Universal dynamics and non-thermal fixed points

Sebastian Erne
Atominstitut, Technische Universität Wien
sebastian.erne@tuwien.ac.at

Non-Equilibrium Universality in Many-Body Physics

27-9-2021 @KITP

If you cannot measure it, it’s not physics

(paraphrased: William D. Phillips, FQMT’19)

If you cannot measure it, it’s not physics

(paraphrased: William D. Phillips, FQMT’19)

From one

to few

to many

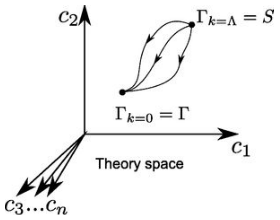
In the many-body limit of QFT, the Hamiltonian, microscopic (‘bare’) interactions, many-body eigenstates,... often play a less significant role!

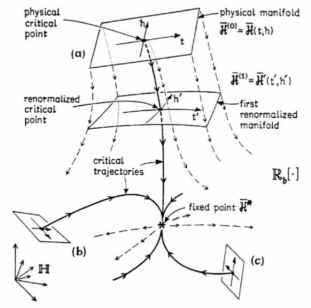
→ *complexity prevent measurement of all details*

Better: Phrase the Problem in accessible (i.e. observable) quantities

Correlations

Any QFT completely determined by its correlations

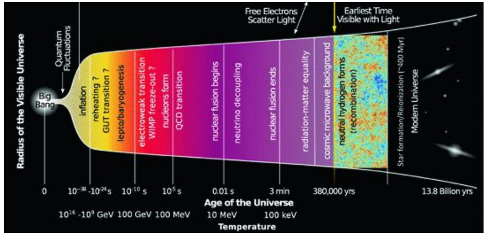




Schwinger Proc. Natl. Acad. Sci. USA 37, 206 452–459 (1951)
RG: Kadanoff, Wilson, Fisher, Polchinski, Morris, Wetterich, ...

If you cannot measure it, it's not physics

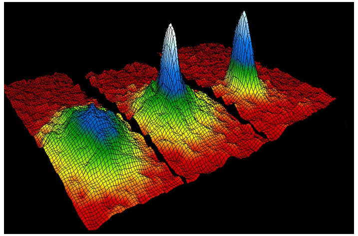
(paraphrased: William D. Phillips, FQMT'19)



'Universality' and

⟷

analogue quantum simulators



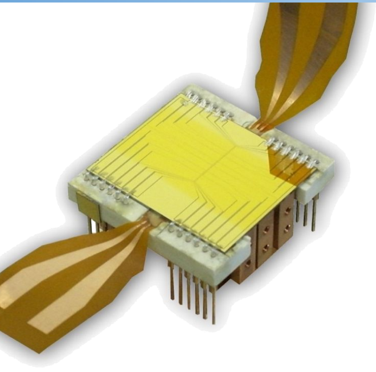
What can we learn about the fundamental processes?

➔ Quantum field theories	⟷	emergent / effective QFT descriptions
➔ Re-/Preheating, KZ, ...	⟷	Universality classes, critical exponents, ...
➔ False vacuum decay	⟷	first-order phase transitions
➔ General relativity	⟷	non-trivial geometries
➔ Black holes ➔ Inflation ➔ Unruh radiation	⟷	analog horizons
➔ Defects, phases of matter, …	⟷	symmetry, topology, …

Outline

- Cooling quenches on an AtomChip
- Kibble-Zurek mechanism <-> short time dynamics
- Non-thermal fixed points <-> intermediate times and relaxation
- Scaling dynamics in He^* condensation <-> preliminary results!
- Outlook & open questions

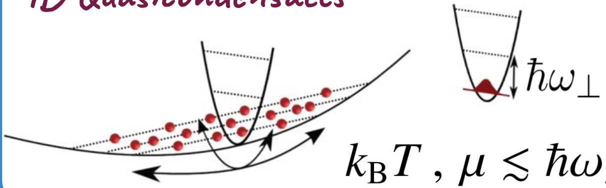
Cooling quenches on an AtomChip



AtomChip Integrated Circuits for Ultracold Quantum Matter

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

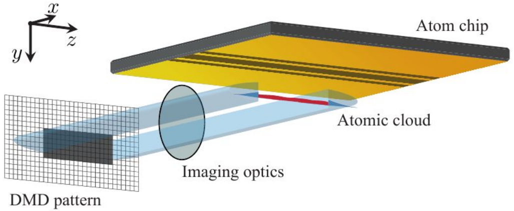
1D Quasicondensates



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

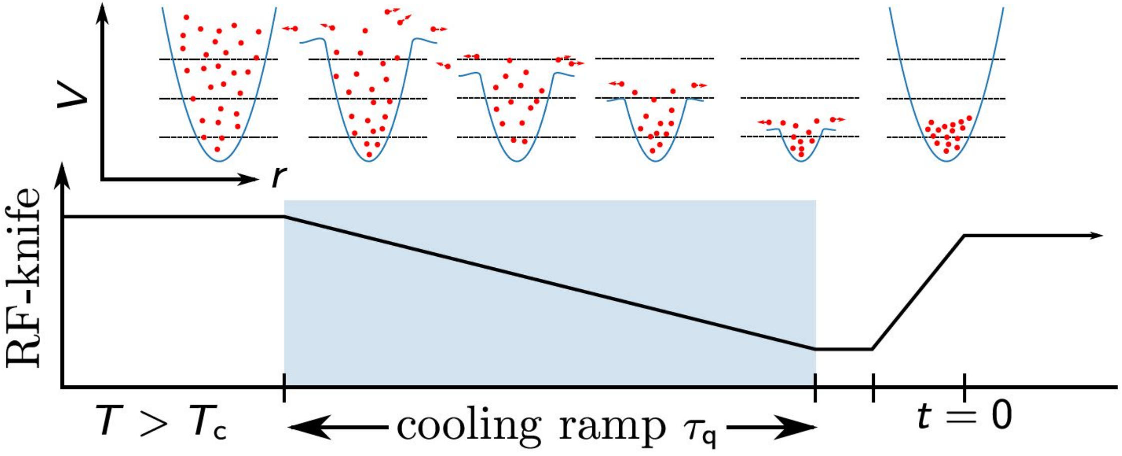
Tailored potential

DMD potential painting



3D thermal gas just above quantum degeneracy

1D gas very far out of equilibrium



Unitary evolution of isolated system

➔ Dynamics of phase transition

➔ Far-from equilibrium dynamics

➔ Relaxation of isolated systems

⇨ Expect relaxation to thermal QC

The question here is how?

What can we measure in experiments?

