THE STABILITY OF CONDENSED DARK MATTER CANDIDATES

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Department of Physics

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Introduction

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- The Dark Matter Problem
  - Flat galactic rotation curve
  - Bullet Cluster collision
  - 5x as abundant as luminous matter

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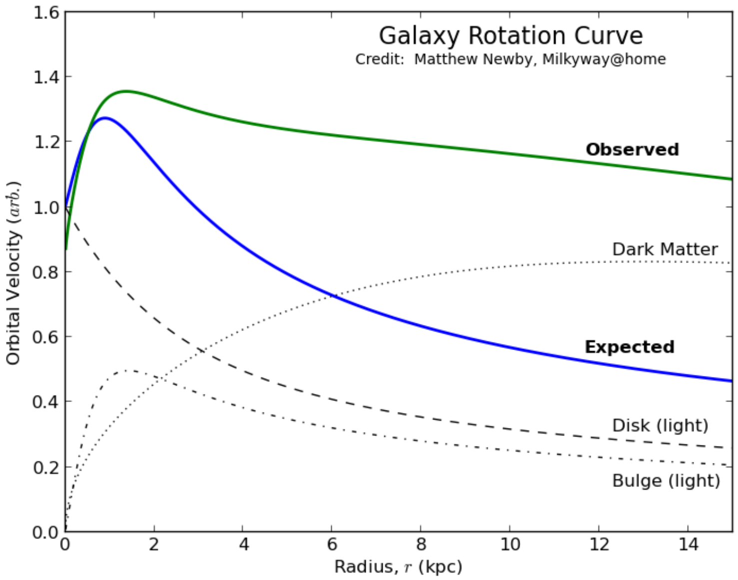

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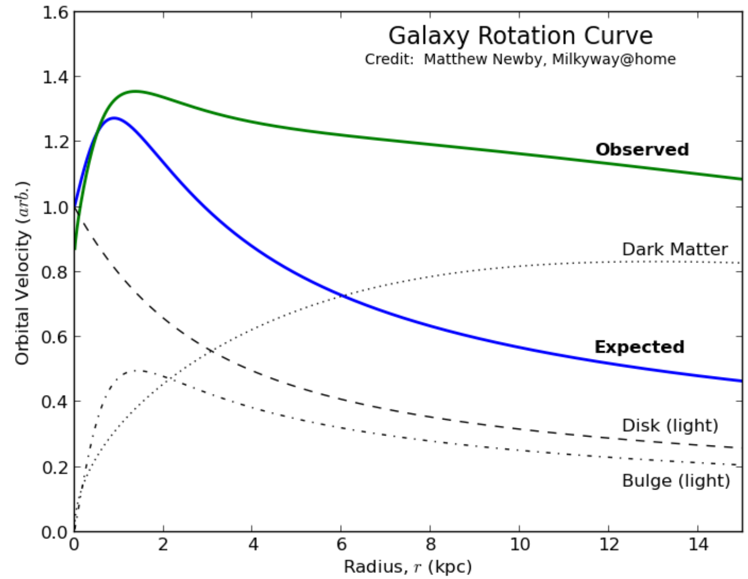

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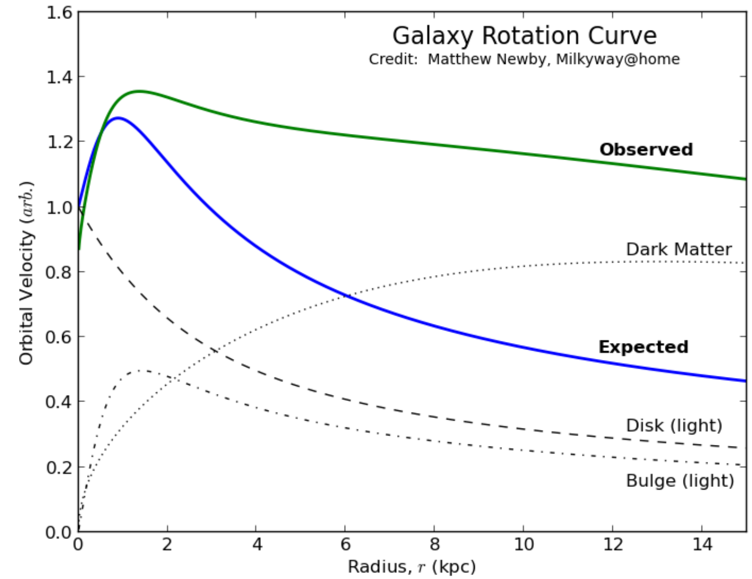
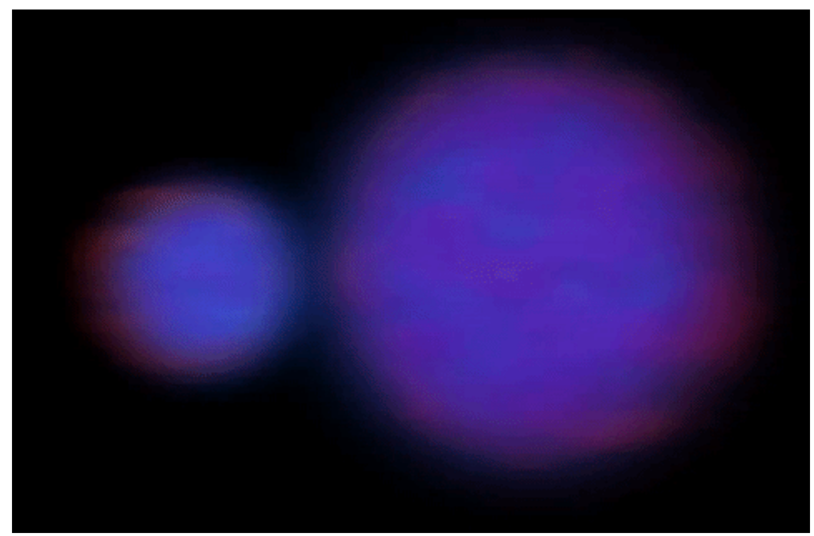
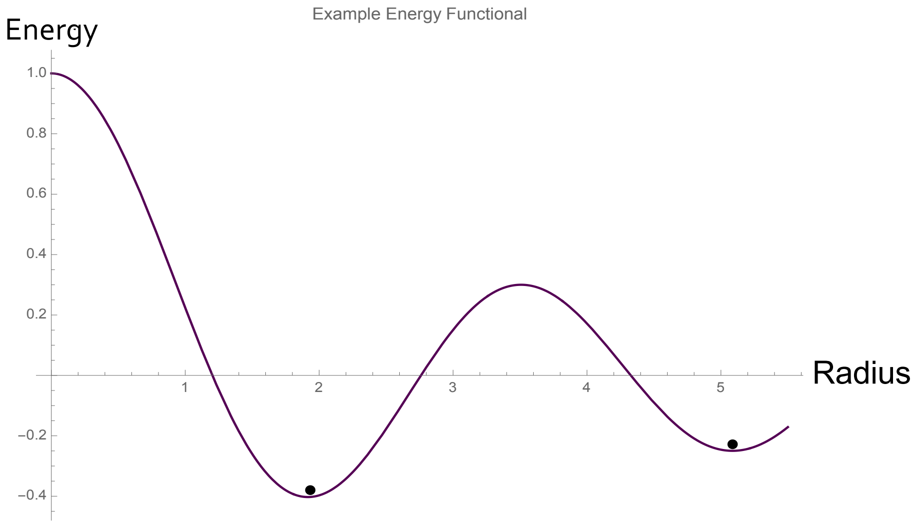




