Astrophobic axions, precisely

Federico Mescia

Universitat de Barcelona

- *Outline*

✓ **Introduction:**

Axion models and current experimental bounds

✓ **Model Building:** *Re-opening the axion window (*SN/RG bound*)*

- *astrophobic axion → family-dependent PQ symmetry!*
- *What about renormalization group effects on astrophobic axions*

Portorož 2023, 11th - 14th April 2023

Axion benchmark UV models

- **All you need to solve the strong CP problem is**

Axion: a spin-0 boson ⇒ PGB of a QCD-anomalous global $U(1)_{PQ}$ group

anomalous breaking by quark + spontaneously breaking by scalar

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

SM quarks
+ scalar singlet
+ 2HD

BSM quarks
+ scalar singlet
+ SM

Zhitnitsky '80, Dine, Fischler, Srednicki '81

Kim '79, Shifman, Vainshtein, Zakharov '80

DFSZ model:
universal 2HDM + 1 singlet

KSVZ model:
SM Higgs + BSM quarks + 1 singlet

"Invisible" axion models: $\langle \mathrm{Singlet} \rangle \gg v$

Axion: model independent features

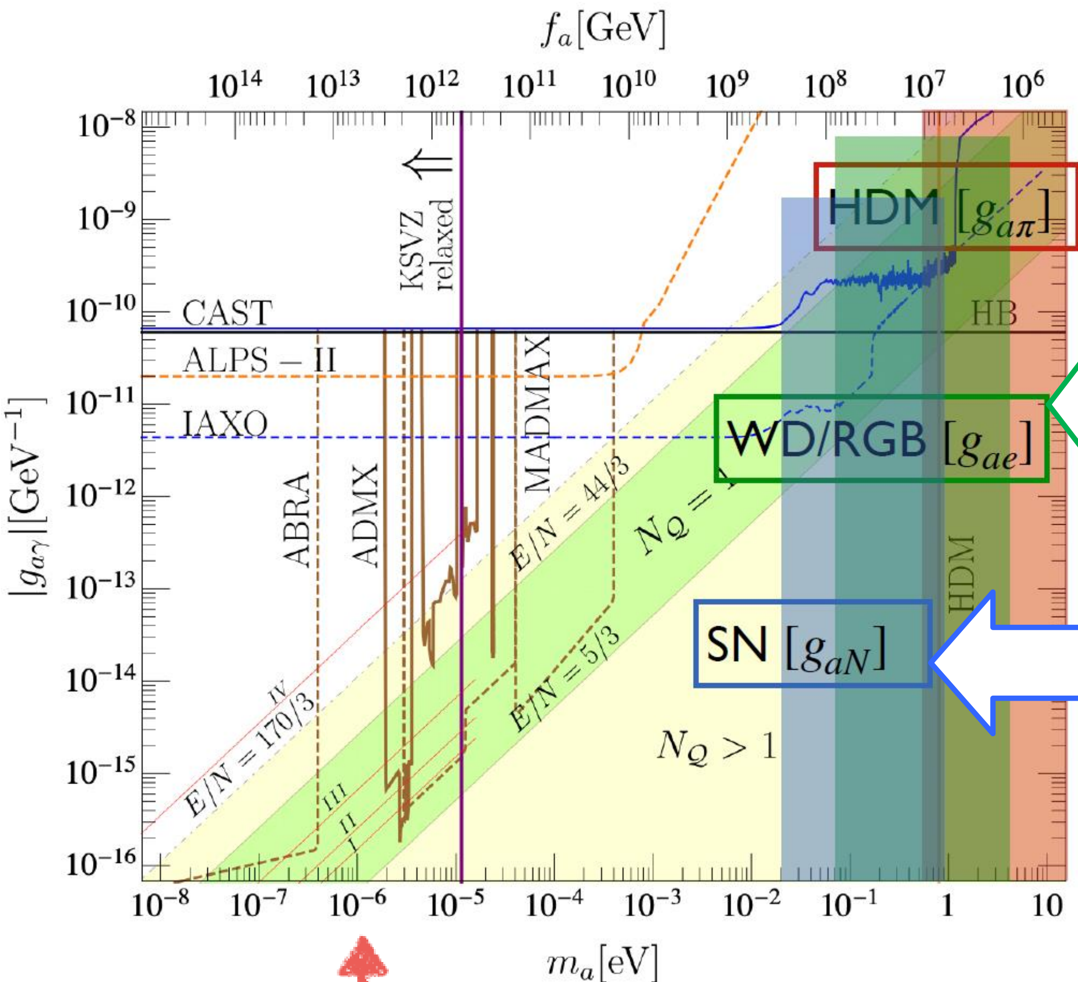
✓ **<u>Axion mass</u>**: $m_a \approx 0.1\,\mathrm{eV}\,\dfrac{10^8\,\mathrm{GeV}}{\boxed{f_a}}$

✓ **<u>All axion couplings</u>**: $\sim 1/f_a$

The lighter is the axion, the weaker are its interactions!

