Institut für Astrophysik Göttingen

Structure Formation with Axion and ALP Dark Matter

Göttingen group:

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Collaborator:

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Simplifications

In the context of structure formation, we usually assume that axions are

- classical

  disagreeing views:

  1. Sikivie et al.
  2. Lentz, Quinn, Rosenberg

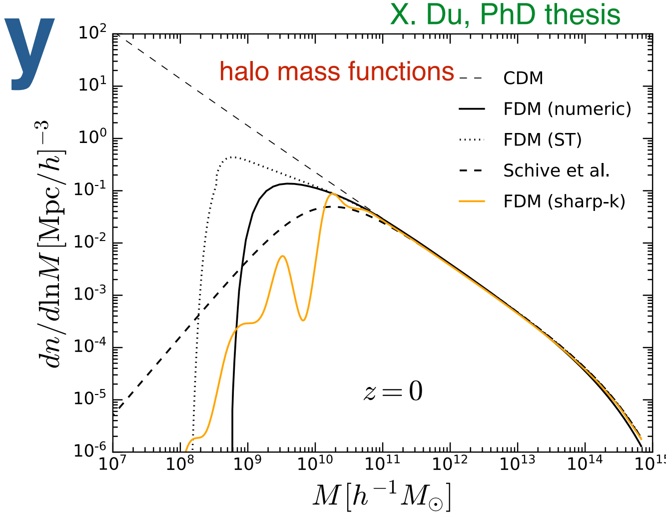
- nonrelativistic

- only gravitationally coupled

→ m is the only free parameter

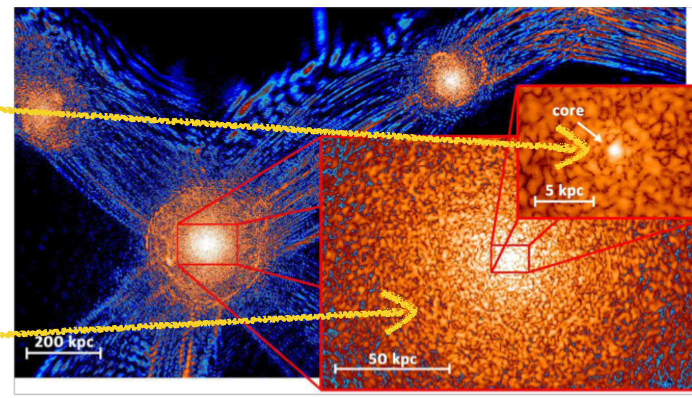
Axion DM phenomenology

X. Du, PhD thesis



Ultralight axions

- Suppression of small-scale perturbations *(„WDM-like“)*
  - high-z luminosity functions (Bozek+ '15, Schive+ '16, Corasaniti+ '17, Menci+ '17)
  - Lyman-α forest (Iršič+ '17, Armengaud+ '17) → m ≳ 10^{-21} eV
  - reionization (Bozek+ '15; Schneider '18; Lidz, Hui '18)
- Formation of coherent solitonic halo cores
  - cusp-core etc., halo substructure (Marsh,Silk '13, Schive+ '14, Marsh,Pop '15, Calabrese,Spergel '16, Du+ '16)



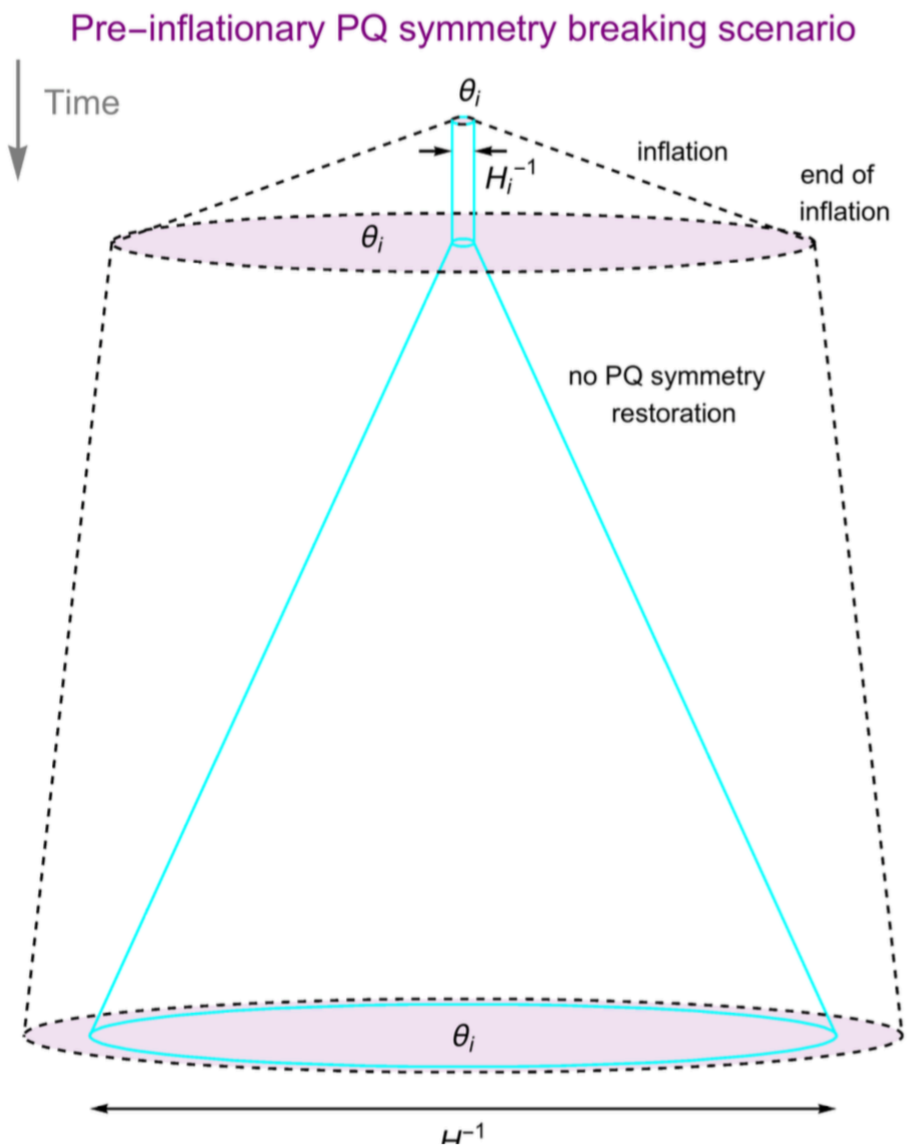
Schive+ '14

- Incoherent interference patterns and granularity on scales of $\lambda_{dB} \sim 1 \ldots 100$ kpc
  - „quasi-particle relaxation“ → dynamical friction / heating / diffusion (Hui+ '17, Bar-Or ´18, Marsh & JN ´18) *(„PBH-like“)*

QCD axions

- Formation of axion miniclusters (Tkachev '86; Hogan,Rees '88; Kolb,Tkachev '93/94; Zurek+ '07)
  - relevant for direct detection experiments
  - potentially observable in fast radio bursts, tidal streams, microlensing (Tkachev '15, Tinyakov+ '16, Fairbairn+ '17)
- Formation of axion stars (e.g. Levkov+ '18)

I. Ultralight axions



K. Saikawa

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

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

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

Scaling symmetry of the Schrödinger-Poisson equations:

$$\{t, \mathbf{x}, V, \Psi\} \to \{\lambda^{-2}t, \lambda^{-1}\mathbf{x}, \lambda^2 V, \lambda^2\Psi\}$$
$$\{\rho, M, K, W\} \to \{\lambda^4\rho, \lambda M, \lambda^3 K, \lambda^3 W\}\ .$$

Dimensional analysis for Newtonian boson stars / axion stars / solitonic cores:

- dynamical time: $t \sim M^{-1/2}\, R^{3/2} \sim \rho^{-1/2}$
- radius: $R \sim m^{-1}\, R^{-1}\, t \sim m^{-1/2}\, \rho^{-1/4}$
- mass: $M \sim \rho\, R^3 \sim m^{-3/2}\, \rho^{1/4} \sim m^{-2}\, R^{-1}$

Simulations with bosonic dark matter

Different scales / physics require different numerical methods.

