Universal Dynamics near Non-Thermal Fixed Points

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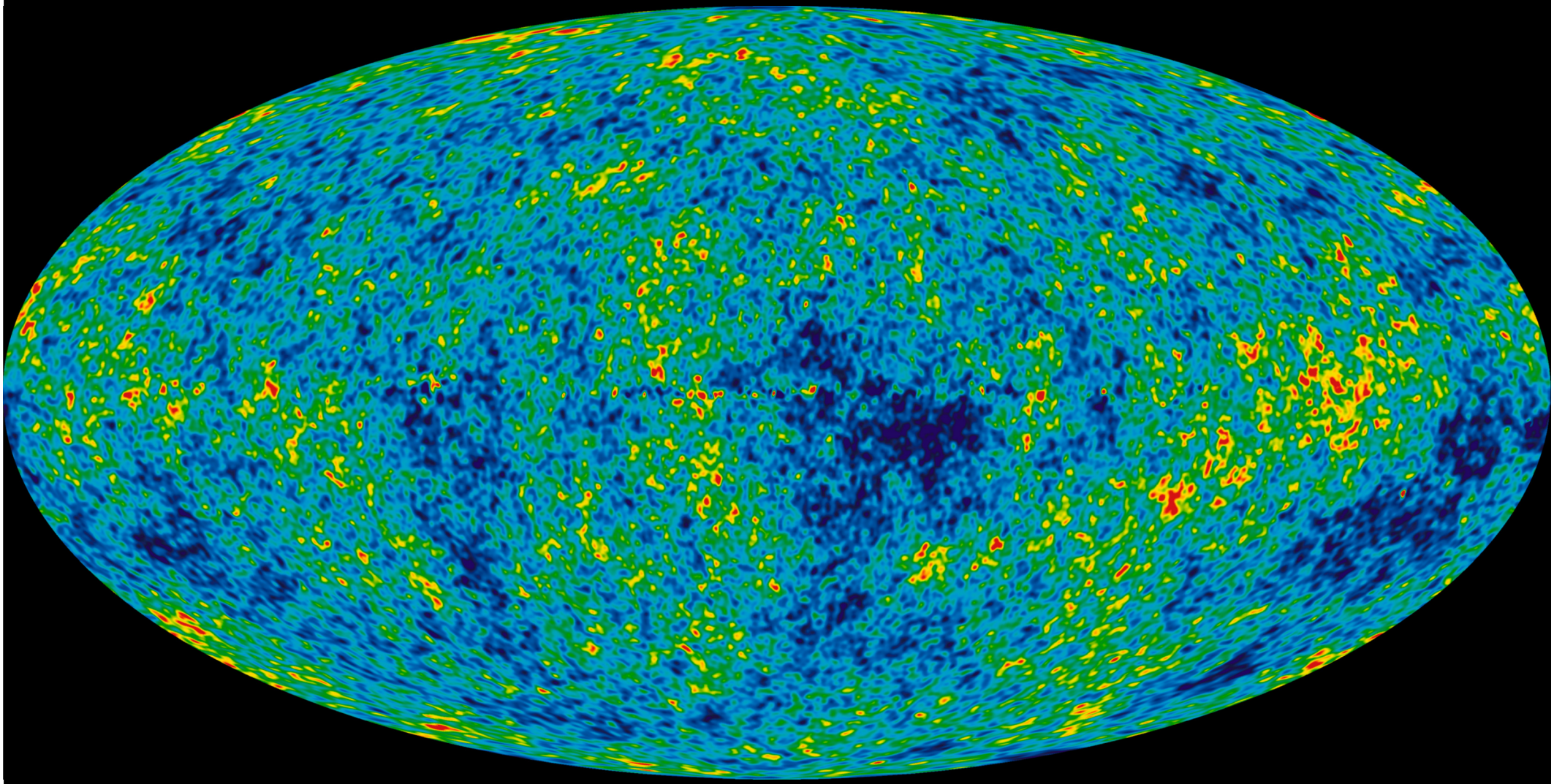
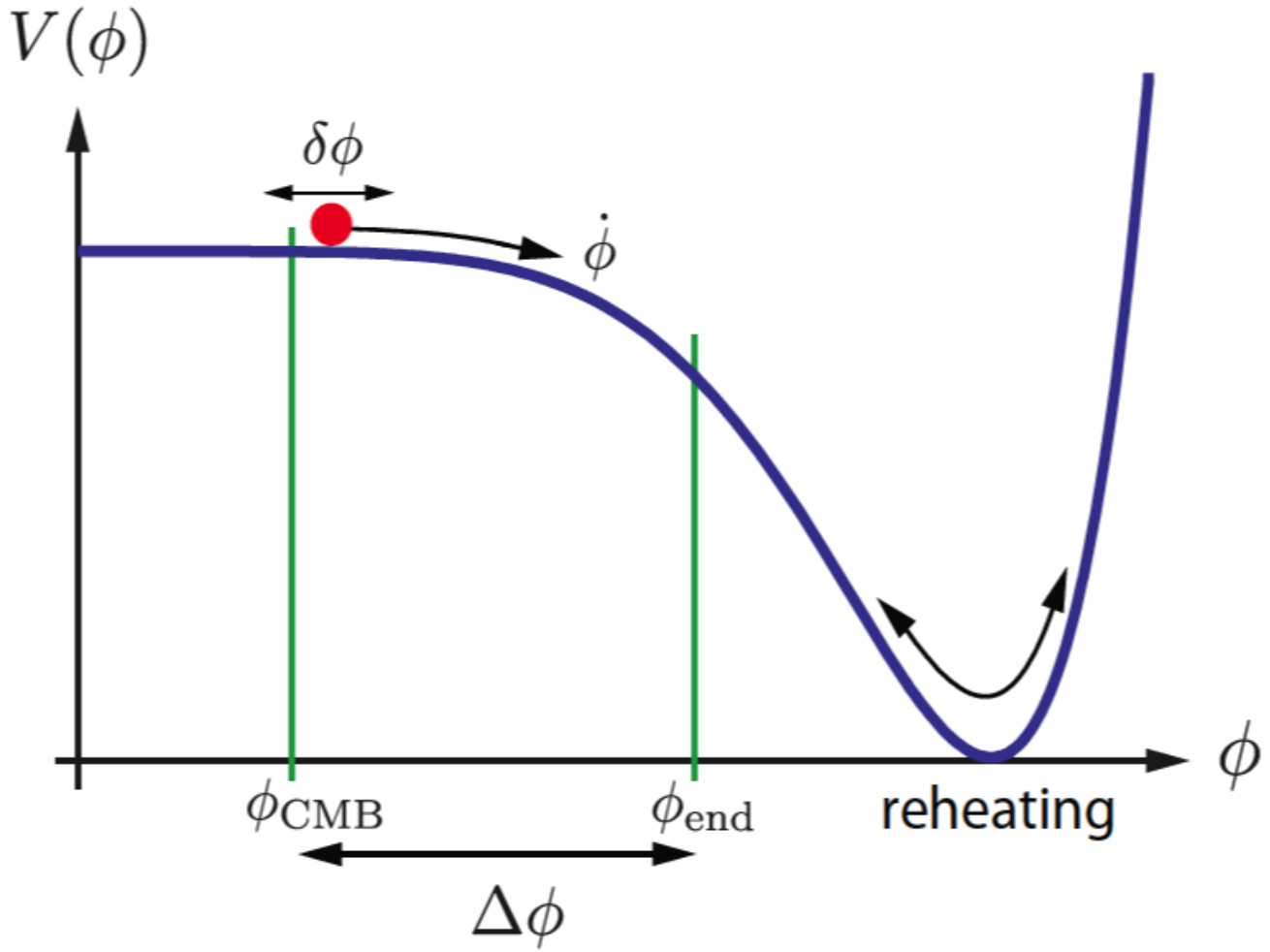
The Big Bang Theory – Turbulent ?



