Coulomb and spin-orbit interactions in nanorings

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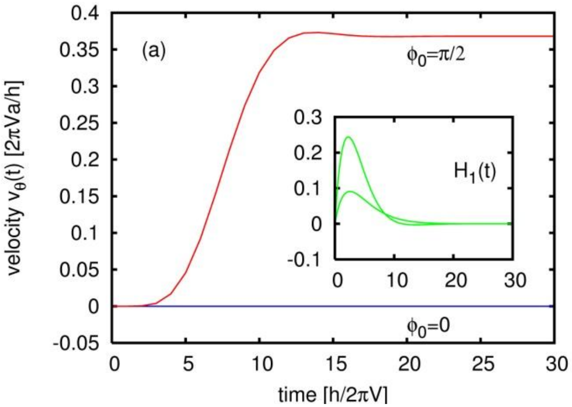
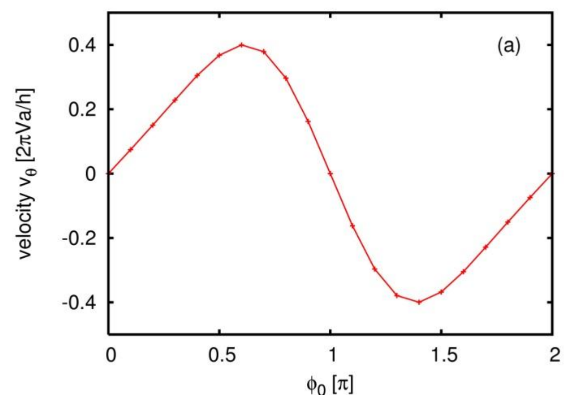
Persistent charge and spin currents

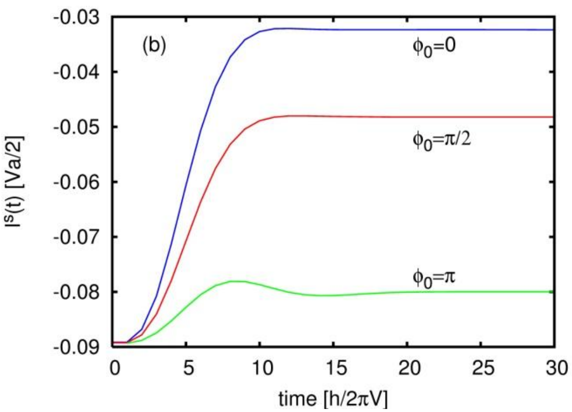
1D ring with SOI interaction excited by an external EM pulse

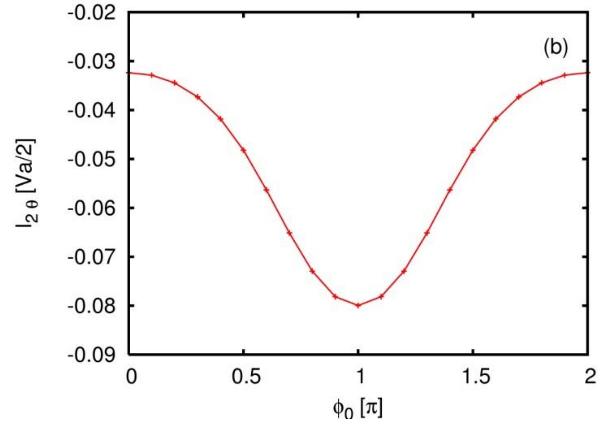
$$V_{pulse}(t) = Ae^{-\Gamma t}\left[\sin(\omega_1 t)\cos\varphi + \sin(\omega_2 t)\cos(\varphi+\varphi_0)\right]$$





Charge current





Spin current

M. Niţă, D.C. Marinescu, A. Manolescu, V. Guðmundsson, e-print arXiv:1012.4952

SOI models

Rashba - Due to the vertical confinement

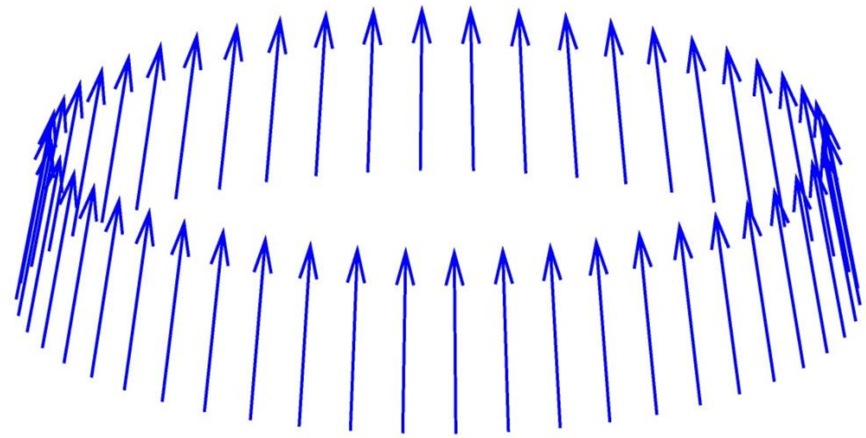
$$H_R = \frac{\alpha_R}{\hbar}\left(\sigma_x p_y - \sigma_y p_x\right)$$

Dresselhaus – Due to the electric field in the crystal

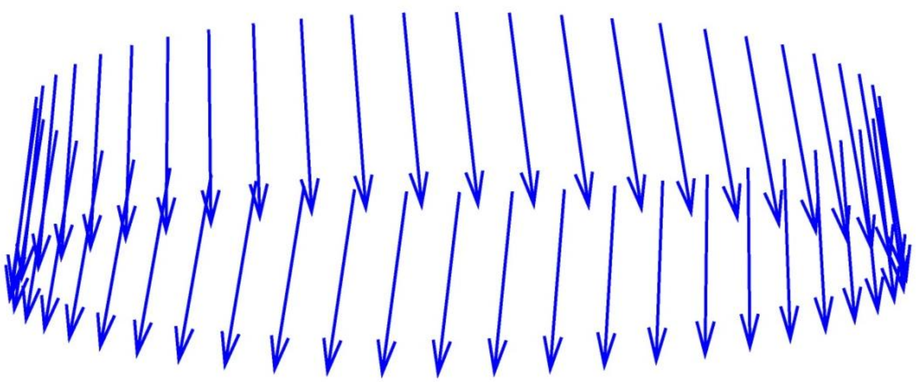
$$H_D = \frac{\beta_D}{\hbar}\left(\sigma_x p_x - \sigma_y p_y\right)$$

