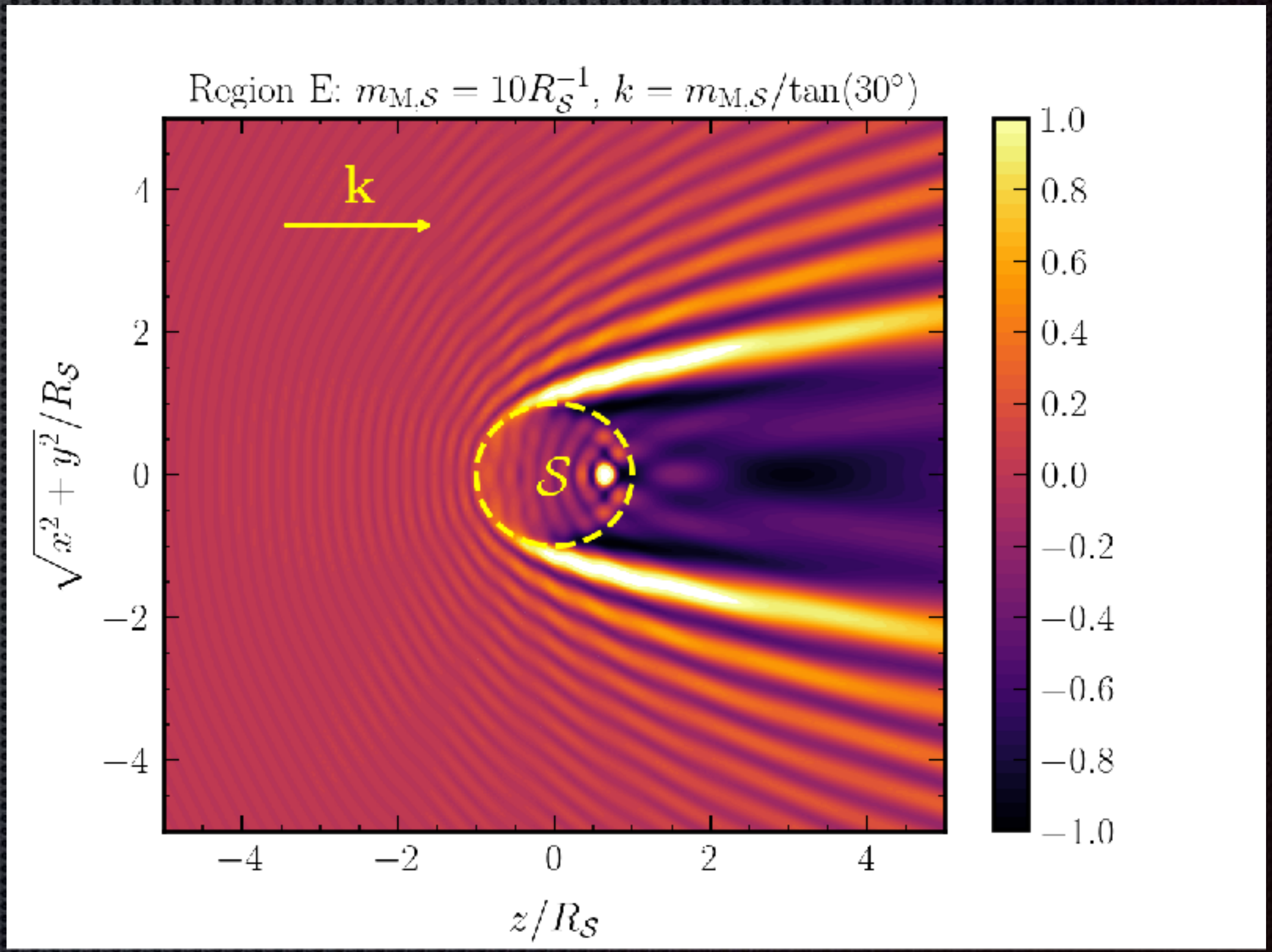
$$\langle V_{\rm bg}\rangle_{\mathbf{k}} = \frac{1}{n_\phi}\int_{\mathbf{k}} f_\phi(\mathbf{k}) V_{\rm bg}(\mathbf{k})$$