Commonly: **Destructive measurements** ➡ The best we can **measure** is **every constituent** (and their internal states)

Experiment → $\mathcal{U}$ → **'image'** → **Evaluation**

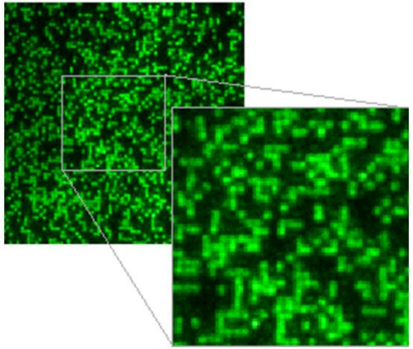
Quench, …
& isolated evolution

Unitary operation

Projective measurement of many body wavefunction

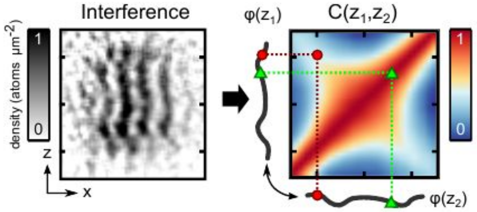
Extracted observables, full counting statistics, (higher-order) correlations, …

in situ ➜ position



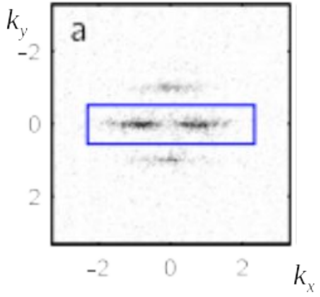
W.S. Bakr, et al.,Nature 462, 74 (2009).
J.F. Sherson, et al. Nature 467, 68 (2010).

interference ➜ phase



Langen et al., Nat. Phys. 9, 460 (2013)
Gring et al., Science 337, 1318 (2012)
Langen et al., Science 348, 207 (2015)
Schweigler et.al, Nature 545, 323, (2017)
Rauer et al., Science 360, 307 (2018)
Zache et.al, PRX 10, 011020 (2020)
…

time of flight ➜ momentum



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

$$n(k,t) \equiv \alpha\rho\left(\alpha^{-1}z_{\mathrm{tof}}\right)$$

$$= \int \mathrm{d}z\, f\left(z, k - \alpha^{-1}(z + vt_{\mathrm{tof}}), t\right)$$

Additional bulk velocity v

→ *condensate focusing*

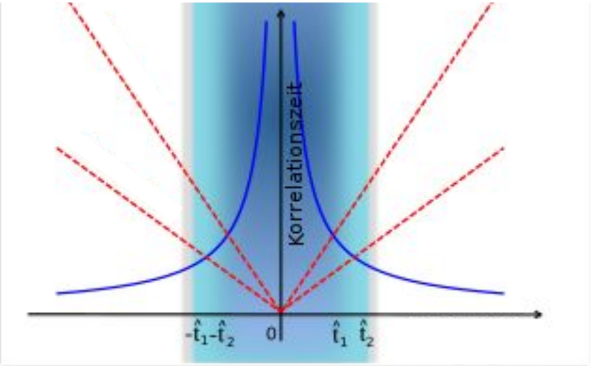
Enables measuring momenta in IR for finite time of flight

Kibble-Zurek mechanism

Critical slowing down near a second-order phase transition

$$\tau = \tau_0/|\epsilon|^{\nu z} \qquad \xi = \xi_0/|\epsilon|^{\nu} \qquad \epsilon = \frac{T_C - T}{T_C}$$

➔ system departs from equilibrium near the critical point (due to causality / sonic horizons)



$\longrightarrow$ *new broken symmetry phase is chosen locally*

$\longrightarrow$ *for transition at finite rate, 'causality' limits establishment of coherence over large scales*

$\longrightarrow$ *nucleation of defects between different regions*

Defect density predicted by universal (inhomogeneous) **Kibble-Zurek scaling:** $n_s \sim R_{\mathrm{q}}^{\frac{1+2\nu}{1+\nu z}}$

Theory: Kibble 1980, Zurek 1993, … e.g. Review: Int. J. Mod. Phys. A 29, 1430018 (2014) for 1d (solitons): e.g. Zurek PRL 102, 105702 (2009)

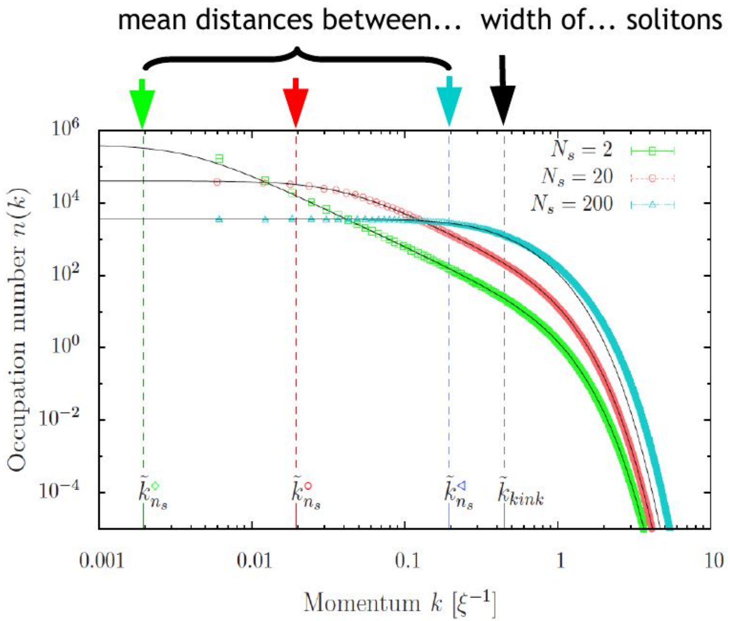
Experiments: Donner et al Science 315, 1556 (2007), Kessling et al Nature 568, 207 (2019), Navon et al Science 347, 167 (2015), Lamporesi et al Nat. Phys. 9, 656 (2013), ...

Solitonic defects

M. Schmidt, SE, et al., New J. Phys. 14, 075005 (2012)
SE, 10.11588/heidok.00025106 (2018)

Counting defects: ➔ very subjective (especially for solitons)
➔ requires additional 'waiting time'
➔ non-linear relaxation before measurement

Better: ➔ determine defects through ***correlation measures***
(correlation length, momentum distribution, …)
➔ enables measurement directly following the quench



$\longrightarrow$ *Random defect model for solitonic excitations*

$$n(k) = \int \mathrm{d}n_\mathrm{s}\; p(n_\mathrm{s})\,[n_0(k,T) * n_\mathrm{s}(k,n_\mathrm{s})]$$

$$n_\mathrm{s}(k) = \left[\frac{k/k_{\xi_\mathrm{s}}}{\sinh(k/k_{\xi_\mathrm{s}})}\right]^2 n_{\xi_\mathrm{s}\to 0}(k)$$

$$g_1(z_1,z_2) = n_{1\mathrm{D}}\left[1 - \frac{2}{L}\,\mathcal{I}_L(z_1,z_2)\right]^{N_s}$$

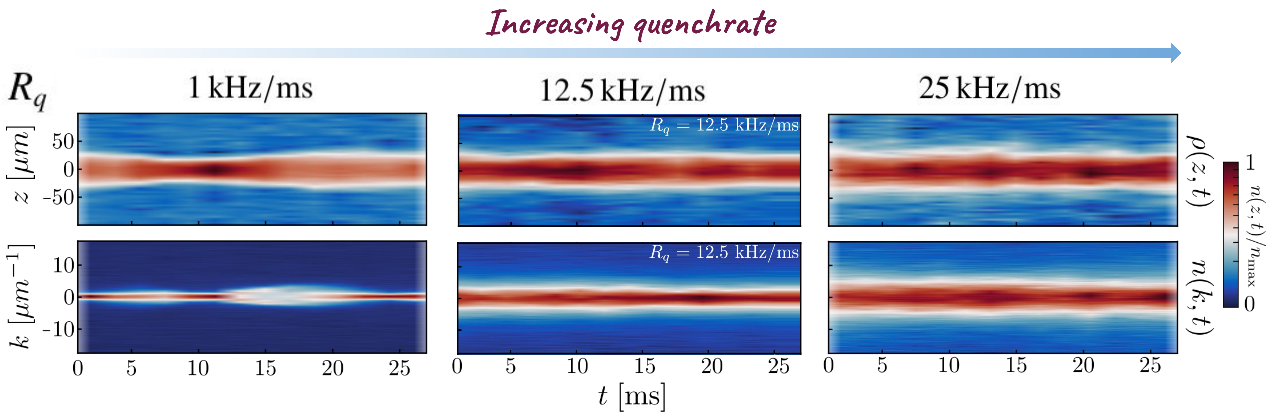
$$\mathcal{I}_L = \frac{L}{2}\int_{(z_1,-1)}^{(z_2,+1)} \mathrm{d}z\,\mathrm{d}\nu\; P(z,\nu)\left[1-\mathrm{e}^{\mathrm{i}\beta(\nu)}\right] = L\,\chi\int_{z_1}^{z_2}\mathrm{d}z\; P_1(z)$$

