Title: Building Quantum Simulators for QuFTs

Speakers: Jorg Schmiedmayer

Collection: Quantum Simulators of Fundamental Physics

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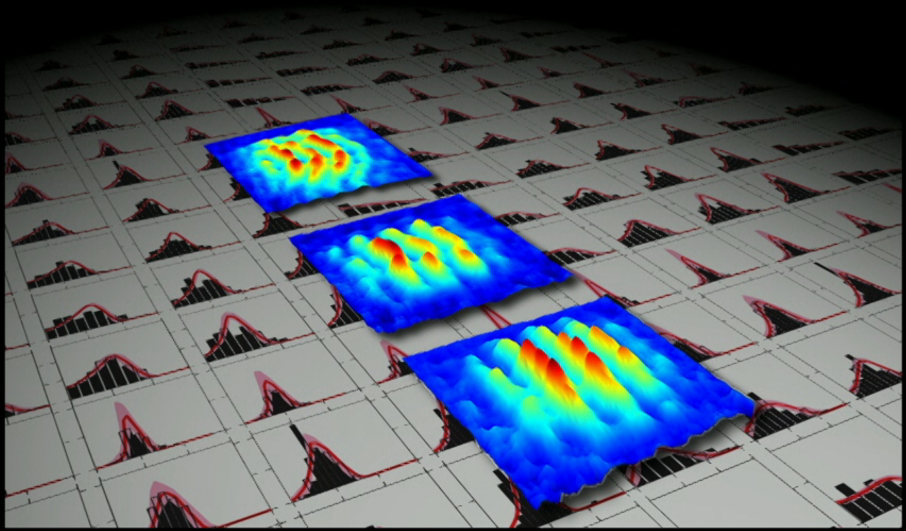
Abstract: ZOOM: https://pitp.zoom.us/j/95722860808?pwd=REYwSDdiK3pFamRJcjJwOW5FV1RPZz09

Quantum Simultors for QuFT



Jörg Schmiedmayer

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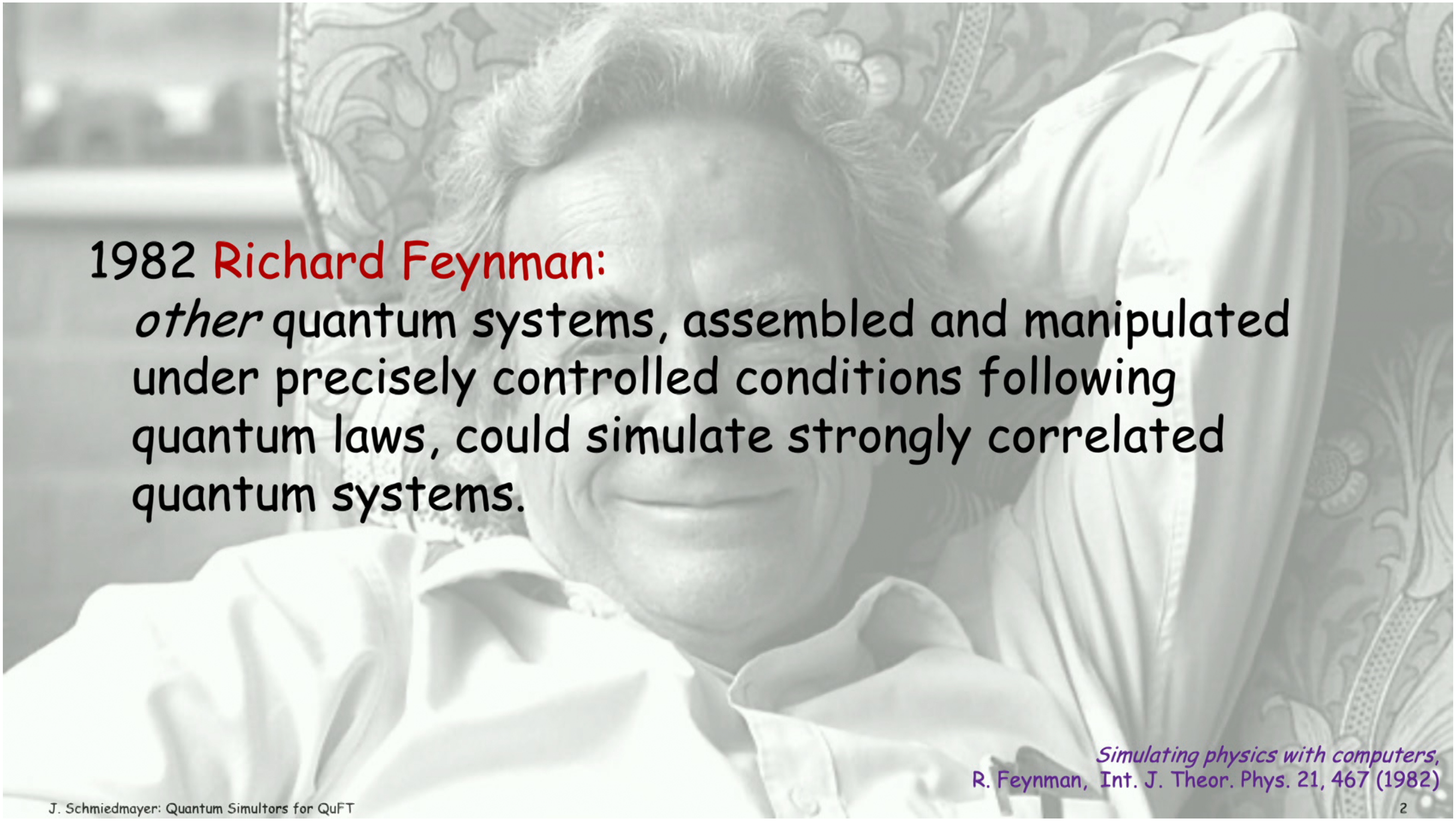

1982 Richard Feynman:

other quantum systems, assembled and manipulated under precisely controlled conditions following quantum laws, could simulate strongly correlated quantum systems.

Simulating physics with computers,
R. Feynman, Int. J. Theor. Phys. 21, 467 (1982)

Quantum Simulation

Digital Quantum Simulators:

Trotter-Suzuki's decomposition of the many-body evolution operator into sequences of of elementary quantum gates.

Example:

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer
E. A. Martinez et al. Nature **534**, 516 (2016)

Analog Quantum Simulators:

Build the desired Hamiltonian directly in the Lab and prepare the ground state, observe time evolution.

Example: Hubbard Model, ...

Quantum simulation with ultracold atomic gases,
I. Bloch, et al. Nature Phys. 8, 267 (2012).

Emergent Quantum Simulators

The complexity of the many body wave function does not allow to 'observe' all the details. Every measurement we do is a 'coarse graining' which leads to an emerging effective description that is very different from the microscopic physics.

Example: relativistic quantum fields
Sine-Gordon model <-> two tunnel coupled superfluids
emergent Hydrodynamics
....

Schweigler , et al. Nature **545**, 323 (2017)
Zache et al. PRX **10**, 011020 (2020)
Cataldini et al. arXiv:2111.13647

Many Body Quantum Systems <-> QuFT 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?

Quantum Gas <-> QuFT

(Effective) Quantum Field Theories are a powerful tool to describe many body quantum systems.

Quantum Gases are ideal tools to quantum simulate QuFTs

T=0	<->	vacuum
excitations	<->	particles
energy density	<->	geometry
...		

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Examples:

- 1d superfluid <-> Luttinger liquid (relativistic QuFT)
- Tunnel coupled super fluid <-> Sine-Gordon model
- …

Quantum Gas <-> QuFT

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Examples:

- 1d superfluid <-> Luttinger liquid (relativistic QuFT)
- Tunnel coupled super fluid <-> Sine-Gordon model
- ...

Interesting questions:

- Microscopic Physics <-> effective QuFT description
- Granularity of the MB system <-> Planck scale?
- ...

Outline

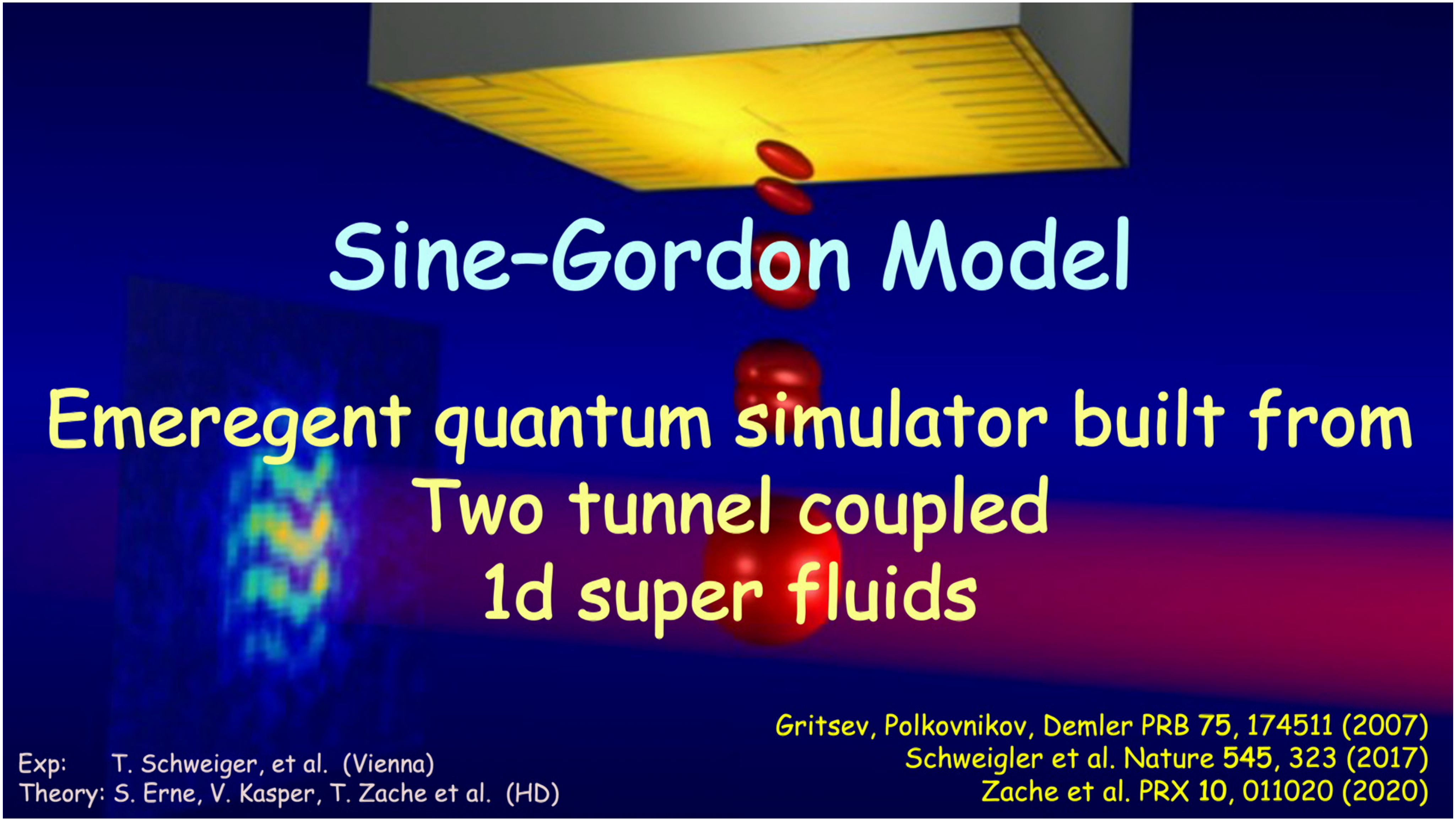
Sine Gordon Model

- Tunnel coupled 1d superfluids <-> SG model
- Verifying Sine-Gordon model
- Extracting the 1PI vertices
- Some recent examples and old unpublished experiments
  - Area law of mutual information in a QuFT
  - Floquet engineering
  - Decay of self trapping

Emerging Generalized Hydrodynamics (GHD)

- Generalized Hydrodynamics (GHD) for 1d systems
- Rapidities <-> Luttinger Liquid Phonons
- Pauli blocking and the limit of integrability

Outlook


Sine-Gordon Model
Emeregent quantum simulator built from
Two tunnel coupled
1d super fluids
Gritsev, Polkovnikov, Demler PRB 75, 174511 (2007)
Schweigler et al. Nature 545, 323 (2017)
Zache et al. PRX 10, 011020 (2020)
Exp: T. Schweiger, et al. (Vienna)
Theory: S. Erne, V. Kasper, T. Zache et al. (HD)

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

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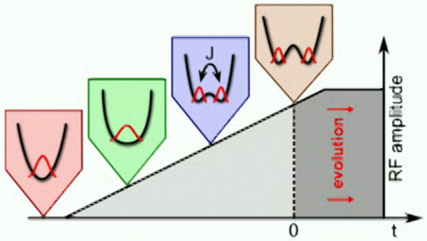


$$H = \sum_{j=1}^{2} \int dz \left[\frac{\hbar^2}{2m} \frac{\partial \psi_j^\dagger}{\partial z} \frac{\partial \psi_j}{\partial z} + \frac{g_{1\mathrm{D}}}{2} \psi_j^\dagger \psi_j^\dagger \psi_j \psi_j + U(z) \psi_j^\dagger \psi_j - \mu \psi_j^\dagger \psi_j \right] - \hbar J \int dz \left[\psi_1^\dagger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

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

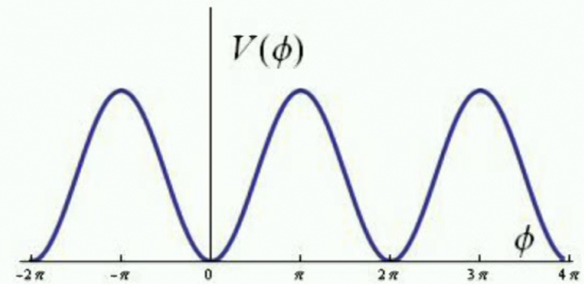
- Density phase representation
- Expanding the Hamiltonian in density fluctuations $\delta\rho_j$ and phase gradients $\partial_z \varphi_j$ up to second order and neglecting mixed terms separates H in symmetric and antisymmetric degrees of freedom
- Neglecting terms $|\delta\rho/n_0| \ll 1$

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

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

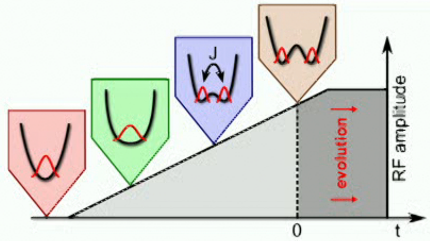
"uncoupled harmonic oscillators"

anharmonic, non-gaussian, gapped,



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

VCQ Vienna Center for Quantum Science and Technology



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

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"uncoupled harmonic oscillators"

anharmonic, non-gaussian, gapped,

phase coherence length

$$\lambda_T = 2\hbar^2 n_{1D}/(mk_BT)$$

phase (spin) healing length

$$l_J = \sqrt{\hbar/(4mJ)}$$

Characteristic parameters

$$q = \lambda_T/l_J$$

Quantum Sine Gordon Model

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

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

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.

