Axion Stars and How to Find Them

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Energy conservation and axion back-reaction in an external magnetic field

Srimoyee Sen and Lars Sivertsen, JHEP 03 (2023) 097, arxiv: 2210.01149

Srimoyee Sen and Lars Sivertsen, JHEP 05 (2022) 192, arxiv: 2111.08728

Outline of the Talk

- Axions and axion-like particles
- Axion Condensates (Axion Stars)
- The modified Maxwell's Equations
- Electromagnetic Radiation from Axion Condensates
- Decay of axion stars
- Take Home Message

Axions

- The full QCD Lagrangian has a CP violating term leading to a non-zero magnetic dipole moment for the neutron
- Axions suggested as a solution to the strong CP problem
- To solve the strong CP problem, need $m_a f_a \approx m_\pi f_\pi \approx \Lambda_{\mathrm{QCD}}^2$
- Axions turns out to be extremely light (order eV or smaller), and interact very weakly with ordinary matter
- Excellent candidate for dark matter as well!

Axions and Axion-like Particles

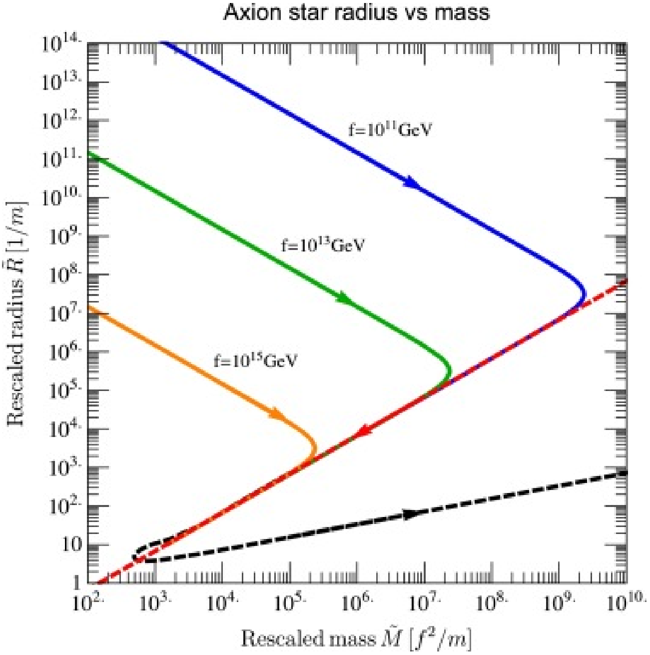
- Particles with axion like properties are predicted by string theory
- Multiple different axions spanning many orders of magnitude
- f_a determined by string compactifications
- This motivates the search for axion-like particles with $m_a f_a \neq \Lambda_{\mathrm{QCD}}^2$

Axion Condensates

- Axions can form spherically symmetric, coherently oscillating lumps of Bose-Einstein condensates (axion stars) $\phi(\boldsymbol{x}, t) \approx \phi_0 \mathrm{sech}(r/R) \cos(\omega t)$.

- Can be dense ($m_a R \sim 1$)
  - Dominated by self interactions
  - $\omega \lesssim m_a$
  - $\phi(\boldsymbol{x} = 0, t) \sim f_a$

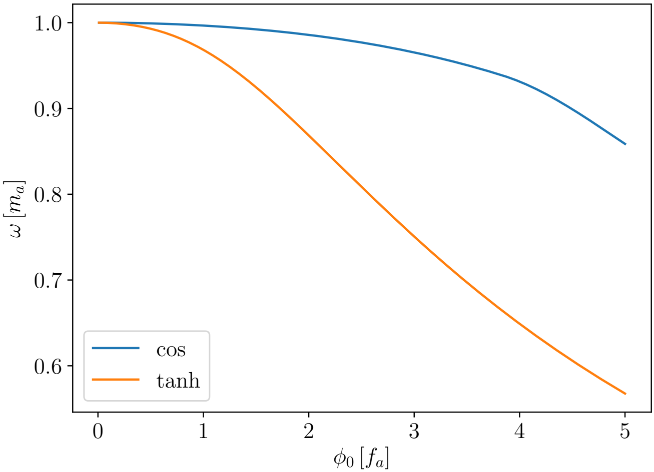
- Or dilute ($m_a R \gg 1$)
  - Dominated by gravitational interactions
  - $\omega \approx m_a$
  - $\phi(\boldsymbol{x} = 0, t) \ll f_a$



Luca Visinelli et al. Phys.Lett.B 777 (2018) 64-72

Axion Condensates

- The frequency of the condensate is dependent on the central amplitude



Elextromagnetic Radiation from Axion Stars in an External Magnetic Field

- Axion-photon Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + J^{\mu}_{m}A_{\mu} + \frac{C\beta}{4\pi f_a}\phi\epsilon^{\mu\nu\lambda\rho}F_{\mu\nu}F_{\lambda\rho} + \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - V(\phi) \quad (1)$$

