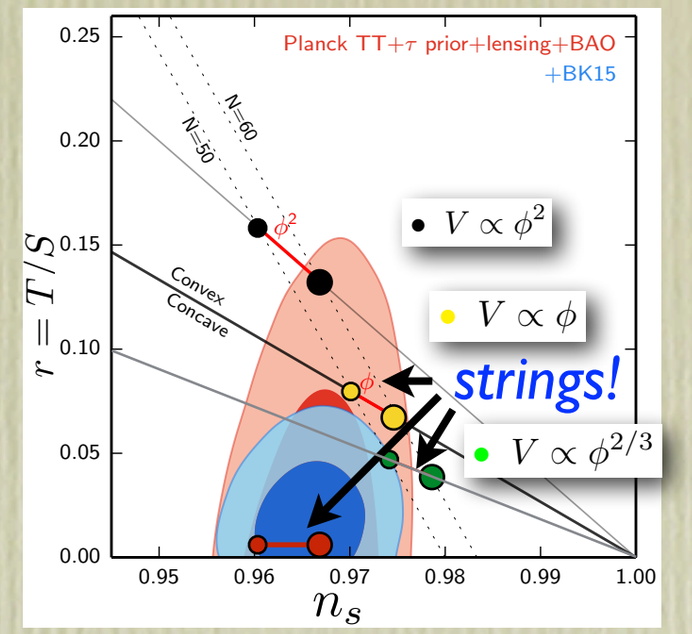
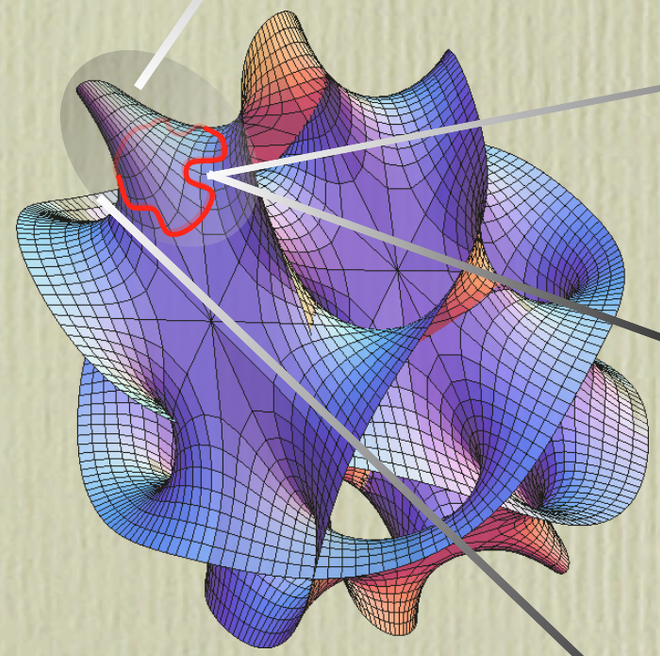
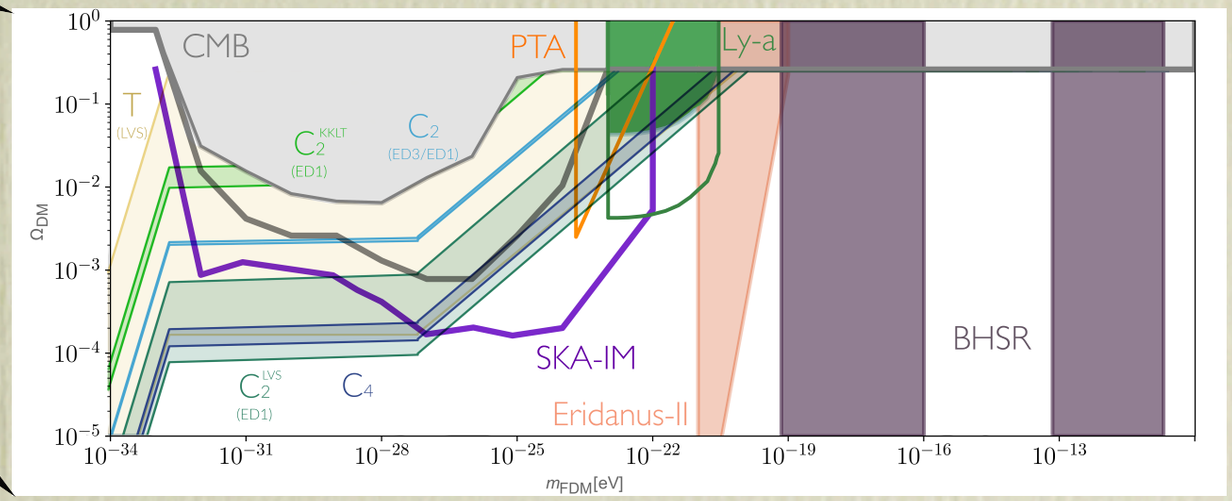
The Top-Down Case for (String) Axions







Alexander Westphal
(DESY)

