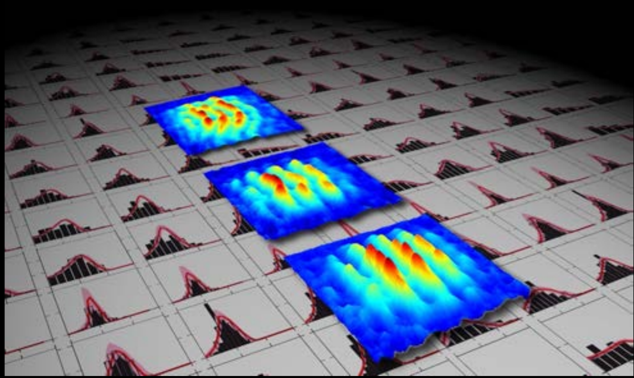
Quantum Simulation

an introduction



Jörg Schmiedmayer
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Outline

Lecture 1: Introduction

- Simulating physics with computers -> Quantum simulation
- Basic concepts

Lecture 2: Examples

- Analog quantum simulation
- Digital quantum simulation

Lecture 3: Simulating quantum fields in the lab

- Relativisitc quantum fields
- Emergent Sine-Gordon quantum simulator

Outline

Lecture 3: Simulating quantum fields in the lab

- Analog quantum simulation for continouse systems
- 1d quantum liquid (Luttinger Liquid) as a model system for relativisitc quantum fields
  - Light cones
  - Prethermalization and GGE
  - Recurrences for quantum systems with 1000's of particles
- Emergent Sine-Gordon quantum simulator
  - Characterizing quantum fields by high order correlations
  - 1PI correlations: extracting the parameters of the model (propergators, vertices …)
  - Gaussification

Many Body Quantum Systems <-> QFT description

Quantum Many Body systems are an ideal staring point to build QuFT's

✧ The complexity of the many body wave function does not allow to 'observe' all the details -> We can only measure **few body observables**.

✧ Measurement on a many body system is therefor a '**coarse graining**'. Within the RG framework this leads to an **effective description** of the system that can be very different from the microscopic physics.

✧ A natural way to describe quantum many body systems is then through these **emerging effective models** (field theories)

Question: how good are these emerging quantum simulators for QuFT
When and how do they break down

A natural way to probe these models is through **correlation functions.**

Question: which QuFT do we simulate?
Can we extract the parameters for an effective field theory directly from experimental data?

Building Relativistic QuFT's
the simple minded point of view of an experimentalist

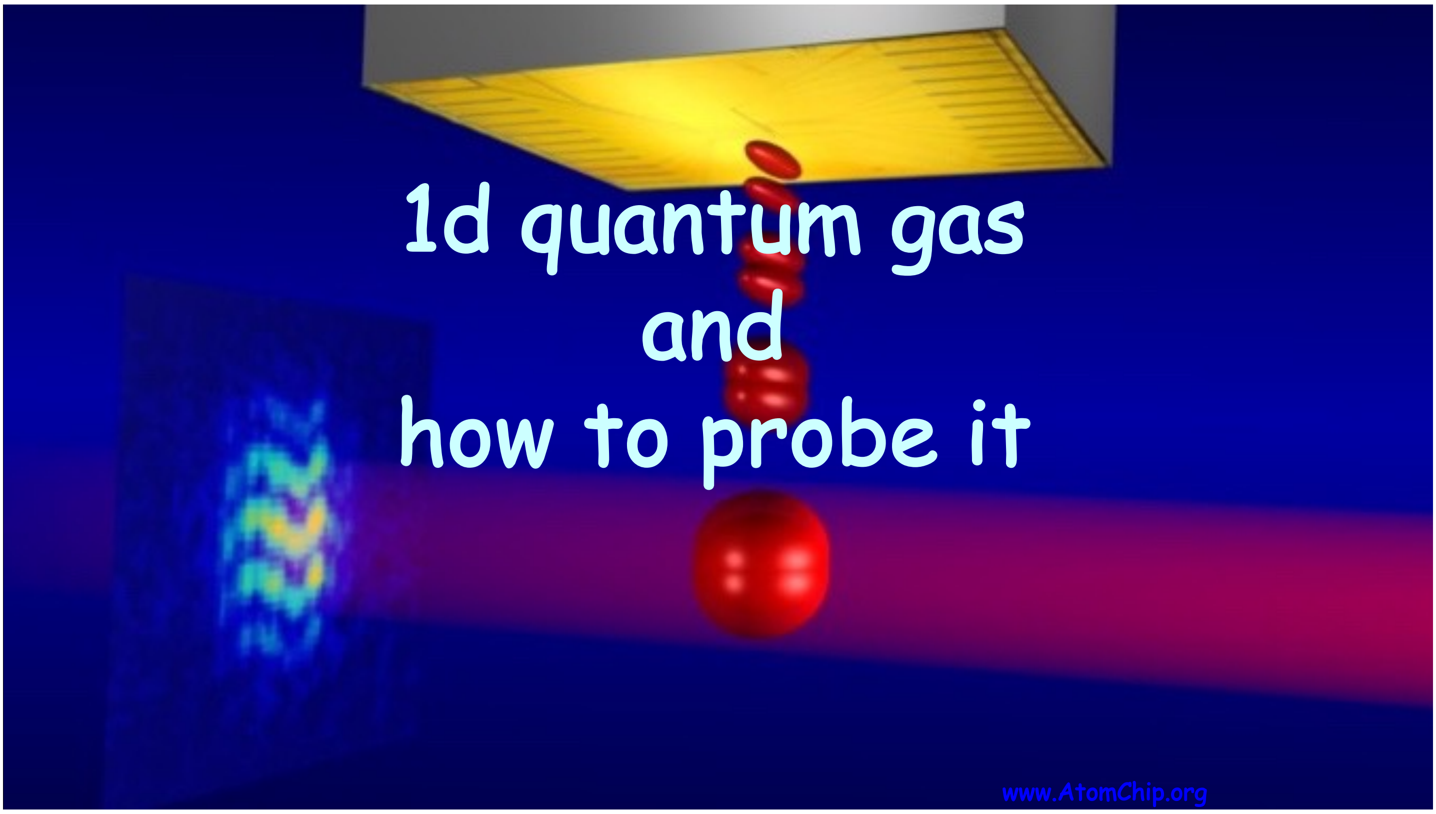
Take a quantum many body system (QuMBS) where the effective description has excitations that looks like a relativistic particle.

- Well studied model from solid state physics (Giamarchi book on 1d phys.)
- QuMBS @ zero temperature = Vacuum

Conjecture: low energy physics relates to relativistic QuFT

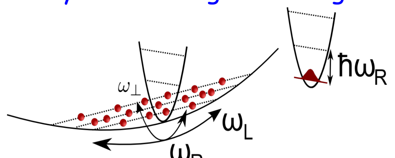
Example: Bogoliubov excitations in a quantum gas
Caveat: at very high energies the linear dispersion relation breaks down (@UV one sees the microscopic physics)

How far does the analogy with relativistic QuFT go?
- Light cones
- Lorenz transformation of temperature
- Horizons
- Unruh radiaton
- Casimir effects
- …



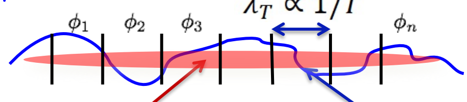
System under investigation

Weakly interacting 1d Bose gas



All energies $\mu,\ k_B T << \hbar\omega_R$

quasi-condensate



uniform density fluctuating phase

$$\hat{\psi}(x) = e^{i\hat{\phi}_1(x)}\sqrt{\rho + \hat{n}_1(x)}$$

thermally populated

Lieb-Liniger model

Exactly solvable integrable theory

low energy effective field theory:

Luttinger-liquid

$$H = \frac{c}{2}\int dx \left[\frac{K}{\pi}(\nabla\hat{\varphi})^2 + \frac{\pi}{K}\hat{n}^2\right]$$

- excitations are soundwaves (phonons)
- linear dispersion relation
  -> model for relativistic quantum fields

coupled 1d systems:

Sine-Gordon model

$$\hat{H}_{SG} = \frac{\hbar c}{2}\int_{-\mathcal{L}/2}^{\mathcal{L}/2} dz \left[\frac{\pi}{K}\hat{n}^2(z) + \frac{K}{\pi}\left(\frac{\partial}{\partial z}\hat{\theta}(z)\right)^2\right] - 2n_{1D}J\int_{-\mathcal{L}/2}^{\mathcal{L}/2} dz \cos[\sqrt{2}\,\hat{\theta}(z)]$$

Model for interacting many body systems which can be described by a field theory with long lived excitations.

The longitudinal phase fluctuations are key for our experiments

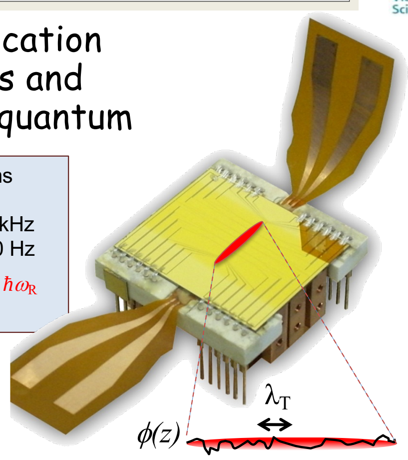
AtomChip

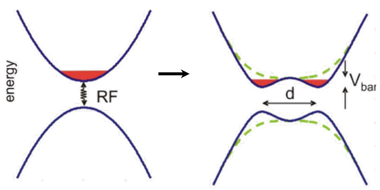
Integrated Circuits for Ultracold Quantum Matter

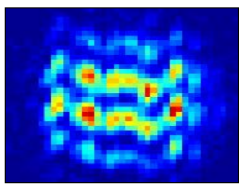
Combine the robustness of nano-fabrication an the quantum tools of atomic physics and quantum optics to build a toolbox for quantum experiments

- 1d elongated traps
- Easy to create a BEC
- Very stable and reproducible laboratory for quantum experiments
- Fast operation
- Well controlled splitting and interference

300-10000 atoms
T = 10-100 nK
$\omega_R \sim 2\pi$ x 2 - 3 kHz
$\omega_L \sim 2\pi$ x 3 - 10 Hz
$k_B T \sim 0.1 - 0.7\ \hbar\omega_R$
$k_B T \sim 0.2 - 1\ \mu$







