

# Emission of Photons and Relativistic Axions from Axion Stars



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**U.S. DEPARTMENT OF  
ENERGY**



# Outline



➤ **Axions**

➤ **Axion EFT**

*PRD 94, 076004 (2016)*

➤ **(Dilute) Axion Star**

➤ **Dense Axion Star**

*PRL 117, 121801 (2016)*

➤ **Emission from Axion Stars**

*arXiv:1609.05182*

➤ **Conclusions**

# 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*

highly nonrelativistic, huge occupation numbers, coherent.

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

## *cosmic string decay*

highly nonrelativistic, huge occupation numbers, incoherent.

*Davis (1986)*

- Gravitational interactions can thermalize the axions, so they can 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  $\phi$  and a model potential given by:

*Instanton Potential*

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

*m*: axion mass

*Chiral Potential*

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

*f*: axion decay constant

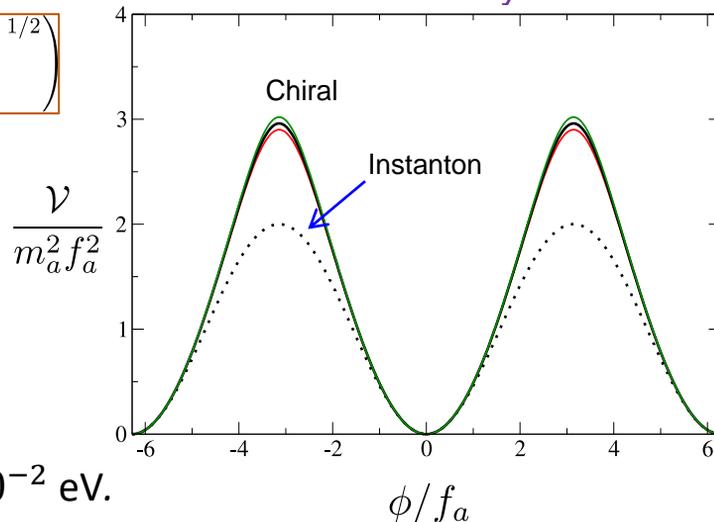
$$z = m_u/m_d \approx 0.48 \pm 0.03$$

*Vecchia & Veneziano (1980)*

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

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

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



# Axion EFT



- Axions produced from vacuum misalignment and cosmic string decay mechanism have **energy scales** less than  $m_a$ . **Non Relativistic Axions**
- NR axions: described by nonrelativistic effective field theory (**axion EFT**) with **complex scalar field**  $\psi$ .

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

- **Effective potential** : obtained by matching **low energy scattering amplitudes** at **tree level** in **relativistic theory** and **axion EFT**.

