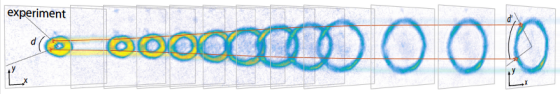
Rapidly expanding BEC ring: analog cosmology in a lab



Phys. Rev. X 8, 021021 – April 2018

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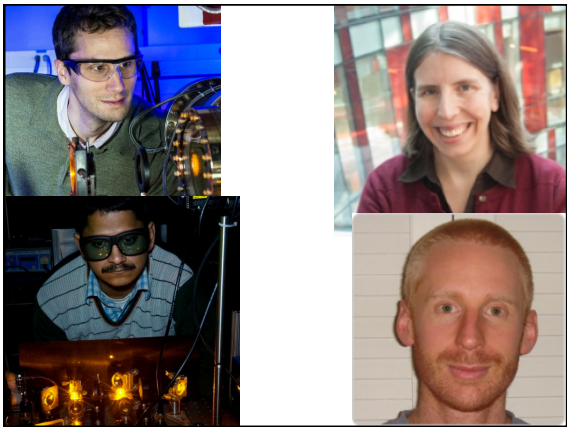


Observed phenomena

- redshifting of azimuthal phonons — *classical*
- (hints of) Hubble friction
- turbulent decay of homogeneous mode: dark soliton -> vortex dipoles -> turbulent state
- terminal persistent current

Experiment

- ^{23}Na in optical dipole trap, 1-4 x 10^5 atoms, T ~ μ ~ 50 nK
- vertical trap frequency 650 Hz
- ring trap created by imaging digital micromirror device (DMD)
- ring radius values between 10 to 45 μm, expanded at various supersonic speeds
- approximate form of potential: (dominates confinement)

$$V = \tfrac{1}{2}M\omega_r^2(\rho - R(t))^2 + \lambda(\rho - R(t))^4$$

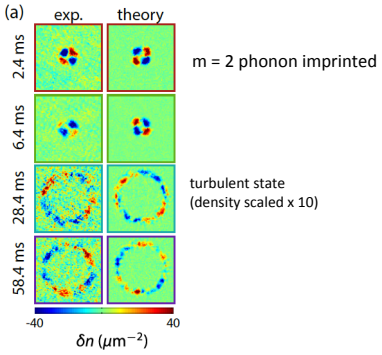
$$\omega_r \approx 2\pi \times 100\,\mathrm{Hz}, \quad \lambda/h \approx 0.8\,\mathrm{Hz}\,(\mu m)^{-4}$$

Imaging

- partial transfer absorption imaging (PTAI); resolution: e^{-2} intensity @ ~ 4-5 μm (new experiment ~ 2 μm)
- persistent currents measured by interference with auxilliary disc condensate in center of ring, which expands to overlap the ring

Simulations

- stochastic projected GP eqn.
- imaging process simulated to produce radial/azimuthal potential
- imaginary potential outside some radius mimics loss of atoms during expansion



m = 2 phonon imprinted

turbulent state
(density scaled x 10)

Linearized GP modes: curved spacetime wave equation

condensate wavefunction: $\psi = \sqrt{n}e^{i\phi}$

linearize: $n = n_0 + n_1, \quad \phi = \phi_0 + \phi_1$

neglect "quantum potential", solve for n_1 in terms of ϕ_1 and $\phi_{0,i}$ to obtain

$\partial_\mu(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi_1) = 0$, with

$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = c_0[-c_0^2dt^2 + (dx^i - v^i dt)^2]$

$c_0 = (4\pi\hbar^2 a_s n_0/M^2)^{1/2}, \quad v^i = (\hbar/M)\phi_{0,i}$

Reduction to 1+1

comoving radial coordinate: $\tilde{\rho} := \rho - R(t)$

$ds^2 = c_0[-c_0^2dt^2 + d\tilde{\rho}^2 + (R(t)+\tilde{\rho})^2 d\theta^2 + dz^2]$

$\sqrt{-g}g^{\mu\nu} = \mathrm{diag}[-(R+\tilde{\rho}), \frac{c_0^2}{R+\tilde{\rho}}, c_0^2(R+\tilde{\rho}), c_0^2(R+\tilde{\rho})]$