Reheating after Cosmological Inflation

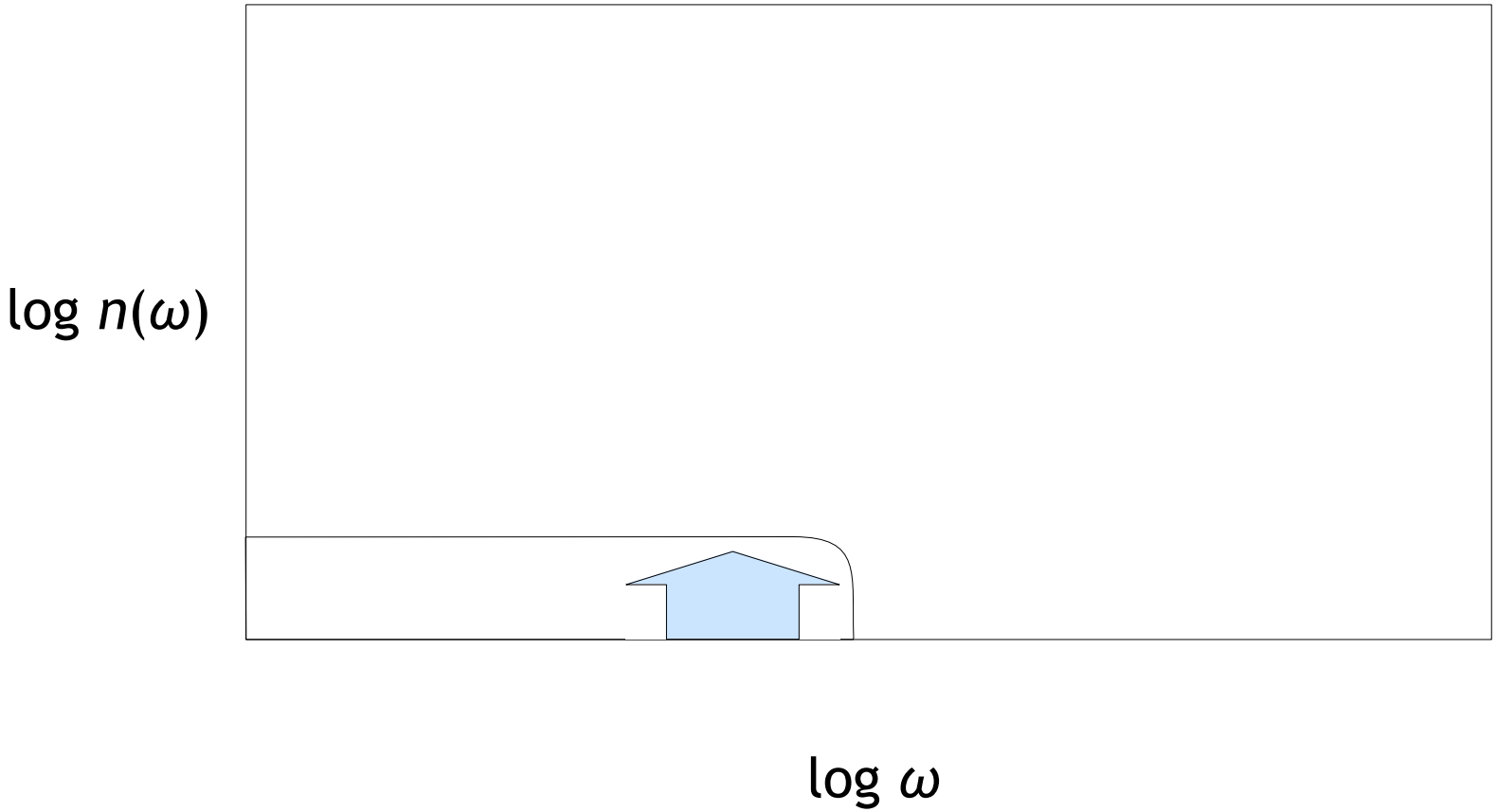
Slow-roll inflation scenario



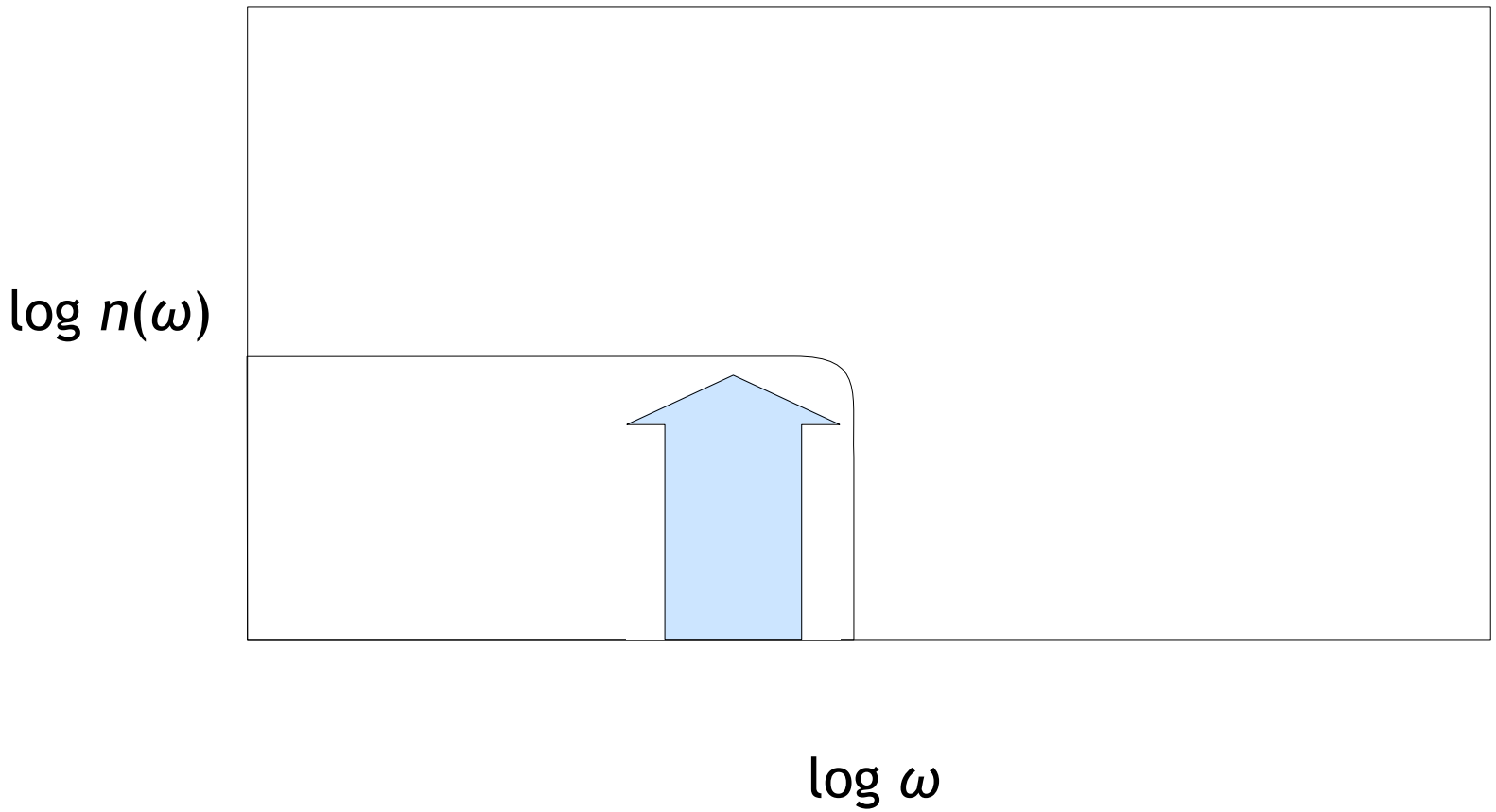
L. Kofman, A. Linde, A. Starobinsky, PRL **73**, 3195 (1994)
J. Berges, A. Rothkopf, J. Schmidt, PRL **101**, 041603 (2008) (non-thermal fixed point)

Instability: fast growth

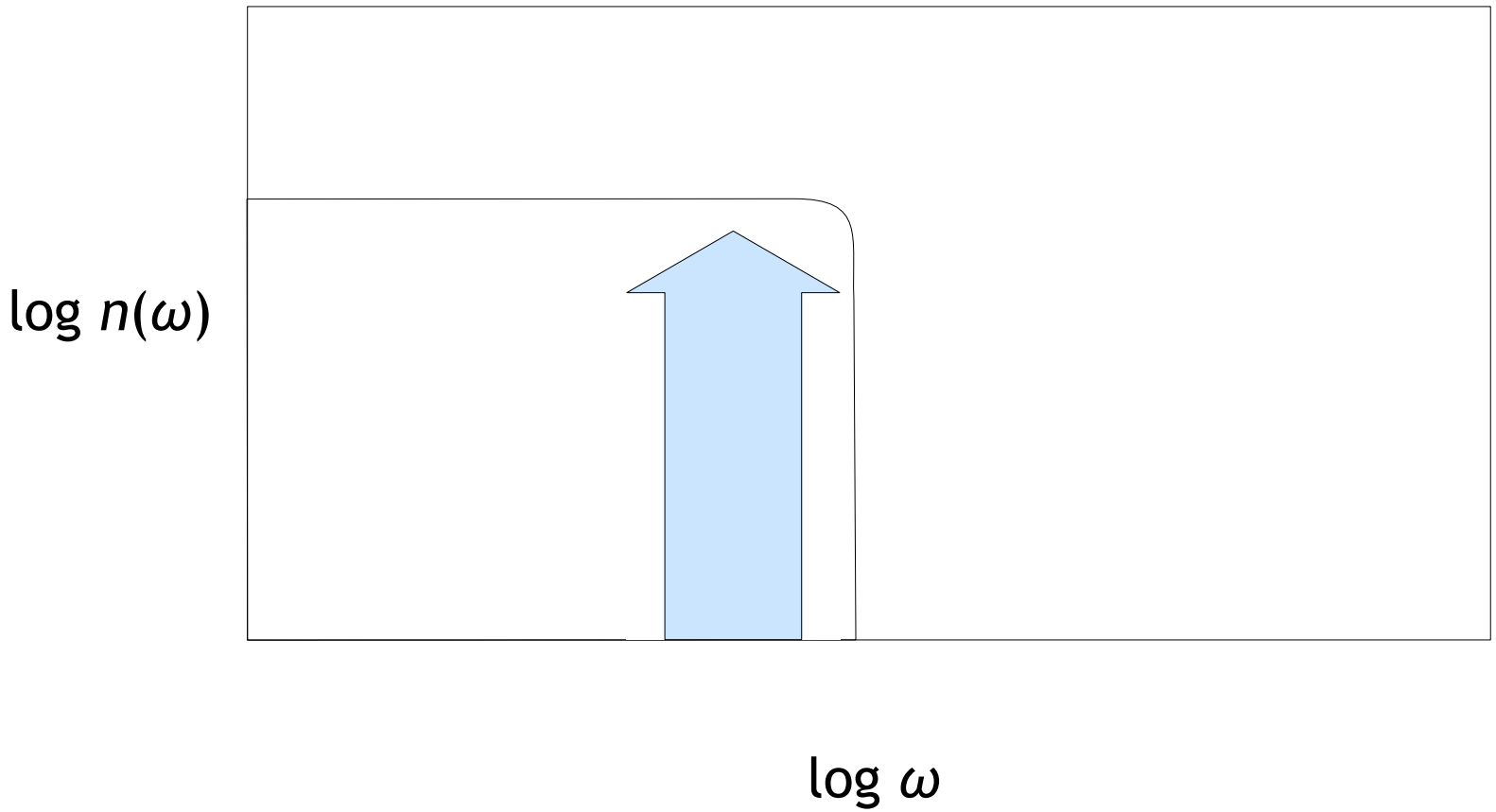
of mode occupancies n:



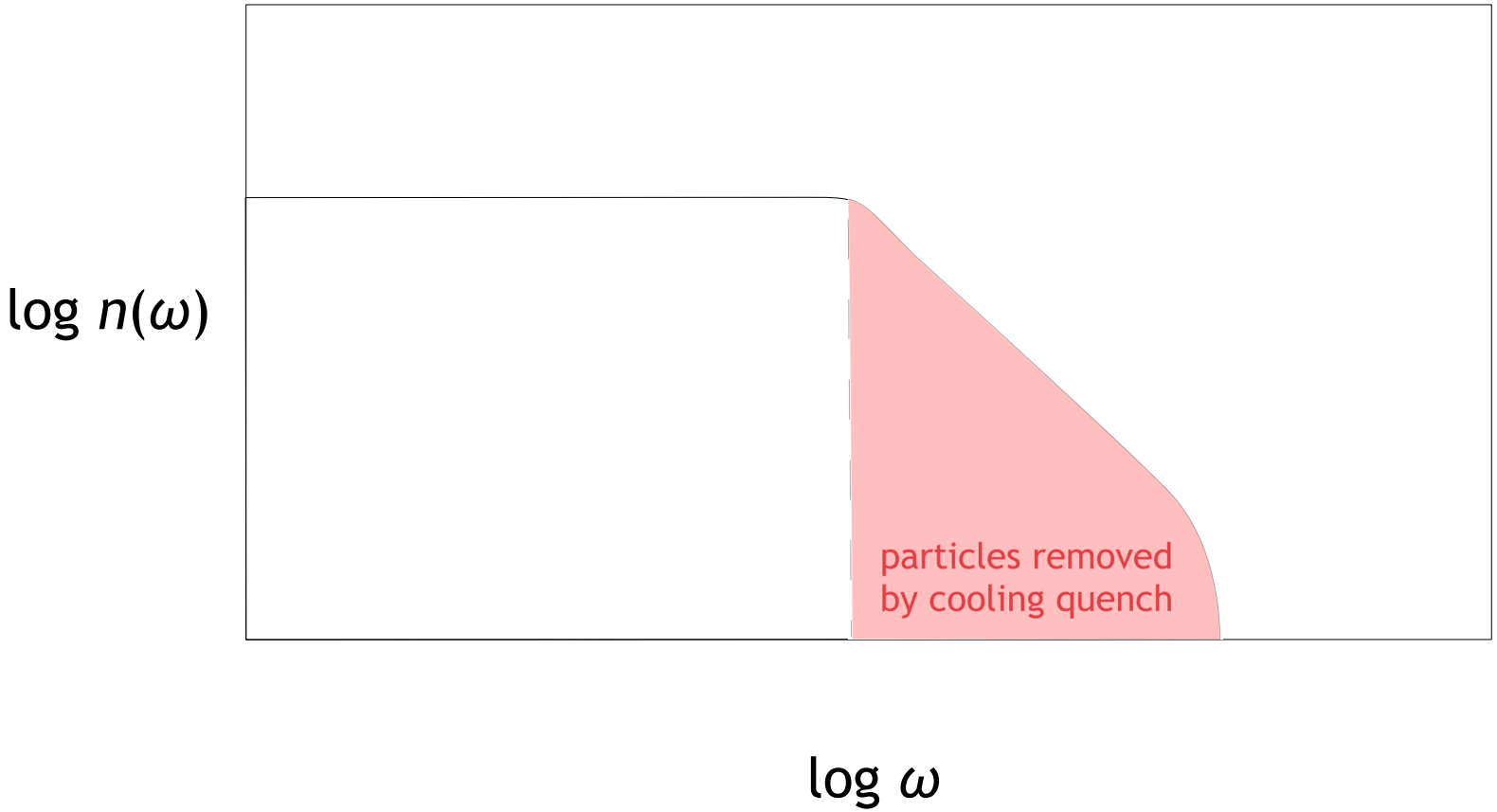
Instability: fast growth



Instability: fast growth

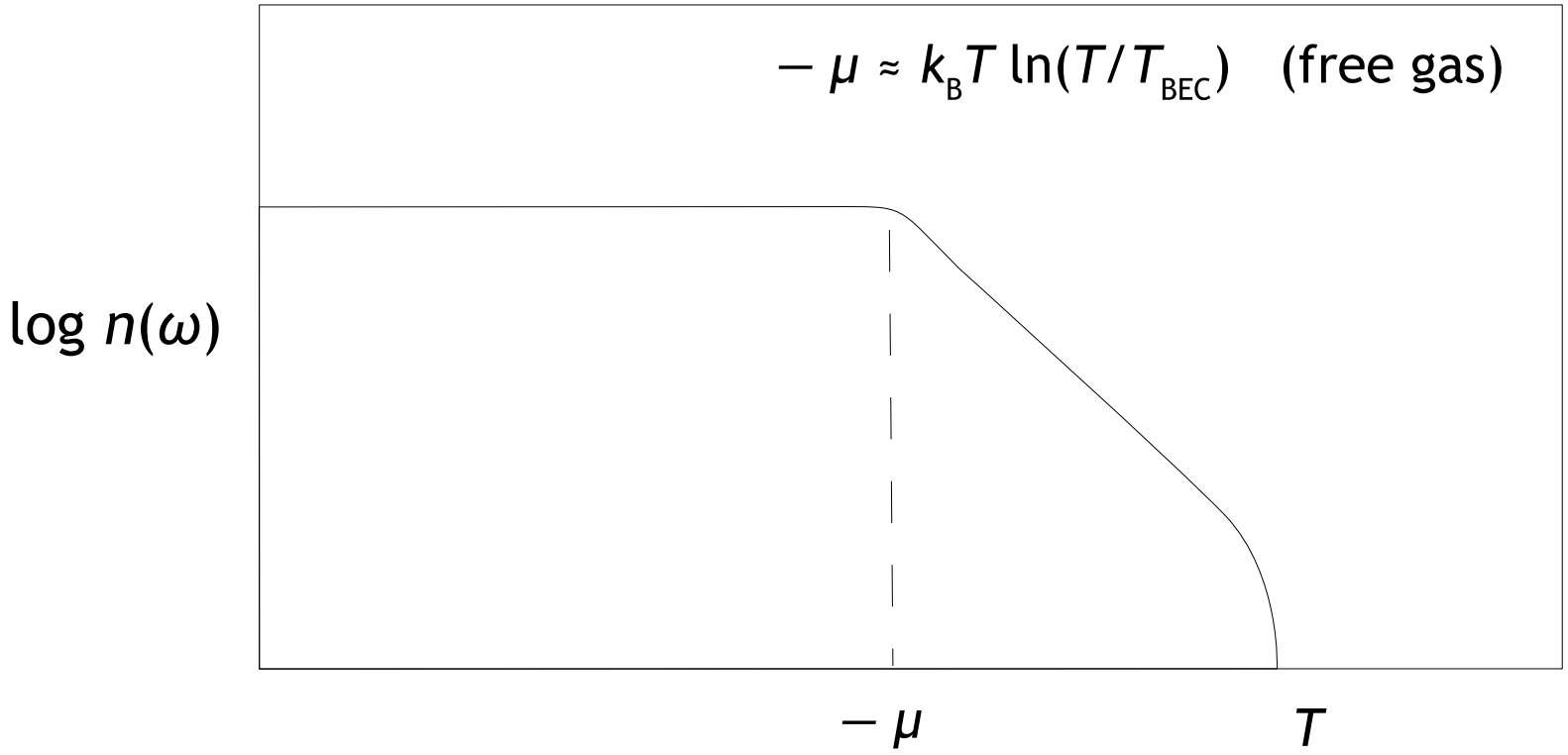


As after a **strong** cooling quench



As after a **strong** cooling quench...

➡ ... of a **thermal Bose-Einstein distribution**

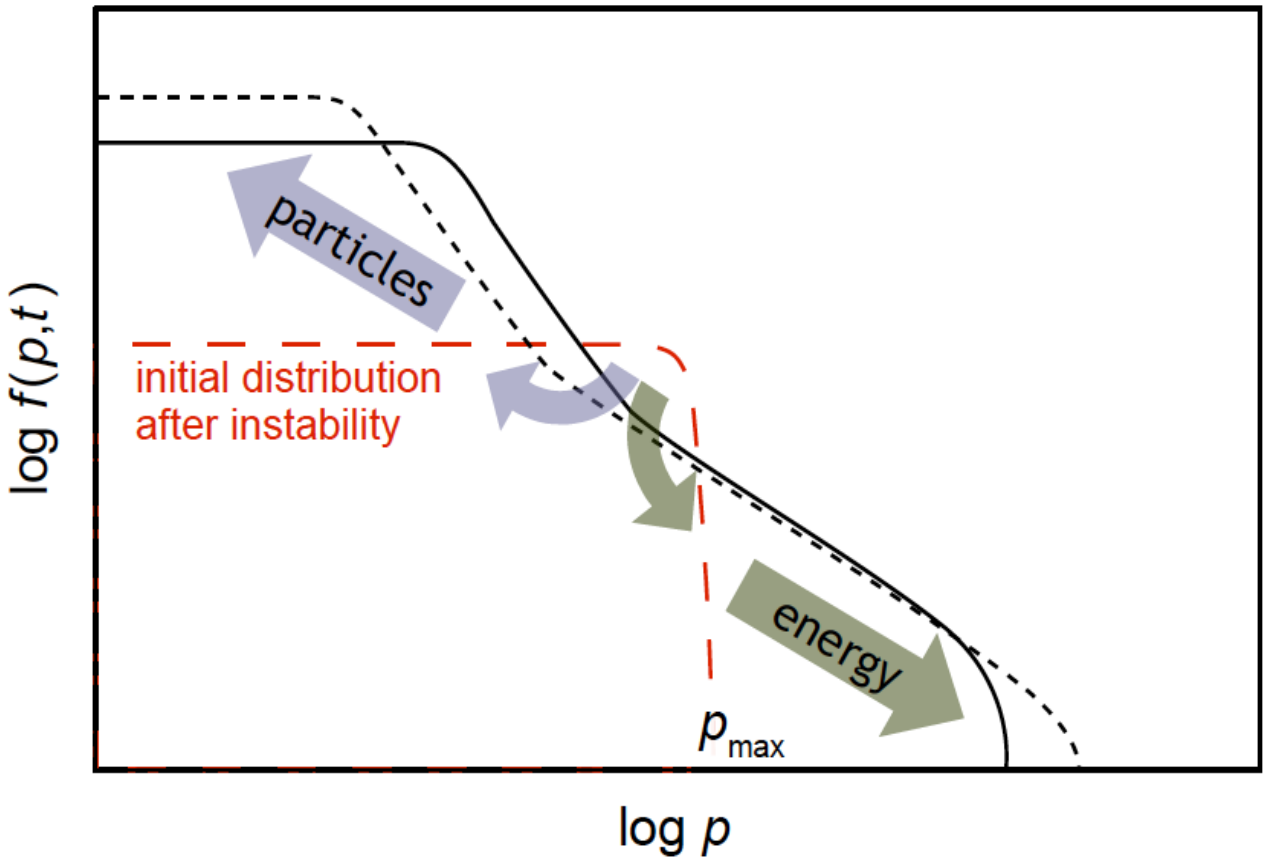


$$n(\omega) = \frac{1}{e^{(\omega-\mu)/T} - 1}$$

(**double-log!** - here sketched for $T_{BEC} < T \ll 2T_{BEC}$)

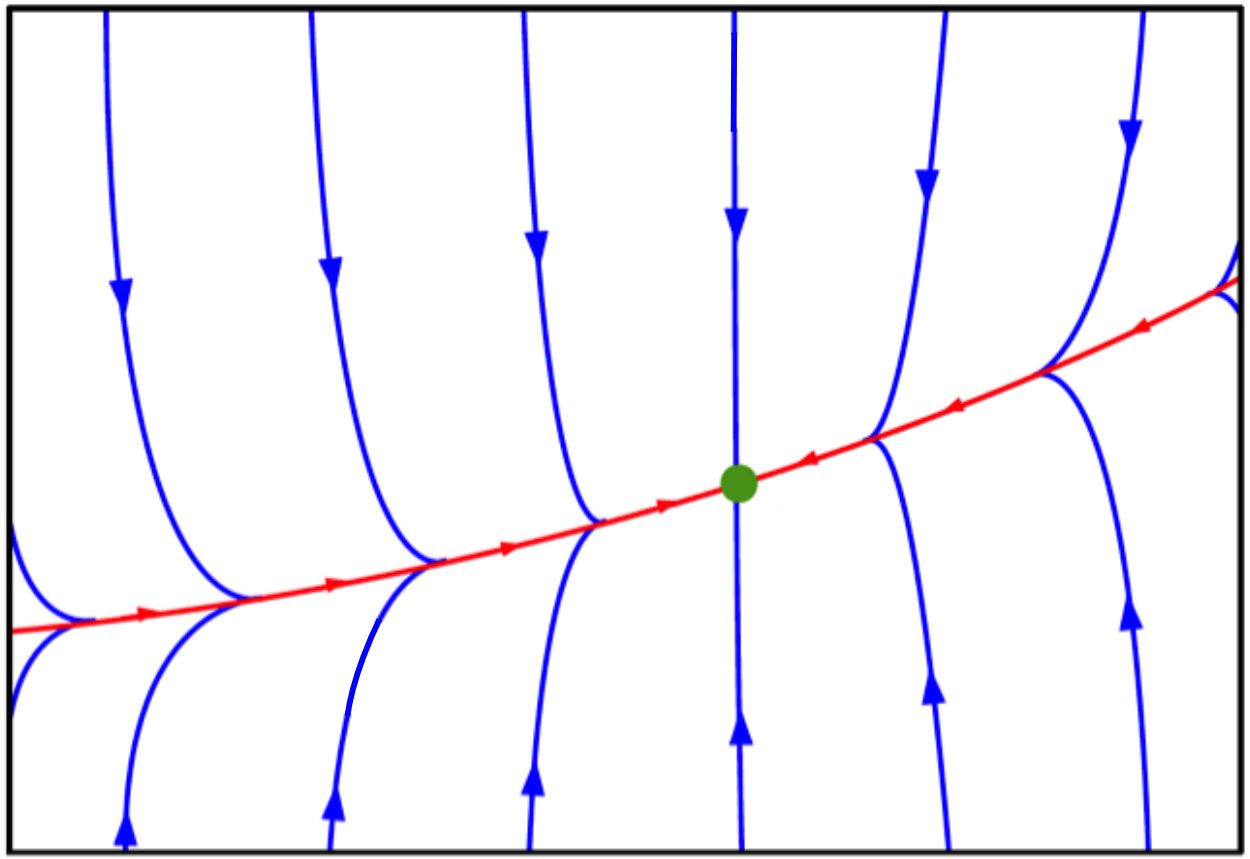
An instability/strong cooling quench…

…leads to **far-from-equilibrium** bidirectional transport:



I. Chantesana, A. Piñeiro Orioli, TG, PRA 99, 043620 (2019)

Partially universal quantum dynamics

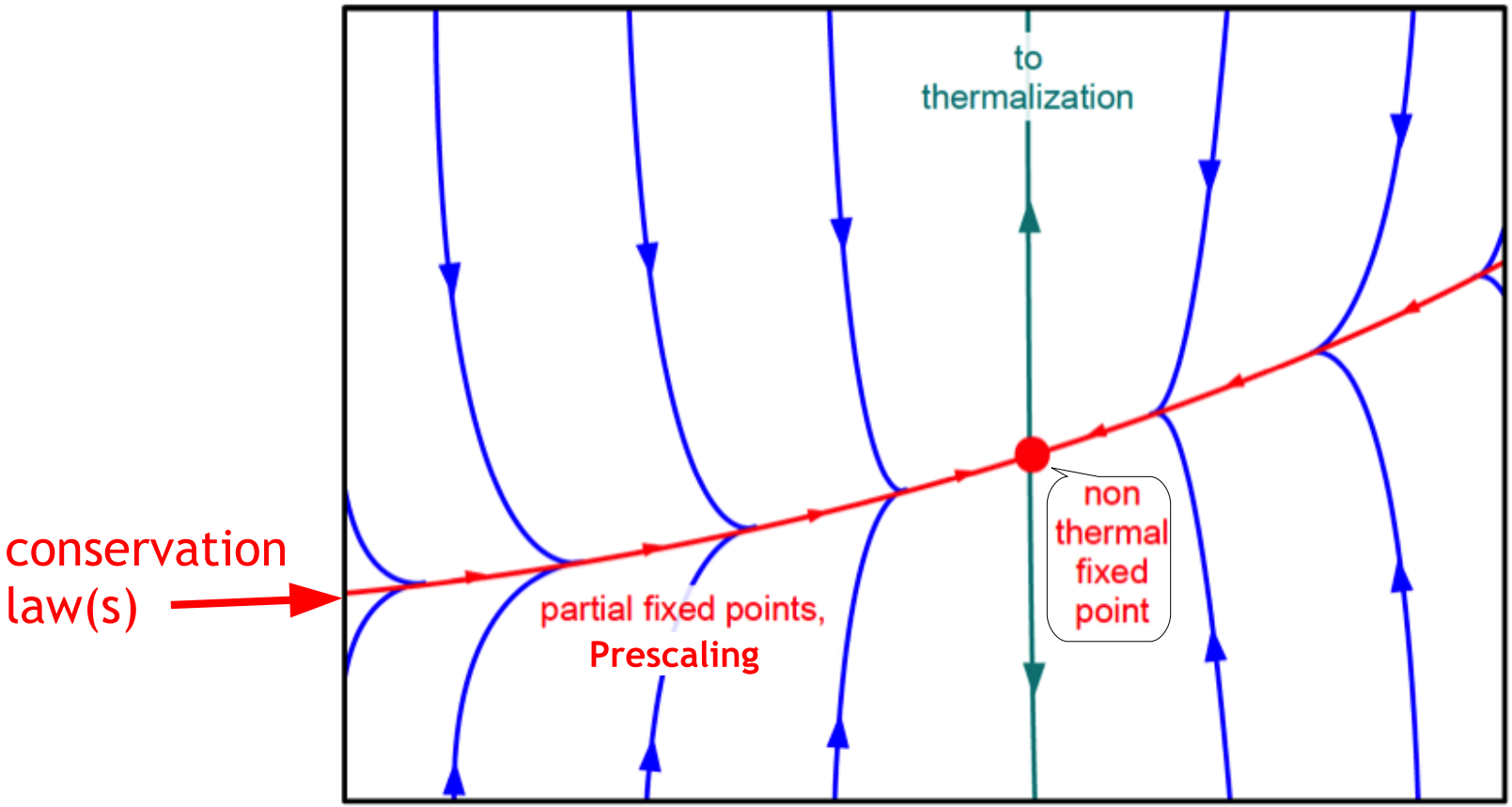


[Sketch after C. Wetterich]

(partial) loss of information about initial conditions

e.g. in terms of density matrix: loss of off-diagonal phase relations
(between non-degenerate levels)

Prescaling and Non-Thermal Fixed Point

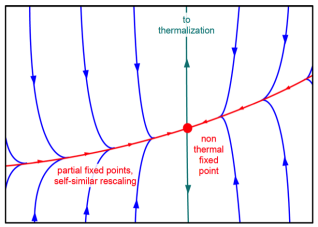


Non-thermal Fixed Points:
Berges, Rothkopf, Schmidt (08), Hoffmeister, Sexty, Schlichting, Piñeiro Orioli, Boguslavski, … Berges (09-)
Scheppach, Berges, TG (10), Nowak, Sexty, Schole, Schmidt, Erne, Karl, Schmied, ... TG (11-)
Chantesana, Piñeiro Orioli, TG: PRA **99**, 043620 (19);

Prescaling:
Mikheev, Schmied, TG: PRL **122**, 170404 (2019); PRA **99**, 063622 (2019)

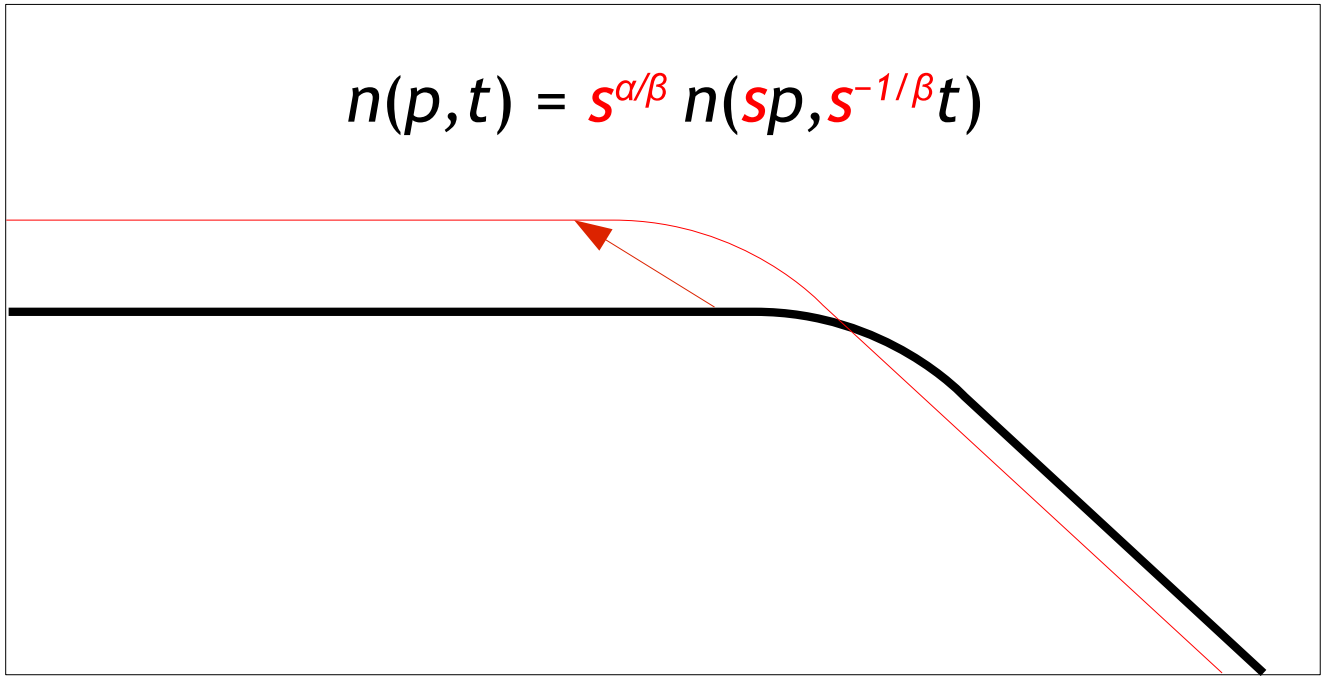
See also the **review:** T. Langen, TG, J. Schmiedmayer, JSTAT 064009 (2016); arXiv:1603.09385
Recent **overview article:** Schmied, Mikheev, TG, arXiv:1810.08143

Close to Non-Thermal Fixed Point: scaling in space & time



Time evolution ≙ Scaling transformation (*real-time* critical slowing down)

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

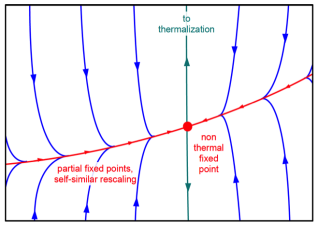


choose $s = (t/t_0)^{\beta}$ $\Rightarrow$ scaling form: $n(p,t) = (t/t_0)^{\alpha}\, n(\,[t/t_0]^{\beta} p,\, t_0)$

$$\equiv (t/t_0)^{\alpha}\, f_s(\,[t/t_0]^{\beta} p\,)$$

A. Piñeiro Orioli, K. Boguslavski, J. Berges, PRD **92**, 025041 (15)

Close to Non-Thermal Fixed Point: scaling in space & time



Time evolution ≙ Scaling transformation (*real-time* critical slowing down)

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

log $n(p)$

universal scaling function $f_s(k)$

log p

choose $s = (t/t_0)^{\beta}$ ⇒ scaling form: $n(p,t) = (t/t_0)^{\alpha}\, n(\,[t/t_0]^{\beta} p,\, t_0)$

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A. Piñeiro Orioli, K. Boguslavski, J. Berges, PRD **92**, 025041 (15)

Universal scaling dynamics in a three-component 3D Bose gas

$$H_{U(3)} = \int \mathrm{d}^3x \left[-\Phi_a^\dagger \frac{\nabla^2}{2m} \Phi_a + \frac{g}{2} \Phi_a^\dagger \Phi_b^\dagger \Phi_b \Phi_a \right]$$

$a,\ b = 1,2,3.$ $U(3)$ symmetric!

[C.M. Schmied, A.N. Mikheev, TG, PRL **122**, 170404 (2019); PRA **99**, 063622 (2019)]

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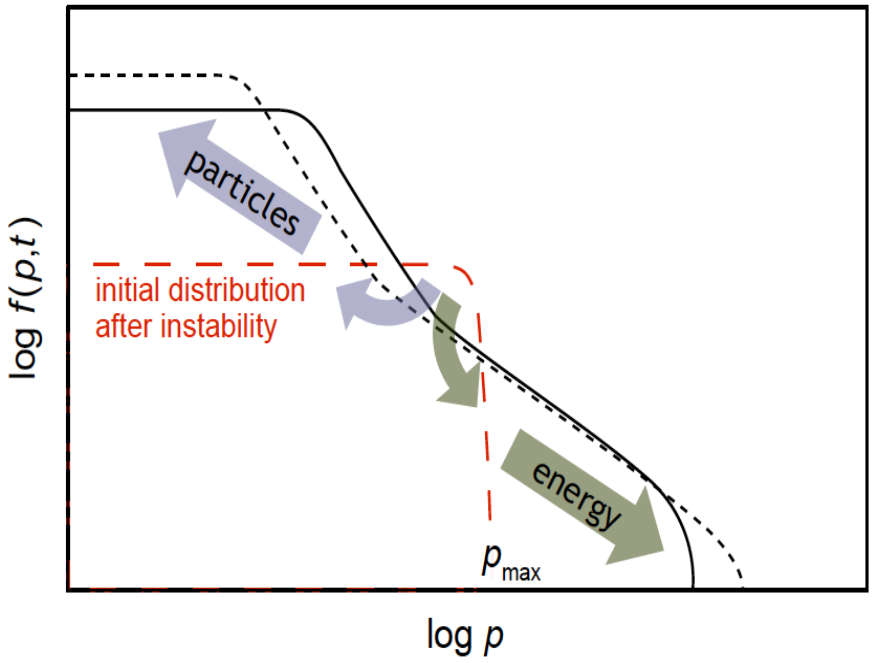

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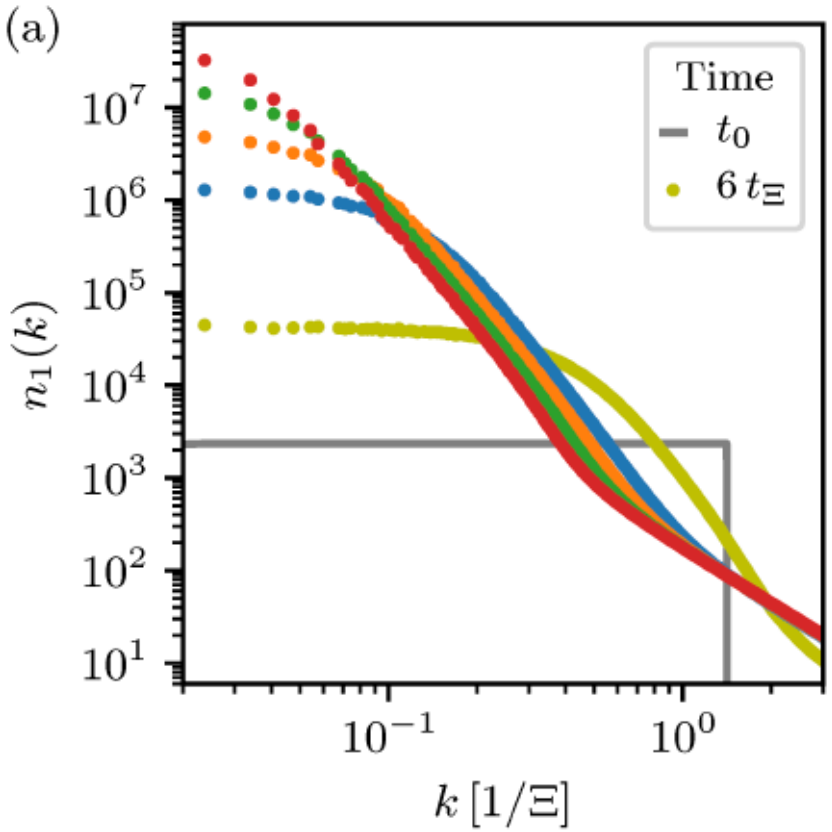

