Optimal persistent currents for interacting bosons on a ring with gauge field

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Johannes Gutenberg-Universität Mainz

Benasque - 28.08.2014

M.Cominotti, D. Rossini, M. Rizzi, F. Hekking, A. Minguzzi, PRL 113, 025301 (2014)

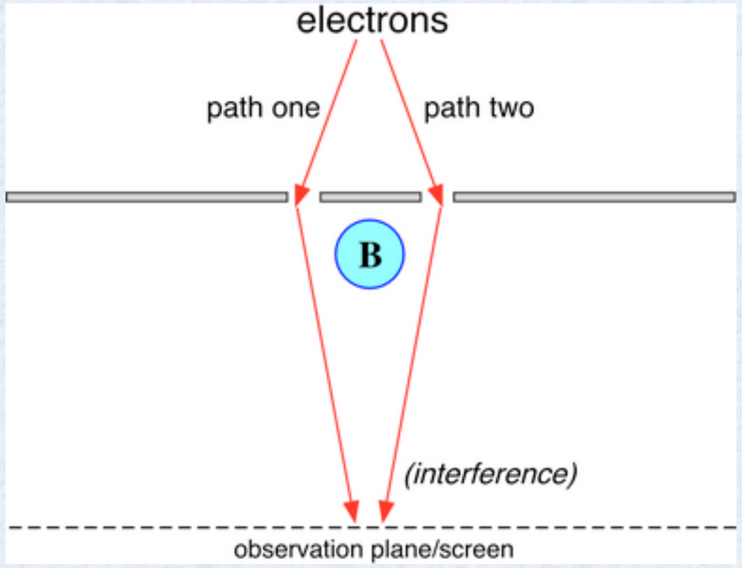
OUTLINE

- Introduction & connection to experiments
- Definition of the problem
- Analytical treatment
- Numerical approach (MPS & co.)
- Conclusions & open problems

M.Cominotti, D. Rossini, M. Rizzi, F. Hekking, A. Minguzzi, PRL 113, 025301 (2014)

Aharanov-Bohm effect & persistent current

Introduction



- U(1) gauge potential ==> geometric phase

$$\vec{\nabla} \times \vec{A} = \vec{B} \qquad \varphi = \int \vec{A} \cdot \mathrm{d}\vec{x}$$

- threaded flux $\Phi = \oint \vec{A} \cdot \mathrm{d}\vec{l} = \int_\circ \vec{B} \cdot \mathrm{d}\vec{S}$
- flux quantum $\Phi_0 = h/e$

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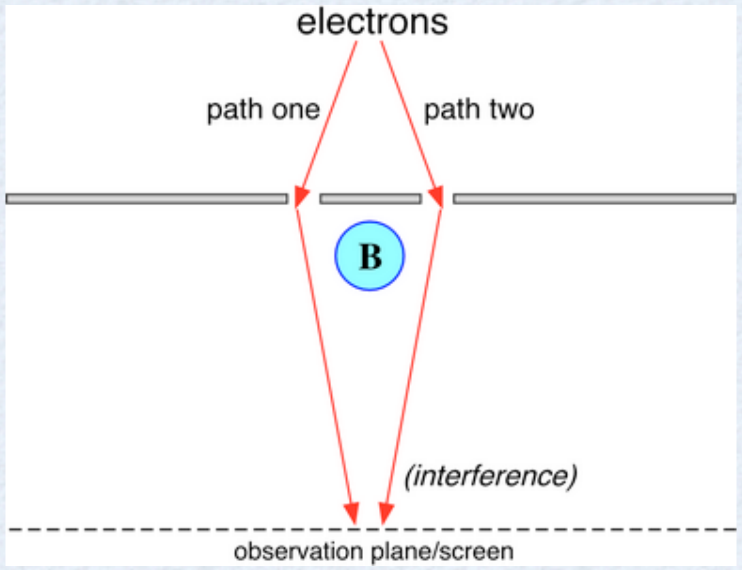

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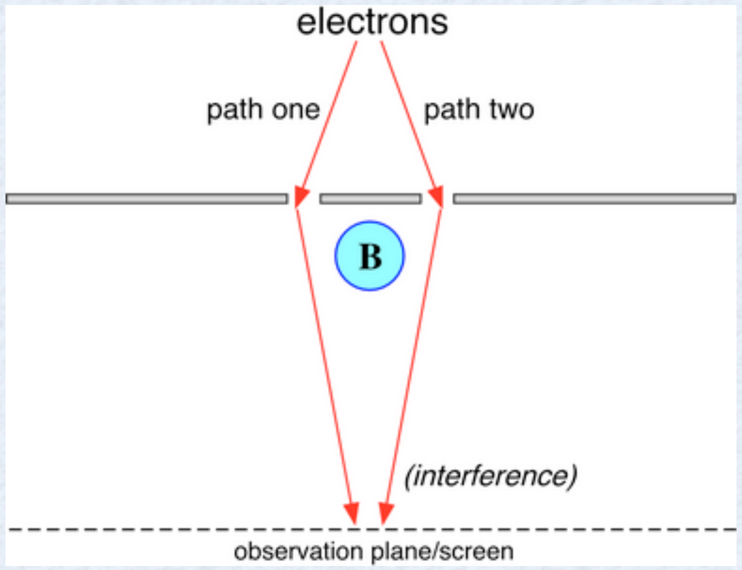

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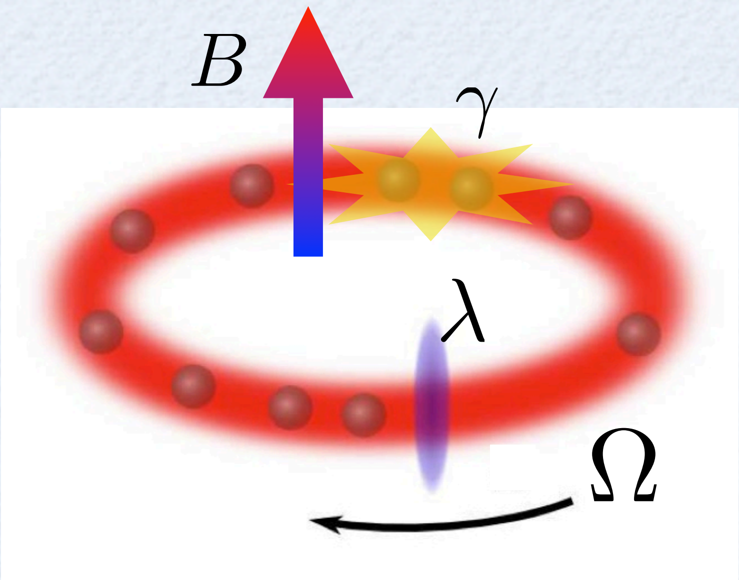


- quantum fluid + multiply connected geometry
  ==> persistent current $I(\Omega) = -\frac{1}{2\pi\hbar}\frac{\partial E(\Omega)}{\partial \Omega}$
  Bloch, PRB 2, 109 (1970)
- physics periodic in terms of $\Omega = 2\pi\Phi/\Phi_0$
  (inequivalent sectors … winding number...)

Persistent currents in condensed matter

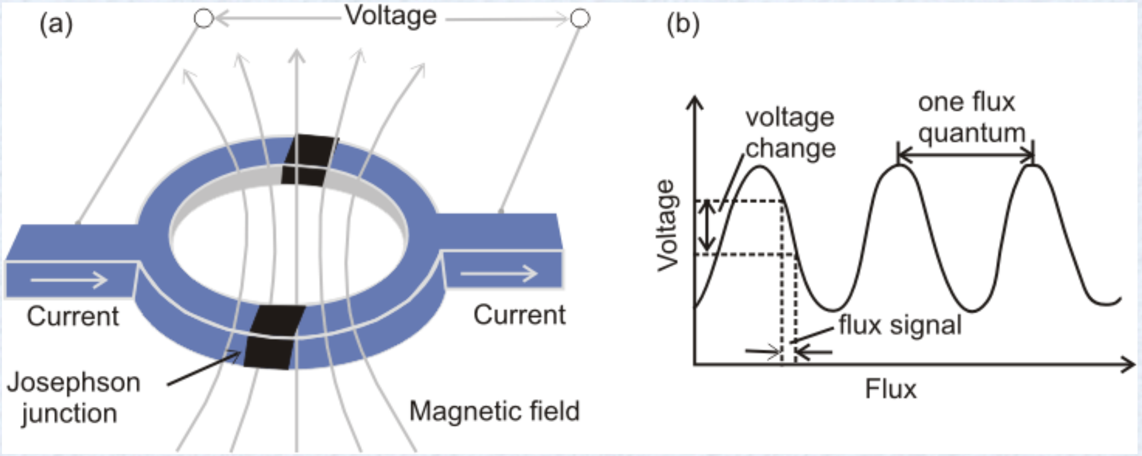
Introduction

Persistent Current <==> *macroscopic many-body quantum coherence*

- bulk superconductors

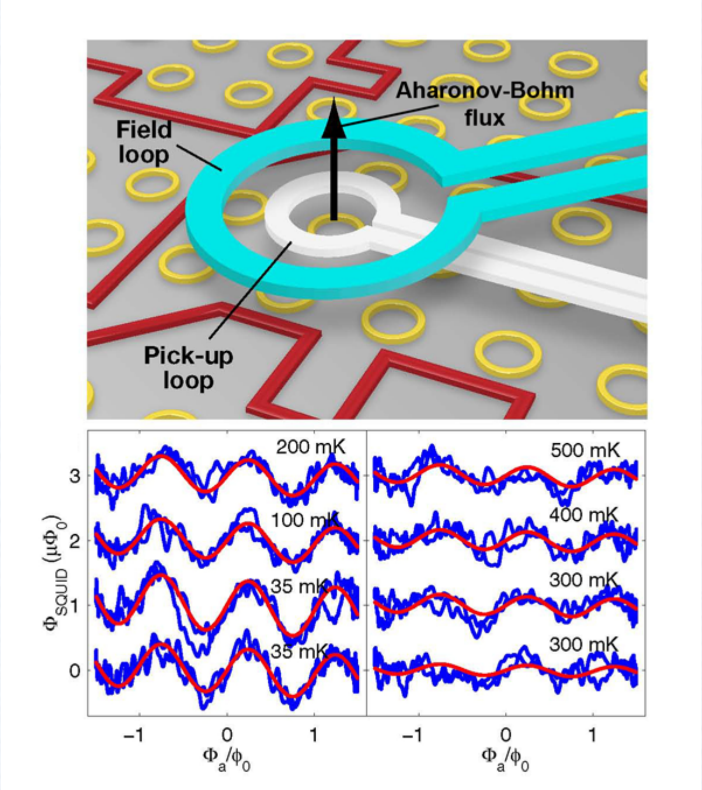
B. S. Deaver and W. M. Fairbank, PRL 7, 43 (1961)
N. Byers and C. N. Yang, PRL 7, 46 (1961)
L. Onsager, PRL 7, 50 (1961)

- SQUID = superconducting quantum interference device



- normal metallic rings

L. P. Levy, et al., PRL 64, 2074 (1990)
D. Mailly, et al., PRL 70, 2020 (1993)
H. Bluhm et al., PRL 102, 136802 (2009)
A. C. Bleszynski-Jayich, et al., Science 326, 272 (2009)



Persistent currents in condensed matter

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Persistent Current <==> *macroscopic many-body quantum coherence*

? Effects of interactions & barrier/impurities & statistics ?

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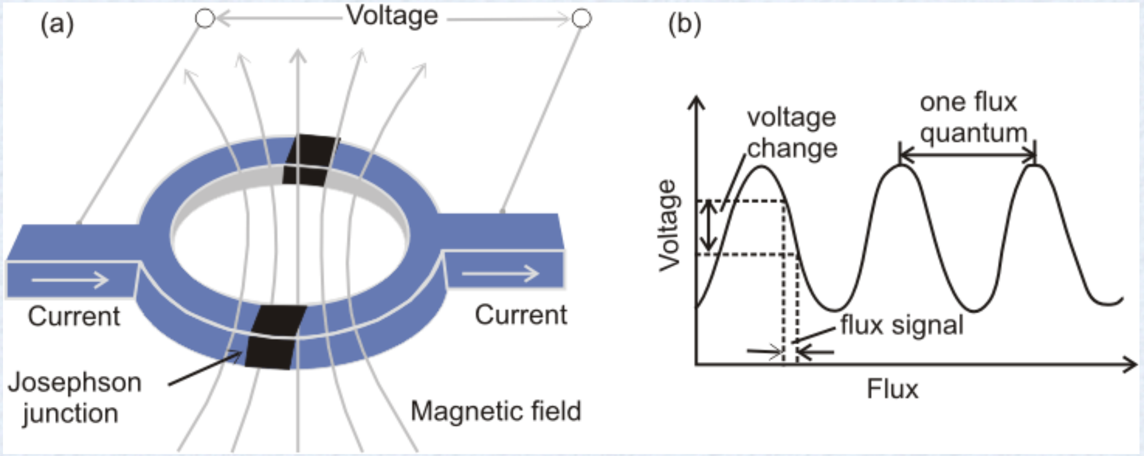

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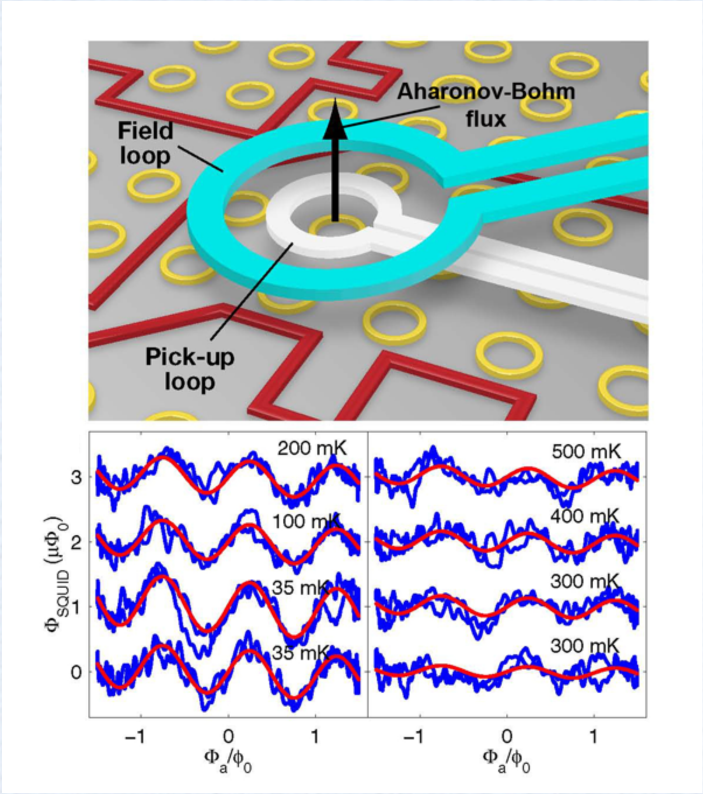
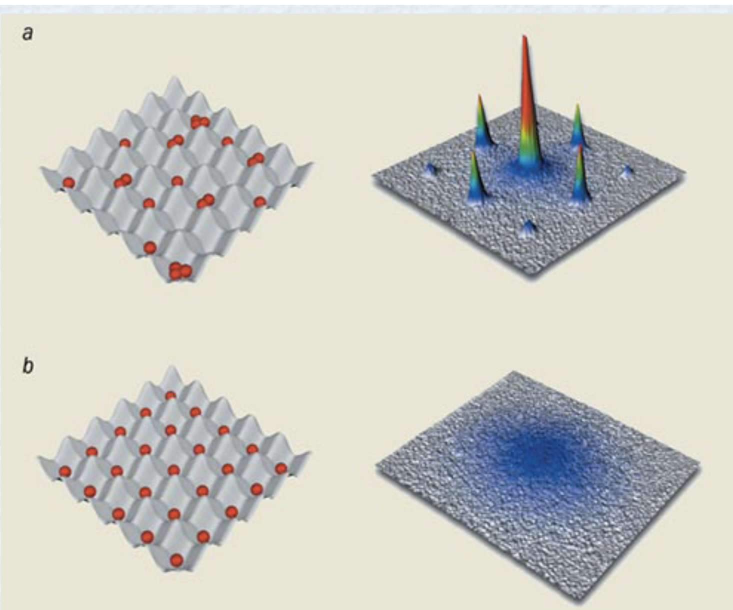


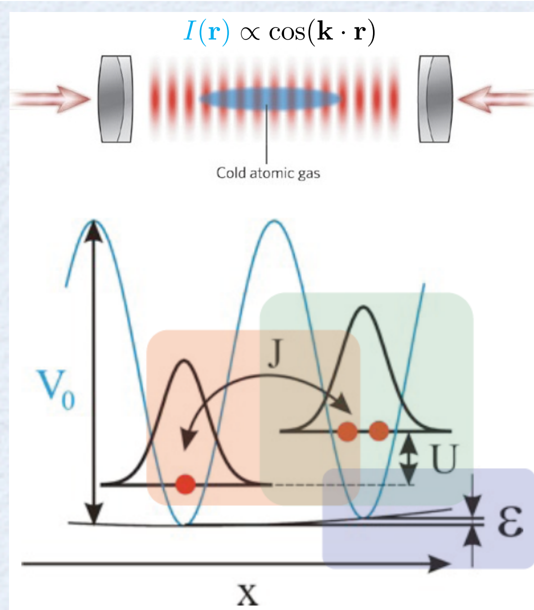
Ultracold atoms: a quantum engineering platform

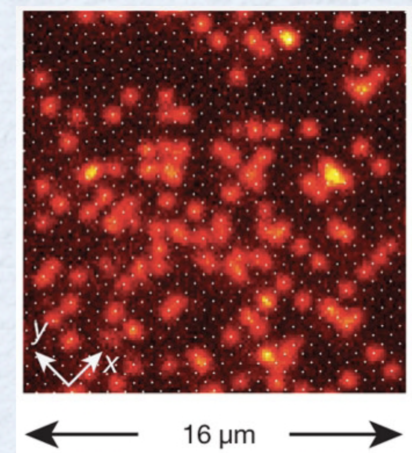
Introduction

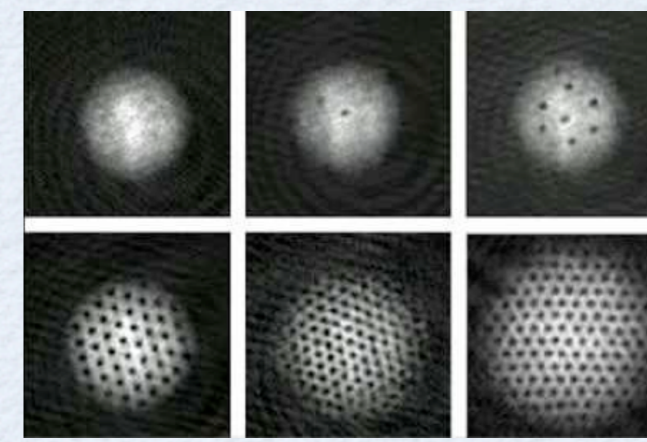
- isolated neutral quantum systems (long coherence times)
- high tunability of microscopic parameters (also interactions!)
- possibility of inducing artificial gauge potentials
- access to many microscopic observables

