Neravnovesna dinamika koreliranih sistemov

Janez Bonča[1,2]

L. Vidmar[2], D. Golež[2], P. Prelovšek[1,2], M. Mierzejewski[3],
S. A. Trugman[4], T. Tohyama[5], and S. Maekawa[6]

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[5]*Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
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Ljubljana, 21.3.2013

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Pregled

- **Motivacija** - meritve v sistemih izven ravnovesja
- **Model Holsteina:** dinamika polarona pod vplivom električnega polja
- **Model *t-J*:** ena in dveh vrzeli pod vplivom električnega polja v **2D**
- **Model *t-J*-Holstein:** ena vrzel pod vplivom električnega polja v **2D**
- **Zaključki**

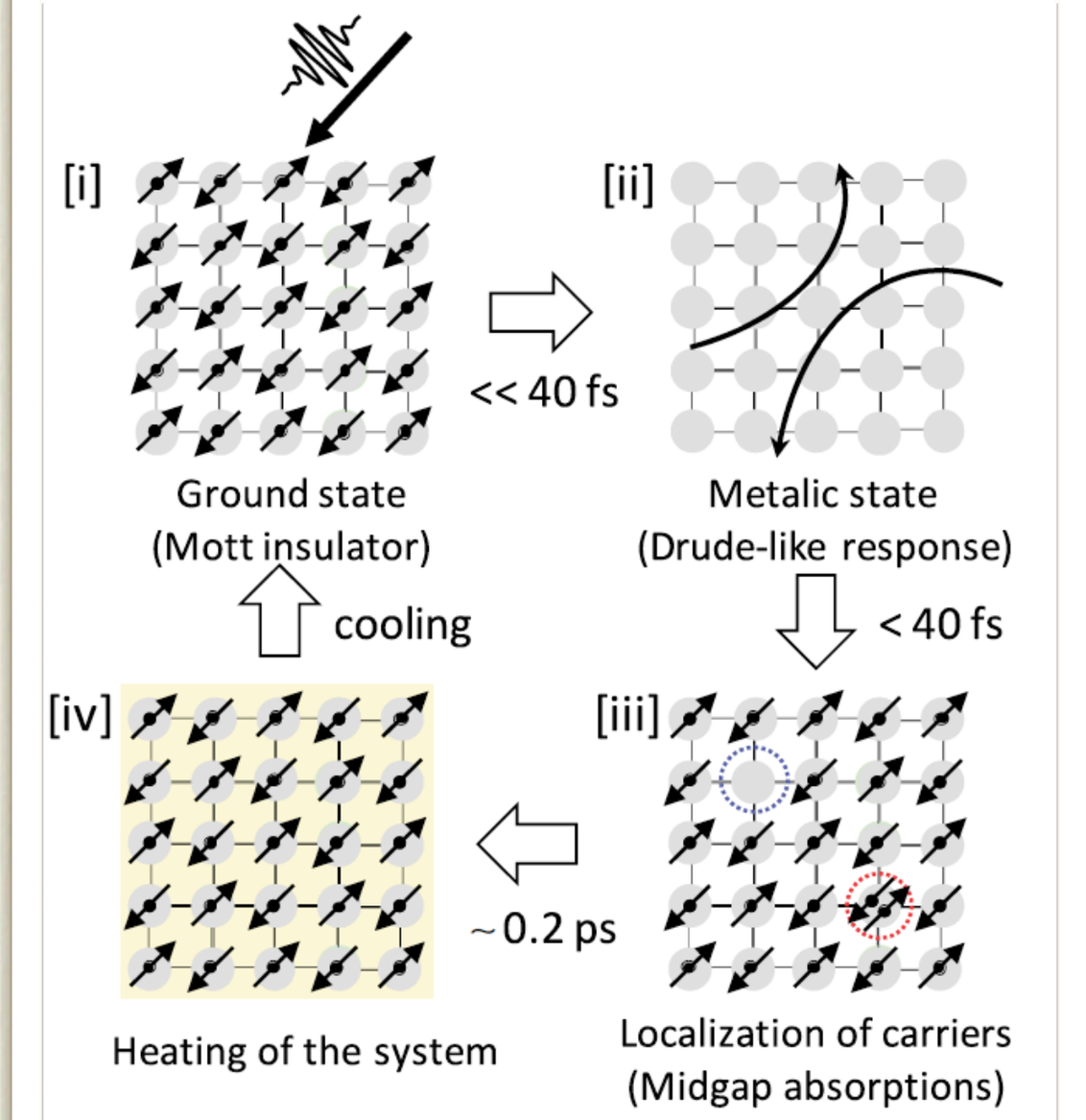
Uvod

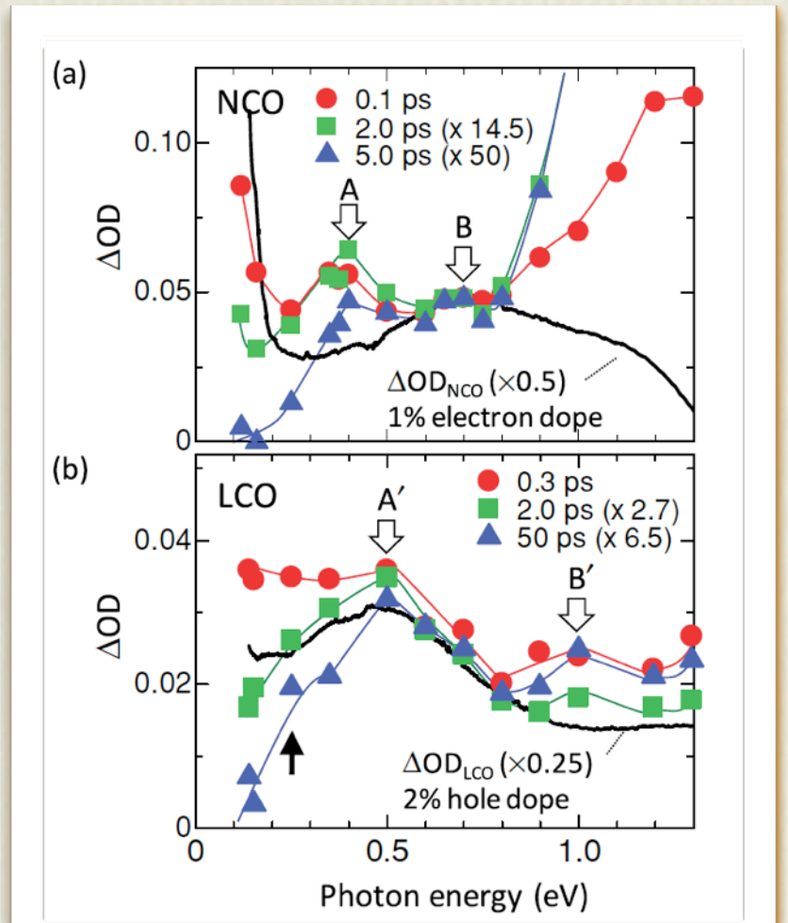
- Neravnovesni odziv sklopljenih več-delčnih elektronskih sistemov
  - ultra-hitra optična spektroskopija
  - časovno odvisne meritve na optičnih rešetkah
  - časovno odvisna fotoemisija
  - teoretični izziv - fundamentalni problemi, razvoj novih numeričnih ter analitičnih metod

Numerične metode za časovno propagacijo večdelčnih kvantnih sistemov

- točna diagonalizacija (T. Oka, *et al*., PRL (2003))
- časovno-odvisna metoda numerične renormalizacijske grupe z uporabo gostotnih matrik (DMRG) (1D) (White & Feiguin, PRL (2006))
- neravnovesna metoda dinamičnega povprečnega polja (neskončno dimenzij) (Freericks, *et al.*, PRL (2006))
- Lindbladova enačba (Prosen, Pižorn PRL (2008) z uporabo DMRG (Prosen, Žnidarič PRL (2010))
- diagonalizacija v omejenem funkcijskem prostoru Vidmar, *et al.* PRB (2011), Vidmar, *et al.* PRL (2011), Mierzejewski, *et al. 2x*PRL (2011), Golež, *et al.* PRL (2012), Bonča, *et al.* PRL (2012)

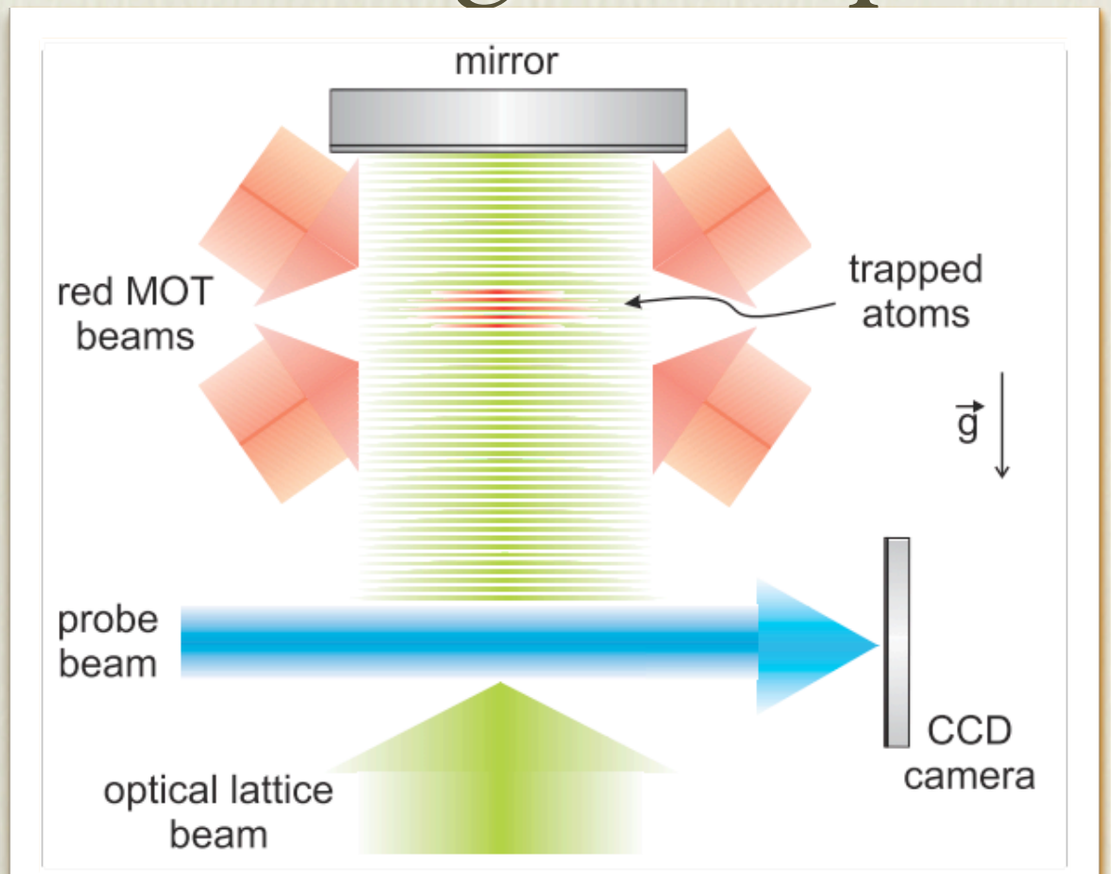
Foto-induciran prehod med Mottovim izolatorjem ter kovino

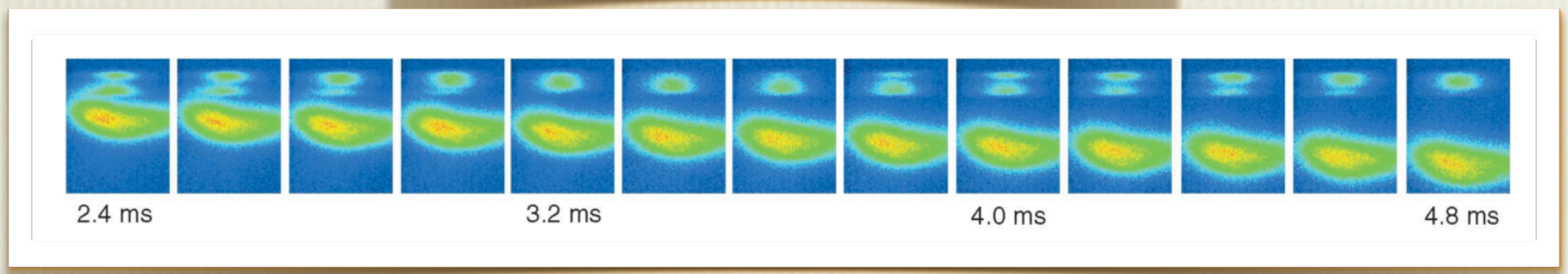




Okamoto *et al.* PRB **83**, 125102 (2011)

Blochove oscilacije Sr ultra hladnih atomov v magneto-optični pasti





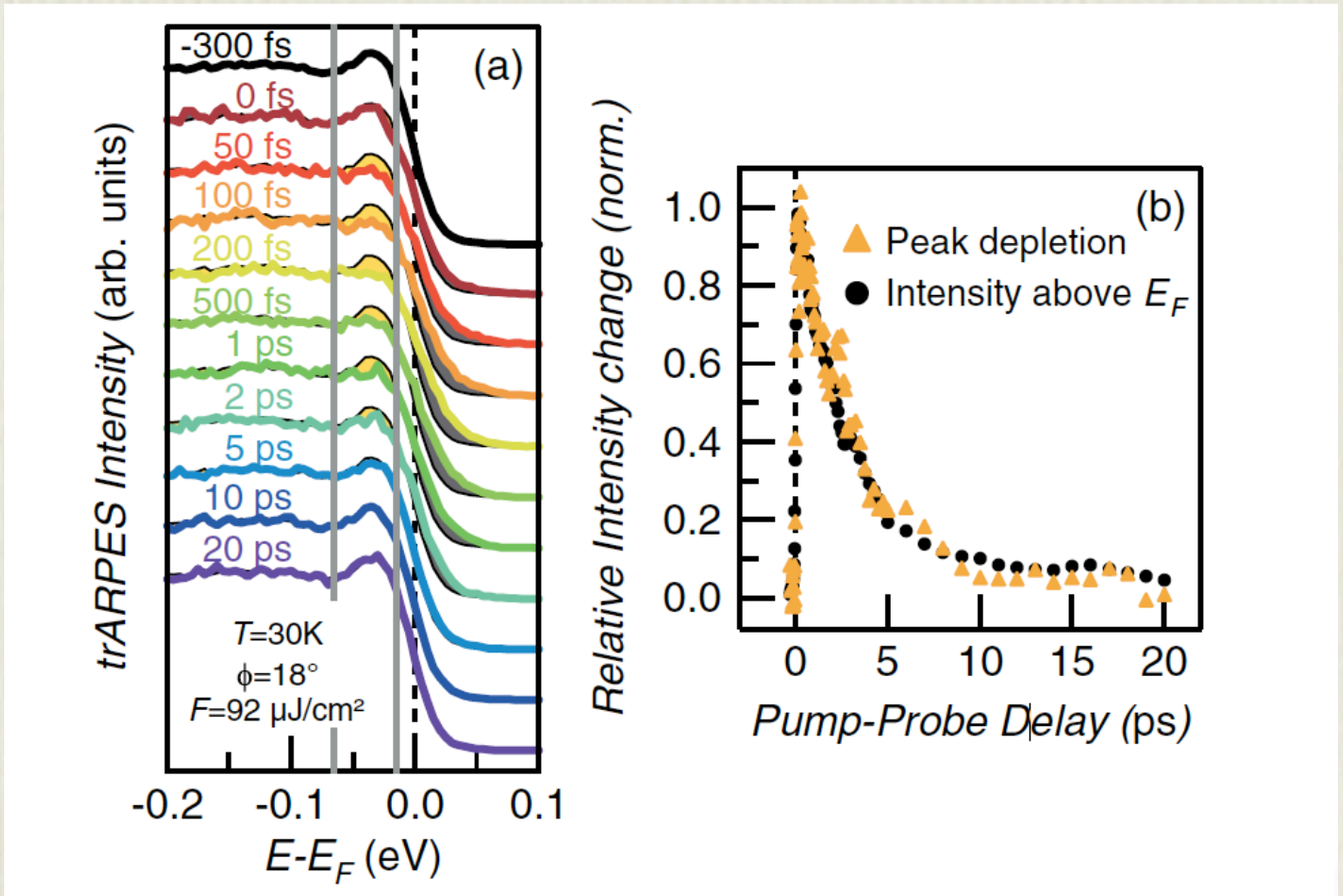
Ferrari *et al.* PRL **97**, 060402 (2006)