Known results on the 1D ring

Rashba



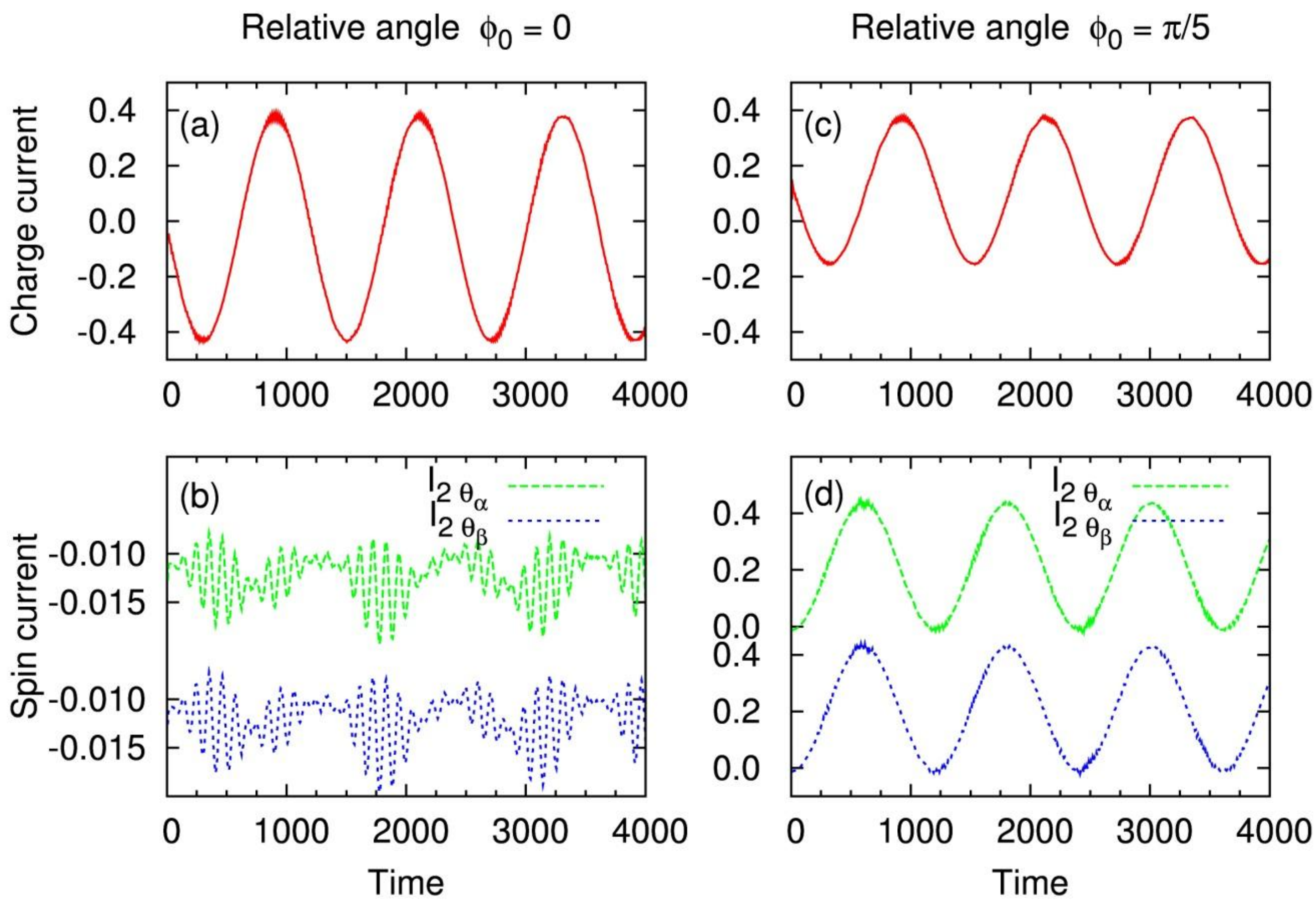
Dresselhaus



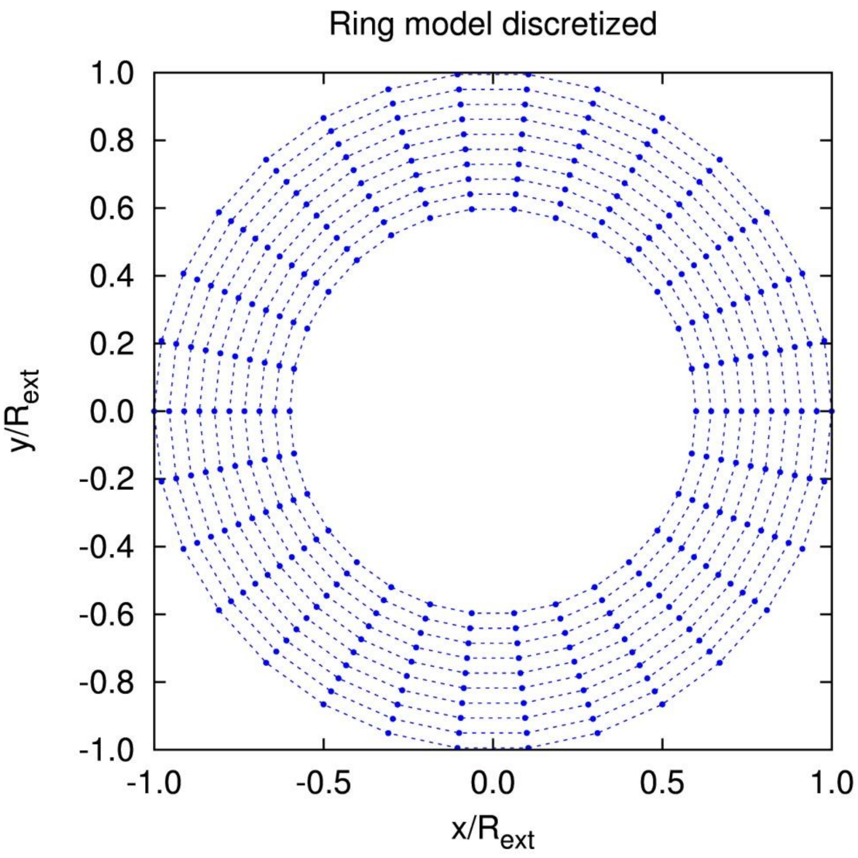
3 electrons, no
Coulomb interaction

J. S. Cheng and K. Chang PRB 74, 235315 (2006)

Charge and spin currents for R+D SOI



The sample



Between 1-10 rings and 20-100 angular sites all connected by hopping matrix elements

The sample Hamiltonian

$$H = -\frac{\hbar^2}{2m}\Delta = -\frac{\hbar^2}{2m}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2}\right]$$

Matrix elements for discrete polar coordinates:

$$\langle r\varphi | H | r'\varphi'\rangle = t_r\left(2\delta_{rr'} - \delta_{r,r'-1} - \delta_{r,r'+1}\right)\delta_{\varphi\varphi'} + t_\varphi\left(2\delta_{\varphi\varphi'} - \delta_{\varphi,\varphi'-1} - \delta_{\varphi,\varphi'+1}\right)\delta_{rr'}$$

$$t_R = \frac{\hbar^2}{2mR^2} \quad t_r = t_R\left(\frac{R}{\delta r}\right)^2 \quad t_\varphi = t_R\left(\frac{R}{r\delta\varphi}\right)^2$$

The Coulomb interaction

One particle: $H_1\psi_a = \varepsilon_a \psi_a$

N particles: $H_N = \sum_a \varepsilon_a c_a^\dagger c_a + \frac{1}{2}\sum_{a,b;c,d} V_{ab,cd} c_a^\dagger c_b^\dagger c_d c_c$

Coulomb matrix elements: $V_{ab,cd} = \int d\vec{r} d\vec{r}' \psi_a^*(\vec{r})\psi_b^*(\vec{r}') \frac{e^2}{|\vec{r}-\vec{r}'|}\psi_c(\vec{r})\psi_d(\vec{r}')$

Many-body states for independent electrons: $\left(V_{ab,cd} = 0\right)$

