Impact of damping on superconducting gap oscillations induced by Terahertz pulses

Tianbai Cui, Rafael M. Fernandes

University of Minnesota

Xu Yang, Chirag Vaswani, Jigang Wang, Peter P. Orth

Iowa State University and Ames Laboratory

U.S. DEPARTMENT OF ENERGY

UNIVERSITY OF MINNESOTA
Driven to Discover℠

Equilibrium superconductivity

[1] R. Matsunaga and R. Shimano, *Phys. Scr.,* **92**(2), 24003 (2017).
[2]A. F. Kemper, M. A. Sentef, B. Moritz, J. K. Freericks, and T. P. Devereaux, *Phys. Rev. B,* **92**, 224517 (2015).

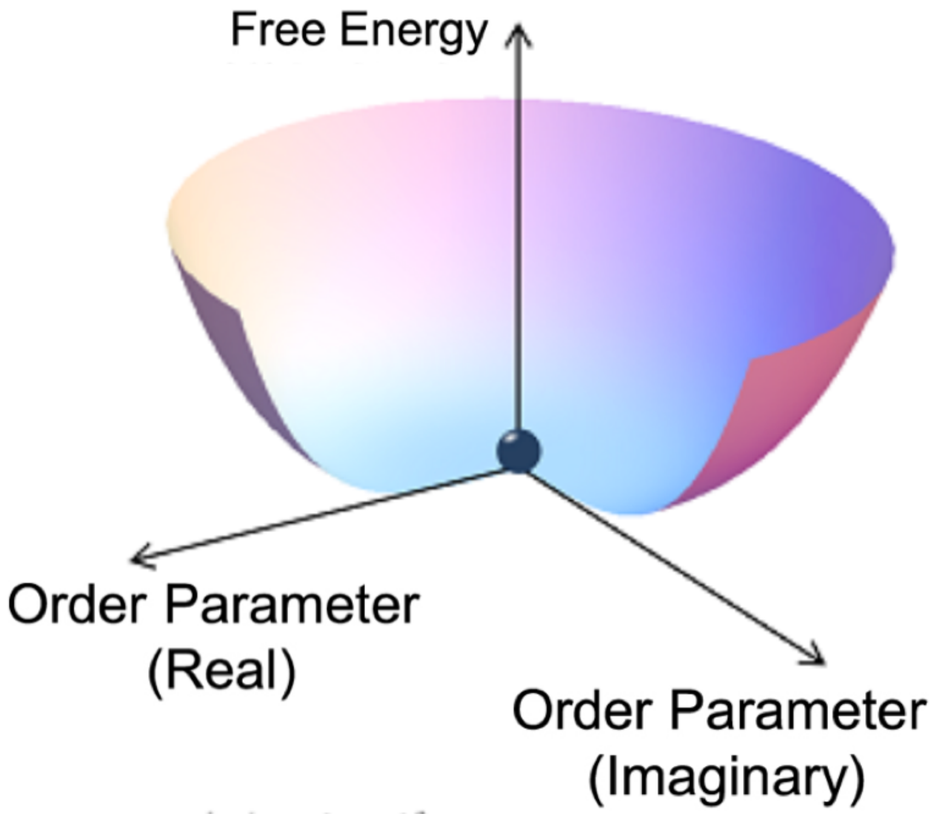
Equilibrium superconductivity

$$\Delta = -U \sum_{\mathbf{k}} \left\langle c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow} \right\rangle$$

[1] R. Matsunaga and R. Shimano, *Phys. Scr.,* **92**(2), 24003 (2017).
[2]A. F. Kemper, M. A. Sentef, B. Moritz, J. K. Freericks, and T. P. Devereaux, *Phys. Rev. B,* **92**, 224517 (2015).

Equilibrium superconductivity

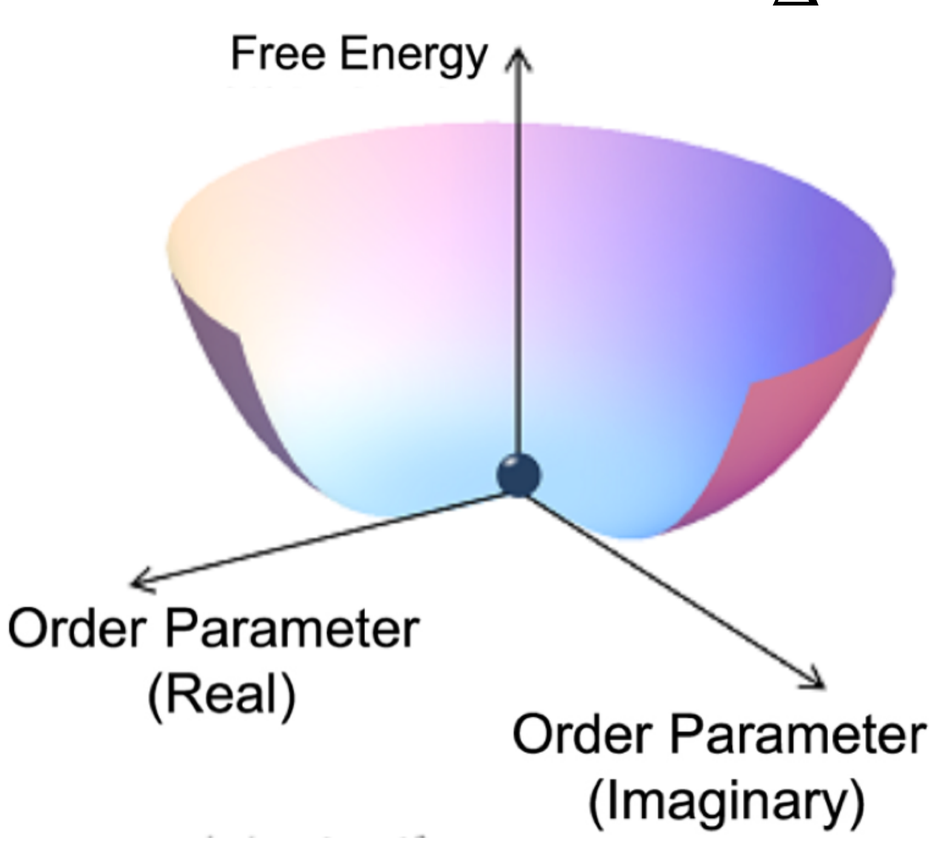
$$\Delta = -U \sum_{\mathbf{k}} \left\langle c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow} \right\rangle$$

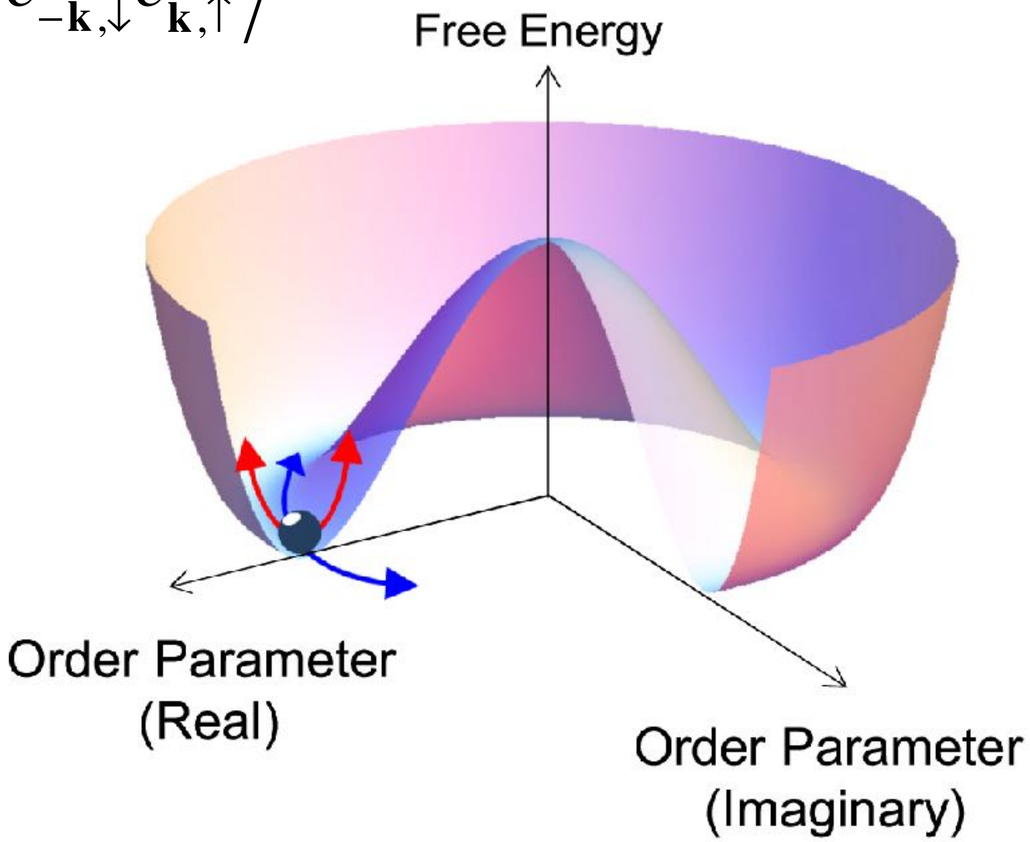


[1] R. Matsunaga and R. Shimano, *Phys. Scr.,* **92**(2), 24003 (2017).
[2]A. F. Kemper, M. A. Sentef, B. Moritz, J. K. Freericks, and T. P. Devereaux, *Phys. Rev. B,* **92**, 224517 (2015).

Equilibrium superconductivity

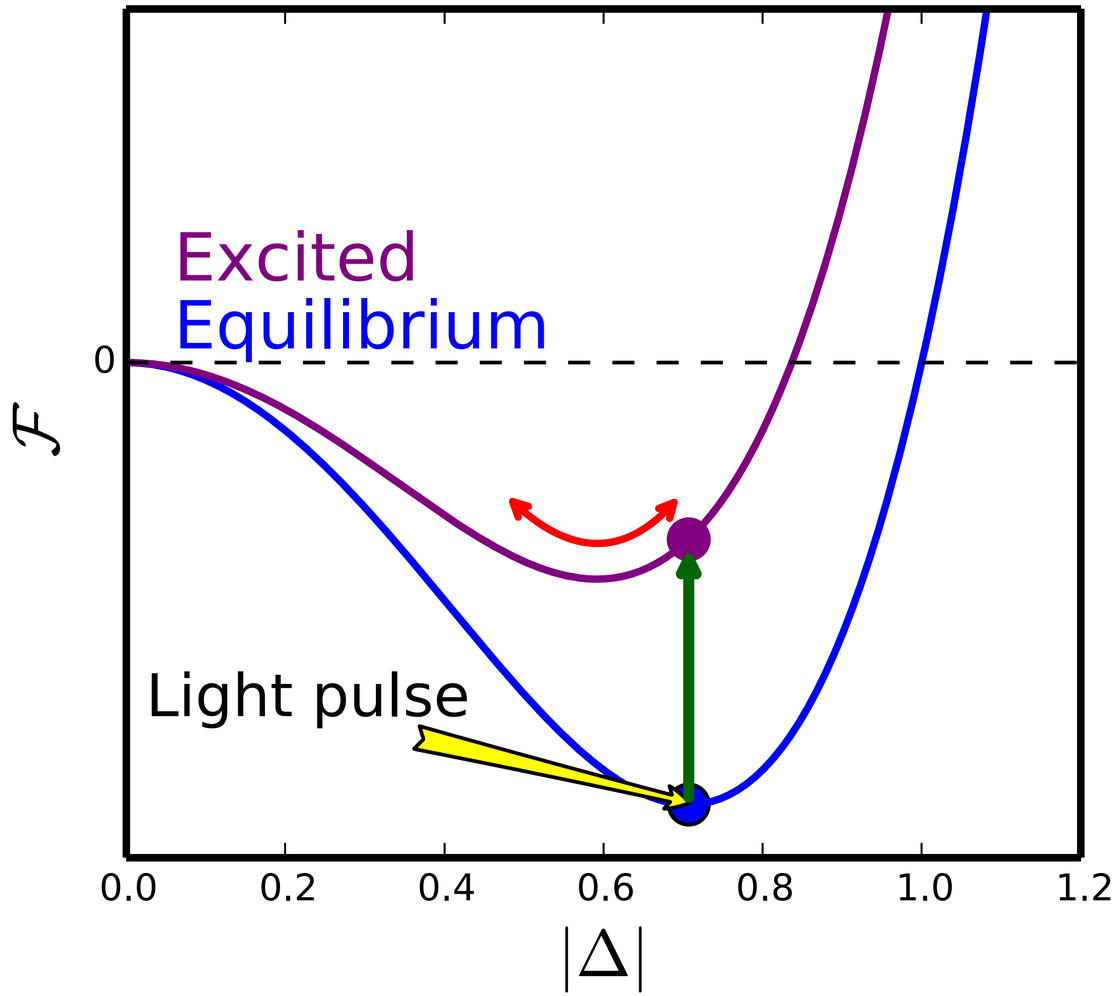
$$\Delta = -U \sum_{\mathbf{k}} \left\langle c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow} \right\rangle$$

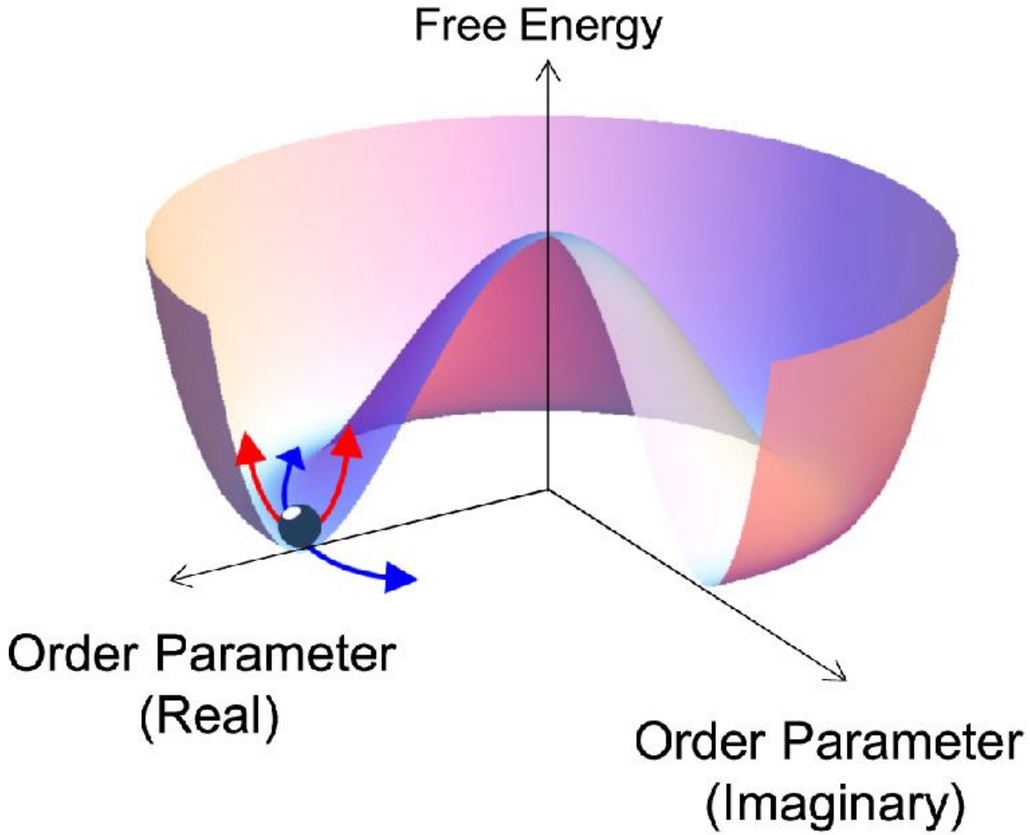




[1] R. Matsunaga and R. Shimano, *Phys. Scr.,* **92**(2), 24003 (2017).
[2]A. F. Kemper, M. A. Sentef, B. Moritz, J. K. Freericks, and T. P. Devereaux, *Phys. Rev. B,* **92**, 224517 (2015).

Non-equilibrium superconductivity

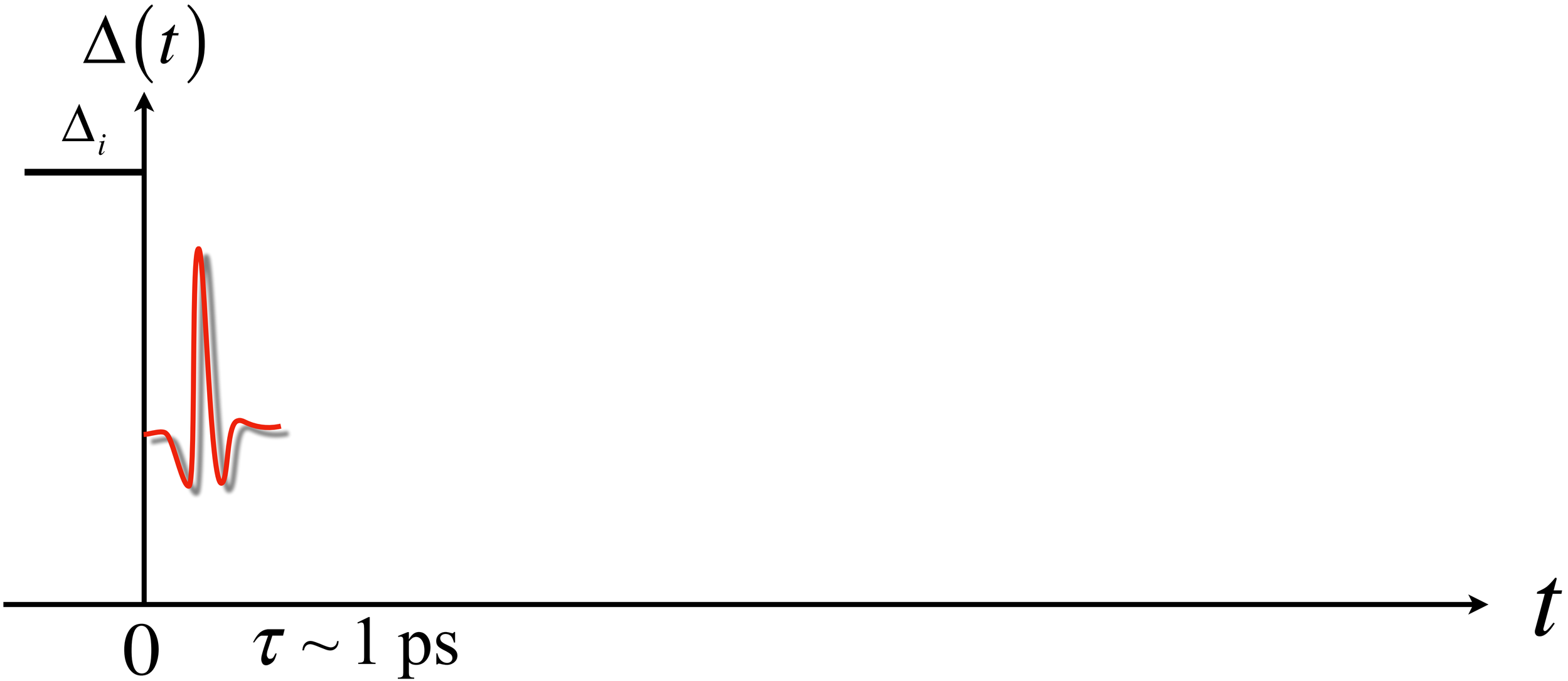




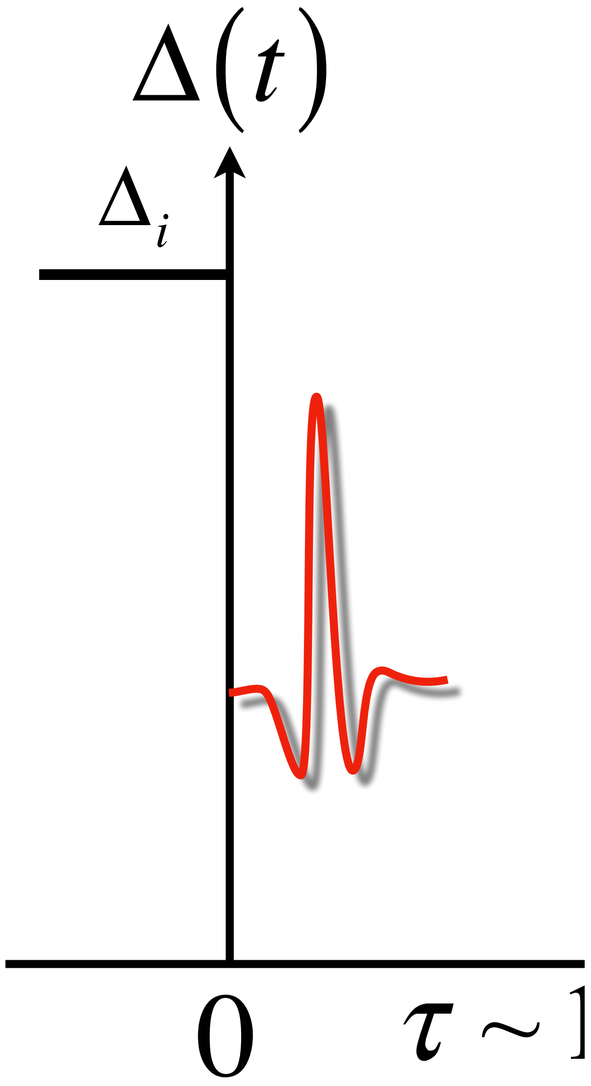
[1] R. Matsunaga and R. Shimano, *Phys. Scr.,* **92**(2), 24003 (2017).
[2]A. F. Kemper, M. A. Sentef, B. Moritz, J. K. Freericks, and T. P. Devereaux, *Phys. Rev. B,* **92**, 224517 (2015).

