Strongly correlated states of trapped ultracold fermions in a U(2) gauge potential

Matteo Rizzi
Johannes Gutenberg-Universität Mainz

Frontiers in quantum simulations with cold atoms
INT-Seattle, 9 April 2015

M.Burrello, **MR**, M.Roncaglia, A.Trombettoni, PRB 91, 115117 (2015)

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

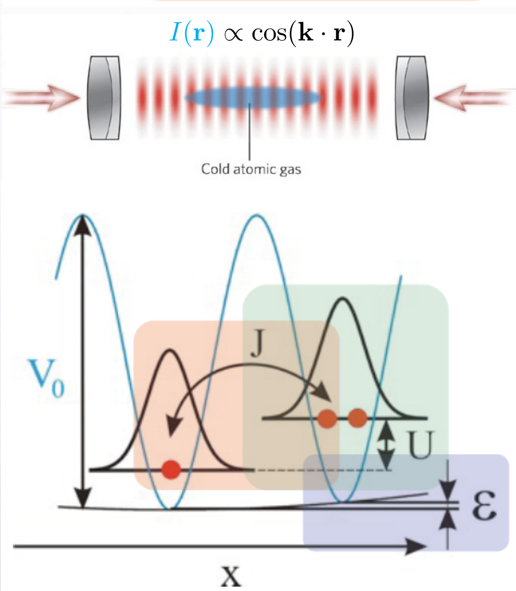
M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni

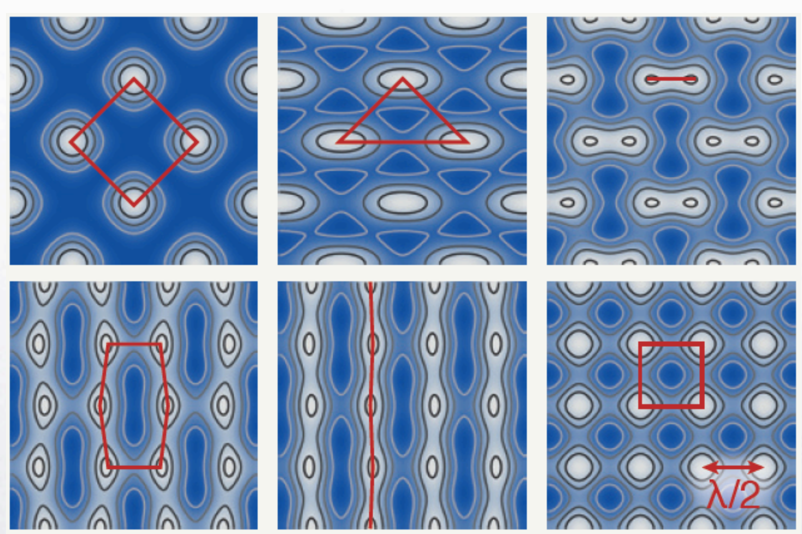
arXiv:1411.5962

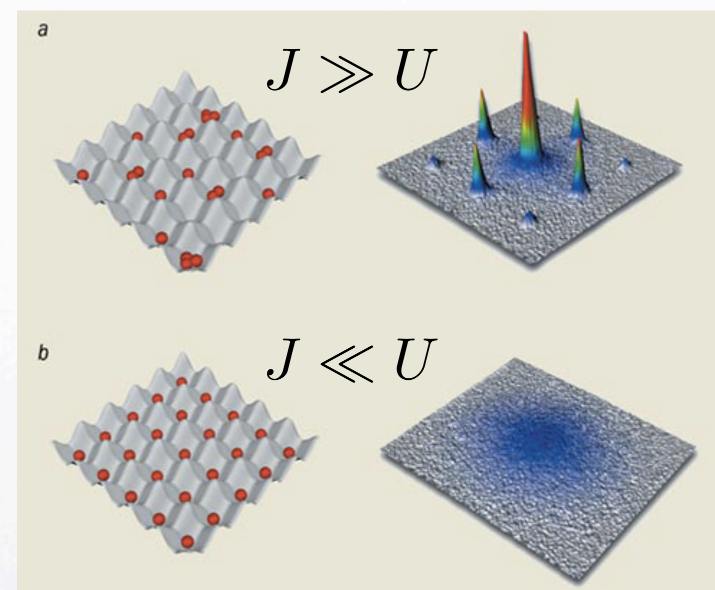
Quantum Engineering

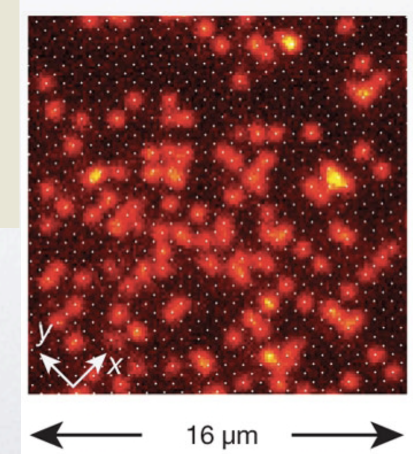
- analog implementation of solid-state systems, with added values:
  - isolated neutral quantum systems (long coherence times)
  - high tunability of microscopic parameters (also interactions!)
  - access to many microscopic observables
- GOAL: answering questions untreatable by classical calculations (!?)

$$H = -J \sum_{<i,j>} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i(\hat{n}_i - 1)$$









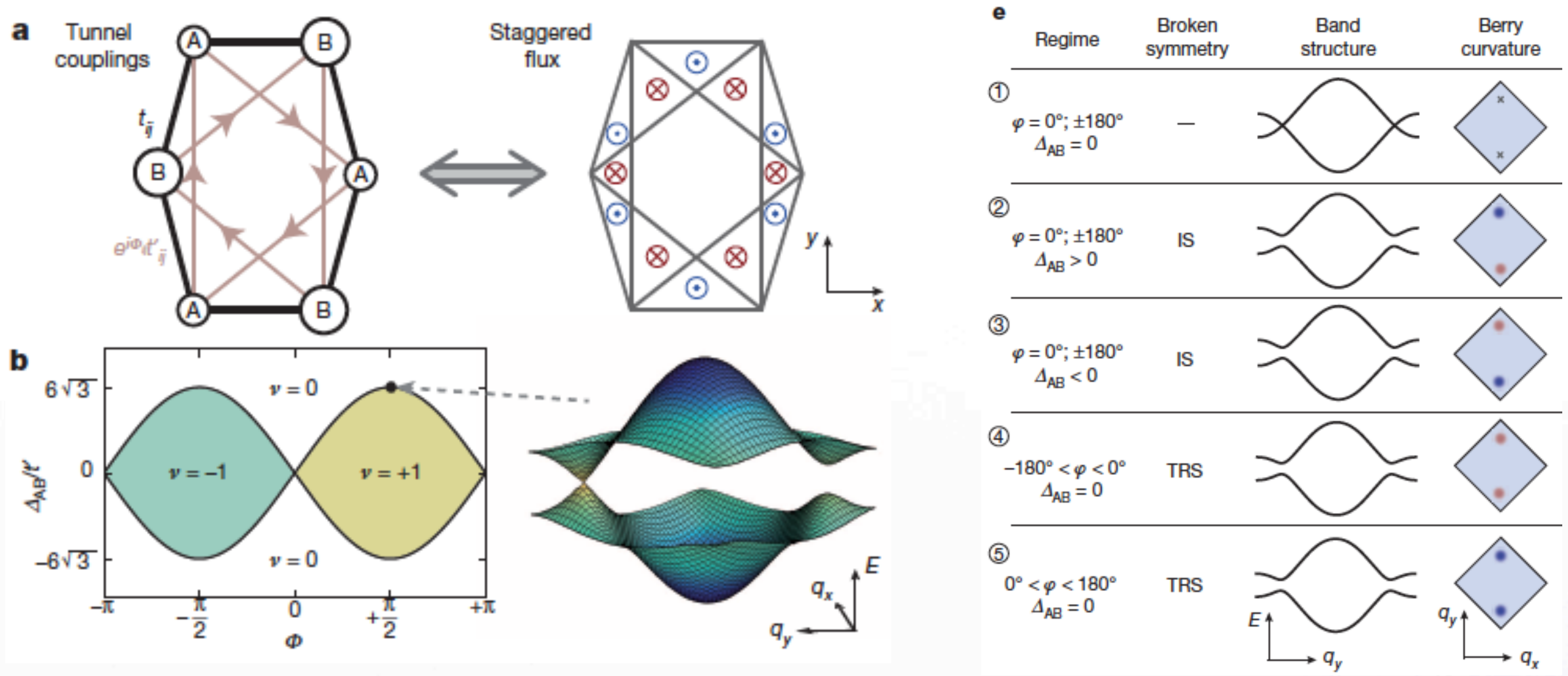
M. Lewenstein, et al., Adv Phys 56, 243–379 (2007).
I. Bloch, J. Dalibard, W. Zwerger, RMP 80, 885 (2008)

Quantum Engineering

- BUT can we go beyond emulation / simulation of *existing* regimes?

e.g.
Haldane model @ ETH

G. Jotzu, et al., Nature **515**, 237 (2014)

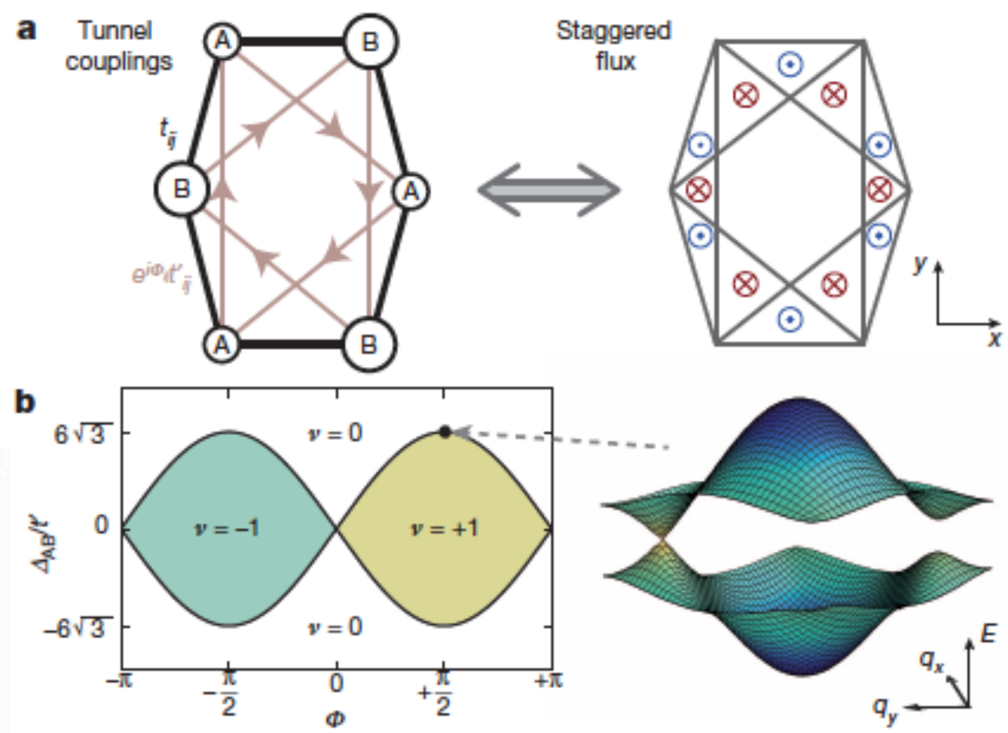


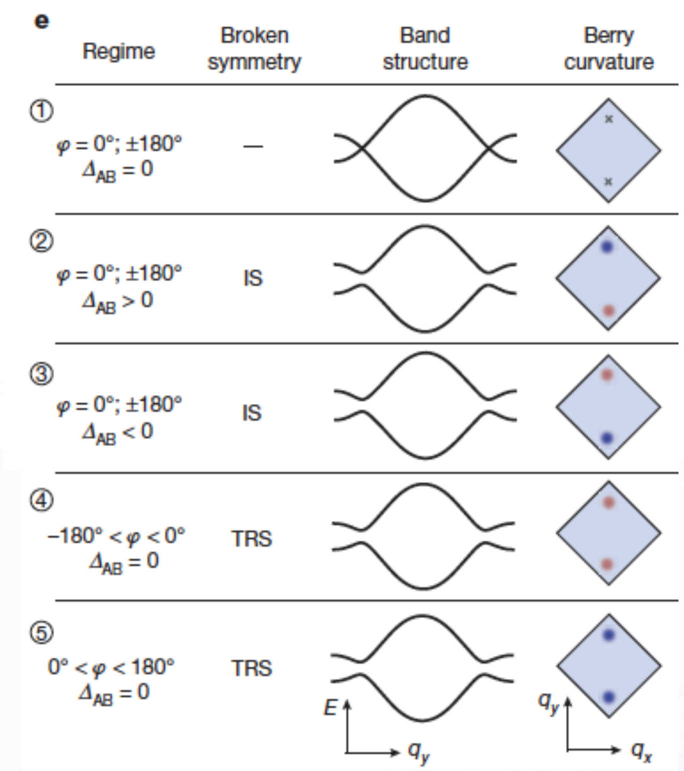
Quantum Engineering

- BUT can we go beyond emulation / simulation of *existing* regimes?

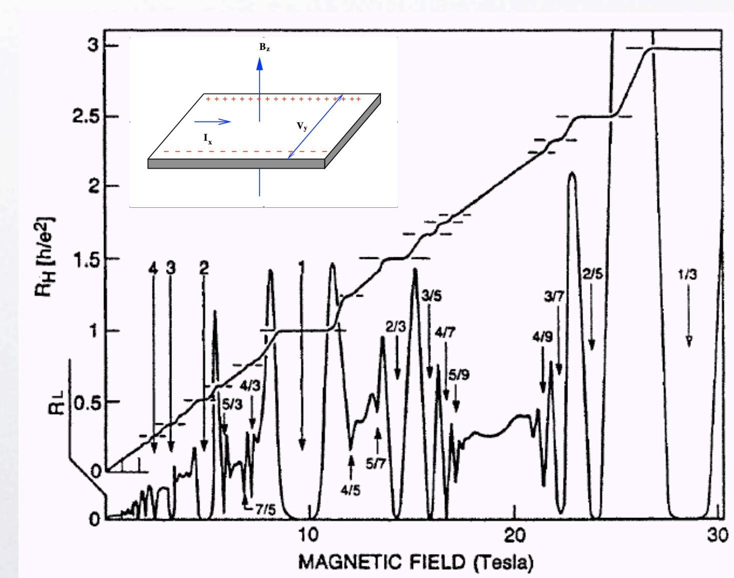
e.g.
Haldane model @ ETH

G. Jotzu, et al., Nature **515**, 237 (2014)





- HERE, focus on Fractional Quantum Hall states:
  - a wealth of exotic states & topological properties predicted "mathematically" for "strange" interaction & gauge potential forms
  - but in semiconductors 2DEG, almost no tunability !



Strongly correlated states of trapped ultracold fermions in a U(2) gauge potential

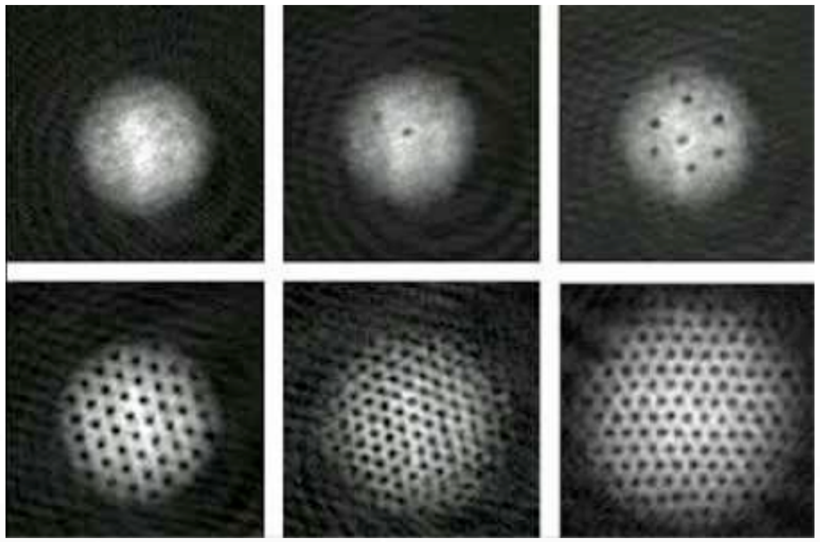
matteo.rizzi@uni-mainz.de

M.Burrello, **MR**, M.Roncaglia, A.Trombettoni

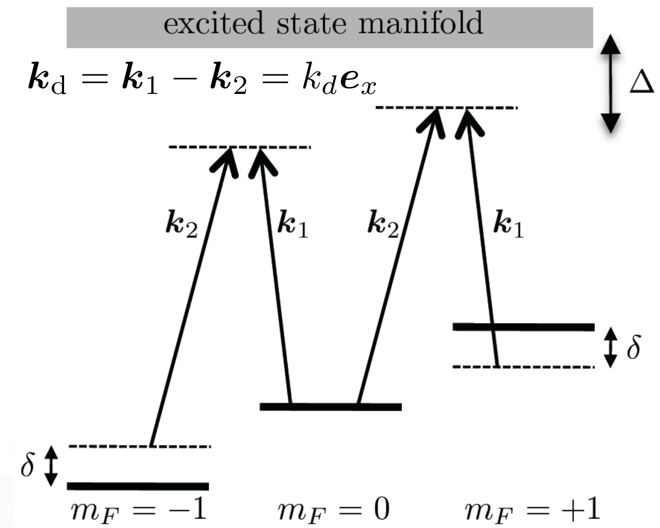
PRB 91, 115117 (2015)

