Axion EFT and Dense Axion Stars

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arXiv:1512.00108, arXiv:1604.00669

Axion EFT and Dense Axion Stars

- axions
- dilute axion stars
- Axion Effective Field Theory arXiv:1604.00669
- dense axion stars arXiv:1512.00108
- questions?

Axion

strongly motivated candidate for dark matter particle

strong CP problem of QCD can be solved
by spontaneous breaking of a U(1) symmetry

Peccei & Quinn (1977)

pseudo-Goldstone boson: "axion"

spin-0 particle with tiny mass and extremely weak interactions

Weinberg (1978), Wilczek (1978)

produced in early universe by nonthermal mechanisms

<u>vacuum misalignment</u>

Preskill, Wise & Wilczek (1983)
Abbot & Sikivie (1983)
Dine & Fischler (1983)

<u>cosmic string decay</u>

Davis (1986)
Hararie & Sikivie (1987)

Axion

axions produced in early universe:

vacuum misalignment

highly nonrelativistic

high occupation numbers

coherent

cosmic string decay

highly nonrelativistic

high occupation numbers

incoherent

gravitational interactions can thermalize axions so they remain in a Bose-Einstein condensate

Sikivie & Yang (2009)

Axion

<u>Relativistic Field Theory</u> for axions

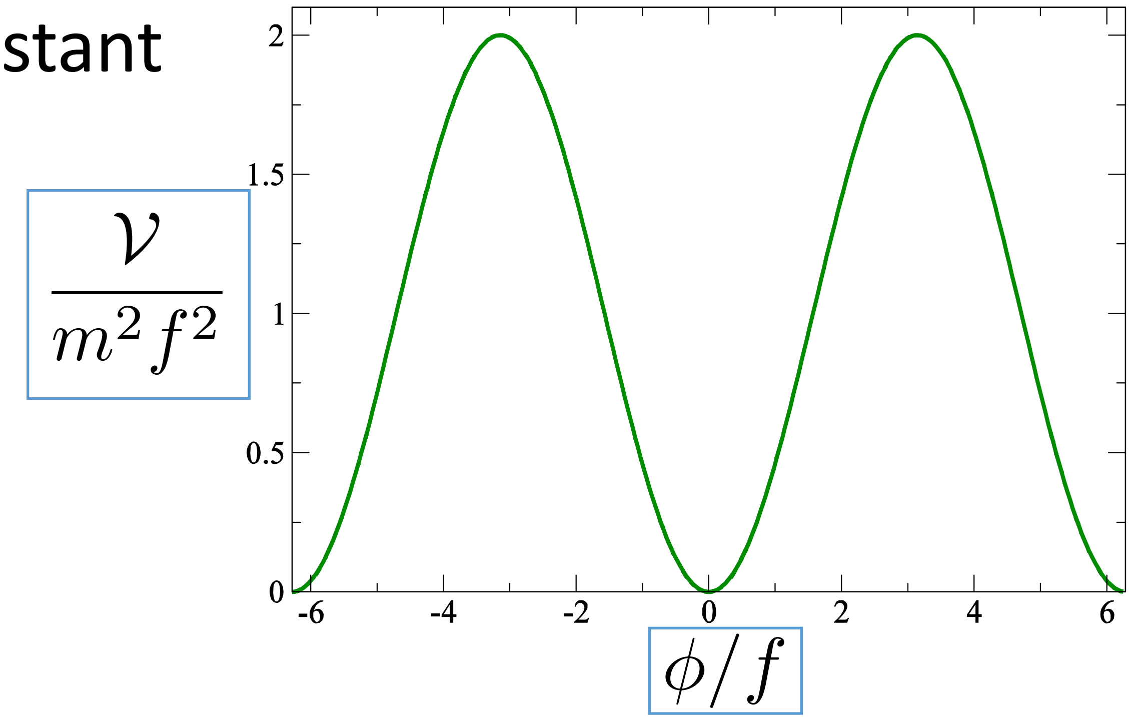
real scalar field *φ(x)*

simple model potential*:

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

m: axion mass

f: decay constant



* more accurate potential depends on up/down quark mass ratio   Di Vecchia & Veneziano 1980

Axion

relativistic axion potential

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

constraint from QCD $m\, f = (80 \text{ MeV})^2$

axion decay constant

astrophysics + cosmology $\Longrightarrow$ $10^8 \text{ GeV} < f < 10^{13} \text{ GeV}$

axion mass $10^{-6} \text{ eV} < m < 10^{-2} \text{ eV}$

specific choice: $m = 10^{-4} \text{ eV}$

Dilute Axion Stars

<u>Axion star</u>

stable configuration of axions bound by gravity

Tkachev (1981)

previously known axion stars are <u>dilute</u>: $|\varphi(x)| \ll f$

Barranco & Bernal (2011)

kinetic pressure of axions
balances attractive forces
from gravity and
from axion pair interactions

lowest-energy state of axion star
is Bose-Einstein condensate!

