New Structures in Axion Halos on Super-de Broglie Scales

Erik W. Lentz, Tom Quinn, Leslie Rosenberg

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

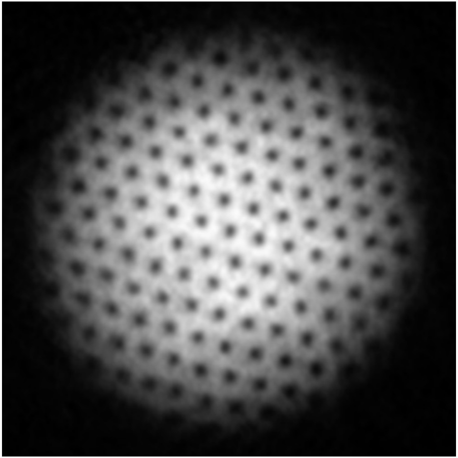
INSTITUT FÜR ASTROPHYSIK GÖTTINGEN

UNIVERSITY OF WASHINGTON

15th PATRAS Workshop on Axions, WIMPs and WISPs, 4 June, 2019

QCD Axion Structure Formation

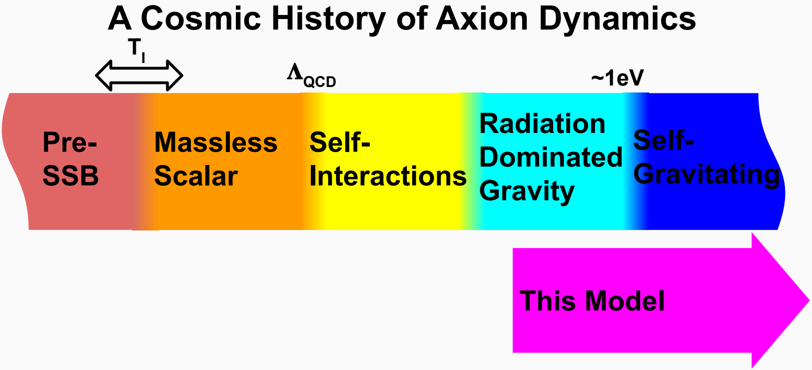
- Axion DM forms a degenerate Bose fluid at low masses ($m_a \lesssim 1$ eV)
- Mean Field Theory of axion DM produces a Gross-Pitaevskii model of axion infall
- What are the contributions of inter-axion correlations?



(Super-de Broglie structure in super-fluid sodium with vortices, credit: Martin Zwierlein)

Quantum Mechanical Axions

- Self-gravity dominates during significant structure formation.
- Quantum mechanics is a sufficient description for the relic axion fluid during this time.



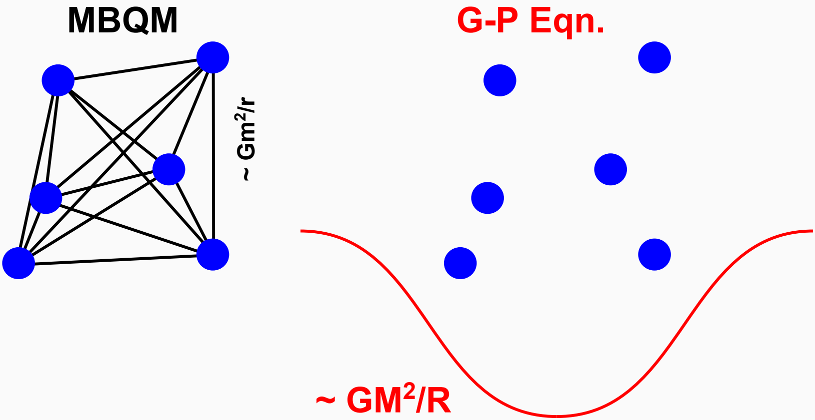
Exchange and the Correlated Hamiltonian

- Schrödinger equation uses Hamiltonian with Coulombic inter-axion gravity
- Inherits exchange symmetry

$$H = -\sum_{i}^{N} \frac{\hbar^2 \nabla_i^2}{2a^2 m} - \sum_{i<j}^{N} \frac{Gm^2}{|\vec{x}_i - \vec{x}_j|},$$

