# A model of random center vortex lines in continuous 2+1 dimensional space-time

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in cooperation with

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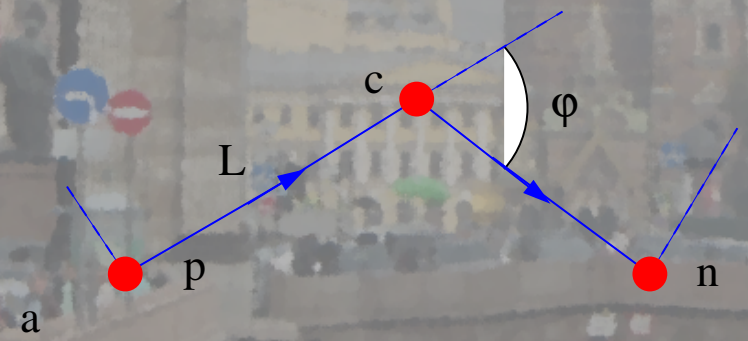
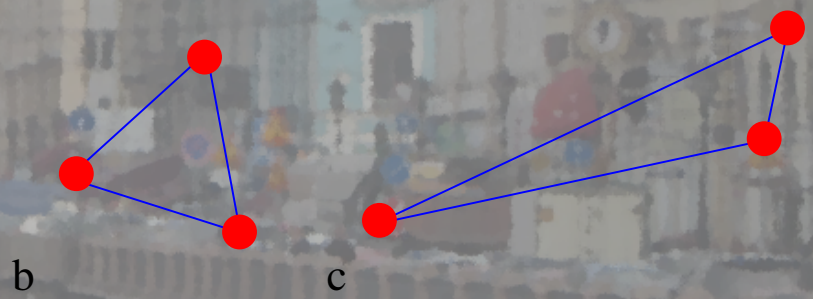
# Center Vortices

- QCD vacuum is a condensate of closed magnetic flux-lines, they have topology of tubes (3D) or surfaces (4D),
- magnetic flux corresponds to the center of the group,
- Vortex model explains...
  - **Confinement** $\rightarrow$ piercing of Wilson loop $\equiv$ crossing of static electric flux tube and moving closed magnetic flux
  - **Topological charge**: intersection points, writhing points and color structure
  - **Spontaneous chiral symmetry breaking**: also center-projected configurations show $\chi$SB, topological lumps attract Dirac zero modes and create finite chiral condensate from near-zero modes

# Random Vortex Line Model

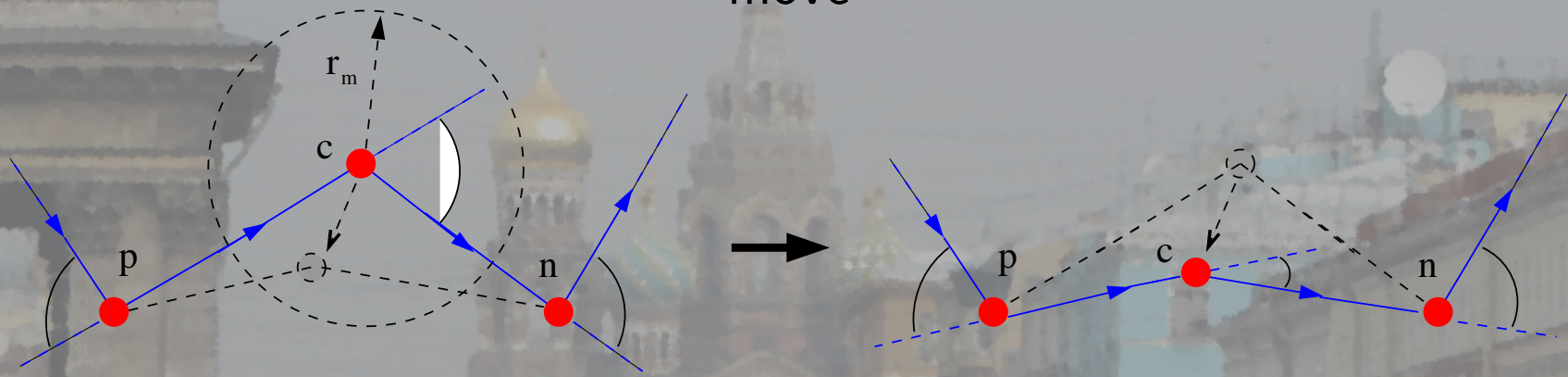
- closed random lines in continuous 3D space-time
- piece-wise linear vortices of varying lengths
- random start config and Monte Carlo updates
- Metropolis action $S = \alpha L + \gamma \varphi^2$



# Monte Carlo Updates I

move




add

# Monte Carlo Updates II

delete


recombination

# Parameters

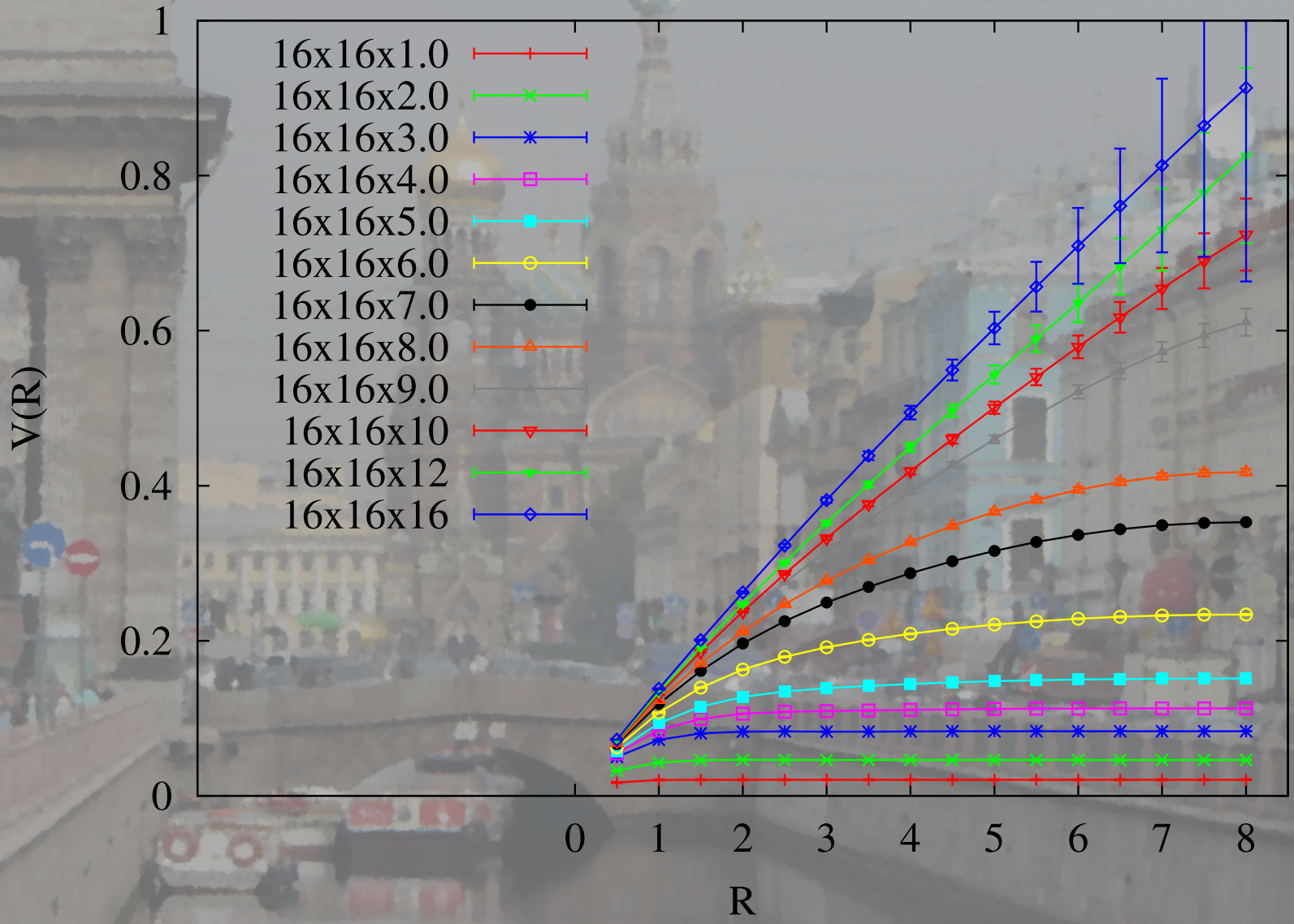
- vortex length action parameter $\alpha = 0.11$
  action $S = \alpha L + \gamma\psi^2$, vortex length $L$
- vortex angle action parameter $\gamma = 0.33$
- maximal vortex length $L_{max} = 1.7$
- minimal vortex length $L_{min} = 0.3$
  - maximal radius of the move update $r_m = 4L_{min}$
  - maximal radius of the add update $r_a = 3L_{min}$
  - reconnection length $r_r = L_{min}$
- recombination angle $\epsilon = 5°$
  maximal angle $\epsilon$ between recombining vortex lines
- vortex density cutoff $d = 8$, number of nodes in a $3 \times 3 \times 3$ volume

# Monte Carlo Algorithm

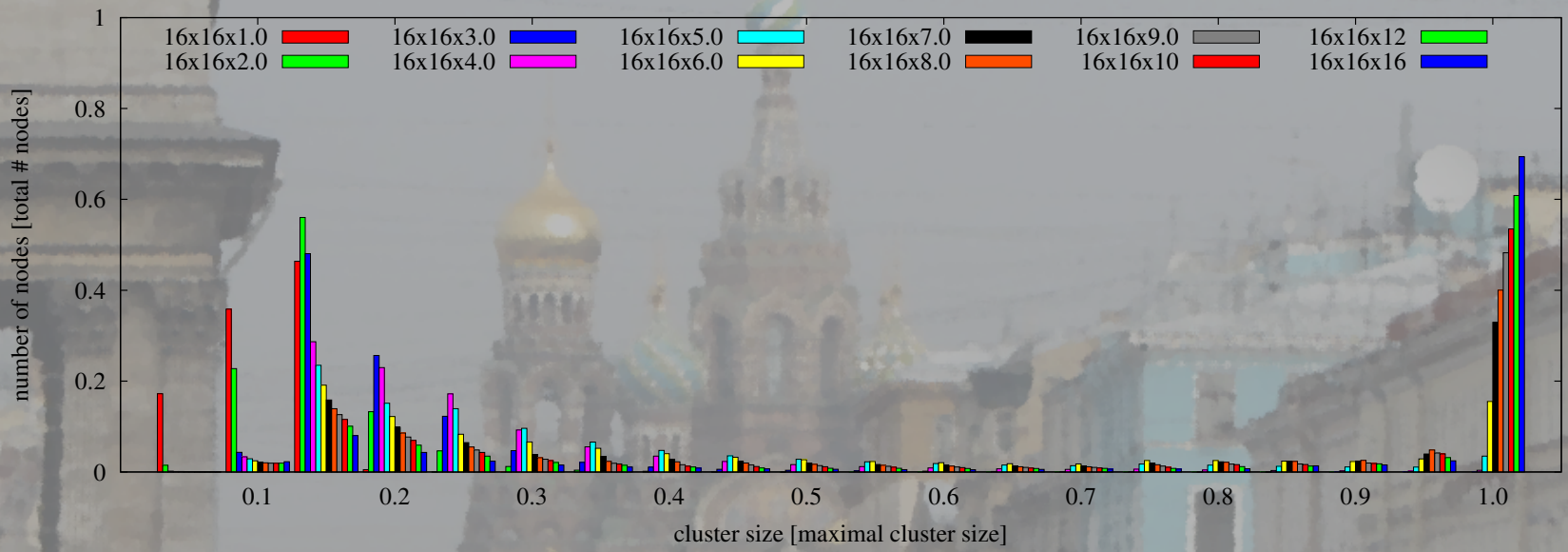
$n_r = n_w + n_m * n_s$ runs, with $n_w = 10^4$ warm-ups, $n_m = 2 - 5 \times 10^5$ measurements and $n_s = 10$ sweeps between the measurements.