The Top-Down Case for (String) Axions

image credit: J. Leedom & Midjourney

Alexander Westphal
(DESY)

EFT of axion couplings

[Peccei & Quinn '77]
[Weinberg '78]
[Wilczek '78]

4d Lagrangian: $$\mathcal{L} = \frac{1}{2} f^2 \partial_\mu a \partial^\mu a + a \frac{g^2}{32\pi^2} \mathrm{tr}\, G_{\mu\nu} \tilde{G}^{\mu\nu}$$

non-perturbative effects: instantons of action S generate scalar potential

$$\mathcal{L} = \frac{1}{2} f^2 (\partial a)^2 - M_p^4 A e^{-S} \cos(a)$$

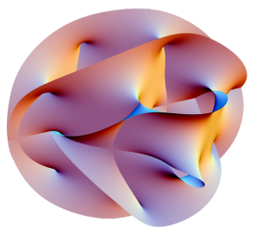
continuous shift symmetry broken to:

$$a \to a + 2\pi n \,,\; n \in \mathbb{Z}$$

Axion mass: $$m_a^2 = M_p^4 \frac{A\, e^{-S}}{f^2}$$

Axion-SM couplings: $$\mathcal{L} \supset -\frac{e^2}{32\pi^2} \frac{C_{i\gamma}}{f_{a_i}} a_i \, F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{C_{ie}}{2 f_{a_i}} \bar{e} \gamma^\mu \gamma_5 e \partial_\mu a_i$$

Chern-Simons (CS) term



$M_{\rm P}^2$

$M_S^2 = \dfrac{1}{\alpha'}$

m_{KK}^2

$m_{c.s.}^2\ ,\ m_\tau^2$

$m_{KK,warped}^2$

$m_{\mathcal{V}}^2\ ,\ m_\rho^2$

H^2

m_ϕ^2

desert ??

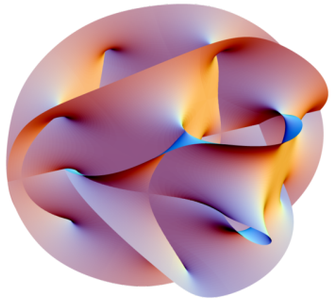
generically YES !!

$SM + axions$

strings live in 10D
-› extra dim.s:
— many light scalars
(moduli & axions)…

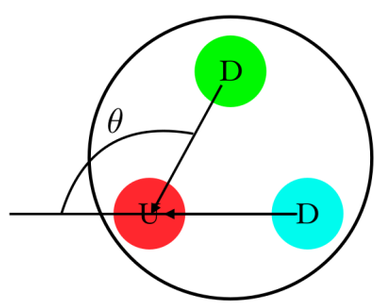
… *unless* ***epicycles****:*

- KK modes: ADD or RS
- clockwork …
- little Higgs
- composite Higgs
- …



From Top-Down

And Bottom-Up



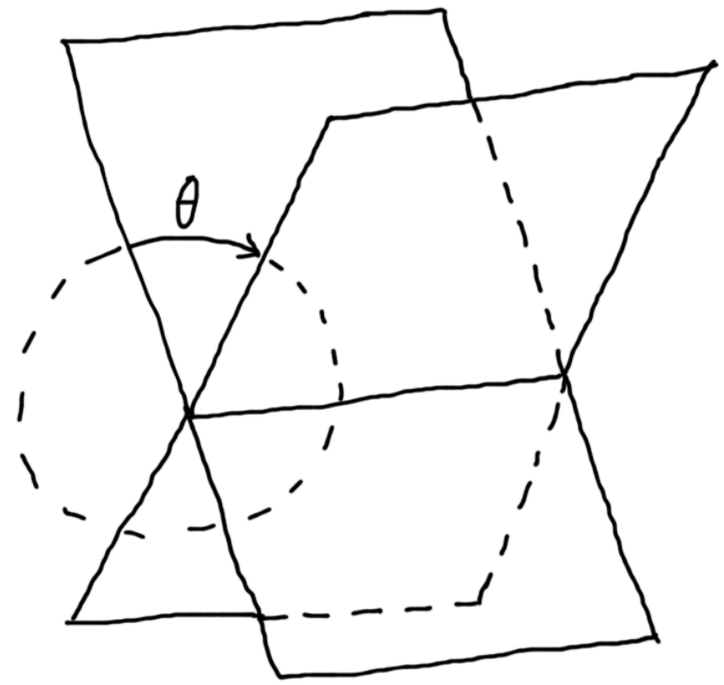
How can we find them?

image credit: J. Leedom

axions in string theory ...

