Simulations of ultralight axion dark matter halos

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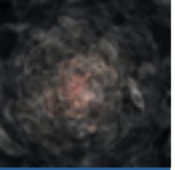
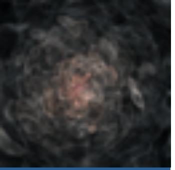


Overview

3 kinds of simulations, from small to large scales:

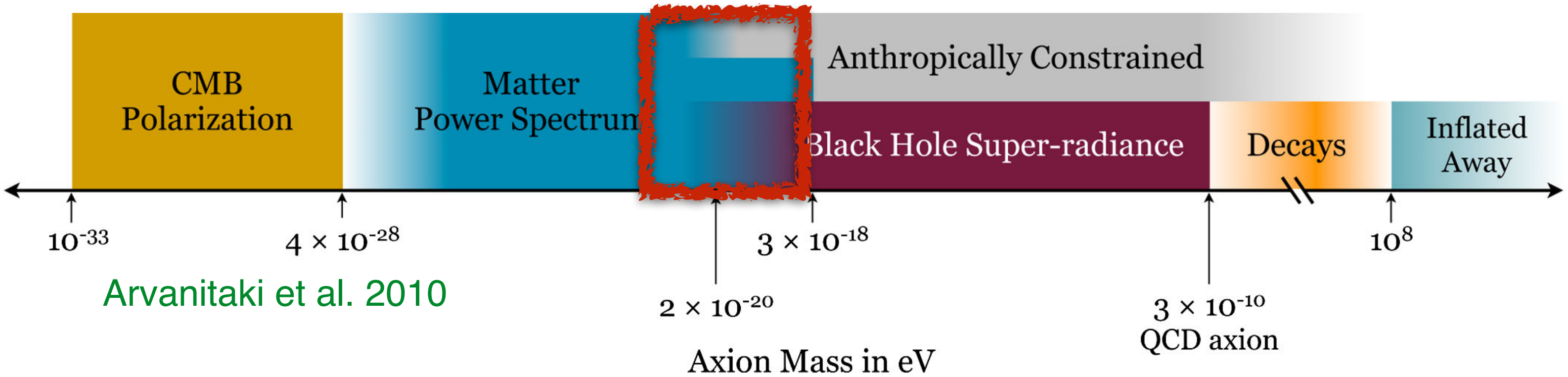
- Grid-based Schrödinger-Poisson simulations: mergers of solitonic halo cores (arXiv:1606.05151)
- Particle-mesh Madelung-Poisson simulations: cosmological simulations with and without „quantum pressure“ (arXiv:160x.xxxxx)
- Stochastic merger trees and semi-analytic models for subhalo evolution: subhalo and core mass function (arXiv:160x.xxxxx)



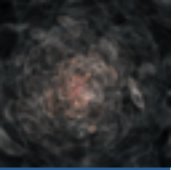
Ultralight Axion Dark Matter

- Conceptual overlap of „scalar field DM“, „BEC DM“ (Gross-Pitaevskii equ.), „ultralight axion DM“, and „fuzzy DM“ (Hu et al. 2000), albeit with different particle physics and/or cosmological motivations
- Production by *misalignment* (non-thermal) → cold condensate
- Small mass → large occupation numbers → classical field equations
- H ≪ m , k → Newtonian dynamics
- Change background expansion and growth of structure → constraints from:
  - CMB, LSS (Hlozek et al. 2015)
  - reionization, high-z UV luminosity function (Bozek et al. 2015, Schive et al. 2016)
  - halo density profiles and substructure (Marsh & Silk 2013, Schive et al. 2014, Marsh & Pop 2015, Calabrese & Spergel 2016)

} nonlinear



Arvanitaki et al. 2010



ULAs and small-scale structure

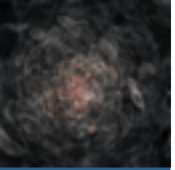
- „Quantum pressure“ prevents gravitational collapse of structures ~ below de Broglie wavelength (e.g., Hu et al. 2000):

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

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

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

- 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

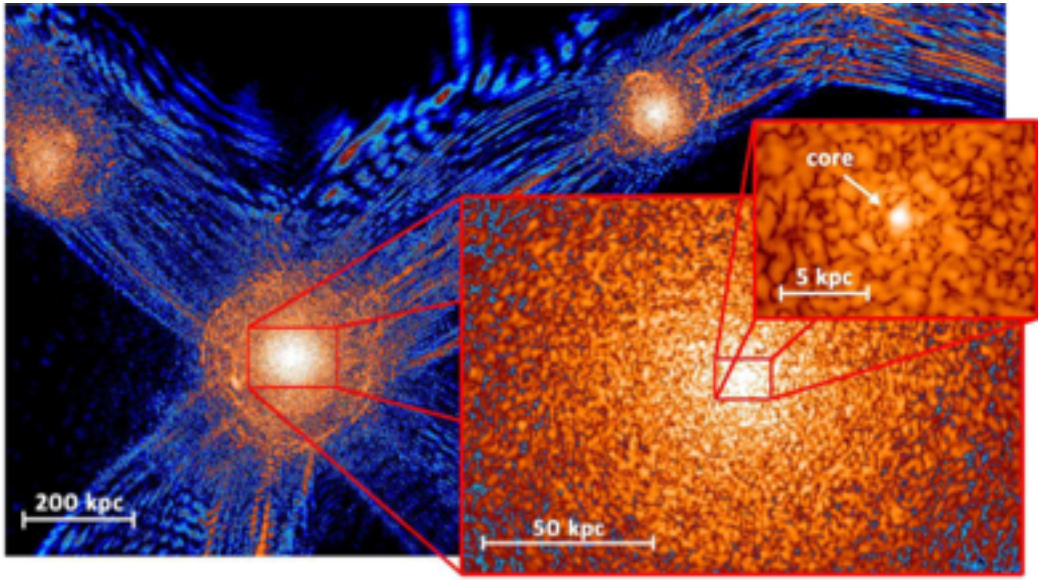
- In the Newtonian limit, ULAs obey the Schrödinger-Poisson (SP) equations:

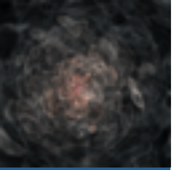
$$i\hbar\frac{\partial\psi}{\partial t}=-\frac{\hbar^2}{2a^2m}\nabla^2\psi+mV\psi$$

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

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

- First (2 Mpc)^3 simulation resolving solitonic halo cores 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

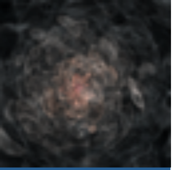
additional physics:

