Soiltons as the early stage of quasicondensate formation during evaporative cooling

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E. Witkowska, PD, M. Gajda, K. Rzążewski, Phys. Rev. Lett. **106**, 135301 (2011)

Outline

1. Cooling of a 1D Bose gas
2. Appearance and dynamics of solitons
3. Coherence amidst the solitons
4. Attempts at a local "thermodynamic" description
5. Soliton statistics

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 ~ 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 $L < l_\phi$

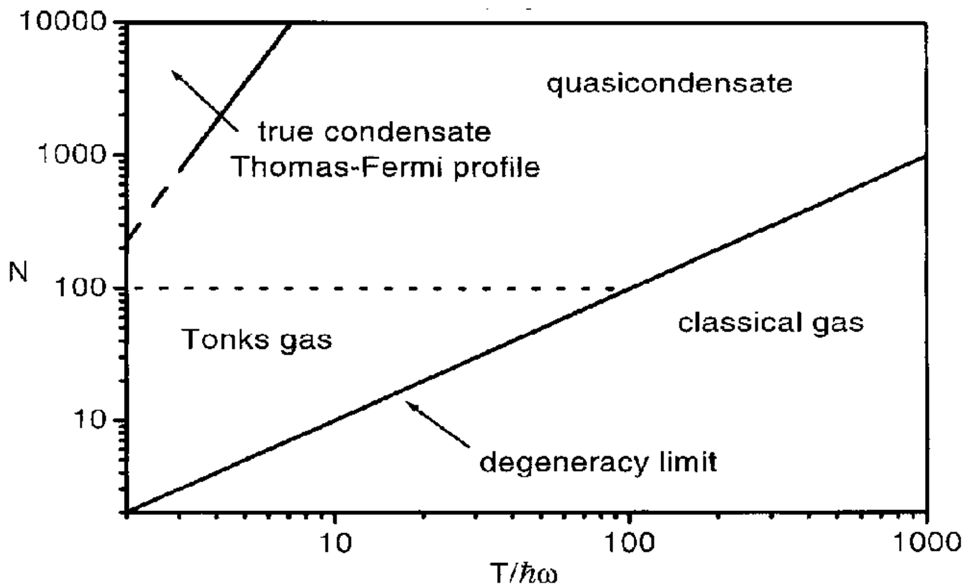
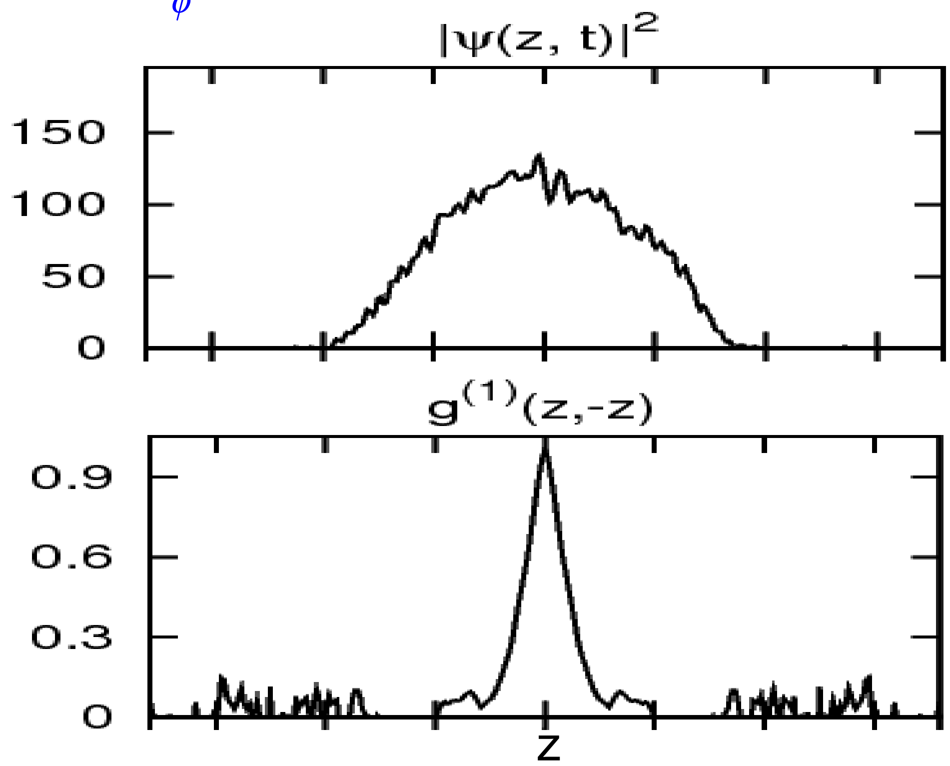


FIG. 1. Diagram of states for a trapped 1D gas.

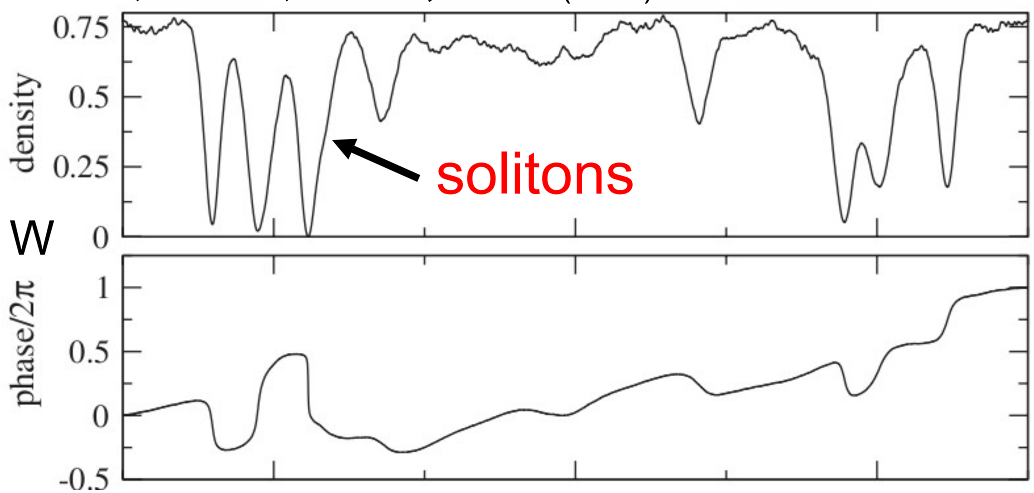
D. Petrov, G. Shlyapnikov, J. Walraven, PRL **85,** 3745 (2000)



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

W. Żurek, PRL **102,** 105702 (2008)

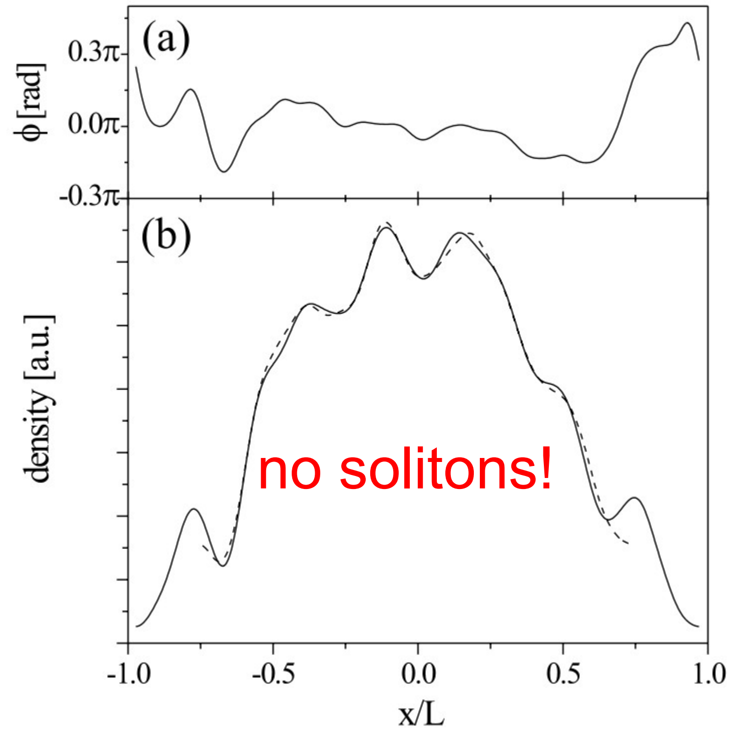
B. Damski, W. Żurek, PRL **104,** 160404 (2010)



Quench of μ in a thermal bath

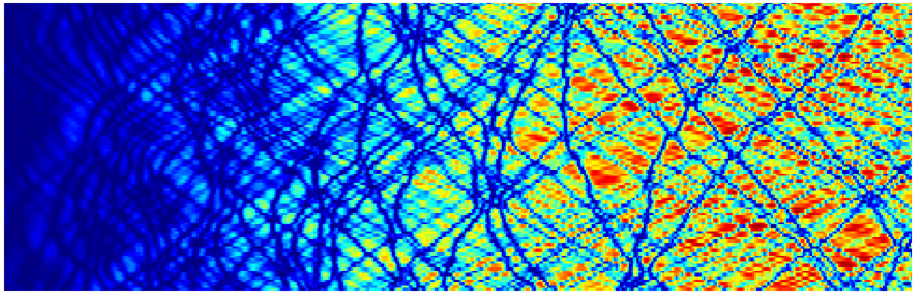
What about more realistic cooling?

View 2:
Smooth quasicondensate phase in thermal equilibrium



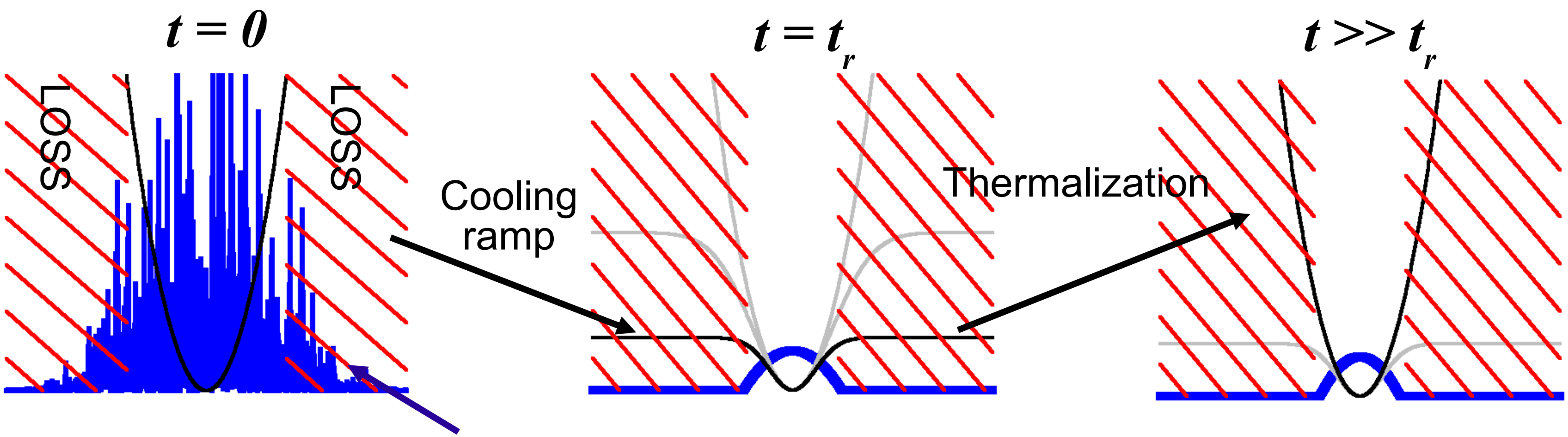
S. Dettmer *et al*, PRL **87,** 160406 (2001)

Also – How does the quasicondensate actually form?



