An even lighter QCD axion.

SEWM 2021 Workshop - 30/06/21

Pablo Quílez Lasanta - *pablo.quilez@desy.de*

Based on "*An even lighter QCD axion*" 2102.00012 **JHEP** 05 (2021) 184
"*Dark matter from an even lighter QCD axion: trapped misalignment*" 2102.01082

In collaboration with L. Di Luzio, B. Gavela and A. Ringwald

The QCD axion

- ➔ Solves the Strong CP problem
- ➔ Excellent Dark Matter candidate

[Peccei+Quinn 77]
[Weinberg, 78]
[Wilczek, 78]

[Abbot+Sikivie, 83]
[Dine and W. Fischler, 83]
[Preskil et al, 91]

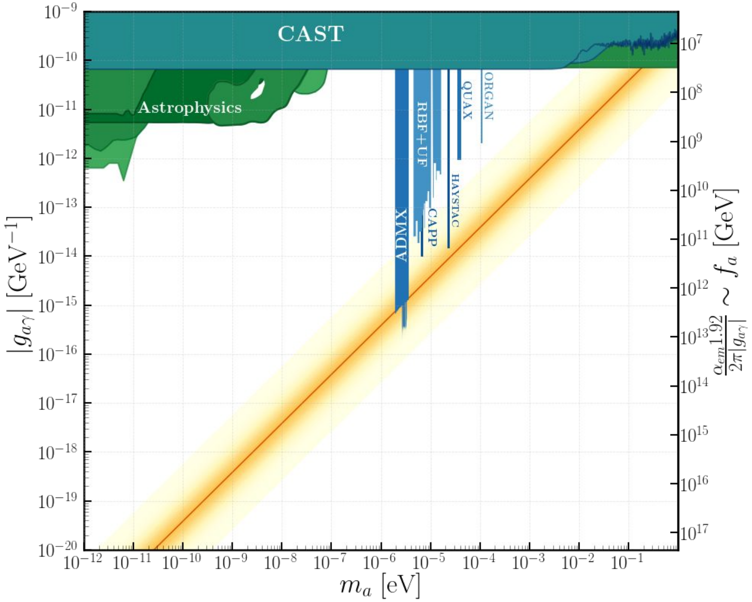
Based on **2102.00012** and **2102.01082**

The QCD axion

- ➔ Solves the Strong CP problem
- ➔ Excellent Dark Matter candidate

[Peccei+Quinn 77]
[Weinberg, 78]
[Wilczek, 78]

[Abbot+Sikivie, 83]
[Dine and W. Fischler, 83]
[Preskil et al, 91]



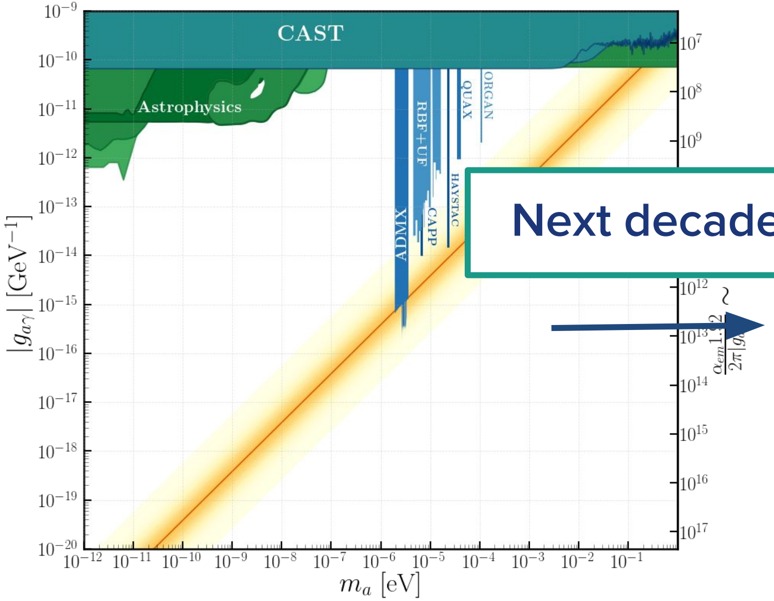
Based on **2102.00012** and **2102.01082**

The QCD axion

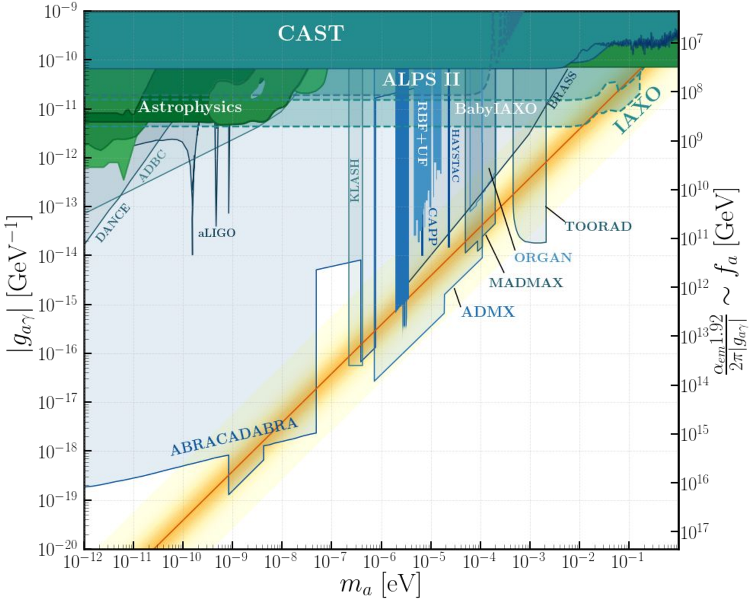
- ➔ Solves the Strong CP problem
- ➔ Excellent Dark Matter candidate

[Peccei+Quinn 77]
[Weinberg, 78]
[Wilczek, 78]

[Abbot+Sikivie, 83]
[Dine and W. Fischler, 83]
[Preskil et al, 91]

