CHARACTERIZATION OF PHONONS IN VISCOUS LIQUIDS

WHAT DOES DARK MATTER SOUND LIKE?

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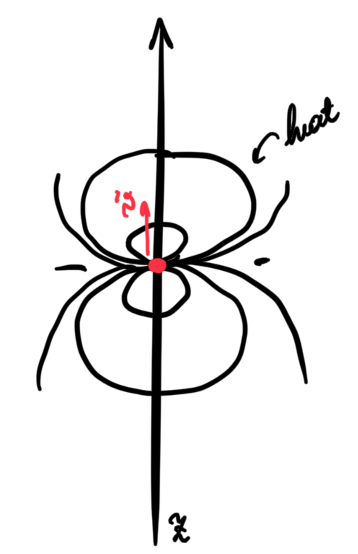
ABSTRACT In an attempt to provide an additional detection channel for direct dark matter experiments involving noble liquid scintillators, we present a theoretical framework for describing the production of sound by single particles through noble liquids. We develop a linear, classical description of the acoustic wave that accounts for viscous strong damping. We proceed with quantizing this description by introducing an effective field theory where we treat strong damping nonperurbatively through the introduction of an interaction between particles and antiparticles of sound. We use Minimum Ionizing Particles (MIPs) as a toy model to obtain quantitative results from our formalism.



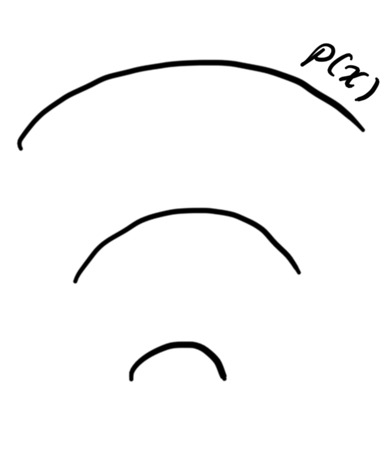
INTERACTING **PARTICLE**

Interacting particle **PASSES THROUGH A LIQUID** with viscosity. Assuming that the particle does not interact nonlinearly (e.g. turbulance, direct collision with atoms, etc.) it **DEPOSITS HEAT**

$$\epsilon_{tt}(\rho, x, t) = \frac{dE}{dx}\bigg|_M \frac{v^2(x - vt)}{(2\pi\sigma^4)^{3/2}} \exp\left\{ -\frac{1}{2\sigma^2}\left[(\rho^2 + (x - vt)^2)\right] \right\}$$

rate of energy density added

Bethe Bloch for charged particles



ACOUSTIC **WAVES**

HEAT depositions **PRODUCE ACOUSTIC WAVES**. To model that we introduced corrections to the wave equation derived from linearized Navier Stokes.

pressure

$$\Box p(\mathbf{x}) + \lambda \Delta \partial_t p(\mathbf{x}) = -\partial_t f(\mathbf{x} - vt\,\hat{z})$$

D'Alembert Operator — viscosity — energy density

To solve we derived a **perturbation** scheme on the constant **viscosity** λ, found the retarded propagator and used it to calculate solutions to arbitrary order in λ.

Perturbation Order

$$\Box^{n+1} p_n(\mathbf{x}) = -(-\Delta\partial_t)^n f(\mathbf{x})$$

Retarded Propagator

$$G_n(\mathbf{x}) = \frac{\Theta(t)}{4^{n+1}\pi r} \sum_{m=0}^{n} \frac{(-2t)^m}{m!} \binom{2n-m}{n} \left[\delta^{(m)}(t-r) - \delta^{(m)}(t+r)\right]$$

The **shape** of the signal is dependent on the speed of the particles. Below are the plots for subsonic and supersonic particles. For fast particles, an observer at O hears the wave from two different points at the same time.

