# Flavored Axions

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MAX-PLANCK-GESELLSCHAFT

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# Recent theoretical motivation

Flaxion: a minimal extension to solve puzzles in the standard model
Yohei Ema (Tokyo U.), Koichi Hamaguchi, Takeo Moroi, Kazunori Nakayama (Tokyo U. & Tokyo U., IPMU). Dec 16, 2016. 23 pp.
Published in **JHEP 1701 (2017) 096**
UT-16-36, IPMU16-0189
DOI: 10.1007/JHEP01(2017)096
e-Print: **arXiv:1612.05492 [hep-ph] | PDF**

Minimal axion model from flavor
Lorenzo Calibbi (Beijing, Inst. Theor. Phys.), Florian Goertz (CERN), Diego Redigolo (Tel Aviv U. & Weizmann Inst.), Robert Ziegler (Karlsruhe U., TTP), Jure Zupan (CERN & Cincinnati U.). Dec 23, 2016. 6 pp.
Published in **Phys.Rev. D95 (2017) no.9, 095009**
TTP16-058, CERN-TH-2016-261
DOI: 10.1103/PhysRevD.95.095009
e-Print: **arXiv:1612.08040 [hep-ph] | PDF**

**The Minimal Flavour Violating Axion**
F. Arias-Aragon, L. Merlo (Madrid, Autonoma U. & Madrid, IFT). Sep 20, 2017. 11 pp.
Published in **JHEP 1710 (2017) 168**
DOI: 10.1007/JHEP10(2017)168
e-Print: **arXiv:1709.07039 [hep-ph] | PDF**

**Supersymmetric Flaxion**
Yohei Ema, Daisuke Hagihara (Tokyo U.), Koichi Hamaguchi, Takeo Moroi (Tokyo U., IPMU & Tokyo U.), Kazunori Nakayama (Tokyo U., IPMU & Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan & Tokyo U.). Feb 21, 2018. 31 pp.
Published in **JHEP 1804 (2018) 094**
UT-18-1, IPMU18-0036
DOI: 10.1007/JHEP04(2018)094
e-Print: **arXiv:1802.07739 [hep-ph] | PDF**

A Common Source for Scalars: Axiflavon-Higgs Unification
Tommi Alanne, Simone Blasi, Florian Goertz (Heidelberg, Max Planck Inst.). Jul 26, 2018. 8 pp.
e-Print: **arXiv:1807.10156 [hep-ph] | PDF**

# Phenomenological motivation

Astrophobic Axions
Luca Di Luzio (Durham U., IPPP), Federico Mescia (ICC, Barcelona U.), Enrico Nardi (Frascati), Paolo Panci, Robert Ziegler (CERN). Dec 13, 2017. 6 pp.
Published in **Phys.Rev.Lett. 120 (2018) no.26, 261803**
IPPP-17-102, CERN-TH-2017-256
DOI: 10.1103/PhysRevLett.120.261803
e-Print: **arXiv:1712.04940 [hep-ph] | PDF**

Note that these are the invisible version of the VARIANT axion models discussed to avoid some experimental constraints on the original PQ axion… is a fun story here to tell ;-)

The photo-philic QCD axion
Marco Farina (Rutgers U., Piscataway), Duccio Pappadopulo (New York U., CCPP & New York U.), Fabrizio Rompineve (New York U., CCPP & U. Heidelberg, ITP & New York U.), Andrea Tesi (Chicago U., EFI & Chicago U.). Nov 29, 2016. 21 pp.
Published in **JHEP 1701 (2017) 095**
DOI: 10.1007/JHEP01(2017)095
e-Print: **arXiv:1611.09855 [hep-ph] | PDF**

**Experimental Targets for Photon Couplings of the QCD Axion**
Prateek Agrawal (Harvard U., Phys. Dept.), JiJi Fan (Brown U.), Matthew Reece (Harvard U., Phys. Dept.), Lian-Tao Wang (Chicago U., EFI & Chicago U., KICP). Sep 18, 2017. 23 pp.
Published in **JHEP 1802 (2018) 006**
DOI: 10.1007/JHEP02(2018)006
e-Print: **arXiv:1709.06085 [hep-ph] | PDF**

B. Doebrich from NA62 gave a recent talk where she shows some slides and axion-flavon sensitivity

https://indico.in2p3.fr/event/17826/attachments/49465/62902/marseille_2018.pdf

# The Axion

- Motivation: Strong CP Problem
- Peccei-Quinn (PQ) mechanism [Peccei, Quinn, '77]
- spontaneous breaking of the global $U(1)_{PQ}$ at PQ scale $f_a$ (or $f_{PQ}$)
- pseudo-Nambu Goldstone boson [Weinberg '78, Wilczek '78]
- axion mass: $m_a = 5.70(6)(4)\,\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$
- Lagrangian:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}C_{a\gamma}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

solves strong CP problem

axion searches

allows for axion dark matter

# Axion Models

$U(1)_{\rm PQ} \times SU(3)_c^2$

SM fermions

BSM fermions

origin of QCD anomaly

2Higgs

2Higgs+Singlet

Higgs+Singlet

**PQWW**

[Peccei, Quinn, Wilczek, Weinberg '78]

**DFSZ**

[Dine, Fischler, Srednicki, Zhitnitsky '80]

**KSVZ**

[Kim, Shifman, Vainshtein, Zakharov '80]

[from Robert Ziegler's Talk]

Original Axion

"Invisible" Axion

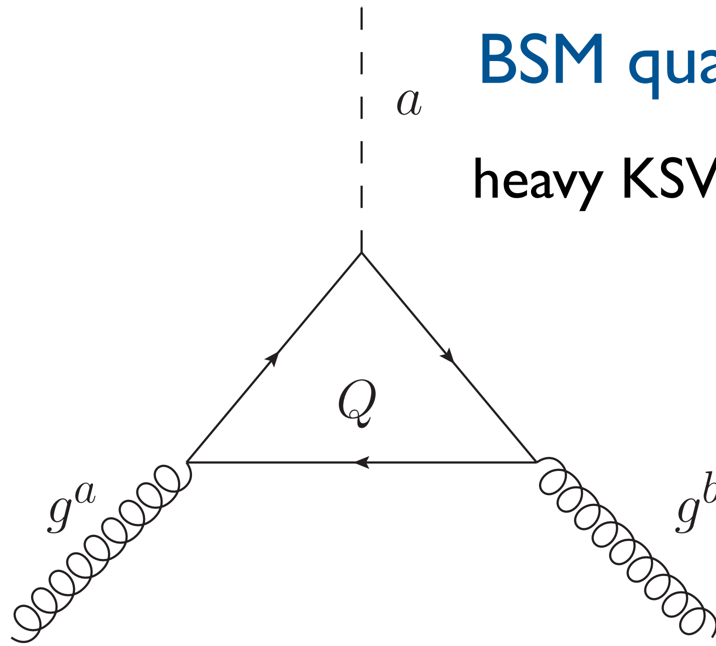
$\langle \Phi \rangle = v_{\rm PQ} \gg v$

