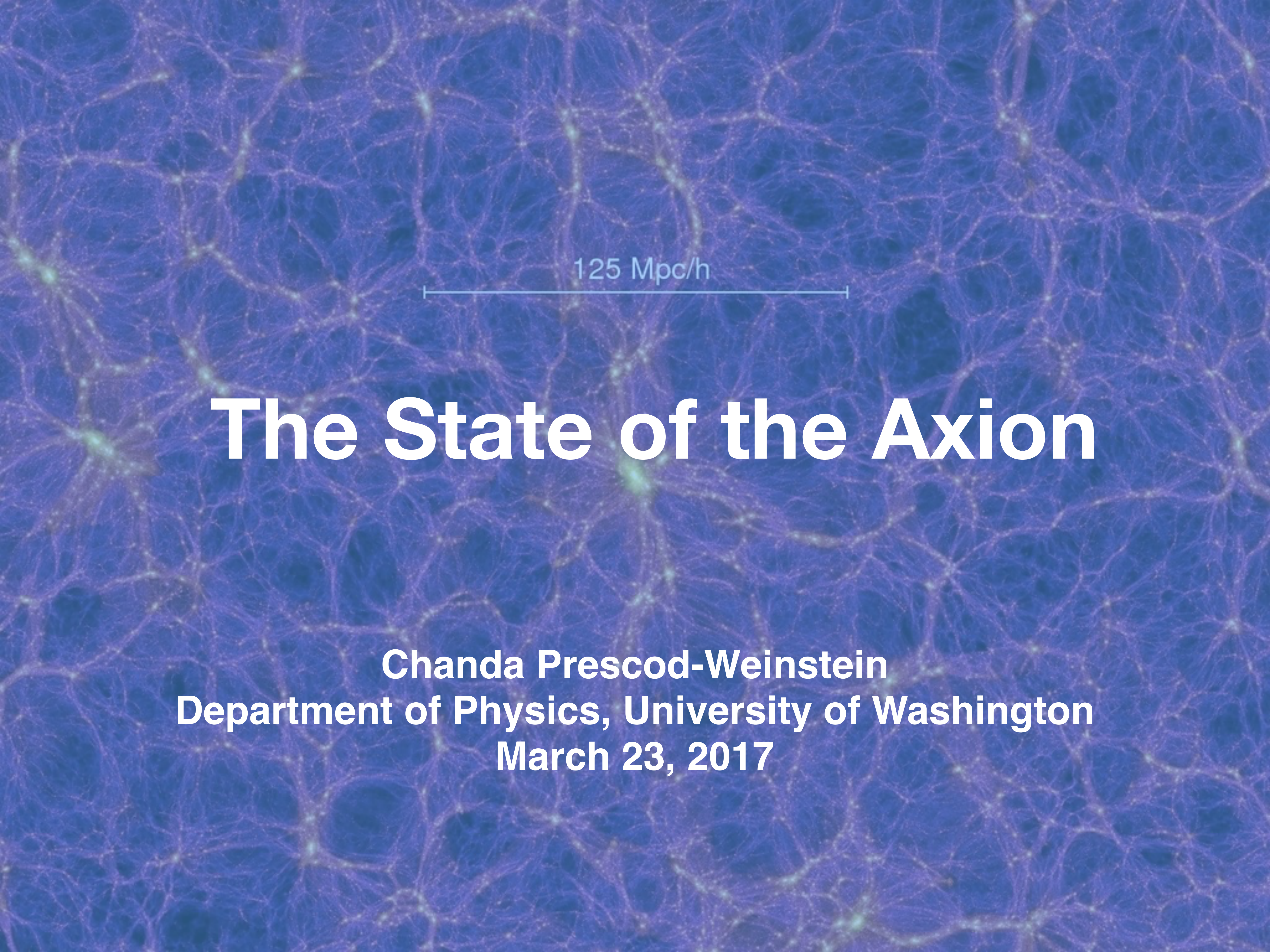


The State of the Axion

Chanda Prescod-Weinstein
Department of Physics, University of Washington
March 23, 2017

