The many physics cases for axions

Enrico Nardi

Abridged story of the axion

- QCD before 1975: <u>U(1) problem:</u> why the **η'** does not behave as a 9th NGB?
- Instantons (Belavin et al. '75), Yang-Mills vacuum periodicity (Callan et al. '76; Jackiw et al. '76). => Non-trivial vacuum + U(1) axial anomaly -> no conserved axial current -> no NGB
- New problem: $\mathcal{L}_{\text{QCD}} \rightarrow \mathcal{L}_{\text{QCD}} + \theta^{\alpha_s}_{8\pi} G^{\mu\nu}_a \tilde{G}^a_{\mu\nu}$ brings in QCD P,T violation, and thus CP violation, intolerable (nEDM) unless $\theta \leq 10^{-10}$ [no anthropic expl.]
- PQ solution ('77): $\theta \rightarrow \theta(x)$; $V(\theta)$ s.t. $\langle \theta \rangle = 0$. It also predicts a m ≈ 0 scalar: the NGB of a spontaneously broken global and QCD-anomalous $U(1)_{PQ}$: the Axion
- Unexpectedly, the axion has also the right properties to account for the DM !
- Axions physics still holds out a certain number of crucial open issues. Their solution might shed light on other unsolved problems of the SM
- Axion physics is replete with interconnections between particle physics, astrophysics, cosmology, & forefront detection technologies. This drives the axion hypothesis within the reach of experimental verification

The strong CP problem *^q* ! *^ei*5✓*q/*² *^q* (33) ✓*^q* ! ✓*^q* + 2↵ (56) **d** <u>d</u> 21 pi voicille de la provincia de la p *q iD/ ^mqeⁱ*✓*^q ^q* ¹ ↵*s*

^q ! *^ei*5↵*^q* (53)

- QCD is defined in terms of two parameters which are not predicted by the theory. Measurements yield: <mark>isur</mark>en α *g* α *d* β ↵*s* $\frac{1}{2}$ $\frac{1}{2}$ 10 de Cine d'intervier de Cohure incrementant un déce *q* and the state of two parameters which a *G^µ*⌫ *^a G^a ^µ*⌫ ✓ *q q in* terms of *a*
alignary **1** سمست
arameters **V** *u*
µ Aich are not _
- $\alpha_s \sim O(1)$ [Λ_{QCD} ~ 200 MeV] and $\overline{\theta}$ < 10⁻¹⁰ $L_{s} \sim O(1)$ [A_{OCD} \sim 200 MeV] and 6 *q* M ₀ c ^{*n*} \sim 200 $Me¹$ $\ddot{}$ *a no* θ \ θ \overline{P} < 10⁻¹⁰ $\boldsymbol{\theta} < 10^{\text{-}10}$

$$
\mathcal{L}_{\text{QCD}} = \overline{q} \left(i \mathbf{D} - m_q e^{i \theta_q} \right) q - \frac{1}{4} G_a^{\mu \nu} G_{\mu \nu}^a - \theta \frac{\alpha_s}{8 \pi} G_a^{\mu \nu} \tilde{G}_{\mu \nu}^a
$$

- The difference $\overline{\theta} = \theta \theta_q$ gives the amount CP viol. in QCD ✓*^q* ! ✓*^q* + 2↵ (56)
	- \overline{a} $\mathcal{L} \left(\begin{array}{ccc} q & q & q \\ q & q & q \end{array} \right)$ $q \to e^{i\gamma_5\alpha}q$ $\qquad \qquad \theta_q \to \theta_q + 2\alpha$ and $\qquad \theta \to \theta + 2\alpha$ and $\rightarrow \sigma_q + 2\alpha$ and $\sigma \rightarrow \sigma + 2\alpha$
- y the change of the path integral measure: $\overline{}$ α *in A* is *Q iven* by the change of t *R* 11 *V* is given by the change of 1. Field Spin *SU*(3)*^C SU*(2)*^L U*(1)*^Y U*(1)*P Q* • Change in *θ* is given by the change of the path integral measure:

$$
\mathcal{D}q\mathcal{D}\overline{q} \to \exp\left(-i\alpha \int d^4x \, \frac{\alpha_s}{4\pi} G^{\mu\nu}_a \tilde{G}^a_{\mu\nu}\right) \mathcal{D}q\mathcal{D}\overline{q} \qquad \text{[Fujikawa (1979)]}
$$