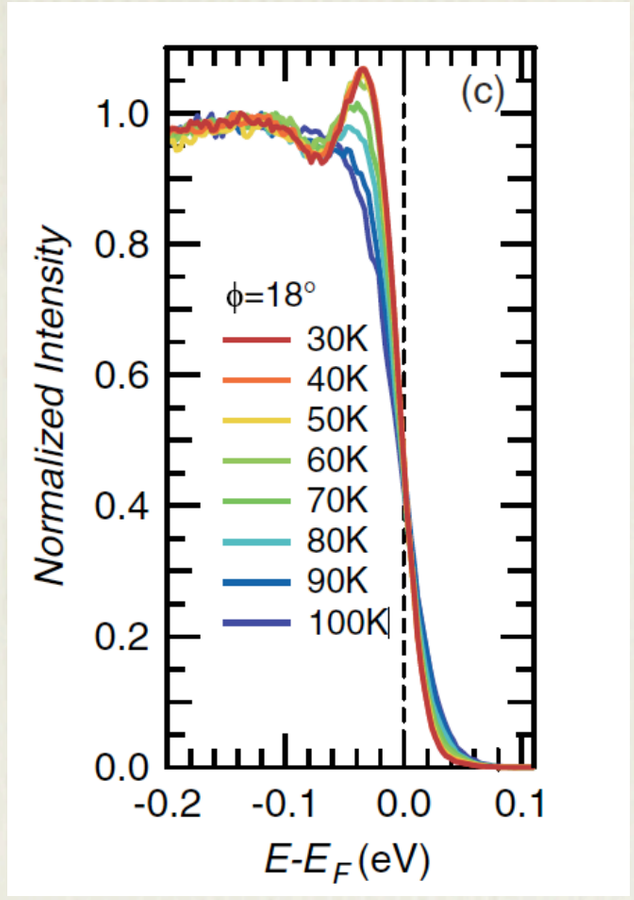
Bloch oscillations

$$\begin{aligned}
\hbar\frac{dk}{dt} &= -eE \\
k(t) &= k(0) - \frac{eE}{\hbar}t \\
v(k) &= \frac{1}{\hbar}\frac{d\epsilon}{dk} \\
\epsilon(k) &= -2t_0 \cos ka \\
v(k) &= \frac{2t_0 a}{\hbar}\sin ka \\
x(t) &= \int v(k(t))dt = \frac{2t_0}{eE}\cos\left(\frac{aeE}{\hbar}t\right) \\
t_B &= \frac{h}{aeE}; \quad x_B = \frac{2t_0}{eE}
\end{aligned}$$

Časovno odvisna foto emisija (meritev spektralnih lastnosti kvazidelcev)

Bi-2212, Tc=88K





Cortez *et al.*, PRL, **107**, 097002 (2011)

Elektron v električnem polju sklopljen z mrežnimi nihanji

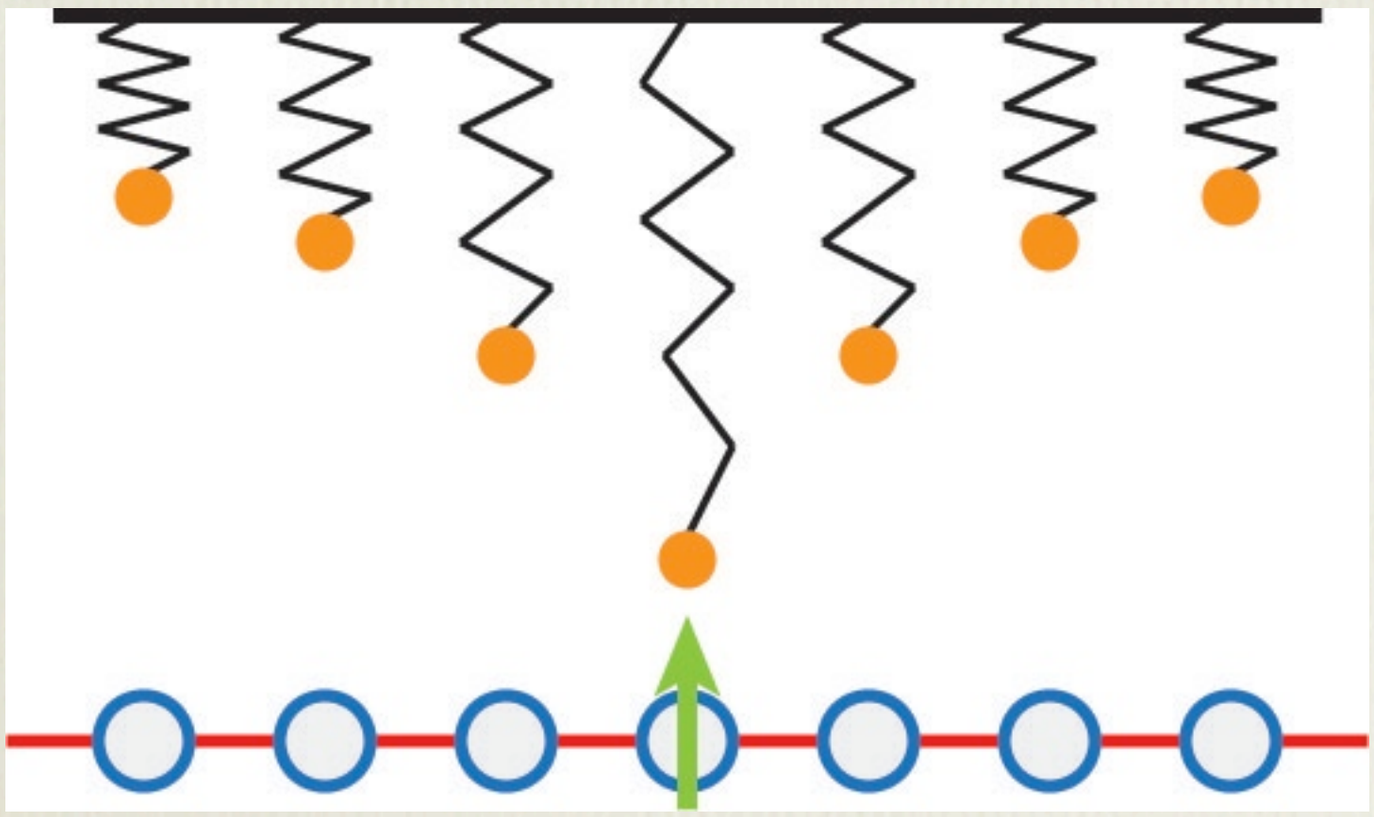
$$\begin{aligned} H &= -t_0 \sum_l (e^{i\theta(t)} c_l^\dagger c_{l+1} + \text{H.c.}) \\ &+ g \sum_i n_i (a_i^\dagger + a_i) + \omega_0 \sum_i a_i^\dagger a_i, \end{aligned}$$

Phase: $$\theta(t) = 2\pi \frac{e_0}{h} \int_{r_l}^{r_{l+1}} \mathbf{A} \mathrm{d}\mathbf{s} = -Ft$$

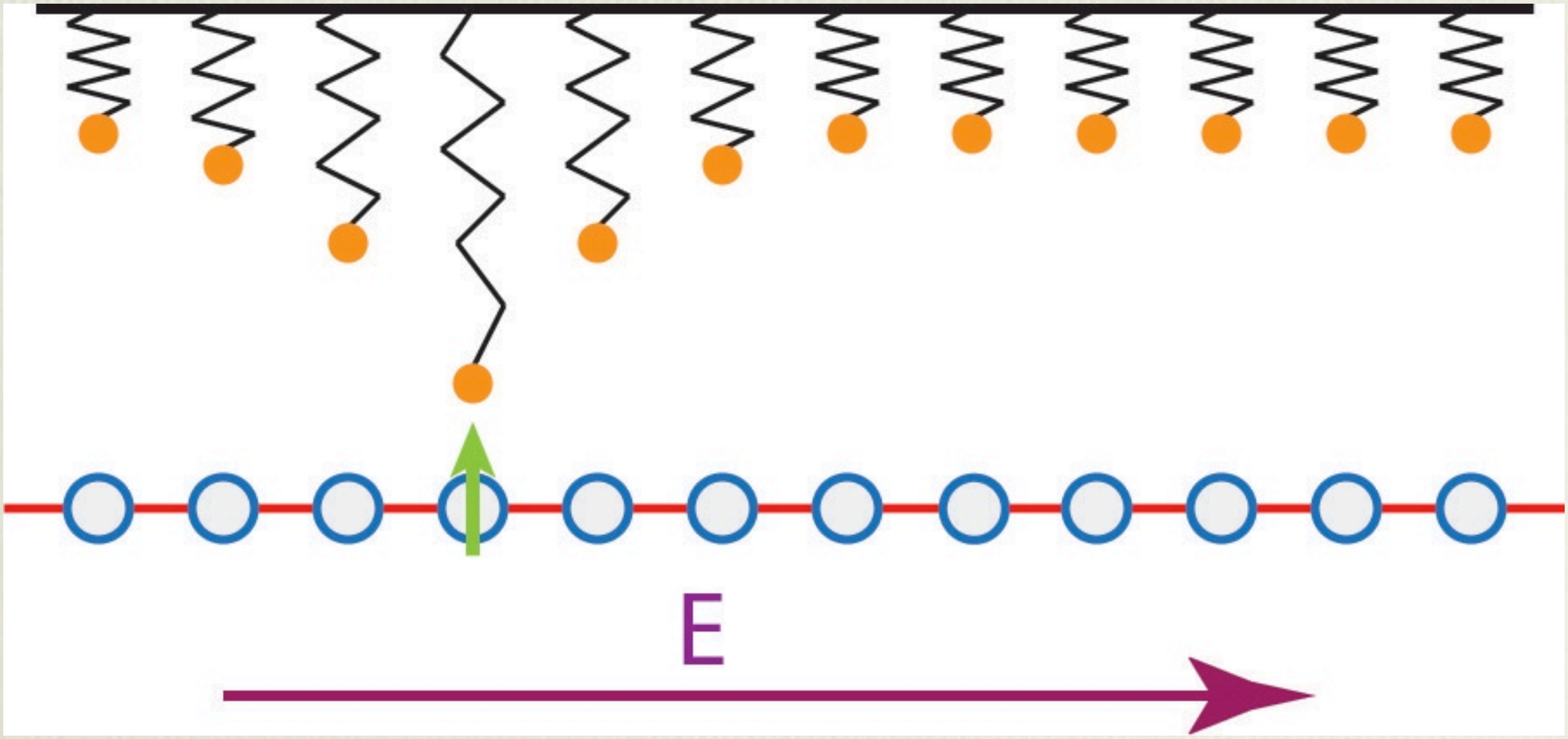
Units: $$F[t_0/e_0 a], t[\hbar/t_0], a = e_0 = \hbar = t_0 = 1$$

Elektron v električnem polju sklopljen z mrežnimi nihanji

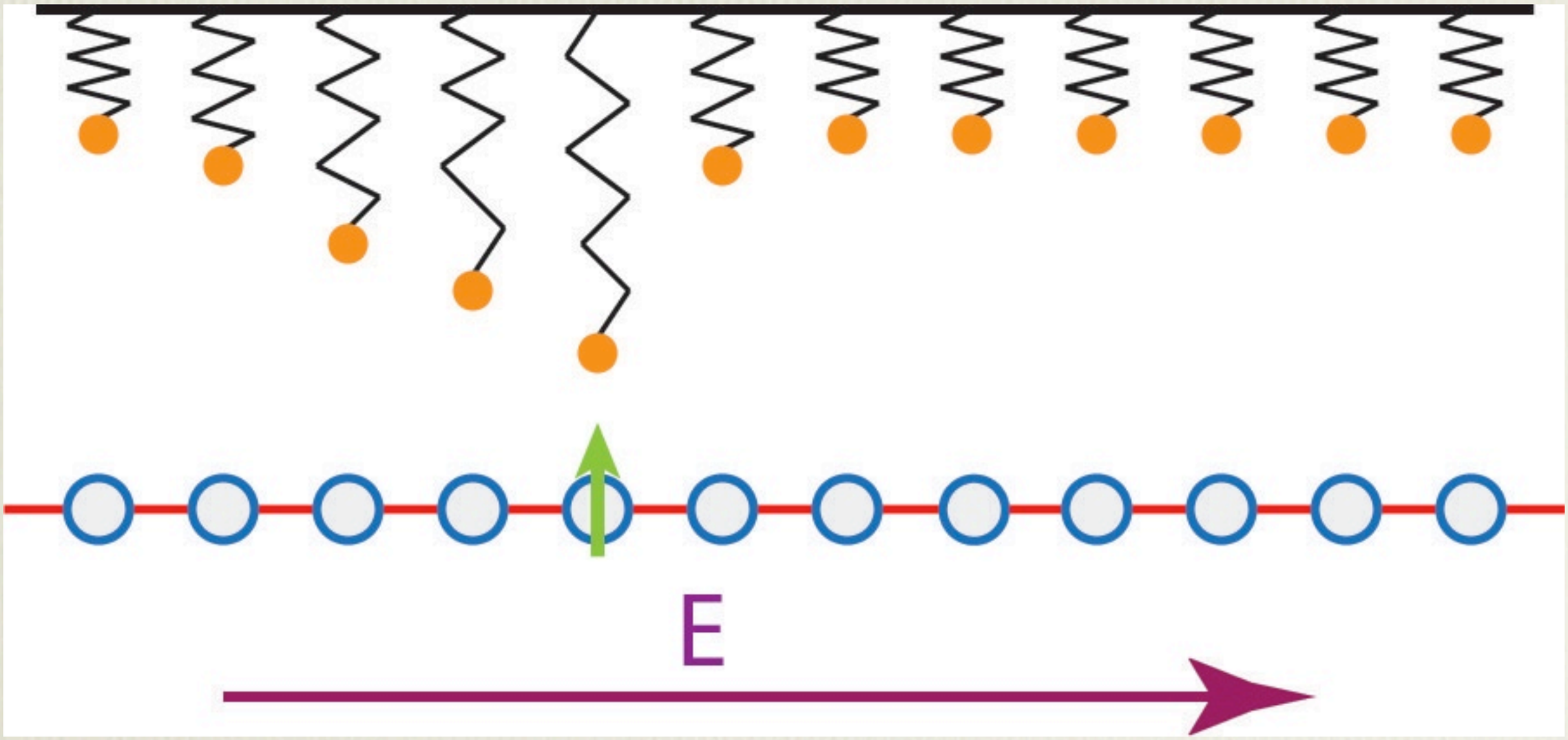
$$
\begin{aligned}
H &= -t_0 \sum_l (e^{i\theta(t)} c_l^\dagger c_{l+1} + \text{H.c.}) \\
&+ g \sum_i n_i (a_i^\dagger + a_i) + \omega_0 \sum_i a_i^\dagger a_i,
\end{aligned}
$$



