Gravitational waves from the Axiverse

Francesc Ferrer, Washington University in St. Louis

✉ ferrer@wustl.edu

VI Barcelona Initiative for Gravitation Meeting

Saurav Das & FF, arXiv:2502.12153

Outline

Walls in the early Universe

Axionic strings and walls

Many axions

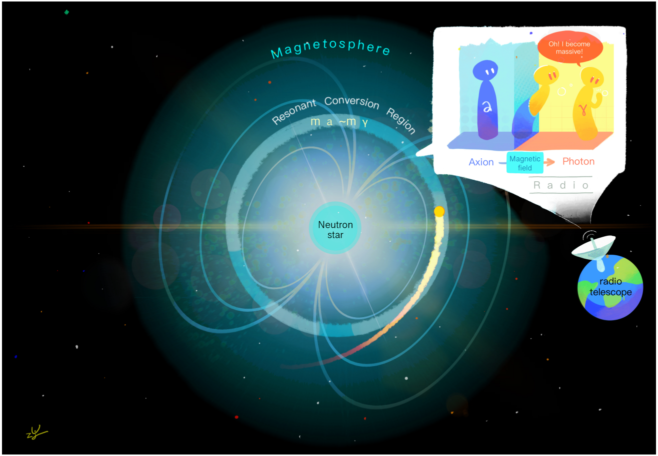
Field theory walls

- It is likely that the Universe was in a more symmetric state at early times and high temperatures.
- The present state was reached after several phase transitions, that possibly generated domain walls.
- Their decay might have generated detectable signals in the form of GWs, PBHs, ...

Why axions?

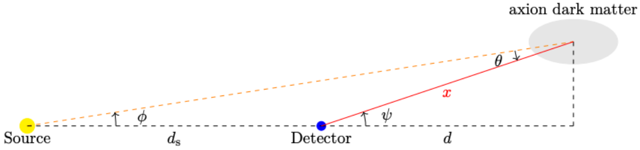
- Well-motivated: strong CP-problem, promising DM candidates, ...
- Broad experimental program based on the Primakoff process: axions transform into photons in external magnetic fields (and vice versa).
- Less constrained ALPs naturally appear in UV completions of the SM.
- Interesting phenomenology of dark matter distribution.

Axion signals



Buckley, Dev, FF, F Huang, arXiv:2004.06486

Axion signals



Ghosh, Salvadó & Miralda-Escudé, 2008.02729; Bhupal Dev, FF & Takuya Okawa, arXiv:2311.13653

Field theory axions

The PQ axion is realized by

$$\mathcal{L} = |\partial_\mu \Phi|^2 - \lambda \left| |\Phi|^2 - \frac{f_a}{2} \right|^2 .$$

At high temperatures $|\Phi|$ is in thermal equilibrium and has a thermal mass $\sim \sqrt{\lambda} T$. PQ symmetry breaking results in a heavy radial mode and a Goldstone boson a:

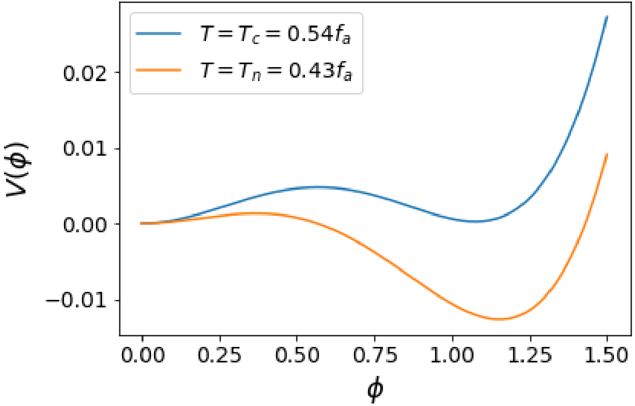
$$\Phi = \frac{f_a + s}{\sqrt{2}} e^{ia/f_a} .$$

