Axions couplings in non-standard axion models (about axions and their many phobias)

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In 10 years from now ?

- ✤ A great opportunity to discover the QCD axion !
- \star Time <u>now</u> to get prepared and rethink the QCD axion

[See also talks by Prateek Agrawal and Rachel Houtz yesterday]

Figure 25: Overall panorama plot in the (*ga*,*ma*) plane. As usual laboratory, helioscopes and haloscopes

- 1. Astro bounds on axion mass [critical approach]
- 2. Axion couplings [in standard axion models]
- 3. Re-opening the axion window [astrophobia = nucleophobia + electrophobia]
- 4. Flavour complementarity

Based on: LDL, Mescia, Nardi 1610.07593 (PRL) + 1705.05370 (PRD) LDL, Mescia, Nardi, Panci, Ziegler 1712.04940 (PRL)

Astro bounds

- Stars as powerful sources of light and weakly coupled particles [see e.g. Raffelt, hep-ph/0611350]
	- light: $m_a \lesssim 10 \, T_\star \;$ (e.g. typical interior temperature of the Sun \sim 1 keV)
	- weakly coupled (otherwise we would have already seen them in labs)

Astro bounds

- Stars as powerful sources of light and weakly coupled particles I. INTRODUCTION [see e.g. Raffelt, hep-ph/0611350]
	- light: $m_a \lesssim 10 \, T_\star \;$ (e.g. typical interior temperature of the Sun \sim 1 keV) *m^a* . 10 *T*? (1)
	- I_{α} dech diction in I_{α} - weakly coupled (otherwise we would have already seen them in labs)
- constraints from "energy loss", relevant when more interacting than neutrinos *m^a* . 3 *T* (2)

neutrino interactions (d=6 op.) axion interactions (d=5 op.) *G^F m*² *^e* ' 10¹² (3) G $H = 5 \text{ on } 1$

$$
G_F m_e^2 \simeq 10^{-12} \qquad \qquad \frac{m_e}{f_a} \simeq 10^{-12} \left(\frac{10^8 \text{ GeV}}{f_a} \right)
$$

m^e fa ons are a perfect ta *fa* axions are a perfect targ $m_a \sim \Lambda_{\rm QCD}^2/f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a}\right)$ f_a ◆ 。
○ $m_a \sim \Lambda_{\rm QCD}^2/f_a \simeq 0.1 \; {\rm eV} \left(\frac{10^8 \; {\rm GeV}}{f}\right)$ axions are a perfect target ! f_a ◆

^m^a ⇠ ⇤²

[Ringwald, Rosenberg, Rybka, Particle Data Group (2016)]

Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Example 20 (6) EXP = 0 (6) AXION EARLY Axion landscape

are translated into limits on m^A and f^A usb (IPPP, Durham) - Axions couplings in non-stand L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models **1986**

Cⁿ = 0*.*02(3) (5) Axion landscape

ing *m*
L. Di Luzio (IPPP, Durham) - Axions couplings in non-stand *m^u* + *m^d*]*^u* + [*Cad ^m^u* mon-star L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models 04/14

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p

b (IPPP, Durham) - Axions couplings in non-stand *E ^N* ² 4*m^d* + *m^u ^Cap* ' [*Cau ^m^d* **L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models 04/14**

• Bound on axion mass is of practical convenience, but misses model dependence ! proximate ADMX, CASPEr, CAST, and IAXO

- All you need is (to solve the strong CP problem) *^Lef f* ⁼ *^LSM* ⁺ ✓ *^g*² *a g*2
	- a new spin-0 boson with pseudo-shift symmetry $a \rightarrow a + \alpha f_a$ \overline{a} *µ* @*^µa*@*µ^a* ⁺ *^L*(@*µa,*) (76)

broken by	$\frac{a}{f_a} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$	$E(0) \le E(a)$	[Vafa-Witten theorem, PRL 53 (1984)]
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 \overline{I} *^Lef f* ⁼ *^LSM* ⁺ ✓ *^g*² *a g*2 • All you need is (to solve the strong CP problem)

a new spin-0 boson with pseudo-shift symmetry $a \rightarrow a + \alpha f_a$ \overline{a} *µ* @*^µa*@*µ^a* ⁺ *^L*(@*µa,*) (76)

$$
\frac{\text{broken by}}{f_a} \frac{a}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}
$$

- generates "model independent" axion couplings to photons, nucleons, electrons, … *C* = *E/N* 1*.*92(4) (2) *C^p* = 0*.*47(3) (3) *C^e* ' 0 (1) zenerates "r *n dependent axion couplings to priotons, nuclearly* \blacksquare imodel independent'' axion couplings to photons, nucleons, electrons, \dots ptons. nucleons. electrons. . . .