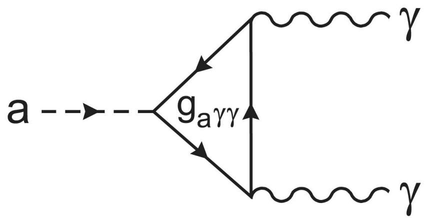


Next decades

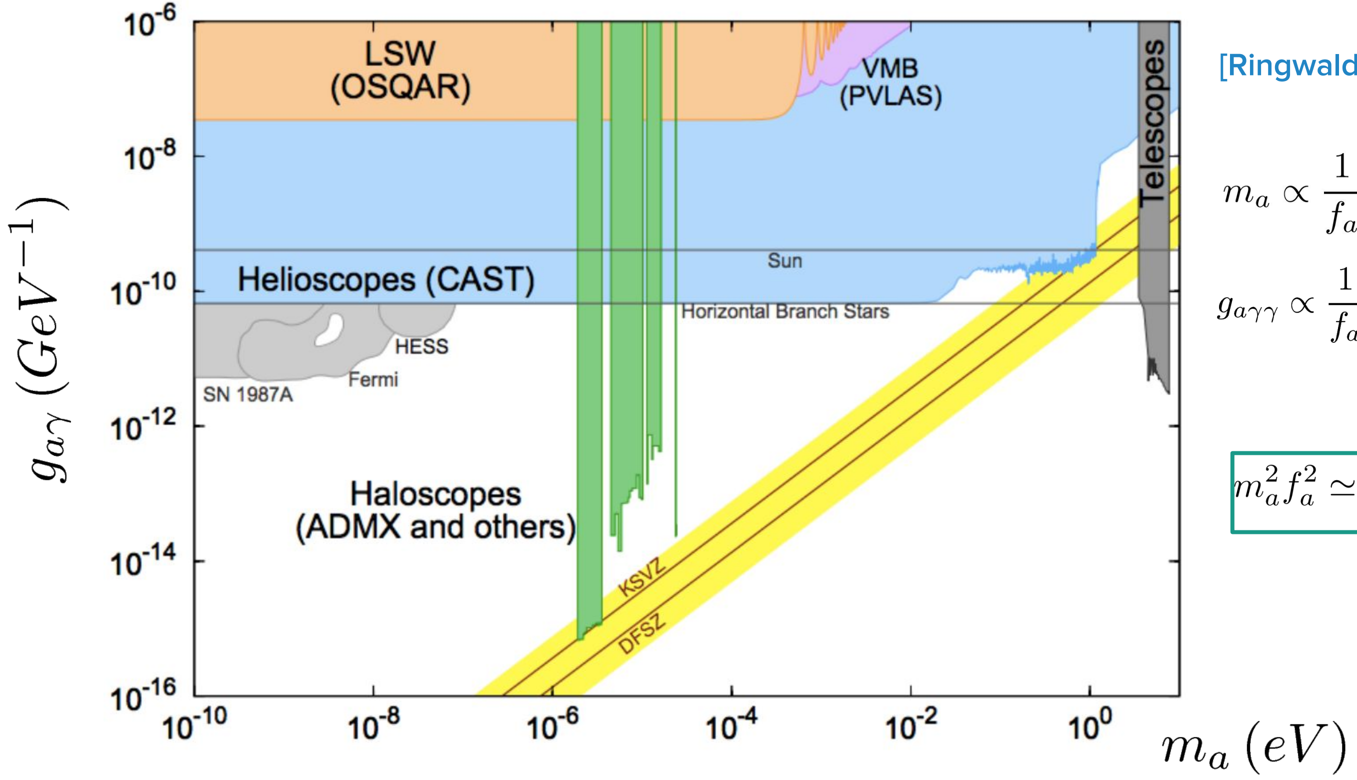


Based on **2102.00012** and **2102.01082**

Invisible axion parameter space



[Ringwald, PDG 17]



$$m_a \propto \frac{1}{f_a}$$

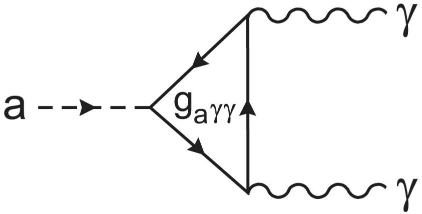
$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

