

D a a D a c F a
S - a d T a M a

Hans Christian Schneider

T a

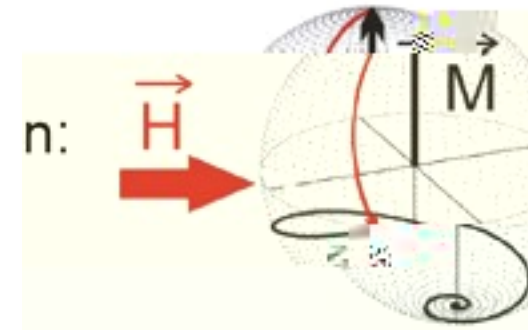
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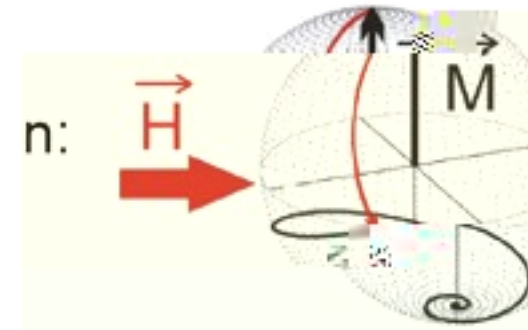
H S a & Fa Ca⁺⁺ Ma /S c G ?



Ma a D a c : Sc a
F a



Ma a D a c : Sc a
F a



U a a O 'ca S c D a d

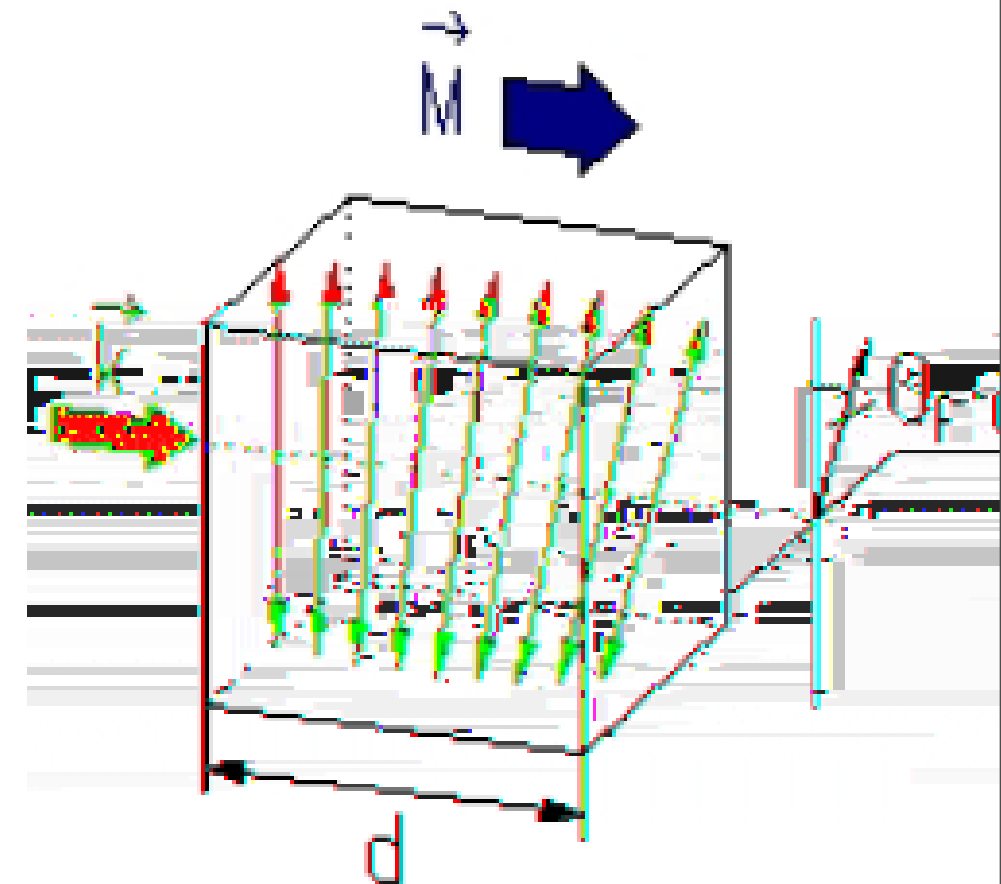


Ma -O ca K E c': MOKE

Kerr

*M
Faraday*

$\ominus$

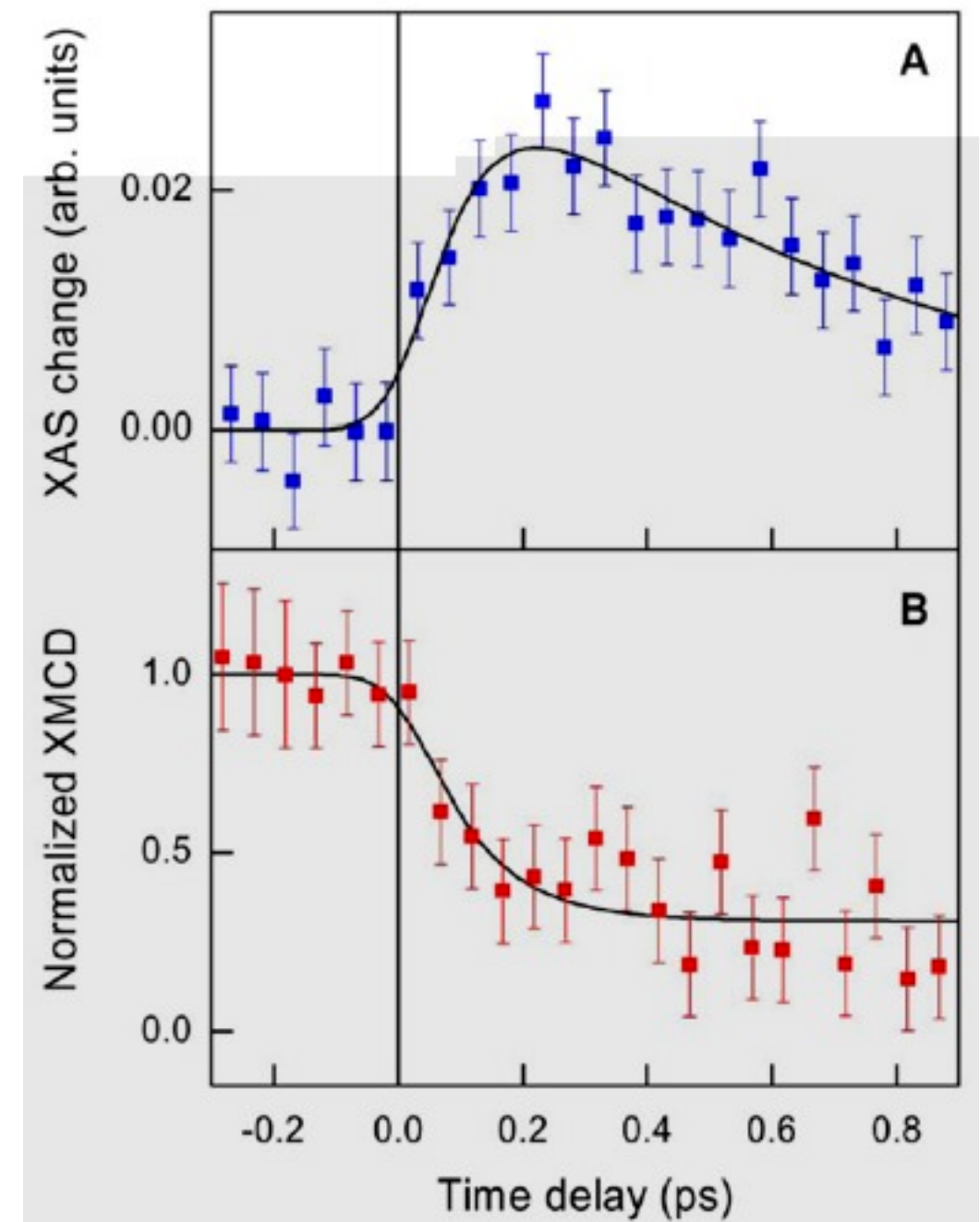
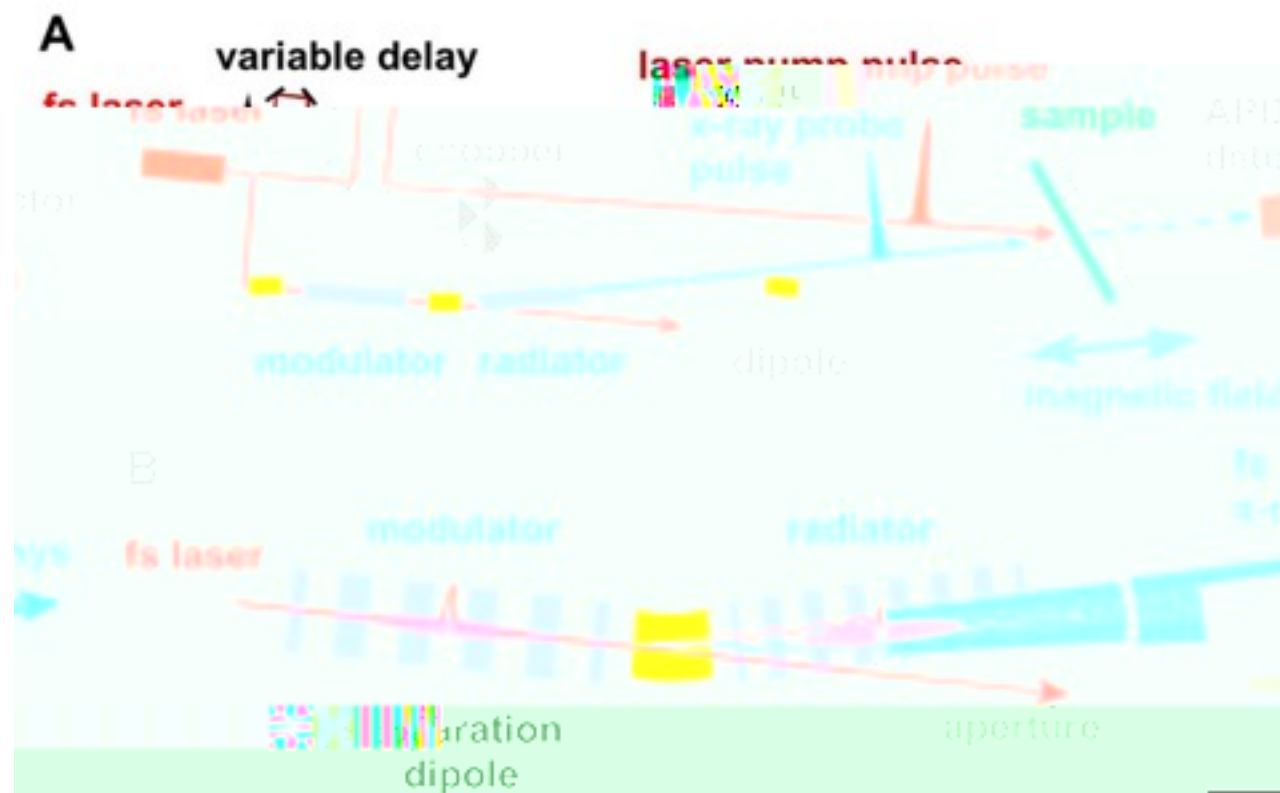


U a a D ' a a E

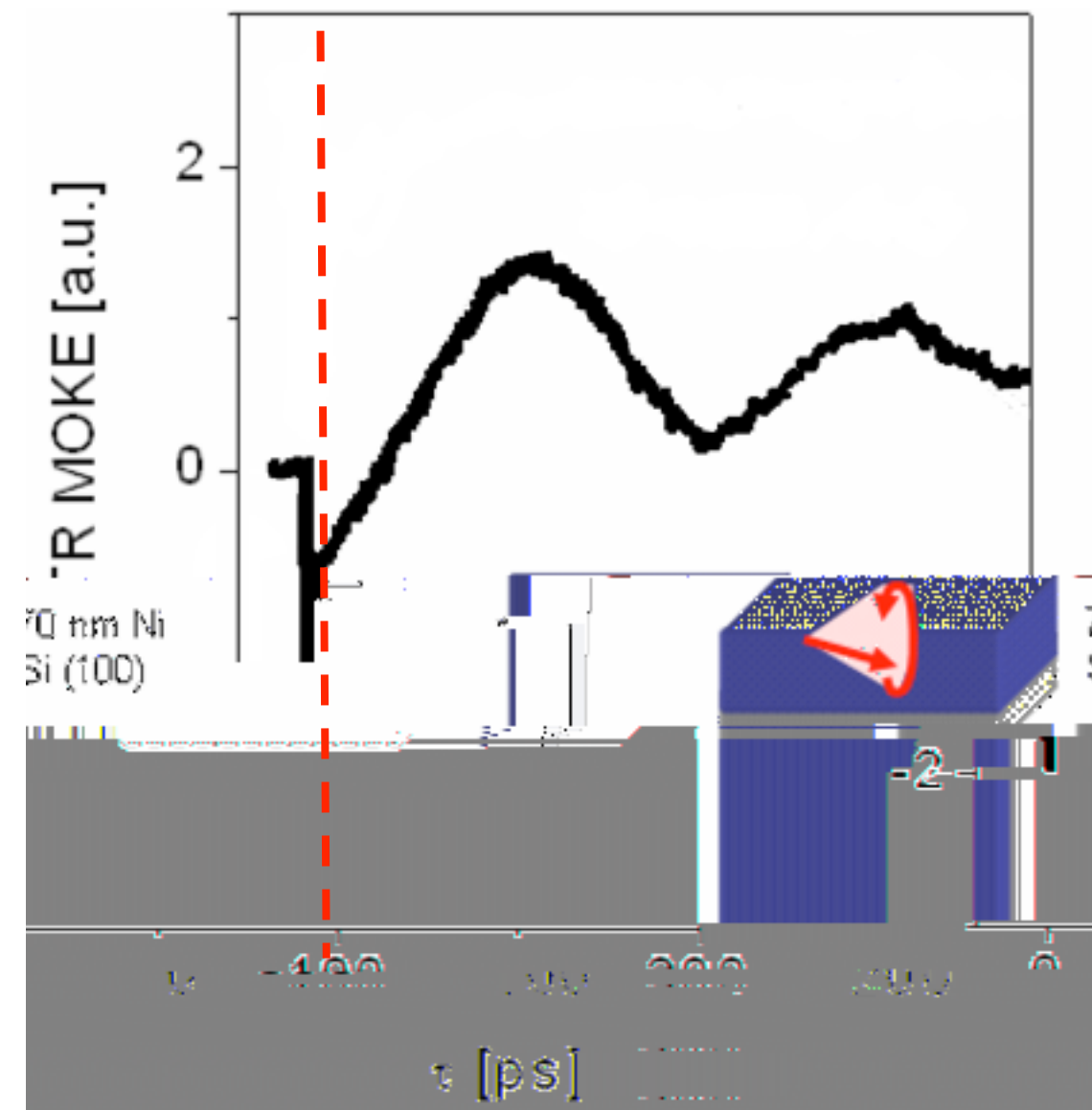
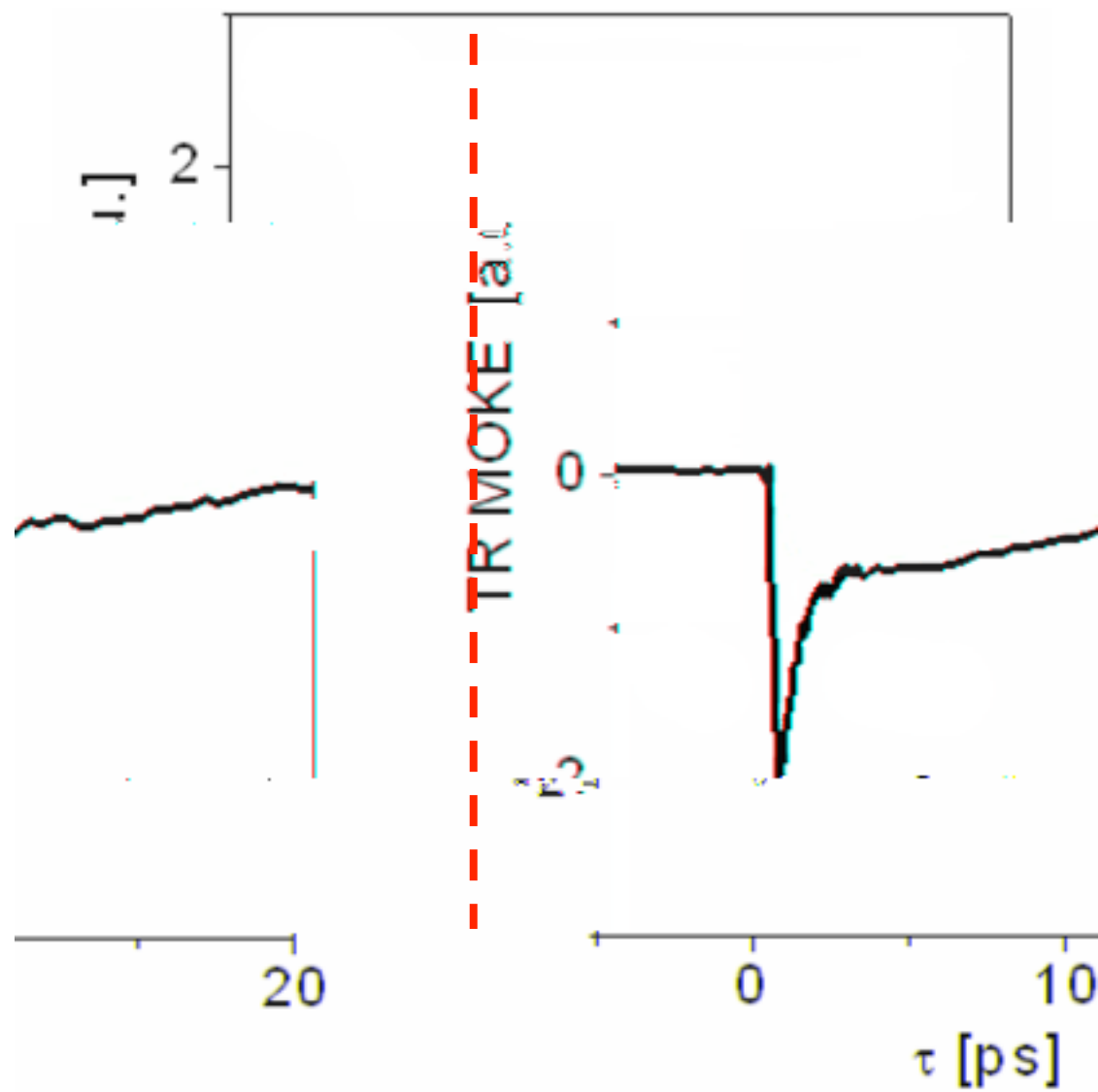


PUMP

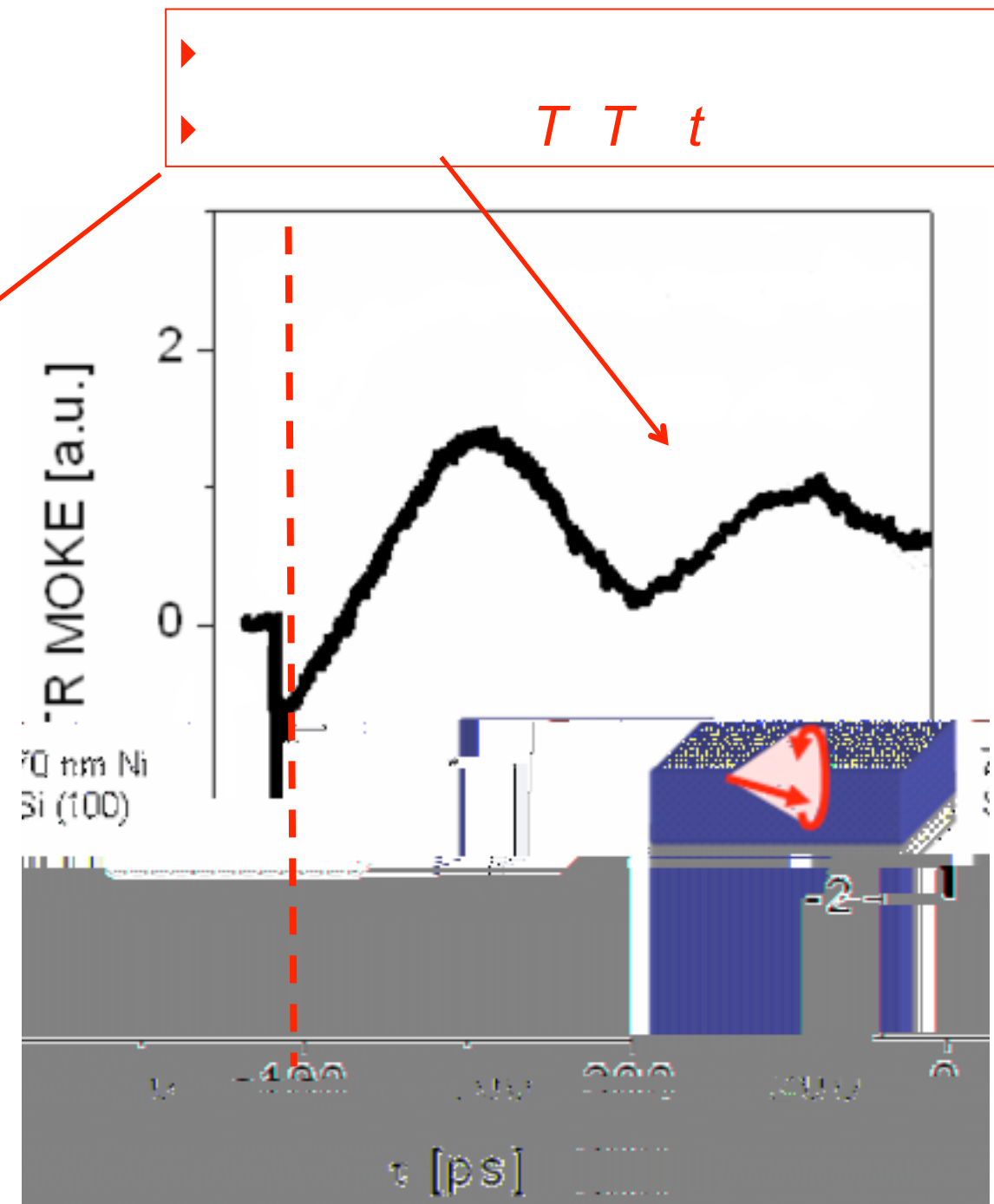
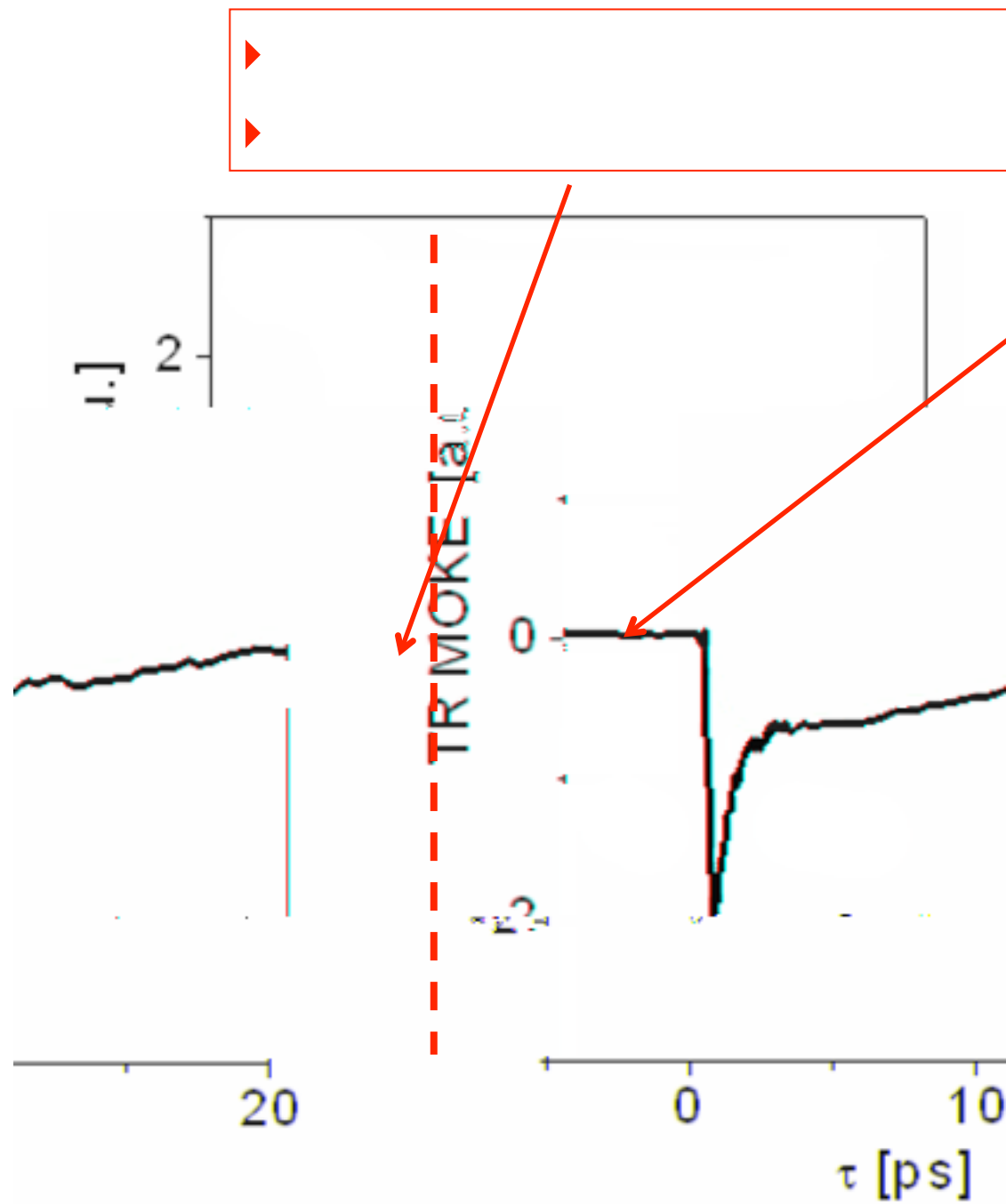
Ultrafast X-ray Free-Electron Laser