Dilute Axion Stars

<u>vacuum misalignment mechanism</u>

spacial fluctuations in axion field $\Rightarrow$

gravitationally bound “miniclusters” of axions

Hogan & Rees (1988), Kolb and Tkachev (1993)

typical masses around $10^{-12}\,M_\odot$

gravitational thermalization $\Rightarrow$

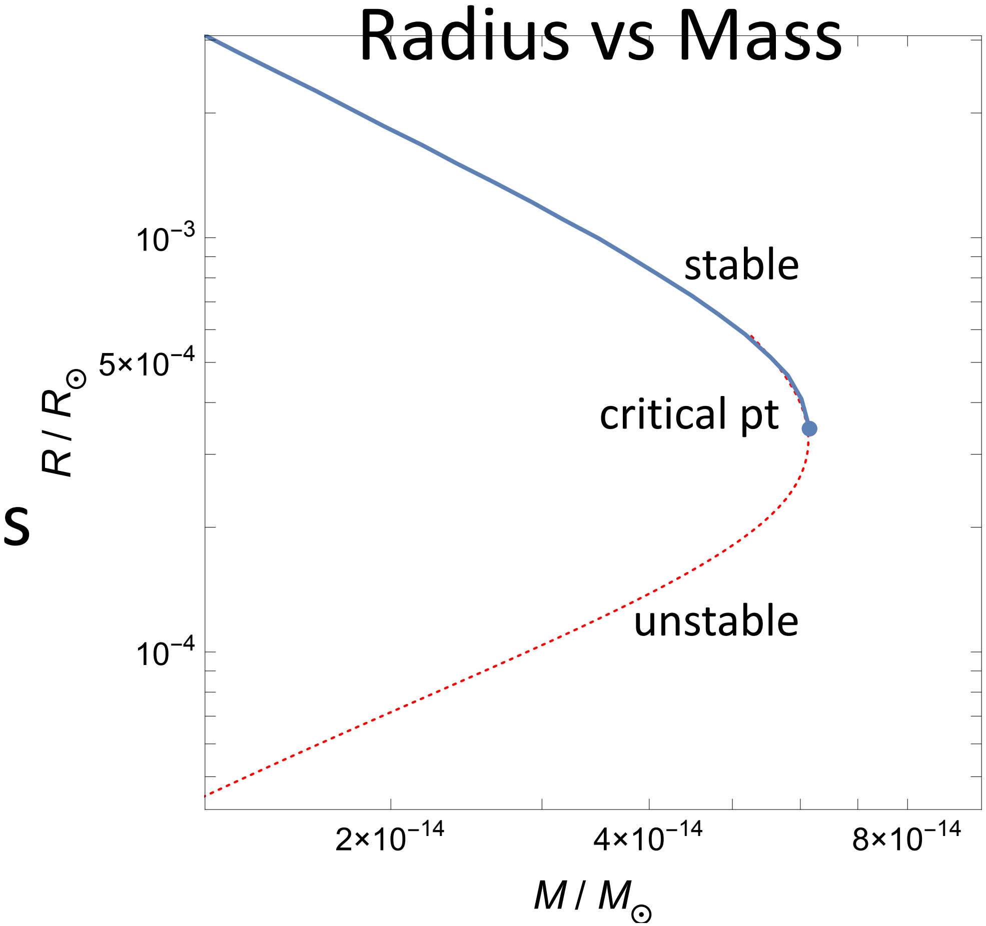
dilute axion star

instabilities prevent much larger coherence lengths

Guth, Herzberg & Prescod-Weinstein 2015

Dilute Axion Stars

as axion star accretes more and more axions, its Mass increases and its Radius decreases



critical mass M_* beyond which kinetic pressure cannot balance attractive forces

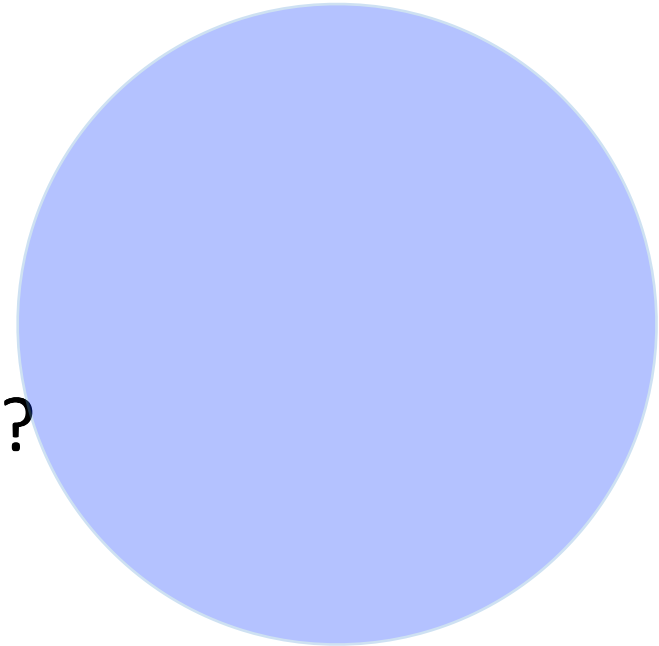
$$M_* = 10.2\, f/G^{1/2} m$$

Chavanis and Delfini (2011)

$$= 6 \times 10^{-14}\, M_\odot$$

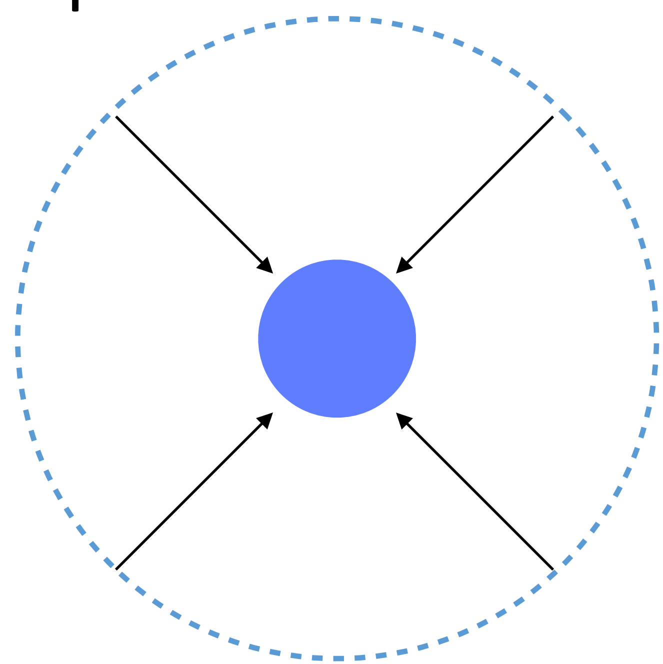
$$R_* = 3 \times 10^{-4}\, R_\odot = 200 \text{ km}$$

Dilute Axion Stars



What happens to dilute axion star
with the critical mass
when it accretes additional axions?

