CLOCKWORK INSPIRED MODELS FOR ULTRA-LIGHT SCALARS

Based on: Axions in a highly protected gauge symmetry model

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FIELD THEORETICAL APPROACH: ultra-light scalars-→ (pseudo)NG bosons of some spontaneously broken (at some scales f_i) global symmetries.

May play important role; focus in this talk on the strong CP problem and dark matter.

Beyond SM: many hidden sectors with many GB, playing different roles?

Those global symmetries have to be also explicitly broken.

VARIOUS SOURCES OF EXPLICIT BREAKING (PERTURBATIVE OR NON-PERTURBATIVE): CHIRAL ANOMALIES, INSTANTON EFFECTS OF ONE KIND OR ANOTHER, QUANTUM GRAVITY, OTHERS…

ONE GETS $m_a = F(c_i, f)$

FOR THE NGB TO „SERVE” A GIVEN PURPOSE,
EXPLICIT BREAKING MUST BE UNDER CERTAIN CONTROL

CLASSICAL QCD AXION

$$m_a^{QCD} \sim \Lambda^2/f$$

$$\Lambda \sim 0.1 GeV, \quad 10^9 GeV \leq f \leq 10^{12} GeV$$

(FOR THE UPPER BOUND ON f - SEE LATER)

TWO QUESTIONS:

1) THE ORIGIN OF THE GLOBAL U(1) AND THE SCALE OF ITS BREAKING
2) CONTROL OVER GRAVITATIONAL CORRECTIONS TO THE AXION POTENTIAL; THEY CAN DESTROY THE PQ SOLUTION TO THE STRONG CP PROBLEM

A BRIEF REMINDER:

AXION SOLUTION

$$\phi = (f/\sqrt{2})\exp(ia/f)$$

$$\mathcal{L} \supset (\Theta + \frac{a}{f})G^{a\mu\nu}\tilde{G}_{a\mu\nu}$$

QCD INSTANTON EFFECTS GIVE THE POTENTIAL

$$V_a = \Lambda^4(1 - \cos(a/f + \Theta))$$

MINIMIZING THE POTENTIAL

$$a/f = -\Theta$$

AN EXPLICIT BREAKING BY GRAVITY EFFECTS, OF DIMENSION D=2m+n and PQ CHARGE n:

$$V_g(\phi) = \frac{g}{M_{PL}^{2m+n-4}} |\phi|^{2m} \phi^n + \ h.c.$$

$$g = |g| \exp(i\delta)$$

SO

$$V_g(a) = (g f^D / M_{PL}^{D-4})[1 - cos(na/f + \delta)]$$

GRAVITATIONALLY INDUCED MASS

$$(m_a^g)^2 \sim |g| f^2 (\frac{f}{M_{PL}})^{D-4} n$$

MINIMIZING THE FULL POTENTIAL, WE STILL NEED

$$(a/f) + \Theta \leq 10^{-10}$$

SO, ONE GETS

$$(gf^{D}/M_{PL}^{D-4}) \leq 10^{-10}\Lambda^{4}$$

$$(m_a^g \leq 10^{-5} m_a^{QCD})$$

FOR $\Lambda = 0.1 GeV$ AND $f \geq 10^{9}$ ONE GETS

D>10

MOTIVATION CONTINUED: QCD AXION OR/ AND ALP IN GENERAL-GOOD CANDIDATES FOR COLD DM

IT IS PRODUCED NON-THERMALLY, BY THE SO-CALLED MISALLIGNMENT MECHANISM.

The mechanism relies on assuming that the axion field has some initial value in the early universe, and one determines its behaviour in an expanding Universe (FRW) by solving the classical equation of motion for a field that depends on time only:

