Simulations of ultralight axion dark matter halos

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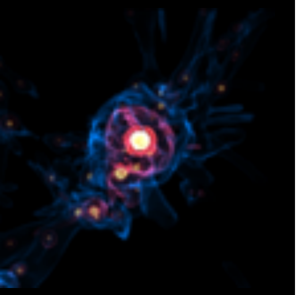
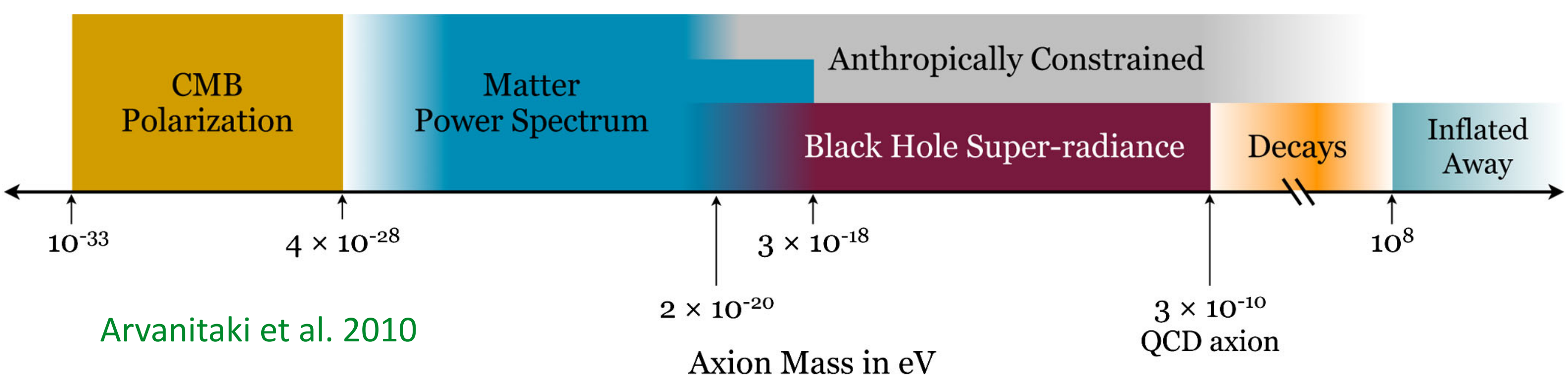
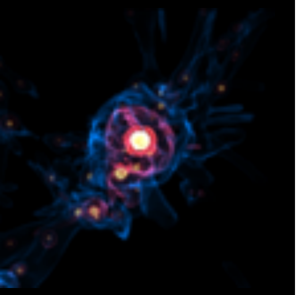


Ultralight Axion (ULA) Dark Matter

- Alternatively to the often considered WIMPs (m ~ 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):

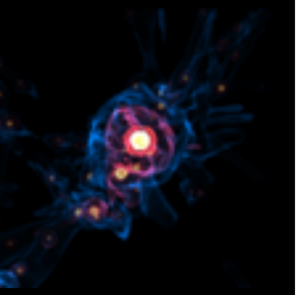


Arvanitaki et al. 2010



ULA Cosmology

- See David Marsh's recent review (arXiv:1510.07633) for details and references
- Production by *misalignment* (non-thermal) → cold condensate
- Frozen for H ≫ m (→dark energy), oscillating for H ≪ m (→dark matter)
- Change background expansion and growth of structure → 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

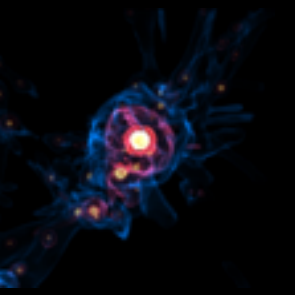
- „Quantum pressure“ prevents gravitational collapse of structures ~ below de Broglie wavelength (e.g., Hu et al. 2000):

$$v \sim (G\rho)^{1/2} r \qquad \Rightarrow \qquad \lambda \sim (mv)^{-1} \sim m^{-1}(G\rho)^{-1/2} r^{-1}$$

- This introduces a „Jeans length“ $r_J = \lambda =: r$

$$r_J = 2\pi/k_J = \pi^{3/4}(G\rho)^{-1/4} m^{-1/2}\,,$$
$$= 55 m_{22}^{-1/2} (\rho/\rho_b)^{-1/4} (\Omega_m h^2)^{-1/4} \mathrm{kpc} \qquad m_{22} = m/10^{-22}\mathrm{eV}$$