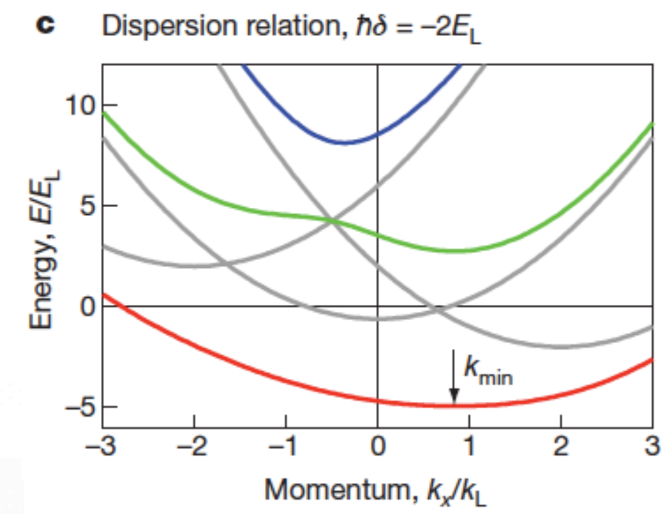
Gauge potentials in cold atoms

- fast rotation

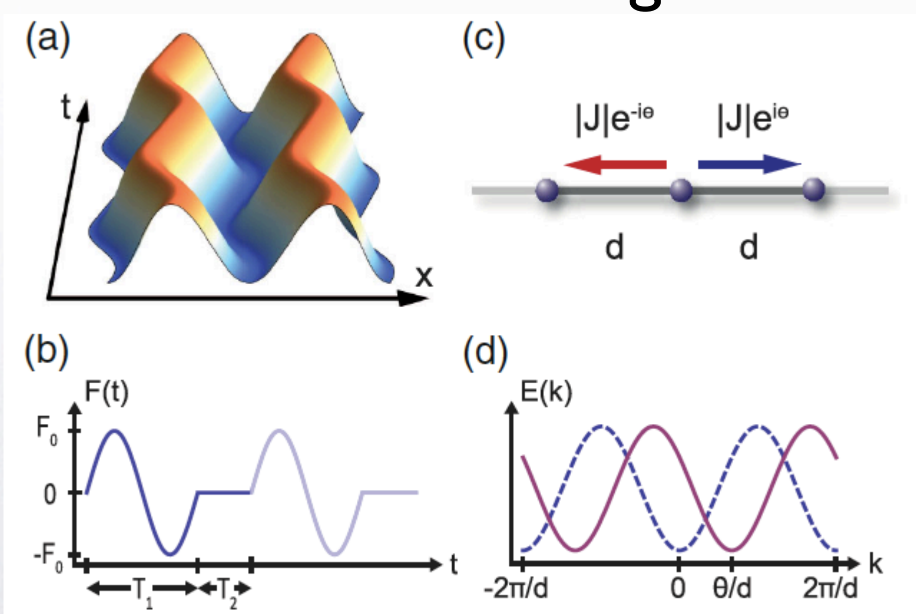


- adiabatic Berry phase

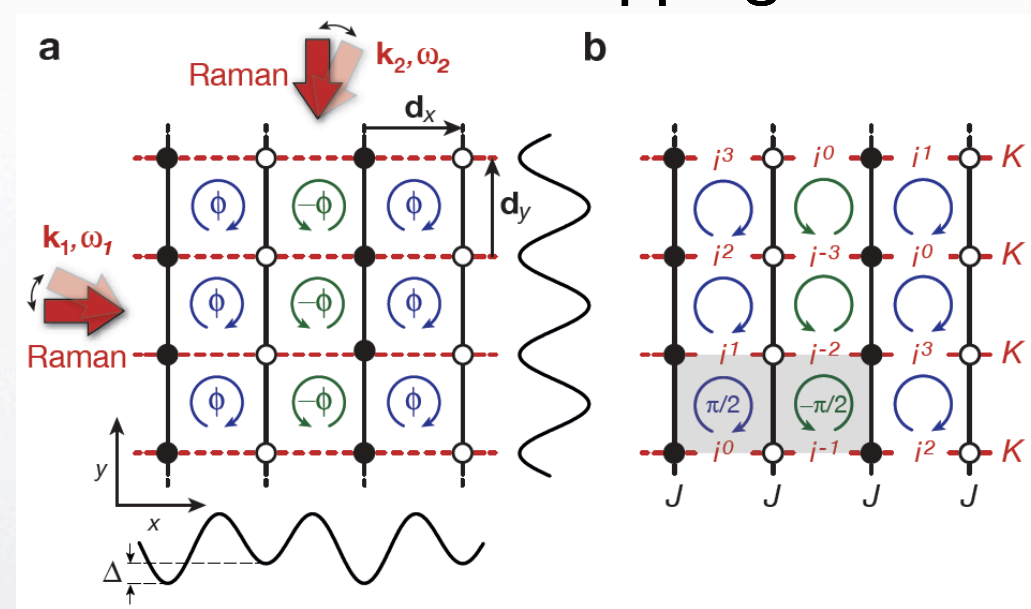




- lattice shaking



- Raman hopping



Dalibard, Gerbier, Juzeliunas, and Öhberg, RMP 83, 1523 (2011)
Goldman, Juzeliunas, Öhberg, and Spielman, Rep. Prog. Phys. **77** 126401 (2014)

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
arXiv:1411.5962

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni

arXiv:1411.5962

Single particle Hamiltonian

$$H = (p_x \mathbb{I} + \mathcal{A}_x)^2 + (p_y \mathbb{I} + \mathcal{A}_y)^2$$

$m = 1/2$

$\hbar = e = c = 1$

- U(1) magnetic field + SU(2) spin-orbit = U(2) gauge

$$\vec{\mathcal{A}} = \left(-\frac{y\mathcal{B}}{2}\mathbb{I} + q\sigma_x ; \frac{x\mathcal{B}}{2}\mathbb{I} + q\sigma_y , ; 0 \right)$$

$$[\mathcal{A}_x, \mathcal{A}_y] \neq 0$$

- spatial components of $F^{\mu\nu} = [D^\mu, D^\nu]$ are not everything !

$$\vec{F} = \vec{\nabla} \times \vec{\mathcal{A}} + i\vec{\mathcal{A}} \times \vec{\mathcal{A}} = (\mathcal{B}\,\mathbb{I} - 2q^2\sigma_z)\,\hat{z}$$

$$U(2) \neq U(1) \times U(1)$$

Single particle Hamiltonian

$$H = (p_x \mathbb{I} + \mathcal{A}_x)^2 + (p_y \mathbb{I} + \mathcal{A}_y)^2 + \frac{\omega^2 r^2}{4}\mathbb{I}$$

$m = 1/2$
$\hbar = e = c = 1$

- U(1) magnetic field + SU(2) spin-orbit = U(2) gauge

$$\vec{\mathcal{A}} = \left(-\frac{y\mathcal{B}}{2}\mathbb{I} + q\sigma_x ; \frac{x\mathcal{B}}{2}\mathbb{I} + q\sigma_y, ; 0 \right) \qquad [\mathcal{A}_x, \mathcal{A}_y] \neq 0$$

- spatial components of $F^{\mu\nu} = [D^\mu, D^\nu]$ are not everything !

$$\vec{F} = \vec{\nabla} \times \vec{\mathcal{A}} + i\vec{\mathcal{A}} \times \vec{\mathcal{A}} = (\mathcal{B}\mathbb{I} - 2q^2\sigma_z)\,\hat{z} \qquad U(2) \neq U(1) \times U(1)$$

- weak harmonic confinement

$$B \equiv \sqrt{\mathcal{B}^2 + \omega^2}$$
$$\Delta \equiv B - \mathcal{B} \sim \omega^2/2B \longrightarrow -L_z\Delta$$

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**, M.Roncaglia, A. Trombettoni
PRB 91, 115117 (2015)

Single particle Hamiltonian

$$H = (p_x \mathbb{I} + \mathcal{A}_x)^2 + (p_y \mathbb{I} + \mathcal{A}_y)^2 + \frac{\omega^2 r^2}{4}\mathbb{I} + V_s(x,y)$$

$m = 1/2$

$\hbar = e = c = 1$

- U(1) magnetic field + SU(2) spin-orbit = U(2) gauge

$$\vec{\mathcal{A}} = \left(-\frac{y\mathcal{B}}{2}\mathbb{I} + q\sigma_x ; \frac{x\mathcal{B}}{2}\mathbb{I} + q\sigma_y, ; 0 \right) \qquad [\mathcal{A}_x, \mathcal{A}_y] \neq 0$$

- spatial components of $F^{\mu\nu} = [D^\mu, D^\nu]$ are not everything !

$$\vec{F} = \vec{\nabla} \times \vec{\mathcal{A}} + i\vec{\mathcal{A}} \times \vec{\mathcal{A}} = \left(\mathcal{B}\mathbb{I} - 2q^2\sigma_z\right)\hat{z} \qquad U(2) \neq U(1) \times U(1)$$

- weak harmonic confinement

$$B \equiv \sqrt{\mathcal{B}^2 + \omega^2}$$
$$\Delta \equiv B - \mathcal{B} \sim \omega^2/2B \longrightarrow -L_z\Delta$$

- compensating Zeeman field $V_s(x,y) = -q\Delta\left(y\sigma_x - x\sigma_y\right)$

matteo.rizzi@uni-mainz.de

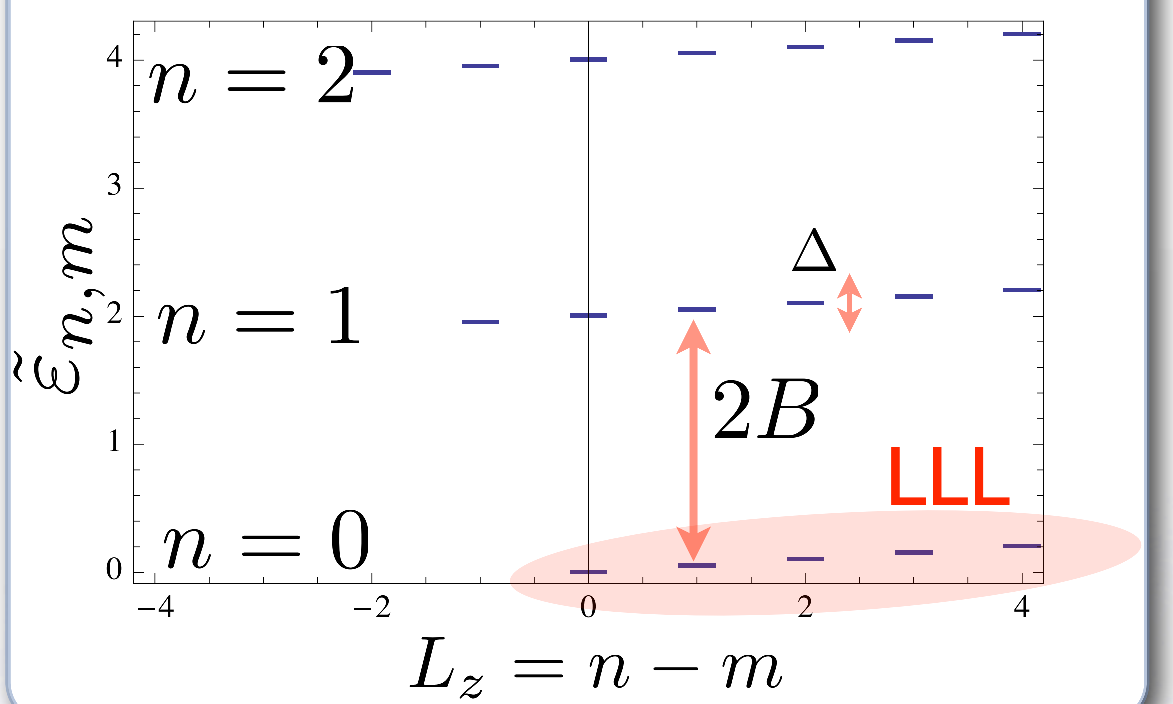
M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni
PRB 91, 115117 (2015)

Deformed Landau Levels

$$H = \left(p_x - \frac{yB}{2} + q\sigma_x\right)^2 + \left(p_y + \frac{xB}{2} + q\sigma_y\right)^2 - L_z\Delta$$

- q=0: orbital eigenstates $\psi_{n,m}$
- Lowest Landau Level (LLL) approx.

$N\Delta \ll 2B \qquad k_{\rm B}T \ll 2B$



Deformed Landau Levels

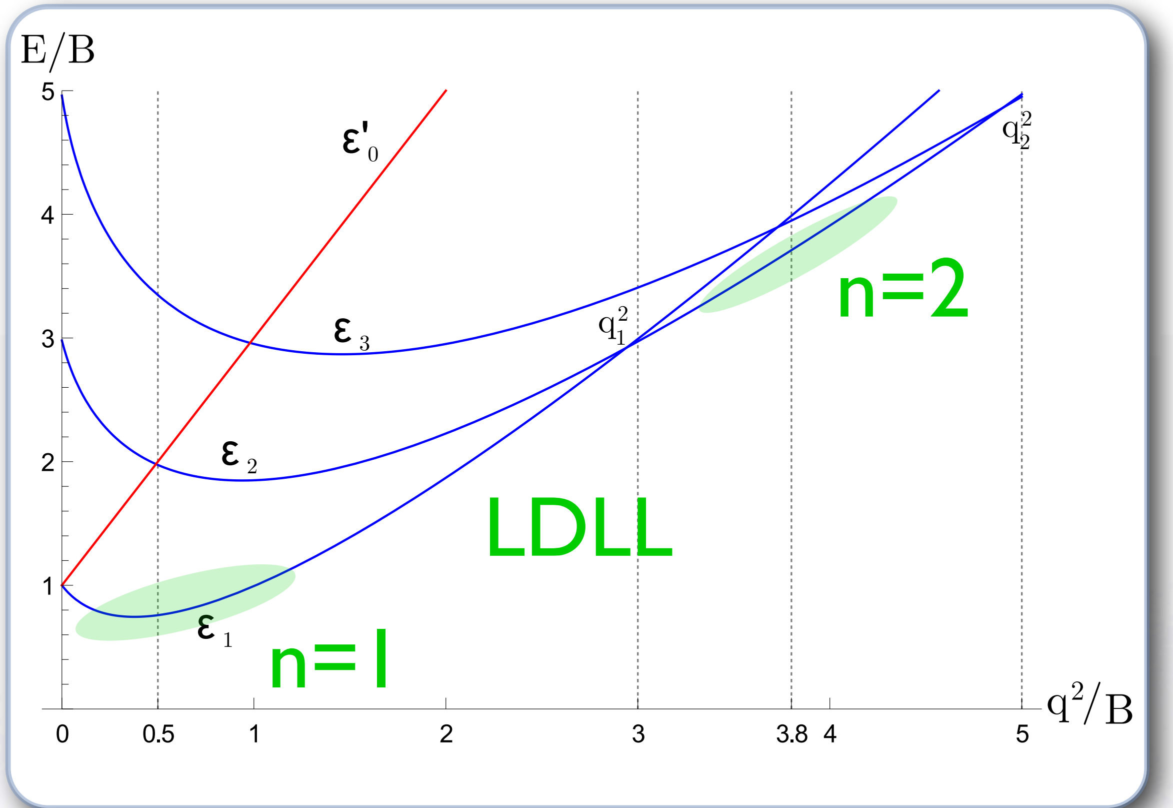
$$H = \left(p_x - \frac{yB}{2} + q\sigma_x\right)^2 + \left(p_y + \frac{xB}{2} + q\sigma_y\right)^2 - L_z\Delta$$

- q=0: orbital eigenstates $\psi_{n,m}$
- Lowest Landau Level (LLL) approx.

  $N\Delta \ll 2B \qquad k_{\mathrm{B}}T \ll 2B$

- q≠0: Jaynes-Cummings in the basis

  $\{\psi_{n-1,m}|\uparrow\rangle,\ \psi_{n,m}|\downarrow\rangle\}$



$$H_{n,m} = \tilde{\varepsilon}_{n,m}\,\mathbb{I} + D_n \begin{pmatrix} -\cos\varphi_n & \sin\varphi_n \\ \sin\varphi_n & \cos\varphi_n \end{pmatrix}$$

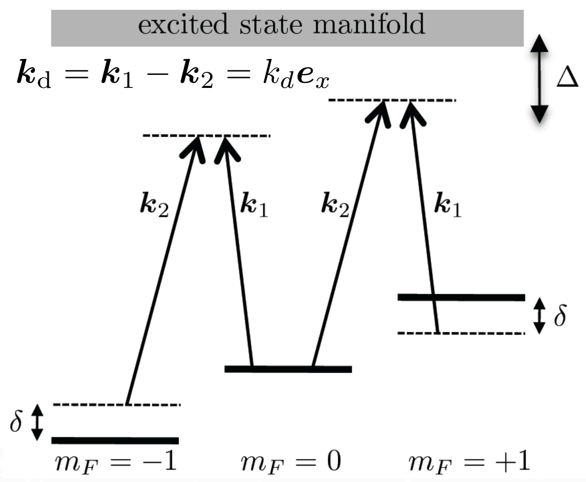
$$\sin\varphi_n = \frac{2q\sqrt{2Bn}}{\sqrt{(B-\Delta/2)^2+8q^2Bn}}$$

- <u>Deformed Landau Levels (DLL)</u> $\chi_{n,m}$ $\qquad \varepsilon_{n,m} = \tilde{\varepsilon}_{n,m} - D_n$

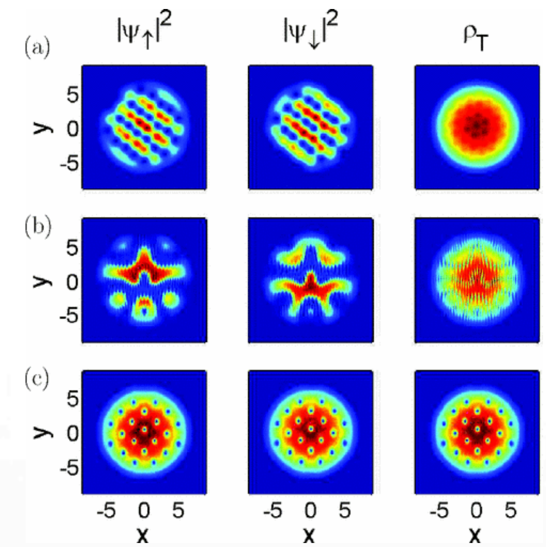
Experimental considerations

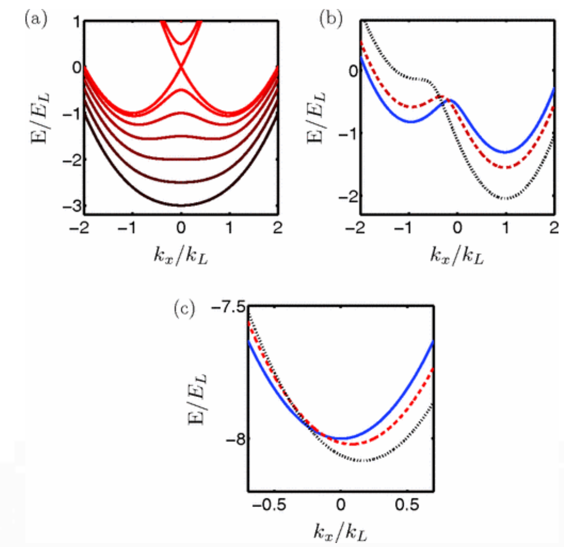
- U(1) magnetic field + SU(2) spin-orbit