Credit: NASA/CXC/M.Weiss

Goal


Example Energy Functional
Energy
1.0
0.8
0.6
0.4
0.2
−0.2
−0.4
1
2
3
4
5
Radius

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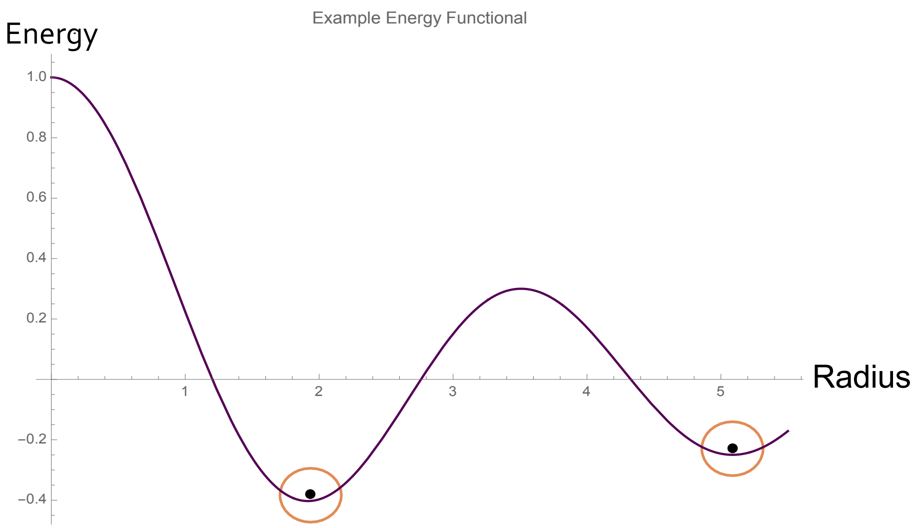
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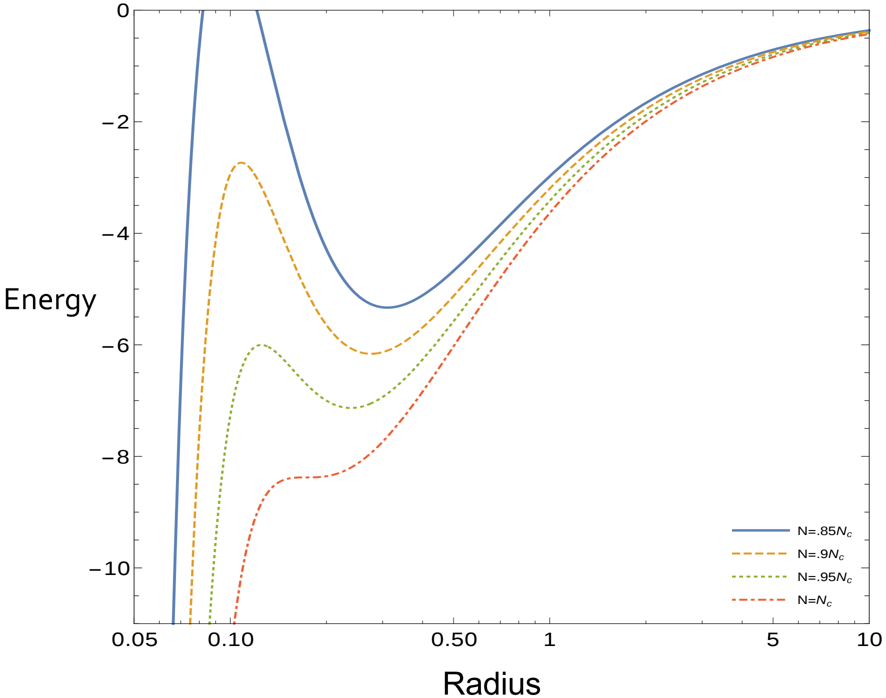
0
−2
−4
−6
−8
−10
Energy
0.05
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0.50
1
5
10
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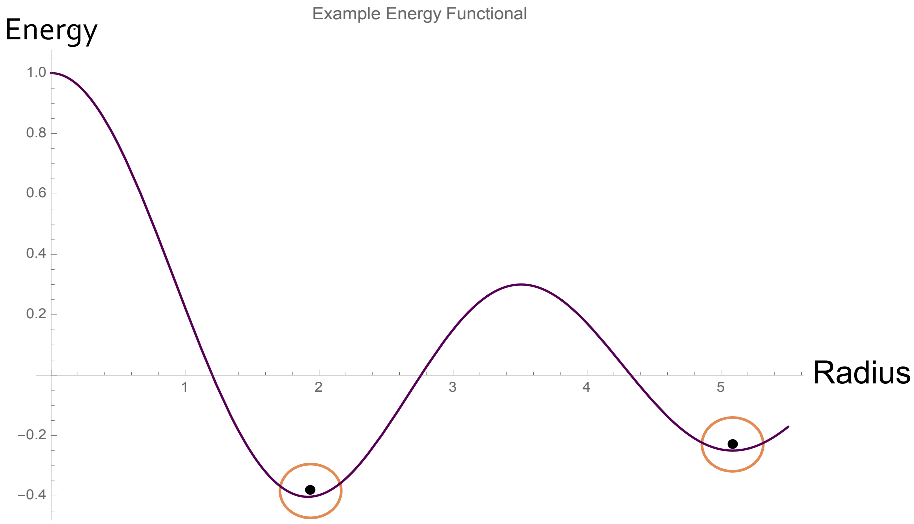
N=.85N_c
N=.9N_c
N=.95N_c
N=N_c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  - Postulated to collapse to a black hole
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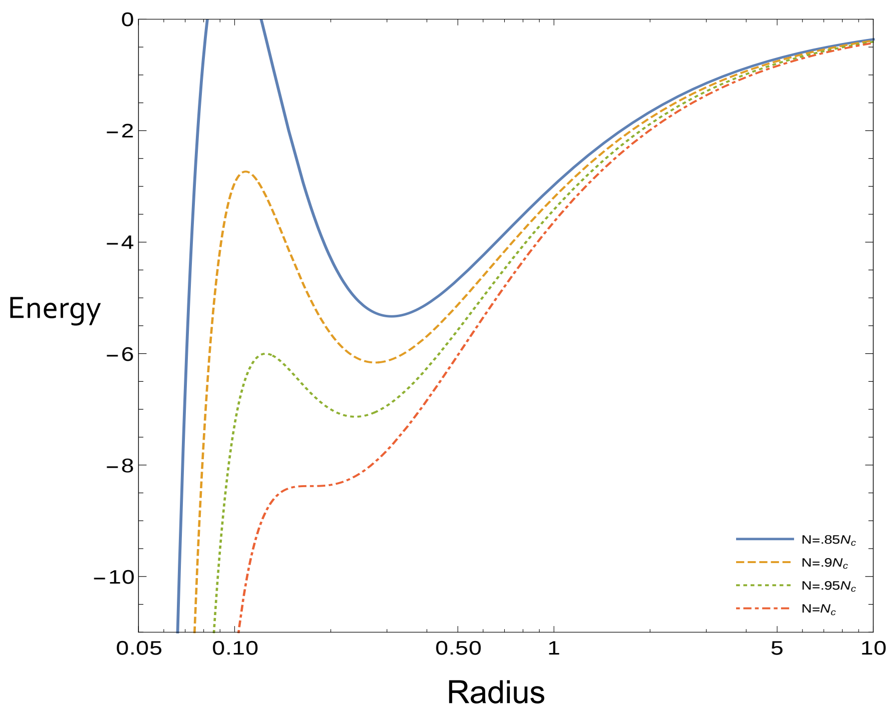

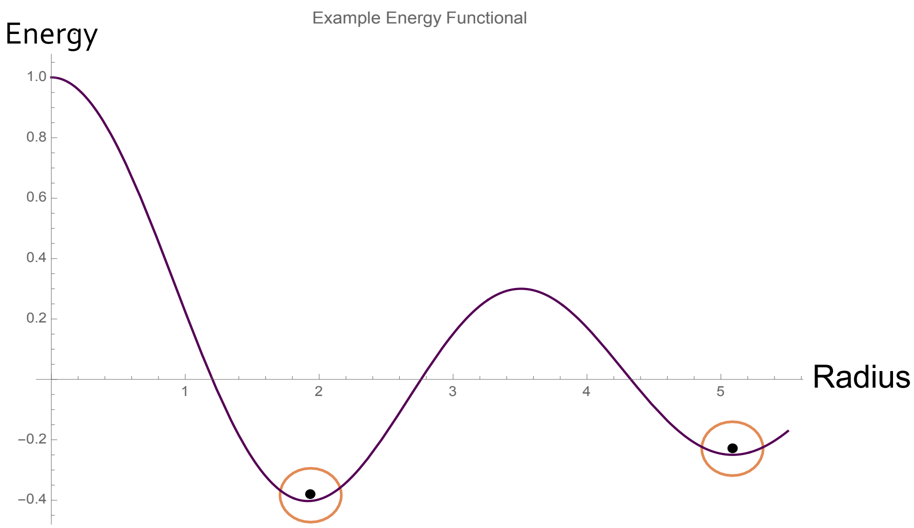

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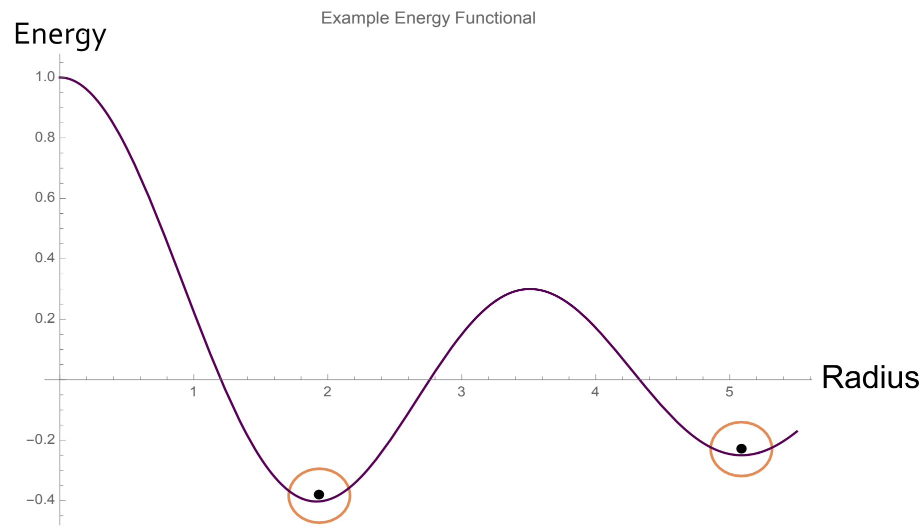