Invisible *(light)* particle *(not yet measured)*

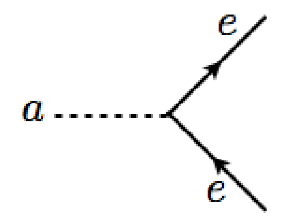
Bounds in DFSZ/KSVZ benchmark models



DFSZ & KSVZ benchmark models

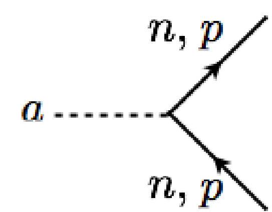
- **The strongest bounds are from astro/cosmo**

WD/RGB



$$\frac{\partial_\mu a}{2 f_a} \boldsymbol{c_e} \bar{e}\gamma^\mu\gamma_5 e$$

SN1987A



$$\frac{\partial_\mu a}{2 f_a} \boldsymbol{C_N} \bar{N}\gamma^\mu\gamma_5 N$$

Mind: *bounds are largely model-dependent!*

Astrophobic axion: $C_N \sim 0$ + $c_e \sim 0$

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

➔ nucleophobia + electrophobia = astrophobia

- **No:** **in KSVZ-like models!**
- **Yes:** **in DFSZ-like models with generation dependent PQ charges!**

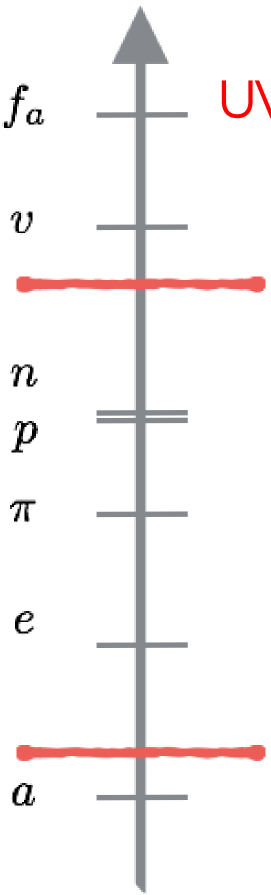
1. It will allow to relax the upper bound on axion mass by ~ 1 order of magnitude

2. It will improve visibility at IAXO (axion-photon)

3. unexpected connection to flavour physics

Di Luzio, F.M. Nardi, Panci, Ziegler, (2017)
Björkeroth, Di Luzio, F.M. Nardi, (2018)
Di Luzio, F.M. Nardi, Okawa, (2022)

Axion-nucleon couplings



UV-theory PQ invariant

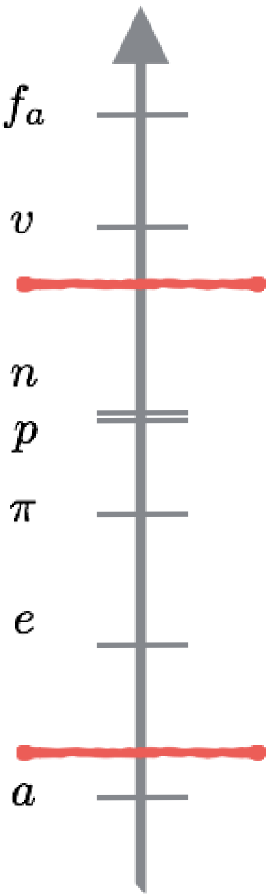
$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \bar{q} \gamma^\mu \gamma_5 q \qquad q = (u, d, s, \ldots)$$

EFT-I: quarks

$$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \overline{N} S^\mu N \qquad N = (p, n)$$

EFT-II: non-relativistic nucleons

Axion-nucleon/quark couplings



$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \bar{q} \gamma^\mu \gamma_5 q$$

$$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \overline{N} S^\mu N$$

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

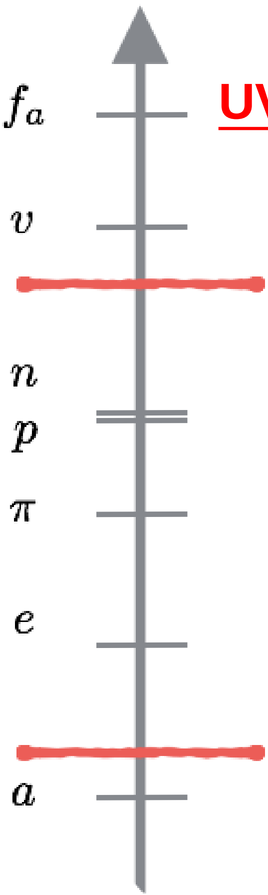
$$s^\mu \Delta q \equiv \langle p | \bar{q} \gamma_\mu \gamma_5 q | p \rangle$$

$$\begin{aligned} C_p + C_n &= (c_u + c_d)\,(\Delta_u + \Delta_d) - 2\delta_s \qquad [\delta_s \approx 5\%] \\ C_p - C_n &= (c_u - c_d)\,(\Delta_u - \Delta_d) \end{aligned}$$

independently from matrix elements and UV models:

$$\begin{array}{lllll} (1): & C_p + C_n & \approx & 0 & \text{if} \quad c_u + c_d = 0 \\ (2): & C_p - C_n & = & 0 & \text{if} \quad c_u - c_d = 0 \end{array}$$

Axion-quark couplings



UV-theory PQ invariant

@ f_a scale

$$\mathcal{L}_a \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + \frac{\partial_\mu a}{2f_a}\underbrace{\left[\frac{X_u}{N}\,\bar{u}\gamma^\mu\gamma_5 u + \frac{X_d}{N}\,\bar{d}\gamma^\mu\gamma_5 d\right]}$$