Ma a D a c D T Sca



Ma a D a c D T Sca





T

Sca

Ma

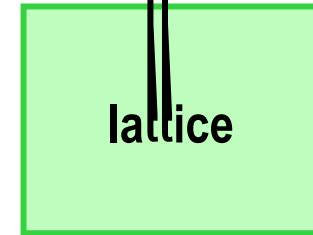
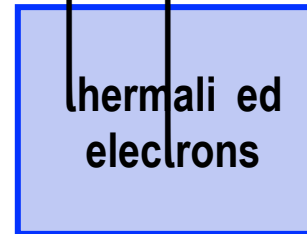
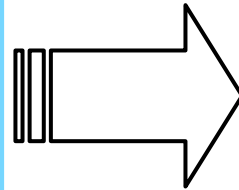
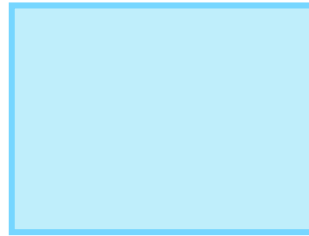
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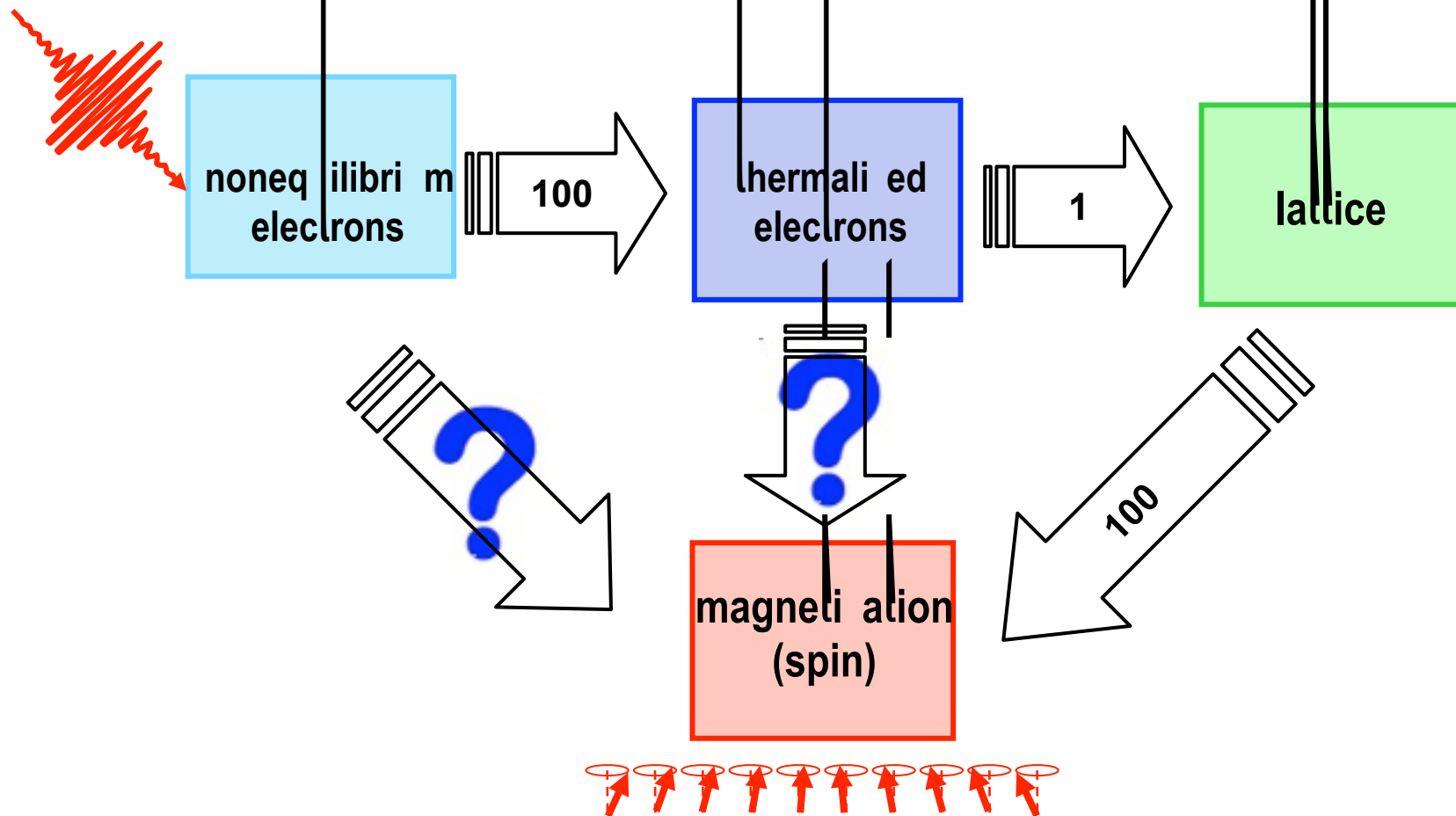


thermalized
electrons

lattice



T Sca Ma a D a c



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E (-Ya)'M c a D a a '

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$$|\Psi_k\rangle = a_k |\uparrow\rangle + b_k |\downarrow\rangle$$

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$$|\langle\Psi|S_z|\Psi\rangle| \leq \frac{\hbar}{2}$$

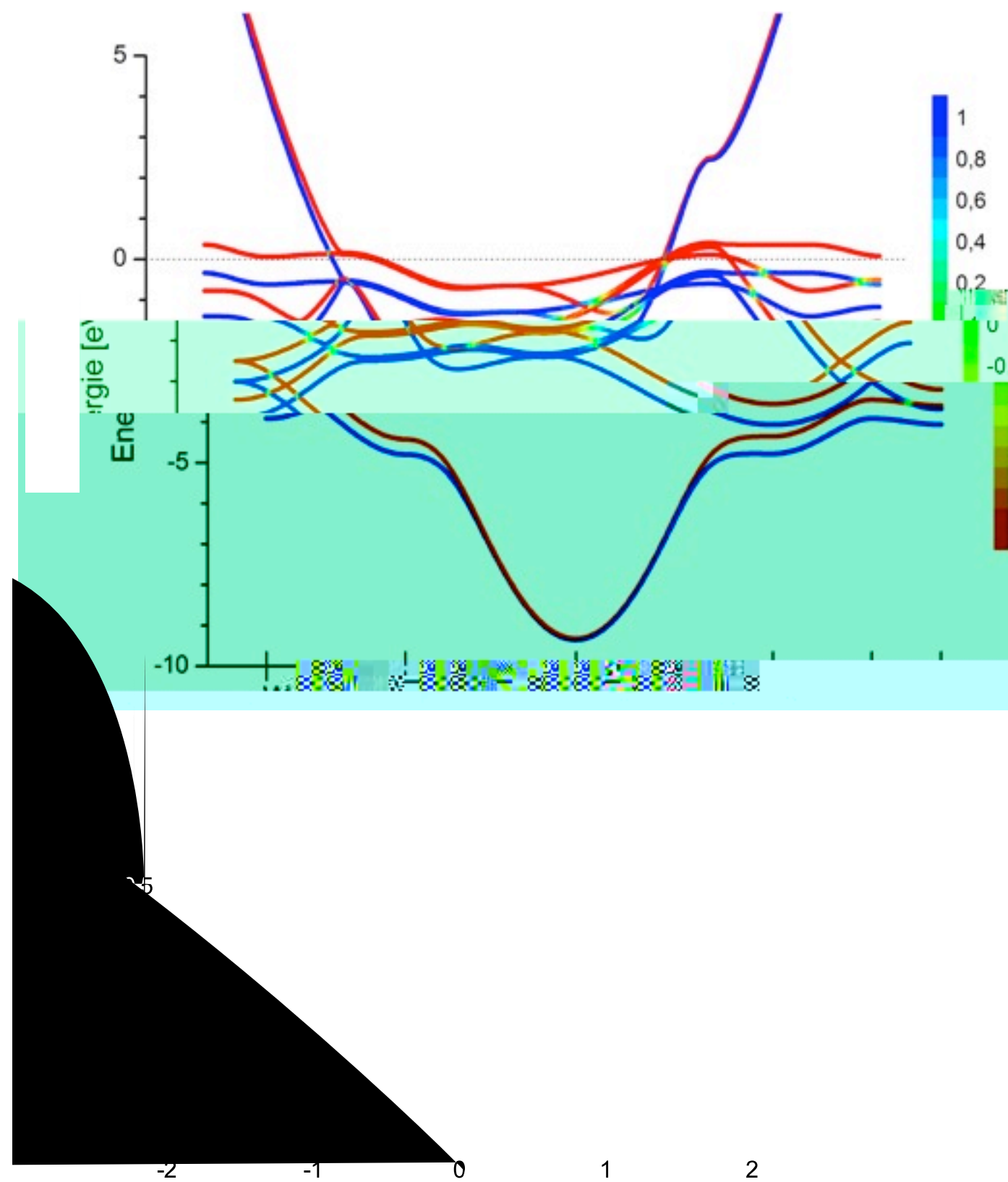
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$$|\Psi\rangle = a|\uparrow\rangle + b|\downarrow\rangle \longrightarrow |\Psi'\rangle = a'|\uparrow\rangle + b'|\downarrow\rangle$$

$$\langle\Psi|S_z|\Psi\rangle \neq \langle\Psi'|S_z|\Psi'\rangle$$

$$\frac{d}{dt}\langle S_z \rangle \neq 0$$

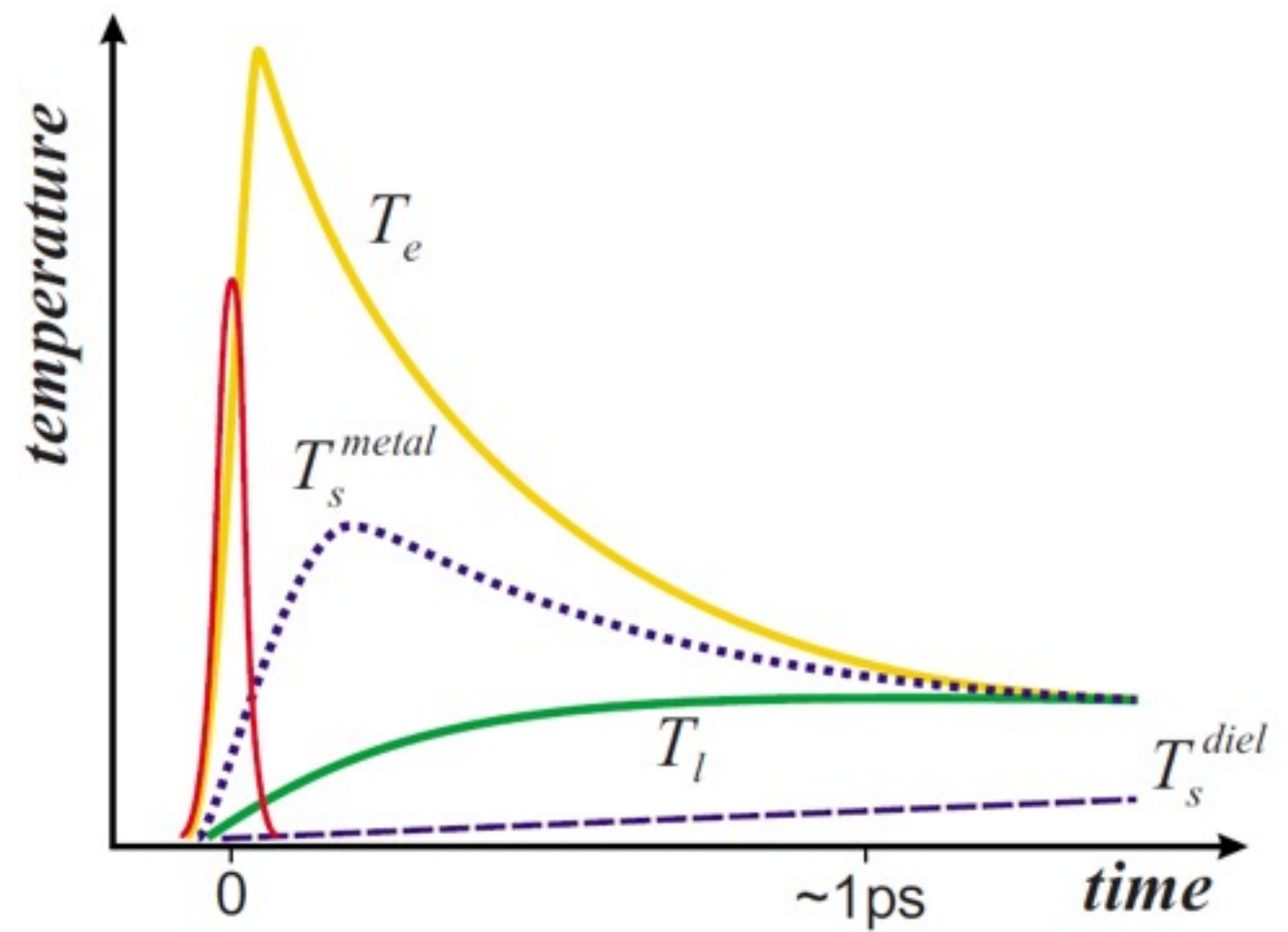
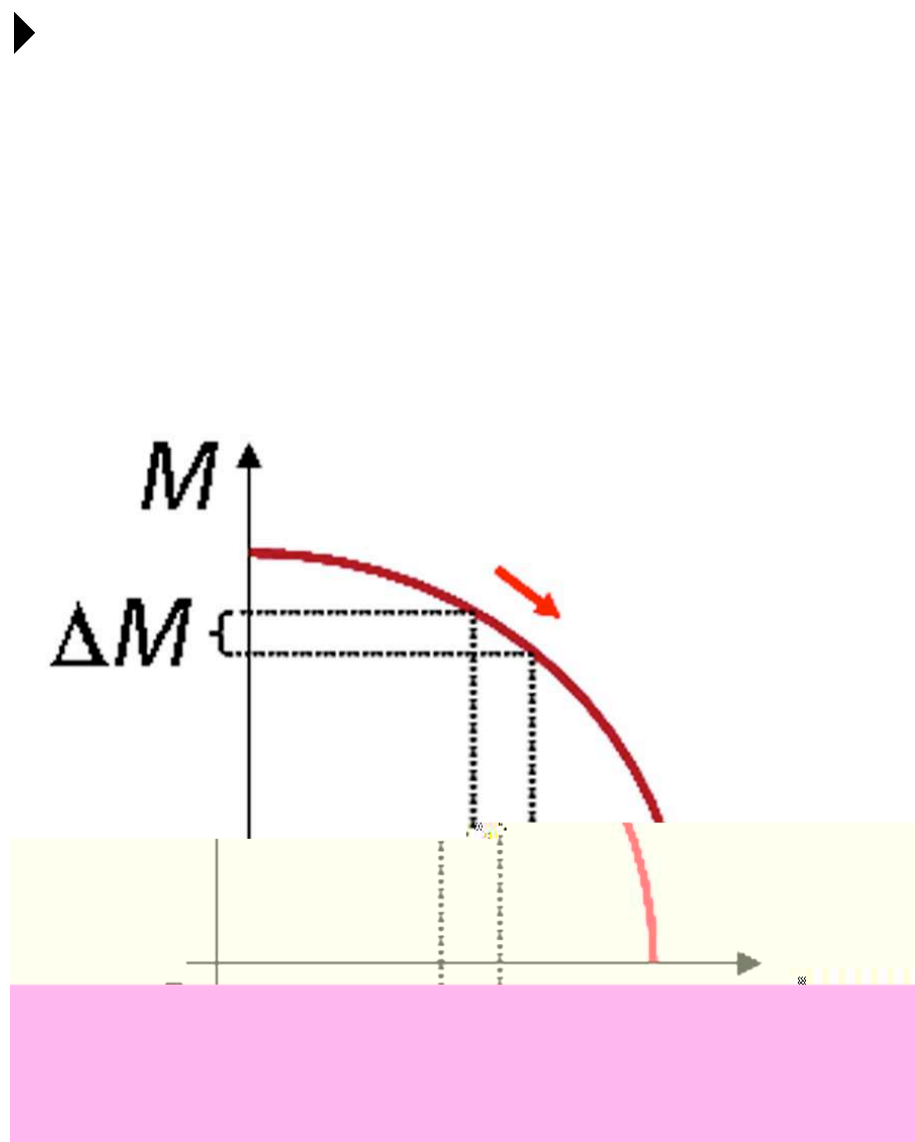
81



O A ac



(P ca) T - T a M d

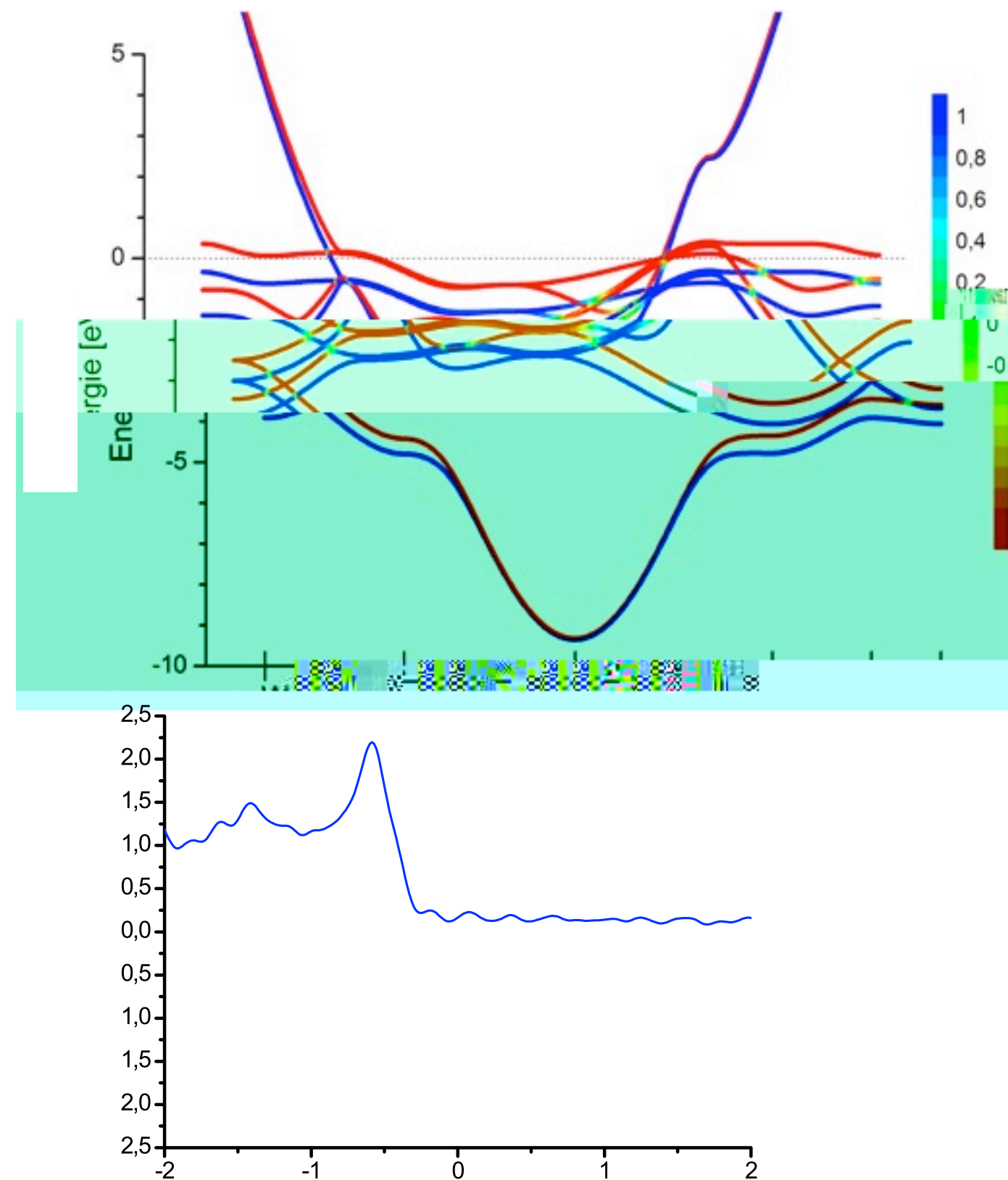


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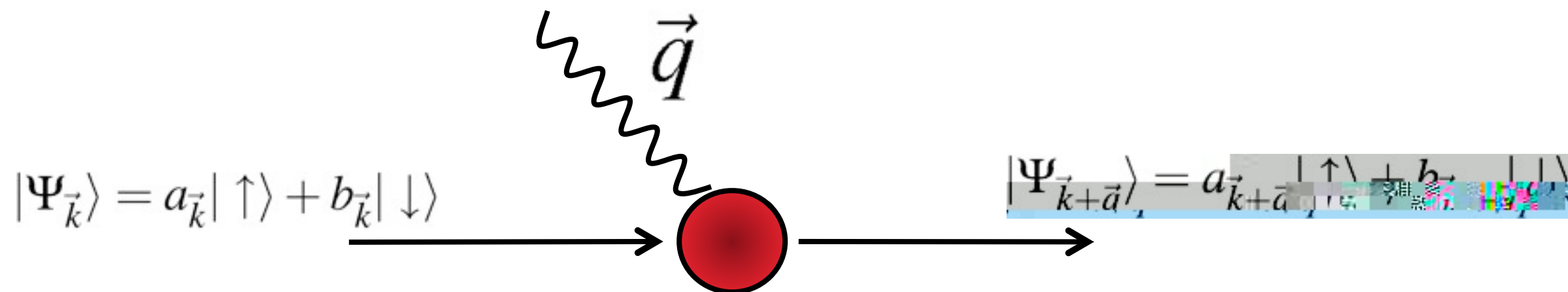
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Scandium Data Band

81



E -Ya M c a : S R a a d
E c -P Sca



$$\langle \Psi_{\vec{k}} | \hat{S}_z | \Psi_{\vec{k}} \rangle \neq \langle \Psi_{\vec{k}+\vec{q}} | \hat{S}_z | \Psi_{\vec{k}+\vec{q}} \rangle \Rightarrow \frac{d}{dt} \langle S_z \rangle \neq 0$$

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- d E c · Sca · D a c



$$\frac{d}{dt} f^\mu(\vec{k}) = \left. \frac{d}{dt} f^\mu(\vec{k}) \right|_{e-ph} + \left. \frac{d}{dt} f^\mu(\vec{k}) \right|_{opt}$$



$$\left. \frac{d}{dt} f^\mu(\vec{k}) \right|_{opt} = \frac{2\pi}{\hbar} \sum_{\nu \neq \mu} \left| \vec{d}_{\mu\nu} \cdot \vec{E} \right|^2 \left(f^\nu(\vec{k}) - f^\mu(\vec{k}) \right) g \left(\left| \epsilon^\nu(\vec{k}) - \epsilon^\mu(\vec{k}) \right| - \hbar\omega \right)$$

-R

dE c

-P

Sca



$$\frac{d}{dt} f^\mu(\vec{k}) = \sum_\lambda \sum_{\vec{q}} \left[w_{\vec{k}+\vec{q},\mu' \rightarrow \vec{k},\mu}^\lambda f^{\mu'}(\vec{k}+\vec{q}) (1 - f^\mu(\vec{k})) - w_{\vec{k},\mu \rightarrow \vec{k}+\vec{q},\mu'}^\lambda f^\mu(\vec{k}) (1 - f^{\mu'}(\vec{k}+\vec{q})) \right]$$

$$w_{\vec{k},\mu \rightarrow \vec{k}+\vec{q},\mu'}^\lambda = \frac{2\pi}{\hbar} \left| \begin{array}{c} \text{wavy line } \vec{q} \\ \downarrow \\ \text{red dot} \\ \leftarrow \text{arrow} \quad \text{red dot} \rightarrow \text{arrow} \end{array} \right|^2 \left[\tilde{n}_q^\lambda \delta \left(\epsilon^{\mu'}(\vec{k}+\vec{q}) - \epsilon^\mu(\vec{k}) - \hbar\omega_{\vec{q}}^\lambda \right) + (\tilde{n}_{-\vec{q}}^\lambda + 1) \delta \left(\epsilon^{\mu'}(\vec{k}+\vec{q}) - \epsilon^\mu(\vec{k}) + \hbar\omega_{-\vec{q}}^\lambda \right) \right]$$

