A visualization of the cosmic web, showing a complex network of dark matter filaments and clusters. The filaments are represented by thin, glowing blue lines, while the clusters are denser regions of yellow and orange. A horizontal scale bar is positioned above the title.

125 Mpc/h

# Do Dark Matter Axions Form a Bose-Einstein Condensate with Long-Range Correlation?

Chanda Prescod-Weinstein

MLK Postdoctoral Fellow, Department of Physics, M.I.T.

Guth, Hertzberg, & CPW [arXiv:1412.5930](https://arxiv.org/abs/1412.5930)





# Does Axion Dark Matter form Bose–Einstein Condensates?

Yes, in small, locally-correlated  
clumps such as Bose stars.

# Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Asymmetric DM

Dark Photon

Light Force Carriers

Warm DM

Sterile Neutrinos

Axion DM

QCD Axions

Axion-like Particles

Soliton DM

Quark Nuggets

T-odd DM

UED DM

6d

5d

RS DM

Extra Dimensions

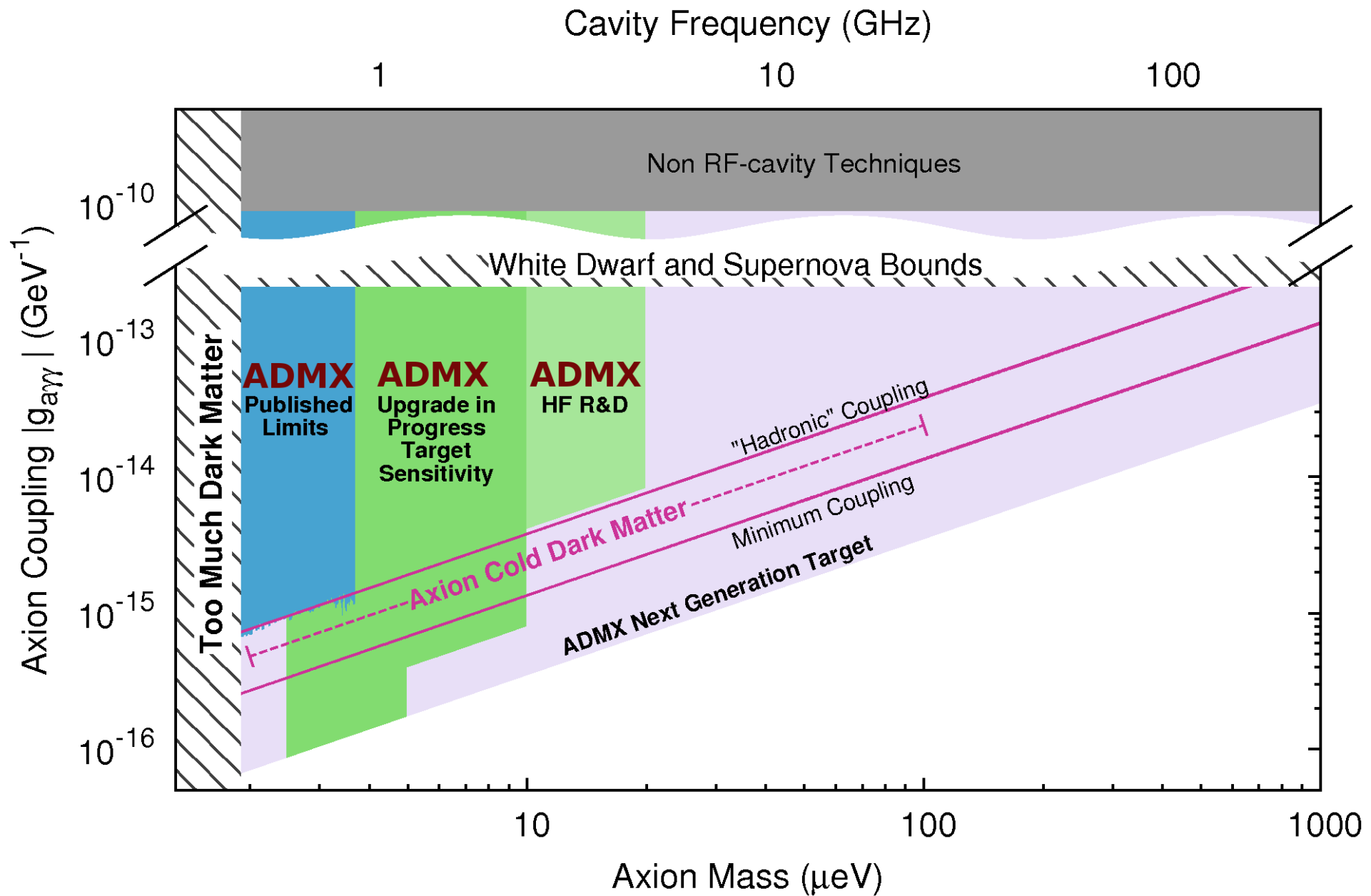
Warped Extra Dimensions

Little Higgs

Littlest Higgs

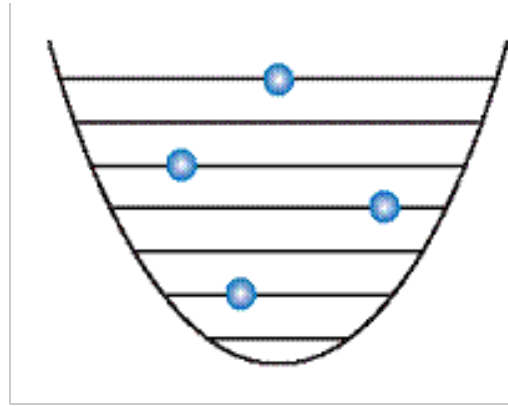
# Axion Dark Matter eXperiment

## ADMX Achieved and Projected Sensitivity

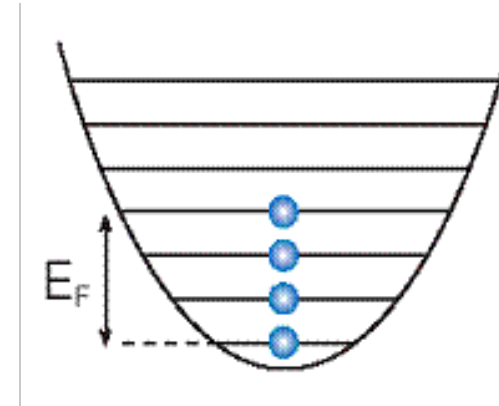


Theory and experiment bound possible coupling and mass of axion dark matter.

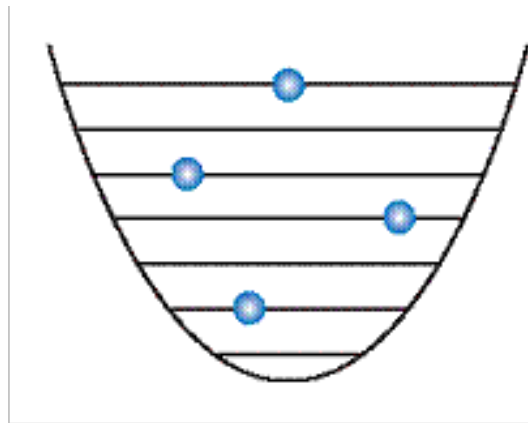
# Fermions (WIMPS) vs. Bosons (Axions, WISPS)



