Axions in Astrophysics

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Axions: the motivation

Axions as dark matter

Axions as IR remnants of the UV

Axions as a solution to the strong CP problem

Light Pseudoscalars

(QCD axion)
Motivation #1: The strong CP problem

Why does QCD seem to conserve charge-parity (CP) symmetry?

CP violating term in QCD Lagrangian:

$$\mathcal{L}_{CPV} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G \tilde{G}$$

Neutron electric dipole moment (eDM) $\propto \bar{\theta}$

Current limit: $\bar{\theta} \leq 5 \times 10^{-11}$

Abel et al (2020)
The strong CP problem

**Solution:** Introduce goldstone boson $a$ to make theta term dynamical

\[ \mathcal{L}_\theta = - \left( \bar{\theta} + \frac{a}{f_a} \right) \frac{g^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

“QCD Axion”

$m_a \sim 10^{-6} \text{ eV} \left( \frac{10^{12} \text{ GeV}}{f_a} \right)$

Original $f_a \sim$ EW scale

“Invisible axion”: $f_a \gg$ EW scale

QCD generates potential

Neutron eDM = 0

Motivation #2: Dark matter

Galaxy rotation curves
Merging galaxy clusters
Large scale structure
Cosmic microwave background

Requirements:
• Production mechanism
• Cosmologically long-lived
• Feeble interactions

\[
\tau \propto m_a^{-3} \quad \lambda \propto f_a^{-1}
\]

Natural for light axions from high energy scale

~kpc  ~Mpc  ~100 Mpc  ~10 Gpc
Axions from the misalignment mechanism

Equation of motion: 

\[ \ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0 \]

\[ \Omega_{DM} h^2 \sim 0.05 \left( \frac{\bar{\theta}_i}{1} \right)^2 \left( \frac{f_a}{10^{17} \text{ GeV}} \right)^2 \left( \frac{m_a}{10^{-22} \text{ eV}} \right)^{1/2} \]
Axions from topological defects

*Cosmic strings network in the early Universe*

Strings/walls dominate for QCD axion with high inflationary scale

*Axion density field*

Collapse leads to “axion miniclusters” and “axion stars”

Also leads to rich cosmic structure

Image credit: Bernabou et al (2023)

Image credit: Ellis et al (2022)
Motivation #3: Probes of high energies

For some recent examples see e.g.: Agrawal & Platschorre (2023), Gendler, Marsh, McAllister, Moritz (2023), Agrawal, Nee, Reig (2022), Agrawal, Hook, Huang (2020)…
Example: axions as a probe of GUTs

Detection of axion here implies:

- QCD axion is tuned light
- no GUT
Astrophysics as a laboratory

Can we use Nature’s laboratories to search for axions?
Parameter space overview

\[ \mathcal{L} \supset - \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]

- ✓ Dark matter
- ✓ QCD Axion

https://cajohare.github.io/AxionLimits/
Axion decay

\[ \tau_a \propto \frac{g_{\alpha \gamma}^2}{m_a^3} \]

Upside: Very robust
Difficulty: Hard to make progress

https://cajohare.github.io/AxionLimits/
Simulating axion decay

\[ \tau_a \propto \frac{g_{a\gamma\gamma}^2}{m_a^3} \left(1 + 2f_\gamma\right)^{-1} \]

\[ E_\gamma \sim m_a/2 \]

\[ \nu_\gamma \sim \frac{m_a}{2} \]

\[ 2f \]

\[ m_a [\text{eV}] \]

\[ \nu_\gamma [\text{GHz}] \]

\[ \theta < 1 \text{ deg} \]

\[ \theta < 0.01 \text{ deg} \]

\[ f_{\text{CMB}} \]

\[ f_{\text{ext-bkg}} \]

\[ f_{\text{gal}} \]

Simulating axion decay

\[ \tau_a \propto \frac{g_{a\gamma\gamma}^2}{m_a^3} \left(1 + 2f_\gamma\right)^{-1} \]