M. Burrello, A. Trombettoni, PRA **84**, 043625 (2011)



J. Ruseckas, et al., PRL **95**, 010404 (2005).

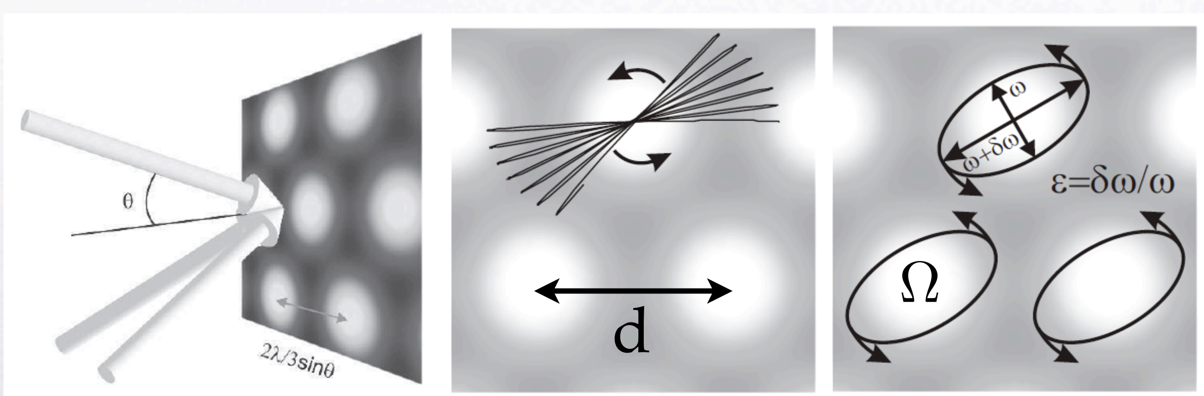


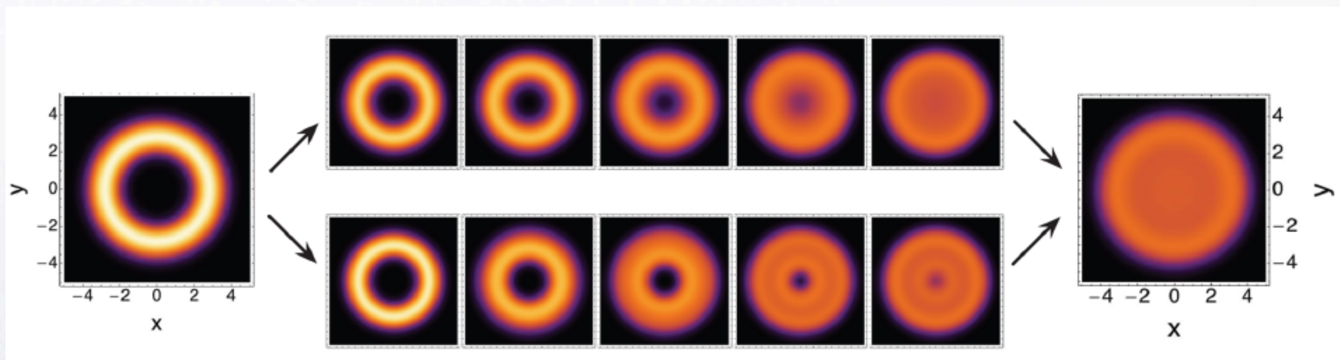


J. Radic, et al., Phys. Rev. A **84**, 063604 (2011).

- access to LLL regime: difficult by rotation!

N. R. Cooper, Adv Phys 57, 539 (2008)
A. L. Fetter, Rev. Mod. Phys. 81, 647 (2009)





Popp, et al, PRA **70**, 053612 (2004) / Gemelke et al., arXiv:1007.2677

Roncaglia, Rizzi, Dalibard, Sci. Rep. **1**, 43 (2011)

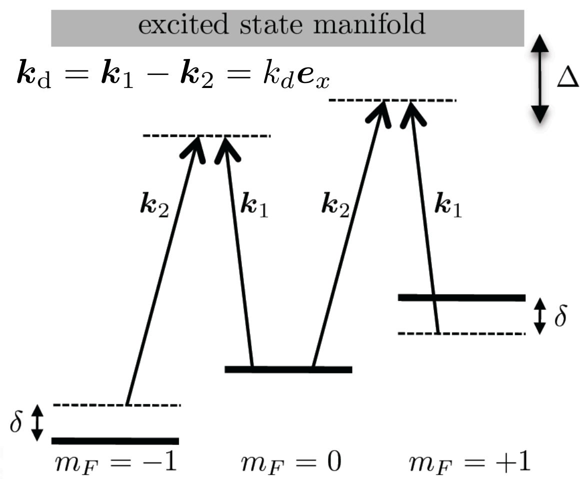
matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni
PRB 91, 115117 (2015)

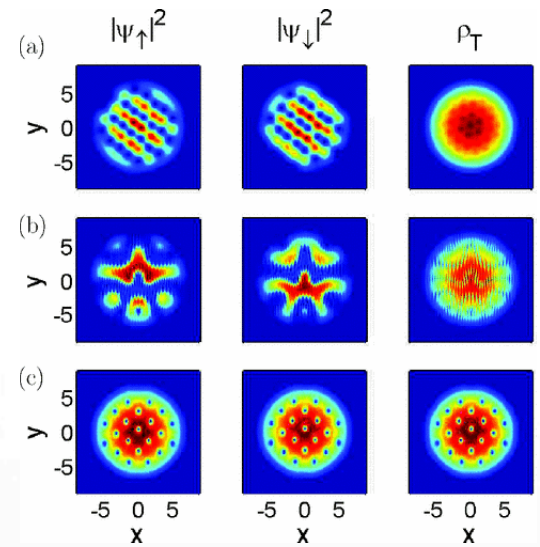
Experimental considerations

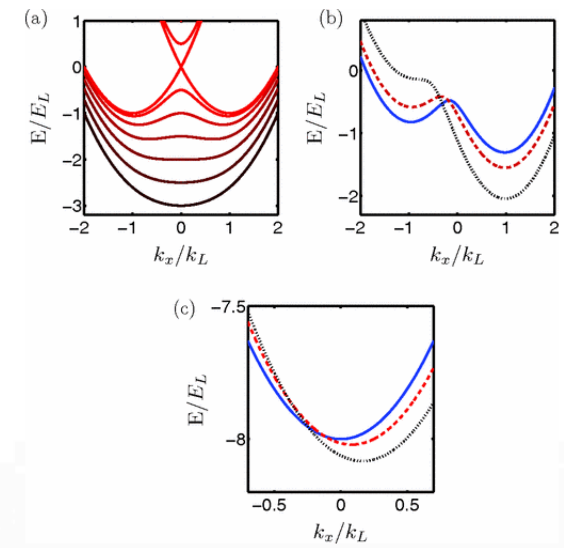
- U(1) magnetic field + SU(2) spin-orbit

M. Burrello, A. Trombettoni, PRA **84**, 043625 (2011)



J. Ruseckas, et al., PRL **95**, 010404 (2005).





J. Radic, et al., Phys. Rev. A **84**, 063604 (2011).

- new hopes: synthetic optical gauge potentials & dimensions

see I. Spielman, I. Bloch, M. Lewenstein, etc.

- some rough estimates

$$\mathcal{B}\ell^2 \simeq 1 \ \wedge \ \ell \simeq 0.5\mu m \longrightarrow \mathcal{B} \simeq 4 \cdot 10^{-19} g/s$$

$$\omega \simeq 10 \div 100\,\mathrm{Hz} \ \longrightarrow \ \Delta/\mathcal{B} \simeq 0.005 \div 0.05$$

$$\hbar/q \simeq 1\mu m \ \longrightarrow \ q^2/\hbar\mathcal{B} \simeq 0.1 \div 5$$

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
arXiv:1411. 5962

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
arXiv:1411.5962

Haldane pseudopotentials

- partial wave decomposition of (central) interaction potentials

$$\mathcal{H}_{\text{int}} = \sum_{M} \sum_{m_{\text{rel}}} \boxed{W_{m_{\text{rel}}}} \sum_{m_1,m_2} g\left[m_{\text{rel}}, M, m_1\right] g\left[m_{\text{rel}}, M, m_2\right] c^{\dagger}_{M-m_1} c^{\dagger}_{m_1} c_{m_2} c_{M-m2}$$

- polarized electrons in Coloumb potential $W_1 \gg W_3 \gg \dots$

==> Laughlin Ansatz ! $\nu = 1/3$ $\Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3$

- s-wave scattering approx. for cold bosons ! *only* $W_0 \neq 0$

$$\mathcal{H}_2 = c_2 \sum_{i<j} \delta(z_i - z_j) \qquad c_2 = \sqrt{8\pi} a/\xi_z$$

$\nu = 1/2$ $\Psi_{1/2} = \prod_{i<j} (z_i - z_j)^2 \equiv \Theta^2$

- LL filling factor $\nu \simeq \lim_{N \to \infty} \frac{N}{m_{\max}}$

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni

PRB 91, 115117 (2015)

Haldane pseudopotentials

$$\mathcal{H}_{\text{int}} = \sum_{M} \sum_{m_{\text{rel}}} \boxed{W_{m_{\text{rel}}}} \sum_{m_1, m_2} g\left[m_{\text{rel}}, M, m_1\right] g\left[m_{\text{rel}}, M, m_2\right] c^{\dagger}_{M-m_1} c^{\dagger}_{m_1} c_{m_2} c_{M-m2}$$

- spin1/2 fermions within U(2) DLL

$z = x - iy$

$$W^{(n)}_{m_{\text{rel}}} = V^{n-1,n-1}_{m_{\text{rel}}} \cos^4 \frac{\varphi_n}{2} + V^{n,n}_{m_{\text{rel}}} \sin^4 \frac{\varphi_n}{2} + V^{n,n-1}_{m_{\text{rel}}} \frac{\sin^2 \varphi_n}{2}$$

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
PRB 91, 115117 (2015)

Haldane pseudopotentials

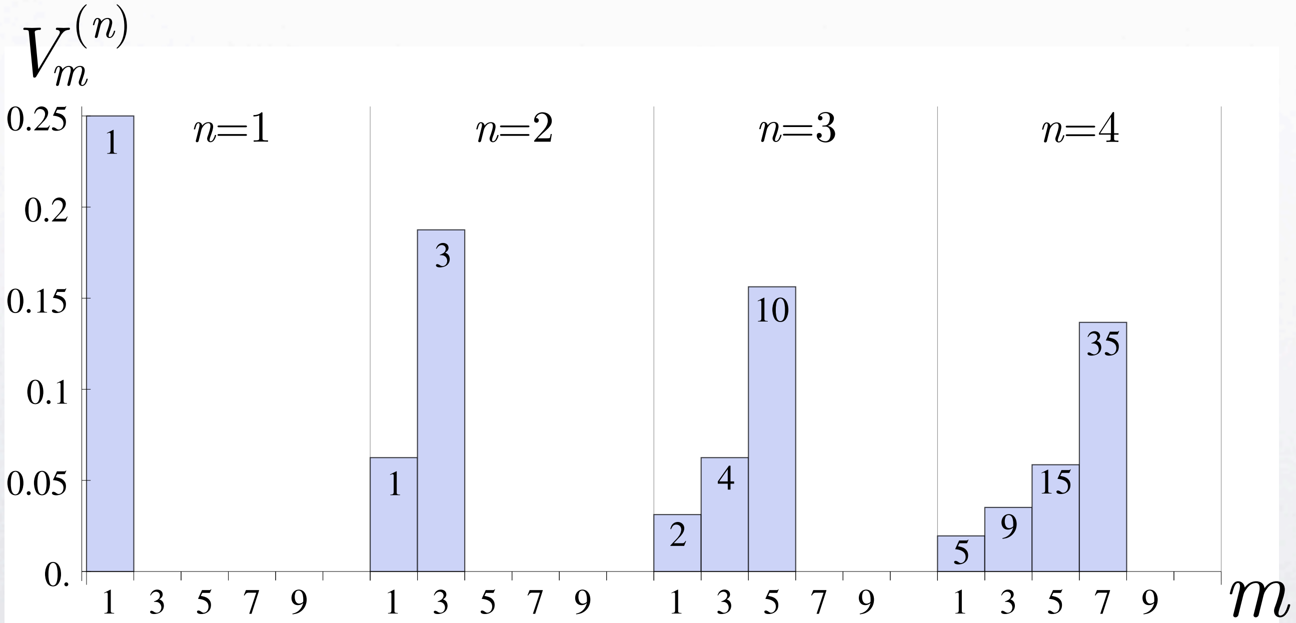
$$\mathcal{H}_{\text{int}} = \sum_{M} \sum_{m_{\text{rel}}} \boxed{W_{m_{\text{rel}}}} \sum_{m_1, m_2} g\left[m_{\text{rel}}, M, m_1\right] g\left[m_{\text{rel}}, M, m_2\right] c^{\dagger}_{M-m_1} c^{\dagger}_{m_1} c_{m_2} c_{M-m2}$$

- spin1/2 fermions within U(2) DLL

$$z = x - iy$$

$$W^{(n)}_{m_{\text{rel}}} = V^{n-1,n-1}_{m_{\text{rel}}} \cos^4 \frac{\varphi_n}{2} + V^{n,n}_{m_{\text{rel}}} \sin^4 \frac{\varphi_n}{2} + V^{n,n-1}_{m_{\text{rel}}} \frac{\sin^2 \varphi_n}{2}$$

- only interspecies contact interactions $\hat{V} = v \sum_{i<j} \delta\left(z_i - z_j\right) | \uparrow\downarrow\rangle\langle\uparrow\downarrow |$



! Non-Monotonic HP !

? new FQH states ?

Haldane pseudopotentials

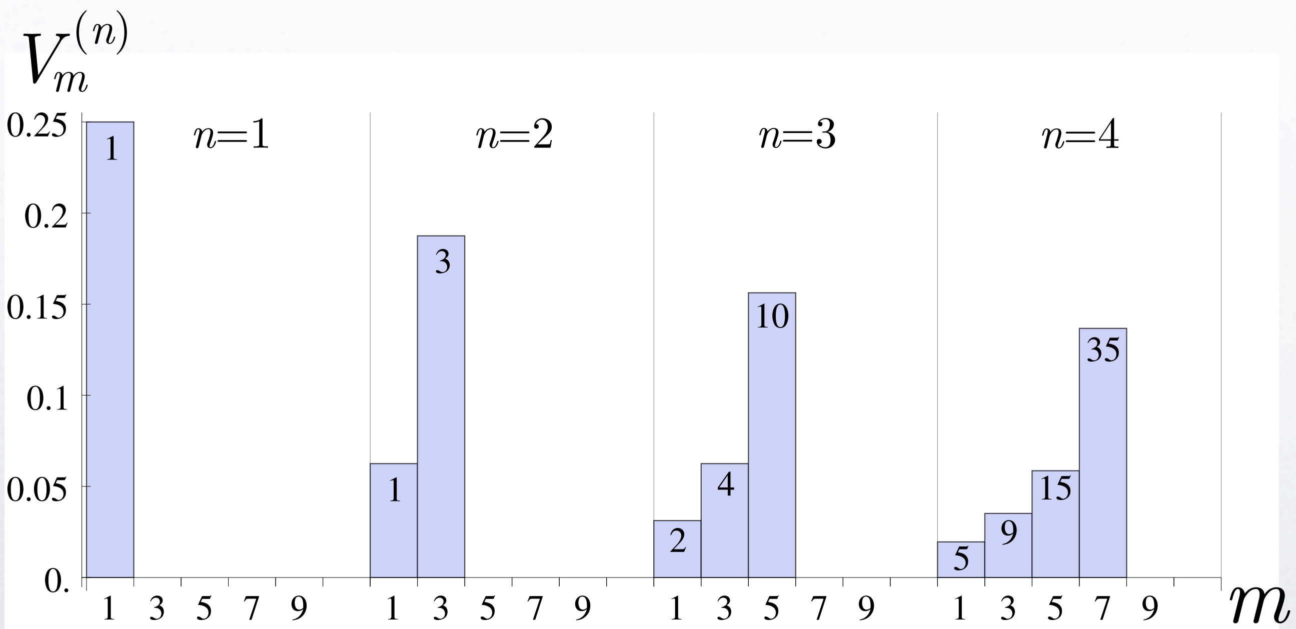
$$\mathcal{H}_{\text{int}} = \sum_M \sum_{m_{\text{rel}}} W_{m_{\text{rel}}} \sum_{m_1, m_2} g\left[m_{\text{rel}}, M, m_1\right] g\left[m_{\text{rel}}, M, m_2\right] c^\dagger_{M-m_1} c^\dagger_{m_1} c_{m_2} c_{M-m2}$$

- spin1/2 fermions within U(2) DLL

$z = x - iy$

$$W^{(n)}_{m_{\text{rel}}} = V^{n-1,n-1}_{m_{\text{rel}}} \cos^4 \frac{\varphi_n}{2} + V^{n,n}_{m_{\text{rel}}} \sin^4 \frac{\varphi_n}{2} + V^{n,n-1}_{m_{\text{rel}}} \frac{\sin^2 \varphi_n}{2}$$

- only interspecies contact interactions $\hat{V} = v \sum_{i<j} \delta\left(z_i - z_j\right) |\uparrow\downarrow\rangle\langle\uparrow\downarrow|$



! Non-Monotonic HP !

? new FQH states ?