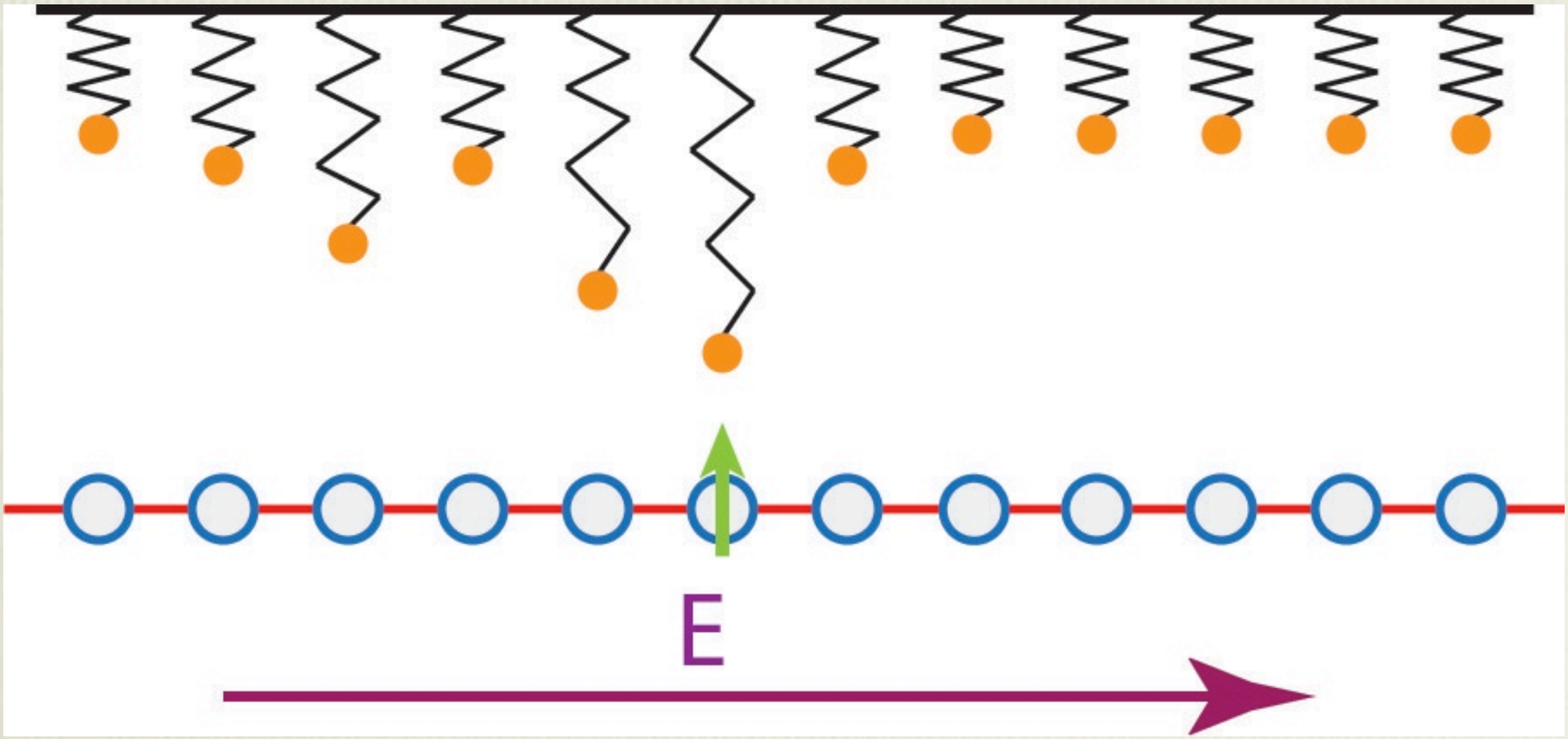
Vključimo električno polje



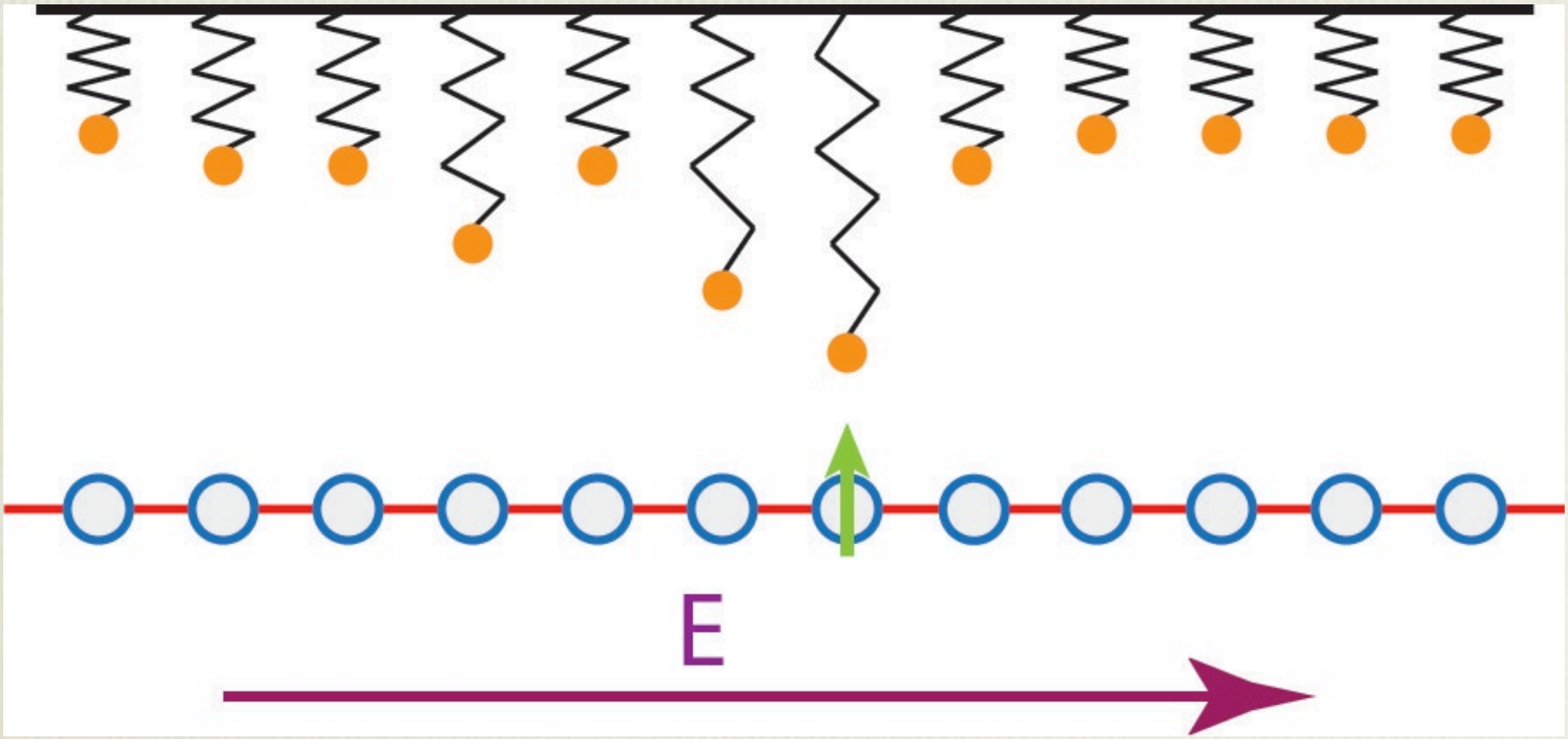
Vključimo električno polje



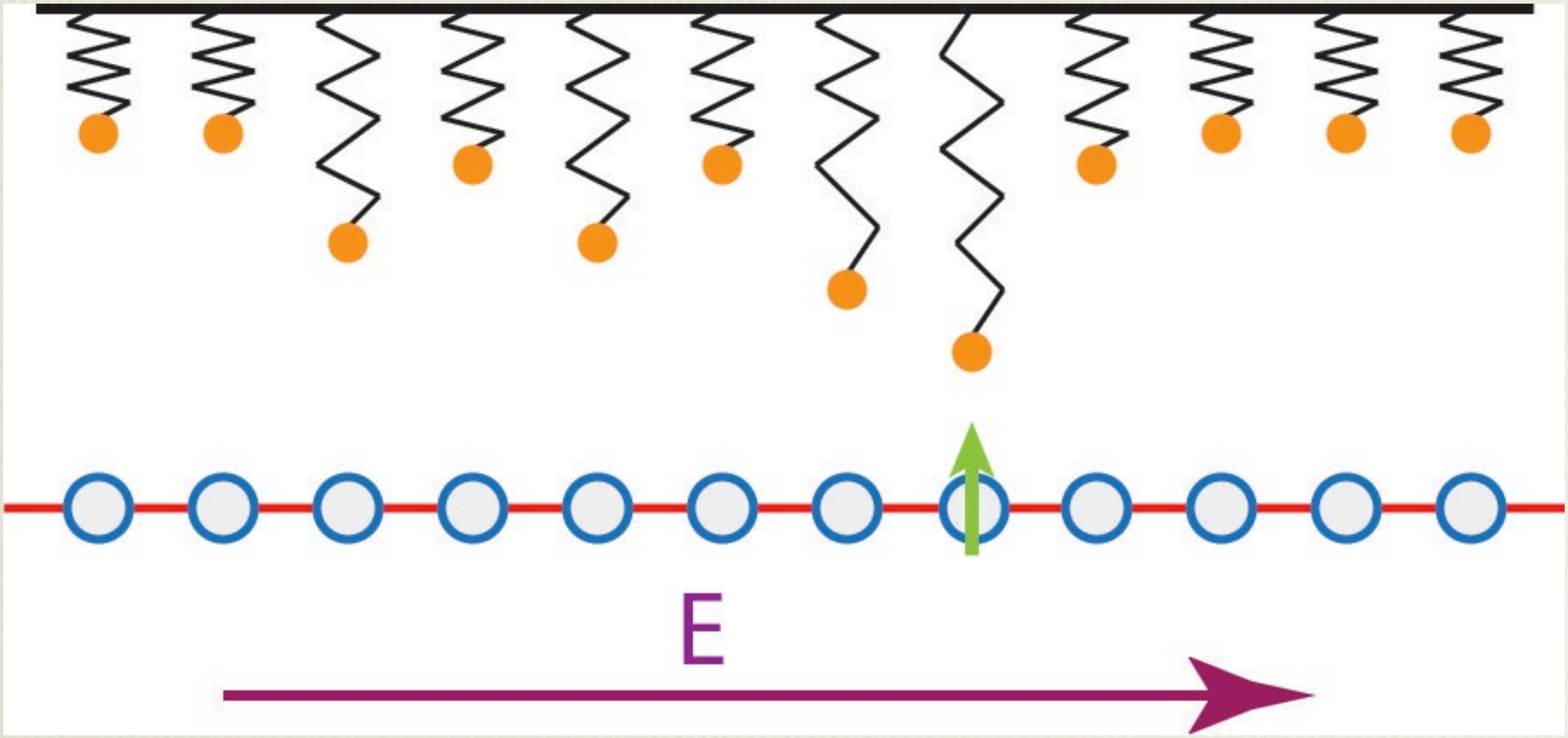
Vključimo električno polje



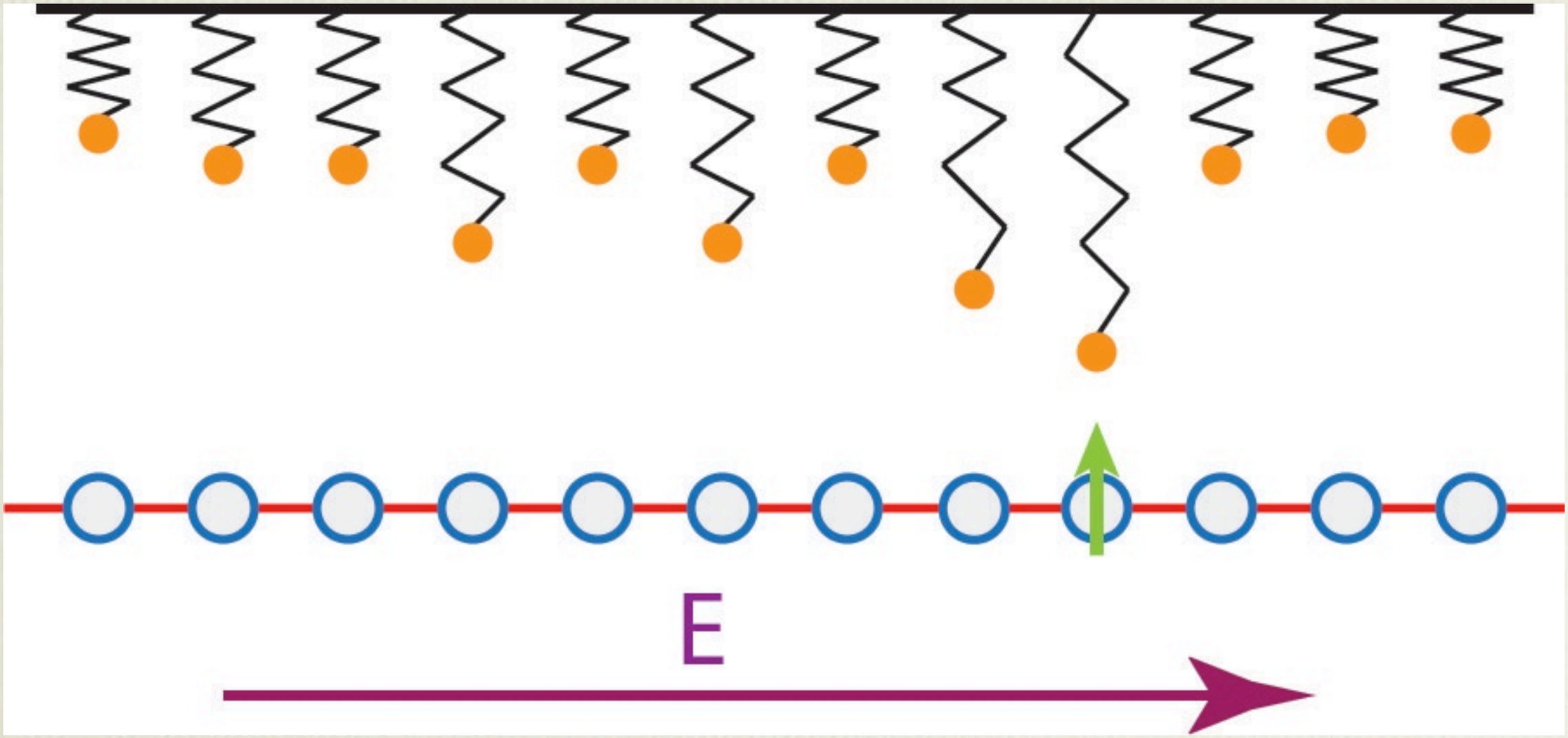
Vključimo električno polje



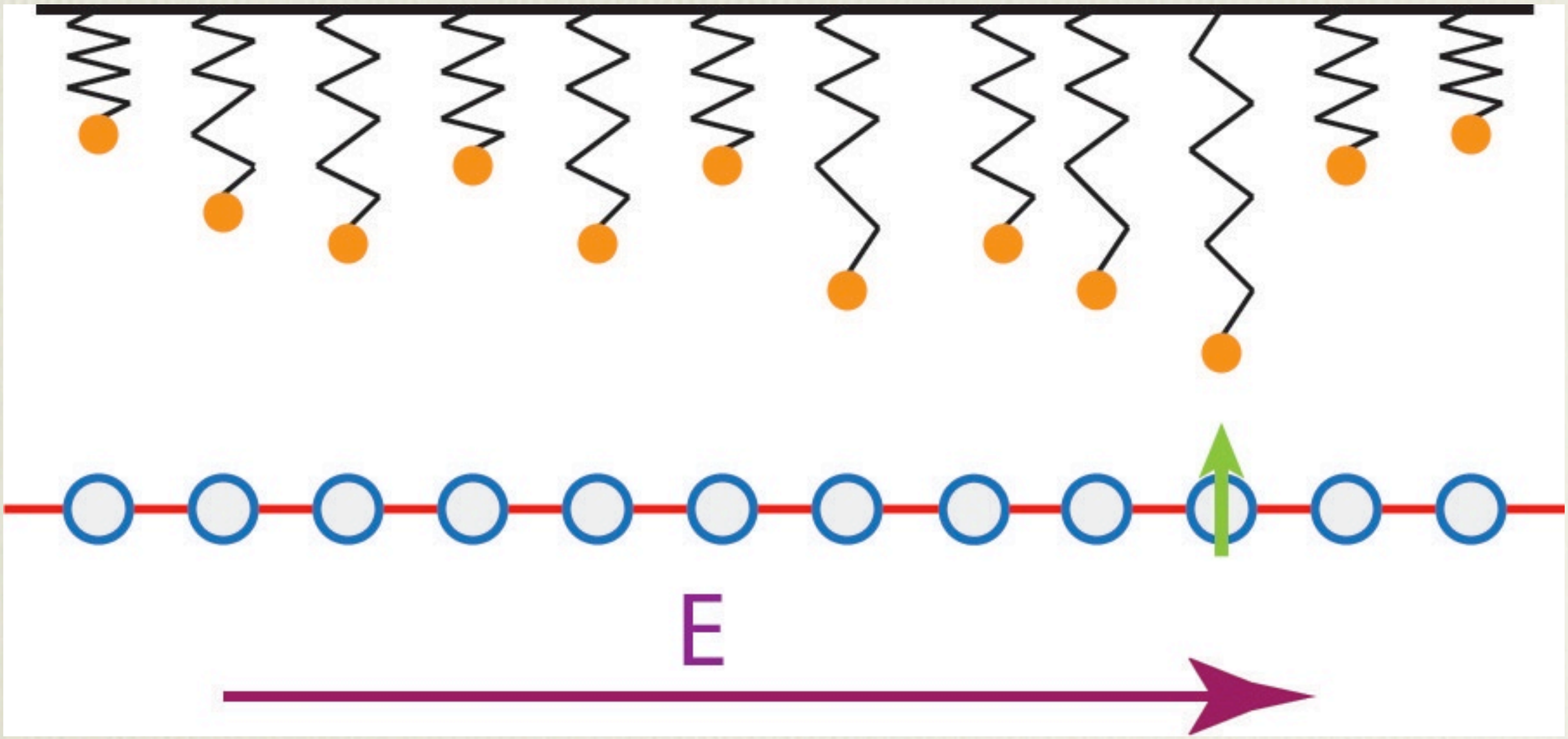
Vključimo električno polje



Vključimo električno polje



Vključimo električno polje



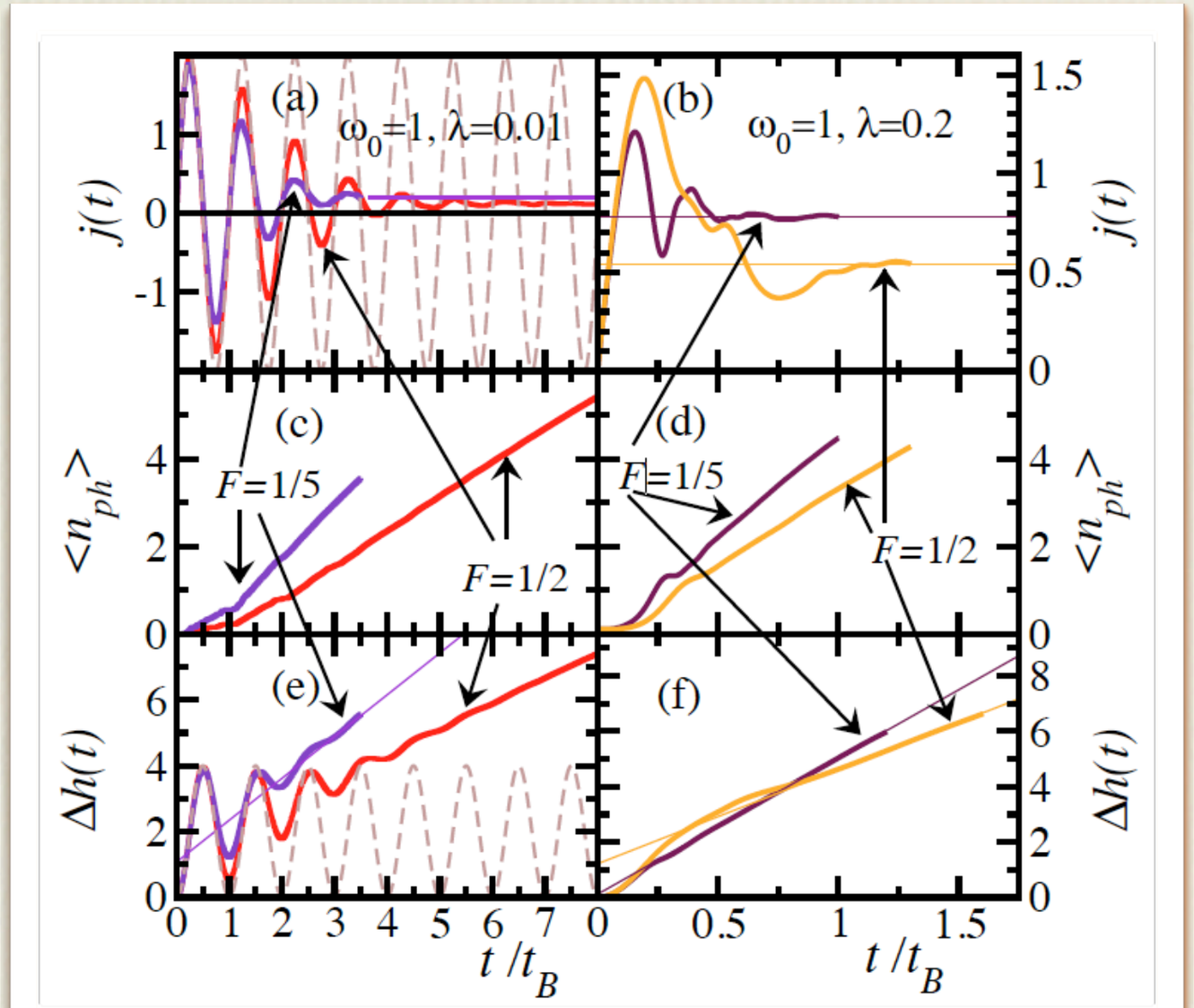
Časovni razvoj - numerično eksaktno

$$\hat{I}(t) = i\sum_l e^{-iFt} c_l^\dagger c_{l+1} - \text{H.c.},$$

$$j(t) = \langle \hat{I}(t) \rangle,$$

$$\bar{j} = \lim_{t\to\infty} j(t)$$

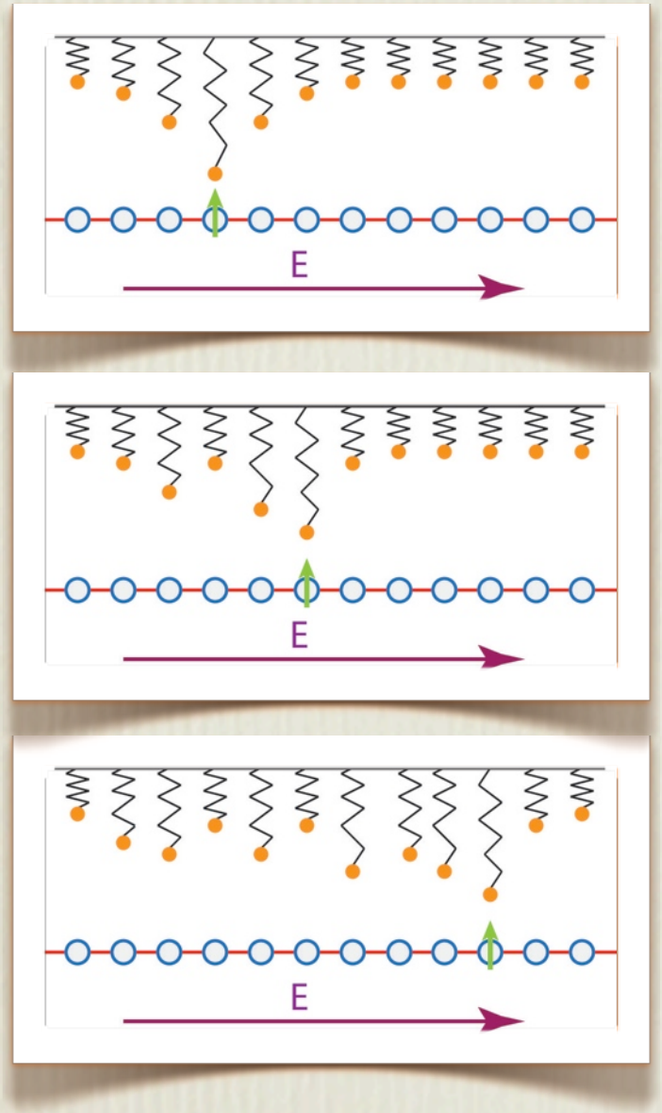