 $F = N$ ardi (Axion++ 2023, Annecy) 03 under color (*C* = 1), but otherwise generic. 6 σ ⁺⁺ 2023 Annecy *Q^L* 1*/*2 *C^Q I^Q Y^Q X^L* Table i. Fig. $\frac{1}{2}$ and $\frac{1}{2}$ axion model. (*I*^{*I*} *I*^{*I*} *I*^{*I*}

q

A small value problem **d** \overline{A} **d** \overline{A} *^DqD^q* ! exp ✓ *i*↵ *DqDq* (58) 4⇡ ✓ = ✓ ✓*^q* (59) ✓ *^m*² A small value problem ✓ e construction of the construction
The construction of the con ✓ = ✓ ✓*^q* (59)

*d*⁴*x*

µ⌫

^a G˜*^a*

G^µ⌫

^a G˜*^a*

µ⌫

DqDq (58)

⇡

 $\frac{1}{2}$

 $\overline{\theta} \lesssim 10^{-10}$

e

• $\overline{\theta} \neq 0$ implies a non-zero neutron EDM [Baluni (1979), Crewther et al. (1979)] *m*³ *n i*mp $rac{1}{2}$ *m*³ non-zero neutron EDM [Baluni (1979), Crewther et al. (1979)]

$$
d_n \approx \frac{e|\overline{\theta}| \, m_\pi^2}{m_n^3} \approx 10^{-16} |\overline{\theta}| \, e \, \text{cm}
$$

- •However, $d_n \lesssim 3 \cdot 10^{-26} e\,{\rm cm}$ implying: unsatisfactory as a theoretical construction: it does not explain under $\overline{0}$ and $\overline{0}$ and $\overline{1}$ **However**, $d_n \lesssim 3 \cdot 10^{-20} e \text{ cm}$ Implying: $\sim 10^{-10}$ Field Spin *SU*(3)*^C SU*(2)*^L U*(1)*^Y U*(1)*P Q* $d_n \lesssim 3 \cdot 10^{-26} e \text{ cm}$ implying: \rightarrow \rightarrow 10²⁶
- •This is qualitatively different from other small values problems: **• This is qualitatively different from other small values probler** tively different from other smal Field Spin *SU*(3)*^C SU*(2)*^L U*(1)*^Y U*(1)*P Q* tivoly diffonant from othon amall values nu
- $\frac{1}{\sqrt{1-\frac{1}{n}}}\int_{-\infty}^{\infty}$ $\frac{1}{\sqrt{1-\frac{1}{n}}\int_{-\infty}^{\infty}$ $\frac{1}{\sqrt{1-\frac{1}{n}}\int_{-\infty}^{\infty}$ $\frac{1}{\sqrt{1-\frac{1}{n}}\int_{-\infty}^{\infty}$ $\frac{1}{\sqrt{1-\frac{1}{n}}\int_{-\infty}^{\infty}$ \bullet In the SM $\,\theta\,$ receives the first finite Log corrections $\,$ at $O(a^2)\,$ [Ellis, Gaillard (19 Unlike m_{H}^{2} that is quadratically sensitive to Λ^{2} UV *Q^R* 1*/*2 *C^Q I^Q Y^Q X^R* $\overline{\theta}$ $\overline{\theta}$ receives the first finite Log corrections *Q^R* 1*/*2 *C^Q I^Q Y^Q X^R* Unlike m_H^2 that is quadratically sensitive to Λ^2 UV *I. Introduction.* In spite of its indisputable phenomenological success, the standard model (SM) remains • In the SM $\bm{\theta}$ receives the first finite Log corrections at $\bm{U}(\alpha^2)$ [Ellis, Gaillard (1979)] • In the SM $\overline{\theta}$ receives the first finite Log corrections at O(α^2) [Ellis, Gaillard (1979)] receives the first finite Log corrections at $O(\alpha^2)$ [Ellis, Gaillard (1979)] *H* \cdot **F** \cdot **H** \cdot **H** \cdot **H** \cdot **H** \cdot **A** \cdot

\n- Unlike
$$
y_{e,u,d} \sim 10^{-6} \div 10^{-5}
$$
 it evades explanations based on environmental selection [Ubaldi, 0811.1599]
\n

^DqD^q ! exp ✓

✓

dⁿ ⇡

i↵

Three types of solutions

- •A massless quark. One exact chiral symmetry: $\overline{\theta} \to 0$
	- From lattice: $m_u \neq 0$ by more than 20 σ (Aoki (2013)]

[Manhoar & Sachrajda, PDG(2014)]

•CP symmetry + Spontaneous CP violation [Barr (1984), Nelson (1984)]

