Soiltons as the early stage of quasicondensate formation during evaporative cooling

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trapped 1D Bose gas

$$\hat{H} = \int dx \left\{ \hat{\Psi}^\dagger(x) \left[V(x) - \frac{\hbar^2}{2m}\nabla^2 \right] \hat{\Psi}(x) + \frac{g}{2} \hat{\Psi}^\dagger(x)^2 \hat{\Psi}(x)^2 \right\}$$

$N \sim 10^3$-10^4

g > 0 → repulsive contact interactions

Quasicondensate in a trap

- In the uniform 1D gas, there is no true condensate for T>0
- *However:* finite coherence length l_ϕ

$$g^{(1)}(x,x') \sim \exp\left[-\frac{|x-x'|}{l_\phi}\right] \quad ; \quad l_\phi \sim \frac{N^{2/3}}{T}$$

- → In the trap, BEC occurs when $L < l_\phi$

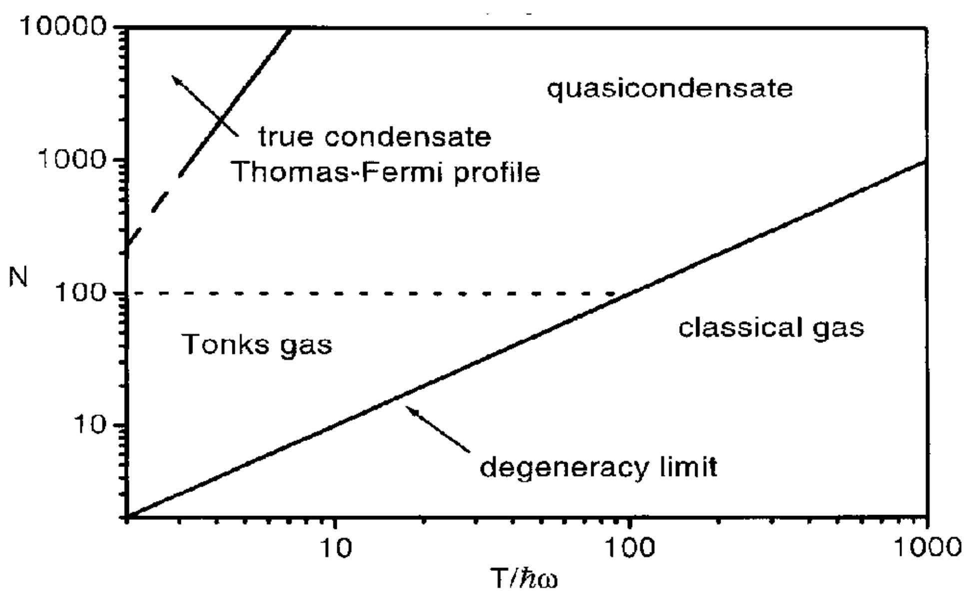
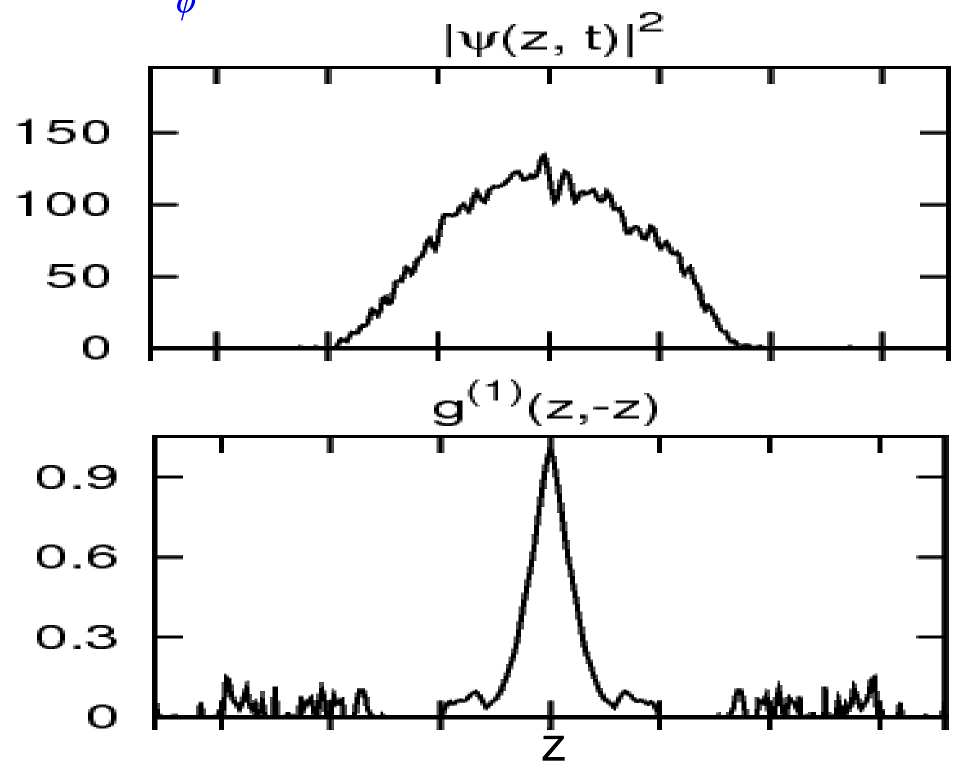


FIG. 1. Diagram of states for a trapped 1D gas.