[Svrcek & Witten '06]

- string theory:
  - extra dimensions
  - higher p-form gauge fields
  - branes



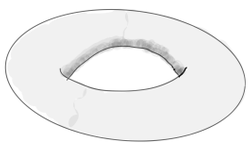
- axions:
  - Kaluza-Klein 0-modes of gauge fields
  - angles θ_a between branes
  - ~~phases of open-string matter fields~~

type IIB closed string axions

$$\int_{\Sigma^{(p)}} C_p = A_0$$

A_0 = 0-form, i.e. an axion

$\Sigma^{(p)}$ = internal p-cycle of the Calabi-Yau



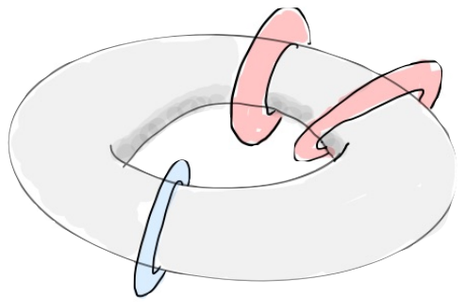
in particular, in type IIB we have :

$$\int_{\Sigma_i^{(4)}} C_4 = \theta_i \qquad \int_{\Sigma_a^{(2)}} C_2 = c_a \qquad \int_{\Sigma_a^{(2)}} B_2 = b_a$$

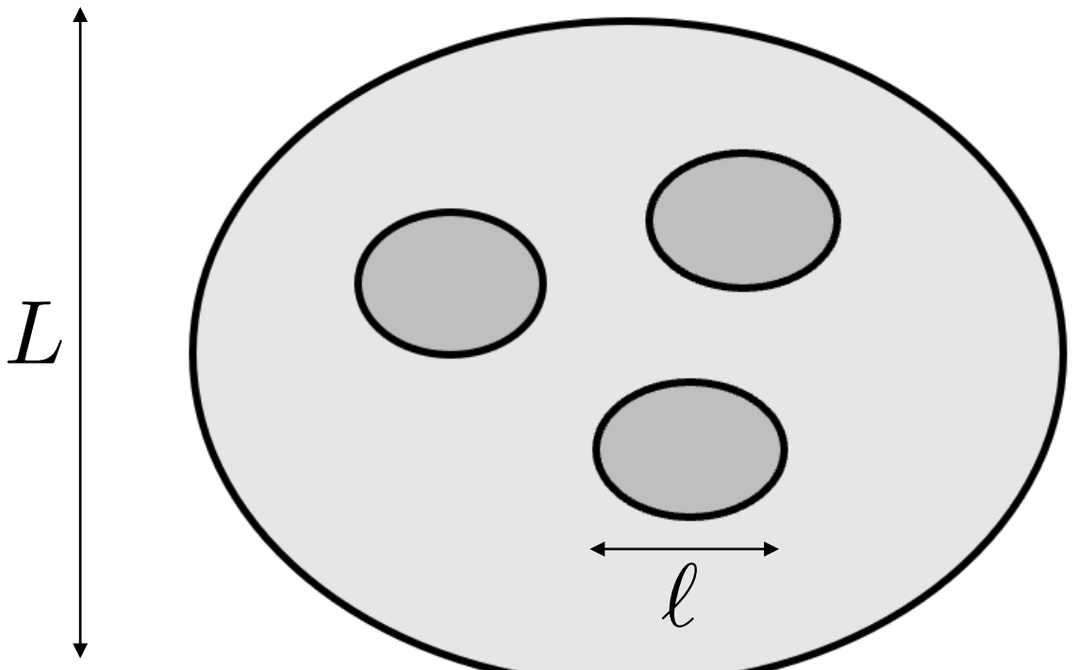
we call them axions because:

- after compactification: continuous shift symmetry
  inherited from the 10d gauge invariance

- introduce branes: shift symmetry broken to a discrete one
  ⇕ + generate a potential (hence a mass) for the axions
  instantons of complex action S



string theory matching of axion EFT



[Banks, Dine, Fox & Gorbatov '03; Svrcek & Witten '06]

$$\mathcal{L}_{\rm kin.} \sim M_{\rm P}^2 \frac{\ell^{q'}}{L^p} \partial_\mu a \partial^\mu a \ , \ q' < p \ , \ \ell \lesssim L \ \Rightarrow f \lesssim M_{\rm P}$$

$$\delta V \sim {\rm Re}(e^{-S}) \ , \ {\rm Re}\, S = \frac{\ell^q}{g_s^\#}$$

in most cases:

$$S f \lesssim M_{\rm P}$$

(axionic WGC)

[Arkani-Hamed, Motl, Nicolis & Vafa '06]

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell '09]
[Cicoli, Goodsell & Ringwald '12] , many many more …

- consequence of string extra dimensions:
  - many cycles — $O(100)$
  - each cycle: a p-form 0-mode axion

★ string theory generically contains **many axions**

★ **decay constants** are **high**
… **power-law** in extra-dim. size

★ **masses** distribute **exponentially wide**
… **exponential** in extra-dim. size

★ couplings to SM: mostly no …
… exceptions highly model-dependent (e.g. kinetic mixing)

a string theory axiverse !