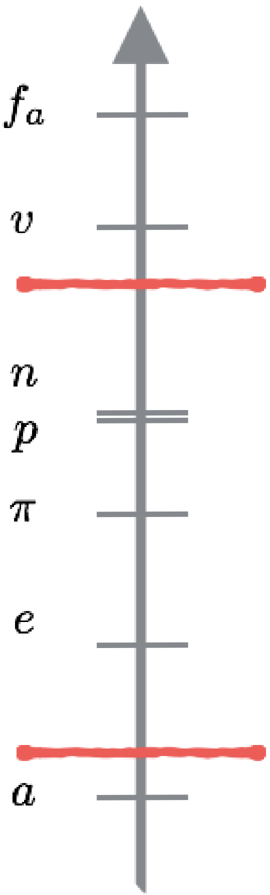
@ f_a scale

- the $U(1)_{PQ}$ Noether current
- X_q are the $U(1)_{PQ}$ charges normalized to the QCD-anomaly contribution
- $N \rightarrow$ QCD-anomaly contribution from each generation

$$N = \underbrace{(X_u + X_d)}_{N_1} + \underbrace{(X_c + X_s)}_{N_2} + \underbrace{(X_t + X_b)}_{N_3}$$

$$X_q = X_{qR} - X_{qL} \quad (q=u,\, d,\, ..)$$

Axion-quark couplings



EFT-I: quarks

$$\mathcal{L}_a \supset \underbrace{\frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + \frac{\partial_\mu a}{2f_a}\left[\frac{X_u}{N}\,\bar{u}\gamma^\mu\gamma_5 u + \frac{X_d}{N}\,\bar{d}\gamma^\mu\gamma_5 d\right]}_{\text{@ low energy scale} \sim 2\text{ GeV}}$$

$$\mathcal{L}_q = \frac{\partial_\mu a}{2f_a} c_q\, \bar{q}\gamma^\mu\gamma_5 q$$

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

$$X_q = X_{qR} - X_{qL} \quad (q=u, d, ..)$$

Nucleophobia conditions

$$\begin{aligned} (1): \quad C_p + C_n &\approx 0 \quad \text{if} \quad c_u + c_d = 0 \\ (2): \quad C_p - C_n &= 0 \quad \text{if} \quad c_u - c_d = 0 \end{aligned}$$

$$\mathcal{L}_q = \frac{\partial_\mu a}{2f_a} c_q \, \bar{q}\gamma^\mu\gamma_5 q$$

$\longrightarrow$

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

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

2nd condition $\quad 0 = c_u - c_d = \dfrac{X_u - X_d}{N} - \underbrace{\dfrac{m_d - m_u}{m_d + m_u}}_{\simeq 1/3}$

Nucleophobia conditions: KSVZ/DFSZ no-go

$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \bar{q} \gamma^\mu \gamma_5 q$$

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

1st condition

$$0 = c_u + c_d = \frac{X_u + X_d}{N} - 1 \quad \left\} \begin{array}{l} \xrightarrow[X_u = X_d = 0]{\text{KSVZ}} \quad -1 \\[2ex] \xrightarrow[N = n_g (X_u + X_d)]{\text{Universal DFSZ}} \quad \dfrac{1}{n_g} - 1 \end{array} \right.$$

Nucleophobia conditions: KSVZ/DFSZ no-go

$$\boxed{\begin{array}{lccccl} (1): & C_p + C_n & \approx & 0 & \text{if} & c_u + c_d = 0 \\ (2): & C_p - C_n & = & 0 & \text{if} & c_u - c_d = 0 \end{array}}$$

$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \overline{q} \gamma^\mu \gamma_5 q$$

NO

1st condition

$$0 = c_u + c_d = \frac{X_u + X_d}{N} - 1 \left\} \begin{array}{l} \xrightarrow[X_u = X_d = 0]{\text{KSVZ}} \quad \cancel{-1} \\ \xrightarrow[N = n_g (X_u + X_d)]{\text{Universal DFSZ}} \quad \cancel{\frac{1}{n_g} - 1} \end{array} \right.$$

Nucleophobia conditions

Nucleophobia can be obtained in DFSZ-type models BUT only in presence of non-universal (i. e. generation dependent) PQ charges, such that

$$\boxed{N = N_1 + \cancel{N_2 + N_3}^{\,0} = N_1}$$

Only first generation quarks contribute to the QCD anomaly

1st condition

$$0 = c_u + c_d = \frac{X_u + X_d}{N} - 1 = \frac{N_1}{N} - 1$$

QCD-anomaly for each generation

$$N = \underbrace{(X_u + X_d)}_{N_1} + \underbrace{(X_c + X_s)}_{N_2} + \underbrace{(X_t + X_b)}_{N_3}$$

Implementing Nucleophobia

$$N \equiv N_1 + \cancel{N_2 + N_3}^{\,0} = N_1$$

- $N_2 + N_3 = 0$ easy to implement with DFSZ family-dependent 2HDM couplings

$$\boxed{\begin{aligned} \mathcal{L}_Y \supset\ & \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 ... + \ldots) \\ + \ & \bar{q}_2 u_2 H_2 + \bar{q}_2 d_2 \tilde{H}_1 + (\bar{q}_2 d_3 ... + \ldots) \end{aligned}} \longrightarrow \boxed{\begin{aligned} \mathbf{N_3} &= X_{u3} + X_{d3} - 2X_{q3} = X_2 - X_1 \\ \mathbf{N_2} &= X_{u2} + X_{d2} - 2X_{q3} = X_1 - X_2 \end{aligned}}$$

$$N_1 = N_2 = -N_3$$

- 1st condition <u>automatically</u> satisfied

$$c_u + cd = \frac{N_1}{N} - 1 = 0$$

Implementing Nucleophobia

$$
\begin{aligned}
(1): \quad & C_p + C_n \approx 0 \quad \text{if} \quad c_u + c_d = 0 \\
(2): \quad & C_p - C_n = 0 \quad \text{if} \quad c_u - c_d = 0
\end{aligned}
$$

