Dense Axion Stars

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arXiv:1512.00108, arXiv:1604.00669

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Outline

- ❑ **Axions**
- ❑ **Dilute Axion Stars**
- ❑ **NonRelativistic Effective Field theory [1].**
- ❑ **Dense Axion Star [2]**
- ❑ **Questions**

[1] E. Braaten, A. Mohapatra, H. Zhang, arXiv:1604.00669

[2] E. Braaten, A. Mohapatra, H. Zhang, arXiv:1512.00108

Axions

- A strongly motivated candidate for dark matter from particle physics perspective.

- Pseudo-Goldstone boson associated with the *U(1) PQ symmetry* that solves the *strong CP problem* of QCD. ***Peccei & Quinn (1977)***

- Produced in early universe by non-thermal mechanism:

vacuum misalignment	***cosmic string decay***
highly nonrelativistic, huge occupation numbers, coherent.	highly nonrelativistic, huge occupation numbers, incoherent.
Preskill, Wise & Wilczek (1983) ***Abbott & Sikivie, 1983 , Dine & Fischler (1983)***	***Davis (1986)*** ***Harare & Sikivie (1987)***

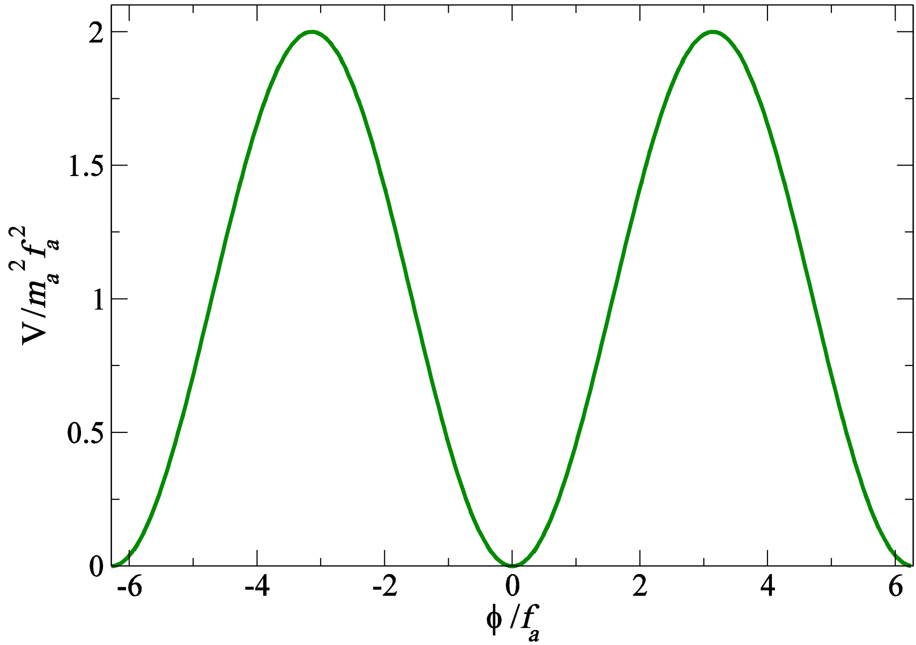
- Gravitational interactions can thermalize the axions, so they form Bose-Einstein Condensate. ***Sikivie & Yang (2009), Erken, Sikivie, Tam and Yang (2012)***.

Axions

- In relativistic field theory, the axions are described by a real scalar field ϕ and simple model potential given by:

Axion decay constant

$$\boxed{\mathcal{V}(\phi) = m^2 f^2 \left[1 - \cos(\phi/f)\right]}$$



- Astrophysical and cosmological constraints restrict ***f*** to be 10^8 to 10^{13} GeV.

- Mass of the axion : 10^{-6} *to* 10^{-2} eV.

