5.4 Alternative ultra-light DM candidates

5.4.1 Axion-like particles

Goldstone theorem:

A spontaneously broken global symmetry gives rise to a massless "Goldstone" boson $a$

$\Rightarrow$ Shift symmetry $a \rightarrow a + \epsilon$

If the global symmetry is not exact, the new boson acquires a small mass ("Pseudo-Goldstone" boson)

Examples:

- Axion

  Global symmetry: Peccei-Quinn symmetry

  Explicit breaking: QCD effects at scale $f_a$

  $\Rightarrow m_a \sim \frac{f_T}{f_a} \ll 1$

- Majorons

  Global symmetry: Lepton number

  Spontaneously broken in models of neutrino mass generation
String theory axions

String theory requires 10 dim. out of which 6 need to be compactified.

Closed cycles give rise to spin-0 fields with vanishing potential.

Realistic string theories can have 100s of axions ("Axiverse")

Allowed interactions of PGBs dictated by shift symmetry

\[ L_{\text{int}} = \frac{1}{32\pi^2} \frac{a}{b_a} G^{a\mu\nu} \bar{G}^{a\mu\nu} \left( -\frac{1}{4} g_{aj} a F_{\mu\nu} F^{\mu\nu} + \sum \frac{2}{c} g_{ae} z_a \bar{E} y^c y^s y + \sum \frac{2}{q} g_{aj} z_a \bar{y} y^j y^q \right) \]

- \( g_{aj}, g_{ae}, g_{aj} \) are typically of order \( \frac{1}{\beta a} \) but vary from model to model

- \( w_a \) is a free parameter!
5. 4. 2 Hidden photons

Similar to the dark photon $A'$ discussed in § 4.2 + 4.3

$\Rightarrow$ New U(1)' gauge boson coupling to SM particles via kinetic mixing $\varepsilon$

$\Rightarrow$ Very small mass $M_{A'} \ll 1$ MeV

$\Rightarrow$ Only allowed decay channel

\[ A' \rightarrow e^+ e^- \]

$\Rightarrow$ Lifetime long compared to age of Universe

Production in the early Universe via non-thermal processes:

- Oscillations
  \[ \gamma \rightarrow A' \]

- Coupling to electrons
  \[ \gamma \rightarrow e^- e^+ A' \]

Can be all of DM for $\varepsilon \sim 10^{-12}$ - $10^{-3}$
5.5 Astrophysical constraints on axions (and other ultra-light particles)

Stars can produce axions via a number of processes:

Prima-hoff process:

\[ R \xrightarrow{\text{gap}} a \]
\[ e^- \]
\[ e^- \]

Bremsstrahlung:

\[ e^- \xrightarrow{g_{ae}} e^- \]
\[ \gamma \]
\[ z \]
\[ z \]

Compton scattering:

\[ e^- \xrightarrow{g_{ae}} a \]
\[ R \xrightarrow{\gamma} e^- \]

Typical energy \( \sim \) core temperature of star

\( E_a \sim T_{\text{star}} \) (e.g. \( T_{\odot} \sim 1 \text{ keV} \))

For \( g_{ae} = 10^{-10} \text{ GeV}^{-1} \) the axion flux corresponds to 0.2% of sun's luminosity

\[ \Rightarrow \text{Flux on Earth: } F_a = 4 \cdot 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \]
5.5.1 Helioscopes

Basic idea:

\[ P_{\gamma} \propto \mathcal{F}(q \cdot L) \text{ with } q = \frac{m_a^2}{2E_a} \]

which requires \( q \cdot L \lesssim 1 \)

But now \( E_a \sim \text{keV} \) (and \( L \sim 10 \text{ m} \))

\( \Rightarrow \) Sensitivity up to \( m_a \sim 10 \text{ meV} \)

\( \Rightarrow \) Even larger masses possible when using buffer gas

\( \Rightarrow \) Can probe heavier axions than other searches

CAST (at CERN)

- \( B \sim gT \)
- Trace sun for several hours per day
- Constraint: \( g_{mp} \lesssim 10^{-10} \text{ GeV}^{-1} \)

IAXO will improve this to \( 5 \cdot 10^{-12} \text{ GeV}^{-1} \)

\( \Rightarrow \) probe QCD axions in meV range
5.5.2 Axion electric effect

If \( g_{ae} \neq 0 \), axions can ionize neutral atoms

\[ a \rightarrow e^- \rightarrow \odot \rightarrow e^- \]

\[ \Rightarrow \text{Search for ionization events in low-background detectors} \]

\[ \Rightarrow \text{Same technology as for WIMP direct detection} \]

\[ \text{LUX: } g_{ae} \lesssim 10^{-8} \text{ GeV}^{-1} \]

5.5.3 Horizontal Branch (HB) stars

All stars can produce axions.