mean *density of defects*

$$\boxed{n_\mathrm{s}(k) = \left[\frac{2n_{1\mathrm{D}}k_{n_\mathrm{s}}}{k_{n_\mathrm{s}}^2 + (k-k_0)^2}\right]\left[\frac{k/k_{\xi_\mathrm{s}}}{\sinh(k/k_{\xi_\mathrm{s}})}\right]^2}$$

mean *width of defects*

Soliton defect nucleation

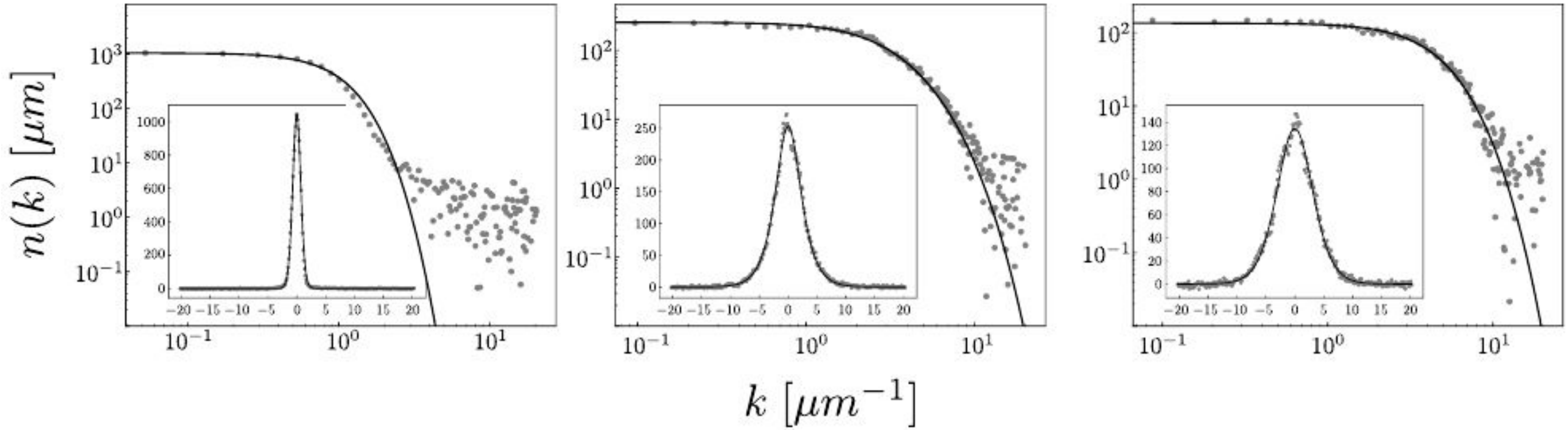


→ **Measurement** of the system

immediately after cooling quench

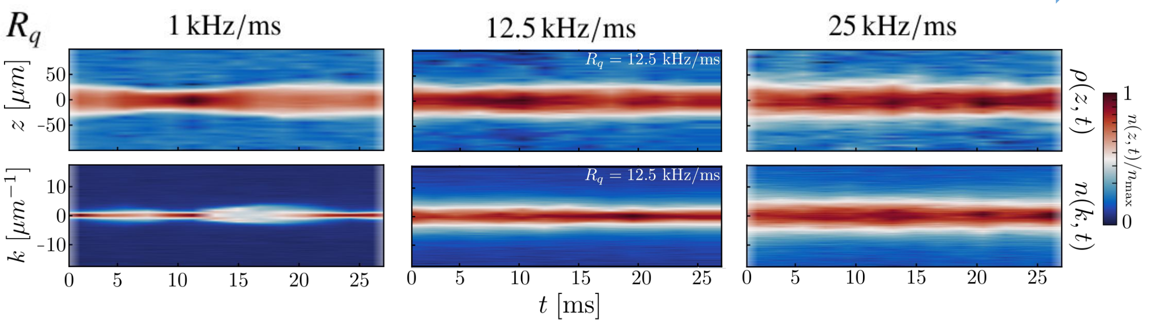
→ Utilise **breathing excitation**

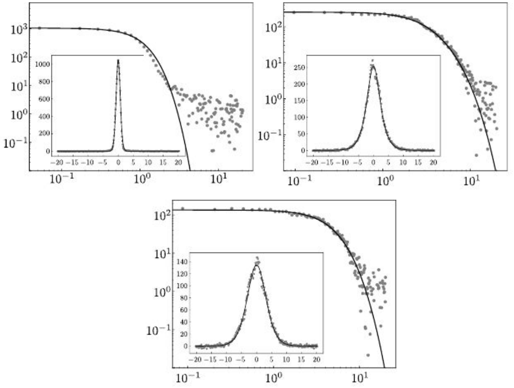
self-focusing in time of flight



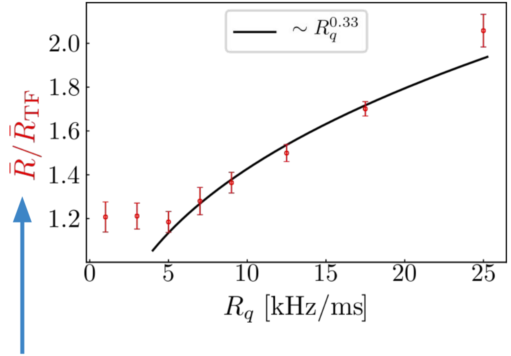
Soliton defect nucleation

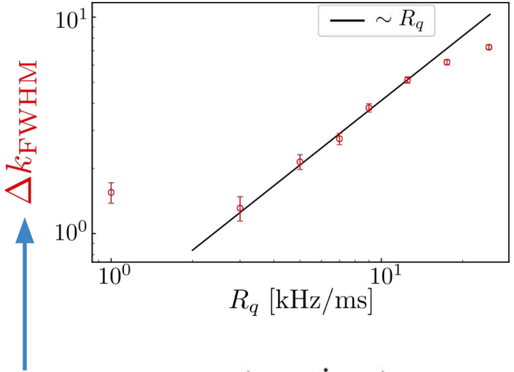
Increasing quenchrate





Strongly broadened density and momentum distribution





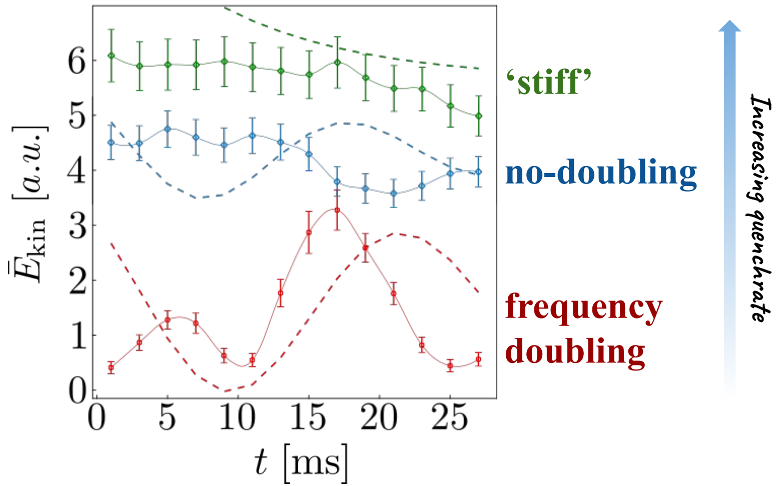
Via scaling Ansatz

$$\rho(z,t) = b(t)^{-1}\rho_0(z/b(t))$$

measured at focus point

$$\left(1 + \frac{\dot{b}}{b}t_{\mathrm{tof}}\right) = 0$$