- 1st condition <u>automatically</u> satisfied

$$c_u + cd = \frac{N_1}{N} - 1 = 0$$

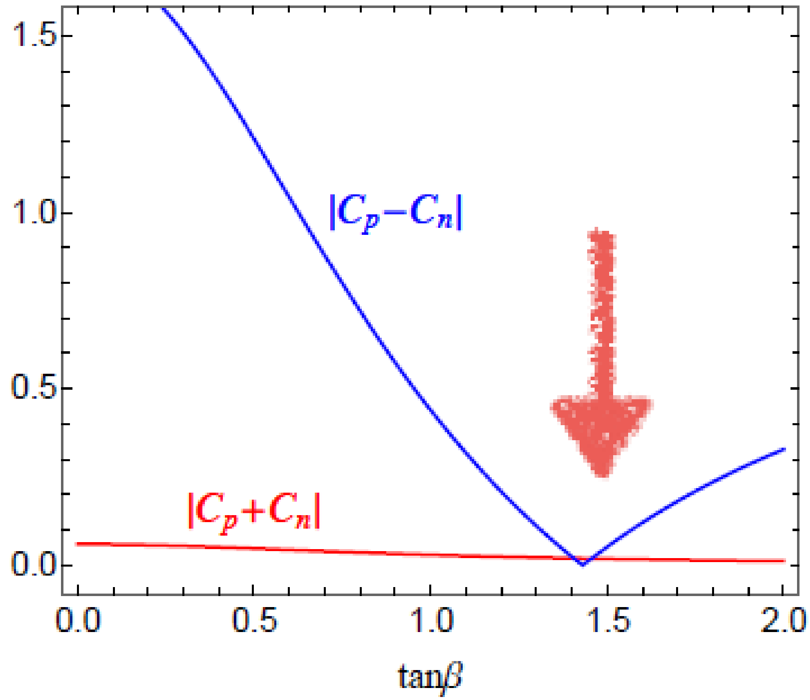
$$N = N_1$$

- 2nd condition can be implemented setting a specific value for the vev (10% tuning)

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

$$c_u - c_d = \underbrace{\frac{X_u - X_d}{N}}_{c_\beta^2 - s_\beta^2} - \underbrace{\frac{m_d - m_u}{m_u + m_d}}_{\simeq \frac{1}{3}} = 0 \quad \longrightarrow \quad c_\beta^2 \simeq 2/3$$

Implementing Nucleophobia



- 2nd condition can be implemented setting a specific value for the vev (10% tuning)

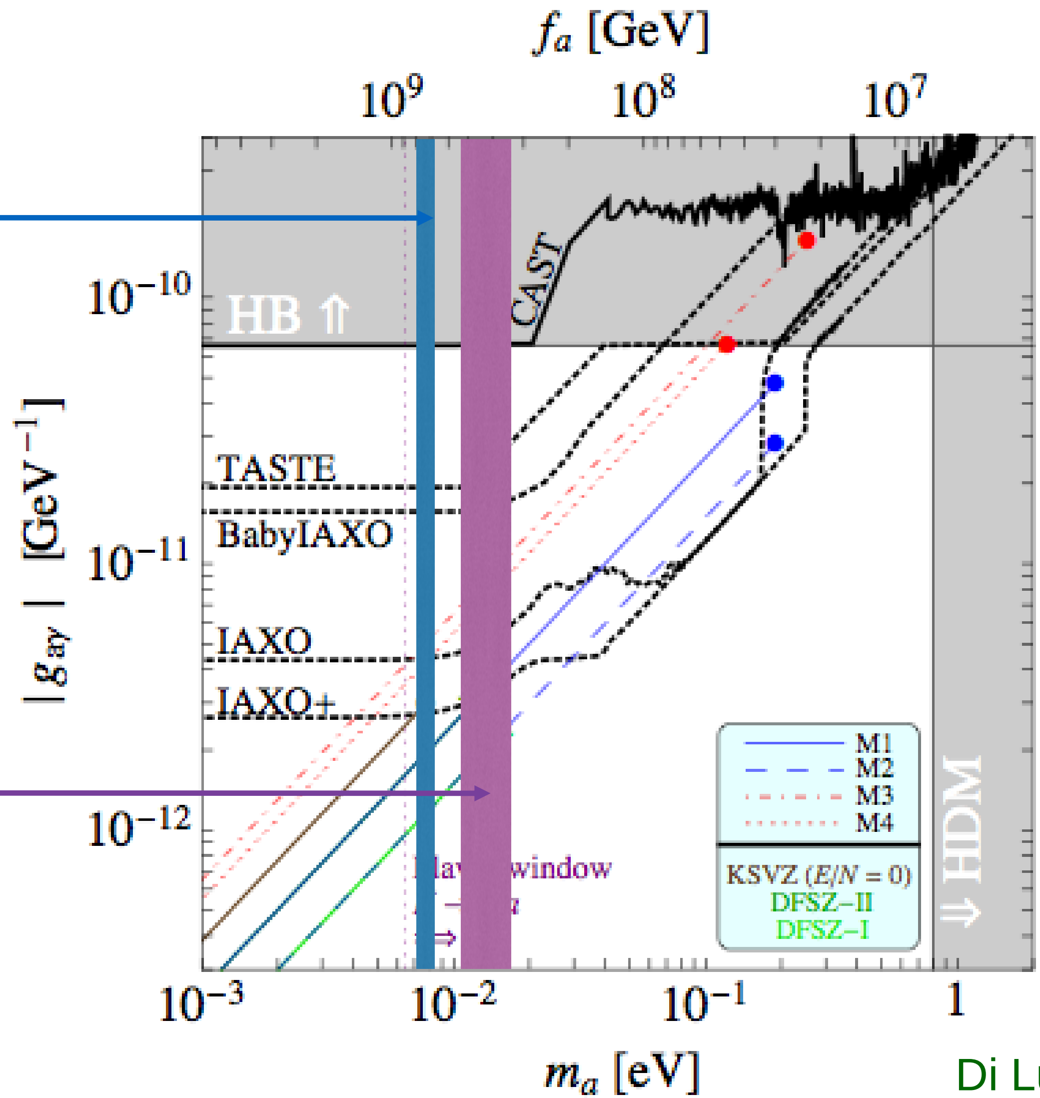
$\tan\beta = v_2/v_1$

$$c_u - c_d = \underbrace{\frac{X_u - X_d}{N}}_{c_\beta^2 - s_\beta^2} - \underbrace{\frac{m_d - m_u}{m_u + m_d}}_{\simeq \frac{1}{3}} = 0 \quad \longrightarrow \quad c_\beta^2 \simeq 2/3$$

