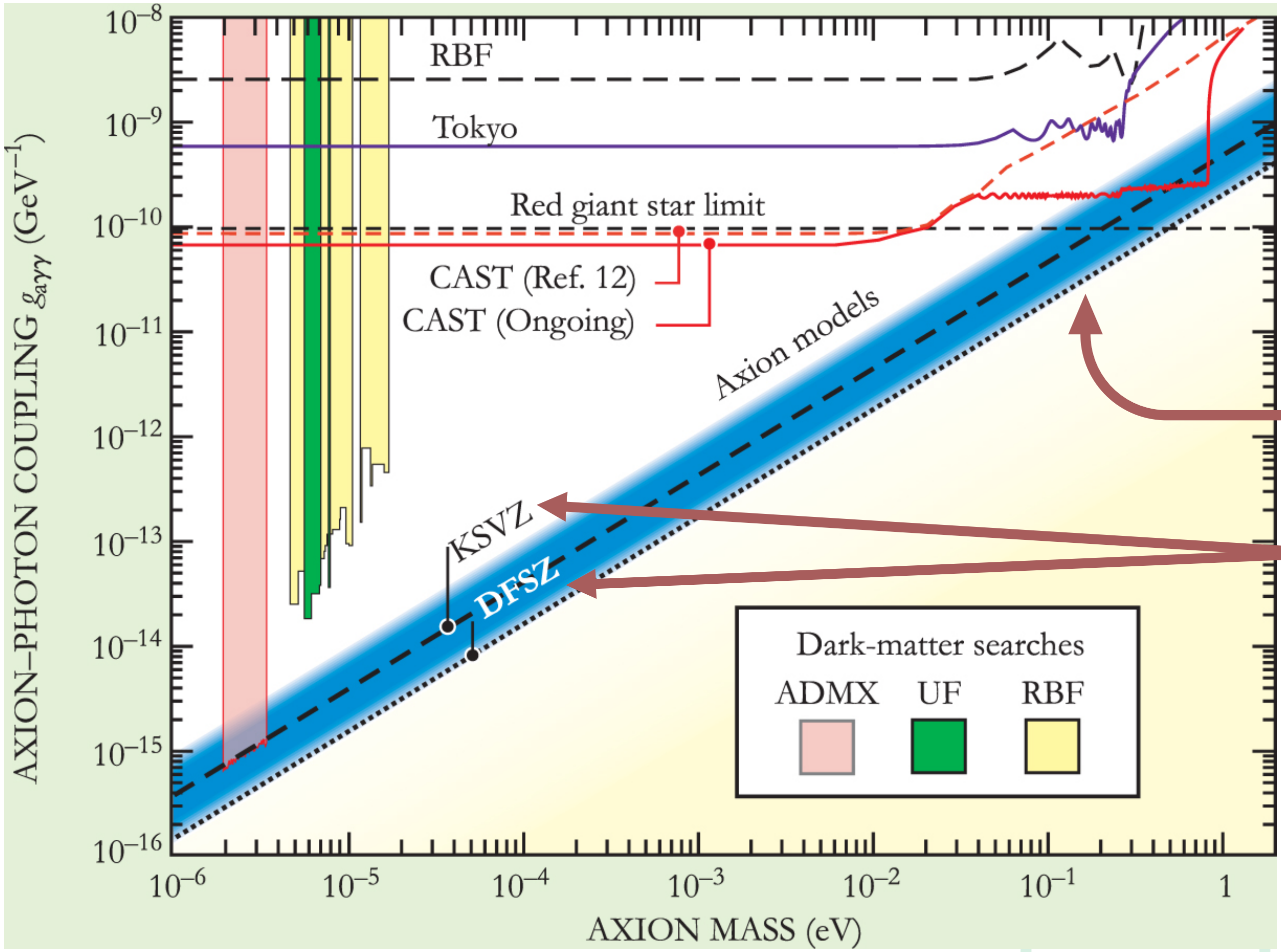
DFSZ Axions and Where to Find Them

Johannes Diehl
Emmanouil Koutsangelas

MAX PLANCK INSTITUTE FOR PHYSICS

Paper @ arXiv: 2302.04667
+ Code @ Github
+ Data @ Zenodo

Typical exclusion plot



What exactly is this region?!

Which models are that?!

Physics Today, v Bibber (2006)

Which models are that?!