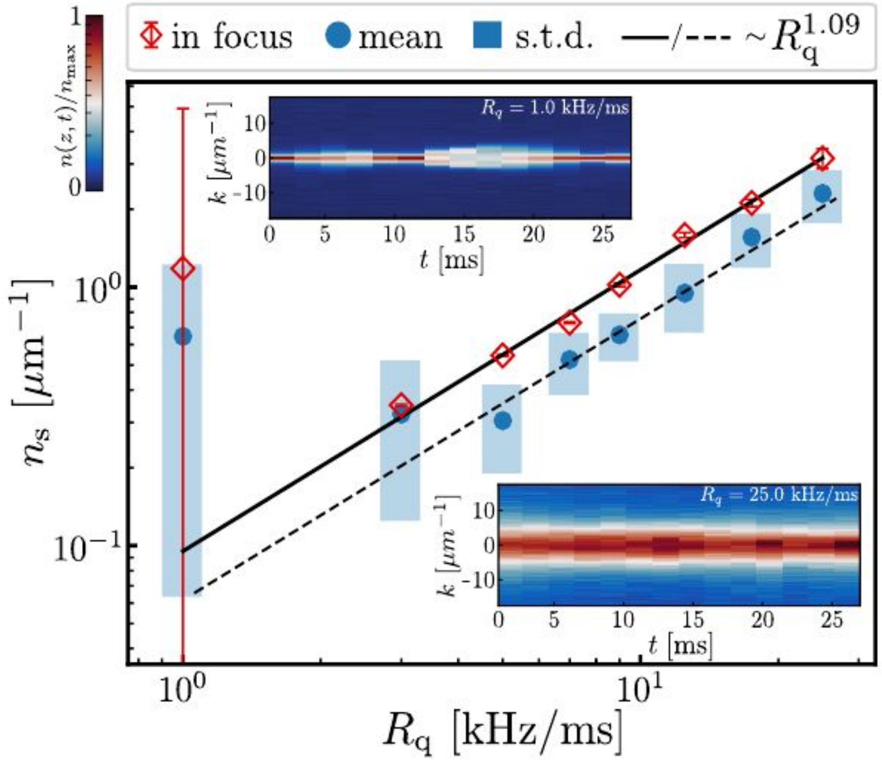
Condensate 'stiffness'



Close to equilibrium see e.g.: Fang et al, PRL 113, 035301 (2014)

Kibble-Zurek scaling exponent

Correlation measures enable counting the defects immediately after the quench unimpeded by spatial resolution or additional relaxation dynamics



KZ scaling exponents

Experiment

$$\zeta = 1.09 \pm 0.04$$

$$\zeta = 1.20 \pm 0.07$$

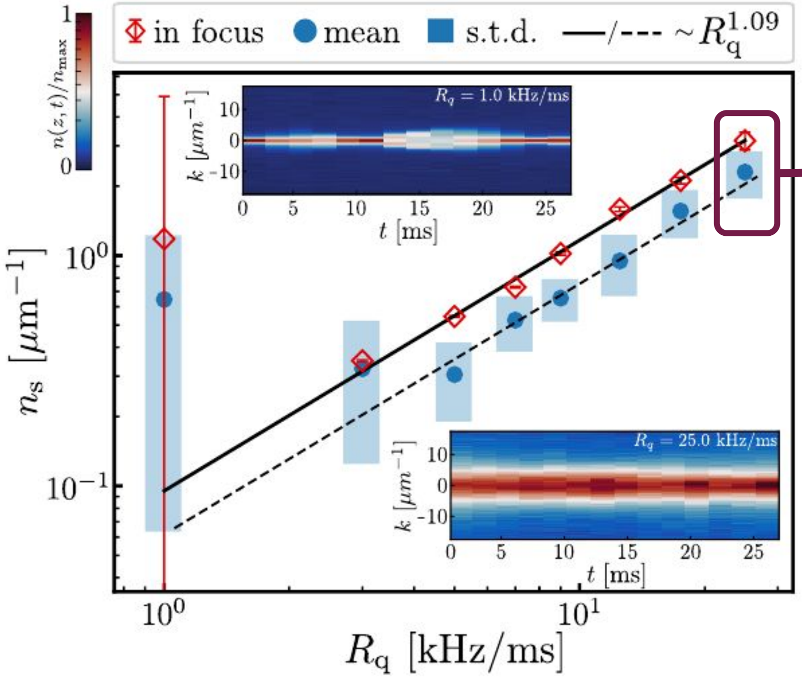
Theory

$\zeta = 1$ (mean field)

$\zeta = 7/6$ (Model F)

$\rightarrow$ *suggests beyond mean-field scaling*

Reaching the far from equilibrium regime



Experiment

$\zeta = 1.09 \pm 0.04$

$\zeta = 1.20 \pm 0.07$

Theory

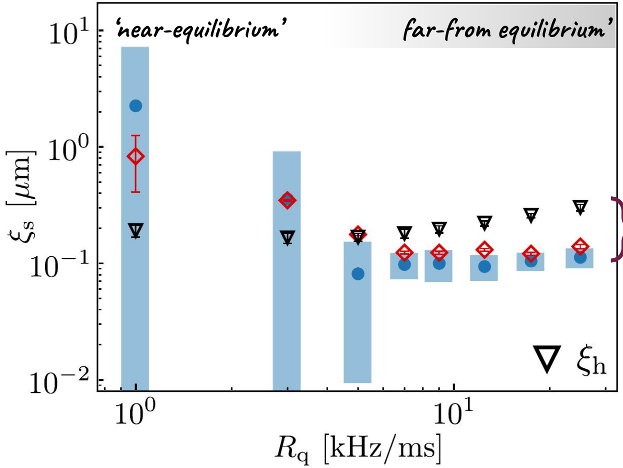
$\zeta = 1$ (MF)

$\zeta = 7/6$ (Model F)

→ **KZ** scaling prediction valid for **almost instantaneous quenches** (~O(100) faster than typical experiments)

