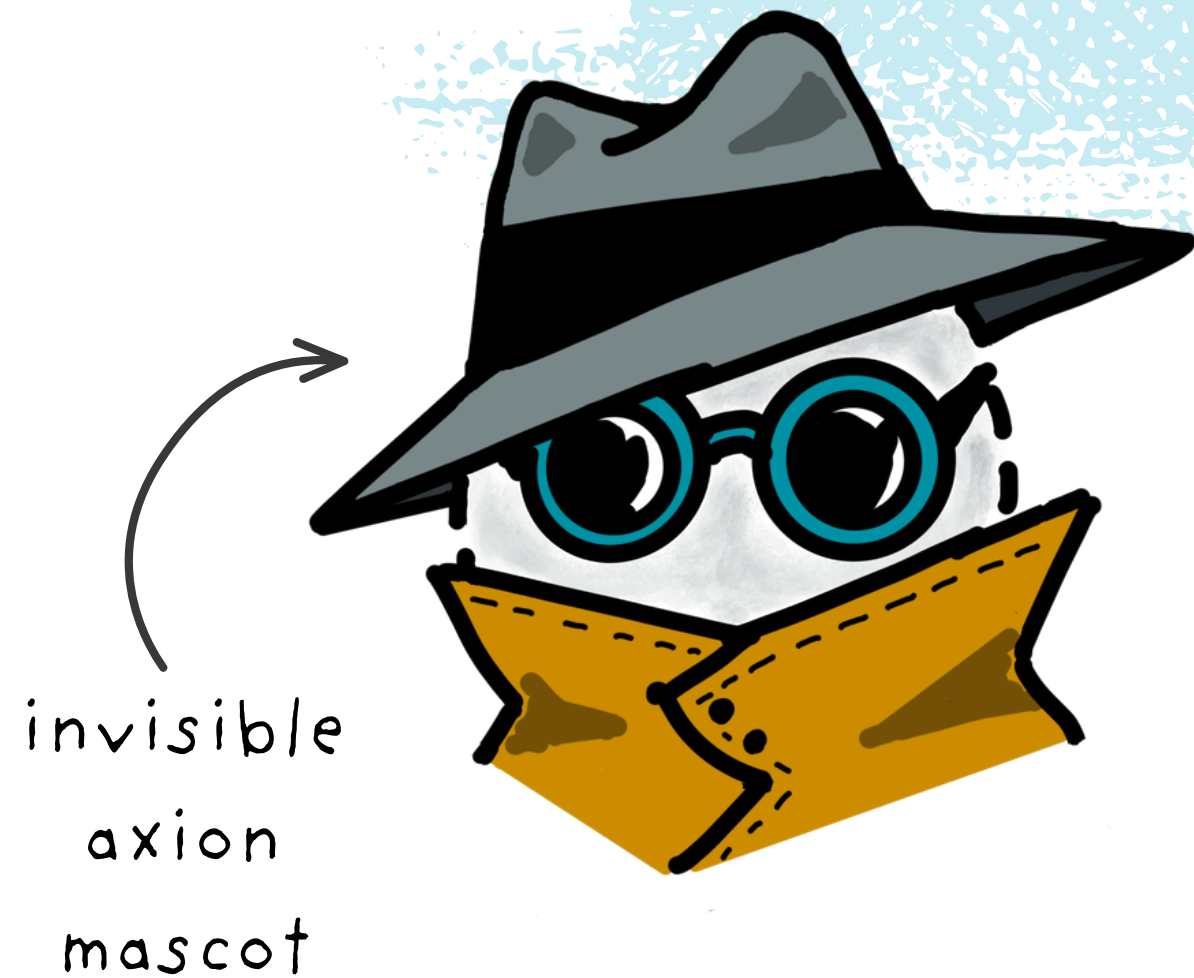


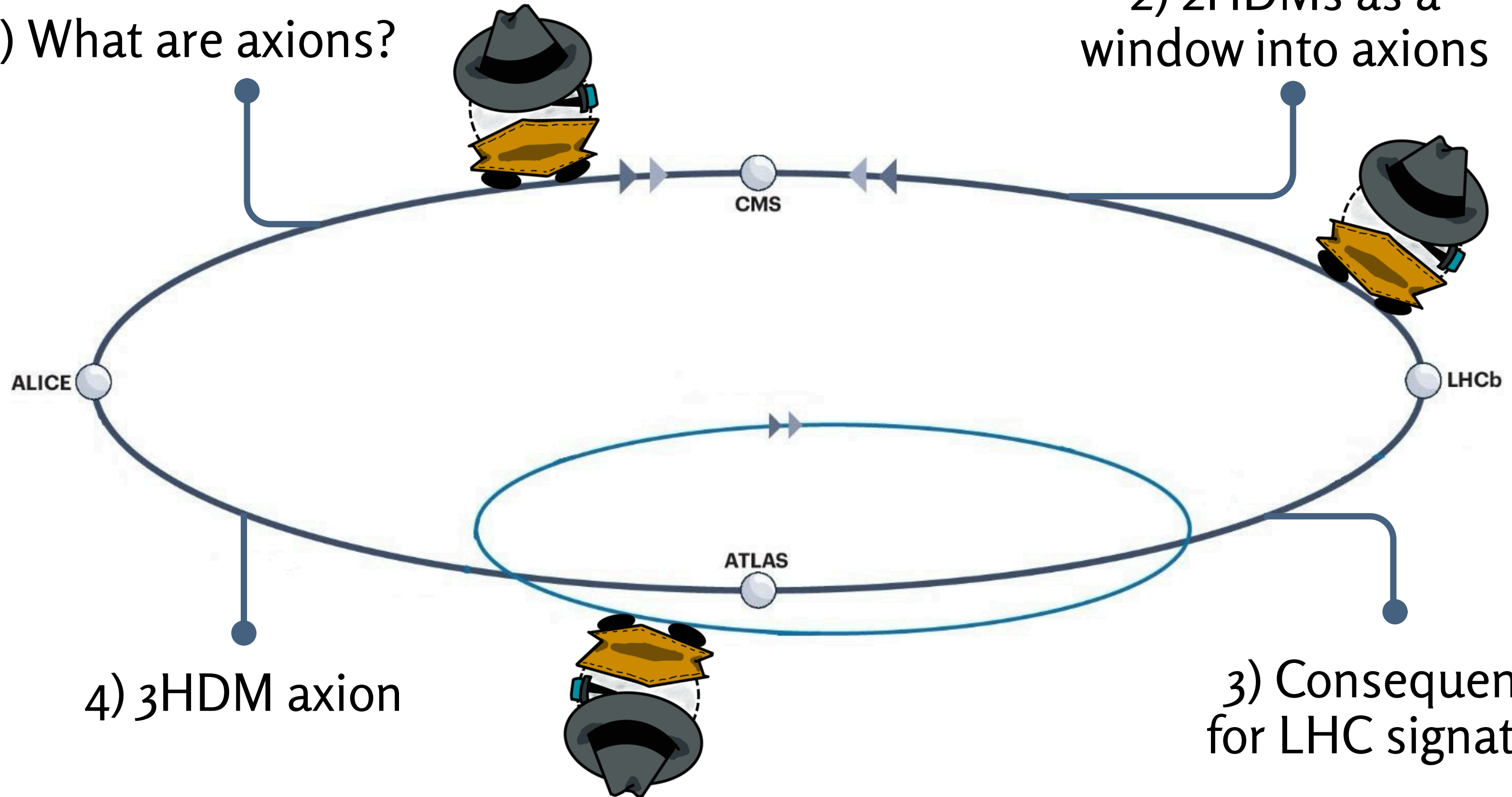
What can collider experiments tell us about axions in multi-Higgs models?



