Cosmic web in an alternative theory of gravity with Euclid

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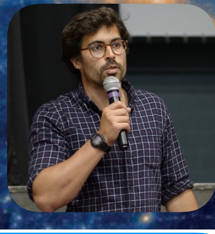


Motivation

How to constrain the nature of the dark matter?

Now we have several observational programs such as Gaia, JWST & Euclid to constrain the properties of dark matter (DM). These missions will verify the ΛCDM model, corresponding to the cold DM or require a substantial revision of our understanding of the nature of DM. Indeed, there are still challenges in the current DM paradigm such as the σ8 tension or the cusp-core problem. Therefore, we need to propose alternative theories to DM in particular, but also alternative theories of gravity that can be tested on cosmological scales especially with the Euclid mission.

Which alternative theory of gravity?

Recently, it has been suggested that the Monge-Ampère equation may provide an alternative model for self-gravitating systems [1,2]. Yann Brenier has shown that Monge-Ampère gravity can arise from a microscopic system in which a finite number of indistinguishable particles move on independent Brownian trajectories without any interaction. Then, gravity emerges through application of a principle of statistical physics, namely the large deviation principle [1].

How to distinguish gravity models at cosmological scales?

One way we have decided to explore is computing cosmic connectivity, namely the number of filaments connected to a given galaxy group. Fig. 1 displays the mean connectivity from observations and from ΛCDM simulations assuming Poisson gravity. As it is an important ingredient in shaping galaxy properties, it should be sensitive to the dynamics of DM governed by the assumed gravity model. Filament properties have already been explored as alternative probes of cosmologies [3,4].

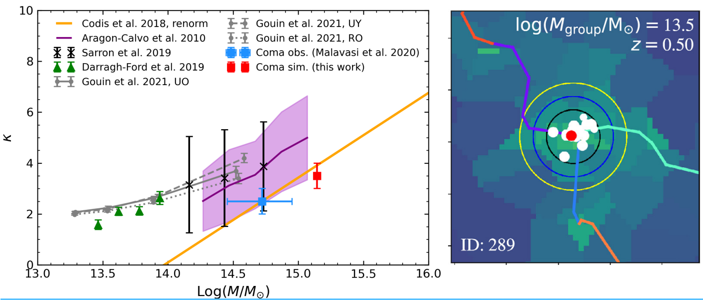


Fig. 1 Mean connectivity as function of M_{200} or M_{vir} (left panel) and example of the connectivity for a galaxy group in COSMOS2015 catalogue (right panel). From ΛCDM simulated samples, it has been measured a connectivity between 2 and 4 in this mass range. Figures are taken from [5] and [6], respectively.

Aim

To test the validity of the Monge-Ampère gravity model at cosmological scales

More precisely, this project intends to

1. Develop a DM only cosmological simulation for this alternative theory of gravity by using efficient algorithm from optimal transport theory
2. Explore the cosmic web properties to distinguish gravity models

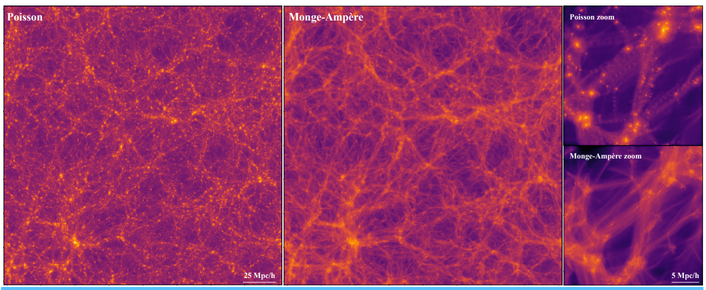


Fig. 2 Distribution of DM at z=0 in our simulated volume of roughly 300 Mpc sampled by 512^3 particles for both Monge-Ampère and Poisson simulations. Colours indicate projected density, on a logarithmic scale. We have run a first three dimensional cosmological simulation of Monge-Ampère gravity from z = 49 to z = 0, using the latest algorithms based on optimal transport-based theory. Our simulation uses ΛCDM initial conditions, but modifies the DM dynamics by replacing the Poisson equation by the Monge-Ampère equation.