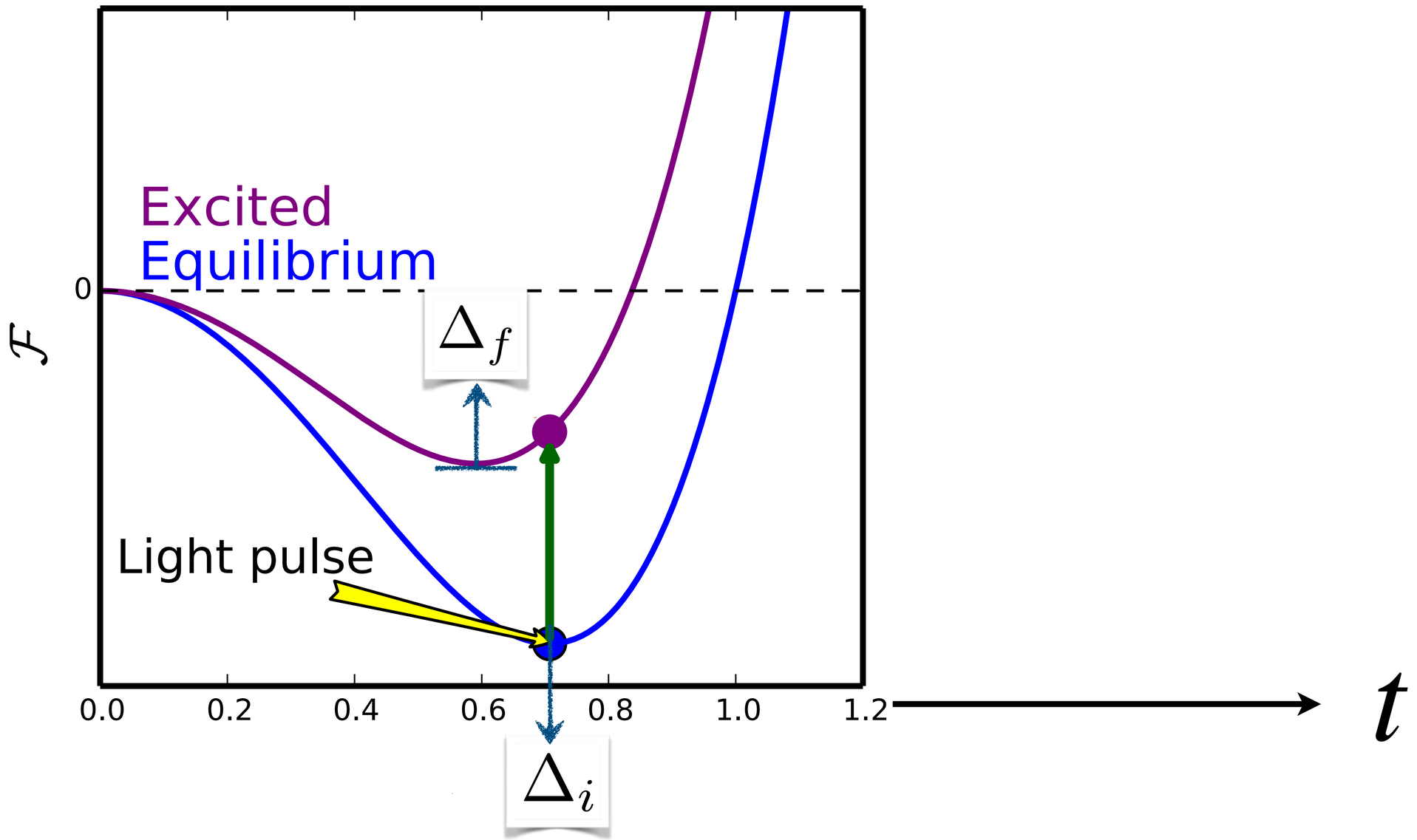
Typical time scales

Typical time scales

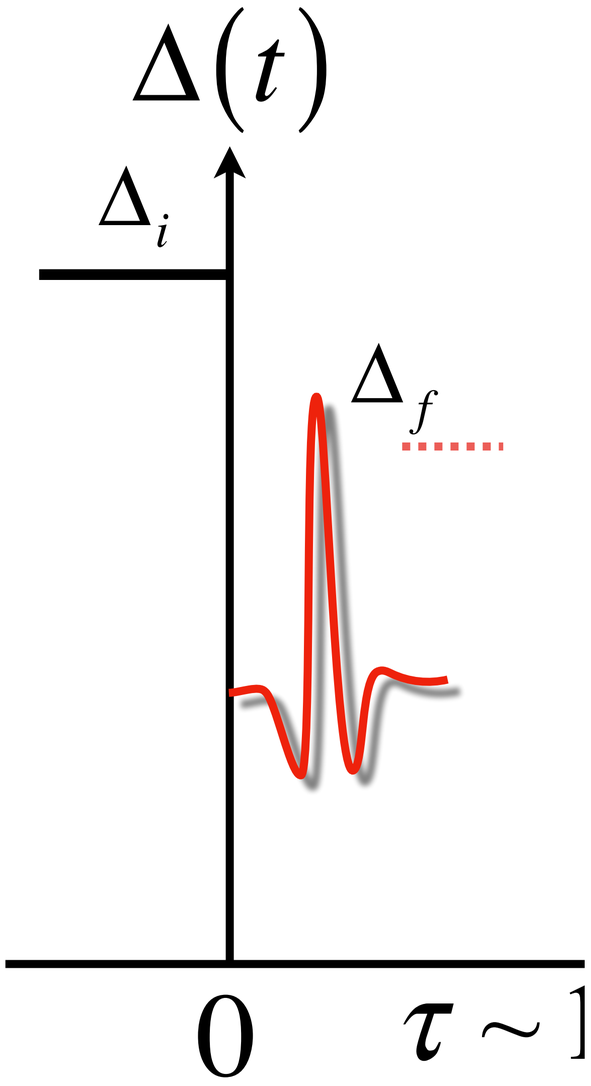


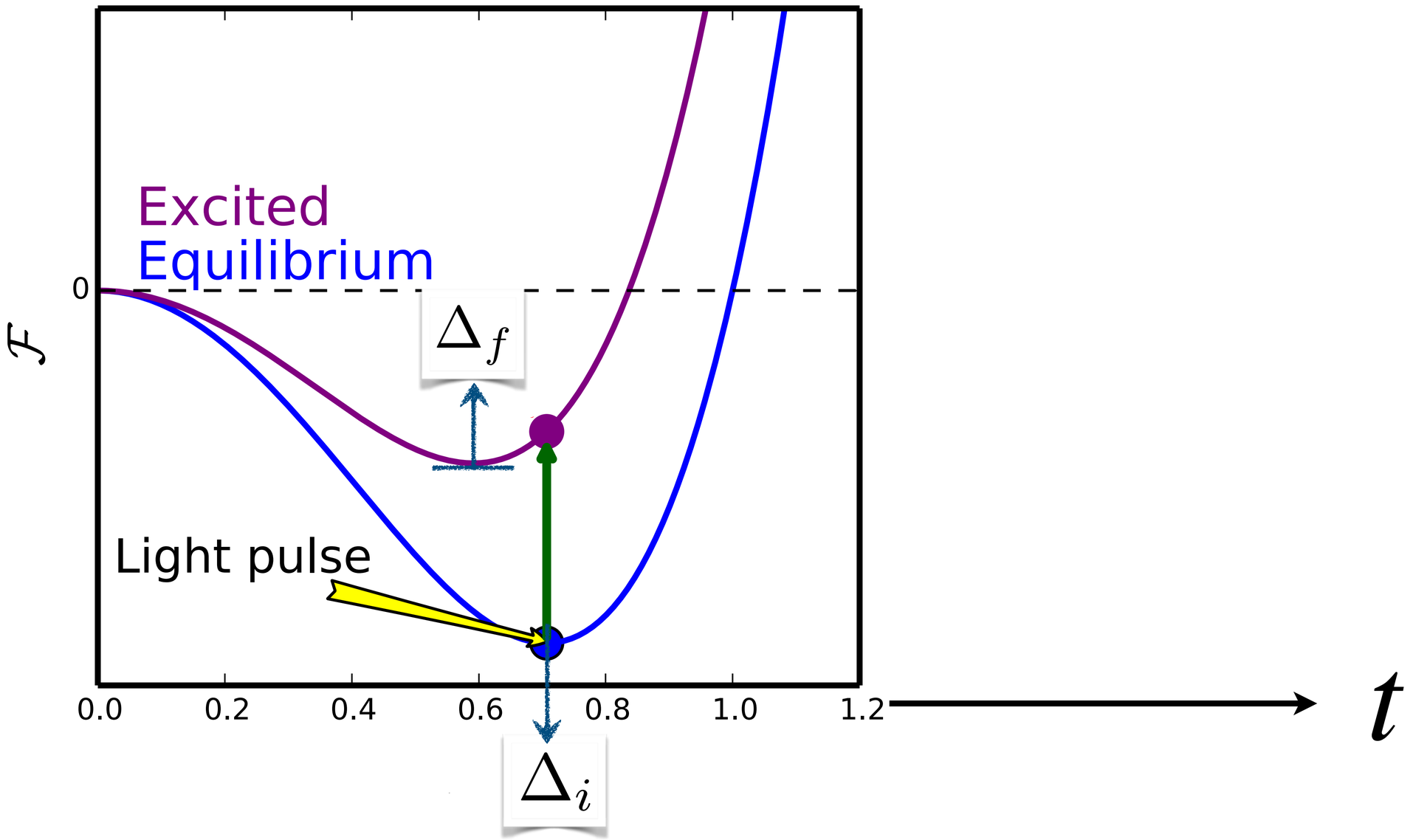
Typical time scales



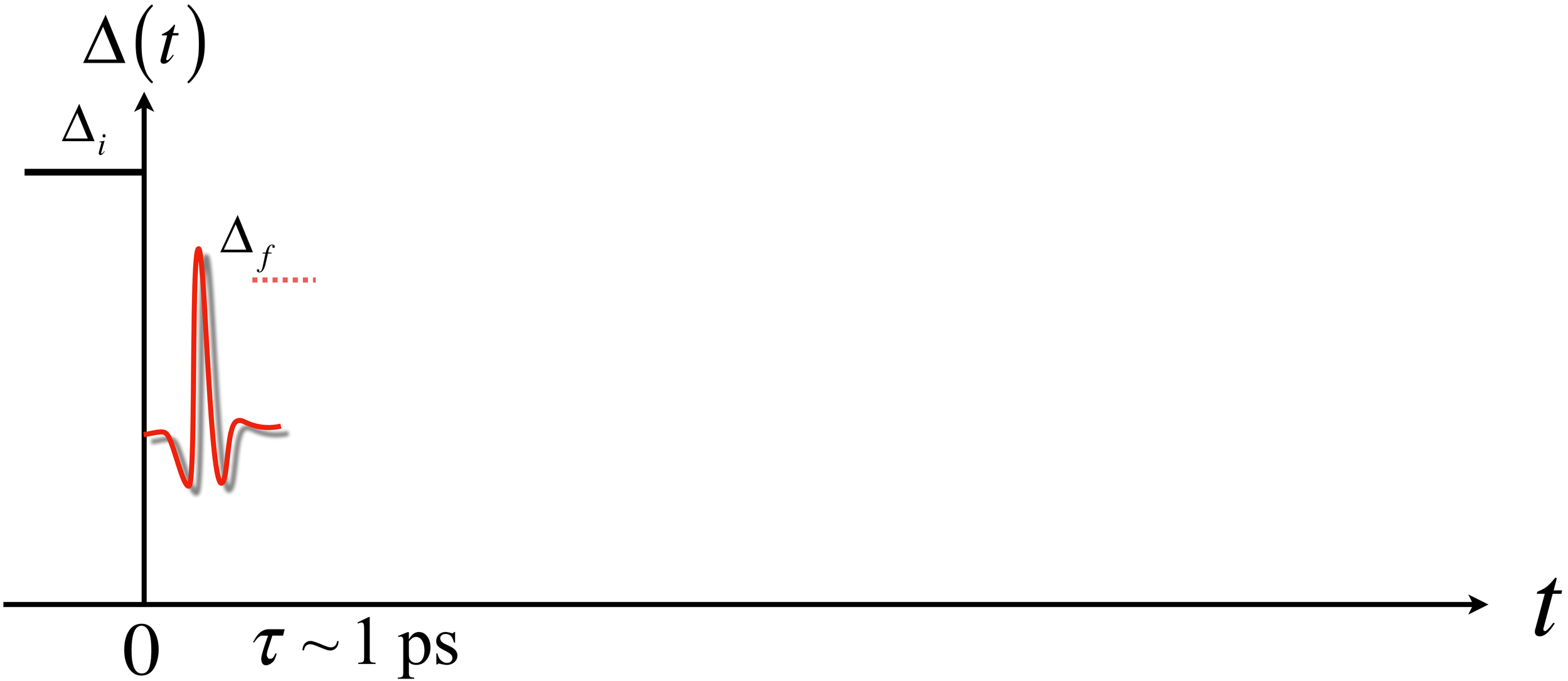


Typical time scales

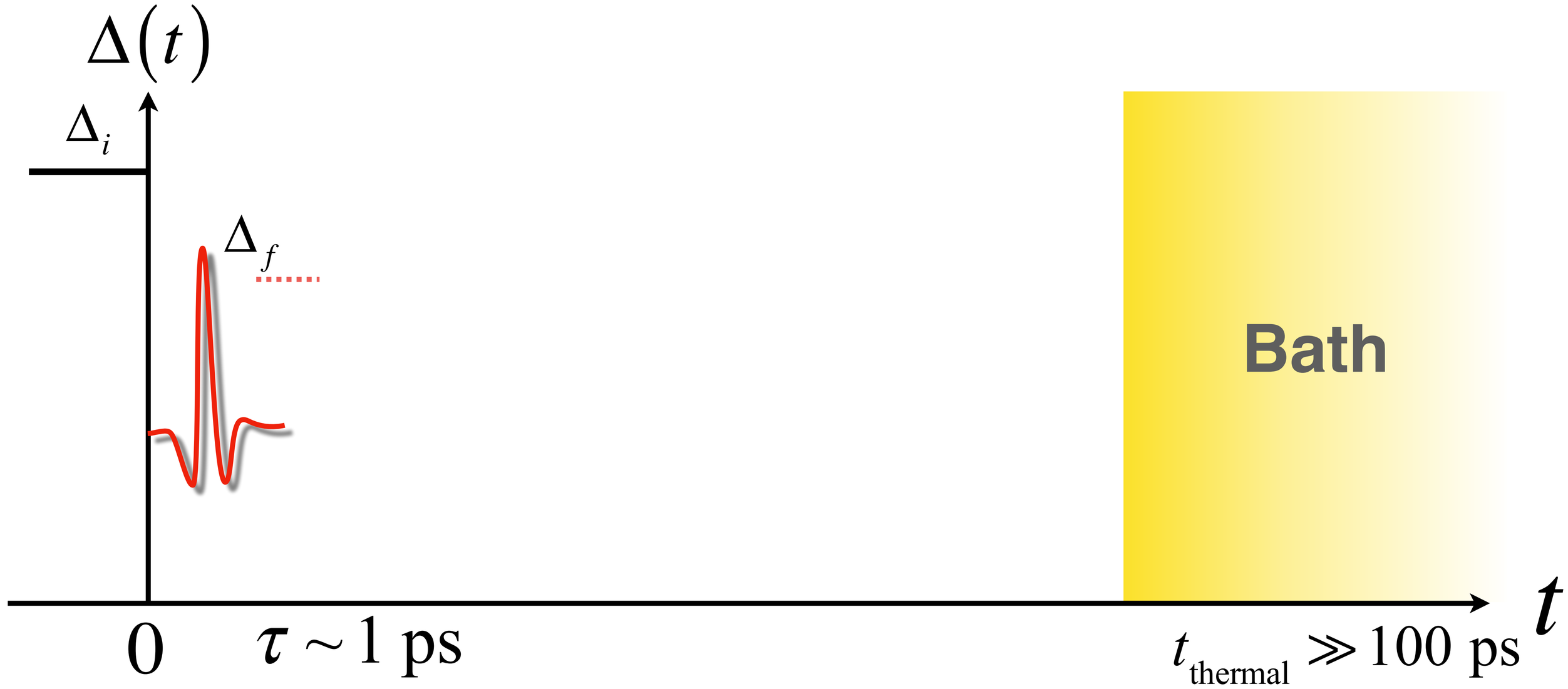




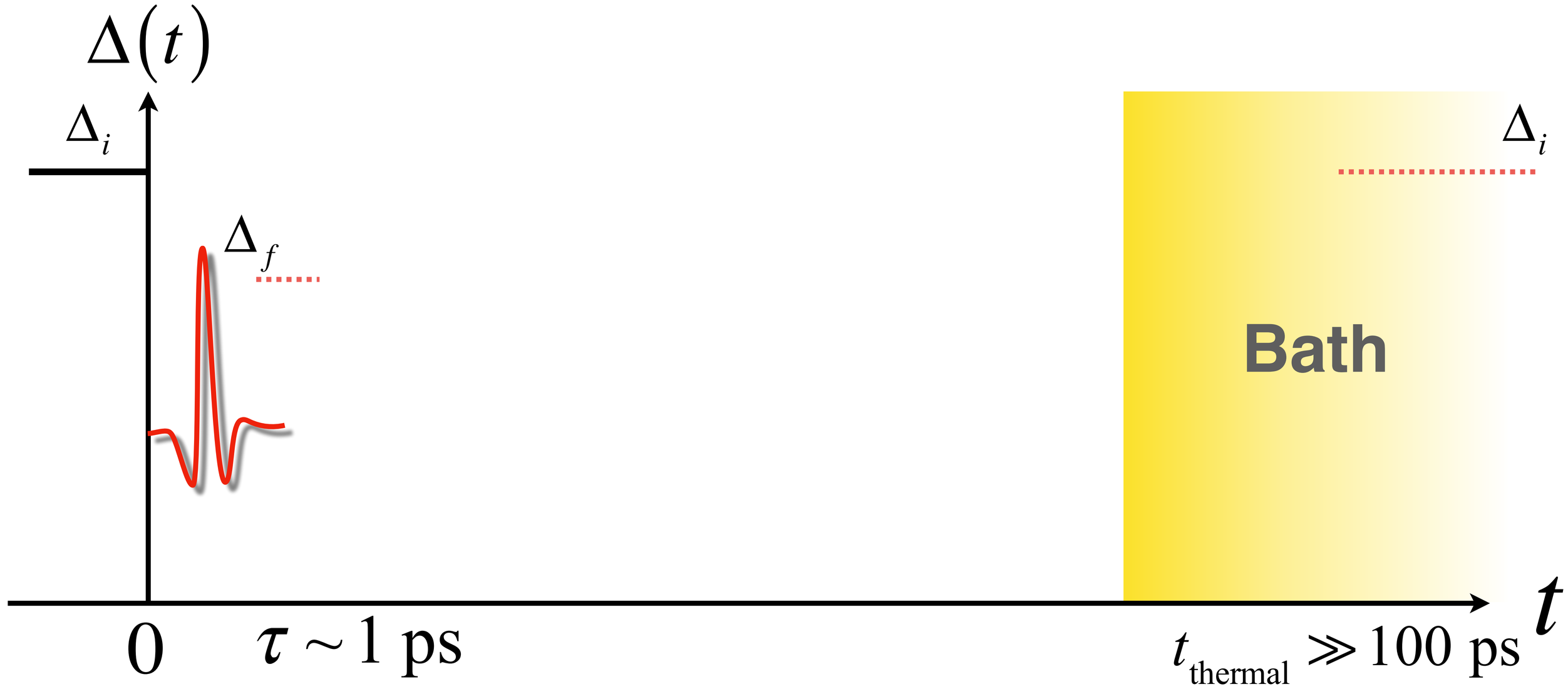
Typical time scales



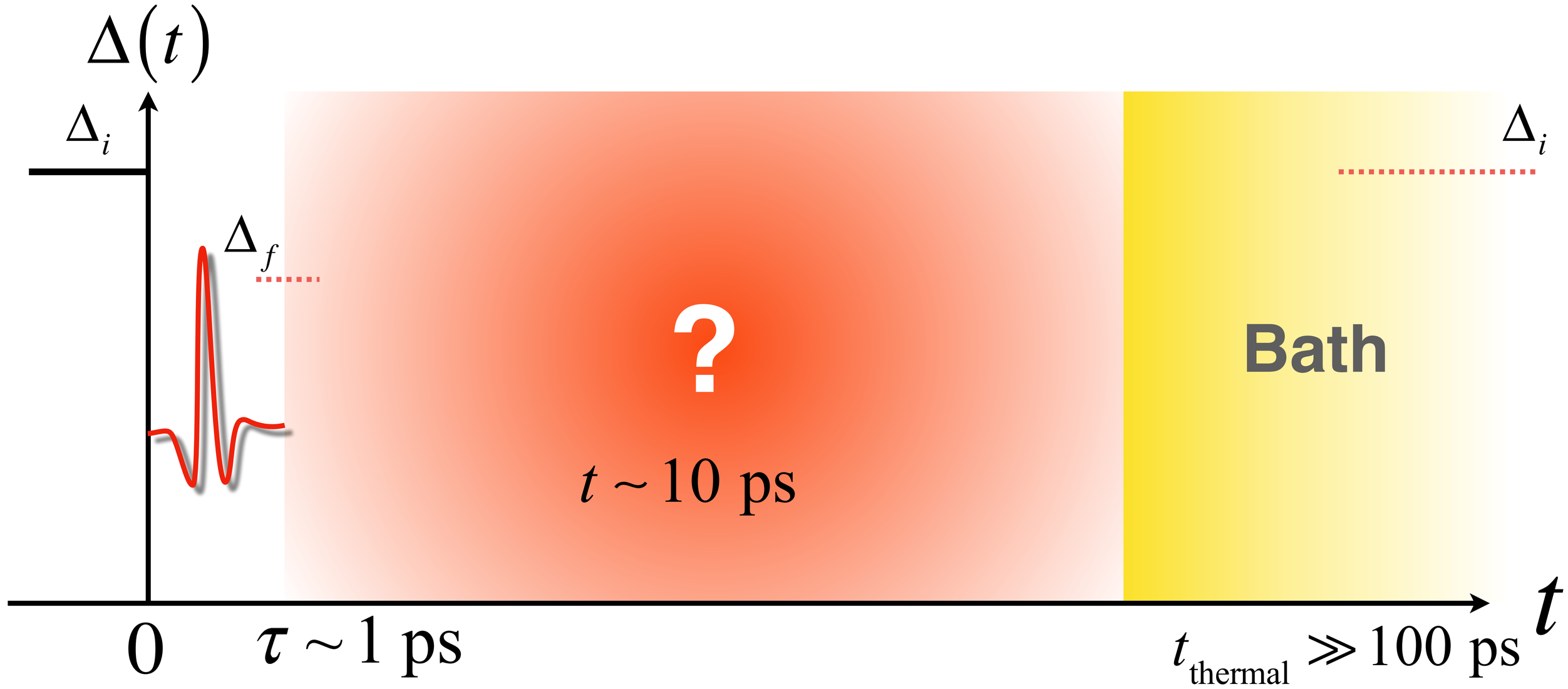
Typical time scales



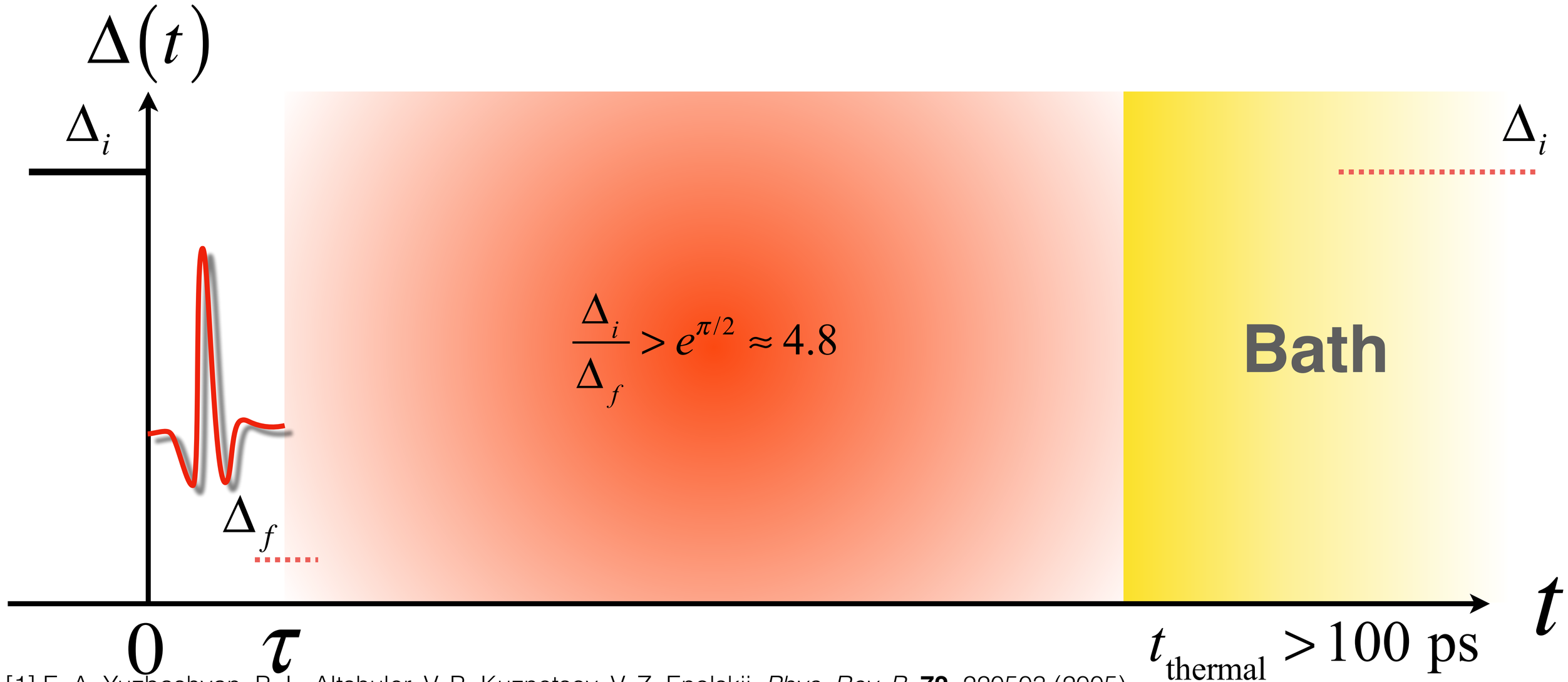
Typical time scales



Typical time scales

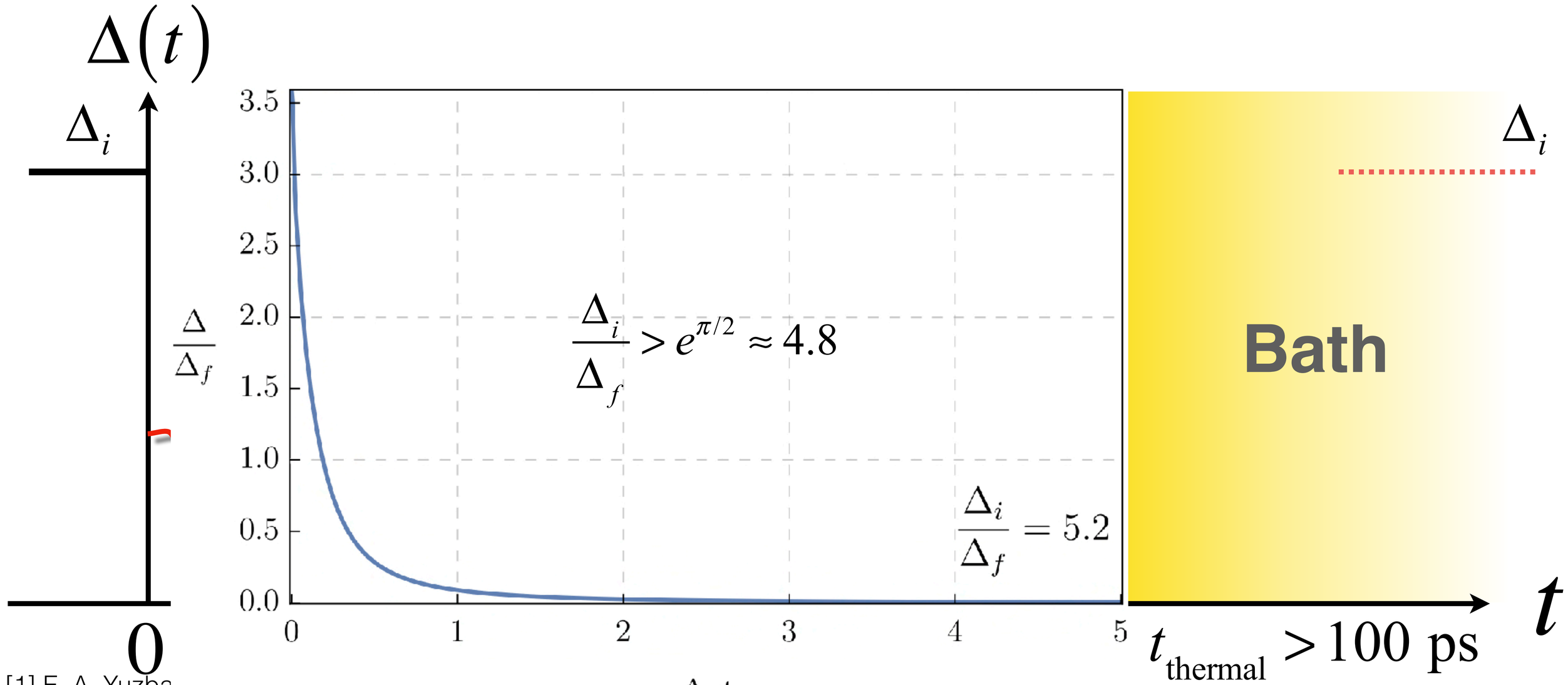


Transient dynamics



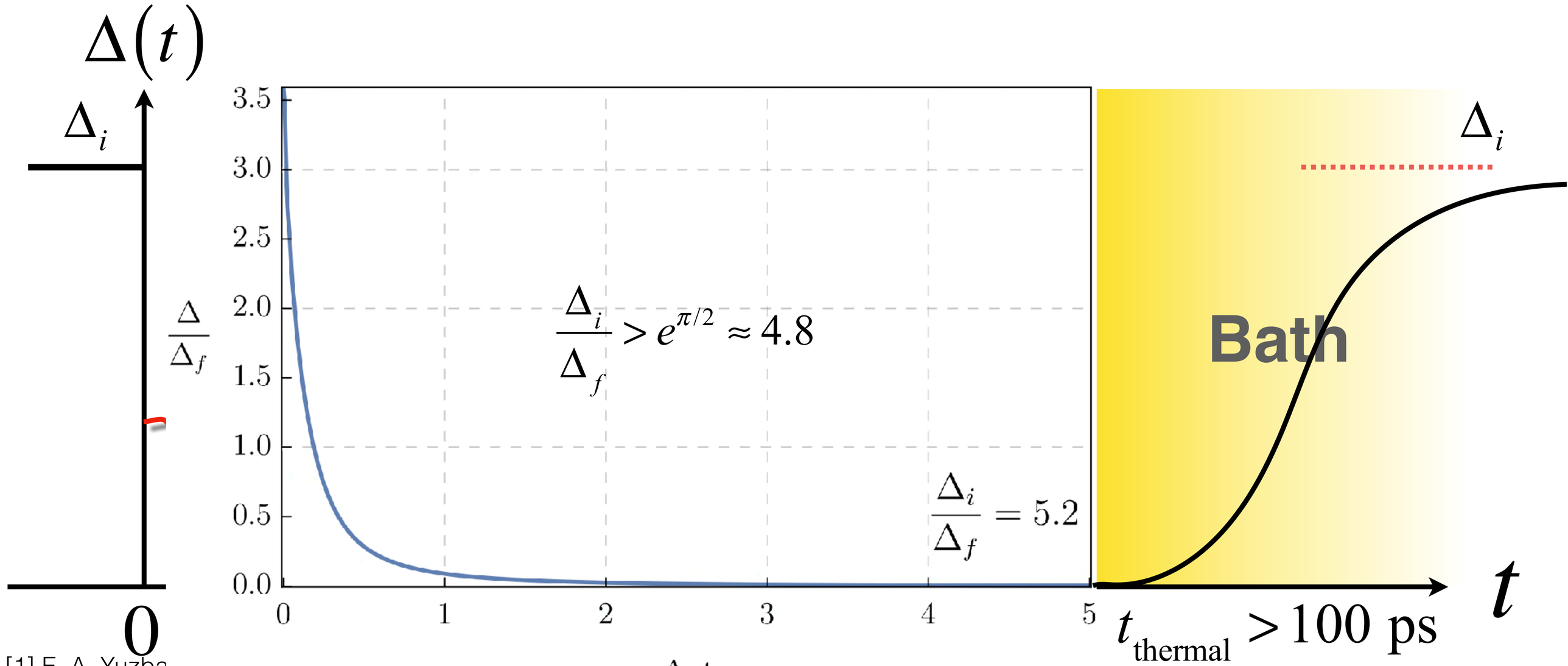
[1] E. A. Yuzbashyan, B. L. Altshuler, V. B. Kuznetsov, V. Z. Enolskii, *Phys. Rev. B*, **72**, 220503 (2005)
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006)

Transient dynamics



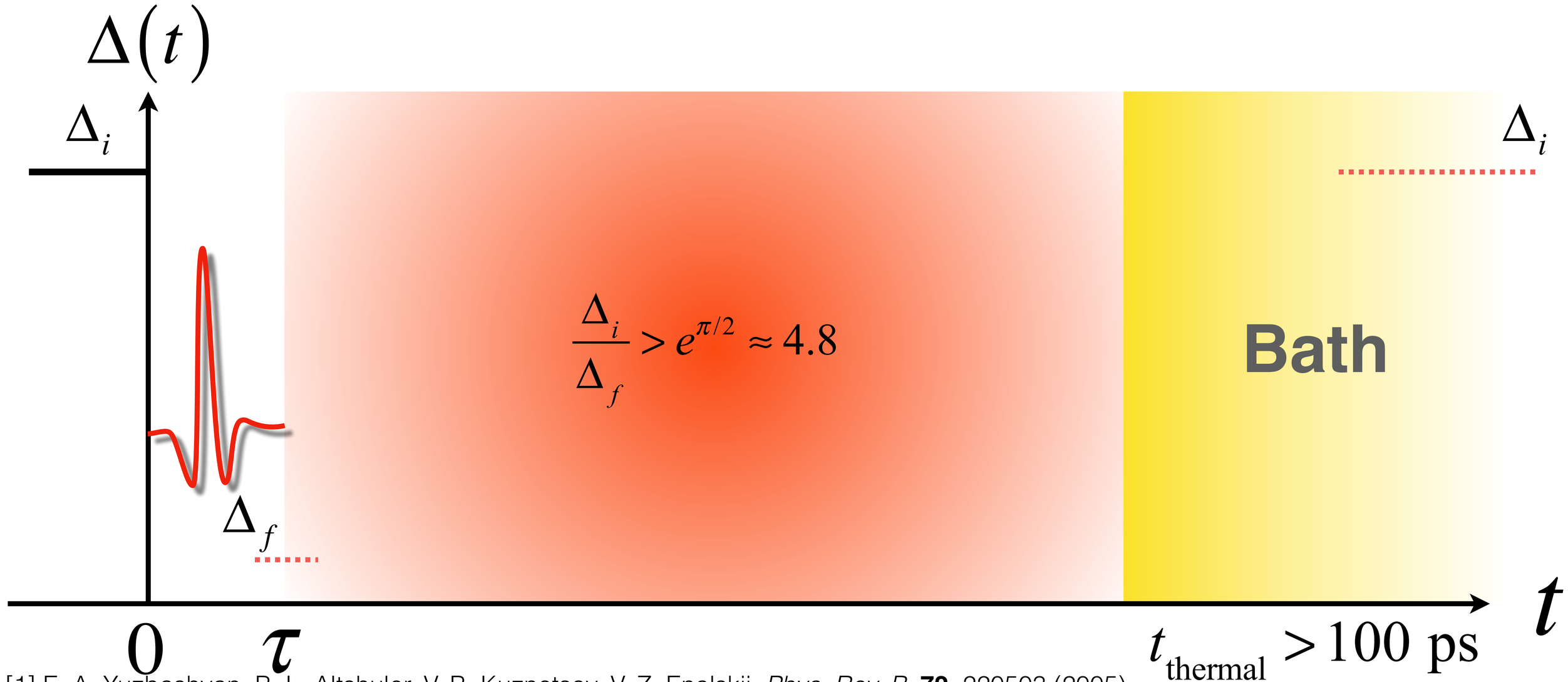
[1] E. A. Yuzba
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006)

Transient dynamics



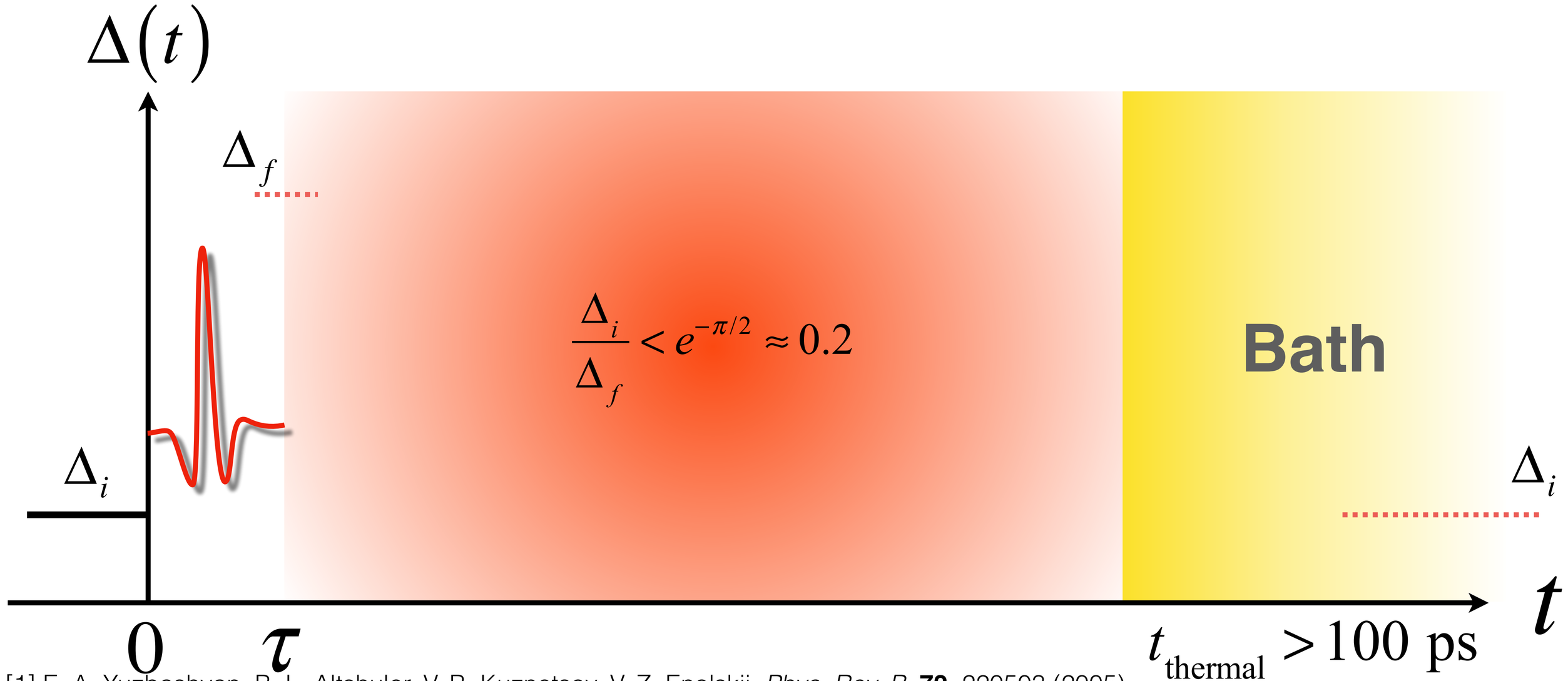
[1] E. A. Yuzba
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006)

