Localization and glassiness of ultracold bosons in optical lattices

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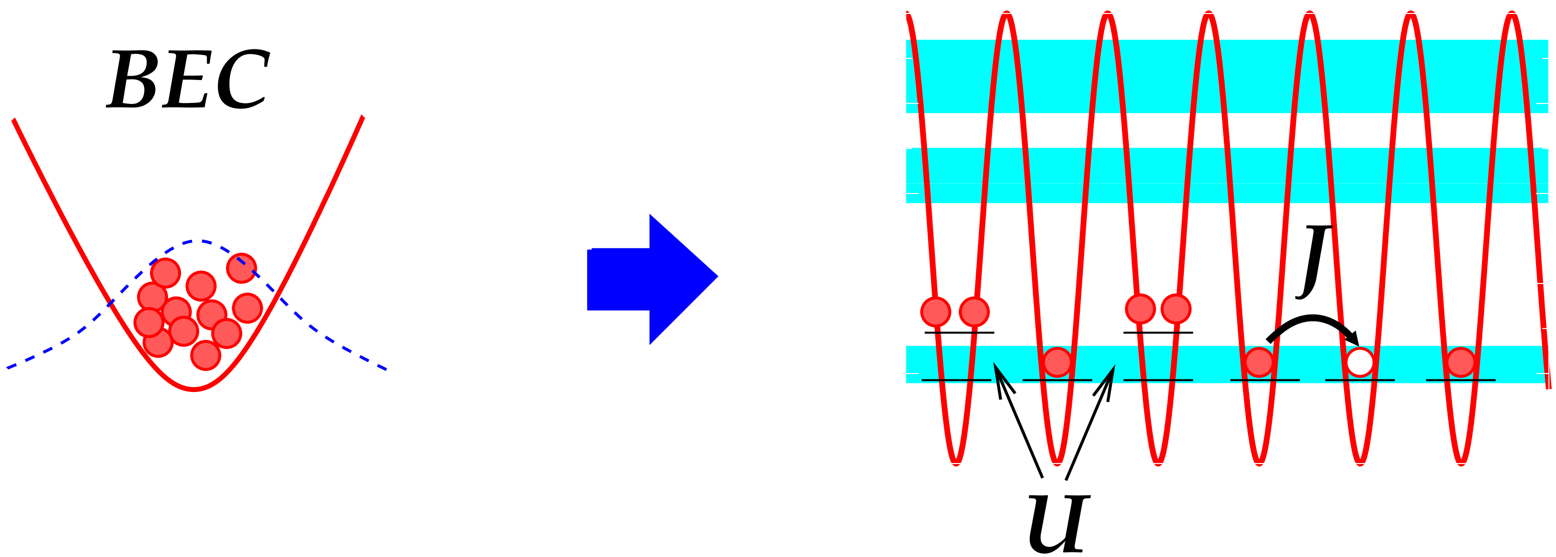
Outline

- Disorder through unequal Bose-Bose mixtures in optical lattices;
- Out-of-equilibrium Anderson localization;
- Glassiness;

Many-body physics in optical lattices

- Optical potential: laser standing wave
- Ultracold atoms (*e.g.* alkali atoms starting from a BEC)
- Upon adiabatic loading into a deep lattice: ideal realization of a **single-band Bose-Hubbard model**;

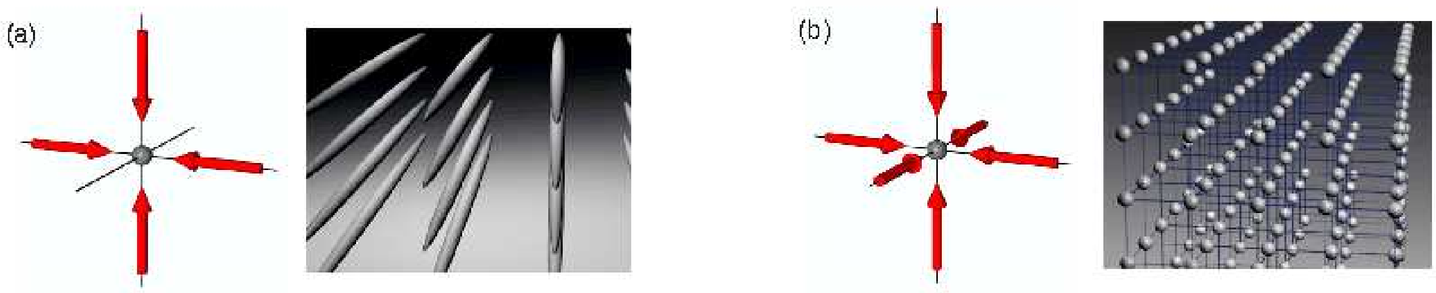
$$\mathcal{H} = -J \sum_{\langle ij \rangle} (b_i b_j^\dagger + \text{h.c.}) + \frac{U}{2} \sum_i n_i (n_i - 1)$$



D. Jaksch et al., Phys. Rev. Lett. 81, 3108 (1998).

Many-body physics in optical lattices

- Dimensionality



3D: *M. Greiner et al., Nature 415, 39 (2002)*

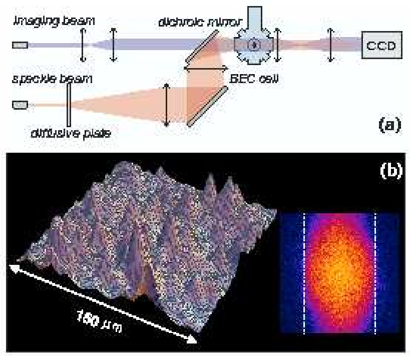
2D: *I.B. Spielman et al., Phys. Rev. Lett. 98, 080404 (2007)*

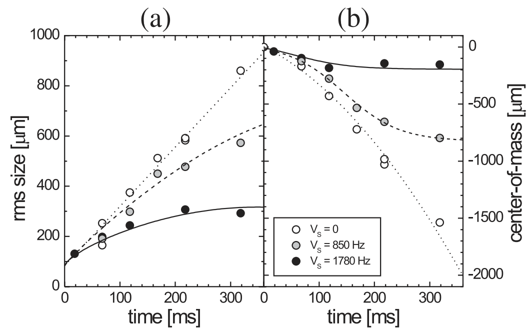
1D: *T. Stöferle et al., Phys. Rev. Lett. 92, 130403 (2004)*

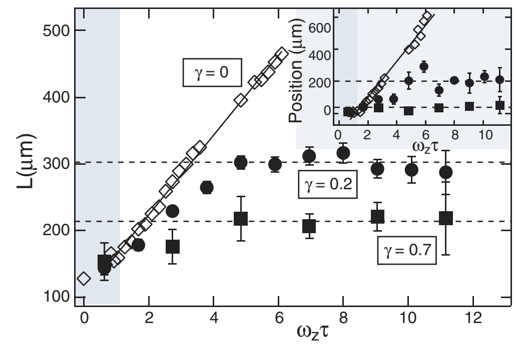
- Interactions
  - J/U tuned by the laser intensity;
  - U tuned by a magnetic field (Feshbach resonance);
  - ....

How about disorder?

- Suppression of expansion after trap release



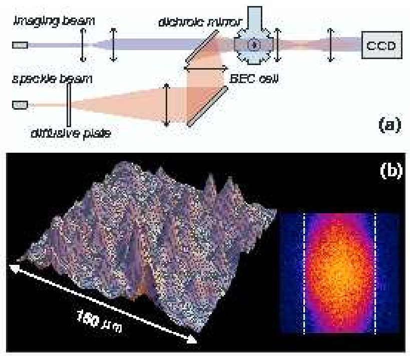


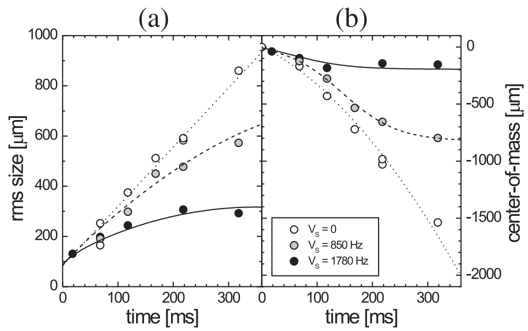


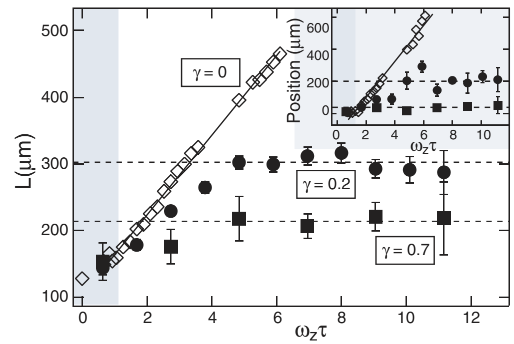
J. Lye et al., Phys. Rev. Lett. 95, 070401 (2005); D. Clément et al., Phys. Rev. Lett. 95, 170409 (2005); C. Fort et al., Phys. Rev. Lett. 95, 170410 (2005); T. Shulte et al., Phys. Rev. Lett. 95, 170411 (2005).

Pioneering experiments with laser speckles

- Suppression of expansion after trap release

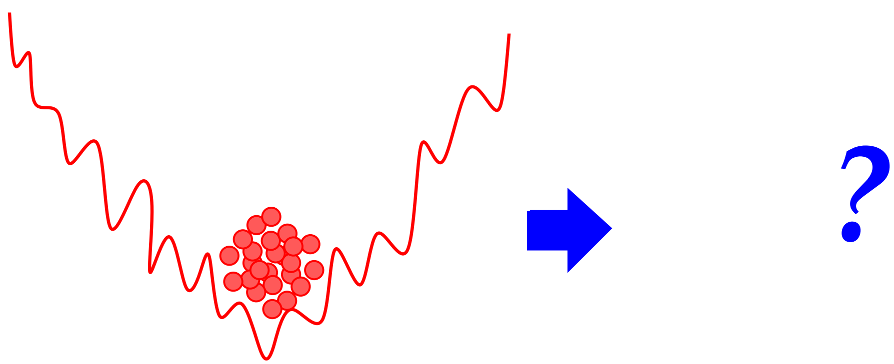






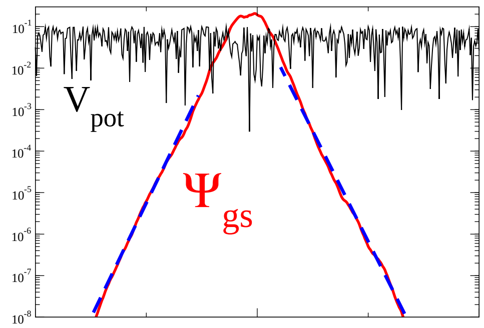
J. Lye et al., Phys. Rev. Lett. 95, 070401 (2005); D. Clément et al., Phys. Rev. Lett. 95, 170409 (2005); C. Fort et al., Phys. Rev. Lett. 95, 170410 (2005); T. Shulte et al., Phys. Rev. Lett. 95, 170411 (2005).

- Anderson localization ?



Pioneering experiments with laser speckles

- Anderson localized wave-function



Pioneering experiments with laser speckles

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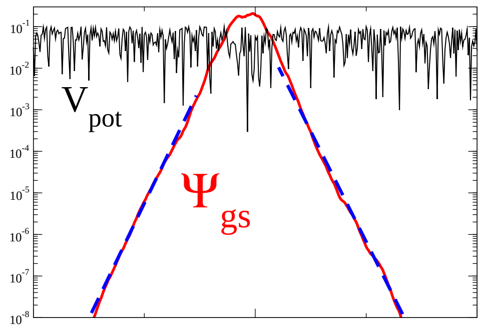

- laser speckles are 'big' optical defects in the trap;

Pioneering experiments with laser speckles

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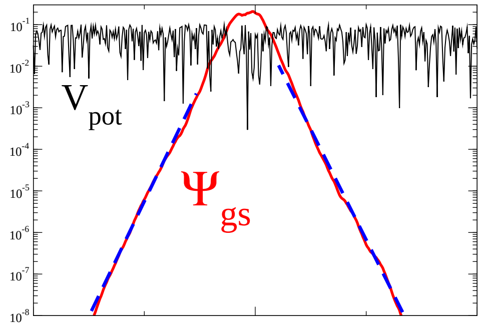

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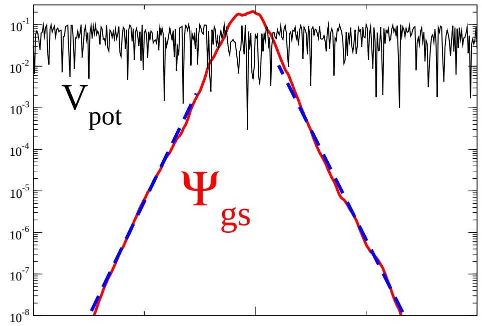
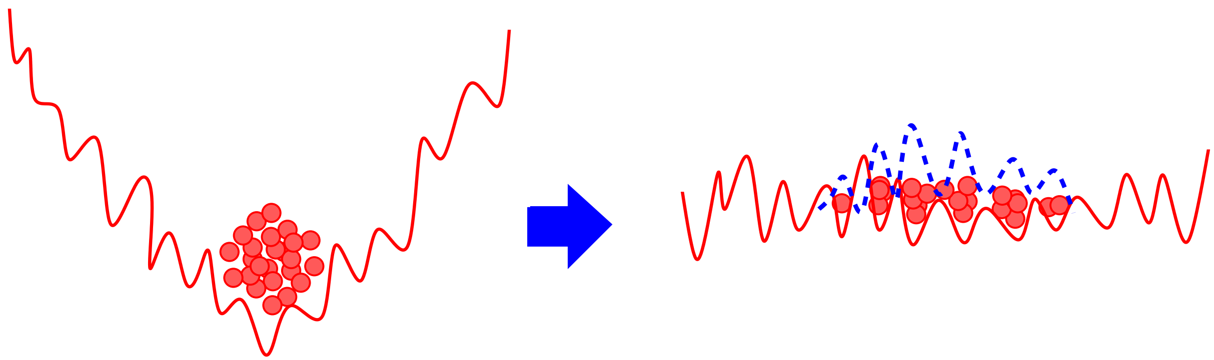
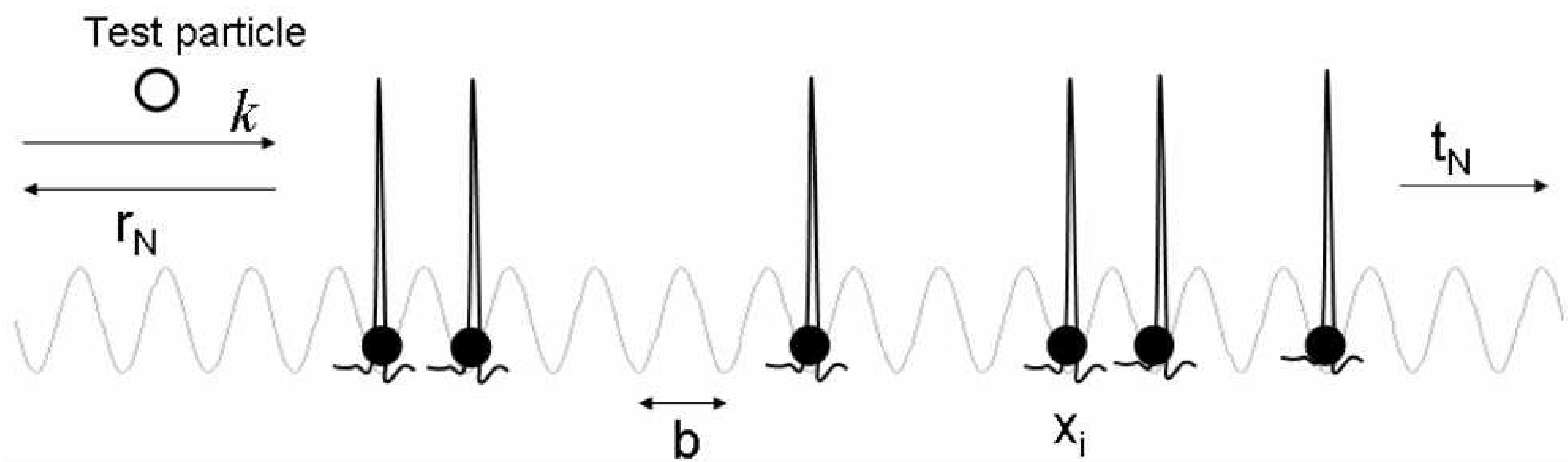


- laser speckles are 'big' optical defects in the trap;
- $d_{\mathrm{speckle}} \gg \xi$ ξ = healing length $\sim 1/\sqrt{m}$
- classical trapping in potential valleys rather than quantum localization



Disorder realized by a secondary species

A *secondary species* of bosons/fermions is randomly trapped in the minima of the optical lattice (negligible tunneling).



U. Gavish and Y. Castin, PRL 95, 020401 (2005);

B. Paredes, F. Verstraete, and J.I. Cirac, PRL 95, 140501 (2005).

Unequal mixtures in optical lattices

EXPERIMENTS

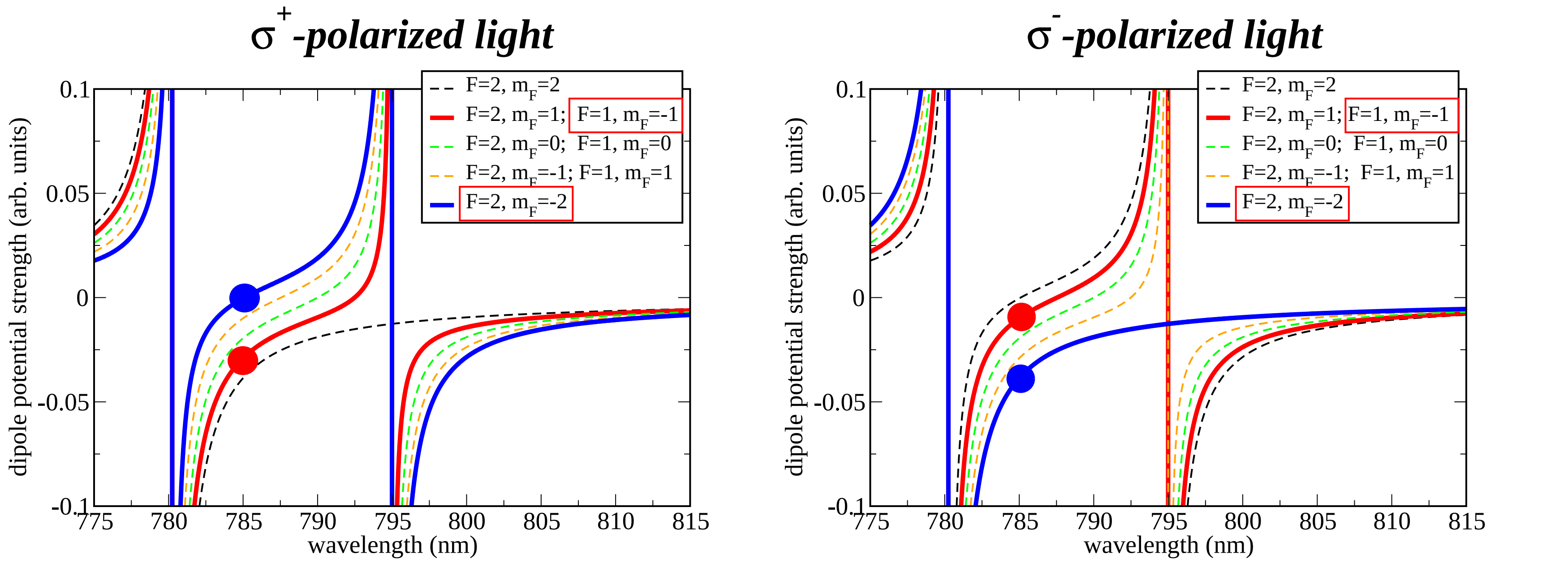
- **Bose-Bose mixtures**
  ^{87}Rb in different hyperfine states *O. Mandel et al., Phys. Rev. Lett. 91, 010407 (2003)*; ...
  ^{87}Rb-^{39}K *J. Catani et al., arXiv:0706.2781*
- **Bose-Fermi mixtures**: ^{87}Rb-^{40}K
  K. Günther et al., Phys. Rev. Lett. 96, 180402 (2006); S. Ospelkaus et al., ibid. 96, 180403 (2006); ...

