Axion Stars

(Super Light Bose-Einstein Dark Matter)

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In collaboration with Eric Braaten and Abhishek Mahapatra

Based on the recent review: Braaten, HZ, arXiv: 1810.11473

Matter To The Deepest, Katowice, Sept. 6^{th}, 2019

Outline

- ✧ Axion
  - Properties
  - Different from other DM
- ✧ Coherent Bound Configurations
  - (Dilute) Axion Star
  - Dense Axion Star
- ✧ Observations

Strong CP Problem

- Strong CP-violating term $\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$

Neutron electric dipole moment measurement: $\theta \lesssim 10^{-10}$

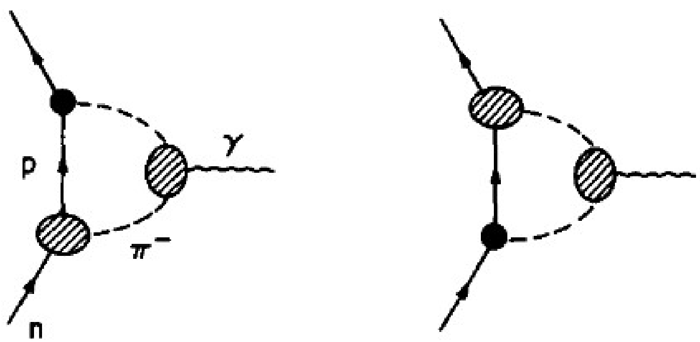


Fig. 1. Mechanism responsible for the $O(m_\pi^2 \ln m_\pi^2)$ contribution to the electric dipole moment of the neutron. The dark blob indicates a *CP* violating πNN interaction induced by the parameter θ.

Figure from Crewther et.al. (1979)

Surprisingly small because

- High-energy physics breaks CP
- "Anthropic boundary" : $\theta \lesssim 10^{-3}$

Peccei-Quinn U(1) & Axions

- Peccei-Quinn U(1) symmetry solves strong CP problem

Peccei & Quinn (1977)

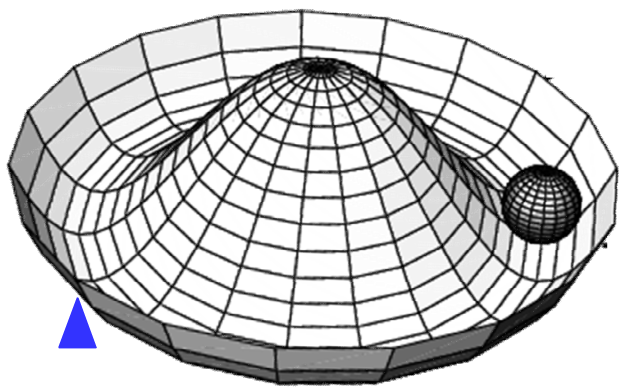
- Introduces a Goldstone boson -- Axion

Weinberg (1978), Wilczek (1978)

$$\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} \longrightarrow \phi \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

Unnaturally small parameter

Dynamical field: Axion.



The potential is **tilted** by quark condensate
The axion field **slides** down to $\phi = 0$
Restore the CP symmetry

Relativistic Axions

Real pseudoscalar field

Energy scale below 1GeV

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

Attractive force when ϕ is small

Two models for potential

- Instanton $\mathcal{V}(\phi) = m_a^2 f_a^2 \left[1 - \cos(\phi/f_a)\right] = \frac{1}{2}m_a^2\phi^2 - \frac{m_a^2}{4! f_a^2}\phi^4 + \cdots$

m_a : axion mass

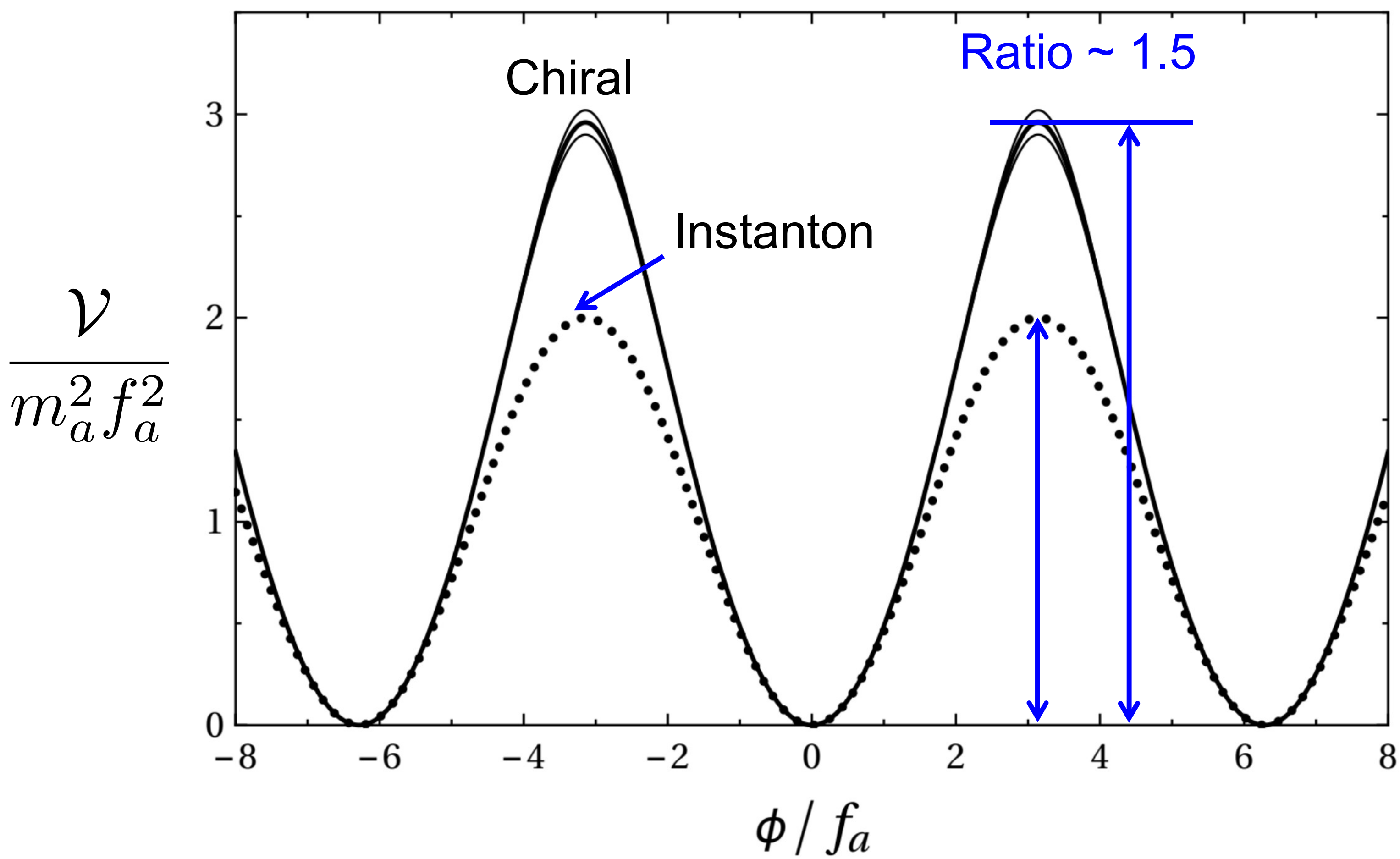
f_a : axion decay constant

- Chiral $\mathcal{V}(\phi) = m_\pi^2 f_\pi^2 \left(1 - \left[1 - \frac{4z}{(1+z)^2}\sin^2(\phi/2f_a)\right]^{1/2}\right)$

$$z = m_u/m_d \approx 0.48$$

Relativistic Axion Potential

Periodic potentials $\mathcal{V}(\phi) = \mathcal{V}(\phi + 2\pi f_a)$



Parameters & Current Constraints

- Two parameters in relativistic axion Lagrangian:

$$m_a \text{ and } f_a$$

- Not independent, related for QCD axion

$$m_a^2 f_a^2 = \frac{z}{(1+z)^2} m_\pi^2 f_\pi^2 \quad \Longrightarrow \quad m_a f_a = (80 \text{ MeV })^2$$

$$z = m_u/m_d \approx 0.48$$

- Constraints from astrophysics & cosmology

$$10^8 \text{ GeV} < f_a < 10^{13} \text{ GeV} \quad \Longrightarrow \quad 10^{-6} \text{ eV} < m_a < 10^{-2} \text{ eV}$$

Very weak self-interaction ! Tiny Mass !!

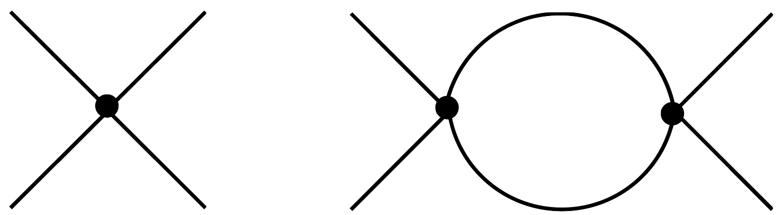
In this talk, I choose $m_a = 10^{-4}$ eV .

(See Braaten, HZ (2018) for formulas for ALPs)

Self-interactions

- Diagrams with loops can be safely ignored.

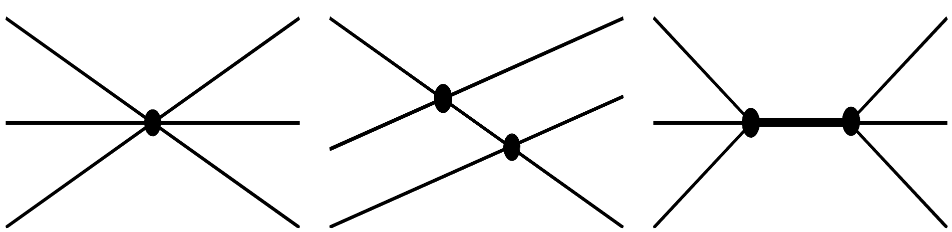
Each loop is suppressed by $(m_a/f_a)^2 \sim 10^{-48}$



Classical Field Theory!