flavor-universal U(1) charges

# Hadronic (KSVZ) Axion Model

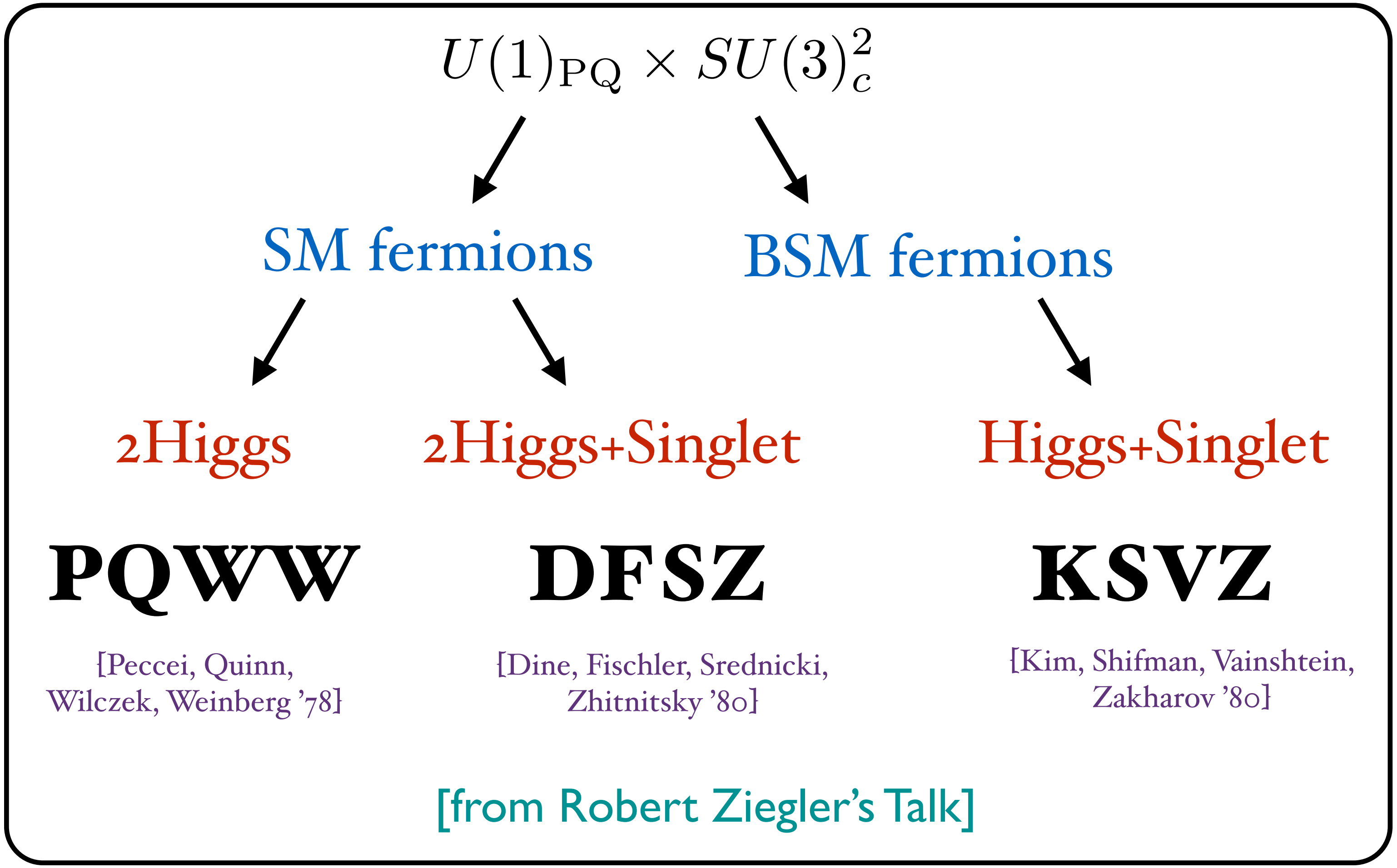
BSM quarks

heavy KSVZ quark loops




KSVZ [Kim '79; Shifman, Vainshtein, Zakharov '80]

# Axion Models




origin of QCD anomaly

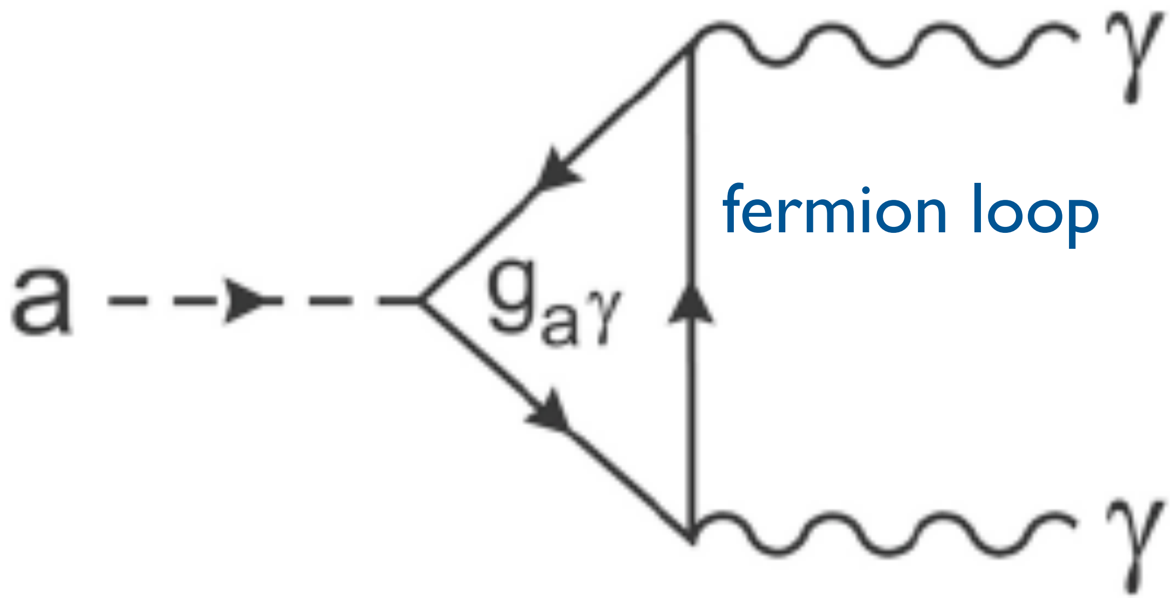
Original Axion

"Invisible" Axion

$$\langle \Phi \rangle = v_{\rm PQ} \gg v$$

flavor-universal U(1) charges

# Axion-Photon Interaction: Primakoff




**→ "see" the "invisible" axion**

# Axion-Photon Interaction: Effective Lagrangian

photon　　axion　　interaction

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

- EM field-strength tensor $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$
- Dual EM field-strength tensor $\widetilde{F}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$
- Vector Potential $A^{\mu} = (A_0, \mathbf{A})$
- 4-Current $J^{\mu} = (\rho, \mathbf{J})$