Evaporative cooling of 1D Bose gas

THE MODEL



- Initial condition: gas at thermal equilibrium, $l_\phi << L$

Simulation: *c-field method*

"Quantum field theory, without discretized particles"

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

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

C-field initial conditions

e.g. in a plane wave basis

Full quantum field c-fields

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

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

Thermal Initial state

- $|\alpha_{\mathbf{k}}|^2$ Sampled by Metropolis Monte Carlo as per
  E. Witkowska, M. Gajda, K. Rzążewski Opt. Commun. **283**, 671 (2010)
- Cutoff matched to give correct distribution of $N_{\text{incoherent}}$ for an ideal Bose gas at chosen temperature
- Use many realizations to get thermal ensemble

Validity – my rough take on it

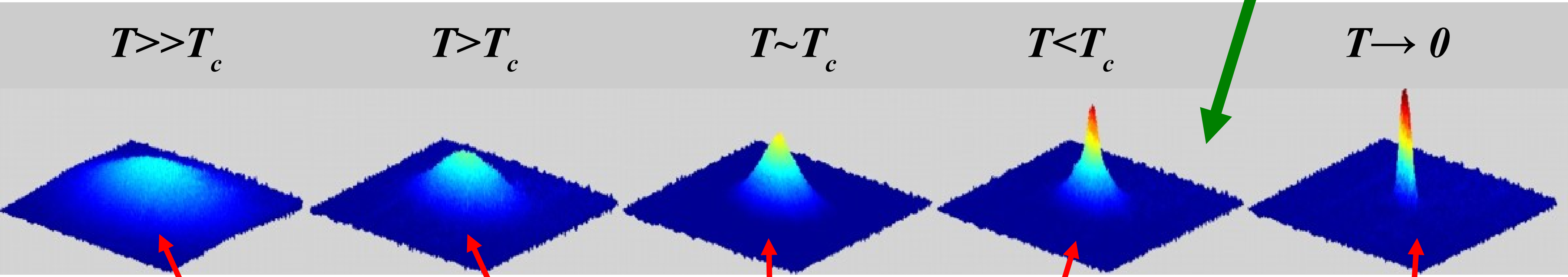
$$\left[\hat{\Psi}(x), \hat{\Psi}^\dagger(x')\right] = \delta(x - x') \qquad \rightarrow \qquad [\psi^*(x), \psi(x')] = 0$$

$\rightarrow$ it will be fine, ...

.... as long as there are always many atoms involved

in whatever it is we are studying

Quasicondensate



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

Mode occupation getting small

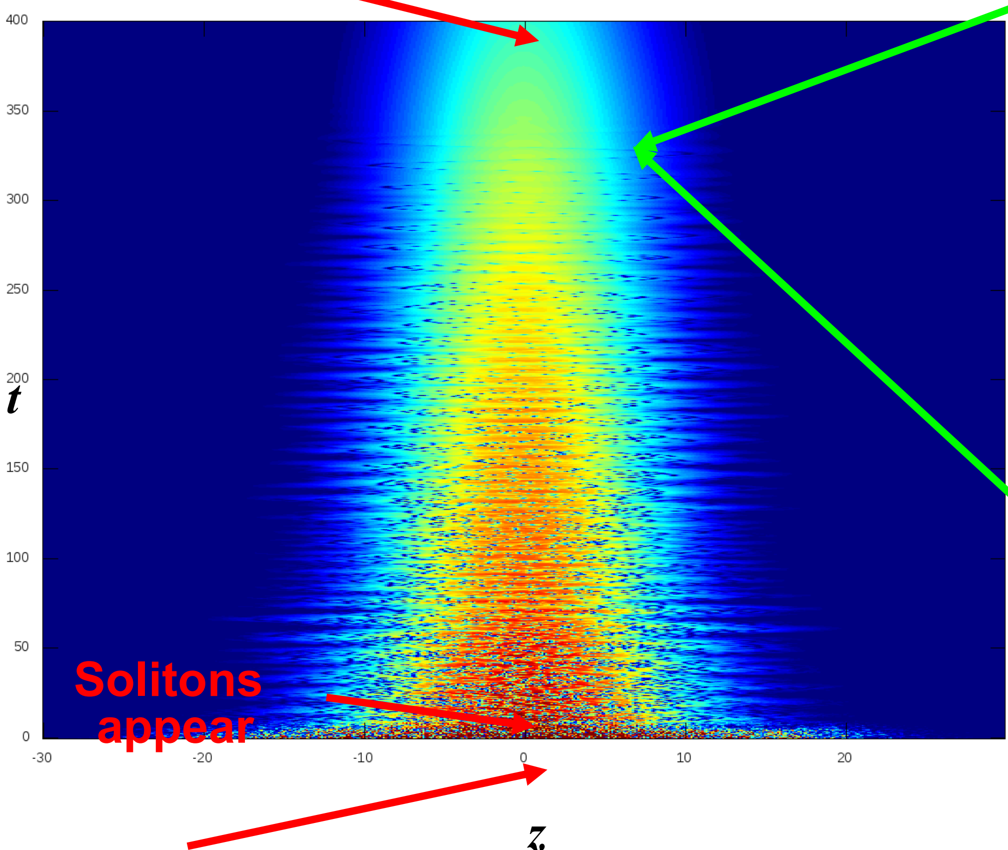
OK for Classical-field method:
All relevant modes highly occupied

Occupation in excited modes getting small

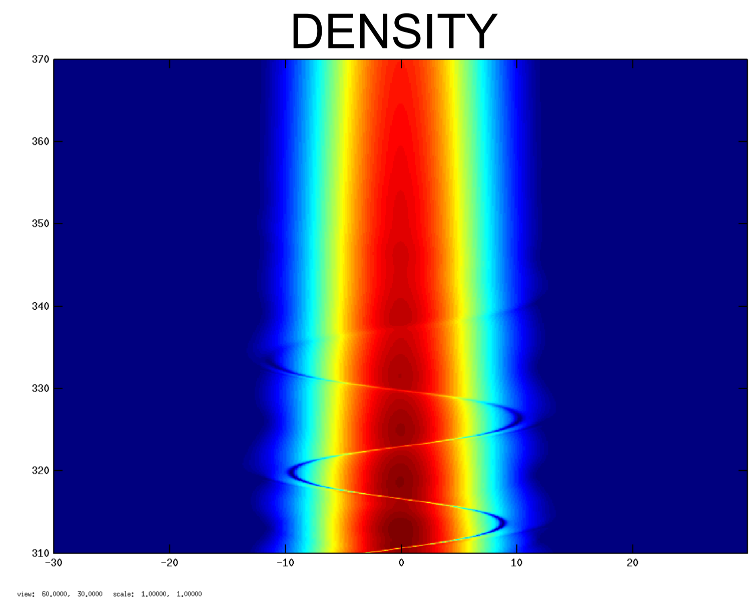
Slow ramp $\omega\, t_r = 400$

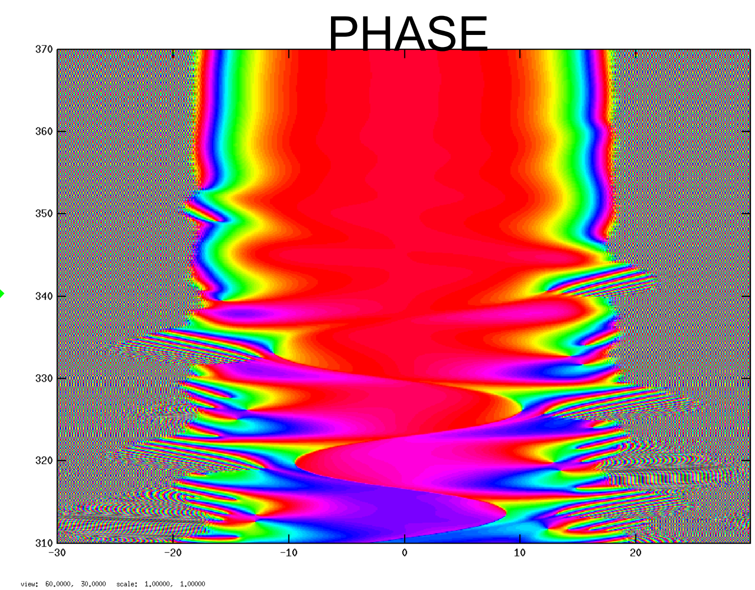
F

End of evaporation ramp



Beginning of ramp



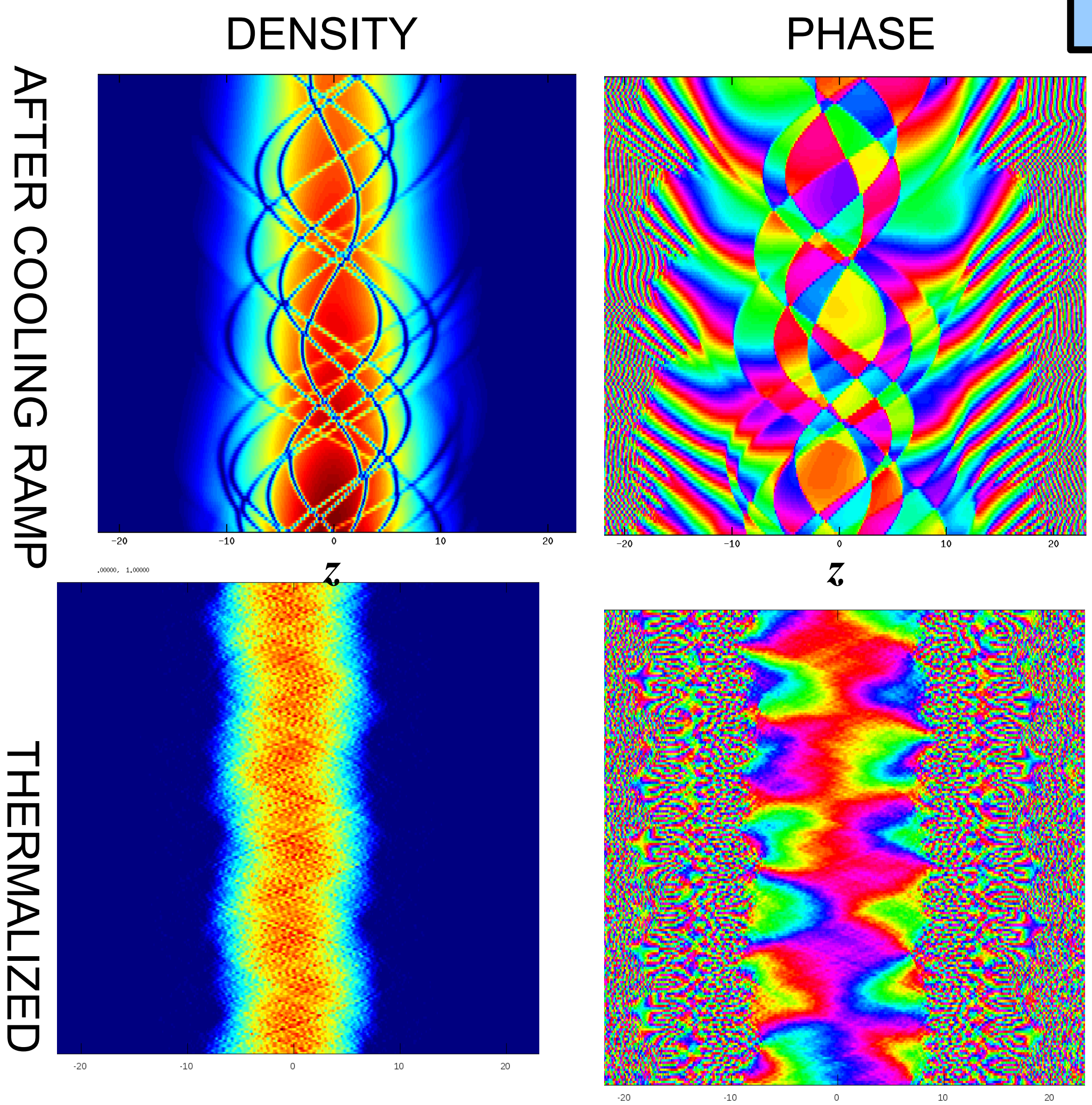


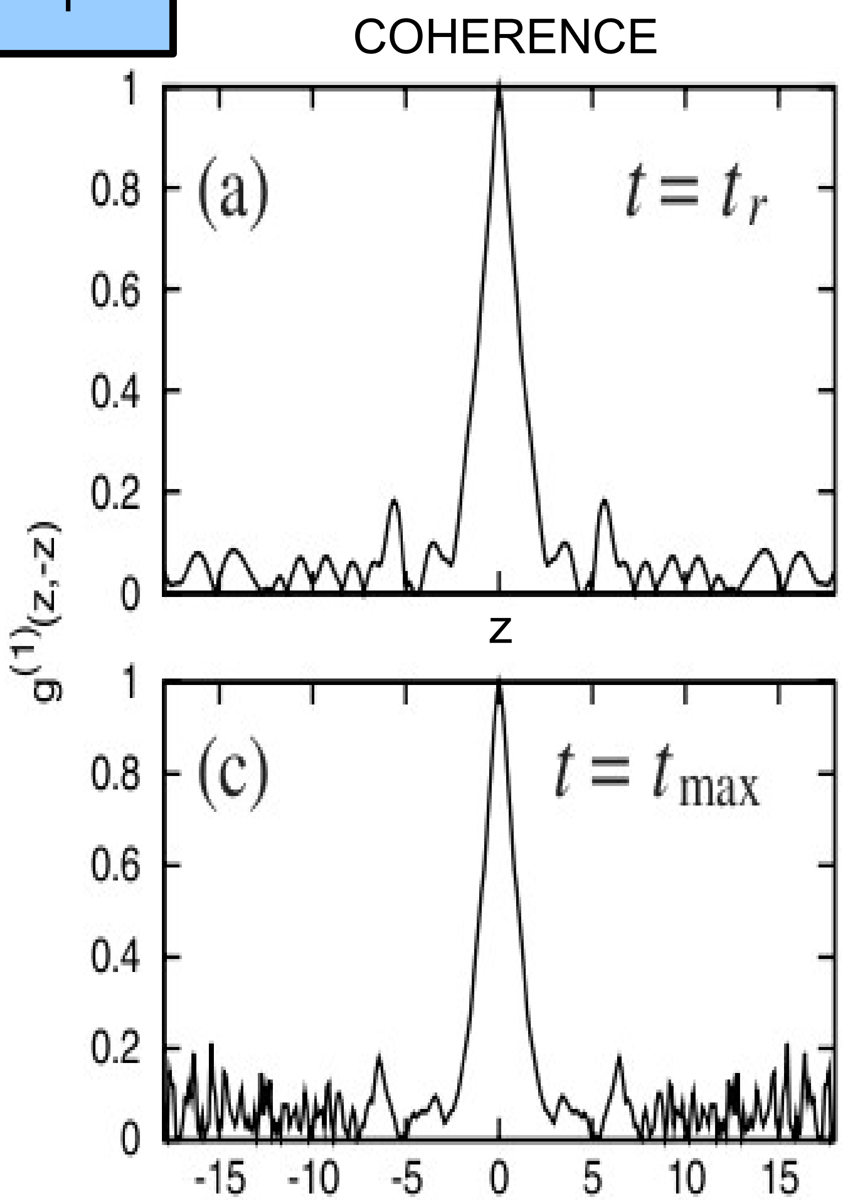
E. Witkowska, PD, M. Gajda, K. Rzążewski
Phys. Rev. Lett. **106**, 135301 (2011)