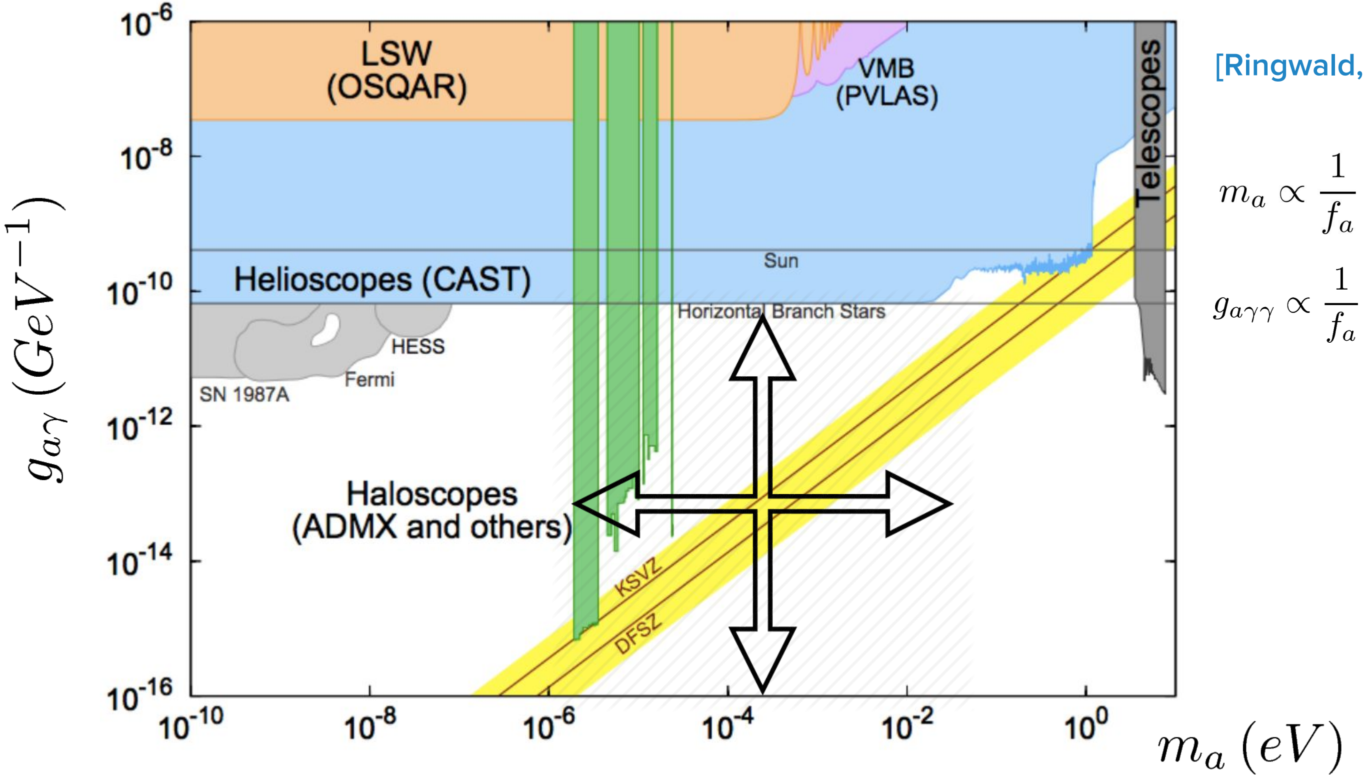
$$\Longrightarrow \quad g_{a\gamma\gamma} \propto m_a$$

$$\boxed{m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}}$$

Based on **2102.00012** and **2102.01082**

Are there other possibilities?





[Ringwald, PDG 17]

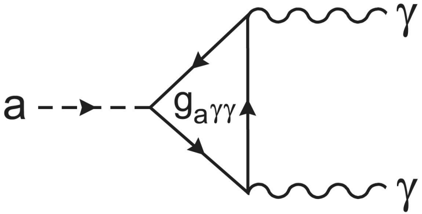
$$m_a \propto \frac{1}{f_a}$$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

$$\Longrightarrow \quad g_{a\gamma\gamma} \propto m_a$$

Based on **2102.00012** and **2102.01082**

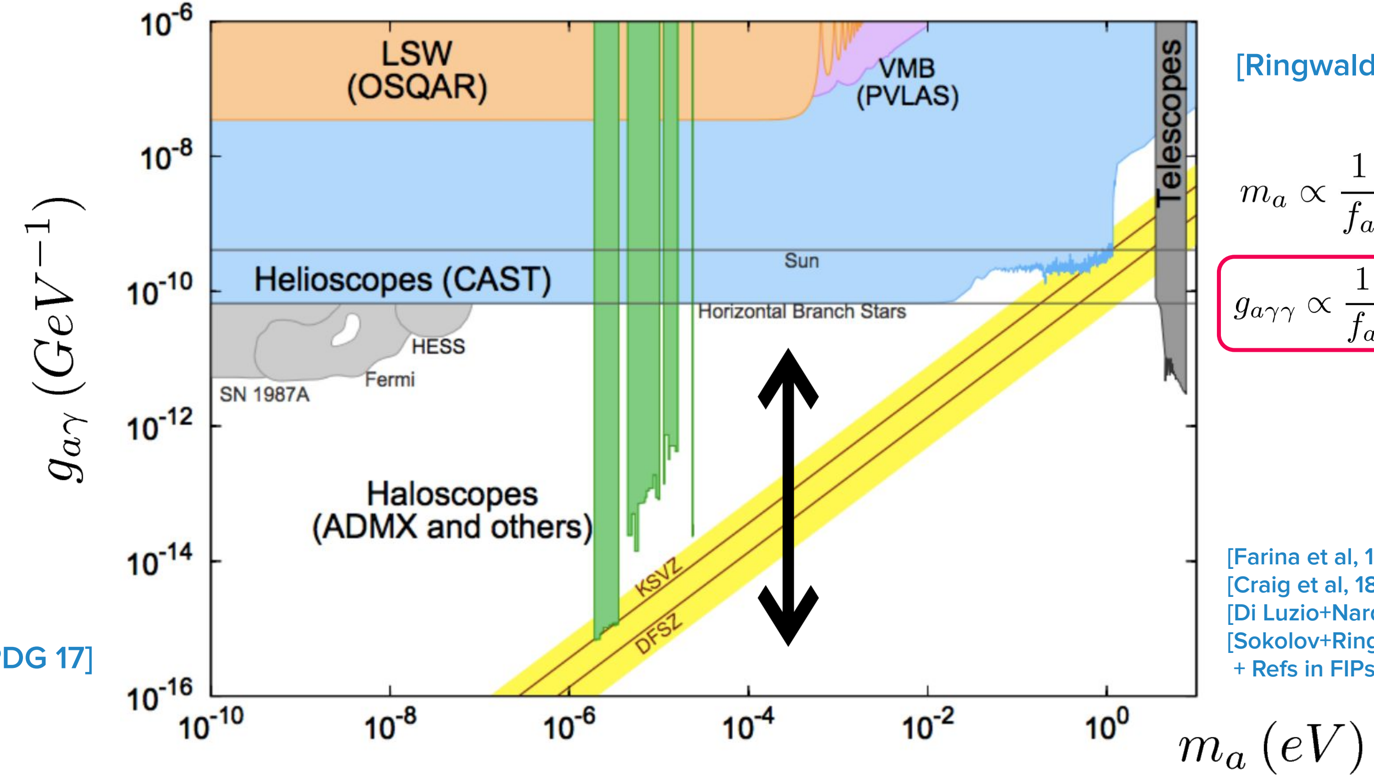
Photophilic/photophobic



[Ringwald, PDG 17]

$$m_a \propto \frac{1}{f_a}$$

$$\boxed{g_{a\gamma\gamma} \propto \frac{1}{f_a}} \implies g_{a\gamma\gamma} \propto m_a$$