$$\frac{d^2a}{dt} + 3H\frac{da}{dt} + m_a^2 a^2 = 0$$

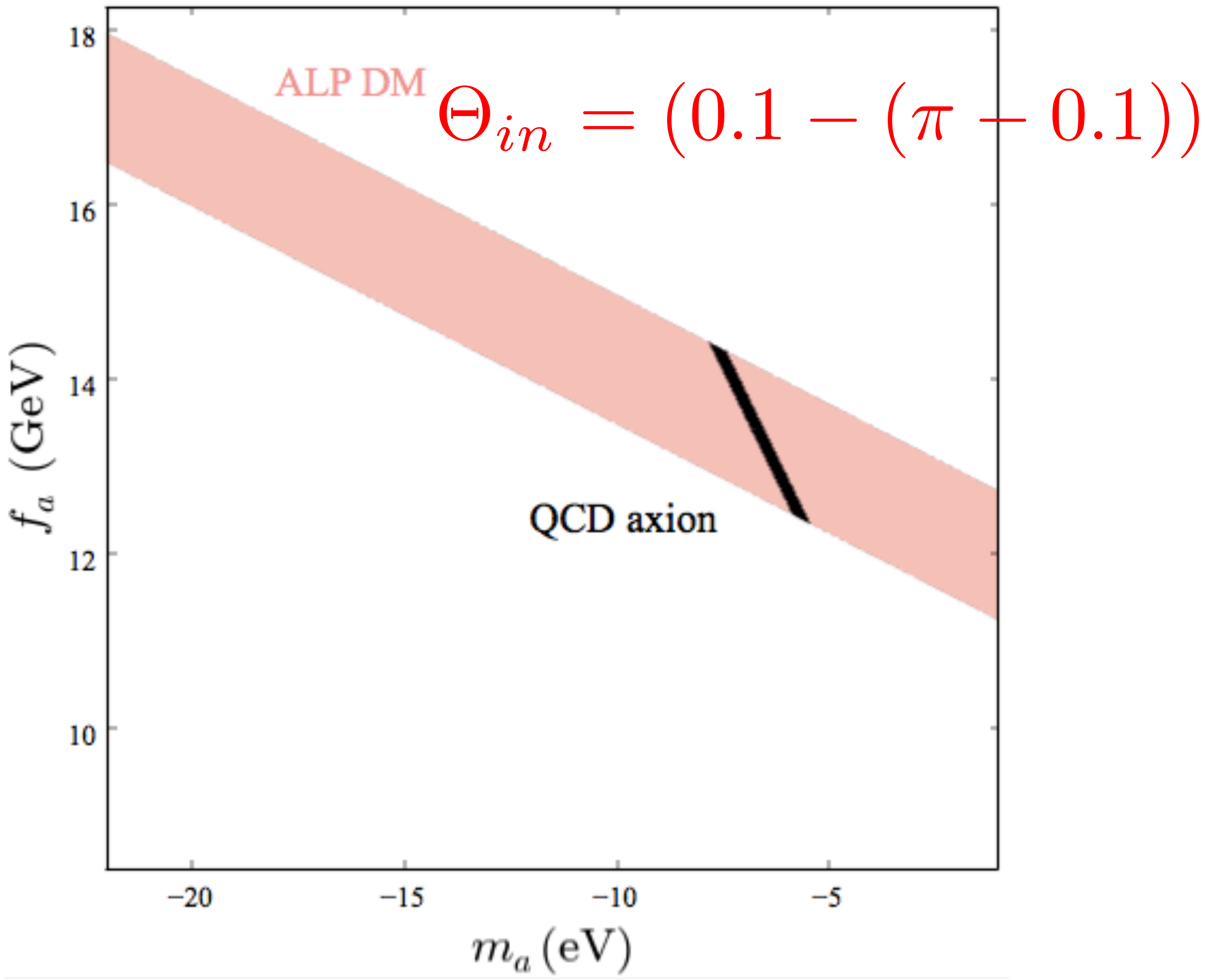
MANY DETAILS IN CALCULATING DM ABUNDANCE, DIFFERENT FOR QCD AXION AND ALP; QUALITATIVELY, DM ENERGY DENSITY IS