$|\alpha\rangle: \quad |1,0,0,\ldots\rangle \quad |0,1,0,\ldots\rangle \quad |1,1,0,\ldots\rangle \quad |1,1,1,\ldots\rangle$

"bit strings" with N particles

$V_{ab,cd} \neq 0 \Rightarrow H_N|\mu\rangle = E_\mu|\mu\rangle$

States for interacting electrons: $|\mu\rangle = \sum_\alpha A_{\alpha\mu}|\alpha\rangle$ and

The “exact diagonalization”

$$H_N \left| \mu \right\rangle = E_\mu \left| \mu \right\rangle$$

We want eigenvalues/vectors of the matrix $\left\langle \alpha \right| H_N \left| \beta \right\rangle$

All we need are the matrix elements $V_{ab,cd}$ and $\left\langle \alpha \right| c_a^\dagger c_b^\dagger c_c c_d \left| \beta \right\rangle$

Creation/destruction (annihilation) operators:

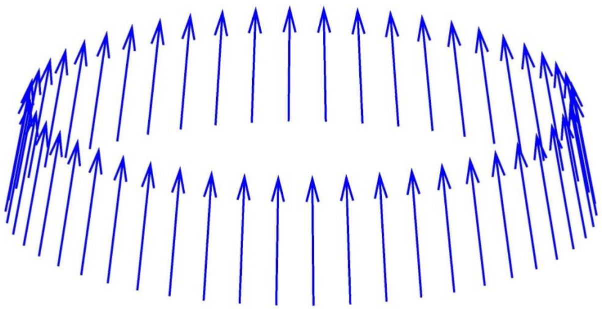
$$c_1^\dagger \left| \underline{0}, 1, 0, \ldots \right\rangle = \left| \underline{1}, 1, 0, \ldots \right\rangle \qquad c_1 \left| \underline{1}, 1, 0, \ldots \right\rangle = \left| \underline{0}, 1, 0, \ldots \right\rangle$$

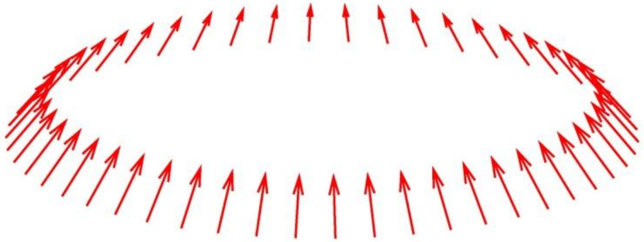
$$c_1^\dagger \left| \underline{1}, 1, 0, \ldots \right\rangle = 0 \qquad c_1 \left| \underline{0}, 1, 0, \ldots \right\rangle = 0$$

$$\left\langle \alpha \right| c_a^\dagger c_b^\dagger c_c c_d \left| \beta \right\rangle = \left\langle c_a c_b \alpha \mid c_c c_d \beta \right\rangle = 0, \pm 1$$

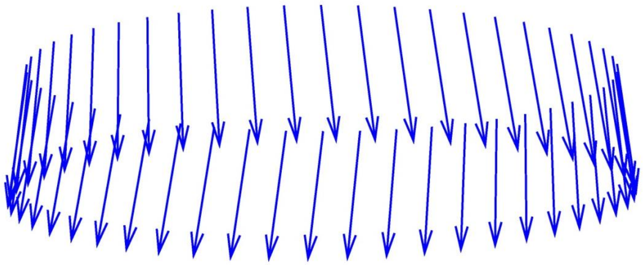
Combined Coulomb and SOI effects (groundstate)

