# Gap Oscillations in Superconductors Driven Out of Equilibrium

Tianbai Cui, Michael Schuett, Peter Orth, Rafael Fernandes

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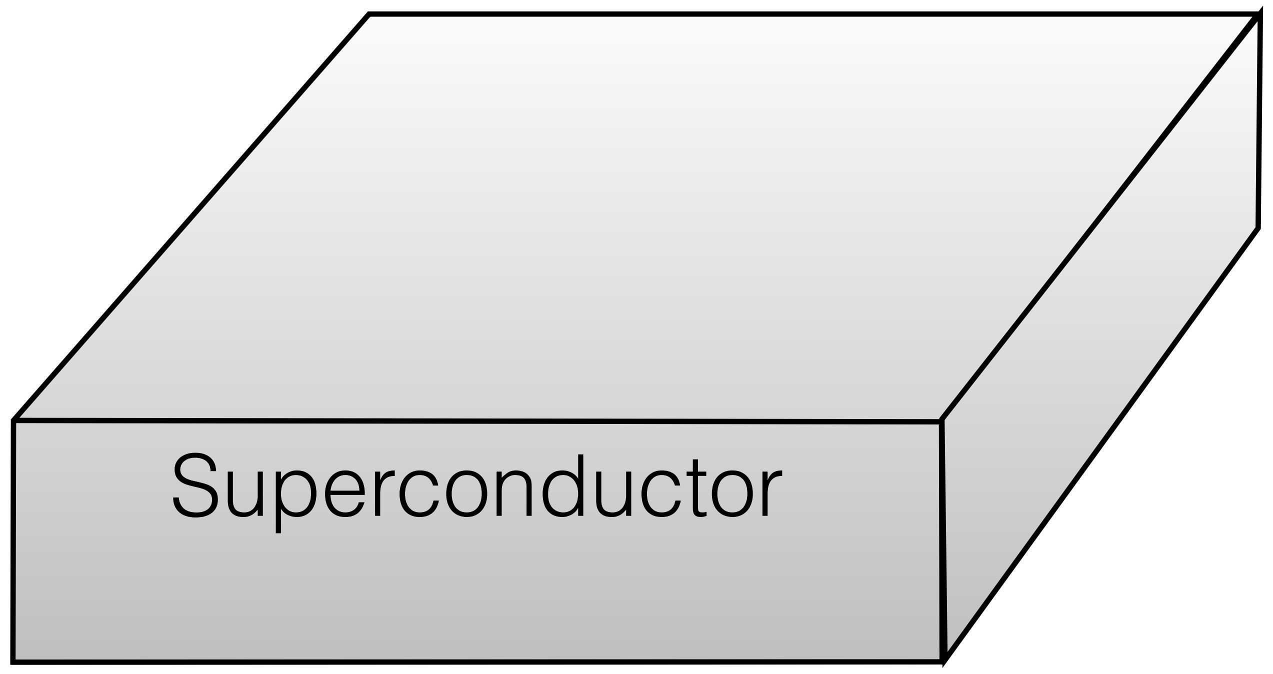
# Non-equilibrium superconductivity



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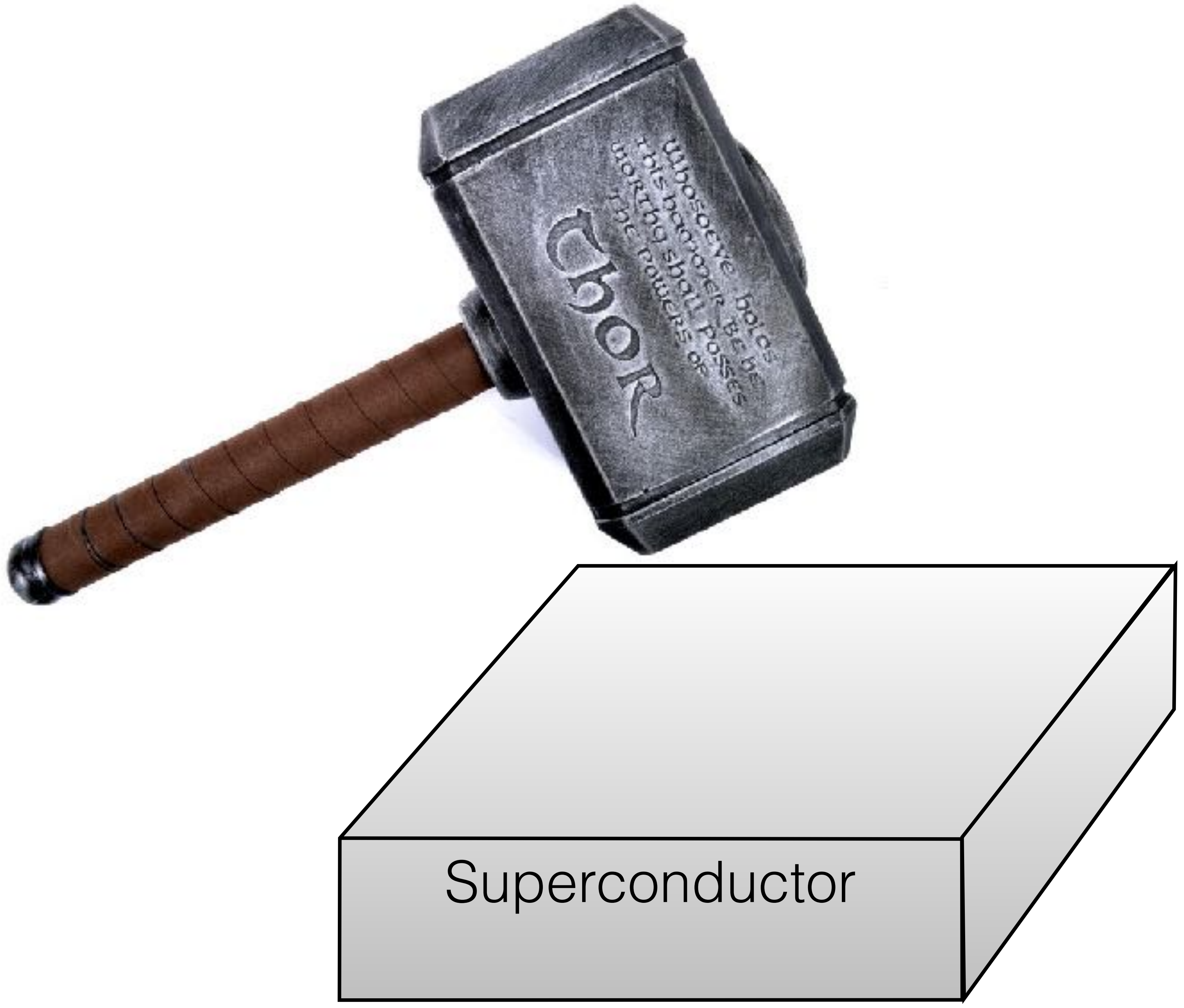

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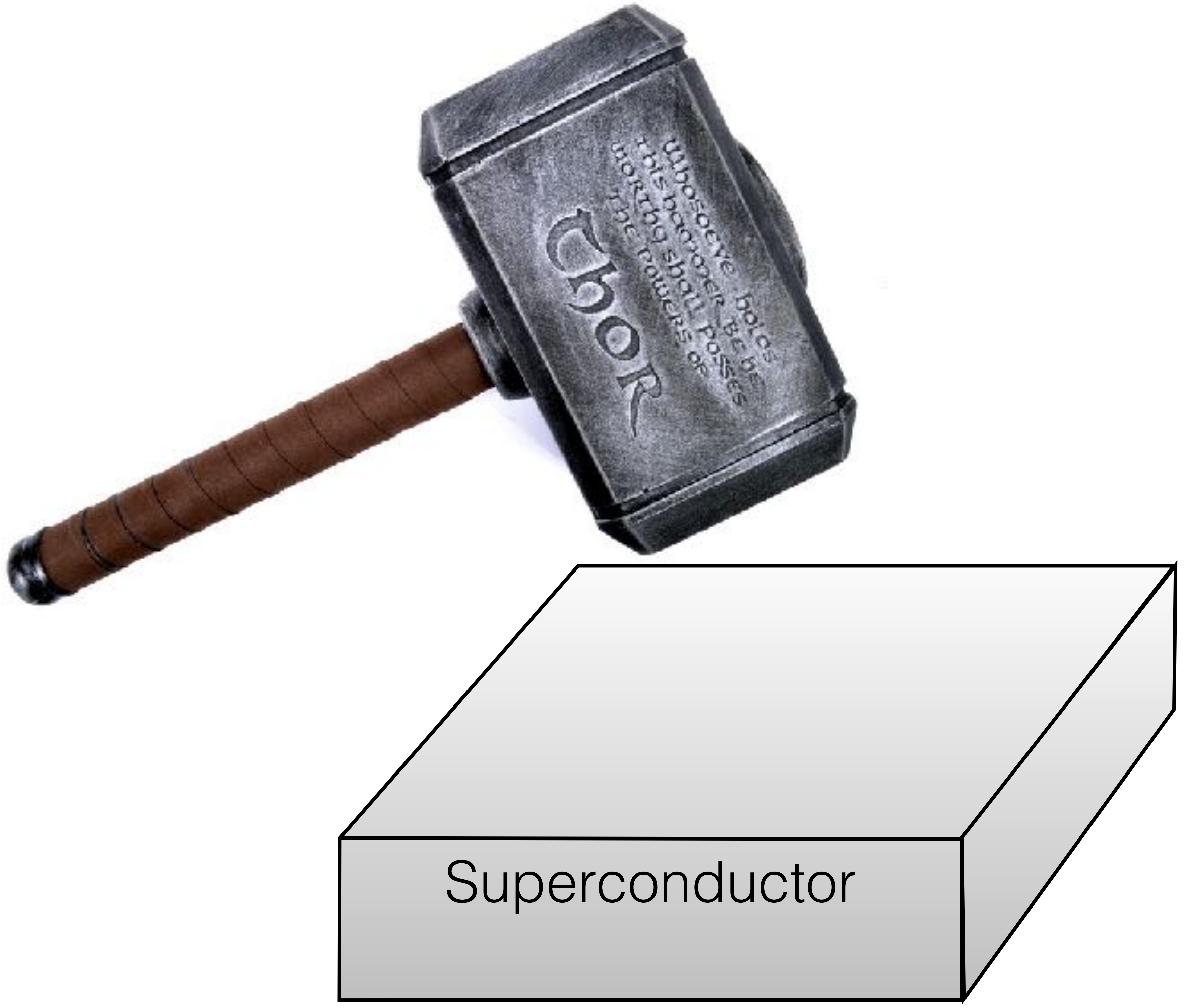


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$$\tau_{\mathrm{qp}} \approx \frac{\hbar}{\Delta^2/\varepsilon_F}$$

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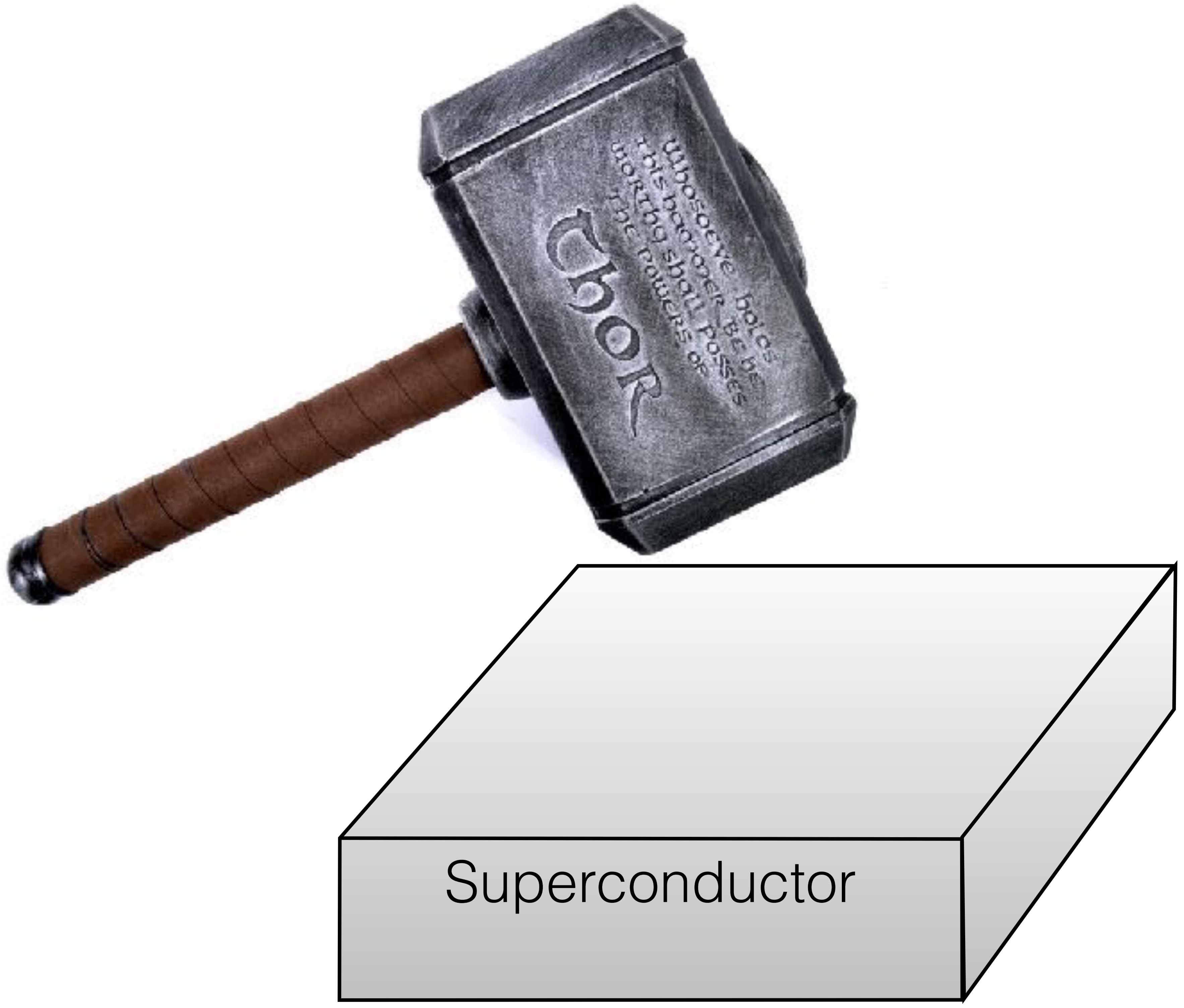


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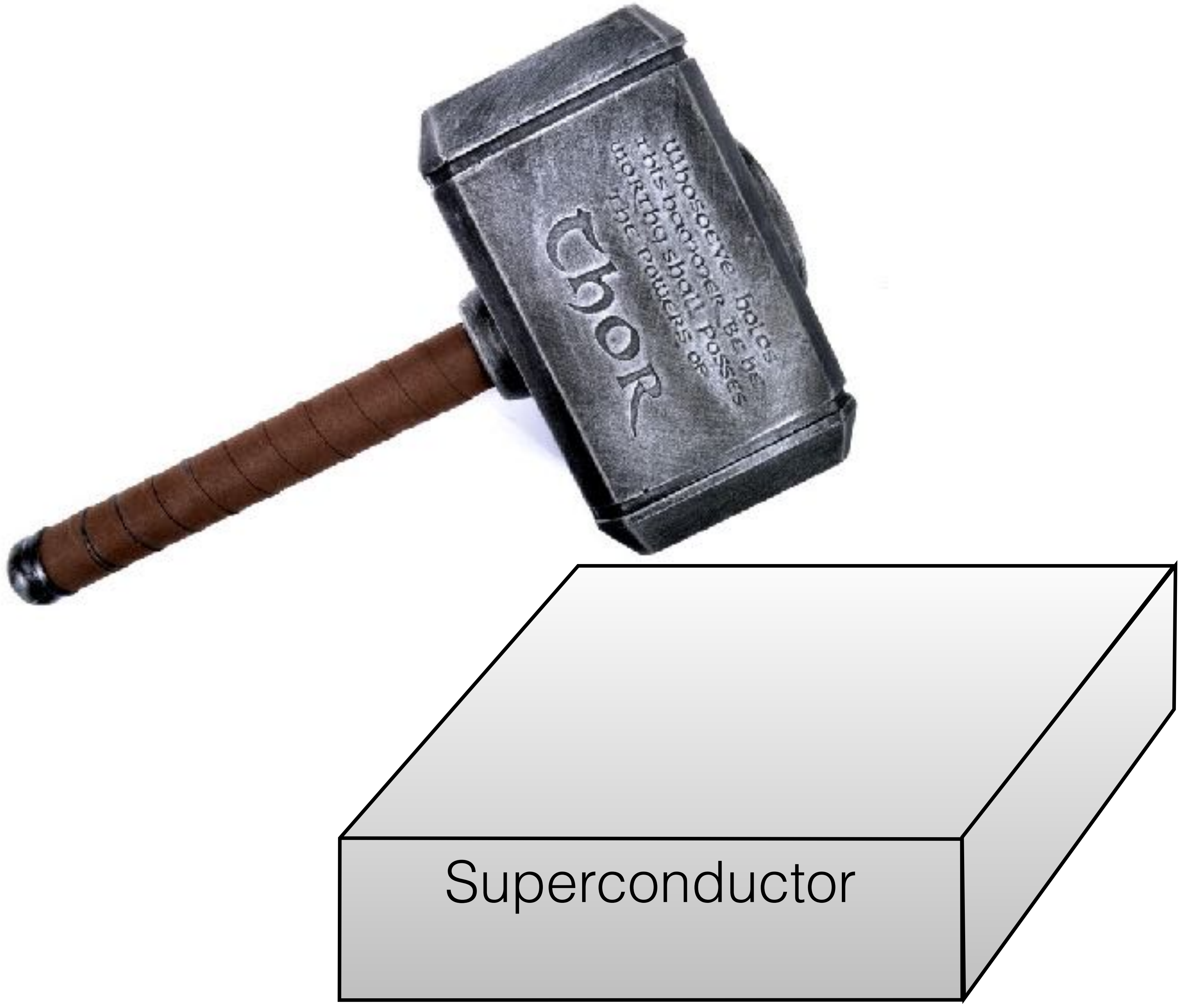


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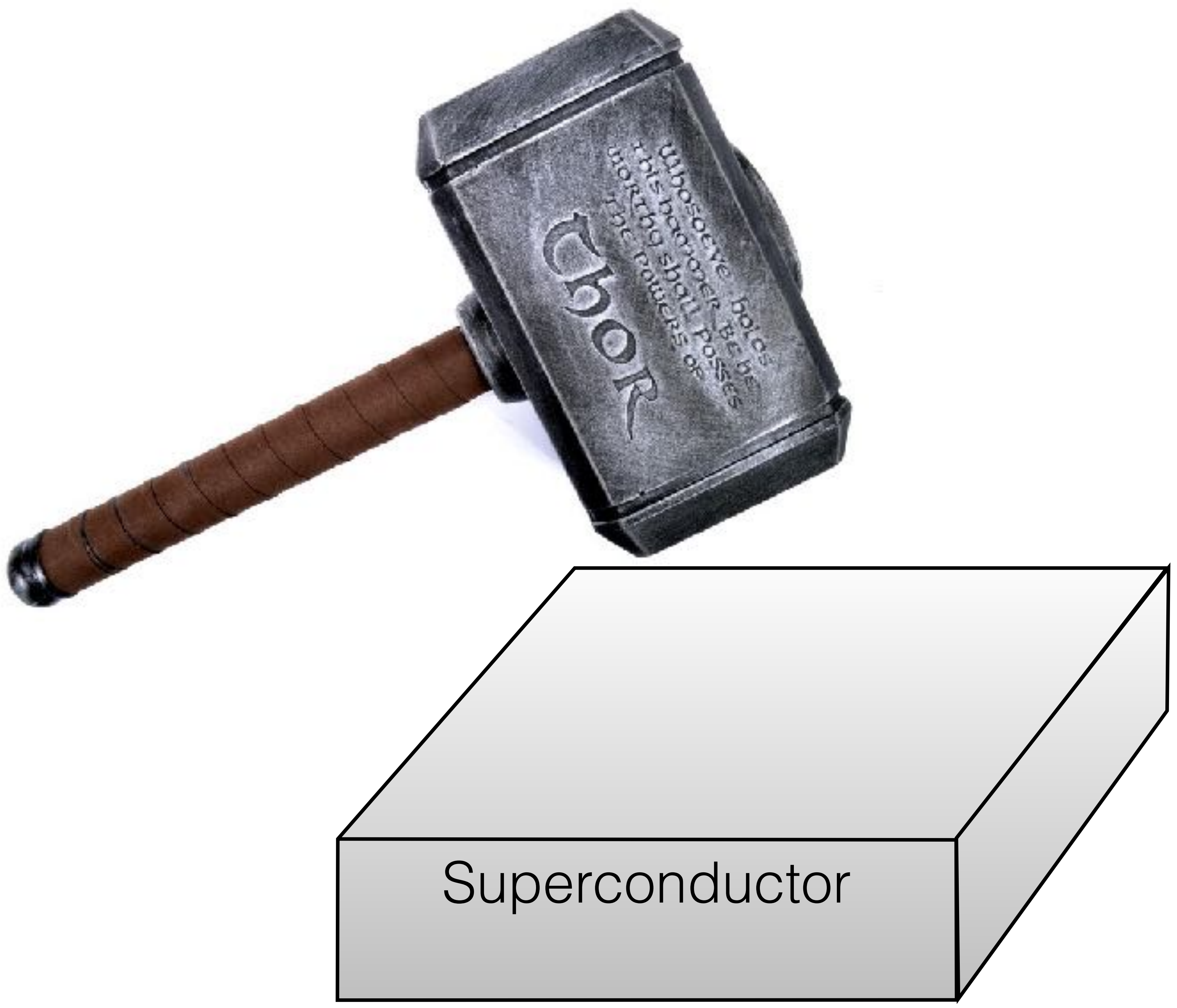


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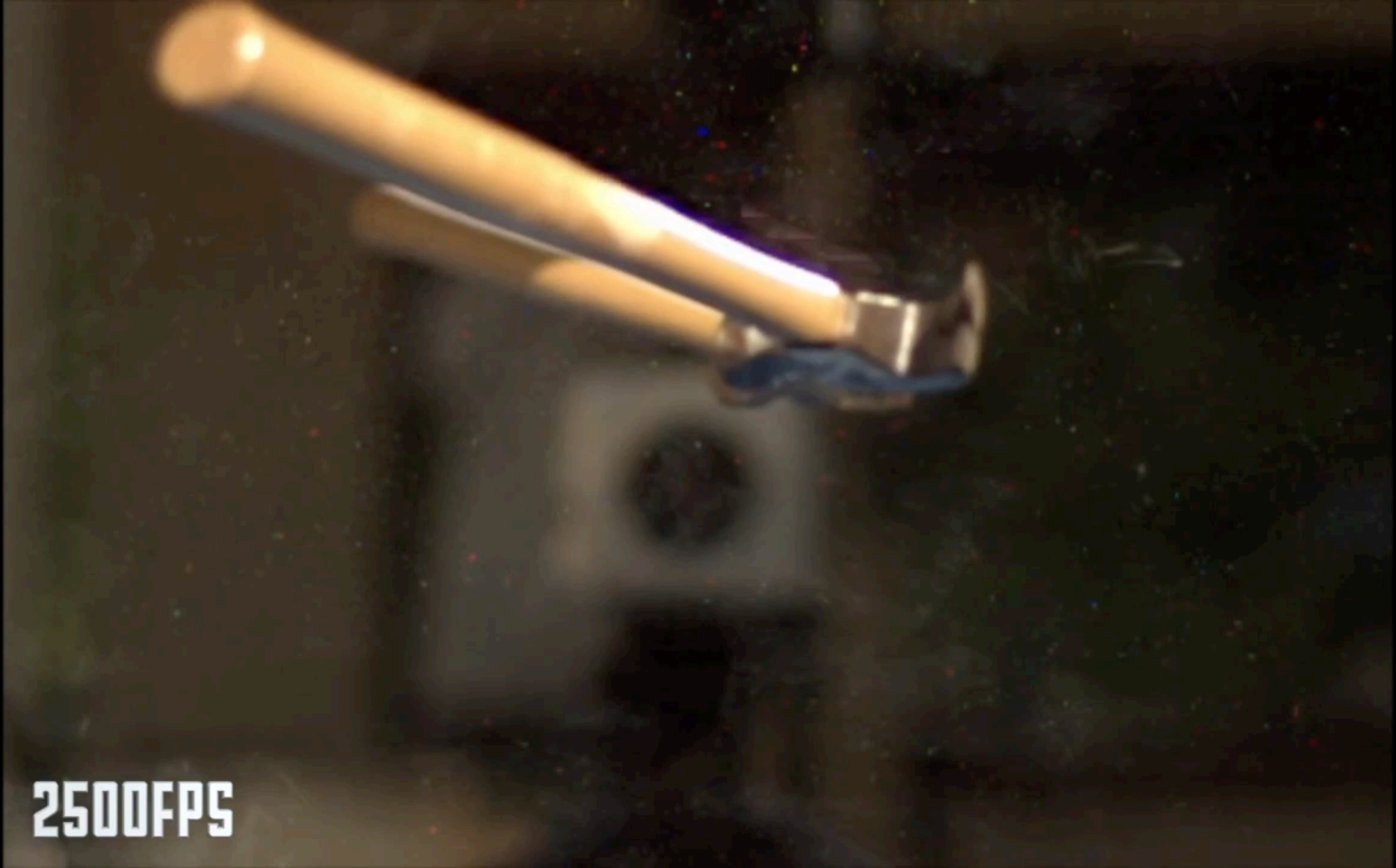
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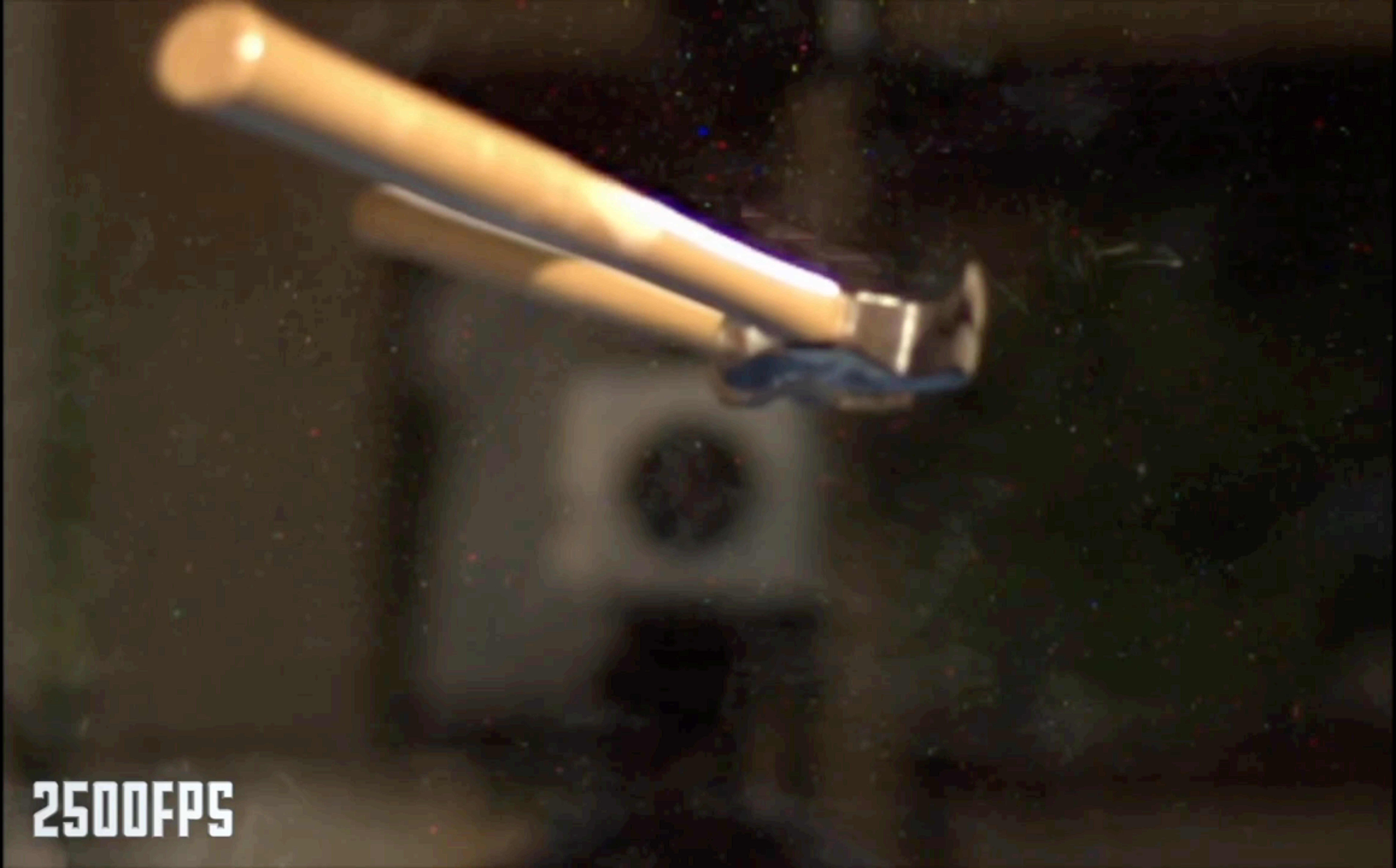
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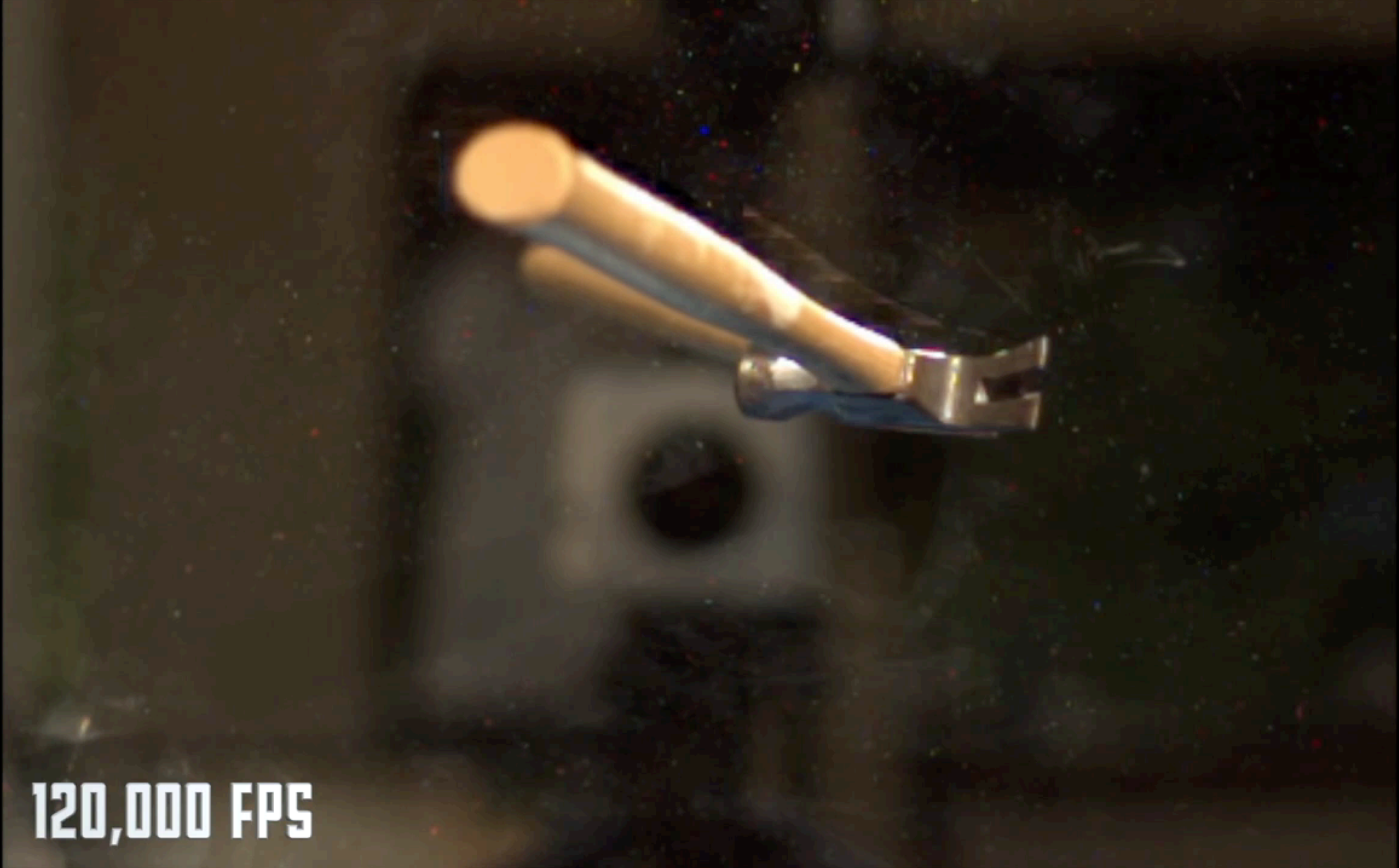
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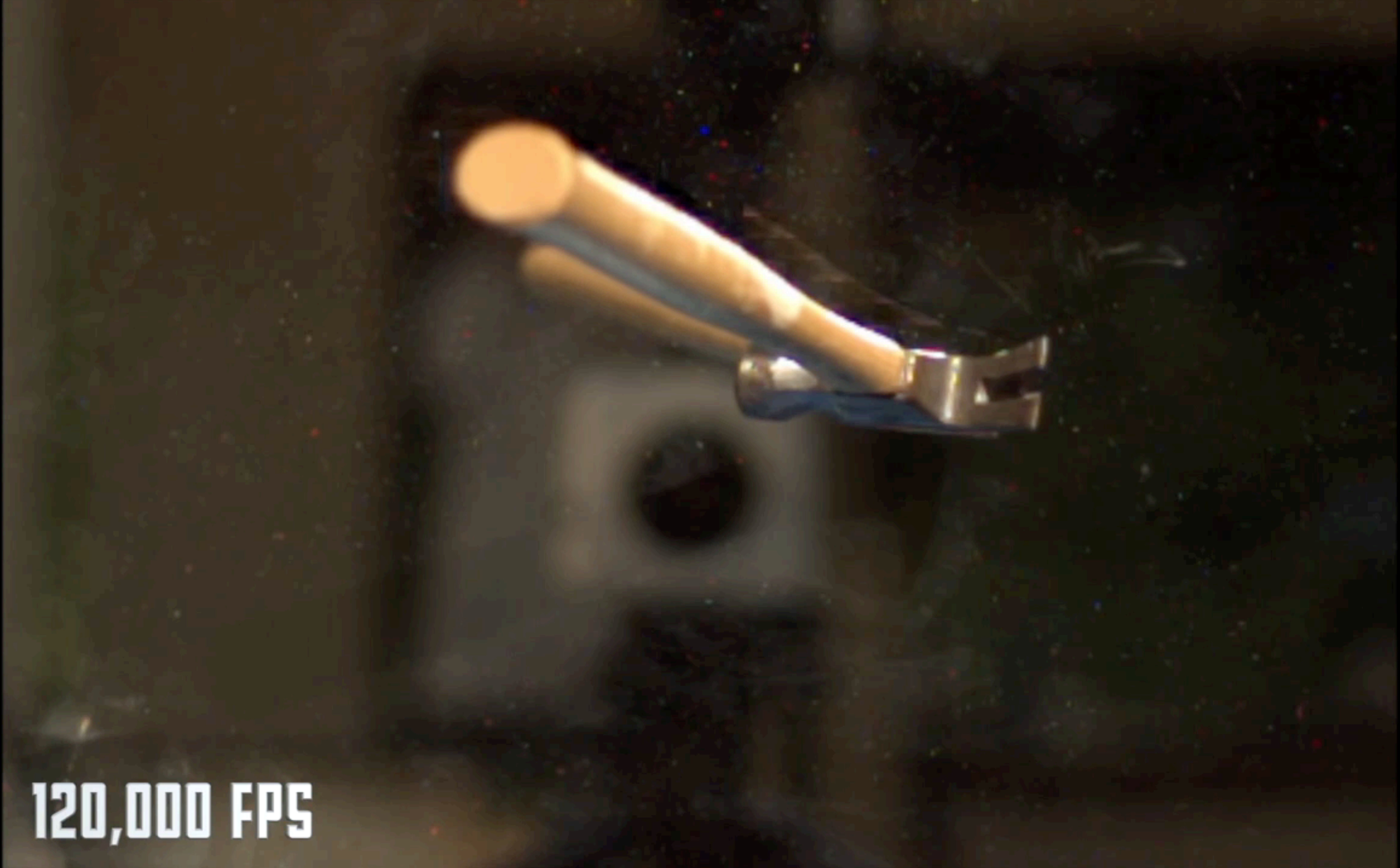
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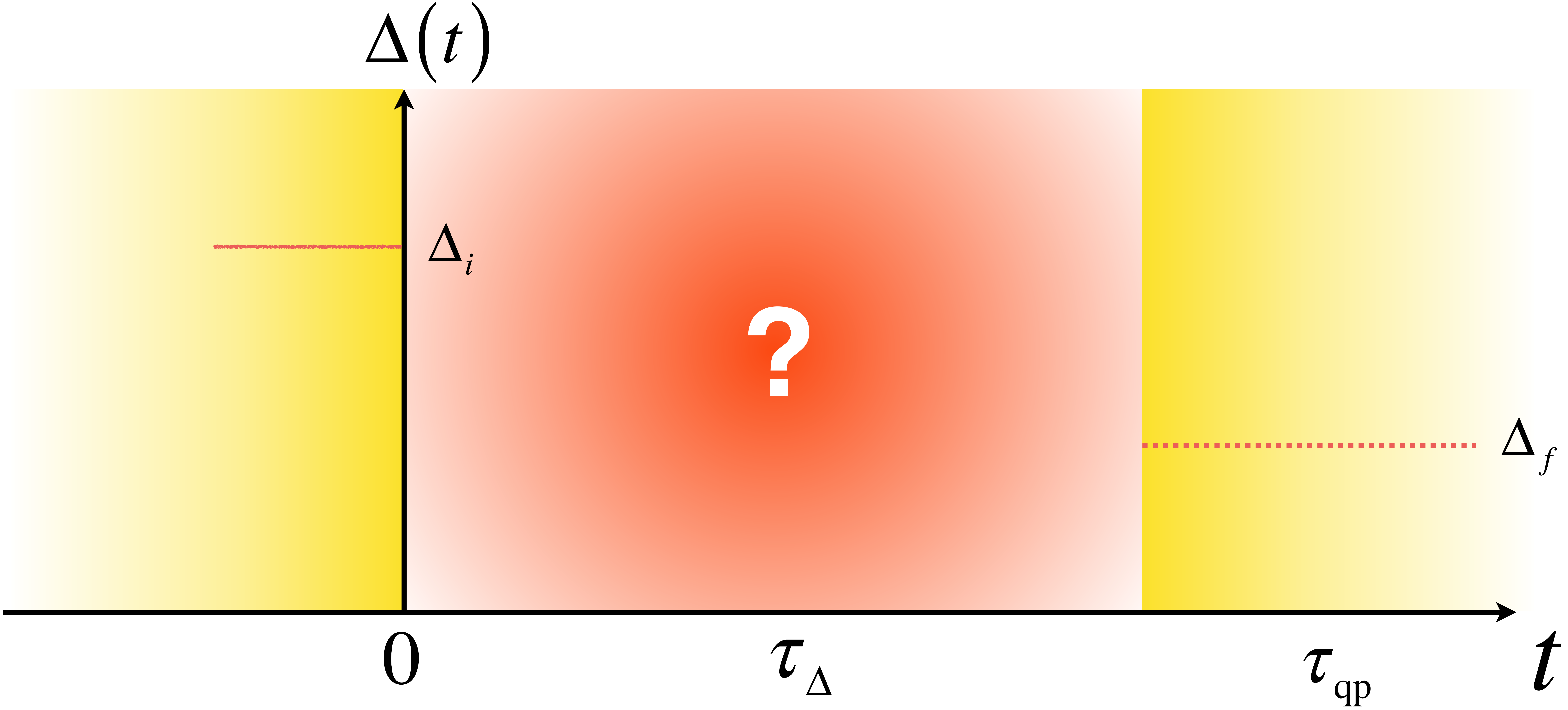

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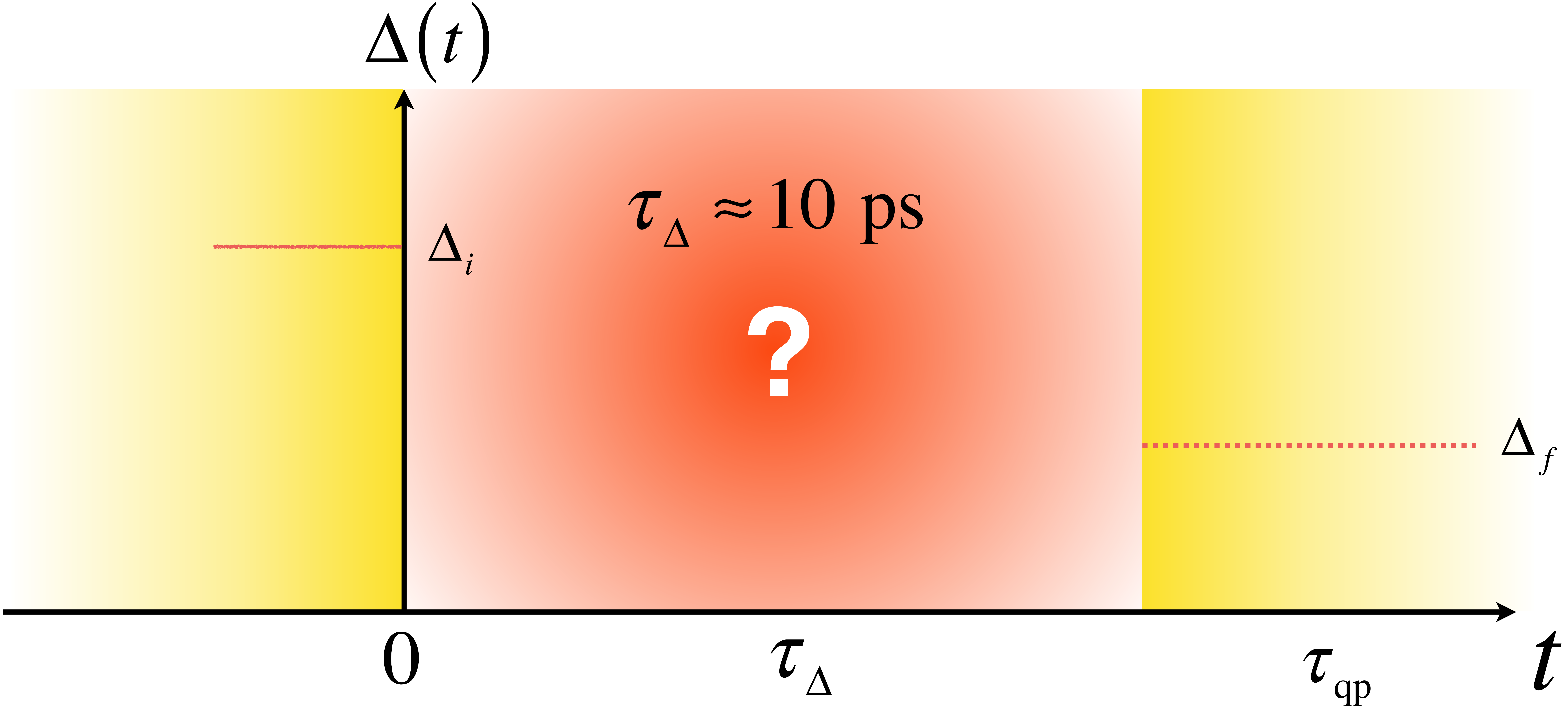

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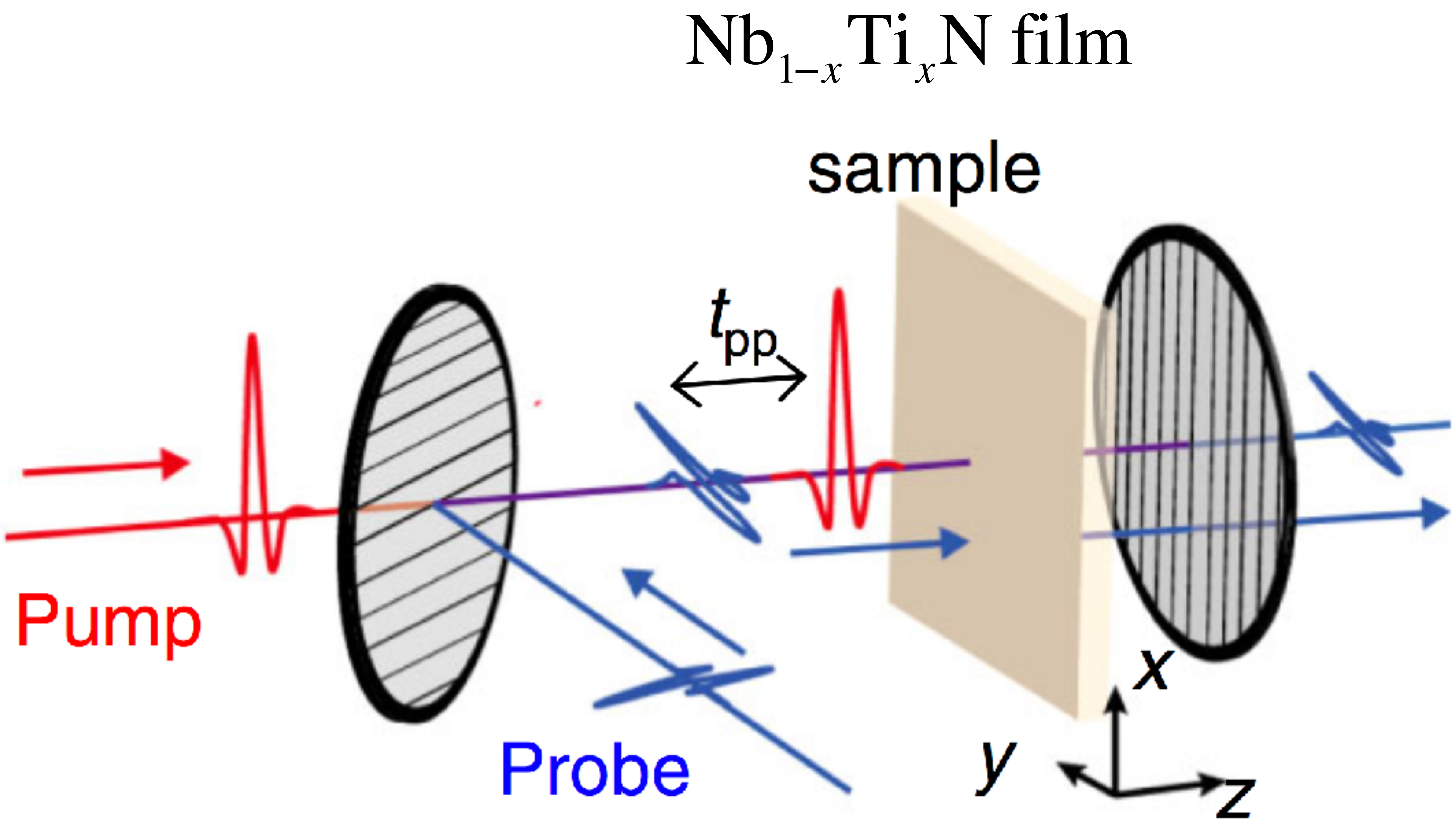



[1] R. Matsunaga *et al.*, Phys. Rev. Lett., **111**, 057002 (2013).