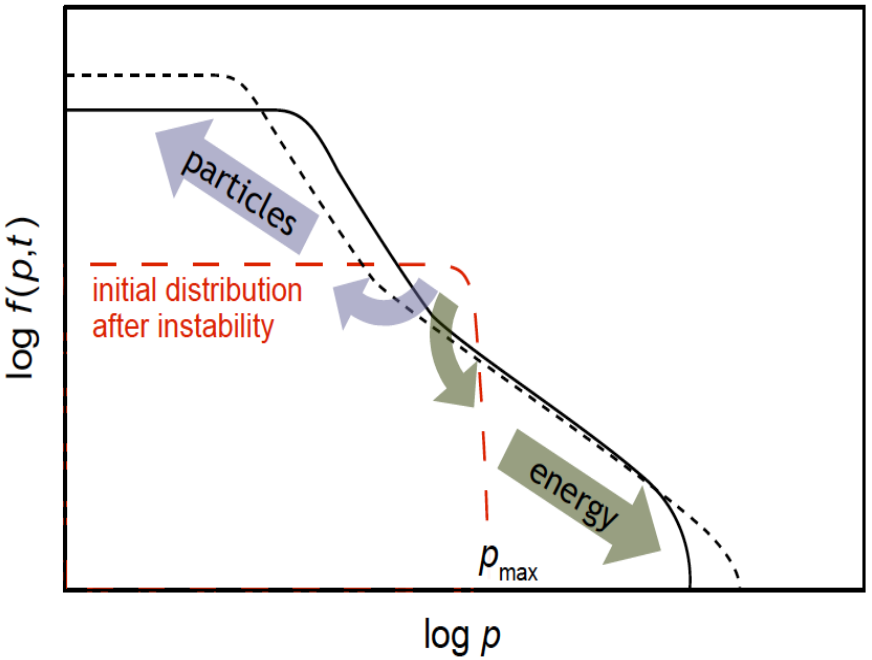

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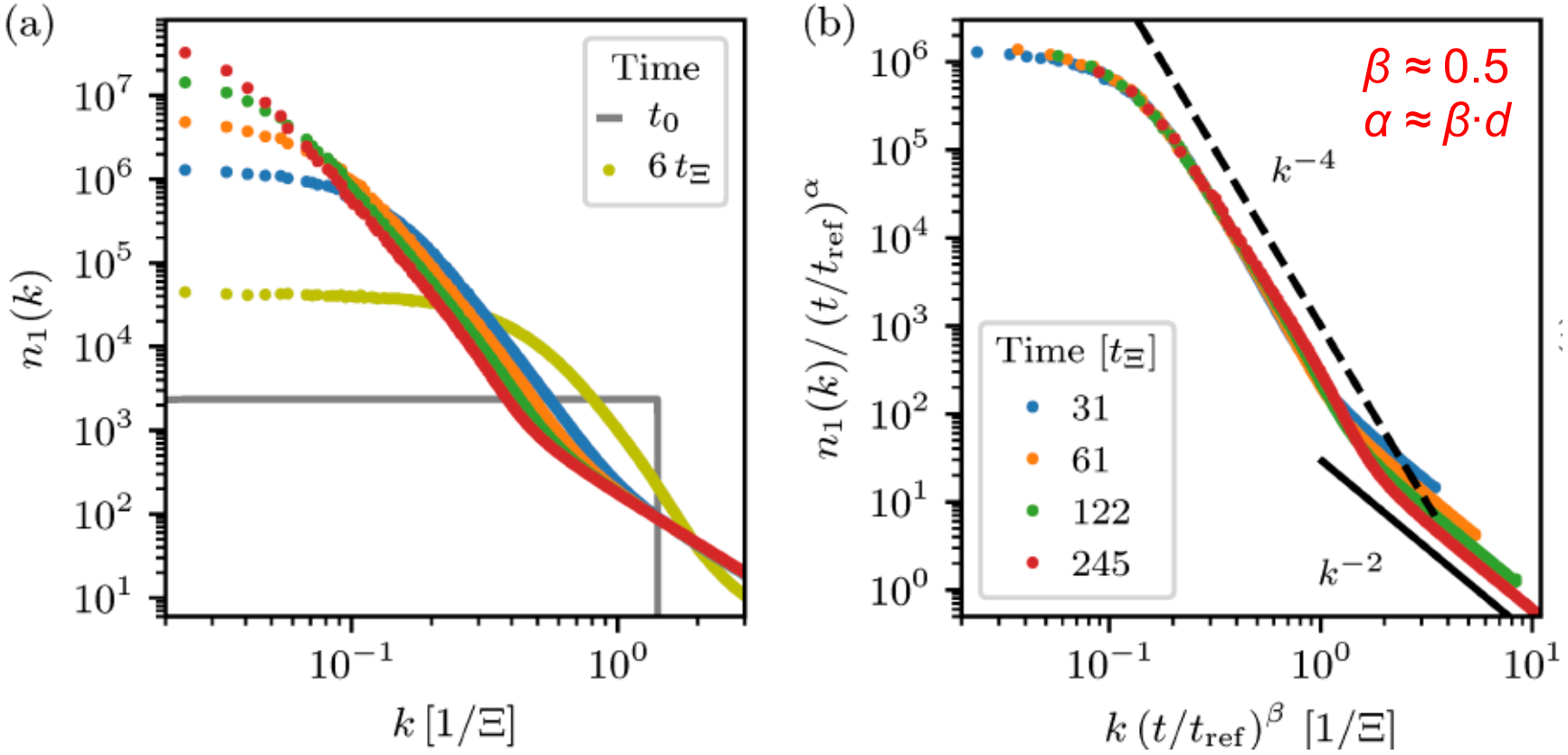
$$n_1(p,t) = (t/t_0)^{\alpha}\ f_s(\,[t/t_0]^{\beta} p\,)$$



[C.M. Schmied, A.N. Mikheev, TG, PRL **122**, 170404 (2019); PRA **99**, 063622 (2019)]

Video: Approach of a strongly anomalous non-thermal fixed point in a 1-component 2D gas

https://www.kip.uni-heidelberg.de/gasenzer/projects/lowenergyeffectiveu3a

[C.M. Schmied, A.N. Mikheev, TG, PRL **122**, 170404 (2019); PRA **99**, 063622 (2019)]

Scaling analysis of Boltzmann transport

Radial transport equation as fixed-point equation:

$$\partial_t n_Q(\mathbf{p},t) = I[n_Q](\mathbf{p},t)$$

$$I[n_Q](\mathbf{p},t) = \int_{\mathbf{kqr}} |T_{\mathbf{pkqr}}|^2 \delta(\mathbf{p}+\mathbf{k}-\mathbf{q}-\mathbf{r})\, \delta(\omega_\mathbf{p}+\omega_\mathbf{k}-\omega_\mathbf{q}-\omega_\mathbf{r}) \times [(n_\mathbf{p}+n_\mathbf{k})n_\mathbf{q}n_\mathbf{r} - n_\mathbf{p}n_\mathbf{k}(n_\mathbf{q}+n_\mathbf{r})]$$

$$n_\mathbf{p} \equiv n_Q(\mathbf{p},t) = (t/t_0)^\alpha \; f_s(\,[t/t_0]^\beta p\,)$$

$$t^{\alpha-1} \sim t^{-\beta(3d+2m-d-z)+3\alpha}$$

$$\alpha = \beta[d+m-z/2]-1/2$$

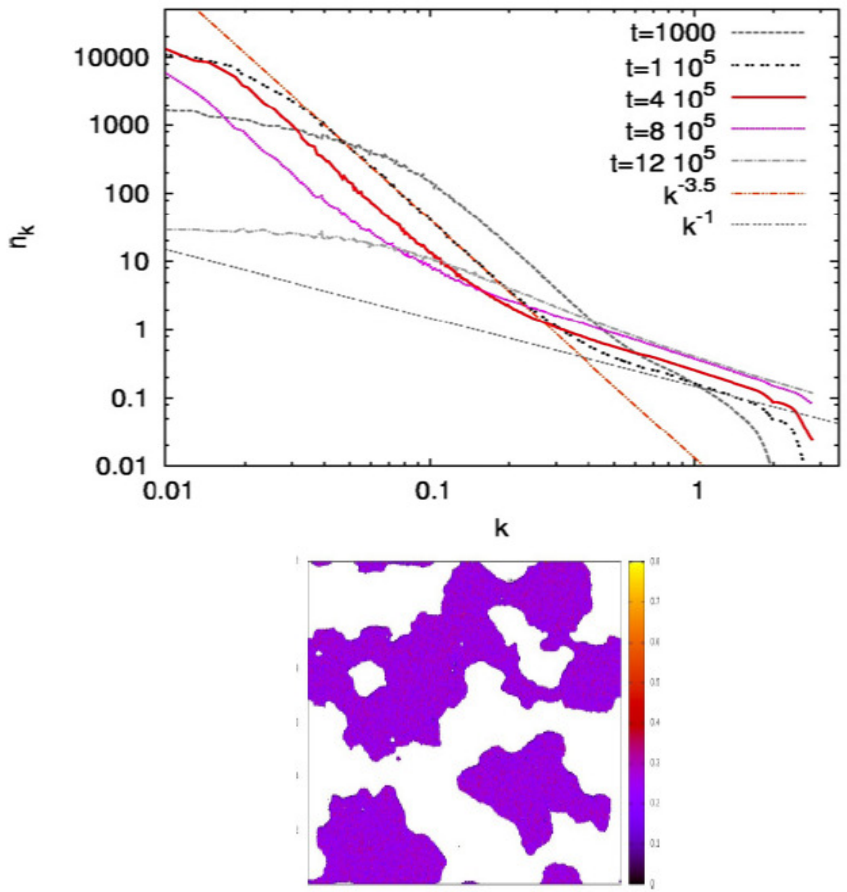
fixes, together with relation from conservation laws, both, α & β.