- 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

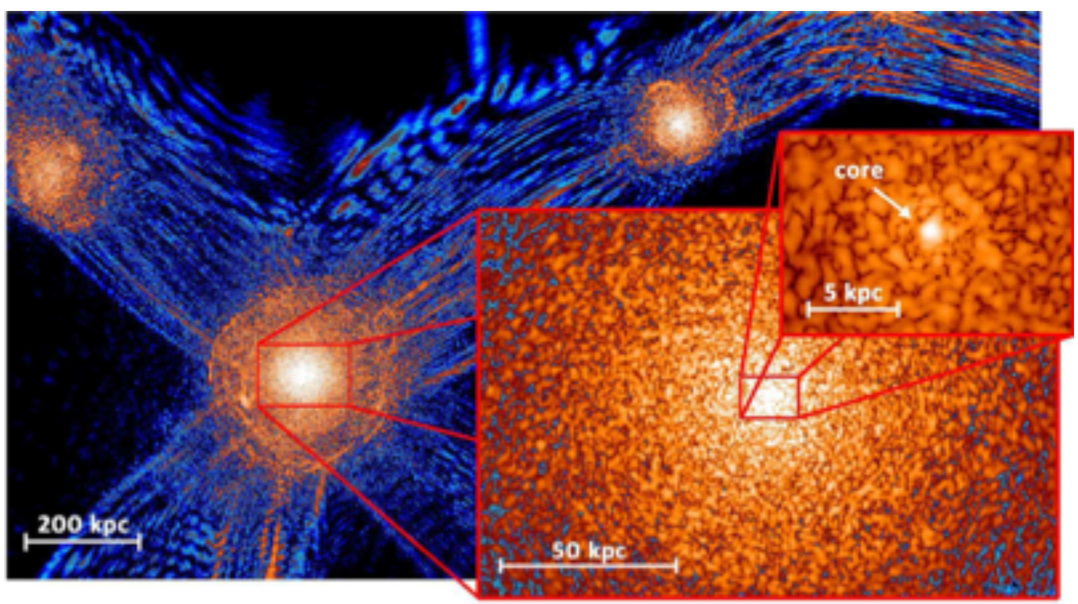
- In the newtonian limit, ULAs obey the Schrödinger-Poisson (SP) equations:

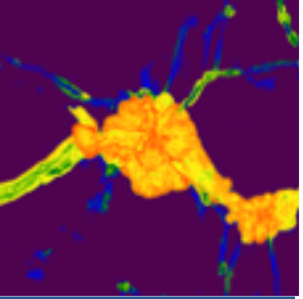
$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2a^2 m}\nabla^2 \psi + mV\psi$$

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

(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

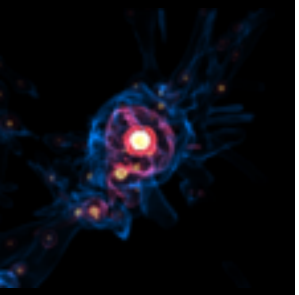
additional physics:

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

$$\dot{\rho} + \nabla(\rho \mathbf{v}) = 0 \qquad \dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla(Q + V)$$

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

„quantum pressure“



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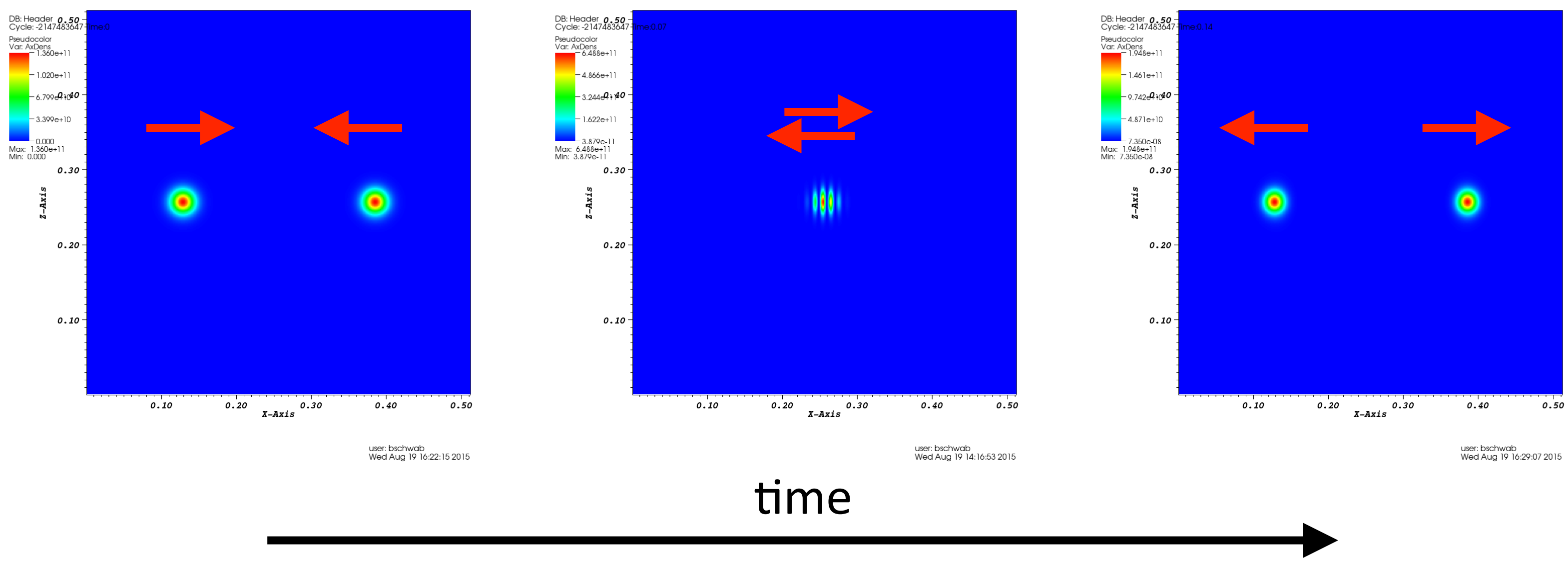
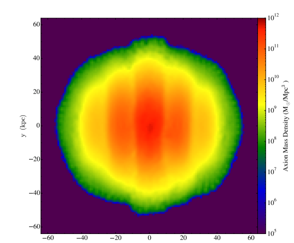
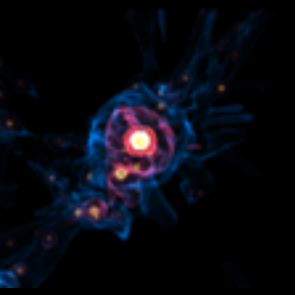
Boson star (or halo) collisions

