Exploring dynamics of 1d systems using interference experiments of ultracold atoms
Analogues of CMB anisotropy

Theory:

Ehud Altman, Anatoli Polkovnikov, Vladimir Gritsev,

Adilet Imambekov, Takuya Kitagawa, Kartiek Agarwal,

Emanuele Dalla Torre

Experiment: Joerg Schmiedmayer et al.

Adilet Imambekov, 1981 - 2012

Graduate student at Harvard, 2002-2007

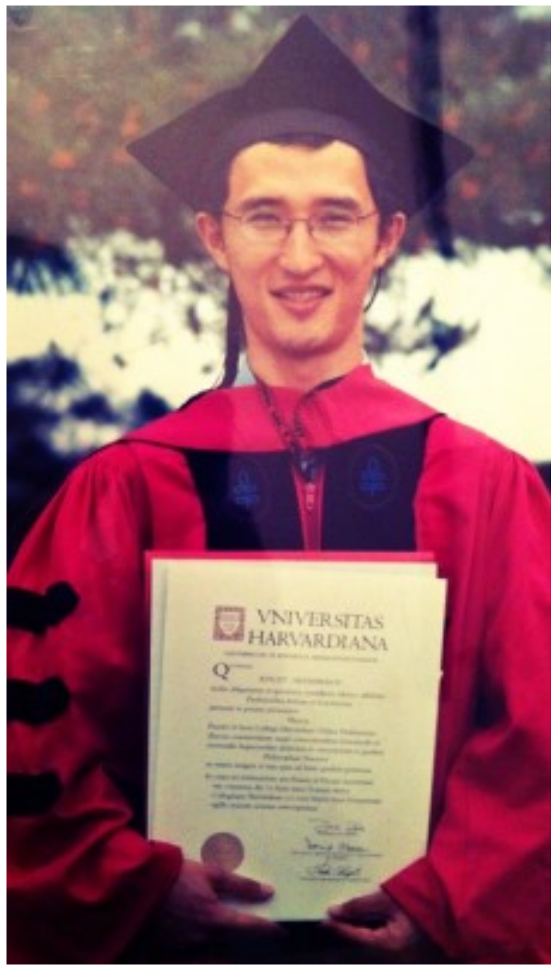

Photo courtesy of
Vladimir Gritsev

Adilet at Harvard

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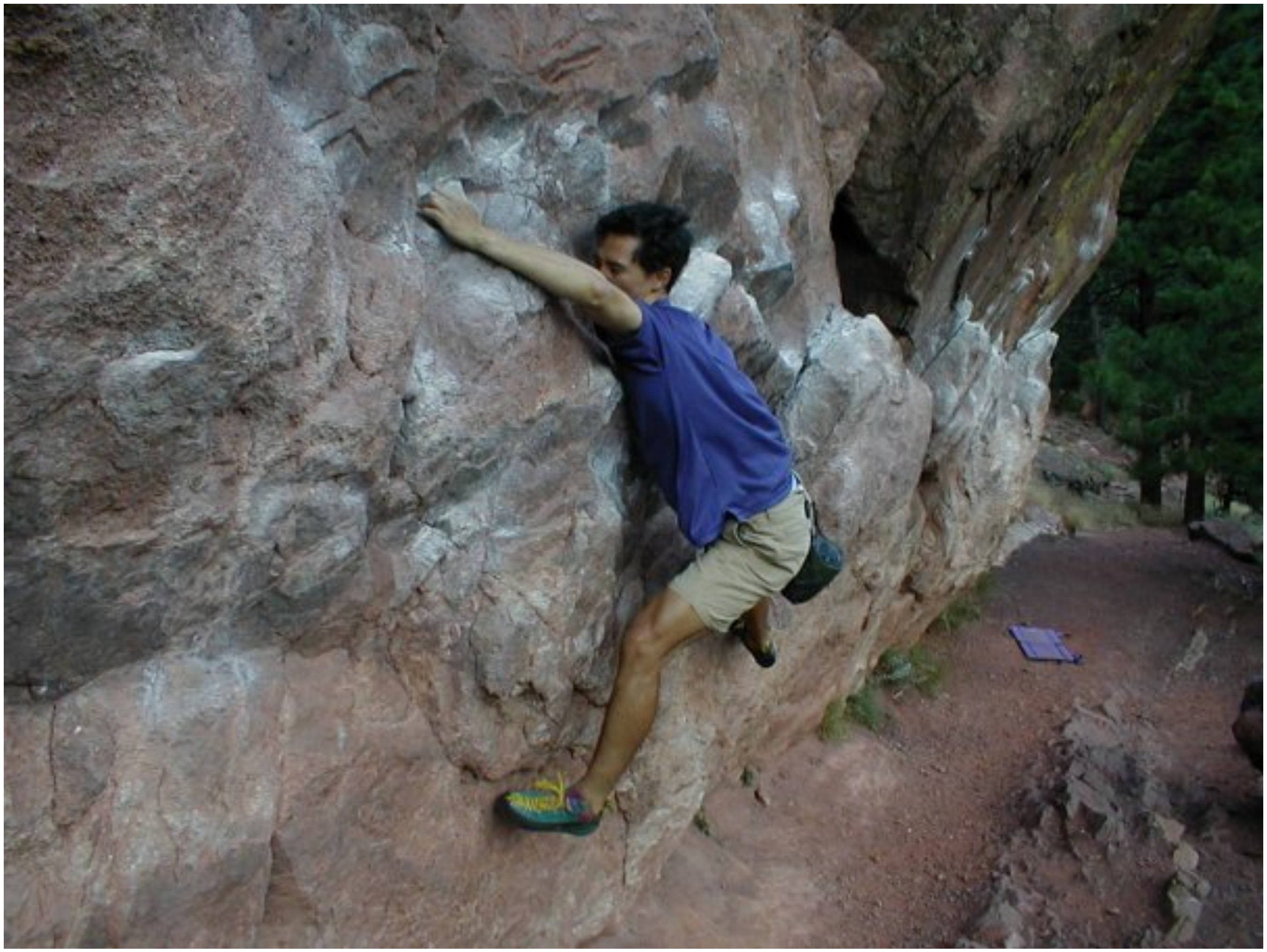

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PHYSICAL REVIEW A **68**, 063602 (2003)

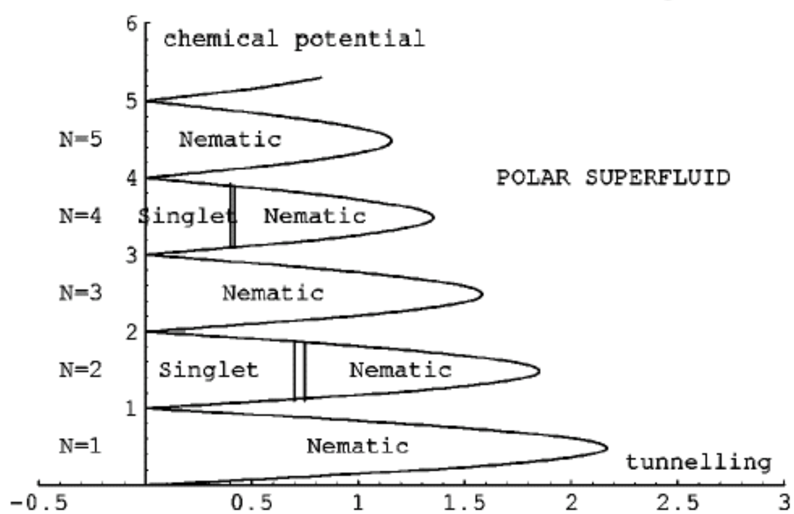
Spin-exchange interactions of spin-one bosons in optical lattices: Singlet, nematic, and dimerized phases

Adilet Imambekov, Mikhail Lukin, and Eugene Demler
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 8 June 2003; published 4 December 2003)

$$\mathcal{H} = -t \sum_{\langle ij \rangle} a^{\dagger}_{im} a_{jm} + U_0 \sum_i n_i^2 + U_2 \sum_i \vec{S}_i^2 - \mu \sum_i n_i$$

Effective S=1 spin model

$$\mathcal{H} = -J_1 \sum_{\langle ij \rangle} \vec{S}_i \vec{S}_j - J_2 \sum_{\langle ij \rangle} \left(\vec{S}_i \vec{S}_j \right)^2$$



PHYSICAL REVIEW A **73**, 021602(R) (2006)

Exactly solvable case of a one-dimensional Bose–Fermi mixture

Adilet Imambekov and Eugene Demler
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 25 May 2005; published 24 February 2006)

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Annals of Physics 321 (2006) 2390–2437

