Emission of Photons and Relativistic Axions from Axion Stars

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Outline

➤ **Axions**

➤ **Axion EFT**   *PRD 94, 076004 (2016)*

➤ **Dense Axion Star**   *PRL 117, 121801 (2016)*

➤ **Emission from Axion Stars**   *arXiv:1609.05182*

➤ **Axion stars and Fast radio burst**

➤ **Summary**

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.   *Pecci & Quinn (1977)*

- Produced in early universe by non-thermal mechanisms:

  vacuum misalignment   *cosmic string decay*

  highly nonrelativistic, huge occupation numbers, coherent.

  highly nonrelativistic, huge occupation numbers, incoherent.

  Preskill, Wise & Wilczek (1983)   *Davis (1986)*
  Abbott & Sikivie, 1983 , Dine & Fischler (1983)

- Gravitational interactions can thermalize the axions, so they can form Bose-Einstein Condensate

  Sikivie & Yang (2009), Erken, Sikivie, Tam and Yang (2012).

Axions

- Relativistic field theory: Axions are described by a real scalar field ϕ and a potential $\mathcal{V}(\phi)$
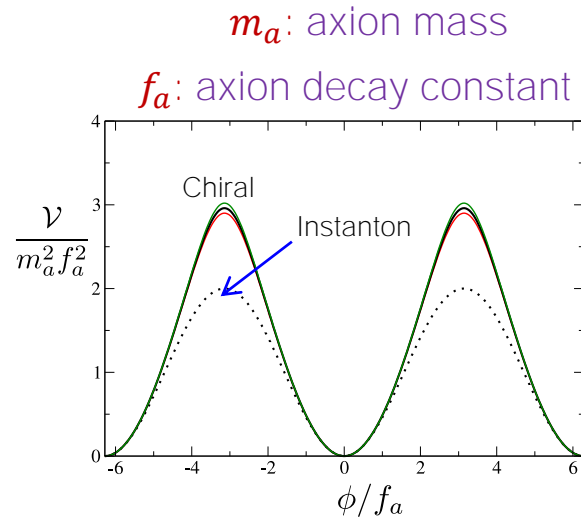
Instanton Potential

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

Chiral Potential

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

$z = m_u/m_d \approx 0.48 \; \pm 0.03$ **Vecchia & Veneziano (1980)**

m_a: axion mass

f_a: axion decay constant

- Astrophysical and cosmological constraints restricts f_a: **10^8 - 10^{13} GeV.**

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

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

4

Axion EFT

$\longleftrightarrow$

- Axions produced from non-thermal mechanism have **energy** much less than m_a. ***Non Relativistic (NR) Axions***

- NR axions: described by nonrelativistic effective field theory (**axion EFT**) with **complex scalar** field ψ.

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

- **Effective potential :** obtained by matching **low energy scattering amplitudes** at tree level in relativistic theory and axion EFT. *Braaten, AM, Zhang, PRD (2016)*

- **Naïve effective potential:**

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

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

$$\hat{\psi} = \left(2\psi^* \psi / m_a f_a^2 \right)^{1/2}$$

Eby, Suranyi, Vaz, Wijewardhana (2015)

Axion Stars

■ Stable configuration of axions bound by gravity is called an *axion star.*
Tkachev (1991)

| Dilute Axion Star *Barranco & Bernal (2011)*	Dense Axion Star *Braaten, AM, Zhang, PRL (2016)*

• characterized by $\psi^*\psi < 10^{-15} m_a f_a^2$
 	
 • In stable star,
   repulsive force from kinetic energy
           =
   attractive force from gravity
   + attractive force from axion pair
         interactions
 	
 • **Critical mass** beyond which the axion star will **collapse**.
   $\mathbf{6 \times 10^{-14} M_\odot}$ for $\boldsymbol{m = 10^{-4}}$ eV.
 	