Transient dynamics



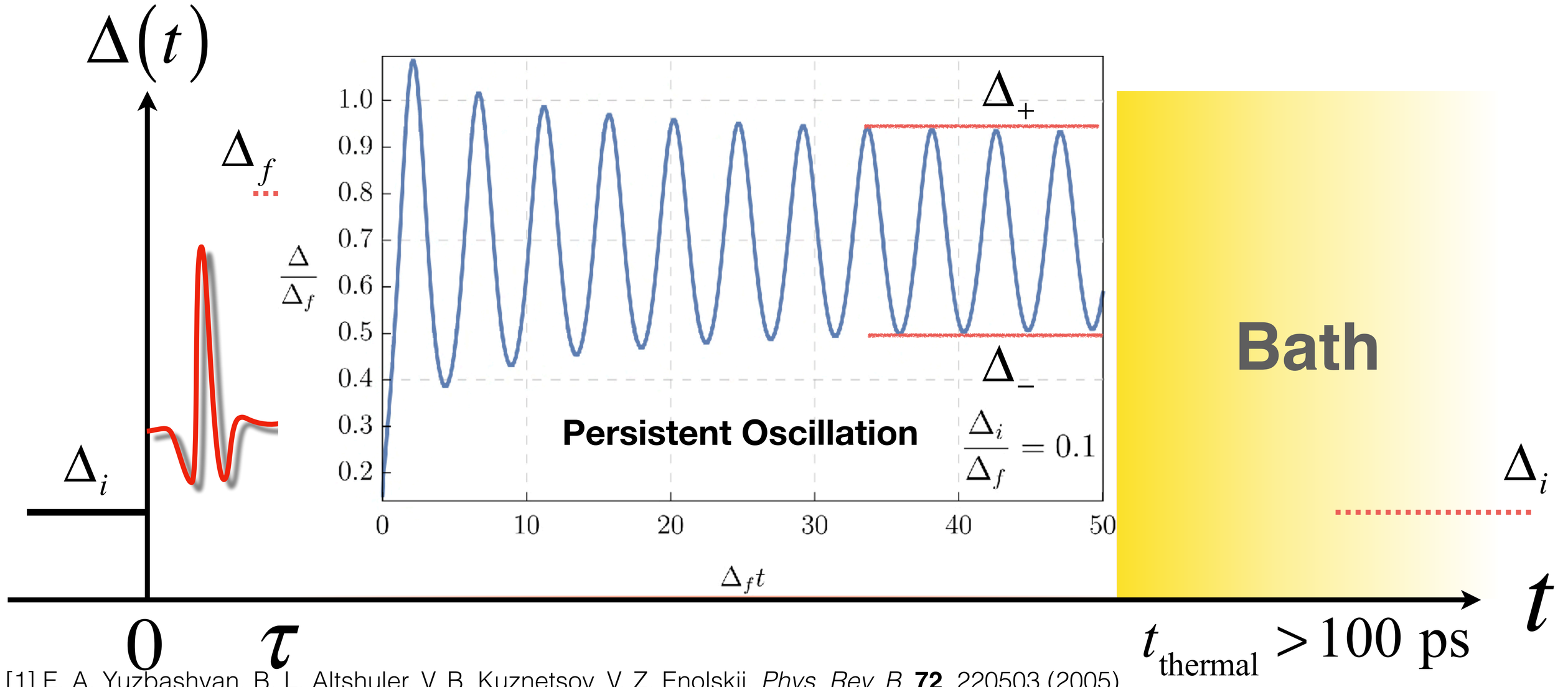
[1] E. A. Yuzbashyan, B. L. Altshuler, V. B. Kuznetsov, V. Z. Enolskii, *Phys. Rev. B*, **72**, 220503 (2005)
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006)

Transient dynamics



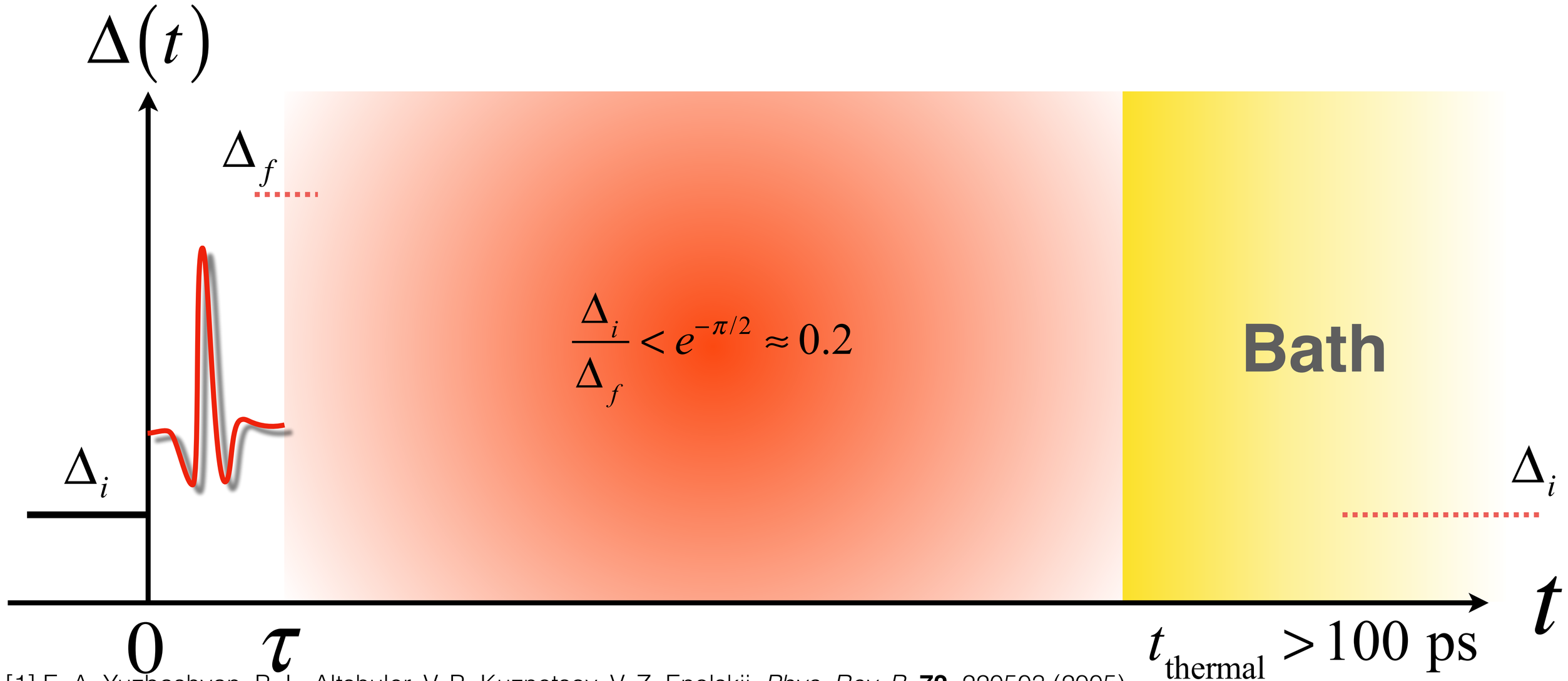
[1] E. A. Yuzbashyan, B. L. Altshuler, V. B. Kuznetsov, V. Z. Enolskii, *Phys. Rev. B*, **72**, 220503 (2005)
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006)

Transient dynamics



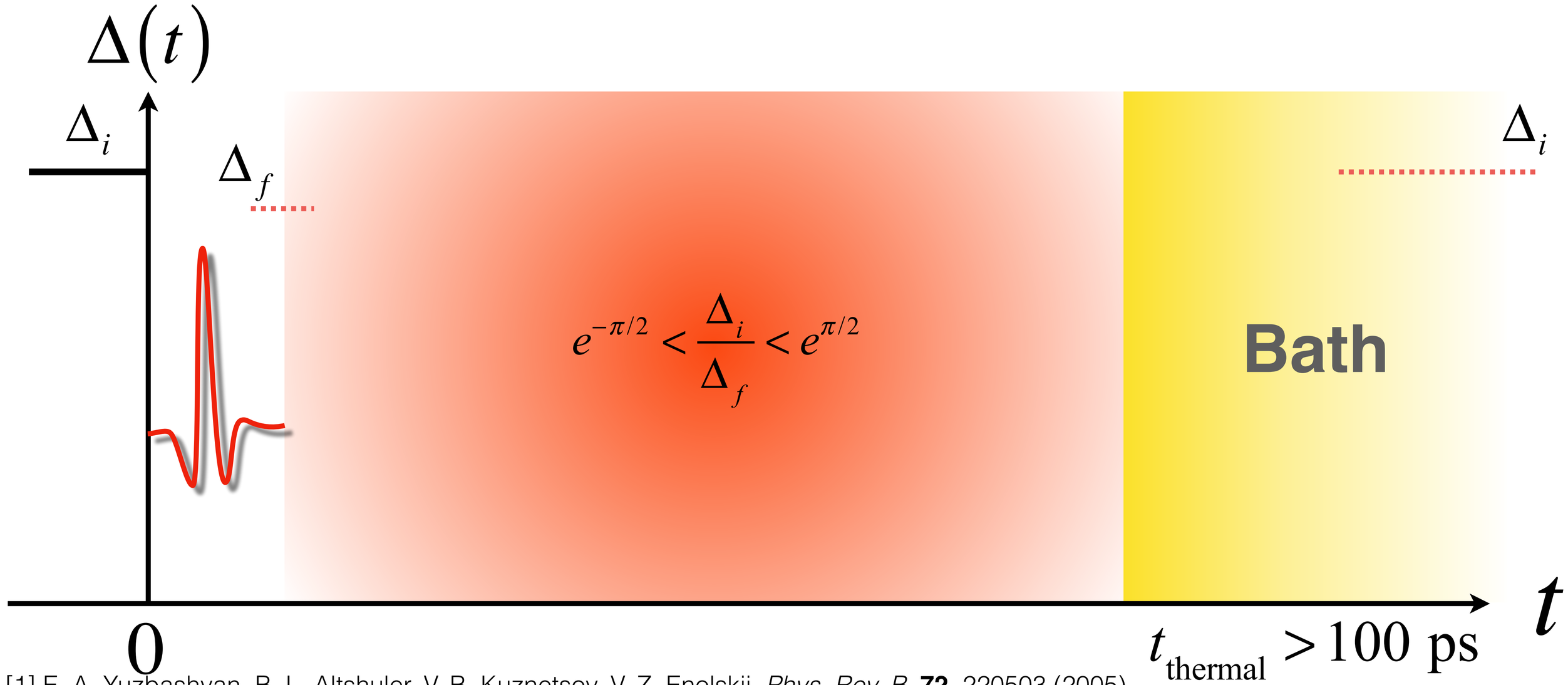
[1] E. A. Yuzbashyan, B. L. Altshuler, V. B. Kuznetsov, V. Z. Enolskii, *Phys. Rev. B*, **72**, 220503 (2005)
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006)

Transient dynamics



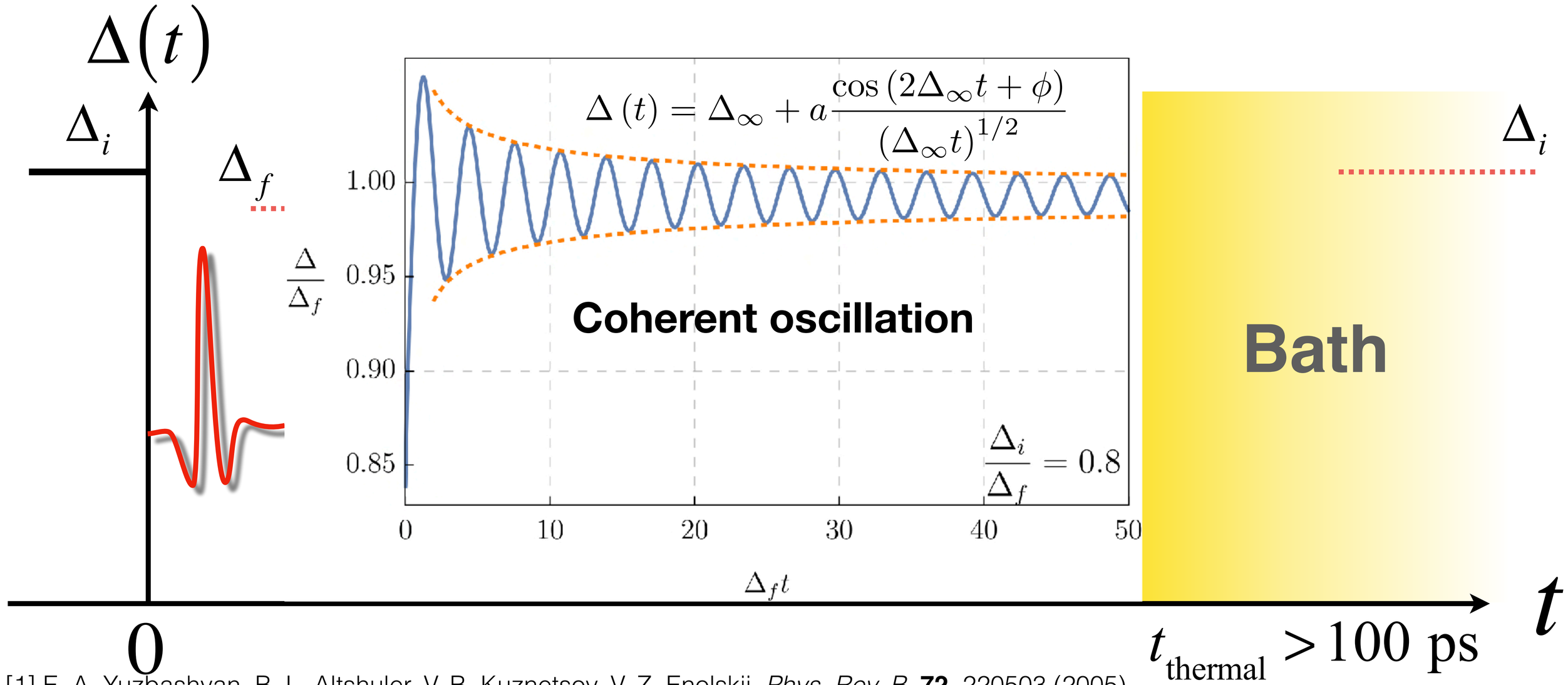
[1] E. A. Yuzbashyan, B. L. Altshuler, V. B. Kuznetsov, V. Z. Enolskii, *Phys. Rev. B*, **72**, 220503 (2005)
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006)

Transient dynamics



[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). [3] A.F. Volkov, S.M. Kogan, Sov. Phys. JETP, **38**(5), 1018 (1974).

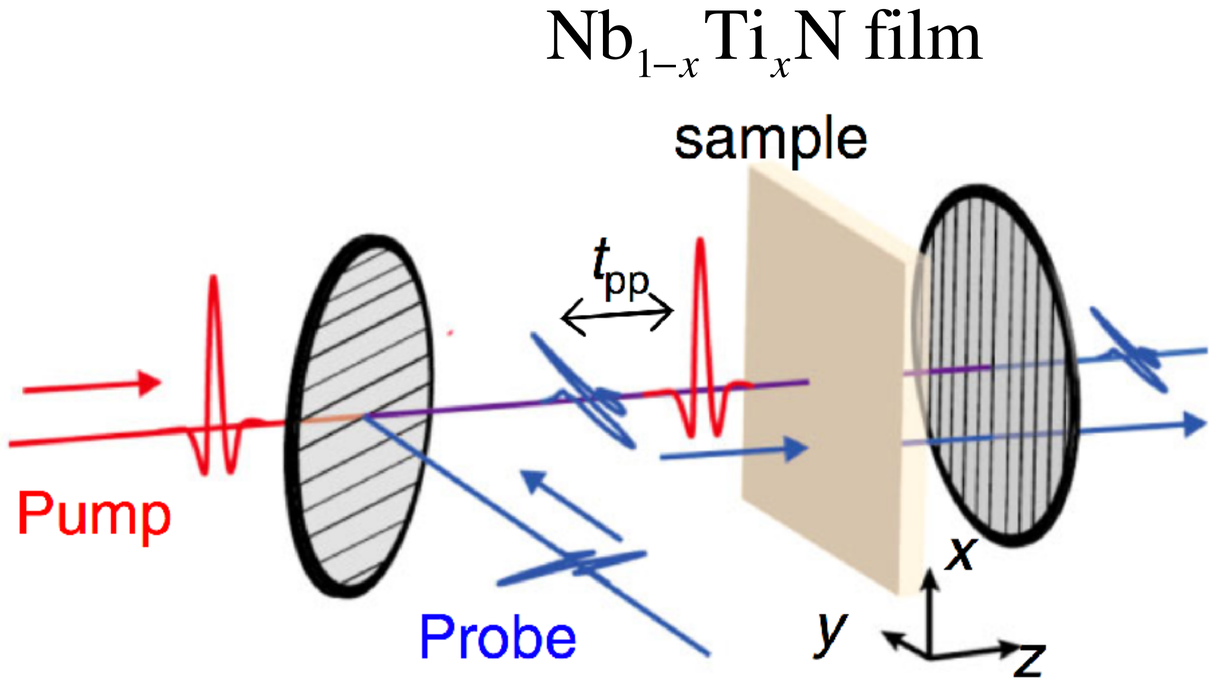
Transient dynamics

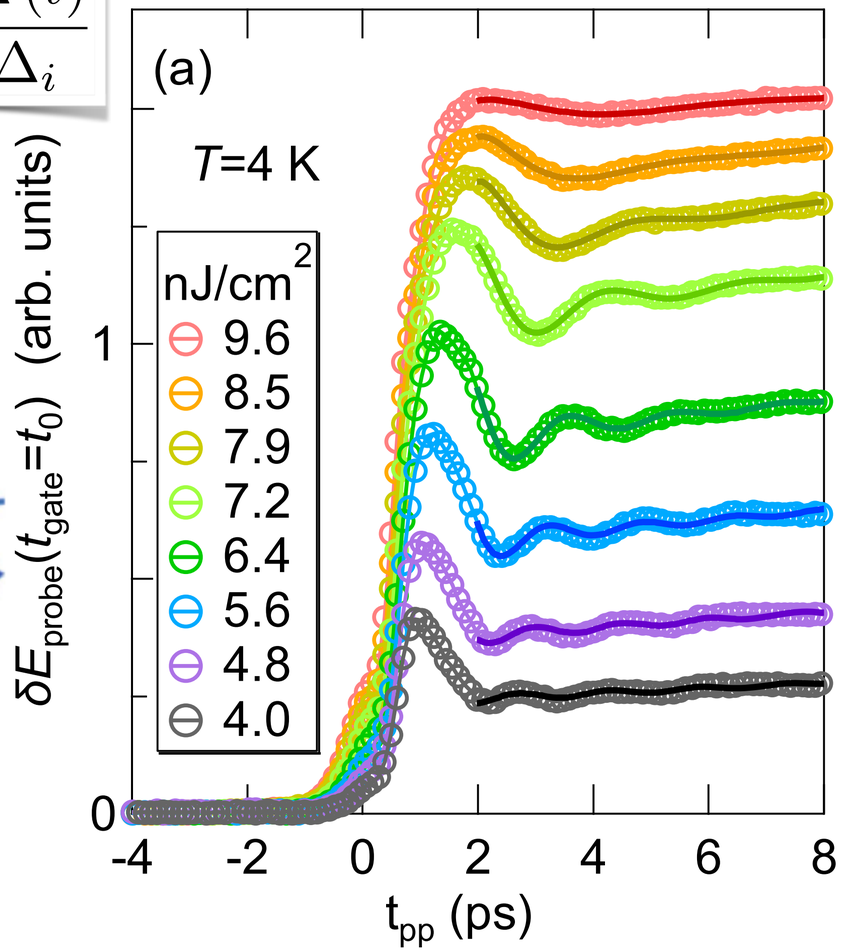


[1] E. A. Yuzbashyan, B. L. Altshuler, V. B. Kuznetsov, V. Z. Enolskii, *Phys. Rev. B*, **72**, 220503 (2005)
[2] R. A. Barankov, L. S. Levitov, *Phys. Rev. Lett.*, **96**, 230403 (2006). [3] A.F. Volkov, S.M. Kogan, Sov. Phys. JETP, **38**(5), 1018 (1974).

THz-pump-probe-experiment

$$\delta E \propto 1 - \frac{\Delta(t)}{\Delta_i}$$

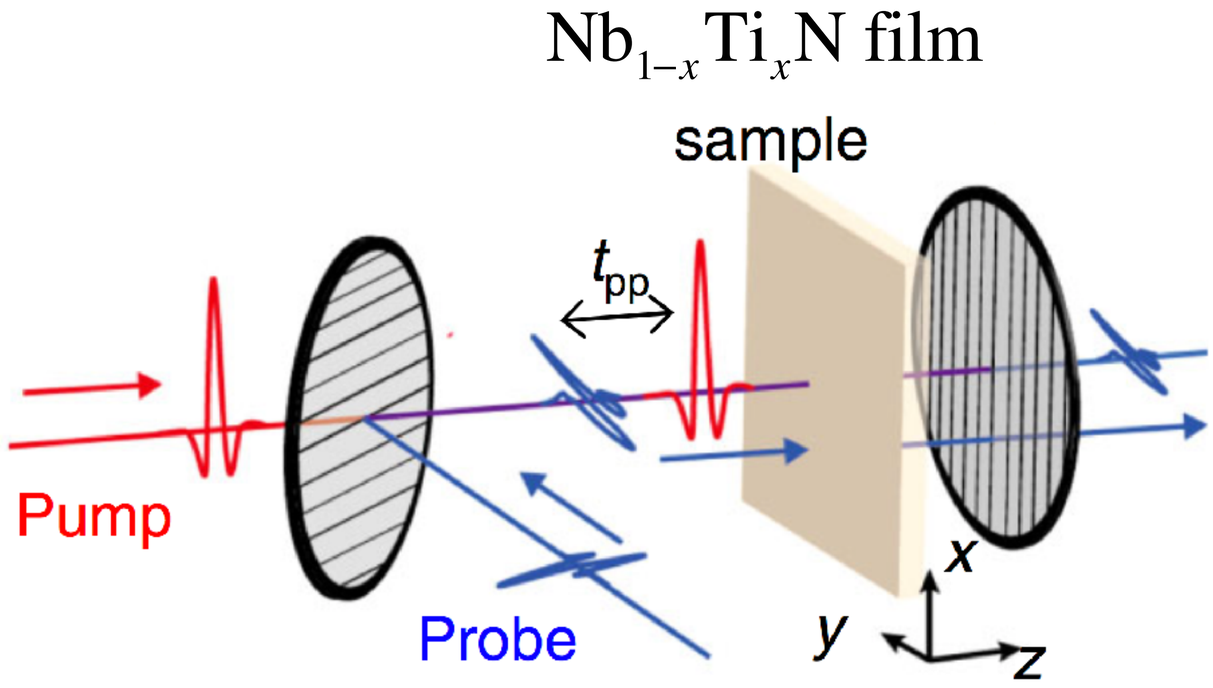


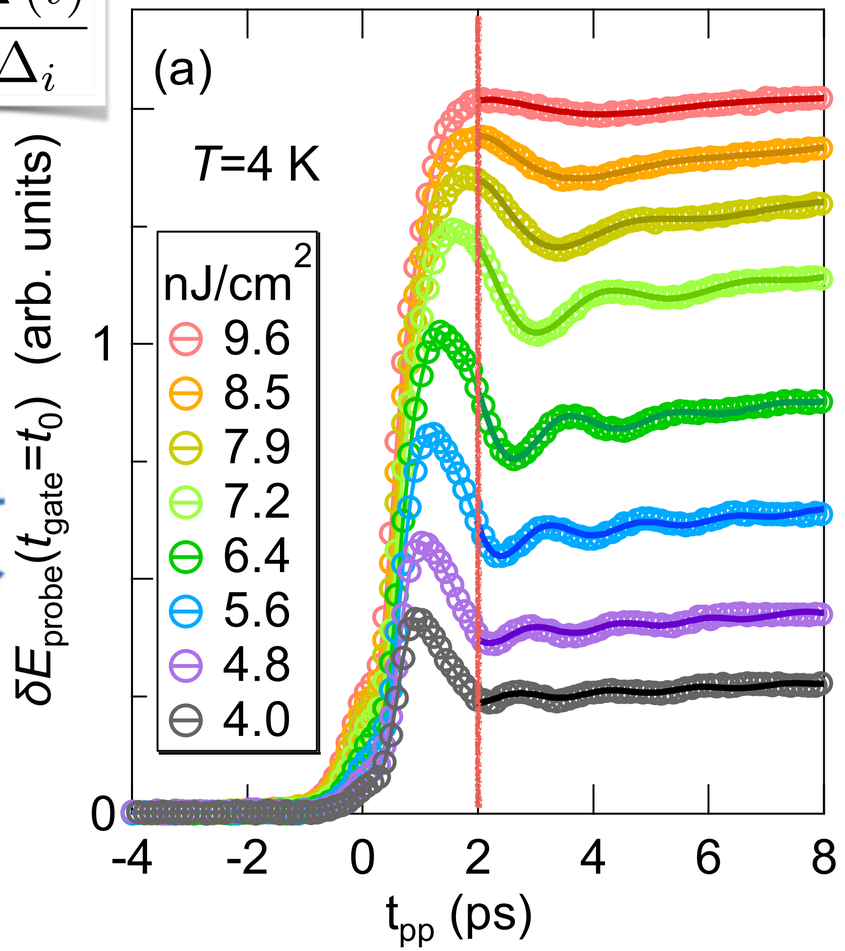


[1] R. Matsunaga *et al.*, *Phys. Rev. Lett.*, **111**, 057002 (2013).

THz-pump-probe-experiment

$$\delta E \propto 1 - \frac{\Delta(t)}{\Delta_i}$$

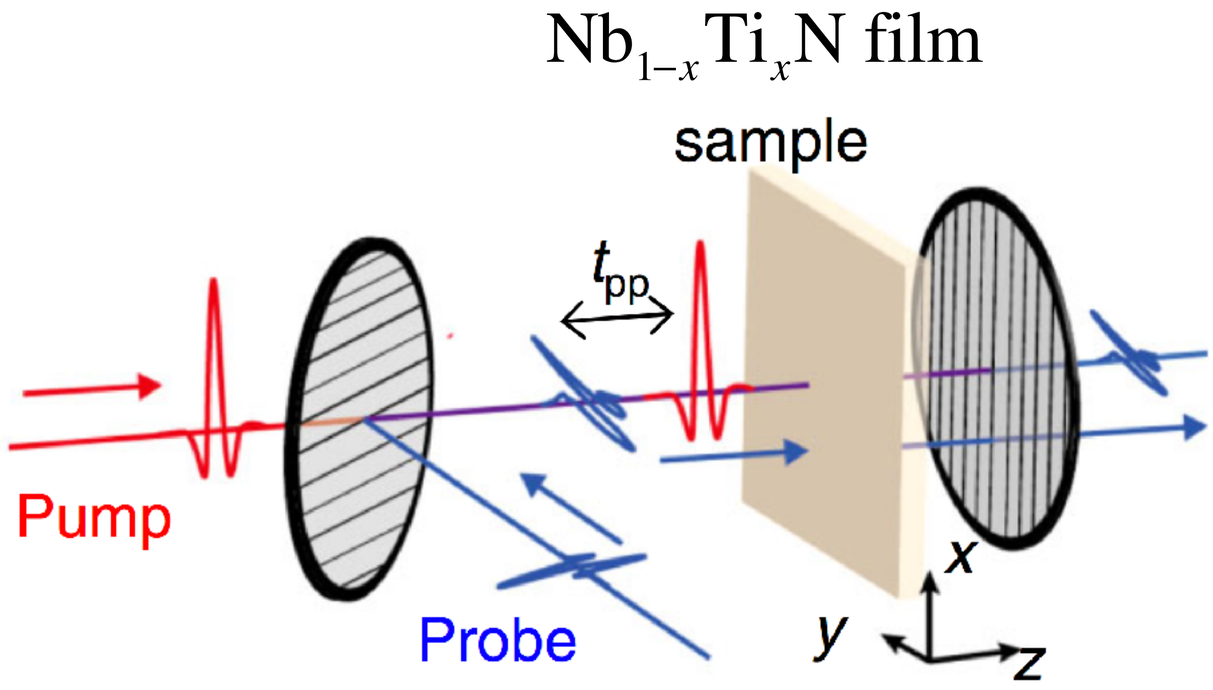


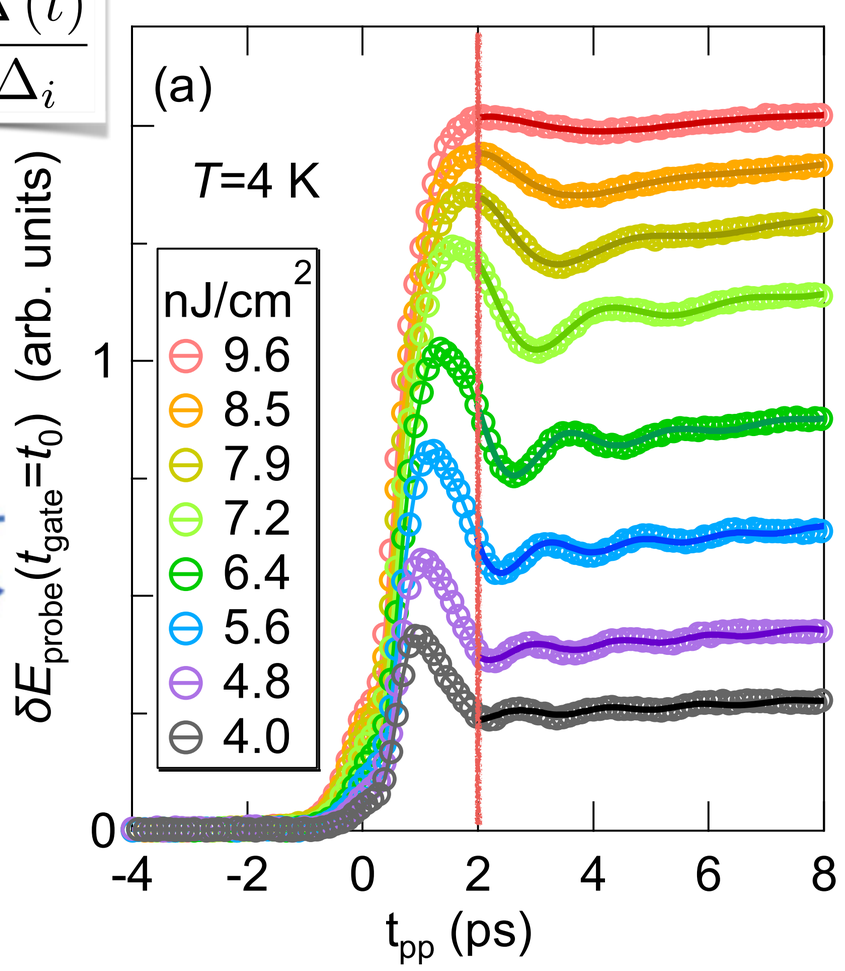


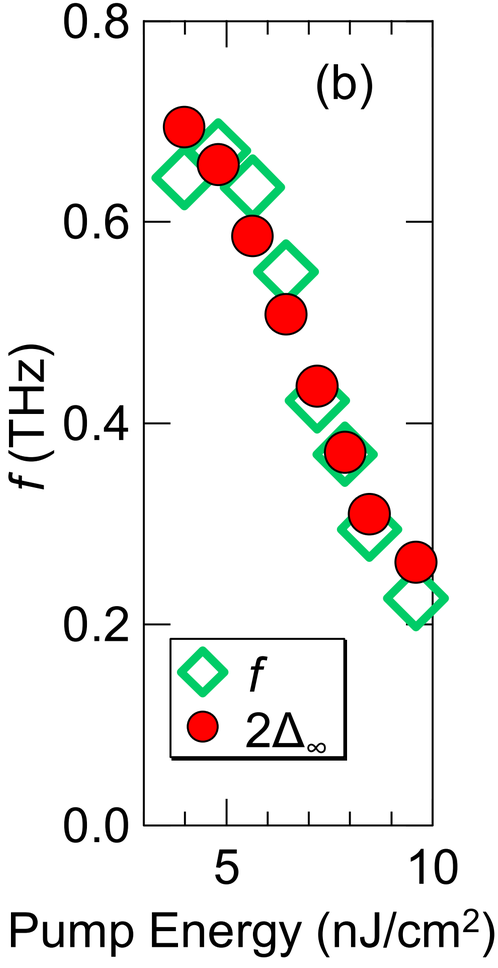
[1] R. Matsunaga *et al.*, *Phys. Rev. Lett.*, **111**, 057002 (2013).