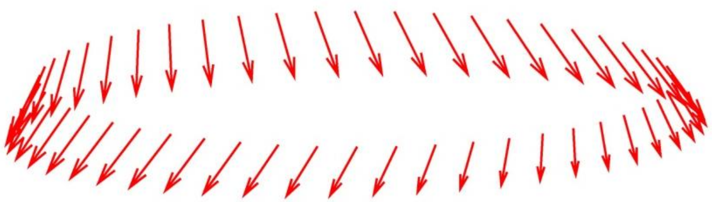
Rashba





Dresselhaus





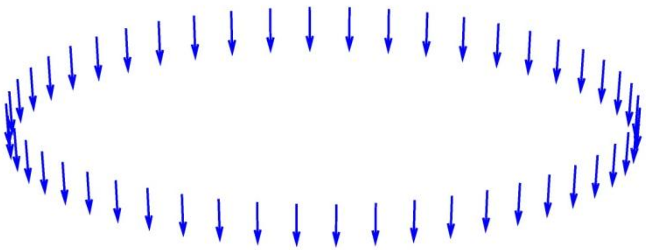
N=3 no interaction

N=3 with interaction

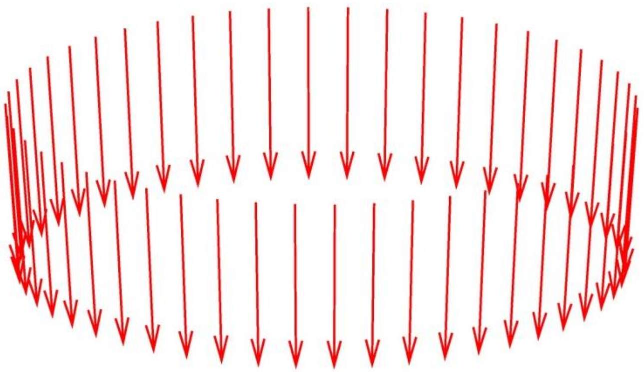
The spin polarization may be reduced by the Coulomb interaction ...