- dušene Blochove oscilacije λ=0.01
- vzpostavi se stacionarni električni tok tok!

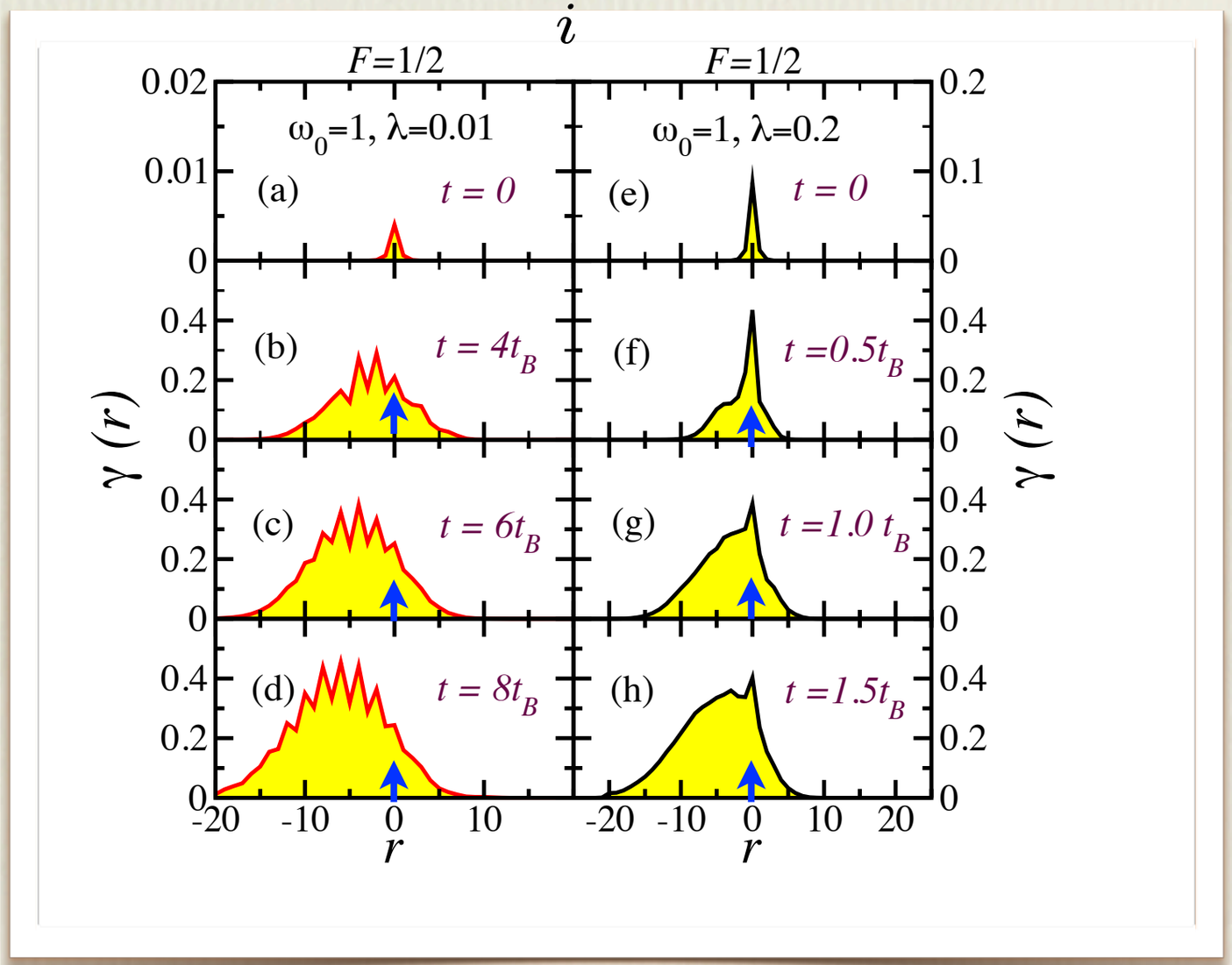


Lev Vidmar, J.B., M. Mierzejewski, P. Prelovšek, and S. A. Trugman, PRB **83**, 134301 (2011)

Časovni razvoj polarona pod vplivom električnega polja

$$\gamma(r) = \langle \sum_i n_i a^+_{i+r} a_{i+r} \rangle$$





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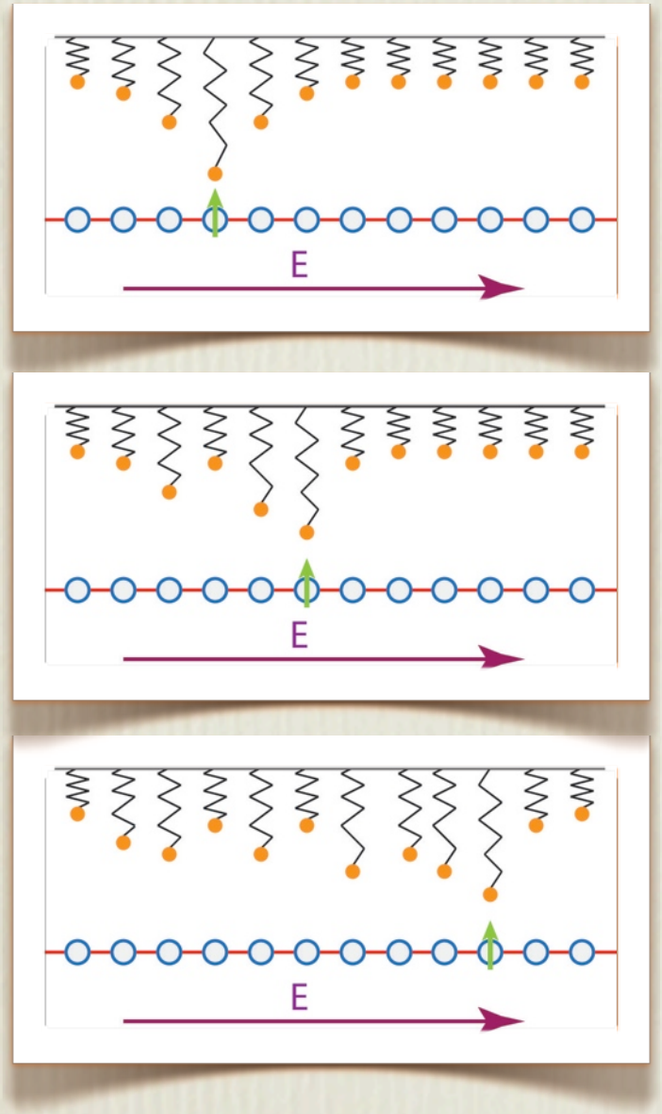
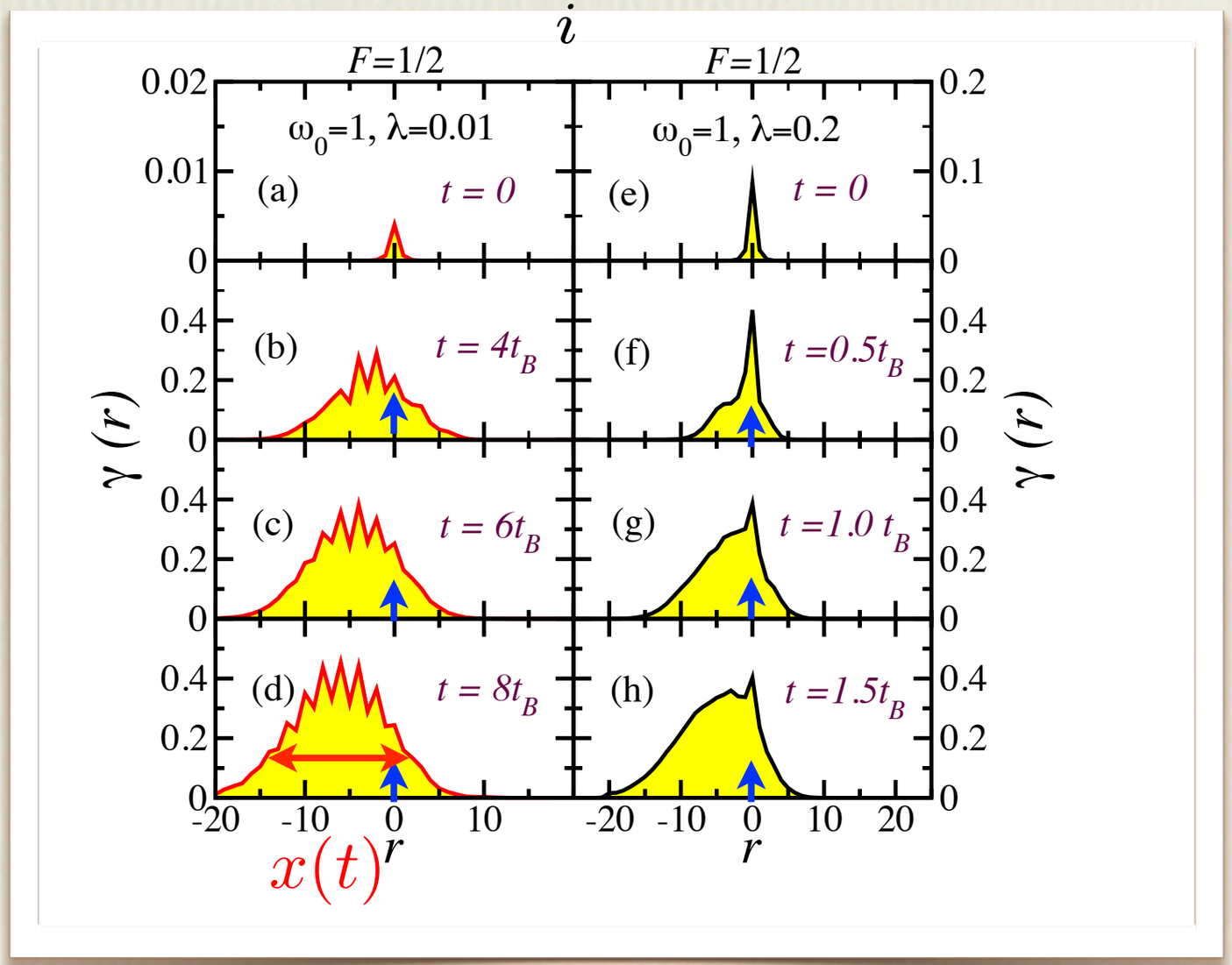
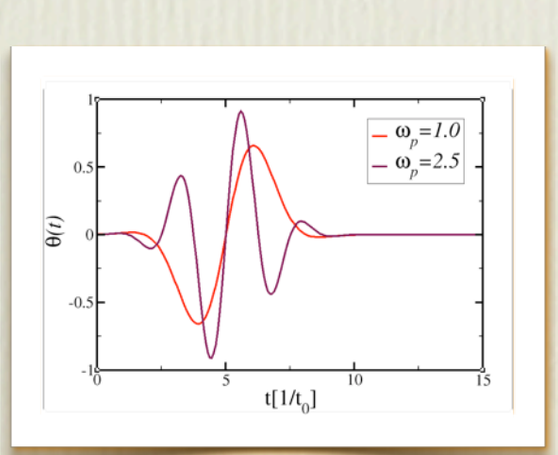


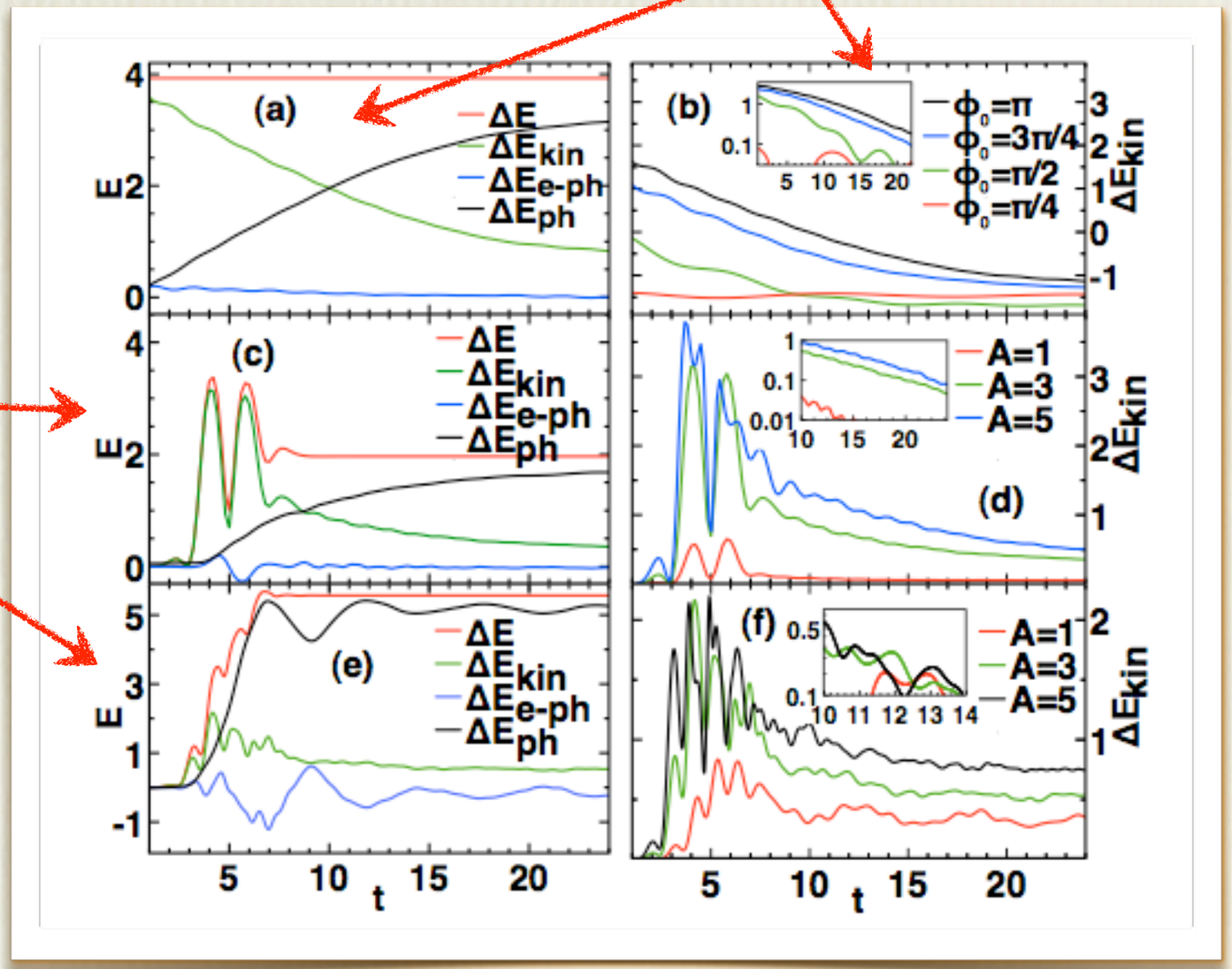


Lev Vidmar, J.B., M. Mierzejewski, P. Prelovšek, and S. A. Trugman, PRB **83**, 134301 (2011)