- Spin-0 particle with very small mass and extremely weak self-interactions

Dilute Axion Stars

- A stable configuration of axions bound by gravity is called an ***axion star.***

  Tkachev (1991)

- The previously known axion stars are dilute : $\phi(x) \ll$ f

  Barranco & Bernal (2011)

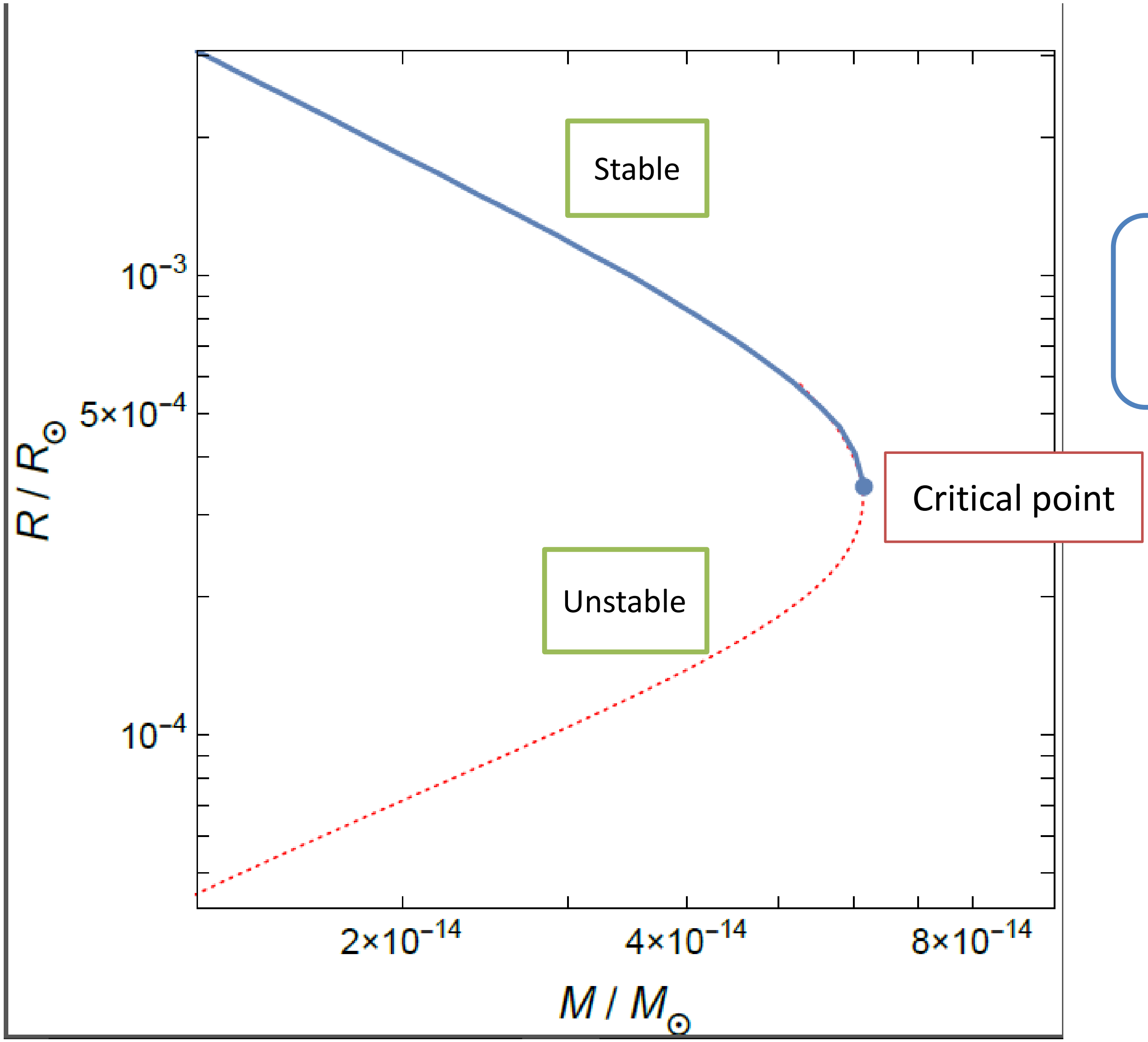
  Only terms up to ϕ^4 are important

$$\mathcal{V} = m^2\phi^2/2 - m^2\phi^4/4!f^2 + ...$$

- In dilute axion star, repulsive force from **kinetic energy** balances attractive forces from **gravity** and from **axion pair interactions**.

