Magnetization of confined and extended 2DEG's

Viðar Guðmundsson

Science Institute

University of Iceland

Dunhaga 3, IS-107 Reykjavík

vidar@raunvis.hi.is

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Cooperation

Reykjavík:

- **Ingibjörg Magnúsdóttir → COM Copenhagen**
- **Sigurður I. Erlingsson → TU Delft**
- **Andrei Manolescu → deCode Reykjavík**

Hamburg:

- **Detlef Heitmann**
- **Dirk Grundler**
- **Ines Meinel**

Why magnetization?

- The electron state in a system is measured by FIR-absorption, tunneling, Raman-scattering, magnetization, and transport...
- FIR-absorption excites mostly center-of-mass modes, correlation effects block tunneling spectroscopy
- Magnetization is not limited by selection rules...
- In magnetization many-electron effects are seen...
- Direct access to the ground state
- Valuable addition, good experiments...

Magnetization

Magnetization is defined in terms of current- and spin-density:

$$M_o + M_s = \frac{1}{2}\int_{\mathbf{R^2}} d\mathbf{r}(\mathbf{r} \times \langle \mathbf{J}(\mathbf{r})\rangle) \cdot \hat{\mathbf{n}} - \mathbf{g}\mu_{\mathbf{B}} \int_{\mathbf{R^2}} \mathbf{dr}\langle \sigma_{\mathbf{z}}(\mathbf{r})\rangle,$$

or total energy:

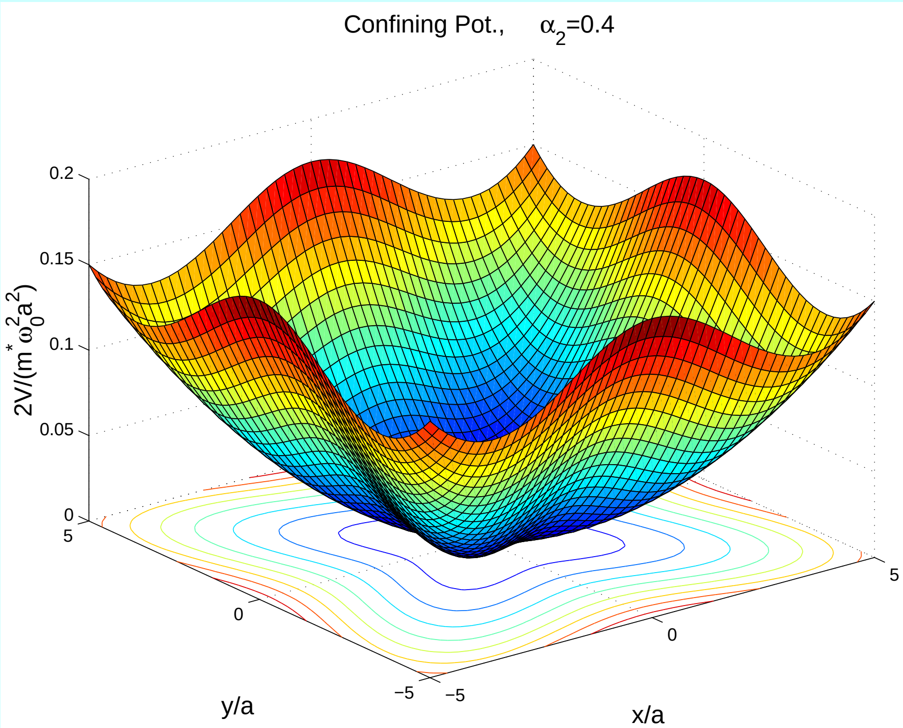
$$M_o + M_s = -\frac{\partial}{\partial B}(E_{\text{total}} - TS)$$

Systems

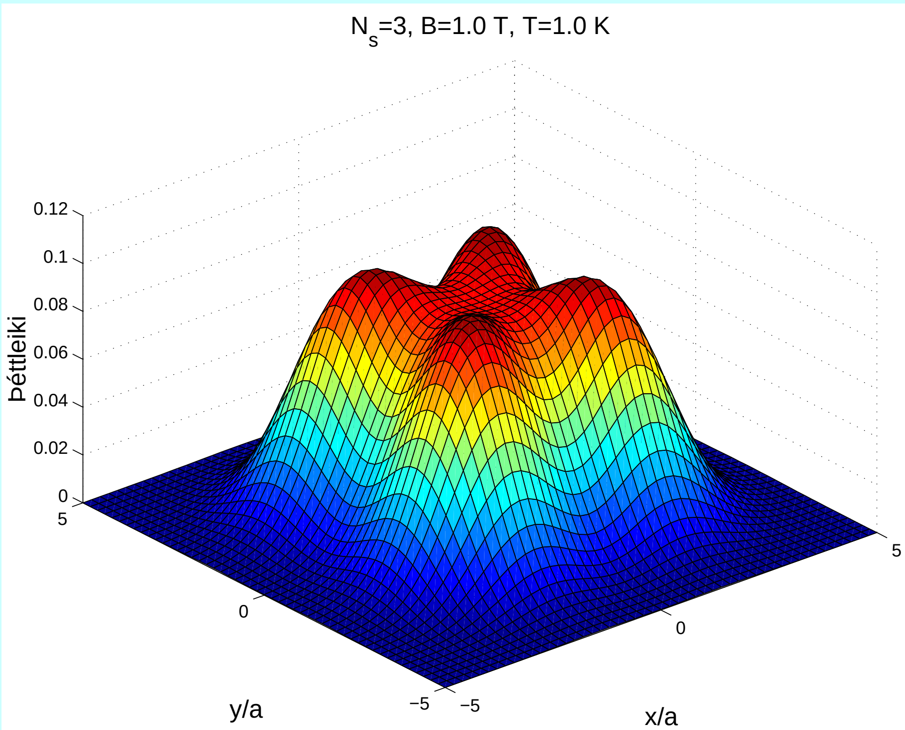
- Quantum Dots, noncircular
- Finite system, increasing size
- Infinite 2D-systems, 1D modulation
- Infinite 2D-systems, 2D modulation
- Infinite 2D-systems, Hysteresis

Quantum dot, (IM)

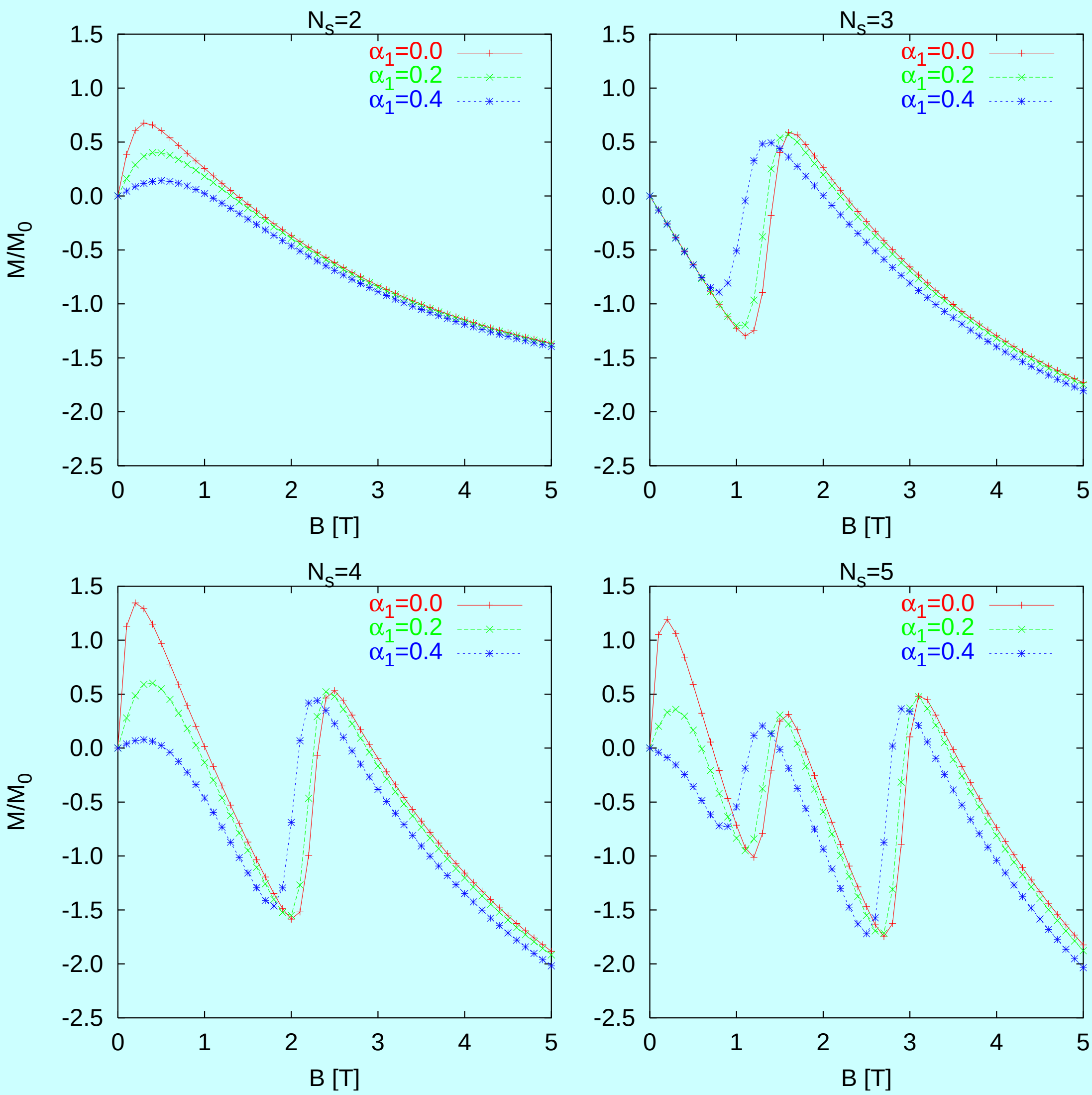
Confining potential for electrons in a dot