1. **N-body with modified initial conditions**:
   CDM-like dynamics, linear / weakly nonlinear scales (Ly alpha forest, HMF)

2. **Madelung (fluid) formulation** (SPH, PM, or finite volume):
   same as above, includes „quantum pressure“ effects, resolution requirements and validity unclear

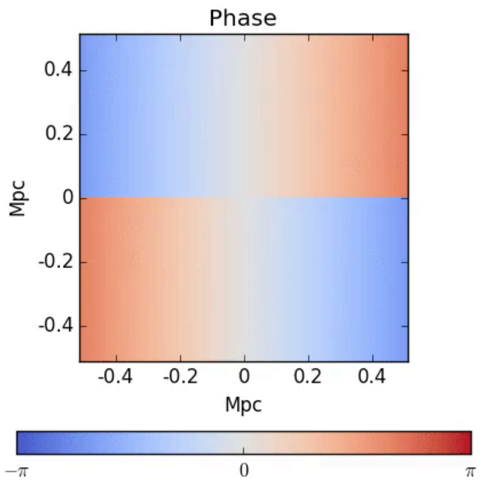
$$\dot{\rho} + \nabla(\rho \mathbf{v}) = 0 \qquad \dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla(Q + V)$$

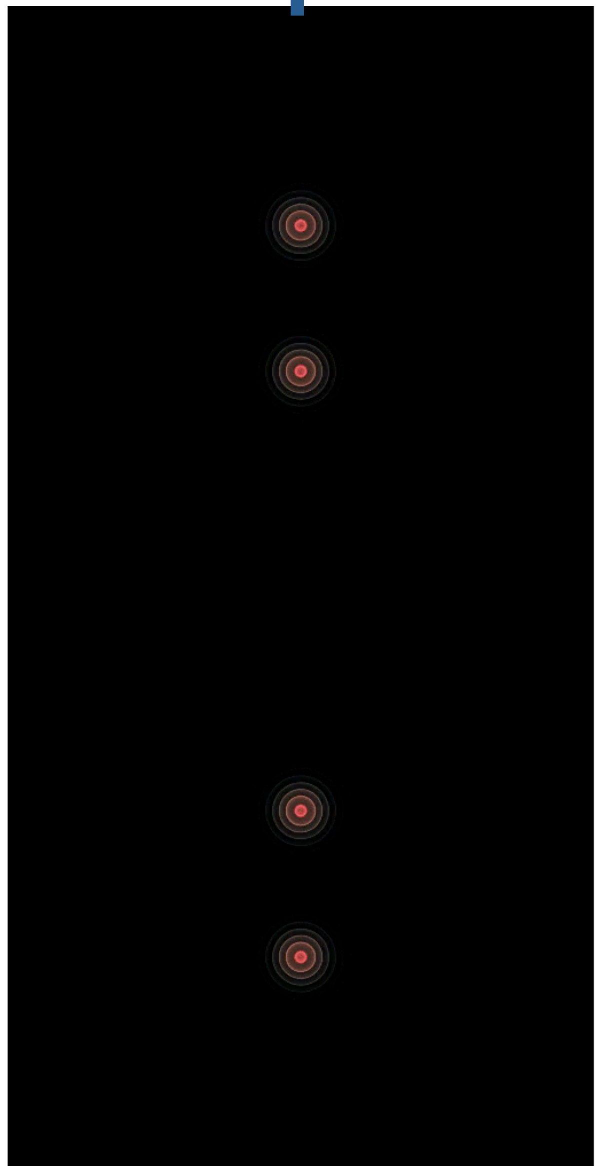
$$\mathbf{v} = m^{-1} \nabla S \qquad Q = -\frac{\hbar^2}{2m^2} \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}$$ „quantum pressure“

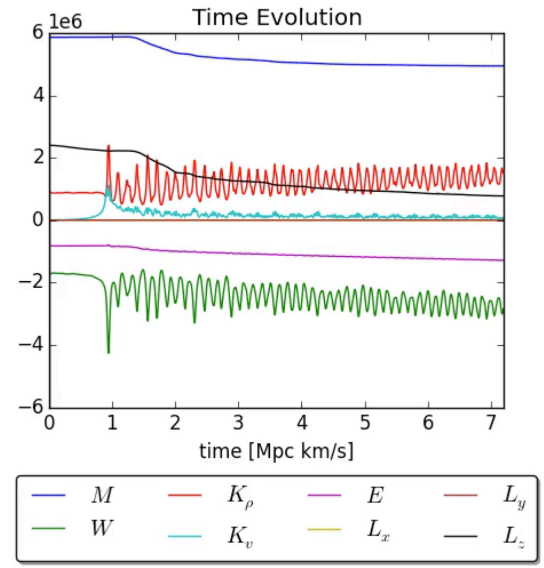
4. **Schrödinger formulation** (finite difference or pseudo-spectral):
   full wave-like dynamics, requires phase resolution, can only handle relatively small boxes, nonlinear scales

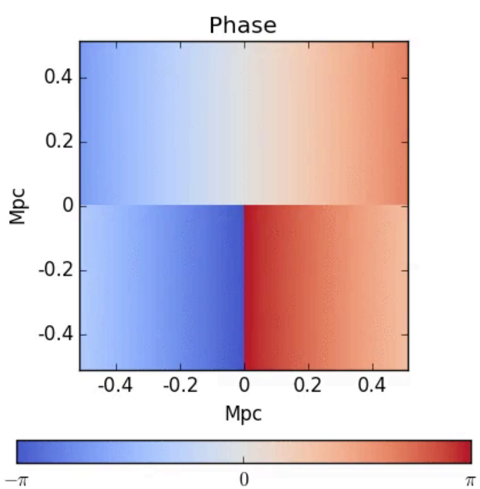
5. **Hybrid zoom-in method** (N-body on coarse grids, Schrödinger on finest grid):
   dynamics CDM-like on large scales, wave-like on small (nonlinear) scales