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



- Madelung equation:





Halo merger simulations with Schrödinger-Poisson solver

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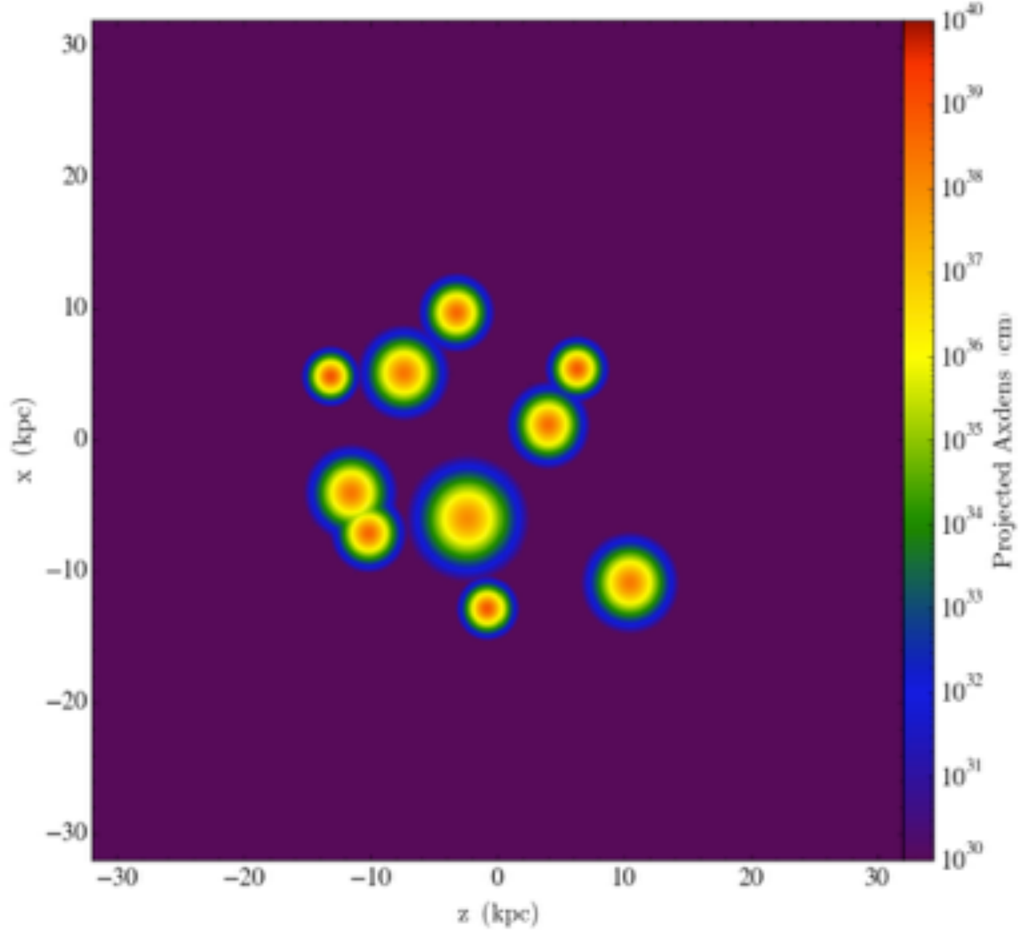
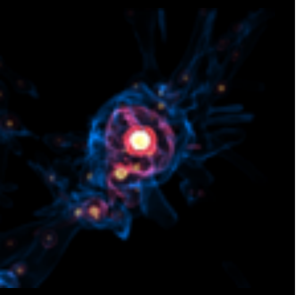


