The Fate of Axion Stars

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PRL 117, 121801 (2016)   PRD 94, 076004 (2016)

arXiv:1609.05182

Outline

- ✧ Axions
- ✧ (Dilute) Axion Star
- ✧ Dense Axion Star — PRL 117, 121801 (2016)
- ✧ Observables — arXiv:1609.05182
- ✧ Axion EFT — PRD 94, 076004 (2016)
- ✧ Summary

Axions

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

  Peccei & Quinn (1977)

- Introduces a Goldstone boson -- Axion

  Weinberg (1978), Wilczek (1978)

- Strongly motivated candidate for cold dark matter.

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

Relativistic Axions

Real pseudoscalar field

Energy scale below 1GeV

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

Two models for potential

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

  m_a : axion mass

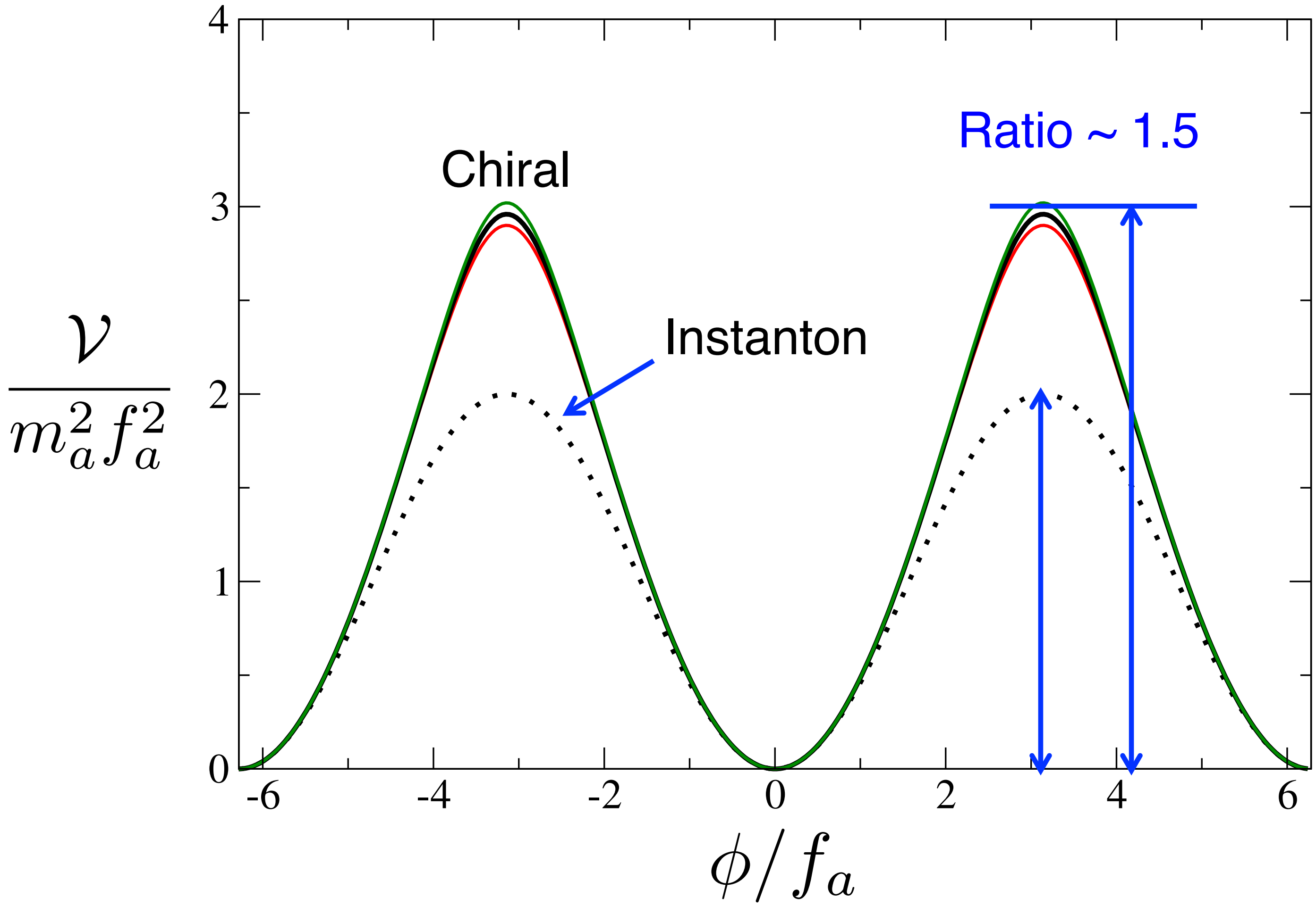
  f_a : axion decay constant

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

  $z = m_u/m_d \approx 0.48$

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 and f_a

- Not independent, related by QCD

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

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

- Constraints from astrophysics & cosmology

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

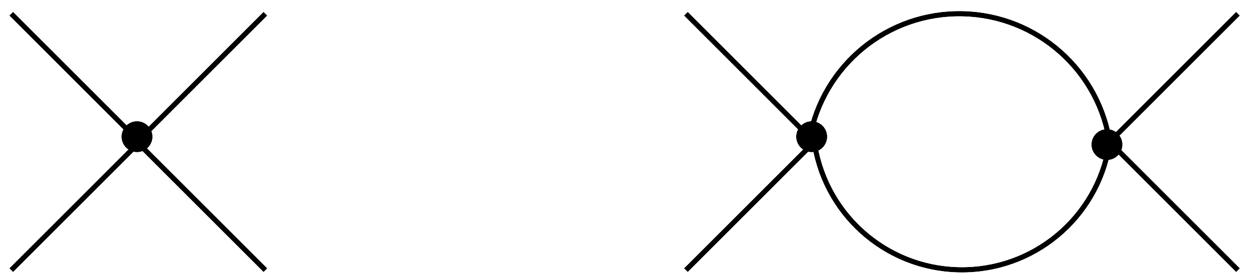
Very weak self-interaction ! Tiny Mass !!

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

Loop Contribution is Small

Each loop is suppressed by

$$(m_a/f_a)^2 \sim 10^{-48}$$



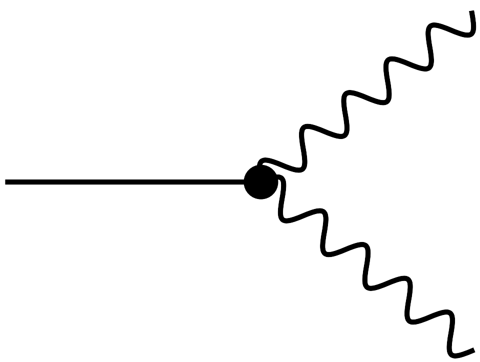
- Diagrams with loops can be safely ignored.

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-relativistic axion production mechanism

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

- Vacuum misalignment — Coherent — Preskill, Wise & Wilczek (1983); Abbot & Sikivie (1983); Dine & Fischler (1983)
- Cosmic string decay — Incoherent — Davis (1986); Hararie & Sikivie (1987)

Occupation number $n_a \lambda_{dB}^3 |_{T=1GeV} \approx 10^{58}$

Sikivie & Yang PRL (2009)

Form Bose-Einstein condensate if can be effectively thermalized

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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- ✧ Observables — arXiv:1609.05182
- ✧ Axion EFT — PRD 94, 076004 (2016)
- ✧ Summary

Non-relativistic EFT (Part I)

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

Chavanis PRD (2011)
Chavanis & Delfini PRD (2011)

Real Scalar

Instanton potential / Chiral potential

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

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

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

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

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Dilute limit

Attractive interaction!