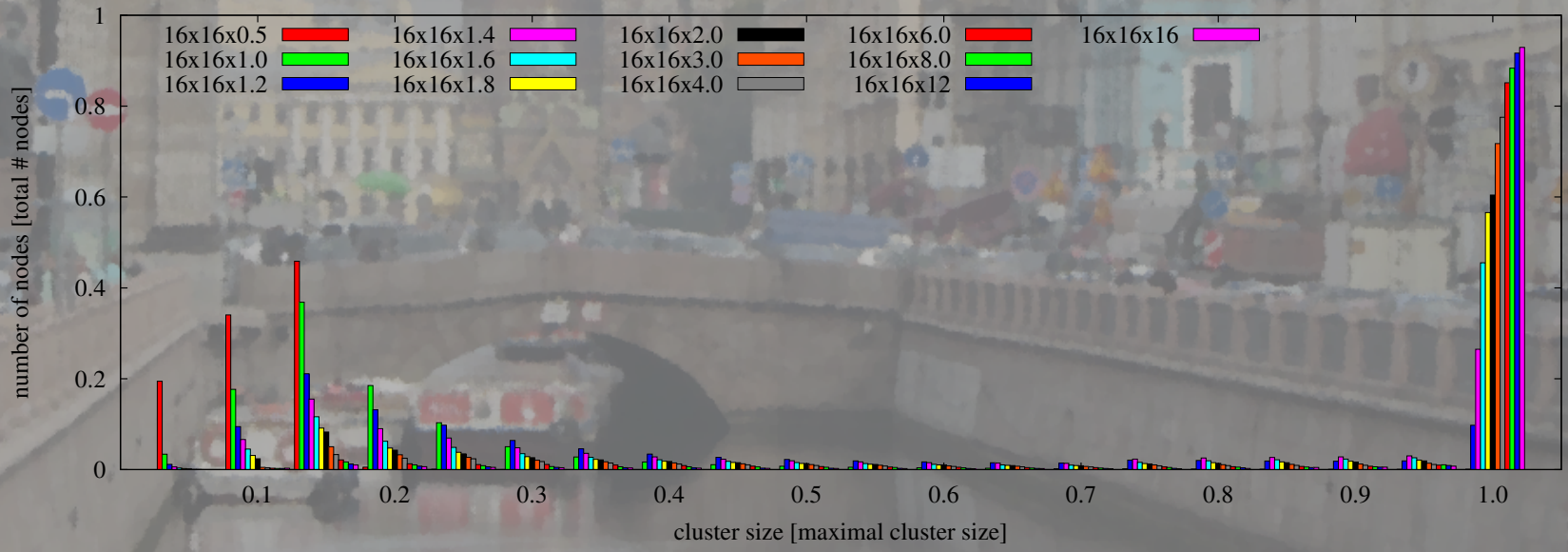
- The Metropolis algorithm for one 3-node cluster pop-up is called before the node updates, therefore the new nodes will also be updated and do not directly influence the measurement.
- Monte Carlo sweep over all nodes in the configuration:
  - Metropolis move, add and delete updates are applied to the node with rates $66\%, 28\%$ and $6\%$.
  - If the node is not deleted possible reconnections will be considered.
- After $n_w = 10^4$ warm-up iterations, $n_m = 2 - 5 \times 10^5$ measurements will be performed, separated by $n_s = 10$ sweeps.

