Solitons as the early stage of quasicondensate formation during evaporative cooling

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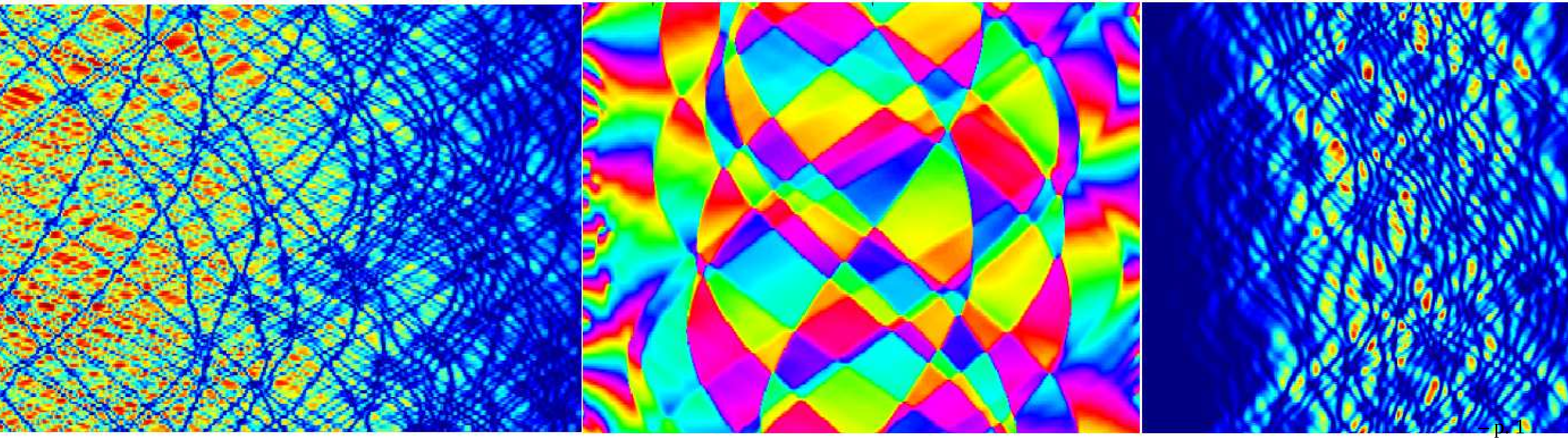
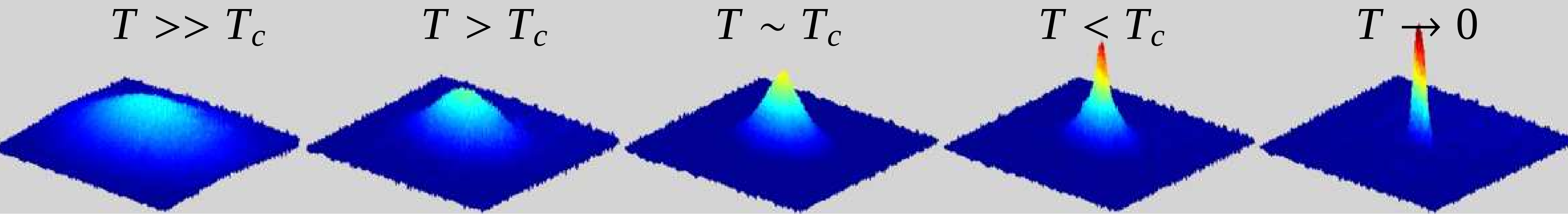


Introduction

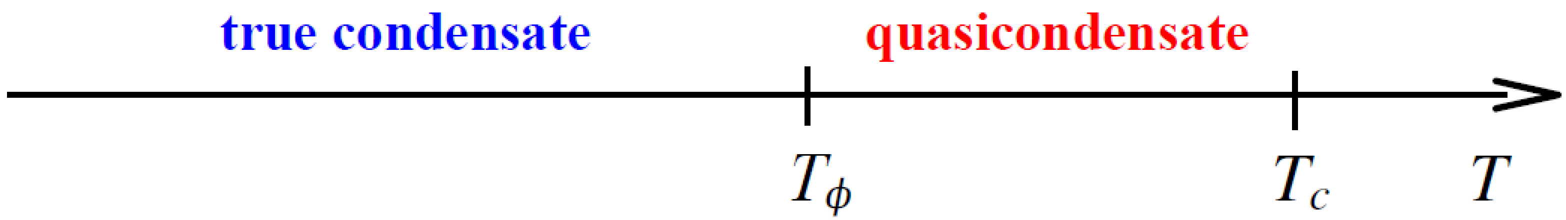


http://www-matterwave.physics.ox.ac.uk/node/1

- **How the coherence is born during evaporation cooling?**
- **System study: weakly interacting 1D Bose gas in a trap**

1D Bose gas in trap

In the regime of weakly interacting gas at thermal equilibrium two characteristic temperatures*: $\mathbf{k_B T_c} = \mathbf{N}\hbar\omega$, $\mathbf{k_B T_\phi} = \mathbf{k_B T_c}\frac{\hbar\omega}{\mu}$



true condensate:

coherence length: $l_\phi \approx L$

populations from one-body density matrix: $N_0 >> N_1$

quasicondensate:

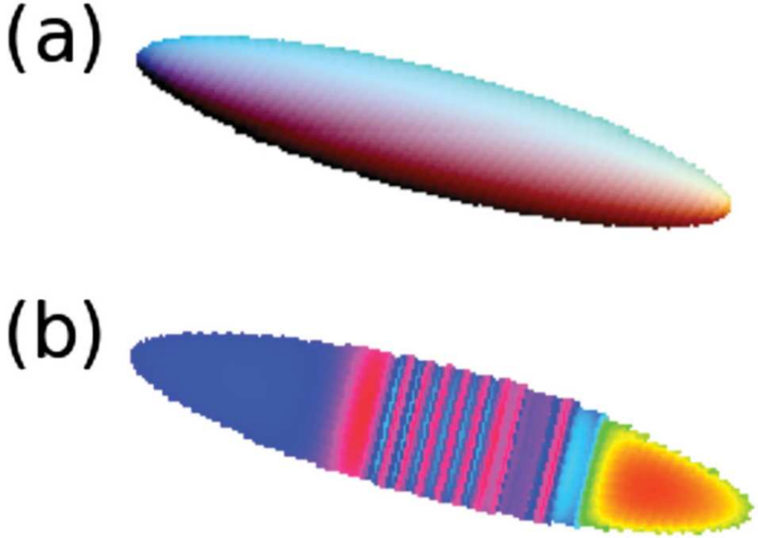
coherence length: $l_\phi < L$

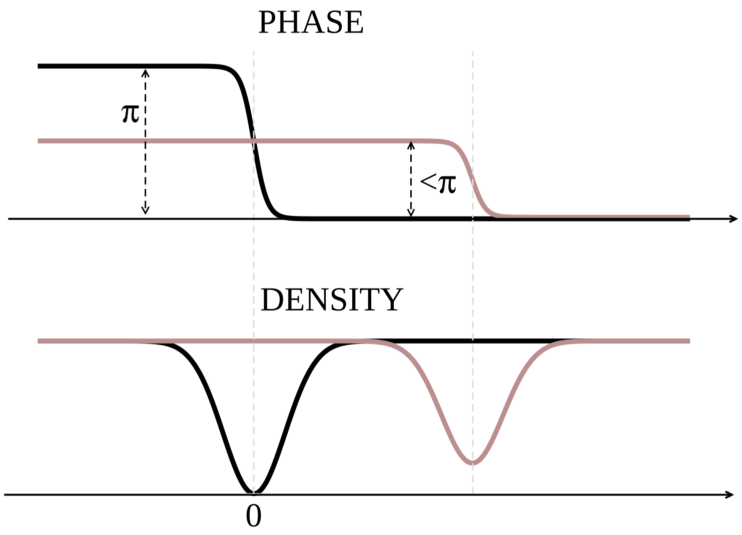
populations from one-body density matrix: $N_0 \gtrsim N_1 \gtrsim N_2 \gtrsim ...$

*D. S. Petrov *et al*, PRL **85**, 3745 (2000); D. S. Petrov *et al*, PRL **87**, 050404 (2001)

Quanched 1D Bose gas in trap

Spontaneous solitons formation* **via Kibble-Zurek mechanism:**



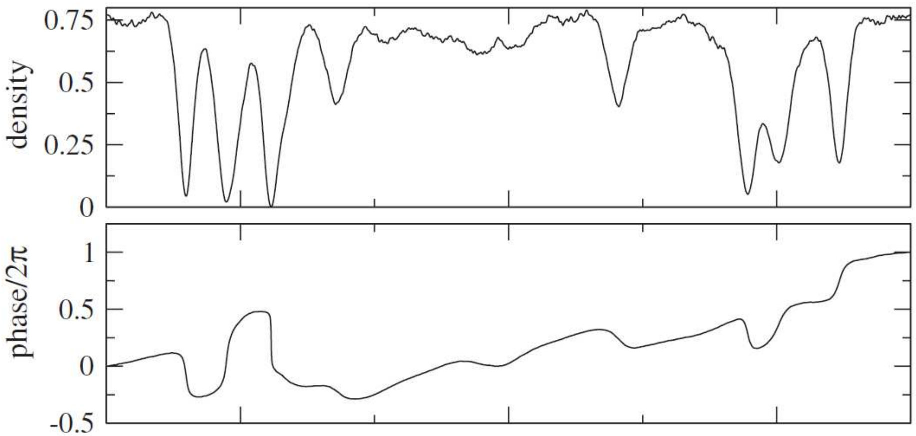


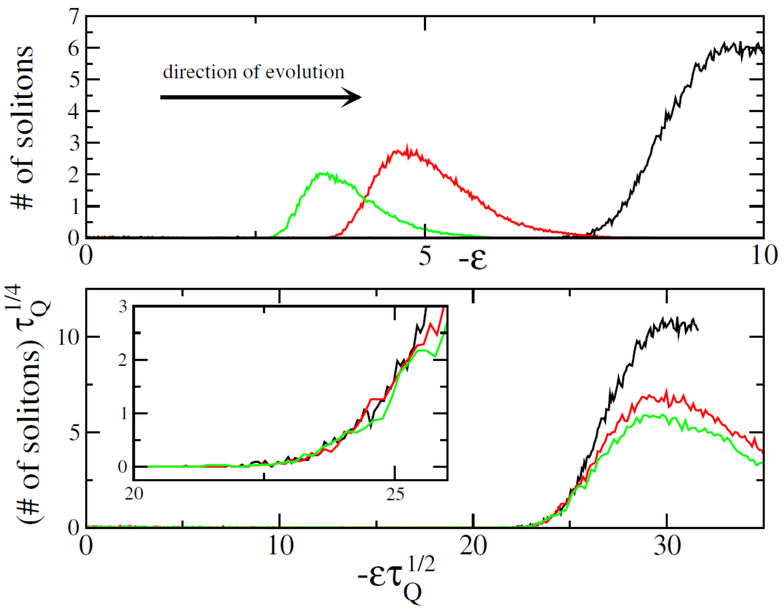
- there exists a **condensate front**
- when velocity of the front is larger than speed of sound then solitons are form
- **number of solitons** scales as $\sim \tau_Q^{-\alpha}$, where τ_Q is a quench time

*W. H. Zurek, PRL **102**, 105702 (2009)

What was done?