→ Strong **overpopulation** of **high-momentum modes**

→ **Very high density of defects** leads to **deformation of solitons**



decreasing soliton width

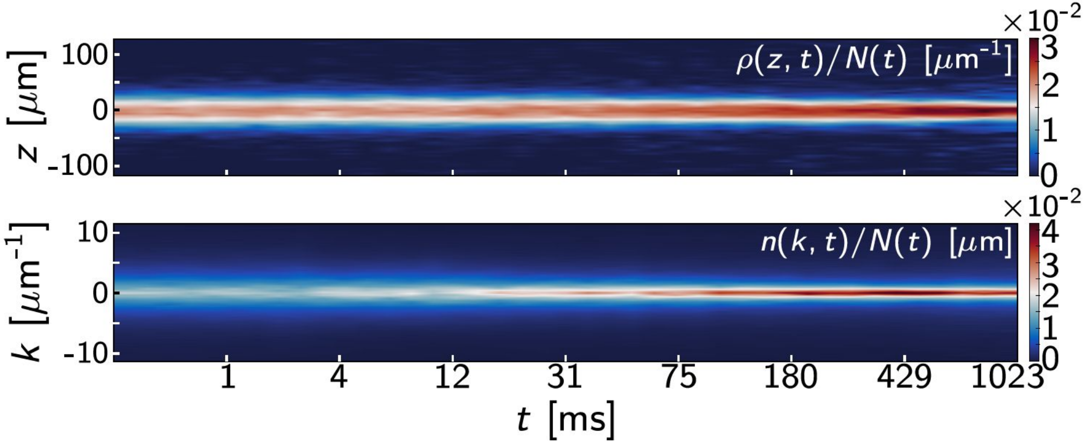
→ reaching far from equilibrium initial conditions

Relaxation after fast quenches

SE, R. Bücker et al. Nature 563, 225 (2018)

strongly broadened density & momentum distribution

→ *generalized soliton state*

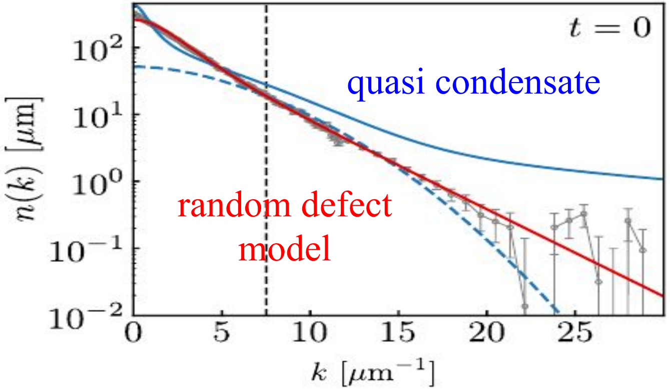


quasi-stationary at early times

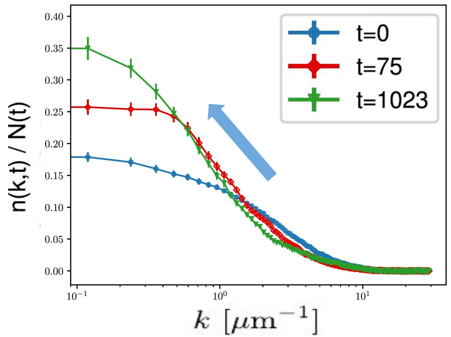
→ *incompressibility*

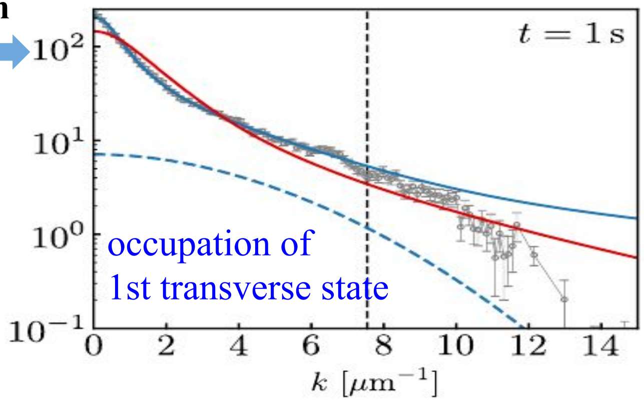
collapse signals buildup of quasi-condensate

→ *transport*

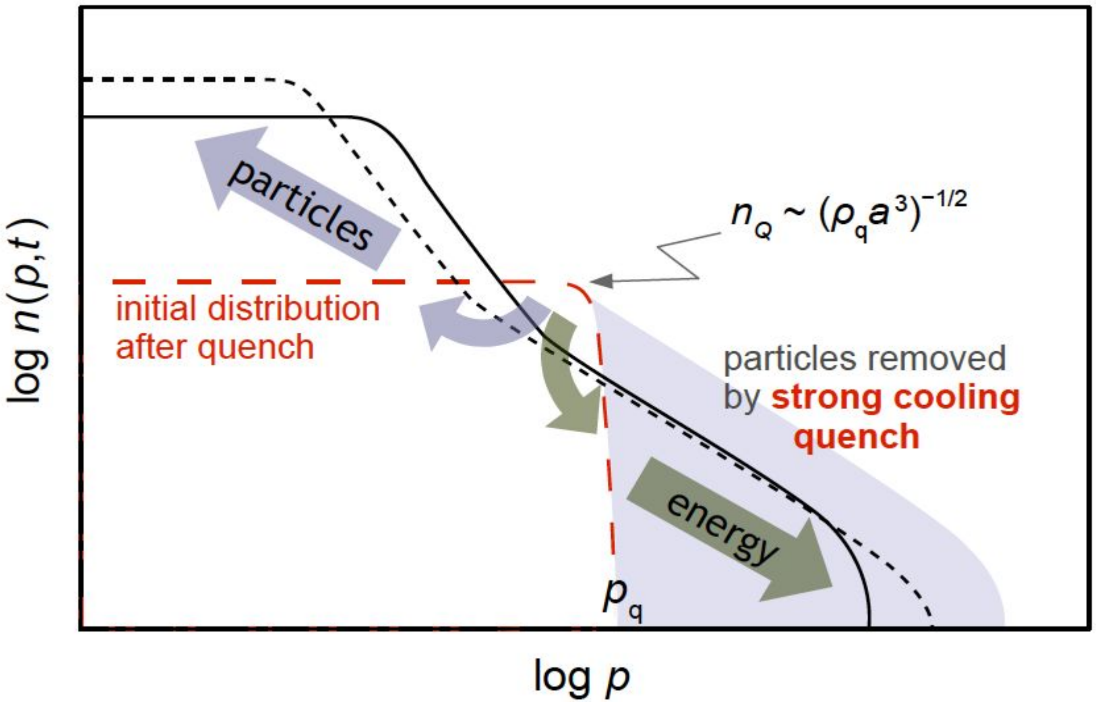


unitary evolution / ‘isolated’ system





Non-thermal fixed points I

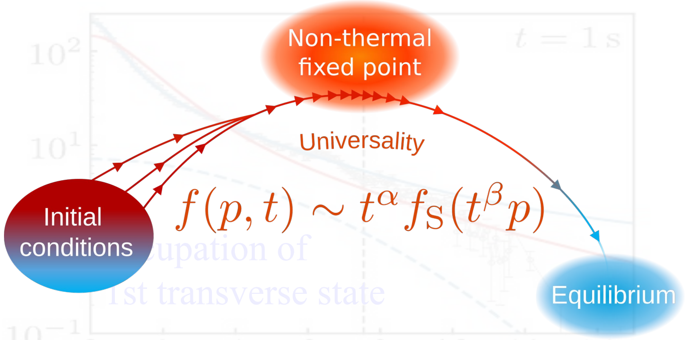


Theory

Berges, Rothkopf, Schmidt (08)
Hoffmeister, Berges (09)
Sexty, Schlichting, et al Berges (10)
Scheppach, Berges, Gasenzer (10)
Nowak, Sexty, Schole, Schmidt, Erne, Karl, Gasenzer (11-17)
Piñeiro Orioli, Boguslavski, Berges, PRD 92, 025041 (2015)
Berges, Wallisch, PRD 95, 036056 (2017)
⋮