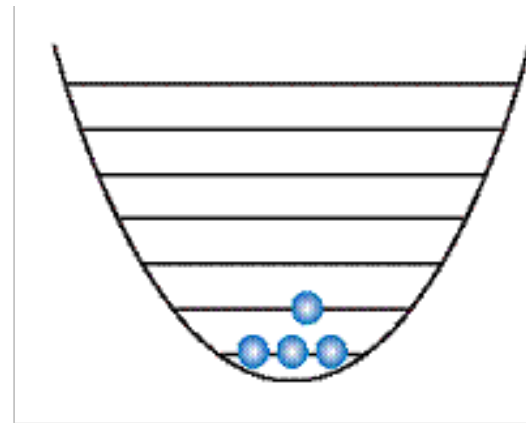
Thermal Fermions:  $T > T_F$



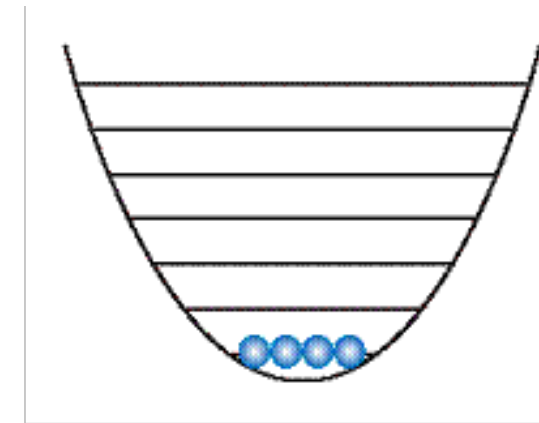
Degenerate Fermions:  $T \ll T_F$



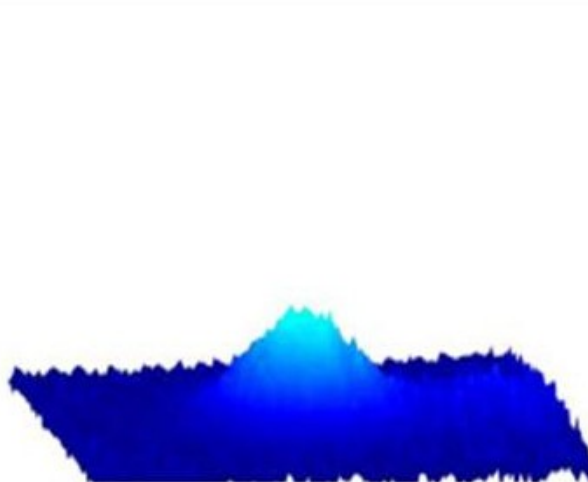
Thermal Bosons:  $T > T_c$



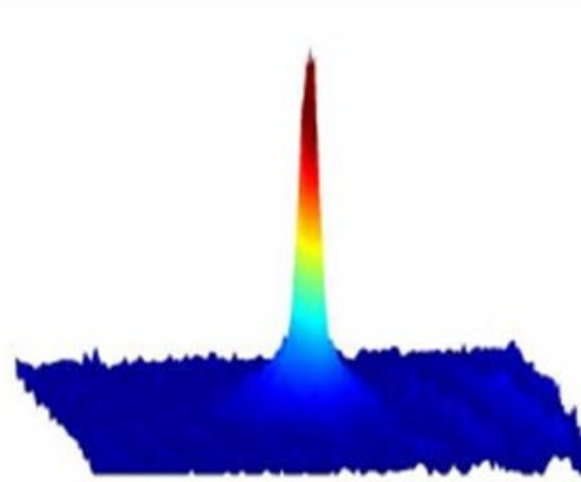
BEC+Thermal Bosons:  $T \lesssim T_c$



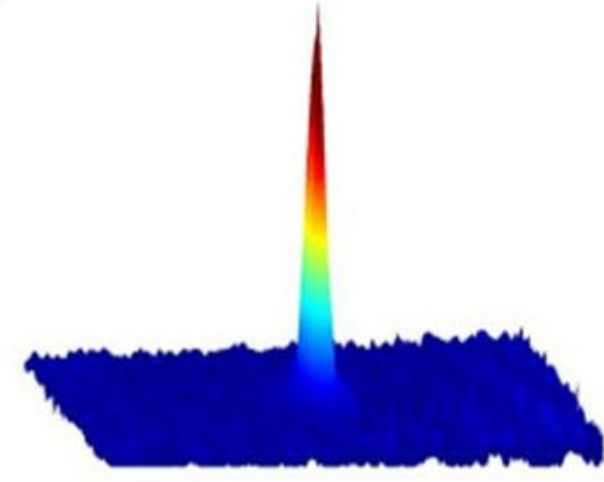
pure BEC:  $T \ll T_c$