ANNALS of PHYSICS
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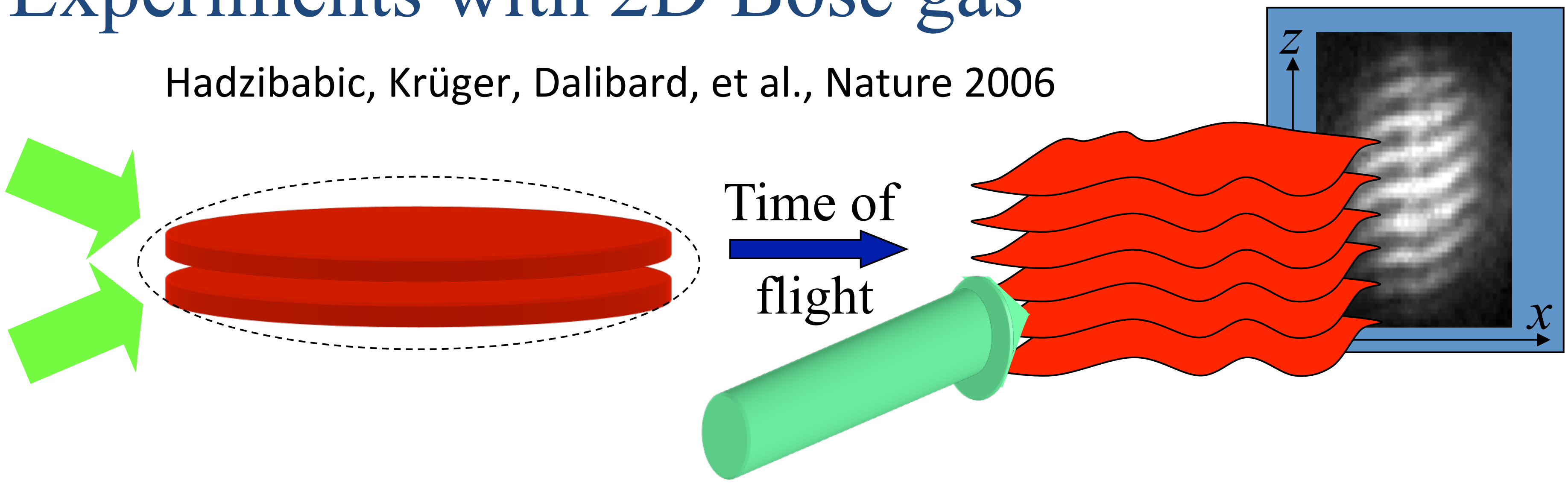
Applications of exact solution for strongly interacting one-dimensional Bose–Fermi mixture: Low-temperature correlation functions, density profiles, and collective modes

Adilet Imambekov *, Eugene Demler

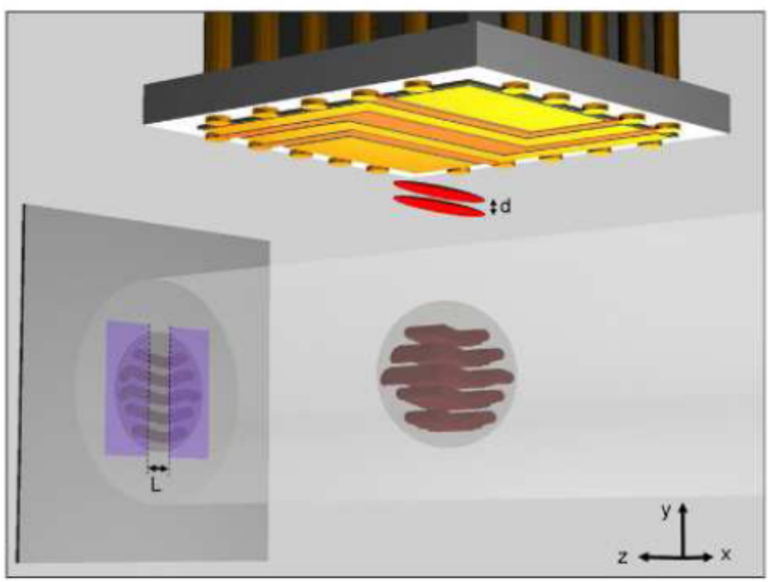
Interference of independent condensates

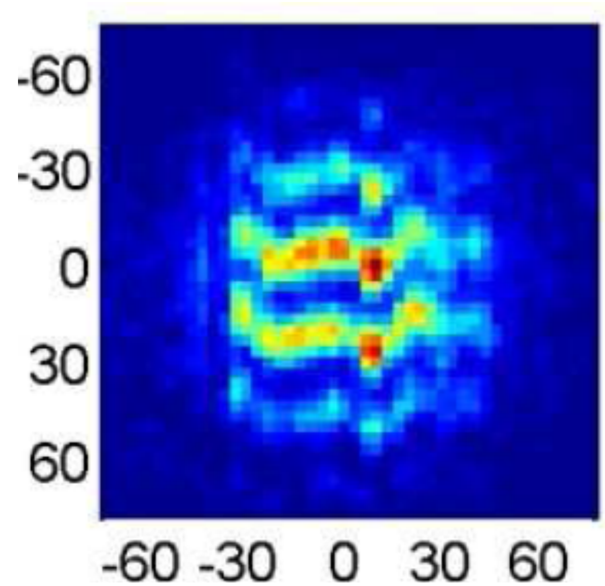
Experiments with 2D Bose gas

Hadzibabic, Krüger, Dalibard, et al., Nature 2006

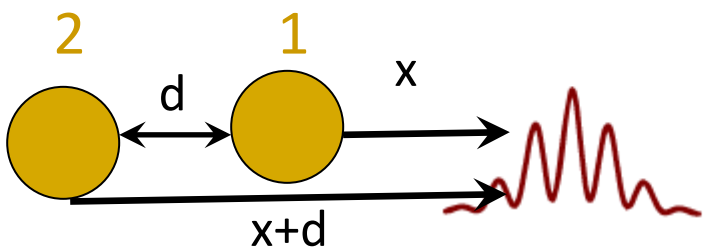


Experiments with 1D Bose gas Hofferberth et al., Nat. Physics 2008





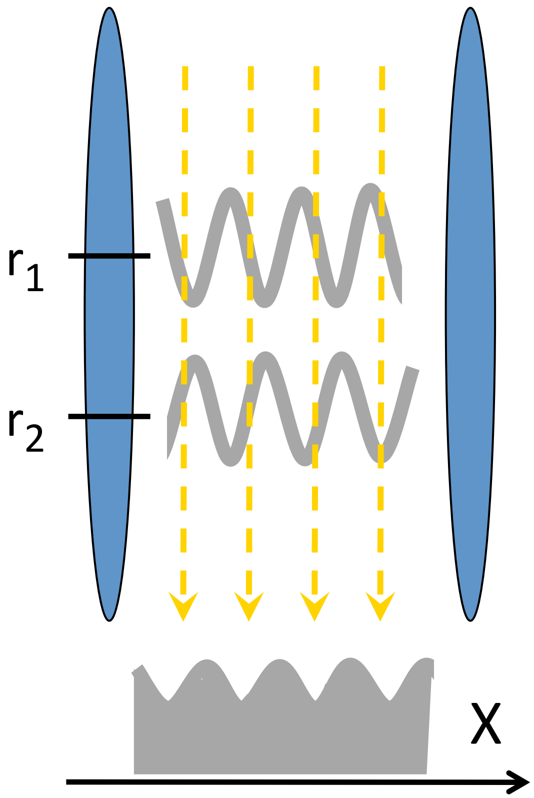
Interference experiments with condensates



A $\psi(x) = \psi_1(x) + \psi_2(x)$

$$\rho_{\text{int}}(x) = \psi_1^*(x)\psi_2(x) + \text{c.c.}$$

$$\boxed{\rho_{\text{int}}(x) = e^{i\frac{mdx}{\hbar t}}\, e^{i(\phi_2-\phi_1)} + \text{c.c.}}$$



Interference of fluctuating condensates

Polkovnikov et al. (2006)

Amplitude of interference fringes

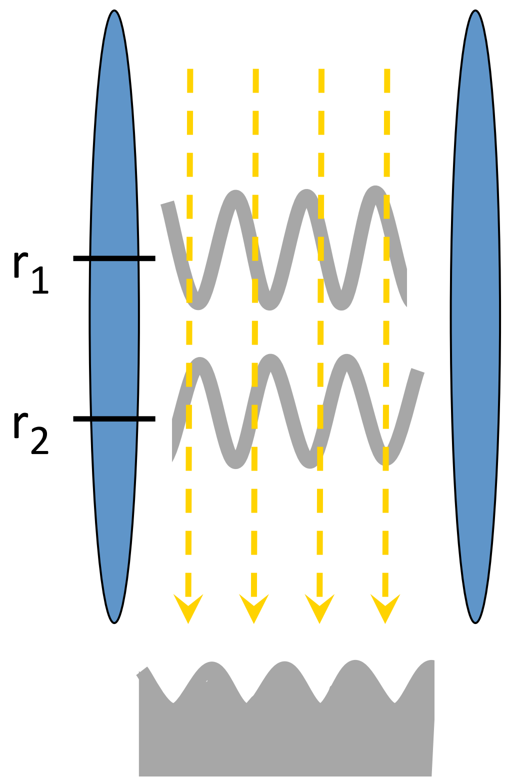
$$\mathcal{C} = \int_{-\frac{l}{2}}^{\frac{l}{2}} dr\, e^{i(\phi_1(r)-\phi_2(r))}$$

$$\mathcal{C} = |\mathcal{C}|\, e^{i\theta}$$

$$\rho_{\text{int}}(x) = |\mathcal{C}| \cos\left(\frac{mdx}{\hbar t} + \theta\right)$$

Distribution function of phase and contrast

Polkovnikov et al. (2006), Gritsev et al. (2006), Imambekov et al. (2007)



C is a quantum operator.