Axion benchmark models

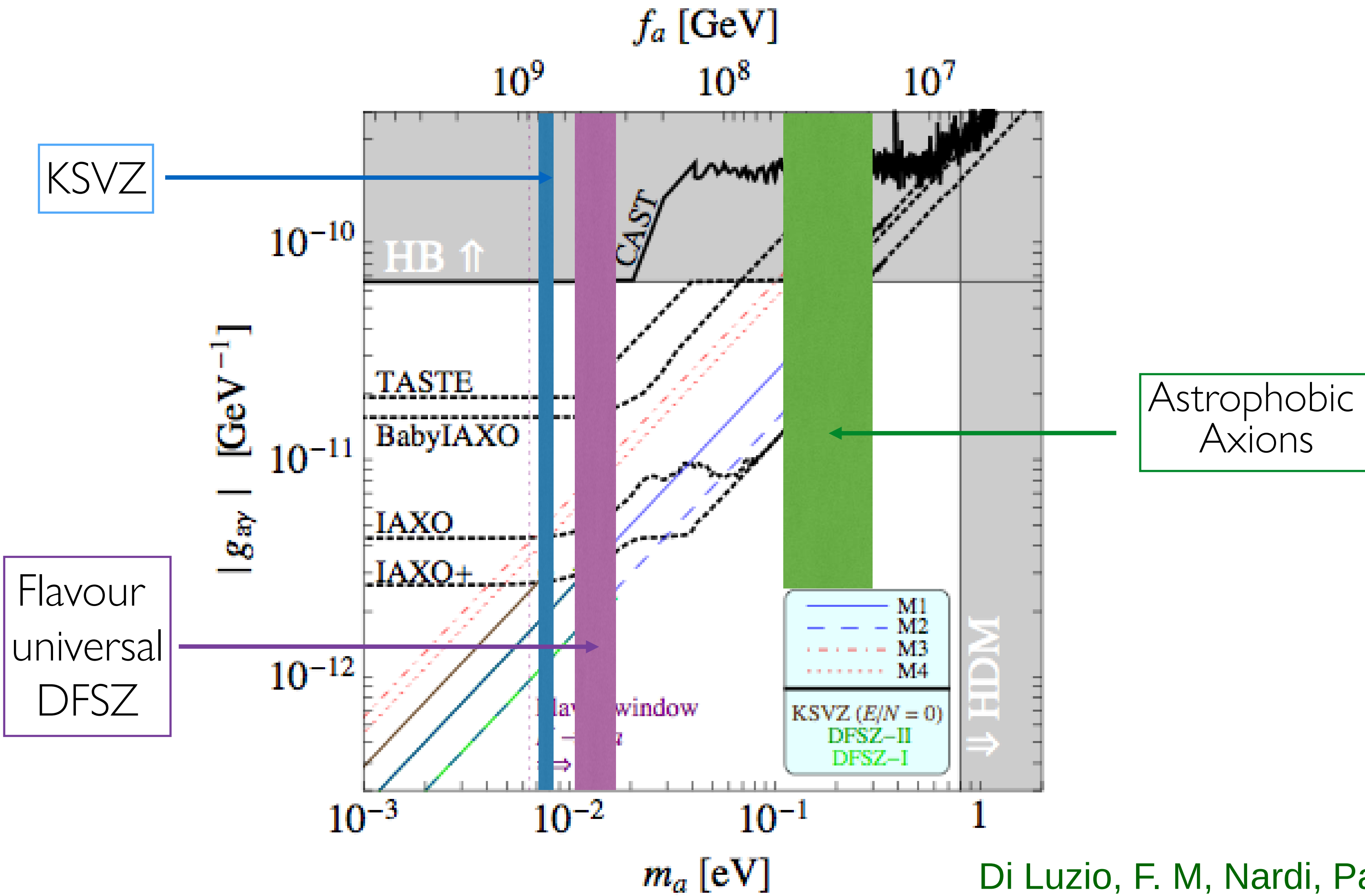
KSVZ

Flavour universal DFSZ



Di Luzio, F. M, Nardi, Panci, Ziegler 2017

Astrophobic axion models



Di Luzio, F. M, Nardi, Panci, Ziegler 2017

GIFT = Axion-Flavour Connection

- Astrophobia implies flavour violating axion couplings!

$$[\mathrm{PQ}_d, Y_d^\dagger Y_d] \neq 0 \quad \longrightarrow \quad C_{ad_id_j} \propto (V_d^\dagger \, \mathrm{PQ}_d V_d)_{i\neq j} \neq 0$$

e. g. RH down rotations become physical

- Plethora of low-energy flavour experiments probing $\frac{\partial_\mu a}{2 f_a} \overline{f}_i \gamma^\mu (C^V_{ij} + C^A_{ij}\gamma_5) f_j$

$K \to \pi a$ $\quad m_a < 1.0 \times 10^{-4} \frac{\mathrm{eV}}{|C^V_{sd}|}$ - [E787, E949 @ BNL, 0709.1000] $\longrightarrow$ NA62

