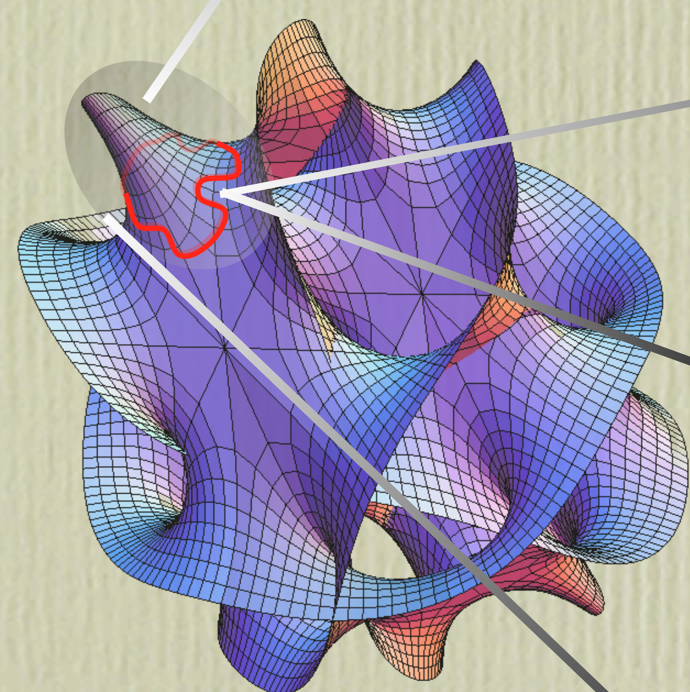
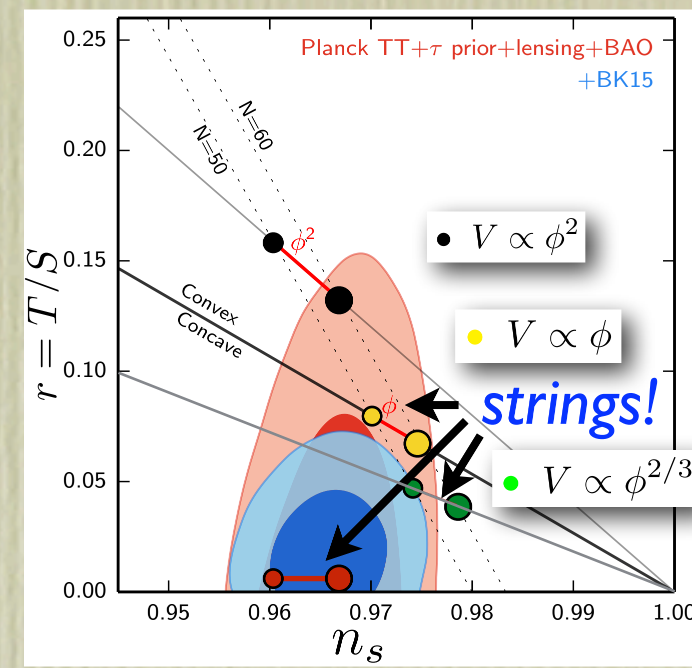
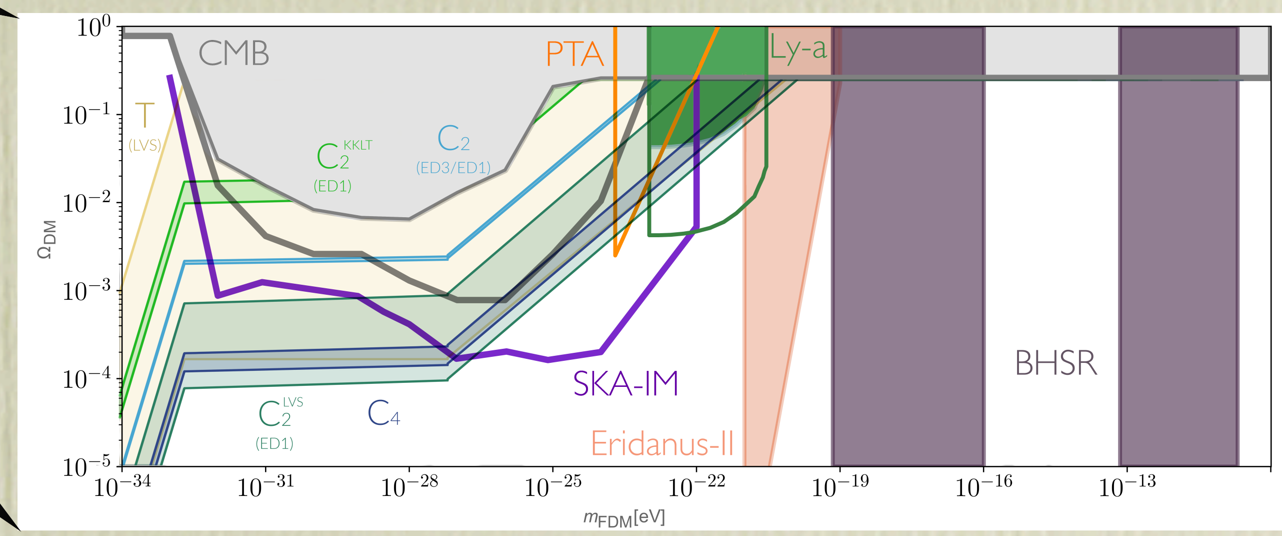
Closed String Axions







Alexander Westphal
(DESY)

type IIB closed string axions, WGC & Fuzzy Dark Matter

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

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

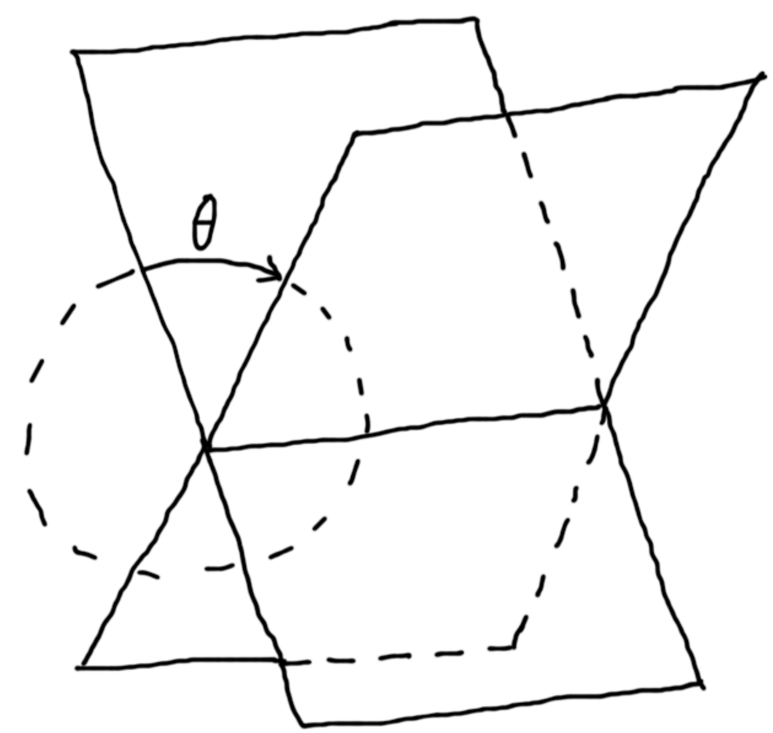
continuous shift symmetry broken to:

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

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

axions in string theory ...