[Theoretical errors from NLO Chiral Lagrangian, Grilli di Cortona et al., 1511.02867] *f^a v* (81) *C^p* = 0*.*47(3) (3) *C^p* = 0*.*5 (6) $\frac{1}{2}$ Theoretical errors from NLO Chiral Lagrangian. **E** \blacksquare **Exercical errors** \Box *n* (3) $\frac{1}{2}$ errors from NL *m^u* + *m^d Crian* III *Craul Lagrangian, et al., 1511.028671* ا at al
ا at al *p* (3) *a* (5) **a** *E* Theoretical errors from NLO Chiral Lagrangian

*m*UV

^u ⁶⁼ *^m*PT

(4)

^Lef f ⁼ *^LSM* ⁺ ✓ *^g*² *a g*2 • All you need is (to solve the strong CP problem) \overline{I}

a new spin-0 boson with pseudo-shift symmetry $a \rightarrow a + \alpha f_a$ \overline{a} *µ* @*^µa*@*µ^a* ⁺ *^L*(@*µa,*) (76)

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$$
C_{\gamma} = -1.92(4)
$$
 $C_p = -0.47(3)$ $C_n = -0.02(3)$ $C_e \simeq 0$

- EFT breaks down at energies of order f_a *C*₁ = 0*.* Dreaks down at energies of order I_a

Cⁿ = 0*.*02(3) (5)

Axion models [UV completion]

• Axion: PGB of QCD-anomalous global $U(1)_{PQ}$; anomalous PQ breaking (fermion sector) + spontaneous PQ breaking (scalar sector) $\frac{1}{2}$

Axion models [UV completion]

• Axion: PGB of QCD-anomalous global $U(1)_{PQ}$; anomalous PQ breaking (fermion sector) + spontaneous PQ breaking (scalar sector) C

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Axion-photon coupling

- Red line set by perturbativity [KSVZ] (going above requires more exotic constructions)
- Blue line corresponds to a 2% 'tuning in theory space'

about photophobia: "… such a cancellation is immoral, $\begin{bmatrix} \text{but not unnatural''} \end{bmatrix}$ [D. B. Kaplan, (1985)] $\begin{bmatrix} \text{c.} \\ \text{c.} \\ \text{c.} \end{bmatrix}$ $\begin{bmatrix} \text{ADMX}, \ldots \\ \text{CDMX}, \end{bmatrix}$

Axion-photon coupling

- Message for experimentalists:
- 1. The QCD axion might already be in the reach of your experiment !
- 2. Don't stop at $E/N = 0$ (go deeper if you can)

Astrophobia

- Is it possible to decouple the axion both from nucleons and electrons?
	- $nucleophobia + electrophobia = astrophobia$
- Why interested in such constructions ? [LDL, Mescia, Nardi, Panci, Ziegler 1712.04940]
	- 1. is it possible at all ?
	- 2. would allow to relax the upper bound on axion mass by \sim 1 order of magnitude
	- 3. would improve visibility at IAXO (axion-photon)
	- 4. would improve fit to stellar cooling anomalies (axion-electron) [Giannotti et al. 1708.02111]
	- 5. unexpected connection with flavour

Astrophobia

• Is it possible to decouple the axion both from nucleons and electrons ?

nucleophobia + electrophobia $* =$ astrophobia

• Why interested in such constructions ? [LDL, Mescia, Nardi, Panci, Ziegler 1712.04940]

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*conceptually easy (e.g. couple the electron to 3rd Higgs uncharged under PQ)

Conditions for nucleophobia I. INTRODUCTION *f* (1) conditions for nuclear *f^a* (1)

 \overline{c}

 f_a \qquad $\sum_{n=1}^{\infty} \frac{2f_a}{2f_a}$ (a, a, b, c, c, c, c, c) **p** (3) $\frac{1}{2}$ (3) $\frac{$ $\mathcal{C}_{11} = \frac{\partial_{\mu} a}{\partial \mu} \frac{\partial}{\partial \mu} \frac{\partial^{\mu} N}{\partial \mu} \frac{\partial^{\mu} N}{\partial \mu} \frac{N}{\partial \mu} \frac{\partial^{\mu} N}{\partial \mu}$ • Axion-nucle *f***a** $\frac{1}{\sqrt{2}}$ $n \t 2Ja$ *p* (3) $\mathcal{L}_N = \frac{\partial \mu^{\alpha}}{\partial f} C_N N S^{\mu} N \qquad N = (p, n)$ *f^a* (1) *n* (2) $p = \blacksquare$ EFT-1: quarks and gluons (in the basis wh ϵ (4) $a \rightarrow a$ (5) *n* (2) $\rho_{\alpha} = \frac{\partial_{\mu} a}{\partial \gamma^{\mu}} c_{\alpha} \bar{q} \gamma^{\mu} \gamma_5 q \qquad \qquad q = (u, d, s, \ldots)$ π (4) *e* (5) **P** EFT-11: non-relativistic nucleons PLB 169 (1986), ..., Grilli di Cortona et al. 1511.02867] *p* (3) \overline{p} \equiv \overline{r} \overline{r} \overline{r} (\overline{r} and \overline{r} and \overline{r} and \overline{r} (in the basis when *e* (5) *n* (*2*) *n* (*1*, 00), *n* (*1*, 00), *n* (*1*, 01), *n* (*n* 0*n*) **p** (3) $\frac{1}{2}$ (3) $\frac{$ *e* (5) I. INTRODUCTION $v \leftarrow$ *f* LITT. Qual is and glubits (in the basis with *n* (3) *p* (4) EFT-1: quarks and gluons (in the basis where c_q contains aGGtilde contrib.) • Axion-nucleon couplings [Kaplan NPB 260 (1985), Srednicki NPB 260 (1985), Georgi, Kaplan, Randall \mathcal{I} $\mathcal{L}_N =$ $\partial_{\mu}a$ $2f_a$ $C_N \overline{N} S^{\mu} N$ $N = (p, n)$ @*µa* \cup $\mathcal{L}_q =$ $\partial_{\mu}a$ $2f_a$ $c_q \overline{q} \gamma^\mu \gamma_5 q$ $q = (u,d,s,\ldots)$ @*µa* 8⇡ *fa* aF*µ* (4) and $N = (p, n)$ *q* = (*u, d, s, . . .*) (2)