Experimental procedure

Experiment

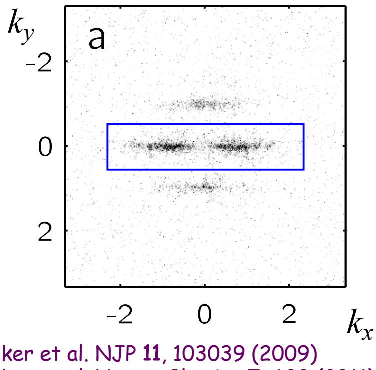
U

`Imaging´

evaluati
on

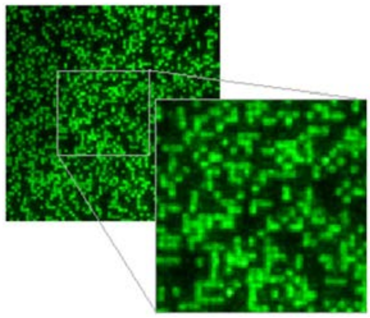
extracted values of measurements

time of flight -> momentum



R. Bücker et al. NJP **11**, 103039 (2009)
R. Bücker et al. Nature Physics **7**, 608 (2011)

in situ -> position



W. S. Bakr, et al.,Nature **462**, 74 (2009).
J. F. Sherson, et al. Nature **467**, 68 (2010).

single shot projective measurements of the many body wavefunction: n-point function

Theory: Single-shot simulations of dynamic quantum many-body systems
K. Sakmann, M. Kasevich, Nature Physics (2016)

Experimental procedure

Experiment

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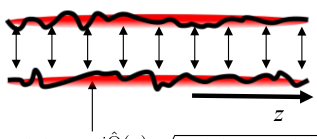
`Imaging´

evaluati
on

extracted values of measurements

1D gas of ^{87}Rb atoms

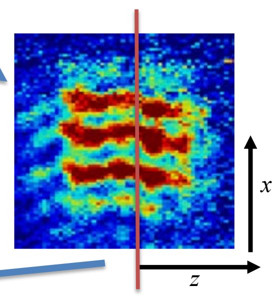


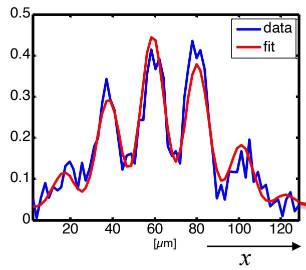
$$\psi(z) = e^{i\hat{\Theta}(z)}\sqrt{\rho_0(z) + \delta\hat{\rho}(z)}$$

adjustable tunnelling J

In our case: J=0
two separated 1d gas

time of flight





fit

phase difference between condensates
$\varphi(z) = \theta_1(z) - \theta_2(z)$

Projective phase measurements in one dimensional Bose Condensates
Y. D. van Nieuwkerk, J. Schmiedmayer, F. Essler. SciPost Phys. **5**, 046 (2018)

Experimental procedure

Experiment

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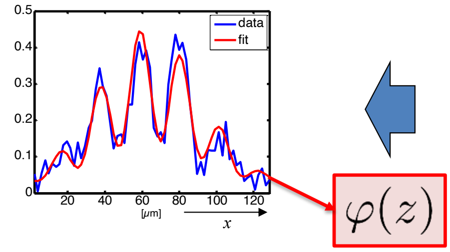
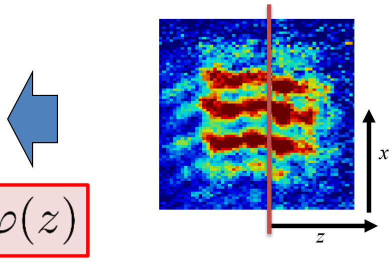
`Imaging´

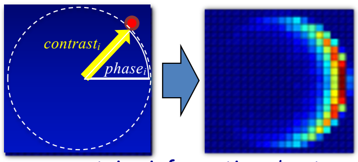
evaluation

extracted values of measurements



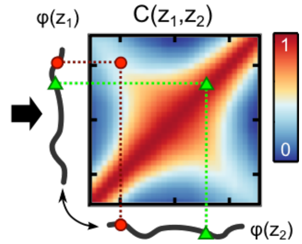


Full Distribution Function of phase and contrast



contains information about all order correlation functions

phase correlation

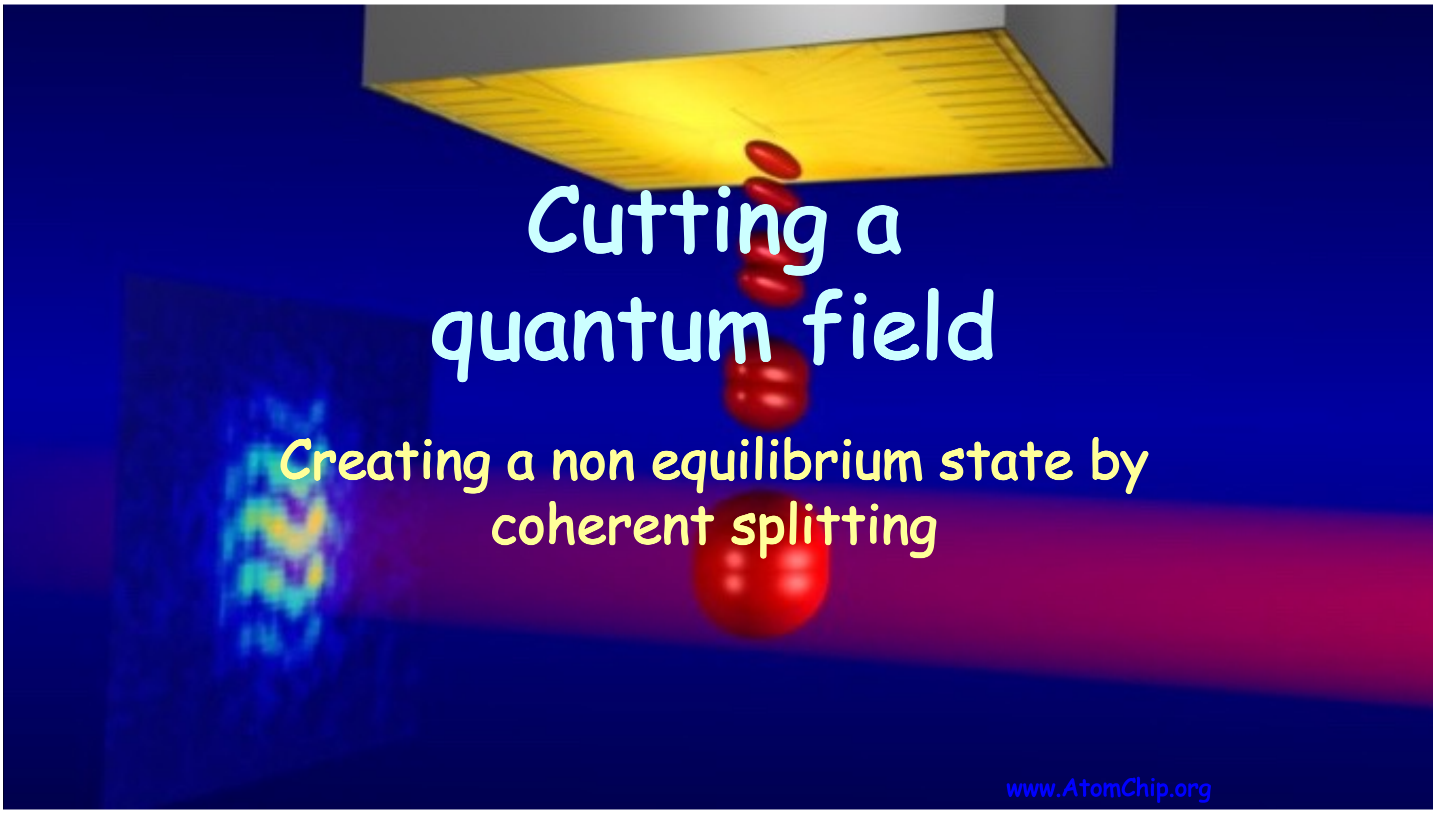


Evaluated up to 10[th] order

Theory: Polkovnikov et al. PNAS **103**, 6125 (2006)
Gritsev et al. Nature Phys. **2**, 705 (2006)

Exp: Hofferberth et al. Nature Phys. **4**, 489 (2008)

Langen et al. Science **348**, 207 (2015)
Schweigler et al. Nature **545**, 323 (2017)

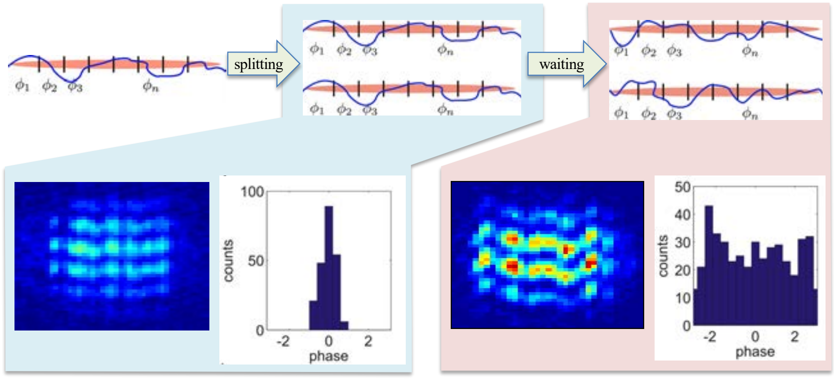


Splitting a QuantumField
quantum noise of cutting

Initial single system
1d quantum gas

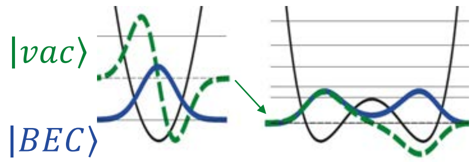
Initial state
coherently split quantum gas

thermal state
two independent 1d BEC



symmetric $\hat{n}_s = \hat{n}_1 + \hat{n}_2, \quad \hat{\phi}_s = (\hat{\phi}_1 + \hat{\phi}_2)/2$ thermally populated

anti symm. $\hat{n}_a = \hat{n}_1 - \hat{n}_2, \quad \hat{\phi}_a = \hat{\phi}_1 - \hat{\phi}_2$ populated by quantum fluctuations