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



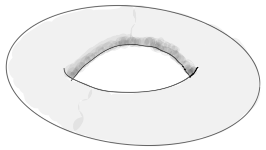
- axions:
  - Kaluza-Klein 0-modes of gauge fields
  - angles θ_a between branes
  - ~~phases of open-string matter fields~~

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



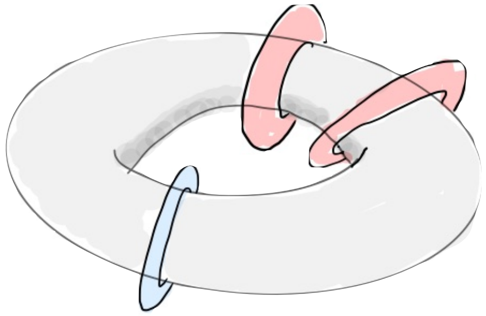
in particular, in type IIB we have :

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

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

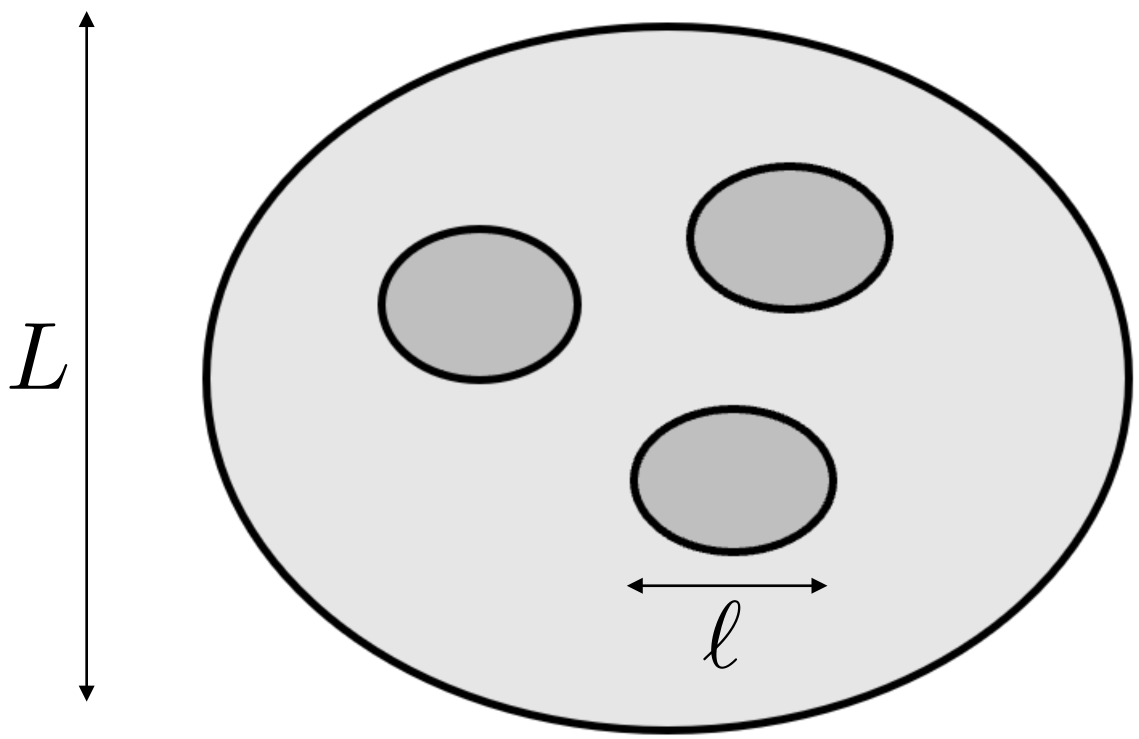


$\Updownarrow$

instantons of complex action S

string theory matching of axion EFT

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



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

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

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:

  - high-scale — inflation

natural inflation does not work: $f < M_{\rm P}$

$$\mathcal{L} = (\partial_\mu \phi)^2 - \Lambda^4 \cos(\phi/f) \;\; \text{needs} \;\; f > M_{\rm P}$$

several axions: aligned inflation, N-flation, hierarchical or winding inflation, axion hybrid inflation, …

[Kim, Nilles & Peloso '04] [Dimopoulos, Kachru, McGreevy & Wacker '05] [Ben-Dayan, Pedro & AW '14]

[Hebecker, Mangat, Rompineve & Witkowski '15] . . . [Carta, Righi, Welling & AW '20]

axion monodromy: fluxes break shift symmetry

$$|F_5 + C_2 \wedge H_3|^2\Big|_{10D} \to (\partial a)^2 + |F_4|^2 + \mu a F_4\Big|_{4D} \Rightarrow V \sim m^2 a^2$$

[McAllister, Silverstein & AW '08] [Kaloper & Sorbo '08] . . .

generic: $aF\tilde{F}$-coupling produces gauge fields & gravitational waves

[Anber & Sorbo '09] . . . review: [Barnaby, Pajer & Peloso '12]

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

- closed string axion pheno:
  - dark radiation

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

[Cicoli, Conlon & Quevedo '12]

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

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

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

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

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canonically normalize:

$$\tau_1 = \exp\left(\sqrt{\frac{2}{n_1}\frac{\phi_{\tau_1}}{M_{\mathrm{P}}}}\right) \qquad a_1 \to \theta_{a_1} = \frac{2}{n_1}\frac{a_1}{M_{\mathrm{P}}}$$

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

- **closed string axion pheno:**
  - dark matter

high-scale decay constants: $f > H$ 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

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axion abundance: $(H < f)$

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

[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

  - other production mechanisms …

    … from topological defects, cosmic strings (see Javier Redondo's talk yesterday)

- closed string axions - open questions:

  - axion-moduli couplings in kinetic terms & NP potentials determined by compactification data — e.g intersection #s or fluxes

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

need both:

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

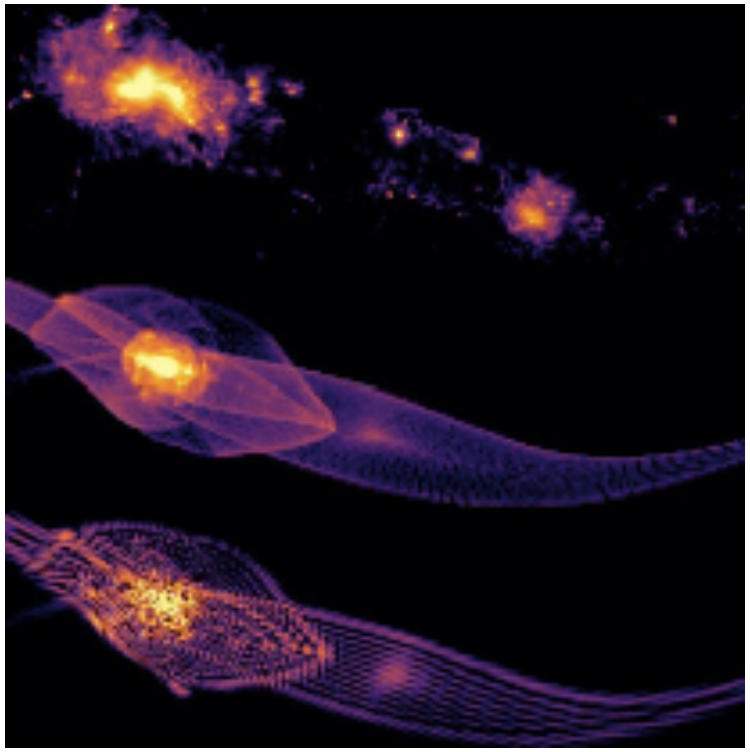
- **scans** over large sets of string vacua **to get** number frequency **distribution of axion EFT parameters**

type IIB closed string axions, WGC & Fuzzy Dark Matter

FDM = DM made of ultralight particles [Hu, Barkana & Gruzinov '00]

Ultralight axions as FDM [Hui, Ostriker, Tremaine & Witten '16]

$$m \sim 10^{-21}\,\text{eV} \qquad f \sim 10^{16\div17}\ \text{GeV}$$



[Mocz et al '19]

⟶ Possible sign of the string axiverse?

