SPICE Workshop: Non-equilibrium Quantum Matter, Mainz Germany, 5/31/2017

Inflation and coherent dynamics in a Bose-Einstein condensate driven across a quantum critical point

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National Science Foundation

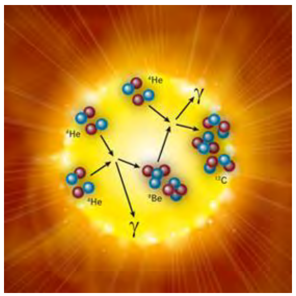
Army Research Office

Material Research Science & Engineering center

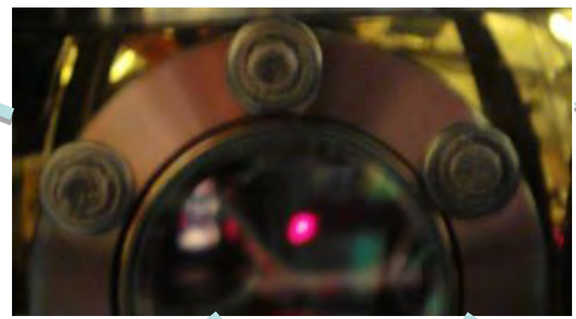
MRSEC

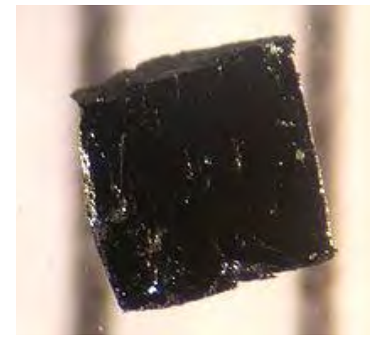
Cold atom research at UChicago

THE UNIVERSITY OF CHICAGO

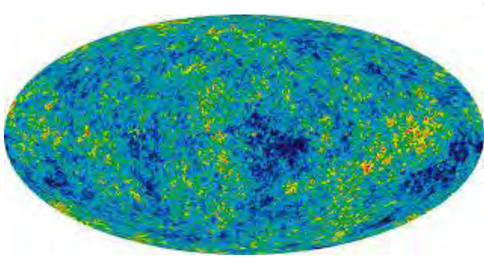


Nuclear Physics:
Feshbach molecules
Efimov physics
Quantum droplet

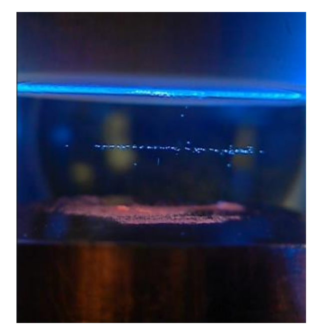




Condensed Matter:
Scale invariance
Quantum criticality

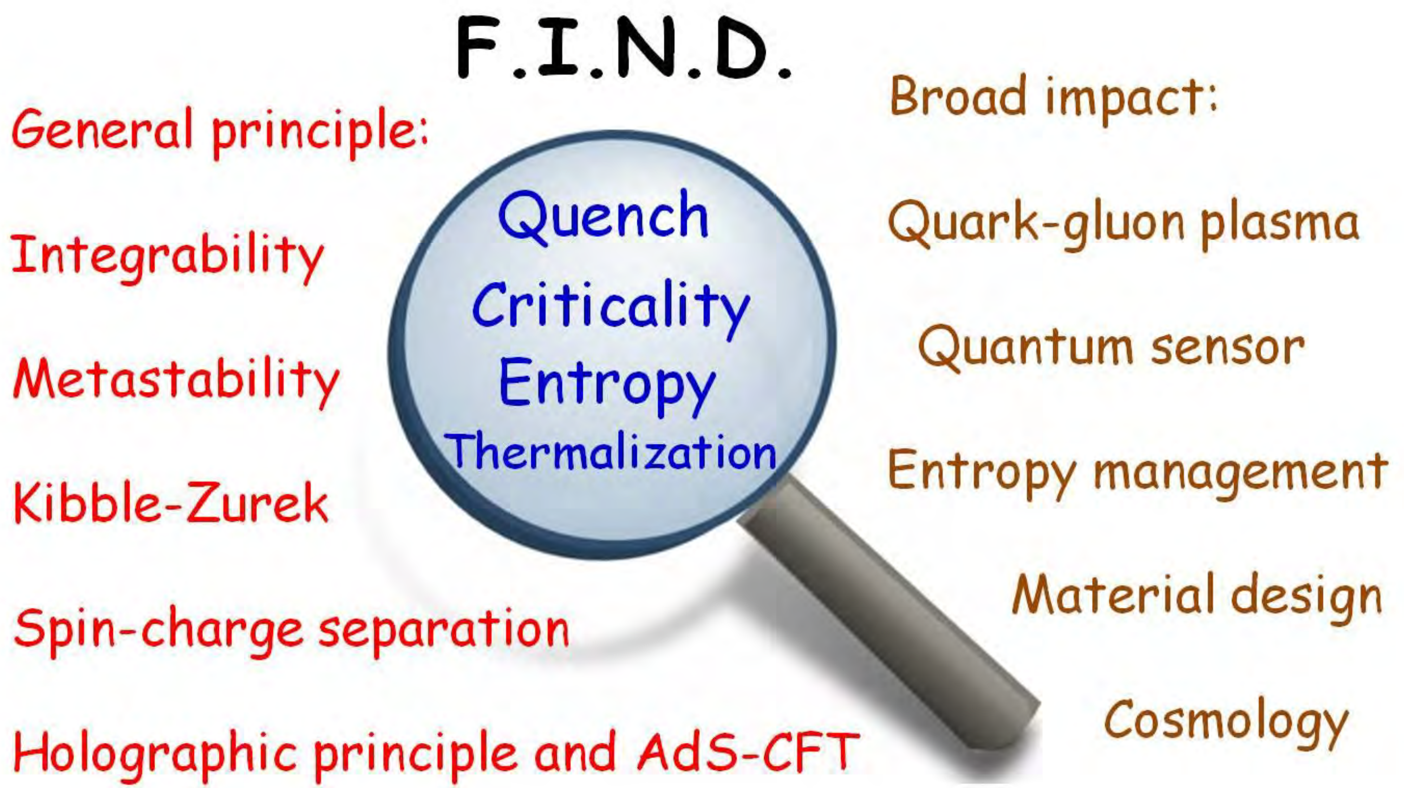


Cosmology:
Sakharov oscillations
Kibble mechanism
Inflation



Thermal Levitation

ARO MURI: Fundamental Issues in Non-equilibrium Dynamics



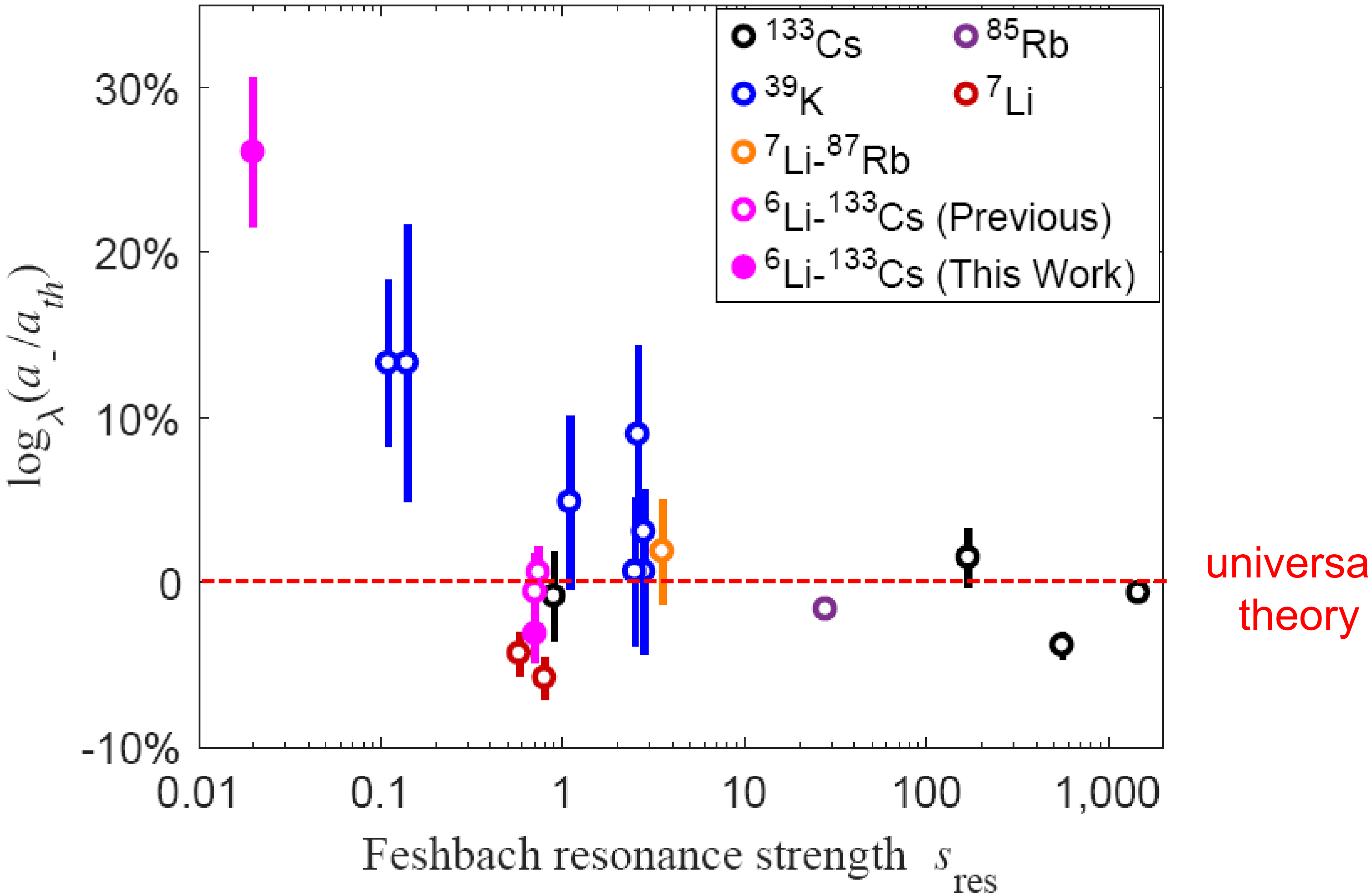
Consortium: Chicago, Harvard, MIT, Rice, Cornell, Ohio State