Relaksacija kinetične energije po pulzu E polja

$$H = H_{\mathrm{kin}} + H_{\mathrm{e-ph}} + H_{\mathrm{ph}} \quad F(t) = -\Phi_0 \delta(t); \quad \phi(t) = \Phi_0 \theta(t)$$

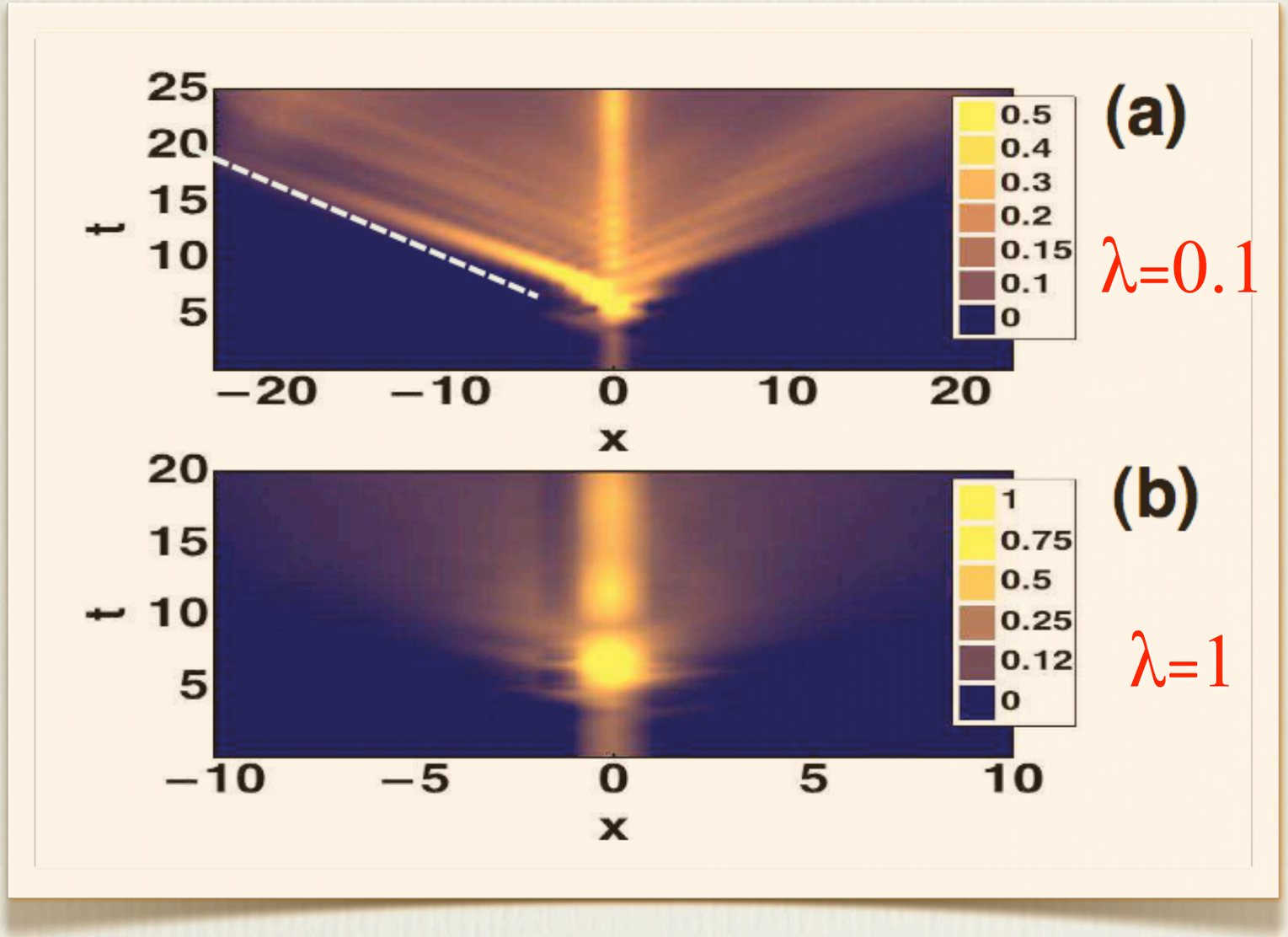




D. Golež, J.Bonča, L. Vidmar, and S.A. Trugman: Phys. Rev. Lett. **109**, 236402 (2012).

Elektronsko fononska korelacijska funkcija

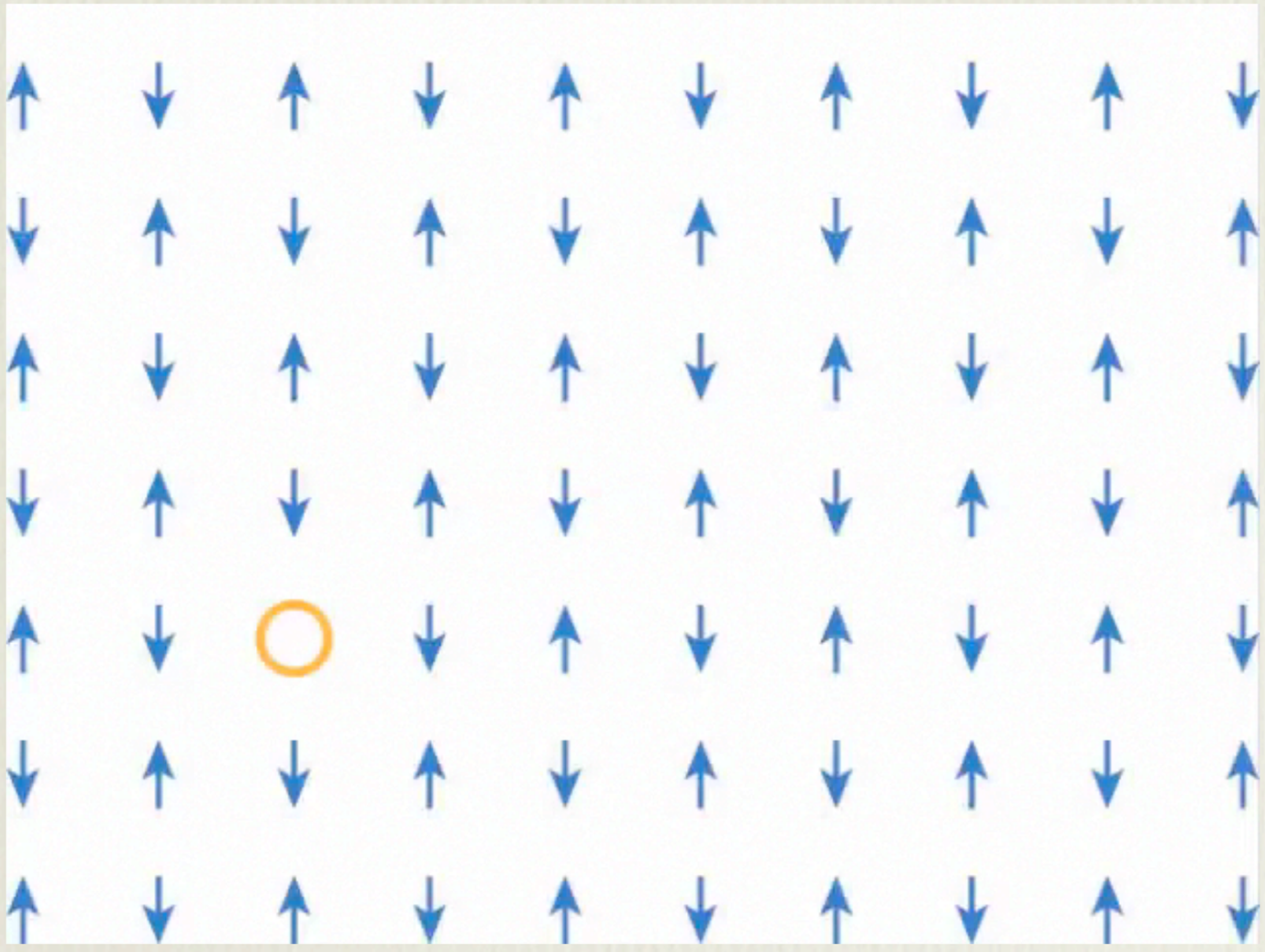
$$\gamma(x) = \langle \sum_i n_i a^\dagger_{i+x} a_{i+x} \rangle,$$



D. Golež, J.Bonča, L. Vidmar, and S.A. Trugman: Phys. Rev. Lett. **109**, 236402 (2012).

Model *t-J* z eno vrzeljo

$$H \quad = \quad -t_0 \sum_{\langle \mathbf{lj} \rangle, \sigma} \left[\mathrm{e}^{i \phi_{\mathbf{lj}}(t)} \; \tilde{c}^{\dagger}_{\mathbf{l},\sigma} \tilde{c}_{\mathbf{j},\sigma} + \mathrm{h.}c. \right] + J \sum_{\langle l,j \rangle} \mathbf{S_l} \mathbf{S_j},$$



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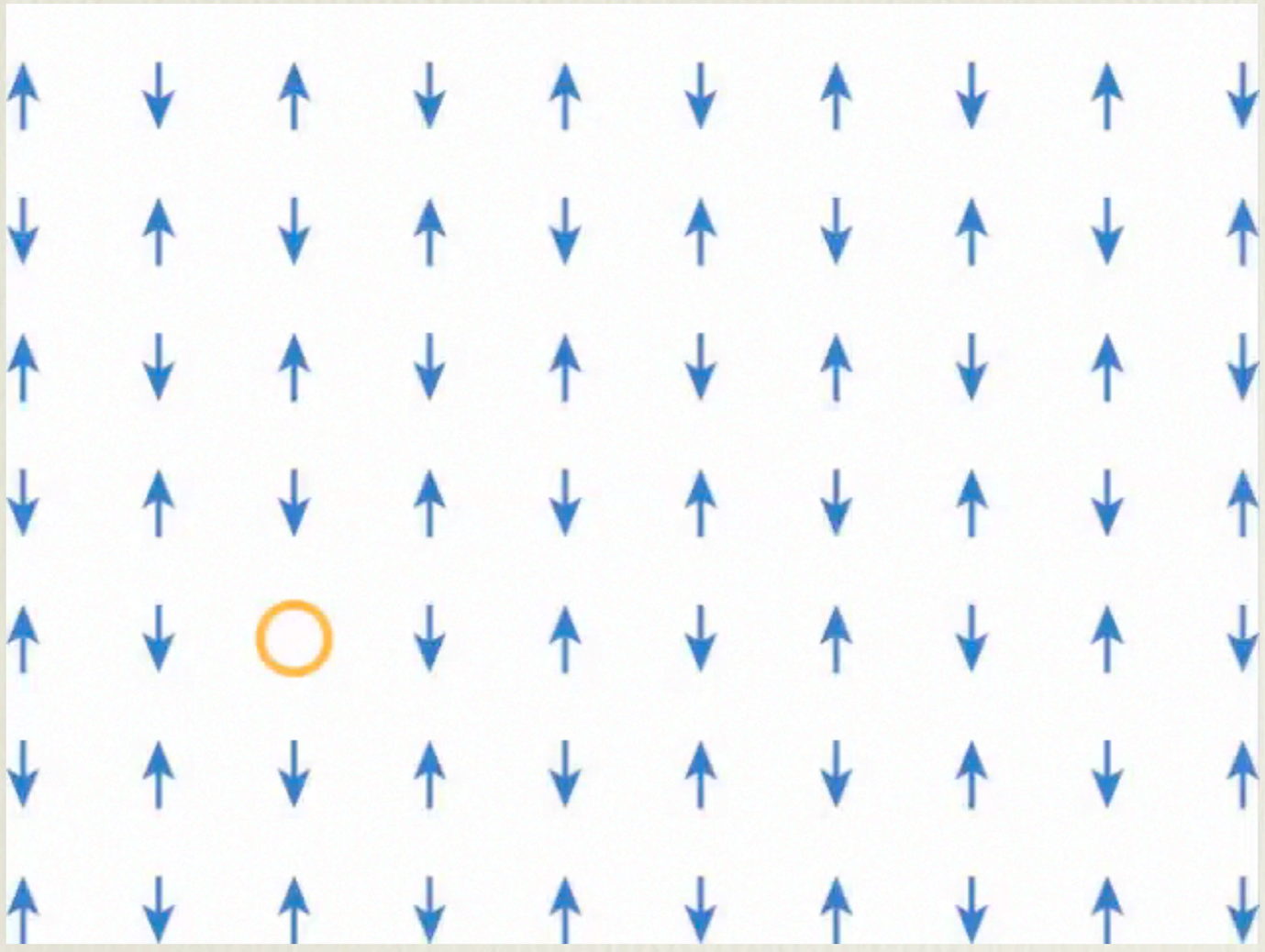