Thermalization to a quasicondensate

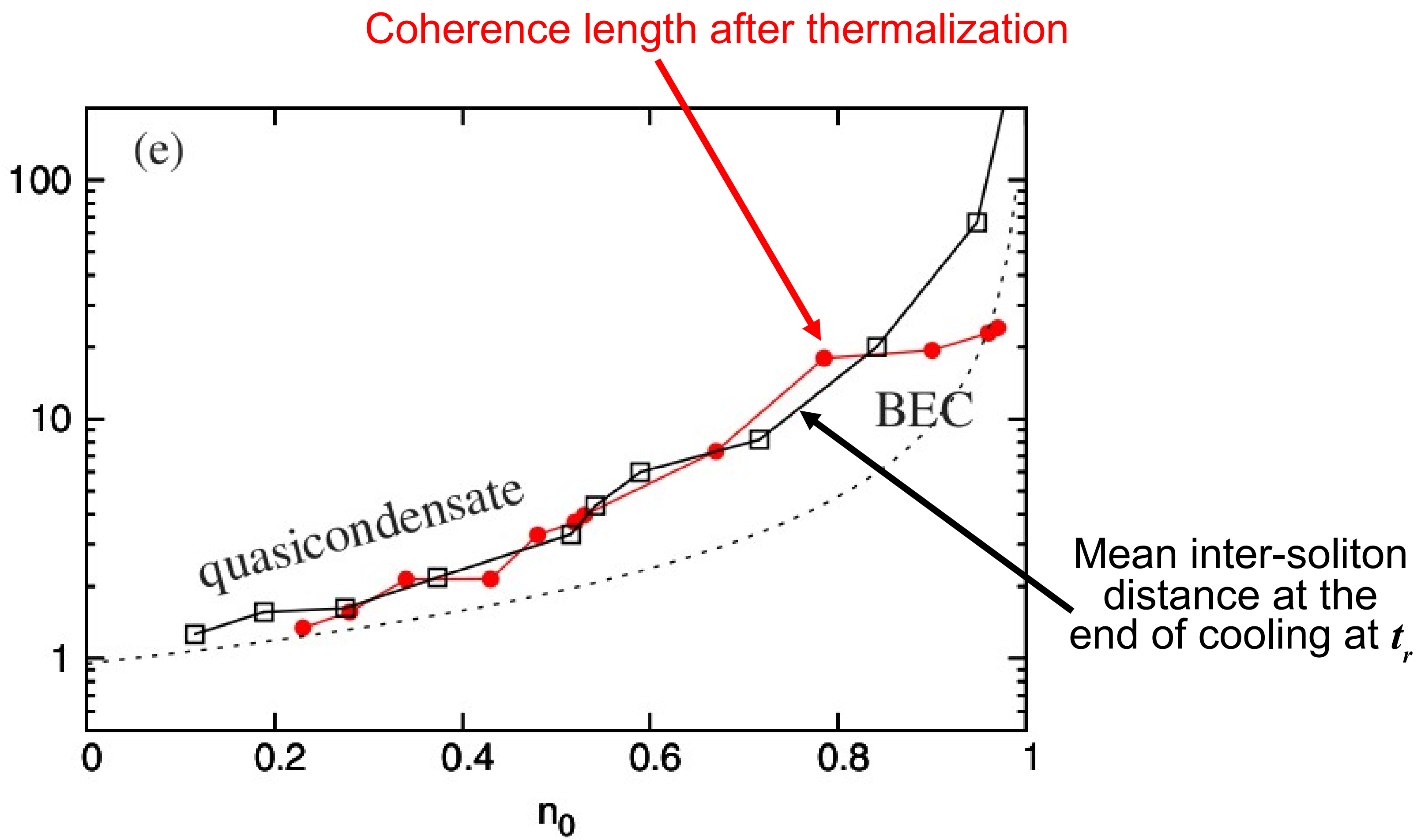
Fast ramp $\omega\, t_r = 75$

F





Solitons as the "larval stage" of equilibrium fluctuations



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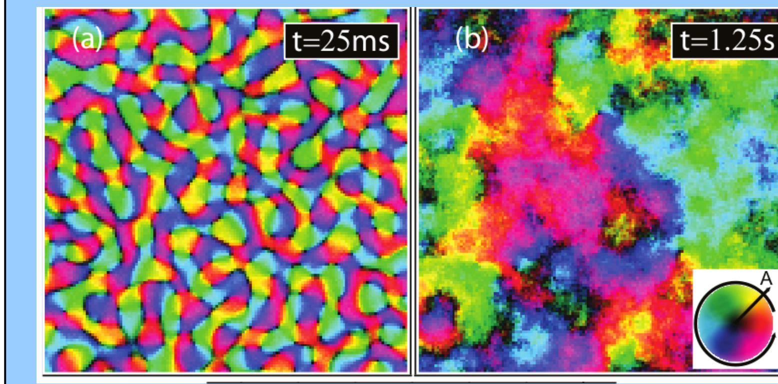
Quasicondensate formation

<u>We did NOT see the usual Kibble-Zurek scenario</u>

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

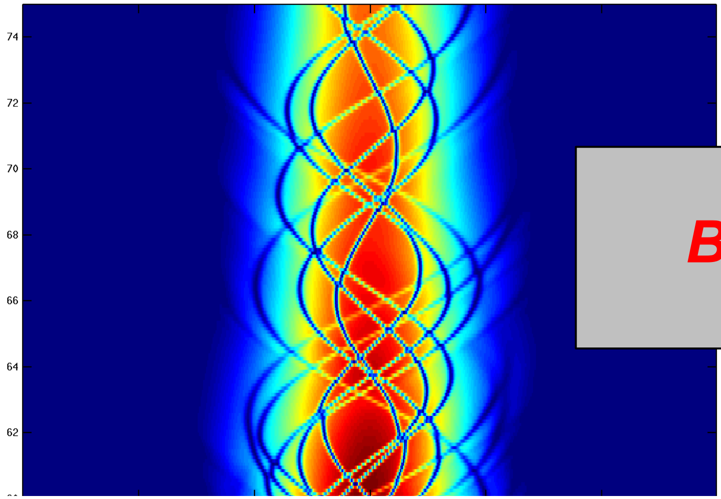


compare e.g. to 2D spin-1 gas:
Barnett, Polkovnikov, Vengelattore,
arXiv:1009.1646

<u>Instead:</u>

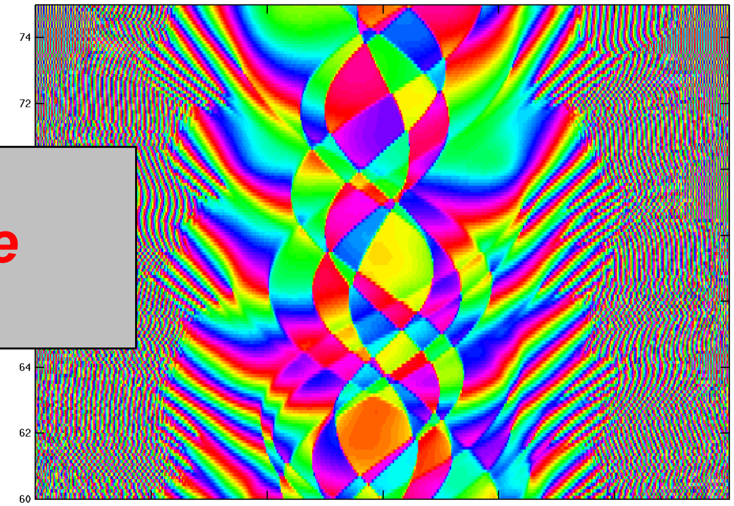
- domains are fleeting
- solitons are the stable entities
- "domain size" conserved

