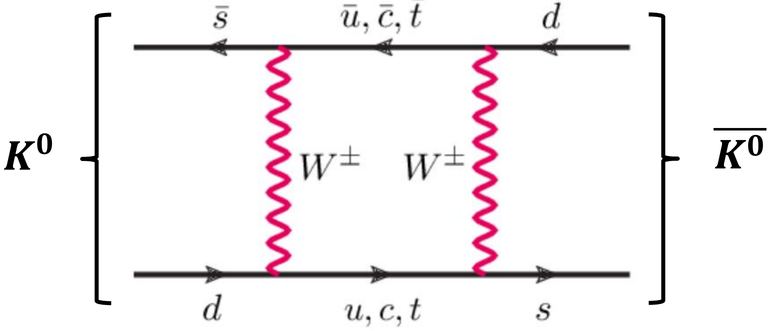
CP violation in the quark sector



The neutral meson formed by s and d - (anti) quarks is always a mixture of two states since *strangeness* is not conserved in the weak interaction.

→ Observed particles correspond to mixture of $\boldsymbol{K^0}$ and $\overline{\boldsymbol{K^0}}$. Assume CP-invariance

$$C|\,\boldsymbol{K^0}, \boldsymbol{p} >= -|\overline{\boldsymbol{K^0}}, \boldsymbol{p} >$$

For Kaons (negative parity)

$$P|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0} >= -|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0} > \text{and } P|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0} >= -\,|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0} >$$

Thus:

$$CP|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0} >= \,|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0} > \text{and } CP|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0} >= \,|\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0} >$$

➔ Thus there are two CP Eigenstates:

$$|\boldsymbol{K^0_{1/2}}, \boldsymbol{p} = \boldsymbol{0} >= \frac{1}{\sqrt{2}}\{|\,\boldsymbol{K^0}, \boldsymbol{p} = \boldsymbol{0} > \pm\,|\overline{\boldsymbol{K^0}}, \boldsymbol{p} = \boldsymbol{0} >\}$$

With

$$CP|\boldsymbol{K^0_{1/2}}, \boldsymbol{p} = \boldsymbol{0} >= \pm|\boldsymbol{K^0_{1/2}}, \boldsymbol{p} = \boldsymbol{0} >$$

$\boldsymbol{K^0_1}$ ALWAYS has to decay into states with *CP=1*

$\boldsymbol{K^0_2}$ ALWAYS has to decay into states with *CP=-1*

Experimentally: Two states observed:

$\boldsymbol{K^0_L} \to \boldsymbol{\pi\pi\pi}$ and $\boldsymbol{K^0_S} \to \boldsymbol{\pi\pi}$ corresponding to (CP states) $\boldsymbol{K^0_L} = \boldsymbol{K^0_2}$ and $\boldsymbol{K^0_S} = \boldsymbol{K^0_1}$

1964: Christenson, Cronin, Fitch and Turlay at Brookhaven national Lab also observed: ➔
$\boldsymbol{K^0_L} \to \boldsymbol{\pi\pi}$ ➔**Nobel Prize 1980**

This is a CP violating decay! (similar CP violating decays appear in b-mesons: BELLE/Babar)

→ CP violation appears as complex phase in the CKM matrix

CP violation in the QCD vacuum

SU(3)$_c$ is a non-Abelian gauge group: gauge transformations of the Lie group are not commutative.

Consequence: QCD has “large gauge transformations”, which come with gauge in-equivalent ZERO energy states $|n\rangle$, separated by potential barrier. Potential barrier can be tunneled (Instantons) or “jumped” thermally (Sphalerons).

→No single $|n\rangle$ (including $|0\rangle$) can be a stable vacuum state (mixing!)