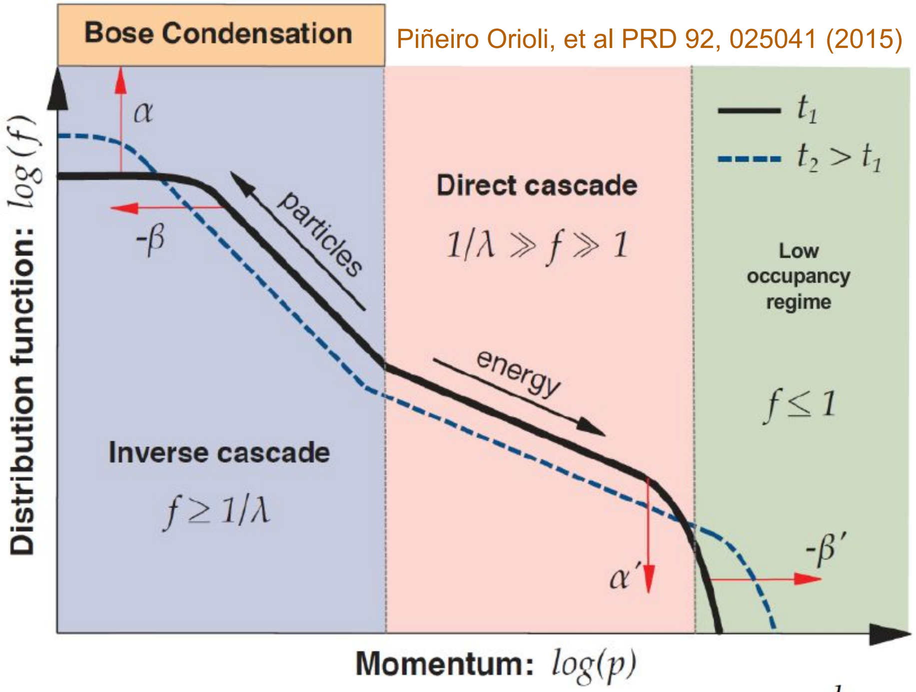
Experiments

Erne et al Nature 563, 225 (2018)
Prüfer et al Nature 563, 217 (2018)
Glidden et al Nature Phys. 17, 457 (2021)
Johnstone et al Science 364, 1267 (2019)



From: I. Chantesana, A. Pineiro Orioli, T. Gasenzer Phys. Rev. A 99: 043620, 2019
C.-M. Schmied, A. N. Mikheev, T. Gasenzer Int. J. Mod. Phys. A 34:1941006, 2019

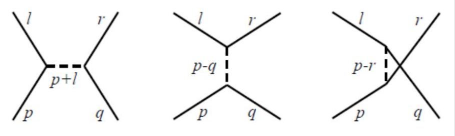
Non-thermal fixed points II



Piñeiro Orioli, et al PRD 92, 025041 (2015)

Kinetic theory - 'collision integral'

$$\frac{\partial f(t,\mathbf{p})}{\partial t} = C[f](t,\mathbf{p})$$



$$g^2_{\text{eff}}(t,\mathbf{p},\mathbf{q})$$

Self-similar scaling ansatz

$$f(t,\mathbf{p}) = s^{\alpha/\beta} f(s^{-1/\beta}t, s\mathbf{p})$$

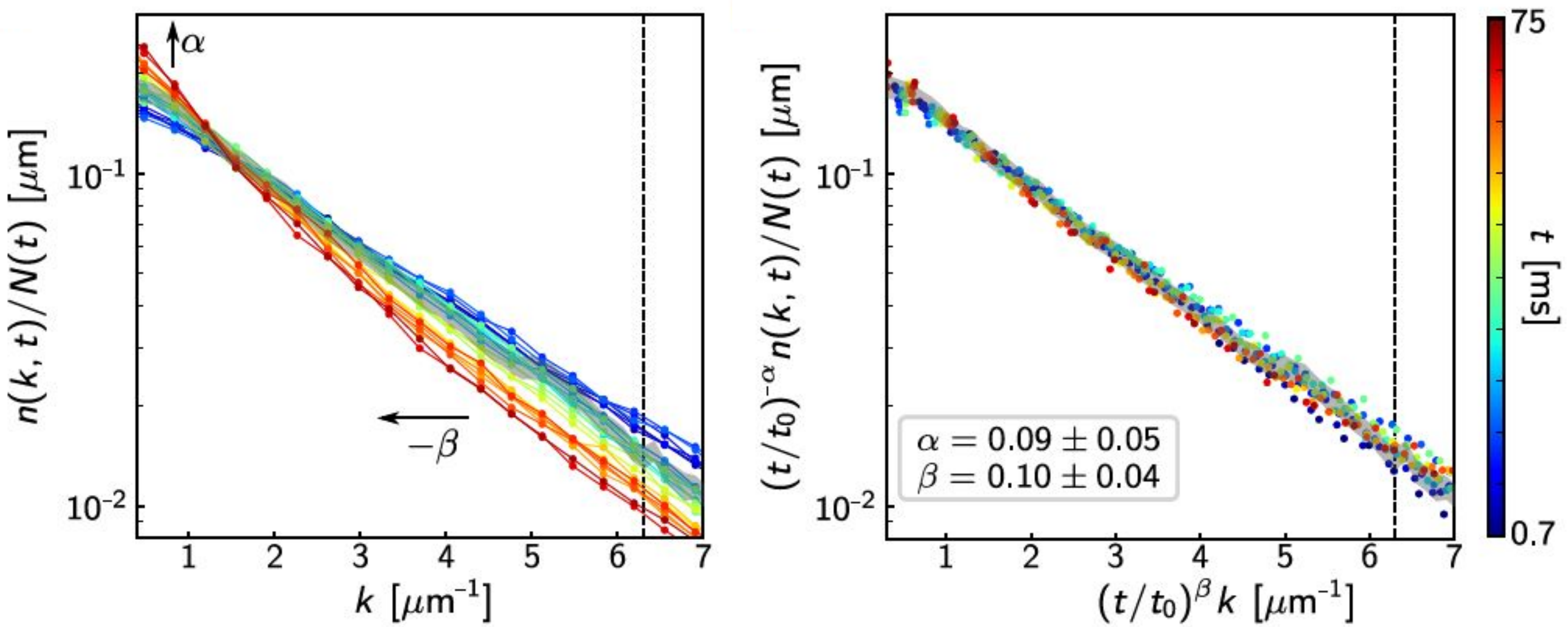
$$s^{-1/\beta}t = 1$$

- Perturbative exponents $\alpha = -\frac{d}{2},\ \beta = -\frac{1}{2}$ **do not** account for inverse particle transport
- Nonperturbative exponents $\alpha = d/2\ \ \beta = \frac{1}{2}$ **inverse particle cascade!**

