The Axion Quest
(20^{th} Rencontres du Vietnam)
Theory Summary

August 09, Quy Nhon, Vietnam

Kiwoon Choi

Brief History & Overview

Peccei and Quinn (1977) pointed out that theories with a spontaneously broken anomalous global U(1) symmetry (PQ symmetry) naturally avoid the strong CP problem as the QCD angle is fixed to be zero by the QCD instanton effect which solves the QCD $U(1)_A$ problem by providing additional mass to the η' meson.

Quanta Magazine 2017

However they could not realize that their mechanism predicts a light pseudo Nambu-Goldstone boson, which was noticed soon by Weinberg and also independently by Wilczek (1978) with the particle name “axion”.

Wikipedia

The axion of the original PQ model was experimentally excluded almost immediately:

$$m_a \sim m_\pi \frac{100\,\mathrm{MeV}}{f_a}, \quad g_{aX} \propto \frac{1}{f_a} \;\; (X = N, \gamma, \mathrm{mesons}, ...)$$

$$f_a(\mathrm{PQWW}) \lesssim 246\,\mathrm{GeV}$$

However the idea of axion survived in the form of "invisible axion" which can be much lighter and much more weakly coupled:

$$f_a(\mathrm{invisible}) \gg 246\,\mathrm{GeV}$$

* **KSVZ:** Kim (1979); Shifman, Vainshtein, Zakharov (1980)

* **DFSZ:** Dine, Fischler, Srednicki (1981); Zhitnitsky (1980)

New type of invisible axions also have been introduced in mid 80:

* **Extra-dimensional axions:** Witten (1984)
(in the context of string theories)

* **Composite axions:** Kim (1985)

In the early days, “axion” usually meant the QCD axion solving the strong CP problem by the Peccei-Quinn mechanism.

However string theory taught us that generically there can be multiple axions with quite different properties, which was well appreciated already in the early stage of the 1^{st} string revolution.

Witten 84; KC and Kim 85; Dine, Seiberg, Wen, Witten 86; ….

Those multiple axions in string theory can include

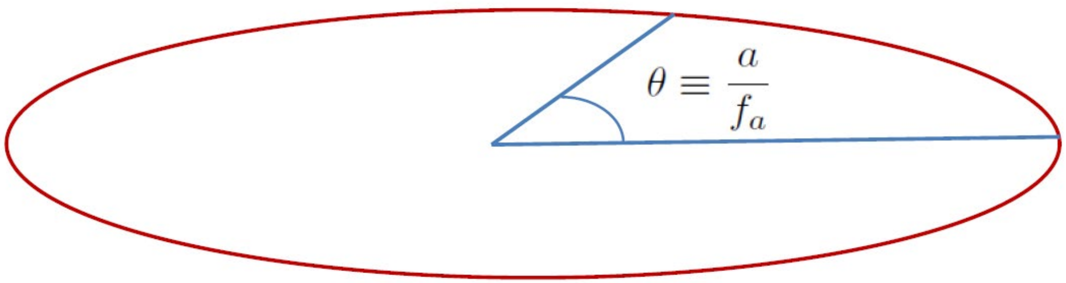
* a QCD axion solving the strong CP problem through the coupling to the gluon anomaly
* heavier axions which obtain a large mass from strong hidden dynamics
* lighter axions which couple neither to the gluon anomaly nor to strong hidden dynamics

This has motivated a new term “axion-like particle” (ALP) to distinguish heavier or lighter axions from the QCD axion.

Nowadays, axion (or ALP) denotes a generic angular field which can be naturally light due to an approximate non-linear PQ symmetry:
(shift symmetry)

$$a(x) \cong a(x) + 2\pi f_a$$

$$(f_a = \text{axion decay constant or axion scale})$$



$$U(1)_{\rm PQ}: \quad a(x) \ \rightarrow \ a(x) + \text{constant}$$

$$V(a) = -\frac{1}{2} m_a^2 a^2 + ...$$

Axion potential induced by $U(1)_{PQ}$-breaking effects.