Combined Coulomb and SOI effects

Rashba



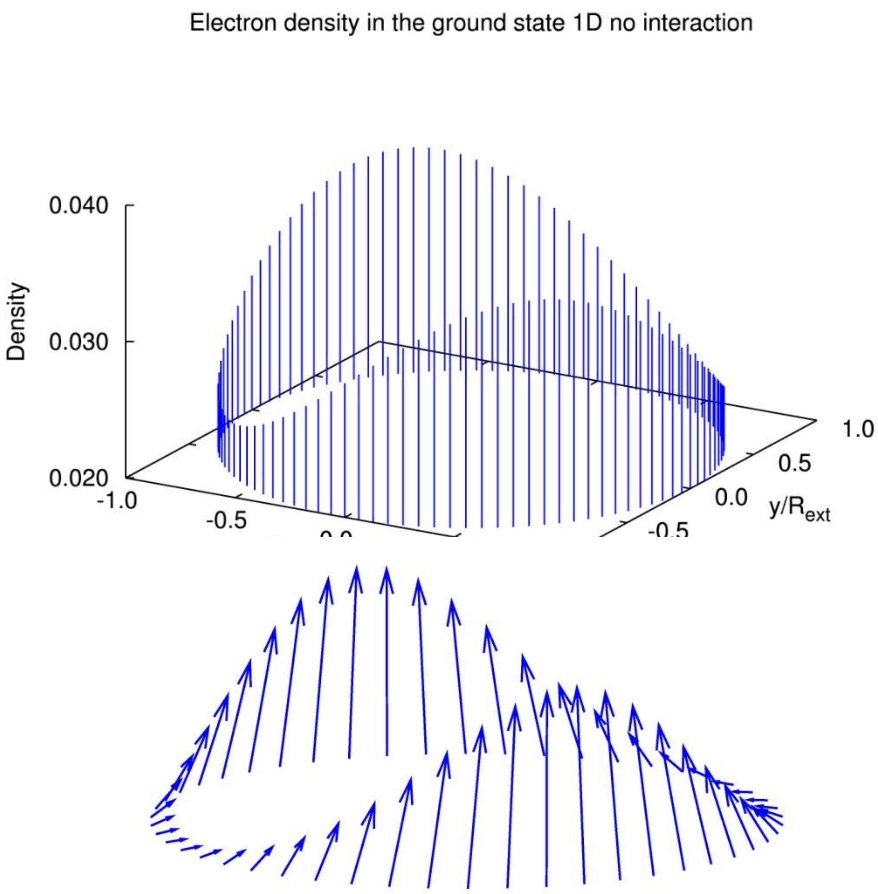
N=4 no interaction



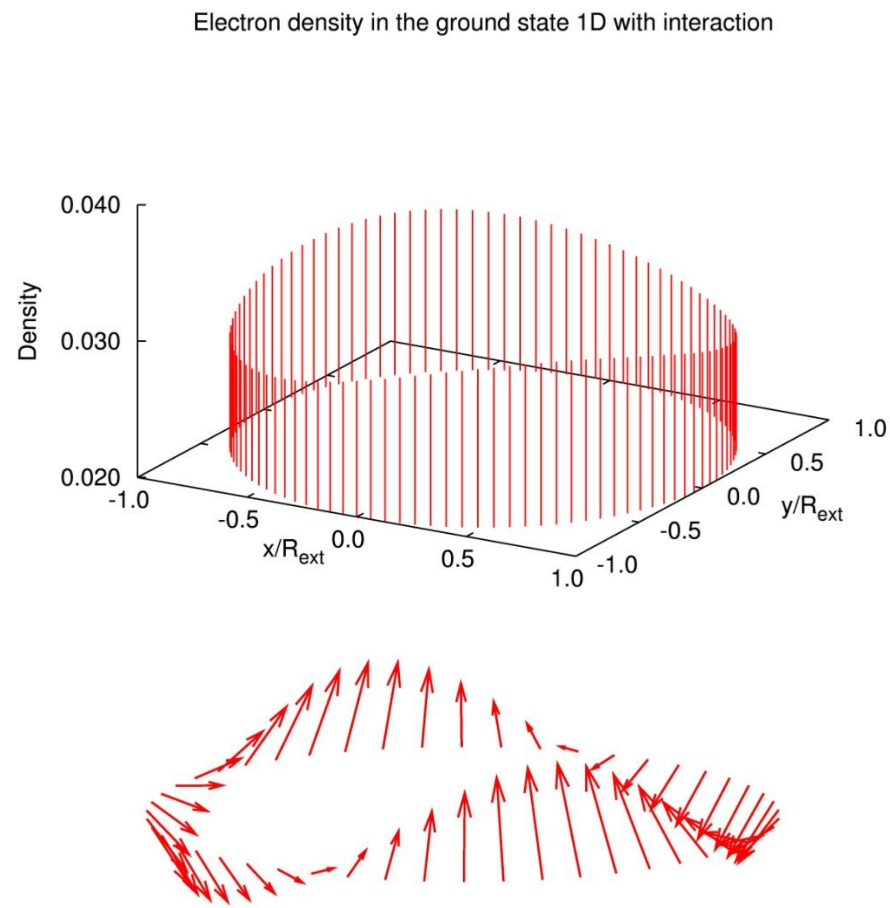
N=4 with interaction

...but the spin polarization may also be amplified by the interaction ...

Combined Rashba and Dresselhaus SOI in 1D

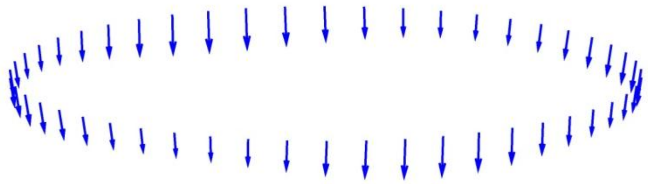


N=3, no interaction,
inhomogeneous charge density
and spin density

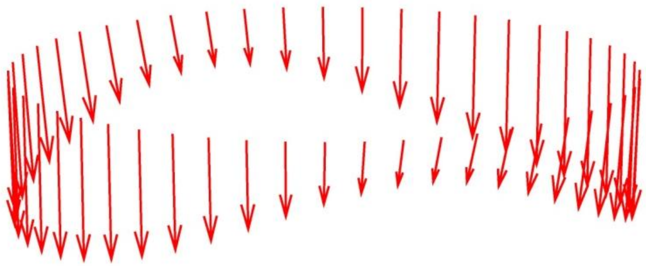


N=3, Coulomb interaction,
screened charge density,
unscreened spin density?

Combined Rashba and Dresselhaus SOI

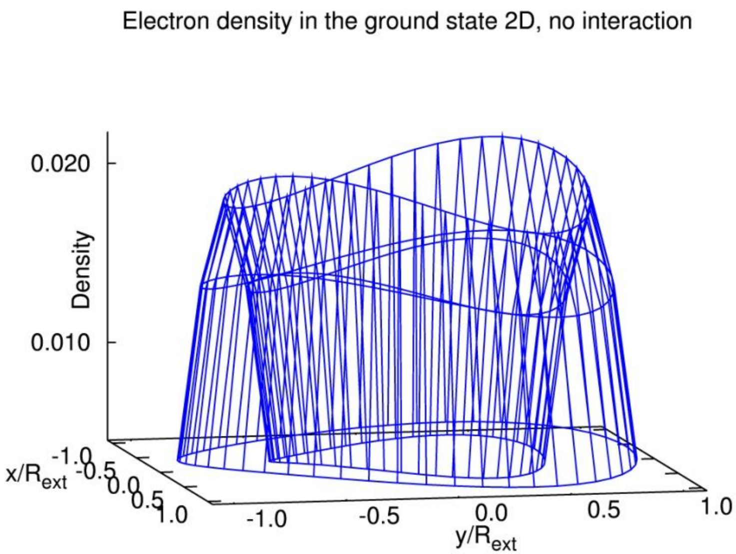


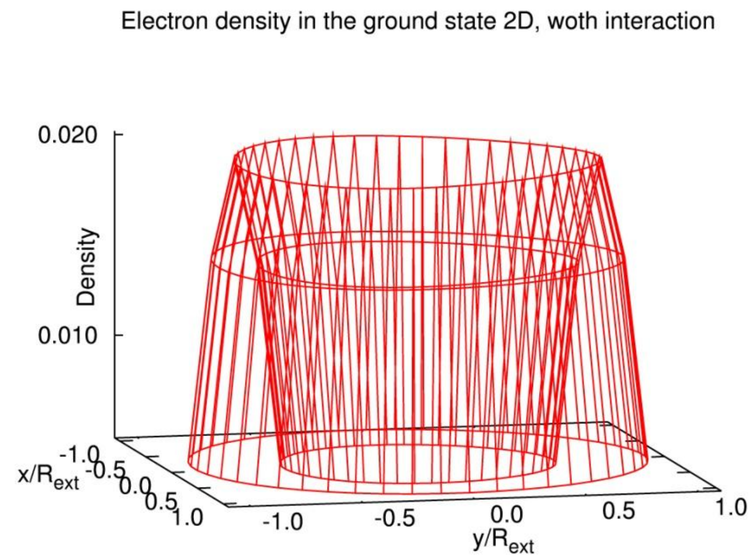
N=4, no interaction,
inhomogeneous spin density

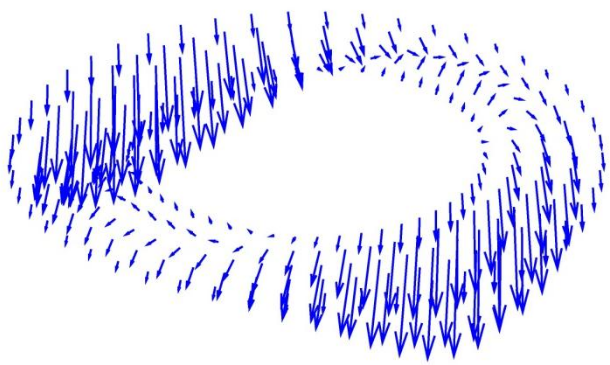


N=4, Coulomb interaction,
unscreened spin density?