$$P_{ij}\Psi = \Psi$$

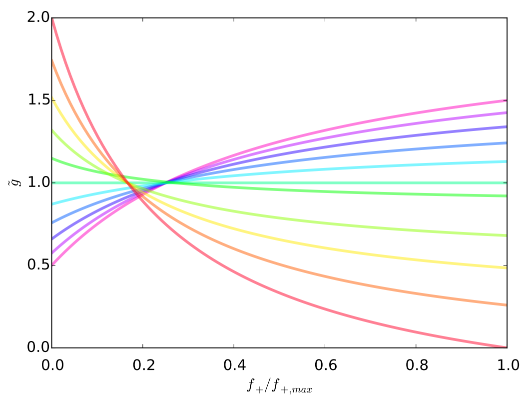
Inter-Axion Potential



Exchange-Correlation of Axions

> Inter-axion gravitation and exchange can create highly-correlated condensates.

> Super-de Broglie dynamics contain exchange-correlation (XC) contributions:

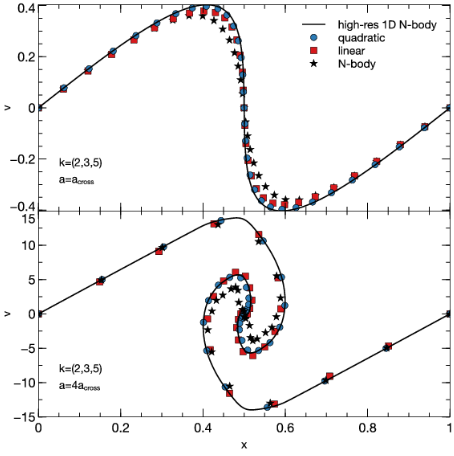


(Correlation in sample systems of identical bosons and fermions, parameterized by distribution value.)
Lentz, Quinn, Rosenberg, 2019, MNRAS, 485, 1809L (arXiv:1810.09226)

$$\partial_t f + \frac{\vec{v} \cdot \vec{\nabla} f}{a^2} - \vec{\nabla}\bar{\Phi} \cdot \vec{\nabla}_v f - \boxed{\int d^6 w_2 \vec{\nabla}\Phi_{12} \cdot \vec{\nabla}_v \left(f \frac{C - 1 - \lambda_+ f_+}{1 + \lambda_2 f_+} f \right)} = O(\hbar)$$

Isolated Collapse

- N-body algorithm tracks elements of the total density
- Initial conditions are spherical, cold with parameters of
  - Shape $\in \{\text{Top-hat}, \text{Gaussian}\}$
  - $C \in [0.5, 1.0]$
  - Solid-body spin ($\lambda \in [0.0, 0.1]$)

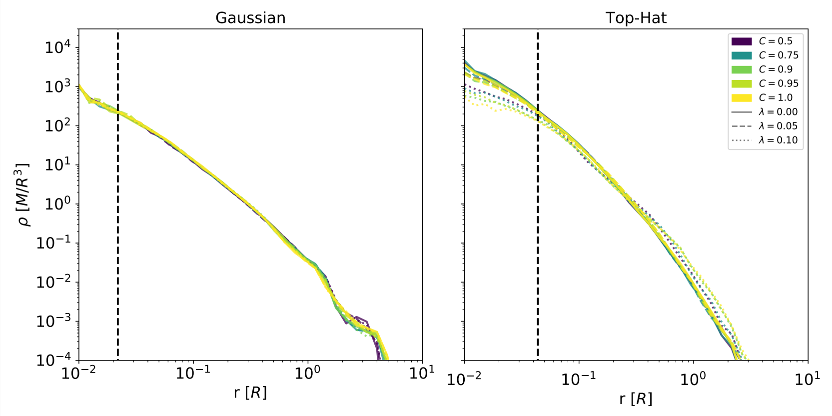


(Hahn et al. 2016)

$$\ddot{\vec{x}} = -\vec{\nabla}\bar{\Phi} - \boxed{\frac{\partial}{\partial \vec{\nabla}_v f} \int d^6 w_2 \vec{\nabla}\Phi_{12} \cdot \vec{\nabla}_v \left(f \frac{C - 1 - \lambda_+ f_+}{1 + \lambda_2 f_+} f \right)}$$