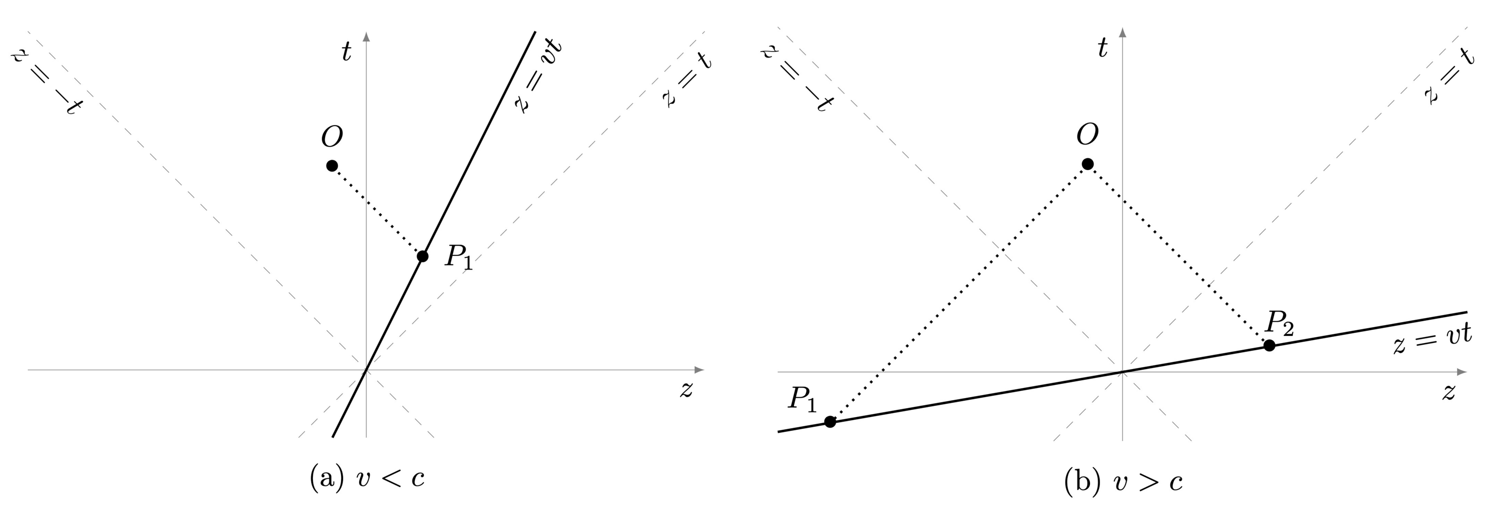


Fig 1. *Minkowski diagrams for slow and fast particles, O is an arbitrary observer and the world line of a moving particle is in bold. Dashed are worldlines of sound normalizing the speed of sound c = 1. (a) is a particle moving slower than sound, and (b) moves faster. The dotted lines are the sound waves reaching the observer. Note that for particles faster the observer hears the particle from two points at opposite phase.*

The pressure for the two different cases is shown below. The subsonic particles produce an acoustic pulse at roughly the same position as them, while supersonic particles do the