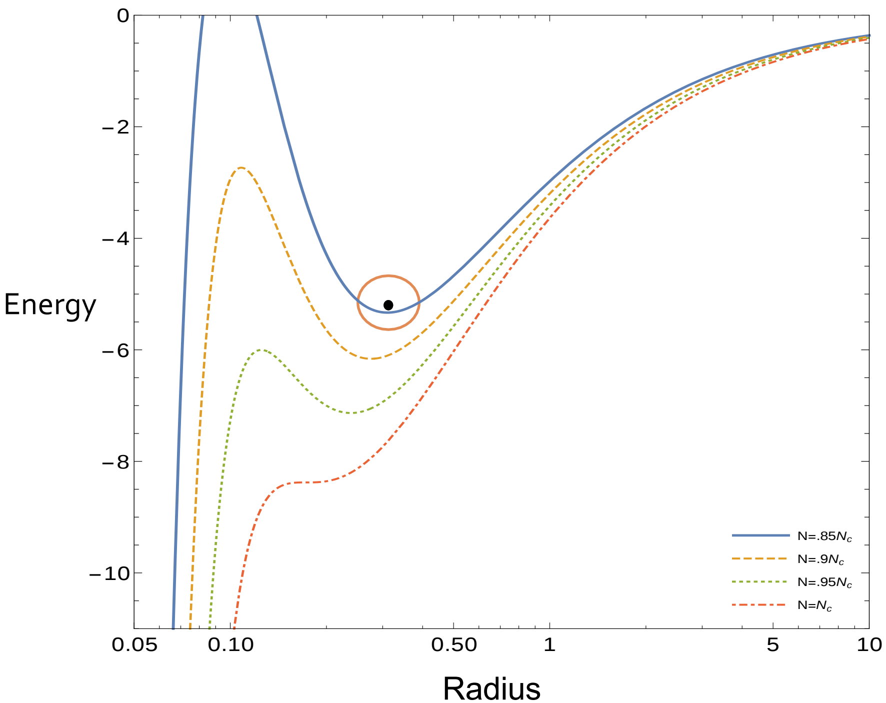

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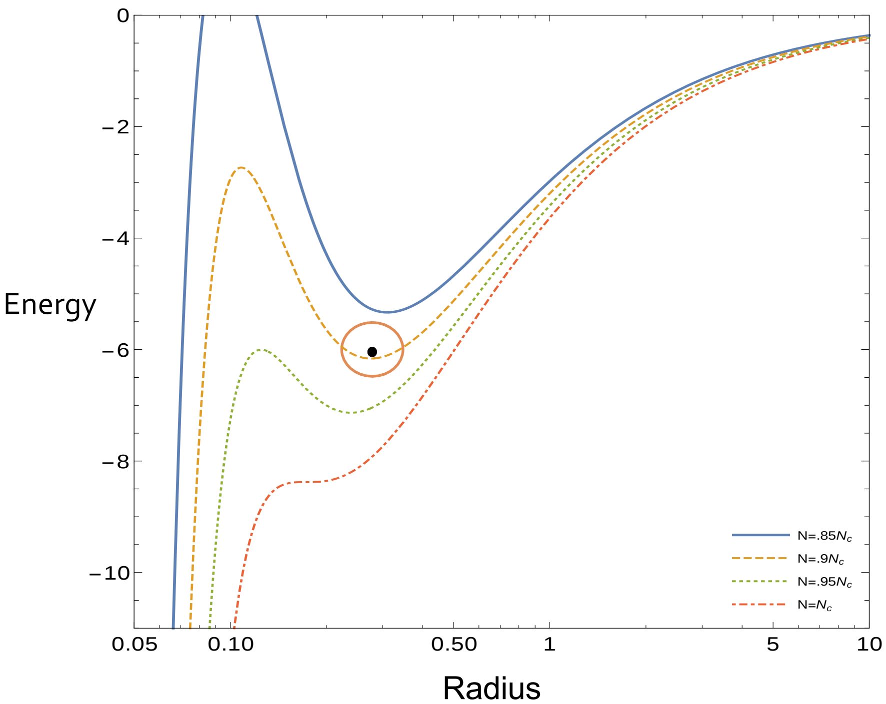

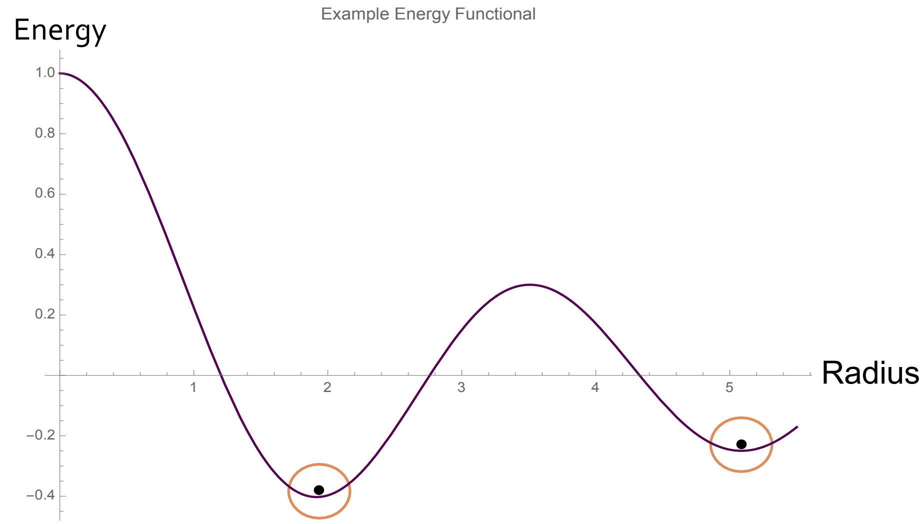

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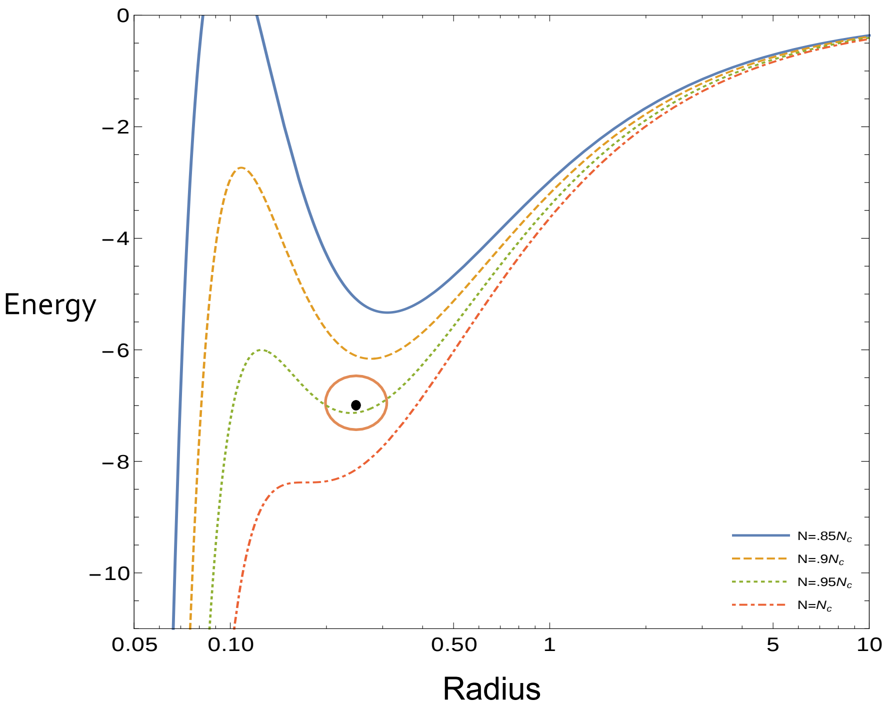

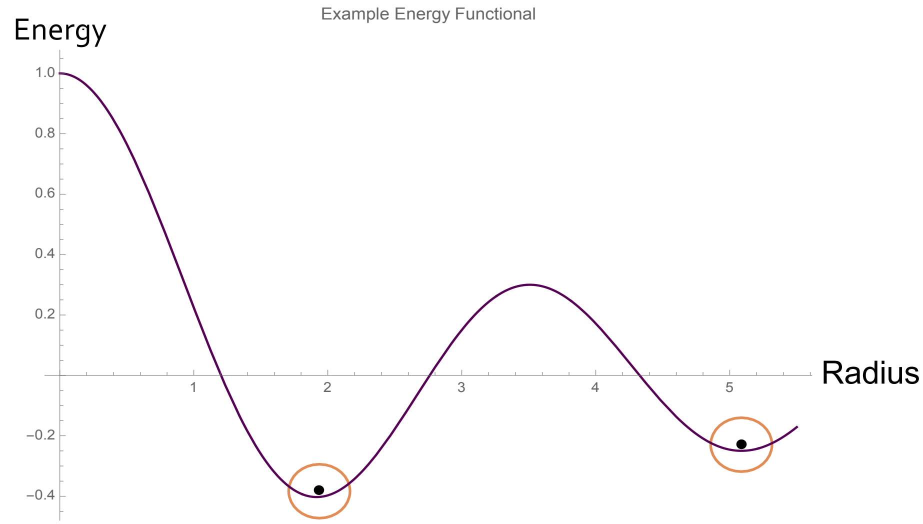

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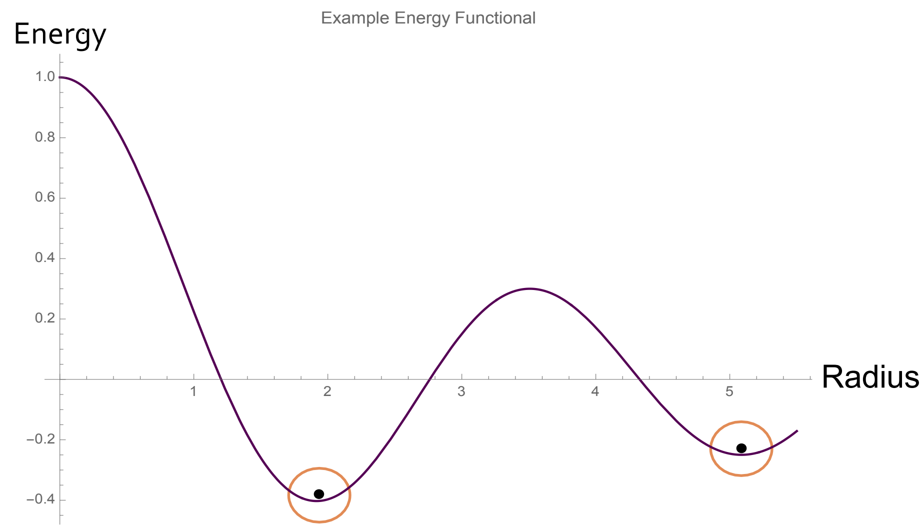