ARO MURI

Synopsis

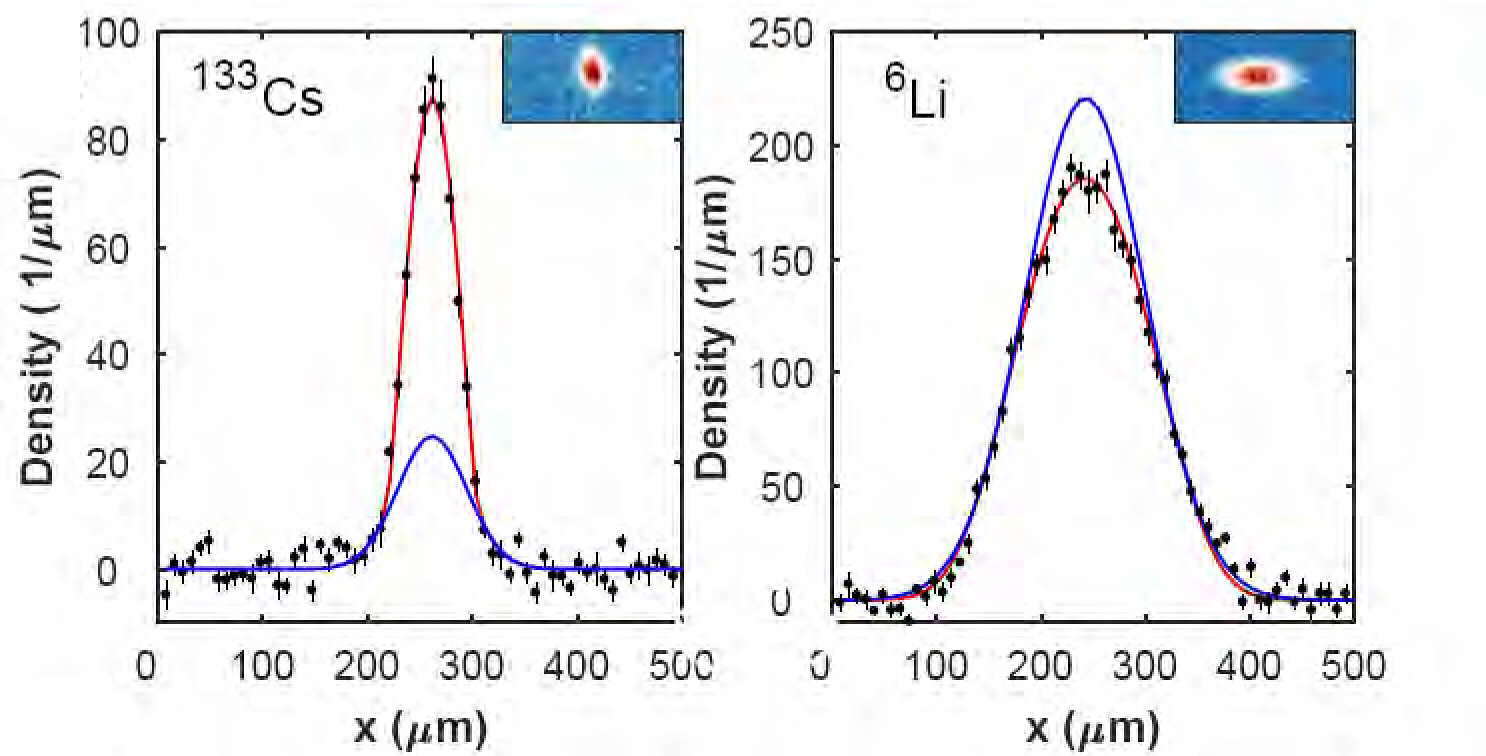
- Bose-Fermi mixture of ^{6}Li and ^{133}Cs
  - Efimov scaling symmetry *PRL 2014, NatPhys 2015*
  - Test of Efimov univesality *NatPhys 2017*
  - Bose-Fermi mixture
- ^{133}Cs: Quantum criticality
  - Equilibrium *Science 12, PRL13*
  - *Domain formation* *NatPhys13*
  - *Roton-Maxon dispersion* *PRL 15*
  - *Kibble-Zurek scaling* *Science 16*
  - *Inflation*

