Quantum Constituents of Inflationary Background & Superfluid Dark Matter

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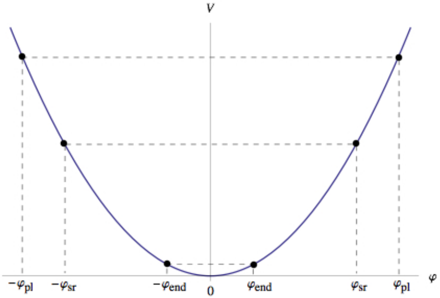
Standard Picture

$$V = \frac{1}{2} m^2 \varphi^2$$



$$g_{\mu\nu} = \bar{g}_{\mu\nu}(t) + \hat{h}_{\mu\nu} \qquad \varphi = \bar{\varphi}(t) + \delta\hat{\varphi}$$

Quantum Picture

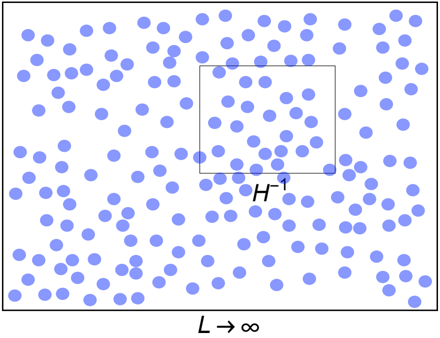
Dvali, Gomez '13

$$g_{\mu\nu} = \eta_{\mu\nu} + \hat{h}_{\mu\nu} \qquad \varphi = \hat{\varphi}$$

Classical background is viewed as BEC of $\hat{h}_{\mu\nu}$ and $\hat{\phi}$.

Scalar Perturbations

LB '16



Sources of fluctuations:

- Uncertainty principle
- Scattering of the constituents

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LB '16

What should be the properties of the constituents in order to give the correct amplitude for density perturbations?

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LB '16

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Inflaton background as a condensate of off-shell φ-quanta in $k = 0$ state with

$$m_{eff} = \frac{m^2}{H} \neq m$$

Interactions of the Constituents

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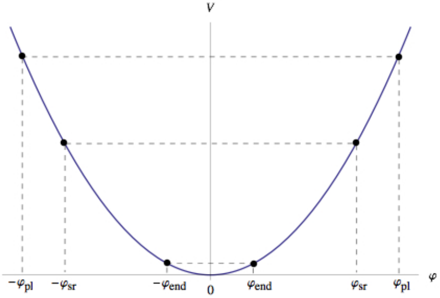

- Origin of perturbations depends on the energy scale.
- Depletion of the condensate becomes significant during eternal inflation.

Recovering Slow-roll

LB, Sebastian Zell, work in progress

If the corpuscular description is valid, we should be able to recover the slow-roll as a result of quantum dynamics of the constituents.

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Maybe we learn something more about the properties of the constituents along the way?!

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Consider massive particles with $\omega_k^2 = m^2 + k^2$ and 2-point contact interaction $\sim \lambda$.

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Landau's criterion: no dissipation for $v < c_s$.

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In order to recover the superfluid properties, it must be viewed as a collection of massive particles with

$$\omega_k = \mu + c_s k \qquad \text{with} \qquad \mu \approx m$$

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For any λ, there are modes which are off-shell.

Superfluid Dark Matter

Introduction

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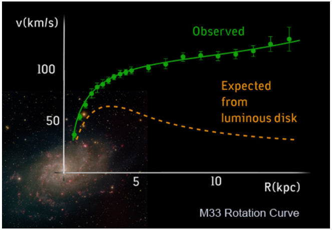
It faces some challenges at galactic scales.