In our experiments: $0.1 < \beta < 1$

Sine Gordon Model
equivalent to (a few examples)

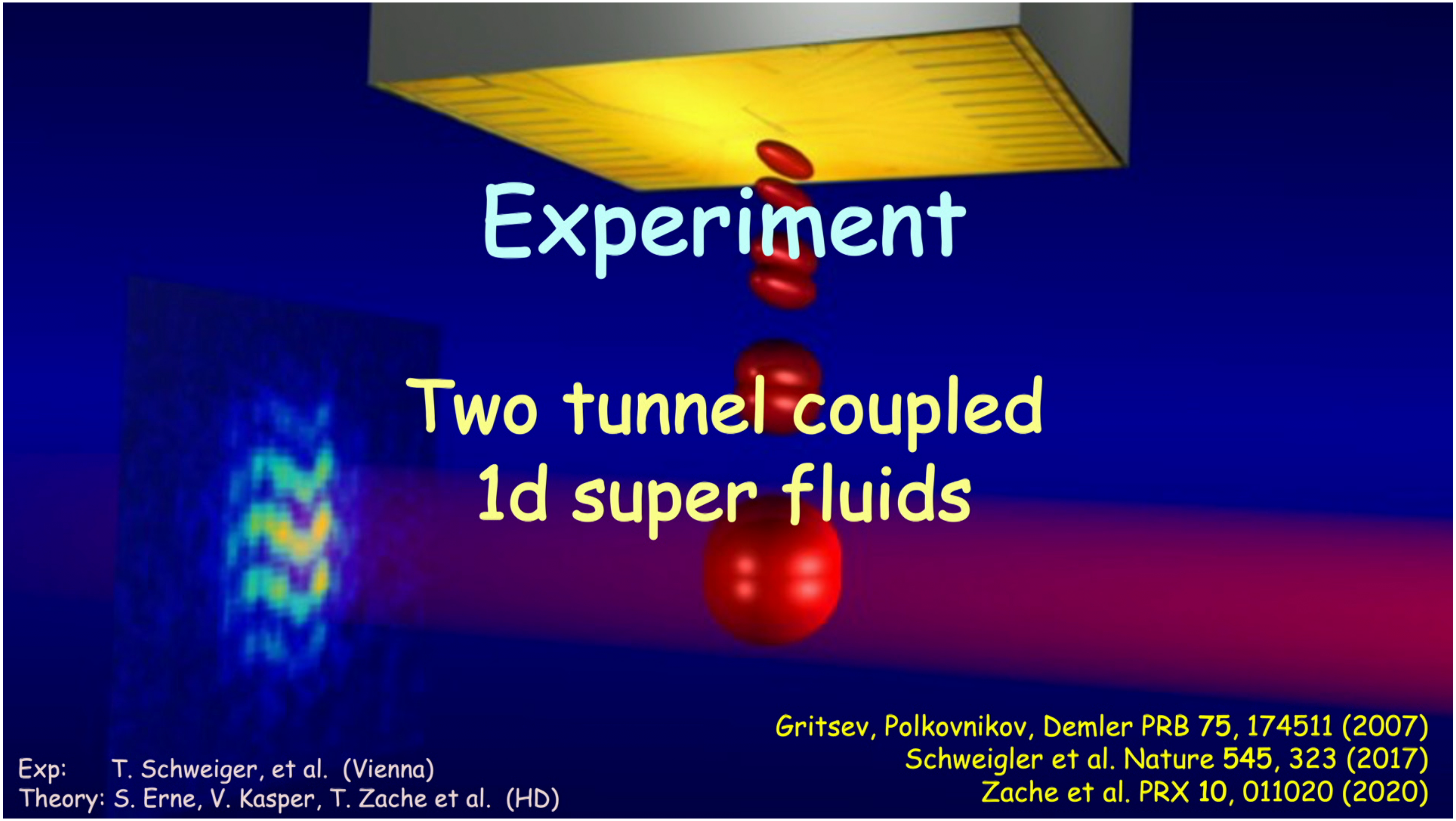
Massive Thirring Model
S. Colman Phys. Rev. D 217 11, 2088 (1975).

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)


Experiment
Two tunnel coupled
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AtomChip

Integrated Circuits for ultra-cold Quantum Matter

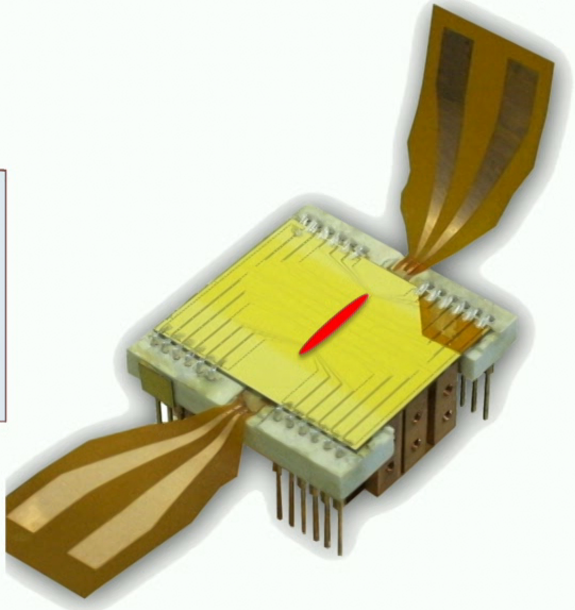
Folman et al. PRL 84, 4749 (2000)

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
- Single atom detection with unit efficiency
- Well controlled splitting and interference
- experiment optimized by genetic algorithm

Rohringer et al. APL 93, 264101 (2008)

3000-10000 atoms
$T = 10\text{-}100$ nK
$\omega_R \sim 2\pi \times 2 - 3$ kHz
$\omega_L \sim 2\pi \times 5 - 10$ Hz
$k_B T \sim 0.1 - 0.7\ \hbar\omega_R$
$k_B T \sim 0.1 - 1\ \mu$



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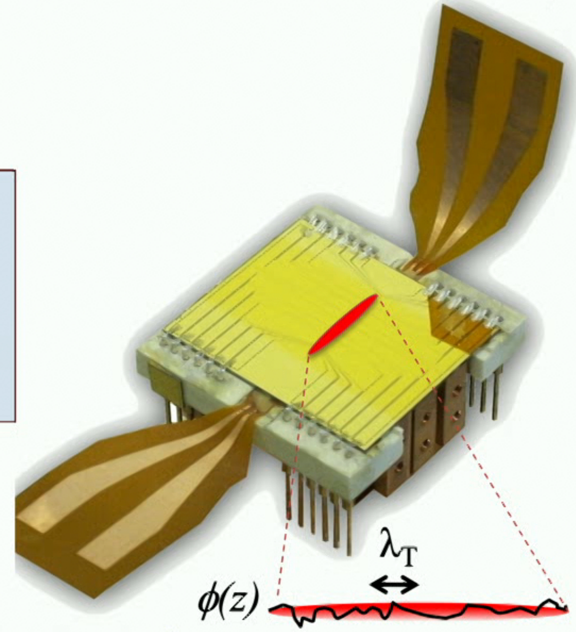
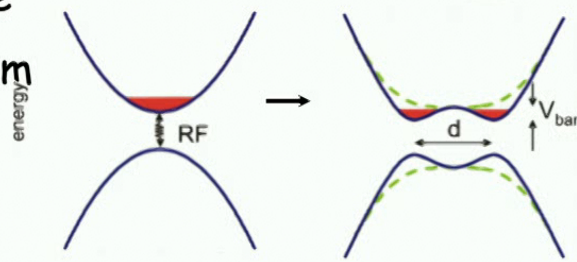
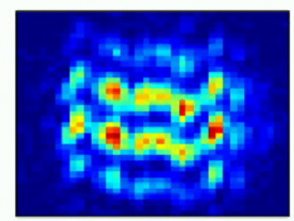






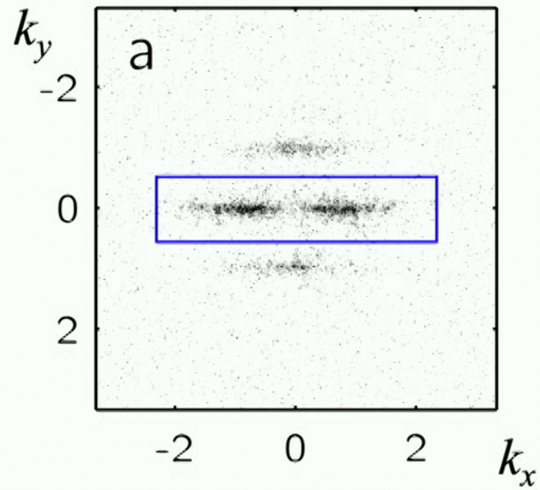
Experiment <-> read out

Experiment

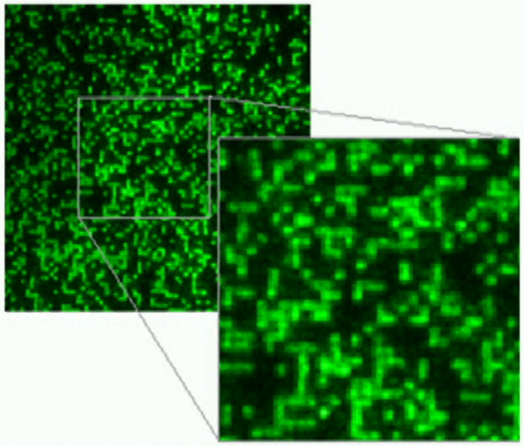
U

`Imaging´

time of flight -> momentum



in situ -> position

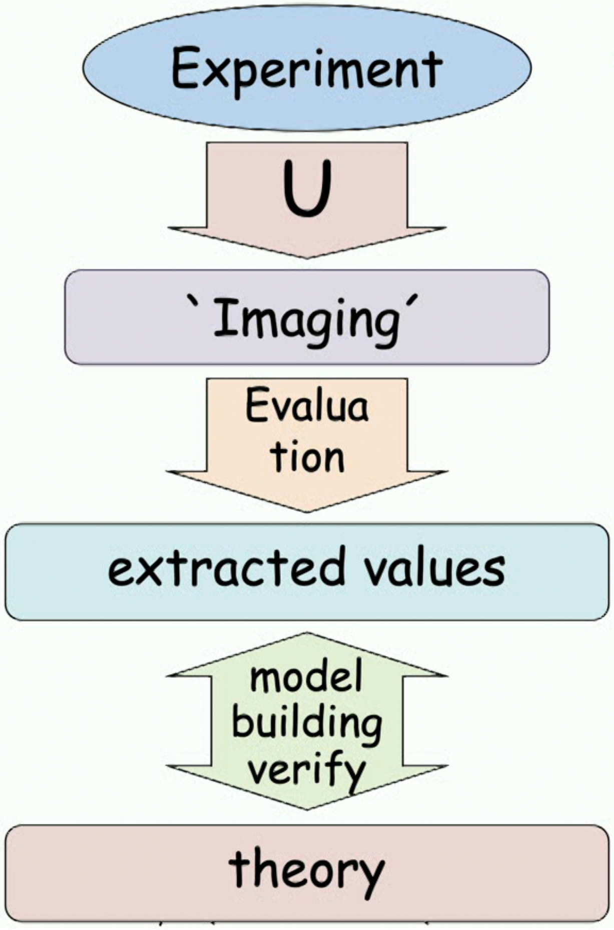


R. Bücker et al. NJP **11**, 103039 (2009)
R. Bücker et al. Nature Physics **7**, 608 (2011)

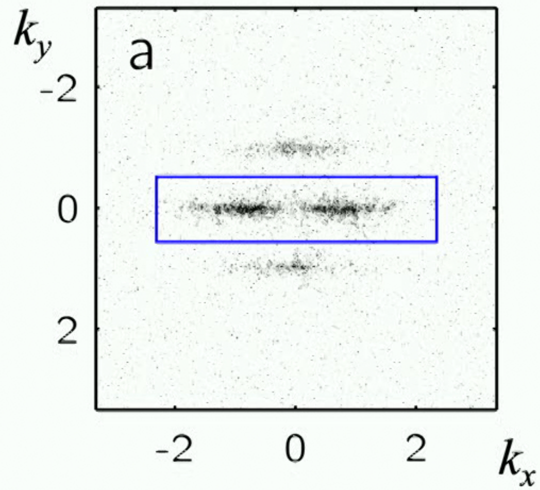
W. S. Bakr, et al.,Nature **462**, 74 (2009)
J. F. Sherson, et al. Nature **467**, 68 (2010)

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

Experiment <-> read out



time of flight -> momentum



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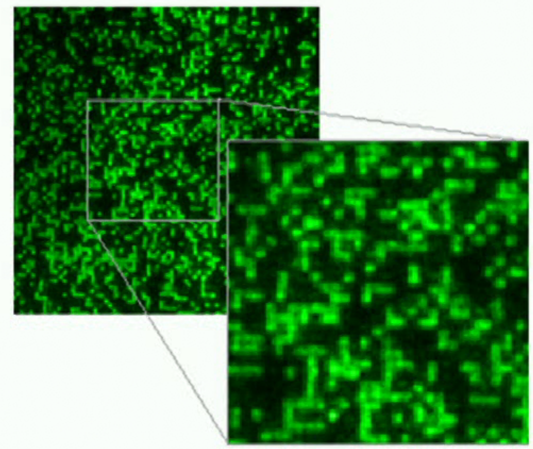

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single shot projective measurements of the many body wavefunction: n-point function

Experiment <-> read out

Vienna Center for Quantum Science and Technology

Schweigler et al. Nature 545, 323 (2017)

Experiment

U

`Imaging´

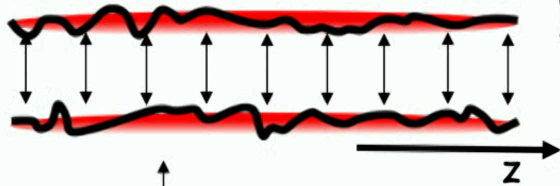
Evalua
tion

extracted values

model
building
verify

theory

1D gas of ^{87}Rb atoms

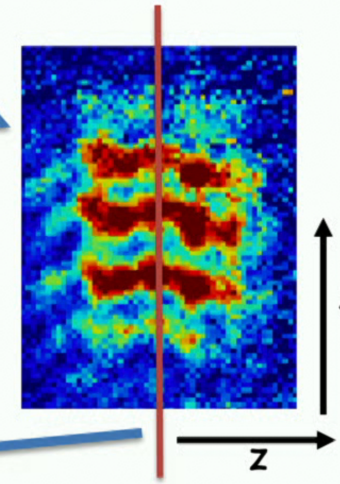


adjustable
tunnelling J

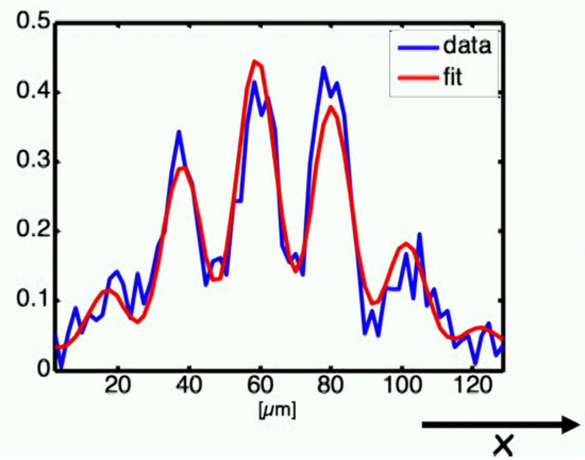
$$\psi(z) = e^{i\hat{\Theta}(z)}\sqrt{\rho_0(z) + \delta\hat{\rho}(z)}$$