DENSITY



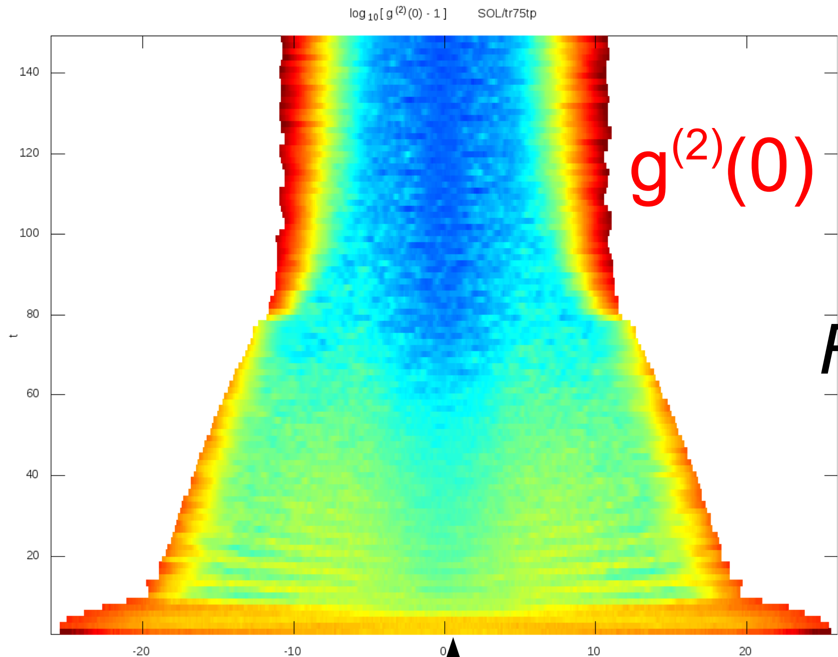
BKT-like

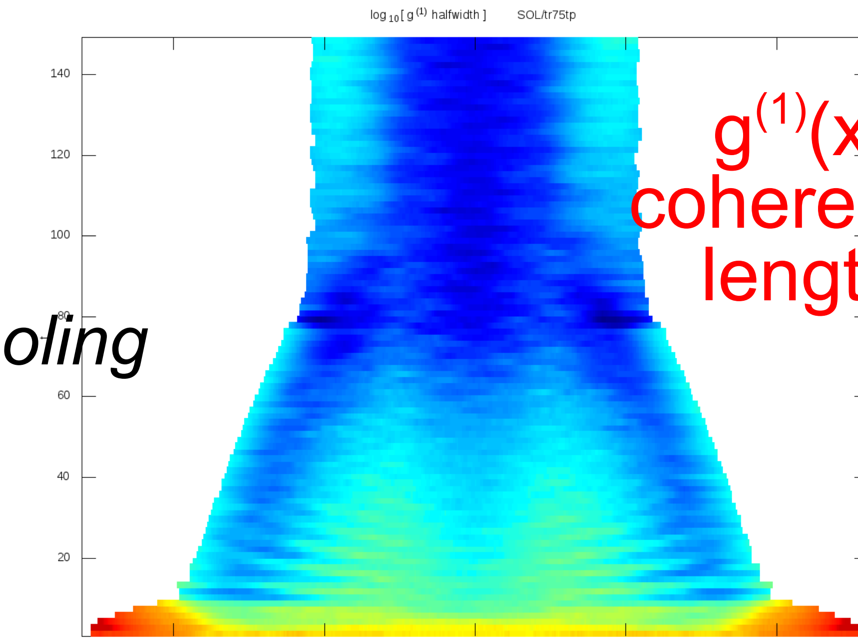
PHASE

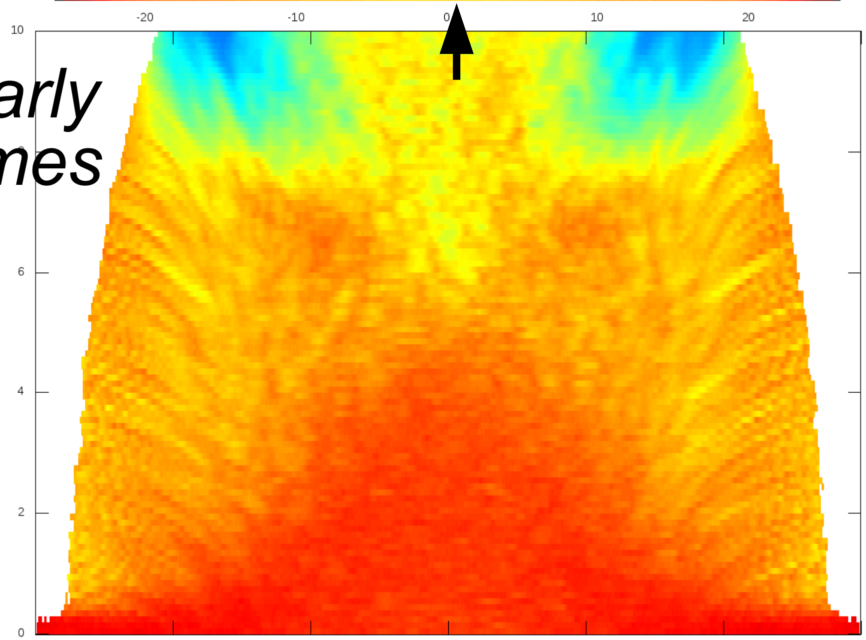


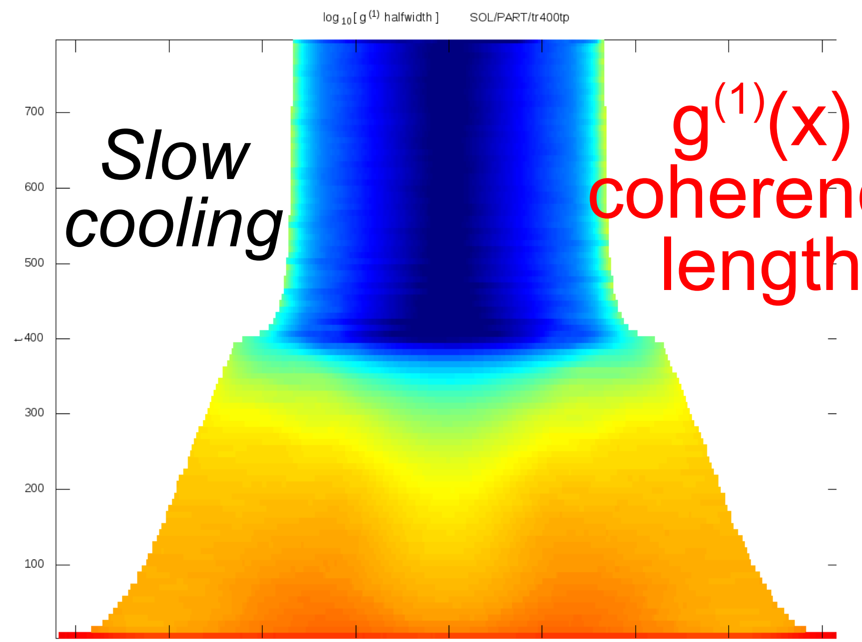
“Local” thermodynamics – ensemble averages

- average over trajectories





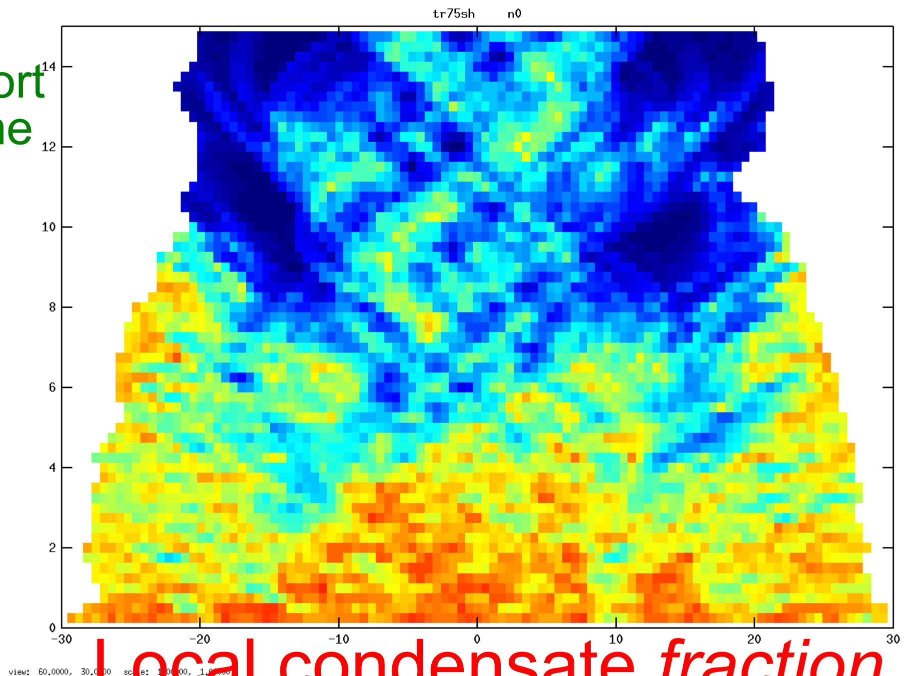


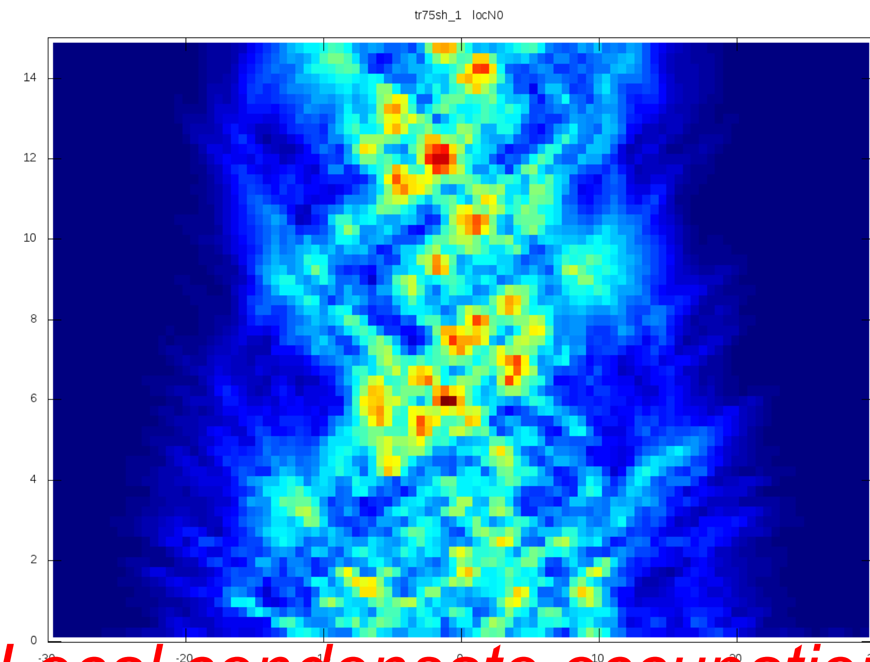


"Local" thermodynamics – 1-trajectory

Chop into small boxes in x-t space, calculate local condensate fraction, coherence length