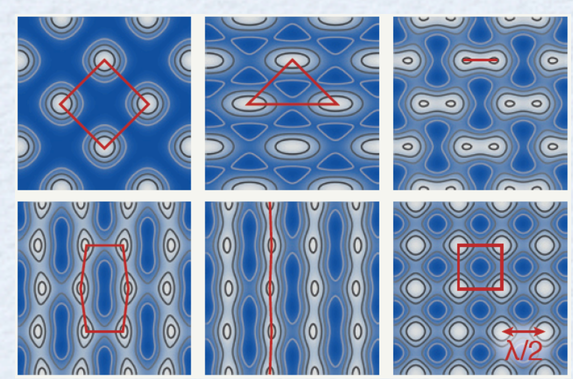
$$\mathcal{H} = -J \sum_{<i,j>} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

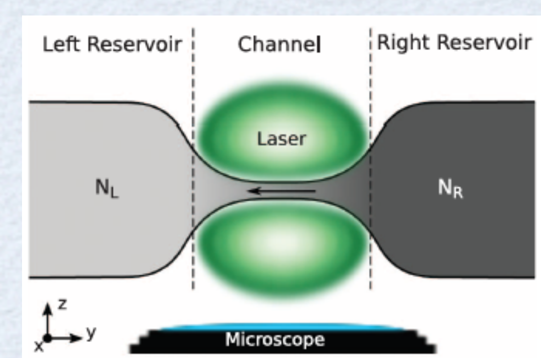








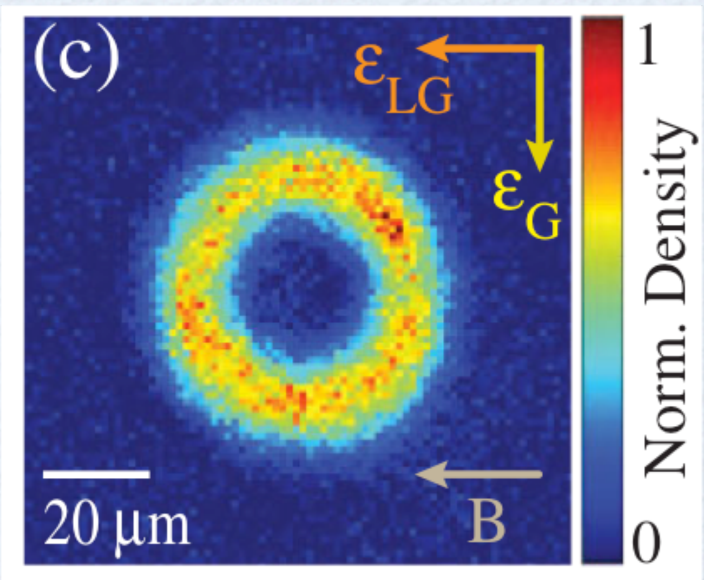


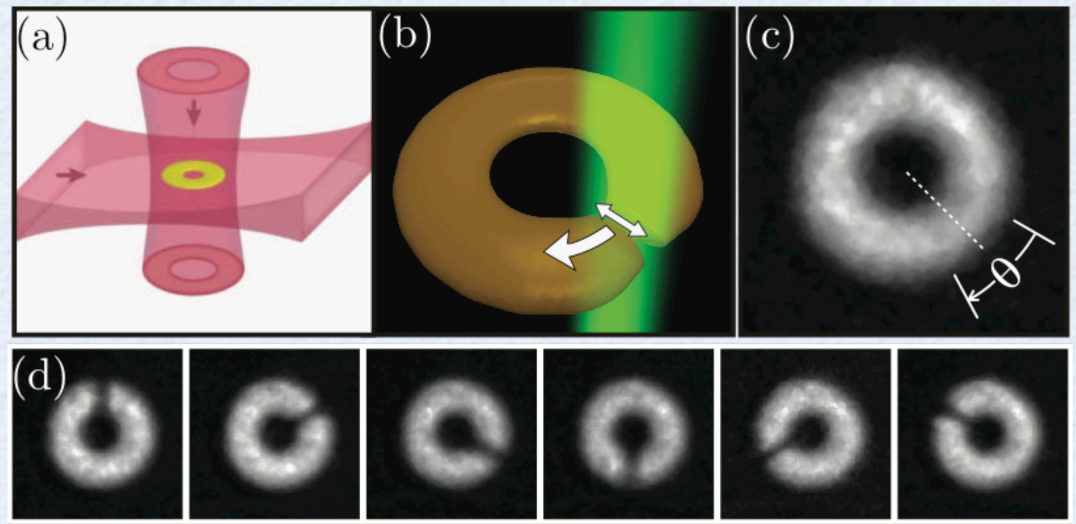


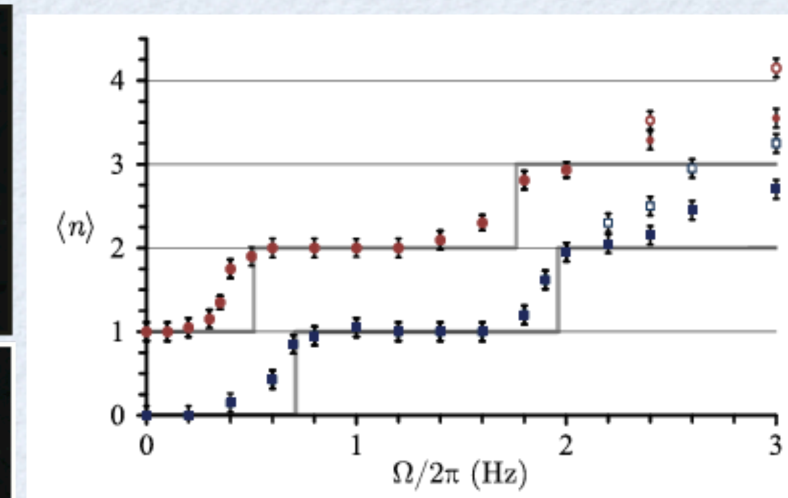
M. Lewenstein, et al., Adv Phys 56, 243–379 (2007).
I. Bloch, J. Dalibard, W. Zwerger, RMP 80, 885 (2008)
J. Dalibard, F. Gerbier, G. Juzeliunas, and P. Öhberg, RMP 83, 1523 (2011)

Cold atoms in ring traps

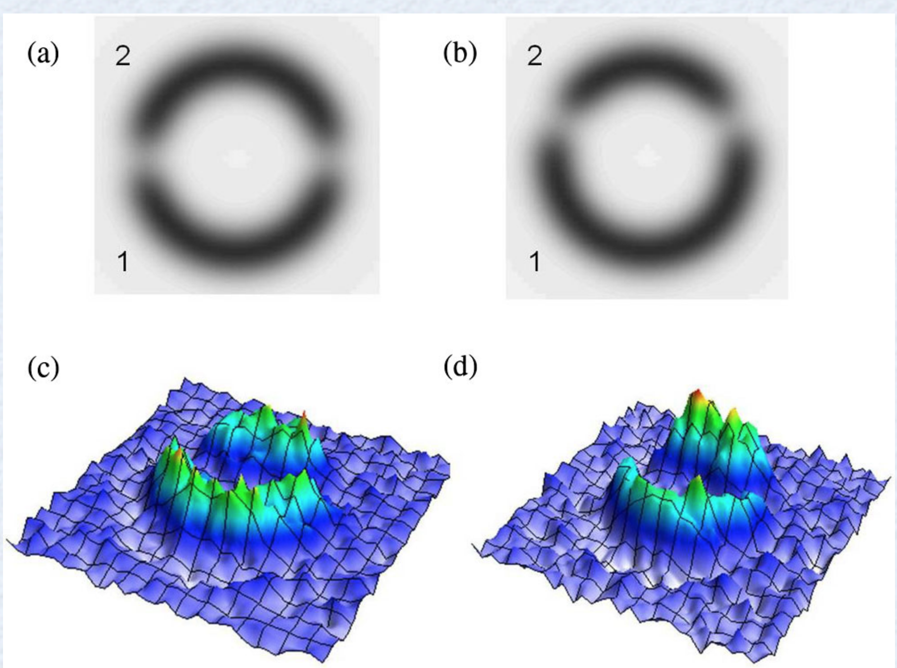
Introduction







Ramanathan et al., PRL 106, 130401 (2011); Wright et al., PRL 110, 025302 (2013);
Moulder et al., PRA 86, 013629 (2012) ; Beattie, et al., PRL 110, 025301 (2013);



Ryu, et al., PRL 111, 205301 (2013),…

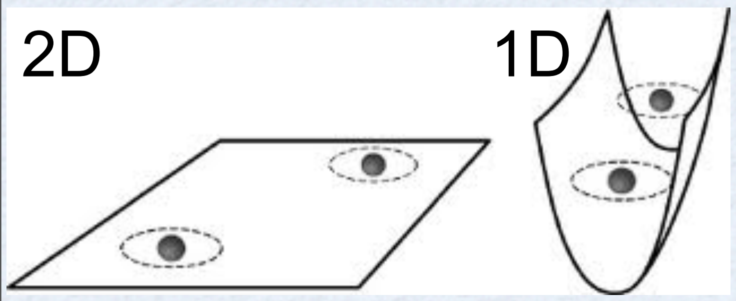
- persistent currents flowing for up to 40s !
- applications for:
  - quantum info [atomic qubit]
  - high-precision measurements [interferometry]
  - **fundamental questions :)**

D. W. Hallwood, et al., PRA 82, 063623 (2010)
D. Solenov, D. Mozyrsky, PRA 82, 061601 (2010)
A. Nunnenkamp, et al, PRA 84, 053604 (2011)
C. Schenke et al., PRA 85, 053627 (2012)

Richness & oddness of a 1D scenario

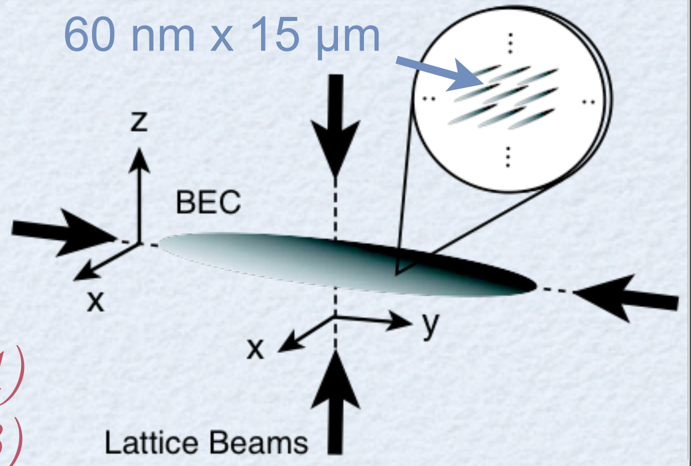
Introduction

- obtained by strong transverse confinement and/or optical lattice



$$\hbar\omega_\perp \gg k_B T,\ \mu$$

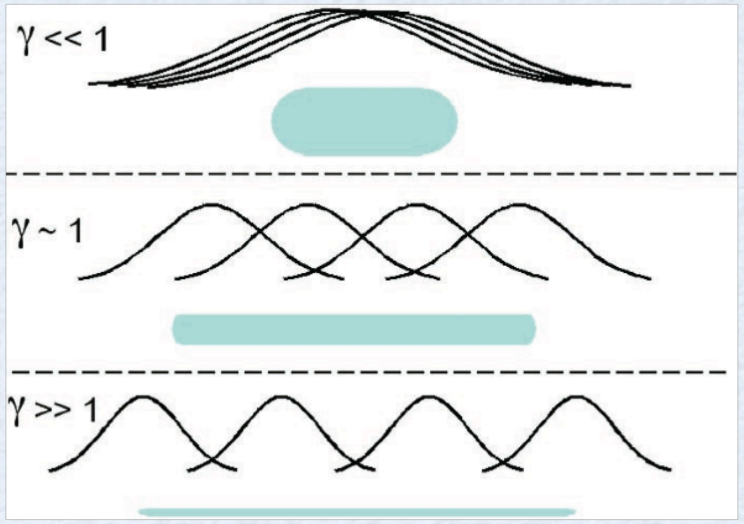
$$\Psi_B(\vec{r}_1,\ldots,\vec{r}_N) = \psi_B^{1D}(x_1,\ldots,x_N)\prod_{i=1}^{N}\phi_0(\vec{r}_i^{\perp})$$



Greiner et al., PRL 87, 160405 (2001)
Moritz et al., PRL 91, 250402 (2003)

- Interaction growth with diluteness !

$$\gamma = \frac{E_{int}}{E_{kin}} = \frac{gn}{\hbar^2 n^2/m} = \frac{gm}{\hbar^2 n} \qquad n = \frac{N}{L}$$



- Fermionization of hard-core bosons

Paredes, et al., Nature 429, 6989 (2004);
Kinoshita et al., Nature 440, 900 (2006);

- Quantum fluctuations are crucial

$$\langle\hat{\Psi}^\dagger(x)\hat{\Psi}(x')\rangle \simeq \frac{1}{|x-x'|^{1/2K}}$$

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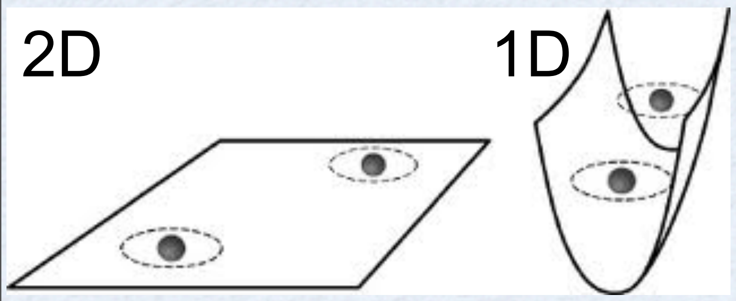

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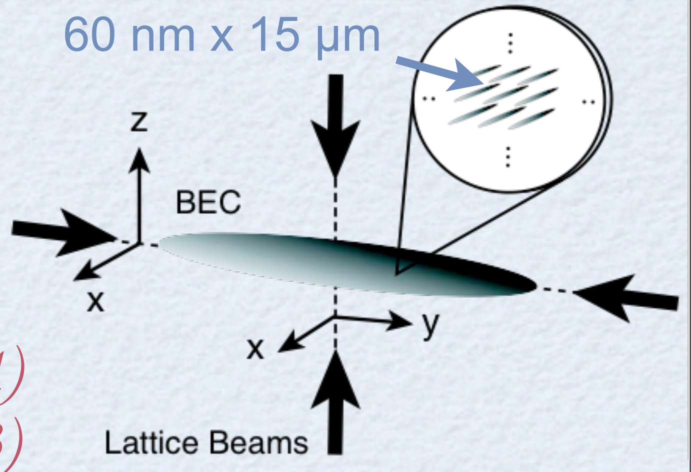

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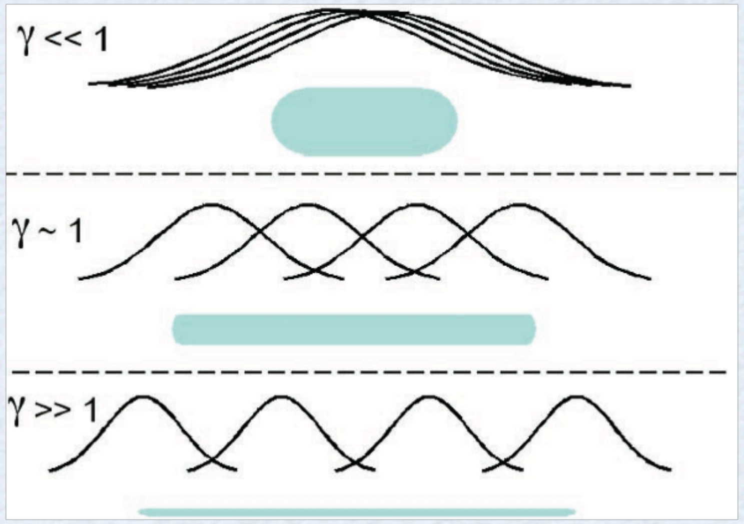

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- **lots of analytics & numerics at hand :)**

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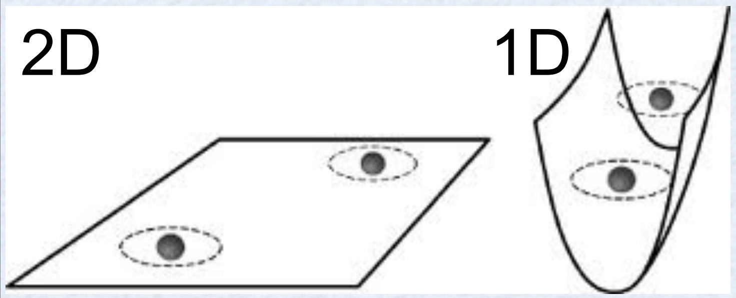

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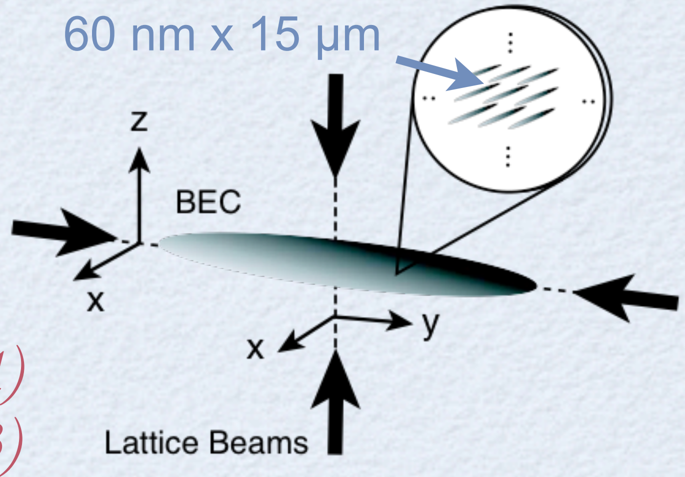
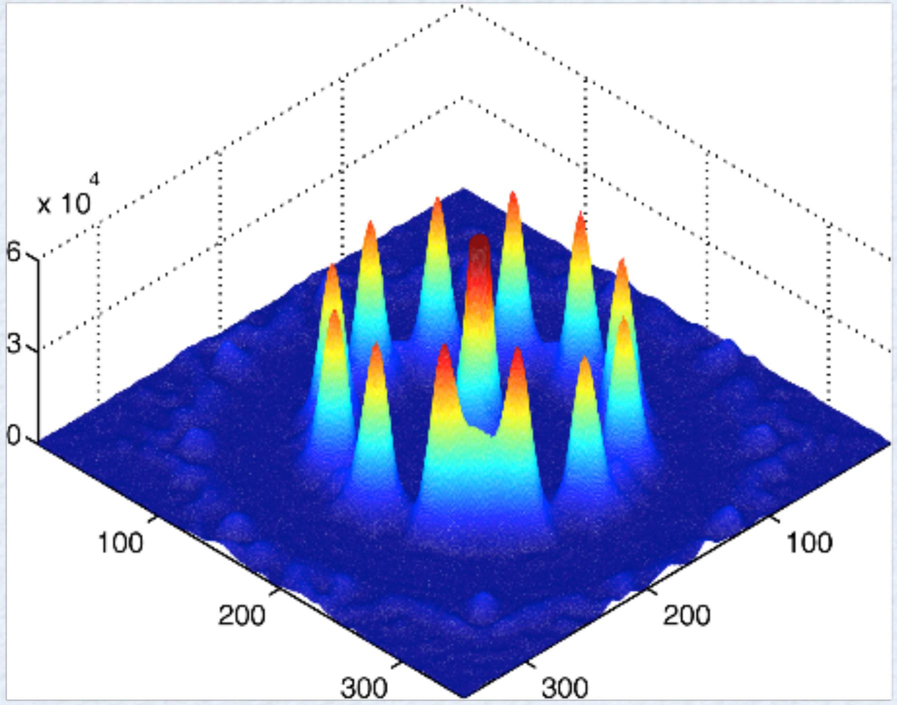


Greiner et al., PRL 87, 160405 (2001)
Moritz et al., PRL 91, 250402 (2003)

- first proposals & proof of principles for **1D rings** available !