THz-pump-probe-experiment

$$\delta E \propto 1 - \frac{\Delta(t)}{\Delta_i}$$

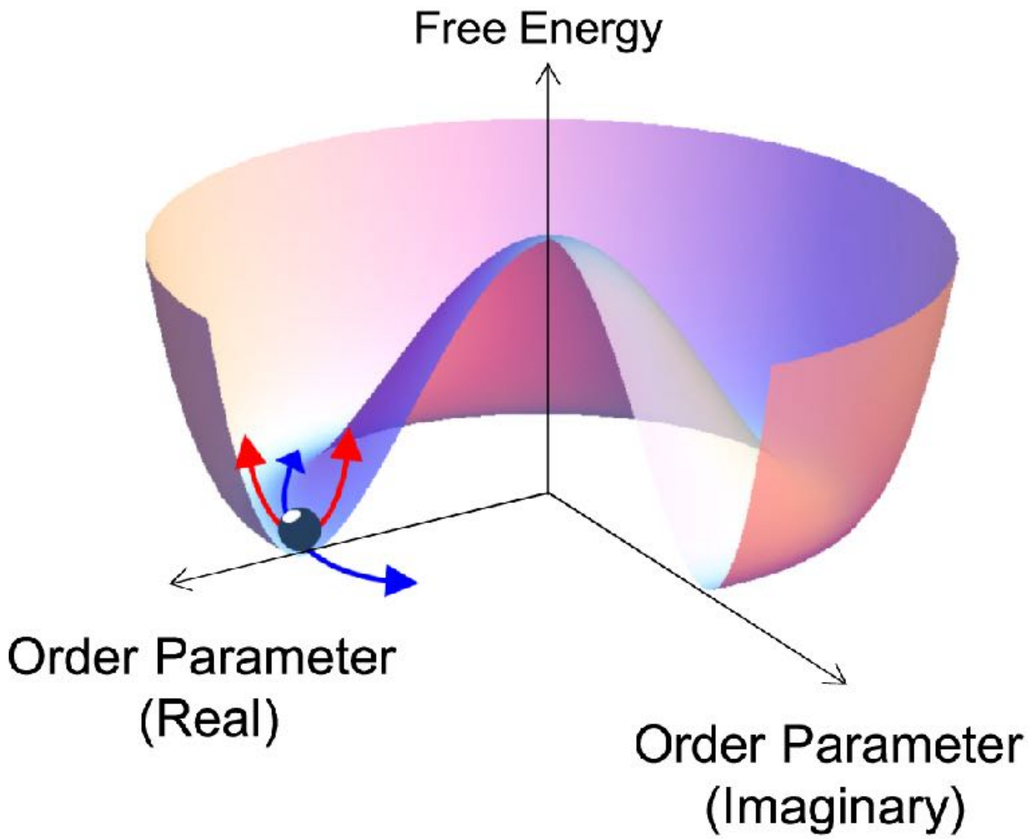




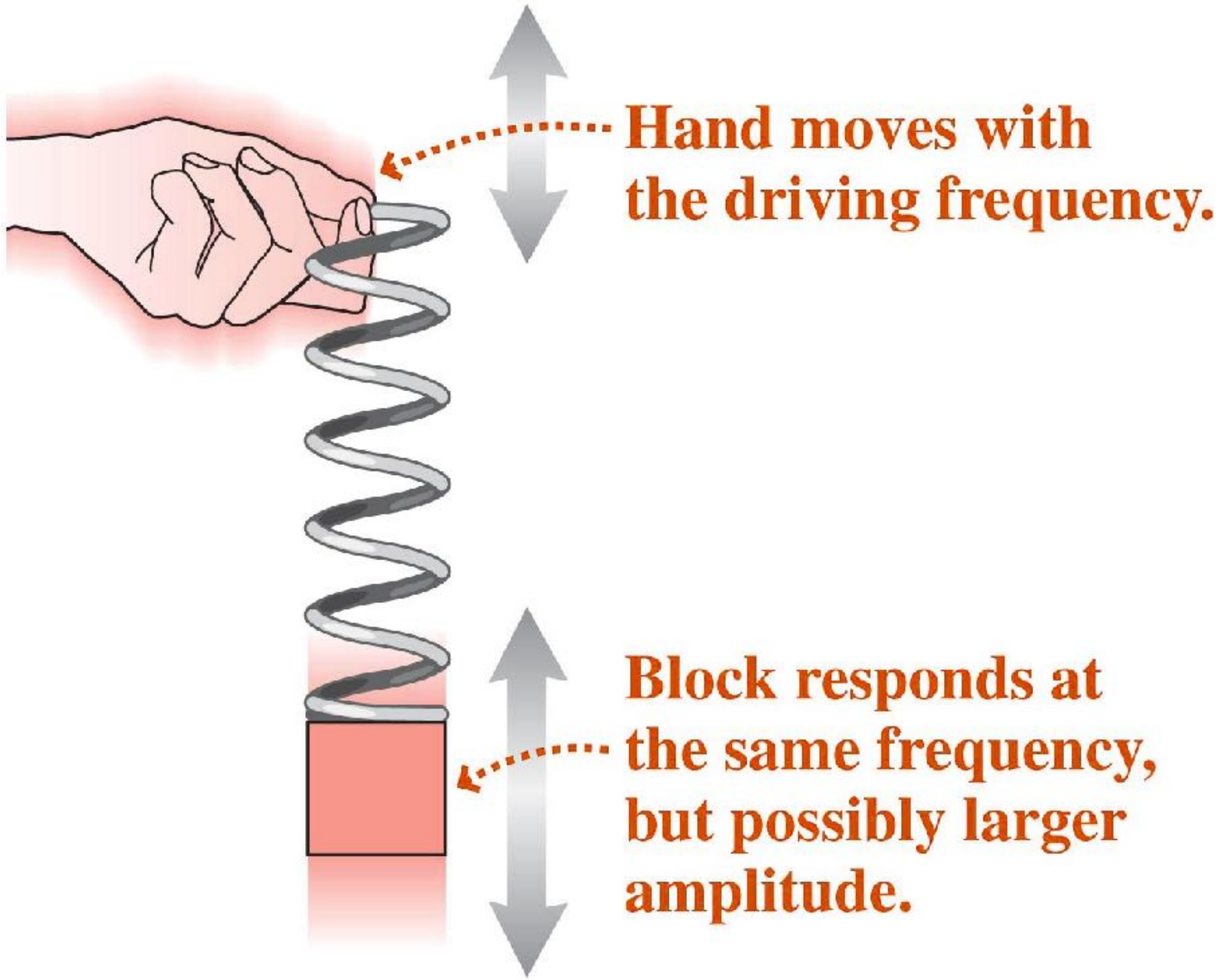


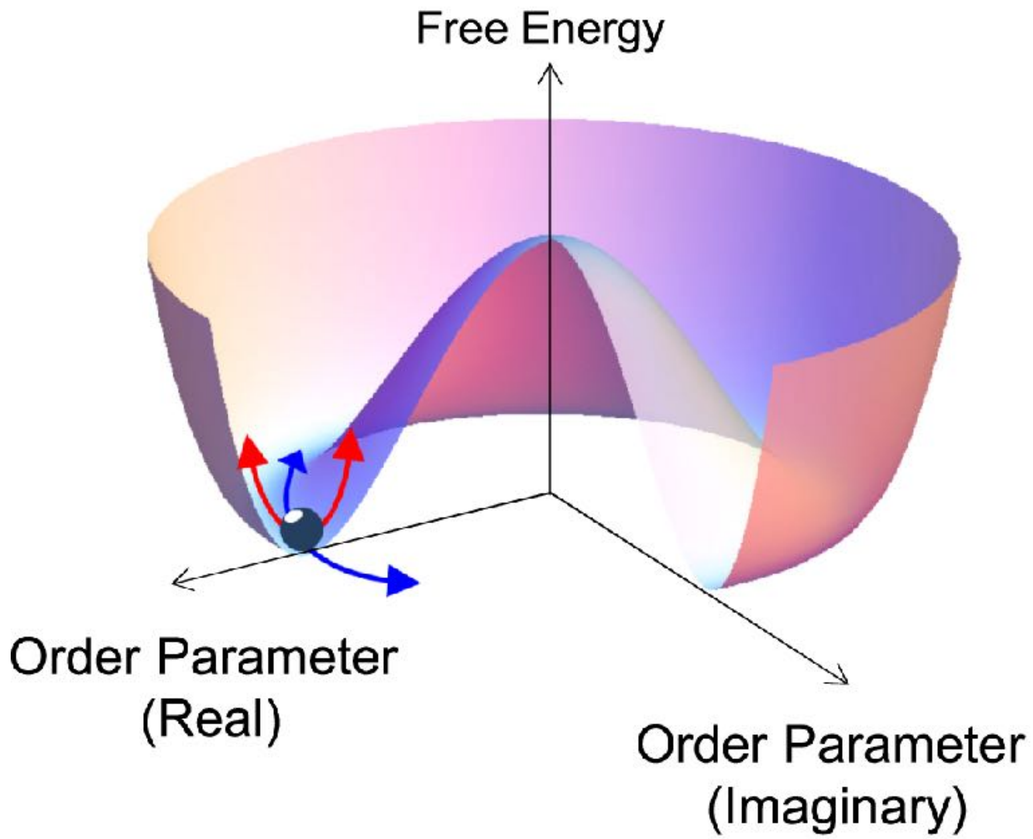
[1] R. Matsunaga *et al.*, *Phys. Rev. Lett.*, **111**, 057002 (2013).

Resonantly driven amplitude mode

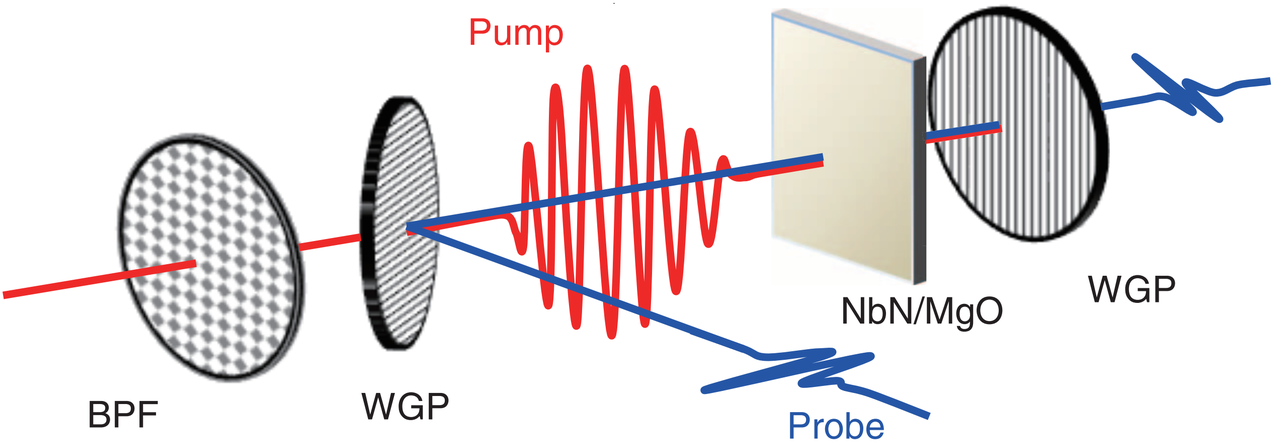


Resonantly driven amplitude mode



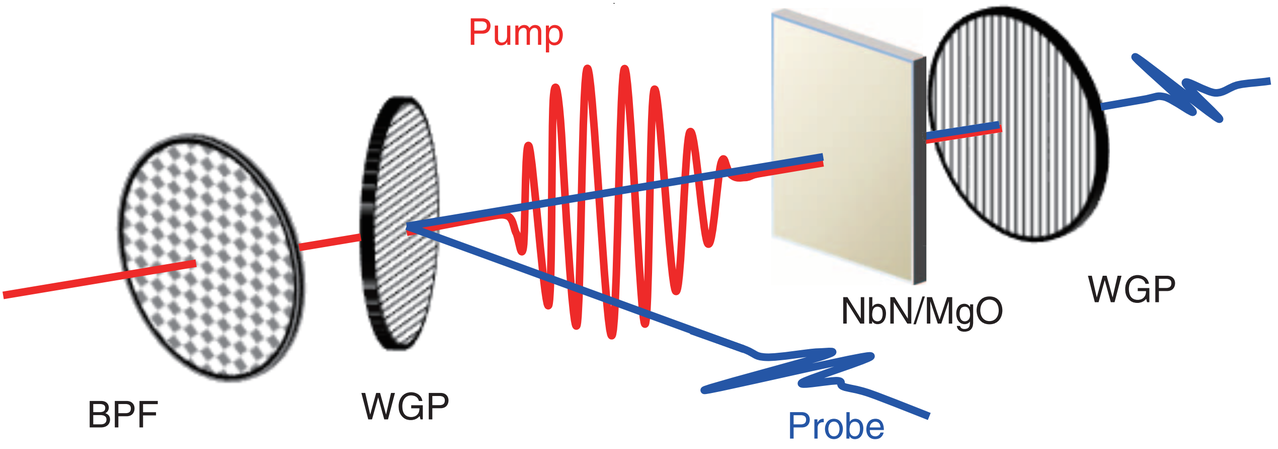


Resonantly driven amplitude mode

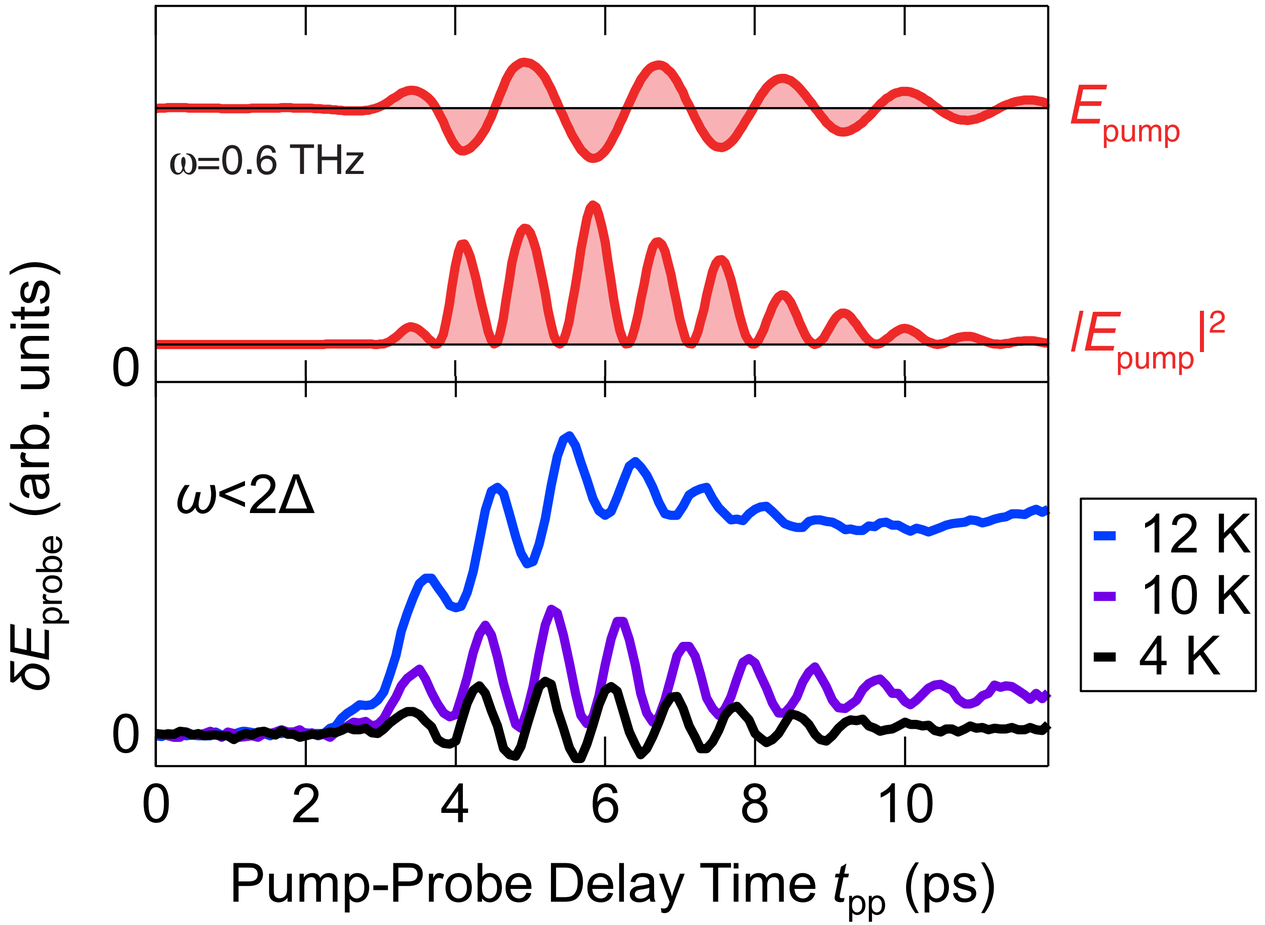


[1] R. Matsunaga *et al.*, *Science*, **345**, 6201 (2014).

Resonantly driven amplitude mode

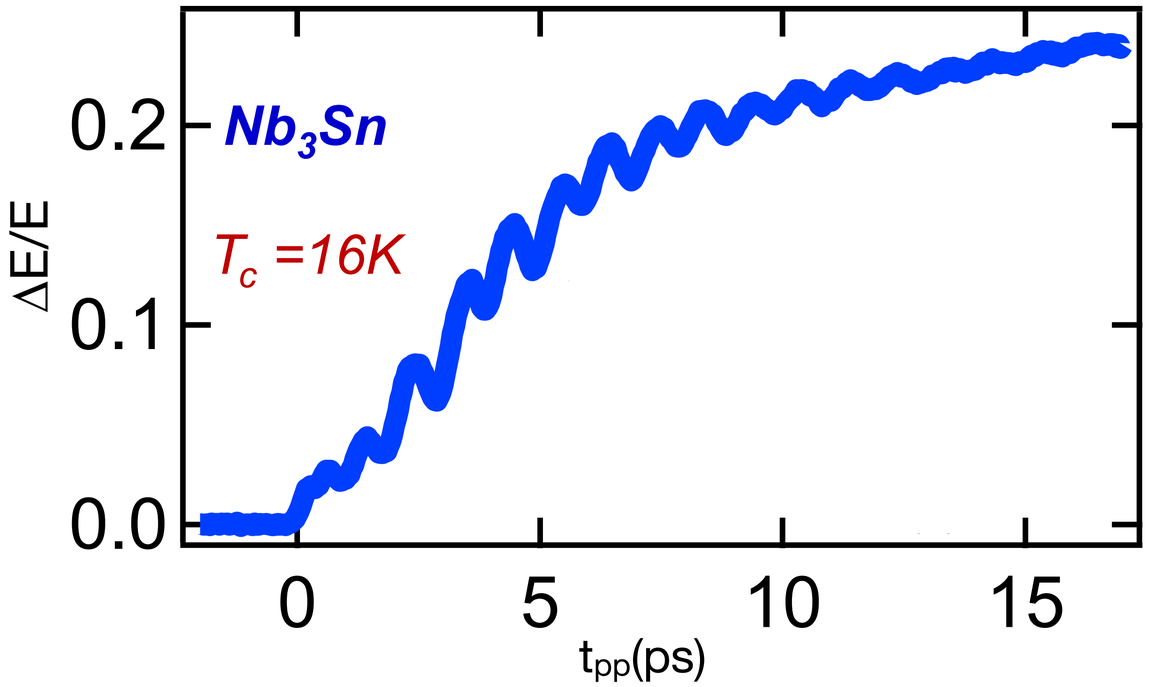


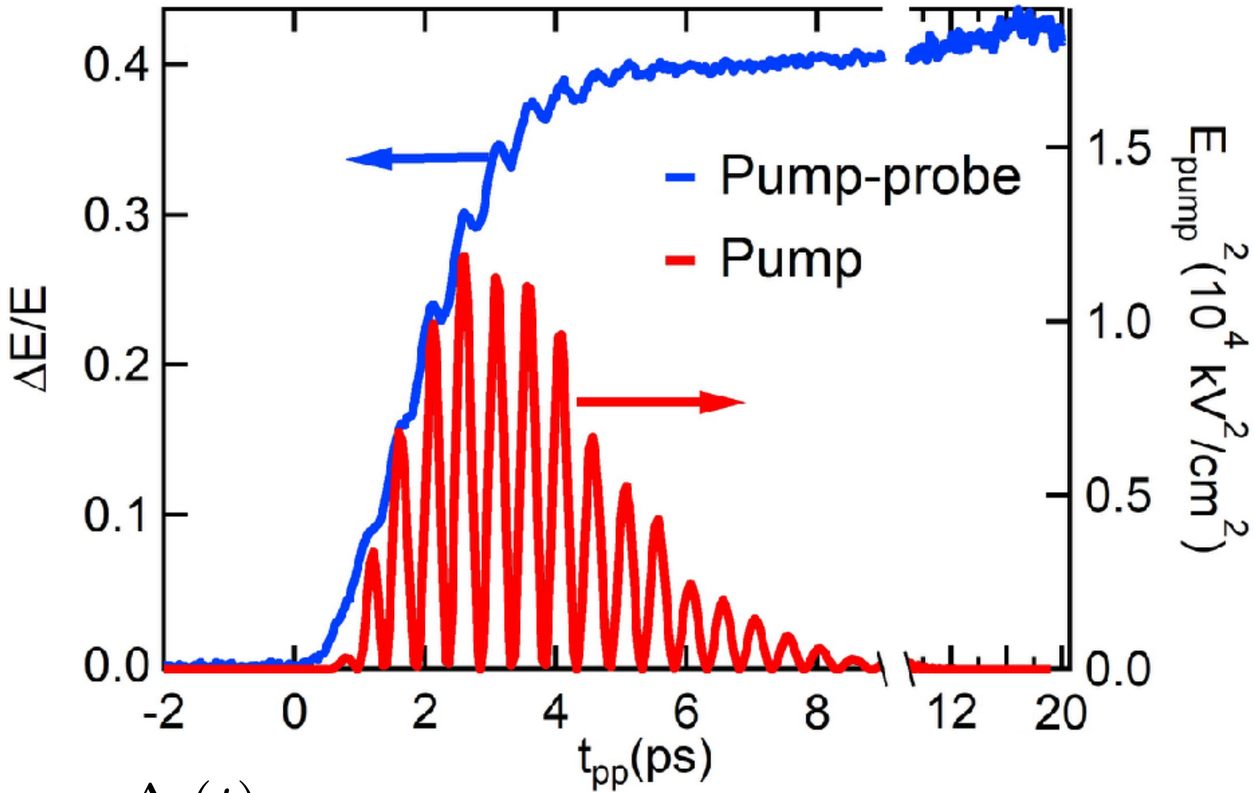
$$\delta E \propto 1 - \frac{\Delta(t)}{\Delta_i}$$