L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion ⇡ (5) 2*f^a* rm) - Axions couplings in non-standard axion models and the second service of the second service of \sim *N N N*² + *N*² $\frac{1}{2}$ *M*² + *N*² +

e (5) and (5)

f^a (1)

 \bullet Axion-nucle

Conditions for nucleophobia I. INTRODUCTION *f* (1) conditions for nuclear *f^a* (1)

 \bullet Axion-nucle • Axion-nucle *f^a* (1)

f^a (1) PLB 169 (1986), ..., Grilli di Cortona et al. 1511.02867] *n* (*2*) *n* (*1*, 00), *n* (*1*, 00), *n* (*1*, 01), *n* (*n* 0*n*) \overline{c} • Axion-nucleon couplings [Kaplan NPB 260 (1985), Srednicki NPB 260 (1985), Georgi, Kaplan, Randall \cup

$$
f_a
$$
\n
$$
c_q = \frac{\partial_\mu a}{2f_a} c_q \overline{q} \gamma^\mu \gamma_5 q
$$
\n
$$
c_p + C_n = (c_u + c_d) (\Delta_u + \Delta_d)
$$
\n
$$
c_p - C_n = (c_u - c_d) (\Delta_u - \Delta_d)
$$
\n
$$
c_p + C_n = (c_u + c_d) (\Delta_u + \Delta_d)
$$
\n
$$
c_p - C_n = (c_u - c_d) (\Delta_u - \Delta_d)
$$
\n
$$
c_p = \frac{\partial_\mu a}{2f_a} C_N \overline{N} S^\mu N
$$
\n
$$
(1): C_p + C_n \approx 0 \text{ if } c_u + c_d
$$
\n
$$
a \longrightarrow C_N = \frac{\partial_\mu a}{2f_a} C_N \overline{N} S^\mu N
$$
\n
$$
(2): C_p - C_n = 0 \text{ if } c_u - c_d
$$

$$
\langle p|\mathcal{L}_q|p\rangle=\langle p|\mathcal{L}_N|p\rangle
$$

@*µa*

2*f^a*

$$
s^\mu \Delta q \equiv \langle p | \overline{q} \gamma_\mu \gamma_5 q | p \rangle
$$

$$
C_p + C_n = (c_u + c_d) (\Delta_u + \Delta_d) - 2\delta_s \qquad [\delta_s \approx 5\%]
$$

$$
C_p - C_n = (c_u - c_d) (\Delta_u - \Delta_d)
$$

@*µa* Independently of matrix elements:

$$
C_N \overline{N} S^{\mu} N \qquad (1): \quad C_p + C_n \quad \approx \quad 0 \quad \text{if} \quad c_u + c_d = 0
$$

$$
C_N \overline{N} S^{\mu} N \qquad (2): \quad C_p - C_n \quad = \quad 0 \quad \text{if} \quad c_u - c_d = 0
$$

e (5) and (5)

a (6)

*c^q q^µ*5*q* (4)

aFµ⌫*F*˜*µ*⌫ (6)

L^q =

@*µa* 2*f^a X^u* /LJF5*u X^d ^N ^d^µ*5*^d* KSVZ/DFSZ no-go

$$
\mathcal{L}_a \supset \frac{a}{f_a} \frac{\alpha_s}{8\pi} G\tilde{G} + \frac{\partial_\mu a}{v_{PQ}} \left[X_u \, \overline{u} \gamma^\mu \gamma_5 u + X_d \, \overline{d} \gamma^\mu \gamma_5 d \right]
$$

@*µa* 2*f^a X^u* /LJF5*u X^d ^N ^d^µ*5*^d* KSVZ/DFSZ no-go

@*µa* 2*f^a X^u* /LJF5*u X^d ^N ^d^µ*5*^d* KSVZ/DFSZ no-go

$$
\frac{X_u}{N} \to c_u = \frac{X_u}{N} - \frac{m_d}{m_d + m_u} \qquad \frac{X_d}{N} \to c_d = \frac{X_d}{N} - \frac{m_u}{m_d + m_u}
$$

 $\frac{1}{2}$ @*µa* 2*f^a C*_N **C**^N² (12) *C_N*² (12) *C_N*² (12) *C_N***² (12) C**_N² (12) **C**_N² (12) L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models 10/14