               Chavanis & Delfini (2011)
	• characterized by $\psi^*\psi \sim 20\, m_a f_a^2$ at center for mass $10^{-14}\, \boldsymbol{M_\odot}$.
	
	 • In stable star,
	   repulsive force from BEC self
	         interaction
	         =
	   attractive force from gravity
	 in most of the bulk except near the surface.

R vs M for Axion Star
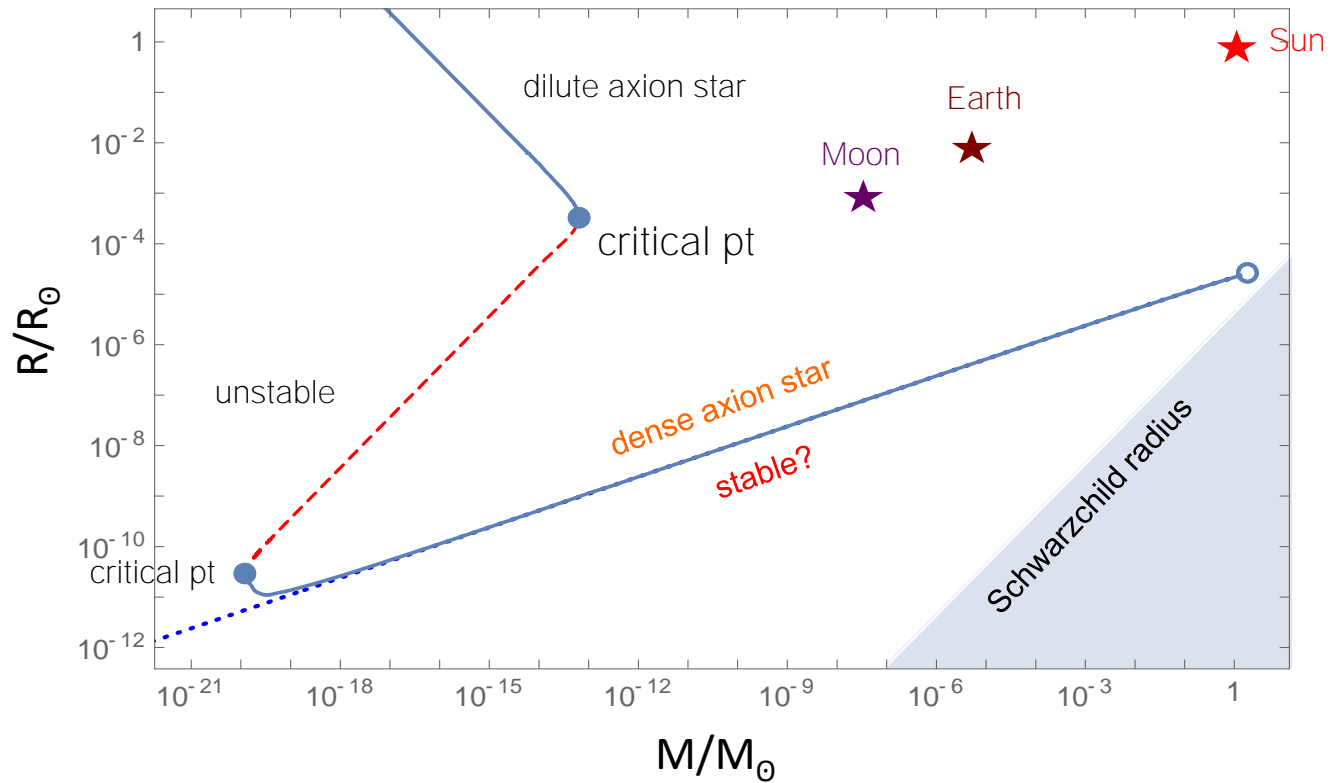
Emission From Axion Stars

■ Inelastic reactions can change the number of nonrelativistic axions in axion stars.