Model *t-J* z eno vrzeljo

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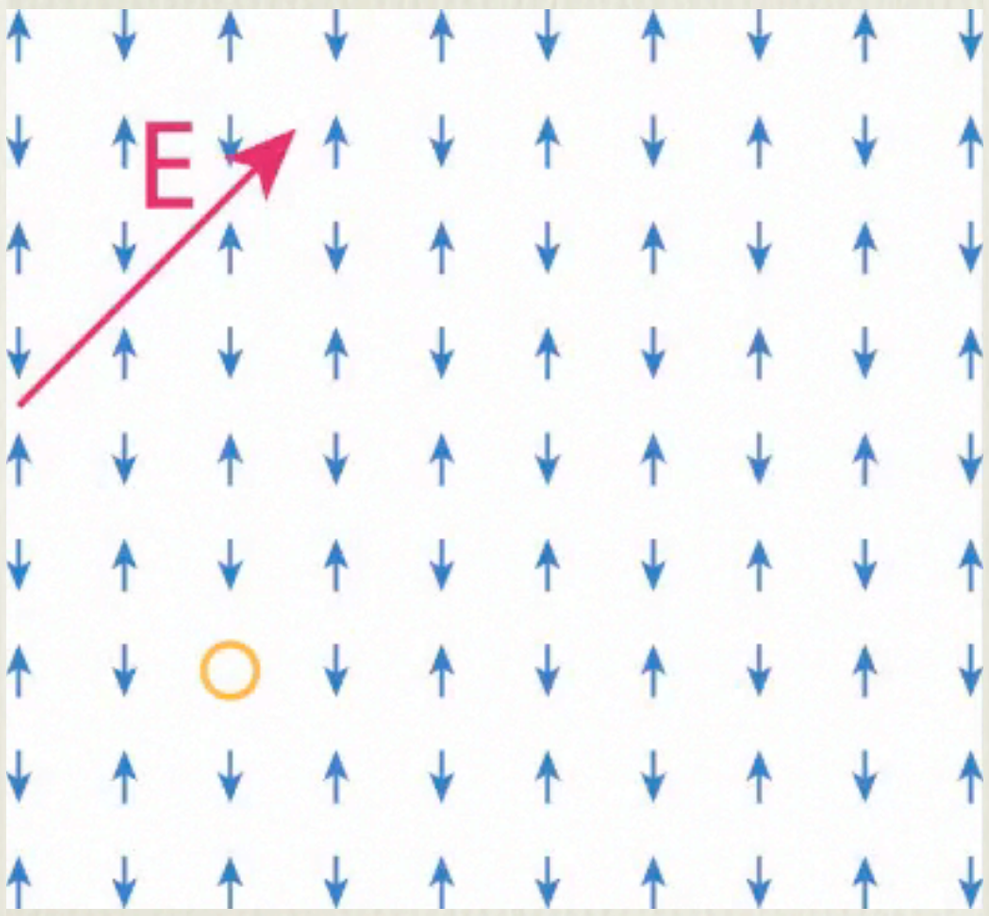
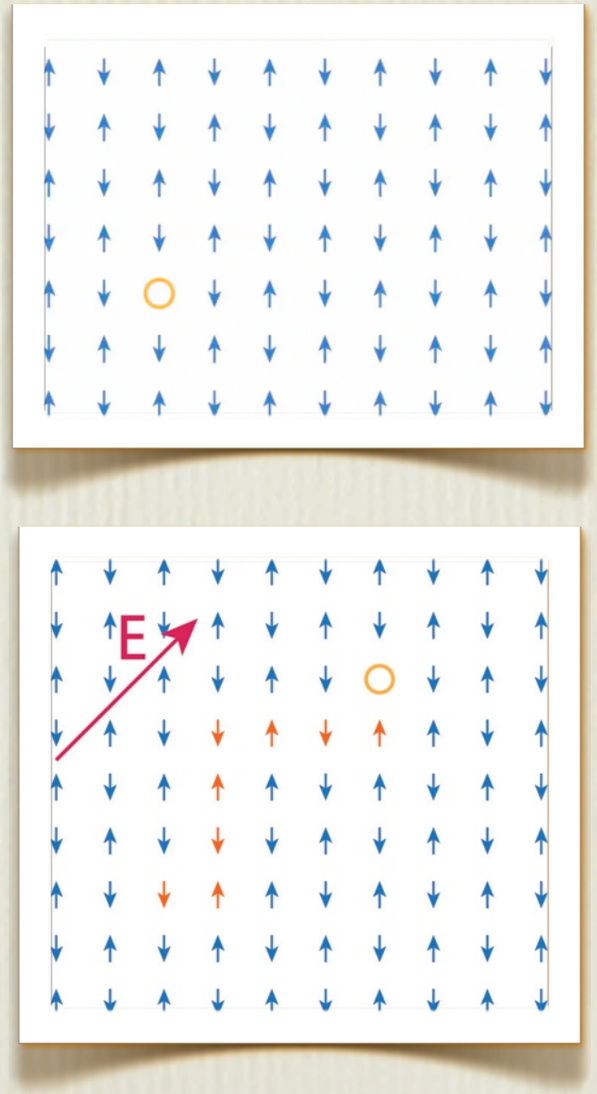
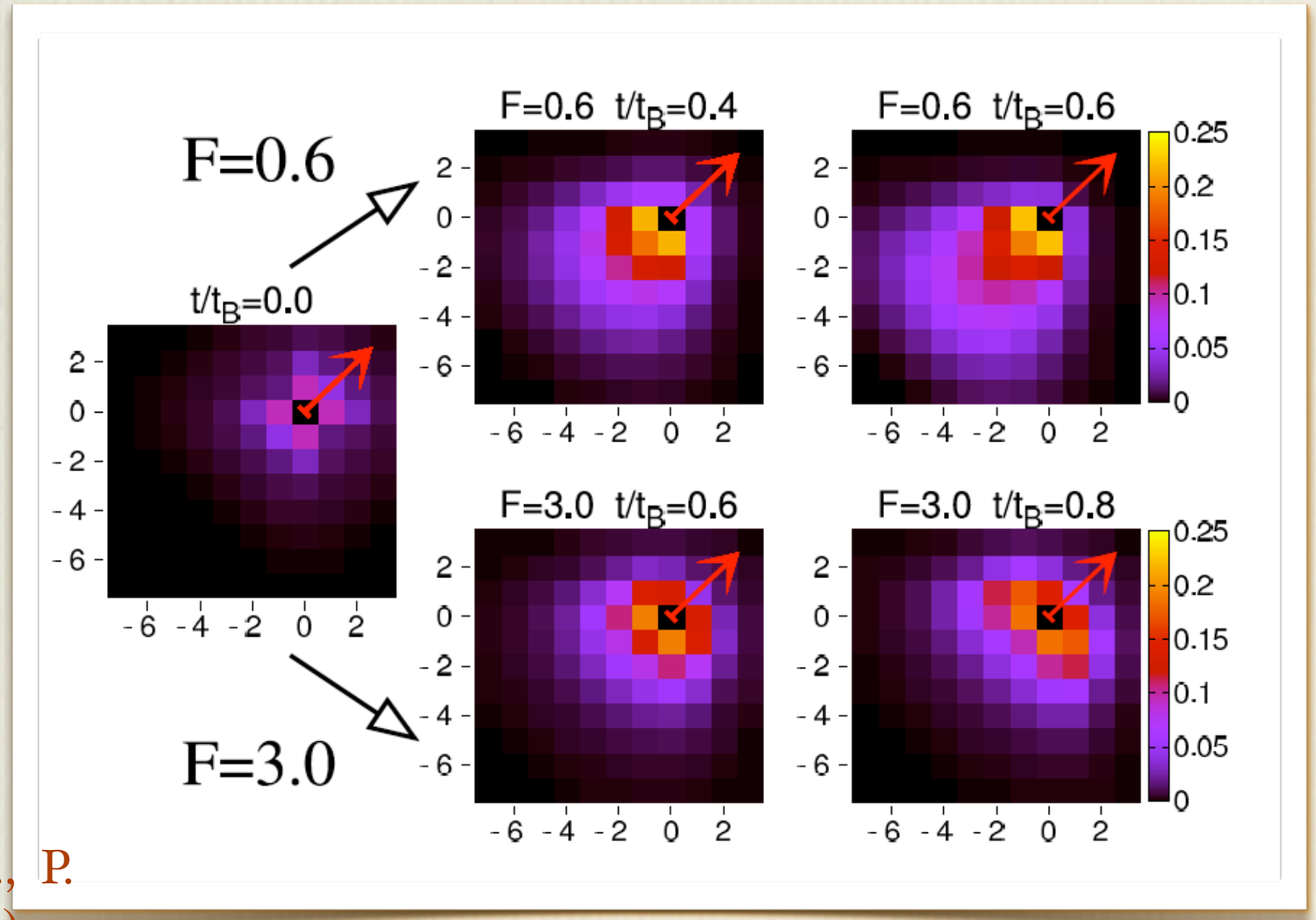


Spinski polaron pod vplivom zunanjega električnega polja

$$C(\mathbf{r}) = \sum_{\mathbf{i}} \langle n_{\mathbf{i}} \mid S^{z,\mathrm{Neel}}_{\mathbf{i}+\mathbf{r}} - S^{z}_{\mathbf{i}+\mathbf{r}} \mid \rangle$$

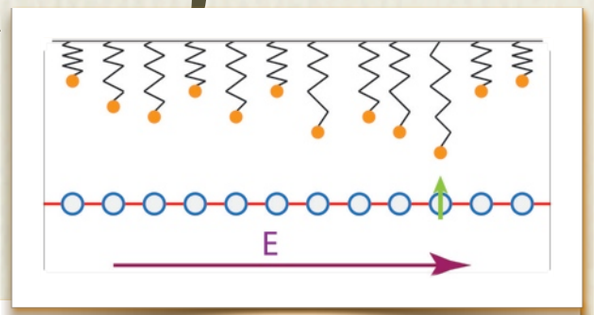


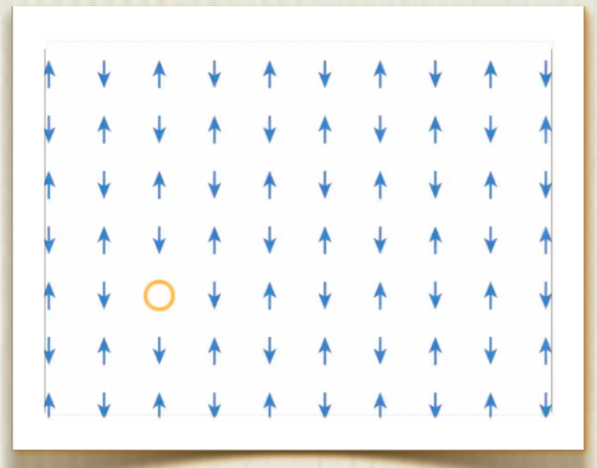


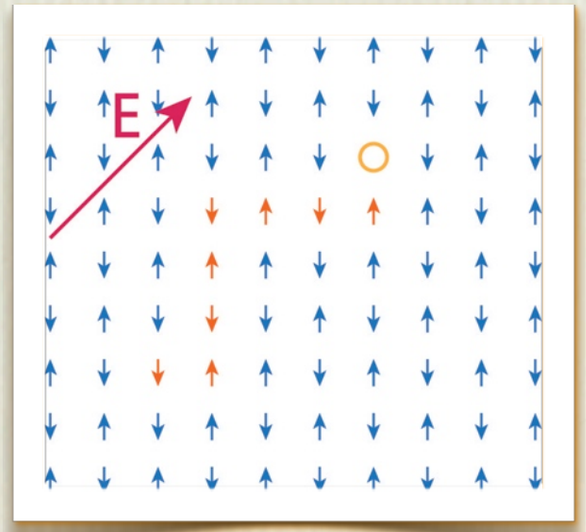
M. Mierzejewski, L. Vidmar, J.B., P. Prelovšek, PRL **106**, 196401 (2011)

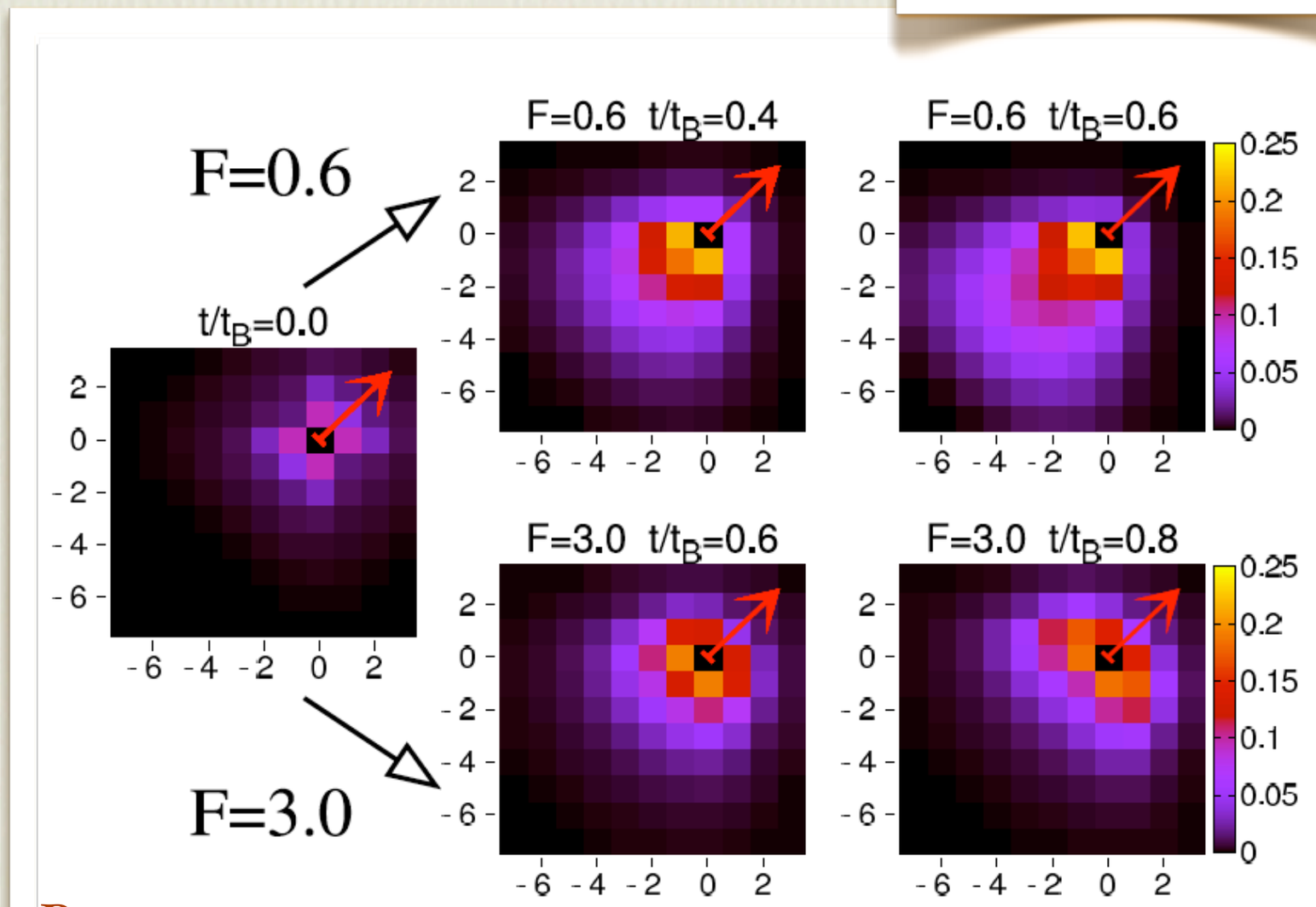
Spinski polaron pod vplivom zunanjega električnega polja

$$C(\mathbf{r}) = \sum_{\mathbf{i}} \langle n_{\mathbf{i}} \mid S^{z,\mathrm{Neel}}_{\mathbf{i}+\mathbf{r}} - S^{z}_{\mathbf{i}+\mathbf{r}} \mid \rangle$$









M. Mierzejewski, L. Vidmar, J.B., P. Prelovšek, PRL **106**, 196401 (2011)

Stacionarni tok

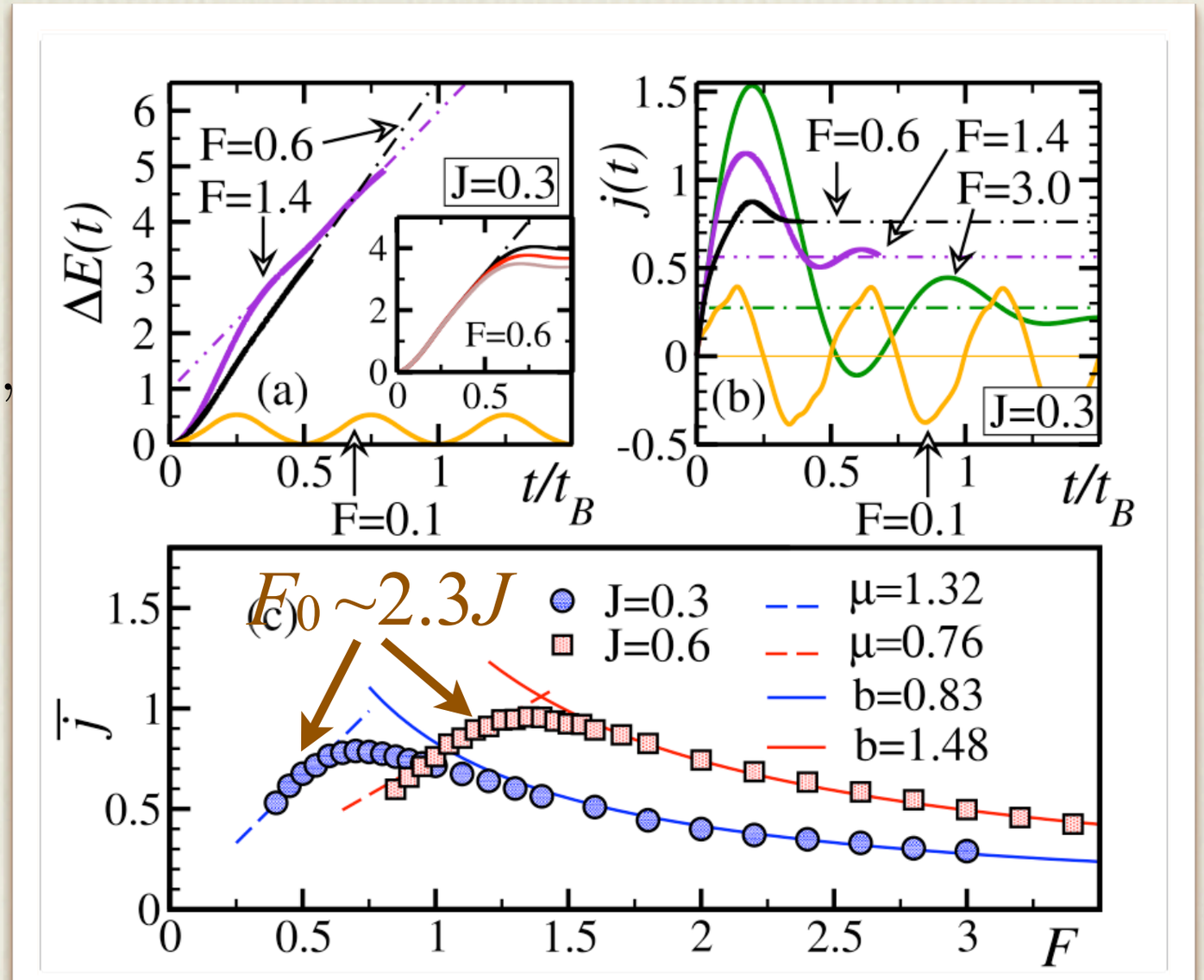
M. Mierzejewski, L. Vidmar, J.B., P. Prelovšek, PRL **106**, 196401 (2011)