@*µa* 2*f^a X^u* /LJF5*u X^d ^N ^d^µ*5*^d* 171007 *ng* 11 empty no-go KSVZ/DFSZ no-go

$$
\mathcal{L}_a \supset \frac{a}{f_a} \frac{\partial_{\zeta}}{\partial \overline{\zeta}} \widetilde{G} + \frac{\partial_{\mu} a}{v_{PQ}} \left[X_u \, \overline{u} \gamma^{\mu} \gamma_5 u + X_d \, \overline{d} \gamma^{\mu} \gamma_5 d \right]
$$
\n
$$
\frac{\partial_{\mu} a}{\partial f_a} \left[\frac{X_u}{N} \, \overline{u} \gamma^{\mu} \gamma_5 u + \frac{X_d}{N} \, \overline{d} \gamma^{\mu} \gamma_5 d \right]
$$

$$
\overbrace{\hspace{15em}}
$$

$$
\frac{X_u}{N} \to c_u = \frac{X_u}{N} - \frac{m_d}{m_d + m_u} \qquad \frac{X_d}{N} \to c_d = \frac{X_d}{N} - \frac{m_u}{m_d + m_u}
$$

m^d + *m^u*

^N ¹ (2)

$$
1 \text{st condition } 0 = c_u + c_d = \frac{X_u + X_d}{N} - 1
$$

2nd condition
$$
0 = c_u - c_d = \frac{X_u - X_d}{N} - \frac{m_d - m_u}{\frac{m_d + m_u}{\approx 1/3}}
$$

$\frac{1}{2}$ @*µa* 2*f^a* Axions couplings in non-standard axion models and the couplings of $\frac{10}{14}$ '1*/*3 $\Delta \vee$ *^N* ! *^c^u* ⁼ *n*gs in non-stand L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models 10/ 14

^N ^m^d ^m^u

m^d + *m^u*

KSVZ/DFSZ no-go

$$
\begin{array}{ccc}\n\text{1st condition} & 0 = c_u + c_d = \frac{X_u + X_d}{N} - 1 \\
\hline\n\text{1st condition} & 0 = c_u + c_d = \frac{X_u + X_d}{N} - 1\n\end{array}\n\qquad\n\begin{array}{ccc}\n\text{KSVZ} & & -1 \\
\hline\n\text{FSZ} & & \frac{1}{n_g} - 1\n\end{array}
$$

m^d + *m^u*

t andard a \overline{A} *X*^{*i*} on *x*^{*u*} *M Mon*-standard axion models $\mathcal{O}(\mathcal{O}(\log n))$ L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models 10/14

m^d + *m^u*

^N ^m^d ^m^u

KSVZ/DFSZ no-go

Nucleophobia can be obtained in DFSZ models with non-universal (i.e. generation dependent) PQ charges, such that $\overline{}$

$$
N = N_1 \equiv X_u + X_d
$$

$$
\begin{array}{ccc}\n\text{1st condition} & 0 = c_u + c_d = \frac{X_u + X_d}{N} - 1 \\
\hline\n\text{1st condition} & 0 = c_u + c_d = \frac{X_u + X_d}{N} - 1\n\end{array}\n\qquad\n\begin{array}{ccc}\n\text{KSVZ} & -1 \\
\hline\n\text{DFSZ} & \frac{1}{n_g} - 1\n\end{array}
$$

m^d + *m^u*

1

t andard a \overline{A} *X*^{*i*} on *x*^{*u*} *M Mon*-standard axion models $\mathcal{O}(\mathcal{O}(\log n))$ ons couplings in no L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models 10/14

m^d + *m^u*

^N ^m^d ^m^u

MOVEMENT

Implementing nucleophobia

• Simplification: assume $2+1$ structure $X_{q_1} = X_{q_2} \neq X_{q_3}$ *N*¹ = *N*² = *N*³ (1)

$$
N \equiv N_1 + N_2 + N_3 = N_1 \qquad \qquad N_1 = N_2 = -N_3
$$

| {z }

*s*²

| {z } '1*/*3

Implementing nucleophobia

• Simplification: assume $2+1$ structure $X_{q_1} = X_{q_2} \neq X_{q_3}$ *N*¹ = *N*² = *N*³ (1)

> *N* = *N*¹ ⌘ *X^u* + *X^d* (2) $N_1 = N_2 = -N_3$ $N \equiv N_1 + N_2 + N_3 = N_1$

• $N_2 + N_3 = 0$ easy to implement with 2HDM (H₁, H₂, Y(H_{1,2}) = -1/2) *X^u X^d ^m^d ^m^u*

$$
\mathcal{L}_Y \supset \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 ... + ...)
$$
\n
$$
\Rightarrow \mathcal{N}_{3^{rd}} = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2
$$
\n
$$
+ \bar{q}_2 u_2 H_2 + \bar{q}_2 d_2 \tilde{H}_1 + (\bar{q}_2 d_3 ... + ...)
$$
\n
$$
\Rightarrow \mathcal{N}_{2^{nd}} = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1
$$

*^s*²

/ *^c*²

m^d + *m^u*

| {z }

*s*²

| {z } '1*/*3

X^u X^d ^m^d ^m^u • Ist condition automatically satisfied *automau de Sausneu*

$Imn₁nonon+₁on n₁on 1$ ues in *{*1*,* 2*}*. It is easy to verify that in each line the charges of the first three quark-bilinears determine *^q*2*d*2*H*˜*c, ^q*3*d*3*H*˜*d, ^q*2*d*3*H*˜*d*+*a^b, ^q*3*d*2*H*˜*^ca*+*b,* (5) where *H*˜ = *i*2*H*⇤, assigning *H*¹ to the first term is Implementing nucleophobia