- **closed string axion pheno:**

  - dark radiation

[Cicoli, Conlon & Quevedo '12]
[Higaki & Takahashi '12]
[Hebecker, Mangat, Rompineve & Witkowski '14]
⋮
[Cicoli, Sinha & Wiley Deal '22]

axion production from moduli decay in type IIB string models of moduli stabilization (LVS, KKLT …)

$$\frac{K}{M_{\rm P}^2} = -n_1 \ln(T_1 + \bar{T}_1) + \dots$$

type IIB on CY:
often has $h^{1,1} > 1$
volume moduli & C_4-axions

e.g. [Demirtas, Gendler, Long, McAllister & Moritz '21]

$$\mathcal{L}_{kin.} = K_{i\bar{\jmath}} \partial_\mu T^i \partial^\mu \bar{T}^{\bar{\jmath}} \supset \frac{M_{\rm P}^2}{4} \frac{n_1}{\tau_1^2} \partial_\mu \tau_1 \partial^\mu \tau_1 + \frac{M_{\rm P}^2}{4} \frac{n_1}{\tau_1^2} \partial_\mu a_1 \partial^\mu a_1$$

mass & couplings from non-pert. effects:

$$V = \Lambda(\tau_i)^4 \cos(a)$$

heavy moduli decay
into relativistic axions **"dark radiation"**

non-linearity of couplings
drives parametric resonance

Cosmic Axion Background
[Conlon & Marsh '13]
[Dror, Murayama & Rodd '21]

- closed string axion pheno:

  - dark matter

[Preskill, Wise & Wilczek '83]
[Abbott & Sikivie '83]
[Dine & Fischler '83]

high-scale decay constants: $f > H$ (PQ broken) even during inflation

but exponentially light: $m << H$ during inflation

population of non-relativistic axion matter density ρ
via misalignment:

random displacement of axion *a* during inflation from de Sitter vacuum fluctuations

every Hubble patch has different ρ , ours is selected anthropically

axion abundance:
$(H < f)$

$$\frac{\Omega_a h^2}{0.112} \simeq 2.2 \times \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} \left(\frac{f}{10^{17}\,\mathrm{GeV}}\right)^2 a_{\mathrm{in}}^2$$

[Cicoli, Goodsell & Ringwald '12]

- closed string axion pheno:

  - what dark matter?

  if $m > 10^{-18}$ eV … cold dark matter

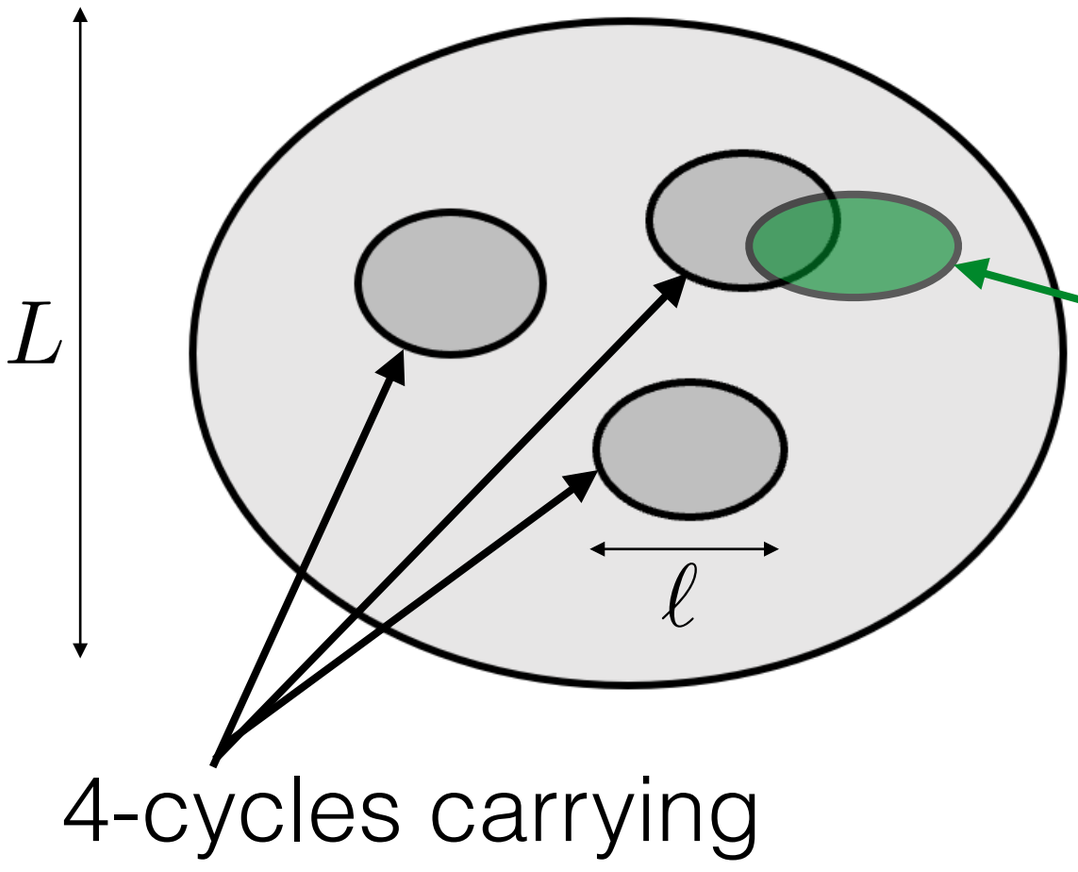
  if 10^{-25} eV $< m < 10^{-19}$ eV … fuzzy (or wave) dark matter