Quenched 1D uniform gas:





B. Damski, W. H. Zurek, PRL 104, 160404 (2010)

important aspects not considered:

- evaporative cooling in a trap
- connection between defects formation (KZM) and defect-less equilibrium state

C-field method

Example: uniform system

$$\hat{\psi}(z) = \sum_k \hat{a}_k e^{ikz} \rightarrow \psi(z) = \sum_{k=-k_{max}}^{k_{max}} \alpha_k e^{ikz}$$

replace operators $\hat{a}_k$ with complex amplitude α_k, then:
It will be ok when:

- modes are highly occupied $|\alpha_k|^2 > 1$
- thermal fluctuations larger than the quantum one, $k_B T > \mu$

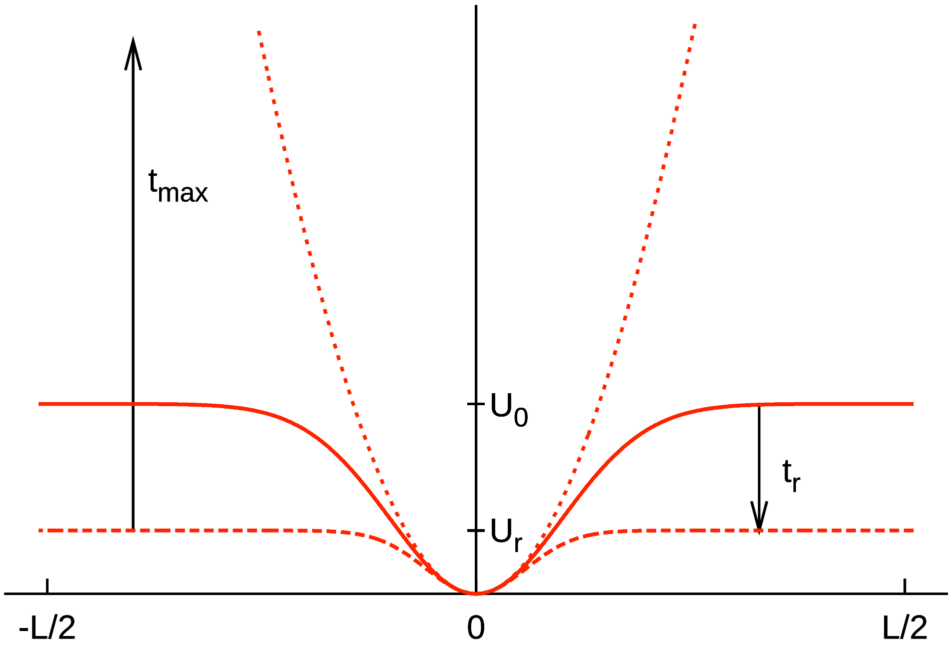
Dynamics

Gross-Pitaevskii equation:

$$i\hbar\partial_t\psi(z,t) = \left(-\frac{\hbar^2}{2m}\Delta + g_{1D}|\psi(z,t)|^2 + H_{ev}(z,t) - i\Gamma(z,t)\right)\psi(z,t)$$

$$H_{ev}(z,t) = U(t)\left[1 - e^{-\frac{1}{2}\left(\frac{z}{s_z}\right)^2 \frac{U_0}{U(t)}}\right]$$

$$\Gamma(z,t) = \Gamma_\infty \left[\frac{H_{ev}(z,t)}{U(t)}\right]^\gamma$$



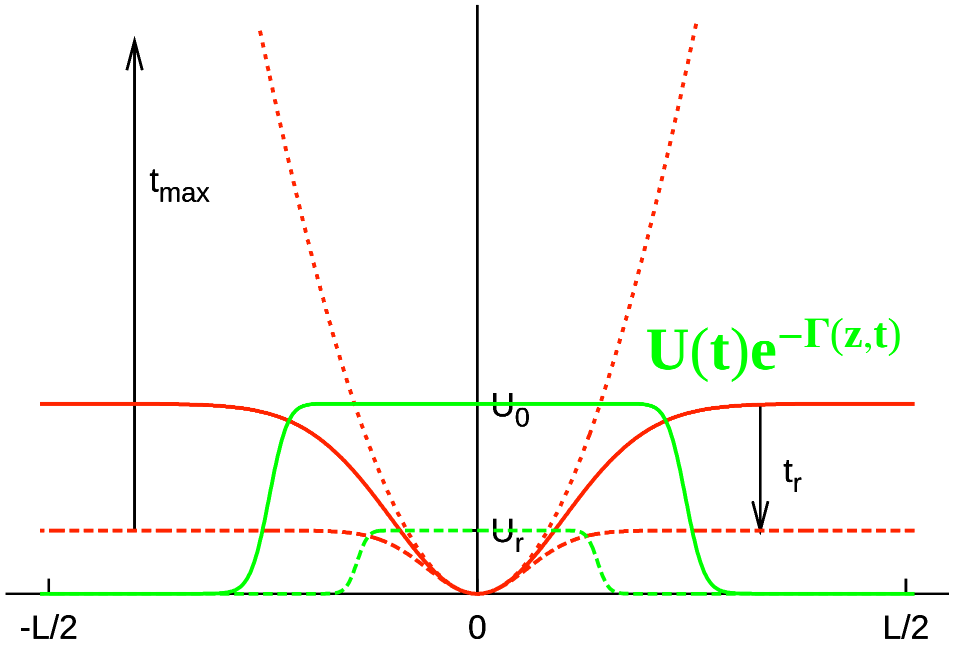
t_r**- evaporation time,** t_{max}**- thermalisation time**