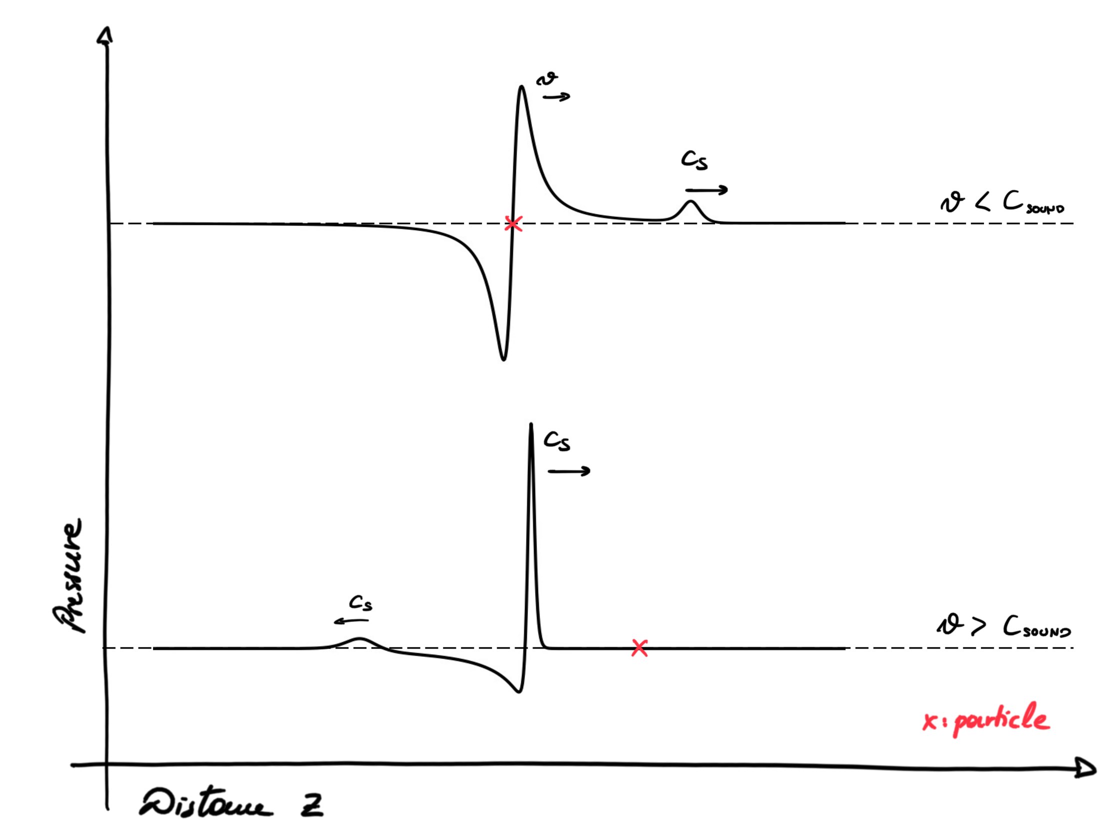
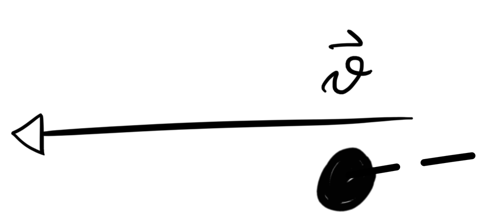
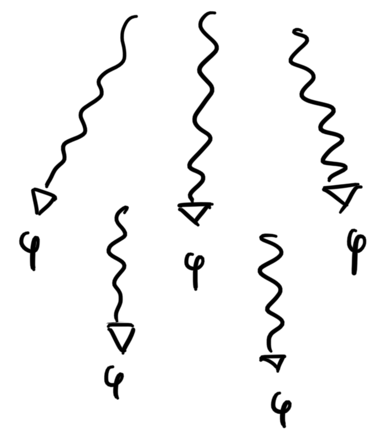


Fig 2. *Analytical solution for the pressure wave at constant distance perpendiccular to the particle over the z axis.*



CLASSICAL TREATMENT

QUANTUM TREATMENT



BALLISTIC **PHONONS**

We **quantize** the **pressure wave** to take into account factors such as **thermal noise** due to the ground energy state of the liquid in order to predict the **decay of phonons** due to viscosity at low temperatures.

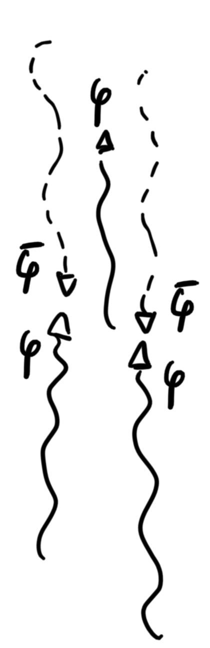
Problem! The viscosity takes energy from the pressure, so a lagrangian that only describes the pressure field has no PT symmetry. We could restore that bby quantizing the lagrangian of Navier Stokes but this brings many variables that we need to keep track of that we will never use (e.g. velocity field, temperature, density, etc.). Instead we perform a transformation on the action that keeps the minima the same, by promoting the pressure field to a complex field. In this way we have a U(1) symmetry that allows for the energy to be dissipated without modelling the fluid. The tradeoff is a harder physical interpretation of the calculations