Even if the axions are undetected, they provide an additional energy loss mechanism.

\[ \Rightarrow \text{Stars cool faster} \]

Particularly sensitive:

Stars that start burning helium after becoming red giants

\[ T_{\text{HB}} \sim 10 \text{ keV} \]
Axion emission reduces lifetime of HB stars

\[ \Rightarrow \text{Observations require} \]
\[ g_{\text{ax}} \ll 10^{-10} \text{ GeV for } m_a \ll 10 \text{ keV} \]

\[ \Rightarrow \text{Excludes QCD axions with } m_a \gg 10 \text{ eV} \]

5.5.4 Cooling hints

White dwarfs have electron-degenerate cores

\[ \Rightarrow \text{efficient axion emission if} \]
\[ g_{\text{ax}} \neq 0 \]

Can measure energy loss via change of pulsation period \((P' / P)\)

\[ \Rightarrow \text{Several systems are found to cool more quickly than expected} \]

\[ \Rightarrow \text{Hint for axions?} \]

Requires \( g_{\text{ax}} \sim 10^3 \text{ GeV} \)
\( m_a \sim 10 \text{ meV} \)

\[ \Rightarrow \text{outside of preferred DM window} \]
5.5.5 Supernova 1987A

Mechanism: Core - collapse SN

- Nuclear fusion insufficient to provide pressure against gravity
- Core heats up to MeV temperatures

=> Significant fraction of rest mass converted into neutrino pulse

=> Visible light is only emitted once shock wave reaches stellar surface

SN 1987a: Distance: 50 kpc

- 25 neutrino events observed within ~10 seconds across 3 experiments
- Visible light only observed several hours later

If axions exist, they can be produced in the SN core and be converted into photons in the galactic magnetic field.
$\Rightarrow$ $\gamma$-ray burst coincident with neutrinos

Conversion again requires coherence:

$q \cdot \mathcal{E} < 1$

$E_a \approx 50 \text{ MeV}$

$l \approx 50 \text{ kpc}$

$\Rightarrow m_a \approx 10^{-10} \text{ eV}$

Very strong bound for ultra-light axion-like particles:

$g_{\gamma p} \lesssim 5 \times 10^{-12} \text{ GeV}^{-1}$

Note: Even if axions are not converted, one finds

$g_{\gamma p} \approx 6 \times 10^{-9} \text{ GeV}^{-1}$

from heat loss
5.6 Fuzzy dark matter

In Lecture 1: Determined shapes of DM halos by solving eq. of hydrostatic equilibrium

\[ \frac{k_B T}{G m} \frac{d}{dr} \left( \frac{r^2}{r} \frac{dE}{dr} \right) = 4 \pi r^2 \Sigma(r) \]

What if quantum effects become important?

\[ \lambda_{dB} = \frac{\hbar}{m_{\text{DM}}} \sqrt{\frac{R}{m(e) c}} \]

\[ \lambda_{dB} \sim \text{kpc} \quad \text{for} \quad m_{\text{DM}} \sim 10^{-22} \text{eV} \]

For QCD axions: \[ m_a = \frac{m_{\pi} f_{\pi}}{2 f_a} \]

\[ \gtrsim \frac{m_{\pi} f_{\pi}}{2 m_{\text{pl}}} \approx 5 \cdot 10^{-13} \text{eV} \]

But axion-like particles can have much smaller masses.

\[ \Rightarrow \text{Need to replace} \quad S \rightarrow m |\psi|^2 \]

where \( \psi \) is the axion wave function

\[ \Rightarrow \text{Gravitational potential } \Phi \text{ given by} \]

\[ \nabla^2 \Phi = 4 \pi G m |\psi|^2 \]

\[ \Psi \text{ must satisfy Schrödinger equation} \]
\[- \frac{t^2}{2m} \nabla^2 \psi + m \bar{\phi} \psi = m E \psi\]

Numerical solutions imply upper bound on central densities of DM halos:

\[S_c \leq 300 \ \text{GeV/cm}^3 \left( \frac{m_p}{10^{-22} \text{eV}} \right)^6 \left( \frac{M_{\text{halo}}}{10^5 M_\odot} \right)^8\]

and lower bounds on their size

\[r \geq 0.3 \ \text{kpc} \left( \frac{m_p}{10^{-22} \text{eV}} \right)^{-2} \left( \frac{M_{\text{halo}}}{10^5 M_\odot} \right)^{-1}\]

\[\Rightarrow \text{Axion-like particles with } m_a \leq 10^{-22} \ \text{eV} \text{ cannot be all of DM}
\]

But for \[m_a \sim 10^{-22} - 10^{-21} \ \text{eV}\] agreement better than for CDM.