- To first order in $\frac{C\beta}{\pi f_a}\phi$ ($\phi \lesssim f_a$)

$$\Box \boldsymbol{A}_{\rm r}(\boldsymbol{x},t) = -\frac{C\beta}{\pi f_a}\big(\partial_t\phi(\boldsymbol{x},t)\big)\boldsymbol{B}_0 \equiv \boldsymbol{J}_a(\boldsymbol{x},t) \quad (2)$$

$$\Box \Phi_{\rm r}(\boldsymbol{x},t) = \frac{C\beta}{\pi f_a}\nabla\phi(\boldsymbol{x},t)\cdot\boldsymbol{B}_0 \equiv \rho_a(\boldsymbol{x},t) \quad (3)$$

$$(\Box + m_a^2)\phi(\boldsymbol{x},t) + \partial_\phi V(\phi) = -\frac{C\beta}{\pi f_a}\boldsymbol{E}_{\rm r}(\boldsymbol{x},t)\cdot\boldsymbol{B}_0(\boldsymbol{x},t) \quad (4)$$

Elextromagnetic Radiation from Axion Stars in an External Magnetic Field

- Axions interact extremely weakly with matter
- However, axion stars have high occupation numbers, resonance effects can occur
- Axion stars in the presence of a (strong) magnetic field will radiate, slowly changing the condensate frequency.
- Presence of a plasma can enhance radiation

Electromagnetic Radiation from Axion Condensates in External Magnetic Field

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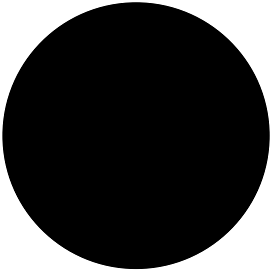

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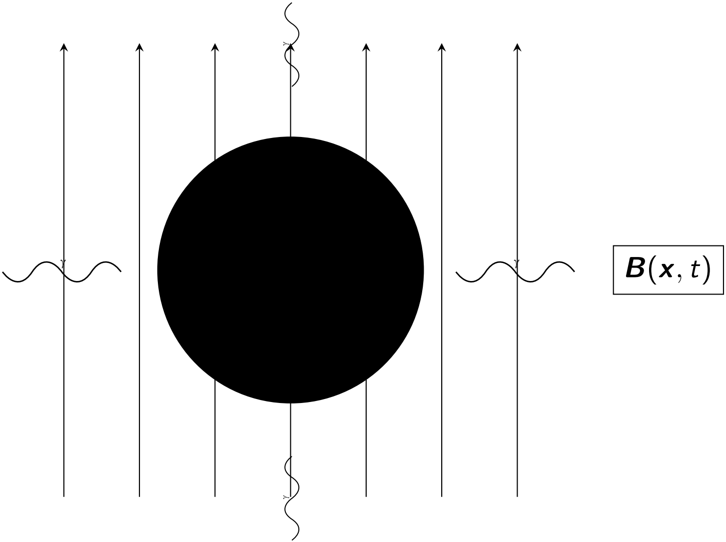

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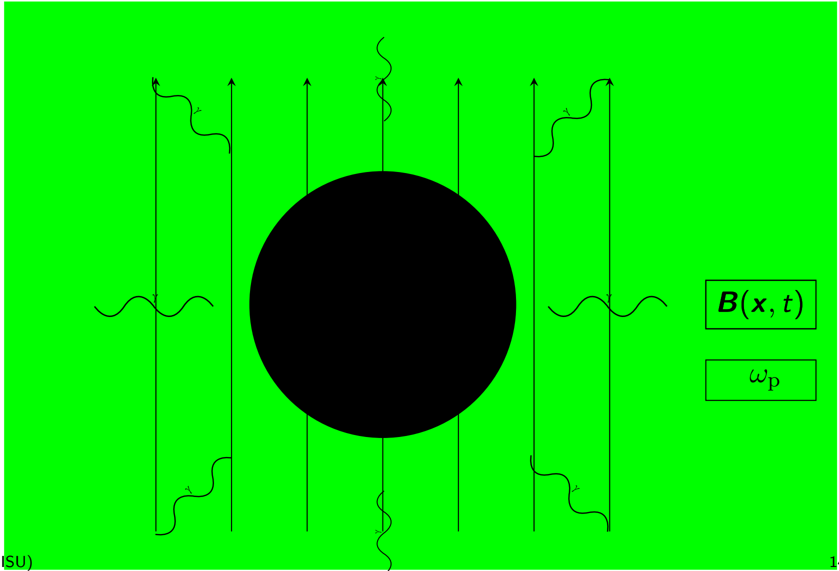