[2] R. Matsunaga *et al.*, Science, **345**, 6201 (2014).

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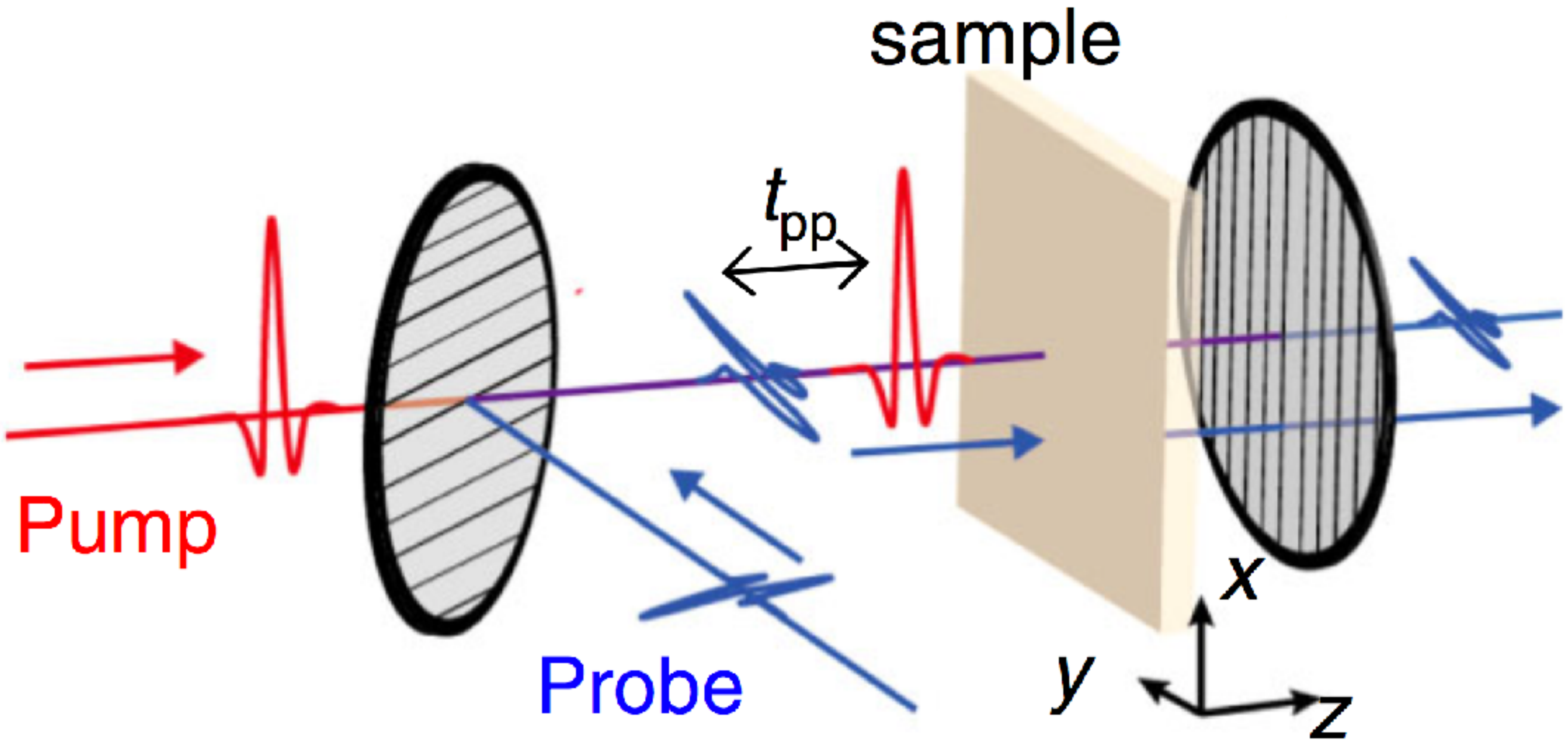
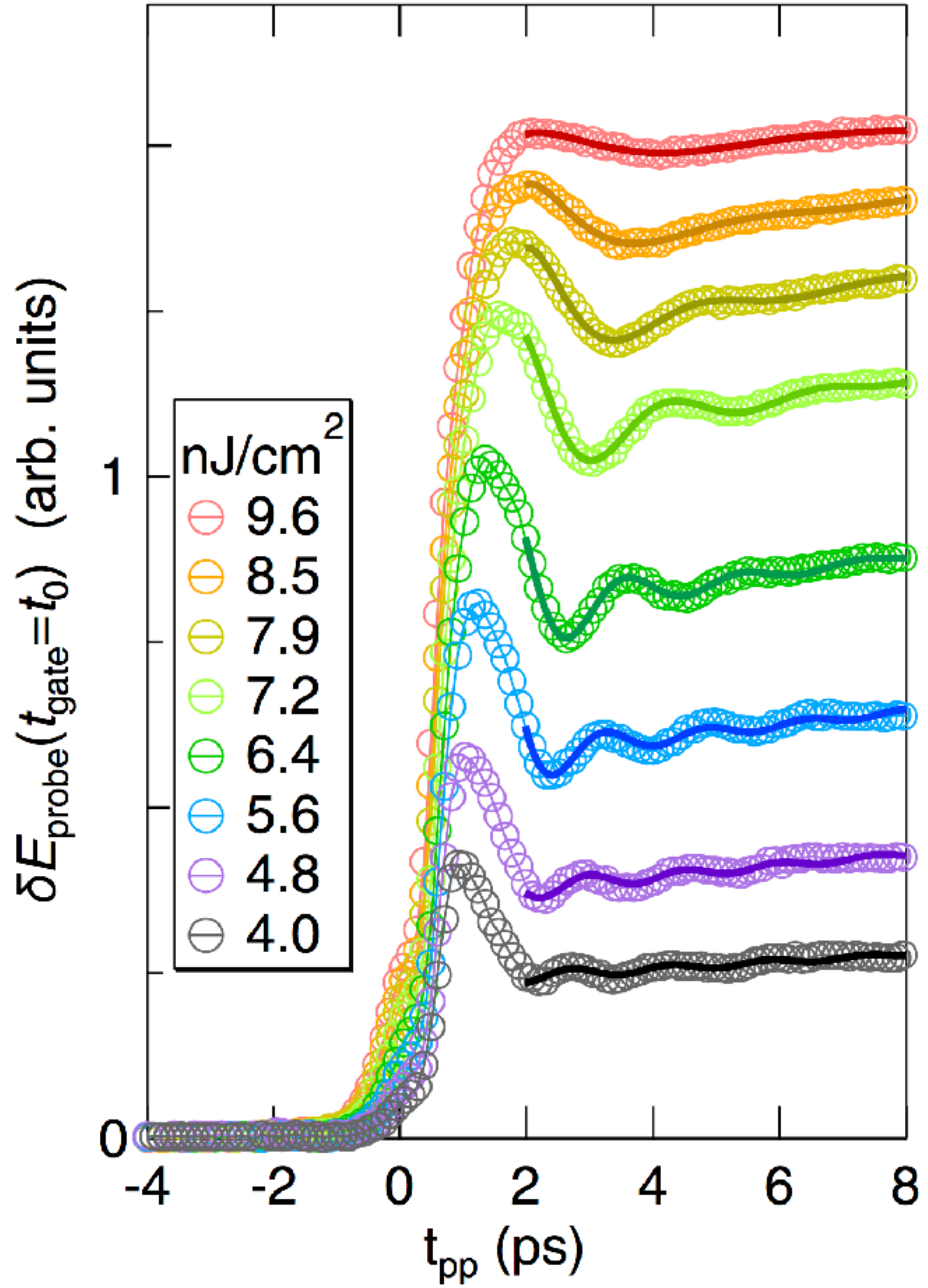
$Nb_{1-x}Ti_xN$ film





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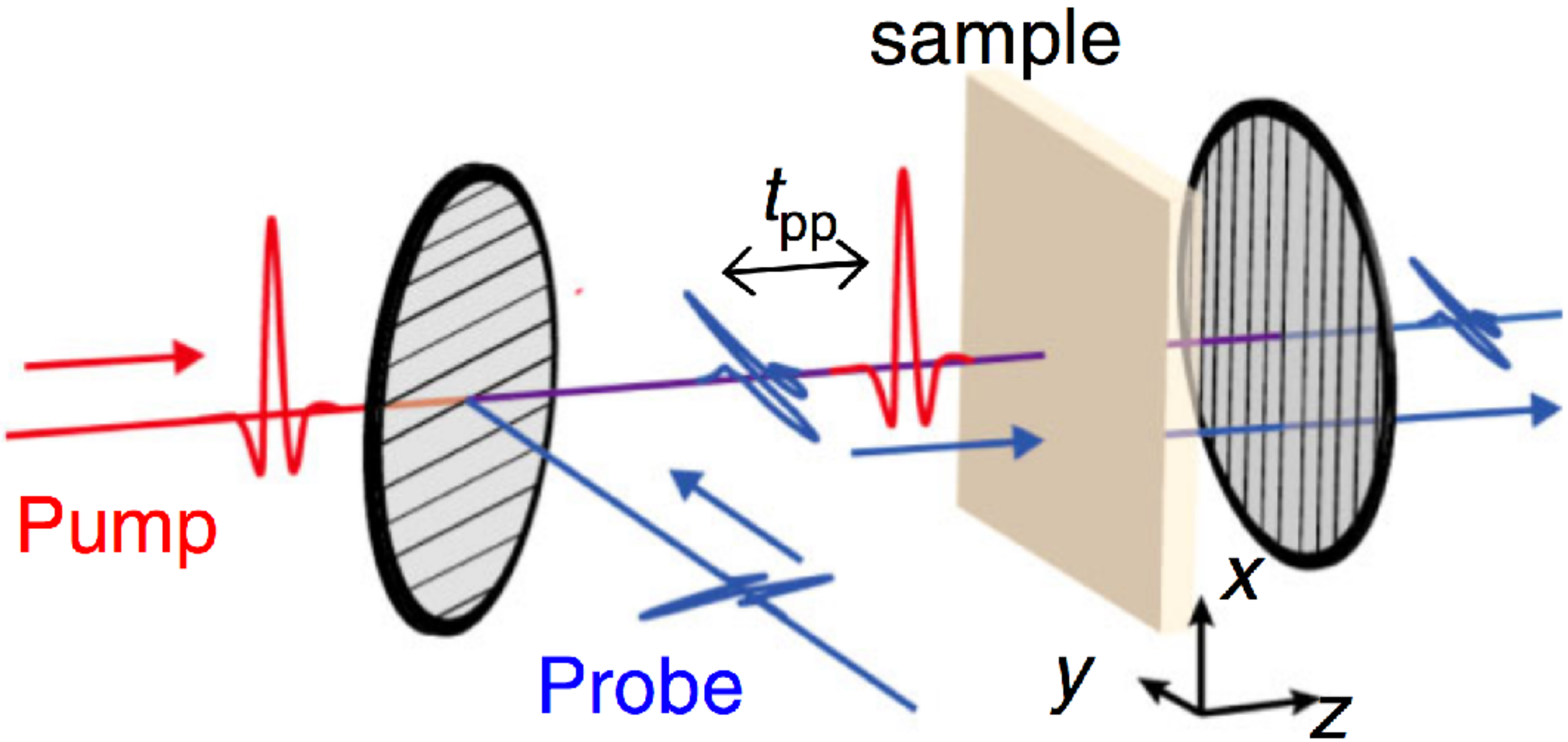


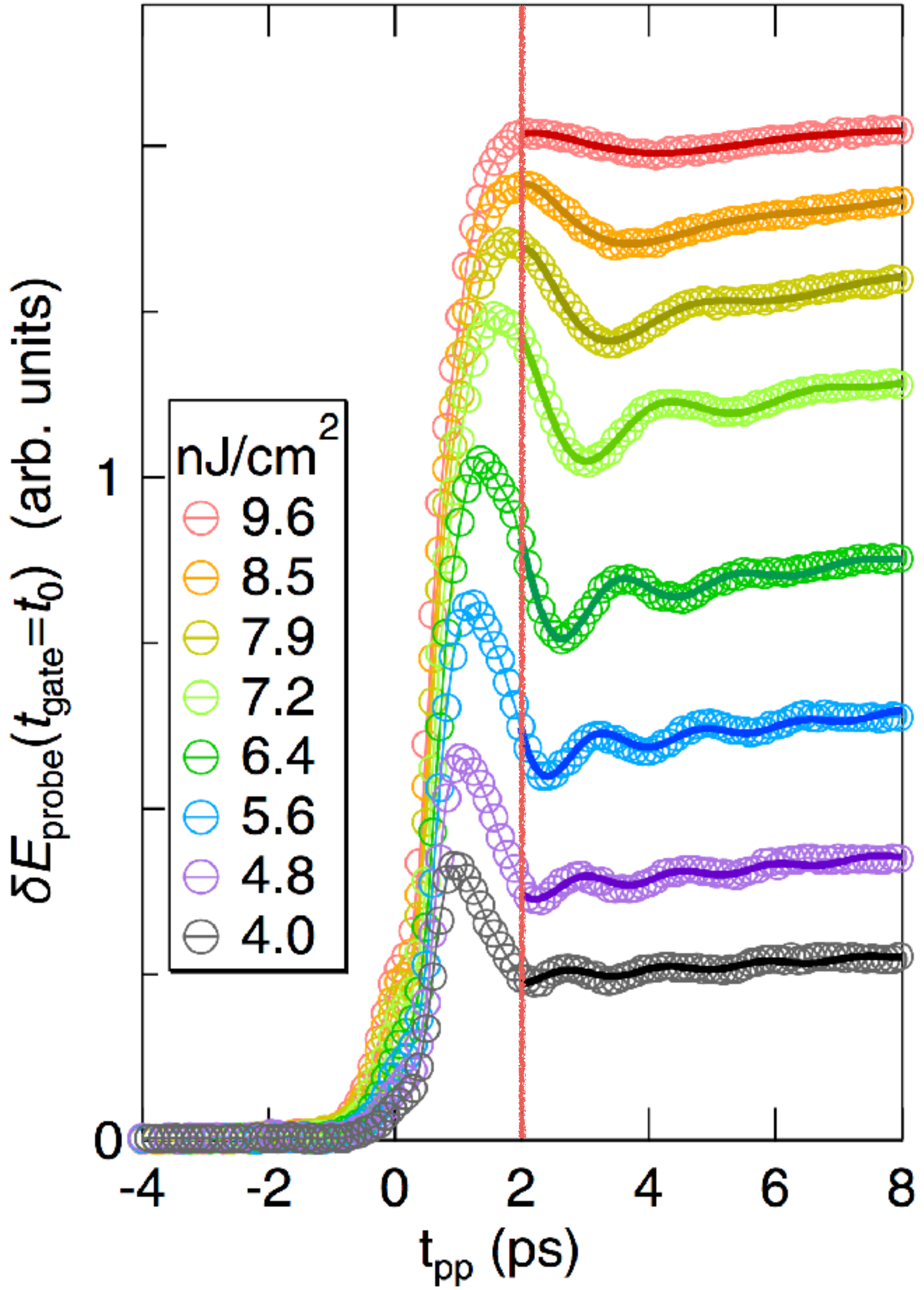


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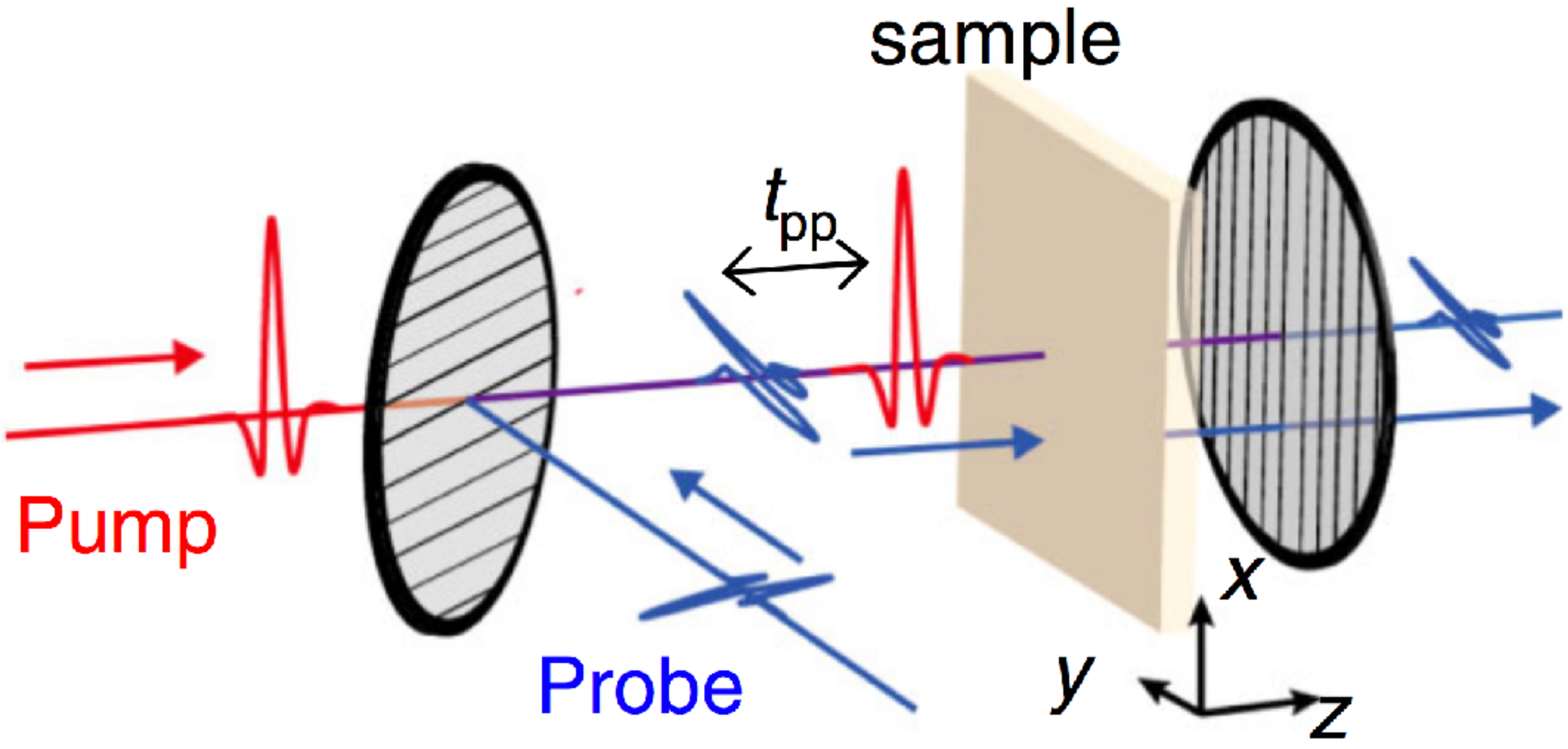
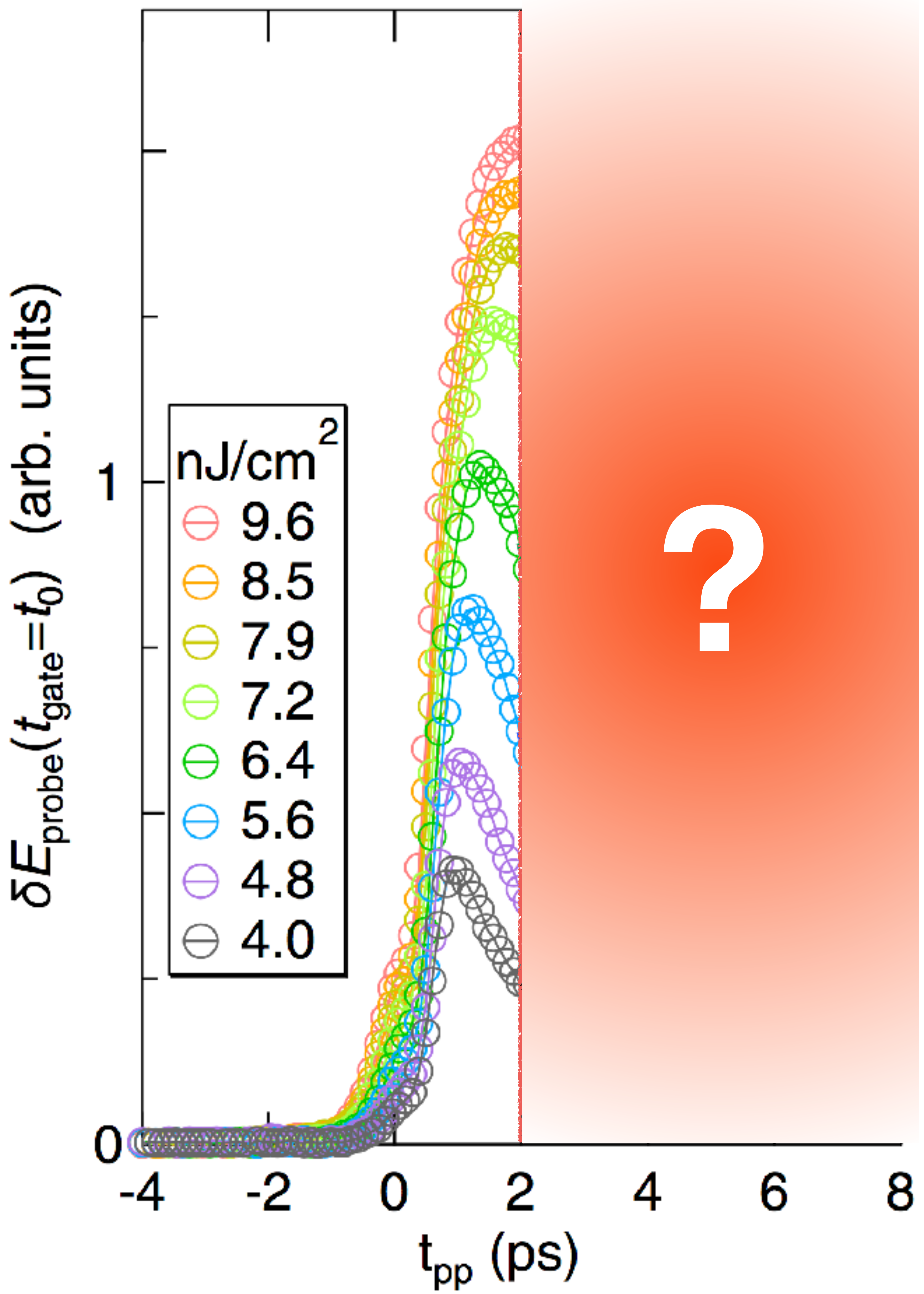
Unconventional Superconductors

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# Outline

- Single-band BCS
- Two-band Superconductors
- Iron-based Superconductors

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## Derive and solve the equations of motion

# BCS model

$$H_{\mathrm{BCS}} = \sum_{\mathbf{k},\sigma} \varepsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k},\sigma} c_{\mathbf{k},\sigma} + U \sum_{\mathbf{k},\mathbf{k}'} c^{\dagger}_{\mathbf{k},\uparrow} c^{\dagger}_{-\mathbf{k},\downarrow} c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow}$$

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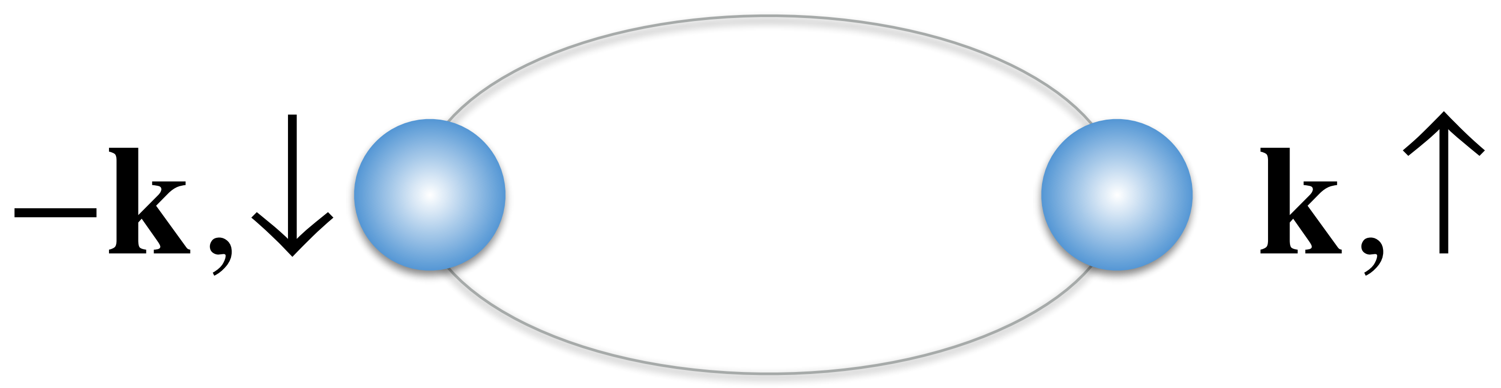

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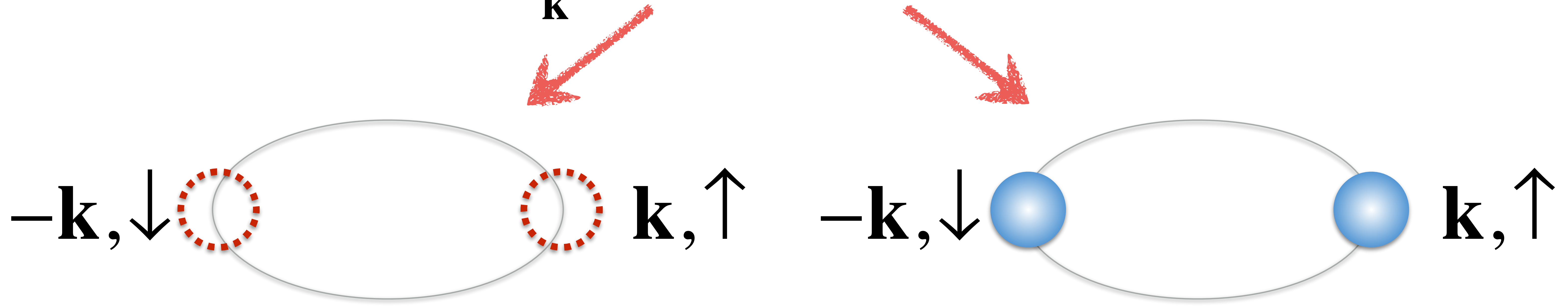

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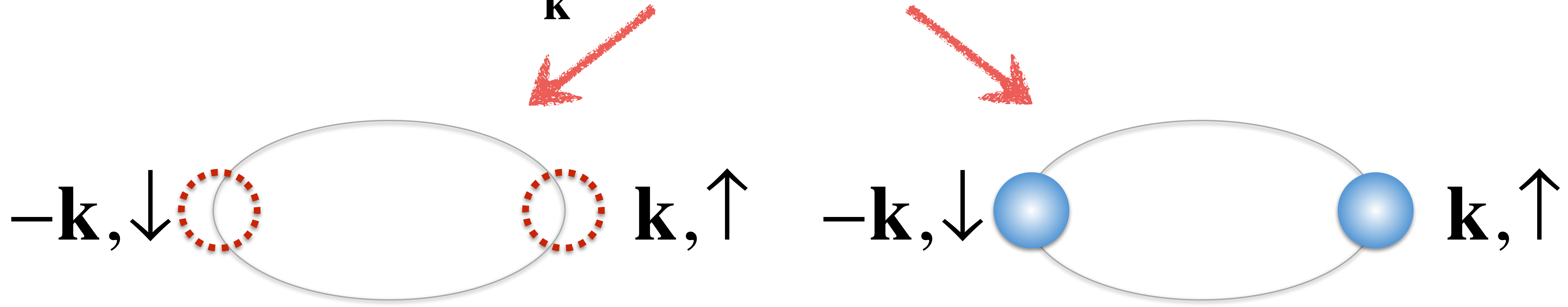


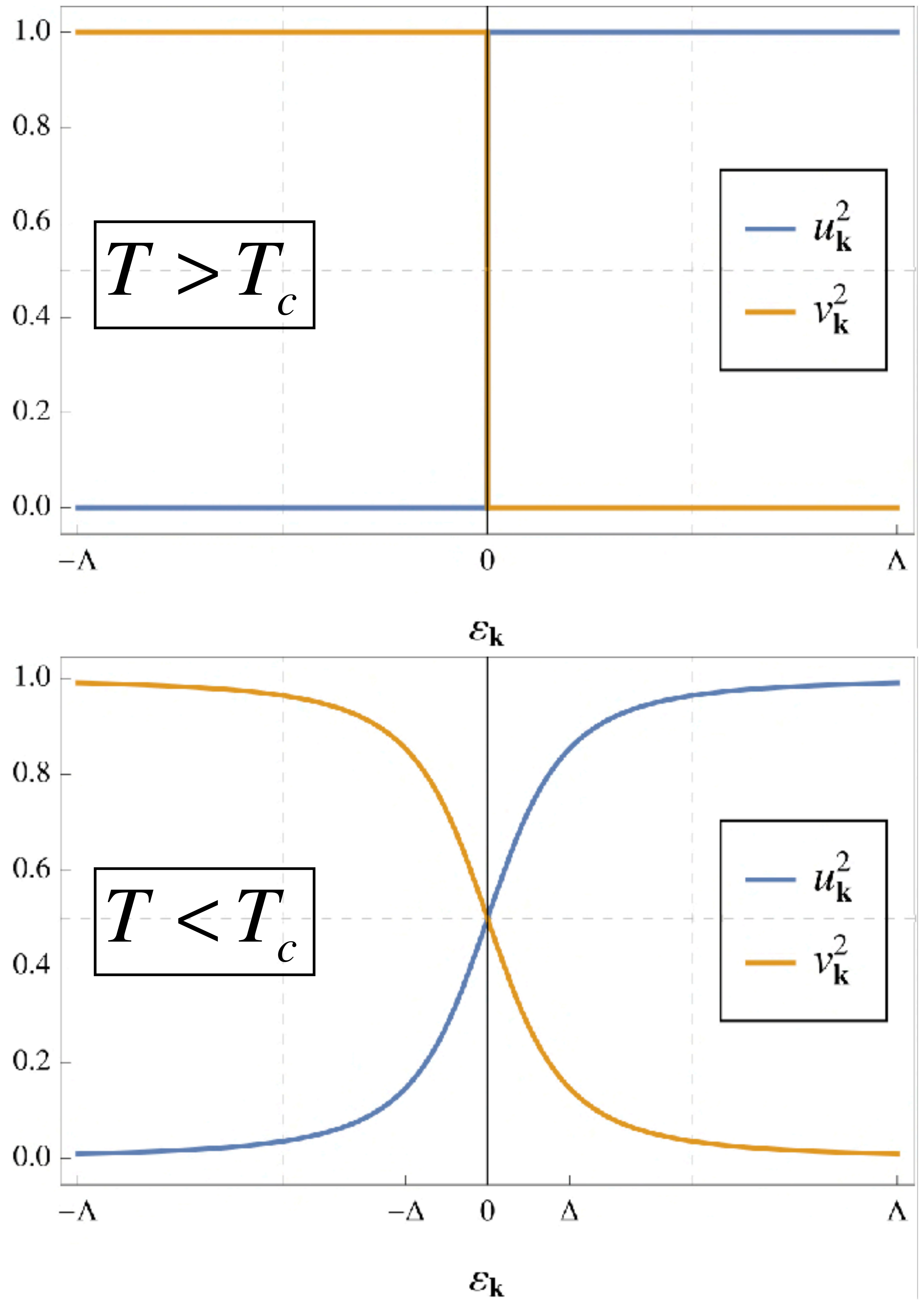

# From particles to pseudo-spins

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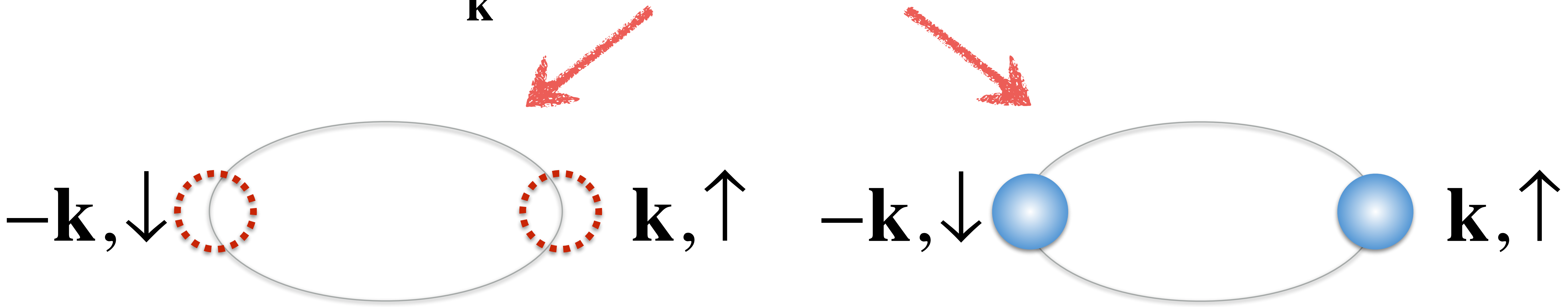

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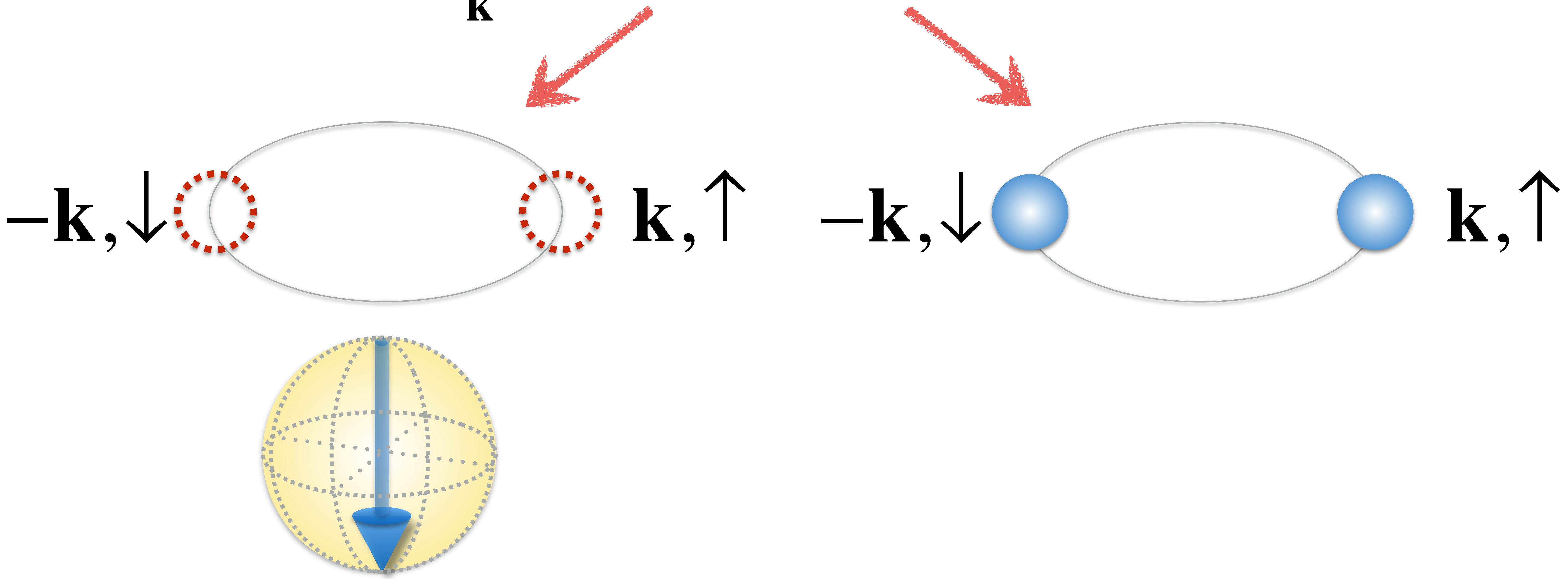

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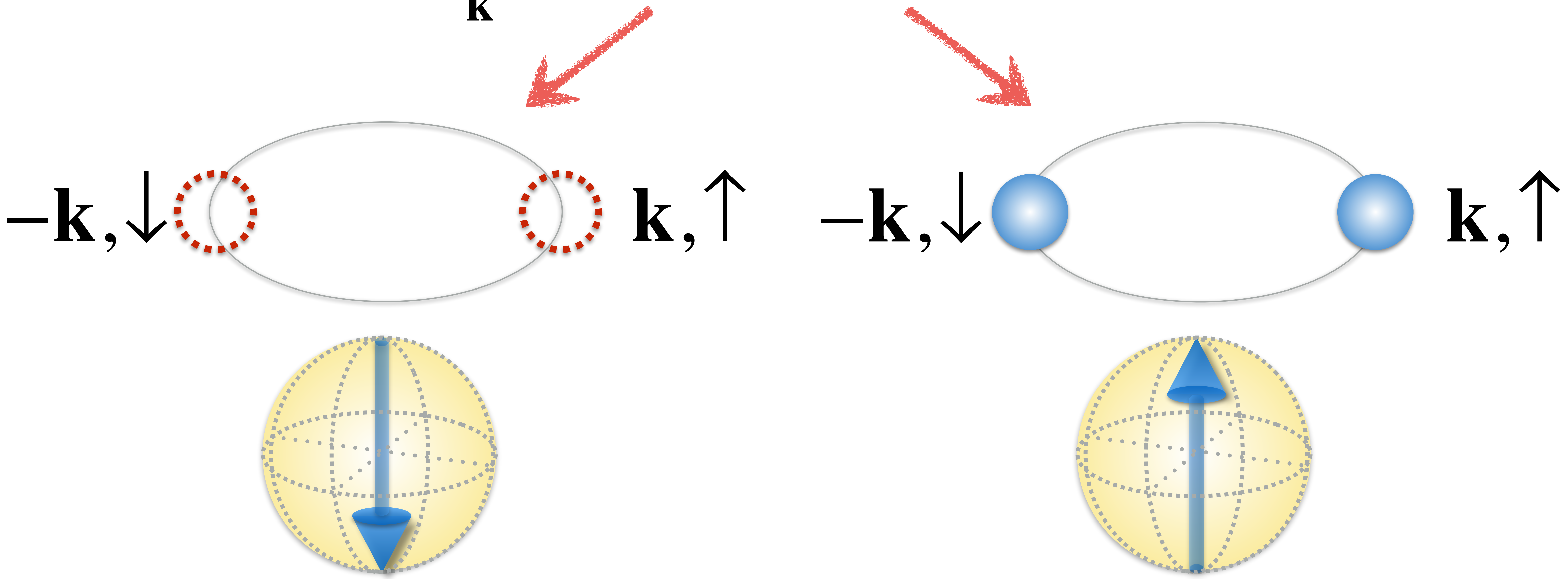

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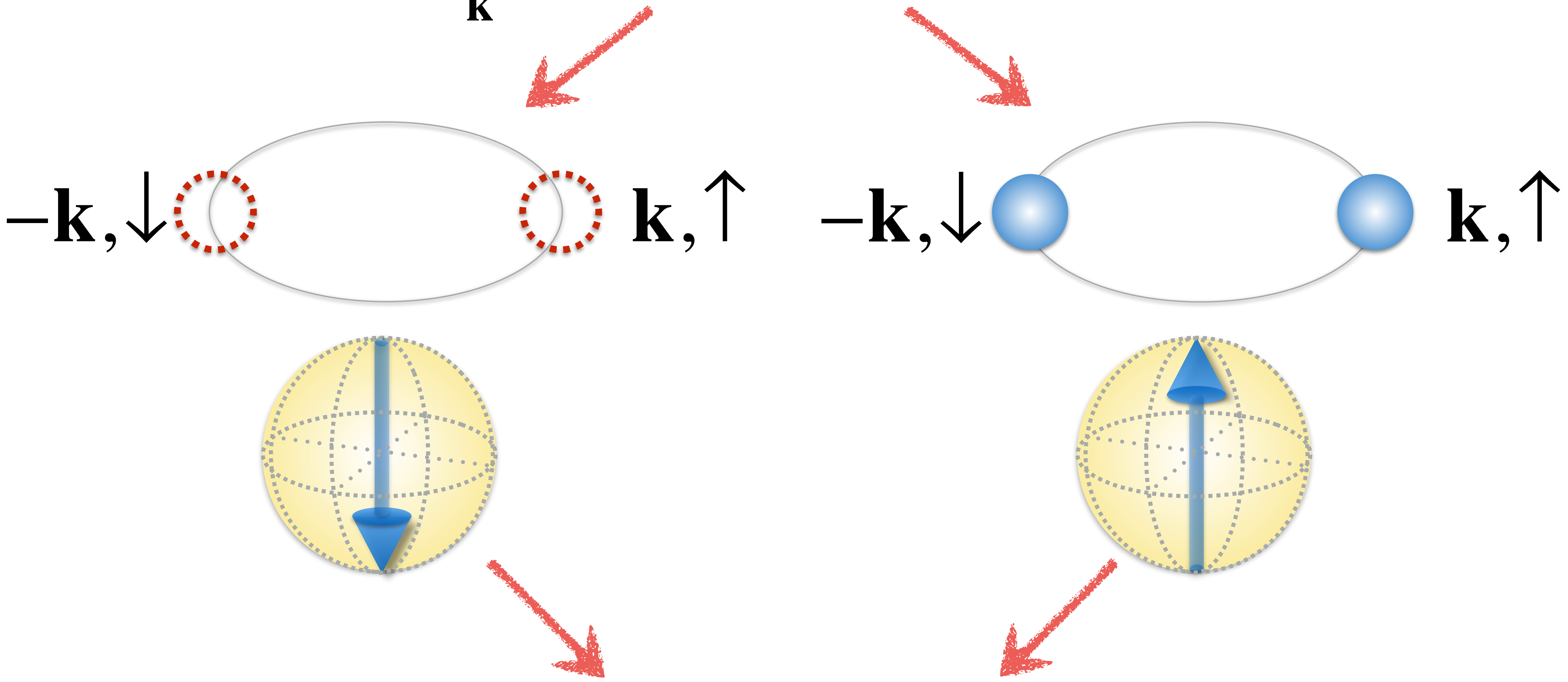