• Simplification: assume $2+1$ structure $X_{q_1} = X_{q_2} \neq X_{q_3}$ *N*¹ = *N*² = *N*³ (1) the fourth one, e.g. *X*(*q*3*u*2) = *X*(*q*2*u*2)+*X*(*q*3*u*3) \bullet <u>Simplification</u>: assu ϵ \int $\cos \theta$ \int \int $\cos \theta$ $\cos \theta$ \int \int \int $\sin \theta$ \int \bullet <u>Simplification</u>: assume $2+1$ structure a

N = *N*¹ ⌘ *X^u* + *X^d* (2) $N_1 = N_2 = -N_3$ $N \equiv N_1 + N_2 + N_3 = N_1$ (2) $N_1 = N_2 = -N_3$ \mathbf{r} second and the second second and the second the second and third terms of both lines. It is now the second and the second and the second second second and

• $N_2 + N_3 = 0$ easy to implement with 2HDM (H₁, H₂, Y(H_{1,2}) = -1/2) *X^u X^d ^m^d ^m^u* \bullet $N + N - 0$ each $\mathbf{v}_1 \mathbf{v}_2 + \mathbf{v}_3 = 0$ edsy N $N = 0$ ency to implement with T_{12} T_{13} T_{2} with the case 20 *km* indicates 2 *x*, e.g. $N_2 + N_3 = 0$ easy to implement with $2HDM$ (H₁, H₂, Y(

$$
\mathcal{L}_Y \supset \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 ... + ...)
$$
\n
$$
\Rightarrow \mathcal{N}_{3^{rd}} = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2
$$
\n
$$
\Rightarrow \mathcal{N}_{2^{nd}} = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1
$$

*^s*²

en de la componentación de
En el componentación de la componentación de la componentación de la componentación de la componentación de la

/ *^c*²

m^d + *m^u*

| {z }

*s*²

| {z } '1*/*3

*N*¹ + *N*³ = 0 (2)

X^u X^d • 2nd condition can be implemented via a 10% tuning (*ii*1) 2*N^l* = 2*N*³ = *X*² *X*¹ and in (*ii*2) 2*N^l* = 2*N*³ = \bullet *Z*₁ with cases *Z*₁ with cases (*ii*1) 2*N^l* = 2*N*³ = *X*² *X*¹ and in (*ii*2) 2*N^l* = 2*N*³ = *V* Znd condition can be implemented via a TO% tuning

$$
\tan \beta = v_2/v_1
$$

$$
c_u - c_d = \frac{X_u - X_d}{N} - \frac{m_d - m_u}{m_u + m_d} = 0
$$

$$
C_{\beta}^2 \simeq 2/3
$$

$$
C_{\beta}^2 \simeq 2/3
$$

/ *c*² / *^c*² *^s*² non-standard axion models and the contract of the Goldston eaten up by the *Z*-boson [8], and the L . Di Luzio (in tr, Dumal charge normalization is given in terms of the light **L.** DI LUZIO (IFFI, DUITIANI) - AXIONS COUPINISS L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models 11/14

Flavour connection

• Nucleophobia implies flavour violating axion couplings !

 $C_{ad_i d_j} \propto (V_d^{\dagger} P Q_d V_d)_{i \neq j} \neq 0$

e.g. RH down rotations become physical

Flavour connection *•* A final note on axion DM: the only possibility left in the high-mass range are topological defects in the post-inflationary PQ breaking scenario with *N*DW *>* 1. This means, on one hand, that the mission method of the mission method of the whole DM (thus does not the whole DM (thus does $F(x) = F(x)$

• Nucleophobia implies flavour violating axion couplings ! $s_{\rm eff}$ and the explicitly broken in order to a fast decay of the DWS before the DWS a in place they denote the energy density. • Nucleophobia implies flavour violating axion *a* • INUCleophobia implies flav ² ⁺ *[|]C^A ,* (69)

 $\left[\begin{array}{cc} 1 & \ll d, & 1 & d \end{array} \right]$ \neq 0

 $[{\rm PQ}_d, Y_d^{\dagger} Y_d] \neq 0$ and $C_{ad_i d_j} \propto (V_d^{\dagger} {\rm PQ}_d V_d)_{i \neq j} \neq 0$

 \textsf{DL} electron the electronic the electronic the axion e \textsf{L} ivi i down rotations become pri e.g. RH down rotations become physical E.g. NH GOWN FOLATIONS DECOTTE PHYSICAL

l
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L
 \overline{a} \overline{a} 2 (@*µa*) ² + *a fa* ↵*s* $\ddot{}$ *r* experim $\overline{1}$ 4 • Plethora of low-energy flavour experiments probing BR(*^B* ! *^K* + inv) *<* ³*.*² ⇥ ¹⁰⁵ • Plethora of low-energy flavour experiments p

$$
\text{By flavour experiments probing} \quad \frac{\partial_{\mu} a}{2f_a} \overline{f}_i \gamma^{\mu} (C_{ij}^V + C_{ij}^A \gamma_5) f_j
$$