For thin ring with azimuthal symmetry, and sufficiently low frequency, can restrict to lowest radial and vertical modes. Integrating over radial and vertical directions, and using Thomas-Fermi approximation and the approximate analytical potential, reduces to 2D wave equation for χ(θ,t), in the above metric with c_0 replaced by:

$$c_\theta = \sqrt{\frac{4}{7}\frac{\mu}{M}} \propto R^{-2/7}$$

Reduction to 1+1: redshift, Hubble friction

$[\sqrt{-g}g^{ab}]_{\mathrm{2d,effective}} = \mathrm{diag}[-R, c_\theta^2/R]$

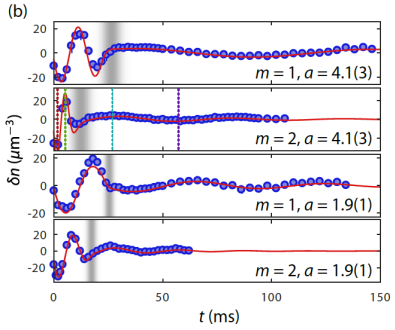
(But for any 2d metric, $\det[\sqrt{-g}g^{ab}]_{\mathrm{2d}} \equiv -1$, so no such metric exists.)

For $\chi_m(t)e^{im\theta}$, $\quad \ddot{\chi}_m + \frac{\dot{R}}{R}\dot{\chi}_m + \omega_m^2\chi_m = 0, \quad \omega_m = \frac{mc_\theta}{R} \propto R^{-9/7}$

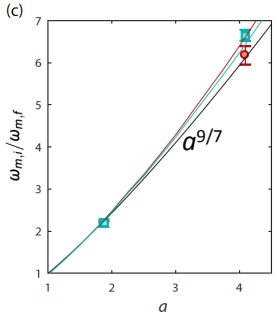
Non-dissipative: can be derived from $L = \frac{1}{2}R\dot{\chi}_m^2 - \frac{1}{2}(m^2c_\theta^2/R)\chi_m^2$

Additional observed friction (Landau damping?): $\gamma_m(t)\,\dot{\chi}_m$

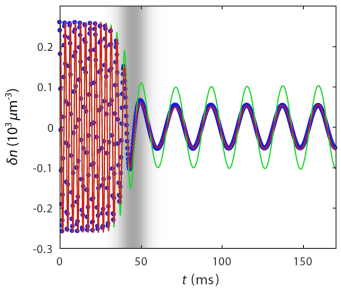
Phonon amplitude evolution



Phonon redshift

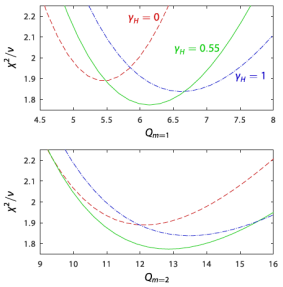


2dGPE simulated phonon evolution in thin ring limit, vs. effective 1+1 equation.



2dGPE result matches effective 1+1 equation extremely well --- when Hubble friction is included.

Probing the experimental friction effect, by fitting data to $\dot{R}/R \to \gamma_H \dot{R}/R$

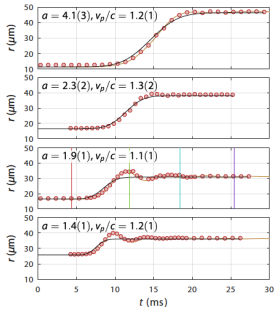


Not very significant, too much noise.

Future improvements:

- Expand when χ changing most rapidly
- Vary Rdot/R
- Contract and well as expand ring.