- Two types of axion models (always w/ Higgs singlet S):
  - KSVZ: heavy quarks Q w/ PQ charge χ_{PQ}
  - DFSZ: Higgs doublets H w/ PQ charge (all SM fermions have too)
- Want axion-photon coupling → need Anomaly Ratio E/N

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$

- E, N are QED and QCD anomalies, calculated from representations of fermions

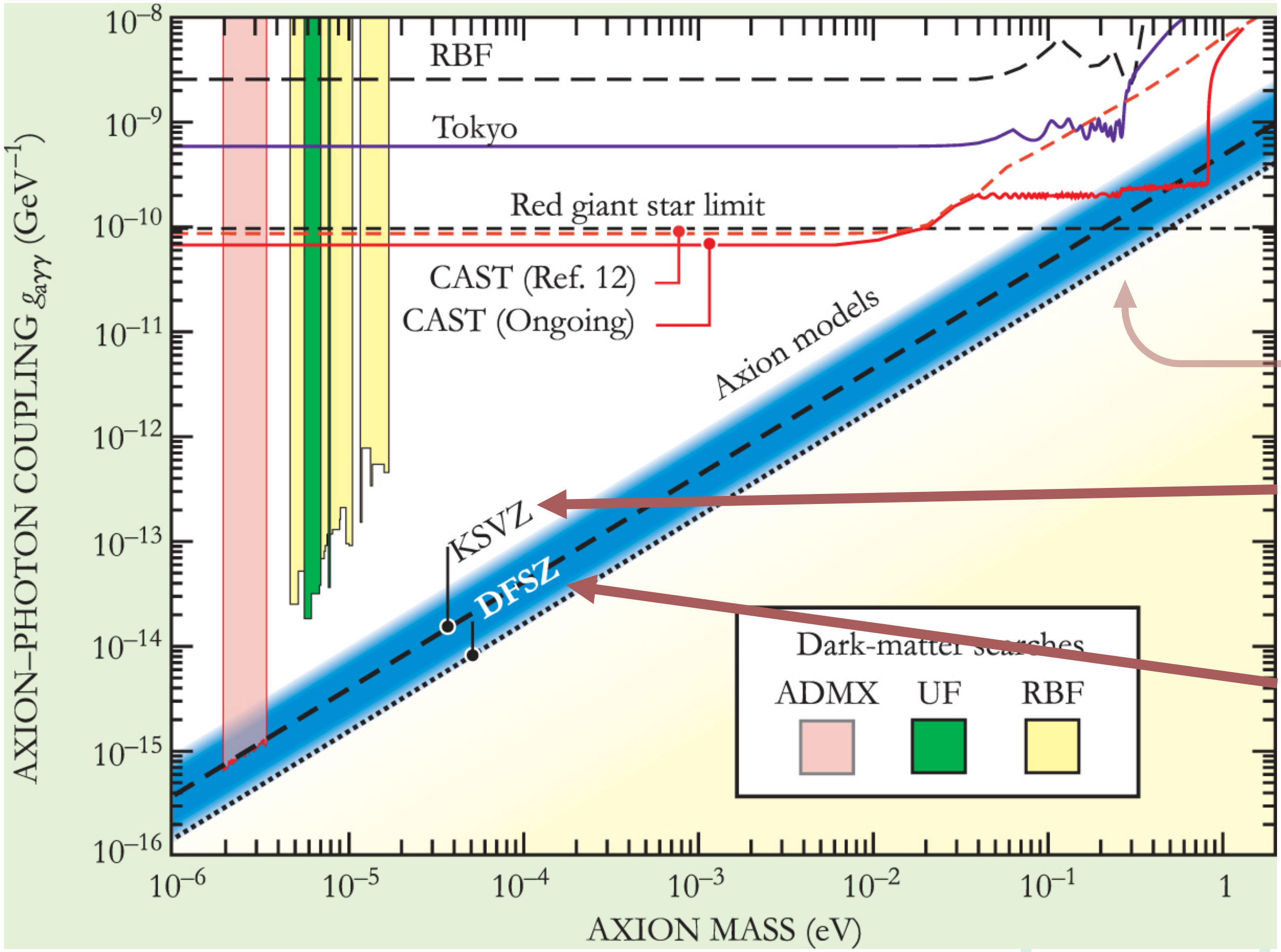
$$E = \chi_{PQ} d(\mathcal{C})\, \mathrm{Tr}(q^2) \qquad N = \chi_{PQ}\, d(\mathcal{J})\, T(\mathcal{C})$$

Which models are that?!