Short time

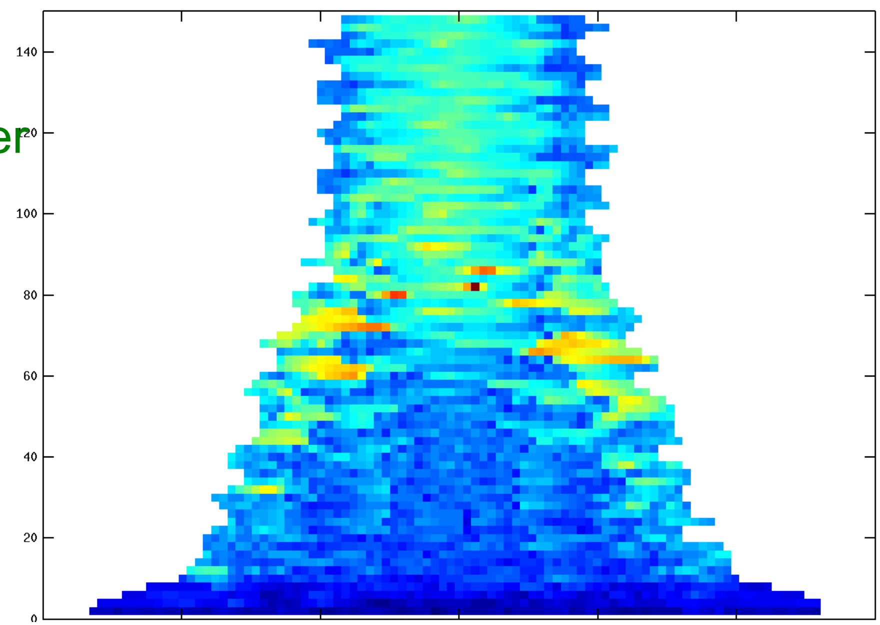


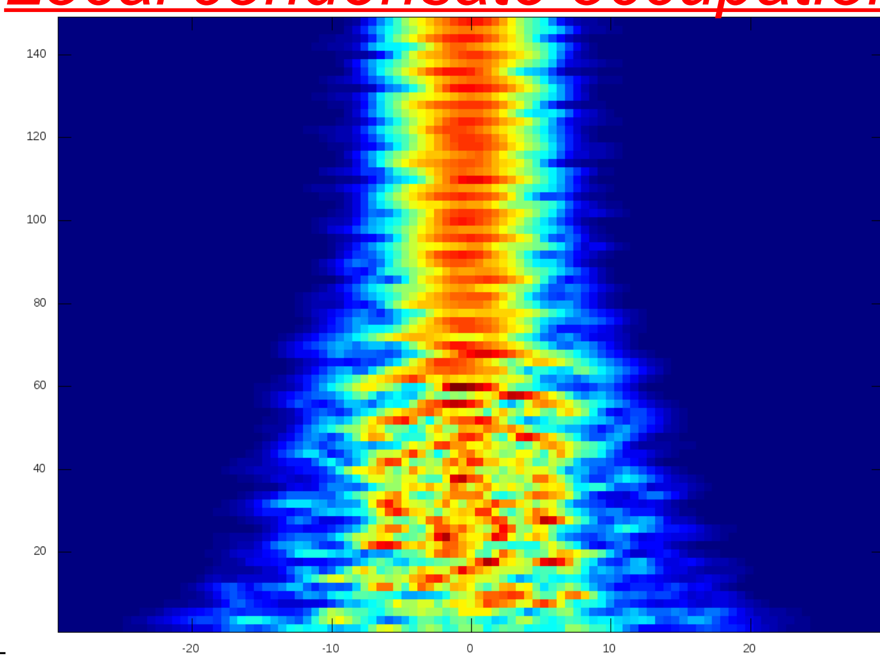


Local condensate *fraction*

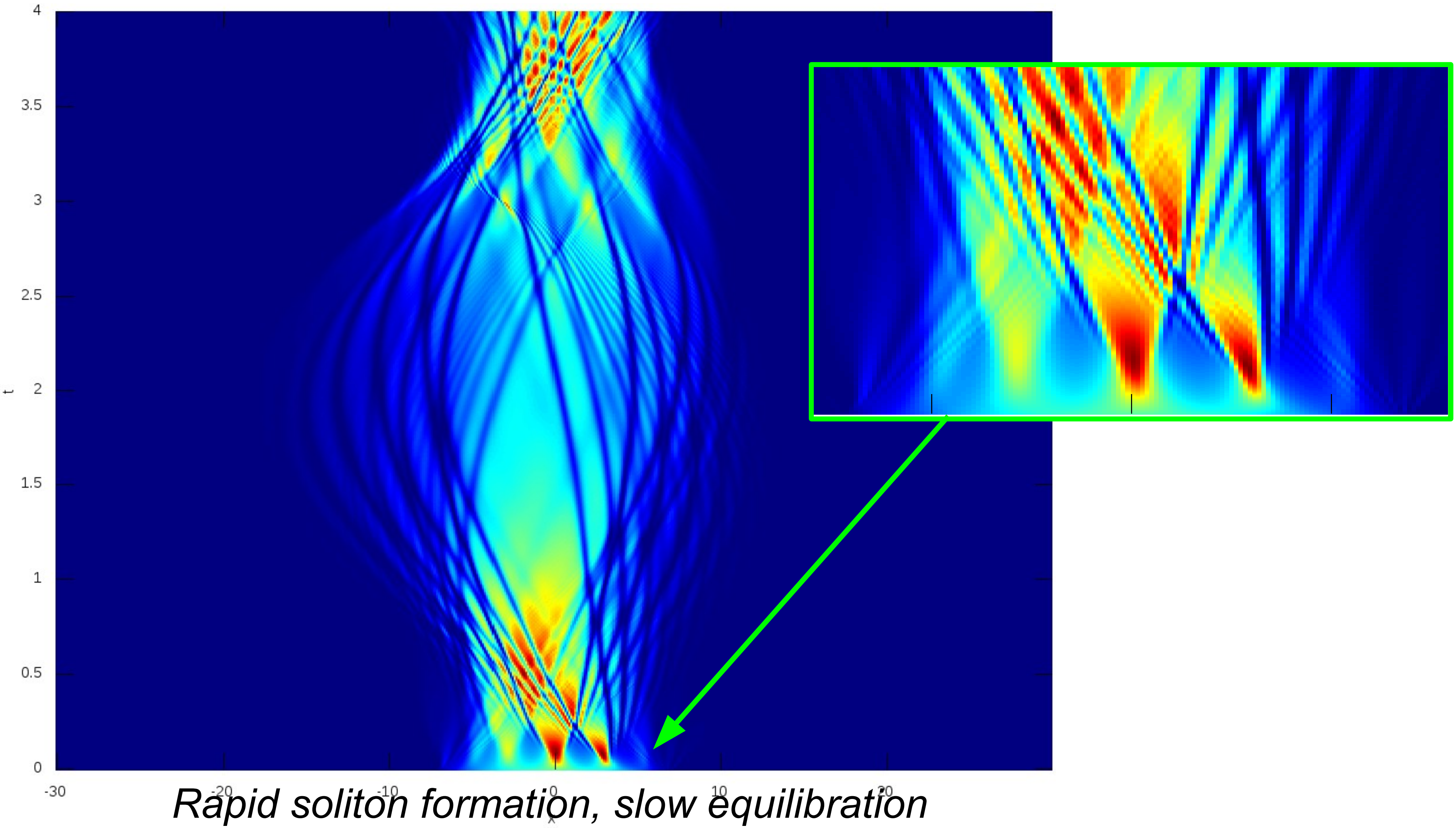
Local condensate occupation

Longer time





Quasicondensate and density fluctuations



Rapid soliton formation, slow equilibration

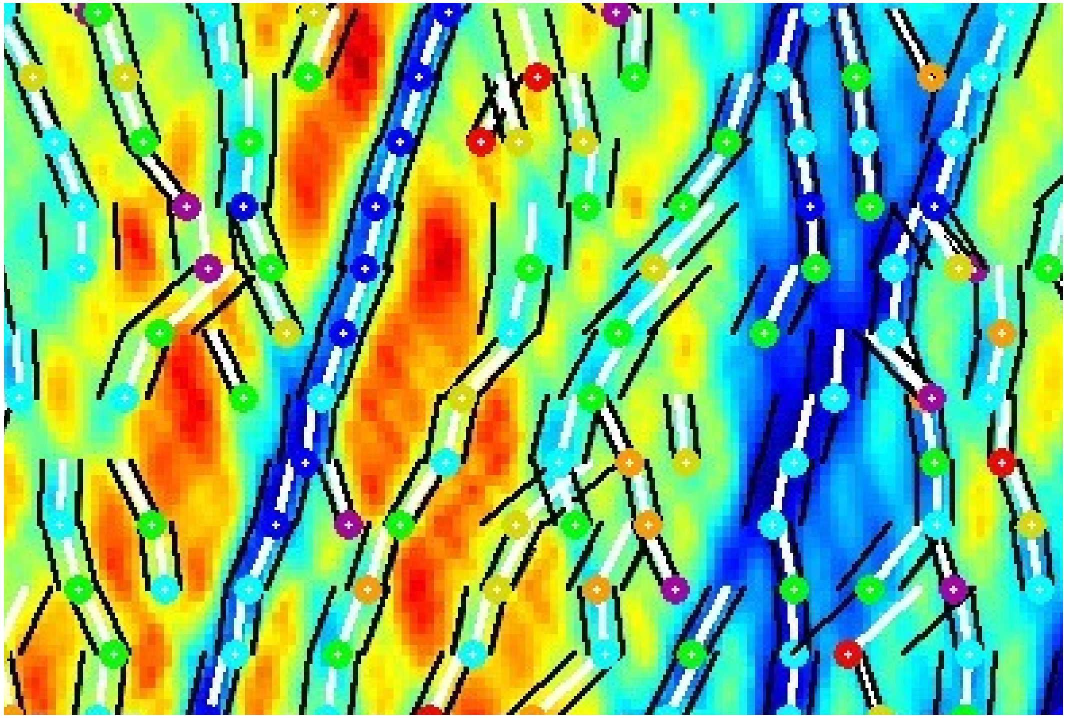
Initial classical field described by model of

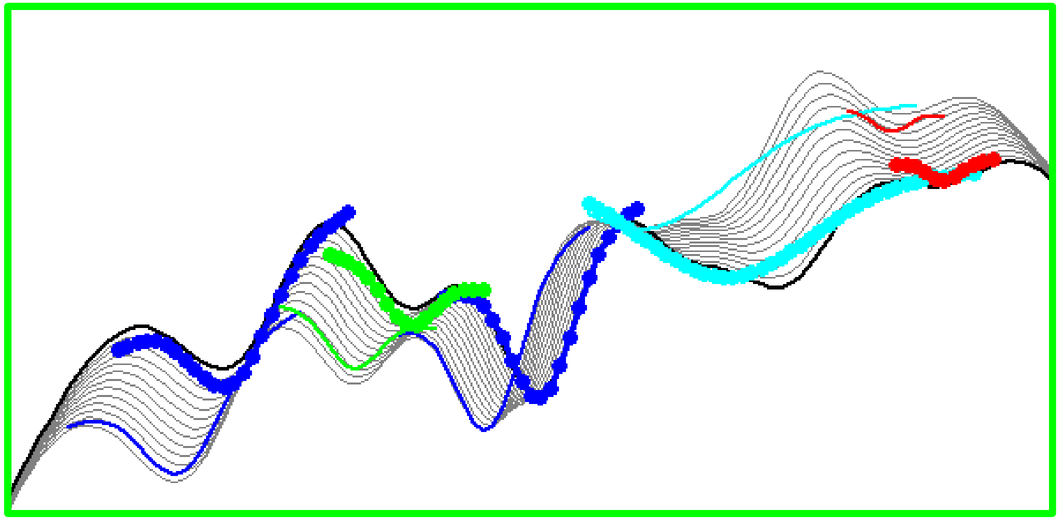
Phase-fluctuating 3D condensates in elongated traps

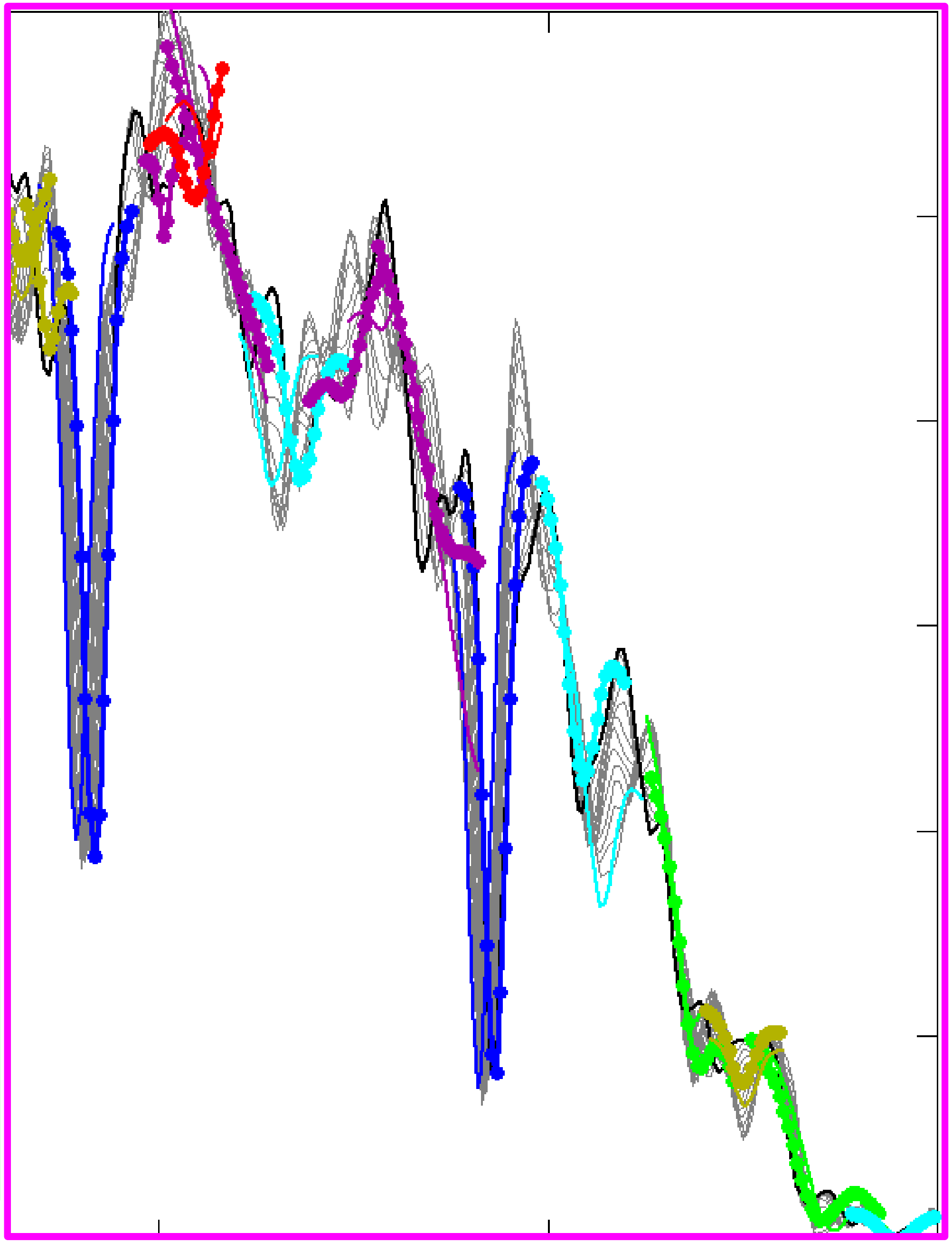
Petrov, Shlyapnikov, Walraven, PRL **87**, 050404 (2001)