- Dilute axion stars have critical mass beyond which the kinetic pressure cannot balance attractive forces. The value of critical mass is $6 \times 10^{-14} M_\odot$ for $m = 10^{-4}$ eV. ***Chavanis & Delfini (2011)***

Dilute Axion Stars: Radius vs Mass



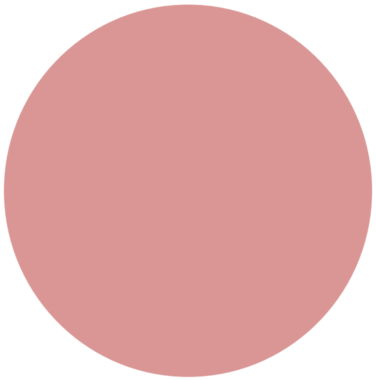
Critical Mass:
$6 \times 10^{-14} M_\odot$

Fate of Collapsing Axion Star

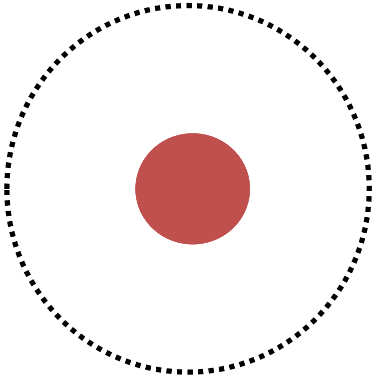
- If dilute axion star exceeds the critical mass, its core will collapse. What is the remnant after the collapse??

- ❑ Black Hole ?

- ❑ Dilute axion star?



- ❑ Dense Axion star?



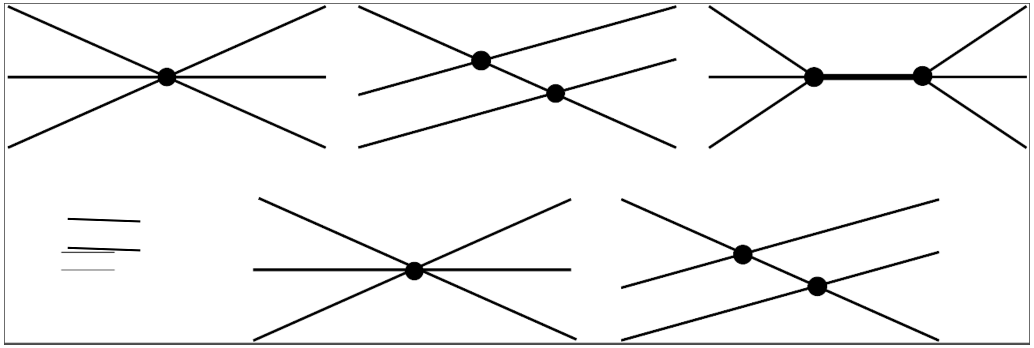
????

NonRelativistic Effective Field theory

- Low- energy axions can be described by nonrelativistic effective field theory (axion EFT) with complex scalar field ψ.

$$\mathcal{H}_{\text{eff}} = \frac{1}{2m}\nabla\psi^* \cdot \nabla\psi + \mathcal{V}_{\text{eff}}(\psi^*\psi).$$

- Effective potential can be obtained by matching low-energy scattering amplitudes at tree level in relativistic theory and axion EFT.
- 3->3 scattering diagrams that contribute in relativistic field theory



Braaten, Mohapatra, Zhang (2016)

- Matching of n->n scattering amplitudes give us coefficient of $(\psi^*\psi)^n$ in effective potential.

$$\mathcal{V}_{\text{eff}} = m\psi^*\psi - (\psi^*\psi)^2/16f^2 - (\psi^*\psi)^3/256mf^4 + \ldots$$

Nonrelativistic reduction

- A simple approximation of effective potential that includes all orders in $\psi^*\psi/mf^2$ is by naive nonrelativistic reduction of relativistic Hamiltonian.

$$\dot{\phi}^2/2 + m^2 f^2[1 - cos(\phi/f)]$$

- Substitute ϕ as

$$\phi(\mathbf{r},t) = \frac{1}{\sqrt{2m}}\left[\psi(\mathbf{r},t)e^{-imt} + \psi^*(\mathbf{r},t)e^{+imt}\right]$$