- Exist vertices with $2n$ axions ($n \geq 2$)

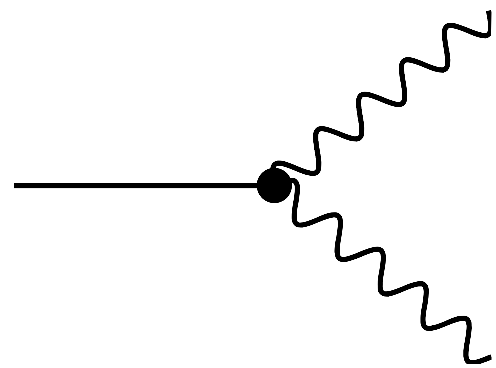
Instanton model: $\mathcal{V}(\phi) = m_a^2 f_a^2 \left[1 - \cos(\phi/f_a)\right]$



Axion-Photon Coupling

- Very weak coupling

$$\mathcal{L}_{\rm em} = \frac{c_{\rm em}\alpha}{16\pi f_a}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}\phi.$$



$c_{\rm em} \sim 1$ Model dependent

Suppressed by $f_a \sim 10^{11}\mathrm{GeV}$

- Decay rate into two photons

$$\Gamma_a = \frac{c_{\rm em}^2\alpha^2 m_a^3}{256\pi^3 f_a^2}.$$

Axion lifetime $\sim 10^{36}$ years

Age of Universe $\sim 10^{10}$ years

Photon energy: $m_a/2 \sim 10\ \mathrm{GHz}$ Radio frequency

Axion Cosmology

- Cold dark matter axions are produced abundantly at QCD phase transition scale T ~ 1 GeV

Non-thermal axion production mechanism

For more details, see Lect. Notes Phys. 741 (2008)

Mostly non-relativistic

- Vacuum misalignment — Coherent

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

- Cosmic string decay — Incoherent → Coherent

  Davis (1986)
  Hararie & Sikivie (1987)

Axion Dark Matter

- spin-0 non-relativistic boson

  with extremely small mass $6 \times 10^{-6}\ \mathrm{eV} \lesssim m_a \lesssim 2 \times 10^{-3}\ \mathrm{eV}$

  and extremely small self-coupling and coupling to SM particles

  (suppressed by $3 \times 10^{9}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{12}\ \mathrm{GeV}$)

  and lifetime much longer than the age of our universe

Good candidate for dark matter!

Axion Dark Matter

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  and lifetime much longer than the age of our universe

- Different from other cold dark matter.

  Take $m_a = 10^{-4}$ eV , de Broglie wave length ~ 2 mm

  Use local density 0.4 GeV/cm^3, $n \times \lambda_{dB}^3 \sim 3 \times 10^{10}$

  Huge occupation number!

- In coherence $\Longrightarrow$ the axions are in BEC!

Gravitational Thermalization

- Axion self-interaction may be too weak to thermalize axions
- Gravitational interaction can thermalize axions

Sikivie & Yang PRL (2009)

  - Bring initially incoherent axions into coherence
  - Keep the axion field as a Bose-Einstein Condensate as the Universe evolves

- Correlation length

Galactic scale? Sikivie & Yang PRL (2009)

Stellar scale due to attractive self-interaction?

Guth, Hertzberg & Prescod-Weinstein PRD (2015)

Is there a (meta)stable axion star solution?

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  - (Dilute) Axion Star
  - Dense Axion Star
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Time-dependent Solution

Einstein-Klein-Gordon action

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} (\partial^\mu \phi)(\partial_\mu \phi) - V(\phi) \right)$$

$\phi(t, r)$: axion field
$\Phi(\mathrm{t}, \mathrm{r})$: grav. potential

Isotropic solution with weak gravity

$$ds^2 = [1 + 2\Phi(r)]dt^2 - [1 - 2\Phi(r)]dr^2 - r^2 d\Omega^2$$

Derrick's theorem:

no time-independent soliton solution with dimension > 2

Must solve the time-dependent equations

$$\frac{\partial^2 \phi}{\partial t^2} = (1 + 4\Phi) \left(\frac{\partial^2 \phi}{\partial r^2} + \frac{2}{r} \frac{\partial \phi}{\partial r} \right) + 4 \frac{\partial \Phi}{\partial t} \frac{\partial \phi}{\partial t} - (1 + 2\Phi) \frac{dV(\phi)}{d\phi}$$

$$\frac{\partial^2 \Phi}{\partial r^2} + \frac{2}{r} \frac{\partial \Phi}{\partial r} = 4\pi G \rho$$

$$\rho = \rho_{\text{kin}} + \rho_{\text{grad}} + \rho_{\text{pot}} = \frac{1}{2} \left(\frac{\partial \phi}{\partial t} \right)^2 + \frac{1}{2} \left(\frac{\partial \phi}{\partial r} \right)^2 + V(\phi)$$

Example: 1-d S-G Oscillon (breather)

EOM (1-d, no gravity)

Ablowitz et.al., PRL (1973)

$$\frac{\partial^2}{\partial t^2}\phi(t,x) - \frac{\partial^2}{\partial x^2}\phi(t,x) + m_a^2 f_a \sin\frac{\phi(t,x)}{f_a} = 0$$

Analytic solution ($0 < \omega < 1$ is the frequency)

$$\phi(t,x) = 4 f_a \arctan\left[\sqrt{\omega^{-2}-1}\,\mathrm{sech}(\sqrt{1-\omega^2}\,m_a x)\cos(m_a \omega t)\right]$$

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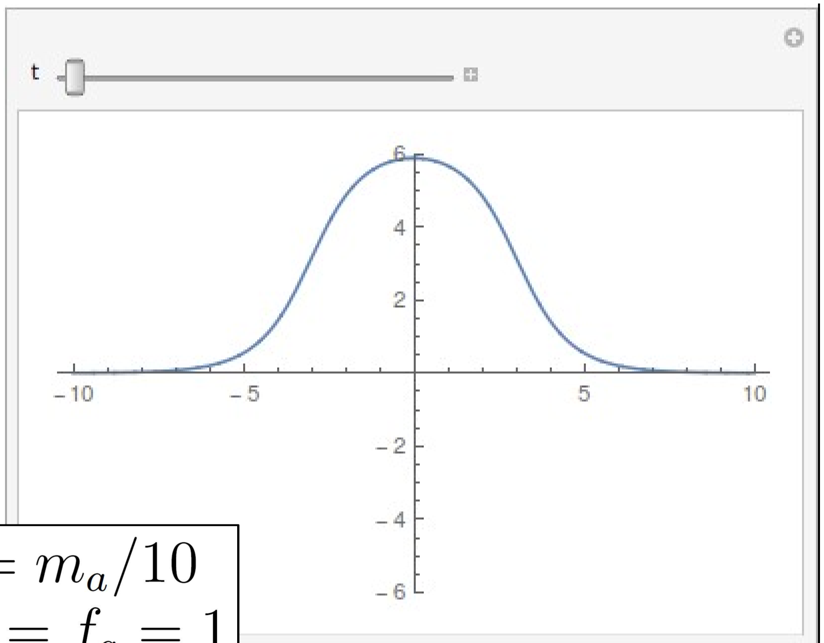

$\omega = m_a/10$
$m_a = f_a = 1$

Features:

- Periodic
- Shape changes slightly
  - --Dominated by ω
  - --Small components with $3\omega, 5\omega$ ...
- Exponentially small at infinity (no radiation)
- Stable against perturbation

Non-relativistic EFT (Part I)

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

Real Scalar

Chavanis, PRD (2011),Chavanis, Delfini, PRD (2011)
Braaten, Mahapatra, HZ, PRD (2016), PRD(2018)
Namjoo, Guth, Kaiser, PRD (2018)

Naïve non-relativistic reduction

Complex scalar

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

Ignore all terms with rapid oscillating phase

$$\mathcal{L}_{\text{eff}} = \tfrac{1}{2}i\left(\psi^*\dot{\psi} - \dot{\psi}^*\psi\right) - \frac{1}{2m_a}\nabla\psi^*\cdot\nabla\psi - \mathcal{V}_{\text{eff}}$$

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

Expand by $\dfrac{\psi^*\psi}{m_a f_a^2}$

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Ignore all terms with rapid oscillating phase

$$\mathcal{L}_{\text{eff}} = \tfrac{1}{2} i \left(\psi^* \dot{\psi} - \dot{\psi}^* \psi\right) - \frac{1}{2m_a} \nabla\psi^* \cdot \nabla\psi - \mathcal{V}_{\text{eff}}$$

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

Dilute limit

Attractive interaction!

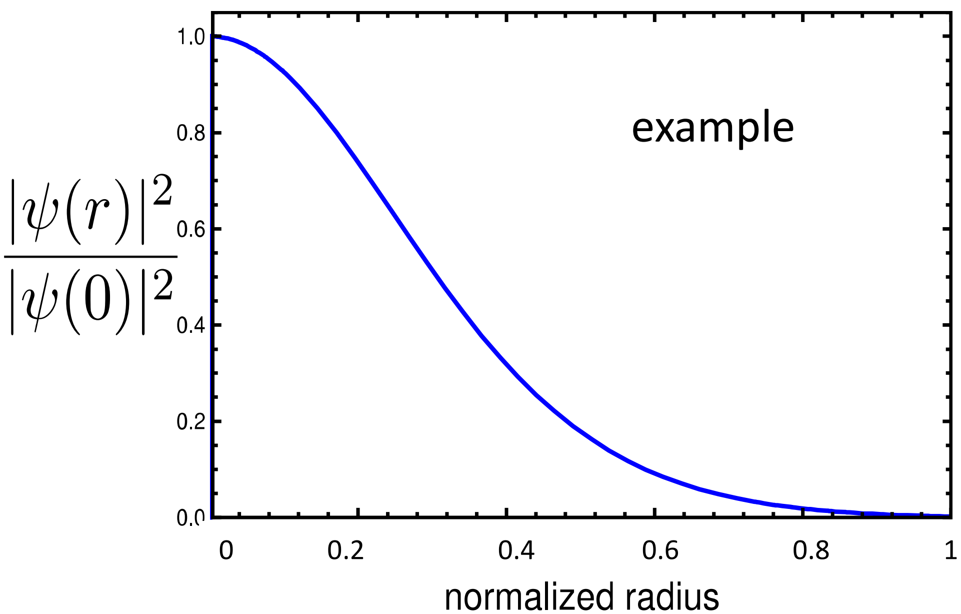
Expand by $\dfrac{\psi^*\psi}{m_a f_a^2}$

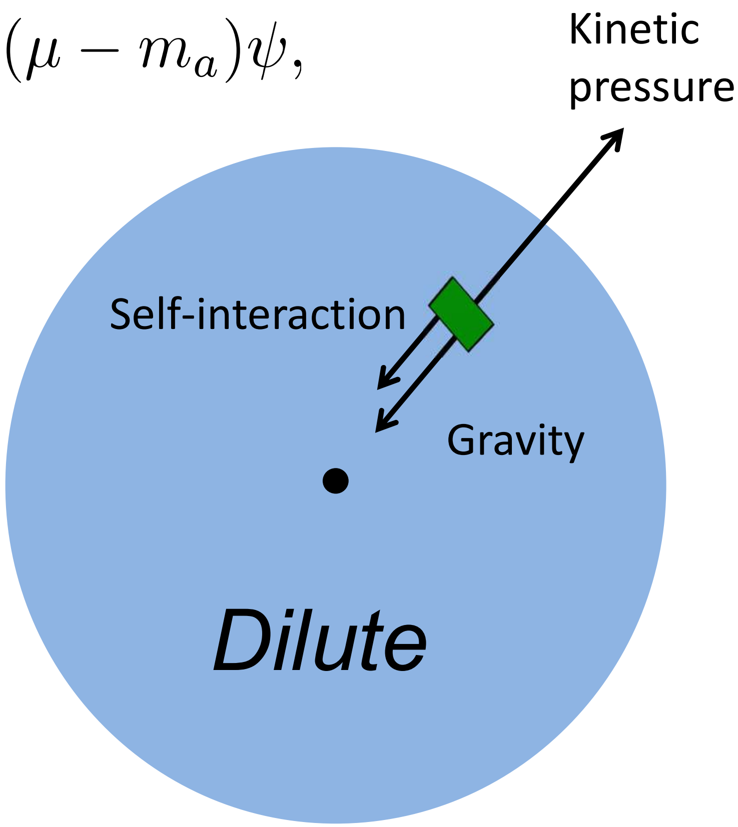
Dilute Axion Stars

Assume:
- Truncated potential, dilute axion limit
- Newtonian gravity
- Spherically symmetric

$$-\frac{\nabla^2}{2m_a}\psi + \left[(\mathcal{V}'_{\text{eff}}(\psi^*\psi) + m_a\Phi\right]\psi = (\mu - m_a)\psi,$$

