Heating up Peccei-Quinn scale

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Poderoso en Agua Fría
Con Activos de Fuerza Fría
AXION
MAXIMO PODER CONTRA LA GRASA
Limón
ELIMINA MALOS OLORES
CREMA LAVAPLATOS


Аксион
СДЕЛАНО В РОССИИ


CLAAS
950
AXION
AXION
CMATIC
TRELLEBORG

Outline

- Why do we need axions?
- QCD axions as Dark Matter.
- Heating up Peccei-Quinn scale.
- Axions through narrow parametric resonance.
- Phenomenology (work in progress).

Strong CP-problem of QCD

$$\mathcal{L}_{CP} = \frac{\theta g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$ θ should be banned!

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θ gives rise to the electric dipole moment of neutron:

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$$d_n \simeq \theta \cdot 10^{-16} \text{ e cm} \,,$$

which is strongly constrained Abel'20

$$|d_n| < 10^{-26} \text{ e cm} \Longrightarrow |\theta| < 10^{-10}$$

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But the situation is a bit worse than that...

$$\boxed{\theta = \bar{\theta} + \text{Arg Det}M}$$

- $\bar{\theta}$ is something one could "put by hands"
- Arg Det$M$ comes from the quark sector

$$\mathcal{L}_{quarks} = -\bar{q}_L M q_R + \text{h.c.}$$

One should admit a strong cancellation, or...

Impose Peccei-Quinn symmetry'77

$$\boxed{q_L \to e^{i\alpha} q_L} \qquad \boxed{q_R \to e^{-i\alpha} q_R}$$

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$$\mathcal{L}_{quark} = -\bar{q}_L M e^{-\frac{2ia}{f_{PQ}}} q_R \Longrightarrow \boxed{\mathcal{L}_{CP} \to \frac{a g_s^2}{32\pi^2 f_{PQ}} G_{\mu\nu} \tilde{G}^{\mu\nu}}$$

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$$V(a) \simeq \frac{m_\pi^2 f_\pi^2}{4} \cdot \left[1 - \cos\left(\frac{a}{f_{PQ}}\right)\right] \Longrightarrow$$

$$m_a \simeq \frac{m_\pi f_\pi}{2 f_{PQ}} \Longrightarrow a \to 0 \Longrightarrow \mathcal{L}_{CP} \to 0$$

Weinberg-Wilczek axion'77

Introducing Peccei-Quinn symmetry clearly means going beyond Standard Model

Two-Higgs doublet model: H_u and H_d

$$f_{PQ} = 246 \text{ GeV} \Longrightarrow m_a \simeq \frac{m_\pi f_\pi}{f_{PQ}} \simeq 100 \text{ keV}$$

So heavy axions are forbidden, because they lead to

$$K^+ \to \pi^+ + a$$

Invisible axion models

Introduce additional complex field S
charged under global $U(1)$-charge

$$S = |S| \cdot e^{\frac{ia}{f_{PQ}}} \qquad \mathcal{L}_S = |\partial S|^2 - \lambda_S \left(|S|^2 - \frac{f_{PQ}^2}{2} \right)^2 \quad f_{PQ} \gg 100 \text{ GeV}$$

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Two Higgs doublets $\sim H_u H_d S^2 + \text{h.c.}$ $\sim |H_u|^2 |S|^2$ $\sim |H_d|^2 |S|^2$

Dine-Fischler-Srednicki-Zhitnitsky type of models

Extra quark field $\sim S \bar{Q} Q + \text{h.c.}$

Kim-Shifman-Vainstein-Zakharov type of models

$$\frac{a\ \alpha}{8\pi f_{PQ}} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad f_{PQ} \gg 10^6\ \text{GeV} \Longrightarrow \Gamma_a \ll H_0$$

Axions are naturally stable on cosmological scales $\Longrightarrow$ which makes them promising Dark Matter candidates

Preskill et al'83, Abbott&Sikivie'83, Dine&Fischler'83

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Misalignment mechanism: initially $m_a(T) \ll H$ and axion picks an arbitrary value $a/f_{PQ} = \theta_i = [0, \pi]$