→Physical ground state is defined by gauge invariant superposition of vacuum states:
$|\theta\rangle = \sum_n e^{in\theta}|n\rangle$

For couplings this means: Evaluating possible amplitudes
→add a general CP violating term to the Lagrangian:

$$\boldsymbol{\Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu}}$$

The strong CP problem and the PQ mechanism: The early universe as a source for axions

As shown before: there are two INDEPENDENT sources for CP violation in QCD.
Physically only one CP violating phase will appear:
$\theta_{eff} = \bar{\theta} = \theta - (phase\ of\ CKM\ matrix)$
leading to additional CP violating term in the QCD Lagrangian:

$$\boldsymbol{\overline{\Theta} \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu}}$$

With α_s the strong coupling constant and $G_{\mu\nu a}$ and $\tilde{G}_a^{\mu\nu}$ the gluon field and its dual.

Consequence of non-vanishing$\bar{\theta}$:

Finite electric dipole moment of elementary particles:

Nonzero EDMs imply P and T (and CP) violation if the system has a non-degenerate ground state. This can be seen as follows:

$$\vec{d} = |\vec{d}|\frac{\vec{\sigma}}{|\sigma|} \rightarrow \Delta E = |\vec{d}|\frac{\vec{\sigma}}{|\sigma|}\cdot \vec{\mathrm{E}}$$

$$P(\vec{\sigma}\cdot\vec{\mathrm{E}}) = -(\vec{\sigma}\cdot\vec{\mathrm{E}})$$

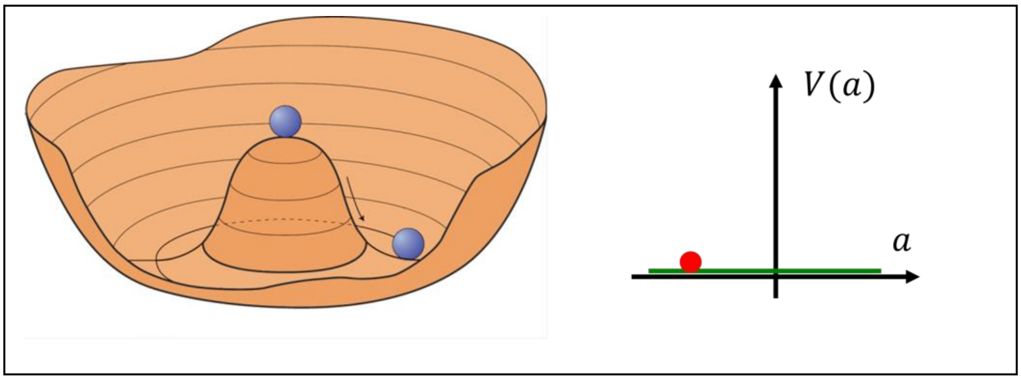
$$T(\vec{\sigma}\cdot\vec{\mathrm{E}}) = -(\vec{\sigma}\cdot\vec{\mathrm{E}})$$

EDM energy Eigenstates are neither P nor T conserving
→ Together with CPT theorem:
Non vanishing dipole moment is CP violating!

→CP violation in QCD should induce EDM in neutron $d_n = \bar{\theta}\cdot 10^{-16} e\ cm$
Experimental limit: $d_n < 3\cdot 10^{-26}\mathrm{e\ cm}$

$$\rightarrow \boldsymbol{\bar{\Theta} = \Theta - \mathbf{arg\ det}\ M_q < 10^{-10}}$$

→Introduce Peccei Quinn symmetry based on spontaneously broken U(1)$_{PQ}$ Complex scalar field: (remember Higgs?). $\boldsymbol{\bar{\Theta}}$ corresponds to phase of the field.