Test of Efimov Universality



J. Johansen, B. DeSalvo, K. Patel, CC, Nature Physics (2017)

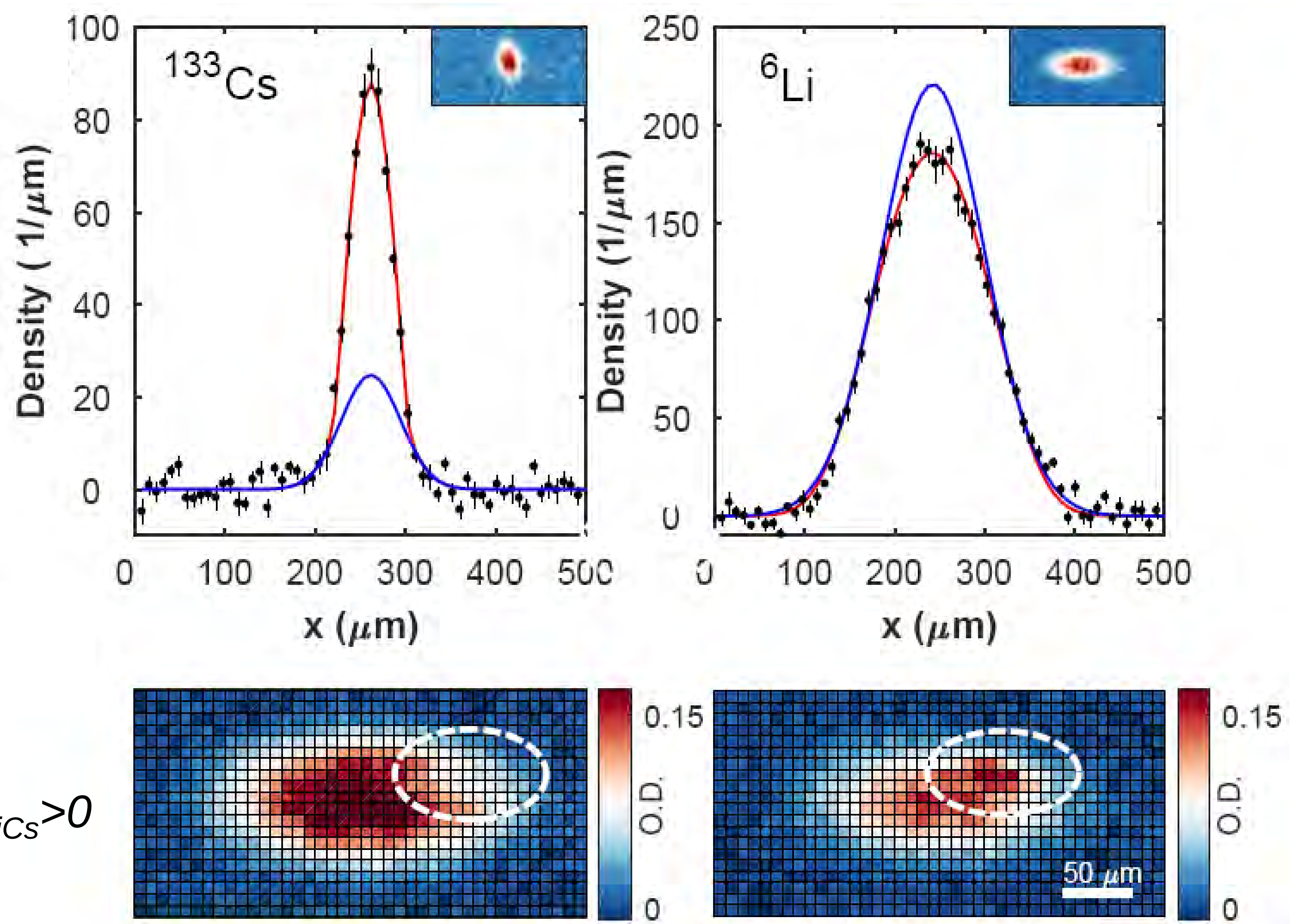
LiCs Fermi-Bose mixture



10,000 atoms
10~20 nK

10,000 atoms
Fermi temperature = 500 nK

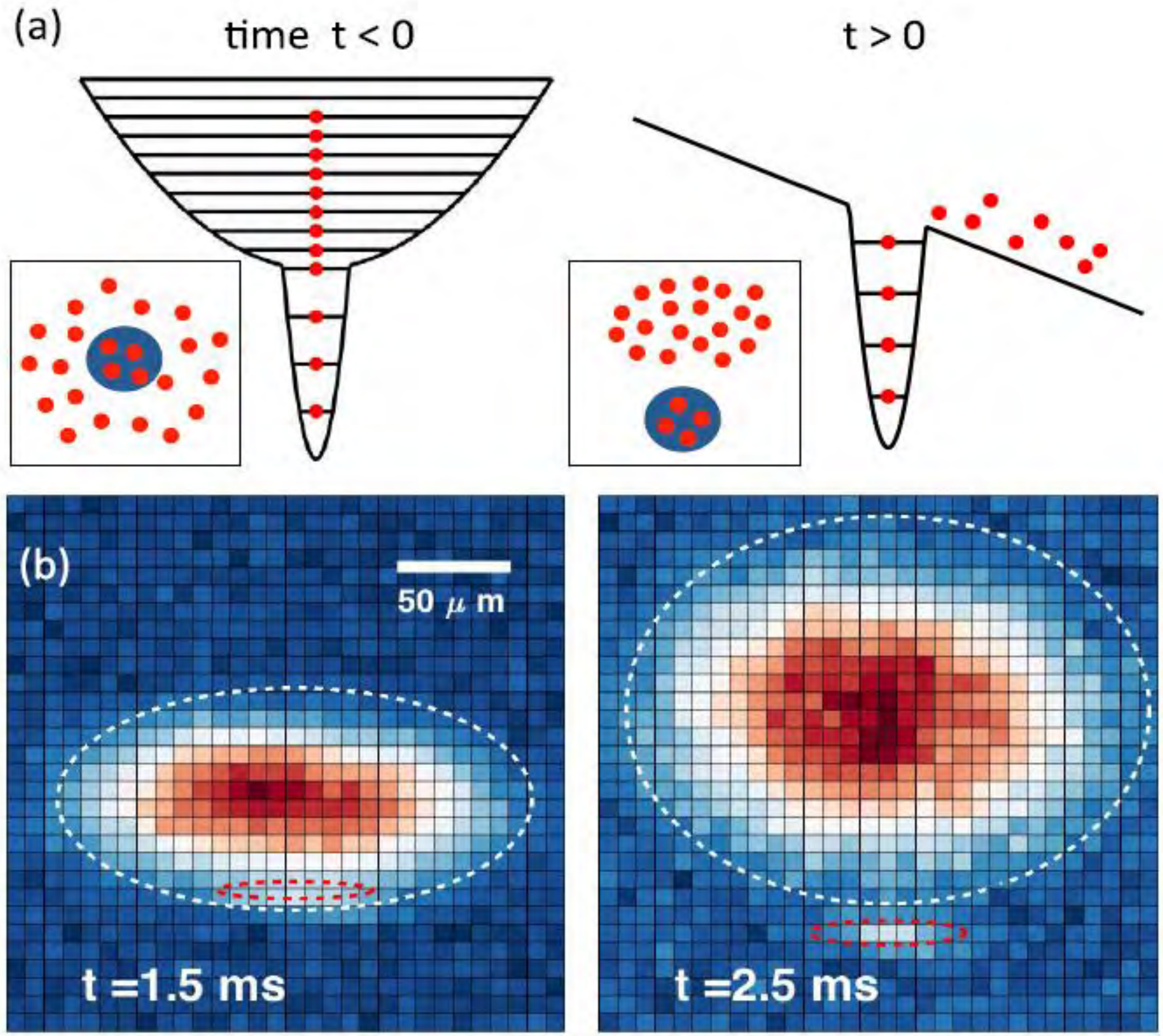
LiCs Fermi-Bose mixture



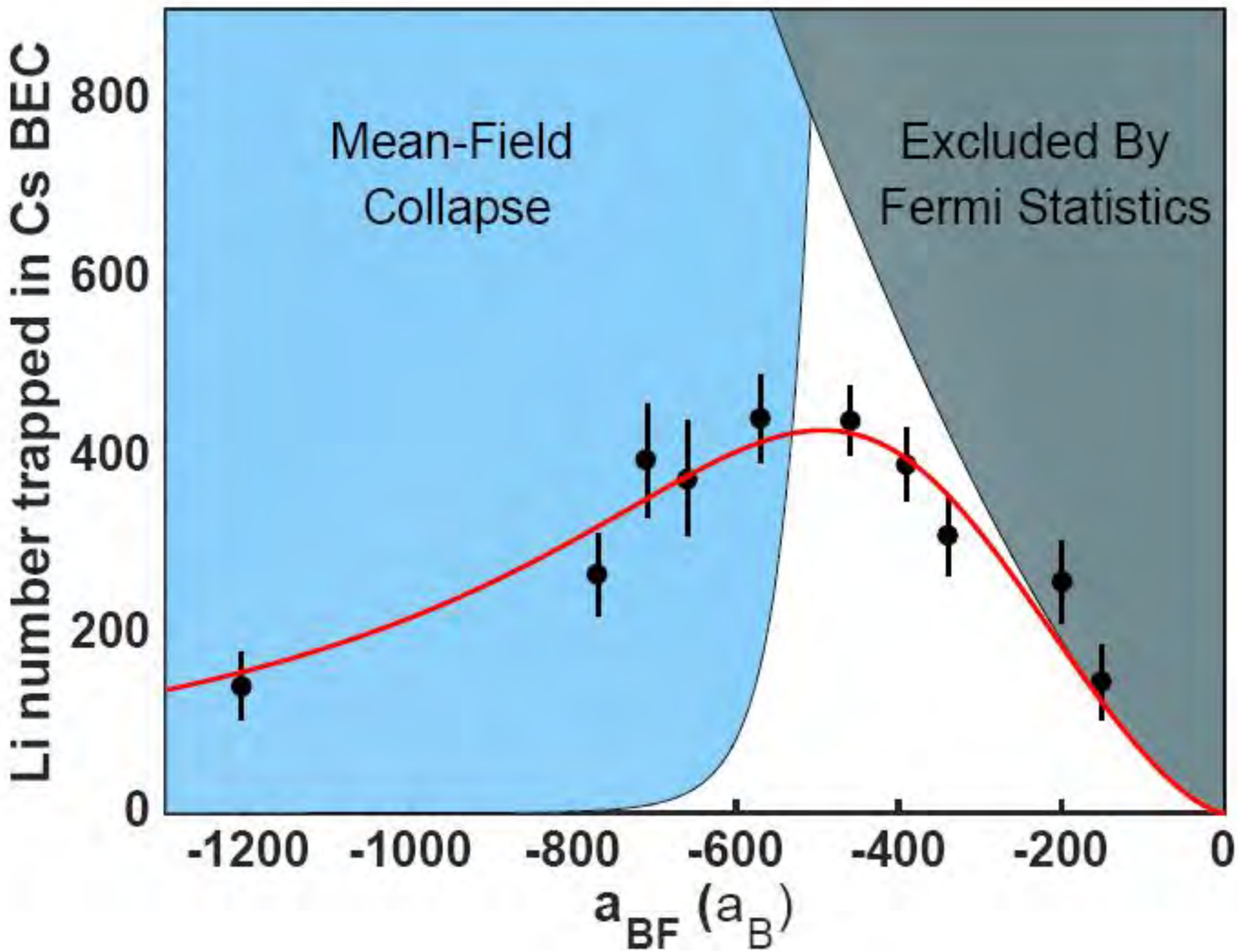
$g_{LiCs}>0$

$g_{LiCs}<0$

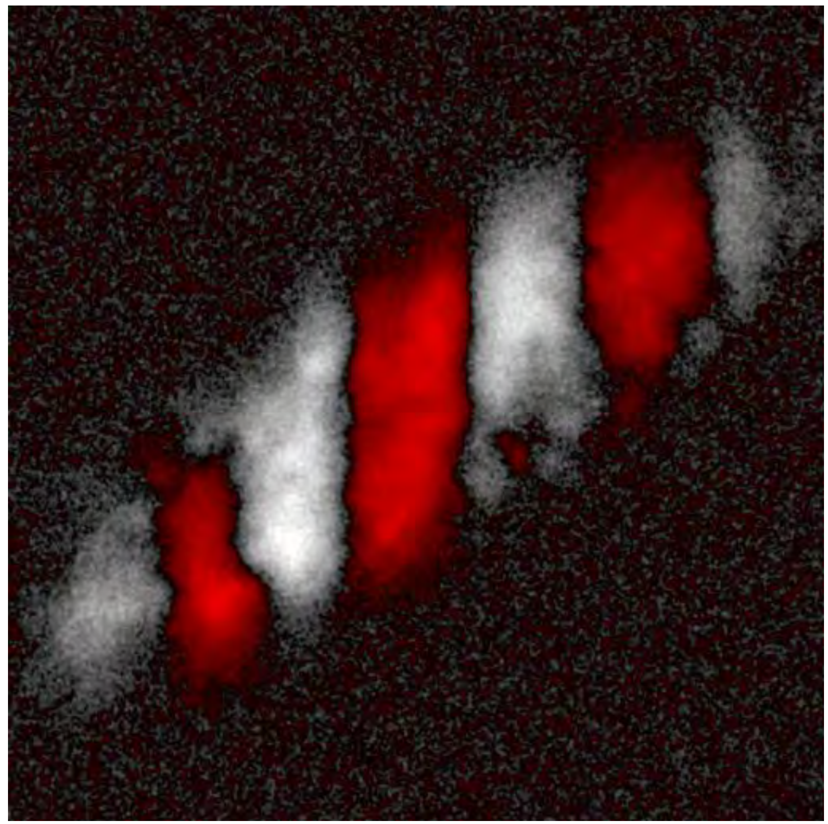
Degenerate Fermi gas inside a Bose Einstein condensate