$B \to K a$ $\quad m_a < 3.7 \times 10^{-2} \frac{\mathrm{eV}}{|C^V_{bs}|}$ - [Babar, 1303.7465] $\longrightarrow$ Belle-II

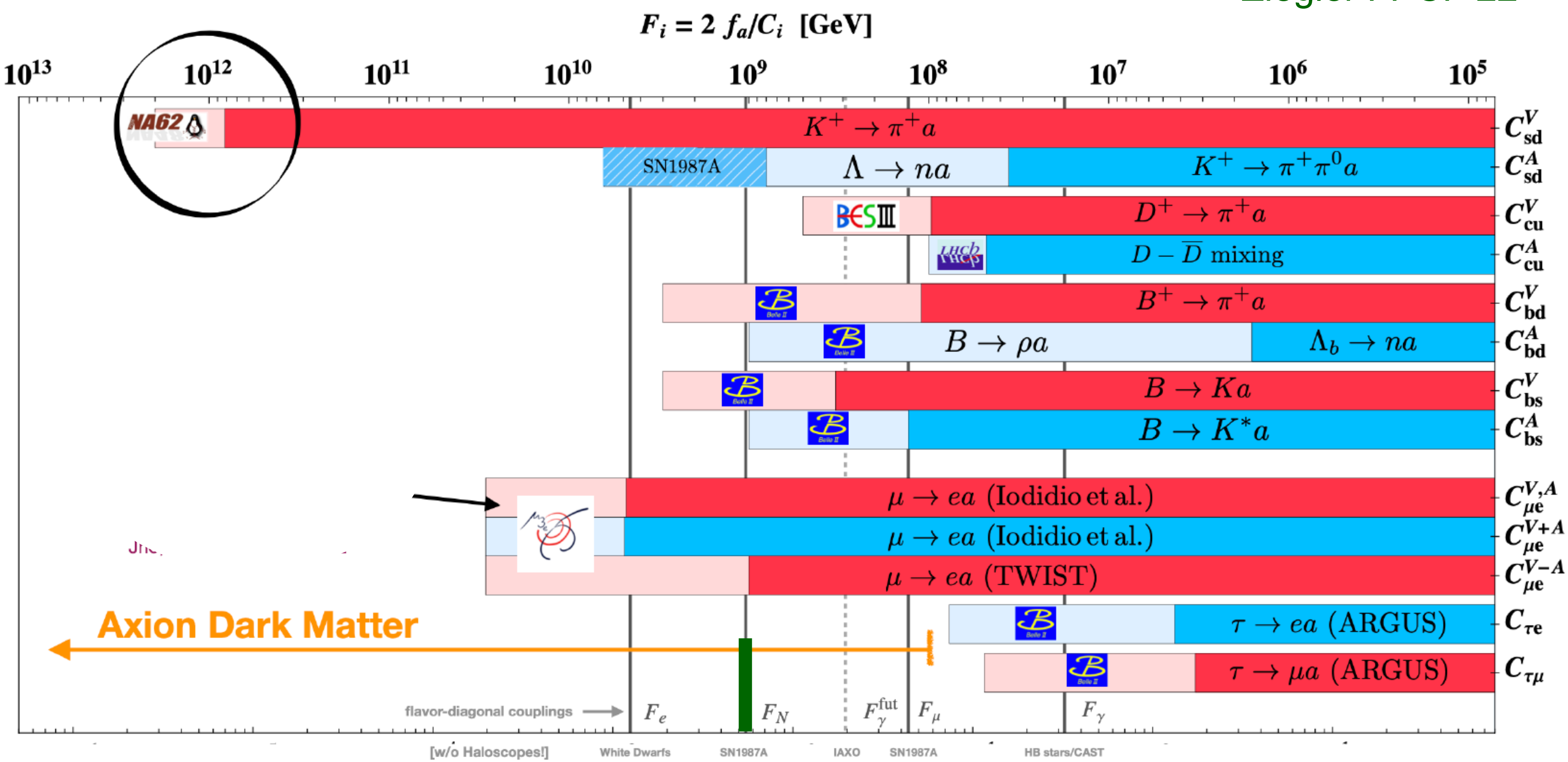
$\mu \to e a$ $\quad m_a < 3.4 \times 10^{-3} \frac{\mathrm{eV}}{\sqrt{|C^V_{bd}|^2 + |C^V_{bd}|^2}}$: [Crystal Box @ Los Alamos, Bolton et al PRD38 (1988)]

$\longrightarrow$ MEG II

GIFT = Axion-Flavour Connection

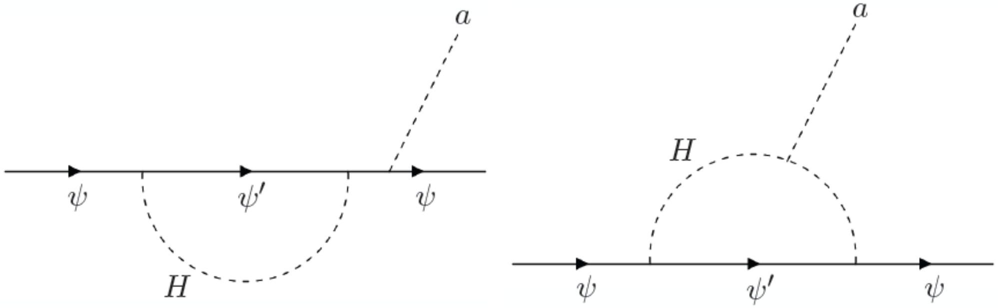
- Astrophobia implies flavour violating axion couplings!