Density of three interacting electrons in magnetic field



Elliptic quantum dot, magnetization

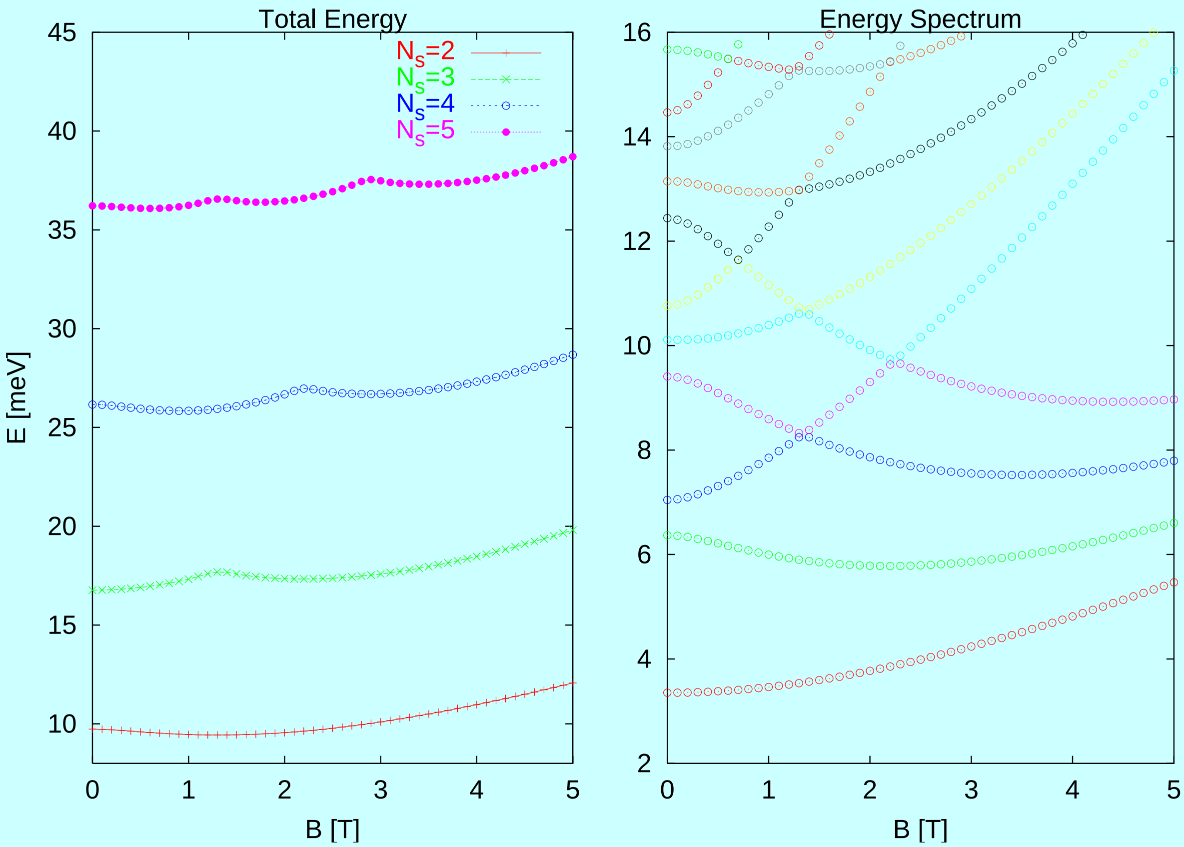


Effects of increased number of electrons and deviation

Noninteracting electrons

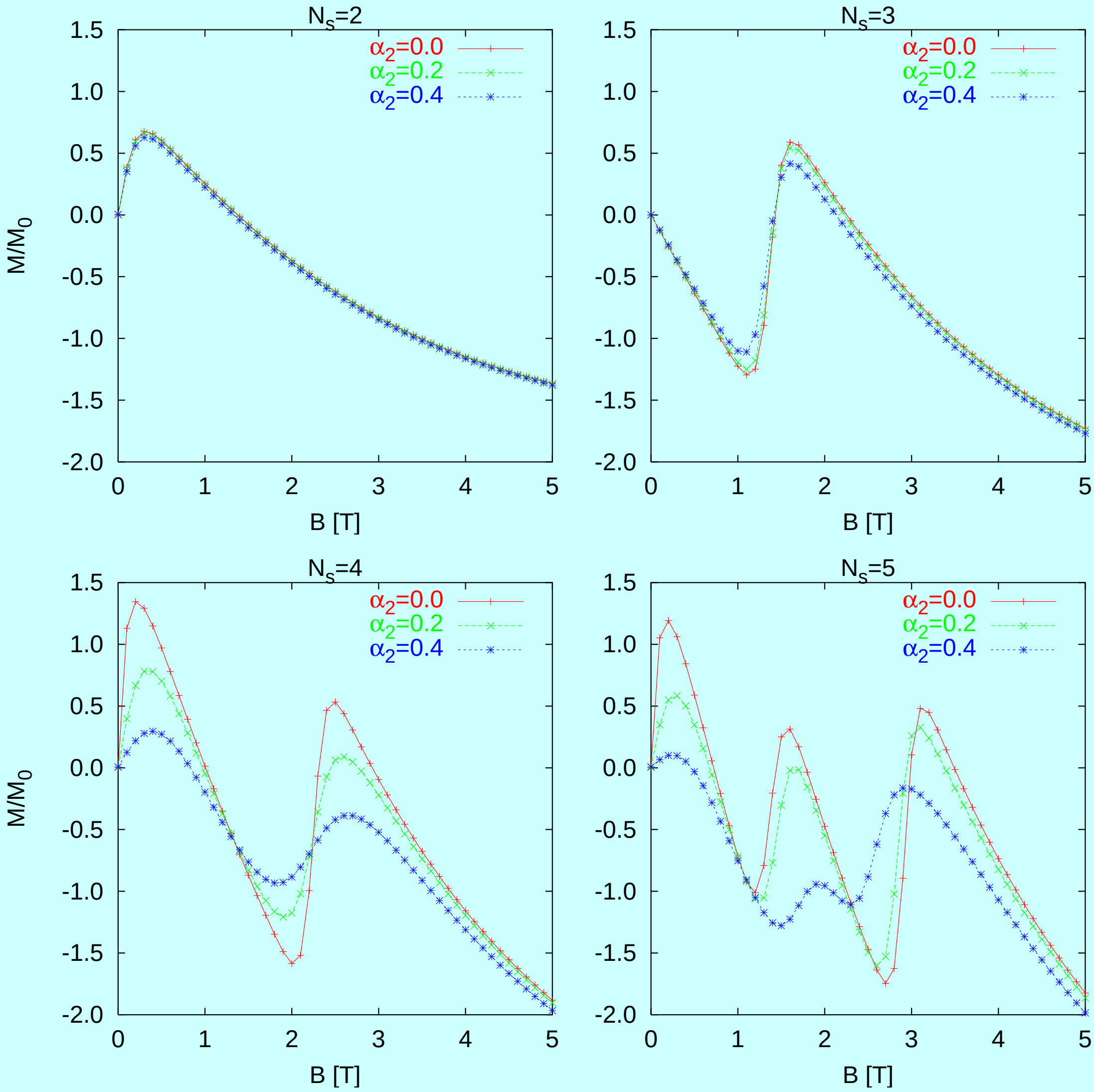
Elliptic dot, energy spectrum

Total energy $\leftrightarrow$ Energy spectrum



noninteracting electrons

Square shaped dot, magnetization

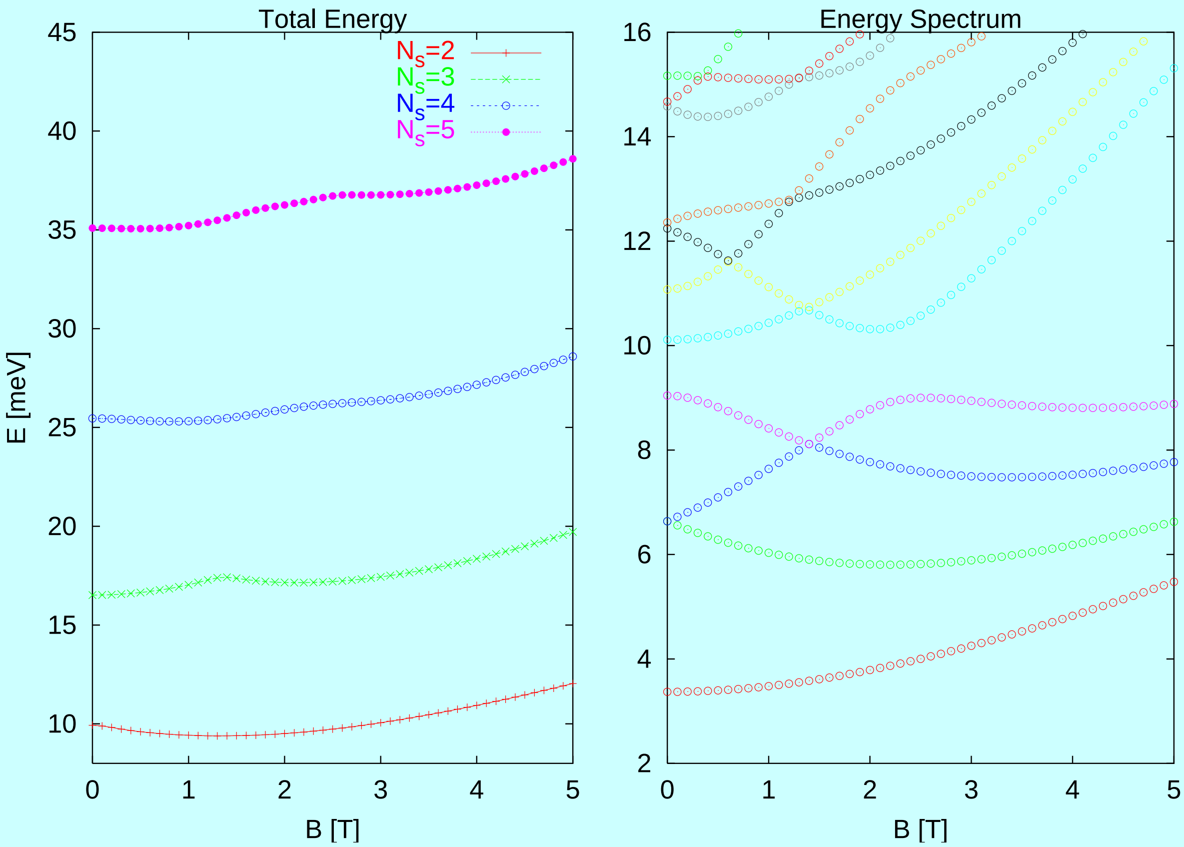


Effects of increased number of electrons and deviation

Noninteracting electrons

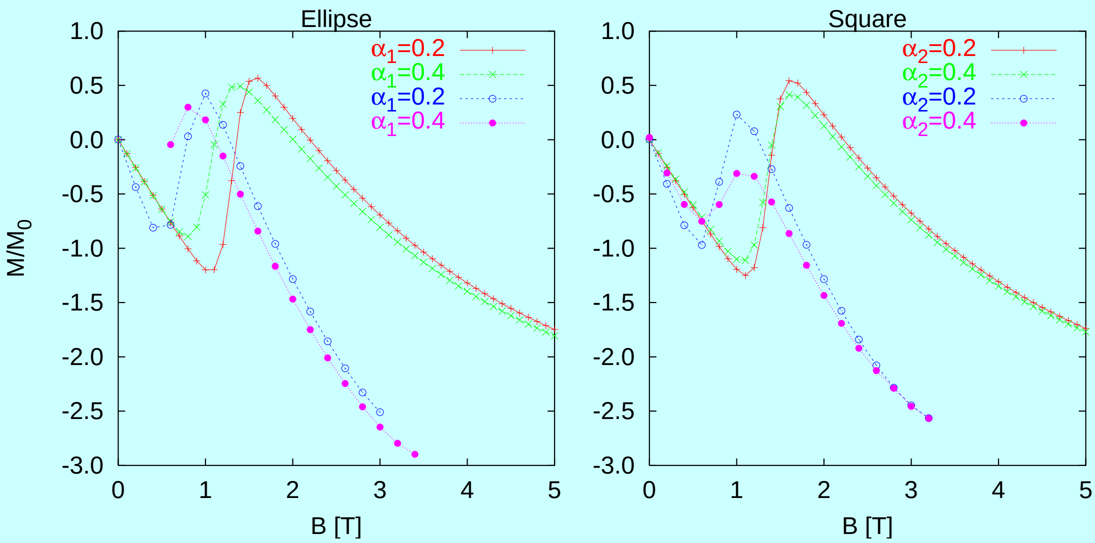