- Throw away rapidly oscillating terms

$$\hat{\psi} = (2\,\psi^*\psi/mf^2)^{1/2}$$

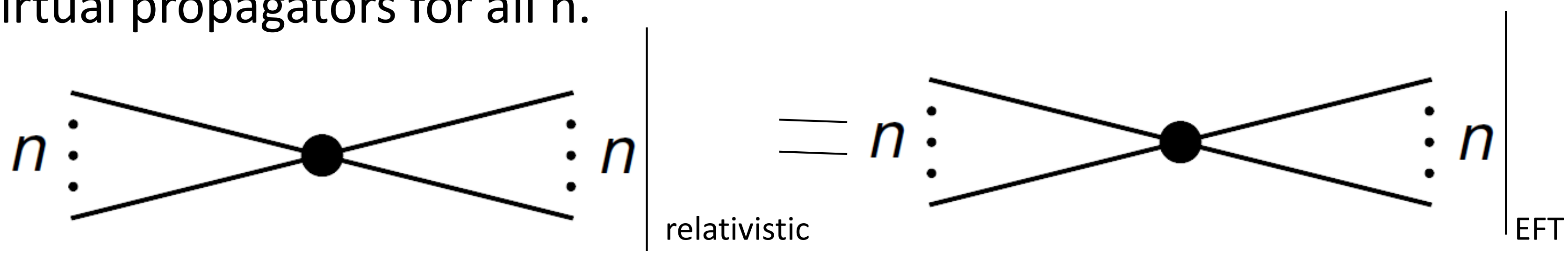
$$\boxed{\mathcal{V}_{\rm eff}(\psi^*\psi) = \tfrac{1}{2}m\psi^*\psi + m^2 f^2[1 - J_0(\hat{\psi})]}$$

Eby, Suranyi, Vaz, Wijewardhana (2015)

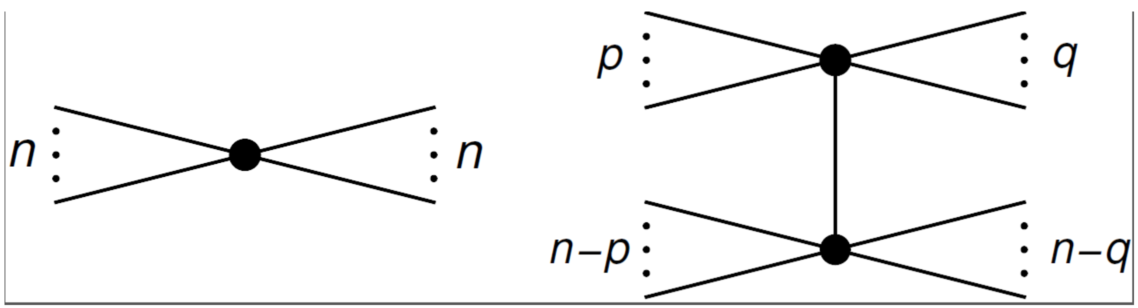
NonRelativistic Effective Field theory

$$\mathcal{V}_{\text{eff}}(\psi^*\psi) = \frac{1}{2}m\psi^*\psi + m^2 f^2[1 - J_0(\hat{\psi})]$$

- Naïve relativistic reduction corresponds to matching n->n diagrams with no virtual propagators for all n.



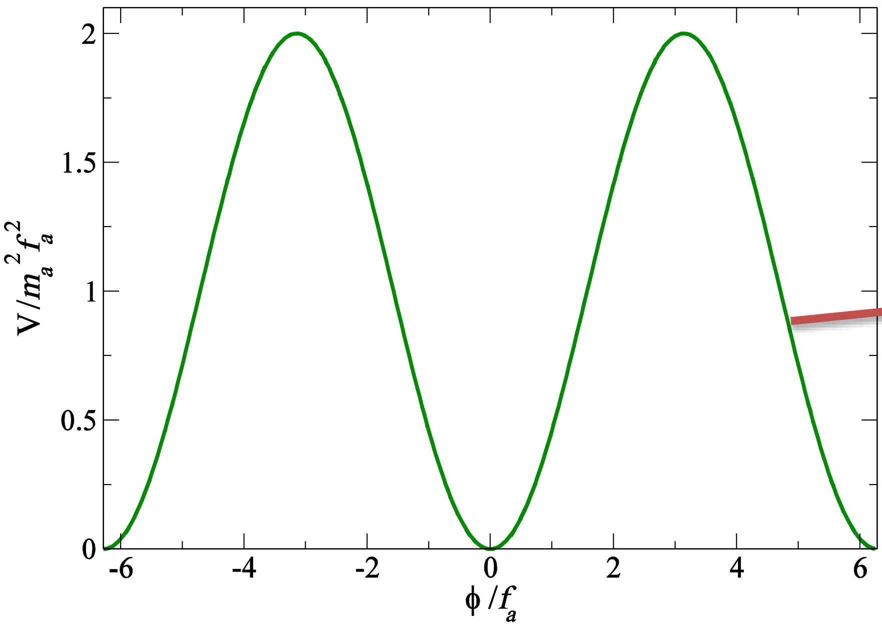
- Effective potential can be improved by matching diagrams with one virtual propagator.