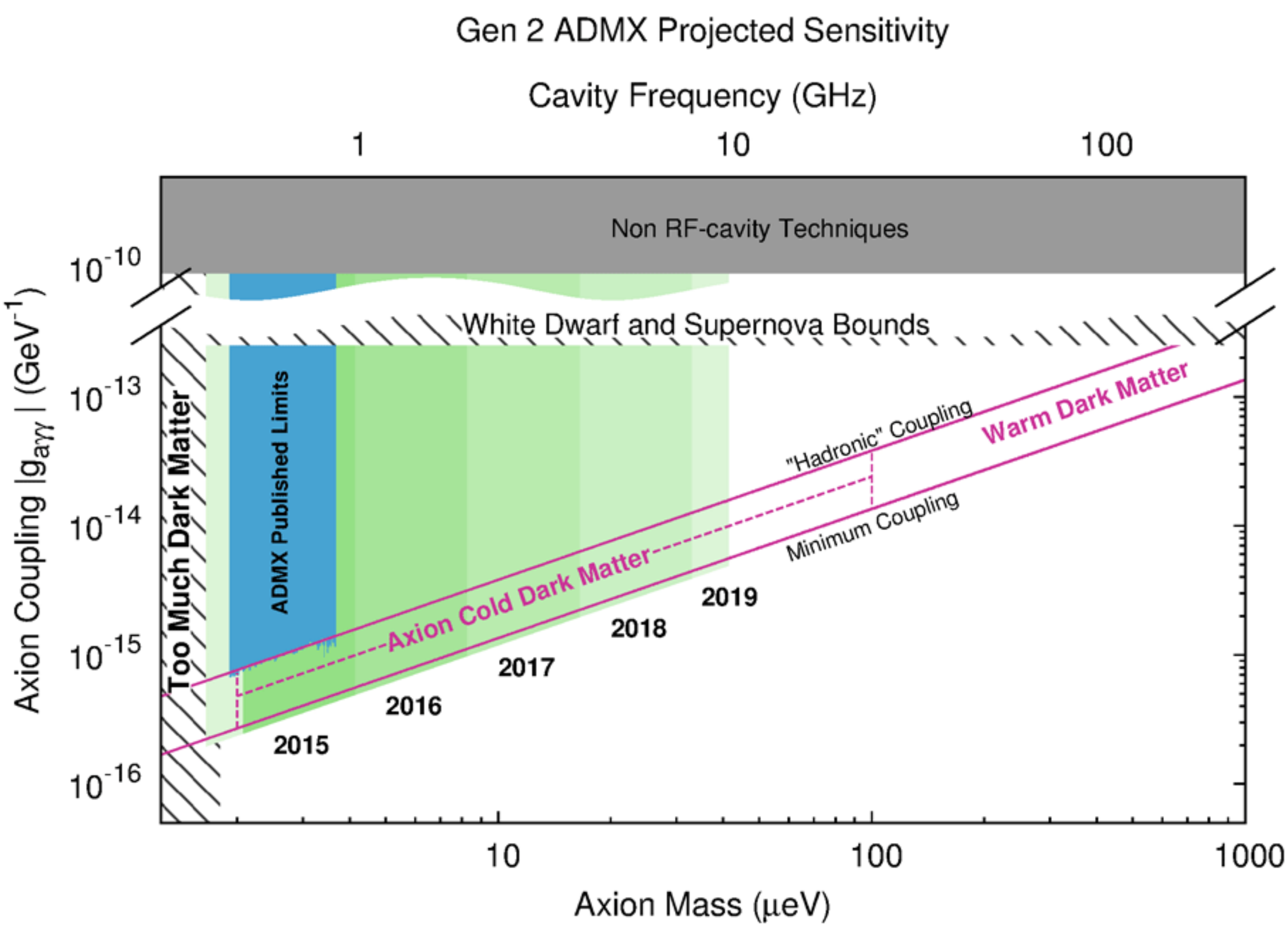
The QCD Axion

- Small mass + mostly gravitational interactions =

Dark Matter Candidate

- "Strong CP Problem"— Symmetry should be broken, never experimentally observed
- Not thermally produced
- No charge & mass ~ 10^{-5} eV/10^{-41} kg
- **Spin-0 bosons**

Axion Dark Matter eXperiment



Axion couples to strong magnetic fields, producing photons via Primakoff Effect

Chanda Prescod-Weinstein, U of Washington

What makes axions different?

Unlike WIMPs, they're bosons.

BECs in Space!

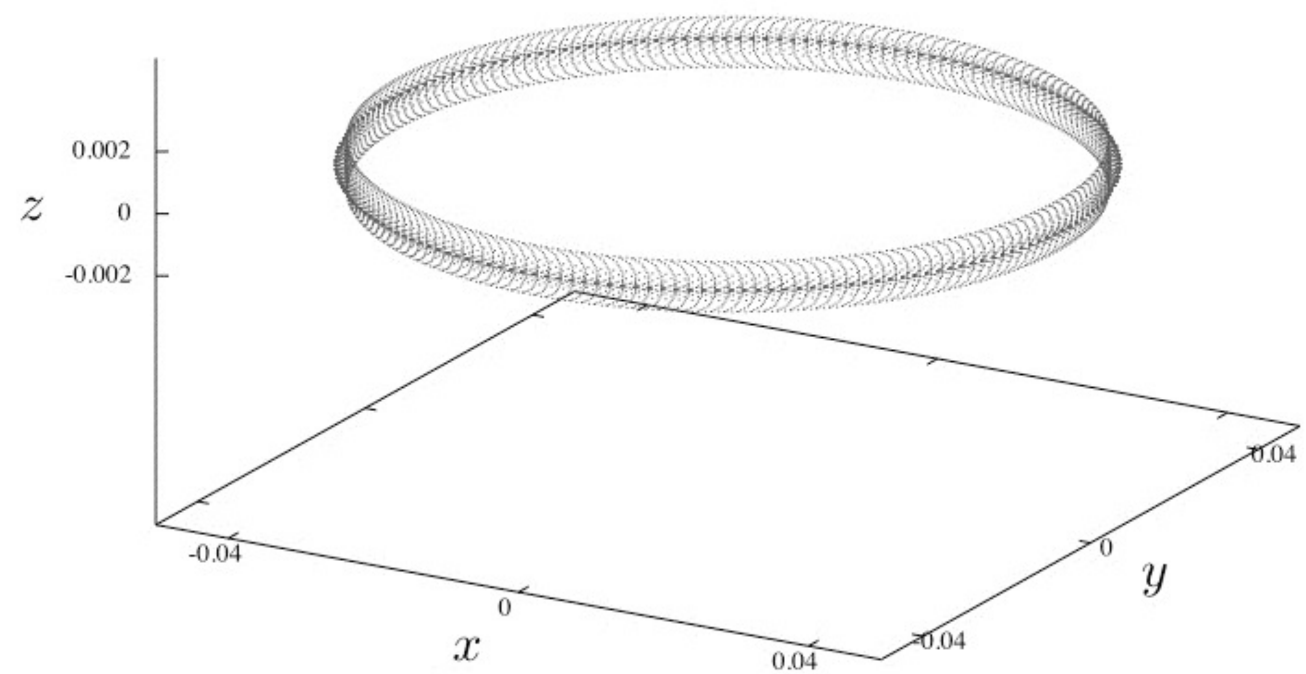
- Sikivie & Yang (2009) propose that **axion** dark matter must form Bose-Einstein condensate state during radiation-dominated era
- Motivation: $$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3} \frac{2\pi\hbar^2}{mk_B} \approx 3.3125 \, \frac{\hbar^2 n^{2/3}}{mk_B}$$
$$\mathcal{N} \sim 10^{61} \quad \& \quad T_{BEC} \sim 500eV * \left(\frac{f_a}{10^{12}GeV}\right)^{\frac{1}{2}}$$
- BEC from gravitational thermalization, not ϕ^4 (self) interactions
- BEC has correlation length that is Hubble scale