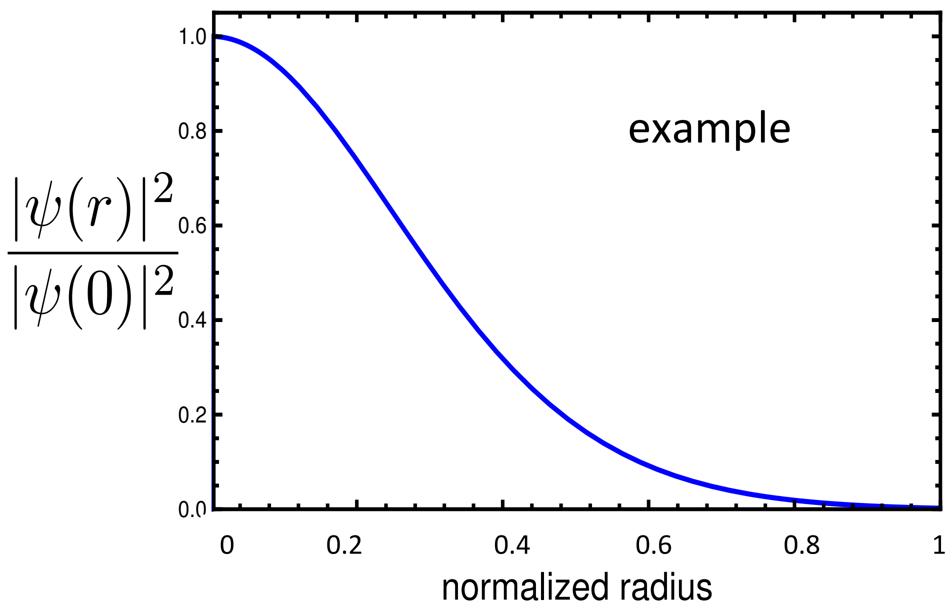
Expand by $\dfrac{\psi^*\psi}{m_a f_a^2}$

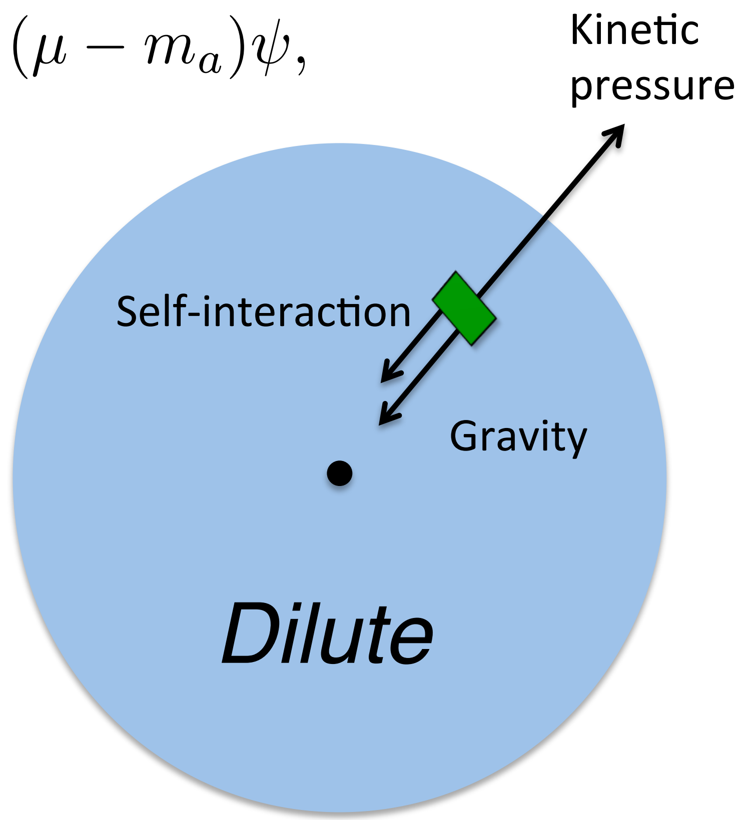
Dilute Axion Stars

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

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

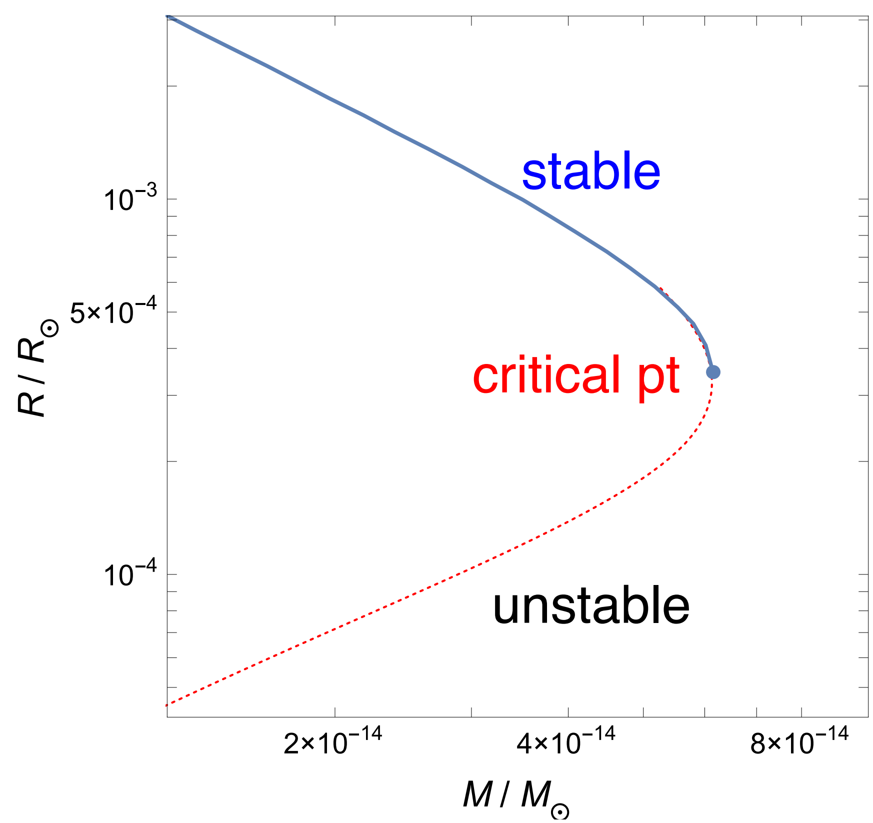
$$\nabla^2\Phi = 4\pi G m_a \psi^*\psi.$$





(First) Critical Point

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



Critical point:

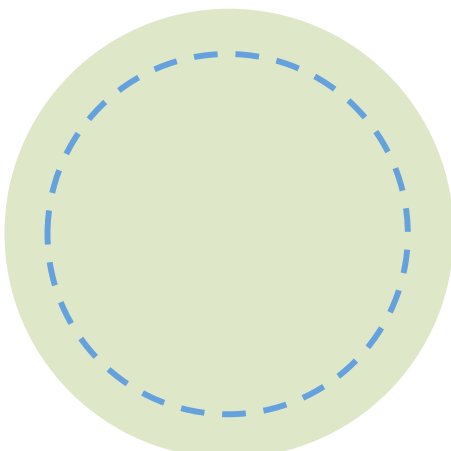
$$M_* = 10.2 f_a / \sqrt{G m_a^2}$$
$$= 6 \times 10^{-14} M_\odot$$
$$R_* = 3 \times 10^{-4} R_\odot$$
$$= 200 \text{ km}$$

Formation of Dilute Axion Stars

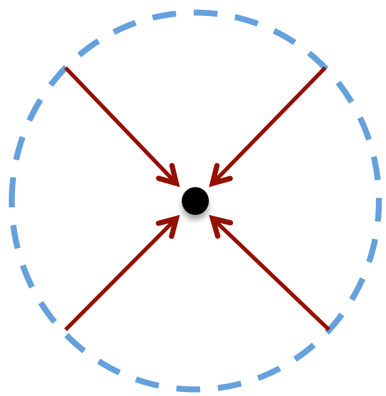
- Dilute axion stars can be produced in early universe.
- Vacuum misalignment mechanism produces coherent and non-relativistic axions.
- Spatial fluctuations in the axion field evolve into gravitationally bound "miniclusters" of axions.
- Gravitational thermalization drives the axion minicluster to form a dilute axion star.
- Dilute axion stars attract more axions and gradually reaches the critical mass.

End of Dilute Axion Stars

- Dilute axion stars collapse when its mass exceeds the critical mass,
- What is the remnant?