Soliton statistics - automation

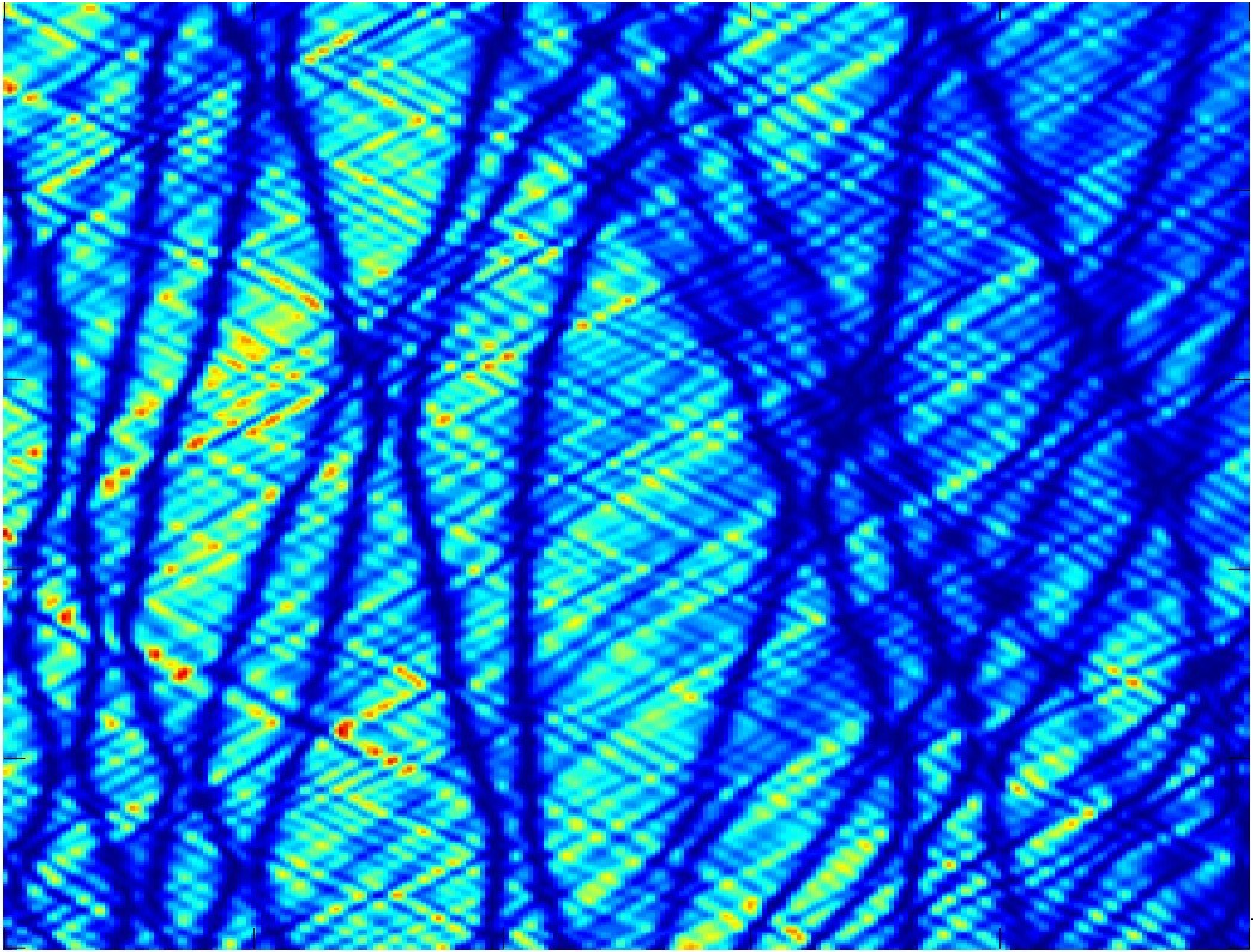
Fitting of Gaussian dips over a finite box in x ***AND*** *t space*