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Ongoing work with:
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1) What are axions?

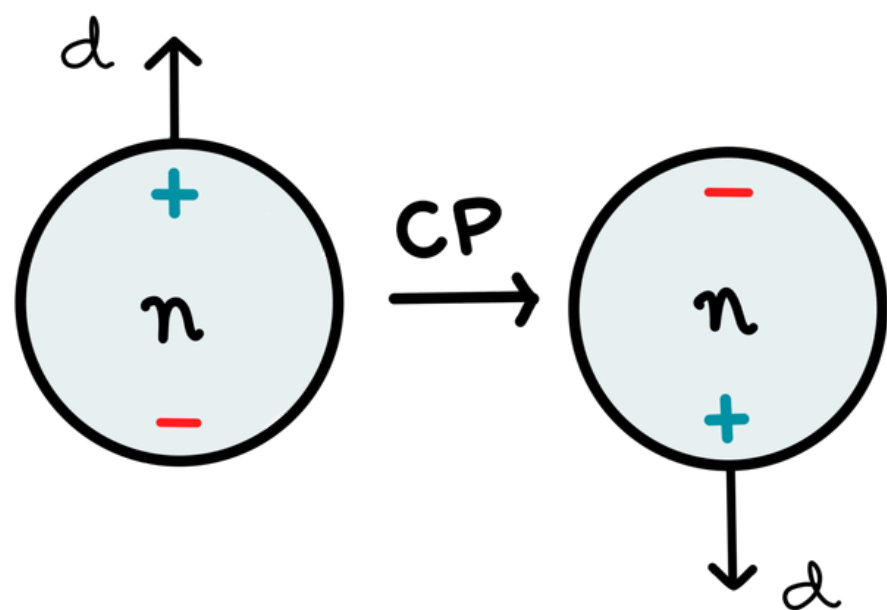
2) 2HDMs as a window into axions



4) 3HDM axion

3) Consequences for LHC signatures

The Strong CP Problem



neutron electric dipole moment

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26} \text{ e}\cdot\text{cm}$$

arXiv:2001.11966v1 [hep-ex]

- Theoretically:

$$\mathcal{L} \supset \theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$$

$$\propto \vec{E}^a \cdot \vec{B}^a \longleftarrow \text{CP violating}$$

- Experimentally:

$$\bar{\theta} \sim \theta < 10^{-9}$$

arXiv:hep-ph/0504231v2

very small!

Problem:

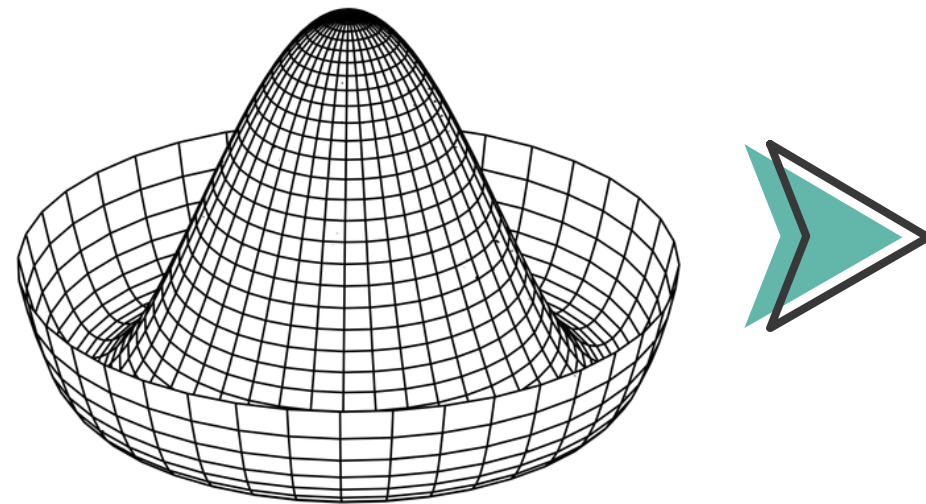
$$\bar{\theta} < 10^{-9}$$



close
to
zero!