Temperature after the Cut

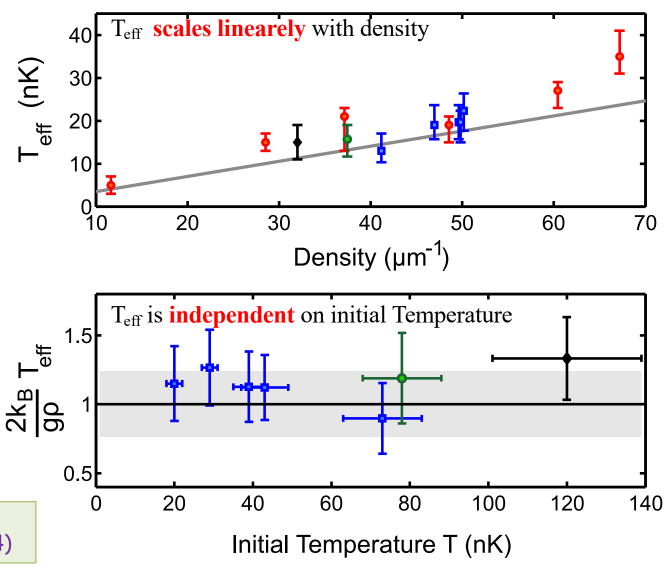
Gring et al., Science **337**, 1318 (2012)
theory: Kitagawa et al., PRL **104**, 255302 (2010); NJP **13** 073018 (2011)

System relaxes to a steady state given by the de-phasing of modes created by the the splitting quench:

Luttinger liquid prediction

$$k_B T_{\text{eff}} = g\rho/2$$

Effective temperature for the quasi steady state given by the quantum shot noise introduced by the splitting process (Beam splitter)



Related to Pre-Thermalization:
J. Berges et al., PRL **93**, 14202, (2004)

Light Cone

How long does it take that the system ‚knows' that it was cut in halve

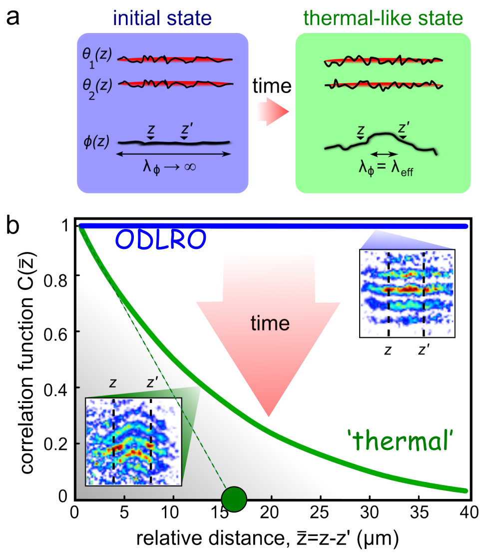
T. Langen et al NatPhys **9**, 460 (2013)

www.AtomChip.org

Decay of coherence

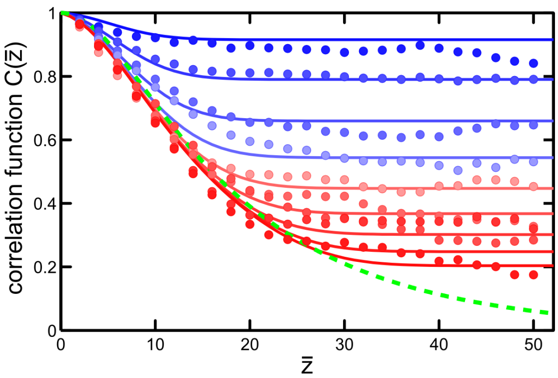
how is the pre-thermalized state established?

T. Langen et al NatPhys **9**, 460 (2013)



$$C(\bar{z} = z - z') = \left\langle e^{i(\varphi(z)-\varphi(z'))} \right\rangle$$

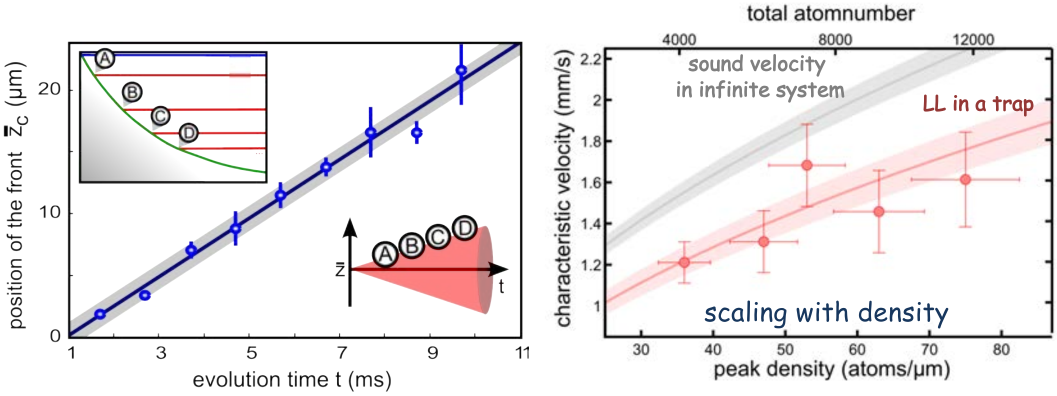
Time evolution of the phase correlation function



CFT: Calabrese, P. & Cardy, J. Phys. Rev. Lett. **96**, 011368 (2006)

Light-Cone
decay of long range order

T. Langen et al NatPhys **9**, 460 (2013)
LL theory in trap: R. Geiger et al. NJP **16**, 053034 (2014)

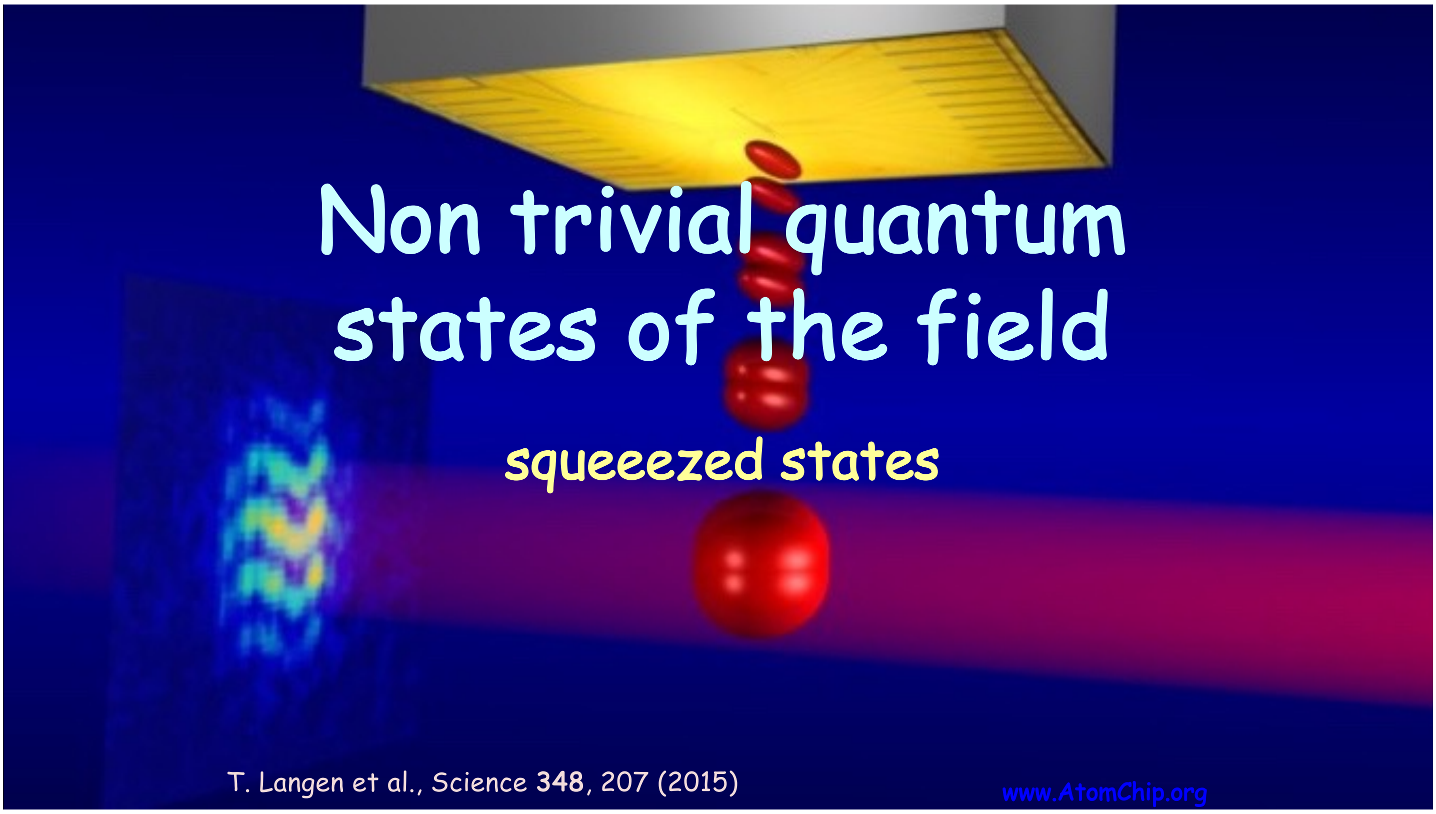


Linear dispersion relation -> Light-Cone dynamics

The region with the final form of the phase correlation function expands with **sound velocity**

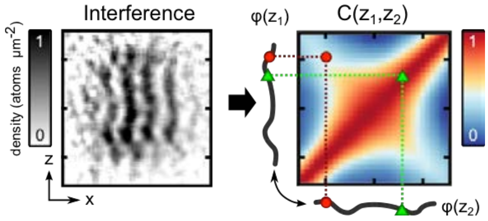
Linear disperison relation of the phonons relates to the questions asked in:

CFT:	Calabrese, P. & Cardy, J. Phys. Rev. Lett. **96**, 011368 (2006)
Lattice model:	Cramer, M., et al. Phys. Rev. Lett. **100**, 030602 (2008).



