Emission of Photons and Relativistic Axions from Axion Stars

TeVPA 2017, Columbus
Aug 10, 2017

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

- Spatial fluctuations in axion field leads to evolution of axions into gravitationally bound "miniclusters" of axions. ***Hogan & Rees (1988) , Kolb & Tkachev (1993)***

- Gravitational interactions can thermalize the axions to 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

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

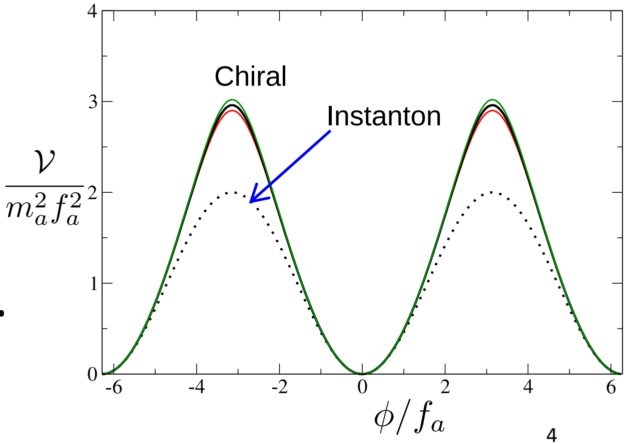
Chiral Potential

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

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

Axion EFT

- 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.

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

- **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:**

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

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

Eby, Suranyi, Vaz, Wijewardhana (2015)

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

Axion Stars

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

Tkachev (1991)

Dilute Axion Star

Barranco & Bernal (2011)

- 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**.

  $\boldsymbol{6 \times 10^{-14} M_\odot}$ for $\boldsymbol{m = 10^{-4}}$ eV.

Chavanis & Delfini (2011)

Dense Axion Star

Braaten, AM, Zhang, PRL (2016)

- characterized by $\psi^*\psi \sim 20\, m_a f_a^2$ at center for mass $10^{-14}\, \boldsymbol{M_\odot}$.
- In stable star,

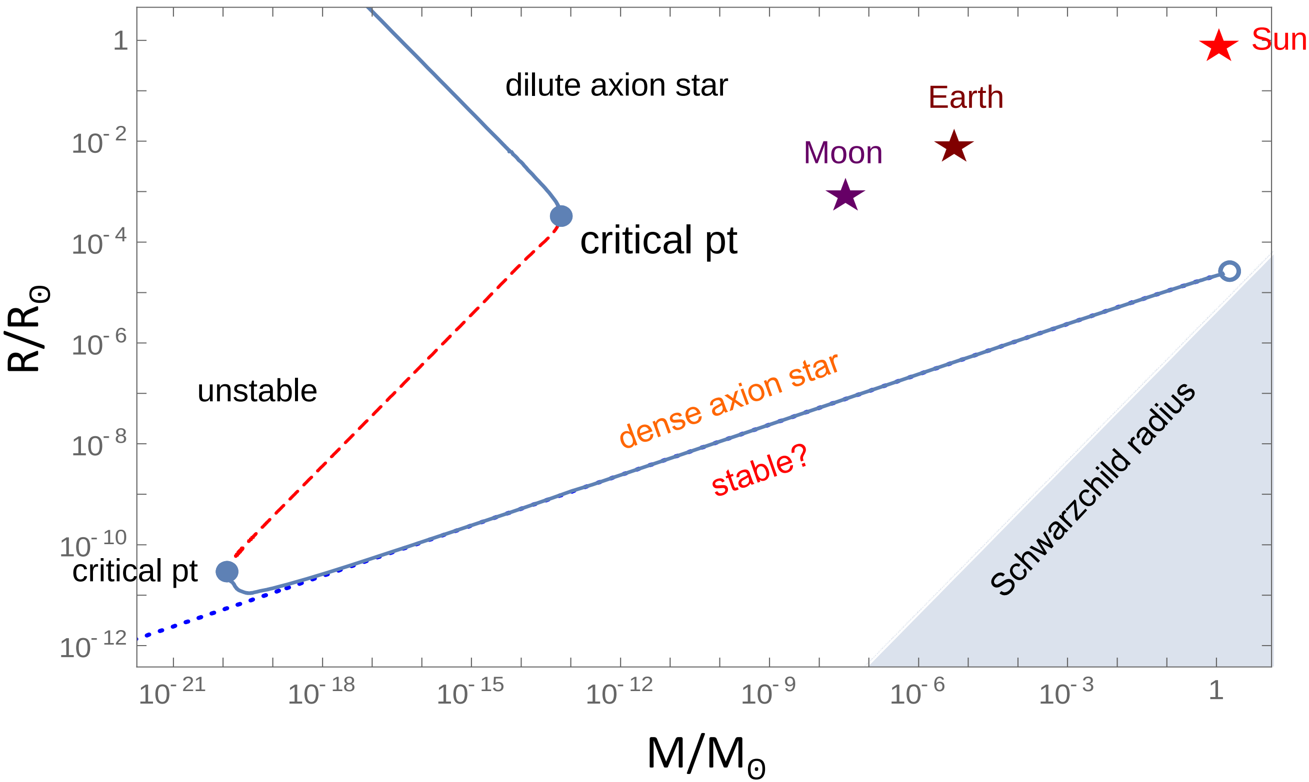
  repulsive force from BEC self interaction