Solution:

Introduce a global U(1) 'Peccei-Quinn' symmetry.



$$\mathcal{L}_{\text{eff}} = \frac{1}{2} \partial_{\mu} a \partial^{\mu} a - \frac{a}{f_a} \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$$

$$\bar{\theta} \rightarrow \bar{\theta} - \frac{a}{f_a}$$

R.D. Peccei, H.R. Quinn (1977)

Axions

Dine-Fischler-
Srednicki-Zhitnitsky
(DFSZ)

Kim-Shifman-
Vainshtein-Zakharov
(KSVZ)



The DFSZ model

A. R. Zhitnitsky (1980); M. Dine, W. Fischler, M. Srednicki (1981)

The following are charged under an additional $U(1)$ symmetry:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (h_1 + ia_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (h_2 + ia_2)/\sqrt{2} \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(h_s + ia_s).$$

Field	$U(1)_{PQ}$
Φ_2	2
Φ_1, ϕ	-2
u_R, d_R, e_R	1
Q_L, L_L	-1

$$\mathcal{L}_Y = -y_u \bar{Q}_L \tilde{\Phi}_2 u_R - y_d \bar{Q}_L \Phi_1 d_R - y_e \bar{L}_L \Phi_1 e_R + \text{h.c.},$$

$$\tilde{\Phi}_2 = i\sigma_2 \Phi_2^*$$

This is a Type-II 2HDM!

Quick aside on 2HDMS

Which doublet couples to which fermions?

DFSZ models are not compatible with type-1 or lepton-specific 2HDMS!

$$\Phi_2 \leftrightarrow u_R; \Phi_1 \leftrightarrow d_R, e_R$$

Type-II 2HDM

$$\Phi_2 \leftrightarrow u_R, e_R; \Phi_1 \leftrightarrow d_R$$

Flipped

$$\Phi_2 \leftrightarrow u_R, d_R, e_R$$

Type-I 2HDM

$$\Phi_2 \leftrightarrow u_R, d_R; \Phi_1 \leftrightarrow e_R$$

Lepton-specific

The DFSZ scalar potential

$$\begin{aligned} V(\Phi_1, \Phi_2, \phi) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{ss}^2 \phi^* \phi + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \frac{1}{2} \lambda_s (\phi^* \phi)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\ & + \lambda_{1s} (\Phi_1^\dagger \Phi_1) (\phi^* \phi) + \lambda_{2s} (\Phi_2^\dagger \Phi_2) (\phi^* \phi) \\ & - \lambda_{12s} (\Phi_1^\dagger \Phi_2 \phi^2 + \Phi_2^\dagger \Phi_1 \phi^{*2}). \end{aligned}$$

ϕ mixes with Φ_1 and Φ_2 !

All the scalar fields get a VEV in their real (neutral) components:

$$\langle \Phi_1 \rangle = v_1, \quad \langle \Phi_2 \rangle = v_2, \quad \langle \phi \rangle = v_s$$

The axion

Recall: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (h_1 + ia_1)/\sqrt{2} \end{pmatrix}$, $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ (h_2 + ia_2)/\sqrt{2} \end{pmatrix}$, $\phi = \frac{1}{\sqrt{2}}(h_s + ia_s)$.