THEORY

- **Bose-Bose mixtures**
  A. Kuklov et al. Phys. Rev. Lett. 92, 050402 (2004); E. Altman et al., New J. Phys. 5, 113 (2003); A. Isacsson et al., Phys. Rev. B 72, 184507 (2005); L.-M. Duan et al., Phys. Rev. Lett. 91, 090402 (2003); ....
- **Bose-Fermi mixtures**
  H. P. Büchler et al., Phys. Rev. Lett. 91, 130404 (2003); M. Cramer et al., Phys. Rev. Lett. 93, 190405 (2004); L. Mathey et al., Phys. Rev. Lett. 93, 120404 (2004); V. Ahufinger et al., Phys. Rev. A 72, 063616 (2005); L. Pollet et al., Phys. Rev. Lett. 96, 190402 (2006); ....

Spin-dependent optical lattices

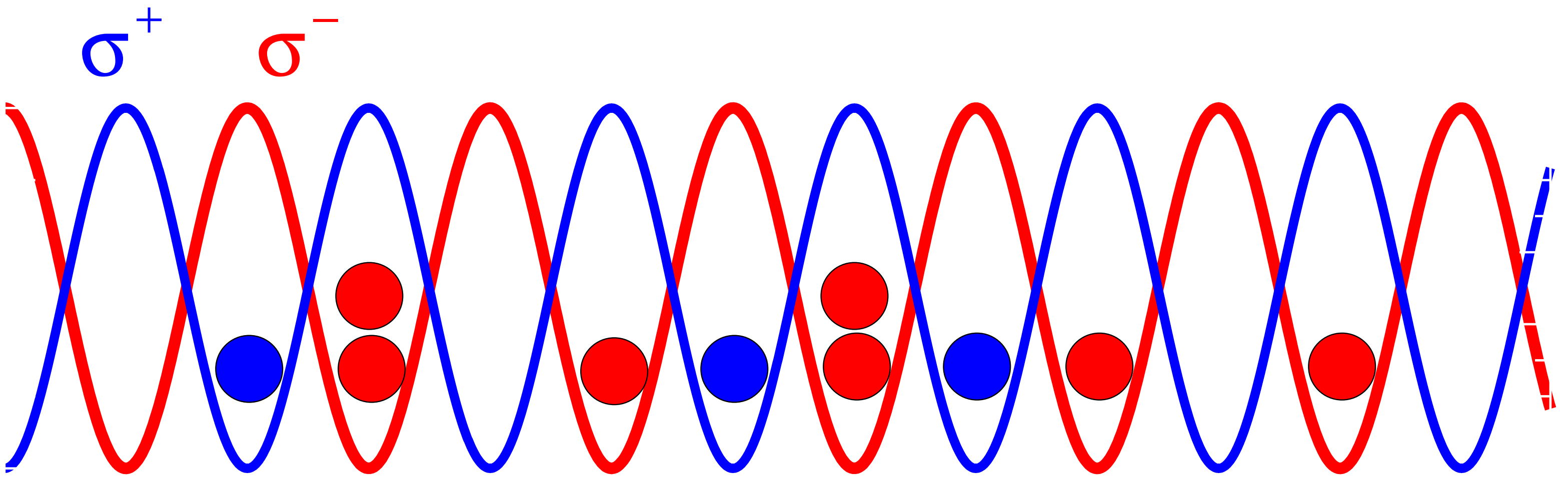
It can be realized in ^{87}Rb with circularly polarized light



E.g. a-bosons = $|F=1, m_F=-1\rangle$ b-bosons = $|F=2, m_F=-2\rangle$

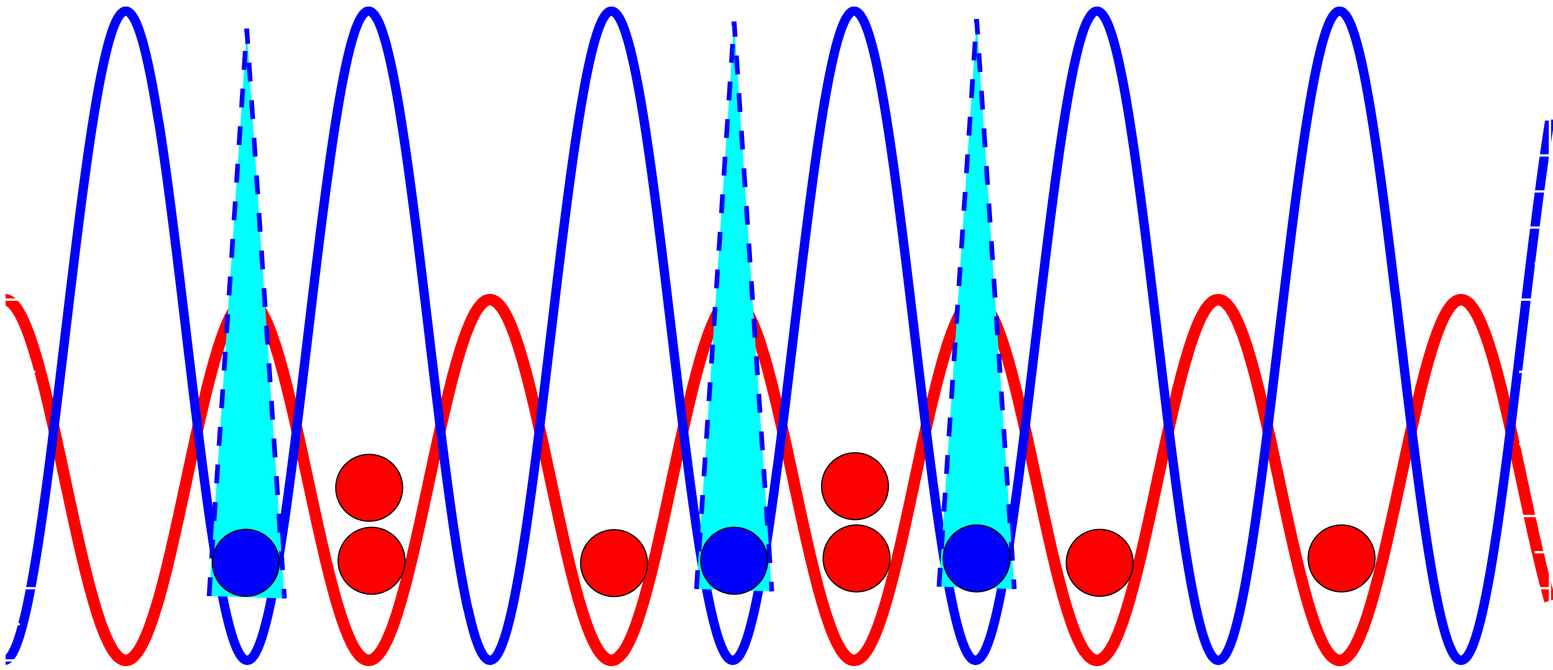
Largely different coupling to different circular polarization depending on the hyperfine state / laser wavelength. *O. Mandel et al., Phys. Rev. Lett. 91, 010407 (2003)*

Two shifted optical lattices



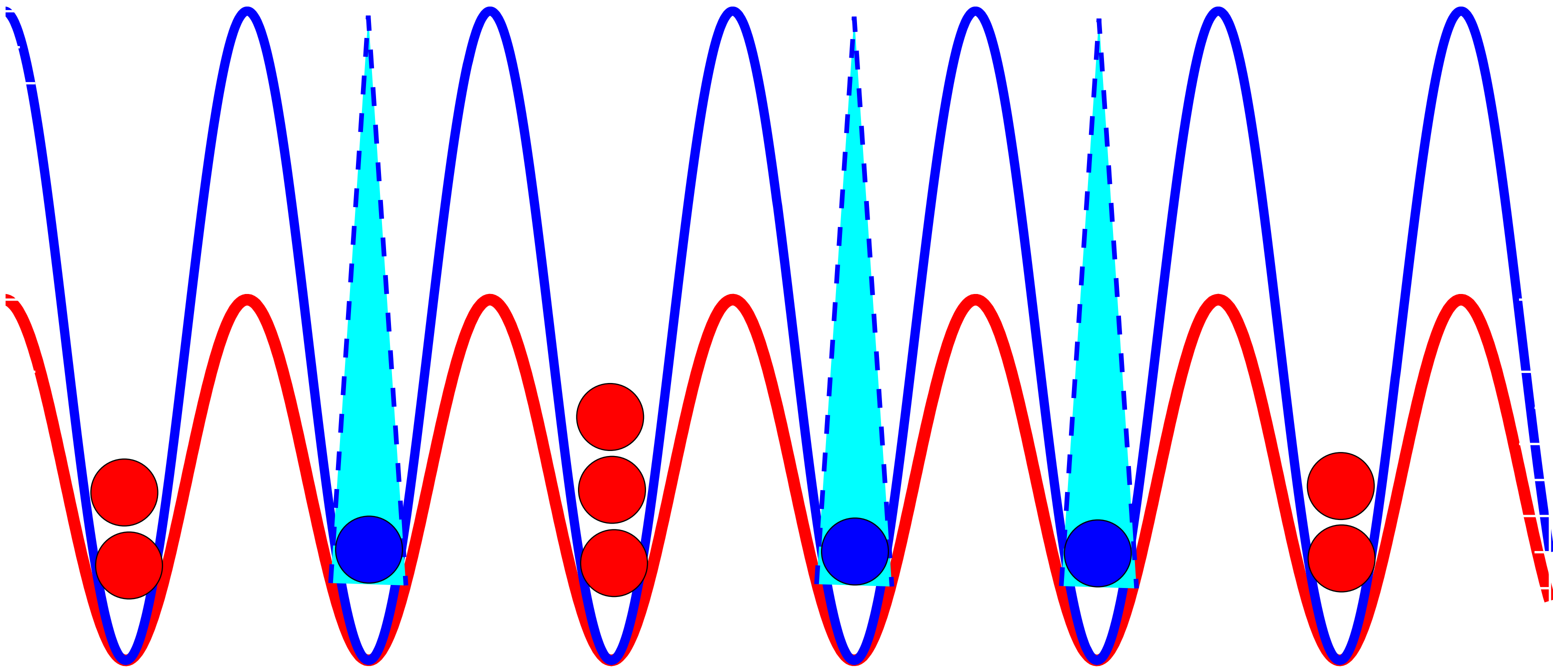
B. Paredes, F. Verstraete, and J.I. Cirac, PRL 95, 140501 (2005).

Freezing one species



B. Paredes, F. Verstraete, and J.I. Cirac, PRL 95, 140501 (2005).

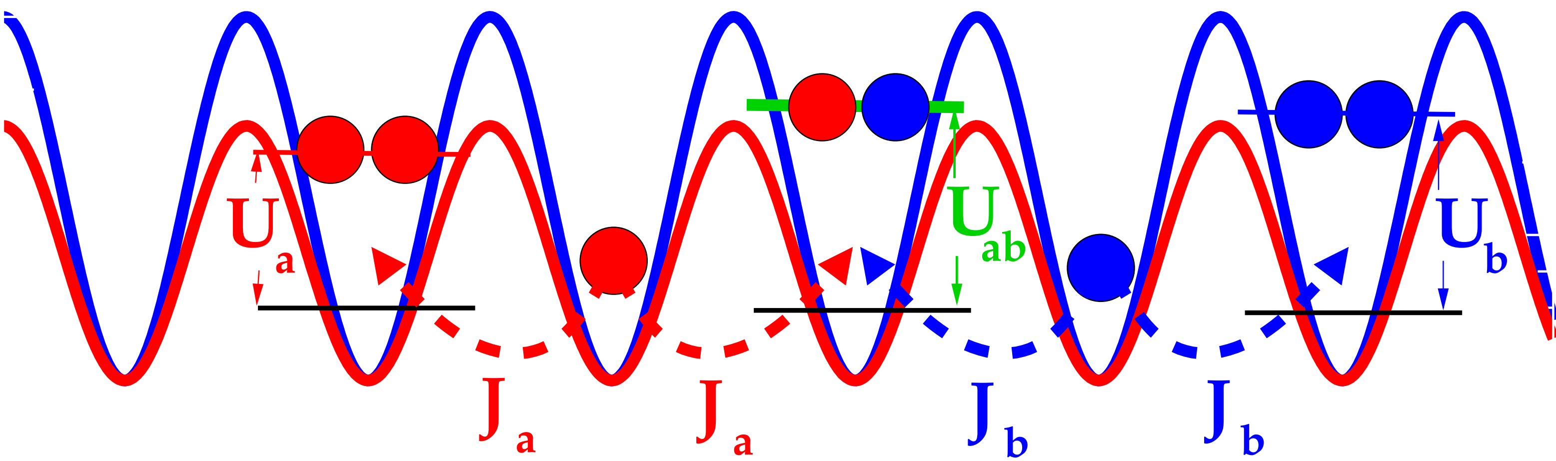
Bringing the species into interaction



B. Paredes, F. Verstraete, and J.I. Cirac, PRL 95, 140501 (2005).

Two-boson Bose-Hubbard model (2BHM)

a-bosons fast (target) bosons **b-bosons** slow (impurity) bosons



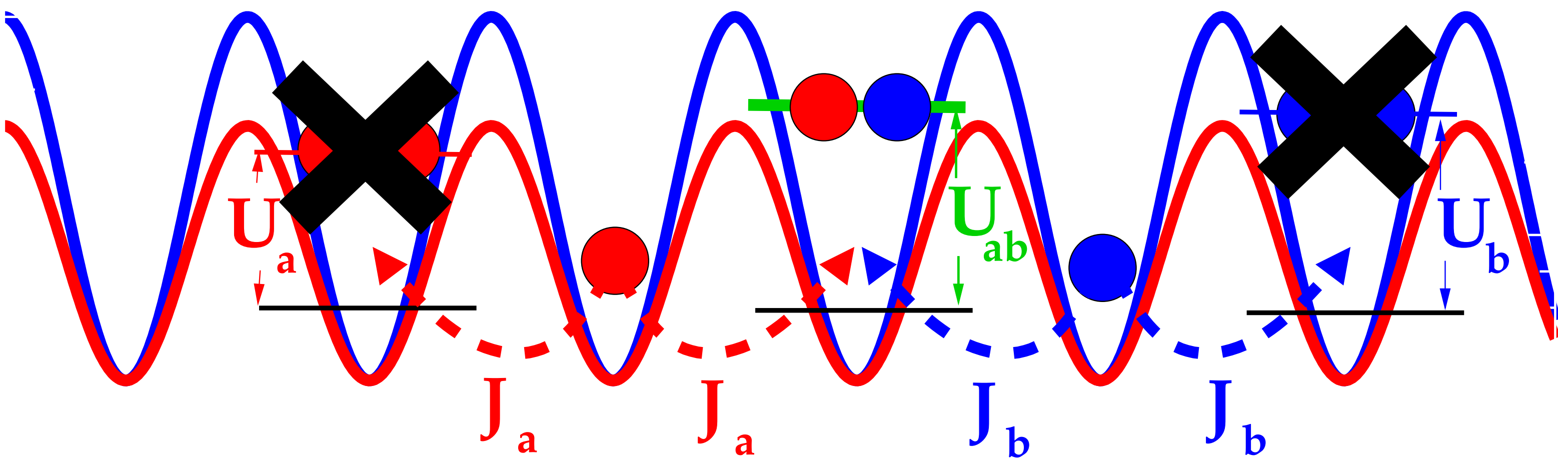
$$\mathcal{H} = \mathcal{H}_a + \mathcal{H}_b + \mathcal{H}_{ab} \qquad \mathcal{H}_a = J_a \sum_{\langle ij \rangle} \left(a_i a_j^\dagger + \text{h.c.} \right) + \frac{U_a}{2} \sum_i n_{a,i}(n_{a,i} - 1)$$

$$\mathcal{H}_b = J_b \sum_{\langle ij \rangle} \left(b_i b_j^\dagger + \text{h.c.} \right) + \frac{U_b}{2} \sum_i n_{b,i}(n_{b,i} - 1)$$

$$\mathcal{H}_{ab} = U_{ab} \sum_i n_{a,i} n_{b,i}$$

Hardcore-boson limit

a-bosons fast (target) bosons **b-bosons** slow (impurity) bosons



$$\boxed{U_a, U_b \longrightarrow \infty} \qquad n_a, n_b < 1$$

no doubly occupied sites $\rightarrow$ exactly solvable in $D = 1$
through Jordan-Wigner transformation