  =

  attractive force from gravity

in most of the bulk except near the surface.

R vs M for Axion Star



Braaten, AM, Zhang, PRL (2016)

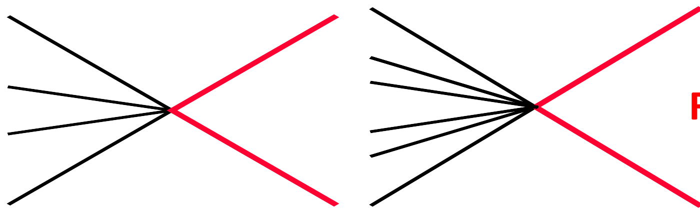
Emission From Axion Stars

- 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

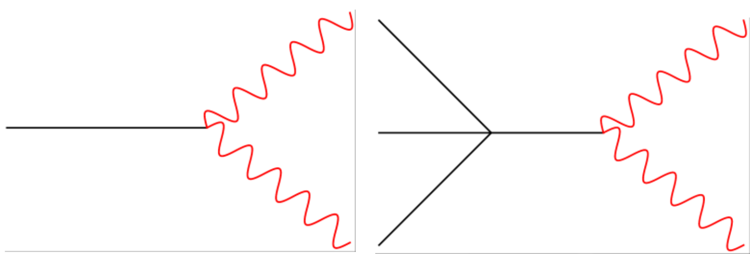


Relativistic axions.

- ***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 $(2j+1)a \to \gamma\gamma$:

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

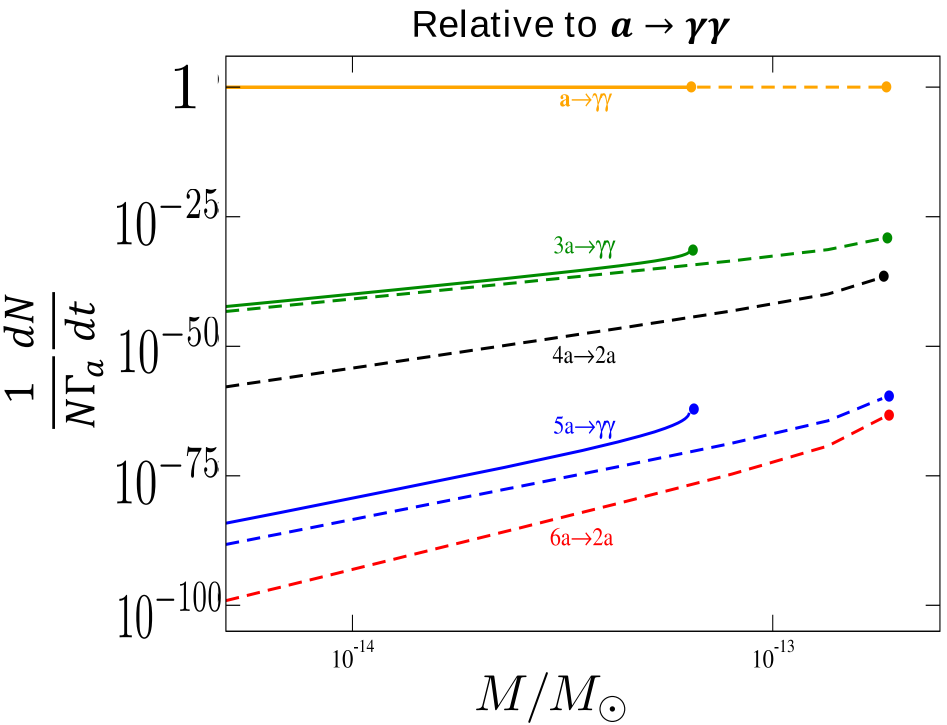
Density dependence !!