Square shaped dot, energy spectrum

Total energy $\leftrightarrow$ Energy spectrum



noninteracting electrons

Interacting electrons, magnetization



Hartree approximation for interaction

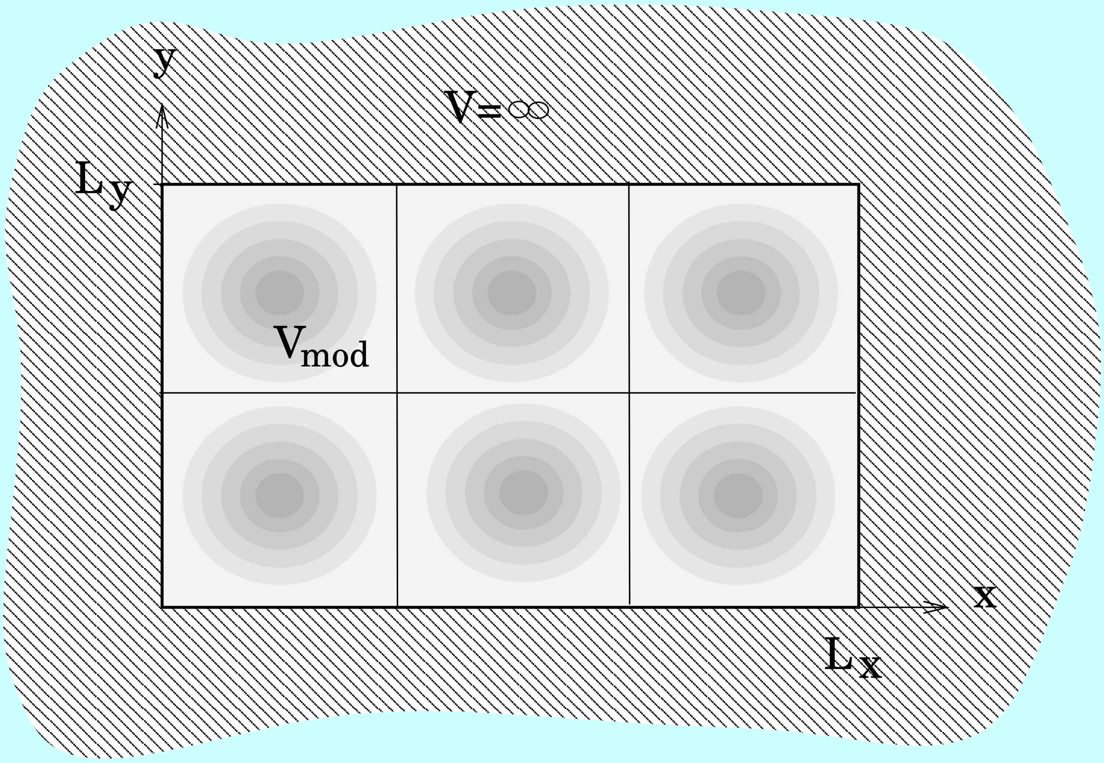
Dots

- Increased $B \rightarrow$ increased momentum of inertia, jumps between many-electron states. Magnified by Coulomb interaction
- For few electrons M depends strongly on N, B, and deviation from circular shape
- Clear signature of many-electron states

Finite system, increased in size, (SIE)