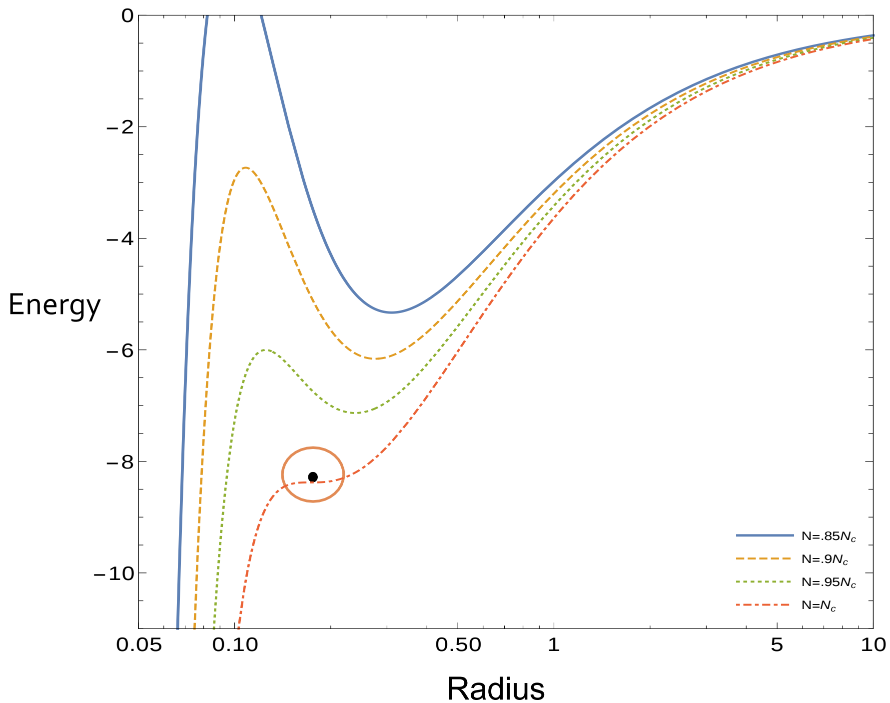

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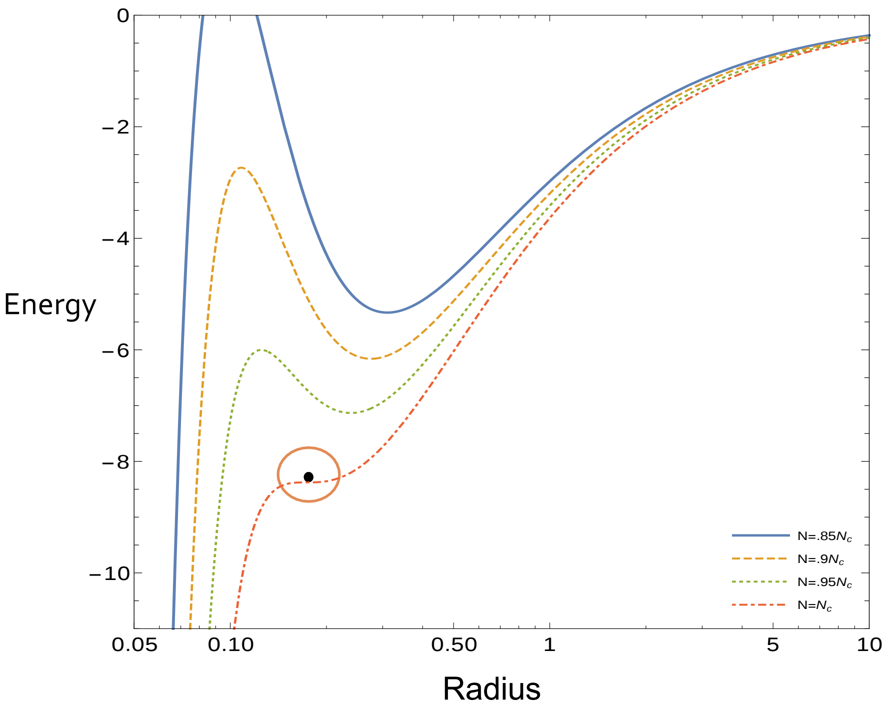

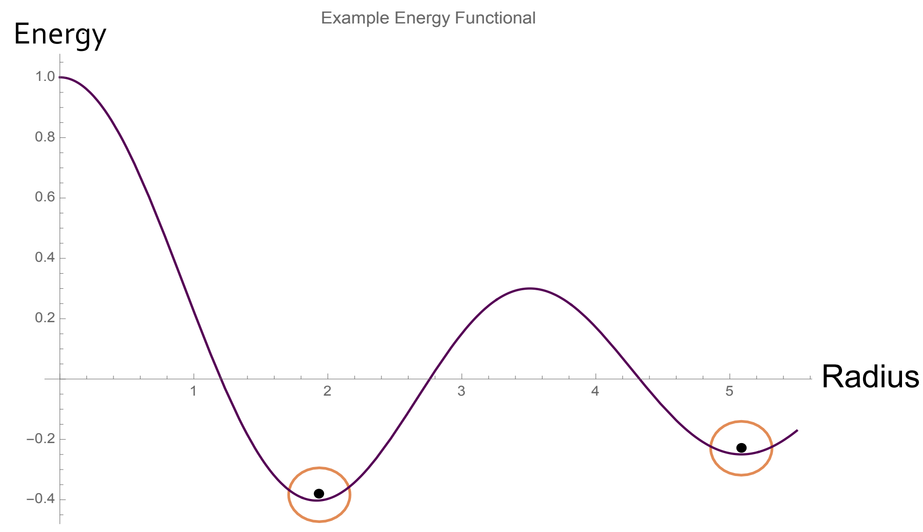

- Stability of an axion star
  - Improve approximations
    - J. Eby, P. Suranyi, C. Vaz, L.C.R. Wijewardhana, JHEP 1503 (2015) 080 arXiv:1412.3430
  - Variational method

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This expansion gives rise to alternating *attractive* and *repulsive* interactions!

5

A Numerical Aside

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- Shooting method
  - Specify the initial conditions to match appropriate end behavior
  - ψ, V_g go to zero at infinity, ψ'(0) = 0
- So why use a variational method?
  - Numerical results exist only for stationary configurations
  - Ansätze are powerful tools for solving *dynamic* problems
  - We use numerical solutions to choose the best ansatz, but use the variational method to model collapse, collision, expansion…

6 *Results*

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$$E\left(\psi\right) = \int d^3r \left[\frac{\left|\nabla\psi\right|^2}{2m} + \frac{1}{2}V_{grav}\left|\psi\right|^2 - \frac{1}{16}\frac{\left|\psi\right|^4}{f^2} + \frac{1}{288}\frac{\left|\psi\right|^6}{mf^4}\right]$$

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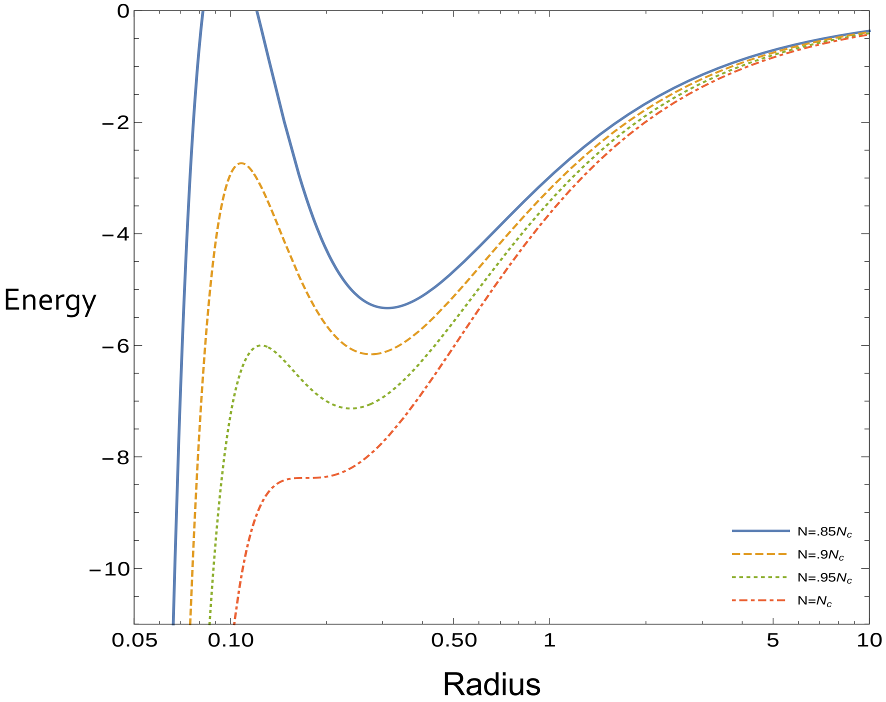

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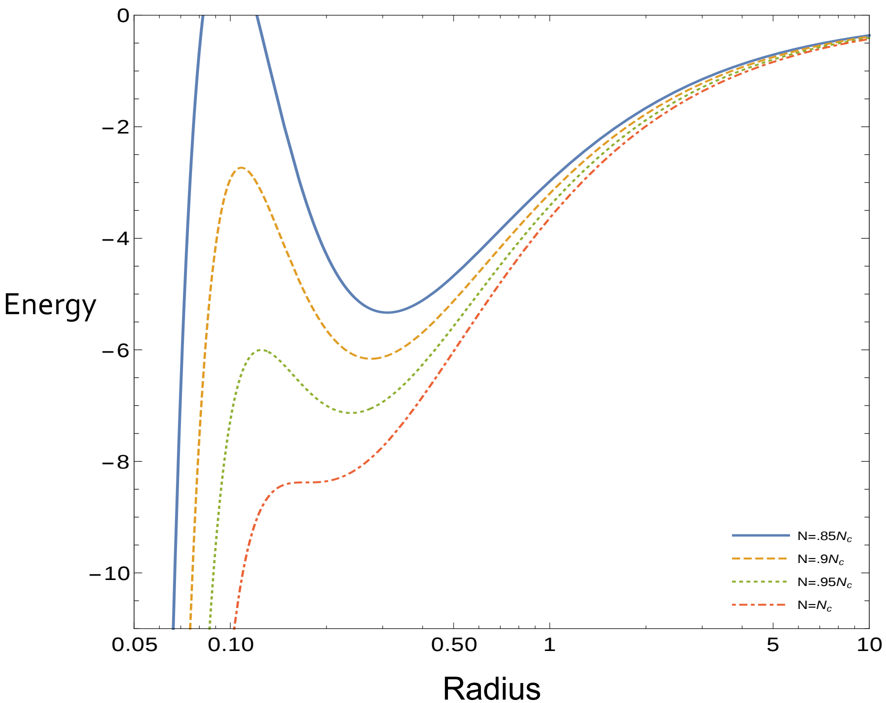

