Fuzzy dark matter from Strings?

Veronica Guidetti

Università di Bologna, INFN

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INFN
Istituto Nazionale di Fisica Nucleare

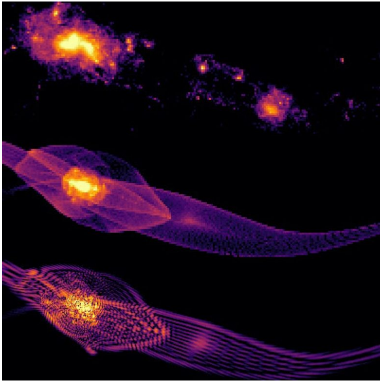
in collaboration with: M. Cicoli, A. Westphal, A. Hebecker

What is FDM?

- DM made of ultra-light particles
- FDM made of axions

$$m \gtrsim 10^{-22} \text{ eV} \quad f \sim 10^{16\div 17} \text{ GeV}$$

- Solitonic structures, BEC
- Solve Core-Cusp problem
- Reduced abundance of low mass halos



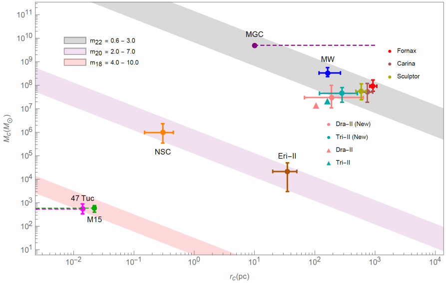
Mocz et al. [1910.01653]

FDM from strings?

- High decay constants related to high energy theory
- Possible multiple nature of FDM

Well known that

- String theory predicts the Axiverse
- Axion appear as massless fields
- Axion stabilisation using n.p. correction: instantons, gaugino condensation



[Broadhurst et al. 1811.03771]

FDM from type IIB

Convention

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

$$\theta = f a$$

DM abundance $\sim 100\%$ $\quad (H < f)$

$$\frac{\Omega_\theta h^2}{0.112} \simeq 1.4 \times \left(\frac{m_\theta}{10^{-22}\text{eV}}\right)^{1/2} \left(\frac{f}{10^{17}\text{GeV}}\right)^2 \theta_{mi}^2 \sim 1$$

Axion mass

$$m_\theta^2 = M_P^4 A e^{-S} / f^2$$

FDM against WGC?

FDM requirements:

- $m_\theta^2 \sim 10^{-22\div21}$ eV
- $f \sim 10^{16\div17}$ GeV

Axion mass

$$m_\theta^2 = M_P^4 A e^{-S}/f^2 \qquad\qquad A = \mathcal{O}(1)$$

Matching right m_a and f implies $\qquad Sf = f \log\left(\frac{M_P^4 A}{f^2 m_\theta^2}\right) \gtrsim M_P$

against WGC!

$(Sf \lesssim M_P)$

not easy to realise it in concrete model building

Closed string axion analysis

We study C_0, C_2, B_2, C_4

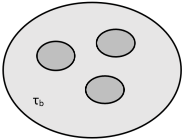
Axion	Sf
C_0	$\sim 1/\sqrt{2}\, M_P$
B_2	$\lesssim\ M_P$
C_2	$\sim \sqrt{g_s}\, M_P$
C_4	$\lesssim \sqrt{3/2}\, M_P$

C_4 axions seem to be the best canditate:

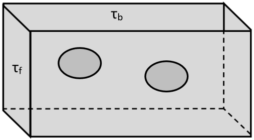
Axion	Sf
C_4 $(1\ dof)$	$\sim \sqrt{3/2}\, M_P$
C_4 $(2\ dof)$	$< \sqrt{3}/2\, M_P$

C_4 axion as FDM

$$\mathcal{V}_{1dof} \sim \tau_b^{3/2}$$



$$\mathcal{V}_{2dof} \sim \tau_b \sqrt{\tau_f}$$



$$m_\theta^2 \simeq g_s A_i W_0 \frac{S^3 e^{-S}}{\mathcal{V}^2} M_p^2$$

Predictions coming from these simple geometries

$$1\ dof: \quad \rightarrow \quad \mathcal{V} \sim 10^2; \qquad g_s W_0 A_i \sim 10^{-70} \div 10^{-50}$$

EFT not under control

$$2\ dof: \quad \rightarrow \quad \mathcal{V} \sim 10^{30}; \qquad g_s W_0 A_i \sim 10^{-13} \div 1$$

TeV string scale

C_4 axion as FDM

Why is it so difficult to reproduce FDM in this context?