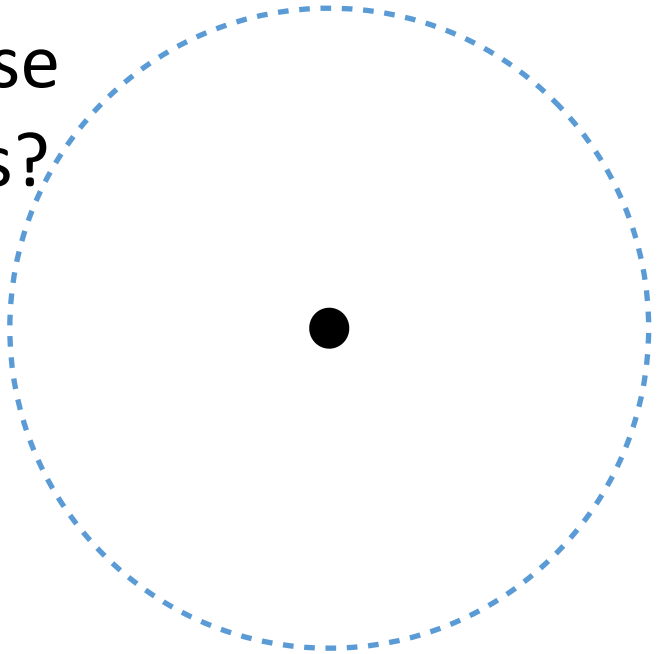
Kinetic pressure cannot prevent collapse



What is the remnant
after the collapse?

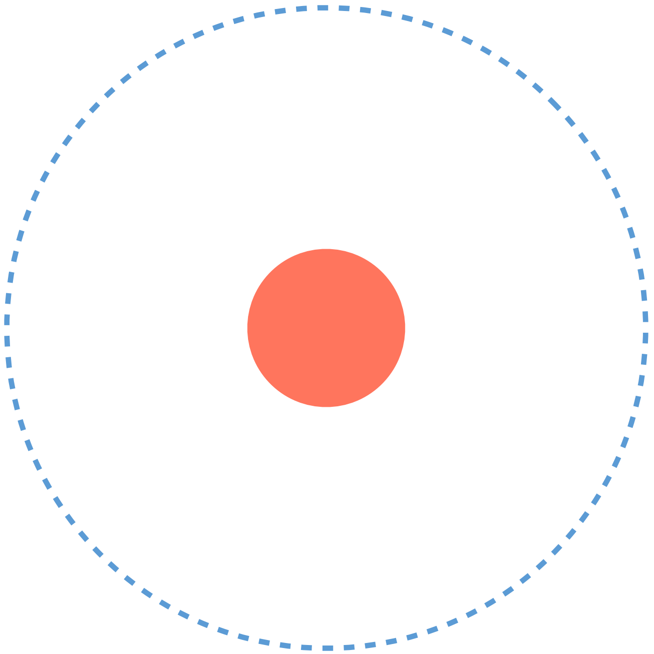
Dilute Axion Stars

What is the remnant after the collapse of an axion star with the critical mass?



black hole?

Schwarzchild radius is smaller by 72 orders of magnitude



dense axion star?

if radius decreases by 5 orders of magnitude, ϕ is or order f

higher order terms in axion potential are important

Axion EFT

Axions can be described by a relativistic field theory with a real scalar field *φ(x)*

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \mathcal{V}(\phi)$$

Low-energy axions can be described by a nonrelativistic Effective Field Theory ("axion EFT") with a complex scalar field *ψ(r,t)* arXiv:1604.00669

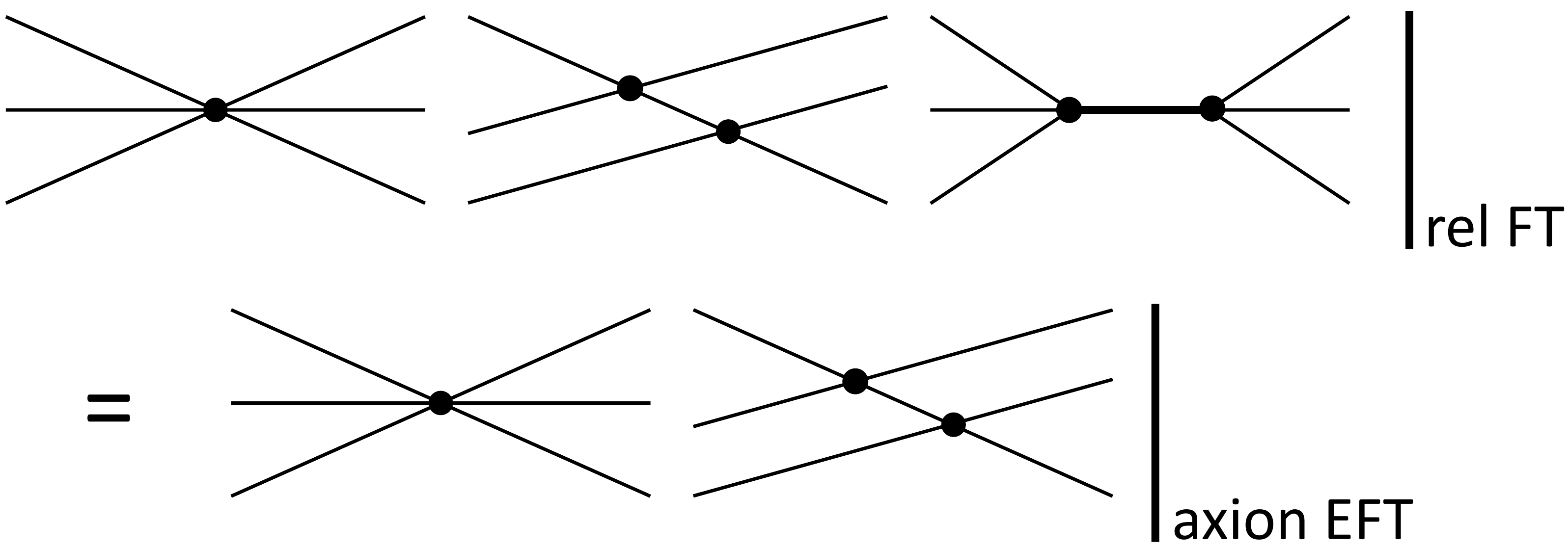
$$\mathcal{H} = \frac{1}{2m}\nabla\psi^* \cdot \nabla\psi + \mathcal{V}_{\text{eff}}(\psi^*\psi)$$