$N_c = n_x \times n_y$ unit cells

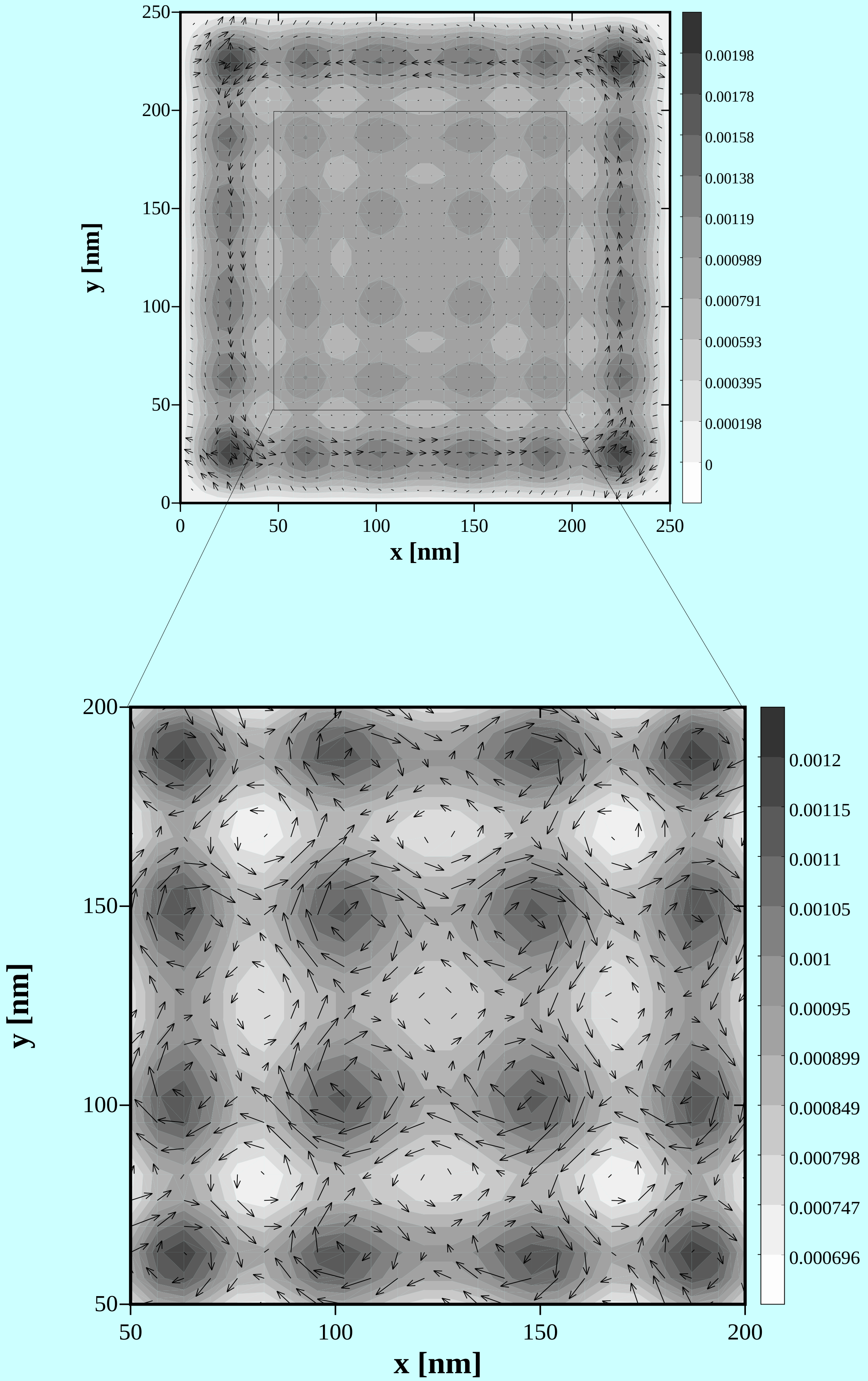
Hartree approximation for interaction



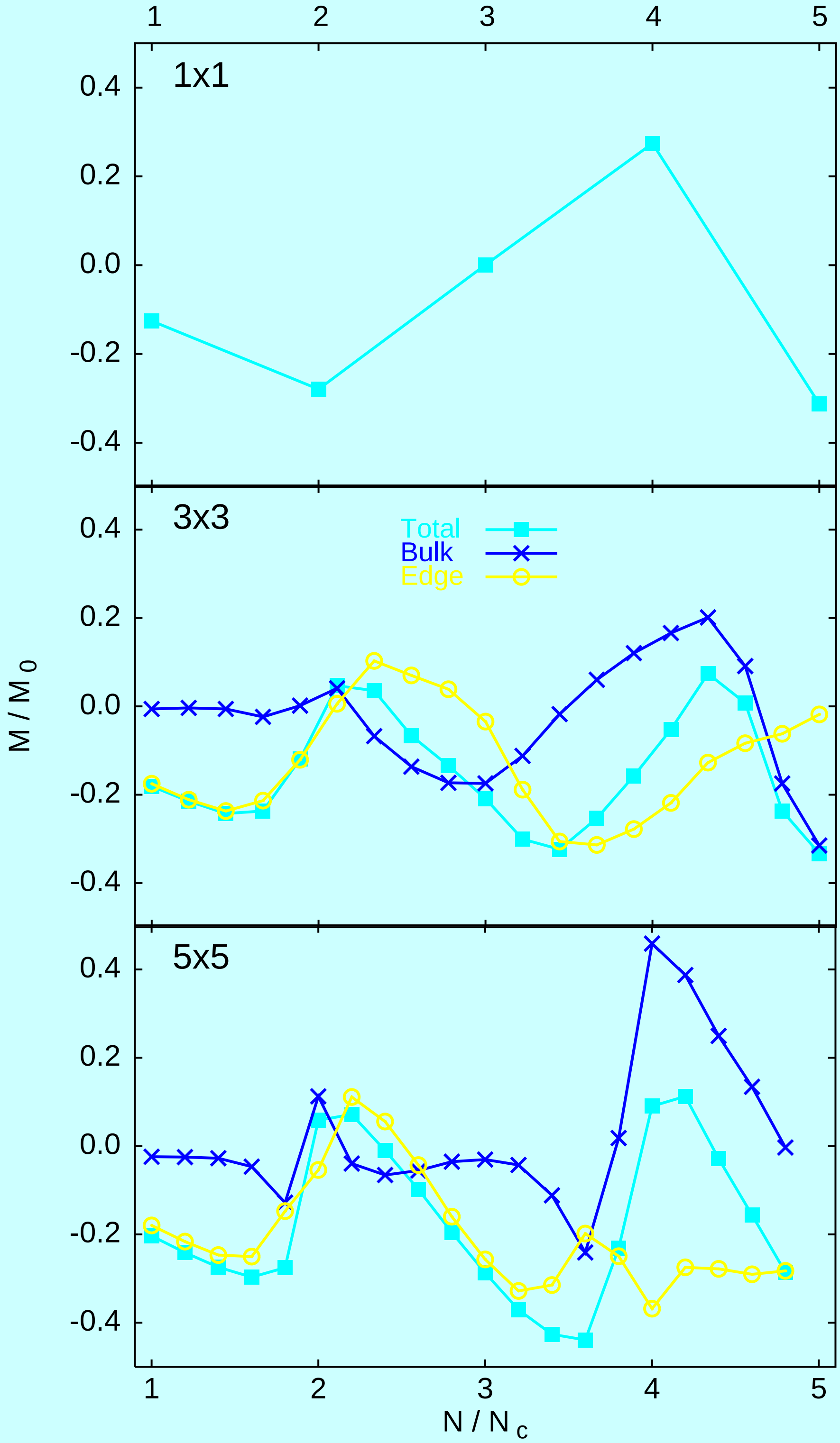
$$V_{\rm sq}(\mathbf{r}) = V_0 \left\{ \sin\left(\frac{n_x \pi x}{L_x}\right) \sin\left(\frac{n_y \pi y}{L_y}\right) \right\}^2 ,$$

$V_0 = -1$ meV, $T = 1$ K, $B = 1.65$ T, $(1 \times \Phi_0$ per cell$)$

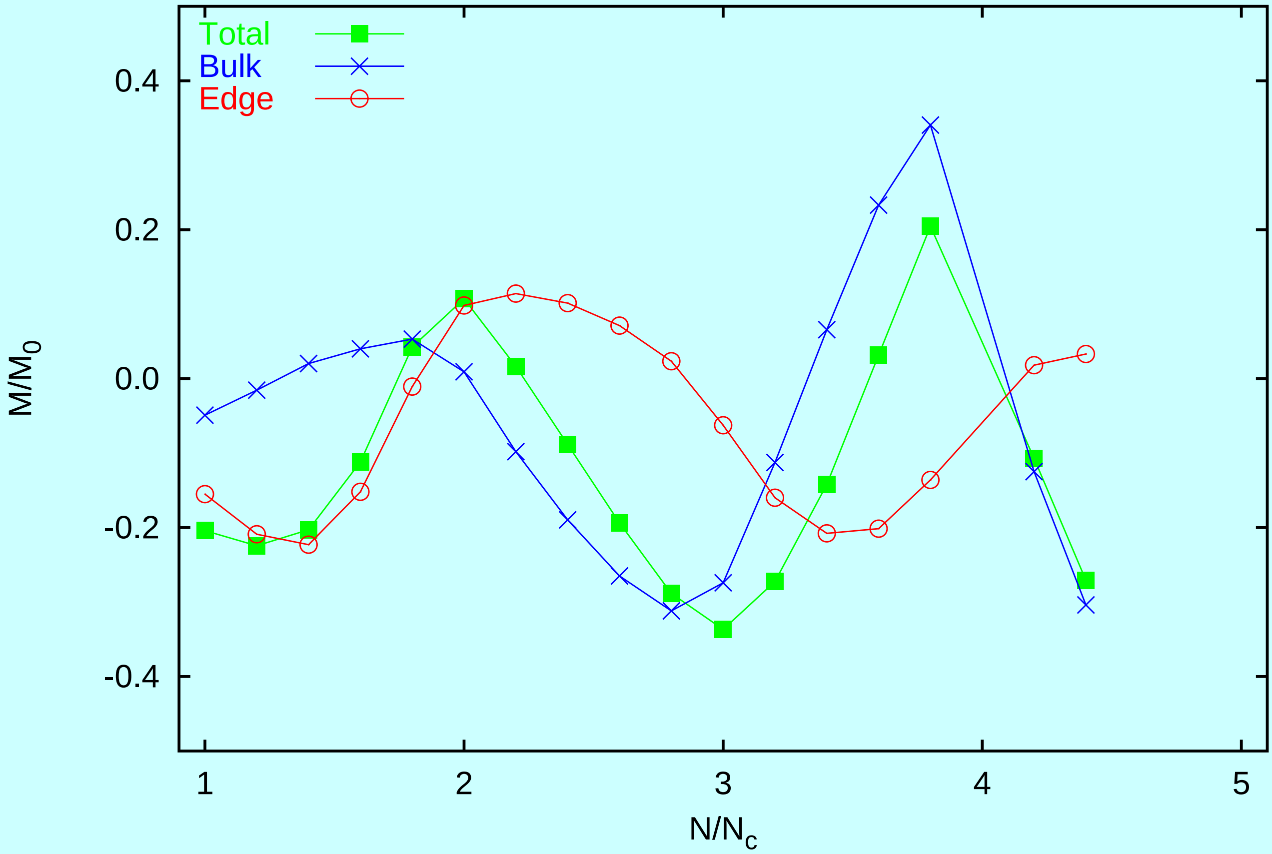
Total = edge + bulk, (arbitrary division)