It starts oscillating, when $m_a(T) \gtrsim H$

Oscillations feed into Dark Matter $\boxed{\Omega_a h^2 \simeq \theta_i^2 \cdot \left(\frac{f_{PQ}}{10^{12}\ \mathrm{GeV}}\right)^{7/6}}$

Assume phase transition in the post-inflationary Universe:

$$\langle S \rangle = 0 \to \langle S \rangle = f_{PQ}/\sqrt{2}$$

Global cosmic strings are formed by Kibble-Zurek mechanism

Global cosmic strings emit axions rather than gravitational waves

Axions can be produced abundantly to make Dark Matter Davis'86, Kawasaki et al'14, Yamaguchi et al'98

Typical range $f_{PQ} \simeq 10^{10} - 10^{11}$ GeV

Typically QCD axion dark matter implies a rather narrow parameter space:

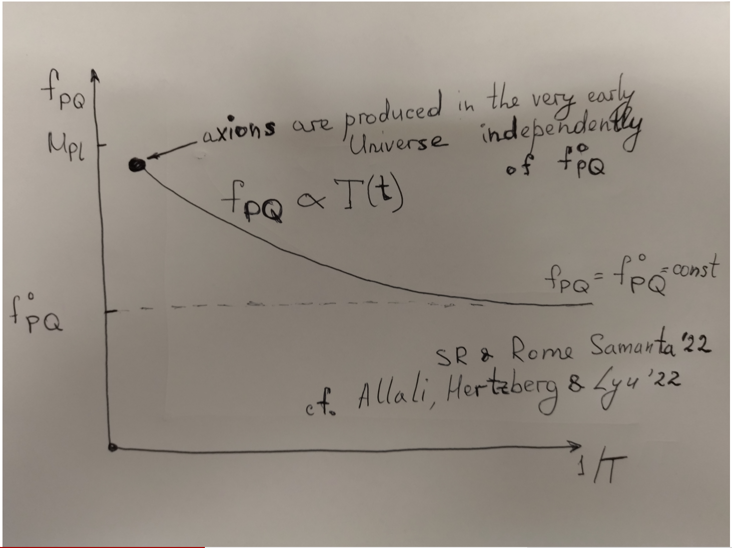
$$f_{PQ} \simeq 10^{10}\text{ GeV} - 10^{12}\text{ GeV} \Longrightarrow m_a \simeq 10^{-4} - 10^{-6}\text{ eV}$$

Can one have QCD axion Dark Matter for $f_{PQ} \simeq 10^{8} - 10^{10}$ GeV?

Perhaps, this range is most interesting from the viewpoint of astrophysics:

- Supernova SN 1987A limit $f_{PQ} \gtrsim 4 \cdot 10^{8}$ GeV
- Present CAST'17 limit $f_{PQ} \gtrsim$ a few $\times\, 10^{7}$ GeV
- Anomalous cooling of horizontal branch stars.

Temperature-dependent Peccei-Quinn scale



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$$v_\phi \lesssim 1 \text{ TeV} \qquad f^0_{PQ} \gtrsim 10^8 \text{ GeV} \qquad g \lesssim 10^{-5} - 10^{-6}$$

High-temperature regime

At high temperatures: $\langle \phi^\dagger \phi \rangle_T = \frac{NT^2}{24} \Longrightarrow$

$$f_{PQ} \equiv \sqrt{2}\langle S \rangle = \sqrt{\frac{N}{24\beta}} \cdot \frac{T}{g}$$

Peccei-Quinn scale is gliding in the early Universe from sub-Planck values to relatively small values, as the Universe cools down

Temperature-dependence $f_{PQ}(t) \propto T(t)$

enables a new production mechanism for axions, efficient independently of low-energy scale f_{PQ}^0.