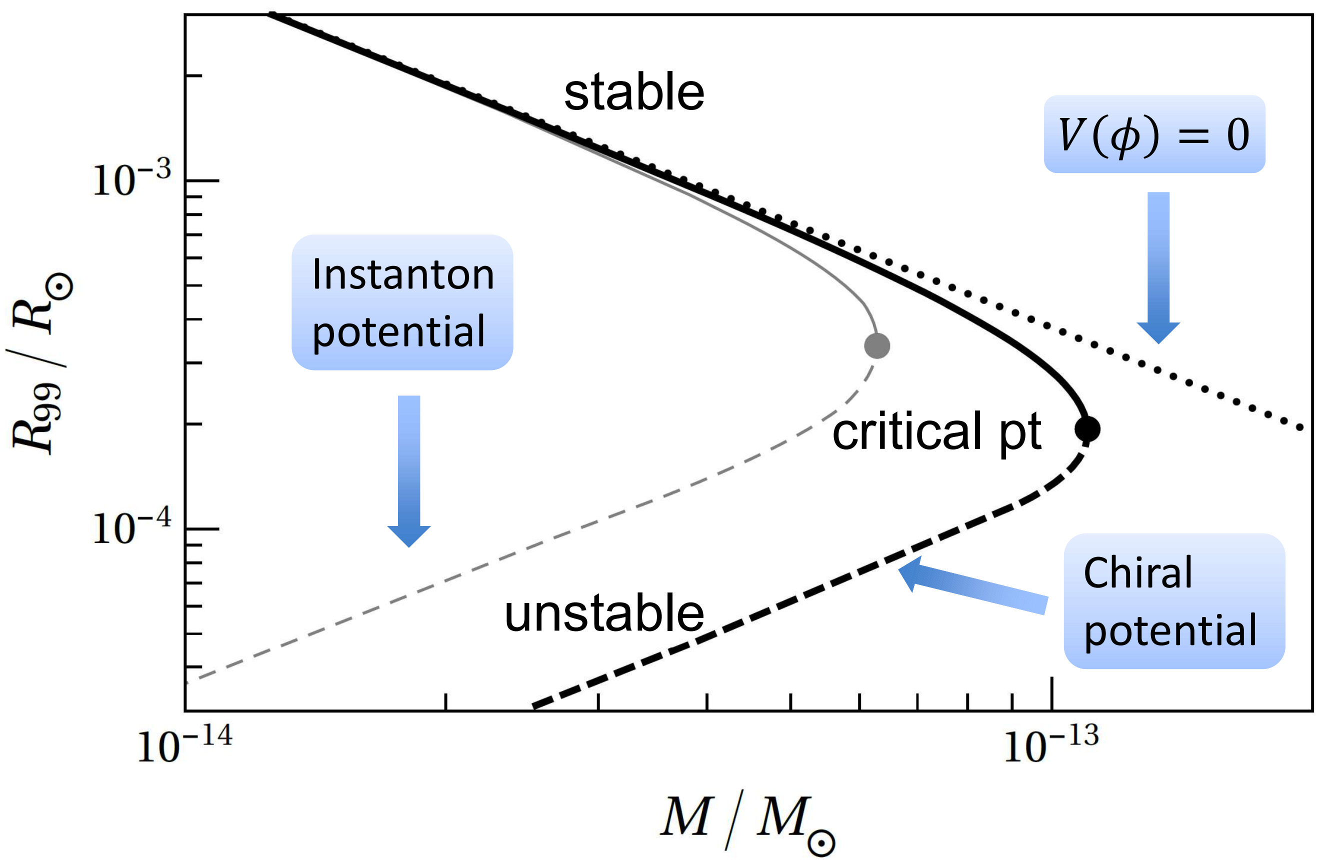
$$\nabla^2\Phi = 4\pi G m_a \psi^*\psi.$$





M vs R

- Heavier dilute axion stars have smaller radii.
- Critical mass: beyond which the kinetic pressure cannot balance the attractive self-interaction and gravity



$$M_* \sim 10^{-13} M_\odot$$

$$R_* \sim 10^{-4} R_\odot \sim R_☽$$

Formation of Dilute Axion Stars

- Dilute axion stars can be produced in early universe.
- Vacuum misalignment mechanism produces coherent and non-relativistic axions.
- Spatial fluctuations in the axion field evolve into gravitationally bound "miniclusters" of axions.
- Axion miniclusters first form light and large dilute axion stars.
- Dilute axion stars attract more axions and gradually reaches the critical mass (attractor). Levkov et.al. PRL (2017)
- Dilute axion stars over the critical mass collapse.
  In this process, the axions are not dilute at certain time.

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  - Dense Axion Star
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Non-relativistic EFT (Part II)

$$\mathcal{L}_{\text{eff}} = \tfrac{1}{2} i \left(\psi^* \dot{\psi} - \dot{\psi}^* \psi \right) - \frac{1}{2m_a} \nabla \psi^* \cdot \nabla \psi - \mathcal{V}_{\text{eff}}$$

- Dilute axion field

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

Dilute limit

- In dense axion field $(\psi^* \psi) \sim m_a f_a^2$, must keep all orders

Both instanton and chiral potential can be summed to all orders

Instanton potential:

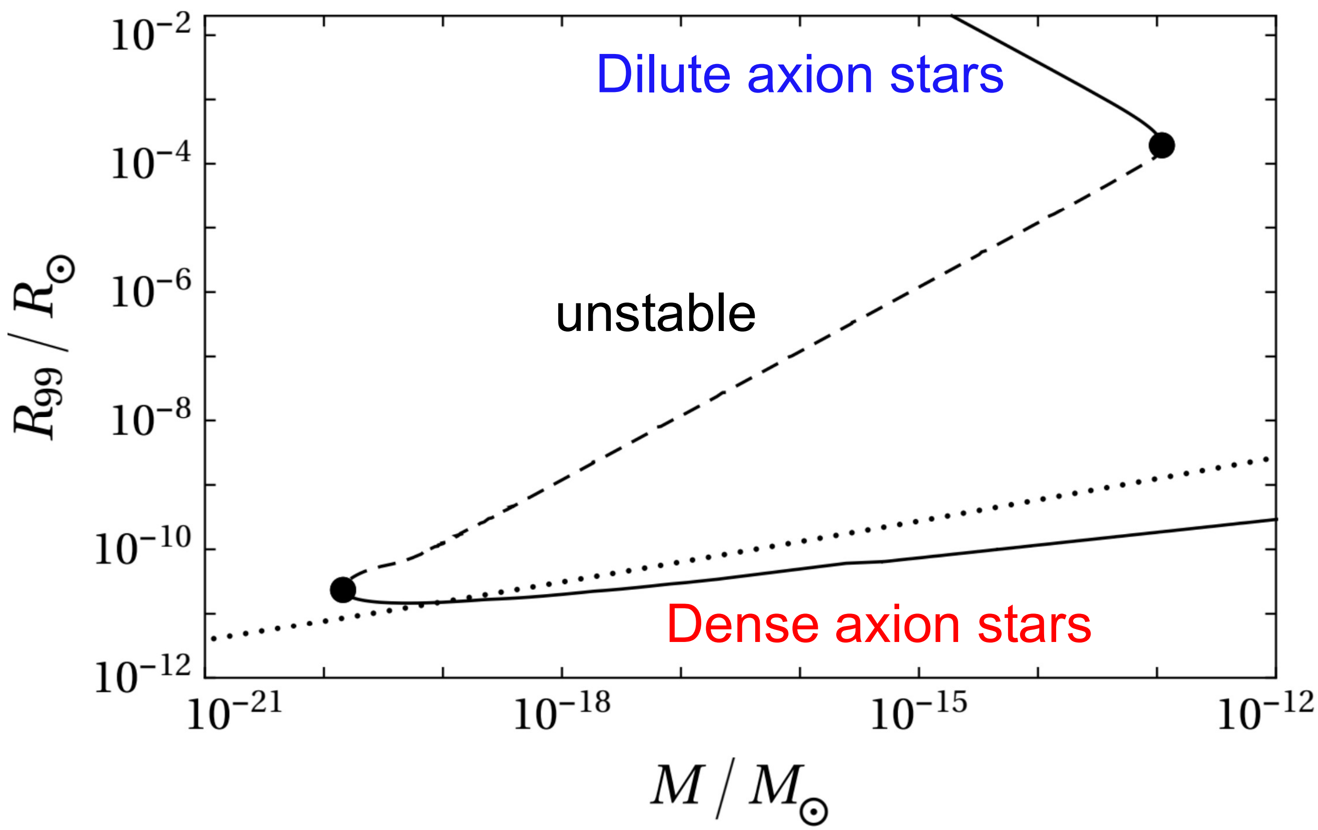
$$\mathcal{V}_{\text{eff}}(\psi^* \psi) = \tfrac{1}{2} m_a \psi^* \psi + m_a^2 f_a^2 \left[1 - J_0(2\psi^* \psi / m_a f_a^2) \right]$$

Eby, Suranyi, Vaz & Wijewardhana (2015)
Braaten, Mahapatra, HZ, PRD (2016), PRD(2018)

Dense Branch

With untruncated potential, a new dense branch is found.