Initial conditions:
stationary „boson halo“ solutions



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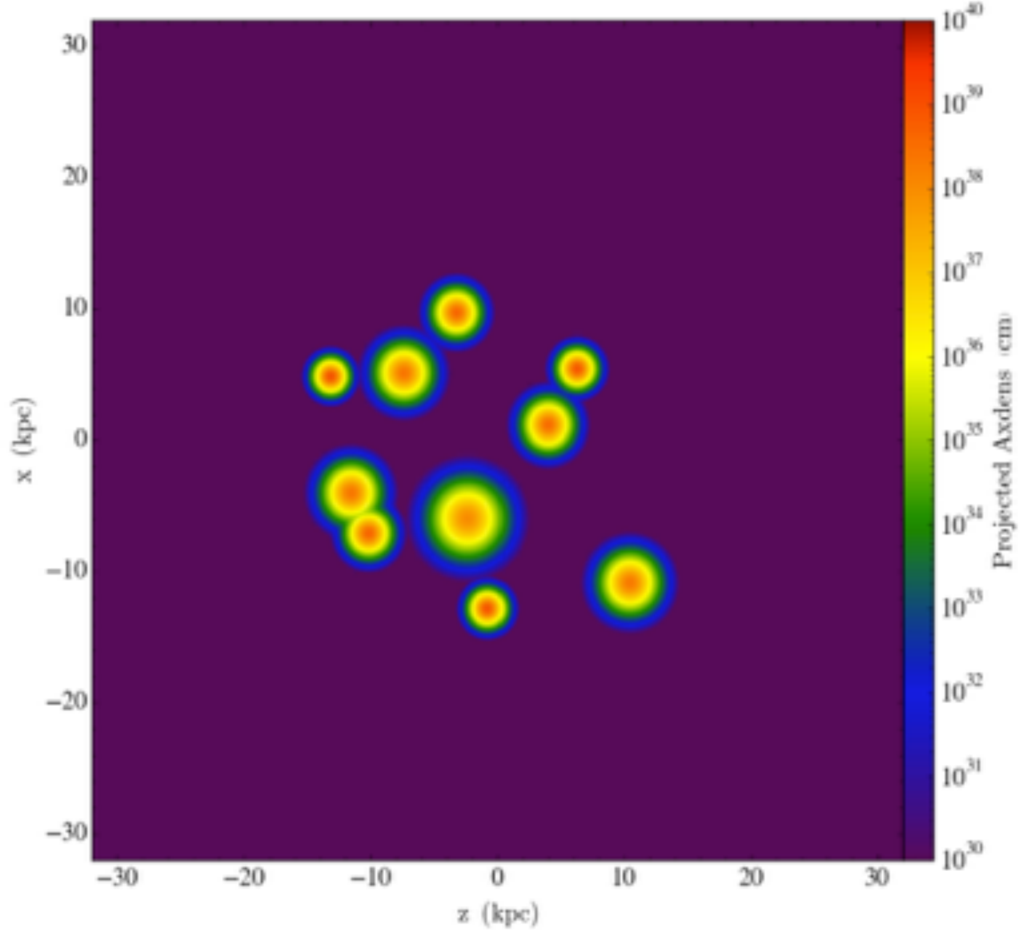
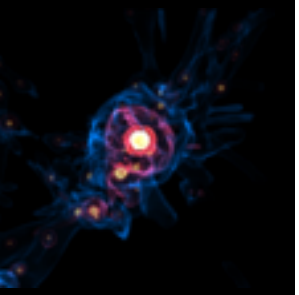


Initial conditions:

stationary „boson halo“ solutions



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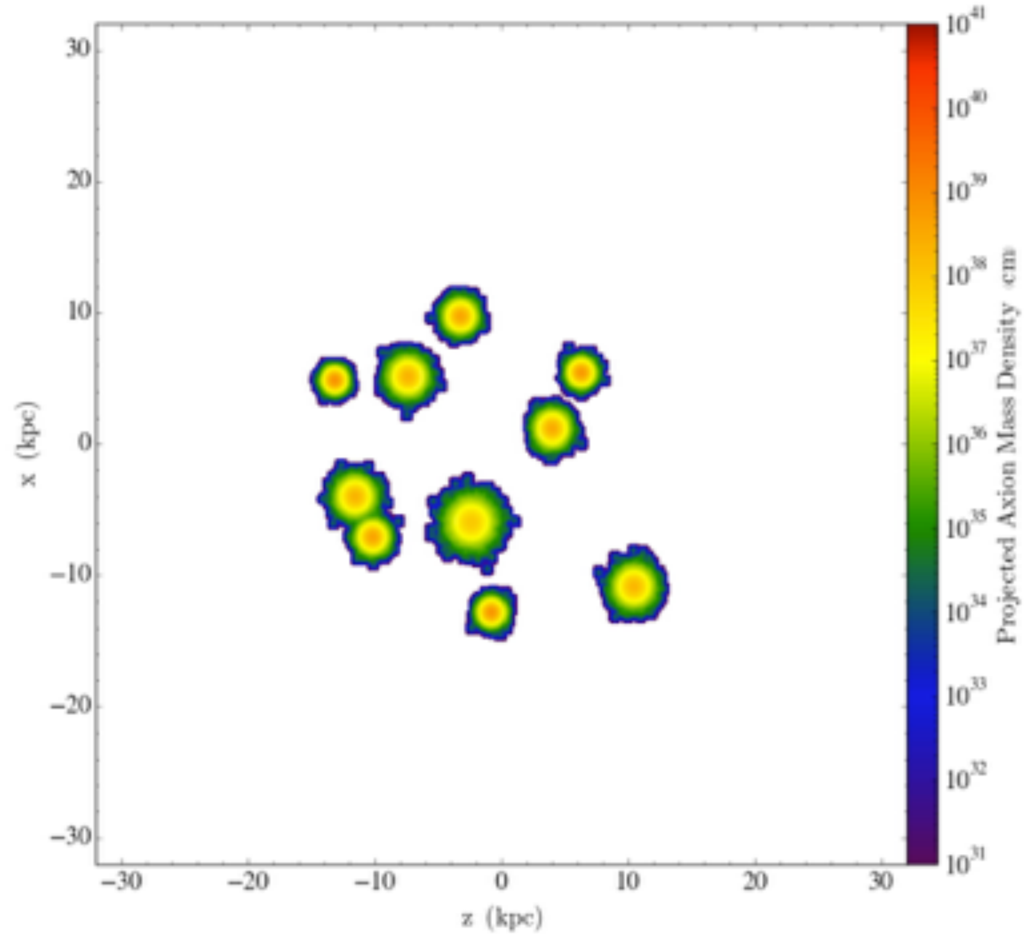
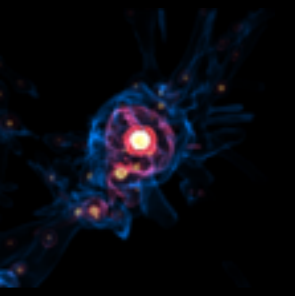
Halo merger simulations with PM solver (Madelung picture)