Axion EFT

effective potential for axion EFT: V_{eff}

expansion of V_{eff} in powers of $\psi^*\psi$ can be calculated by matching low-energy scattering amplitudes

arXiv:1604.00669



$$\mathcal{V}_{\text{eff}} = m\psi^*\psi - \frac{1}{16f^2}(\psi^*\psi)^2 - \frac{1}{288mf^4}(\psi^*\psi)^3 + \ldots$$

Axion EFT

If axion Bose-Einstein condensate is dense with $\psi^*\psi$ of order mf^2, must keep terms in V_{eff} with all powers of $\psi^*\psi$

Naive nonrelativistic reduction

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

insert into relativistic Hamiltonian

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

drop terms with rapidly oscillating phases

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

Eby, Suranyi, Vaz & Wijewardhana

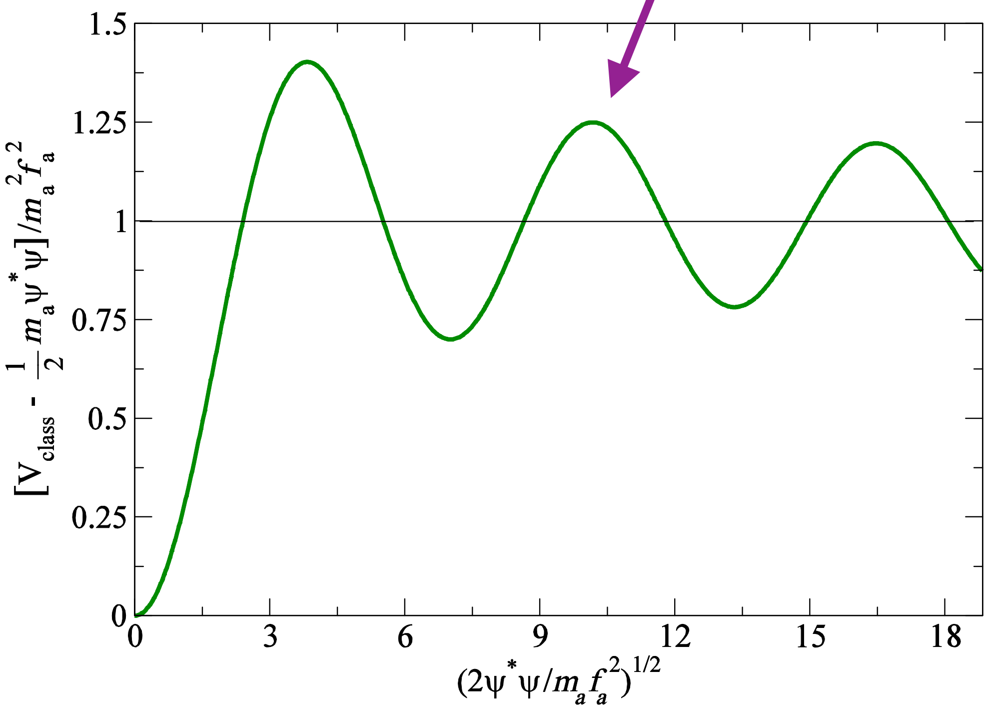
$$\hat{n} = 2\psi^*\psi/mf^2$$

Axion EFT

naive effective potential from nonrelativistic reduction

$$\hat{n} = 2\psi^*\psi/mf^2$$

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



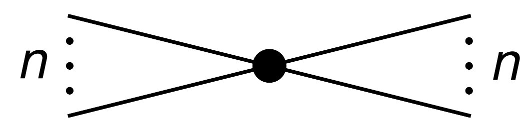
Axion EFT

effective potential V_{eff} for $\psi^*\psi$ of order mf^2 can be obtained by matching low-energy amplitudes for $n \longrightarrow n$ scattering for all n