+ clash with the Weak Gravity Conjecture ?

[Alonso & Urbano '17]
[Hebecker, Mikhail & Soler '18]

FDM abundance:
($H < f$)

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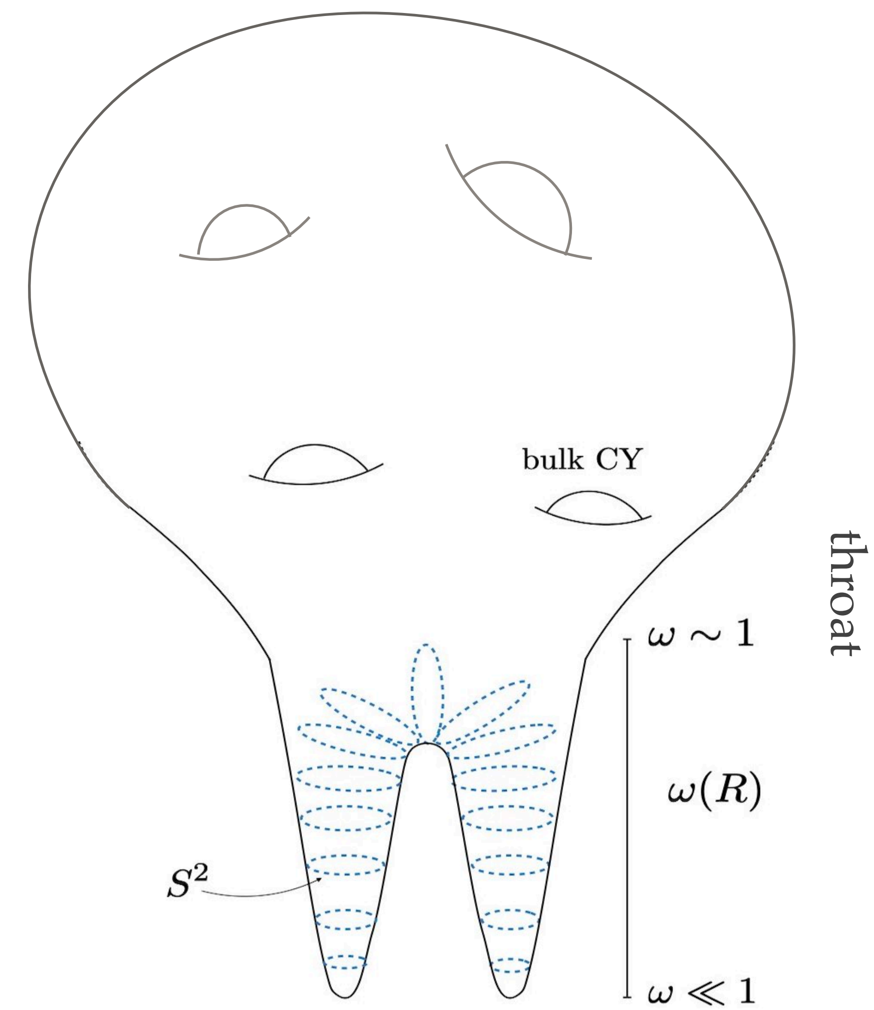
[Cicoli, Goodsell & Ringwald '12]

Special Axionic Modes: Thraxions

[Hebecker, Leonhardt, Moritz & AW '18]
[Carta, Mininno, Righi & AW '21]

Throats carry fluxes, i.e. $F_3 = dC_2$ field strength

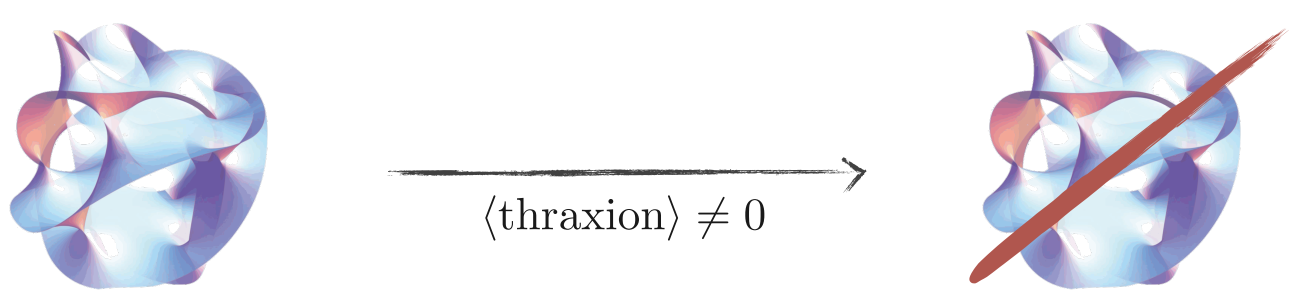
$$c := \int_{S^2} C_2$$



naturally light because $m^2 \sim \omega_{\rm IR}^3$

!

How much control do we have on the EFT? !



to just a complex manifold!

type IIB closed string axions, WGC & Fuzzy Dark Matter

[Cicoli, Guidetti, Righi & AW '21]

	Axion	Sf
✗	C_0	$\sim 1/\sqrt{2}\,M_P$
✗	B_2	$<\ M_P$
✓	C_2	$\begin{cases} S_{ED1} f \lesssim\ M_P \\ S_{ED3} f \lesssim \sqrt{g_s}\,\mathcal{V}^{1/3} M_P \end{cases}$
✓	C_4 (1 dof)	$\lesssim \sqrt{3/2}\,M_P$
✓	C_4 (2 dof)	$\lesssim M_P$
✓	$C_{2,\mathrm{thrax}}$	$\begin{cases} S_{ED1} f \sim \frac{3\sqrt{KM}}{2\mathcal{V}^{1/3}} M_P \\ S_{\mathrm{eff}} f_{\mathrm{eff}} \sim \frac{3\pi K}{\sqrt{g_s}\,\mathcal{V}^{1/3}} M_P \end{cases}$