The measured value of C will fluctuate from shot to shot

$$\langle \mathcal{C}^n \rangle = \int_{-\frac{l}{2}}^{\frac{l}{2}} dr_1 \ldots dr_n \, \langle \, e^{i(\phi_1 - \phi_2)(r_1)} \ldots e^{i(\phi_1 - \phi_2)(r_n)} \, \rangle$$

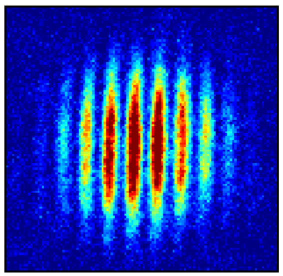
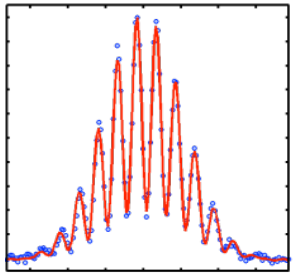
Higher moments reflect higher order correlation functions

$$\rho_{\text{int}}(x) = |\mathcal{C}| \cos\left(\frac{mdx}{\hbar t} + \theta \right)$$

Experiments analyze distribution function of C

FDF of phase and contrast

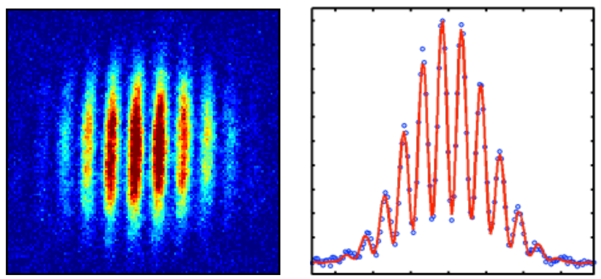
- Matter-wave interferometry

→ phase, contrast

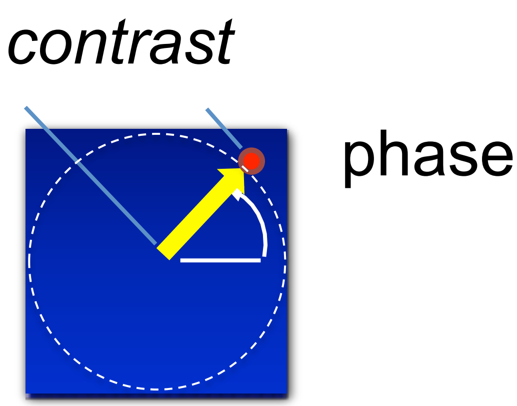
FDF of phase and contrast

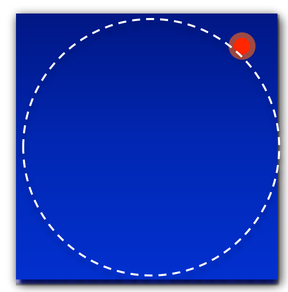
- Matter-wave interferometry



phase, contrast

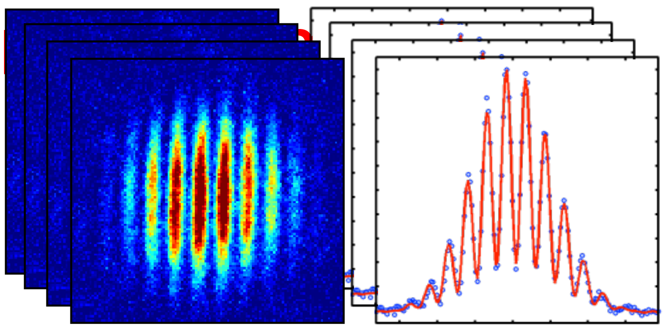
- Plot as circular statistics

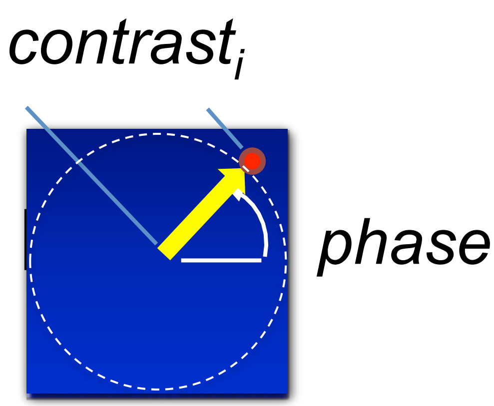




FDF of phase and contrast

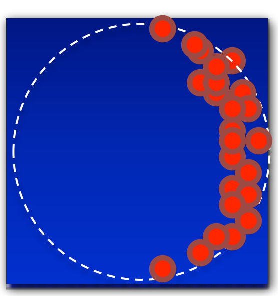
- Matter-wave interferometry: repeat





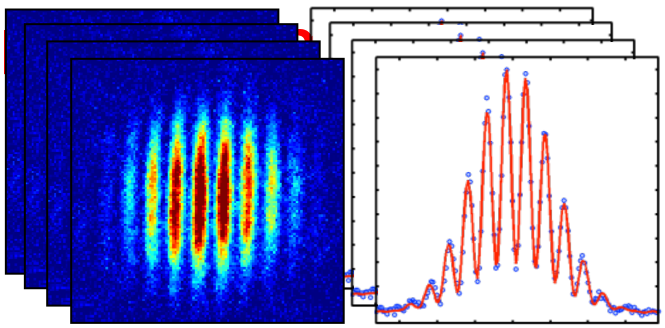
-

accumulate statistics



FDF of phase and contrast

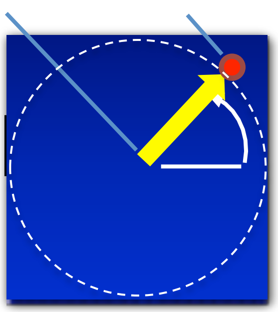
- Matter-wave interferometry: repeat



phase, contrast

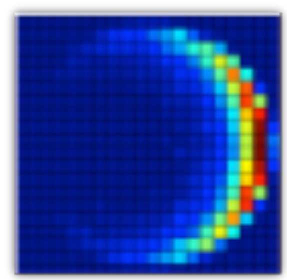
$i>100$

contrast$_i$

- 

phase$_i$

accumulate statistics

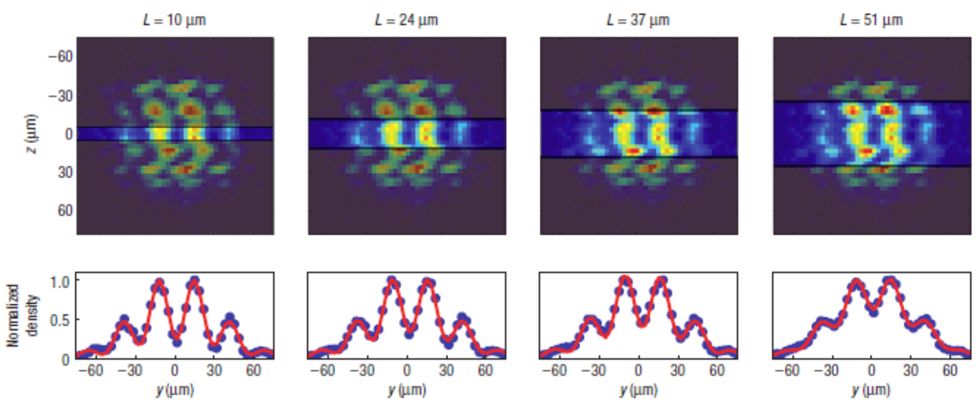


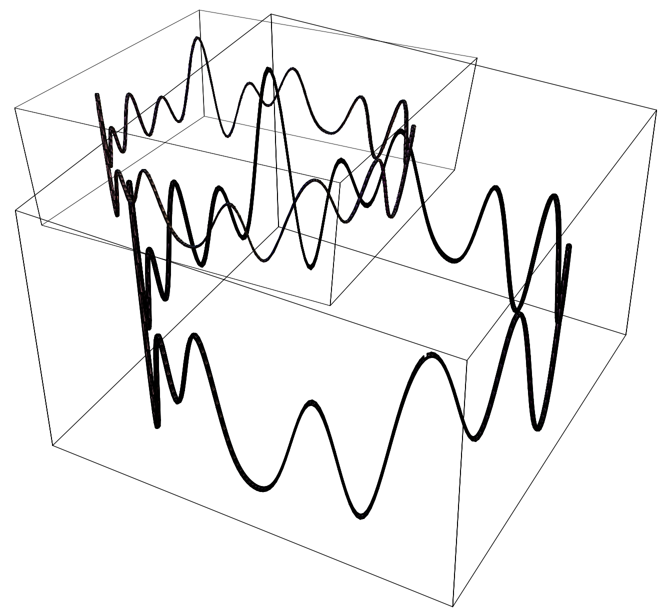
This is the full distribution function of phase & contrast