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

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

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

„quantum pressure“



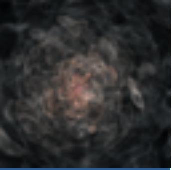
Schrödinger-Poisson simulations of merging solitonic cores

(Schwabe,JN,Engels; arXiv:1606.05151)

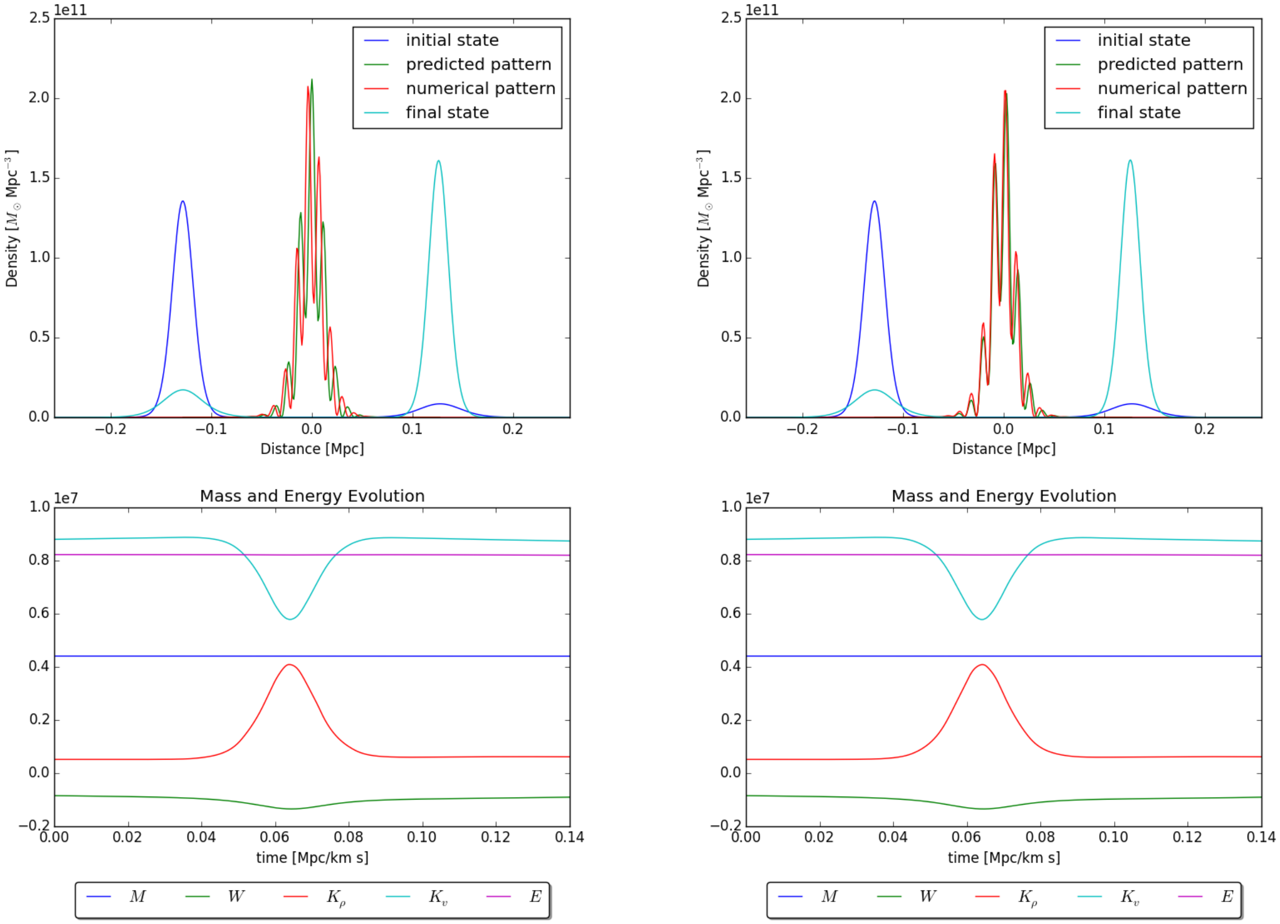
- Motivation: cosmological simulations (Schive et al. 2014) find formation of solitonic halo cores, i.e. Newtonian oscillaton solutions a.k.a. boson stars.

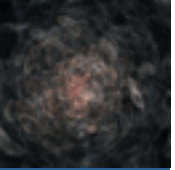
- Potential observable consequences:
  - dwarf galaxy cores (Marsh & Pop 2015, Calabrese & Spergel 2016)
  - offset between dark and visible matter in Abell 3827 from DM cores in phase opposition (Paredes & Michinel 2015)
  - halo substructure (e.g. from lensing power spectrum)
  - first stars / SMBH seeds
  - reionization

- Simulate core mergers to measure:
  - mass loss from gravitational cooling
  - dependence on mass ratio, angular momentum, total energy, relative phase
  - density profile of final core + halo