<u>naive effective potential</u> from nonrelativistic reduction

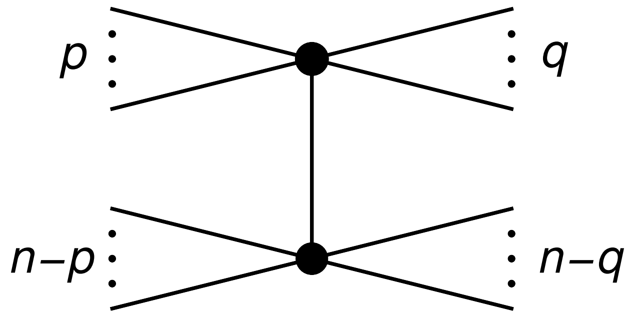
$$\mathcal{V}_{\text{eff}} = \frac{1}{2} m\psi^*\psi + m^2 f^2 \left[1 - J_0(\hat{n}^{1/2})\right]$$

match diagrams with no virtual propagators



<u>1st improvement</u>

also match diagrams with one virtual propagator



Dense Axion Stars

- axions in axion star are nonrelativistic

  $\Longrightarrow$ use Axion EFT

  use naive effective potential

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

- gravity in axion star is weak

  $\Longrightarrow$ approximate General Relativity by Newtonian gravity

- time independent

- spherically symmetric

Dense Axion Stars

coupled equations for axion field $\psi(r)$

and gravity potential $\phi(r)$

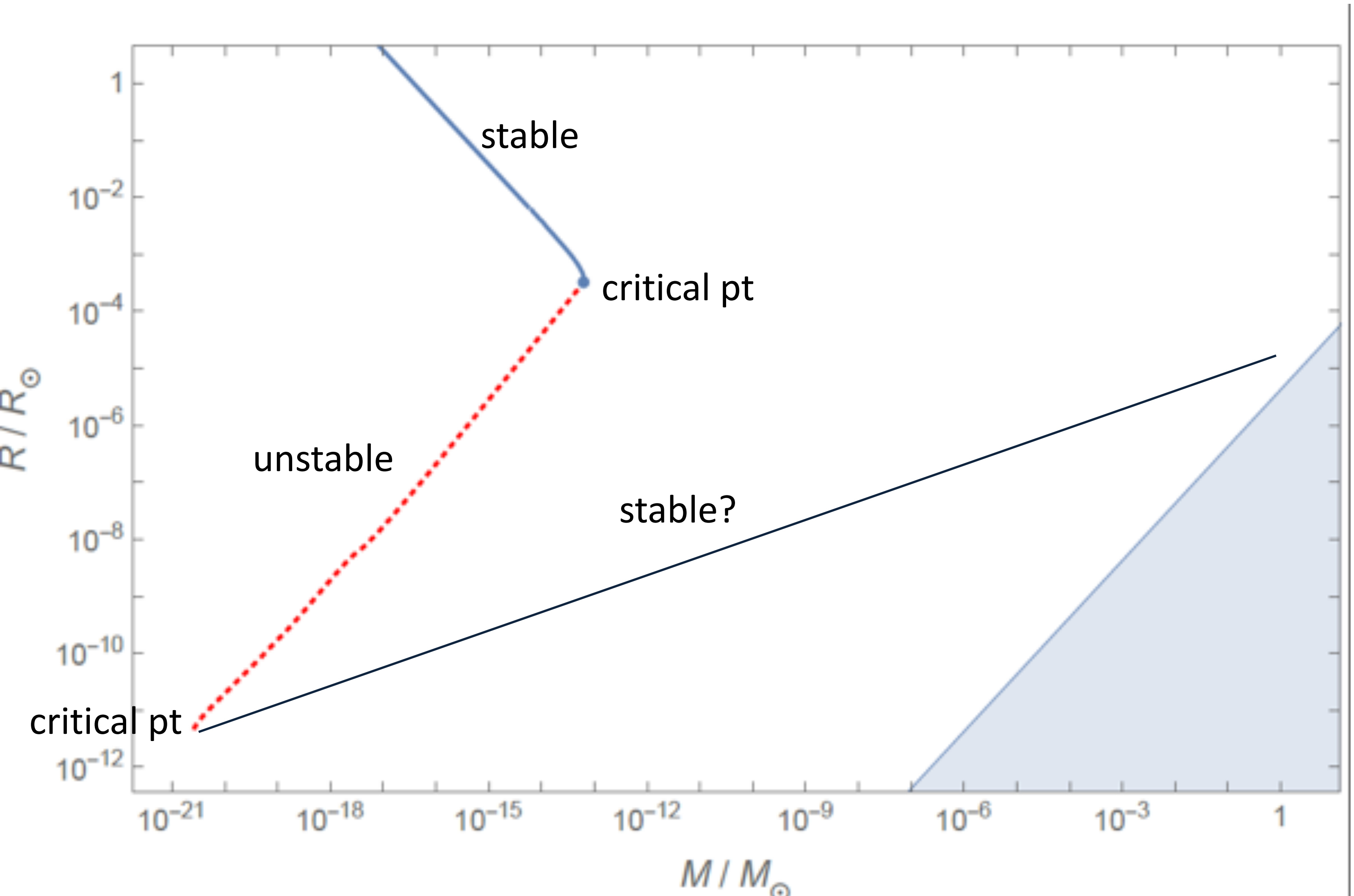
$$\nabla^2 \psi = -2m\left[\mu - (\mathcal{V}'_{\text{eff}}(\psi^*\psi) - m) - m\phi\right]\psi$$
$$\nabla^2 \phi = 4\pi G m \psi^* \psi.$$