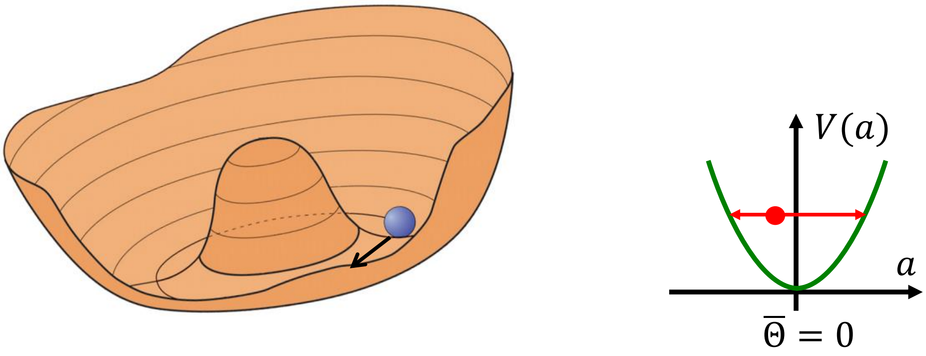


→ Massless Nambu-Goldsonte-Boson

$$\mathbf{a(x)} = \boldsymbol{\bar{\Theta}(x)\cdot f_a}$$

„Topological susceptibility“ (dependence of term $\boldsymbol{G_{\mu\nu a}\tilde{G}_a^{\mu\nu}}$ on $\boldsymbol{\bar{\Theta}}$) of QCD vacuum leads to dependence of field potential on $\boldsymbol{\bar{\Theta}}$**:**

$\boldsymbol{V(\bar{\Theta} = 0)}$ is minimal



→ generation of mass (second derivative of potential at minimum)
→ Pseudo Nambu Goldstone Boson: the Axion

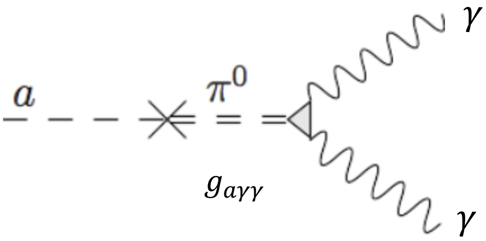
Mass: second derivative at minimum

$$\boldsymbol{m_a = 5.7\mu eV\left(\frac{10^{12}}{f_a}\right)}$$

Correlated to $\boldsymbol{f_a}$ by QCD

Pion has same quantum numbers: also achieves mass through chiral symmetry breaking of QCD!

→ Axion mixes with Pion!



→ In an external static field a photon can be converted into an axion and vice versa. Process can occur in the field of nuclei (Primakoff effect) or in a macroscopic magnetic field.

Frequency of photon: $E = m_a c^2 = h\nu$

→Axion couples to Photons with coupling strength $g_{a\gamma\gamma} \propto 1/f_a$
→Supression by "axion decay constant" f_a : distance between origin of field and minimum of trough): Energy scale of symmetry breaking!

Other couplings possible: axion-electrons, axion-nucleon, axion-EDM, … all suppressed by f_a

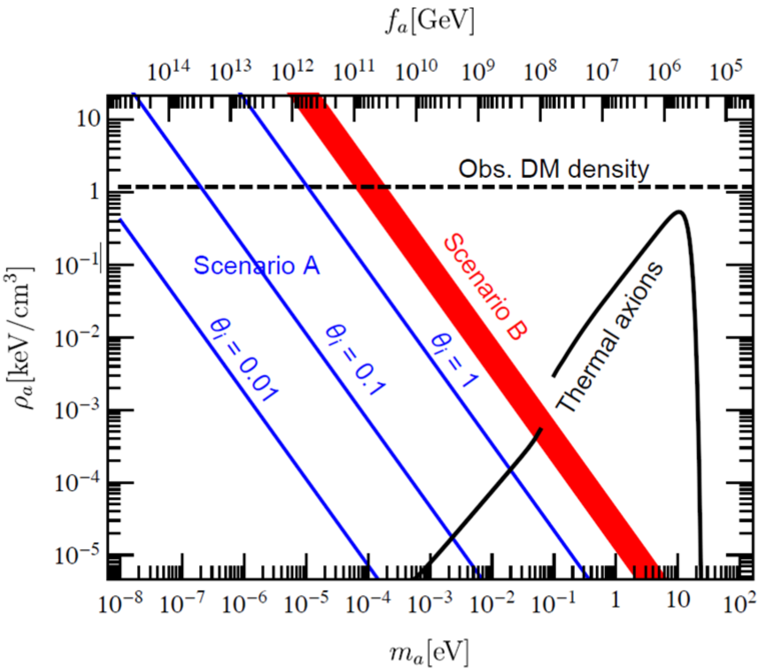
Axions are produces as **NON-THERMAL local field oscillations, i.e. particle population without initial momentum → NON RELATIVISTIC!**