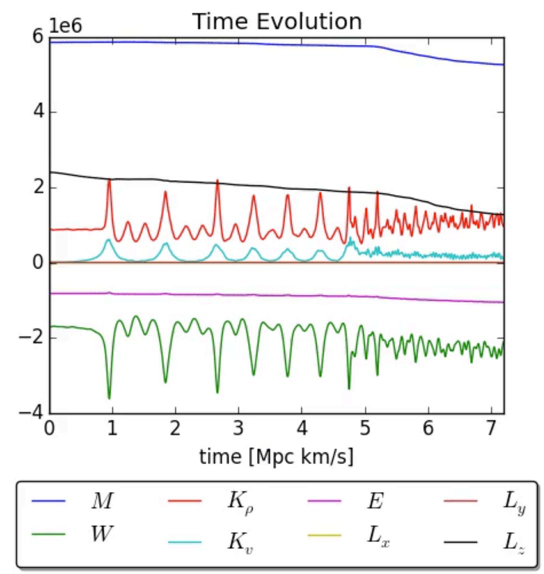
Bound binary mergers: phase dependence







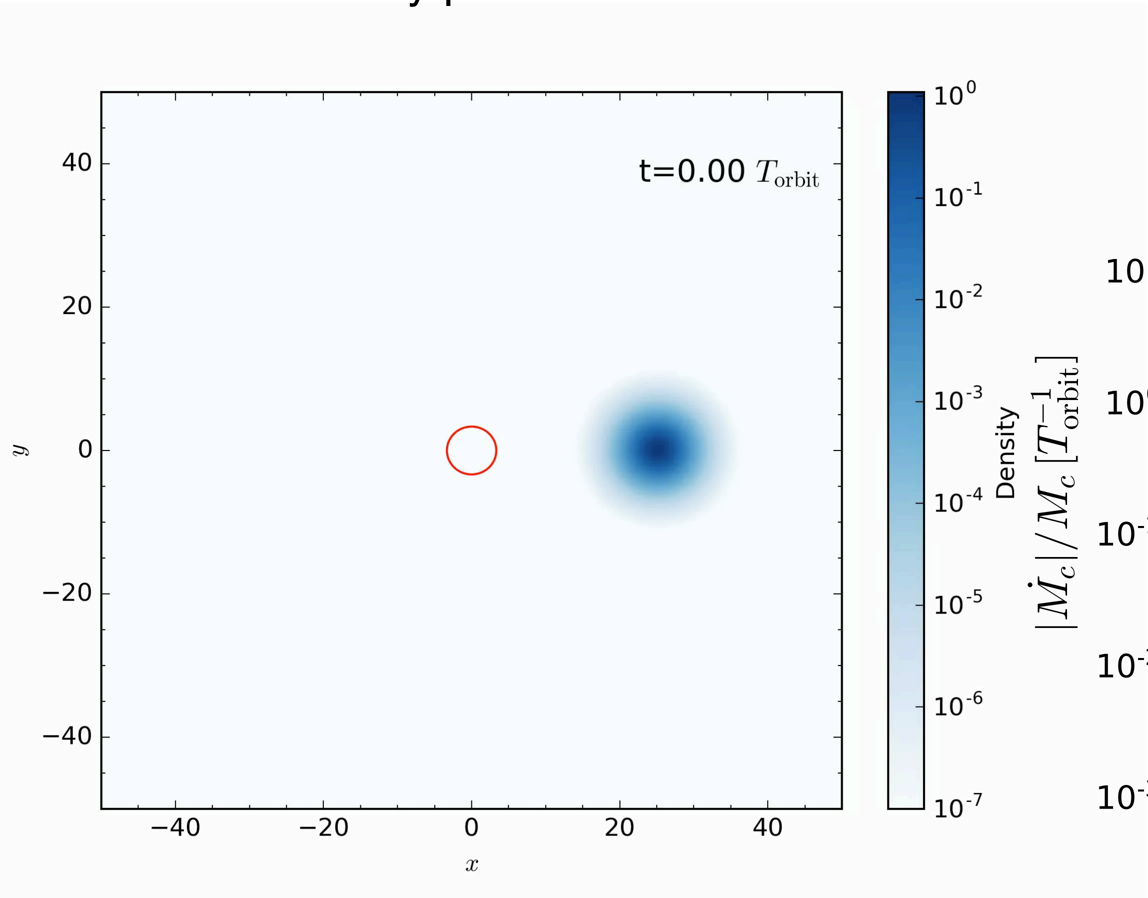




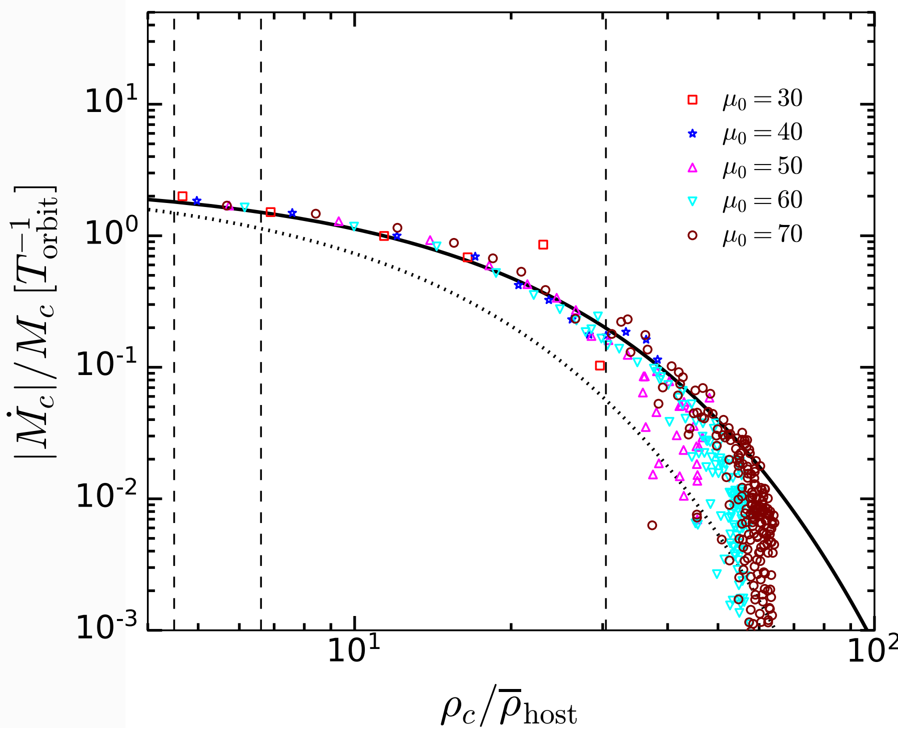
Tidal disruption of FDM substructure halos

(Du,Schwabe,JN+; arXiv:1801.04864)

In addition to classical tidal stripping, FDM halos are unstable to tidal mass loss by „quantum tunnelling“ (Hui+ ’17). The mass loss rate depends only on the ratio of soliton and host density μ.



mass loss rate

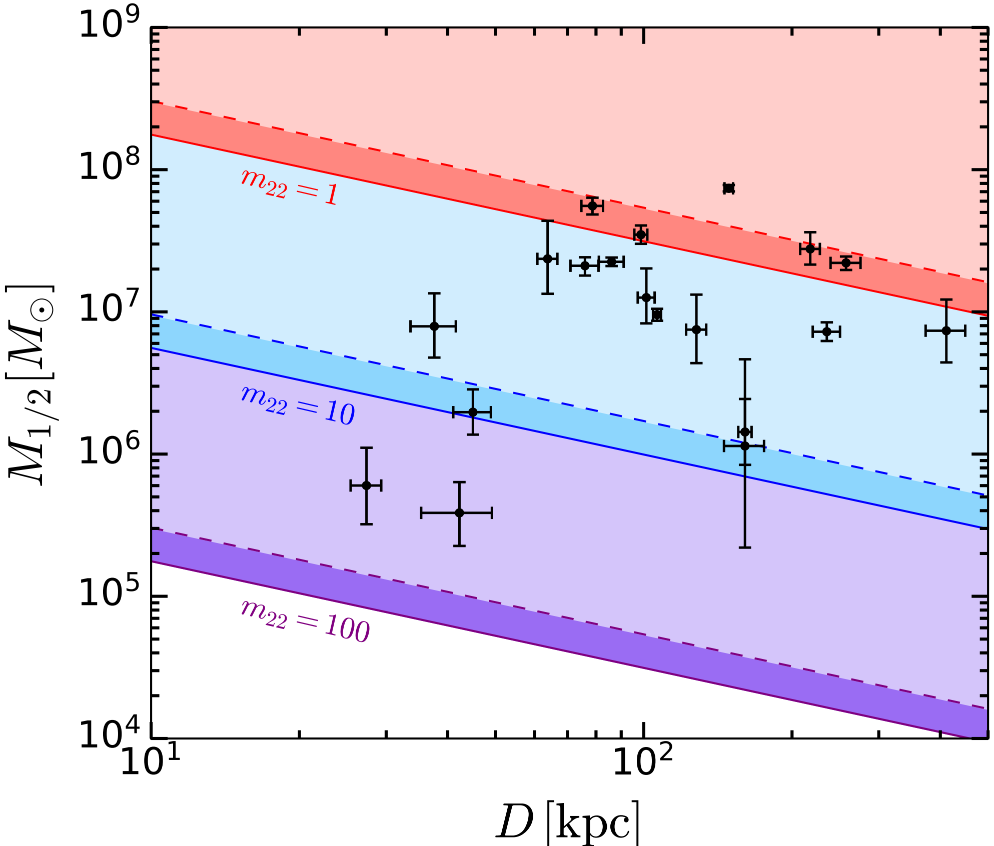


Tidal disruption of FDM substructure halos

(Du,Schwabe,JN+; arXiv:1801.04864)