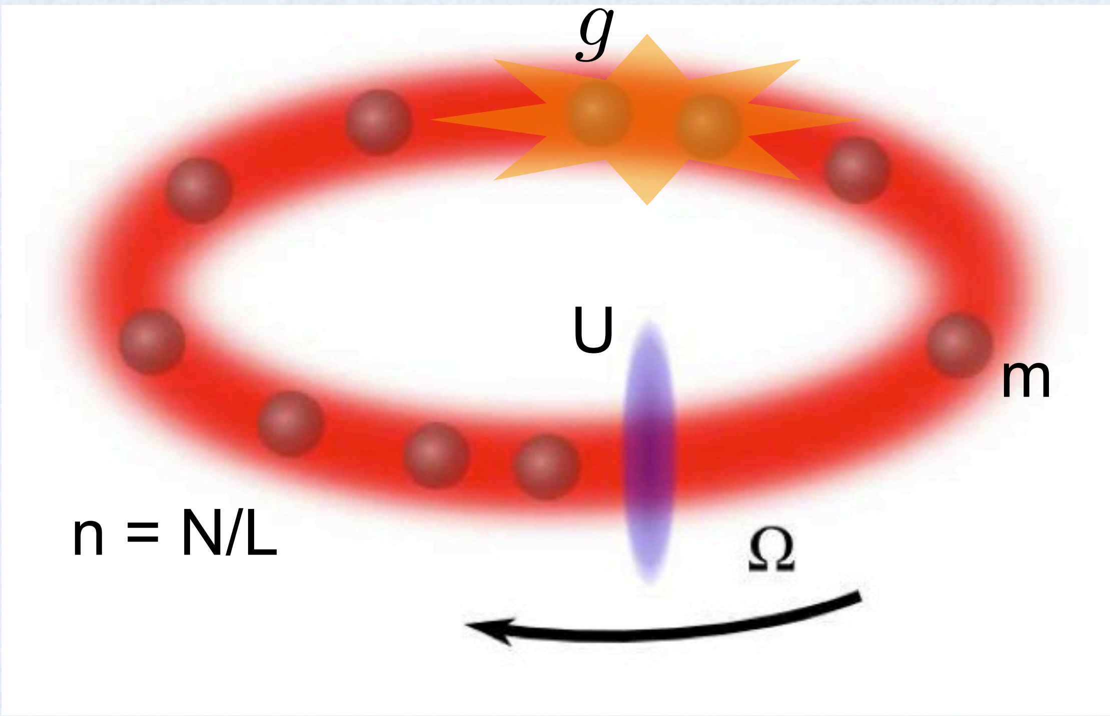


Amico et al., Sci. Rep. 4, 4298 (2014)

The system Hamiltonian

Setup

$$\mathcal{H} = \sum_{j=1}^{N} \left[\frac{\hbar^2}{2M} \left(-i \frac{\partial}{\partial x_j} - \frac{2\pi\Omega}{L} \right)^2 + U\,\delta(x_j) + g \sum_{l<j}^{N} \delta(x_l - x_j) \right]$$



- ultracold bosons (T=0)
- mesoscopic sizes (no TL, for now)
- adimensional couplings

$$\gamma = \frac{gm}{\hbar^2 n} \qquad \lambda = \frac{mUL}{\pi\hbar^2}$$

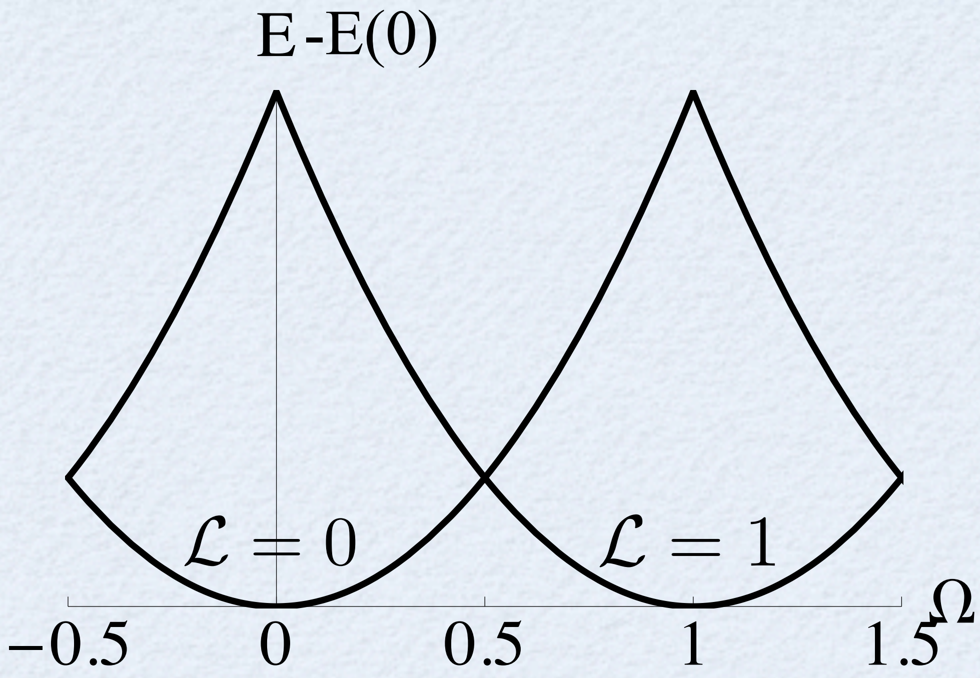
TARGET: Persistent current $I(\Omega) = -\frac{1}{2\pi\hbar}\frac{\partial E(\Omega)}{\partial \Omega}$ in all regimes of γ & λ

for interacting fermions … *Loss, PRL 69, 343 (1992); Mueller-Gröeling et al., EPL 22, 193 (1993)*

and BEC-BCS crossover ... *A. Spuntarelli, P. Pieri, and G. C. Strinati, PRL 99, 040401 (2007)*

Presence of a barrier/defect

Setup



$\lambda = 0$ Rotational Invariance

⇓

total ang. mom. $\mathcal{L}$ preserved

⇓

"internal" energy independent from Ω

⇓

Current = perfect sawtooth $\forall \gamma$

of amplitude $I_0 = \frac{2\pi\hbar\Omega}{mL^2}$

Presence of a barrier/defect

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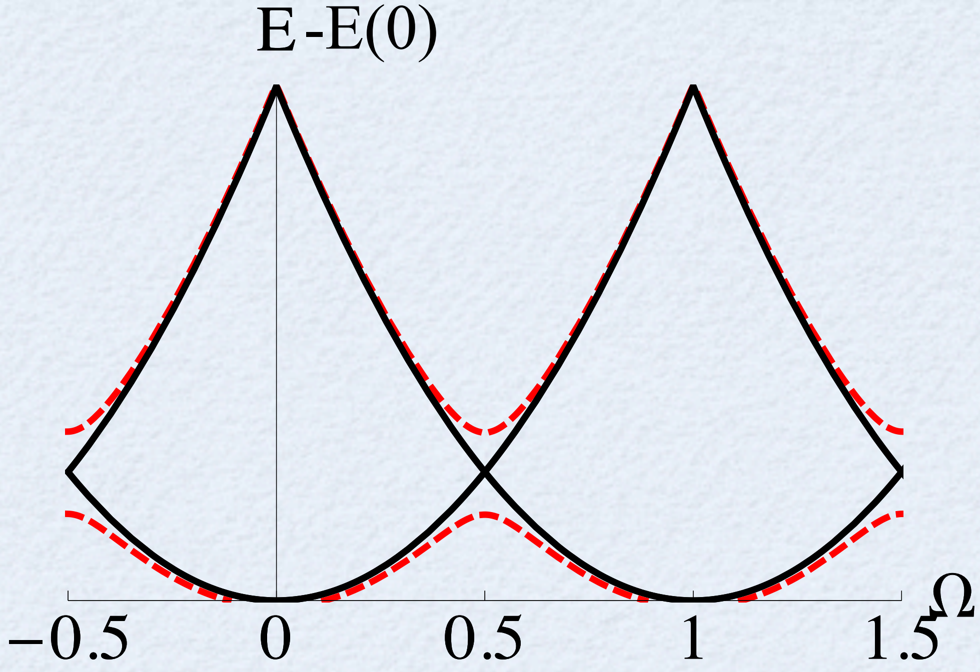

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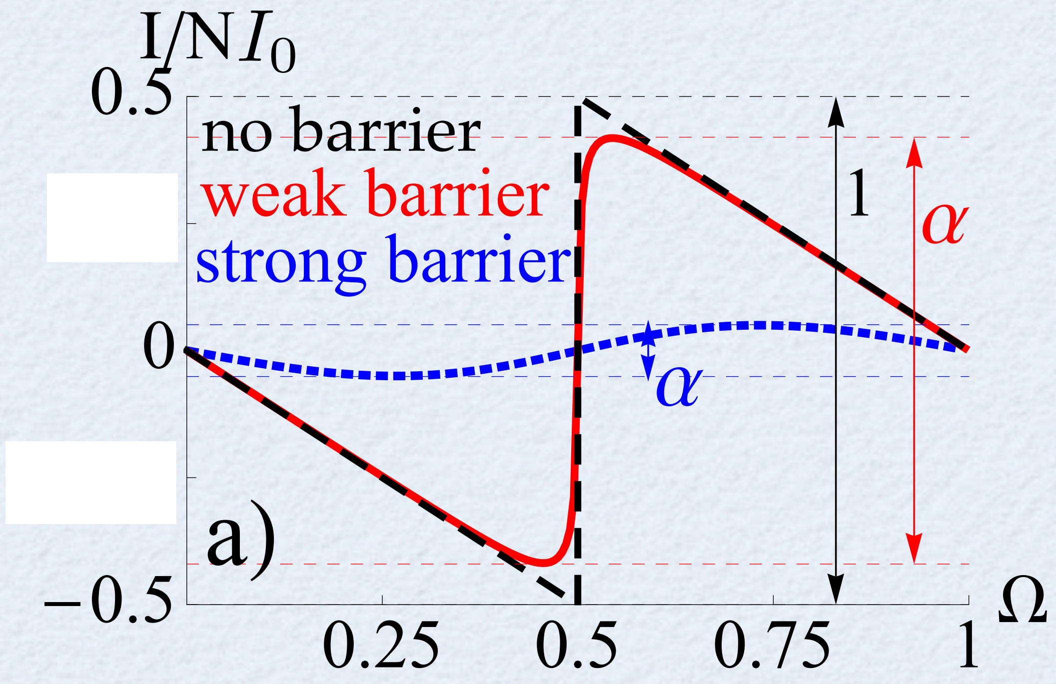


$\lambda > 0$ U(1) Symmetry Breaking

⇓

single particle levels affected differently

⇓

"internal" energy dependent from Ω

⇓

- Current depends on γ !

- flux qubit around $\Omega = 0.5$!?
- Lieb-Liniger integrability destroyed !
- (here) adiabatic raising of barrier & focus on stationary regime...

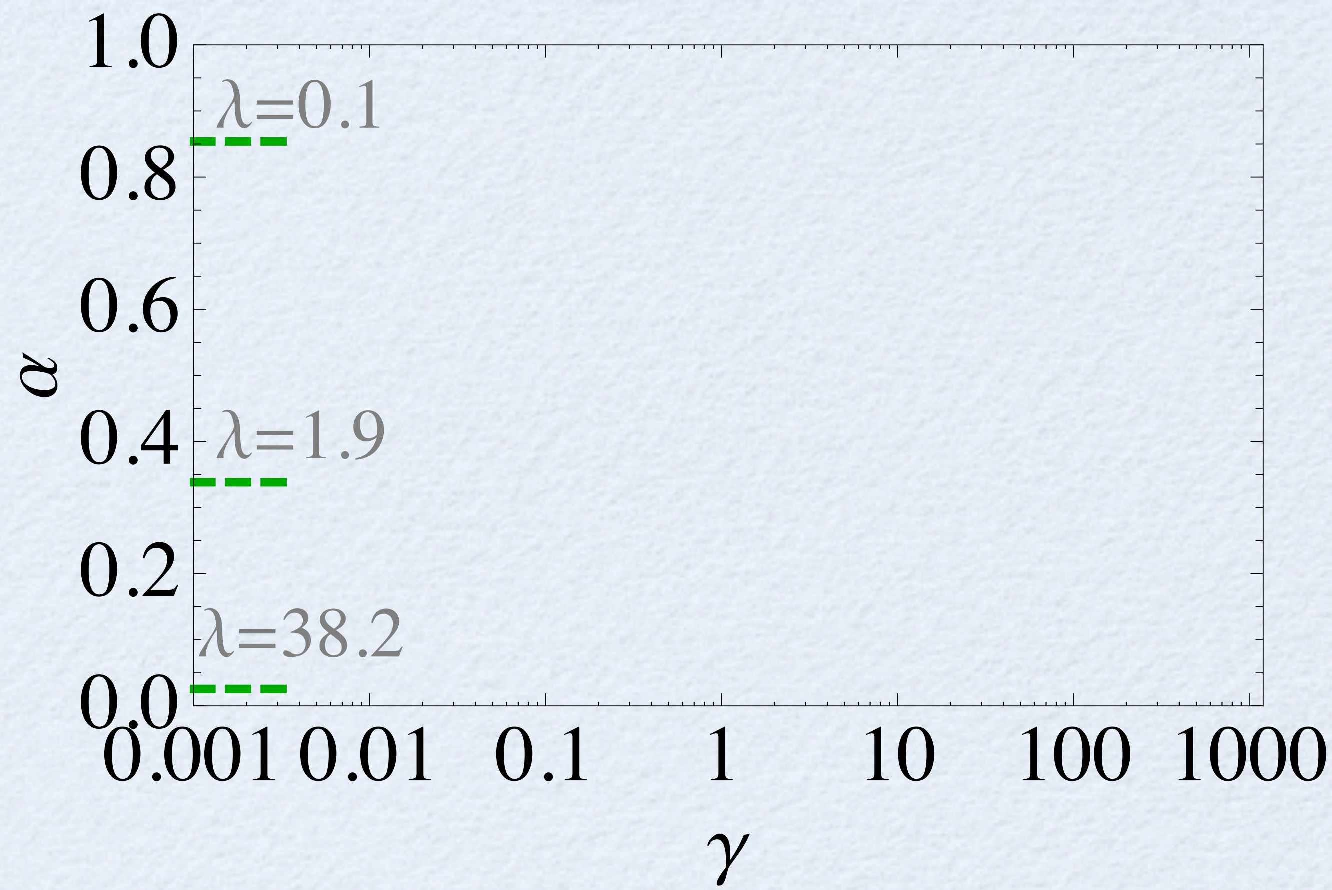
Single-particle regimes: non-interacting

Analytic

✓ eigenfunctions are plane waves
+ twisted boundary conditions
+ cusp at barrier position

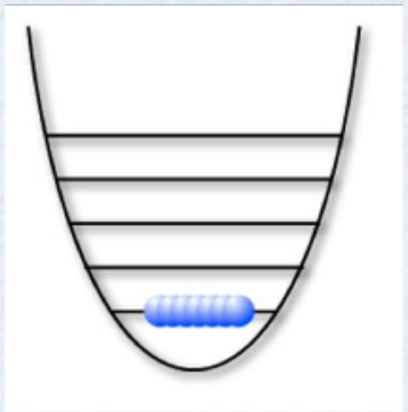
$$k_n = \pm\lambda \frac{\pi}{L} \frac{\sin(k_n L)}{\cos(2\pi\Omega) \mp \cos(k_n L)}$$