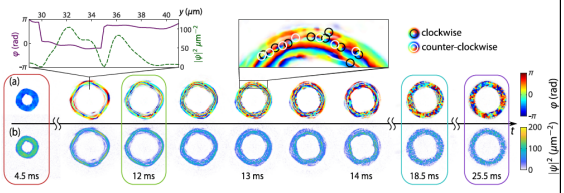
Damping of the homogenous radial mode

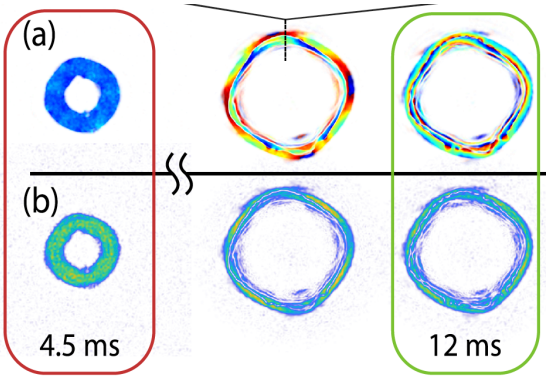


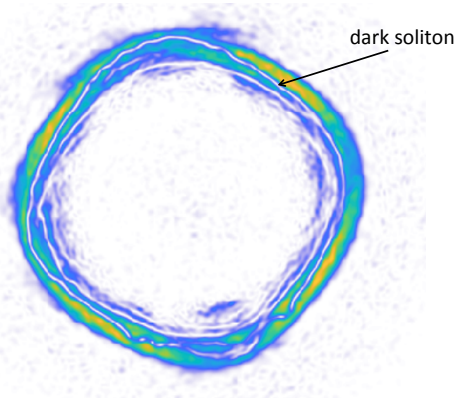
data & simulation match very well…

What is the damping mechanism?

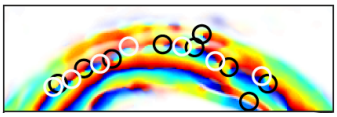
High resolution simulation



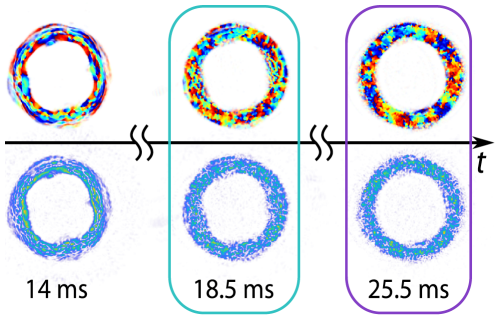




Vortex dipoles from snake instability of dark soliton

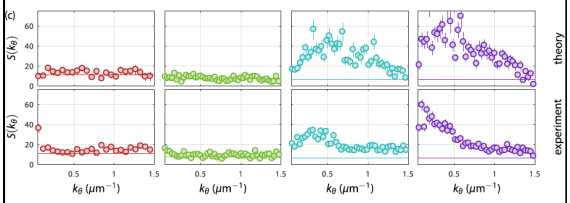


Turbulent evolution

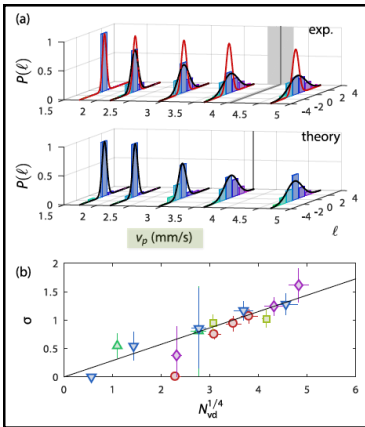


Evolution of the structure factor

$$S(k_\theta) = \left\langle \left| \int \delta n_{1D}(\theta) e^{-ik_\theta R\theta} R\, d\theta \right|^2 \right\rangle$$



Does it fit the universal scaling relation discussed by Thomas Gasenzer on Tuesday?!



$\alpha = 1.4$

Red Gaussians are for *horizon model*: doesn't fit.

Moreover, the phase fluctuations In the condensate are ~ 25 times too low to randomize causal domains. Future experiments might enhance fluctuations by using lower density.

Unexplained power law, Not the naïve square root.

Conclusions

- Observed and simulated in BEC classical cosmological field theory phenomena
- Linear: redshift & hints of Hubble friction
- Nonlinear: transfer of energy from homogeneous mode to turbulent state via `topological' channel (snake instability of dark solitons decaying to vortex dipoles).
- Initially imprinted phonon survives in the turbulent state --- like primordial curvature fluctuations in inflation
- New experiment being built by Gretchen Campbell's group, with improved imaging. Could potentially explore
  -- Hubble friction
  -- horizon mechanism for persistent currents (cf. axion "misalignment")
  -- quantum correlation functions and particle creation…