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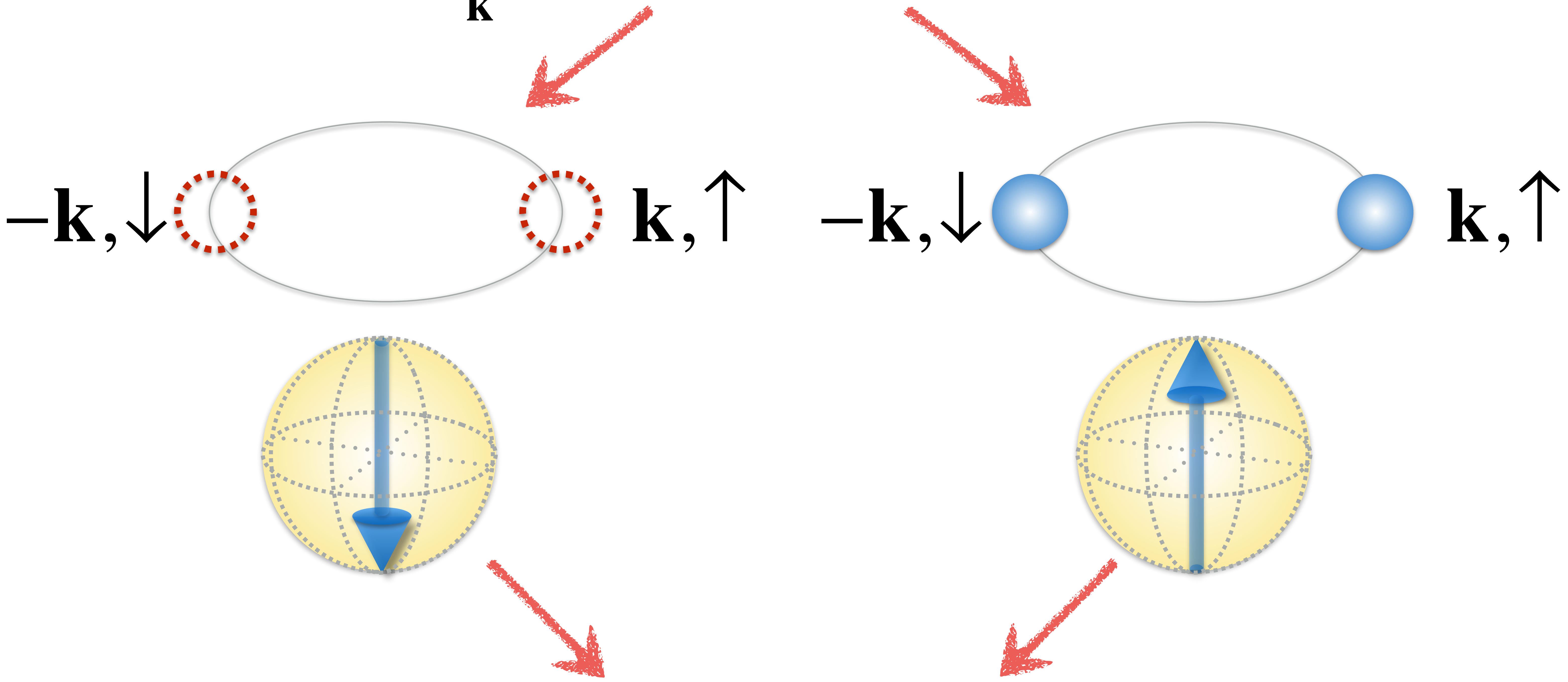
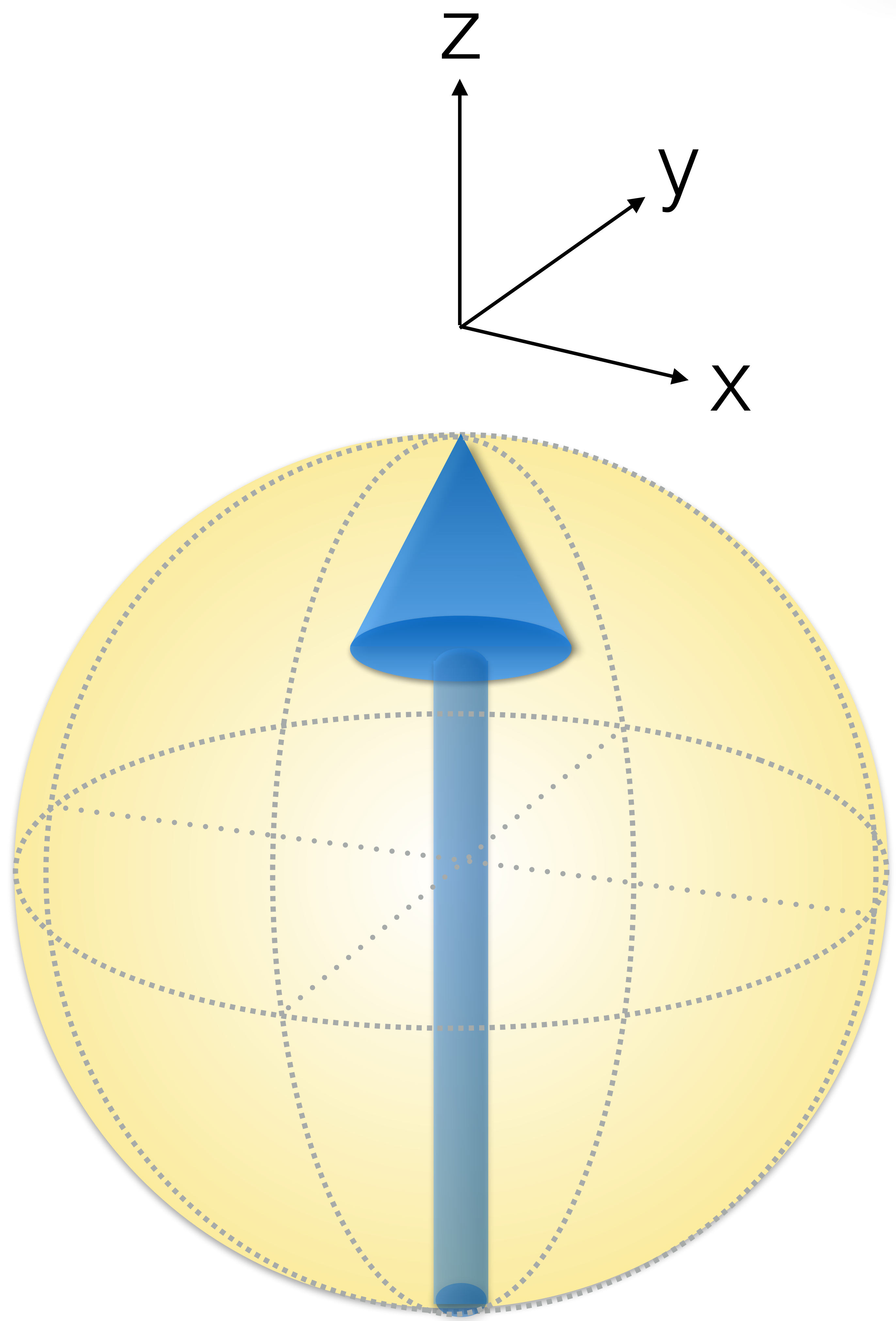



$$\Psi_{\mathrm{BCS}} = \prod_{\mathbf{k}} \left( u_{\mathbf{k}} \left| -\frac{1}{2} \right\rangle_{\mathbf{k}} + v_{\mathbf{k}} \left| \frac{1}{2} \right\rangle_{\mathbf{k}} \right)$$

# Pseudo-spin Formalism




$$\hat{S}^z_{\mathbf{k}} = \frac{1}{2}\left(c^\dagger_{\mathbf{k},\uparrow}c_{\mathbf{k},\uparrow} + c^\dagger_{-\mathbf{k},\downarrow}c_{-\mathbf{k},\downarrow} - 1\right)$$

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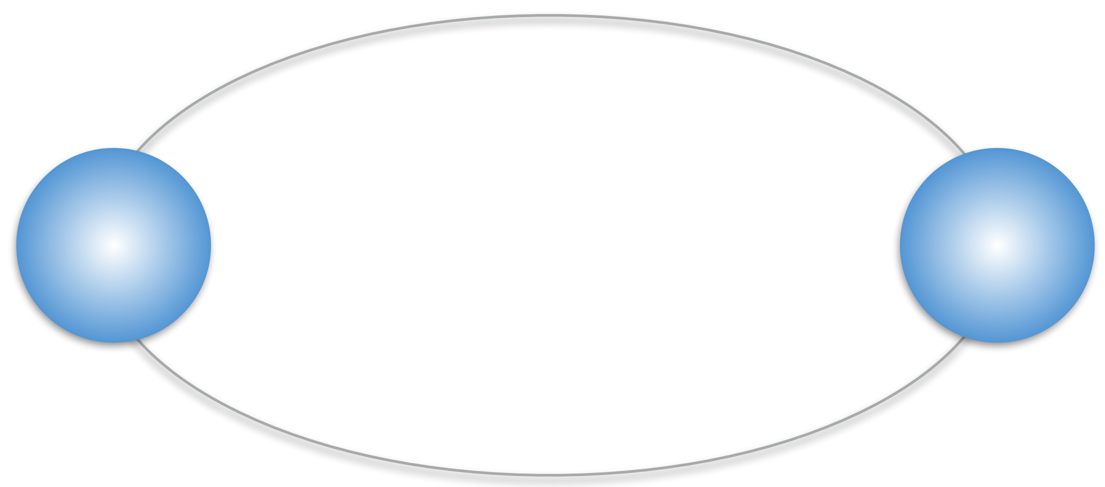

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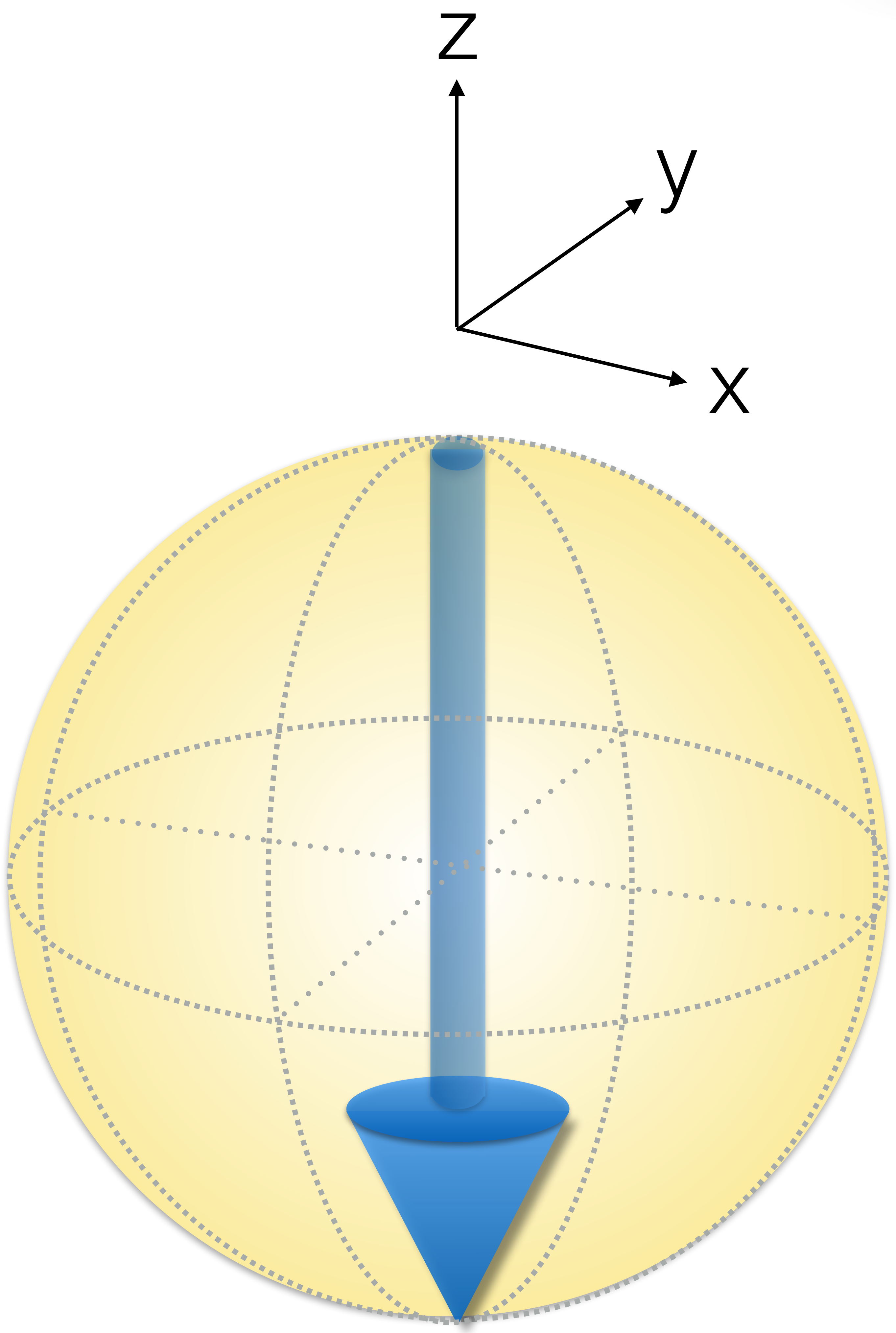


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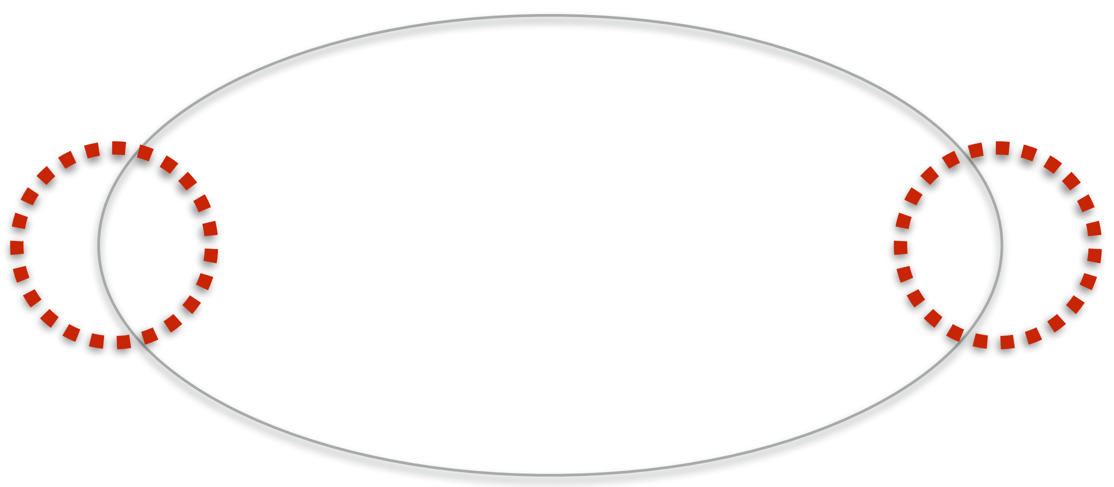

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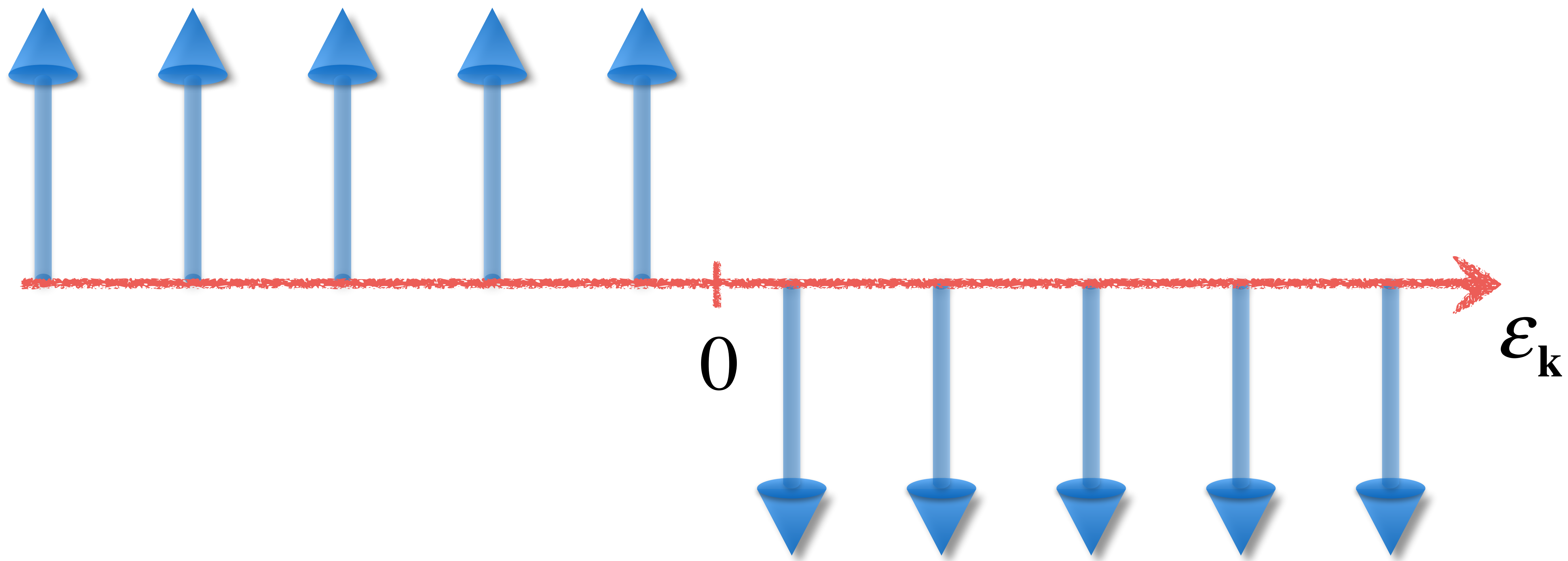

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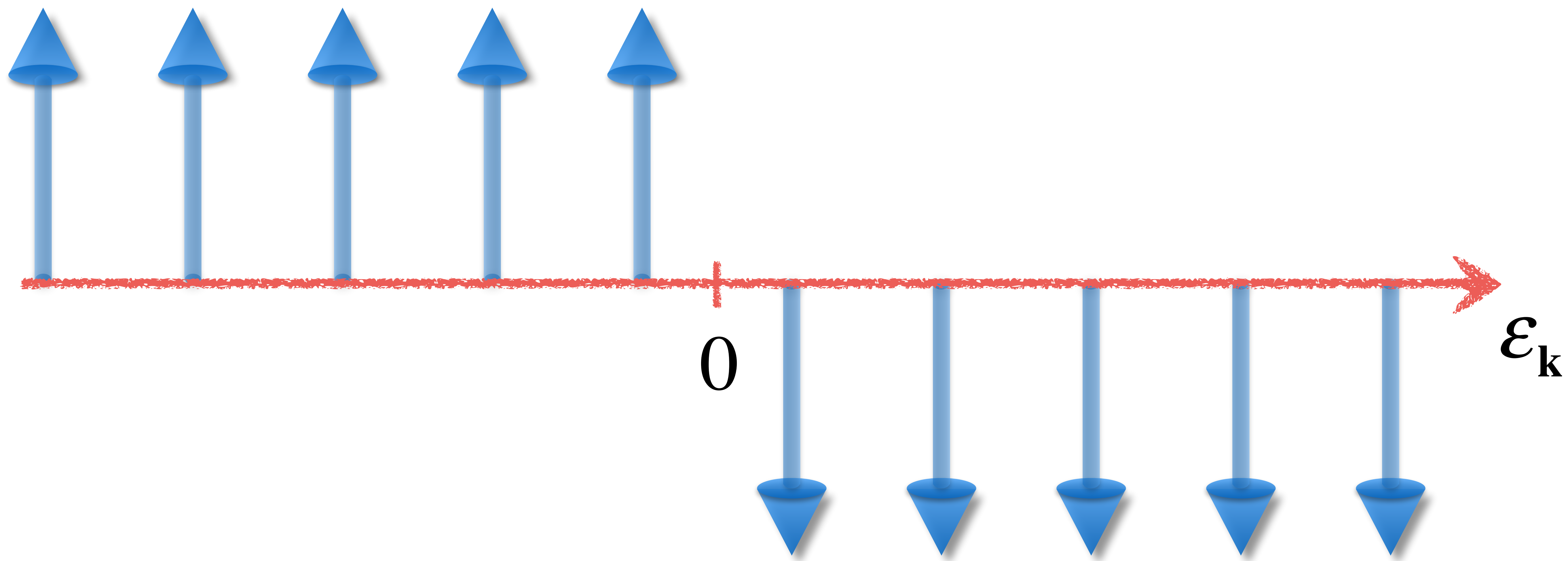



$T < T_c$

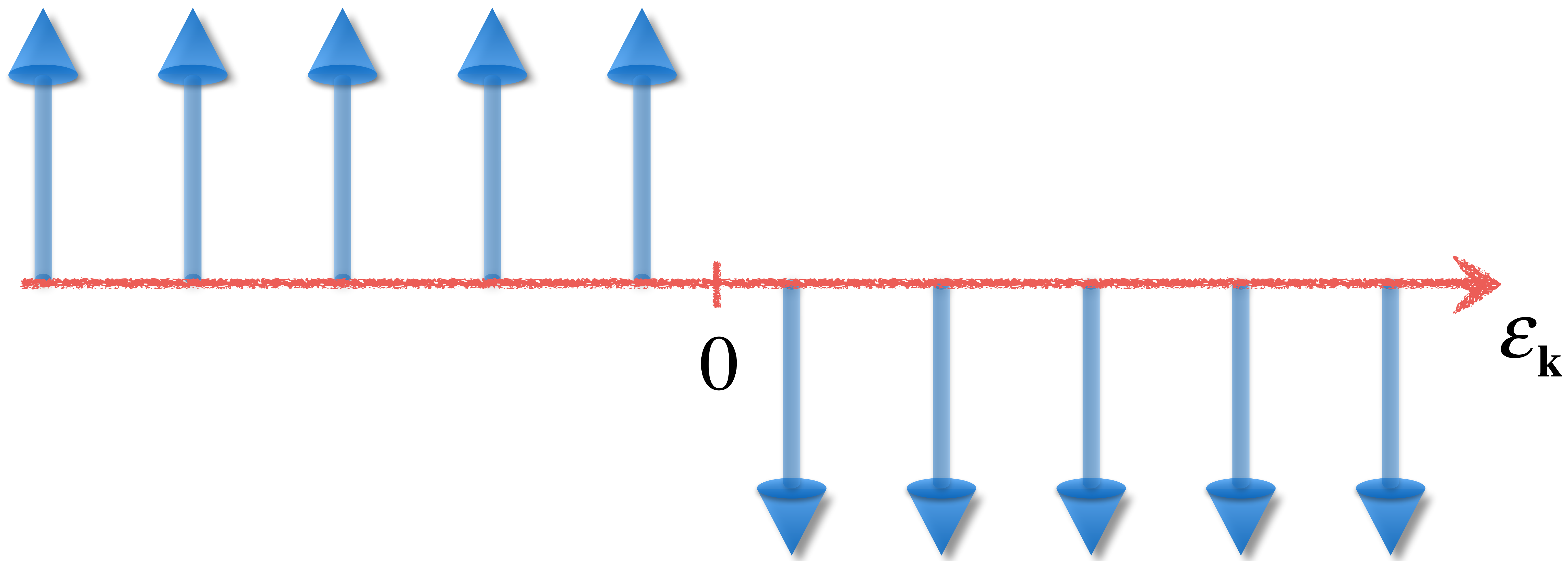
# Ground States

$$H_{\mathrm{BCS}} = -\sum_{\mathbf{k}} \mathbf{B}_{\mathbf{k}} \cdot \hat{\mathbf{S}}_{\mathbf{k}}$$

$$\mathbf{B}_{\mathbf{k}} = \left(-2\mathrm{Re}(\Delta), -2\mathrm{Im}(\Delta), -2\varepsilon_{\mathbf{k}}\right)$$

$T > T_c$

$$\mathbf{B}_{\mathbf{k}} = \left(0, 0, -2\varepsilon_{\mathbf{k}}\right)$$




$T < T_c$

$$\mathbf{B}_{\mathbf{k}} = \left(-2\Delta, 0, -2\varepsilon_{\mathbf{k}}\right)$$

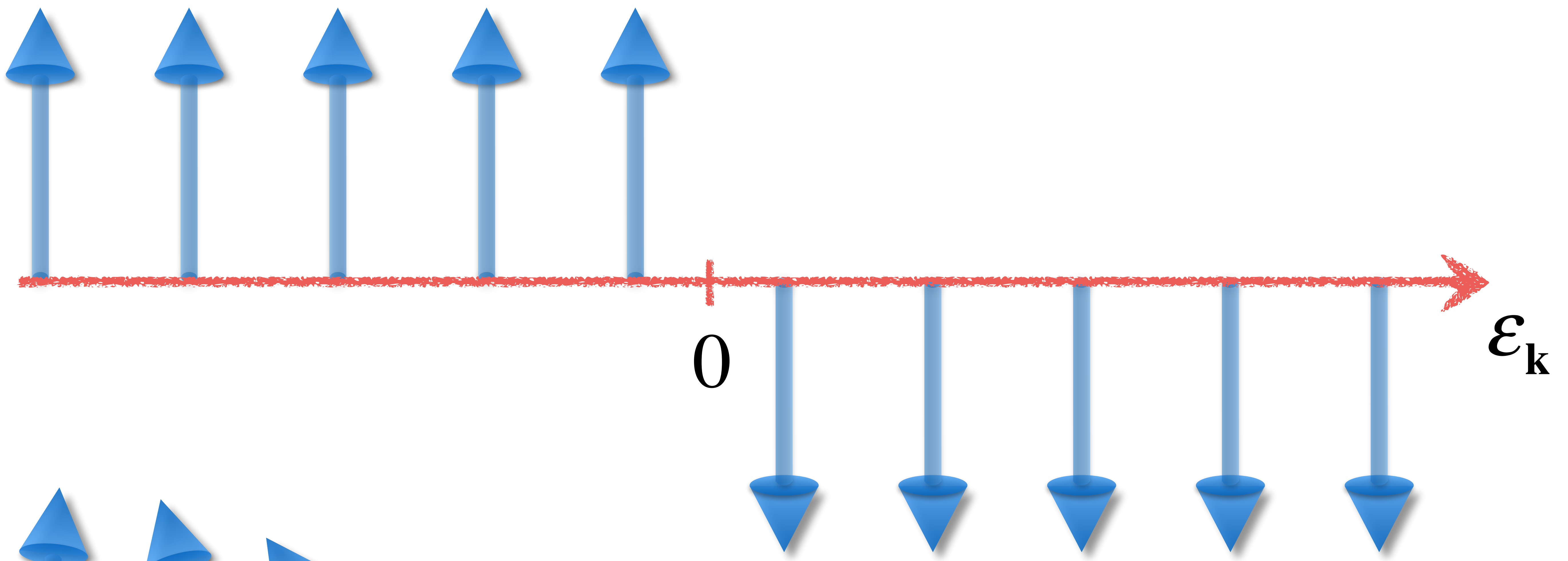
# Ground States

$$\boxed{H_{\mathrm{BCS}} = -\sum_{\mathbf{k}} \mathbf{B}_{\mathbf{k}} \cdot \hat{\mathbf{S}}_{\mathbf{k}}}$$

$$\boxed{\mathbf{B}_{\mathbf{k}} = \left(-2\mathrm{Re}(\Delta), -2\mathrm{Im}(\Delta), -2\varepsilon_{\mathbf{k}}\right)}$$

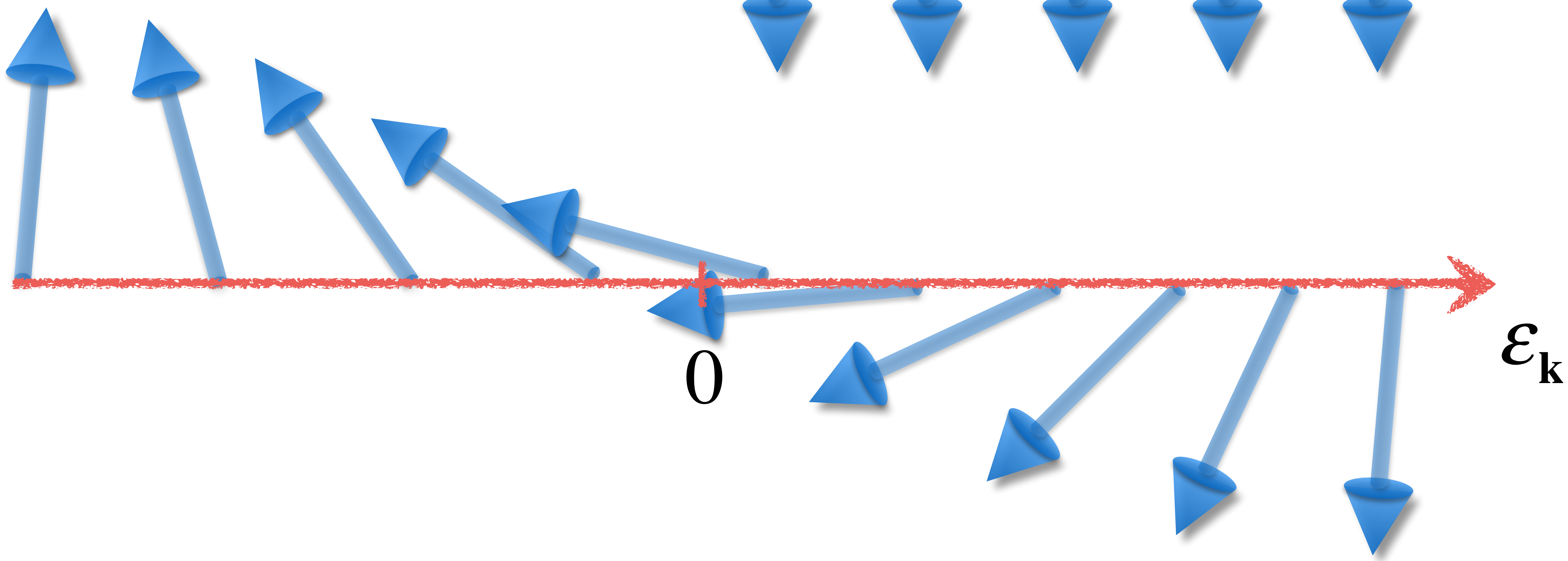
$T > T_c$

$$\mathbf{B}_{\mathbf{k}} = \left(0, 0, -2\varepsilon_{\mathbf{k}}\right)$$



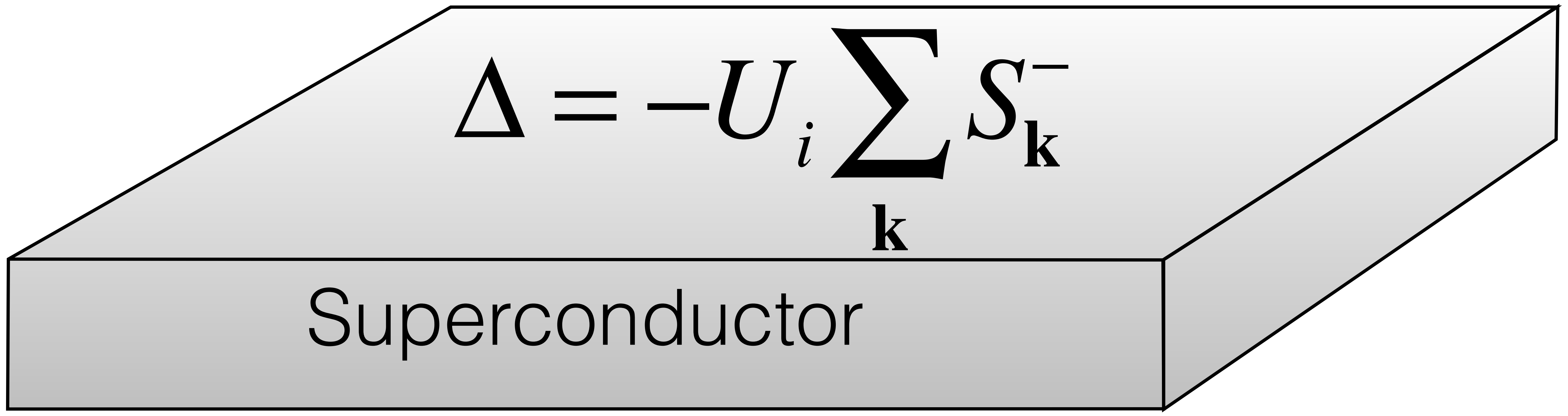

$T < T_c$

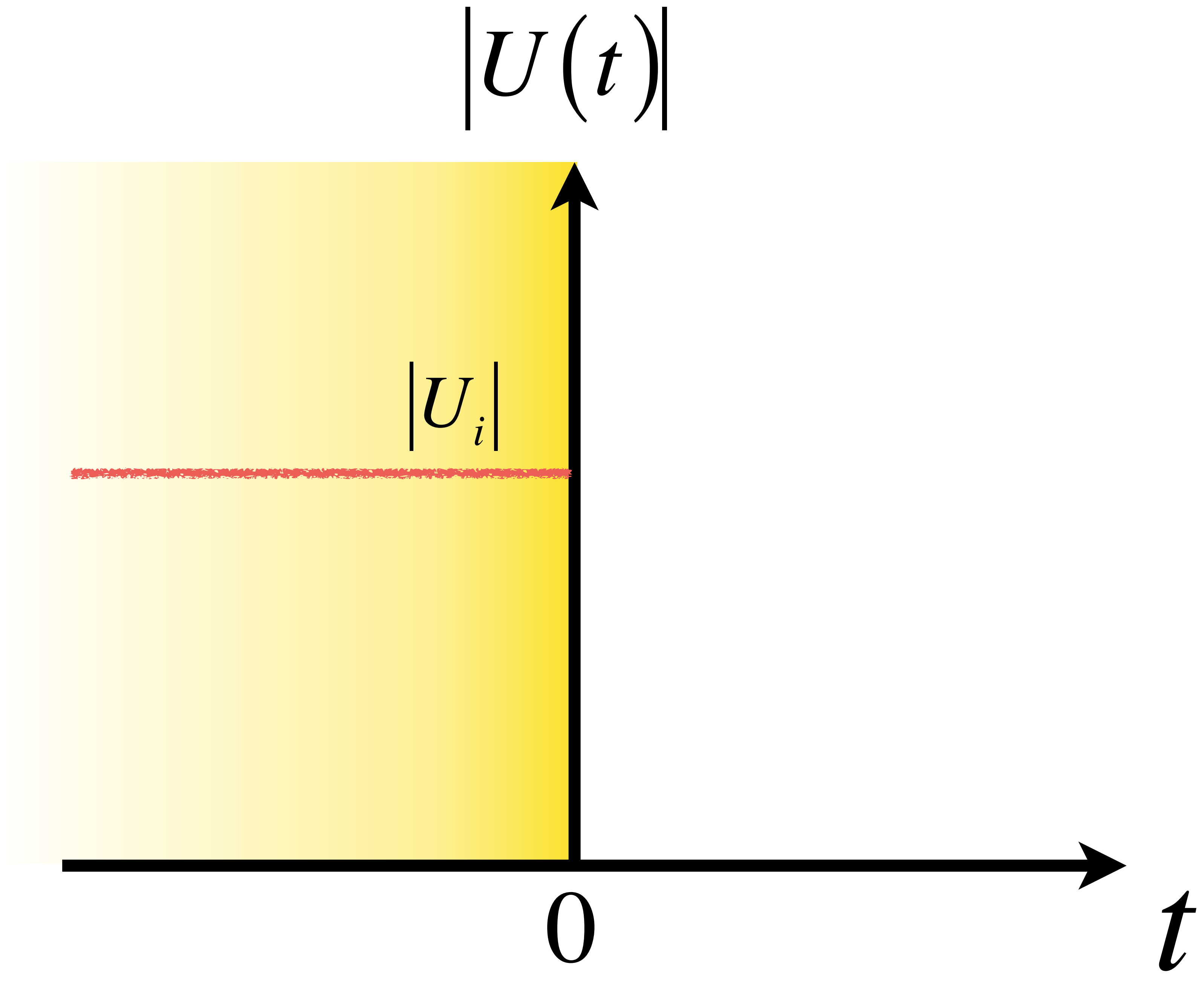
$$\mathbf{B}_{\mathbf{k}} = \left(-2\Delta, 0, -2\varepsilon_{\mathbf{k}}\right)$$



# Quench

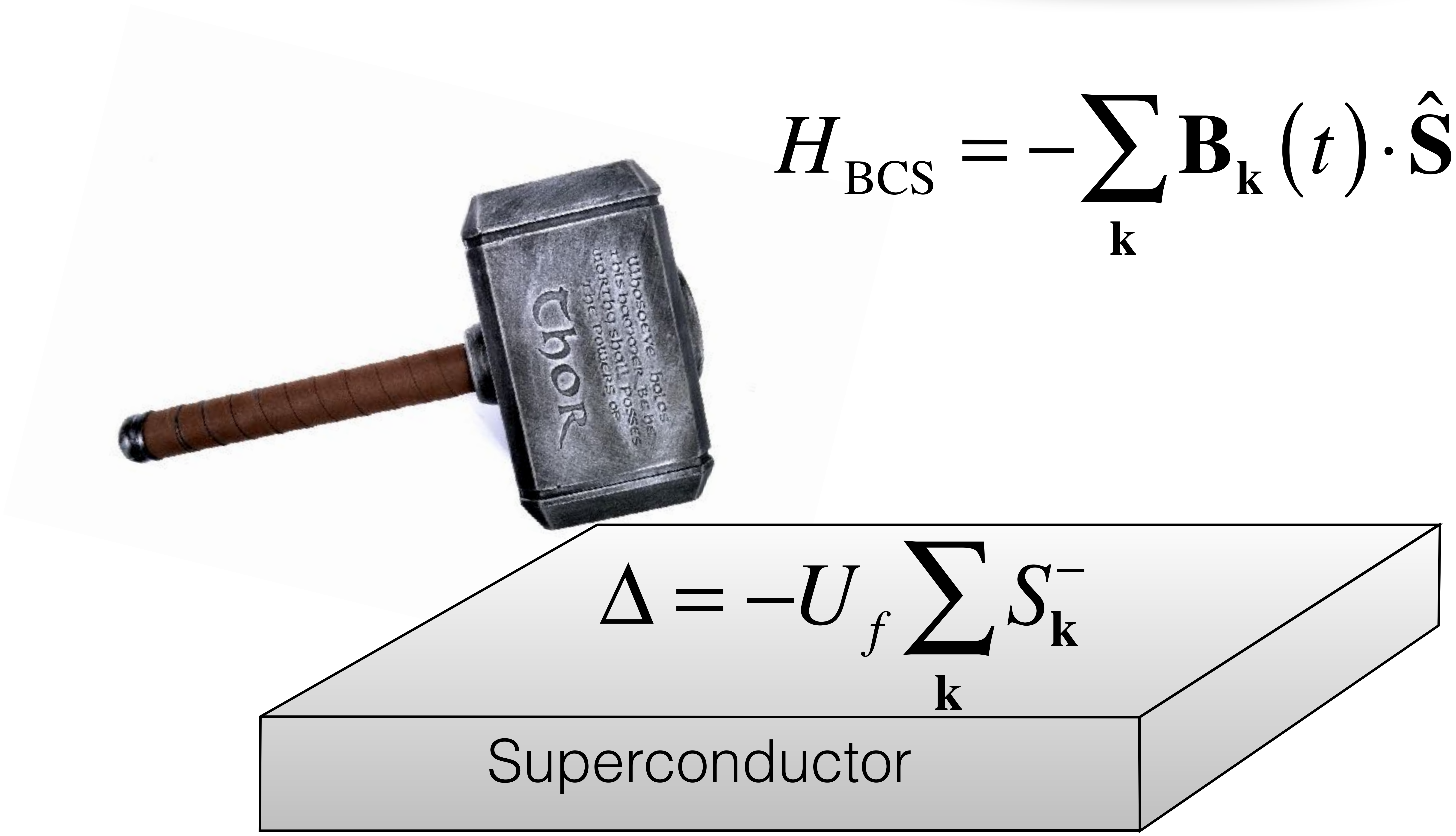
$$H_{\mathrm{BCS}} = -\sum_{\mathbf{k}} \mathbf{B}_{\mathbf{k}}\left(0^-\right)\cdot\hat{\mathbf{S}}_{\mathbf{k}}\left(0^-\right)$$

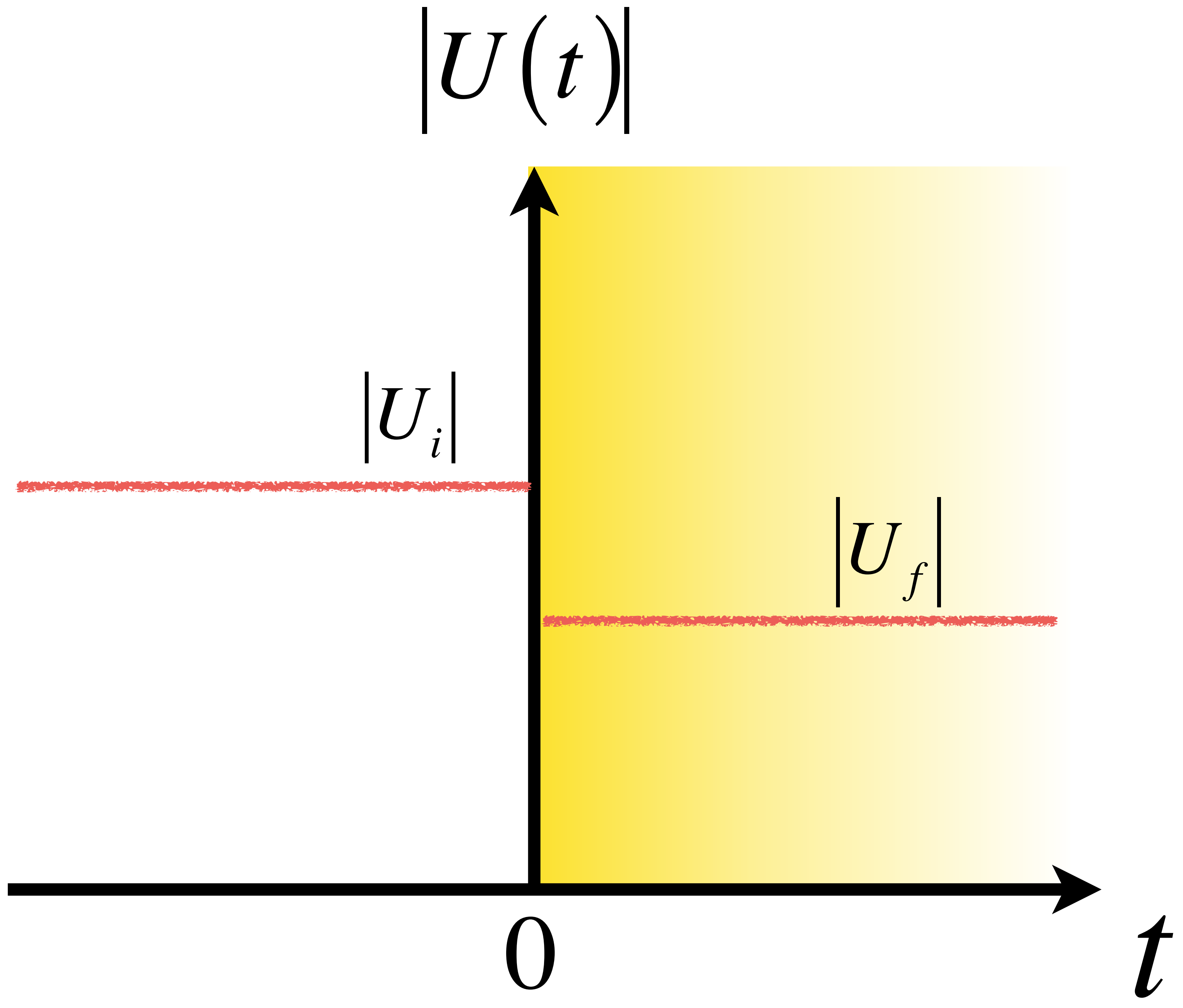


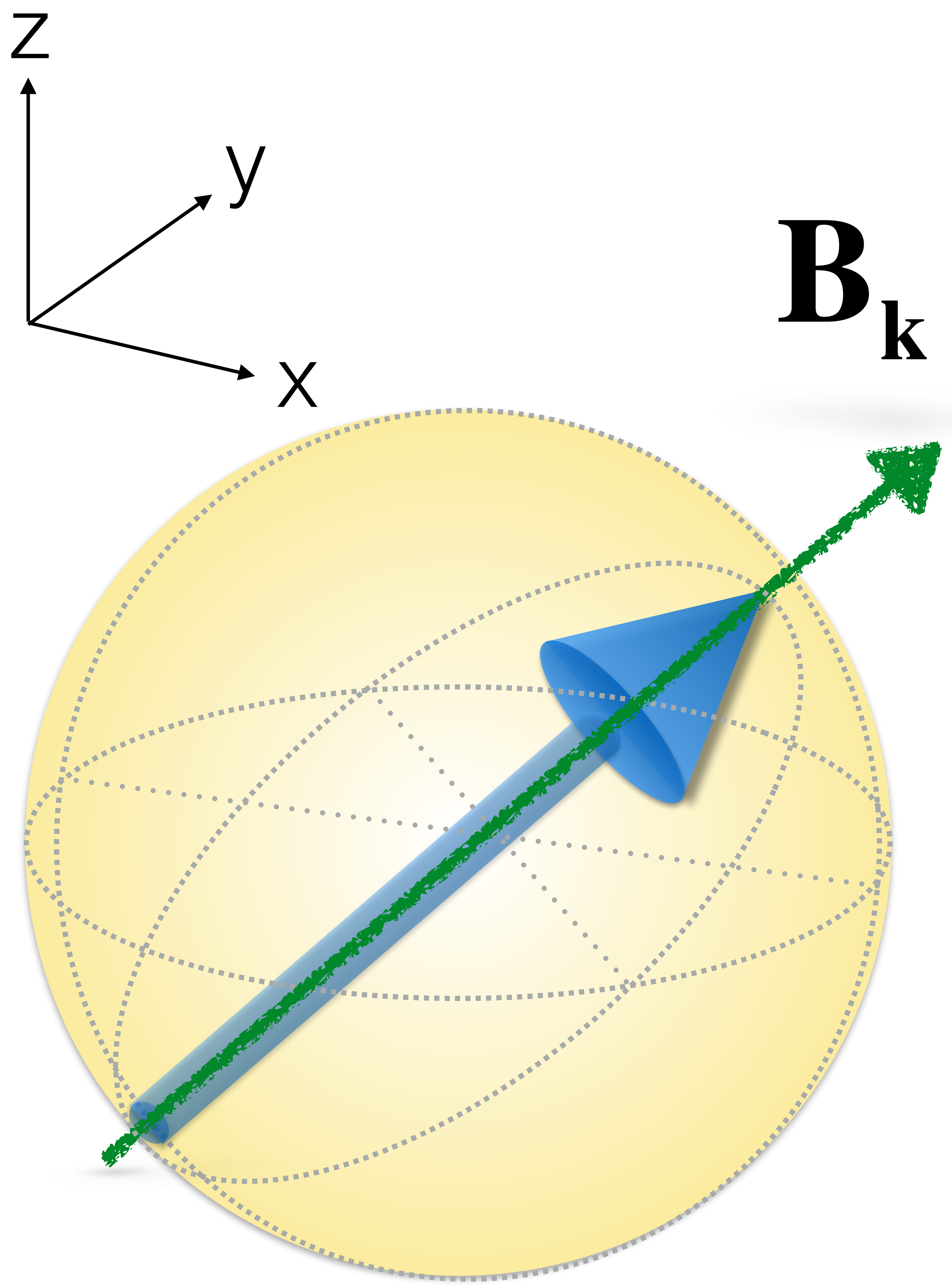
# Quench

$$H_{\mathrm{BCS}} = -\sum_{\mathbf{k}} \mathbf{B}_{\mathbf{k}}(t) \cdot \hat{\mathbf{S}}_{\mathbf{k}}(t)$$