- For large cycles

$$f = \frac{M_P}{S} \qquad\qquad S = c\tau_i$$

$$m_\theta^2 \sim M_P^2 A \frac{S^3 e^{-S}}{\mathcal{V}^2} \qquad c = 2\pi/N$$

- We assume standard value for $\langle \theta_{mi}^2 \rangle \sim \pi^2/3$
- Imposing 100% FDM and $m_\theta = 10^{-22}$eV $\quad \rightarrow \quad S \simeq 60$
- Right mass with $A \sim \mathcal{O}(1)$ requires $S \sim 220$
- 1 dof: $\mathcal{V} \simeq S^{3/2}$, fine tuning of A (not under control)
- 2 dof: fine tuning of $\mathcal{V}$ (anisotropic compactification, TeV string scale)
- 100% of dark matter natural only if $m_\theta = 10^{-19}\, eV$ and $f \sim 10^{16}\, GeV$!
- For multiple FDM axions: heavier axions give higher percentages of DM

Open string axion analysis

Open string axion is related to matter field that lives on a collapsed cycle

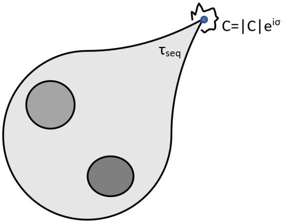
$$C = |C|e^{i\sigma}$$

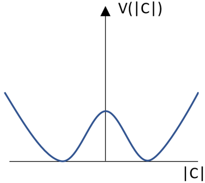
Requirements:

- Brane setup + non-zero world-volume gauge flux: $SU(N) \times U(1)$
- Collapsed cycles carrying $U(1)$ charge: *sequestered scenario*

$$T_{seq} = \tau_{seq} + i\theta_{seq} \, ; \qquad \tau_{seq} \to 0$$

- PQ mechanism: after supersymmetry breaking we get soft terms for $|C|$, possible breakdown of the U(1) symmetry related to $|C|$: $\langle |C| \rangle \neq 0$.





Open string axion analysis

Features of open string axion:

- Decay constant: $f \sim \frac{M_P}{\mathcal{V}^p}$ $\quad p = 1, 2$
- Mass through hidden sector strong dynamics instanton effects

$$m_\sigma^2 = \Lambda_{hid}^4 / f_{seq}^2 \qquad \Lambda_{hid} = M_P e^{-c/g^2}$$

c is fixed by 1-loop β function and $g^{-2} = Re(S)$

Using $p = 1$, imposing 100% FDM and $m_\theta = 10^{-22}$ eV

$$\mathcal{V} \sim 10^2 \qquad \Lambda_{hid} \sim 10^2 \text{eV}$$

$$\langle S \rangle = \frac{1}{c} \ln \left(\frac{M_p}{\Lambda_{QCD}} \right) \simeq \frac{59}{c} \qquad \rightarrow \qquad g \simeq 0.13$$

Less general setup

Possible glueballs production: additional DM!

Accounting for an-harmonicities

We can take care of large misalignment angle ($f >> H$)

$$\frac{\Omega_\theta h^2}{0.112} \simeq 1.4 \times \left(\frac{m_\theta}{10^{-22}\, eV}\right)^{1/2} \left(\frac{f}{10^{17}\, GeV}\right)^2 \theta_{mi}^2\, F(\theta_{mi})$$

Form factor

$$F(\theta_{mi}) = \left[\ln\left(\frac{e}{1-\theta_{mi}^2/\pi^2}\right)\right]^a \qquad a = 7/6$$

To avoid fine-tuning we need $\theta_{mi} \simeq 0.99\pi$

Accounting for an-harmonicities

Domain walls problem?

Quantum fluctuations $<<$ Initial displacement

$$\delta\theta \simeq H/(2\pi f) \qquad \Delta\theta_{in} \simeq 10^{-2}\pi$$

$$H < 0.1 f \sim 10^{15}\, GeV$$

Boundaries from isocurvature perturbations

$$\left(\frac{\delta T}{T}\right)_{iso} \sim \left(\frac{f}{10^{12}\, GeV}\right)^{7/12} \left(\frac{H}{\pi f}\right) < 10^{-5}$$

$$H < \left(\frac{f}{10^{16}\, GeV}\right)^{5/12} 10^{9}\, GeV$$

Conclusions

Despite the presence of many ultralight axions seems generic in strings

FDM with a single axion 100% of DM seems unnatural from strings

- Not easy to get $Sf \gtrsim 1$

Closed string axions:

- Fine-tuning of $\mathcal{V}$
- Fine-tuning of A $(W_0,\ g_s,\ A(\mathcal{U}, S))$
- Fine-tuning of misalignment angle

Open string axions:

- Not general
- Pay attention to glueballs

If FDM is detected: real challenge for String Theory!

Thank you!

C_4 axion as FDM: further analysis

Considering other scenarios:

- presence of ample divisors
- poly-instantons effects
- turn on worldvolume gauge fluxes

the amount of **fine tuning is not reduced**!