-R

dE c

-P

Sca

$$\frac{d}{dt} f^\mu(\vec{k}) = \sum_{\lambda} \sum_{\vec{q}} \left[w_{\vec{k}+\vec{q},\mu' \rightarrow \vec{k},\mu}^{\lambda} f^{\mu'}(\vec{k} + \vec{q}) (1 - f^{\mu}(\vec{k})) - w_{\vec{k},\mu \rightarrow \vec{k}+\vec{q},\mu'}^{\lambda} f^{\mu}(\vec{k}) (1 - f^{\mu'}(\vec{k} + \vec{q})) \right]$$

$$w_{\vec{k},\mu \rightarrow \vec{k}+\vec{q},\mu'}^{\lambda} = \frac{2\pi}{\hbar} \left| \begin{array}{c} \text{diagram: incoming arrow from left, wavy line up labeled } \vec{q}, \text{ outgoing arrow to right} \end{array} \right|^2 \left[\tilde{n}_q^{\lambda} \delta \left(\epsilon^{\mu'}(\vec{k} + \vec{q}) - \epsilon^{\mu}(\vec{k}) - \hbar\omega_{\vec{q}}^{\lambda} \right) + (\tilde{n}_{-\vec{q}}^{\lambda} + 1) \delta \left(\epsilon^{\mu'}(\vec{k} + \vec{q}) - \epsilon^{\mu}(\vec{k}) + \hbar\omega_{-\vec{q}}^{\lambda} \right) \right]$$

$$\begin{array}{c} \text{diagram: incoming arrow from left, wavy line up labeled } \vec{q}, \text{ outgoing arrow to right} \end{array} \propto \sum_{\vec{R}} e^{i\vec{q} \cdot \vec{R}} \left\langle \psi_f \left| \vec{\epsilon}_{\vec{q}} \cdot \nabla_{\vec{R}} \left(V + \frac{\hbar}{4m^2c^2} (\nabla_{\vec{r}} V \times \vec{p}) \cdot \vec{\sigma} \right) \right| \psi_i \right\rangle$$

84

 $\epsilon^{\mu}(\vec{k})$
 $\vec{d}_{\mu\nu}$
 $\omega_{\vec{q}}^{\lambda}$
 $M_{\vec{k},\mu;\vec{k}',\mu'}^{\lambda}$

O ca E c a :D T a ' N c



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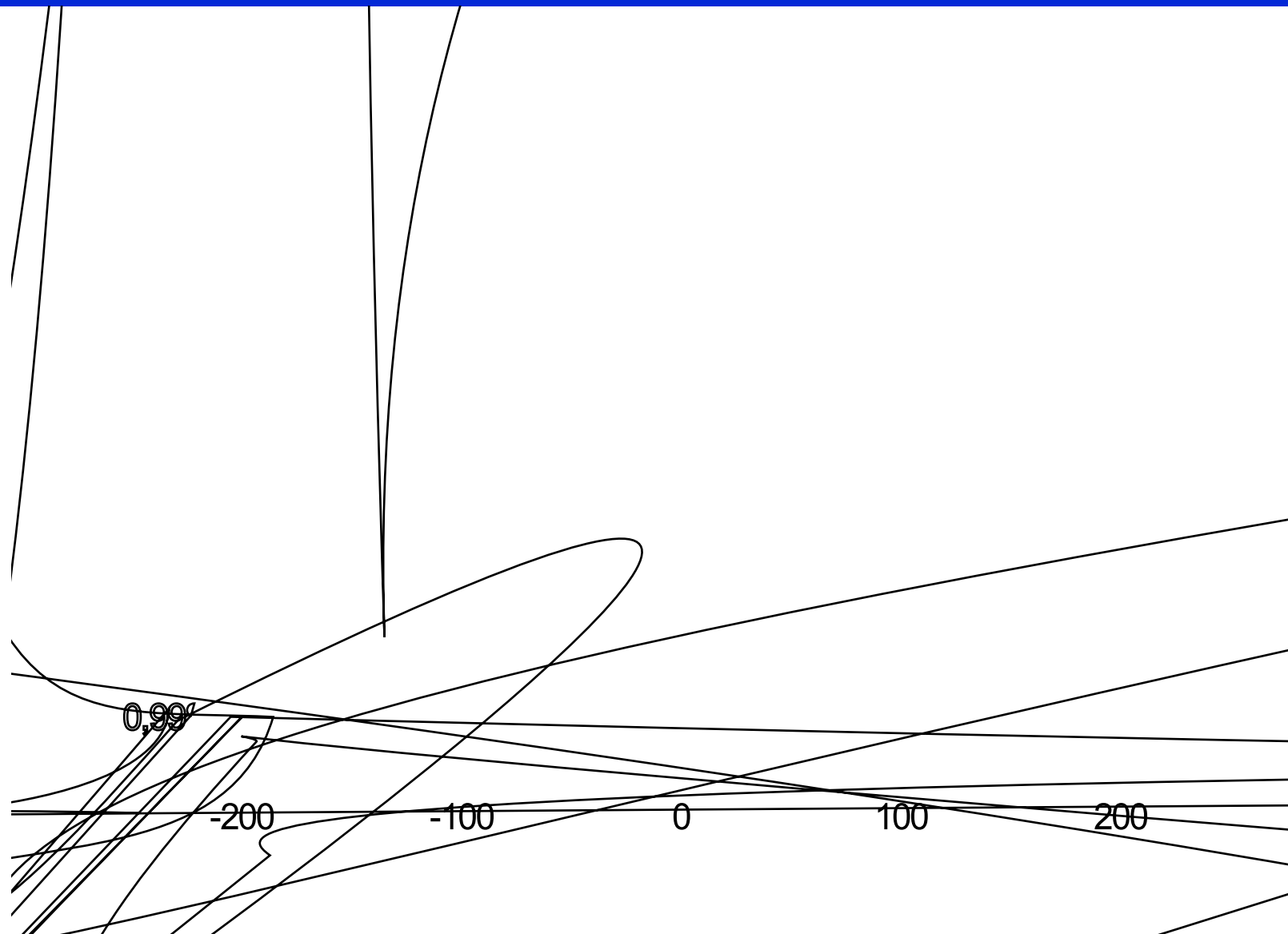
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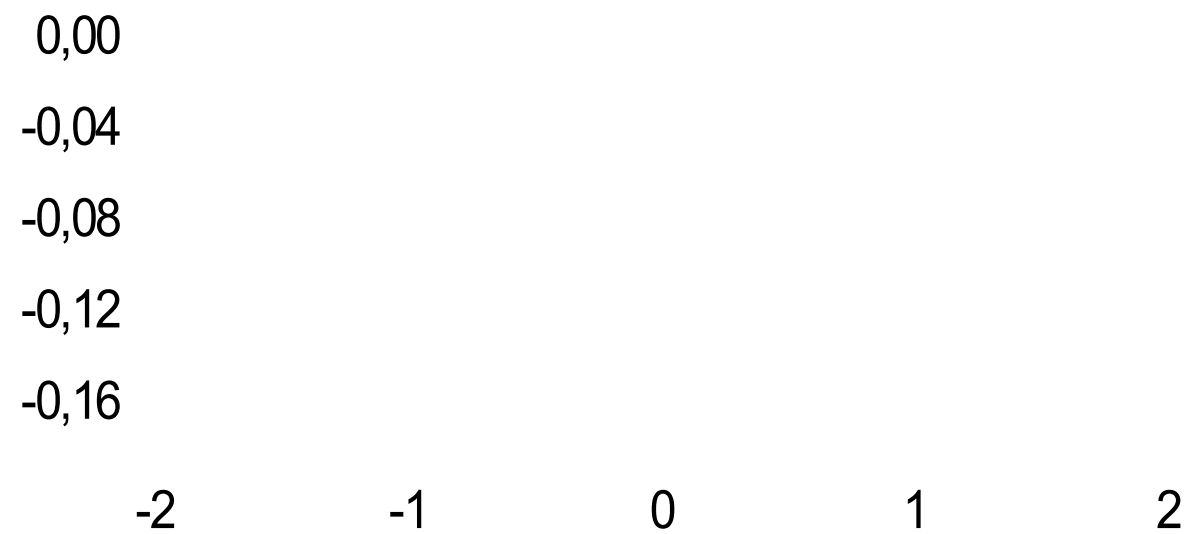
Γ

X

O ca E c a '(2)

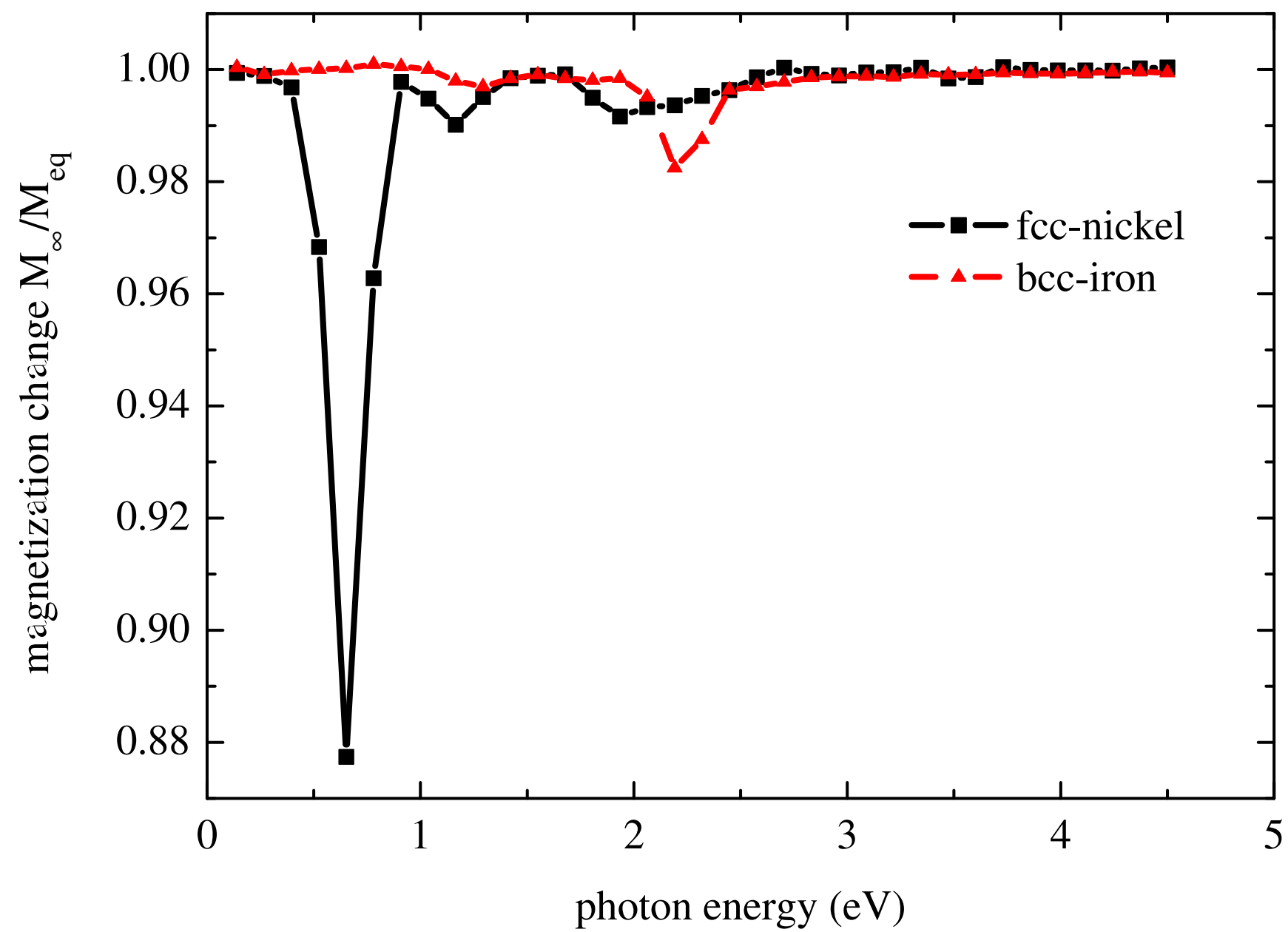


O ca E c a ' N c

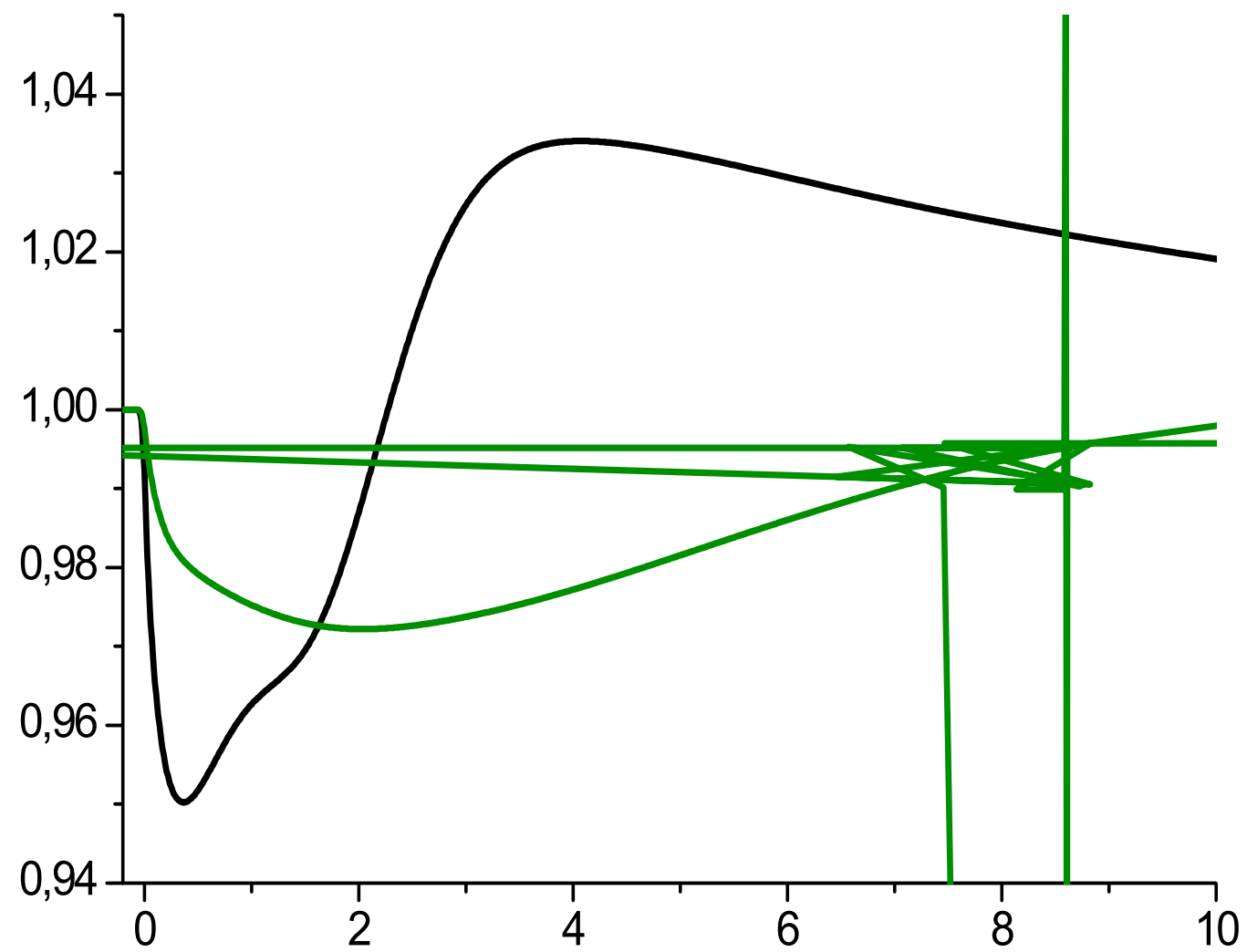


$$\Delta N_\tau(E) = \sum_{\vec{k}} \sum_{\mu} \delta(E - \epsilon_k^\mu) \langle \sigma_\tau \rangle_k^\mu \left[f_{\vec{k}}^\mu(t) - F(\epsilon_{\vec{k}}^\mu, T_0) \right]$$

O ca E c a : F c D d c



Ма а D а с а O са Е с а '





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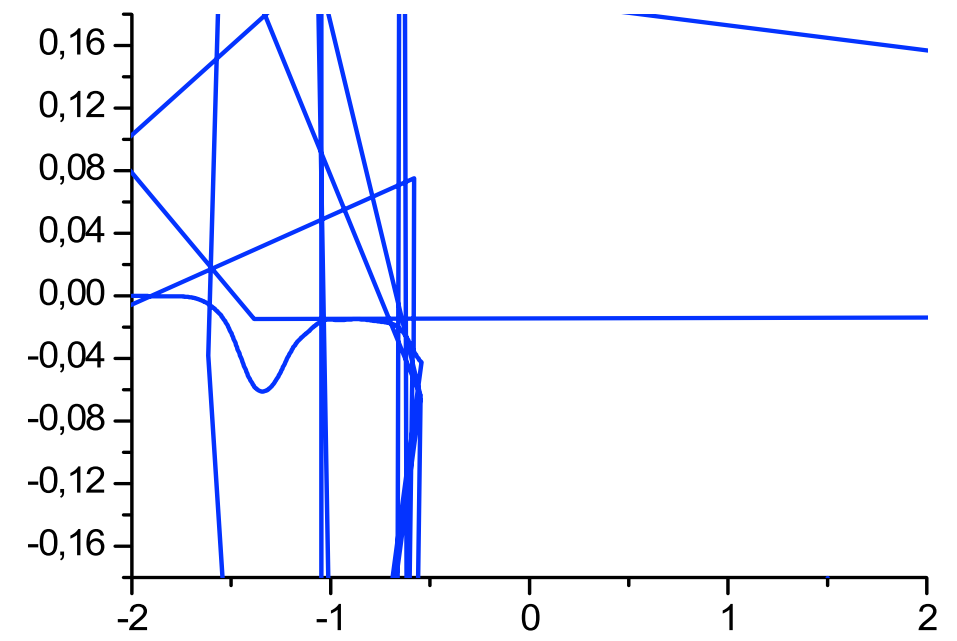
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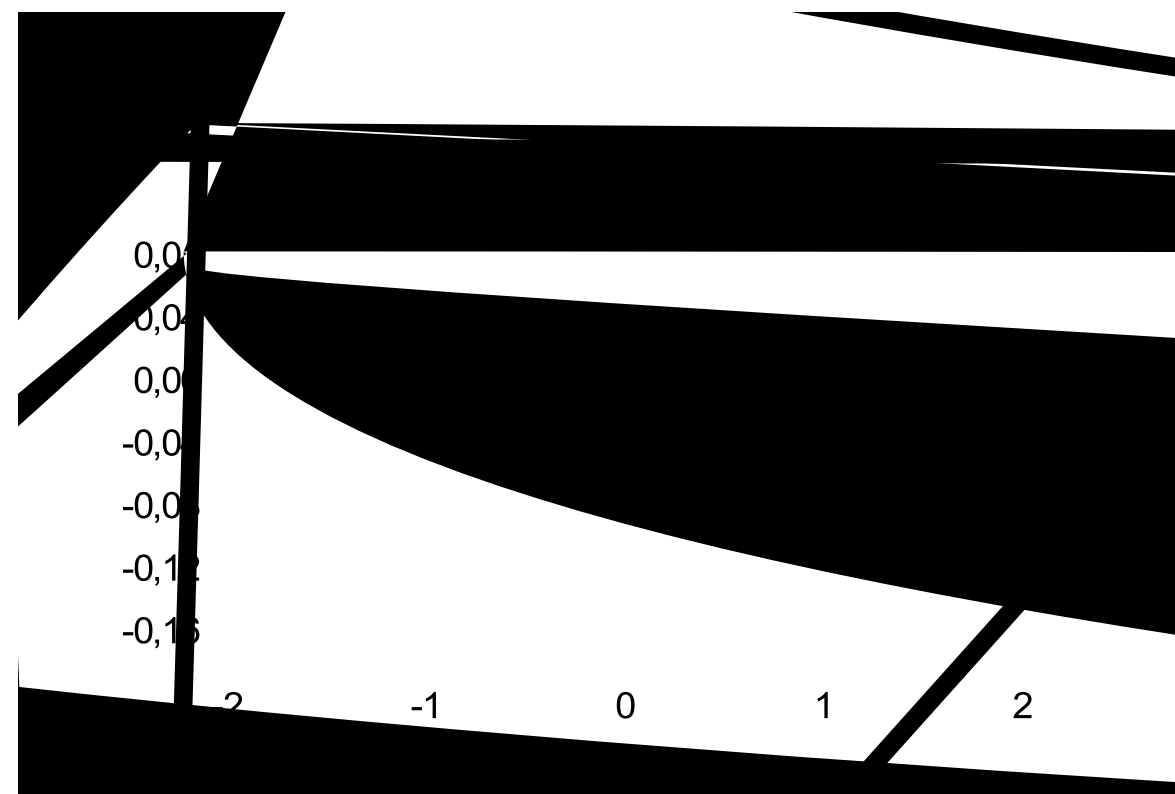
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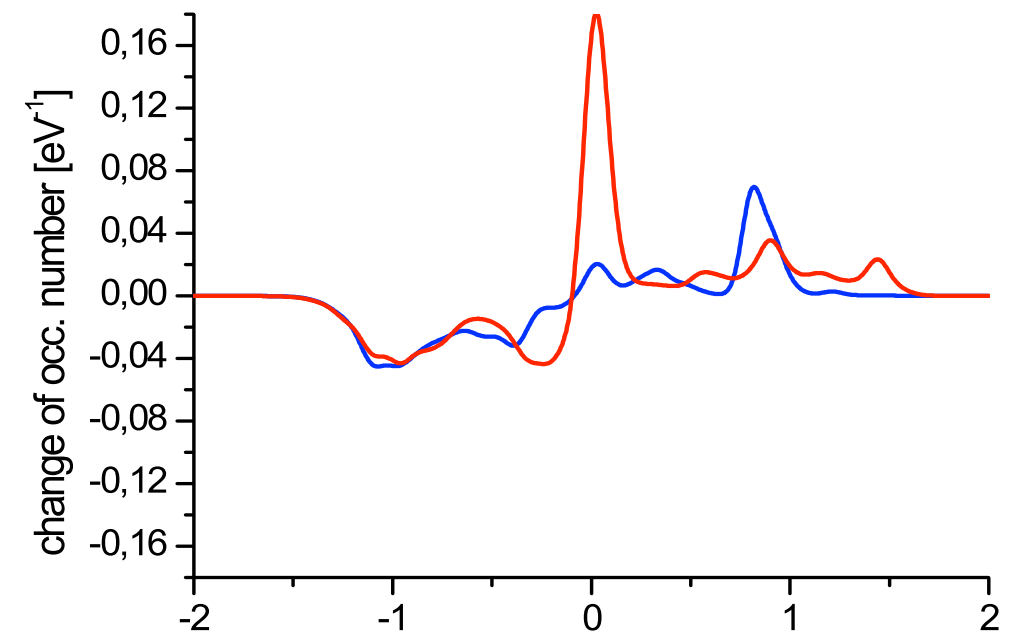
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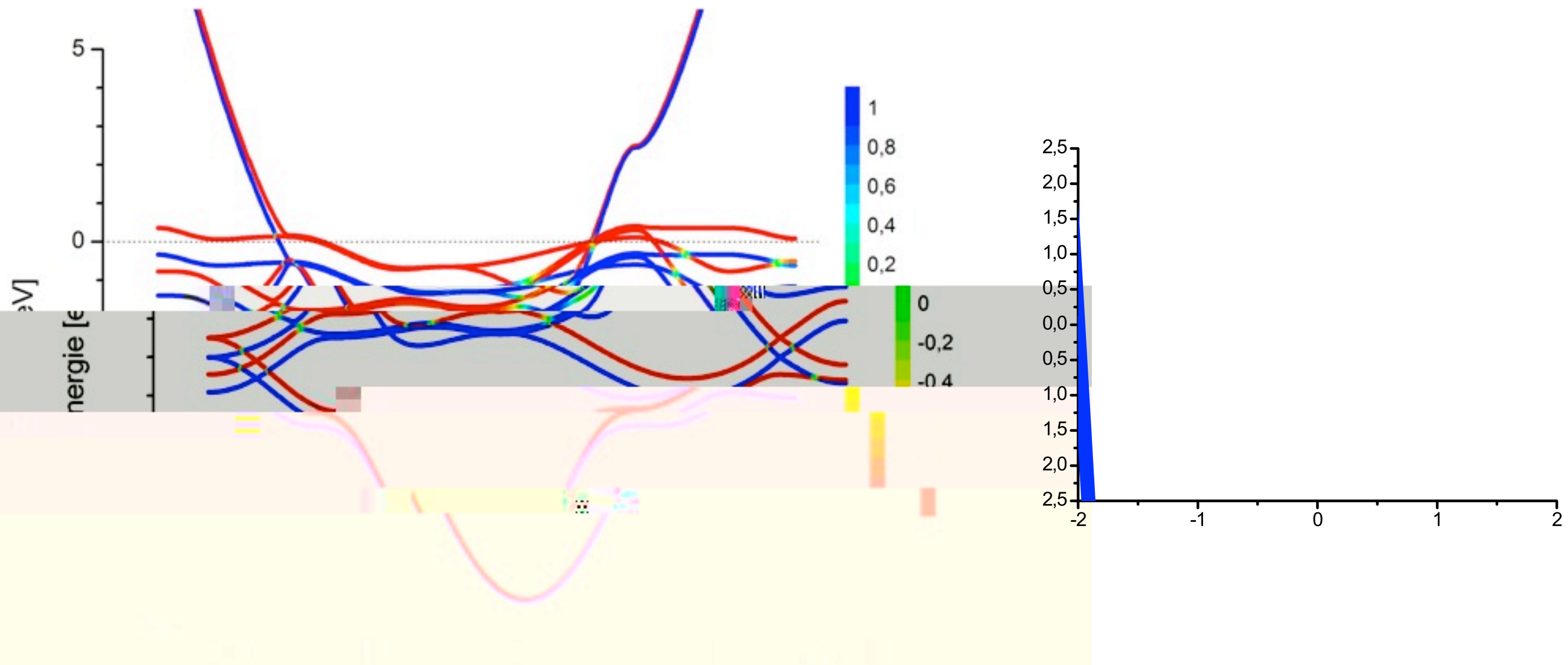
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Ba d S c P



H Acc a Ca Sca a F d Ba d
S c B ?

$$\min_{\{n_{\vec{k}}^{\mu}: 0 \leq n_{\vec{k}}^{\mu} \leq 1\}} \sum_{\vec{k}} \sum_{\mu} n_{\vec{k}}^{\mu}$$

H Acc a Ca Sca a F d Ba d
S c B ?