Bose-Fermi droplet

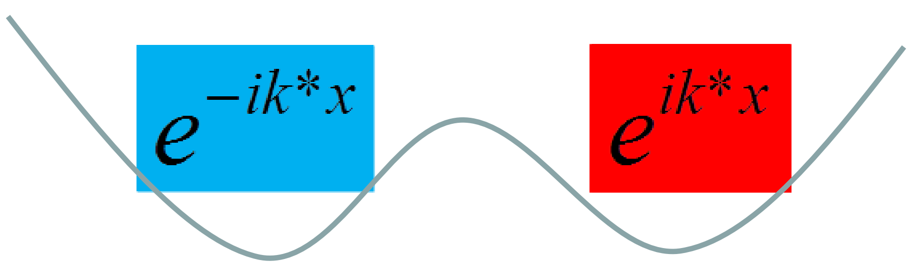


Quantum phase transition in modulated lattices

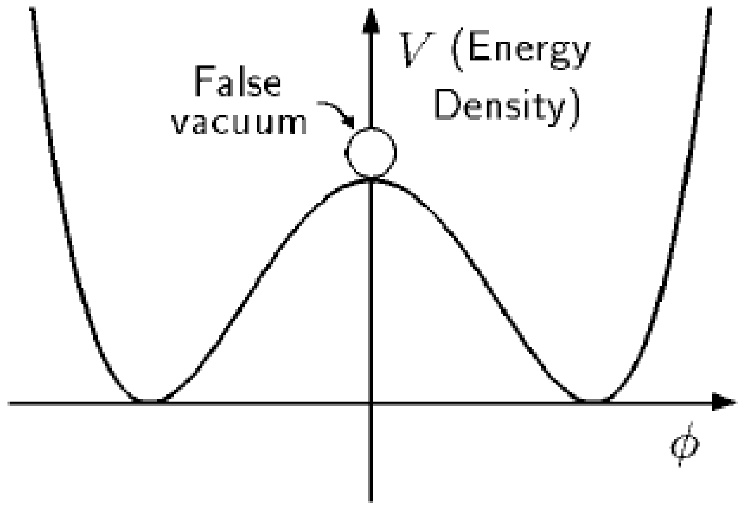


RED:
BEC with k=k*

WHITE:
BEC with k=-k*

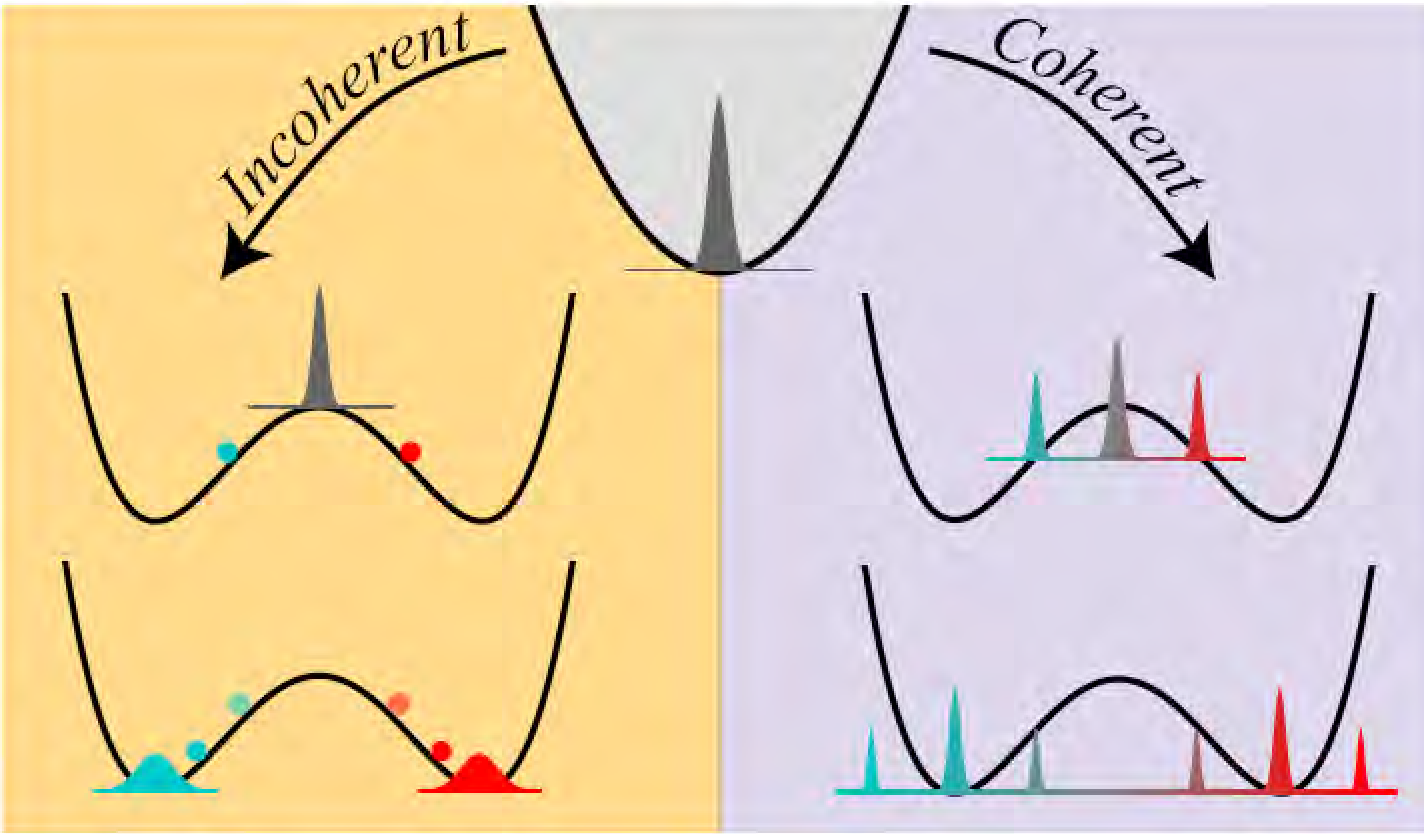


Inflation model and quantum phase transition



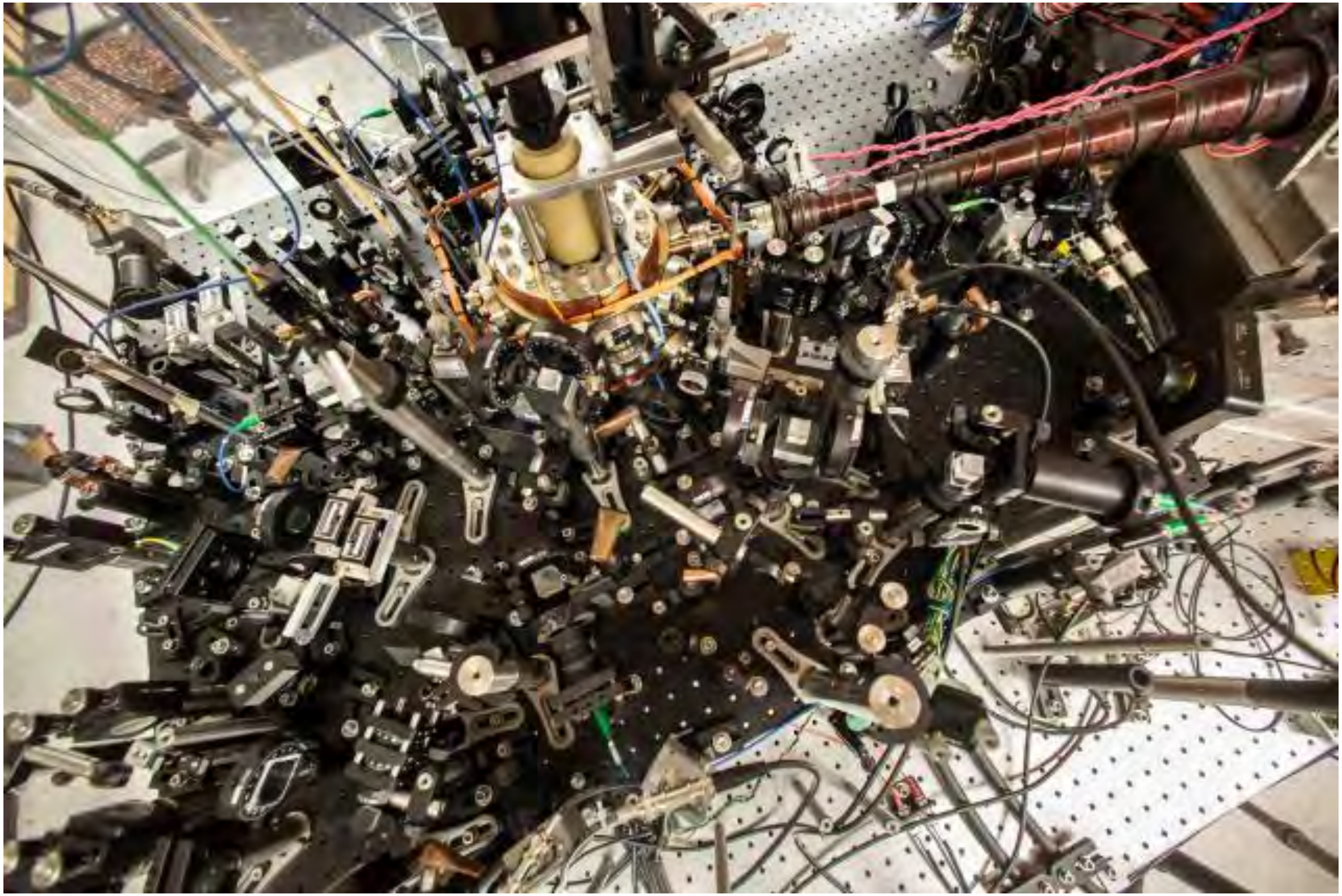
A. Guth 1981

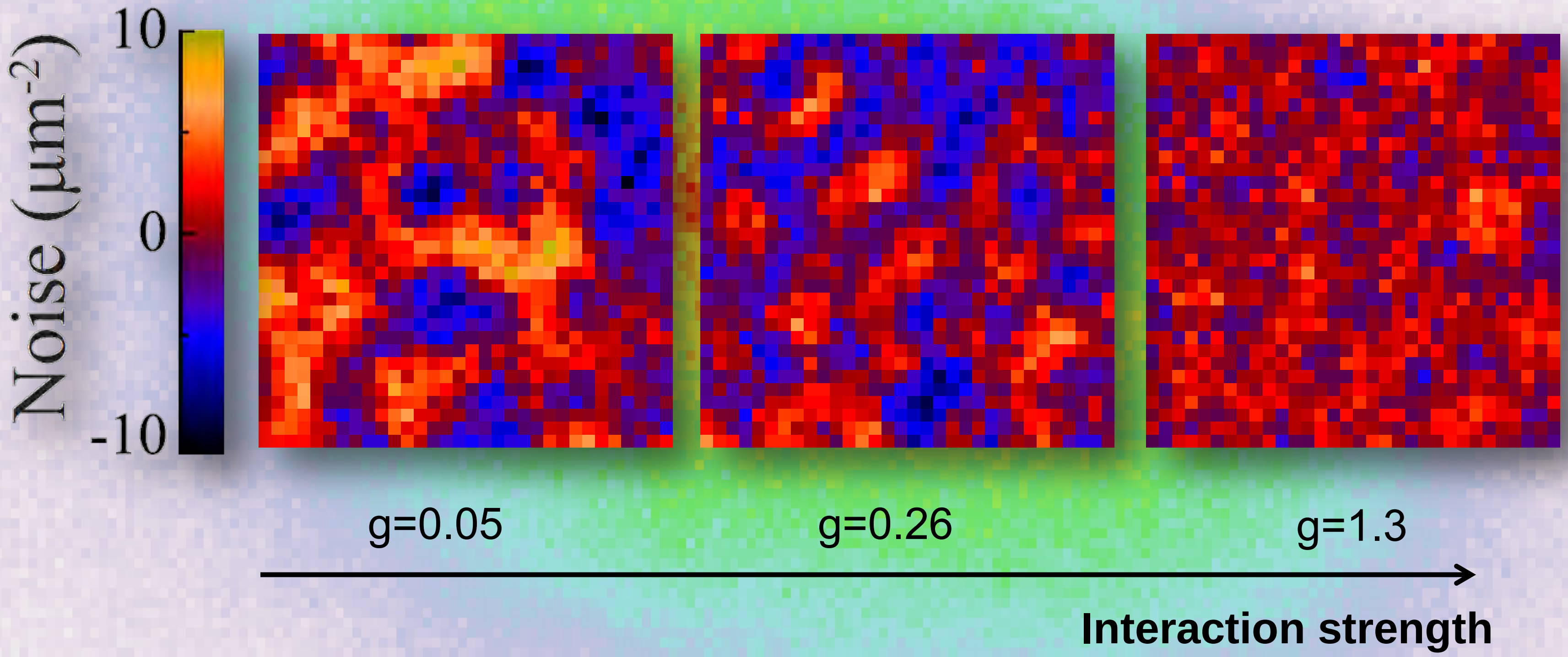
Figure from Alan H Guth, J. Phys. A: Math. Theor. 40 (2007)



T.W.B. Kibble, PHYSICSREPORTS 67, 183 (1980)
M. Morikawa, Progress of Theoretical Physics 93, 685 (1995)
Also see: *More is different*, P. Anderson, Science (1972)