Thermal Rb-87:  $T > T_c$



BEC+Thermal Rb-87:  $T \lesssim T_c$



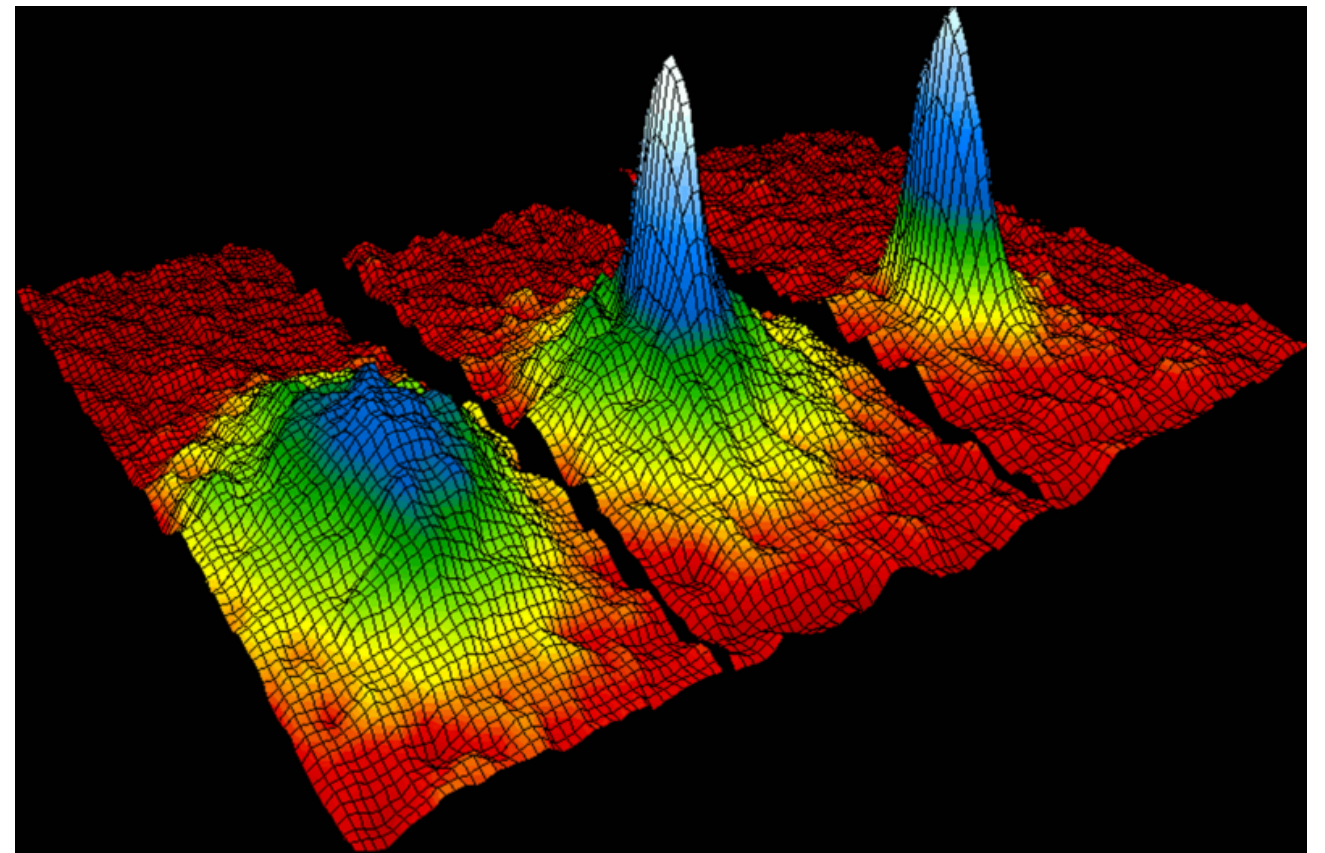
Rb-87 BEC:  $T \ll T_c$

# Bose–Einstein Condensates!

- Usually a lab phenomenon
- Atoms or subatomic particles cooled to critical temperature

$$T_c = \left( \frac{n}{\zeta(3/2)} \right)^{2/3} \frac{2\pi\hbar^2}{mk_B} \approx 3.3125 \frac{\hbar^2 n^{2/3}}{mk_B}$$