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

eigenvalue equations for chemical potential μ

Dense Axion Stars

equations imply new branch of dense axion stars
radius increases with mass



Dense Axion Stars

mass range: from about $10^{-20}\,M_\odot$ to about $M_\odot$

through most of mass range, solutions can be simplified using Thomas-Fermi approximation:

neglect kinetic term for axions

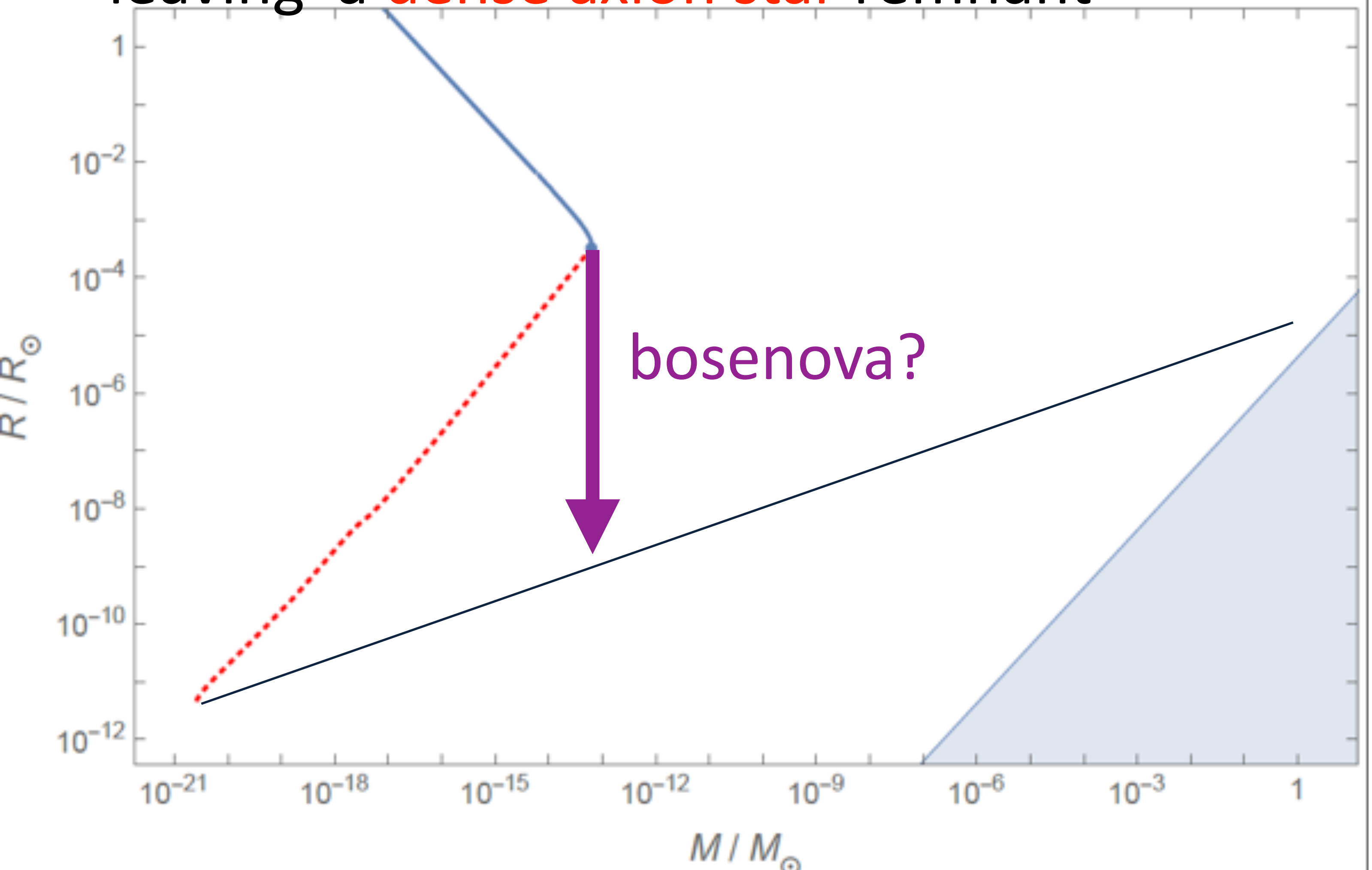
$$\nabla^2\psi = -2m\left[\mu - (\mathcal{V}'_{\rm eff}(\psi^*\psi) - m) - m\phi\right]\psi$$

$$\nabla^2\phi = 4\pi G m \psi^*\psi.$$

attractive force from gravity is balanced by mean-field pressure of axion Bose-Einstein condensate!

Dense Axion Stars

when dilute axion star with critical mass collapses,
it could produce a bosenova
leaving a dense axion star remnant



Bosenova in cold atoms

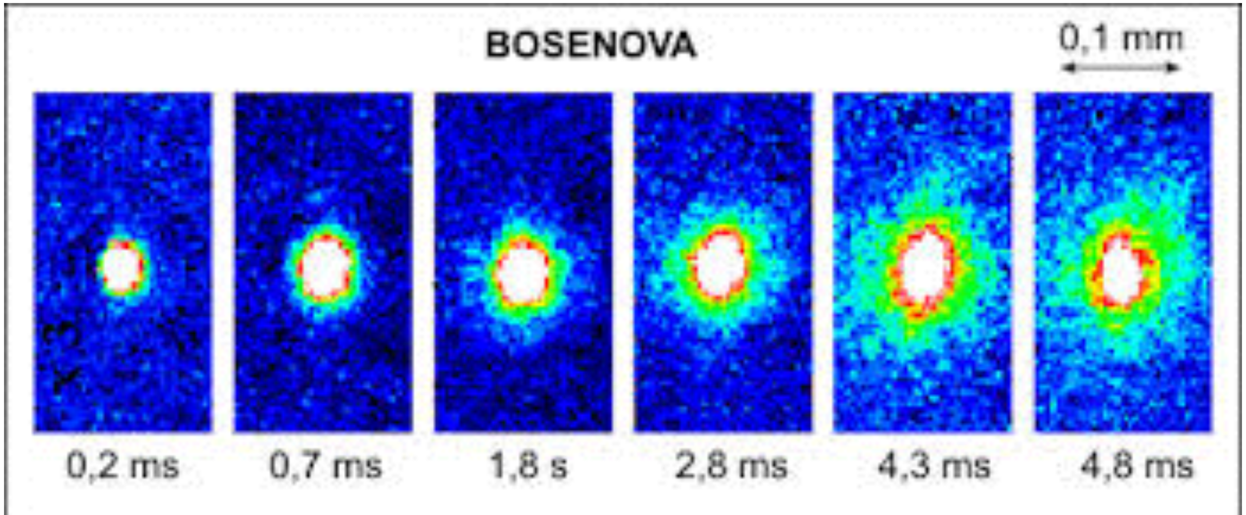
stable Bose-Einstein condensate of atoms
with positive scattering length