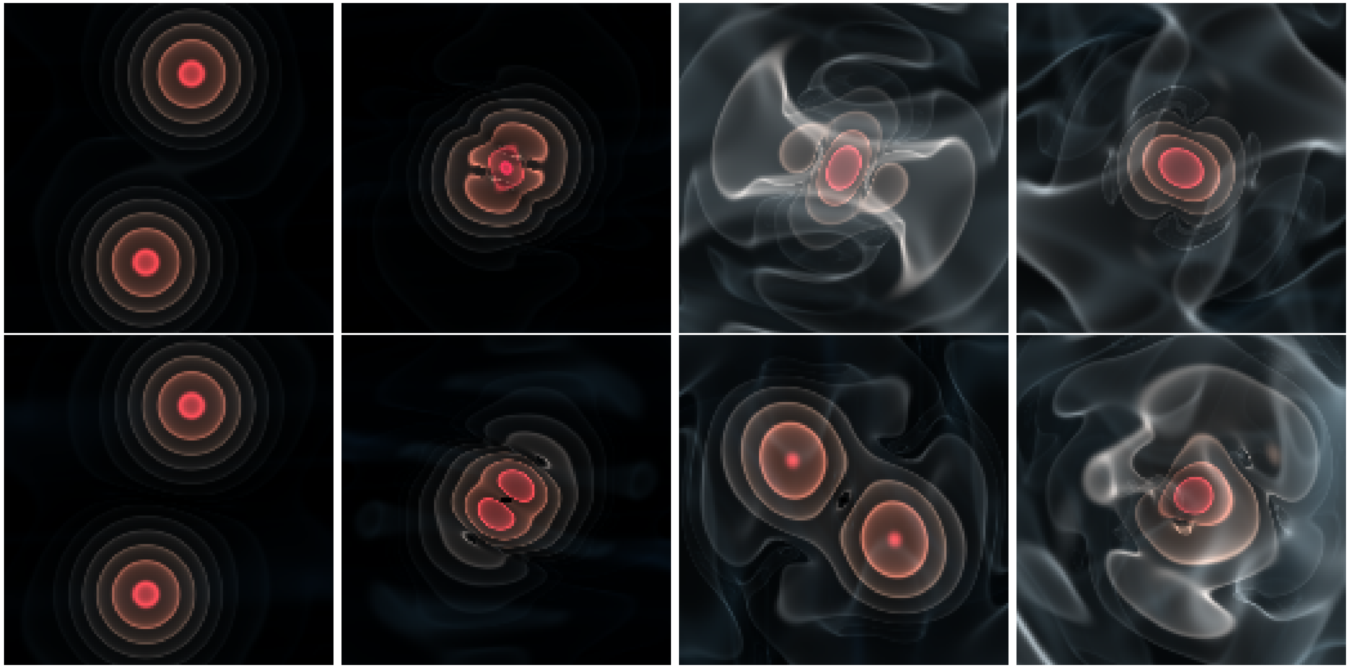


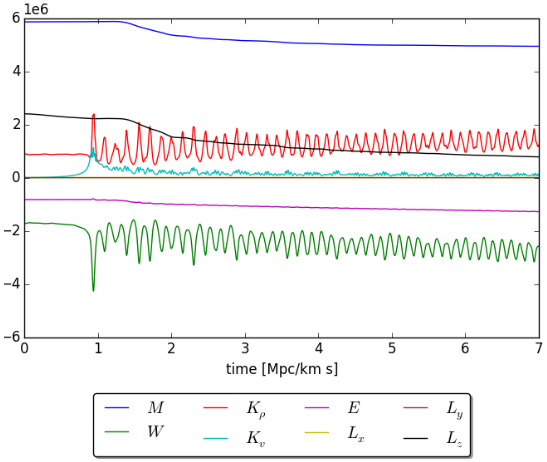
Unbound core collisions

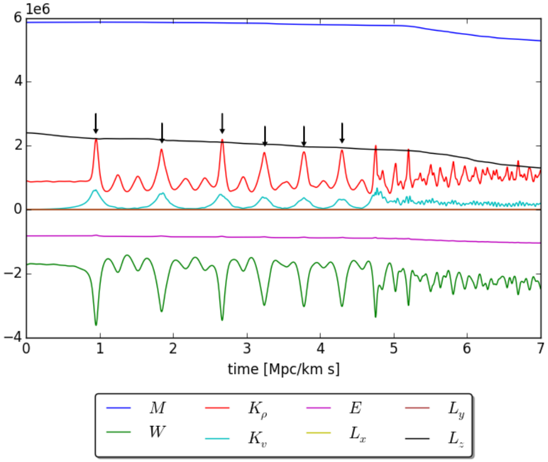


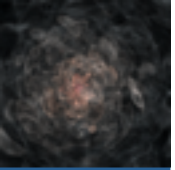


Bound binary mergers: phase dependence

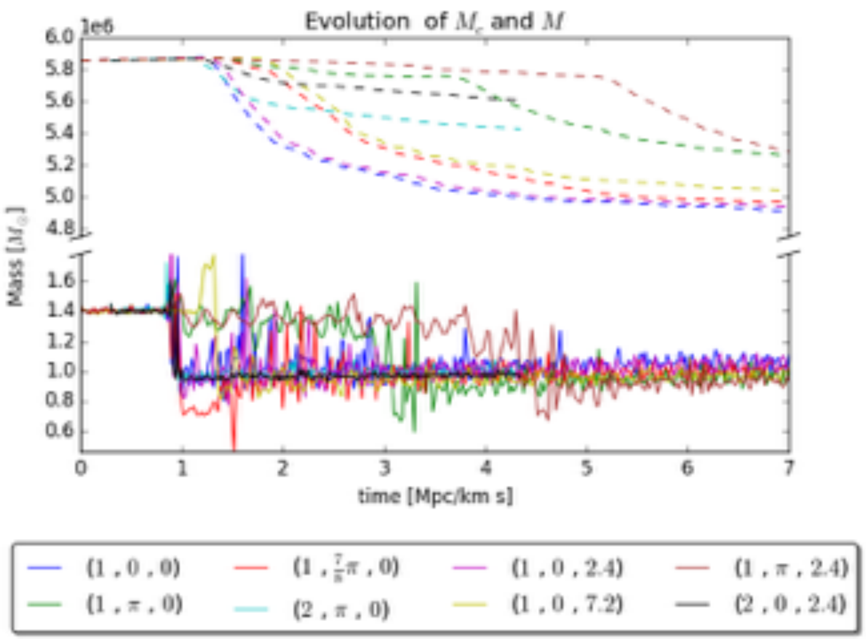


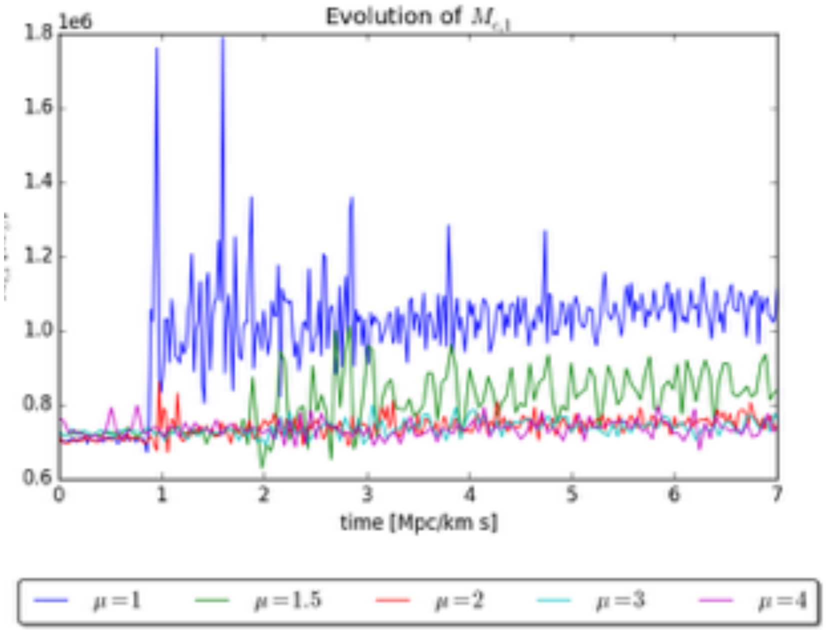




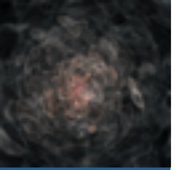


Bound binary mergers: summary

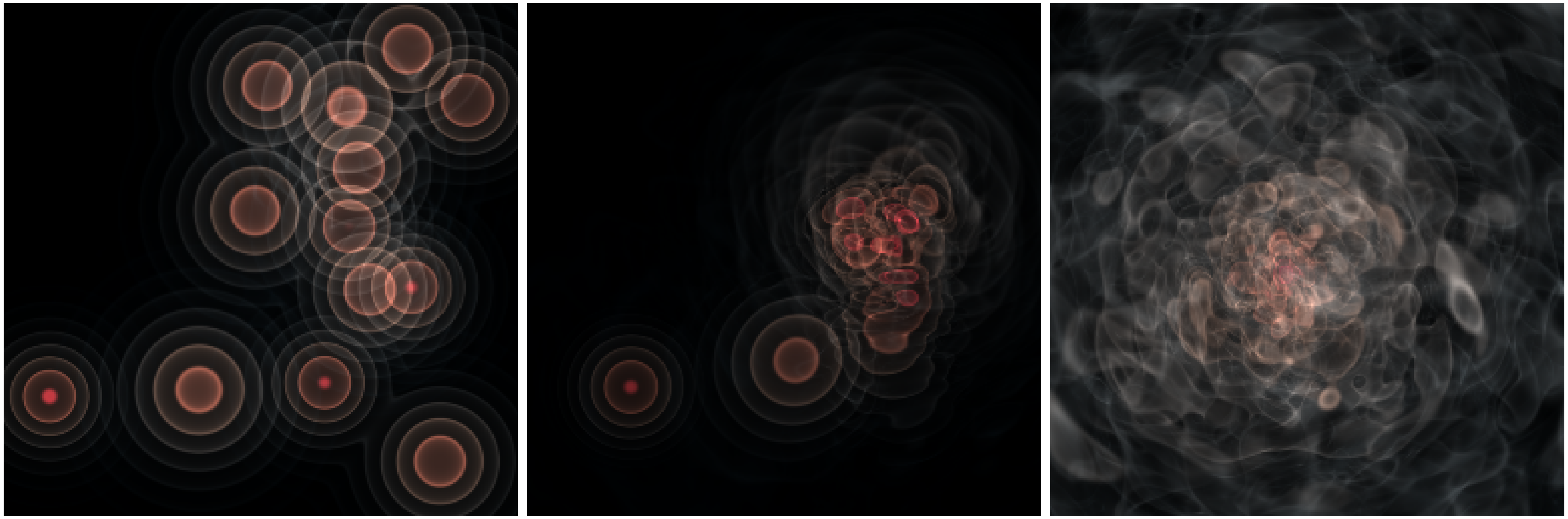