Dynamics

Gross-Pitaevskii equation:

$$i\hbar\partial_t\psi(z,t) = (-\frac{\hbar^2}{2m}\Delta + g_{1D}|\psi(z,t)|^2 + H_{ev}(z,t) - i\Gamma(z,t))\psi(z,t)$$

$$H_{ev}(z,t) = U(t)\left[1 - e^{-\frac{1}{2}\left(\frac{z}{s_z}\right)^2 \frac{U_0}{U(t)}}\right]$$



$$\Gamma(z,t) = \Gamma_\infty\left[\frac{H_{ev}(z,t)}{U(t)}\right]^\gamma$$

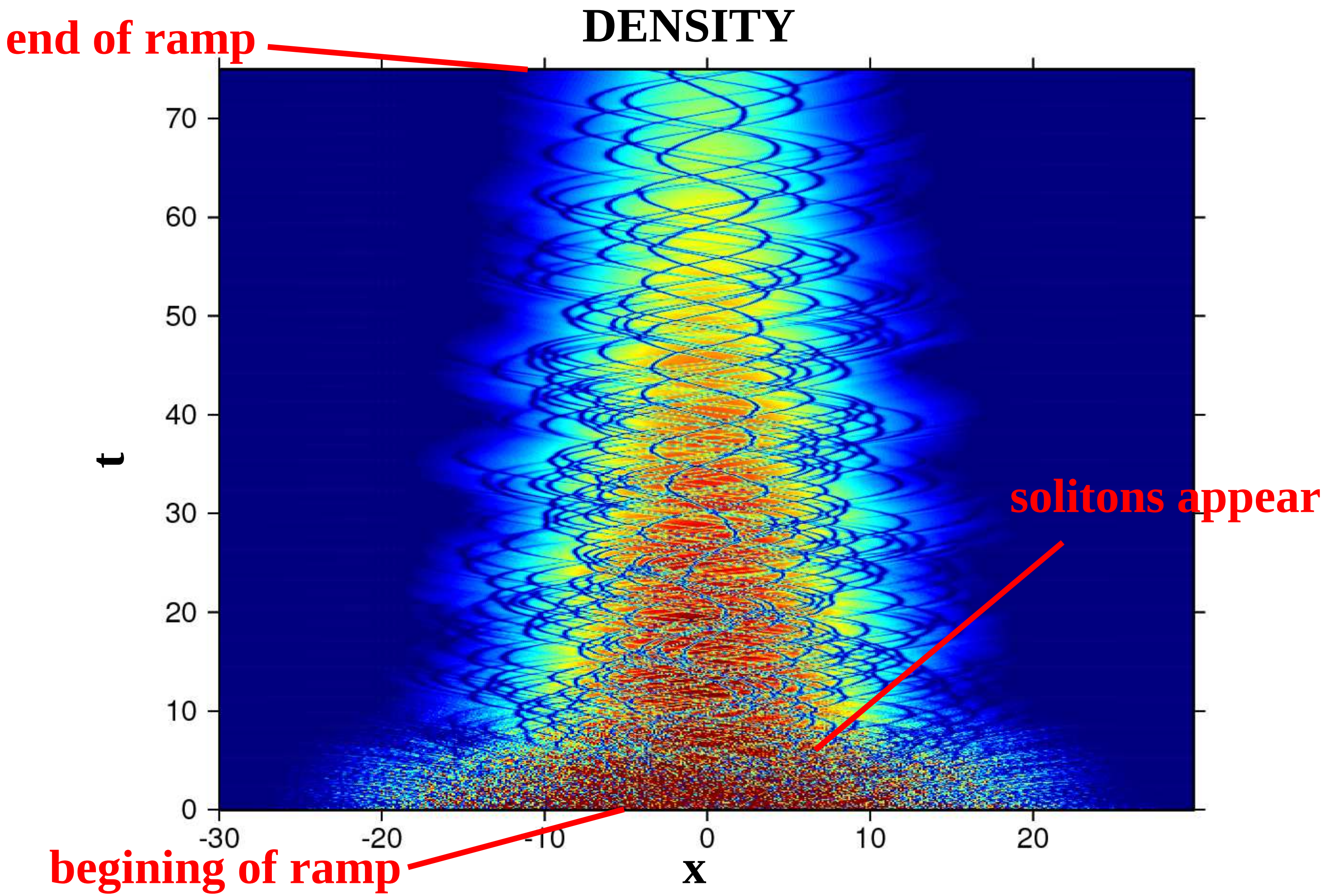
LOSSES:

$$\psi(z,t+\Delta t) \propto e^{-\Gamma(z,t)\Delta t}\psi(z,t)$$

t_r**- evaporation time,** t_{max}**- thermalisation time**

Solution

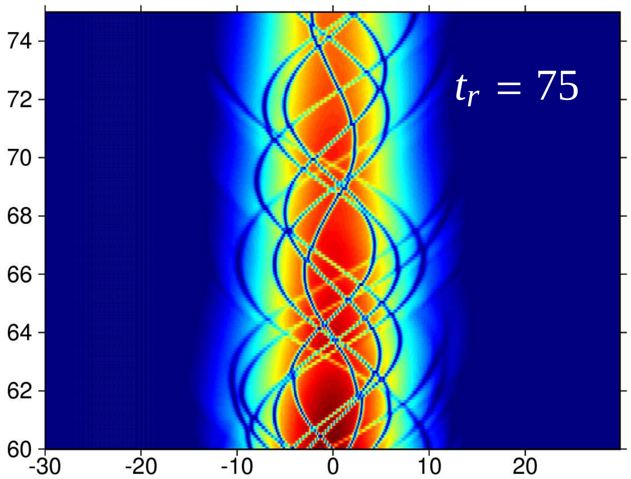
Example for $t_r\omega = 75$ and $t_{max}\omega = 1000$.