During inflation and slightly after

The field S is very weakly coupled $\Longrightarrow$ it has a substantially flat potential $\Longrightarrow$ acquires a rather large expectation value during inflation:

$$\langle\rho\rangle \equiv \sqrt{2}\langle|S|\rangle \simeq \frac{H\sqrt{\mathcal{N}}}{2\pi} \ll M_{Pl}$$

As the Universe is reheated, $M_S \simeq gT$

Initially $M_S \ll H(T) \Longrightarrow$ the field ρ is frozen

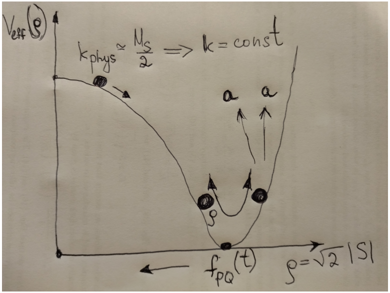
At some point $M_S \gg H(T) \Longrightarrow$ the field ρ starts oscillating.

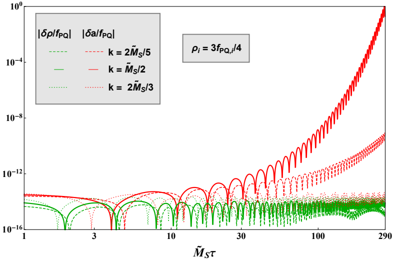
Oscillations lead to parametric resonance production of axions.

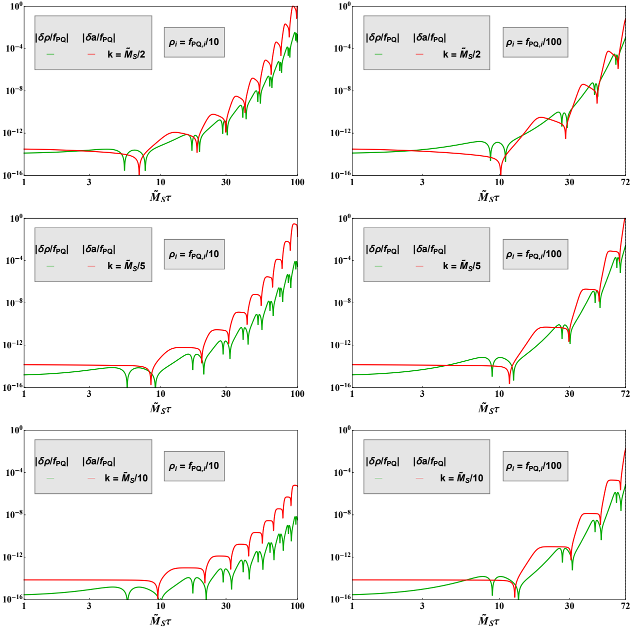
$$\mathcal{L}_{int} \propto \frac{\rho^2(\partial_\mu a)^2}{2}$$

Resonant axion production in the early Universe, when the radial field relaxes to the minimum of its potential, cf. Co, Hall, and Harigaya'17

Similar to (narrow) parametric resonance after inflation.
Compared to inflation, resonance band is stable: redshift of produced axions is compensated by time-decrease of the Peccei-Quinn scale $f_{PQ}(t)$.






10^0
10^{-4}
10^{-8}
10^{-12}
10^{-16}
$|\delta\rho/f_{PQ}|$
$|\delta a/f_{PQ}|$
$k = \tilde{M}_S/2$
$\rho_i = f_{PQ,i}/10$
1
3
10
30
100
$\tilde{M}_S\tau$
10^0
10^{-4}
10^{-8}
10^{-12}
10^{-16}
$|\delta\rho/f_{PQ}|$
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$k = \tilde{M}_S/2$
$\rho_i = f_{PQ,i}/100$
1
3
10
30
72
$\tilde{M}_S\tau$
$|\delta\rho/f_{PQ}|$
$|\delta a/f_{PQ}|$
$k = \tilde{M}_S/5$
$\rho_i = f_{PQ,i}/10$
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Properties of axion Dark Matter

Axions do most of Dark Matter in the Universe for

$$\beta \equiv \frac{\lambda_S}{g^4} \simeq 40 \cdot \left(\frac{1 \text{ TeV}}{v_\phi} \right)^2 \qquad \beta \gg 1 \Longrightarrow v_\phi \ll 10 \text{ TeV}$$

No direct dependence on f^0_{PQ}/axion mass

Resulting axions are initially relativistic, but become non-relativistic at the temperature

$$T_* \simeq 50 \text{ keV} \cdot \sqrt{\frac{\beta}{N}} \cdot \frac{1 \text{ TeV}}{v_\phi}$$

Lyman α : $T_* \gtrsim 10 \text{ keV} \Longrightarrow v_\phi \lesssim 10 \text{ TeV}$

Stability ensures that axions are warm!!!