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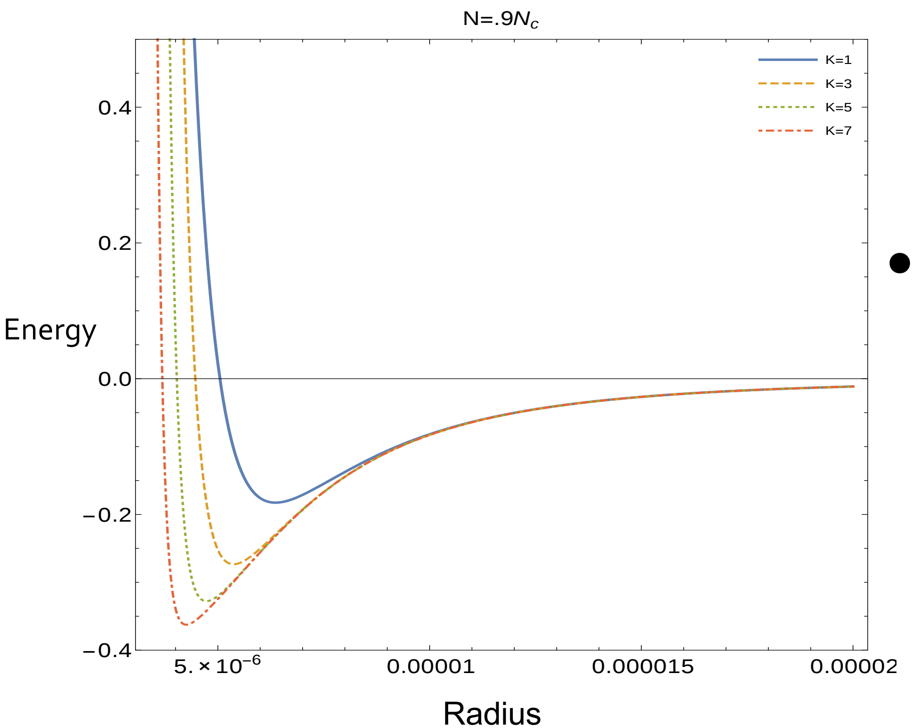

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  - Higher order terms necessary for small radii
- A dense radius exists
  - Stabilized by repulsive self-interactions
  - Corroborated by numerical solutions
  - Star will decay via a $A_N \rightarrow A_{N-3} + \alpha$ process

7

Catalyzed Collapses

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- Collisions with various astrophysical sources
  1. Axion star-axion star
  2. Luminous star-axion star
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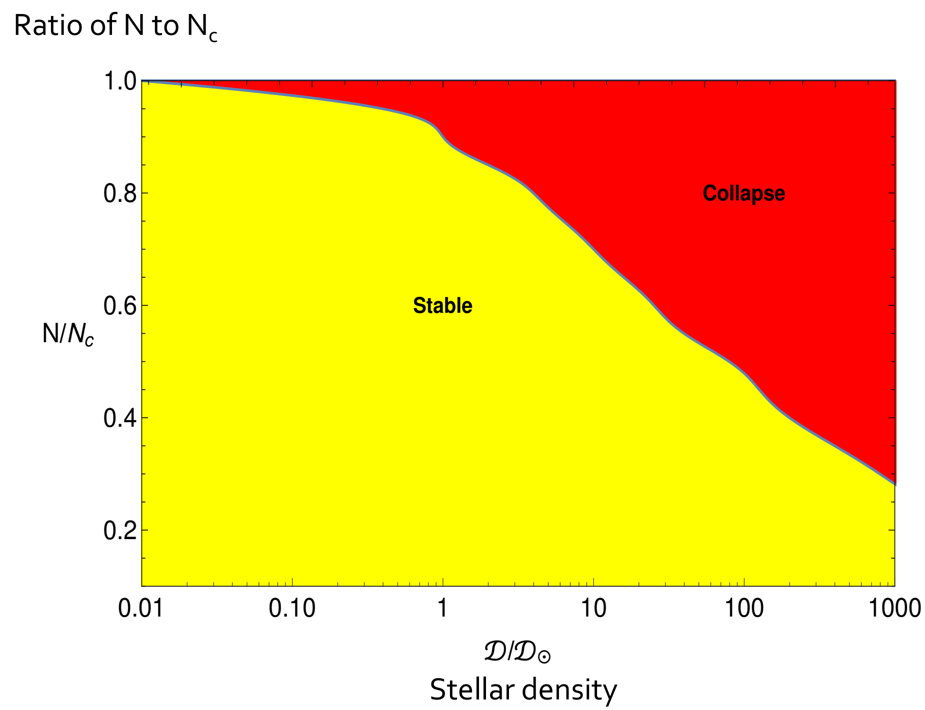

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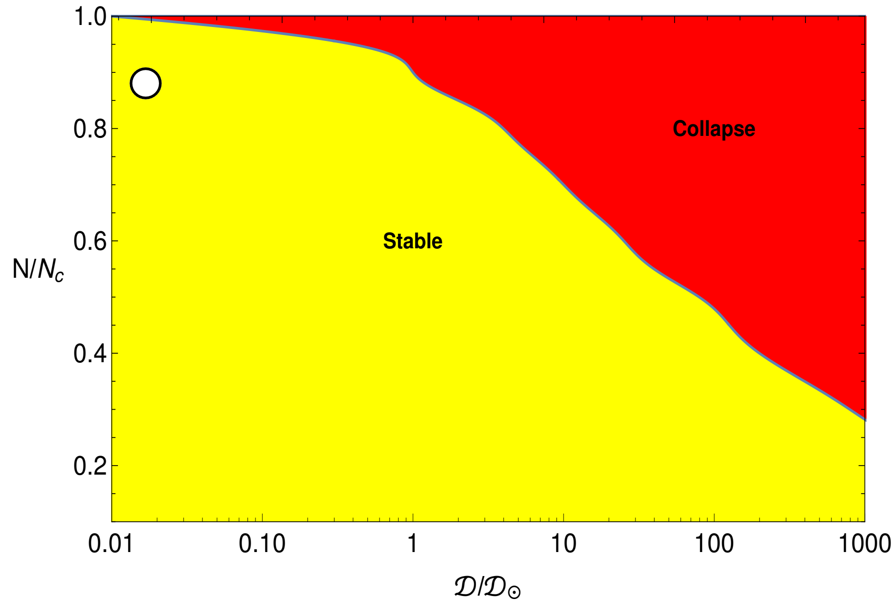

Stellar density

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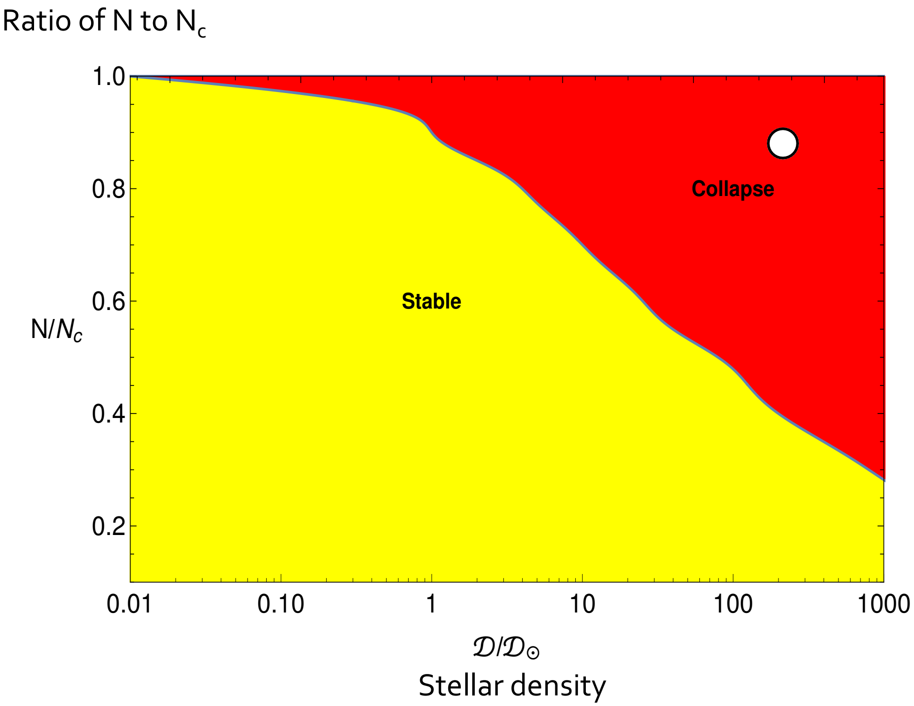

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    - L. Hui, J.P. Ostriker, S. Tremain, E. Witten, Phys. Rev. D 95, (2017) 043541
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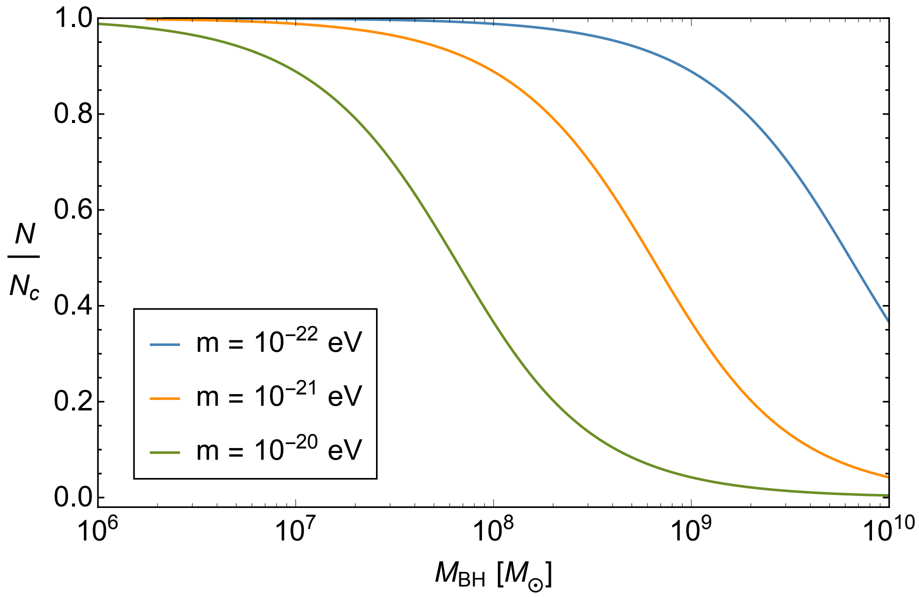