→ If PQ-mechanism solves strong CP problem: Energy is bound in axion field oscillation
→ Ideal cold Dark Matter candidate

Number density depends on initial alignment of θ after symmetry breaking.

Assume: Axions make up all dark matter: If we can calculate axion relic density → prediction for their mass!

Axion relic density depends on: initial misalignment $\overline{\boldsymbol{\Theta_i}}$ and damping of oscillations due to Hubble expansion of universe at QCD phase transition (damping is proportional to ratio between Hubble expansion rate and axion field oscillation frequency)
→ Dependence on axion mass!



Scenario A: Peccei Quinn symmetry breaking occurred before inflation: $\overline{\boldsymbol{\Theta}_i}$ the same everywhere in the observable universe → $0 < |\overline{\boldsymbol{\Theta}_i}| < \pi$

*Scenario B:*Observable universe consists of many patches that were not in causal contact when Peccei Quinn symmetry breaking occurred → Today we see average of all $\overline{\boldsymbol{\Theta}_i}$ of many patches that are now in causal contact → $|\widehat{\overline{\boldsymbol{\Theta}_\iota}}| = \pi/2$!
Problem: Topological defects lead to additional axion population → large uncertainties

Motivation for ALPs

1. Theory

Any Pseudo Nambu Goldstone Boson (Spontaneously broken U1 with explicit symmetry breaking) will come with an Axion like particle

For axions mass is correlated by QCD to spontaneous symmetry breaking energy scale f_a

Any other candidates for Pseudo Nambu goldstone bosons?
→ The Axiverse from string theory arising from compactification of dimensions (Calabi-Yau manifold of extra dimensions)!

→ No correlation between energy scale of spontaneous symmetry breaking and mass, but coupling to photon suppressed by energy scale of spontaneous symmetry breaking (same mechanism of ALP photon mixing and Primakoff efect as for axions).

2. Astrophysical tests

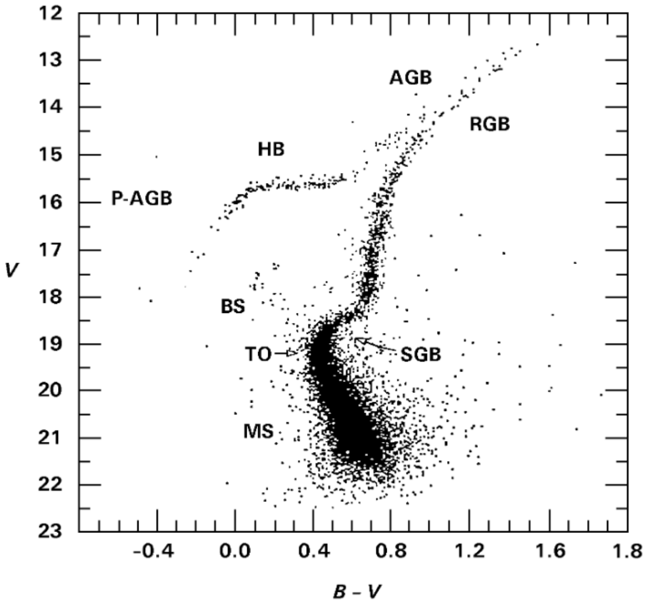
Limits from stellar cooling:

Due to axion couplings: nuclear/electron/gammas:
In “hot media/plasmas”: nuclei can emit axions

→ Stellar cores, supernovae (progenitors), pulsars, white dwarfs would all emit energy in form of axions
→ Additional cooling channel
→ Stellar evolution would be influenced by axion emission
→ Can set limits on f_a!