*Braaten, AM, Zhang, PRD (2016)*

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

- **Naïve effective potential:**

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

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

# Axion Stars



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

*Tkachev (1991)*

## Dilute Axion Star

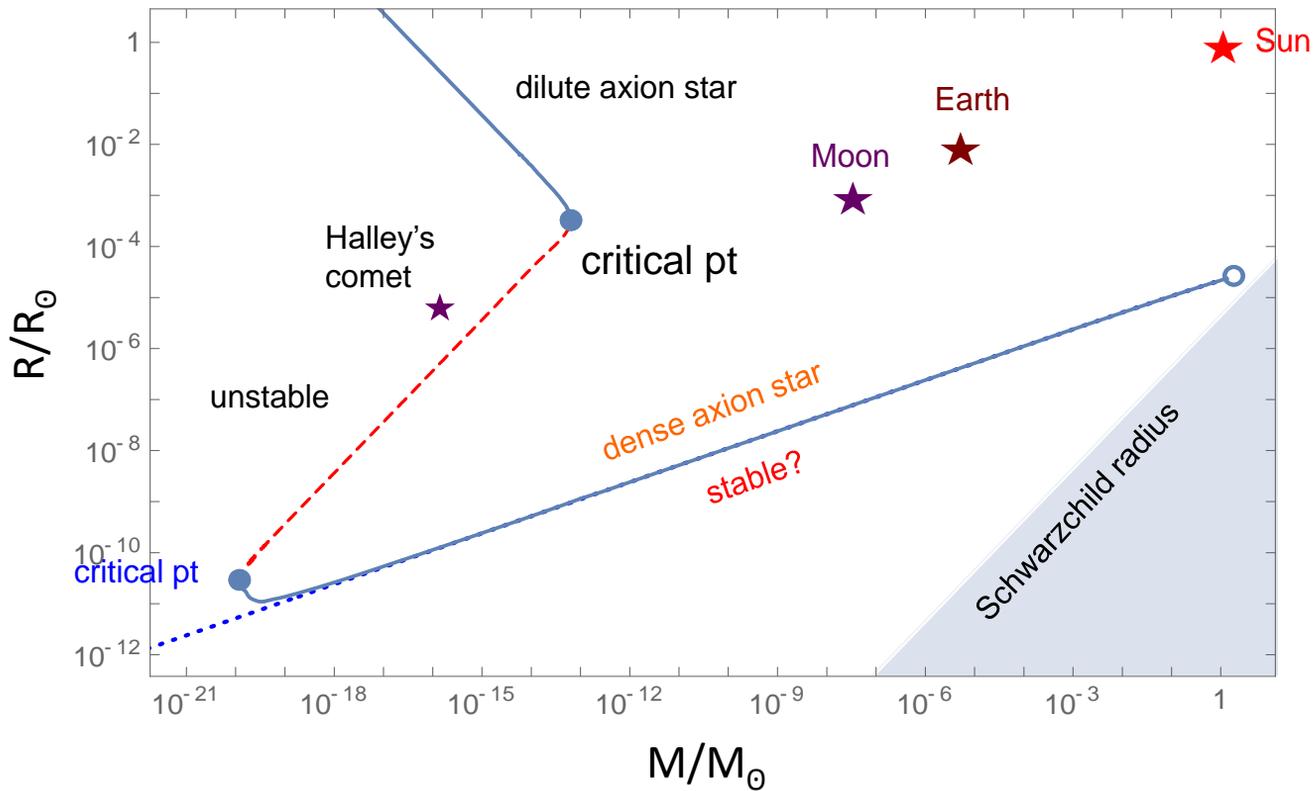
- characterized by  $\psi^* \psi \ll m f^2$   
*Barranco & Bernal (2011)*
- In stable star,  
repulsive force from kinetic energy  
=  
attractive force from gravity +  
attractive force from axion pair  
interactions  
*Chavanis & Delfini (2011)*
- **Critical mass** beyond which the  
axion star will **collapse**.  
 $6 \times 10^{-14} M_{\odot}$  for  $m = 10^{-4}$  eV.

## Dense Axion Star

- characterized by  $\psi^* \psi \approx m f^2$   
at centre.
- In stable star,  
repulsive force from BEC self  
interaction  
=  
attractive force from gravity  
in most of the bulk except near the  
surface.

*Braaten, AM, Zhang, PRL (2016)*

# R vs M for Axion Star



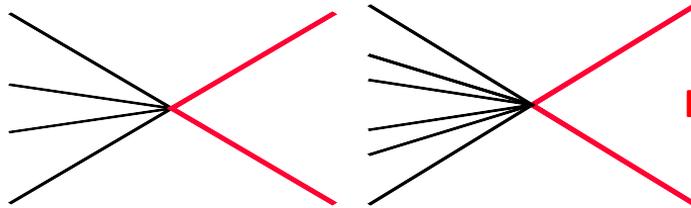
# Emission From Axion Stars

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

$2j$  nonrelativistic axions  $\rightarrow$  2 Relativistic axions

$4a \rightarrow 2a, 6a \rightarrow 2a, 8a \rightarrow 2a$  etc..

NR axions

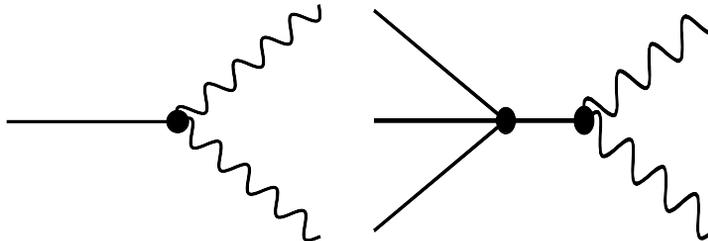


Relativistic axions.

$2j+1$  nonrelativistic axions  $\rightarrow$  2 Photons

$1a \rightarrow 2\gamma, 3a \rightarrow 2\gamma, 5a \rightarrow 2\gamma$  etc...

NR axions



Photon

# Emission From Axion Stars

❖ **Inelastic process**: Effects of photons and relativistic axions can be included within the **axion EFT** through imaginary part of the **effective potential**  $V_{\text{eff}}$ .

