Shedding light on Dark Matter using Bose-Einstein condensates

19th MultiDark Consolider Workshop

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Most part of this work was developed, simultaneously, at the Institute for Theoretical Physics (theory) and the Kirchhoff Institute for Physics (experiment) of the University of Heidelberg, Germany.

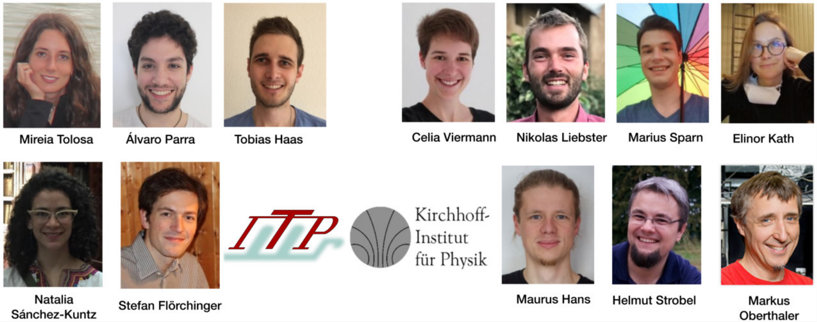

Fig. 1. *Left: theory team. Right: experimental team.*

Motivation

- QFT in curved spacetimes → (DM) Particle production
- Direct detection → Very hard
- Analog model → Simulate with a dynamically equivalent system
- Weakly interacting BEC is described by

$$\Phi = \text{background} + \text{fluctuations} = \sqrt{n_0}e^{iS_0} + \delta\Phi \tag{1}$$

Real world	BEC experiment
Spacetime	n_0, S_0
FLRW metric	Acoustic metric
Massless scalar particle	Phonons (sound)

- We parametrise the field as

$$\Phi = \phi_0 + \frac{1}{\sqrt{2}} \left(\phi_1 + i\phi\right), \tag{2}$$

and expand

$$S[\Phi] = S[\phi_0] + \text{linear in } \phi_1, \phi + S_2[\phi_1, \phi] \tag{3}$$

- EOM for the fluctuations is given by

$$\delta S[\Phi] = \delta S_2[\phi_1, \phi] \stackrel{!}{=} 0 \tag{4}$$

1. Assume excitations have low momentum
2. Integrate out $\phi_1(\phi)$
3. Adjust the background to be static

The action for the fluctuating field ϕ can be written as

$$S_2[\phi] = \frac{1}{2} \int_x \sqrt{g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi, \tag{5}$$

with the line element

$$ds^2 = -dt^2 + \frac{1}{c^2(t,r)} \left(dr^2 + r^2 d\varphi^2 \right) \equiv -dt^2 + \frac{a^2(t)}{n_0(r)} \left(dr^2 + r^2 d\varphi^2 \right), \tag{6}$$

where the speed of sound is

$$c^2(t,r) = \frac{\lambda(t)\, n_0(r)}{m}. \tag{7}$$

We make $r \to u$ so that

$$\frac{dr^2}{n_0(r)} = \frac{du^2}{1-\kappa u^2}, \quad \frac{r^2}{n_0(r)} d\varphi^2 = u^2 d\varphi^2, \tag{8}$$

and the line element reads

$$ds^2 = -dt^2 + a^2(t)\left(\frac{du^2}{1-\kappa u^2} + u^2 d\varphi^2\right). \tag{9}$$

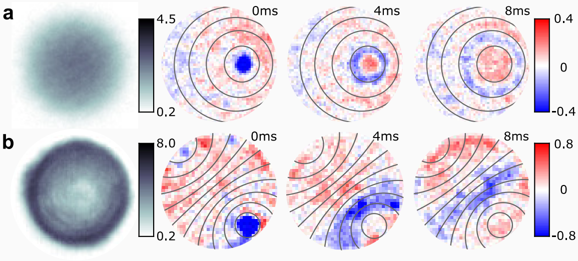

Fig. 2. *Density distribution for hyperbolic (a) and spherical (b) geometry and wave packet propagation. Viermann et al. [2202.10399]*