We therefore introduce the following lagrangian

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \bar{\phi} + \lambda\left[\Delta\phi\partial_t\bar{\phi} - \Delta\bar{\phi}\partial_t\phi\right]$$

kinetic — viscosity interaction

Then we perform canonical quantization with minkowski metric with negative time signature.



PRODUCED **PHOTONS**

Photons can be produced using various mechanisms (Bremsstrahlung, Cherenkov etc.). This is well studied, so we **don't focus on that signal**.

INTERACTION **PHONONS & ANTIPHONONS**

Quantizing a lagrangian with U(1) symmetry we obtain particle antiparticle pairs. There is a linear interaction between the two where one acts as a source of the other, exchanging energy. Therefore viscosity is modelled by exchanging phonons with antiphonons.

We can calculate the hamiltonian to be

$$H = \int \frac{d^3p}{(2\pi)^3} E_p \left[\left(a_p^\dagger a_p + b_p^\dagger b_p\right) - i\lambda \boldsymbol{p}^2 \left(a_p^\dagger a_p - b_p^\dagger b_p\right)\right]$$

Out of which we obtain the following dispersion relation between phonons and antiphonons. Notice that the hamiltonian is not hermitian, which is fine, because the imaginary part quantifies the damping.

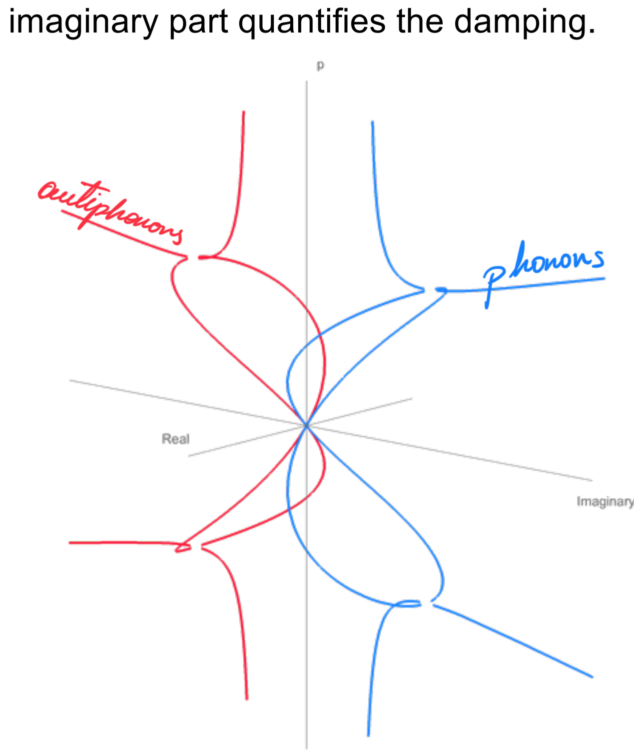


Fig 3. *Hamiltonian Eigenvalues as a function of momentum for phonon and antiphonon states. There is a clear distinction when the eigenvalues for both types of particles become purely imaginary.*

As seen in Fig. 3 after some point the energy becomes imaginary which means that the phase stops oscillating and the amplitude decreases in time.

$$H\, a_p^\dagger |0\rangle = (E_p + i\lambda \boldsymbol{p}^2)\, a_p^\dagger |0\rangle$$

$$H\, a_p^\dagger |0\rangle = \left(\sqrt{\boldsymbol{p}^2 - (\lambda \boldsymbol{p}^2)^2} + i\lambda \boldsymbol{p}^2\right) a_p^\dagger |0\rangle$$

NUMERICAL **SIMULATIONS**

To numerically make predictions of the actual signal that a single particle would create in a viscous fluid two simulations were built from scratch. One introduces an improvement on a 3D Finite Element Method scheme with cyllindrical symmetry to numerically evaluate the complete equation for a gaussian source term. The other was the symbolic calculation for the pertubative expansion solution for a delta function heat distribution using hardware accelaration (CPU clusters and GPU). We were able to successfully predict the location of a shockwave and it's attenuation as a function of distance from the particle track.