Initial conditions:
stationary „boson halo“ solutions



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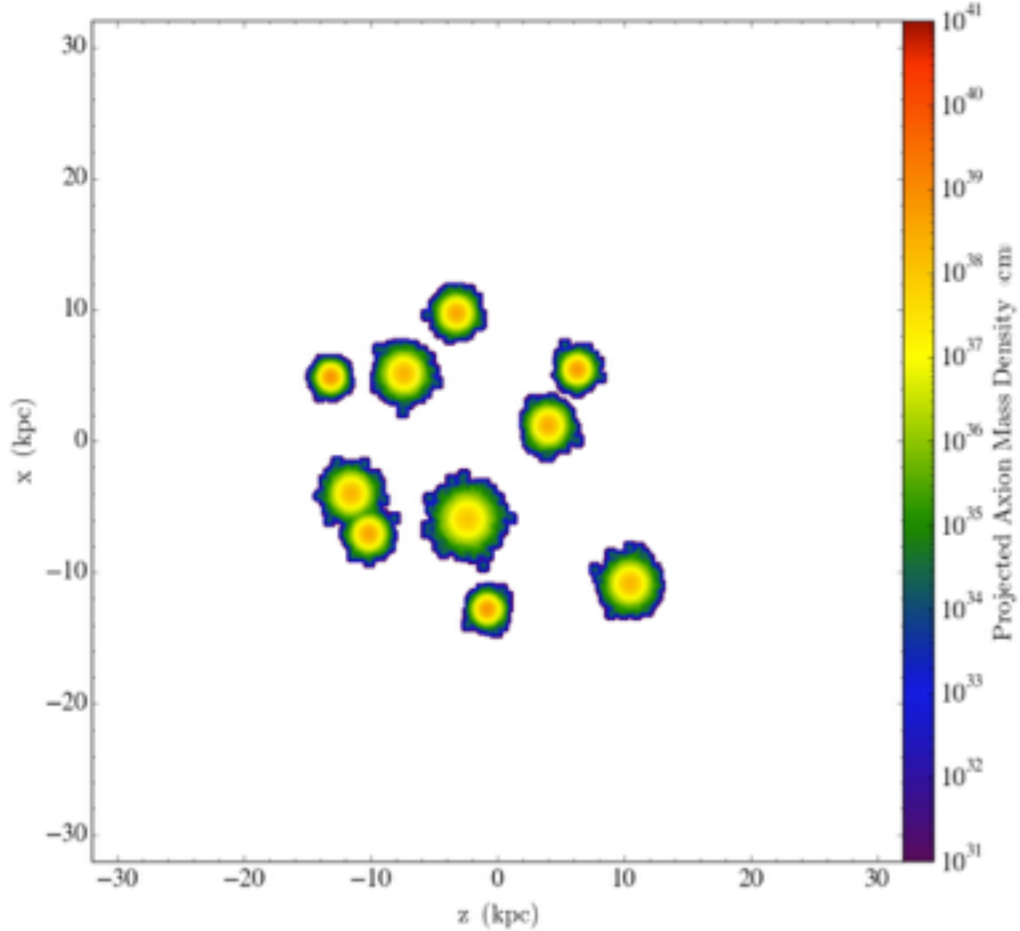
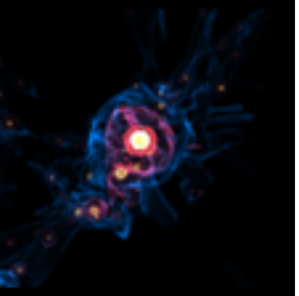
Halo merger simulations with PM solver (Madelung picture)



