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 $a \to a + \varepsilon$

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

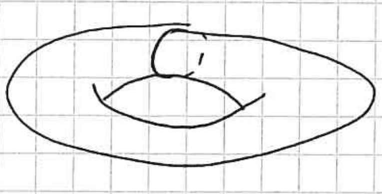
Examples: – Axion
Global symmetry: Peccei-Quinn symm
broken at f_a
Explicit breaking: QCD effects at scale f_π

$$\Rightarrow m_a \sim \frac{f_\pi}{f_a} \ll 1$$

– 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

$$\mathcal{L}_{int} = \frac{1}{32\pi^2} \frac{a}{f_a} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$+ \sum_e g_{ae} \partial_\mu a \bar{e} \gamma^\mu \gamma^5 e + \sum_q g_{aq} \partial_\mu a \bar{q} \gamma^\mu \gamma^5 q$$

- $g_{a\gamma}$, g_{ae}, g_{aq} are typically of order $\frac{1}{f_a}$ but vary from model to model

- m_a is a free parameter!

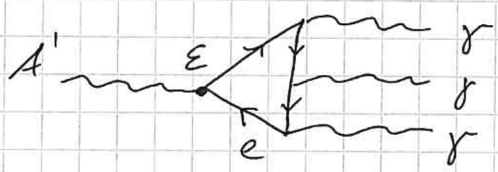
5.4.2 Hidden photons

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

=> New $U(1)'$ gauge boson coupling to SM particles via kinetic mixing ε

=> Very small mass $m_{A'} \ll 1$ MeV

↳ Only allowed decay channel

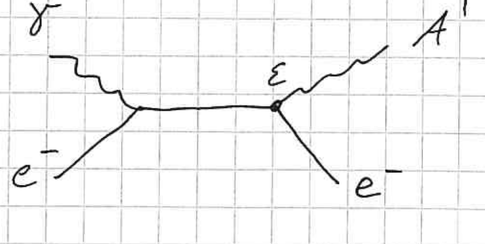


=> Lifetime long compared to age of Universe

Production in the early Universe via non-thermal processes:

oscillations

coupling to electrons



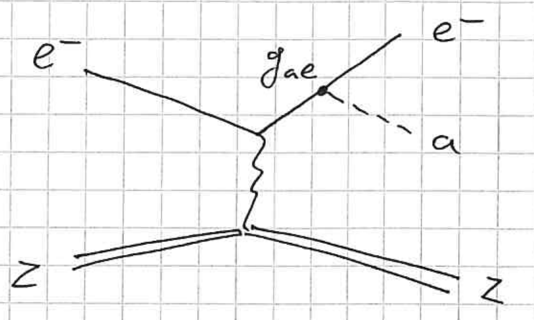
Can be all of DM for $\varepsilon \sim 10^{-12} - 10^{-9}$

5.5 Astrophysical constraints on axions (and other ultra-light particles)

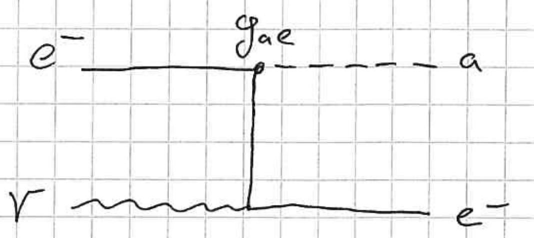
Stars can produce axions via a number of processes:

Primakoff process:

Bremsstrahlung:



Compton scattering:



Typical energy ~ core temperature of star

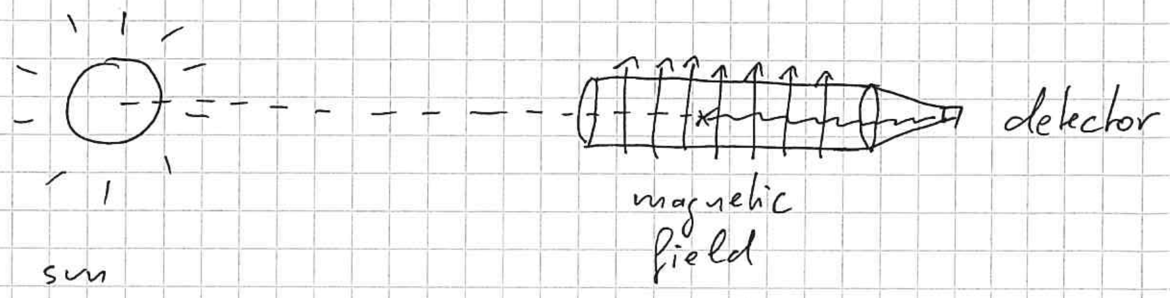
$$E_a \sim T_{star} \quad (\text{e.g. } T_{sun} \sim 1\,\text{keV})$$