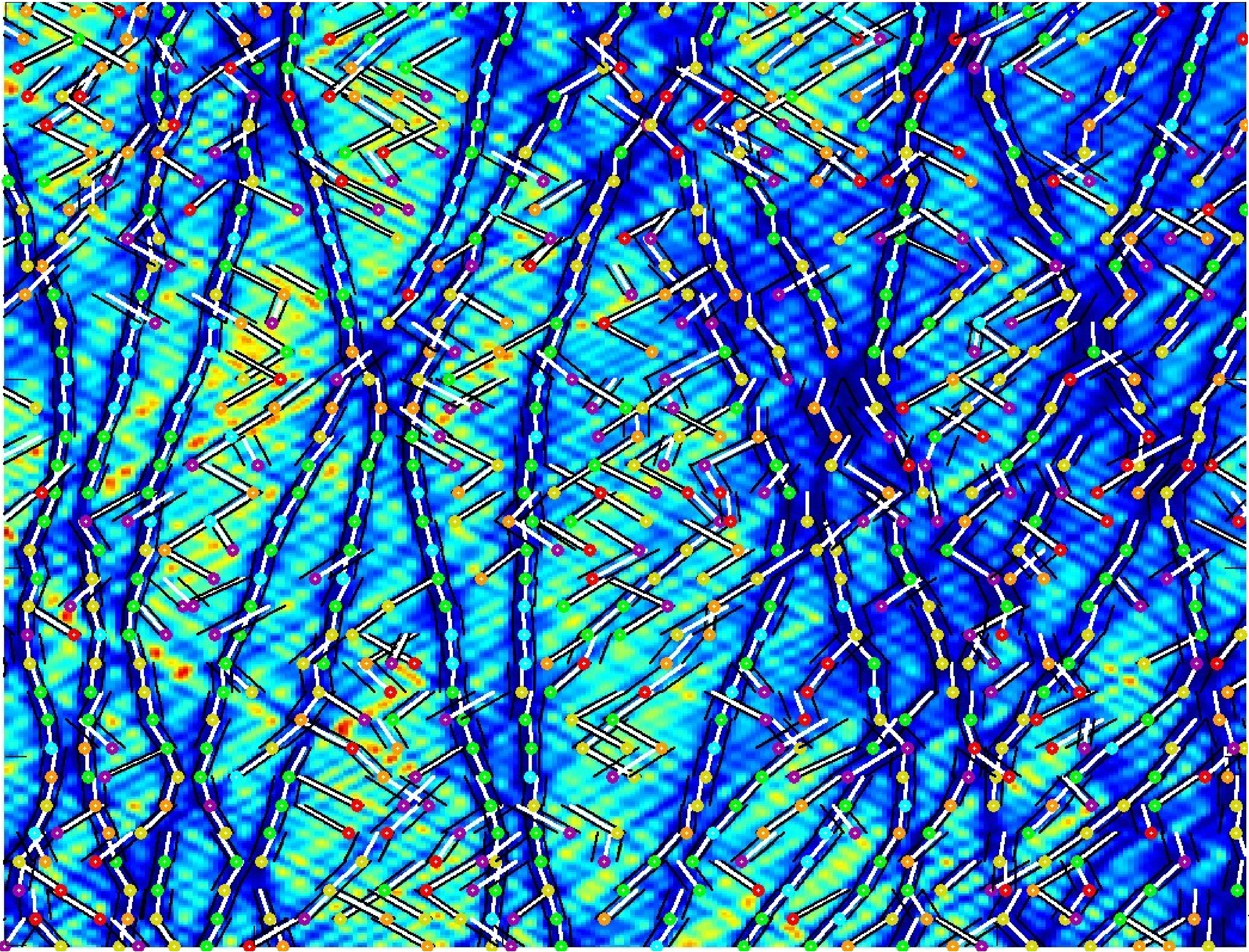




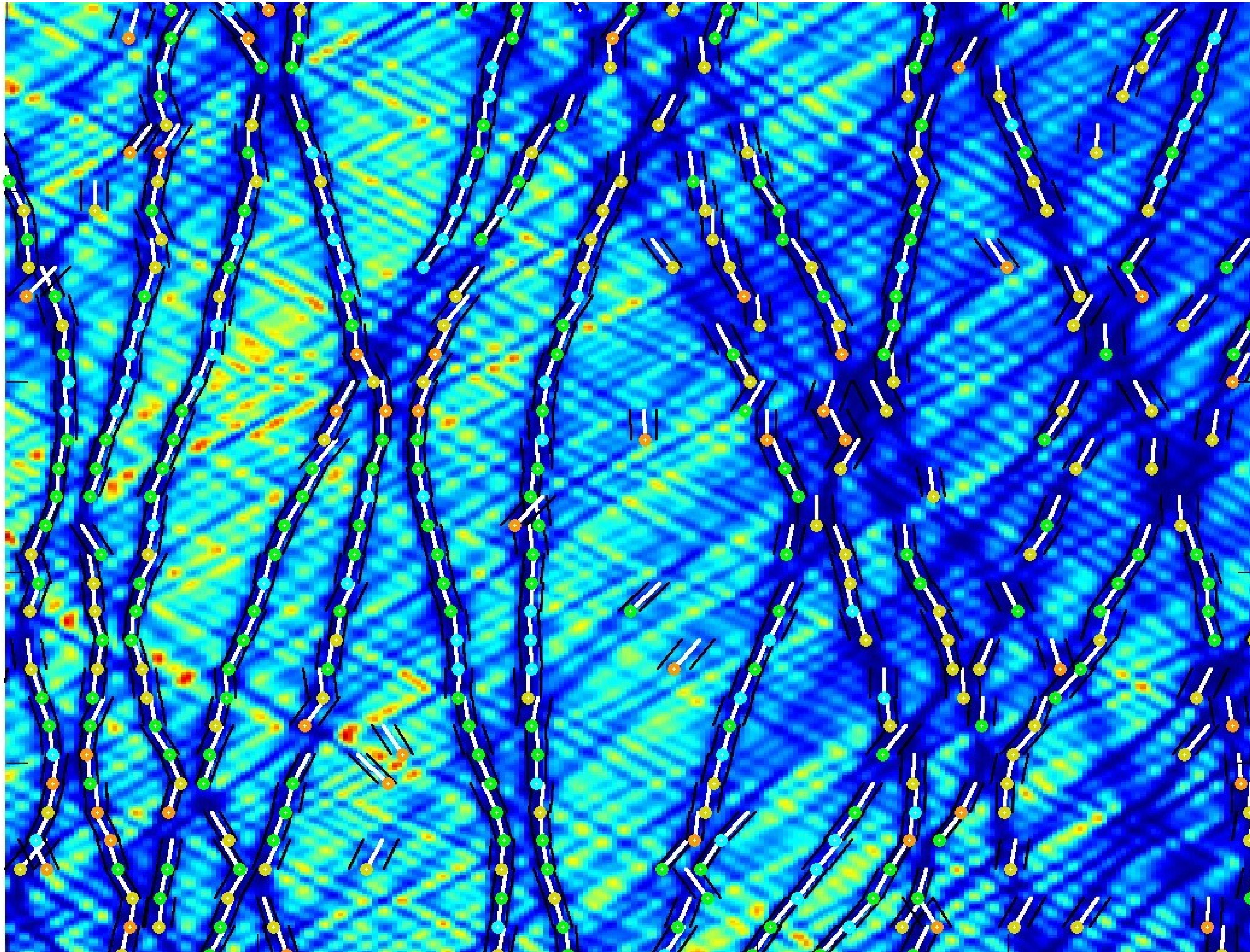
Soliton statistics – before fit



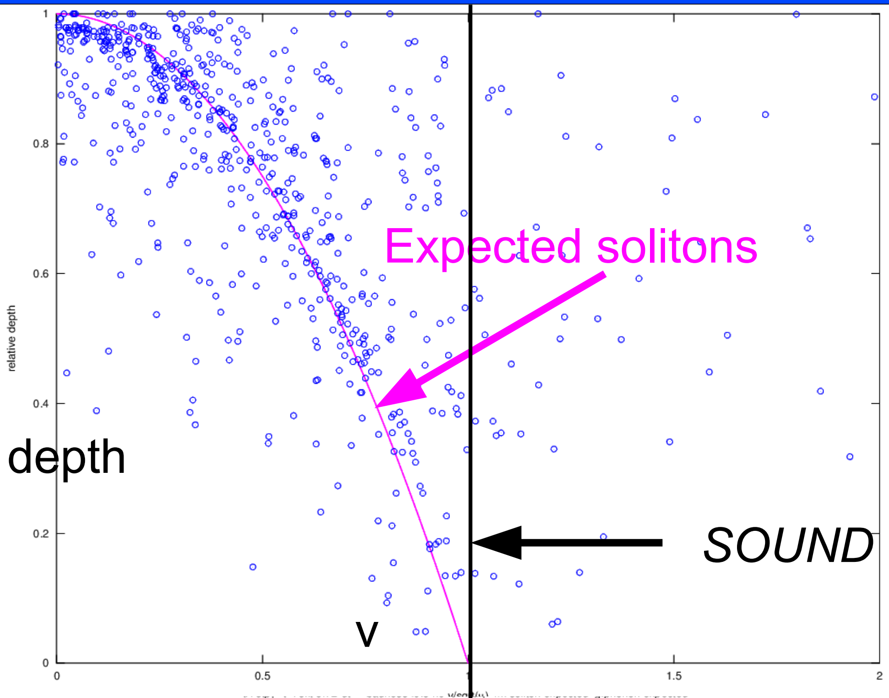
Soliton statistics – fit



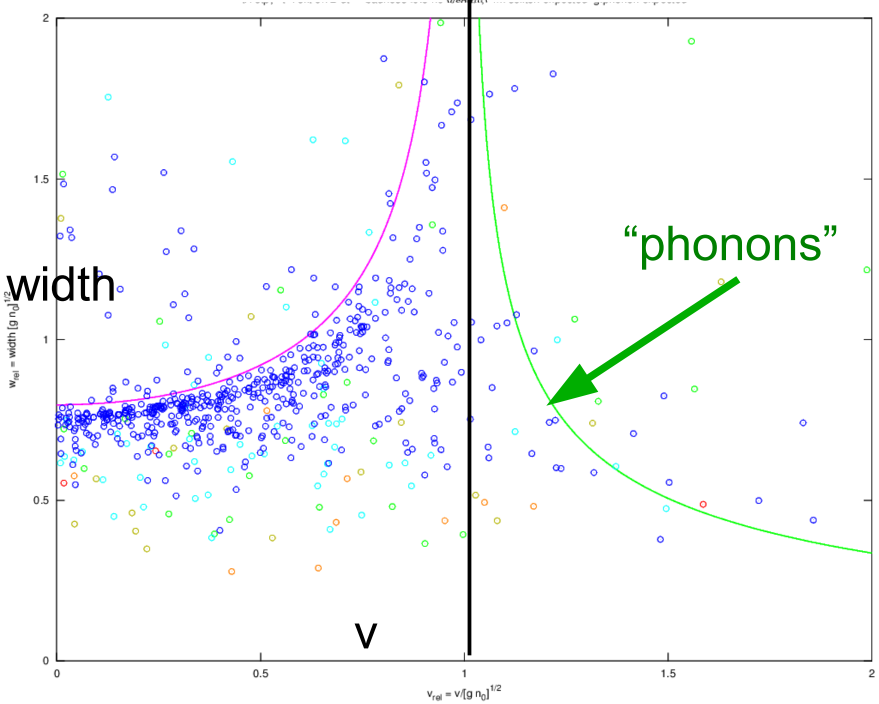
Soliton statistics – filtering

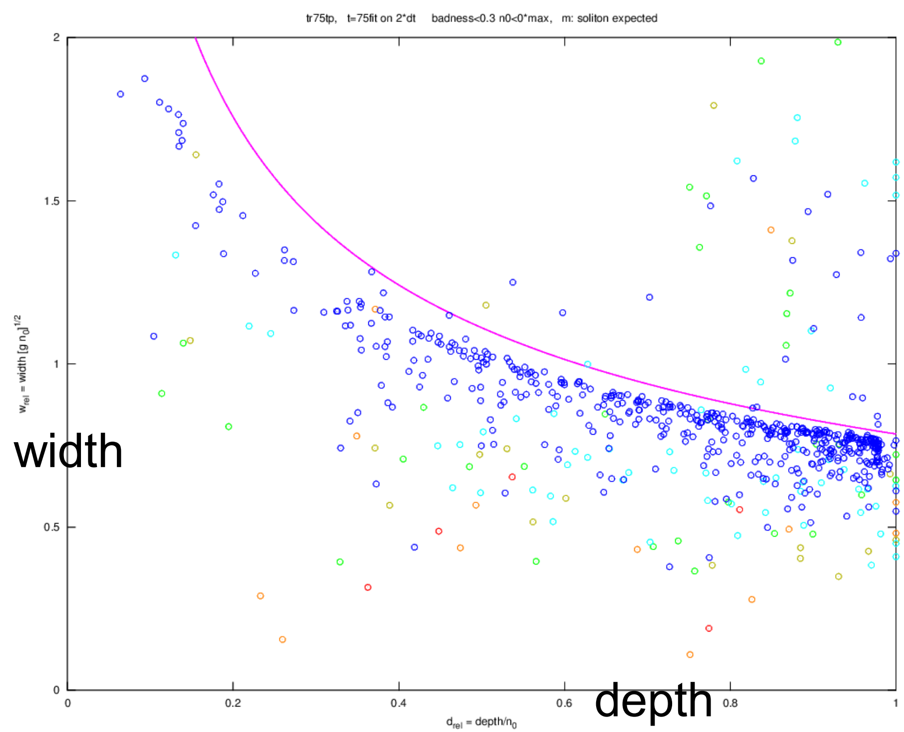


Filtering

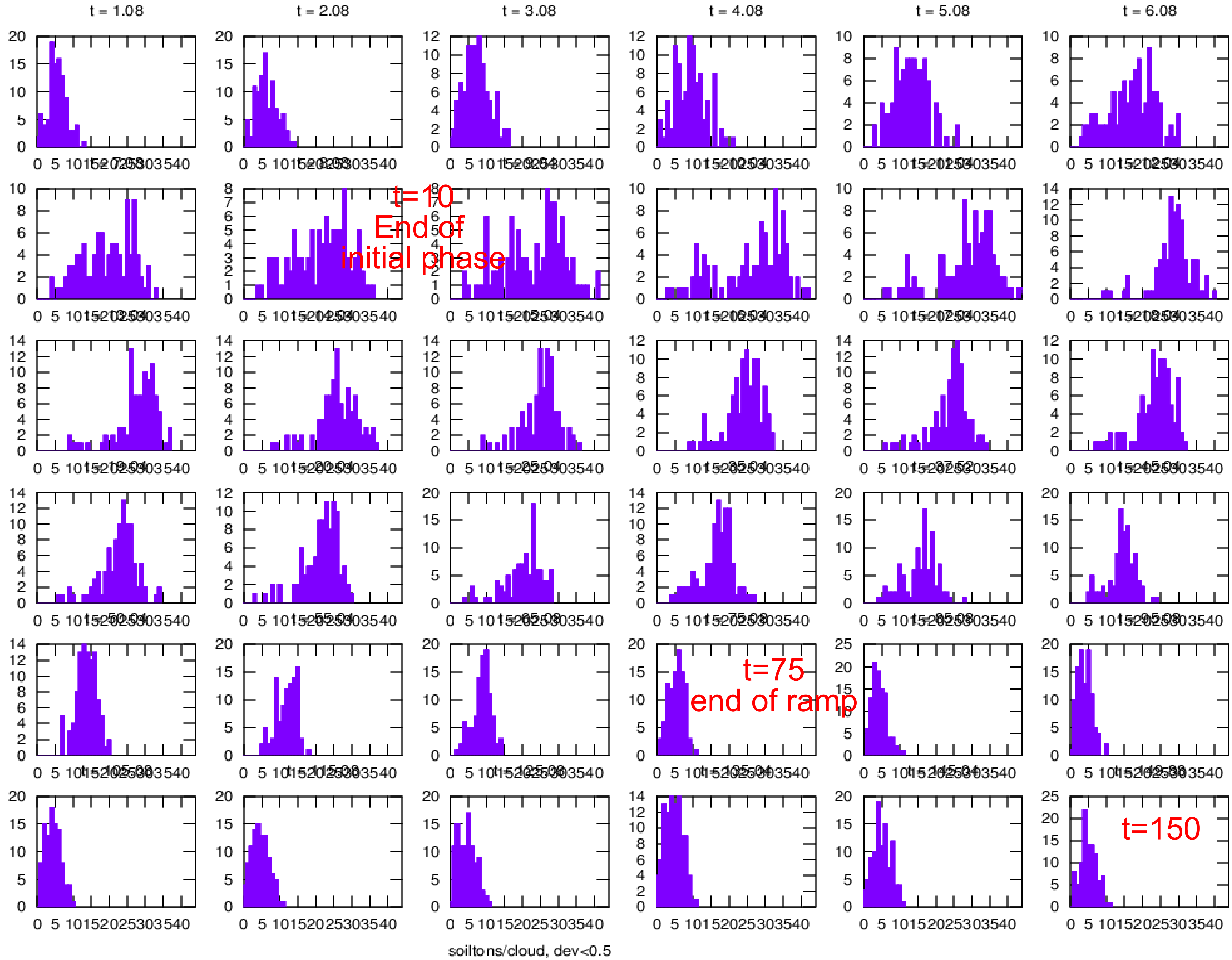


Remove fits far from “soliton” lines from consideration





Soliton statistics - evolution



Conclusions: what of the original questions?

- Kibble-Żurek mechanism?

  Confusion has been sown

- Defects ↔ quasicondensate?

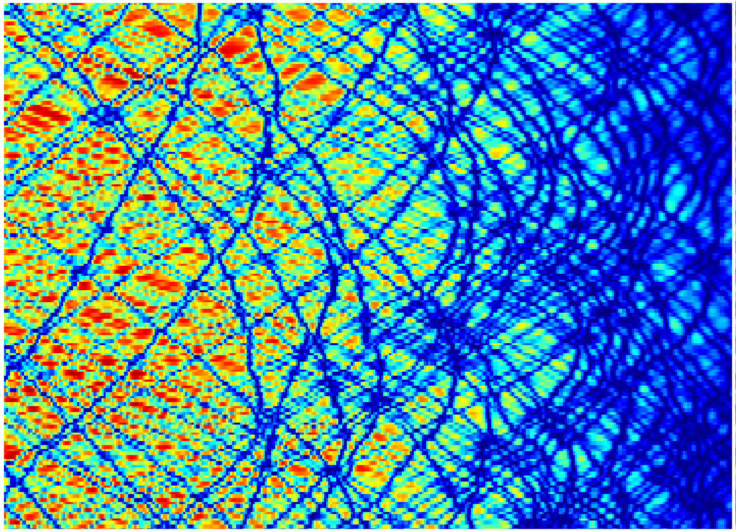
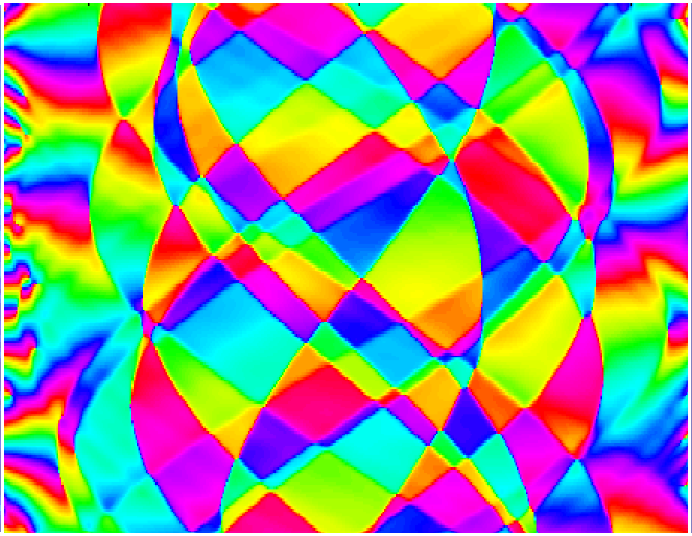
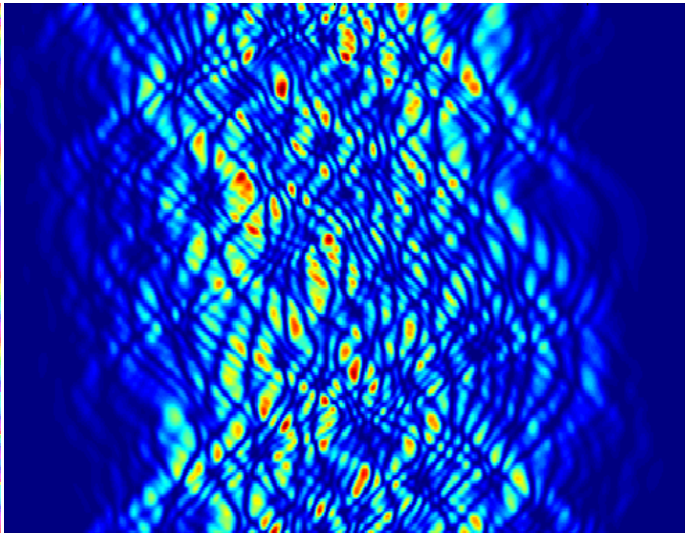
  Solitons = "larval stage" of long time phase fluctuations