Tunnel coupling lead to
phase locking
characterized by $\langle\cos(\varphi)\rangle$

time of
flight



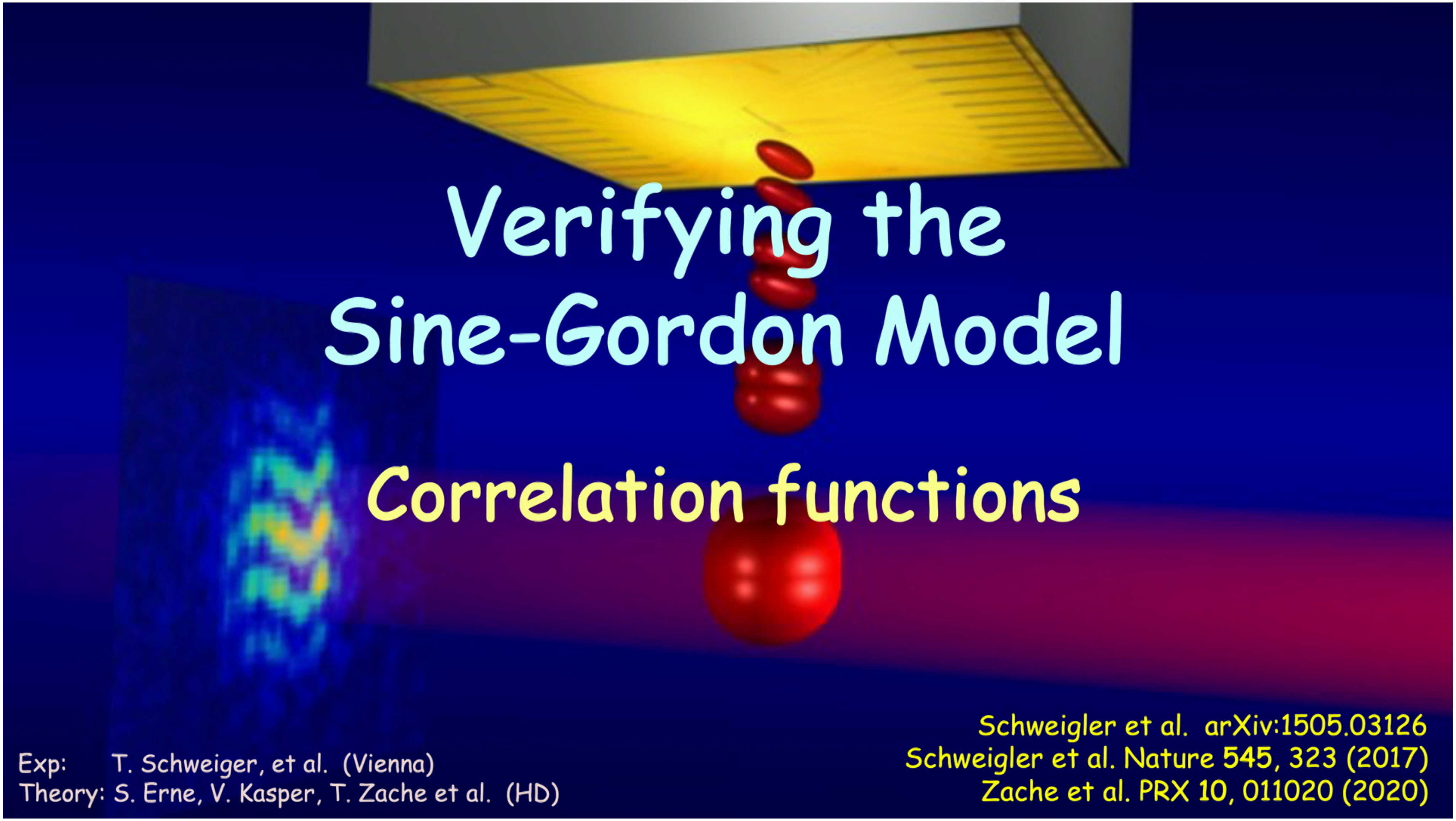
fit



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

Quantum
field
of SG model

15


Verifying the
Sine-Gordon Model
Correlation functions
Exp: T. Schweiger, et al. (Vienna)
Theory: S. Erne, V. Kasper, T. Zache et al. (HD)
Schweigler et al. arXiv:1505.03126
Schweigler et al. Nature 545, 323 (2017)
Zache et al. PRX 10, 011020 (2020)

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

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

-> phase correlators are related to the quasi particles

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

-> quasi particle scattering

Correlation Functions

The N^th order Correlation function

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

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

Correlation Functions

The Nth order Correlation function

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

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

4th order correlations
Connected and disconnected part

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

to study factorization of correlation functions we look at:

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

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

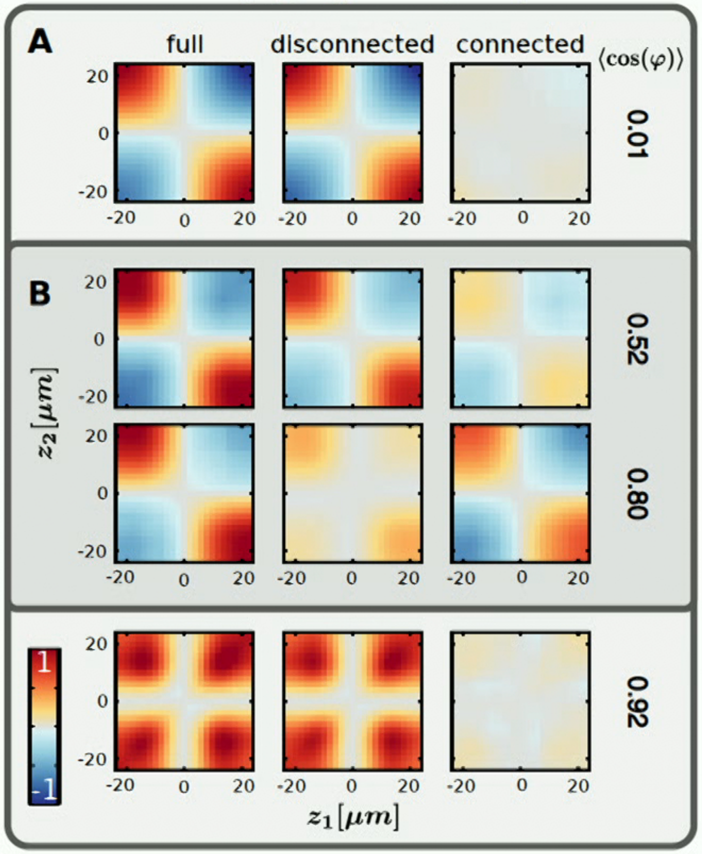
$$\Delta\varphi(z_1, z_2) = \varphi(z_1) - \varphi(z_2)$$

$\Delta\varphi$ *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

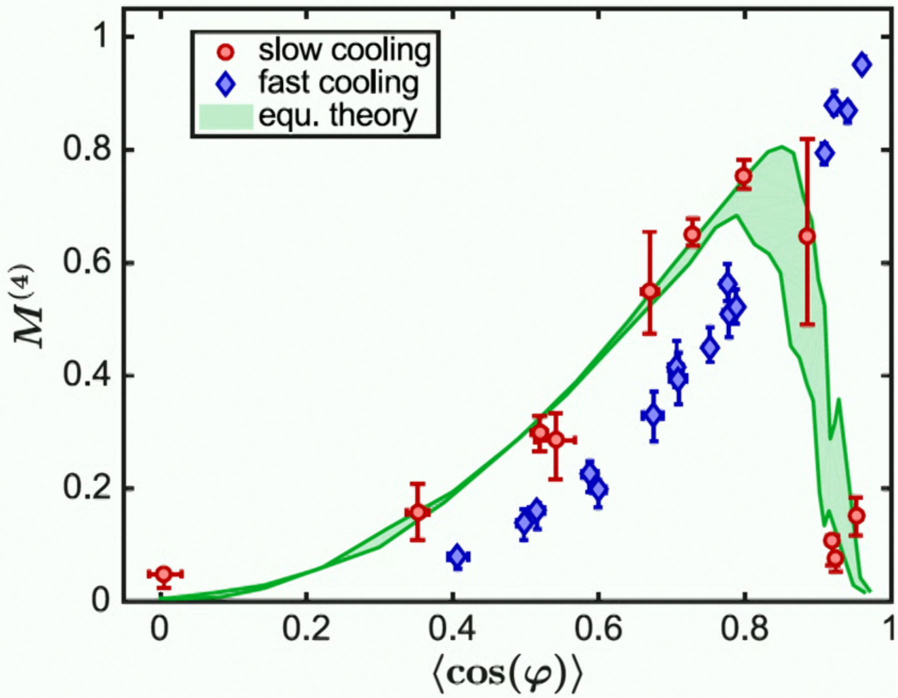
Schweigler et al. Nature 545, 323 (2017)

4th order correlations

Integrated measure

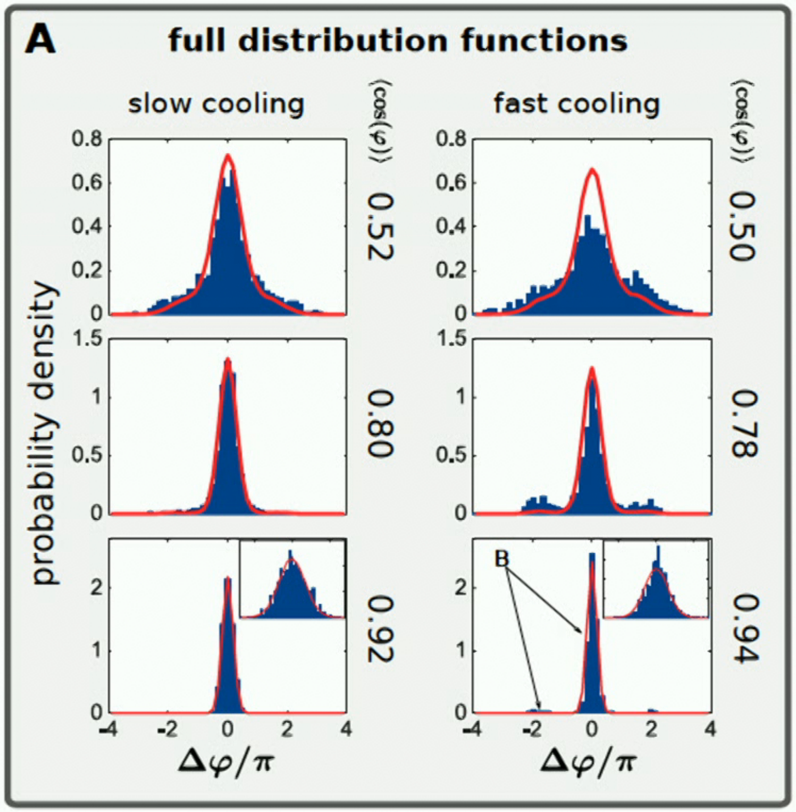
$$M^{(N)} = \frac{\sum_{\mathbf{z}} \left| G_{\text{con}}^{(N)}(\mathbf{z}, 0) \right|}{\sum_{\mathbf{z}} \left| G^{(N)}(\mathbf{z}, 0) \right|}$$

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



Quantifying factorization of correlation functions

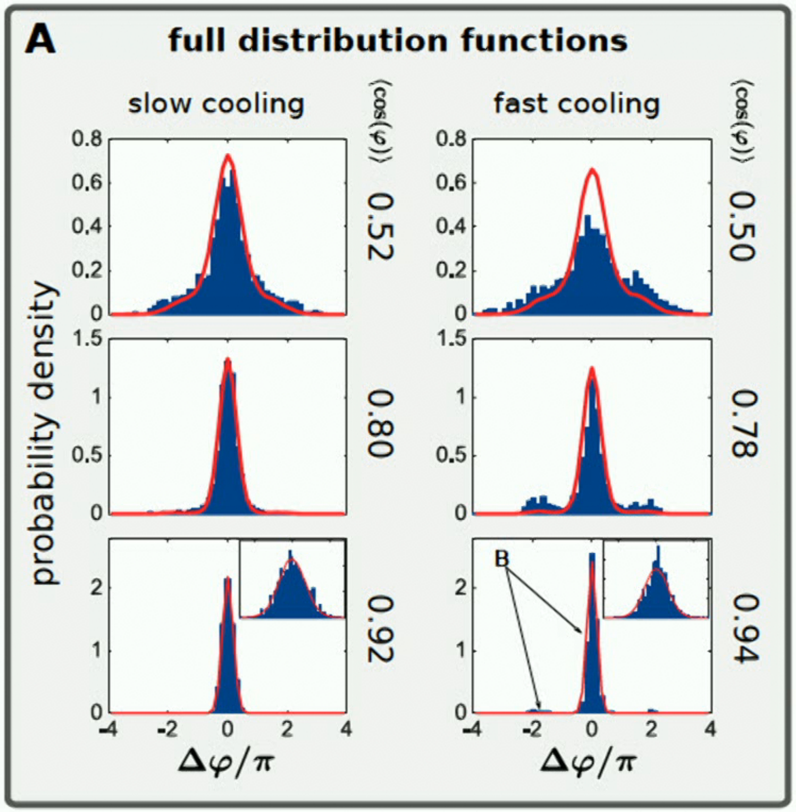
Schweigler et al. Nature **545**, 323 (2017)



- 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

Quantifying factorization of correlation functions

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



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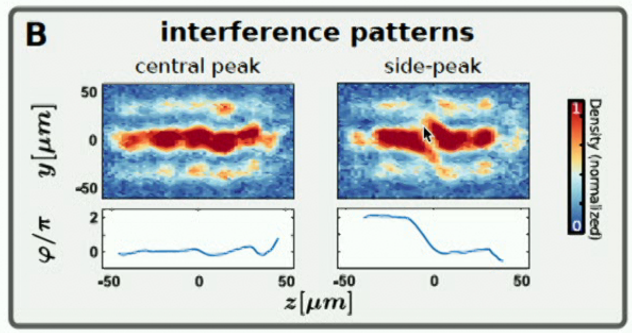
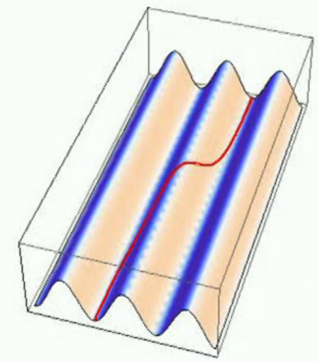
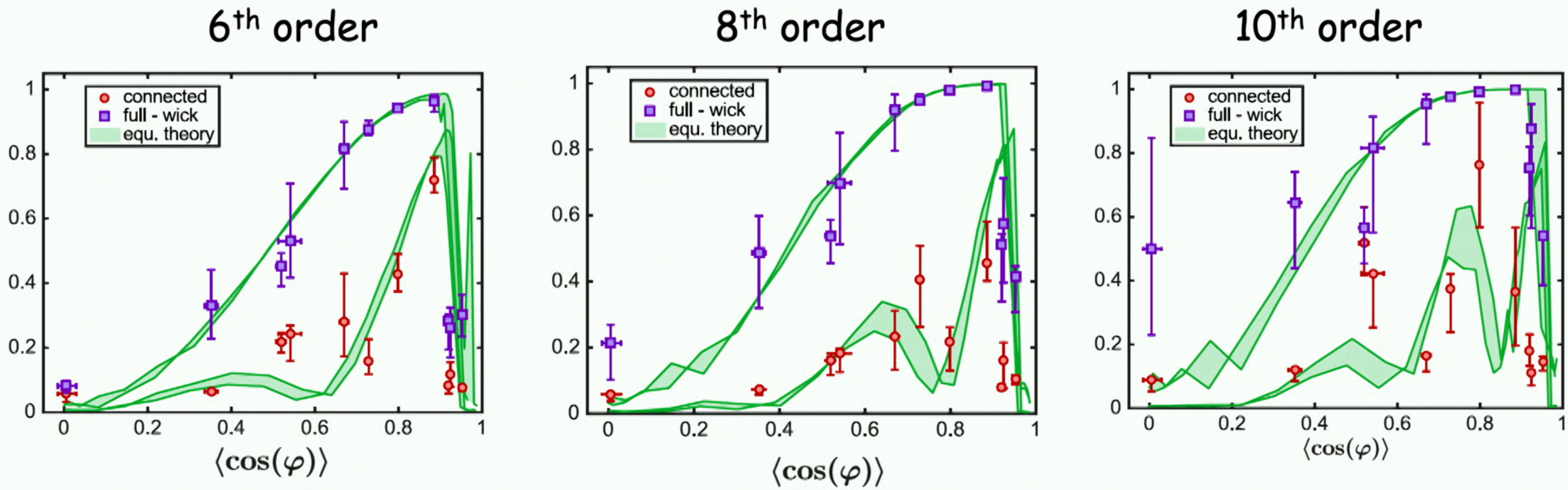