A network of axion strings is generated,

$$\Phi = \frac{f_a}{\sqrt{2}} g(m_s r) e^{i\theta} ,$$

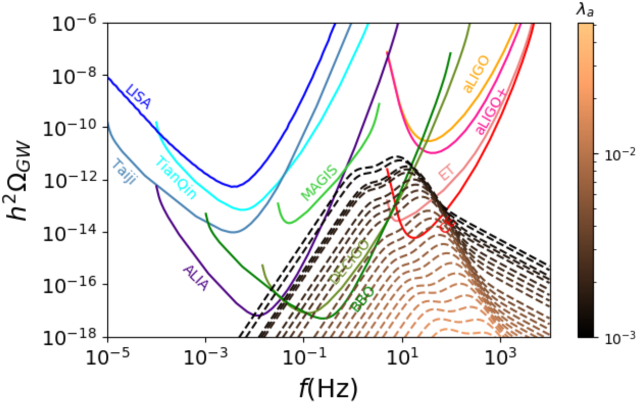
that get dressed by one or more DWs at the QCD epoch, when the axion gets a mass.

PQ phase transition



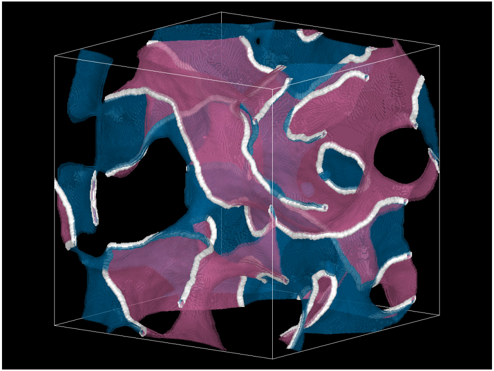
B Dev, FF, Y. Zhang & Y. Zhang, arXiv:1905.0081

PQ phase transition



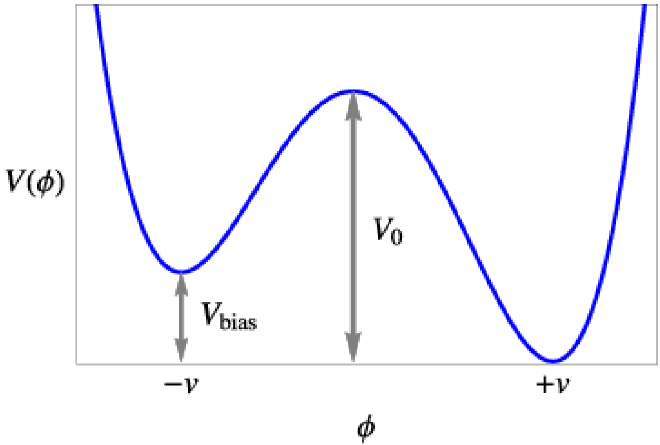
B Dev, FF, Y. Zhang & Y. Zhang, arXiv:1905.0081; B von Harling, A Pomarol, O Pujolàs, F Rompineve, arXiv: 1912.07587