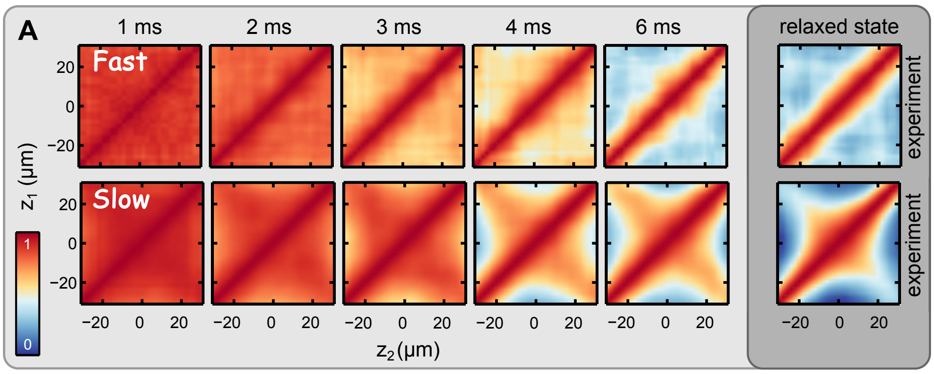
Fast vs. *Slow* splitting
Generalized Gibbs Ensemble

T. Langen et al. Science **348**, 207 (2015)



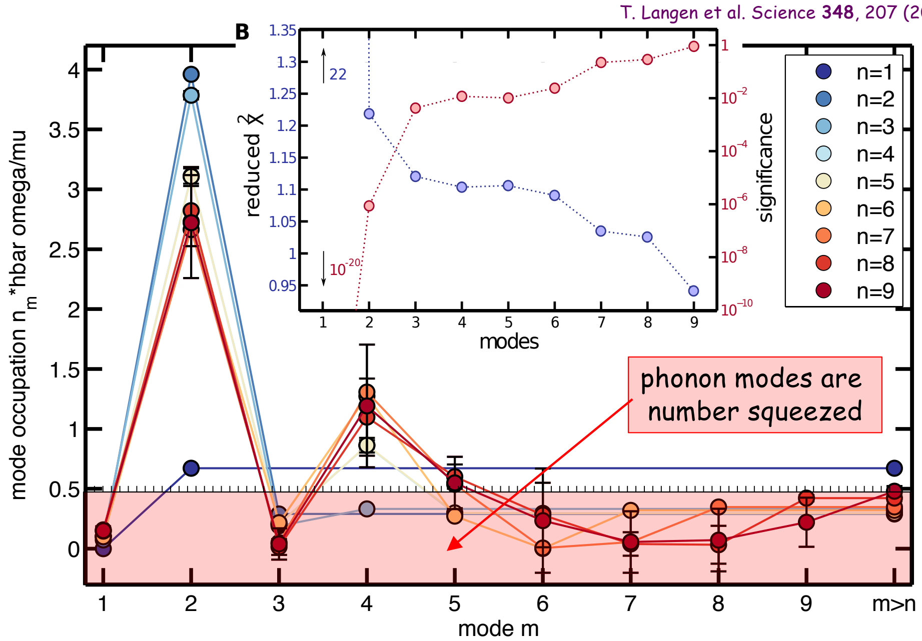
Non-Translation Invariant Correlation Functions

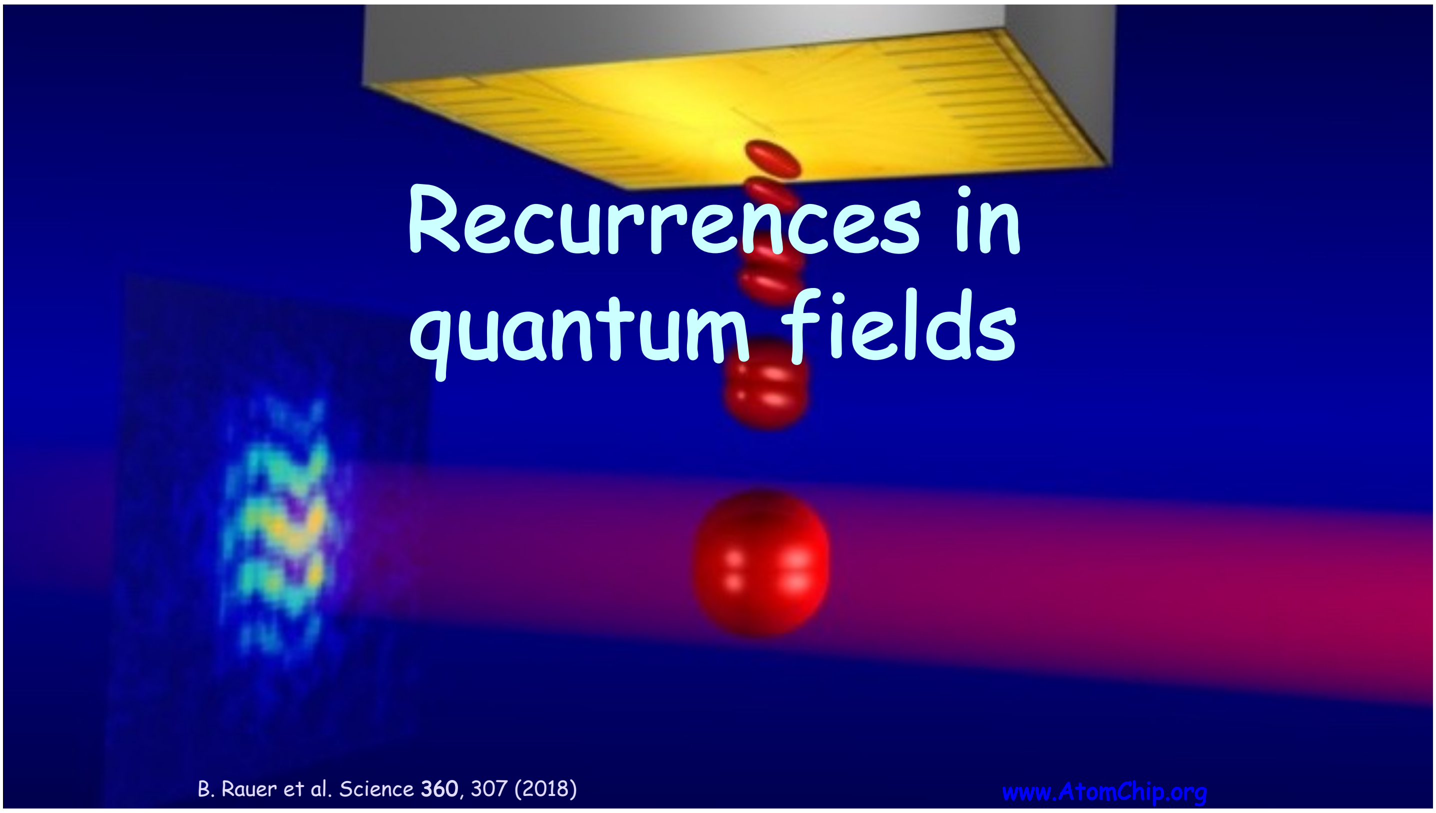
$$C(z_1,z_2)=\left\langle e^{i(\varphi(z_1)-\varphi(z_2))}\right\rangle$$



How many Parameters are needed for the GGE

T. Langen et al. Science **348**, 207 (2015)





Recurrences

Is Quantum alive behind a classical statistical ensemble (GGE) ?

Poincare 1890: Any finite physical system will return arbitrarily close to its initial state in the course of its dynamics

Bocchieri (1957) and Percival (1961): Recurrences in quantum domain
Simplest form: Collapse and revivals in the Jaynes-Cummings model

For large many-body systems it becomes exponentially difficult to observe the many-body eigenstates directly.
⇒ Much simpler measurements of (local) few body observables O.

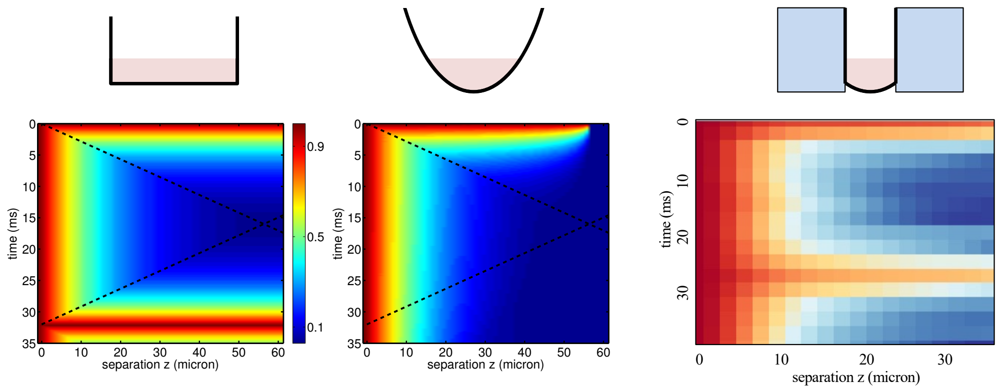
This poses the question if and under which condition one can observe recurrences in these observables O.
⇒ The system does not have to come back close to the initial configuration of many body states, but only needs to satisfy the condition that gives similar result under the evaluation of O.

In quantum many body systems such observables O can be chosen to reflect the collective degrees of freedom in the underlying quantum field theory.