Astrophobic axion models

L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models

- KSVZ and DFSZ are well-motivated minimal benchmarks, but…
	- axion couplings are UV dependent
	- worth to think about alternatives when confronting exp. bounds and sensitivities

- KSVZ and DFSZ are well-motivated minimal benchmarks, but…
	- axion couplings are UV dependent
	- worth to think about alternatives when confronting exp. bounds and sensitivities
- Astrophobic Axions (suppressed couplings to nucleons and electrons)
	- 1. relax astro bounds on axion mass by \sim 1 order of magnitude
	- 2. improve visibility at IAXO
	- 3. improve fit to stellar cooling anomalies
	- 4. can be complementarily tested in axion flavour exp.

L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models

DM in the heavy axion window physical models. The mass ranges predicted in various cosmological scenarios are summarized in various cosmolo Fig. 2. Recently, a lot of new experimental projects are projects are projects are proposed, which enables us to investigate \mathcal{L}

• Post-inflationary PQ breaking with N_{DW} ≠ I in dark matter physics but also in cosmology and fundamental physics. In cosmology and fundamental physics $\mathbb{E}[V]$

[Kawasaki, Saikawa, Sekiguchi, 1412.0789 1709.07091]

 $\mathbb{E}[\mathbf{X}]$ Duniani) - Axions Couplings In Hon-standard axion models $\mathbb{E}[\mathbf{X}]$ 107 10⁸ 10⁹ 1010 1011 1012 L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models

Stellar cooling anomalies q *v*2 *^u* + *v*² *^d* = 246 GeV. It is theoretically constrained from \bigcap

- Hints of excessive cooling in WD+RGB+HB can be explained via an axion \sqrt{U} \cup \sqrt{U}
	- requires a sizeable axion-electron coupling in a region disfavoured by SN bound* \mathbf{r} of the period decrease of the \mathbf{r} pulsating WDs (R548, L 19-2 \mathbf{r}), L 19-2 (113), L 113), coupling in a region distavoured by SIN bound* in globular clusters, which we hereafter label as HB, see appendix A for specifics. The best
- σ 2σ WD+RGB+HB **PS** II IAXO 0.0 0.5 1.0 1.5 2.0 2.5 3.0 0.0
0.0 0.2 0.4 0.6 0.8 g_{ae} [10⁻¹³] \mathcal{G}_α \sum_{λ} -10GeV $\frac{1}{1}$

[Giannotti et al. 1708.02111]

³We follow this approach in our figures 2 and 3, where we show the mass scale on the *x*-axis. The mass Nucleophobic axion improves fit…

*SN bound a factor ~4 weaker than PDG one ?

[Chang, Essig, McDermott 1803.00993]

Figure 1. Combined analysis of the hints from WD+RGB+HB stars in the *gae ga* plane. Also L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models

Axion coupling to photons In this section we summarise the leading order axion properties and the notation that $\overline{\mathbf{c}}$ (@*µa*) ² + *a* ↵*s* 1 indices are implicit, and the coupling to the photon field strength *Fµ*⌫ is 2 *fa* 8⇡ ⁴ *a g*⁰ 2*f^a* where the second term defines *fa*, the dual gluon field strength *G*˜*µ*⌫ = indices are implicit, and the coupling to the photon field strength *Fµ*⌫ is

• Axion effective Lagrangian electroweak (See e.g. Grilli di Cortona et a

where the second field is continued for the dual gluon field strength *f*₂ (See e.g. Grilli di Cortona et al., 1511.02867) where *E/N* is the ratio of the Electromagnetic (EM) and the color anomaly (=8/3 for [See e.g. Grilli di Cortona et al., 1511.02867]

$$
\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 + \frac{a}{f_a} \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{1}{4} a g^0_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad g^0_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a} \frac{E}{N}
$$

field-depended chiral transformation to eliminate aGGtilde: $q = \begin{pmatrix} u \\ d \end{pmatrix} \rightarrow e^{i\gamma_5 \frac{a}{2f_a} Q_a} \begin{pmatrix} u \\ d \end{pmatrix}$

² ✏*µ*⌫⇢*G*⇢, color where *E/N* is the ratio of the Electromagnetic (EM) and the color anomaly (=8/3 for $\binom{m}{k}$ $q =$ $\int u$ *d* ◆ $\rightarrow e^{i\gamma_5} \frac{a}{2f_a} Q_a \begin{pmatrix} u \\ d \end{pmatrix}$ *d* ◆ \overline{C}

$$
\mathrm{tr}\, Q_a=1
$$

L. Di Luzio (IPPP, Durham) - Axions couplings in non-standa *ga* = α ² α ² L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models