H Acc a Ca Sca a F d Ba d
S c B ?



H Acc a Ca Sca a F d Ba d
S c B ?

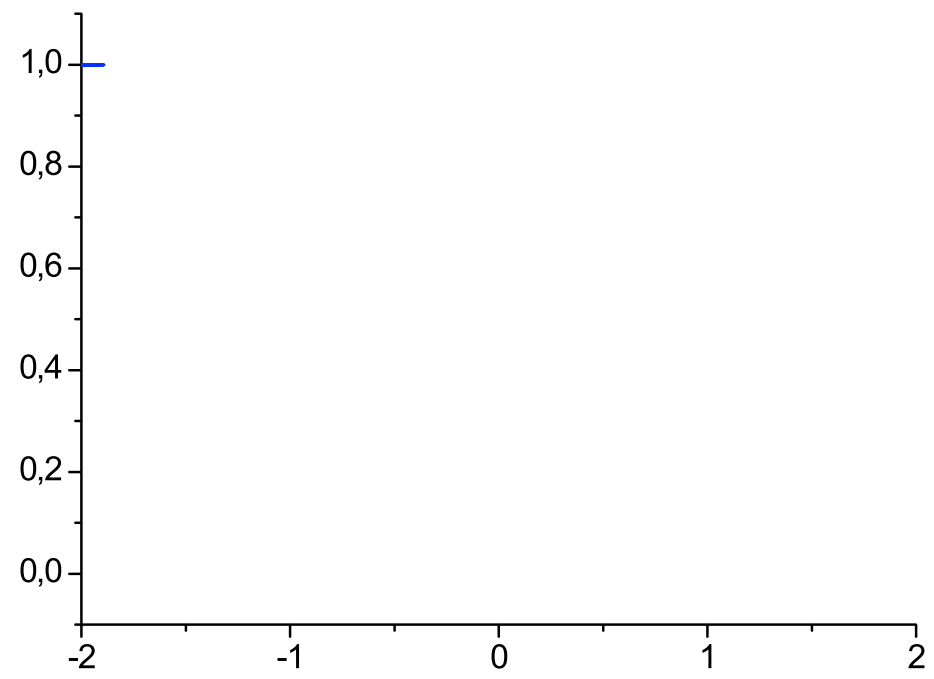


D

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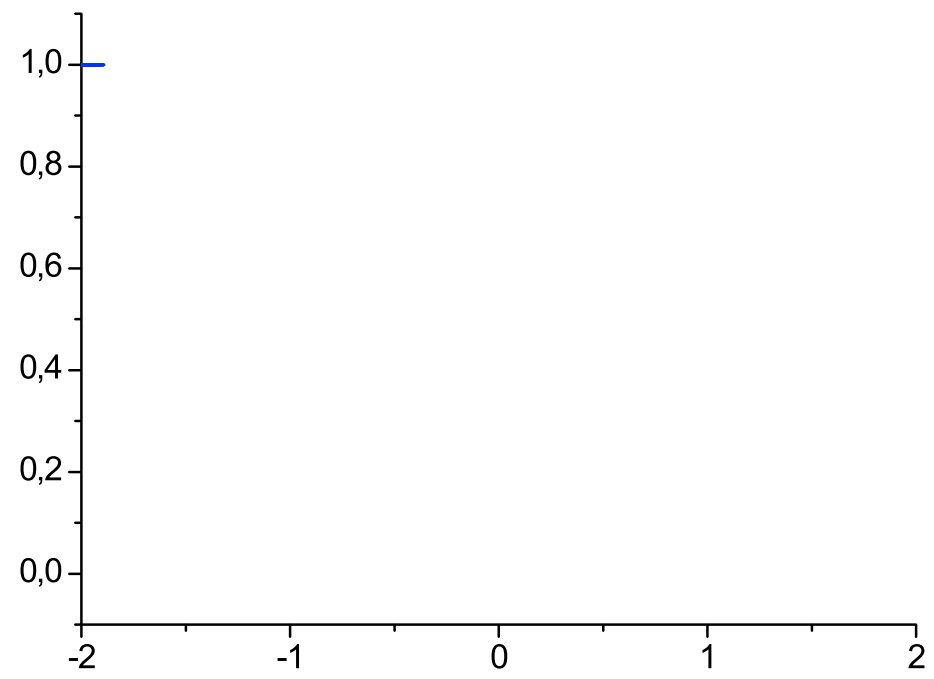


D

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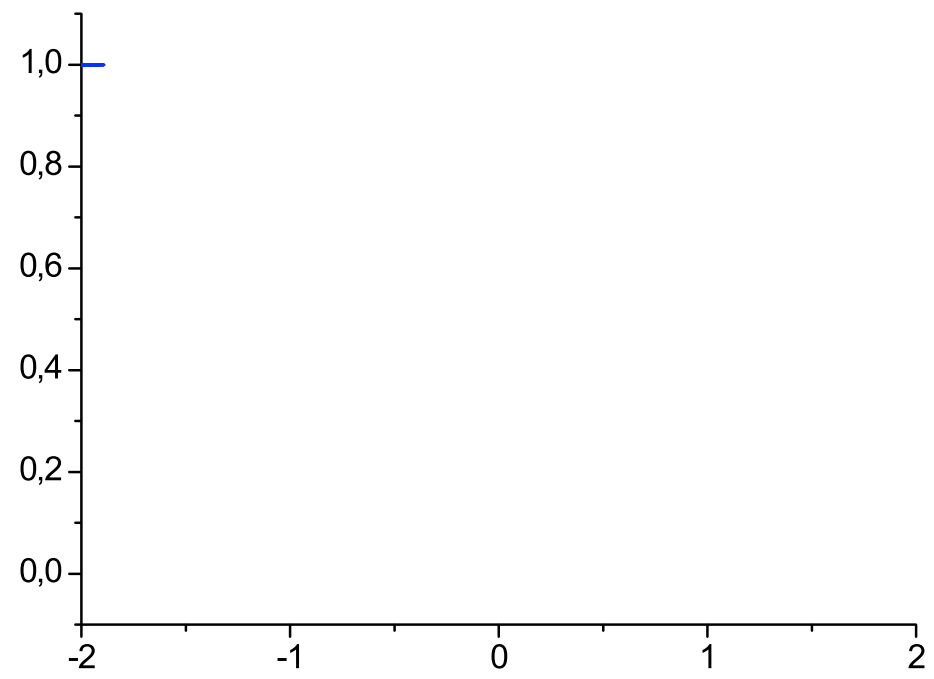


D

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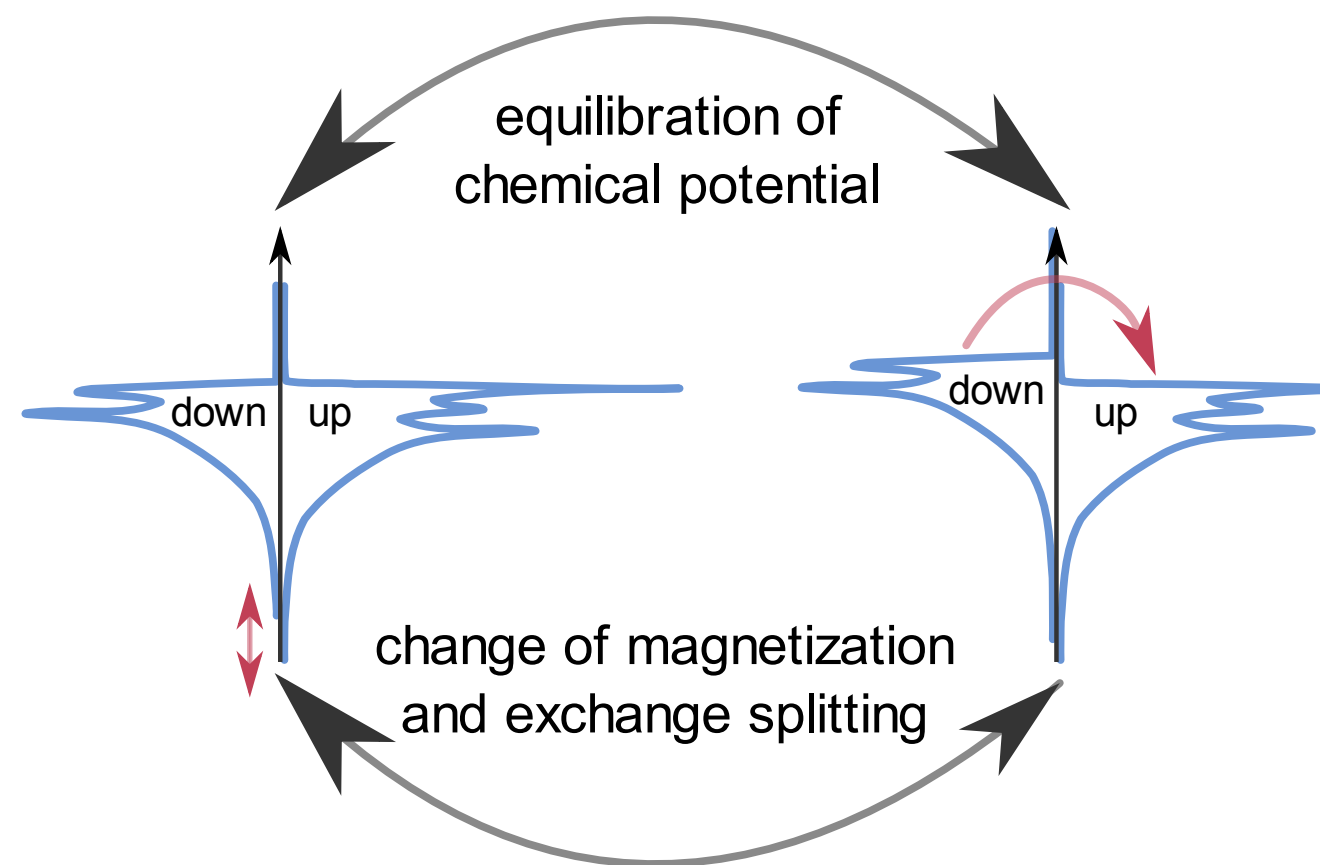
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D a c a E c a : S : M d



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D a c 2-Ba d M d

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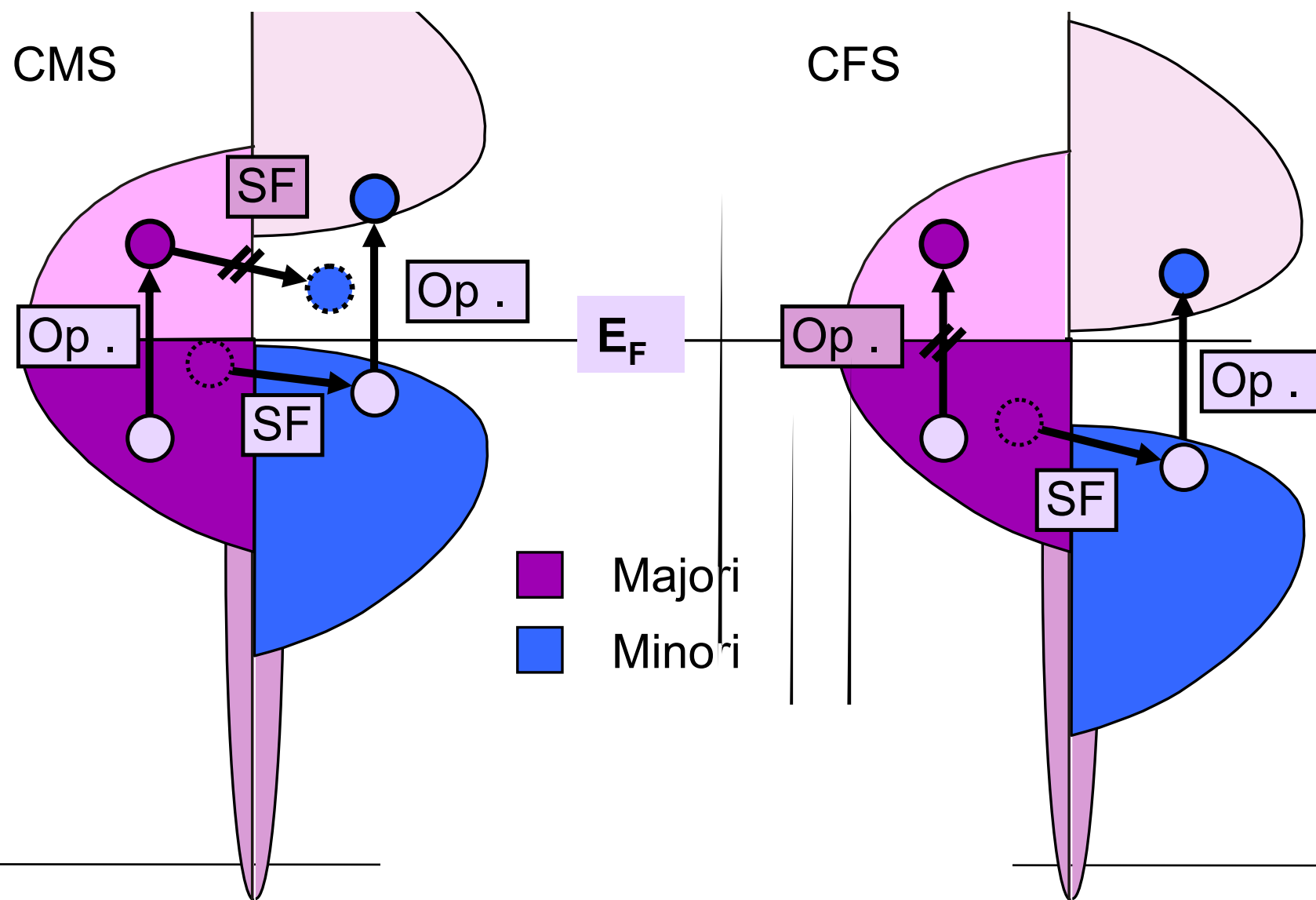


x

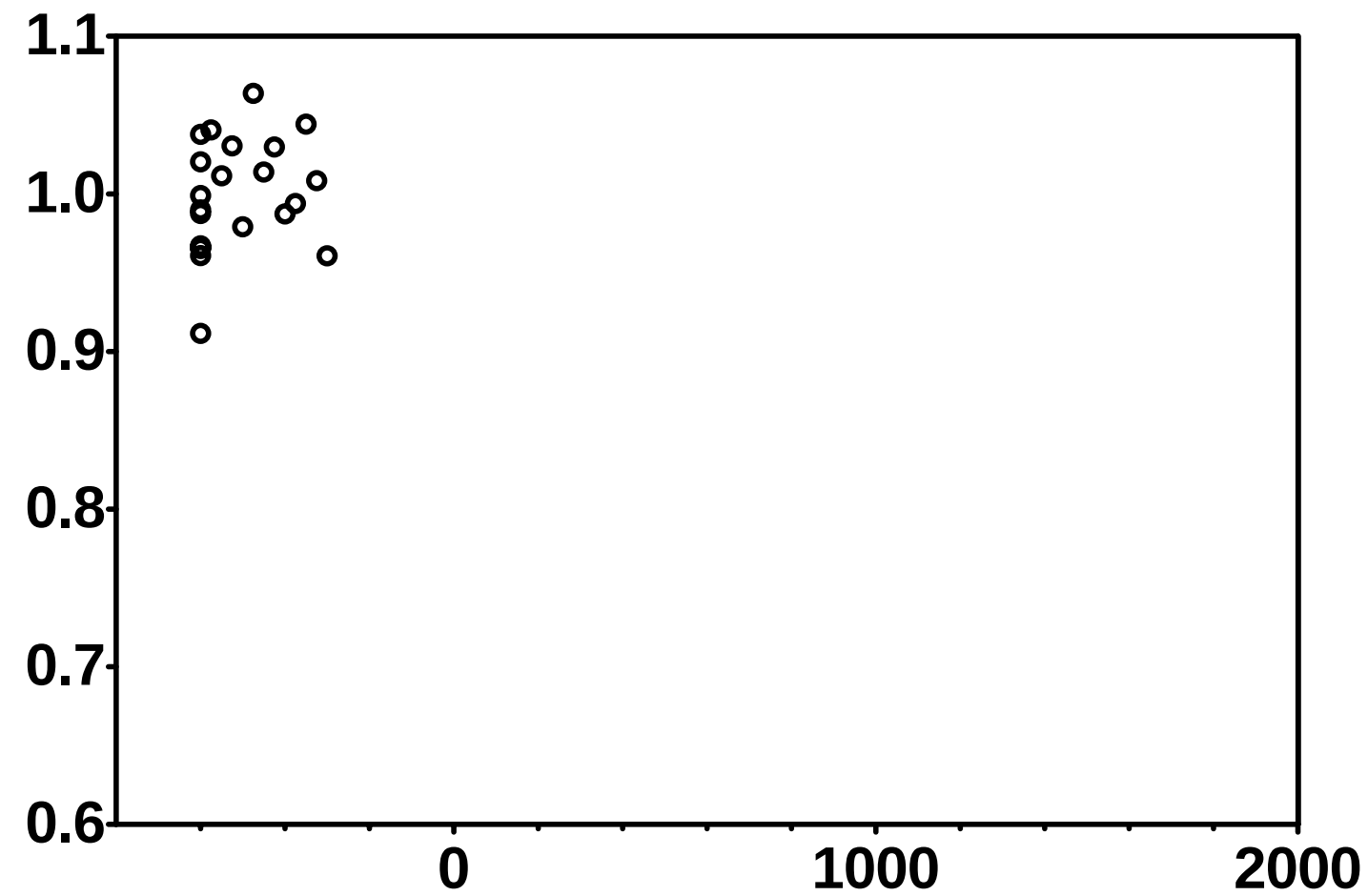
x

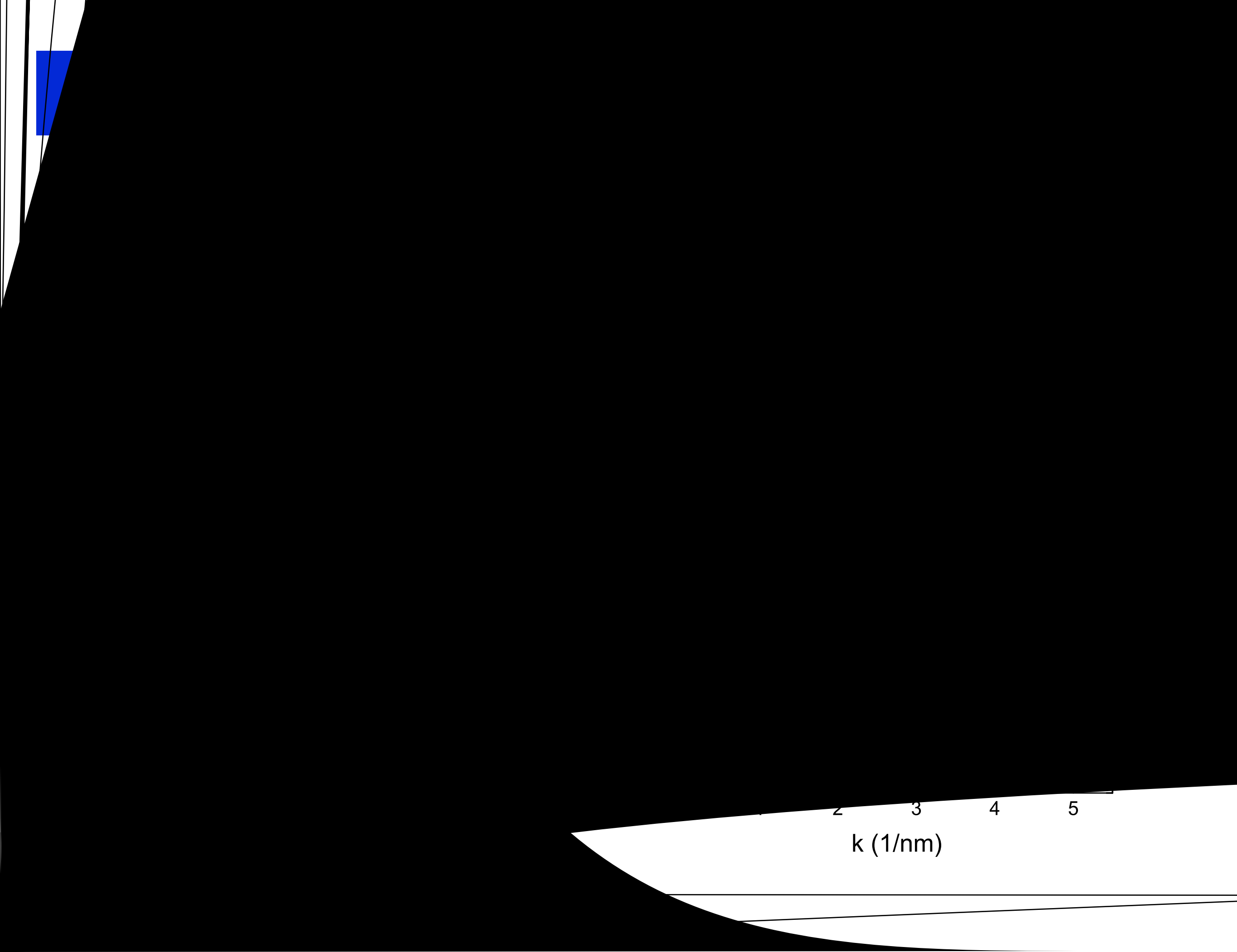
H A : CMS ä d CFS

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- ▶
- ▶
- ▶



D a a D a c CFS a d CMS





C a c a d D ' a ' a D a c

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C c (1) °

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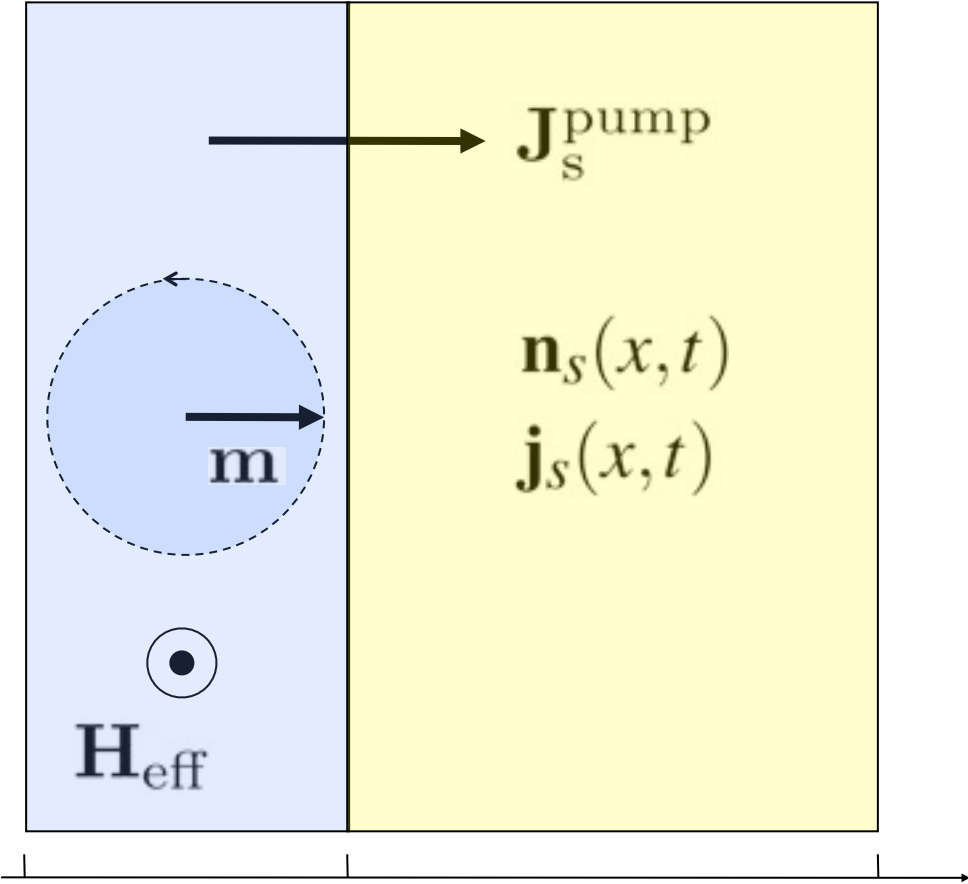
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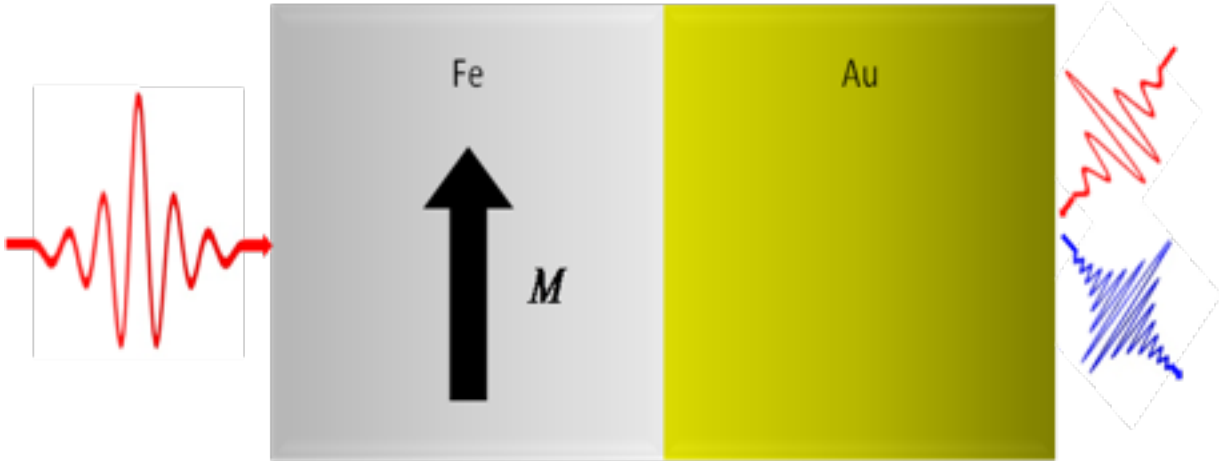
E a P b



$$\vec{j}_s^{\text{pump}} = \frac{1}{2} \frac{g}{S} \vec{m} \frac{d\vec{m}}{dt}$$