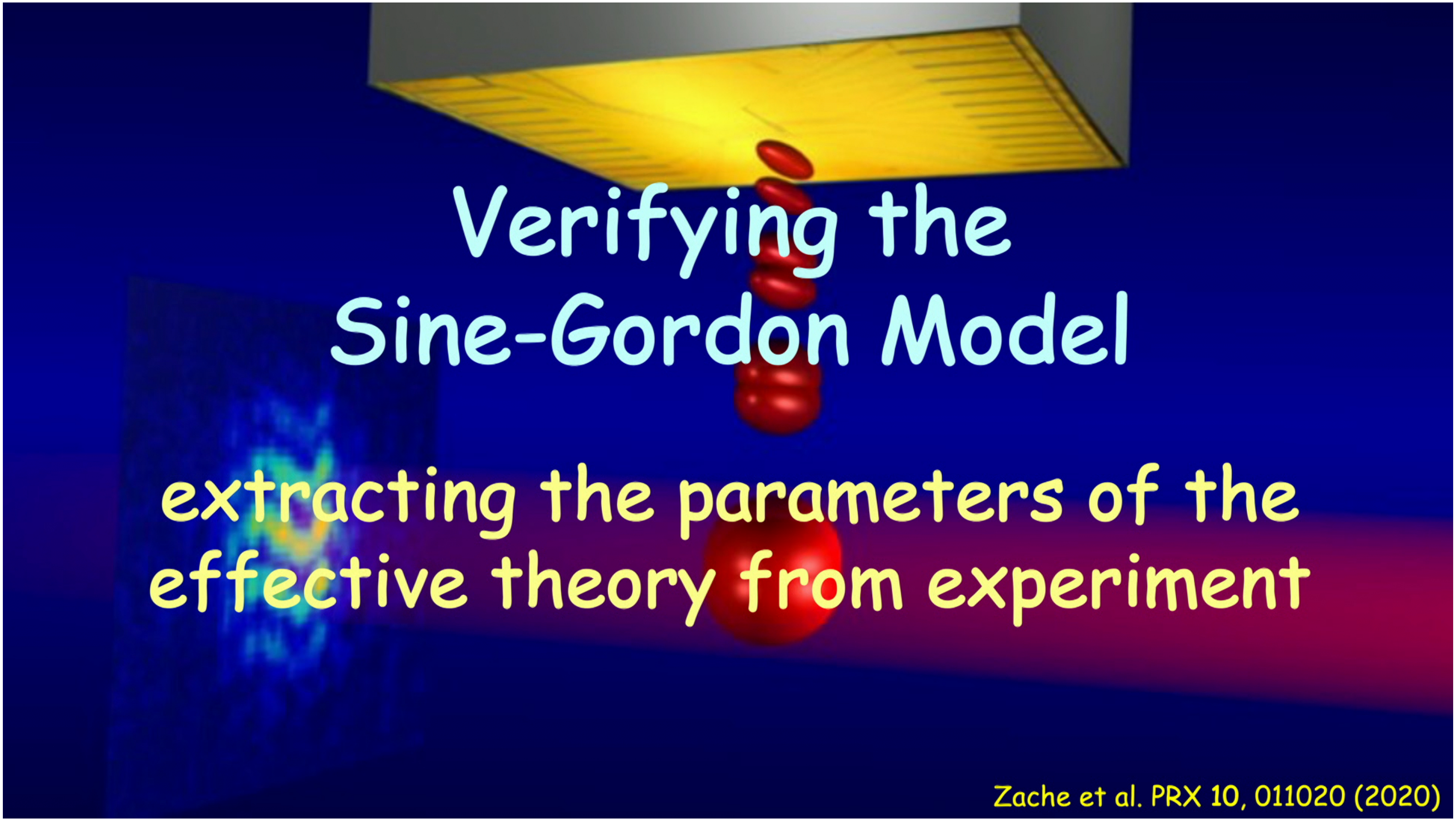
- *SG Solitons* are topological excitations
- Phase fluctuations around *topologically different Vaccua*

Higher order connected correlations

Schweigler et al. Nature 545, 323 (2017)

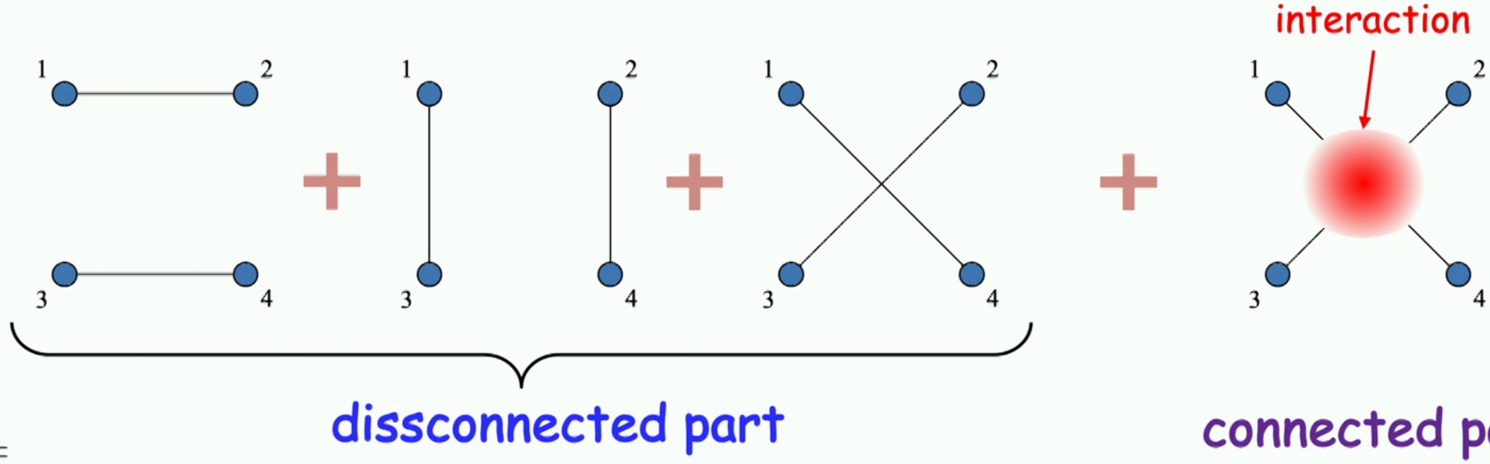


Limit is NOT the data but the
computational complexity of data analysis for strongly fields


Verifying the
Sine-Gordon Model
extracting the parameters of the
effective theory from experiment
Zache et al. PRX 10, 011020 (2020)

Diagrammatics:
one-particle irreducible - 1PI

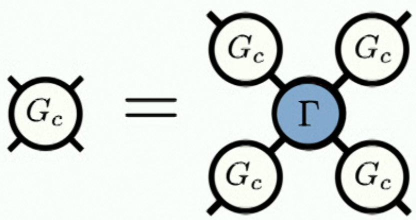
$$G^{(4)}(x_1, x_2, x_3, x_4) =$$



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

$$G^{(2)}(x_1, x_3)G^{(2)}(x_2, x_4) + G^{(2)}(x_1, x_2)G^{(2)}(x_3, x_4) + G^{(2)}(x_1, x_4)G^{(2)}(x_2, x_3)$$

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



1PI correlators:
building blocks of all correlations!

Equal-Time QuFT

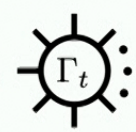
Standard formulation of QuFT is with non-equal time correlators

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

⇒ Equal time formulation of QuFT

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

quantum dynamics leads to a hierarchy of coupled evolution equations
Wetterich *Phys. Rev. E* 56, 2687 (1997)

$i\partial_t$  $= \ldots$

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

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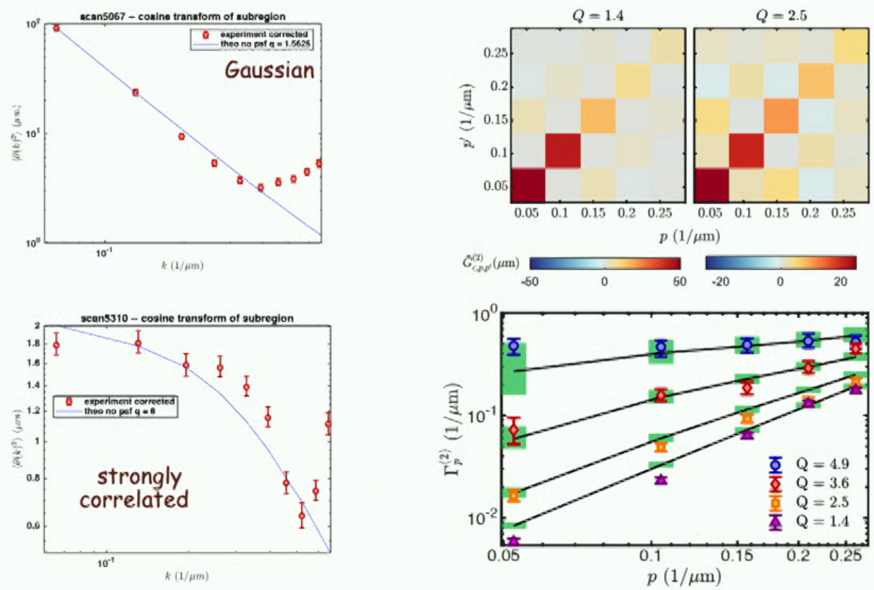
transformed
2-point correlator
(1/propagator)



Extracting the Coupling Constants

Zache et al. PRX 10, 011020 (2020)

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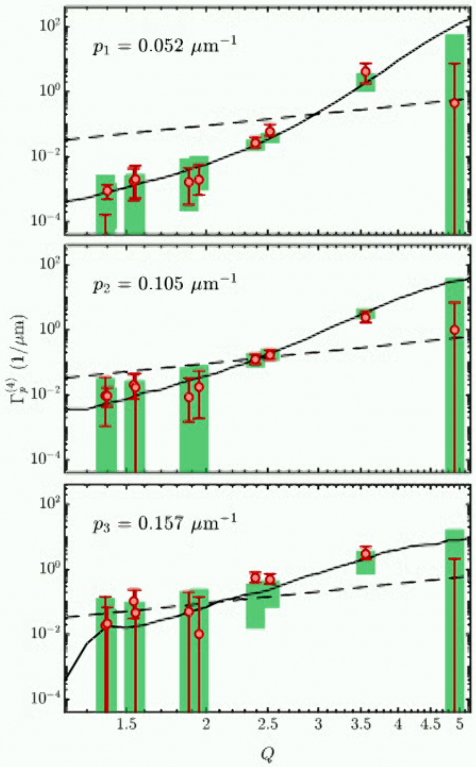
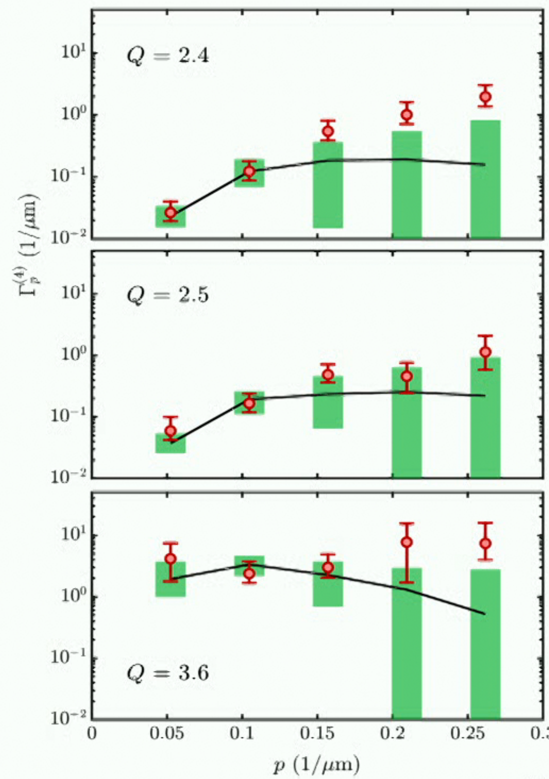
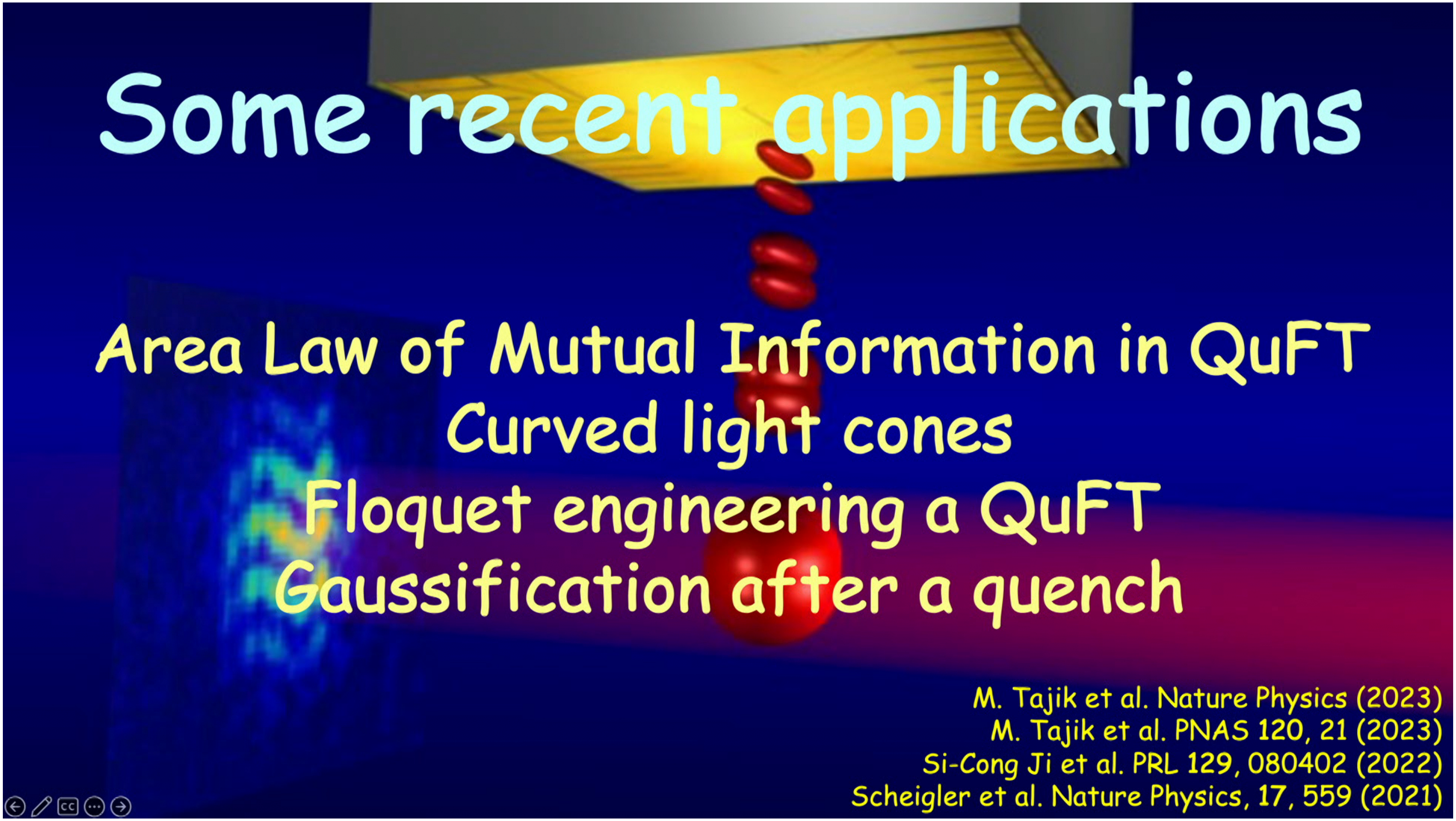
- Transform the correlators to the space of the modes