arXiv:0901.1106

arXiv:1111.1157

BEC Axion Observable: Caustics

- Regions of high density in galaxies, ring-like caustics



- Form when dark matter is collisionless, low velocity dispersion

simulation by Arvind Natarajan

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,...). 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

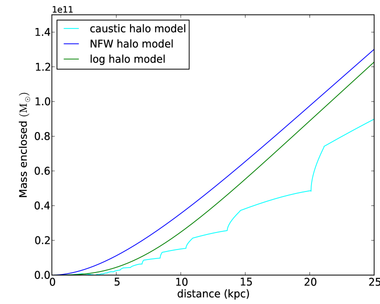


Figure 1. Dark matter mass vs distance from the Galactic center. Note the bumps in the caustic model curve (cyan) where the caustic rings are predicted. The mass of the NFW (blue) and logarithmic halo (green) are shown for comparison.

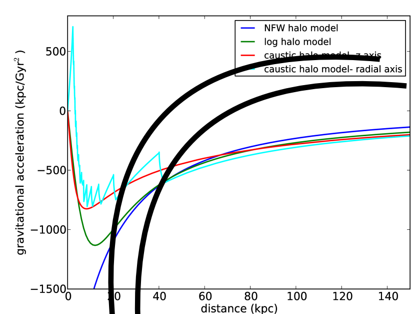


Figure 2. Gravitational acceleration vs distance from the Galactic center. Caustic halo model- radial axis (cyan) is the acceleration along the radial direction in the Galactic plane (z=0). Caustic halo model- z axis (red) is the acceleration along the z axis of symmetry (r=0). Note the bumps in the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

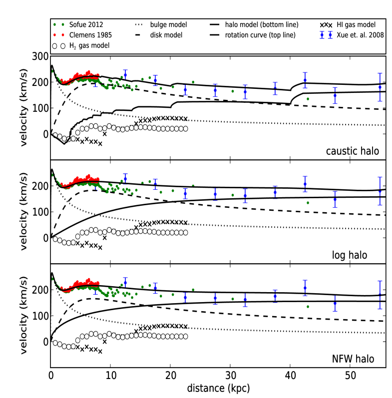


Figure 3. Rotation curve of the Milky Way. The sum of the Hernquist (1990) bulge (dotted line), Miyamoto-Nagai (1975) disk (dashed line), halo (lower solid line), and hydrogen gas (open circles and crosses) models (Olling & Merrifield 2000) produce a rotation curve (upper solid line) that matches observations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

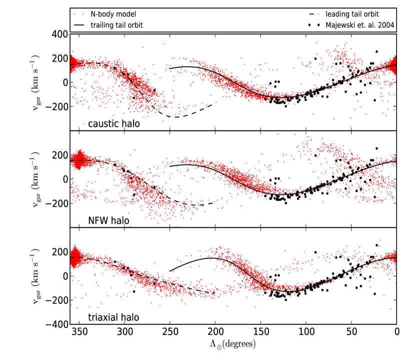


Figure 4. Galactic standard of rest velocities vs. orbital longitude (Sgr Heliocentric spherical coordinate system defined by Majewski et al. 2003) for the Sagittarius (Sgr) dwarf galaxy tidal stream. The leading (dotted line) and trailing (solid line) best-fit orbits to the 2MASS M giant data from Majewski 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.