Initial conditions:
stationary „boson halo" solutions



Halo profiles and core masses

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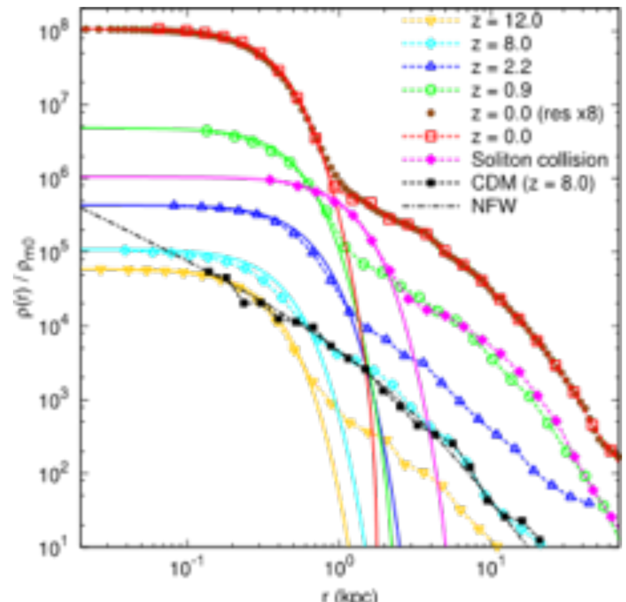
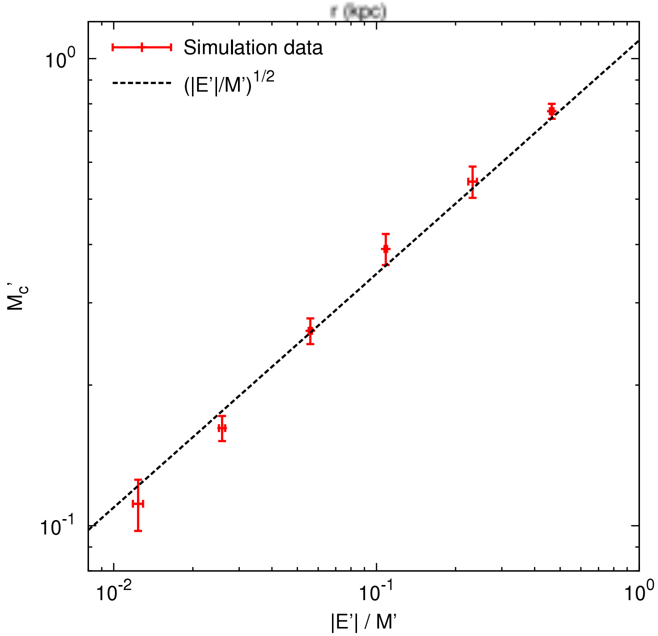
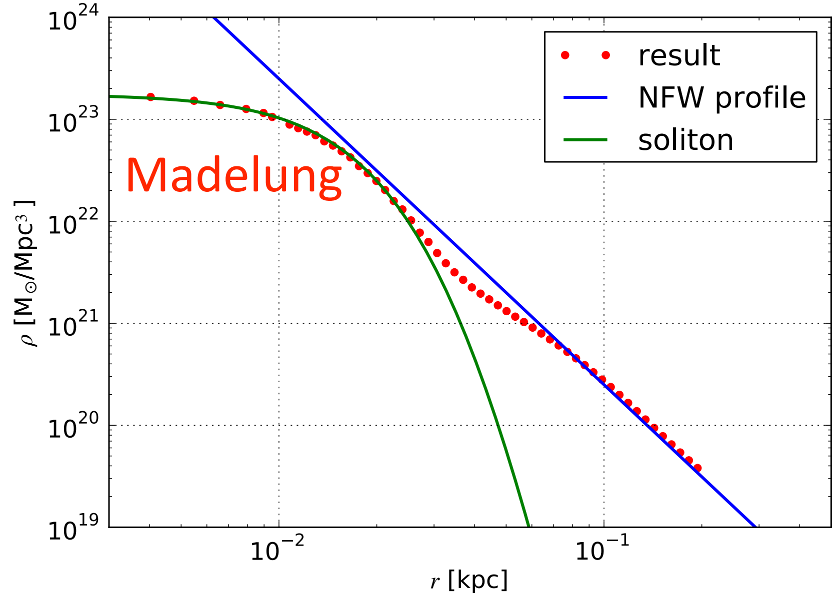
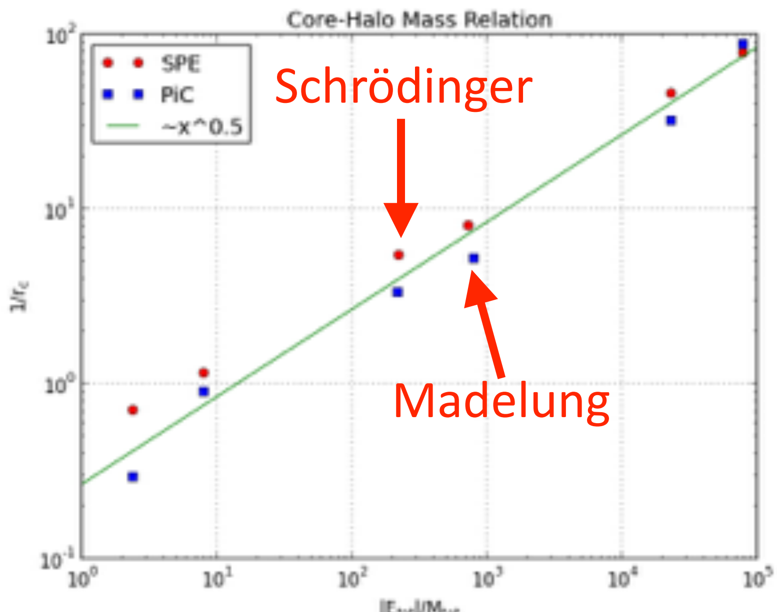
Schive et al. 2014



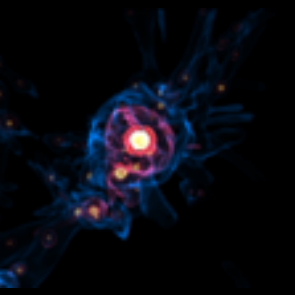


Schwabe, Veltmaat, JN, in prep.