Most sensitive analysis (Raffelt):
Length of neutrino signal of SN87a:
Core collapse SN: creation of a proto-neutron start with short life time.
During life time of neutron star with T~10MeV: Neutrino emission (almost twenty neutrinos could be observed during several seconds)
Life time of neutron star would be shortened by emission of axions/ALPs due to “axion nuclear Bremsstrahlung”:
→ Length of neutrino burst gives limit on axion Bremsstrahlung → Limit on f_a and m_a

Raffelt, arXiv:hep-ph/0611350

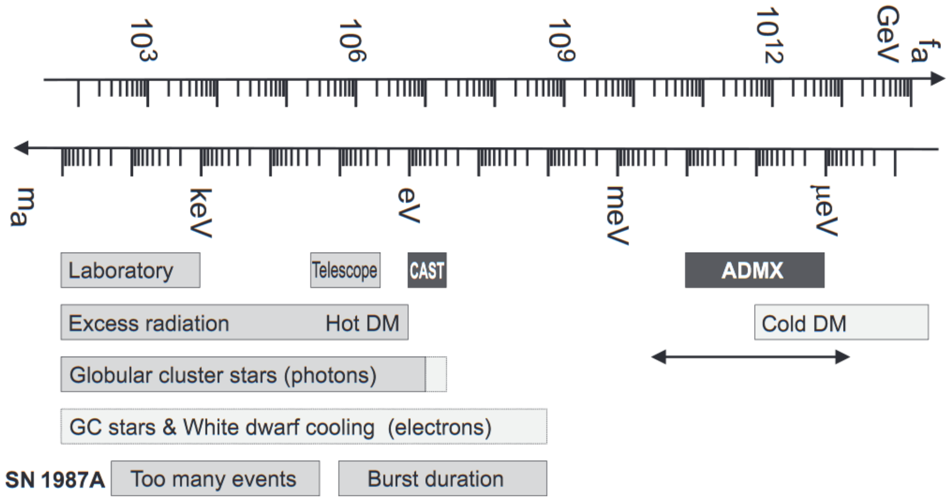


Color-magnitude diagram for the globular cluster M3, basedon 10,637stars. Vertically is the brightness in the visual (V) band, horizontally the dif-ference between B (blue) and V brightness, i.e. a measure of the color and thussurface temperature, where blue (hot) stars lie toward the left. The classificationfor the evolutionary phases is as follows. MS (main sequence): core hydrogenburning. BS (blue stragglers). TO (main-sequence turnoff):central hydrogen is ex-hausted. SGB (subgiant branch): hydrogen burning in a thickshell. RGB (red-giantbranch): hydrogen burning in a thin shell with a growing coreuntil helium ignites.HB (horizontal branch): helium burning in the core and hydrogen burning in a shell.AGB (asymptotic giant branch): helium and hydrogen shell burning. P-AGB (post-asymptotic giant branch): final evolution from the AGB to thewhite-dwarf stage. Taken from Raffelt

Similar arguments for different sources

Primakoff energy loss rate proportional to $\frac{T^7}{\rho}$
→ axion emission rate depends on sequence in stellar evolution
Globular cluster (gravitationally bound system of stars that formed at the same time):

Horizontal branch stars (HB): Helium burning stars after Red Giant Branch (RGB) stage: very hot →.Axion (ALP) coupling to photons $g_{a\gamma\gamma}$could significantly shorten lifetime of HB stars
Count number of stars in HB and compare to RGB expectations based on standard cooling.