D. Petrov, G. Shlyapnikov, J. Walraven, PRL **85,** 3745 (2000)



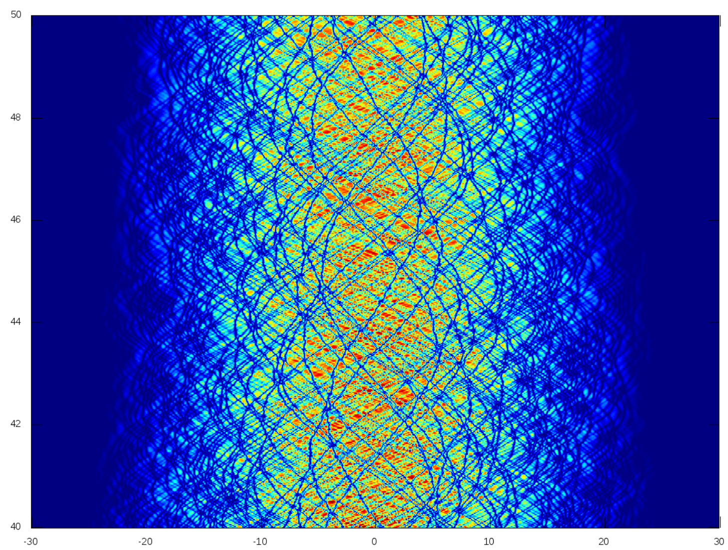
Motivation to simulate evaporative cooling

1. Is the Kibble-Żurek mechanism (KZM) present?

W. Żurek, PRL **102,** 105702 (2008)

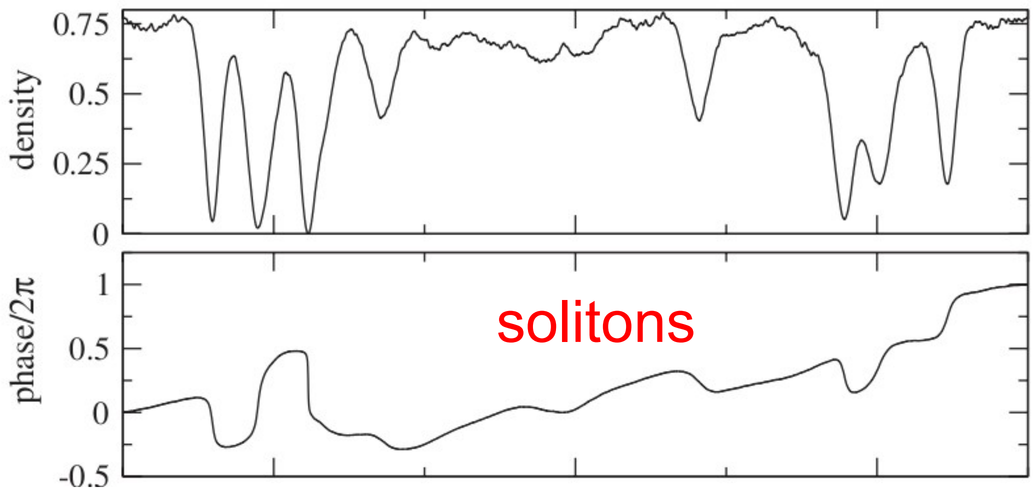
2. Connect defect formation (KZM) with defect-less equilibrium state

3. Curiosity - How does the quasicondensate start?



What actually goes on during the cooling?

View 1:
Solitons formed in a quench via Kibble-Zurek mechanism

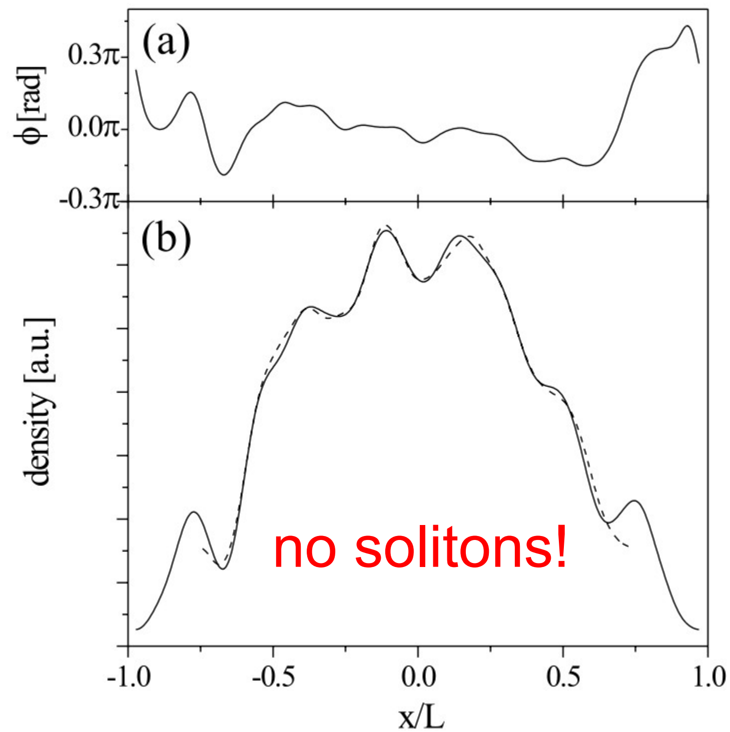


B. Damski, W. Żurek, PRL **104,** 160404 (2010)

Quench of μ in thermal bath

<u>What about realistic cooling?</u>

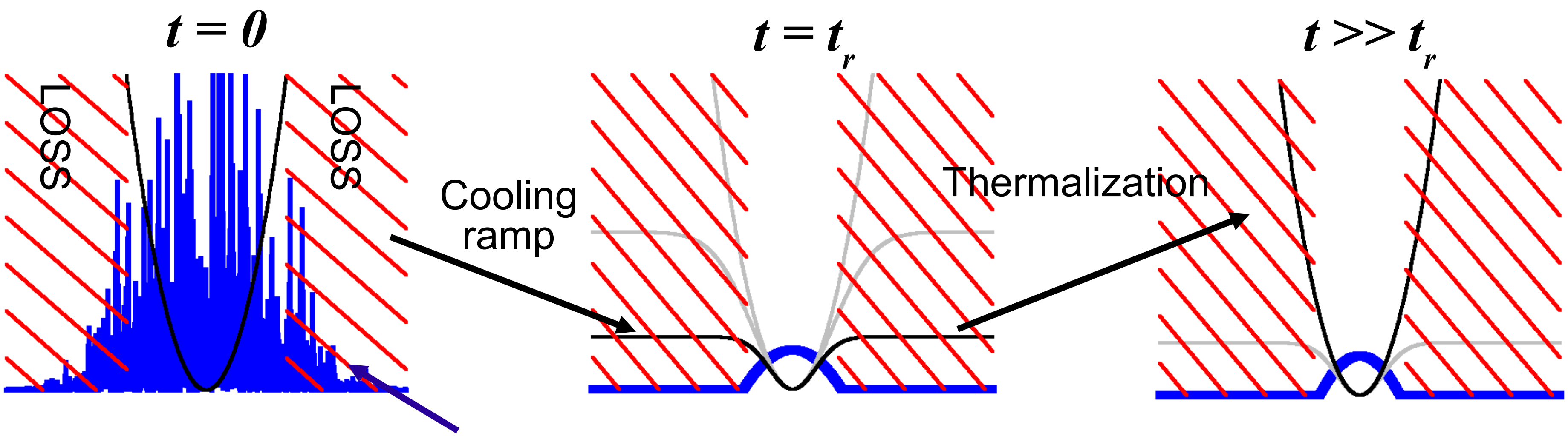
View 2:
Smooth quasicondensate phase in thermal equilibrium