Our ^{133}Cs BEC machine





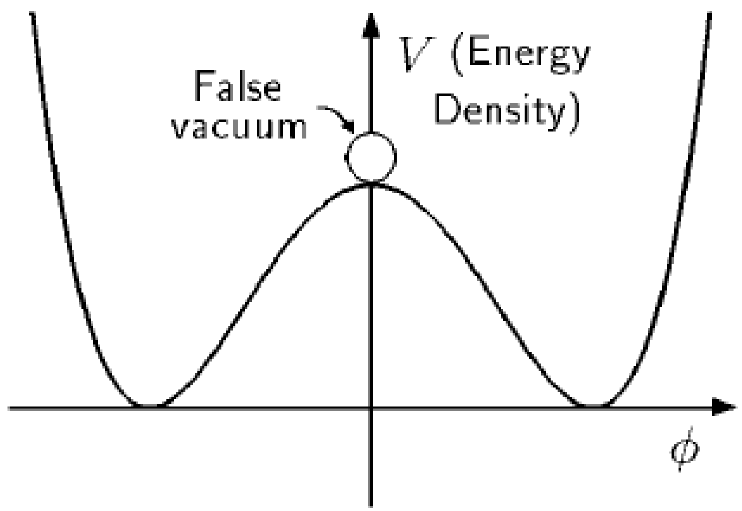
Cs superfluid: 20,000~100,000 atoms

Imaging resolution: 1.0 μm

20~100 atoms/micron^3

Nature 2009, Nature 2011

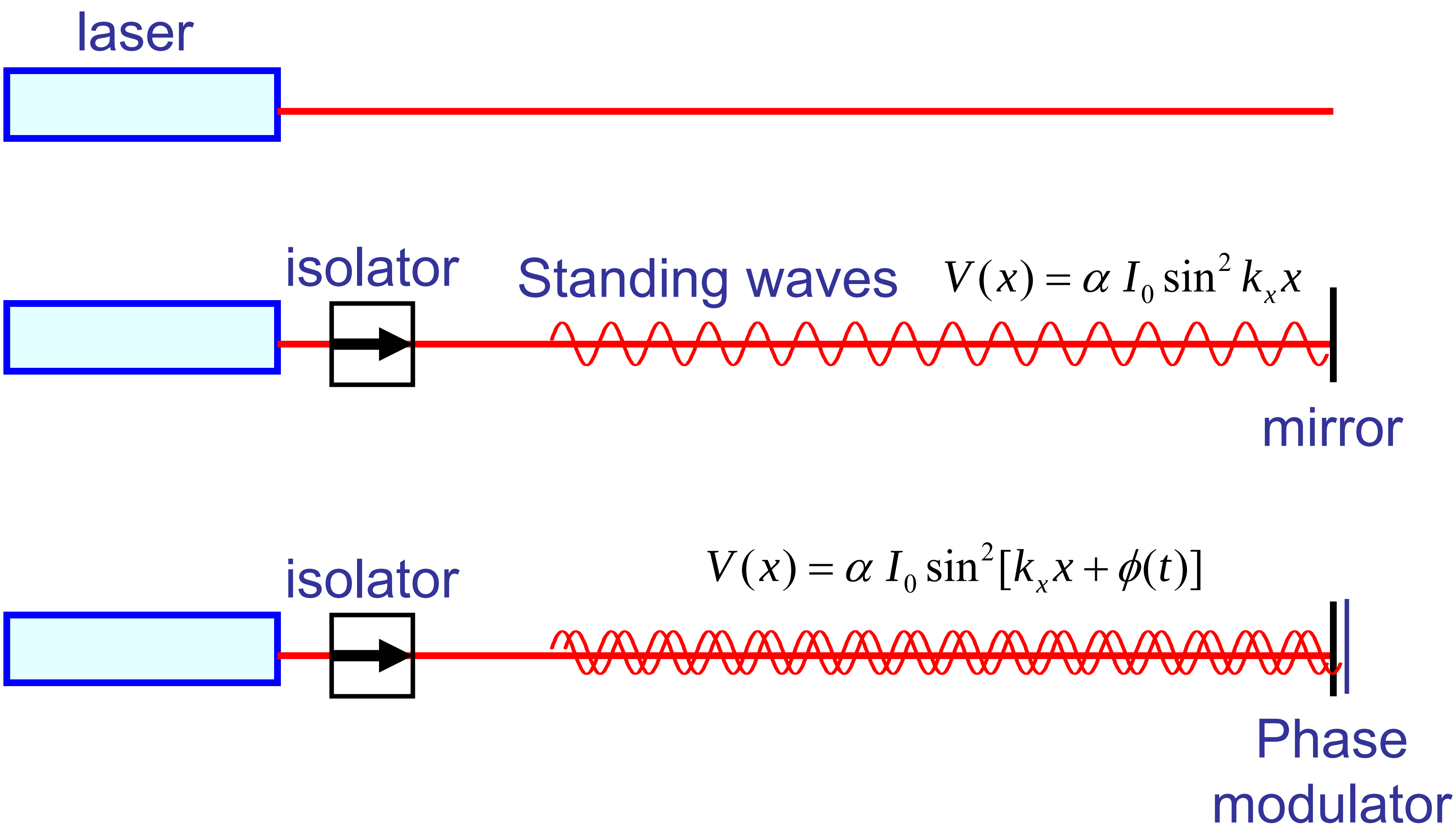
Simplest inflation model



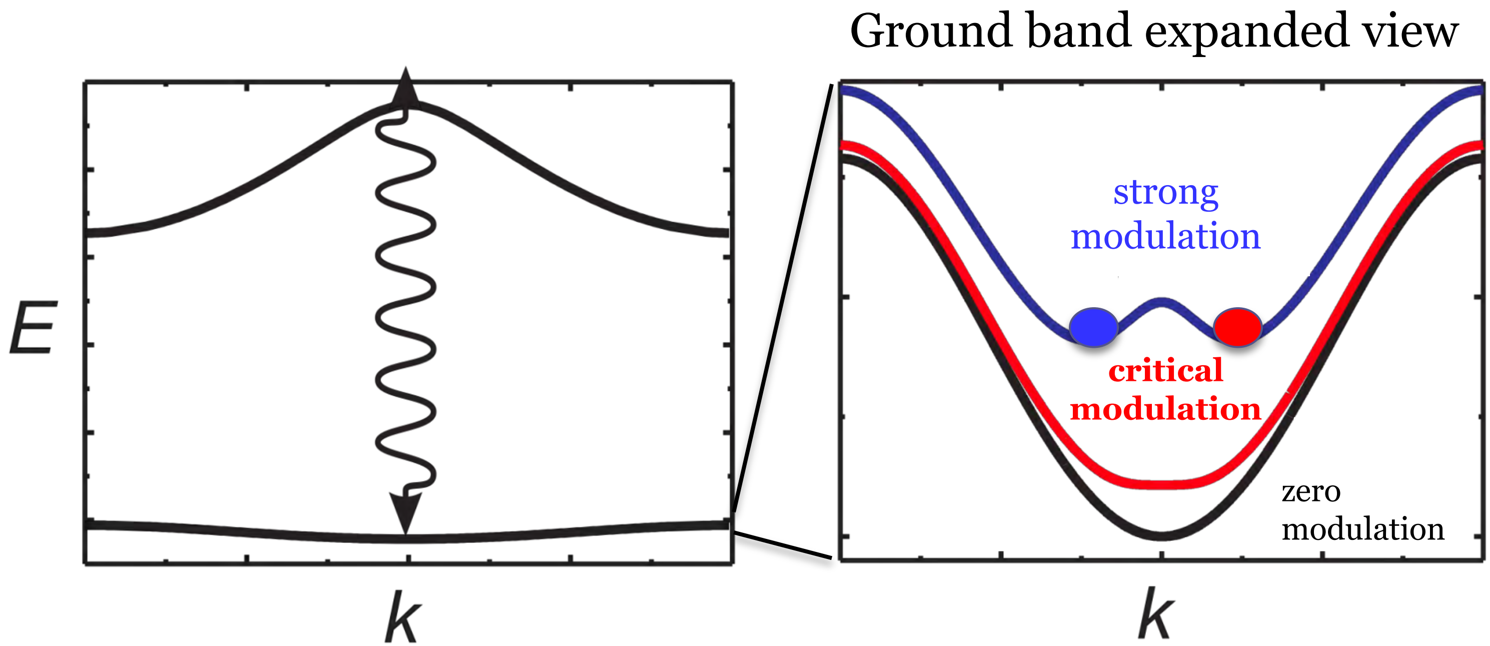
A. Guth 1981

Figure from Alan H Guth, J. Phys. A: Math. Theor. 40 (2007)

Optical lattice phase modulation



Hybridization of Bloch bands



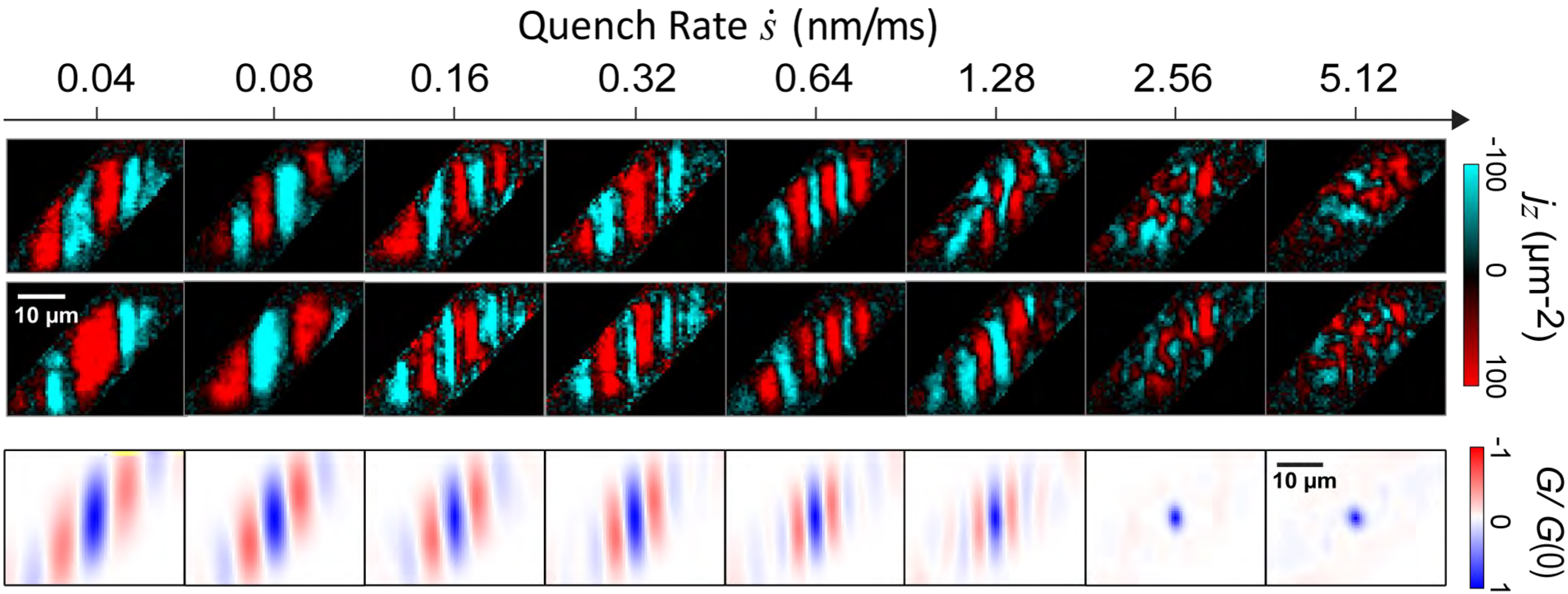
$$H = \begin{pmatrix} E_e(k) & 0 \\ 0 & E_g(k) \end{pmatrix} - \frac{\hbar\omega}{2}\sigma_z + \frac{\Omega}{2}\sigma_x$$

ω: modulation frequency
Ω: modulation strength

Domain Gallery

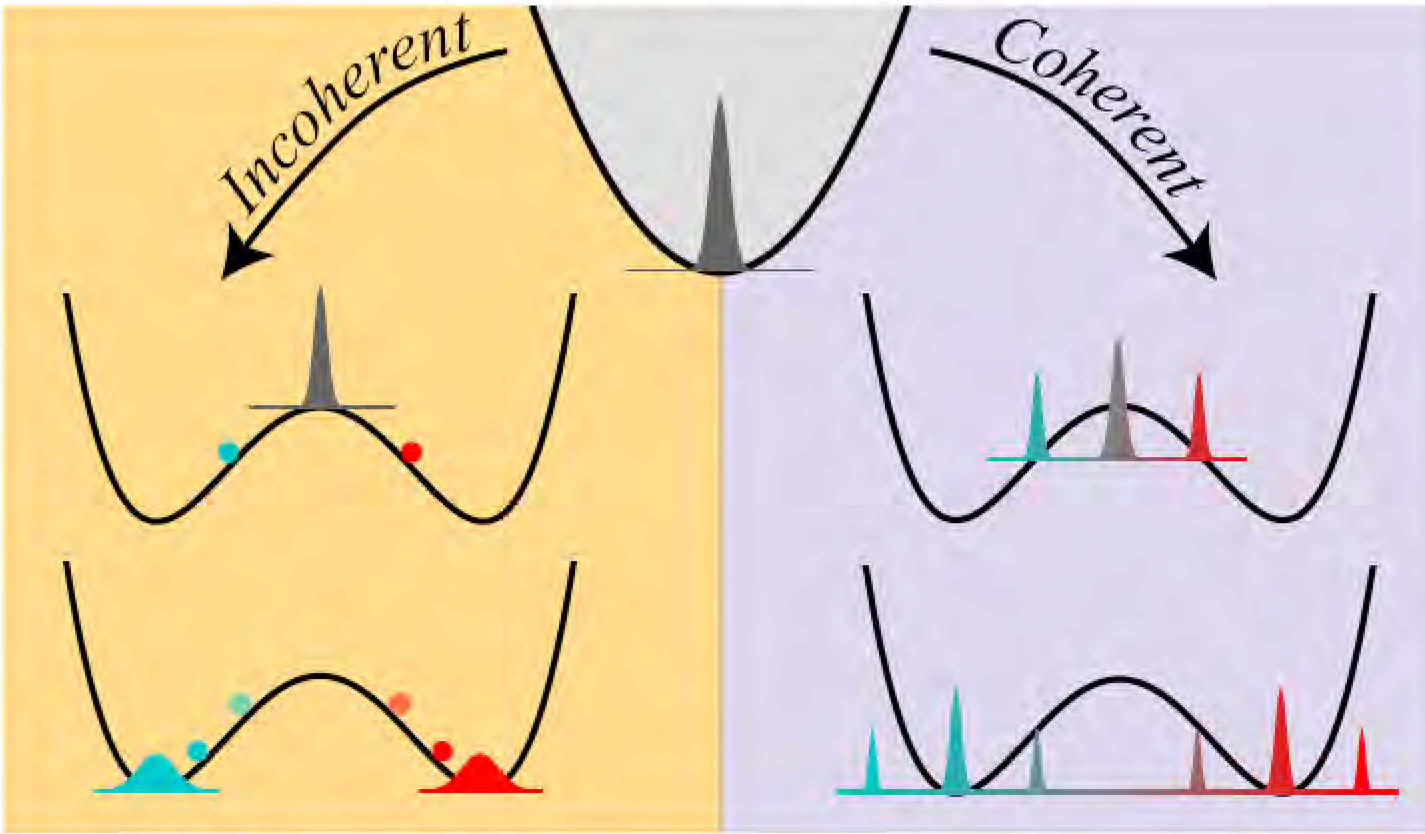
Spin Correlation Function

$$G(d\boldsymbol{r}) = \langle j_z(\boldsymbol{r}) j_z(\boldsymbol{r} + d\boldsymbol{r}) \rangle$$



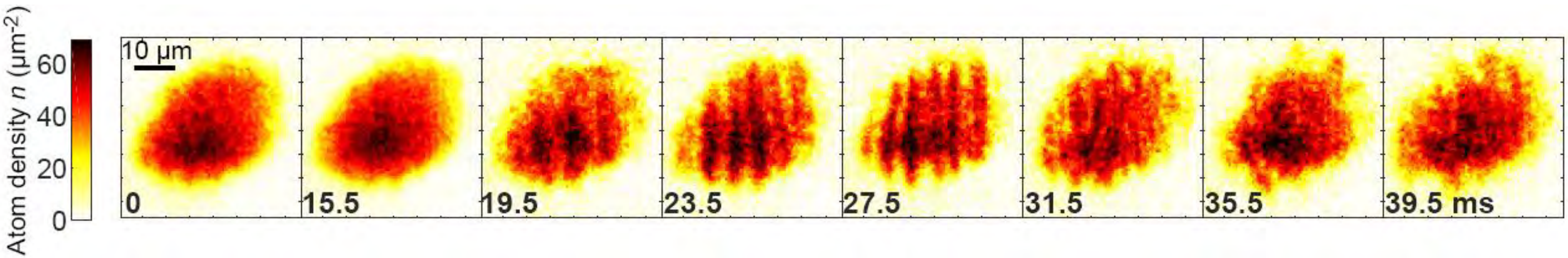
$$F(x,t;\dot{s}) = \dot{s}^{\ell} f\left(\frac{x}{x_{KZ}}, \frac{t}{t_{KZ}}\right)$$

Universal Kibble-Zureck scaling: L. Clark, L. Feng, CC, Science (2016)