❖ Contributions to loss rate of non-relativistic axions:

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

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

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

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

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

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

Dilute:

$$\frac{n(0)}{m_a f_a^2} \sim 10^{-15}$$

Dense:

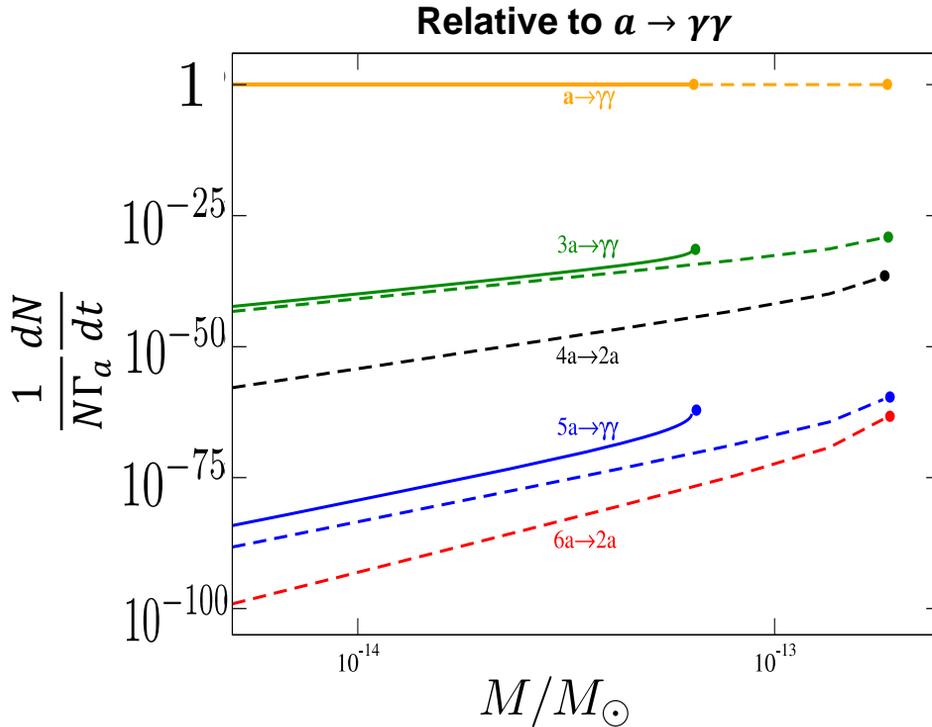
$$\frac{n(0)}{m_a f_a^2} \sim 20$$

**Density dependence !!**

$$m_a^3 / f_a^2 \sim 10^{-54} \text{ eV}$$

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

# Emission from Dilute Axion Star

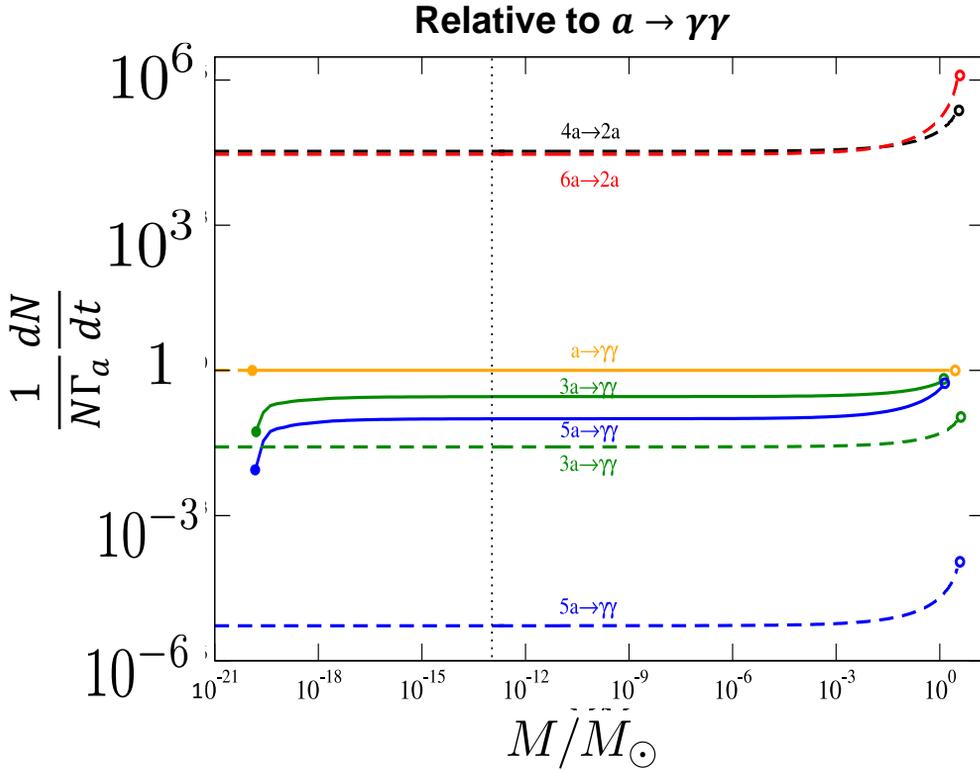


Decay rate:  
 $\Gamma_a \sim 10^{-60} \text{ eV}$

- **Solid:**  
Instanton potential
- **Dashed:**  
Chiral potential

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

# Emission from **Dense** Axion Star



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

- **Solid:**  
Instanton potential
- **Dashed:**  
Chiral potential

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

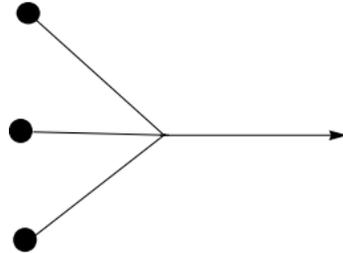
# Is there a ( $3a \rightarrow a$ ) Loss process ??



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  $3a \rightarrow a$  !
- Cincinnati group suggested momentum could be conserved in the reaction  
**N condensed axions  $\rightarrow$  (N-3) condensed axions + 1 relativistic axion**  
through **recoil of (N-3)** 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  