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- Electric Field

$$\mathbf{E} = -\boldsymbol{\nabla}A_0 - \dot{\mathbf{A}}$$

- Magnetic Field

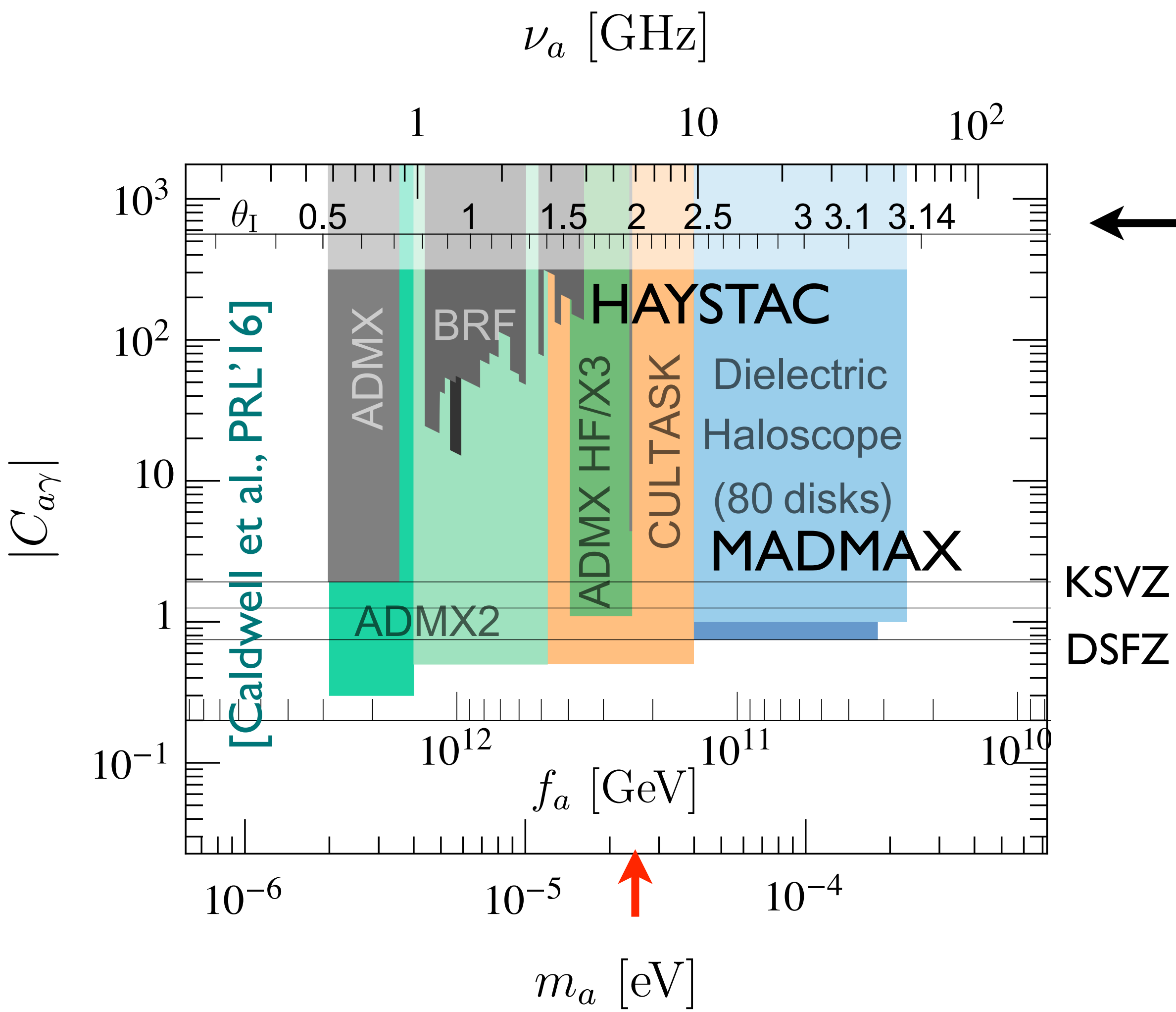
$$\mathbf{B} = \boldsymbol{\nabla}\times\mathbf{A}$$

- Axion Properties

$$g_{a\gamma} = -\frac{\alpha}{2\pi f_a}C_{a\gamma} = -2.04(3)\times 10^{-16}\ \mathrm{GeV}^{-1}\left(\frac{m_a}{1\ \mu\mathrm{eV}}\right)C_{a\gamma}$$