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

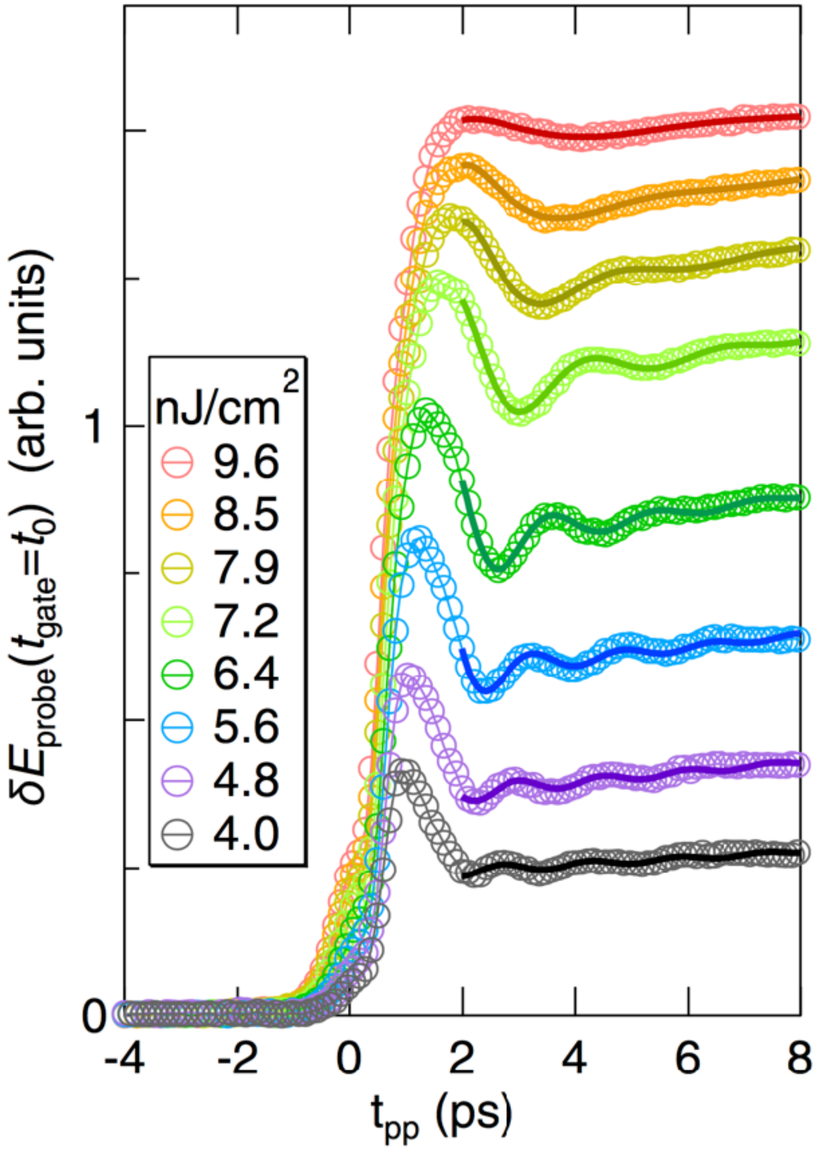
Resonantly driven amplitude mode

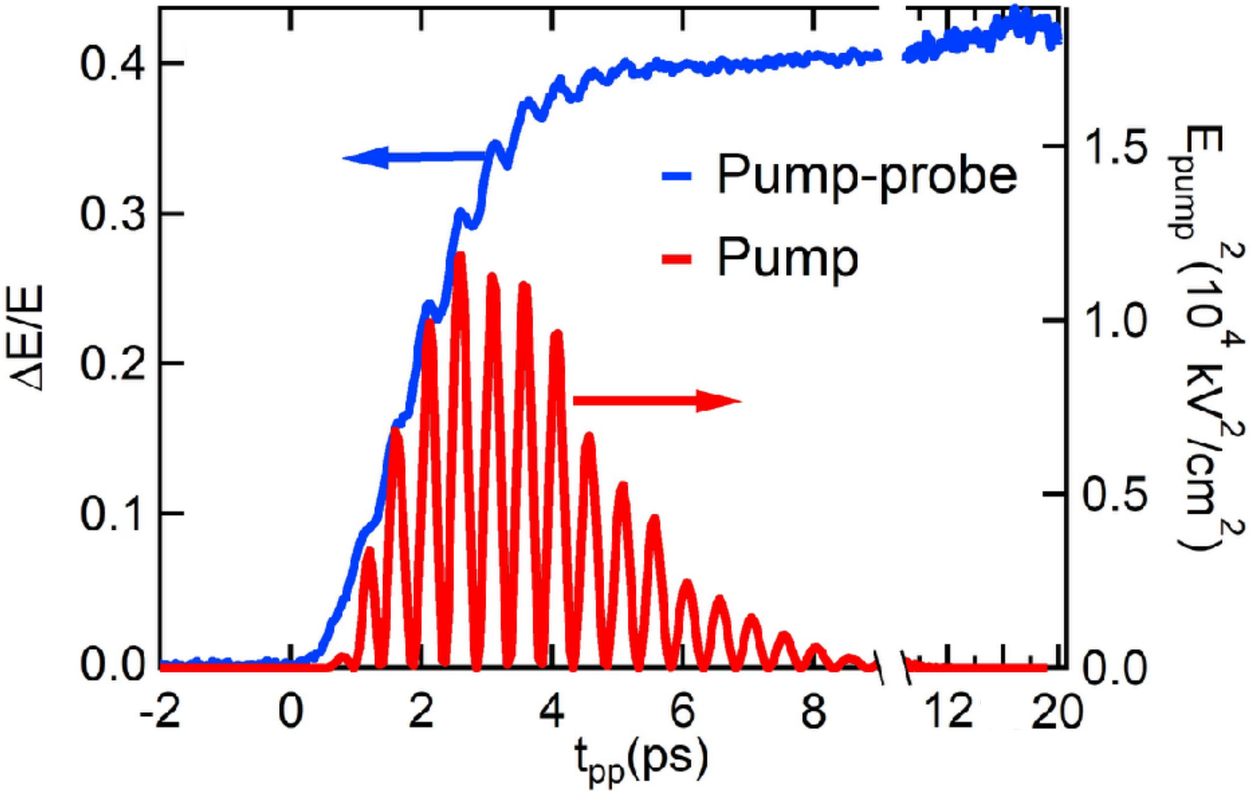




$$\Delta E/E \propto 1 - \frac{\Delta(t)}{\Delta_i}$$

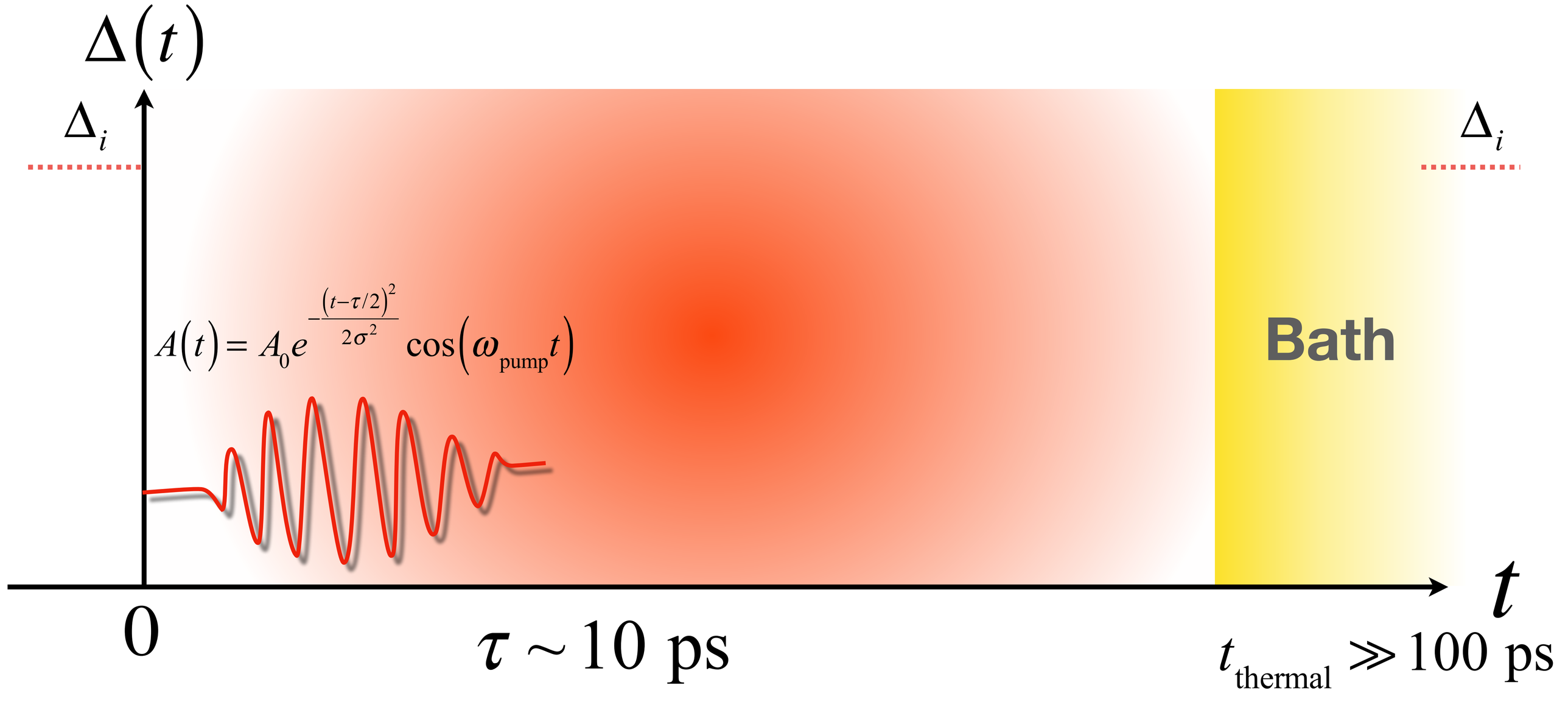
Quench vs Resonant driving



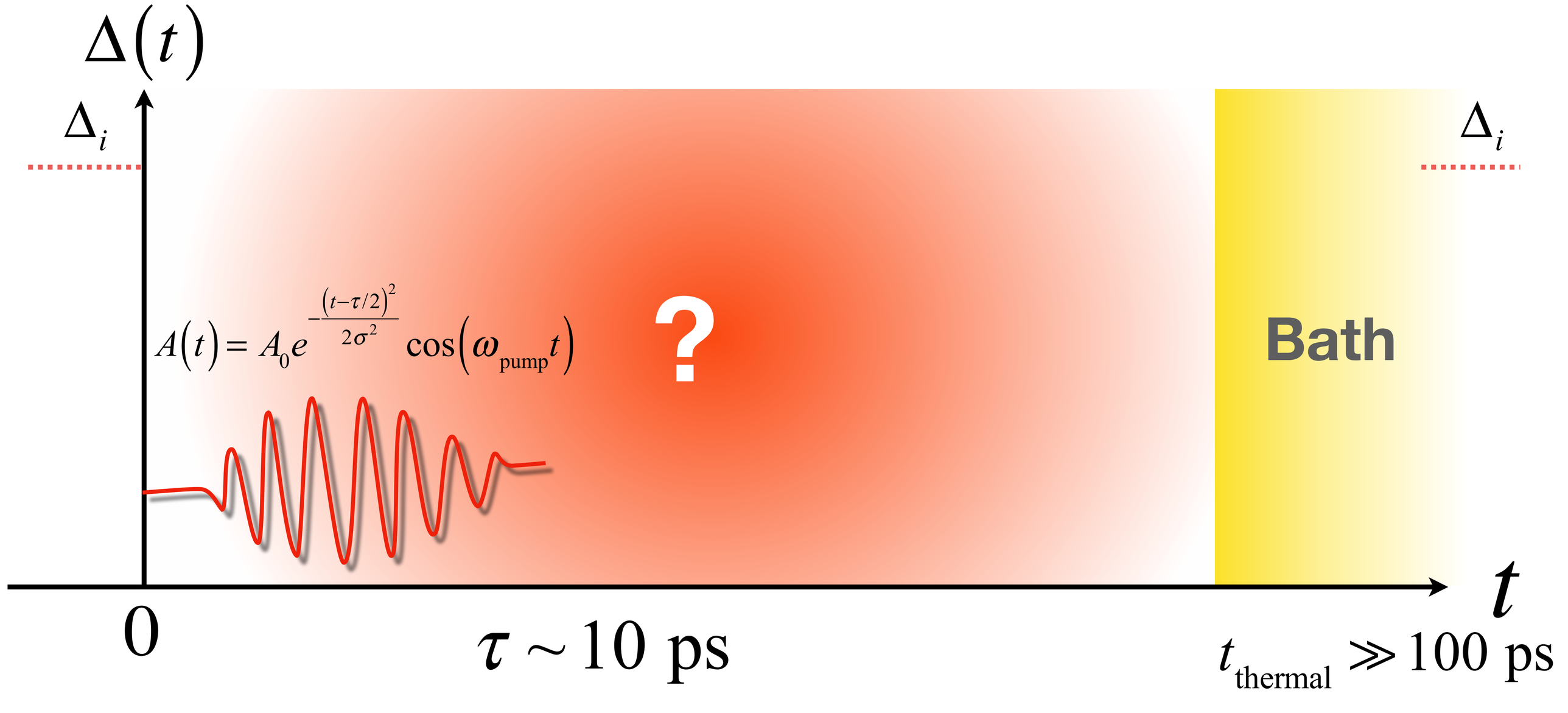


Transient dynamics

Transient dynamics



Transient dynamics



Pseudo-spin formalism

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

[1] PW. Anderson, *Phys. Rev.*, **112**, 1900 (1958)

Pseudo-spin formalism

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

$$\Delta = -U \sum_{\mathbf{k}} \left\langle c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow} \right\rangle$$

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

$$\hat{S}^{+}_{\mathbf{k}} = c^{\dagger}_{\mathbf{k},\uparrow} c^{\dagger}_{-\mathbf{k},\downarrow}$$

$$\hat{S}^{-}_{\mathbf{k}} = c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow}$$

[1] PW. Anderson, *Phys. Rev.*, **112**, 1900 (1958)

Pseudo-spin formalism

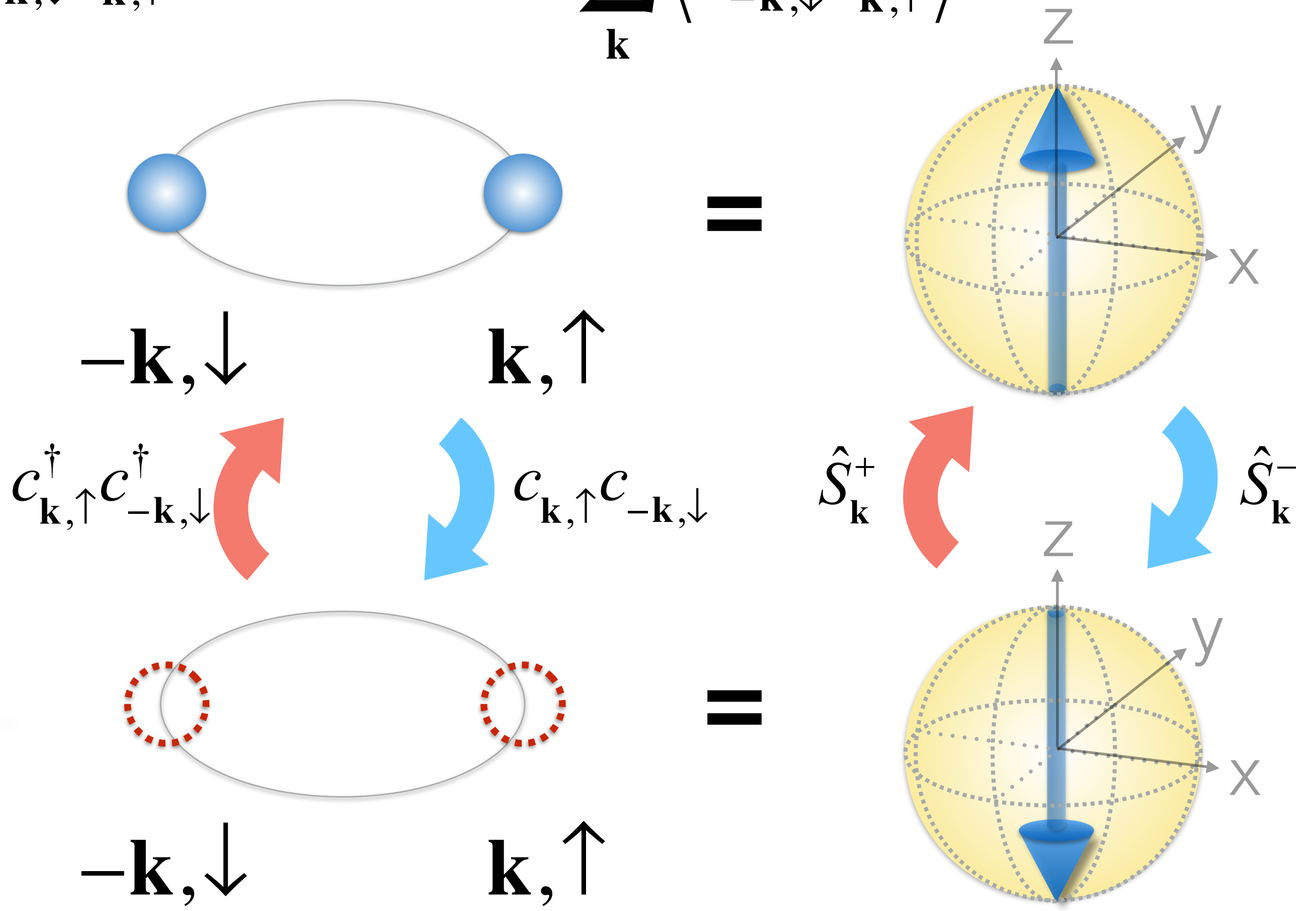
$$H_{\mathrm{BCS}} = \sum_{\mathbf{k},\sigma} \varepsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k},\sigma} c_{\mathbf{k},\sigma} + U \sum_{\mathbf{k},\mathbf{k}'} c^{\dagger}_{\mathbf{k},\uparrow} c^{\dagger}_{-\mathbf{k},\downarrow} c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow}$$

$$\Delta = -U \sum_{\mathbf{k}} \left\langle c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow} \right\rangle$$

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

$$\hat{S}^{+}_{\mathbf{k}} = c^{\dagger}_{\mathbf{k},\uparrow} c^{\dagger}_{-\mathbf{k},\downarrow}$$

$$\hat{S}^{-}_{\mathbf{k}} = c_{-\mathbf{k},\downarrow} c_{\mathbf{k},\uparrow}$$



[1] PW. Anderson, *Phys. Rev.*, **112**, 1900 (1958)

Pseudo-spin formalism

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

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

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

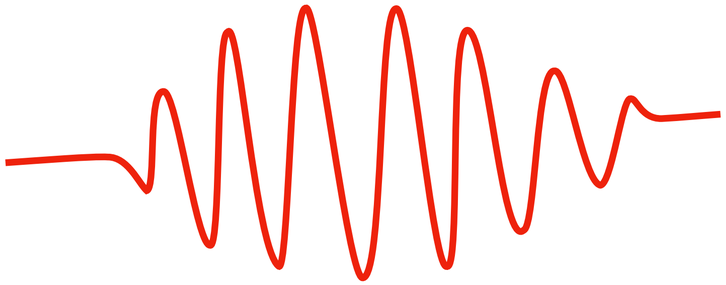
[1] PW. Anderson, *Phys. Rev.*, **112**, 1900 (1958)

Couple BCS to Light

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

$$\Delta = -U \sum_{\mathbf{k}} S_{\mathbf{k}}^{-}$$

Couple BCS to Light



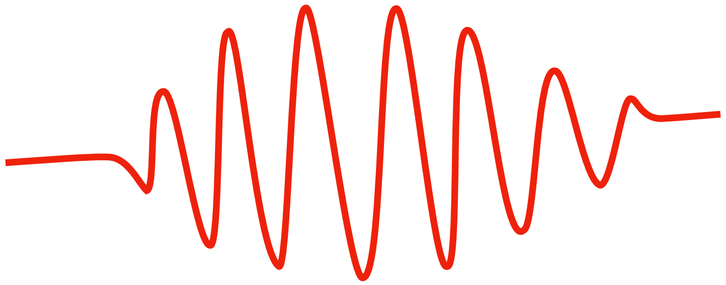
$$H_{\mathrm{BCS}} = -\sum_{\mathbf{k}} \mathbf{B}_{\mathbf{k}} \cdot \hat{\mathbf{S}}_{\mathbf{k}}$$

$$\Delta = -U \sum_{\mathbf{k}} S_{\mathbf{k}}^{-}$$

Couple BCS to Light

Peierls Substitution:

$$\varepsilon_{\mathbf{k}} \rightarrow \varepsilon_{\mathbf{k}-e\mathbf{A}(t)}$$



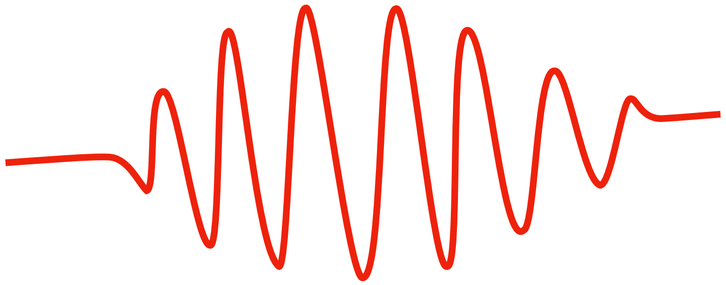
$$H_{\mathrm{BCS}} = -\sum_{\mathbf{k}} \mathbf{B}_{\mathbf{k}} \cdot \hat{\mathbf{S}}_{\mathbf{k}}$$

$$\Delta = -U \sum_{\mathbf{k}} S_{\mathbf{k}}^{-}$$

Couple BCS to Light

Peierls Substitution:

$$\varepsilon_{\mathbf{k}} \rightarrow \varepsilon_{\mathbf{k}-e\mathbf{A}(t)}$$



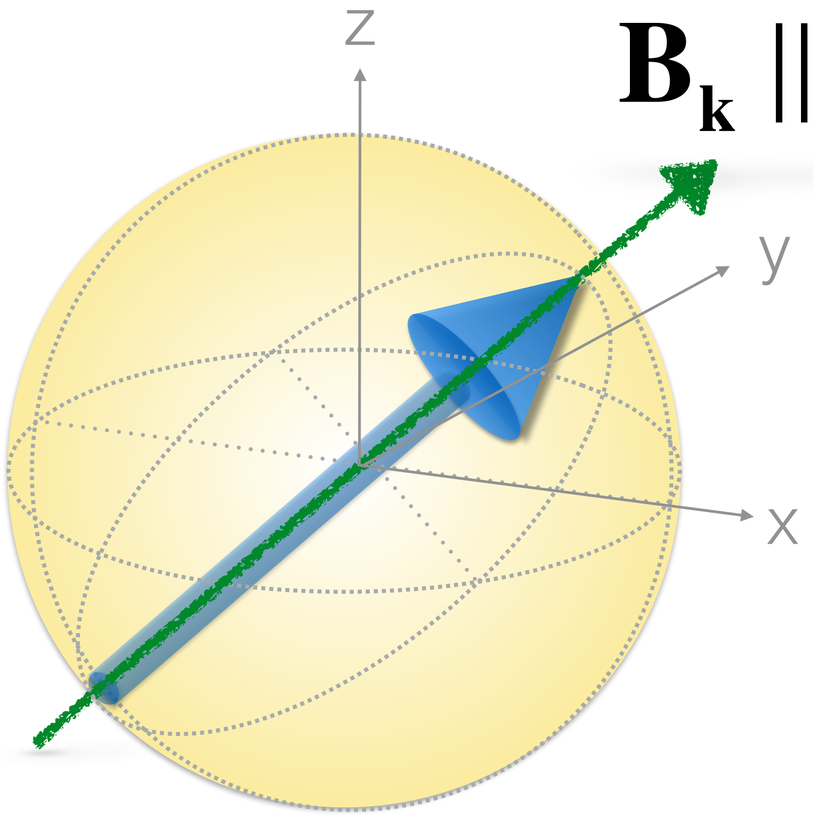
$$H_{\mathrm{BCS}} = -\sum_{\mathbf{k}} \mathbf{B}_{\mathbf{k}} \cdot \hat{\mathbf{S}}_{\mathbf{k}}$$

$$\Delta = -U \sum_{\mathbf{k}} S_{\mathbf{k}}^{-}$$

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

Pseudo-spin dynamics

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



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

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

Initial conditions:

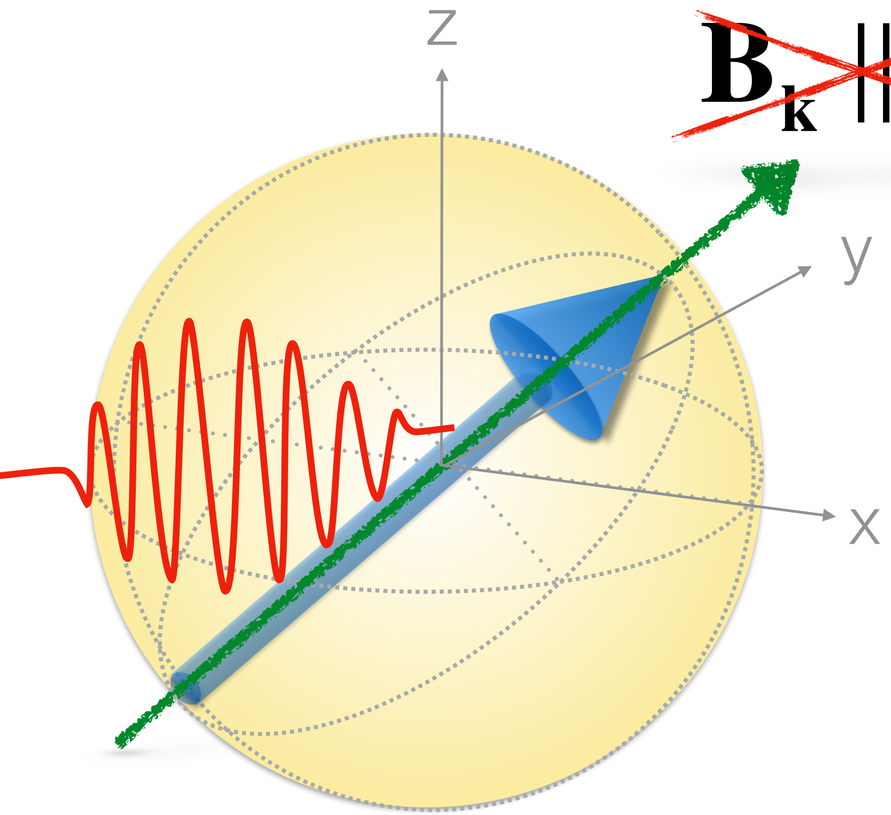
$$S_{\mathbf{k}}^{x}\left(0^{-}\right) = \frac{\Delta_i}{2\sqrt{\varepsilon_{\mathbf{k}}^2 + \Delta_i^2}}$$

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

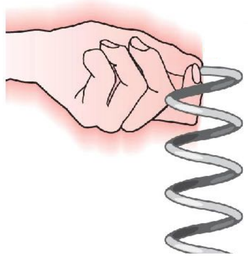
$$S_{\mathbf{k}}^{z}\left(0^{-}\right) = \frac{-\varepsilon_{\mathbf{k}}}{2\sqrt{\varepsilon_{\mathbf{k}}^2 + \Delta_i^2}}$$

Pseudo-spin dynamics

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



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



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

$$-\frac{\varepsilon_{\mathbf{k}-e\mathbf{A}(t)} + \varepsilon_{\mathbf{k}+e\mathbf{A}(t)}}{2}$$

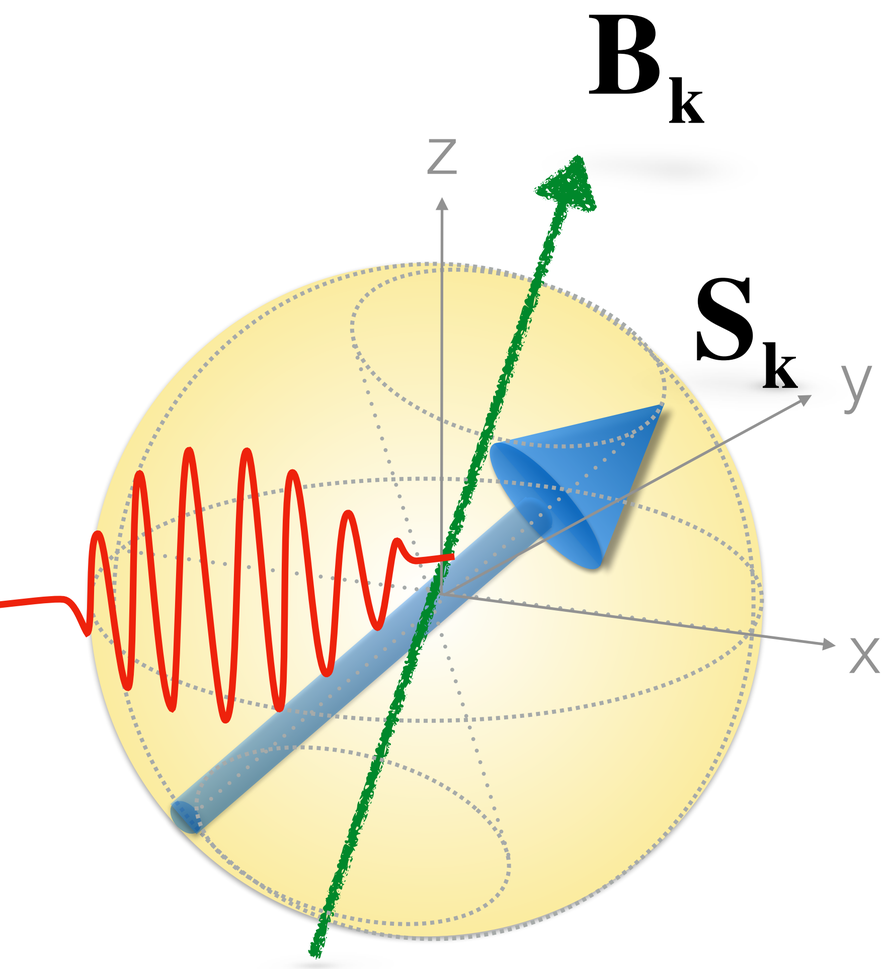
Initial conditions:

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

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

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

Pseudo-spin dynamics

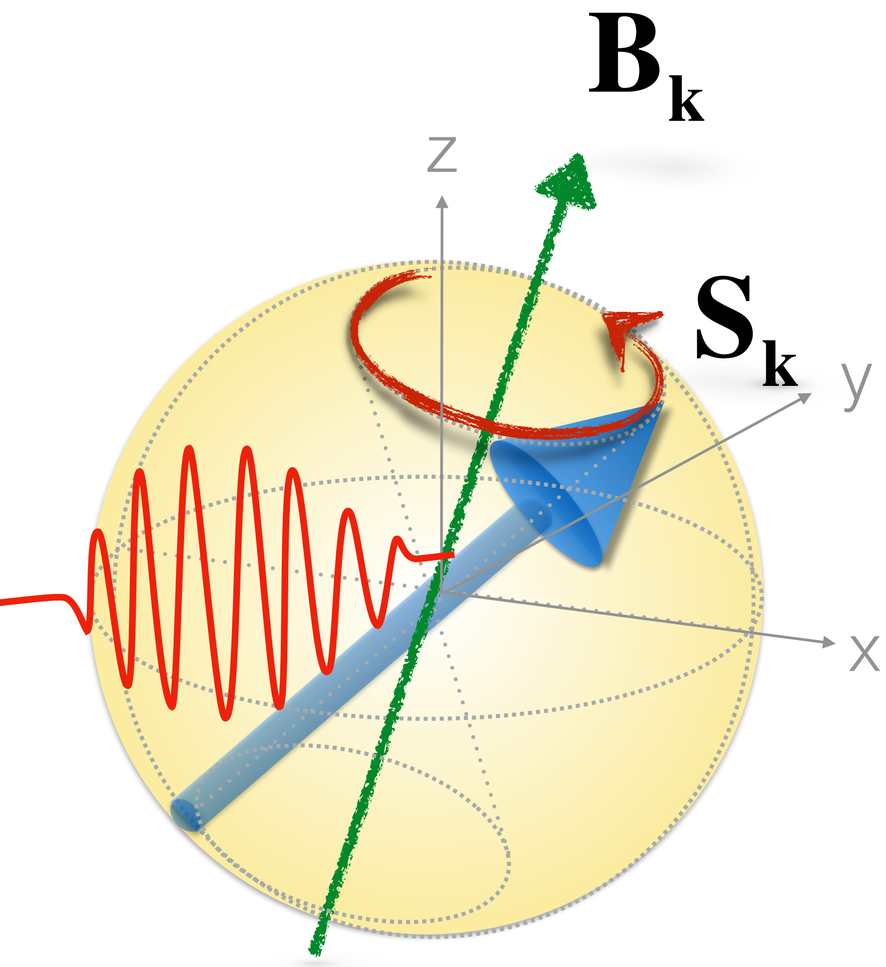


Equations of motion:

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

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

Pseudo-spin dynamics

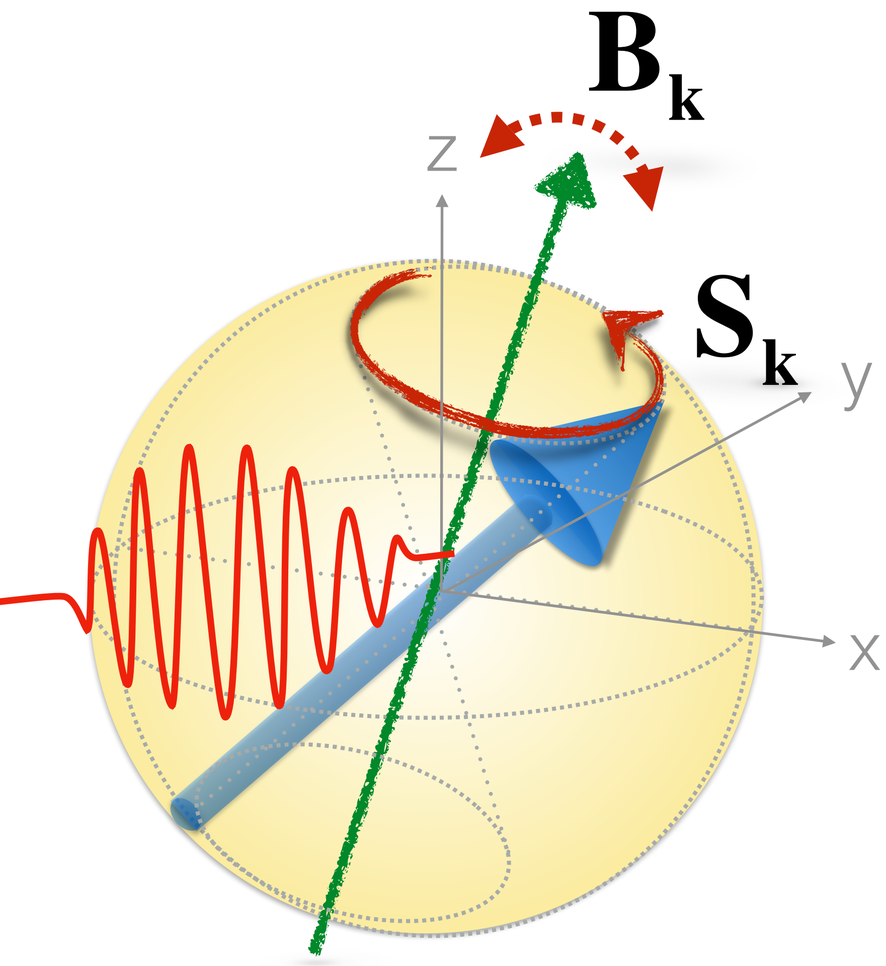


Equations of motion:

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

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

Pseudo-spin dynamics

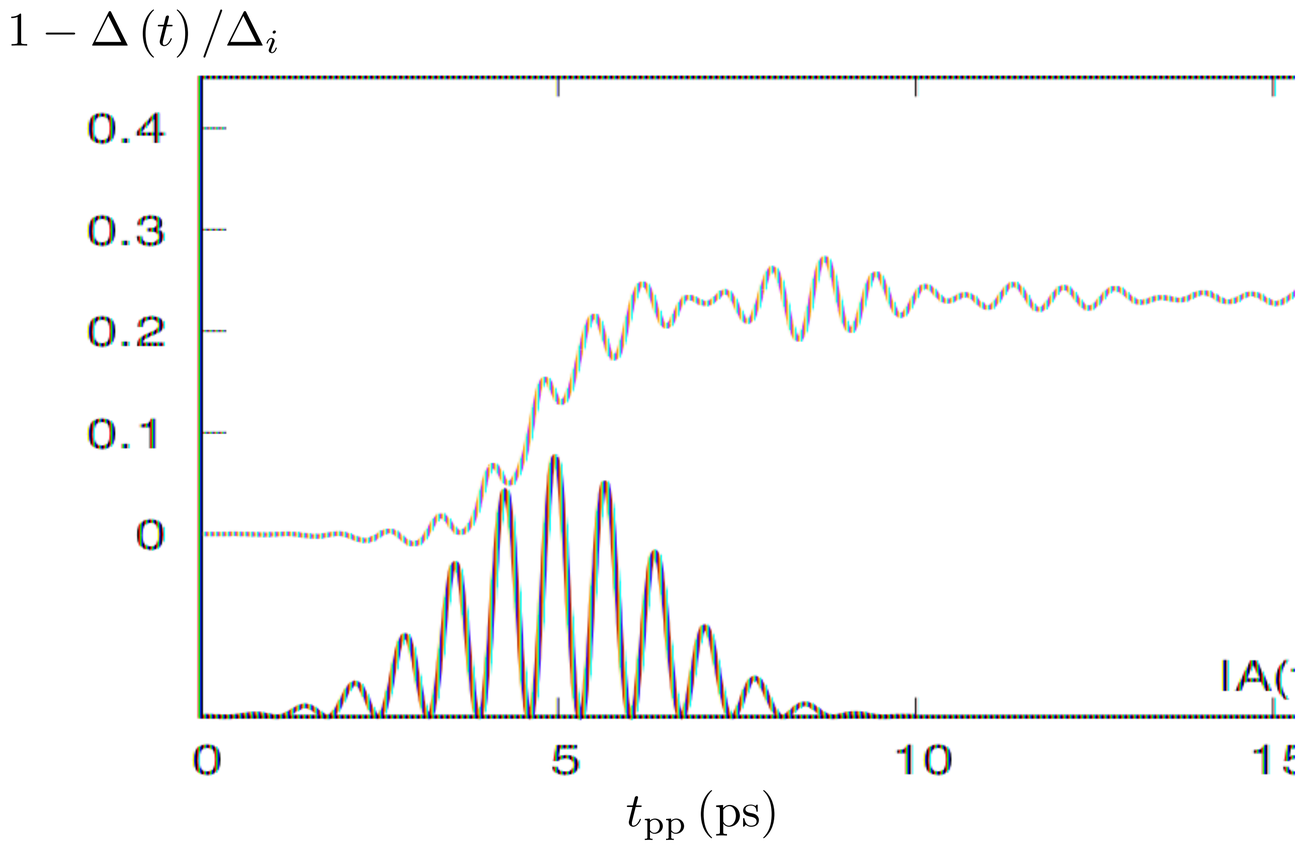


Equations of motion:

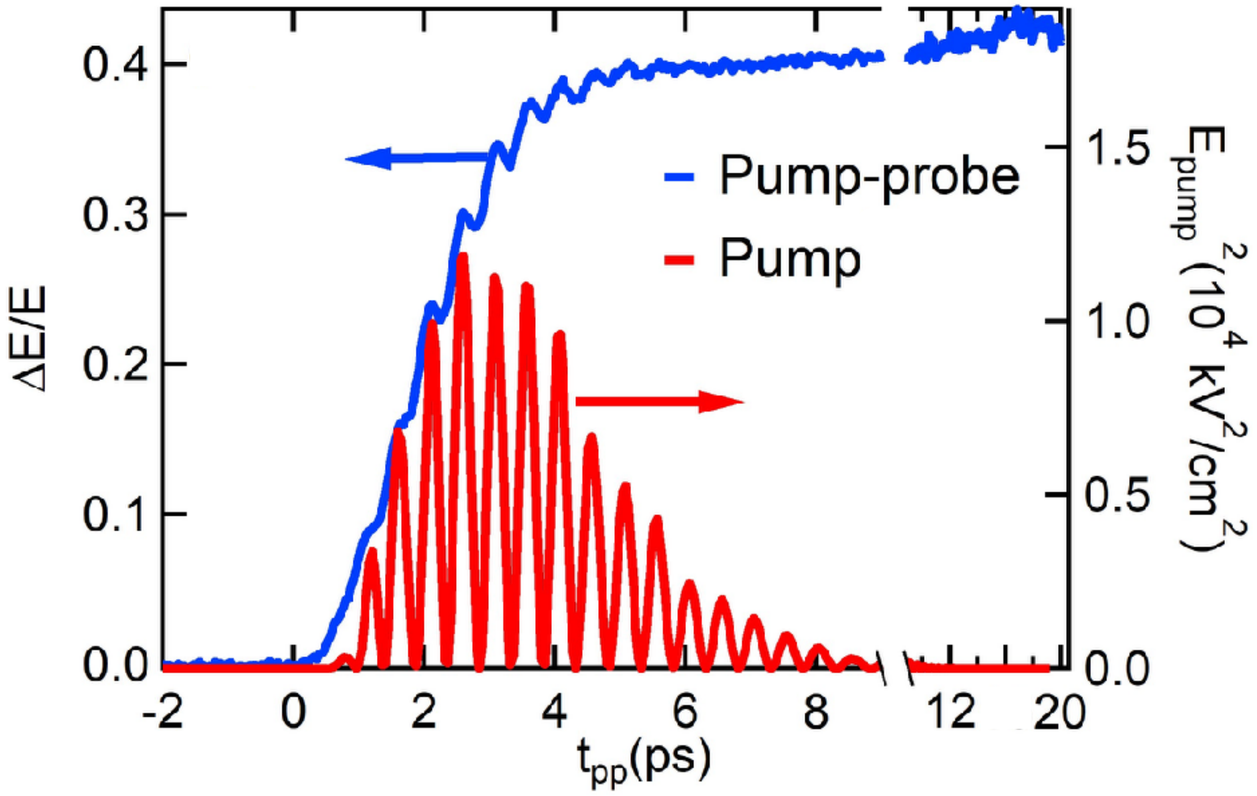
$$\frac{d}{dt}\mathbf{S}_\mathbf{k} = i\left\langle\left[H_{\mathrm{BCS}}, \hat{\mathbf{S}}_\mathbf{k}\right]\right\rangle = -\mathbf{B}_\mathbf{k} \times \mathbf{S}_\mathbf{k}$$

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

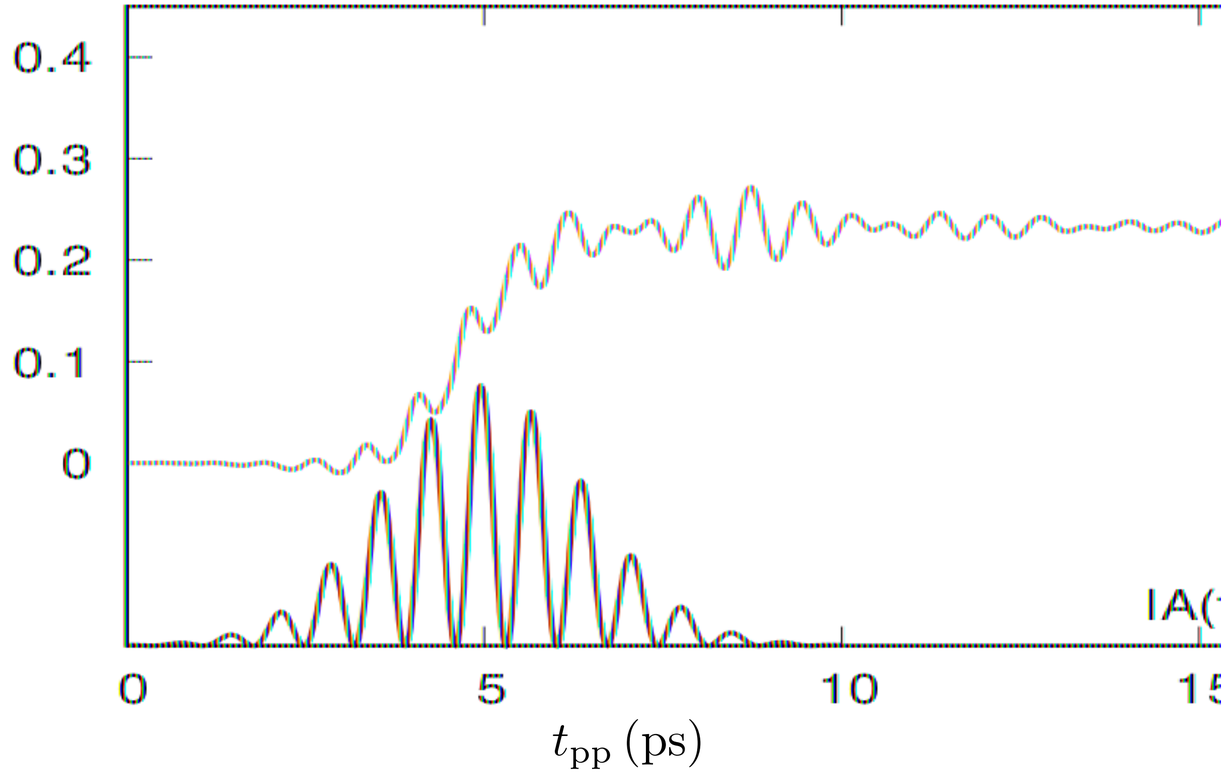
Results



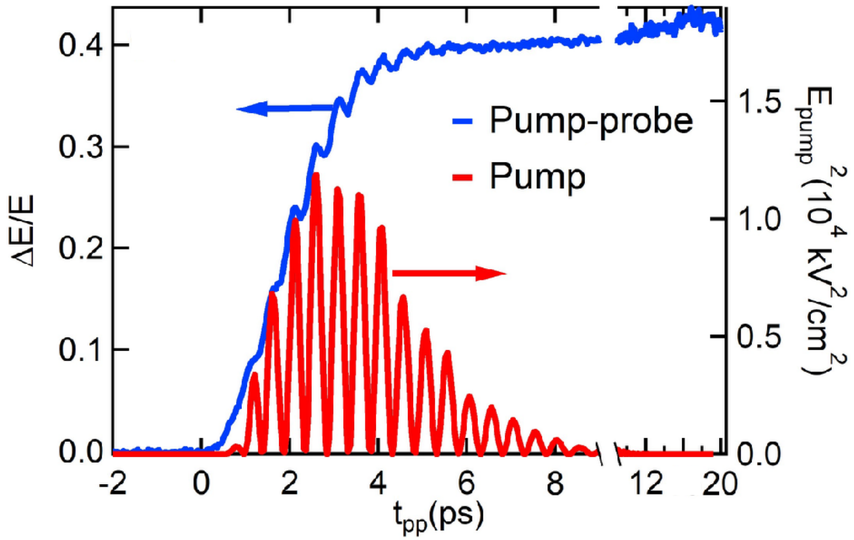
Results

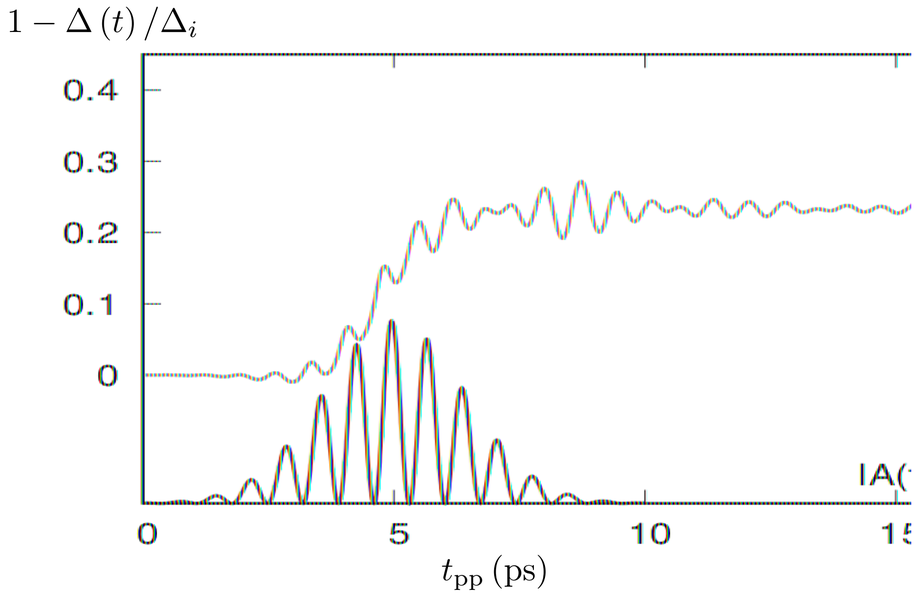


$1-\Delta(t)/\Delta_i$

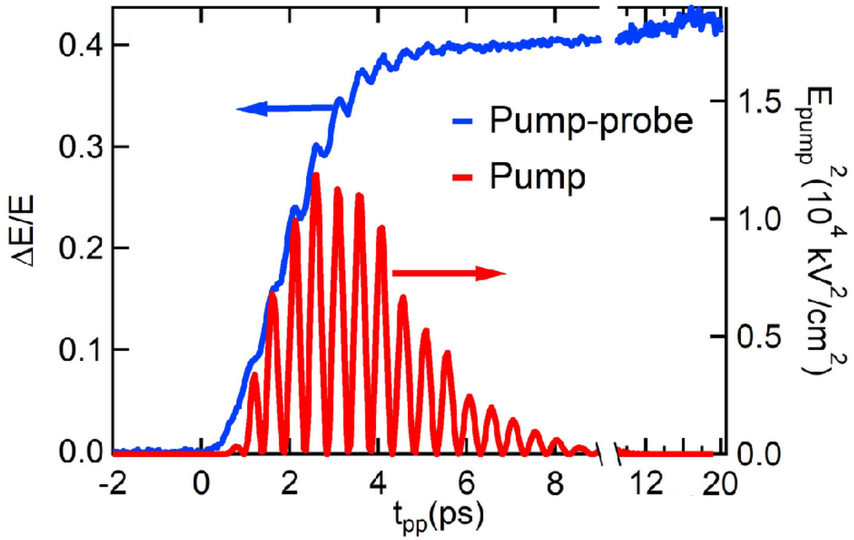


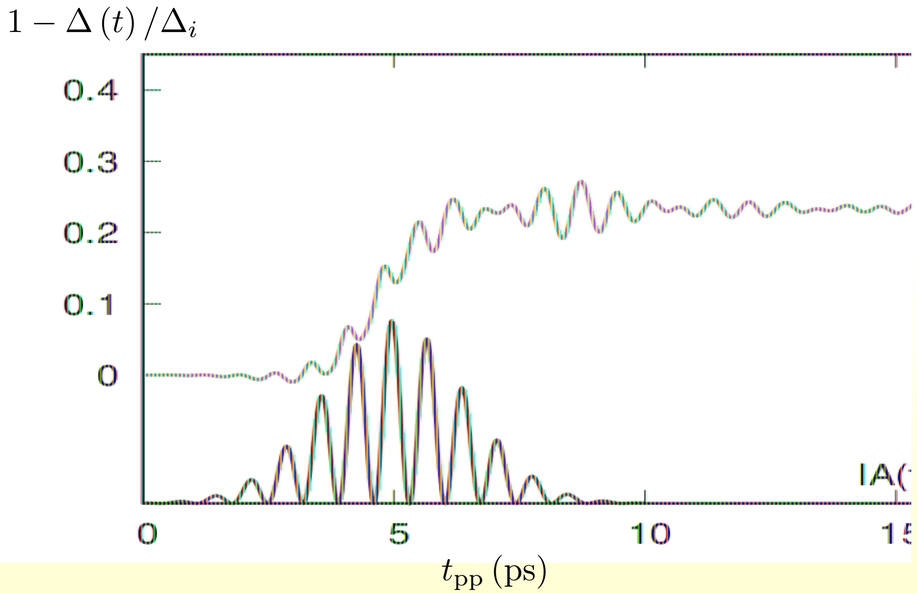
Reality vs BCS





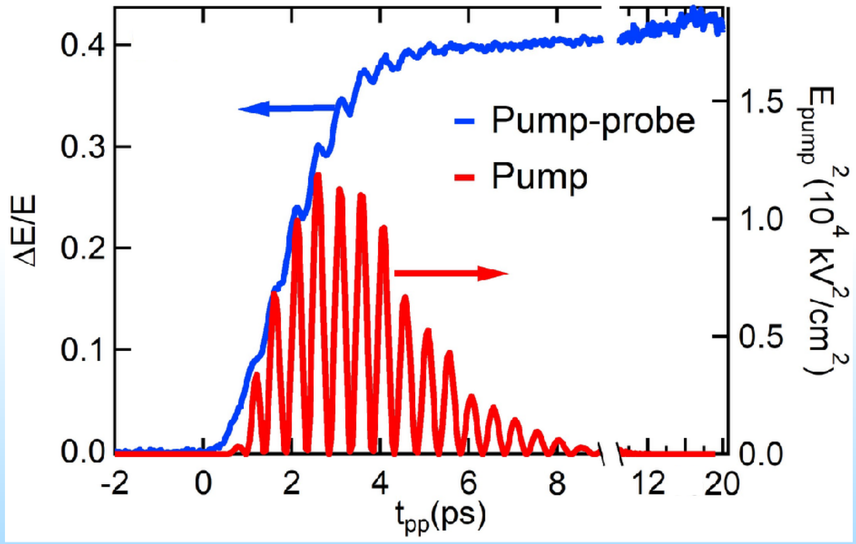
Reality vs BCS



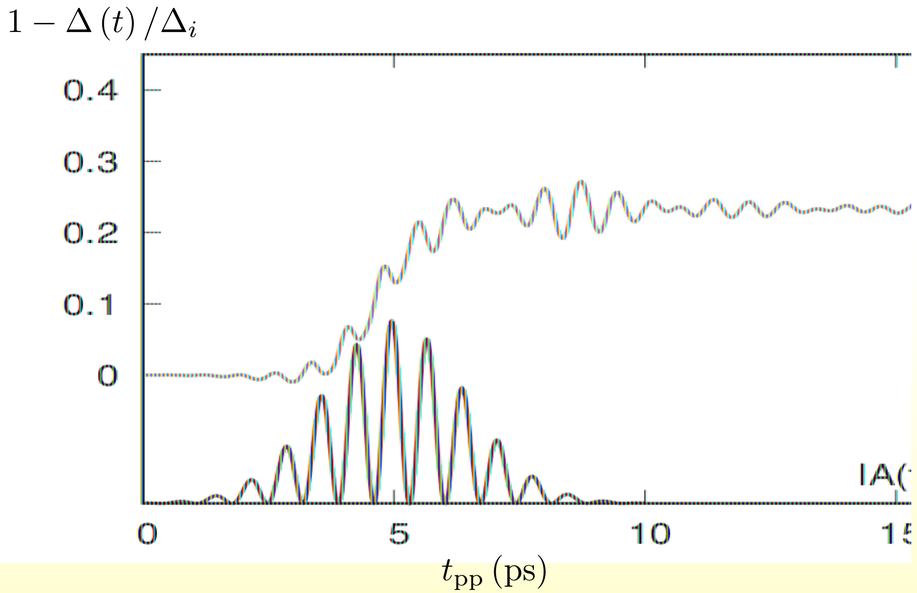


- **Integrable**
- **Collisionless**

Reality vs BCS

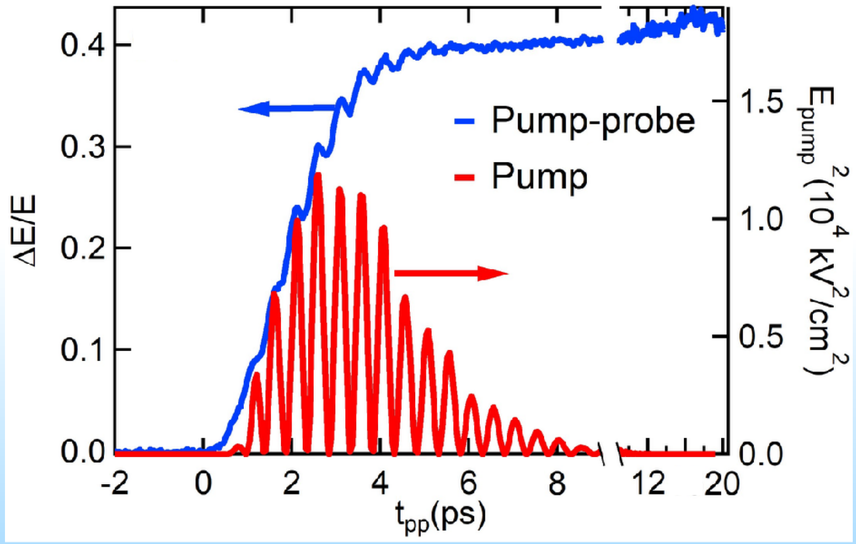


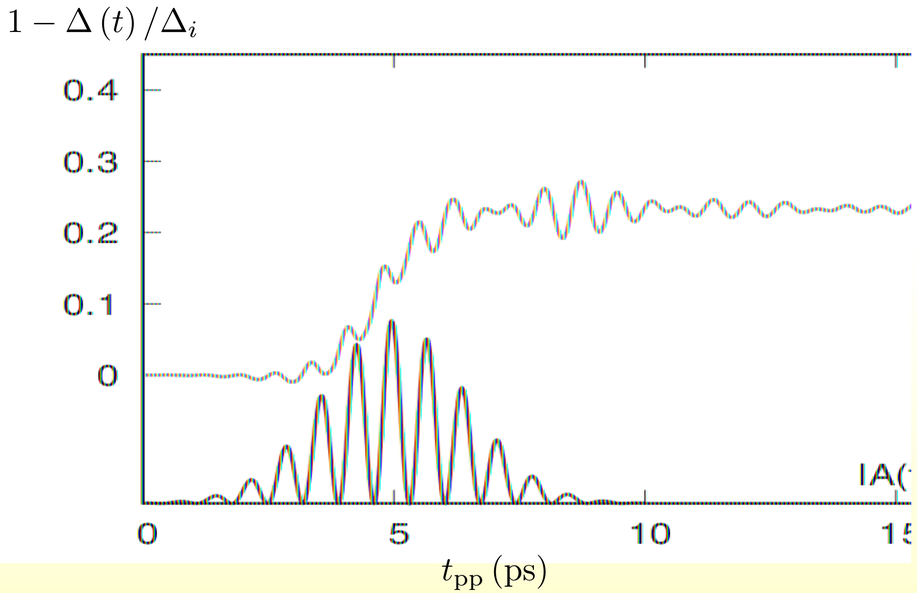
- **Non-integrable**
- **Collision**



- **Integrable**
- **Collisionless**

Reality vs BCS



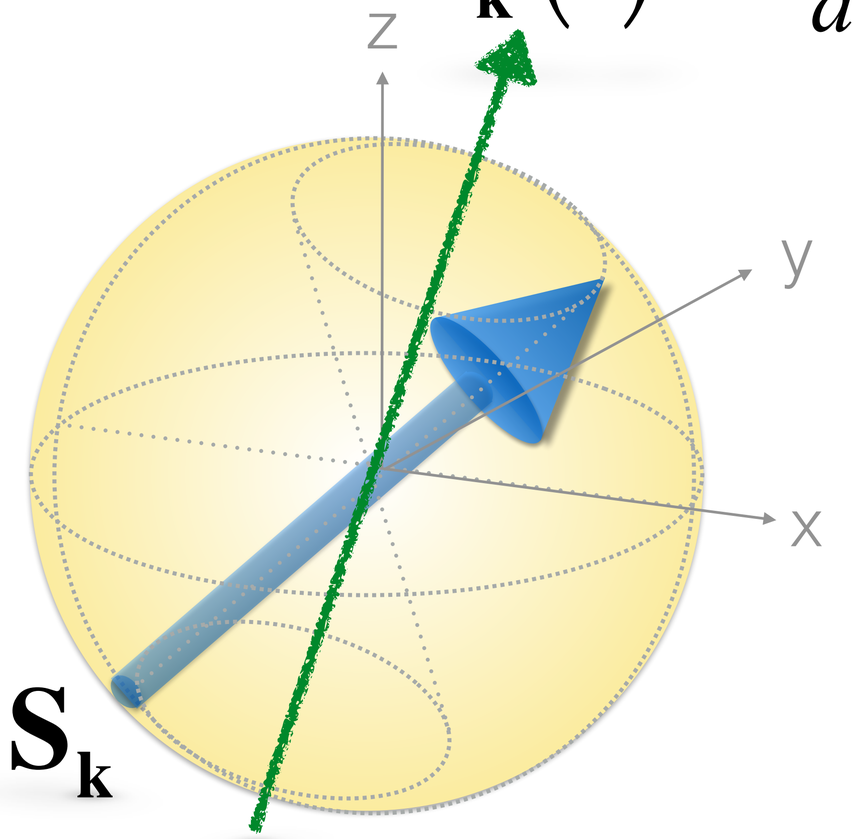


- **Non-integrable**
- **Collision**

- **Integrable**
- **Collisionless**

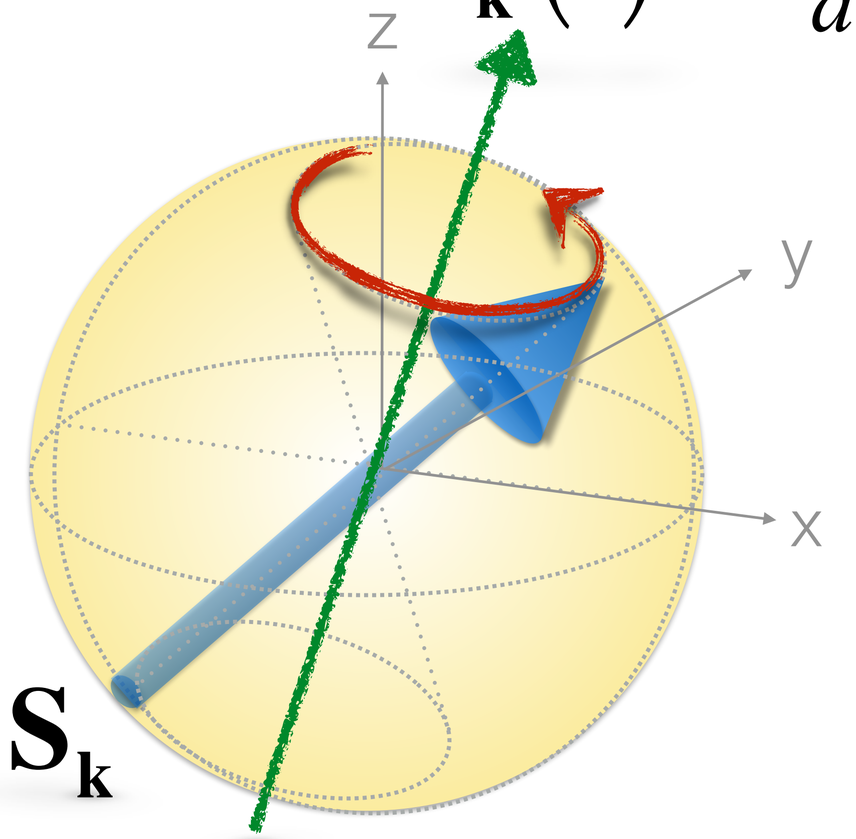
Relaxation of the pseudo-spins

$$\mathbf{B}_\mathbf{k}(t) \qquad \frac{d}{dt}\mathbf{S}_\mathbf{k}(t) = \left\{-\mathbf{B}_\mathbf{k}(t) \times \mathbf{S}_\mathbf{k}(t)\right.$$



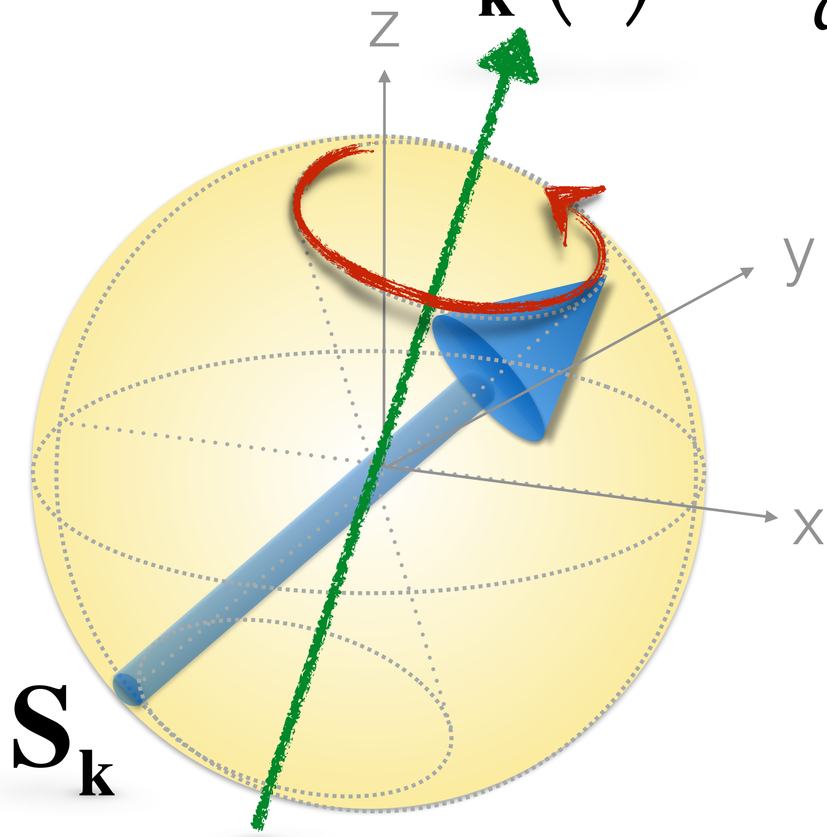
Relaxation of the pseudo-spins

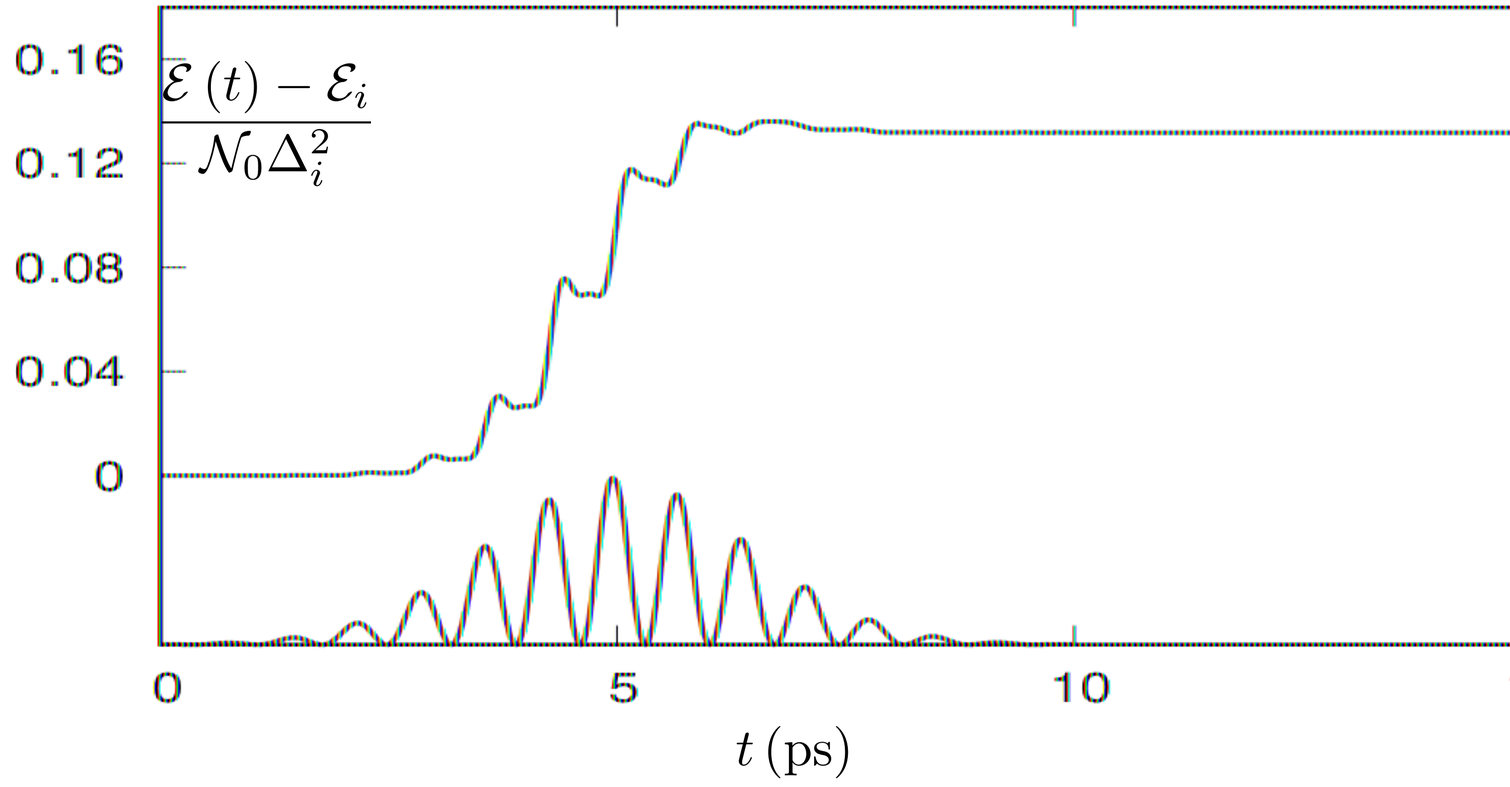
$$\mathbf{B}_\mathbf{k}(t) \qquad \frac{d}{dt}\mathbf{S}_\mathbf{k}(t) = \left\{-\mathbf{B}_\mathbf{k}(t) \times \mathbf{S}_\mathbf{k}(t)\right.$$