sign of scattering length is suddenly reversed

condensate collapses

burst of energetic atoms from inelastic reactions
(3-body recombination)

cold remnant cloud of atoms



JILA group
2001

Dense Axion Stars

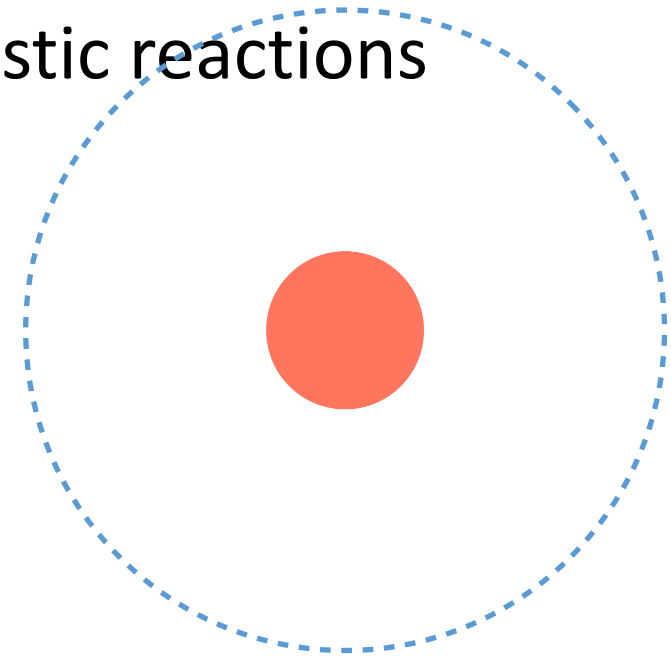
Bosenova in axion star

dilute axion star with critical mass
accretes more axions

axion star collapses
(radius decreases by 5 orders of magnitude)

burst of relativistic axions from inelastic reactions
($4 \longrightarrow 2$ scattering, etc.)

remnant dense axion star?



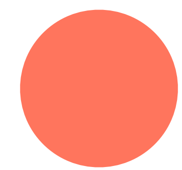
Questions

What is the effective potential for Axion EFT?

How can it be calculated accurately?

Are there dense axion stars?

Is V_{eff} from the naive nonrelativistic reduction qualitatively correct?



What happens to a dilute axion star when it exceeds the critical mass and collapses?

Is the remnant a dense axion star?

Solve the time dependent classical field equations of Axion EFT.

Questions

What is the mass distribution for axion dark matter?

What fraction is in the form of gas of axions?

dilute axion stars?

dense axion stars?

Can dilute and dense axion stars be observed?

bosenova from collapse of dilute axion star?

fast radio burst from collapse of dilute axion star? Tkachev 2014

fast radio burst from collision with neutron star? Iwazaki 1999

gravitational microlensing?

Axion stars have dramatic implications for
the properties of axion dark matter
(especially if dense axion stars exist)