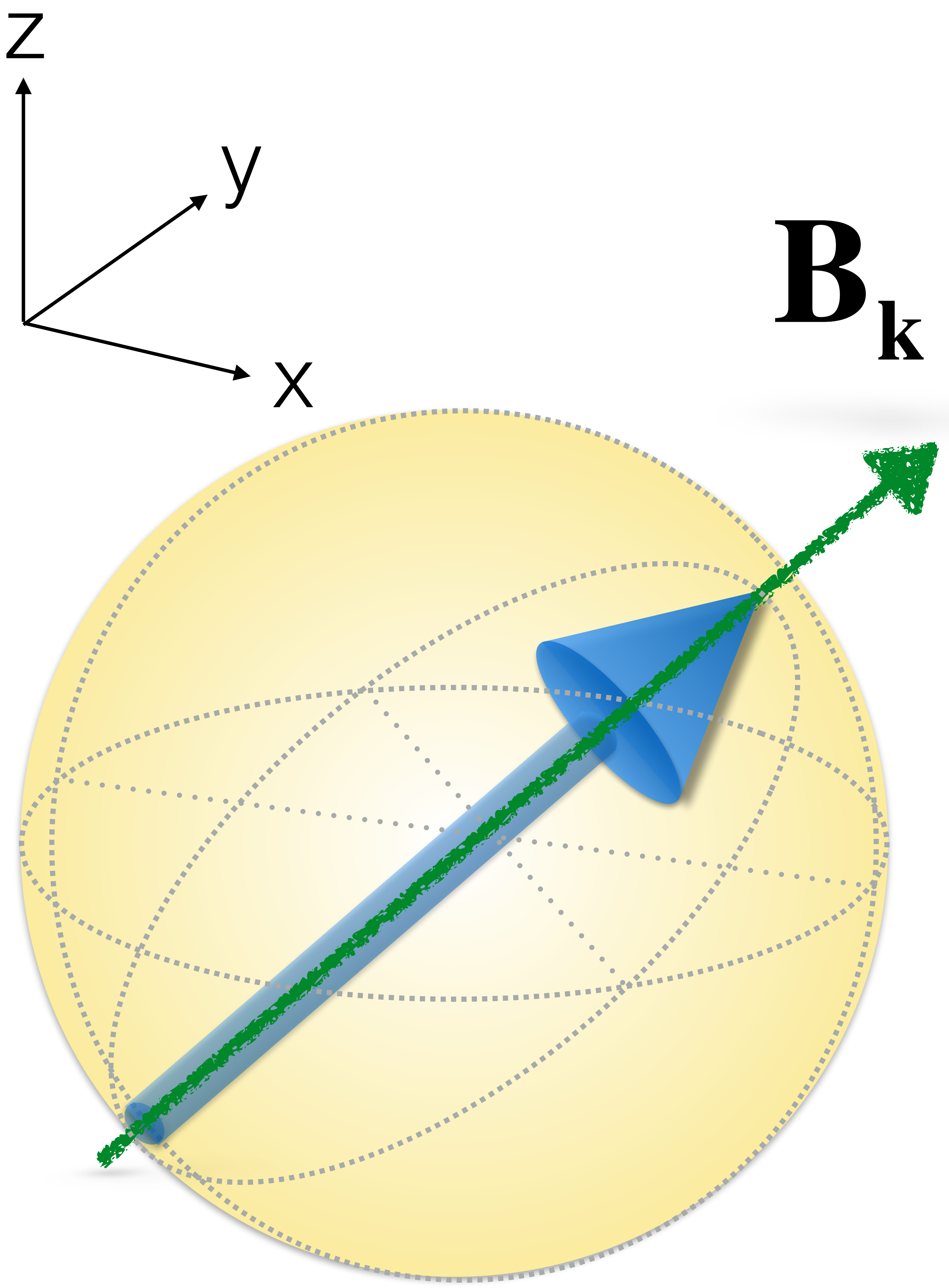



# Quench Dynamics




$$\mathbf{B_k} \parallel \mathbf{S_k}$$

# Quench Dynamics




$$\mathbf{B}_{\mathbf{k}} \parallel \mathbf{S}_{\mathbf{k}}$$

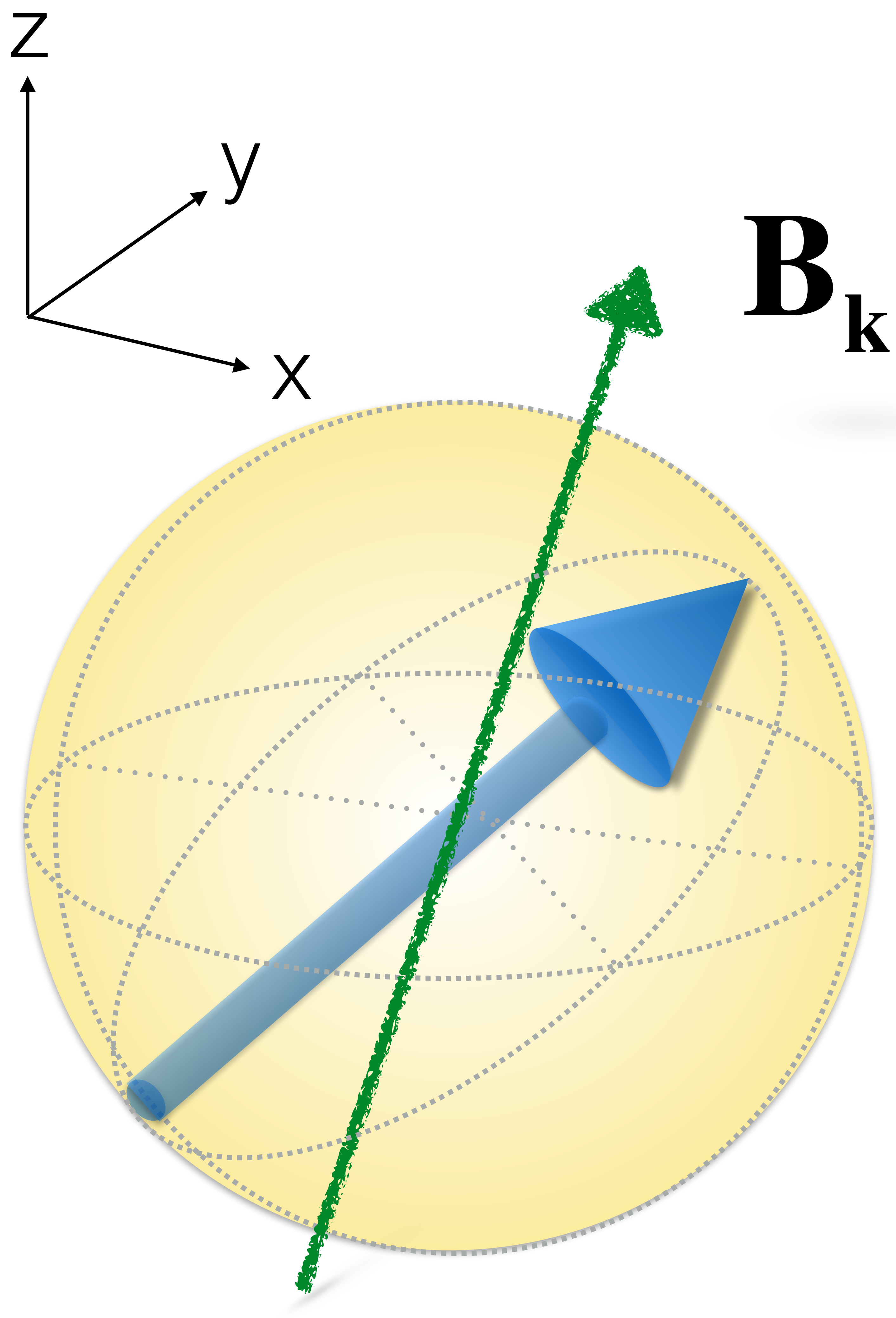
## Initial conditions:

$$S_{\mathbf{k}}^{x}\left(0^{-}\right)=\frac{\Delta_{i}}{2\sqrt{\varepsilon_{\mathbf{k}}^{2}+\Delta_{i}^{2}}}$$

$$S_{\mathbf{k}}^{y}\left(0^{-}\right)=0$$

$$S_{\mathbf{k}}^{z}\left(0^{-}\right)=\frac{\varepsilon_{\mathbf{k}}}{2\sqrt{\varepsilon_{\mathbf{k}}^{2}+\Delta_{i}^{2}}}$$

# Quench Dynamics




$$\mathbf{B}_\mathbf{k} \nparallel \mathbf{S}_\mathbf{k}$$

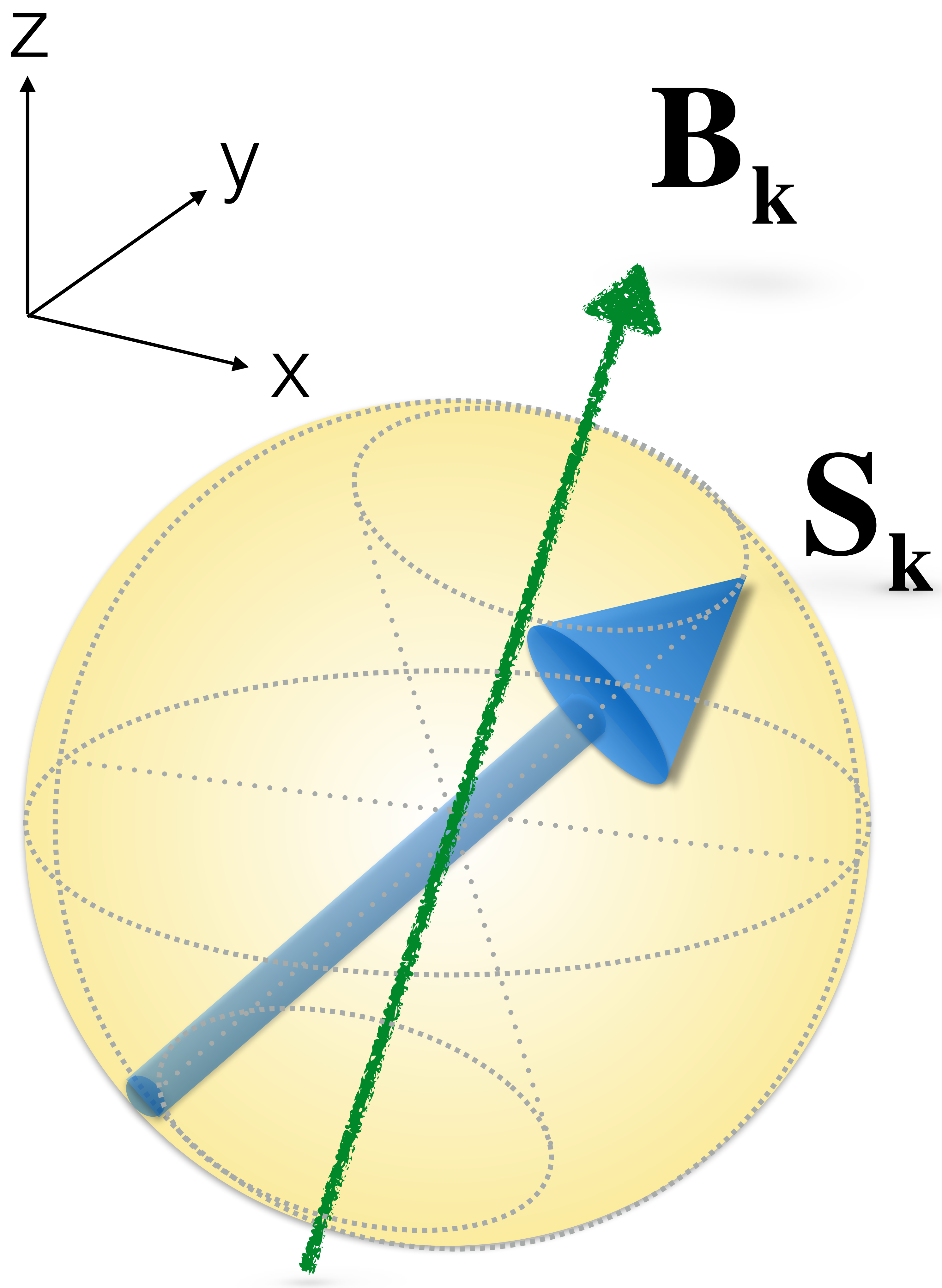
## Initial conditions:

$$S^x_\mathbf{k}\left(0^-\right) = \frac{\Delta_i}{2\sqrt{\varepsilon_\mathbf{k}^2 + \Delta_i^2}}$$

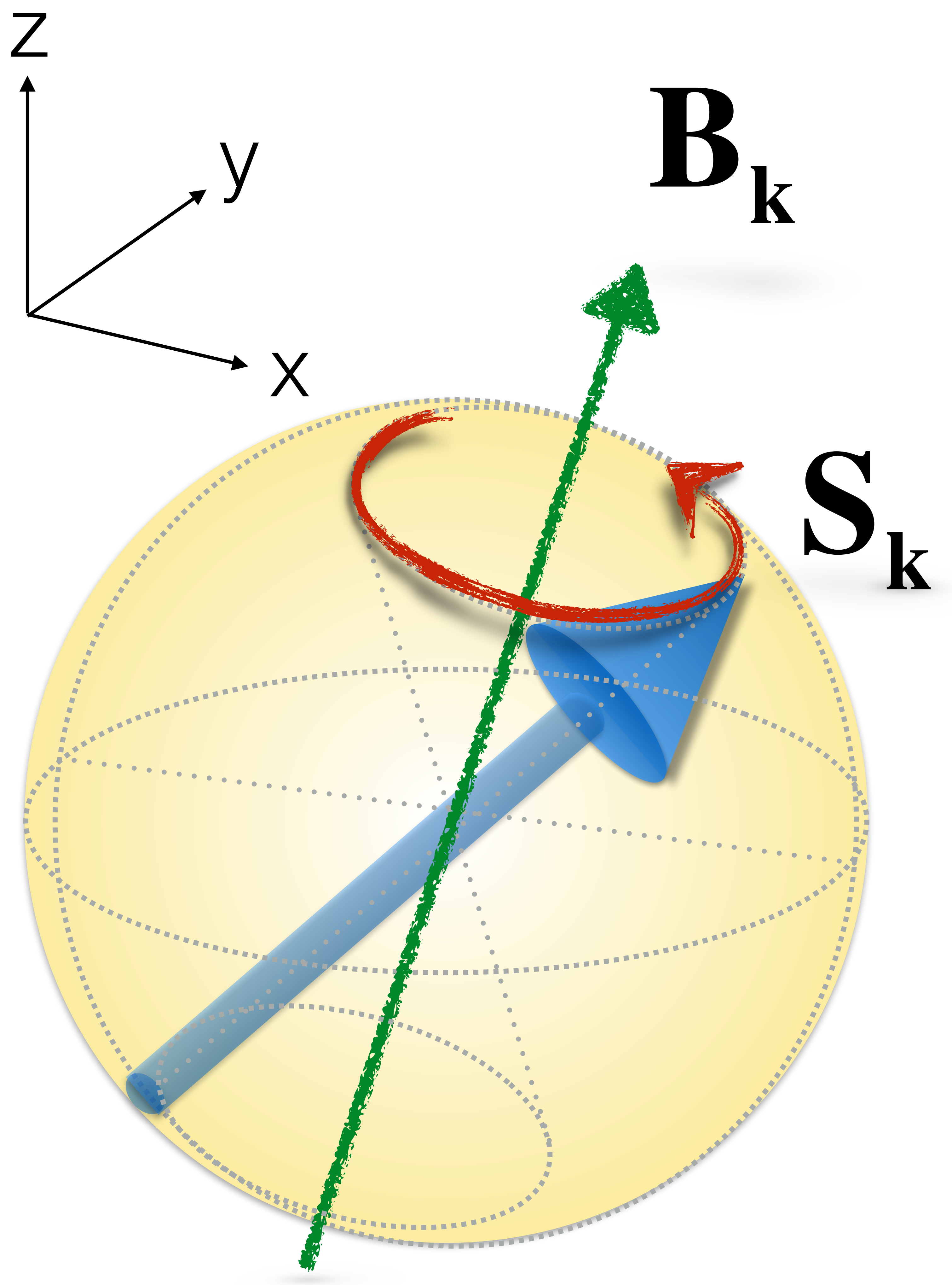
$$S^y_\mathbf{k}\left(0^-\right) = 0$$

$$S^z_\mathbf{k}\left(0^-\right) = \frac{\varepsilon_\mathbf{k}}{2\sqrt{\varepsilon_\mathbf{k}^2 + \Delta_i^2}}$$

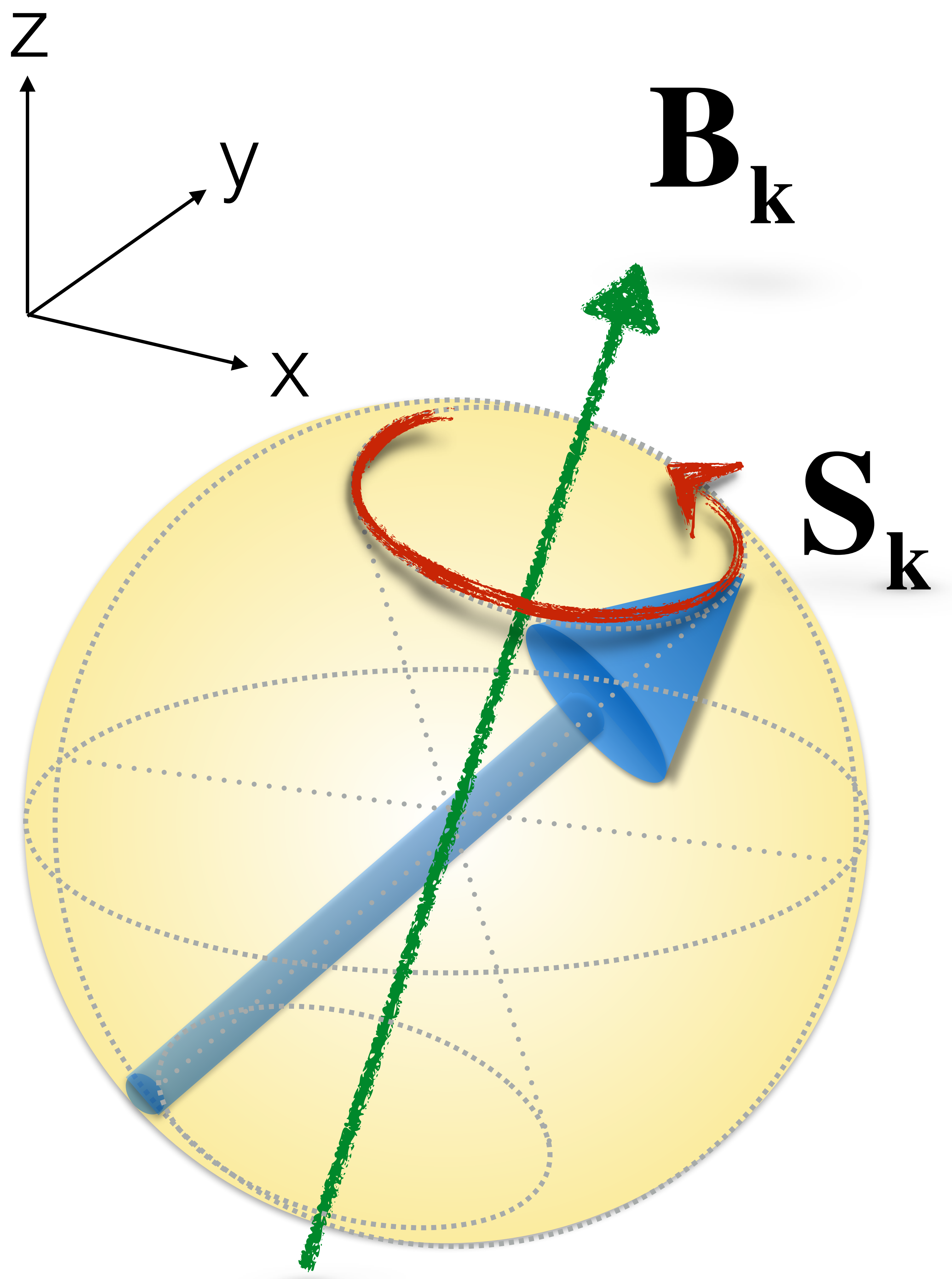
# Quench Dynamics



# Quench Dynamics



# Quench Dynamics

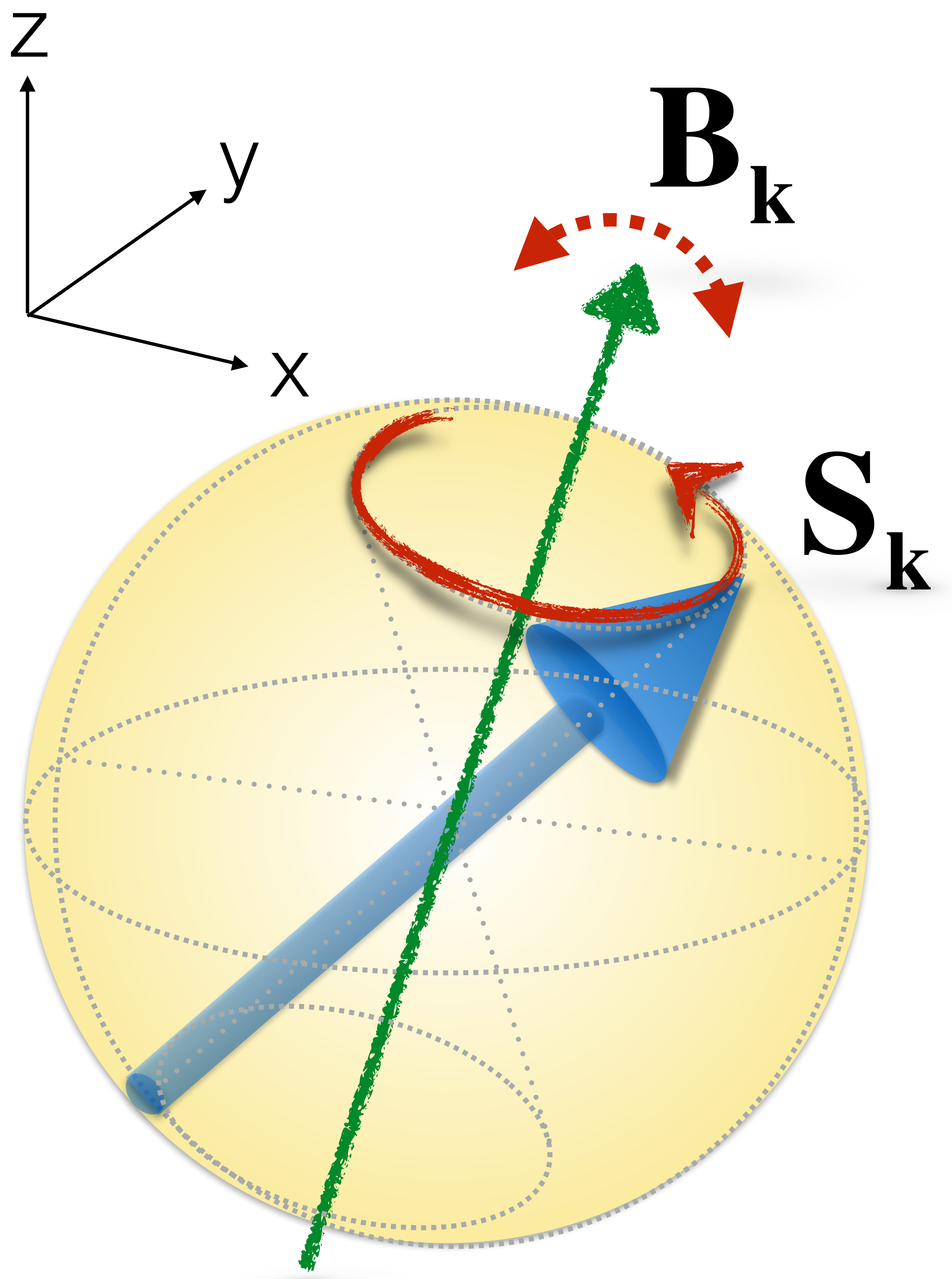



## Equations of motion:

$$\frac{d}{dt}\mathbf{S}_\mathbf{k} = -i\left\langle \left[ H_{\mathrm{BCS}}, \hat{\mathbf{S}}_\mathbf{k} \right] \right\rangle = \mathbf{B}_\mathbf{k} \times \mathbf{S}_\mathbf{k}$$

$$\Delta(t) = -U_f \sum_\mathbf{k} S_\mathbf{k}^-$$

# Quench Dynamics

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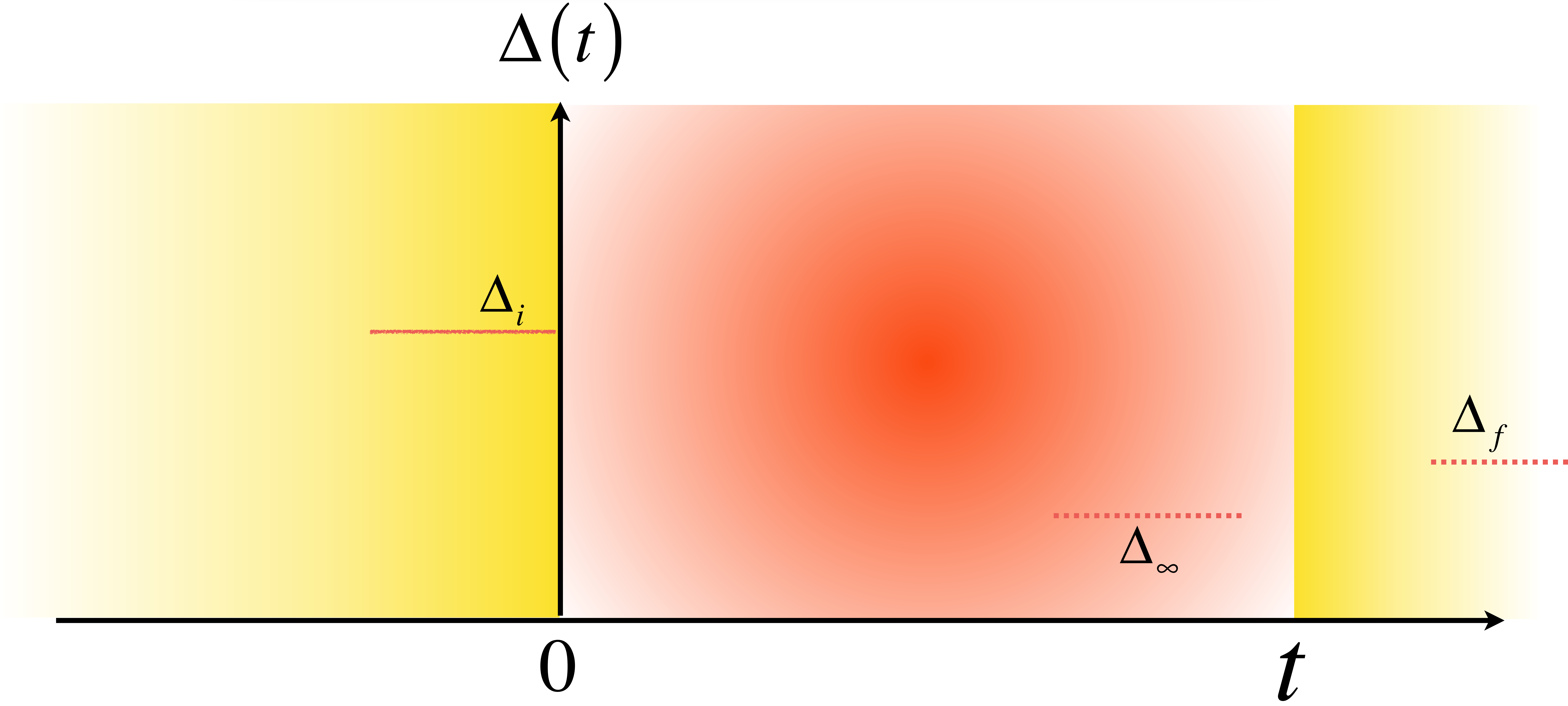
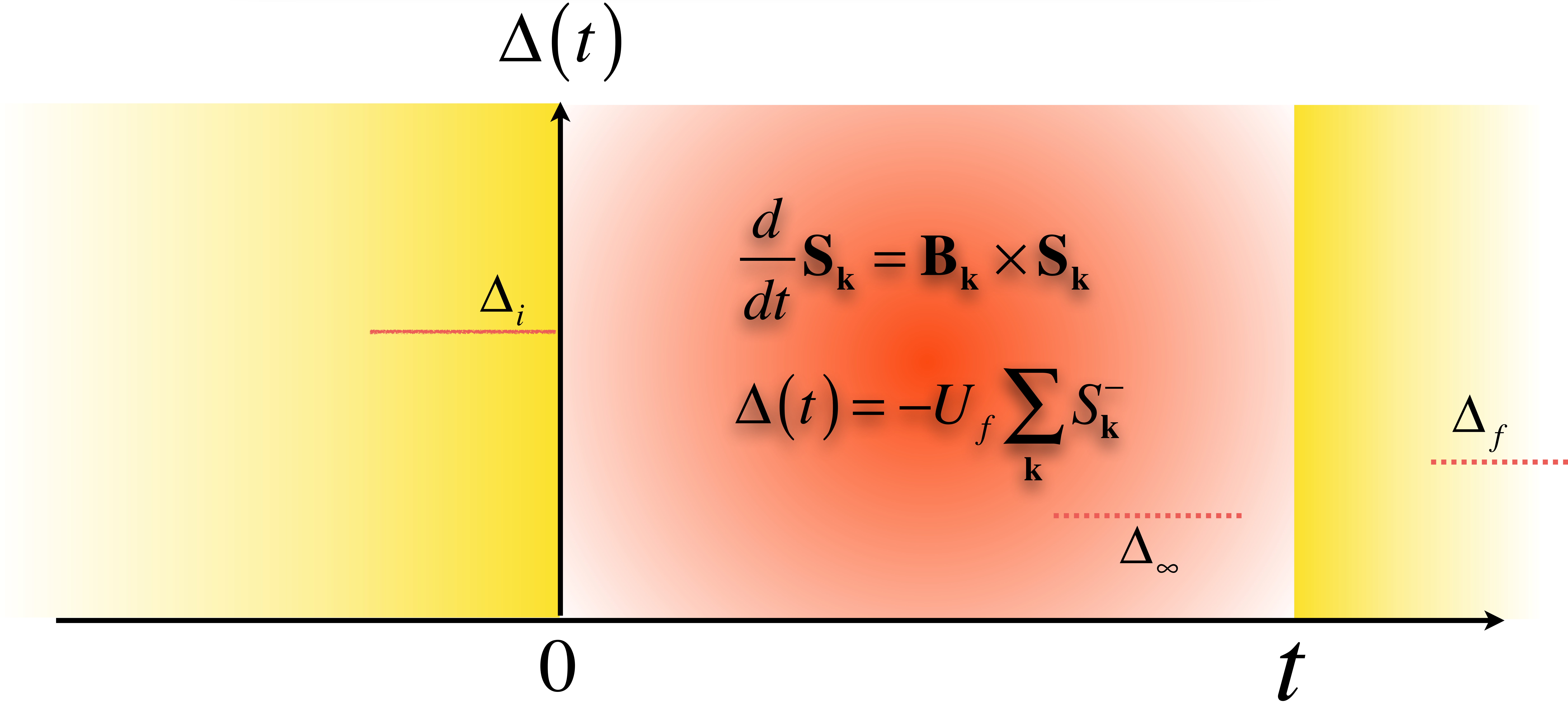
$$\Delta(t) = -U_f\sum_\mathbf{k} S_\mathbf{k}^-$$

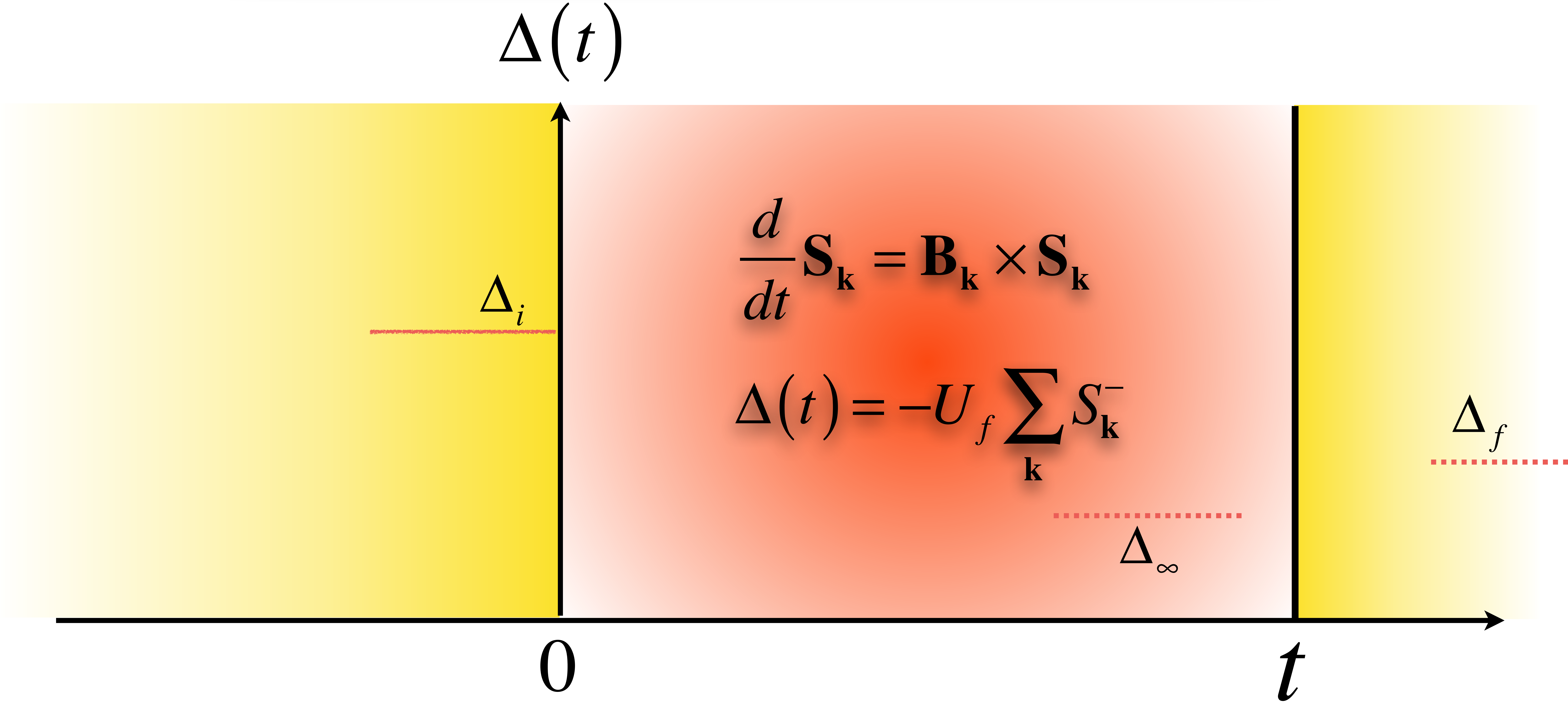
# Transient dynamics in superconductors



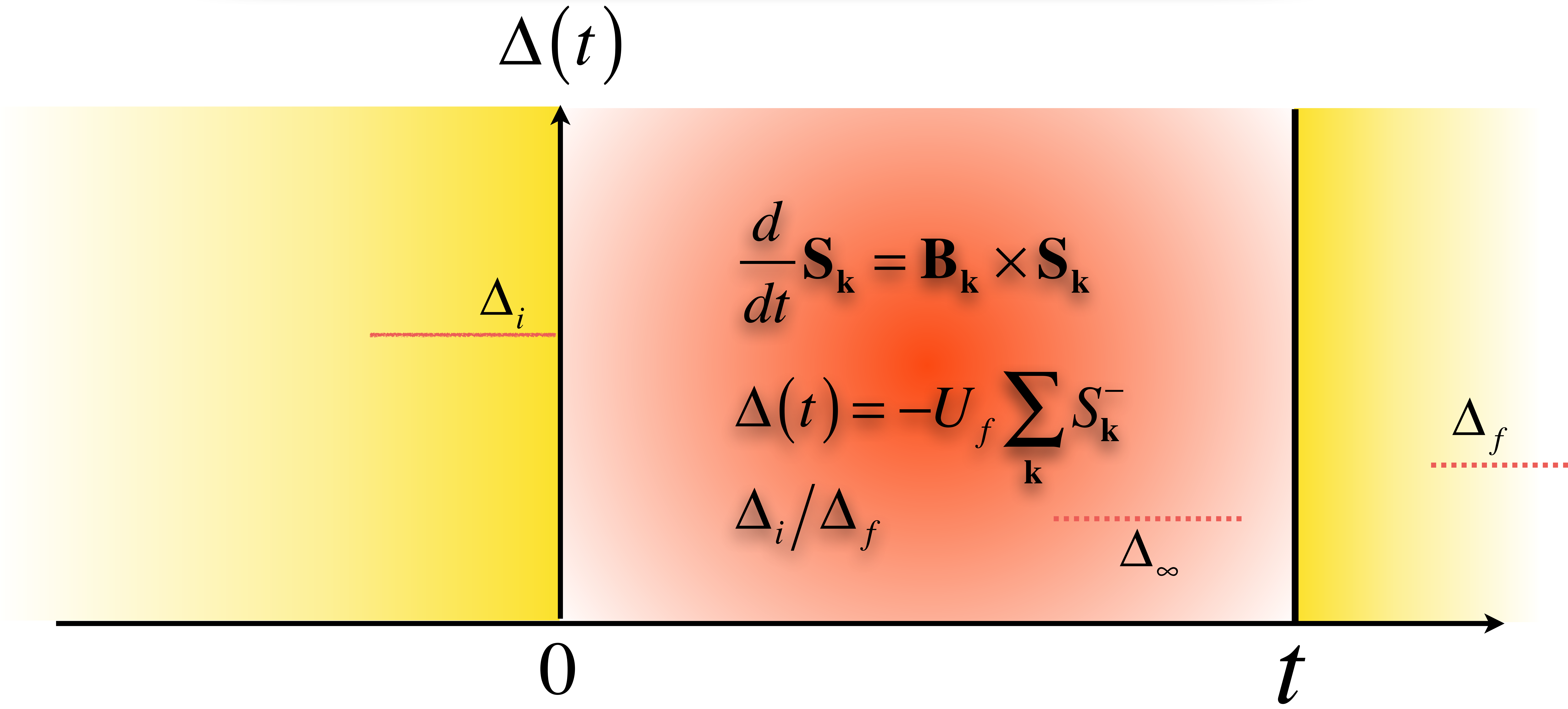
# Transient dynamics in superconductors



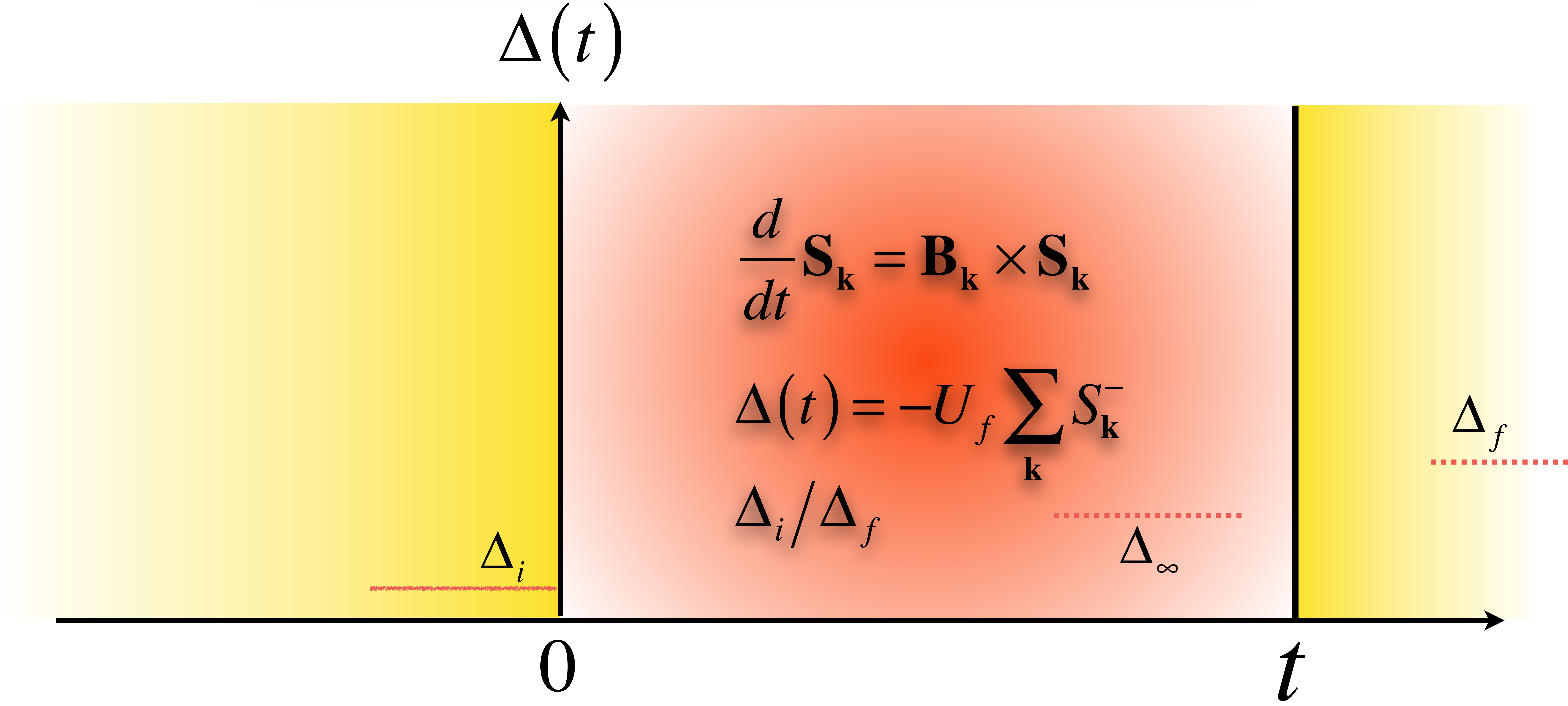
# Transient dynamics in superconductors



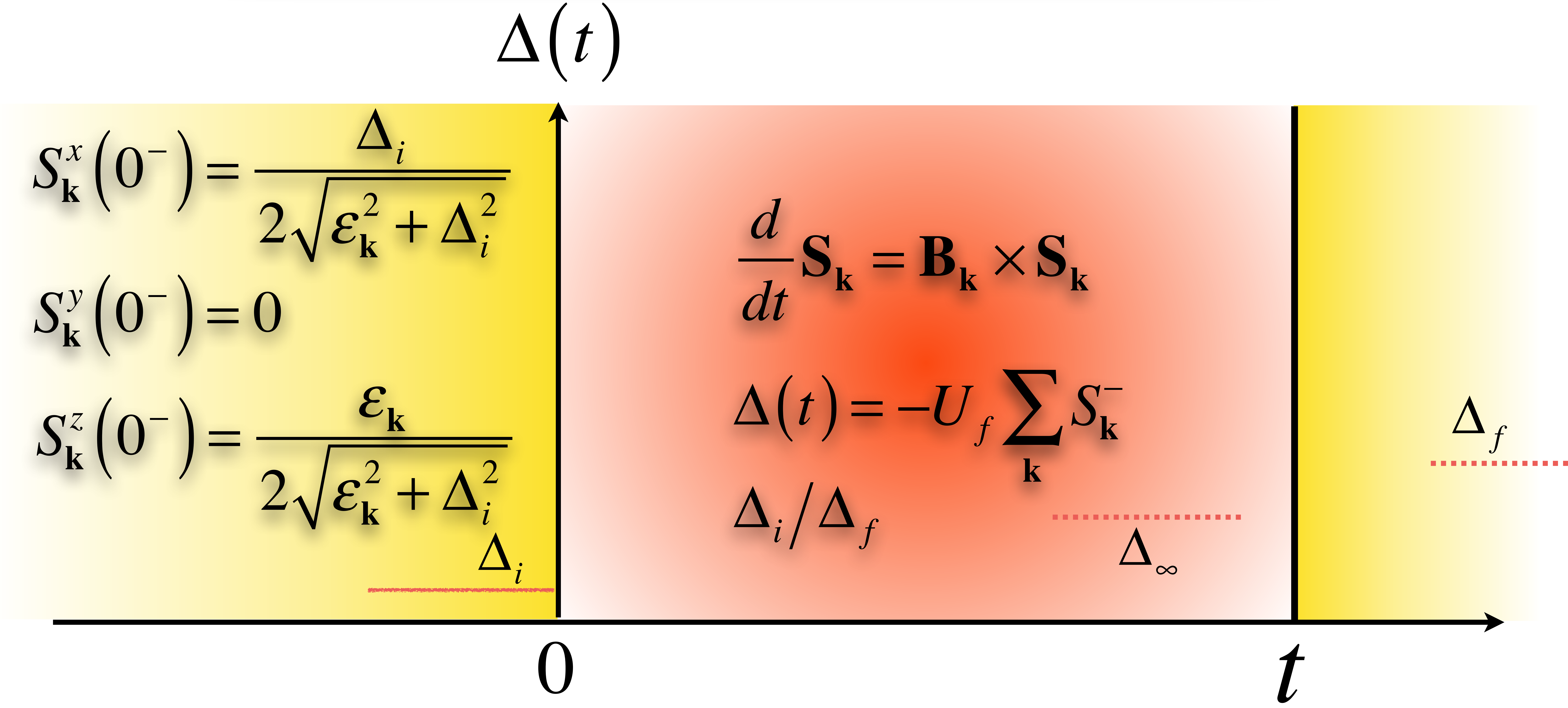
# Transient dynamics in superconductors



# Transient dynamics in superconductors



# Transient dynamics in superconductors




$$S_{\mathbf{k}}^{x}\left(0^{-}\right)=\frac{\Delta_i}{2\sqrt{\varepsilon_{\mathbf{k}}^2+\Delta_i^2}}$$

$$S_{\mathbf{k}}^{y}\left(0^{-}\right)=0$$

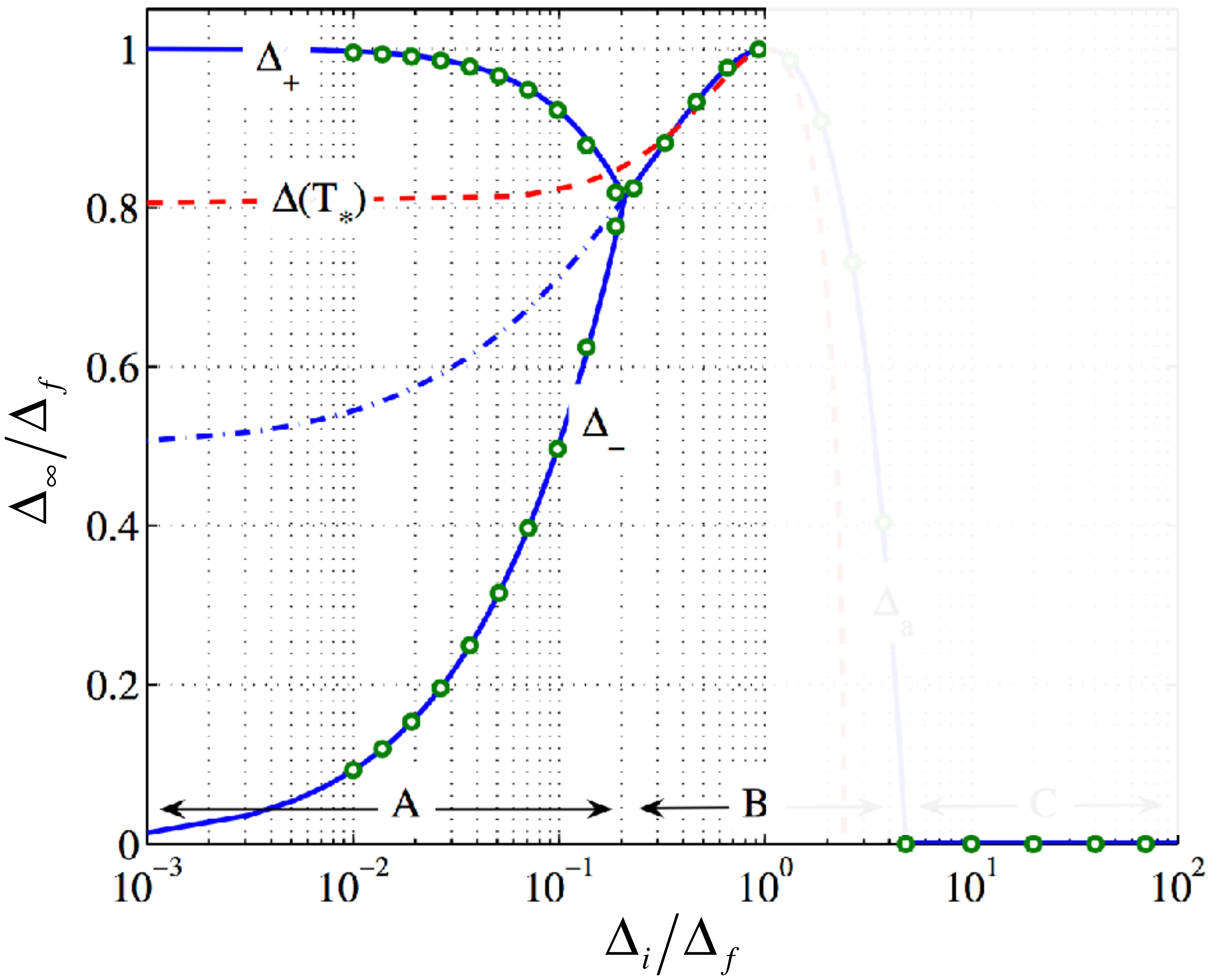
$$S_{\mathbf{k}}^{z}\left(0^{-}\right)=\frac{\varepsilon_{\mathbf{k}}}{2\sqrt{\varepsilon_{\mathbf{k}}^2+\Delta_i^2}}$$

$$\frac{d}{dt}\mathbf{S}_{\mathbf{k}}=\mathbf{B}_{\mathbf{k}}\times\mathbf{S}_{\mathbf{k}}$$

$$\Delta(t)=-U_f\sum_{\mathbf{k}}S_{\mathbf{k}}^{-}$$

$$\Delta_i/\Delta_f$$

# Results





[1] E. A. Yuzbashyan, B. L. Altshuler, V. B. Kuznetsov, V. Z. Enolskii, Phys. Rev. B, **72**, 220503 (2005)