- Set $\theta = 0$ by imposing CP. Need to break spont. for CKM (+BAU) • High degree of fine tuning, or elaborated constructions to keep
- $\overline{\theta}$ < 10⁻¹⁰ at all orders. No unambiguous exp. signatures.
- The axion (or Peccei-Quinn) solution

[Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

Basic ingredient of the axion solution

$$
\frac{\alpha_s}{8\pi} \left(\frac{a(x)}{f_a} + \bar{\theta} \right) G\tilde{G} + \mathcal{L} \left(\partial_\mu a(x), \psi, \varphi, A_\mu \right) + \underbrace{\left[\delta \mathcal{L}_{eff}(a(x), \ldots) \right]}_{\partial_\mu a \to \partial_\mu a} \operatorname{Tolerable if } \widehat{\Lambda}_{eff} \sim m_P \& d \ge 10
$$

1. $\bar{\theta}$ is removed via a shift of the axion field $a \rightarrow a - \bar{\theta} f_a$

2. Minimum of the vacuum energy for $\langle a(x) \rangle \rightarrow 0$ [Vafa-Witten, Phys. Rev. Lett. **⁵³** (6) 535]

Two elegant realizations

The "QFT axion"

The "superstring axion" (or "extra dim. axion")

The axion is the NGB of a global U(1) symmetry, endowed with a QCD anomaly and broken spontaneously

The axion corresponds to gauge field components of extra dimensional theories $M_D \rightarrow M_4 \times V_{D-4}$ $B_{[MN]} \rightarrow B_{[\mu\nu]} + B_{[ij]}$ [see next talk]

Basic ingredients of the QFT axion solution

[Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

- •A scalar potential invariant under a **global** U(1): Φ -> ei^ξ Φ, δ*L*(Φ) = 0
- •U(1) **SSB:** Φ -> va eia(x)/va. Shift symmetry a(x) -> a(x) + ξvα, δ*L*(a) = 0
- Couplings between the scalars and some quarks $\bar{Q}_L \Phi$ q_R -> \bar{Q}_L v_a q_R e^{ia(x)/va</sub>} U(1) is then enforced by identifying chiral PQ charges $X(Q) - X(q) = X(\Phi)$
- The symmetry must have a mixed $U(1)$ -SU(3)² anomaly: $\Sigma_q(X_Q X_q) \neq 0$

By redefining the quark fields in the basis of real masses $\bar{Q}_L v_a q_R$: $(a(x)/v_a)GG \rightarrow (a(x)/v_a + \Theta) G\overline{G} \rightarrow (a(x)/v_a) G\overline{G}$ Instanton related non-perturbative QCD effects generate a potential $V_{QCD}(a) = -(m_{\pi} f_{\pi})^2 cos(a/v_a)$ that drives $\langle a/v_a \rangle \rightarrow 0$ at the minimum

Axion couplings to matter & radiation

"Defining interaction" axion-gluon coupling $(f_a=v_a/N)$

$$
\frac{\alpha_s}{8\pi f_a} a G \tilde{G}
$$

$$
a = - -4 \frac{1}{2} m \cdot \frac{1}{2} \cdot \frac{1}{2} m
$$

Axion-photon coupling (EM anomaly + mixing with π^0) *α* $\overline{8\pi f_a}$ *E* $\frac{D}{N}$ – 1.92) *a FF*

Axion-nucleon coupling: $C_{aN} = C^{O}(X_{u,d}) + \Delta(m_{u,d})$

$$
\frac{C_{aN}}{2f_a} \partial^{\mu} a \, \bar{N} \gamma_{\mu} \gamma_5 N
$$

Axion-electron coupling: $C_{ae} = C^{0}(X_{e}) + \delta_{e}$ loop

$$
\frac{C_{ae}}{2f_a} \partial^\mu a \,\bar{e} \gamma_\mu \gamma_5 e
$$

Xu,d,e: PQ charges (model dependent parameters.)

Astrophysics: Axion production processes

Axion emission affects star evolution

Stellar evolution vs. axion extra cooling

Color-magnitude diagram for globular cluster M5

Figure 6: Contours of the axion energy-loss rates per unit mass, ε_a , in ergg⁻¹s⁻¹, for a pure He plasma. Different lines represent different channels, as shown in the legend. The Primakoff process is calculated for $g_{a\gamma} = 0.65 \times 10^{-10} \text{GeV}^{-1}$, corresponding to the bound from HB stars [386, 387]. The Bremsstrahlung and Compton processes are calculated for g_{ae} = 4.3×10^{-13} , corresponding to the RGB bound from M5 [307]. The onset of the degeneracy region is visible in the bending of the bremsstrahlung contours. The central temperature and density of the Sun [388], RGB stars, HB stars and WDs are also shown, for reference. In the case of HB and RGB, these are the results of a numerical simulation of a 0.8 M_{\odot} model as obtained with the FuNS code [389]. The WD region is estimated using a polytropic model of WDs with mass from 0.6 to $0.7M_{\odot}$, as discussed in Ref. [383], and spans luminosities in the range between 0.5×10^{-4} and $0.5L_{\odot}$. Except for the WD case, the thickness of the lines has no significance.