 $(m_a/f_a)^2 \sim 10^{-48}$ .
3. Axion effective field theory: **No anti-Hermitian term** in the EFT Hamiltonian for  $3a \rightarrow 3a$  from  $3a \rightarrow a$ .  **Must be exponentially suppressed!!**

# Fast Radio Burst



- Burst of **radio frequency** photons over **time scale of 1 ms.**
- No similar observations in optical, X rays and  $\gamma$  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  $\sim$   **$10^{-14} M_{\odot}$**  (If isotropic)
- **Strong linear polarization.**

Recent review: Katz, arXiv:1604.01799

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

# Are Axion star 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:  $\sim 1 \text{ ms}$

➤ Possible sources involve **stellar collapse**, **catastrophic collisions** etc... :  
Collapse of dilute to dense axion star ??

✓ 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)*

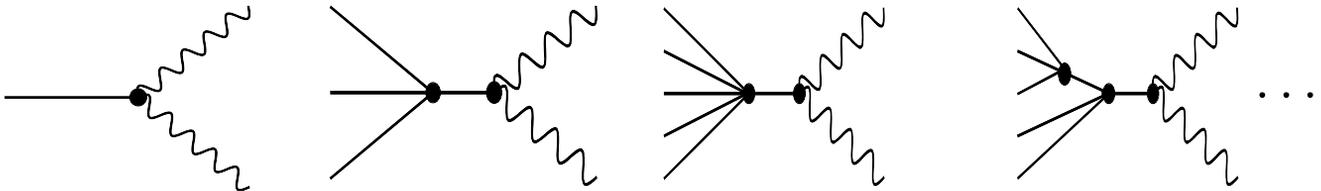
- Collapse of dilute axion stars above the critical mass

FRB signal from coherent radiation through maser mechanism

*Tkachev, arXiv:1411.3900*

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

# NR Axions to Photons



$$\nu_0 = \frac{m_a}{2}$$

$$\nu = 3 \frac{m_a}{2}$$

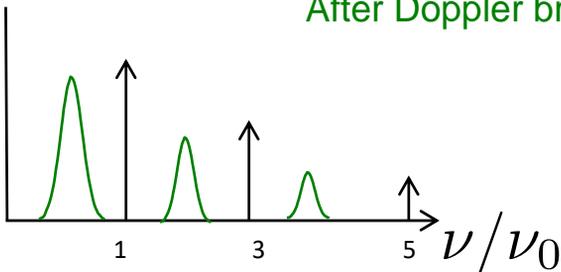
$$\nu = 5 \frac{m_a}{2}$$

❖ 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.

After Doppler broadening and red-shifting



Unique feature  
of dense configuration of axions !!