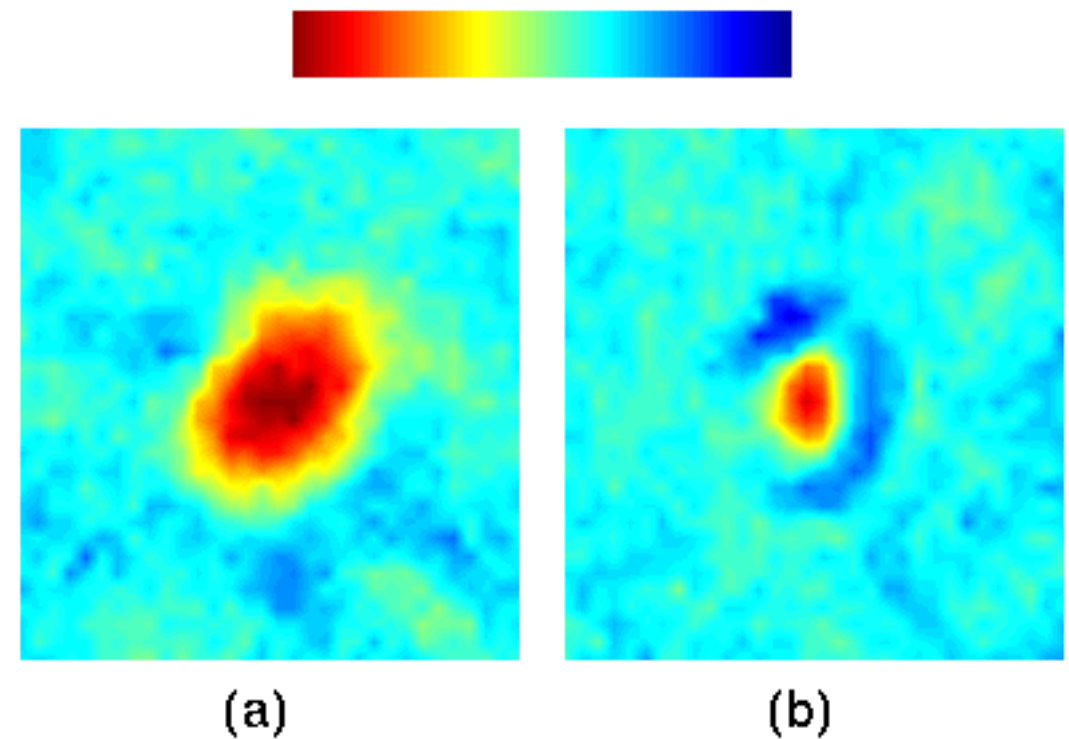
- Unlimited number of bosons can share same ground, zero-mode state





# BEC in Attractive Interactions

- Lithium-7 has 3 protons and 3 electrons  $\rightarrow$  boson
- Negative scattering length  $\rightarrow$  attractive interaction
- Theory said it should not form a stable BEC
- But it did! For 1000 atoms or less.



Hulet Group, Rice University

# BECs in Space!

- Motivation:

$$T_c = \left( \frac{n}{\zeta(3/2)} \right)^{2/3} \frac{2\pi\hbar^2}{mk_B} \approx 3.3125 \frac{\hbar^2 n^{2/3}}{mk_B}$$

- BEC from gravitational thermalization, not  $\phi^4$  (self) interactions  $\mathcal{N} \sim 10^{61}$

$$T_{BEC} \sim 500eV * \left( \frac{f_a}{10^{12}GeV} \right)^{\frac{1}{2}}$$

- BEC has correlation length that is Hubble scale?



# Do axion BECs with long correlations form?

- Describe axion Bose-Einstein condensation in high density regime *with a classical field theory*
- Analytically capture information about impact of gravitation on statistical mechanics
- *As with people, it matters whether particles are attracted or repulsed by one another.*

—> **New result: Sign of the interaction determines correlation length**

# Thermalization with Classical Fields

- Ordinary classical fields do not thermalize due to Rayleigh-Jeans catastrophe at high wave numbers
- Add in a cut-off  $\rightarrow$  well-defined thermal equilibrium
- As long as we have a large number density, the chemical potential will be zero  $\rightarrow$  condensate in ground state

# QCD Axion — Attractive

$$V(\phi) = \Lambda^4 (1 - \cos(\phi/f_a))$$

**Axion potential**

**The QCD scale  $\sim 0.1$  GeV**

**The symmetry  
breaking scale/  
axion decay  
constant**

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$



# Equation of Evolution

**time evolution**

$$i \dot{\psi} = -\frac{1}{2m} \nabla^2 \psi - \frac{\lambda}{8m^2} |\psi|^2 \psi - Gm^2 \psi \int d^3 x' \frac{|\psi(x')|^2}{|x - x'|}$$