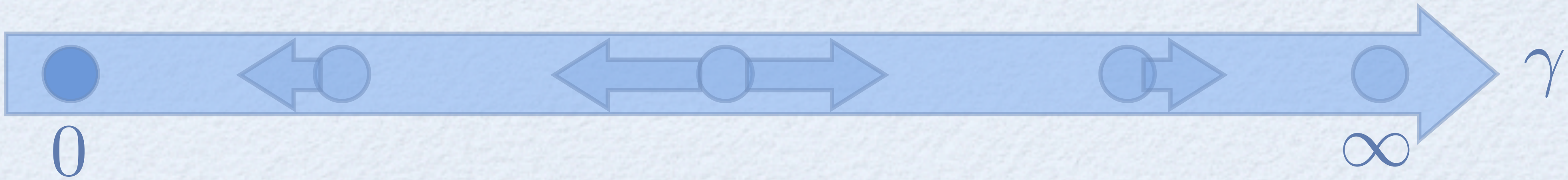
$$\varepsilon_n = \hbar^2 k_n^2 / 2m$$



✓ ideal bosons scenario: condensation in the ground

$$E = N\varepsilon_0$$





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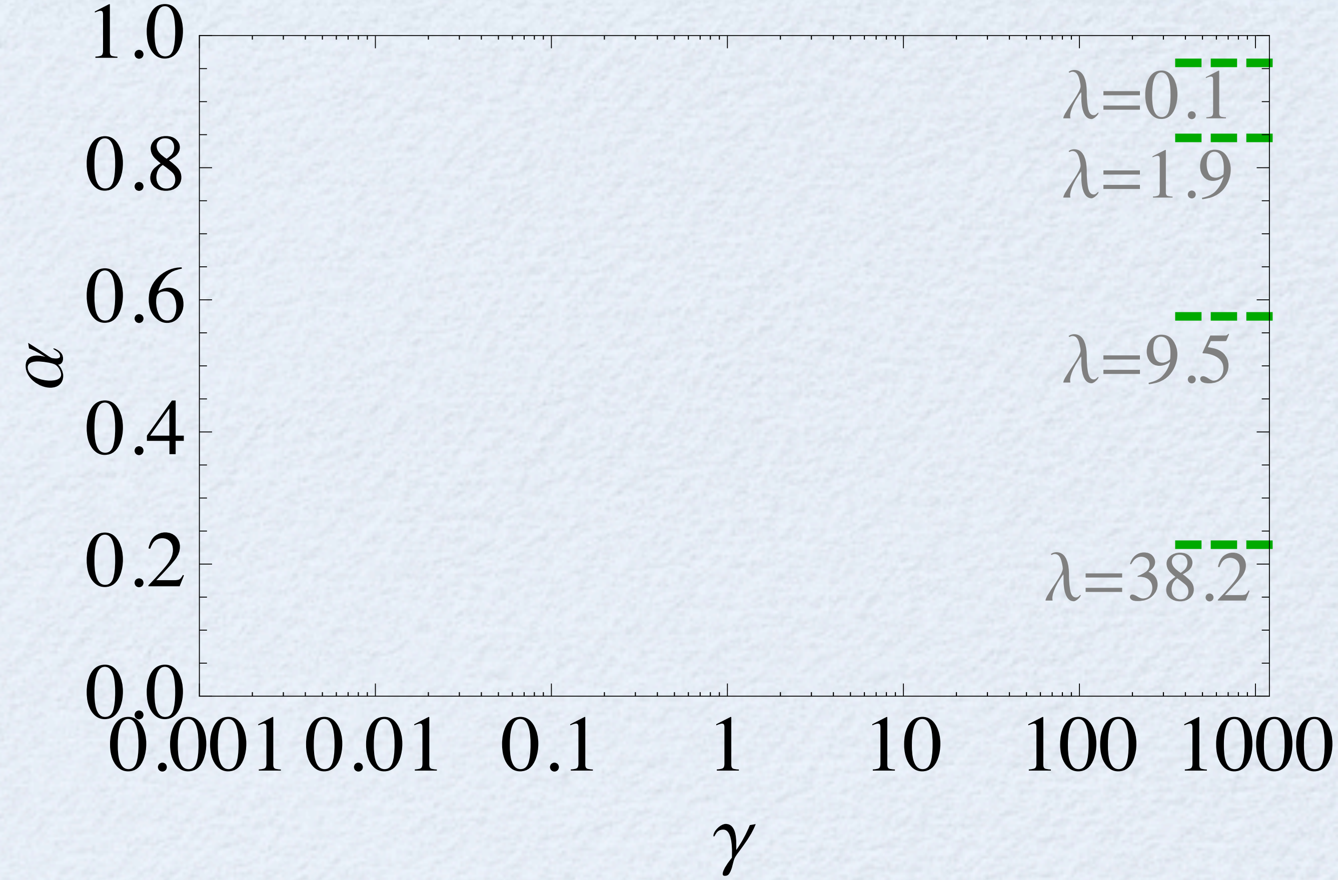
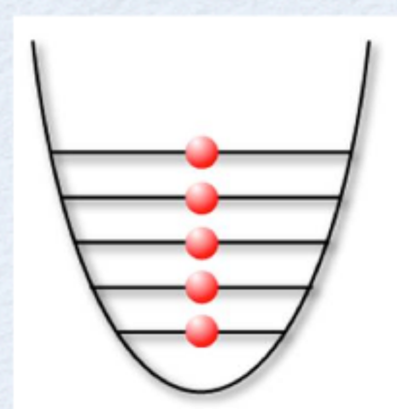
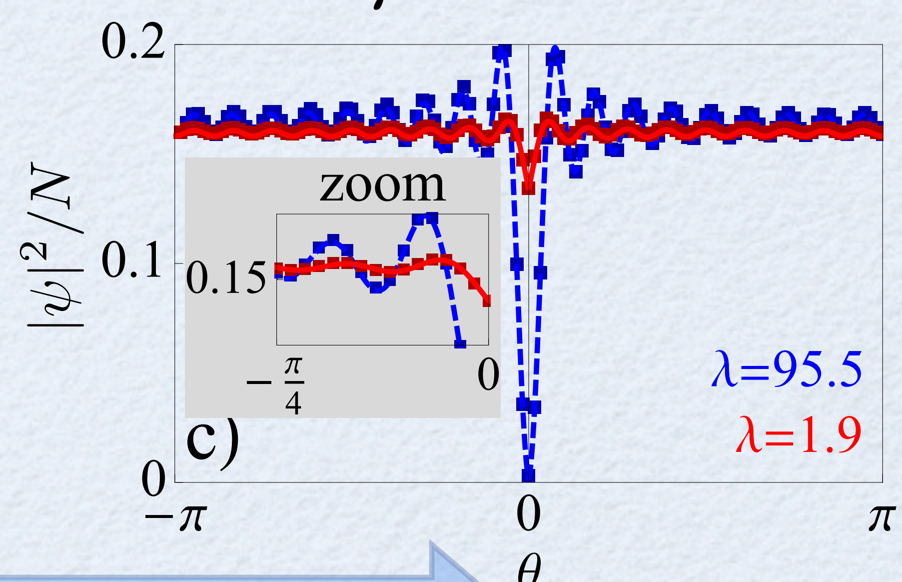
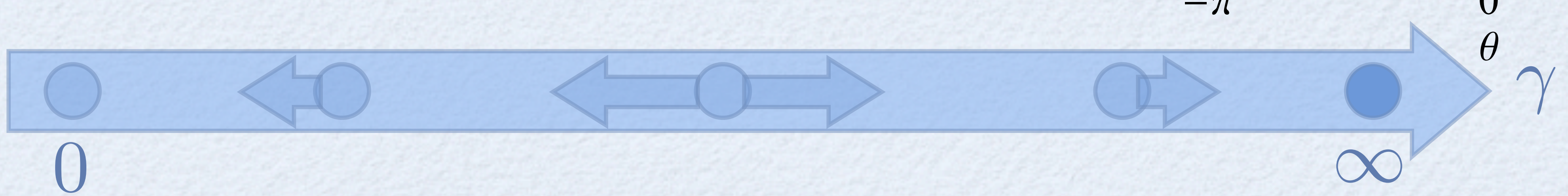


- ✓ ideal "fermionized" scenario
  => Friedel oscillations

$$E = \sum_{n=0}^{N-1} \varepsilon_n$$







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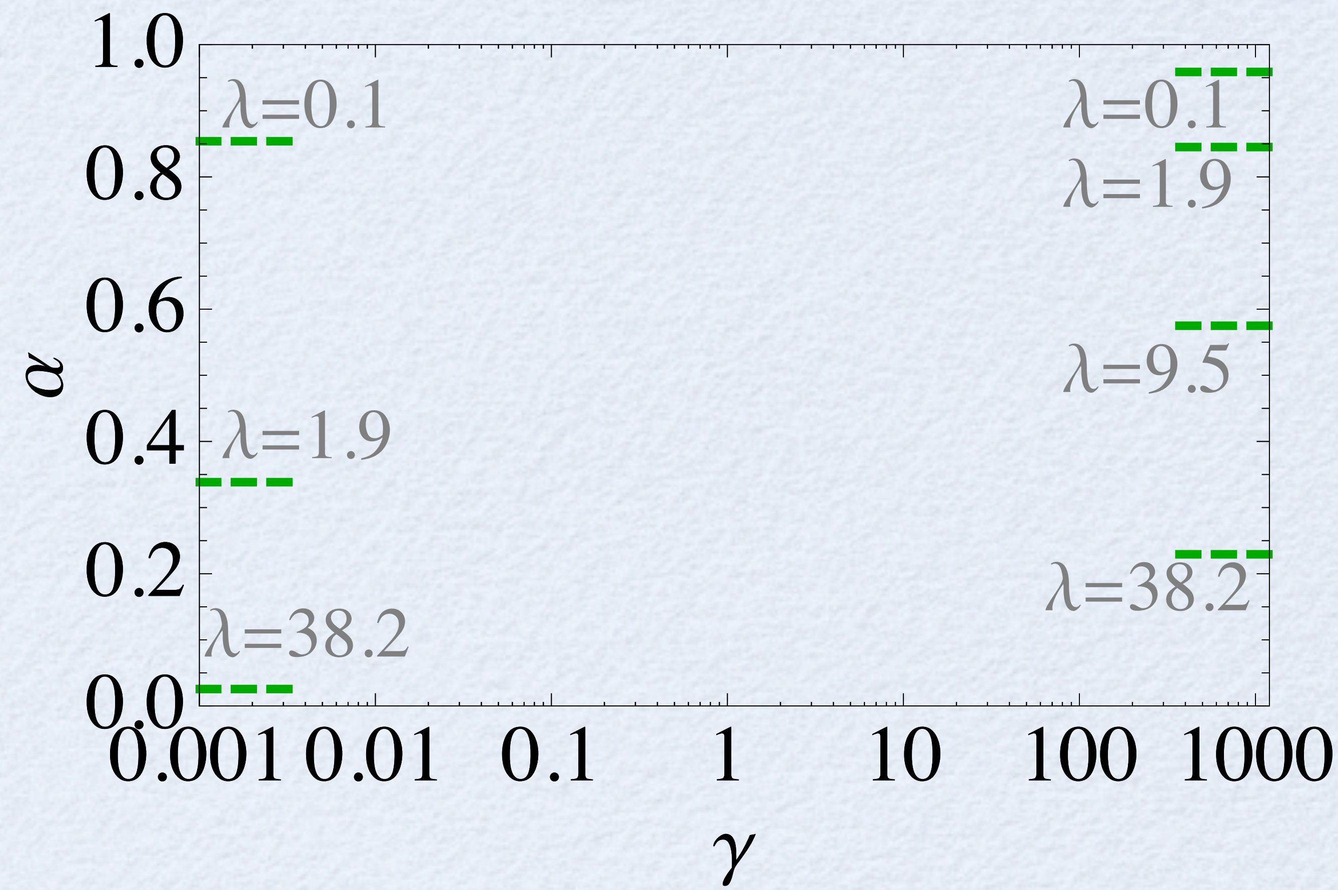

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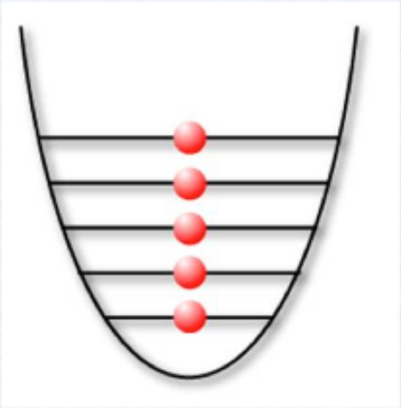
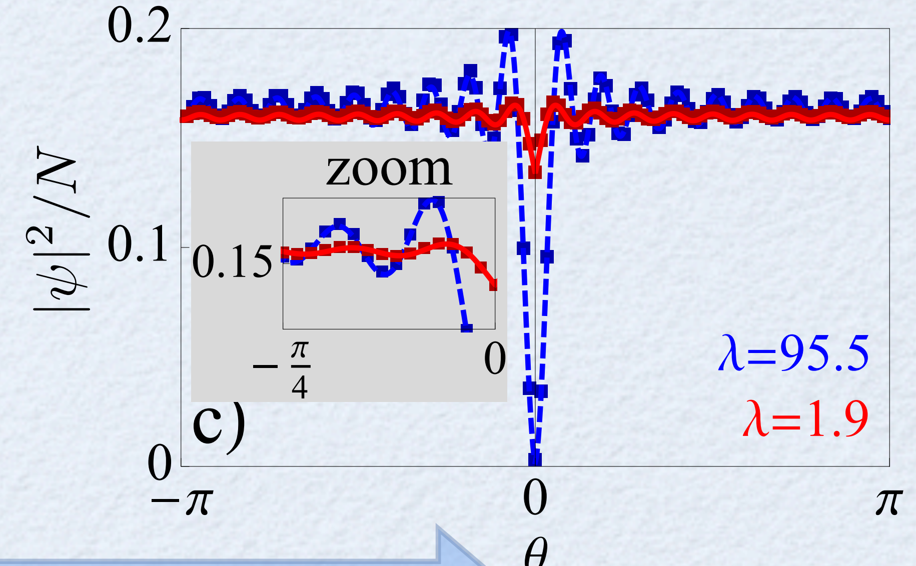
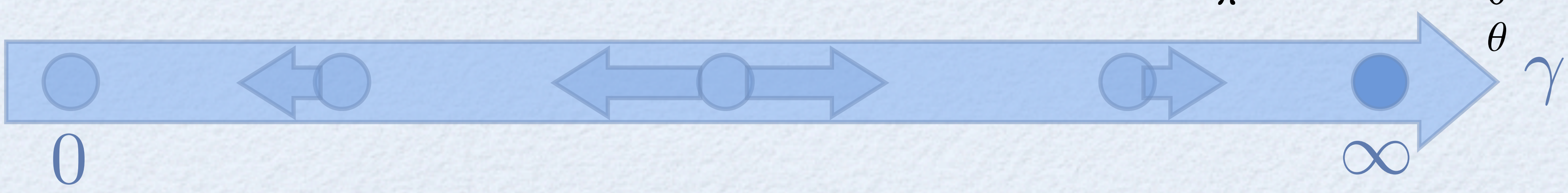






Weakly interacting regime

Analytic

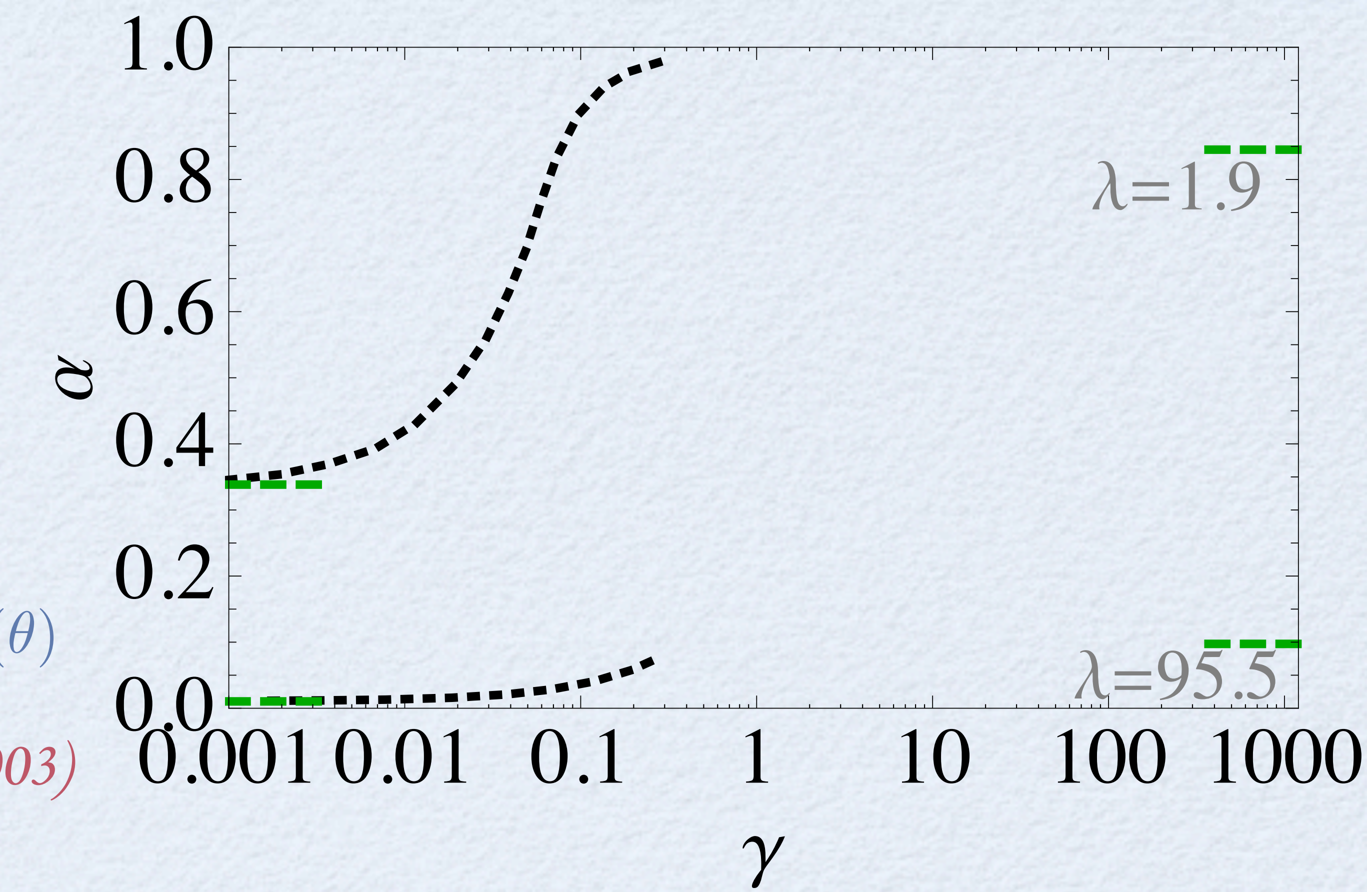
✓ mean-field (~ classical) approach

$$\langle \hat{\psi}(\theta) \rangle = |\Psi(\theta)|\, e^{i\phi(\theta)}$$

◉ non-linear Schrödinger equation
(Gross-Pitaevski equation)

$$\left[\left(-i\frac{\partial}{\partial \theta} - \Omega \right)^2 + \lambda\delta(\theta) + \tilde{g}|\Psi(\theta)|^2 \right] \Psi(\theta) = \mu\Psi(\theta)$$

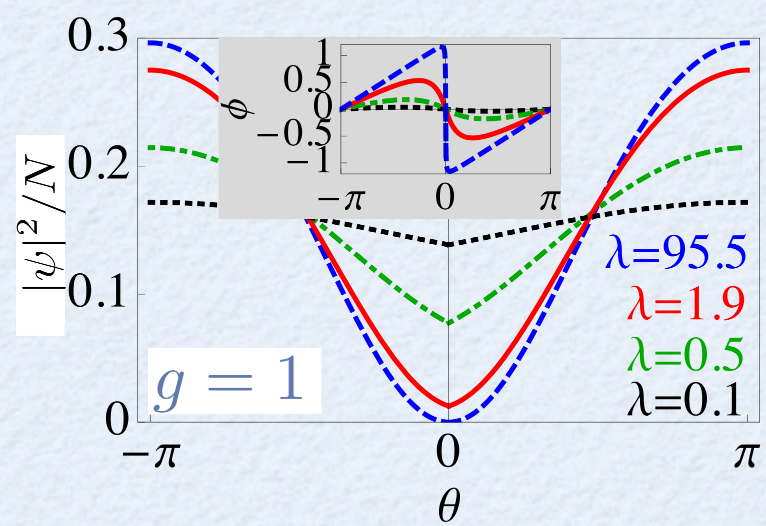
Pitaevskii & Stringari, Bose-Einstein Cond., Oxford (2003)

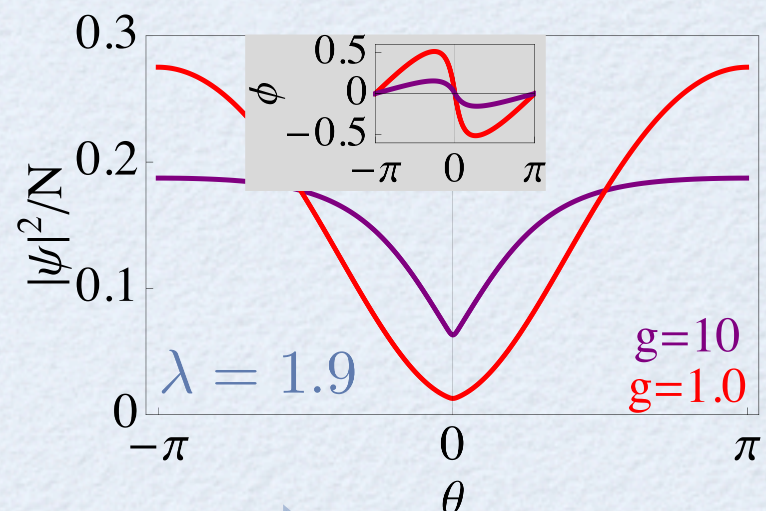


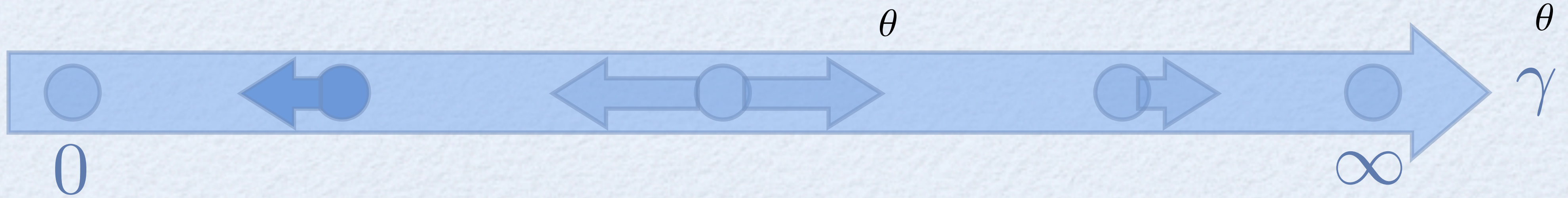
✓ soliton pinned by barrier

$$\xi = \hbar / \sqrt{2mn_0 g}$$

Kanamoto et al., PRL 100, 060401 (2008)