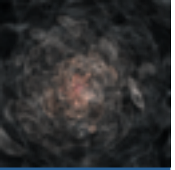


- final core mass practically independent of:
  - – angular momentum
  - – phase (bounces only for exact phase opposition)
- weak dependence on:
  - – total energy
  - – mass ratio (no growth of more massive core for μ > 2)

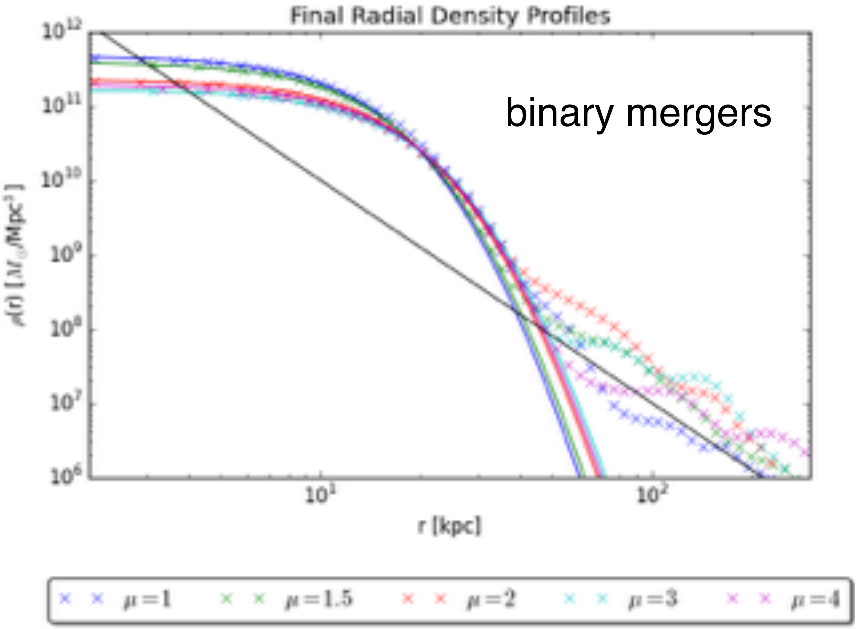


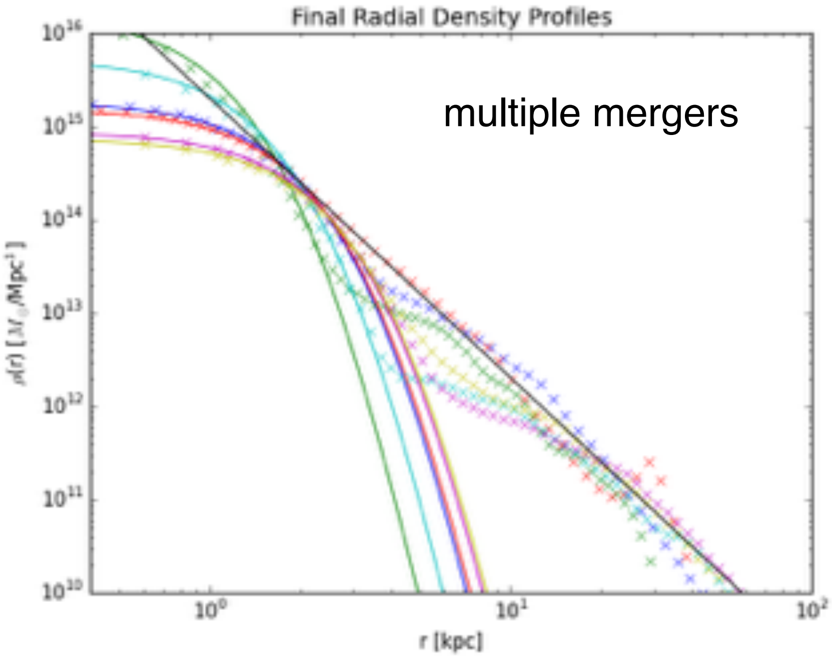
Mergers of multiple cores (random phases and mass ratios)