String-DW networks

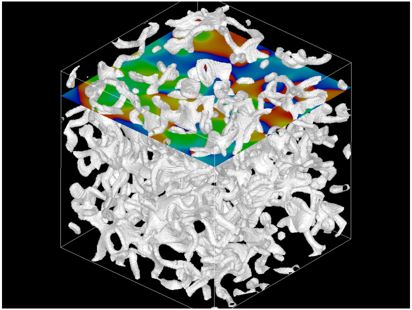


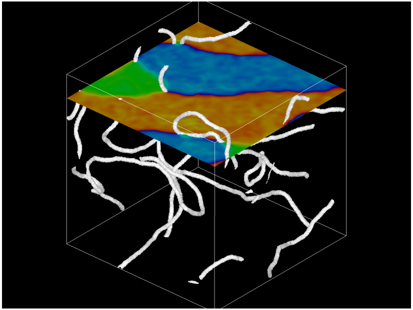
Hiramatsu et al. hep-ph/1207.2206

Axion potential



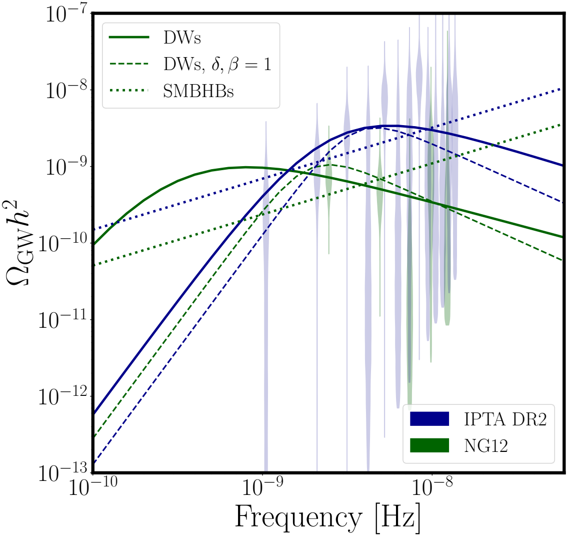
String-DW networks





Hiramatsu et al. hep-ph/1207.2206

TD networks and PTA



R. Ferreira, A. Notari, OP, FR, 2204.04228; ...

The axiverse

- Axion like particles appear in string theory constructions, as the zero modes of higher dimensional gauge fields.
- The higher dimensional gauge symmetry protects the quality of the PQ solution.
- Typically, an ensemble of axions is predicted to exist, that could play an important role in cosmology.

$$\mathcal{L} \supset -\frac{K_{ij}}{2}\partial_\mu a_i \partial^\mu a_j - \Lambda_n^4 \left[1 - \cos\left(N_{ni}\frac{a_i}{f_i} + \delta_n\right)\right] \qquad (1)$$

Svreck & Witten, hep-th/0706206; Arvanitaki et al arXiv:09054720; Benabou et al. arXiv:2312.08425

A two axion toy model

Let's assume the strings source the axion flavor state a_1. The potential generated by the instanton associated with the largest scale Λ is:

$$V(a_1, a_2) = \Lambda^4 \left[1 - \cos\left(N_1 \frac{a_1}{f_1} + N_2 \frac{a_2}{f_2}\right)\right] \tag{2}$$

A different instanton generated potential lifts the degeneracy:

$$V_b(a_1) = \Lambda_b^4 \left[1 - \cos\left(N_b \frac{a_1}{f_1}\right)\right], \tag{3}$$

with $\Lambda_b \ll \Lambda$. Let us consider an example with $N_2 = 2$, $N_1 = N_b = 1$ and instanton scales of $\Lambda = 10$ TeV and $\Lambda_b = 10$ GeV.

String network evolution

Thickness of DW governed by mass of a_1,

$$\delta^{-1} = N_1 \Lambda^2 / f_1,$$

and they are "produced" when $H \sim \delta^{-1}$.
At this time the strings dominate the energy density of the network. For string theory axions with unwarped compactified extra dimensions, strings have tension

$$\mu = \kappa f_1 M_{\mathrm{Pl}},$$

which is parametrically larger than field theory axion strings with $\mu \propto f_1^2$.

J.N. Benabou et al. 2312.08425

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DW network evolution

Initially, the DWs have negligible energy density, but they eventually start dominating at:

$$T_* \simeq \Lambda \left(\frac{f_1}{M_{\rm Pl}} \right)^{\frac{1}{4}} \left(\frac{45}{2\pi^2 g_*} \right)^{\frac{1}{4}} .$$

The DWs eventually decay due to the bias potential

$$\Delta V \approx \Lambda_b^4 \sin^2 \left(\frac{\pi N_b}{N_1} \right) = \Lambda_b^4$$

at the time when the pressure force due to ΔV is equal to the surface tension of the walls $\sigma = 8 f_1 \Lambda^2$,

$$t_{\rm ann} = C_{\rm ann} \frac{\mathcal{A}\sigma}{\Delta V} \approx C_{\rm ann} \frac{8\mathcal{A} f_1 \Lambda^2}{\Lambda_b^4} .$$