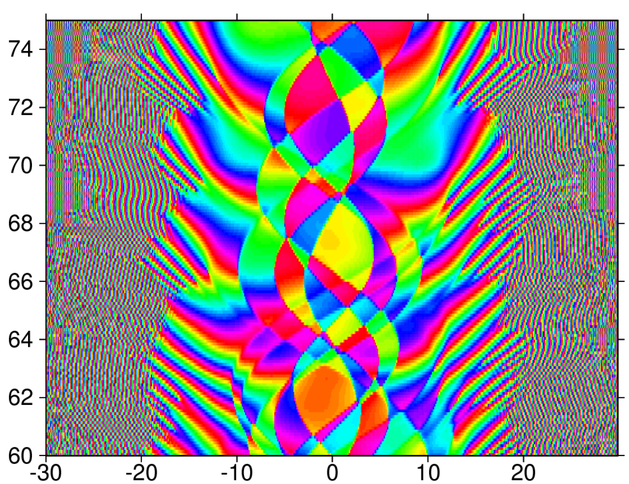
Solution

FAST RAMP

DENSITY

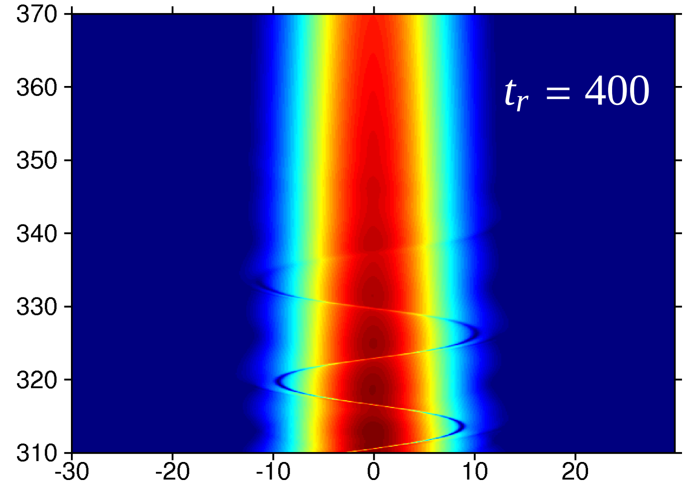


PHASE

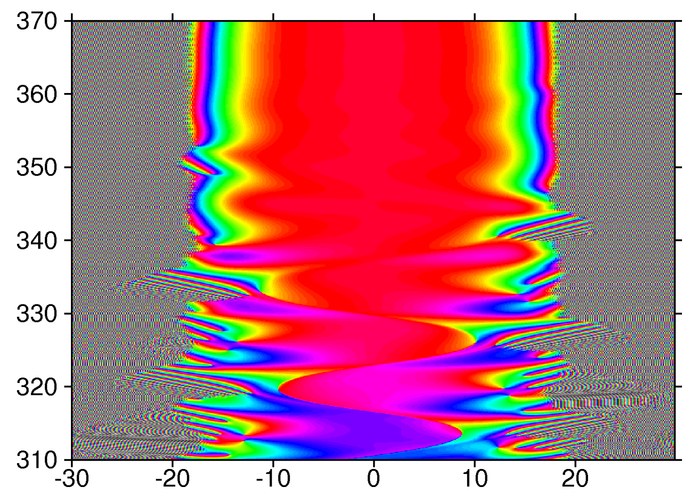


SLOW RAMP

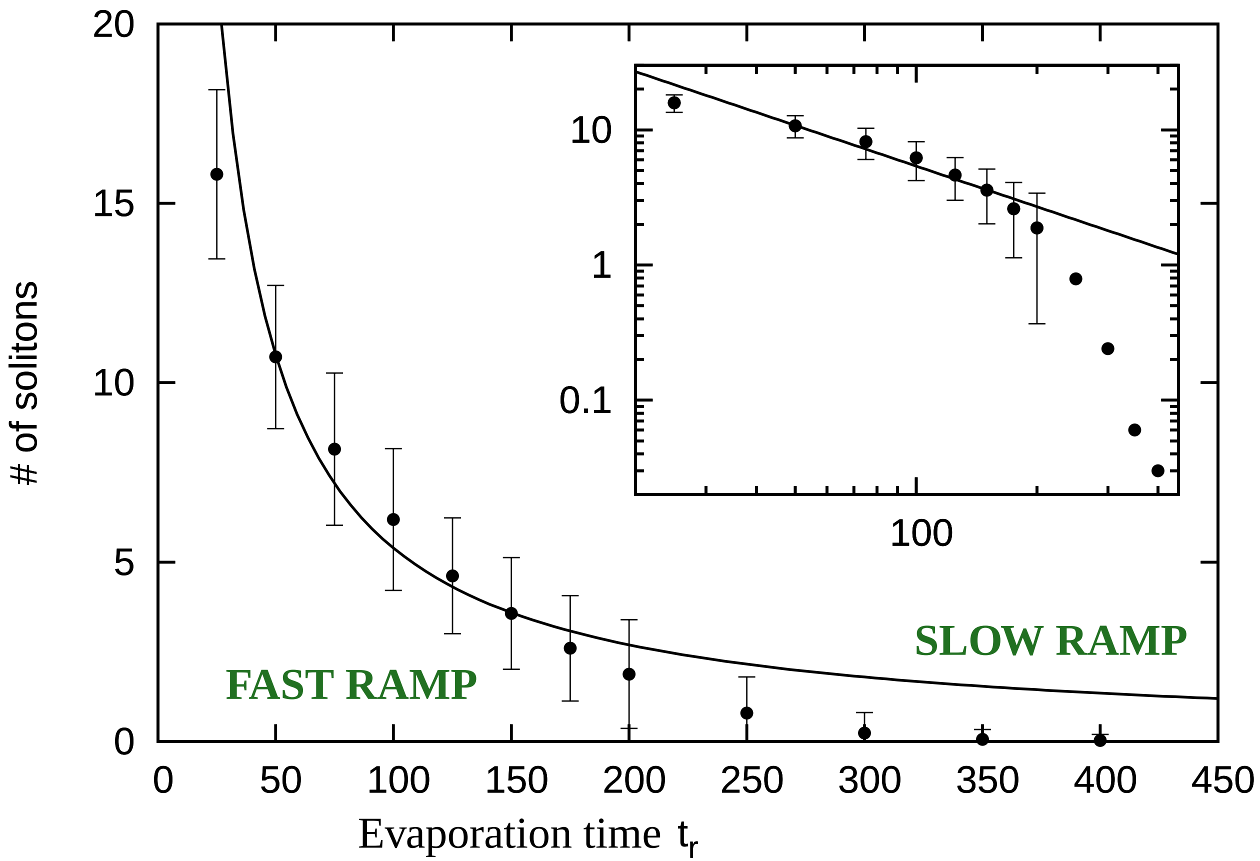
DENSITY



PHASE



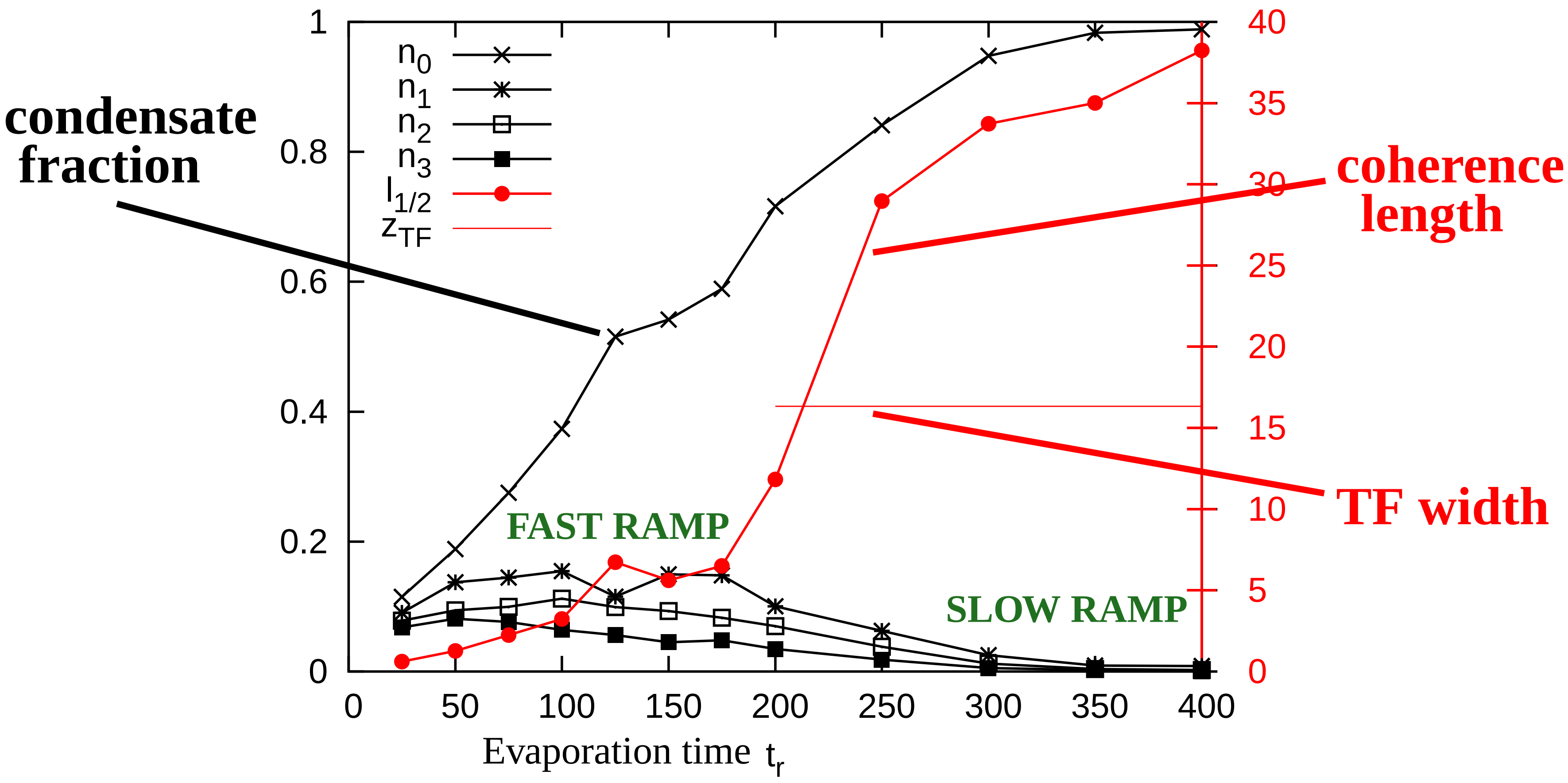
At the end of the ramp