$$C_{a\gamma} = \frac{\mathcal{E}}{\mathcal{N}} - 1.92(4)$$

# MADMAX Goal - probe QCD axion DM scenarios




**Scenario 1**

accidental inital misalignment

$m_A < 100\ \mu eV$

**Scenario 2**

average inital misalignment

but computational challenge

$$m_A = 26.2 \pm 3.4\,\mu\text{eV}$$

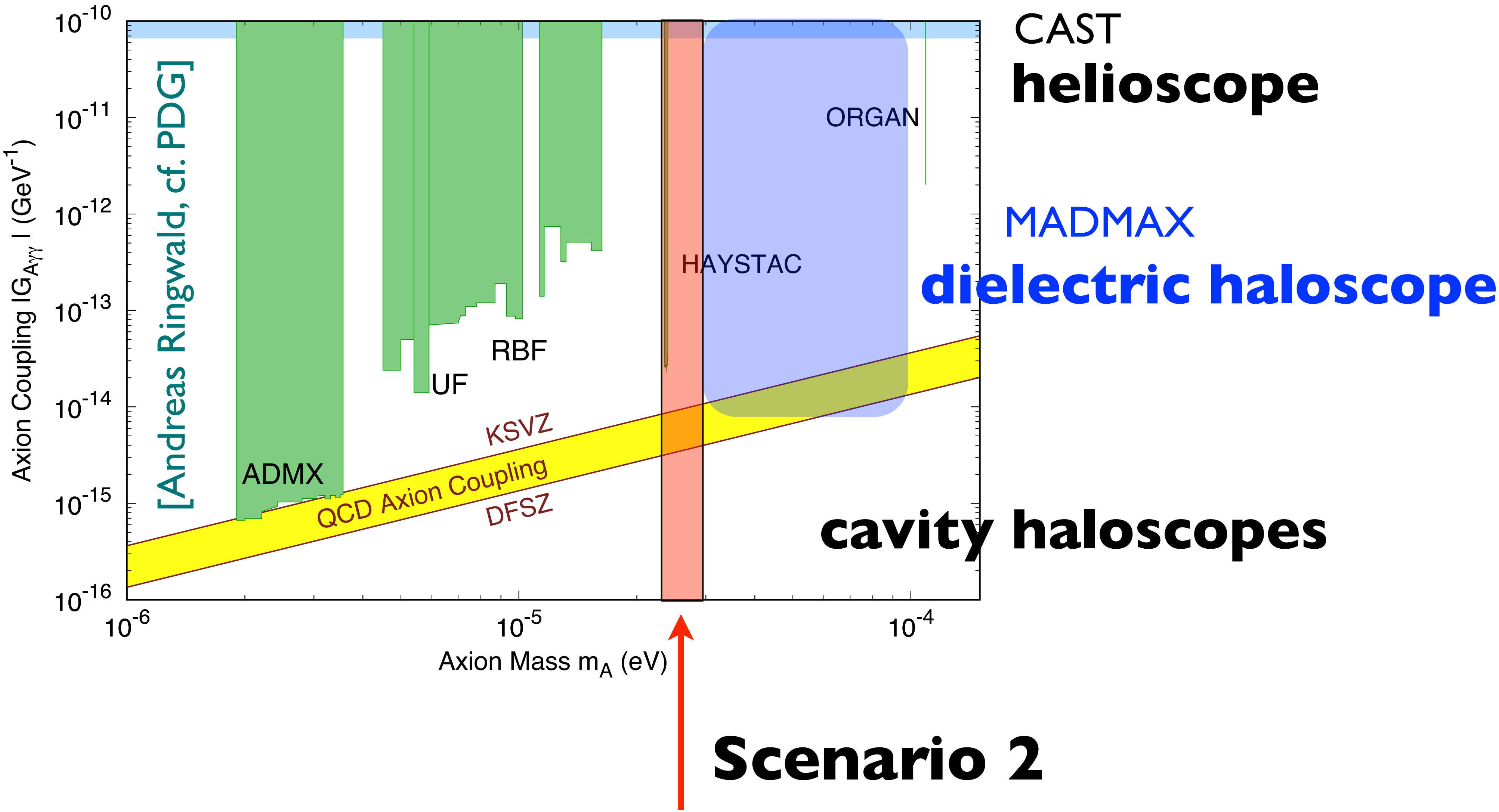
[Klaer, Moore,'17]

$$g_{a\gamma} = -\frac{\alpha}{2\pi f_a} C_{a\gamma} = -2.04(3) \times 10^{-16}\ \text{GeV}^{-1} \left(\frac{m_a}{1\ \mu\text{eV}}\right) C_{a\gamma}$$

$$m_a = 5.70(6)(4)\,\mu\text{eV} \left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

$$C_{a\gamma} = \frac{\mathcal{E}}{\mathcal{N}} - 1.92(4)$$ ← axion model dependent

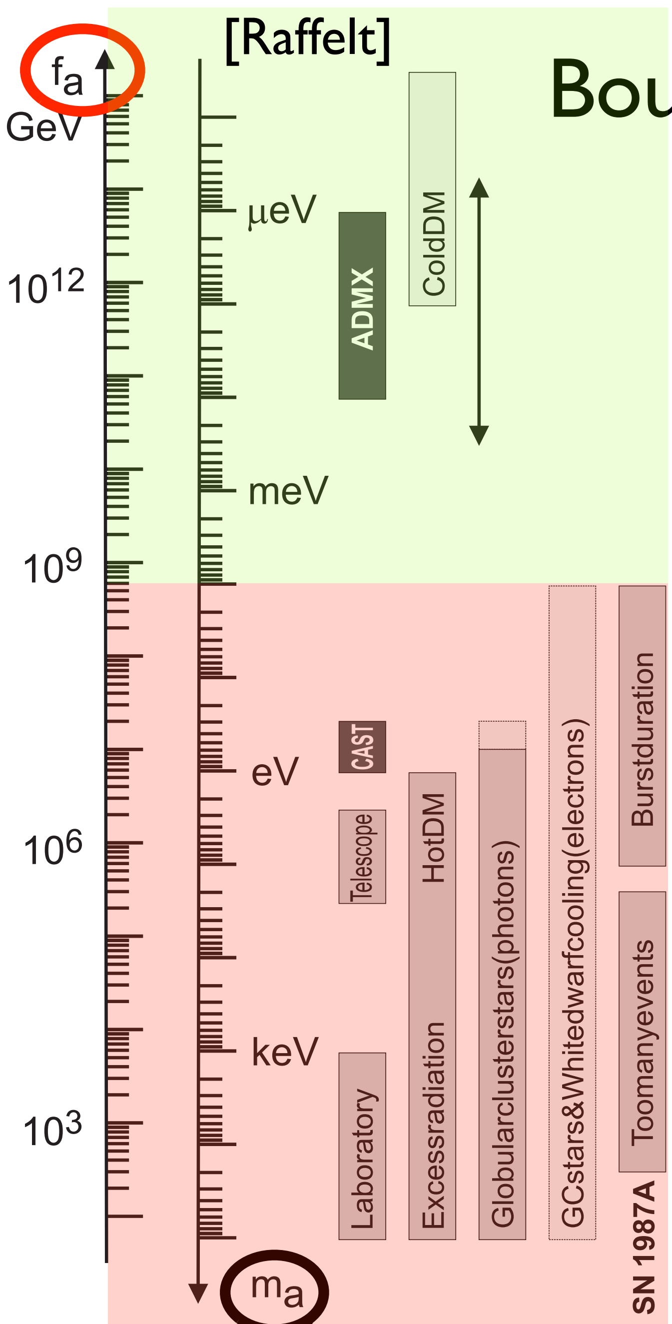
# Existing exclusion limits today




$m_A = 26.2 \pm 3.4\,\mu\text{eV}$

[Klaer, Moore,'17]

# Constraints on the Peccei-Quinn (PQ) scale $f_{PQ}$




Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

**Peccei-Quinn Scale**

$$f_a \gtrsim 6 \times 10^8 \, \mathrm{GeV}$$

**Axion Mass**

$$m_a \simeq 0.6 \;\; \mathrm{meV} \, (10^{10} \, \mathrm{GeV}/f_{\mathrm{PQ}})$$