# FT phase transition - Quark Potentials

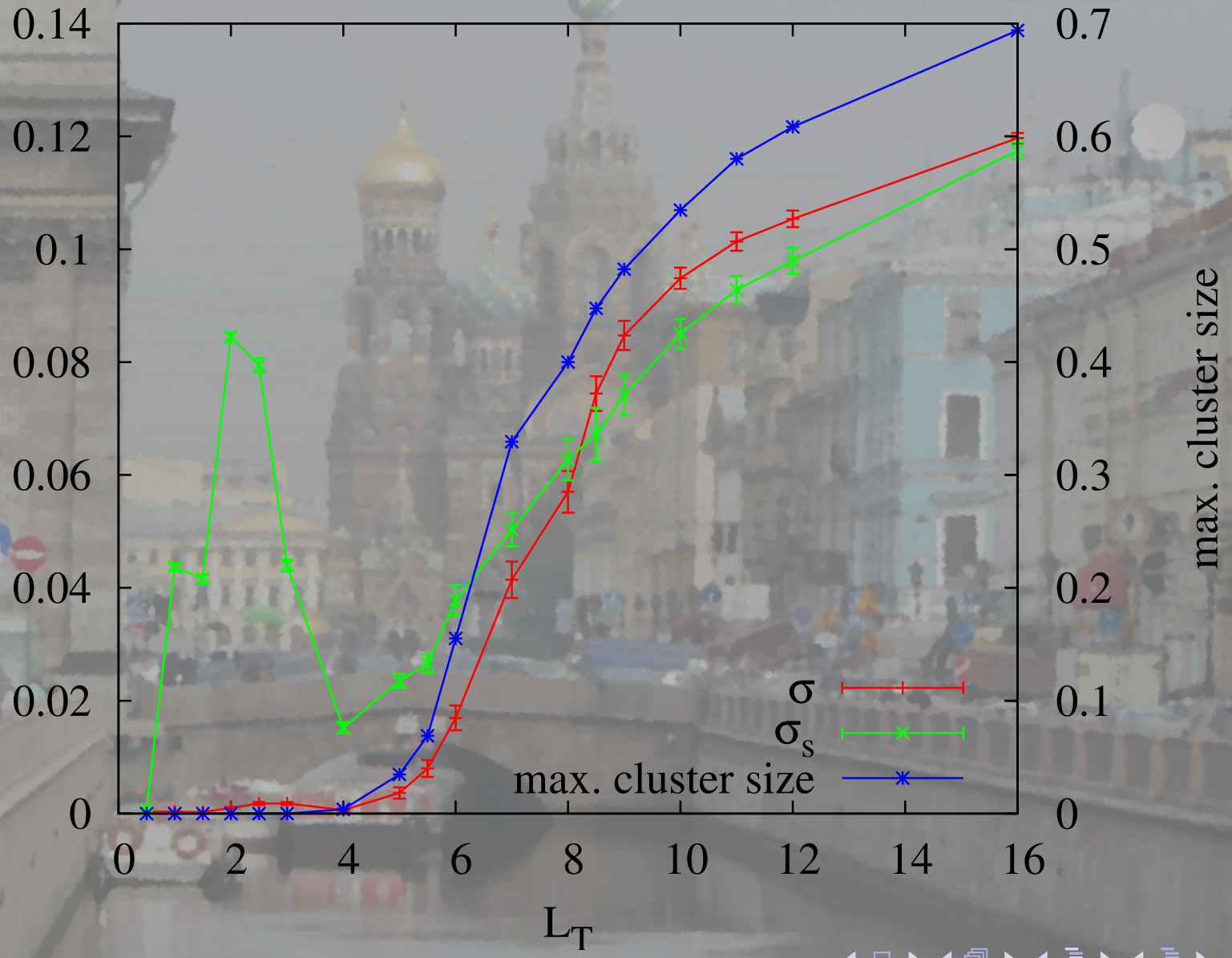


# FT phase transition - Cluster Histogram

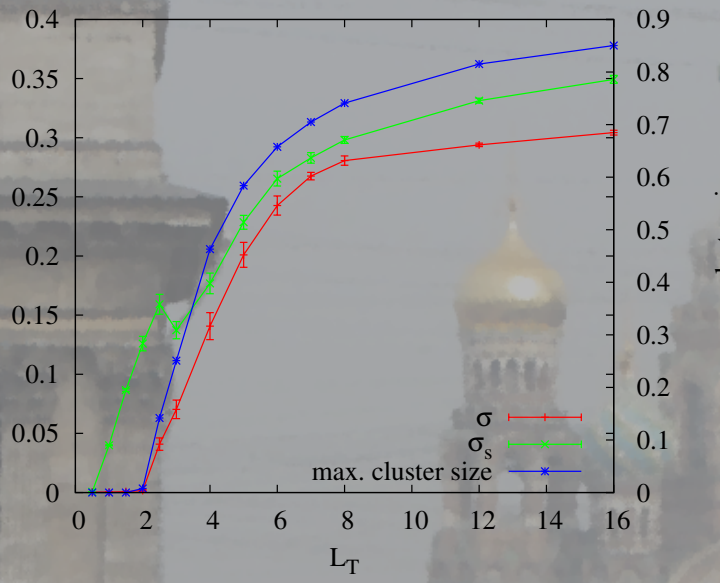


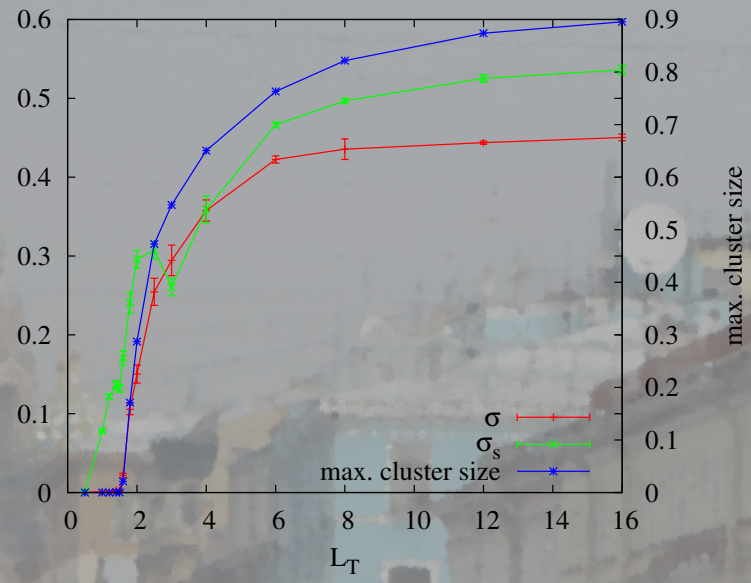



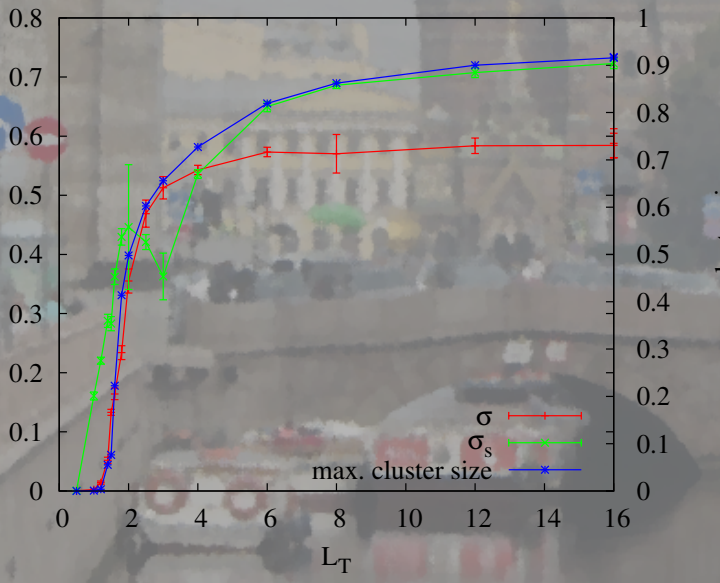
# FT phase transition - String Tensions

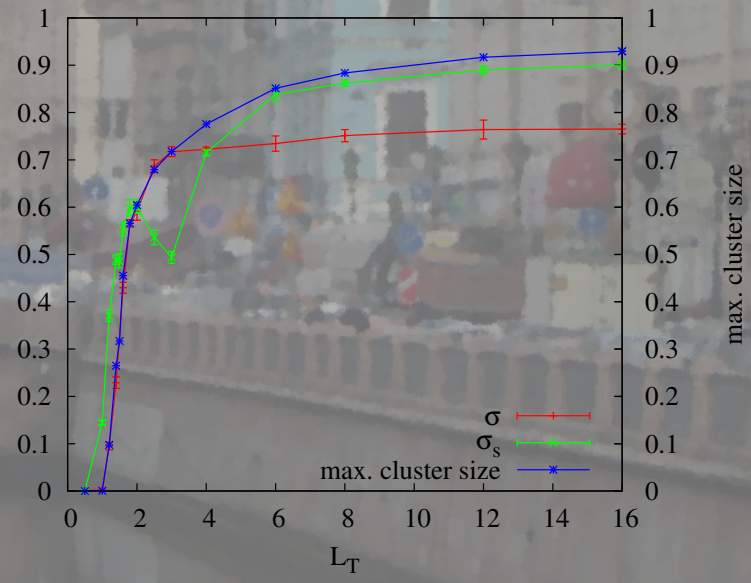