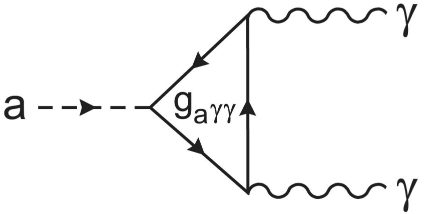


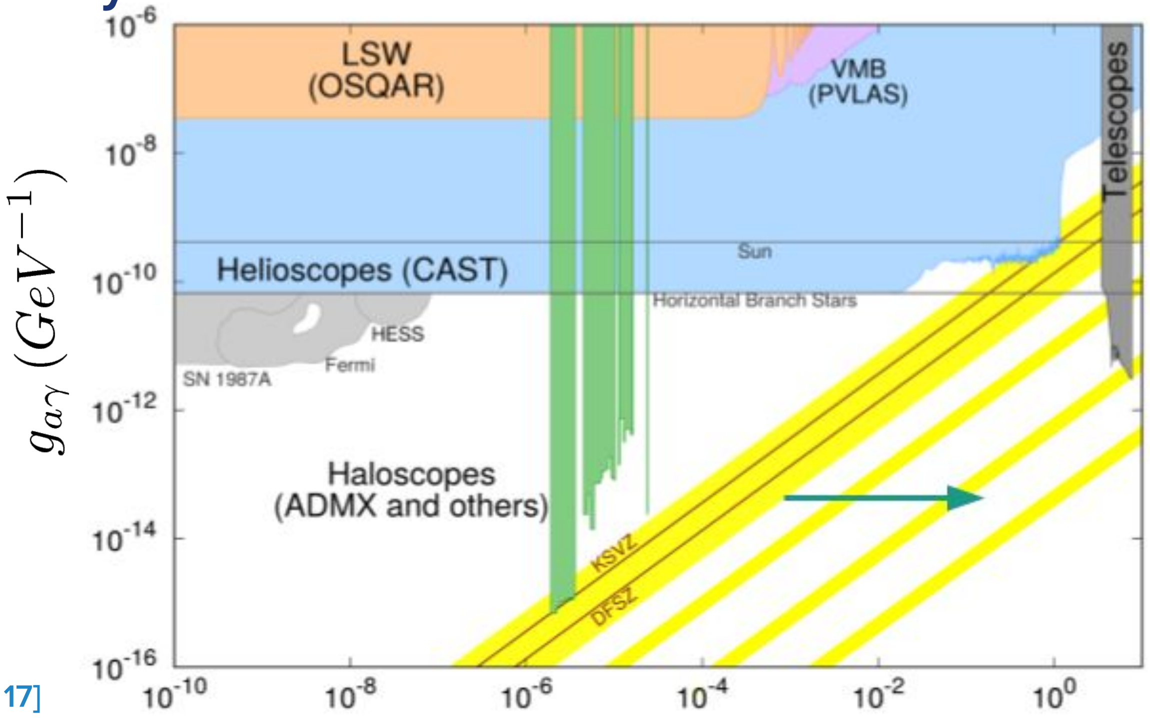
[Ringwald, PDG 17]

[Farina et al, 17]
[Craig et al, 18]
[Di Luzio+Nardi et al, 17]
[Sokolov+Ringwald, 21] ...
+ Refs in FIPs report [2102.12143]

Based on **2102.00012** and **2102.01082**

Heavy axions





$$\boxed{m_a \propto \frac{1}{f_a}}$$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a} \implies g_{a\gamma\gamma} \propto m_a$$