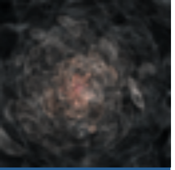


Density profiles for binary and multiple mergers

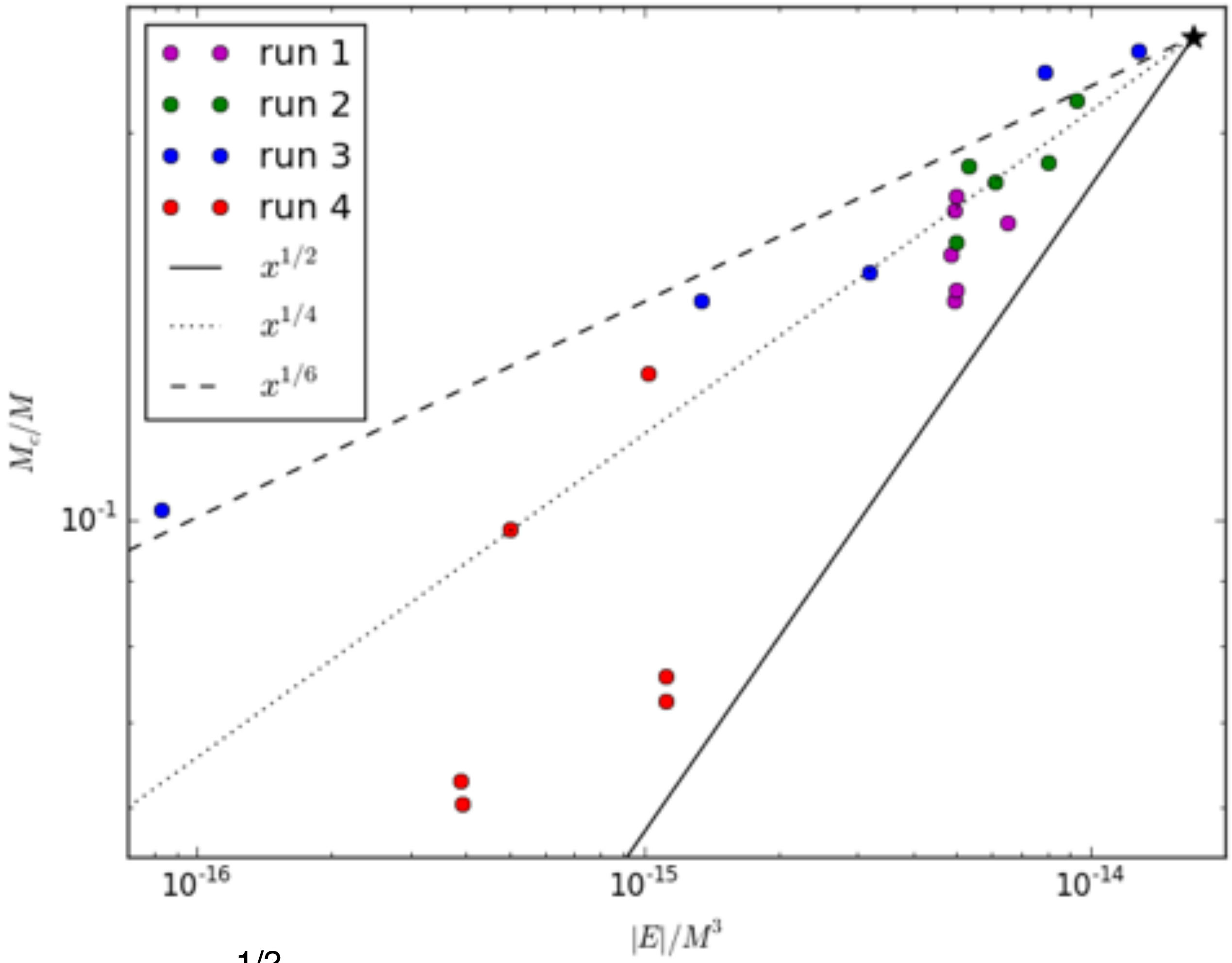




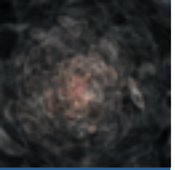
- core follows solitonic boson star profile
- halo has logarithmic slope of -3 like outer part of NFW profile
- agrees with cosmological simulation (Schive et al. 2014)



Dependence on total energy



- $M_c \sim (|E|/M)^{1/2}$ found by Schive et al. 2014 not confirmed
- possible reason for spurious detection: residual scale invariance of SP equations (eliminated above by normalization to M)



Particle-Mesh Simulations of the Madelung-Poisson Equations

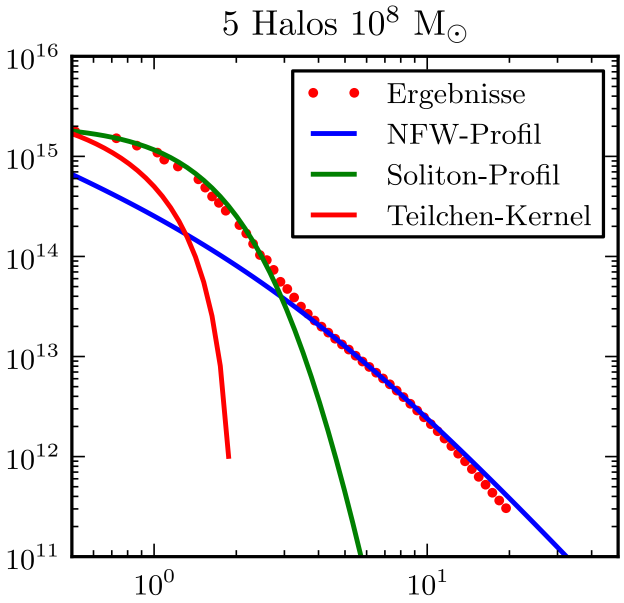
(Veltmaat & JN)

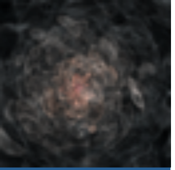
- Madelung transformation of Schrödinger-Poisson equations:

$$\Psi = \sqrt{\frac{\rho(\mathbf{x},t)}{m}} \exp(iS(\mathbf{x},t)/\hbar) \qquad \mathbf{v} = m^{-1}\nabla S \qquad Q = -\frac{\hbar^2}{2m^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}$$