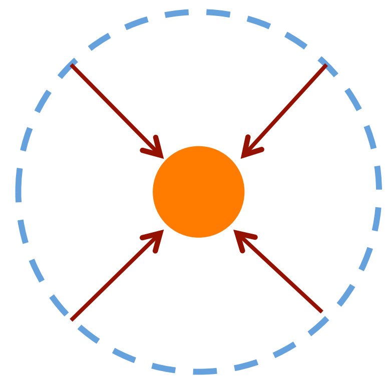


Less massive dilute axion star? by emitting extra axions



Black hole: Schwarzchild radius is ~20 orders of magnitude smaller

Chavanis arXiv: 1604.05904
Helfer et al. arXiv: 1609.04724



Dense axion star? Radius is 5 orders smaller

Eby et al, arXiv: 1608.06911

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Non-relativistic EFT (Part II)

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- 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

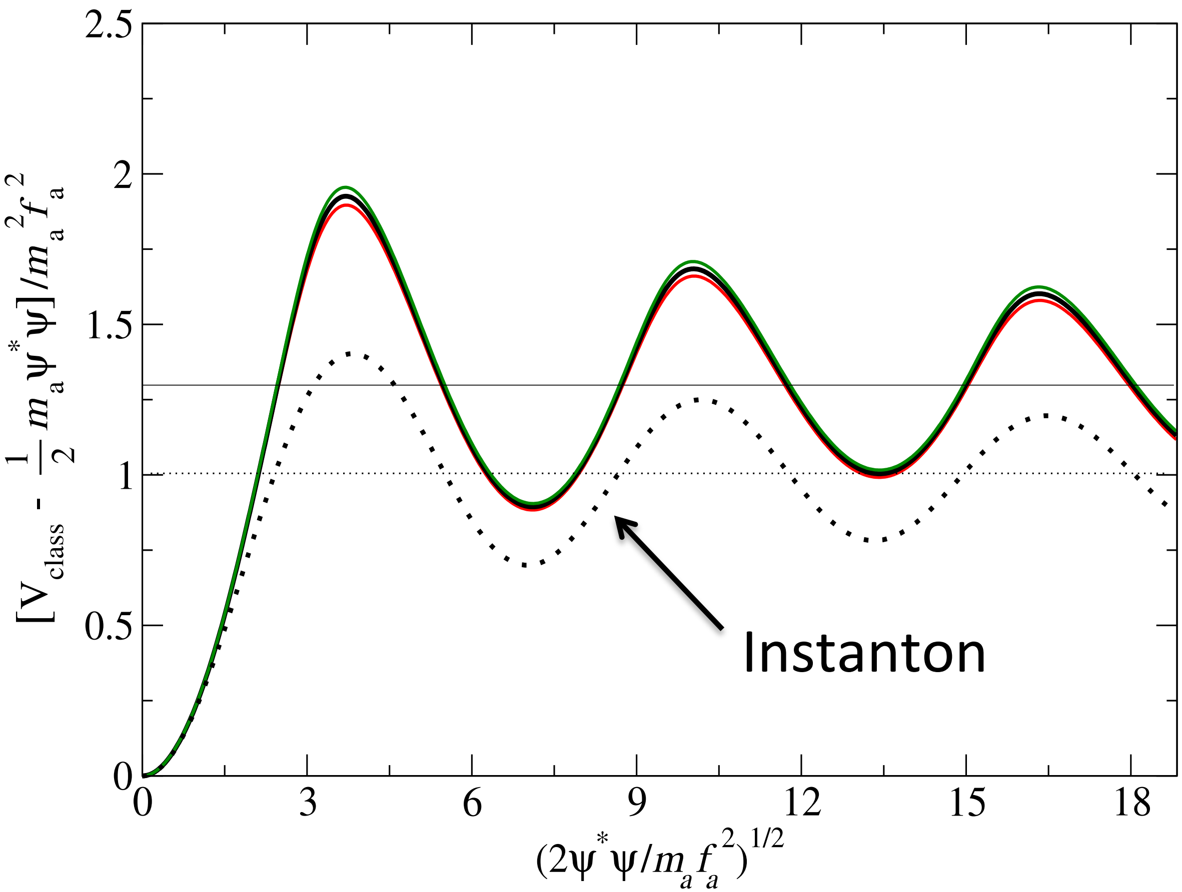
Instanton potential:

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

Eby, Suranyi, Vaz & Wijewardhana (2015)

Non-relativistic Instanton Potential

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



Not periodic

Decreasing Amplitude

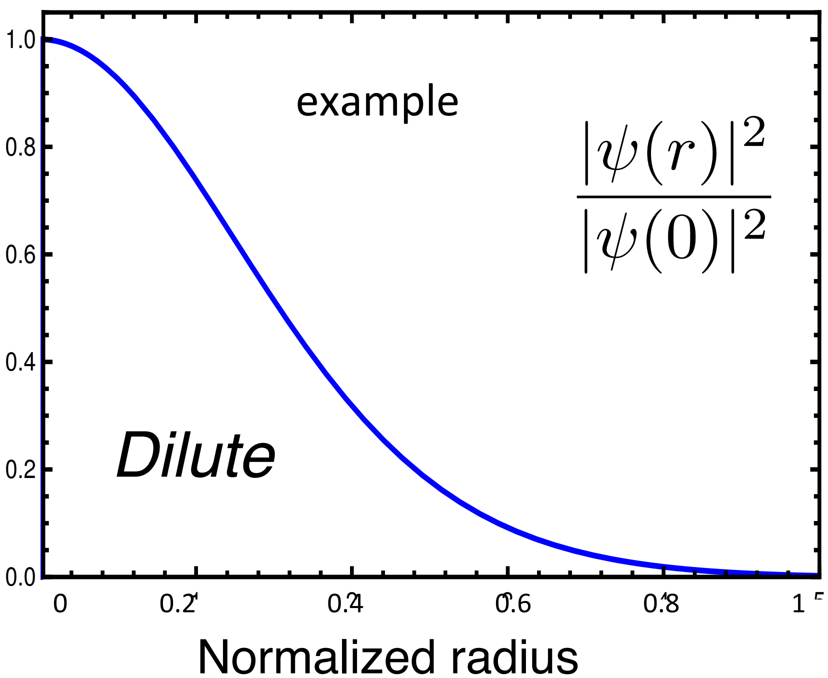
Braaten, Mohapatra, HZ, PRD (2016)

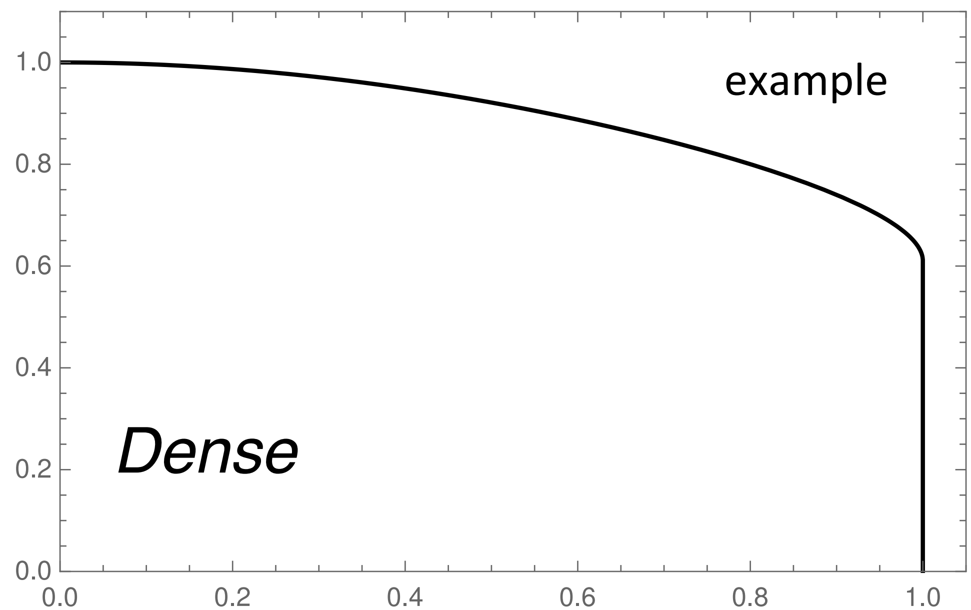
Dense Axion Stars

Assume:
- Instanton potential
- Newtonian gravity
- Spherically symmetric

Compare axion number density

- Dilute axion star: Gaussian-like
- Dense axion star: almost flat, with a fast-dropping edge