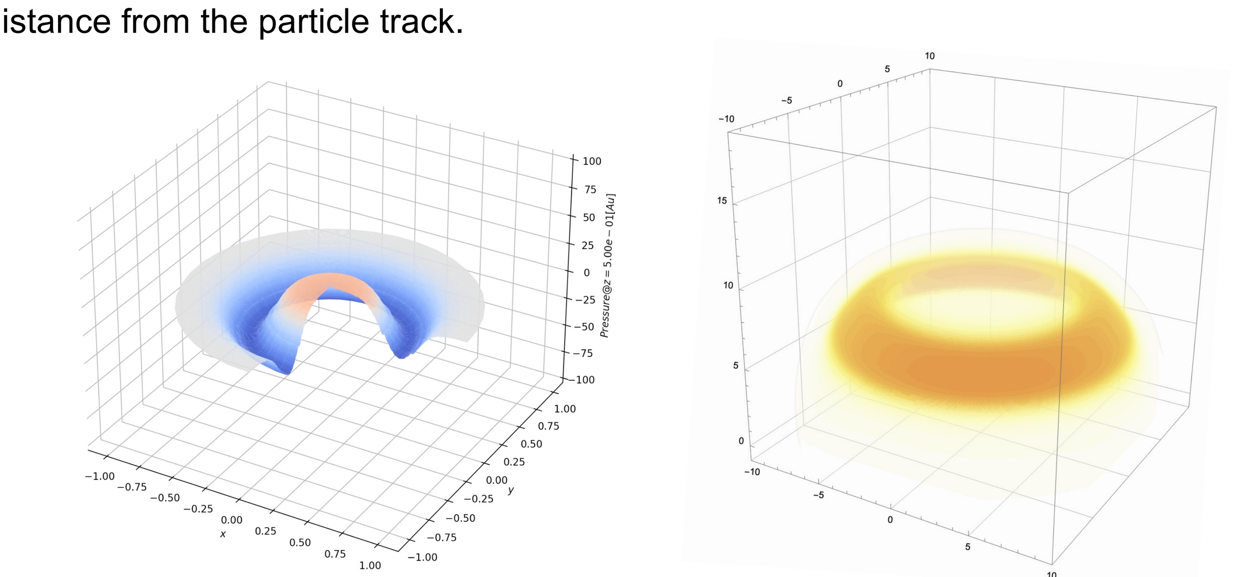


Fig 4. *Outome from the two different simulations in units where (c = λ = 1).* ***(Left)*** *Pressure at a slice where z = 0.5, height and color represent pressure.* ***(Right)*** *3D Density plot from symbolic calculation, color represents intensity. Both are simulations for a particle moving faster than the speed of sound at ($v = \frac{3}{2}c$) captured at t = 1.*

AKNOWLEDGMENTS

This project was carried out under the supervision of Professor Francesco Arneodo and Dr. Laura Manenti at NYUAD. We would like to thank Professor John Learned (UHM), Dr. Mario Motta (CALTECH), and Professor Giorgio Gratta (Stanford) for insightful discussions on acoustics. Furthermore, we want to aknowledge the support of Professor Elena Beretta (NYUAD), Professor Johnathan Goodman (NYU), Professor Johnathan Weare (NYU), Professor Diogo Arsenio (NYUAD), Professor Fracesco Paparella (NYUAD) in understanding the mathematics behind the project. Finally, we would like to thank PhD Student Isaac Sarnoff (NYUAD) for his valuable contribution in classical calculations. This research was carried out on the High Performance Computing resources at New York University Abu Dhabi.