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



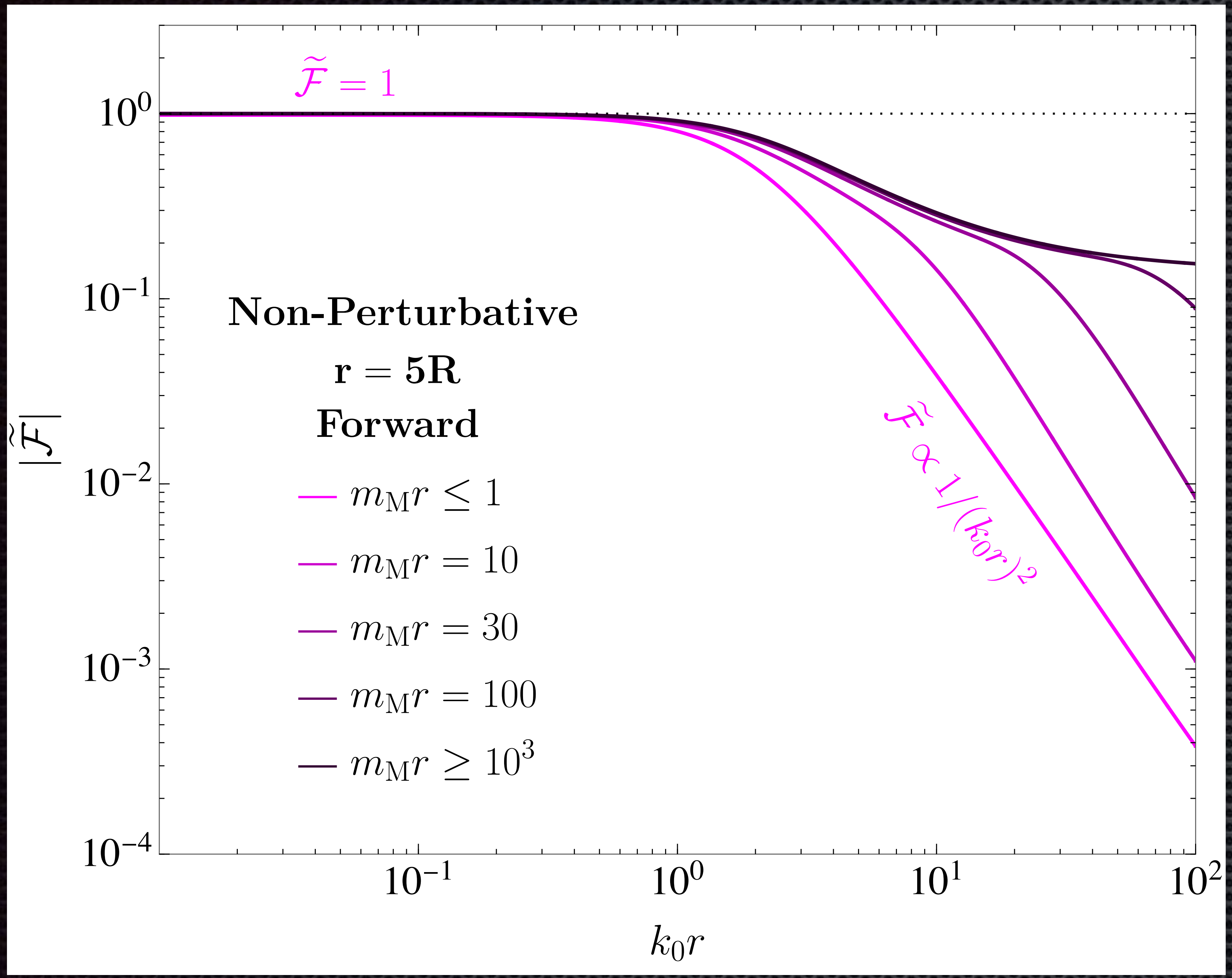
Descreening Effect



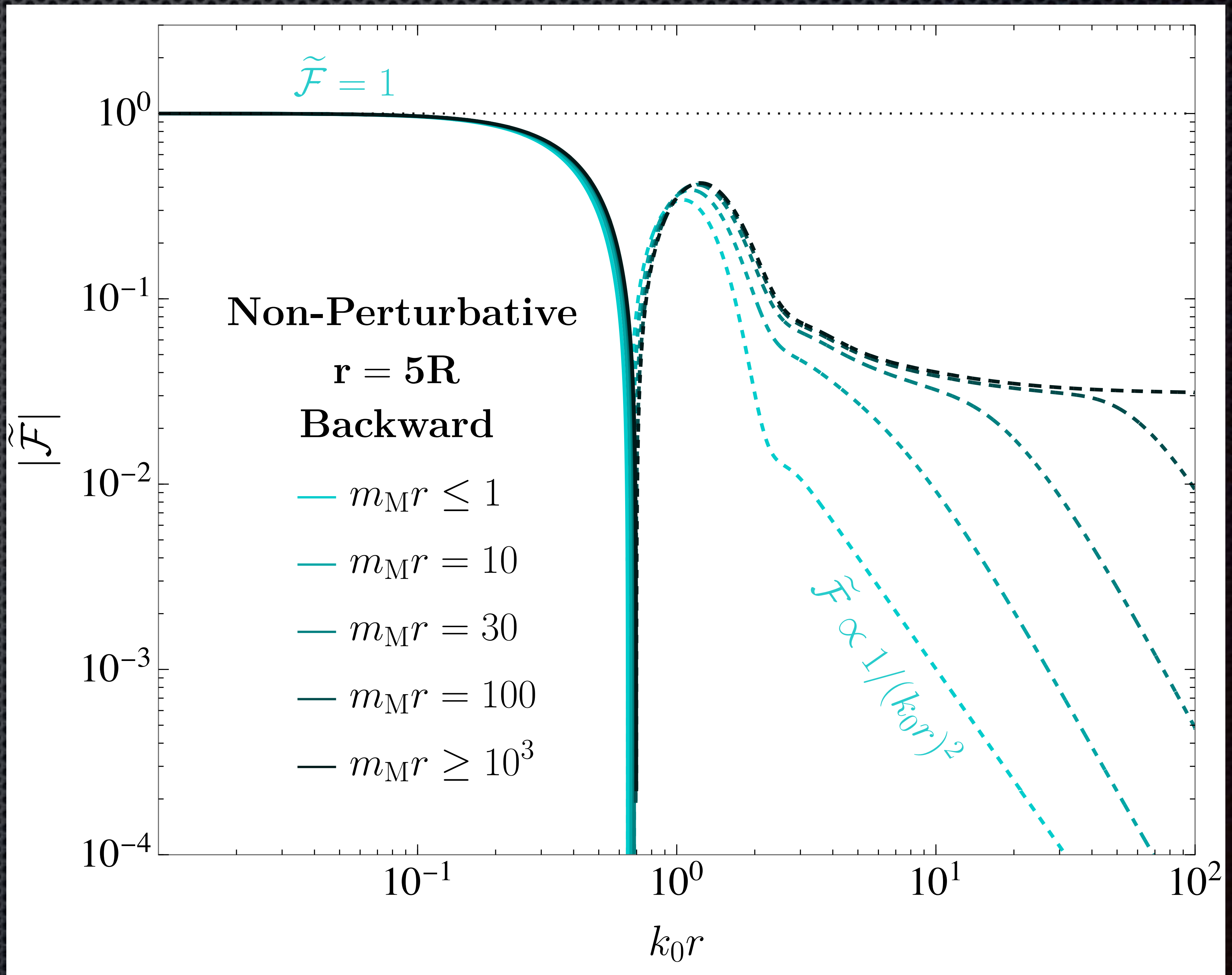


Descreening Effect

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