Hints for extra energy loss in stars

M. J. Dolan, F. J. Hiskens and R. R. Volkas [arXiv:2207.03102]

Figure 2. (Left panel): Predicted values of R as a function of g_{10} given standard convective core overshoot with $f_{ov} = 0.001$ (blue) and $f_{ov} = 0.01$ (green). The observed limit on R is indicated by the region between the dashed black lines (95% C.I.). (Right panel): The full range of R_2 values predicted as functions of g_{10} given standard overshoot with $f_{ov} = 0.001$ (blue) and $f_{ov} = 0.01$ (green). The observed limit is again shown by the dashed black lines.

High statistics GAIA data will allow to improve this situation

Hints for extra energy loss in stars

June 2020: a signal of solar axions ?

XENON1T (WIMP DM detector)

Excess electronic recoil events in XENON1T PRD 102, 072004 (2020)

(Not confirmed by XENONnT [PRL ¹²⁹ (2022) 16, 161805])

Detection via axioelectric effect (gae)

However, confronting astrophysics:

Solar Axions Cannot Explain the XENON1T Excess

Di Luzio, Fedele, Giannotti, Mescia, EN, PRL 125, 131804 (2020)

Values of $q_{\alpha e} \ge 10^{-12}$ as required to account for the XENON1T excess would unavoidably turn other stars into bright "axion light-houses"

Axions in Cosmology

Axion cosmology involves and exceedingly large number of different topics:

- Thermal production and axion contribution to radiation (Neff) $(T \rightarrow \Lambda_{QCD})$: g q a q, g g a g $\sim a g$ $\sim \alpha s^3 T^3/f_a^2$ $(T \cdot \Lambda_{QCD})$: $\pi \pi \leftrightarrow \pi a$ $\langle \sigma v \rangle \sim ...$? (ChiPT)
	- Production via misalignment (pre/post inflation scenarios)
- Isocurvature fluctuations (pre-inflation)
- Cosmic strings and walls contributions (post-inflation)
- Axion miniclusters

Axion CDM from misalignment **Creation of Cosmological Axions** *^D*' *^eS*0+*i*✓eff*^Q* ⁼ \overline{a} **D** $\overline{}$ ľ $\overline{}$ Z $\overline{0}$ Smological Axions

^ga a F · ^F˜ ⁼ *^ga ^a* ^E *·* ^B (4)

^La ⁼ ¹

4

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Initial condition: Pre/Post inflation scenarios

Slice of the universe after PQ phase transition

• Post inflation: Causal patch at T ~ Λ_{QCD}

Spontaneous/explicit PQ symmt. breaking

Post-inflationary scenarios: T_{PQ} < T_{rh}

- n_a independent of initial conditions: $\langle \theta_i^2 \rangle = \pi^2/3$. More
- predictive for misalignment $\rho_{a\text{-mis}} \approx \rho_{DM} \rightarrow m_a \sim 20\text{-}50\mu\text{eV}$
• Strings remain within the horizon (enter/annihilate) Eventually decay and contribute to ρ_a (important debate: spectrum/string density) masses up to $m_a \sim 0.5$ -3.5meV
	- O(1) density contrasts: at matter/radiation equality (T ~ 1eV) overdensities start growing: axion miniclusters $R_{MC} \sim 1$ AU, $M_{MC} \sim 10^{-3}$ M(, $\rho_{MC} \sim 10^{6}$ $\rho_{DM-local}$
- N_{DW} > 1: Strings-DW network is stable. p_{DW} dominates p_{Universe} Solutions exist (e.g. small non-QCD explicit breaking)

The issue of QCD topological susceptibility

•How does the axion mass behave as a function of the temperature ?