Structure in Space

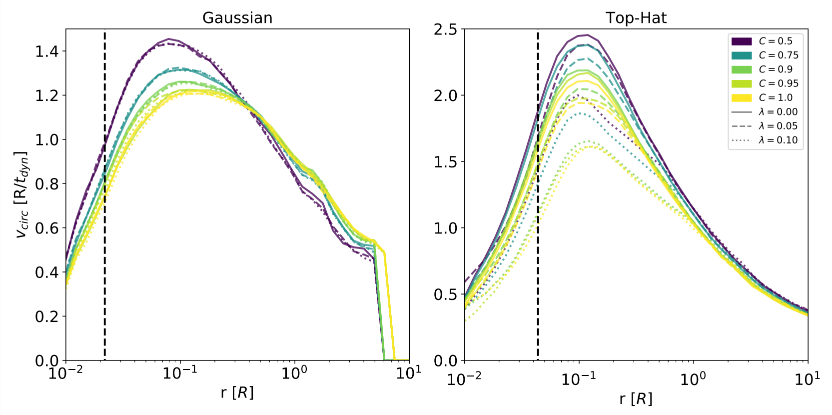
Isolated halo densities are largely similar to classical collapse



(Radial density profiles of N-Body spherical collapse simulations.)
Lentz, Quinn, Rosenberg, arXiv:1904.06948

Augmented Force

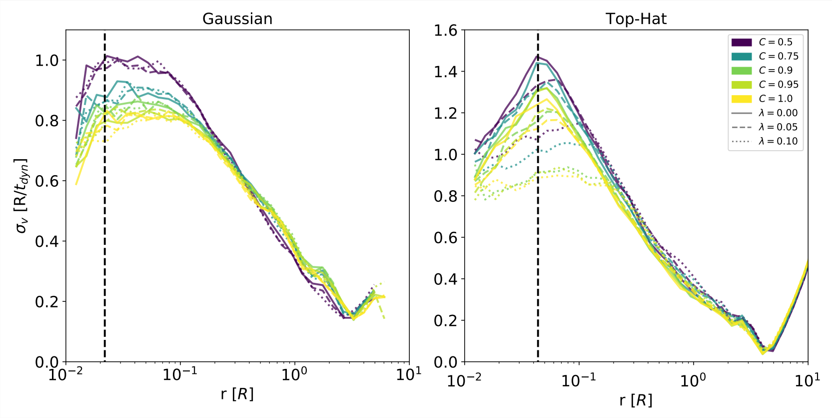
Shape insensitivity is unexpected in light of the forces involved



(Circular rotation curves of N-Body spherical collapse simulations.)
Lentz, Quinn, Rosenberg, arXiv:1904.06948

Velocity Structure

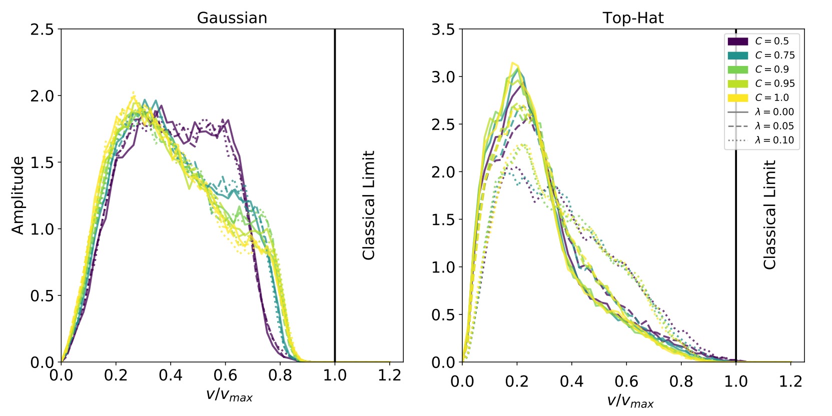
Though the force does alter the velocities



(Spherical velocity dispersion profiles of N-Body spherical collapse simulations.)
Lentz, Quinn, Rosenberg, arXiv:1904.06948

Velocity Substructure

And the velocity distributions, and possibly the orbits of halo substructures (eg. bound dwarf galaxies)