Ziegler FPCP‘22

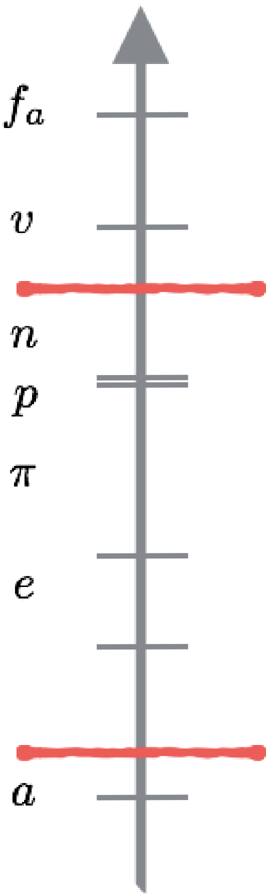


for $C_i = \{C_\gamma, C_e, C_N, C_{sd}, C_{bs}, C_{bd}, C_{\mu e}\} = 1$ *flavour beats astrophysics !*

What about stability of axion astrophobia under RGE?



Radiative stability of axion astrophobia!



$$\mathcal{L}_q = \frac{\partial_\mu a}{2f_a} c_q \, \bar{q}\gamma^\mu\gamma_5 q$$

$$\mathcal{L}_N = \frac{\partial_\mu a}{2f_a} C_N \overline{N} S^\mu N$$

$$(1)\ c_u + c_d \approx 1 \qquad \Leftarrow \text{ non-universality of quark PQ charges}$$

$$\left.\begin{array}{l}(2)\ c_u - c_d \approx 1/3 \\ (3)\ c_e \sim X_3 \approx 0\end{array}\right\} \Leftarrow \text{ a specific VEV ratio}$$

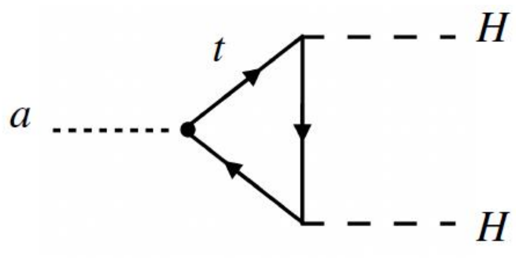
- ➢ all conditions are imposed at tree level
- ➢ spoiled by renormalization group evolution?

❖ No, the axion astrophobia **survives** even after taking the RG corrections into account

Di Luzio, F.M., Nardi, Okawa (2022)

RG corrections to axion couplings

❖ **Leading effects from top-loop in DFSZ-type models**



Choi, Im, Kim, Seong '21
Bauer, Neubert, Renner, Schäuble, Thamm '20

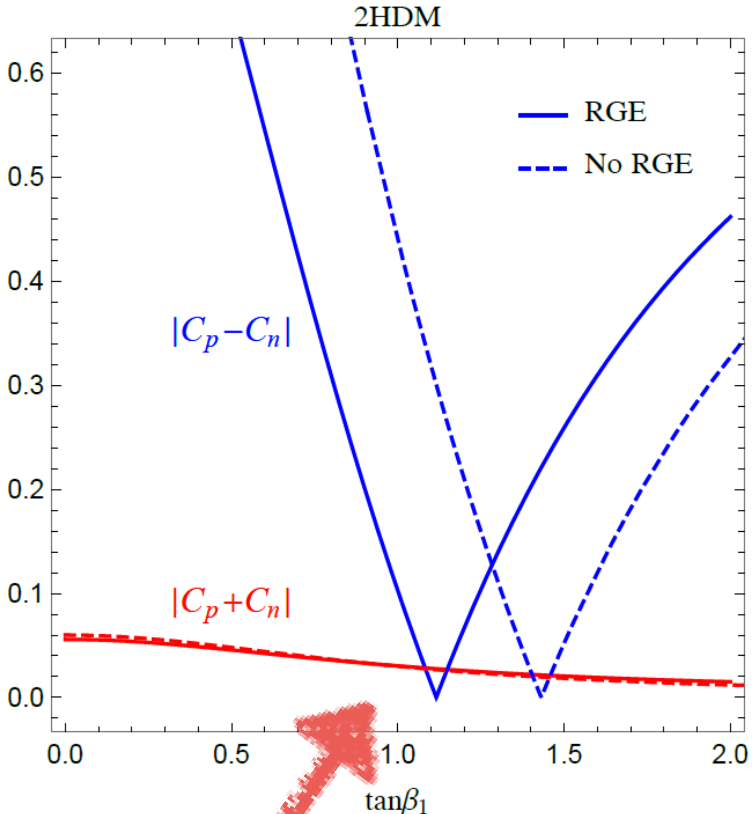
★ $$\frac{\partial_\mu a}{f}(H^\dagger i D_\mu H) \rightarrow \frac{\partial_\mu a}{f}\sum_{\psi=q_L,u_R,\ldots}\beta_\psi\bar{\psi}\gamma_\mu\psi \qquad (\beta_\psi = Y_\psi/Y_H)$$

$$\boxed{\begin{aligned} C_u(2\,\mathrm{GeV}) &\simeq C_u(f_a) - \kappa_t C_t(f_a)\,, \\ C_d(2\,\mathrm{GeV}) &\simeq C_d(f_a) + \kappa_t C_t(f_a)\,, \\ C_e(m_e) &\simeq C_e(f_a) + \kappa_t C_t(f_a)\,. \end{aligned}}$$

$^*\kappa_t(\mu,\Lambda) \approx 30\,\%$ for
$\mu = 2\,\mathrm{GeV}$ and $\Lambda = 10^{10}\,\mathrm{GeV}$