Cosmology of radial excitations.

Parameter space may strongly depend on the ratio $r \equiv \frac{\mathcal{E}_\rho}{\mathcal{E}_a + \mathcal{E}_\rho}$ of produced radial fluctuations $\rho \equiv \sqrt{2}|S|$ along with axions.

Scenario #1: radial excitations remain stable until the moment, when they perturbatively decay into axions $\rho \rightarrow a + a$.

This perturbative decay happens quite late $\Longrightarrow$ potential problem with radial fluctuations, which behave as non-relativistic matter and tend to overclose the Universe $\Longrightarrow$ problems for CMB and BBN.

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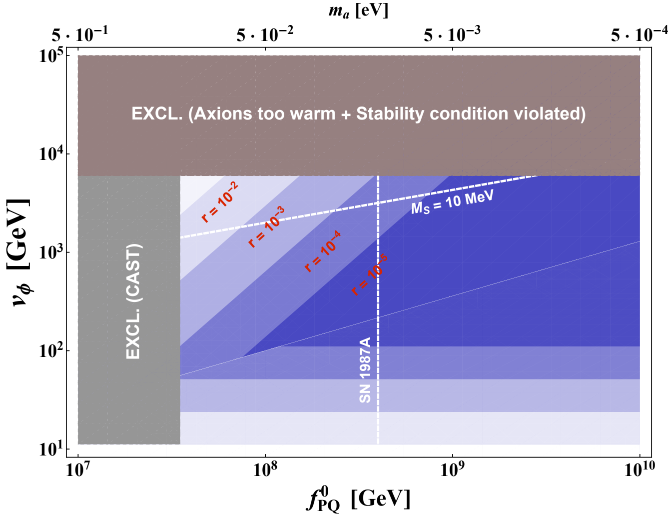

Very constrained parameter space!!!

For $r \gtrsim 10^{-2} - 10^{-3}$, one gets

$$v_\phi \simeq 10 \text{ TeV} \qquad f^0_{PQ} \simeq 10^8 \text{ GeV}$$

Recall SN1987A constraint $f^0_{PQ} \gtrsim 10^8$ GeV.

The scenario #1 with quasi-stable particles ρ is on the way to be excluded!

Scenario #2: particles ρ produced through parametric resonance efficiently dissipate in plasma.

The scenario can be efficient, whenever the thermal particles ϕ are unstable and decay into lighter species, e.g., fermions Ψ.

$$\rho + \phi \to \Psi + \bar{\Psi} \Longrightarrow \Gamma_{diss} \simeq \frac{M_S}{3\pi^2\beta}$$

Dissipation should not be too efficient $\Longrightarrow$ otherwise, axion production during parametric resonance will be grossly affected $\Longrightarrow \beta \gtrsim 10 - 100$

$$\beta \gtrsim 40 \cdot \left(\frac{1\ \text{TeV}}{v_\phi}\right)^2 \Longrightarrow v_\phi \lesssim 1\ \text{TeV}$$

Higgs might be favoured again!

Summary

- Large Peccei-Quinn scale can be induced dynamically due to the interaction with the Higgs(-like field)
- The resulting Peccei-Quinn scale depends on the Universe temperature at very early times
- This time-dependence opens up the possibility of efficient axion production in the narrow parametric resonance regime.
- Resulting axions are automatically cold.
- Non-trivial phenomenology is due to radial excitations of the Peccei-Quinn field.
- Work in progress: possible emission of light radial particles by supernovae, $M_\rho > ....?$

Thanks for your attention!!!