- KSVZ: Plakkot, Hoof '21
  - Minimal model: One $Q \sim (3,1,0) \rightarrow \frac{E}{N} = 0 \; (q_{em} = 0)$ (SU(3), SU(2), U(1))
  - Extend up to 28 Q, above Landau poles (running of coupling constant) phenomenologically prohibitive $\rightarrow \sim 10^7$ models
- DFSZ:
  - Minimal model: two Higgs doublets, couple to right-handed fermions $\rightarrow E/N = 8/3$ or $E/N = 2/3$
  - What about $2 < n_D \leq 9$ doublets?
  - E/N depends only on charges of H: $\frac{E}{N} = \frac{2}{3} + 2\frac{\sum \chi_u + \sum \chi_l}{\sum \chi_u + \sum \chi_d}$

u c t	d s b	e μ τ
H_1	H_2	H_1
	or	
H_1	H_2	H_2

Typical exclusion plot



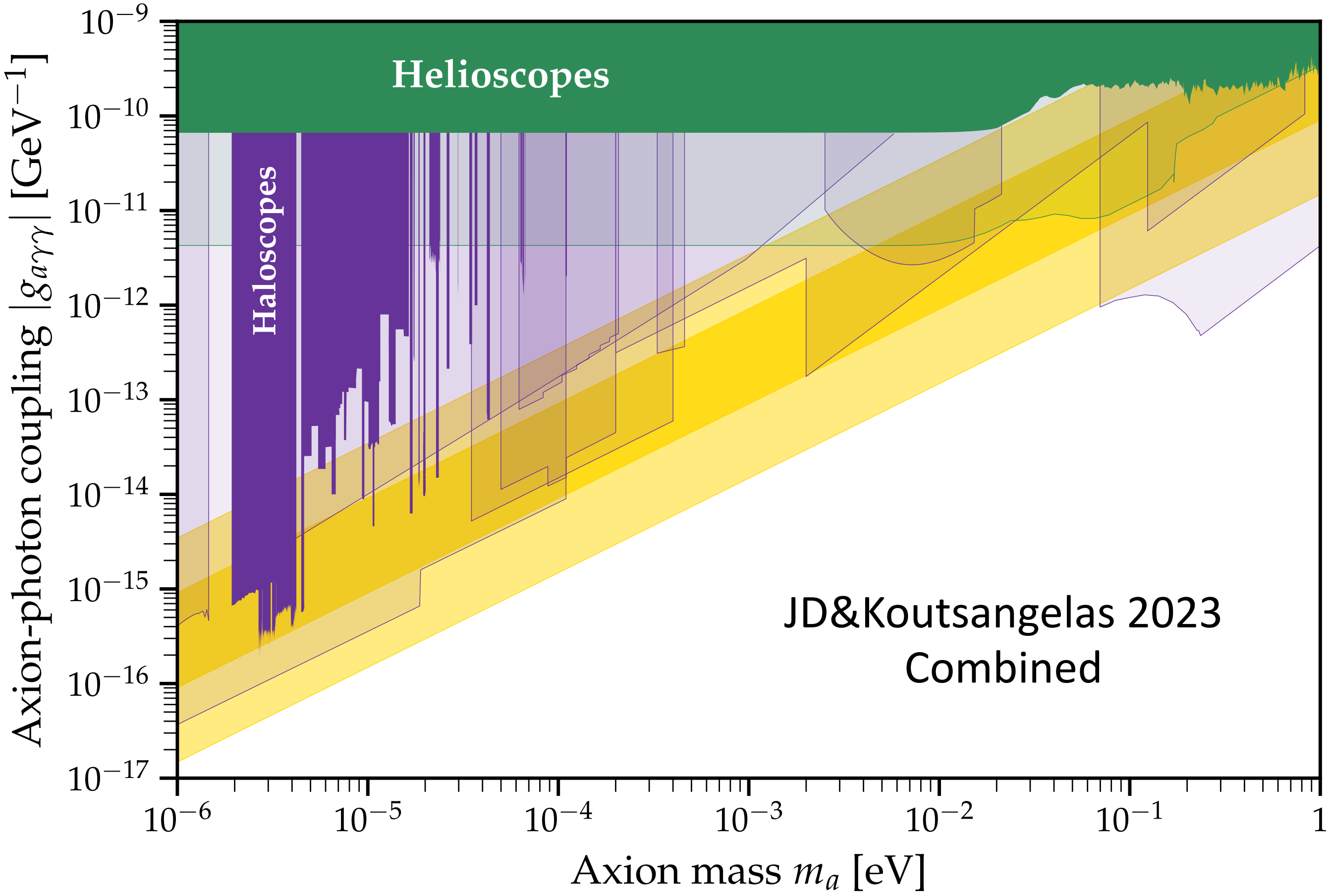
What exactly is this region?!