# FT phase transition - String Tensions

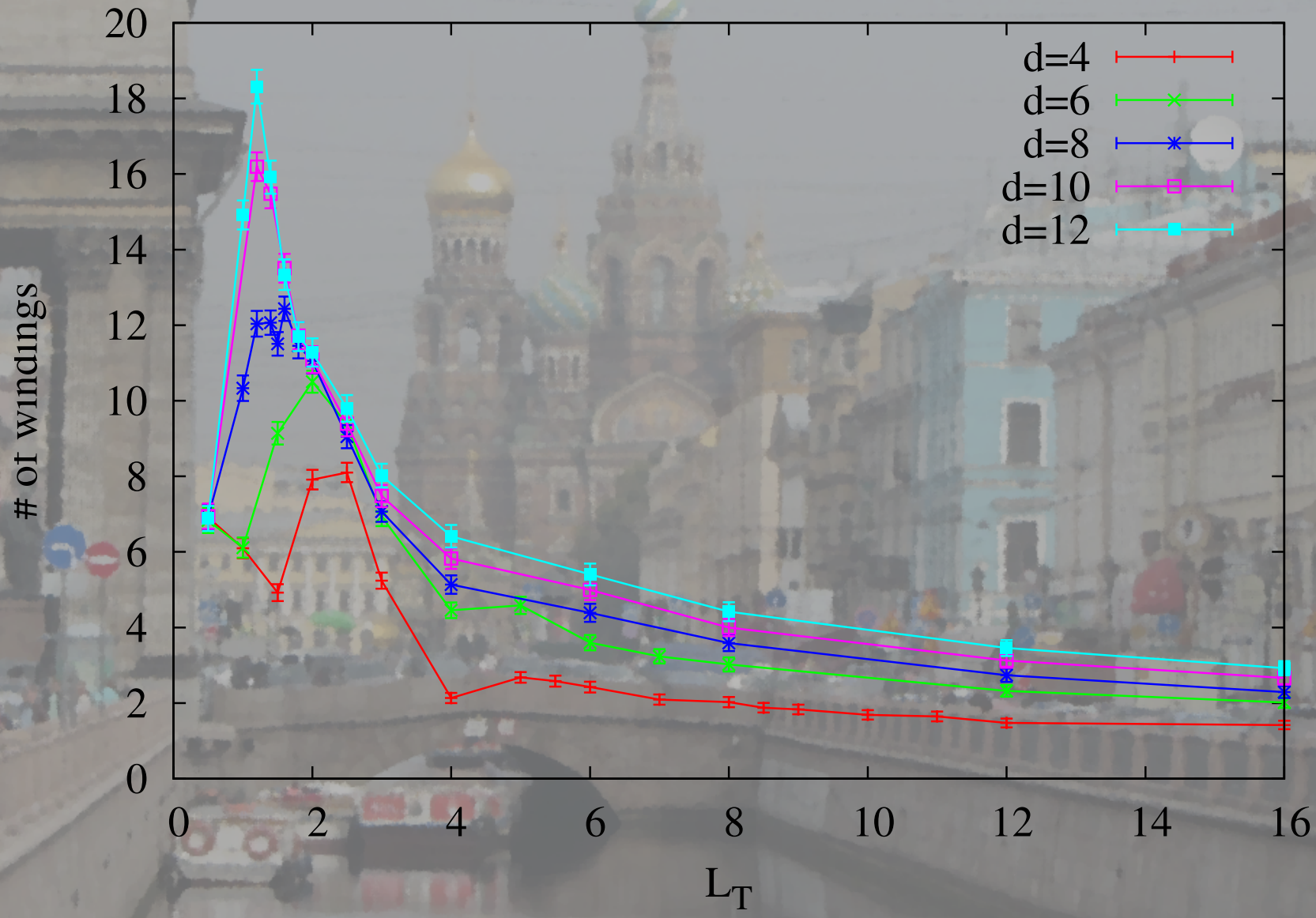


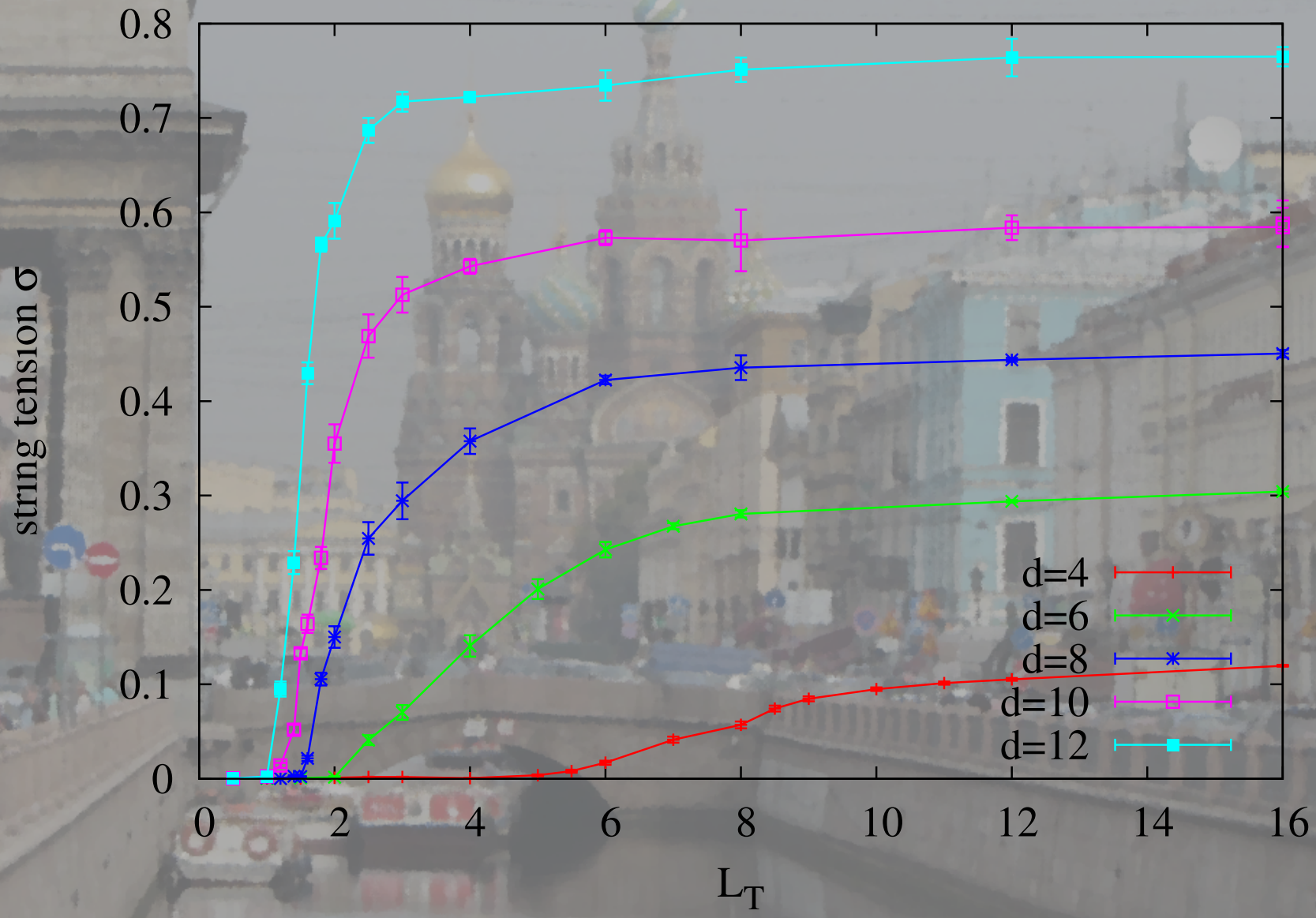



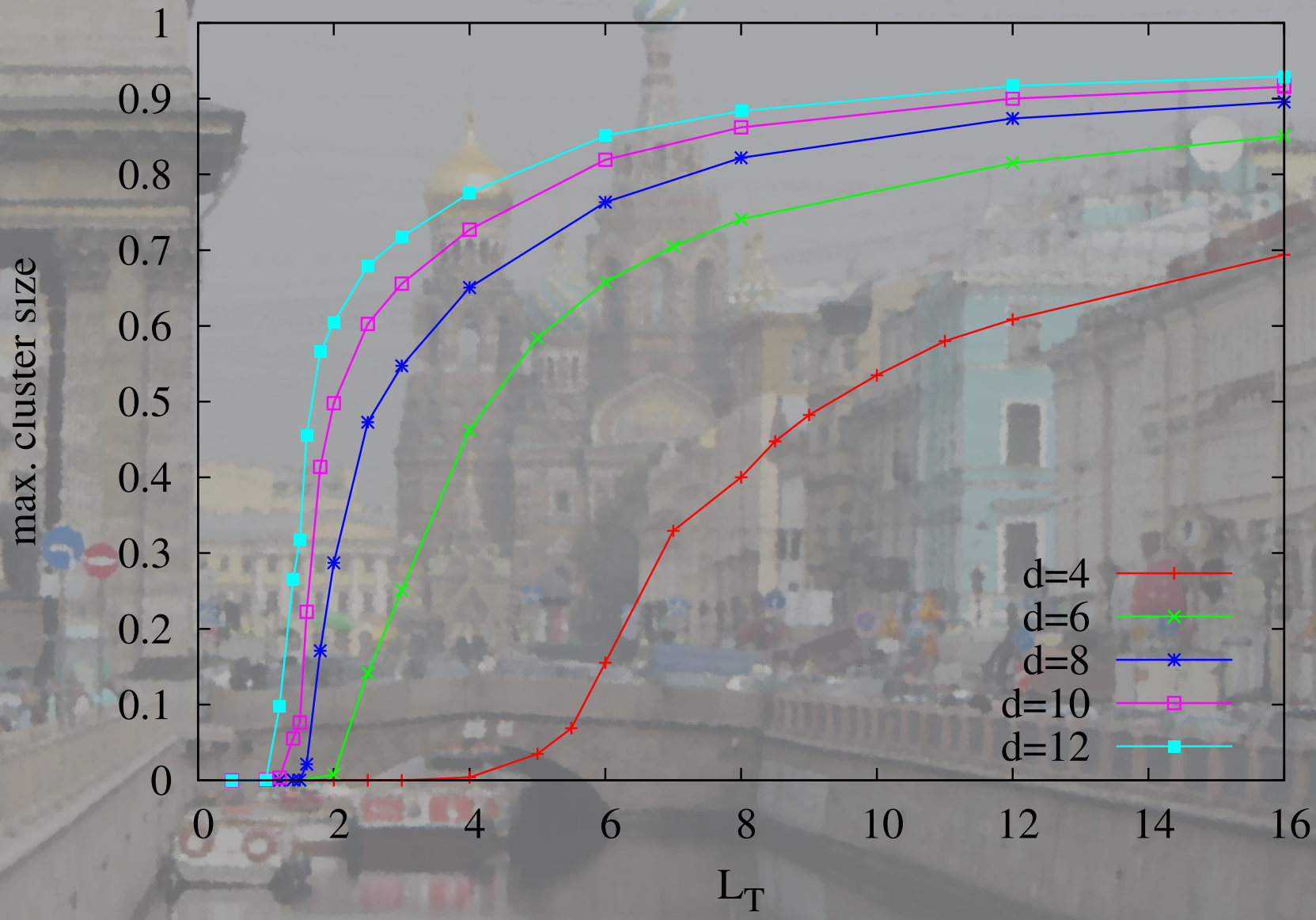
# FT phase transition - Temporal Windings



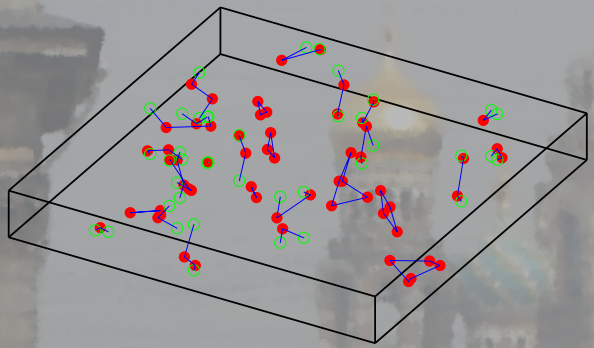
# FT phase transition - String Tensions

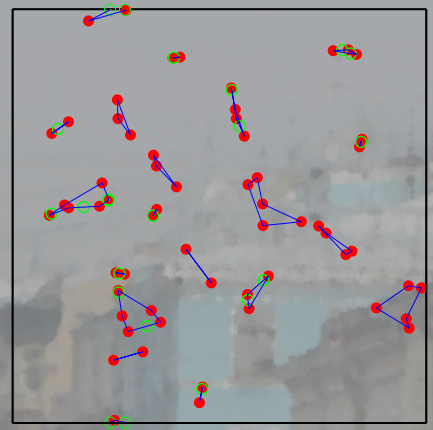


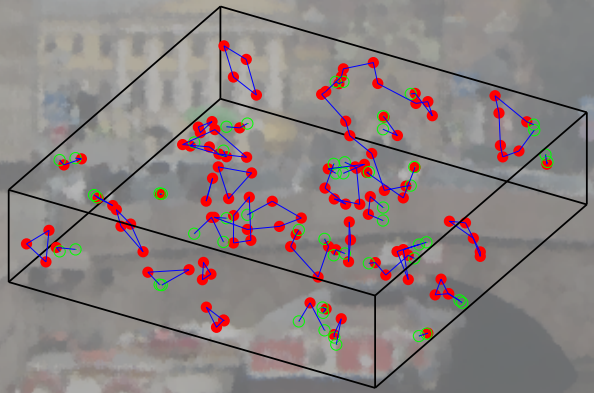
# FT phase transition - Cluster Histograms