I. Chantesana, A. Piñeiro Orioli, TG, PRA 99, 043620 (2019),
A.N. Mikheev, C.M. Schmied, TG, PRA 99, 063622 (2019)

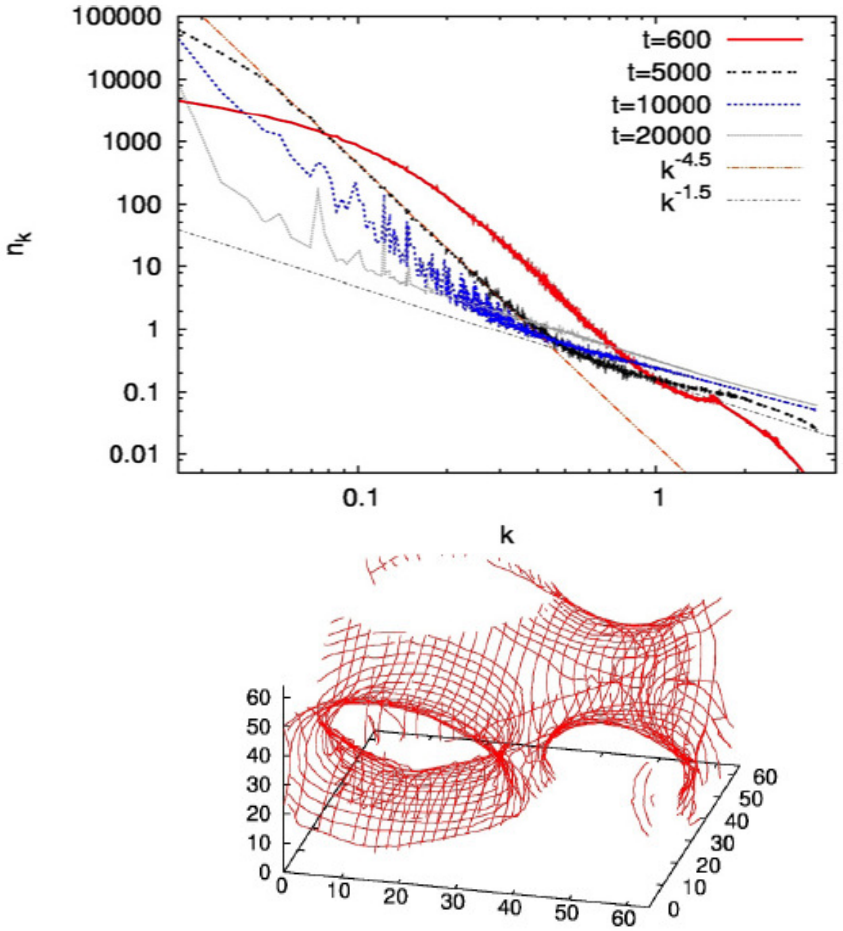
Universal scaling during reheating

Classical field equation: $\left[\partial_t^2 - \Delta + \Phi^2\right]\Phi_a = 0$

d=2



d=3



D. Sexty, B. Nowak, TG, PLB **710** (12)

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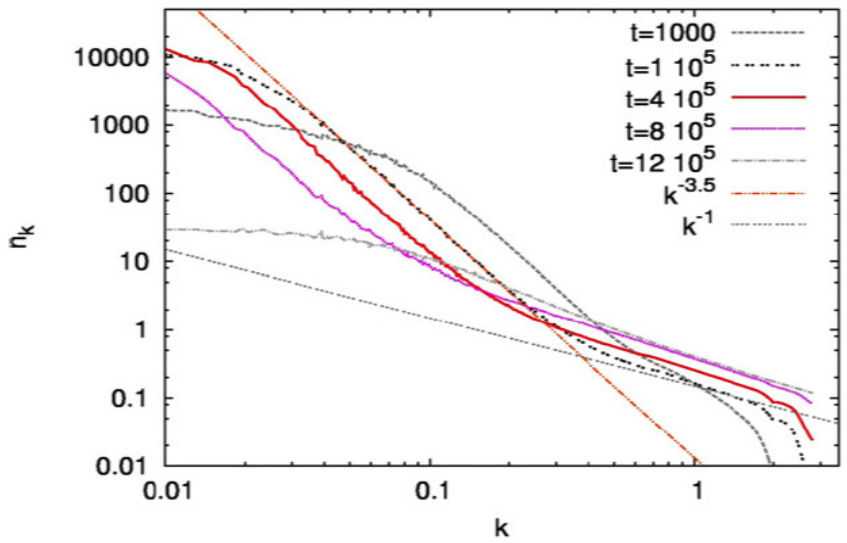
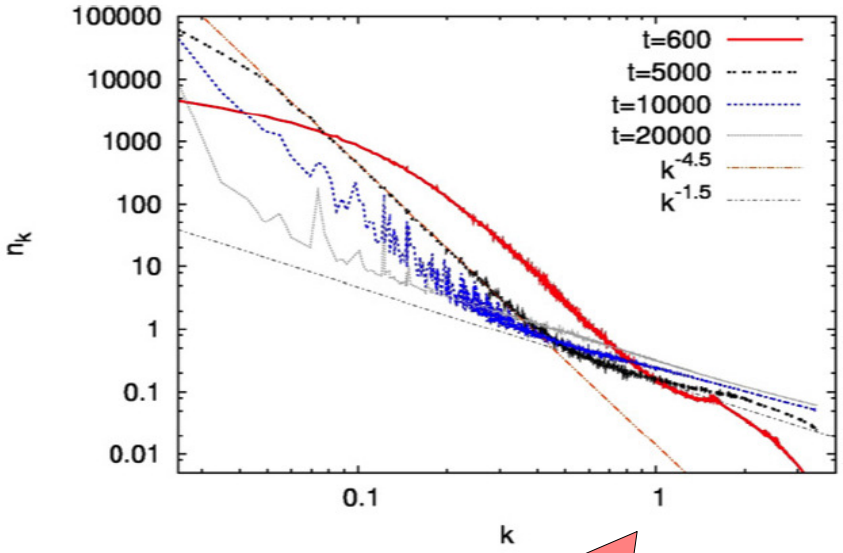
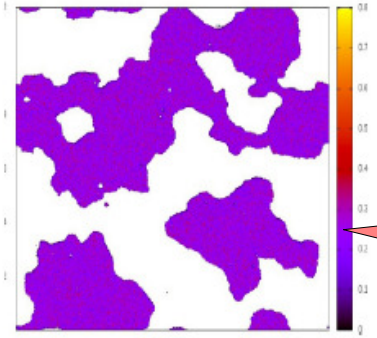


d=3

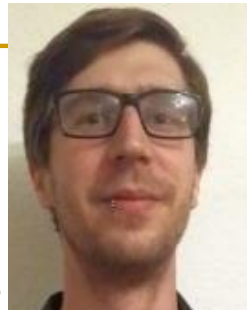




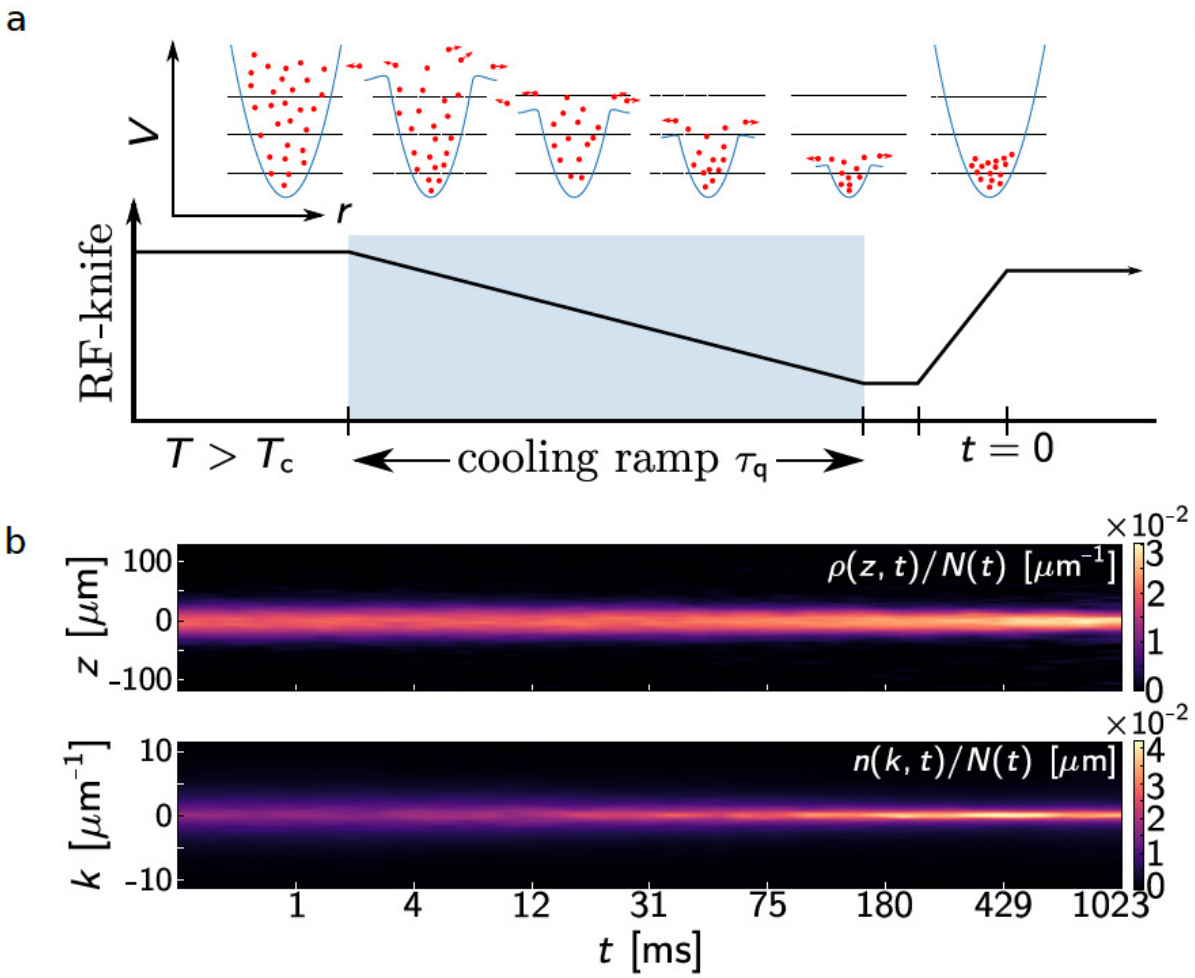
Aleksandr Chatrchyan's talk

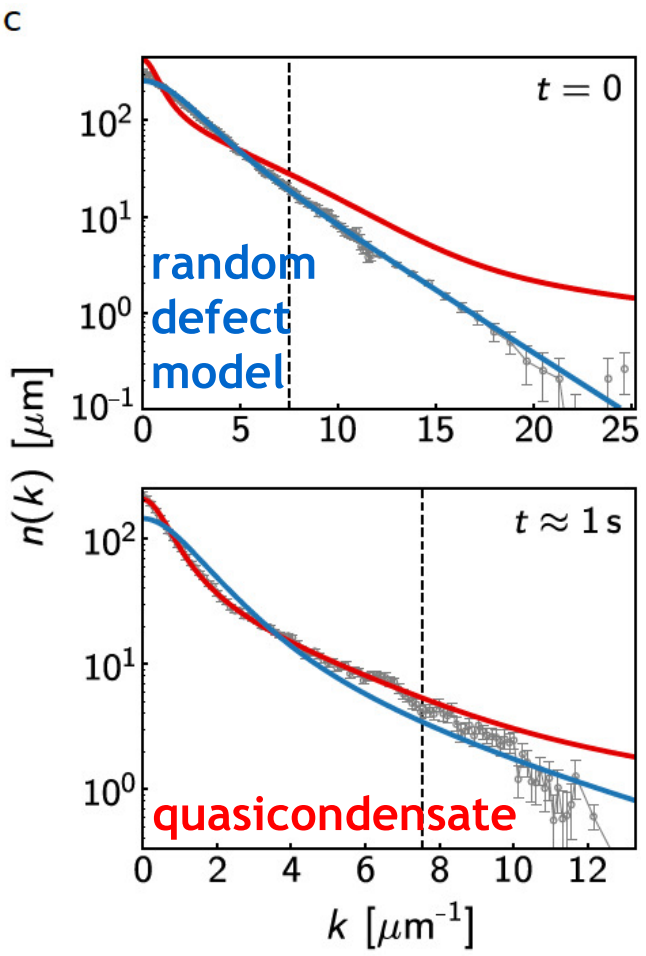
D. Sexty, B. Nowak, TG, PLB **710** (12)