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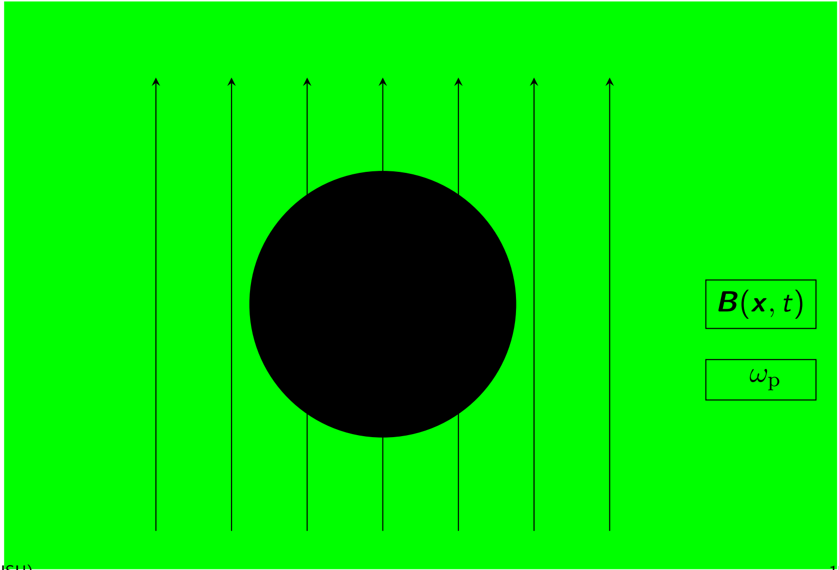
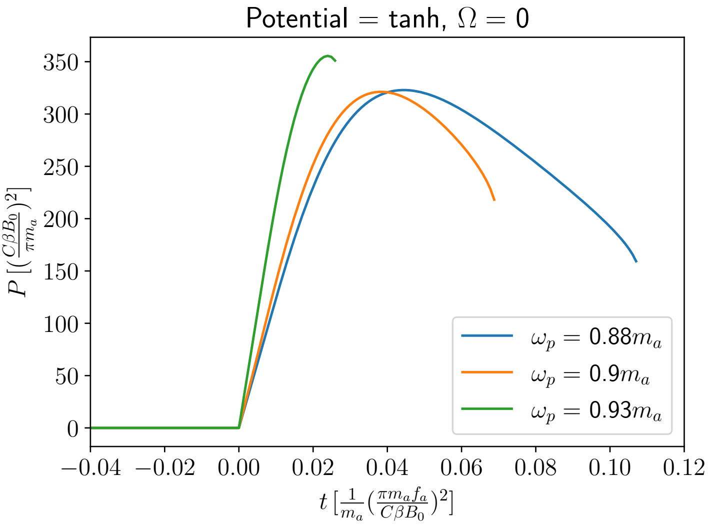


Decay of axion stars



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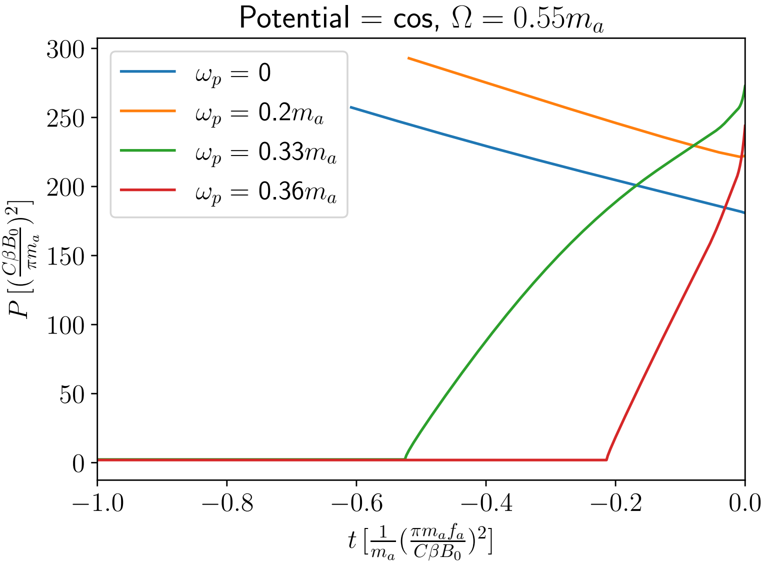


Take Away Message

- Axions can form spherically symmetric axion condensates, axion stars
- Axion BEC start to give of electromagnetic radiation when subject to an external magnetic field
- For dense condensates, the frequency becomes time dependent when back-reaction is included
- Resonances can occur as time passes

Takk for at du kom!

Thanks for listening!

The next slides are extra

Axion Equations of Motion

- Modified Maxwell equations

$$\nabla \times \boldsymbol{B}(\boldsymbol{x}, t) - \partial_t \boldsymbol{E}(\boldsymbol{x}, t) - \boldsymbol{J}_m(\boldsymbol{x}, t) = -\frac{C\beta}{\pi f_a}\Big[\big(\partial_t \phi(\boldsymbol{x}, t)\big)\boldsymbol{B}(\boldsymbol{x}, t) + \nabla\phi(\boldsymbol{x}, t) \times \boldsymbol{E}(\boldsymbol{x}, t)\Big] \quad (5)$$

$$\nabla \times \boldsymbol{E}(\boldsymbol{x}, t) = -\partial_t \boldsymbol{B}(\boldsymbol{x}, t) \quad (6)$$