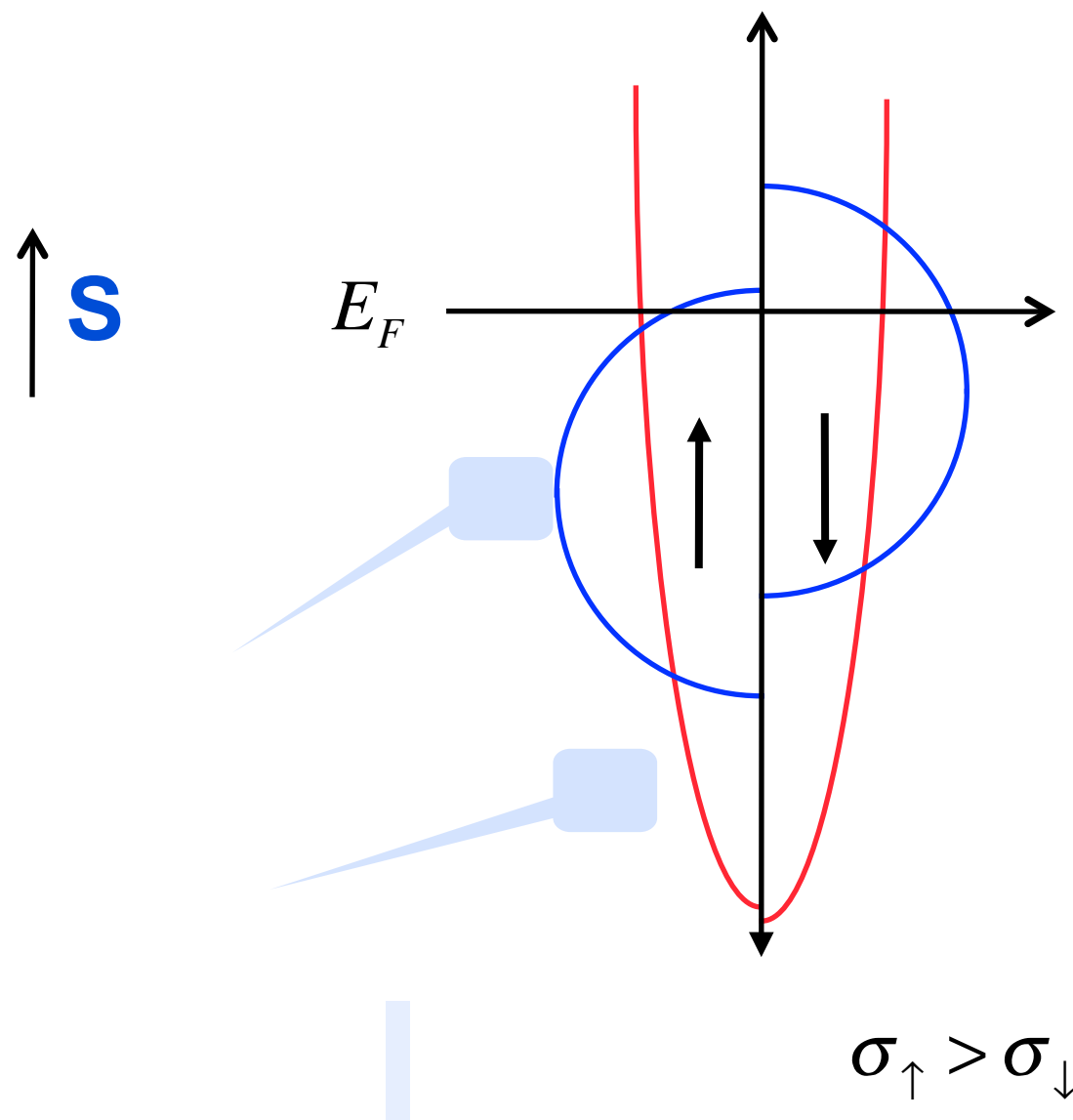
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88



Ba c (1): T -C

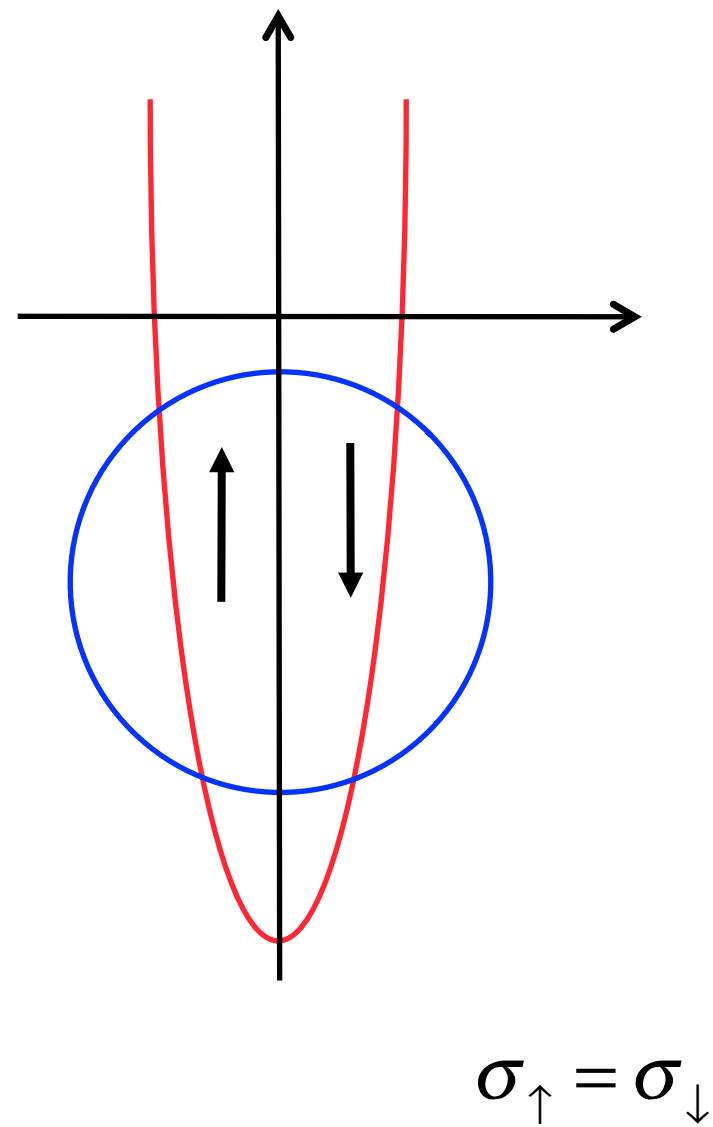
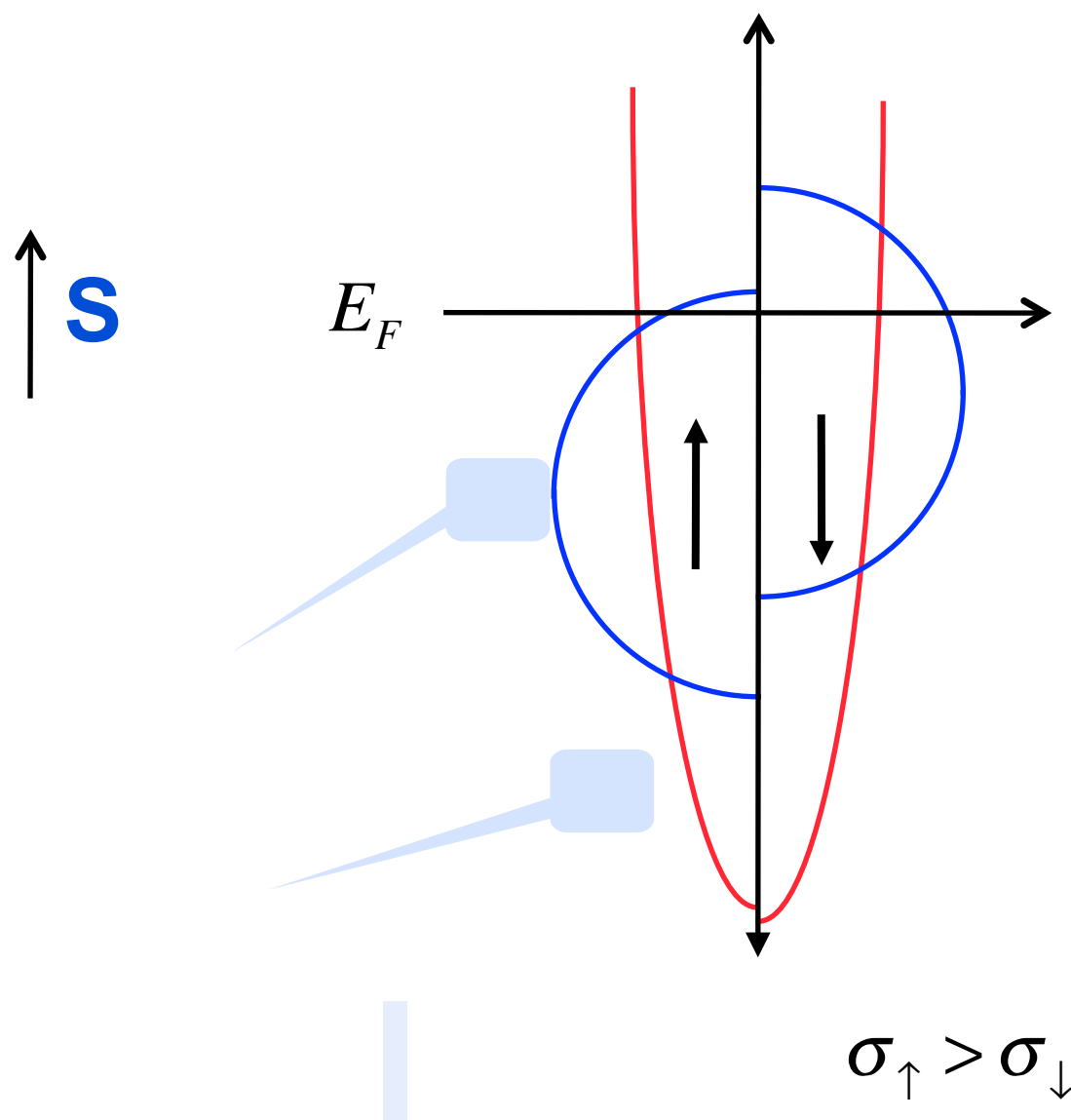
M d



153

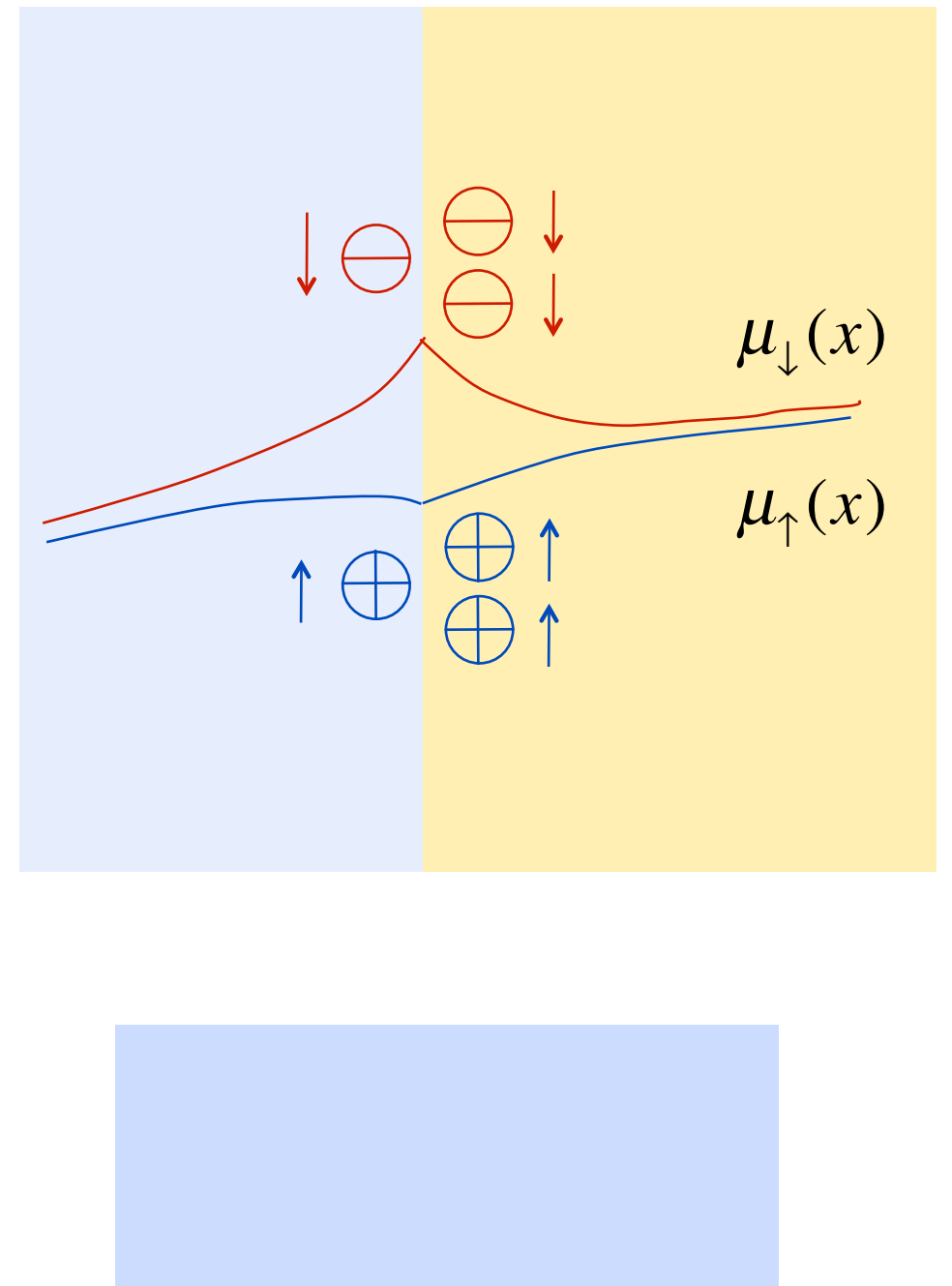
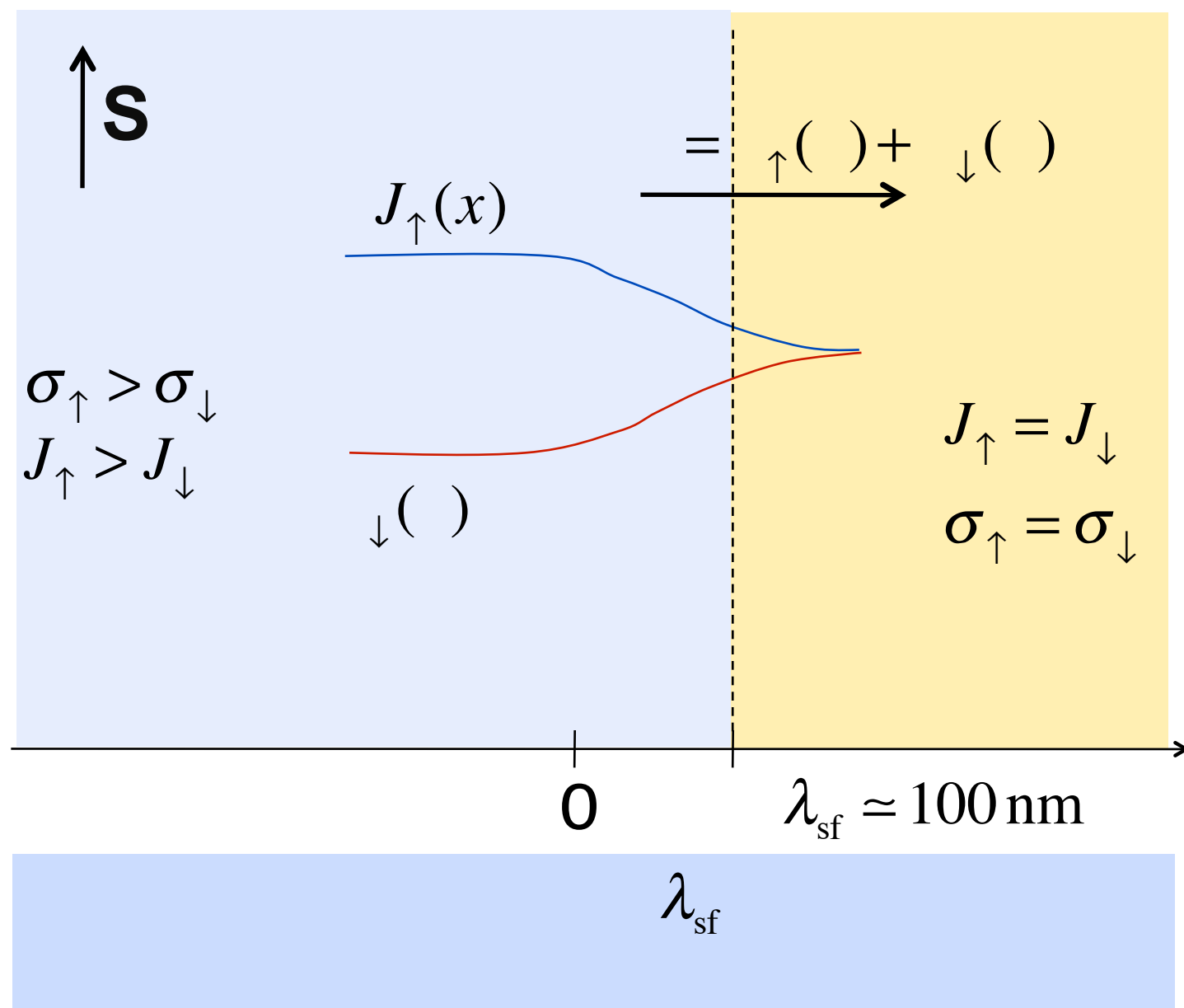
Ba c (1): T -C

M d

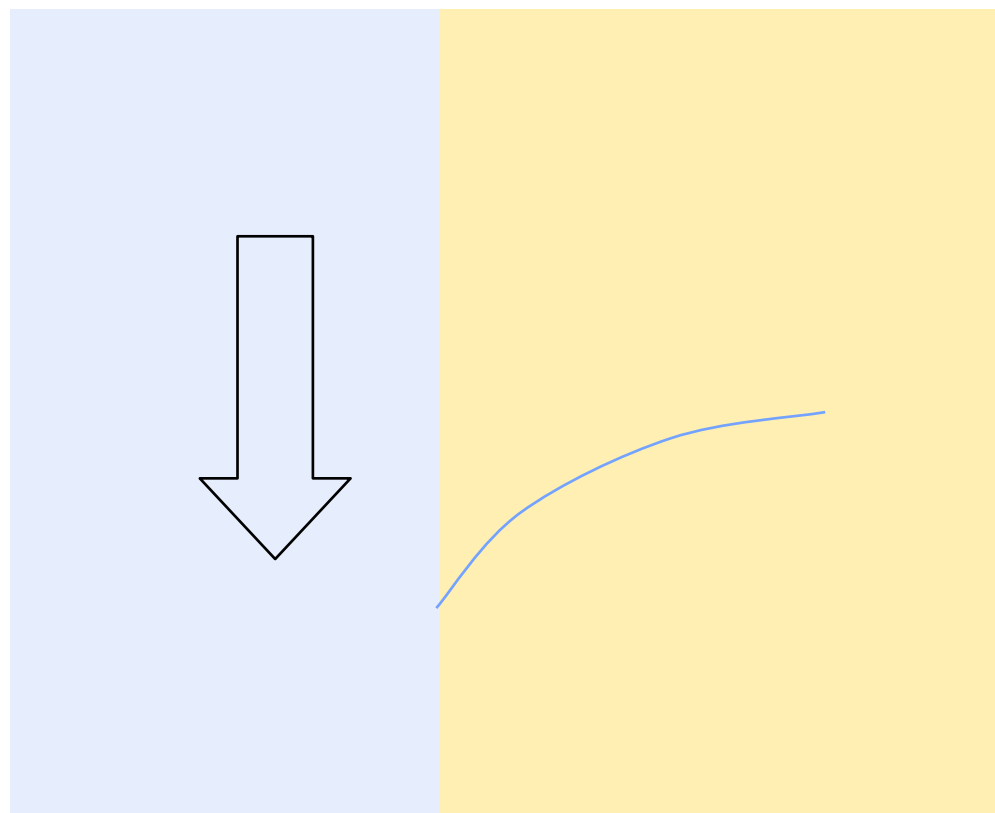


153

Ba c (2): S I c (DC)



S S a-P a a'