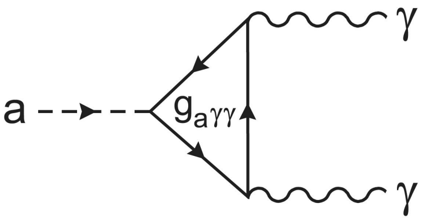
$$m_a^2 f_a^2 \gg m_\pi^2 f_\pi^2$$

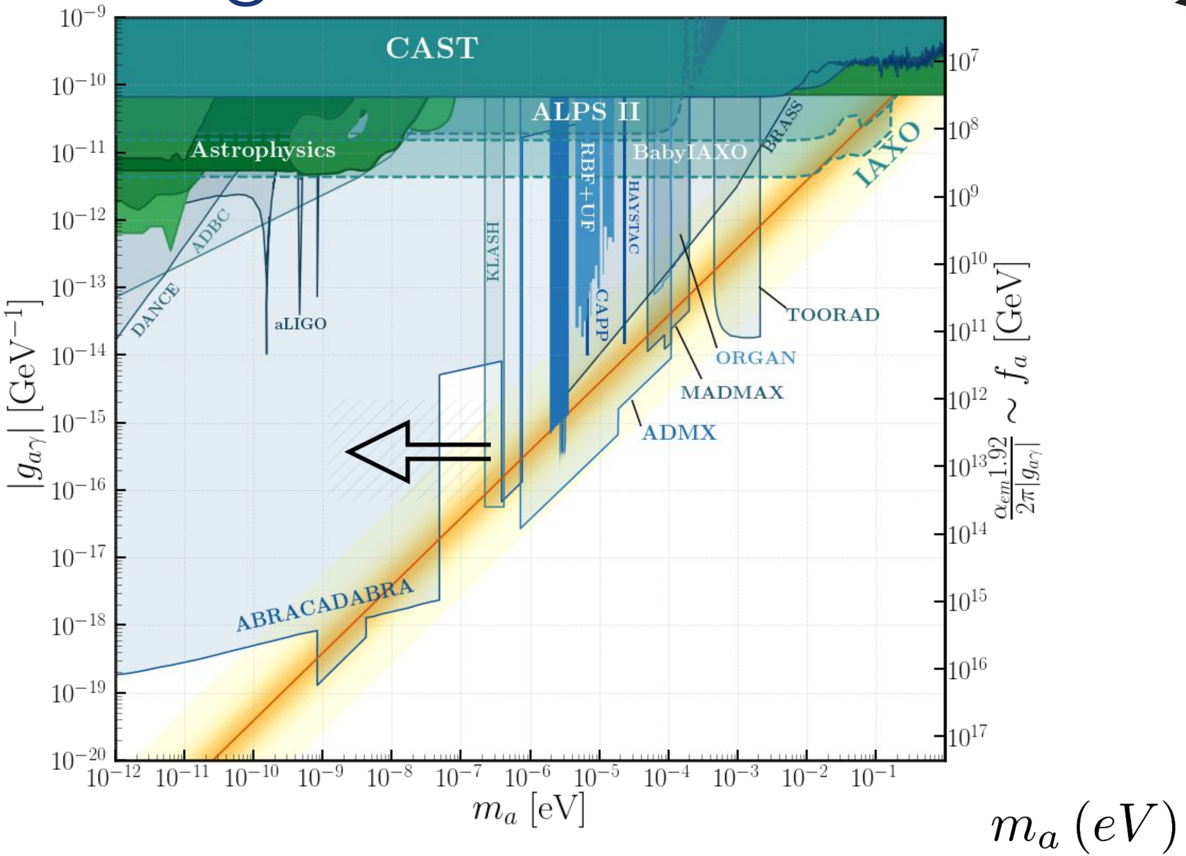
[Ringwald, PDG 17]

[Rubakov, 97]
[Berezhiani et al ,01]
[Fukuda et al, 01]
[Hsu et al, 04]
[Hook et al, 14]
[Chiang et al, 16]
[Khobadize et al,]
[Dimopoulos et al, 16]
[Gherghetta et al, 16]
[Agrawal et al, 17]
[Gaillard et al, 18]
[Fuentes-Martin et al, 19]
[Csaki et al, 19]
[Gherghetta et al, 20]

Based on **2102.00012** and **2102.01082**

What about lighter axions?



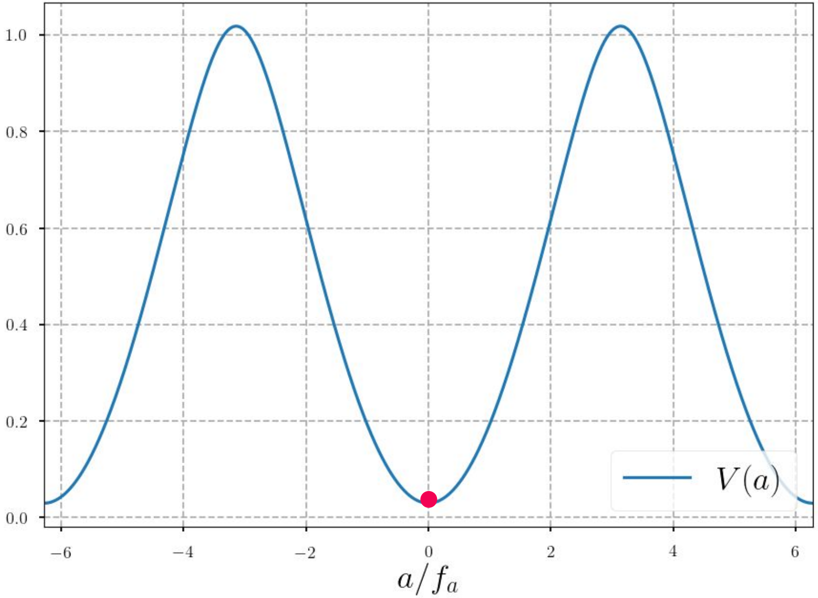


Based on **2102.00012** and **2102.01082**

An even lighter QCD axion

Axion potential

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} \longrightarrow V(a) = -m_\pi^2 f_\pi^2\sqrt{1-\frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$



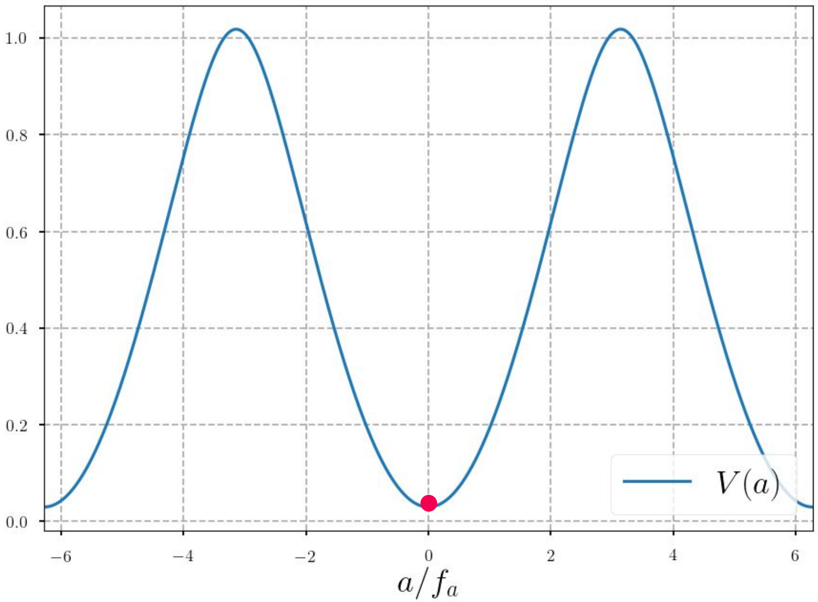
[Di Vecchia +Veneziano,80]
[Leutwyler+Smilga, 92]
[di Cortona et al, 15]

$$\bar{\theta}_{\rm eff} = \langle\bar{\theta} - \frac{a}{f_a}\rangle = 0$$

Based on **2102.00012** and **2102.01082**

Axion potential

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$



[Di Vecchia +Veneziano,80]
[Leutwyler+Smilga, 92]
[di Cortona et al, 15]