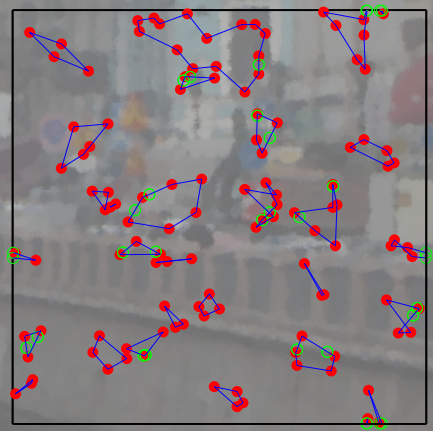


# FT transition - Configs I

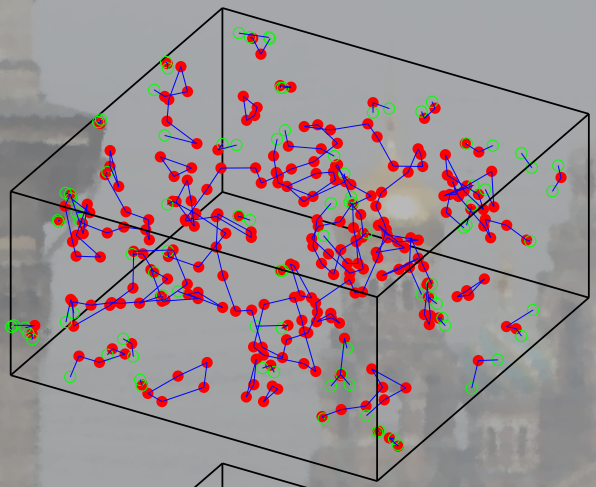


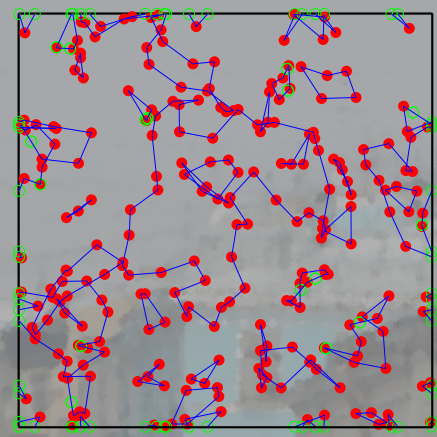


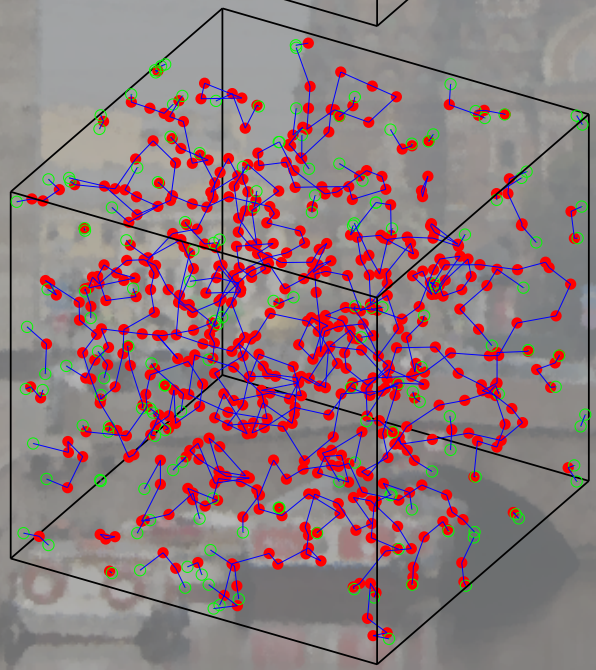


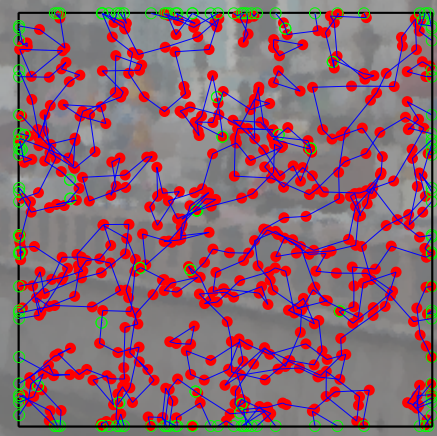


# FT phase transition - Configs II

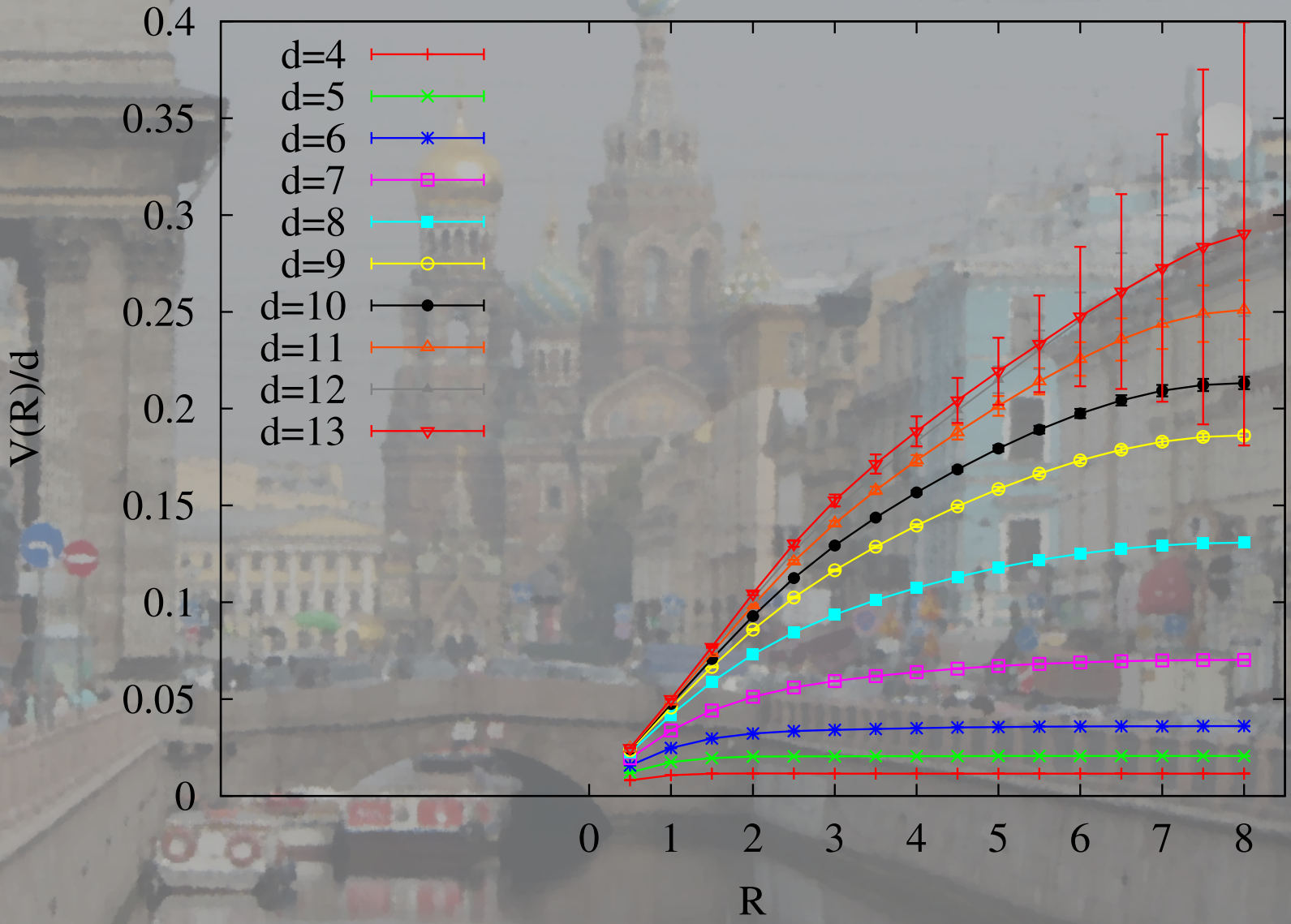




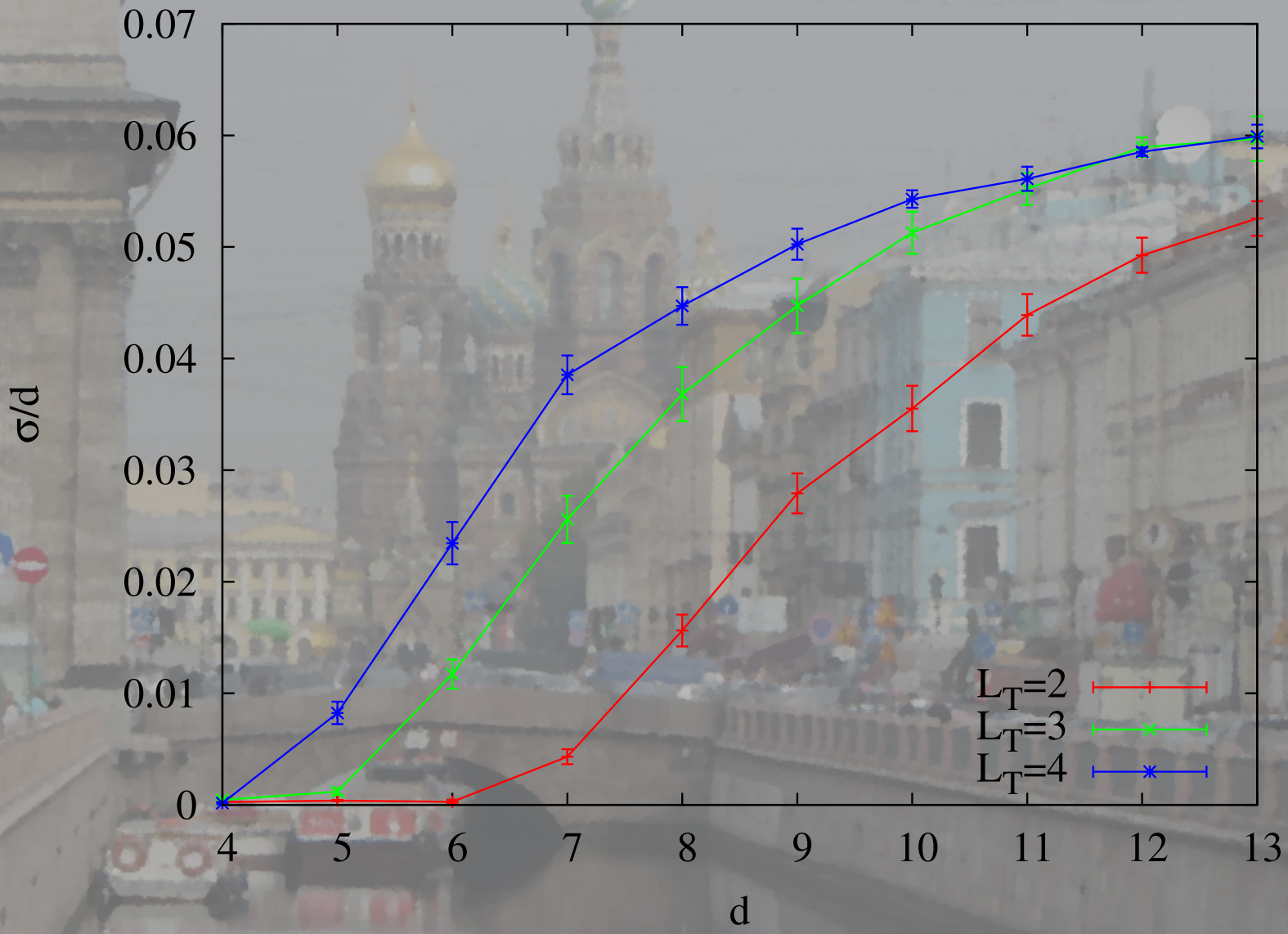




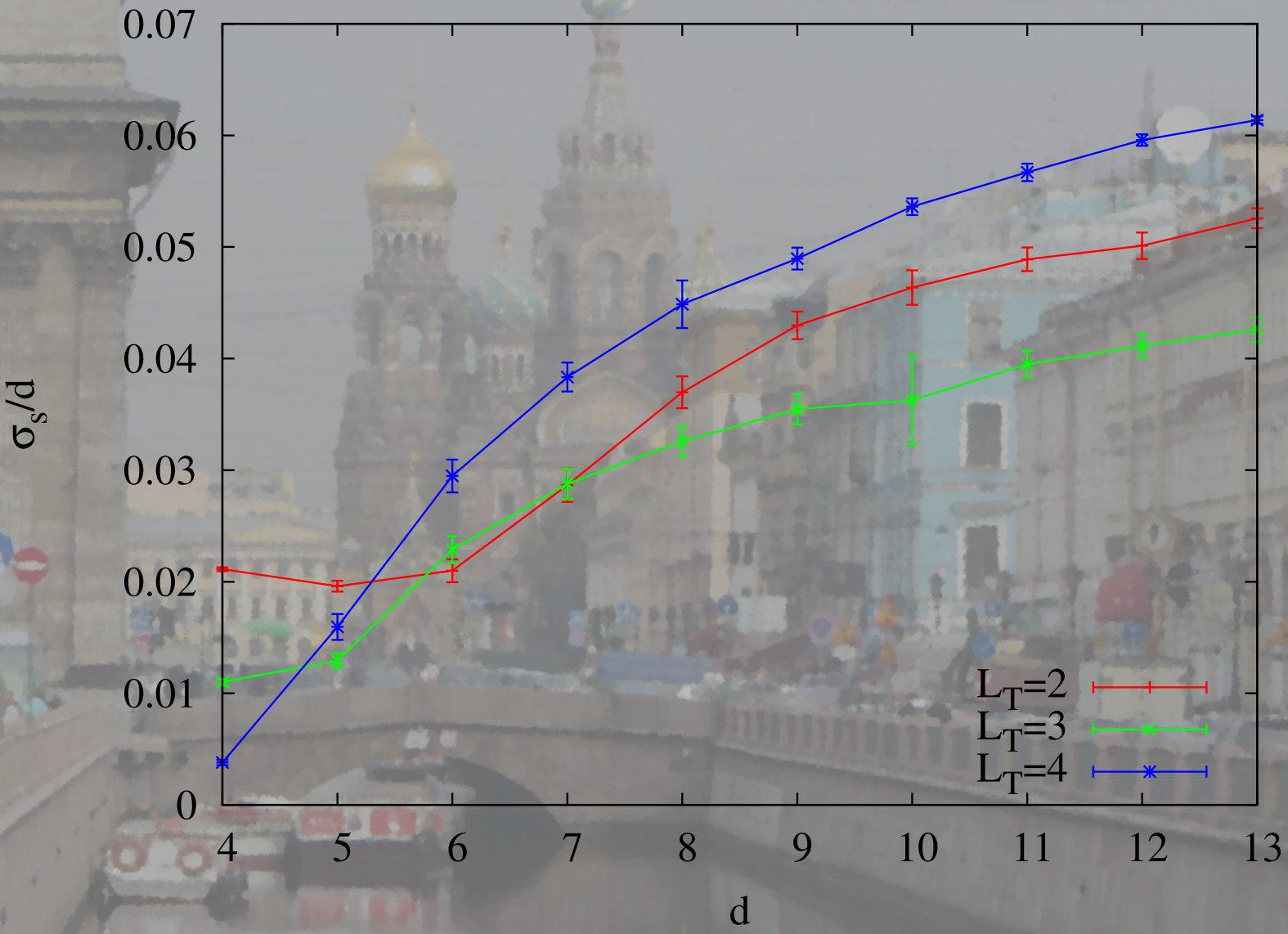
# Phase transition from vortex density cutoff