Monge-Ampère gravity

If you want to describe the movement of particles under gravity, you should write the second newton law and the gravitational force can be written as a the gradient of a potential, where your gravitational potential is described by the Poisson equation:

$$\Delta\phi = 4\pi G(\rho - \bar{\rho})$$

The Poisson equation can be rewritten by using the Hessian matrix D^2 and the trace *Tr*( ).

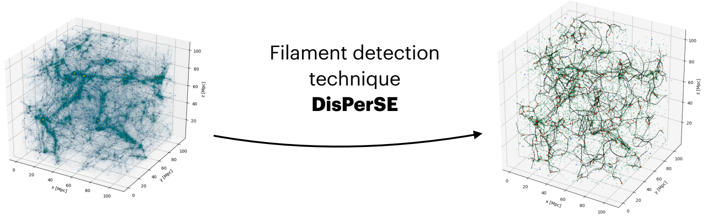
Poisson equation → Monge-Ampère equation

$$Tr(\mathbb{I} + \frac{1}{4\pi G\bar{\rho}} D^2\phi) = \frac{\rho}{\bar{\rho}} \longrightarrow Det(\mathbb{I} + \frac{1}{4\pi G\bar{\rho}} D^2\phi) = \frac{\rho}{\bar{\rho}}$$

The Poisson equation can be rewritten by using the Hessian matrix D^2 and the trace *Tr*( ). Then, Monge-Ampère gravity consists only of replacing the trace by determinant *Det*( ). This is why by expanding the determinant and retaining only the linear part, we retrieve the Poisson equation at the first order. Indeed, Monge-ampère equation is a nonlinear modification of the Poisson equation. In one dimension, Monge-Ampère is equivalent to Poisson. In other fields, in particular meteorology, replacing the Poisson equation by the Monge-Ampère equation was a fruitful approach [7].

We also emphasise that Monge-Ampère equation is invariant under a larger group of symmetries, i.e. SL(3) or unimodular affine symmetry, than the Poisson equation which is invariant only under SO(3) and does not support deformation or shearing transformations. The extra symmetry facilitates the formation of anisotropic structures such as filaments and ellipsoidal halos.

Methodology



We detect and extract the skeleton of the cosmic web using the publicly available algorithm Discrete Persistent Structure Extractor (DisPerSE) [8], applied to the whole DM distribution at z=0 in our cosmological box of 205 Mpc/h on a side for both Poisson and Monge-Ampère simulations. This algorithm identifies the cosmic skeleton from the topology of the density field, using the Discrete Morse Theory and the theory of persistence. Each filament is defined as a set of connected small segments linking extrema to saddle points.

Results

In Fig. 3, we have computed the mean connectivity from our both cosmological simulations. As the extra symmetry enhance the formation of filaments in Monge-Ampère gravity, it results the mean connectivity is higher at all halo mass.

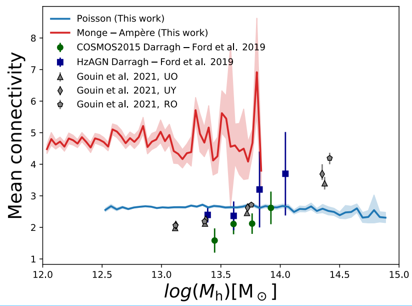


Fig. 3 Mean connectivity as function of the halo mass for both Poisson and Monge-Ampère simulations. We choose a 3σ persistence threshold to extract filaments from our simulations.

The Euclid mission will allow to explore cosmic filaments at higher redshifts with more statistics, hence providing an extraordinary dataset to robustly test the Monge-Ampère gravity model.

This poster shows that

The filament connectivity could be used as a probe of our gravity model at cosmological scales with the Euclid mission

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Based on *Boldrini et al. 2023, in prep.*

References

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