1 In this section we summarise the leading order axion properties and the notation that where the second term defines *fa*, the dual gluon field strength *G*˜*µ*⌫ = indices are implicit, and the coupling to the photon field strength *Fµ*⌫ is \int_{a}^{b} 2⇡*f^a* Ω photons where $E_{\rm eff}$ is the ratio of the ratio of the ratio of the color and the color anomaly ($E_{\rm eff}$ *g*0 *a* = ↵*em* 2⇡*f^a* \overline{E} μ μ μ μ μ **The function of the functions in the functions in the integral form in the integral form in the integral form i** compact. Note that changing the quark masses over the whole possible range, *q* 2 [0*,* 1], only gauge couplings can become relevant at scales approaching *m^P* , and their e↵ect is to delay the emergence of LP [47]. Then, to be conservative, we choose a value of ⇤*LP* for which gravitational corrections can presumably be neglected. Then, our second criterium is that: *(ii) RQ's which do not induce LP in g*1*, g*2*, g*³ α and α and α and α and α and α $\overline{\mathbf{c}}$ (@*µa*) ² + *a* ↵*s* 1 Axion coupling to photons

• Axion effective Lagrangian

See e.g. Grilli di Cortona et al., 151 quark masses is non-analytic, as a consequence of the presence of light Goldstone modes. and ' 9*maf* ² *a* .

to avoid the tree-level mixing between the axion and pions and the vev for the latter.

where *E/N* is the ratio of the Electromagnetic (EM) and the color anomaly (=8/3 for effective Lagrangian

[See e.g. Grilli di Cortona et al., 1511.02867] \mathcal{L} are \mathcal{L} are listed in Table II. The gauge coupling and the energy scale where \mathcal{L} or \mathcal{L} where the second field is continued for the dual gluon field strength *f*₂ (See e.g. Grilli di Cortona et al., 1511.02867)

$$
\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 + \frac{a}{f_a} \frac{\alpha_s}{8\pi} \mathcal{K}_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{1}{4} a g_{a\gamma\gamma}^0 F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma}^0 = \frac{\alpha_{em}}{2\pi f_a} \frac{E}{N}
$$

$$
q = \begin{pmatrix} u \\ d \end{pmatrix} \to e^{i\gamma_5} \frac{a}{2f_a} Q_a \begin{pmatrix} u \\ d \end{pmatrix}
$$

$$
\text{tr}\, Q_a = 1
$$

$$
\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 + \frac{1}{4} a g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}
$$
 tr $Q_a = 1$

(3*,* 3*,* 4*/*3) that gives *Es/N^s* 1*.*92 ⇠ 12*.*75, almost twice the usually adopted value of 7*.*0 [33], while the

$$
g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a} \left[\frac{E}{N} - 6 \operatorname{tr} (Q_a Q^2) \right] = \frac{\alpha_{em}}{2\pi f_a} \left[\frac{E}{N} - \frac{2}{3} \frac{4m_d + m_u}{m_d + m_u} \right] = \frac{m_a}{\mathrm{eV}} \frac{2.0}{10^{10} \mathrm{~GeV}} \left(\frac{E}{N} - 1.92(4) \right)
$$

\n
$$
Q_a = \frac{M_q^{-1}}{\langle M_q^{-1} \rangle} \qquad \text{(no axion-pion mixing)}
$$
 model independent depends on UV completion

plings) or theoretically more challenging to study (as the coupling to EDM operators), or both.

L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard as L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models *ga* = α ² α ² L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models

F˜, where the coupling is given in terms of the anomaly coecients in eq. (33) by [14]: 2*.*0 ¹⁰¹⁰ GeV ✓ *^E ^N* ¹*.*92(4)◆ Pheno preferred Q's in KSVZ *V. Axion coupling to photons.* From the experimental point of view, the most promising way to unveil the axion is via its interaction with photons, which is described by the e↵ective term *La* = (1*/*4)*gaa F · in* KSV7

 R_{ζ}^s

• Q 's short lived + no Landau poles \leq Planck

line) or *d* = 5 ones (next eight rows below the bold horizontal line), and leading to LPs above, or within one order of L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models and the state of the state of the s

Redefining the axion window Helioscopes W

Ec/N^c = (23*/*12*,* 64*/*33*,* 41*/*21). In all these cases the axion could be only detected via its coupling to L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models which which do not rely axion coupling to

Redefining the axion window

L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models

Boosting E/N in DFSZ that the PQ charges of all the fermions and Higgs doublets are interrelated and cannot be chosen arbitrarily. In the most general scenario, each SM fermion field carries a specific PQ charge. However, given that the most *Roosting F/N in DF R* $\frac{1}{2}$ **e** $\frac{1}{2}$ **e** $\frac{1}{2}$ **e** $\frac{1}{2}$ **e** $\frac{1}{2}$ **e** $\frac{1}{2}$ **e** $\frac{1}{2}$ *^f^a* ⁵ *·* ¹⁰¹¹ GeV (10)

• Potentially large E/N due to electron PQ charge \bullet Potentially large F/N due to electron PQ charge

$$
\frac{E}{N} = \frac{\sum_{j} \left(\frac{4}{3} X_u^j + \frac{1}{3} X_d^j + X_e^j \right)}{\sum_{j} \left(\frac{1}{2} X_u^j + \frac{1}{2} X_d^j \right)} \qquad \mathcal{L}_Y = Y_u \overline{Q}_L u_R H_u + Y_d \overline{Q}_L d_R H_d + \sum_{j} \overline{Q}_j \left(\frac{1}{2} X_u^j + \frac{1}{2} X_d^j \right)}
$$