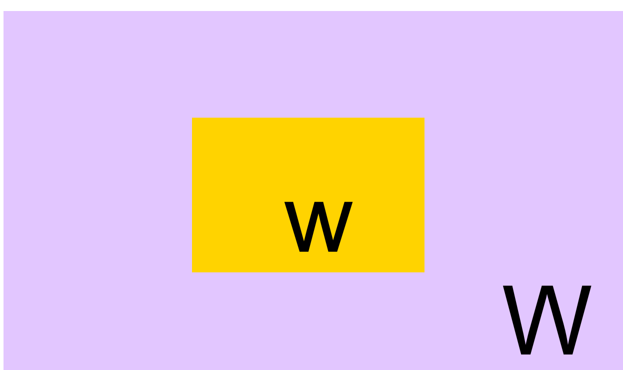
PHYSICAL REVIEW A **77**, 063606 (2008)

Mapping of Coulomb gases and sine-Gordon models to statistics of random surfaces

Adilet Imambekov,[1,2] Vladimir Gritsev,[1] and Eugene Demler[1]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics, Yale University, New Haven, Connecticut 06520, USA*





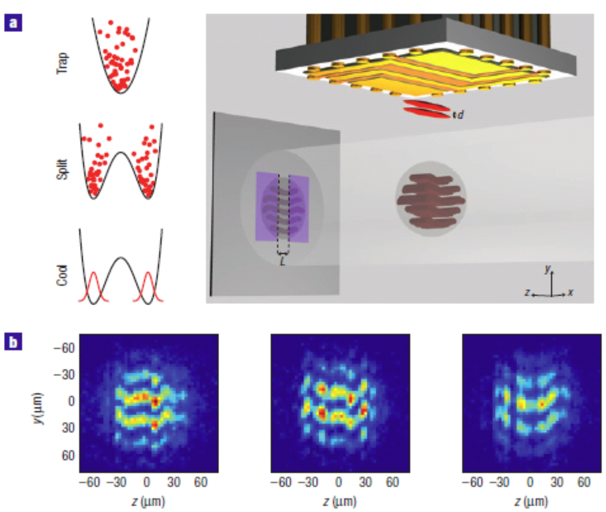


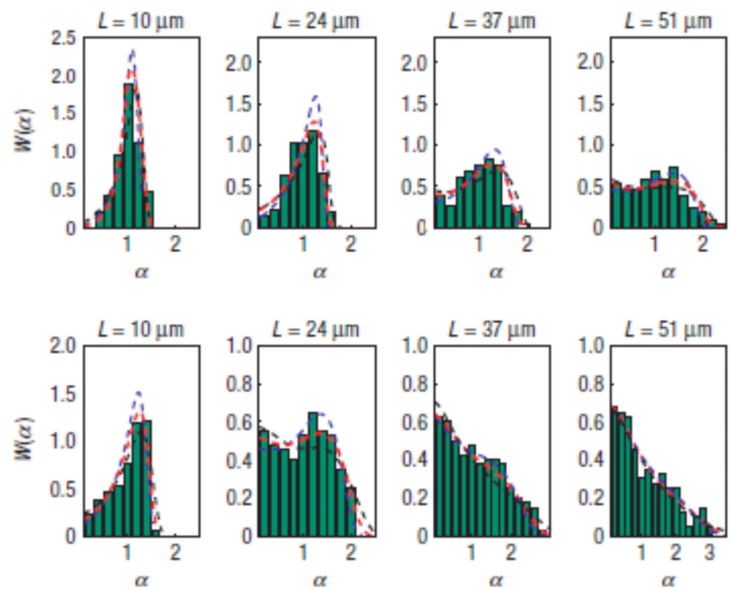
$$\boxed{S = \frac{K}{2}\int_{\Omega} d^2x\,(\nabla\phi)^2 + g\int_{\omega} d^2x\cos\phi}$$

Probing quantum and thermal noise in an interacting many-body system

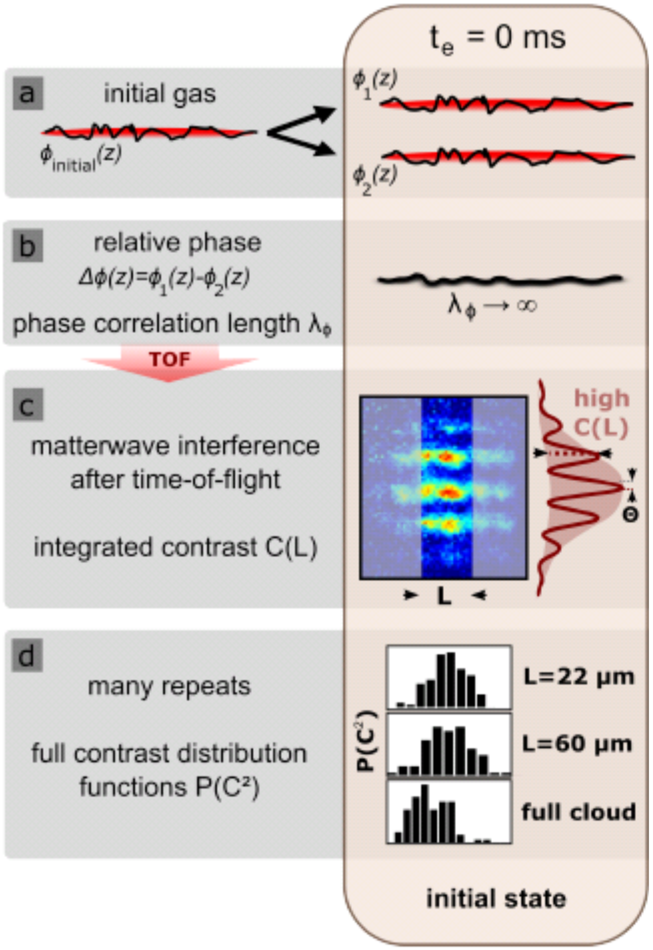
S. HOFFERBERTH[1,2,3], I. LESANOVSKY[2,4], T. SCHUMM[1], A. IMAMBEKOV[3,5], V. GRITSEV[3], E. DEMLER[3] AND J. SCHMIEDMAYER[1,2]*

Nature Physics (2008)





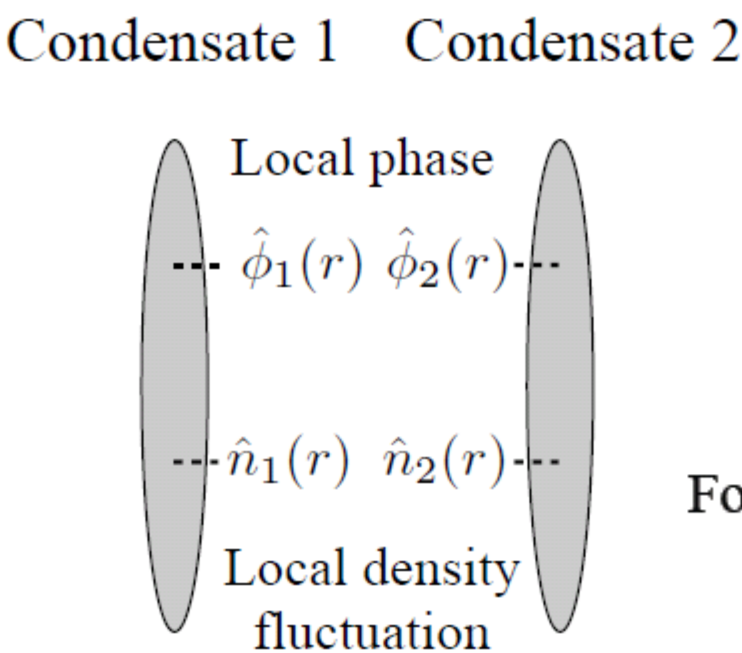
Measurements of dynamics of split condensate