Dipoles needed for bosons

T. Grass, et al, PRA 89, 013623 (2014)

Incompressible states

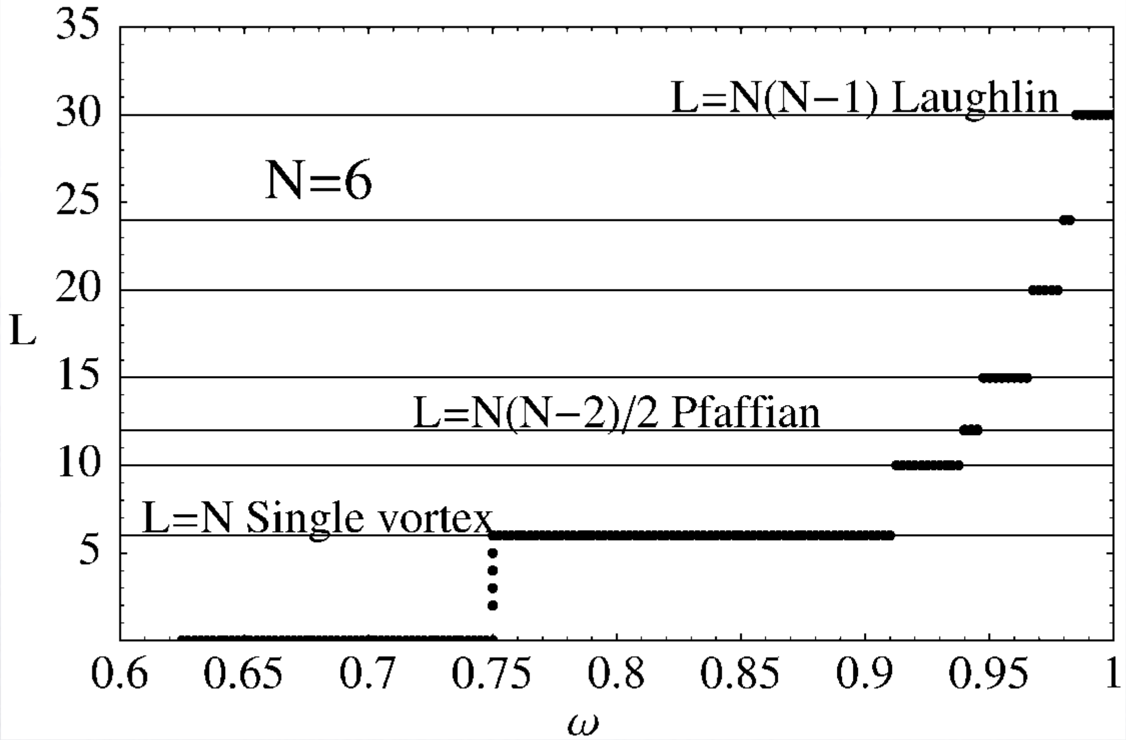
- $[\mathcal{H}, L_z] = 0$: yrast spectrum (disk)

$$\mathcal{E}(L) = E(L) + L\,\Delta \qquad L_z = Nn - \sum m a_m^\dagger a_m$$

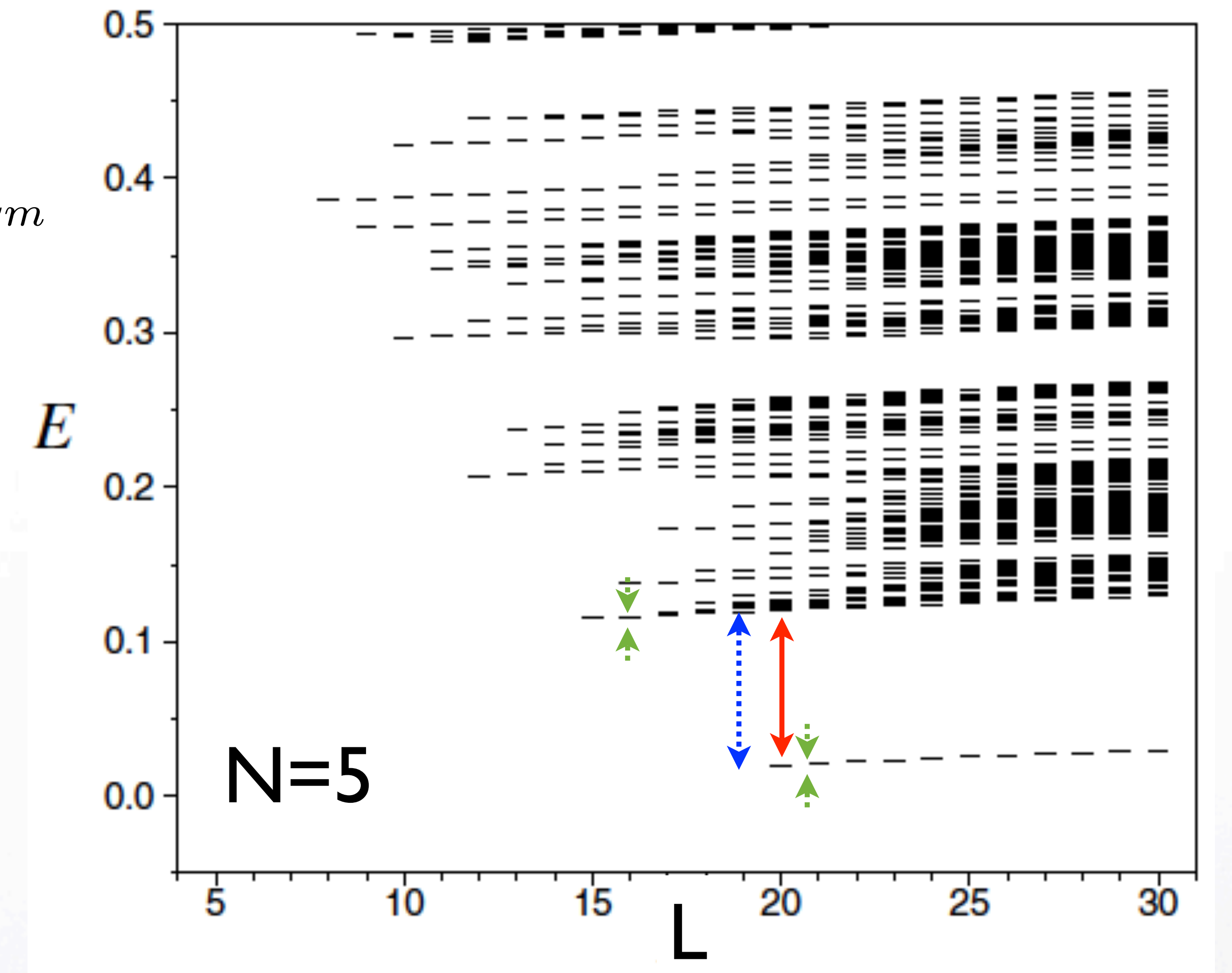
- incompressibility gap

$$\mathcal{D}(L) = \min[\delta E(L),\ E(L) - E(L-1)]$$

decides over stabilized states



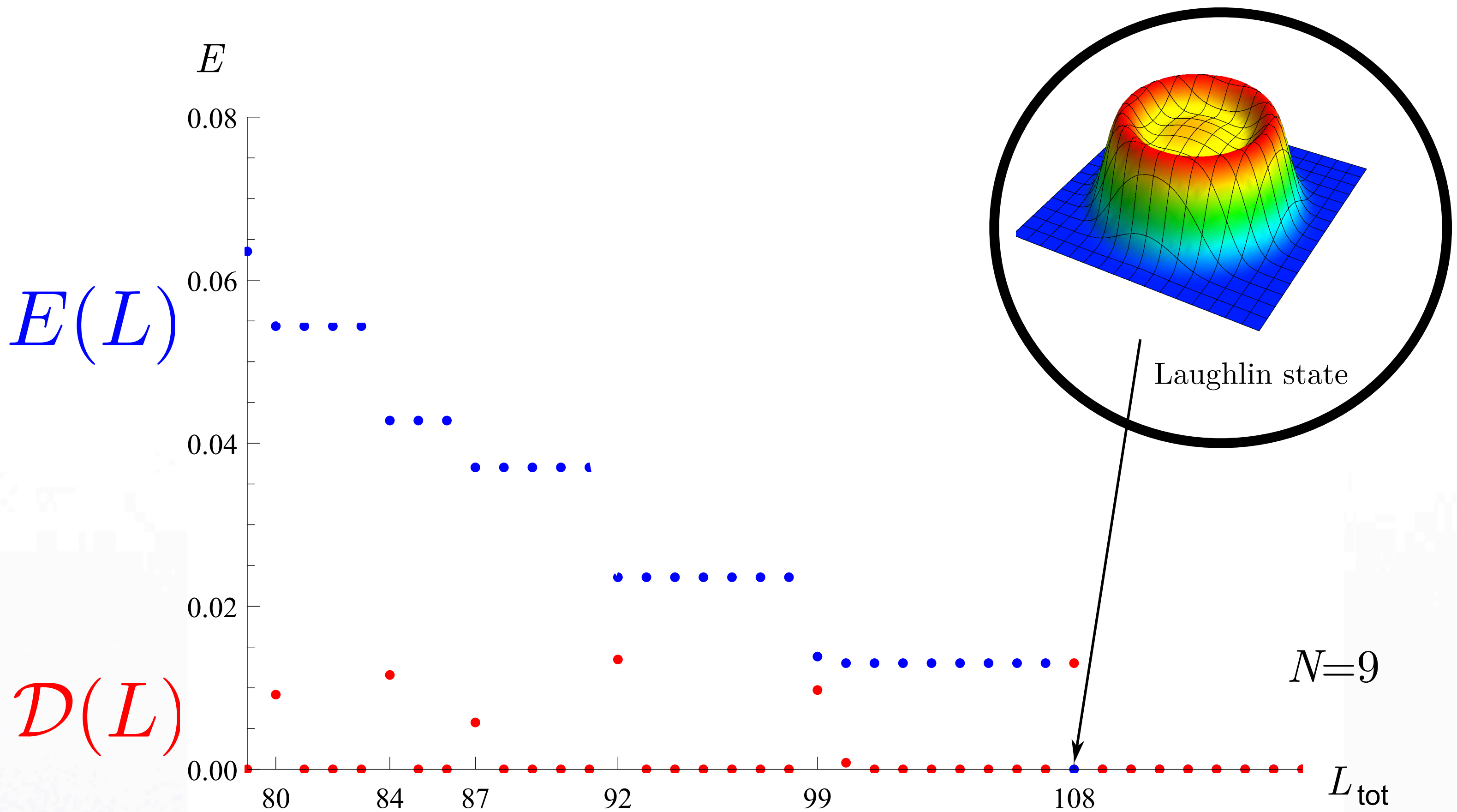
Wilkin,Gunn, PRL **84**, 6 (2000)

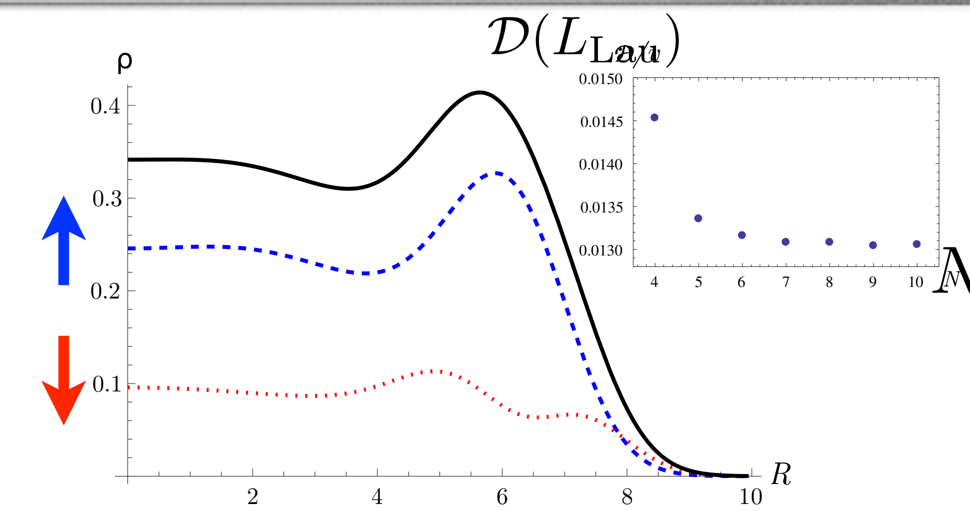


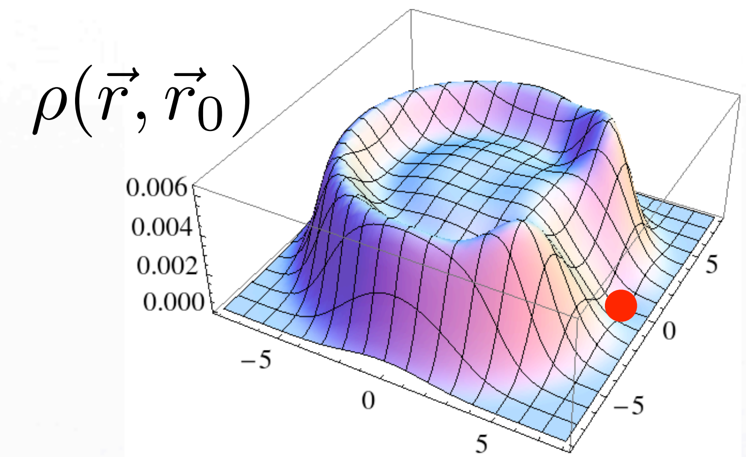
Paredes, et al., PRL **87**, 010402 (2001)

- quasihole excitation $\Delta_{\rm qh} \simeq \delta$

1st DLL: Laughlin





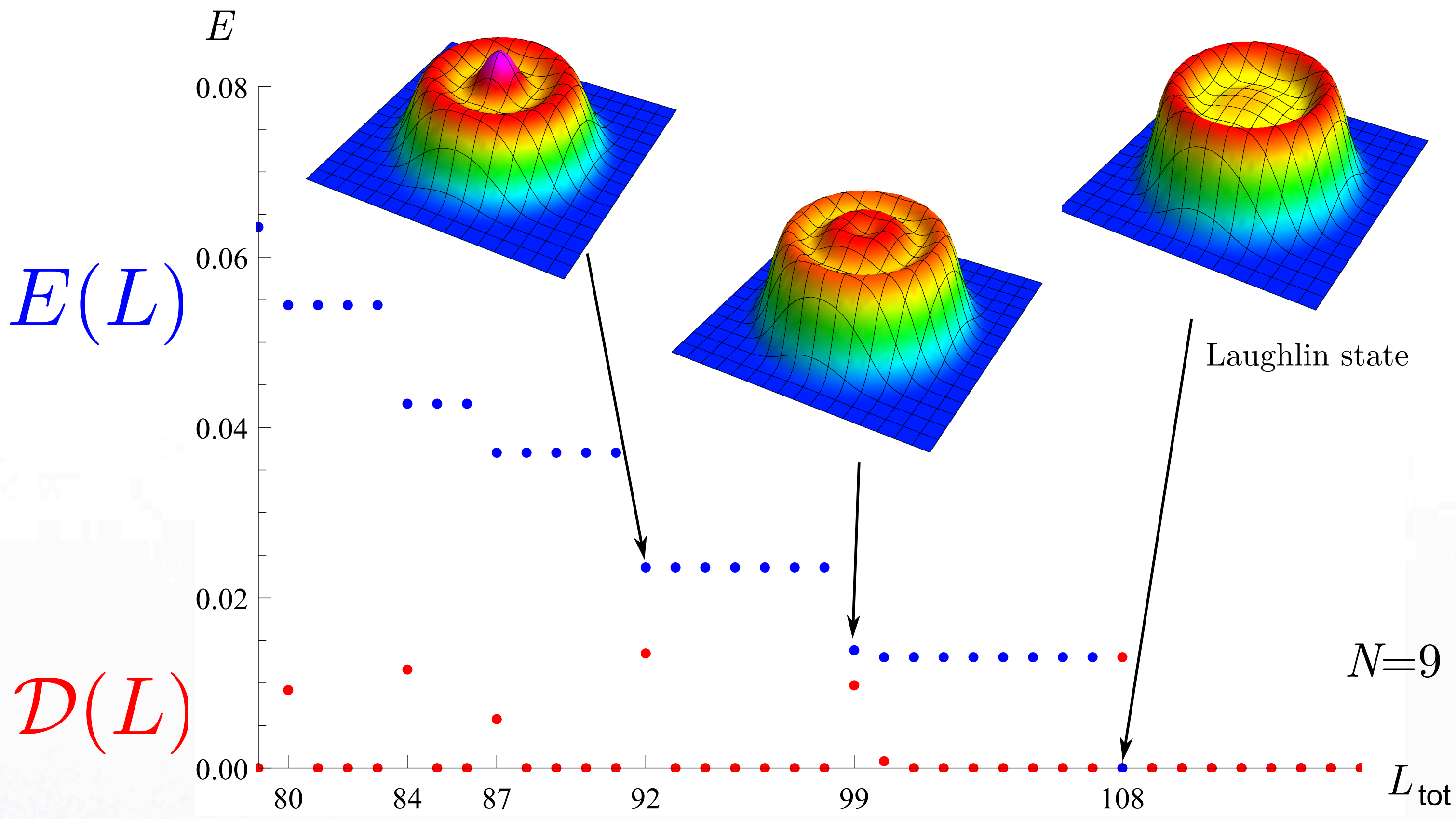


- **Laughlin ansatz** $\nu = 1/3 \qquad \Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3$
- **incompressibility gap** $E_{\text{qp}} \simeq \mathcal{D}(L_{\text{Lau}}) \approx 0.013v \qquad L_{\text{Lau}} \equiv 3N(N-1)/2$

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
PRB 91, 115117 (2015)