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



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

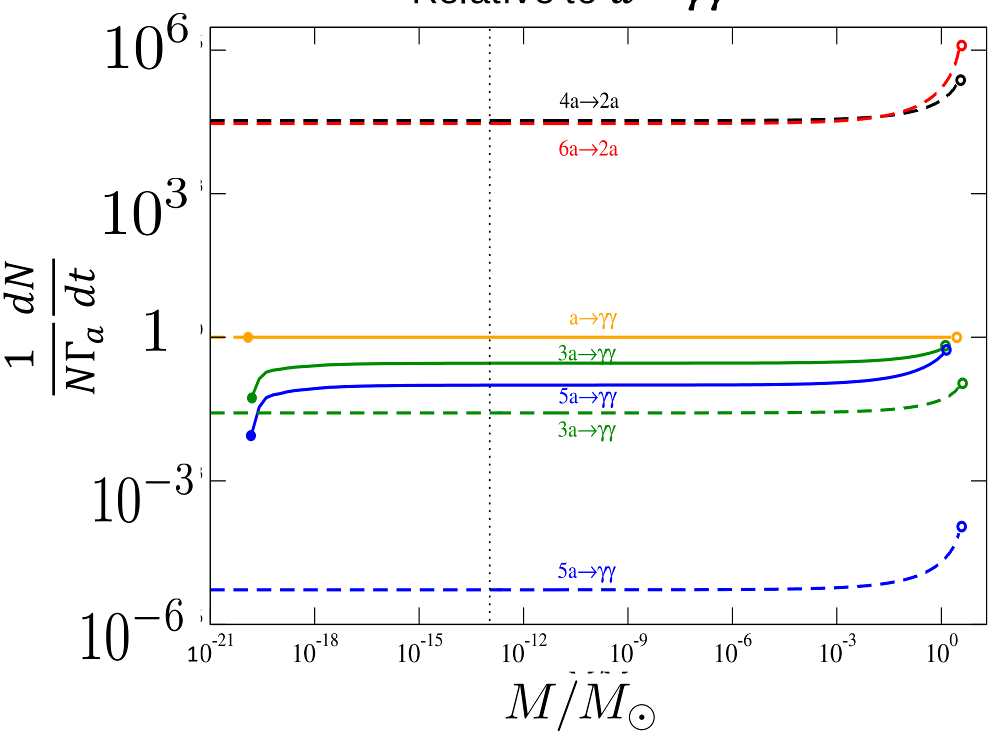
- Solid:
  Instanton potential
- Dashed:
  Chiral potential

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

Braaten, AM, Zhang, arXiv:1609.05182

Emission from Dense Axion Star

Relative to $\boldsymbol{a} \rightarrow \boldsymbol{\gamma\gamma}$



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

- Solid:
  Instanton potential
- Dashed:
  Chiral potential

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

Braaten, AM, Zhang, arXiv:1609.05182

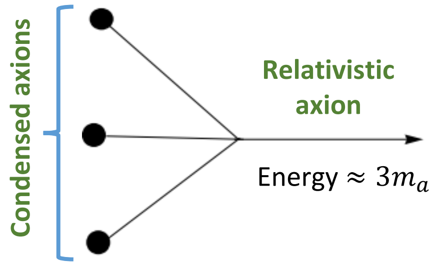
Is there a (3 a ⟶ a) Loss process ??

- *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 (ϕ_0) **Fluctuation** ($\tilde{\phi}$)



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

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

N condensed axions → (N-3) condensed axions + 1 relativistic axion

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

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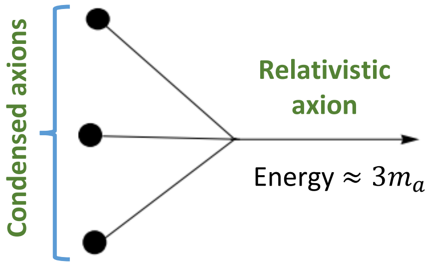

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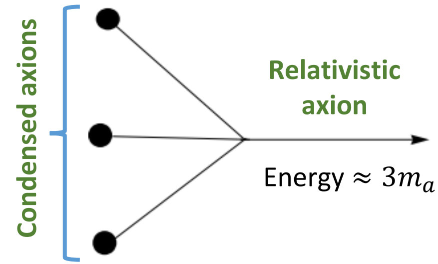