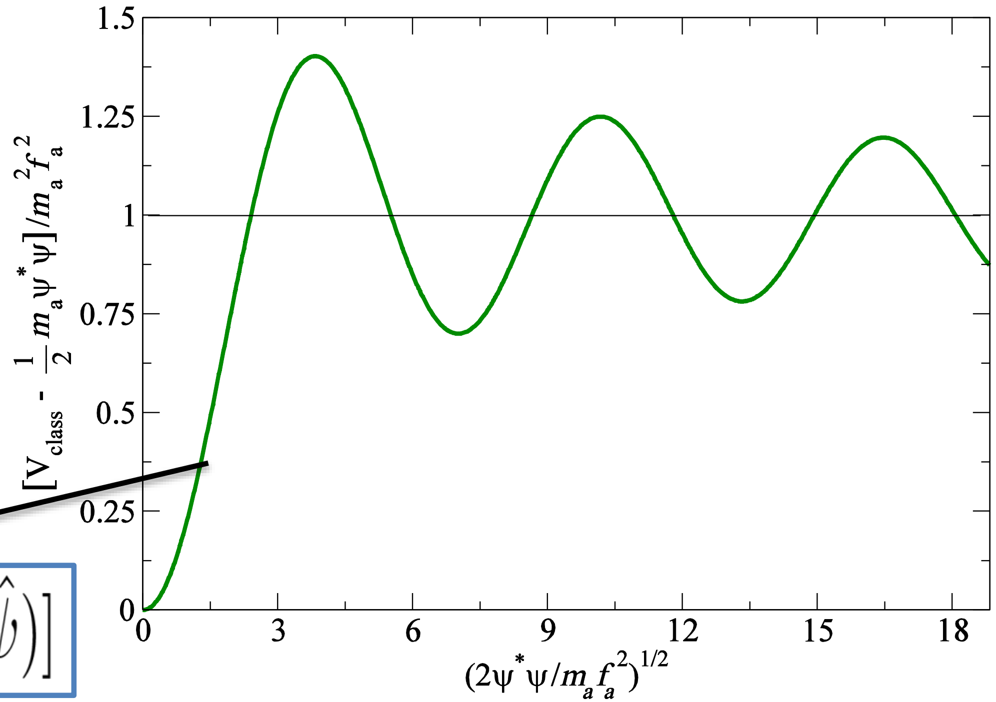
Braaten, Mohapatra, Zhang (2016)

- Effective potential can be systematically improved by matching with more and more virtual propagators.

Relativistic and effective potential



$$\mathcal{V}(\phi) = \boxed{m^2 f^2 \left[1 - \cos(\phi/f)\right]}$$



$$\mathcal{V}_{\rm eff}(\psi^*\psi) = \frac{1}{2} m \psi^* \psi + \boxed{m^2 f^2 [1 - J_0(\hat{\psi})]}$$

Dense Axion Stars

- Dilute axion star is characterized by $\psi^*\psi \ll mf^2$.
- Dense axion star is characterized by $\psi^*\psi \approx mf^2$ at the center.