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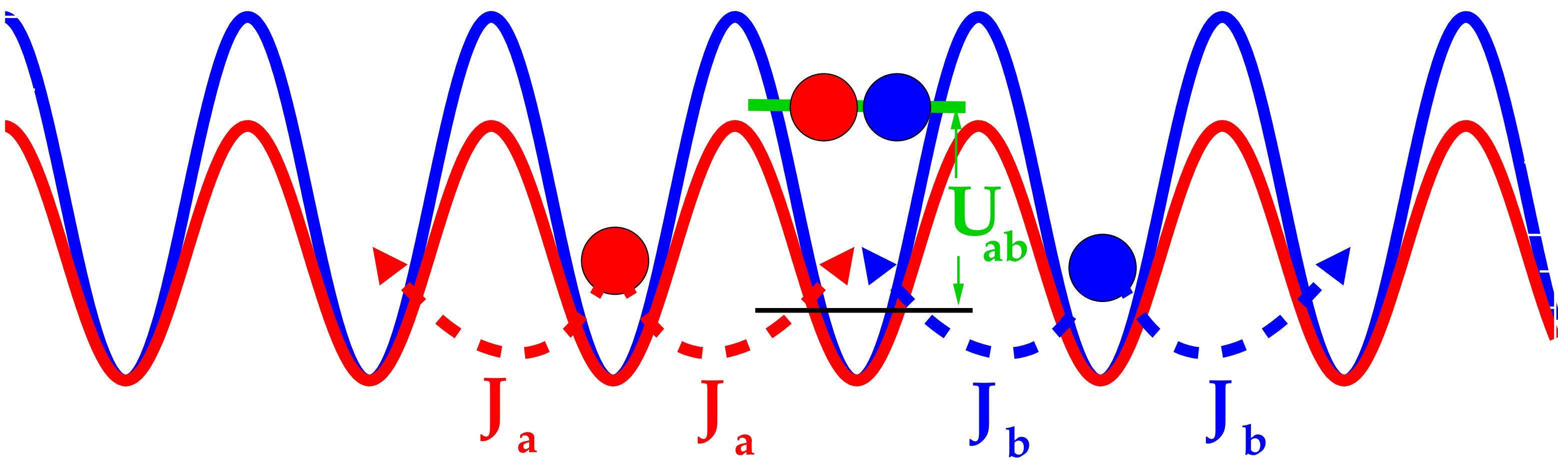
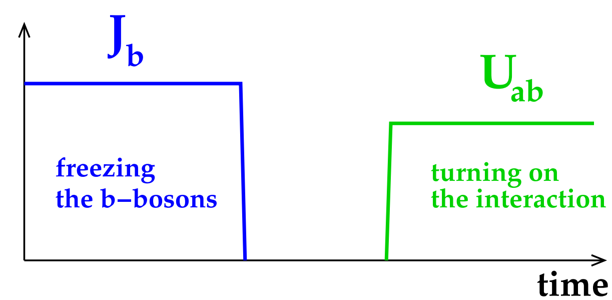


Time sequence



B. Horstmann, J. I. Cirac, and TR, arXiv:0706.0823

Frozen-boson potential

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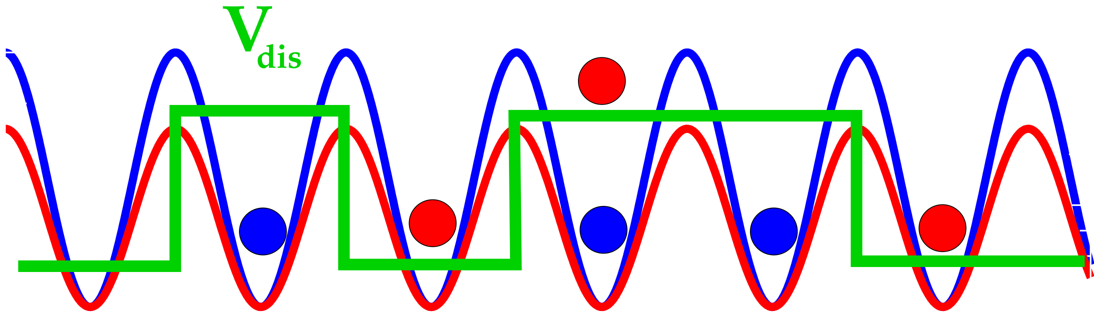

- Freeze the b-bosons in a *superfluid* state;

$$V_{\rm dis}(i) = U_{ab} n_{b,i}$$

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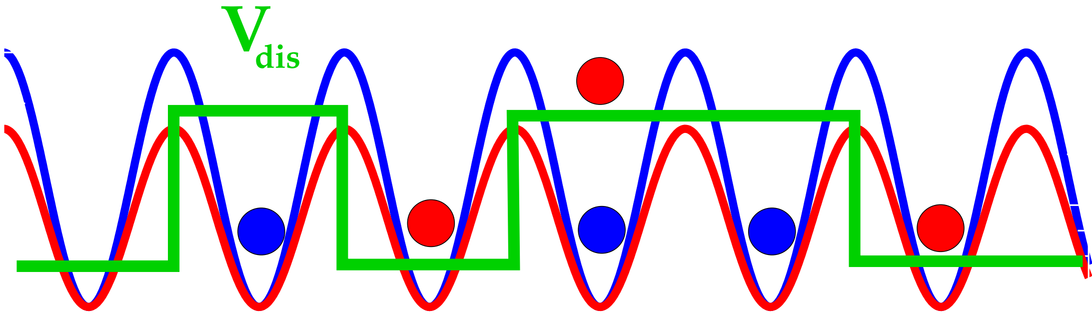

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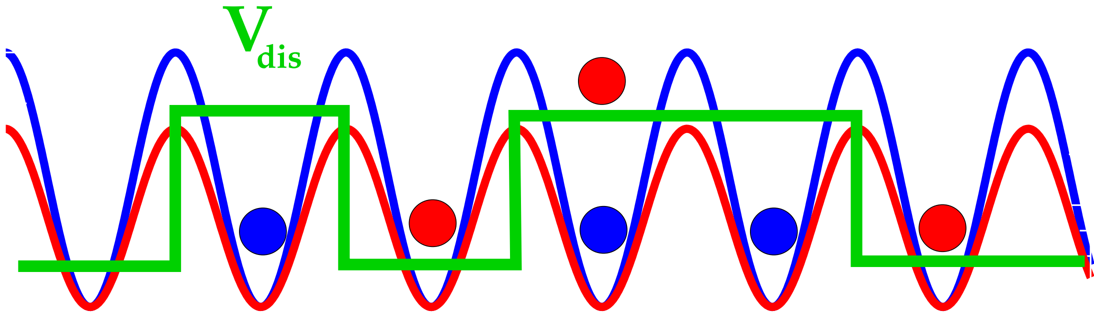

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$$\langle (n_{b,i} - \bar{n}_b)(n_{b,i+r} - \bar{n}_b) \rangle \sim r^{-2}$$

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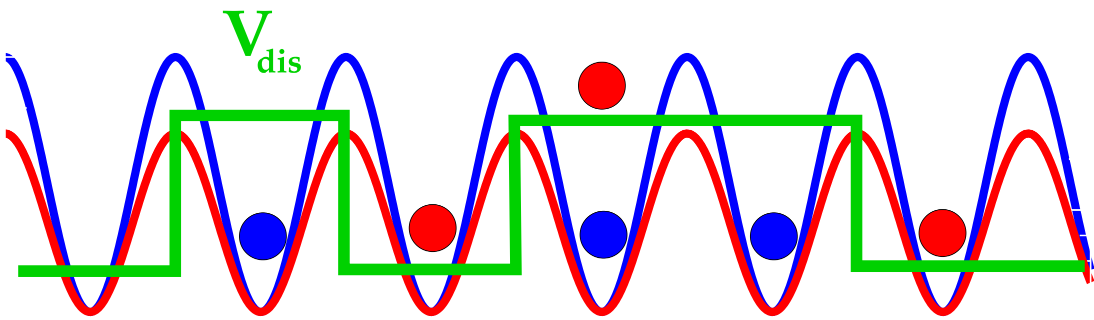

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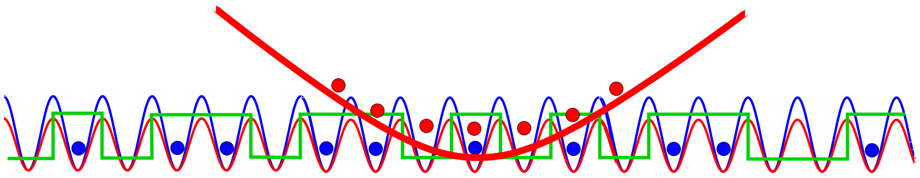
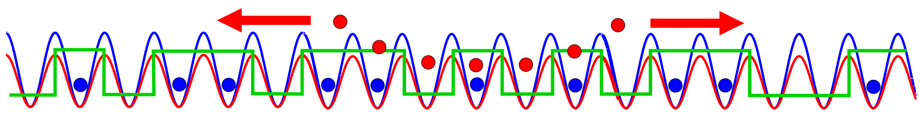
- Study of Anderson localization in a correlated random potential

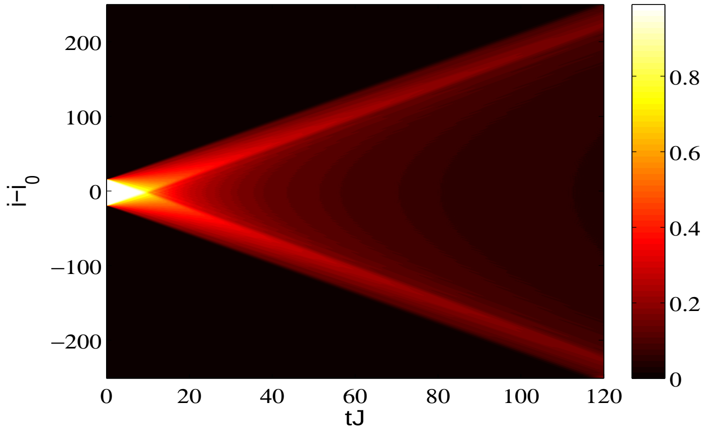
Steady-state Anderson localization

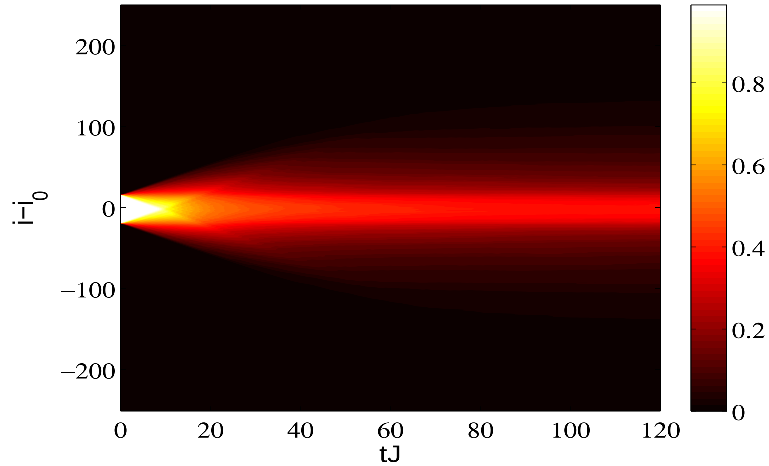
B. Horstmann, J. I. Cirac, and TR, arXiv:0706.0823





Exponential localization after expansion



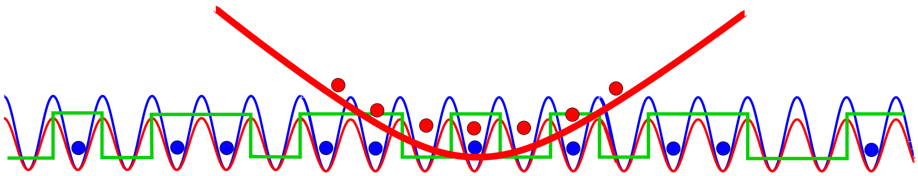


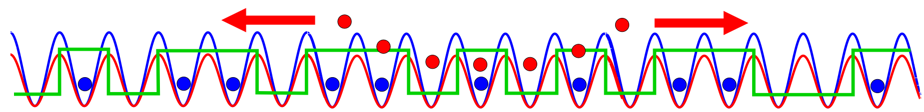
$U_{ab} = 0$

$U_{ab} = 0.5\ J_a$

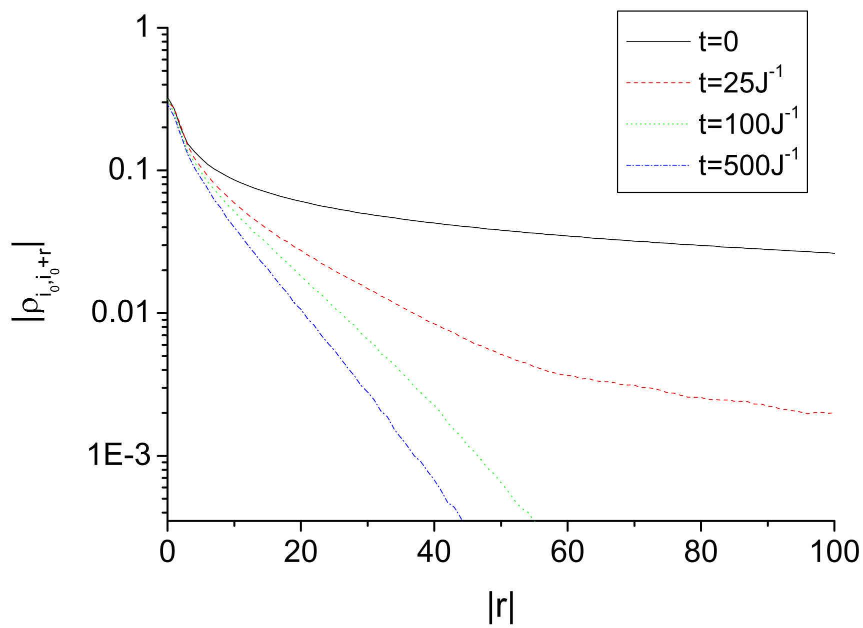
Steady-state Anderson localization

B. Horstmann, J. I. Cirac, and TR, arXiv:0706.0823

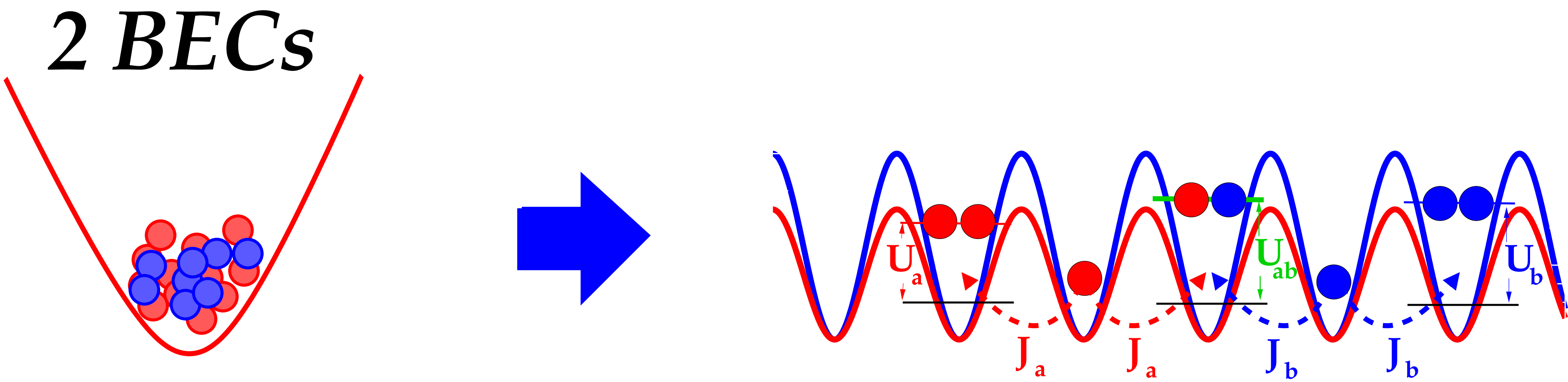




Suppression of phase correlations $\rho_{i,i+r} = \langle a_i^\dagger a_{i+r} \rangle$



- What if we try to **adiabatically** load two *unequal* bosons ($J_a \gg J_b$) in an optical lattice?



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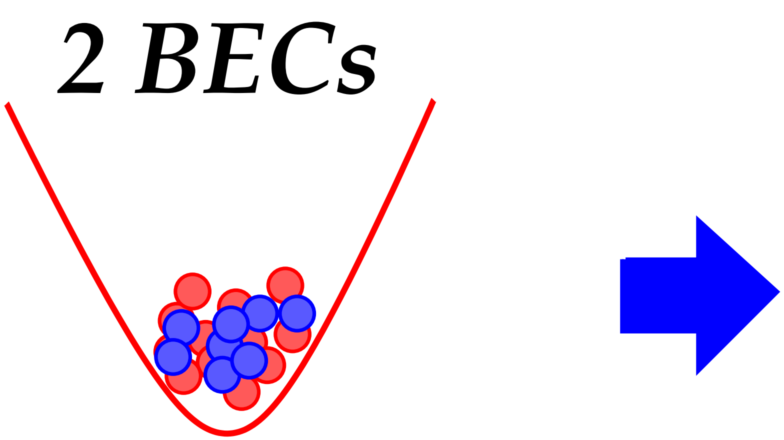
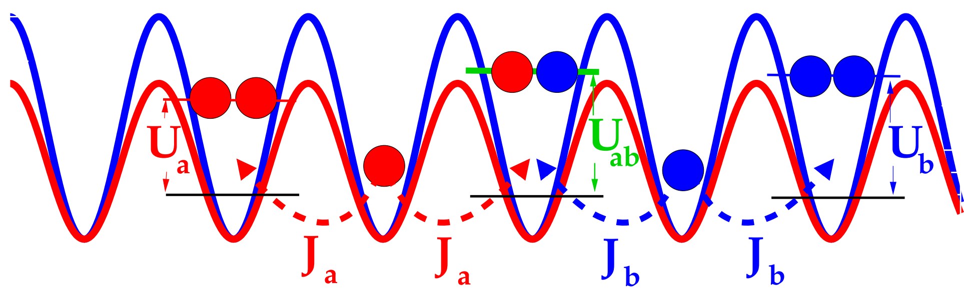




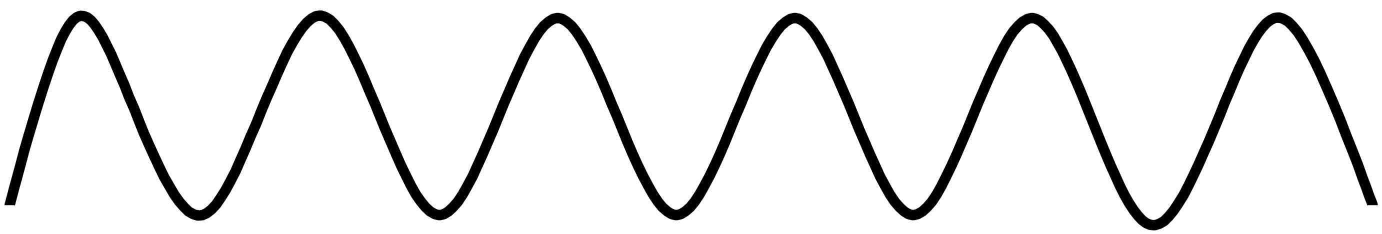
- **Do localization phenomena survive?**

Unequal-boson mixture towards equilibrium

Weakly repulsive a particles, strong b-b and a-b repulsion

$$U_{ab} = U_b \gg U_a \qquad n_a = 1, n_b < 1$$

Classical ground state $(J_a, J_b = 0)$



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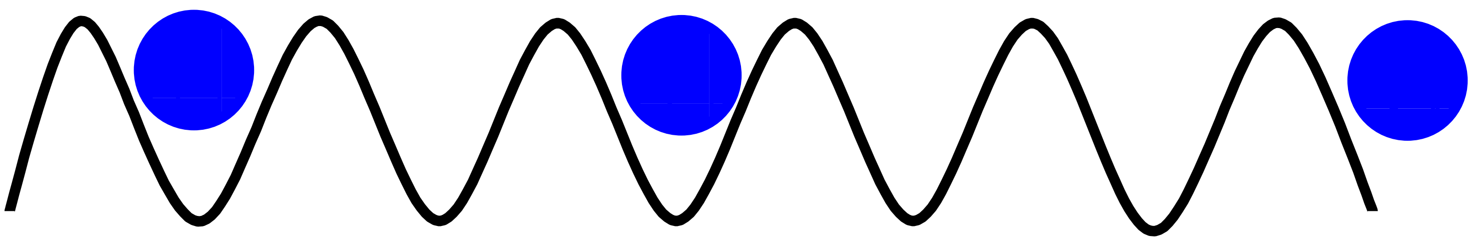