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  - Traditional techniques such as lensing and rotation curves
  - Losing dark matter due to decaying axion stars
  - Collisions with neutron stars could explain Fast Radio Bursts (FRBs)
- Fuzzy ULA condensates
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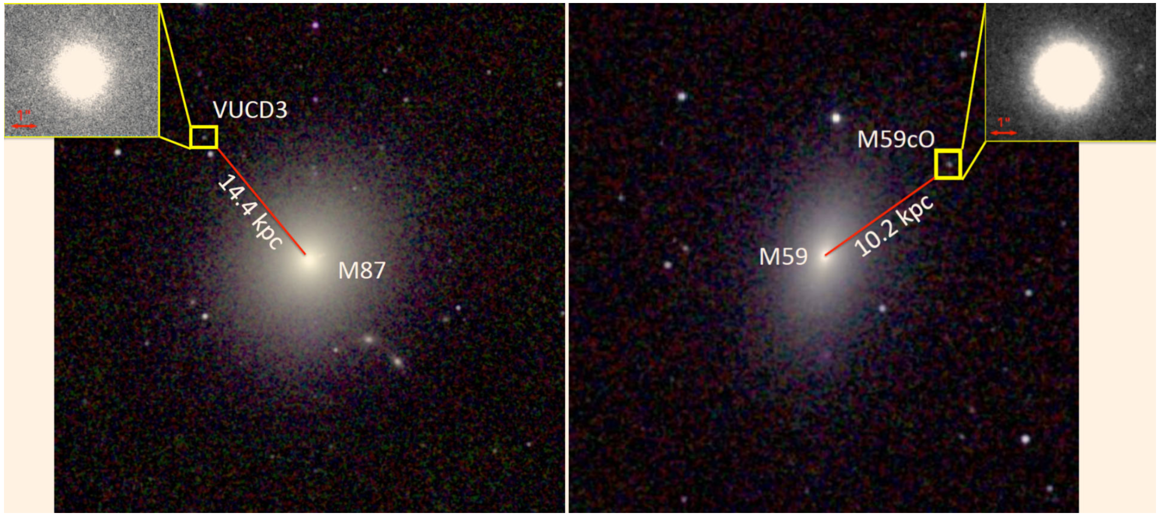

Credit: NASA/Space Telescope Science Institute

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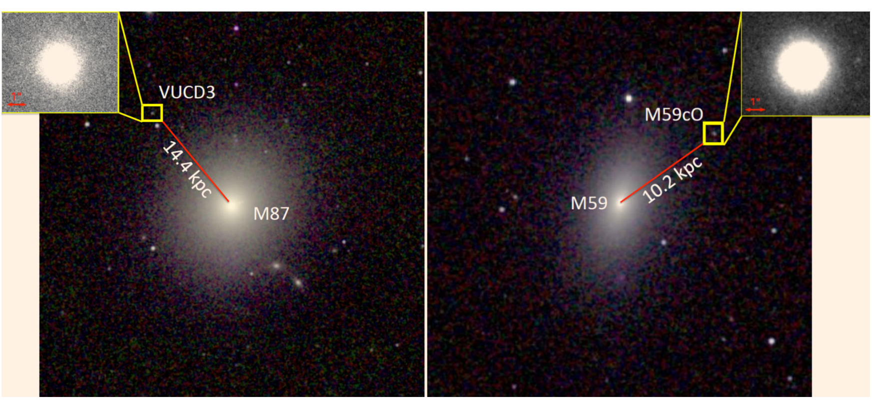
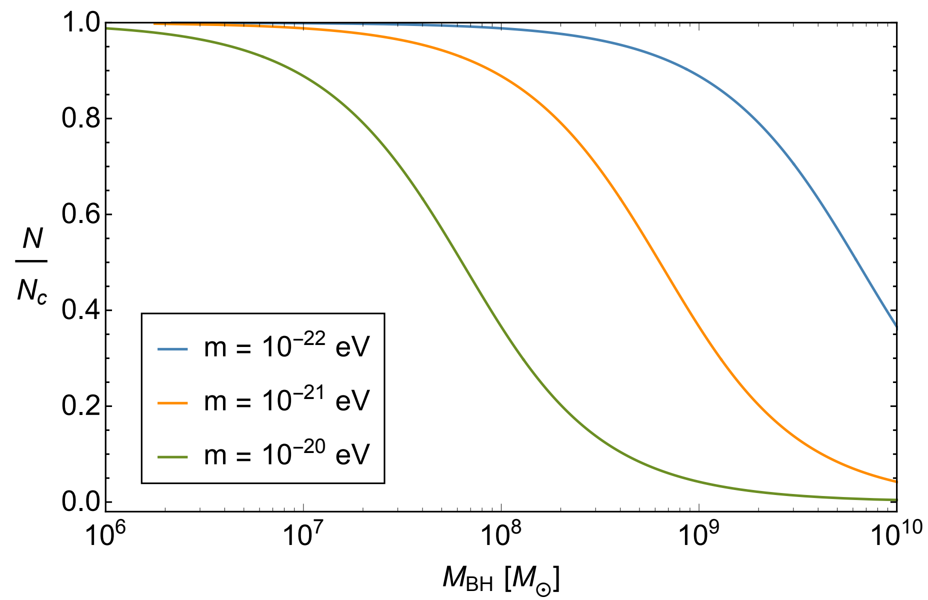


Credit: NASA/Space Telescope Science Institute



Observational Potential

- QCD axion stars
  - Traditional techniques such as lensing and rotation curves
  - Losing dark matter due to decaying axion stars
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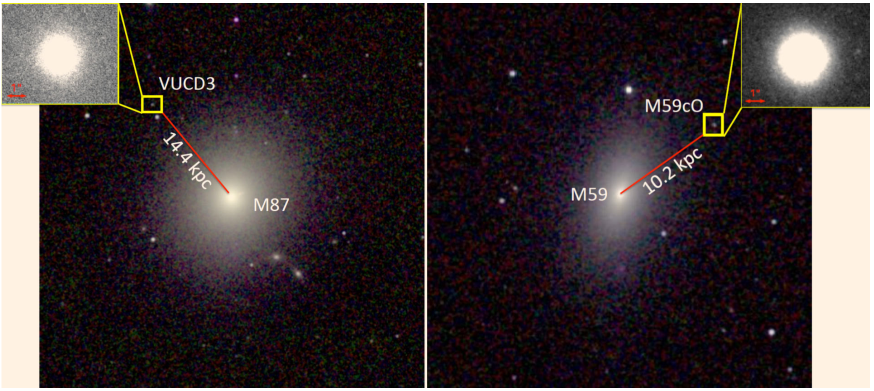

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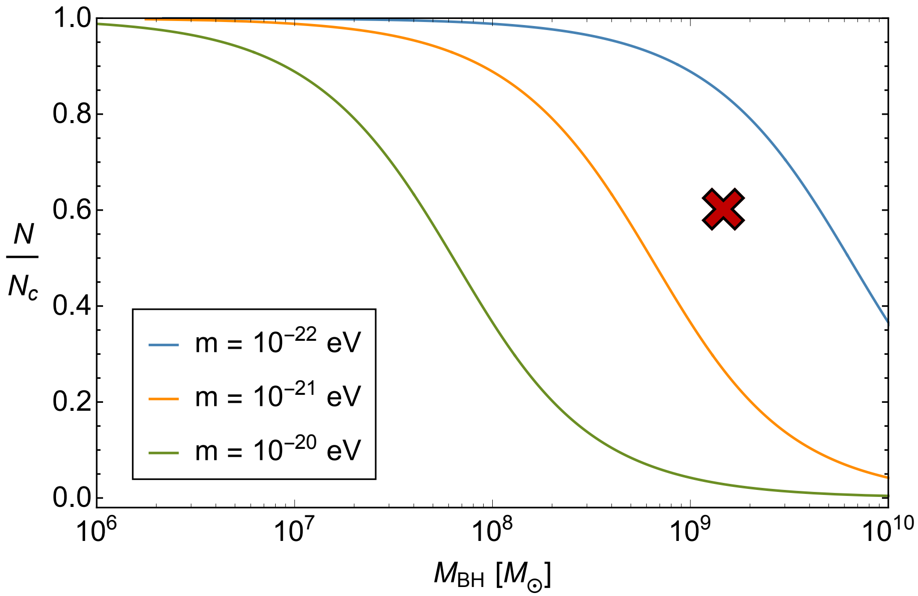

Upcoming: Rotating Dark Matter

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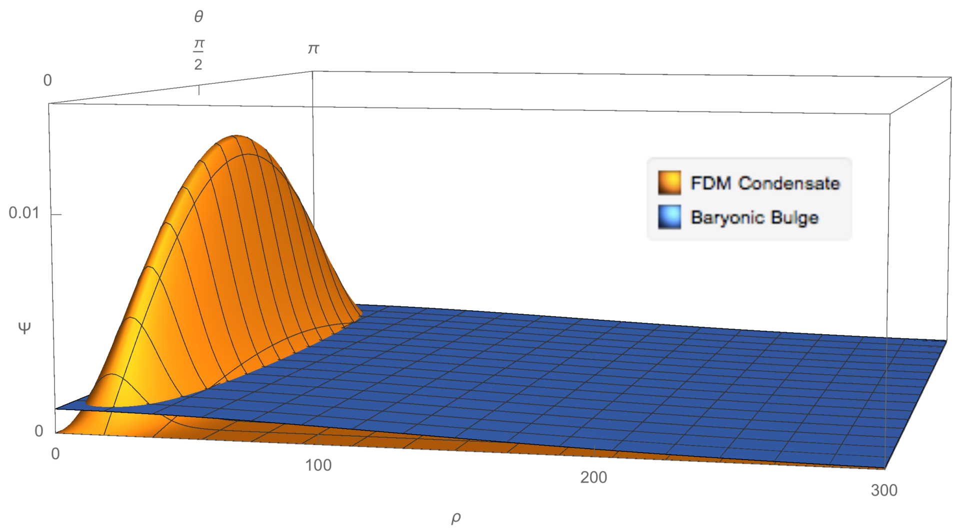
- Galaxies rotate, shouldn't dark matter?
- Rotations affect the distribution of the dark matter BEC
  - Incorporate galaxy's baryonic matter
  - Frame dragging and relativistic effects
  - Constrain using rotation curves