[2] R. A. Barankov, L. S. Levitov, Phys. Rev. Lett., **96**, 230403 (2006)

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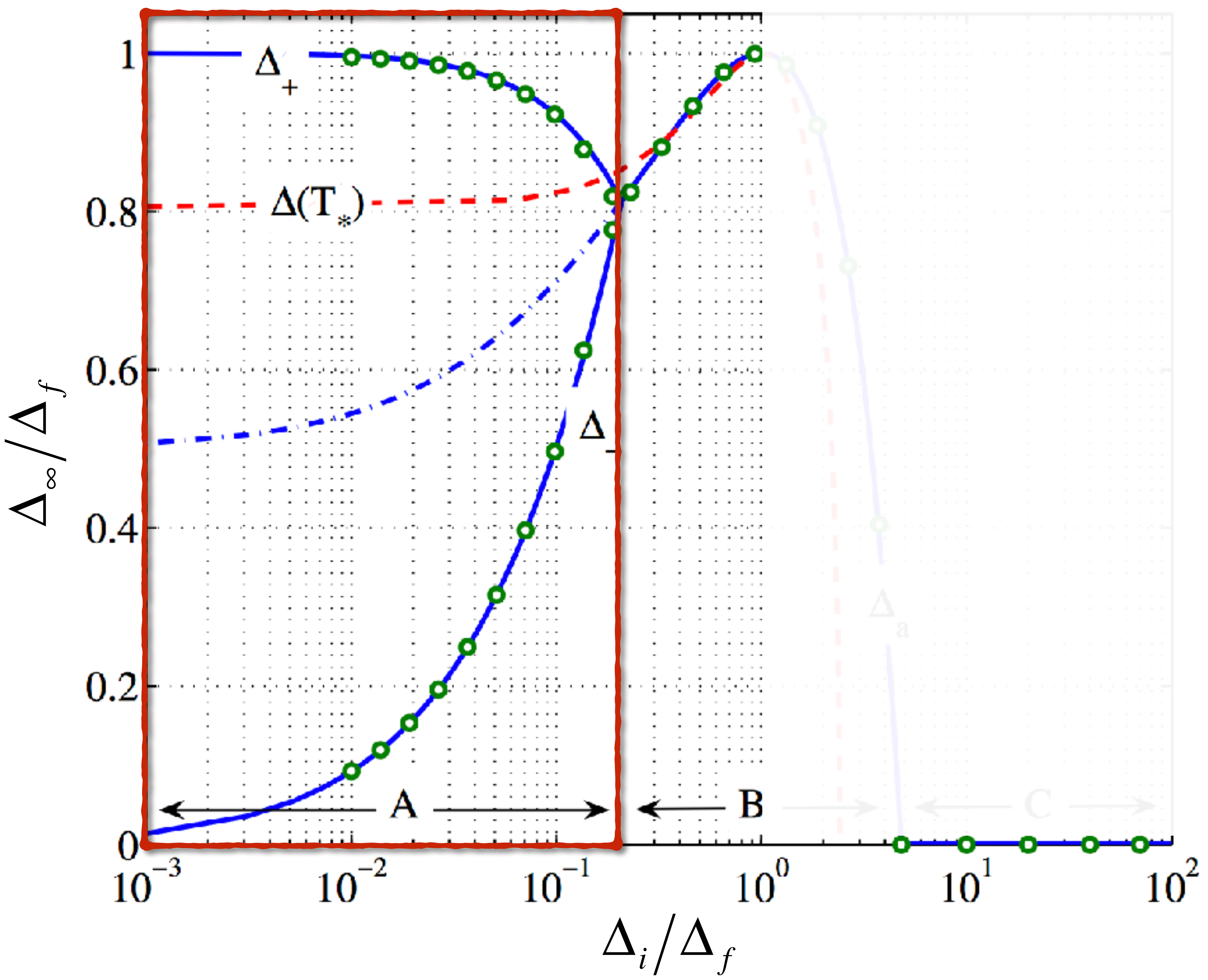



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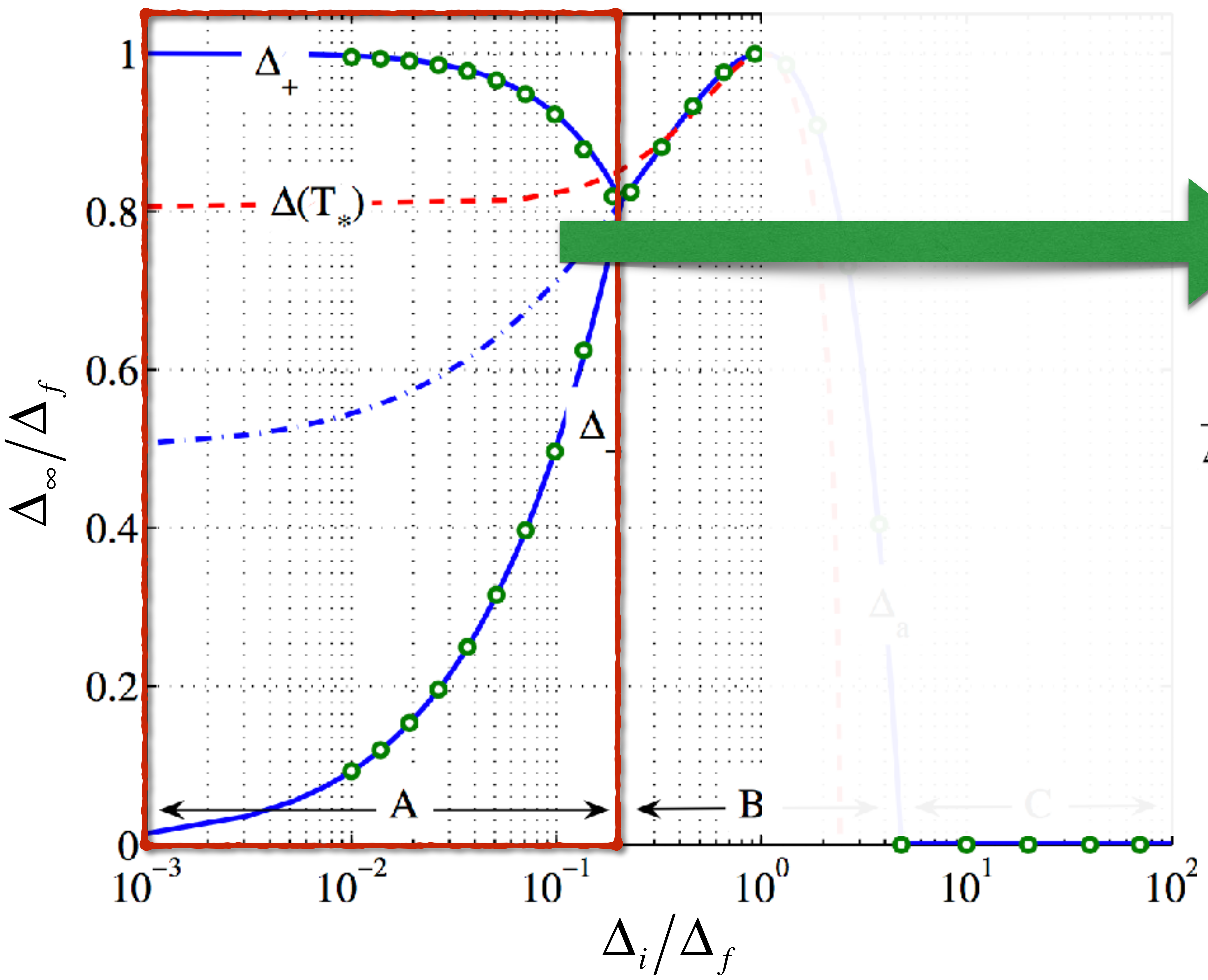


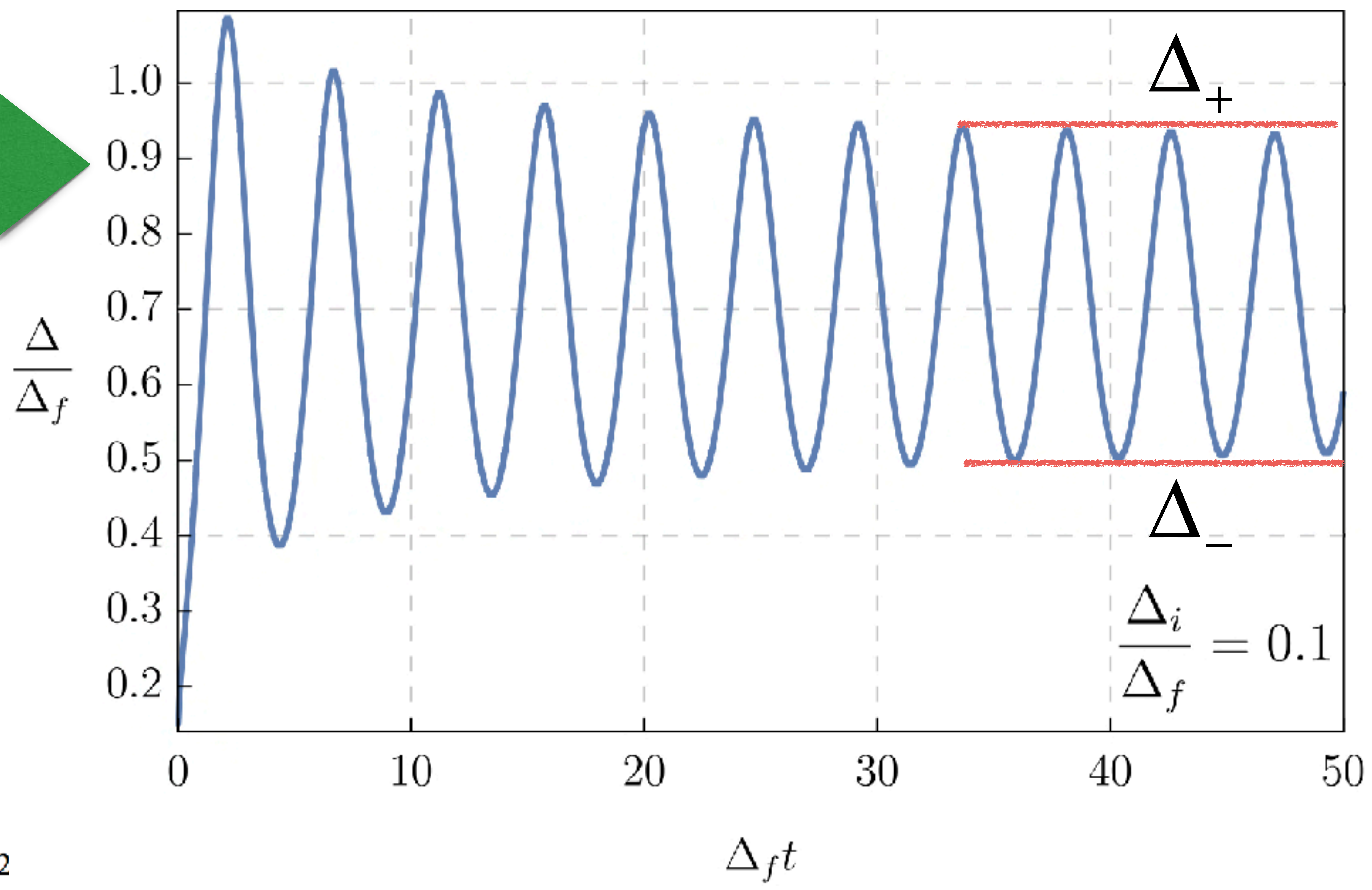



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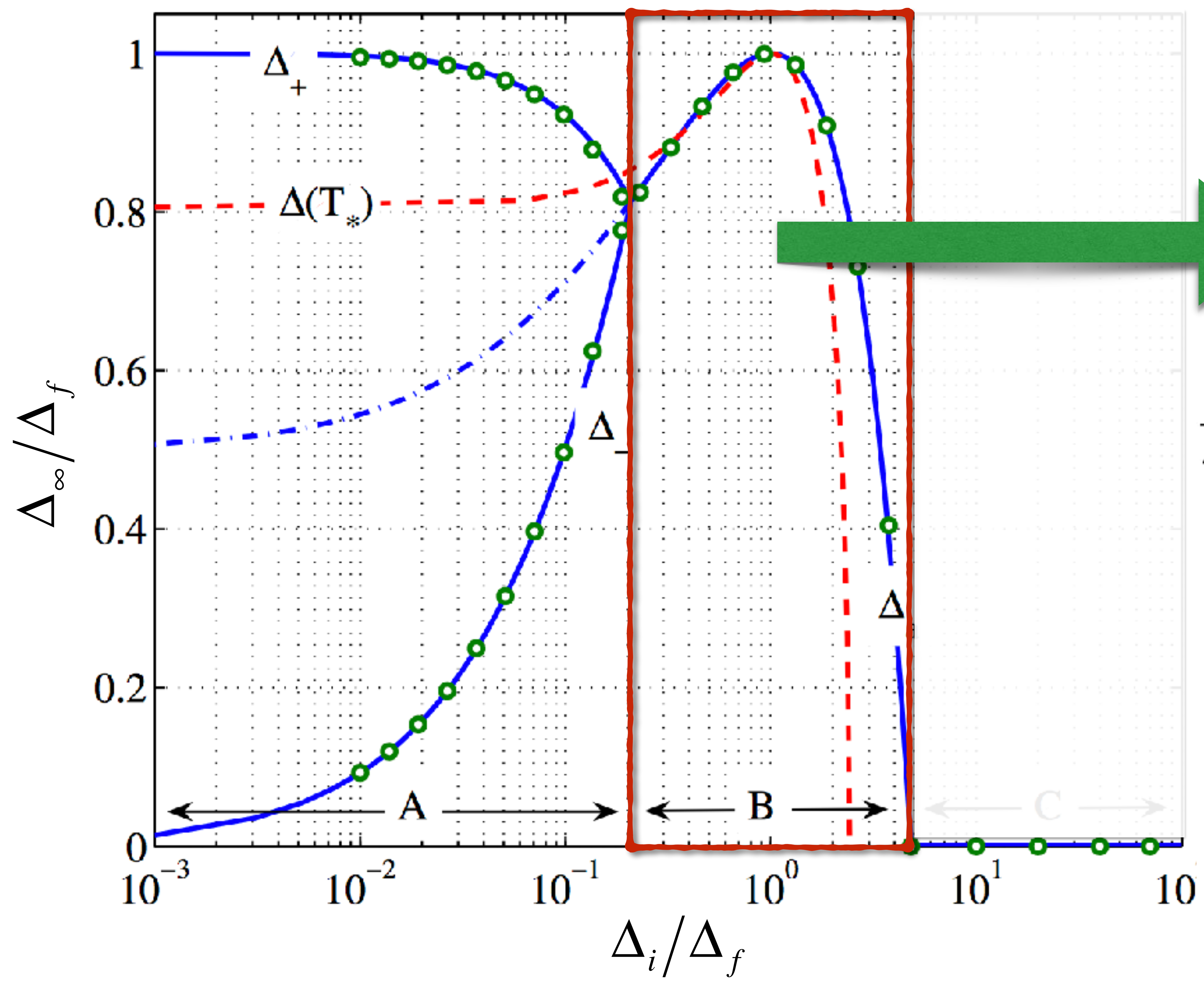


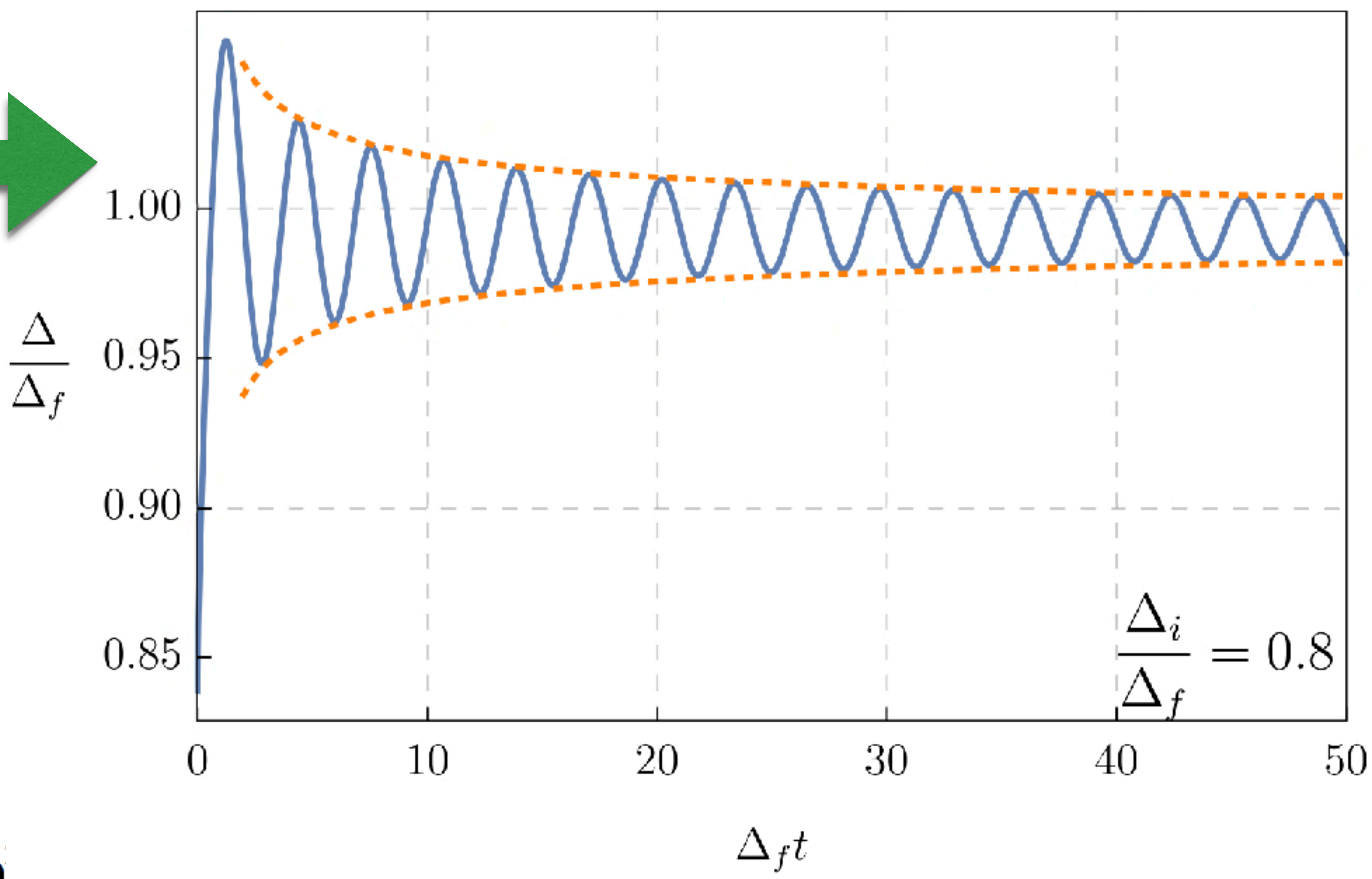



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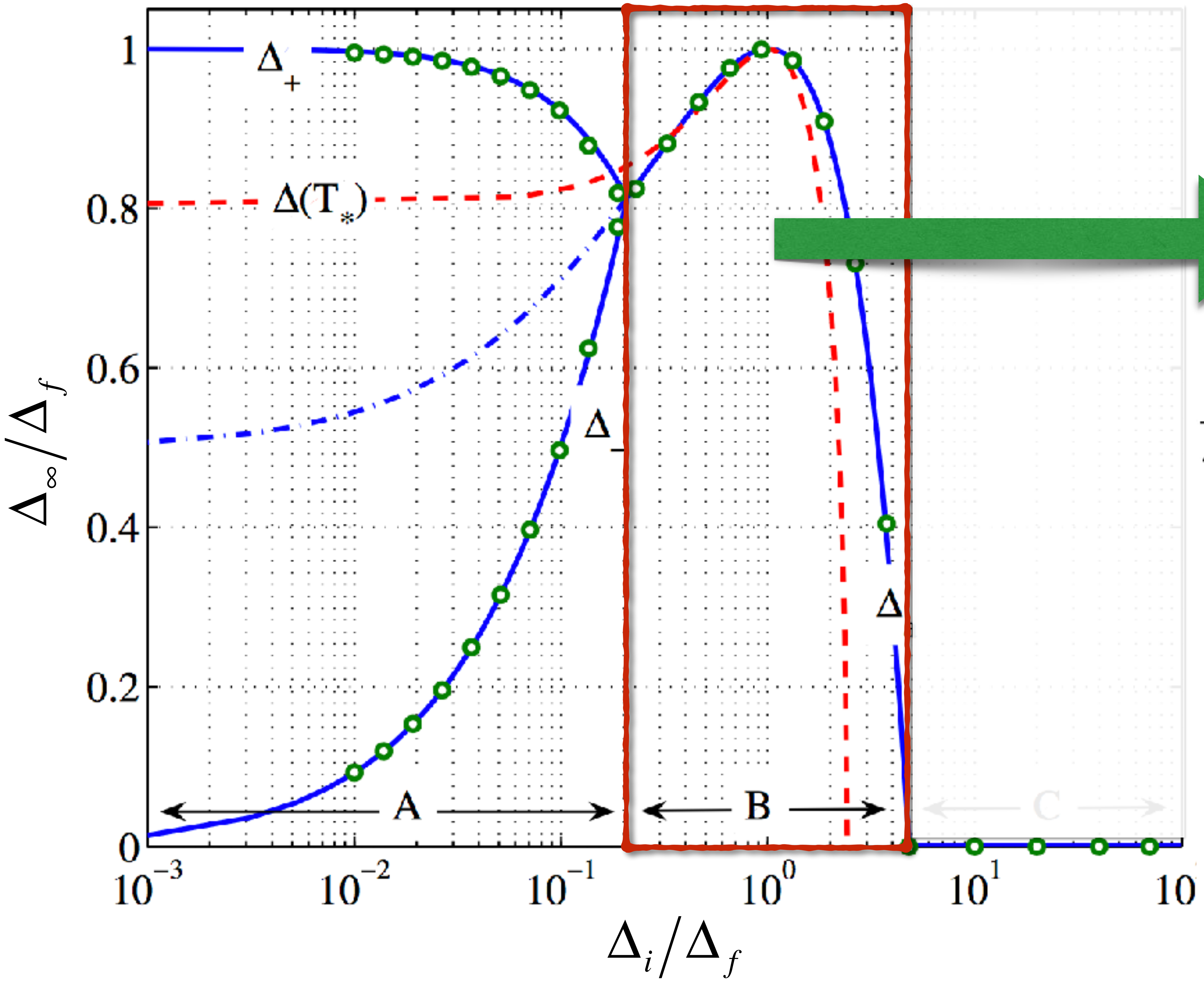


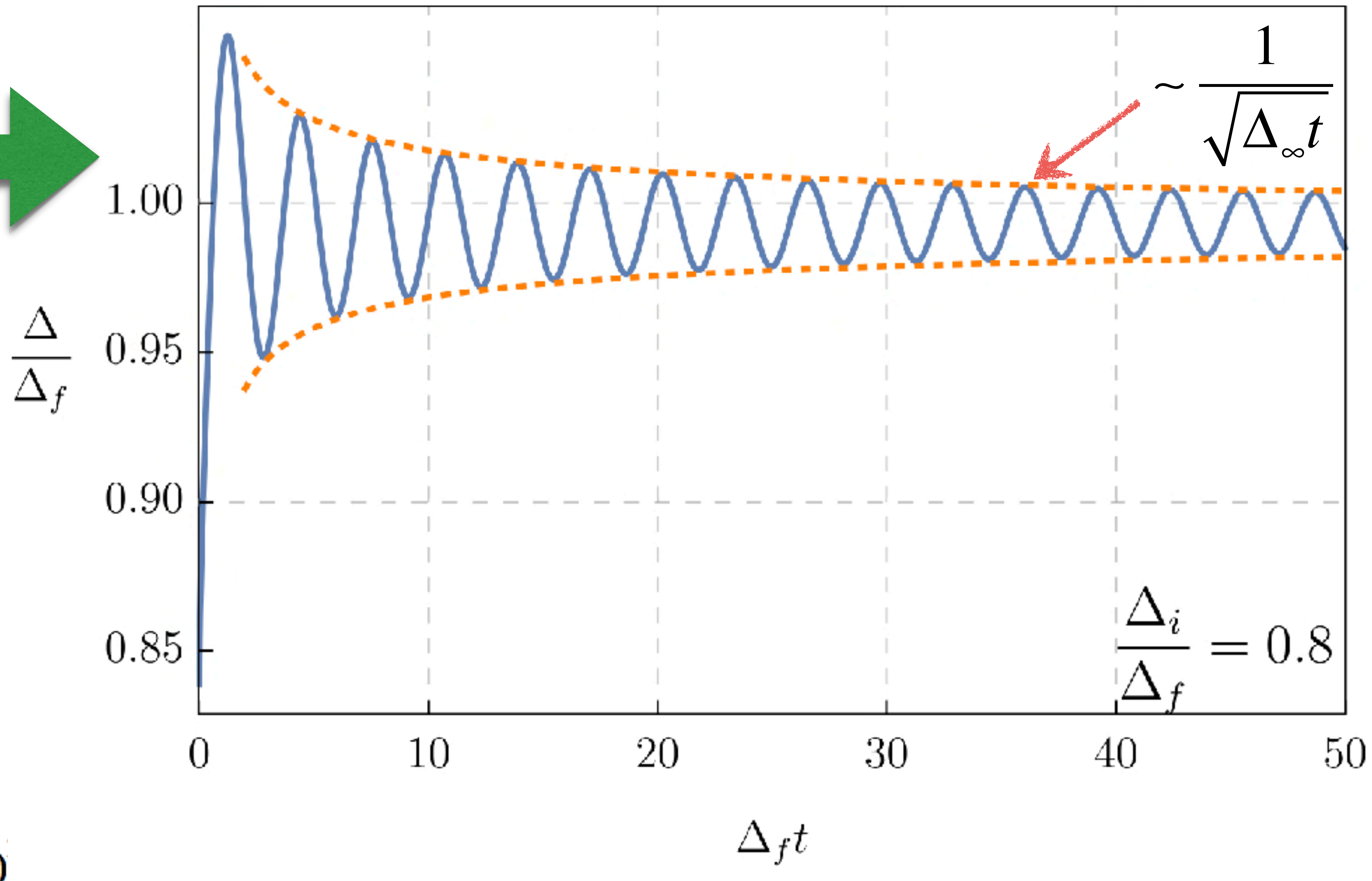



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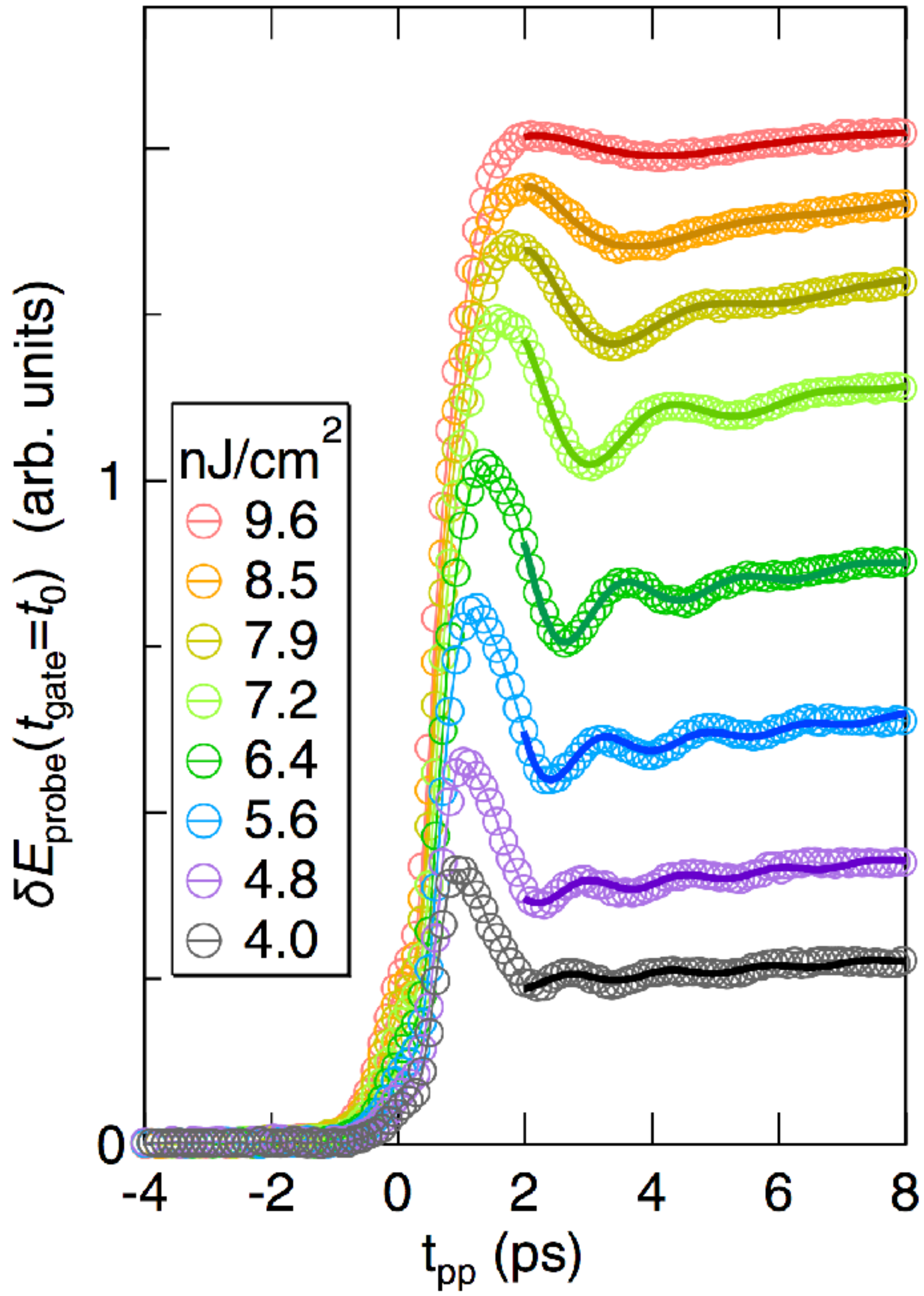


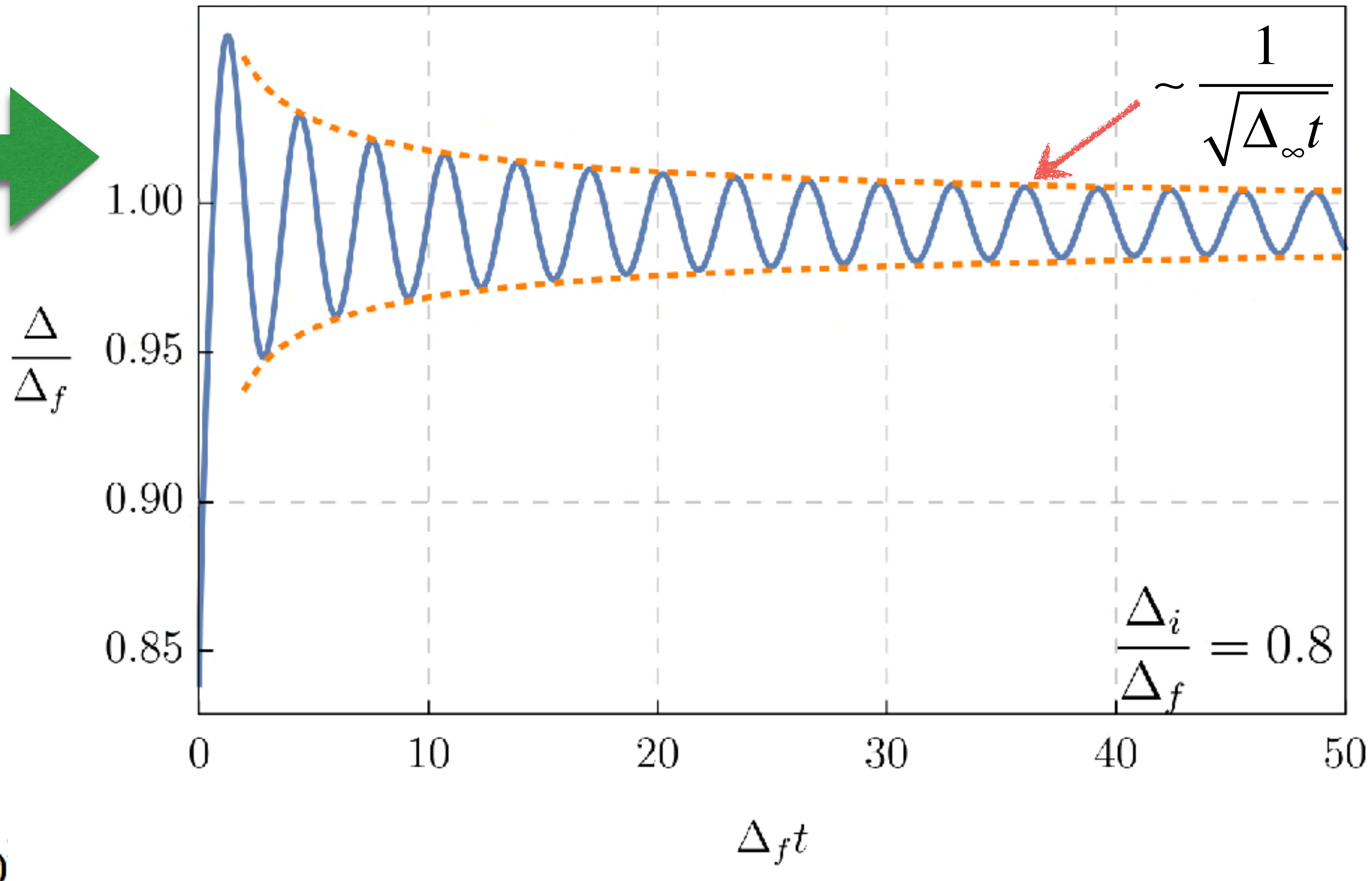


V. Z. Enolskii, Phys. Rev. B, **72**, 220503 (2005)
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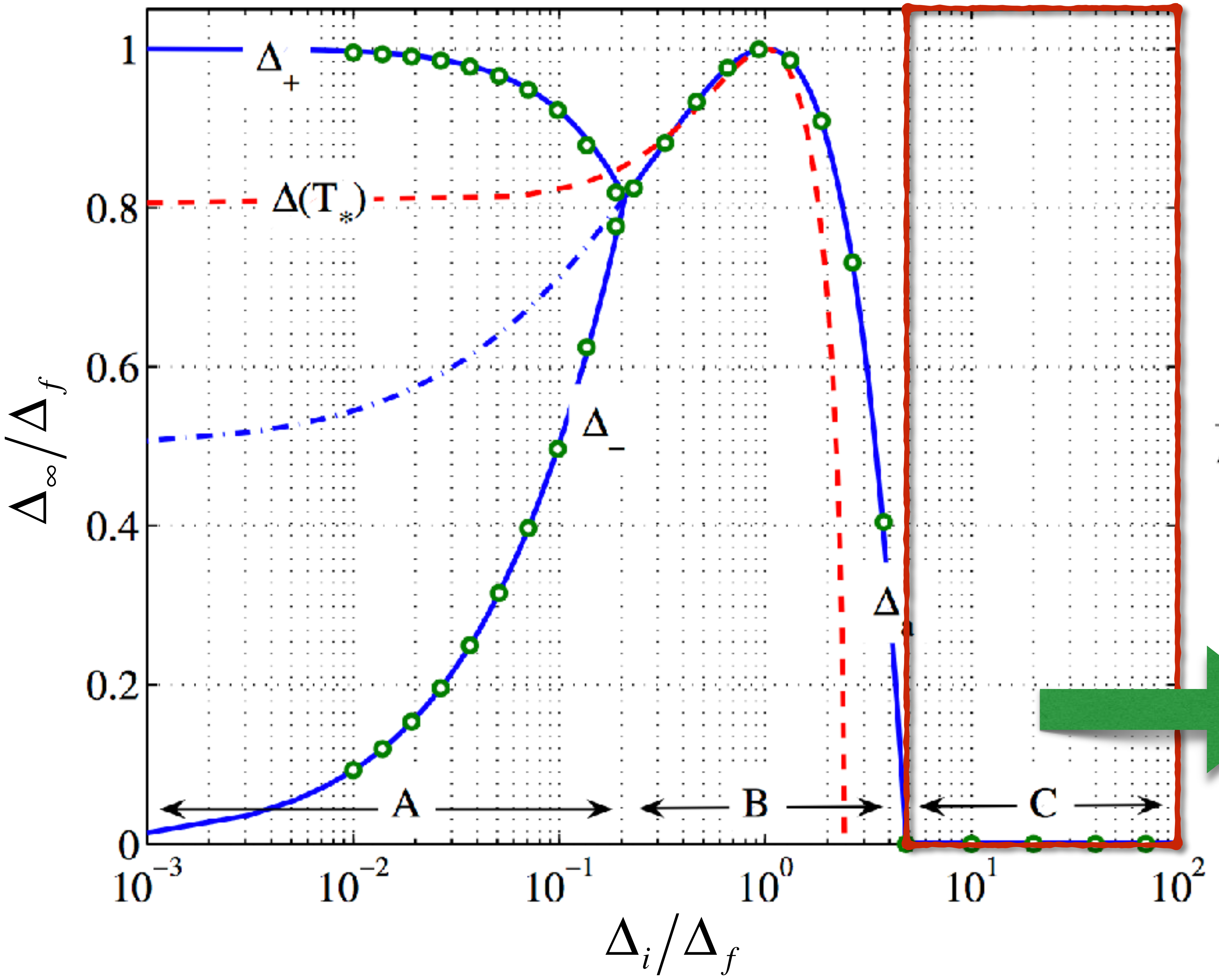