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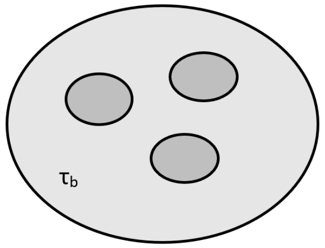
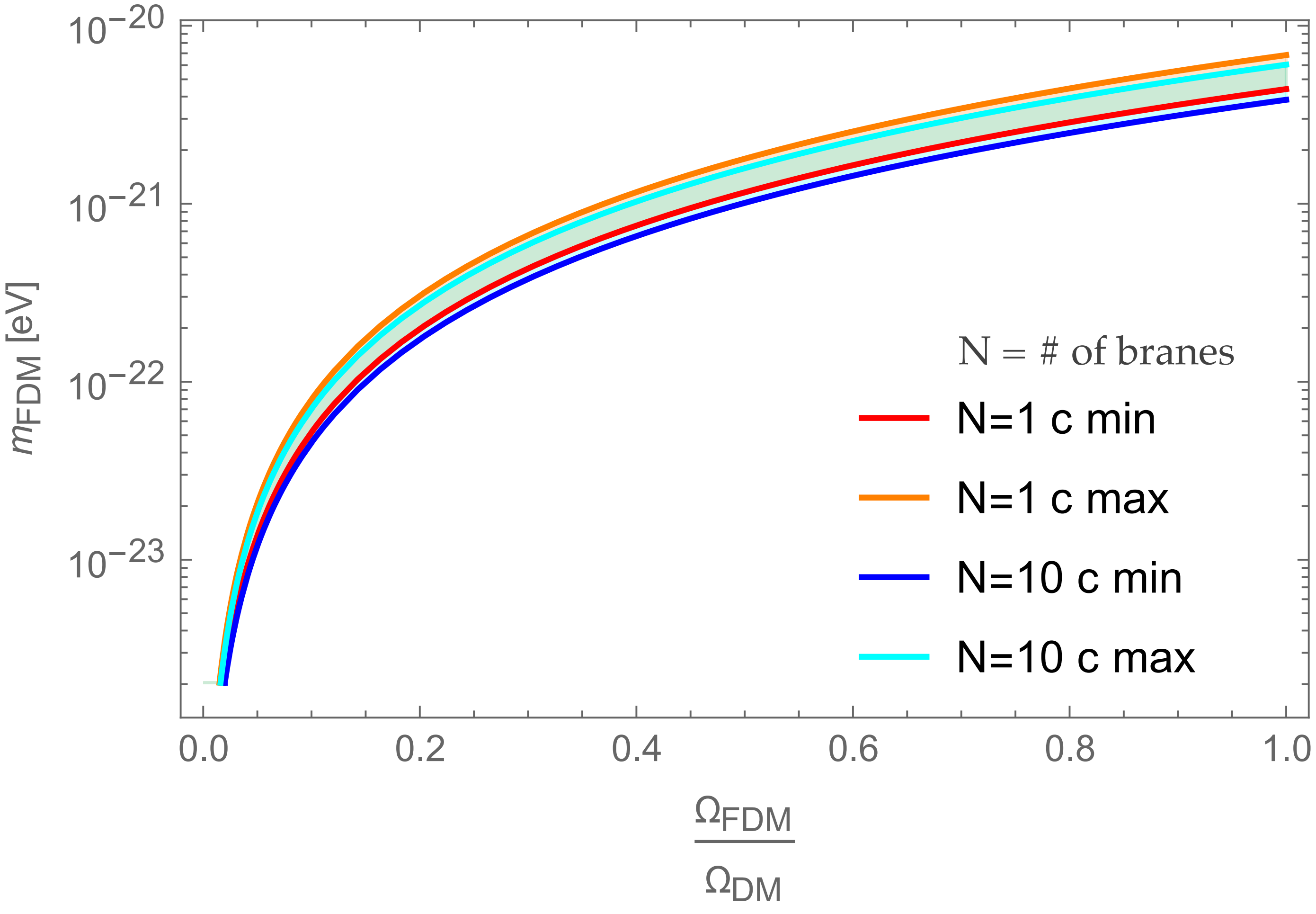
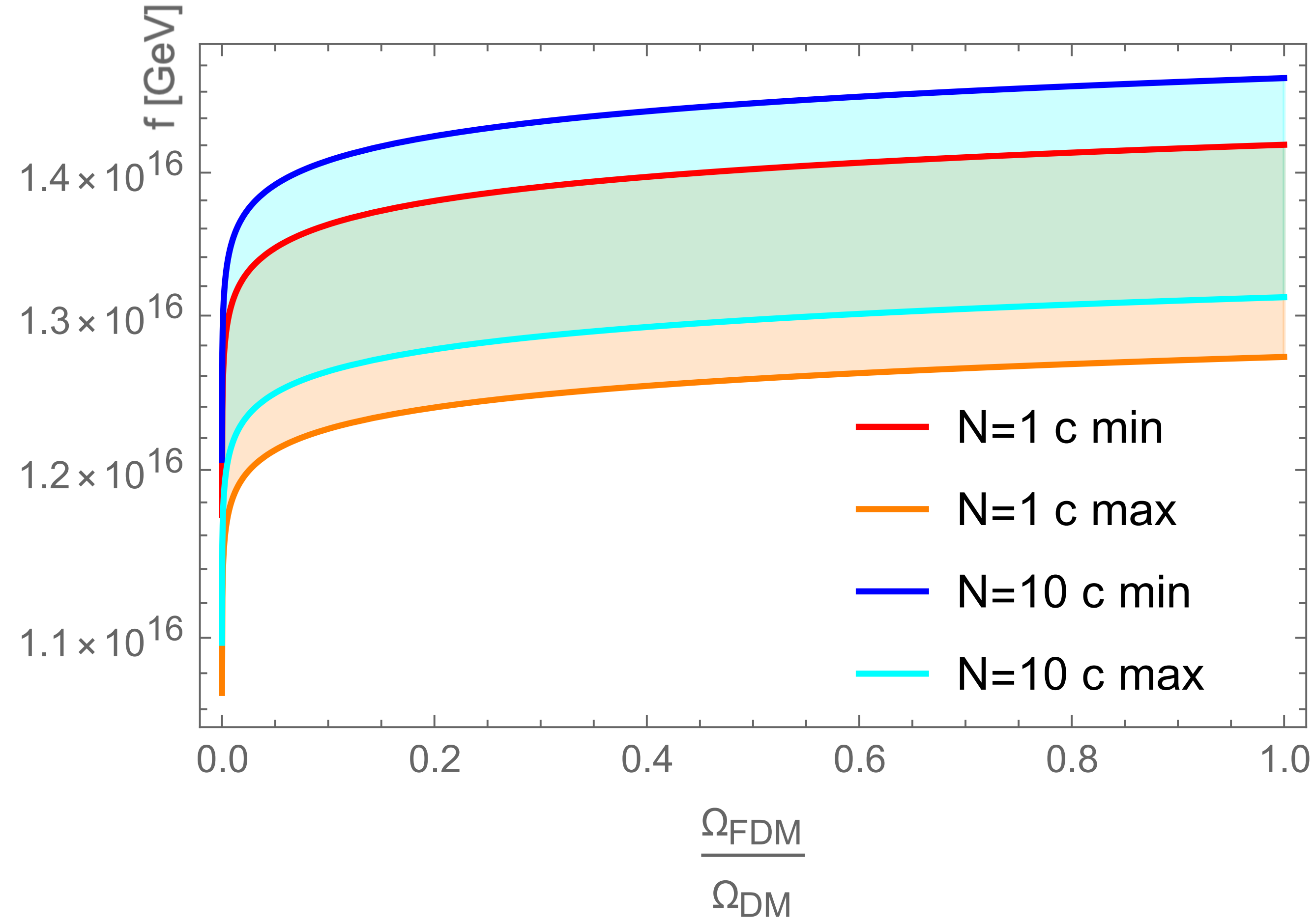
FDM from C4 axion