- Time scales

  Rapid soliton formation, slow equilibration

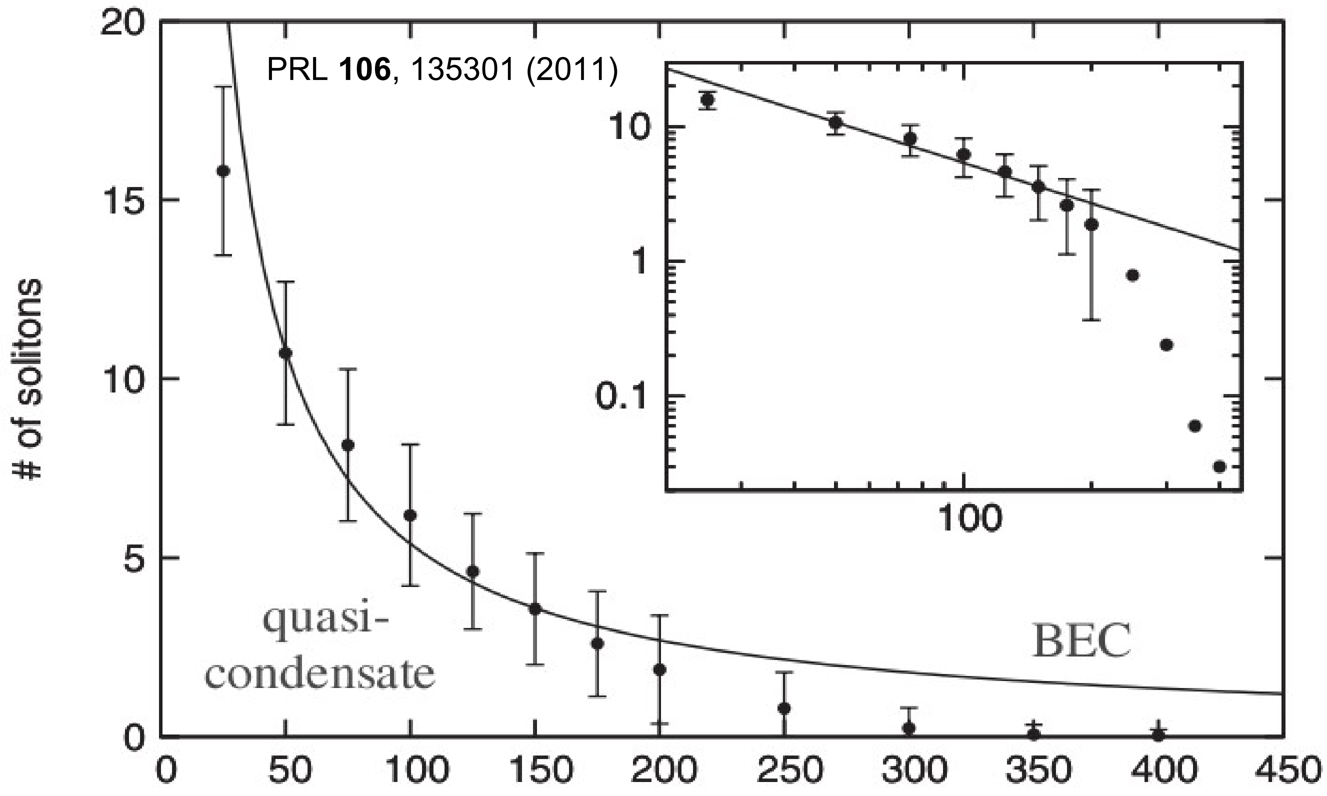
- Analysis

  Local-thermodynamics and automated soliton counting possible

Kibble-Żurek defect formation

Soliton number at the end of the ramp



Evaporation time

prediction:

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

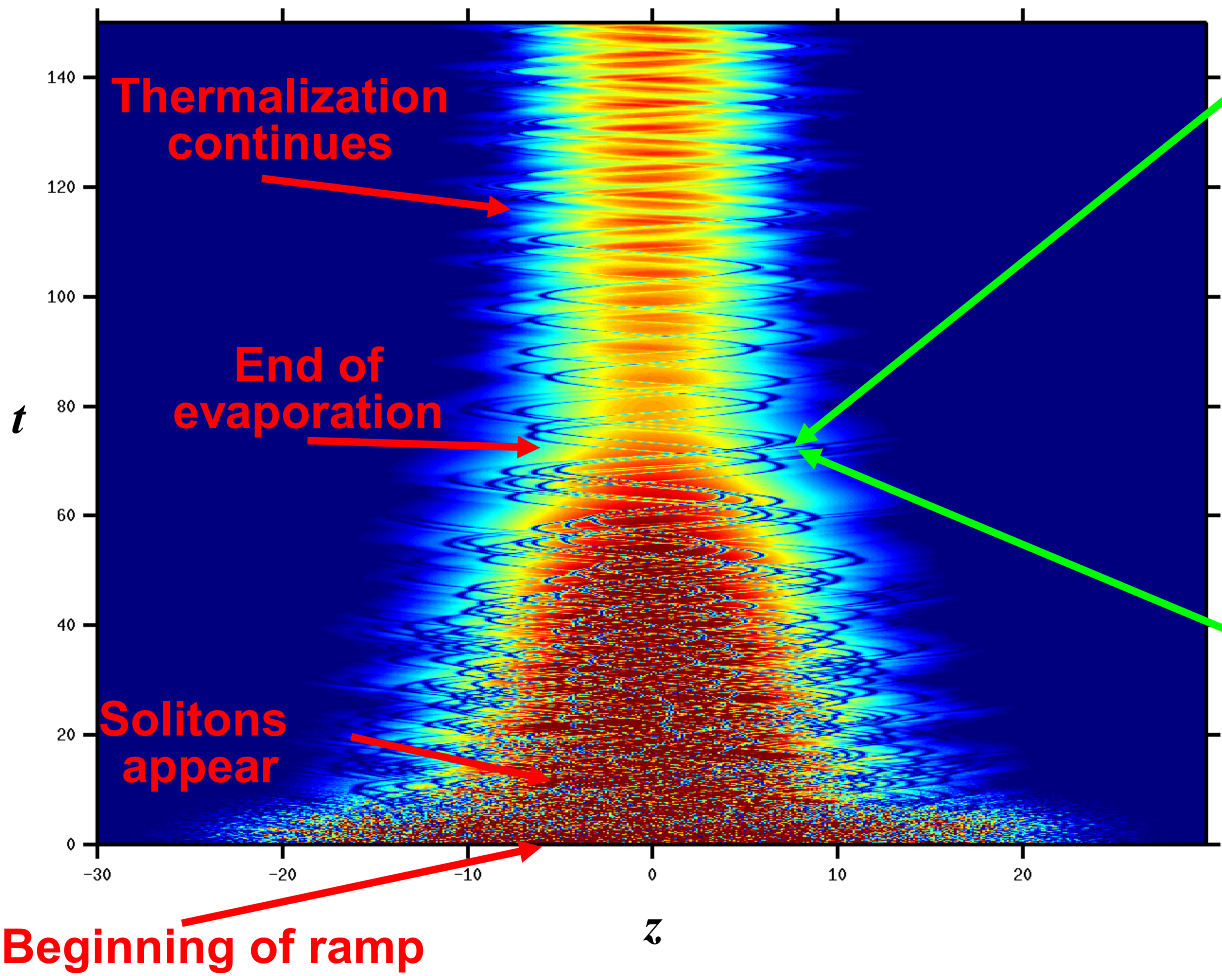
$$N \approx \frac{2\hat{X}}{f\hat{\xi}} = \frac{2\Delta^2}{f\lambda_{\mathrm{dB}}^2}\left(\frac{\tau_0}{\tau_Q}\right)^{(1+2\nu)/(1+\nu z)}$$

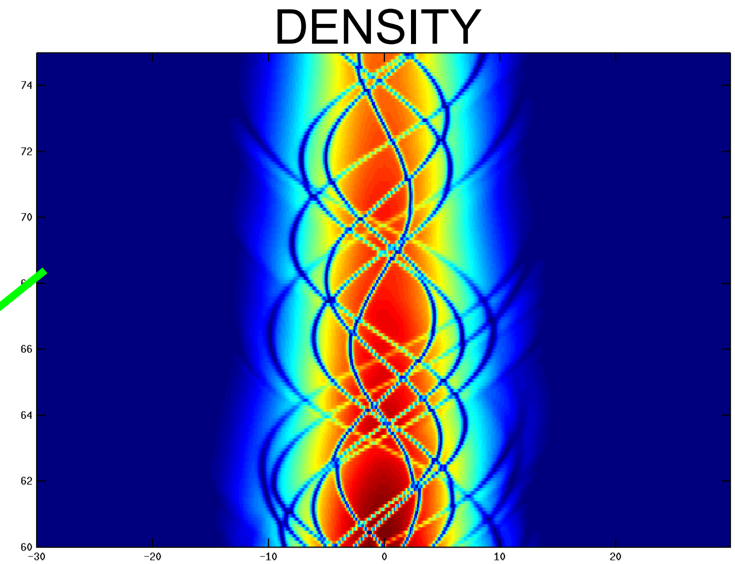
Quench time
= evaporation time t ?

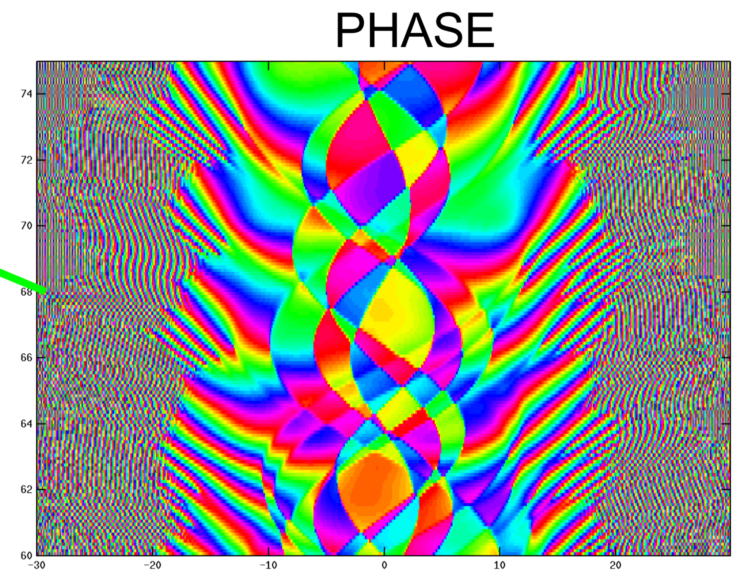
~1

Fast ramp → quasicondensate precursor

Fast ramp $\omega\, t_r = 75$

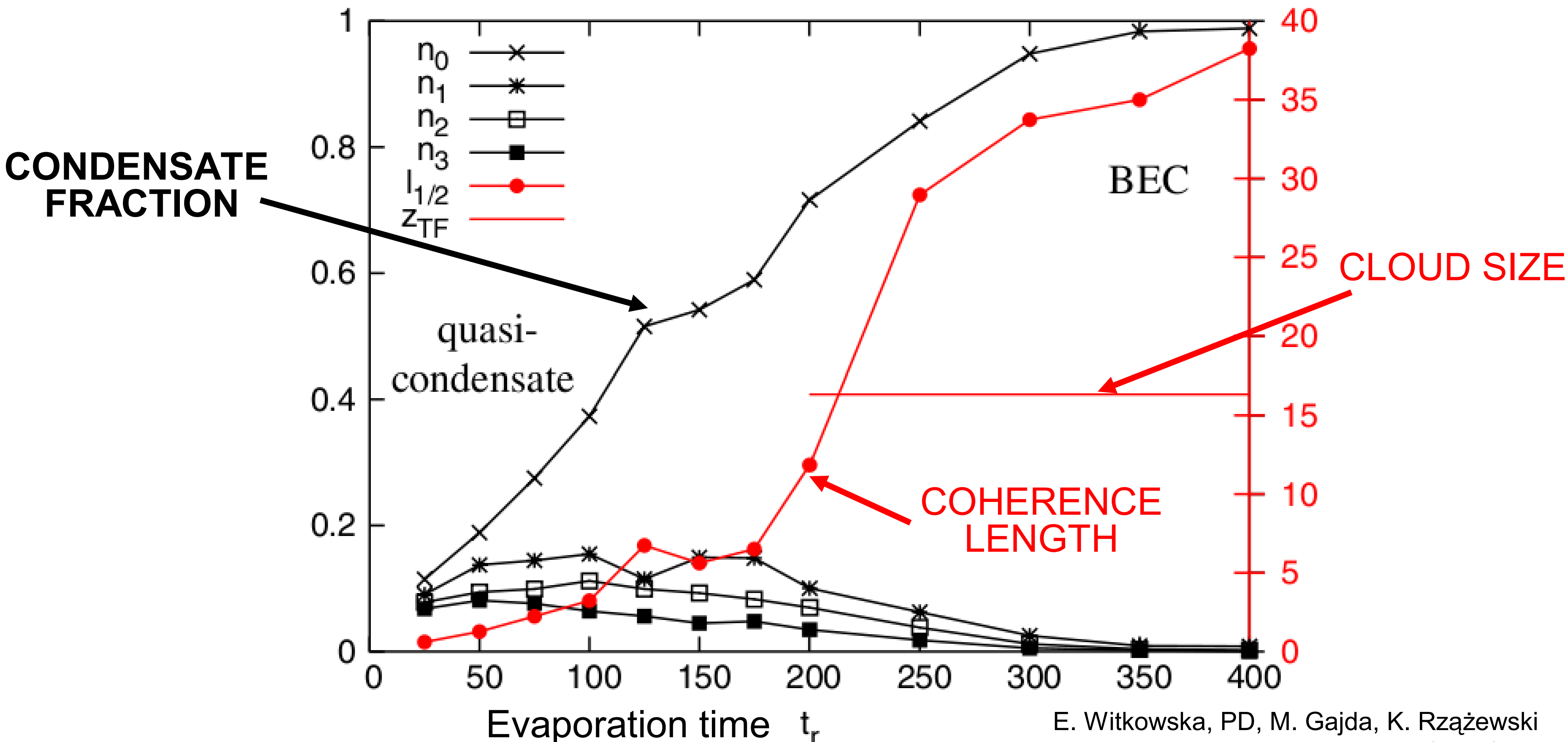






Ramp time

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



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