S. Dettmer *et al*, PRL **87,** 160406 (2001)

Evaporative cooling of 1D Bose gas

THE MODEL



- Initial condition: gas at thermal equilibrium, above T_c

E. Witkowska, M. Gajda, K. Rzążewski Opt. Commun. **283**, 671 (2010)

Simulation: *c-field method*

"Quantum field theory, without discretized particles"

$$\hat{\Psi}(x) \rightarrow \psi(x)$$

$$i\partial_t \psi(z,t) = [H(z,t) - i\Gamma(z,t)]\psi(z,t),$$

$$H(z,t) = -\frac{1}{2}\frac{\partial^2}{\partial z^2} + V(z,t) + g_{1D}|\psi(z,t)|^2$$

In more detail

e.g. free space : plane wave basis

Full quantum field

c-fields

$$\Psi(\mathbf{r}) = \sum_{\mathbf{k}} a_{\mathbf{k}} \frac{1}{\sqrt{V}} e^{i\mathbf{kr}} \longrightarrow \Phi(\mathbf{r}) = \sum_{|\mathbf{k}| \leqslant \mathbf{K}_{max}} \alpha_{\mathbf{k}} \frac{1}{\sqrt{V}} e^{i\mathbf{kr}}$$

Replace mode amplitude operators $a_{\mathbf{k}}$
with complex number amplitudes $\alpha_{\mathbf{k}}$

Thermal initial state:

- $|\alpha_{\mathbf{k}}|^2$ Distributed according to Bose-Einstein distribution
- Phase of $\alpha_{\mathbf{k}}$ is random
- Use many realizations to get thermal ensemble

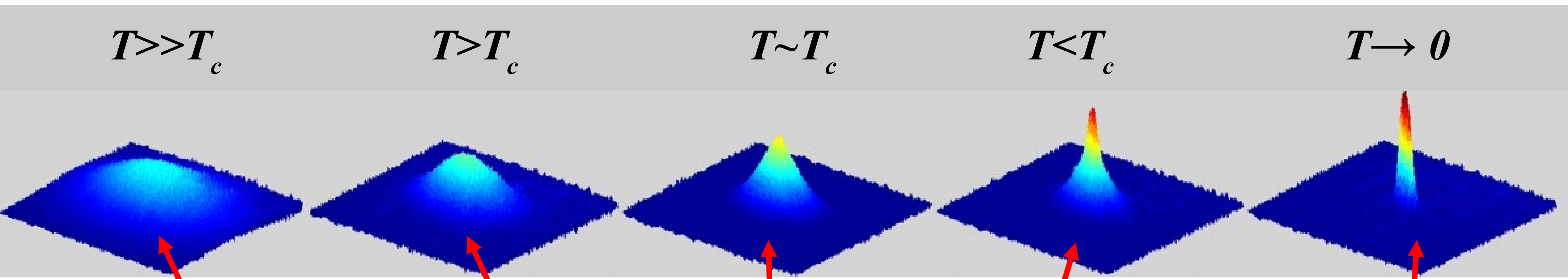
Useful papers: M. Brewczyk *et al,* J. Phys B **40,** R1 (2007); P. Blakie *et al.* Adv. Phys. **57**, 363 (2008)

Validity

$$\left[\hat{\Psi}(x), \hat{\Psi}^{\dagger}(x')\right] = \delta(x - x') \qquad \rightarrow \qquad [\psi^*(x), \psi(x')] = 0$$

→ it will be fine, ...

.... as long as there are <u>always many atoms involved</u>



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

Mode occupation getting small

OK:
All relevant modes highly occupied

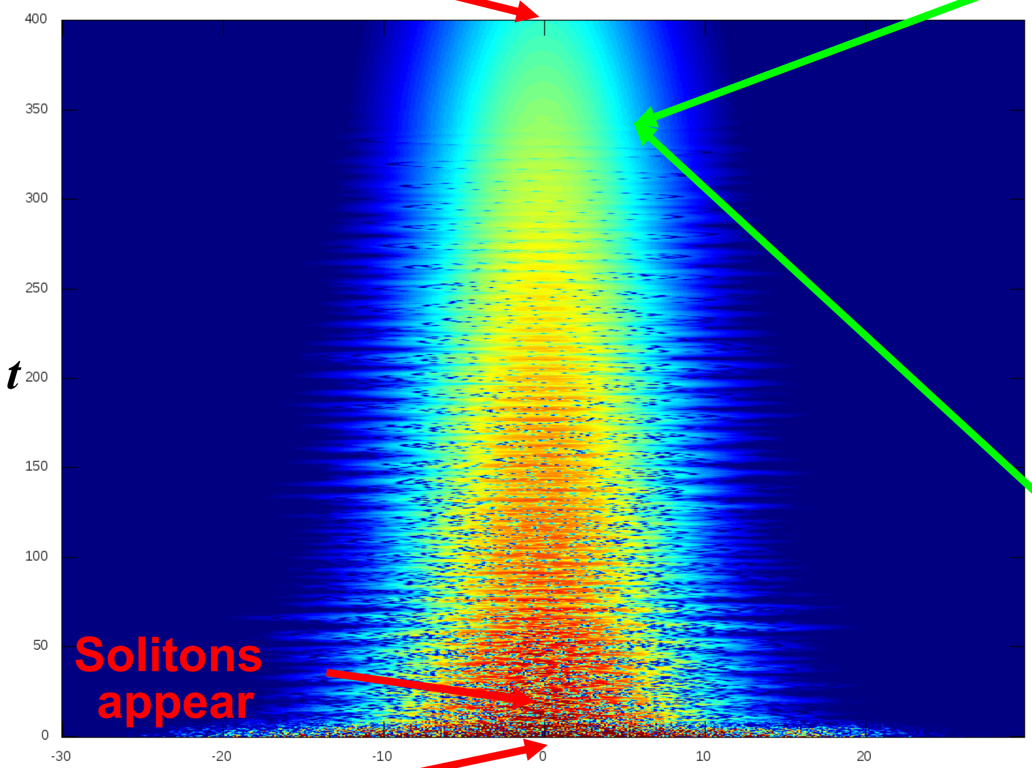
Occupation in excited modes getting small