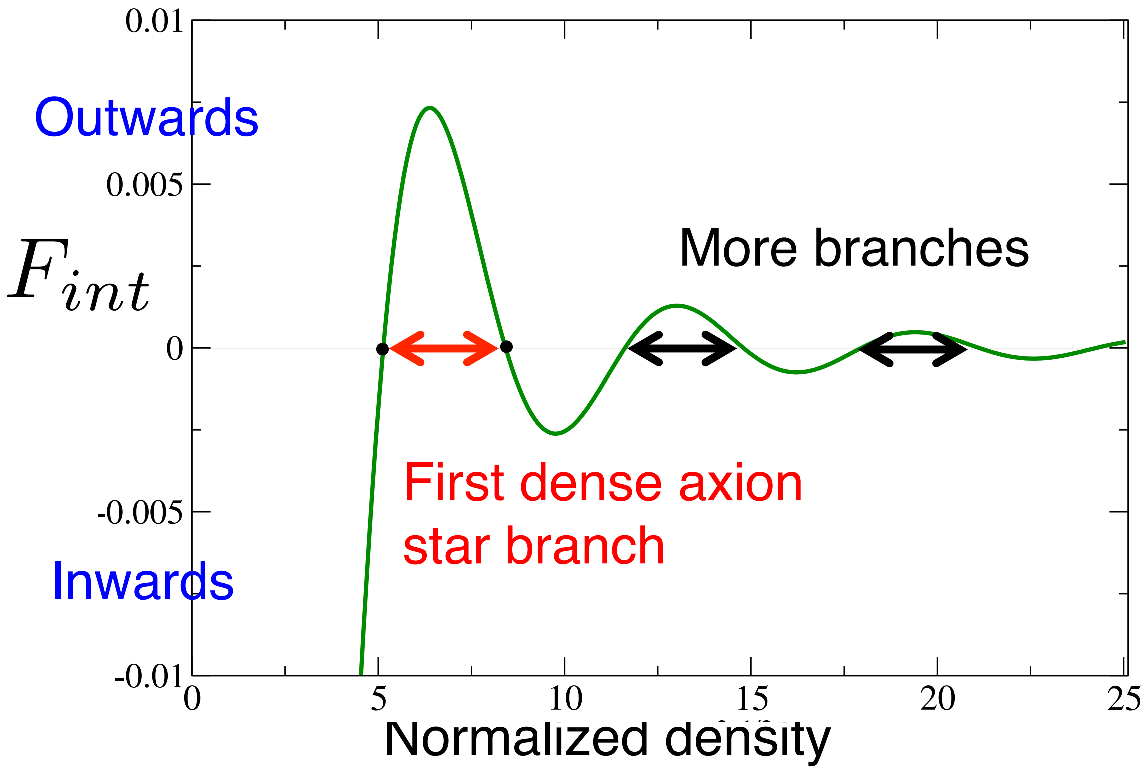


Braaten, Mohapatra, HZ, PRL (2016)

Self-interaction Force

$$-\frac{\nabla^2}{2m_a}\psi + \left[(\mathcal{V}'_{\text{eff}}(\psi^*\psi) + m_a\Phi\right]\psi = (\mu - m_a)\psi, \quad \nabla^2\Phi = 4\pi G m_a \psi^*\psi.$$

- Self-interaction force (mean-field pressure) $F_{int} = -\mathcal{V}''_{\text{eff}}(\psi^*\psi)\underbrace{\frac{d}{dr}(\psi^*\psi)}_{\text{Smaller than 0}}$

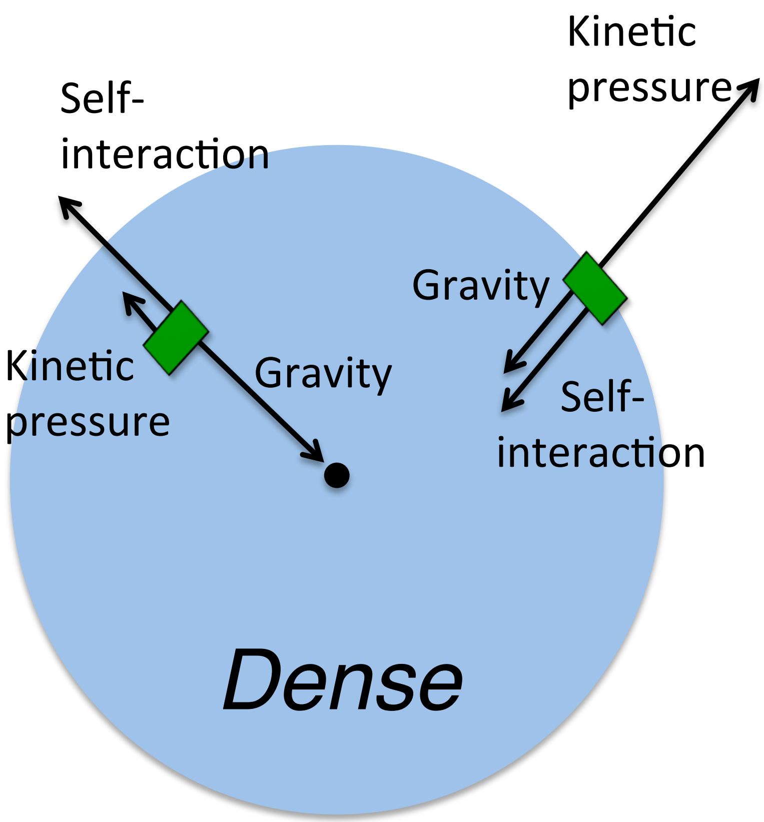


Braaten, Mohapatra, HZ, PRL (2016)

Forces Balancing

$$-\frac{\nabla^2}{2m_a}\psi + \left[(\mathcal{V}'_{\text{eff}}(\psi^*\psi) + m_a\Phi\right]\psi = (\mu - m_a)\psi, \quad \nabla^2\Phi = 4\pi G m_a \psi^*\psi.$$

- Recall in dilute axion star, kinetic pressure balances gravity and self-interaction force



- <u>In dense axion star</u>

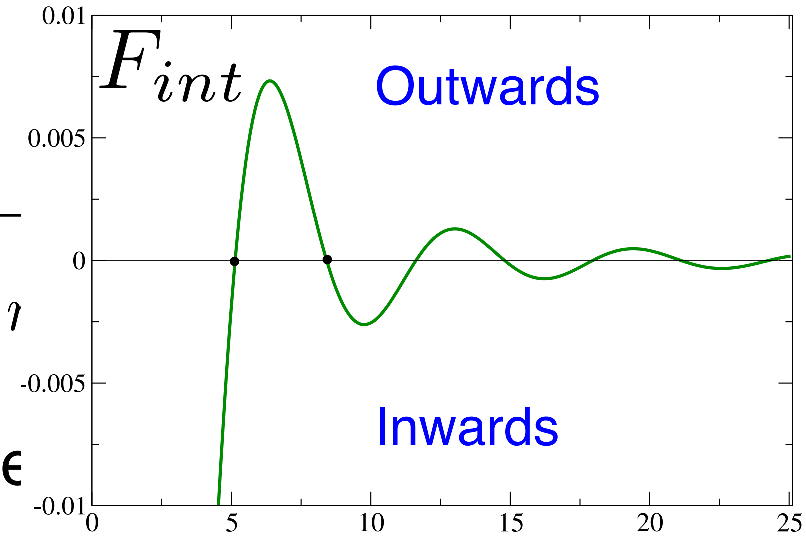
Bulk:
- ➢ self-interaction force balances gravity,
- ➢ kinetic pressure ~ 0
- ➢ wave-function is almost flat

Surface:
- ➢ large kinetic pressure needed to balance the other two,
- ➢ wave-function drop rapidly

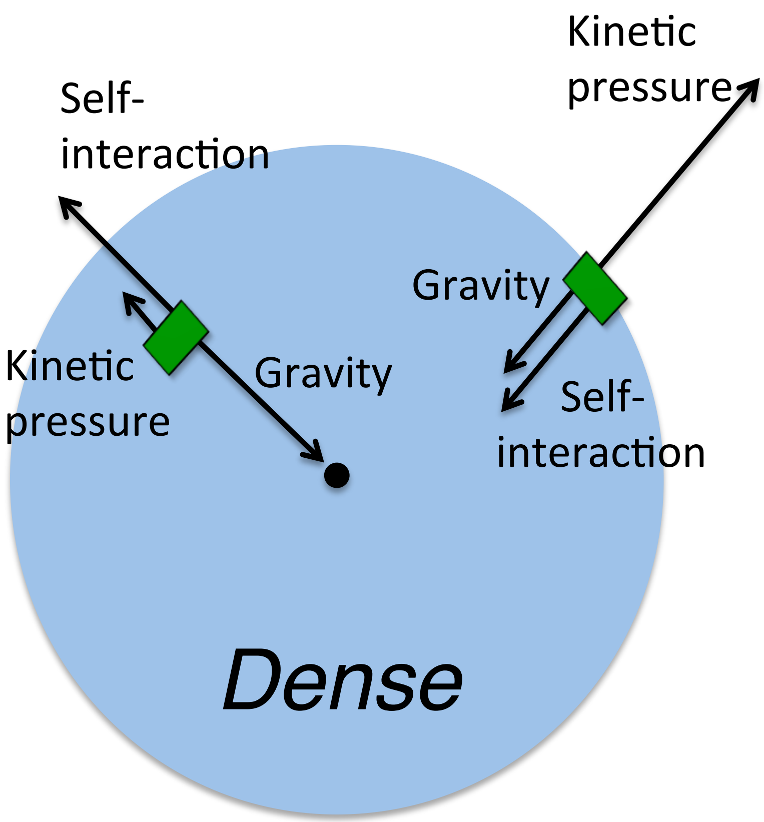
Braaten, Mohapatra, HZ, PRL (2016)

Forces Balancing

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



- Recall in dilute axion star, kinetic pre
and self-interaction force



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- ➢ wave-function drops rapidly

Braaten, Mohapatra, HZ, PRL (2016)

Thomas-Fermi Approximation

- When the surface thickness is small compare to the bulk, Thomas-Fermi approximation can be applied.