Density Profile:

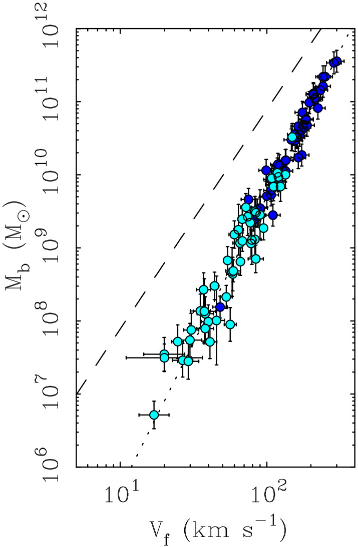
N-body simulations reveal universal density profile:
Navarro, Frenk, White '96

$$\rho_{\mathrm{NFW}} = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$



"Missing satelite"/"Too big to fail" problem

BTFR:



$$M_{\rm b} \sim v_{\rm c}^4$$

$$\text{CDM: } M_{\rm vir} \sim v_{vir}^3$$

Famaey and McGaugh '12

MOND:

Milgrom '83

$$a = \begin{cases} a_{\mathrm{N}} & a_{\mathrm{N}} \gg a_0 \\ \sqrt{a_{\mathrm{N}} a_0} & a_{\mathrm{N}} \ll a_0 \end{cases}$$

$$a_0 \sim H_0$$

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MOND fails on cosmological scales.

Unification

LB, Khoury '15

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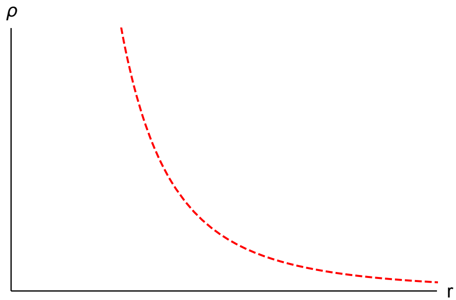
Required ingredients: superfluid with $p \propto \rho^3$ and phonons coupled to baryons $\sim \phi\rho_b$.

Halo Profile:

LB, Famaey, Khoury '17

At virialization



Halo Profile:

LB, Famaey, Khoury '17

Requiring $R_{\rm T} > 60\ \mathrm{kpc}$ for Milky Way-like galaxy

$$m \lesssim 4.2 \left(\frac{\sigma/m}{\mathrm{cm}^2/\mathrm{g}} \right)^{1/4} \ \mathrm{eV}$$

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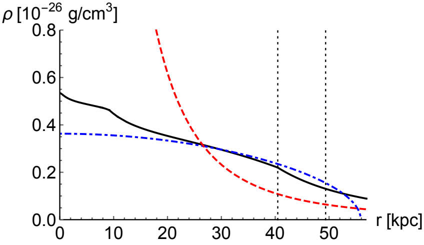
For clusters with $M = 10^{15} M_\odot$, requiring $R_{\rm T} \lesssim 0.1 R_{\rm vir} \approx 200\ {\rm kpc}$

$$m \gtrsim 2.7 \left(\frac{\sigma/m}{{\rm cm}^2/{\rm g}}\right)^{1/4}\ {\rm eV}$$

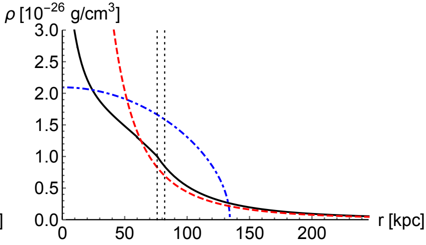
Halo Profile:

LB, Famaey, Khoury '17

IC 2574: $M_b = 2 \times 10^9 M_\odot$



UGC 2953: $M_b = 1.6 \times 10^{11} M_\odot$



Rotation Curves

LB, Famaey, Khoury '17

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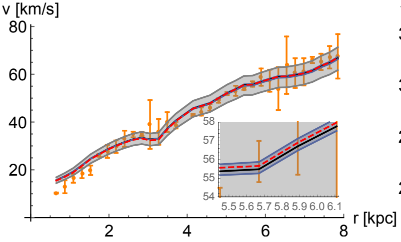