All orders in $\psi^*\psi$ in V_{eff} are important

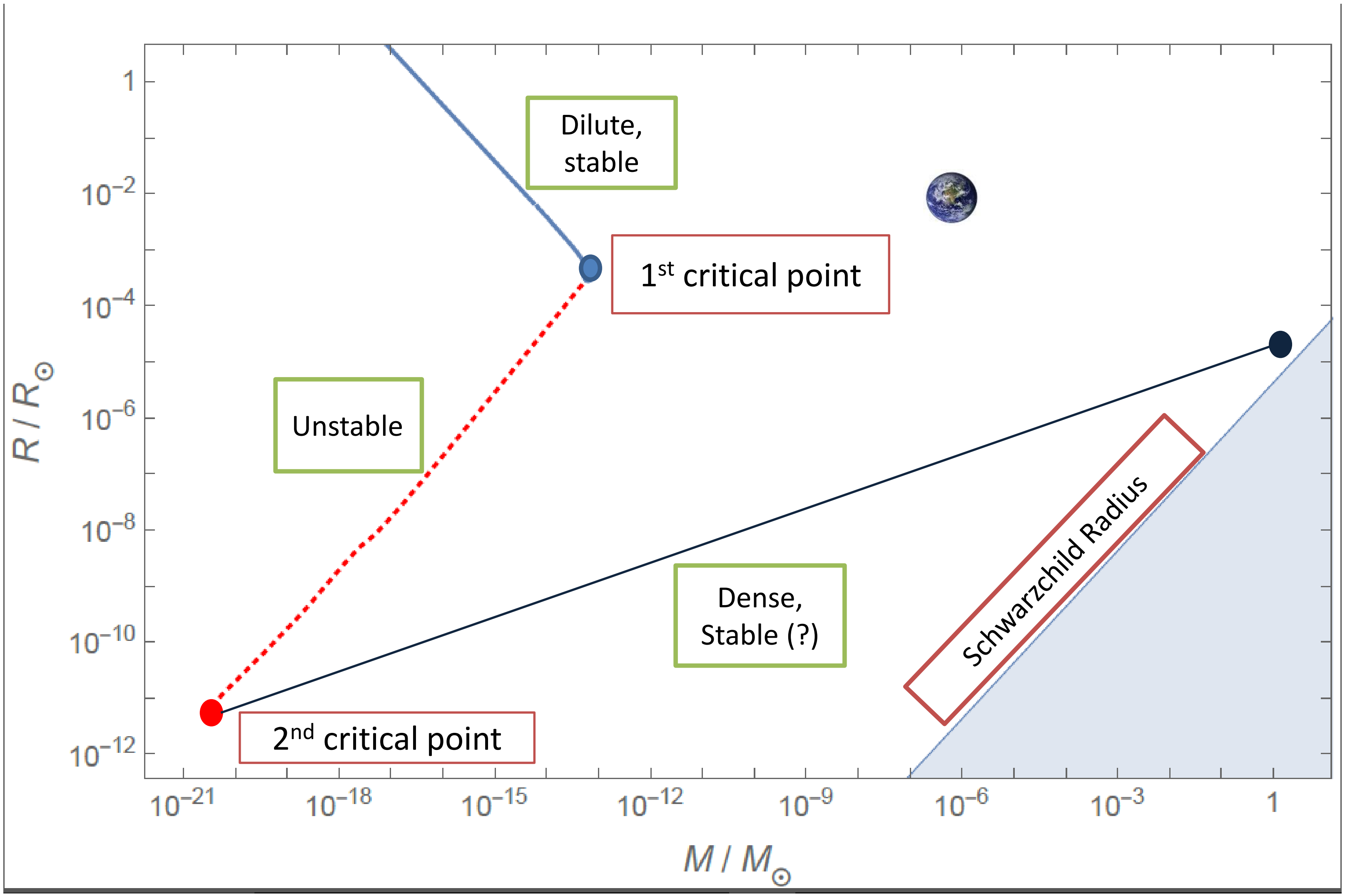
- Differential equations describing the static configuration of axion stars with Newtonian gravity

$$\boxed{\begin{aligned}\nabla^2\psi &= -2m\left[\mu - (\mathcal{V}'_{\text{eff}}(\psi^*\psi) - m) - m\phi\right]\psi \\ \nabla^2\phi &= 4\pi G m \psi^*\psi.\end{aligned}}$$

- Effective potential

$$\mathcal{V}_{\text{eff}}(\psi^*\psi) = \tfrac{1}{2}m\psi^*\psi + m^2 f^2[1 - J_0(\hat{\psi})]$$

Axion Stars: Radius vs Mass plot



Dense Axion Stars

- A simpler way to get the dense axion star solutions is to use the Thomas-Fermi approximation.

- In this approximation, potential energy from interactions $\gg$ kinetic energy. So kinetic energy term can be completely neglected: $\nabla^2\psi \to 0$.

$$\boxed{\begin{aligned} &\cancel{\nabla^2\psi} = -2m\left[\mu - (\mathcal{V}'_{\text{eff}}(\psi^*\psi) - m) - m\phi\right]\psi \\ &\nabla^2\phi = 4\pi G m\psi^*\psi. \end{aligned}}$$

- So, the attractive force from gravity is balanced by the repulsive force from the mean-field pressure of the axion Bose-Einstein condensate.