$U(1)_{PQ}$ assures that axion couples dominantly to the spin density of matter and gauge fields, not to the number density:

$$\mathcal{L}_{\rm axion} = \frac{1}{2}(\partial_\mu a)^2 + \frac{\partial_\mu a}{f_a}\left(\sum_\psi c_\psi \bar{\psi}\sigma^\mu\psi + i\sum_\phi c_\phi(\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*)\right)$$

matter spin density

$$+\sum_{A_\mu^A} c_A \frac{g_A^2}{32\pi^2}\frac{a}{f_a}F^{A\mu\nu}\tilde{F}^A_{\mu\nu}\cdots \qquad \left(\tilde{F}^A_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{A\rho\sigma}\right)$$

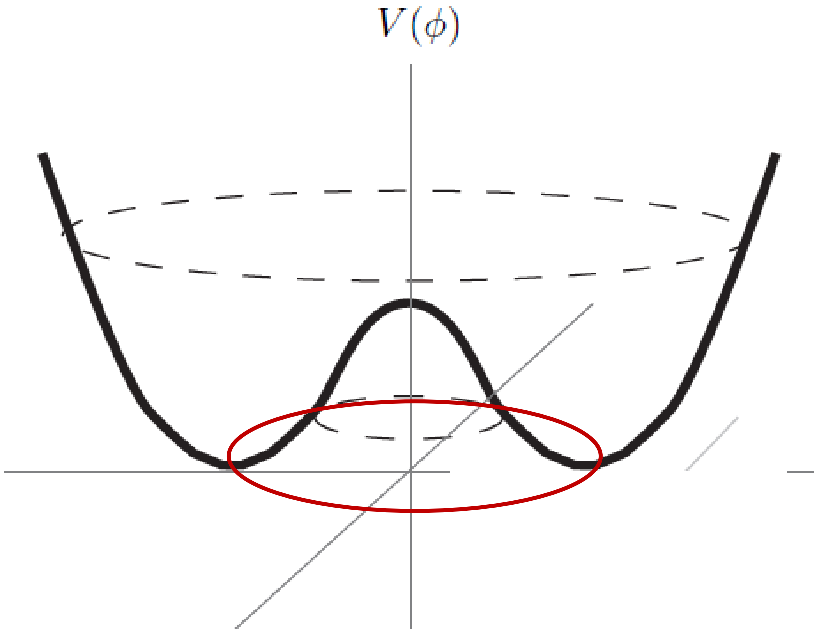
gauge field helicity density

This not only makes light axions naturally light, but also they easily satisfy the strong constraints from the 5th force experiments.

In this notion, QCD axion is a particular type of axion for which the associated PQ symmetry is broken dominantly by the gluon anomaly.

Origin of axions

4-dim axion originating from the phase of a 4-dim (elementary or composite) complex scalar field ϕ developing a nonzero VEV.



$$\phi = \frac{1}{\sqrt{2}}\big(f_a + \rho(x)\big)e^{ia(x)/f_a}$$

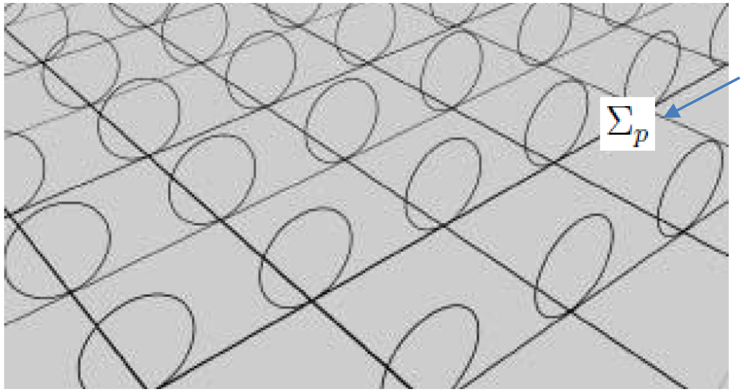
$$\big(f_a = \sqrt{2}\langle\phi\rangle\big)$$

KSVZ-type: PQ-neutral SM fermions

DFSZ-type: PQ-charged SM fermions

Extra-dim axion originating from a higher-dimensional gauge field, which is most naturally realized in string/M theory:

$$\frac{a(x)}{f_a} = \oint dy\, A_5(x,y) \quad \left(\int_{\Sigma_p} dy^{m_1}..dy^{m_p} A_{[m_1..m_p]} \right)$$



Closed p-dimensional surface in extra dimension

Different cosmology:

Pre-inflationary Post-inflationary

* 4-dim axion: $f_a > E_{\rm inf}$ or $< E_{\rm inf}$

* Extra-dim axion: $f_a \sim M_{\rm KK} > E_{\rm inf}$ for generic 4-dim inflation

Pre-inflationary

Even for extra-dim inflation which may allow the post-inflationary scenario with $f_a \sim M_{\rm KK} < E_{\rm inf}$, cosmology of such extra-dim axion is yet quite different from that of post-inflationary 4-dim axion.

