Simulations of ultralight axion dark matter halos

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Ultralight Axion (ULA) Dark Matter

- Alternatively to the often considered WIMPs ($m \sim 100$ GeV), dark matter may consist of ultralight (pseudo)scalar particles (WISPs). Extensive literature on scalar field dark matter (SFDM), e.g. Guzman, Urena-Lopez, Suarez, Matos, Rindler-Daller,...

- Prominent candidate: axion, originally proposed to solve the strong CP problem in QCD via the Peccei-Quinn symmetry breaking mechanism.

- String theory suggests the existence of many light pseudoscalar fields (axion-like particles, ALPs) (Arvanitaki et al. 2010)

- In a broad mass range, cosmology yields the strongest constraints on these ultralight axions (ULAs):

![Diagram showing constraints on axion mass and other processes](image)
ULA Cosmology

- See David Marsh’s recent review (arXiv:1510.07633) for details and references

- Production by *misalignment* (non-thermal) $\rightarrow$ cold condensate

- Frozen for $H \gg m$ ($\rightarrow$ dark energy), oscillating for $H \ll m$ ($\rightarrow$ dark matter)

- Change background expansion and growth of structure $\rightarrow$ constraints from
  - CMB, LSS (Hlozek et al. 2015)
  - reionization (Bozek et al. 2015)
  - halo density profiles and substructure (Marsh & Silk 2013, Schive et al. 2014, Marsh & Pop 2015, ...)
ULAs and small-scale structure

- „Quantum pressure“ prevents gravitational collapse of structures ~ below de Broglie wavelength (e.g., Hu et al. 2000):

\[ v \sim (G\rho)^{1/2} r \quad \Rightarrow \quad \lambda \sim (mv)^{-1} \sim m^{-1}(G\rho)^{-1/2} r^{-1} \]

- This introduces a „Jeans length“  

\[ r_J = \lambda \approx r \]

\[ r_J = 2\pi/k_J = \pi^{3/4}(G\rho)^{-1/4}m^{-1/2}, \]

\[ = 55m_{22}^{-1/2}(\rho/\rho_b)^{-1/4}(\Omega_m h^2)^{-1/4}\text{kpc} \quad m_{22} = m/10^{-22}\text{eV} \]

- This mass range may solve some of the small-scale problems (missing satellites, cusp-core, too-big-to-fail) (Marsh & Silk 2013), but is already under pressure from high-z UV sources (Bozek et al. 2014).
Cosmological simulations with ULA dark matter

- In the newtonian limit, ULAs obey the Schrödinger-Poisson (SP) equations:

\[
i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2a^2m} \nabla^2 \psi + mV \psi.
\]

\[
\nabla^2 V = 4\pi G a^2 \delta \rho = \frac{4\pi G}{a} \rho_0 (|\psi|^2 - 1)
\]

(SP equations also proposed for numerical solution of coarse-grained Vlasov equation for CDM by Widrow & Kaiser 1993)

- First simulations recently published by Schive et al. 2014:
Nyx
Almgren et al. 2013

• cosmology code developed at LBNL (Berkeley)
• C++ / fortran, MPI + OpenMP parallelized
• block-structured adaptive mesh refinement (AMR)
• unsplit PPM hydro scheme + particles + particle-mesh gravity
• star particles with feedback + multi-phase ISM model

additional physics:
• ULA dark matter (alternative methods):
  1. Schrödinger solver (implicit or explicit)
  2. particle-mesh solver for Madelung equations:

\[
\dot{\rho} + \nabla (\rho \mathbf{v}) = 0 \quad \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla (Q + V)
\]

\[
\mathbf{v} = m^{-1} \nabla S \\
Q = -\frac{\hbar^2}{2m^2} \frac{\nabla \sqrt{\rho}}{\sqrt{\rho}}
\]

„quantum pressure“
Boson star (or halo) collisions

- Individual halos are newtonian oscillaton solutions (Guzman & Urena-Lopez 2004), i.e. equilibrium configurations of SP
- Schrödinger equation:

\[ \psi(z, t) = \sum \psi_{n}(z) e^{i \omega_{n} t} \]

- Madelung equation:
Halo merger simulations with Schrödinger-Poisson solver

Initial conditions: stationary „boson halo“ solutions
Halo merger simulations with Schrödinger-Poisson solver

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Halo merger simulations with PM solver (Madelung picture)

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**Halo profiles and core masses**

Schive et al. 2014

Schwabe, Veltmaat, JN, in prep.

**Madelung**

**Schrödinger**

**Madelung**

Simulations with ultra-light axions

Jens Niemeyer, Göttingen
First cosmological simulation with Madelung PM method

Simulations with ultra-light axions

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Stochastic merger trees for ULA halos

- quantum Jeans length $\rightarrow$ modifications w.r.t. CDM (Marsh & Silk 2013):
  - transfer function with small-scale cutoff
  - critical density for collapse higher near Jeans mass
  - scale dependent growth function

- idea: use modified stochastic merger tree (à la Lacey & Cole 1993) in semi-analytic model for galaxy formation, including small-scale cutoff and solitonic core profile

- implemented into semi-analytic code for galaxy evolution *Galacticus* (Benson 2010)

- plan: compute constraints from early structure formation and reionization (Du, JN, Behrens, in prep.)
Stochastic merger trees for ULA halos: substructure

- Halo substructure models from parameter study of
  - dynamical friction
  - tidal stripping
  - tidal heating
- computational challenge: have to solve excursion set barrier distribution function numerically
Summary

- Ultra-light axions can be some or all of dark matter

- Interesting nonlinear phenomenology for LSS if de Broglie wavelength is of order several kpc (i.e. $m \sim 10^{-22}$ eV)

- Constraints from nonlinear clustering, degeneracies with neutrinos, etc. (e.g. from Lyman alpha forest) require simulations

- May or may not affect "$\text{CDM small scale crisis}"$ (missing satellites, cusp-core, too-big-to-fail)

- Newtonian dynamics described by Schrödinger-Poisson equations

- Madelung (fluid) picture appears to be more efficient and robust for cosmological simulations, but resolution issues remain

- Semi-analytic models with modified halo merger trees for constraints from early structure formation and reionization