Theoretical analysis of dephasing

Luttinger liquid model

Luttinger liquid model of phase dynamics



$$\hat{\phi}_s(r) = \hat{\phi}_1(r) - \hat{\phi}_2(r)$$

$$2\hat{n}_s(r) = \hat{n}_1(r) - \hat{n}_2(r)$$

$$[\hat{n}_s(r), \hat{\phi}_s(r')] = -i\delta(r - r')$$

For identical average densities, phase difference modes decouple from the phase sum mode

$$H_s = \frac{c_s}{2} \int \left[\frac{K_s}{\pi} (\nabla \hat{\phi}_s(r))^2 + \frac{\pi}{K_s} \hat{n}_s^2(r) \right] dr$$

Luttinger liquid model of phase dynamics

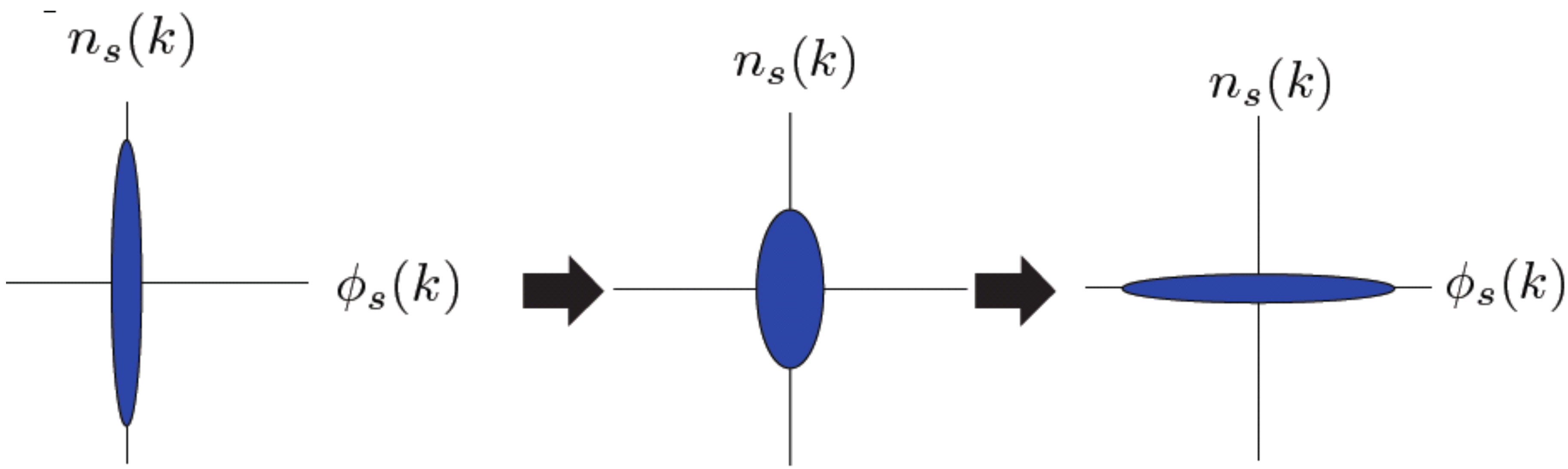
$$H_s = \frac{c_s}{2}\int \left[\frac{K_s}{\pi}(\nabla\hat{\phi}_s(r))^2 + \frac{\pi}{K_s}\hat{n}_s^2(r)\right] dr$$

$$= \frac{c_s}{2}\sum_k \left[\frac{K_s k^2}{\pi}\hat{\phi}_s^\dagger(k)\hat{\phi}_s(k) + \frac{\pi}{K_s}\hat{n}_s^\dagger(k)\hat{n}_s(k)\right]$$

For each k-mode we have simple harmonic oscillators

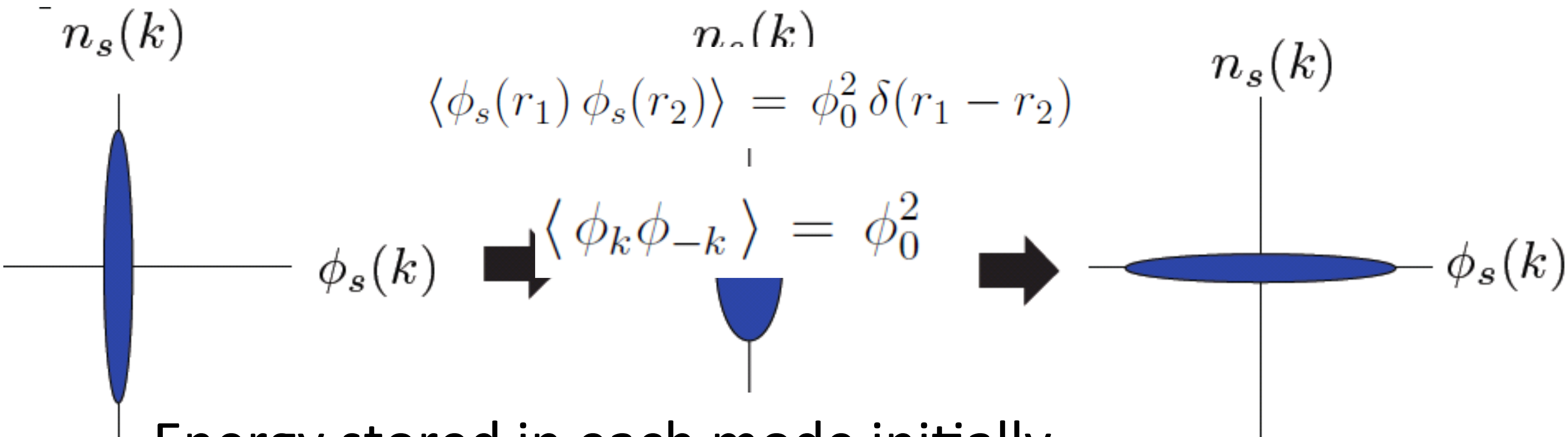
Fast splitting prepares states with
small fluctuations of relative phase

Time evolution



Energy distribution

Initially the system is in a squeezed state with large number fluctuations



$$\langle \phi_s(r_1)\, \phi_s(r_2) \rangle = \phi_0^2\, \delta(r_1 - r_2)$$

$$\langle\, \phi_k \phi_{-k} \,\rangle = \phi_0^2$$

Energy stored in each mode initially

$$E_k = g\, n_s^2(k, t = 0) = \frac{g}{\phi_0^2}$$

Equipartition of energy

For 2d quasi-conendsates pointed out by Mathey, Polkovnikov (2010)

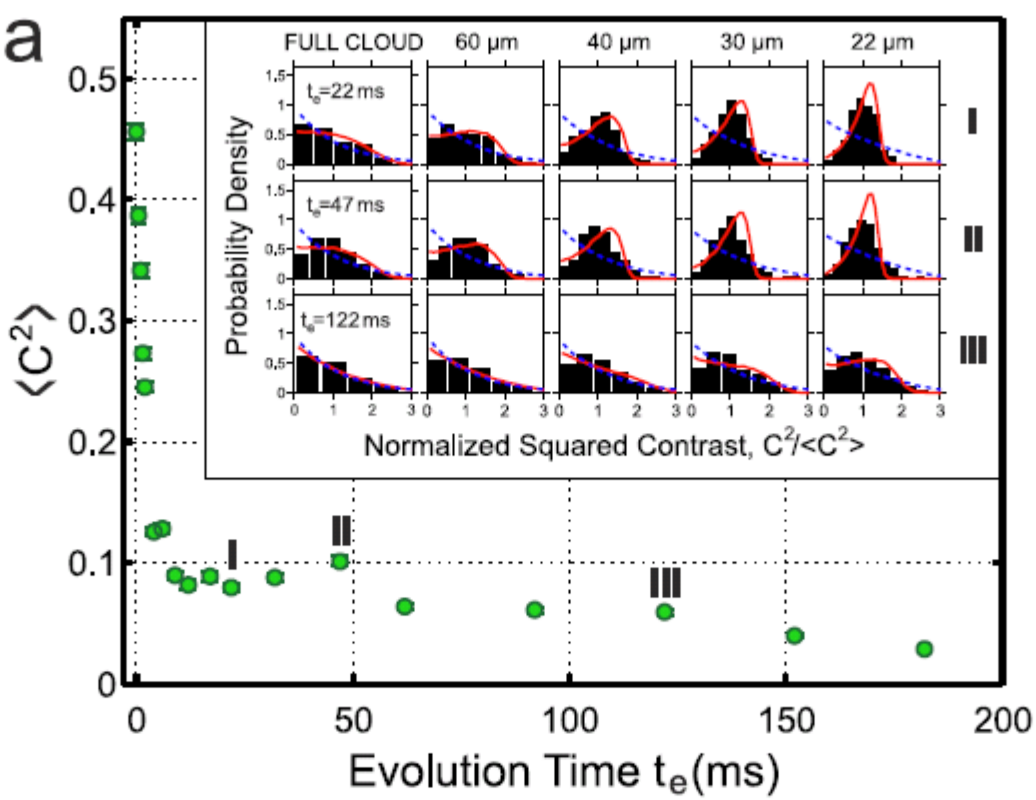
The system should look thermal like after different modes dephase.
Effective temperature is not related to the physical temperature