Size of the bias term

In a radiation dominated universe, the network annihilates at

$$T_{\text{ann}} \equiv T(t_{\text{ann}}) \approx \frac{\Lambda_b^2}{\Lambda}\left(\frac{M_{\text{Pl}}}{f_1}\right)^{\frac{1}{4}},$$

when the DWs contribute

$$\Omega_{\text{DW}}(t_{\text{ann}}) = \frac{4 \cdot 8^2}{3}\mathcal{A}^2 C_{\text{ann}} \frac{f_1^2 \Lambda^4}{\Lambda_b^4 M_{\text{Pl}}^2}.$$

To prevent walls dominating the universe we find the lower bound:

$$\Lambda_b \geq \left(\frac{4\pi}{3}\mathcal{A}^2 C_{\text{ann}}\right)^{\frac{1}{4}} \Lambda \sqrt{\frac{8 f_1}{M_{\text{Pl}}}}.$$

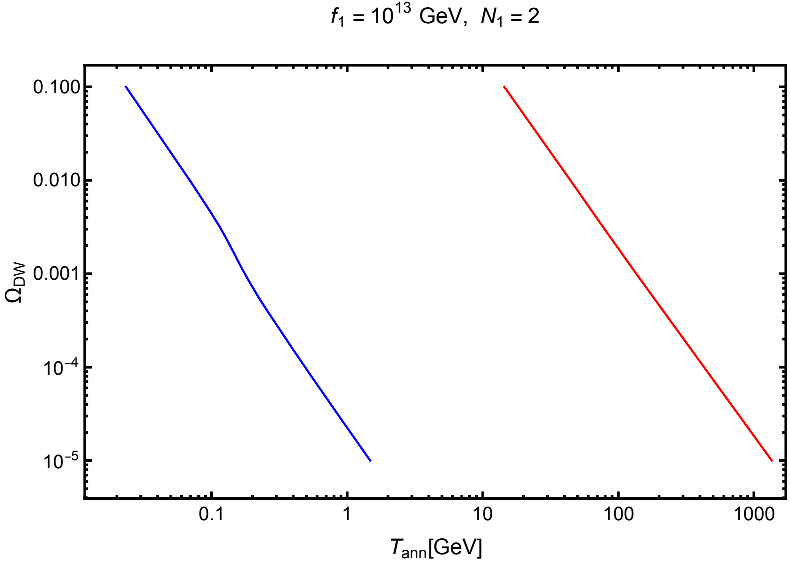
Size of the bias term

On the other hand, unless

$$\Lambda_b \leq \Lambda \left(\frac{f_1}{M_{\mathrm{Pl}}} \right)^{\frac{3}{8}} ,$$

the network annihilates before the walls dominate the strings. In this case, the contribution of the strings to GWs, . . . , cannot be ignored.

Annhilation temperature



Phenomenology

The network annihilates quickly, generating GWs and axion dark matter within one Hubble time of t_{ann}.
In addition, a small surviving fraction at

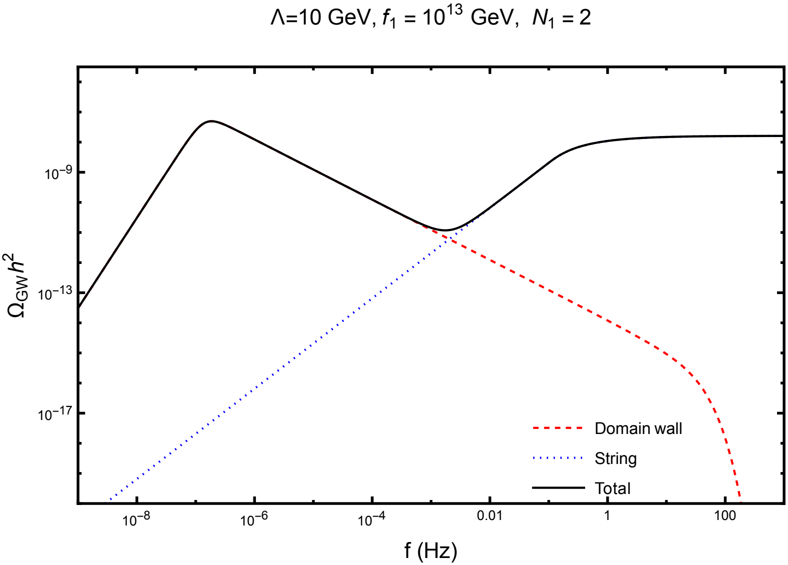
$$f_{\text{DW}} \sim \exp\left[-\left(\frac{t}{t_{\text{ann}}}\right)^{3/2}\right],$$

may give rise to PBHs.