# Astrophysical Bounds - Coupling Dependent

- axion-photon coupling - evolution of Horizontal Branch stars

$$g_{a\gamma\gamma} < \frac{6.6 \cdot 10^{-11}}{\mathrm{GeV}}$$

- axion-electron coupling - white dwarf cooling

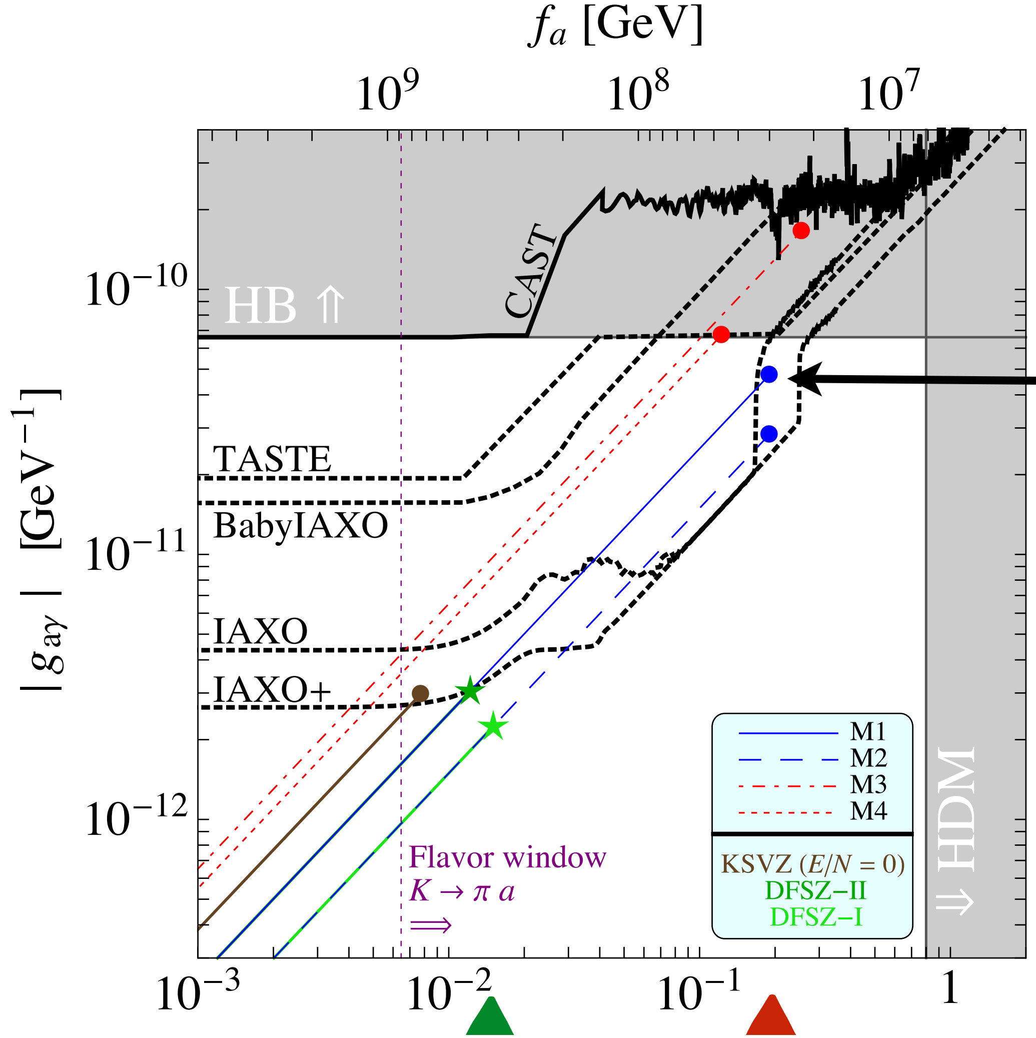
$$C_e < \frac{0.003\,\mathrm{eV}}{m_a}$$

- axion-nucleon coupling - supernova neutrino burst duration

$$C_N < \frac{0.004\,\mathrm{eV}}{m_a}$$

# Astrophobic Axions

[Luzig et al.,'17]




$$m_a = 5.70(6)(4)\,\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right) \quad \text{[eV]}$$

suppression of axion-related energy transfer away from astrophysical objects

combined SN/WD bound

Note: outside of the natural axion dark matter region

$$10^{-7}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-4}\,\mathrm{eV}$$

# Non-Universal DFSZ Axion Models

# Flavored Axion Bounds

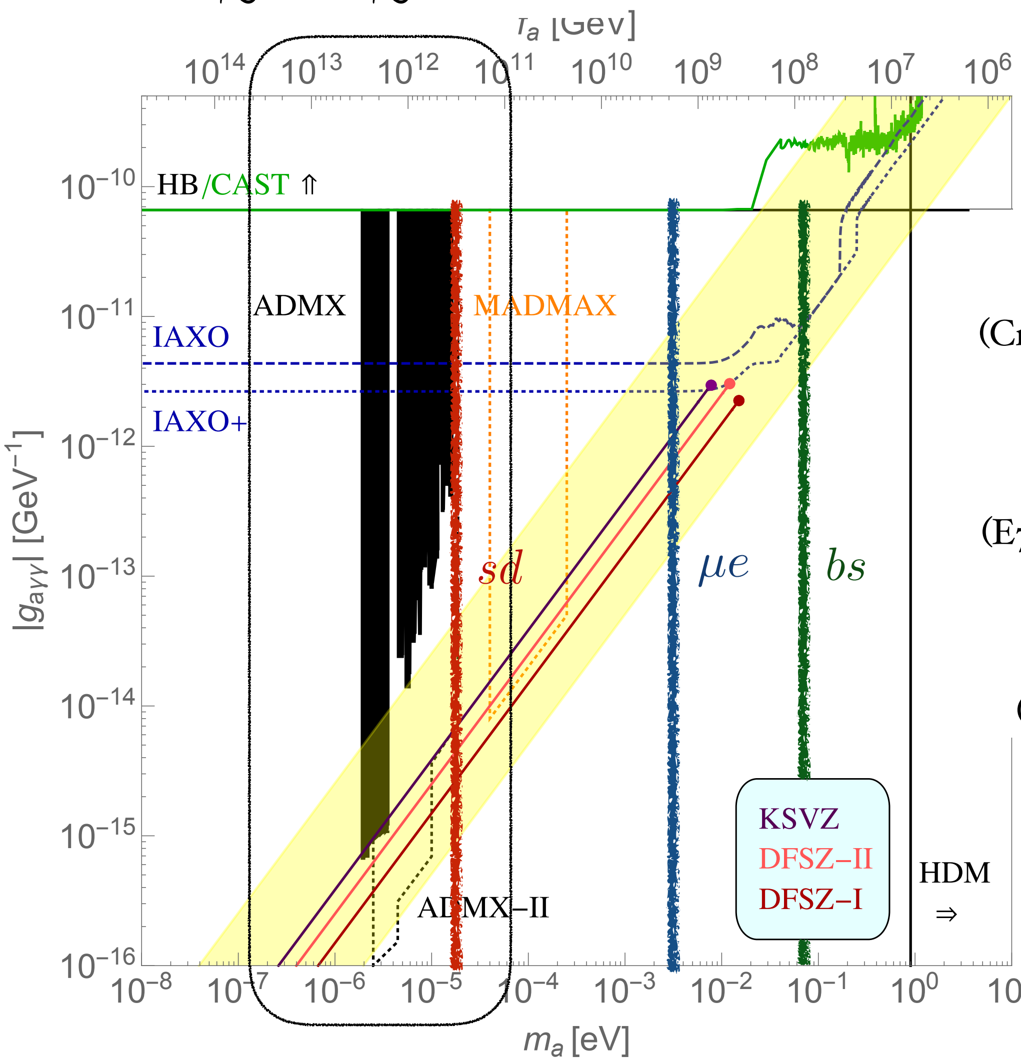
derivative axion-fermion couplings

$$\frac{\partial_\mu a}{2f_a}\,\overline{f}_i\gamma^\mu(C^V_{ij}+C^A_{ij}\gamma_5)f_j$$