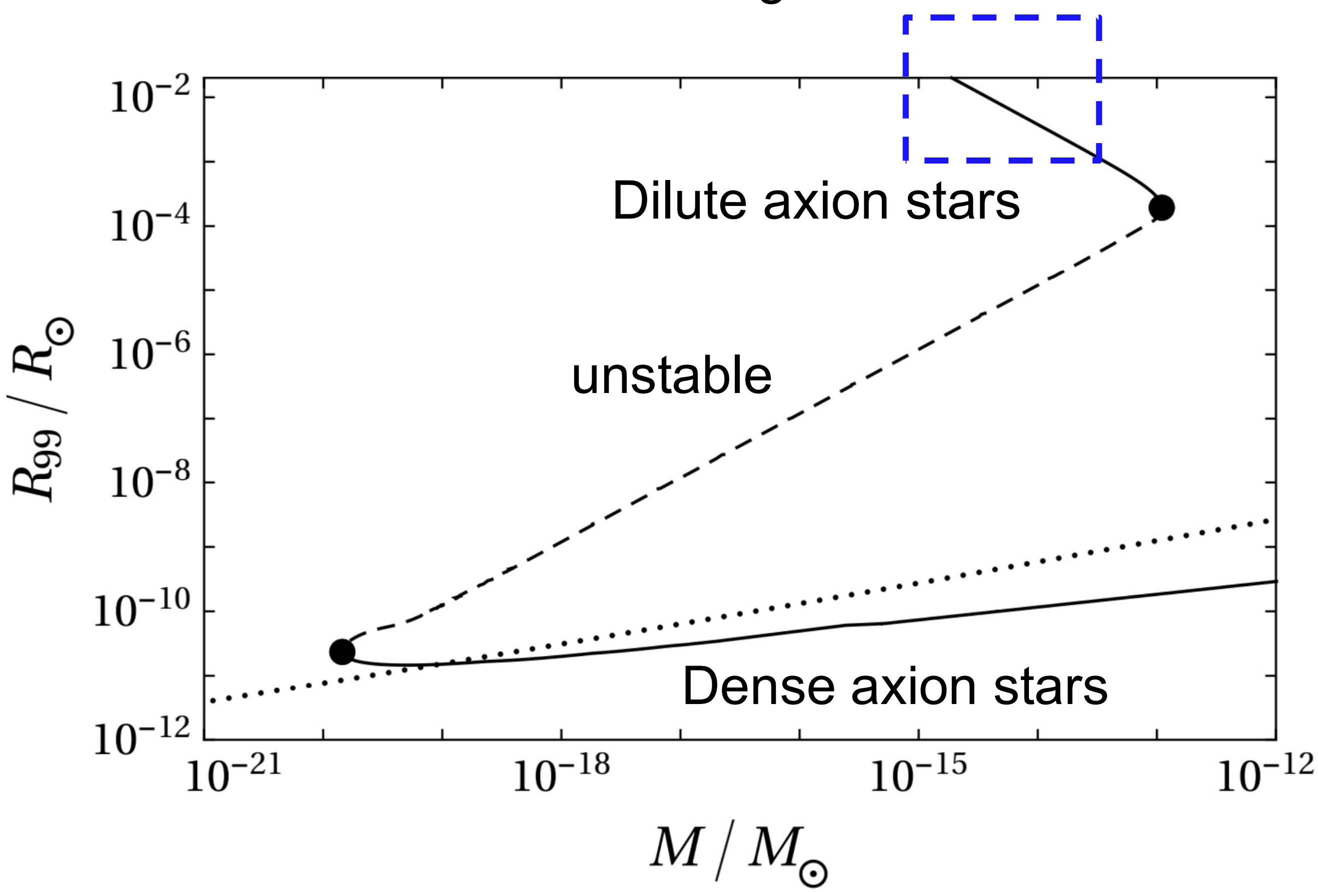
Assume: • NREFT • Newtonian gravity • Isotropic



Braaten, Mahapatra & HZ (2016), Braaten & HZ (2018)

Axion Stars

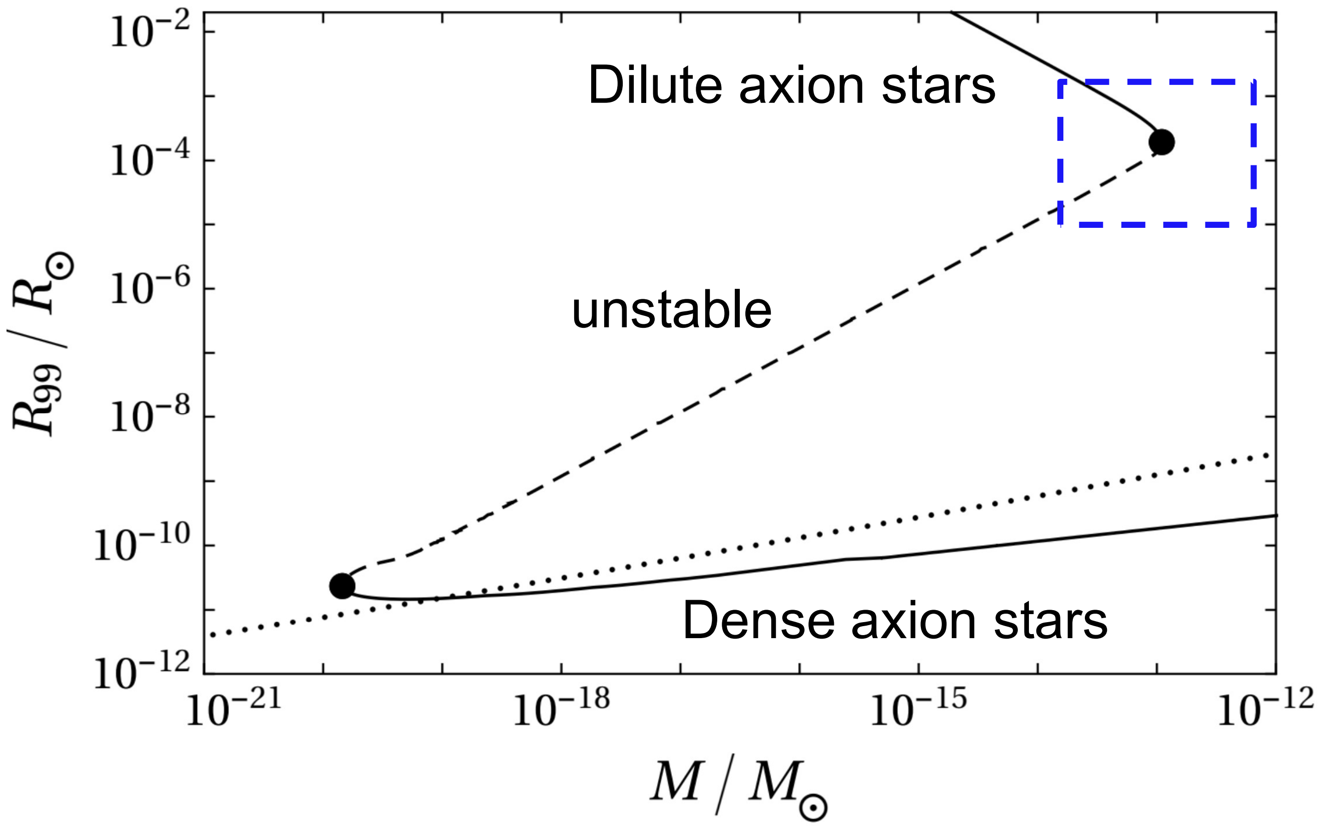
Quantum pressure balances gravity,
All self-interactions can be ignored!



Braaten, Mahapatra & HZ (2016), Braaten & HZ (2018)

Axion Stars

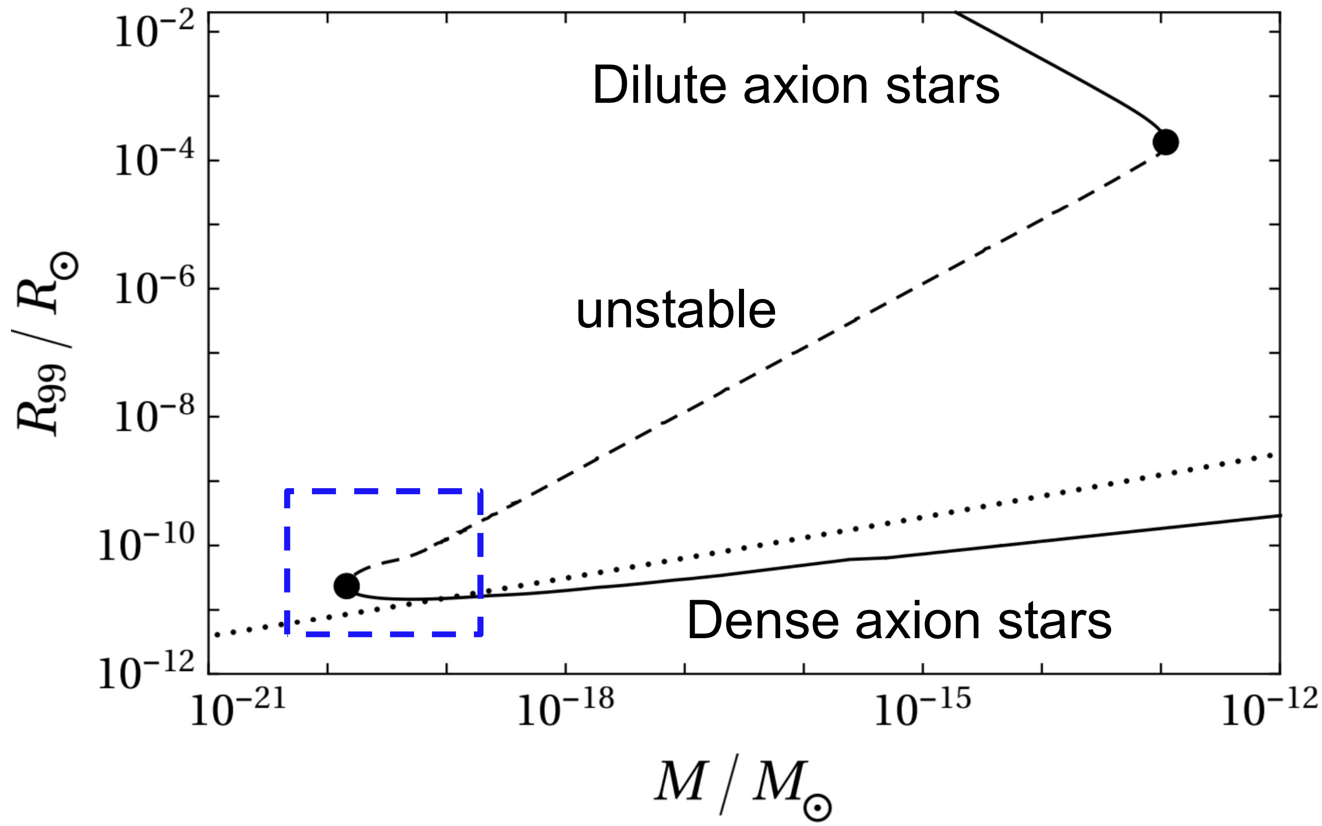
Quantum pressure balances (gravity + ϕ^4 interaction),
Attractive ϕ^4 interaction causes the turning over.