$\nu \approx N/N_c$

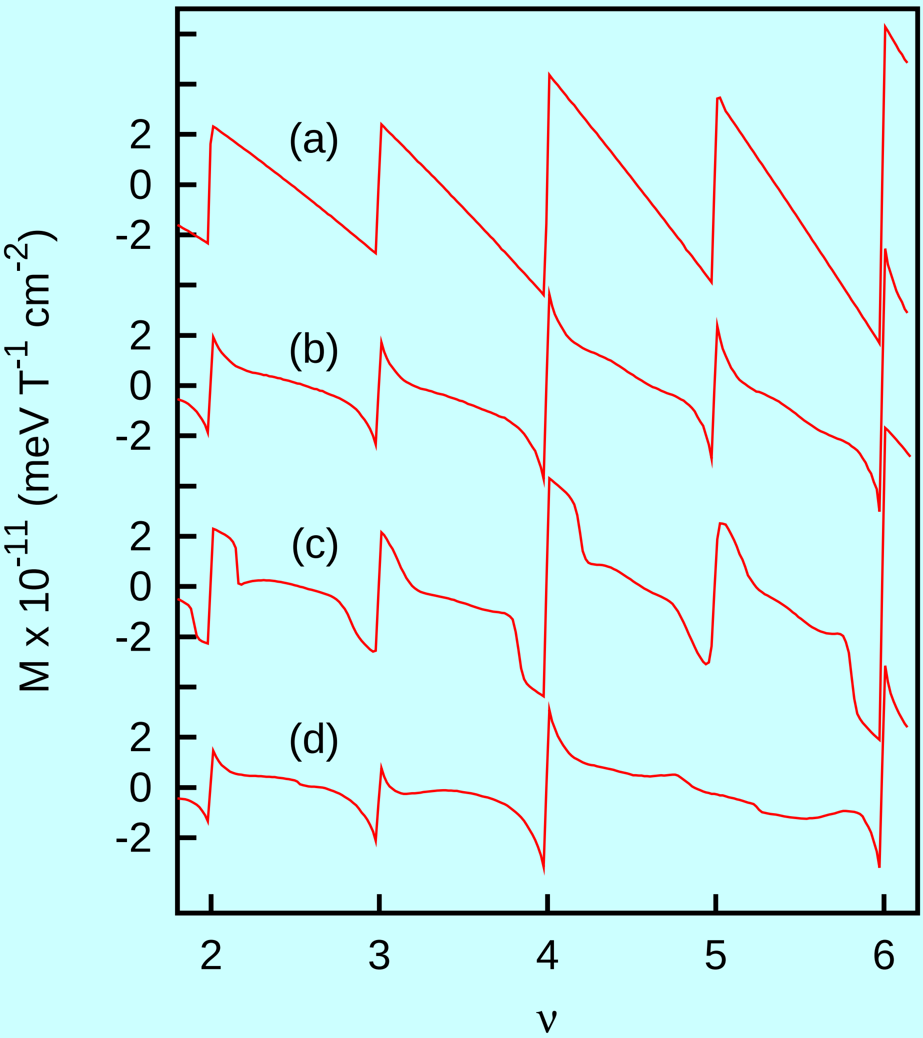


Without interaction, $N_c = 5 \times 5$



- Interaction is important
- Large system $\to$ strong screening, except for $N/N_c \approx \nu =$ integer
- M is similar for weak 1D and 2D modulation
- Bulk contribution is similar to M for an infinite system

Finite 2DEG, 1D modulation, (AM)



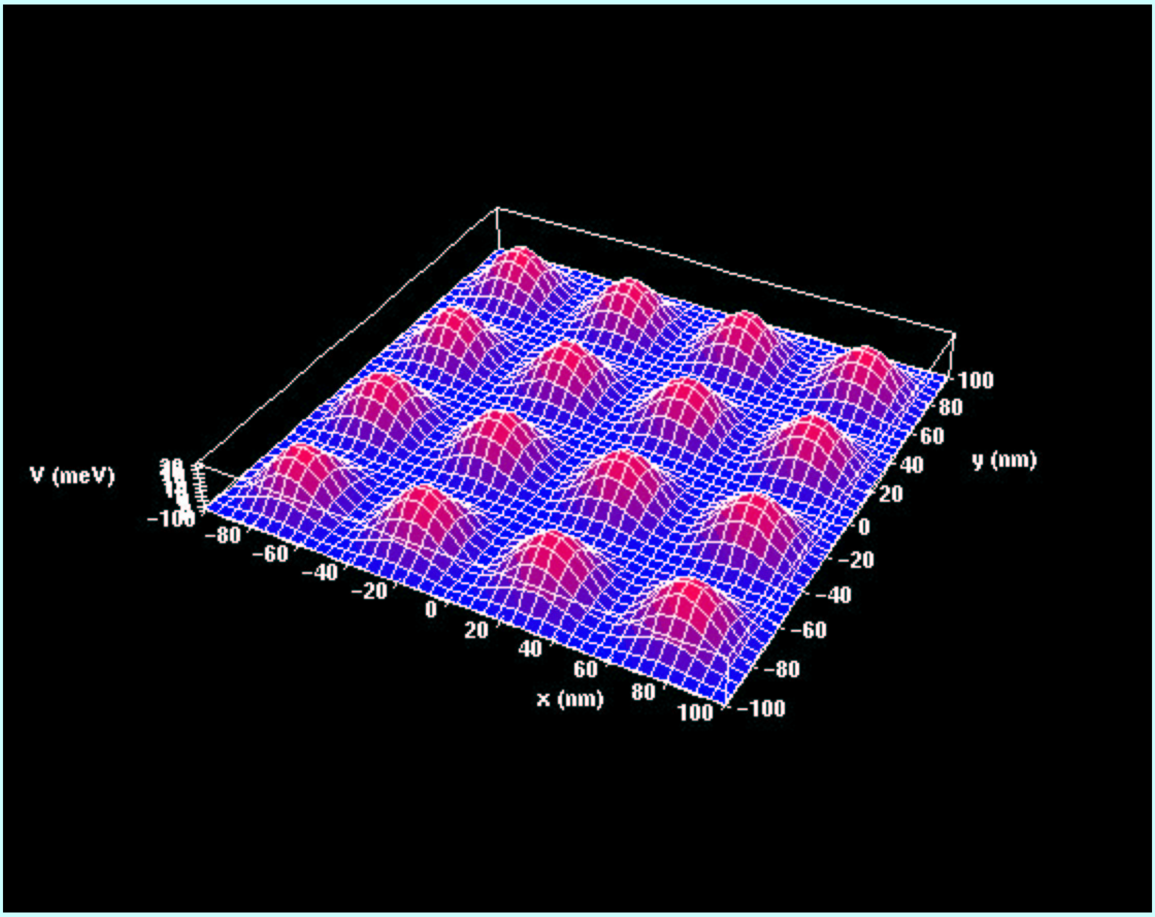
(a): Homogeneous 2DEG (HFA)

(b): 1D modulation, $V_0 = 1.5$ meV, (HFA)

(c): (b)+disorder: $\Gamma = 2.6$ meV

(d): $V_0 = 5$ meV

Finite 2DEG, 2D modulation, (VG)



2D modulation → commensurability problem

→ integer Φ_0 through "unit cell"

→ Hofstadter energy spectrum

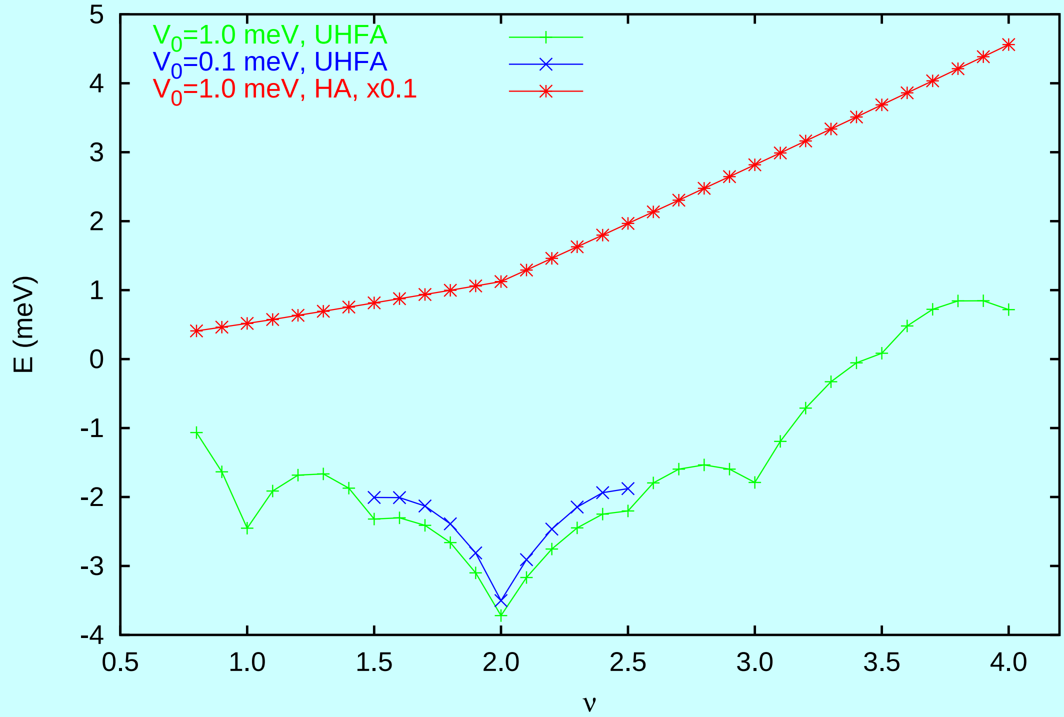
→ technical difficulty calculating $M[E, T, S, B]$