$$C_{i\neq j}=1$$

axion dark matter region

$$10^{-7}\,\mathrm{eV}\lesssim m_a\lesssim 10^{-4}\,\mathrm{eV}$$




Note: tree level flavor violation is strongly constrained

precision flavor experiments

| | | | |
|---|---|---|---|
| $\mu\to ea\gamma$ (Crystal Box, '88) | $m_a<\dfrac{2.6\cdot10^{-3}\mathrm{eV}}{\lvert C_{\mu e}\rvert}$ | $\xrightarrow{?}$ | **MEG, Mu3e** |
| $K\to\pi a$ (E787+E949, '08) | $m_a<\dfrac{1.7\cdot10^{-5}\mathrm{eV}}{\lvert C^V_{sd}\rvert}$ | $\xrightarrow{\times 1/8}$ | **NA62** |
| $B\to Ka$ (CLEO, '01) | $m_a<\dfrac{9.4\cdot10^{-2}\mathrm{eV}}{\lvert C^V_{bs}\rvert}$ | $\xrightarrow{\times 1/10}$ | **BELLE II** |

DFSZ: loop & CKM suppressed

$$m_a\lesssim 0.6\,\mathrm{eV}$$

# Flavored Axion Models

- Minimal DFSZ - universal PQ charges for all generations

- Next-to-minimal DFSZ - universal PQ charges for two generations

allows for nucleophobic axion models - relaxed SN bound

allows for electrophobic axion models - relaxed WD bound

- PQ = Froggatt-Nielsen (FN) - Flaxion/Axiflavon

flavon

$$\hat{y}^u_{ij} \overline{Q_i} H u_{Rj} \quad \longrightarrow \quad y^u_{ij} \left(\frac{\phi}{M}\right)^{q_{Q_i} - q_{u_j}} \overline{Q_i} H u_{Rj}$$

explains hierarchical flavor structure of quarks and leptons

solves strong CP problem

$$\frac{E}{N} = \frac{8}{3} - 2\delta \quad \in [2.4, 3.0]$$

arXiv:1612.05492 [pdf, ps, other]

**Flaxion: a minimal extension to solve puzzles in the standard model**

Yohei Ema, Koichi Hamaguchi, Takeo Moroi, Kazunori Nakayama

Comments: 23 pages, 1 figure; v2: version published in JHEP

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

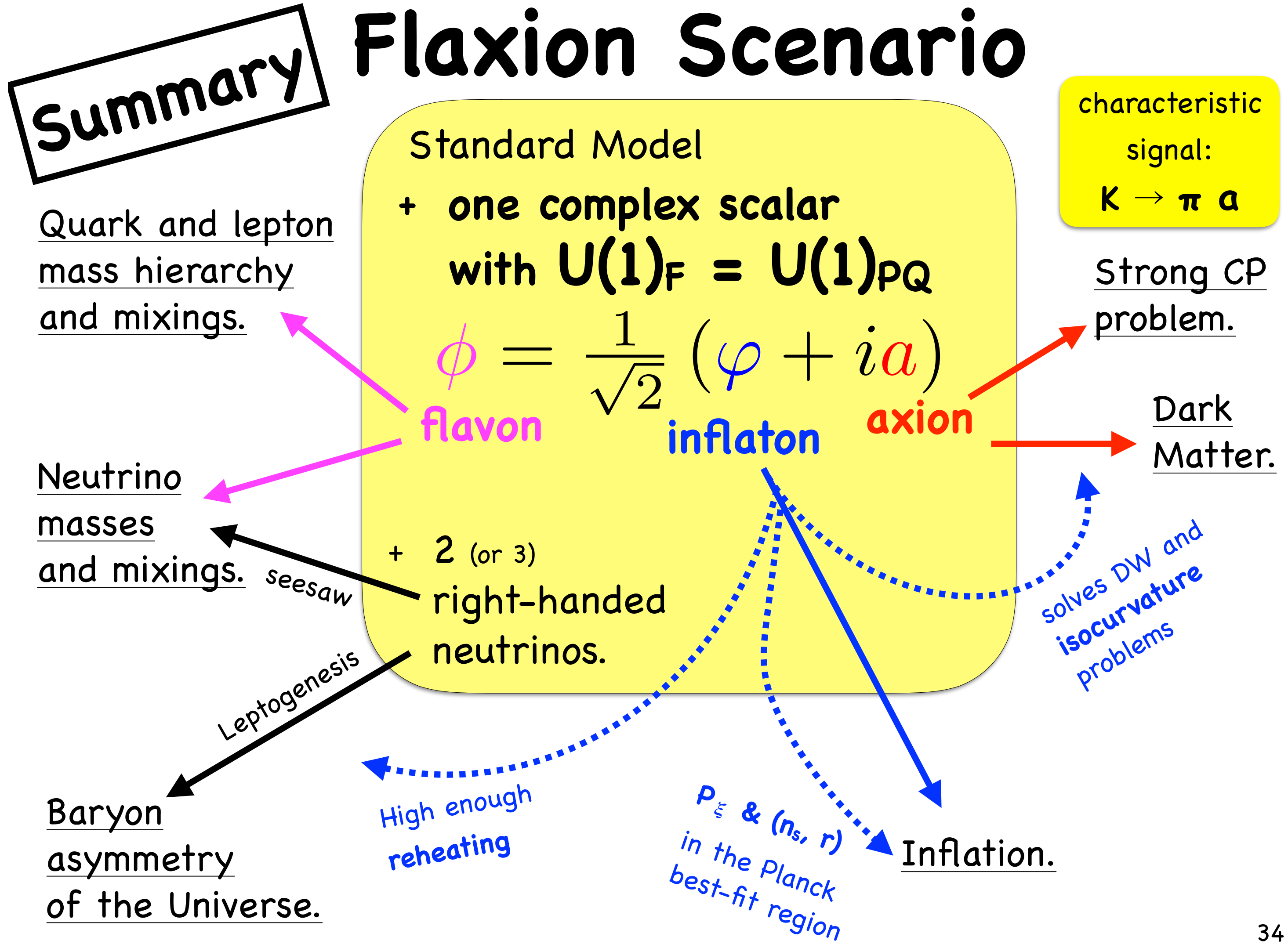
arXiv:1612.08040 [pdf, other]

**The Axiflavon**

Lorenzo Calibbi, Florian Goertz, Diego Redigolo, Robert Ziegler, Jure Zupan

Comments: 6 pages, typos corrected, references added

Subjects: **High Energy Physics - Phenomenology (hep-ph)**




[from Koichi Hamaguchi's talk @ PACIFIC 2018]

# Puzzles of the SM explained by a simple extension

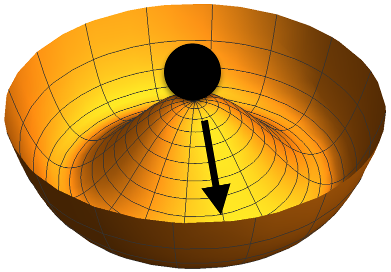
# Flaxion Dark Matter

**Case 1:** U(1) is broken after inflation.

-> **Domain Wall !**

In the flaxion scenario, typically $N_{DW} \neq 1$,

and this possibility is **excluded**.