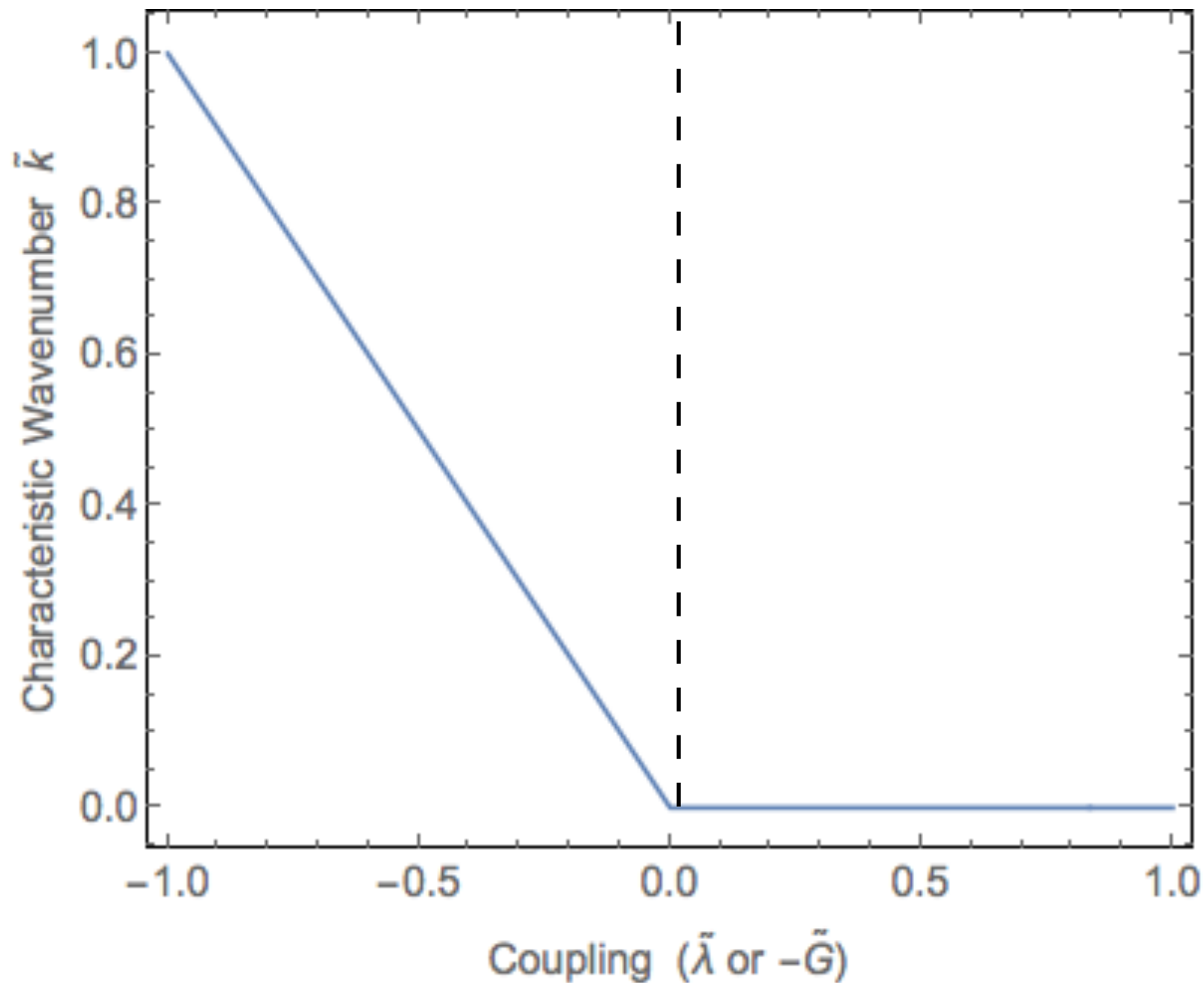
**Kinetic term**

**Self-interaction, with coupling constant  $\lambda$**

**Gravitational interactions**

The diagram illustrates the components of the equation of evolution. A red arrow points from the text 'time evolution' to the time derivative term  $i \dot{\psi}$ . Three red arrows point upwards from the labels 'Kinetic term', 'Self-interaction, with coupling constant  $\lambda$ ', and 'Gravitational interactions' to their respective terms in the equation:  $-\frac{1}{2m} \nabla^2 \psi$ ,  $-\frac{\lambda}{8m^2} |\psi|^2 \psi$ , and  $-Gm^2 \psi \int d^3 x' \frac{|\psi(x')|^2}{|x - x'|}$ .

# Coupling vs. Wave Number



$\lambda > 0 \implies$  stability

$\lambda < 0 \implies$  instability

# BEC Axion Timeline

1. Initially characteristic wavelengths evolve under standard redshifting
2. As relaxation rates become comparable to Hubble time, system will attempt to thermalize and form BEC
3. For repulsive interactions: thermalization towards condensate with almost all particles in  $k=0$  ground state

$$\begin{aligned}\lambda > 0 &\implies \text{stability} \\ \lambda < 0 &\implies \text{instability}\end{aligned}$$