Different pattern of axion couplings:

$$\frac{g_{a\gamma}}{g_{a\psi}} \sim \frac{g^2}{8\pi^2}, \quad \frac{8\pi^2}{g^2}, \quad 1 \quad \text{at} \quad \mu \sim f_a \quad (\psi = \text{SM fermions})$$

DFSZ KSVZ Extra-dim

Low energy couplings including perturbative radiative corrections and nonperturbative QCD effects:

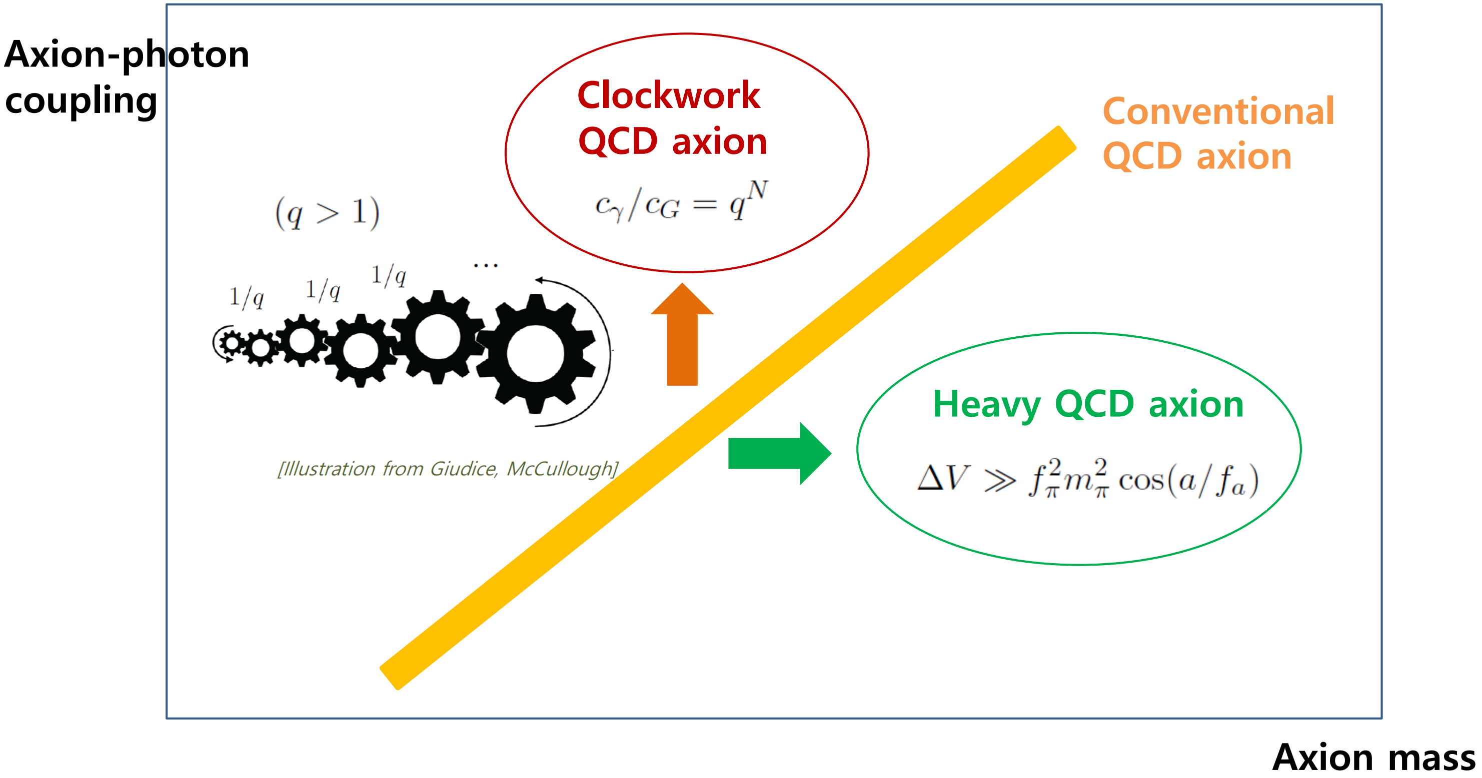
KC, Im, Kim, Seong, arXiv:2106.05816

* DFSZ QCD axion : $\frac{g_{ap}}{g_{a\gamma}} \sim \frac{g_{an}}{g_{a\gamma}} \sim \frac{g_{ae}}{g_{a\gamma}} \sim 10^3,$
* KSVZ (or composite) QCD axion: $\frac{g_{ap}}{g_{a\gamma}} \sim 20\,\frac{g_{an}}{g_{a\gamma}} \sim 10^3\,\frac{g_{ae}}{g_{a\gamma}} \sim 10^3,$
* String theoretic QCD axion: $\frac{g_{ap}}{g_{a\gamma}} \sim 20\,\frac{g_{an}}{g_{a\gamma}} \sim 10^2\,\frac{g_{ae}}{g_{a\gamma}} \sim 10^3,$
  (extra-dimensional)
* KSVZ (or composite) UL ALP: $\frac{g_{ap}}{g_{a\gamma}} \sim \frac{g_{an}}{g_{a\gamma}} \sim (1-10) \times \frac{g_{ae}}{g_{a\gamma}} \sim 10^{-1} - 1,$
* String theoretic UL ALP: $\frac{g_{ap}}{g_{a\gamma}} \sim \frac{g_{an}}{g_{a\gamma}} \sim \frac{g_{ae}}{g_{a\gamma}} \sim 10.$

Over the last few decades, the theory space for axion models has been enormously expanded, part of which relies on assuming multiple axions:

aligned axions, clockwork axions, warped axions,
heavy QCD axions, X-phobic or X-philic axions, ...

If you are ready to do certain amount of model-building efforts, the parameter space for QCD axion can also be greatly expanded:



From the very early stage of axion physics, it has been noticed that axions can have a variety of interesting cosmological and astrophysical implications.

Cosmology:

dark matter, dark radiation, (early or present) dark energy, inflation, axio-genesis, ….

Astrophysics:

star cooling, SN explosion, BH superradiance, axion-photon conversion in astronomical B-field, ….

These cosmological/astrophysical implications have motivated many theoretical/experimental efforts studying/searching for the associated observable signatures of axion.

Two questions on axions