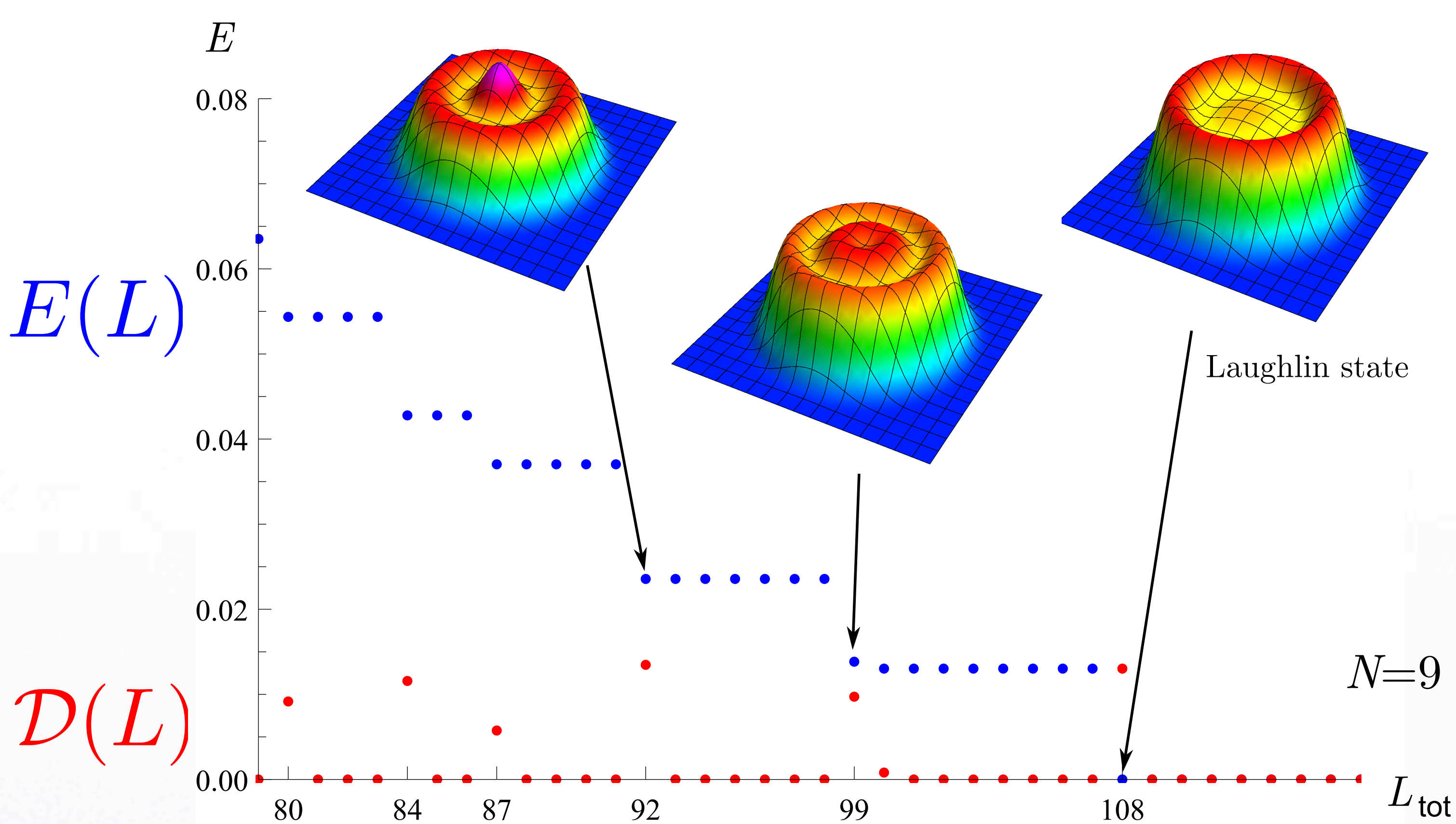
1st DLL: Laughlin

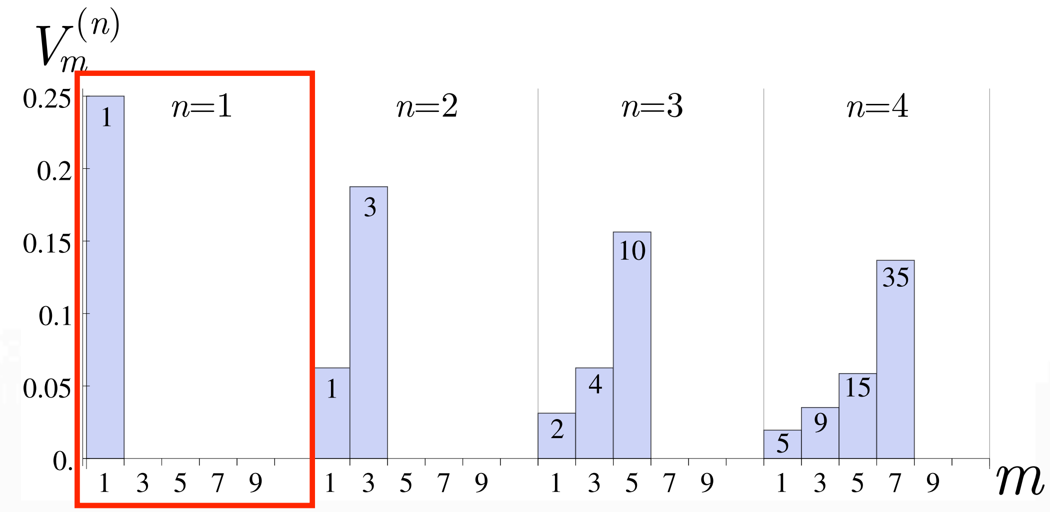


- Laughlin ansatz $\nu = 1/3$ $\Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3$
- incompressibility gap $E_{\text{qp}} \simeq \mathcal{D}(L_{\text{Lau}}) \approx 0.013v$ $L_{\text{Lau}} \equiv 3N(N-1)/2$
- plateau lengths (N, N-2, N-4, …) = CF theory

A. Cappelli, et al, PRB **58**, 16291 (1998)
G. Dev, J. K. Jain, PRB **45**, 1223 (1992)

1st DLL: Laughlin

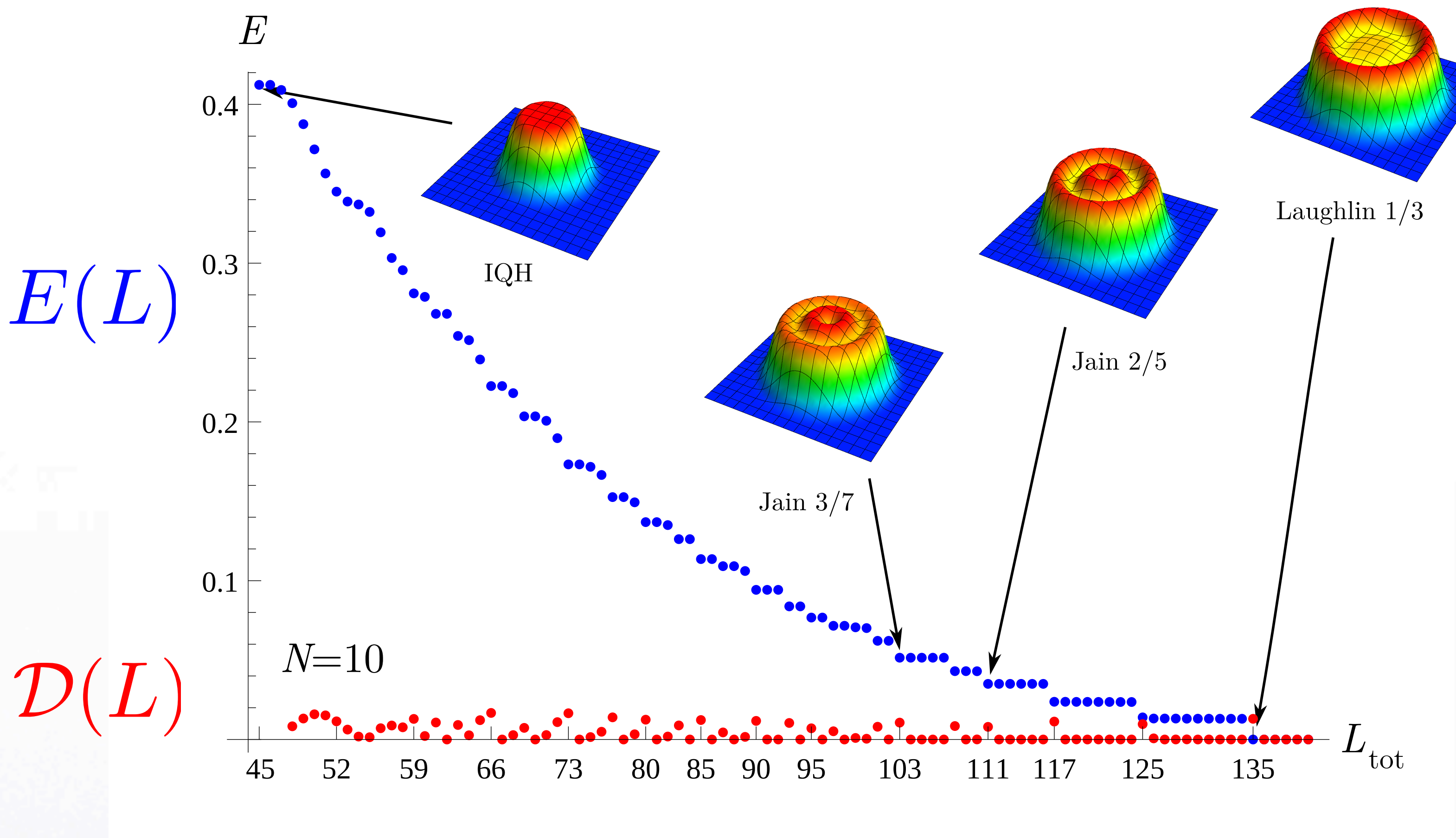


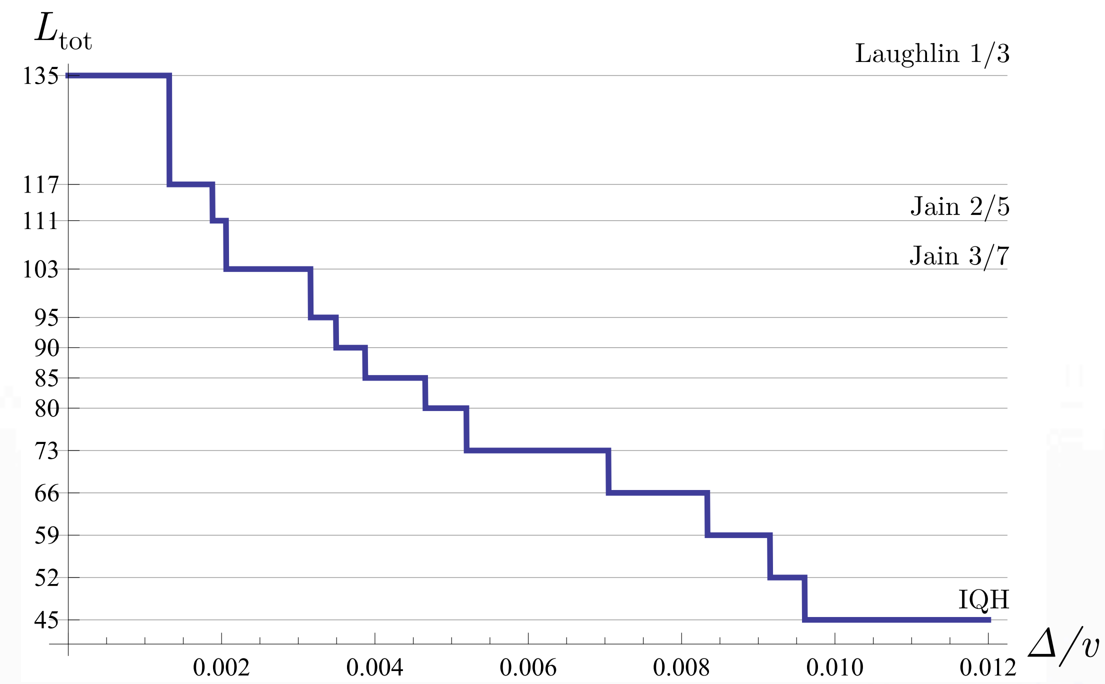


- Laughlin ansatz $\nu = 1/3$ $\Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 \equiv \Theta^3$
- incompressibility gap $E_{\text{qp}} \simeq \mathcal{D}(L_{\text{Lau}}) \approx 0.013v$ $L_{\text{Lau}} \equiv 3N(N-1)/2$
- plateau lengths (N, N-2, N-4, …) = CF theory

A. Cappelli, et al, PRB **58**, 16291 (1998)
G. Dev, J. K. Jain, PRB **45**, 1223 (1992)

1st DLL: Jain states





- numerics with small particle numbers ==> labelling complicated

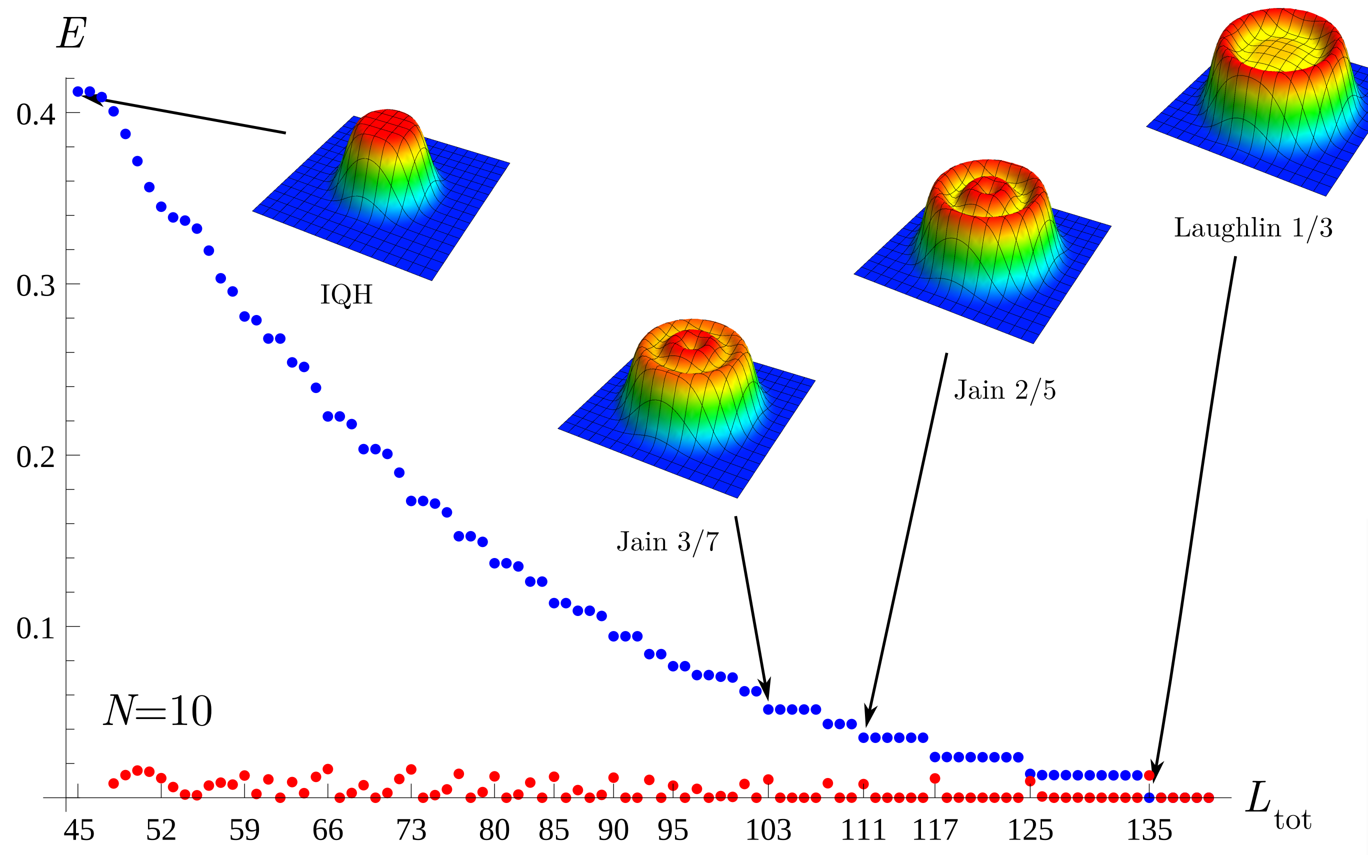
e.g. N=10 L =111 Lau + 3qp or Jain 2/5 ?

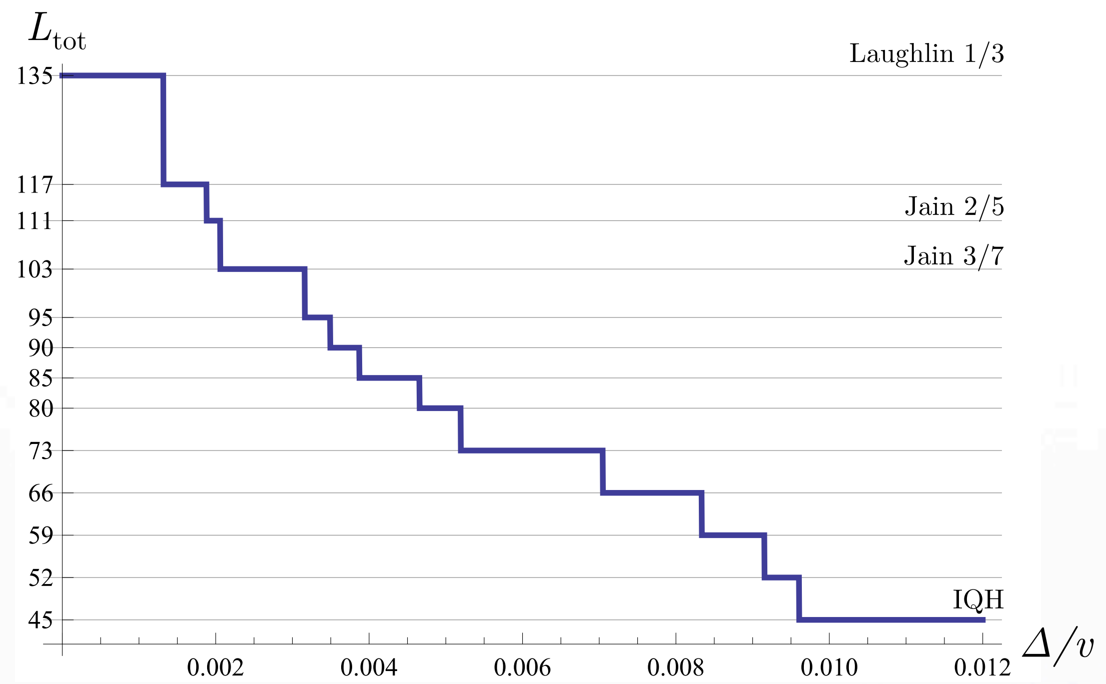
U. Zülicke, J.J. Palacios, A.H. MacDonald, PRB **67**, 045303 (2003)