Weakly interacting regime

Analytic

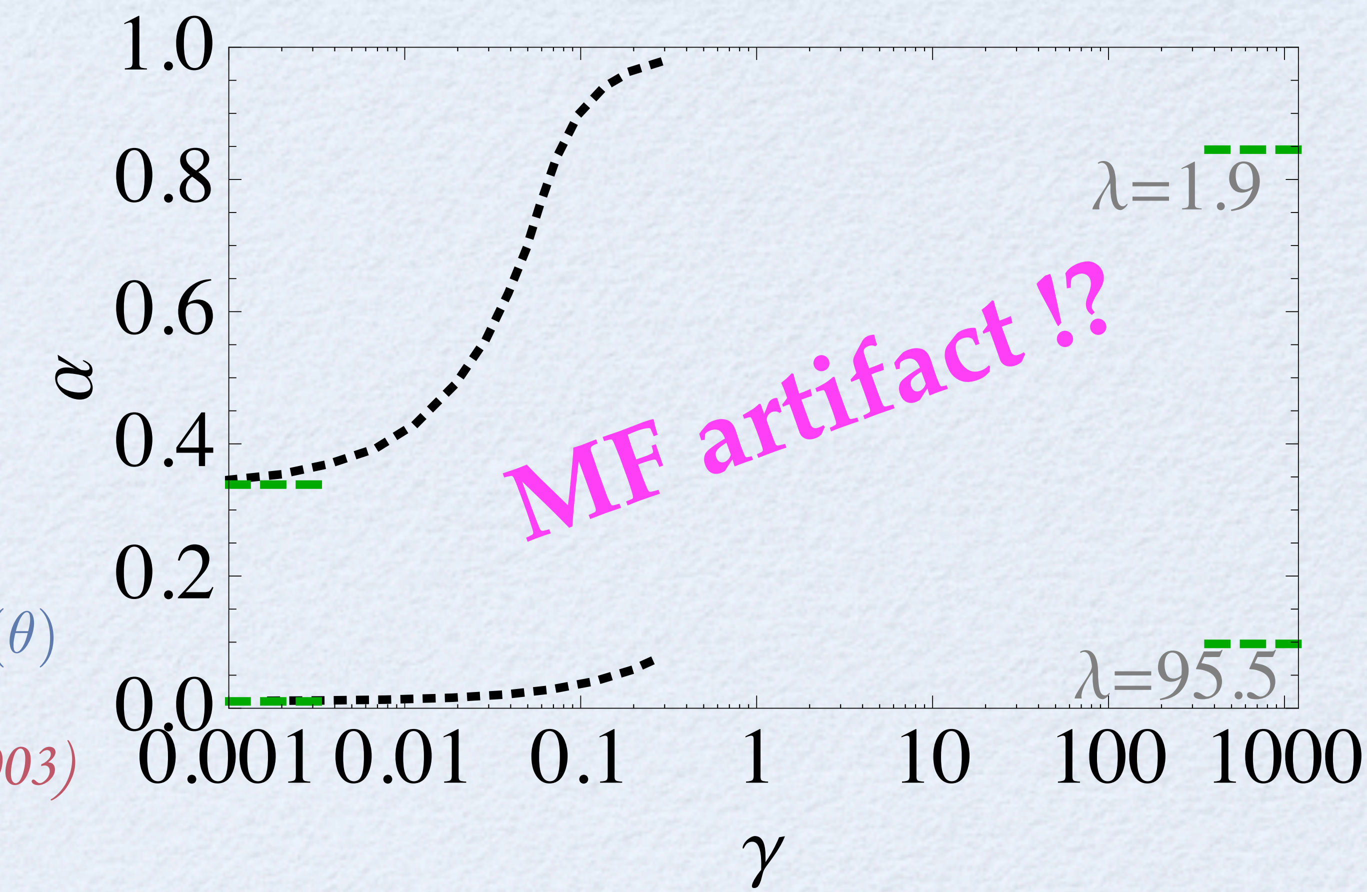
✓ mean-field (~ classical) approach

$$\langle \hat{\psi}(\theta) \rangle = |\Psi(\theta)|\, e^{i\phi(\theta)}$$

- non-linear Schrödinger equation (Gross-Pitaevski equation)

$$\left[\left(-i\frac{\partial}{\partial\theta} - \Omega\right)^2 + \lambda\delta(\theta) + \tilde{g}|\Psi(\theta)|^2\right]\Psi(\theta) = \mu\Psi(\theta)$$

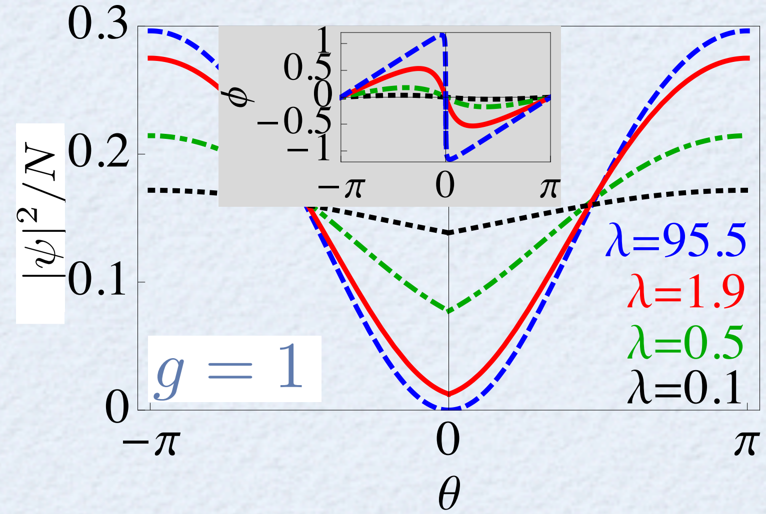
Pitaevskii & Stringari, Bose-Einstein Cond., Oxford (2003)

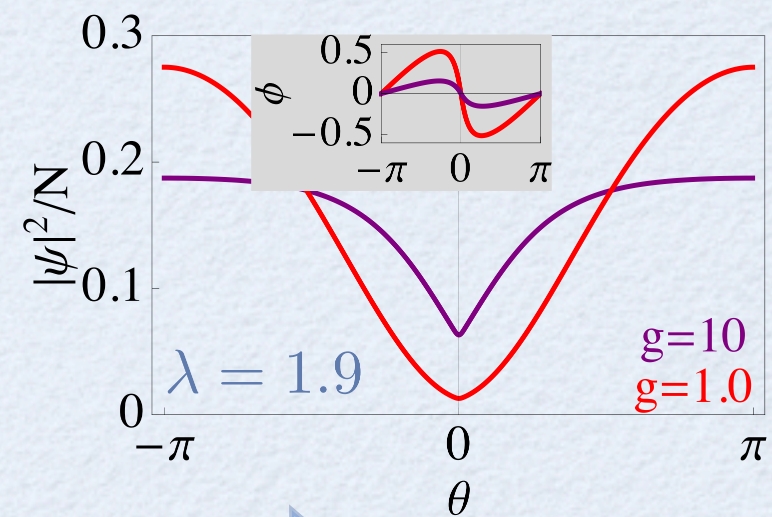


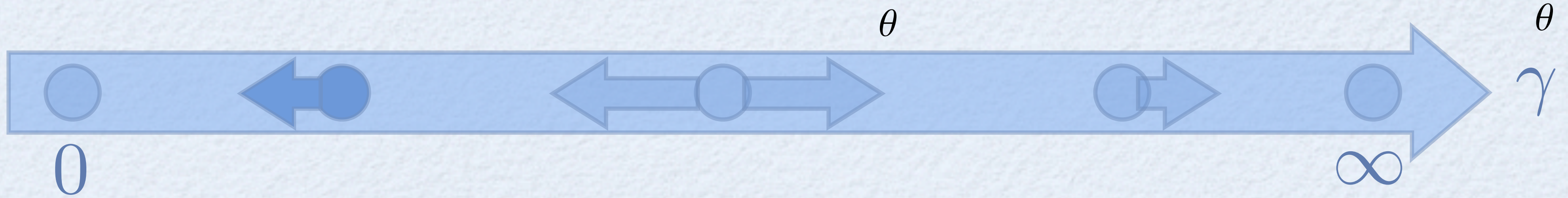
✓ soliton pinned by barrier

$$\xi = \hbar/\sqrt{2mn_0 g}$$

Kanamoto et al., PRL 100, 060401 (2008)







Strongly interacting regime

Analytic

✓ effective field theory: Luttinger liquid

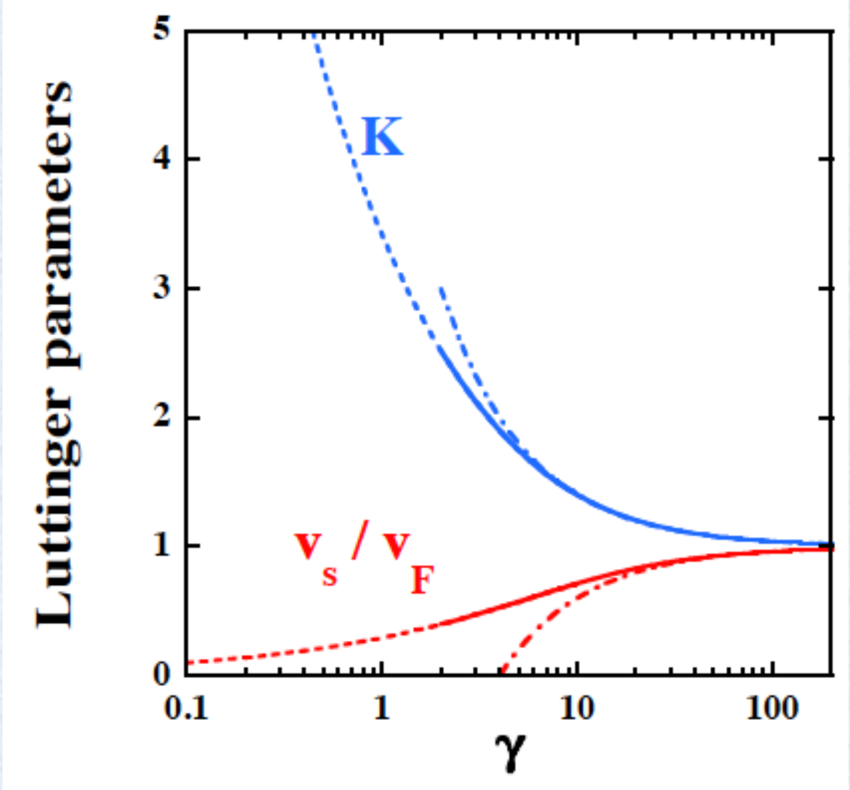
$$\psi(x) = \sqrt{\rho(x)}e^{i\phi(x)} \qquad \omega(k) \simeq \hbar v_s |k|$$

$$\rho(x) \simeq (n_0 + \partial_x \theta(x)/\pi) \sum_{l\in\mathbb{Z}} e^{2il(\theta(x)+\pi n_0 x)} \qquad n_0 = N/L$$

$$[\partial_x \theta(x), \phi(x')] = i\pi\delta(x-x')$$

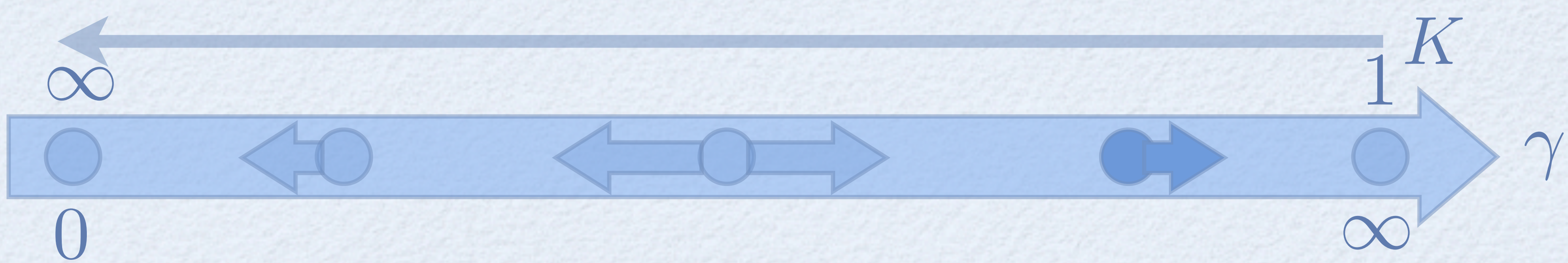
$$\langle \hat{\Psi}^\dagger(x)\hat{\Psi}(x')\rangle \simeq \frac{1}{|x-x'|^{1/2K}}$$

Cazalilla, J. Phys. B: At. Mol. Opt. Phys. 37, S1 (2004)



✓ presence of gauge field ~ shift in the phase field

$$\mathcal{H}_{LL} = \frac{\hbar v_s}{2\pi}\int_0^L \mathrm{d}x \left[K\left(\partial_x\phi(x) - \frac{2\pi}{L}\Omega\right)^2 + \frac{1}{K}(\partial_x\theta(x))^2 \right]$$



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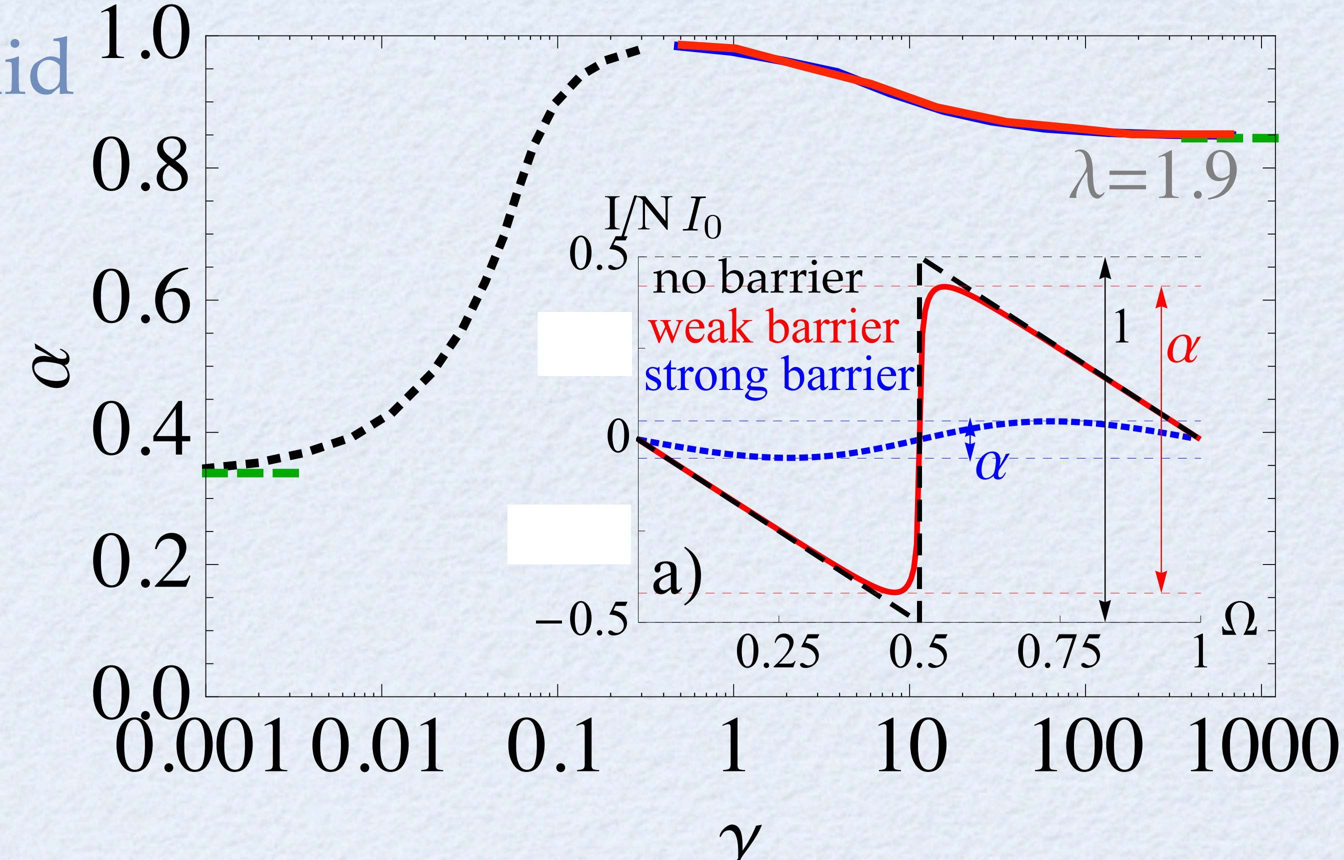
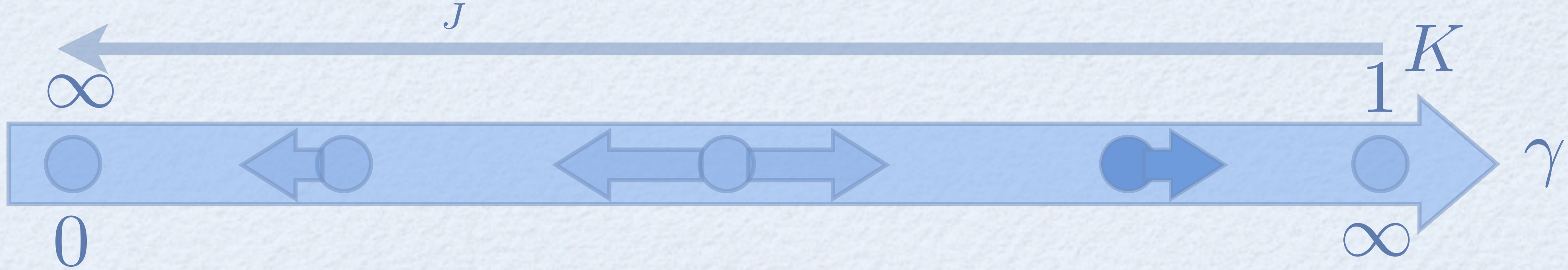