[Bonati et al. 1512.06746, Petreczky et al. 1606.03145, Borsanyi et al. 1606.07494]

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Effective mass, lattice calculations

Lattice QCD: we can compute axion mass

$$
m_a^2 f_a^2 = \chi(T)
$$

At high T (no mesons) we can analytically compute potential (DIGA)

$$
V(\theta)=-\chi(T)\cos\theta
$$

The issue of topological defects contributions

Only in post-inflation scenario (in pre-inflation defects are inflated away) Only for the QFT axion (extra dim. compactified before inflation)

 $|\rho_a|$ = n_a m_a = $(n_{mis} + n_{strings})$ m_a. For which value of m_a ρ_a = ρ_{DM} ?

Current limits and search strategies supernova core. For even larger couplings, axions are trapped in the medium and their emission decreased cristial conco \overline{a} \overline{b} l. ⇣ *ga* 1 **26** Gev $\overline{1}$ 1 STMATRAIRS where Z is the atomic number of the atomic number. It is then possible to derive constraints on the axion mass axions increase and therefore the burst duration shortens. A minimum in the cooling α time is reached when the axiom search size of the axion means to the size of the size of the geometric size of supernova core. For even larger couplings, axions are trapped in the medium and their *LQq* = 0 (43)

time is reached when the axion mean free path corresponds to the geometric size of the

• Astrophysical bounds on axion couplings The Kamiokande-II and the Irvine-Michigan-Brookhaven experiments measured the Irvine-Michigan-Brookhaven experiments measured the Irvine-Michigan-Brookhaven experiments measured the Irvine-Michigan-Brookhaven experiments and the axion-electron comparing the theoretical luminosity function, including $\mathop{\mathsf{strong}}$ rate decrease of the and the rotational from the $\mathop{\mathsf{approximately}}$ emission decreases reaching a point where the cooling time is unaffected by their presence. ¹

by a factor proportional to the axion-photon coupling

- Star evolution, RG lifetime $g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11} \, {\rm GeV}^{-1}$ tar evolution, RG lifetime $g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11}\,{\rm GeV}^{-1}$ $\gamma \sim 0.0 \times 10^{-3}$ 10 C
	- White dwarf cooling
	- Supernova SN1987A Globular cluster stars and cluster stars and

6. Axion searches

- White dwarf cooling $g_{aee} \lesssim 1.3 \times 10^{-13} \text{GeV}^{-1}$ - Supernova SN1987A $g_{aNN} \lesssim 3 \times 10^{-7} \text{ GeV}^{-1} \longrightarrow f_a \gtrsim 2 \times 10^8 \text{ GeV}.$: dwarf cooling $g_{aee} \lesssim 1.3 \times 10^{-13}\,{\rm GeV^{-1}}$ $g_{aNN} \lesssim 3 \times 10^{-7} \text{ GeV}^{-1} \longrightarrow f_a \gtrsim 2 \times 10^8 \text{ GeV}$

> [For a collection see e.g. Raffelt, hep-ph/0611350] Γ or a concern

LQq 6= 0 (42)

does not change the cooling time. As *gaNN* increases, the emission of bremsstrahlung

- Most laboratory search techniques are sensitive to g_{ayy} Black hole superradiance gravitation of systems of stars of stars that the same time that formed at the same time that same time are ca CST IGDOI GIOI γ startin rechniques are sensitive to \mathcal{S} ayy Field Spin *SU*(3)*^C SU*(2)*^L U*(1)*^Y U*(1)*P Q Q^L* 1*/*2 *C^Q I^Q Y^Q X^L*
- Light Shining trough Walls evel and the line of the helium consumers and the state of the late of the state o
Experience of the stars and the helium consumption of the stars and the stars and the late of the stars and th Photon conversion into Axions, reconverted back into photons after passing a wall $t \hbox{ if } t \geq 0$ Shining Trough Walls exponentially research the bound of the bound of the bound of the energy of neutrino emission of the energy of the en $\begin{bmatrix} 1 & 1 & \mathbf{c} & 1 & \mathbf{c} & \math$ $\mathbf{0}$ 1.000 1.000 $\mathbf{0}$ 1.000 $\mathbf{0}$ 1.000 $\mathbf{0}$ 1.000 $\mathbf{0}$ [see e.g. Redondo, Ringwald hep-ph/1011.3741]
- Haloscopes [Sikivie 1983] Search for Axion Dark Matter $\sum_{k=1}^{\infty}$ extracting angular momentum and rotational energy from the black hole. Furthermore, under color (*C* = 1), but otherwise generic. 6
- Helioscopes from the black hole. As a consequence, the black hole spins down. Current black hole U_{α} dark matter (DM), neutrino masses, and the cosmological baryon asymmetry, and it contains fundamental

spin measurements imply an upper bound on the QCD axion decay constant of 2 ⇥ 10¹⁷ tor Axions pr Search for Axions produced in the Sun

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Sikivie 1983 $f_{\rm min}$ the cooling of ~ 1000 into white dwarfs via the processes via the

Light Shining trough Walls (LSW)

•Any Light Particle Search (DESY) Alps 1 (2007-2010) Alps 2

Schematic view of axion (or ALP) production through photon conversion in a magnetic field (left), subsequent travel through a wall, and final detection through photon regeneration (right).