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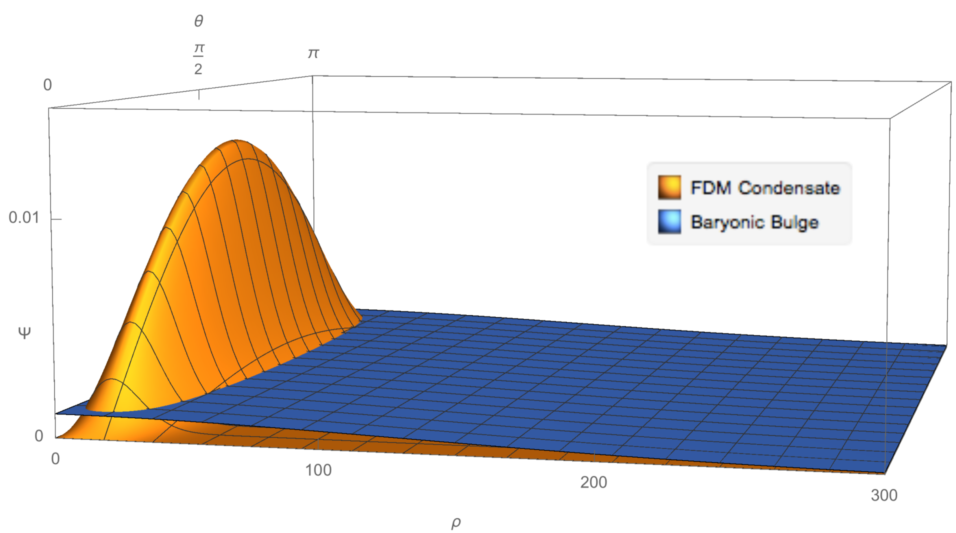

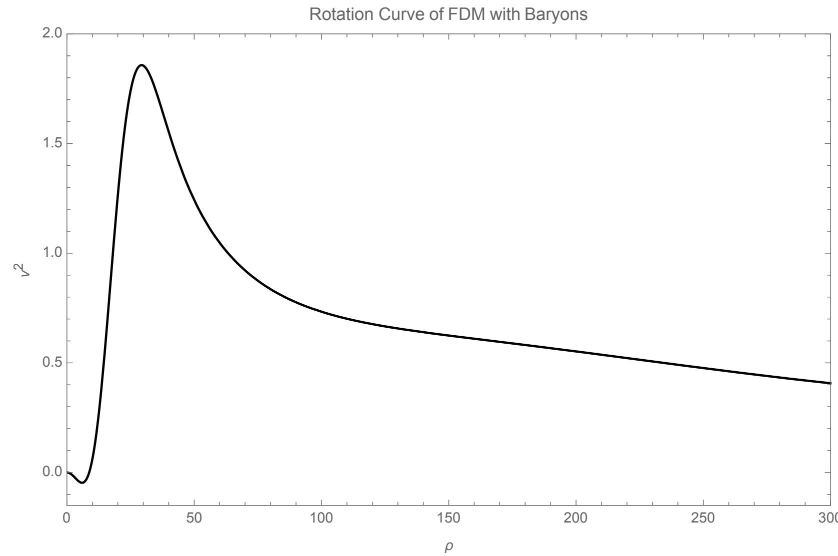

Scaled ρ = 300 corresponds to 2.3 kpc
Scaled $v^2 = 1$ corresponds to v = 245 km/s

Upcoming: Fragmented Condensates

- Is it ever energetically favorable for a self-gravitating condensate to be split between two energy levels?
  - Effective angular momentum
  - Attractive/repulsive self-interactions

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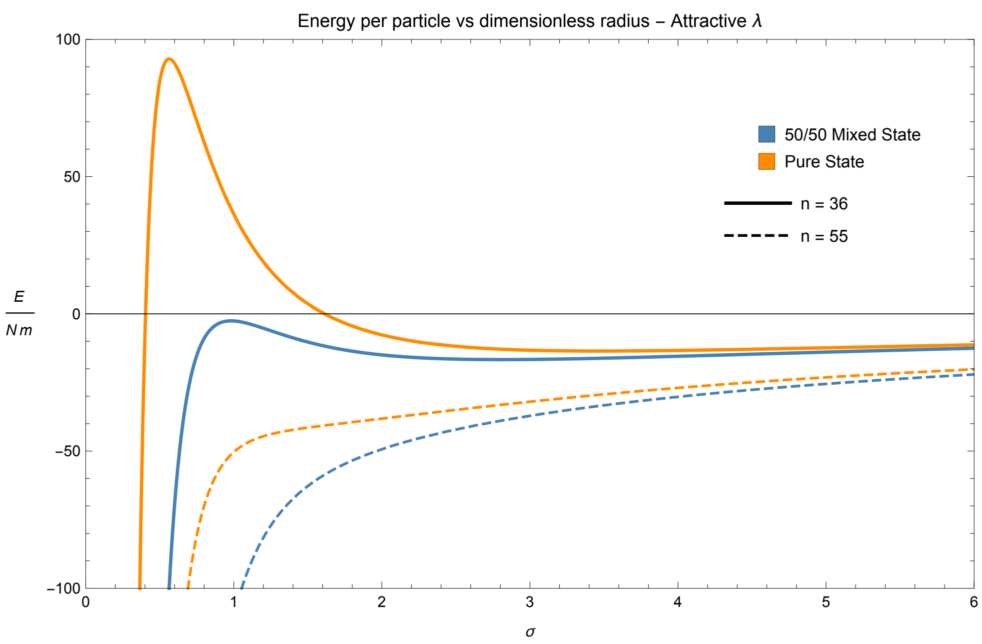

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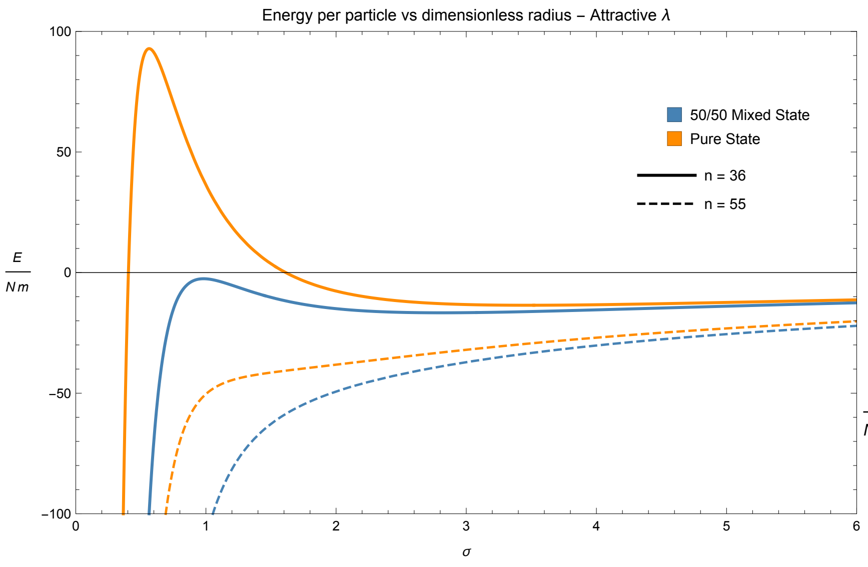

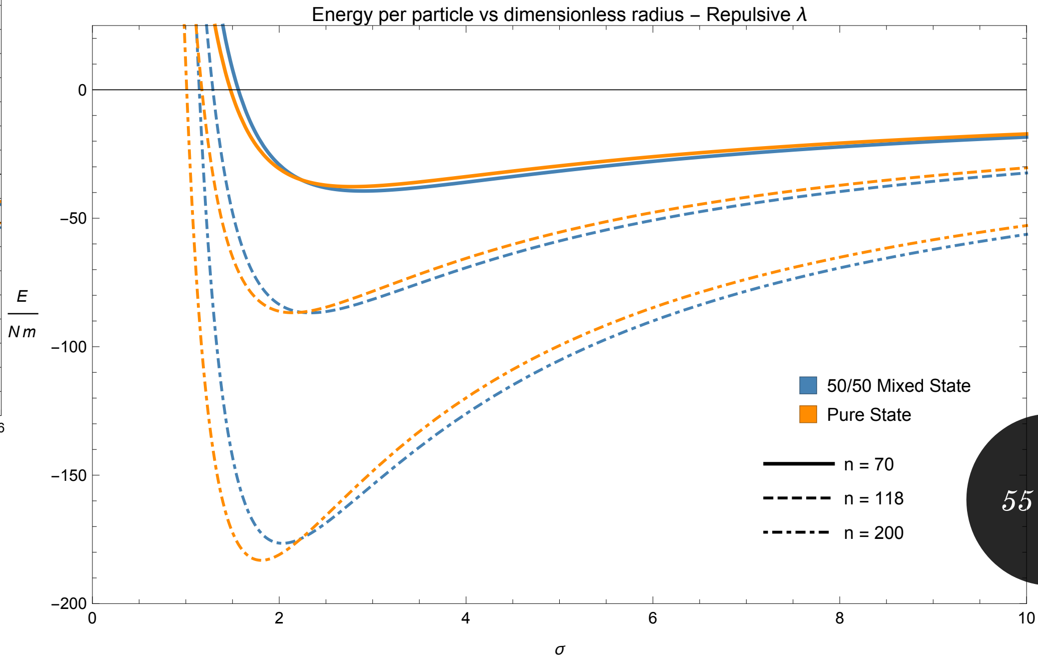

Concluding Thoughts

- Axions are well-motivated dark matter candidates
  - Condensates range from asteroid-size to hundreds of lightyears radii
  - Unique self-interactions
- Testable theories
  - Indirect detection of QCD axion stars
  - Novel use of UCD galaxies to constrain dark matter
- Formalism is broadly applicable
  - Oscillons attached to inflationary and quintessence fields
- Plenty of room to grow
  - A realm of dark photons or gauge bosons to facilitate dark matter energy transitions
  - Rotation curves to test the viability of varying bosonic candidates
  - Develop more precise methods to analyze dynamic condensates

Acknowledgements

- Profs. Wijewardhana, Suranyi, Ma, and Vaz
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- WISE Program and Prof. Ghia
- Funding from:
  - The University of Cincinnati
  - Department of Physics
  - Barry Goldwater Scholarship Foundation

Papers based on this work

- Collapse of Axion Stars
  - J. Eby, **M. Leembruggen**, P. Suranyi, L.C.R. Wijewardhana. JHEP1612 (2016) 066. arXiv: 1608.06911
- Collisions of Dark Matter Axion Stars with Astrophysical Sources
  - J. Eby, **M. Leembruggen**, J. Leeney, P. Suranyi, L.C.R. Wijewardhana. JHEP1704 (2017) 099. arXiv: 1701.01476
- QCD Axion Star Collapse with the Chiral Potential
  - J. Eby, **M. Leembruggen**, P. Suranyi, L.C.R. Wijewardhana. JHEP1706 (2017) 014. arXiv: 1702.05504
- Stability of Condensed Fuzzy Dark Matter Halos
  - J. Eby, **M. Leembruggen**, P. Suranyi, L.C.R. Wijewardhana. Submitted to JCAP_040P_0718. arXiv: 1805.12147
- In preparation:
  - On Approximation Methods in the Study of Boson Stars
  - Fragmented Astrophysical Bose-Einstein Condensates

QUESTIONS?