# Summary



- **Inelastic reactions** in which **photons** and **relativistic axions** are emitted change the number of non-relativistic axions in the axion stars.
- Dilute axion star: Other inelastic processes are highly suppressed compared to  $a \rightarrow \gamma\gamma$ .
- Dense axion star: Emission of relativistic axions is enhanced compared to  $a \rightarrow \gamma\gamma$ .
- These inelastic reactions may be important in the collapse of a dilute axion star to a dense axion star.
- The **odd integer harmonics** of the fundamental radio frequency is a unique signature of a dense configuration of axions.
- Could axion star collapse explain **fast radio burst (FRB)**.??

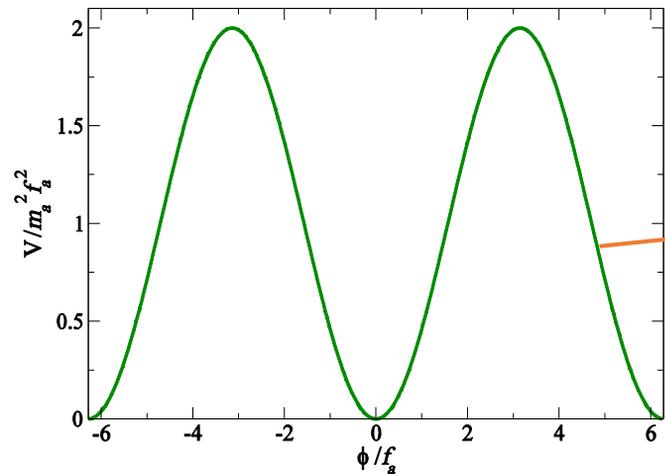
## Other recent works regarding Axion stars:



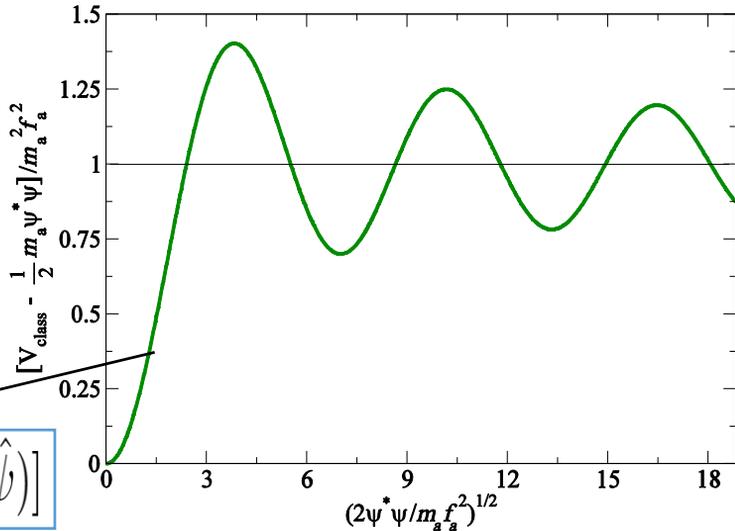
- ❖ Collapse of self-gravitating Bose Einstein condensate with attractive self interactions  
P.H. Chavanis, PRD 94, 083007 (2016).
- ❖ Black Hole formation from Axion stars  
Helfer et al, arxiv 1609:04724.
- ❖ Hydrogen Axion star: Metallic Hydrogen Bound to a QCD Axion BEC.  
Bai et al, arxiv 1612:00438.
- ❖ QCD Axion star collapse with chiral potential.  
Eby et al, arxiv 1702:05504.
- ❖ Relativistic Axions from collapsing Bose stars.  
Levkov et al, arxiv 1609:03611.

**Thank You!!**

# Relativistic and Effective potential



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



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

# Imaginary part for ( $3a \rightarrow a$ ) ??

- By Optical theorem:

$$\text{Im}(A \rightarrow A) \propto \sum_X \Gamma_X(A \rightarrow X)$$

X is set of all possible intermediate states

- So for  $3a \rightarrow a$  loss process: **A** is  $3a$  and **X** is  $a$

$$\Gamma_{3a \rightarrow a} \propto \text{Im} \left[ \begin{array}{c} \diagup \quad \diagdown \\ \text{---} \\ \diagdown \quad \diagup \end{array} \right]$$

- Energy-momentum conservation : **Imaginary part** for  $(3a \rightarrow a) = 0$

- So no imaginary term in the EFT Hamiltonian to take into account the  $3a \rightarrow a$  loss process.