→ Vary electron density, experiment

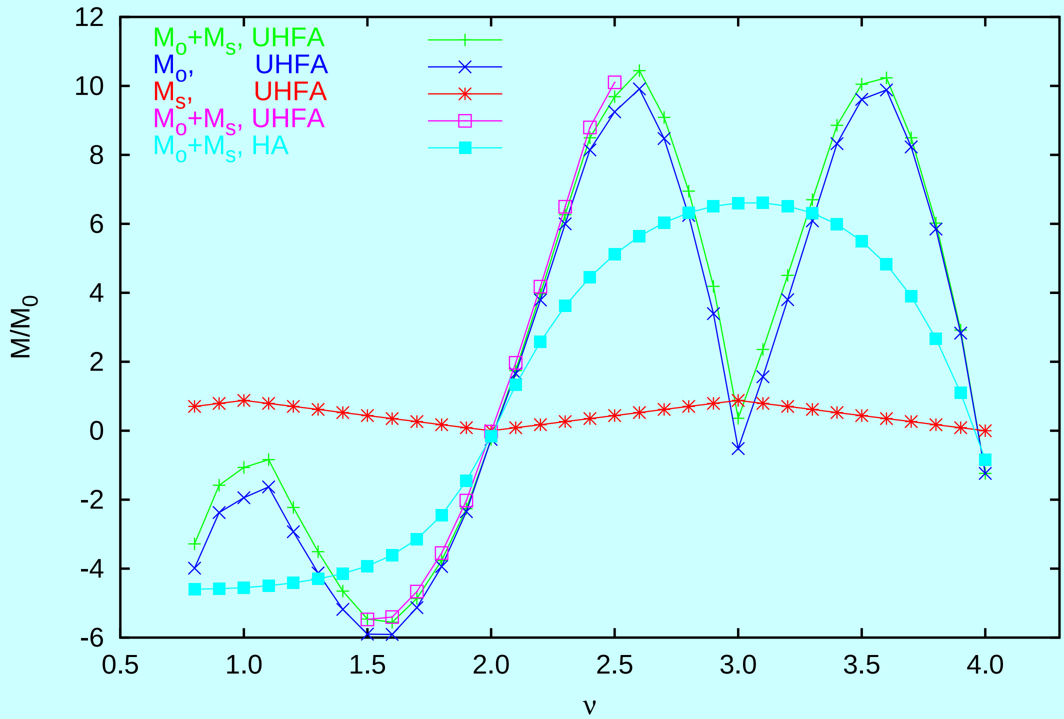
- In a finite system $M[E, T, S, B]$ and $M[J, \sigma, B]$ are equivalent
- $M[E, T, S, B]$ can be derived in a homogeneous infinite system from $M[J, \sigma, B]$ for a finite system in the proper limit "size$\rightarrow \infty$" w.r.t. the edge
- Without the proper limit $M[J, \sigma, B] = 0$ for an infinite homogeneous system $\leftarrow$ no edge
- In our 2D modulated 2DEG $M[J, \sigma, B] \neq 0$ $\leftarrow$ modulation$\neq 0$
- Experiment: SQUID-loop inside system!

Hartree-Fock approximation, $pq \times \Phi_0$ in a unit cell

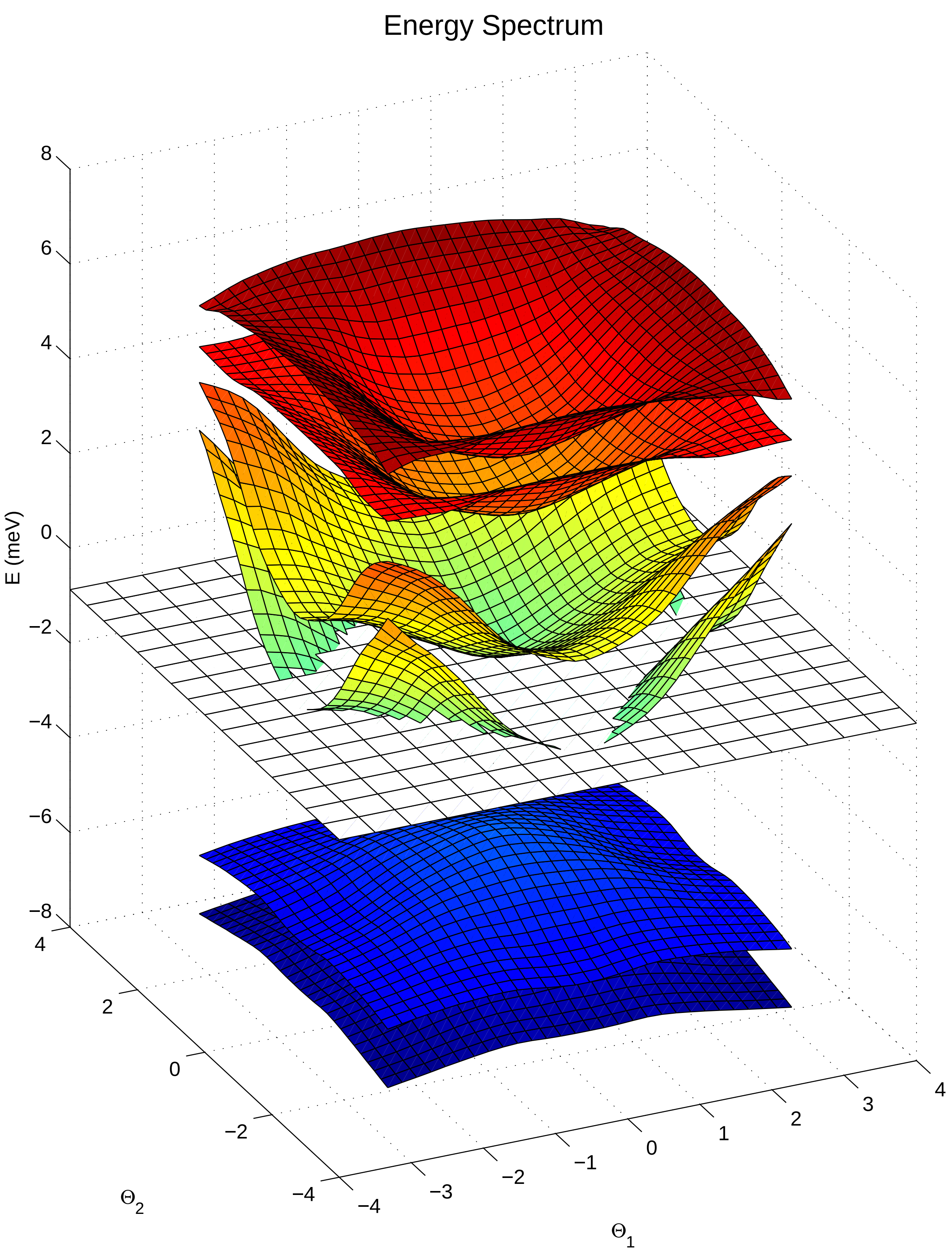
Total energy, $pq=2$



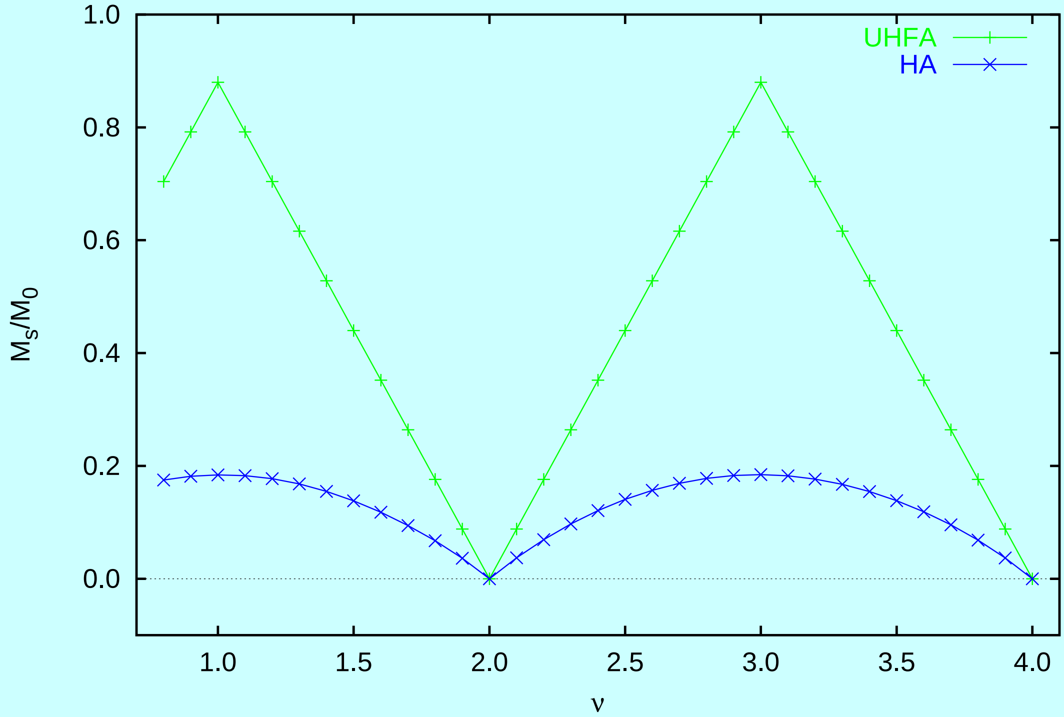
Magnetization, (cosine modulation)



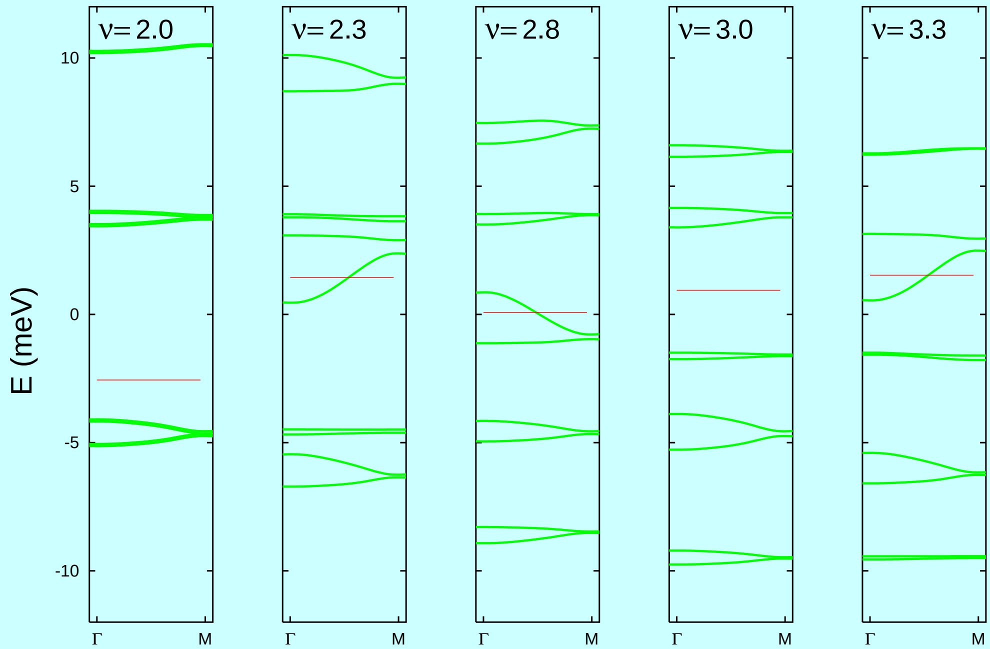
$pq = 1$ 2 fold Landau-bands, (spin), $\nu = 2.55$