[Cicoli, Guidetti, Righi & AW '21]

1) 

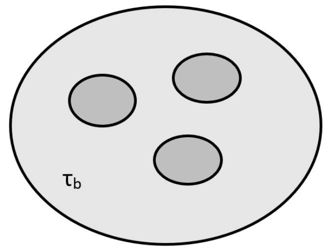
$$S f \sim \frac{3}{2} M_P \qquad \frac{m_{\theta_\mathcal{V}}^2}{M_P^2} \sim \frac{S_\mathcal{V}^3 e^{-S_\mathcal{V}}}{\mathcal{V}^2}$$





FDM from C_4 axion

[Cicoli, Guidetti, Righi & AW '21]

1) 

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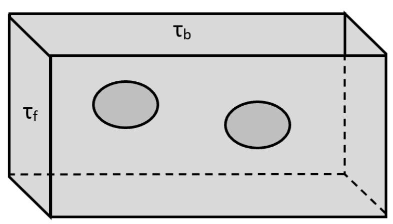
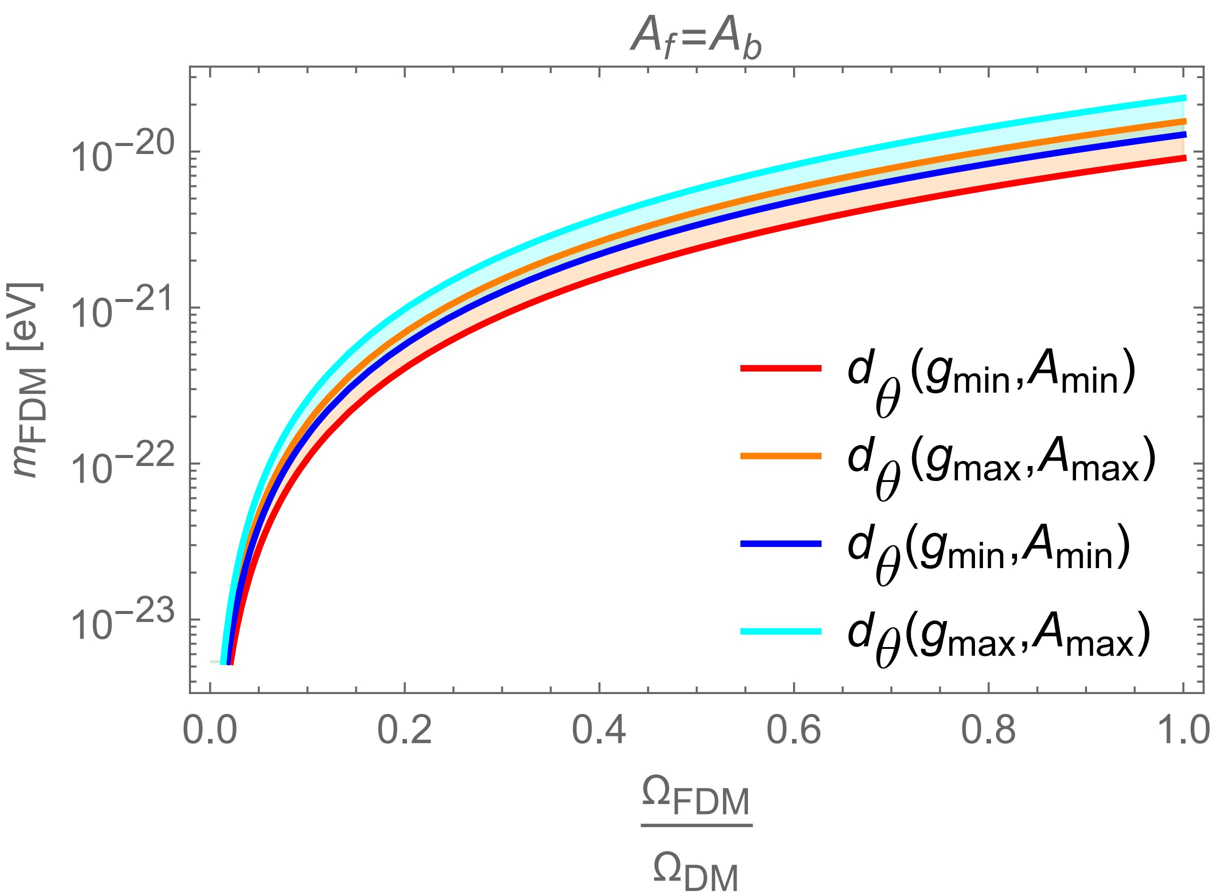
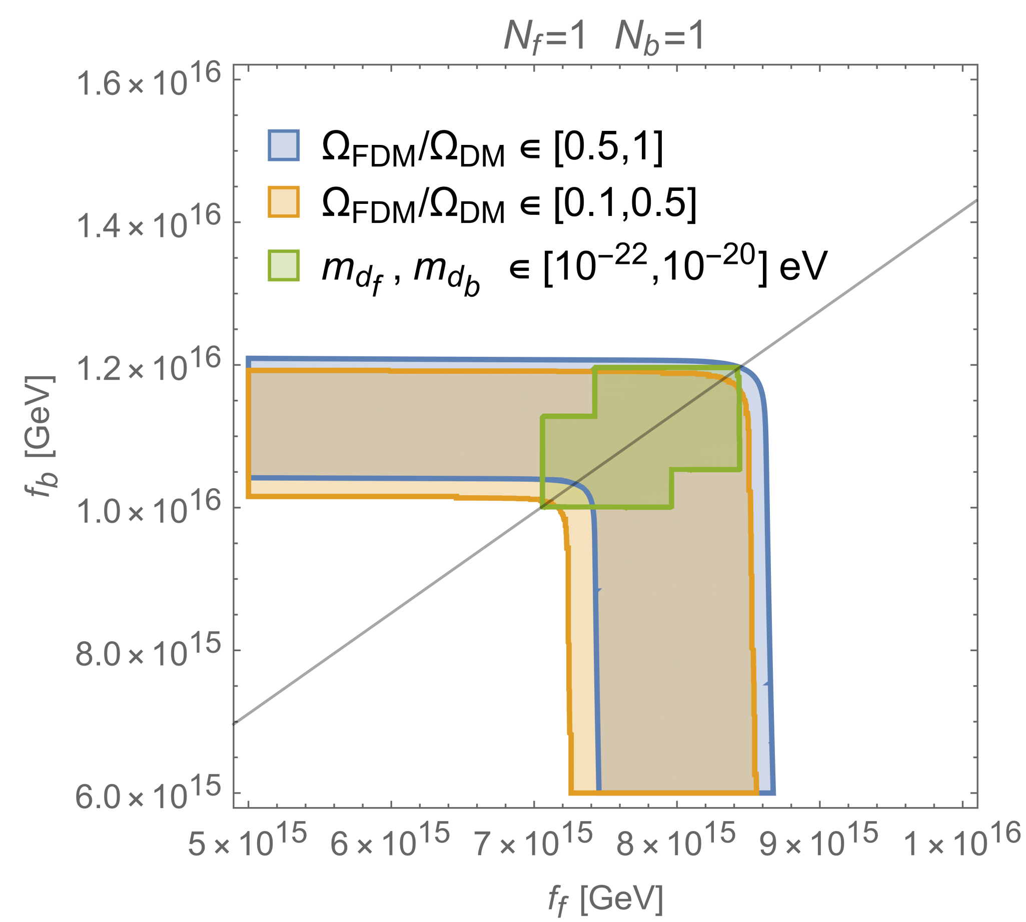
2) 

$$Sf < \frac{3}{2} M_P \qquad \frac{m^2_{\theta_b}}{M_P^2} \sim \frac{S_b^3 e^{-S_b}}{\mathcal{V}^2} \qquad \frac{m^2_{\theta_f}}{M_P^2} \sim \frac{S_f^3 e^{-S_f}}{\mathcal{V}^2}$$