Scaling evolution

Following the scaling ansatz

$$n(k,t) = (t/t_0)^{\alpha}\, f([t/t_0]^{\beta} k)$$

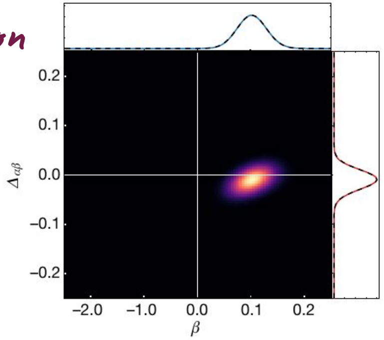


Scaling exponents

Determine via *maximum likelihood function*

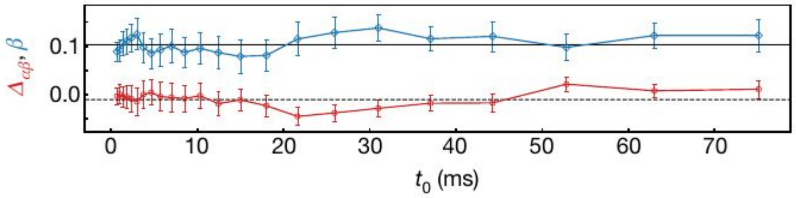
$$L(\Delta_{\alpha\beta},\beta)=\exp\left[-\frac{1}{2}\chi^2(\Delta_{\alpha\beta},\beta)\right]$$

$$\chi^2(\alpha,\beta)=\frac{1}{N_t^2}\sum_{t,t_0}^{N_t}\chi^2_{\alpha,\beta}(t,t_0)$$

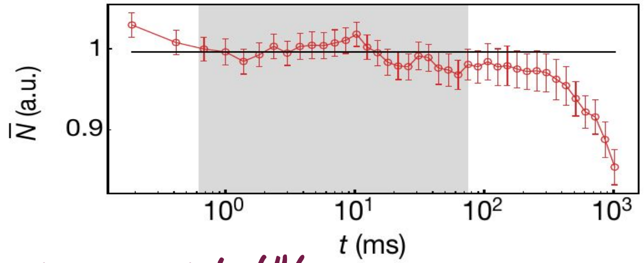


$$\alpha\approx\beta=0.1\pm0.03$$
$$\Delta_{\alpha\beta}=\alpha-\beta=-0.01\pm0.02$$

Independent of reference time



Emergent conserved quantity

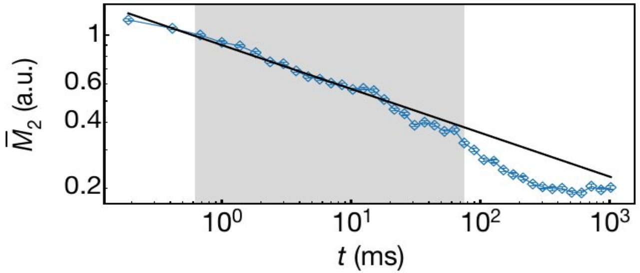


Scaling for *moments of the distribution function*

$$\bar{N}=\int_{|k|\leq(t/t_0)^{-\beta}k_S}\frac{n(k,t)}{N(t)}\mathrm{d}k \qquad \propto(t/t_0)^{-\Delta_{\alpha\beta}}$$

$$\bar{M}_{n\geq1}=\int_{|k|\leq(t/t_0)^{-\beta}k_S}\frac{|k|^n\,n(k,t)}{N\bar{N}(t)}\mathrm{d}k \qquad \propto(t/t_0)^{-n\beta}$$

Energy transport to UV



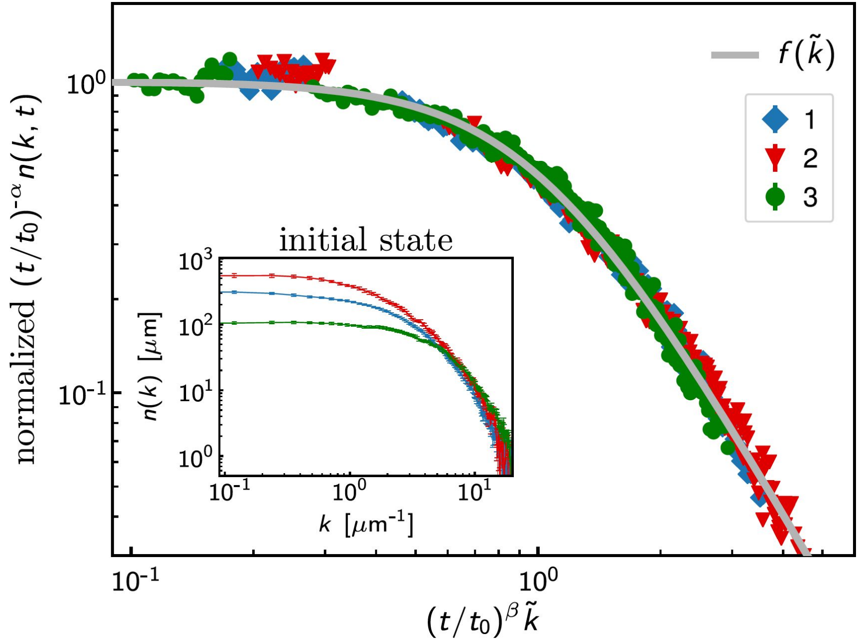
Bi-directional transport → inverse particle transport towards IR

→ direct energy transport towards UV

Universal scaling function

For varying initial conditions the system quickly approaches the same non-thermal fixed point

→ *efficient loss of information about initial state long before thermalization*



Universal scaling function

$$f_S \sim [1 + (\tilde{k}/k_0)^{\zeta}]^{-1} \qquad \zeta = 2.39 \pm 0.18$$

What determines the universal parameters?

$$\alpha \approx \beta = 0.1 \pm 0.03$$
$$\zeta = 2.39 \pm 0.18$$

➔ **Expected**

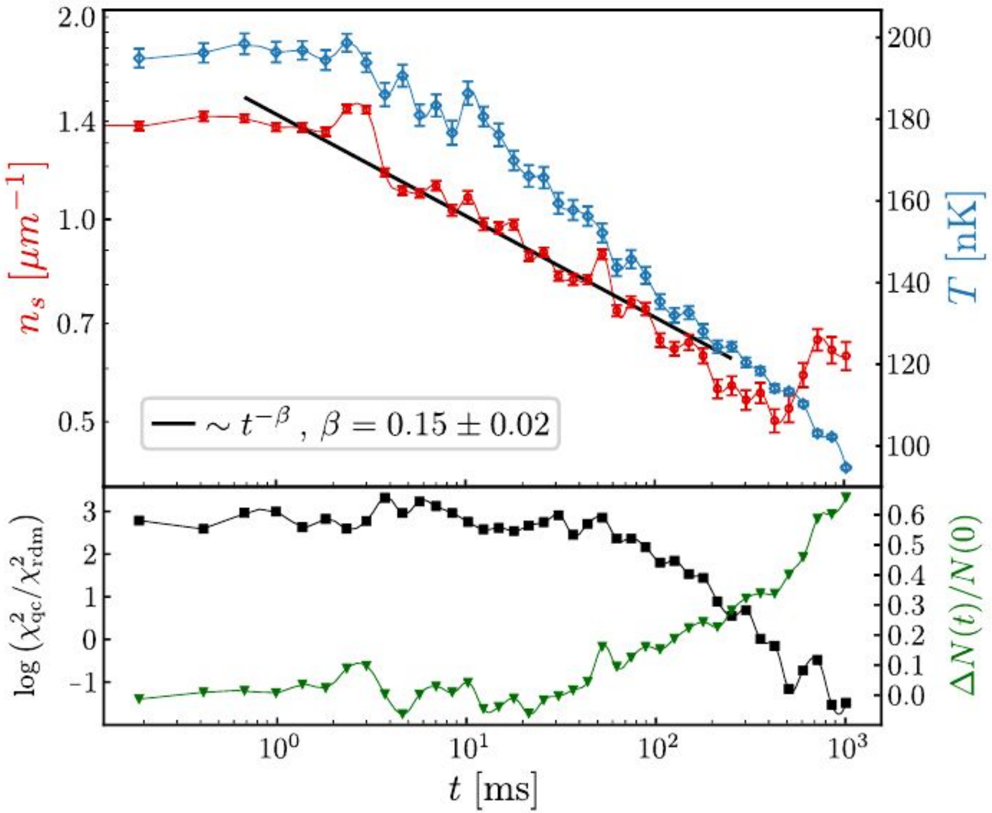
d=1:		$\beta = 0$
d≥2:	$\zeta = d + 1$	$\beta = 1/2$

➔ **However:** transverse excited states break integrability

Is there a continuous connection (fractal dimensions) of fixed-points between 1D and 2D?