**Case 2:** U(1) was already broken during inflation.

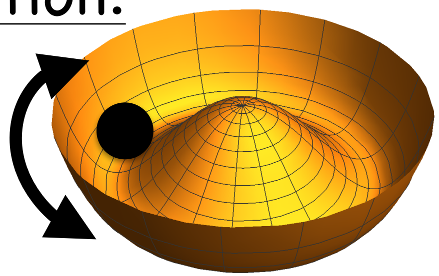
Quantum fluctuation during inflation

leads to **DM isocurvature** perturbation,

which is severely constrained [Planck,'15].

-> **Strong bound on inflation scale.**

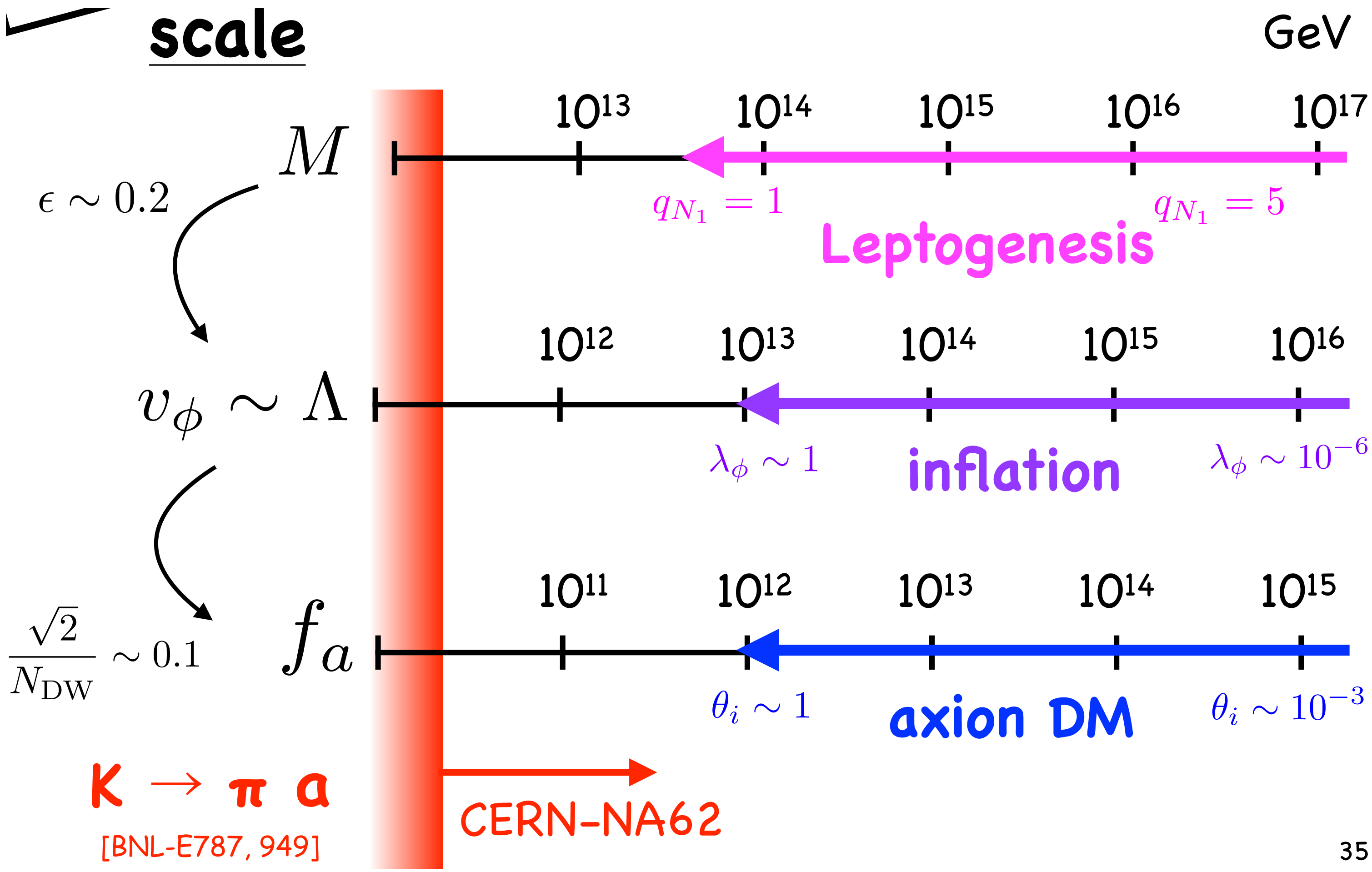
$$H_{\rm inf} \lesssim 3 \times 10^{7}\,{\rm GeV}\,\theta_i^{-1} \left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)^{0.19}.$$



$\delta a \sim H_{\rm inf}$



[from Koichi Hamaguchi's talk @ PACIFIC 2018]




[from Koichi Hamaguchi's talk @ PACIFIC 2018]