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

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

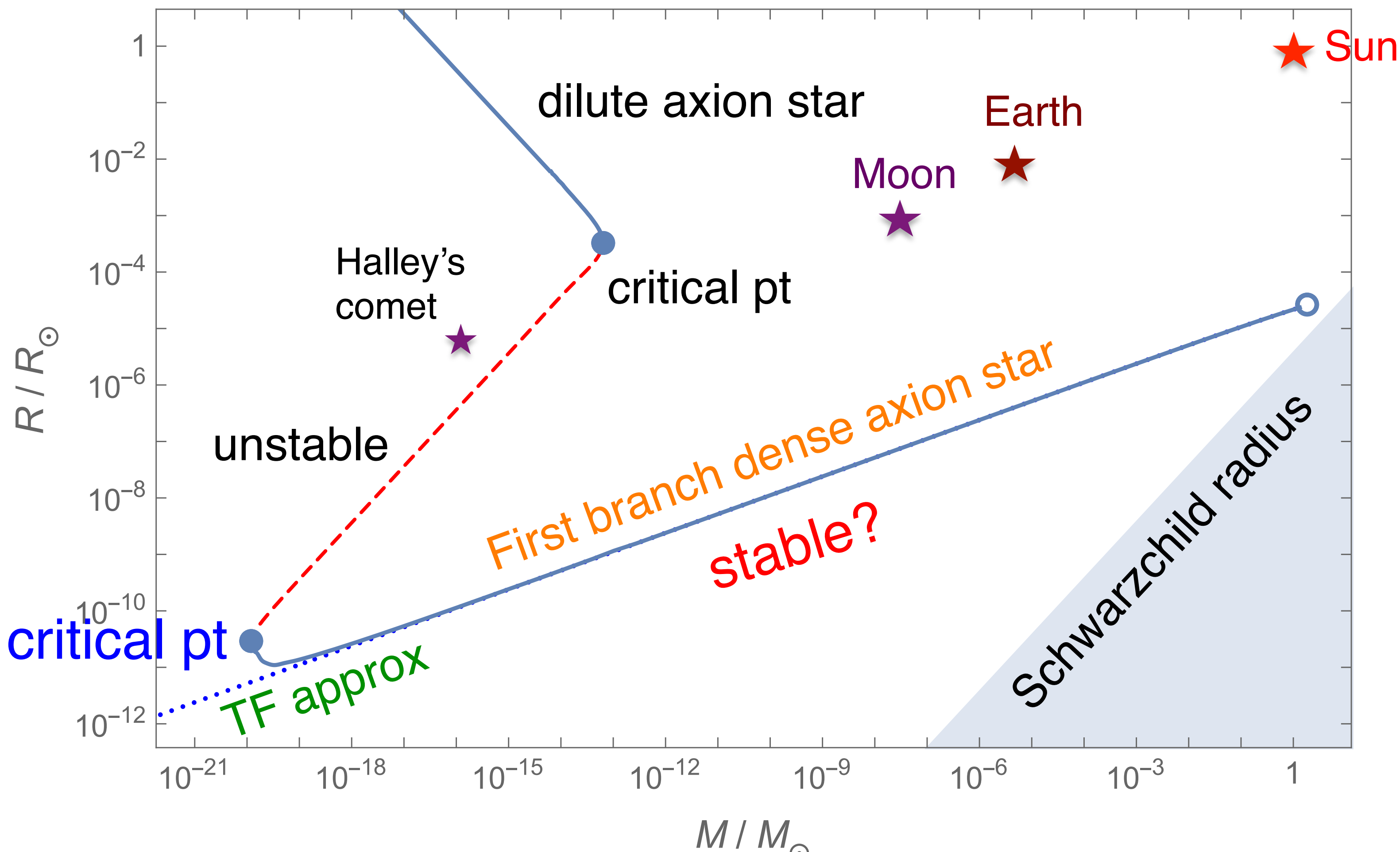
Greatly simplifies!

- Interaction force (mean-field pressure) exactly balances gravitational force

- Not applicable to small dense axion star, in which the surface thickness is important

Braaten, Mohapatra, HZ, PRL (2016)

Radius vs. Mass

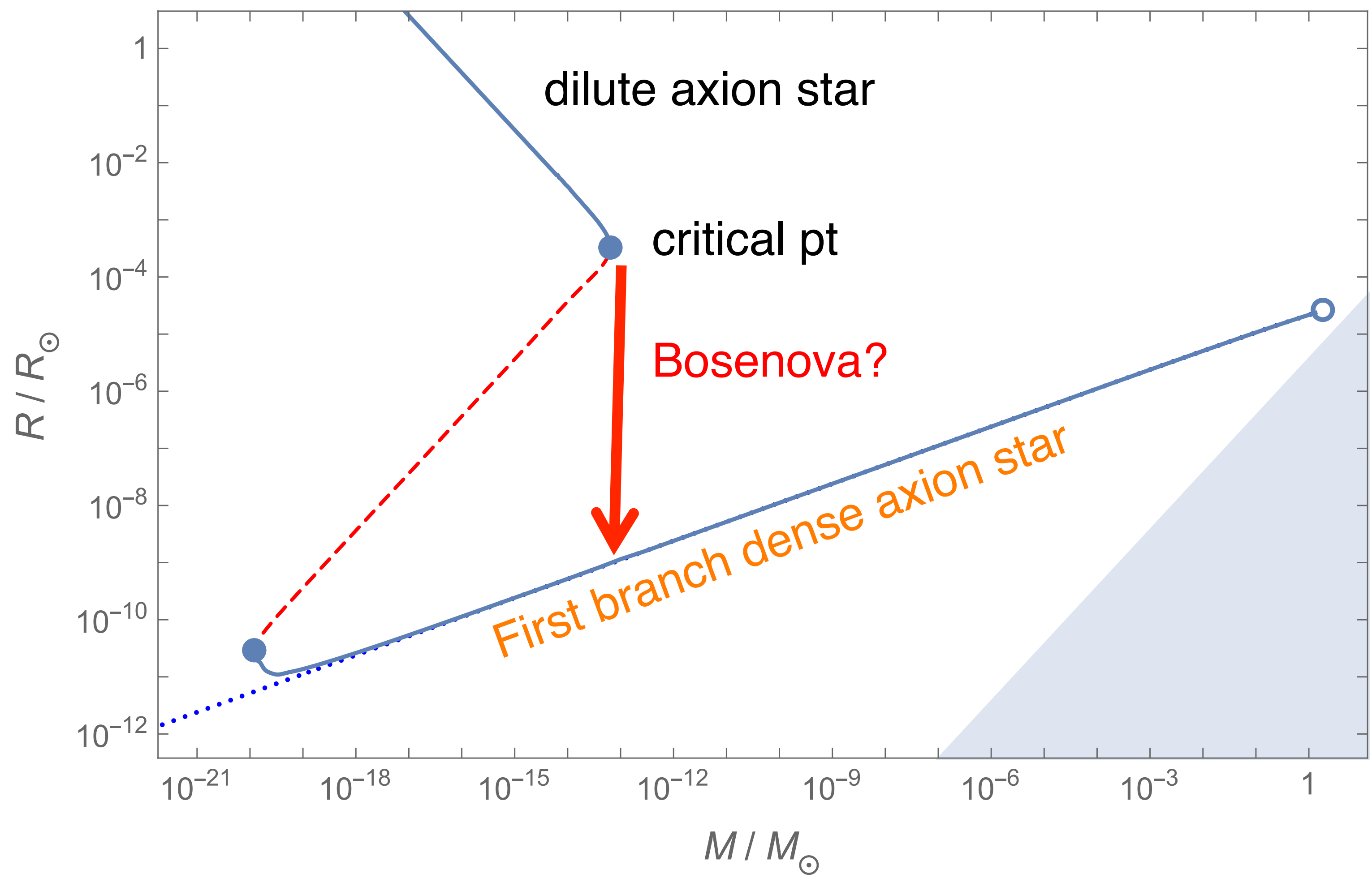


- 2nd critical point
- Newtonian gravity is justified
- Heavier dense axion stars have larger radii