To survive for N_{sur} orbits, the core mass must satisfy

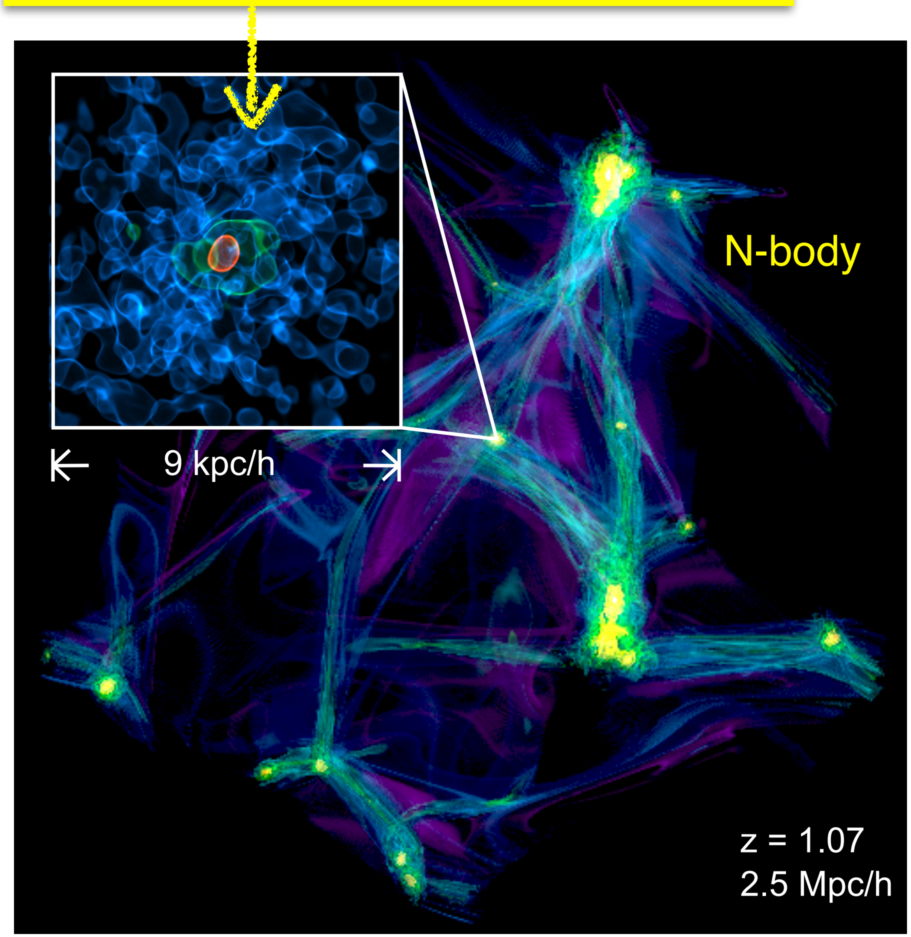
$$M_c > 5.82 \times 10^8 \, [\mu_{\rm min}(N_{\rm sur})]^{1/4} \, m_{22}^{-3/2} \left(\frac{D}{\rm kpc}\right)^{-3/4} \left(\frac{M_{\rm host}}{10^{12} M_\odot}\right)^{1/4} M_\odot$$

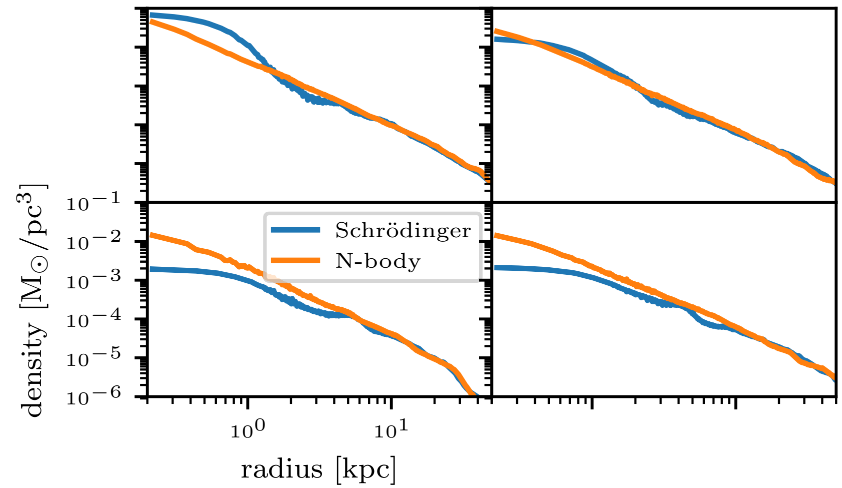


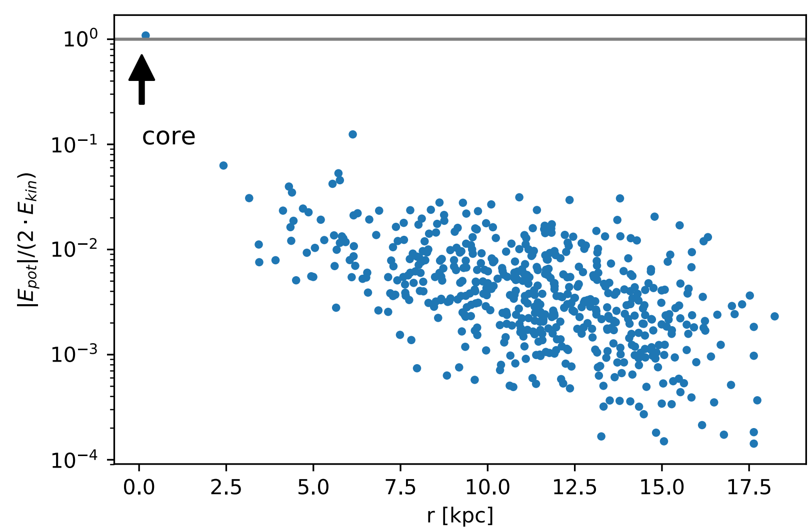
Simulations of halo formation with ultralight axion dark matter