'amputated' connected
4-point correlator (vertex)



running coupling in SG model




Some recent applications
Area Law of Mutual Information in QuFT
Curved light cones
Floquet engineering a QuFT
Gaussification after a quench
M. Tajik et al. Nature Physics (2023)
M. Tajik et al. PNAS 120, 21 (2023)
Si-Cong Ji et al. PRL 129, 080402 (2022)
Scheigler et al. Nature Physics, 17, 559 (2021)

Mutual information
Shared information content between two subsystems

- **Definition:**

$$I(A:B) = S_A + S_B - S_{A\cup B}$$

von Neumann entropy for subsystem A

$$S_A = -\mathrm{Tr}(\rho_A \ln \rho_A) \quad \text{with} \quad \rho_A = -\mathrm{Tr}_B(\rho_{A\cup B})$$

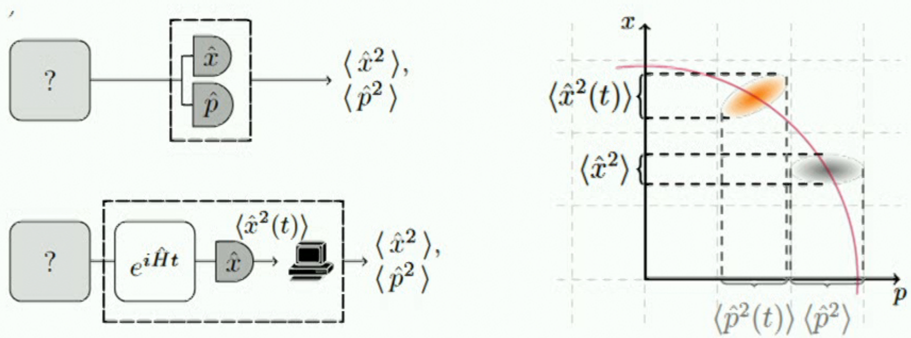
- **Motivation:**
  - Captures the total amount of information of a subsystem about another one.
  - It gives the entanglement entropy in the limit of zero temperature.
  - Shows an **area law** for gapped Hamiltonians.
  - Can the area law be verified experimentally for a system with decaying correlations?

Many Body Tomography

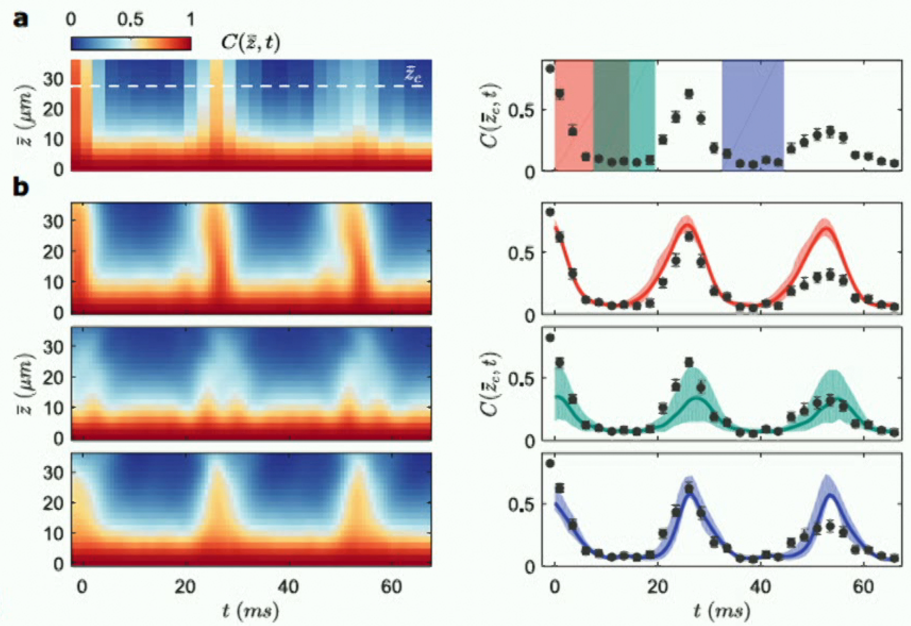
In interference experiments we measure phase quadrature

M. Gulza et al. Communications Physics 3, 12 (2020)
arXiv:1807.04567

Idea:
'free evolution' rotates the Wigner function of the modes in the low energy effective field theory



Example:
data from recurrence experiment



Repeated measurement => tomographic slicing

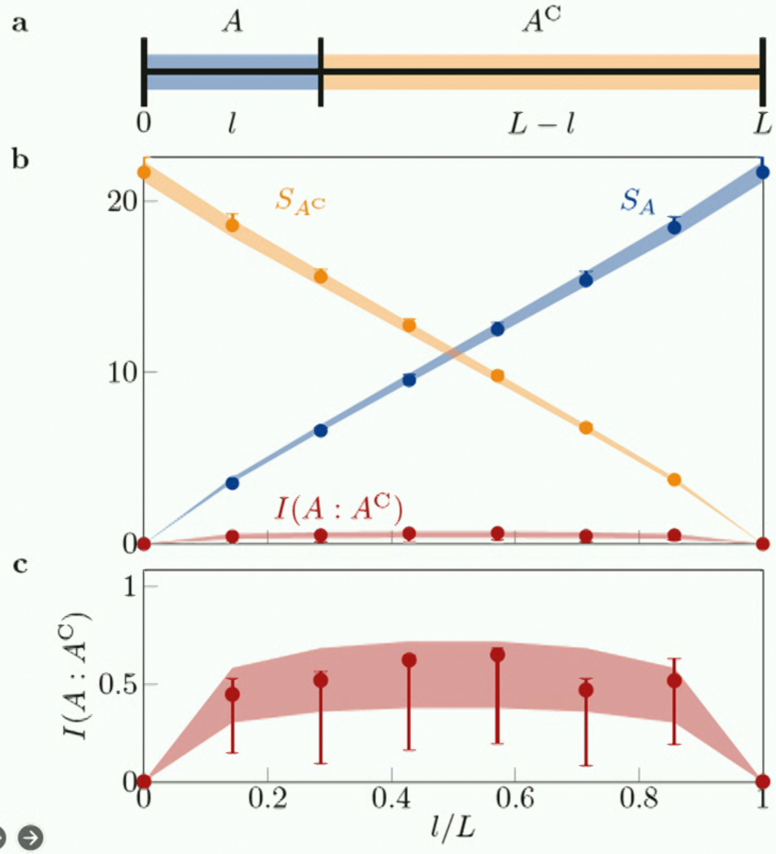
allows reconstruction of the density matrix

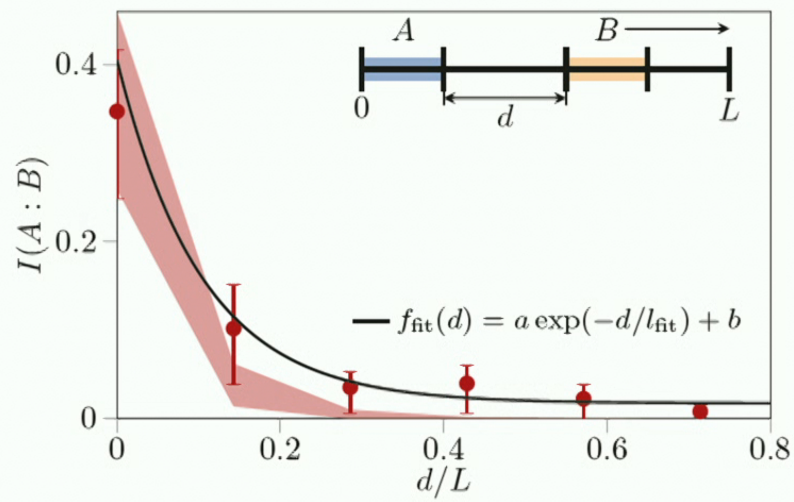
Will give excess to v. Neumann entropy, mutual information and entanglement etc ...

V. Neumann <-> Mutual Information
Experiment in Klein-Gordon

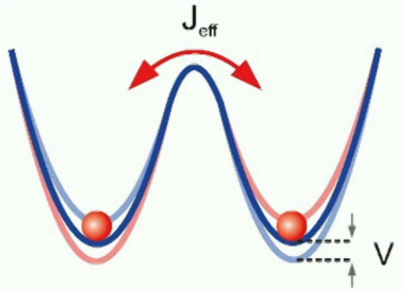
$$I(A:B) = S_A + S_B - S_{A\cup B}$$

M. Tajik et al. Nature Physics (2023)
arXiv:2206.10563

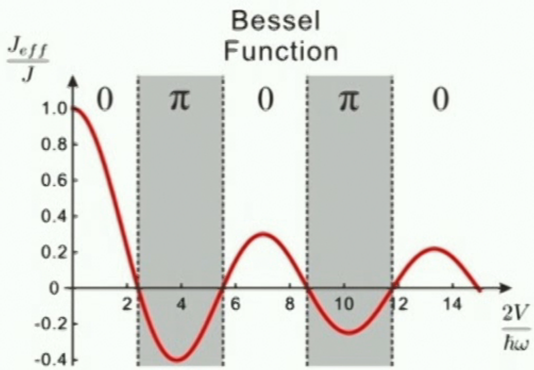




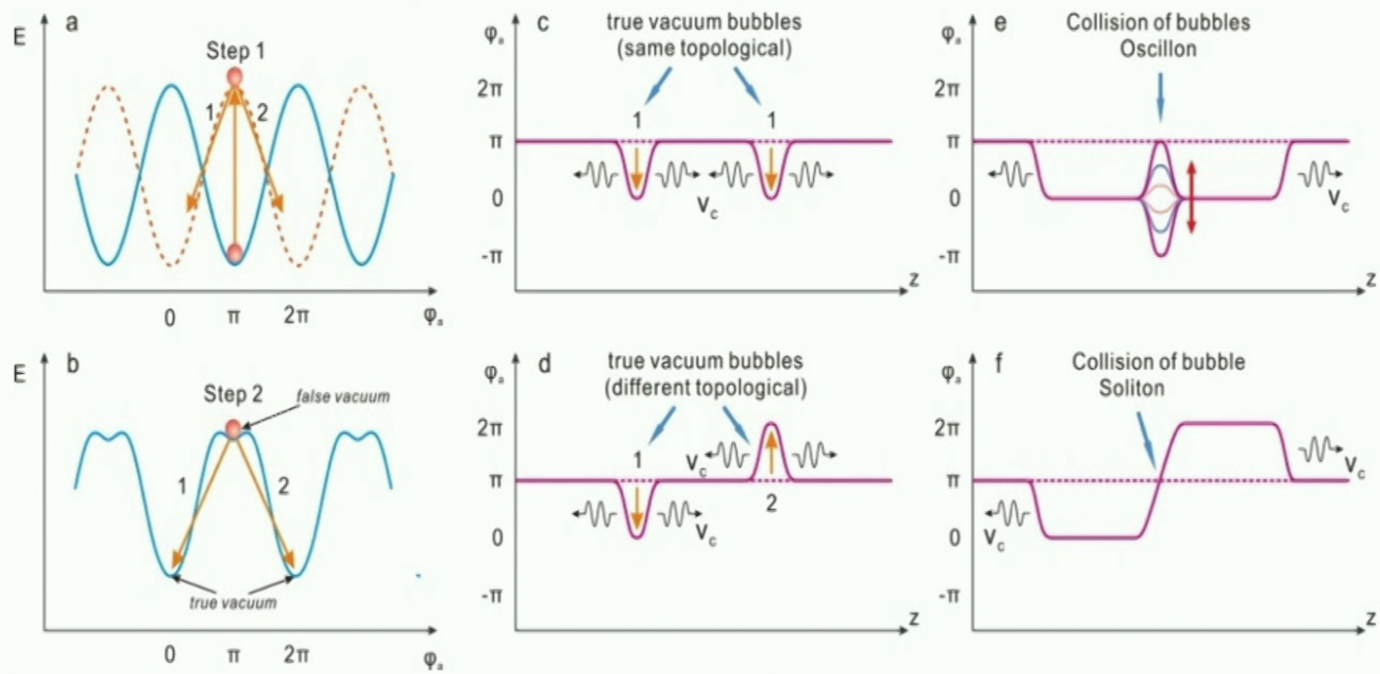
Floquet Engeineering a SG Quantum Field



$$J_{eff} = J_0 \cdot Bessel_0\left(\frac{2V}{\hbar\omega}\right)$$



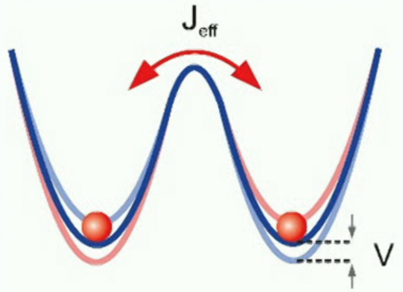
Floquet Engeineering a Sine Gordon QuTF



☹ **observed too much heating** ☹

Floquet Engeineering a SG Quantum Field

Si-Cong Ji et al. PRL 129, 080402 (2022)