$$\rho \sim \frac{1}{2} m_a^2 f_a^2 \Theta_{in}^2$$

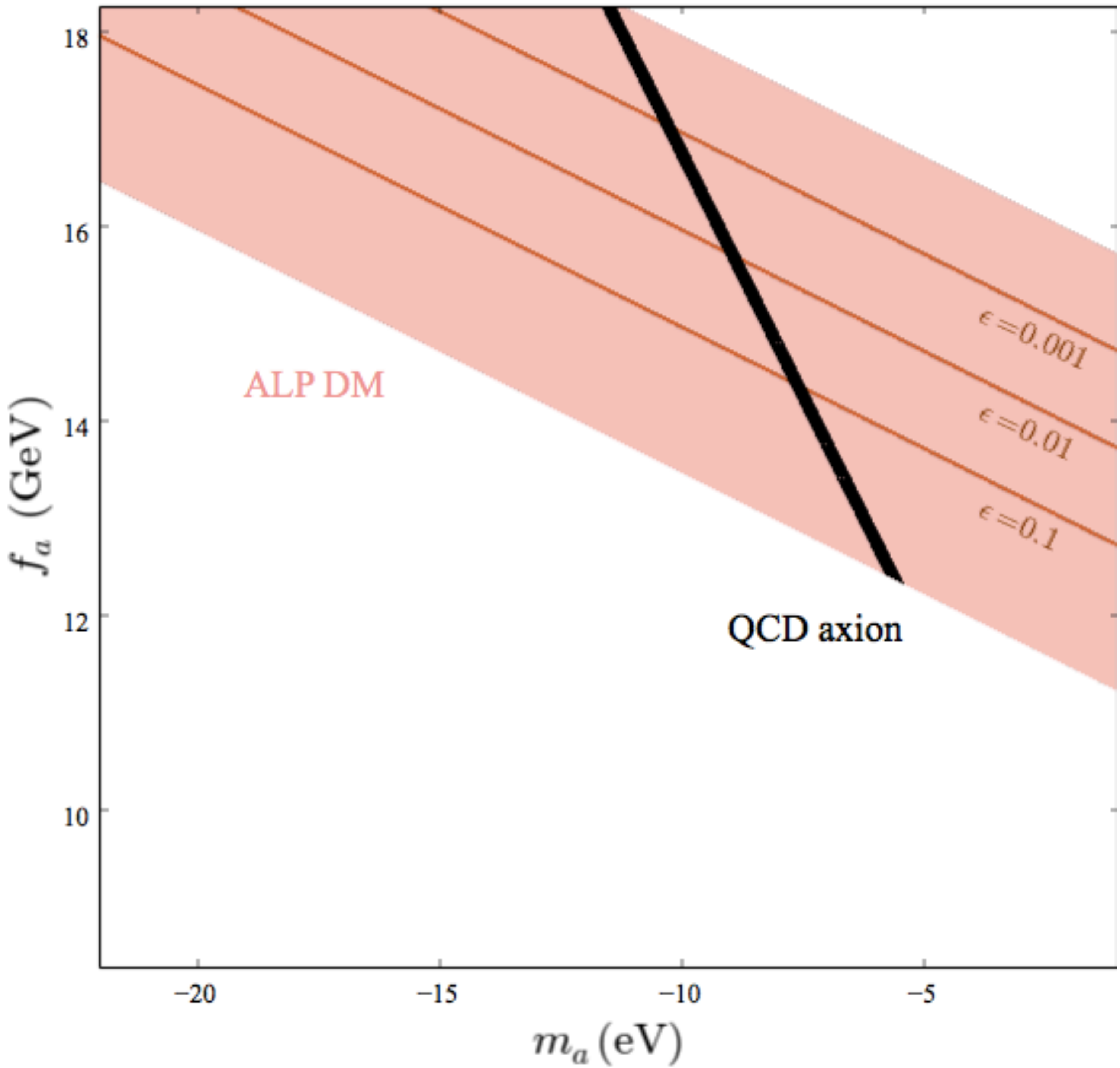
WHERE

$$\Theta_{in} = a_{in}/f_a$$

KEEPING m_a AND f_a AS FREE PARAMETERS, REQUIRING e.g $\Omega_a = 0.25$ ONE GETS A CORRELATION BETWEEN ACCEPTABLE MASSES AND THE SCALES f_a (FOR PRE-INFLATIONARY SPONTANEOUS SYMMETRY BREAKING)



ALP DM
$\Theta_{in} = (0.1 - (\pi - 0.1))$
QCD axion
18
16
14
12
10
f_a (GeV)
−20
−15
−10
−5
m_a (eV)