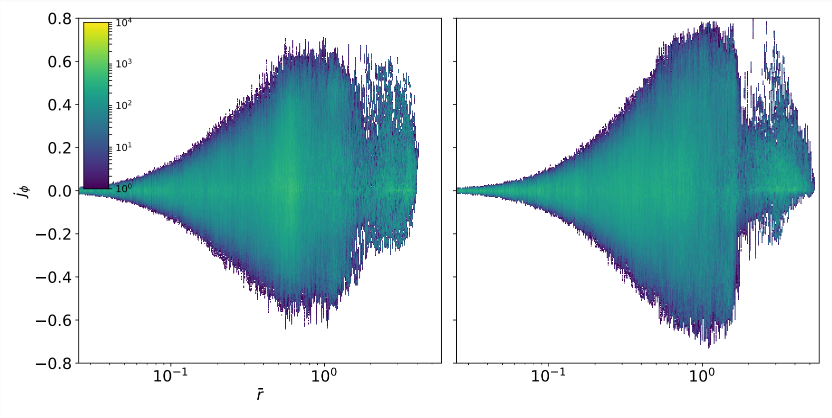


(Inner-halo fractional speed distributions in N-Body spherical collapse simulations.)
Lentz, Quinn, Rosenberg, arXiv:1904.06948

Orbital Actions: Surface Mixing

Mixing across the virial radius may be the result of quasi-particle action

Bose ($C = 0.5$, $\lambda = 0.05$) Classical ($C = 1.0$, $\lambda = 0.05$)

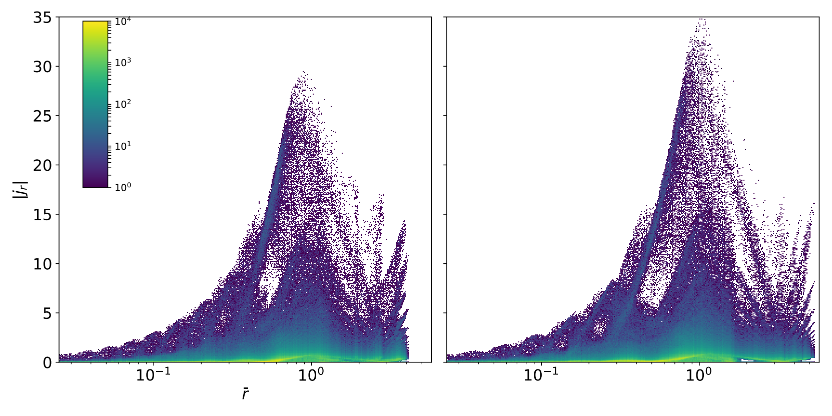


(Co-rotating angular momentum over mean orbital radius in N-Body spherical collapse simulations.)
(Speed vs. Newtonian potential for Top-Hat N-Body spherical collapse simulations at $C = 0.5$ and $C = 1.0$ respectively.)
Lentz, Quinn, Rosenberg, arXiv:1904.06948

Orbital Actions: Resonances

Finer structures begin coming into focus via resonances

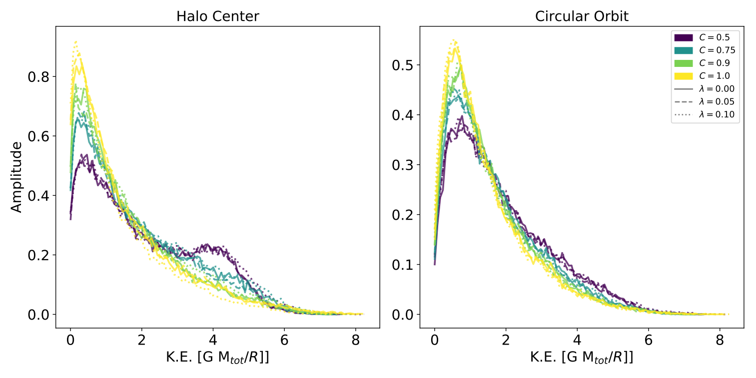
Bose ($C = 0.5$, $\lambda = 0.05$) Classical ($C = 1.0$, $\lambda = 0.05$)



(Radial orbit actions versus mean orbit radius in Gaussian N-Body spherical collapse simulations at $C = 0.5$ and $C = 1.0$ respectively.)

Signal Shape for Axion Search

A first look at the signal a Sikivie process axion search would expect to see.



(Co-moving local energy distributions from Gaussian N-Body Spherical collapse simulations.)
Lentz, Quinn, Rosenberg, arXiv:1904.06948

Summary

- Exchange-correlation has a significant impact on the physics of highly-degenerate and correlated fluids such as axion dark matter
- Several new structures are already seen in simple isolated collapse
- New structures produce new observables for axion searches
- Larger simulations and deeper insight into condensation to be coming soon!

Acknowledgements

Thank you:

Patras Organizing Committee

Albert-Ludwig-Universität Freiburg

U.S. Department of Energy Office of High Energy Physics for support through DOE grant DE-SC0011665