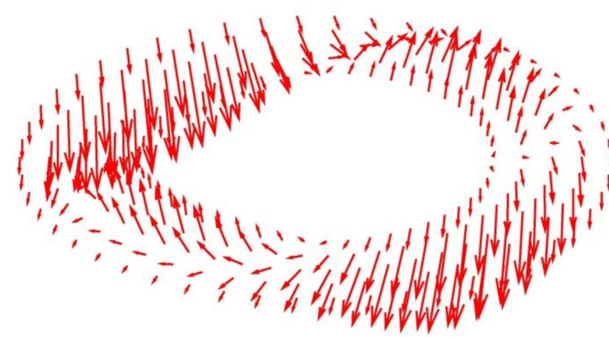
Combined Coulomb and SOI in 2D





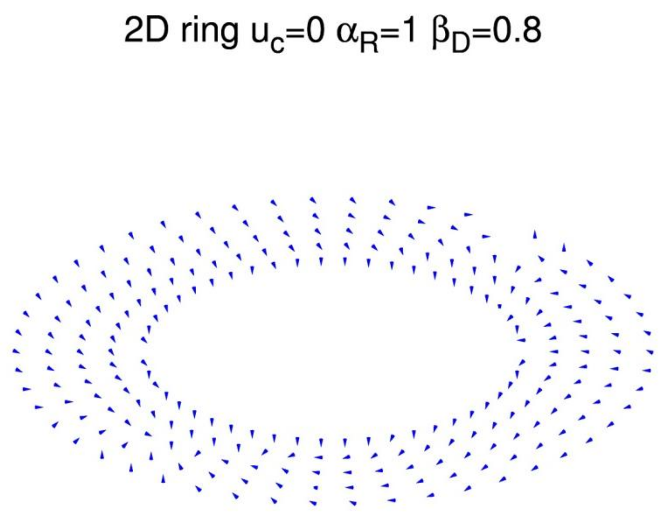


N=3 no interaction

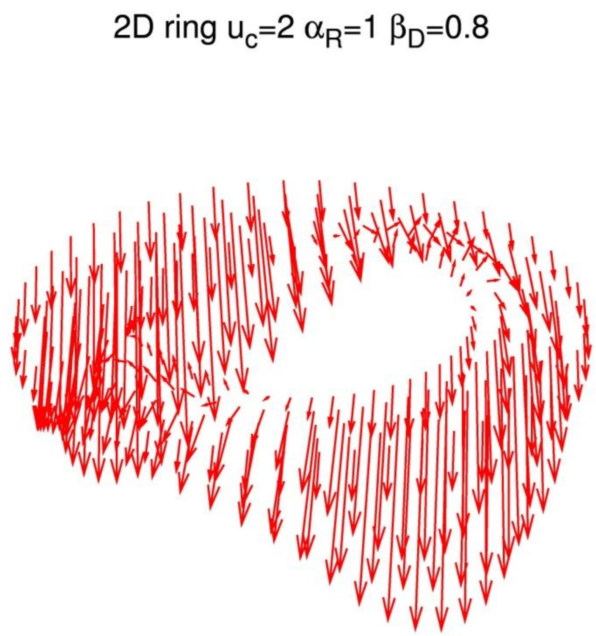


N=3 with interaction

Combined Coulomb and SOI in 2D

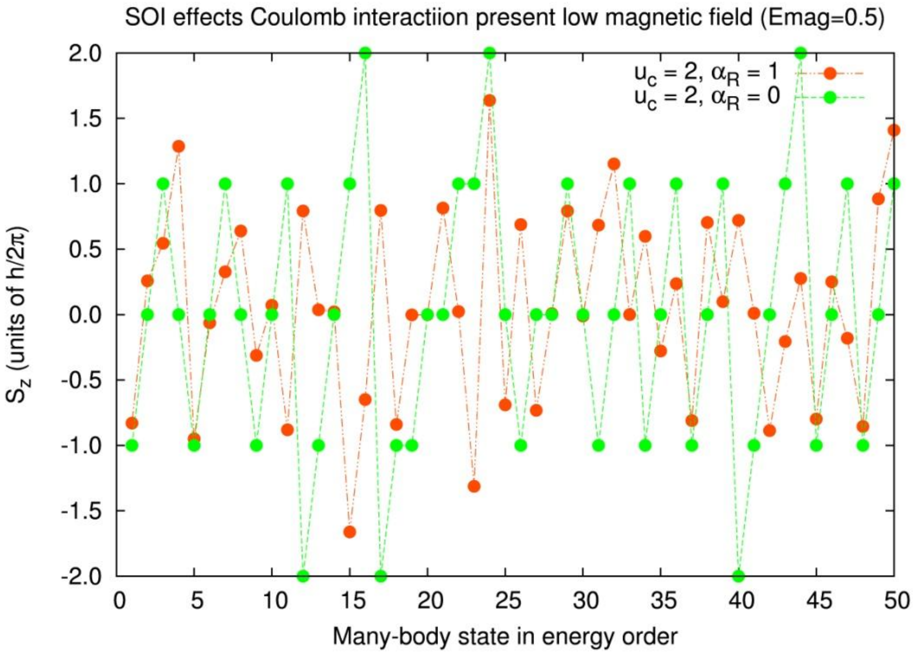


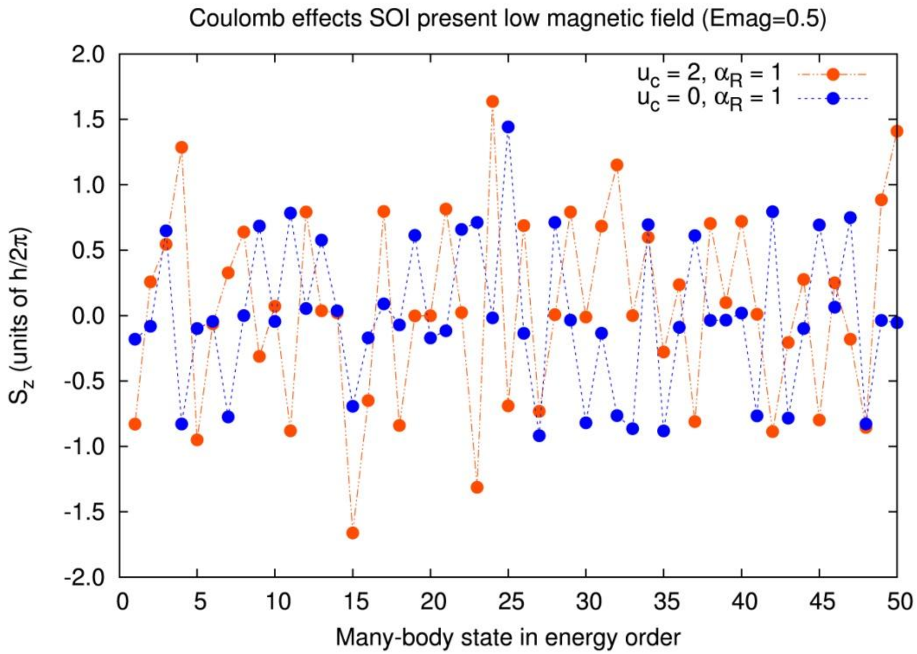
N=4 no interaction



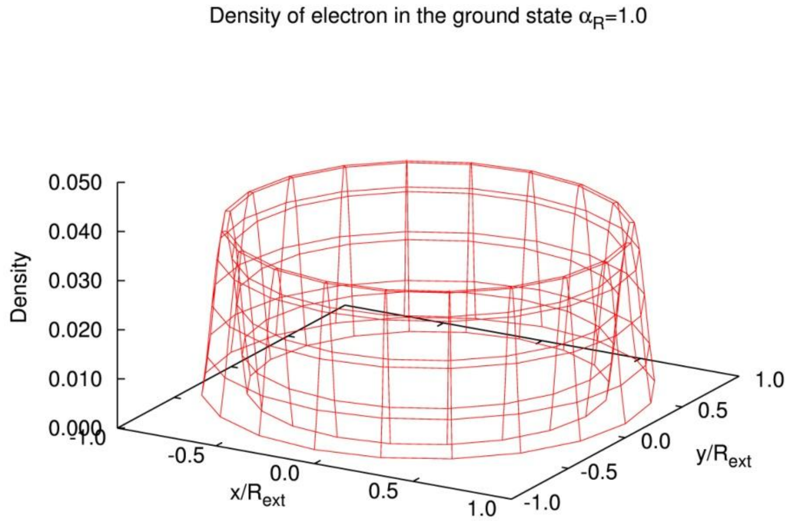
N=4 with interaction

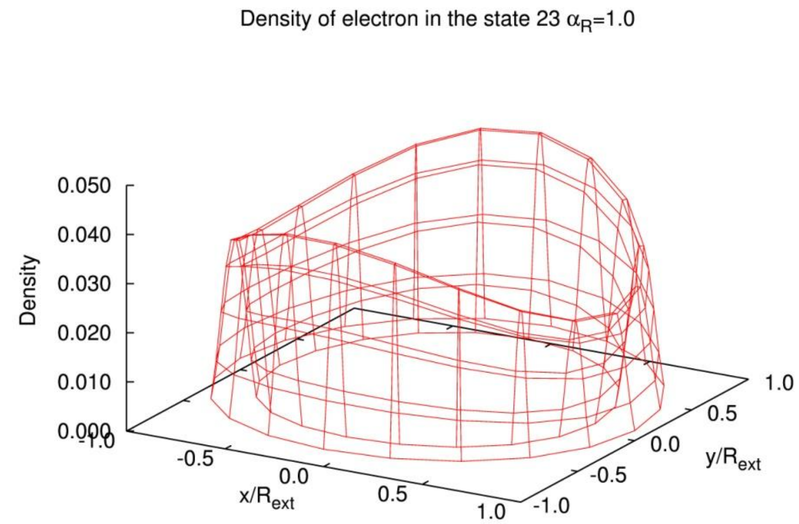
Total spin and excited states

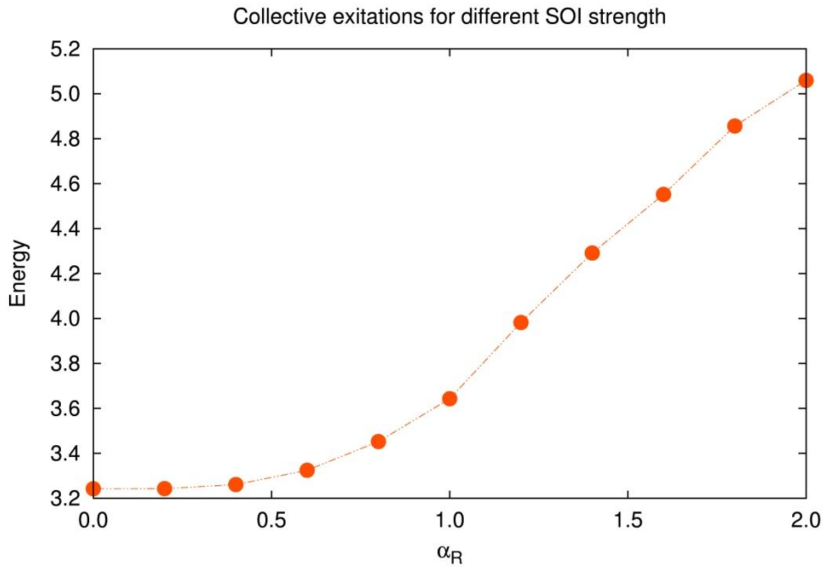


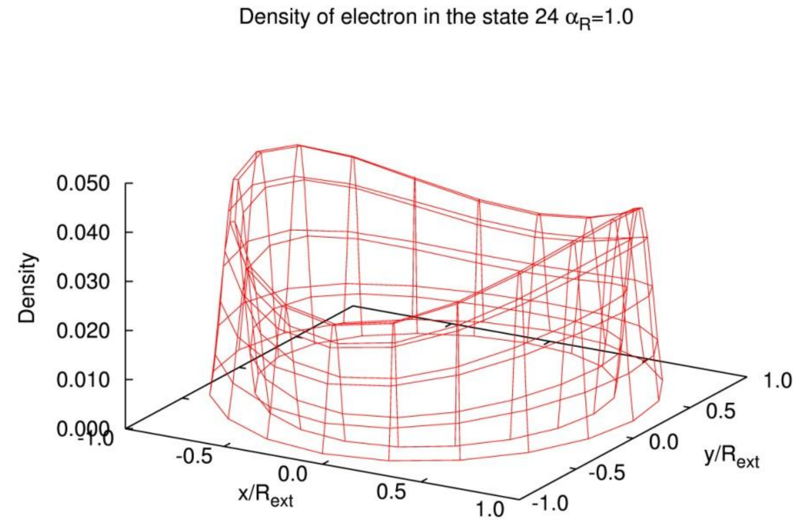