$$\nabla \cdot \boldsymbol{E}(\boldsymbol{x}, t) = \rho_m(\boldsymbol{x}, t) + \frac{C\beta}{\pi f_a}\nabla\phi(\boldsymbol{x}, t) \cdot \boldsymbol{B}(\boldsymbol{x}, t) \quad (7)$$

$$\nabla \cdot \boldsymbol{B}(\boldsymbol{x}, t) = 0 \quad (8)$$

- Axion Equation of motion

$$(\Box + m_a^2)\phi(\boldsymbol{x}, t) + \partial_\phi V(\phi) = -\frac{C\beta}{\pi f_a}\boldsymbol{E}(\boldsymbol{x}, t) \cdot \boldsymbol{B}(\boldsymbol{x}, t) \quad (9)$$

Estimation of Energy Radiated

- Energy stored in condensates $R \sim m_a^{-1}$

$$E_\phi \sim m_a^2 \phi_0^2 R^3 \sim m_a^2 f_a^2 R^3 \sim \frac{f_a^2}{m_a} \tag{10}$$

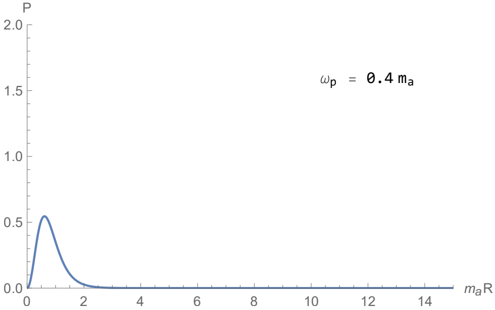
- A few orders of magnitude above or below a solar mass depending on the axion mass

- Energy stored in condensates $R \gg m_a^{-1}$

$$E_\phi \sim m_a^2 \phi_0^2 R^3 \sim \frac{m_{\mathrm{P}}^2}{m_a} \frac{1}{(m_a R)} \tag{11}$$

- Already found by Amin et al. to be ($k_\omega = \sqrt{\omega^2 - \omega_{\mathrm{p}}^2}$)

$$\langle P(t) \rangle_T = \left(\frac{C\beta}{\pi f_a} \right)^2 \left(\frac{\phi_0^2 B_0^2 \omega^3 R^4 \pi^5}{12 k_\omega} \right) \left(\frac{\tanh(\pi k_\omega R/2)}{\cosh(\pi k_\omega R/2)} \right)^2 \quad (12)$$



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Static External Magnetic Field

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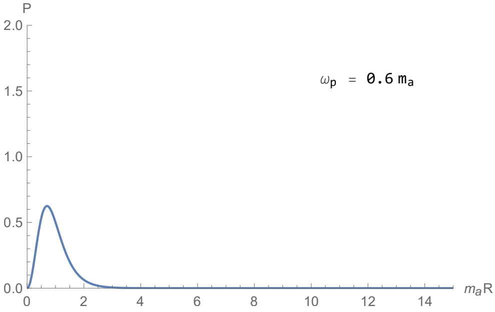

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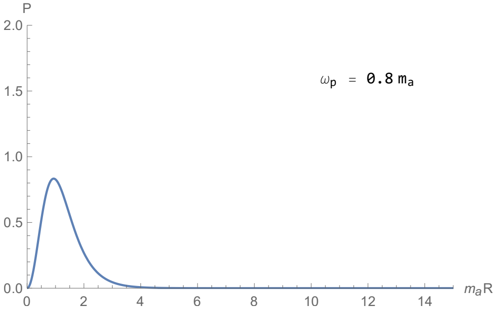

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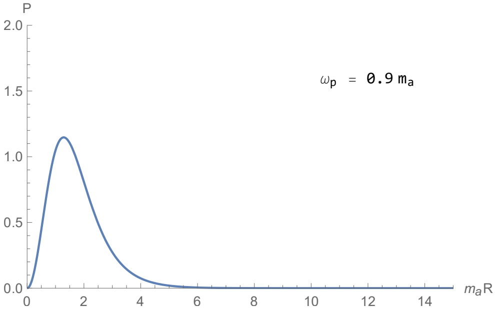

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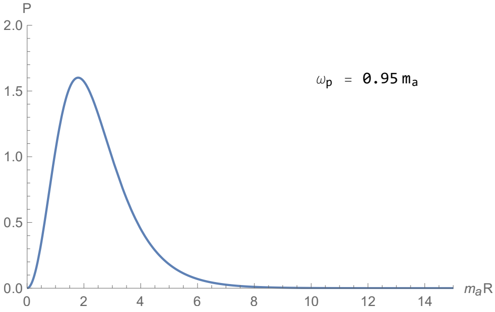