Braaten, Mahapatra & HZ (2016), Braaten & HZ (2018)

Axion Stars

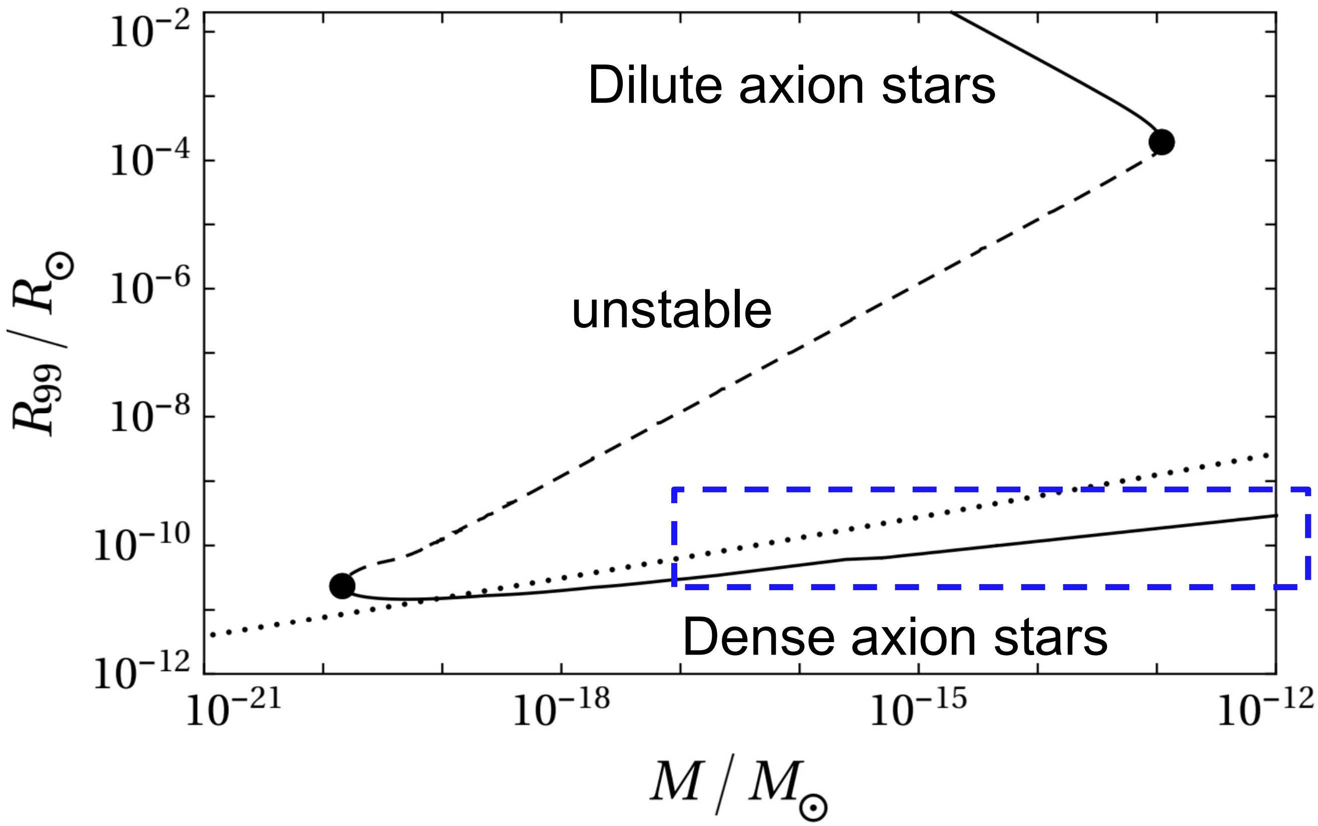
Higher orders in the potential become important.
Quantum pressure balances full potential.
Gravity can be ignored! Same results are obtained without gravity.



Braaten, Mahapatra & HZ (2016), Braaten & HZ (2018)

Axion Stars

Gravity is important at large mass.
Newtonian gravity is not accurate anymore.

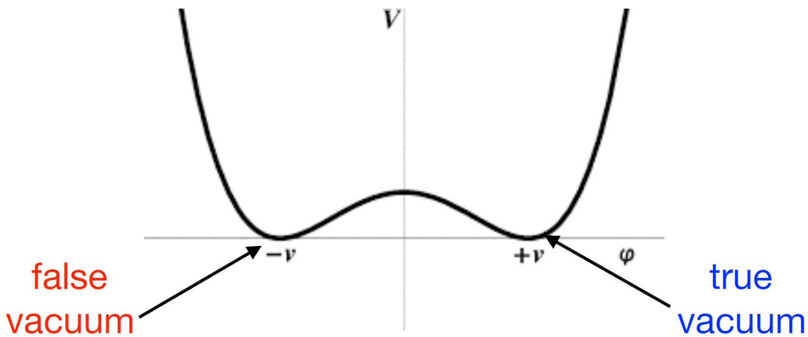


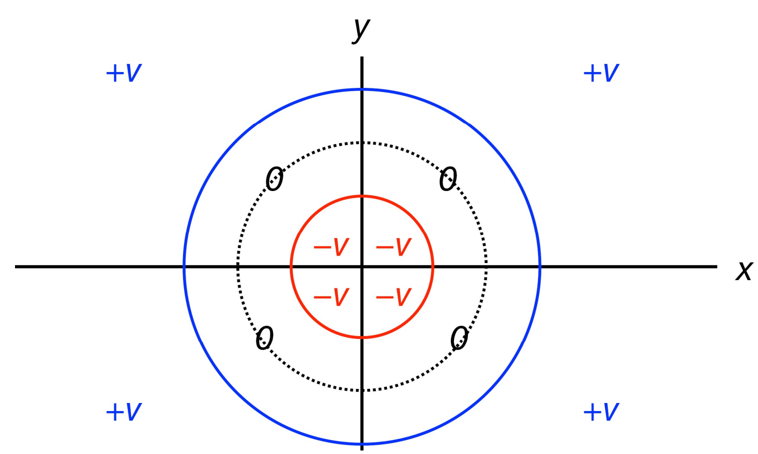
Braaten, Mahapatra & HZ (2016), Braaten & HZ (2018)

Oscillons

- Real scalar field with 3-d isotropic double-well potential

Bogolubsky & Makhankov (1976)





Inside: false vacuum
Outside: true vacuum

- Time evolution?

Time Evolution of Oscillons

Three stages found in some numerical calculation

1. relaxation

Bogolubsky & Makhankov (1976)

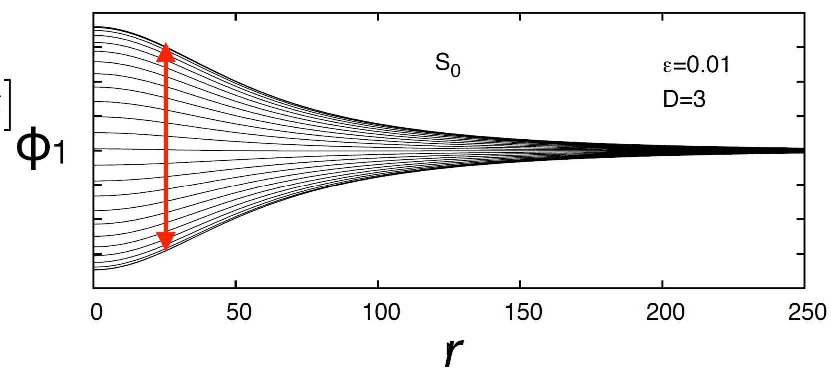
From a given initial profile, radiate a large fraction of energy into outgoing waves

2. **oscillon**!

Localized oscillating configuration stabe for many oscillations, slowly radiates outgoing waves.

$$\phi(r,t) = \sum_{n=1}^{\infty} \phi_{2n+1}(r) \cos[(2n+1)\omega t]$$

$$(\omega \approx m_a)$$



3. Sudden collapse

Configuration suddenly become unstable, disappear into outgoing waves.

Time Evolution of Oscillons

Three stages found in some numerical calculation

1. relaxation

   From a given initia
   into outgoing wave

2. **oscillon**!

   Localized oscillatir
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$$\phi(r,t) = \sum_{n=1}^{\infty} \phi_{2n+1}(r$$

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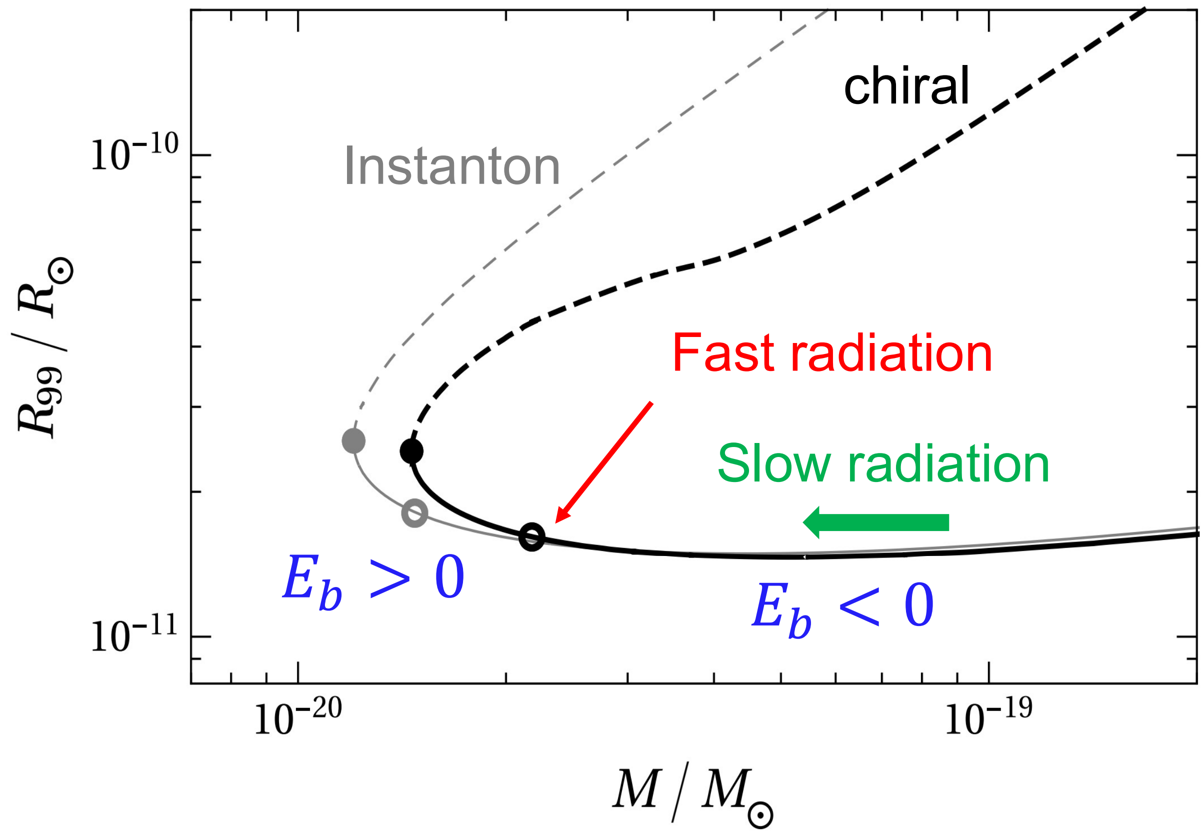


Decay of Dense Axion Star

- It is pointed that the decay rate of dense axion star is too large

  Lifetime t ~ $10^3/m_a$ For $m_a \sim 10^{-4}$ eV, $t \sim 10^{-9}$ s

- The authors truncated the harmonic expansion

  (Gravity can be ignored for dense axion star) Visinelli et.al., PLB (2018)

$$\frac{\partial^2 \phi}{\partial t^2} = \frac{\partial^2 \phi}{\partial r^2} + \frac{2}{r}\frac{\partial \phi}{\partial r} - \frac{dV(\phi)}{d\phi}$$