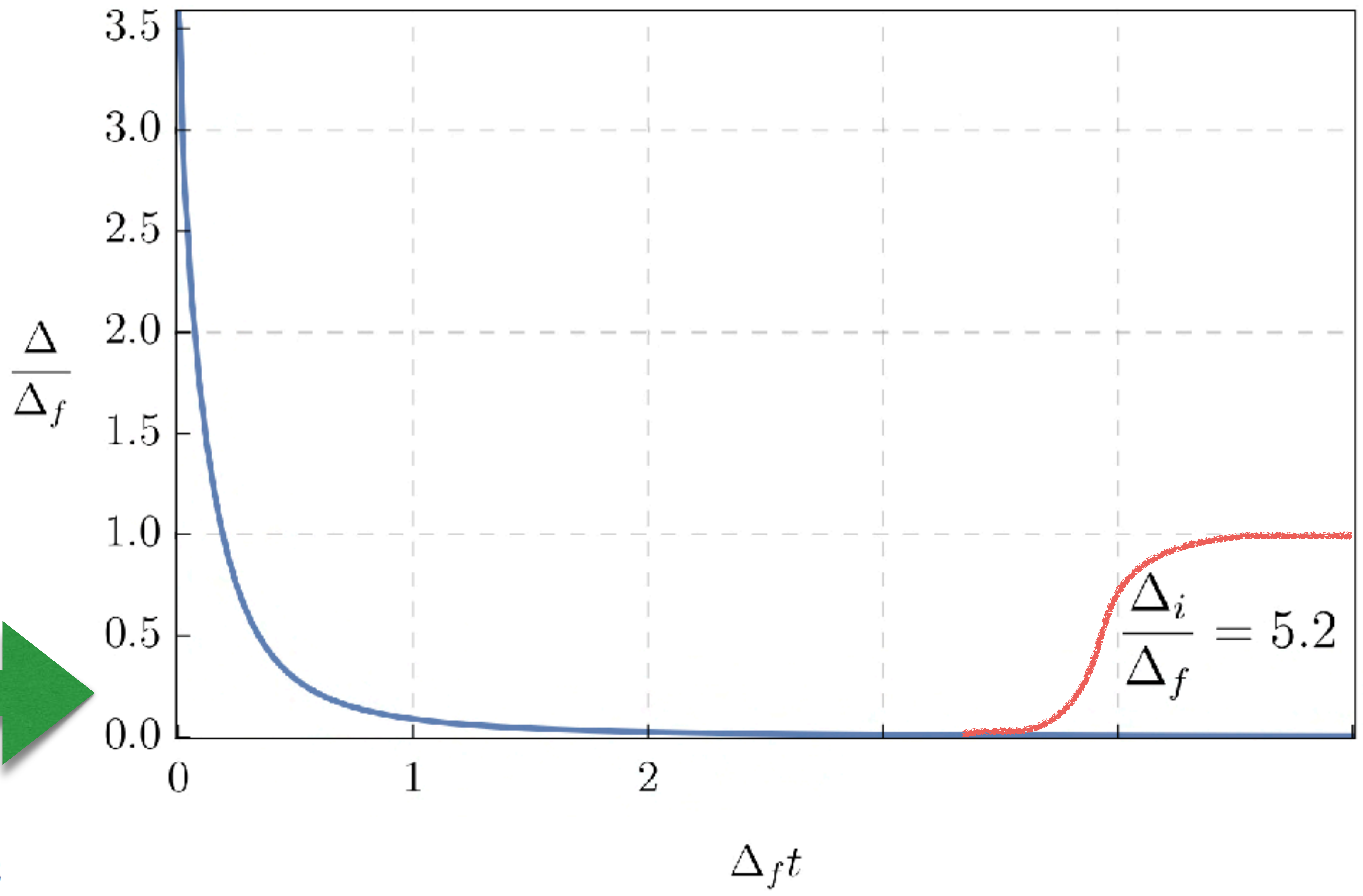



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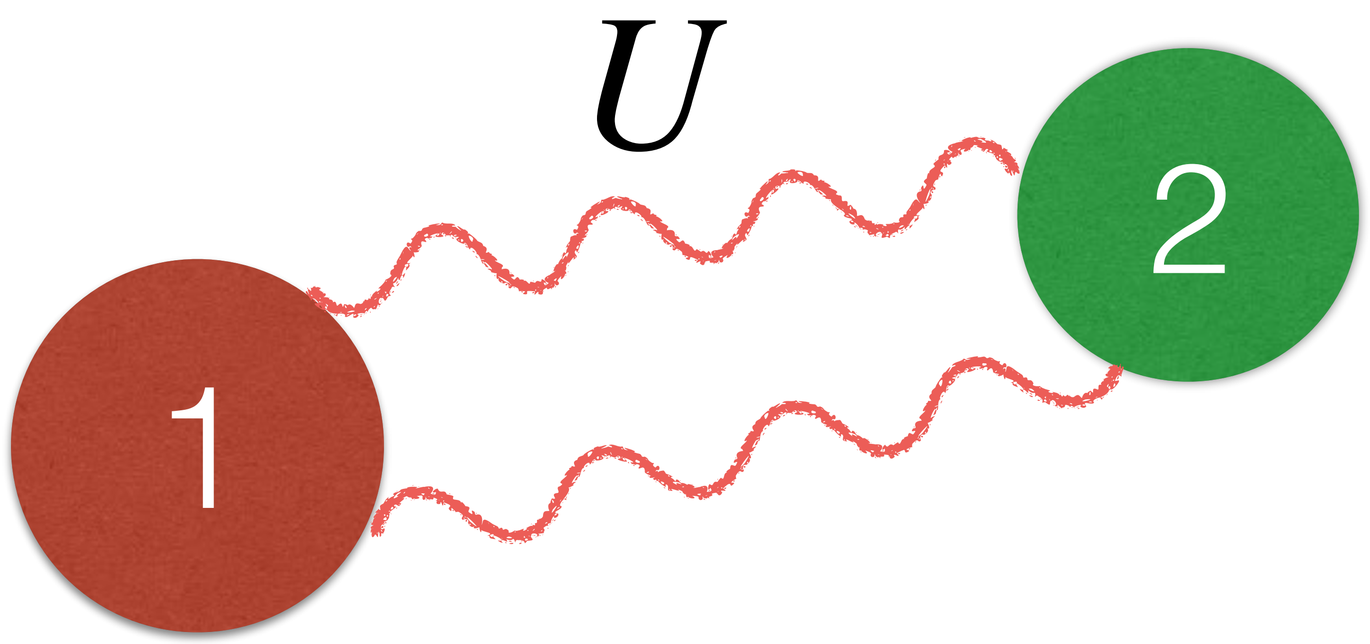
[2] R. A. Barankov, L. S. Levitov, Phys. Rev. Lett., **96**, 230403 (2006)

# Outline

- Single-band BCS
- Two-band Superconductors
- Iron-based Superconductors

# Two-band superconductors

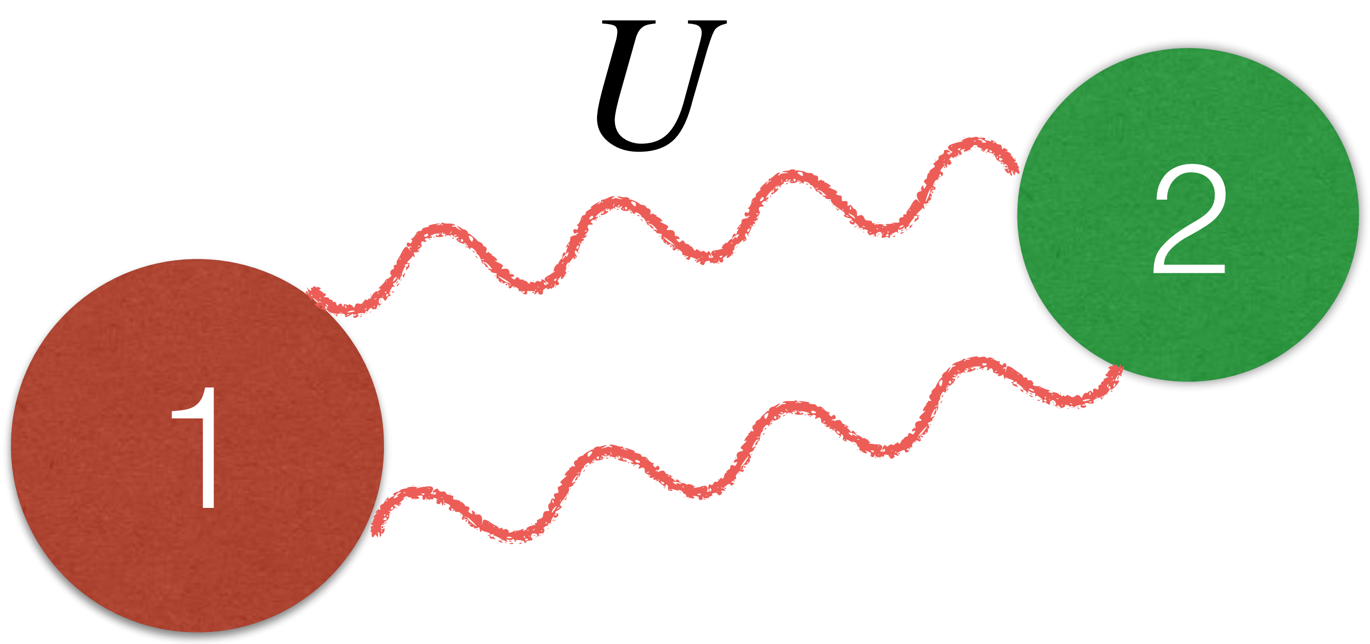
# Two-band superconductors



# Two-band superconductors

$$\Delta_1 = -U \sum_{\mathbf{k}} S^{-}_{\mathbf{k},2}$$

$$\Delta_2 = -U \sum_{\mathbf{k}} S^{-}_{\mathbf{k},1}$$



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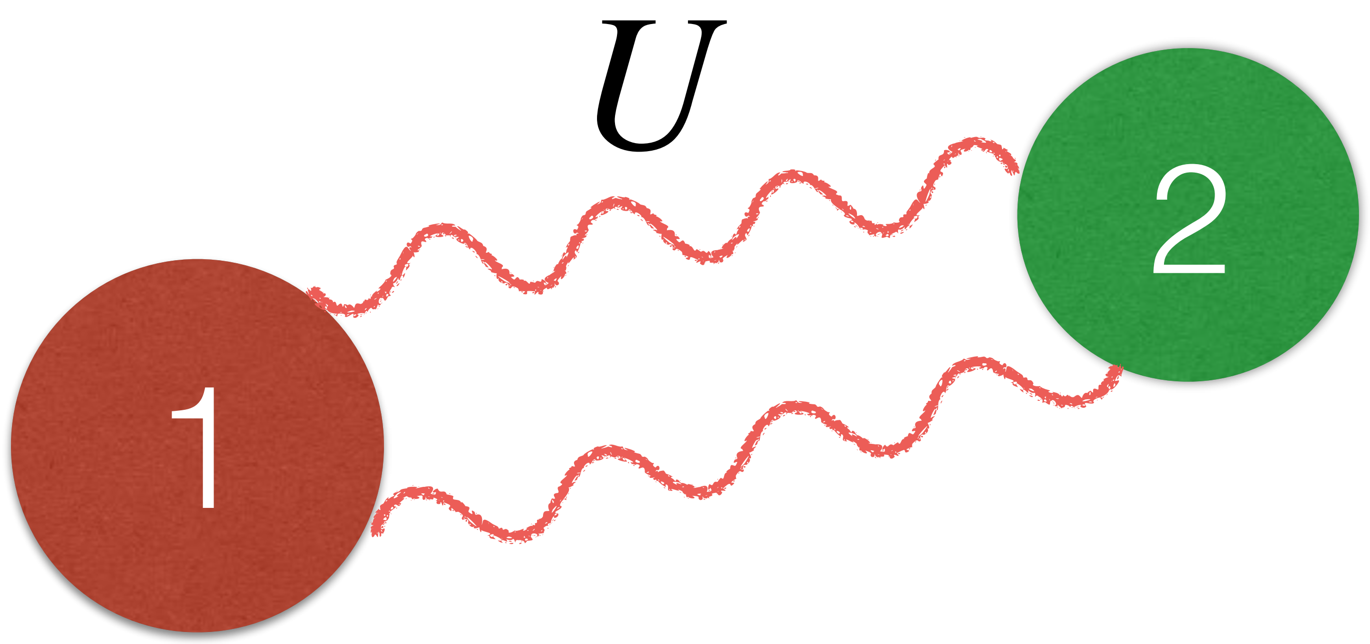
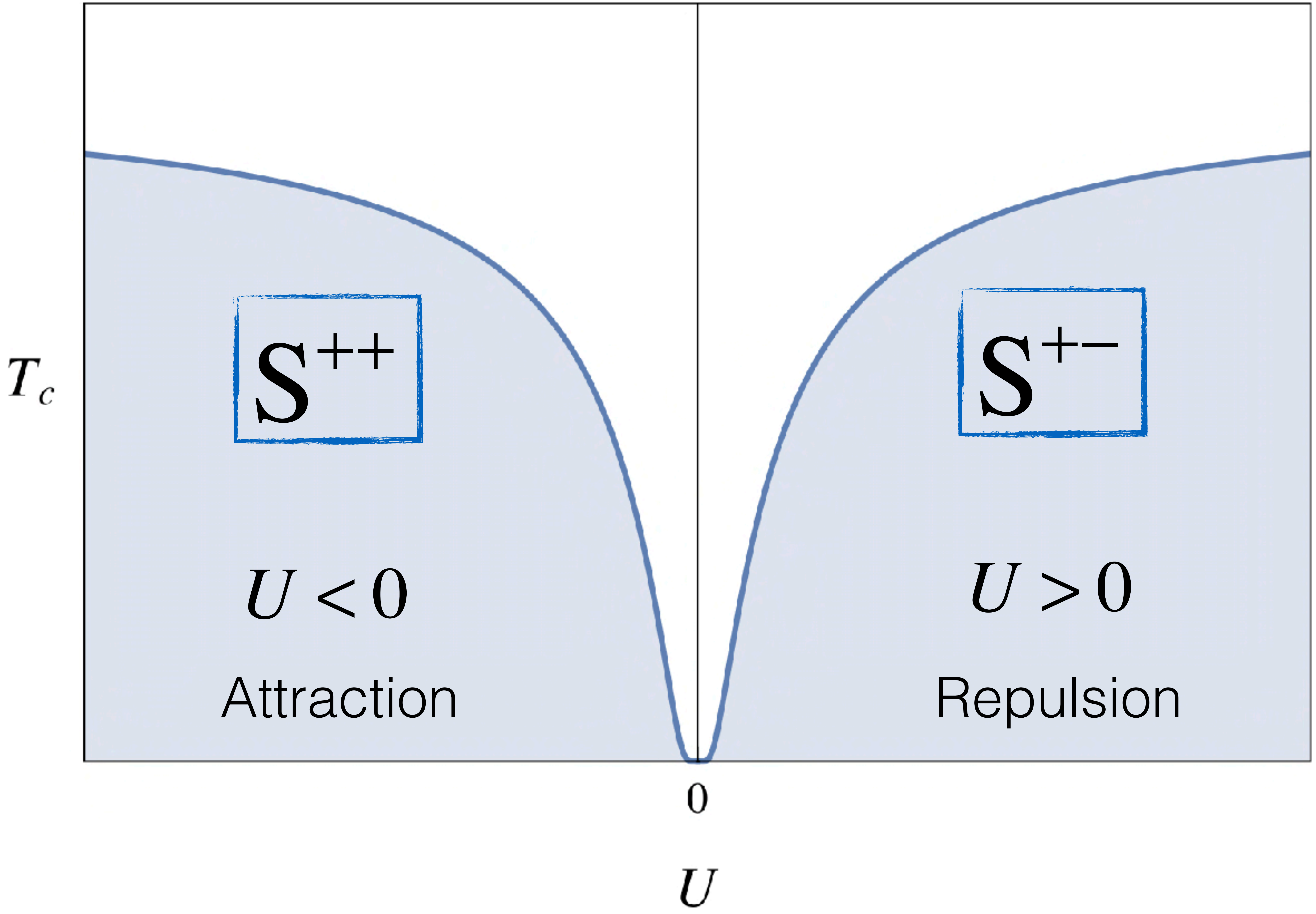
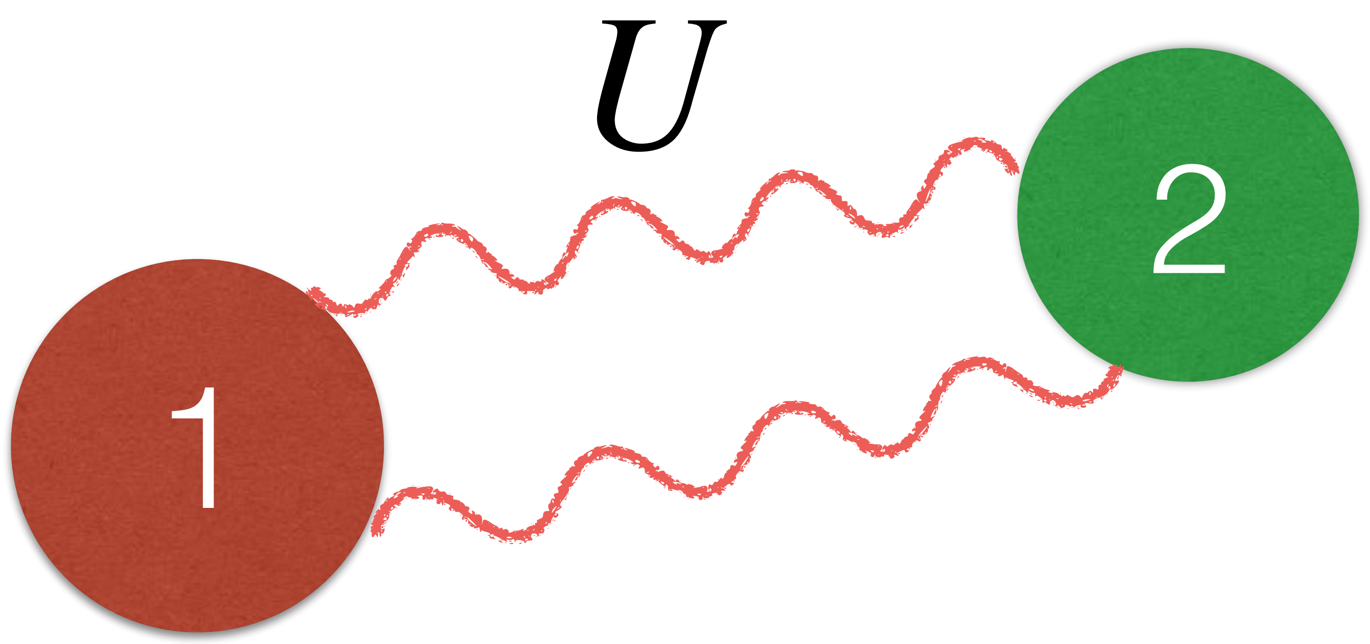


# Two-band superconductors

$$\frac{d}{dt}\mathbf{S}_{\mathbf{k},1} = \mathbf{B}_{\mathbf{k},1} \times \mathbf{S}_{\mathbf{k},1}$$

$$\frac{d}{dt}\mathbf{S}_{\mathbf{k},2} = \mathbf{B}_{\mathbf{k},2} \times \mathbf{S}_{\mathbf{k},2}$$



# Two-band superconductors

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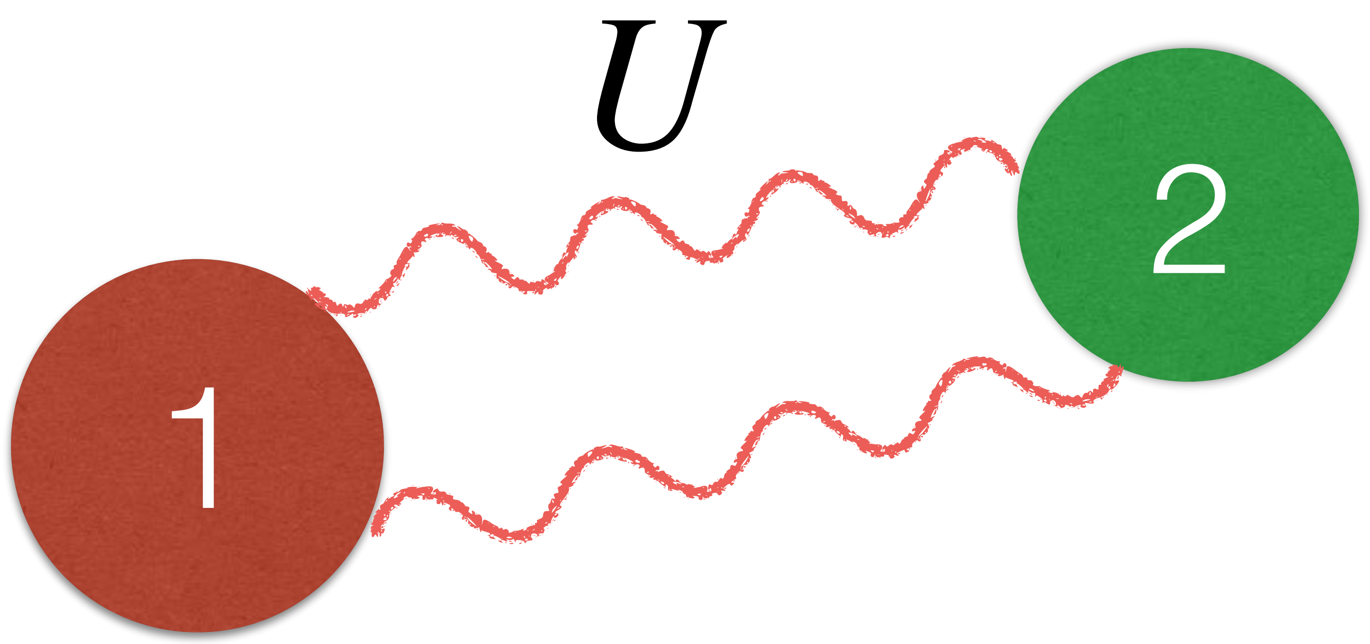
$$\frac{d}{dt}\mathbf{S}_{\mathbf{k},2} = \mathbf{B}_{\mathbf{k},2} \times \mathbf{S}_{\mathbf{k},2}$$

$$\Delta_1 = -U \sum_{\mathbf{k}} S^-_{\mathbf{k},2} = -U \mathcal{N}_2 \int_{-\Lambda}^{\Lambda} S^-_{\varepsilon,2} d\varepsilon$$

$$\Delta_2 = -U \sum_{\mathbf{k}} S^-_{\mathbf{k},1} = -U \mathcal{N}_1 \int_{-\Lambda}^{\Lambda} S^-_{\varepsilon,1} d\varepsilon$$



# Two-band superconductors

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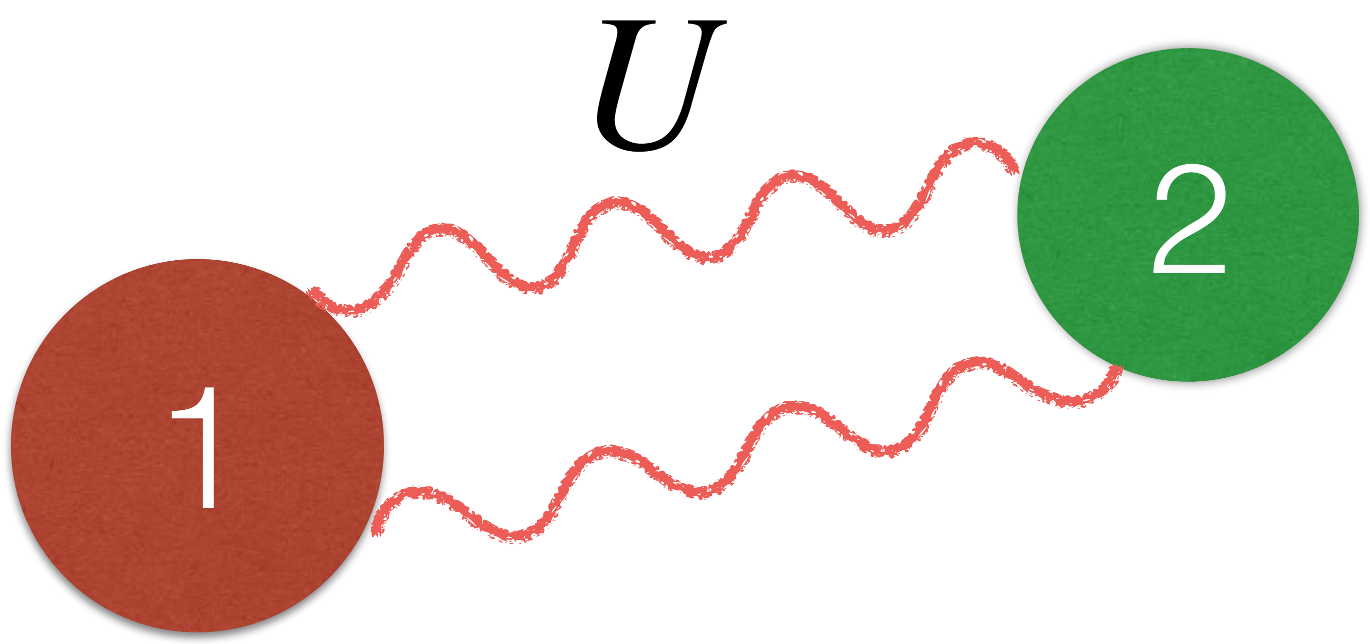


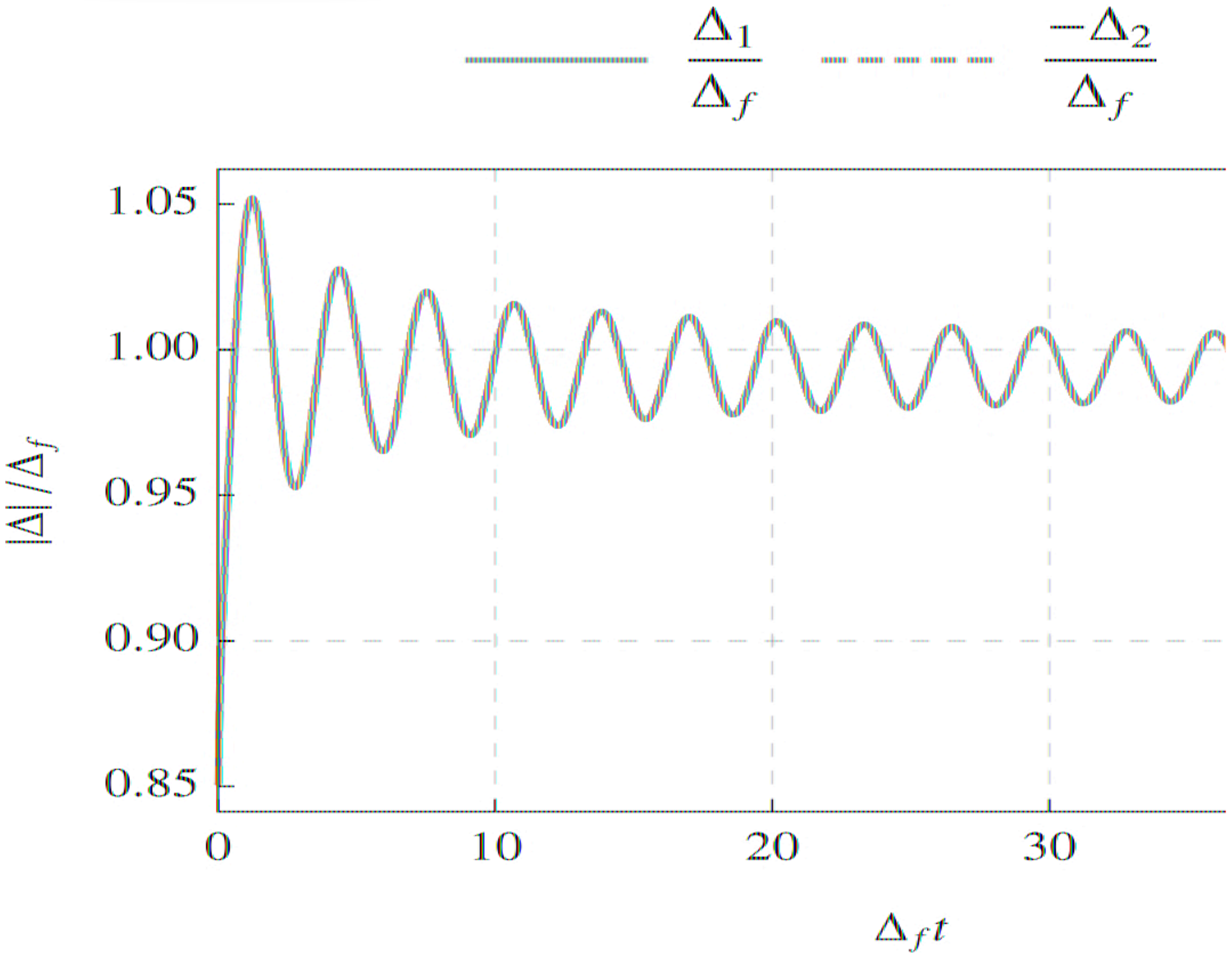

$$\boxed{\eta = \frac{\mathcal{N}_2}{\mathcal{N}_1}}$$

# Results

$$\boxed{\eta = \frac{\mathcal{N}_2}{\mathcal{N}_1} = 1}$$

$$U_i \mathcal{N}_1 = 0.1923$$

$$U_f \mathcal{N}_1 = 0.2$$

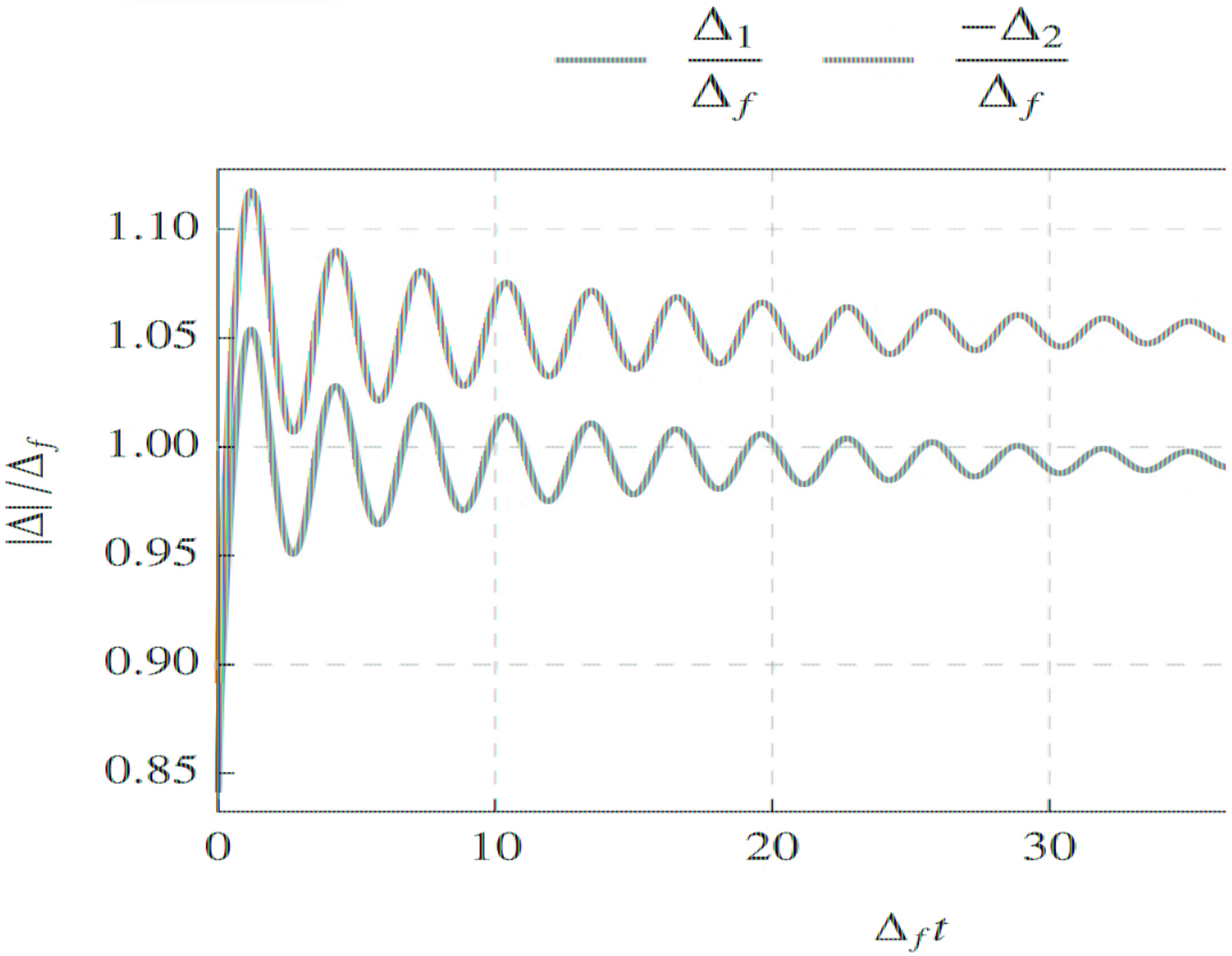


# Results

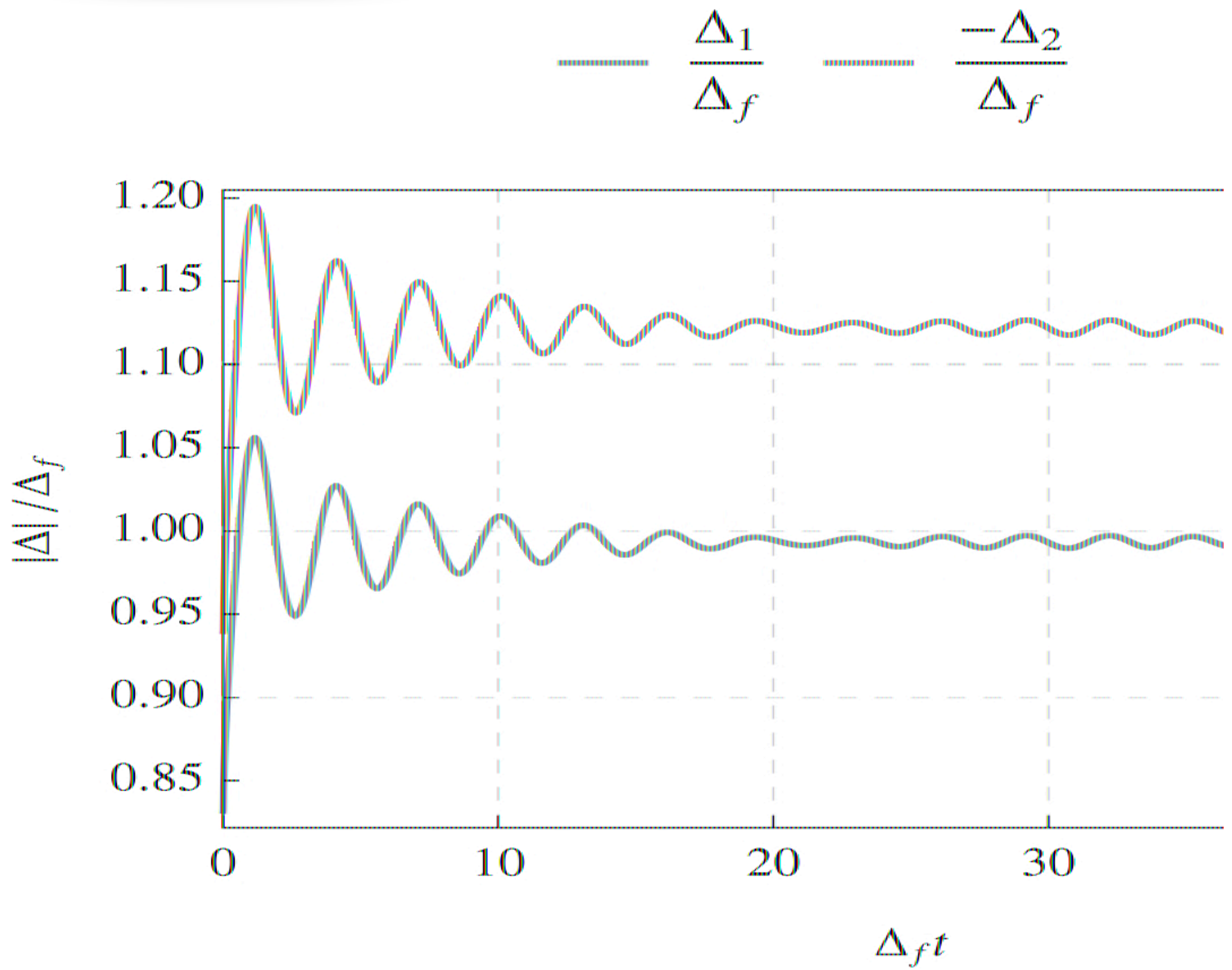
$$\boxed{\eta = \frac{\mathcal{N}_2}{\mathcal{N}_1} = 0.9}$$

$$U_i \mathcal{N}_1 = 0.1923$$

$$U_f \mathcal{N}_1 = 0.2$$



# Results




$$\boxed{\eta = \frac{\mathcal{N}_2}{\mathcal{N}_1} = 0.8}$$

$$U_i \mathcal{N}_1 = 0.1923$$

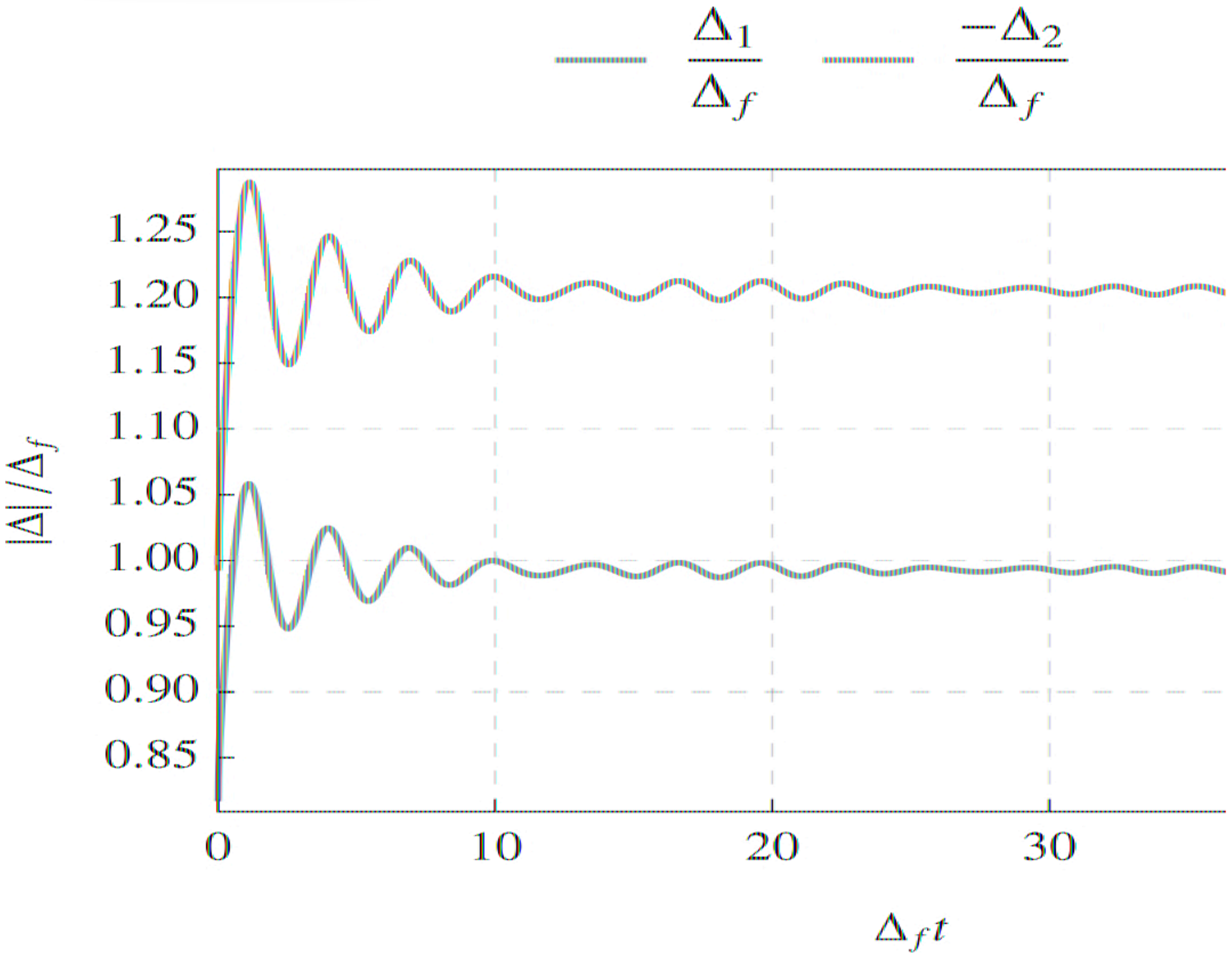
$$U_f \mathcal{N}_1 = 0.2$$

# Results

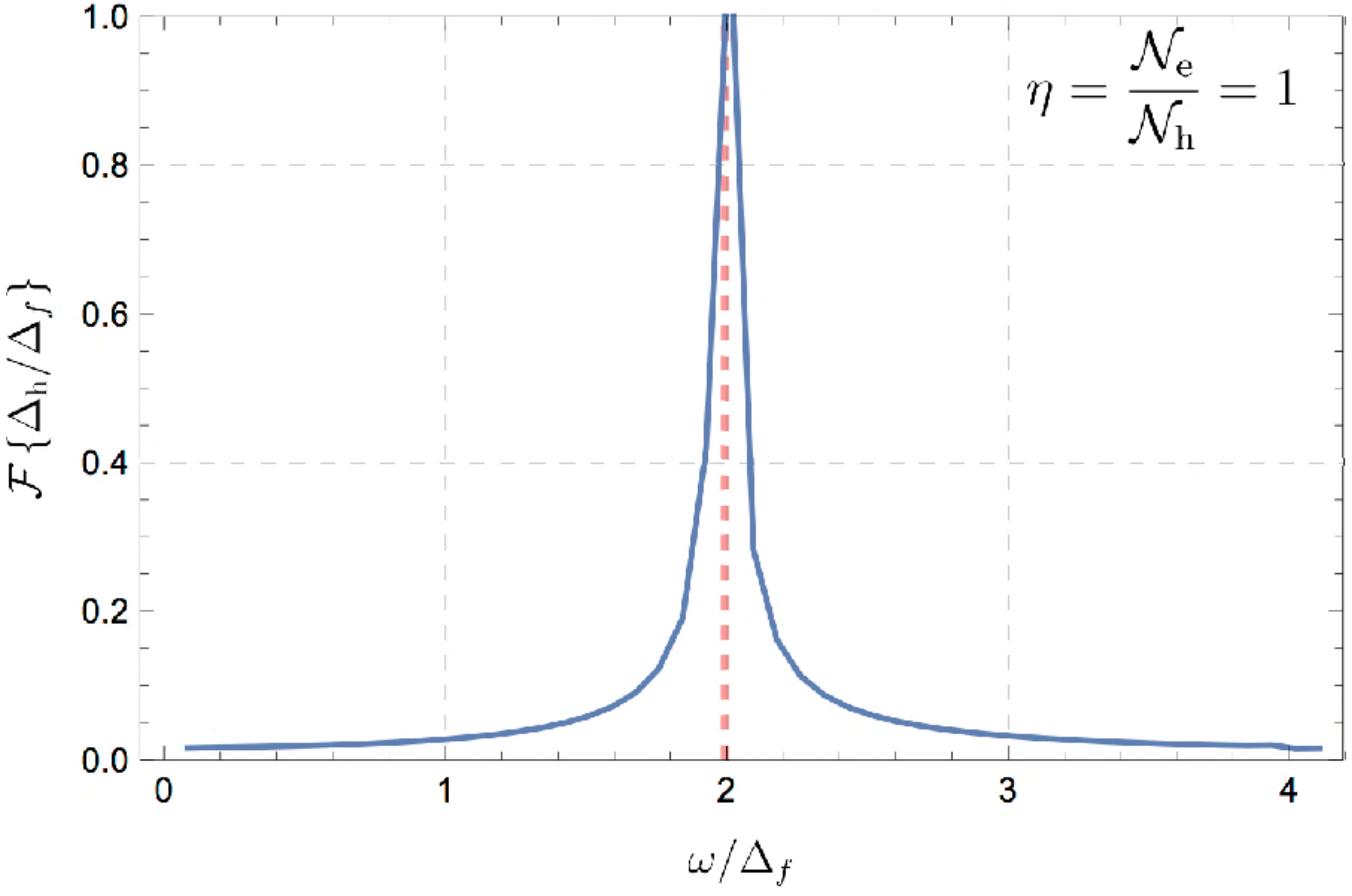
$$\boxed{\eta = \frac{\mathcal{N}_2}{\mathcal{N}_1} = 0.7}$$

$$U_i \mathcal{N}_1 = 0.1923$$

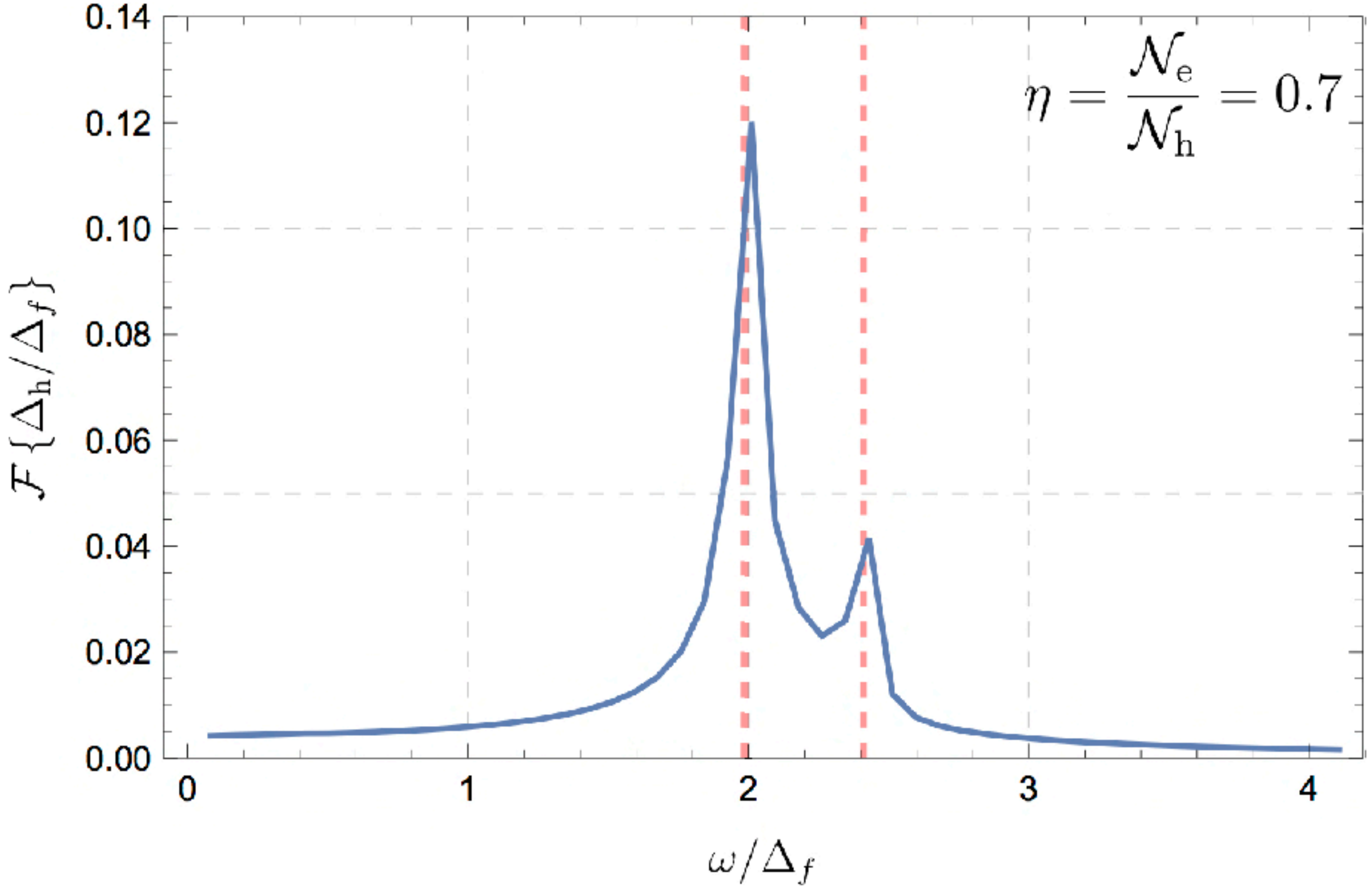
$$U_f \mathcal{N}_1 = 0.2$$



# Results



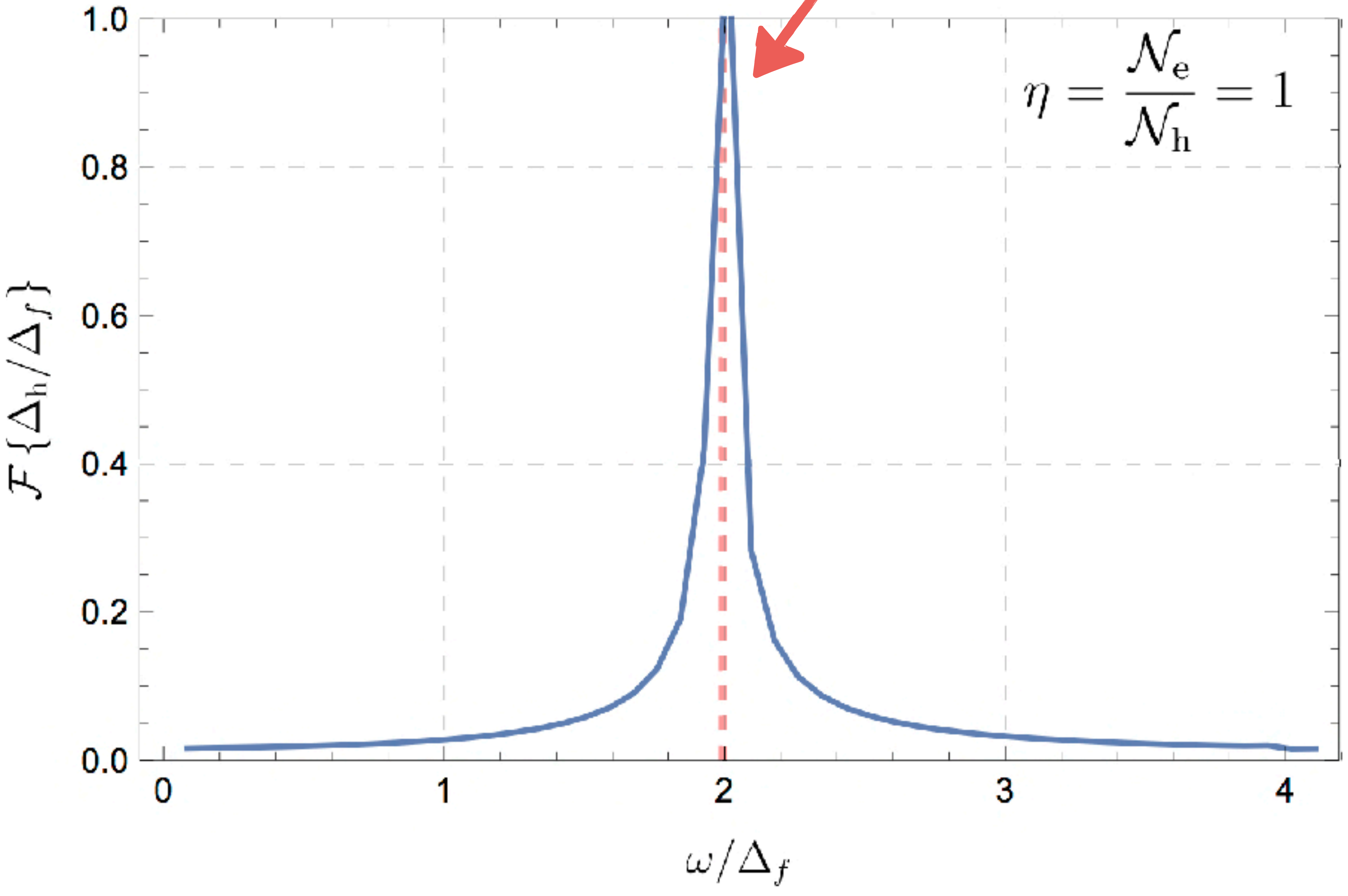
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
$\eta = \frac{\mathcal{N}_e}{\mathcal{N}_h} = 1$
$\mathcal{F}\{\Delta_h/\Delta_f\}$
$\omega/\Delta_f$