Excited states in the presence of an external field. "Collective modes" ?









Increased energy of the "collective modes" with the SOI parameter.

For plasma oscillations: **D.C. Marinescu and F.Lung, PRB 82, 205322 (2010)**

Continuous 2D ring model

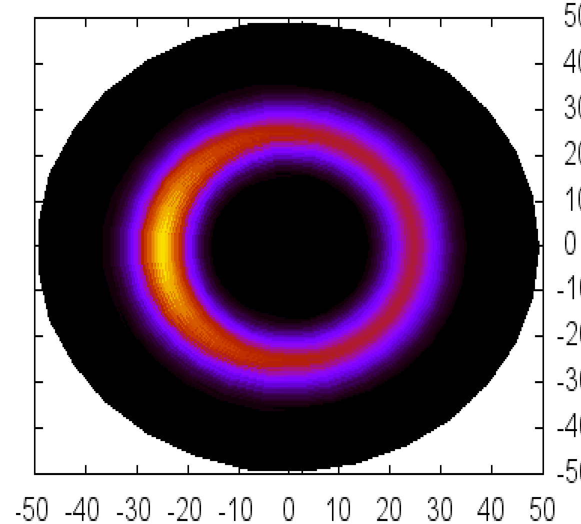
Lateral confinement $V(r) = V_0\left(\frac{r}{r_0} - \frac{r_0}{r}\right)$

Analytical single-particle wave functions

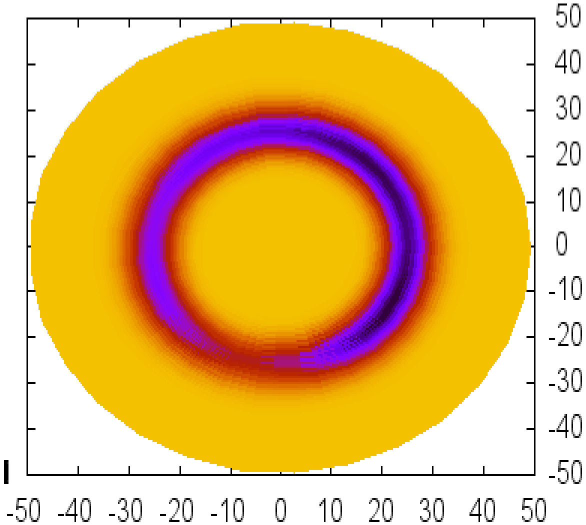
Tan & Inckson, Semic. Sci. Technol., 11 1635 (1996)

We include a Coulomb impurity

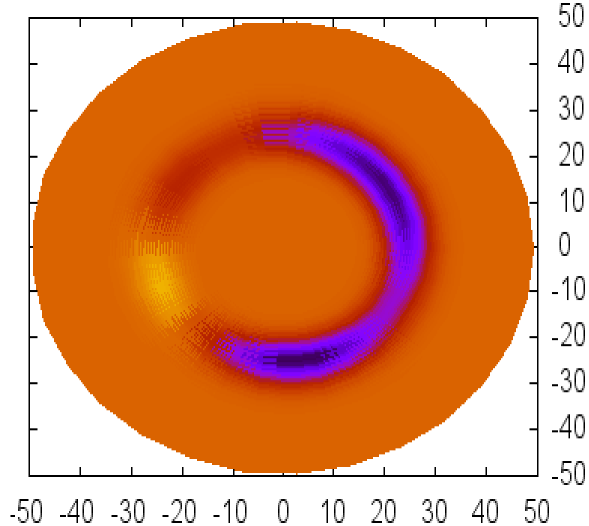