Prediction*: ♯ of solitons $\sim 1/\tau_Q$, $\tau_Q \propto t_r$

*W. H. Zurek, PRL **102**, 105702 (2009)

At the end of the ramp

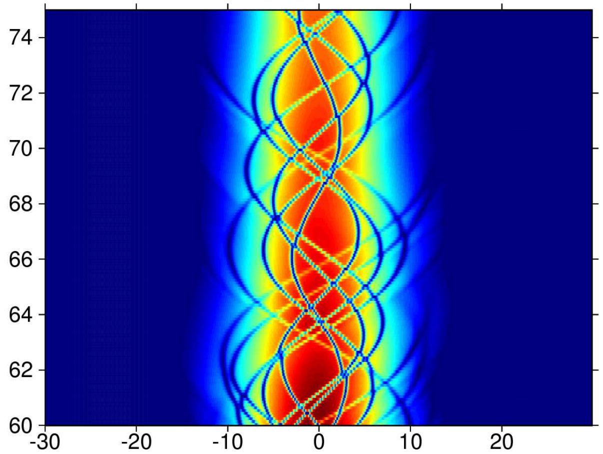


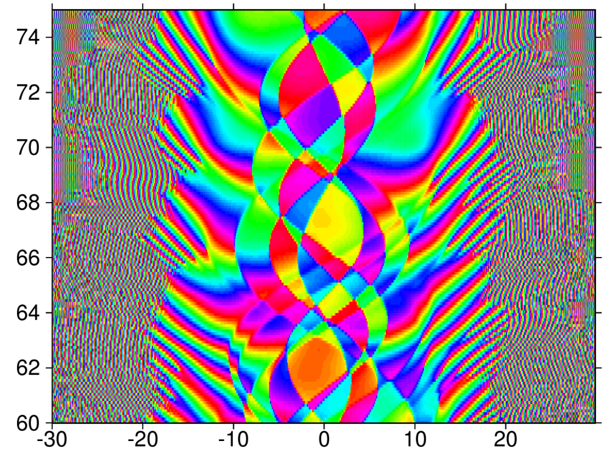
Prediction*: $n_0(T_\phi) \approx 0.84$ (with $n_0(T) \approx 1 - \frac{T}{T_c}$ and $k_B T_\phi = k_B T_c \frac{\hbar\omega}{\mu_{TF}}$)