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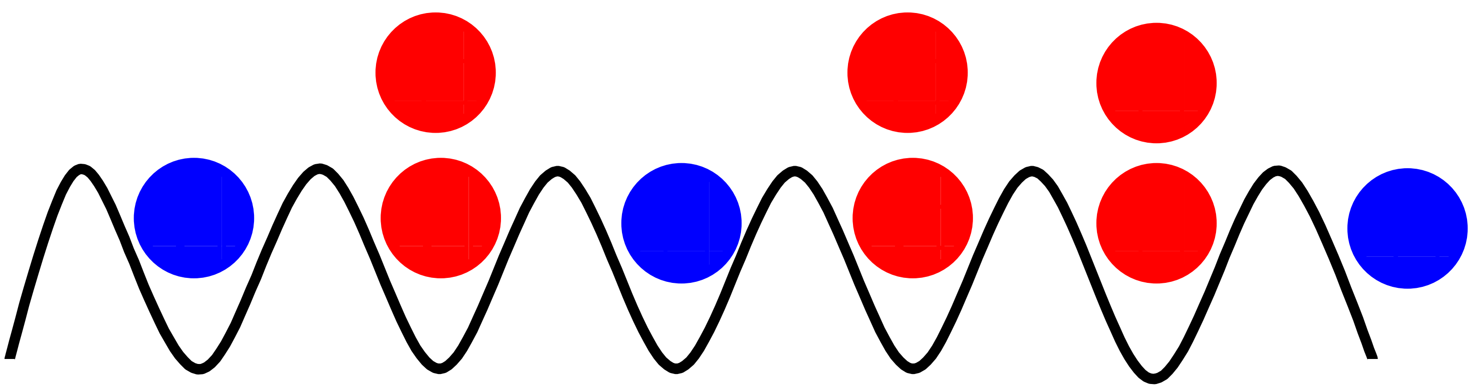

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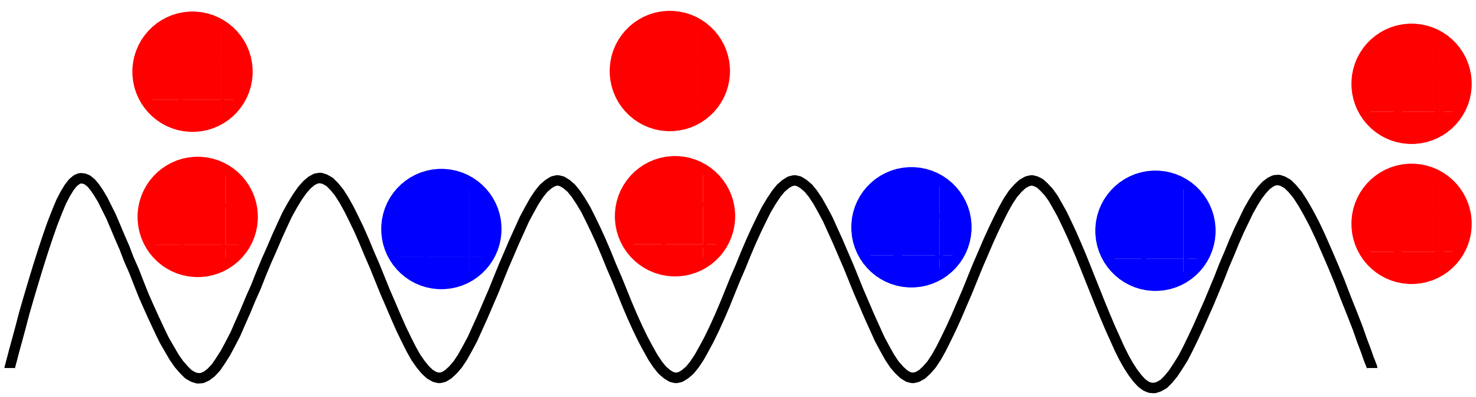

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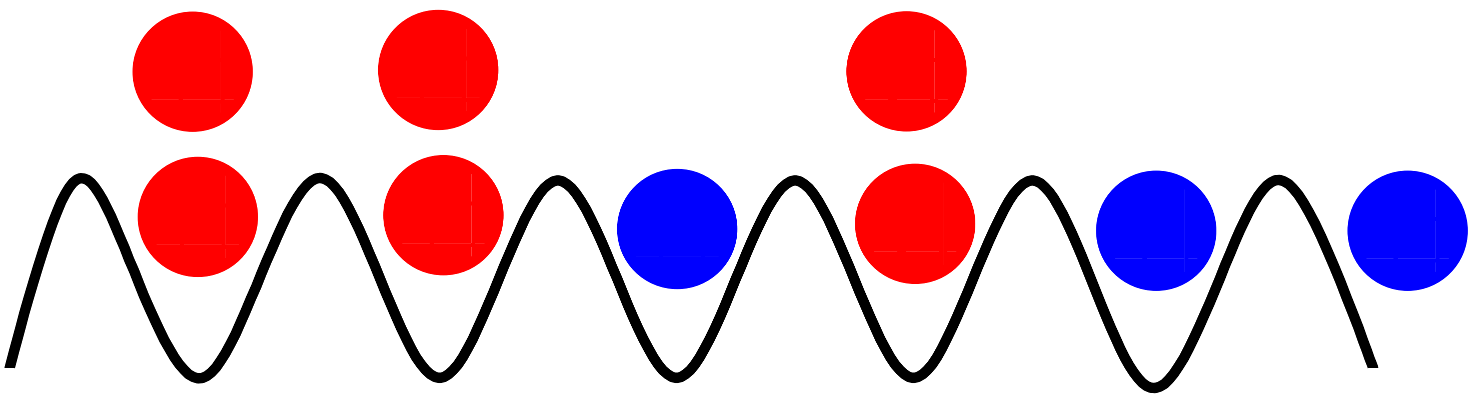

Unequal-boson mixture towards equilibrium

Weakly repulsive a particles, strong b-b and a-b repulsion

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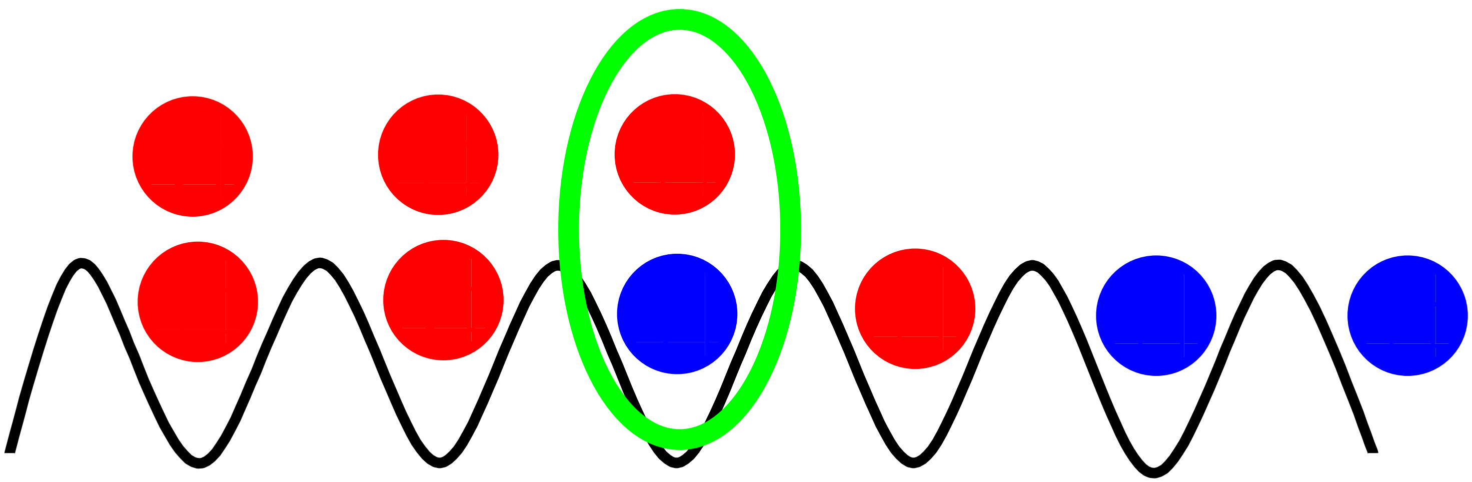
Excited state $\Delta E = U_{ab} - U_a$



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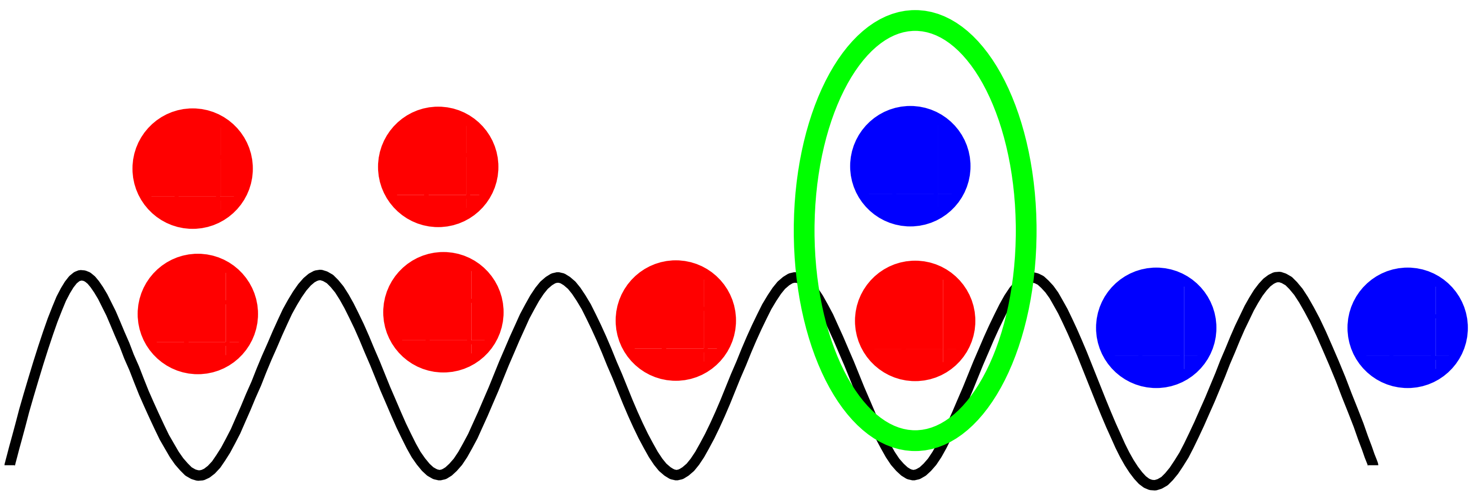

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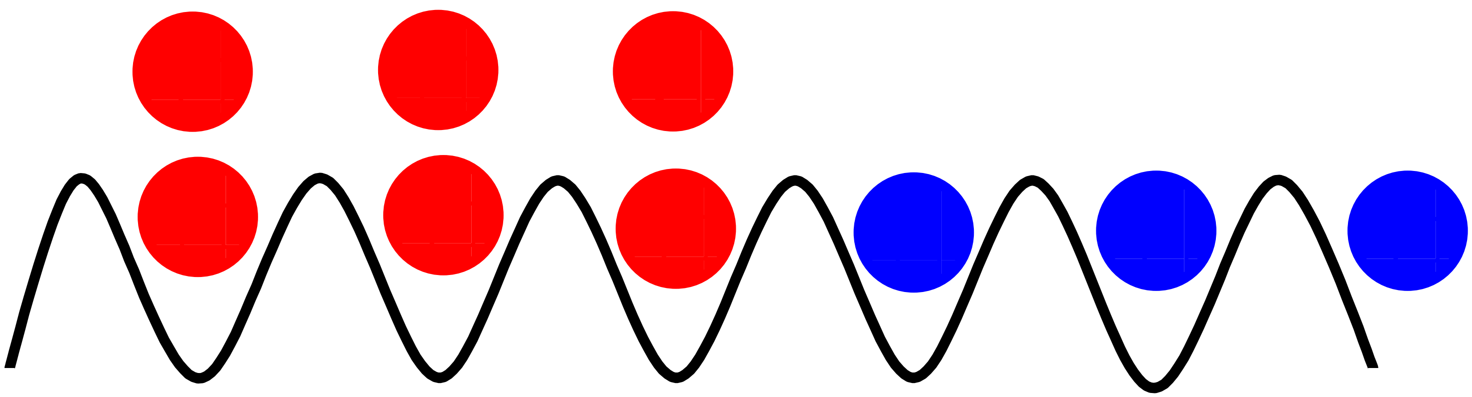
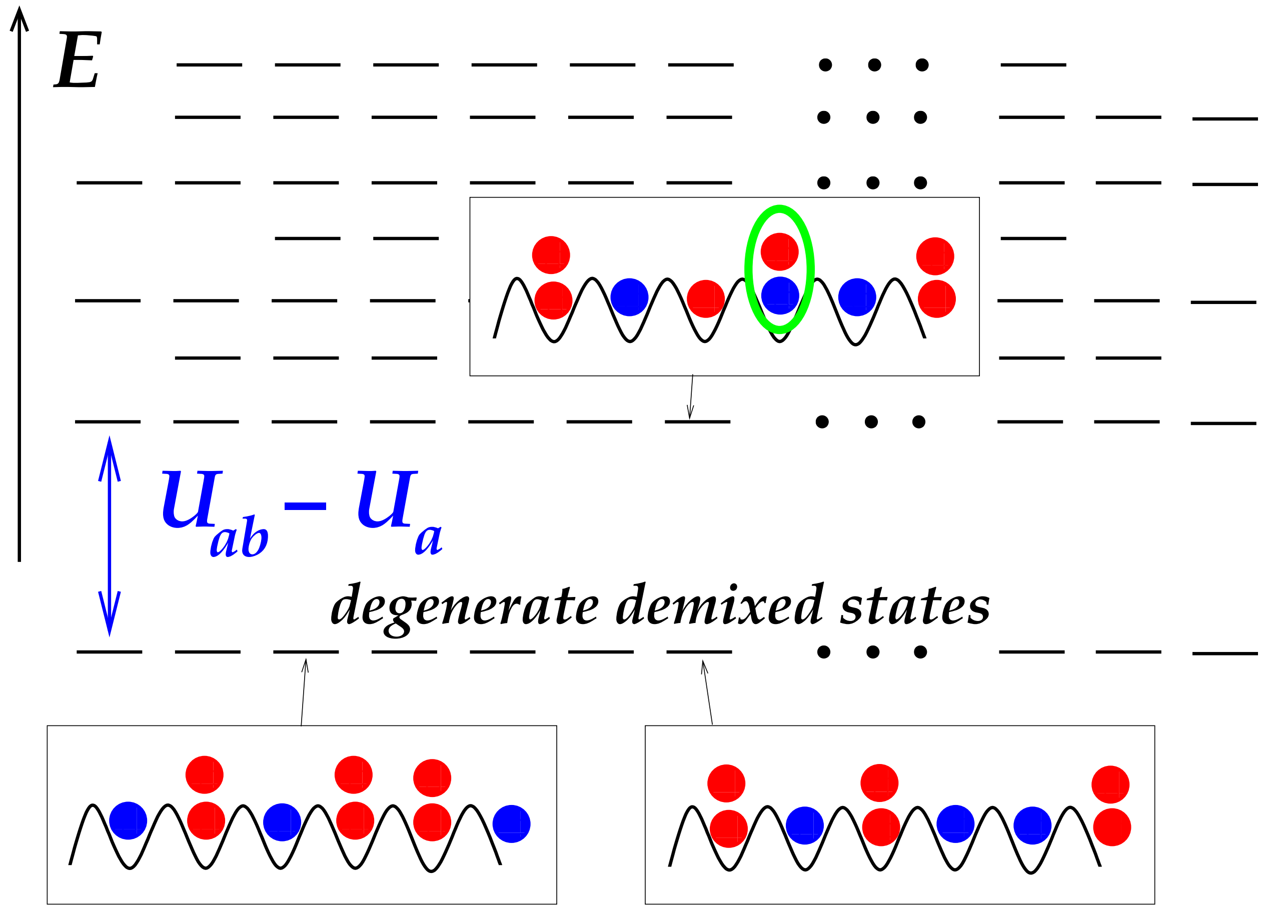
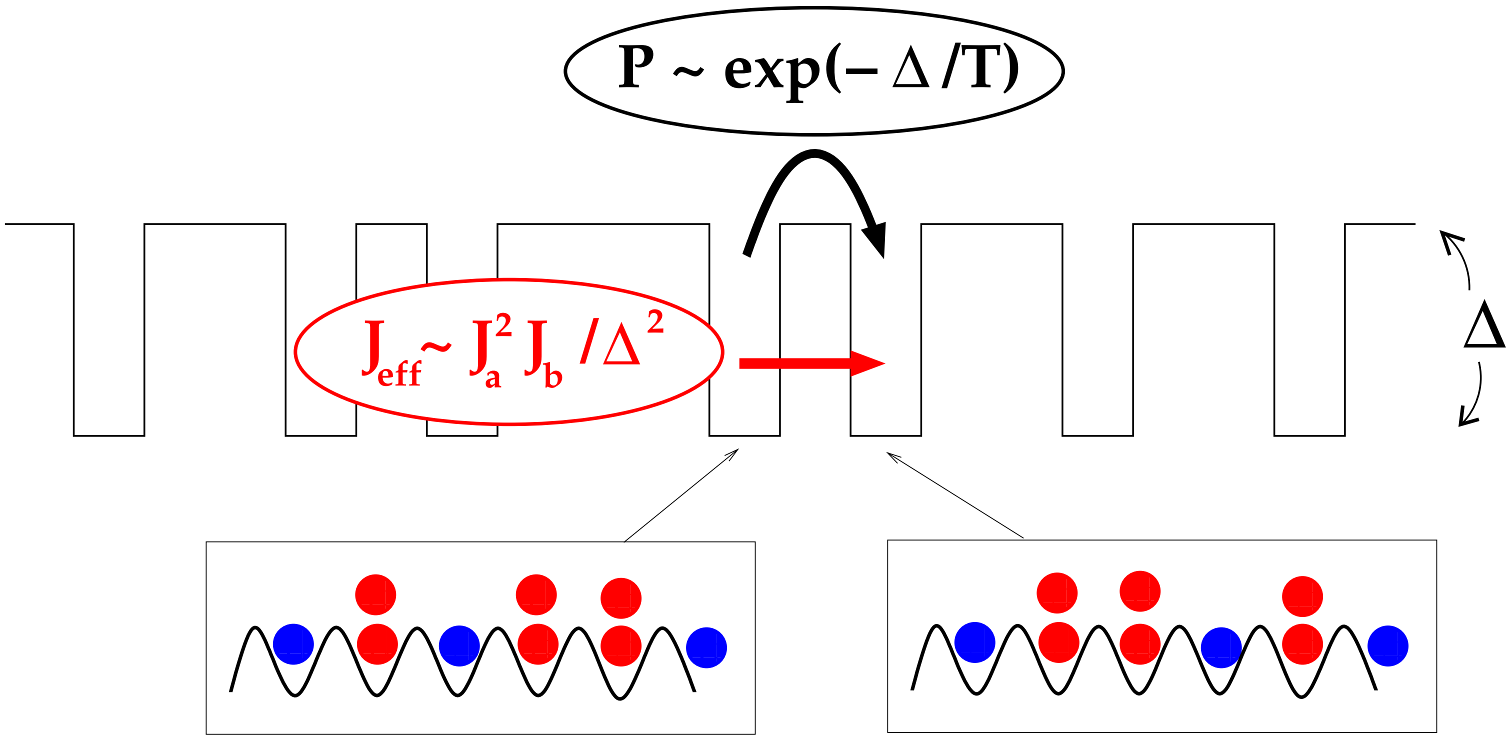


Classical limit $J_a, J_b \to 0$: glassy energy landscape



- **Exponentially** many degenerate ground states ($\sim L!/((N_a/2)!N_b!)$)
- All separated by **energy barriers** $\leq (U_{ab} - U_a)$.