1) Origin of qualified PQ symmetry
(particularly relevant for QCD axion and ultralight ALP)

* PQ (axion) quality problem:

In the world with quantum gravity, we may not be allowed to simply assume a global symmetry. In such world, qualified global symmetry needs an explanation as it can appear in low energy limit only as a consequence of other fundamental structure of the theory.

* Pattern of axion couplings, Pre-inflationary or Post-inflationary, ….

2) What determines the axion scale f_a ?

* axion mass, overall size of axion couplings, pre-inflation or post, ….

Any answer/idea to these questions will provide key information on the observable (laboratory, astrophysical, cosmological) signatures of the associated axion.

Theory talks in this conference

Axion dark matter:

* Echo signals (Ariel Arza)
* Time-varying EDM, spin-precession, fundamental constants due to oscillating axion DM (Yevgeny Stadnik and many experimental talks)
* New form of axion DM: Axion pocket (David Marsh)

Possible implications of multiple axions:

* ALP anarchy (Francesca Chadha-Day)
* Multiple QCD axion (Pablo Quilez)

PQ quality problem:

* Probing the PQ quality with EDMs (KC)
* Spontabeously broken (-1)-form U(1) symmetry (Motoo Suzuki)
* Possible solutions (Ryosuke Sato)
* Small-instanton induced axion potential in SMEFT (Pham Ngoc Hoa Voung)
* 10 MeV QCD axion (Shota Nakagawa)

Astrophysical implications:

* SN explosion with 100 MeV ALP (Kanji Mori)

Collider or laboratory signatures:

* TeV-scale ALP at muon collider (Sudhakantha Girmohanta)
* 10 MeV QCD axion (Shota Nakagawa)
* Many experimental talks

Axion dark radiation:

* Astrophobic QCD axion (Marcin Badziak)

EDM:

* nEDM from lattice QCD (Rajan Gupta, Hiroshi Oki)
* EDM inverse problem (Sanghui Im)

So many thanks to

* all speakers who have delivered excellent and interesting talks
(other participants who have joined active discussions)

* organizers who did an amazing job to organize this wonderful meeting

* all staffs at ICISE who have provided really wonderful service during the conference