1st DLL: Jain states

$E(L)$

$\mathcal{D}(L)$



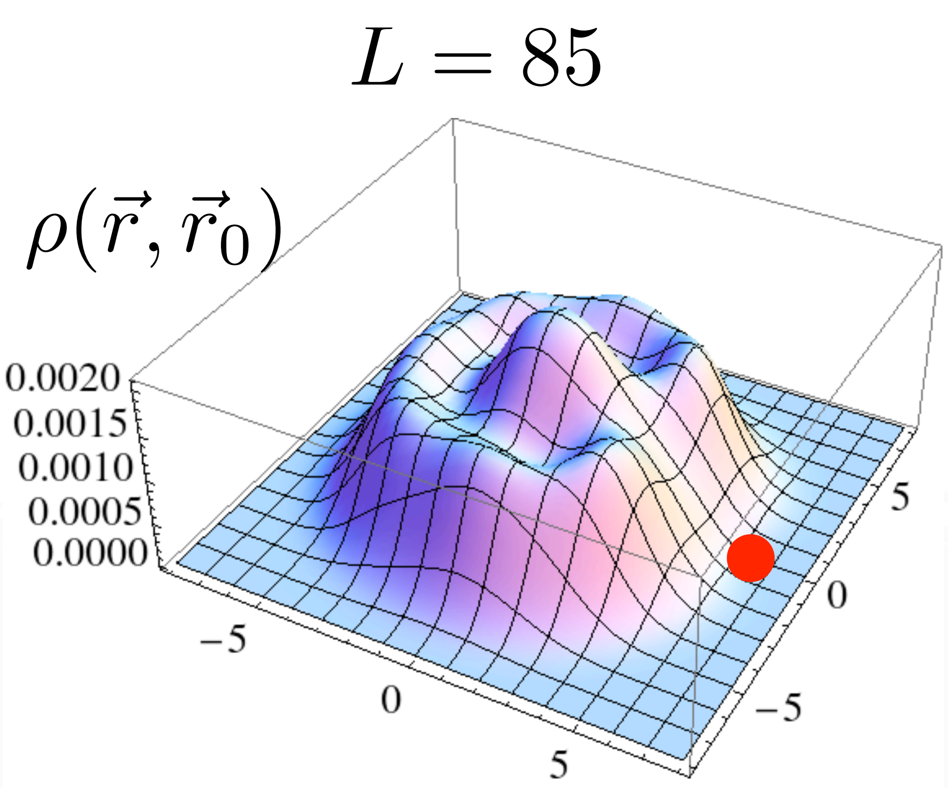


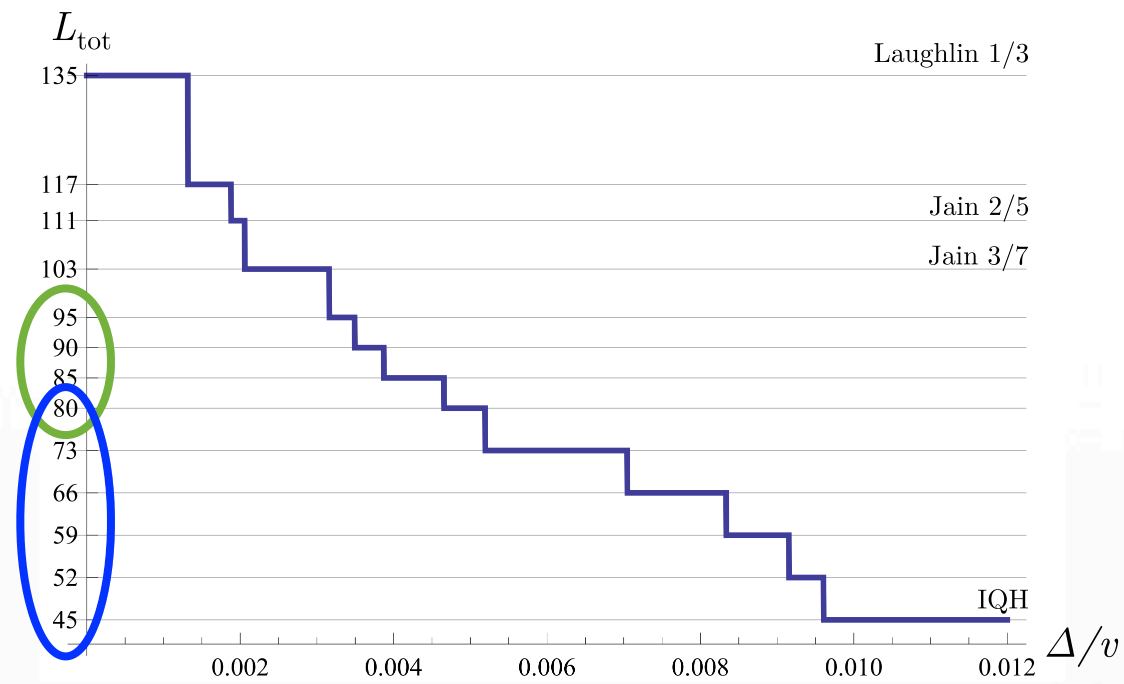
- numerics with small particle numbers ==> labelling complicated

e.g. N=10 L =111 Lau + 3qp or Jain 2/5 ?

U. Zülicke, J.J. Palacios, A.H. MacDonald, PRB **67**, 045303 (2003)

1st DLL: other stable states





- regular pattern of ground states: ~ pseudo-crystals (atoms+fluxes)

NO Pfaffian $\Psi_{\text{Pf}} \propto \text{Pf}\left[\frac{1}{z_i - z_j}\right] \prod_{i<j}(z_i - z_j)^2$ **at** $L = N(N-1) - N/2 = 85$

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni
PRB 91, 115117 (2015)

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni
arXiv:1411.5962

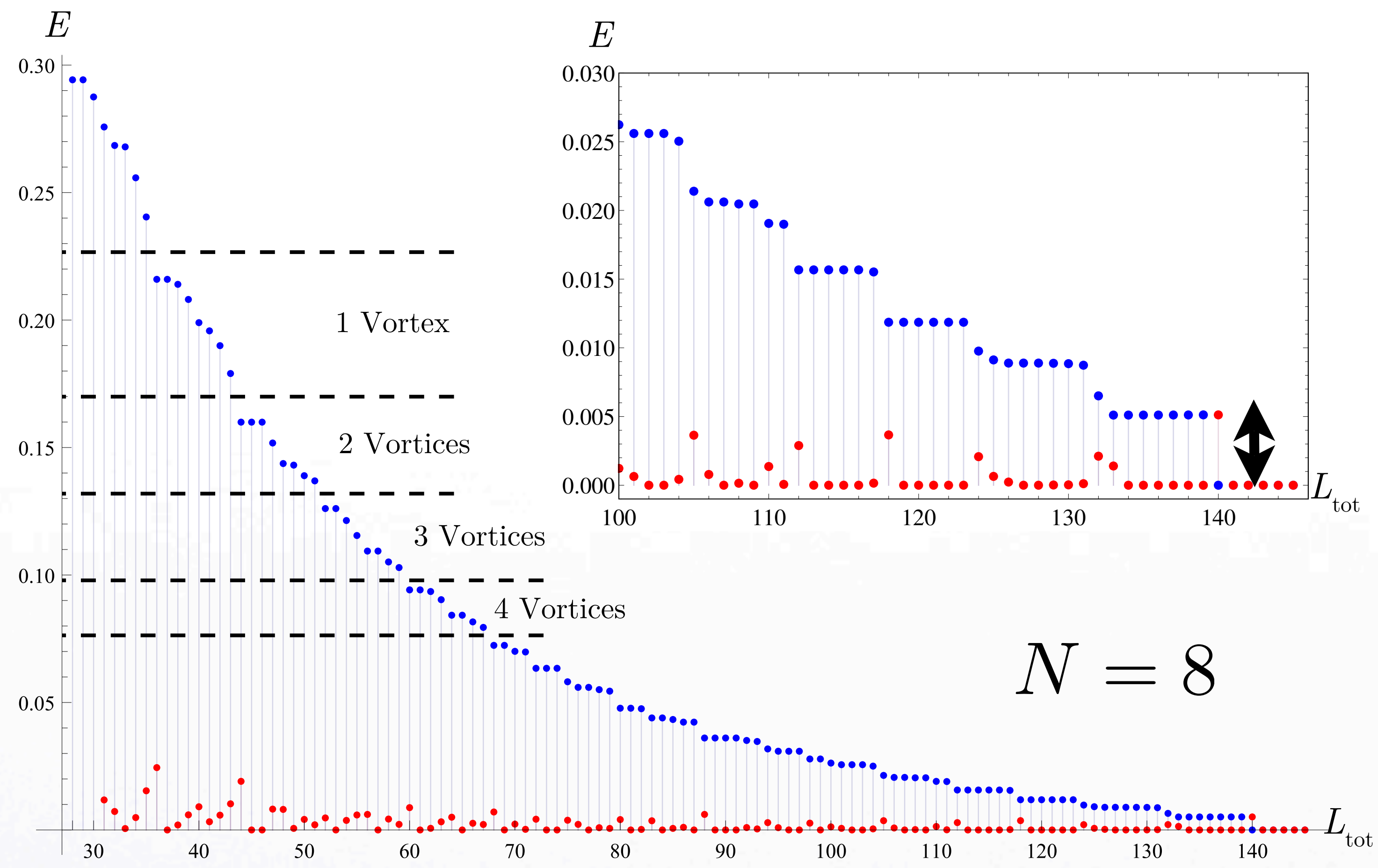
Outline

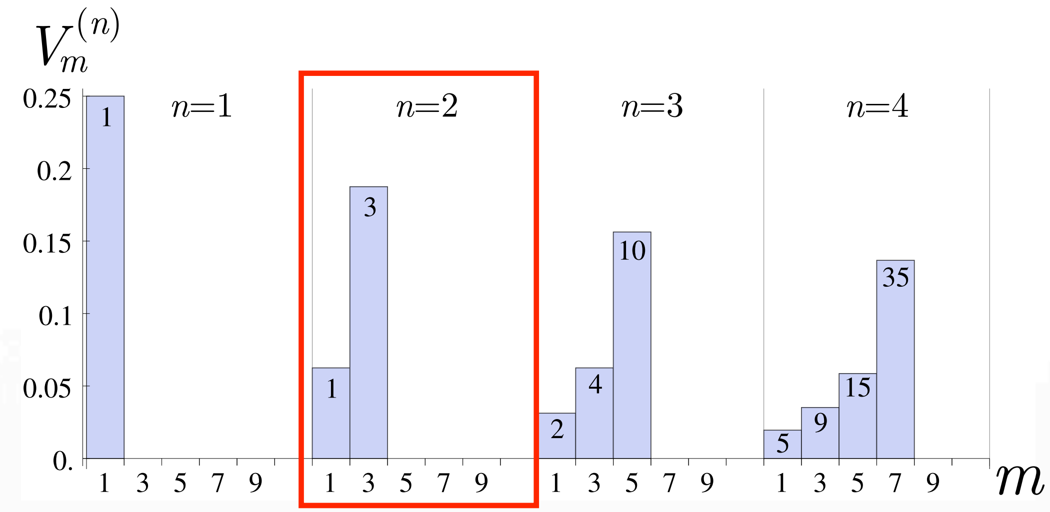
- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
arXiv:1411. 5962

2nd DLL: Laughlin & quasiparticles

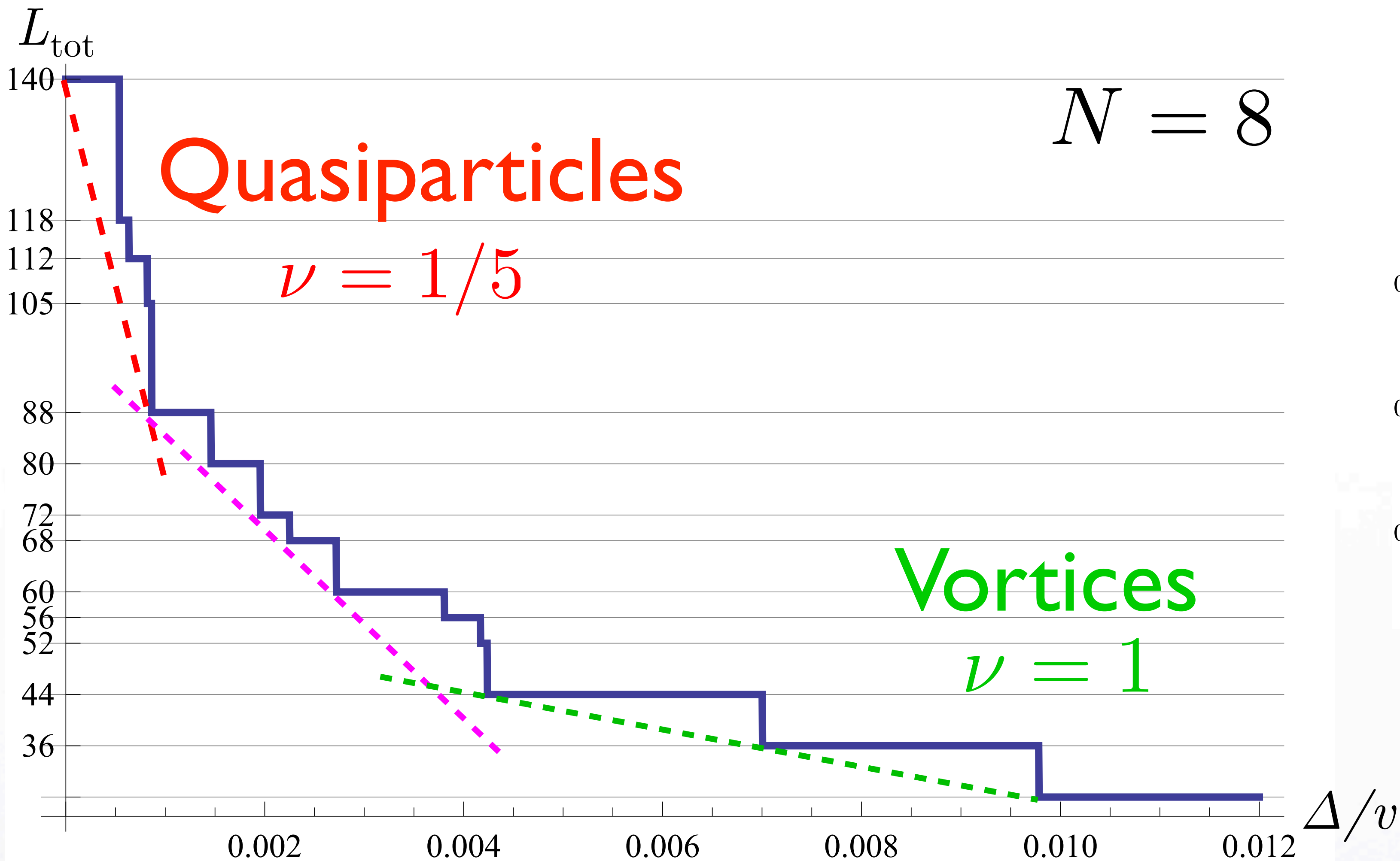


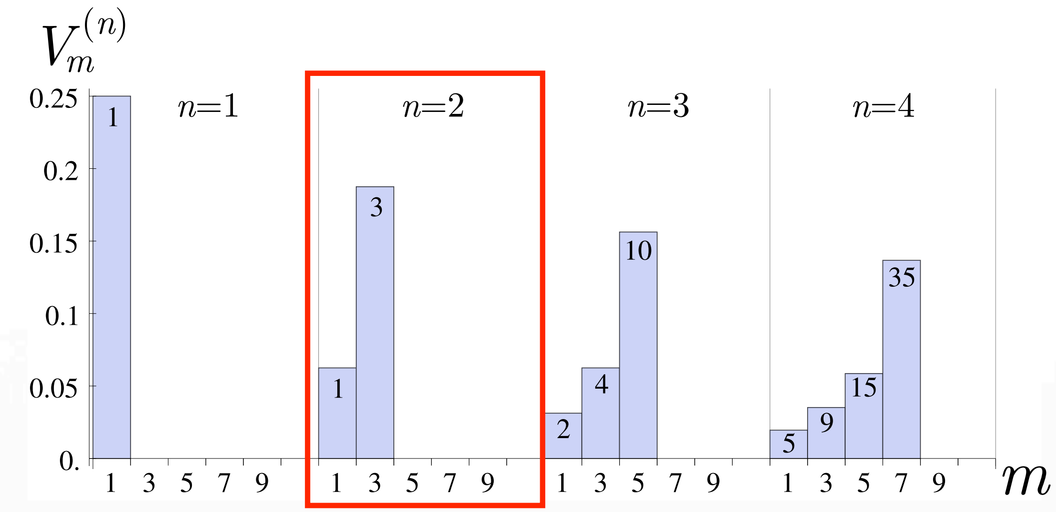


- Laughlin ansatz $\nu = 1/5 \quad \Psi_{1/5} = \prod_{i<j}(z_i - z_j)^5 \equiv \Theta^5$
- incompressibility gap $E_{\rm qp}^{(1/5)} \simeq \mathcal{D}(L_{\rm Lau}) \approx 0.005v \simeq 0.3E_{\rm qp}^{(1/3)}$
- smoothened transitions due to W_3 …