✓ weak barrier ~ backscattering term

$$\mathcal{H}_b = \int \mathrm{d}x\, U_0\delta(x)\rho(x)$$

$$\mathcal{H}_{LL} = \frac{\hbar v_s}{2\pi}\int_0^L \mathrm{d}x \left[K\left(\partial_x\phi(x) - \frac{2\pi}{L}\Omega\right)^2 + \frac{1}{K}(\partial_x\theta(x))^2\right] + 2U_0 n_0 \cos[2\theta(0)]$$

$$\mathcal{H}_J = E_0(J-\Omega)^2 + n_0 U_{\text{eff}}\sum_J |J+1\rangle\langle J| + h.c. \qquad \lambda_{\text{eff}} = \lambda(d/L)^K$$



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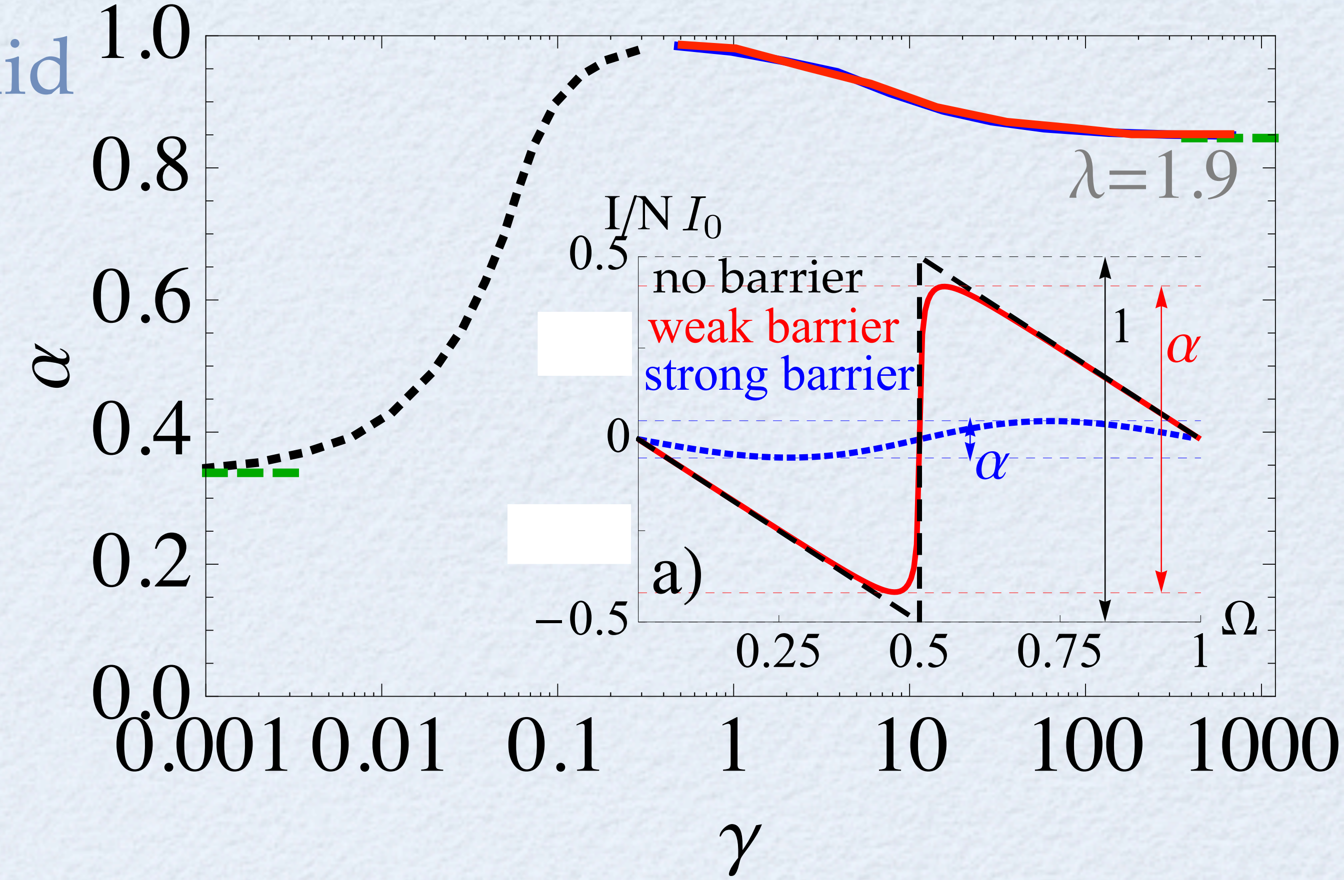
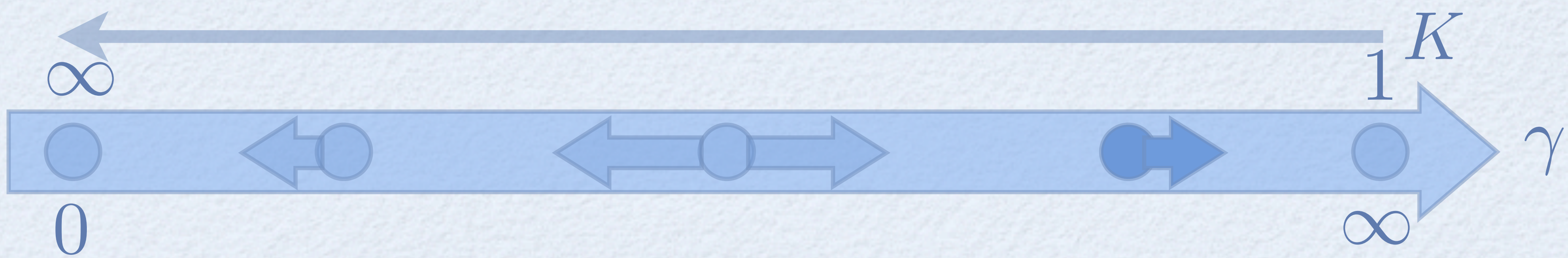


✓ weak barrier ~ backscattering term

less interactions ==> more number fluctuations ==> screen the barrier

$$\delta E(0.5 + \delta\Omega) \propto \left(\delta\Omega^2 - \sqrt{\delta\Omega^2 + \lambda_{\rm eff}^2}\right)$$

$$\lambda_{\rm eff} = \lambda(d/L)^K$$



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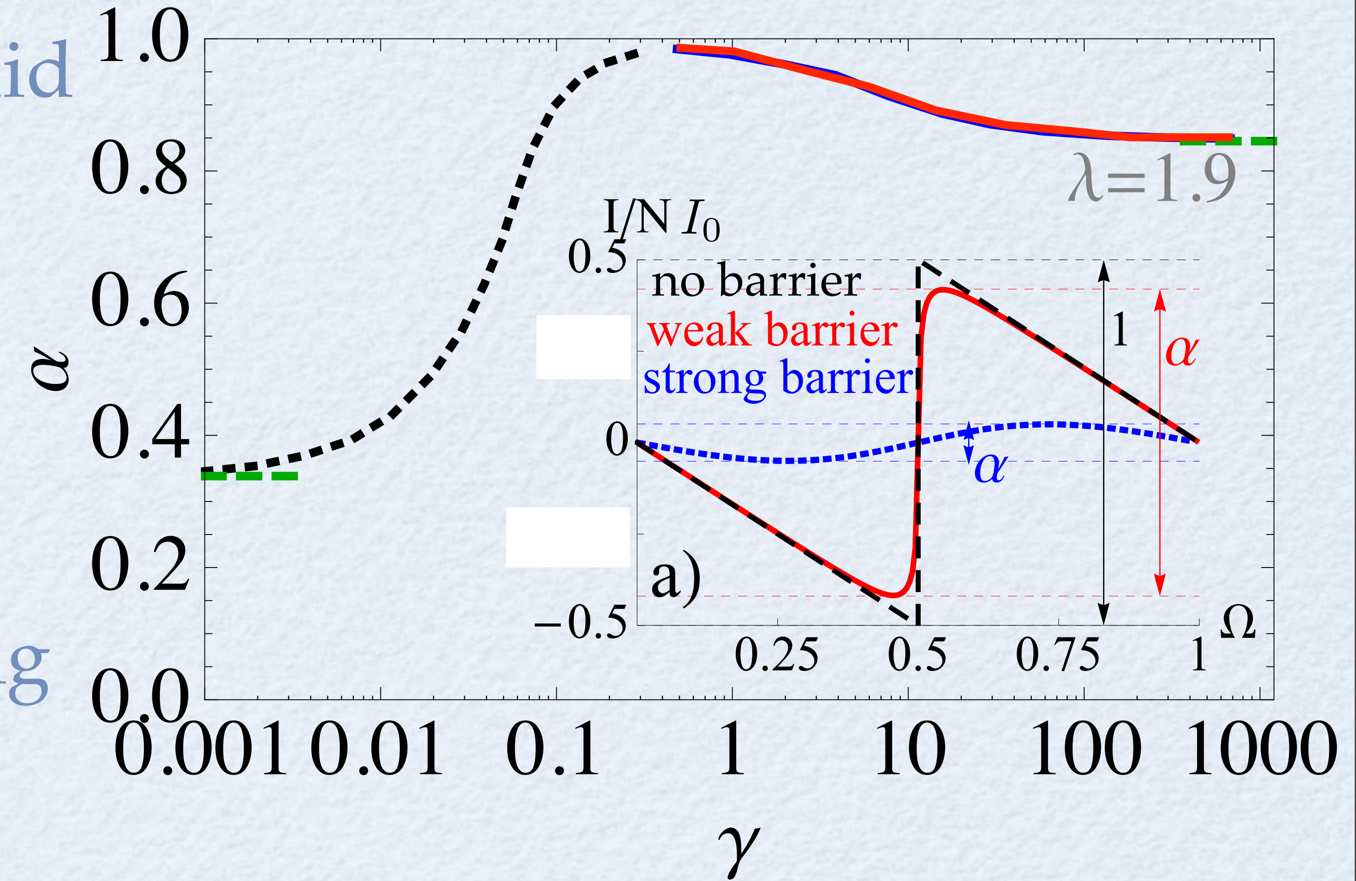


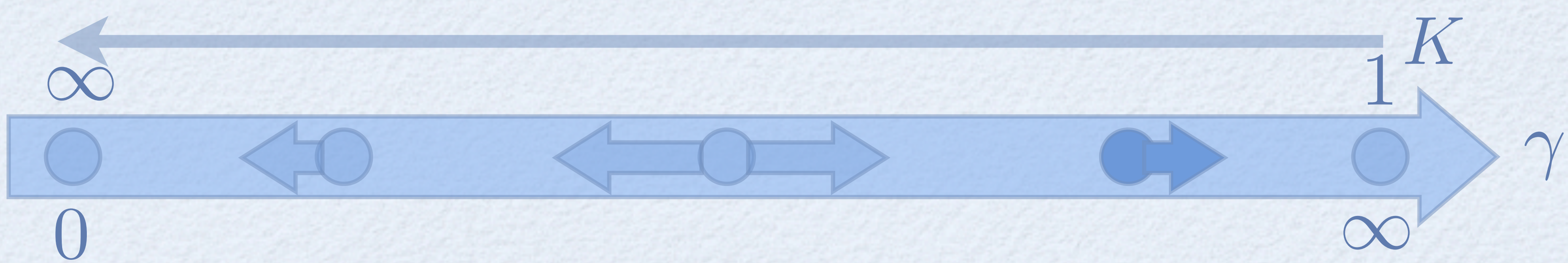
✓ strong barrier ~ weak link tunnelling

i.e. almost obc with $t = f(K)\,\lambda^{-K}$

$$\mathcal{H}_{LL} = \frac{\hbar v_s}{2\pi}\int_0^L \mathrm{d}x\,\left[K\left(\partial_x\phi(x) - \frac{2\pi}{L}\Omega\right)^2 + \frac{1}{K}(\partial_x\theta(x))^2\right] - 2\,t\,n_0\cos[\phi(L) - \phi(0) + 2\pi\Omega]$$

$$E(\Omega) = -2\,t_{eff}\,n_0\cos(2\pi\Omega)$$

$$t_{\mathrm{eff}} = t(d/L)^{1/K}$$



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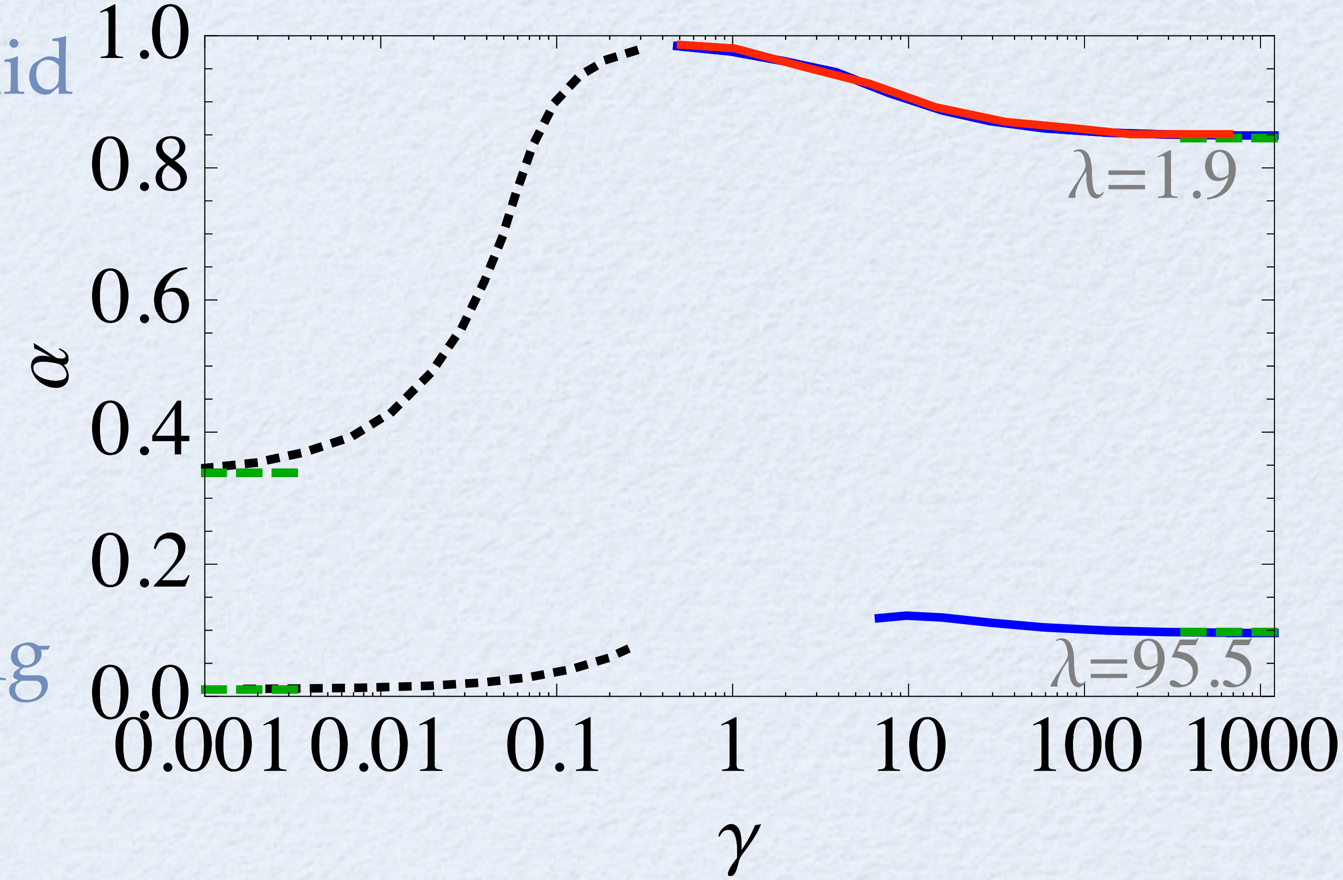

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i.e. almost obc with $t = f(K)\,\lambda^{-K}$

more interactions ==> more phase fluctuations ==> weaker current

$$E(\Omega) = -2\,t_{eff}\,n_0\cos(2\pi\Omega)$$

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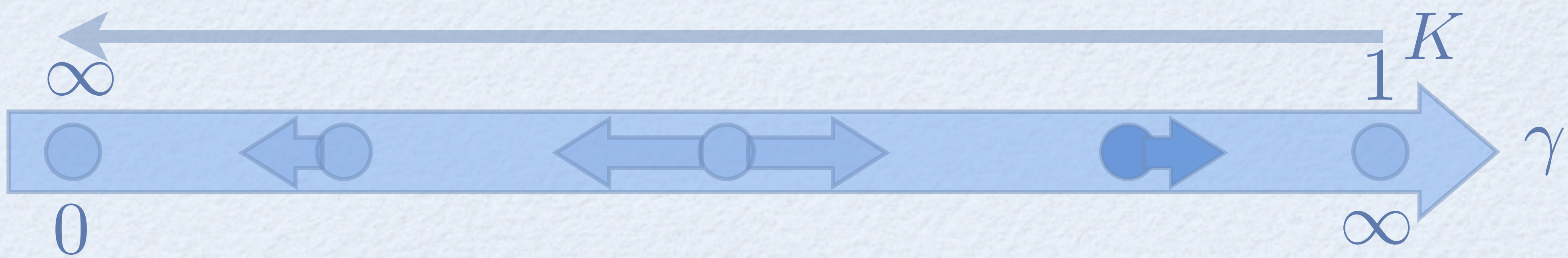
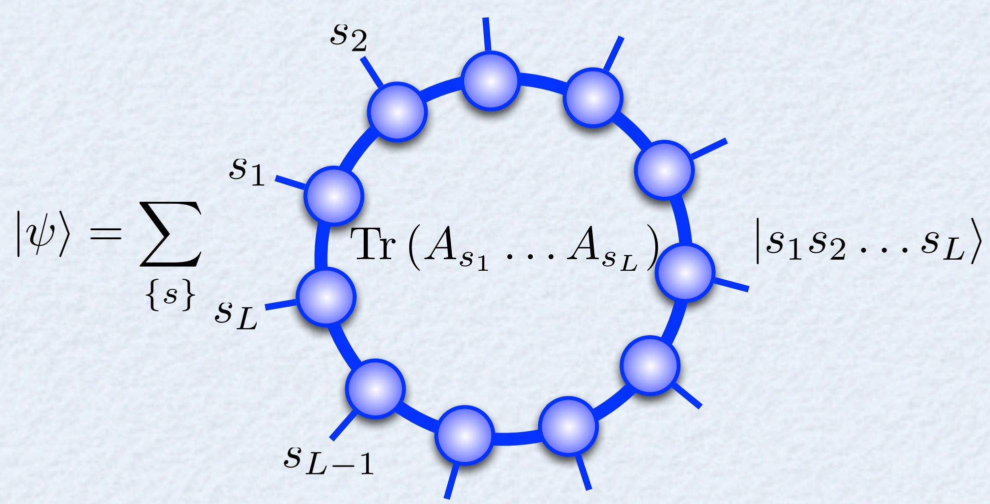
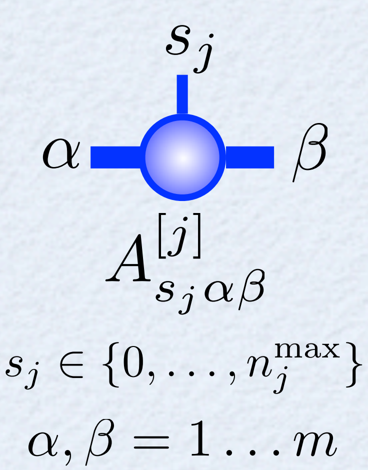