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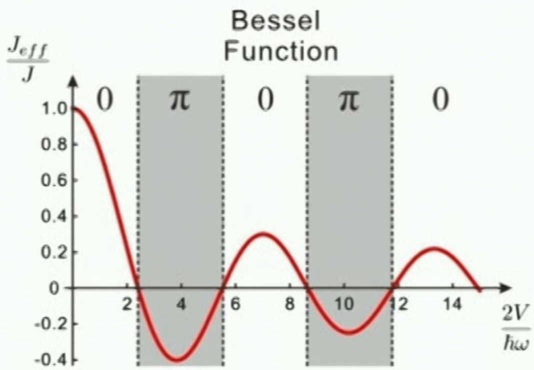
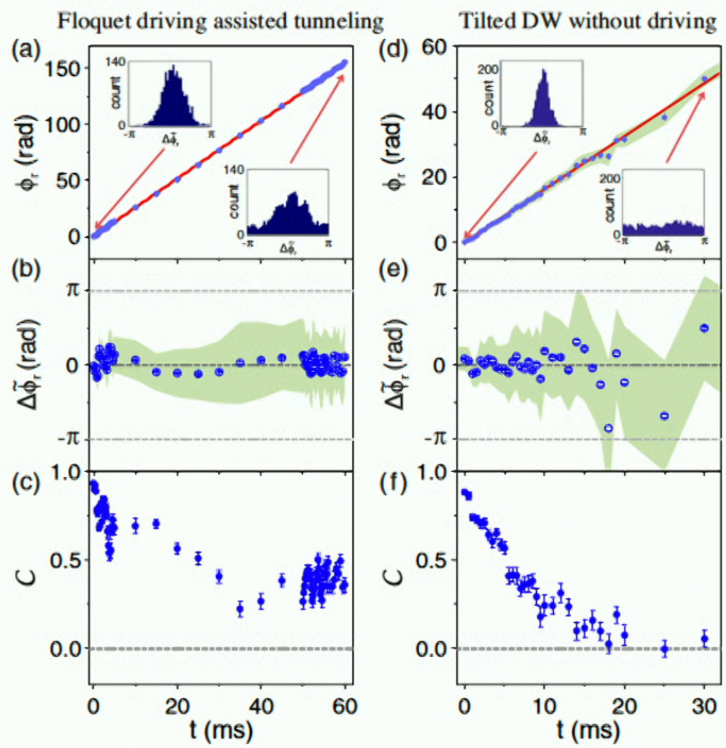
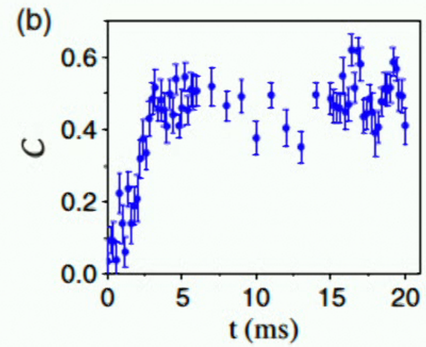
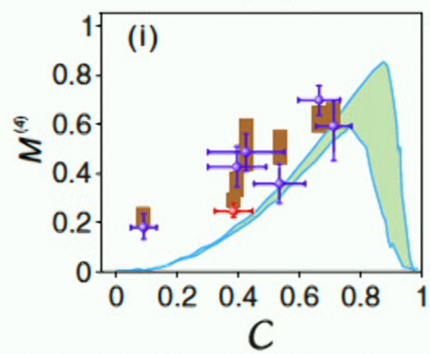


Floquet Engeineering a Sine Gordon QuTF

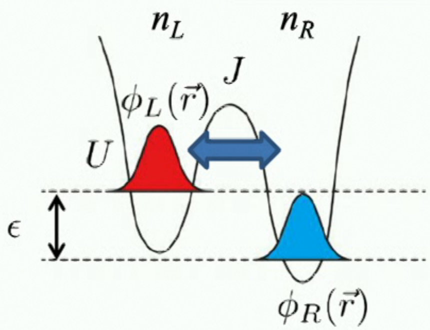




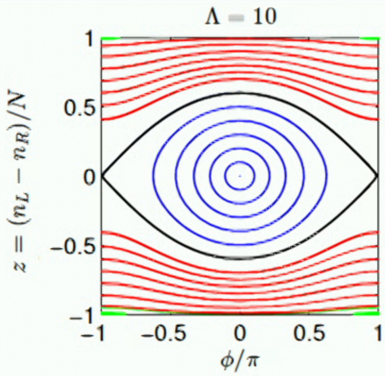


Decay of Self-Trapping

? Decay of false vacuum in a 1d bosonic Josephson Junction ?

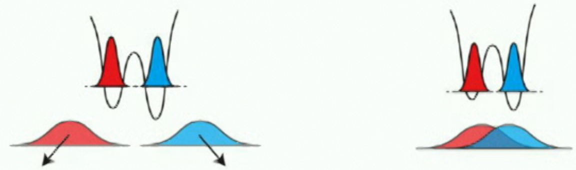


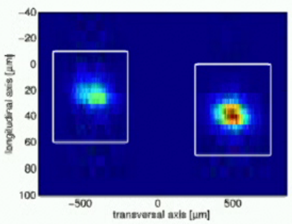
0D: self trapping
1D: Decay of self trapped state

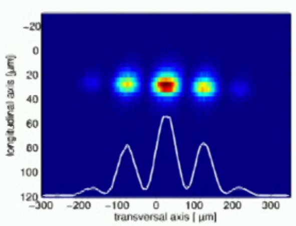


population imbalance measurement

relative phase measurement







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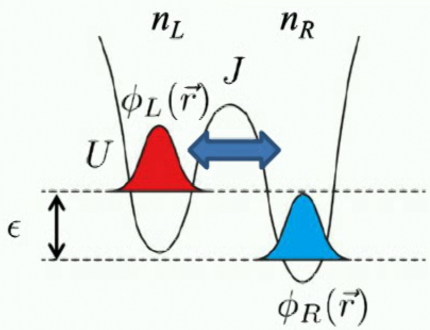

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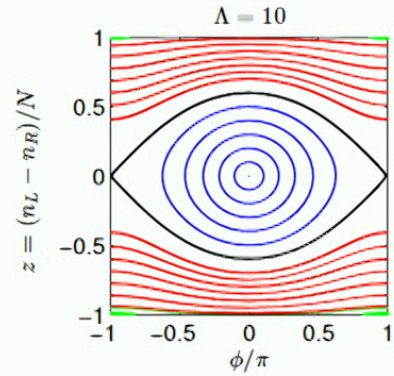
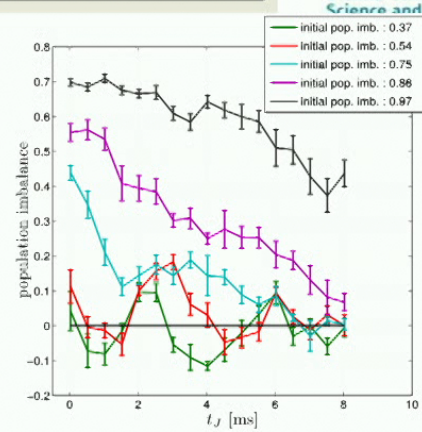
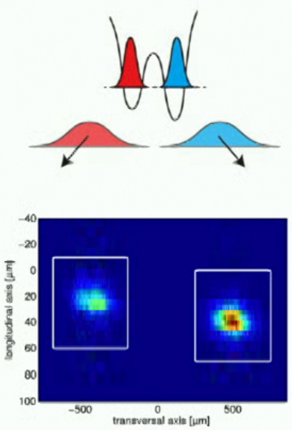
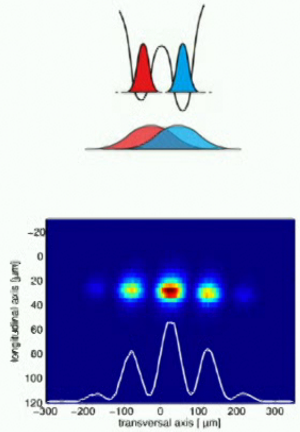


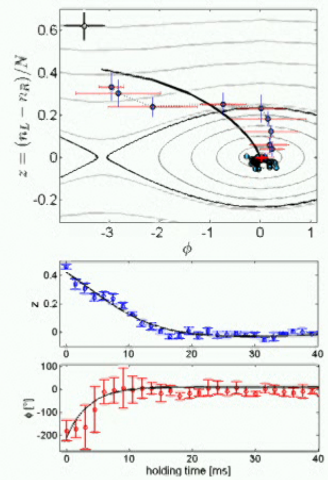


population imbalance measurement

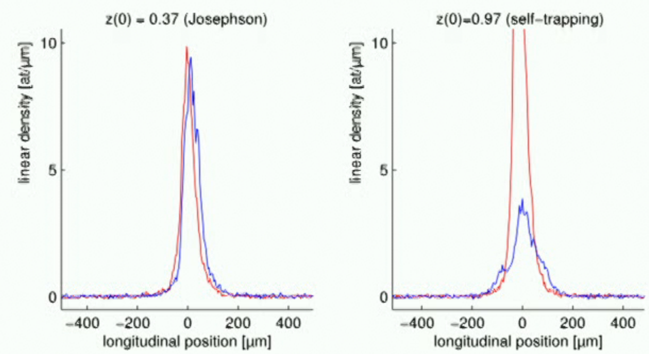


relative phase measurement





longitudinal momentum



J. Schmiedmayer: Quantum Simultors for QuFT

Older quantum simulations of QuFT physics

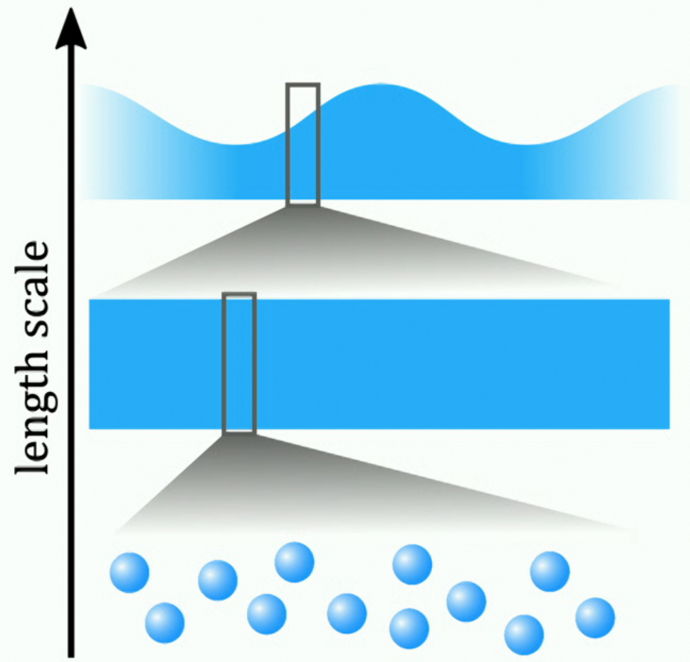
Relaxation in isolated system:	Hofferberth et al Nature **449**, 324 (2007)
Pre-thermalization:	Gring et al., Science **337**, 1318 (2012)
	Kuhnert et al., PRL **110**, 090405 (2013)
Light cone spreading of correlations:	Langen et al., Nature Physics **9**, 460 (2013)
Generalized Gibbs Ensemble:	Langen et al., Science **348**, 207 (2015)
Recurrences in QuFT:	Rauer et al. Science **360**, 307 (2018)
Universality in non-equilibrium:	Erne et al., Nature **563**, 225 (2018)


Outlook Sine Gordon
Hamiltonian learning
SG close to quantum vacuum
SG out of equilibrium
Decay of self trapping
...
Pokrovsky-Talapov model
Other SG models
www.AtomChip.org


Emergent description of 1d systems
Luttinger Lqiuid
<->
Generlaized Hydro Dynamics
Møller et al. SciPost Physics 8, 041 (2020)
Møller et al. PRL 126, 090602 (2021)
Cataldini et al. Phys. Rev. X 12, 041032 (2022)

Emergence of hydrodynamics
in 1d systems

B. Bertini
JS Caux
B. Doyon,
J. Dubai
....



Macroscopic: Slow variations

Thermodynamic Bethe Ansatz

Mesoscopic: Homogeneous
Local equilibrium

Microscopic: Atoms

Generalized Hydro Dynamics (GHD)
OA. Castro-Alvaredo et al., PRX 6, 041065 (2016)
B. Bertini et al., PRL. 117, 207201 (2016)
+ very many papers since then

Emergence of hydrodynamics

$$\partial_t \rho(\theta,t,z) + \partial_z \left(v^{\mathrm{eff}}(\theta,t,z)\ \rho(\theta,t,z) \right) = 0$$

B. Bertini
JS Caux
B. Doyon,
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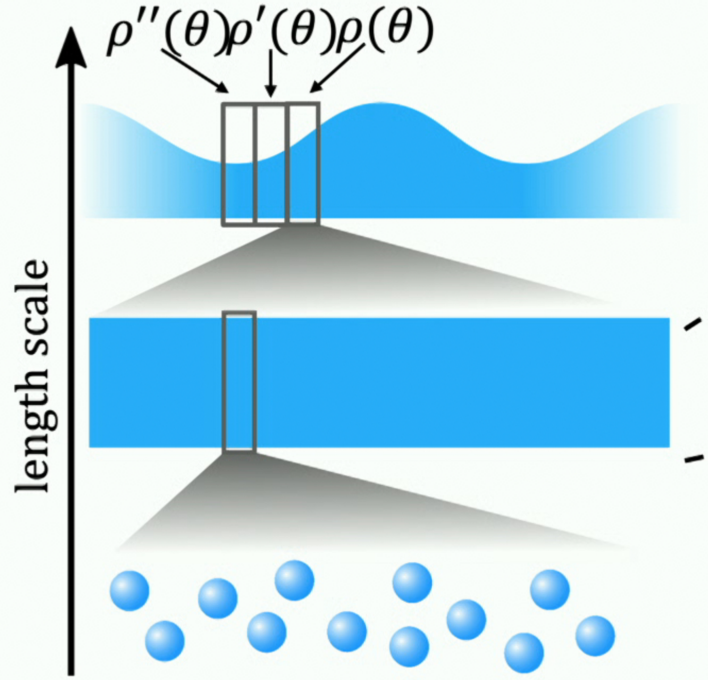
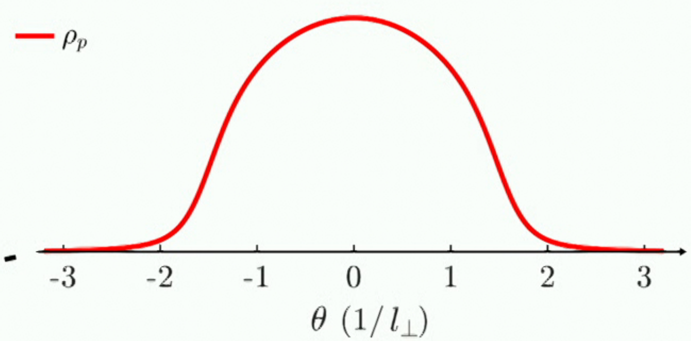
....