18
16
14
12
10
−20
−15
−10
−5
f_a (GeV)
m_a (eV)
ALP DM
QCD axion
$\epsilon = 0.001$
$\epsilon = 0.01$
$\epsilon = 0.1$

COSMOLOGY- TO SUPRESS SMALL SCALE STRUCTURE FORMATION- INTERESTING MASS RANGE FOR DM

$$10^{-22} - 10^{-21} eV$$

FOR $\Omega_a = 0.25$ THOSE VALUES OF MASS CORRESPOND TO

$$f_a \approx 10^{17} - 6 \times 10^{16} GeV$$

BY THE WAY, FOR THE QCD AXION

$$m_a = 10^{-21} eV \rightarrow f_a = 10^{28} GeV!!$$

FIELD THEORETICAL MODELS THAT ADDRESS THE TWO QUESTIONS FOR THE QCD AXION OR POPULATE THE ALP BAND GIVEN BY THE DM CONSTRAINT?

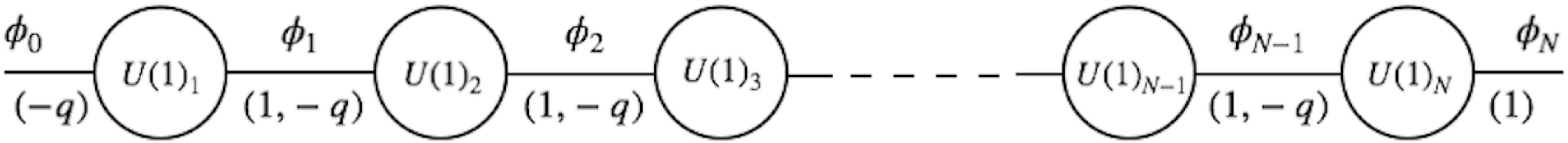
Clockwork (CHOI, RATTAZZI, GIUDICE, MCCULLOUGH)

inspiration: models linked to the latticized 5th dimension

$U(1)^{N+1}$ GLOBAL INVARIANCE WITH $U(1)^{N}$

GAUGED SUBGRUP

CLOCKWORK CHARGES FOR THE LINK SCALAR FIELDS



$$\mathcal{L} = -\frac{1}{4}\sum_{i=1}^{N} F_{\mu\nu,i}F_i^{\mu\nu} - \sum_{k=0}^{N} |D_\mu \phi_k|^2 + m_k^2|\phi_k|^2) - \sum_{k,l=0}^{N} \lambda_{kl}|\phi_k|^2|\phi_l|^2$$

$$D_\mu \phi_k = (\partial_\mu + i(1-\delta_{k,0})\frac{A_{\mu,k}}{2} - iq(1-\delta_{k,N})\frac{A_{\mu,k+1}}{2})\phi_k$$

THE ABOVE 4D MODEL CAN BE OBTAINED FROM A 5D ABELIAN GAUGE MODEL, AFTER LATTICIZING THE FIFTH DIMENSION

$$S_1/Z_2$$

$$\text{conformally flat metric } ds^2 = a(z)^2[\eta_{\mu\nu}dx^\mu dx^\nu + dz^2]$$

$$\text{with } a(z) = \exp(-kz)$$

WITH BOUNDARY CONDITIONS ON THE BOUNDARIES:
DIRICHLET FOR THE 4d COMPONENTS OF THE GAUE FIELD

$$A_\mu(z=0) = A_\mu(z=\pi) = 0$$

NEUMANN FOR $\partial_5 A_5(z=0) = \partial_5 A_5(z=\pi) = 0$

$$\phi_k = \frac{f + r_k}{\sqrt{2}} e^{i\frac{\theta_k}{f}}$$

FULL GLOBAL $U(1)^{N+1}$ IS SPONTANEOUSLY BROKEN

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} A_{\mu,i}(-qf\partial_\mu \theta_{i-1} + f\partial_\mu \theta_i)$$