- LSW experiments pay a (*gaγγ*)4 suppression

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Artist view of a light shining

through a wall experiment

Kaloscopes Peccei-Quinn (PQ) solution [7–10] arguably stands \blacksquare challenge explaining through which mechanism the global *U*(1)*P Q* symmetry, on which the solution rewhere *E* and *B* are respectively the standard electric and magnetic field of the coupling

- Look for halo DM axions with a microwave resonant cavity [Sikivie (1983)] **[Sikivie (1983)]** *m^a* ' *m*⇡ *fa* λ exiency with a *fa* $\overline{2}$ lies (and that presumably arises as an accident) re- ${\sf cov}$ for halo DM axions with a microwave resonant cavity religions (1983)] ${\sf cov}$
- Macroscopic B-field can provide a nai $\ddot{ }$ $\mathbf{1}$ accuracy $\mathbf{1}$ accuracy $\mathbf{1}$. PROTON TEQUISTION IN EXTERNAL — exploits inverse <u>Primakoff effect</u>: axion-photon transition in external the cavity resonant frequency !*^a* matches with the axion mass *ma*. Relic axions from the Big Bang are gravitationally bound to the Milky Way with a E or B field

$$
\mathcal{L}_{a\gamma\gamma}=-\frac{1}{4}g_{a\gamma\gamma}\,a\,F\cdot\tilde{F}=g_{a\gamma\gamma}\,a\,\mathbf{E}\cdot\mathbf{B}
$$

6. Axion searches

$$
\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F \cdot \tilde{F} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}
$$

rather elaborated theoretical structures [6]. The

and Ceorg Raffelt, MPI Physics, Munich.

and Matter of axions converting into photons in an FM cavity remains under the term of the theoretical construction of the The vast majority of axion search techniques are $-$ power of axions converting into photons in an EM cavity **with energy dispersion of axions**

$$
P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\text{eff}}
$$

ral values, like the coecient *µ*² of the quadratic \blacksquare i espriume condition, need to tune to on the axion mass *[good knowledge* strong CP violating angle ✓ *<* 10¹⁰. This last - resonance condition: need to tune the frequency of the EM cavity possibly to *g* and *n*²/²/_{*m*} (DM) would be important m_a(DM) would be important] on the axion mass *Loopd knowledge* of m *(DM) would be important*? is smaller or the cavity factor interneting α _{*L*} and α _{*L*} and the α _{*L*} and the quality factor for the α on the axion mass [good knowledge of $m_a(DM)$ would be important]

 α and α is somewhat special: its value is stable with special: its value is stable with α

Haloscopes

- Look for DM axions with a microwave resonant cavity
	- Axion Dark Matter eXperiment (ADMX) (U. of Washington) Avier Derk Metter eVreriment (ADMV)

Helioscopes

. The Sun is a potential source of a copious axion flux rial source of a cop

 $F = 0.5$ and $F = 1.5$ solar axion helioscope: $F = 0$ and $F = 1.5$ and $F = 1.5$ - macroscopic transverse B-field over a large volume (figure from [2]). Right: The solar axion flux as expected at the Earth. A value of 1 [×] ¹⁰−¹⁰ GeV−¹ for *ga*^γ is assumed. Detection via inverse-Prim energy range of 1–10 kg v. The operation of a helio- $\mathsf{df}(a)$ and $\mathsf{d} \rightarrow \mathsf{S}$ Detection via inverse-Primakoff (g_{ay}) a dipole magnetic triggers axion to photon (x-ray) conversion $A = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$ \mathcal{L} axions with \mathcal{L} $(x - r\alpha)$ conversion $a \Rightarrow \sum_{\alpha} \gamma$

Axion helioscope: •

E. Nardi (Axion++ 2023, Annecy) 28 background data when there is no alignment with the there is no alignment with the α a big volume (low-mass axions) axions) axions) axions) axioms axioms axioms axio

scope consists in following the Sun as long as techni-

Helioscopes

- The Sun is a potential axion source (3rd and 4th generation axion-Sun telescopes)
- CERN Axion Solar Telescope (CAST) \overline{C}