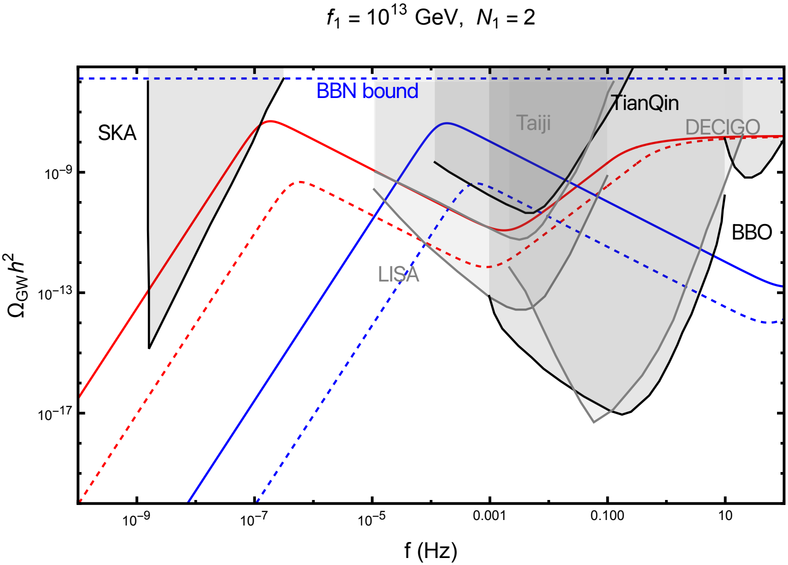
R. Ferreira, A. Notari, O. Pujolàs and F. Rompineve, 2401.14331; FF, E. Masso, G. Panico, O. P. & F. R., 1807.01707; Dunsky & Kongsgore, 2402.03426

The contribution of strings remains important until much later compared to FT strings, enhancing GW and axionic DM production.

GWs from network annihilation



Experimental limits



Axion dark matter

The annihilation of the network produces mildly relativistic axions of the a_1 flavour eigenstate, but the abundance in the late universe is dictated by the properties of the mass eigenstates.
The constraint on Λ and Λ_b that prevents DW from dominating the universe, but at the same time allows the walls to dominate the strings and have observable effects, demands that the instanton scales be well separated, $\Lambda \gg \Lambda_b$. In this regime, the heavier mass eigenstate predominantly couples to the instanton with the largest scale:

$$\phi_2 \sim N_1 a_1 + N_2 \left(\frac{f_1}{f_2}\right) a_2.$$

Properties of the mass eigenstates

Axions can decay into SM particles and other axions. Couplings to other axions are suppressed due to large hierarchies between instanton scales, and SM couplings are highly model dependent.
But, in many explicit constructions, the coupling to photons appears to be robust:

$$\tau_{\phi_2} = \frac{256\pi^3 f^5}{(N_1^2 + N_2^2)^{\frac{3}{2}} \alpha_{\rm EM}^2 \Lambda^6} = 8.8\times10^{20}\ \mathrm{s} \left(\frac{f}{10^{10}\mathrm{GeV}}\right)^5 \left(\frac{10^2\mathrm{GeV}}{\Lambda}\right)^6$$