[Hu, Barkana & Gruzinov '00]
[Hui, Ostriker, Tremaine & Witten '16]
[Cicoli, Guidetti, Righi & AW '21]

  - other production mechanisms …

  … from topological defects, cosmic strings

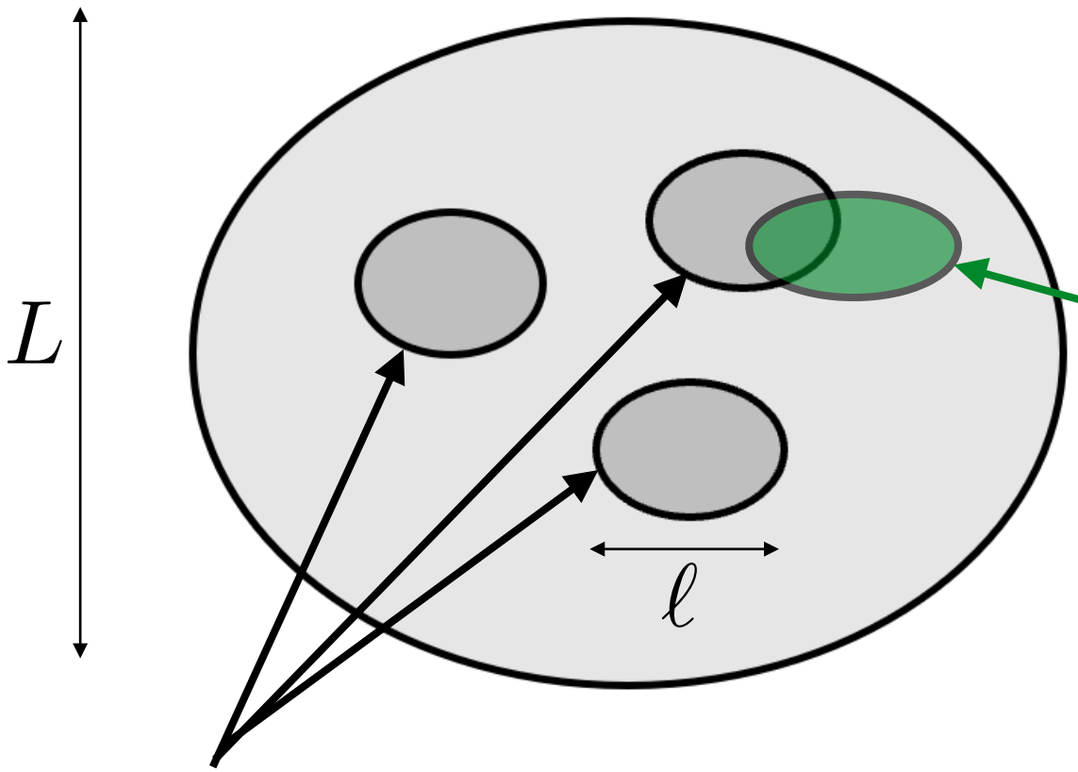
SM couplings of closed string axions ?



4-cycle carrying the branes producing the SM

4-cycles carrying string axions

SM couplings of closed string axions ?