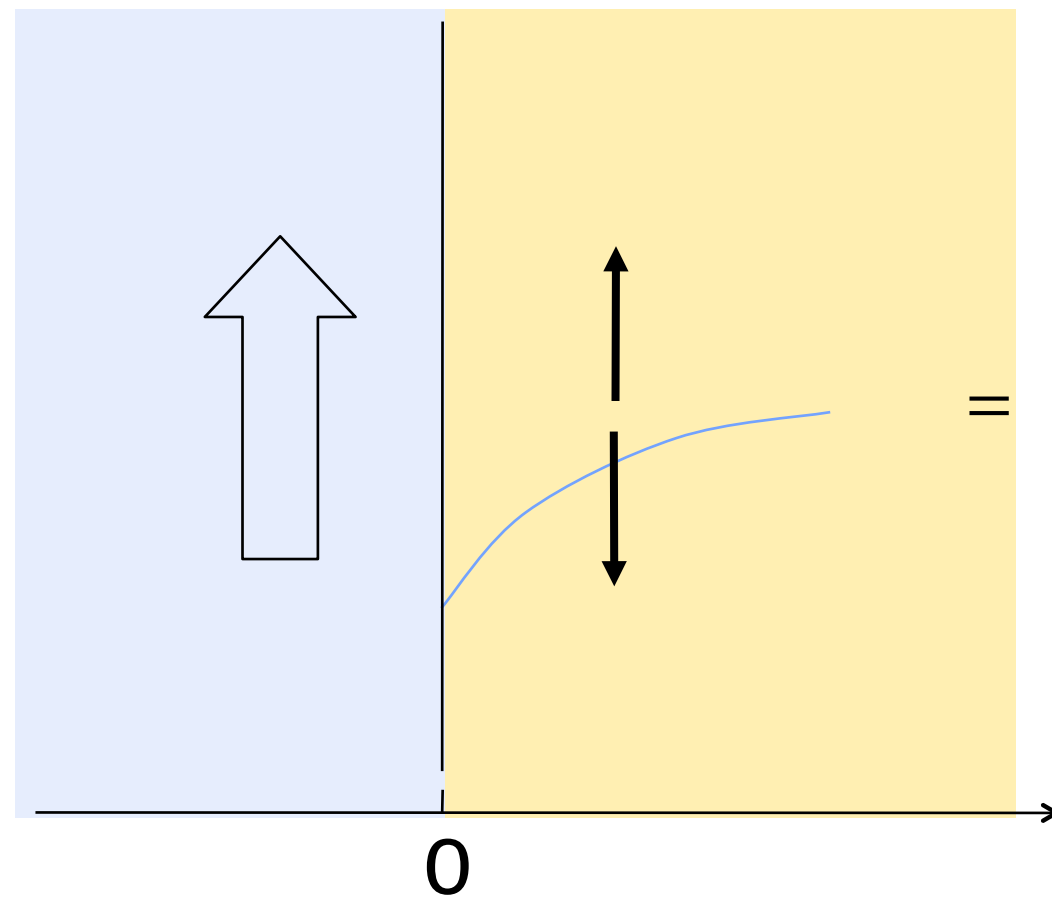


S S a-P a a'



$$J = J_{\uparrow}(x) + J_{\downarrow}(x)$$

→

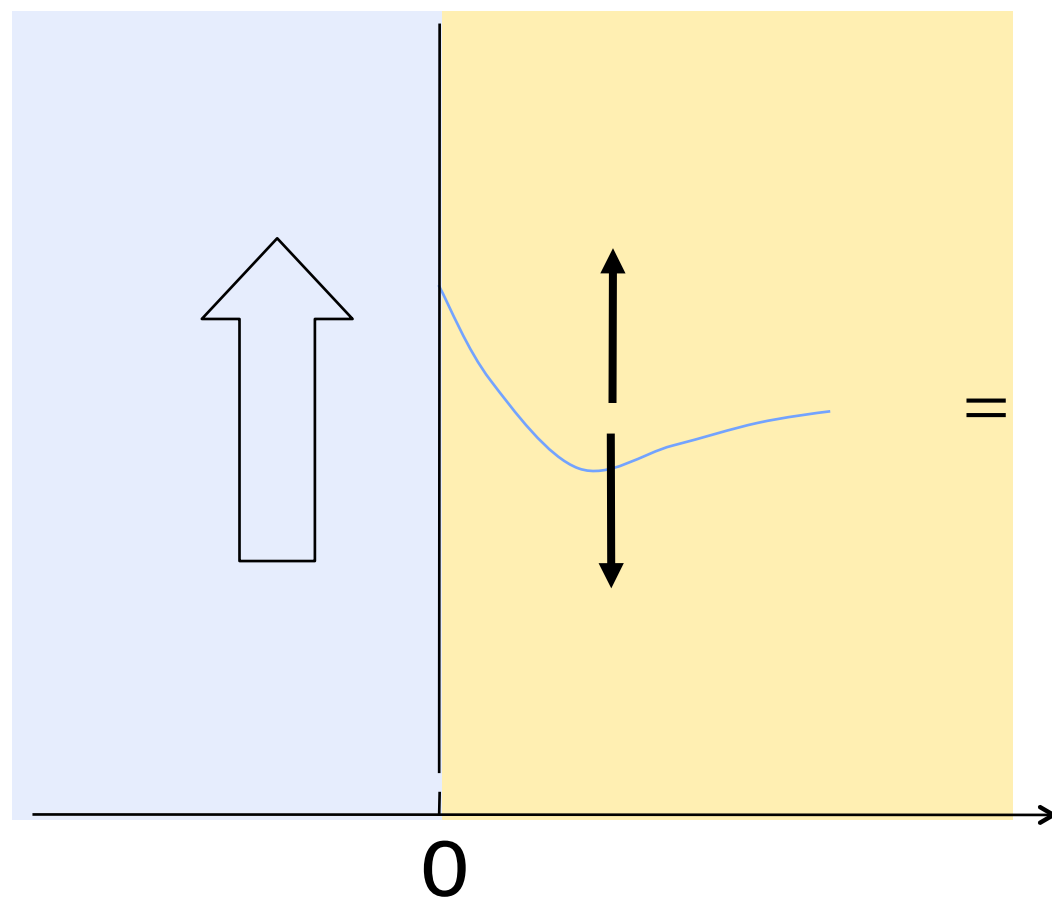


$$= \uparrow(\) - \downarrow(\)$$

S S a-P a a



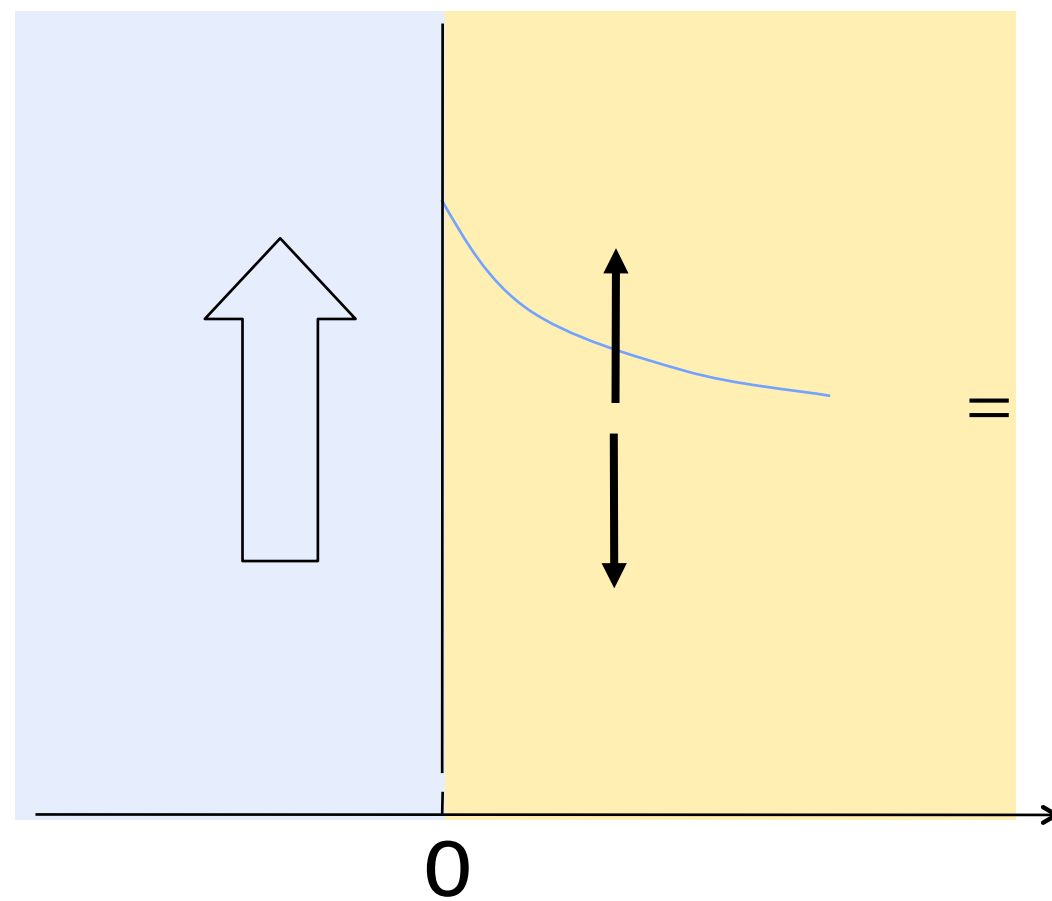
$$J = J_{\uparrow}(x) + J_{\downarrow}(x)$$



S S a-P a a'



$$= \begin{matrix} () + () \\ \longrightarrow \end{matrix}$$

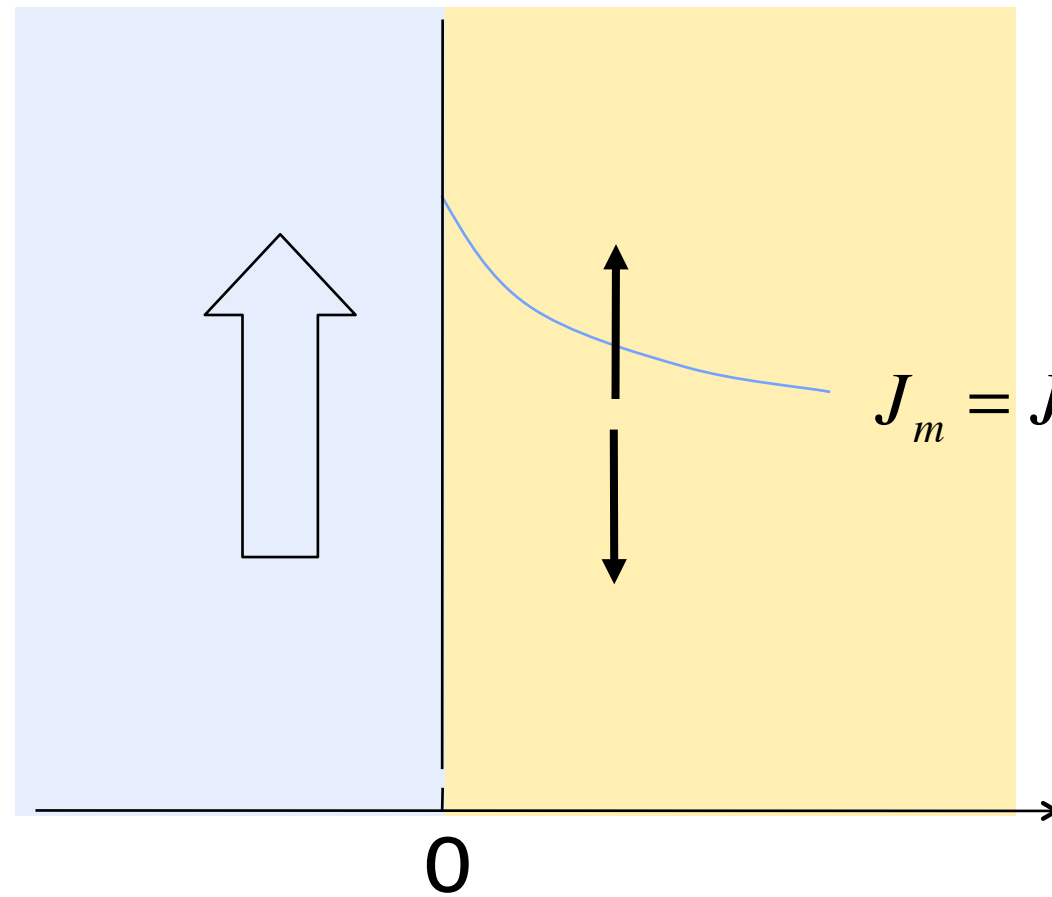


$$= \begin{matrix} \uparrow () - \downarrow () \end{matrix}$$

S S a-P a a



$$= \uparrow + \downarrow$$



$$J_m = J_{\uparrow}(x) - J_{\downarrow}(x)$$

$$\mu_m(z, t) \propto \int_0^t \frac{1}{\sqrt{\pi \bar{D} t'}} \exp \left[-\frac{z^2}{4 \bar{D} t'} - \frac{t'}{T_1} \right] dt'$$

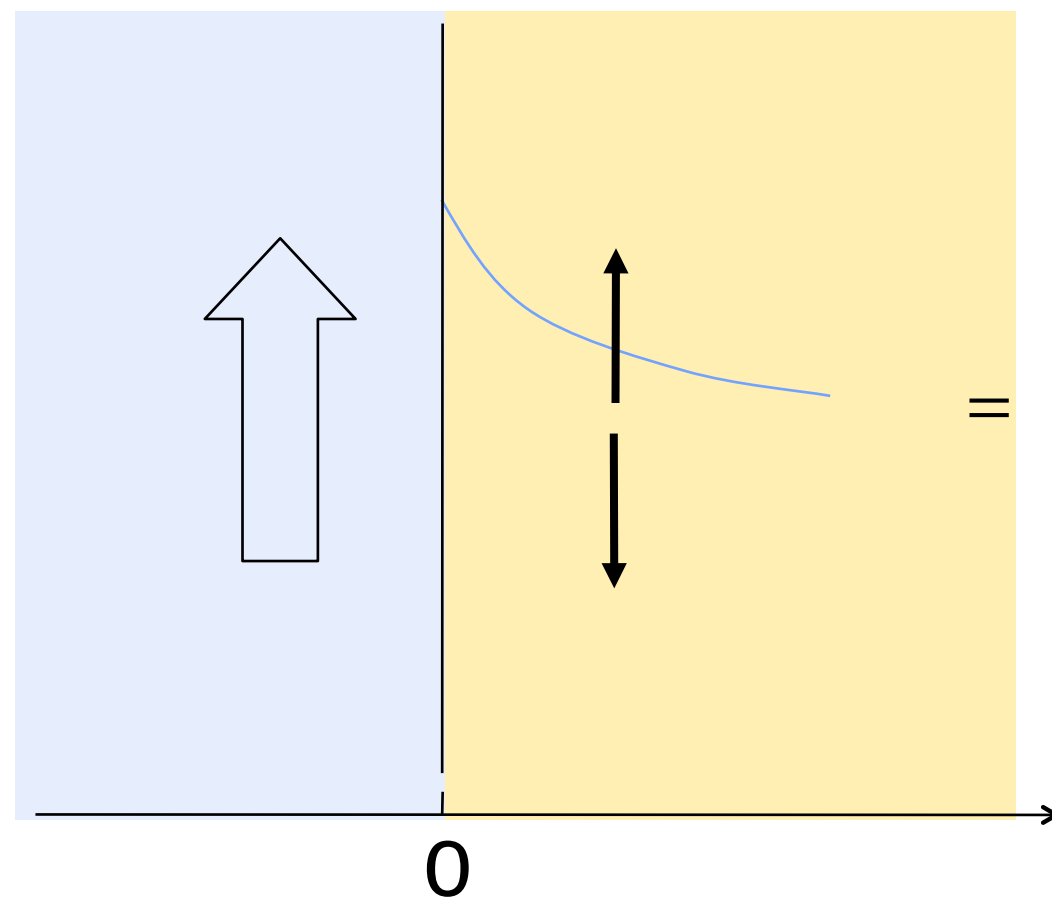
$$J_m(z, t) \propto \frac{\partial \mu_m(z, t)}{\partial z}$$

S S a-P a a



$$J = J_{\uparrow}(x) + J_{\downarrow}(x)$$

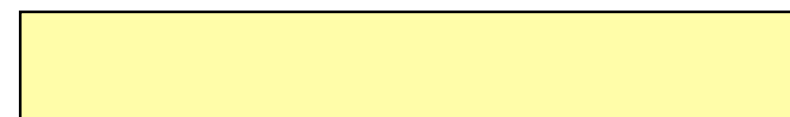
→



$$= \uparrow(\) - \downarrow(\)$$

$$\mu_m(z, t) \propto \int_0^t \frac{1}{\sqrt{\pi \bar{D} t'}} \exp \left[-\frac{z^2}{4 \bar{D} t'} - \frac{t'}{T_1} \right] dt'$$

$$J_m(z, t) = -D \frac{\partial \mu_m(z, t)}{\partial z}$$



B a E ' a (c a) ''

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$$\rho_{\sigma,\sigma'}(\vec{r}_1, \vec{r}_2) = \langle \psi_{\sigma}(\vec{r}_1) \psi_{\sigma'}(\vec{r}_2) \rangle \rightarrow \rho_{\sigma,\sigma'}(\vec{k}, \vec{r})$$

•

•

$$\hat{\rho} = \begin{pmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{pmatrix}$$

$$\left. \frac{\partial \hat{\rho}}{\partial t} \right|_{\text{relax}}$$

$$\frac{\partial \hat{\rho}}{\partial t} + v_x \frac{\partial \hat{\rho}}{\partial x} - \frac{eE}{m^*} \frac{\partial \hat{\rho}}{\partial v_x} + \frac{1}{2} \gamma (\vec{u} \times \vec{B}_s) \cdot \vec{\sigma} = -\frac{\hat{\rho} - \langle \hat{\rho} \rangle_a}{\tau} - \frac{\langle \hat{\rho} \rangle_a - (\hat{I}/2) \text{Tr} \langle \hat{\rho} \rangle_a}{T_1}$$

•

$$\vec{u} = \text{Tr}[\vec{\sigma} \hat{\rho}]$$

B a E ' a (c a) ''

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$$\hat{\rho}_{\sigma,\sigma'}(\vec{r}_1, \vec{r}_2) = \langle \psi_{\sigma}^{\dagger}(\vec{r}_1) \psi_{\sigma'}(\vec{r}_2) \rangle \rightarrow \hat{\rho}_{\sigma,\sigma'}(\vec{k}, \vec{r})$$

•

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$$\hat{\rho} = \begin{pmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{pmatrix}$$

$$\left. \frac{\partial \hat{\rho}}{\partial t} \right|_{\text{relax}}$$

$$\frac{\partial \hat{\rho}}{\partial t} + v_x \frac{\partial \hat{\rho}}{\partial x} - \frac{eE}{m^*} \frac{\partial \hat{\rho}}{\partial v_x} + \frac{1}{2} \gamma (\vec{u} \times \vec{B}_s) \cdot \vec{\sigma} = -\frac{\hat{\rho} - \langle \hat{\rho} \rangle_a}{\tau} - \frac{\langle \hat{\rho} \rangle_a - (\hat{I}/2) \text{Tr} \langle \hat{\rho} \rangle_a}{T_1}$$

•

$$\vec{u} = \text{Tr}[\vec{\sigma} \hat{\rho}]$$

$$\vec{S}(\vec{r}, t) = \frac{\hbar}{2V} \sum_{\vec{k}} \vec{u}(\vec{k}, \vec{r}, t)$$

$$Q_{\alpha,\beta}(\vec{r}, t) = \frac{\hbar}{2V} \sum_{\vec{k}} v_{\alpha} u_{\beta}(\vec{k}, \vec{r}, t)$$

$$\vec{r}(\vec{k}, t)$$

$$J_{m\gamma}^{\alpha} x t = Q_{\alpha\gamma} x t$$

G a Mac c ' c D a ca E a ' .



$$\frac{\partial \vec{S}(x,t)}{\partial t} = -\gamma \vec{S} \times \vec{B} - \frac{\partial \vec{J}_m}{\partial x} - \frac{\partial \vec{S}(x,t)}{\partial t} \Big|_{\text{relax}} \quad c_{\text{sig}} = \frac{v_F}{\sqrt{3}}$$

$$\frac{\partial \vec{J}_m(x,t)}{\partial t} = -c_{\text{sig}}^2 \frac{\partial S}{\partial x} - \frac{e}{m^*} E(x,t) \vec{S} - \gamma \vec{J}_m \times \vec{B} - \frac{\partial \vec{J}_m}{\partial t} \Big|_{\text{relax}}$$



$$T = T = -\tau$$

$$\tau$$

$$\frac{\partial \vec{S}(x,t)}{\partial t} = -\gamma \vec{S} \times \vec{B} - \frac{\vec{S}}{T_1} - \frac{\partial \vec{J}_m}{\partial x}$$

$$\frac{\partial \vec{S}(x,t)}{\partial t} = -c_{\text{sig}}^2 \frac{\partial S}{\partial x} - \frac{e}{m^*} E(x,t) \vec{S} - \gamma \vec{J}_m \times \vec{B} - \frac{1}{\tau} \vec{S}$$

G a Mac c ' c D a ca E a ' .



$$\frac{\partial \vec{S}(x,t)}{\partial t} = -\gamma \vec{S} \times \vec{B} - \frac{\partial \vec{J}_m}{\partial x} - \frac{\partial \vec{S}(x,t)}{\partial t} \bigg|_{\text{relax}} \quad \overline{\sqrt{}}$$

$$\frac{\partial \vec{J}_m(x,t)}{\partial t} = -c_{sig}^2 \frac{\partial S}{\partial x} - \frac{e}{m^*} E(x,t) \vec{S} - \gamma \vec{J}_m \times \vec{B} - \frac{\partial \vec{J}_m}{\partial t} \bigg|_{\text{relax}}$$



$$T_2 = T_1 = \frac{1}{2} \tau_{sf}$$

τ

$$\frac{\partial \vec{S}(x,t)}{\partial t} = -\gamma \vec{S} \times \vec{B} - \frac{\vec{S}}{T_1} - \frac{\partial \vec{J}_m}{\partial x}$$

G a Mac c ' c D a ca E a ' .



$$\frac{\partial \vec{S}(x,t)}{\partial t} = -\gamma \vec{S} \times \vec{B} - \frac{\partial \vec{J}_m}{\partial x} - \frac{\partial \vec{S}(x,t)}{\partial t} \Big|_{\text{relax}}$$

$$\frac{\partial \vec{S}(x,t)}{\partial t} = -$$



$$\frac{\partial \vec{S}(x,t)}{\partial t} = -\gamma \vec{S} \times \vec{B} - \frac{\vec{S}}{T} - \frac{\partial \vec{J}_m}{\partial x}$$

$$\vec{J}(x,t) = -D \frac{\partial}{\partial x} - \mu E(x,t) \vec{S} - \tau \gamma \vec{J} \times \vec{B} - \tau \frac{\partial \vec{J}}{\partial t}$$

C a Mac'' c c E a



t

A a ca S

$$\boxed{\frac{\partial^2 n_m}{\partial t^2}} + \frac{1}{\epsilon_0} \frac{1}{T_1}$$

$$n_m = n_+ - n_-$$

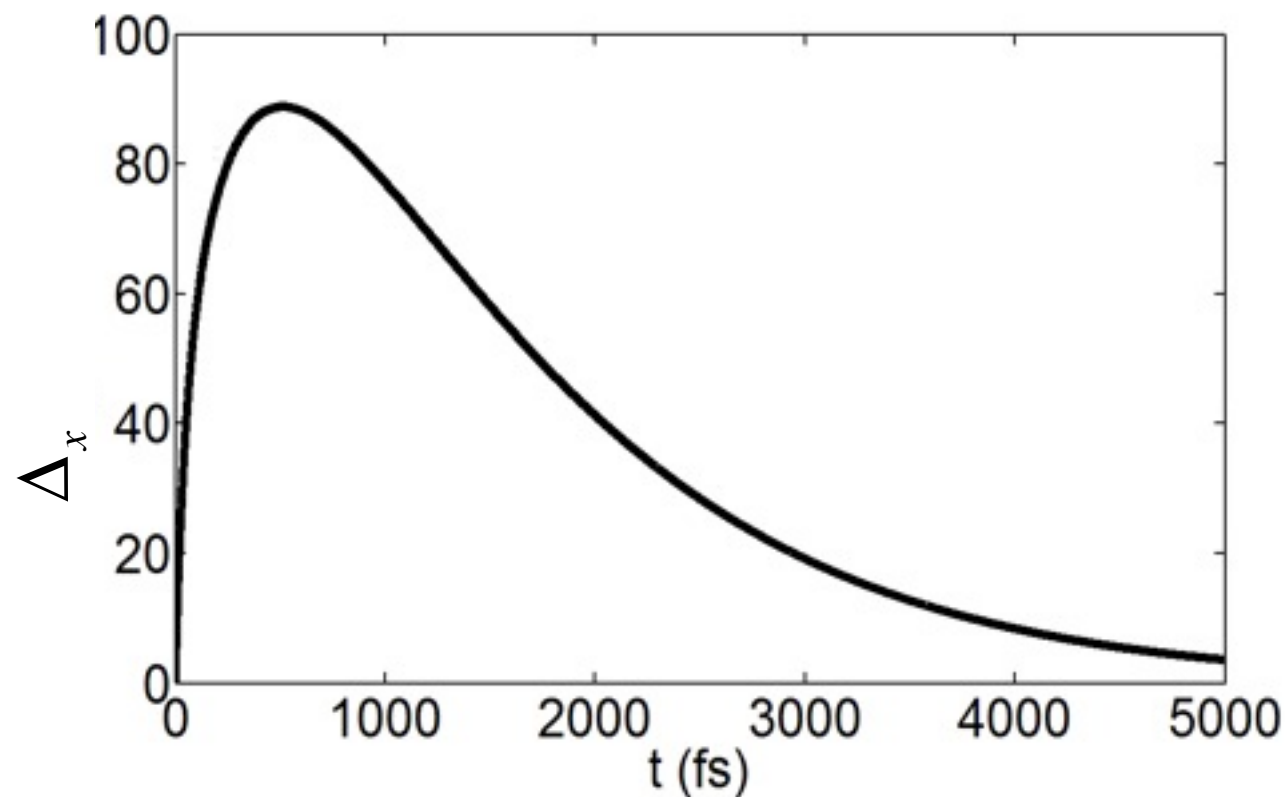
S Wa -D S E a : A a ca (2)