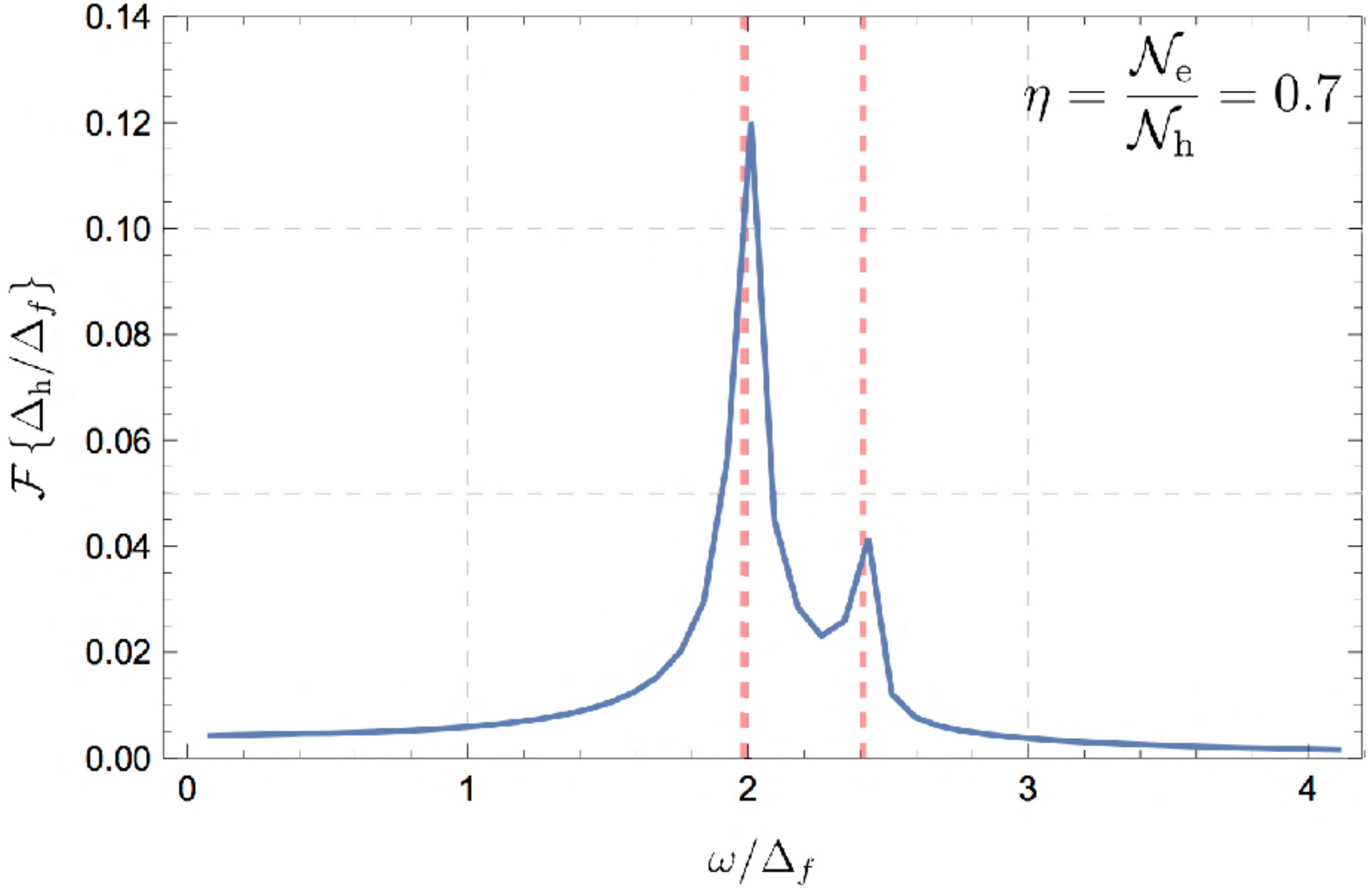



0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
1
2
3
4
$\eta = \frac{\mathcal{N}_e}{\mathcal{N}_h} = 0.7$
$\mathcal{F}\{\Delta_h/\Delta_f\}$
$\omega/\Delta_f$

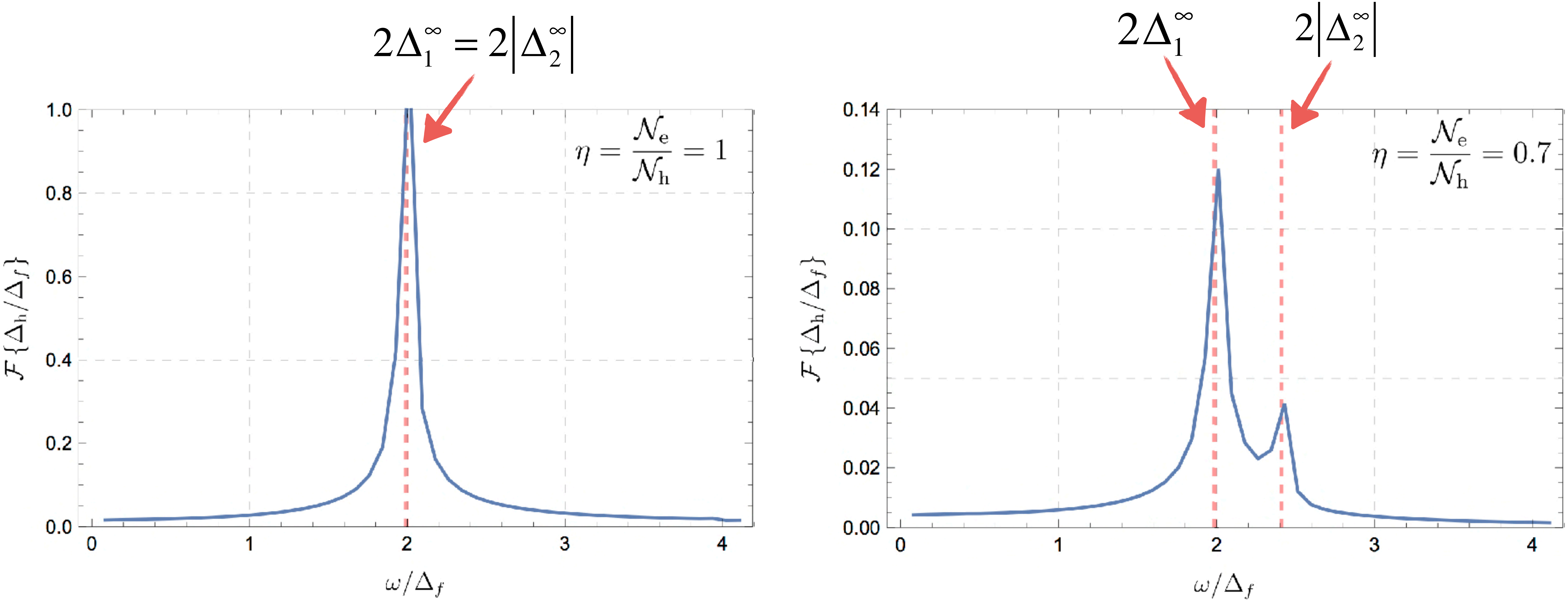
# Results

$$2\Delta_1^\infty = 2\left|\Delta_2^\infty\right|$$



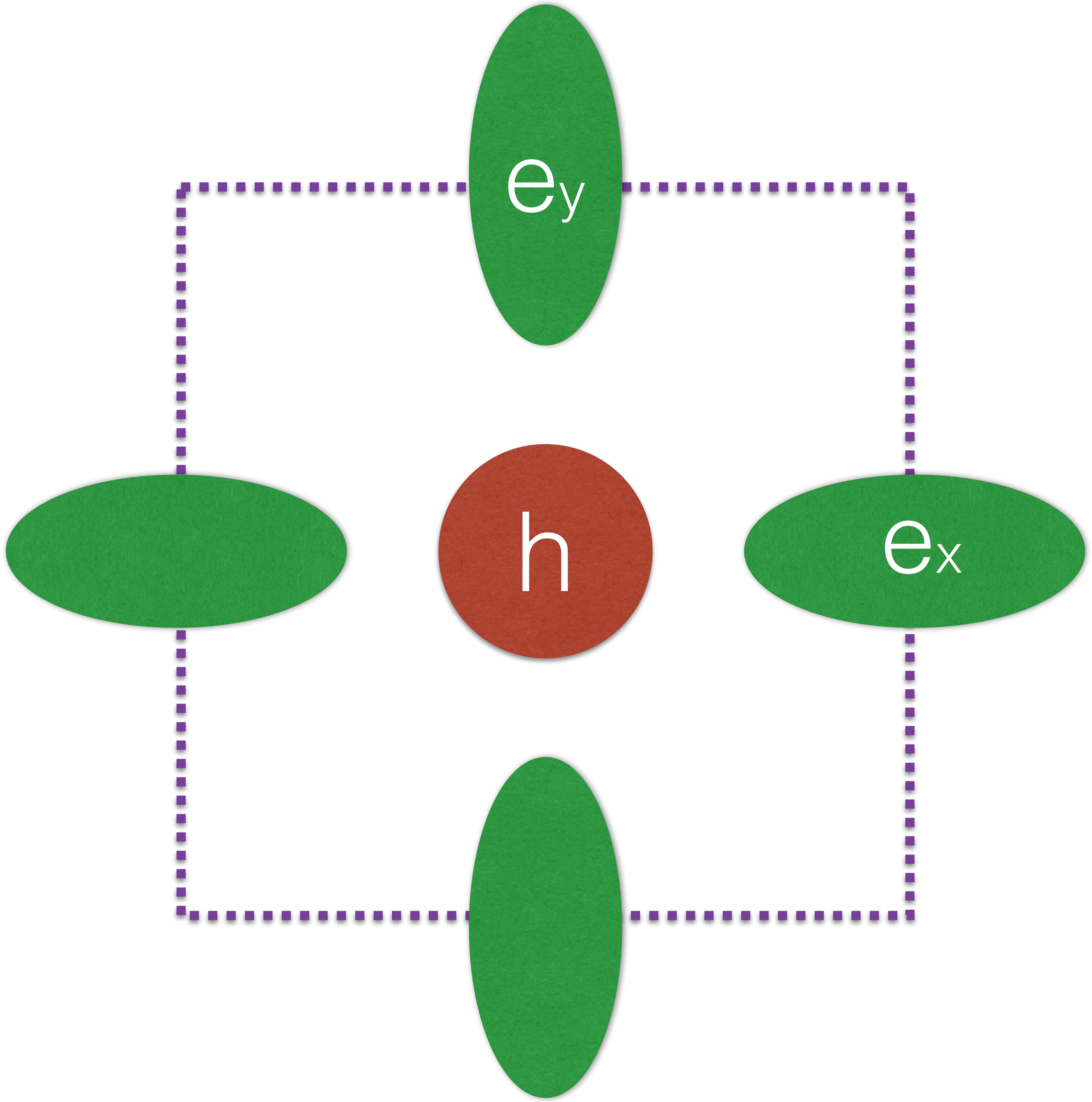
# Results


$2\Delta_1^\infty = 2|\Delta_2^\infty|$
$\eta = \frac{\mathcal{N}_e}{\mathcal{N}_h} = 1$
1.0
0.8
0.6
0.4
0.2
0.0
$\mathcal{F}\{\Delta_h/\Delta_f\}$
0
1
2
3
4
$\omega/\Delta_f$
$2\Delta_1^\infty$
$2|\Delta_2^\infty|$
$\eta = \frac{\mathcal{N}_e}{\mathcal{N}_h} = 0.7$
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$\mathcal{F}\{\Delta_h/\Delta_f\}$
0
1
2
3
4
$\omega/\Delta_f$

# Outline

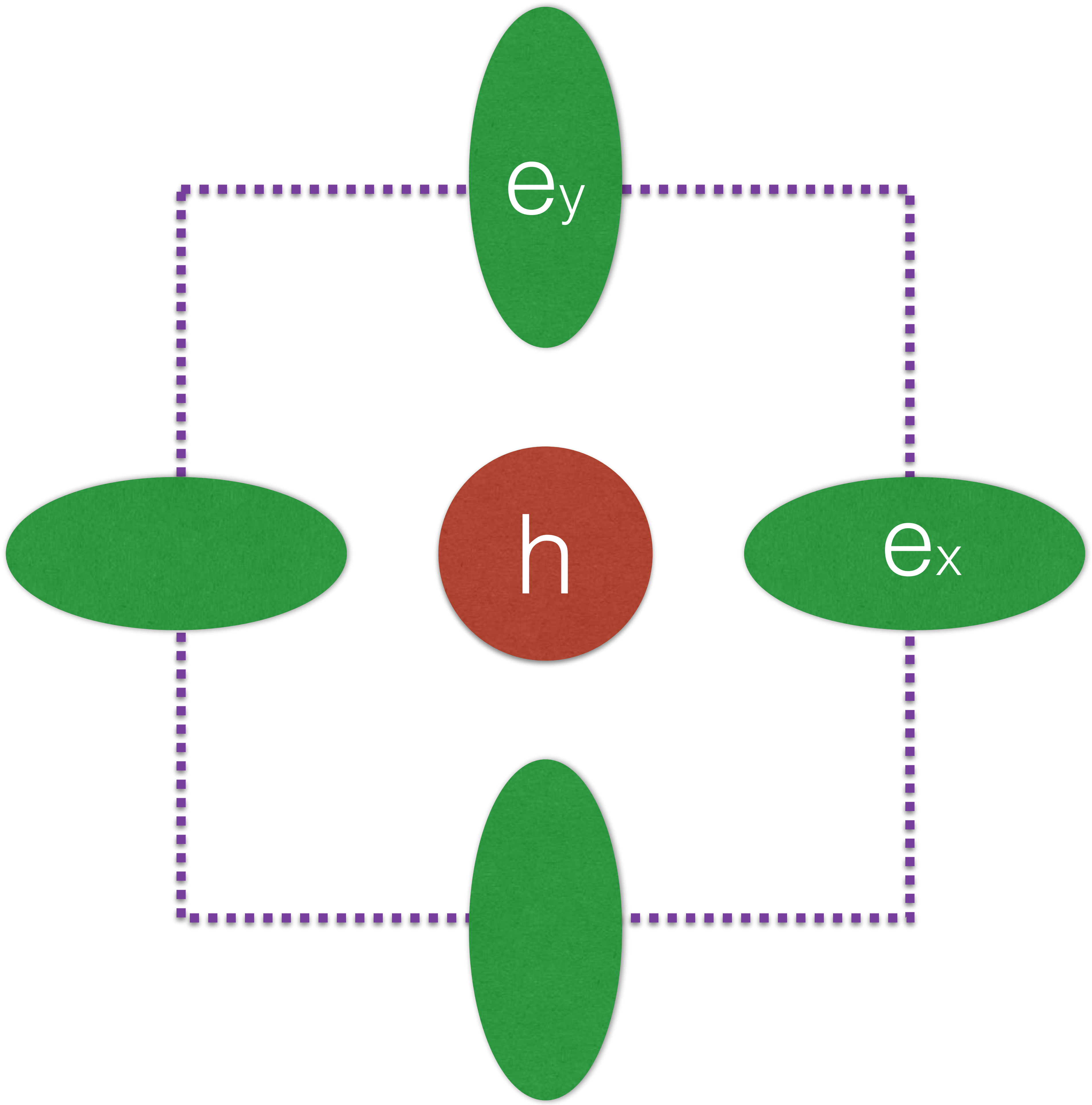
- Single-band BCS
- Two-band Superconductors
- Iron-based Superconductors

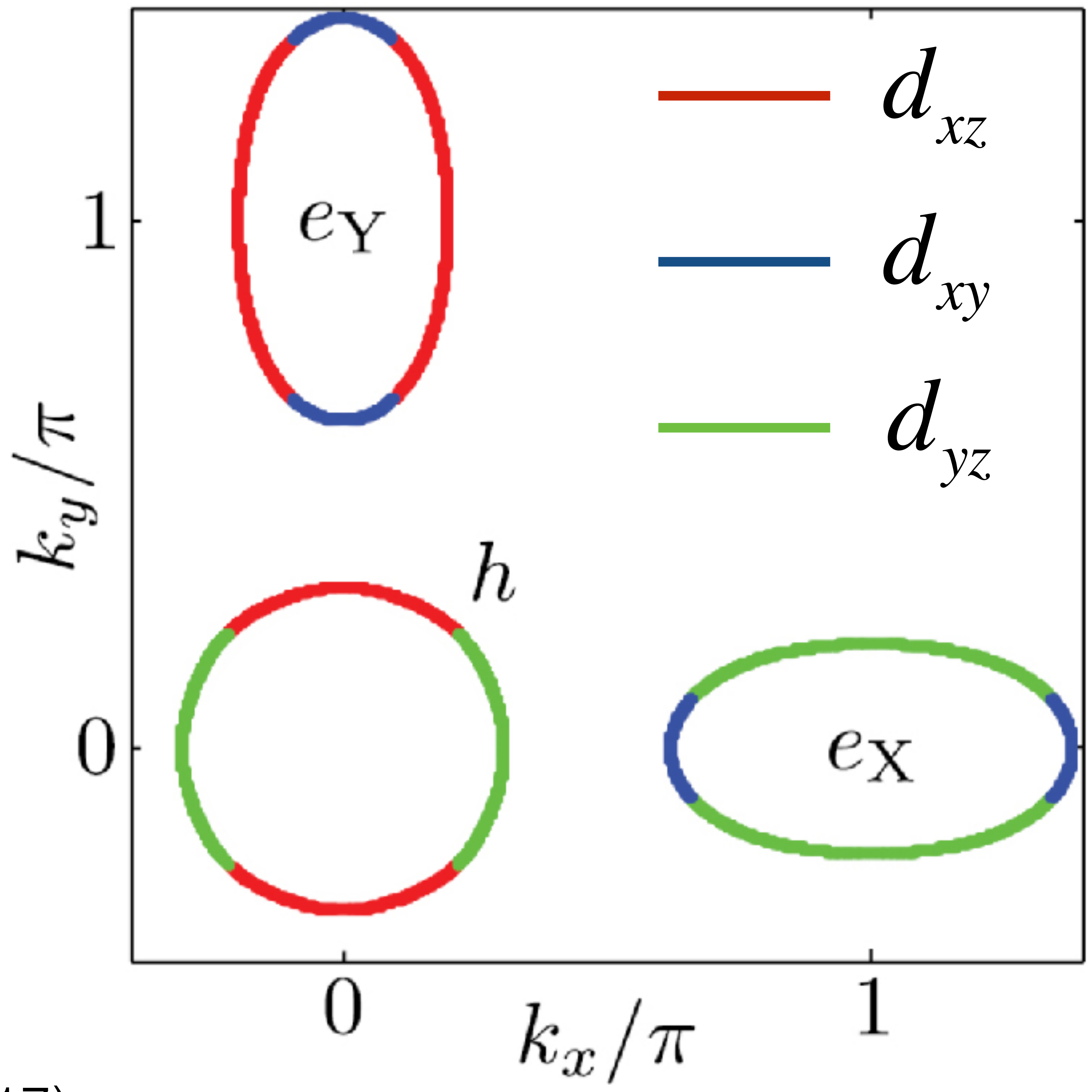
# Orbital-projected three-band model




[1] R. M. Fernandes, A. V. Chubukov, Rep. Prog. Phys., **80**(1), 14503 (2017)

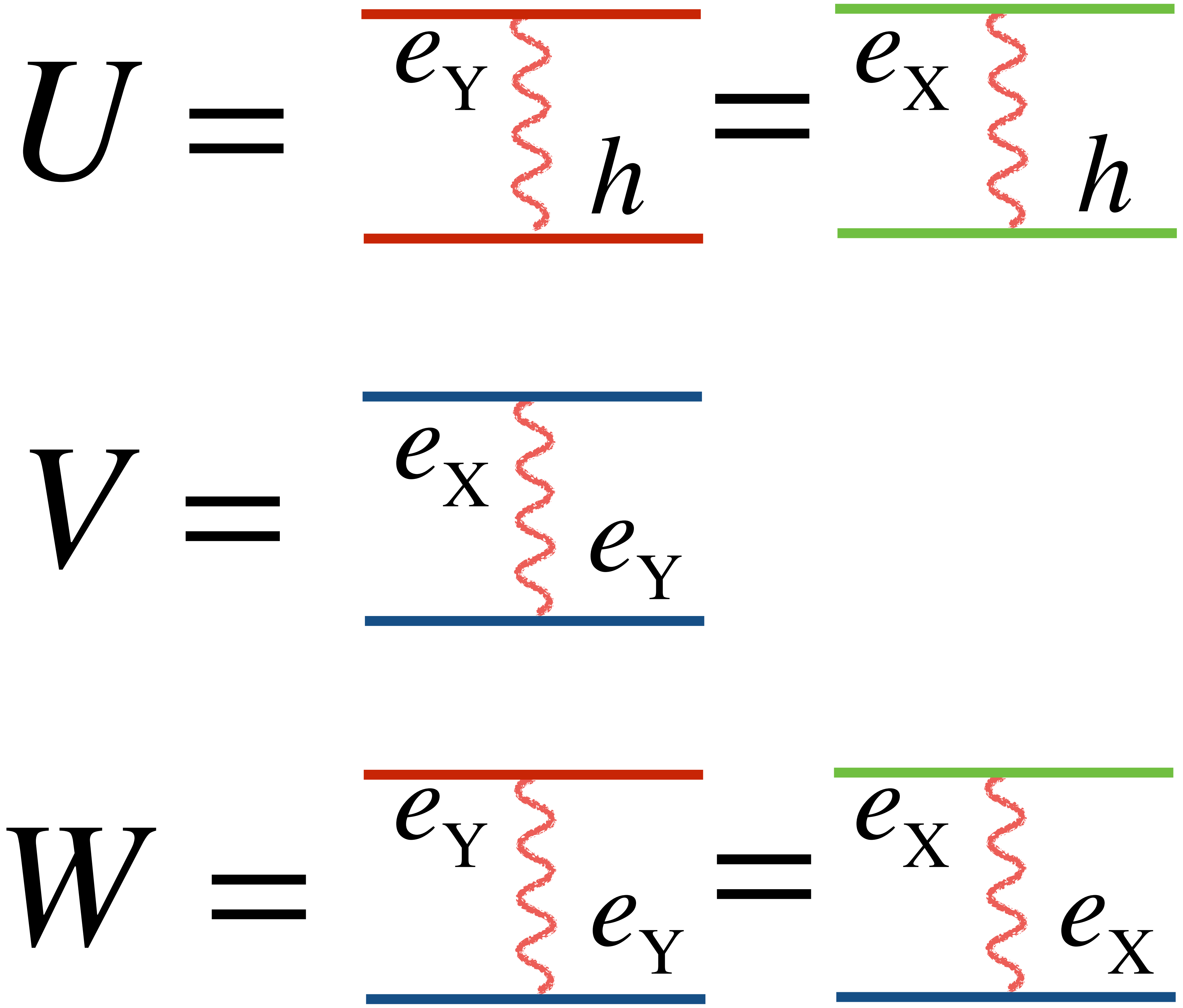
# Orbital-projected three-band model

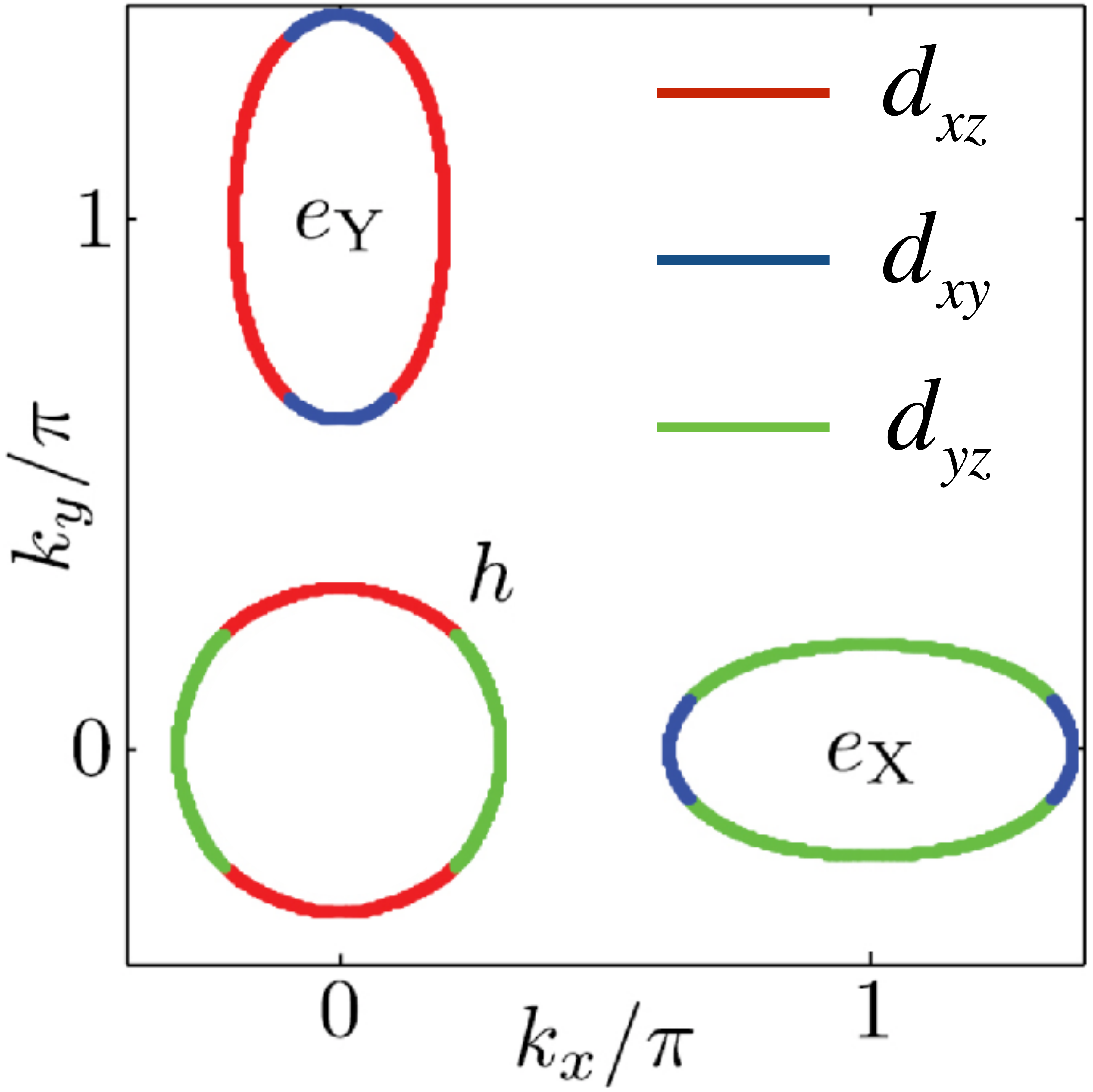


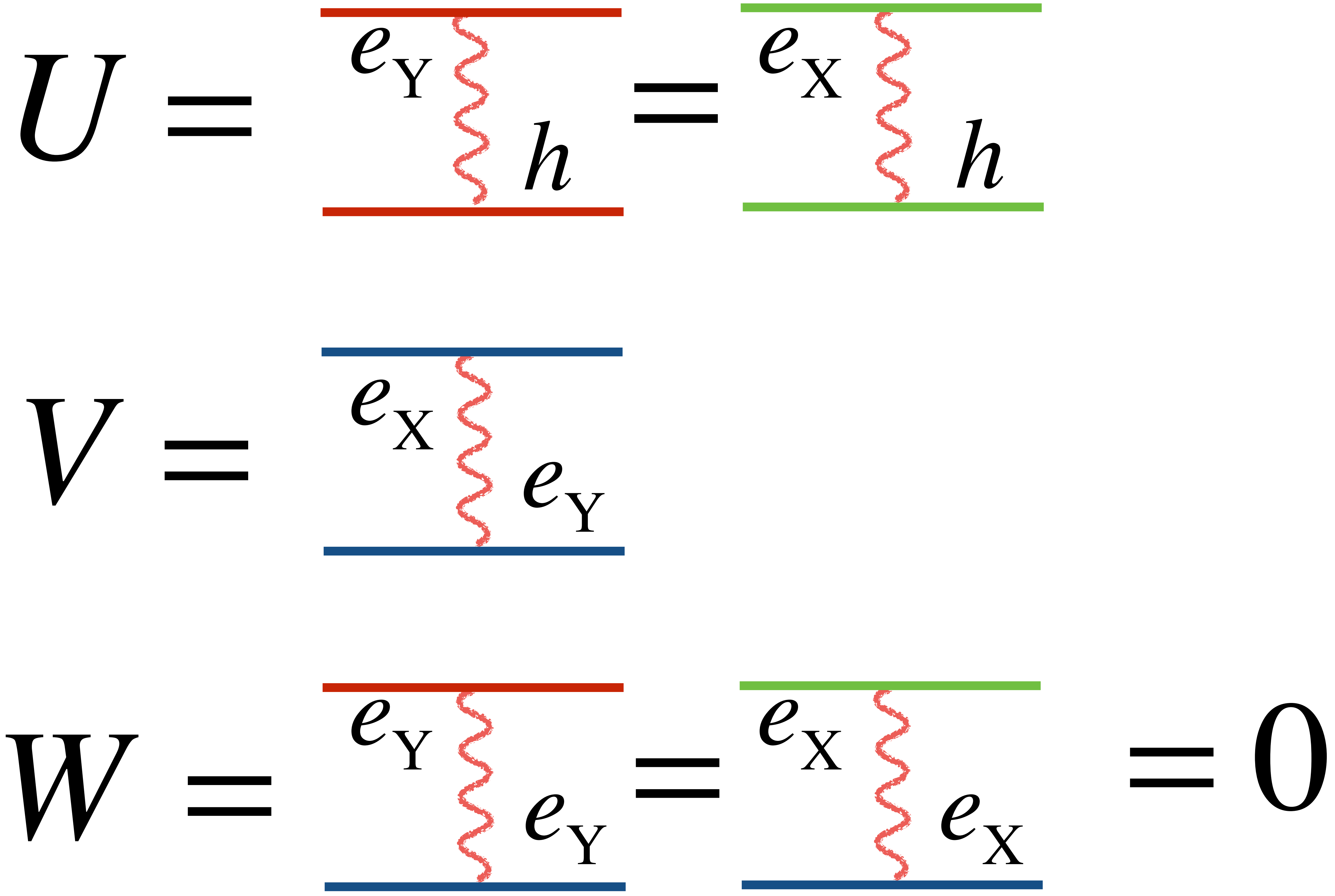

[1] R. M. Fernandes, A. V. Chubukov, Rep. Prog. Phys., **80**(1), 14503 (2017)

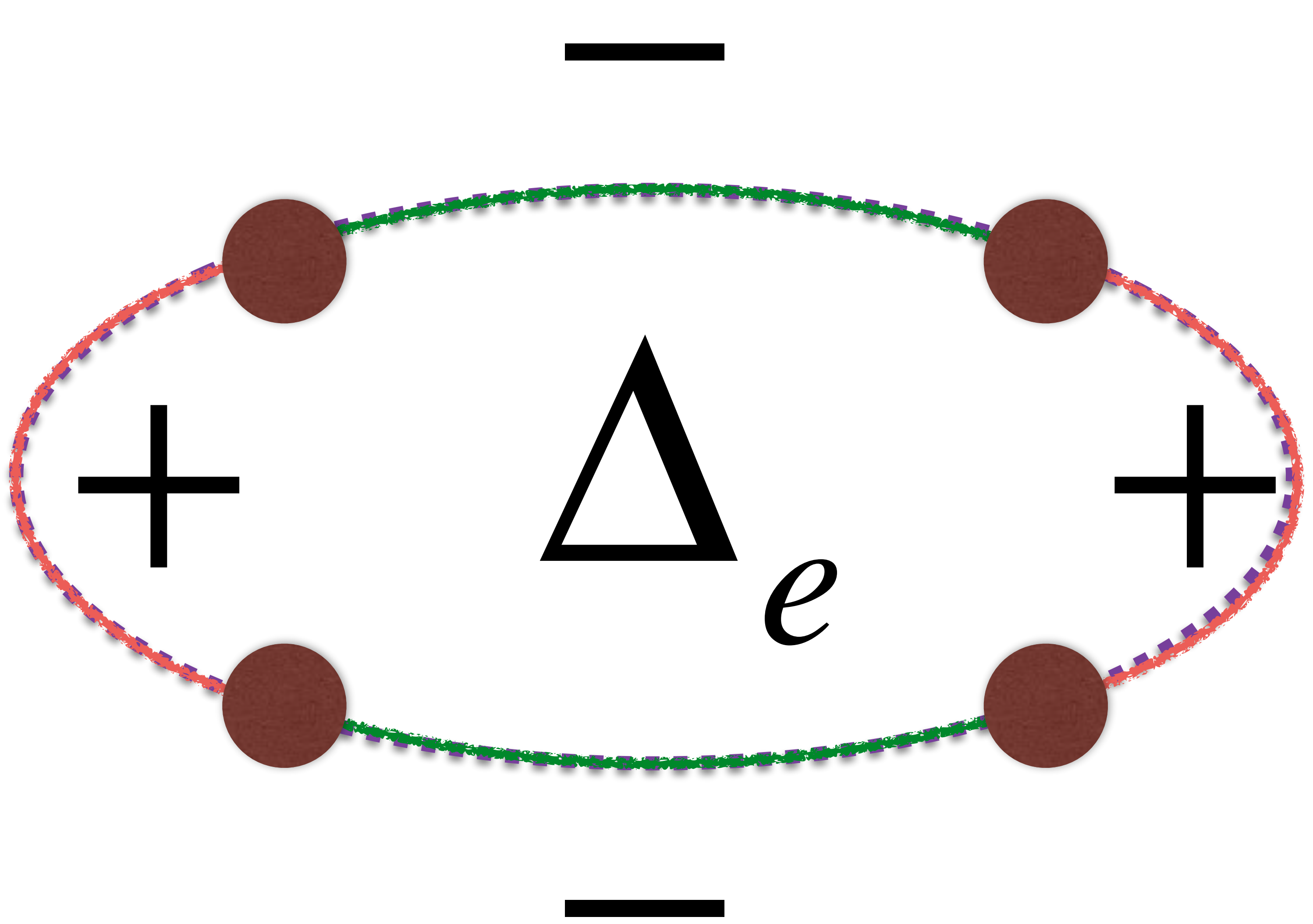
# Pairing interactions



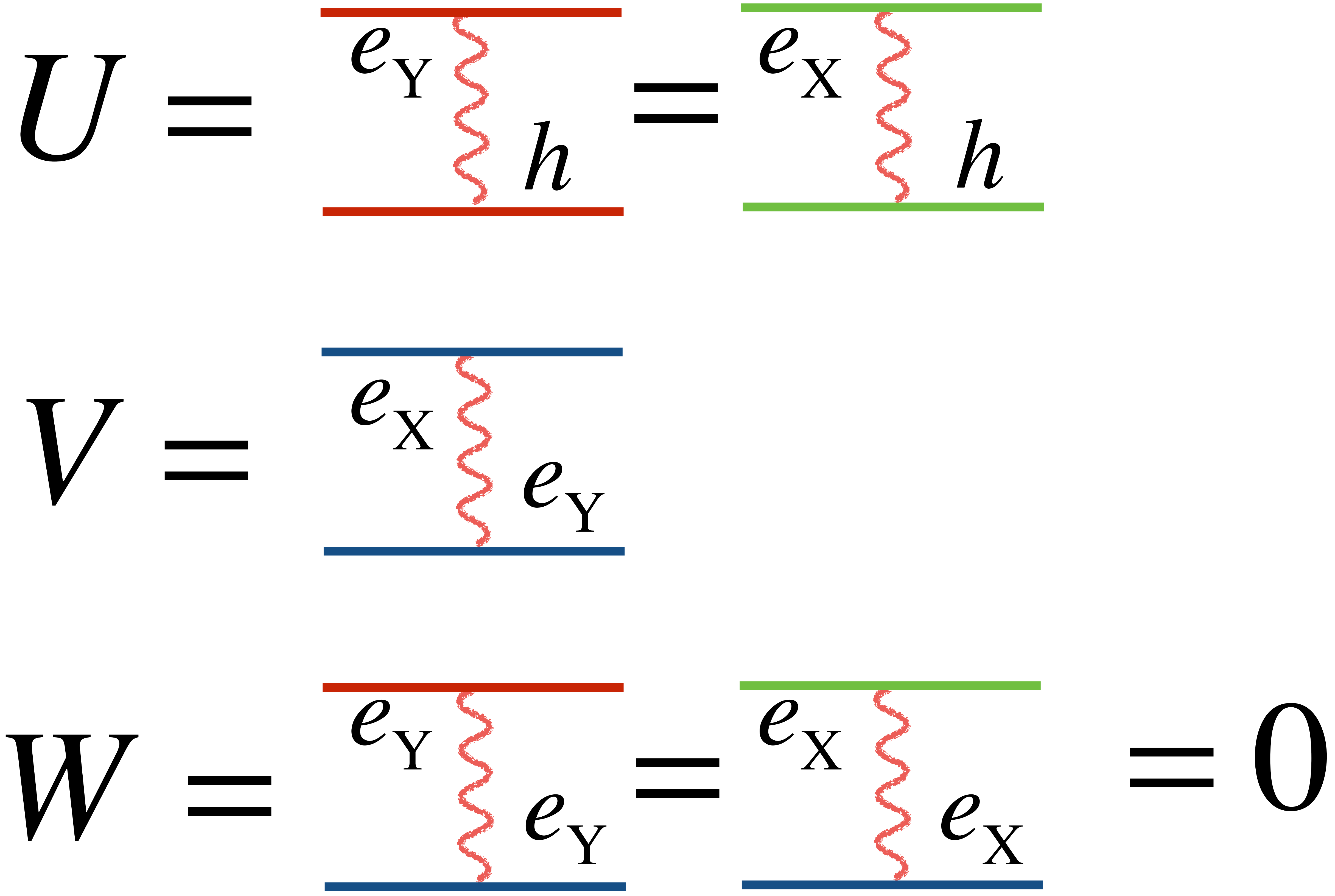
# Nodal vs nodeless gap

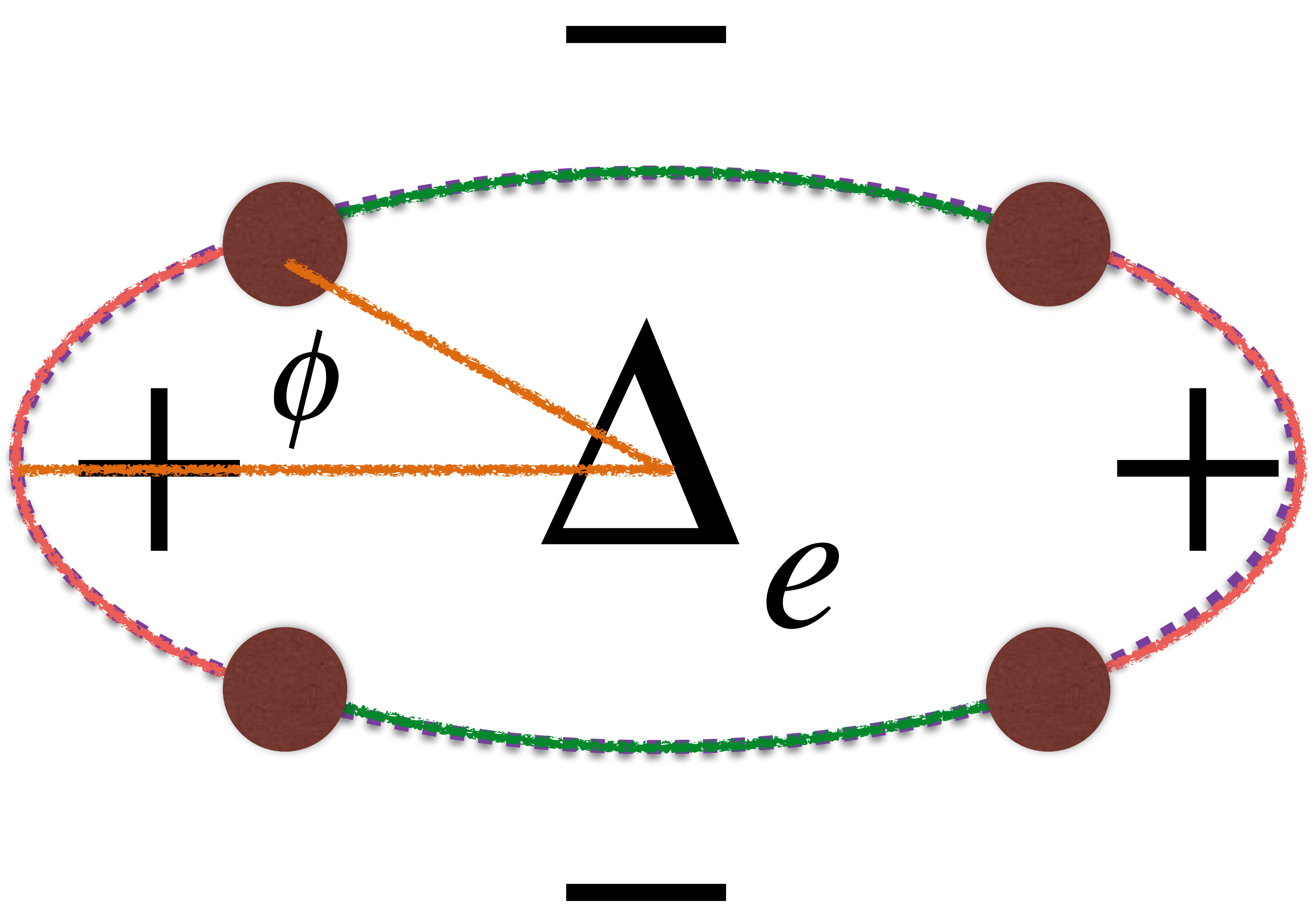



[1] J. Kang, A. F. Kemper, R. M. Fernandes, Phys. Rev. Lett., **113**, 217001 (2014)