- International AXion Observatory (IAXO)

Figure 26: Close-up of the high mass part of parameter space of Fig. 25 (1 meV *< m^a <* 1 eV). [IAXO "Letter of intent", CERN-SPSC-2013-022]

(electron-ion and electron-electron-electron-electron-electron-electron-electron-electron-electron-electron-electron-electron-electron-electron-electron-electro-electro-electro-electro-electro-electro-electro-electro-elec E. Nardi (Axion++ 2023, Annecy) 29

Dmitry Budker,^{1,2} Peter W. Graham,³ Micah Ledbetter,⁴ Surjeet Rajendran,³ and Alexander O. Sushkov⁵

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Axion theory (QFT axion)

The PQ solution suffers from one serious issue: Most model realizations can be considered "incomplete"

-The "origin" of the PQ "symmetry" is left unexplained

-The "high quality" of the PQ symmetry remains a puzzle

"quality" = absence of sources of explicit PQ-symmetry breaking, up to effective operators of dimension D≿10

This problem can be avoided in extra dim. axion models (gauge origin) [see Dvali talk]

The PQ "origin" and "quality" problems

• $U(1)_{PQ}$ is <u>anomalous</u>. Is not a (fundamental) symmetry of the theory: At the quantum level the theory is not invariant under $\psi \rightarrow e^{i\alpha y}$, ψ

$$
Z \sim \int [DA_{\mu} D\Phi] D\psi D\bar{\psi} \exp(iS) \rightarrow \int [DA_{\mu} D\Phi] D\psi D\bar{\psi} \exp(iS + i\int d^4x \frac{\alpha}{16\pi} G\tilde{G})
$$

•In benchmark axion models, Φ is a complex scalar, and a gauge singlet. Renormalizable terms $\mu^3 \Phi$, $\mu^2 \Phi^2$, $\mu \Phi^3$, $\lambda \Phi^4$ do not break gauge or Lorentz and are not forbidden. No reasons not to write them in the Lagrangian... However, they would completely destroy the PQ solution !

• Moreover: Non-pt. quantum gravity effects break all global `symmetries' Controlled semiclassical solutions [Euclid. wormholes] give:

 $O_{PQ} \sim M_{P}^{3}e^{-S_{wh}}\Phi + h.c.$

Safe suppression requires $S_{wh} > 190$ (while typical wh actions are $S_{wh} \sim Log(M_P/v_a) \sim 15$)

[Kallosh et al. '95, Alonso & Urbano '17, Alvey & Escudero '20]

The PQ "origin" and "quality" problems

•PQ breaking higher dim. effective opts. $\lambda \Phi d/\Lambda d-4$ are also dangerous:

$$
\lambda \frac{\Phi^d}{\Lambda^{d-4}} + \text{h.c.} \approx |\lambda| \left(\frac{v_a}{\Lambda}\right)^{d-4} v_a^4 \cos(a/v_a + \varphi_\lambda) \text{ vs. } V_{\text{QCD}}(a) = -(m_\pi f_\pi)^2 \cos(a/v_a)
$$

To preserve $\langle a/v_a \rangle \approx 0$ we need: Eng. density eff.opt. < 10⁻¹⁰ $V_{QCD}(a)$ $|\lambda| (v_a/\Lambda)^{d-4}$ < 10-10 $(m_{\pi} f_{\pi}/v_a^2)^2$ E.g. $|\lambda| \sim 1$, $\Lambda \sim M_P$ and $v_a \sim 10^{10}$ GeV imply $d \ge 10$ [with $\lambda = g_{wh}$ $d \ge 9$] **a** [Barr & Seckel '92, Kamionkowski & March-Russel '92, Holman et al. '92, Ghigna et al. '92] E

The QFT axion solution requires a PQ symmetry of an excellent quality: No PQ symmetry breaking operators up to a very large dimension $d \ge 10$ In comparison, in the SM L-number can be violated at $d=5$, B-number at $d=6$

A sample of proposed solutions

U(1)_{PQ} should arise automatically as a consequence of first principles. SSB requires VEVs \Rightarrow Lorentz singlets. Rely on <u>local gauge symmetries</u>