One additional quark, $q_{em} = 0$

$DFSZ_2$, smaller $g_{a\gamma}$

Physics Today, v Bibber (2006)

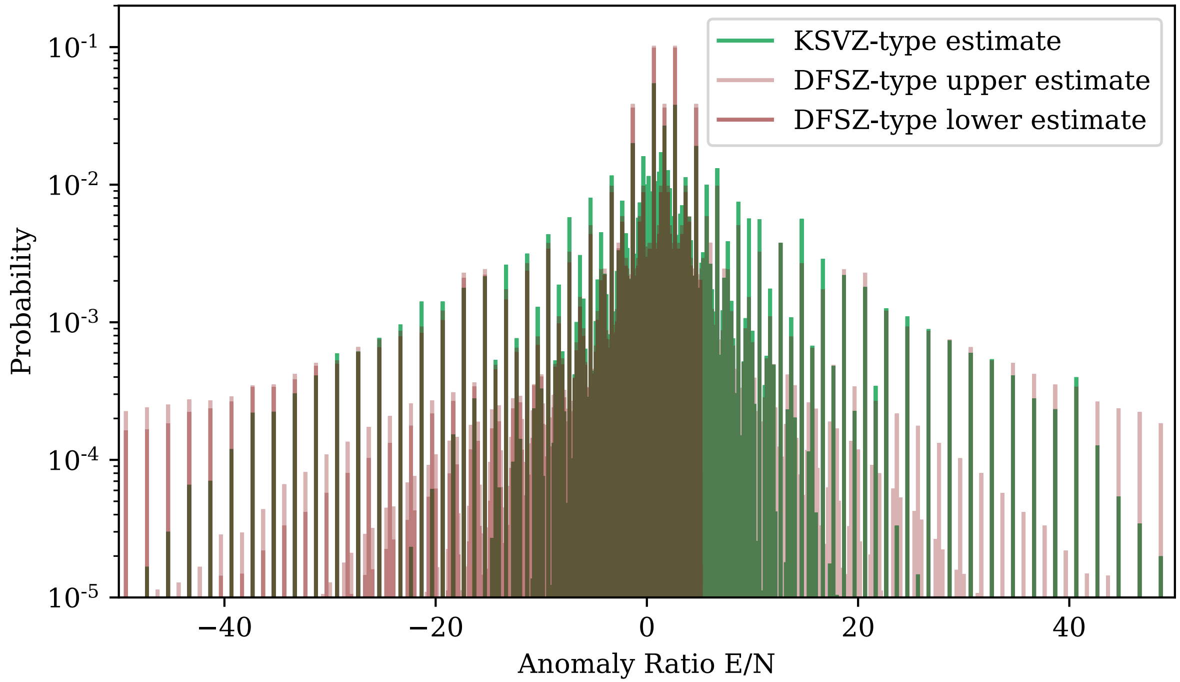
What exactly is this region?



A Very Short Cooking Recipe

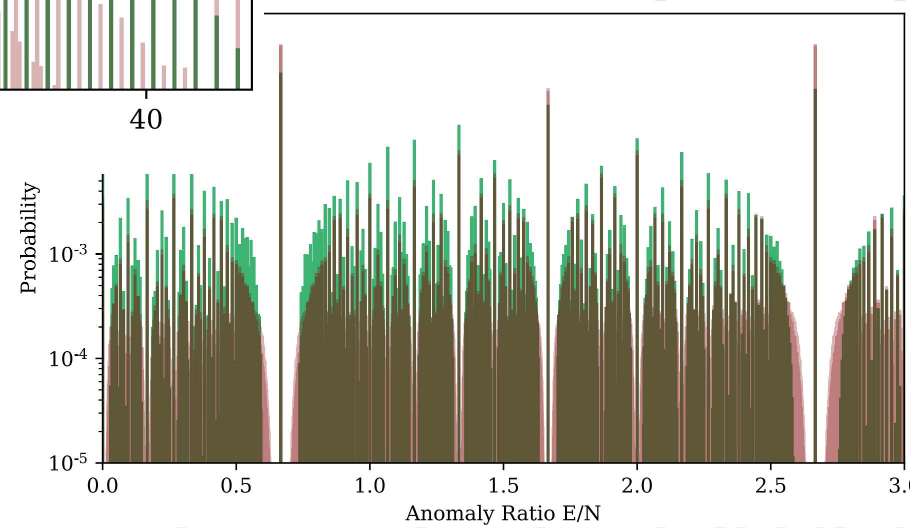
- Specify which Higgs couples to which fermion
- Introduce explicit symmetry breaking potential
  e.g. $\mathrm{n_D} = 4 \rightarrow U(1)_{H_1} \times U(1)_{H_2} \times U(1)_{H_3} \times U(1)_{H_4} \times U(1)_S \rightarrow U(1)_Y \times U(1)_{PQ}$
- Use to fix PQ charges (1 potential term = 1 condition)
- Solve linear equation system
- Equal solutions → add all terms to one big potential
- Compute E/N.
- Come up with relative probabilities