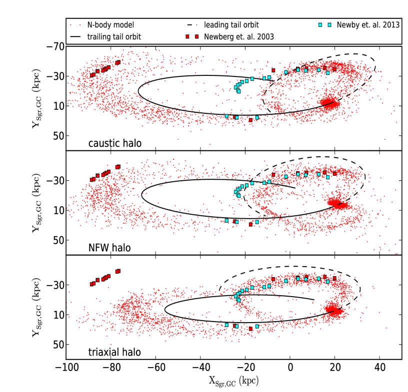


Figure 5. Ysgr,gc vs. Xsgr,gc (Sgr Galactocentric spherical coordinate system defined by Majewski et al. 2003) for N-body simulations (red dots) of the Sagittarius (Sgr) dwarf galaxy tidal stream. The galaxy was evolved in a caustic (top), NFW (middle), and triaxial (bottom) halo model. The leading (dotted 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

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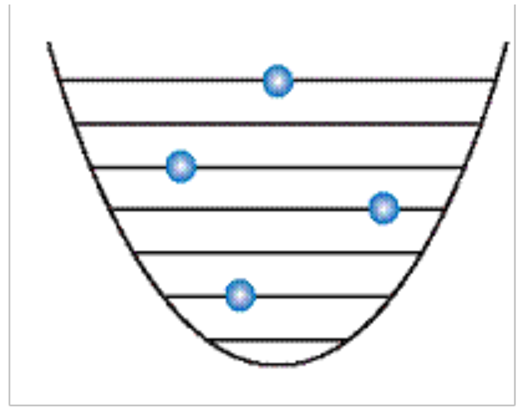
Does Axion Dark Matter form Bose-Einstein Condensates?

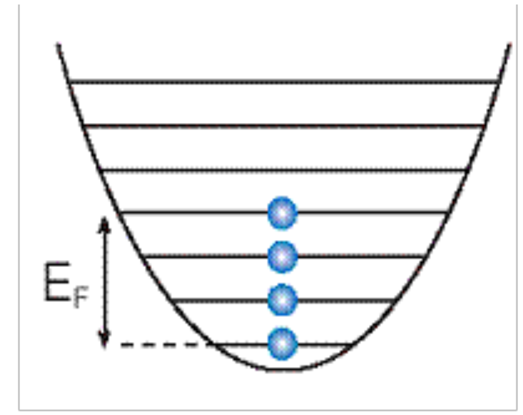
Yes, in small, locally-correlated clumps — axitons.