Thermodynamic state fully characterised by distribution of quasi-momenta (rapidities θ)



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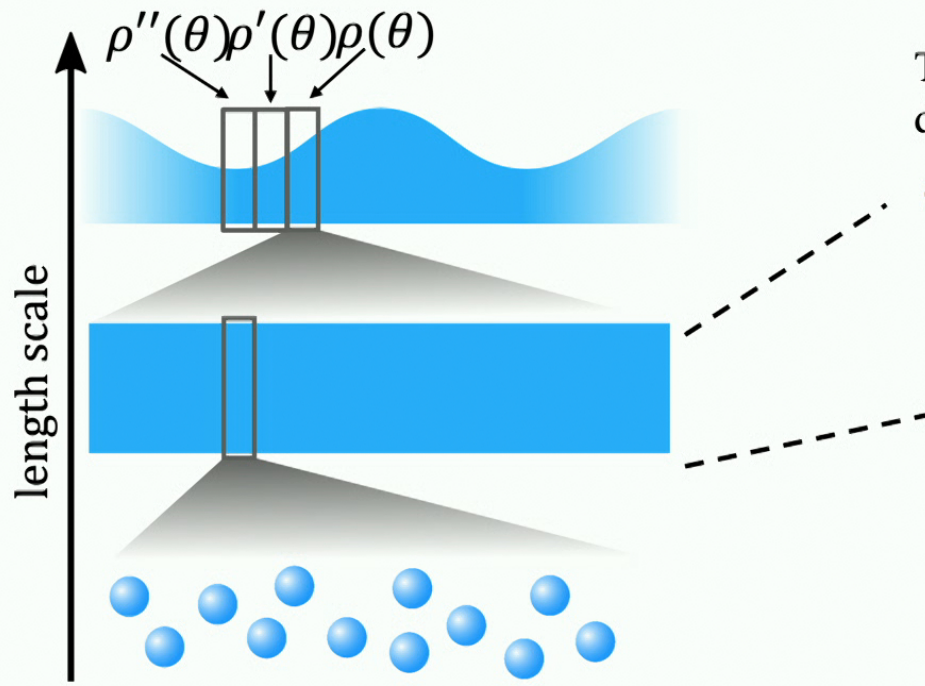
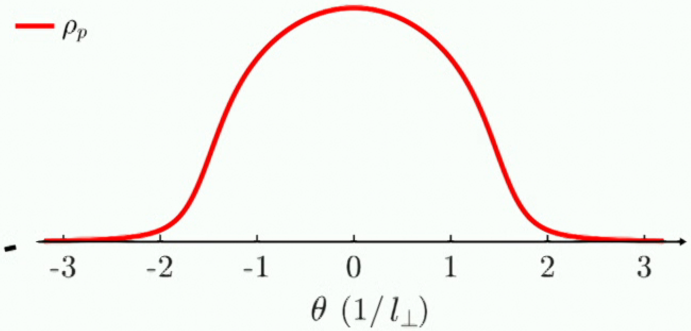
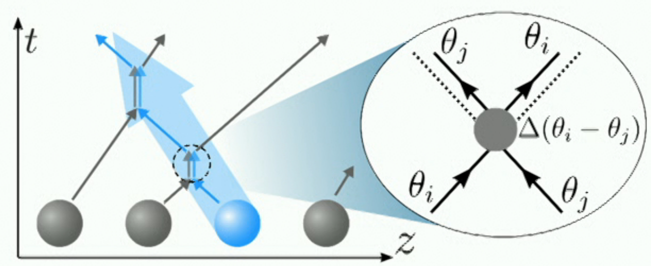
J. Dubai
....



Thermodynamic state fully characterised by distribution of quasi-momenta (rapidities θ)



Rapidities behave like Fermions

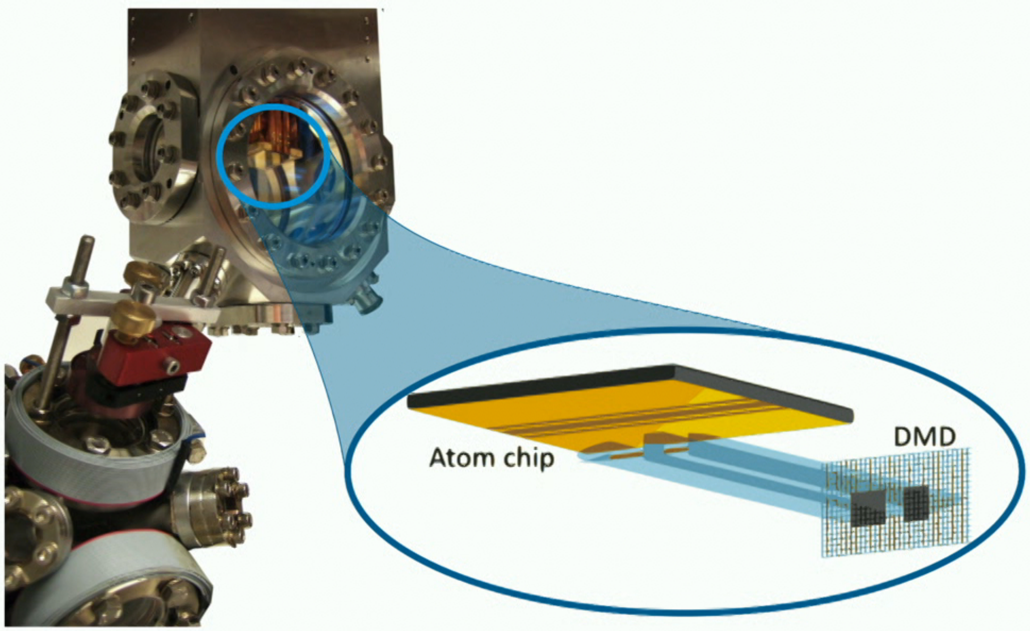


Excitating a single mode in a 1d quantum gas

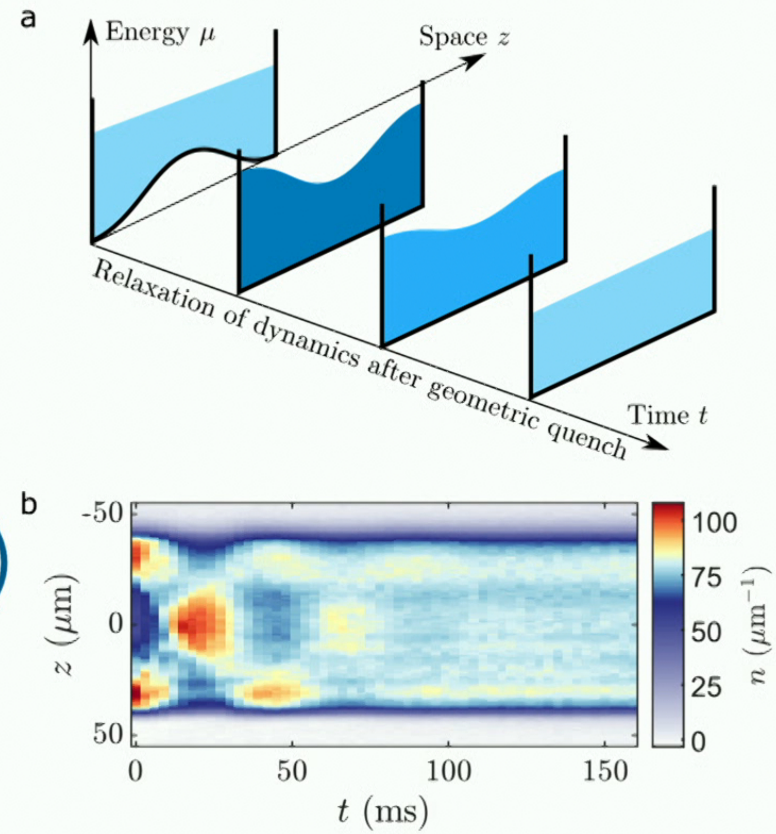
F. Cataldini, F. Möller

Cataldini et al. Phys. Rev. X 12, 041032 (2022)

1. Imprint cosine-shaped density perturbation.



Tajik et al. Optics Express, 27, 33474 (2019)

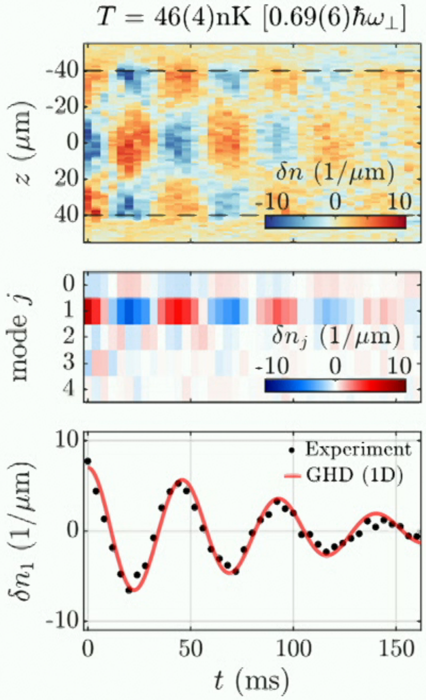


Relaxation dynamics

Vienna Center for Quantum Science and Technology

Cataldini et al. Phys. Rev. X 12, 041032 (2022)

low temperature
small amplitude



Long lived dynamics!

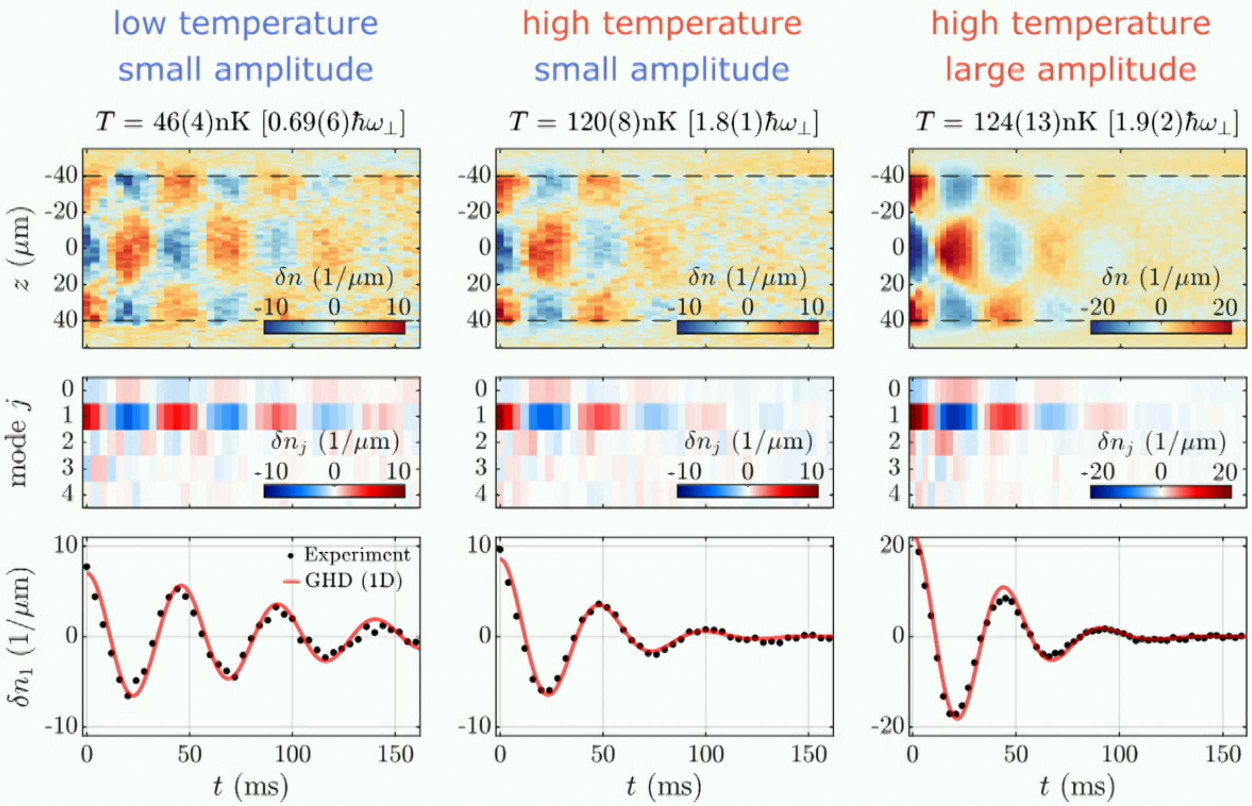
(Almost) single mode excitation!

Fast damping of the phonon mode

GHD gives a perfect description of the damping
no free parameters

Relaxation dynamics

Cataldini et al. Phys. Rev. X 12, 041032 (2022)



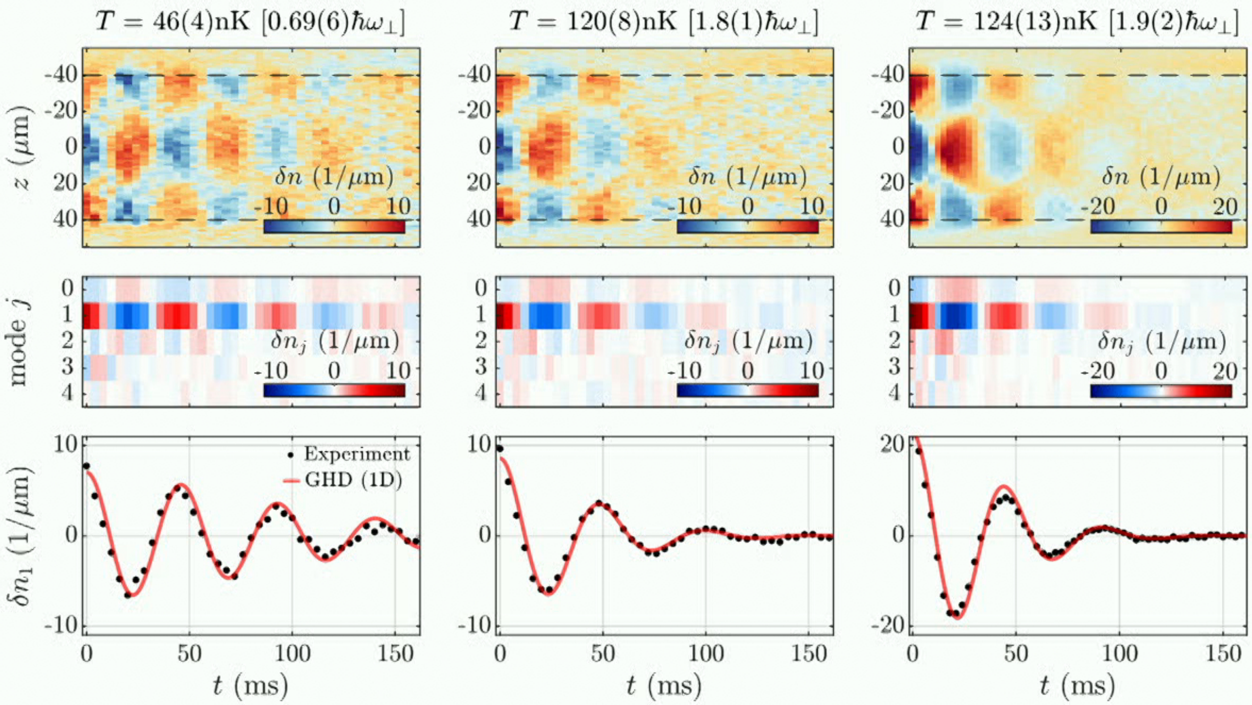
Standard 1D condition:

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

Relaxation dynamics

Cataldini et al. Phys. Rev. X 12, 041032 (2022)

low temperature small amplitude | high temperature small amplitude | high temperature large amplitude



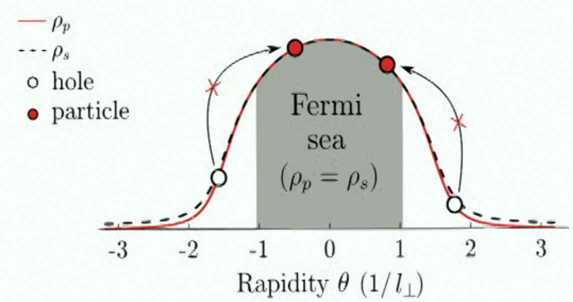
Standard 1D condition:

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

Even far above this condition, the observed relaxation is consistent with 1D GHD theory!

Interpretation:

In a **box** the rapidities fill the complete Fermi sea and thereby prevent thermalizing collisions much longer.