Slow dynamics

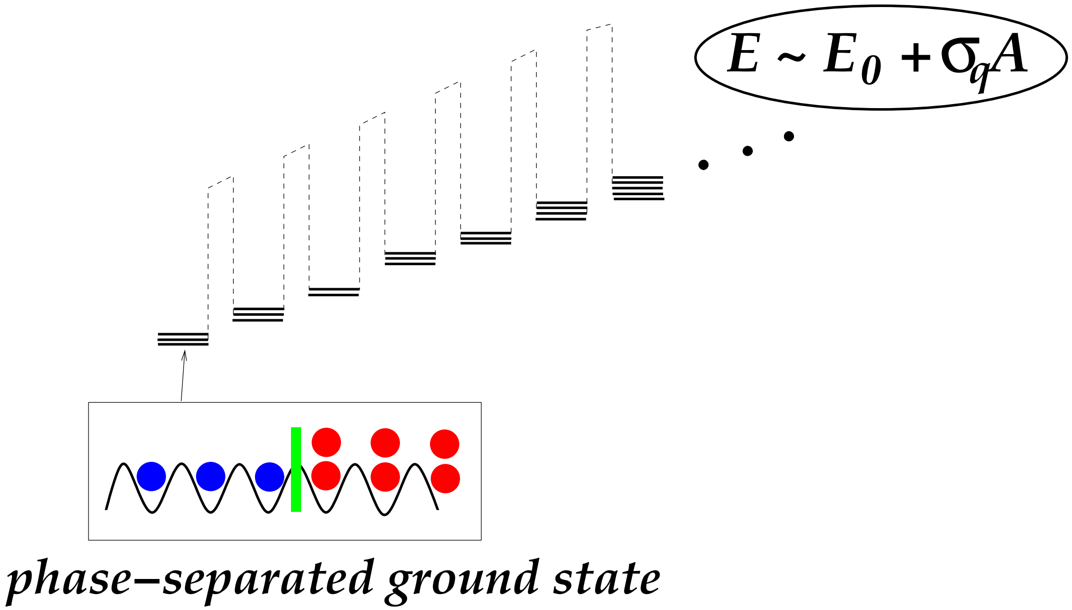


Energy barriers suppress thermal hopping / quantum tunneling

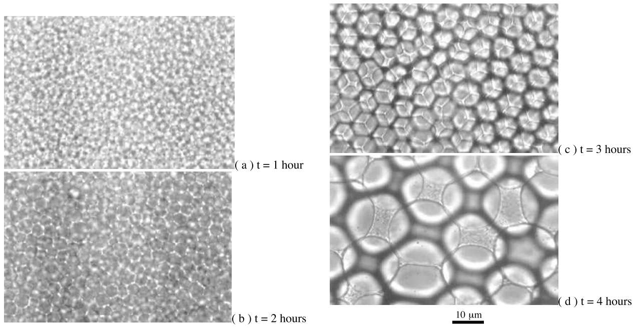
- $J_a \approx 2$ kHz, $J_b \approx 0.4$ kHz
- $U_a = J_a, U_{ab} = 5J_a$

$$\tau = \hbar / J_{\text{eff}} \sim 36 \text{ ms}$$ for ^{87}Rb

Quantum correction $J_a, J_b \ll U_{ab}, U_b$: immiscibility



Quantum surface tension: $\sigma_q \sim J_a^2, J_b^2$
analogous to immiscible fluids



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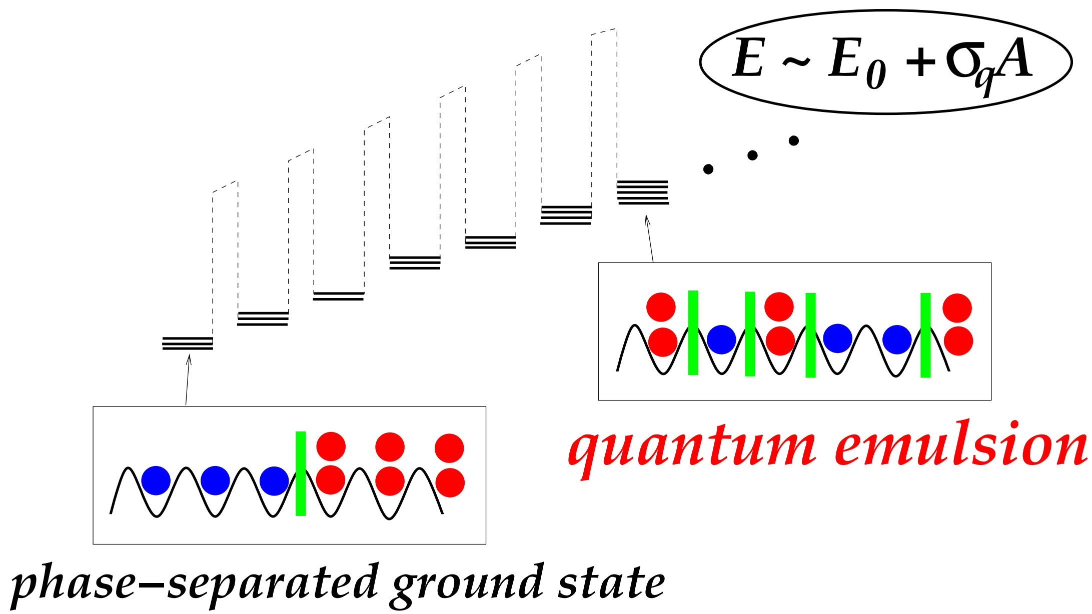

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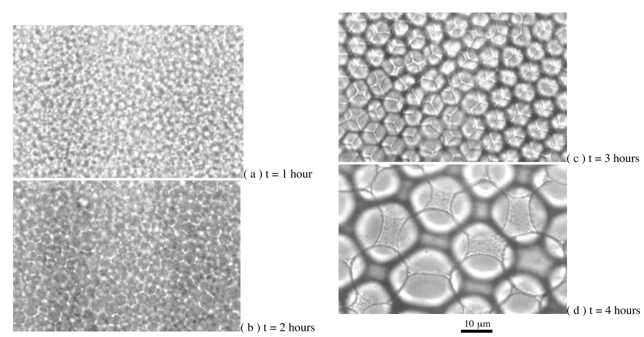

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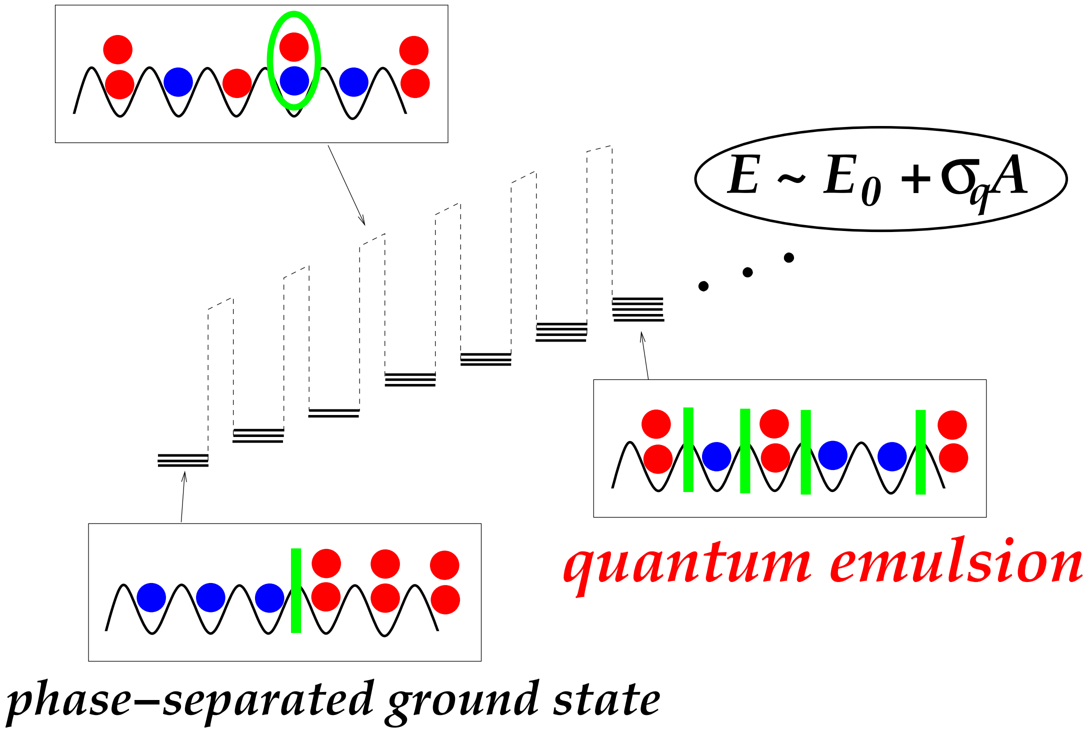

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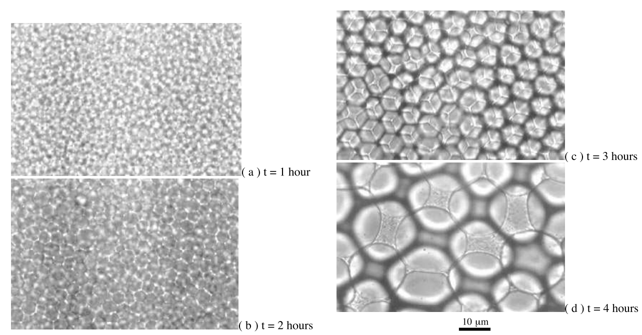
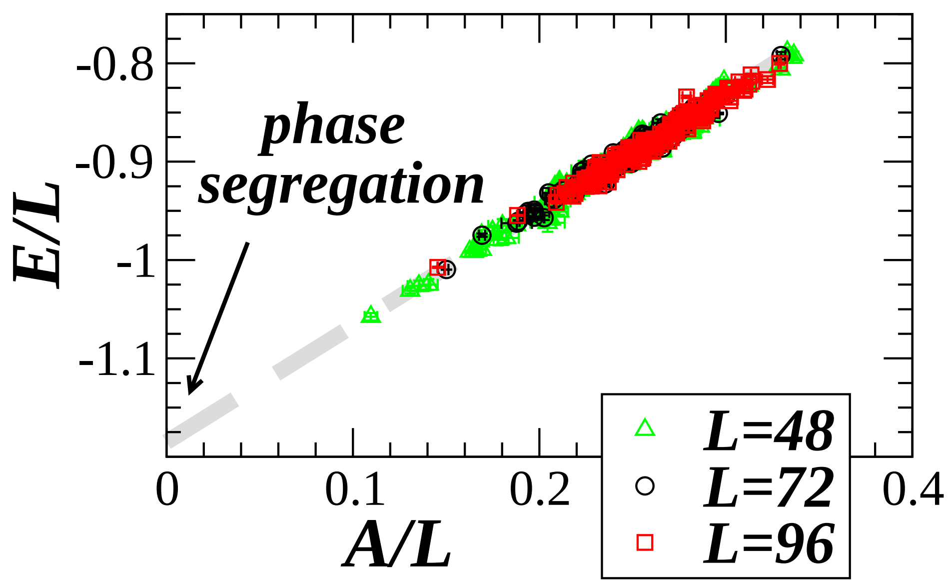
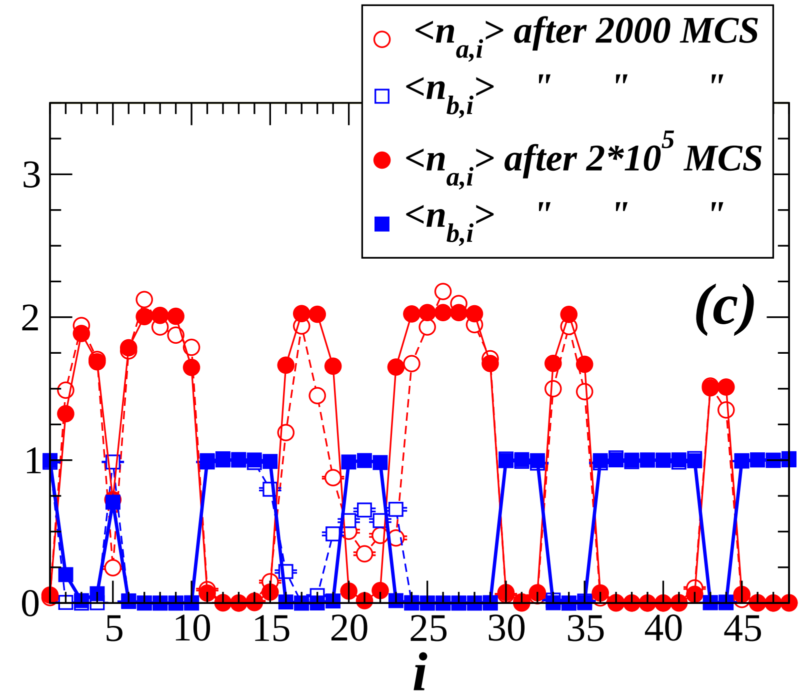


Quantum Monte Carlo study

TR and J. I. Cirac, Phys. Rev. Lett. 98, 190402 (2007)

- Stochastic Series Expansion in a mixed ensemble (a grand-canonical, b canonical) and in the canonical ensemble; *double-worm* update;
- Trapping of the simulation in metastable states;
- Probe the metastable states as **fictitious equilibrium states**;

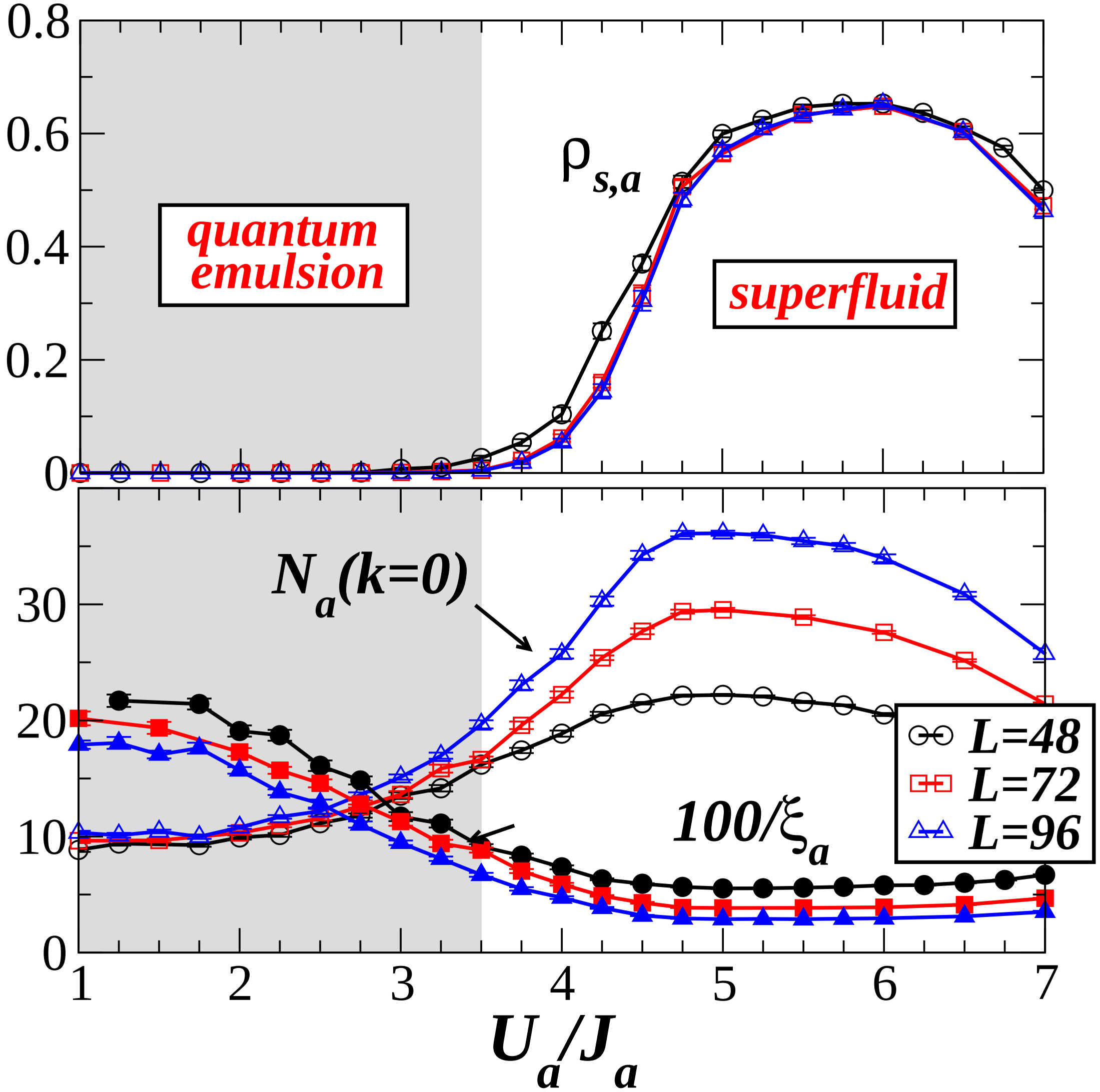


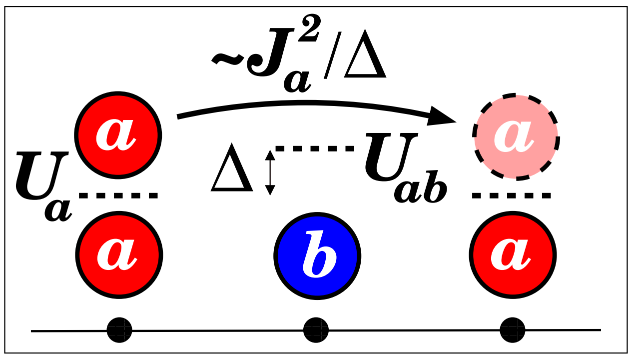


$U_a = J_a \quad U_b = U_{ab} = 5J_a \quad J_b = 0.2J_a \quad N_a = L \quad N_b = L/2;$