# Attractive Interactions: Clumpy, Bose Stars

- Compact phase-correlated object or *macroscopic quantum state*

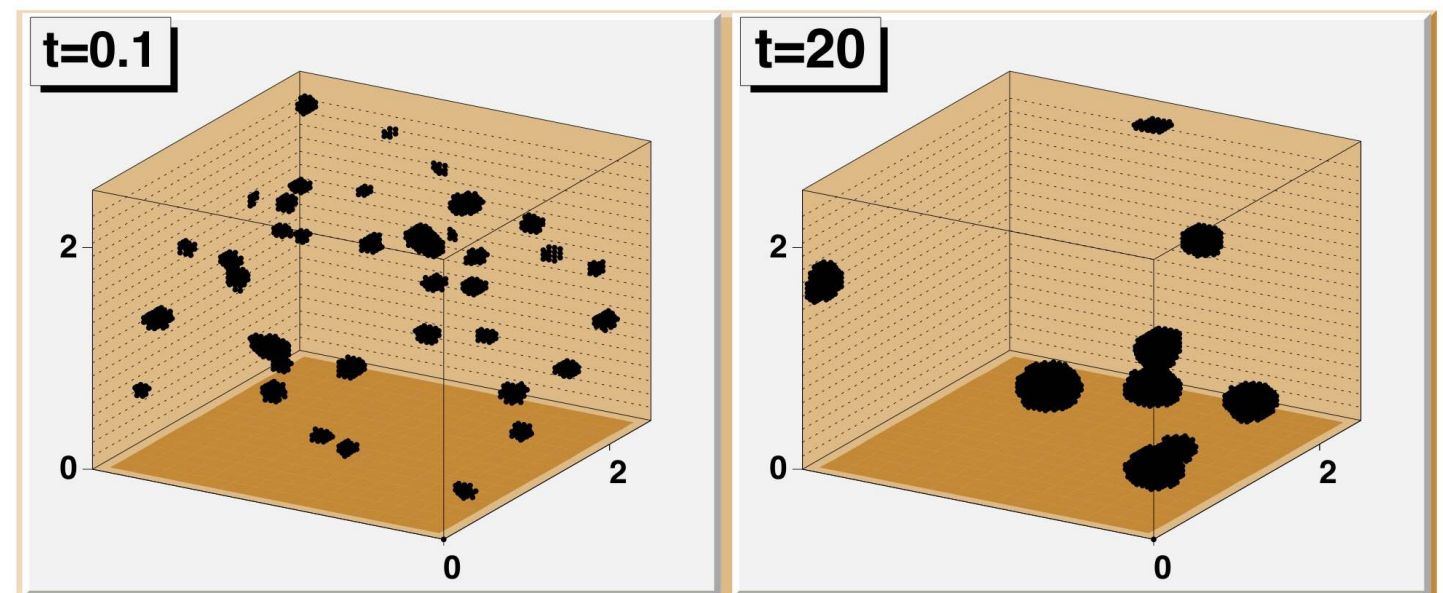
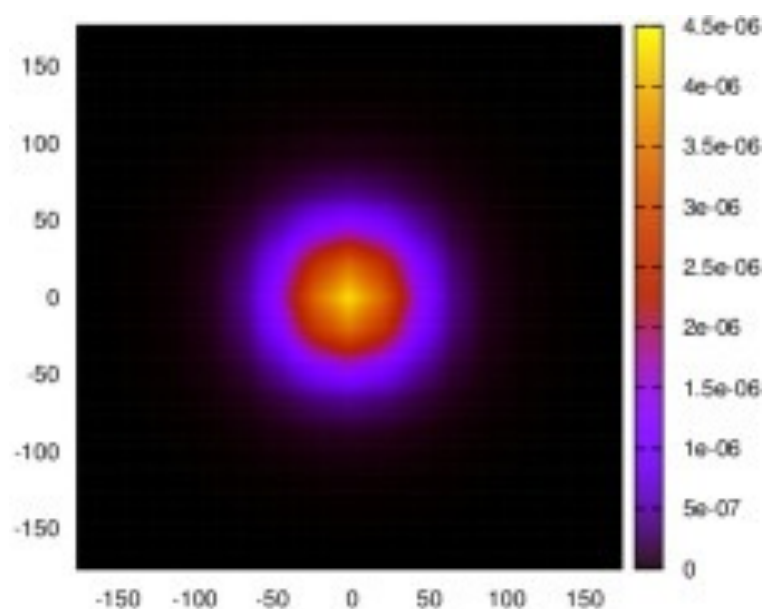


FIG. 1. Drops of dew at different moments of time.

- Depending on axion mass  $M = 10^{-10}$  solar masses

$$\xi \sim \frac{1}{Gm^3 N} \sim \frac{(10^{19} \text{ GeV})^2}{(10^{-5} \text{ eV})^3 \times 10^{61}} \sim km$$

# Does Axion Dark Matter form Bose–Einstein Condensates?

Yes, in small, locally-correlated  
clumps such as Bose stars.

# Completing the BEC Axion Story

- Stability checks — Eby et al. [10.1007/JHEP03\(2015\)080](https://arxiv.org/abs/10.1007/JHEP03(2015)080)
- N-body simulations
- Characterising potential for microlensing observations
- Behavior of Bose star in neutron star magnetic field?
- Studying how the dynamics change if there are multiple axion fields
- If there are blobs in a gas halo, is this a warm-cold axion situation with evaporative cooling-like process?



See Pierre Sikivie's Talk  
This Afternoon!