Charge density



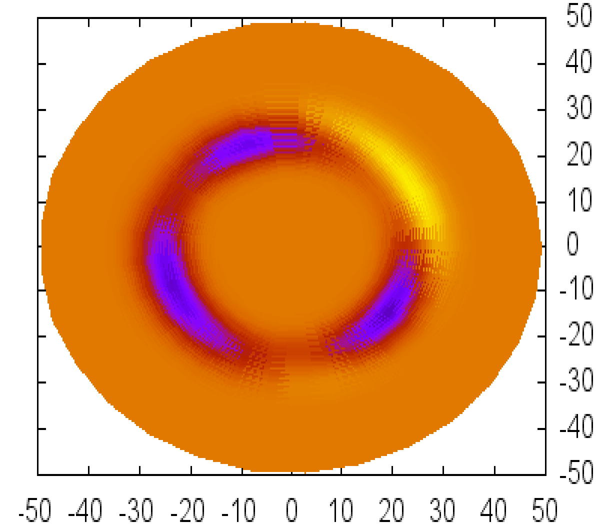
Spin density GS



Spin density ES1



Spin density ES2



(Preliminary) conclusions

- The Coulomb interaction has strong effects on the spin polarization
- The spin density may propagate on longer distances than the charge density
- The spin density may have a richer structure in space than the charge density
- Collective modes have higher energy due to SOI ?

Co-workers

- Csaba Daday (Reykjavik)
- Marian Niţă (Bucharest)
- Catalina Marinescu (Clemson)
- Viðar Guðmundsson (Reykjavik)