matteo.rizzi@uni-mainz.de

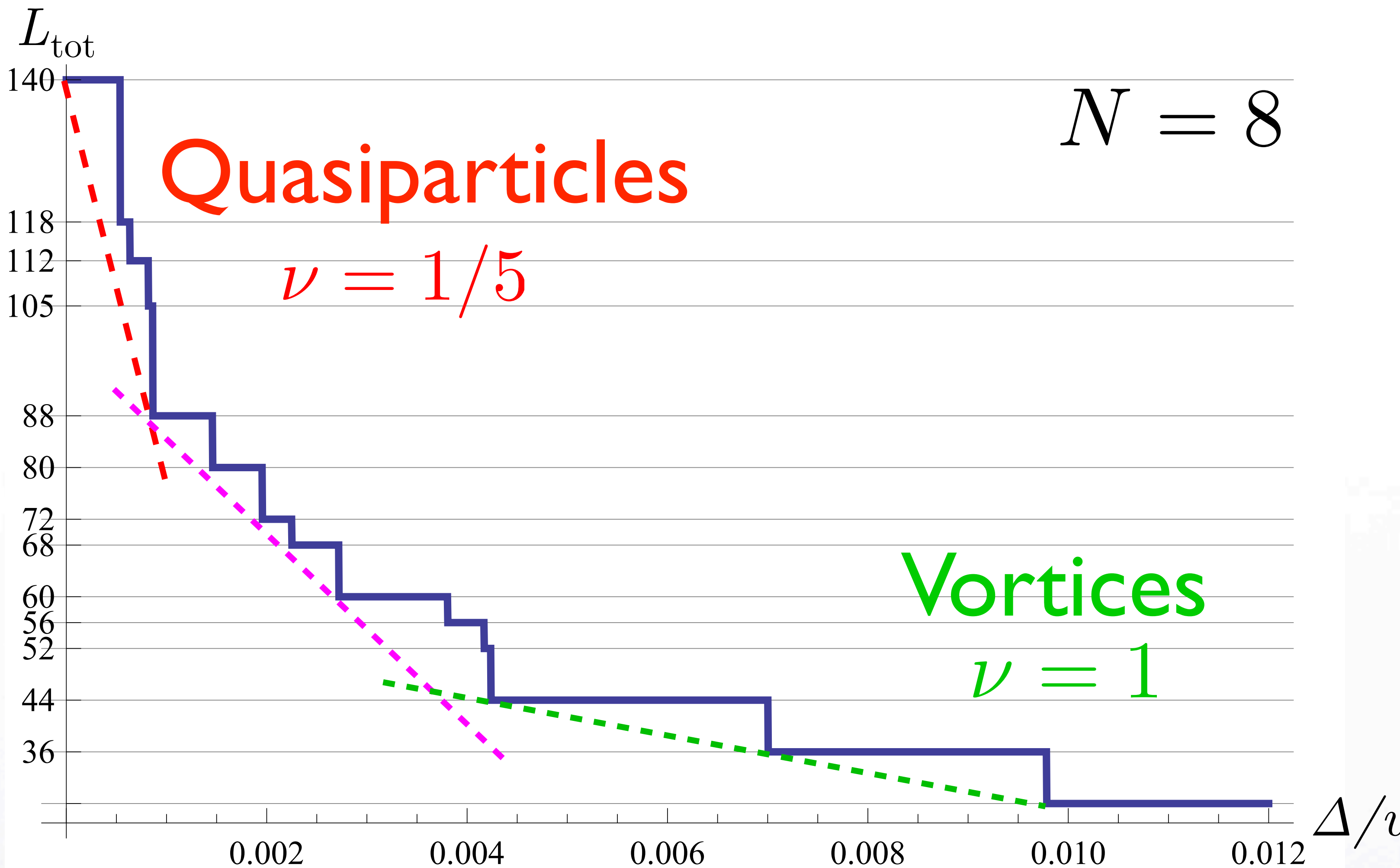
2nd DLL: three regimes

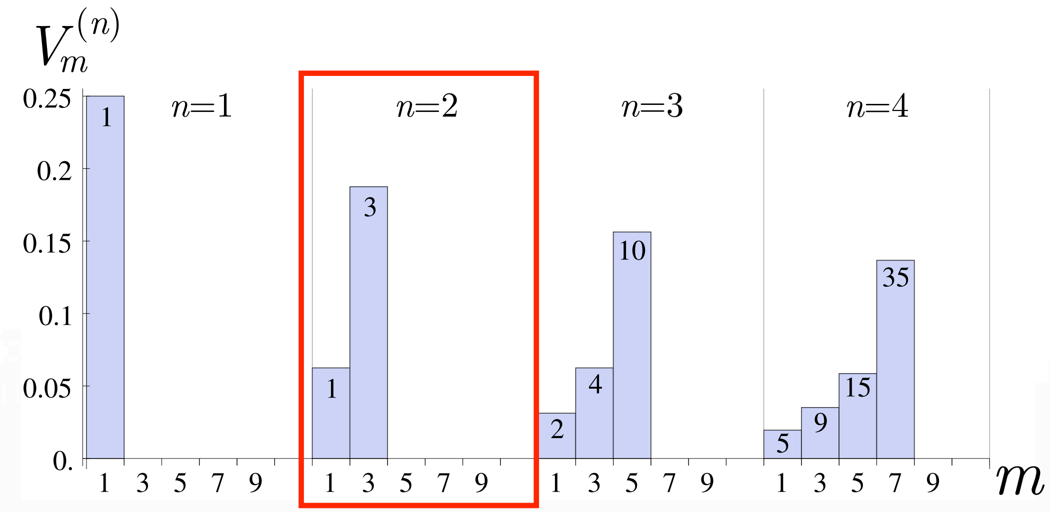




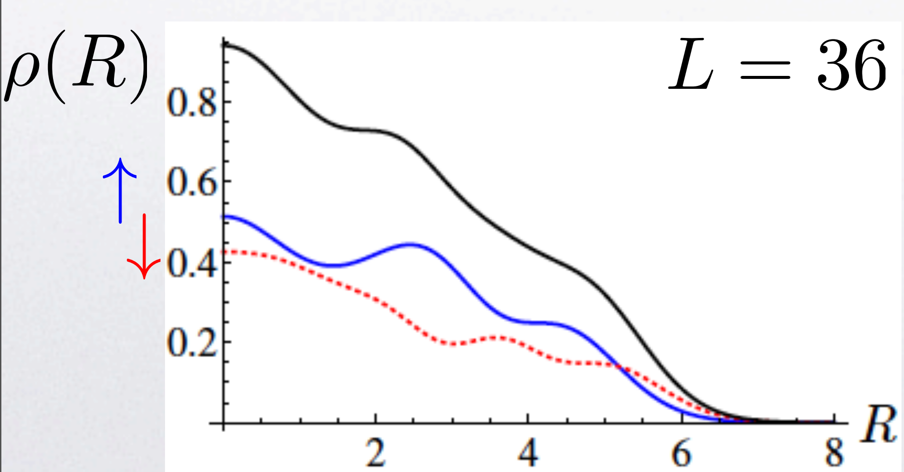
- Laughlin ansatz $\quad \nu = 1/5 \quad \Psi_{1/5} = \prod_{i<j} (z_i - z_j)^5 \equiv \Theta^5$

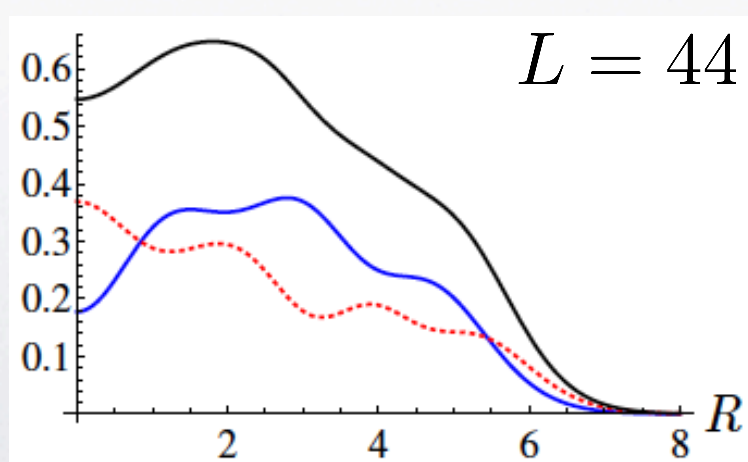
2nd DLL: three regimes

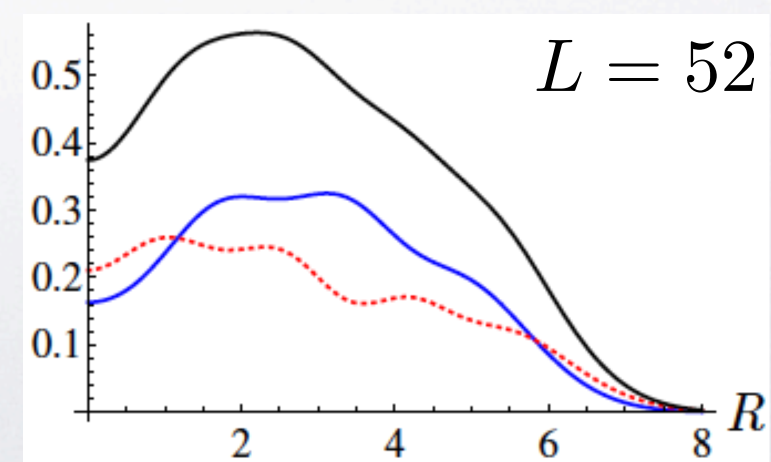




- skyrmionic spin texture around vortex cores





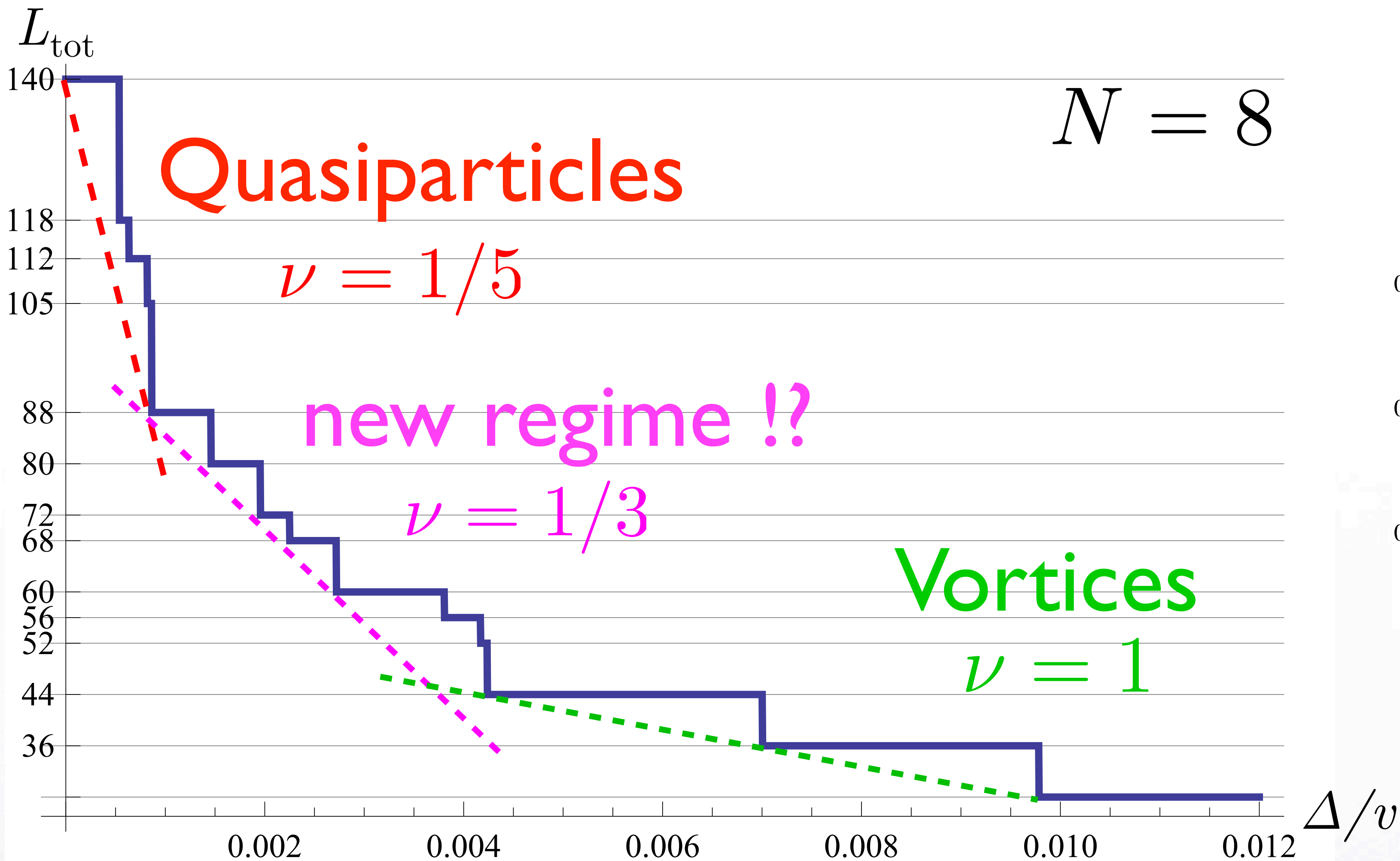


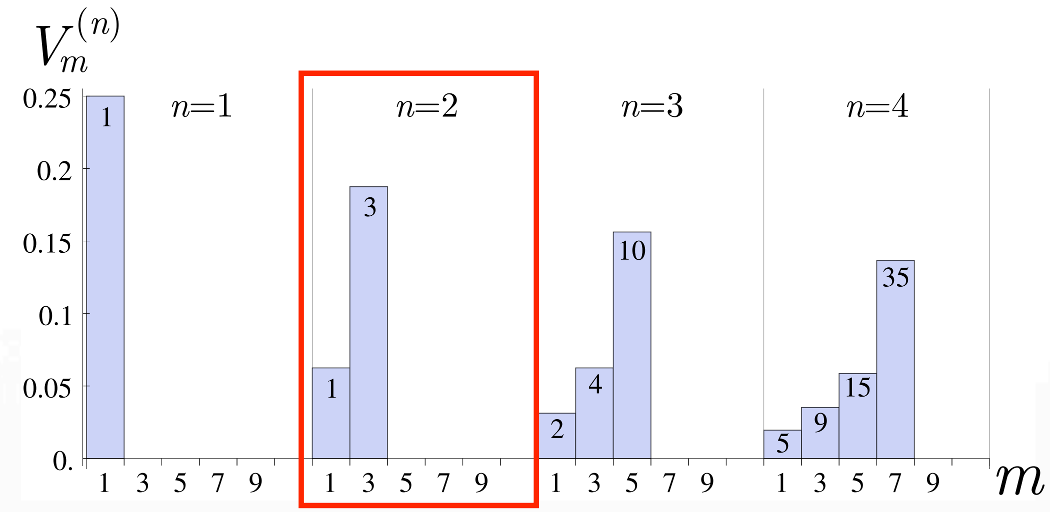
matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni

PRB 91, 115117 (2015)

2nd DLL: three regimes





- NO Laughlin ~~$\nu = 1/3 \quad \Psi_{1/3} = \prod_{i<j} (z_i - z_j)^3 = \Theta^3$~~

- Haffnian !? $\nu = 1/3 \quad \Psi_{\text{Hf}} \sim \mathcal{S}\left(\frac{1}{(z_1 - z_2)^2 \ldots (z_{N-1} - z_N)^2}\right) \prod_{i,j} (z_i - z_j)^3$

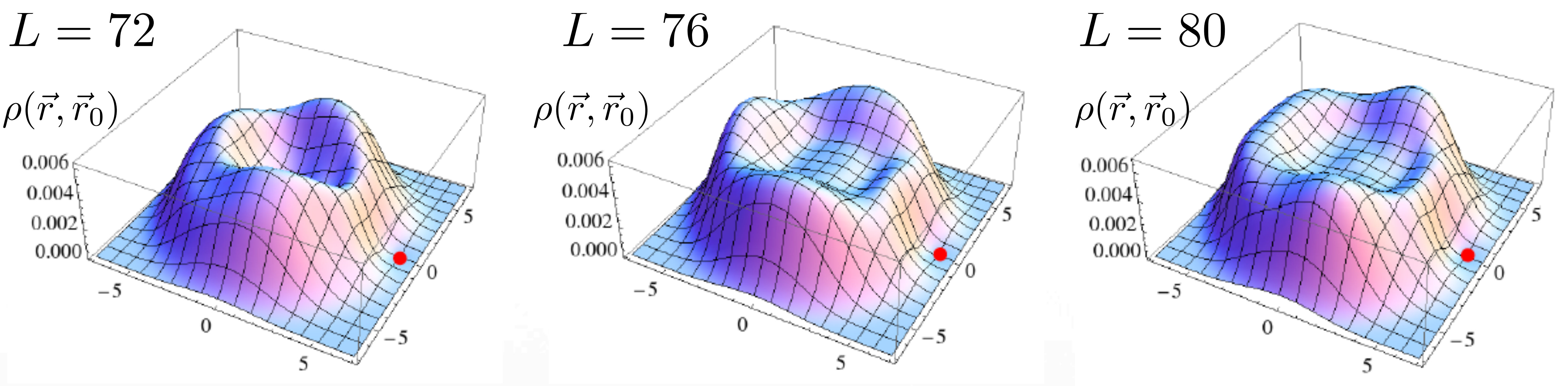
  $L_{\text{Hf}} = 76$

X.-G. Wen, Nucl. Phys. B **419**, 455 (1994) // D. Green, arXiv:cond-mat/0202455

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
PRB 91, 115117 (2015)

2nd DLL: Haffnian !?