- Discrete gauge symm. \mathbb{Z}_n : $\Phi \rightarrow e^{i 2\pi/n} \Phi$; 1st PG opt. $A^{4-n} \Phi^n$ Requires \mathbb{Z}_{10} or larger [Krauss & Wilczek '89, Dias & al. '03, Carpenter & al. '09, Harigaya & al. '13]
- •Local U(1) + 2 scalars with charges $q_1+q_2 \ge 10$ 1st $PG: A^{4-q_1-q_2}(\Phi_1^+)^{q_2}(\Phi_2)^{q_1}$ (q1 and q2 relatively prime) [Barr & Seckel '92]
- Non-Abelian $SU(n)_L \times SU(n)_R$, $a(x) \in Y_{n \times n} \sim (n, \bar{n})$ For $n > 4$ the ren. potential is very simple: $V(Y) = (T - \mu^2)^2 \pm T_4$ where $T = Tr(Y^{\dagger}Y)$, $T_4 = Tr(Y^{\dagger}Y^{\dagger}Y^{\dagger})$. Automatic rephasing symm. $Y \rightarrow e^{i\xi} Y$ 1st PQ opt. A^{4-n} det Y dim = n. This requires again $n \geq 10$
[Fong, EN '14 [in SU(3)xSU(3)], Di Luzio, Ubaldi, EN '17]

G Can we do any better?

Local gauge symmetries seem to be the only tool we have at disposal to generate accidentally a PQ symmetry and enforce the required level of protection….

- But can we obtain the required PQ protection without putting a "10" by hand ? $(\mathbb{Z}_{10}$, $q_1+q_2 \ge 10$, $SU(10) \times SU(10)$, ...)
- Can we link the PQ origin and quality problem to other SM puzzles ?
- Hint: a gauge symmetry acting on scalars coupled to quarks, must also act on the quarks. Thus, it is by definition a Flavour Symmetry!

The "PQ quality - flavour" connection

By implementing accidentally a PQ symmetry via non-Abelian gauge protection, can we learn something beyond 'axion issues' ?

Origin + quality of acc. symmt. => Certain Non-Abelian gauge groups G_F acting on some set of scalar multiplets.

Promoting $U(1)$ to a PQ symmt. requires a mixed QCD anomaly.

- \Rightarrow Quarks must transform under the U(1) $_{PQ}$ symmt.
- => Hence they must couple to the scalar multiplets
- => Hence they must also transform under GF

Hence the local GF is a flavour symmetry!

A property of certain gauge symmetries

•We have found that local SU(M) x SU(N) (M≠N) spontaneously broken by scalar multiplets Y_{ai} ~ (m, \bar{n}) [+ (m,1), (1, \bar{n})] are well suited to enforce and protect an accidental global U(1)

Already with $SU(3) \times SU(2)$ the potential $V(Y)$ for a scalar multiplet $Y_{ai} \sim (3,\bar{2})$ enjoys an <u>automatic</u> & <u>exact</u> global U(1) (Unfortunately, non-anomalous) [Darmé & EN (2021)]

We have recently proven that with semi-simple gauge groups GF, sufficient PQ protection together with det $M_q \neq 0$ implies a vanishing PQ anomaly [Darmé, EN, Smarra, JHEP 02 (2023) 201]

Useful groups are non-simple, of the form $G_F \times U(1)_F$

Non-simple gauge symmetries

The argument is circumvented by adding a U(1) gauge factor

[Darmé, EN, Smarra, JHEP 02 (2023) 201]

 $G_F \rightarrow G_F = G_F \times U(1)$ F **'**

Curiously, the simplest symmt.: $G_F = [SU(3) \times SU(2) \times U(1)]_F$

 \cdot PQ: $U(1)_{PQ}$ remains protected up to d=11 (no PQ breaking opts. at d=12, next ones at d=13) • The physical axion is "invisible": $f_a \sim v_F \sim [10^8 - 10^{12}]$ GeV

•Flavor: First result: d/u-mass hierarchies arise naturally. Reproducing CKM mixings from dynamical minimization of V(S) is a computationally demanding task (ongoing effort). No reason to suspect that this should not happen.

Summary and conclusions

- The axion mechanism provides an elegant and convincing solution to the strong CP problem. Axions can arise as NGB in QFT or from gauge forms in extr. dim. models. It might be possible, in some case, to identify the origin of the axion.
- The axion has far reaching implications in particle physics, astrophysics, and cosmology, and it represents an excellent (and discoverable) DM candidate. The (post-inflation) axion DM window can be fully probed within the next decade
- Ongoing and forthcoming cosmological surveys, astrophysics observations, and laboratory experiments will soon provide a wealth of data to exhaustively probe the axion hypothesis.
- Certain theoretical and computational issues should be addressed with dedicated efforts, and hopefully will be clarified soon. It is conceivable that a better understanding of the origin of the axion might shed light on some other unsolved puzzles in the SM.

Thank you !