First cosmological simulation with Madelung PM method



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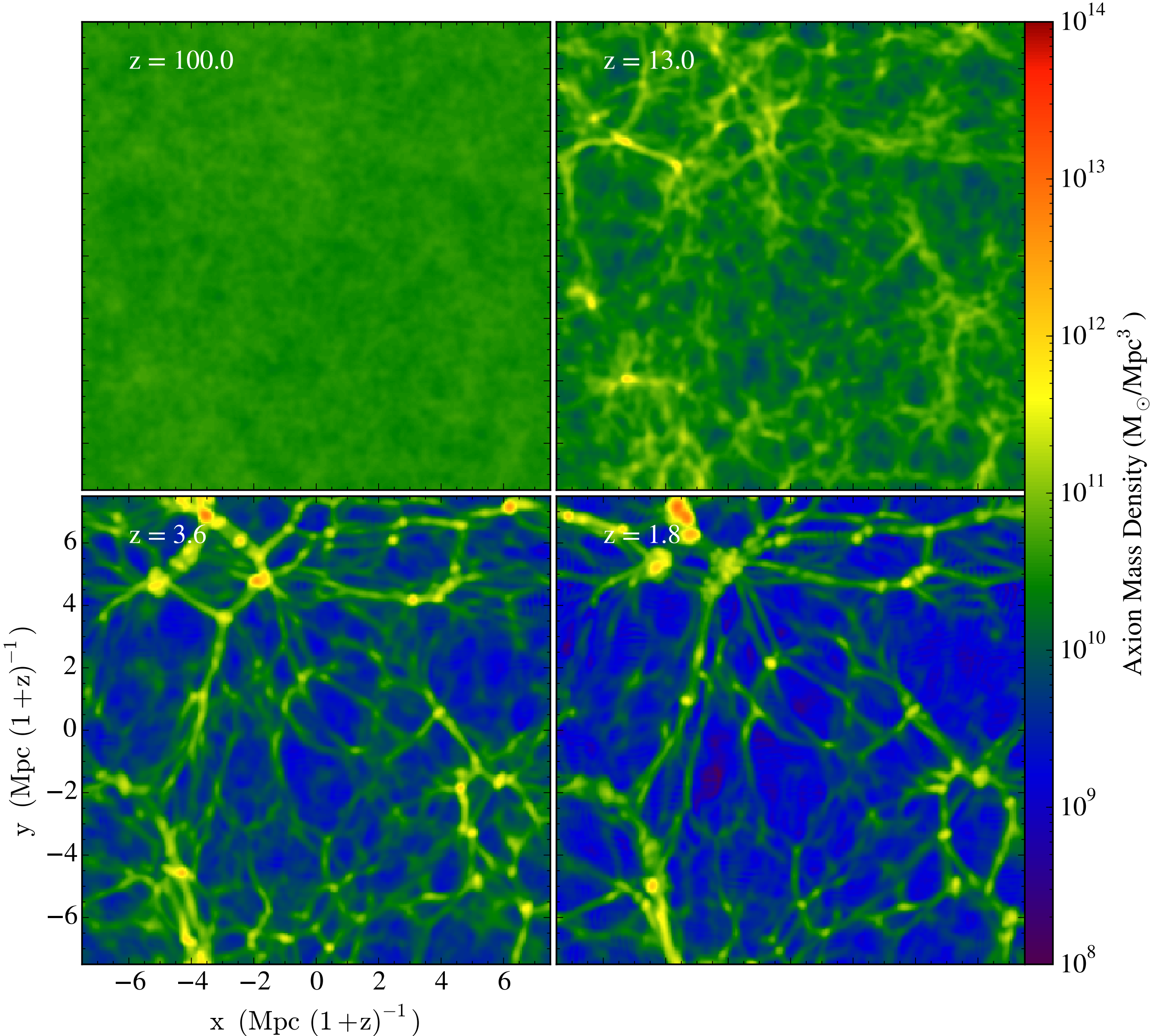
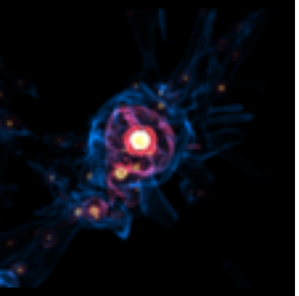
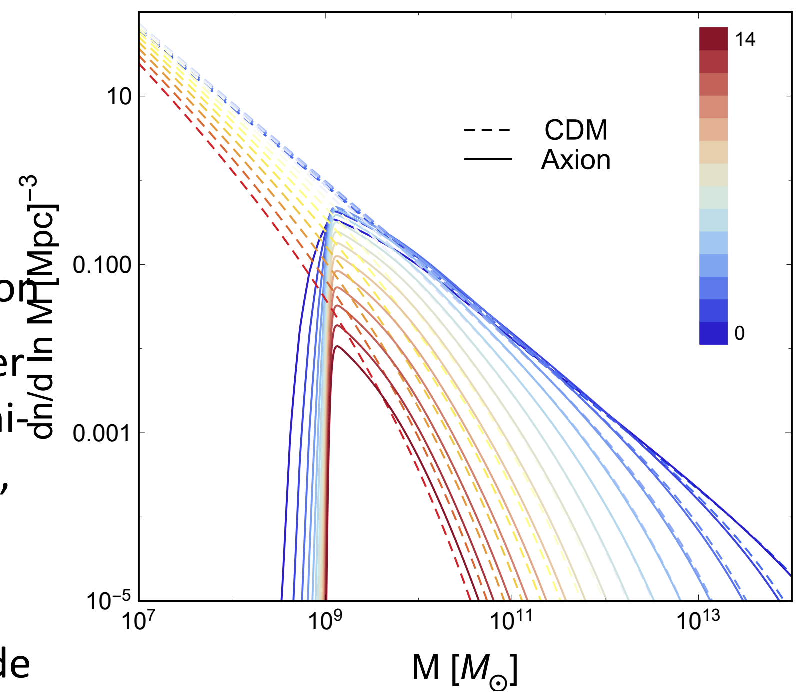
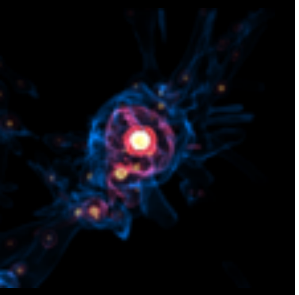