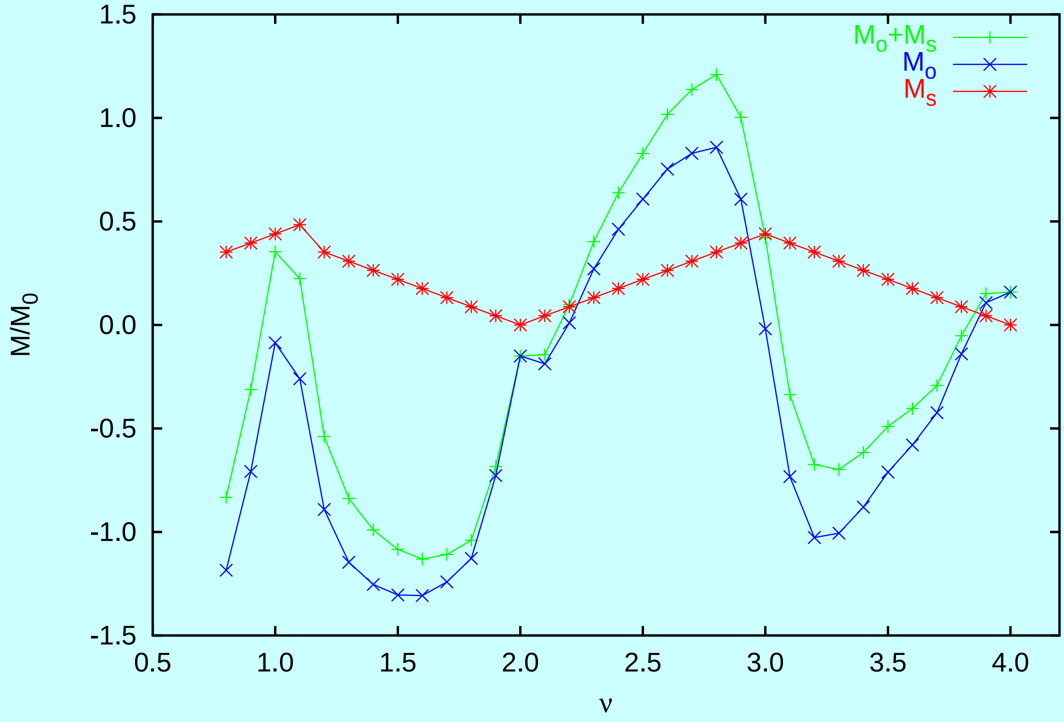
M_s: Spin contribution HA or UHFA



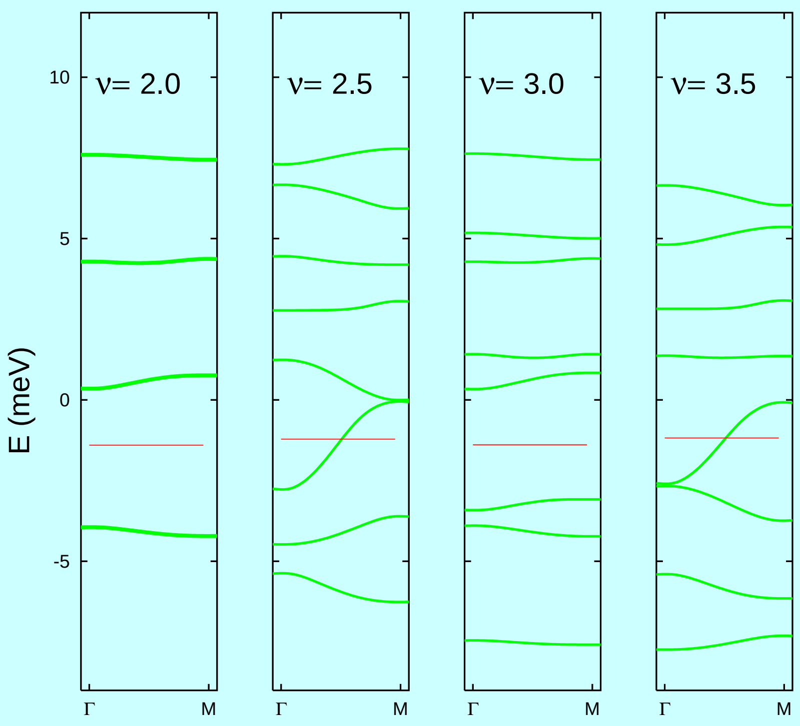
Bandstructure $pq = 2$, 4 fold Landau-bands, (2 spin, 2 Hofstadter)



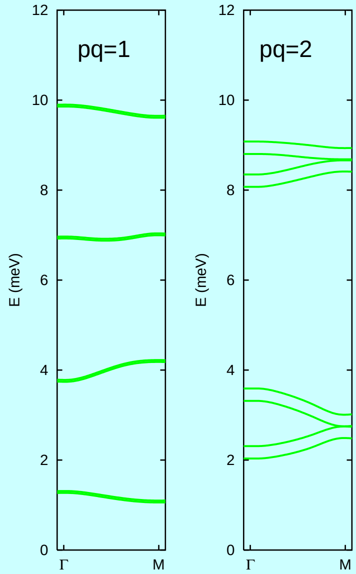
Magnetization $pq = 1$



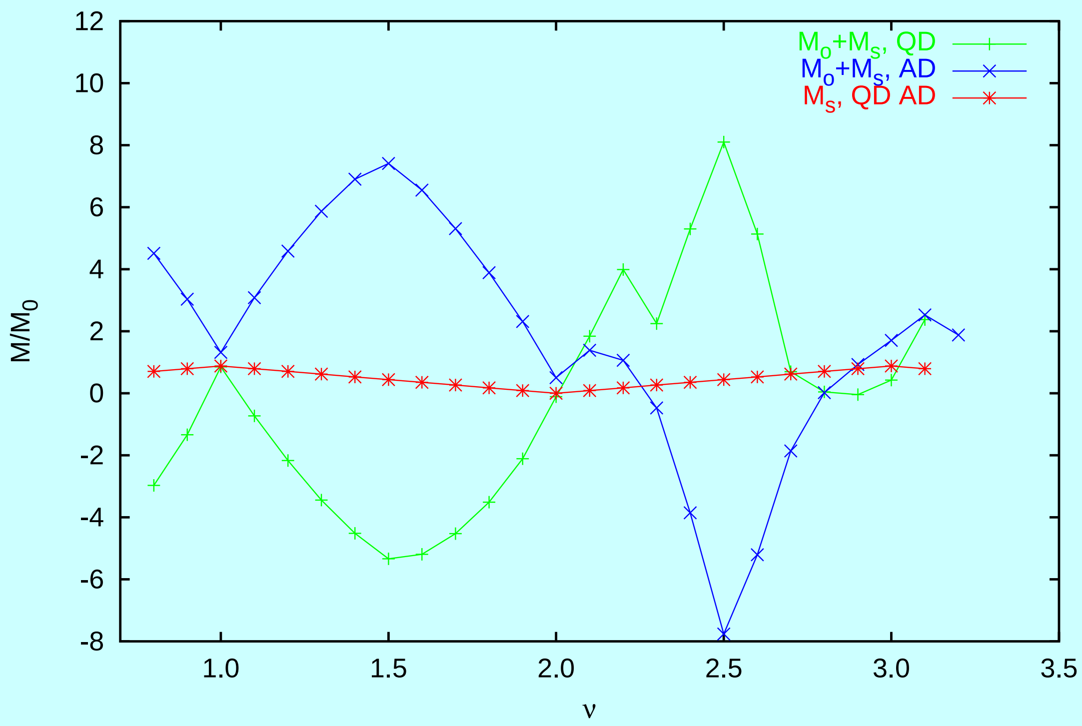
Bandstructure $pq = 1$, 2 fold Landau-bands, (2 spin, 1 Hofstadter)