RG corrections to axion couplings

Di Luzio, F.M., Nardi, Okawa (2022)



$$(1)\ c_u + c_d \simeq c_u^0 + c_d^0 = 1$$ unaffected

$$(2)\ c_u - c_d \simeq c_u^0 - c_d^0 - 2\kappa_t c_t^0 \approx f_{ud}$$

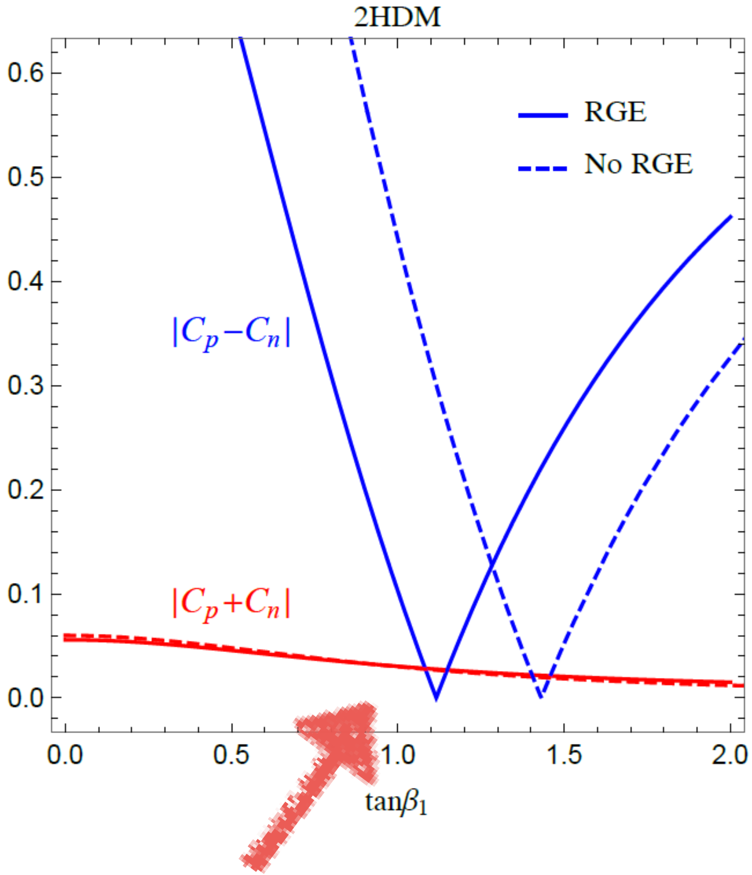
$$(3)\ c_e \simeq c_e^0 + \kappa_t c_t^0 \approx 0$$

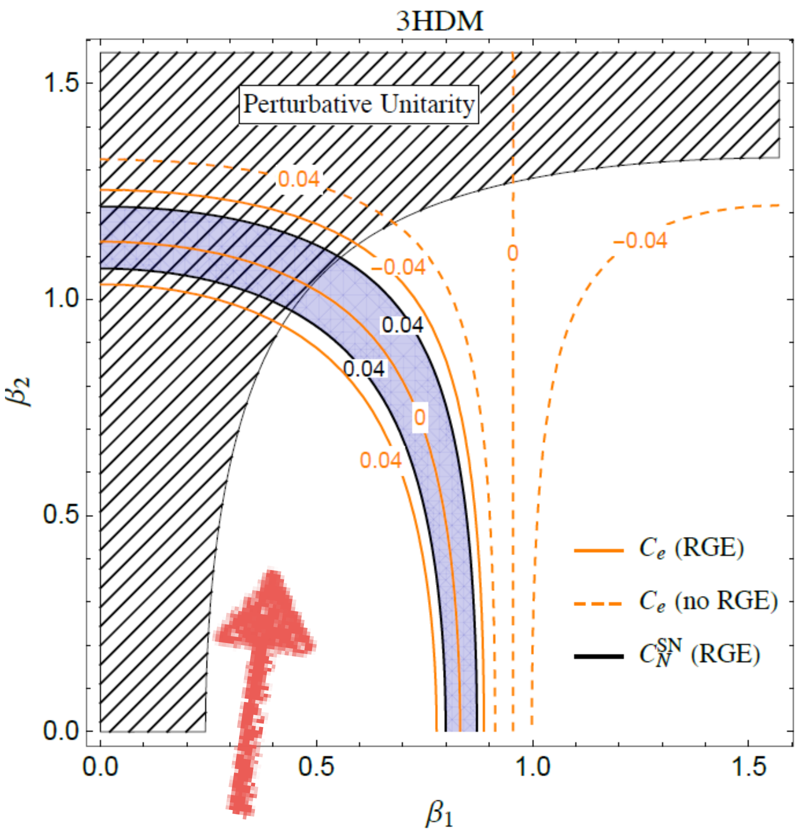
shifted by k_t factor

Axion astrophobia is stable against the RG corrections, but with a shift of parameter space [3HDM case $X_3 = 0 \rightarrow X_3 = k_t/(1 - k_t)$]

RG corrections to axion couplings

Di Luzio, F.M., Nardi, Okawa (2022)





Axion astrophobia is stable against the RG corrections, but with a shift of parameter space [3HDM case $X_3 = 0 \rightarrow X_3 = k_t/(1- k_t)$]

Conclusion

❖ The axion hypothesis provides a well motivated BSM scenario

- solves the strong CP problem
- provides a DM candidate
- **is unambiguously testable by detecting the axion**

❖ Flavour non-universal PQ charges open new pathways:

- relaxing SN/RGB: heavier axion!
- flavoured axion searches
- connection to SM flavour puzzle: textures a la FN?
- astrophobic feature keeps holding even after taking the RG corrections into account, albeit within a different parameter space