CPW, Guth & Hertzberg, **arXiv:1412.5930**

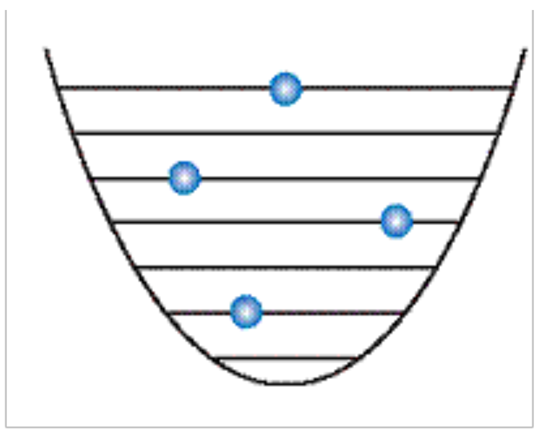
Fermions vs. Bosons



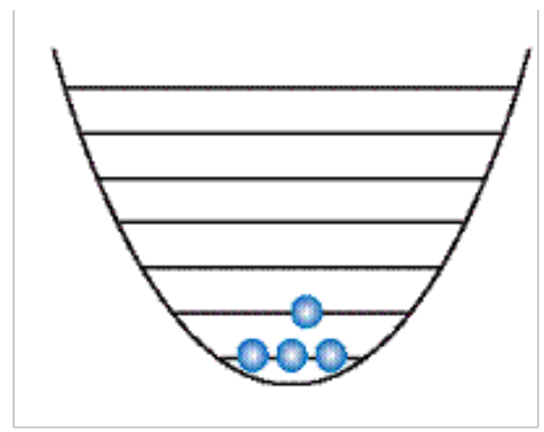
Thermal Fermions: $T>T_F$



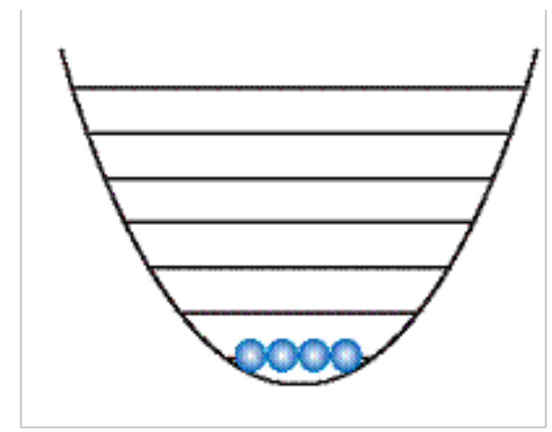
Degenerate Fermions: $T<<T_F$



Thermal Bosons: $T>T_c$

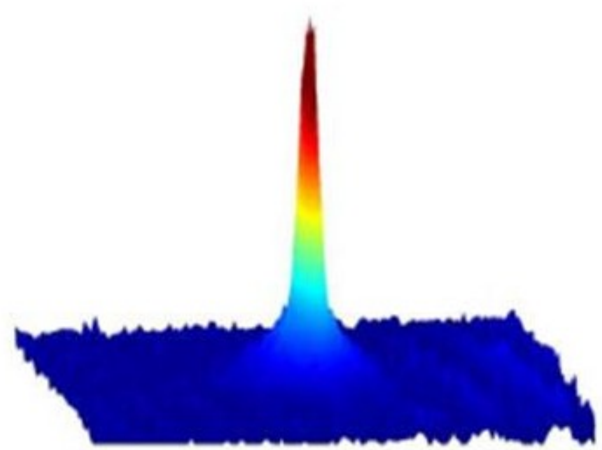


BEC+Thermal Bosons: $T\lesssim T_c$

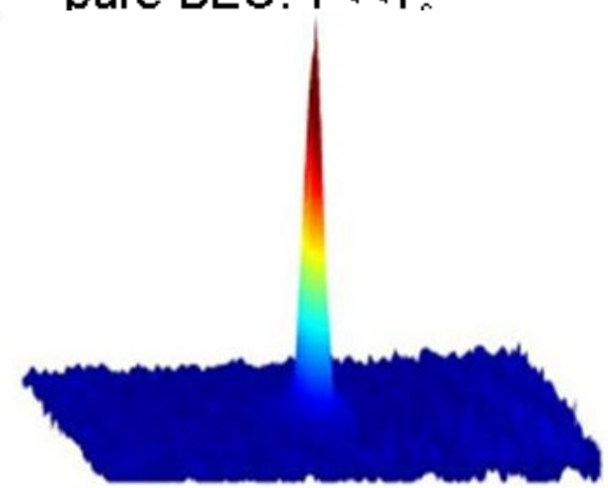


pure BEC: $T<<T_c$

Thermal Rb-87: $T>T_c$



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



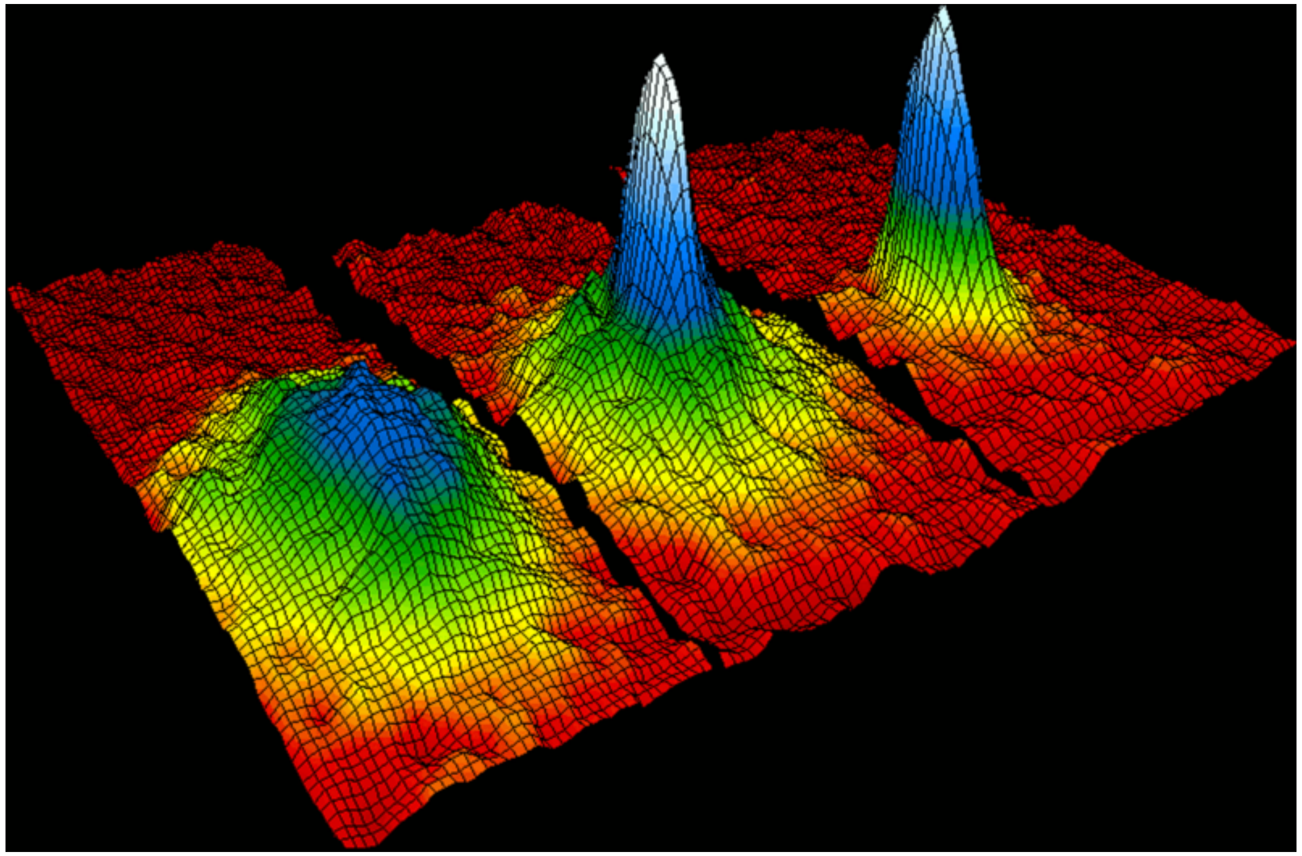
Rb-87 BEC: $T<<T_c$

Bose-Einstein Condensates!