Forward Direction



Backward Direction

Spherical Symmetric Ansatz

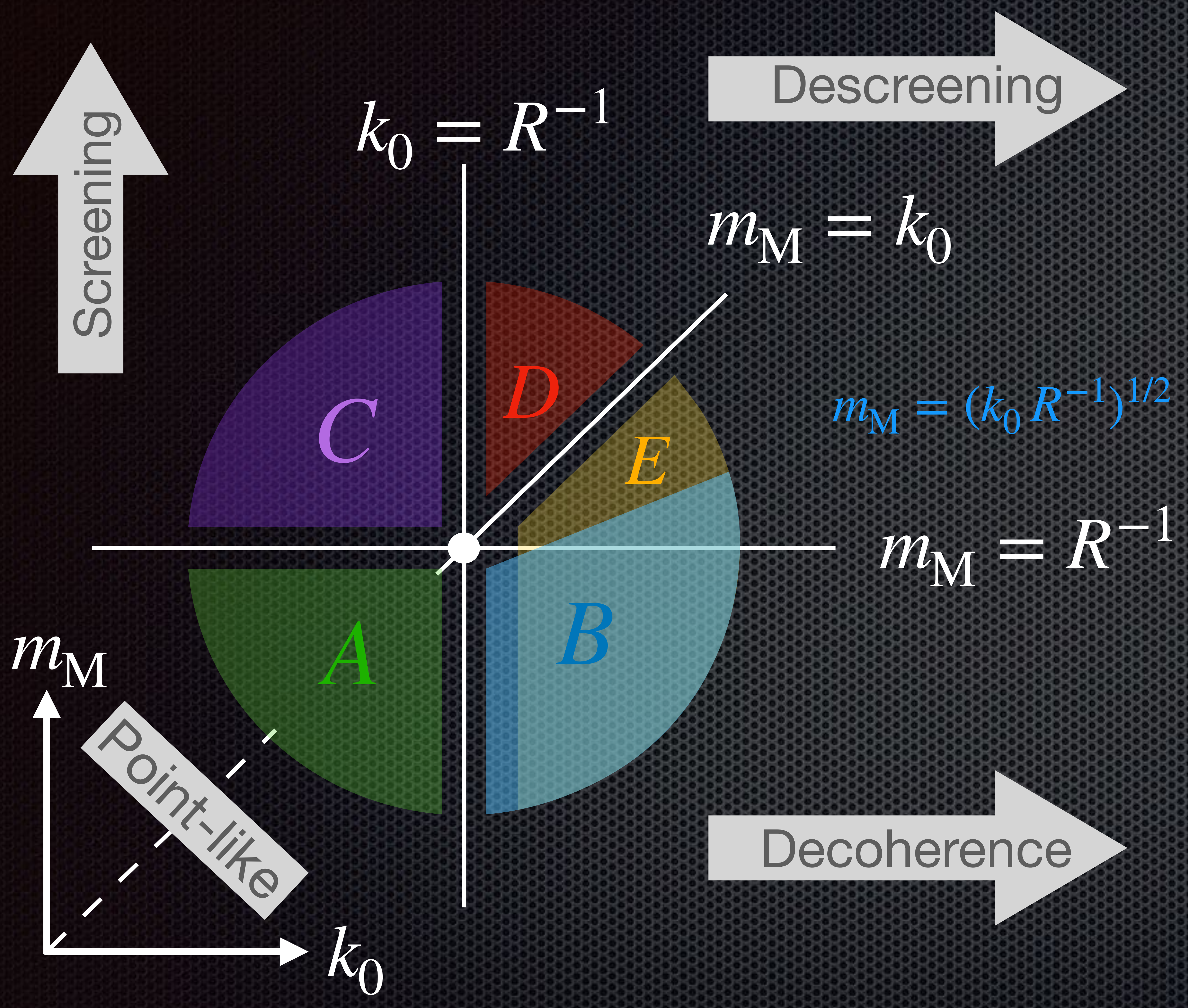
$$\nabla^2 \psi_{\rm sph} = m_{\rm M}^2 \, \theta(R - r) \, \psi_{\rm sph}$$

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

Screening Effect

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

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



★ 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