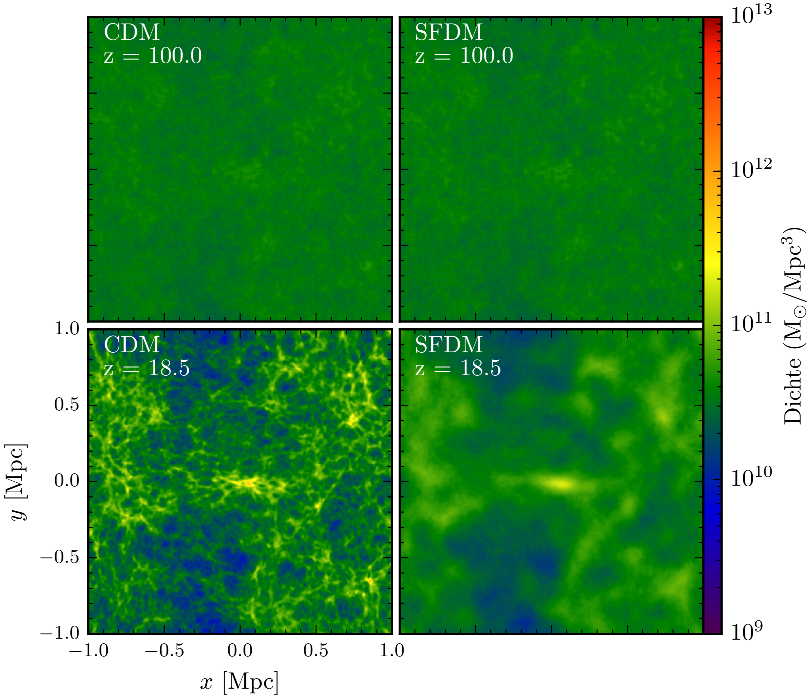
$$\dot{\rho} + \nabla(\rho\mathbf{v}) = 0 \qquad \dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla(Q+V)$$

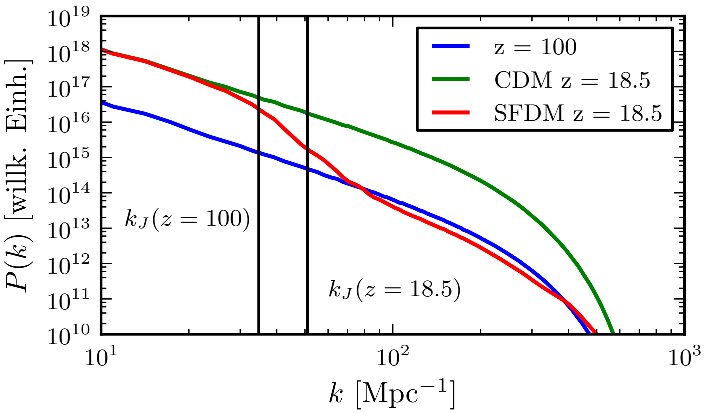
- SPH-like implementation of Q with energy conserving formalism
- tested with binary / multiple core mergers
- core collisions / mergers:
  - – reproduces core-halo profile
  - – interference patterns unresolved
  - – superior velocity representation

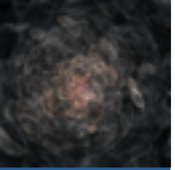




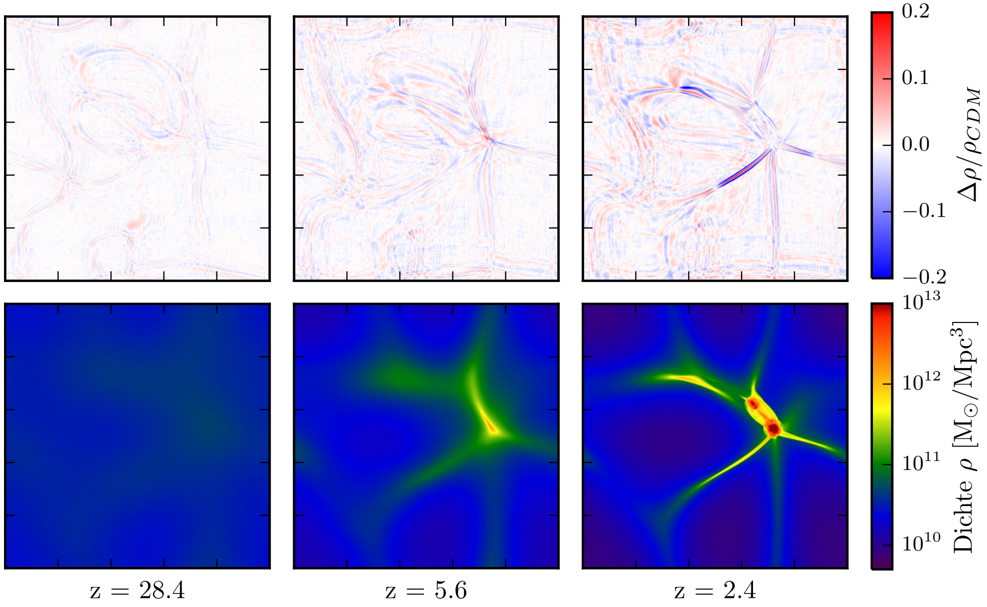
CDM initial conditions: effect of quantum pressure