2HDM:

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

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

DFSZ:

$$\begin{pmatrix} G^0 \\ A' \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$$\begin{pmatrix} A \\ a \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} A' \\ a_s \end{pmatrix}$$

$$\tan\vartheta \equiv 2v_1v_2/(vv_s)$$

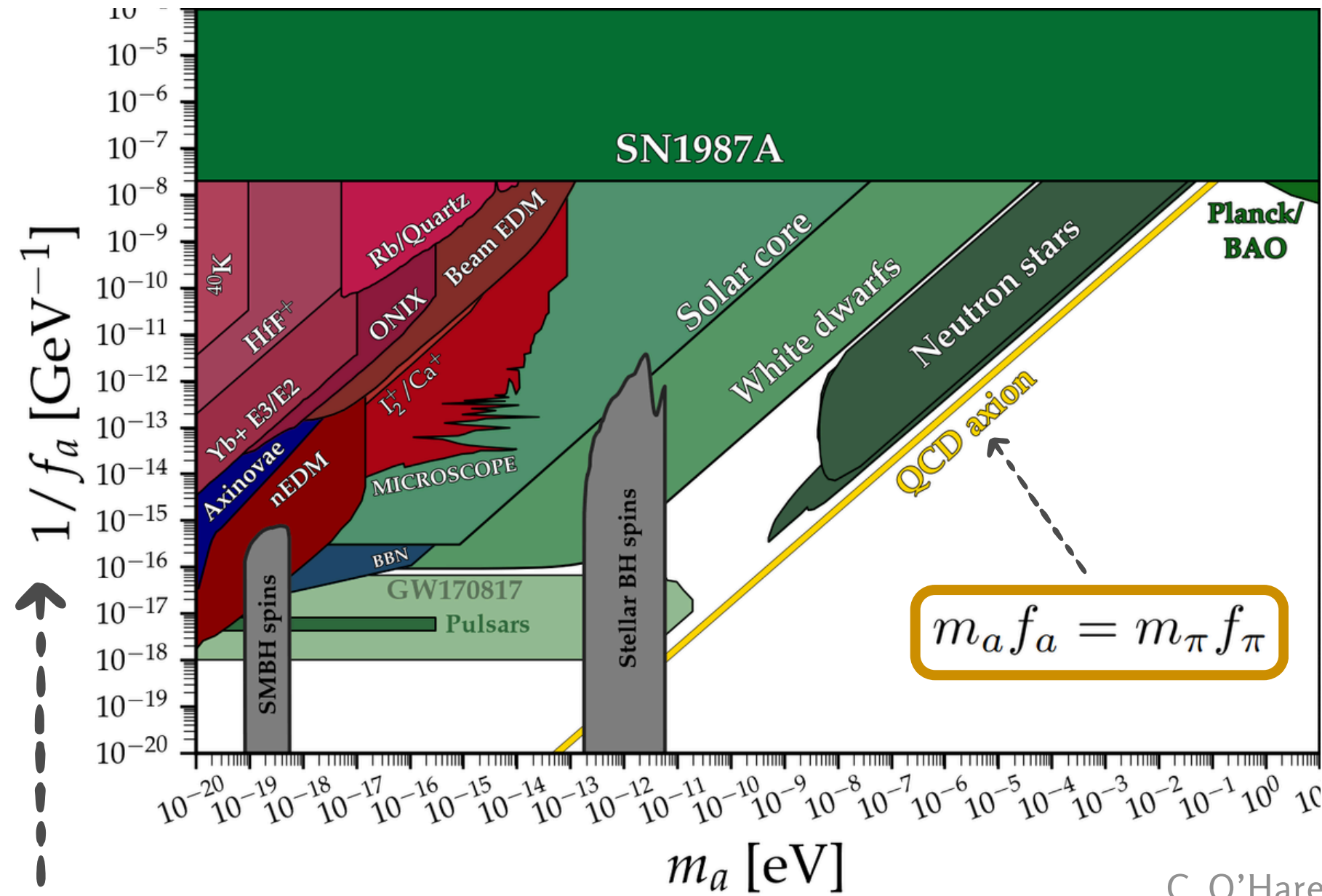
new mixing angle - very small!

$$a = \cos\vartheta a_s - \sin\vartheta (-\sin\beta a_1 + \cos\beta a_2)$$

$$\mathcal{L}_{\text{eff}} \supset \frac{a}{f_a} \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a$$