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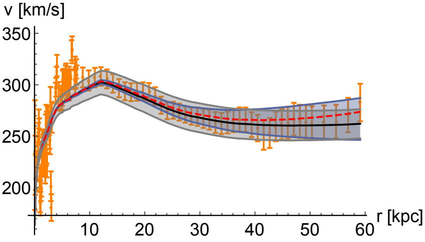


Works in progress

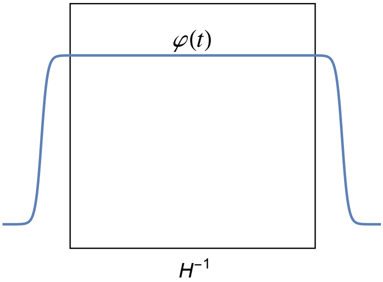
Finding microscopic model and the origin of the phonon-baryon coupling LB, Khoury . . .

Reduced dynamical friction LB, Elder, Khoury

Setting aside the exotic ingredients, simple paradigm of the superfluid dark matter requires reconsideration LB, Max Warkentin

Beginning of Inflation

In order to start inflation the scalar field must be homogeneous over the Hubble patch.



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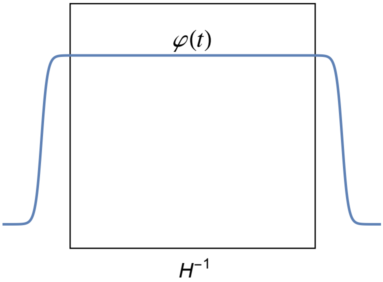
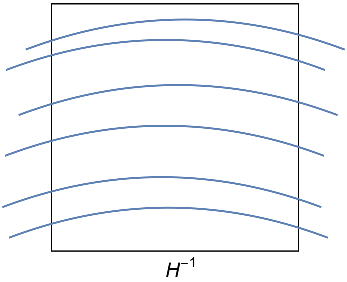
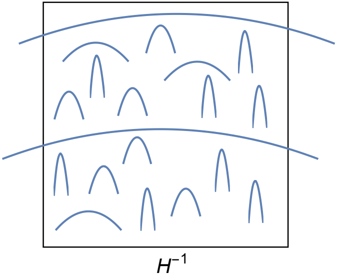




Initial State

LB, Trodden '15



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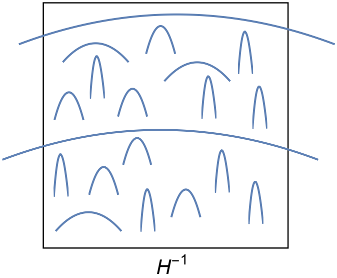

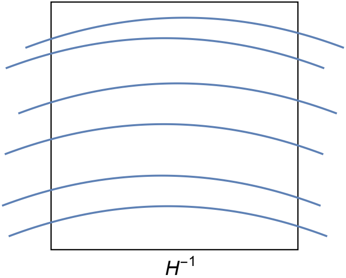

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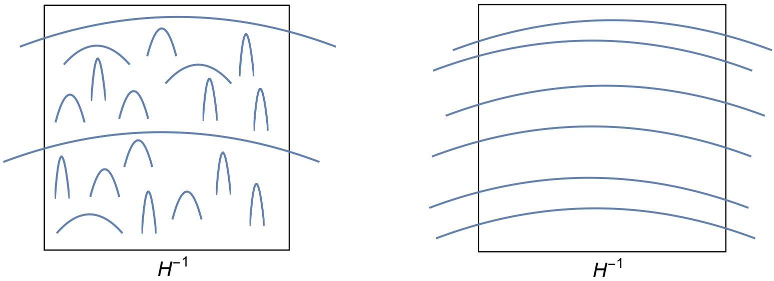

Option 1: There will be some regions that are homogeneous enough; this could be sufficient.