Motivation for the Axion

- The Strong CP Problem
  - QCD has very small CP violations
  - Peccei and Quinn suggest treating the CP-violation parameter as a field
    - R. D. Peccei, H. R. Quinn, Phys. Rev. Lett. 38 (1977) 1440
  - Through the "misalignment mechanism" the field produces cold axions
  - An early universe overabundance could lead to condensation
  - Spin zero bosons, electrically neutral, real scalar field
- Ultra-Light Axions
  - String theory allows for the existence of lighter classes of "axions" or axion-like particles (ALPs)
    - A. Arvanitaki et al, Phys. Rev. D 81 (2010) 123530
  - Solves cusp-core and missing satellites problems
  - Calculations can also be treated as generic bosons with various self-interactions

Searching for the Axion

- Coupled to the EM field

$$\Delta\mathcal{L} \propto \phi\vec{E}\cdot\vec{B}$$

  - Added to EM Lagrangian, modifies Maxwell's equations accordingly
    - F. Wilczek, Phys. Rev. Lett. 58 (1987) 1799
  - Interaction of axion field with B field produces oscillating E fields
  - Frequency of E field oscillations depends on mass of axion
- Direct Detection Searches
  - ADMX, ABRACADABRA
  - CASPEr, atomic clocks
  - ALPS
  - Radio telescopes, CAST

Gross-Pitaevskii + Poisson from Klein-Gordon + Einstein

- Klein-Gordon + Einstein equations

$$\Box\phi + V'(\phi) = 0 \qquad 8\pi G T_{\mu\nu} = G_{\mu\nu}$$

  – Expand ϕ in creation and annihilation operators:

$$\phi = a e^{-iEt} R(r) + a^\dagger e^{iEt} R(r) + \sum_{l\neq 0}\sum_{m}\left(a_{lm} Y^l_m R_{lm} e^{-iE_{lm}t} + h.c.\right)$$

$$|N> = \frac{1}{\sqrt{N!}} a^{\dagger N}|0>$$

  – Assuming most of the action comes from the lowest modes, drop the higher harmonics
  – Non-trivial expectation values:

$$< N\,|\Box\phi + V'(\phi)|\,N-1 >= 0$$

$$< N\,|8\pi G T_{\mu\nu}|\,N >=< N\,|G_{\mu\nu}|\,N >$$

- Write the field in terms of a wave function:

$$\phi = \frac{1}{2m}\left(\psi e^{-imt} + \psi^* e^{imt}\right)$$

The Axion Potential

- Instanton Potential

$$V_I(\phi) = m^2 f^2 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$

  – m, f are the mass and decay parameter, ϕ is the axion field

- Chiral Potential

$$V_C(\phi) = m^2 f^2 \frac{1+z}{z}\left[1 + z - \sqrt{1 + z^2 + 2z\cos\left(\frac{\phi}{f}\right)}\right]$$

  – $z = m_u/m_d$, the ratio of the up quark mass to the down quark mass
  – *QCD Axion Star Collapse with the Chiral Potential* shows that using either potential yields the same qualitative results numerically

More on Bose-Einstein Condensates

- BEC basics
  - Fermions are subject to the Pauli Exclusion principle
  - Bosons prefer the same energy state
  - In low temperature/high pressure conditions, bosons condense into a macroscopic quantum system
    - Bose-Einstein Condensation in Dilute Gases by C.J. Pethick and H. Smith
  - Described by a single wavefunction
- History
  - Predicted by Bose and Einstein in the 1920s
  - Created in the lab in 1995

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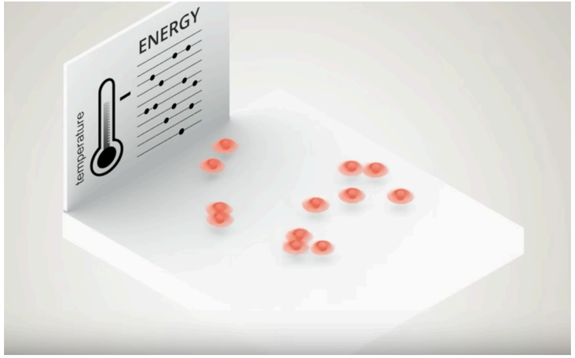

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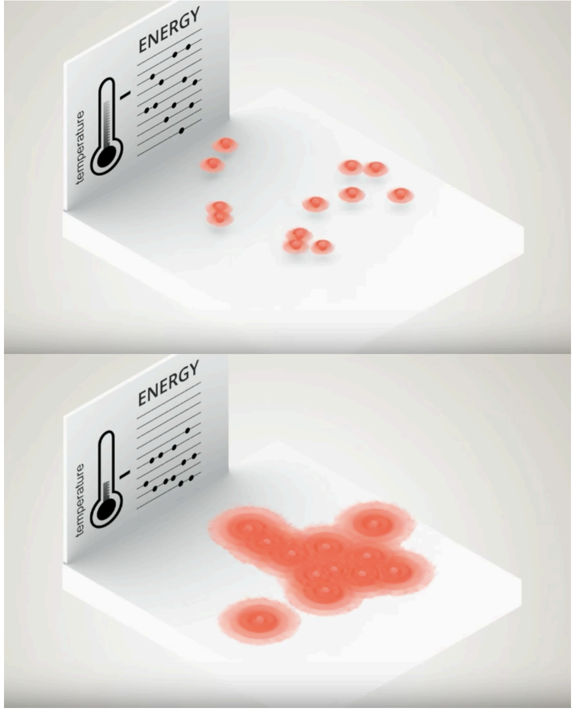

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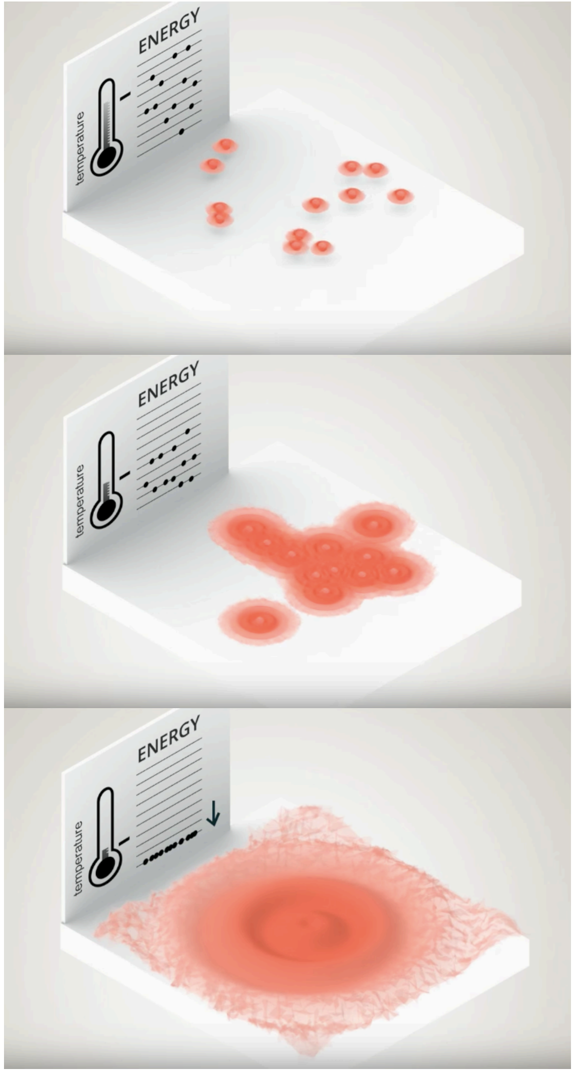

Credit: Université Paris Sud/Labex Palm

More on Ultra Compact Dwarf Galaxies

- UCD formation theories
  - Small galaxies which were stripped of their stars by a larger host galaxy
  - Globular clusters from the high-mass tail of GC distribution
    - S. Mieske, M. Hilker, I. Misgeld, A&A 2012, vol. 537, A3
  - Independently formed dense galaxies
- Size and mass
  - Radii in the 100 ly range
  - Mass ranging up to 10^{10} solar masses
  - Often contain SMBHs
    - A.C. Seth et al, Nature 513, 398-400 (2014)

Why doesn't the black hole eat the FDM particles?

$$\psi(r) = \sqrt{\frac{N}{\pi^{3/2}R^3}}\; e^{-\frac{r^2}{2R^2}} \qquad P = 4\pi \int_0^{R_{bh}} r^2 \left|\psi\right|^2 dr$$

- ULAs have deBroglie wavelength much larger than R_{bh}
  - Somewhat analogous to optical wavelength vs lens diameter
- P(absorption by black hole) = P(particle within R_{bh})
- Estimate probability with integral:
  - Dilute condensate with N = 0.9 N_c
  - 10^8 solar mass black hole with corresponding Schwarzschild radius
  - P = 5 x 10^{-19}