$$\Delta E(t) = \langle H(t)\rangle - \langle H(t=0)\rangle$$

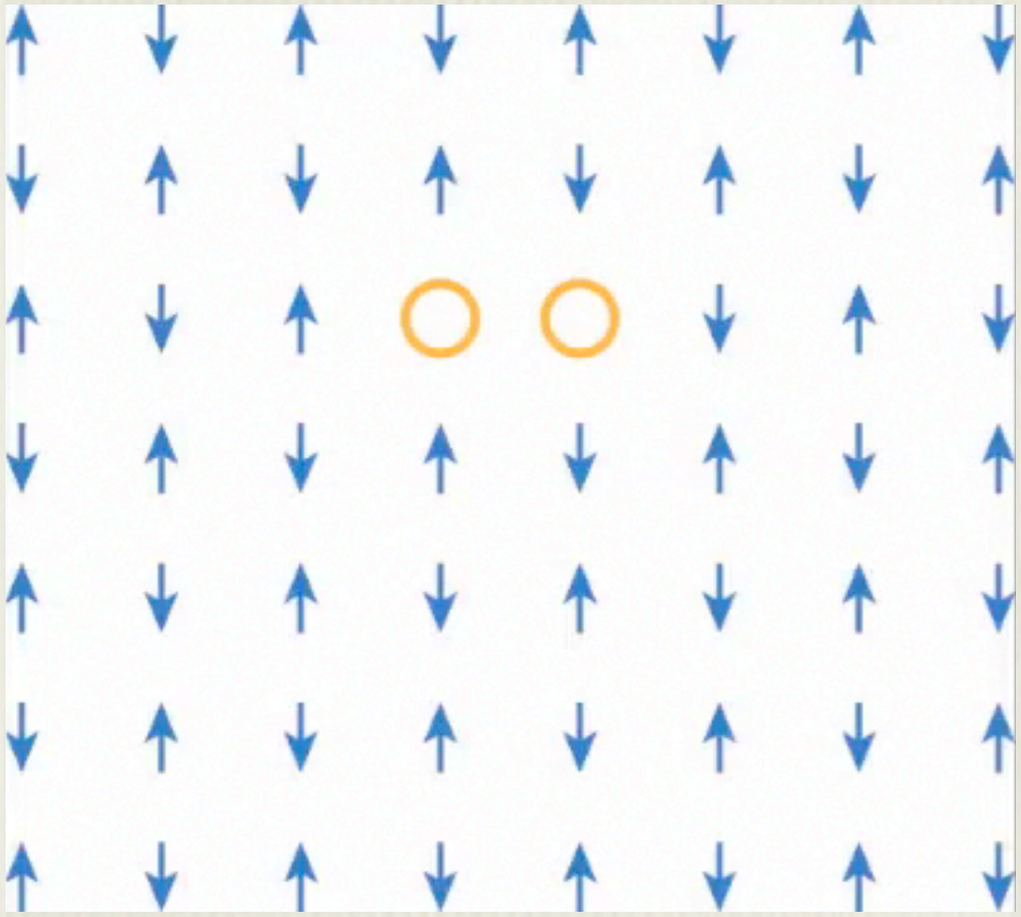
$$\hat{I}(t) = i\sum_l e^{-iFt} c_l^\dagger c_{l+1} - \text{H.c.},$$

$$j(t) = \langle \hat{I}(t)\rangle,$$

$$\bar{j} = \lim_{t\to\infty} j(t)$$

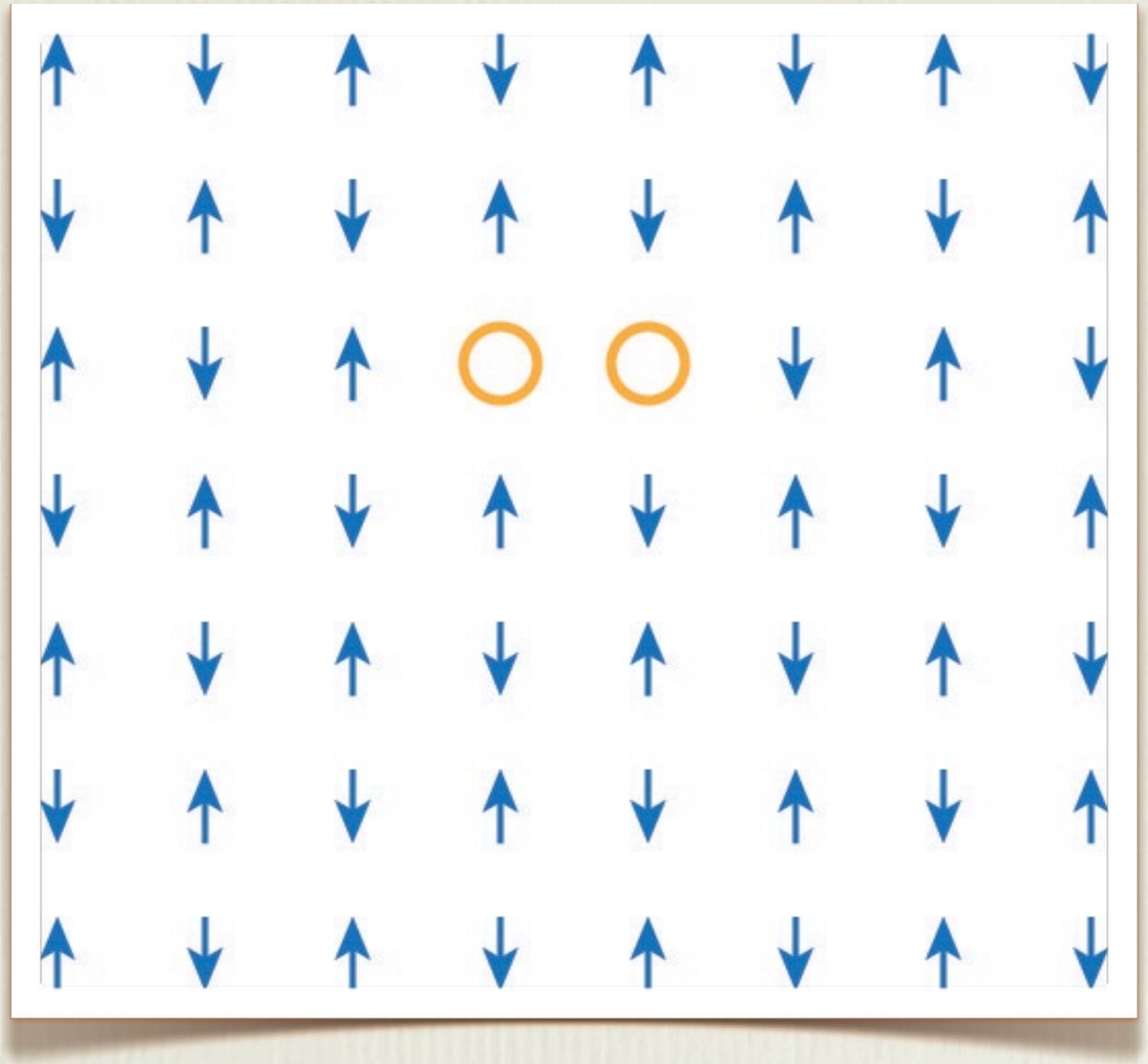


Model *t-J*, dve vrzeli - spinski bipolaron



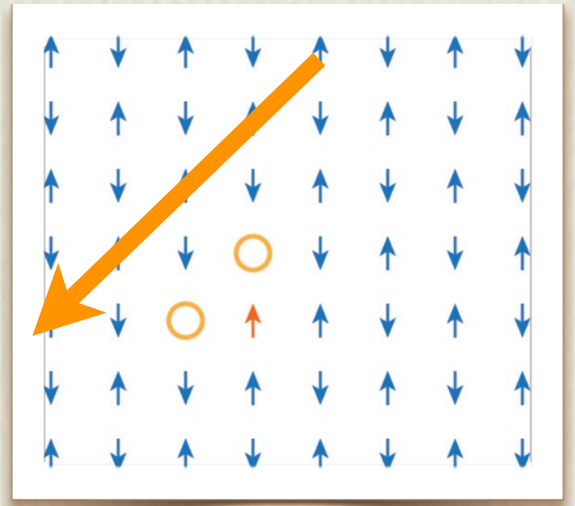
Model *t-J*, dve vrzeli - spinski bipolaron

Sklopitev s transferzalnimi mrežnimi nihanji stabilizira d-simetrijo vezanega para

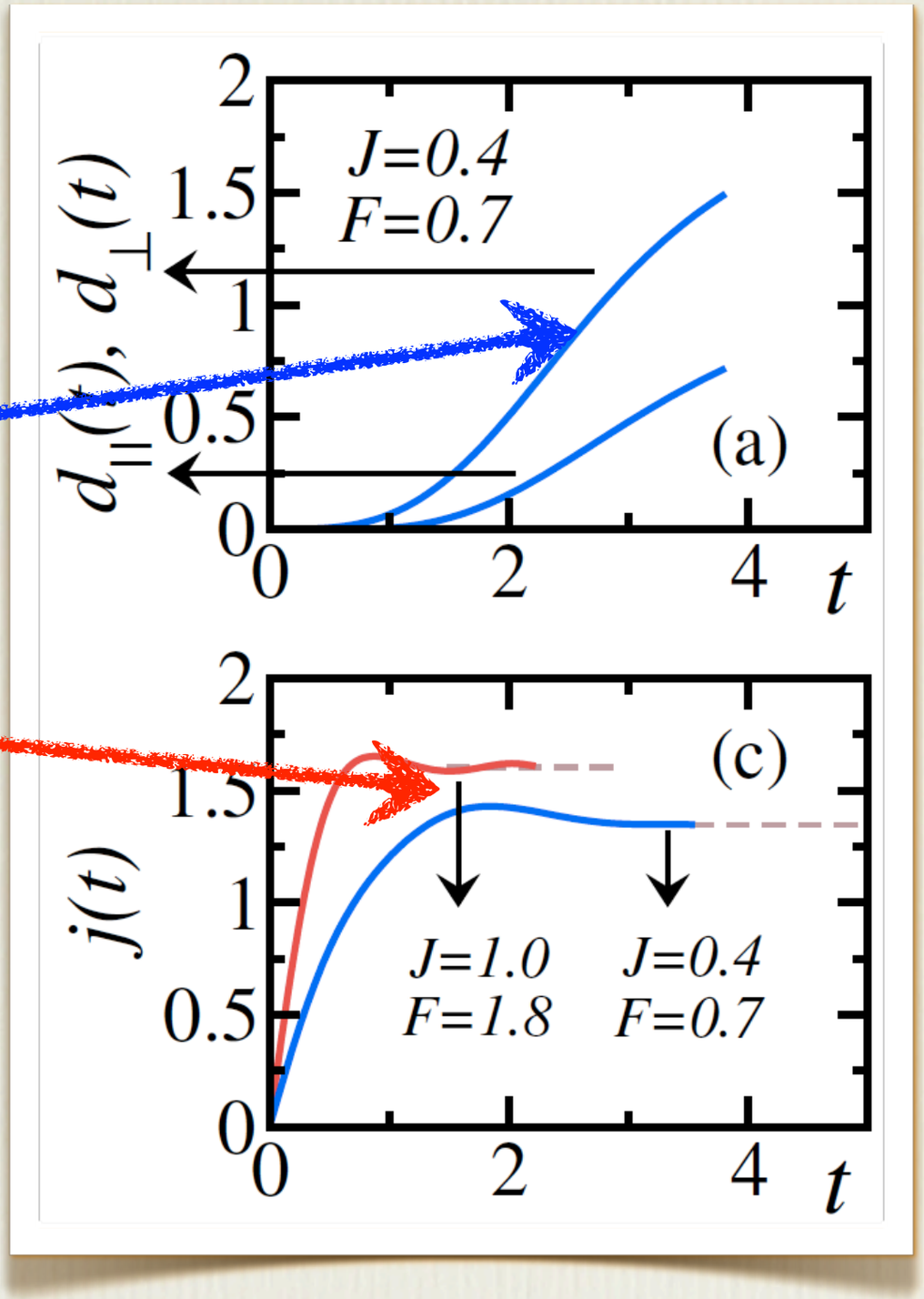


L. Vidmar, J.B., T. Tohyama, and S. Maekawa, PRL, **103**, 186401(2009)

Model *t-J*, dve vrzeli pod vplivom konstantnega električnega polja



Razdalja med vrzelma začne naraščati ko tok doseže stacionarno vrednost.

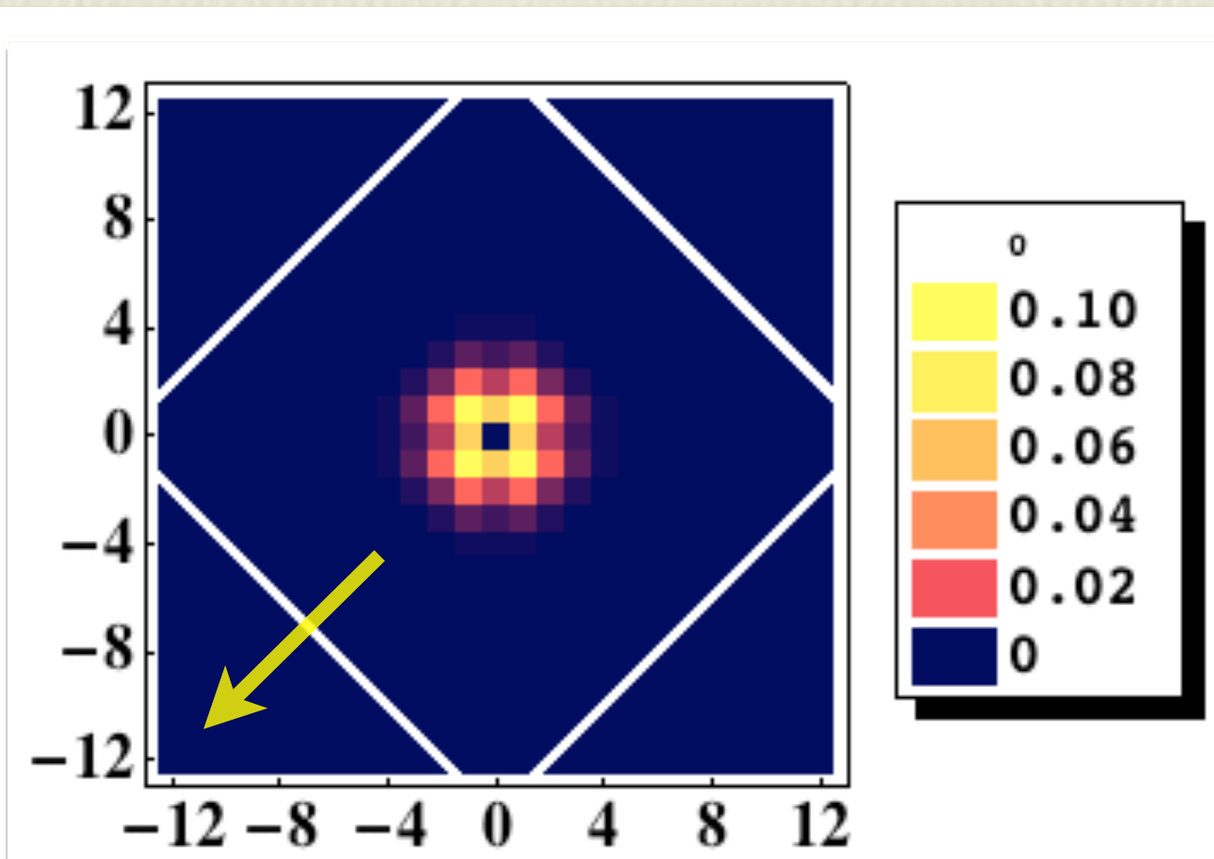


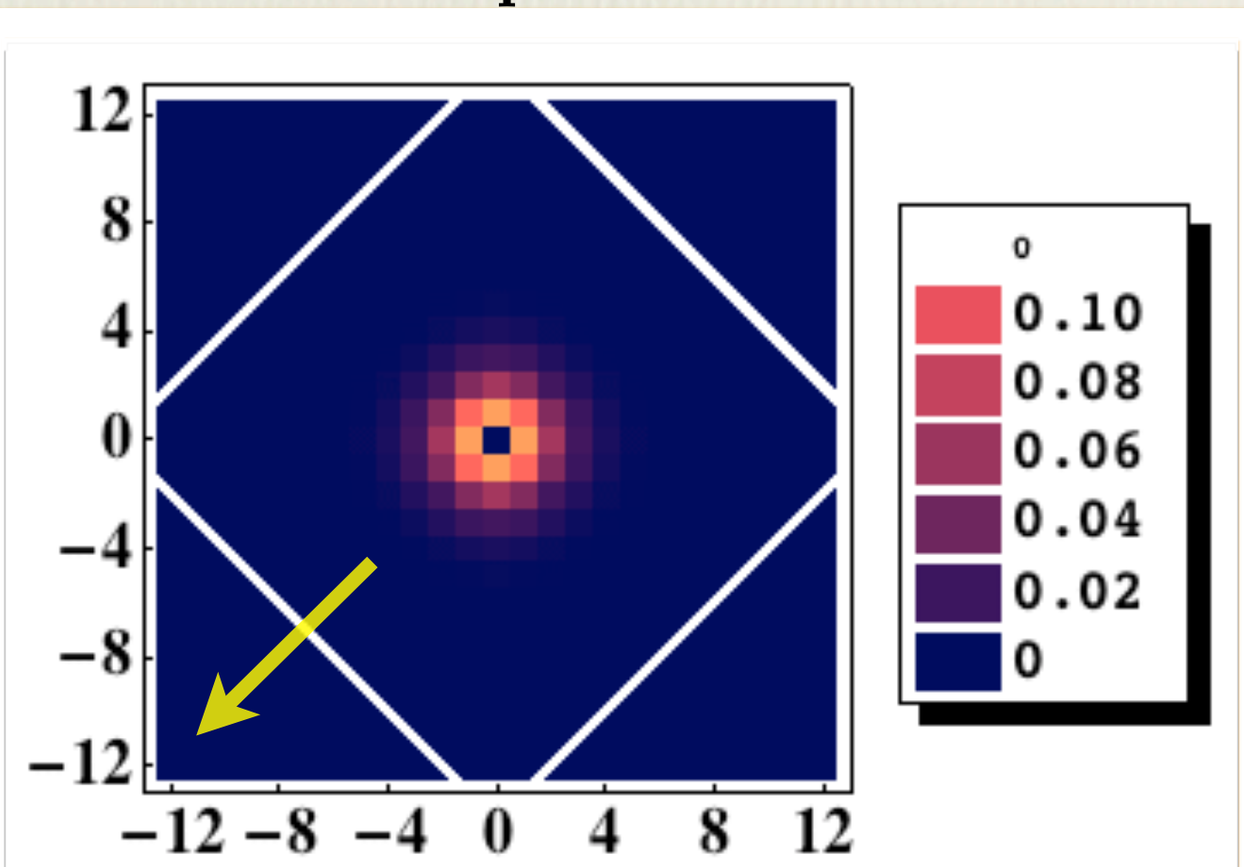
J.B., M. Mierzejewski, L. Vidmar, PRL **109**, 156404 (2012).