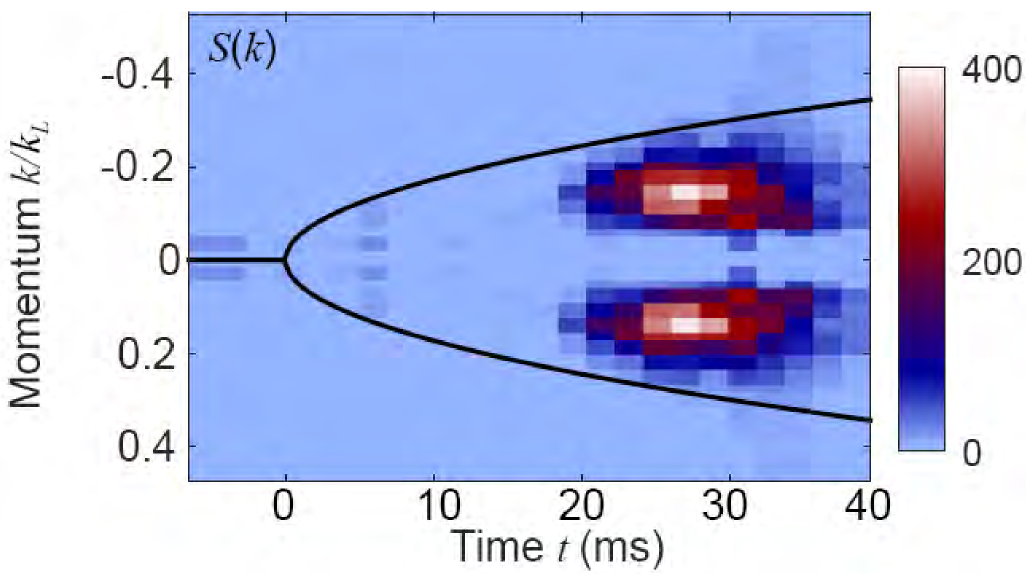


T.W.B. Kibble, PHYSICSREPORTS 67, 183 (1980)
M. Morikawa, Progress of Theoretical Physics 93, 685 (1995)
Also see: *More is different*, P. Anderson, Science (1972)

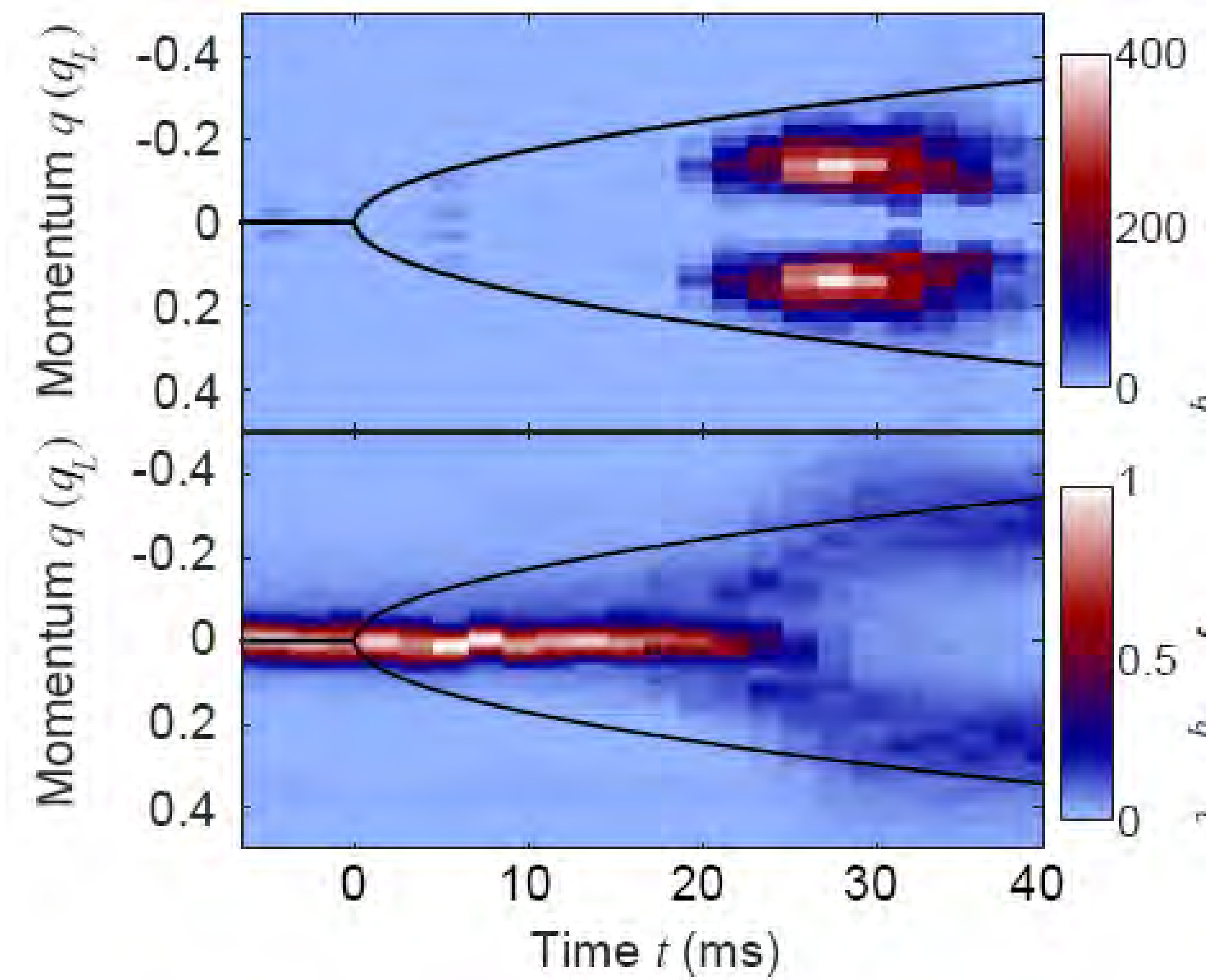
Observation of density wave order

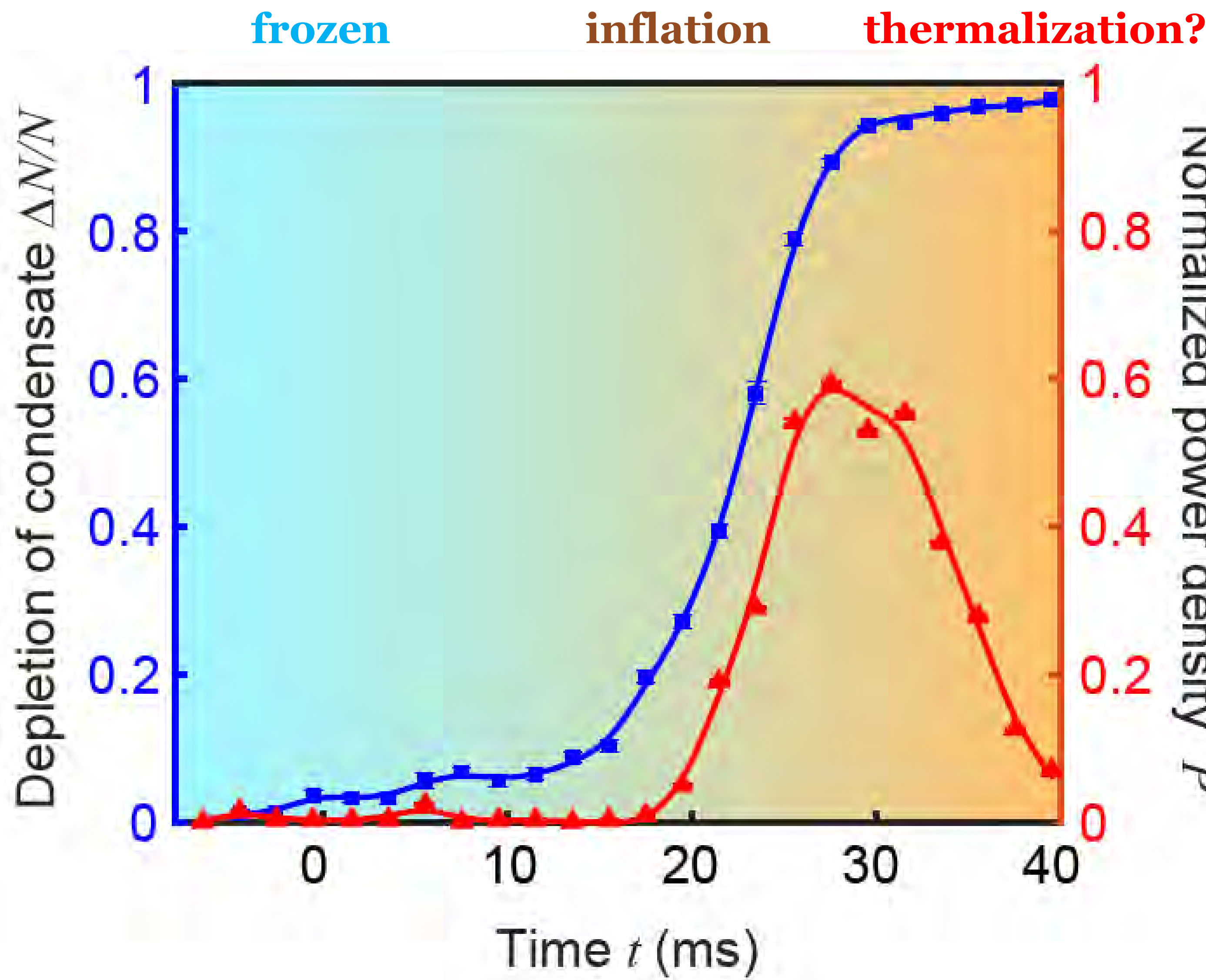


S(k)
Structure
Factor



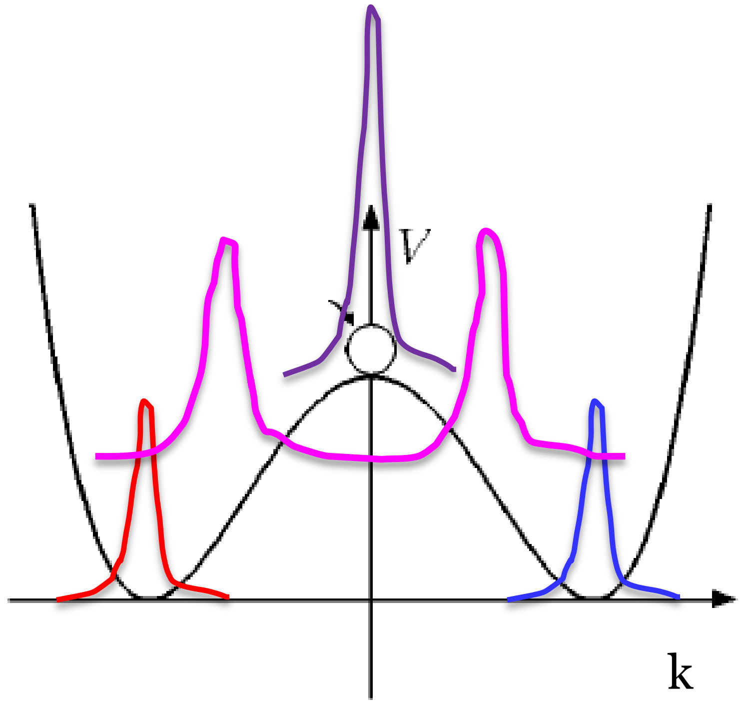
(Real space) Density wave vs. Time-of-flight





frozen
inflation
thermalization?
Depletion of condensate $\Delta N/N$
Normalized power density P
Time t (ms)
0
0.2
0.4
0.6
0.8
1
0
10
20
30
40