- *2j* nonrelativistic axions → *2* Relativistic axions

  4a-> 2a , 6a-> 2a, 8a-> 2a etc..
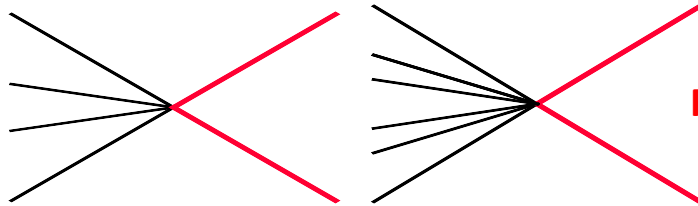
NR axions   **Relativistic axions.**

- *2j+1* nonrelativistic axions → 2 Photons

  1a-> 2γ, 3a-> 2γ, 5a-> 2γ etc…
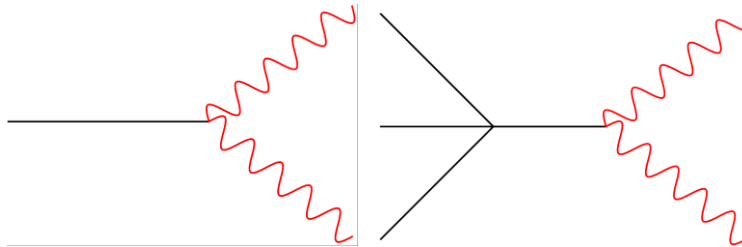
NR axions   **Photon**

Emission From Axion Stars

❖ **Inelastic reactions** that decrease axion number can be included within the **axion EFT** through imaginary part of the **effective potential** V_{eff} .

❖ Contributions to loss rate of non-relativistic axions:

    a.   Loss due to $a \to \gamma\gamma$:

$$-\frac{1}{N}\frac{dN}{dt} \propto \Gamma_a$$

    b. Loss due to $(2j+1)a \to \gamma\gamma$:

$$-\frac{1}{N}\frac{dN}{dt} \propto \Gamma_a \frac{\langle n^{2j} \rangle}{(m_a f_a^2)^{2j}}$$

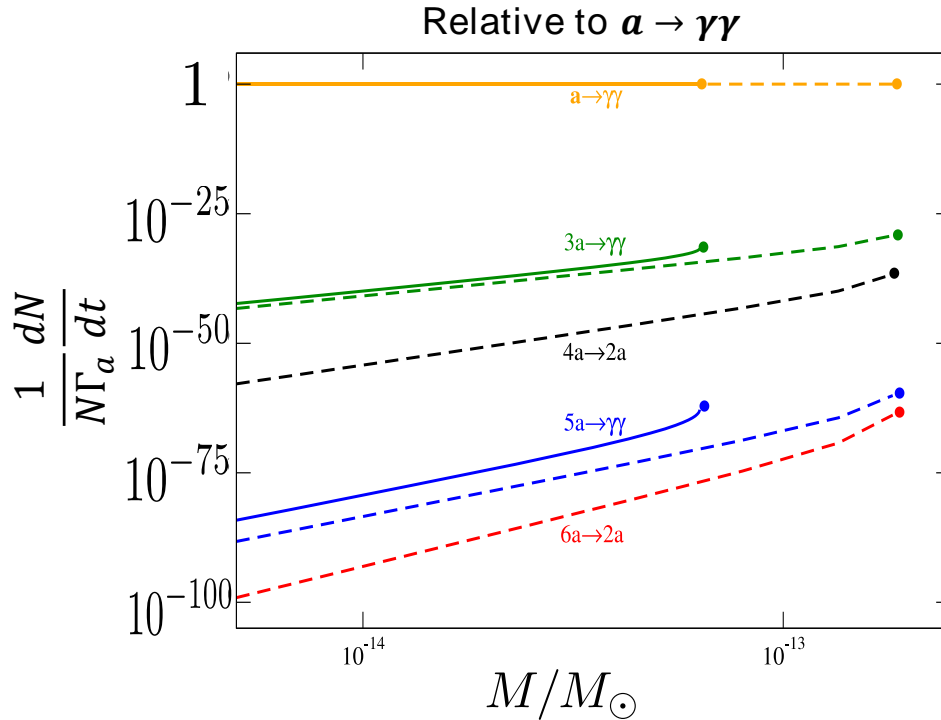**Density dependence !!**

    c. Loss due to relativistic axions $(2j\, a \to aa)$:

$$-\frac{1}{N}\frac{dN}{dt} \propto \frac{m_a^3}{f_a^2}\frac{\langle n^{2j-1}\rangle}{(m_a f_a^2)^{2j-1}}$$