Comparison to KSVZ



- Peaks at $\frac{E}{N} = \frac{5}{3} + k$, $k \in \mathbb{Z}$
- KSVZ models also peaked

- $DFSZ_2$ remains important
- DFSZ and KSVZ look similar



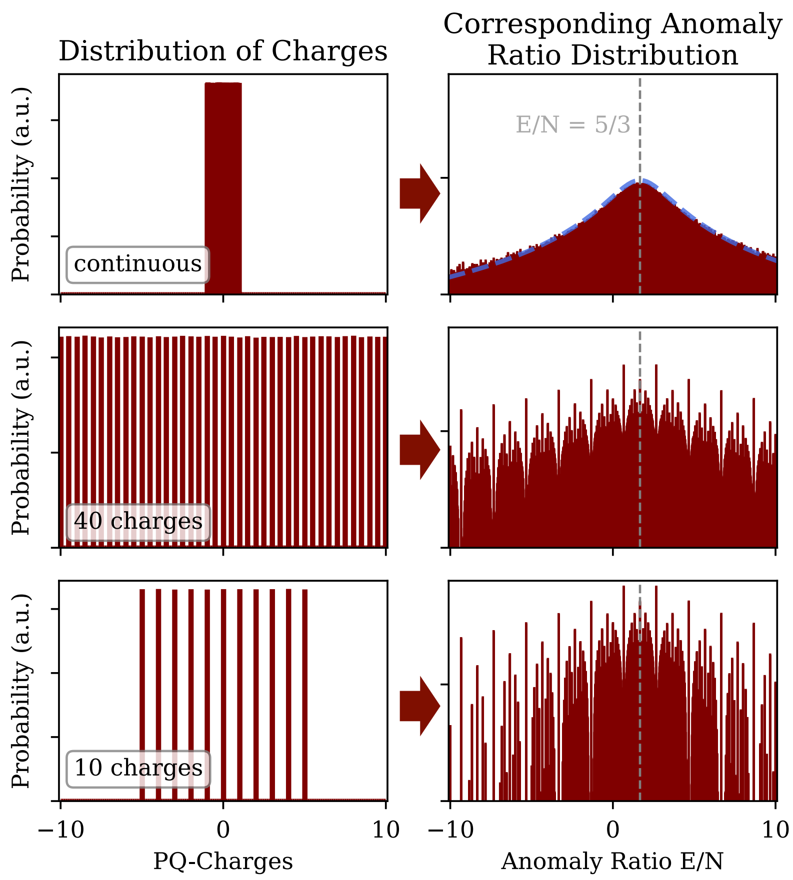
Comparison to KSVZ

- Remember: $E = \chi_{PQ} d(\mathcal{C})\,\mathrm{Tr}(q^2)$
  $N = \chi_{PQ}\, d(\mathcal{J})\, T(\mathcal{C})$