X-ray / Gamma-ray searches for axions
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Astrophysical source of x-rays / gamma-rays

High-Energy Photons

Galactic/Cluster Magnetic Field

High-Energy Axions

Energy

Flux
X-ray / Gamma-ray searches for axions

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Flux

$p_{\gamma \rightarrow a} \sim g_{a\gamma} B^2 \text{[Length]}^2$

$\gamma$ $\rightarrow$ $a$ $\rightarrow$ $B$
X-ray / Gamma-ray searches for axions

Astrophysical source of x-rays / gamma-rays

High-Energy Photons

Galactic/Cluster Magnetic Field

High-Energy Axions

\[ p_{\gamma \rightarrow a} \sim g_{\gamma a}^2 B^2 \text{[Length]}^2 \]

\[ \begin{cases} \text{Length of magnetic field} \\ (k_\gamma - k_a)^{-1} \sim 2E_\gamma / m_a^2 \end{cases} \]

\( (m_a \rightarrow 0) \) (Large \( m_a \))
Magnetic fields, ugh….

See e.g. Matthews et al (2022), Carenza et al (2023)

Upside: Reasonably straight-forward physics

Difficulty: Large-scale magnetic fields *(progress limited by finding idealised systems that we understand)*
Axions & Gravity

https://cajohare.github.io/AxionLimits/
The gravitational footprint of ultralight axions

\[ \ddot{\delta}_k + 2H\dot{\delta}_k + \left(\frac{k^4}{4m^2a^2} - 4\pi G\bar{\rho}\right)\delta_k = 0 \]

Gradient ("quantum") pressure

Quantum mechanics limits "packing" of low mass particles

\[ \delta x \times \delta v \gtrsim m^{-1} \]
The gravitational footprint of ultralight axions

Density profile
ultra-faint dwarf

Implications:
• Soliton core at center
• Heat stellar orbits

Upside: Purely gravitational
Difficulty: Modelling small scales / feebly bound objects

Image credit: Dalal & Kravtsov (2022)
See e.g. reviews by Hui (2014), Niemeyer (2020), Ferreira (2021), O’Hare (2024)
Axions near extreme compact objects

https://cajohare.github.io/AxionLimits/
Axions near extreme compact objects

https://cajohare.github.io/AxionLimits/
Enhancing axion-photon transitions

\[ p_{\gamma \rightarrow a} \sim g_{a \gamma}^2 B^2 [\text{Length}]^2 \]

\[ (k_\gamma - k_a)^{-1} \sim \frac{2E_\gamma}{m_a^2} \]  

Length of magnetic field  

Limitation: Strength of \( B \) and \( (k_\gamma - k_a) \)

\( (m_a \rightarrow 0) \)  

\( \text{(Large } m_a \text{)} \)
Enhancing axion-photon transitions

\[ p_{\gamma \rightarrow a} \sim g_{a\gamma}^2 B^2 [\text{Length}]^2 \]

\[
\begin{align*}
\text{Length of magnetic field} &\sim \frac{1}{(k_\gamma - k_a)^{-1}} \sim \frac{2E_\gamma}{m_a^2} \\
\text{(Large } m_a) \end{align*}
\]

Limitation: Strength of \( B \) and \((k_\gamma - k_a)\)

Modify photon dispersion relation

(E.g. in a cold plasma \( k_\gamma = \sqrt{\omega^2 - \omega_p^2} \), and \( k_a \sim k_\gamma \) possible)

Compact Objects
Resonant axion transitions in radio

Resonant axion transitions in radio

Radio lines near neutron stars


Upside: Unique signatures

Difficulty: Modelling
Axion production in pulsars

\[(\Box + m_a^2) a = g_{\alpha\gamma} \vec{E} \cdot \vec{B}\]

Rotating \(\vec{B}\) induces \(\vec{E}\)