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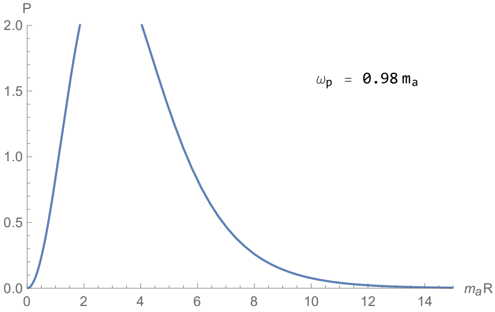
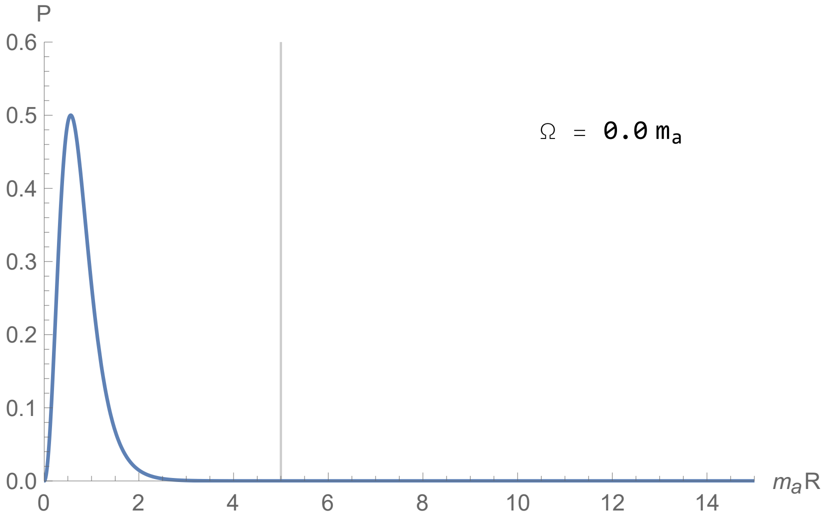


Static External Magnetic Field, takeaways

- Radiated power vanishes exponentially with system size ωR
- Tuning plasma frequency ω_{p} allows larger condensates to radiate efficiently
- Want to see if we can have similar effects by making the external magnetic field oscillate

Oscillating External Magnetic Field

- When $\boldsymbol{B}_0 \to \boldsymbol{B}_0 \cos(\Omega t)$, the effective frequency splits in two $\omega \to \omega \pm \Omega$, wavenumber $k_{\pm} = |\Omega \pm \omega|$



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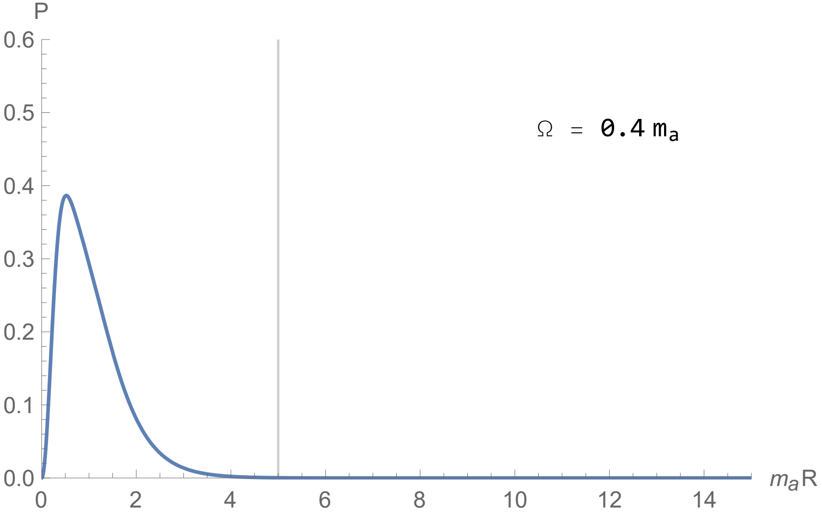

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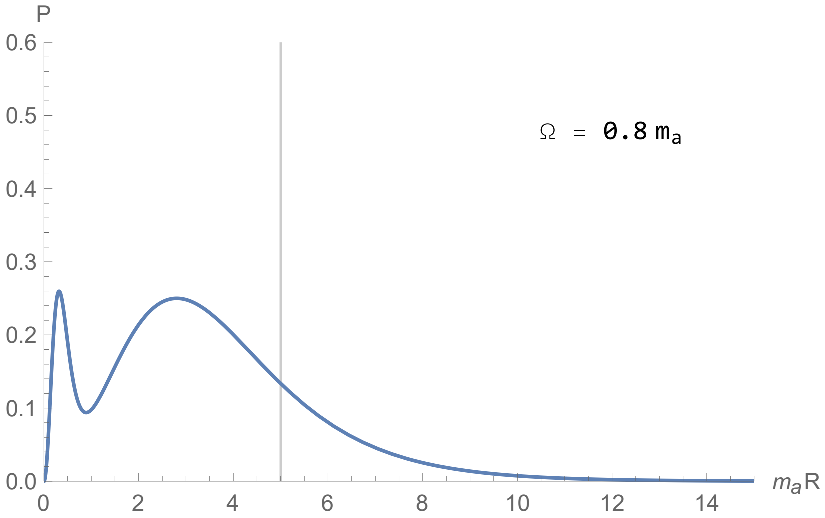