Inflation Hamiltonian and inflaton



$\hat{b}, \hat{b}^{+}$: boson

$\hat{\imath}_k, \hat{\imath}_k^{+}$: inflaton

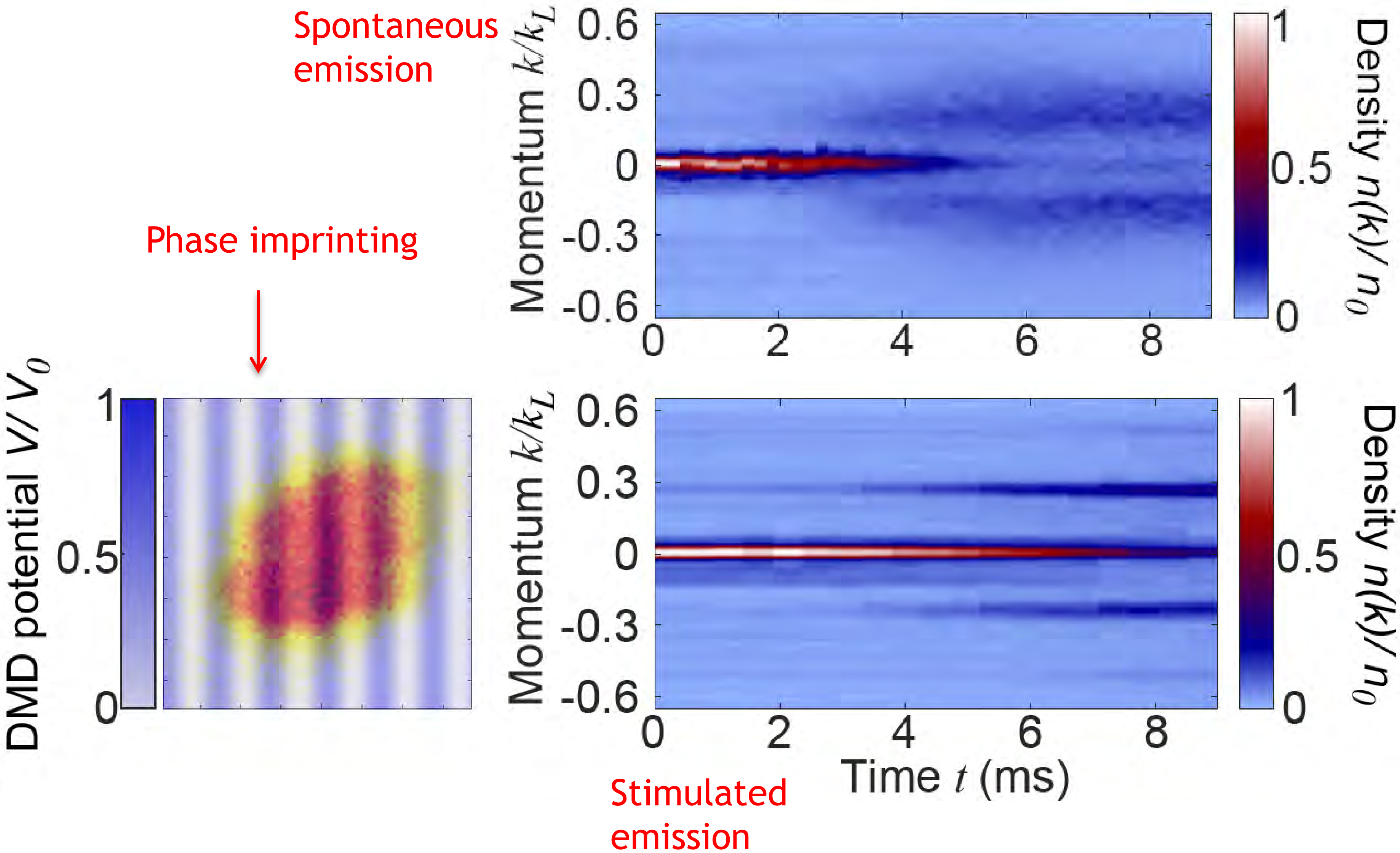
Model: $$H = H_0 + \sum_{k>0} \lambda_k (\hat{\imath}_k^{+} \hat{\imath}_{-k}^{+} + \hat{\imath}_k \hat{\imath}_{-k})$$

Solution: $n_k << n_o$

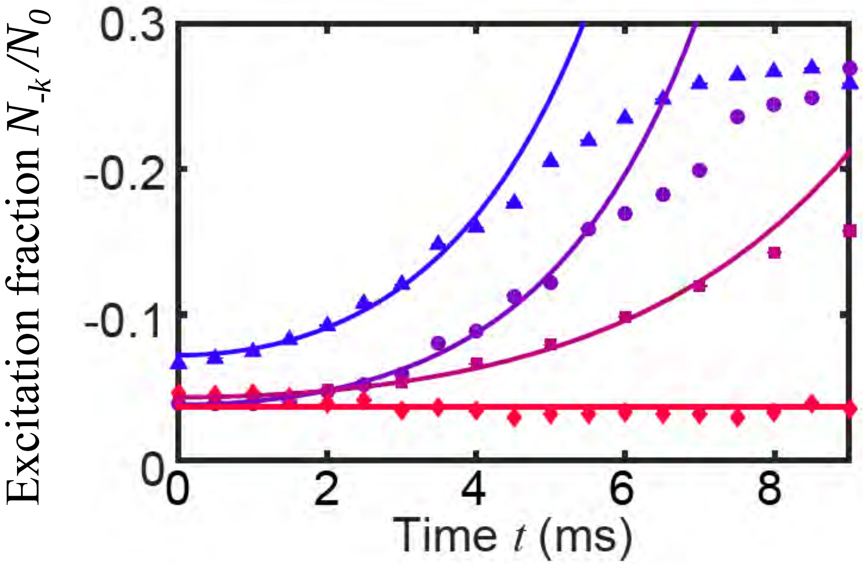
$$n_k(t) = \boxed{n_k(0)\cosh^2 \lambda_k t} + \boxed{n_{-k}(0)\sinh^2 \lambda_k t} + \sinh^2 \lambda_k t$$

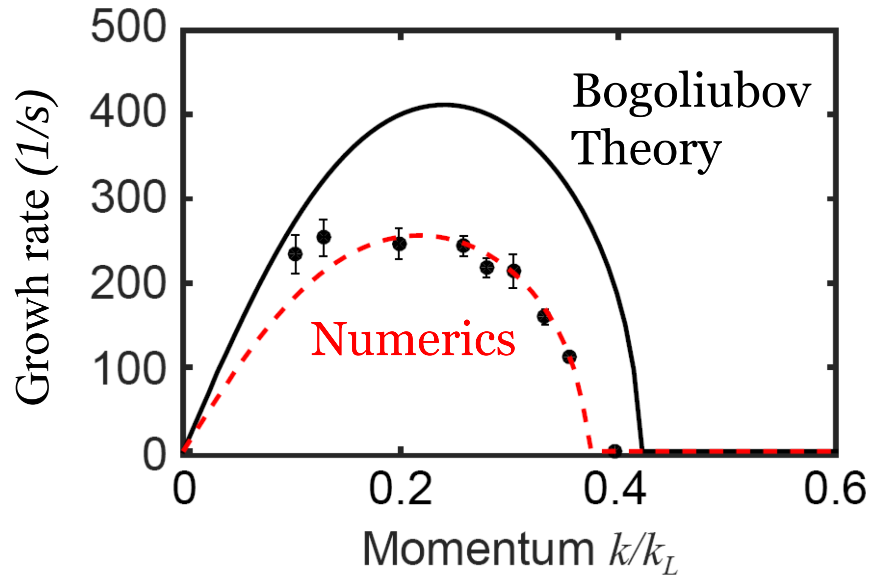
Bose stimulation — stimulated emission — spontaneous emission

Stimulated inflation by seeding quantum fluctuations



Inflaton dispersion (growth rate)

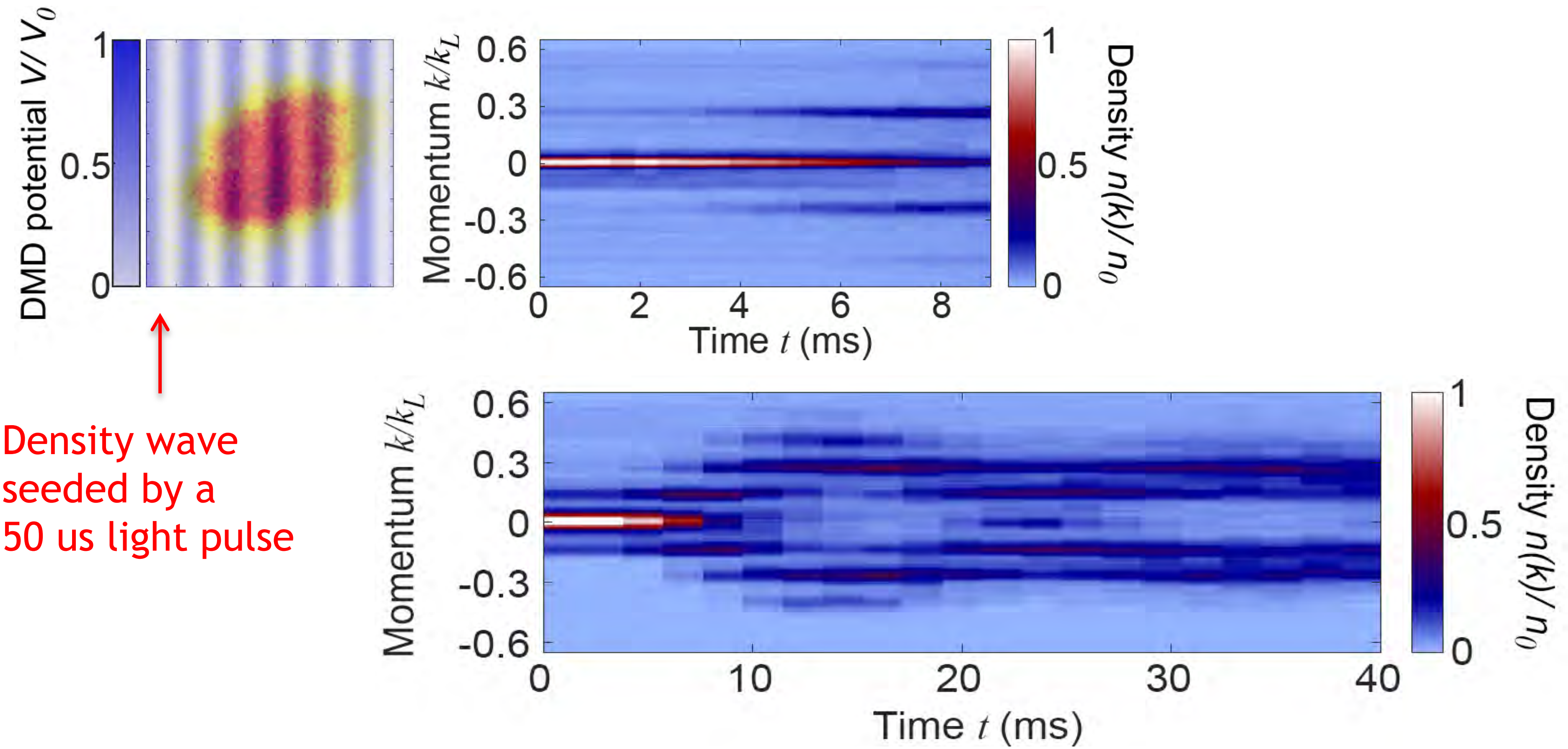




Fit function: $n=n_o \cosh 2\lambda_k t$

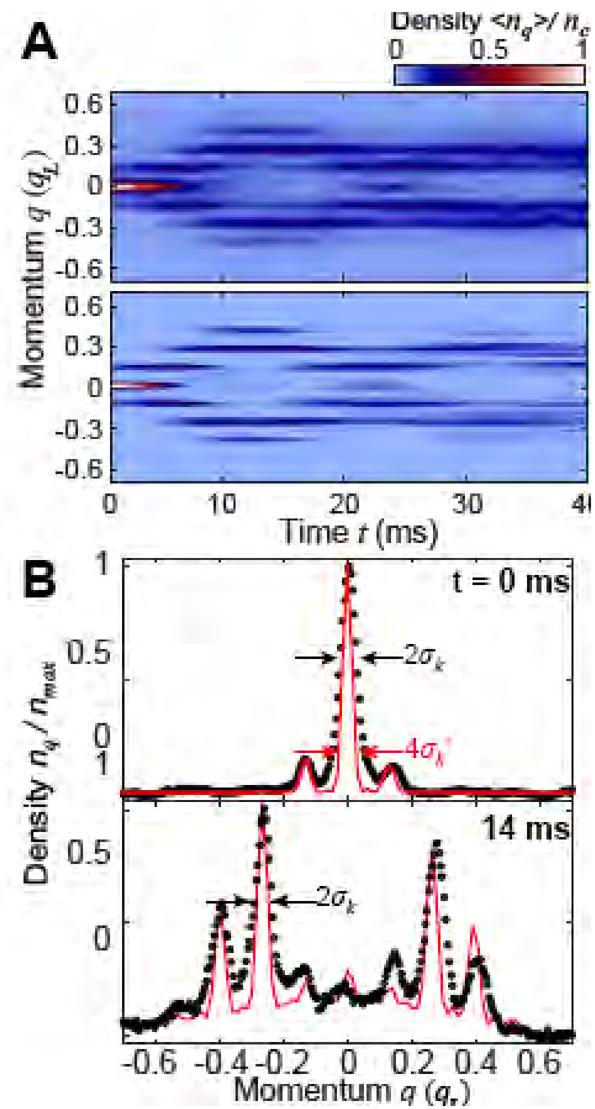
Theory: $\lambda_k = \frac{1}{\hbar}\sqrt{(\varepsilon_0-\varepsilon_k)(2\mu-\varepsilon_0+\varepsilon_k)}$

