Snowmass2021 - Letter of Interest

Probing Small Scale Structures with Pulsars Timing

Thematic Areas:
☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (TF09) Astro-particle physics & cosmology

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In the ΛCDM model, the birth of structures is seeded by a spectrum of primordial curvature fluctuations generated during inflation, and then imprinted on the DM density field. On large scales (roughly for comoving wavenumbers $k \lesssim 1\,\mathrm{Mpc}^{-1}$), we can infer the spectrum of these fluctuations by looking at the cosmic microwave background anisotropies. These observations point to a nearly scale-invariant spectrum of primordial fluctuations, which is compatible with the structure that we observe on galactic and extra-galactic scales.

However on smaller length scales, theories of DM leave unique fingerprints on primordial perturbations and/or their evolution. Notable examples are: WIMP models, where DM free streaming suppresses the growth of perturbations on small scales ($k \gtrsim \mathrm{pc}^{-1}$) [1]; post inflationary axion models, where isocurvature fluctuations increase the amplitude of small scale ($k \gtrsim \mathrm{pc}^{-1}$) perturbations [2, 3]; models featuring an early stage of matter domination, during which the growth of sub-horizon perturbations is enhanced [4, 5]. These model-specific features in the primordial seeds and their evolution translate in different predictions for the amount of sub-galactic DM halos. Therefore, measuring this population of halos will be crucial in pinning down the correct model of DM.

Unfortunately these sub-galactic halos are elusive objects, mostly because they are expected to contain very little baryonic matter and therefore to be almost invisible. Because of this, gravitational probes are the natural candidate to look for such objects. Many such probes have been proposed (*e.g.* [6–9]), however their discovery power depends on the halos masses and density profiles (concentration parameters). At small masses ($M \lesssim 10^{-2} M_\odot$), where these probes lose sensitivity, Pulsar Timing Arrays (PTA) may be powerful [10–14]. The ability to test extremely light halos (as light as $M \sim 10^{-13}$) is what makes PTA searches particularly interesting. Indeed, as we mentioned above, many DM models predict an enhanced number of halos at those extremely small mass scales. Moreover, given the hierarchical formation of structures, these light halos are formed earlier in the cosmological history and therefore are generally more dense. This makes them more likely to survive tidal disruption processes which take place inside the Milky Way.

However, estimating the impact of tidal effects or, more generally, relating the power of primordial perturbations to the local population of DM halos is a task that requires expensive and dedicated numerical simulations. While these simulations are available for standard CDM [15, 16] (at least for halos in the mass range $10^4 - 10^{12} M_\odot$), little work has been done for more exotic DM models. In many cases this forces us to rely on analytic approximations whose level of accuracy is hard to establish, jeopardizing the possibility of using limits on the local population of halos to reliably constrain specific DM models. This is true not only for PTA searches, but for most of the gravitational probes that are mostly sensitive to the local population of halos, including astrometric lensing [6], strong and micro-lensing [7, 8], and photometric monitoring of caustic transiting stars [9].

The goal of the research line that we propose with this letter of interest (LoI) is twofold. In relation to the problem of deriving the local population of halos given a primordial power spectrum for density perturbations we aim to:

- By means of dedicated numerical simulations, derive the Subhalo Mass Function for well motivated DM models that increase the amplitude of density perturbations on smalls scales
- Determine the impact of tidal disruption for halos with concentration parameters larger than those predicted by standard CDM
- Develop semi-analytic models able to reproduce the numeric results mentioned in the two previous points

In relation with the use of PTAs as a probe of sub-galactic DM halos, we aim to:

- Utilize PTA data from the NANOGRAV collaboration to validate the methods proposed in [13, 14], and find the PTA parameters necessary to constrain realistic models of DM
- Further the analysis in [13, 14] from a top down approach, by projecting constraints for specific, well-motivated DM models (e.g. the axion miniclusters mentioned above) which inject power on small scales
- Determine whether the local subhalo population predicted by standard CDM can be probed by current or future PTAs

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