- Thomas-Fermi approximation is accurate except near the surface of the dense axion star.

Questions

What happens to dilute axion star with critical mass, when it accretes more axions and collapses?

- **What is the remnant?**
  - **Black Hole ??**
  - **Dilute axion star with smaller mass ??**
  - **Dense axion star ??**

Most likely the possibility is a dense axion star.

- **How does collapsing dilute axion star evolve into dense axion star?**

Solve the time-dependent classical field equations of axion EFT.

Questions

- Gravitational microlensing could detect dense axion stars (if they exists **???**).
- Gravitational microlensing implies most of the dark matter is in objects with mass less than $10^{-9} M_{\odot}$.
- Dilute axion star : $M < 6.8 \times 10^{-14} M_{\odot}$.
- Dense axion star: $10^{-21} M_{\odot} < M < M_{\odot}$.
- What is the mass distribution of dilute and dense axion stars?.
- How much of the dark matter is in the form of gas of axions ?, dilute axion stars ? and dense axion stars ?.
- If most of the axion distribution is in dense axion stars, then these could provide new constraints on axion dark matter.

Thank you

Back up Slides

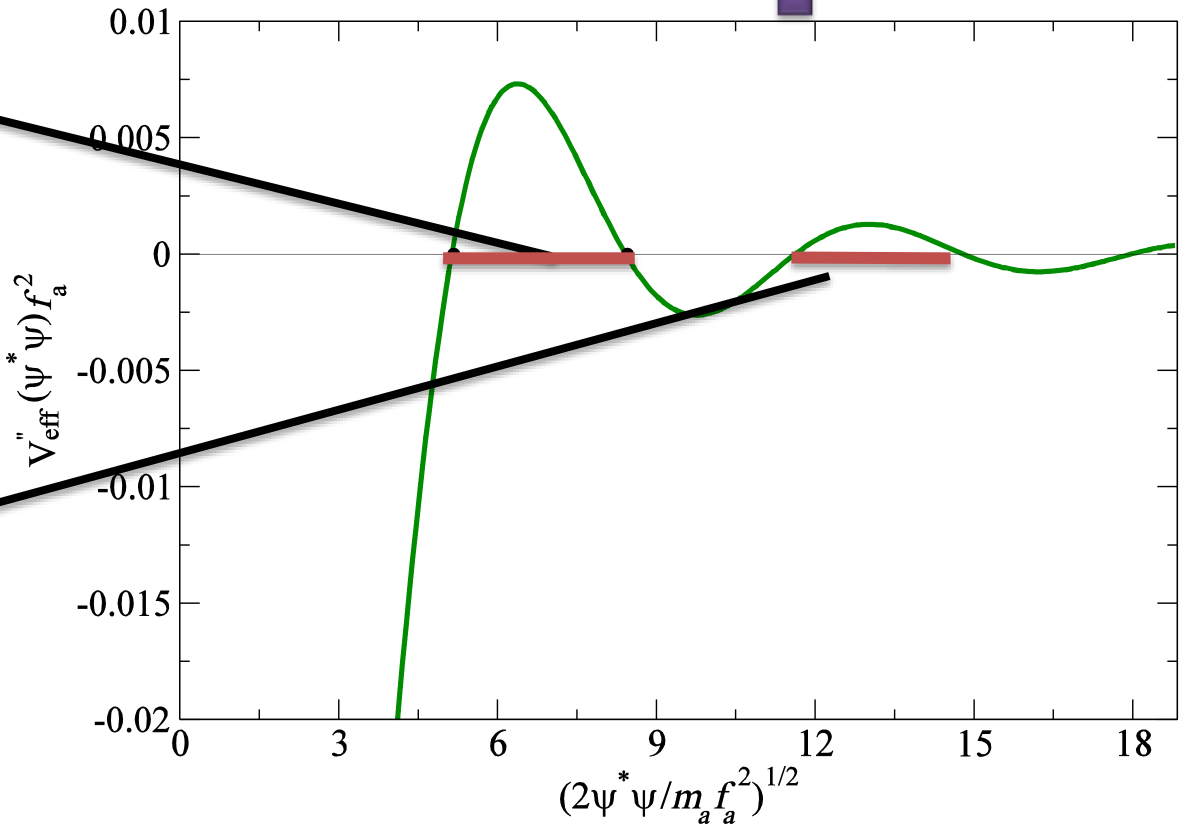
Dense Axion Stars: Branches

- Balancing repulsive mean-field pressure of Bose-Einstein condensate with the attractive force from gravity:

Double Derivative of Effective Potential

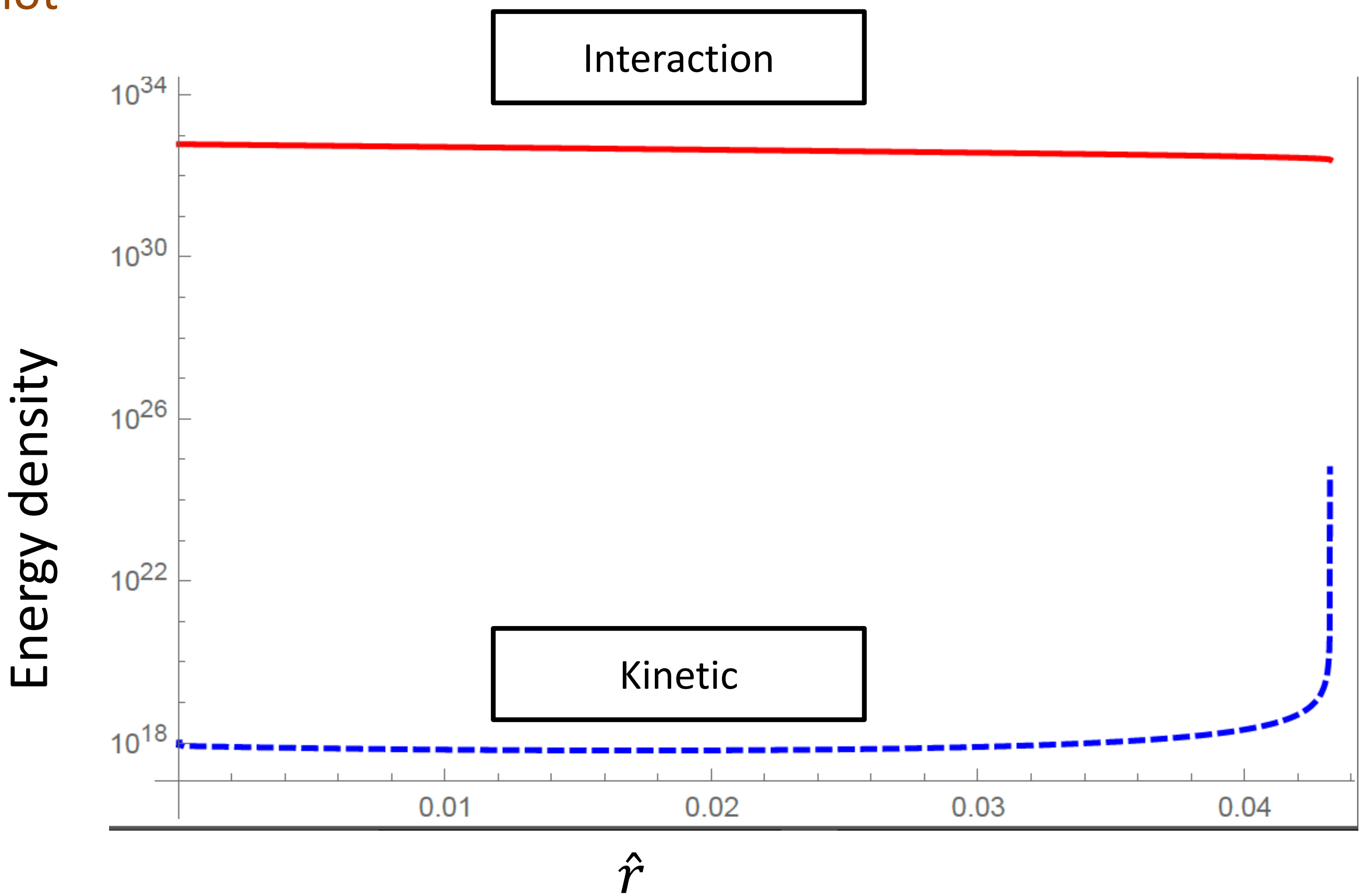
Range of central density for first branch of dense axion stars

Range of central density for second branch of dense axion stars



Dense Axion Stars: Validity of TF Aproximation

Log plot



$\hat{r} = (Gm^2 f^2)^{1/2} r$