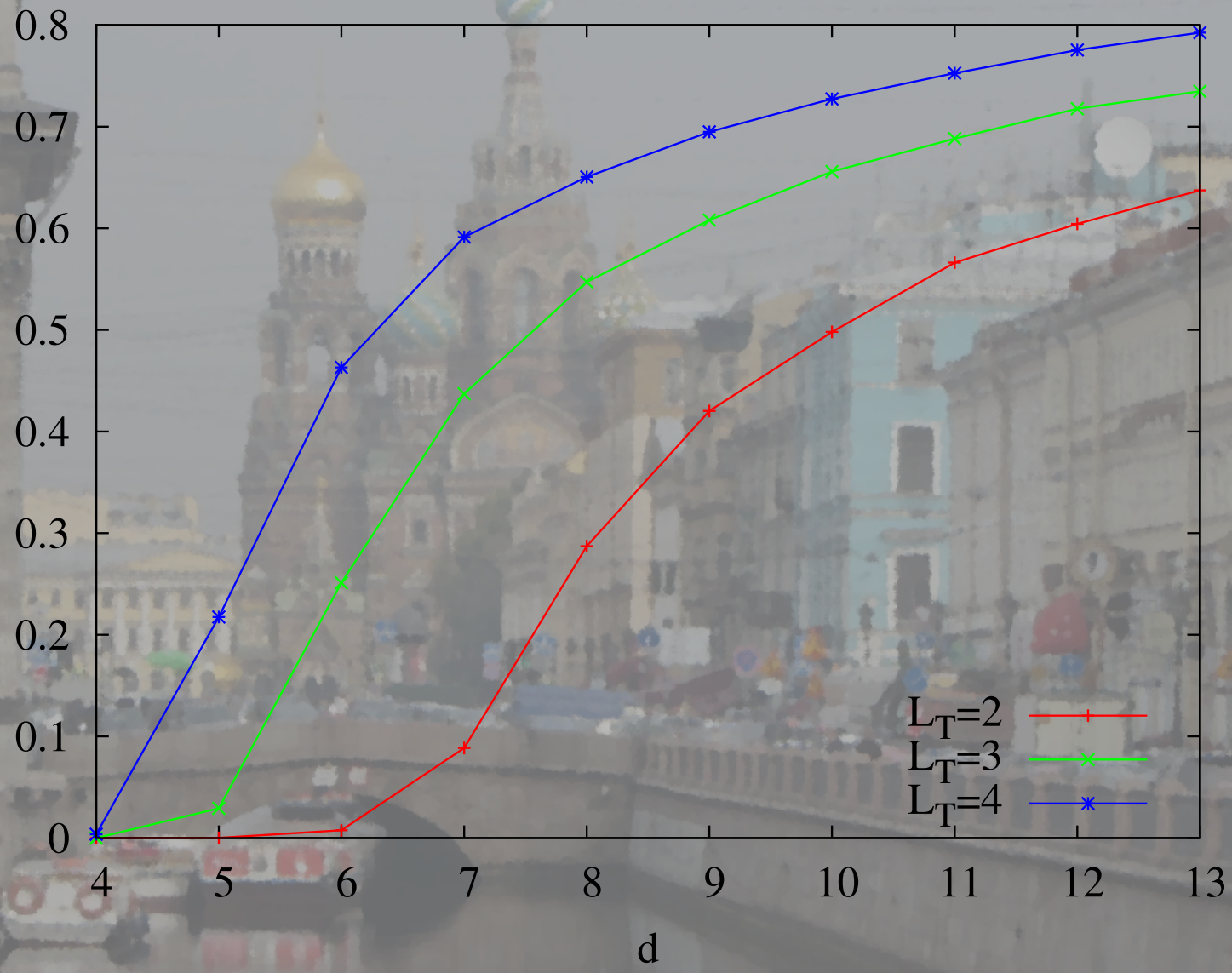
# String Tension



# Spatial String Tension

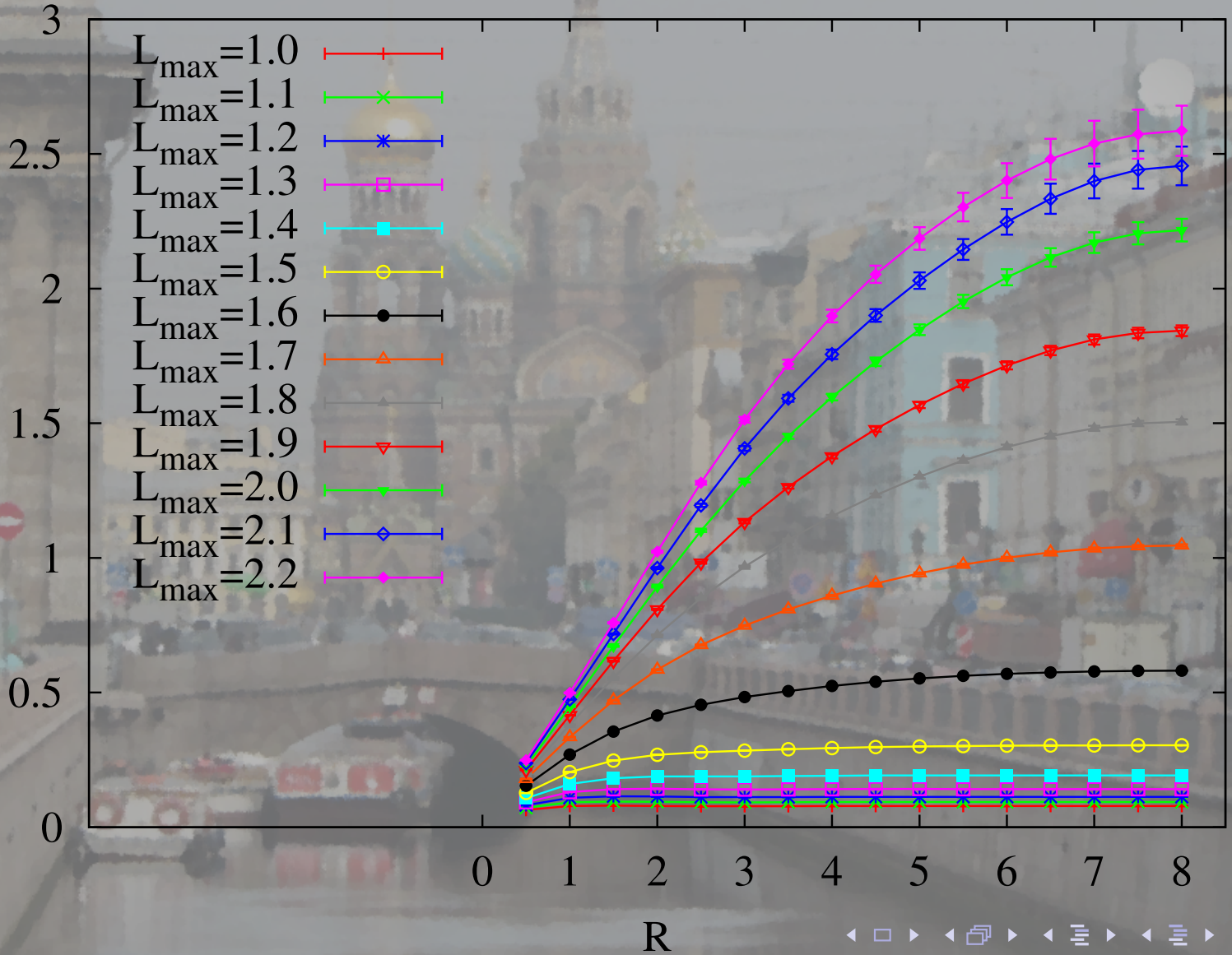


# Maximal Cluster Size

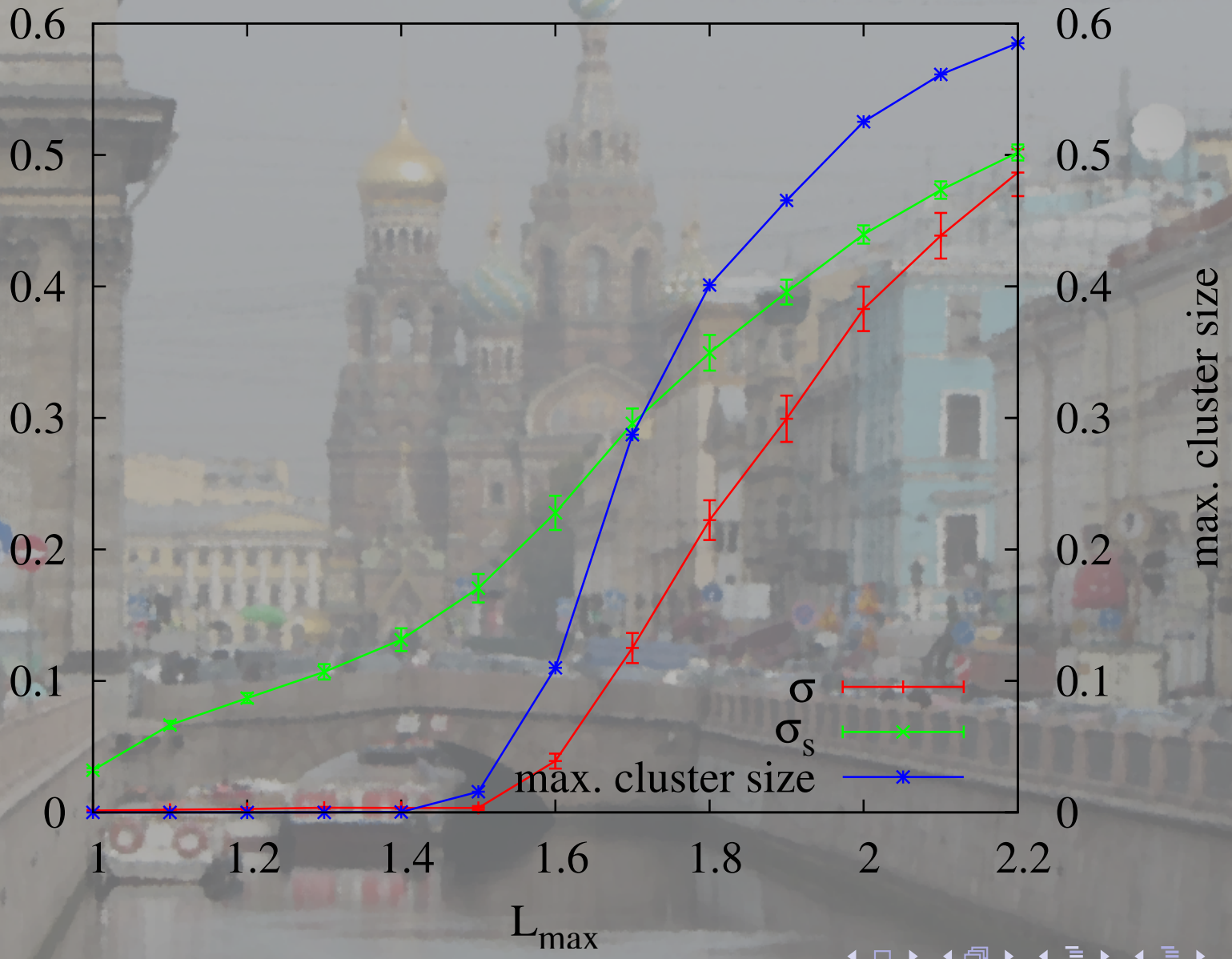


# Phase transition from maximal vortex