➔ Alignment

➔ Cancelation

$$\bar{\theta}_{\text{eff}} = \langle \bar{\theta} - \frac{a}{f_a} \rangle = 0$$

Based on **2102.00012** and **2102.01082**

The Z_2 case: Mirror world

$$Z_2: \quad \mathrm{SM} \longrightarrow \mathrm{SM}'$$
$$a \longrightarrow a + \pi f_a$$

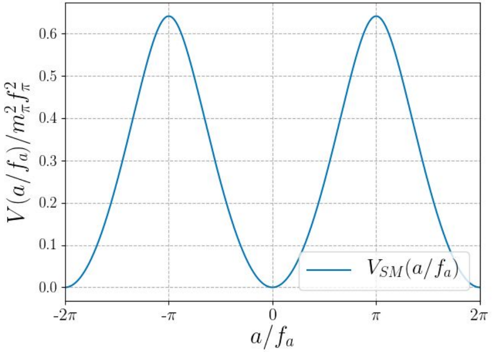
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{SM}'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right)G\widetilde{G} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta + \pi\right)G'\widetilde{G}'$$

QCD **QCD'**

Based on **2102.00012** and **2102.01082**

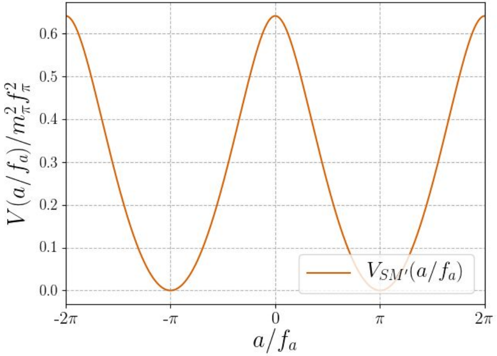
What about lighter axions?

SM



$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a}\right)}$$

SM'

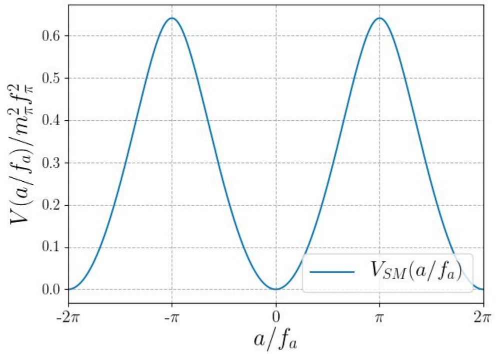


$$V'(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} + \frac{\pi}{2}\right)}$$

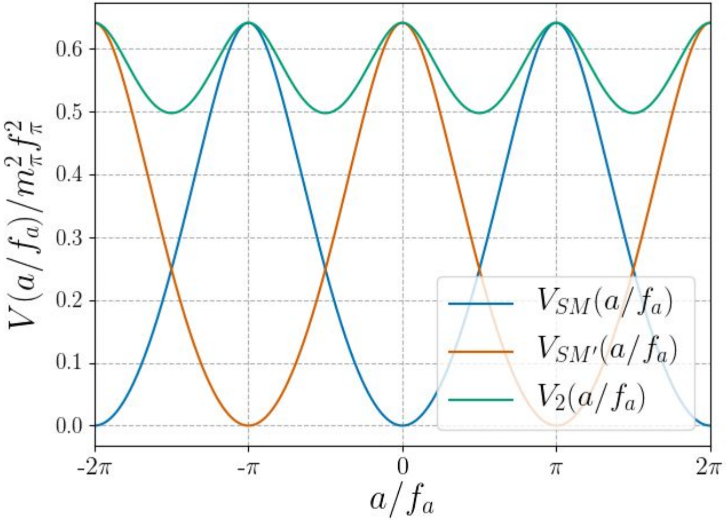
Based on **2102.00012** and **2102.01082**

What about lighter axions?

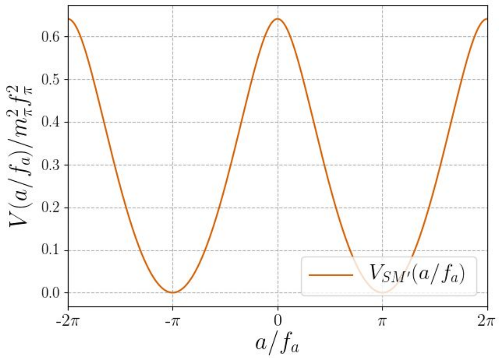
SM



$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$



SM’

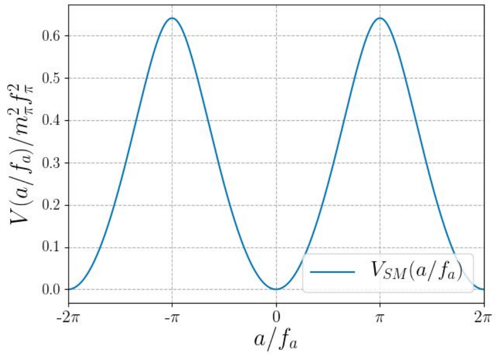


$$V'(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi}{2}\right)}$$

Based on **2102.00012** and **2102.01082**

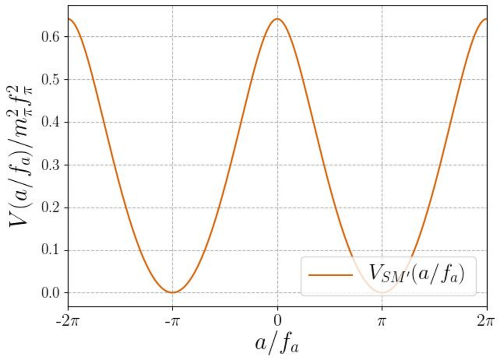
What about lighter axions?