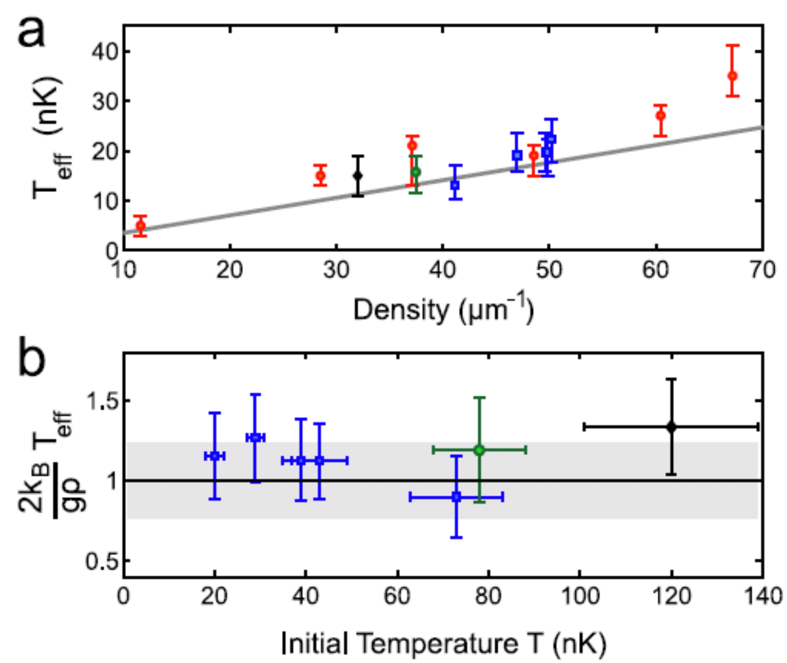
Analogous to thermalization of Calabrese and Cardy in CFT, PRL (2006)

Prethermalization

Theory: T. Kitagawa, A. Imambekov, et al., PRL(2010), NJP (2011)
Expt: M. Gring et al., Science 2012

$$k_B T_{\mathrm{eff}} = g\rho/2$$





Exploring Lorenz transformations of temperature in split atomic condensates

K. Agarwl, E. Dalla Torre, EAD, in preparation

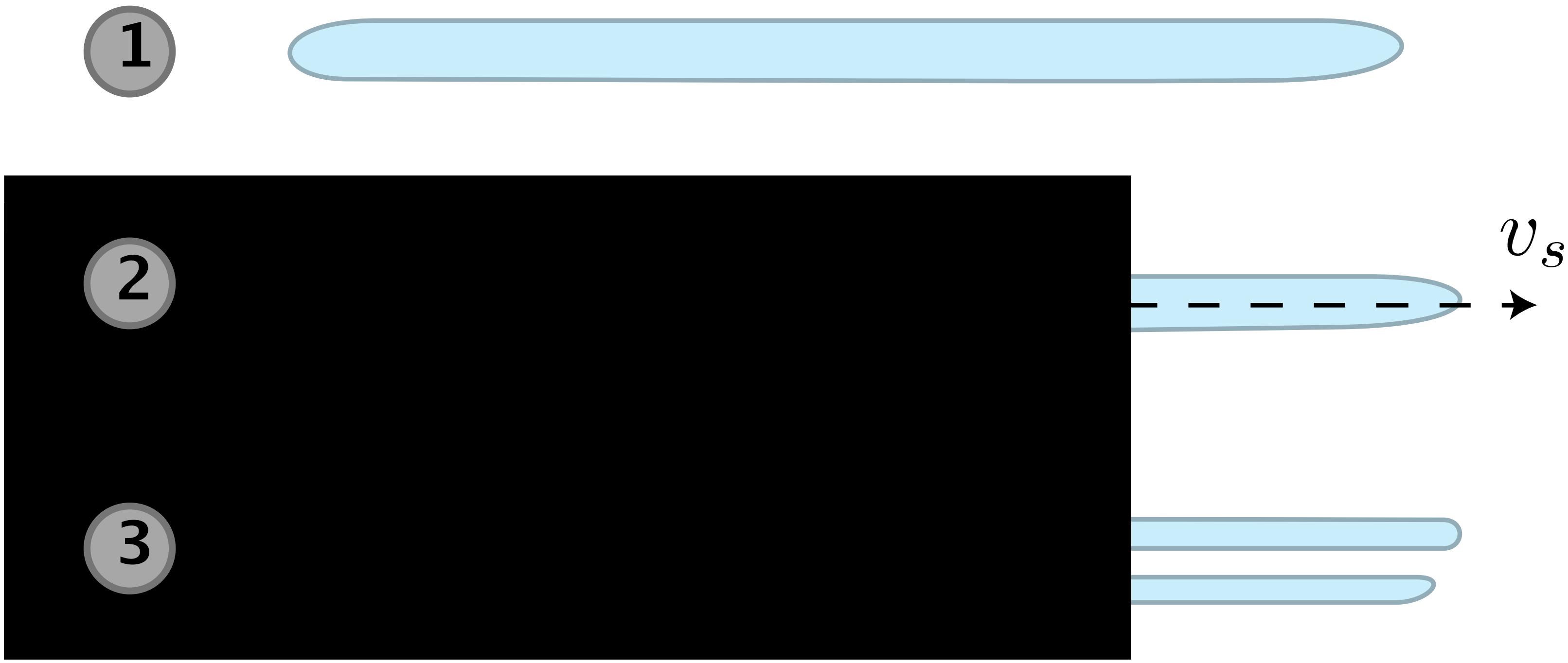
How do basic thermodynamic quantities transform under a Lorentz boost?

- For example, temperature T of a moving body, which in its rest frame, appears thermal at temperature T_0:

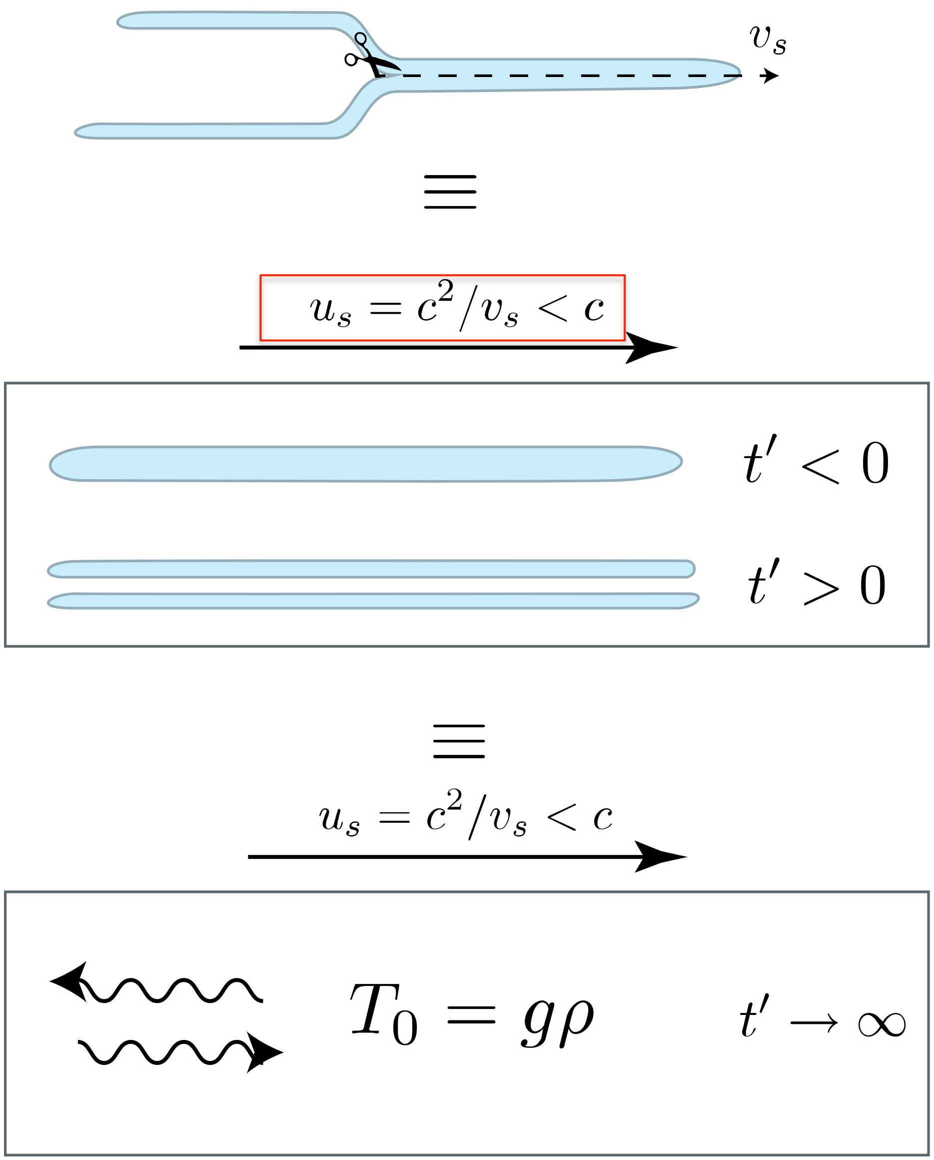
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