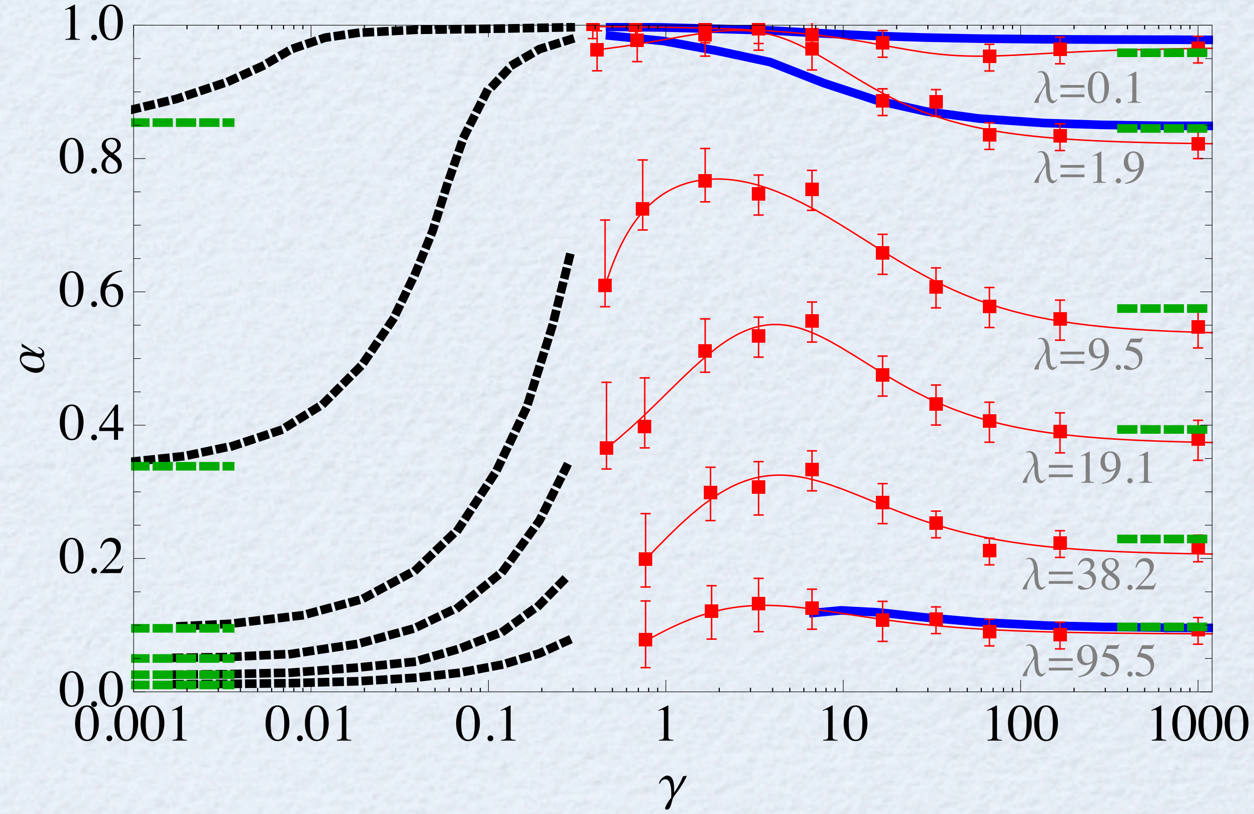
Scanning through diverse regimes: MPS

Numeric

✓ MPS-PBC variational ansatz



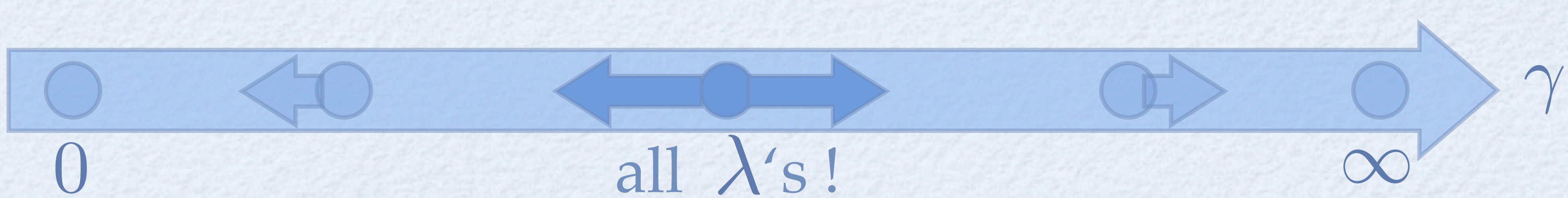




Verstraete, et al, PRL 93, 227205 (2004);
Schollwock, Ann. Phys. 326, 96 (2011);

◉ lattice discretization (@ low filling): Bose-Hubbard + Peierls phase

$$\mathcal{H}_{\mathrm{lat}} = -t_{\mathrm{BH}} \sum_{j=1}^{N_s} \left(e^{-\frac{2\pi i \Omega}{N_s}} b_j^\dagger b_{j+1} + \mathrm{H.c.} \right) + \frac{U_{\mathrm{BH}}}{2} \sum_{j=1}^{N_s} n_j (n_j - 1) + \sum_j \left(\lambda_{\mathrm{BH}}\, \delta_{j,1} n_j - \mu\, n_j \right)$$



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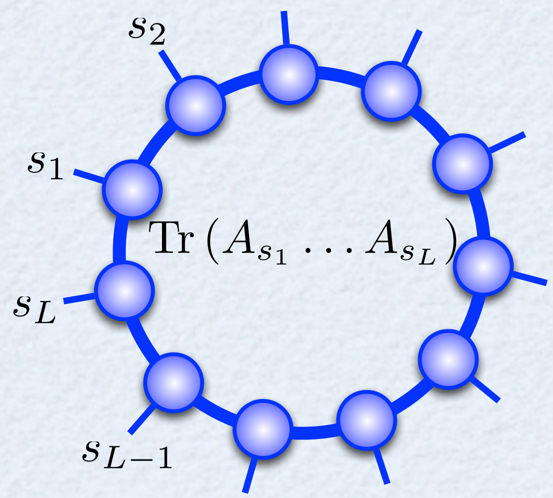
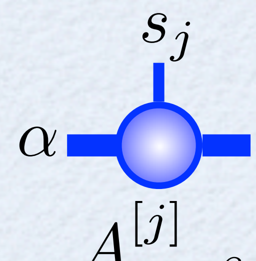


$$|\psi\rangle = \sum_{\{s\}} \mathrm{Tr}\left(A_{s_1} \dots A_{s_L}\right) |s_1 s_2 \dots s_L\rangle$$



$$A^{[j]}_{s_j \alpha\beta}$$

$$s_j \in \{0, \dots, n_j^{\max}\}$$

$$\alpha, \beta = 1 \dots m$$

Verstraete, et al, PRL 93, 227205 (2004);
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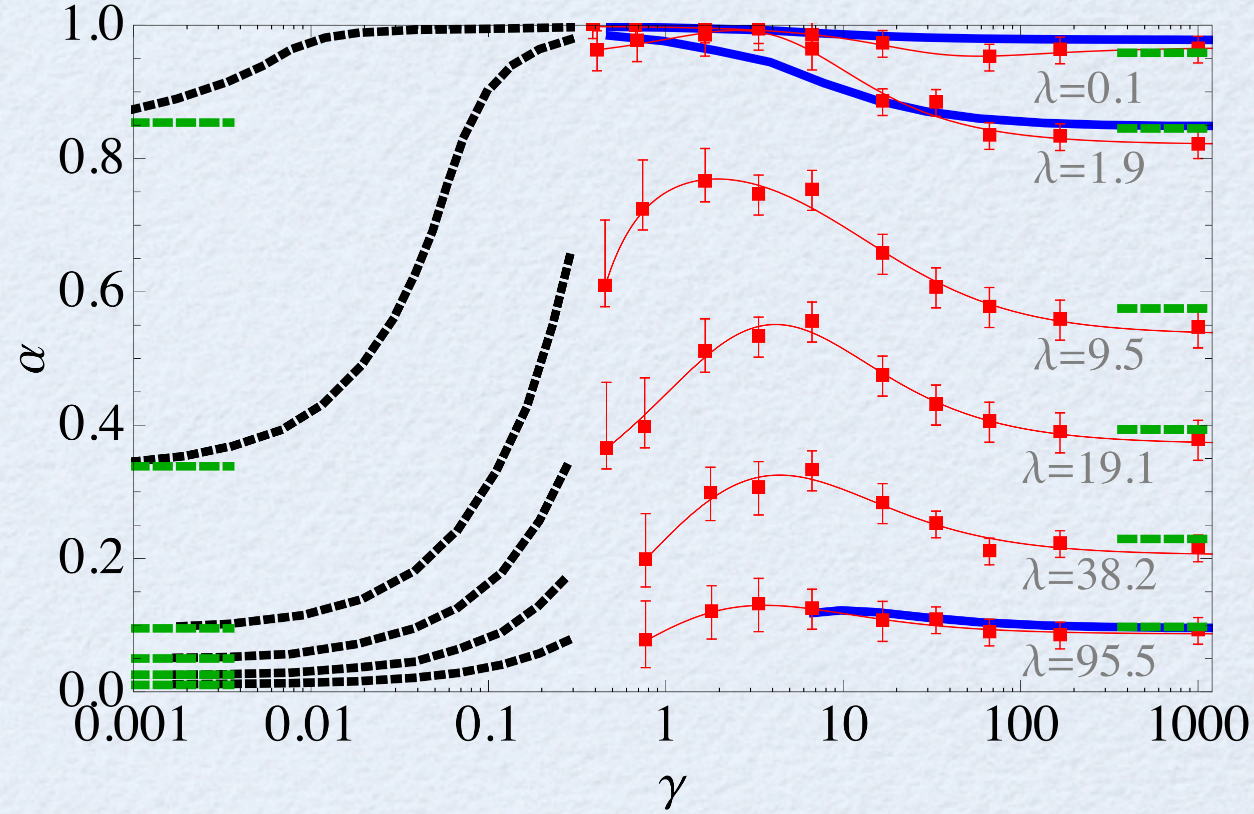
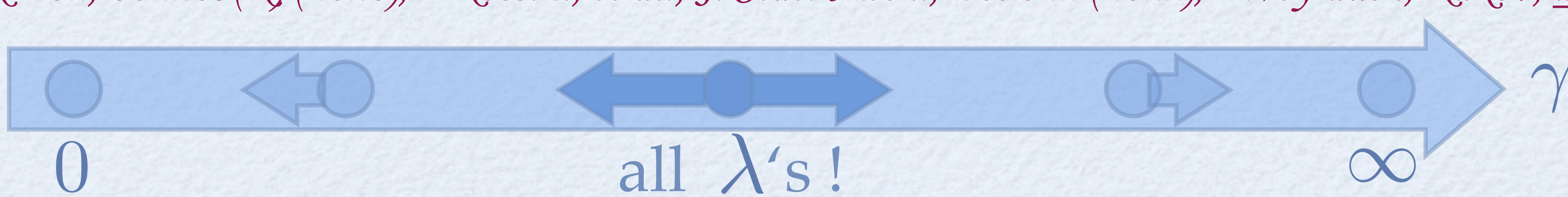


… not so stable, accurate & fast as for OBC …

- absence of a fully isometric gauge ==> need for generalized eival. problem :(
- transfer matrices of long sub-chains: keep p dominant eivals/eivecs
  ==> costs $O(pm^3)$ vs. $O(m^5)$ BUT p often scales like $O(m)$:(

Pippan, et al. PRB 81, 081103(R) (2010); Rossini, et al., J. Stat. Mech., P05021 (2011); Weyrauch, Rakov, arXiv:1303.1333



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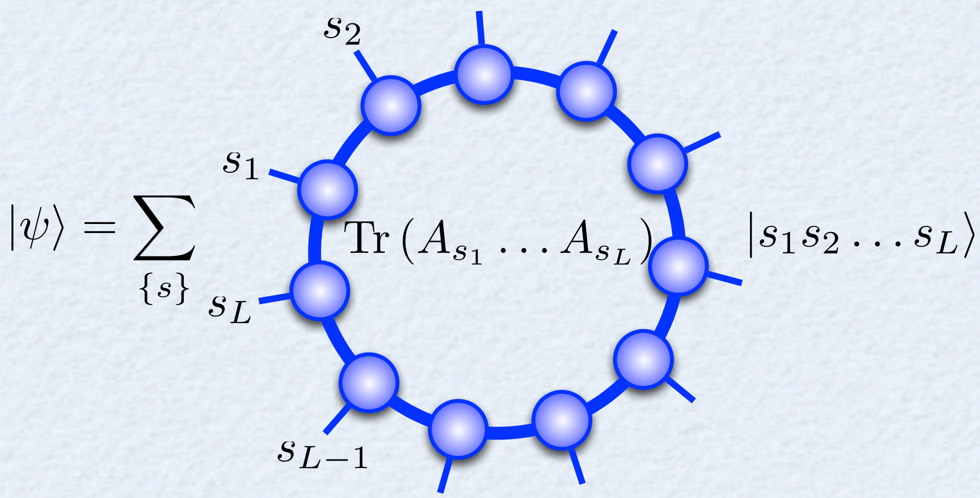

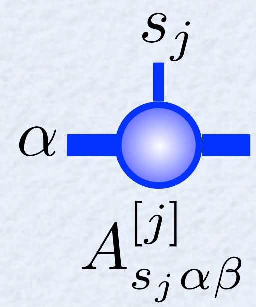

$s_j \in \{0, \dots, n_j^{\max}\}$

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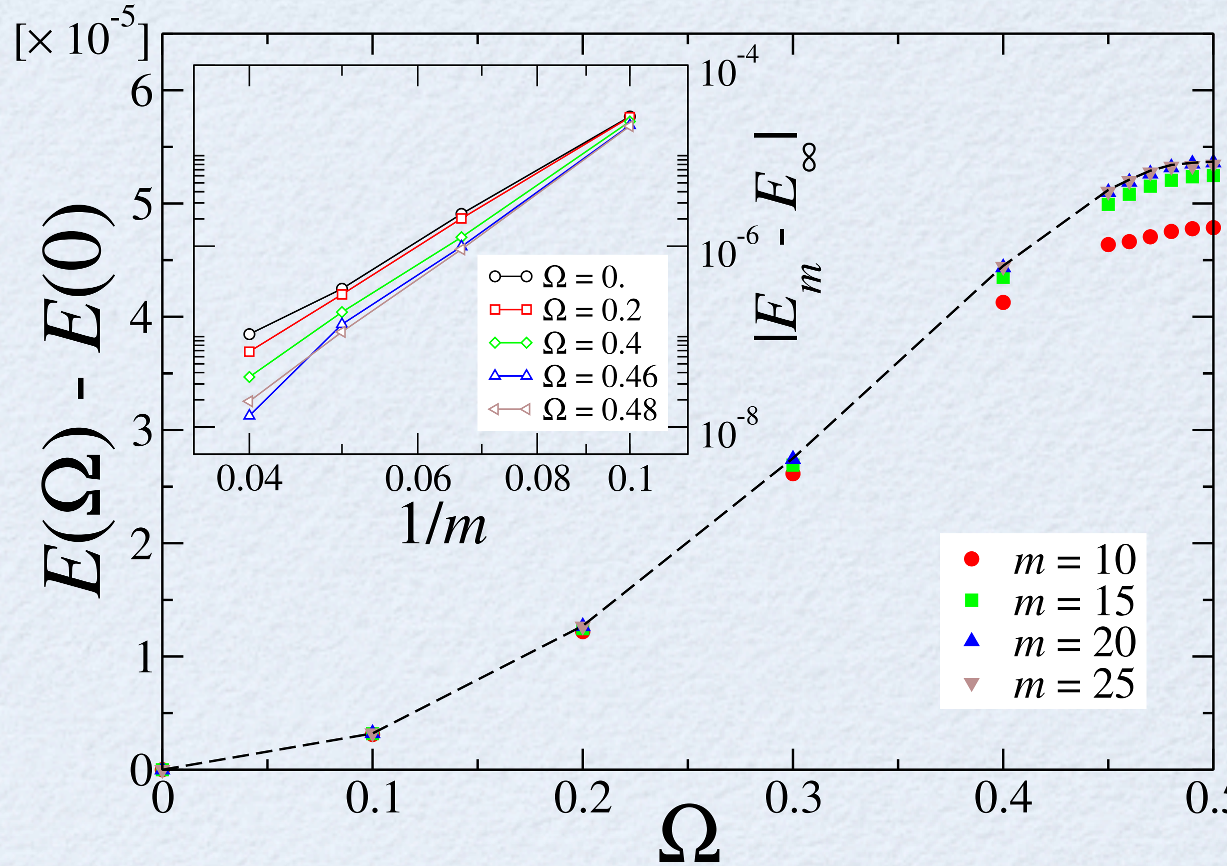

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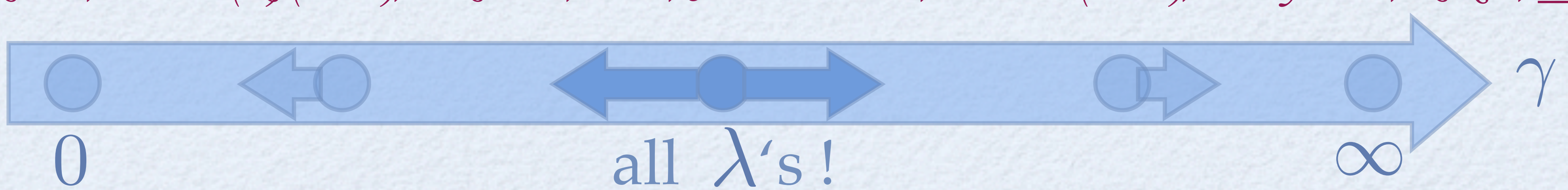
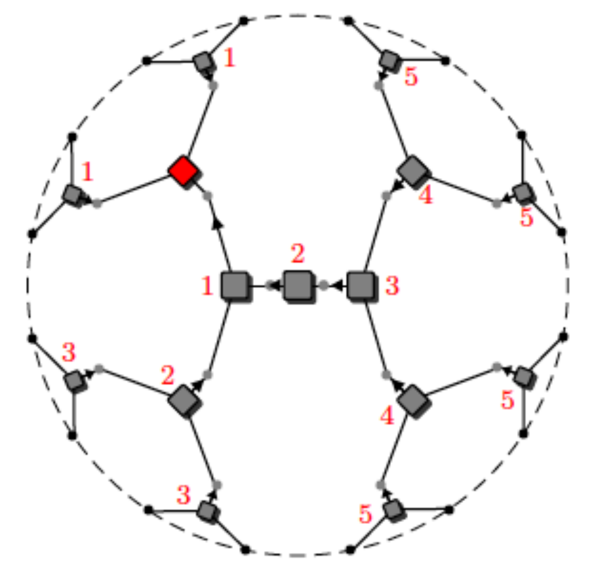