Axion production

Moderately relativistic axions are produced from the collapse of the network. For instance, the evolution of the energy density of the walls is given by:

$$\frac{\mathrm{d}\rho_{\mathrm{dw}}}{\mathrm{d}t} = -H\rho_{\mathrm{dw}} - \left.\frac{\mathrm{d}\rho_{\mathrm{dw}}}{\mathrm{d}t}\right|_{\mathrm{emission}}, \tag{4}$$

$$\frac{\mathrm{d}\rho_a}{\mathrm{d}t} = -3H\rho_a + \frac{\mathrm{d}\rho_{\mathrm{dw}\to a}}{\mathrm{d}t}, \tag{5}$$

$$\frac{\mathrm{d}\rho_{\mathrm{gw}}}{\mathrm{d}t} = -4H\rho_{\mathrm{gw}} + \frac{\mathrm{d}\rho_{\mathrm{dw}\to \mathrm{gw}}}{\mathrm{d}t}, \tag{6}$$

and at later times the total energy in axions is then found to be:

$$E_a(t) \simeq R^3(t)\left(\mathcal{A}\frac{\sigma_{\mathrm{dw}}}{t} - \frac{4}{3}\epsilon_{\mathrm{gw}} G\sigma_{\mathrm{dw}}^2\mathcal{A}^2\right), \tag{7}$$

from which we can find the abundance of different mass eigenstates.

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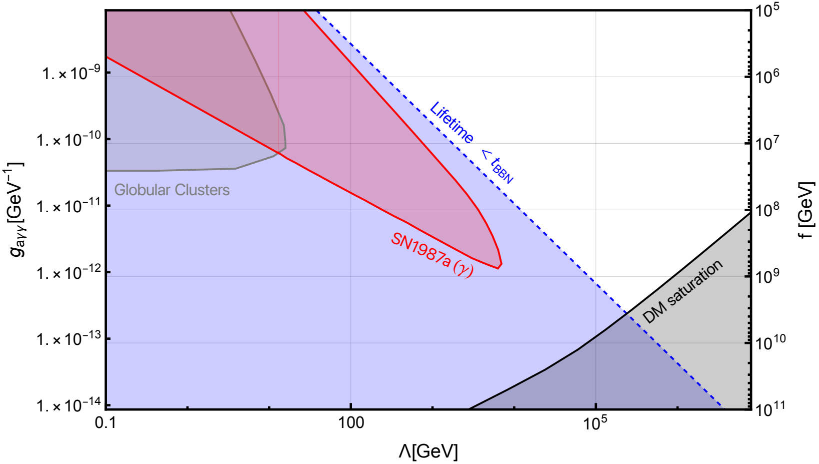
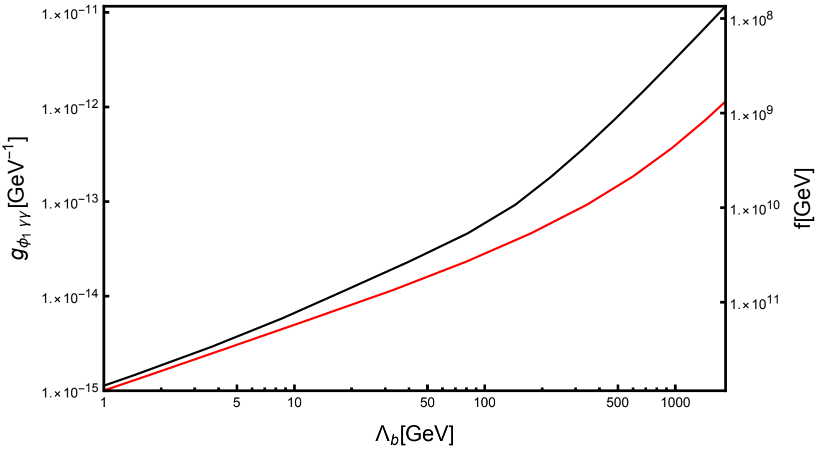
To this, we need to add the emission from strings and a contribution from misalignment.