Recurrences in non-equilibrium evolution

look at evolution of $g^{(2)}(x_1\text{-}x_2)$

Box potential homogeneous system | harmonic trap | experiment trap with hard walls



clear revivals with an '*inverse light cone*'

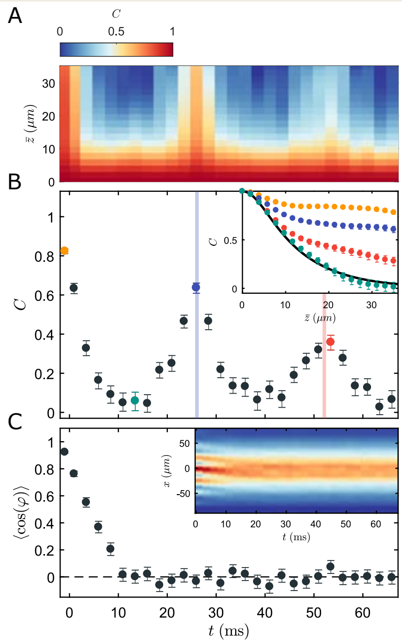
no short time revival due to *unequal spacing* of phonon frequencies

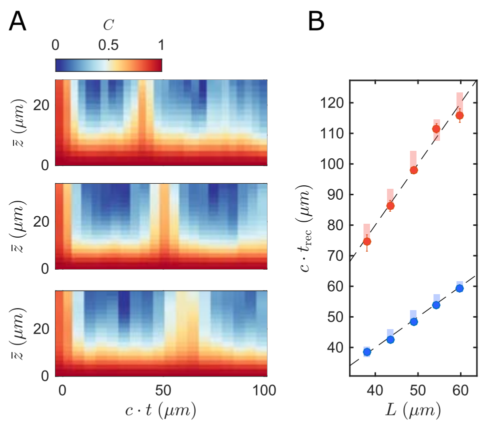
R. Geiger et al. NJP **16** 053034 (2014)

B. Rauer et al. Science **360**, 307 (2018)

Recurrences in non-equilibrium evolution

B. Rauer et al. Science **360**, 307 (2018)





Quantum Sine Gordon Model

Theory of a massive scalar field $\hat{\phi}$ in one space and time dimension with an interaction density proportional to $\cos\beta\hat{\phi}$

$$H_{SG} = \frac{\hbar v_s}{2}\int dz \left[\left(\partial_t\hat{\phi}\right)^2 + \left(\partial_z\hat{\phi}\right)^2 - \frac{2\,M^2}{\beta^2}\cos\beta\hat{\phi}\right]$$

For the energy to be bounded β is limited to: $0 < \beta < \sqrt{8\pi}$

β plays the role of the Planck constant, $\beta \ll 1$ being the (semi)-classical limit.

Sine Gordon Model
equivalent to (a few examples)

Massive Thirring Model
S. Colman Phys. Rev. D **217** 11, 2088 (1975).

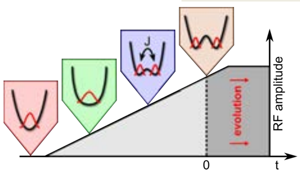
Coulomb Gas
Polyakov, A. M. *Nuclear Physics B*, *120*, 429-458 (1977).
Samuel, S. *Physical Review D*, *18*, 1916 (1978).

XY Model
José, J. V. et al., *Physical Review B*, *16*, 1217 (1977).

Half-integer spin chains and extended Hubbard models
Essler and Konik in: From Fields to Strings
WORLD SCIENTIFIC, pp. 684–830 (2005)

String breaking and entanglement in expanding Qu-fields
Berges et al., Phys. Lett. B 778, 442 (2018)
Journal of High Energy Physics, 2018(4), 145. (2018)

Two tunnel coupled 1d super fluids
Emergent quantum simulator for the Sine Gordon model



$$H = \sum_{j=1}^{2} \int dz \left[\frac{\hbar^2}{2m} \frac{\partial \psi_j^\dagger}{\partial z} \frac{\partial \psi_j}{\partial z} + \frac{g_{1\mathrm{D}}}{2} \psi_j^\dagger \psi_j^\dagger \psi_j \psi_j + U(z) \psi_j^\dagger \psi_j - \mu \psi_j^\dagger \psi_j \right] - \hbar J \int dz \left[\psi_1^\dagger \psi_2 + \psi_2 \psi_1^\dagger \right]$$

Following: Gritsev, Polkovnikov, Demler Phys. Rev. B **75**, 174511 (2007)

- Density phase representation
- Expanding the Hamiltonian in density fluctuations $\delta\rho_j$ and phase gradients $\partial_z \varphi_j$ up to second order and neglecting mixed terms separates H in symmetric and antisymmetric degrees of freedom
- Neglecting terms $|\delta\rho/n_0| \ll 1$

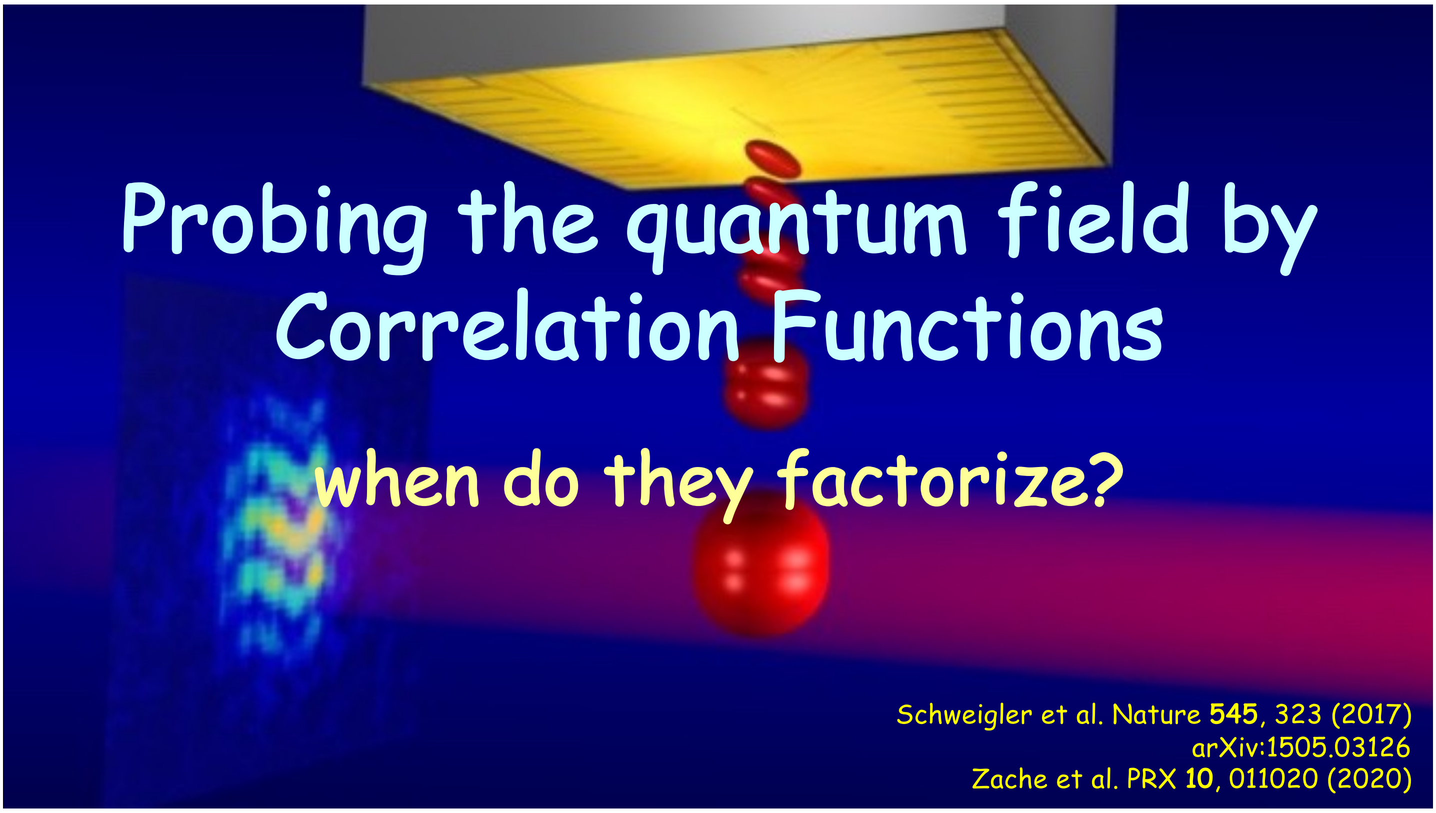
One arrives at **Quantum Sine-Gordon model**:

$$\hat{H}_{\mathrm{SG}} = \int dz \left[\frac{\hbar^2 n_{1\mathrm{D}}}{4m} (\partial_z \hat{\varphi})^2 + g \delta\hat{\rho}^2 \right] - \int dz \; 2 J n_{1D} \left[1 - \cos \hat{\varphi} \right]$$

"uncoupled harmonic oscillators"

anharmonic, non-gaussian, gapped,

phase coherence length
$$\lambda_T = 2\hbar^2 n_{1D}/(m k_B T)$$
phase (spin) healing length
$$l_J = \sqrt{\hbar/(4mJ)}$$
Characteristic parameters
$$q = \lambda_T / l_J$$



Probing the quantum field by Correlation Functions

when do they factorize?

Schweigler et al. Nature **545**, 323 (2017)
arXiv:1505.03126
Zache et al. PRX **10**, 011020 (2020)

Correlation Functions

The Nth order Correlation function

$$G^{(N)}(\mathbf{z}) = \langle \mathcal{O}(z_1)\mathcal{O}(z_2)\ldots\mathcal{O}(z_N)\rangle$$

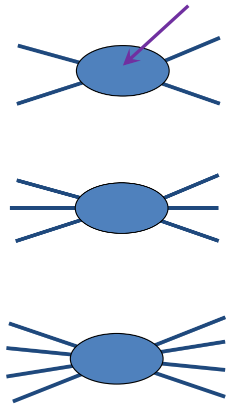
Characterizes the propagation and the interactions of the degrees of freedom connected to the operators $\mathcal{O}(z_i)$

It can be decomposed: $G^{(N)}(\mathbf{z}) = G^{(N)}_{\text{dis}}(\mathbf{z}) + G^{(N)}_{\text{con}}(\mathbf{z})$

- The disconnected part $G^{(N)}_{\text{dis}}$ is fully determined through lower order correlations
- The connected part $G^{(N)}_{\text{con}}$ contains genuine new information about the system at order N

What can we learn from connected correlations

Connected diagram
can not be decomposed in
lower order diagrams



4^{th} order $\sum$ — 2 body interaction

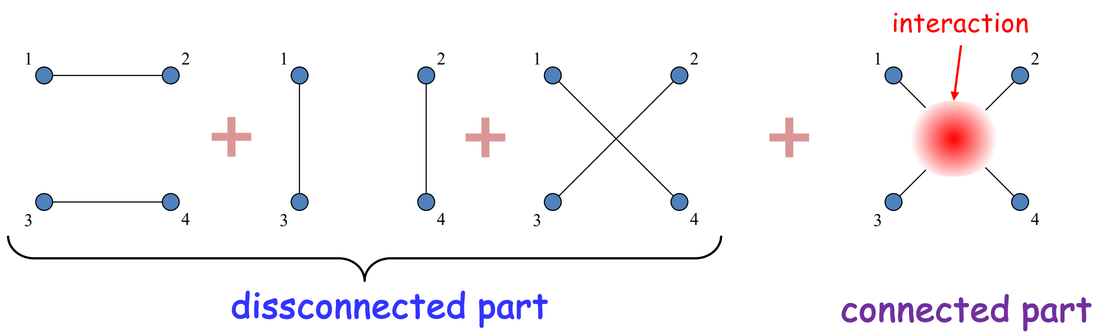
6^{th} order $\sum$ — 3 body interaction

8^{th} order $\sum$ — 4 body interaction

...