Recall: $\mathcal{L}_Y = -y_u \bar{Q}_L \tilde{\Phi}_2 u_R - y_d \bar{Q}_L \Phi_1 d_R + \text{h.c.}$

VEVS and Masses in the scalar sector



- 7 physical Higgs bosons
- all masses except axion and SM Higgs $\sim \mathcal{O}(\text{TeV})$
- $v_s = (4 \times 10^9 - 10^{13-14.5}) \text{ GeV}$
- $m_a = (10^{-5} - 0.1) \text{ eV}$

dark matter over-produced (not in the plot)

supernova cooling

$$f_a = \frac{v_s}{6}$$

axion decay constant

LHC signals can rule out
the DFSZ axion model!

(minimal)



How to distinguish 2HDM types at the LHC

Type-I:

$$h^0 f \bar{f} : -i \frac{m_f \cos \alpha}{v_{\text{SM}} \sin \beta}$$

$$H^0 f \bar{f} : -i \frac{m_f \sin \alpha}{v_{\text{SM}} \sin \beta}$$

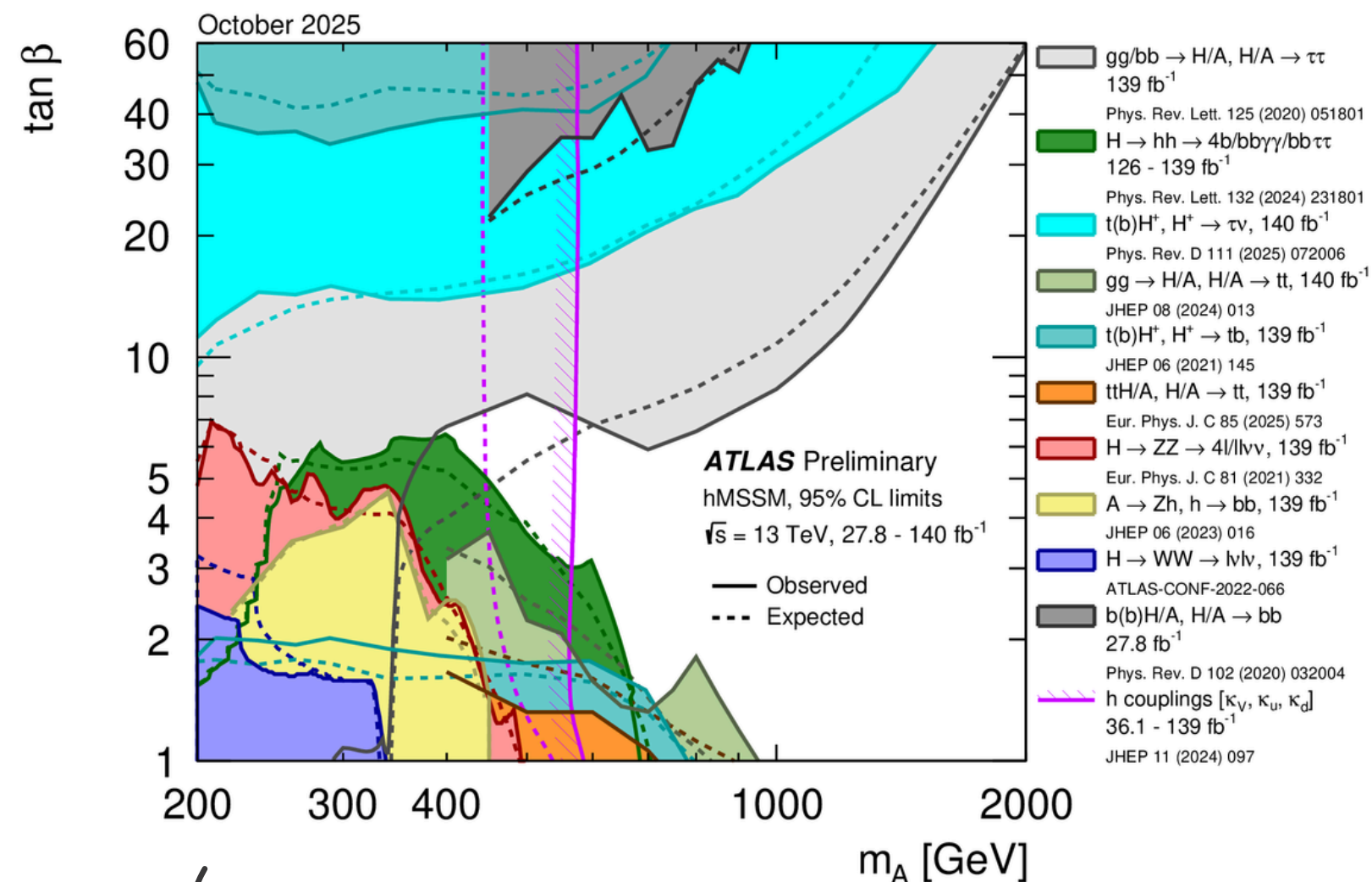
Type-II:

$$h^0 u \bar{u} : -i \frac{m_u \cos \alpha}{v_{\text{SM}} \sin \beta}$$

$$h^0 d \bar{d} : -i \frac{m_d - \sin \alpha}{v_{\text{SM}} \cos \beta}$$

$$H^0 u \bar{u} : -i \frac{m_u \sin \alpha}{v_{\text{SM}} \sin \beta}$$

$$H^0 d \bar{d} : -i \frac{m_d \cos \alpha}{v_{\text{SM}} \cos \beta}$$



Recall: the DFSZ model requires type-II (or flipped)!

possible $A \rightarrow ll$ enhancement

possible loophole?

LHC signals can ~~rule out~~
the DFSZ axion model!



A 3-Higgs-doublet axion model



$$\Phi_3 = \begin{pmatrix} \phi_3^+ \\ (h_3 + ia_3)/\sqrt{2} \end{pmatrix}$$

Field	$U(1)_{PQ}$
Φ_2	2
Φ_1, ϕ	-2
u_R, d_R, e_R	1
Q_L, L_L	-1
Φ_3	6

$$\begin{aligned}
 V(\Phi_1, \Phi_2, \Phi_3, \phi) = & V(\Phi_1, \Phi_2, \phi) + m_{33}^2 \Phi_3^\dagger \Phi_3 + \frac{1}{2} \lambda (\Phi_3^\dagger \Phi_3)^2 + \lambda_{31} (\Phi_1^\dagger \Phi_1) (\Phi_3^\dagger \Phi_3) \\
 & + \lambda_{32} (\Phi_2^\dagger \Phi_2) (\Phi_3^\dagger \Phi_3) + \lambda_{41} (\Phi_1^\dagger \Phi_3) (\Phi_3^\dagger \Phi_1) + \lambda_{42} (\Phi_2^\dagger \Phi_3) (\Phi_3^\dagger \Phi_2) \\
 & + \lambda_{3s} (\Phi_3^\dagger \Phi_3) (\phi^* \phi) - \lambda_{23s} (\Phi_2^\dagger \Phi_3 \phi^2 + \Phi_3^\dagger \Phi_2 \phi^{*2}) \\
 & + \lambda_{123} [(\Phi_2^\dagger \Phi_3) (\Phi_2^\dagger \Phi_1) + (\Phi_3^\dagger \Phi_2) (\Phi_1^\dagger \Phi_2)]
 \end{aligned}$$

some terms missing due to PQ charge!

Outlook

- Φ_3 acts like inert doublet from type-I 2HDM
- Higgs particles from first two doublets pushed to higher mass scale
- below this scale, the effective theory looks like a type-I 2HDM
- looking for fingerprints of the axion in 2HDM phenomenology