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

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

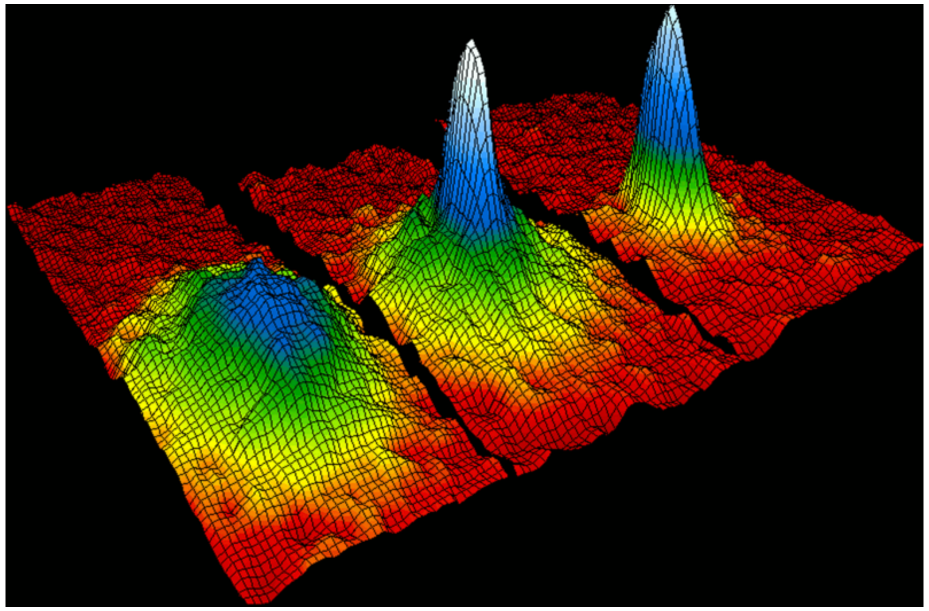
- Unlimited number of bosons can share same ground, zero-mode state



Davis et al. (1995)

Bose-Einstein Condensates?

- Einstein made argument for spinless, noninteracting bosons
- Macroscopic # of particles occupy one single state; but there are fragmented BECs
- Even in Penrose-Onsager formalism, definitions are wonky
- "It is obvious that there cannot be a general theorem to the effect that BEC will always occur in an interacting Bose system, even at T = 0, since the crystalline solid phase of 4He is a counter example." — Leggett



Thermal Equilibrium?

Davis et al. (1995)

Atoms vs. Axions

- We control the trap and the potential
- Gravity's relevance is fairly different
- Time scales are different
- In either case, how do we know it's a BEC? How did it get there?

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 axion statistical mechanics

- *As with people, it matters whether particles are attracted or repulsed by one another.*