Simulation - slow ramp → BEC

<u>Slow ramp</u> $\omega\, t_r$=400

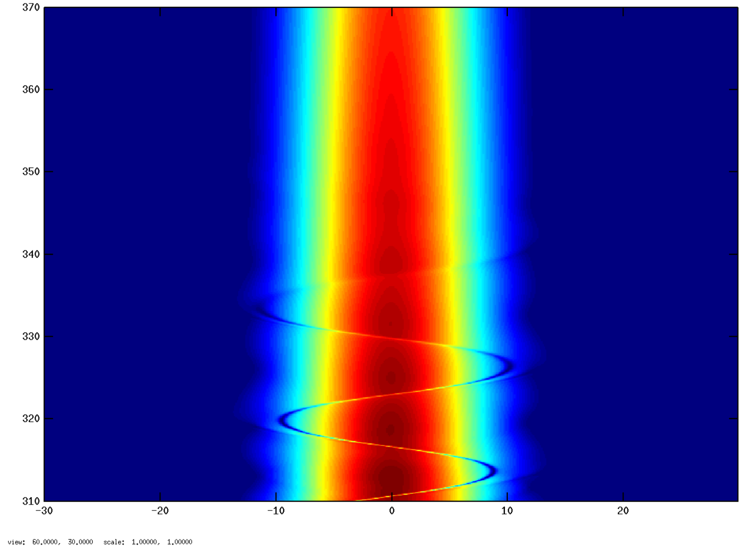
F

End of evaporation ramp

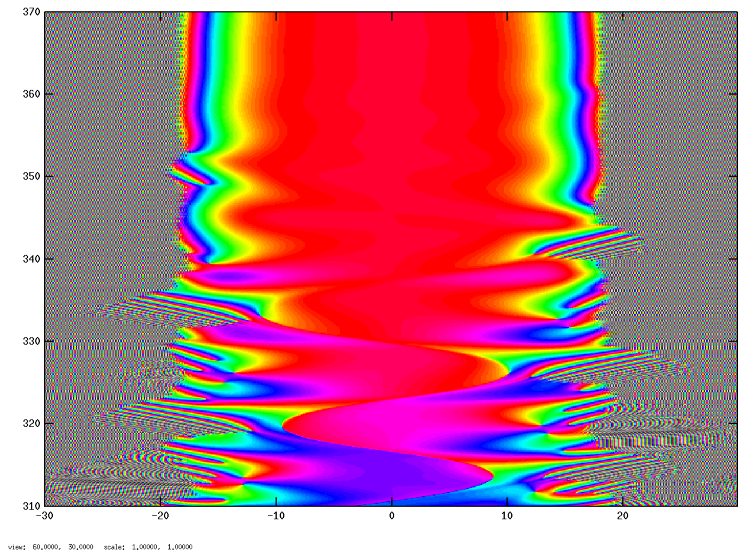


Beginning of ramp

DENSITY



PHASE



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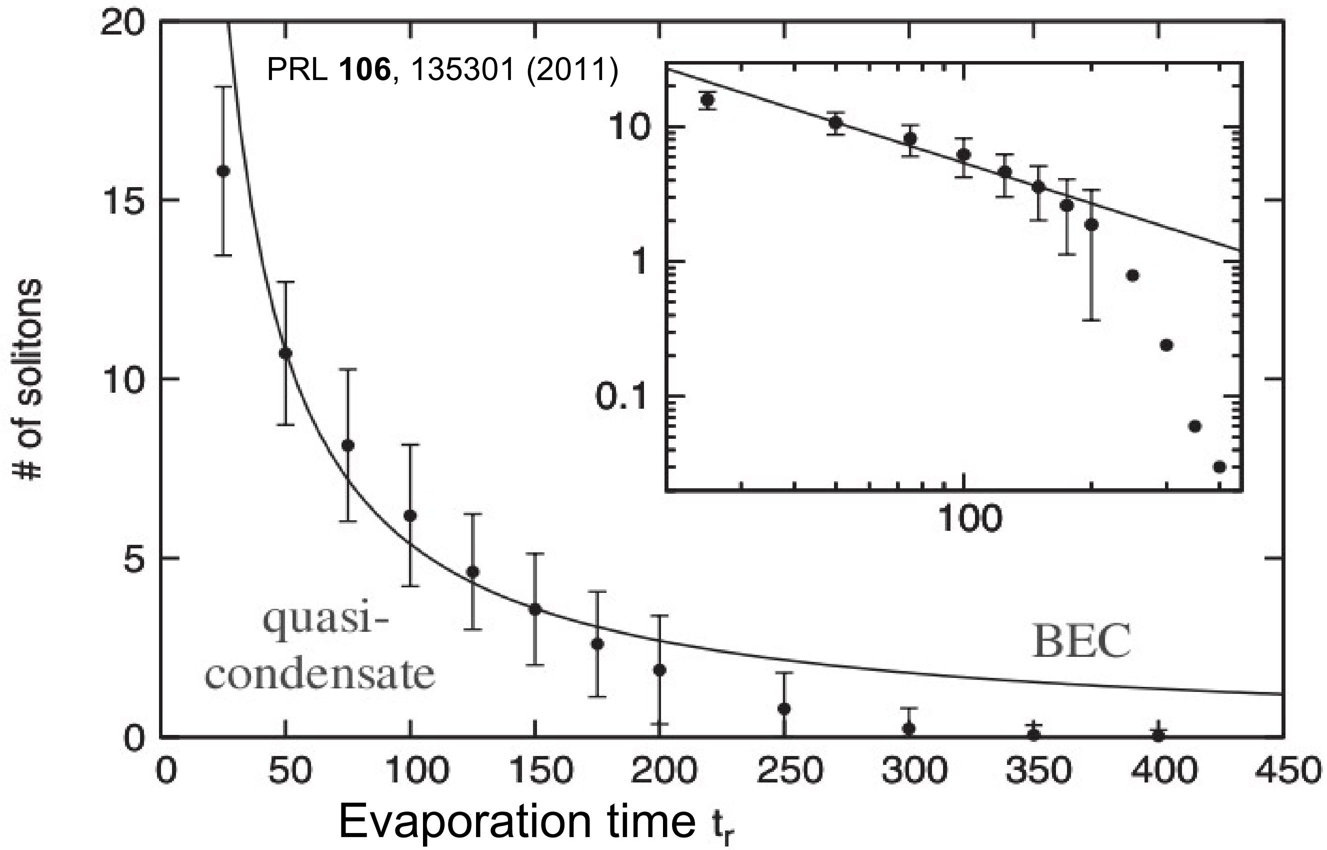
Kibble-Żurek defect formation