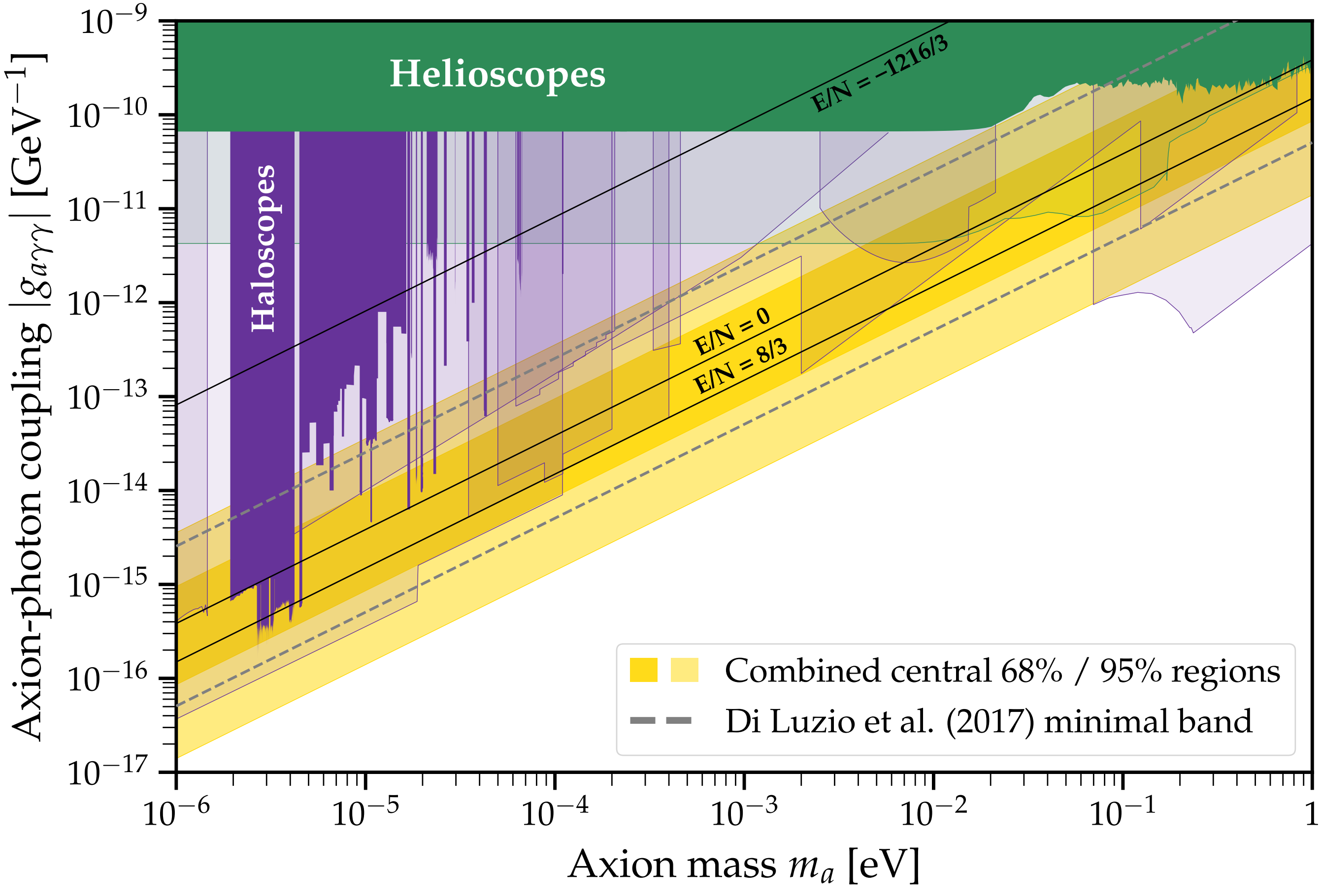
Free parameter

Other fermion parameters Fixed in DFSZ, free in KSVZ

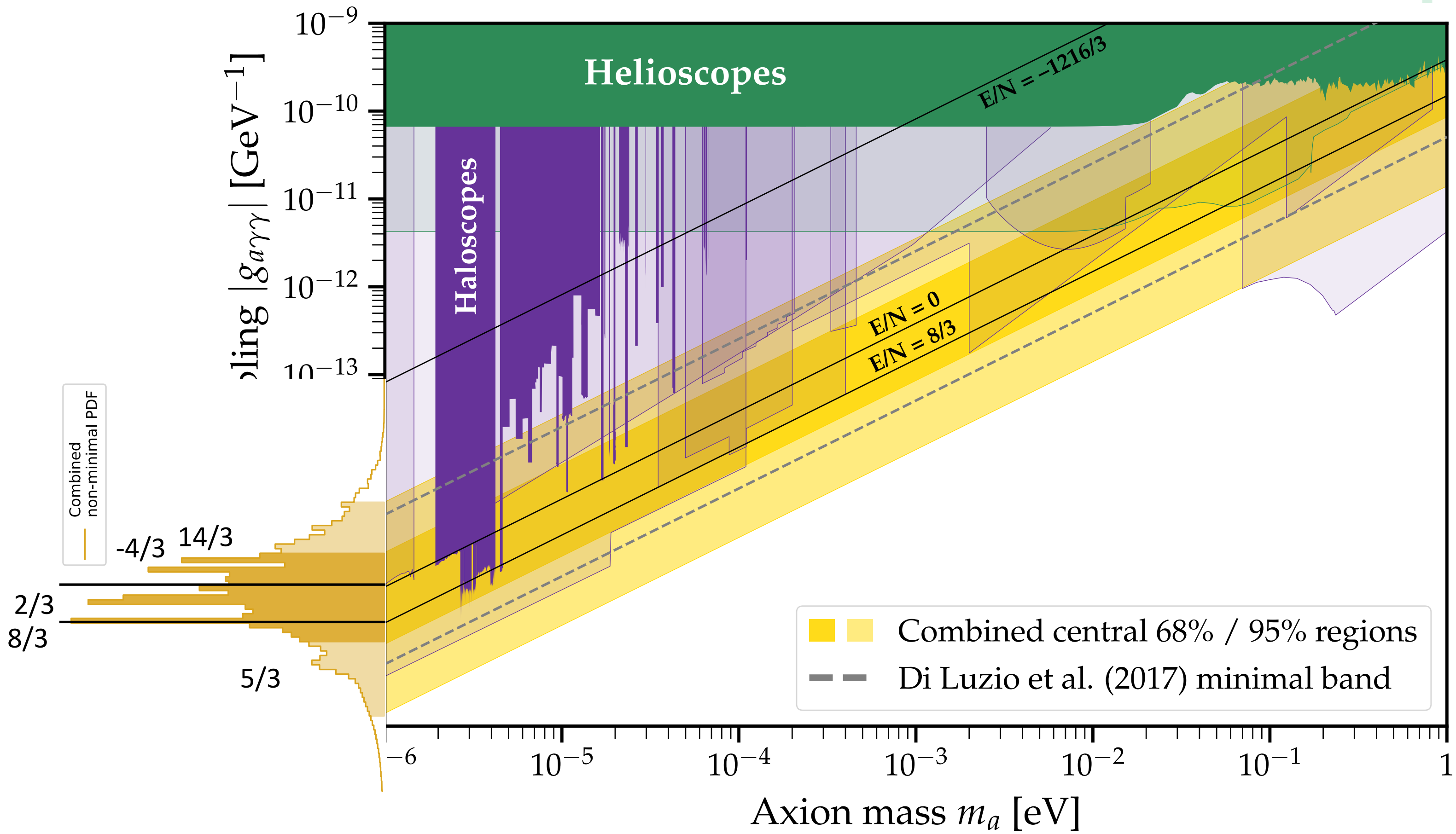
- Same formula as DFSZ if freedom is pulled into charges $\frac{E}{N} = \frac{2}{3} + 2\frac{\sum \chi_u + \sum \chi_l}{\sum \chi_u + \sum \chi_d}$