# Testing the Dark Matter Caustic Ring Theory Against Observations in the Milky Way

Julie Dumas, Heidi J. Newberg, Bethany Niedzielski, Adam Susser, Jeffery M. Thompson

Rensselaer Polytechnic Institute



## Abstract

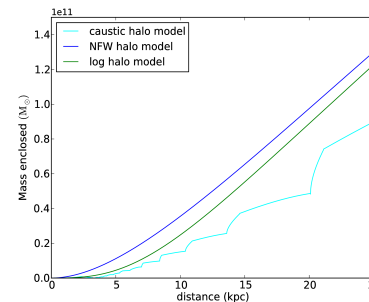
We test a particular theory of dark matter, in which dark matter axions form ring “caustics” in the plane of the Milky Way. According to this theory, cold collisionless dark matter particles with angular momentum flow in and out of the Milky Way as it forms. These flows form caustic rings (at the positions of the rings, the density of the flow is infinite) at the locations of closest approach to the Galactic center. We show that the caustic ring dark matter theory reproduces a roughly logarithmic halo, with large perturbations near the rings. We show that the theory can reasonably match the known Galaxy rotation curve. We explore the effects of the caustic rings on dwarf galaxy tidal disruption using N-body simulations. Simulations of the Sagittarius dwarf galaxy in a caustic halo potential match observations as far as 90 kpc from the Galactic center. The source code for calculating the caustic halo acceleration has been made publicly available in the NEMO Stellar Dynamics Toolbox and the Milkyway@home client repository.

## Introduction

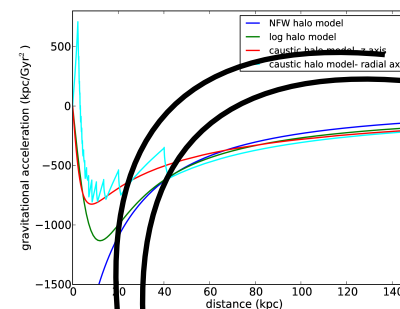
The dark matter caustic ring theory has been developed by Pierre Sikivie (Sikivie, Tkachev, & Wang 1995; Sikivie 2003; Natarajan & Sikivie 2007; Duffy & Sikivie 2008; Sikivie 2011; Banik & Sikivie 2013) over the past 20 years. Although Sikivie started from the spherically symmetric self-similar models of Fillmore & Goldreich (1984) and Bertschinger (1985), it is important to note that the Sikivie model has evolved to include physics of dark matter particles beyond a simple gravitational interaction. The physics results in dark matter flows that rotate with the stellar disk.

For the Milky Way (rotation speed of 220 km/s at 8.5 kpc from the Galactic center and the current accelerating model of the Universe age = 13.7 Gyr), the inner ring caustics are predicted to exist at radius:  $a_n = 40/n$  kpc, ( $n = 1, 2, 3, \dots$ ). The first four caustics should be rings at distances of 40, 20, 13, and 10 kpc from the center of the Galaxy (Duffy & Sikivie 2008). Here we compare results where the gravitational potential of the Milky Way dark matter halo is represented by the caustic ring, Navarro, Frenk, and White (NFW; 1996), logarithmic, and triaxial (Law & Majewski 2010) models. A future goal is to investigate whether the gravitational field of dark matter caustic rings could cause a migration of stars similar to what is observed in the stellar ring structures in the Milky Way (Monoceros Ring; Newberg et al. 2002).

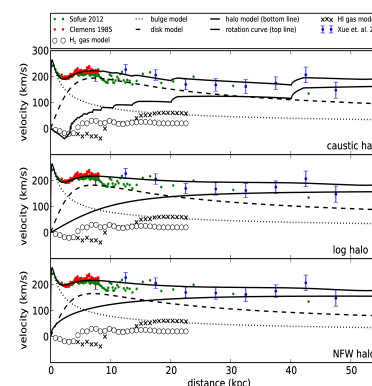
## Results



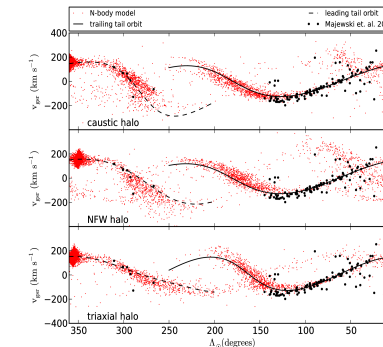
**Figure 1. Dark matter mass vs distance from the Galactic center.** Note the bumps in the caustic model curve (cyan) where the caustic rings are predicted. The mass of the NFW (blue) and logarithmic halo (green) are shown for comparison.



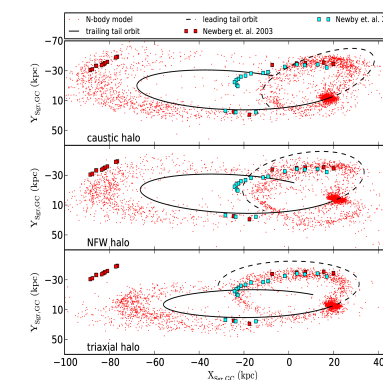
**Figure 2. Gravitational acceleration vs distance from the Galactic center.** Caustic halo model- radial axis (cyan) is the acceleration along the radial direction in the Galactic plane ( $z=0$ ). Caustic halo model- z axis (red) is the acceleration along the z axis of symmetry ( $r=0$ ). Note the bumps in the caustic model curve where the caustic rings are predicted. The acceleration of the NFW (blue) and logarithmic halo (green) are shown for comparison.



**Figure 3. Rotation curve of the Milky Way.** The sum of the Hernquist (1990) bulge (dotted line), Miyamoto-Nagai (1975) disk (dashed line), halo (lower solid line), and hydrogen gas (open circles and crosses) models (Olling & Merrifield 2000) produce a rotation curve (upper solid line) that matches observations from Clemens 1985, Sofue 2012, and Xue et al. 2008 (red, green, and blue points respectively).