Soliton number at the end of the ramp



prediction:

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

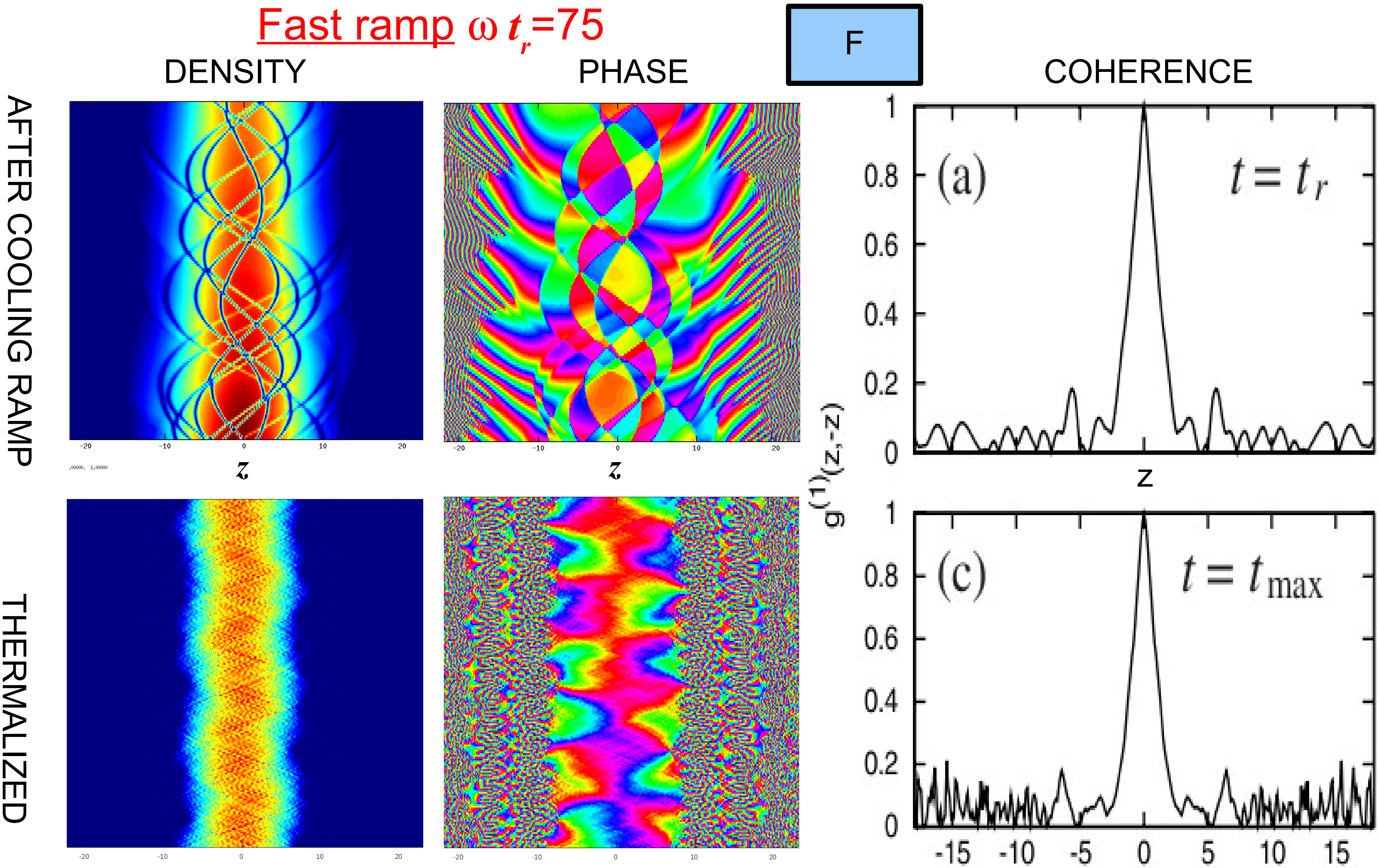
$$N \approx \frac{2\hat{X}}{f\hat{\xi}} = \frac{2\Delta^2}{f\lambda_{\mathrm{dB}}^2}\left(\frac{\tau_0}{\tau_Q}\right)^{(1+2\nu)/(1+\nu z)}$$

Quench time
= evaporation time t_r ?