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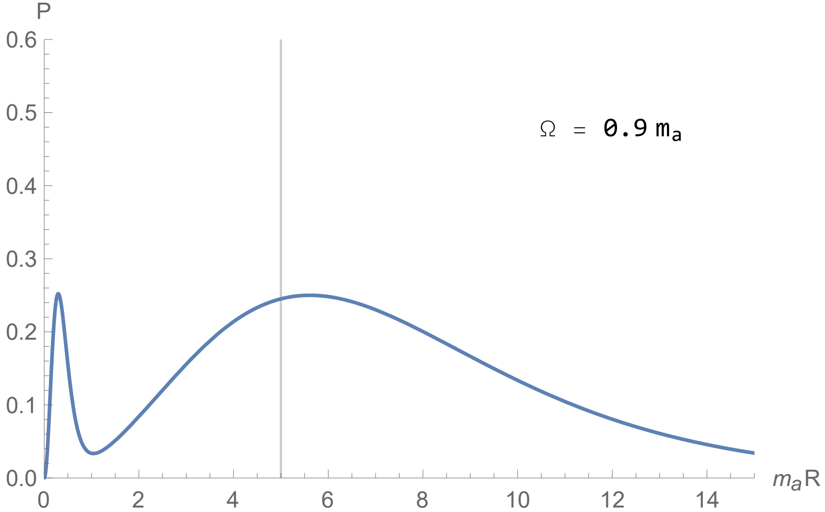

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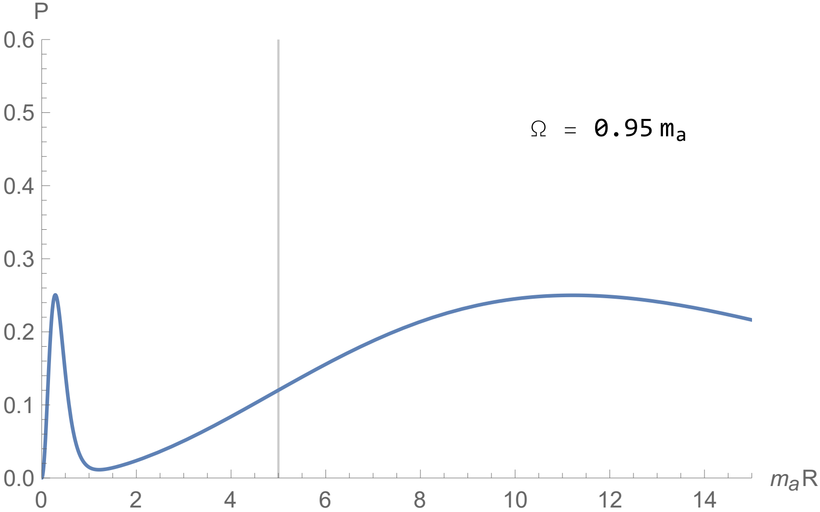

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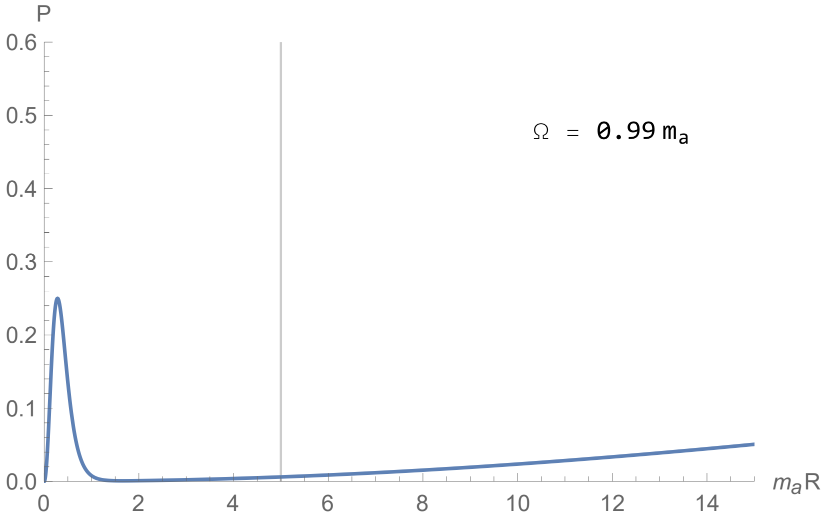