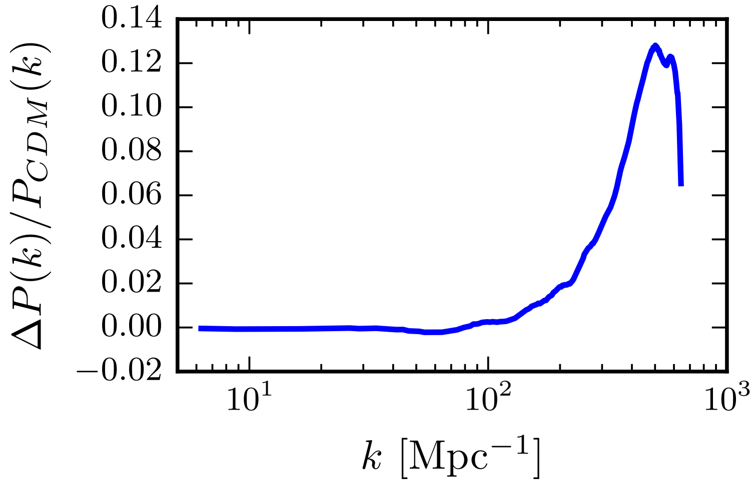




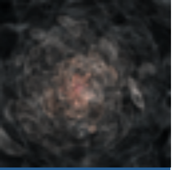


Axion DM initial conditions: effect of „quantum pressure“





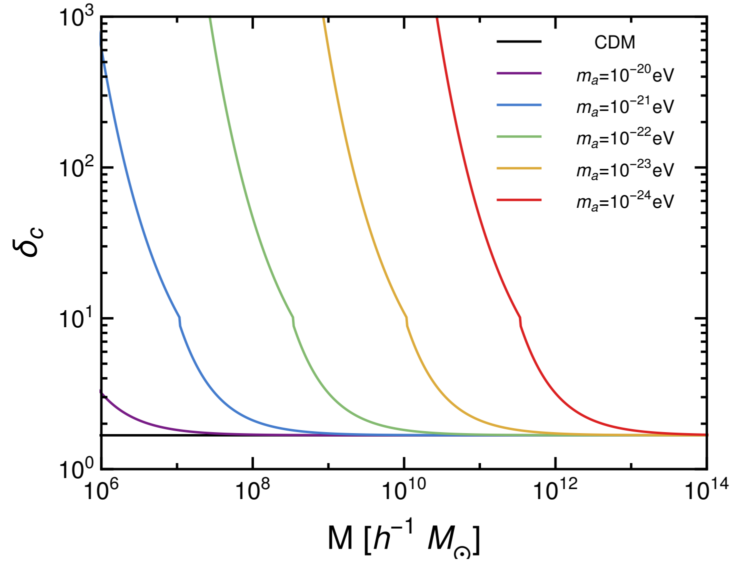
O(10%) difference in power spectrum compared to CDM

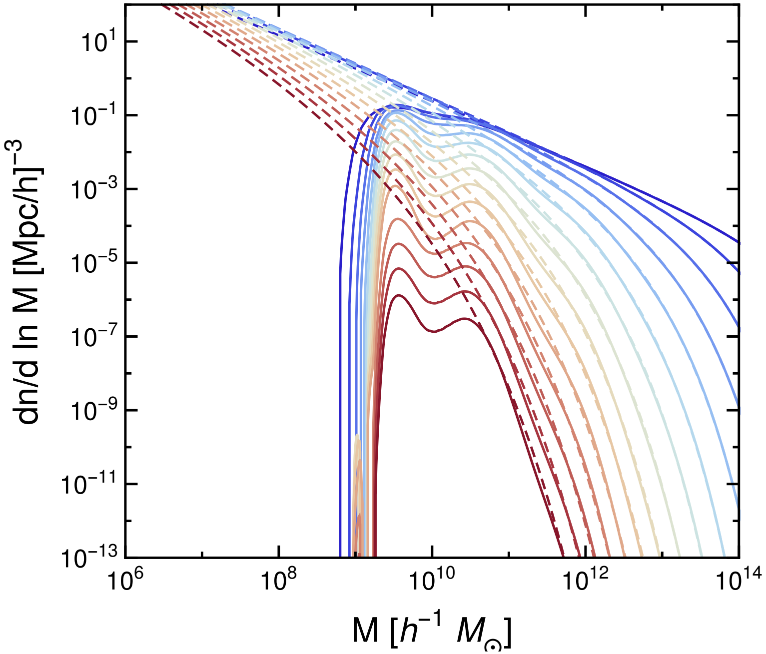


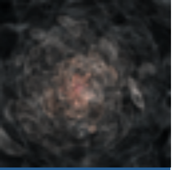
Stochastic merger trees for ULA halos

(Du,JN,Behrens)

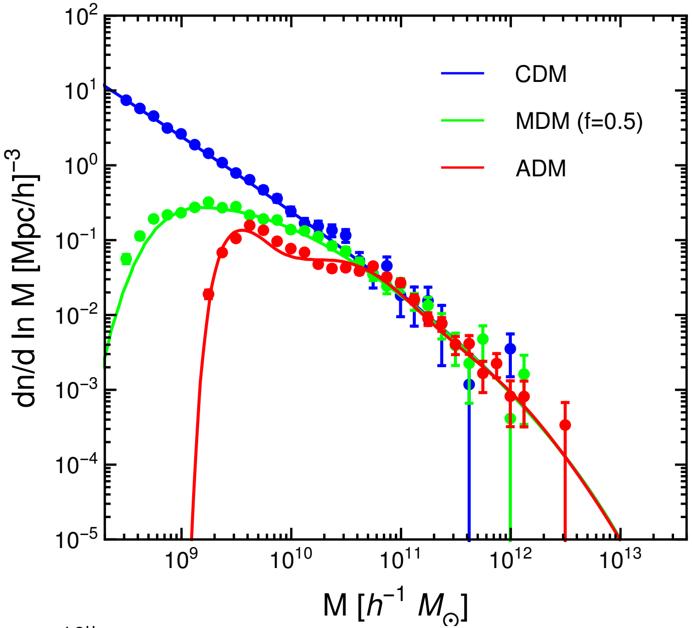
- quantum Jeans length → modifications w.r.t. CDM (Marsh & Silk 2013):
  - transfer function with small-scale cutoff
  - critical density for collapse higher near Jeans mass
  - scale dependent growth function
- use modified stochastic merger tree (Lacey & Cole 1993) including small-scale cutoff and solitonic core
- implemented into semi-analytic code for galaxy evolution *Galacticus* (Benson 2010)
- computational challenge: need to solve excursion set barrier distribution function numerically
- compute constraints from subhalo statistics