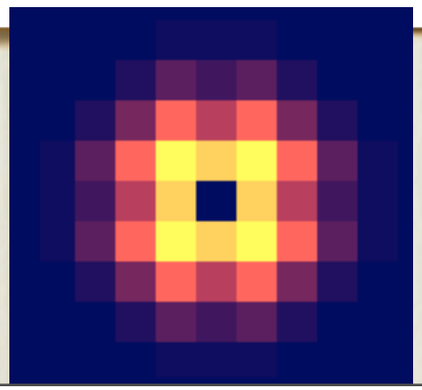
Časovni razvoj gostotne ter spinske korelacijske funkcije okoli para vrzeli

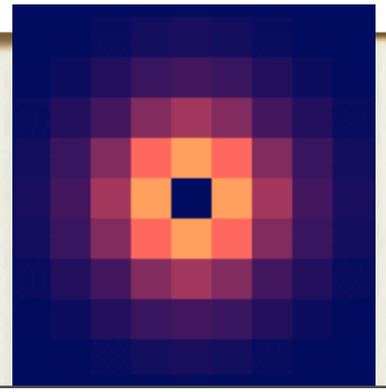
$$g(\mathbf{r}) = \sum_{\mathbf{l}} \langle n_{\mathbf{l}} n_{\mathbf{l}+\mathbf{r}} \rangle$$

$$s(\mathbf{r}) = \sum_{\mathbf{l}} \langle n_{\mathbf{l}} \Delta S^z_{\mathbf{l}+\mathbf{r}} \rangle$$







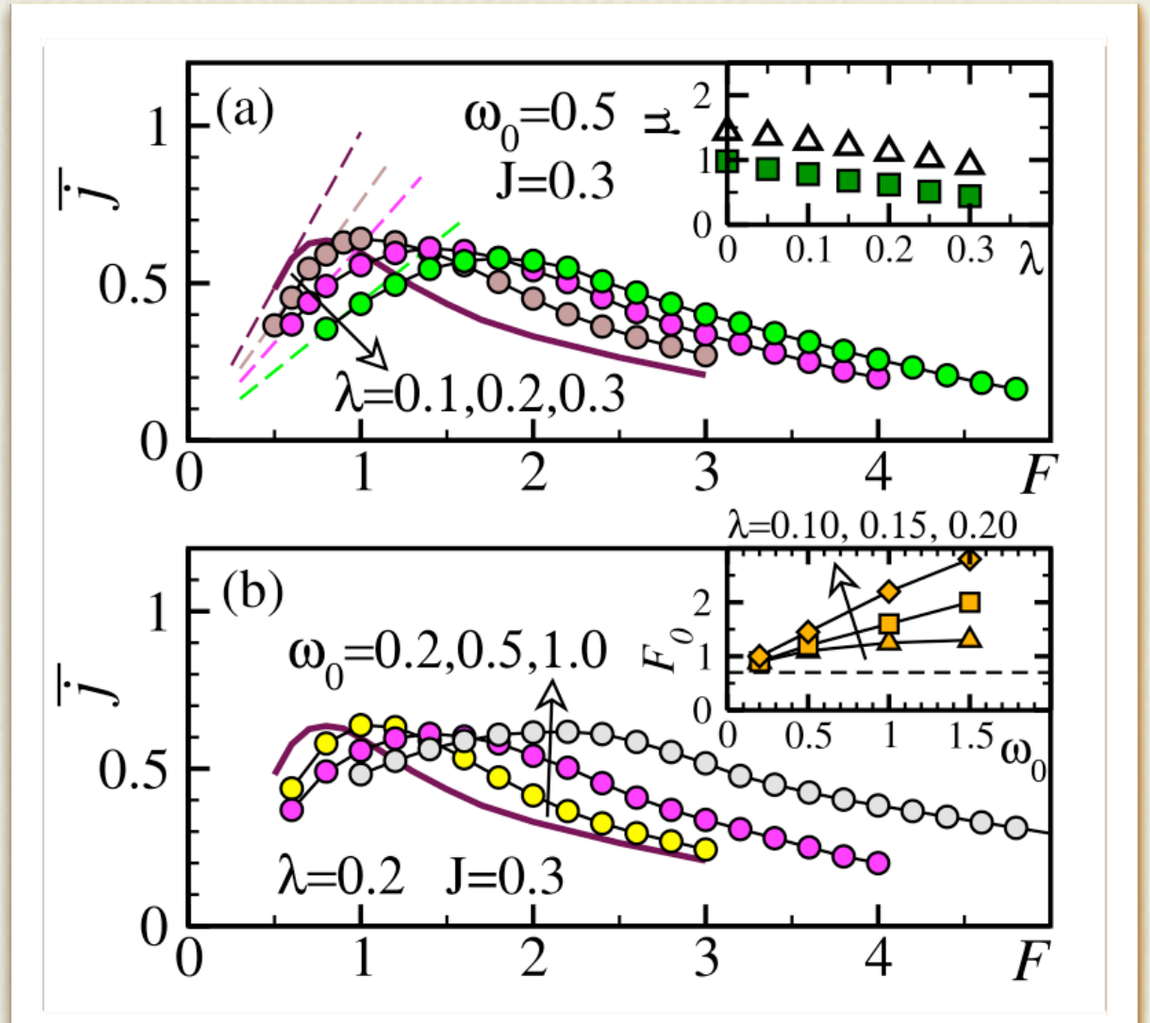


J.B., M. Mierzejewski, L. Vidmar, PRL **109**, 156404 (2012).

Model *t*-*J*-Holsteina z eno vrzeljo

$$H = -t_0 \sum_{\langle \mathbf{lj} \rangle, \sigma} \left[\mathrm{e}^{i\phi_{\mathbf{lj}}(t)} \, \tilde{c}^{\dagger}_{\mathbf{l},\sigma} \tilde{c}_{\mathbf{j},\sigma} + \mathrm{H.}c. \right] + J \sum_{\langle \mathbf{lj} \rangle} \mathbf{S_l} \cdot \mathbf{S_j}$$

$$+ \quad g \sum_{\mathbf{j}} n_{\mathbf{j}} (a^{\dagger}_{\mathbf{j}} + a_{\mathbf{j}}) + \omega_0 \sum_{\mathbf{j}} a^{\dagger}_{\mathbf{j}} a_{\mathbf{j}},$$

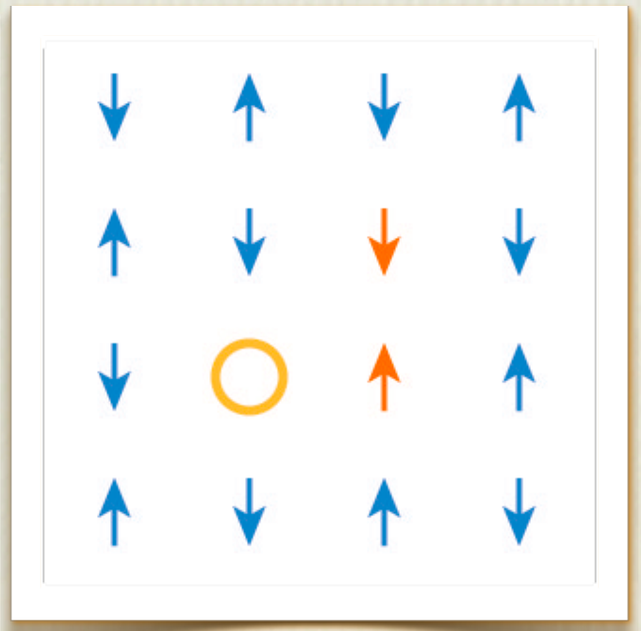


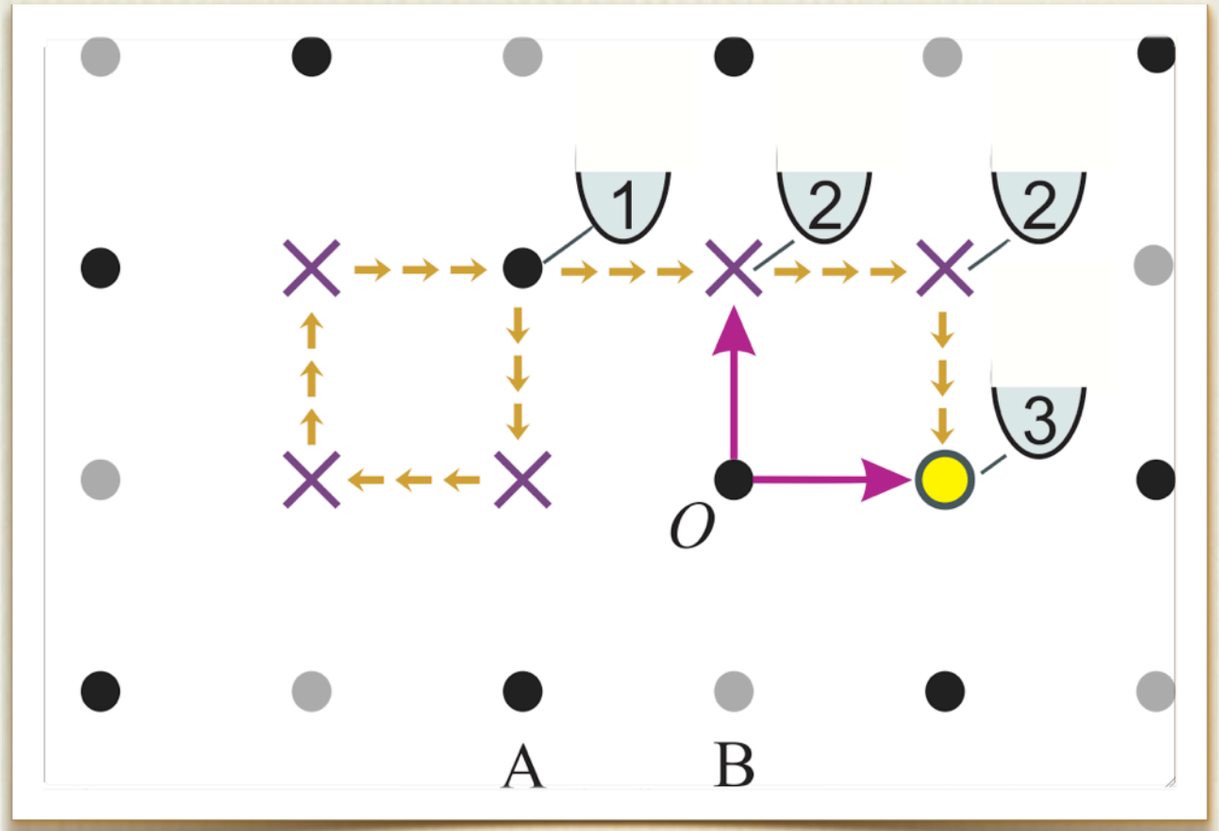
L. Vidmar, J.B., T. Tohyama, and S. Maekawa, PRL, **107**, 246404(2011)

Točna diagonalizacija v omejenem funkcijskem prostoru

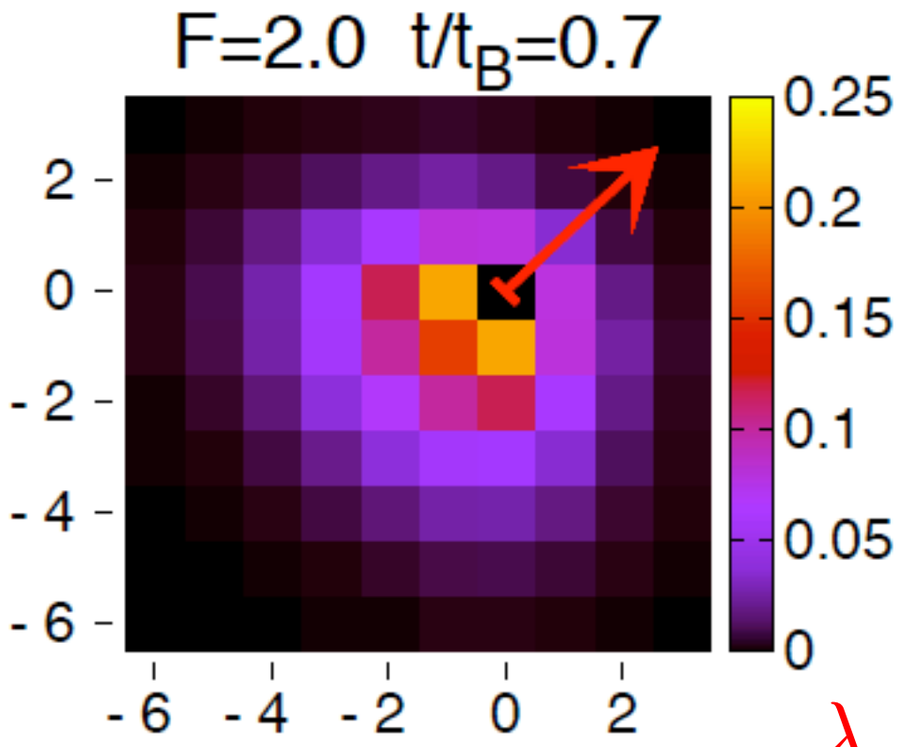
$$\left\{|\phi_{\mathbf{k},l}^{(N_h,M)}\rangle\right\} = \left(H_{\mathrm{kin}} + \sum_{m=1}^{M} {H_{\mathrm{g}}}^m\right)^{N_h} c_{\mathbf{k}}^{\dagger}|\emptyset\rangle,$$

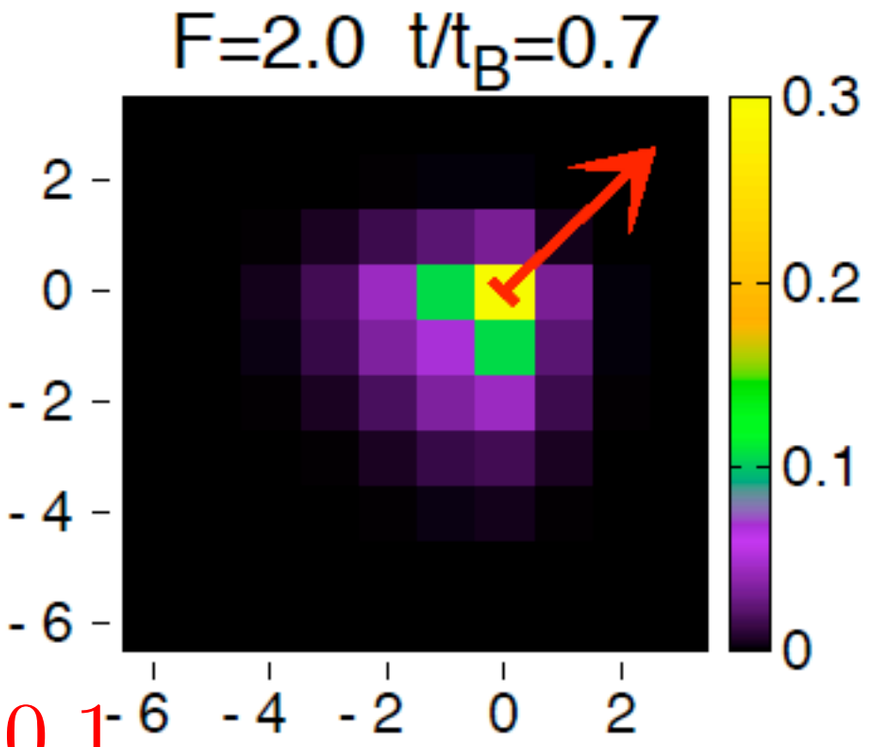
J.B., S. Maekawa, T. Tohyama, and P. Prelovšek PRB 77, 054519 (2008)





Deformacija spinov ter mreže v okolici vrzeli pod vplivom električnega polja





$\lambda = 0.1$

$\omega_0 = 1$

$$C(\mathbf{r}) = \sum_{\mathbf{i}} \langle n_{\mathbf{i}} \mid S^{z,\mathrm{Neel}}_{\mathbf{i}+\mathbf{r}} - S^{z}_{\mathbf{i}+\mathbf{r}} \mid \rangle \qquad N(\mathbf{r}) = \sum_{\mathbf{i}} \langle n_{\mathbf{i}} a^{+}_{\mathbf{i}+\mathbf{r}} a_{\mathbf{i}+\mathbf{r}} \rangle$$

Zaključki

1.Razvili smo učinkovito numerično metodo za izračun časovne dinamike sistemov koreliranih elektronov.

2.Metoda omogoča račun v okviru točnega kvantno mehanskega pristopa.

3.Določili smo stacionarni tok v modelu Holsteina ter koreliranem modelu t-J pod vplivom konstantnega električnega polja. Določili smo tudi relaksacijski čas po vzbuditvi sistema s kratkim laserskim sunkom.

4. Pokazali smo, da vezano stanje spinskega bipolarona vedno razpade pod vplivom zunanjega električnega polja.

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