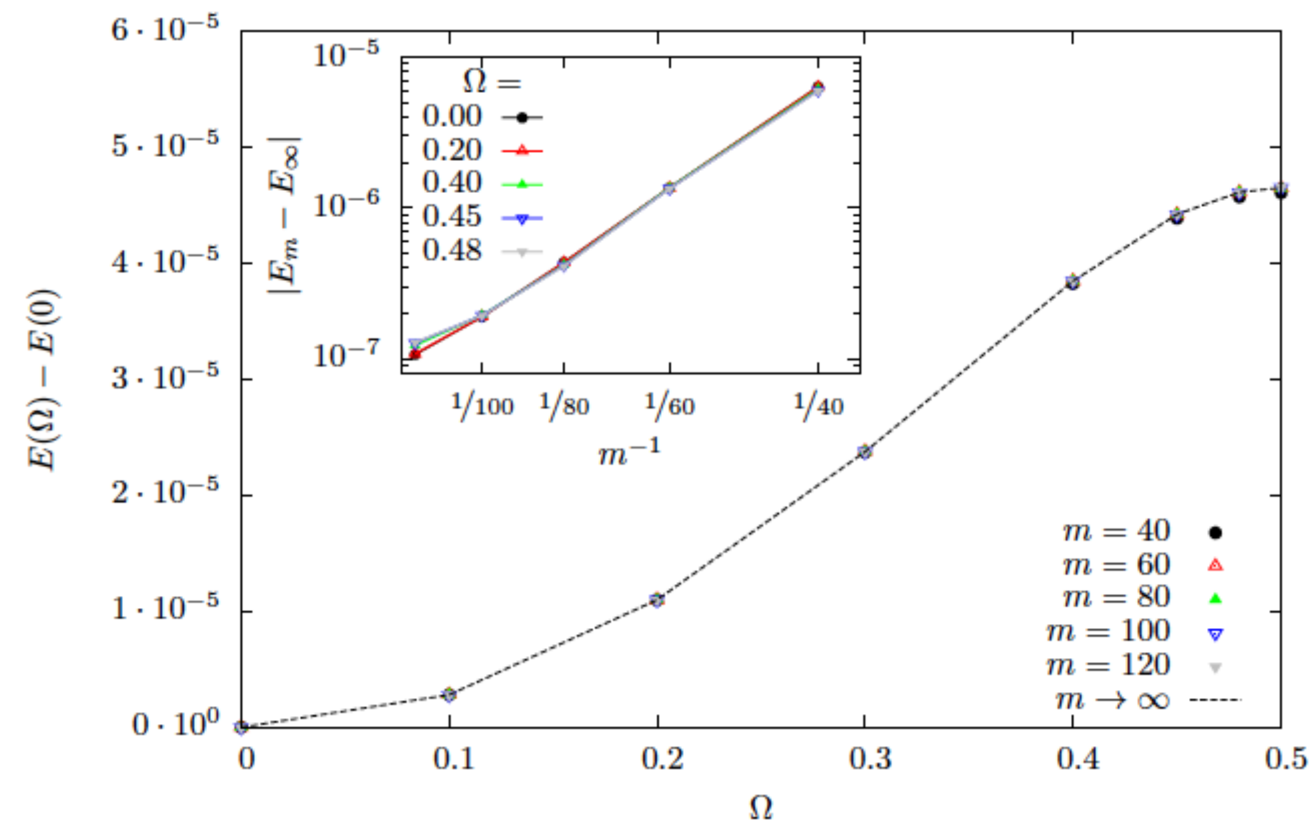
Scanning through diverse regimes: TTN ?

Numeric

✓ binary TTN variational ansatz



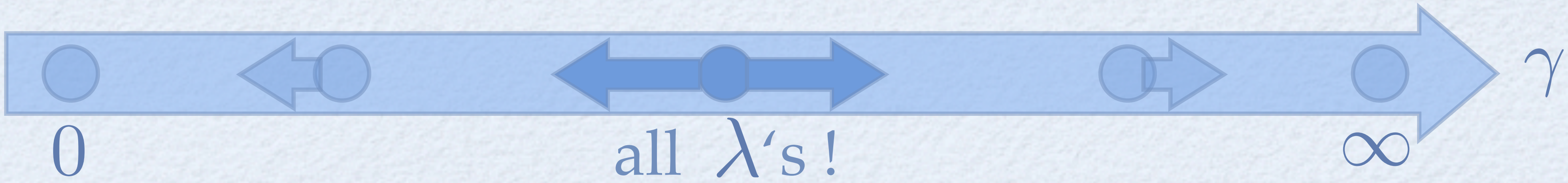
M. Gerster, et al. arXiv:1406.2666



✓ equal treatment for OBC & PBC's

- adaptive isometric gauge ==> always standard eigenvalue problem :)
- contraction costs are $O(m^4)$ & overheads much smaller :)
- observables are also fairly nicely reproduced (weakly site-dependent error)

Shi, Duan, Vidal, PRA 74, 022320 (2006); A. J. Ferris, Phys. Rev. B 87, 125139 (2013)



Scanning through diverse regimes: TTN ?

Numeric

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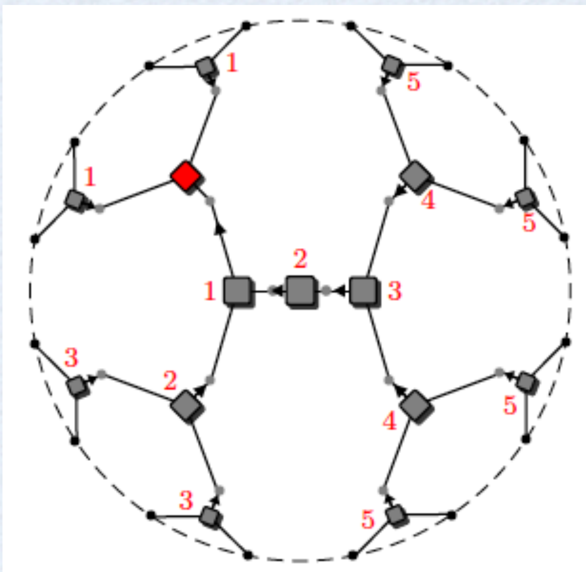

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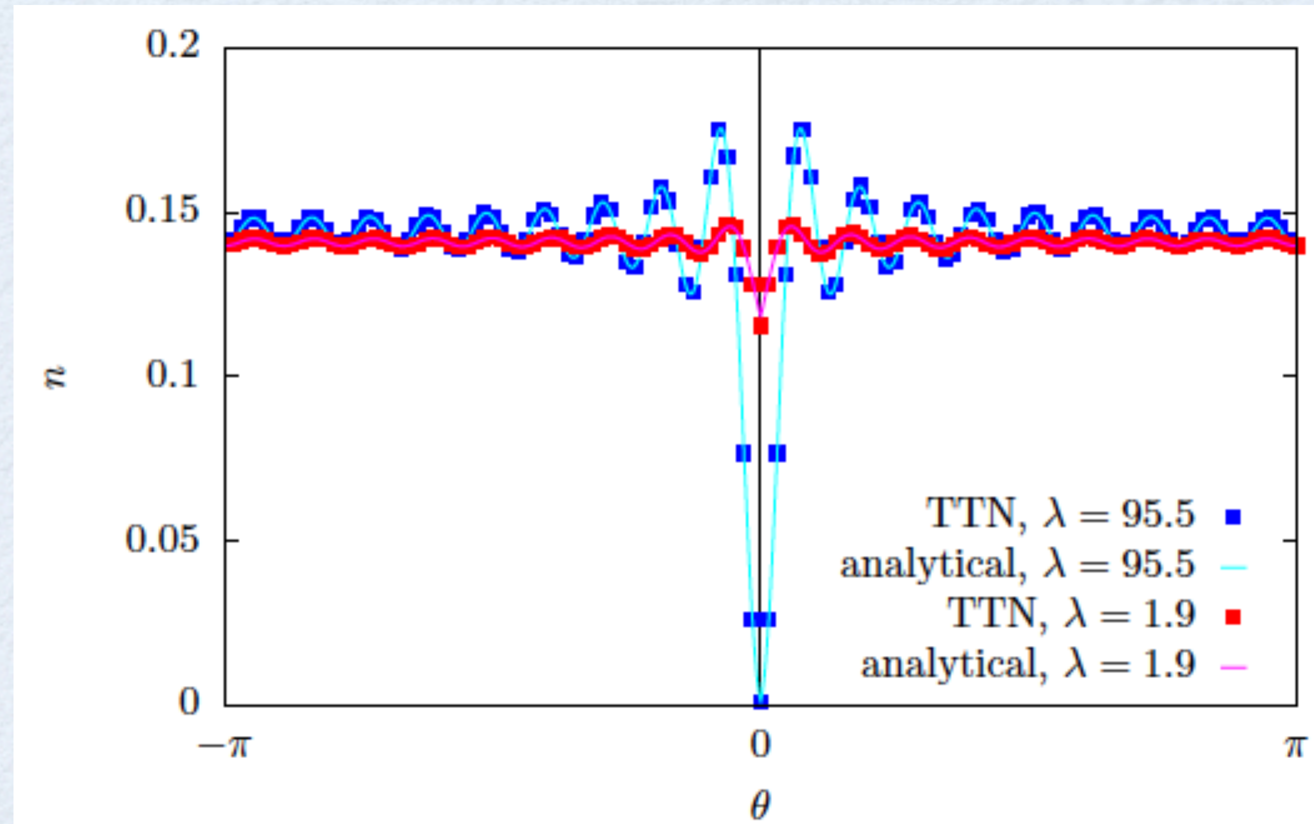

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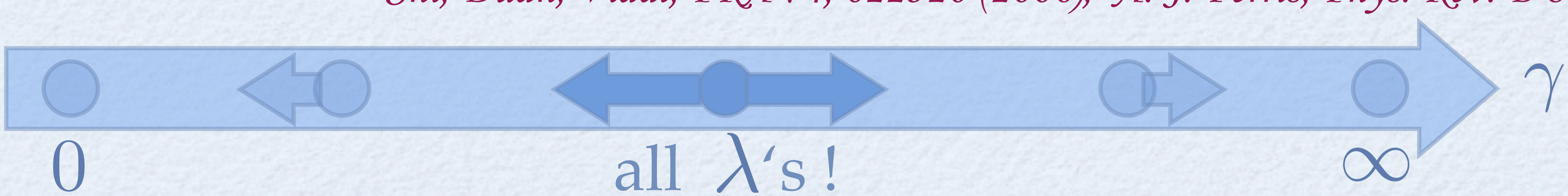
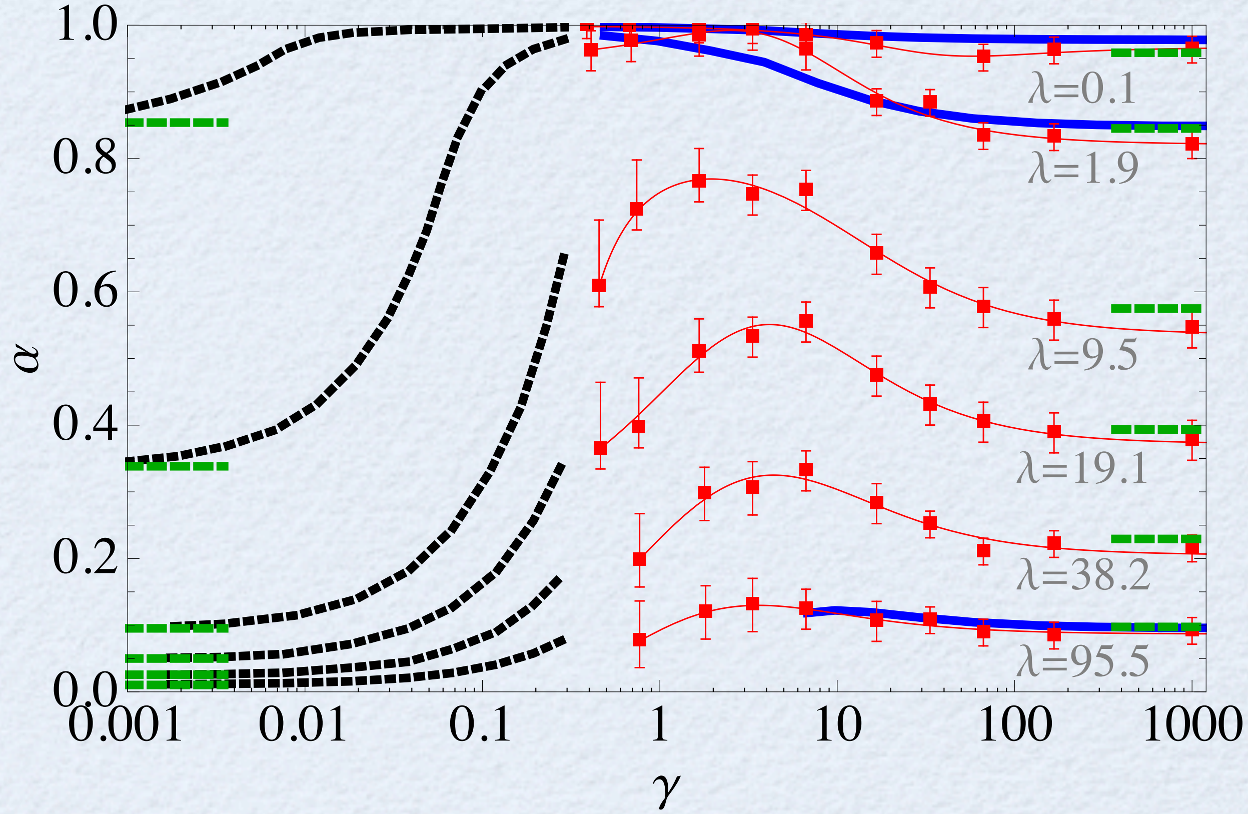


Take-Home message

Conclusion

✳ MF regime, i.e. low $\gamma = (gm)/(\hbar^2 n)$:
interaction ↗ ==> barrier effect ↘
(shorter density-density healing length …)

✳ LL regime, i.e. large $\gamma = (gm)/(\hbar^2 n)$:
interaction ↗ ==> barrier effect ↗
(faster decay of phase-phase correlations…)



❖ quantum fluctuations counteract the barrier screening by interactions

❖ existence of an optimal regime where the defects are less influential !

❖ need to choose extremals for an effective quantum state manipulation !

✓ results relevant also for: thin supercond. rings, photonic waveguides, …

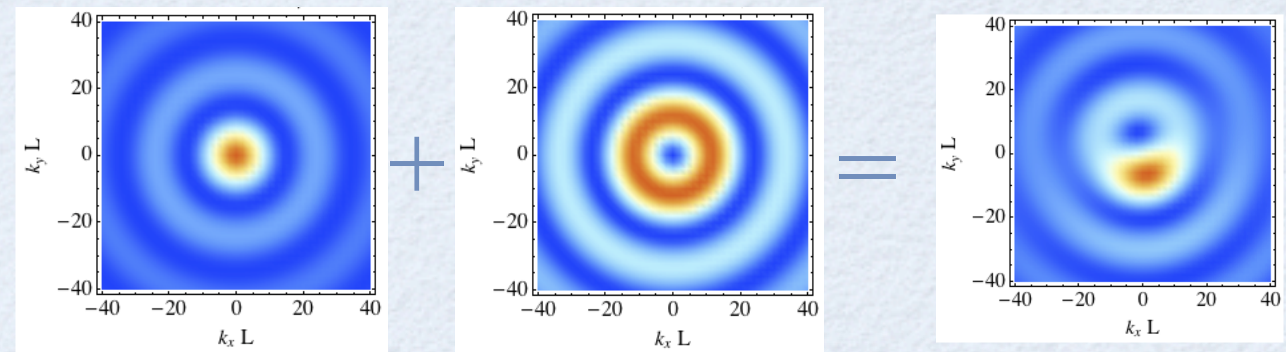
M.Cominotti, D. Rossini, M. Rizzi, F. Hekking, A. Minguzzi, PRL 113, 025301 (2014)

Open questions

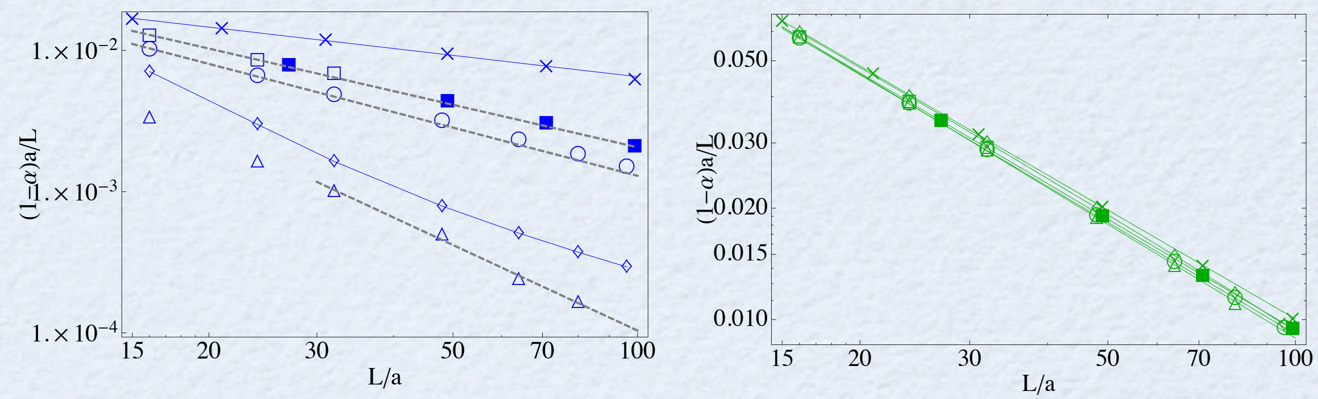
Conclusion

- superpositions in time-of-flight momentum distributions

$$n(\mathbf{k}) = \int \mathrm{d}\mathbf{x} \int \mathrm{d}\mathbf{x}' \, e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')} \rho_1(\mathbf{x},\mathbf{x}')$$



- scaling of currents with ring size



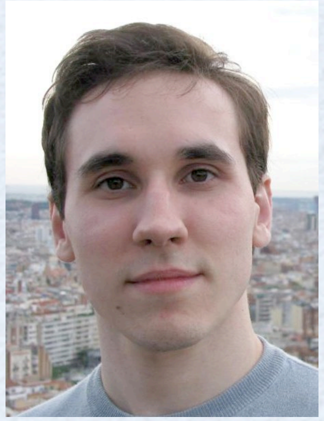
- behaviour of currents with particle density (=> SF fraction?)
- finite temperature / entropy effects (relevant even in cold atoms)
- non-equilibrium dynamics due to barrier intensity / speed quench ...

M.Cominotti, D. Rossini, M. Rizzi, F. Hekking, A. Minguzzi, PRL 113, 025301 (2014)

Thanks to …

Conclusion

Anna Minguzzi
LPMMC, Grenoble, FR



Marco Cominotti
LPMMC, Grenoble, FR

Frank Hekking
LPMMC, Grenoble, FR

Davide Rossini
SNS, Pisa, IT

… all of you for your attention !

M.Cominotti, D. Rossini, M. Rizzi, F. Hekking, A. Minguzzi, PRL 113, 025301 (2014)