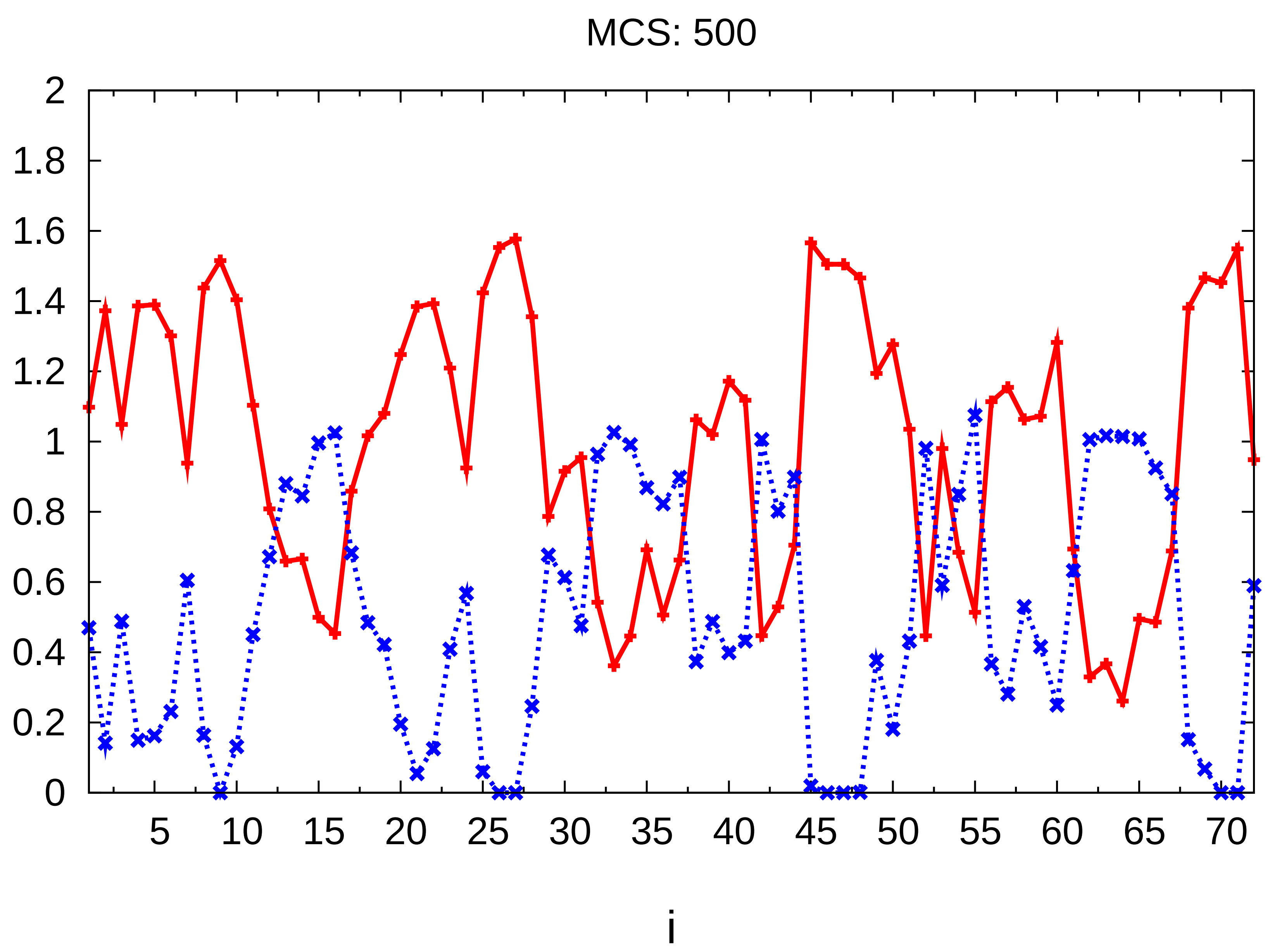
Moulding the quantum glass

Changing the U_a repulsion through a Feshbach resonance





A strange superfluid!



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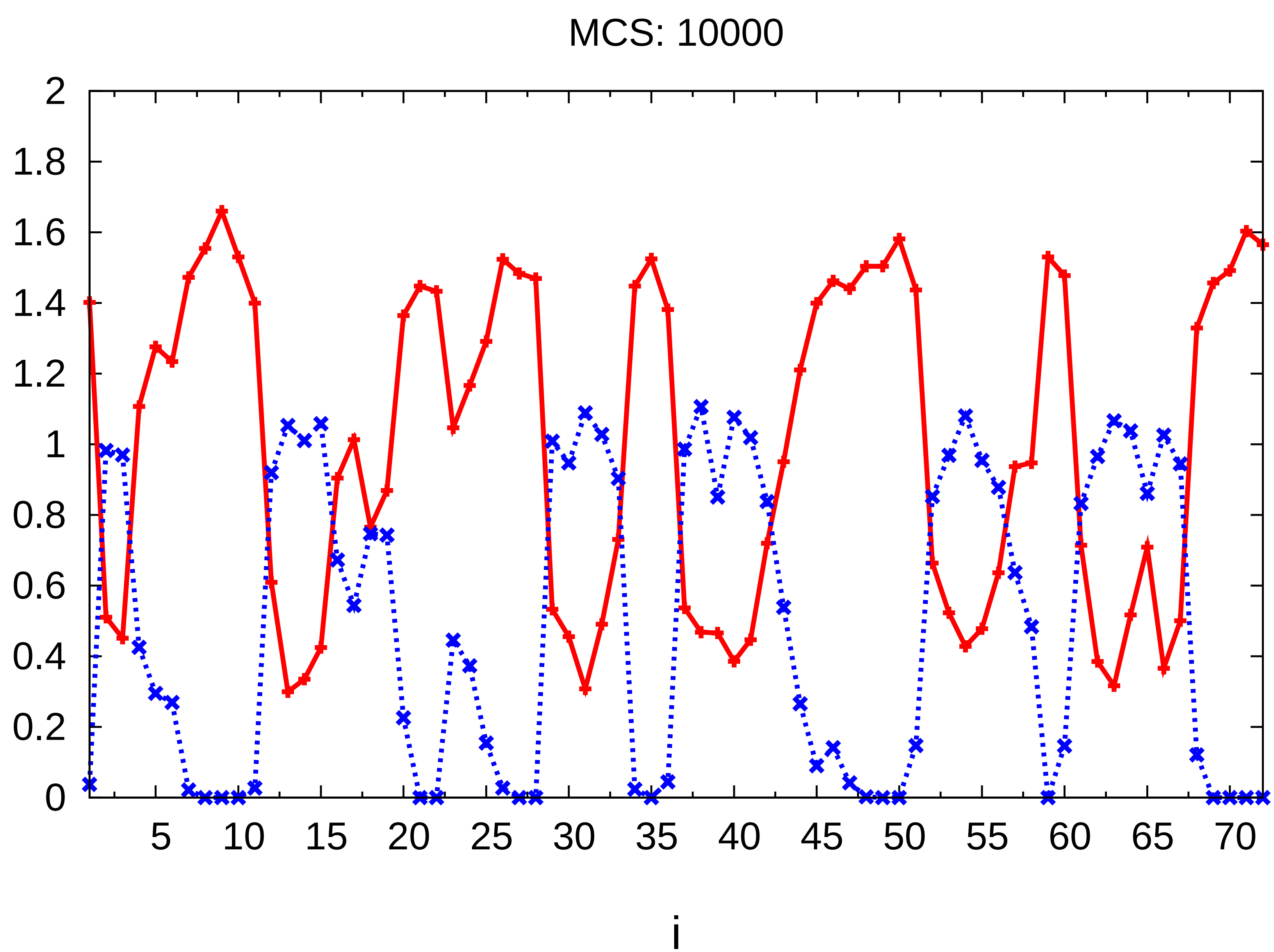

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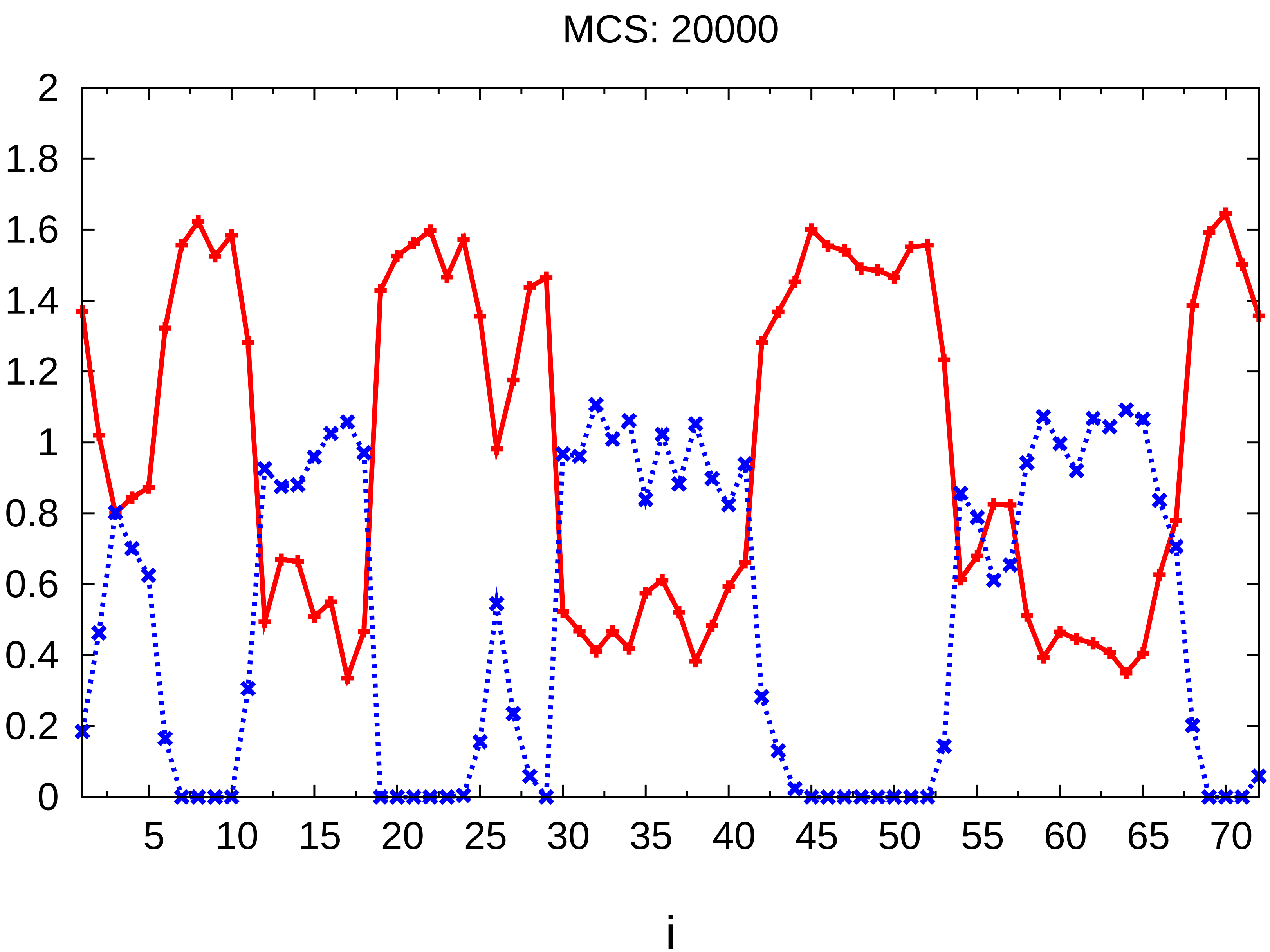

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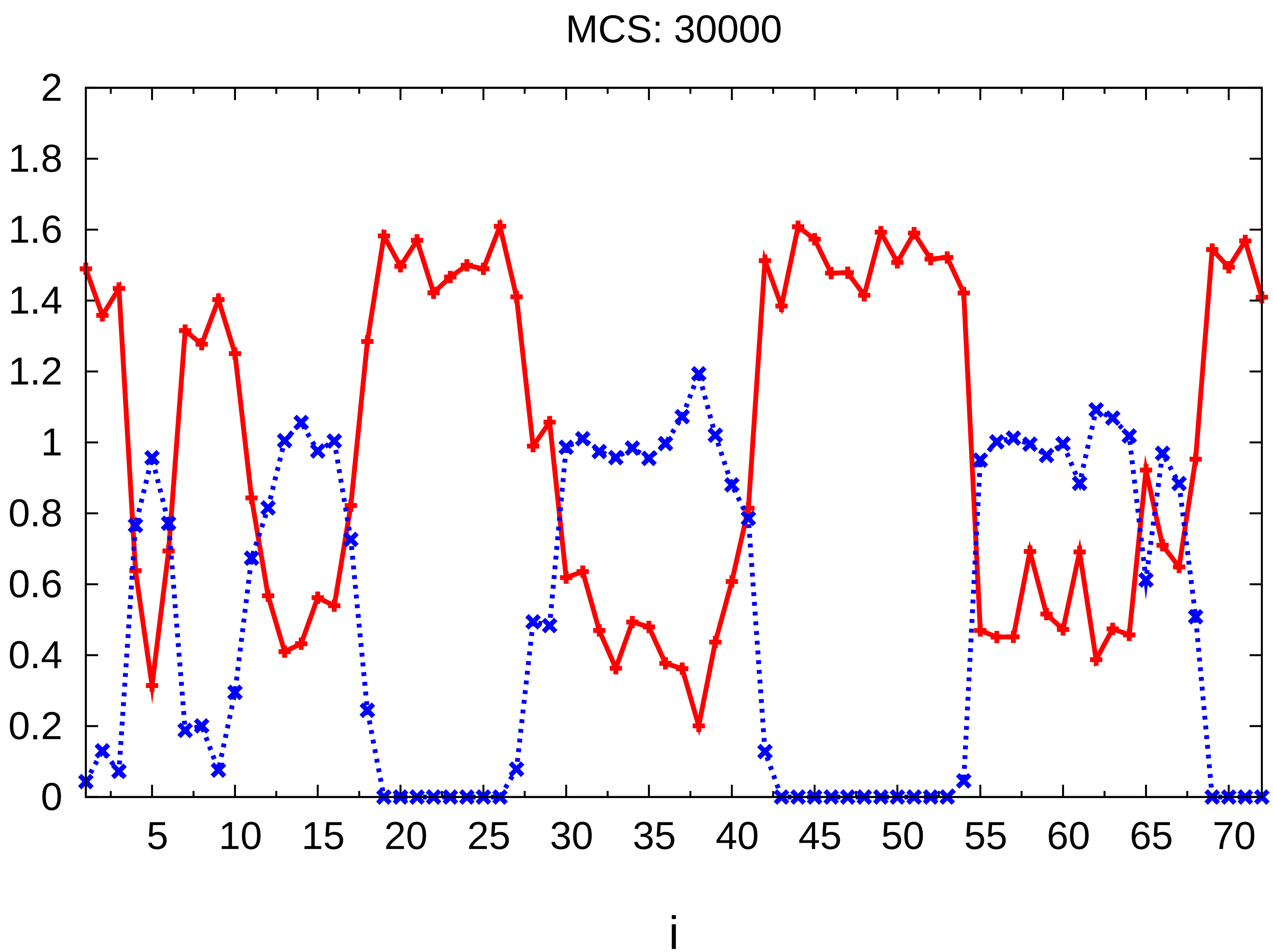

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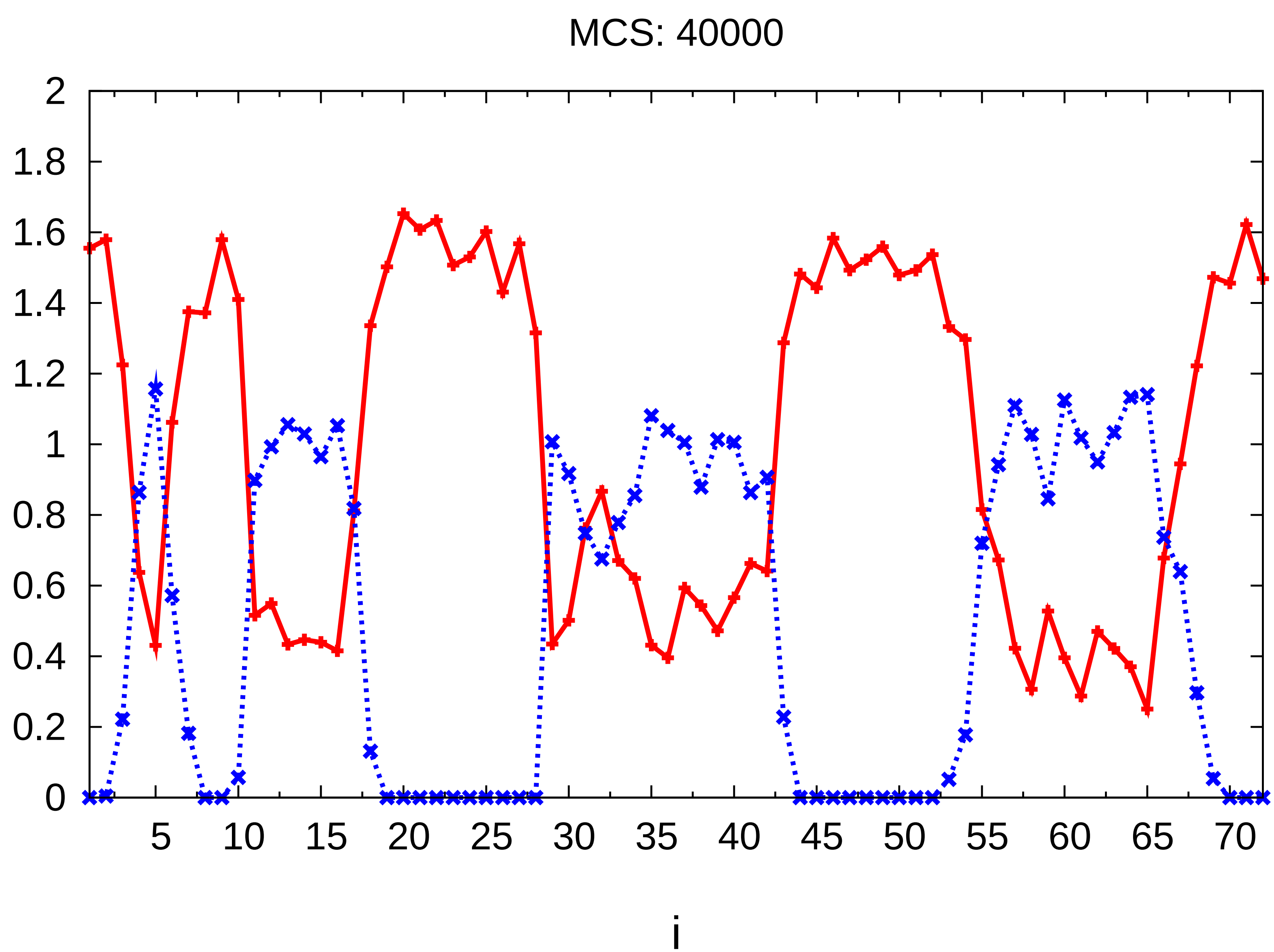