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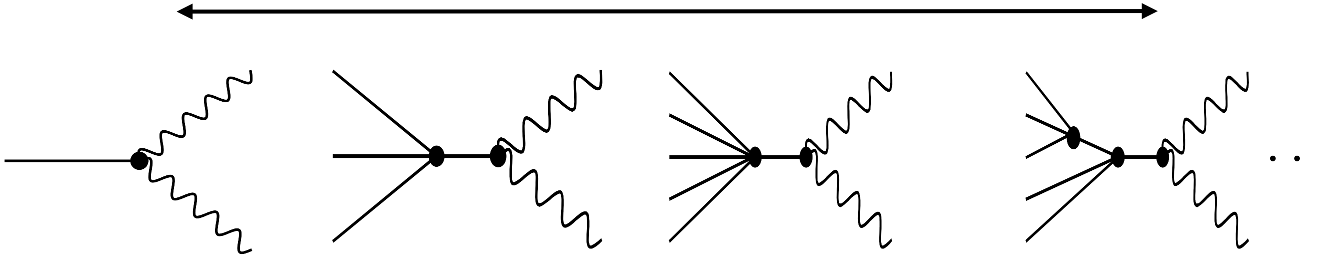
○ **There is no 3a→a loss process:**

- 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.

Braaten, AM , Zhang, arXiv:1609.05182

NR Axions to Photons

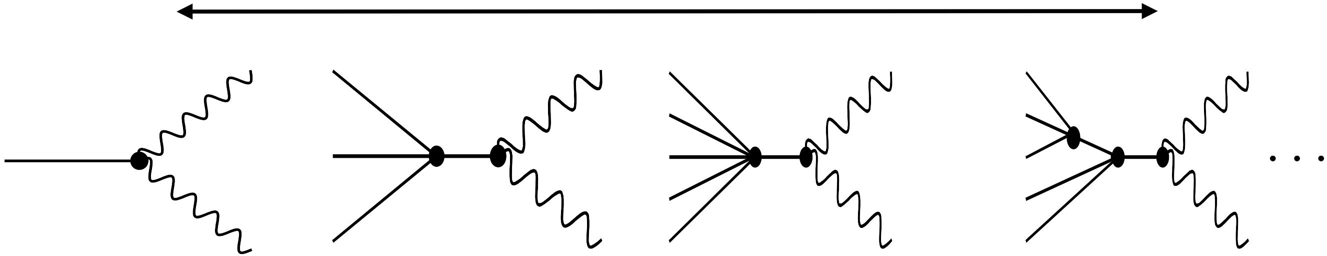


$$\nu_0 = \frac{m_a}{2} \qquad \nu = 3\frac{m_a}{2} \qquad \nu = 5\frac{m_a}{2} \qquad \cdots$$

- 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.

Braaten, AM , Zhang, arXiv:1609.05182

NR Axions to Photons



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- Odd-integer harmonics of the fundamental radio frequency.

Unique feature of dense configuration of axions !!

Braaten, AM , Zhang, arXiv:1609.05182

Fast Radio Burst

- Burst of radio frequency photons over **time scale of 1 ms**.
- No similar observations in optical, X rays and γ rays till now.
- 23 events observed since 2007.
- Have only been observed at 1.4 GHz (Parkes) & 0.8 GHz (UTMOST)
- 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: $10^{-6}\,\mathrm{eV} < \mathrm{m}_a < 10^{-2}\mathrm{eV}$, photons emitted have $1\ \mathrm{GHz} < \nu < 1000\ \mathrm{GHz}$

- **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 axion stars with the accretion disk of black hole

FRB signal from coherent oscillation of electrons in strong magnetic field

Tkachev, arXiv:1707.04827

- 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.

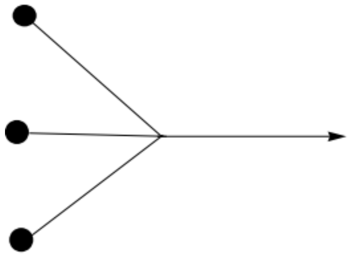
- QCD Axion star collapse with chiral potential.
  Eby et al, arxiv 1702:05504.

Thank You!!

Is there a (3 a ⟶ 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 → (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 $\left({m_a}/{f_a}\right)^2 \sim 10^{-48}$.
3. Axion effective field theory: No anti-Hermitian term in the EFT Hamiltonian for $3a \rightarrow 3a$ from $3a \rightarrow a$. ⟹ Must be exponentially suppressed!!

Braaten et.al, arxiv 1604.00669