•

$$\Delta_x^2 = \int dx x^2 n_m(x, t) \propto c_{\text{sig}}^2 t \left(\frac{1}{\tau} + \frac{1}{T_1} \right) (e^{-t/\tau} - e^{-t/T_1})$$

• $\Delta_x^2 \propto c_{\text{sig}}^2 t^2$

• $\Delta^2 \propto$



$$v_F = 1.4 \text{ nm/fs}$$

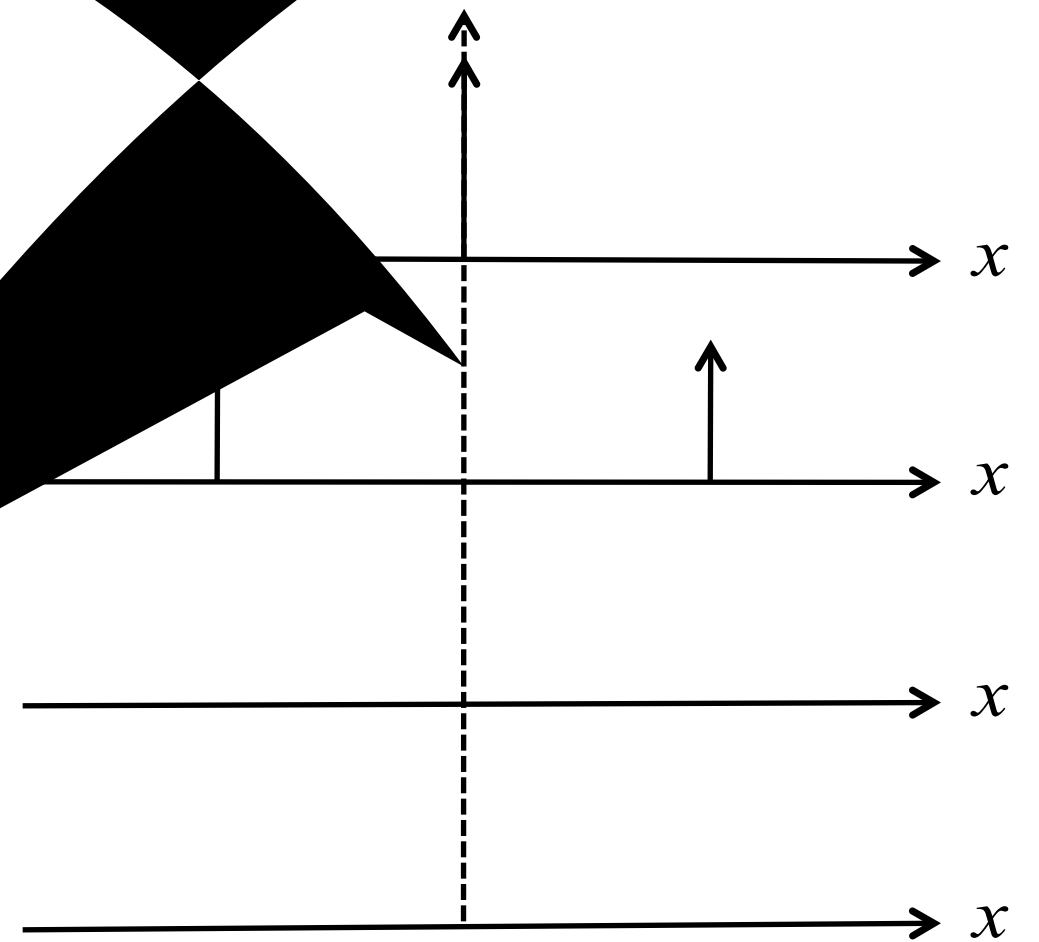
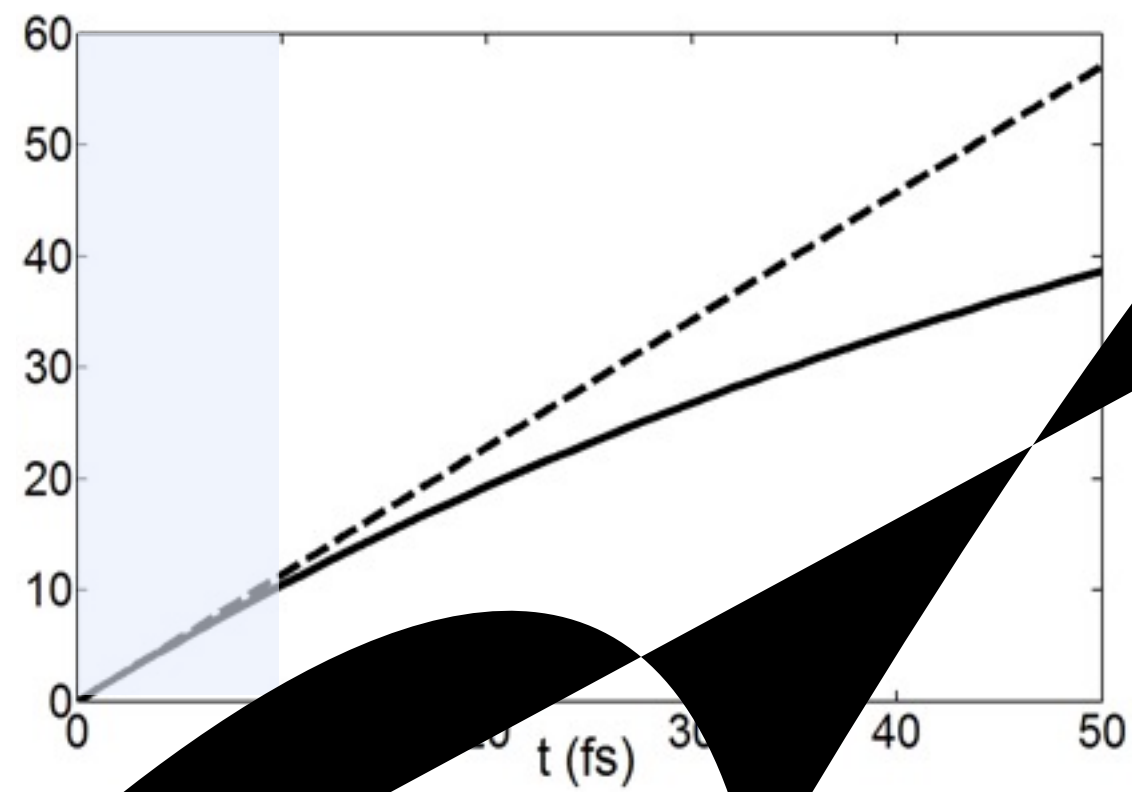
$$\tau = 30 \text{ fs}$$

$$T_1 = 515 \text{ fs}$$

Ba

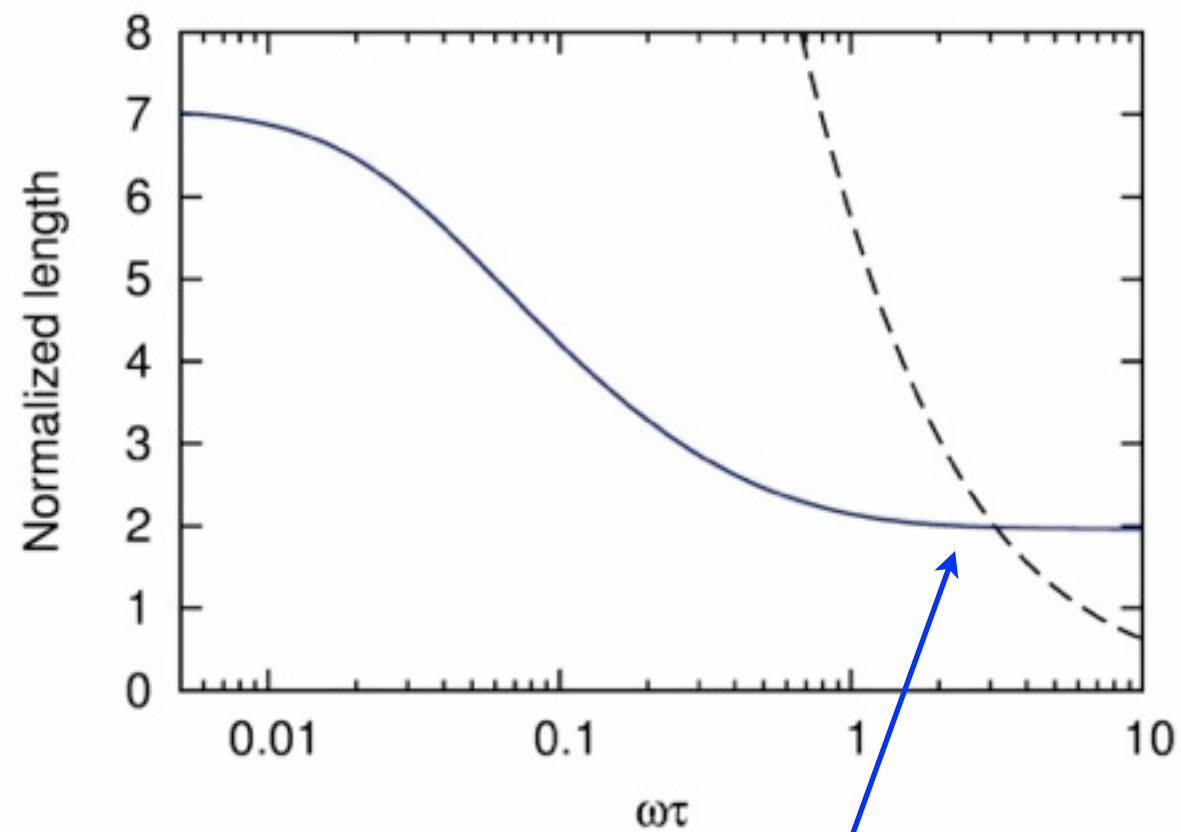
ca dD'

Ta



S Wa -D S E a : A a ca (3)

- $J_m x t \propto i kx - \omega t$
- $k(\omega) = k_R(\omega) + k_I(\omega)$
-



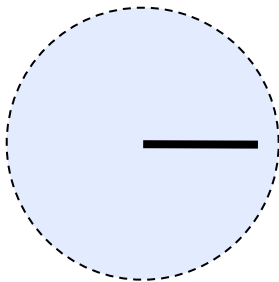
$\nu_c = 7.1$ THz for Cu

78

45

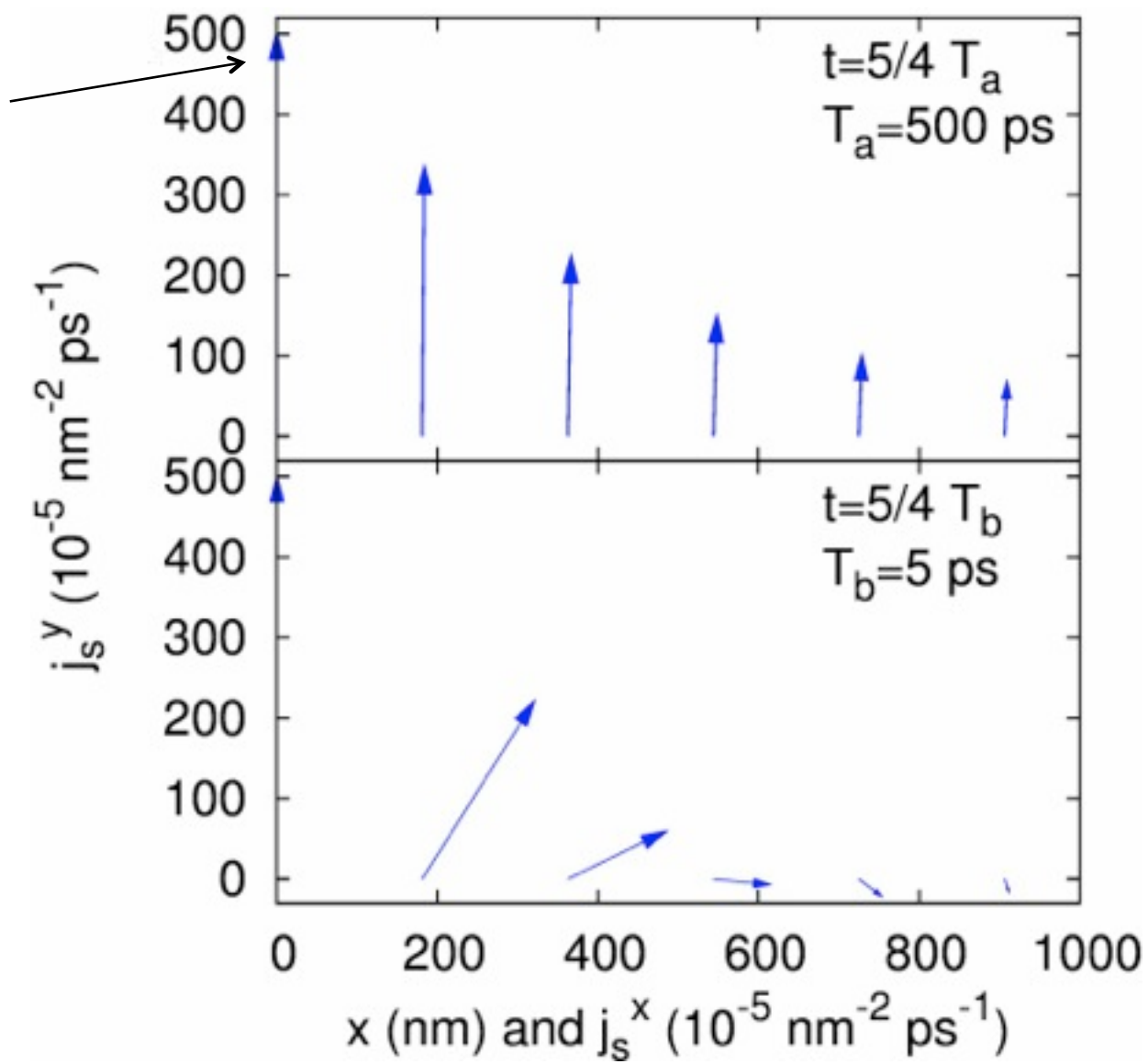
O

■

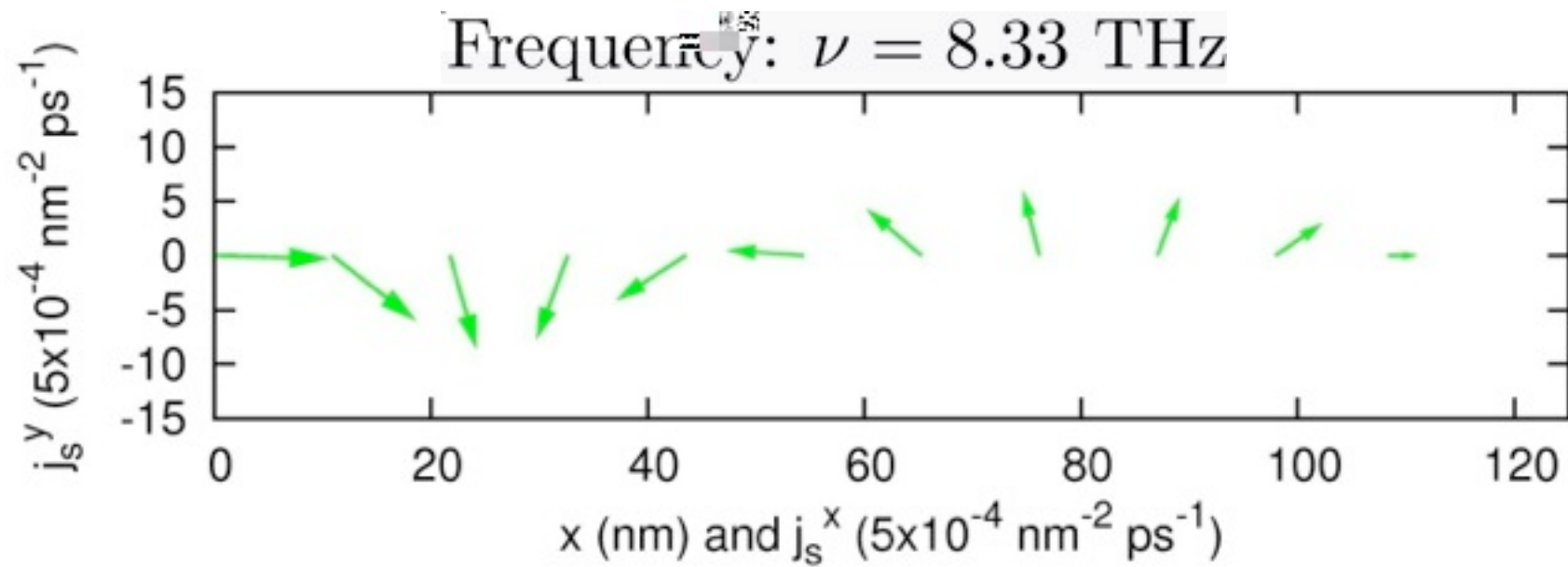


D -D a d R

•

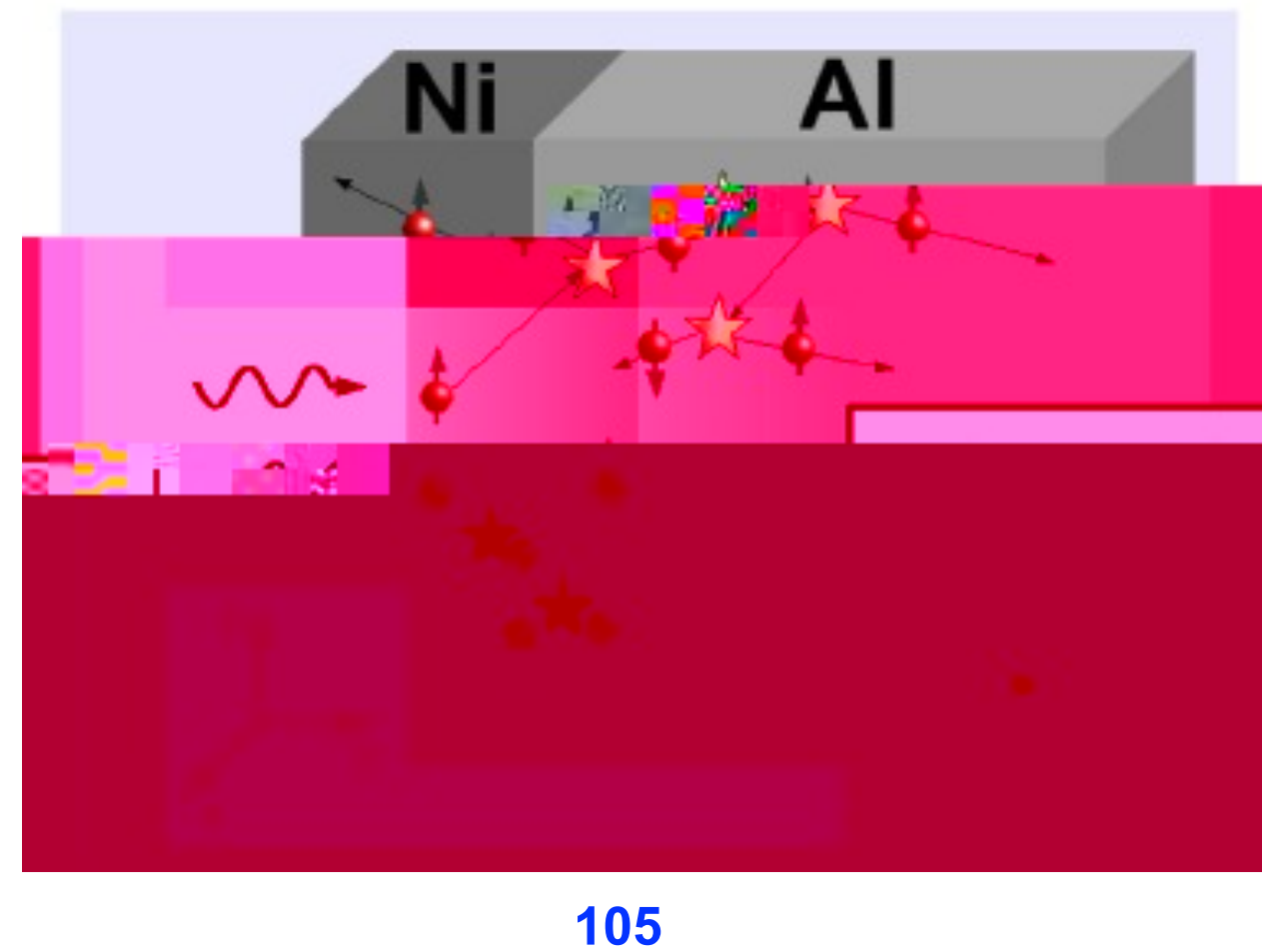
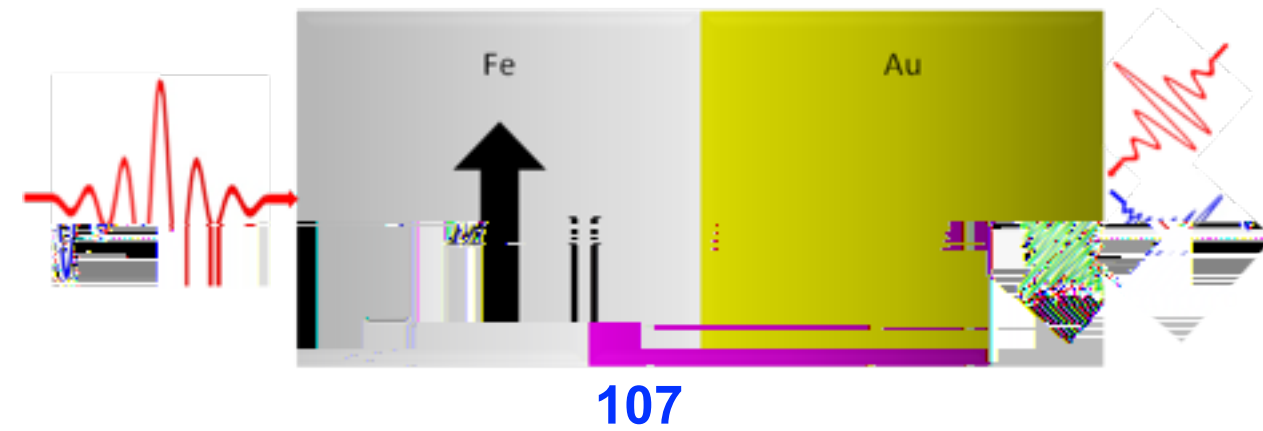