❖ Decay rate of axion to 2 photons: $\Gamma_a \sim \frac{\alpha^2 m_a^3}{f_a^2} \sim 10^{-60} \, eV$.

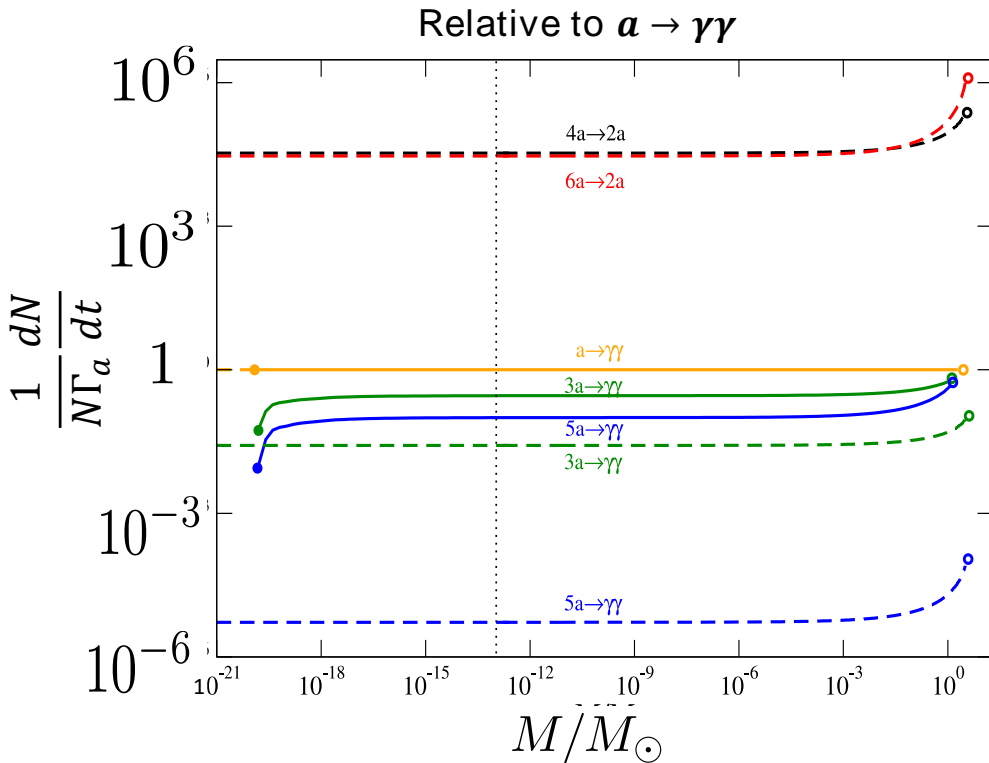# Emission from Dilute Axion Star

Relative to $a \to \gamma\gamma$

Decay rate:
$\Gamma_a \sim 10^{-60} \, eV$

- Solid: Instanton potential

- Dashed: Chiral potential

Other reactions are highly suppressed compared to $a \to \gamma\gamma$!!!

Emission from Dense Axion Star

Relative to $a \to \gamma\gamma$

Decay rate:
$\Gamma_a \sim 10^{-60} \, eV$

- Solid:
  Instanton potential

- Dashed:
  Chiral potential

Emission of relativistic axions are enhanced compared to $a \to \gamma\gamma$!!!