  - Einstein('08), Planck('08) : $T = T_0/\gamma$
  - Ott('63),Arzieles('65),Gamba('65),Kibble('66) : $T = \gamma T_0$
  - Landsberg('66) : $T = T_0$
  - Pathria('66) : $T = T_0/\gamma$: Planck and Einstein were right!
  - Callen,Horwitz ('71) : $T = T_0$ is most sensible.
  - Landsberg('86) : does not exist
  - Sewell (2008) : does not exist

Ultracool approach to the old problem



Transforming to a quench problem

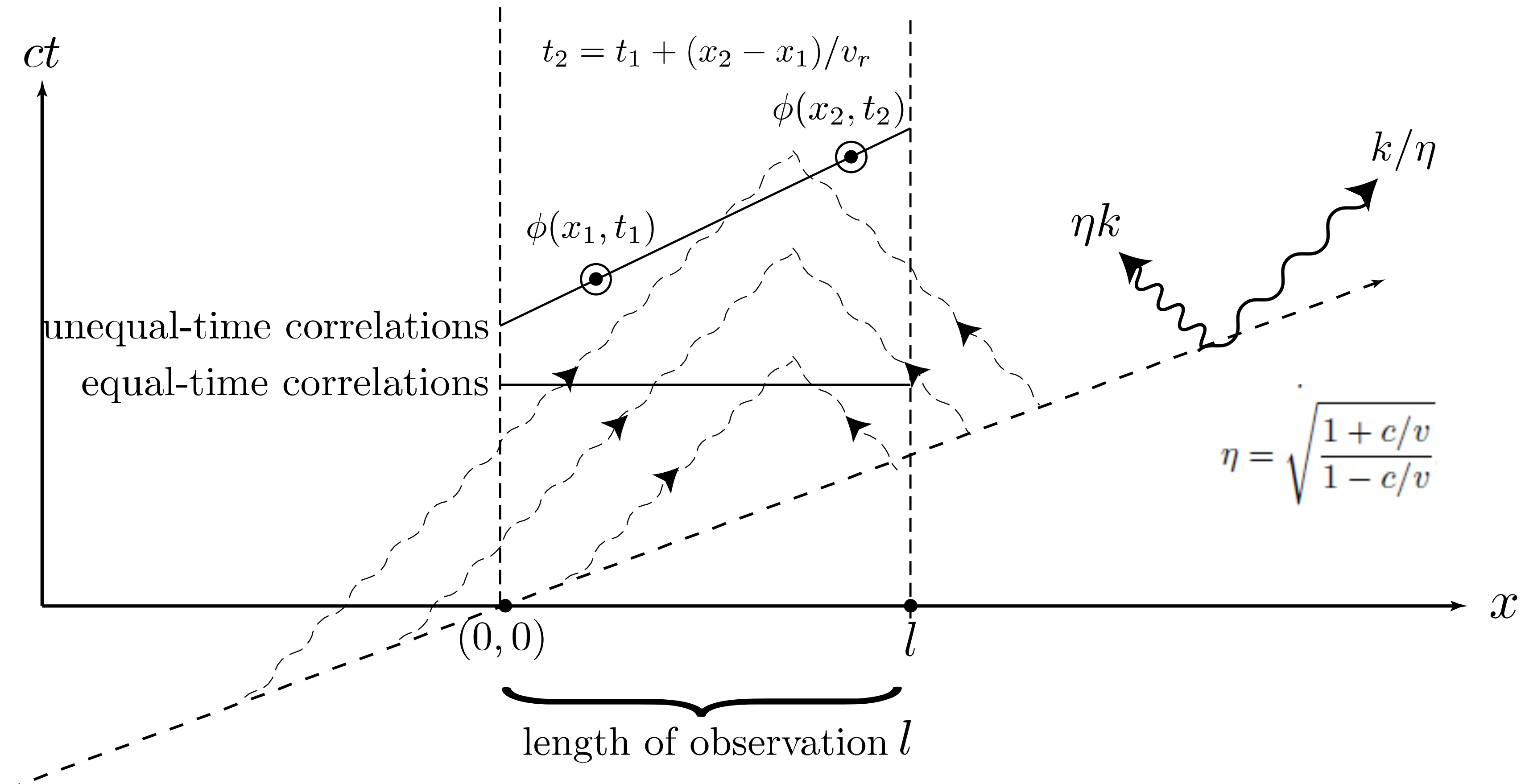


The dynamical problem can be analyzed in a Lorentz Boosted frame, where the problem is equivalent to the sudden splitting case.

For such a case, we know that the system thermalizes at a temperature T_0

Making measurements in the lab frame is equiv. to making measurements on a *moving body,* at rest frame temperature T_0

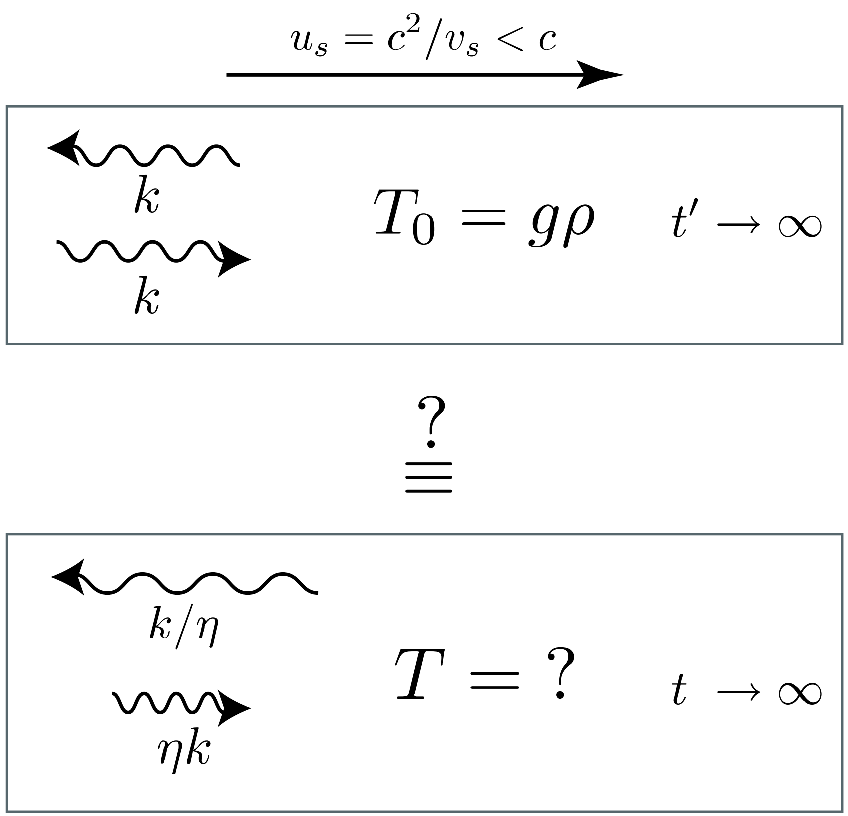
Interpretation : Measurement of Doppler-shifted ripples



equal time correlations are affected by left and right movers equally

unequal time correlations sample the waves differently. Special cases : $v_r = \pm c$

Interpretation : Measurement of Doppler-shifted ripples



Momenta are Doppler shifted in the Lab frame. Note : Right and left movers shifted differently.