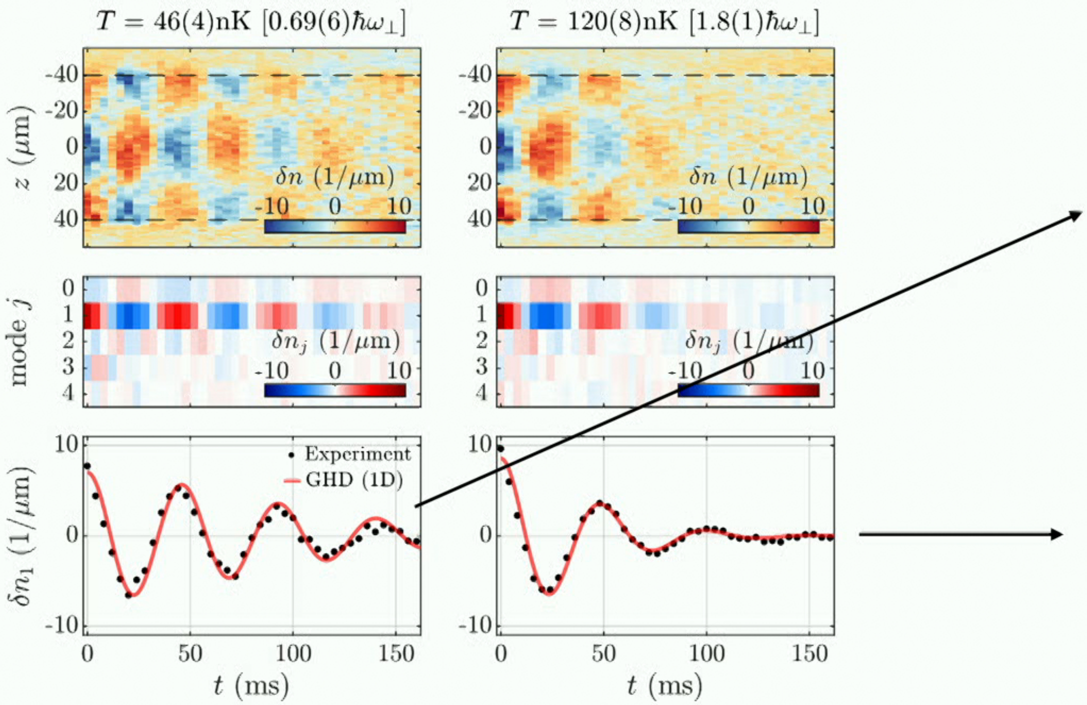


Relaxation dynamics

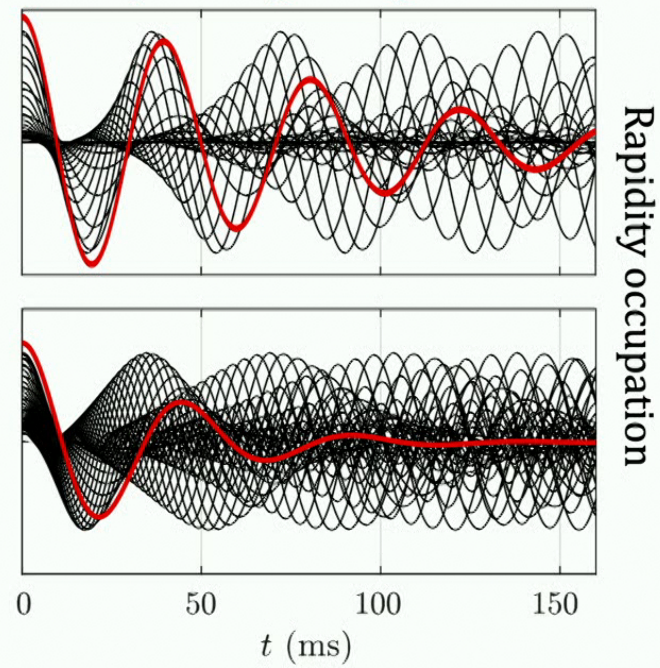
Cataldini et al. Phys. Rev. X 12, 041032 (2022)

low temperature
small amplitude

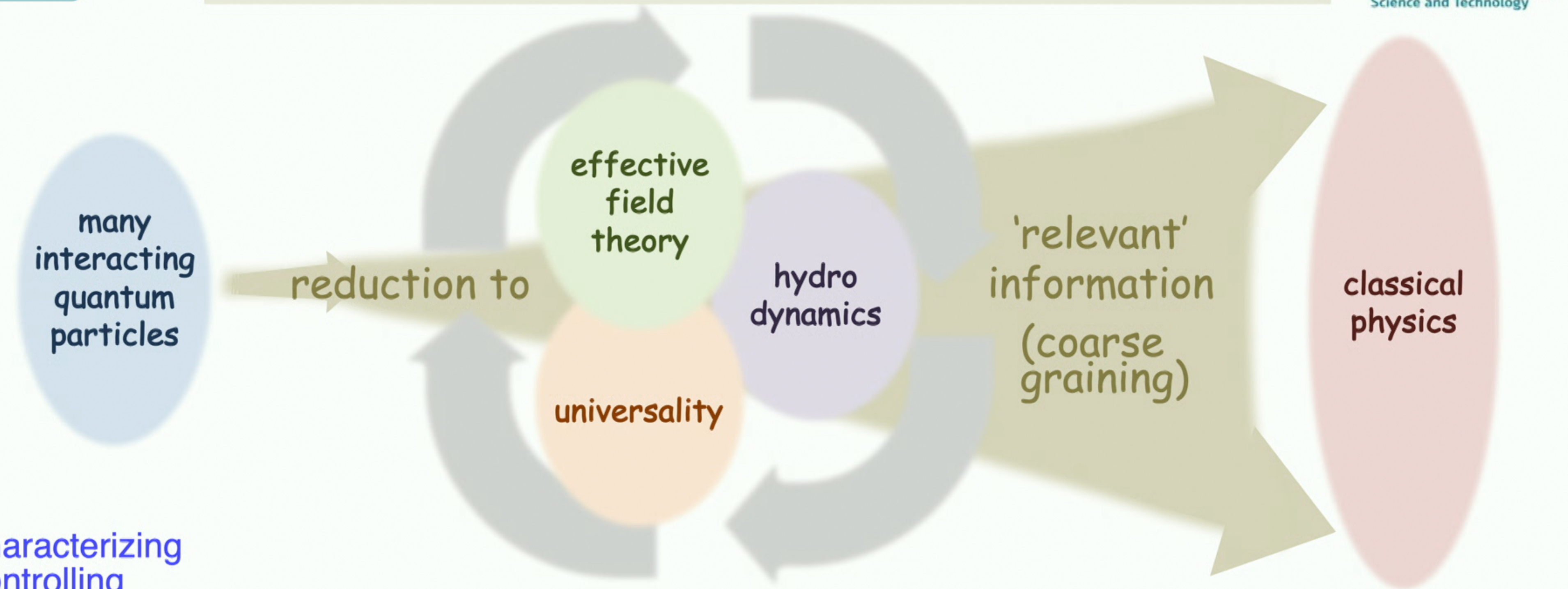
high temperature
small amplitude



Relaxation is caused by dephasing of rapidities!

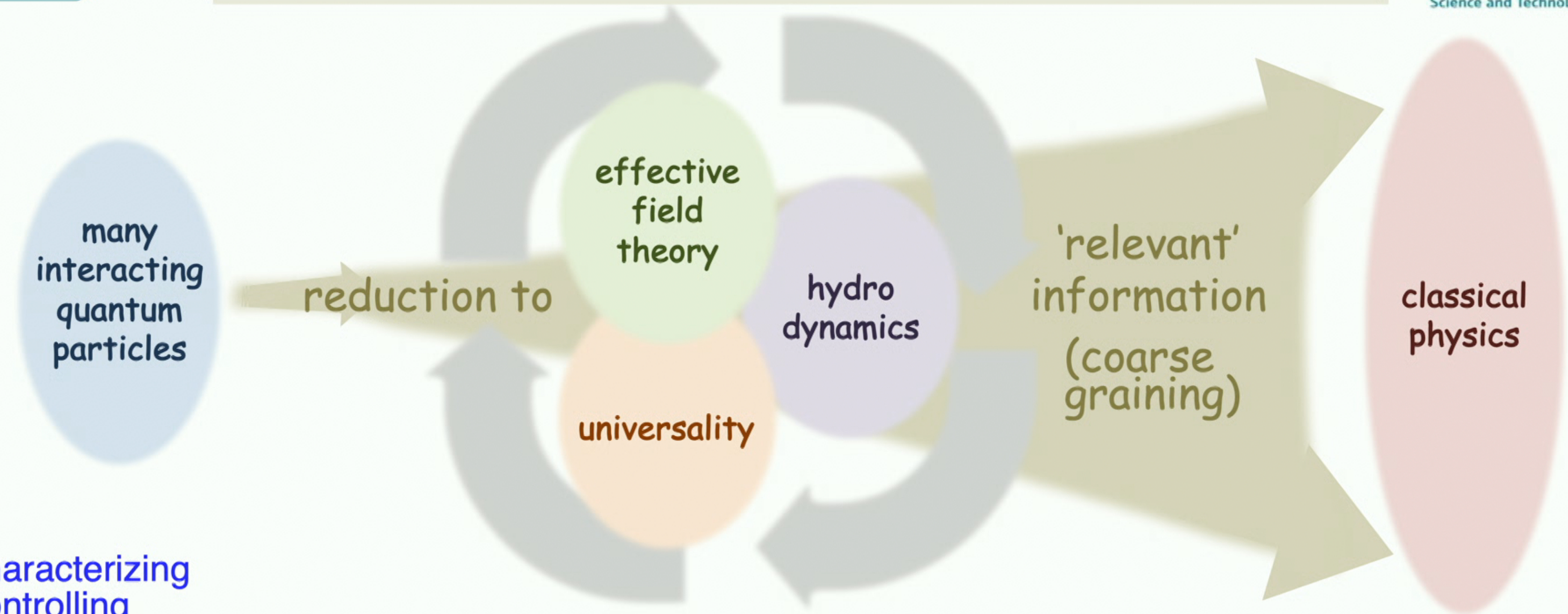


Emergence in Quantum Physics



Characterizing
Controlling
in full detail
is impossible

Emergence in Quantum Physics



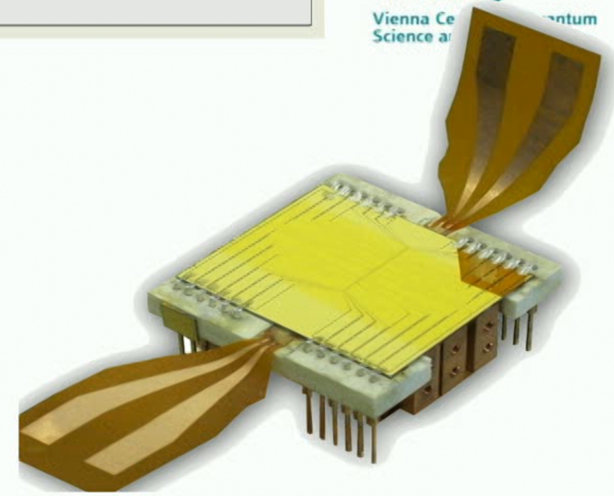
Characterizing
Controlling
in full detail ⇒ "Loss" of information
is impossible ⇒ Reduction to "relevant" information
⇒ Emergence of novel descriptions

Experiments with **ultra cold quantum gases**:
Measure each constituent with unit efficiency
Computational complexity of data analysis is limitation !
Choose which part of the information to retain/analyse
Experimentally study emergence in detail

What have we learned

- Higher order correlation functions (full distribution functions) and the question if they factorize gives insight in the effective quantum field theories describing the many body system.
- Verified Sine-Gordon model as emergent from the microscopic physics of two tunnel coupled super fluids
- Identified the topological excitations in the SG model.
- Extracted parameters of the model from experimental data
- Compared two emerging descriptions of 1d systems: Luttinger Liuid <-> GHD (emerging fermionic excitations)
- Building and probing quantum field theories in the lab as emergent quantum simulators
- Verify and probe emergent models

Schweigler et al., Nature **545**, 323 (2017) arxiv: 1505.03126
Zache et al. PRX, 10, 011020 (2020)
Cataldini et al. Phys. Rev. X 12, 041032 (2022)
Tajik et al. Nature Physics (2023)



Quantum Field Simulator Experiments:
Hofferberth et al. Nature **449**, 324 (2007)
Gring et al., Science **337**, 1318 (2012)
Kuhnert et al., PRL **110**, 090405 (2013)
Smith et al., NJP **15**, 075011 (2013)
Langen et al., Nature Physics **9**, 460 (2013)
Berrada, et al., Nat. Comm **4**, 2077 (2013)
Geiger et al., NJP **16** 053034 (2014)
Van Frank, et al., Nat. Comm **5**, 4009 (2014)
Langen et al., Science **348**, 207 (2015)
Steffens, et al., Nature Comm. **6**, 7663 (2015)
Rauer, et al., PRL **116**, 030402(2016)
Rauer et al. Science **360**, 307 (2018)
Erne et al., Nature **563**, 225 (2018)
Scheigler et al. Nature Physics, **17**, 559 (2021)
Si-Cong Ji et al. PRL **129**, 080402 (2022)
Tajik et al. PNAS **120**, 21 (2023)

Atom Chip Experiment

R. Bücker, T. Berrada, S. vanFrank, M. Pigeur,, M. Bonneau, F. Borselli,
M. Maiwöger, TianTian Zhou, Y Kuratnikov, M. Prüfer

F. Cataldini, F. Moller, B. Rauer, Th. Schweigler, M. Tajik, S. Erne, M. Prüfer

Atom Chip Fabrication

D. Fischer, M. Trinker, M. Schamböck (ATI)
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Theory Collaboration

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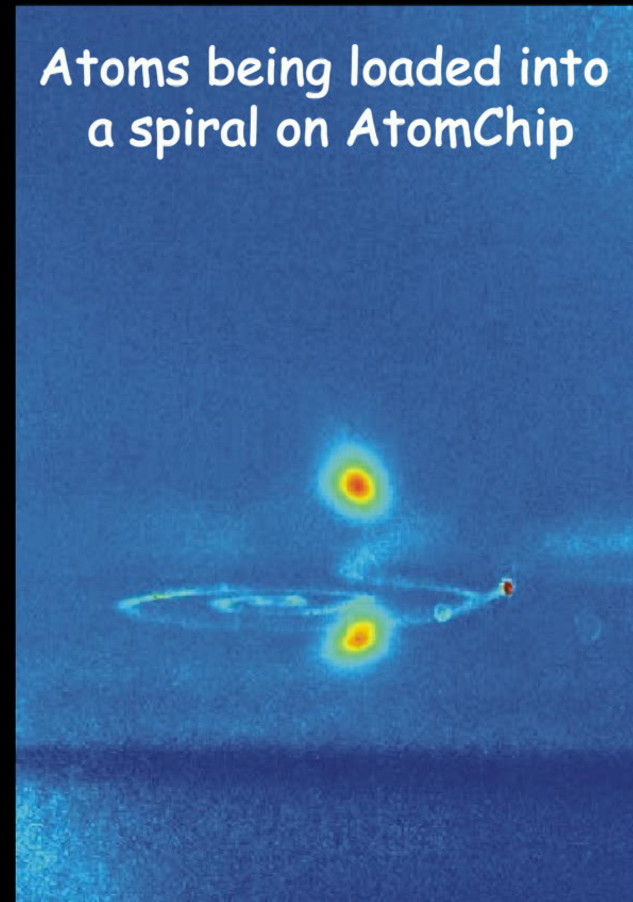
EU: SIQS, QIBEC, AQuS, …
AT: FWF, CoQuS, Wittgenstein, Stadt Wien
ERC AdG: QuantumRelax + EmQ



www.AtomChip.org