4-point correlation function

$G^{(4)}(x_1, x_2, x_3, x_4) =$



$$G^{(4)}(x_1, x_2, x_3, x_4) = G^{(2)}(x_1, x_3)G^{(2)}(x_2, x_4) + G^{(2)}(x_1, x_2)G^{(2)}(x_3, x_4) + G^{(2)}(x_1, x_4)G^{(2)}(x_2, x_3) + \int d^D y_1 \ldots d^D y_4 \, G^{(2)}(x_1, y_1)G^{(2)}(x_2, y_2)G^{(2)}(x_3, y_3)G^{(2)}(x_4, y_4)\, \Gamma^{(4)}(y_1, y_2, y_3, y_4)$$

Probing factorization
extracting connected correlations

Schweigler et al. Nature **545**, 323 (2017)

Correlation function of the phase

$$G^{(N)}(\mathbf{z},\mathbf{z}') = \langle [\varphi(z_1) - \varphi(z_1')] \dots [\varphi(z_N) - \varphi(z_N')] \rangle$$

Calculate the connected part of the correlation:

$$G^{(N)}_{\text{con}}(\mathbf{z},\mathbf{z}') = \sum_{\pi} \left[(|\pi| - 1)!\ (-1)^{|\pi|-1} \prod_{B\in\pi} \left\langle \prod_{i\in B} [\varphi(z_i) - \varphi(z_i')] \right\rangle \right]$$

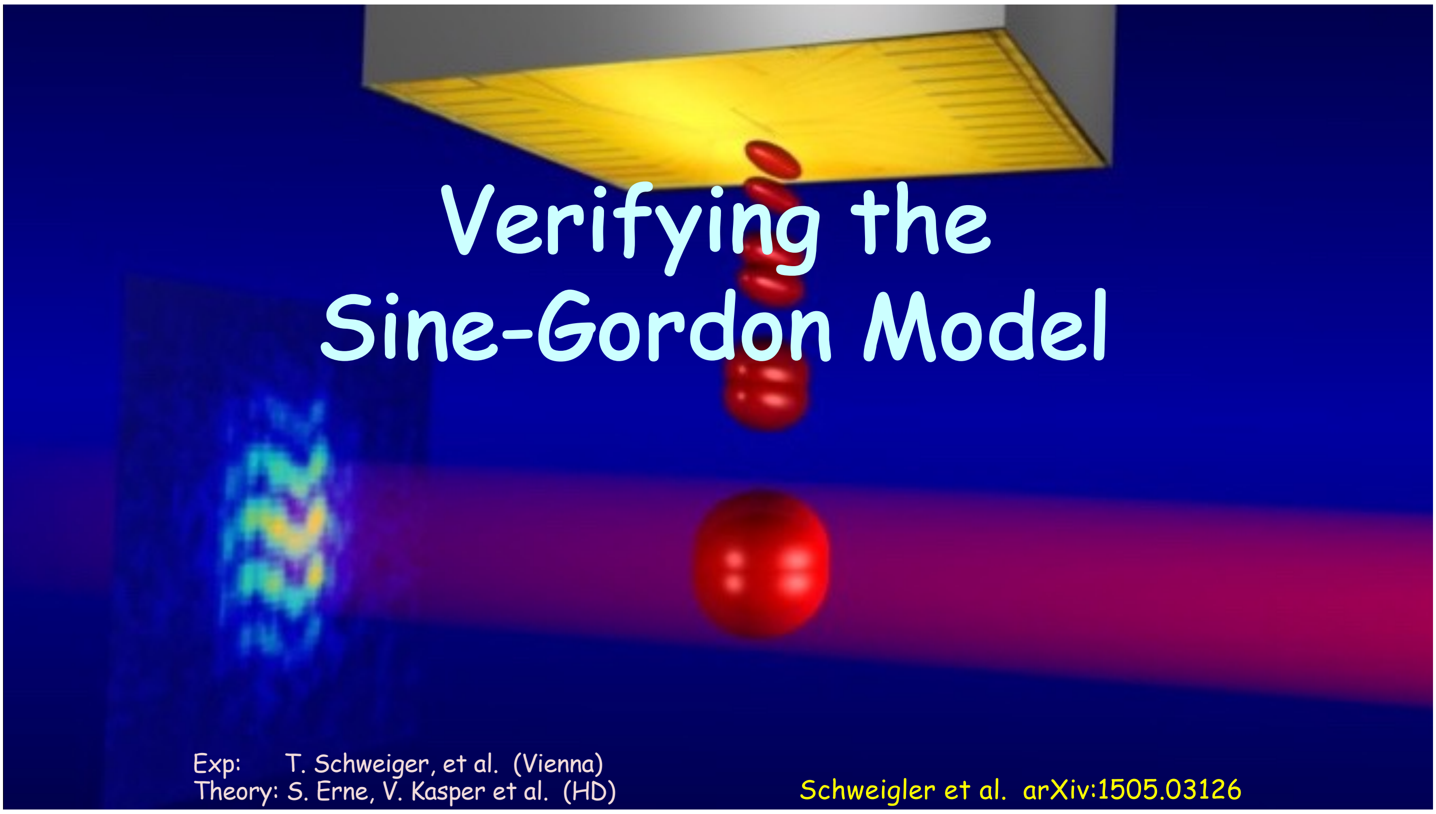
Sum runs over all possible partitions π, the first product over all blocks B of the partition, the second over all elements of the block.

The number of partitions to consider grows rapidly with N.
For N=10 there are already >10^5 terms to consider !!!!

Complexity of a many body problem

Decomposition into 2nd order correlations (Wick decomposition)

$$G^{(N)}_{\text{wick}}(\mathbf{z},\mathbf{z}') = \sum_{\pi_2} \left[\prod_{B\in\pi_2} \left\langle [\varphi(z_{B_1}) - \varphi(z'_{B_1})][\varphi(z_{B_2}) - \varphi(z'_{B_2})] \right\rangle \right]$$



Correlation functions
excitations <-> phase

in experiment we measure the phase $\varphi(z)$ directly
-> look at phase correlators

$$C^{(2)}(z_1, z_2) = \langle[\varphi(z_1) - \varphi(z_2)]^2\rangle = \langle[\Delta\varphi(z_1,z_2)]^2\rangle$$

with $\Delta\varphi(z_1, z_2) = \varphi(z_1) - \varphi(z_2)$ Note: $\Delta\varphi$ is NOT restricted to 2π

using
$$\varphi(z) = \frac{1}{\sqrt{L}}\sum_{k\neq 0}\left[(-i)\sqrt{\frac{\pi}{|k|K}}(b_k^\dagger - b_{-k})e^{ikz}\right]$$

$$\Rightarrow \langle[\varphi(z_1) - \varphi(z_2)]^2\rangle = \sum_{k_1,k_2}\frac{\pi}{K\sqrt{|k_1 k_2|}} b_{k_1}^\dagger b_{-k_2} e^{ik_1 z_1 + ik_2 z_2} + \ldots$$

-> phase correlators are related to the **quasi particles**

4th order

$$C^{(4)}(z_1, z_2, z_3, z_4) = \langle[\varphi(z_1) - \varphi(z_2)]^2 [\varphi(z_3) - \varphi(z_4)]^2\rangle$$
$$\propto b_{k_1}^\dagger b_{k_2}^\dagger b_{-k_3} b_{-k_4} + \ldots$$

-> quasi particle scattering

4th order correlations
Connected and disconnected part

Schweigler et al. Nature **545**, 323 (2017)

to study factorization of correlation functions we look at:

$$G^{(2)}(z_1, z_2) = \langle[\varphi(z_1) - \varphi(z_2)]^2\rangle$$

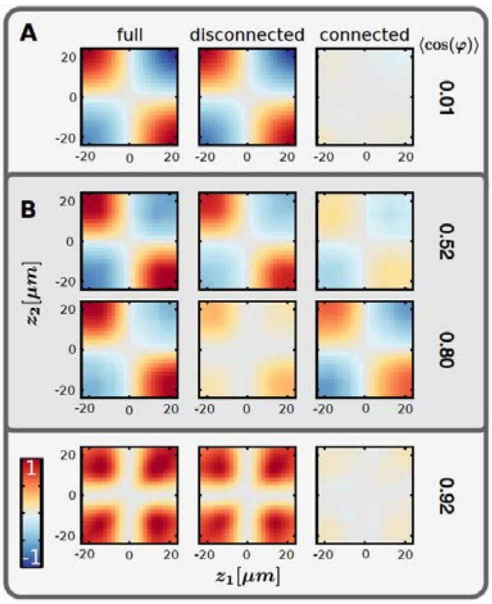
$$G^{(4)}(z_1, z_2, z_3, z_4) = \langle[\varphi(z_1) - \varphi(z_2)]^2 [\varphi(z_3) - \varphi(z_4)]^2\rangle$$

$\Delta\varphi(z_1, z_2) = \varphi(z_1) - \varphi(z_2)$
$\Delta\varphi$ *is* NOT restricted to $[-\pi, \pi)$

Connected/Disconnected part

$$G^{(N)}(\mathbf{z}) = G^{(N)}_{\mathrm{con}}(\mathbf{z}) + G^{(N)}_{\mathrm{dis}}(\mathbf{z})$$

$C^{(4)}(z_1, z_2, -15, 15)$



Characterizing Connected Correlations

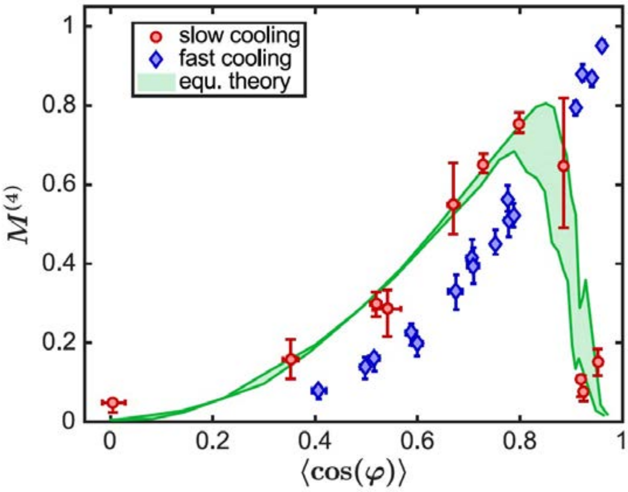
Schweigler et al. Nature **545**, 323 (2017)