Relaxation of the pseudo-spins

$$\mathbf{B}_{\mathbf{k}}(t) \qquad \frac{d}{dt}\mathbf{S}_{\mathbf{k}}(t) = \left\{-\mathbf{B}_{\mathbf{k}}(t) \times \mathbf{S}_{\mathbf{k}}(t)\right.$$



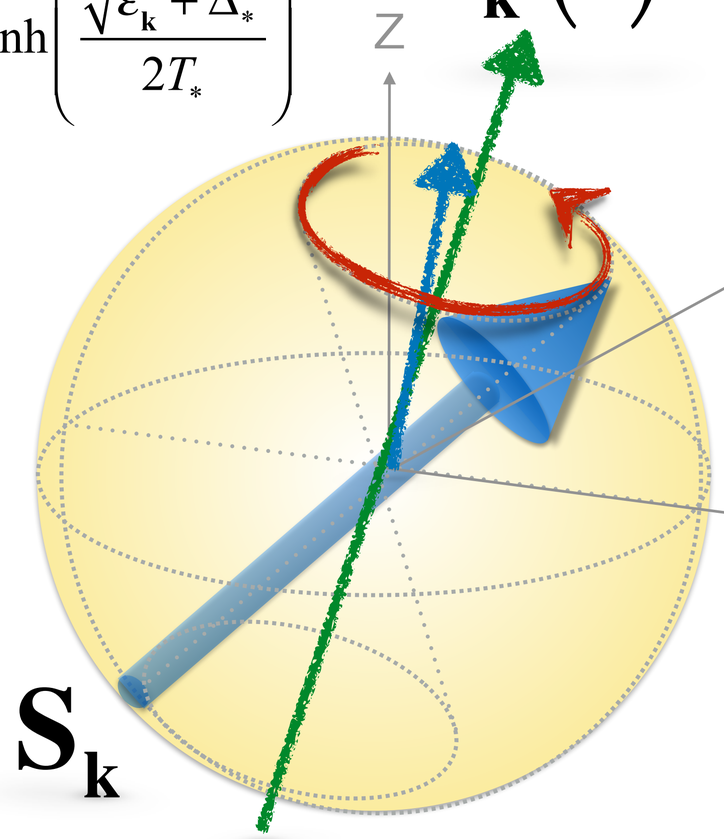


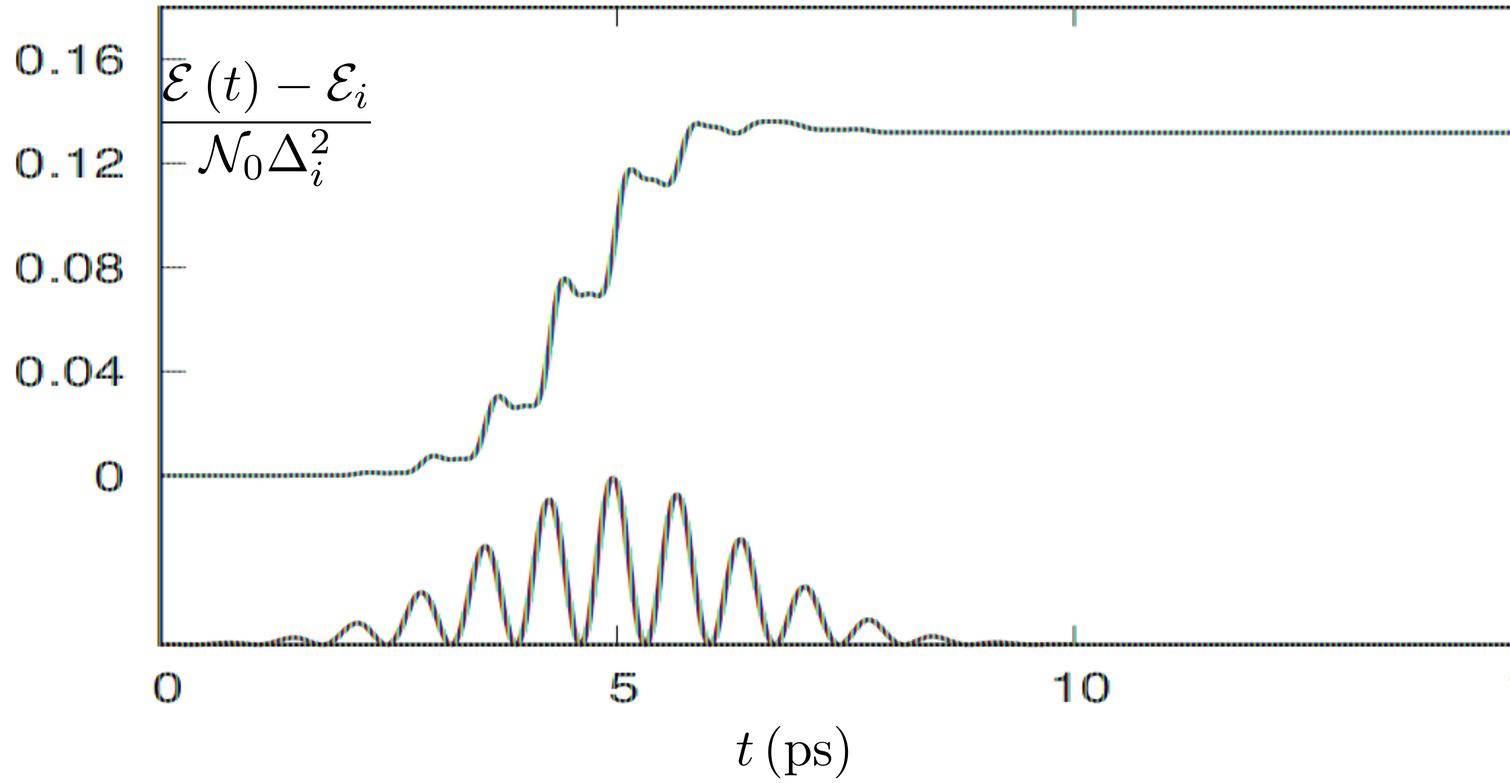
Relaxation of the pseudo-spins

$$\mathbf{S}_{\mathbf{k}}^{*}=\frac{\hat{s}_{\mathbf{k}}^{*}}{2}\tanh\left(\frac{\sqrt{\varepsilon_{\mathbf{k}}^{2}+\Delta_{*}^{2}}}{2T_{*}}\right)$$

$$\mathbf{B}_{\mathbf{k}}(t)$$

$$\frac{d}{dt}\mathbf{S}_{\mathbf{k}}(t)=\left\{-\mathbf{B}_{\mathbf{k}}(t)\times\mathbf{S}_{\mathbf{k}}(t)\right.$$

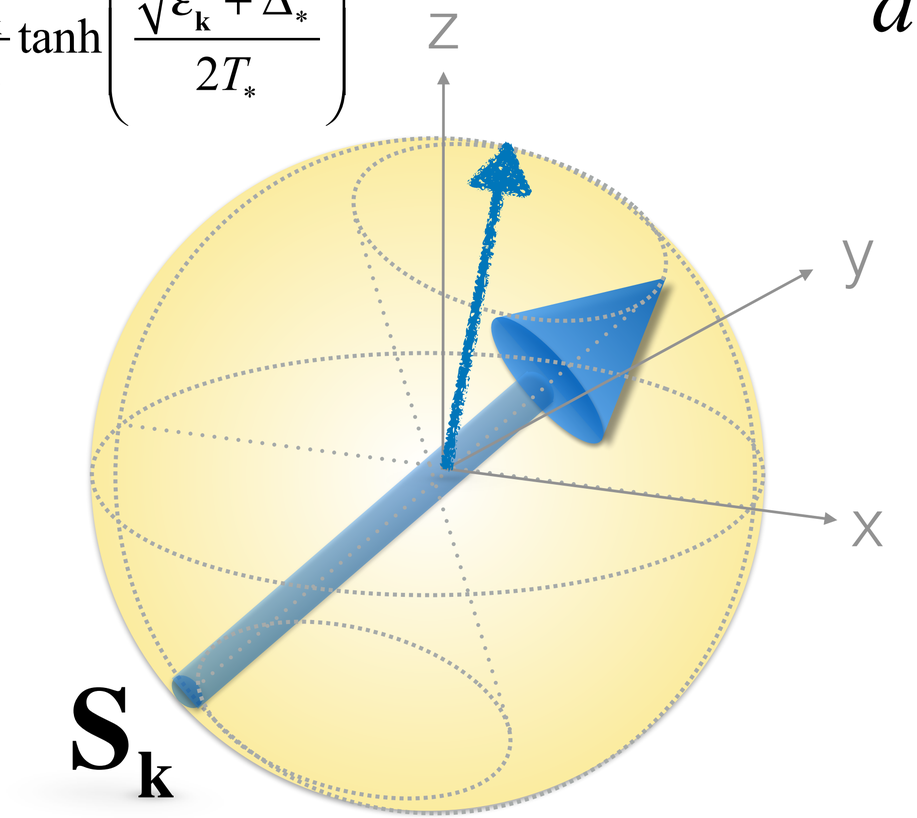




Relaxation of the pseudo-spins

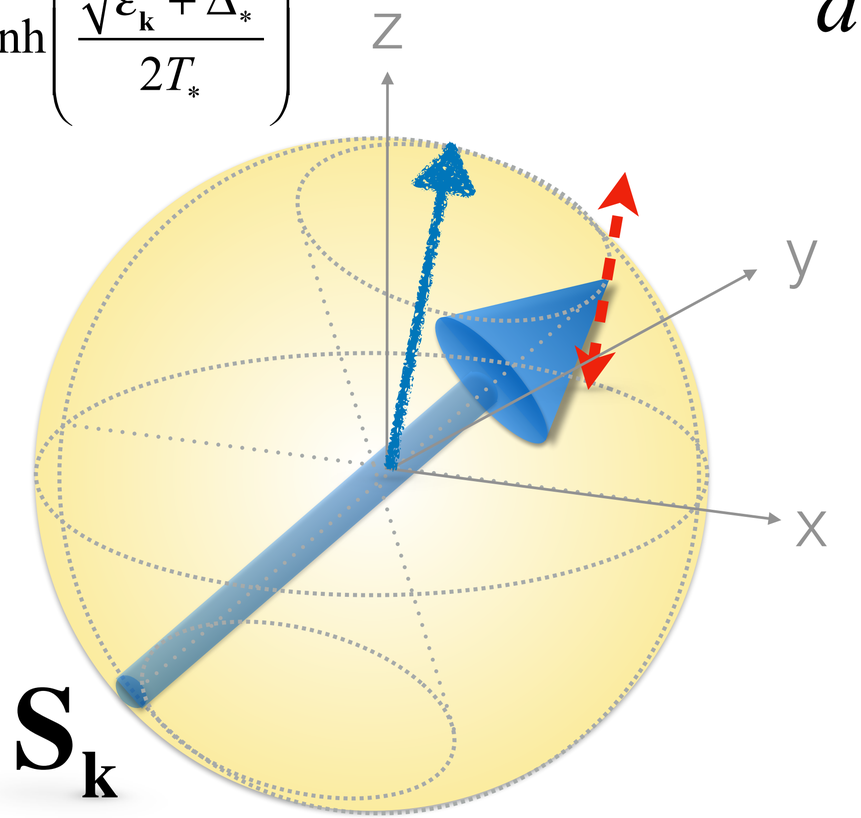
$$\mathbf{S}_{\mathbf{k}}^{*}=\frac{\hat{s}_{\mathbf{k}}^{*}}{2}\tanh\left(\frac{\sqrt{\varepsilon_{\mathbf{k}}^{2}+\Delta_{*}^{2}}}{2T_{*}}\right)$$

$$\frac{d}{dt}\mathbf{S}_{\mathbf{k}}(t)=\left\{-\mathbf{B}_{\mathbf{k}}(t)\times\mathbf{S}_{\mathbf{k}}(t)\right.$$



Relaxation of the pseudo-spins

$$\mathbf{S}_{\mathbf{k}}^{*}=\frac{\hat{s}_{\mathbf{k}}^{*}}{2}\tanh\left(\frac{\sqrt{\varepsilon_{\mathbf{k}}^{2}+\Delta_{*}^{2}}}{2T_{*}}\right)$$

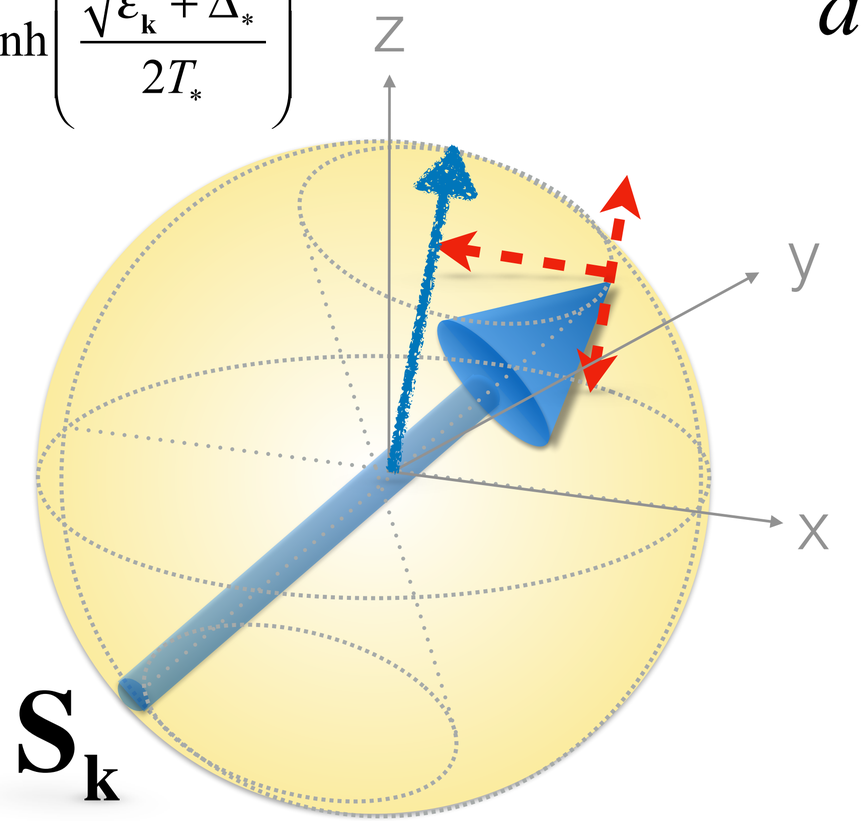


$$\frac{d}{dt}\mathbf{S}_{\mathbf{k}}(t)=\left\{-\mathbf{B}_{\mathbf{k}}(t)\times\mathbf{S}_{\mathbf{k}}(t)\right.$$

$$\left.-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_{1}}\hat{s}_{\mathbf{k}}^{*\parallel}\right.$$

Relaxation of the pseudo-spins

$$\mathbf{S}_{\mathbf{k}}^{*} = \frac{\hat{s}_{\mathbf{k}}^{*}}{2}\tanh\left(\frac{\sqrt{\varepsilon_{\mathbf{k}}^{2}+\Delta_{*}^{2}}}{2T_{*}}\right)$$

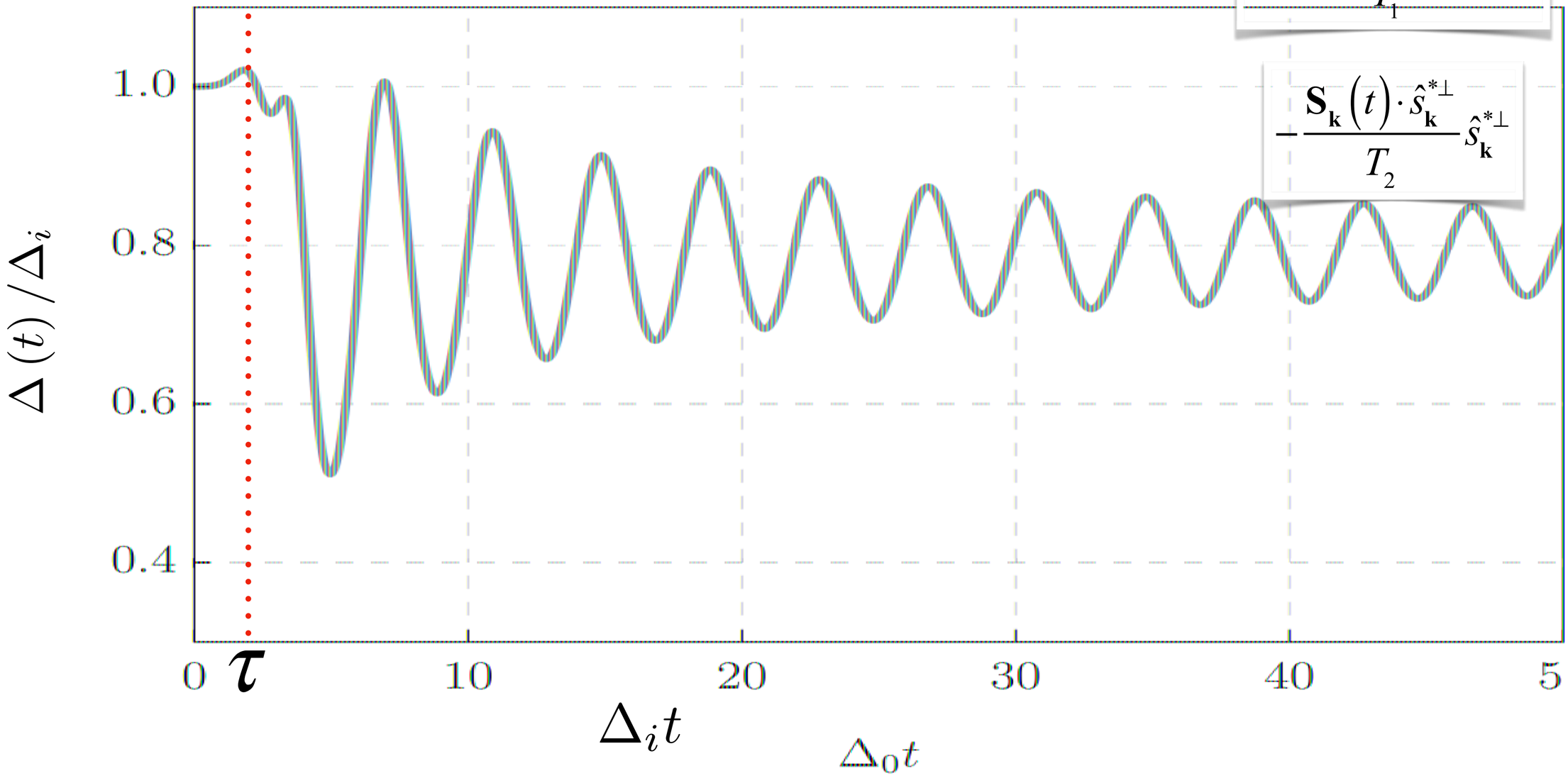


$$\frac{d}{dt}\mathbf{S}_{\mathbf{k}}(t) = \Big\{-\mathbf{B}_{\mathbf{k}}(t)\times\mathbf{S}_{\mathbf{k}}(t) - \frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel} - \left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel} - \frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}\Big\}$$

Damped quench dynamics

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

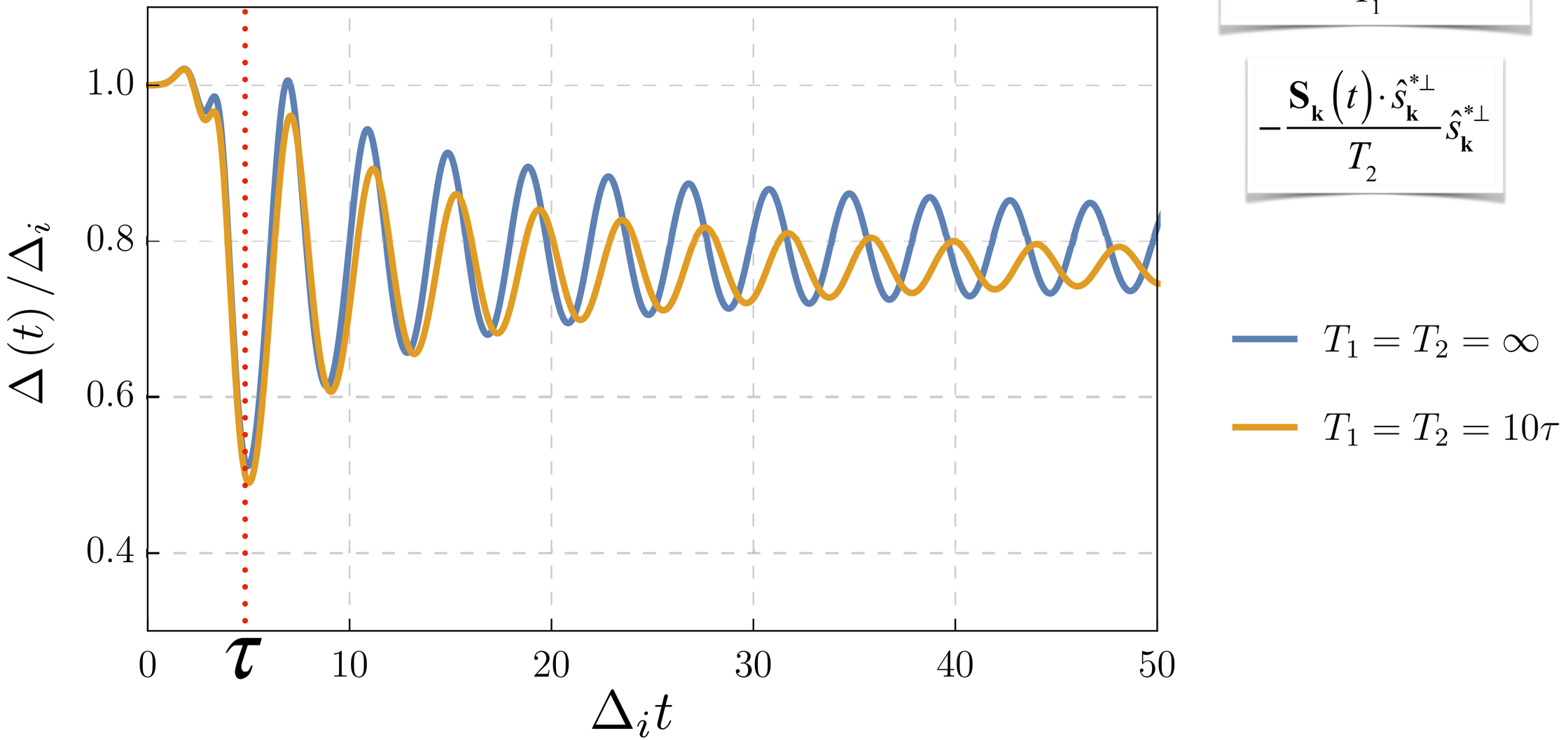
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Damped quench dynamics

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

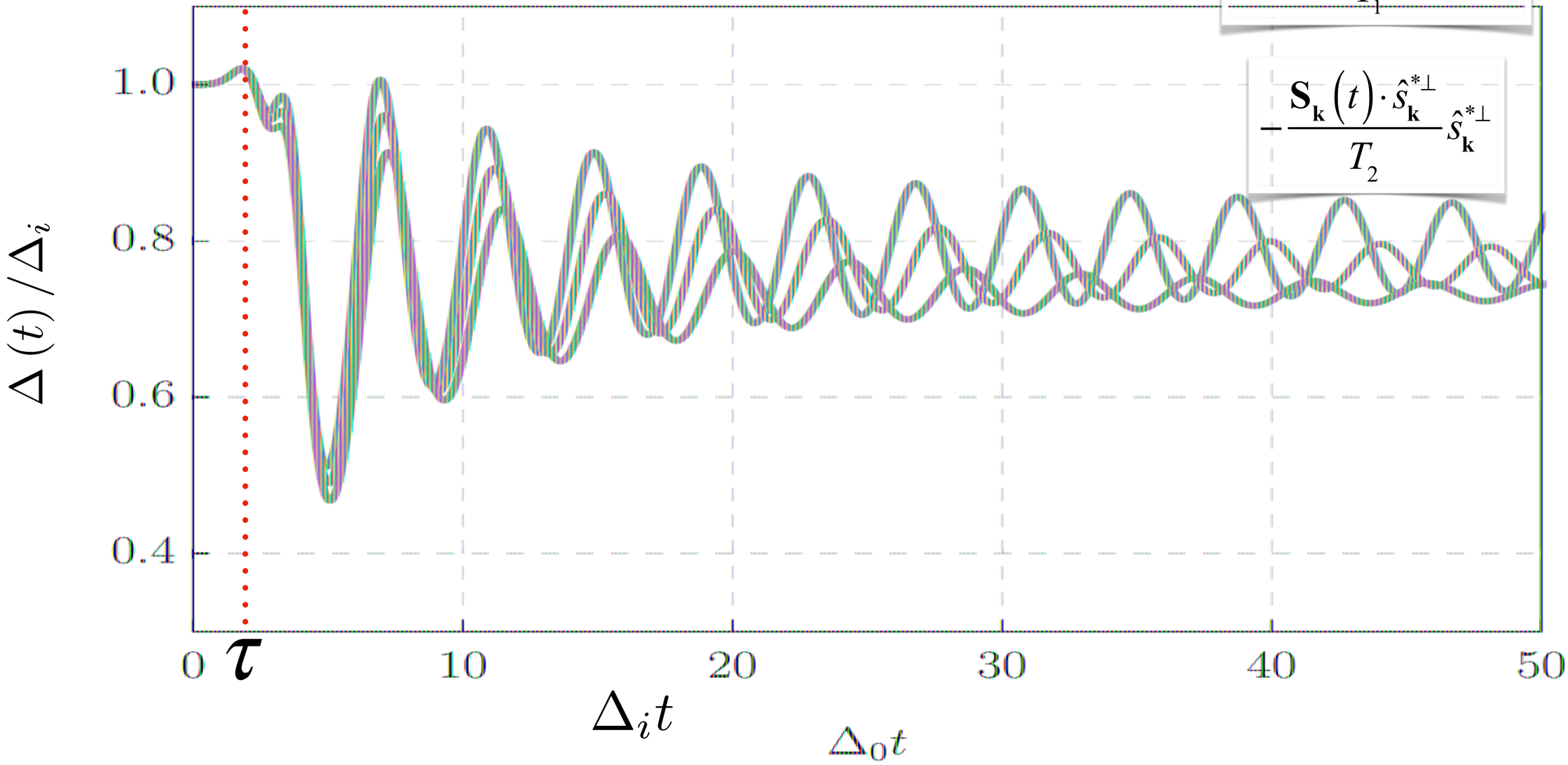
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Damped quench dynamics

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

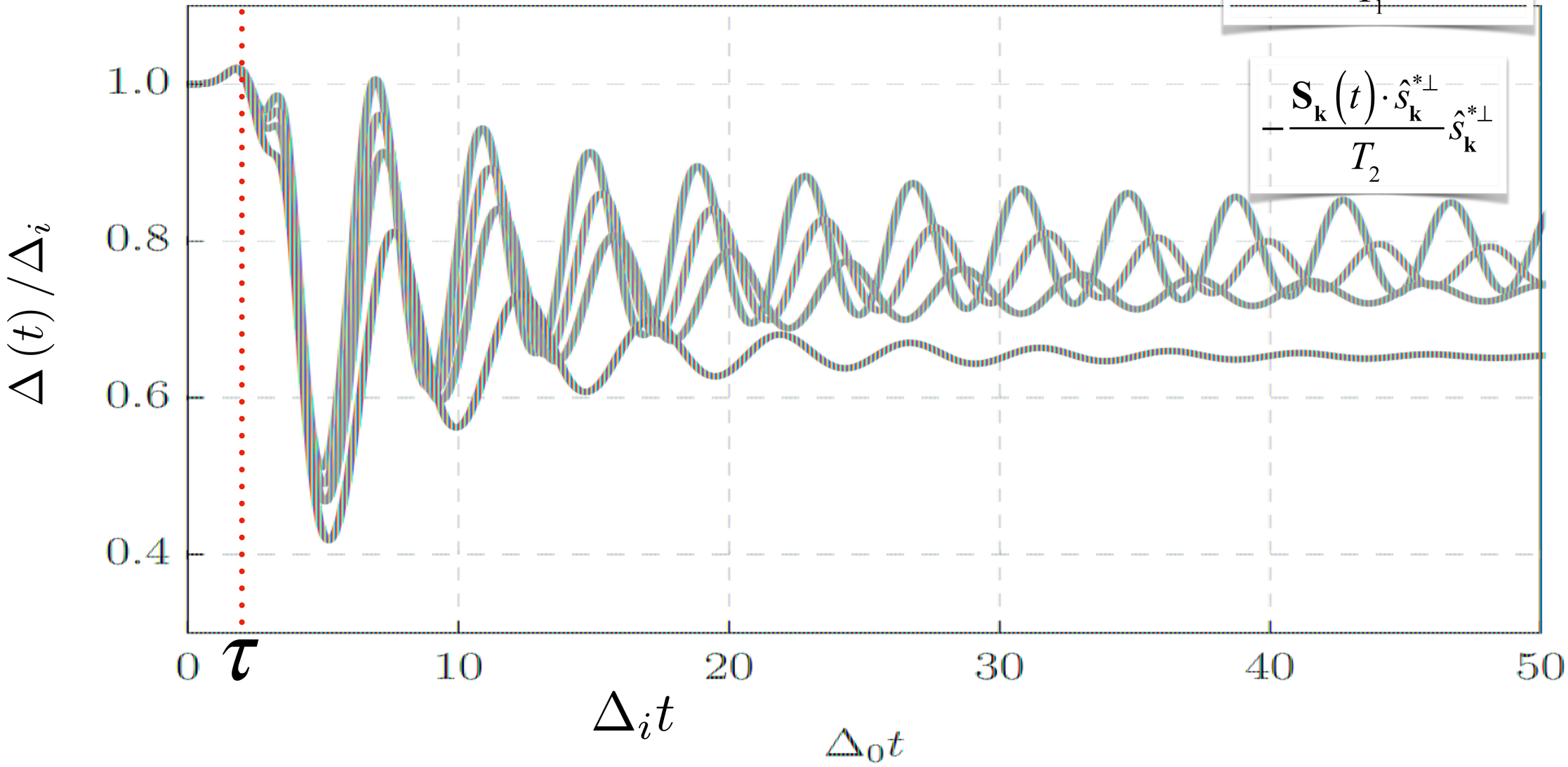
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Damped quench dynamics