Wave-Driven And R



Wave-front velocity estimated: $\approx c_s = \frac{v_F}{\sqrt{3}}$

O ca E c a ; Sca T a M a / F a



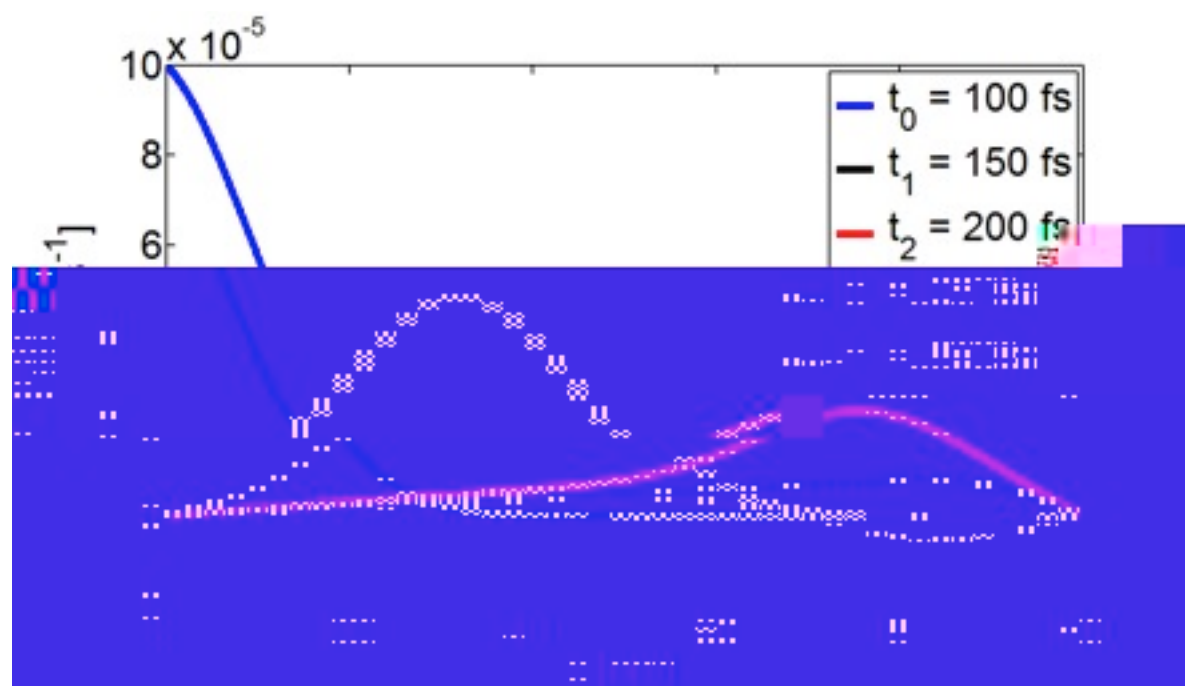
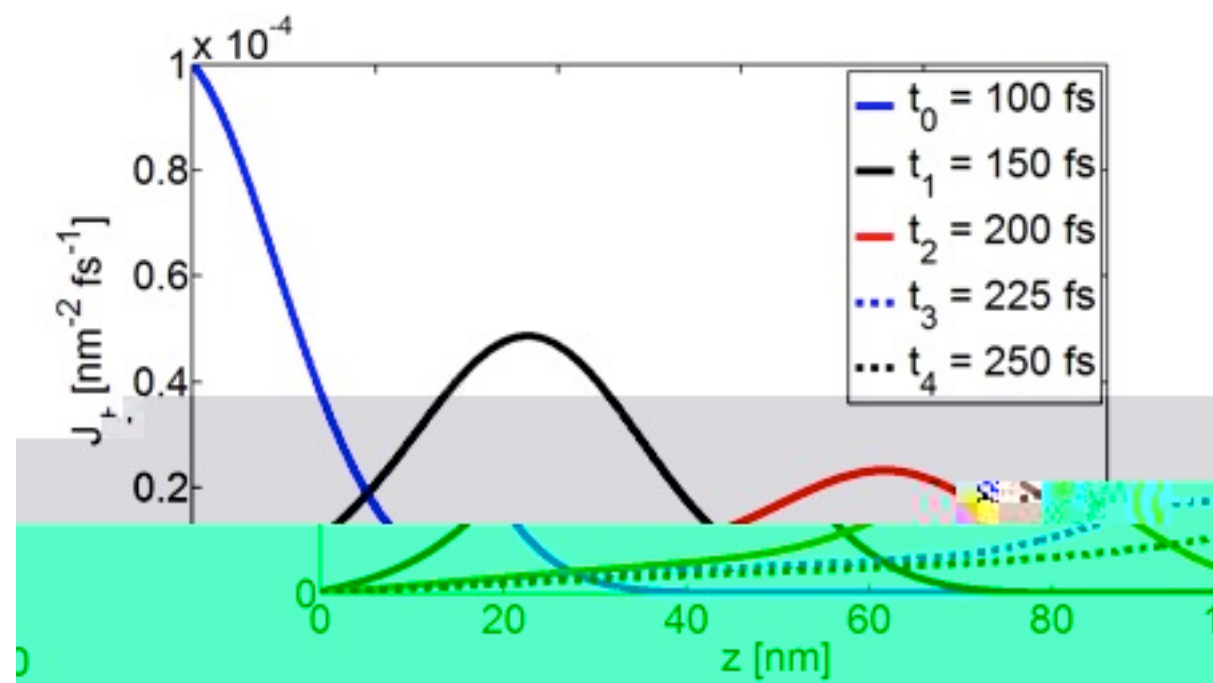
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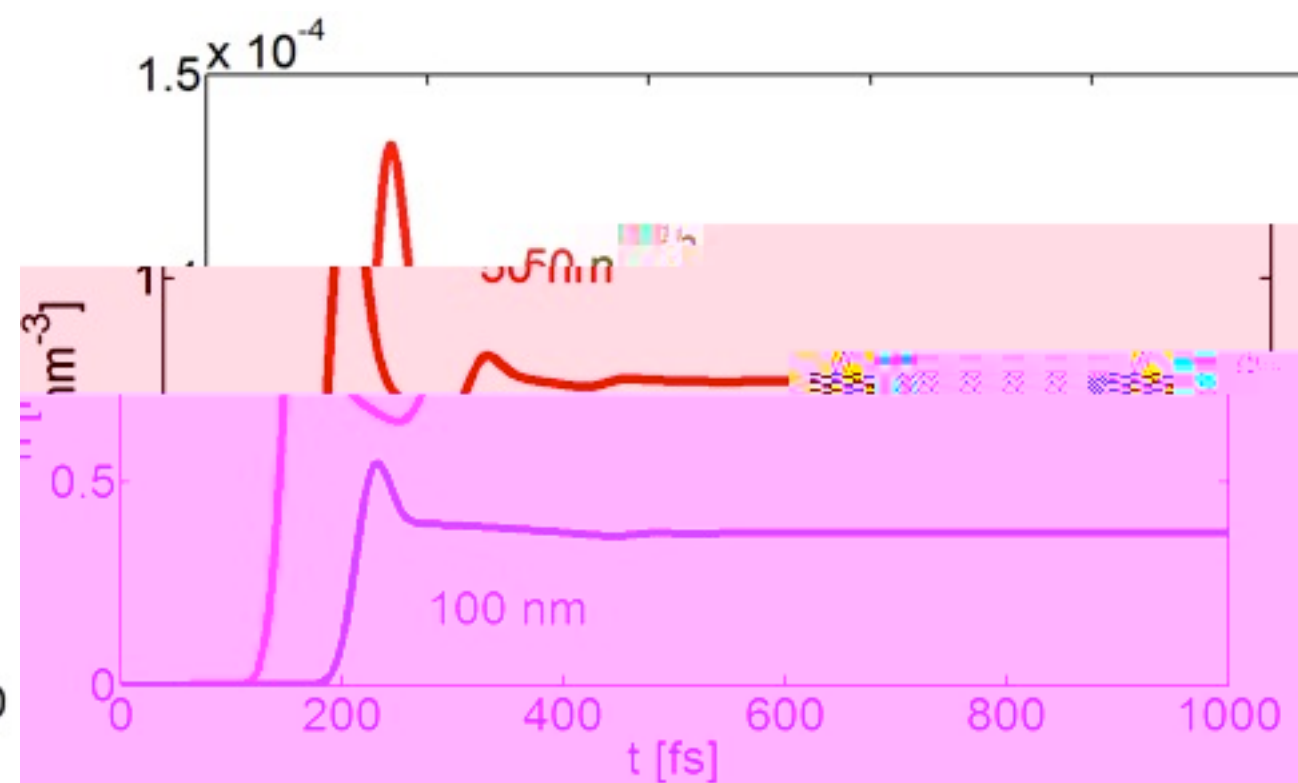
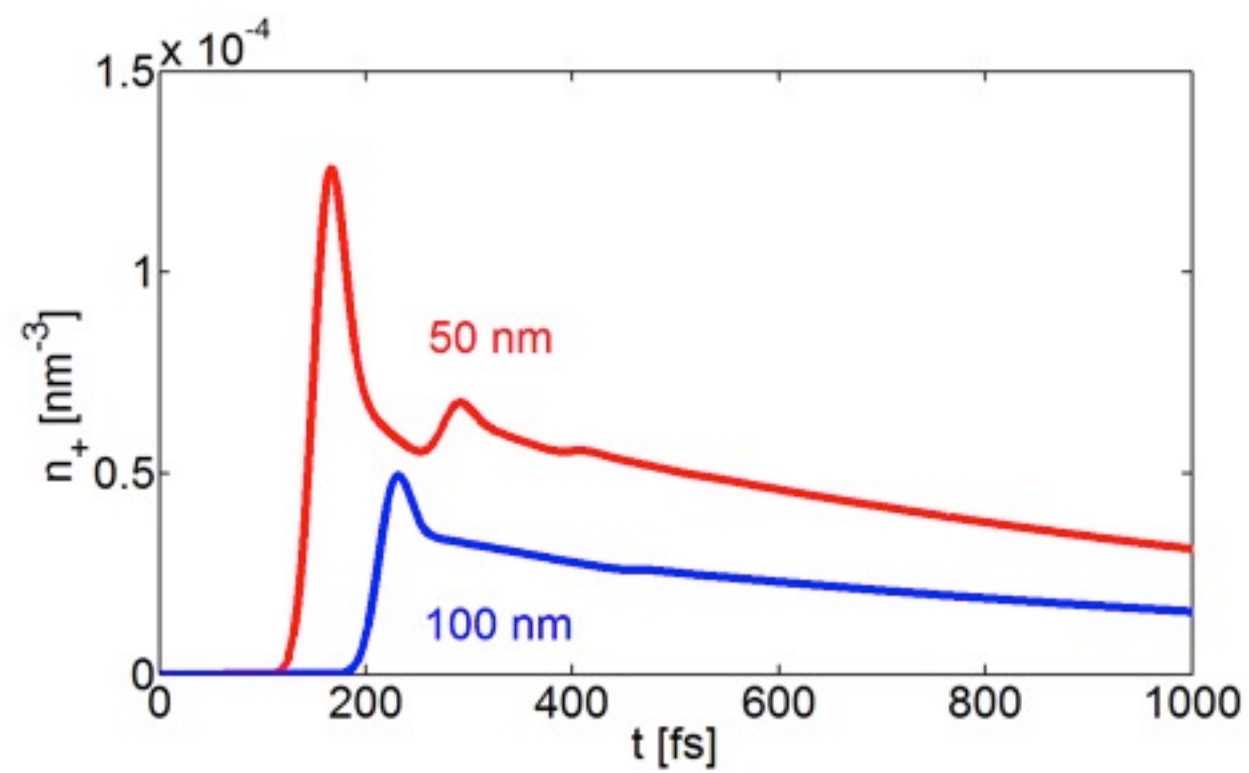
O ca E c d D a c G d

_____) (,)
sf

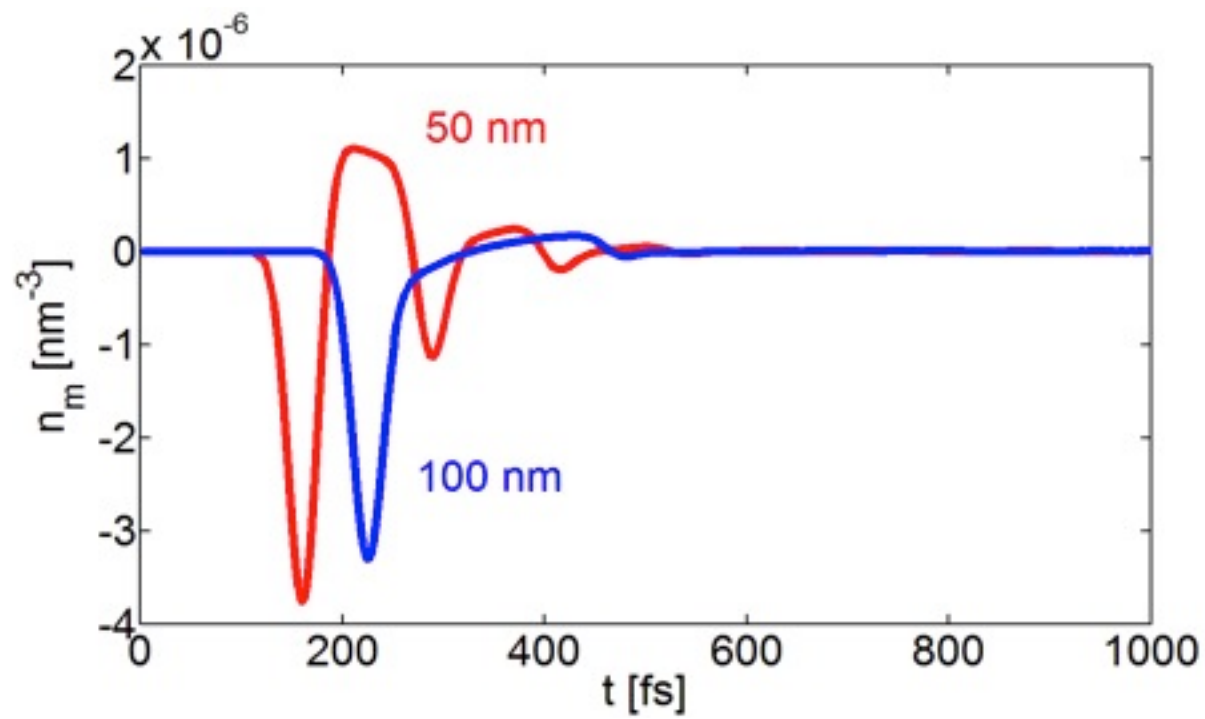
C D a c



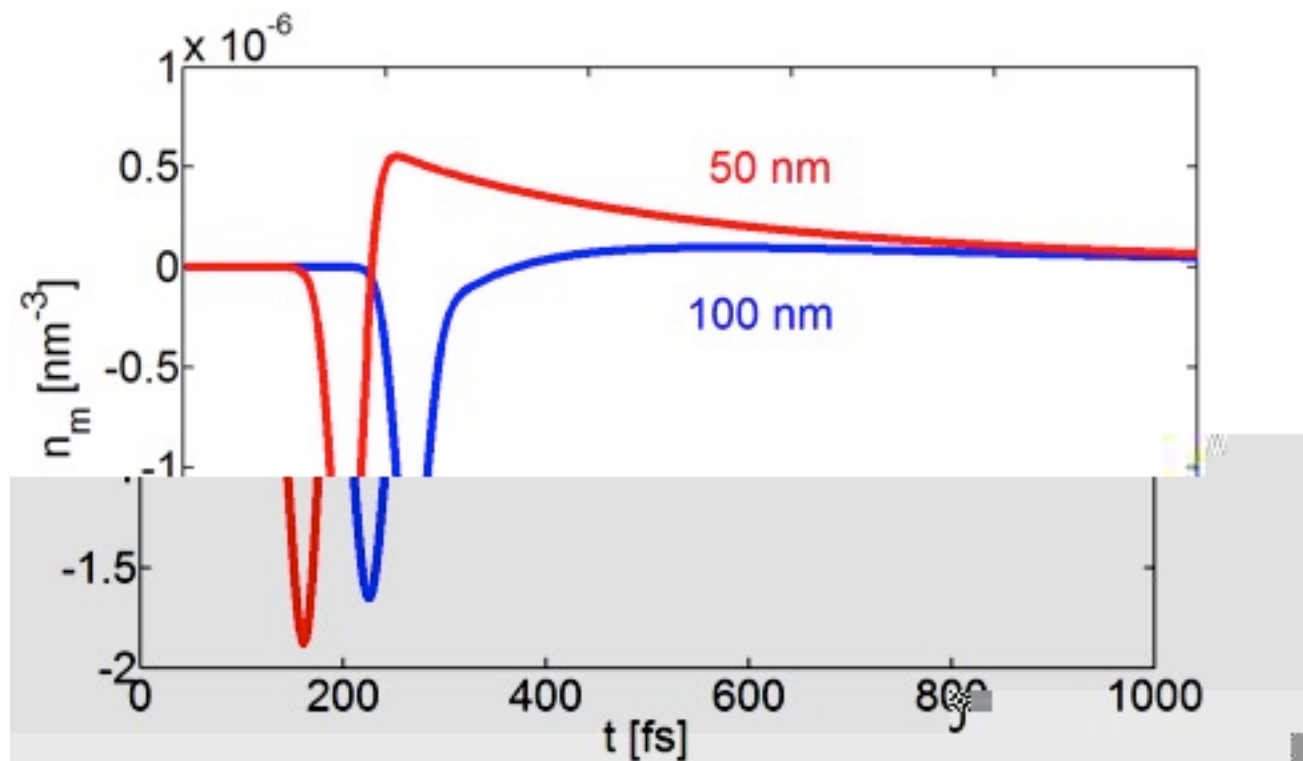
D D a c



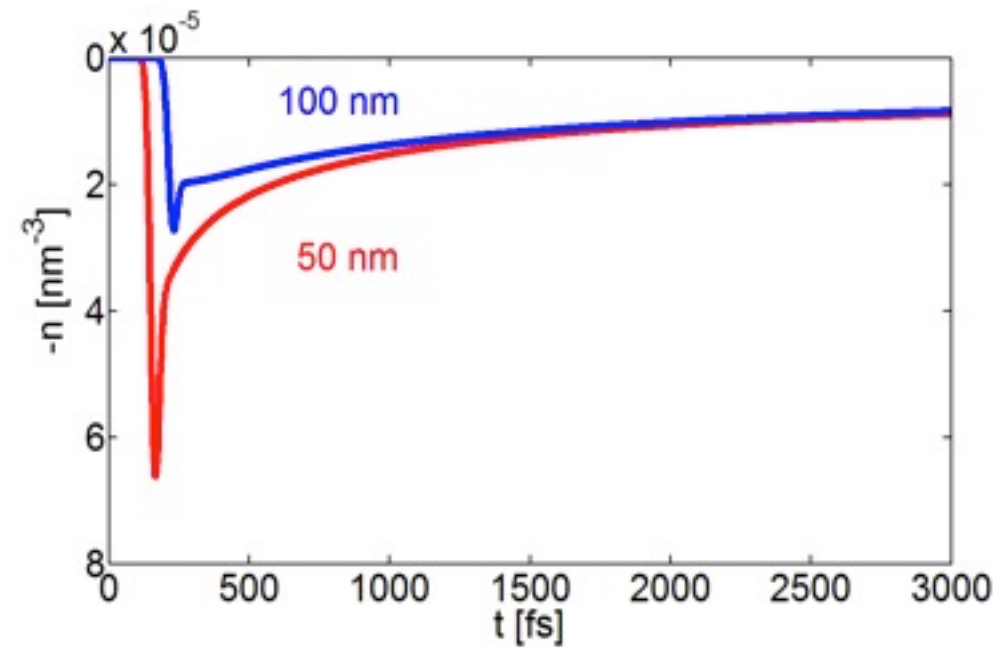
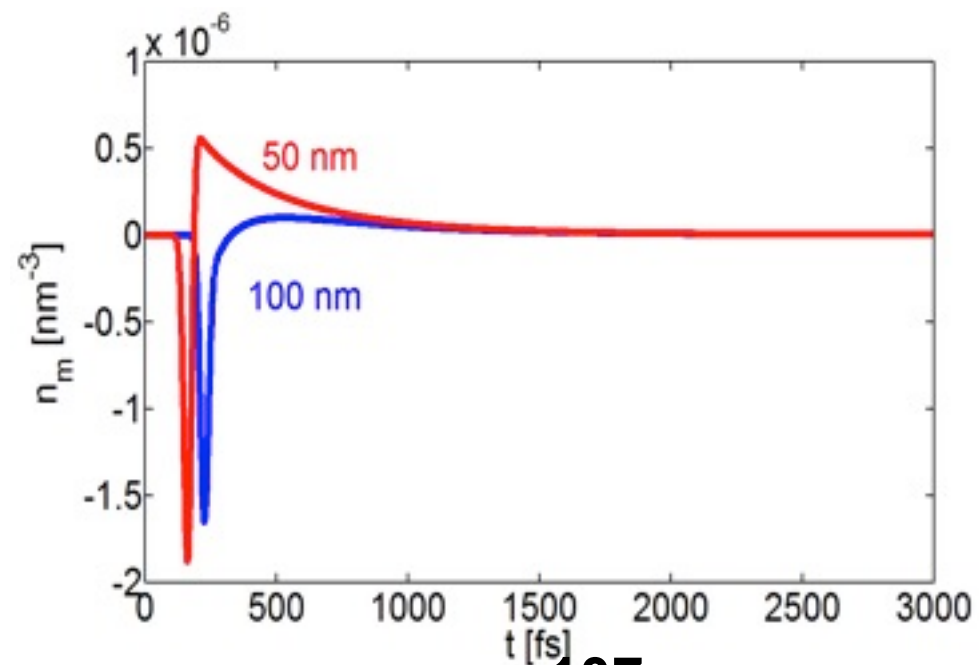
D a c a R B da



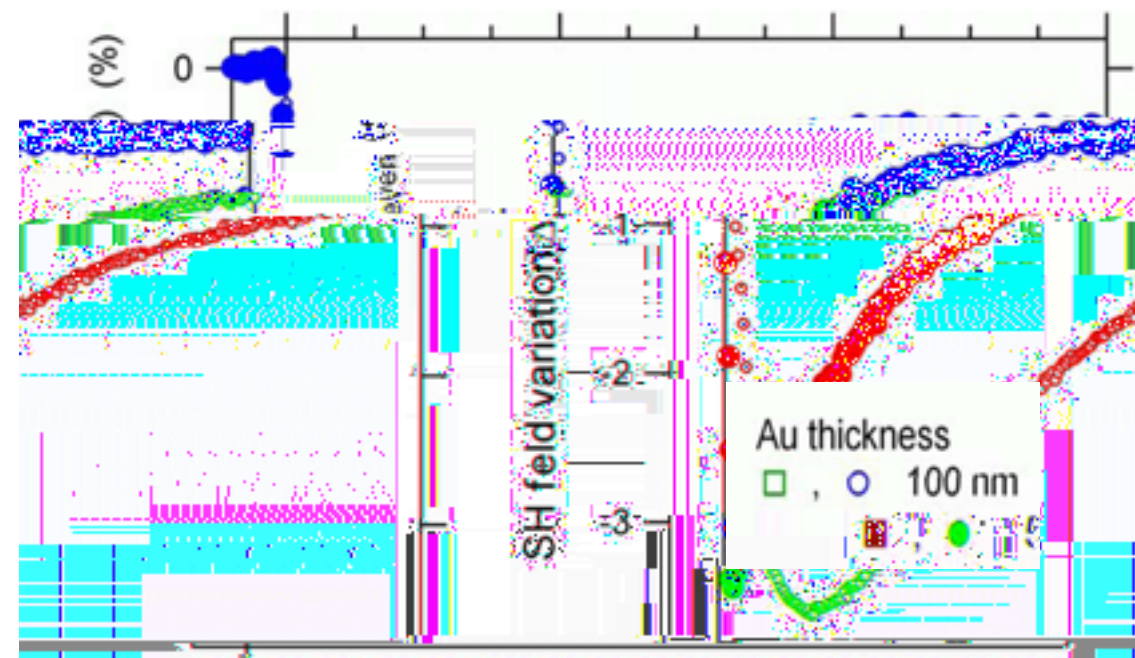
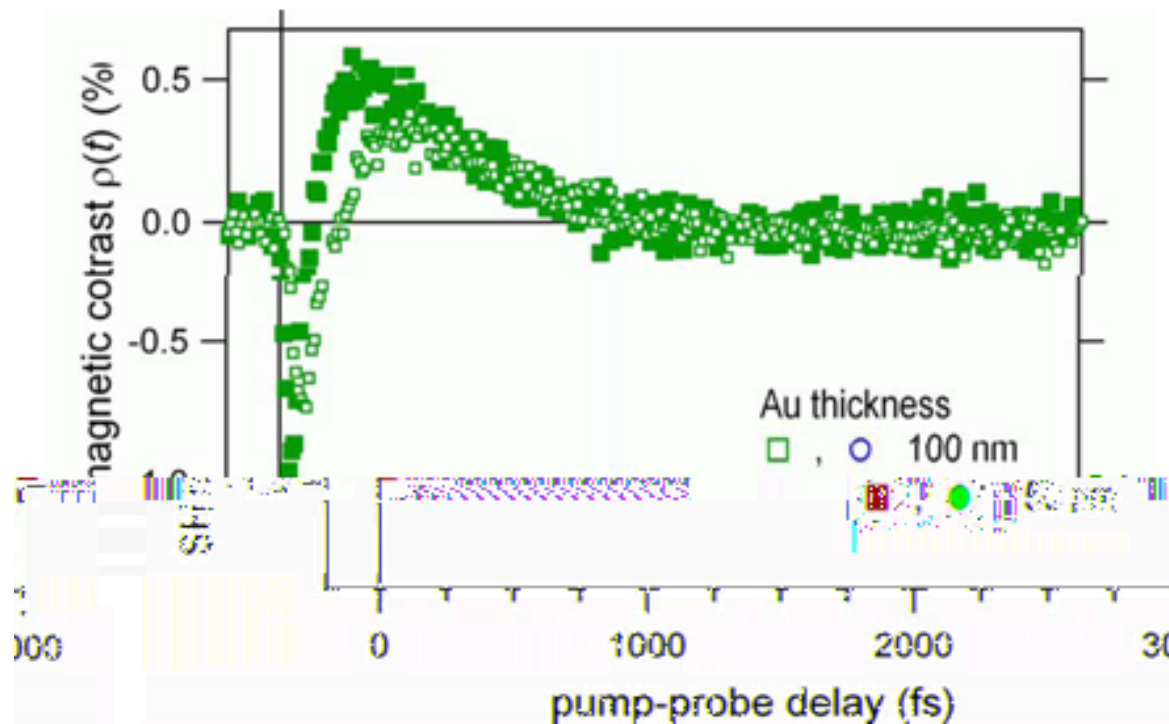
$$\tau_+ = 30 \text{ fs} \neq \tau_- = 31.5 \text{ fs}$$



S a d C a D a c : E . . T



107



C c

(2) °