length

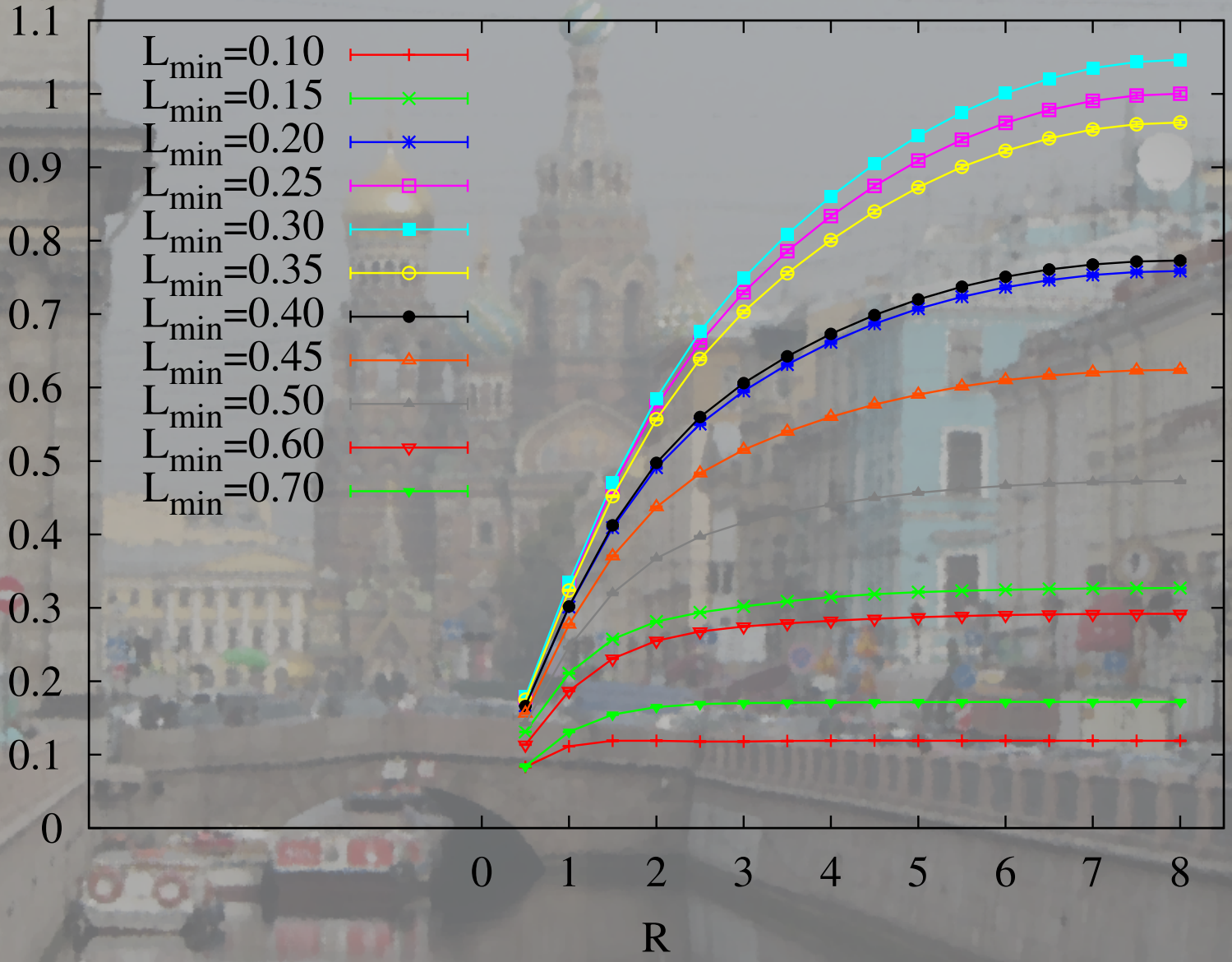
$L_{max}$



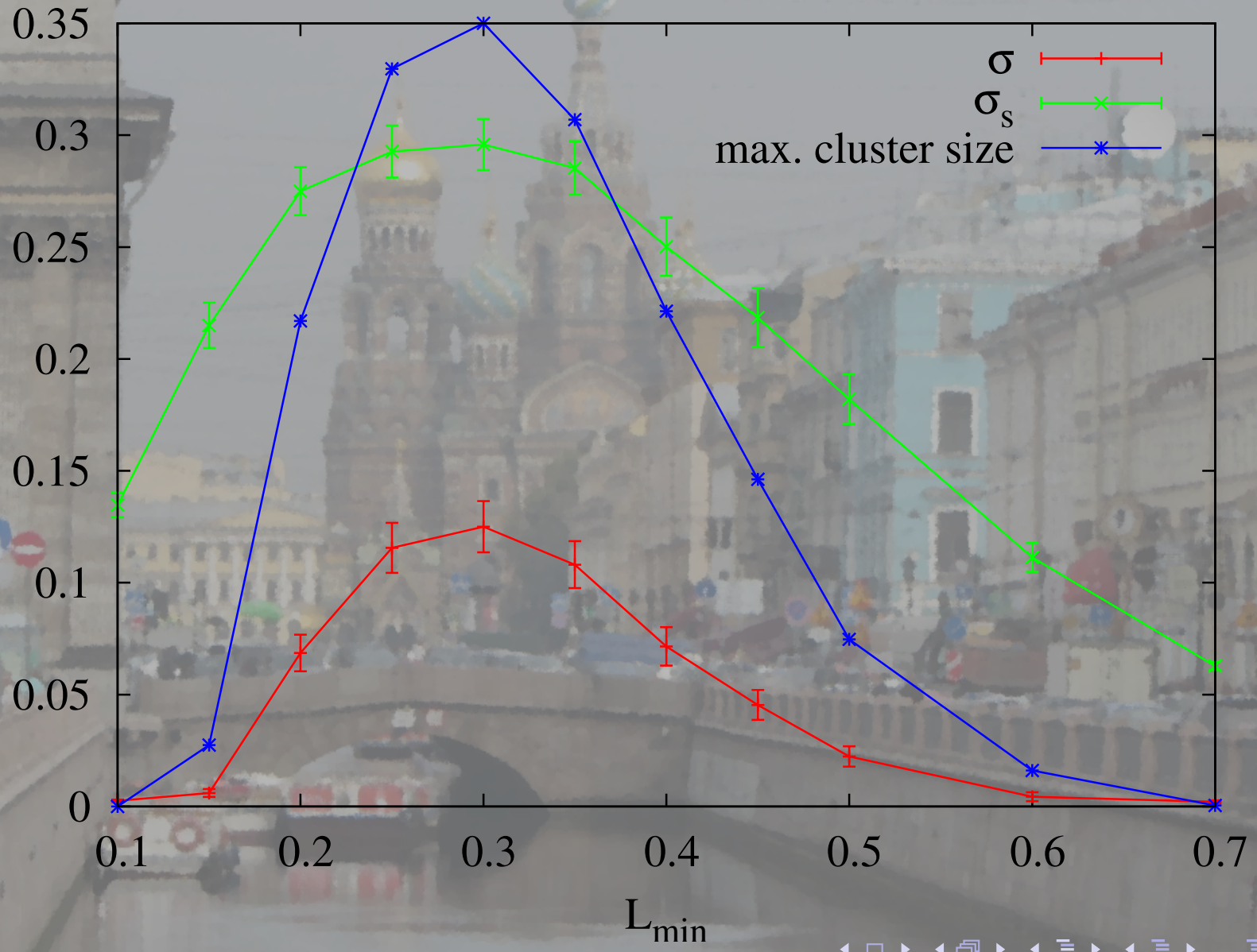
# String Tension and Maximal Cluster Size



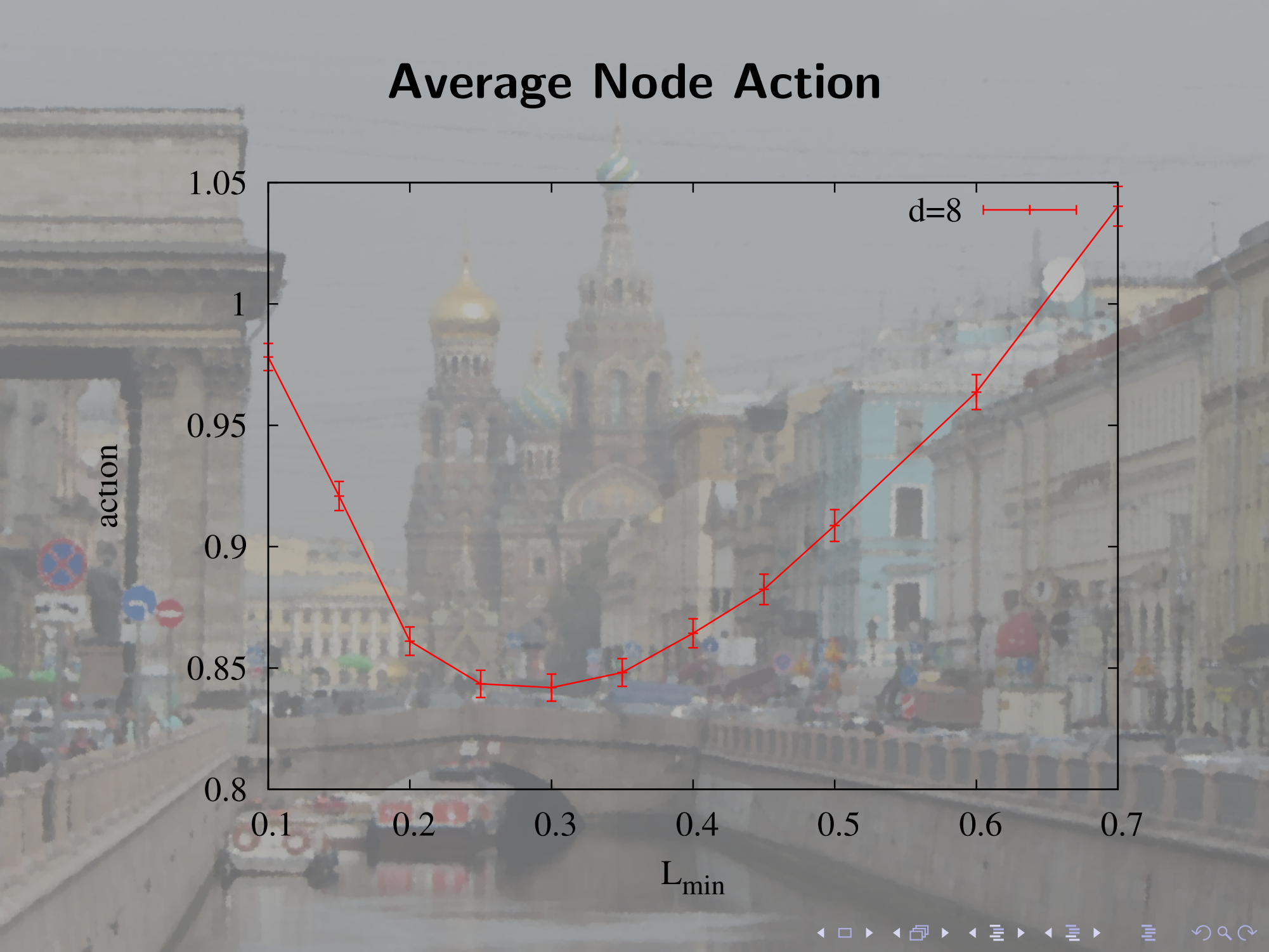
# Minimal vortex/reconnection length $L_{min}$