Integrated measure

$$M^{(N)} = \frac{\sum_{\mathbf{z}} \left| G^{(N)}_{\mathrm{con}}(\mathbf{z}, 0) \right|}{\sum_{\mathbf{z}} \left| G^{(N)}(\mathbf{z}, 0) \right|}$$

Compared to predictions fo
a thermal equilibrium state
of the sine-Gordon model

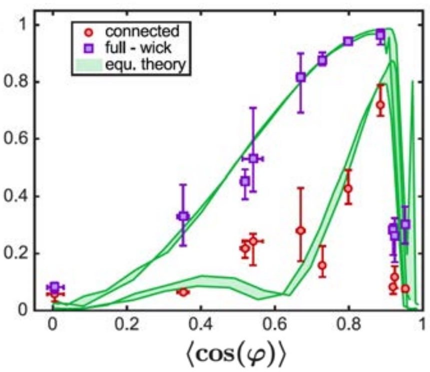
4th order correlations



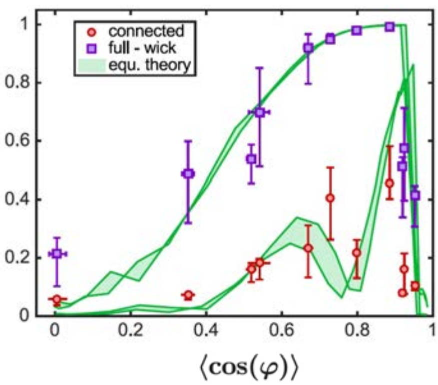
Higher order connected correlations

Schweigler et al. Nature **545**, 323 (2017)

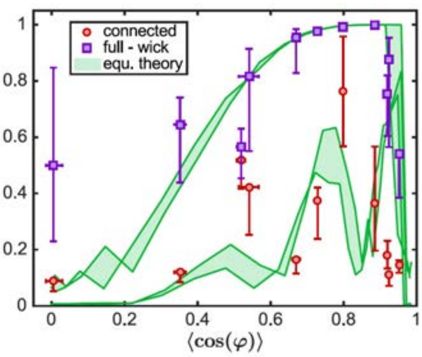
6th order



8th order

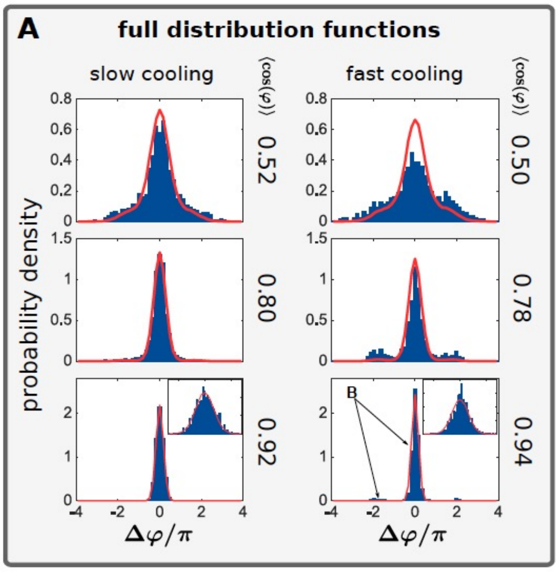


10th order

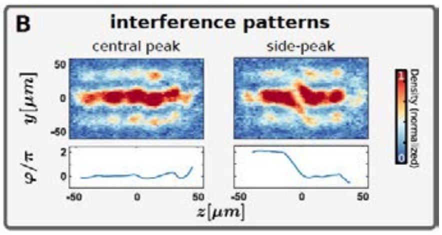


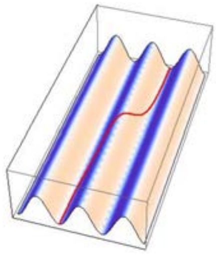
Quantifying factorization of correlation functions

Schweigler et al. Nature **545**, 323 (2017)



- the breakdown of factorization is evident in the **full distribution functions** of the phase by new peaks at multiples of 2π
- caused by the 2π ***periodic*** SG Hamiltonian -> 2π phase jumps, 'kinks' = SG solitons



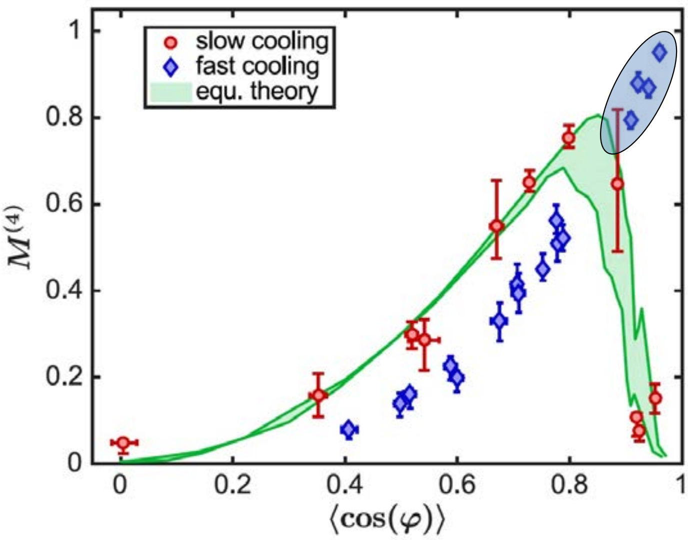


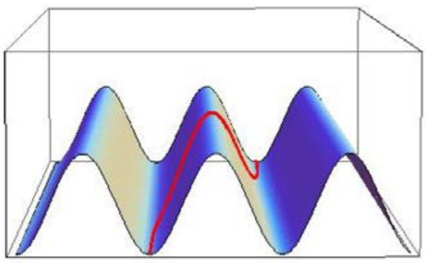
- **SG Solitons** are topological excitations
- Phase fluctuations around *topologically different Vaccua*

'False' Vacuum

Schweigler et al. Nature **545**, 323 (2017)

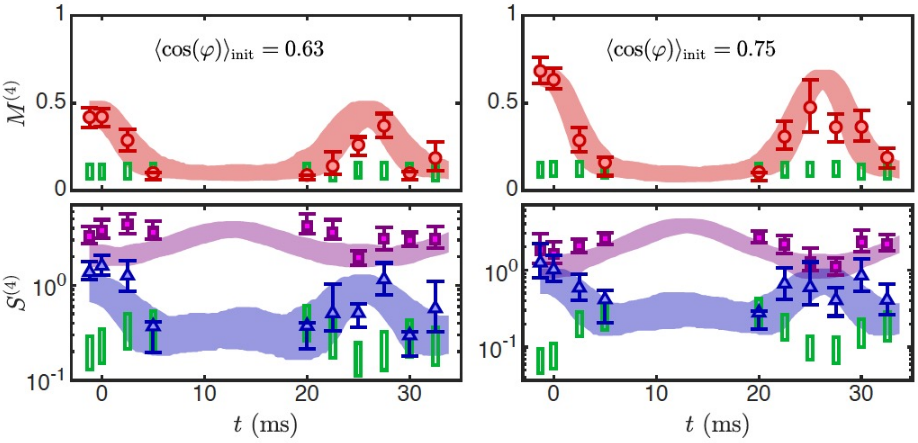
4th order correlations





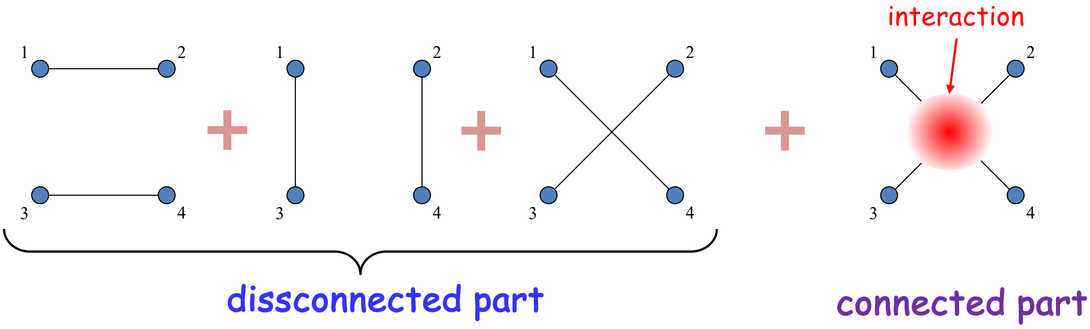
Recurrences of connected correlations

Schweigler et al., Nature Physics **17**, 559 (2021)



4-point correlation function

$G^{(4)}(x_1, x_2, x_3, x_4) =$



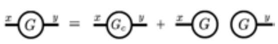
$$G^{(4)}(x_1, x_2, x_3, x_4) = G^{(2)}(x_1, x_3)G^{(2)}(x_2, x_4) + G^{(2)}(x_1, x_2)G^{(2)}(x_3, x_4) + G^{(2)}(x_1, x_4)G^{(2)}(x_2, x_3) + \int d^D y_1 \dots d^D y_4 \, G^{(2)}(x_1, y_1)G^{(2)}(x_2, y_2)G^{(2)}(x_3, y_3)G^{(2)}(x_4, y_4)\Gamma^{(4)}(y_1, y_2, y_3, y_4)$$

How to extract a coupling from experiment

1. Measure 'full' correlations

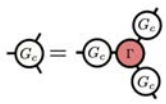
$$G^{(n)}(x_1, \dots, x_n) = \langle \varphi(x_1) \cdots \varphi(x_n) \rangle \approx \frac{1}{N} \sum_{j=1}^{N} \varphi_j(x_1) \cdots \varphi_j(x_n)$$

2. Substract the 'disconnected' contributions



$$G_c^{(n)}(x_1, \dots, x_n) = G^{(n)}(x_1, \dots, x_n) - G_{\text{dis}}^{(n)}(x_1, \dots, x_n)$$