4-cycle carrying the branes producing the SM

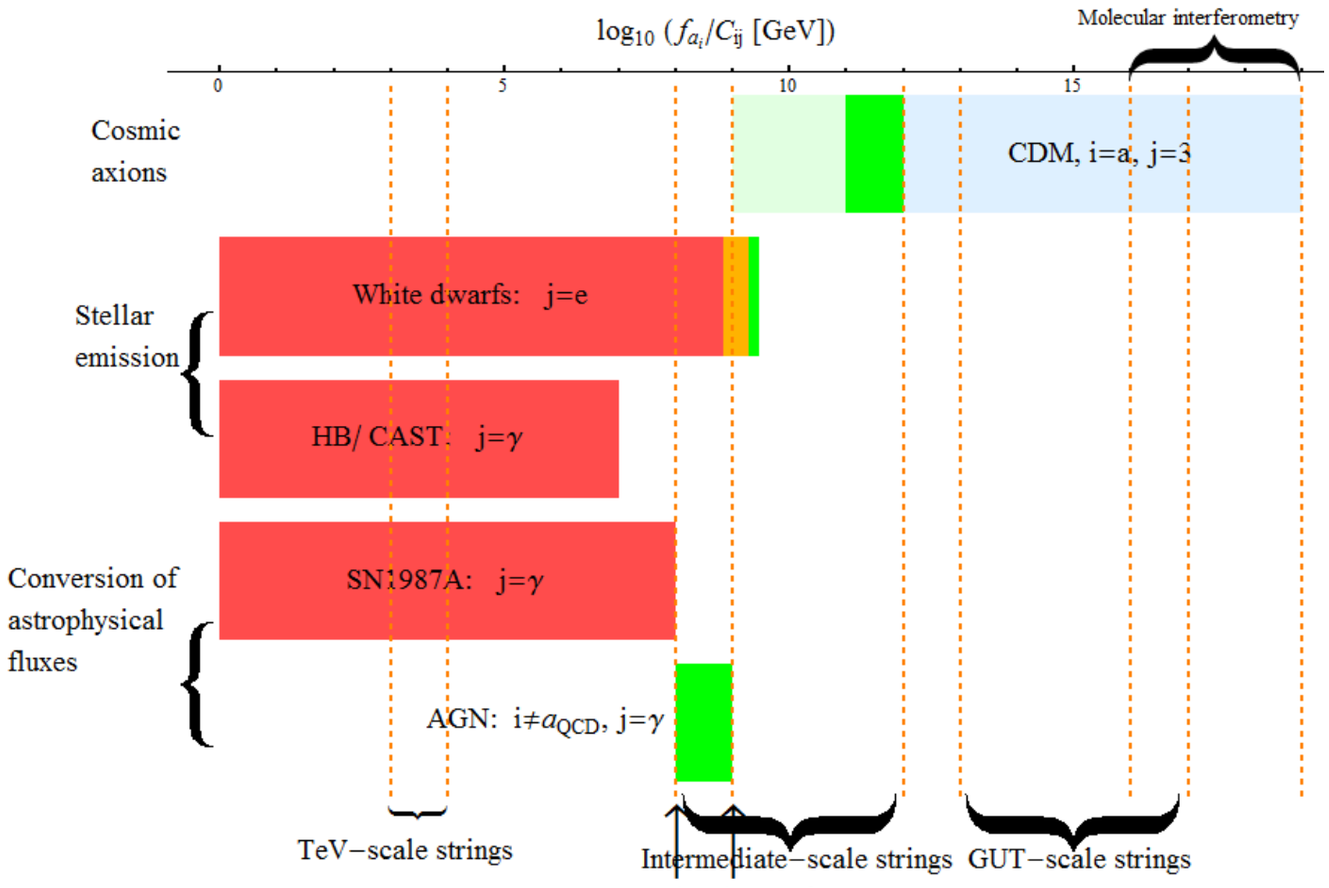
4-cycles carrying string axions

- closed string axion pheno:

[Gendler, Marsh, McAllister & Moritz '23]

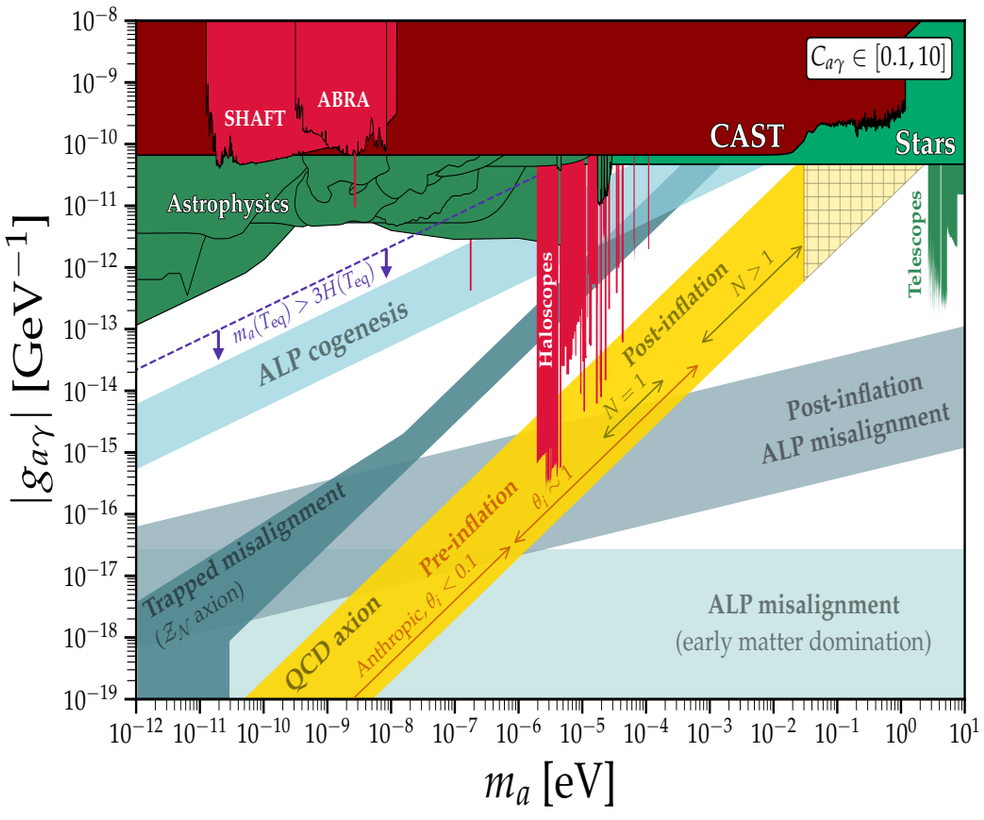
- handful of axions visible to SM, most are DARK !!
- SM-couplings depend on extra-dim. size & cycle intersection data
- kinetic mixing between U(1) gauge fields coupled to dark axions and SM U(1) gauge field often small