NTFP in a 1D soliton gas



Sebastian Erne



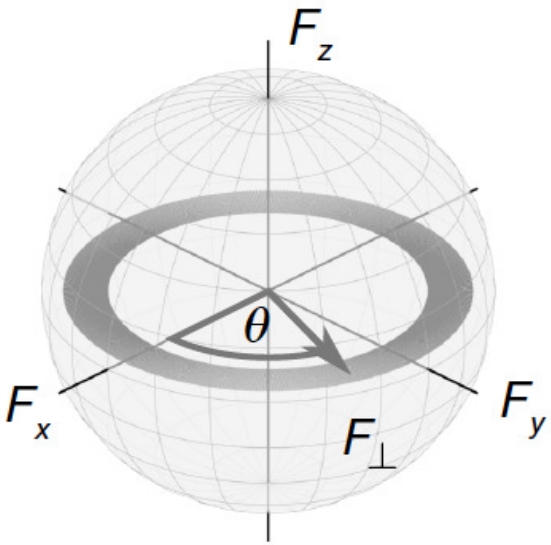


S. Erne, R. Bücker, TG, J. Berges, J. Schmiedmayer, Nature **563**, 225 (2018)

Experiment: Quench in a quasi-1D Spin-1 gas

$$H = \int dx \left[\vec{\Phi}^\dagger \left(-\frac{\hbar^2}{2M}\frac{\partial^2}{\partial x^2} + q f_z^2 \right) \vec{\Phi} + \frac{c_0}{2} n^2 + \frac{c_1}{2} |\vec{F}|^2 \right]$$

$$\vec{\Phi} = (\Phi_1, \Phi_0, \Phi_{-1})^T$$

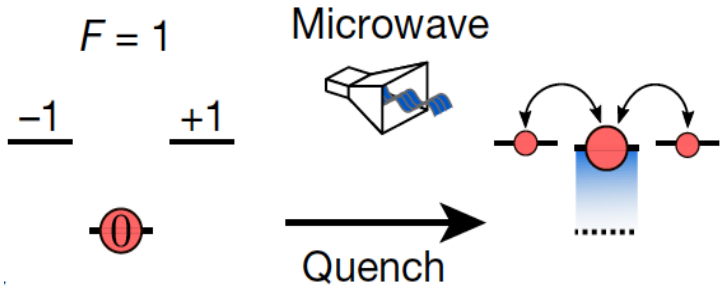


$$F_\perp = F_x + iF_y$$

Quench from polar to easy-plane (broken axisymmetric) phase

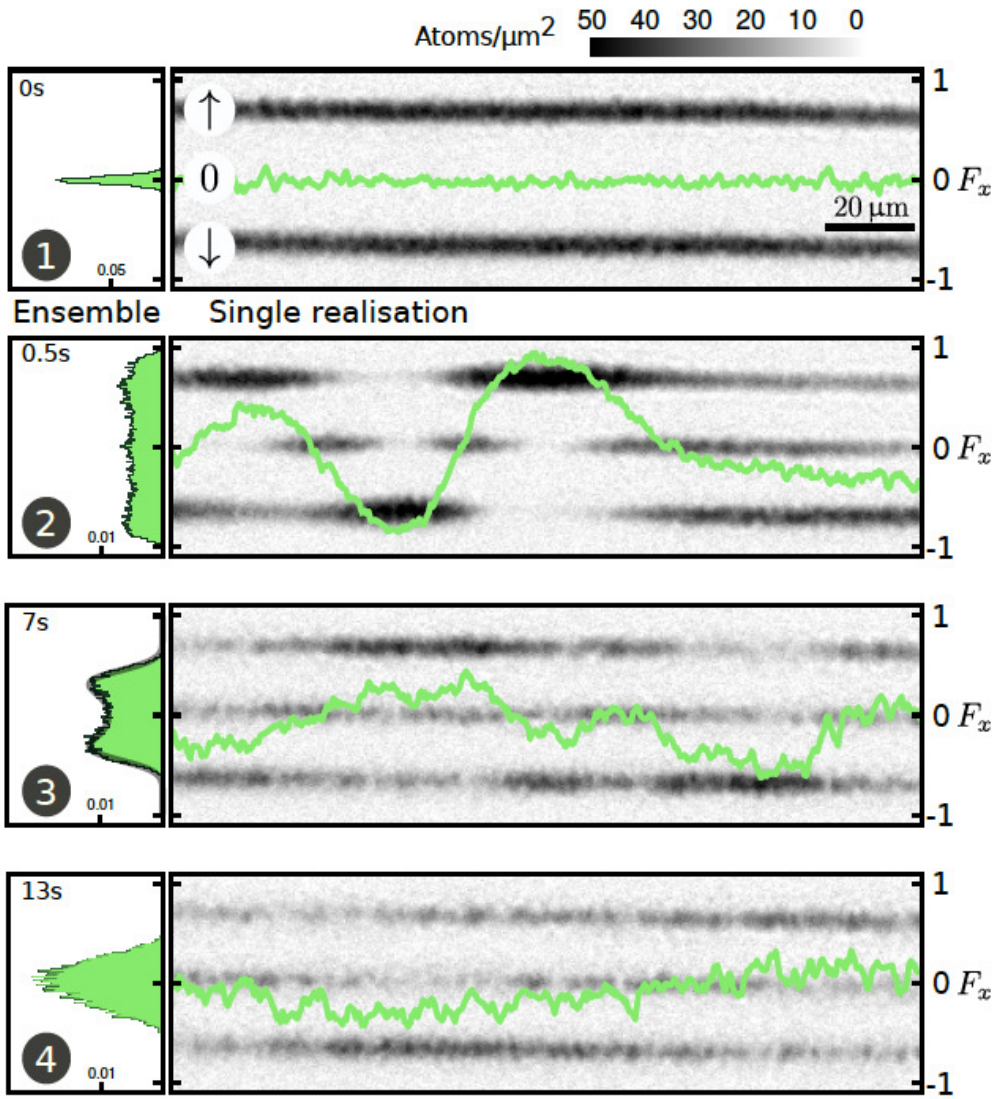
Measurement of Structure Factor:

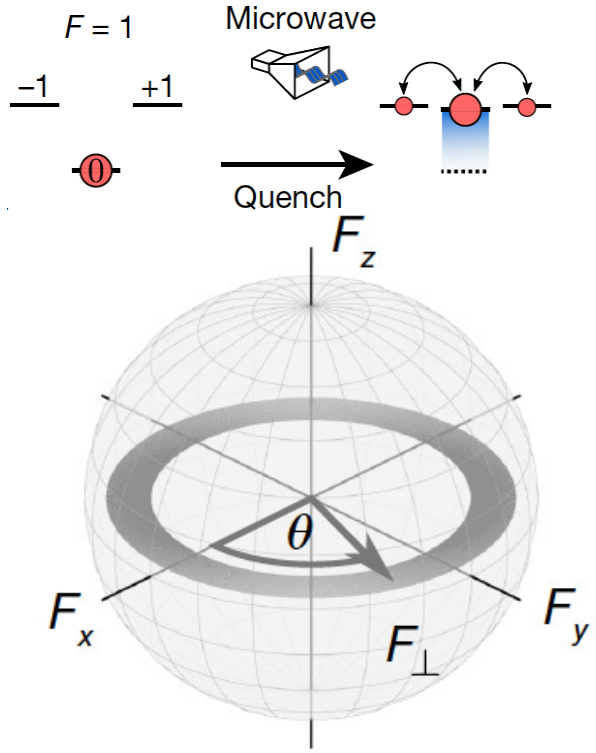
$$S(k,t) = \langle |F_\perp(k,t)|^2 \rangle$$

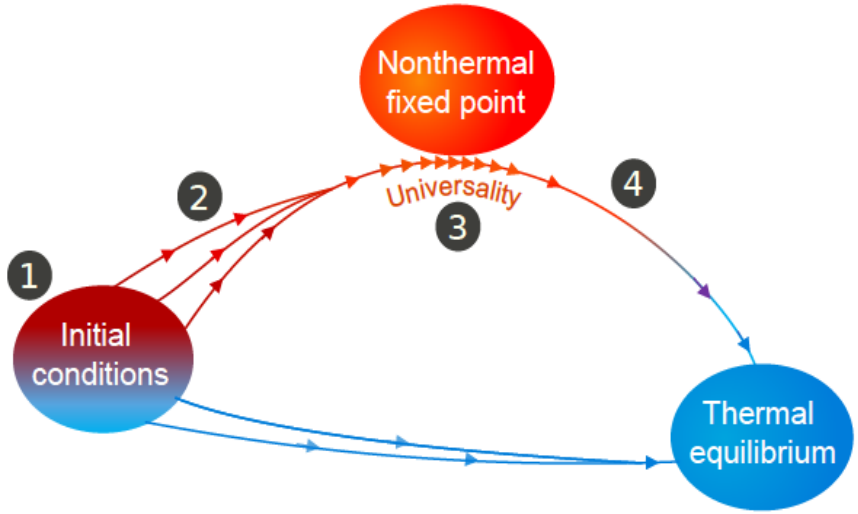


M. Prüfer, P. Kunkel, H. Strobel, S. Lannig, D. Linnemann, C.-M. Schmied, J. Berges, TG, M.K. Oberthaler, Nature **563**, 217 (2018)