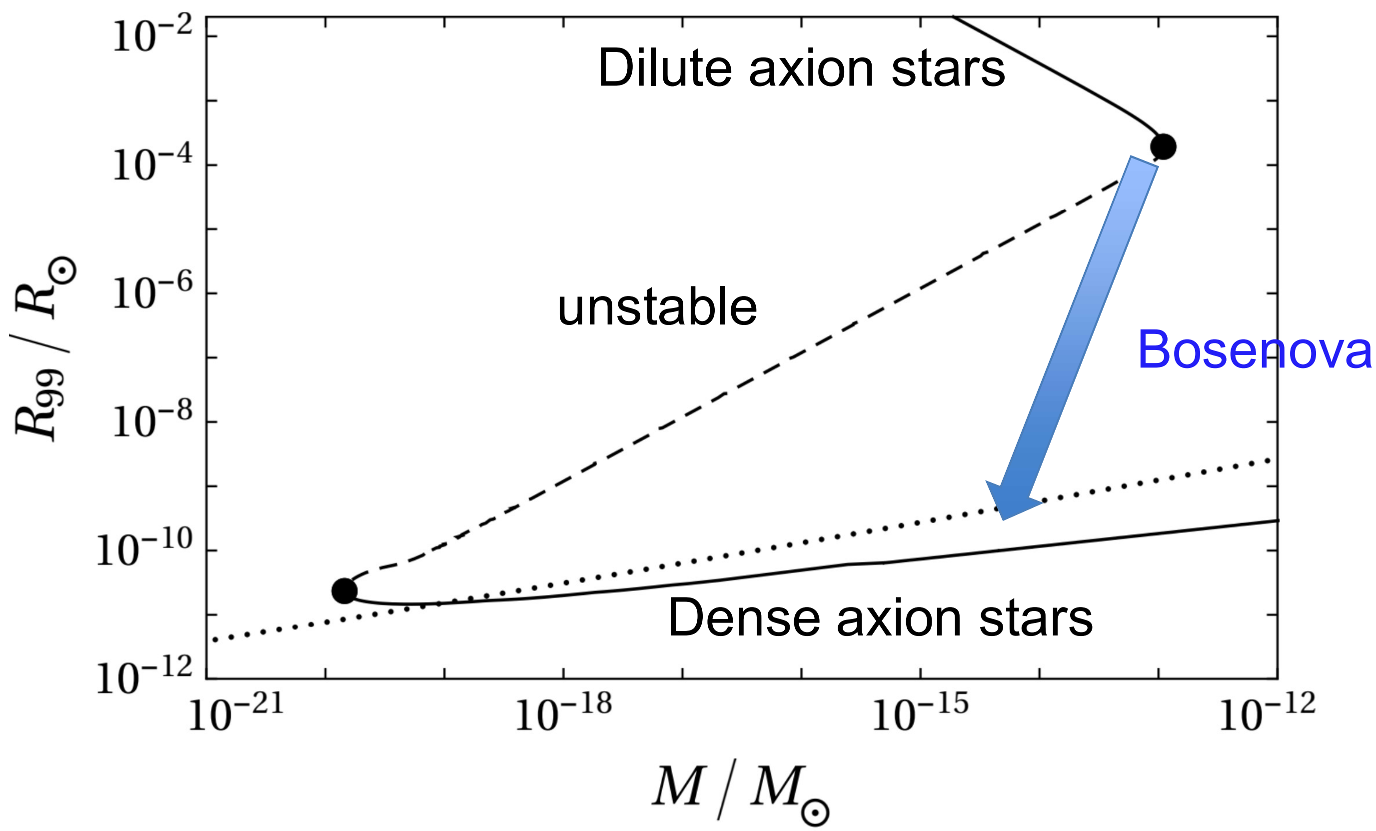
$$\phi(r,t) = \sum_{n=1}^{\infty} \phi_{2n+1}(r) \cos[(2n+1)\omega t] = \phi_1(r)\cos(\omega t) + \phi_3(r)\cos(3\omega t)$$

- Inconsistent: the same method also predicts the analytic stable breather solution has a short lifetime.
- The decay rate of dense axion star is still unclear.

  (See Braaten, HZ (2018) for previous efforts.)

Formation of Dense Axion Star

- Naively, the dense axion stars are most likely produced as remnants in the collapse of dilute axion stars over critical mass.
- Implied in the simulations. Levkov et.al. PRL (2017)



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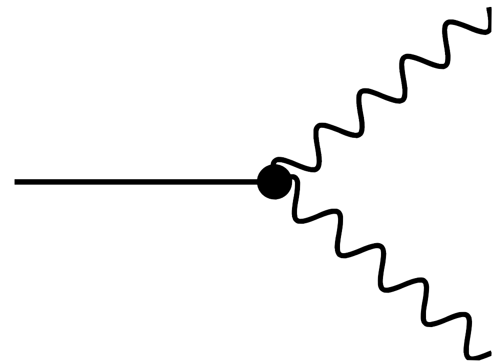
Axion Detection

- Depends on the tiny axion-photon coupling

$$\mathcal{L}_{\rm em} = \frac{c_{\rm em}\alpha}{16\pi f_a}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}\phi.$$



$c_{\rm em} \sim 1$ Model dependent

Suppressed by $f_a \sim 10^{11}\,\mathrm{GeV}$

$$\Gamma_a = \frac{c_{\rm em}^2\alpha^2 m_a^3}{256\pi^3 f_a^2}.$$

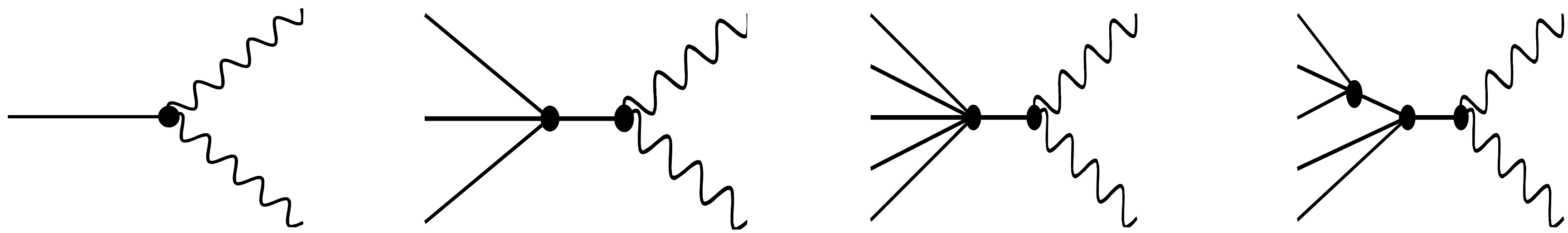
Axion lifetime $\sim 10^{36}$ years

Age of Universe $\sim 10^{10}$ years

- Many detection techniques (skip)

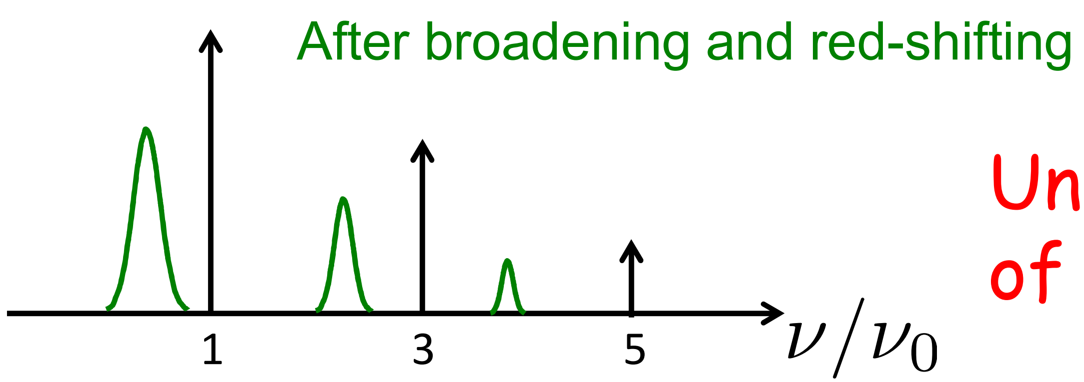
Lect. Notes Phys. 741 (2008), A recent review: Kim & Carosi (2010)

Odd-Integer Harmonics



$$\nu_0 = \frac{m_a}{2} \qquad \nu = 3\,\frac{m_a}{2} \qquad \nu = 5\,\frac{m_a}{2} \qquad \cdots$$

- Odd-integer harmonics of the fundamental radio frequency.



Unique feature of axions !!

Braaten, Mohapatra, HZ, arXiv:1609.05182

Two Types of Sources

- Continuous photon emission
  - ➢ Stable axion stars
- Catastrophic phenomenon:

  a lot of energy released in a short time
  - ➢ Collapse of dilute Axion stars
  - ➢ Collision of an axion star with a neutron star
  - ➢ …

Photon Flux Estimate

- Single axion decay to two photons is independent of the configuration.
- Solar system

radius ~ 125,000 AU, DM density ~ $0.3\mathrm{GeV}/\mathrm{cm}^3$

Total DM in Solar system $\sim 0.01 M_\odot$ 10^{68} axions

Photon production rate $\sim 10^{22}/\mathrm{sec}$

Energy released: $\sim 10^9 \mathrm{GeV}/\mathrm{sec} \sim 0.4\ \mathrm{Watt}$

- Milky way:

Total DM: $\sim 10^{12} M_\odot$ 10^{82} axions

dense axion star close to Schwatzschild radius has ~10^{70} axions $\sim 10^{11}\mathrm{GeV}/\mathrm{sec} \sim 40\ \mathrm{Watt}$

Catastrophic Phenomena

Fast Radio Burst (FRB)

- A ultra-fast (milli-sec) burst of photons in radio frequency.
- Nothing similar observed in optical, X rays and ϒ rays
- Since 2001, 69 events have been reported.
- Estimated rate ~ 10^4 sky $^{-1}$ day $^{-1}$
- Reported frequencies: 0.8, 1.4 , 7 GHz (telescope design)
- Extra-galactic sources from dispersion measure
- Energy released up to 10^{40} erg ~ $10^{-14}\,M_{\odot}$ (If isotropic)
- Strong linear polarization observed (3 events).

Online database: http://www.astronomy.swin.edu.au/pulsar/frbcat

Are Axion Stars an Explanation?

- ✓ Observed frequency: 0.8, 1.4, 7 GHz

  $10^{-6}\mathrm{eV} < m_a < 10^{-2}\mathrm{eV}$ $\quad$ $0.2\ \mathrm{GHz} < \nu < 2400\ \mathrm{GHz}$

  Also explains why such burst is not observed in other bands.

- ✓ Total energy released: up to $\sim 10^{-14} M_\odot$
  - Dilute axion star critical mass $6 \times 10^{-14} M_\odot$
  - Dense axion star mass $10^{-20} M_\odot$ to $2\, M_\odot$
- ✓ Time duration: ~ 1 ms
  - Dilute axion star critical radius: 200 km
  - Dense axion star radius: 10 m to 10 km
- ✓ Polarized photons

  Axions in axion stars are in coherence

Scenarios with Axion Stars

- Collision of a dilute axion star with a neutron star

  Coherent electric dipole radiation

  - From electrons in atmosphere — Iwazaki, hep-ph/9908468
  - From neutrons in outer core — Raby, PRD (2016)

- Collapse of dilute axion stars above the critical mass

  Tkachev, JETP Lett. (2014)

- Collision of two axion stars — Eby et.al., arXiv:1701.01476

- Collision of a dense axion star with a neutron star

Observe Odd-integer Harmonics

- One unique feature of axion stars:
  odd-integer harmonics of the fundamental radio frequency.