Coherent proliferation of inflatons

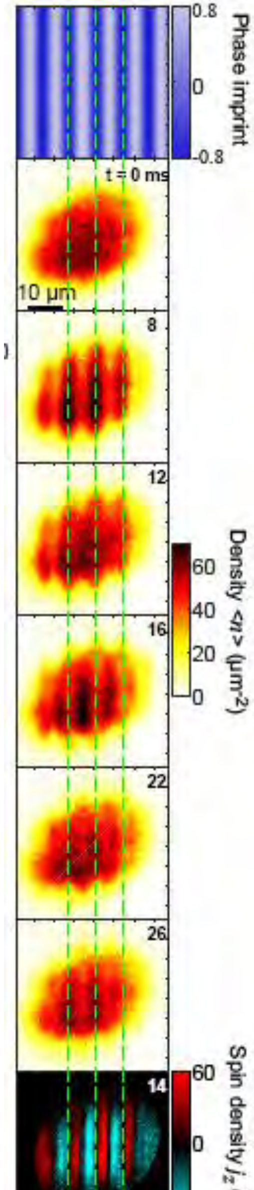


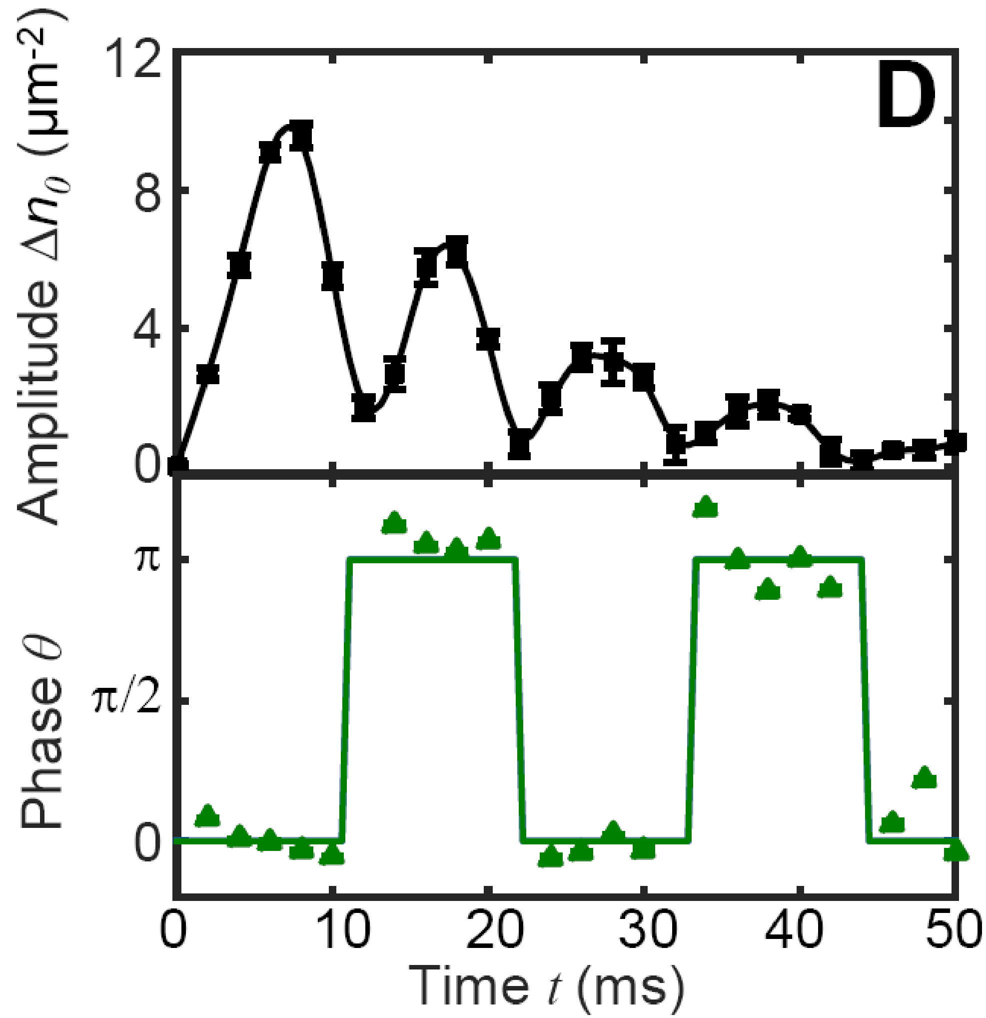
Density wave
seeded by a
50 us light pulse

Compare experiment and theory



Density wave oscillations in real space



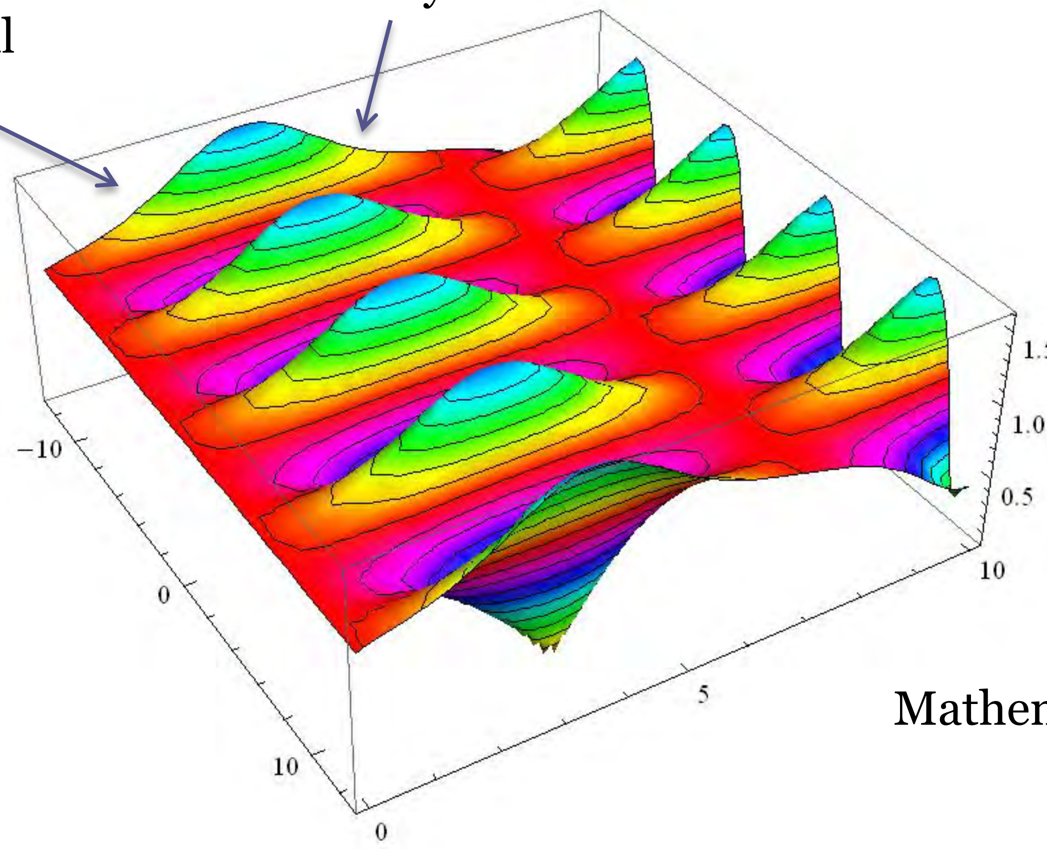


Coherent Inflation dynamics

Full model: $$H = \sum_k \varepsilon_k a_k^+ a_k + g \sum \hat{b}_{k1}^+ \hat{b}_{k2}^+ \hat{b}_{k3} \hat{b}_{k1+k2-k3}$$

Exponential decay

Exponential growth



Mathematica

Conclusion

Universal domain formation in quantum critical dynamics

- Kibble-Zurek temporal exponent 0.50(2) and
  spatial exponent 0.26(2)

Coherent dynamics of inflation and inflaton

- Exponential growth and poliferation
- inflaton energy

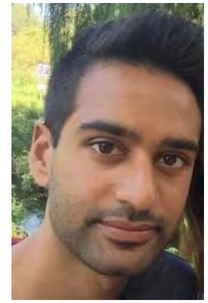
Future

- Coherent control of quantum phase transition

Current group members:

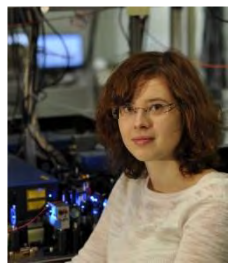
Li Cs mixture

Dr. Brian DeSalvo

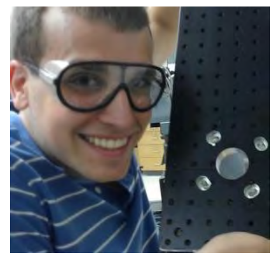


KrutikPatel

Critical Dynamics



Dr. Anita Gaj

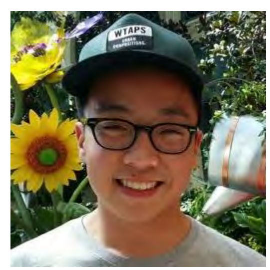


Logan Clark

Lei Feng

Quantum Matter synthesizer

Dr. Mickey McDonald



Jonathan Trisnadi

Theory collaboration

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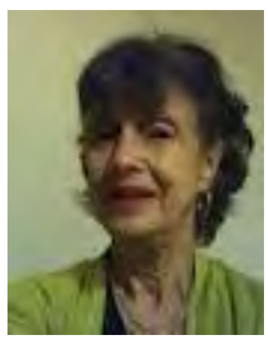
(Cornell)

Jason Ho
(Ohio State)

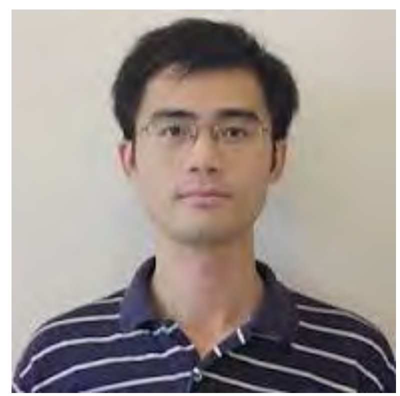
Subir Sachdev
(Harvard)

Hui Zhai
(Tsinghua Univ)

Brandon Anderson
(UChicago)



Kathryn Levin
(UChicago)



Qi Zhou
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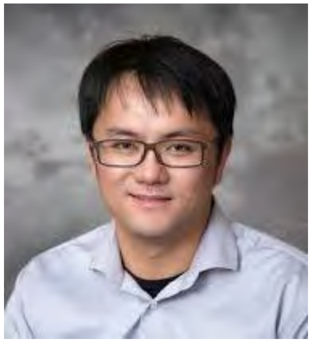
Tongtong Liu
(Peking Univ)

Former members



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Xibo Zhang
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Li-chun Ha
(PostDoc, UT-Austin)

Nate Gemelke
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Colin Parker
(Asst.Prof. GaTech)

Eric Hazlett
(Asst. Prof. Carleton)

Shih-Kuang Tung
(Assit. Prof. Tsinghua)

Kathy-Ann Solderberg
(Gov Agent, BAH)