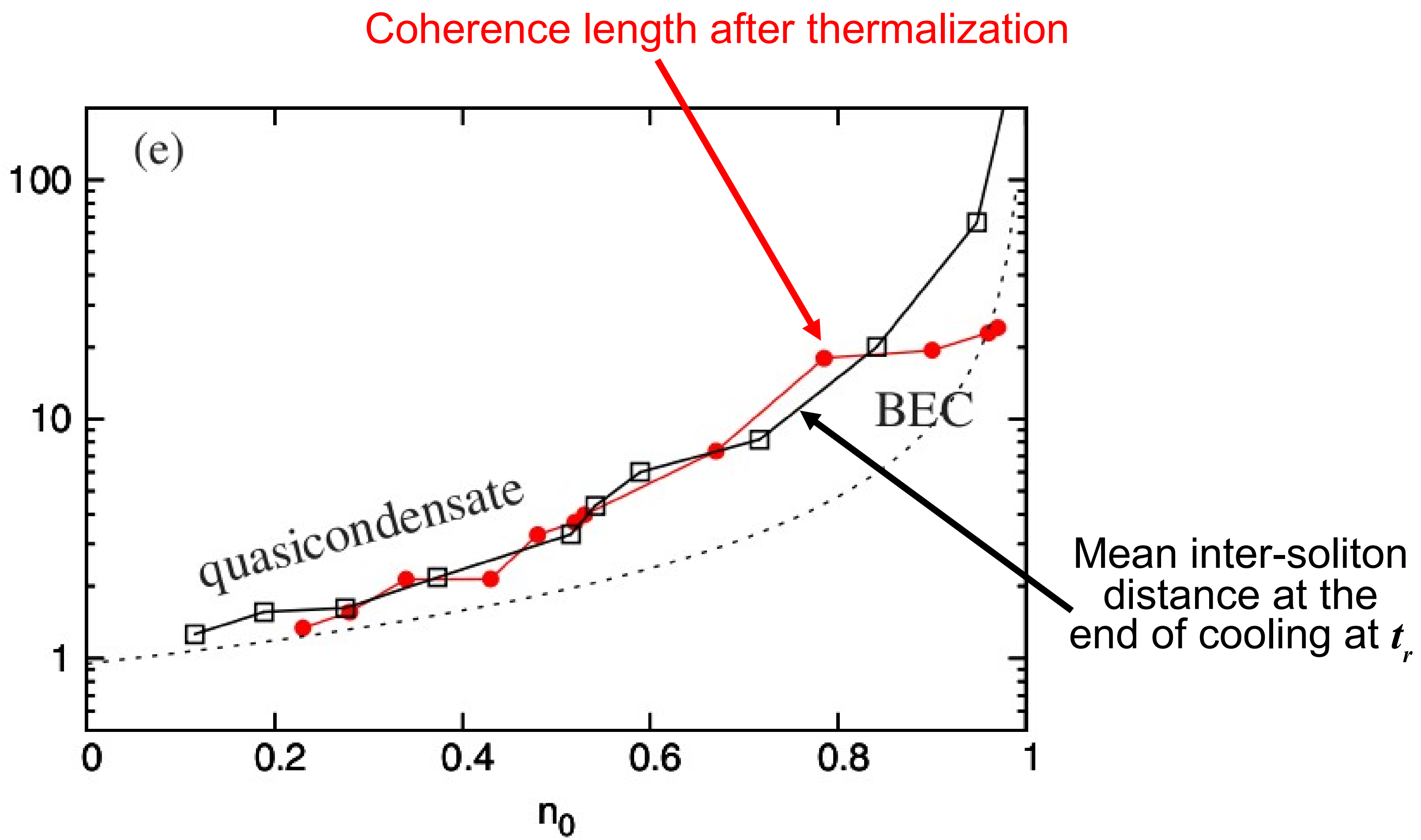
~1

Thermalization to a quasicondensate

Fast ramp $\omega\, t_r$=75



Solitons as the "larval stage" of equilibrium fluctuations



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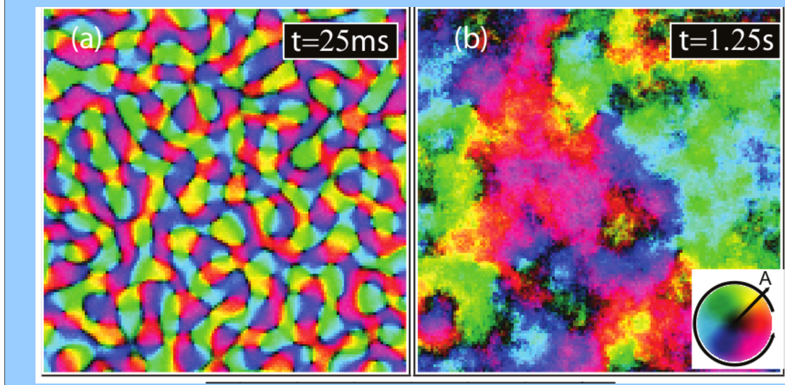
Quasicondensate formation

We did NOT see the usual Kibble-Zurek scenario

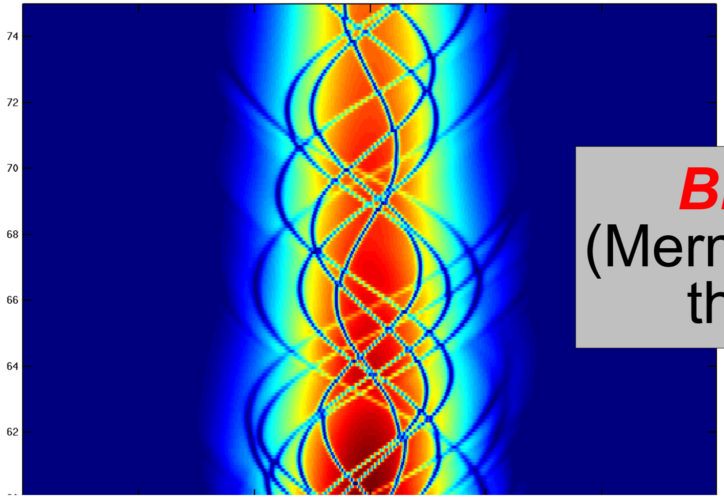
"domain seeds grow with time,
and defects form where they meet"



compare e.g. to 2D spin-1 gas:
Barnett, Polkovnikov, Vengelattore,
arXiv:1009.1646

Instead:
- domains are fleeting
- solitons are the stable entities
- "domain size" conserved

DENSITY



BKT-like
(Mermin-Wagner
theorem)

PHASE

Conclusions: what of the original questions?

- Is the Kibble-Żurek mechanism present?