Stellar hints for ALPs:

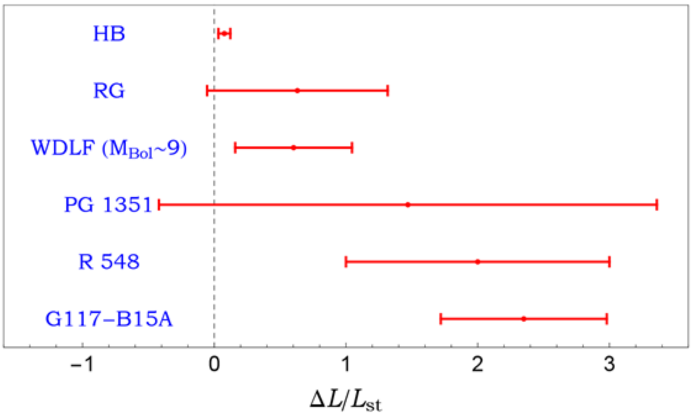
Some systems show cooling anomalies, i.e. more energy loss than expected:

Pulsating white dwarf G117-B15A with P=215s:
Frequency is decreasing due to cooling:
Expected: $\dot{P}_{th} = (2-6)\cdot 10^{-15} ss^{-1}$
Measured: $\dot{P}_{obs} = (12.0 \pm 3.5)\cdot 10^{-15} ss^{-1}$
(two more variable white dwarfs with slightly too efficient cooling found: R548, PG1351)

Possible loss mechanism in white dwarfs: “axion electron Bremsstrahlung”

Some additional hints:
White dwarf luminosity function (number of white dwarfs per luminosity bin) points towards additional cooling

Slight tendency in red giants and HB stars towards extra cooling channel.



Missing energy loss ΔL, normalized over a reference luminosity, L_{ref}

All hints together: If interpreted as ALPs cooling: $g_{a\gamma\gamma} \sim 5 \cdot 10^{-11} GeV^{-1}$

Transparency hint:

Some astrophysical sources can emit very high energy gamma rays $\gg 1\ TeV$. Especially for blazars (AGN with jet pointing towards earth) they can be detected at earth.

But (remember GZK): Photons can interact with infrared band of Extra Galactic Background Light (EBL) resulting from stars, interstellar dust emission, etc.

→ High energy gamma rays are absorbed (pair creation)
→ Optical depth τ not zero
→ Fluxx is attenuated

$$\Phi_{obs}(E_\gamma) = \Phi_s(E_\gamma) \cdot e^{-\tau(E_\gamma, z_s)}$$

Where Φ_s and Φ_{obs} are the fluxes emitted by the source and observed at earth and z_s is the red shift of the source with

$$\tau(E_\gamma, z_s) = \int_0^{z_s} \int_{E_{th}}^{\infty} \sigma_{\gamma\gamma}(E_\gamma, E) \cdot n_{EBL}(z, E)\ dE\ \ dl(z)$$

With $l(z)$ the path of the photons, taking into consideration cosmological evolution (expansion),· $n_{EBL}(z, E)$ the EBL density at redscift z and energy E and $\sigma_{\gamma\gamma}(E_\gamma, E)$ the angle averaged pair creation cross section.

Photons can evade EBL scattering by: $\gamma \rightarrow ALP \rightarrow \gamma$

Photon to ALPs conversion in magnetic field of source or intergalactic medium

Source: blazers: few mG on 10pc scale, intergalactic medium: µG on hundred kpc scale, back conversion in (inter)galactic magnetic field: µG over more than 10kpc, depending of line of sight: Calculate oscillation probabilities as function of direction.

→ $\Phi_{obs}(E_\gamma)$ influenced by population of gammas transformed in to ALPs propagating through most of their path as ALPs (suppressed interaction with EBL) back-transforming to gammas close to observer

→Investigation of energy dependent flux from blazars, compare to expectations taking into account $\tau(E_\gamma, z_s)$
→ For ALP scenario: expect power law as function of energy will be different, depending on line of sight (different back-oscillation probabilities).

Analysis of high energy spectra from 12 high z_s sources Consistent with ALPs with $g_{a\gamma\gamma} \sim 2\ 10^{-11}\ GeV^{-1}$ for few hundred neV ALP mass.