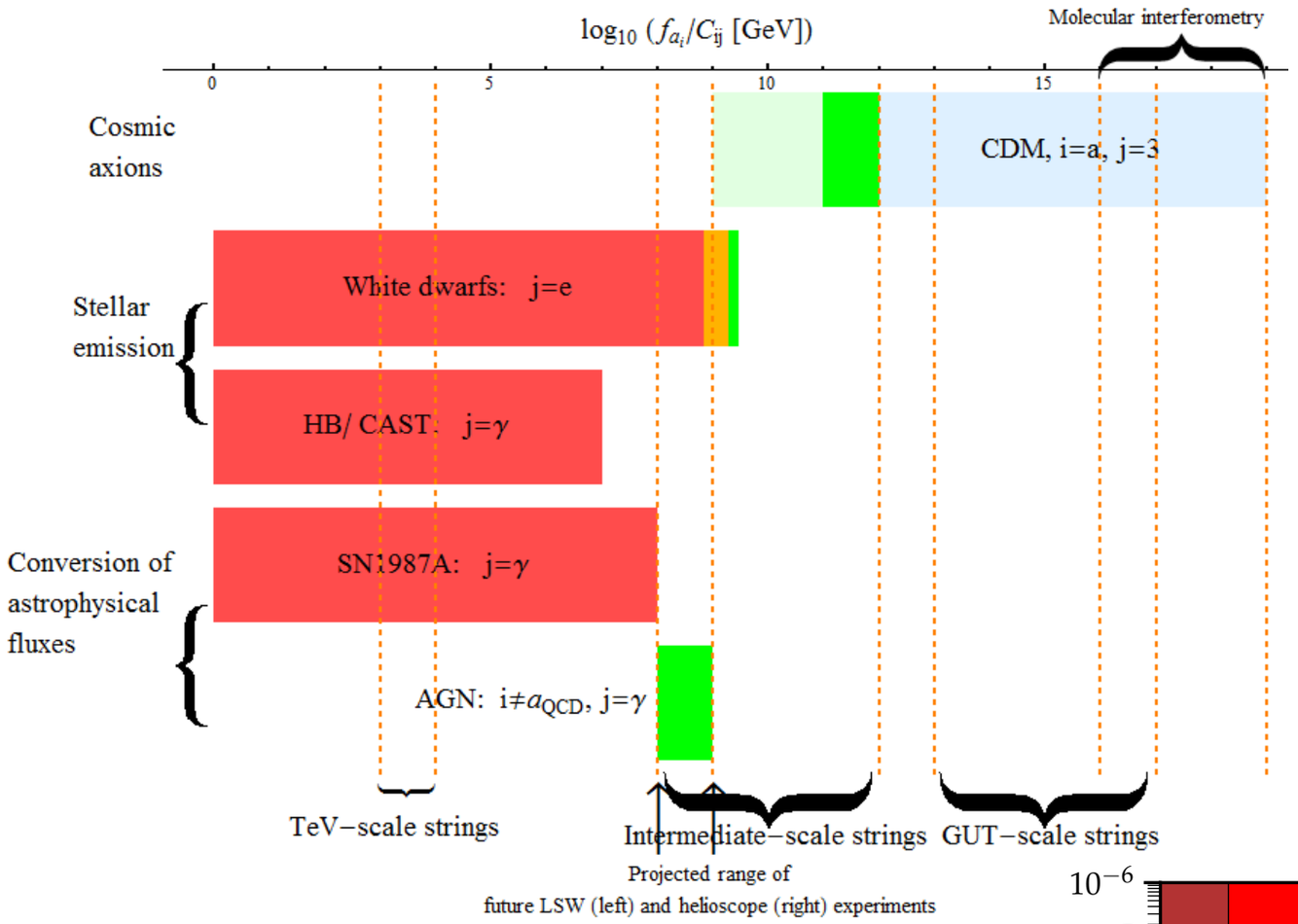
[Berg, Marsh, McAllister & Pajer '10]
[Hebecker, Jaeckel & Kuespert '23]