- Can we observe the fast radio burst at other frequencies?

  0.8 GHz, 3 × 0.8 GHz, 5 × 0.8 GHz …

  or

  1/3 × 0.8 GHz, 0.8 GHz, 5/3 × 0.8 GHz …

  Many possible combinations

- Need more events in more frequency windows.

Summary

- Axion is a very promising dark matter candidate which also solve strong CP problem.

- A large proportion of axions can exist in form of axion stars (dilute or dense).

- The formation and decay of axion stars are still unclear.

- Catastrophic phenomena of axion stars may explain fast radio burst.

- The photons in odd-integer harmonics of a fundamental radio frequency are a unique signature of axions.

Thank you!

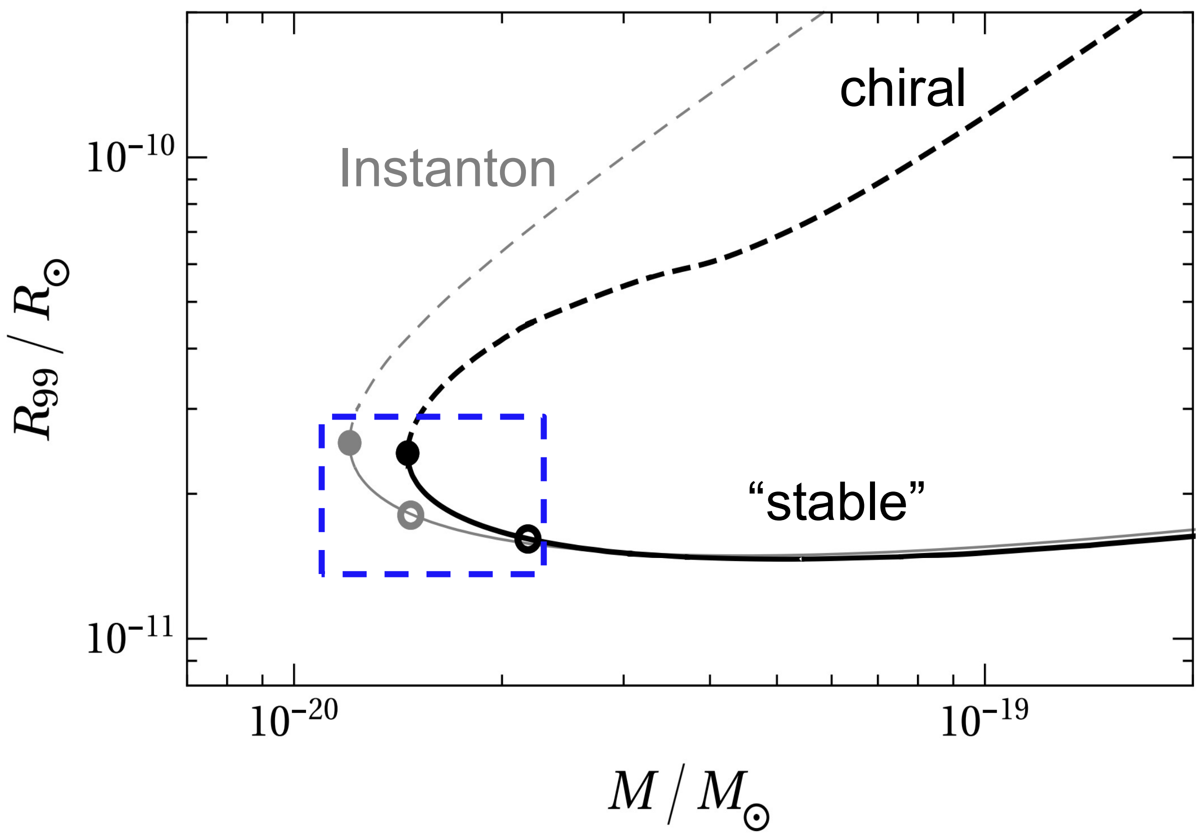
Sorry I have to disappear shortly after the session.
For more discussions, please email hong.zhang@tum.de

Backup Slides

“Stability” of Dense Branch

Close to the turning point, $E_b > 0$, unstable to large fluctuations.

At large M, $E_b < 0$, “stable” to both large and small fluctuations.



Braaten, Mahapatra, HZ (2016), Braaten, HZ (2018)

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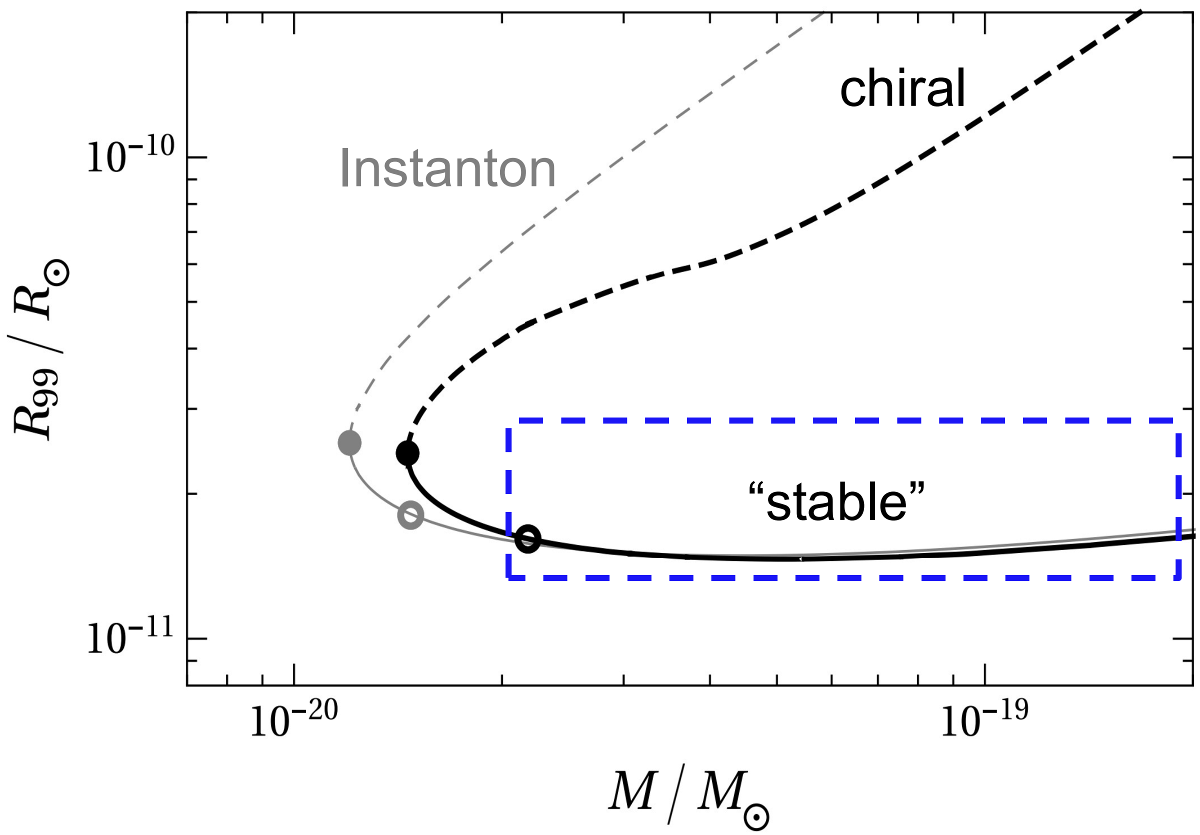
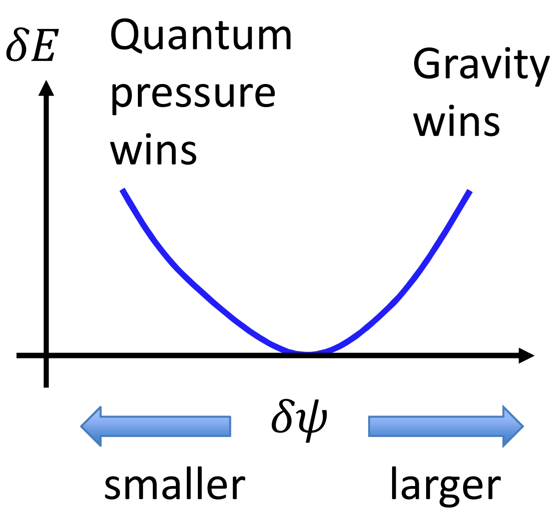


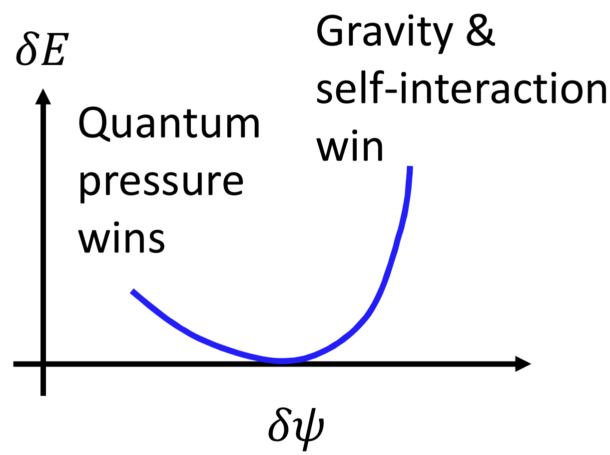
Braaten, Mahapatra, HZ (2016), Braaten, HZ (2018)

(First) Critical Point

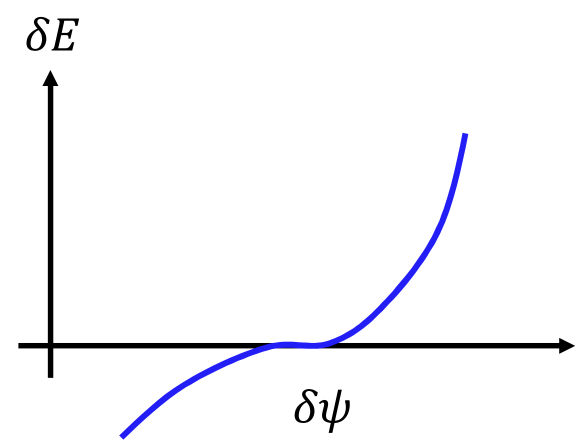
The critical point is because of the attractive interaction.