Quench in a quasi-1D Spin-1 gas







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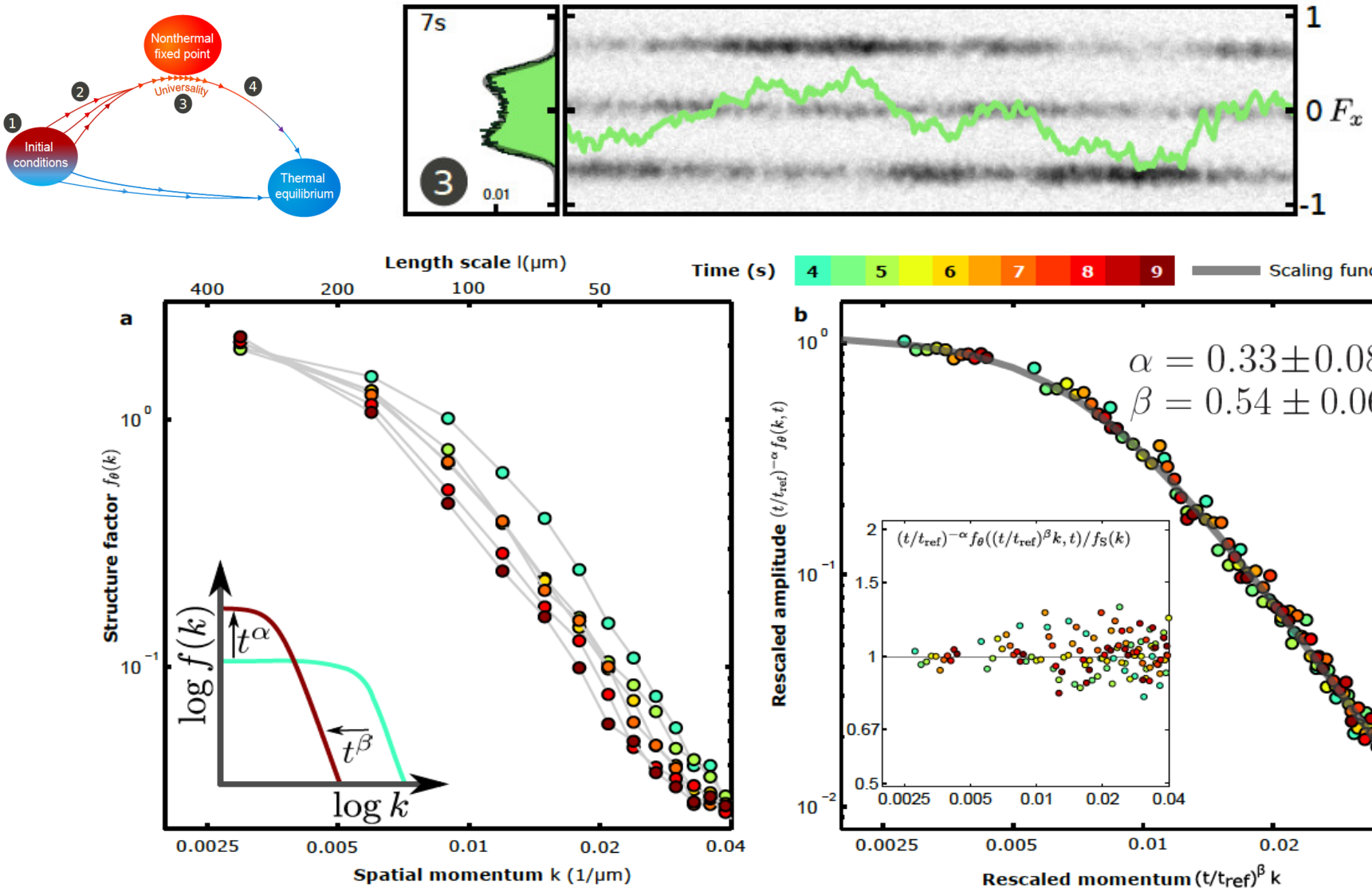
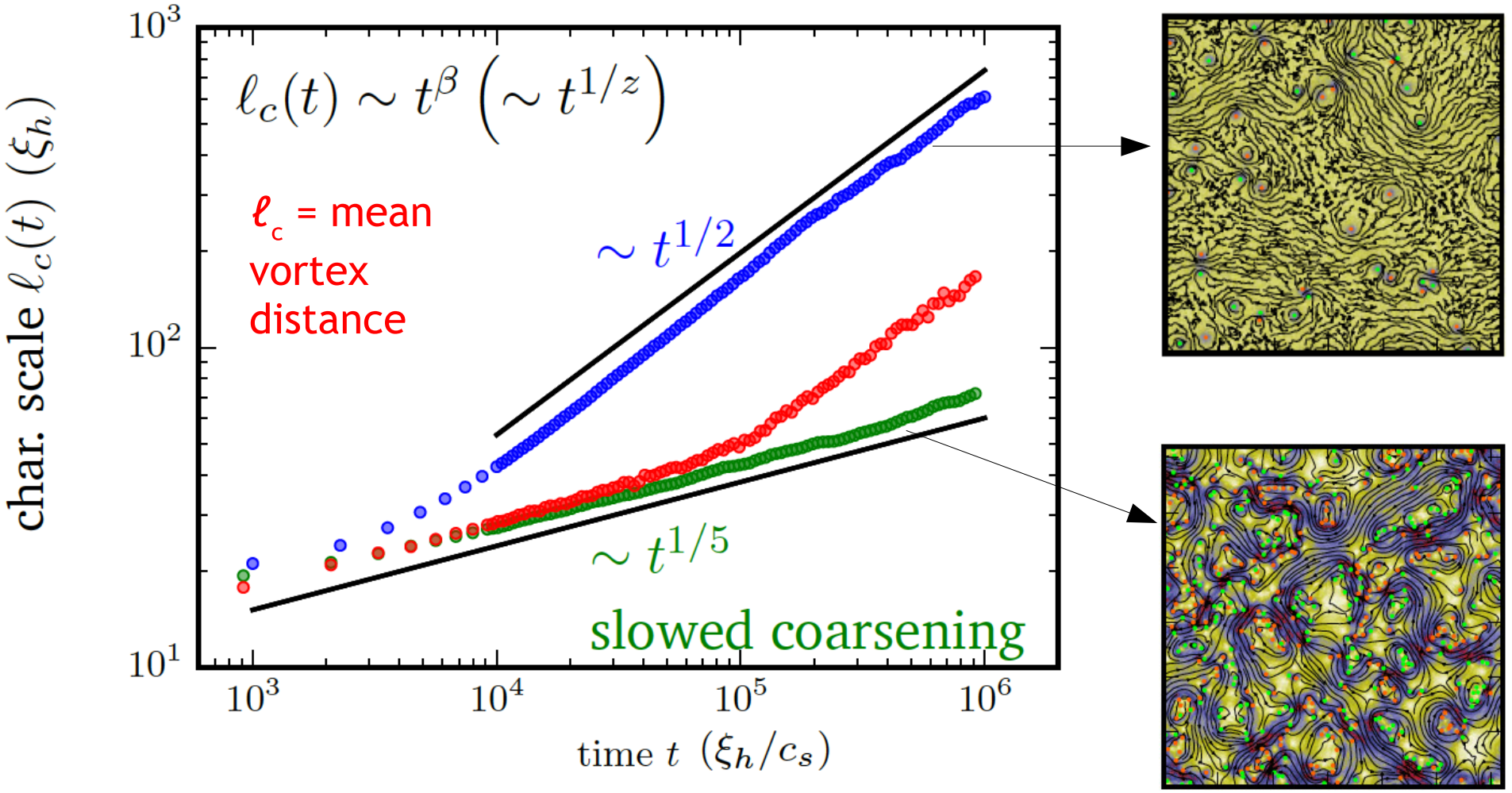
Universal dynamics near NTFP: scaling



M. Prüfer, P. Kunkel, H. Strobel, S. Lannig, D. Linnemann, C.-M. Schmied, J. Berges, TG, M.K. Oberthaler, Nature **563**, 217 (2018)

Anomalous vs near-equilibrium NTFP

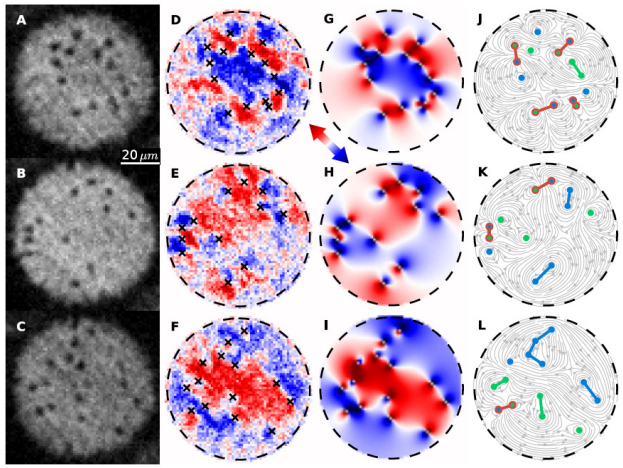


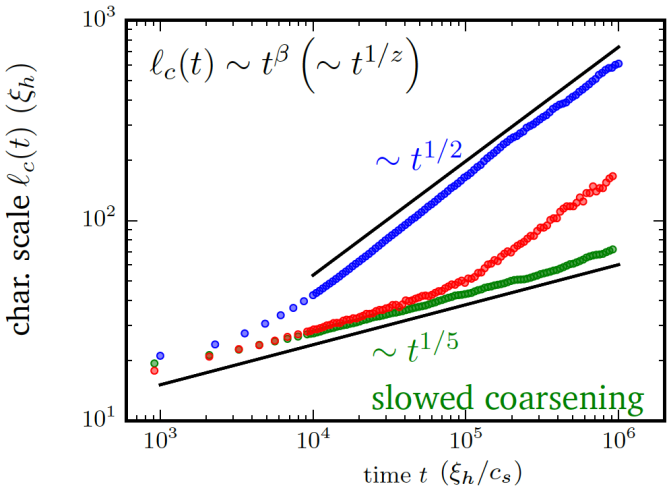
$z_d \approx 5$

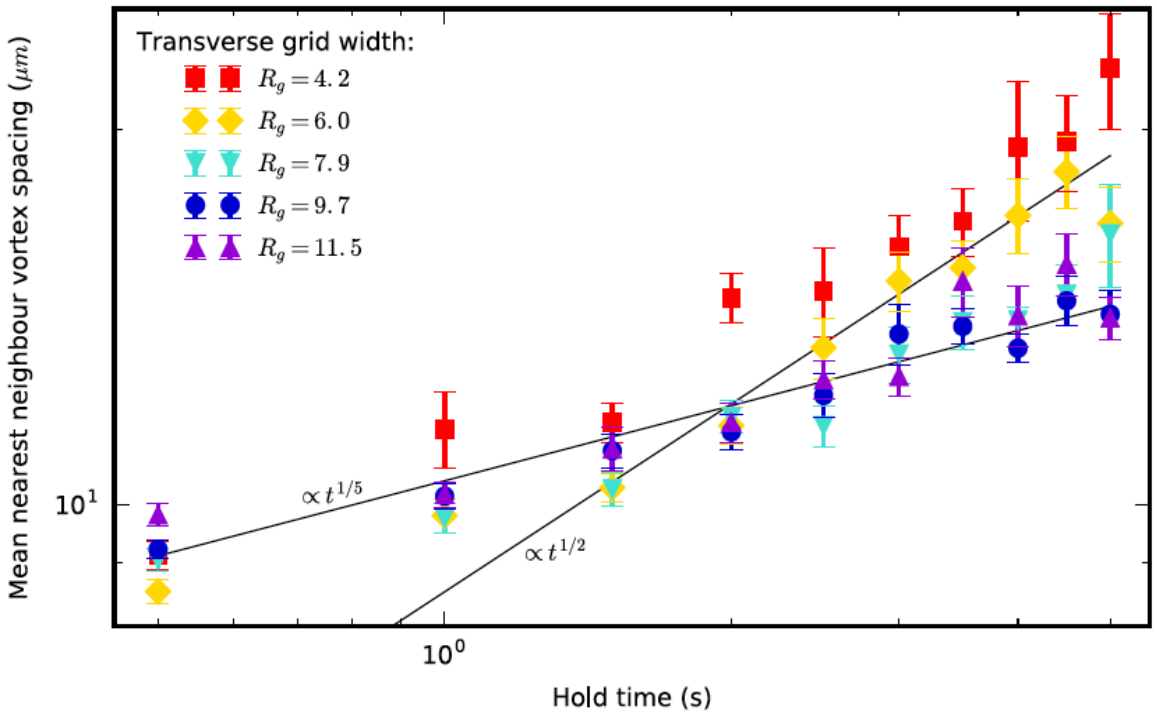
(glass-like z-exponent)

M. Karl, TG, NJP **19**, 093014 (2017), 1611.01163 [cond-mat.quant-gas]
See also:
J. Deng, S. Schlichting, R. Venugopalan, Q. Wang, PRA 97, 053606 (2018)
A. Groszek, M. Davis, T. Simula, 1903.05528 [cond-mat.quant-gas]

Vortex dynamics in experiment (Monash U)







S.P. Johnstone et al., 1801.06952v2 [cond-mat.quant-gas] (Helmerson group)

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Expt. PIs:

Fred Jendrzejewski

Markus Oberthaler

Theory PIs:

Martin Gärttner

TG

Philipp Hauke

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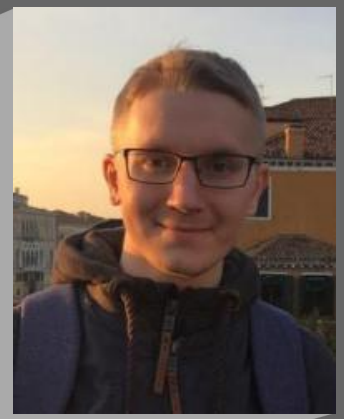
Aleksandr Mikheev



Christian Marcel Schmied

Reviews, Lecture notes, Summary articles, & recent Progress:

Non-thermal fixed points: Universal dynamics far from equilibrium
C.-M. Schmied, A. N. Mikheev, TG,
in Proc. Julian Schwinger Centennial Conf. and Workshop, Singapore, 7-12 Feb 2018.
arXiv:1810.08143 [cond-mat.quant-gas]

Low-energy effective theory of non-thermal fixed points in a multicomponent Bose gas
A. N. Mikheev, C.-M. Schmied, TG,
arXiv:1807.10228 [cond-mat.quant-gas]; Phys. Rev. A, to appear

Prescaling in a far-from-equilibrium Bose gas
C.-M. Schmied, A. N. Mikheev, TG,
Phys. Rev. Lett. **122**: 170404, 2019

Kinetic theory of non-thermal fixed points in a Bose gas
I. Chantesana, A. Piñeiro Orioli, TG,
Phys. Rev. A **99**, 043620 (2019)

Prethermalization and universal dynamics in near-integrable quantum systems
T. Langen, TG, J. Schmiedmayer,
JSTAT **064009**, 2016; arXiv:1603.09385 [cond-mat.quant-gas]

Non-thermal fixed points: universality, topology, & turbulence in Bose gases
B. Nowak, S. Erne, M. Karl, J. Schole, D. Sexty, and TG,
in Proc. Int. School on Strongly Interacting Quantum Systems Out of Equilibrium,
Les Houches, edited by T. Giamarchi et al. (OUP, Oxford, 2016)
arXiv:1302.1448 [cond-mat.quant-gas]

The End