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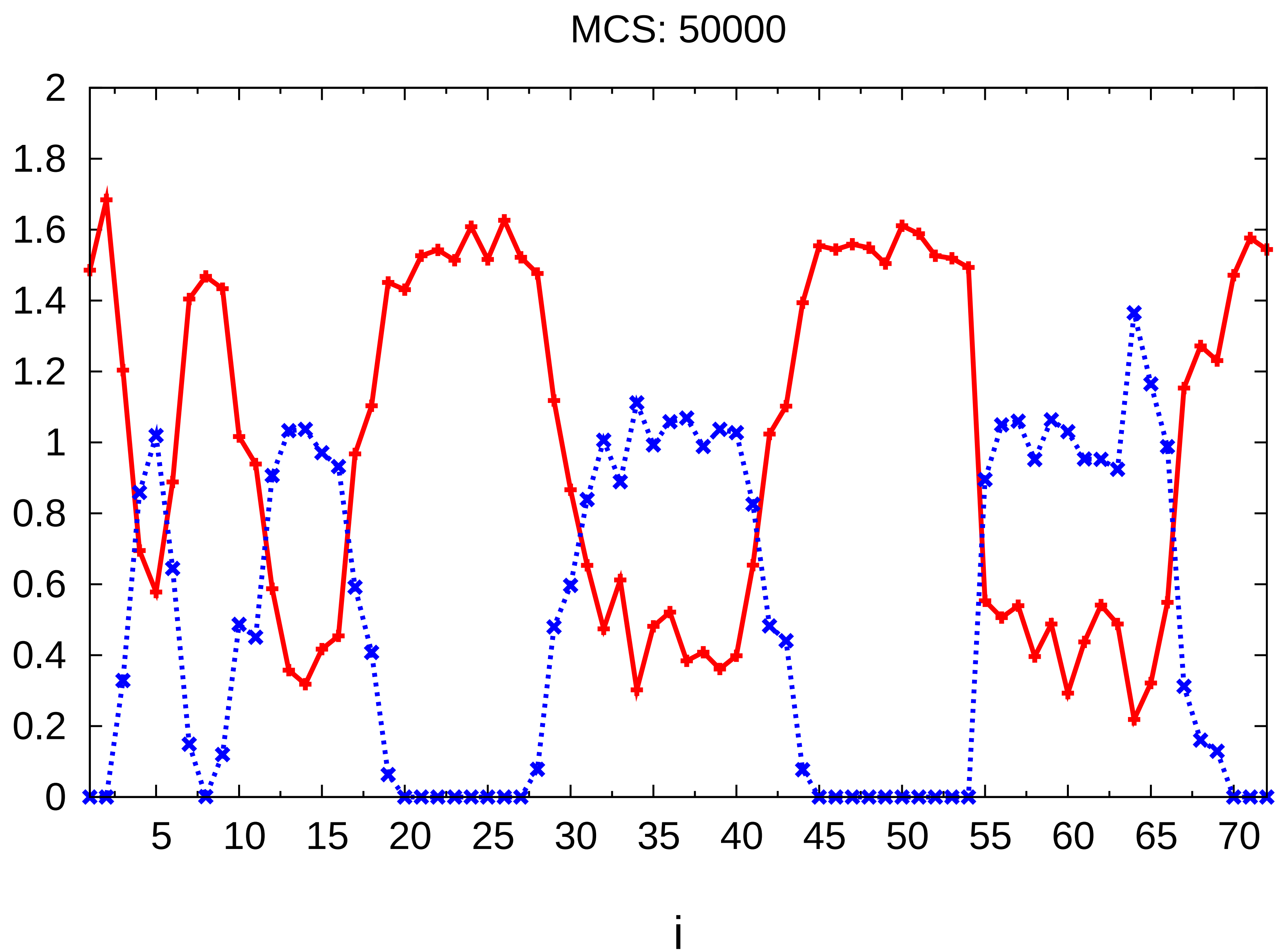

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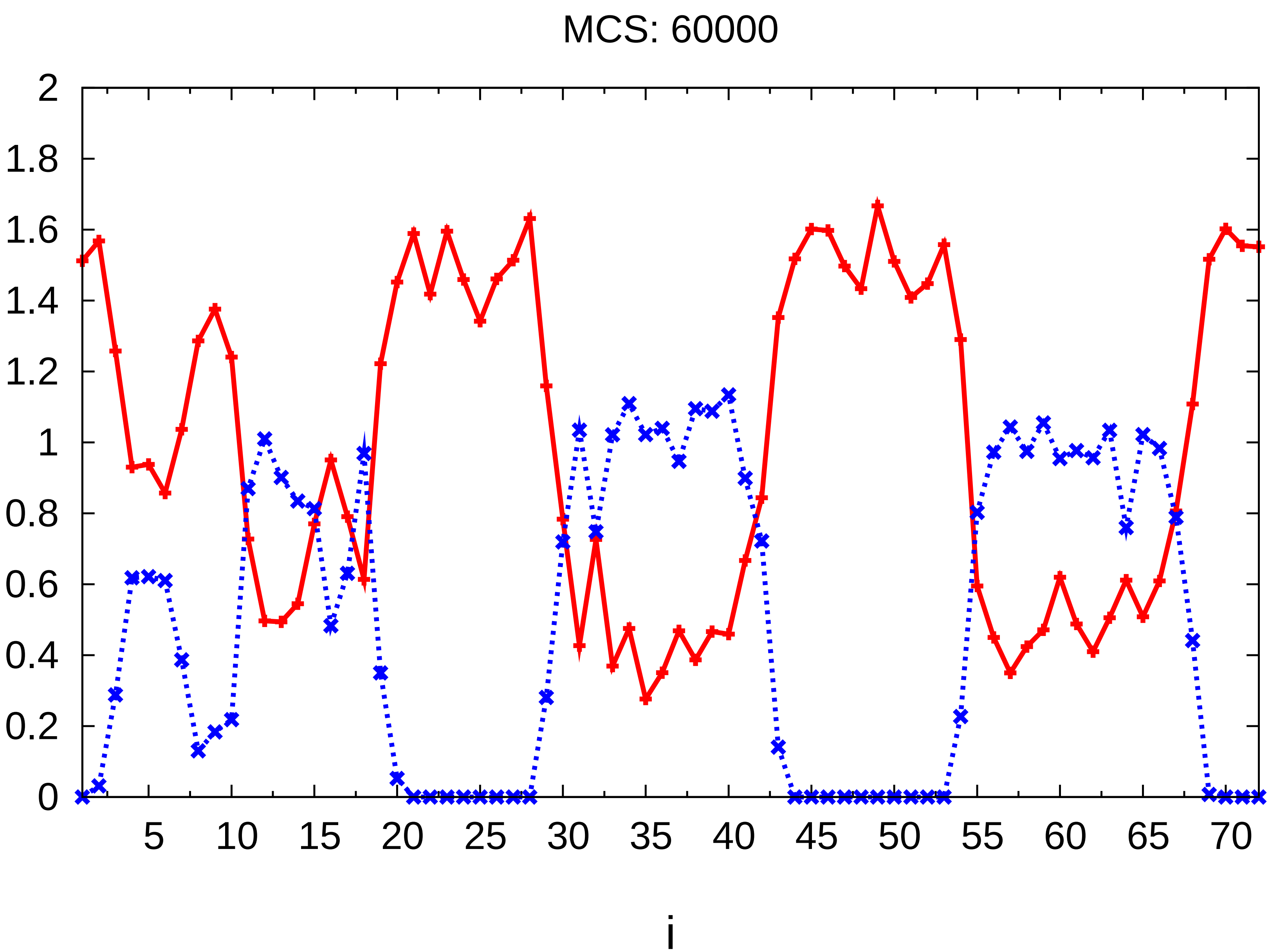

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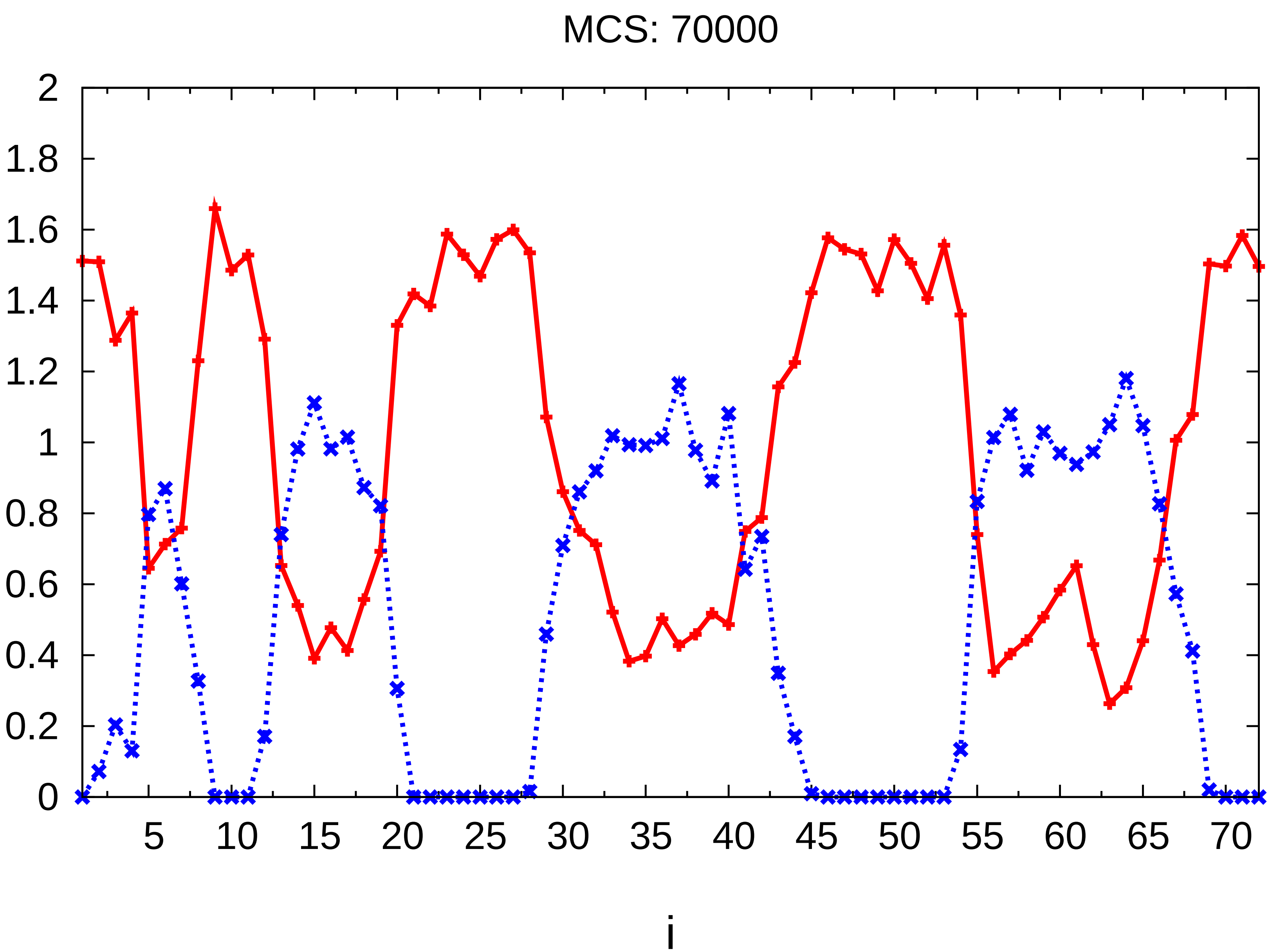

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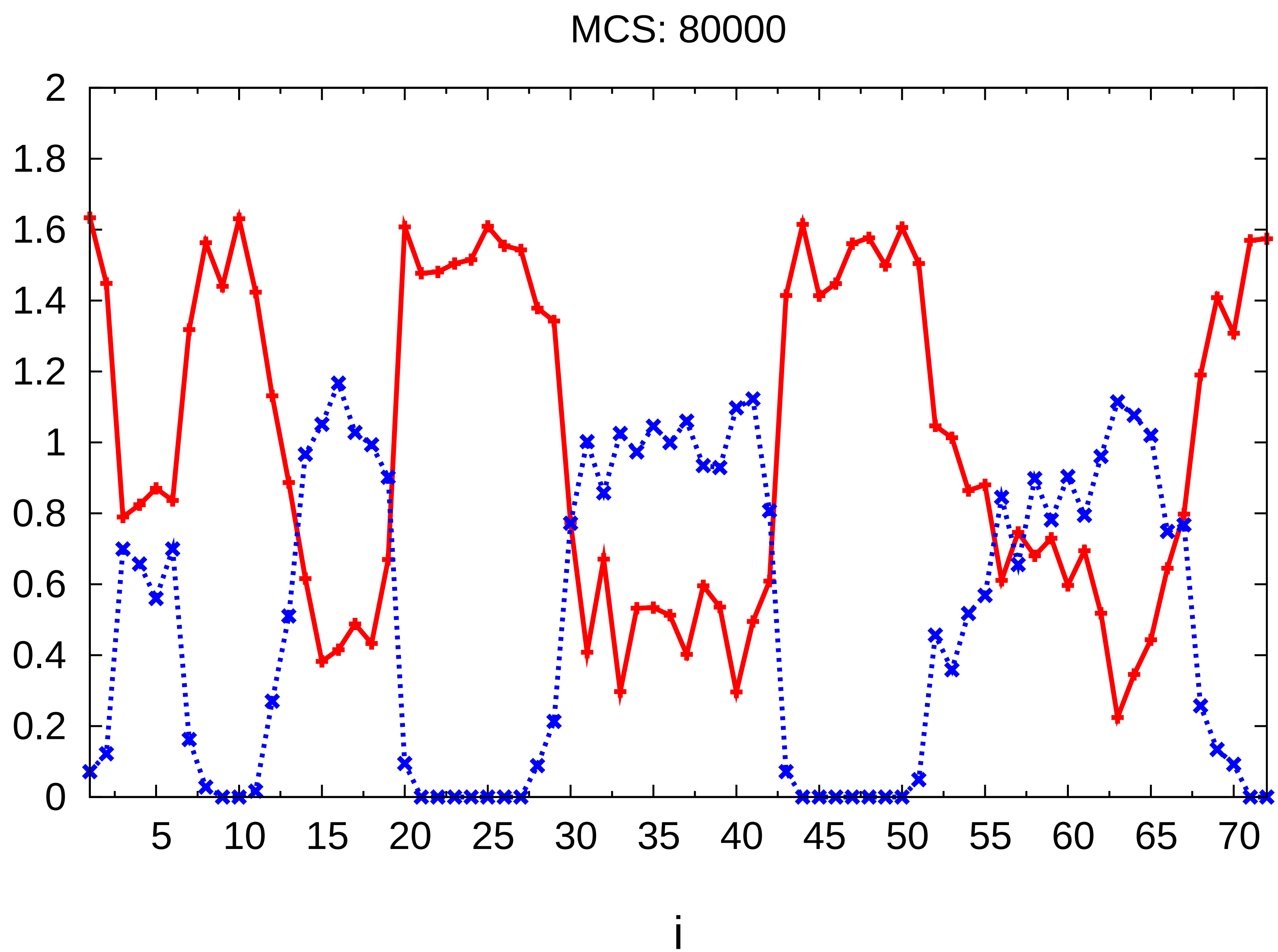

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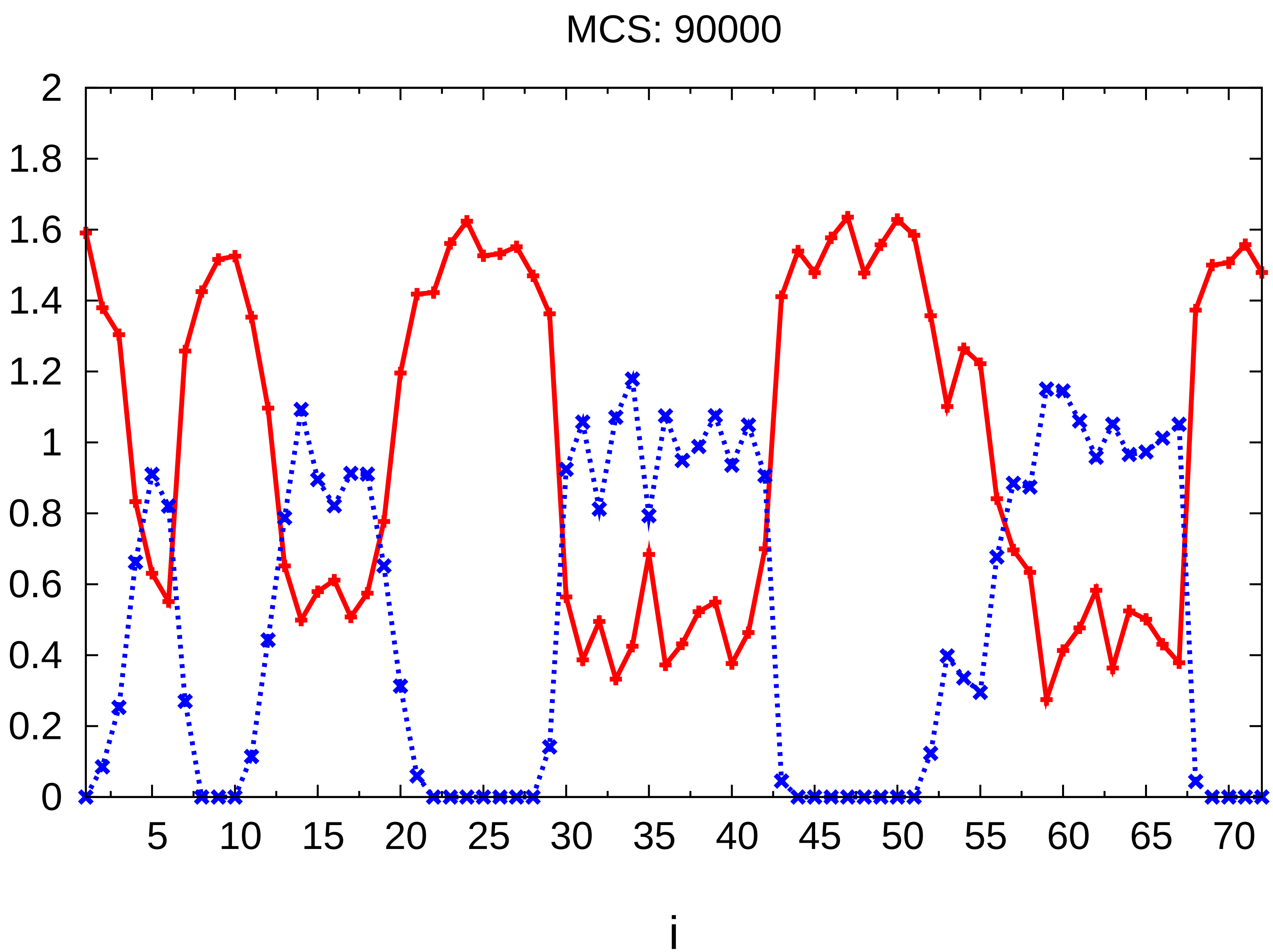