For $g_{a\gamma} = 10^{-10}\,\text{GeV}^{-1}$ the axion flux corresponds to 0.2% of sun's luminosity

$\Rightarrow$ Flux on Earth: $\Phi_a \sim 4 \cdot 10^{11}\,\text{cm}^{-2}\,\text{s}^{-1}$

5.5.1 Helioscopes

Basic idea:



As for LSW experiments,

$P_{a\gamma} \sim \mathcal{F}(q \cdot L)$ with $q = \frac{m_a^2}{2E_a}$

which requires $q \cdot L \lesssim 1$

But now $E_a \sim$ keV (and $L \sim 10\,m$)

=> Sensitivity up to $m_a \sim 10$ meV

↳ Even larger masses possible when using buffer gas

=> Can probe heavier axions than other searches

CAST (at CERN)

- $B \sim 9T$
- Trace sun for several hours per day
- Constraint: $g_{a\gamma} \lesssim 10^{-10}\ GeV^{-1}$

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

=> probe QCD axions in meV range

5.5.2 Axioelectric effect

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

=> Search for ionization events in low-background detectors

↳ Same technology as for WIMP direct detection

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

=> Stars cool faster

Particularly sensitive:
Stars that start burning helium after becoming red giants

$T_{HB} \sim 10\ \text{keV}$

Axion emission reduces lifetime of HB stars

$\Rightarrow$ Observations require $g_{a\gamma} \lesssim 10^{-10}$ GeV for $m_a \lesssim 10$ keV

$\Rightarrow$ Excludes QCD axions with $m_a \gtrsim 10$ eV

5.5.4 Cooling hints

White dwarfs have electron-degenerate cores

$\Rightarrow$ efficient axion emission if $g_{ae} \neq 0$

Can measure energy loss via change of pulsation period $(\dot{P}/P)$

$\Rightarrow$ Several systems are found to cool more quickly than expected

$\hookrightarrow$ Hint for axions?

Requires $f_a \sim 10^9$ GeV
$m_a \sim 10$ meV

$\Rightarrow$ 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

SN1987a: 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

$\Rightarrow$ γ-ray burst coincident with neutrinos

Conversion again requires coherence:

$$q \cdot \ell < 1$$

$$E_a \sim 50 \text{ MeV}$$

$$\ell \sim 50 \text{ kpc}$$

$$\Rightarrow \quad m_a \lesssim 10^{-10} \text{ eV}$$

Very strong bound for ~~lit~~ ultralight axion-like particles:

$$g_{a\gamma} \lesssim 5 \cdot 10^{-12} \text{ GeV}^{-1}$$

Note: Even if axions are not converted, one finds

$$g_{a\gamma} \lesssim 6 \cdot 10^{-9} \text{ GeV}^{-1}$$

from heat loss

5.6 Fuzzy dark matter

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

$$\frac{k_B T}{G m} \frac{d}{dr}\left(\frac{r^2}{\rho} \frac{d\rho}{dr}\right) = 4\pi r^2 \rho(r)$$

What if quantum effects become important?

$$\lambda_{dB} = \frac{h}{m_{DM}} \sqrt{\frac{R}{M(R)\, G}}$$

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

For QCD axions: $m_a = \dfrac{m_\pi f_\pi}{2 f_a}$

$$\gtrsim \frac{m_\pi f_\pi}{2 M_{Pl}} \sim 5 \cdot 10^{-13}\,\text{eV}$$

But axion-like particles can have much smaller masses.

=> Need to replace $\rho \to m|\psi|^2$ where ψ is the axion wave function

=> Gravitational potential Φ given by

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

ψ must satisfy Schrödinger equation

$$-\frac{\hbar^2}{2m}\nabla^2\psi + m\Phi\psi = mE\psi$$

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

$$\rho_c \leq 300\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}\left(\frac{m_{DM}}{10^{-22}\,\mathrm{eV}}\right)^6\left(\frac{M_{halo}}{10^9 M_\odot}\right)^4$$

and lower bounds on their size

$$r \gtrsim 0.3\ \mathrm{kpc}\left(\frac{m_{DM}}{10^{-22}\,\mathrm{eV}}\right)^{-2}\left(\frac{M_{halo}}{10^9 M_\odot}\right)^{-1}$$

$\Rightarrow$ Axion-like particles with $m_a \lesssim 10^{-22}\,\mathrm{eV}$ cannot be all of DM

But for $m_a \sim 10^{-22} - 10^{-21}\,\mathrm{eV}$ agreement better than for CDM!