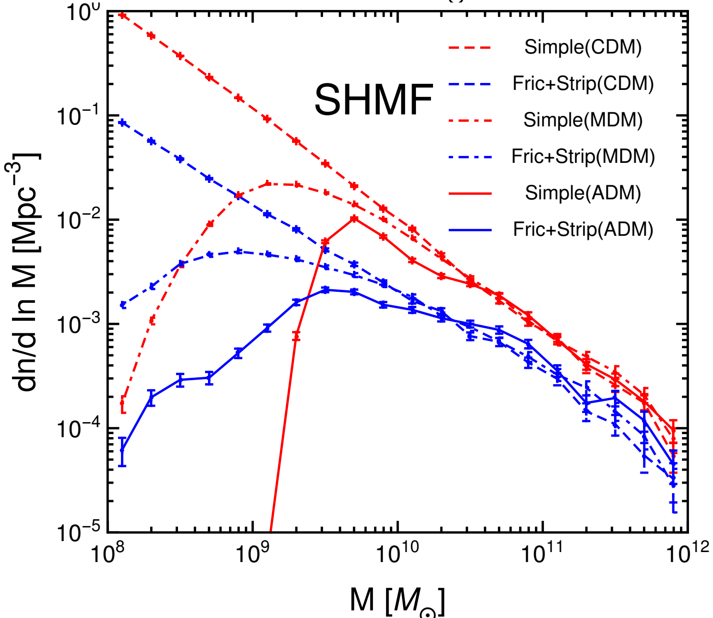




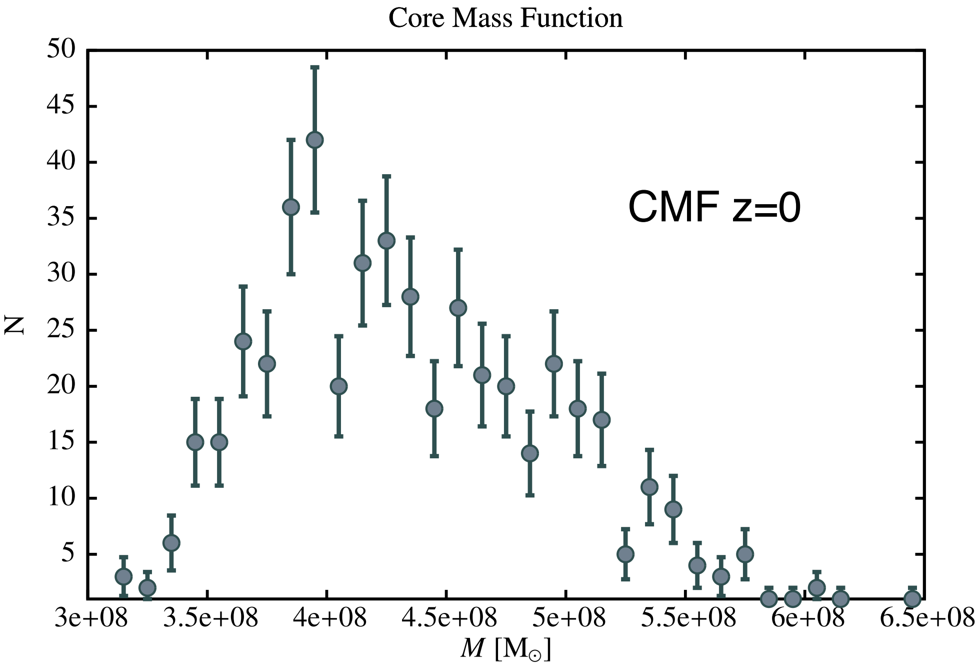


Stochastic merger trees for ULA halos: substructure

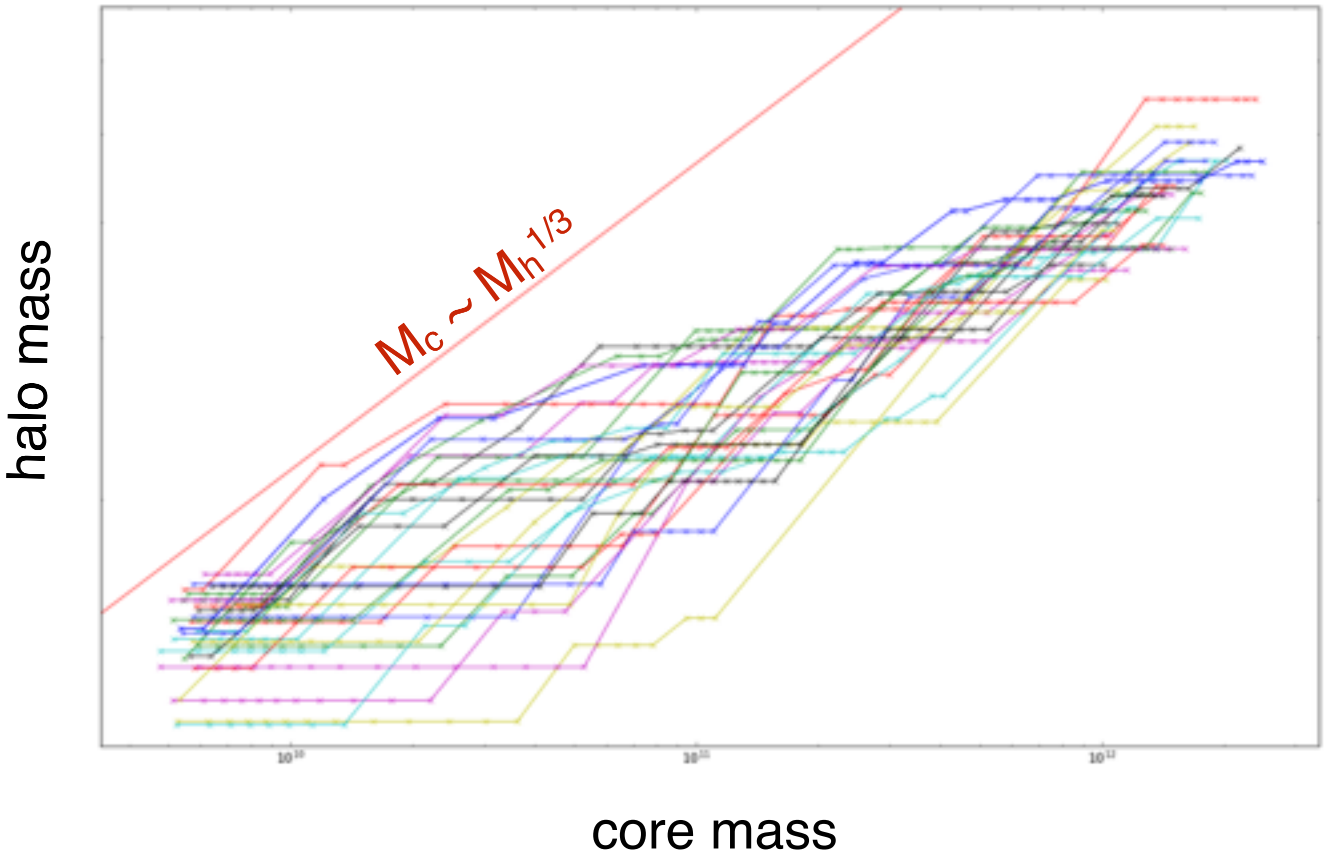




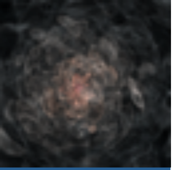
- Halo substructure models from parameter study of
  - – different ULA/CDM fractions
  - – tidal stripping stopped at solitonic core
- Core mass function using growth dynamics from merger simulations (very preliminary)



Core growth trajectories



$M_c \sim M_h^{1/3}$



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 „CDM small scale crisis“ (missing satellites, cusp-core, too-big-to-fail); rich phenomenology from solitonic cores
- Grid-based simulations of Schrödinger-Poisson equations used for systematic investigation of core mergers
- Madelung (fluid) picture appears to be more efficient for cosmological simulations (no resolution constraints from velocity); O(10%) effect on power spectrum on scales of ~ 5-10 kpc
- Semi-analytic models with stochastic halo merger trees (constructed using the simulations above) for constraints from subhalo statistics, reionization, ….