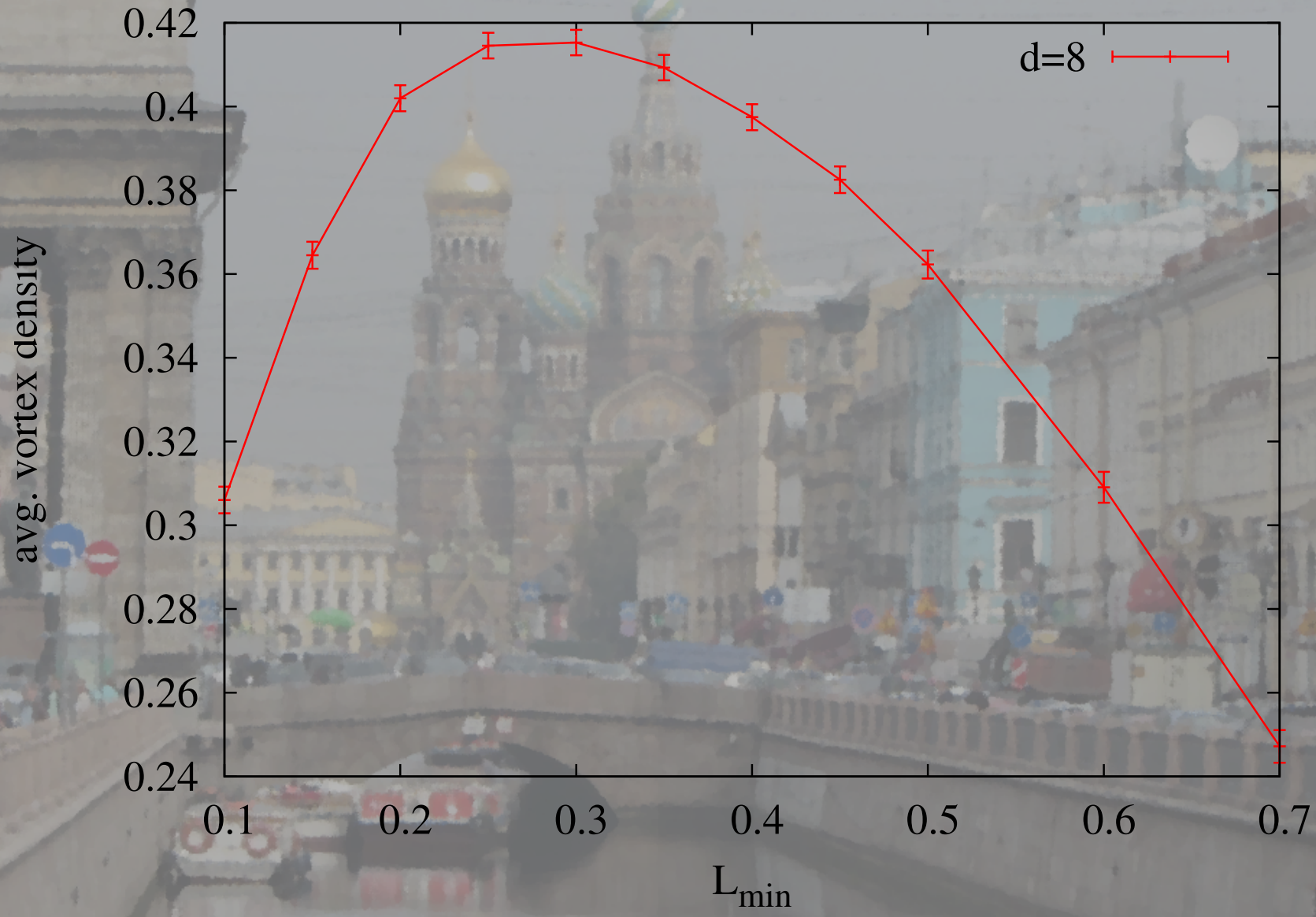
# String Tension and Maximal Cluster Size



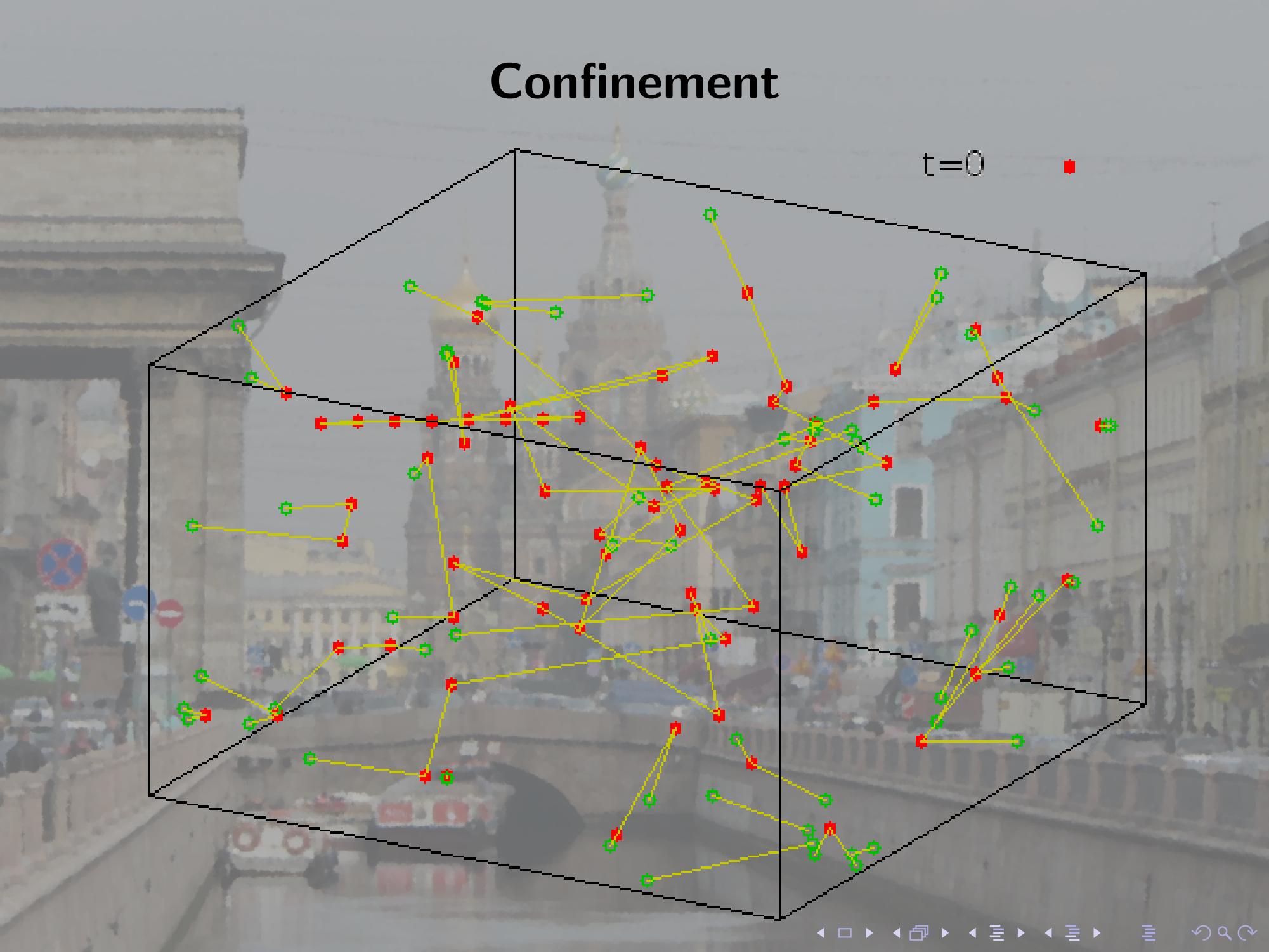
# Average Node Action



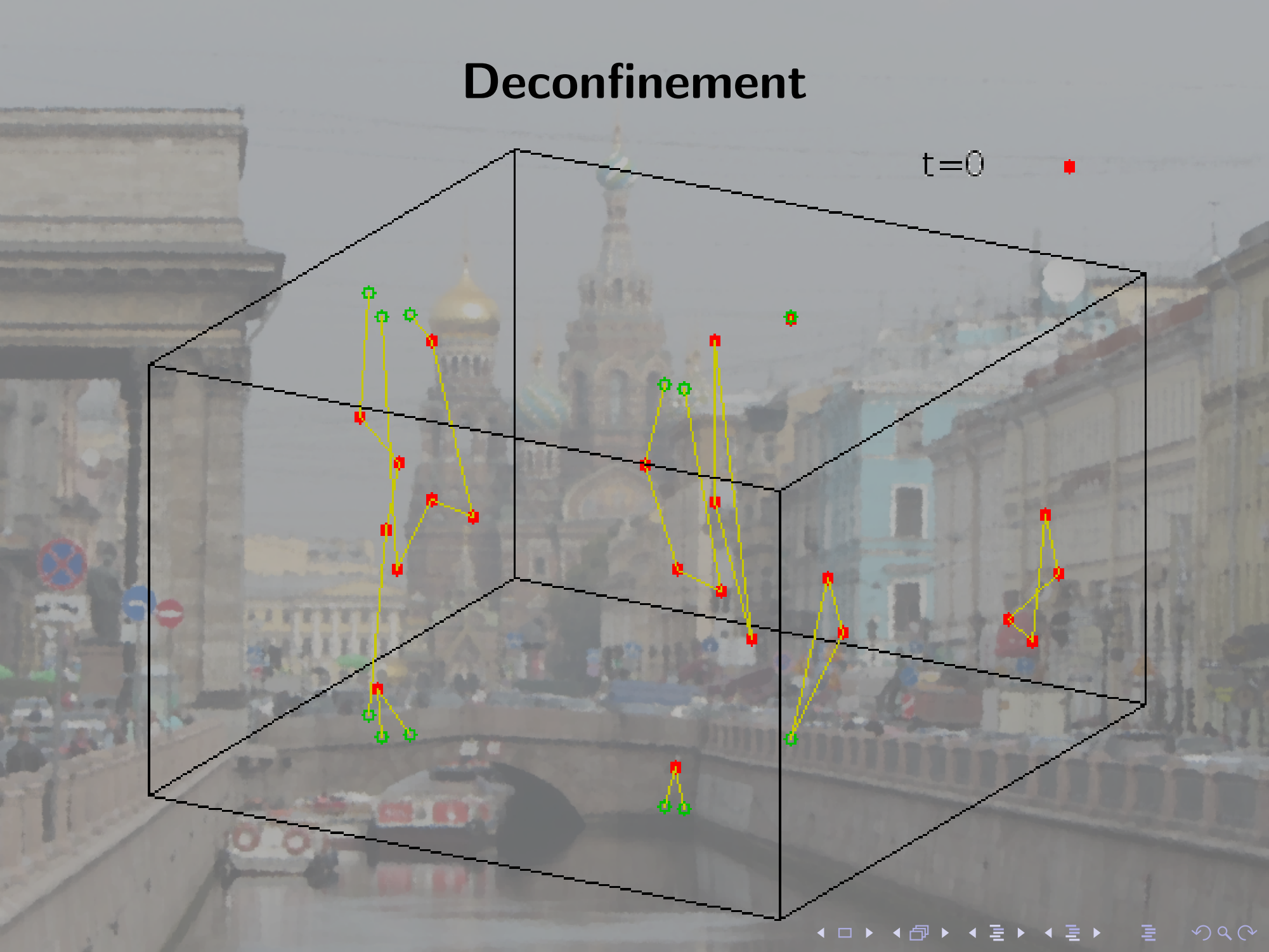
# Average Vortex Density



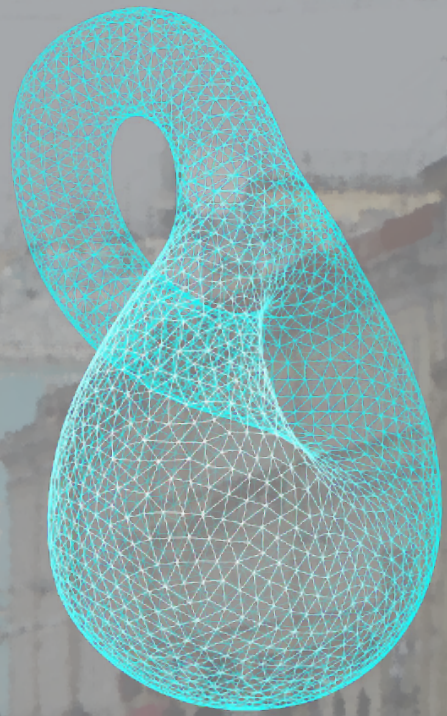
# Confinement



# Deconfinement



# Conclusions & Outlook



- Simple 3D Vortex Line Model of Confinement
- Finite Temperature Deconfinement Phase Transition
- Further Phase Transitions from Vortex Density and Segment Lengths
- Extend the Continuous Vortex Model to 4D...
- Study Topological Charge without Lattice Ambiguities

# Thank you for your attention!

# Questions?