Is there a (**3 a ⟶ a**) Loss process ?? **No!!**

○ *Proposed by Cincinnati group :* *arXiv:1512.01709, 1608.06911*

- Expands axion field ϕ around a classical field ϕ_0:
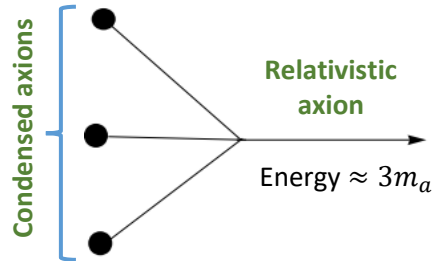
$$\phi = \phi_0 + \tilde{\phi}$$

  Condensate **Fluctuation**

- Expansion of the interaction potential gives a $\phi_0^3 \tilde{\phi}$ term.

- This seems to allow 3a→a loss process??

N condensed axions → (N-3) condensed axions + 1 relativistic axion
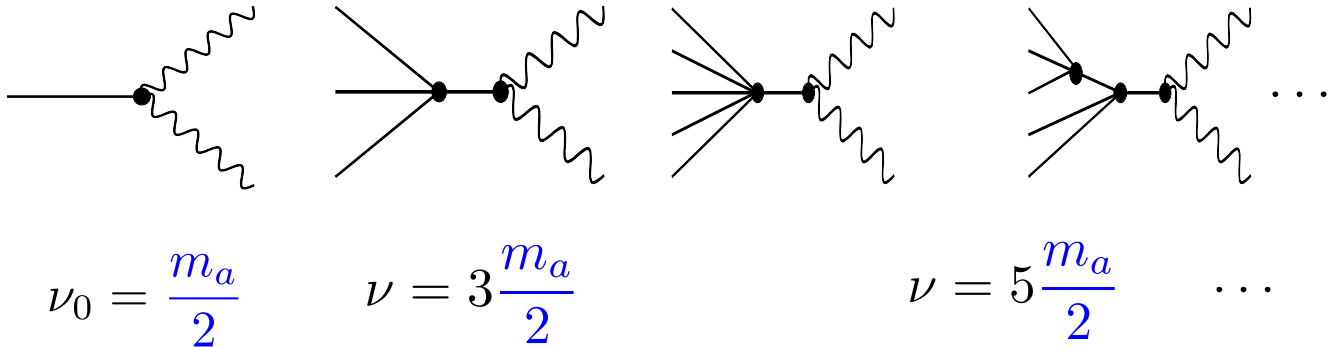
○ **There is no 3a→a loss process:**

- Equation of motion for ϕ_0 **guarantees** terms **linear** in $\tilde{\phi}$ add to **zero**.

- $\phi_0^3 \tilde{\phi}$ term cancelled by other linear terms.

○ Axion effective field theory: **No anti-Hermitian** term in the EFT Hamiltonian for $3a \to 3a$ from intermediate single axion state.

12

Braaten, AM , Zhang, arXiv:1609.05182

NR Axions to Photons

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

- For axion mass $m_a \sim 10^{-4}$ ev, frequency $\nu_0 \sim 10$ GHz. **Radio frequency**

- Odd-integer harmonics of the fundamental radio frequency.

Unique feature of dense configuration of axions !!

Braaten, AM , Zhang, arXiv:1609.05182

Fast Radio Burst

$\longleftrightarrow$

- Burst of radio frequency photons over **time scale of 1 ms**.

- No similar observations in optical, X rays and γ rays till now.

- 20 events observed since 2007.

- Have only been observed at 1.4 GHz (radio telescope sensitivity)

- Probably coming from extra-galactic sources (large dispersion measure)

- Energy released on the scale of 10^{40} erg ~ $10^{-14} M_{\odot}$ (If isotropic)

- Strong linear polarization.

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

Are Axion stars the source of Fast Radio Burst??