- with n_H Higgs doublets and a SM singlet φ , enhanced global symmetry *^f^a* ⁵ *·* ¹⁰¹¹ GeV (10) $\sum_{i=1}^{n}$ \overline{c} $\frac{2}{3}$ in gro $+$ $\overline{ }$ *j x* enhanced giudai symmetry *F* (*X*^{*i*}) *X* with n_H Higgs doublets and a SM singlet ϕ , enhanced global symmetry also contains fundamental parameters with highly university with the coefficient *y*
2 <u>º</u> Octobres with a ² º O ⁽¹⁰⁰ GeV)² · O ^{(100 GeV)² · O (100 GeV)² · O (100 GeV)² · O (100 GeV)² · O (100 GeV)² · O (1}

$$
U(1)^{n_H+1} \to U(1)_{\rm PQ} \times U(1)_Y
$$

It is well known that the standard model (SM) of particle physics does not explain some well established well established as $\mathcal{I}(\mathcal{S})$ must be expilcitly broken in the scalar potential via non-trivial invariants (e.g. $H_u H_d \Psi^2$) must be explicitly broken in the scalar potential via non-trivial invariants (e.g. $H_u H_d \Phi^2$) "small values" problems is theoretically motivated. While most of the problems of the SM can be addressed

 L et us now consider the so called DFSZ-III variant \tilde{z} in which the scalar sector is enlarged to contain the scalar sector is enlarged to contain the scalar sector is enlarged to contain the scalar sector is enlarg

106 106 106 105 and the strong Constraints on PQ charges of SM fermions of the quadratic term in the Higgs potential, the Yukawa couplings of the first family fermions *he,u,d* ⇠ is stable with respect to higher order corrections [1] (unlike *µ*²) and (unlike *he,u,d* [2]) it evades explanations zolling in the political set of $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ in $\frac{1}{2}$ begin put forth sometimest possibility, and the simple of the simple of SM formings deviations of the society. The so-called Nelson-Barris and the so-called Nelson-Barr (Nelson-Barr (Nelson-Barr (

Roosting F/N in DF j ^R (36) *^f^a* ⁵ *·* ¹⁰¹¹ GeV (10) $E = \Gamma / N + 1$ In all the models we have some implicit assumption regarding the models was uncertainty of α E. Clockwork scenarios Boosting E/N in DFSZ

• Potentially large E/N due to electron PQ charge each SM fermion mass, for a total of nine EW doublets. The small of nine EW doublets. The small of nine EW doublets. \bullet Dotoptially large E/N due to olectron PO charge Colonically ia ge LITY due to ciced of FC charge

$$
\frac{E}{N} = \frac{\sum_{j} \left(\frac{4}{3} X_u^j + \frac{1}{3} X_d^j + X_e^j \right)}{\sum_{j} \left(\frac{1}{2} X_u^j + \frac{1}{2} X_d^j \right)} \qquad \mathcal{L}_Y = Y_u \overline{Q}_L u_R H_u + Y_d \overline{Q}_L d_R H_d + \sum_{j} \overline{Q}_j \left(\frac{1}{2} X_u^j + \frac{1}{2} X_d^j \right)}
$$

 $\frac{1}{\sqrt{1+\frac{1}{2}}}\left\vert \frac{1}{\sqrt{1+\frac{1}{2}}}\right\vert + \frac{1}{2}\left\vert \frac{1}{\sqrt{1+\frac{1}{2}}}\right\vert$ $E = \sum_j \left(\frac{4}{3} X_u^j + \frac{1}{3} X_d^j + X_e^j \right)$ ${\cal L}_Y = Y_u \overline{Q}_L u_R H_u + Y_d \overline{Q}_L d_R H_d$ $\frac{D}{\mathbf{M}} = \frac{-J \left(\mathbf{0} \times \mathbf{0} \times \mathbf{0} \times \mathbf{0} \right)}{2 \left(\mathbf{0} \times \mathbf{0} \times \mathbf{0} \right)}$

- \bullet • Clockwork-like scenarios allow to boost E/N [LDL, Mescia, Nardi 1705.05370] also contains fundamental parameters with highly unnatural values, like the coecient *^µ*² ⇠ *^O*((100 GeV)²) **CIOCINYOTIN TINC SCCHIGHOS GITOYY CO DOOSE LITTY** LEPE, Meseng, March Mesiassing Define *H*¹ = *H^u* and next let us add a whole set of up-type Higgs doublets *Hⁿ* with *n* = 2*,* 3*,...,m* coupled • Clockwork-like scenarios allow to boost E/N [LDL, Mescia, Nardi 1705.05370]
- $\overline{\mathcal{L}}$ $\overline{}$ blets
2 *j ^e ^X^j d X^j* ⇣ *Xj ^u* + *X^j F* is up-type doublets which *do not couple* to SM fermions (n ≤ 50 from LP condition) 106 and the strong Completed and the fillions (¹¹ ≈ 30 month of Condition) puntupe deublets which de pet couple t - n up-type doublet

high-energies phenomena may lie much close to, and possible energies. In this case of the energies of the energies L. Di Luzio (IPPP, Durham) - Axions couplings in non-standard axion models