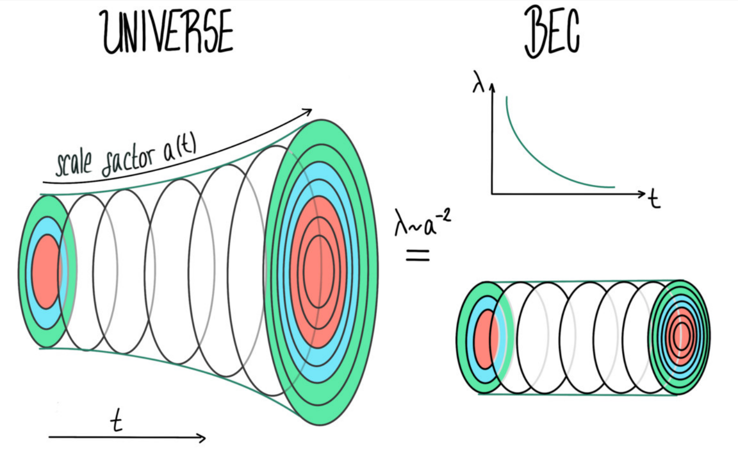

Fig. 3. *Analogy between the expanding universe and the condensate. The relation between the interaction strength λ and the scale factor is sketched.*

Particle production

- We make predictions for the spectrum of fluctuations S_k
- We measure correlations of density contrast $\langle \delta_c(t, \mathbf{u}) \delta_c(t, \mathbf{u}') \rangle$

We can relate $\langle \delta_c(t, \mathbf{u}) \delta_c(t, \mathbf{u}') \rangle \sim \langle \dot{\phi}(t, \mathbf{u}) \dot{\phi}(t, \mathbf{u}') \rangle \sim S_k(t)$.

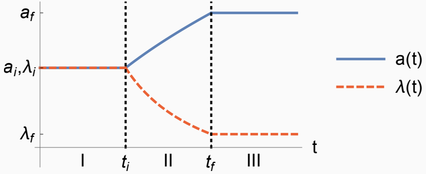

Fig. 4. *Time evolution of the scattering length $\lambda(t)$ and the scale factor $a(t)$ for a polynomial expansion during the experiment. Tolosa-Simeón et al [2202.10441].*

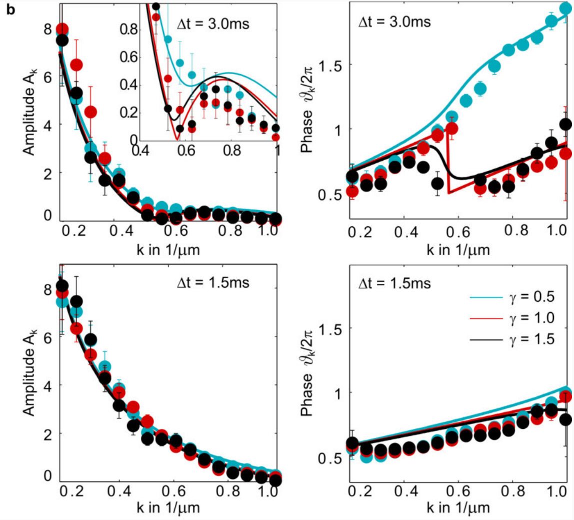

Fig. 5. *Phase and amplitude of the oscillating spectum* $S_k(t)$*. The phase allows for a qualitative distinction between expansion with different scale factors* $a(t) \sim t^\gamma$*. Viermann et al. [2202.10399].*

Outlook

The abundance of DM can be explained by gravitational production during inflation alone.

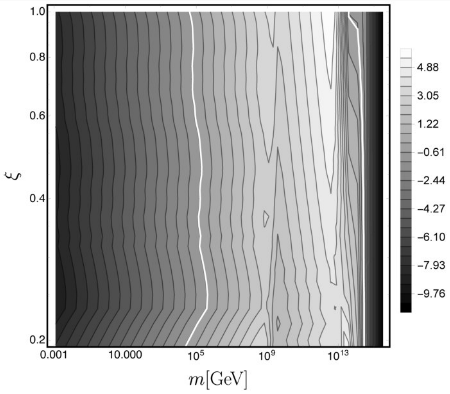

Fig. 6. *Abundance for a scalar field ϕ in logarithmic scale, considering $T_{rh} = 10^{15}$ GeV. White contours represent the observed value. Here, ξ is the coupling to the Ricci scalar and m is the mass of the DM particle. Cembranos et al, JHEP 2020, 84.*

- We achieved a 1-1 mapping from BECs to curved FLRW universes
- We measured particle production in an actual experiment and extracted information of the type of expansion
- Tools from analogue gravity (curvature and phase of S_k) can be used in cosmological analyses.
- Particle production is very sensible to the inflaton scheme
- Spin-1 BECs allow to extend the analogy to massive complex scalar fields

Any questions?