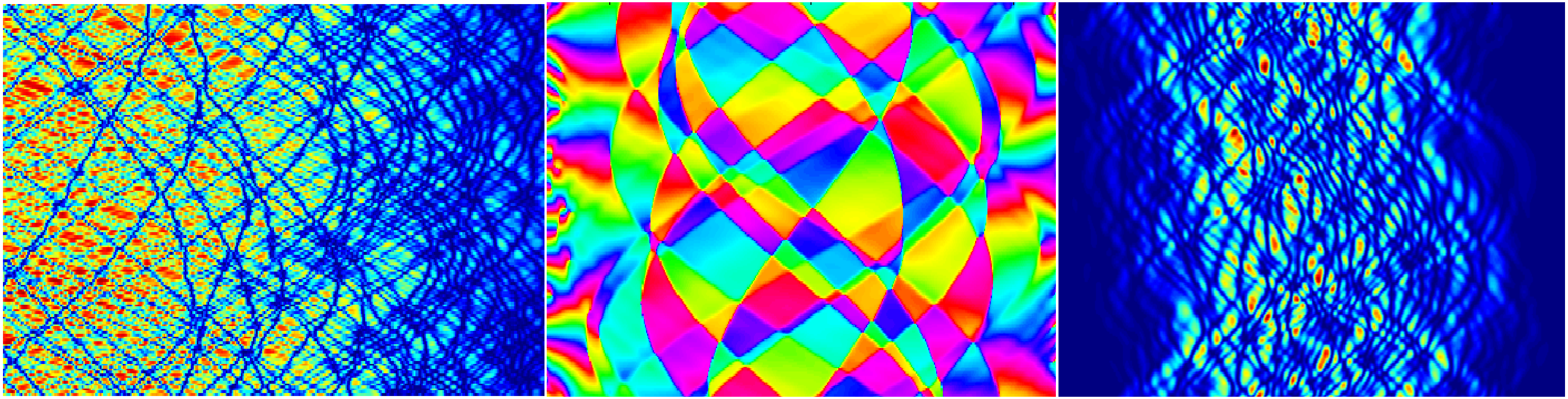
  Yes, but not quite like the usual story

- Connect defect formation (KZM) with equilibrium state

  Solitons = "larval stage" of long time phase fluctuations

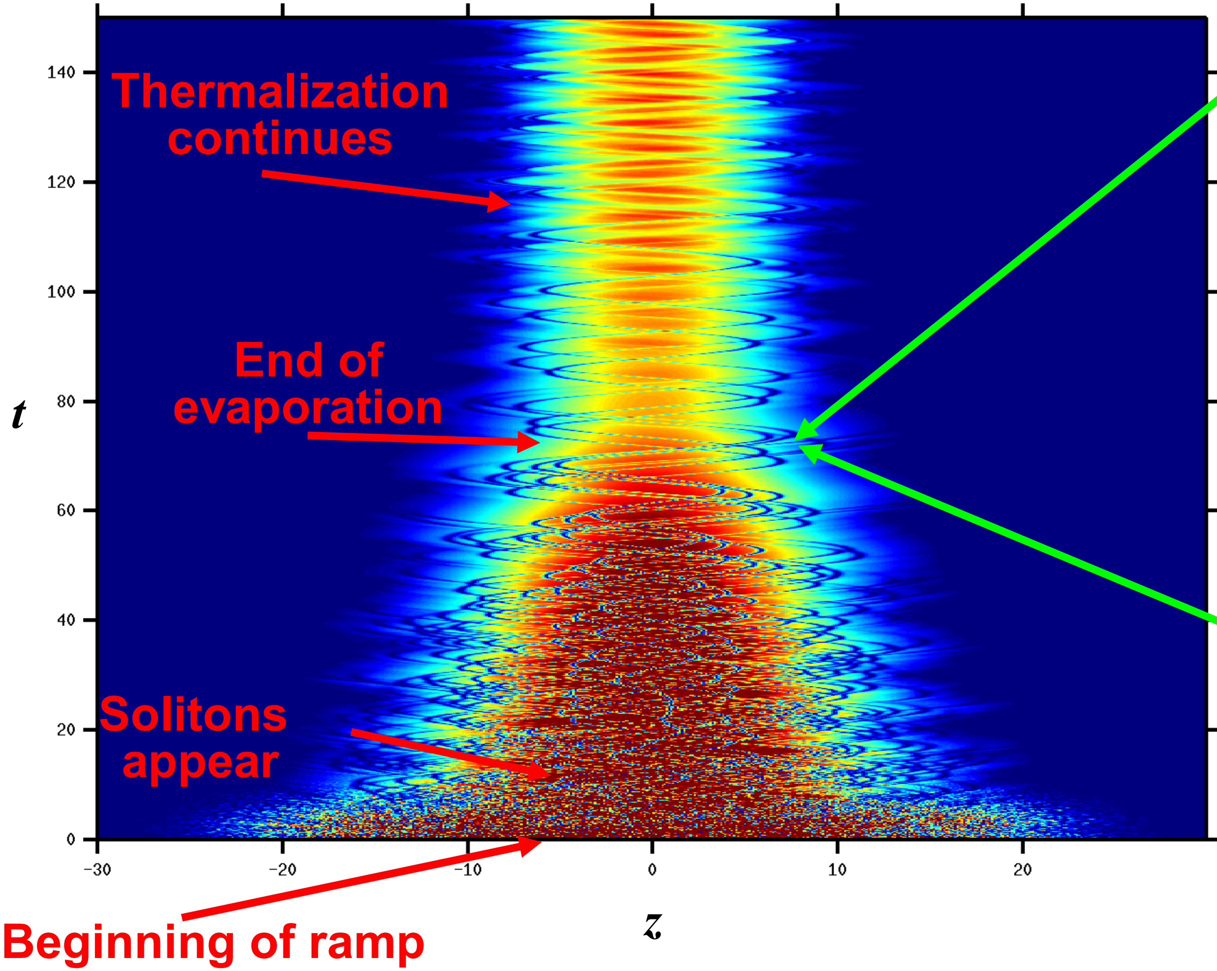
- How does the quasicondensate start?