Braaten, Mohapatra, HZ, PRL (2016)

Formation of Dense Axion Stars

- Possible remnants of dilute axion stars collapsing



Braaten, Mohapatra, HZ, PRL (2016)

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- ✧ **Observables** — arXiv:1609.05182
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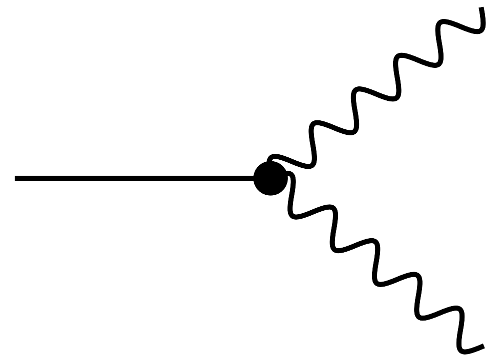
Axion Detection

- 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

- Direct detection, indirect detection and laser experiment.

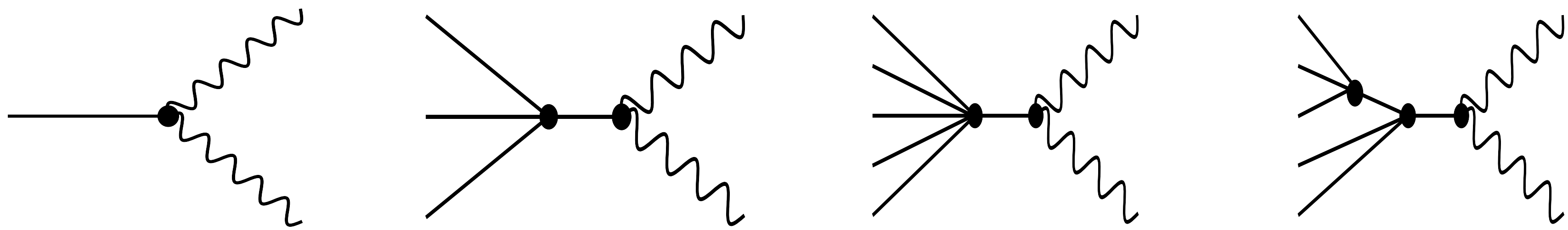
Lect. Notes Phys. 741 (2008)

A recent review: Kim & Carosi (2010)

Indirect Detection

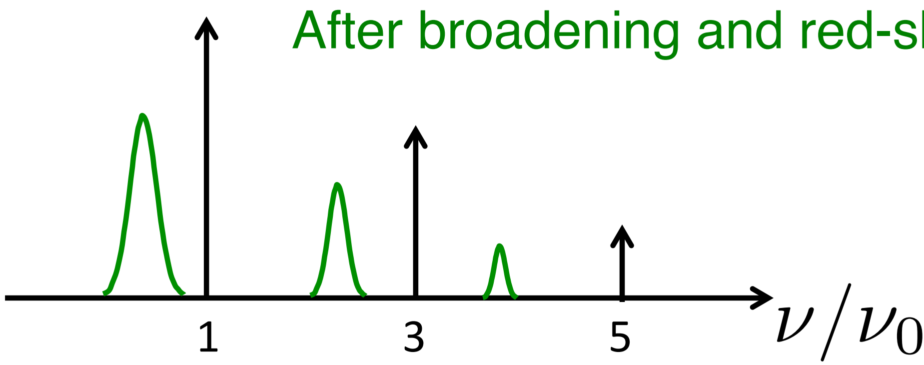
- Detect radio-frequency photons
- Currently no experiment available (tiny $a\gamma\gamma$ coupling)
- Two photon-production channels
  - One-step: NR axions $\longrightarrow \gamma$
  - Two-step: NR axions $\longrightarrow$ relativistic axions $\longrightarrow \gamma$

1^{st} Channel: NR Axions to Photons



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

- Odd-integer harmonics of the fundamental radio frequency.



Unique feature of axions !!

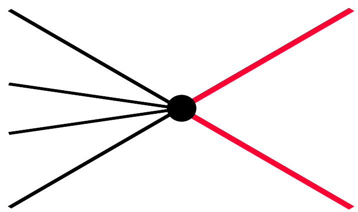
Braaten, Mohapatra, HZ, arXiv:1609.05182

$2^{\rm nd}$ Channel

- <u>Two relativistic axions production</u>

  suppressed by one power of $(m_a^2/f_a^2) \sim 10^{-48}$

$$4a \to 2a$$



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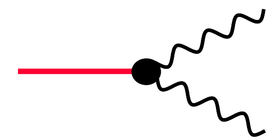
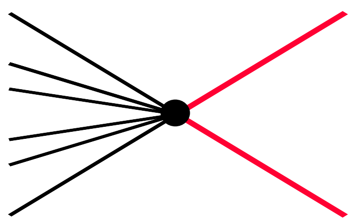


$$6a \to 2a$$



$\cdots$

- <u>More relativistic axions</u> suppressed by more powers

- Much weaker photon signal than 1st channel

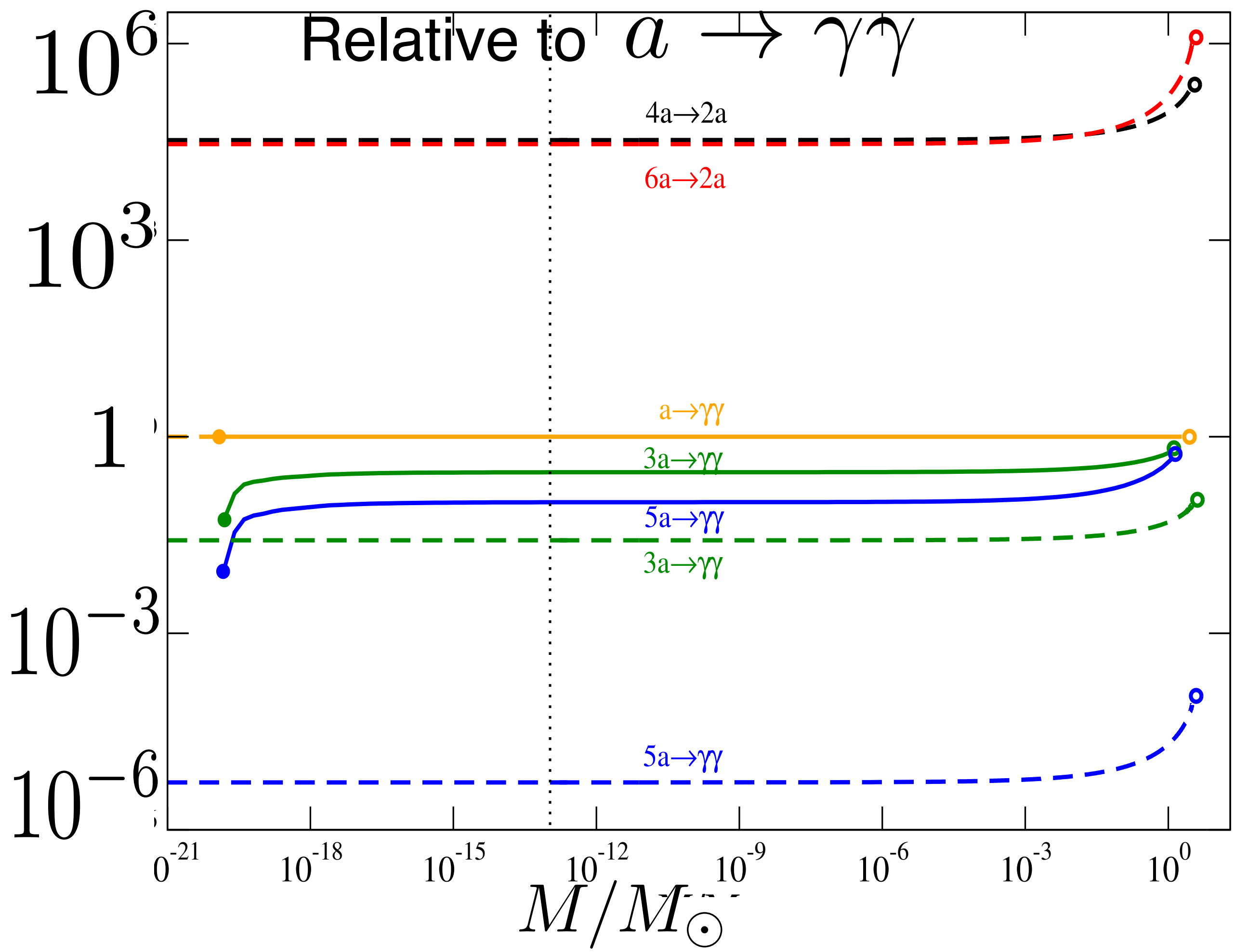
Braaten, Mohapatra, HZ, arXiv:1609.05182