- **Haffnian !?**
  $L_{\mathrm{Hf}} = 76$

$$\nu = 1/3 \quad \Psi_{\mathrm{Hf}} \sim \mathcal{S}\left(\frac{1}{(z_1 - z_2)^2 \dots (z_{N-1} - z_N)^2}\right) \prod_{i,j} (z_i - z_j)^3$$

X.-G. Wen, Nucl. Phys. B **419**, 455 (1994) // D. Green, arXiv:cond-mat/0202455

- effective (d-wave) pairing <==> N/2 = 4 peaks
- stabilized states (by Δ) are rather $L_{\mathrm{Hf}} \pm N/2$
- three-body interactions needed …

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni

arXiv:1411.5962

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
arXiv:1411. 5962

Entanglement spectrum: intro

- quantum information approach: (robust & intrinsic)

$$S = A \cup \bar{A} \qquad \rho_A = \mathrm{Tr}_{\bar{A}} |\psi\rangle\langle\psi| = \sum_l \lambda_l |l\rangle\langle l| \qquad \mathrm{ES}_l \equiv -\ln \lambda_l$$

H. Li and F.D.M. Haldane, PRL **101**, 010504 (2008)

- orbital partition ~ real space partition $\rho_A^{(O)} = \left(\sum_{\{\vec{n}''\}_{\bar{A}}} \Psi^*_{\vec{n}\otimes\vec{n}''} \Psi_{\vec{n}'\otimes\vec{n}''} \right) |\vec{n}\rangle_A \langle \vec{n}'|$

$\mathrm{ES}^{(O)}$ ~ info. on edge excitations

X.-L. Qi, H. Katsura, A.W. Ludwig, PRL **108**, 196402 (2012)

- particle partition irrespective of position $\rho_A^{(P)} = \left(\langle\psi| \prod_{j \le N_A} a^\dagger_{m_j} \prod_{k \le N_A} a_{m'_k} |\psi\rangle \right) |\vec{m}\rangle\langle\vec{m}'|$

$\mathrm{ES}^{(P)}$ ~ bulk & excitation properties

A. Sterdyniak, N. Regnault and B. A. Bernevig, PRL **106**, 100405 (2011)

matteo.rizzi@uni-mainz.de

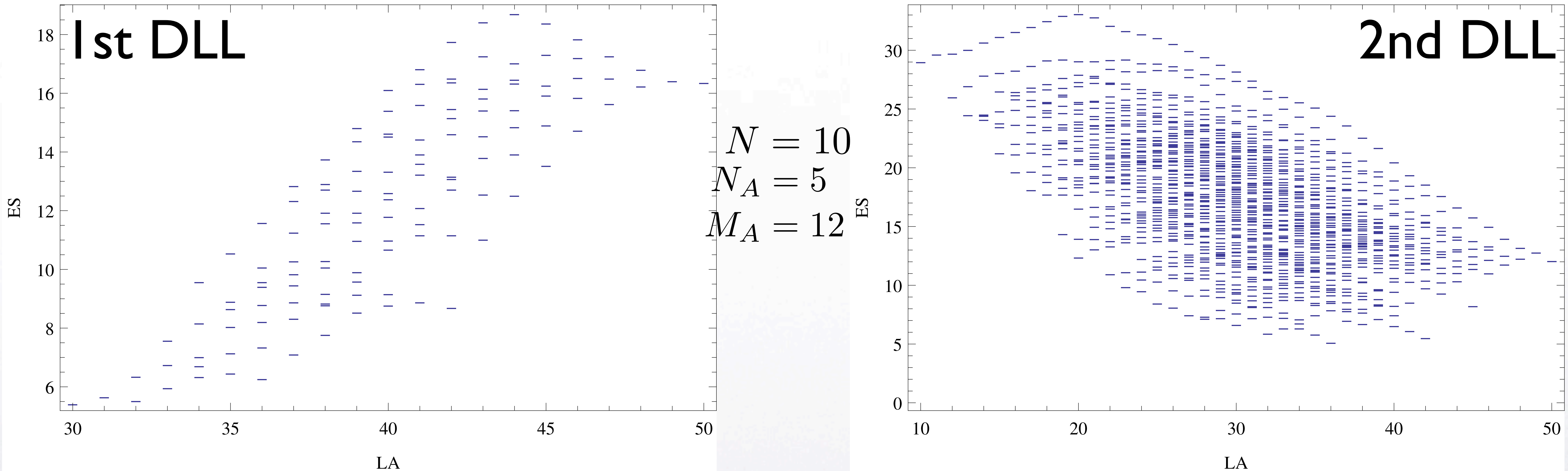
M.Burrello, **MR**,
M.Roncaglia, A.Trombettoni
PRB 91, 115117 (2015)

ES: Laughlin 1/3

- orbital partition ~ real space partition $\rho_A^{(O)} = \left(\sum_{\{\vec{n}''\}_{\bar{A}}} \Psi^*_{\vec{n}\otimes\vec{n}''} \Psi_{\vec{n}'\otimes\vec{n}''} \right) |\vec{n}\rangle_A \langle \vec{n}'|$

$N_A = \sum_{m \leq M_A} n_m \qquad L_A = \sum_{m \leq M_A} m\, n_m$

$$L_{1/3} = 3N(N-1) = 135$$



- counting Laughlin edge modes 1, 1, 2, 3, 5, 7, 11, …

- no clear ES gap …

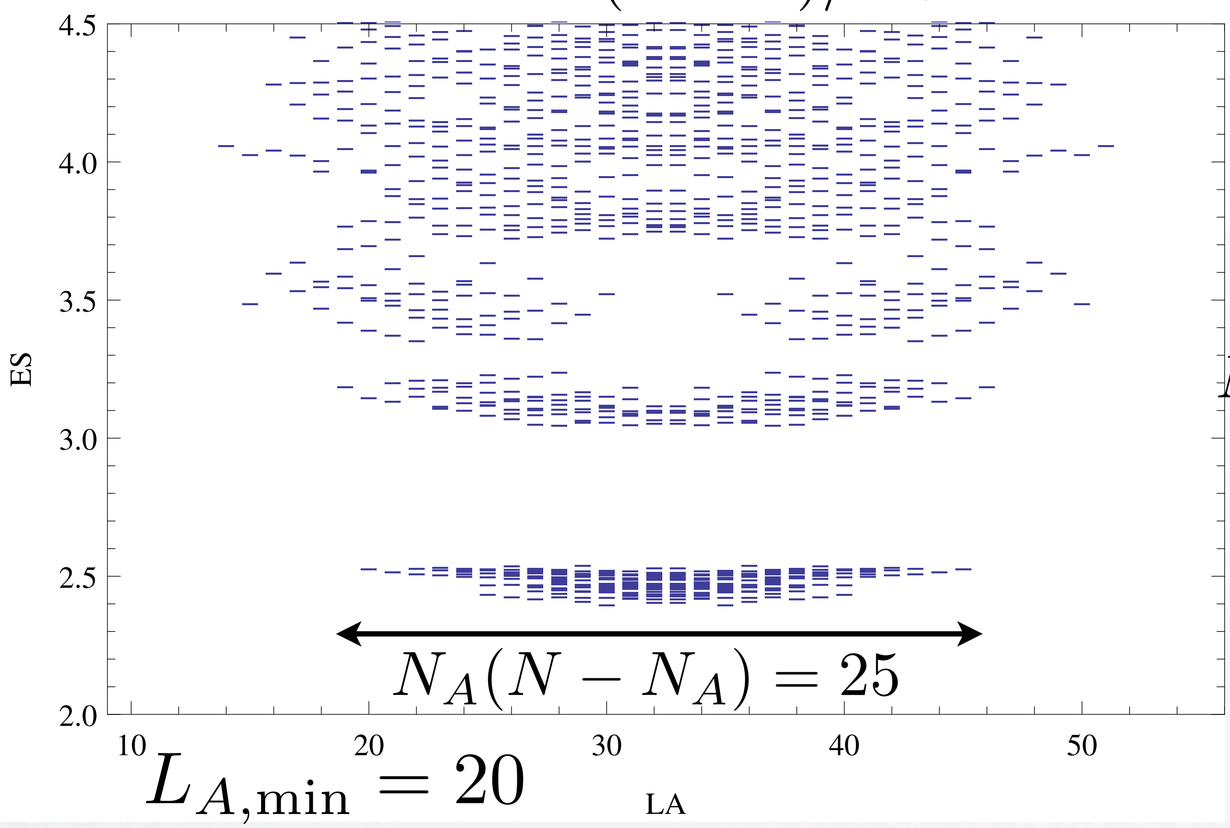
matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
PRB 91, 115117 (2015)

ES: vortices

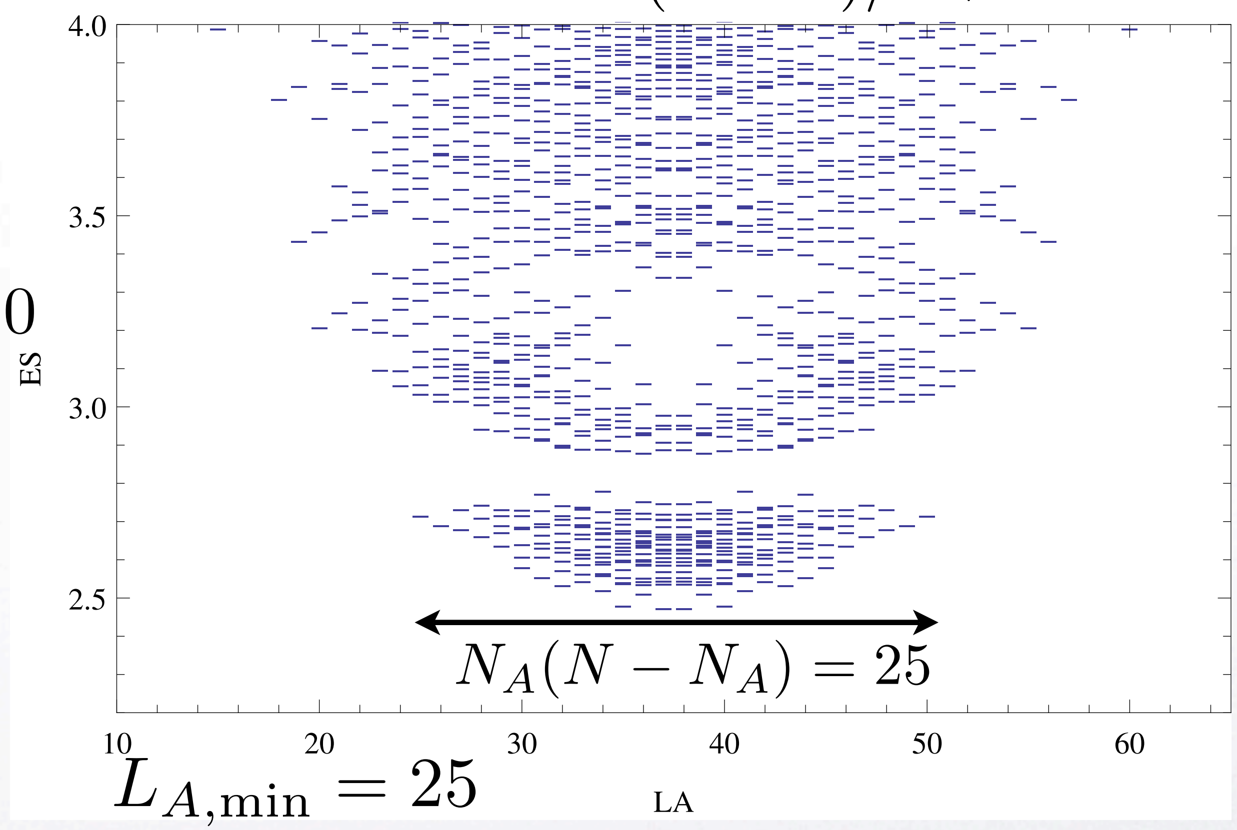
- particle partition irrespective of position $\rho_A^{(P)} = \left(\langle\psi| \prod_{j \le N_A} a^\dagger_{m_j} \prod_{k \le N_A} a_{m'_k} |\psi\rangle \right) |\vec{m}\rangle\langle\vec{m}'|$

$L = 65 = N(N-1)/2 + 2N$



$N = 10$
$N_A = 5$

$L = 75 = N(N-1)/2 + 3N$



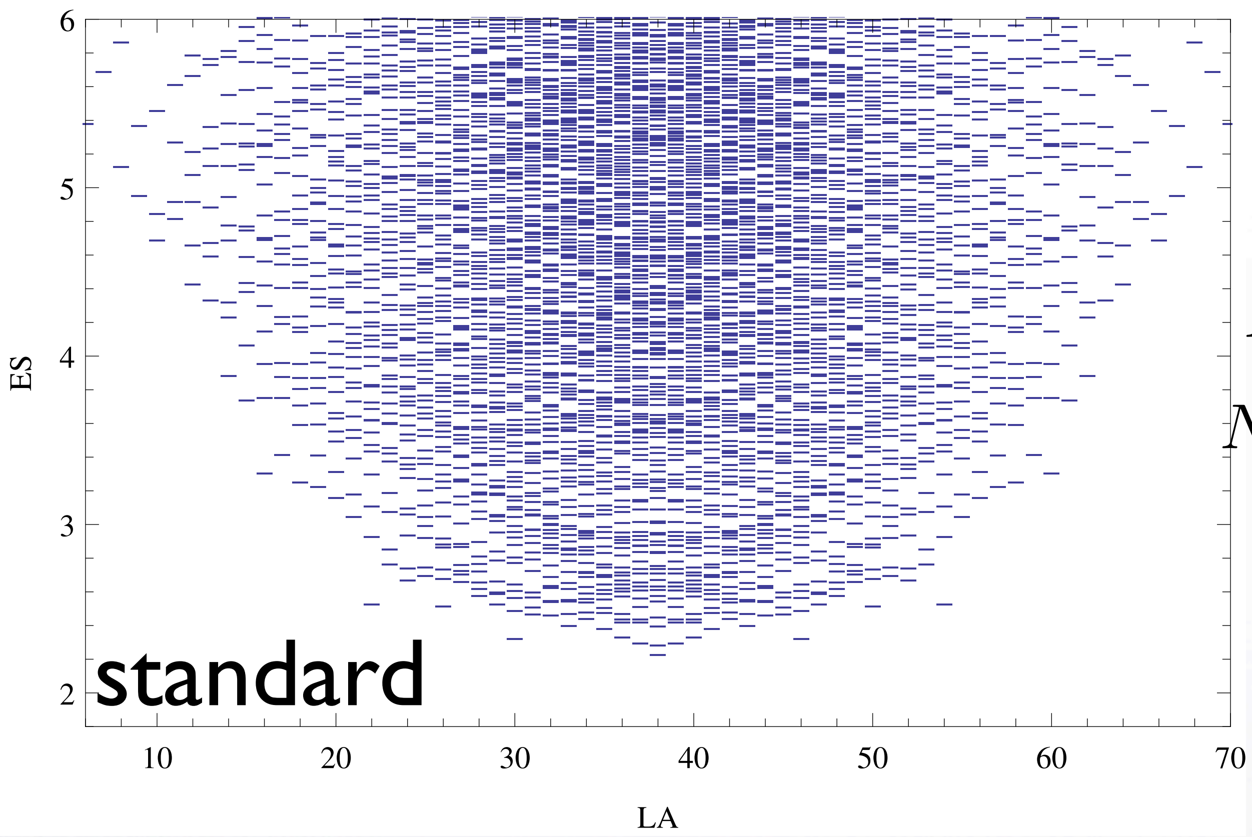
- consistent with central vortex ansatz

$$\Psi_{\mathrm{V}p} = \prod_i z_i^p \prod_{i<j}(z_i - z_j) \longrightarrow L_{A,\min} = N_A(N_A-1)/2 + pN_A$$

ES: Haffnian candidate

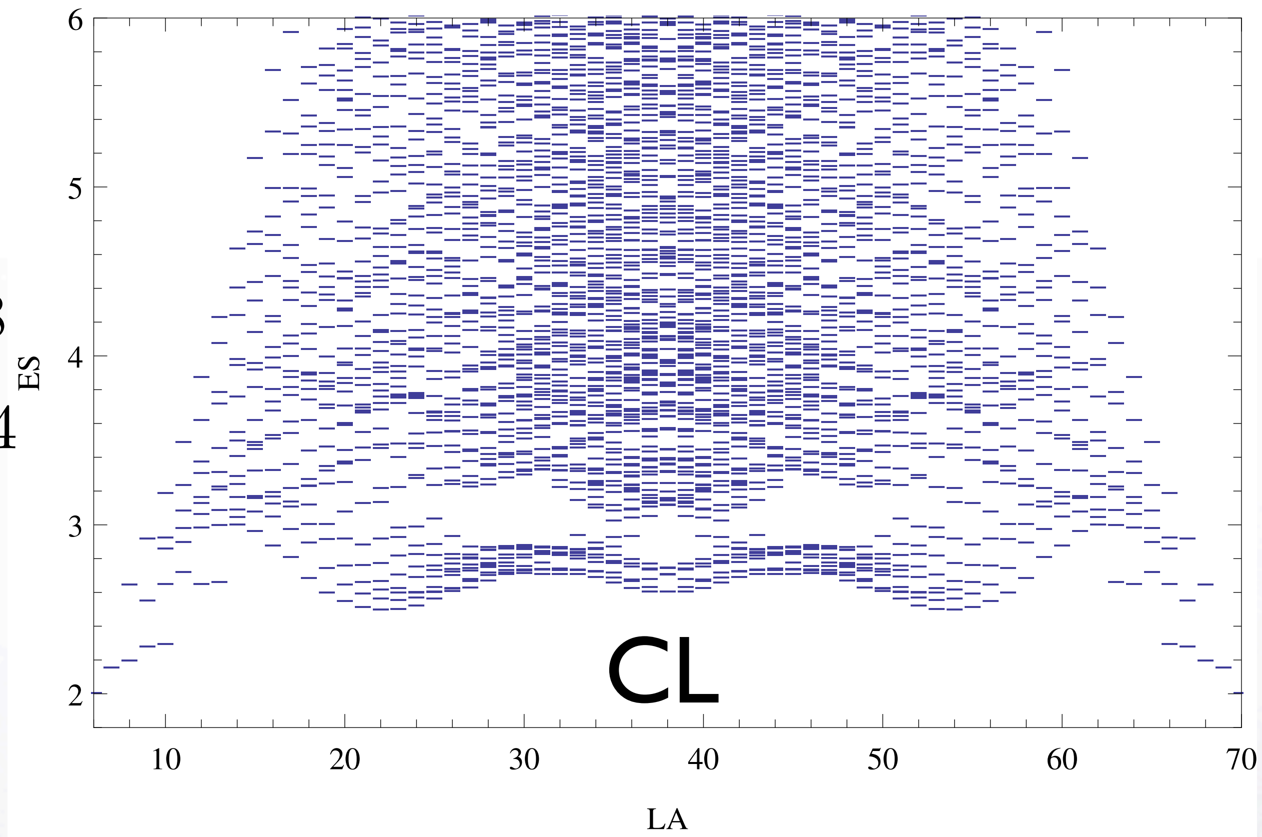
- particle partition irrespective of position $\rho_A^{(P)} = \left(\langle \psi | \prod_{j \le N_A} a^\dagger_{m_j} \prod_{k \le N_A} a_{m'_k} | \psi \rangle \right) |\vec{m}\rangle\langle\vec{m}'|$

$$L = 3N(N-1) - N = 76$$



$N = 8$

$N_A = 4$



- conformal limit to cancel geom. factors $\psi_{\vec{m}}^{(\mathrm{CL})} \equiv \psi_{\vec{m}} \cdot \prod_{j \le N} \sqrt{m_j!}$

R. Thomale, A Sterdyniak, N. Regnault, B.A. Bernevig, PRL **104**, 180502 (2010)

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni

arXiv:1411. 5962

Outline

- Motivation: beyond standard
- U(2) potential & deformed LL
- non-monotonic Haldane pseudopotentials
- Novel incompressible states: Haffnian?
- Entanglement spectrum
- Conclusions

matteo.rizzi@uni-mainz.de

M.Burrello, **MR**,
M.Roncaglia, A. Trombettoni
arXiv:1411. 5962

Conclusions & Outlook

- U(2) potential:
  - i) deformed LL (spin textures…)
  - ii) non-monotonic HP from s-wave only
- Novel incompressible states: Haffnian? d-wave pairing?
- Entanglement spectrum -- theoretical detector

- other LL deforming potentials? absence of Zeeman comp.?
- degeneracy points between LL's ?
- three-body terms? dissipation-induced?

M.Roncaglia, MR, J.I. Cirac,
PRL 104, 096803 (2010)

matteo.rizzi@uni-mainz.de

Special thanks to

M. Burrello
MPQ-Garching

M.Roncaglia
INRIM-Torino

A. Trombettoni
SISSA-Trieste

Burrello, Rizzi, Roncaglia, Trombettoni, PRB 91, 115117 (2015)

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MATERIALS SCIENCE IN MAINZ

CSM Computational Science Mainz

all of you for attention !