No self-interaction,
no critical mass



with self-interaction,
$M < M_*$



with self-interaction,
$M = M_*$

$$\delta E = \delta^2 E = 0$$

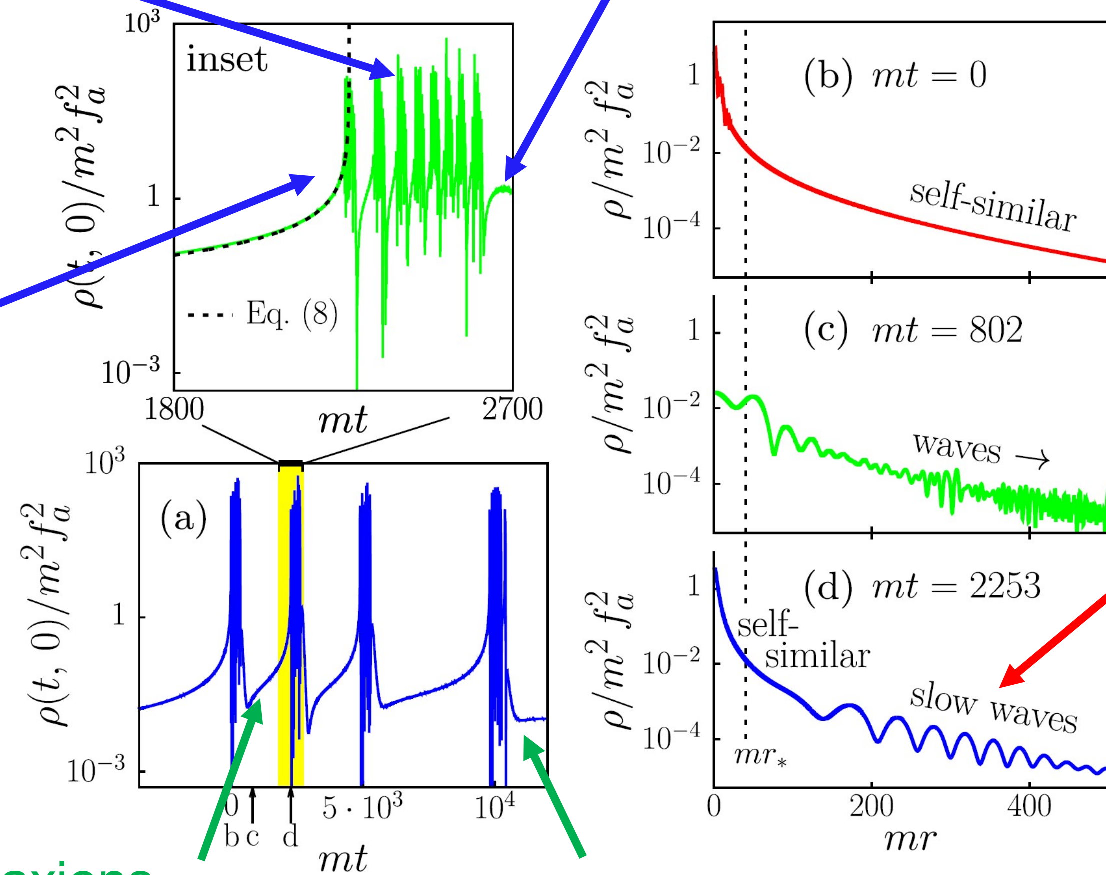
Simulation of Collapse

Simulation: no stable dense core is produced after the collapse.

Core density oscillates fastly

drops to ~1% of saturation density

Core density
Increases rapidly



Levkov et.al.
PRL (2017)

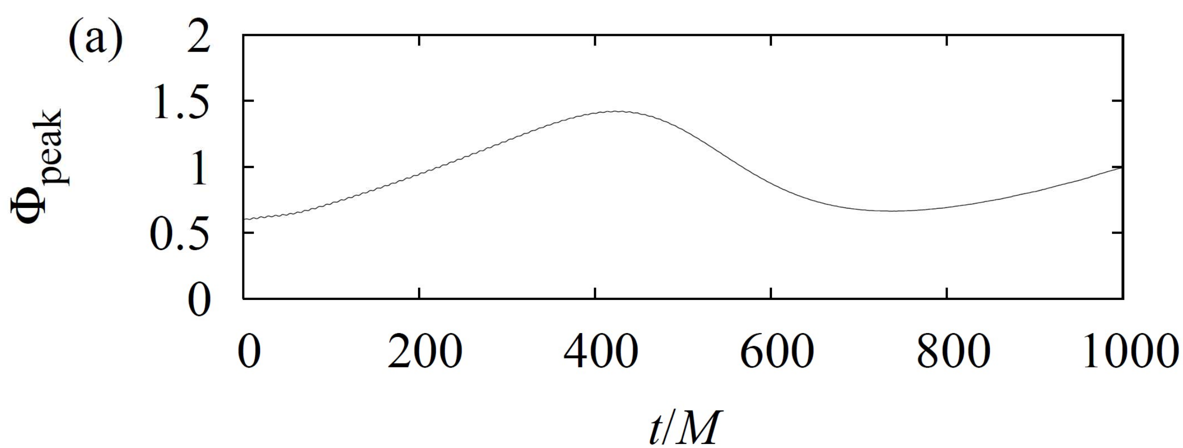
Radiate
relativistic
axions
(~30% loss)

Accumulate axions,
Prepare for the next collapse

Finally no sufficient axions
for more collapse

Existence of Dense Axion Star

- The collapse of an isolated dilute axion star may not leave a stable dense core behind.
- However, similar dense profiles may exist if there is other object providing additional
  - gravitational potential
  - axion source
  - both (e.g. blackhole superradiance)



Yoshino and H. Kodama, Prog. Theor. Phys. (2012)

Fast Radio Burst

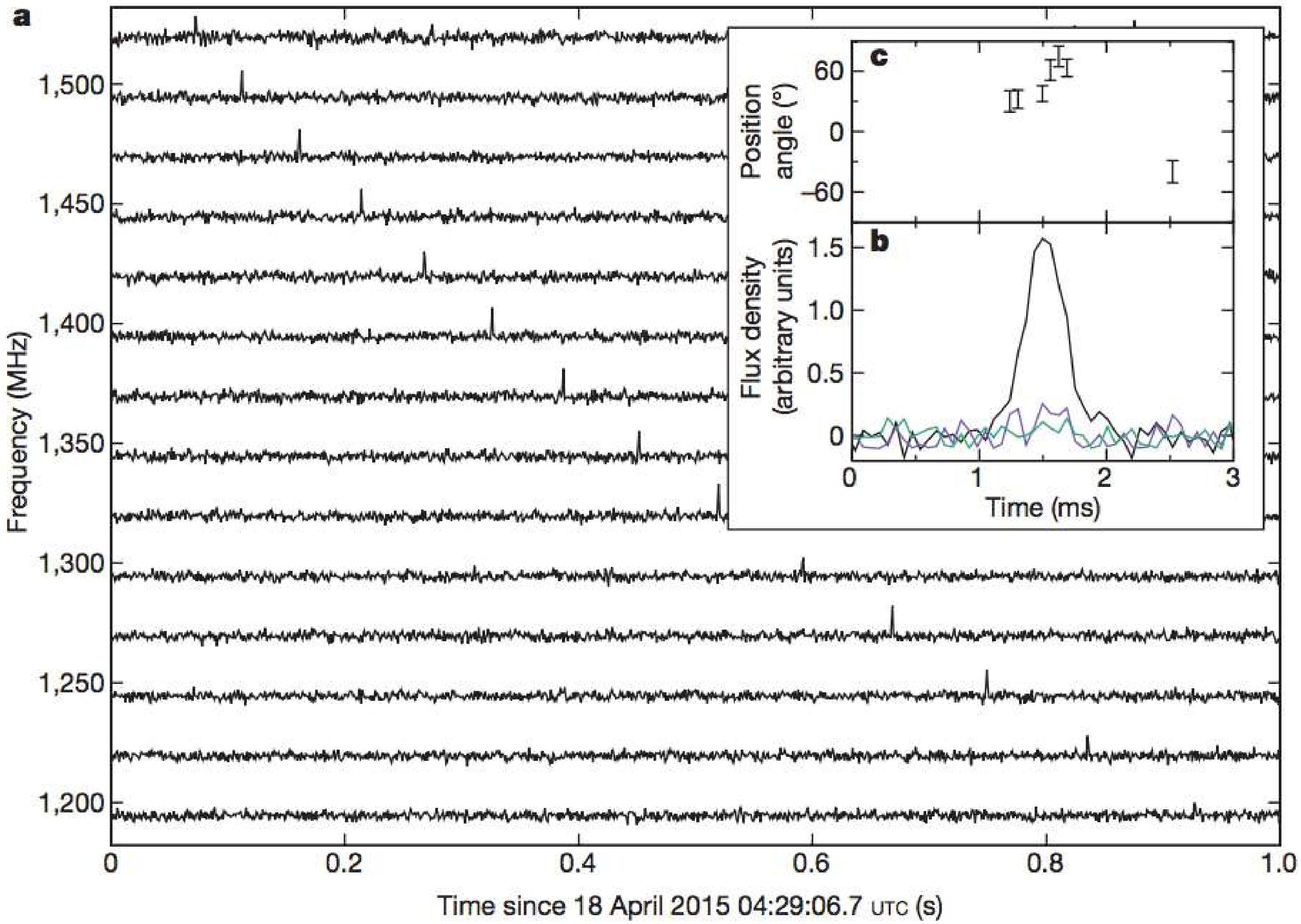


Figure from Nature 530, 453 (2016)

Non-relativistic EFT

- Canonical transformation: $(\phi, \dot{\phi}) \rightarrow (\psi, \psi^*)$

Namjoo, Guth & Kaiser (2018)

$$\phi(\boldsymbol{r}, t) = \left[4(m_a^2 - \nabla^2)\right]^{-1/4} \left[\psi(\boldsymbol{r}, t) e^{-im_a t} + \psi^*(\boldsymbol{r}, t) e^{im_a t}\right]$$

Obtained EFT with real potential

$$\mathcal{L}_{\text{eff}} = \frac{i}{2}\left(\psi^* \dot{\psi} - \dot{\psi}^* \psi\right) - \frac{1}{2m_a} \nabla\psi^* \nabla\psi - \underline{V_{\text{eff}}(\psi^*\psi)}$$

Real potential

U(1) symmetry $\psi \rightarrow e^{i\alpha}\psi$. Particle number conservation?

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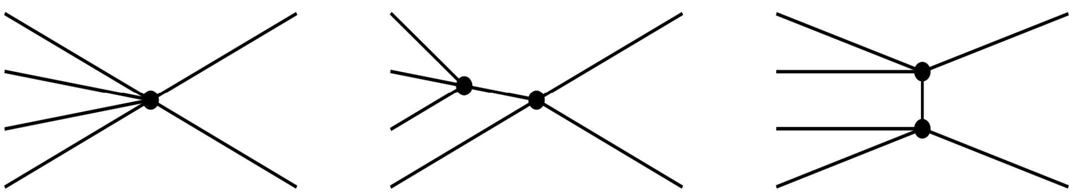
Real potential

U(1) symmetry $\psi \rightarrow e^{i\alpha}\psi$. Particle number conservation?

- Particle changing process is included by $Im(V_{eff})$

Added with Optical theorem

Braaten, Mahapatra & HZ (2017)
Braaten, Mahapatra & HZ (2018)



Match Low-power Couplings

- Expand the NR potential

$$\mathcal{V}_{\text{eff}}(\psi^*\psi) = m_a \psi^*\psi + m_a^2 f_a^2 \sum_{n=2}^{\infty} \frac{v_n}{(n!)^2} \left(\frac{\psi^*\psi}{2 m_a f_a^2} \right)^n .$$

- Check (v_2, v_3, v_4, v_5) for instanton potential

NR reduction:	(-1, 1, -1, 1)
With matching:	$(-1, -1.125, -2.25, 1.76)$
Deviation:	(0, -189%, -56%, -43%)

Contribution of virtual axions is important !

Braaten, Mohapatra, HZ, PRD (2016)