Plasma cannot screen \(\vec{E}\) everywhere

“Vacuum gaps” support \((\vec{E} \cdot \vec{B})(t) \neq 0\)
Axion production in pulsars

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Axion production in pulsars

Resonant photon production from locally sourced axions

Upside: No assumption of dark matter
Difficulty: Modelling more difficult
Difficulty/Upside: Emission scales like $g_{a\gamma\gamma}^4$

Noordhuis, Prabhu, SJW, Cruz, Chen, Weniger (2022)
Axion clouds around pulsars

Axion mass

$10^{-10} \text{eV} \lesssim m_a \lesssim 10^{-4} \text{eV}$

Noordhuis, Prabhu, Weniger, SJW (2023), Caputo, SJW, Philippov, Jacobson (2023)

$m_a = 10^{-6} \text{eV}
\quad g_{a\gamma\gamma} = 5 \times 10^{-13} \text{GeV}^{-1}$
Observables from axion clouds

\[ \nabla \cdot E = \rho - g_{a\gamma}B \cdot \nabla a \]

- Back-reaction
- Periodic modulation of radio emission
- Axions in under-dense plasma produce radio
- Radio Endpoint
- Axion + Magnetic field = Oscillating E dipole
- Non-resonant emission
- Transient Bursts
- At end of lifetime, all axions \( \rightarrow \gamma \)

Noordhuis, Prabhu, Weniger, SJW (2023)
Caputo, SJW, Philippov, Jacobson (2023)
Sensitivity to axion clouds

**Axion Back-Reaction**

- Continuum Emission
- Transients

![Graphs showing sensitivity to axion clouds](image)

**Upside:** Very powerful new probes

**Difficulty:** Work to be done on modelling
Black hole superradiance

Gravity creates bound states

Axion

$\Omega$

$e^{-i\omega t + i m \phi}$

Black hole

Amplification

$\omega < m\Omega$

Black hole superradiance

Gravity creates bound states

Axions extract black hole spin, and grow dense clouds

Axion superradiance

Black hole spin distributions

Gravitational waves from axion cloud

Image credit: Brito & Pani (2022)
Superradiance in the non-interacting limit

\((\Box + \mu^2) a = 0\)

Bound states form discrete hydrogen-like energy spectrum: \(|nlm\rangle\)

\[ \omega_{nlm} = E_{nlm} + i\Gamma_{nlm} \]
Superradiance in the non-interacting limit

\((\Box + \mu^2) a = 0\)

Bound states form discrete hydrogen-like energy spectrum: \(|nlm\rangle\)

**Black hole spin**

\(\Omega \sim \omega\)

\(\Omega \sim \omega/2\)

**Normalized occupation numbers**

\(|211\rangle\)

\(|322\rangle\)
Self-interactions in superradiance

\[ \mathcal{L} \supset \frac{m_a^2}{f_a^2} a^4 \]

\[ |211\rangle \quad |322\rangle \quad |322\rangle \quad |211\rangle \]

\[ |211\rangle \quad \text{BH} \quad |322\rangle \quad \infty \]

Self-interactions in superradiance

Large self couplings dramatically slow spin extraction!

Self-interactions in superradiance

\[ n = 4 \text{ is a mess} \ldots \]

Baryakhtar et al (2021), SJW & Mummery (To appear)
Superradiance limits

**Upside:** Very powerful, can cover huge range of parameter space

**Difficulty:** Modelling self-interactions (especially near black hole) is not fully understood

**Difficulty from astro side:**
- How to do we obtain reliable spin measurements
- Environmental effects (*not isolated objects!*)

See e.g. Baumann et al (2019, 2022)
Conclusions

- **Self-interactions**
- **Spin inference**
- **Astrophysics**

- **Gravitational Footprint**
- **X-ray/Gamma-ray**
- **Pulsars**
- **Black holes**
- **Axion Decay**

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