SM

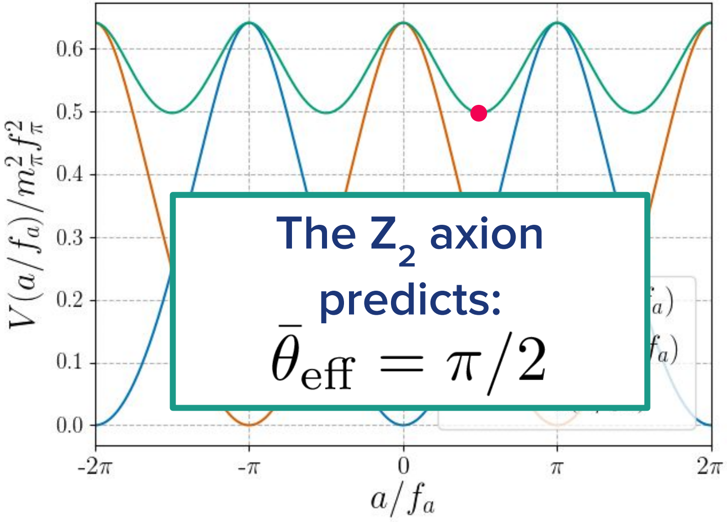


$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$

SM'



$$V'(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi}{2}\right)}$$



The Z_2 axion predicts:

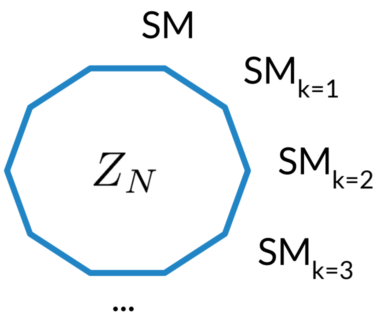
$$\bar{\theta}_{\text{eff}} = \pi/2$$

Based on **2102.00012** and **2102.01082**

Z_N axion: N-mirror worlds

[Hook, 18]

$$Z_N: \quad \mathrm{SM} \longrightarrow \mathrm{SM}^k$$
$$a \longrightarrow a + \frac{2\pi k}{N} f_a$$



➔ The axion realizes the Z_N non-linearly.

➔ N degenerate worlds with the same couplings as in the SM except for the theta parameter

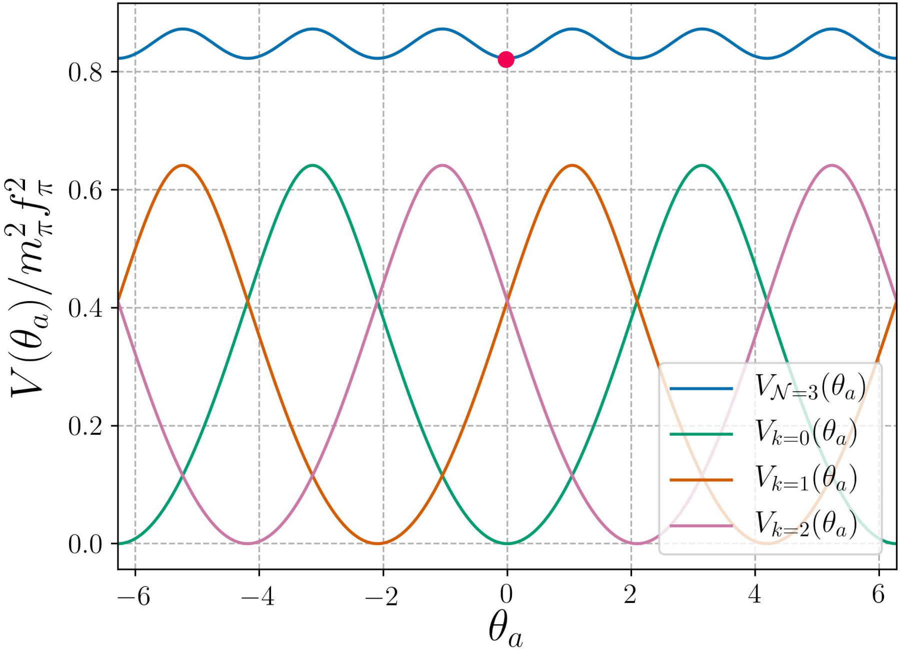
$$\mathcal{L} = \sum_{k=0}^{\mathcal{N}-1} \left[\mathcal{L}_{\mathrm{SM}_k} + \frac{\alpha_s}{8\pi} \left(\theta_a + \frac{2\pi k}{\mathcal{N}} \right) G_k \widetilde{G}_k \right] + \ldots$$

Based on **2102.00012** and **2102.01082**

Z_N axion: N-mirror worlds

[Hook, 18]

➔ N needs to be odd. Example: Z3



$$\frac{m_a(N)}{m_a(N=1)} \sim \frac{4}{2^{N/2}}$$

Based on **2102.00012** and **2102.01082**

Z_N axion: N-mirror worlds

[Hook, 18]

➔ N needs to be odd. Example: Z3

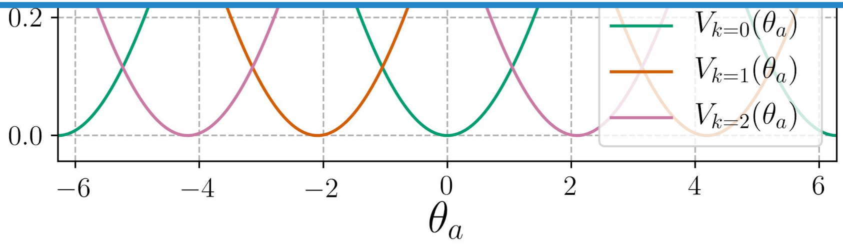
Solving the Hierarchy Problem Discretely

Anson Hook[1]

[1] *Maryland Center for Fundamental Physics, Department of Physics University of Maryland, College Park, MD 20742.*

We present a new solution to the Hierarchy Problem utilizing non-linearly realized discrete symmetries. The cancelations occur due to a discrete symmetry that is realized as a shift symmetry on the scalar and as an exchange symmetry on the particles with which the scalar interacts. We show how this mechanism can be used to solve the Little Hierarchy Problem as well as give rise to light axions.

$$\sim \frac{4}{2^{N/2}}$$



Based on **2102.00012** and **2102.01082**

Why exp. suppressed?