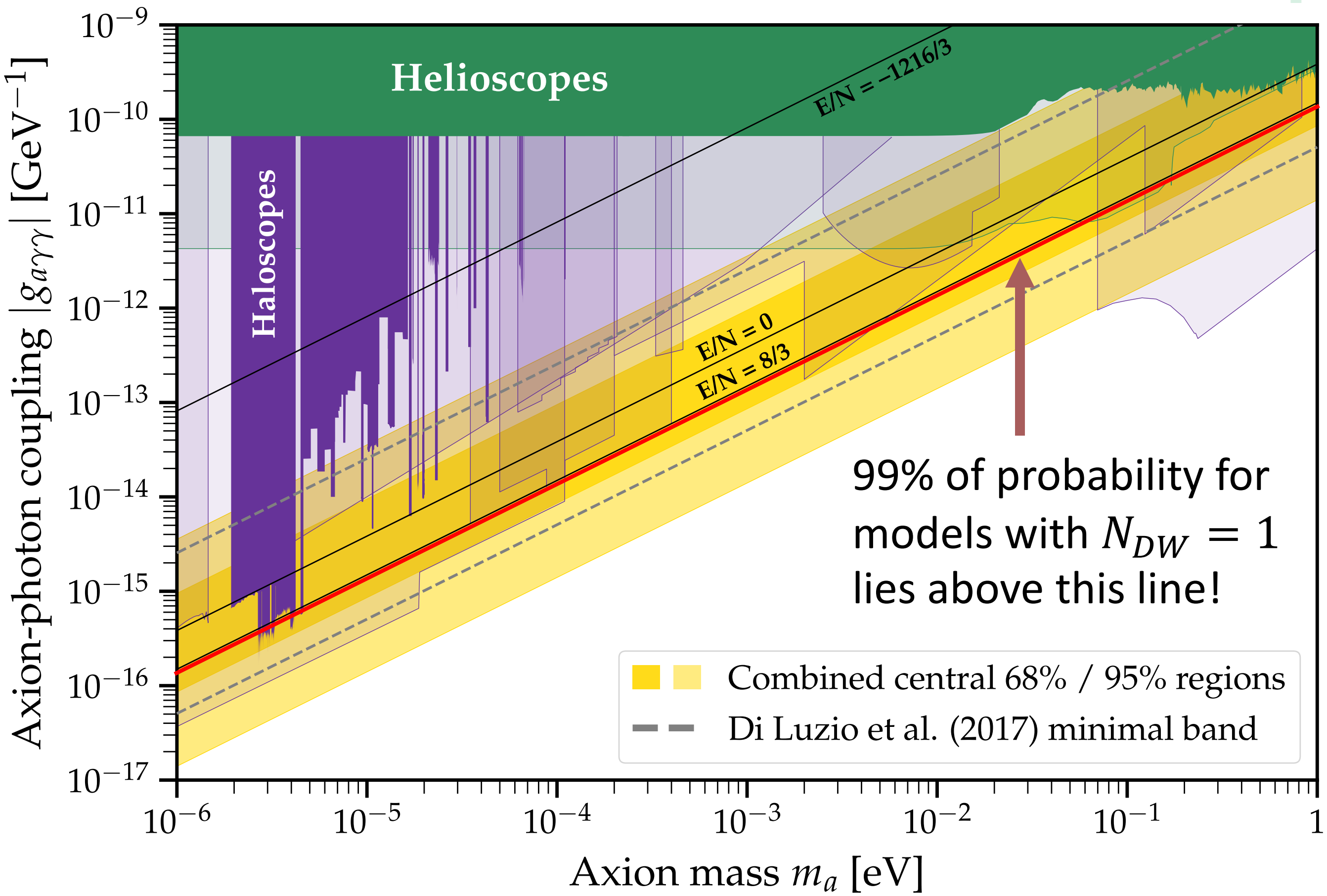
Axion sensitivity requirement



Axion sensitivity requirement



The case of $N_{DW} = 1$



99% of probability for models with $N_{DW} = 1$ lies above this line!

Summary

- DFSZ-type axions produce highly peaked E/N histogram, just like KSVZ.
- $E/N = 2/3$ and $E/N = 8/3$ of minimal DFSZ remain important.
- Sensitivity requirement for non-minimal DFSZ similar to non-minimal KSVZ but relaxed in case of $N_{DW} = 1$.

Addendum

Cooking Recipe - full

- Specify Yukawa sector
  - Allow breaking of generation symmetry (ignore FCNC)
  - Don‘t couple across fermion type
  - E.g. $n_D = 4 \rightarrow 9$ options (but only 2 unique)

u	c	t	d	s	b	e	μ	τ
H_1	H_1	H_2	H_3	H_3	H_3	H_4	H_4	H_4

- Fix PQ charges with minimal explicit symmetry breaking potential $U(1)_{H_1} \times U(1)_{H_2} \times U(1)_{H_3} \times U(1)_{H_4} \times U(1)_S \rightarrow U(1)_Y \times U(1)_{PQ}$
  - At least one term coupling doublets to singlet, e.g.
  - $n_D - 2$ more conditions to fix E/N, choose freely from bilinears (e.g. $H_1 H_4 S^\dagger S^\dagger$) or quadrilinears (e.g. $H_2 H_3 H_1^\dagger H_2$)
  - Terms define cond. for charges: $H_1 H_3 S^\dagger S^\dagger \rightarrow \chi_{H_1} + \chi_{H_3} - 2\chi_S = 0$
  - One $n_D = 4$ yukawa sector $\rightarrow \sim \binom{6}{1} \cdot \binom{25}{2}$ options (explodes for higher n_D)
- Solve linear equation system, add minimal potentials with same solution, compute E/N.

Probability & Assumptions

- Basic assumption: Probabilistic, Bayesian view of nature. Realized model is chosen at random, not due to underlying physical reason.
- Assumptions made on relative probabilities:
  - One model is defined by biggest possible potential, i.e. no set of PQ charges for Higgs particles can occur twice
  - All models with equal number of Higgs doublets are equally likely, i.e. different Yukawa sectors with different numbers of possible models may not be equally likely
  - All numbers of Higgs doublets are equally likely, i.e. any single model with $n_D = 3$ is much more likely than any $n_D = 9$ model (Plakkot, Hoof '21 made different choice)

Treatment of $n_D > 7$

- Sampling would introduce bias (remember: „add minimal potentials with same solution")
- Only relevant question: How smooth is PDF?
  - Histograms become smoother with increasing n_D
  - Difference becomes smaller with increasing n_D

$\rightarrow n_D = 7$ as one estimate, subtract difference between $n_D = 6$ and 7 from $n_D = 7$ as second estimate

- Difference between two estimates $< 1\%$