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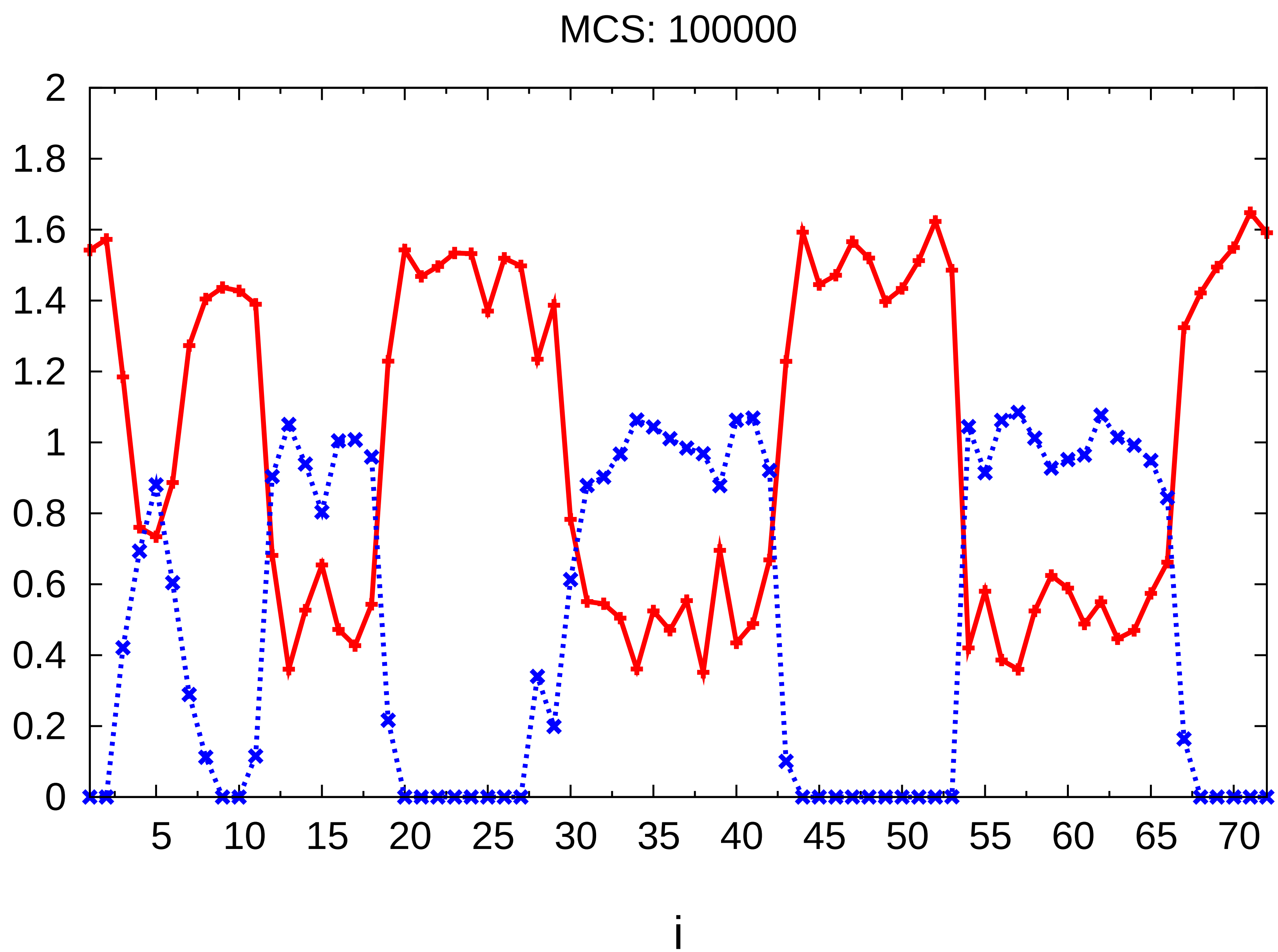

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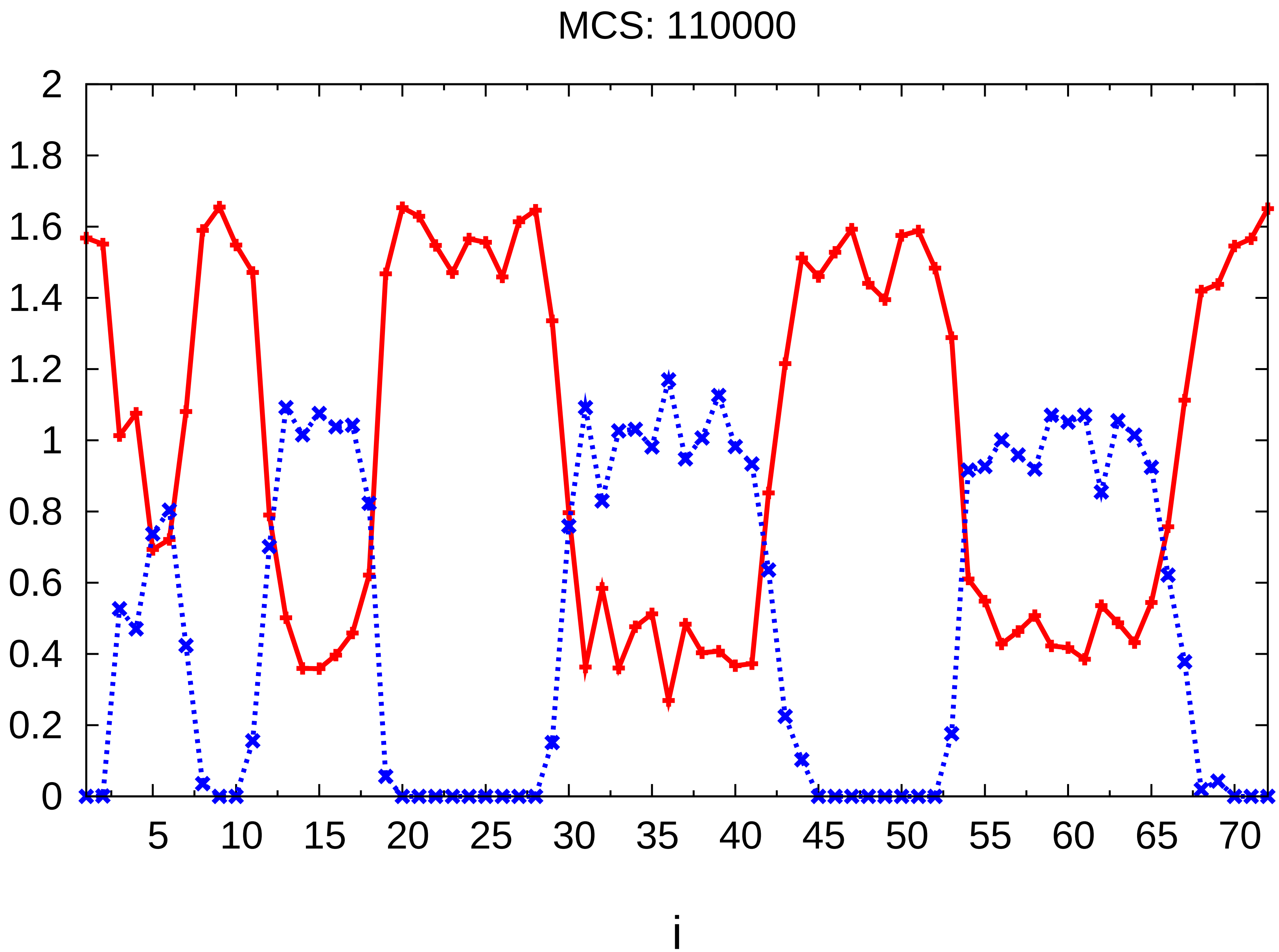

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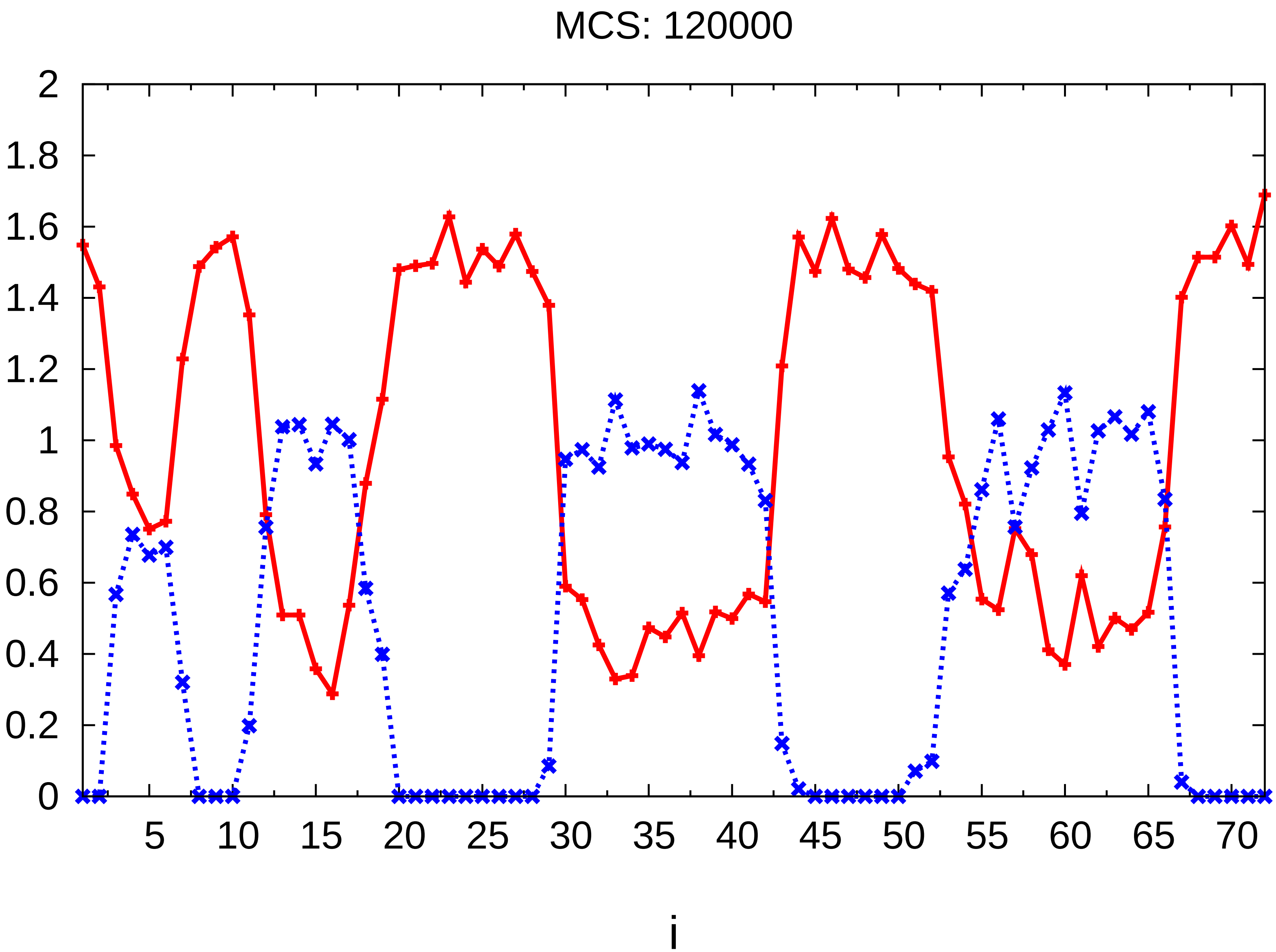

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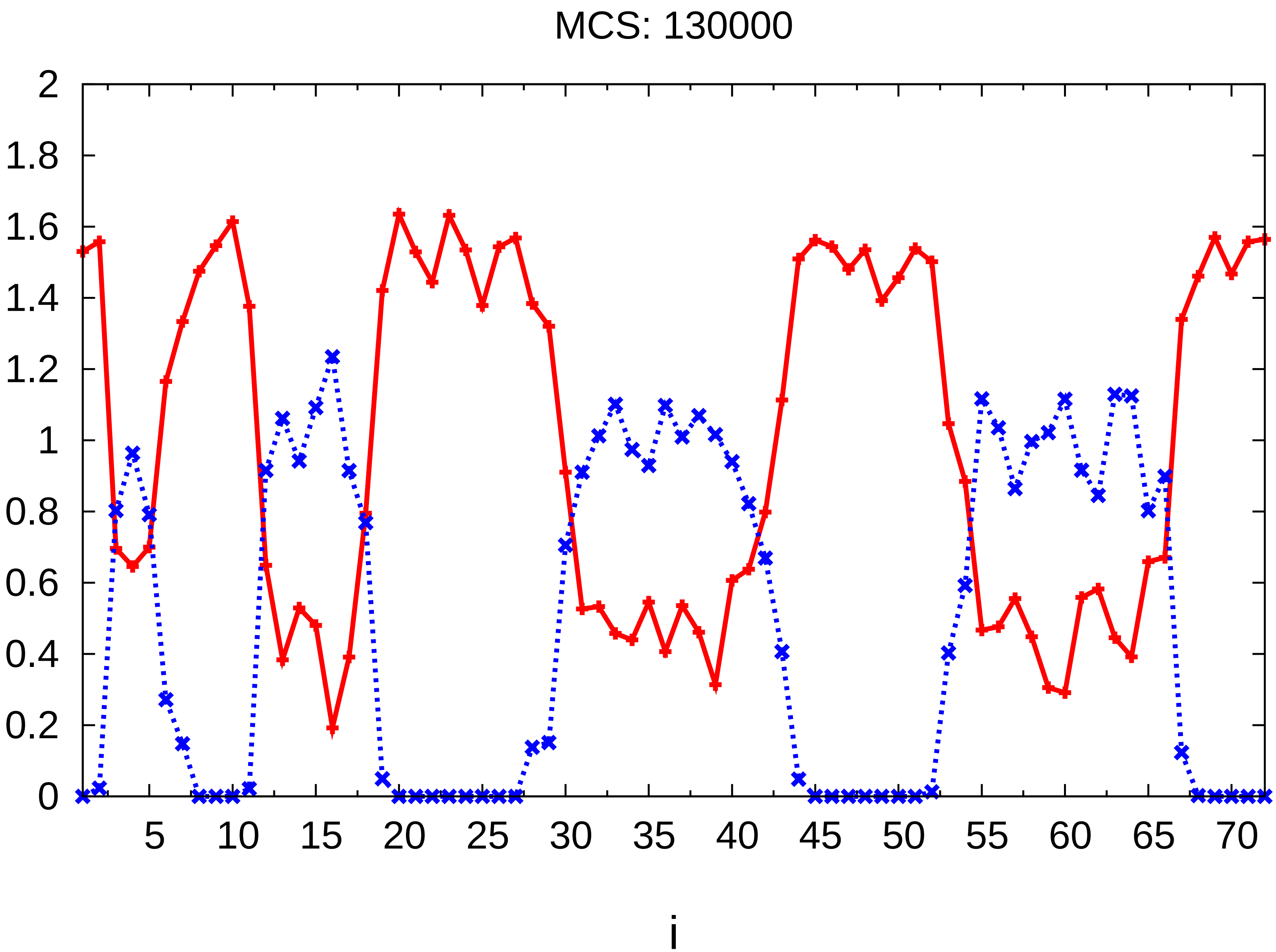

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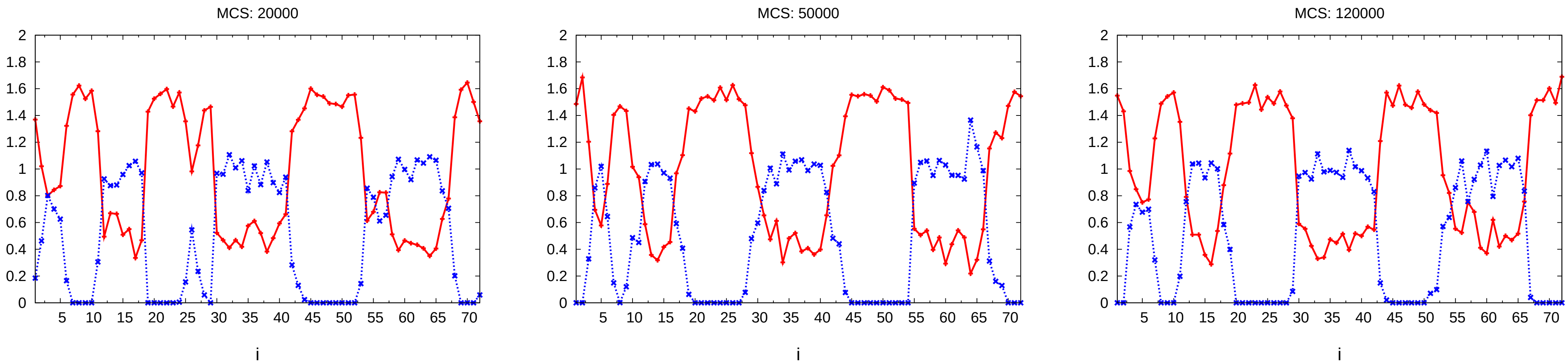

Superfluidity of a fraction of a bosons along with persistent glassiness of b bosons and the rest of a bosons

SUPERGLASS

cfr. supercooled ^{4}He: M. Boninsegni, N. Prokof'ev, and B. Svistunov, Phys. Rev. Lett. 96, 105301 (2006)

Optical lattices enter the *glass arena*

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  [see also C. Menotti et al., Phys. Rev. Lett. 98, 235301 (2007)]

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- Optical lattices have a unique advantage

  TIME SCALES FOR RELAXATION CAN BE TUNED!

Thanks to...

Birger Horstmann

Ignacio Cirac

and, for important discussions, to

Stephan Dürr, Thomas Volz, Niels Syassen, Dominik Bauer, and Gerhard Rempe @ MPQ;

B. Horstmann, J. I. Cirac, and TR, arXiv:0706.0823
TR and J. I. Cirac, Phys. Rev. Lett. **98**, 190402 (2007)

Quantum emulsion in a trap

Bose Mixture, $N_a = N_b = 25$, $U_a = 2J_a$, $U_b = U_{ab} = 5J_a$, $J_b = 0.2J_a$, $V_T = 0.01J_a$, $\beta J_a = 24$, $L = 65$