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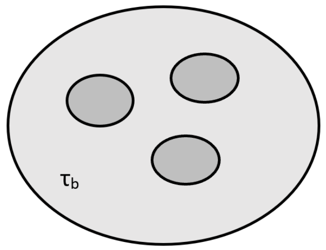
1) 

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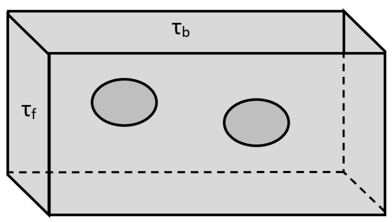
2) 

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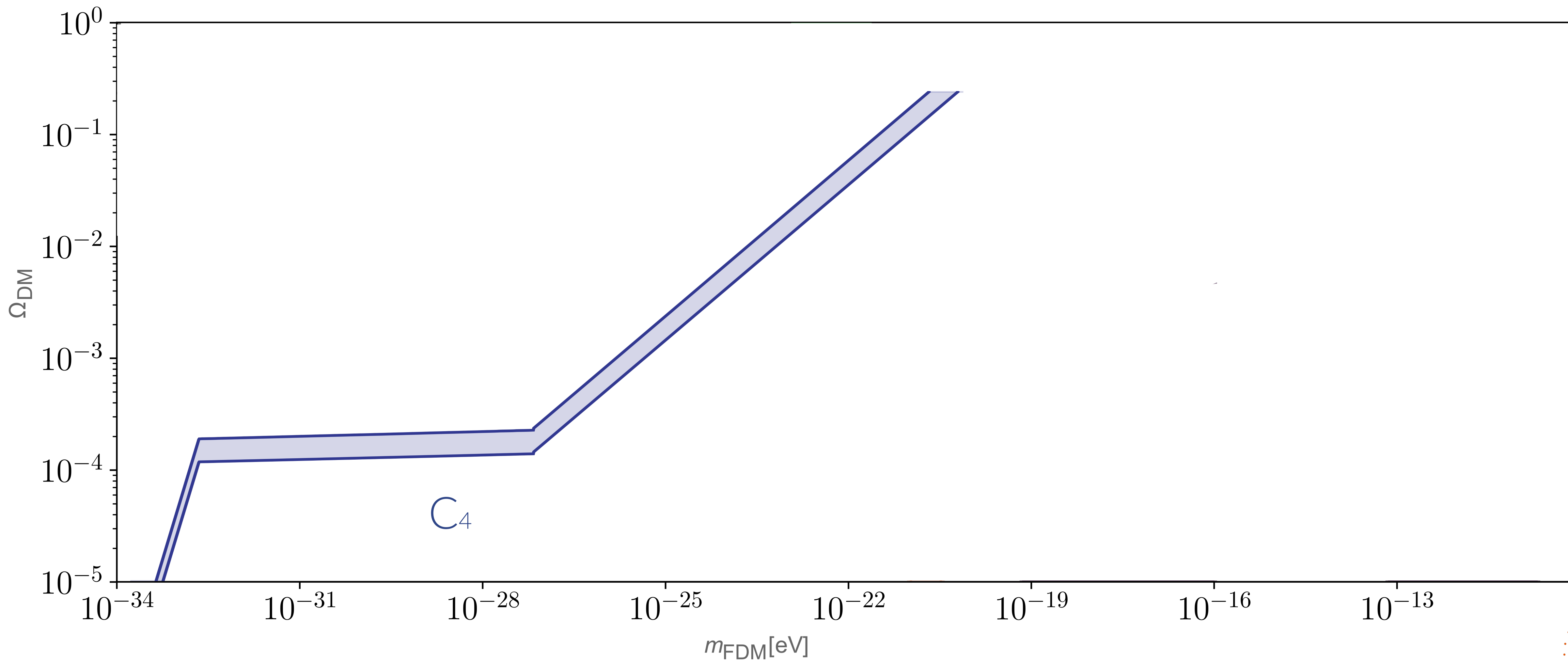


type IIB closed string axions, WGC & Fuzzy Dark Matter

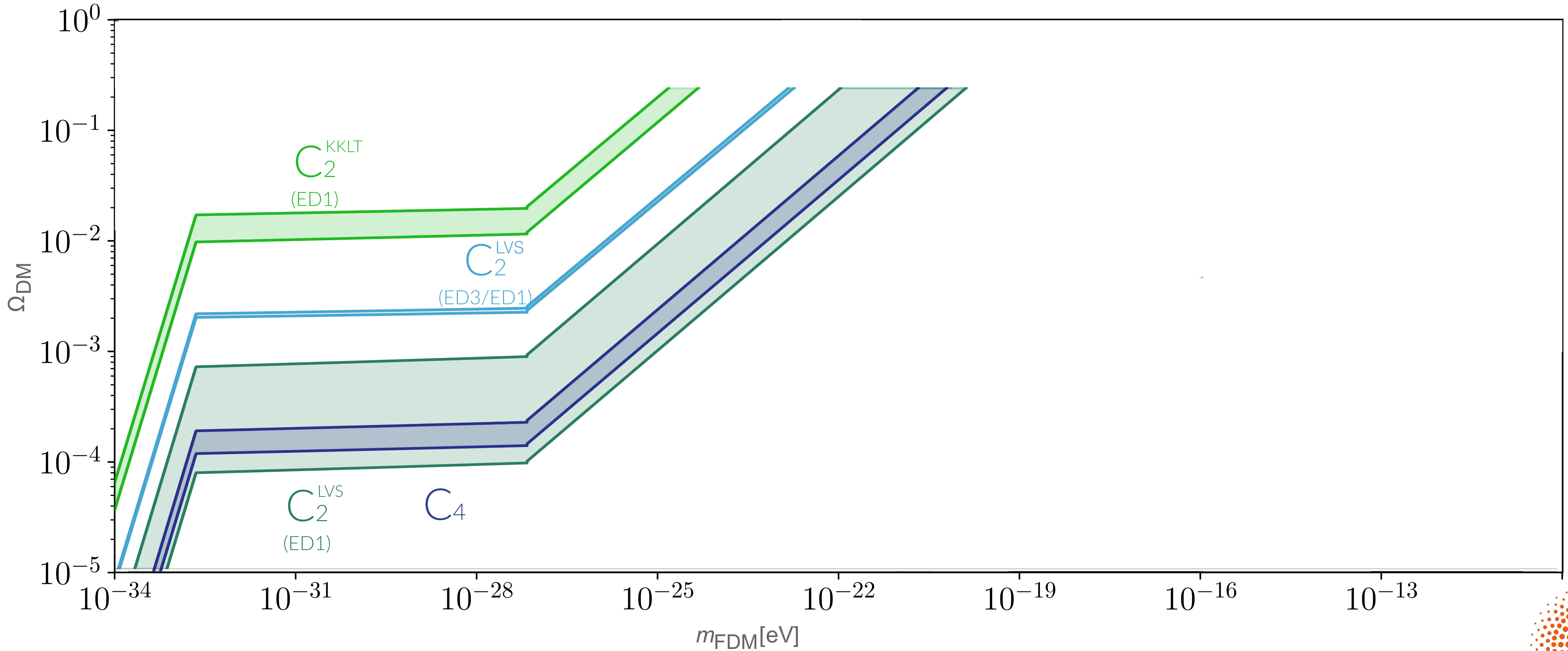
FDM from C2 axion

[Cicoli, Guidetti, Righi & AW '21]