- **Observed frequency**: 1.4 GHz

For axion mass: $10^{-6} \text{ eV} < m_a < 10^{-2} \text{eV}$, photons emitted have
$1 \text{ GHz} < \nu < 1000 \text{ GHz}$

- **Time duration**: ~ 1 ms

Possible sources involve remnants of stellar collapse, collision of compact objects like neutron stars, collapse of dilute axion star to dense axion star ?? , etc…

- **Energy released**: up to $\sim 10^{-14} M_{\odot}$

Dilute axion star critical mass : $6 \times 10^{-14} M_{\odot}$

FRB scenarios involving axion stars

- Collision of a dilute axion star with a neutron star

    FRB signal generated from coherent electric dipole radiation

    ➢ From electrons in atmosphere   *Iwazaki, hep-ph/9908468*

    ➢ From neutrons in outer core of neutron star

                                                        Raby, PRD 94, 103004 (2016)

- Collapse of dilute axion stars above the critical mass

    FRB signal from coherent radiation through maser mechanism

                                                        Tkachev, arXiv:1411.3900

- Collision of a dense axion star with a neutron star ??

Summary

- **Inelastic reactions** like $(2j+1)a \to \gamma\gamma$ and $(2j)a \to aa$ change the number of non-relativistic axions in the axion stars.

- Inelastic reactions like $3a \to a$ not possible.

- Dilute axion star: All other processes are highly suppressed compared to $a \to \gamma\gamma$.

- Dense axion star: Emission of relativistic axions is enhanced compared to $a \to \gamma\gamma$.

- The inelastic reactions can be important during collapse of dilute axion star to dense axion star.

- The odd integer harmonics of fundamental radio frequency is a **unique** signature of dense configuration of axions.

- Could axion stars explain fast radio burst (FRB).??

Other recent works regarding Axion stars:

❖ Collapse of self-gravitating Bose Einstein condensate with attractive self interactions
   P.H. Chavanis, PRD 94, 083007 (2016).

❖ Relativistic Axions from collapsing Bose stars.
   Levkov et al, arxiv 1609:03611.

❖ Black Hole formation from Axion stars
   Helfer et al, arxiv 1609:04724.

❖ Hydrogen Axion star: Metallic Hydrogen Bound to a QCD Axion BEC.
   Bai et al, arxiv 1612:00438.

❖ QCD Axion star collapse with chiral potential.
   Eby et al, arxiv 1702:05504.

Thank You!!

Is there a ($3a \longrightarrow a$) Loss process ??

Proposed by Cincinnati group : *arXiv:1512.01709, 1608.06911*

- Condensed axions : $E \approx m_a$.
  $$p \sim 1/(\text{radius of axion star}) \sim 10^{-17} m_a.$$

- Conservation of Energy, emitted axion: $E \approx 3m_a$; $p \approx \sqrt{2}\, m_a$.

- Momentum cannot be conserved in $3a \to a$!

- Cincinnati group suggested momentum could be conserved in the reaction
  N condensed axions → (N-3) condensed axions + 1 relativistic axion
  through **<u>recoil of (N-3)</u>** condensed axions.
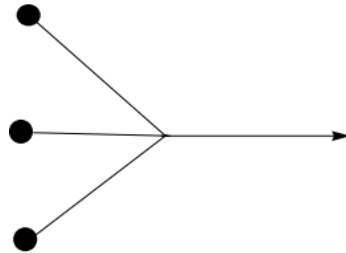
❑ **Can momentum of emitted axion be balanced by recoil of axion star?**
  1. Axion star : Superfluid of condensed axions. So cannot absorb the recoil momentum like a rigid body.
  2. Weak coupling: Momentum transfer for each additional axion costs factor $\left(m_a/f_a\right)^2 \sim 10^{-48}$.
  3. Axion effective field theory: No anti-Hermitian term in the EFT Hamiltonian for $3a \to 3a$ from $3a \to a$. ➡ Must be exponentially suppressed!!

Braaten et.al, arxiv 1604.00669