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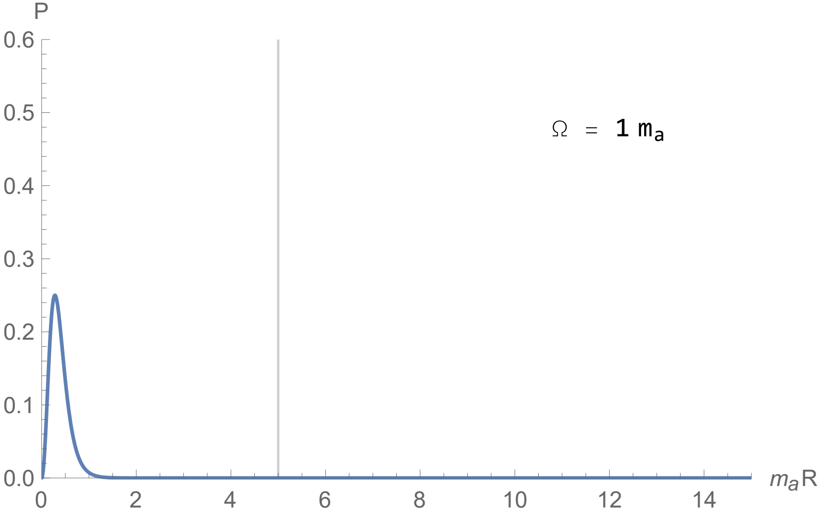

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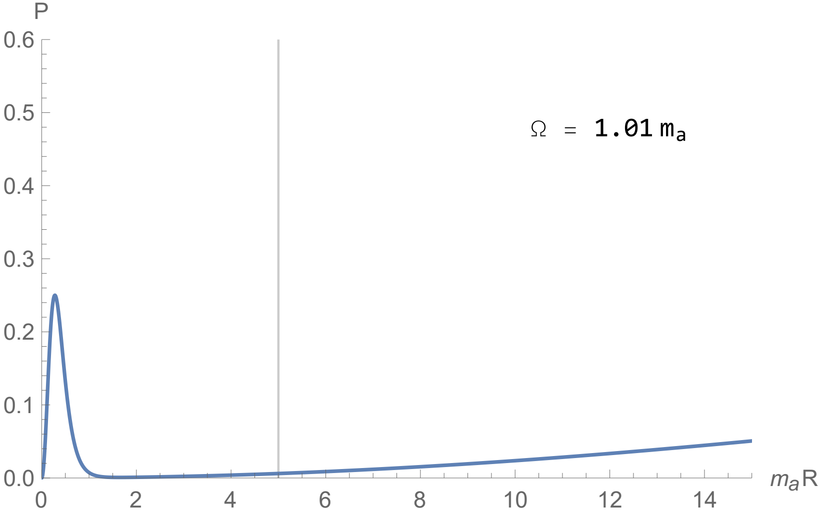

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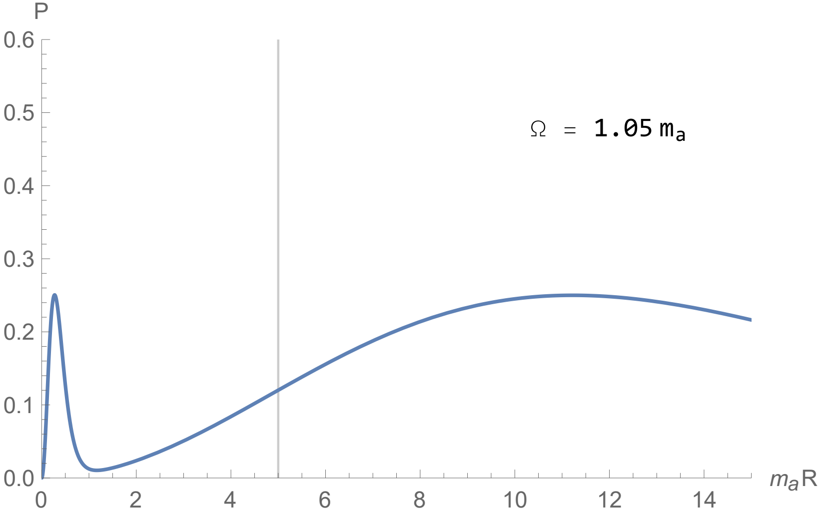

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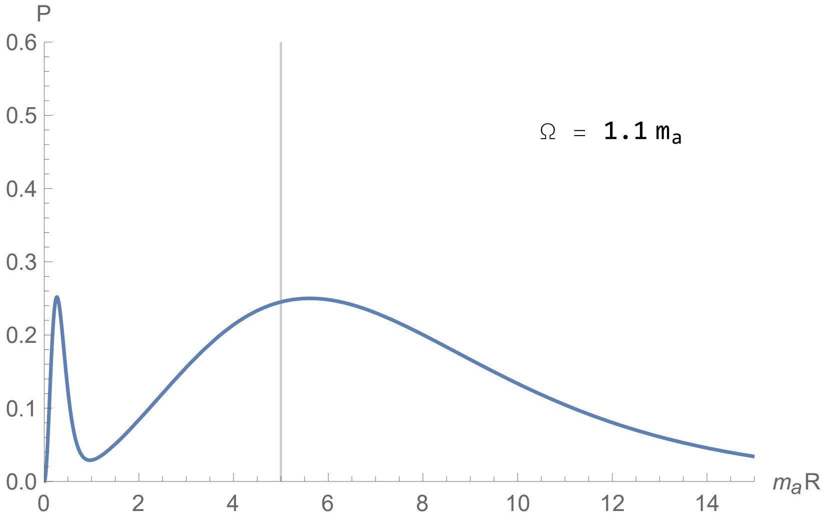