# Nodal vs nodeless gap




[1] J. Kang, A. F. Kemper, R. M. Fernandes, Phys. Rev. Lett., **113**, 217001 (2014)

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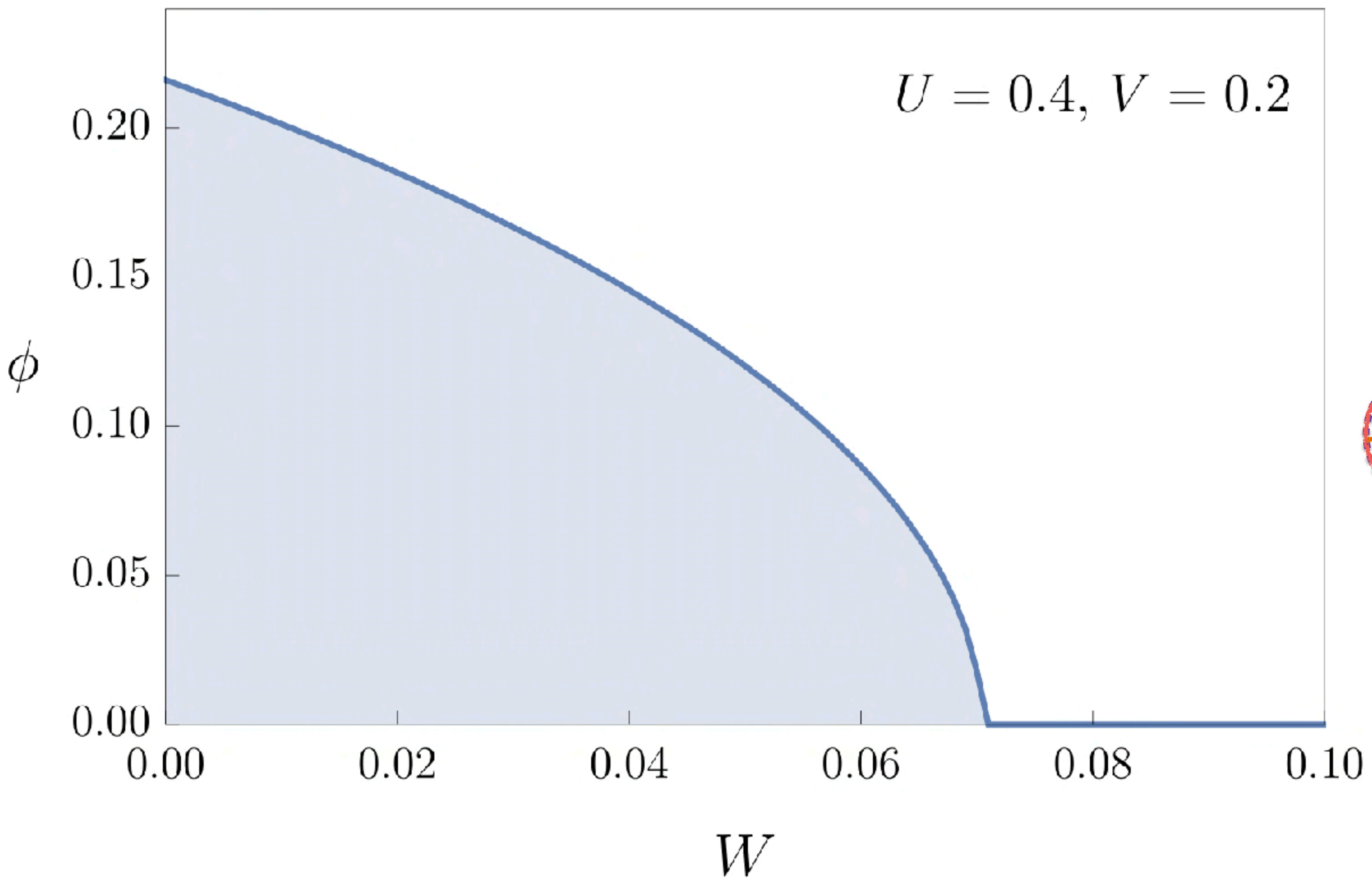


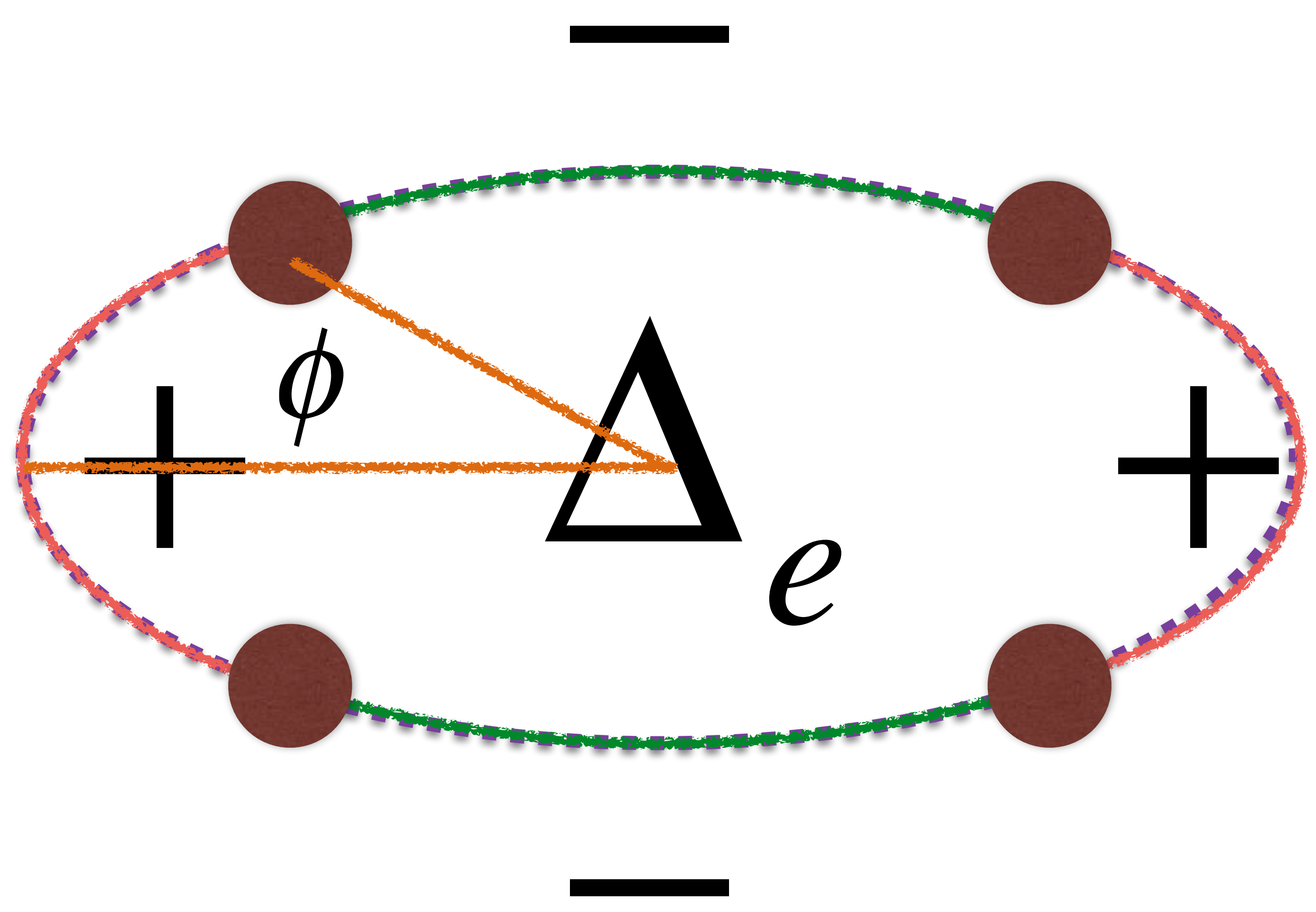

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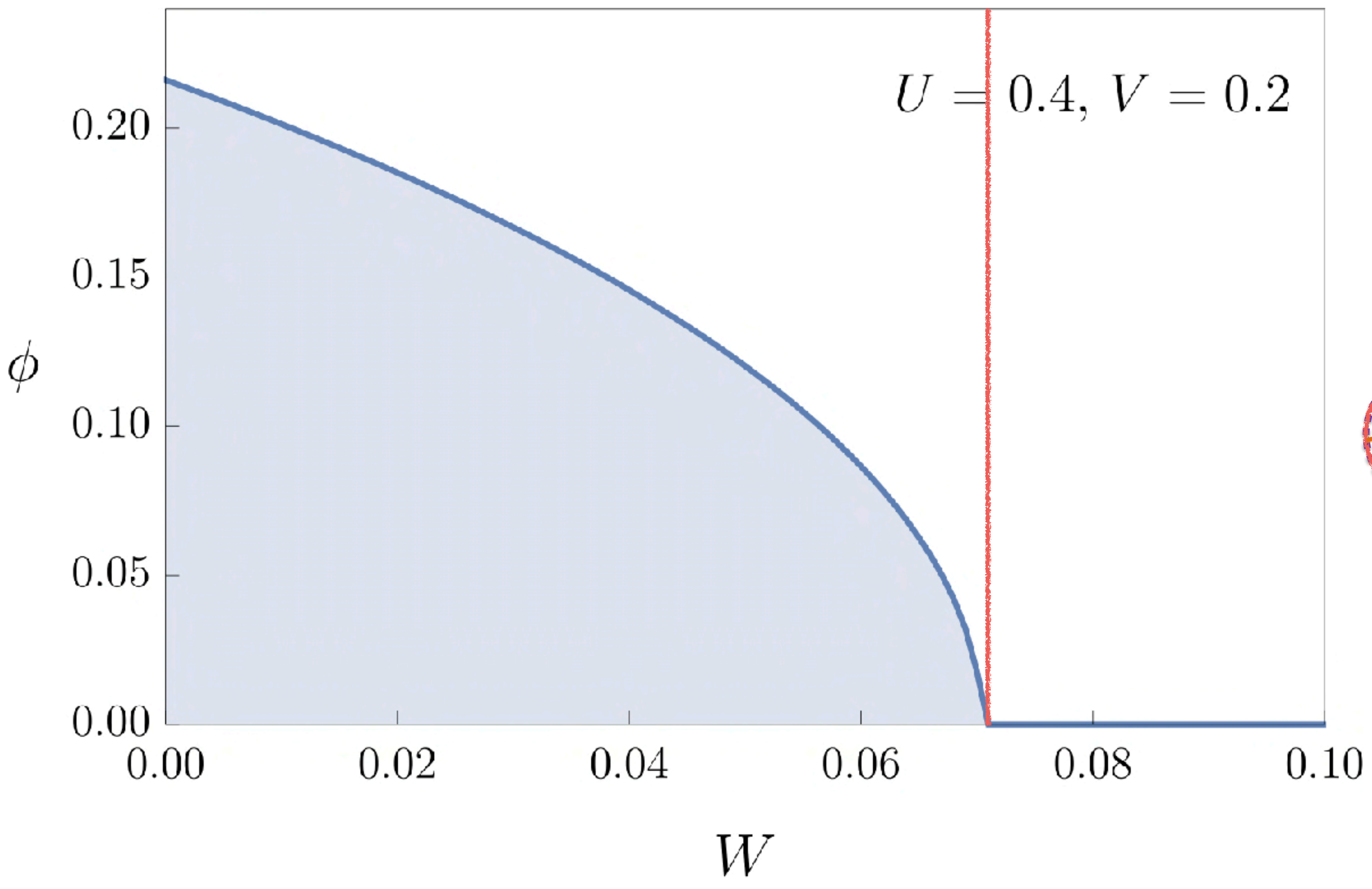


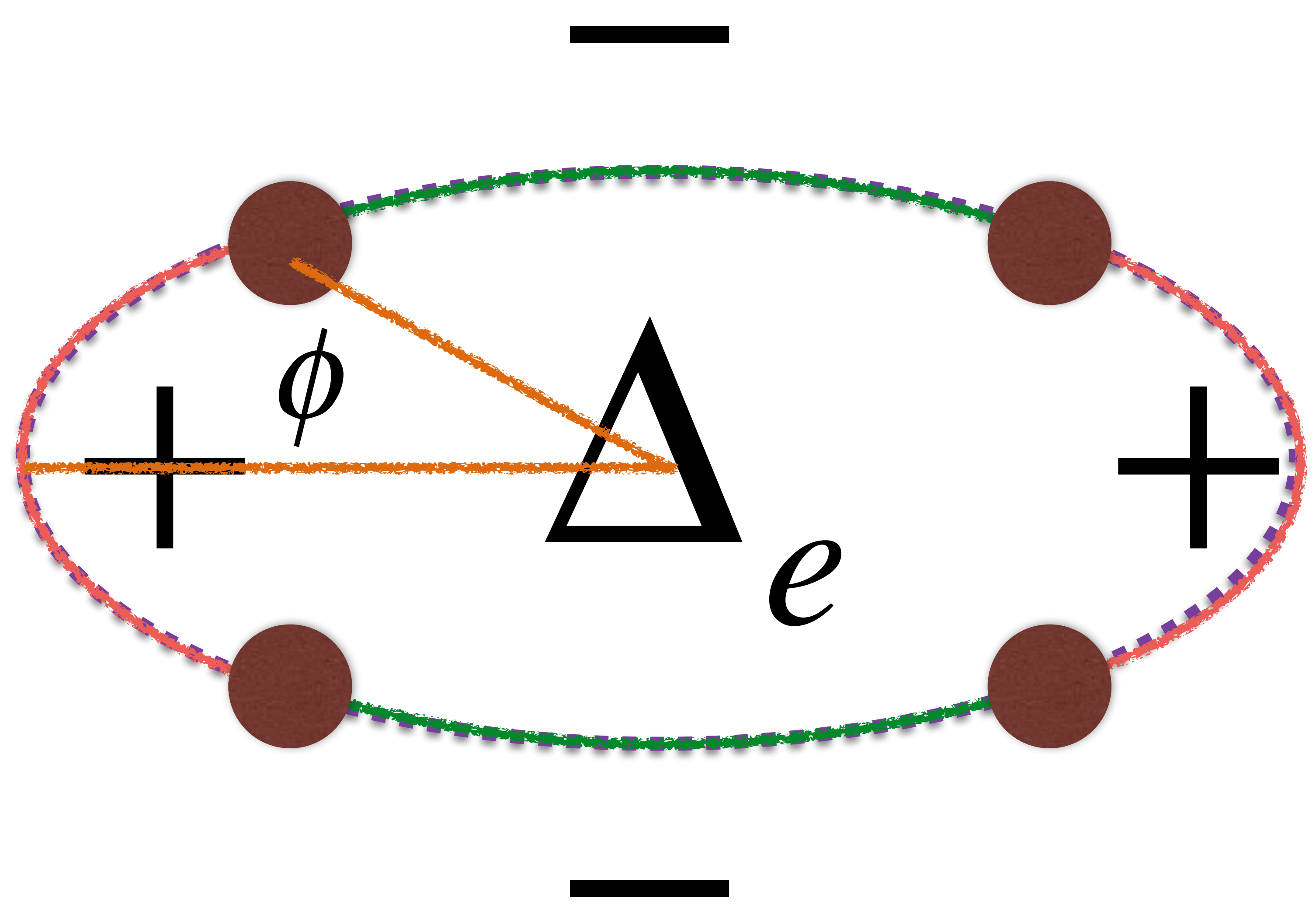

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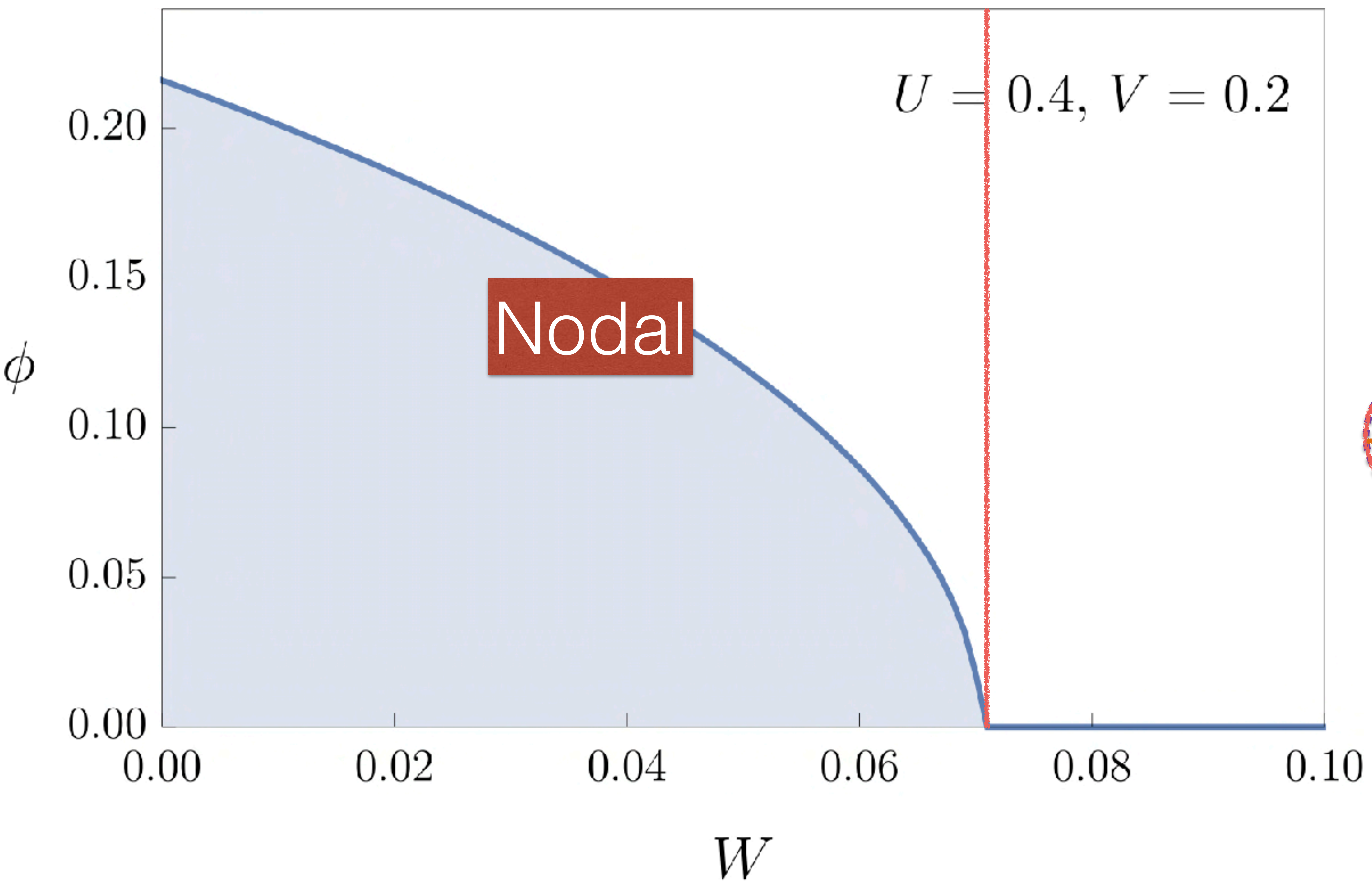


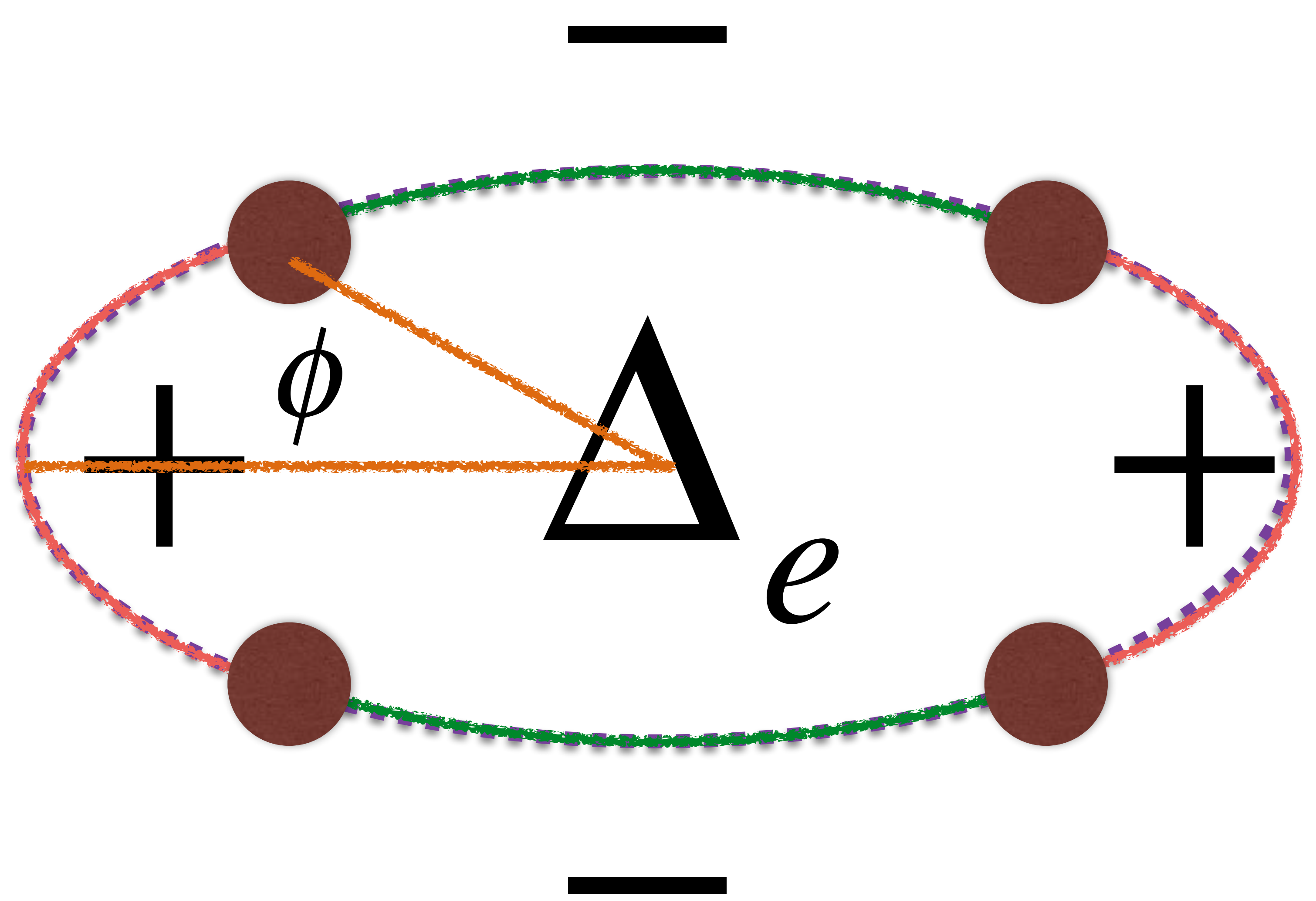

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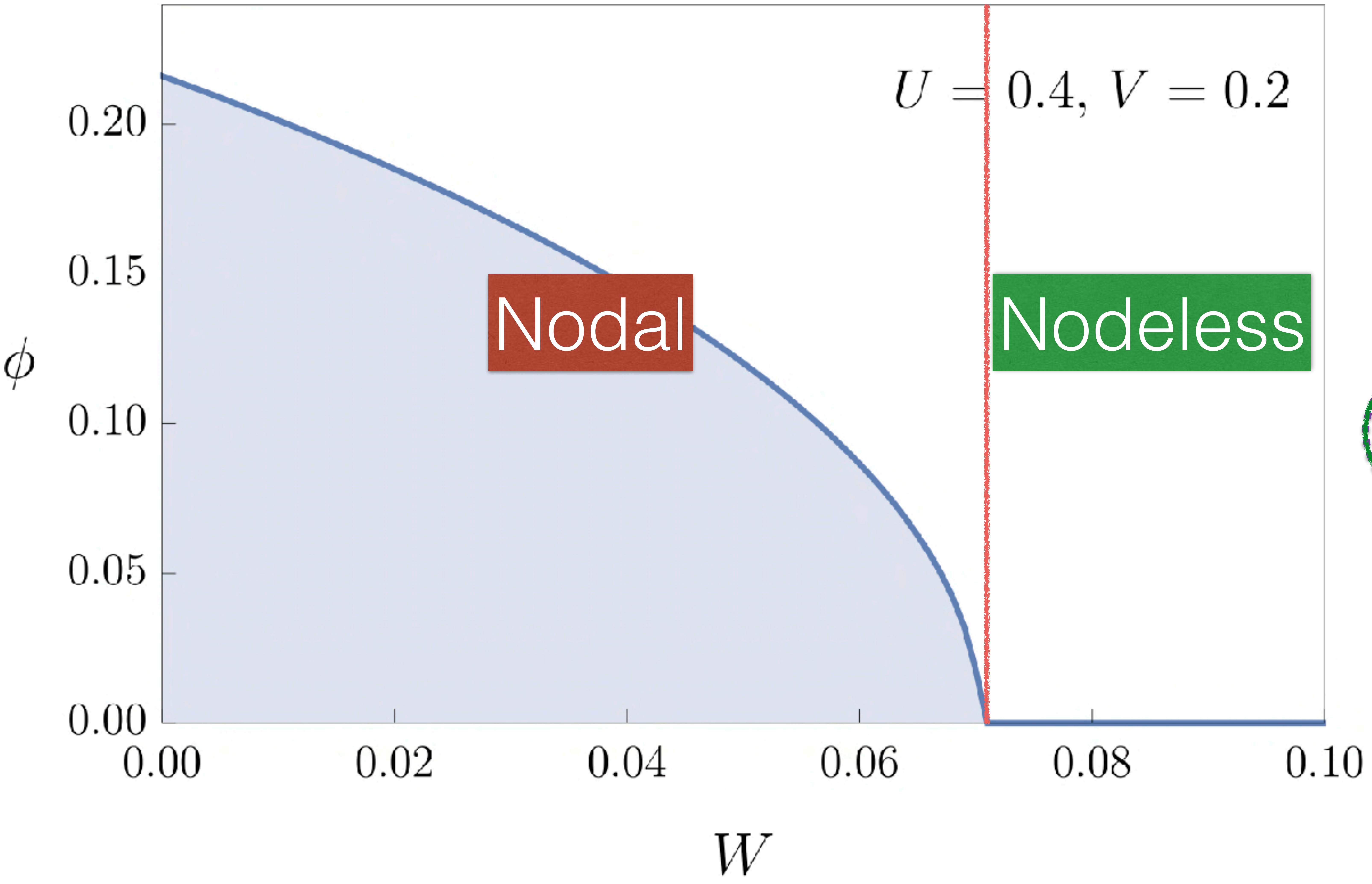


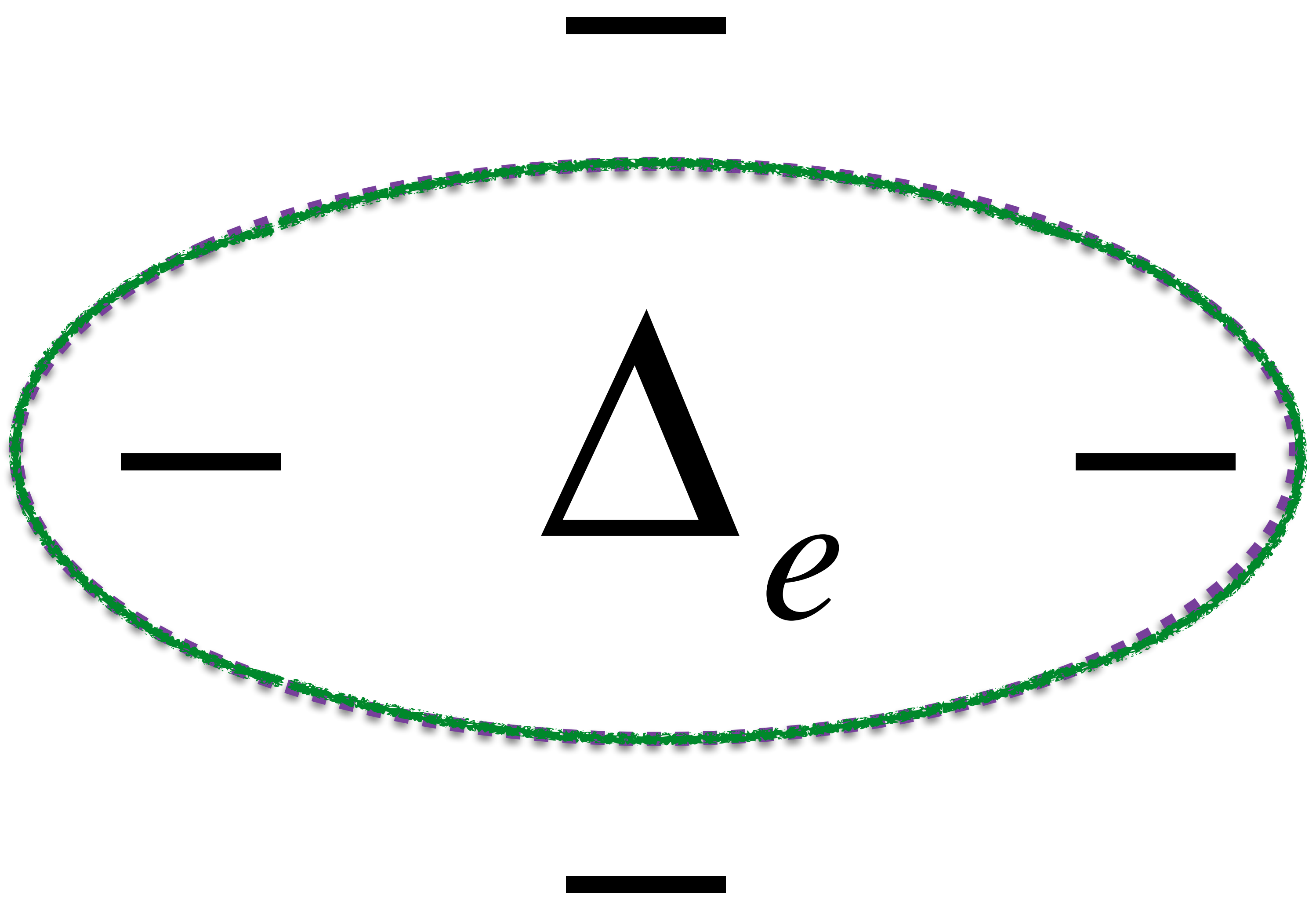

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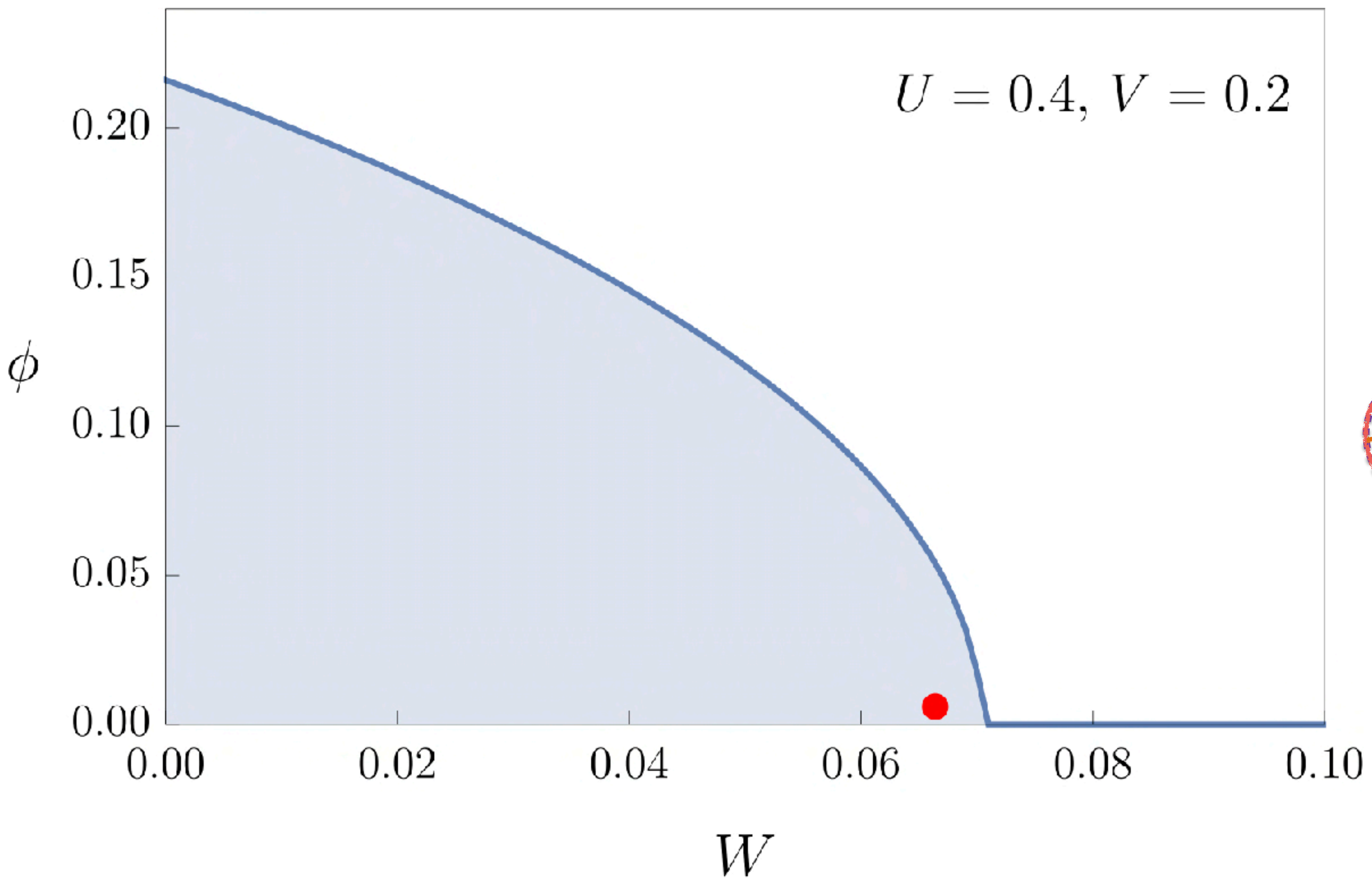


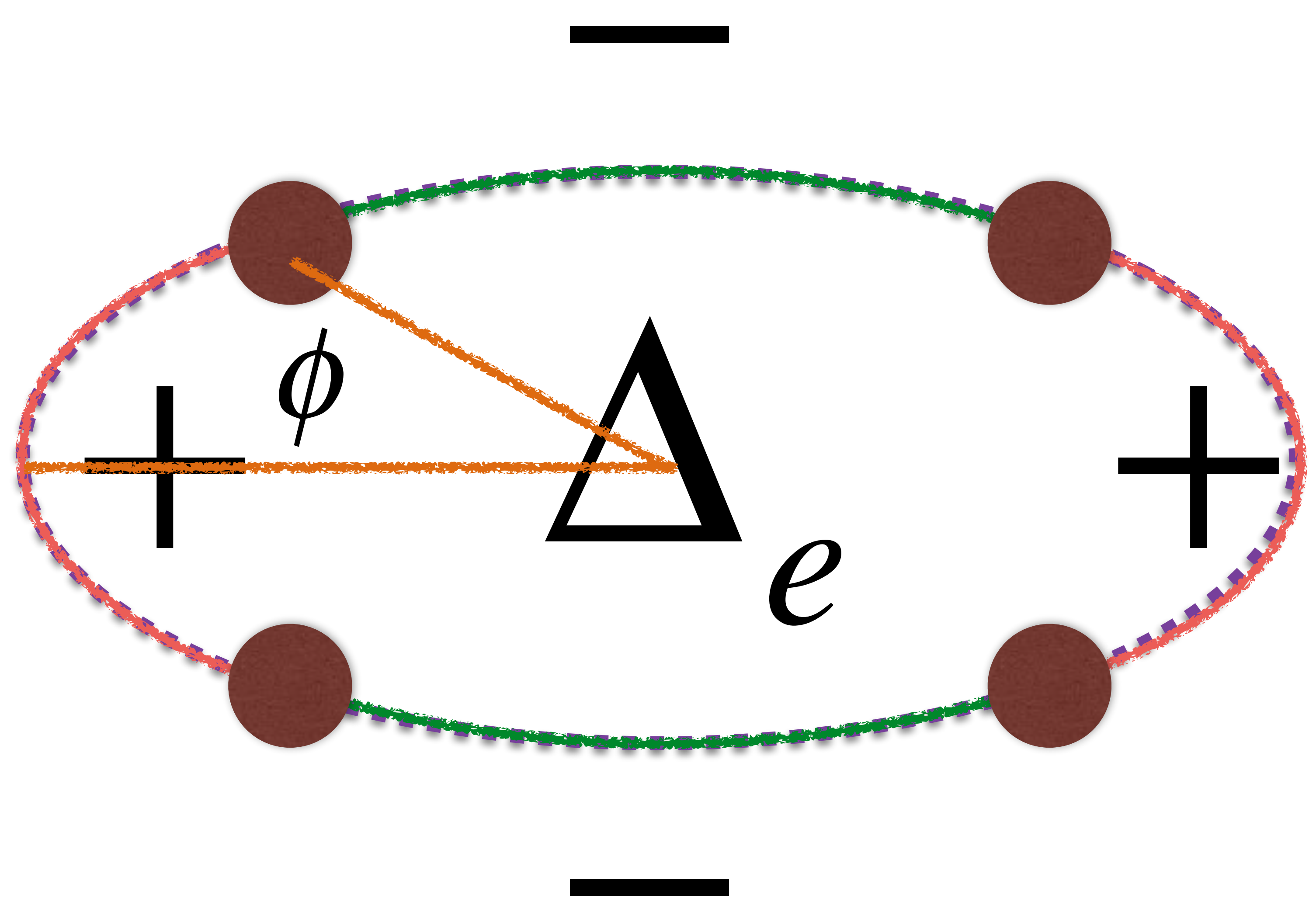

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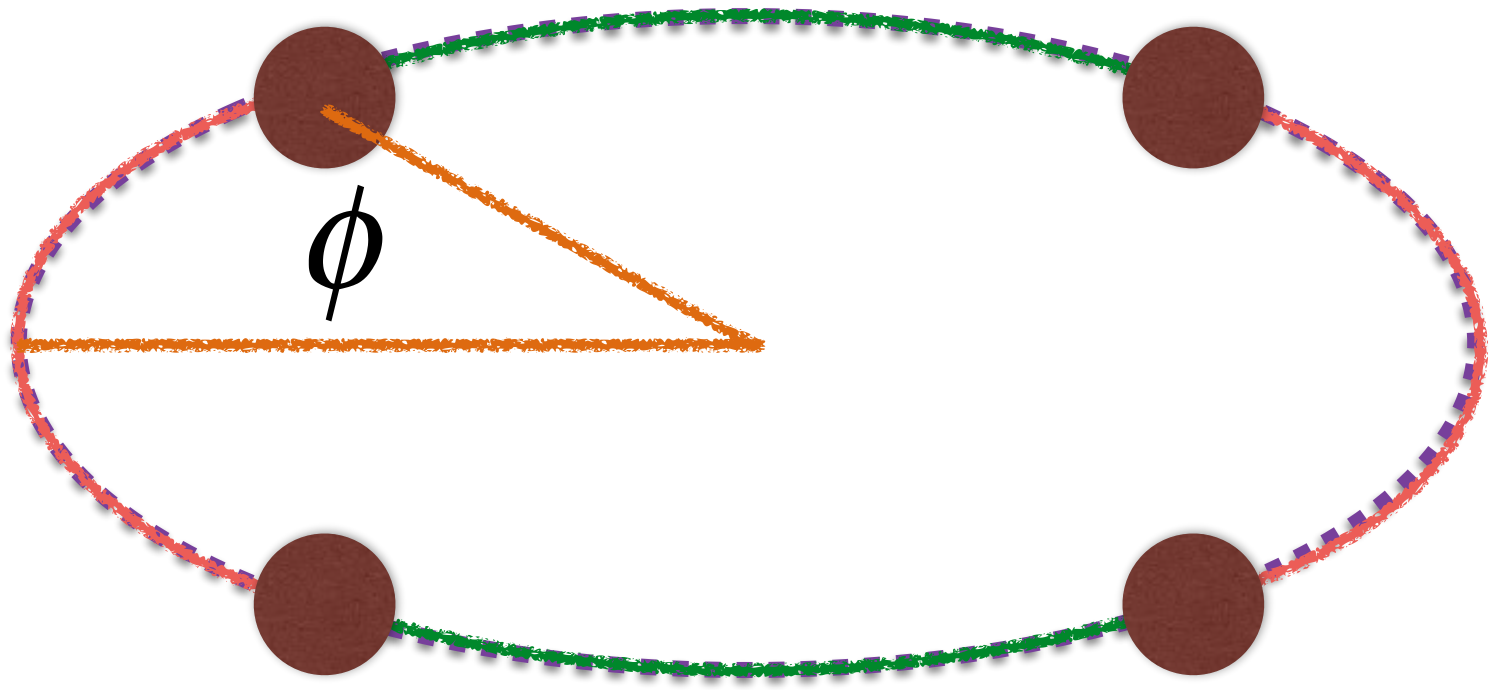


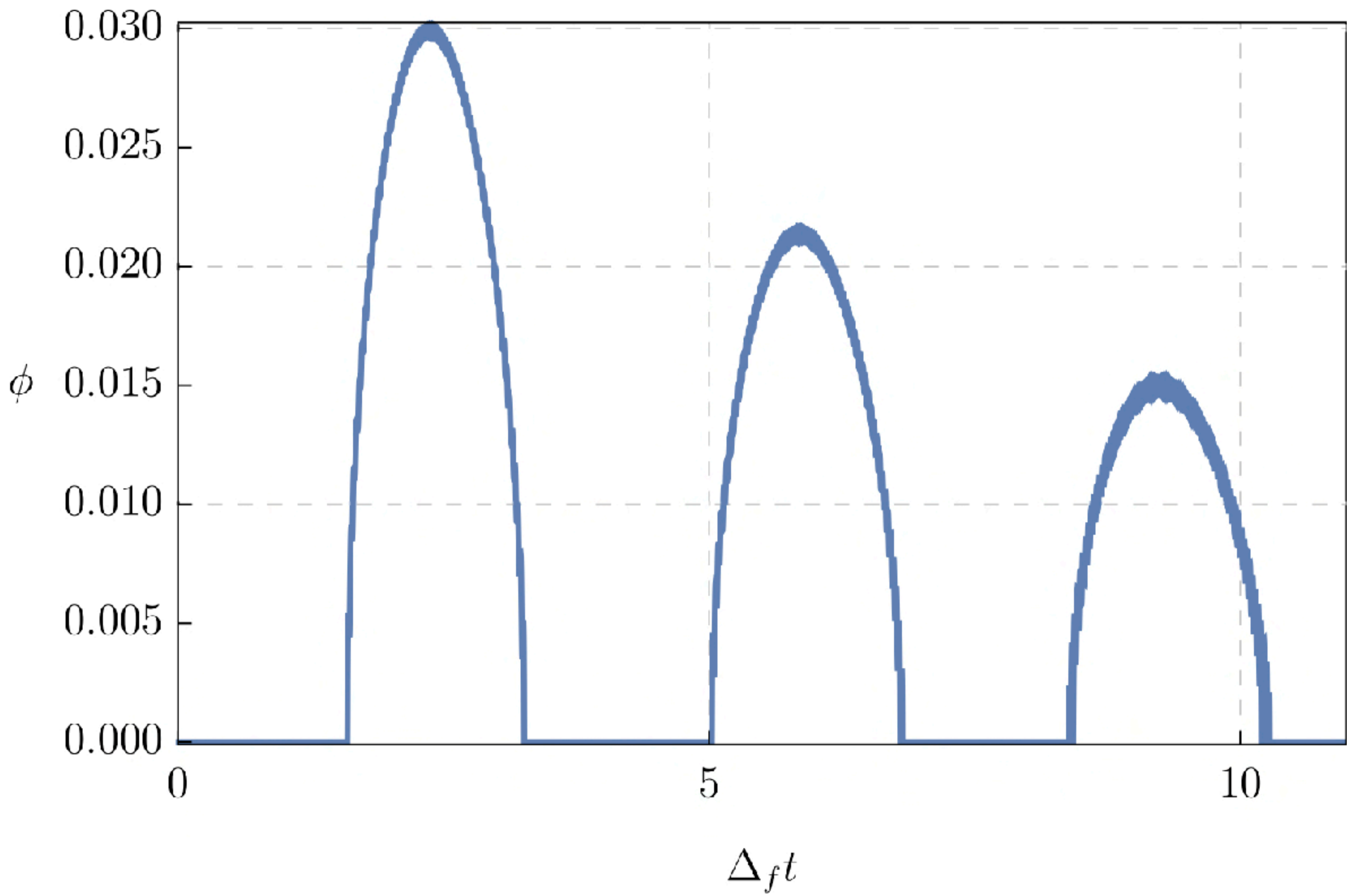

# Conclusions

- The ultra-fast pump-prob technique provides a new perspective of the study of unconventional superconductors by investigating the transient dynamics.

- Find the non-equilibrium features that will bring new insights on the gap symmetries of unconventional superconductors.