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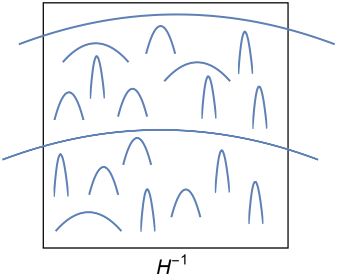

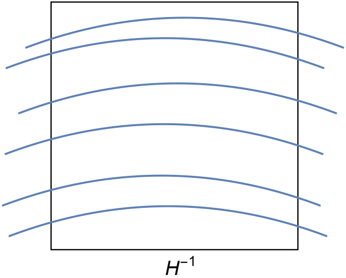

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Options 2: Initially inhomogeneous region may evolve into the homogeneous one.

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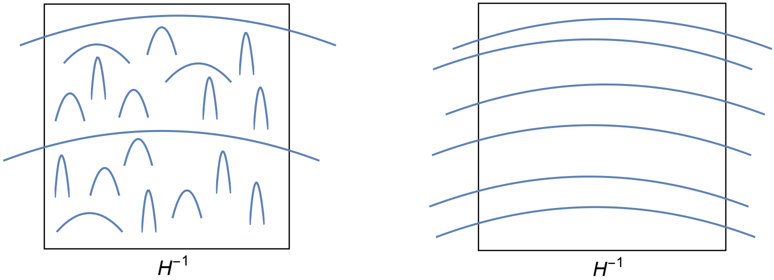
LB, Trodden '15



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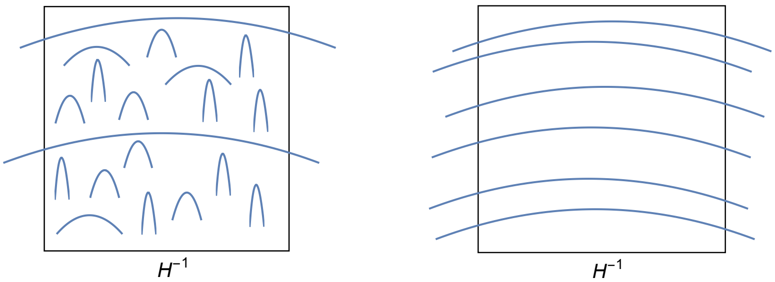

Probability for a given region to be homogeneous enough is very small.

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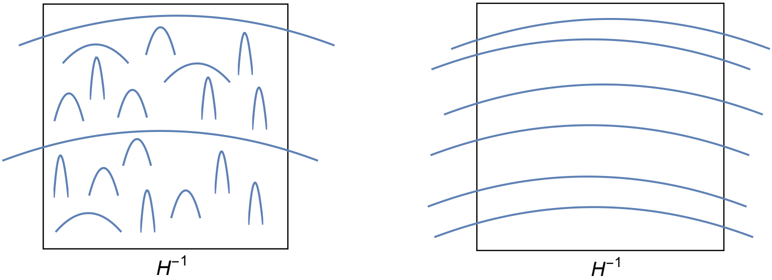
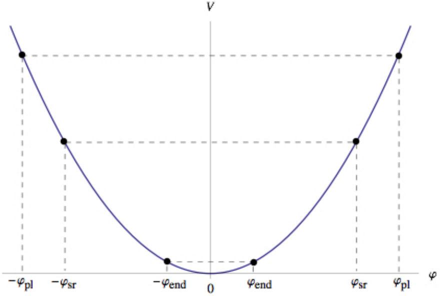


Probability for a given region to be homogeneous enough is very small.

Could the volume factor boost the probability?

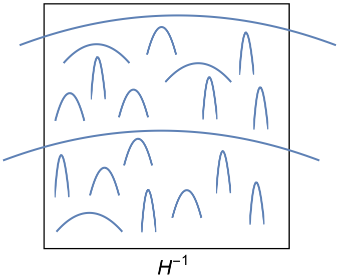
Option 1

Yes, but only if inflation has started in eternally-inflating regime.



Option 2

LB, Trodden, work in progress



Even if initially not homogeneous enough, could it become homogeneous at later times?