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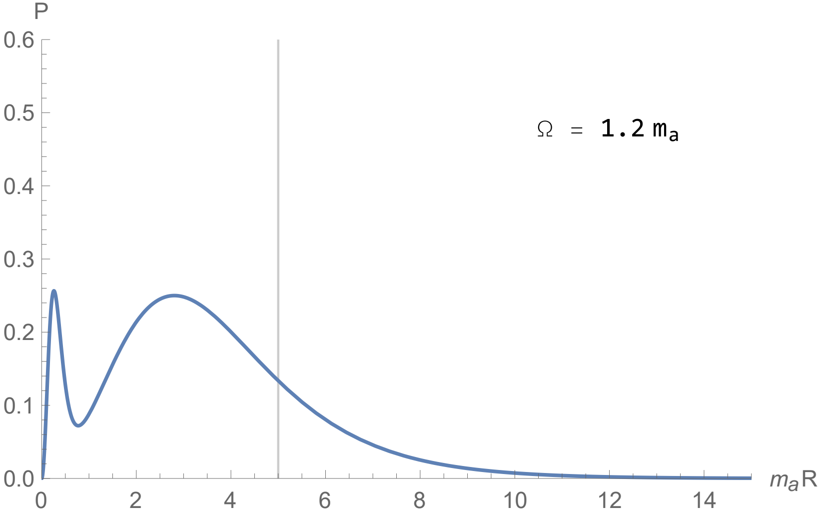

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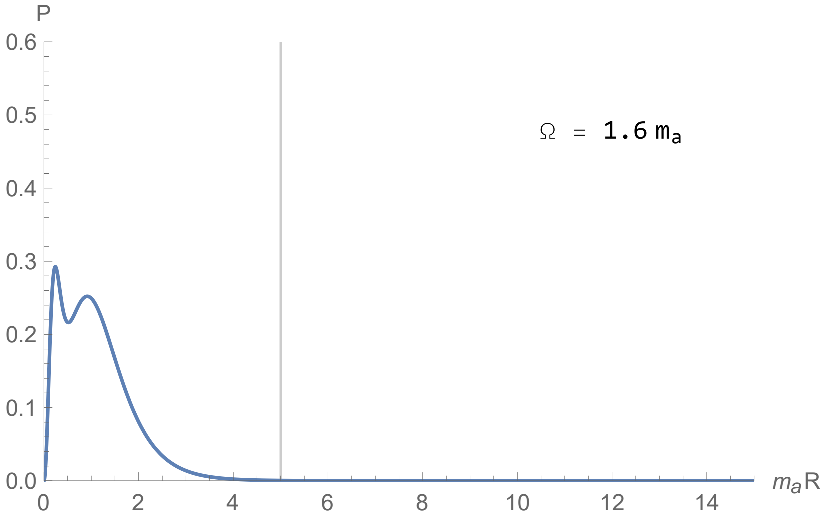

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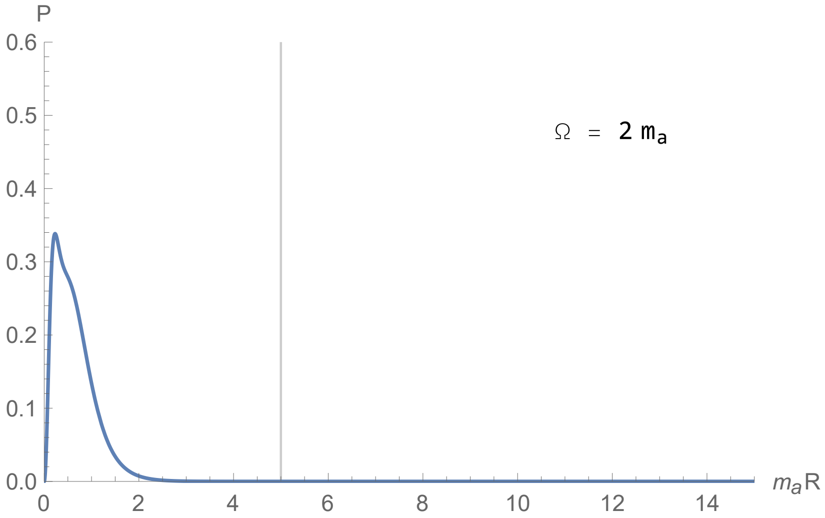

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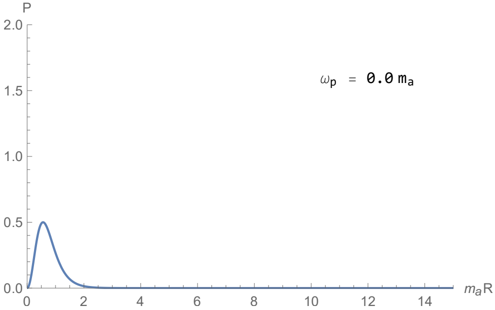

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