* W. Ketterle, N.J. van Druten, PRA **54**, 656 (1996); D. S. Petrov *et al*, PRL **85**, 3745 (2000)

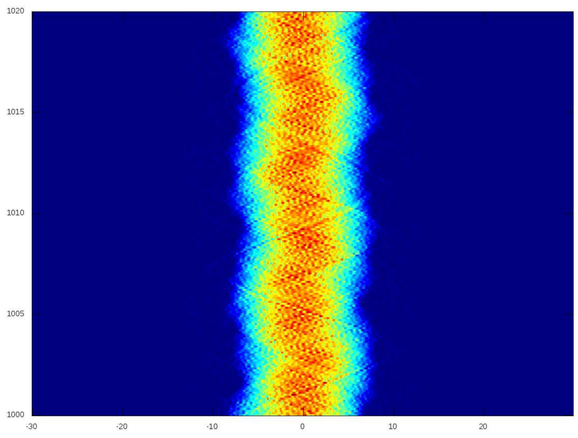
Thermalisation to quasi-BEC

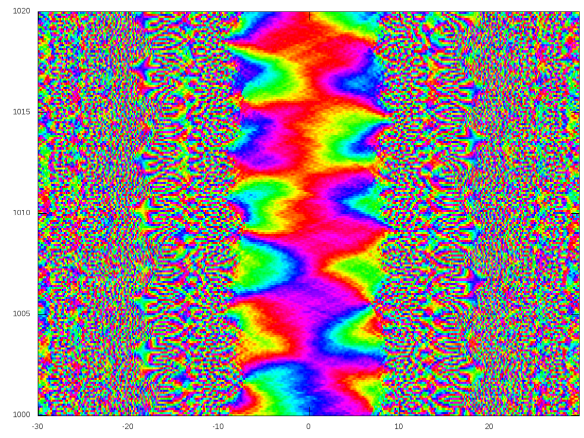
at the end of the ramp



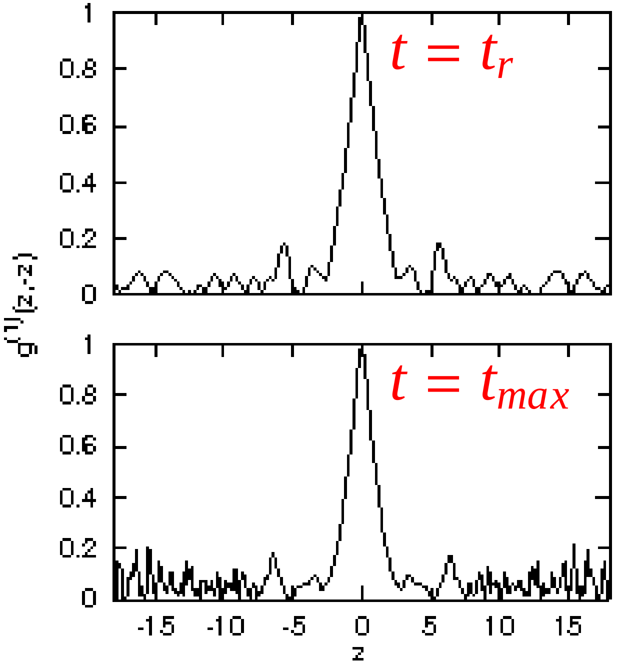


at the end of the thermalisation time





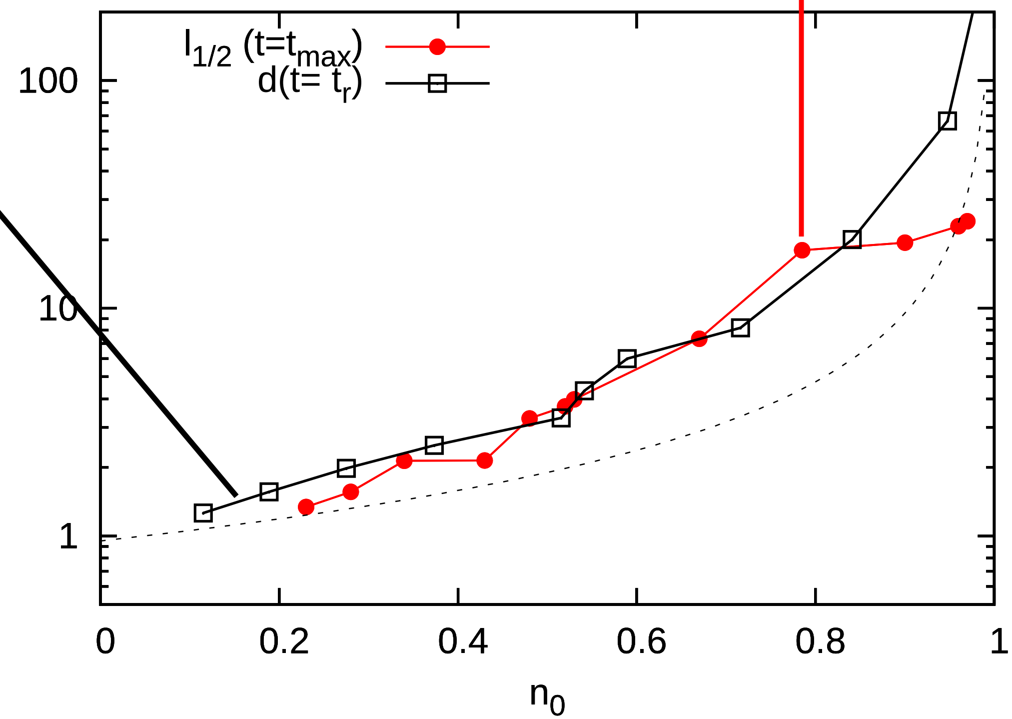
COHERENCE



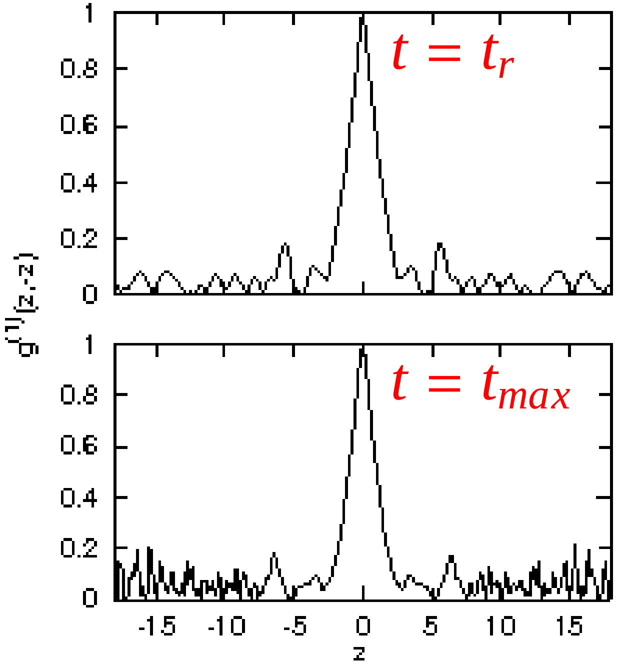
Important observation

inter solitons distance

coherence length



COHERENCE