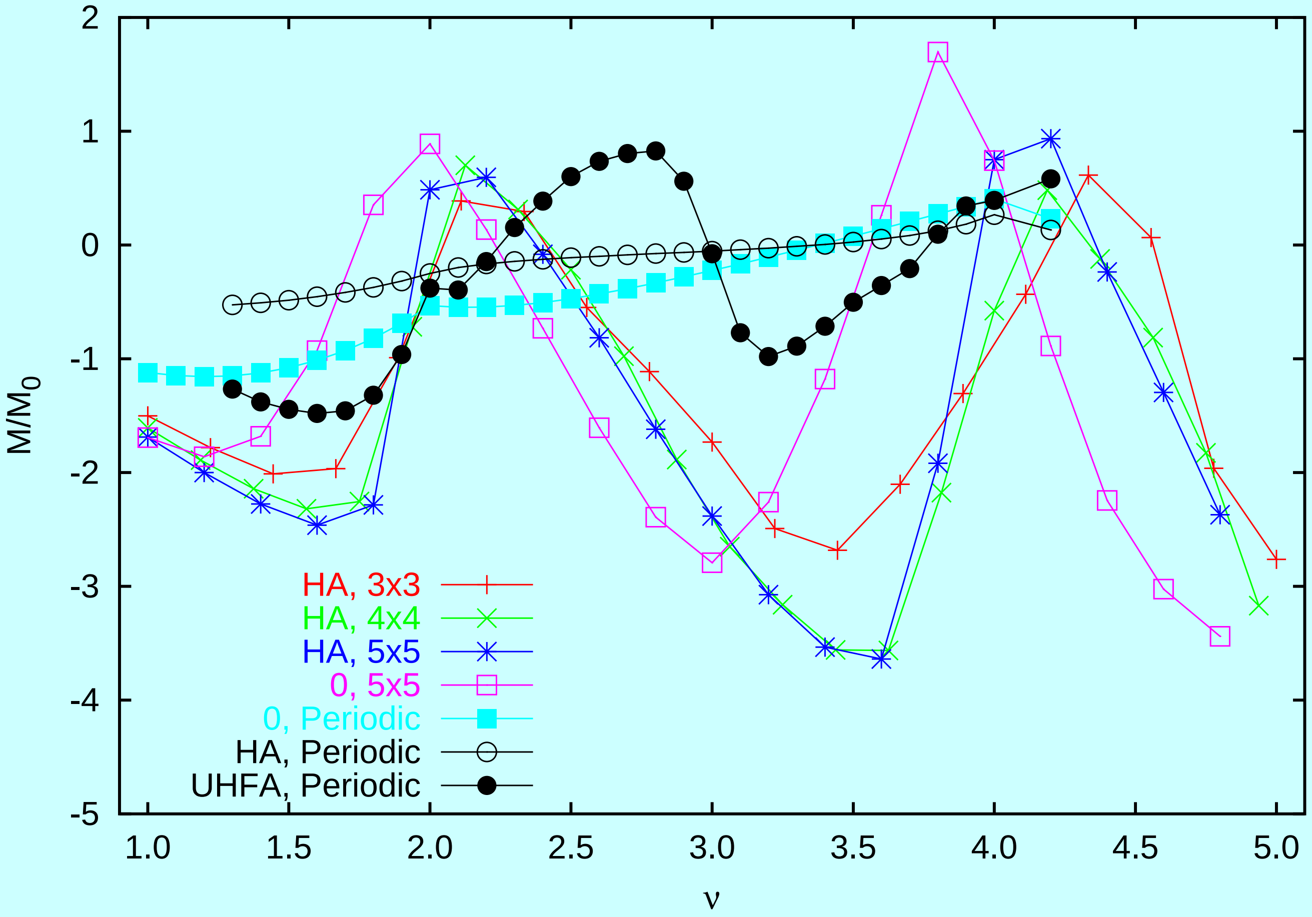
Noninteracting Bandstructure, (static)



$pq = 2$, Dot- antidot array, $V_0 = \pm 5$ meV



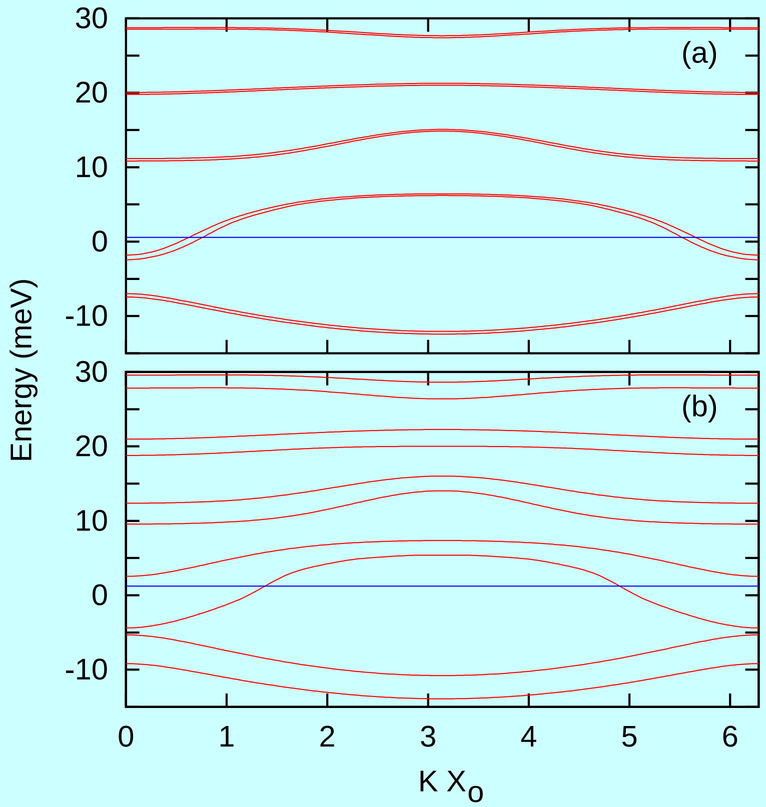
Symmetry ← finite M only due to modulation

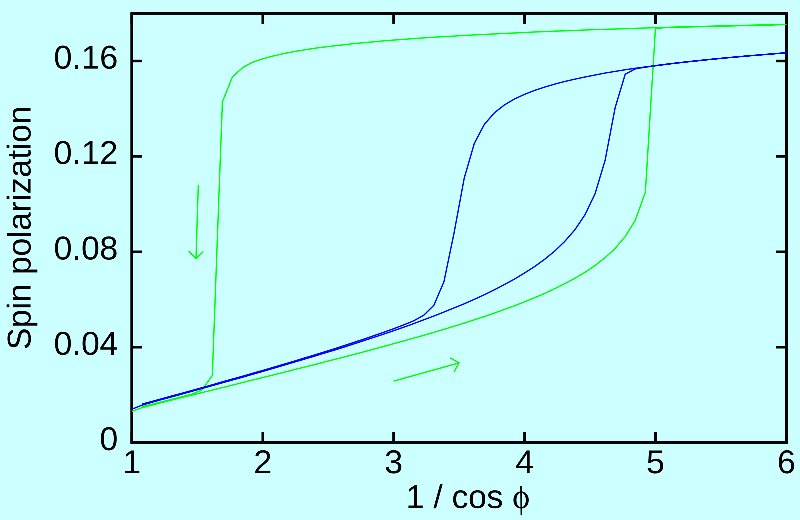


- Infinite 2D modulated 2DEG has no boundary
- Effects of edge states is not simple
  - Direct effects on M_e
  - Indirect effects on M_b through self-consistent shape of energy bands
  - Connected to motion of μ through bands

Hysteresis, (AM)

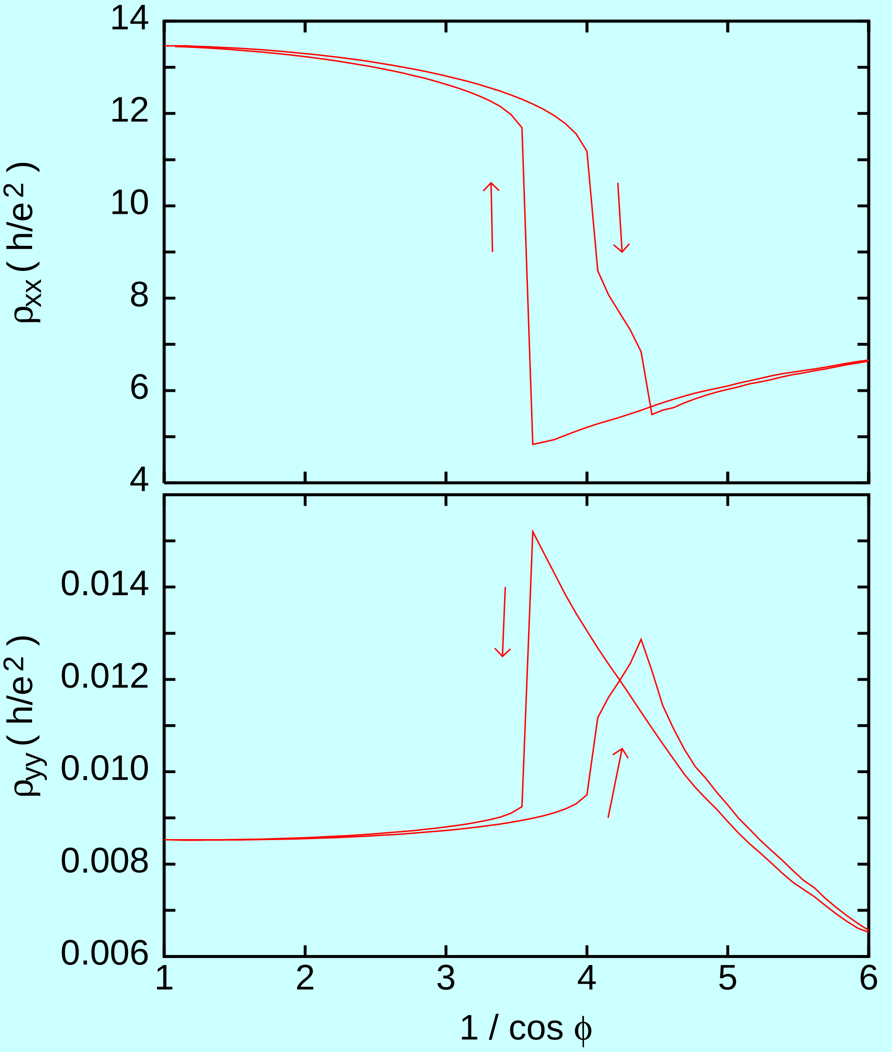
1D modulation, short period: $a = 40$ nm, $V_0 = 9$ meV, cosine modulation





Sample tilted ϕ, $T =$ 5 K, 7 K

Visible in transport



Short period, strong modulation

→ weak screening of exchange force

Results

- Magnetization is promising for investigation of the ground state
- Magnetization of a Hofstadter system?
- Essential to improve and study approximation of the Coulomb interaction
- Magnetization measurements of structured systems