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
  - …

Emission From Dense Axion Star



Axion to photon decay rate

$$\Gamma_{a\to 2\gamma} = 10^{-60}\mathrm{eV}$$

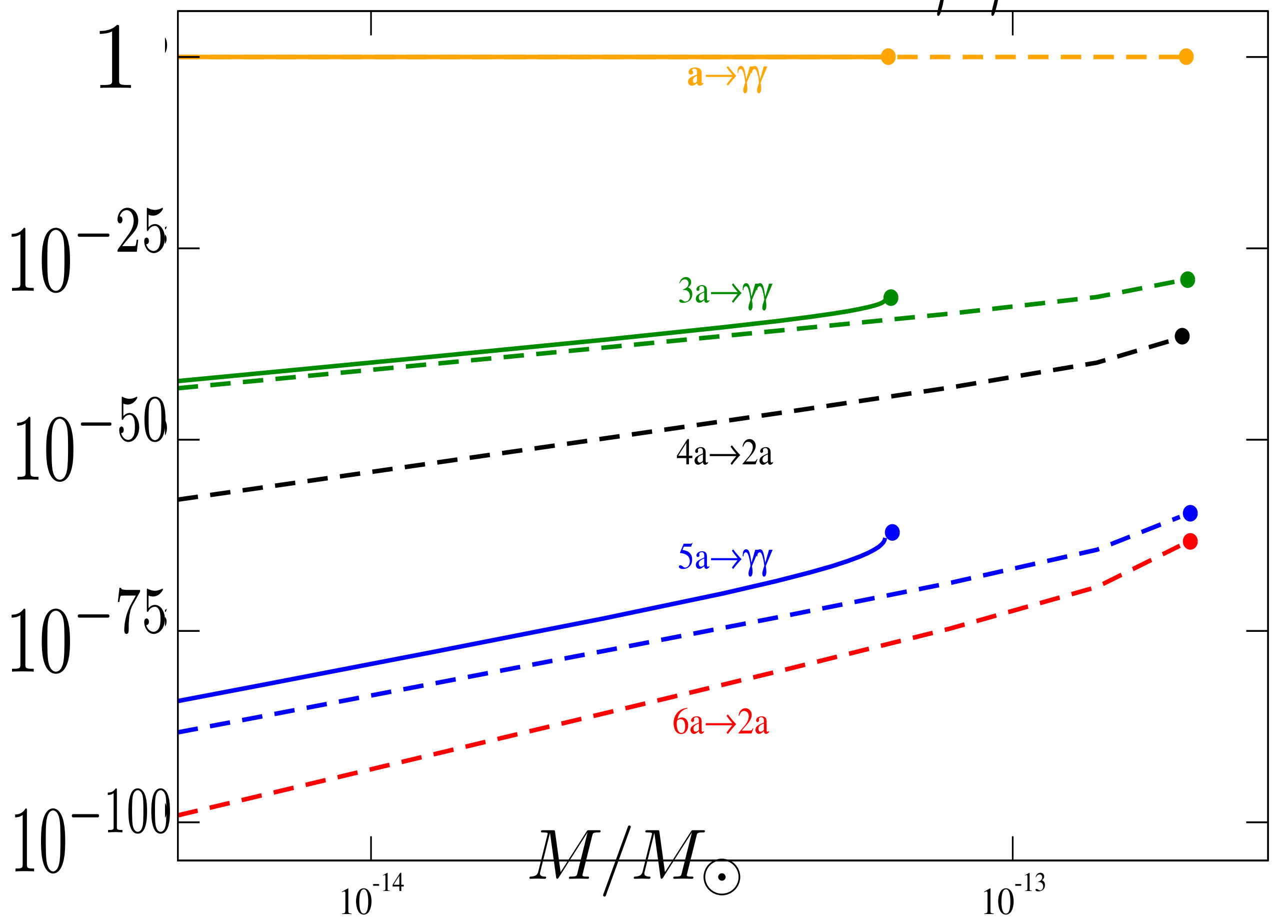
- Solid: Instanton potential
- Dashed: Chiral potential TF approximation

$4a \to 2a, 6a \to 2a, 8a \to 2a$ are all zero for instanton potential

Braaten, Mohapatra, HZ, arXiv:1609.05182

Emission From Dilute Axion Star

Relative to $a \to \gamma\gamma$



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Braaten, Mohapatra, HZ, arXiv:1609.05182

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: $\sim 10^{9}\mathrm{GeV}/\mathrm{sec} \sim 0.4$ Watt
- Milky way:

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

  Largest 1st branch dense axion star has ~10^{70} axions

  $\sim 10^{11}\mathrm{GeV}/\mathrm{sec} \sim 40$ Watt

Axion Stars are Not So Bright !

PRL 117, 121801 (2016) Editors' suggestion

Picture chosen by PRL

Hydrogen Axion Star ?

- Hydrogen gas is captured by the gravitational potential well of axion star, forming dense metallic fluid state.

- Electron interacts with axion, generating heat, resulting in blackbody radiation with peak in the UV region.

- Energy released: $10^{13}\ \mathrm{W} \times \left(\frac{m_a}{5\ \mathrm{meV}}\right)^4$

- The signal should be readily visible to current high-resolution telescopes.

Bai, Barger and Berger, JHEP (2016)

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 2007, 17 events have been reported.
- Estimated rate ~ 10^4 sky $^{-1}$ day $^{-1}$
- Reported frequency is 1.4 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.

Recent review: Katz, arXiv:1604.01799
Online database: http://www.astronomy.swin.edu.au/pulsar/frbcat