# Lagrangian

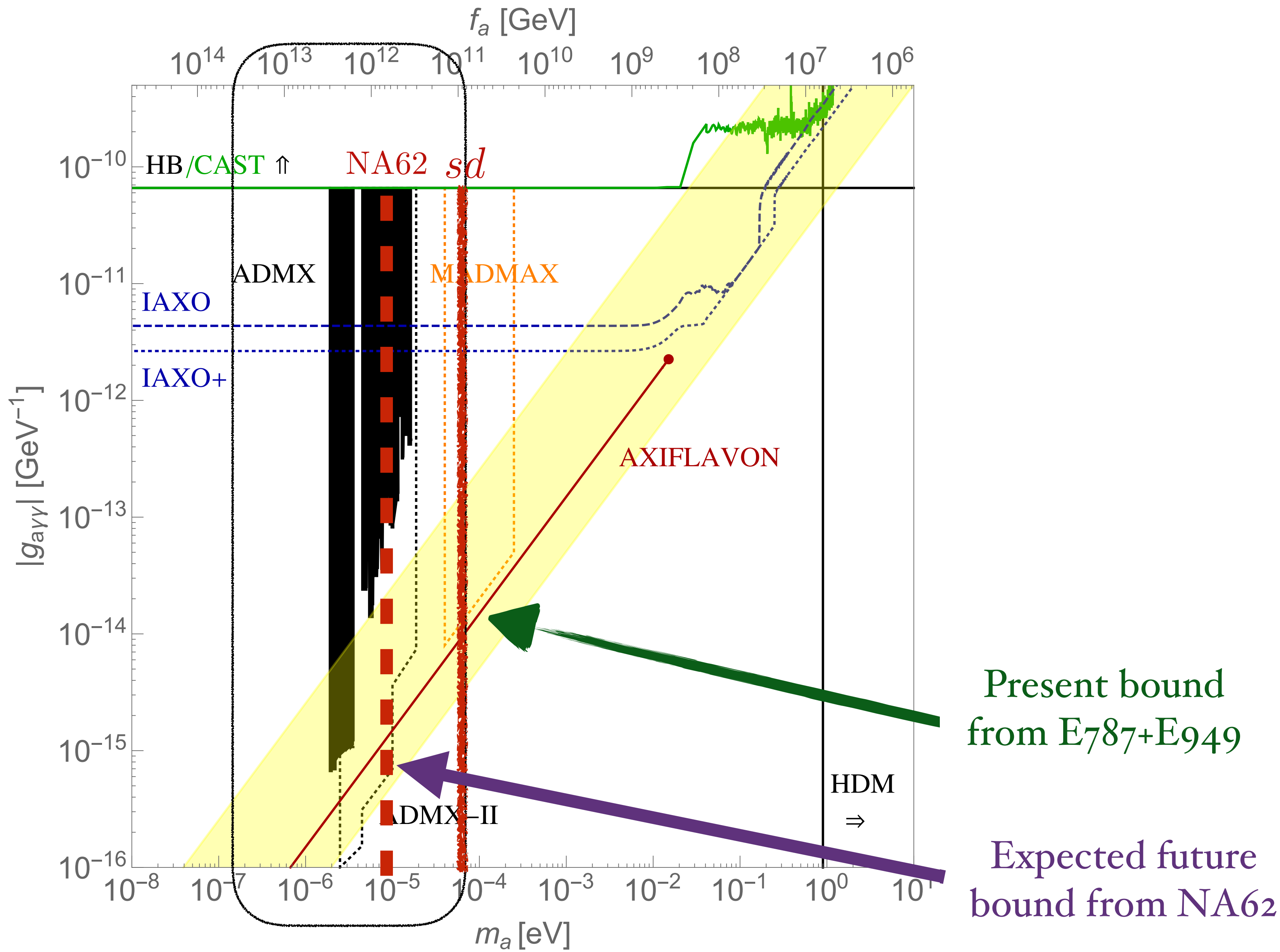
$$\mathcal{L} = -\frac{|\partial\phi|^2}{\left(1-|\phi|^2/\Lambda^2\right)^2} - \lambda_\phi \left(|\phi|^2 - v_\phi^2\right)^2$$

$$+ y_{ij}^d \left(\frac{\phi}{M}\right)^{n_{ij}^d} \overline{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M}\right)^{n_{ij}^u} \overline{Q}_i \widetilde{H} u_{Rj}$$

$$+ y_{ij}^l \left(\frac{\phi}{M}\right)^{n_{ij}^l} \overline{L}_i H l_{Rj} + y_{i\alpha}^\nu \left(\frac{\phi}{M}\right)^{n_{i\alpha}^\nu} \overline{L}_i \widetilde{H} N_{R\alpha}$$

$$+ \frac{1}{2} y_{\alpha\beta}^N \left(\frac{\phi}{M}\right)^{n_{\alpha\beta}^N} M \overline{N_{R\alpha}^c} N_{R\beta} + \text{h.c.}$$

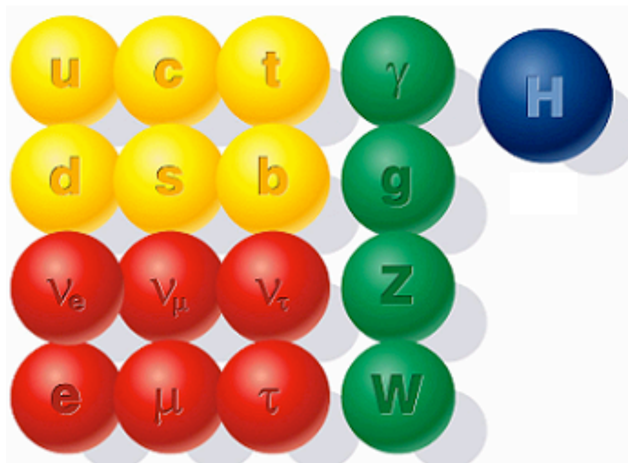
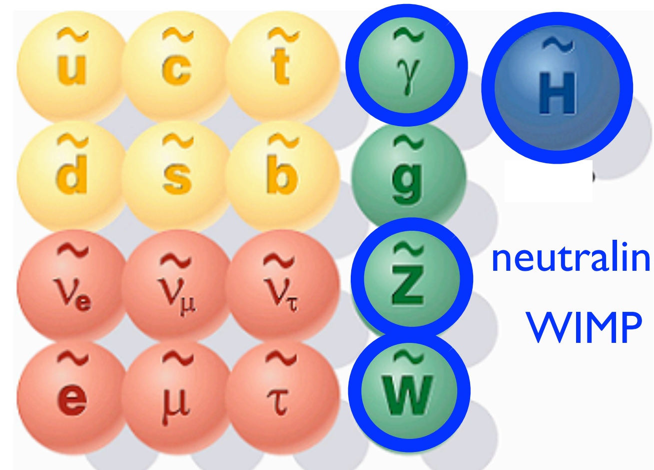
# The Axiflavon



# Conclusions

- flavored axion models - non-universal axion-fermion couplings
- astrophysical constraints can be relaxed - new (mini)IAXO opportunities
- but: there a non-axion dark matter explanation will be required
- flavor precision experiments provide stringent tests of such models
- flaxion/axiflavon models - allow for solutions of many SM puzzles
- but: hierarchy problem may require SUSY in a somewhat intrigued way
- CERN NA62: K -> pi a will test such models soon
- MADMAX may test such models independently from NA62

# Fundamental Constituents of Matter

| interactions | standard particles | superpartners |
|---|---|---|
| strong & electroweak<br>$\propto (p/M_W)^n$<br>$M_W \sim 10^2$ GeV | **Standard Model**<br> | **Supersymmetry**<br> |
| extremely weak<br>$\propto (p/M_{Pl})^n$<br>$M_{Pl} = 2.4 \times 10^{18}$ GeV | **Gravity**<br>G graviton | **Supergravity**<br>$\tilde{G}$ gravitino<br>EWIP |
| $\propto (p/f_{PQ})^n$<br>$f_{PQ} > 10^9$ GeV | **Peccei-Quinn (PQ) Symmetry**<br>a axion<br>EWIP | $\tilde{a}$ axino<br>EWIP |

**Axions → Extremely Weakly Interacting Particles (EWIPs)**