Stochastic merger trees for ULA halos

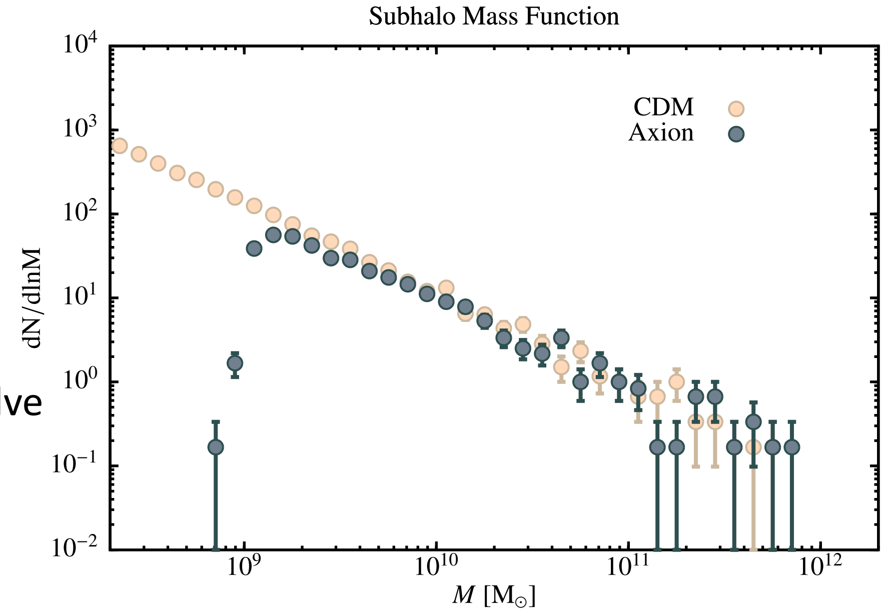
- quantum Jeans length → modifications w.r.t. CDM (Marsh & Silk 2013):
  - transfer function with small-scale cutoff
  - critical density for collapse higher near Jeans mass
  - scale dependent growth function
- idea: use modified stochastic merger tree (à la Lacey & Cole 1993) in semi-analytic model 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.)

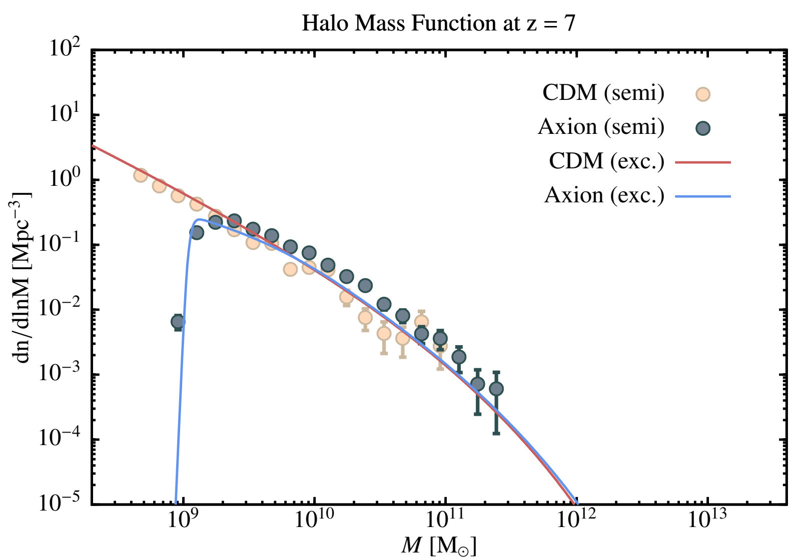


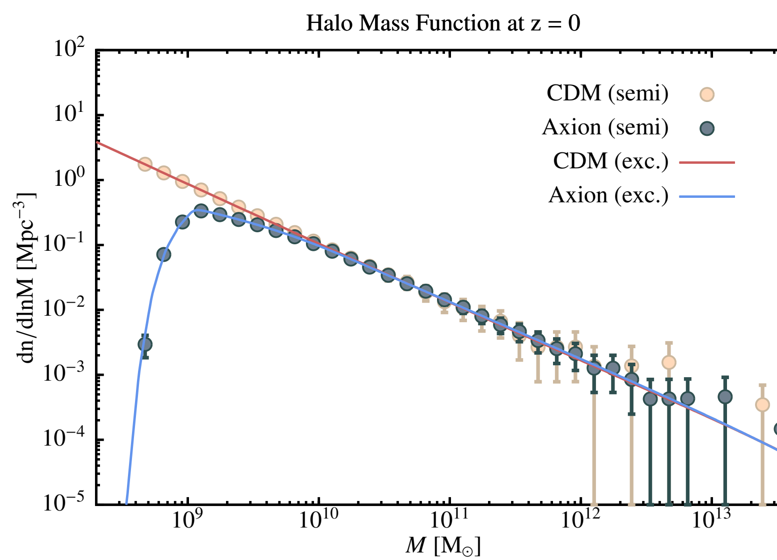


Stochastic merger trees for ULA halos: substructure

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







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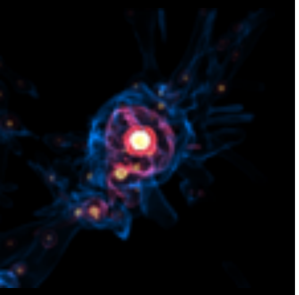

Summary

- 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 ~ 10^{-22} eV)
- Constraints from nonlinear clustering, degeneracies with neutrinos, etc. (e.g. from Lyman alpha forest) require simulations
- May or may not affect „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