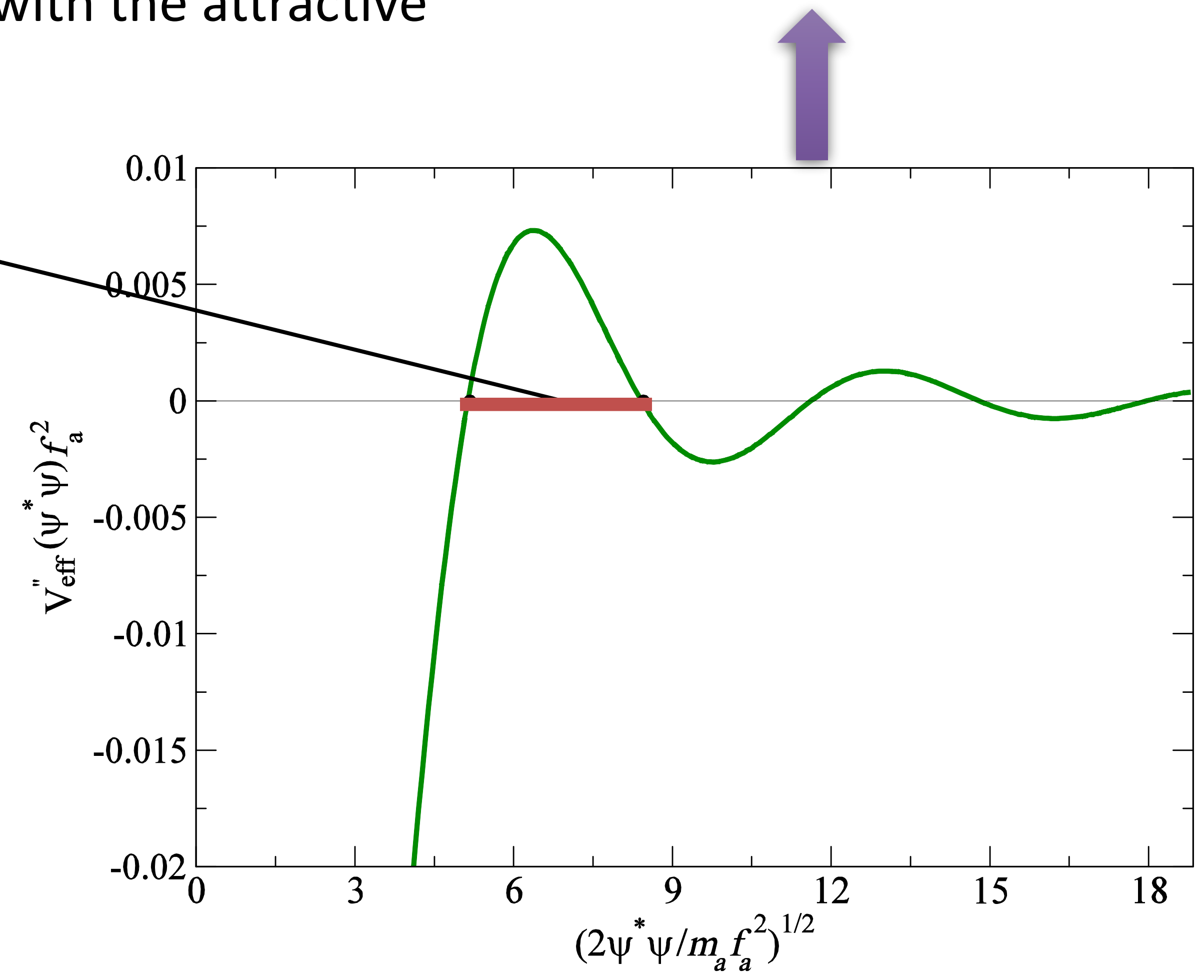
Dense Axion Stars: Branches

- Balancing repulsive mean-field pressure of

  Bose-Einstein condensate with the attractive force from gravity:

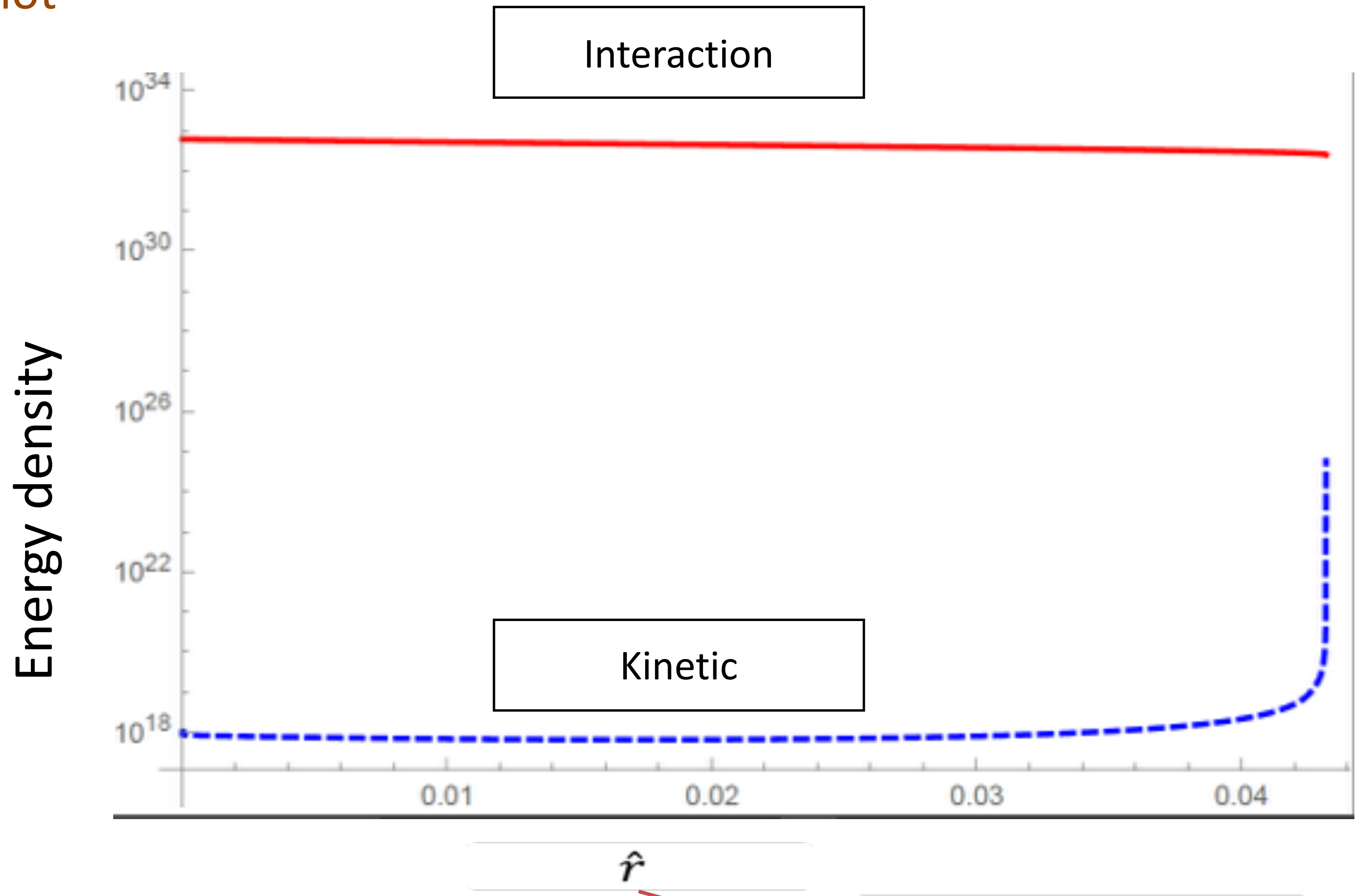
Double Derivative of Effective Potential

Range of central density for first branch of dense axion stars



Dense Axion Stars: Validity of TF Aproximation

Log plot



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