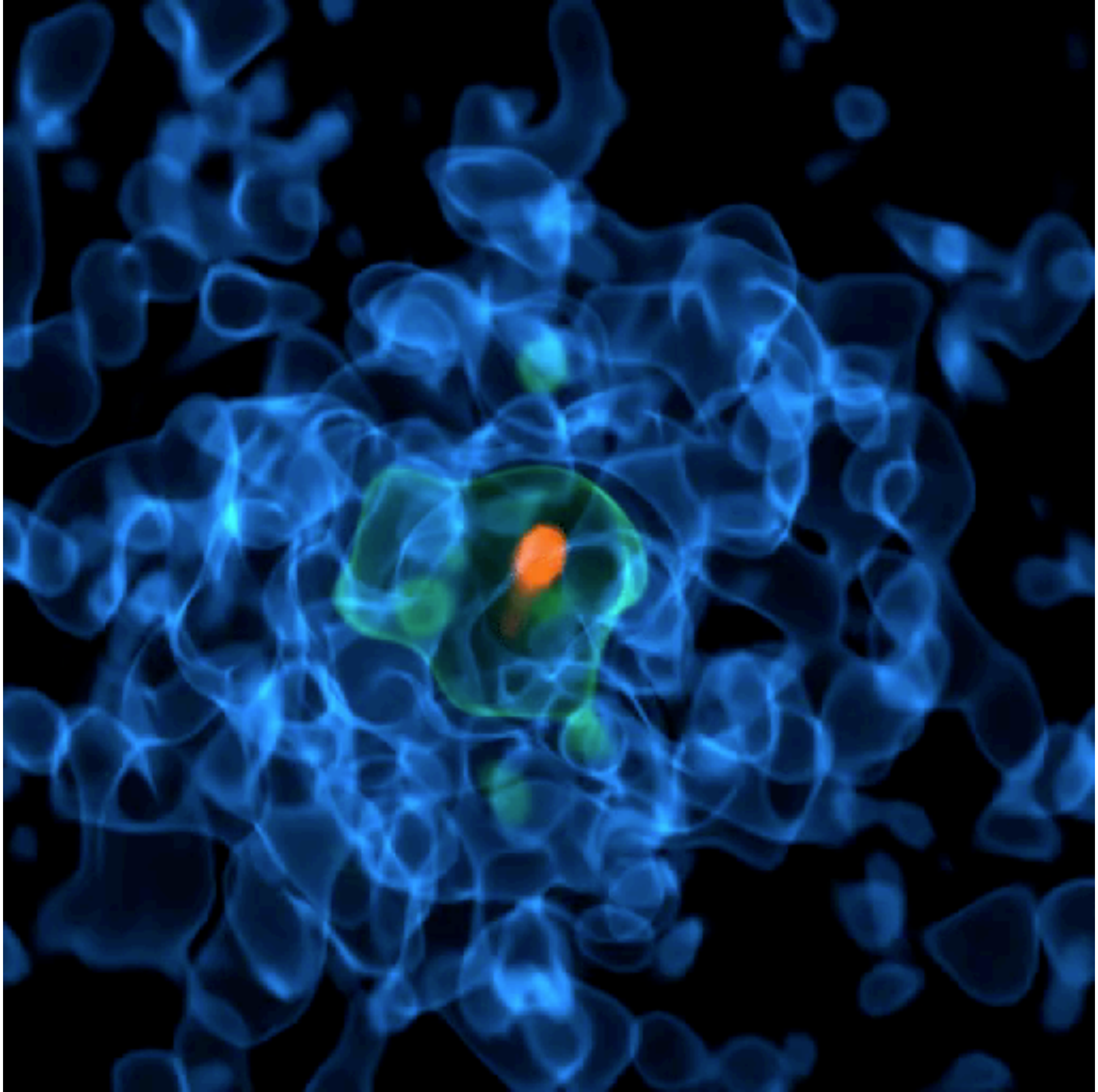
(Veltmaat, JN, Schwabe '18, arXiv:1804.09647)

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

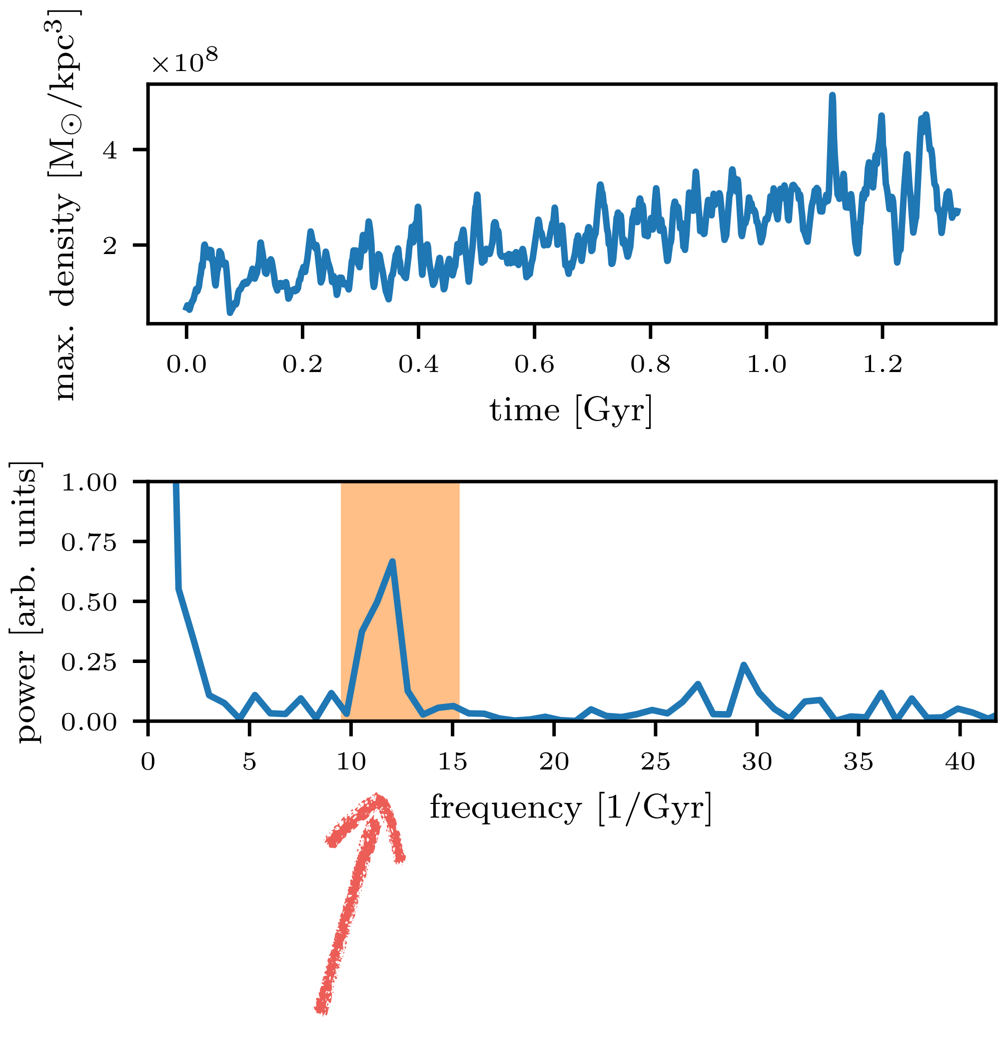






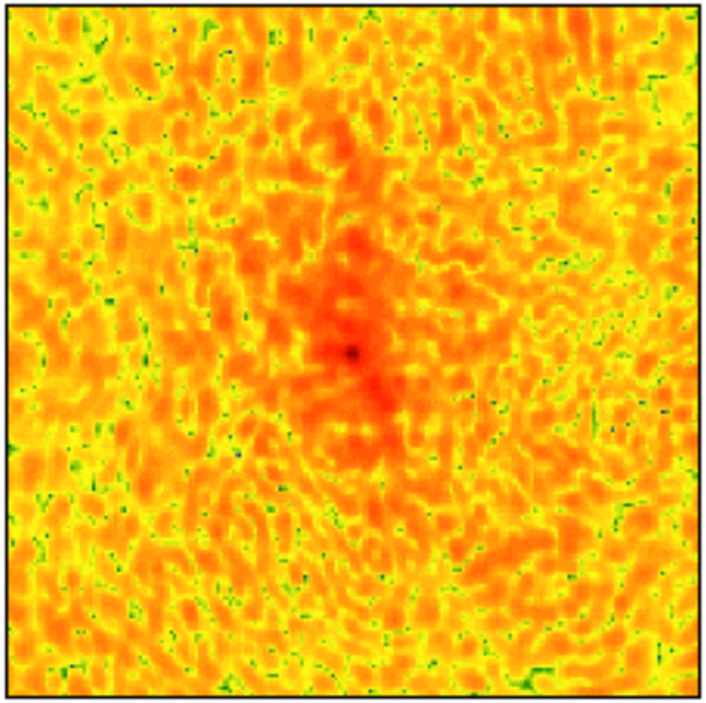


Core oscillations



FDM with baryons and star formation

dark matter vs. baryon density:



Gravitational relaxation from wave interference noise

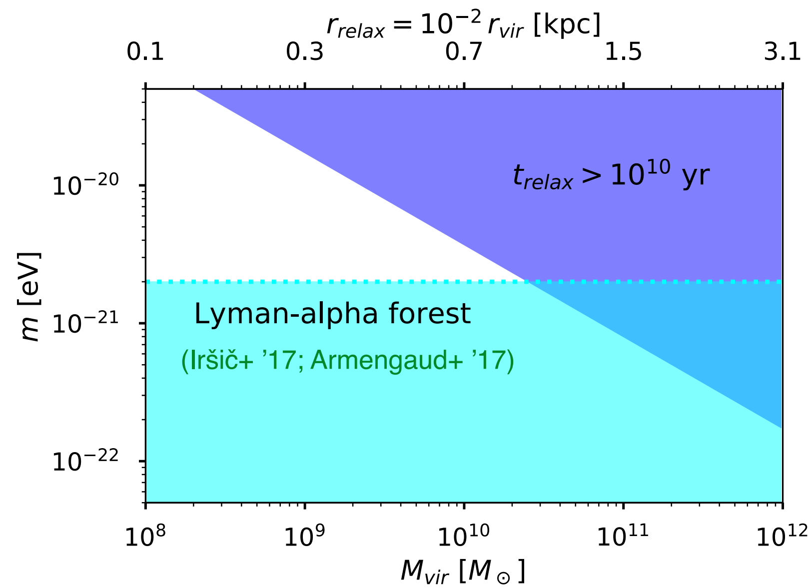
Wave nature of FDM produces O(1) density fluctuations on scale of λ_{dB}

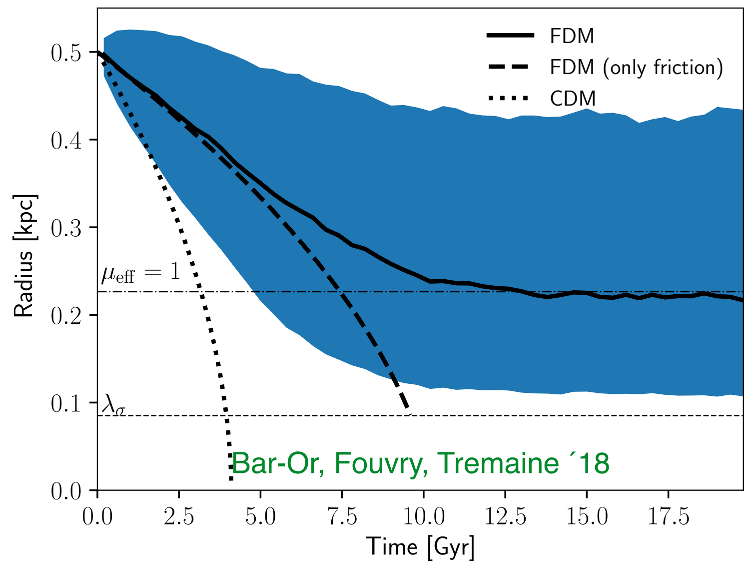
Gravitational scattering → relaxation / condensation time scale:

$$\tau \sim \frac{m^3 v^2 R^4}{h^3} \sim \left(\frac{R}{\lambda_{\rm dB}}\right)^3 \frac{R}{v}$$

from quasi-particle approximation (Hui+ ´17), shot noise diffusion (Marsh, JN ´18), or wave condensation (Levkov+ ´18).

Dynamical friction (cooling) vs. diffusion (heating) (Bar-Or+ ´18) → inspiral of SMBHs or globular clusters can be stalled by FDM.

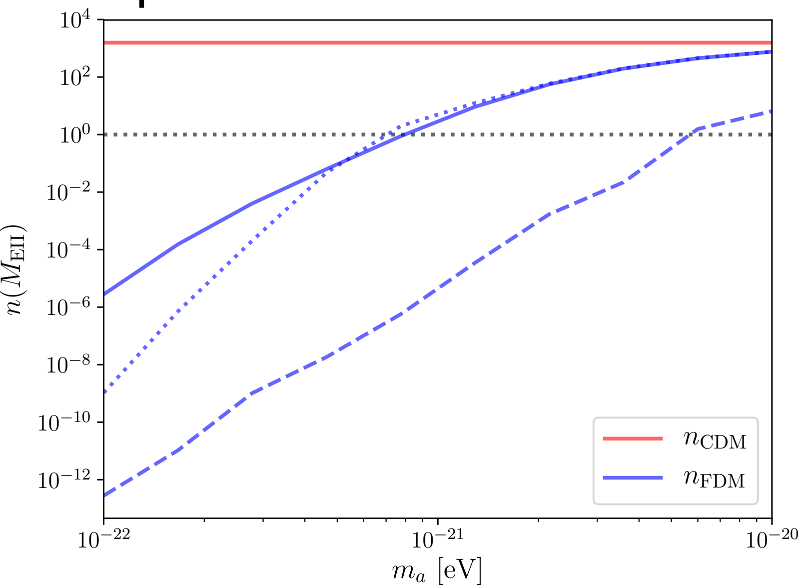


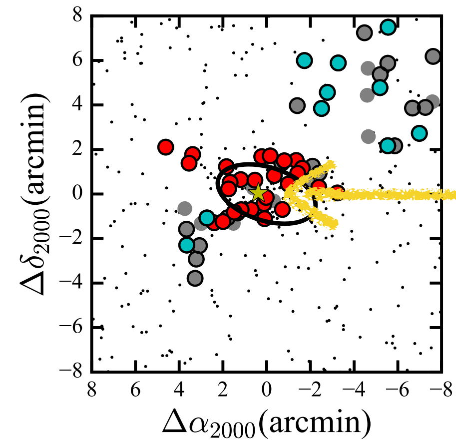


Gravitational heating constraints: Star cluster in UFD Eridanus II

(Marsh & JN, arXiv:1810.08543)

expected number of subhalos:

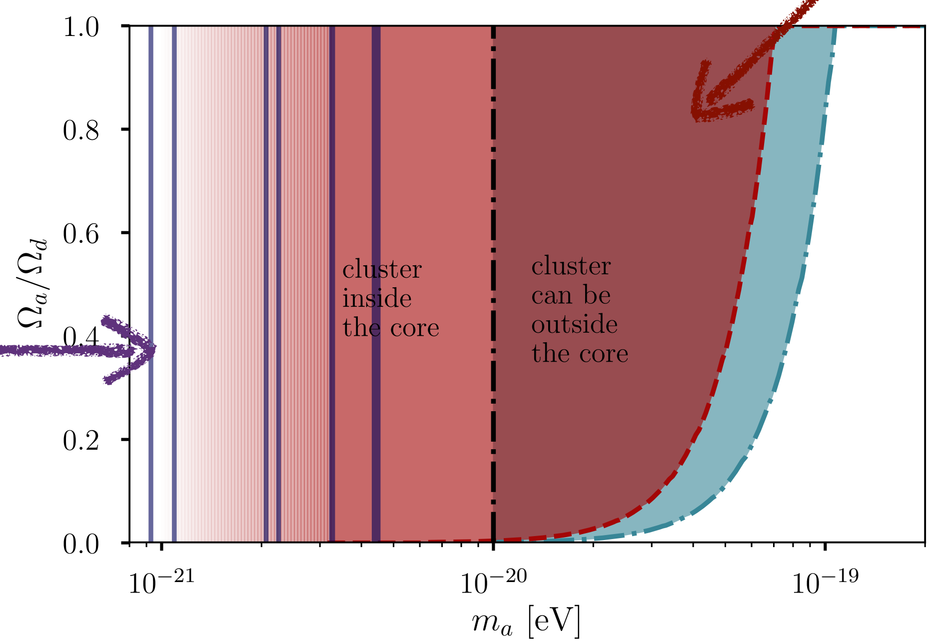




Li+ ´17

central star cluster

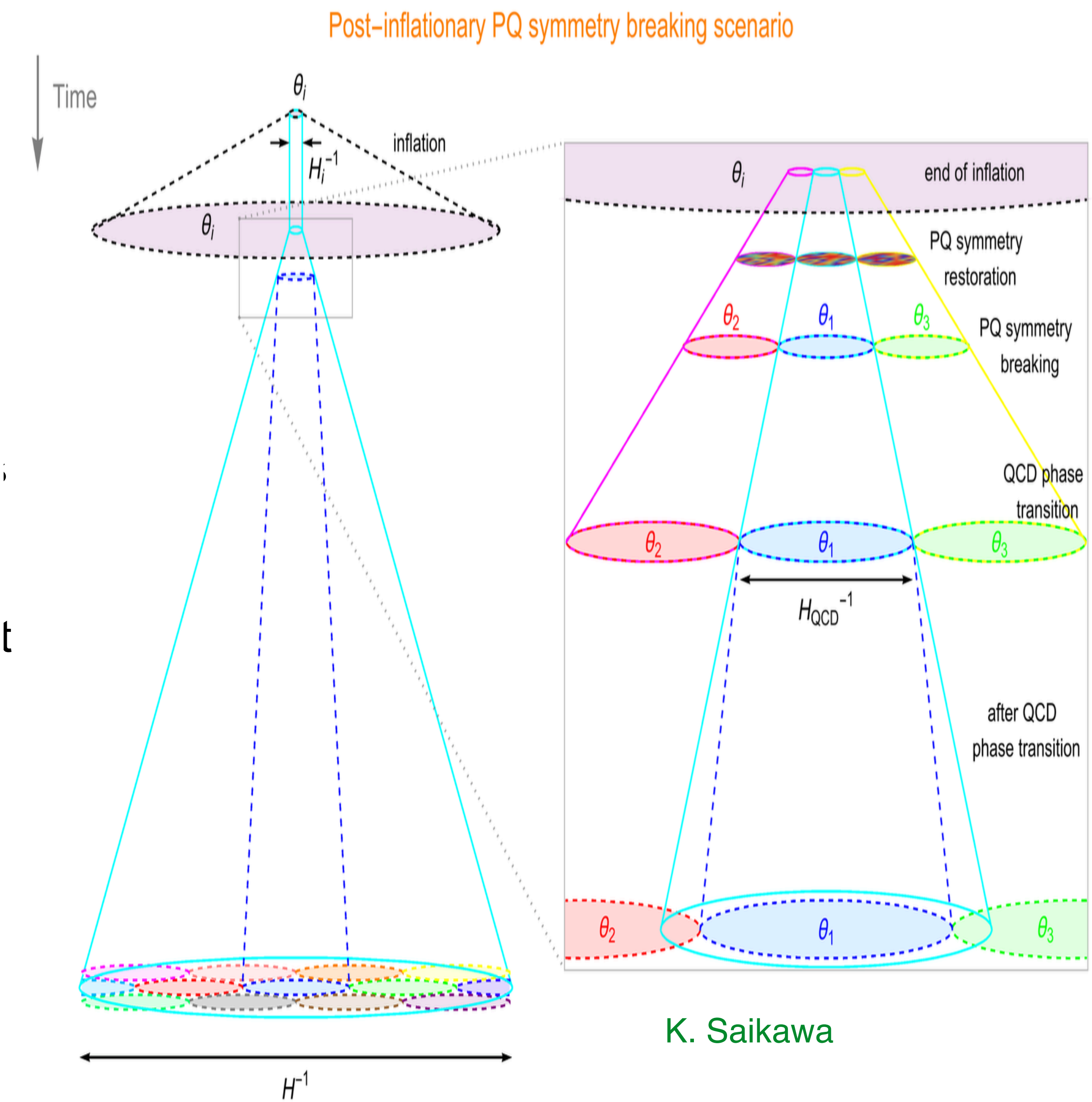
diffusion / heating



resonance

many uncertainties,
need simulations!

II. QCD axions



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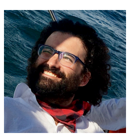
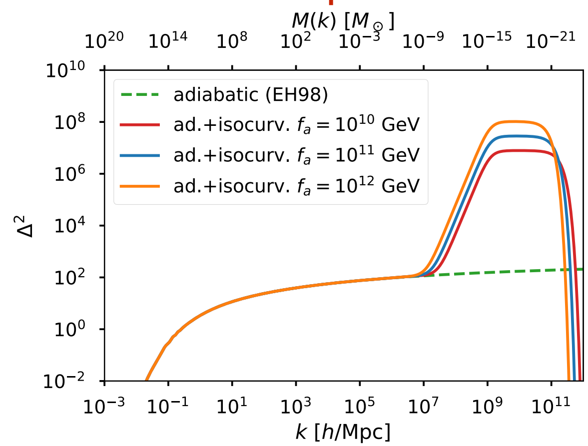
Formation of QCD axion miniclusters

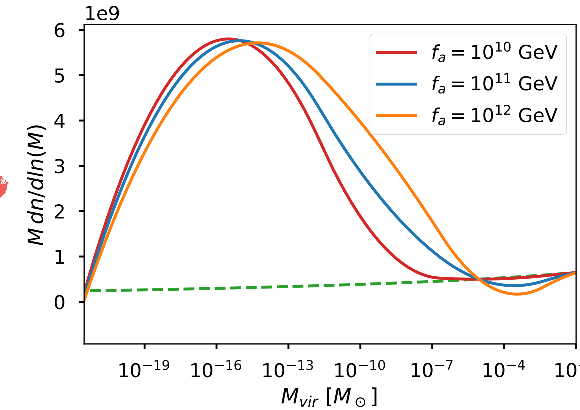
N-body simulations of nonlinear density perturbations during radiation-dominated epoch:

- Initial conditions from simulations of complex axion field (Vaquero, Redondo, Stadler ´18)
- Questions: minicluster mass function, total mass bound in miniclusters, …

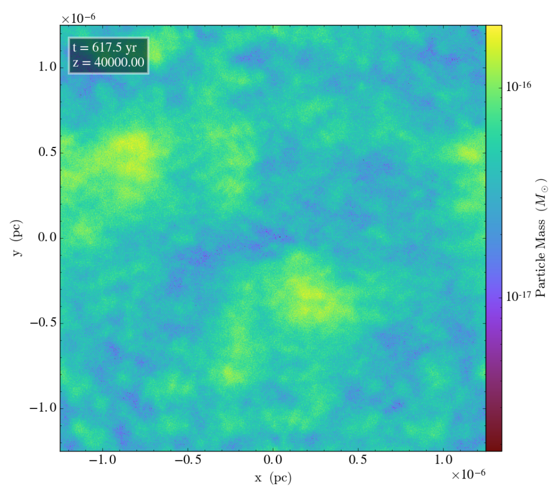


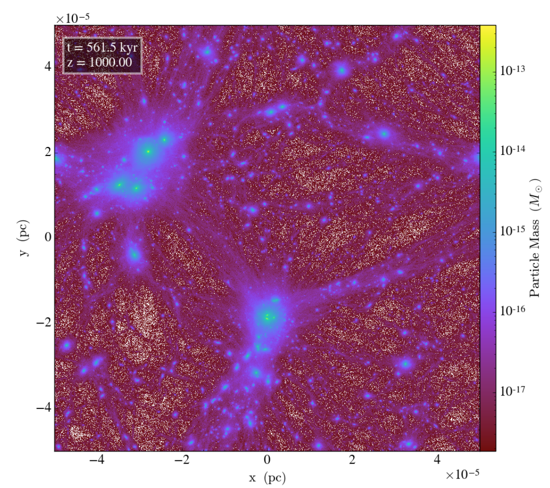
Simple estimates of power spectrum and HMF:



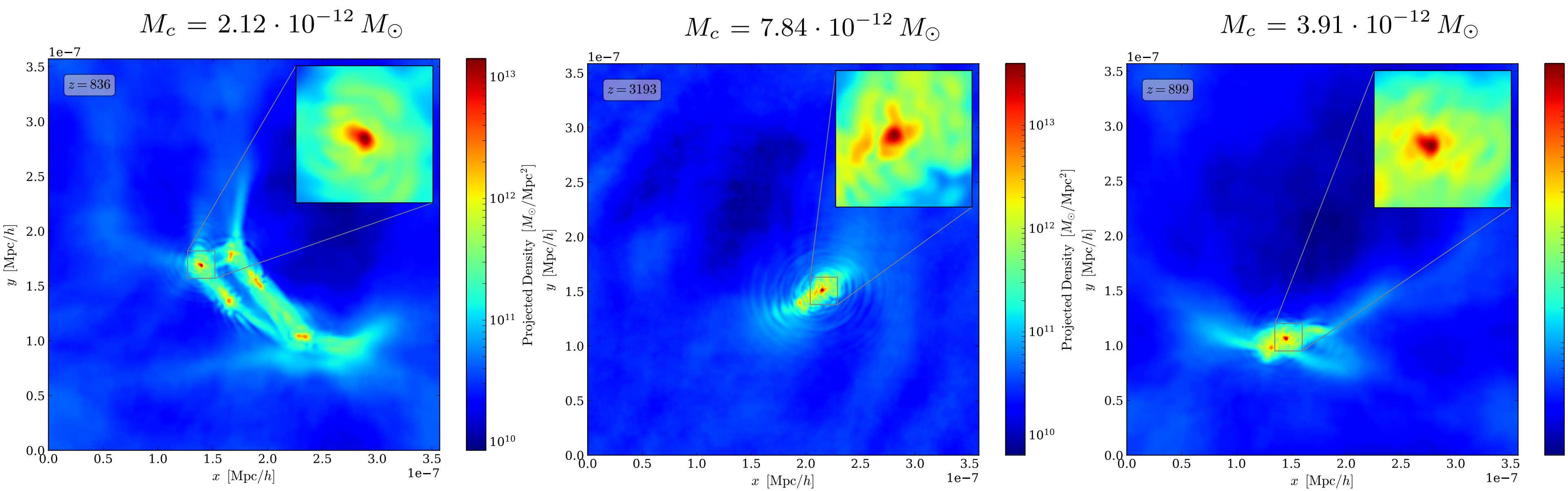


Simulations:





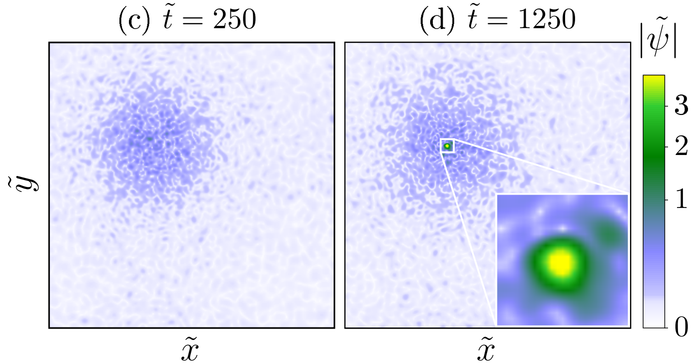
Axion star formation in miniclusters

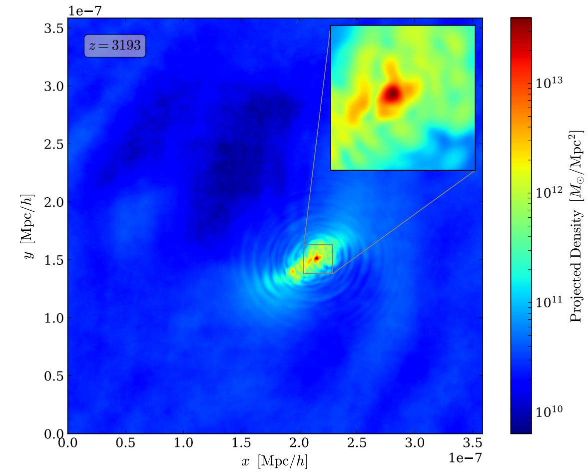


- initial conditions from Vaquero, Redondo, Stadler ´18
- pseudo-spectral code, smoothed boundary conditions
- $m_a = 10^{-8}$ eV (to resolve the axion star)

Axion star formation

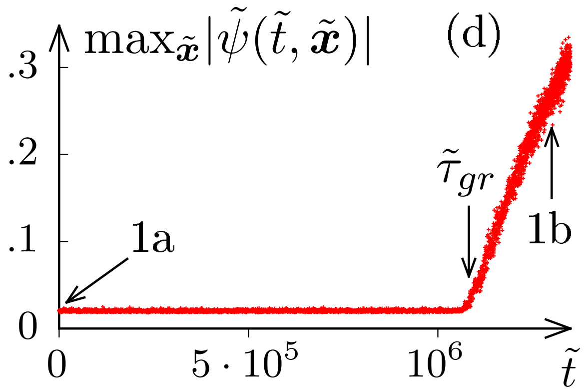
- Wave condensation or violent relaxation (or both)?

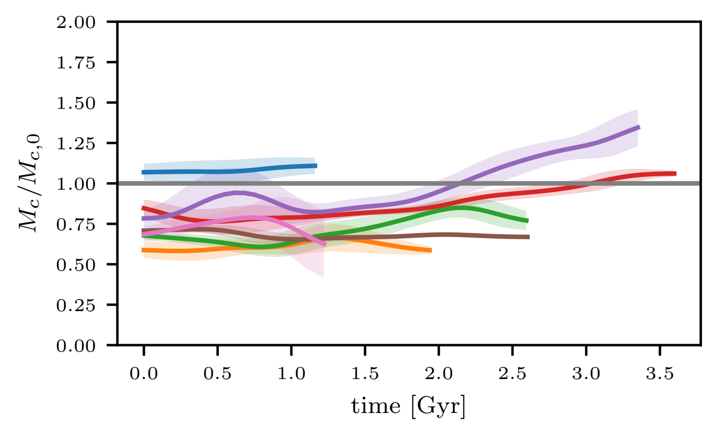




- Mass growth?

Levkov, Panin, Tkachev '18





Veltmaat, JN, Schwabe '18

- Initial mass function, stability, detectability, …

Summary

- The confrontation of ΛCDM (+ inflation) predictions for small-scale structure with observations provides ongoing motivation for studying physics beyond CDM

- Prominent classes of modifications predict suppression of small-scale power (*WDM-like*), enhanced transport effects (*SIDM-like*), and the production of compact objects (*PBH-like*)

- Axion cosmology has a little bit of all:
  - Primordial suppression of high-k power (ultralight axions)

    probes: Lyman-alpha forest, high-z luminosity functions, reionization, galactic streams, substructure lensing,…
  - Dynamical enhancement of gravitational relaxation

    probes: morphology of inner parts of disk galaxies, orbital stability of SMBHs and globular clusters, heating of stellar systems
  - Production of axion miniclusters / axion stars / solitonic cores

    probes (QCD axion miniclusters and axion stars): micro-, nano-, pico-, femto-, attolensing; non-gravitational probes

    probes (FDM cores): dwarf galaxy rotation curves, core oscillations