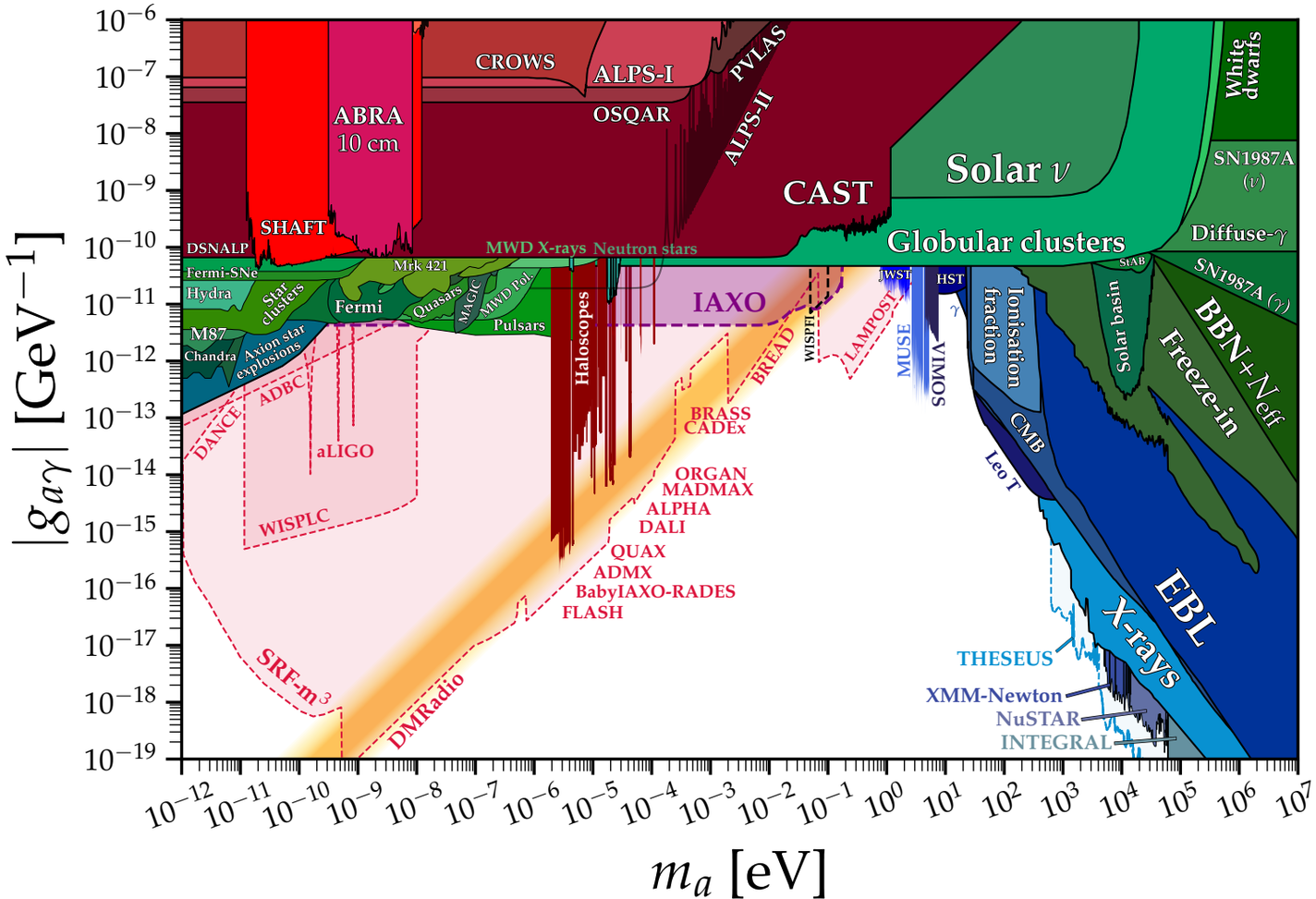
Projected range of
future LSW (left) and helioscope (right) experiments

the 1…3 string axions with SM couplings





the 1…3 string axions with SM couplings



the many other string axions are dark …

- couplings are either gravitational (Planck-suppressed):

  - can be part of dark matter
  - or dark radiation: visible e.g. in CMB as $\Delta N_{\rm eff}$ [Cicoli, Conlon & Quevedo '12] [Higaki & Takahashi '12]
  - axion clouds around fast-spinning BHs deplete spin: detection via BH superradiance [Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell '09]

- and/or to dark sectors, e.g. dark U(1) gauge fields:

  - spectator role during inflation [Biagetti, Dimastrogiovanni, Fasiello & Peloso '14] [Dimastrogiovanni, Fasiello & Fujita '16] [Obata & Soda '17]
  - slow-rolling axion coupled to dark U(1) during inflation: production of dark gauge field & induced peaked GWs [Anber & Sorbo '09, Sorbo '11] [Adshead & Wyman '12] … [Namba, Peloso, Shiraishi, Sorbo & Unal '15] [Dimastrogiovanni, Fasiello & Fujita '16], [Domcke, Pieroni & Binetruy '16] …
  - for string axions quite generic & constrains axiverse [Dimastrogiovanni, Fasiello, Leedom, Putti & AW '23]

summary

- axion pheno to large part determined by couplings in kinetic term and NP scalar potential + matter & gauge field couplings

- these couplings are top-down determined by compactification data — e.g intersection #s, fluxes, or topological data (e.g. for thraxions)

- axion-matter couplings depend on axion type and SM realization (7-branes on 4-cycle, 3-branes at CY singularity, thraxions ?)

need both:

- **explicit** string model **constructions** to study structure & parameter range of axion couplings

- **scans** over large sets of string vacua **to get** number frequency **distribution of axion EFT parameters**