**Figure 4. Galactic standard of rest velocities vs. orbital longitude (Sgr Heliocentric spherical coordinate system defined by Majewski et al. 2003) for the Sagittarius (Sgr) dwarf galaxy tidal stream.** The leading (dotted line) and trailing (solid line) best-fit orbits to the 2MASS M giant data from Majewski et al. 2004 (black dots) is shown with corresponding N-body simulations (red dots). The fits for the caustic (top), NFW (middle), and triaxial (bottom) halo models are shown for comparison.



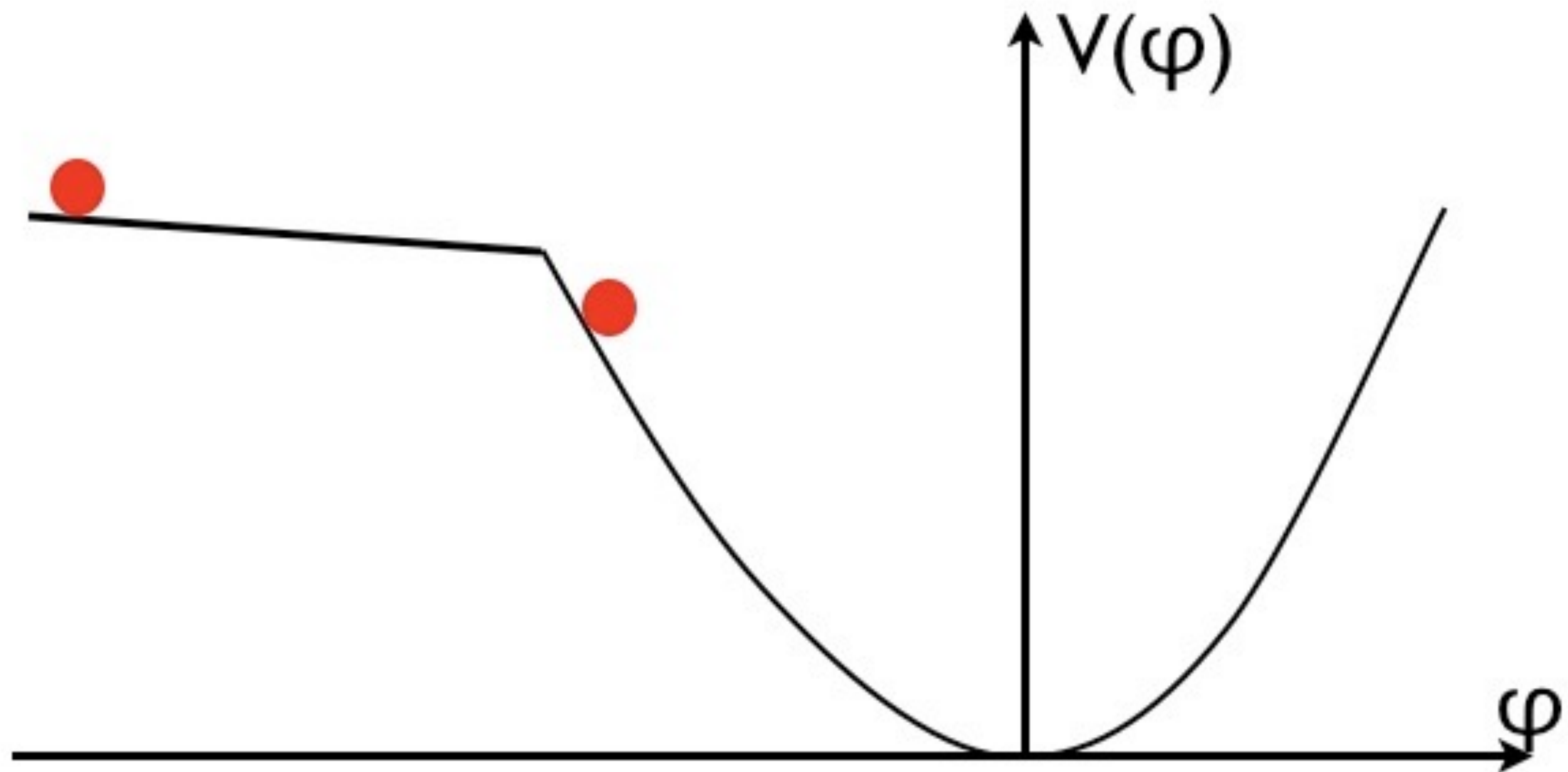
**Figure 5.  $Y_{sgr,gc}$  vs.  $X_{sgr,gc}$  (Sgr Galactocentric spherical coordinate system defined by Majewski et al. 2003) for N-body simulations (red dots) of the Sagittarius (Sgr) dwarf galaxy tidal stream.** The galaxy was evolved in a caustic (top), NFW (middle), and triaxial (bottom) halo model. The leading (dotted line) and trailing tail (solid line) orbits are also plotted. Recent observations from Newby et al. 2013 (cyan squares) and Newberg et al. 2003 (red squares) are also shown for comparison. Note the caustic halo tidal debris matches observations out to 90 kpc.

## Acknowledgements

This research is based upon work supported by the NSF grant AST 10-09670, the NASA-NY Space Grant, and the American Fellowship from AAUW.



How do we go from quantum fields  
on a classical background . . .





. . . to large scale structure?





We're just beginning!  
But this is the end of the talk.

- There is exciting phenomenology in the axion-Bose-Einstein condensate idea, but maybe not over large, correlated length scales.
- Future work: full nonlinear simulation of the field theory in  $3+1$
- For more details: **arXiv:1412.5930**