Annhilation temperature



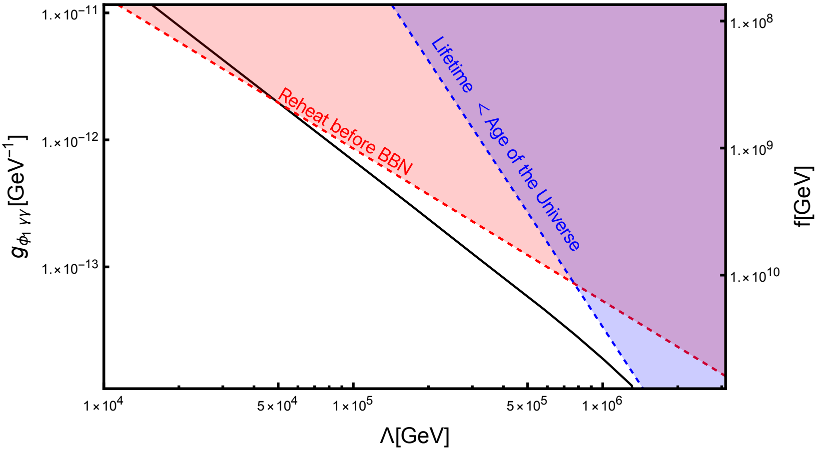


$1.\times10^{-11}$
$1.\times10^{-12}$
$1.\times10^{-13}$
$1.\times10^{-14}$
$1.\times10^{-15}$
$g_{\phi_1\,\gamma\gamma}$[GeV^{-1}]
$1.\times10^{8}$
$1.\times10^{9}$
$1.\times10^{10}$
$1.\times10^{11}$
f[GeV]
1
5
10
50
100
500
1000
Λ_b[GeV]

Conclusions

- Axion-like-particles generically appear in string theory constructions, naturally addressing the PQ quality problem.
- Axionic strings accompanied by DWs are expected to exist in the early universe.
- In some constructions, the strings have tensions parametrically larger than in typical FT constructions. This gives rise to interesting GW signals upon network decay.
- The decay also produces axion particles. The lightest state might have a lifetime larger than the age of the Universe, and could constitute the dark matter.
- Further consequences to be explored include PBHs, ...

Additional Slides



Lifetime < Age of the Universe
Reheat before BBN
1×10^{-11}
1×10^{-12}
1×10^{-13}
$g_{\phi_1\gamma\gamma}[\mathrm{GeV}^{-1}]$
1×10^{8}
1×10^{9}
1×10^{10}
f[GeV]
1×10^{4}
5×10^{4}
1×10^{5}
5×10^{5}
1×10^{6}
Λ[GeV]

Mass eigenstates

The mass matrix for the flavour states

$$\mathcal{L} \supset -\frac{1}{2} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}^{\top} \begin{pmatrix} M^2_{a_1} & M^2_{a_1 a_2} \\ M^2_{a_1 a_2} & M^2_{a_2} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix},$$

can be diagonalized by a rotation to obtain the massess of the mass-eigenstates:

$$M^2_{\varphi_1} = \frac{1}{2}\left(M^2_{a_1} + M^2_{a_2} - \Delta^2\right),$$
$$M^2_{\varphi_2} = \frac{1}{2}\left(M^2_{a_1} + M^2_{a_2} + \Delta^2\right),$$

where we assumed $M_{\phi_2} > M_{\phi_1}$. Here the elements of the mass matrix are:

$$\begin{aligned} M^2_{a_1} &= \frac{N_1^2 \Lambda^4 + N_b^2 \Lambda_b^4}{f_1^2}, \\ M^2_{a_2} &= \frac{N_2^2 \Lambda^4}{f_2^2}, \\ M^2_{a_1 a_2} &= \frac{N_1 N_2 \Lambda^4}{\cdots} \end{aligned} \tag{8}$$

String axiverse details

Conjecture: Given an extra-dimensional axion with decay constant f_a there exists an associated axion string with core tension

$$\mu_* \approx 2\pi S_{\rm inst} f_a^2 .$$

Reece, 2406.08543

Example: axion descending from C_4 in type IIB has an associated axion string of a $D3$ brane wrapped on the 2-cycle dual to the circle on which C_4 is dimensionally reduced. The instanton action in the absence of warping is $S_{\rm inst} \sim M_{\rm Pl}/f_a$ so $\mu \sim \pi f_a M_{\rm Pl}$.