Gresista, Zache, Berges, arXiv:2107.11749 (2021)

Leaving the fixed-point - approach of thermal equilibrium



Scaling analysis via **random defect model** gives (roughly) compatible results

➔ role of (deformed) defects?
➔ is there a connection to coarsening dynamics for defect dominated NTFPs?

Here complete **thermalization** is driven by

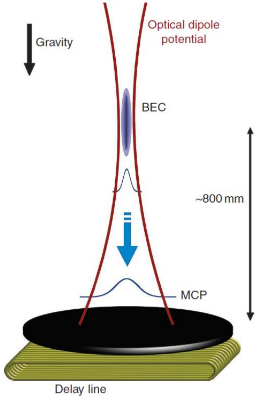
➔ transverse excited states
➔ atom loss at late times

The latter leads to dynamics beyond isolated systems

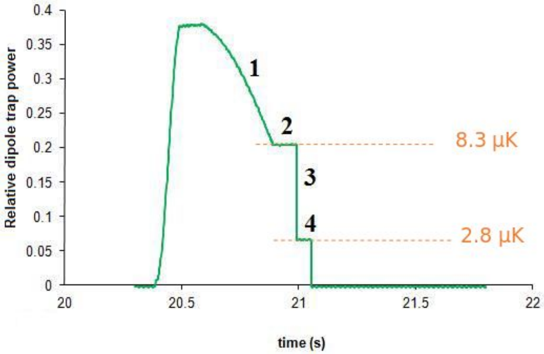
Scaling dynamics He* condensation

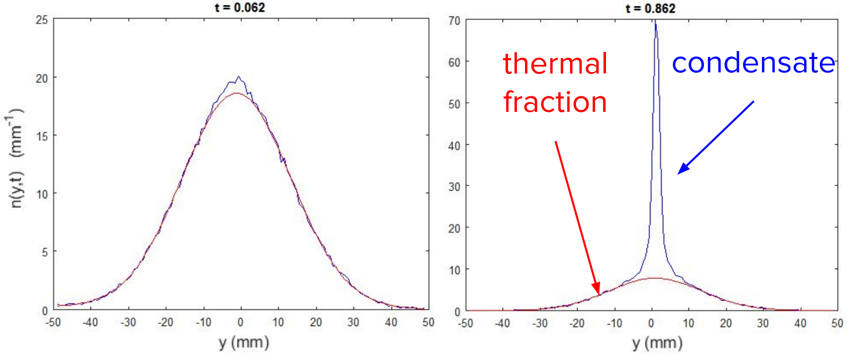
preliminary results

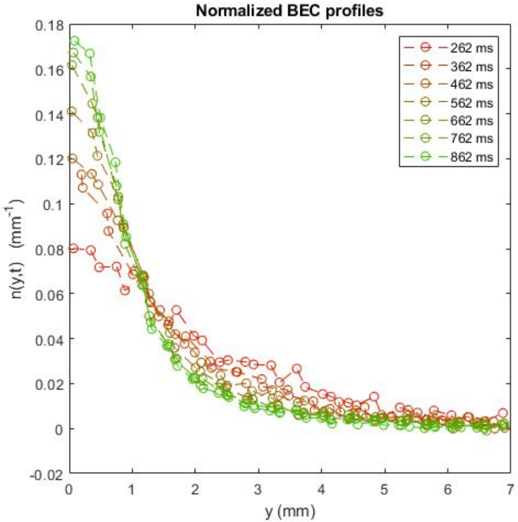
@RSPhys, ANU, Australia



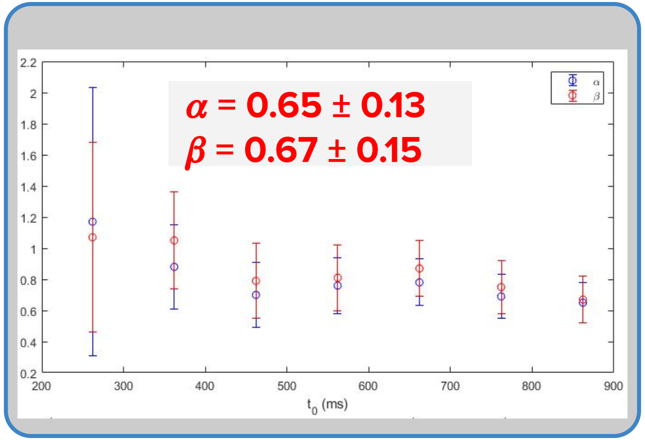
cooling sequence

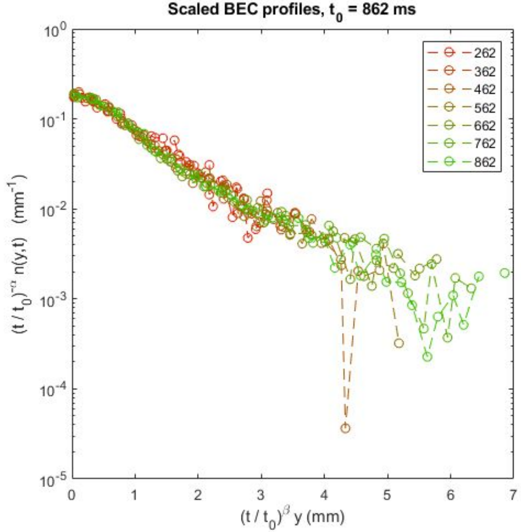






scaling Ansatz





Outlook & questions

Thank you for your attention!

- ❏ Kibble-Zurek scaling
  - ➜ Reach low quenchrate regime through flat-bottom potentials
- ❏ Universal scaling far from equilibrium and NTFPs
  - ➜ Emergence of scaling dynamics for cooling quenched gases and connection to equilibrium FP
  - ➜ Strongly interacting systems: bosonic Li^2-molecules, sine-Gordon model, ...
  - ➜ Dimensional crossover, Pre-scaling and departure from NTFP, ...
- ❏ Defect dominated NTFPs and connection to e.g. coarsening dynamics

J. Berges (Heidelberg)

T. Gasenzer (Heidelberg)

R. Bücker (MPI Hamburg)

J. Schmiedmayer (TU Wien) & the whole AtomChip group!

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 801110 and the Austrian Federal Ministry of Education, Science and Research (BMBWF). It reflects only the author's view, the EU Agency is not responsible for any use that may be made of the information it contains.

TU WIEN

ATOMINSTITUT

VCQ Vienna Center for Quantum Science and Technology

isoQuant SFB1225

Federal Ministry Education, Science and Research