Due to linear dispersion, the energy is also doppler shifted giving rise to doppler shifting of temperature

η : Relativistic doppler shift

$$\eta = \sqrt{\frac{1 + c/v_s}{1 - c/v_s}} = \sqrt{\frac{1 + u_s/c}{1 - u_s/c}}$$

Effective Temperature(s)

$$\boxed{T(v_s, \pm\infty) = T_0/(\eta + 1/\eta)/2 = \gamma_{v_s} T_0 \quad \text{(equal time)}}$$

Equal time correlations measure an average of the temperatures of left and right movers, as shown above. This transformation is in agreement with Ott-Kibble.

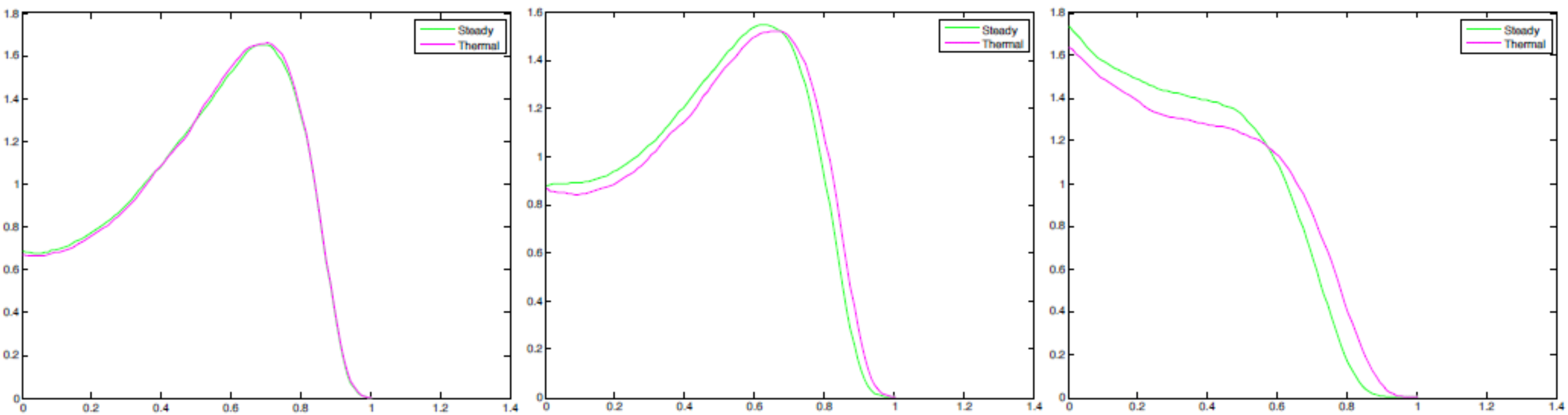
Note: $\gamma_{v_s} = \dfrac{1}{\sqrt{1 - c^2/v_s^2}} = \dfrac{1}{\sqrt{1 - u_s^2/c^2}}$

$$u_s = c^2/v_s : \text{Lorentz Boost velocity}$$

Experimental signatures of different Effective Temperatures

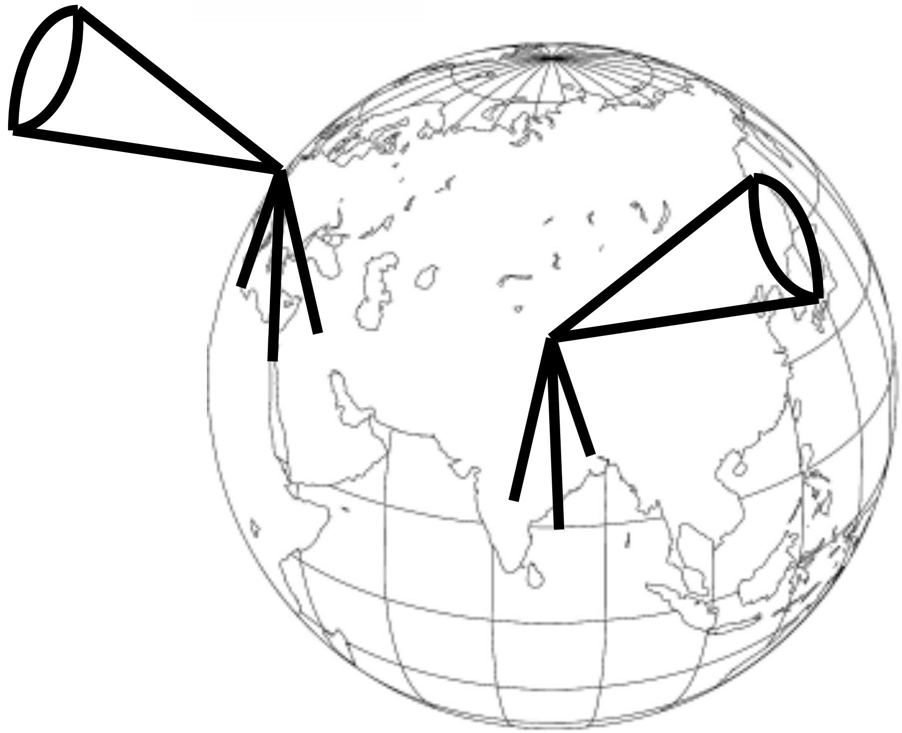
(a) $\bar{v}/c = 10$, (b) $\bar{v}/c = 2$ and (b) $\bar{v}/c = 1.2$

K=10



(a) (b) (c)

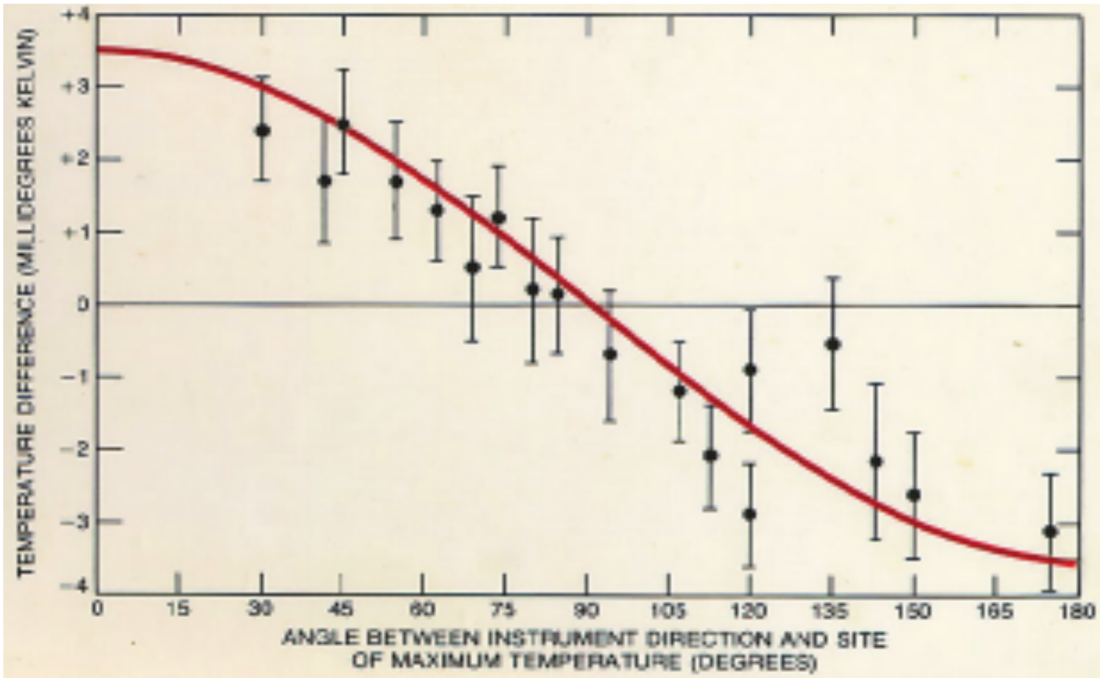
Analogy to the Cosmic Microwave Background Radiation



Depending on how you orient your telescopes, you measure, different effective temperatures.

Analogy to the Cosmic Microwave Background Radiation

ηT_0



$$\gamma T_0 = (\eta + \frac{1}{\eta}) T_0 / 2$$

T_0/η

The U2 Anisotropy Experiment
http://aether.lbl.gov/www/projects/u2/

η here, as before, is the relativistic doppler shift. In the context of the CMBR, it gives an estimate of the speed at which our galaxy is currently traveling away from the CMBR rest frame

Summary: interesting effects due to interplay of interactions, disorder, and temperature in quantum many-body systems

Quantum noise is a powerful tool for studying 1d many-body systems in and out of equilibrium

- Exploring Lorenz transformations of temperature in split atomic condensates

K. Agarwl, E. Dalla Torre, EAD, in preparation

We cheered you on last year
At the top of heart Break Hill.
Not knowing that you so young
Will run away so far too soon,
breaking our hearts

Olga Demler