- ED1-brane instantons $S_{ED1} f \sim M_P$

- ED3/ED1-brane instantons $S_{ED3} f \sim \sqrt{g_s}\,\mathcal{V}^{1/3} M_P$

See e.g. [Grimm '08] [Cicoli, Schachner, Shukla '21]



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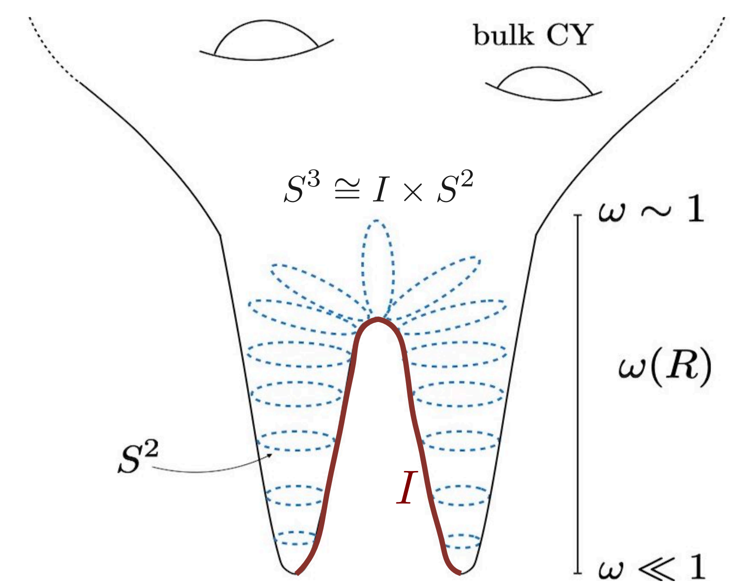
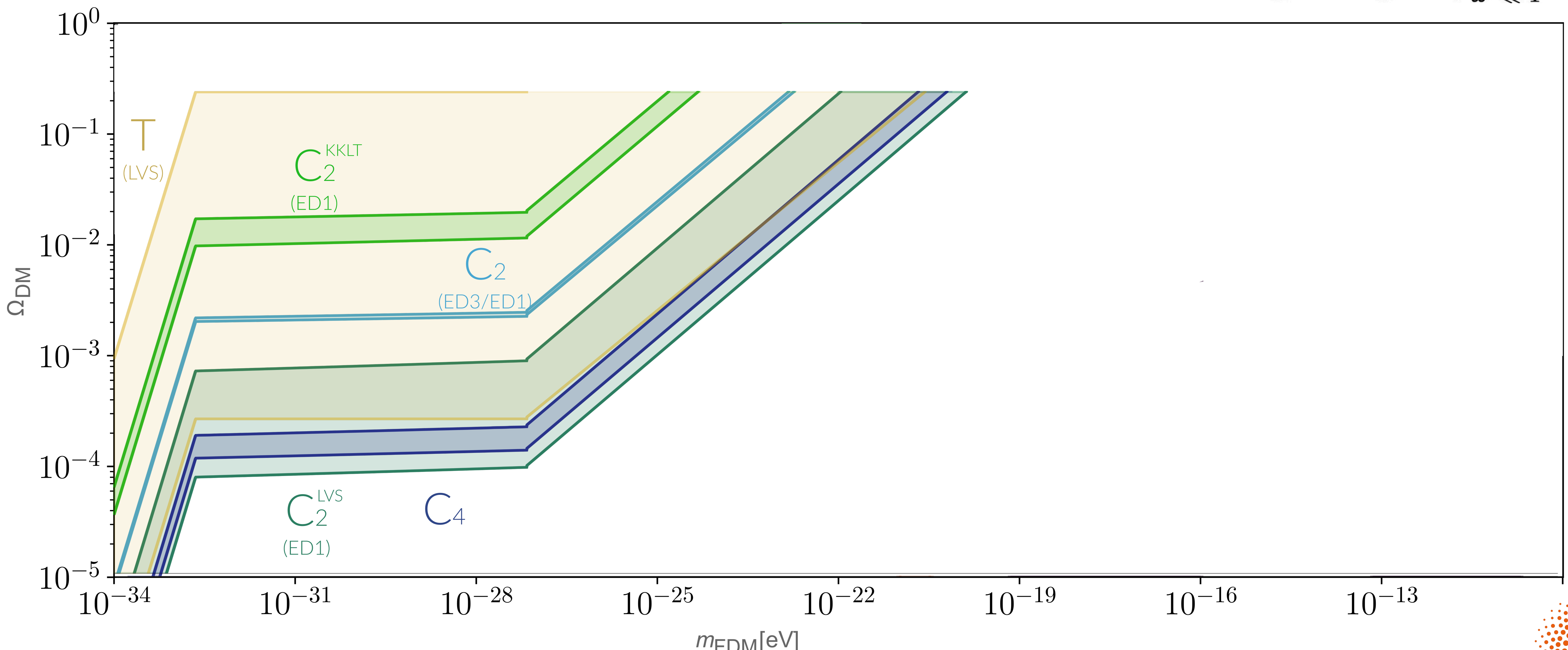
FDM FROM THRAXIONS

[Cicoli, Guidetti, Righi & AW '21]

$$\omega_{\rm IR}^3 \sim e^{-\frac{2\pi K}{g_s M}} = e^{-S_{\rm eff}} \quad \Rightarrow \quad S_{\rm eff} f_{\rm eff} \sim \frac{3\pi K}{\sqrt{g_s}\, \mathcal{V}^{1/3}} M_P$$

$$\frac{m^2}{M_P^2} \sim \frac{g_s\ \omega^3}{\log(\omega^{-1})^{3/4} \mathcal{V}^{2/3} M^2} \times V_{\rm mod.stab.}$$





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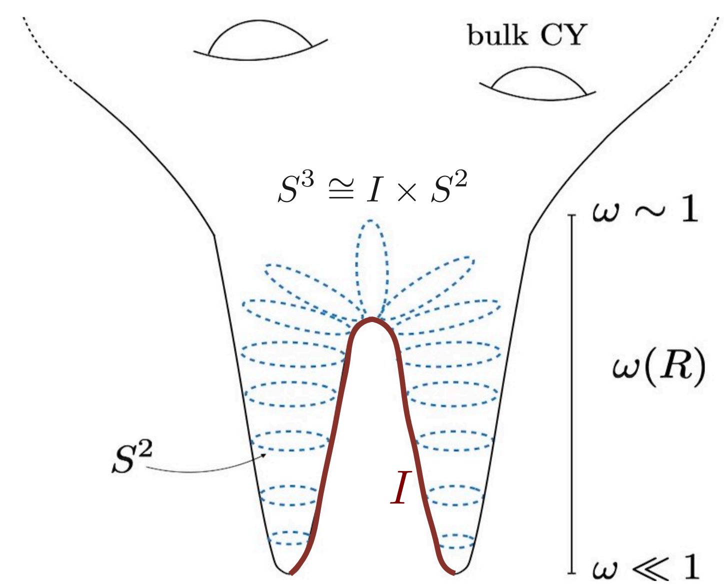