Fast Radio Burst

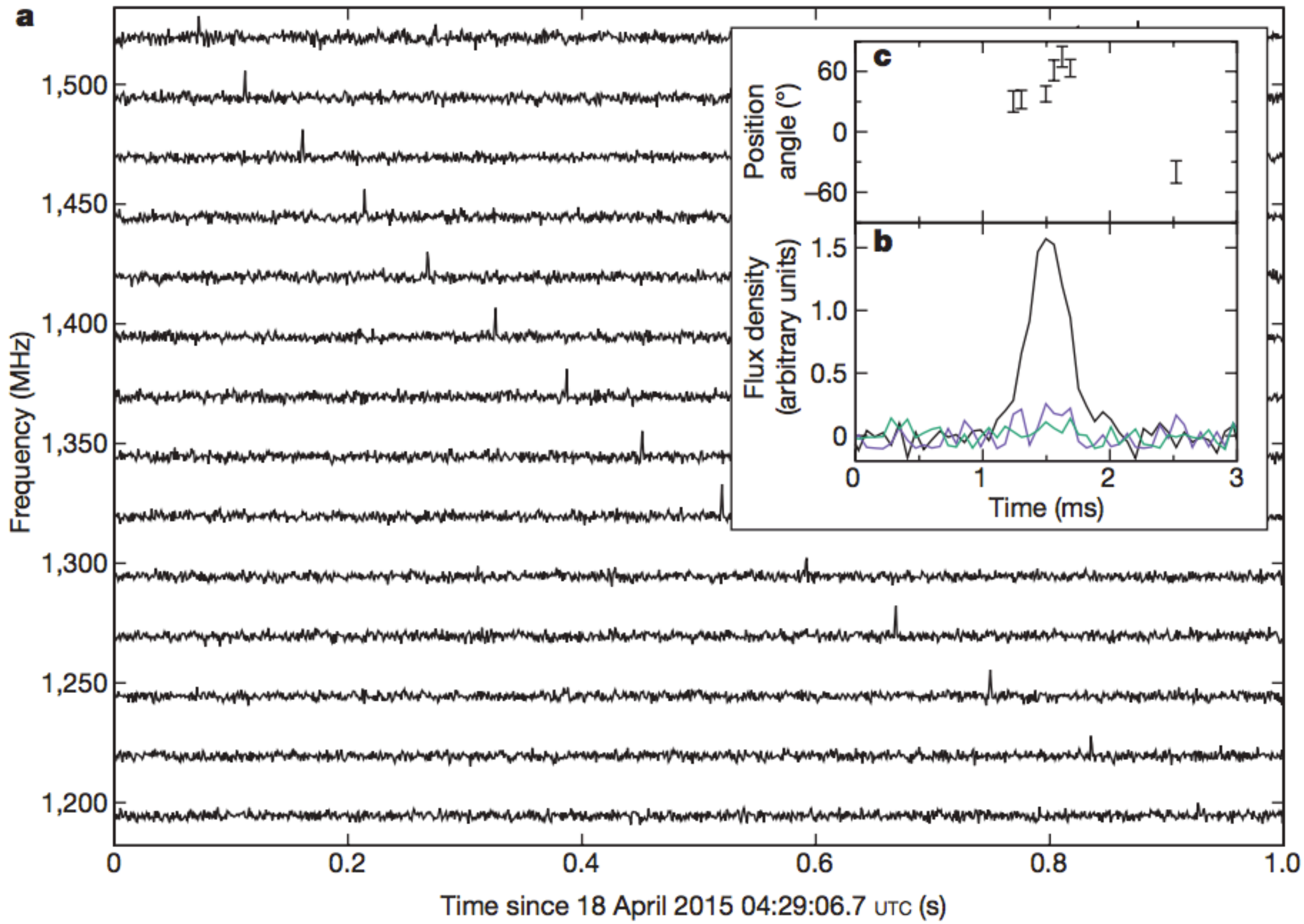


Figure from Nature 530, 453 (2016)

Are Axion Stars an Explanation?

- ✓ Observed frequency: 1.4 GHz

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

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: 1m 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?

  1.4 GHz, 3×1.4 GHz, 5×1.4 GHz …

  or

  $1/3 \times 1.4$ GHz, 1.4 GHz, $5/3 \times 1.4$ GHz …

  Many possible combinations

- Need more events in more frequency windows.

Outline

- Axions
- (Dilute) Axion Star
- Dense Axion Star PRL 117, 121801 (2016)
- Observables arXiv:1609.05182
- Axion EFT PRD 94, 076004 (2016)
- Summary

Axion EFT

- Relativistic Axions: real scalar

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

Instanton or chiral potential

- Non-relativistic axions: complex scalar

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

  - Integrate out axion mass scale
  - Much simpler, but equally accurate in the NR limit

- Need to find the NR potential $\mathcal{V}_{\rm eff}(\psi^*\psi)$

Naïve NR Reduction

- Zeroth order approximation

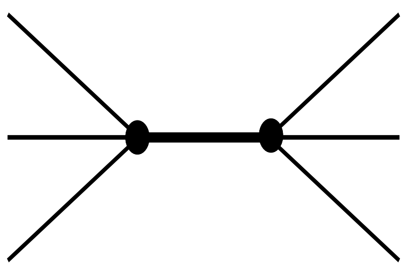
$$\phi(\mathbf{r},t) = \frac{1}{\sqrt{2m_a}}\left[\psi(\mathbf{r},t)e^{-im_a t} + \psi^*(\mathbf{r},t)e^{+im_a t}\right]$$

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

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

- Used to get dilute and dense axion star solutions

- Not considering virtual axions



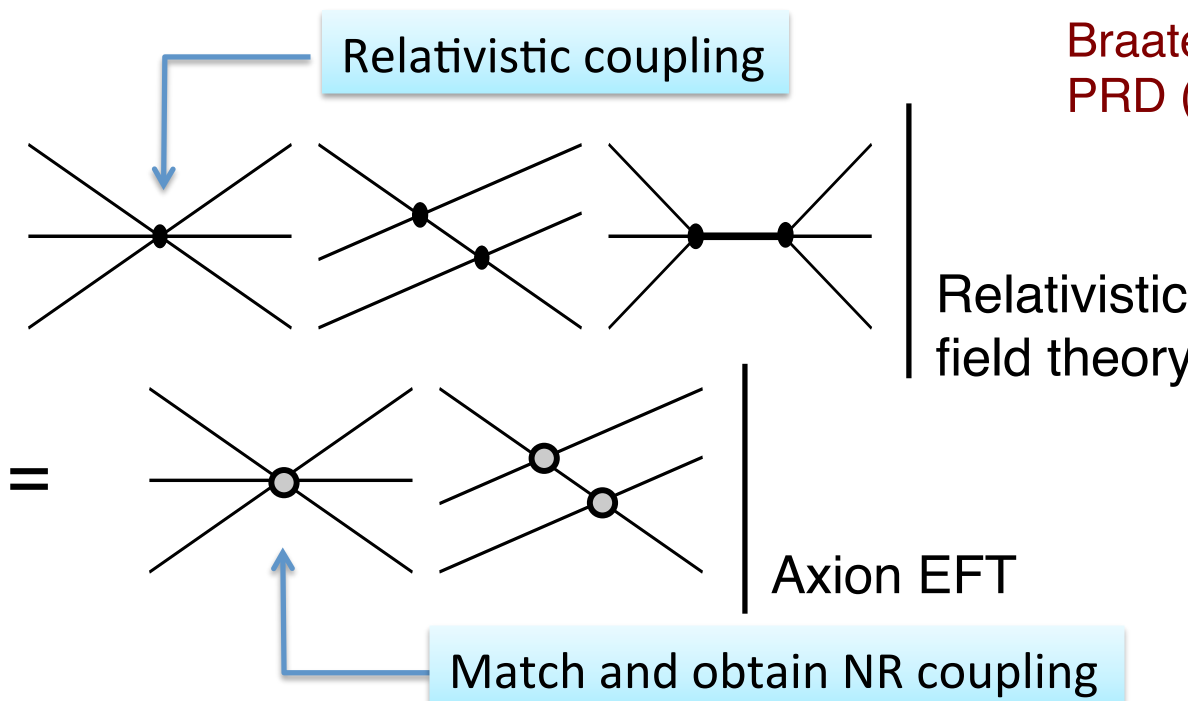
$$(3m_a, \mathbf{p})$$

Braaten, Mohapatra, HZ, PRD (2016)

Match the amplitude

- Matching low-energy scattering amplitudes.
- Includes all virtual axion contributions
- Only tree diagram: loops are suppressed by $(m_a/f_a)^2 \sim 10^{-48}$
- Example: 3 to 3 scattering

Braaten, Mohapatra, HZ, PRD (2016)



Match Low-power Couplings

- Expand the NR potential

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

- 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 !

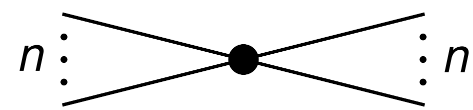
Braaten, Mohapatra, HZ, PRD (2016)

Dense Regime

- Cannot truncate the power expansion
- Impossible to extract all couplings by matching (infinitely many)
- One scheme: include more and more virtual axion propagators in the matching

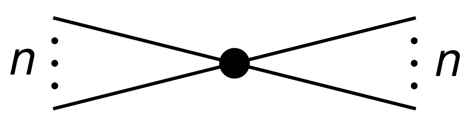
Naïve NR reduction

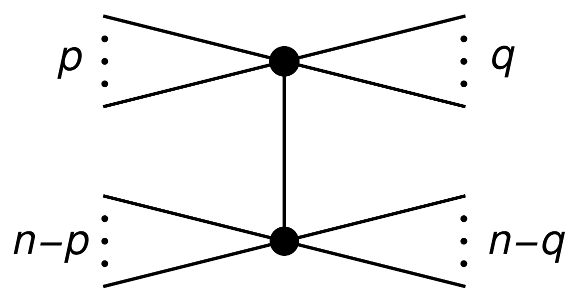
Match diagrams with no virtual propagator



1st improvement

Match diagrams with 0 or 1 virtual propagator





Braaten, Mohapatra, HZ, PRD (2016)

Summary

- Gravity can thermalize axions toward Bose-Einstein condensates and form dilute axion stars.
- A dilute axion star accumulates axions and collapses once its mass exceeds the critical mass $10^{-14} M_{\odot}$
- Dense axion star is a possible remnant.
- Catastrophic phenomena involving axion stars can release a large amount of coherent radio-frequency photons in a very short time, which may explain fast radio burst.
- The photons in odd-integer harmonics of a fundamental radio frequency are a unique signature of axions.