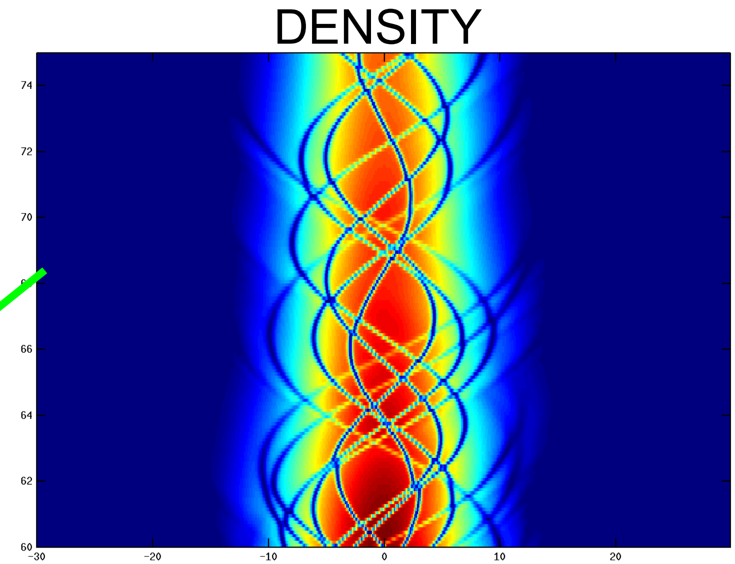
  So far – we are looking at it but do not truly "see"

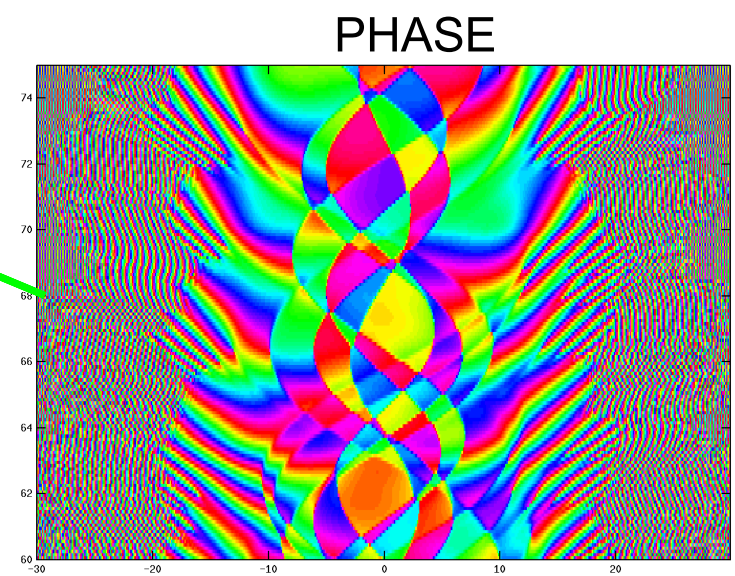


Fast ramp → quasicondensate precursor

Fast ramp ωt_r=75

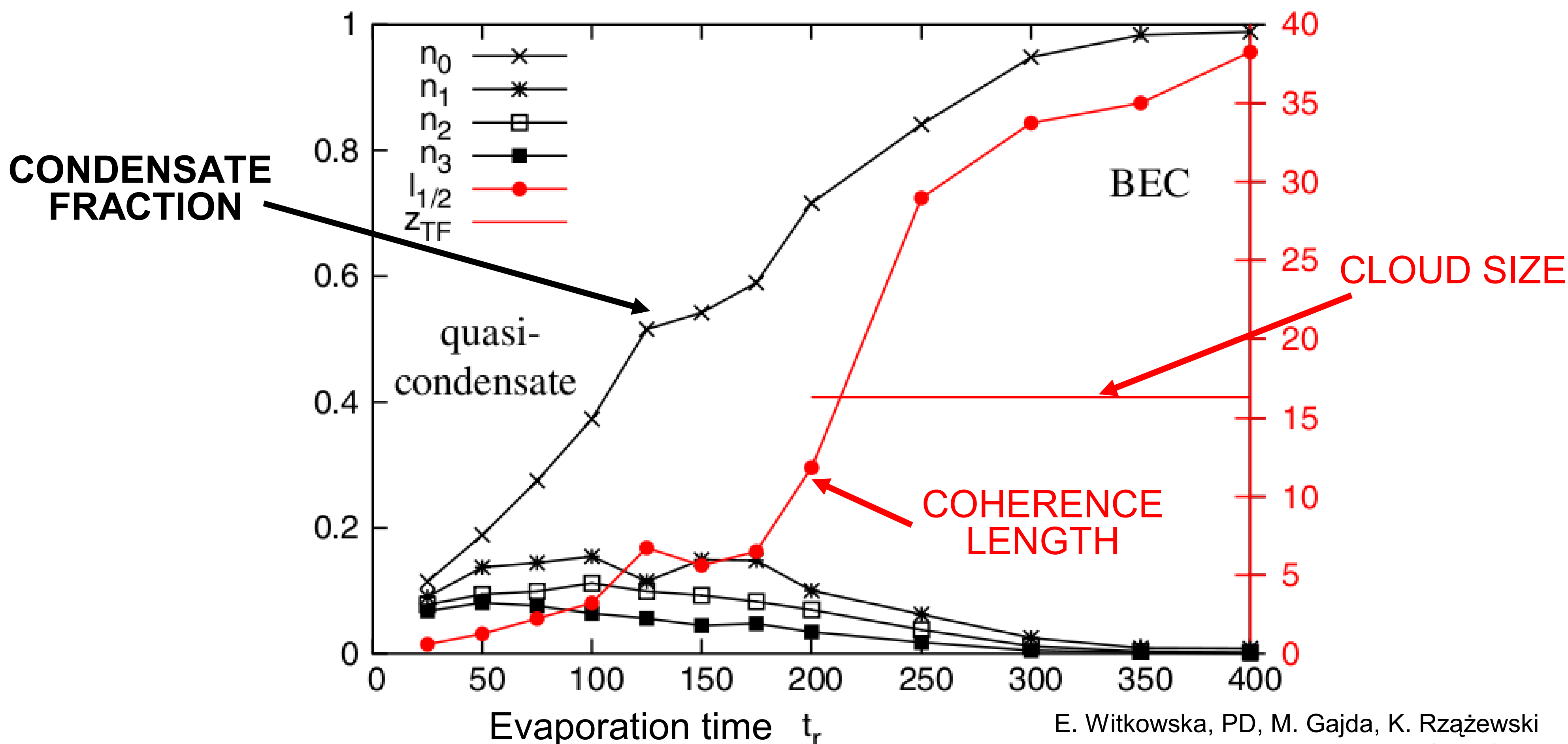






Ramp time

- Slow ramp → BEC
- Fast ramp → quasicondensate
- Very fast ramp → thermal gas



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