3. Divide out the two-point functions ('amputation')

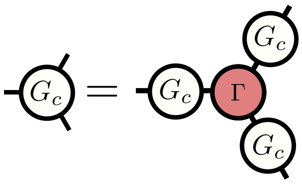


$$\Gamma^{(2)}(x, y) \sim \left[G_c^{(2)}\right]^{-1}(x, y)$$

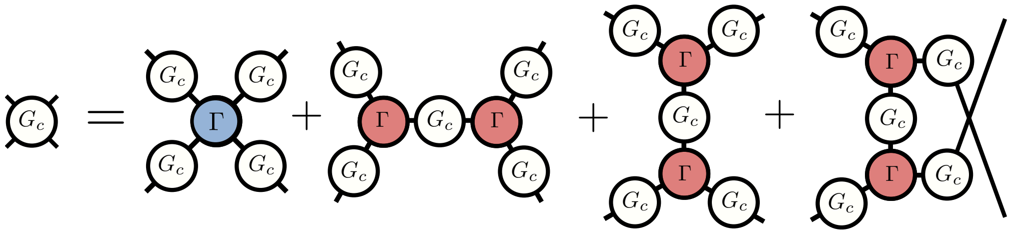
$$\Gamma^{(3)}(x, y, z) \sim \int dx' \int dy' \int dz' \, \Gamma^{(2)}(x, x') \, \Gamma^{(2)}(y, y') \, \Gamma^{(2)}(z, z') \, G_c^{(3)}(x', y', z')$$

$$\dots$$

Diagrammatics: 'one-particle irreducible' – 1PI



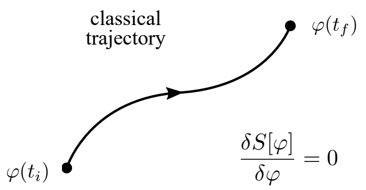
1PI correlators: *building blocks of all correlations!*

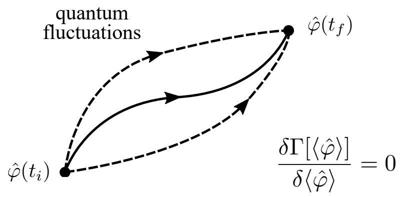


Extracting the Effective Theory

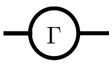
Effective action -> Vertex -> Hamiltonean

classical action $S[\varphi]$ quantum effective action $\Gamma[\langle\hat{\varphi}\rangle]$

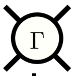




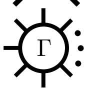
$$\Gamma[\phi] = S[\phi] + (\text{all quantum corrections})$$



effective mass $m = m_0 + \ldots$



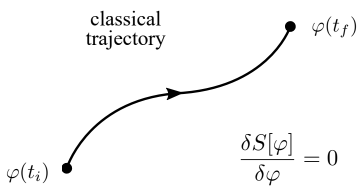
effective four-vertex $V_4 = \lambda_0 + \ldots$

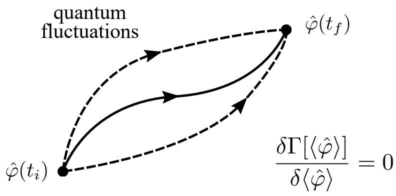


effective n-vertex $V_n = \ldots$

Extracting the Effective Theory
Effective action -> Vertex -> Hamiltonean

classical action $S[\varphi]$ — quantum effective action $\Gamma[\langle\hat{\varphi}\rangle]$





QFT:

$$\Gamma_t[\Phi] = \sum_{n=2}^{\infty} \frac{1}{n!} \Gamma^{(n)}_{\mathbf{x}_1,\ldots,\mathbf{x}_n}(t) \prod_{j=1}^{n} (\Phi_{\mathbf{x}_j} - \bar{\Phi}_{\mathbf{x}_j}(t))$$

$$\Gamma^{(n)}_{\mathbf{x}_1,\ldots,\mathbf{x}_n}(t) = \left. \frac{\delta^n \Gamma_t[\Phi]}{\delta \Phi_{\mathbf{x}_1} \cdots \delta \Phi_{\mathbf{x}_n}} \right|_{\Phi = \bar{\Phi}}$$

In thermal equilibrium:

'bare' Hamiltonean

$$\Gamma_\beta[\Phi] = \beta H[\Phi] + \Gamma'_\beta[\Phi]$$

quantum corrections
running coupling

Equal-Time QFT

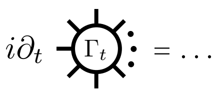
Standard formulation of QFT is with **non-equal time** correlators

Experiment: **equal time** correlations are much more accessible (extracted from the pictures)

⟹ Equal time formulation of QFT

State $\hat{\rho}_t$ is completely characterized by all equal-time correlation functions

quantum dynamics leads to a hierarchy of coupled evolution equations



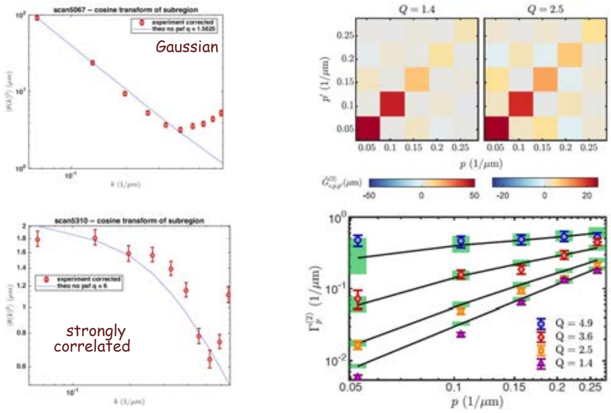
Ch. Wetterich *Phys. Rev. E* 56, 2687 (1997)

Extracting the Coupling Constants

Zache et al. PRX **10**, 011020 (2020)

- The measured connected correlators contain contributions from the propagators (the 'legs')
- To extract the information about the coupling constants in the scattering vertices one has to ‚amputate' the correlators
- Best done in momentum representation.
- In our finite system we have a discrete momentum spectrum (the modes of the system)
- Transform the correlators to the space of the modes

transformed
2-point correlator
(1/propagator)



Extracting the Coupling Constants

Zache et al. PRX **10**, 011020 (2020)

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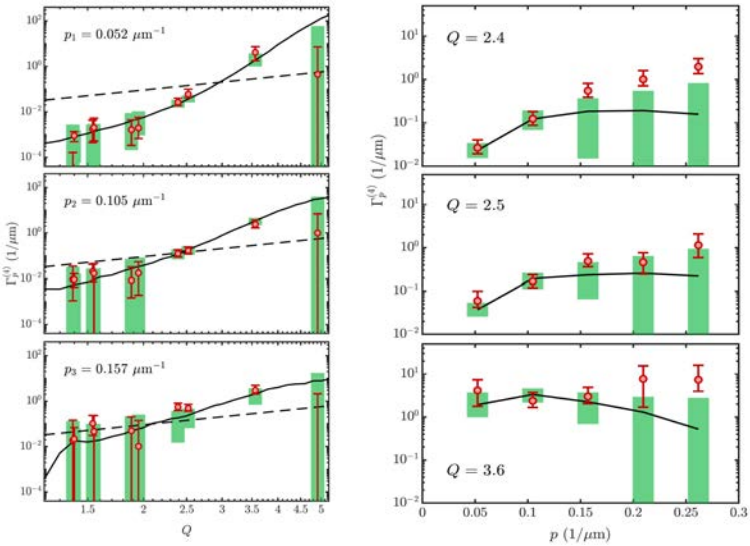
- Best done in momentum representation.
- In our finite system we have a discrete momentum spectrum (the modes of the system)
- Transform the correlators to the space of the modes

'amputated' connected
4-point correlator (vertex)

running coupling in SG model



What have we learned

- Ultra cold quantum gases are a good system to quantum simulate relativistic QuFT
  - Cutting Quantum fields: Temperature given by the quantum noise created by cutting the vacuum state
  - Light cone: emergence of the final state after a cut
  - 'Slow cuts' -> interesting quantum field states
  - Sine Gordon QuFT: strongly correlated QuFT with
    - massive excitations
    - topological excitations
  - Recurences in quantum fields -> long time quantum evolution
- Higher order correlations and the full distribution functions give insight in the quantum simulated QuFT
- Qu: how far can one push the QuSim. when will they break down

Hofferberth et al, Nature, **449**, 324 (2007)
Hofferberth et al, Nature Physics, **4**, 489 (2008)
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Schweigler et al., Nature **545**, 323 (2017)
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Schweigler et al., Nature Physics **17**, 559 (2021)

S. Erne et al., Nature **563**, 225 (2018)

Homework

How much can we push these quantum simulators

First for flat space time, only then can we have some confidence in simulating general space times

Density (relates to sound velocity) can be used to implement different space times, but these are imposed

Can we implement dynamical created space times?

Atom Chip Experiment

S. Manz, T. Betz, R. Bücker, **T. Berrada**, S. vanFrank, **M. Pigeur**, A. Perrin, T Schumm, JF Schaff, R. Wu, **M. Bonneau**

M. Kuhnert, M. Gring, **B. Rauer**, **Th. Schweigler** D. Smith, R. Geiger, **T. Langen**

Atom Chip Fabrication

D. Fischer, M. Trinker, M. Schamböck
S. Groth (HD), Israel Bar Joseph

Theory Coll

I. Mazets,
J. Grond, U.
E. Demle
T. Gasenzer, J.
T.

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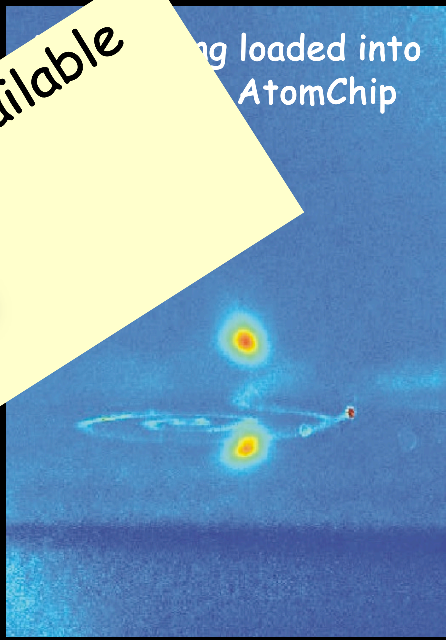

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