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

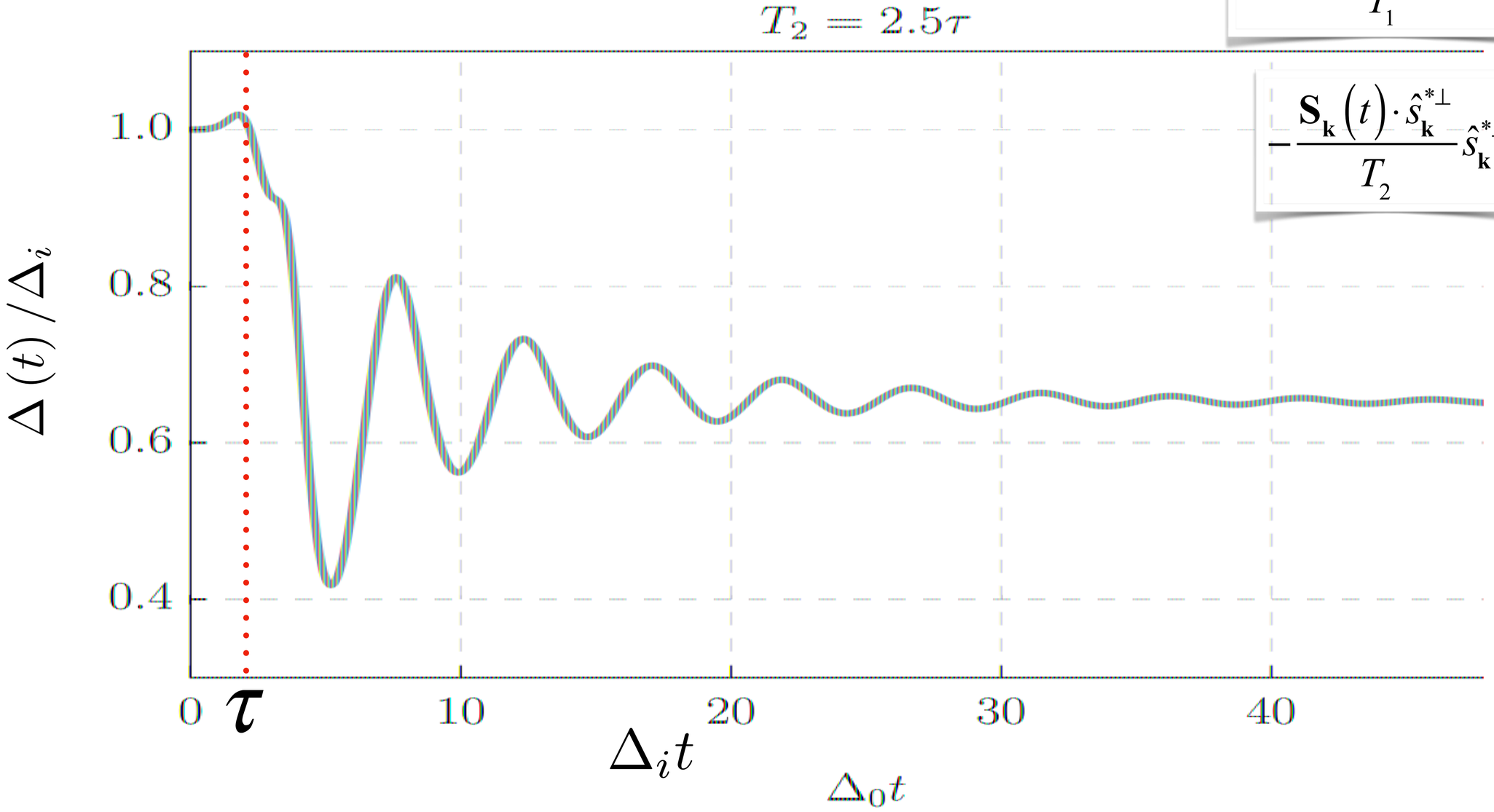
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Impact of T1 relaxation process

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

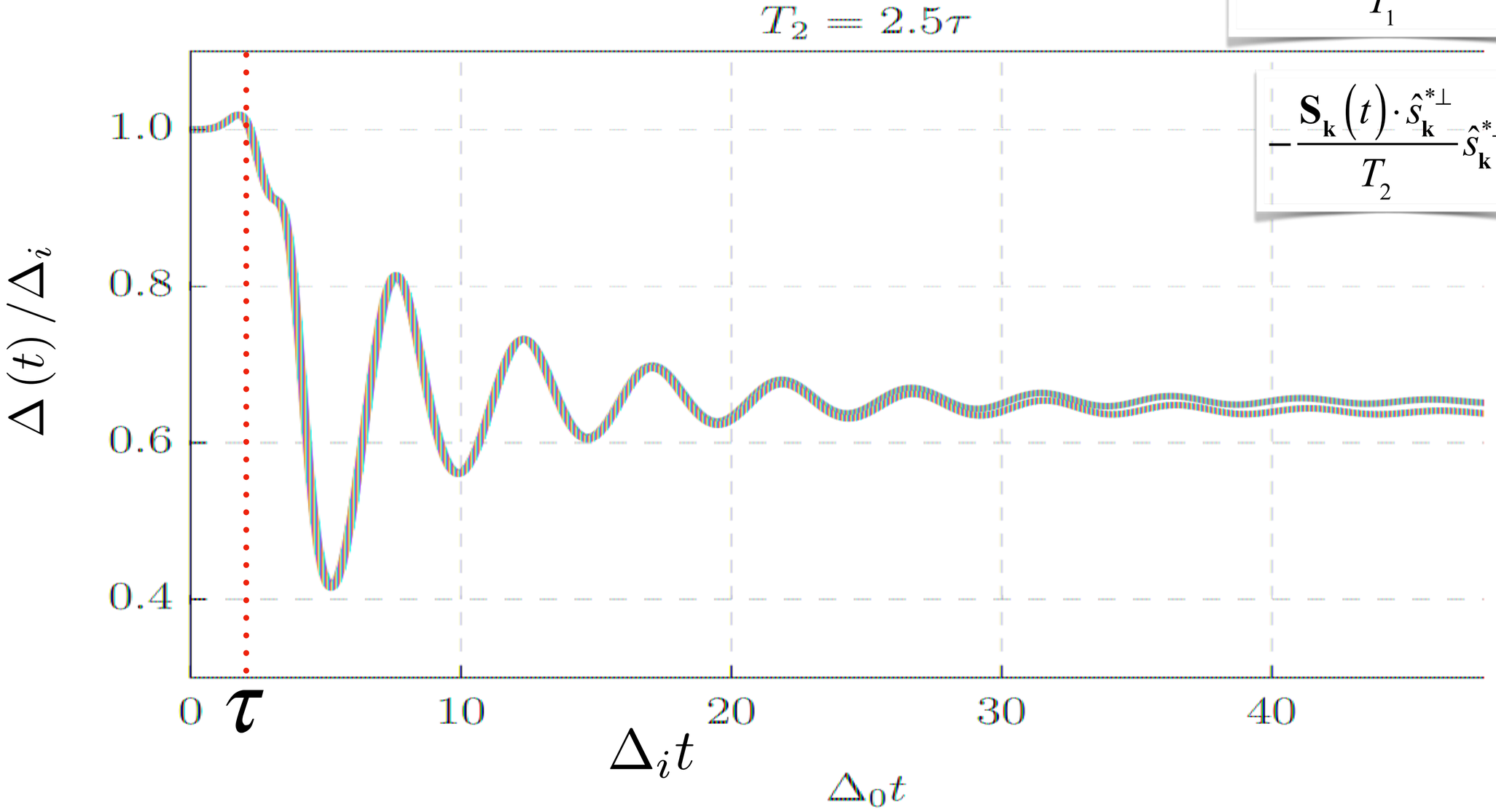
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Impact of T1 relaxation process

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

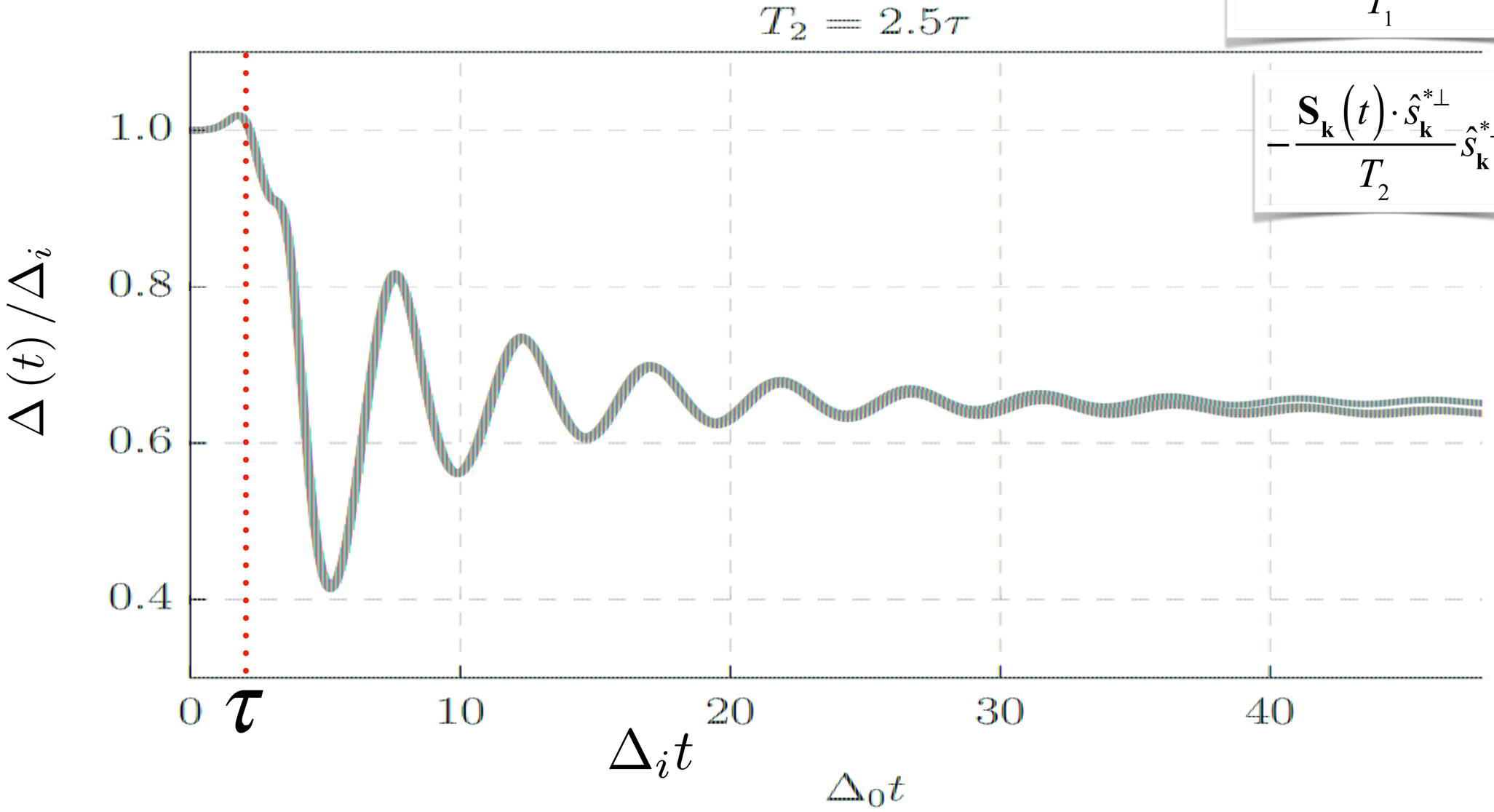
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Impact of T1 relaxation process

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

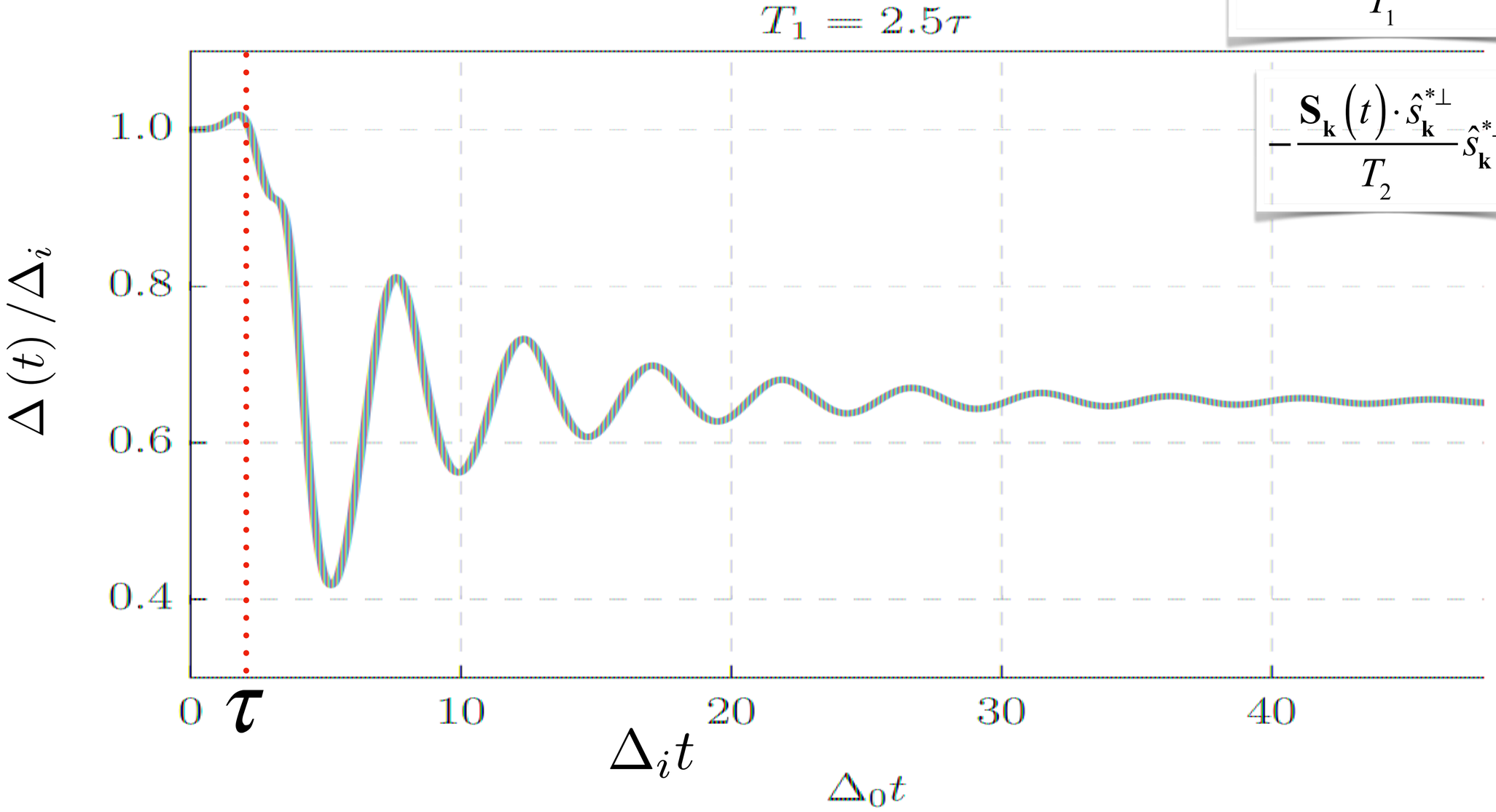
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Impact of T2 relaxation process

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

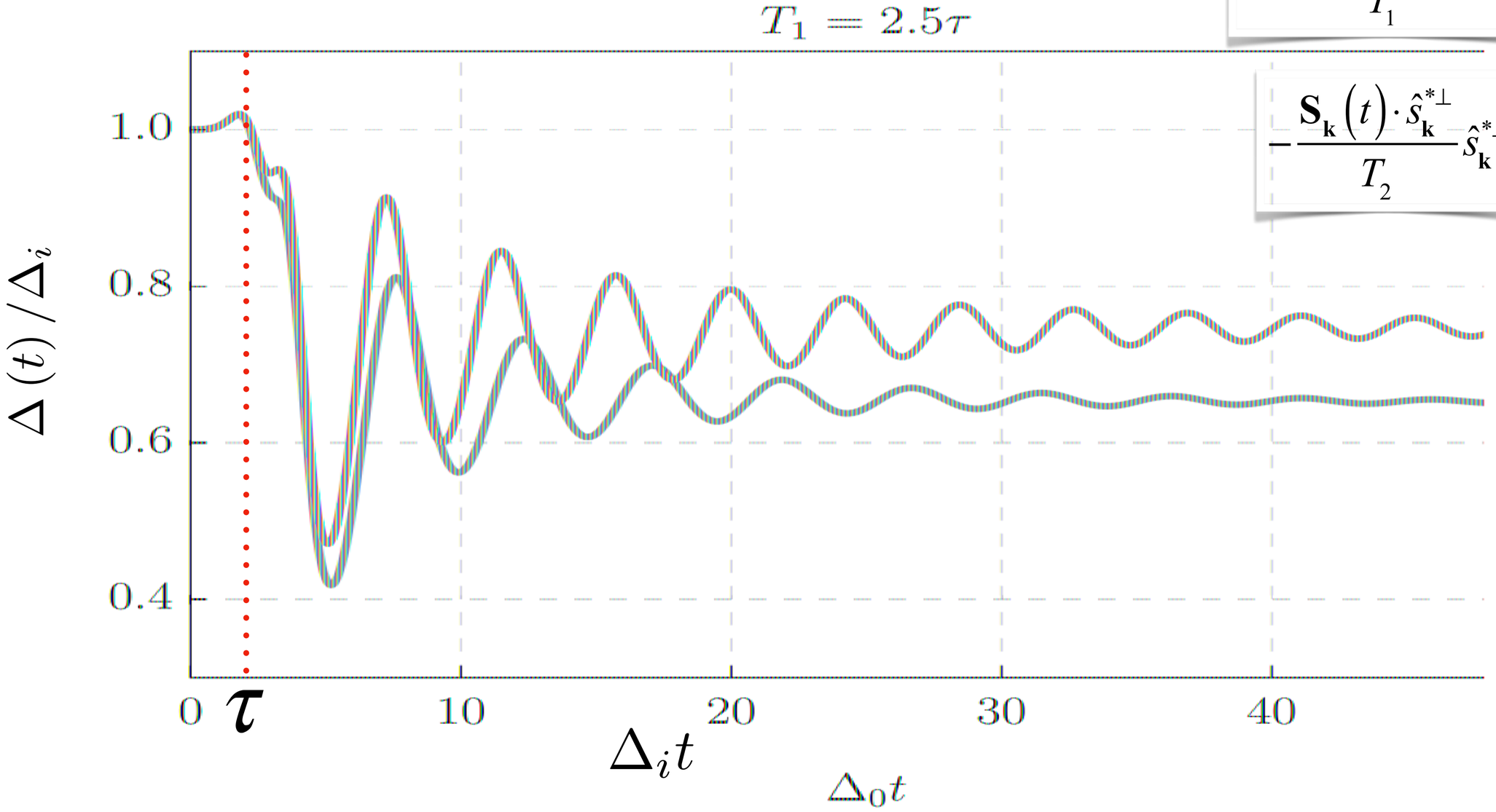
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Impact of T2 relaxation process

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

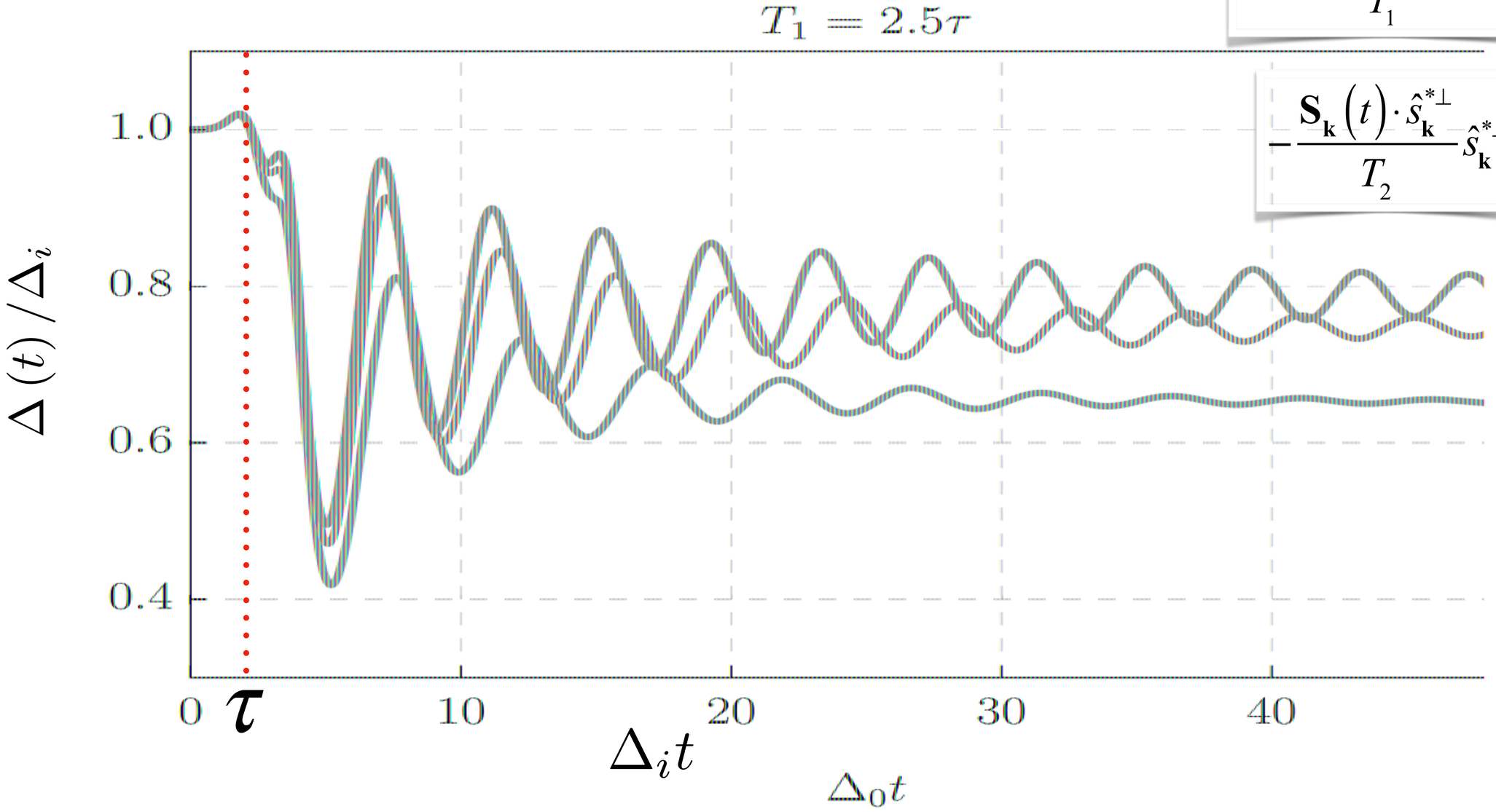
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



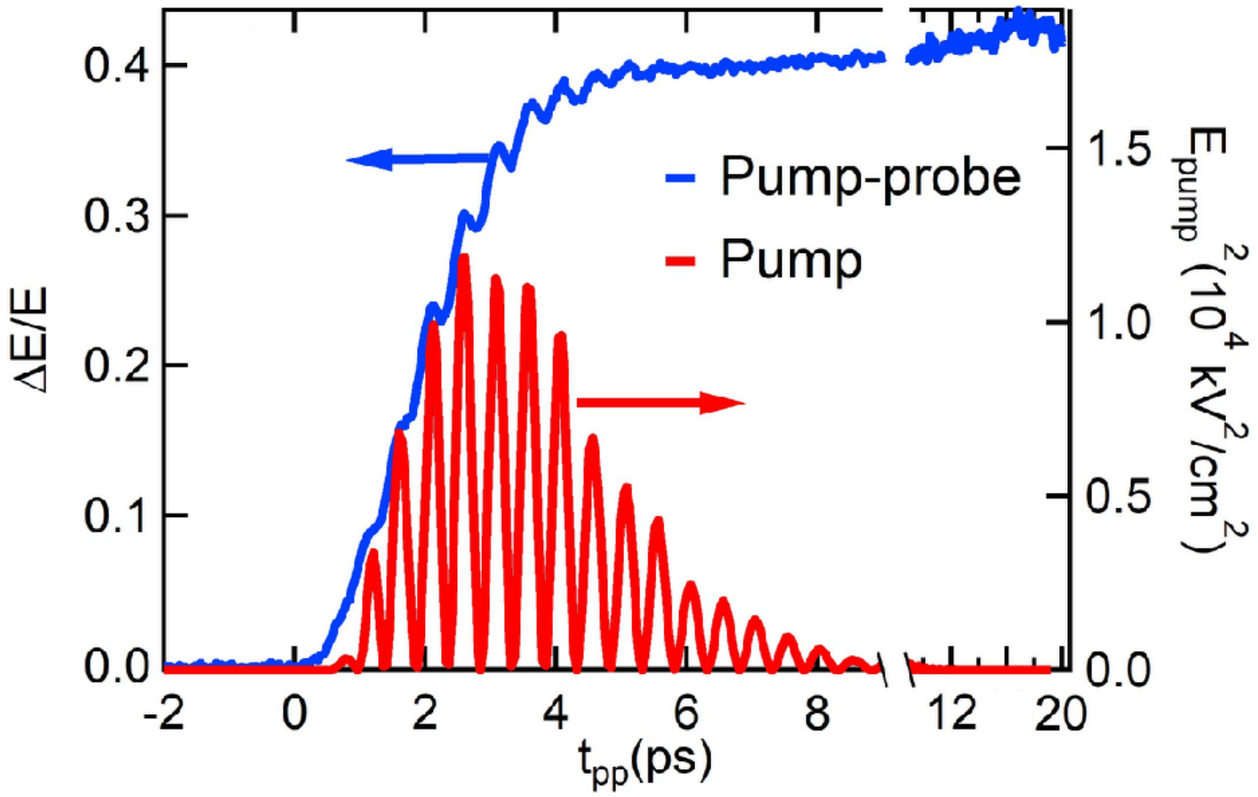
Impact of T2 relaxation process

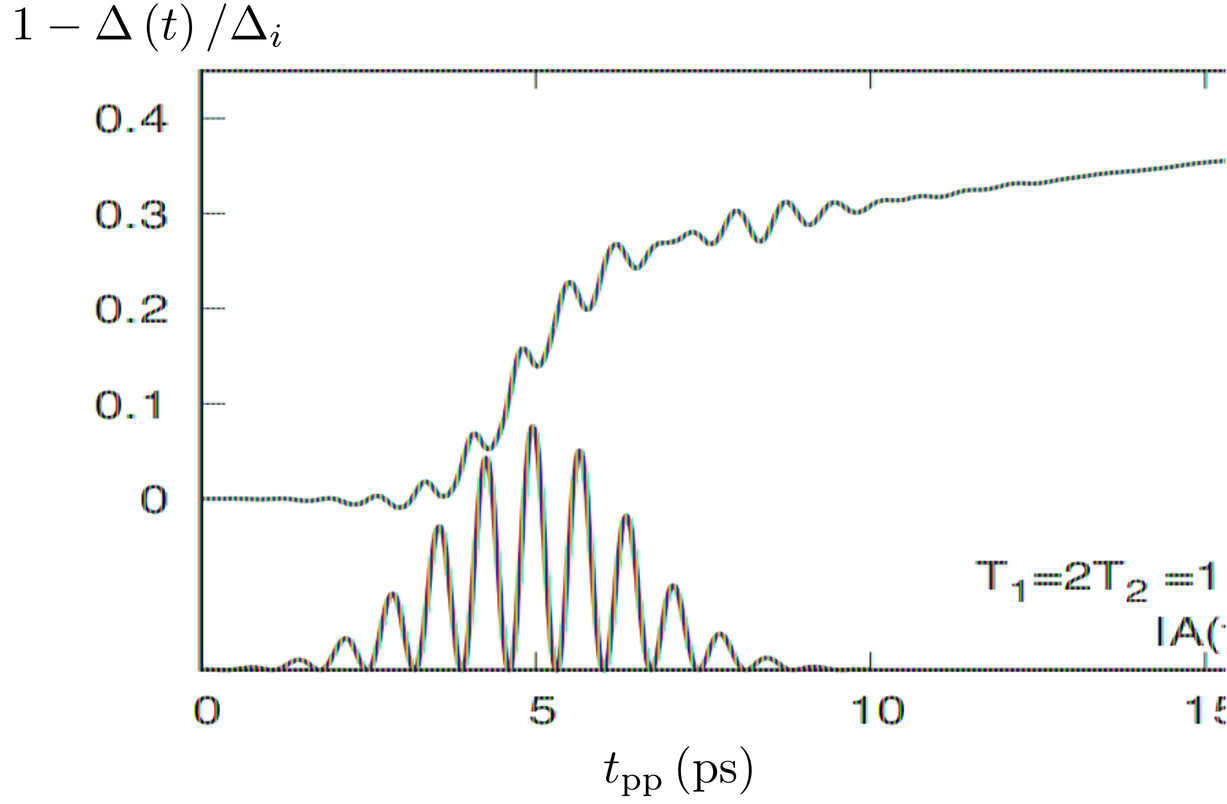
$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\parallel}-\left|\mathbf{S}_{\mathbf{k}}^{*}\right|}{T_1}\hat{s}_{\mathbf{k}}^{*\parallel}$$

$$-\frac{\mathbf{S}_{\mathbf{k}}(t)\cdot\hat{s}_{\mathbf{k}}^{*\perp}}{T_2}\hat{s}_{\mathbf{k}}^{*\perp}$$



Results with damping effects





Conclusions

- A semi-phenomenological framework is established to incorporate **damping** in the **transient** dynamics of the superconducting gap within the **electronic subsystem**.

- Application of this approach to **different** superconductors will allow one to **distinguish** the type of relaxation processes **dominant** in each system.

- Future work: **microscopic models** for different relaxation processes.