—> **Sign of the interaction determines correlation length**

CPW, Guth & Hertzberg, **arXiv:1412.5930**

Self-Interaction: Attractive

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

Axion potential

The QCD scale ~ 0.1 GeV

The symmetry breaking scale/ axion decay constant

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

$m = \Lambda^2/f_a$

$\lambda = -\Lambda^4/f_a^4 < 0$

Attraction is Everywhere

time evolution

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

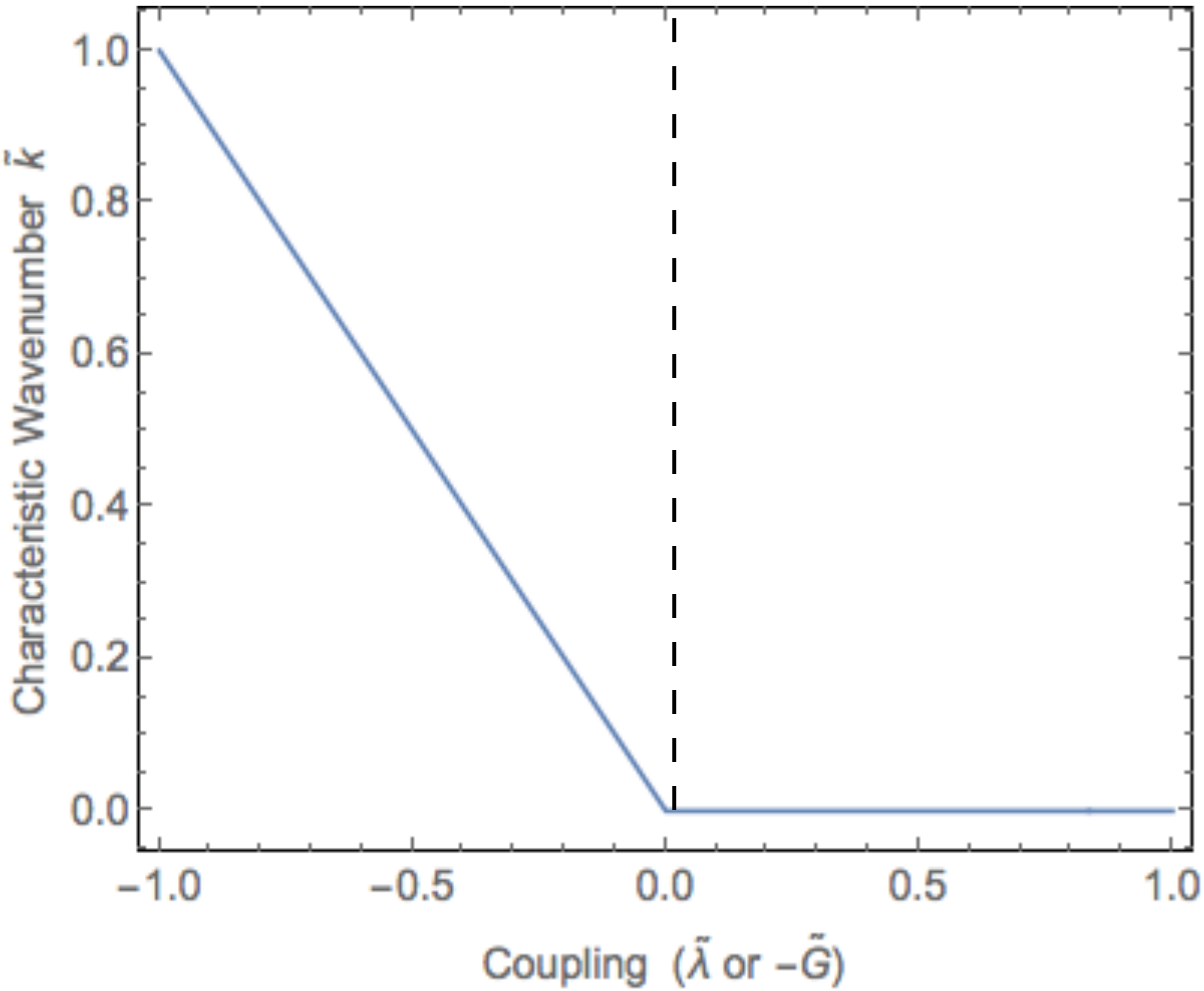
Kinetic term

Self-interaction, with coupling constant λ

Gravitational interactions

CPW, Guth & Hertzberg, **arXiv:1412.5930**

Coupling vs. Wave Number



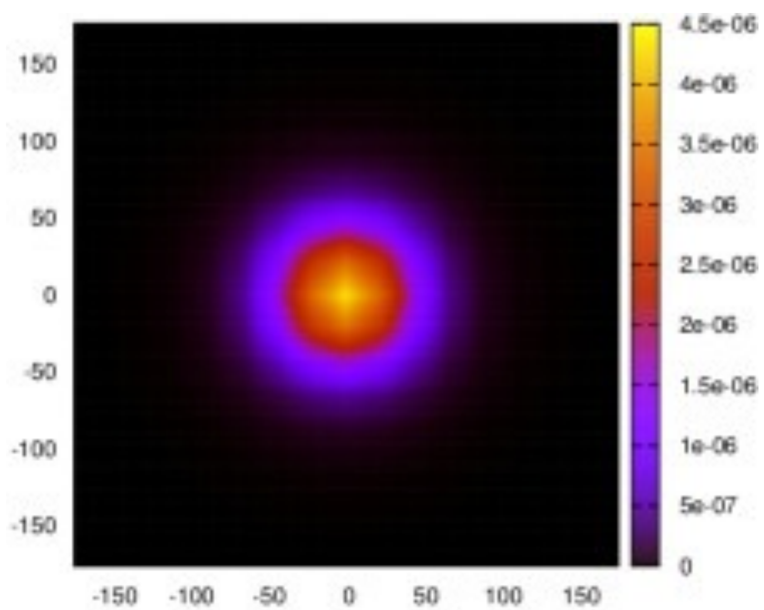
$$\lambda > 0 \implies \text{stability}$$