ONE GOLDSTONE BOSON IS LEFT OVER, ORTHOGONAL TO THE GAUGE GOLDSTONE BOSONS PROFILES $-qf\theta_{i-1} + f\theta_i$

$$a = \frac{\theta_0 + q\theta_1 + ...q^N\theta_N}{\sqrt{1 + q^2 + ... + q^{2N}}}$$

THE GOLDSTONE BOSON DISPLAYS EXPONENTIAL LOCALIZATION ALONG THE SITES

GOLDSTONE BOSON PROTECTION BY GAUGE INVARIANCE:

GAUGE INVARIANT OPERATORS

$$|\phi_k|^2 \text{ and } \phi_0 \phi_1^{q} \ldots \phi_N^{q^N}$$

$U(1)_a$ IS BROKEN ONLY BY THE SECOND ONE

$U(1)_a$ AS PECCEI-QUINN SYMMETRY

CONSIDER THE COUPLING (IT HAS TO BE GAUGE INVARIANT TO AVOID $U(1)_i \times SU(3)^2$ ANOMALIES)

$$i \log(\phi_0 \phi_1^{q} \ldots . \phi_N^{q^N}) Tr(G^{\mu\nu} \bar{G}_{\mu\nu}) \supset -\frac{a}{f^a} Tr(G^{\mu\nu} \bar{G}_{\mu\nu})$$

UV ORIGIN OF THE AXION ANOMALOUS COUPLING:
CHIRAL WITH RESPECT TO PQ SYMMETRY AND VECTOR LIKE WITH RESPECT TO ALL GAUGE SYMMETRIES
SET OF COLOURED HEAVY FERMIONS (~ f)

GOLDSTONE BOSON DECAY CONSTANT

$$f_a = \frac{f}{\sqrt{1 + q^2 + ...q^{2N}}}$$

ONE POSSIBLE APPLICATION: FOR q>1 AND LARGE N
ONE OBTAINS HIERARCHY OF SCALES

$$(3^{20} = 3,5 \times 10^9)$$

CLASSICAL AXION WINDOW CAN BE OBTAINED WITH

$$f \sim M_{PL}$$

GRAVITATIONAL CORRECTIONS

$$\frac{\phi_0 \phi_1^q \ldots \phi_N^{q^N}}{M_{PL}^{1+q+\ldots q^N-4}} + h.c. \to 2\left(\frac{f}{\sqrt{2}M_{PL}}\right)^{1+q+\ldots+q^N} M_{PL}^4 \cos\left(\frac{a}{f_a}\right)$$

IN THE PRESENCE OF THE GRAVITATIONAL CORRECTIONS IN THIS MODEL, THE CONDITION

$$|\frac{a}{f_a} - \Theta| < 10^{-10}$$

AT THE MINIMUM OF THE POTENTIAL TRANSLATES INTO

$$\frac{\Lambda^2}{f_a} > 10^5 \times (\frac{f}{M_{PL}})^{\frac{1}{2}(q+\ldots q^{N-1})} \frac{f}{f_a} M_{PL}$$

EXAMPLES:

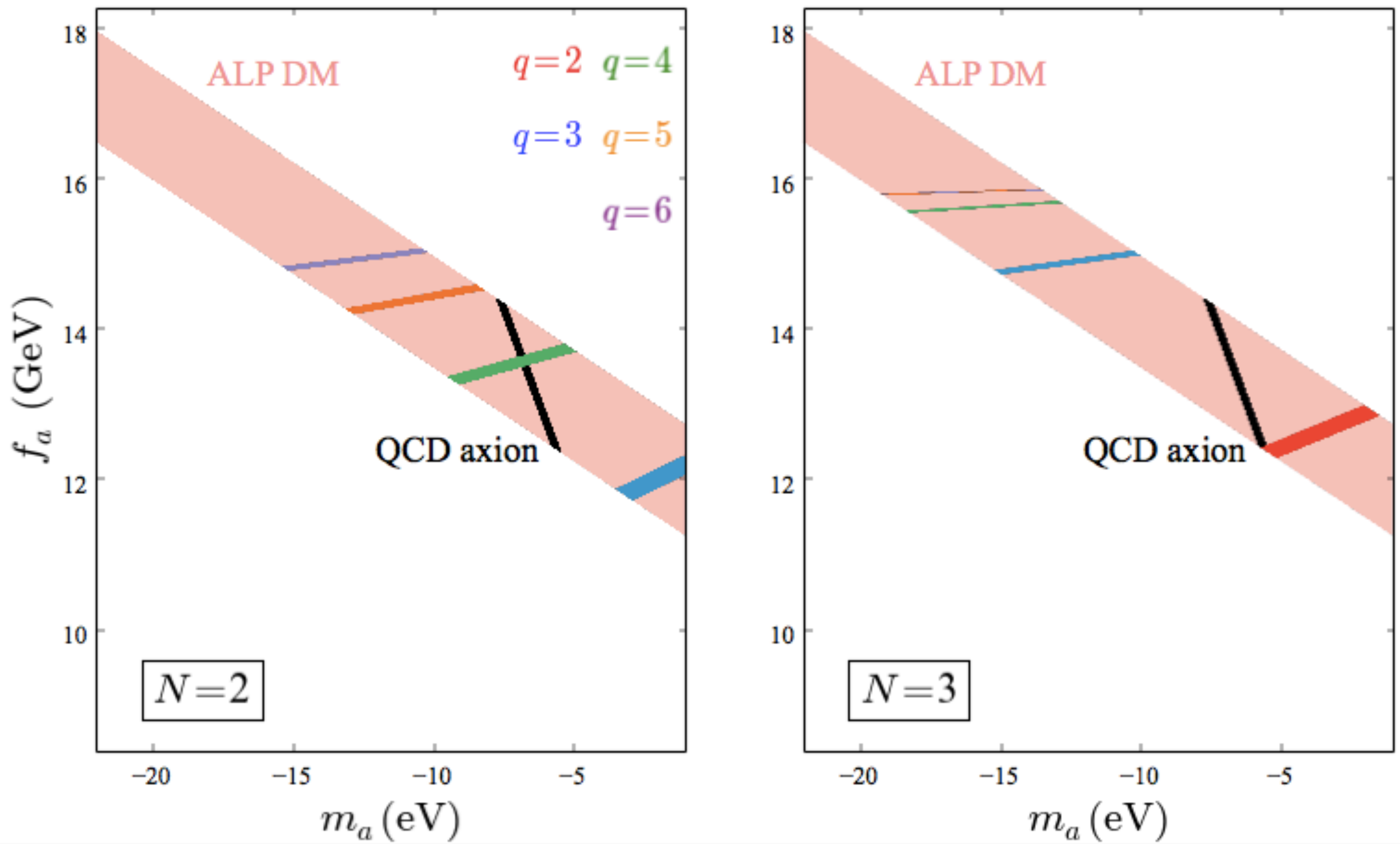
$$q = 3, \quad f = 10^{16} GeV \rightarrow N \geq 3$$

ALP's AS DARK MATTER ONLY, NOT DESIGNED TO SOLVE THE STRONG CP-PROBLEM.

NO NEED FOR ANOMALOUS COUPLING; JUST EXPLICIT BREAKING BY GRAVITY

THE ALP MASS IS GENERATED SOLELY BY THAT BREAKING

$$m_a \sim \left(\frac{f}{\sqrt{2}M_{PL}}\right)^{\frac{1}{2}(q+\ldots+q^N-1)} \sqrt{1+q^2+\ldots q^{2N}}\, M_{PL}$$



ALP DM
$q=2$ $q=4$
$q=3$ $q=5$
$q=6$
QCD axion
$N=2$
$N=3$
18
16
14
12
10
−20
−15
−10
−5
f_a (GeV)
m_a (eV)

SUMMARY

CLOCKWORK INSPIRED QUIVER GAUGE MODELS PROVIDE EXAMPLES OF FIELD THEORETICAL MODELS WITH

1) QCD AXIONS WITH THE AXION DECAY CONSTANT MUCH LOWER THAN THE SCALE OF SPONTANEOUS SYMMETRY BREAKING; WITH SMALL GRAVITATIONAL CORRECTONS TO THE AXION POTENTIAL

2)ULTRA-LIGHT ALPs AS POTENTIAL DARK MATTER CANDIDATES