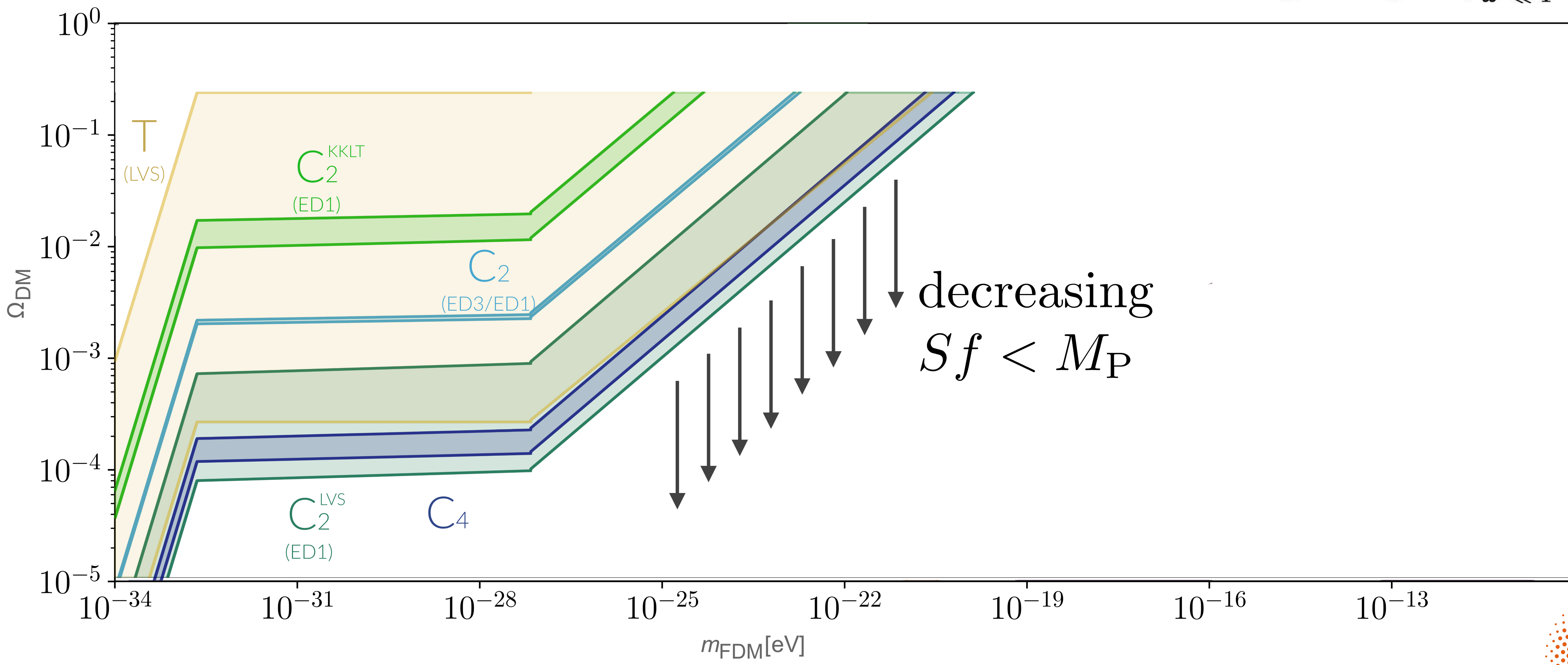

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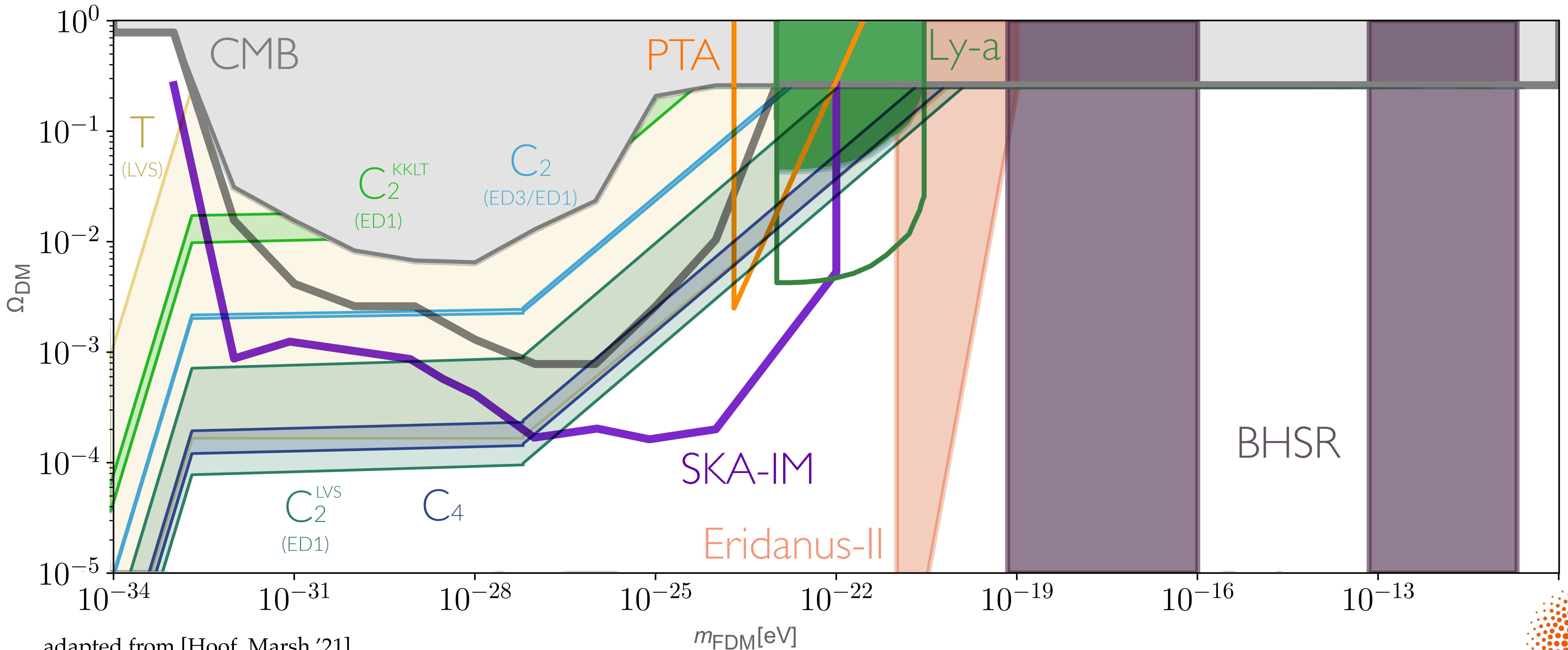
Constraints on Stringy FDM

[Cicoli, Guidetti, Righi & AW '21]

FDM particles detectable by next-generation experiments

- ★ first detection of ULAs ⟶ string theory gives perfect candidates
- ★ we can tell which string axion + details on the compactification



adapted from [Hoof, Marsh '21]

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)

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**