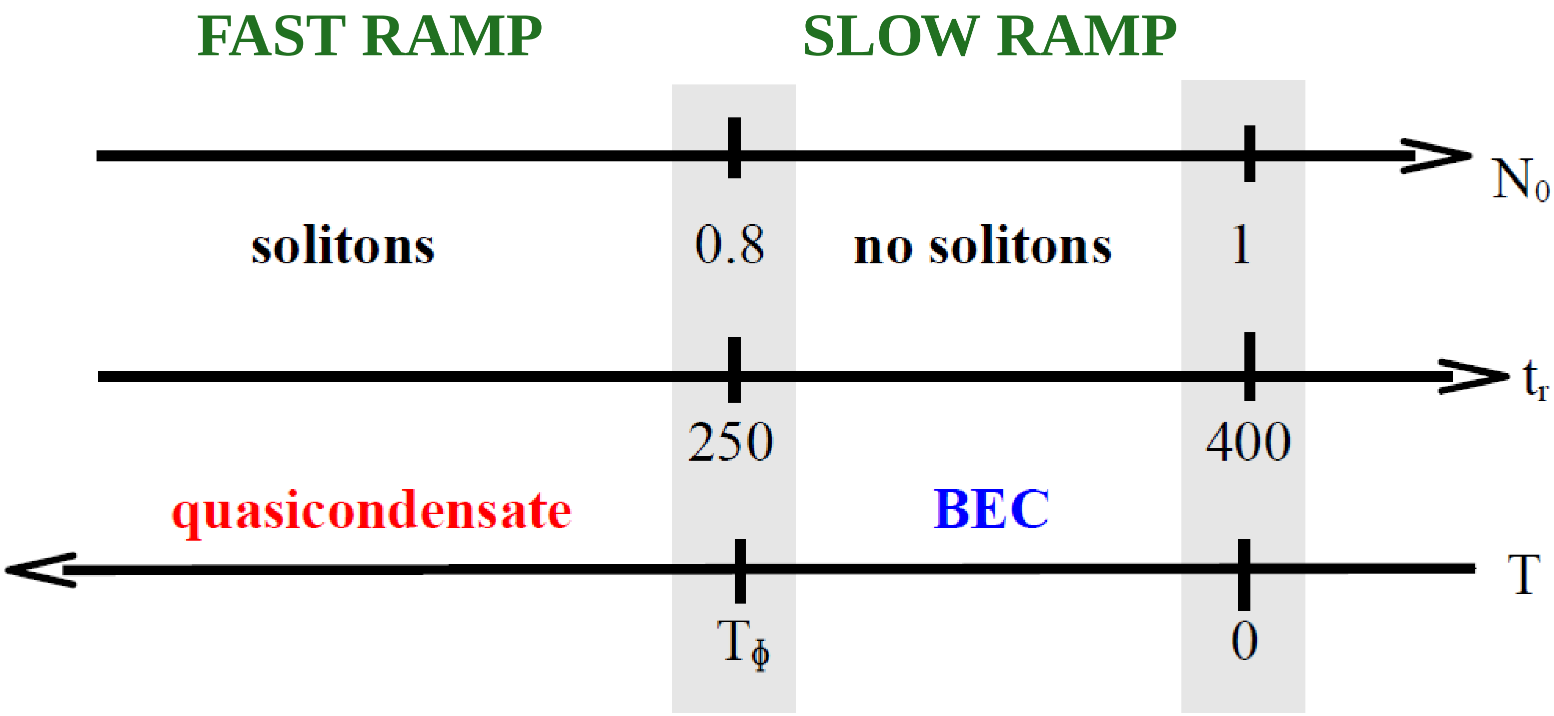


1) **coherence lengths at the end of the ramp** ($t = t_r$) **and at thermal equilibrium** ($t = t_{max}$) **are aprox. equal**

2) **inter solitons distance** (at $t = t_r$) **is comparable with the coherence length at thermal equilibrium**

Summary

In the scheme of evaporative cooling we studied:
1) the Kible-Zurek mechanism is present
2) we observe connection between solitons and the long time phase fluctuations



E.Witkowska, P.Deuar, M.Gajda, K.Rzążewski, PRL, **106** 135301 (2011)