$$\lambda < 0 \implies \text{instability}$$

CPW, Guth & Hertzberg, **arXiv:1412.5930**

Attractive Interactions: Clumpy, Bose Stars

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



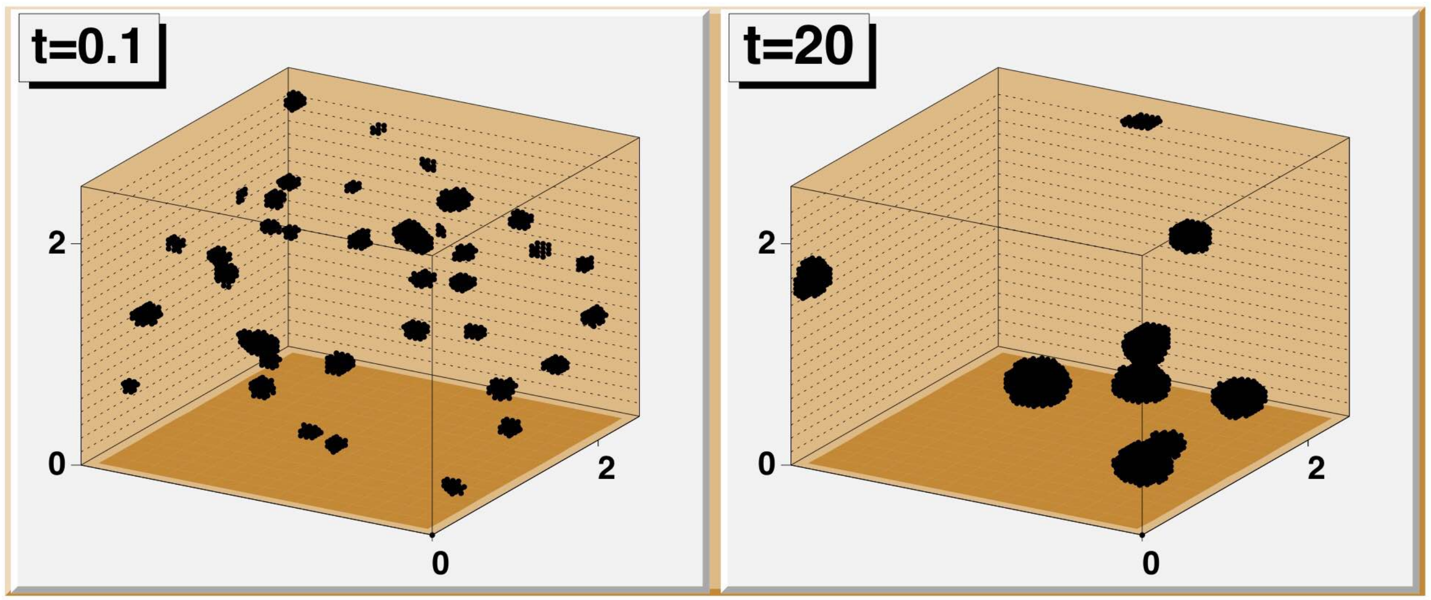


FIG. 1. Drops of dew at different moments of time.

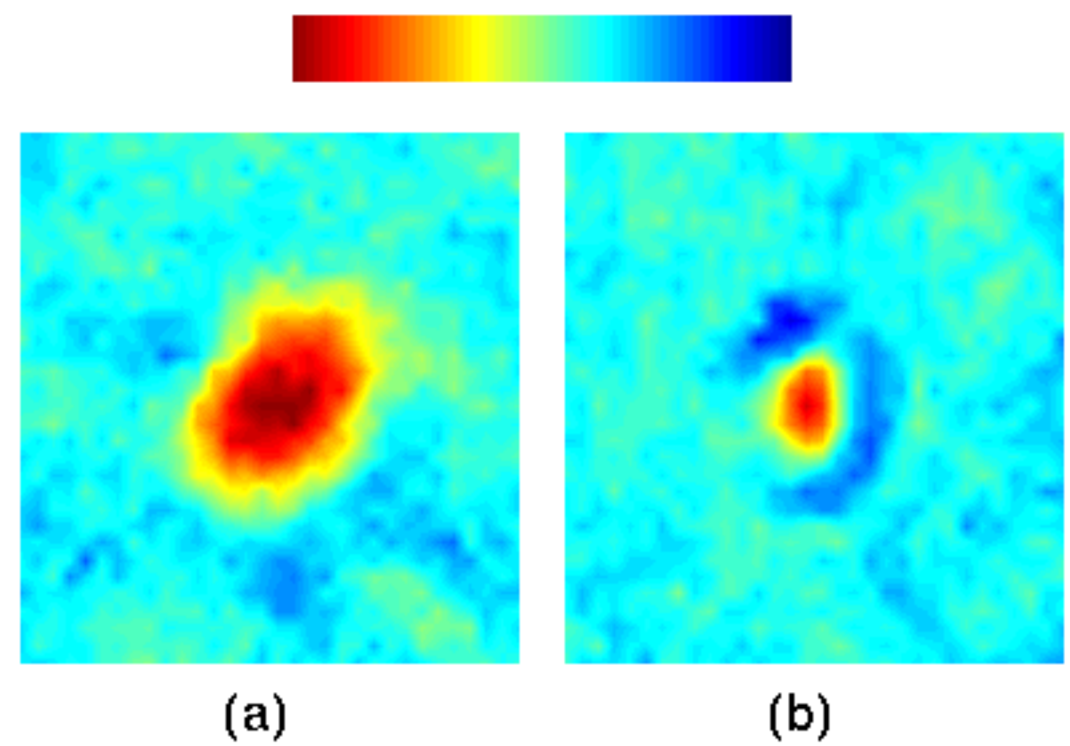
- Depending on axion mass M= 10^{-10} solar masses

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

Toth (2014); Khlebnikov & Tkachev (2000)

Attractive Interactions in the Lab

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



Hulet Group, Rice University

Does it matter?

- Attractive BECs are locally stabilized by a trap -> axion's trap is gravity -> axions *are locally* stabilized
- ADMX-type experiments (Kolb, Tkachev, etc.)
- Large scale phenomenology is different (Sikivie et al)
- Neutron star collisions (Iwazaki; Barranco et al; Tkachev)
- Axion Bosenovas (Eby et al 2016; Braaten et al 2016)

BEC structure governs internal dynamics of objects

Completing the BEC Axion Story

- Stability checks — Eby et al. (2015, 2016)
- Numerical scalar field & N-body simulations
- Characterising potential for microlensing observations
- **HOT:** Behavior of Bose star in neutron star magnetic field? Strobe-X??
- Studying how the dynamics change if there are multiple axion fields
- Axion minicluster -> bose star process?

Does Axion Dark Matter form Bose–Einstein Condensates?

Yes, in small, locally-correlated clumps — axitons/bose stars/ axsteroids.

CPW, Guth & Hertzberg, **arXiv:1412.5930**