$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{N-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi k}{N}\right)}$$

➔ One would expect:

$$m_a^2 f_a^2 \sim \mathcal{N} m_\pi^2 f_\pi^2$$

Why exp. suppressed?

$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{N-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} + \frac{\pi k}{N}\right)}$$

➔ One would expect: $\cancel{m_a^2 f_a^2 \sim \mathcal{N} m_\pi^2 f_\pi^2}$

➔ Let's understand the cancelation:

$$V_{\mathcal{N}}(\theta_a) = \sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right)$$

$$\theta_a \equiv \frac{a}{f_a}$$

Based on **2102.00012** and **2102.01082**

Why exp. suppressed?

$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{N-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} + \frac{\pi k}{N}\right)}$$

- ➔ One would expect: $\cancel{m_a^2 f_a^2 \sim \mathcal{N} m_\pi^2 f_\pi^2}$
- ➔ Let’s understand the cancelation:

$$V_{\mathcal{N}}(\theta_a) = \frac{\mathcal{N}}{2\pi} \sum_{k=0}^{\mathcal{N}-1} \frac{2\pi}{\mathcal{N}} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right)$$

$$\theta_a \equiv \frac{a}{f_a}$$

Why exp. suppressed?

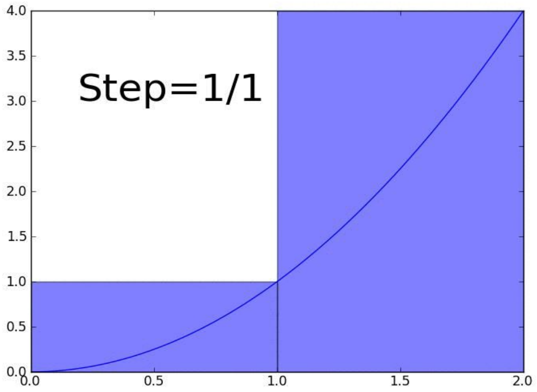
$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{N-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi k}{N}\right)}$$

- ➔ One would expect: $\cancel{m_a^2 f_a^2 \sim \mathcal{N} m_\pi^2 f_\pi^2}$
- ➔ Let's understand the cancelation:

$$V_{\mathcal{N}}(\theta_a) = \frac{\mathcal{N}}{2\pi} \sum_{k=0}^{\mathcal{N}-1} \frac{2\pi}{\mathcal{N}} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) = \frac{\mathcal{N}}{2\pi} \int_0^{2\pi} V(x) dx + \mathcal{O}\left(\mathcal{N}^0\right)$$

$$\theta_a \equiv \frac{a}{f_a}$$

Source: Wikipedia



Based on **2102.00012** and **2102.01082**

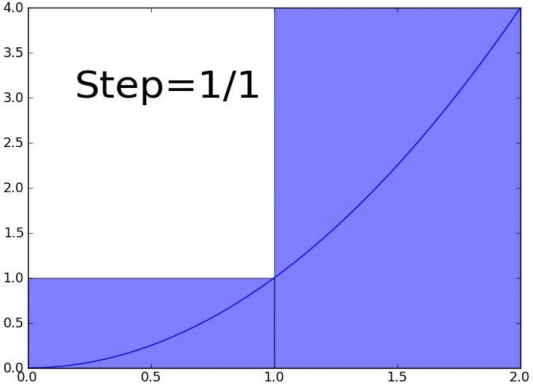
Why exp. suppressed?

$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{N-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi k}{N}\right)}$$

- ➔ One would expect: $\cancel{m_a^2 f_a^2 \sim \mathcal{N} m_\pi^2 f_\pi^2}$
- ➔ Let’s understand the cancelation:

$$V_{\mathcal{N}}(\theta_a) = \frac{\mathcal{N}}{2\pi} \sum_{k=0}^{\mathcal{N}-1} \frac{2\pi}{\mathcal{N}} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) = \boxed{\frac{\mathcal{N}}{2\pi} \int_0^{2\pi} V(x) dx} + \mathcal{O}\left(\mathcal{N}^0\right)$$

Source: Wikipedia



Does not depend on the axion!

$$= \text{cte}$$

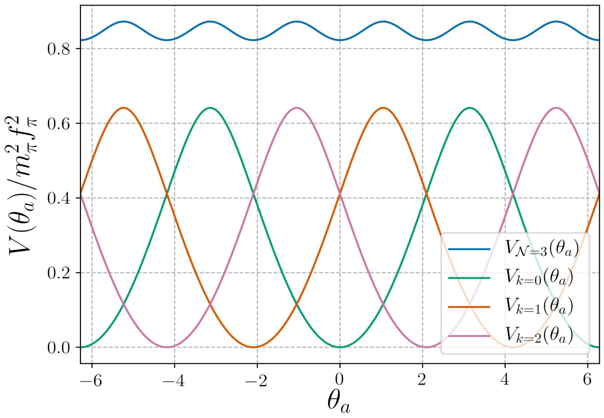
Based on **2102.00012** and **2102.01082**

Why exp. suppressed?

$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{N-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a} + \frac{\pi k}{N}\right)}$$

- ➔ One would expect: $\cancel{m_a^2 f_a^2 \sim \mathcal{N} m_\pi^2 f_\pi^2}$
- ➔ Let's understand the cancelation:

$$V_{\mathcal{N}}(\theta_a) = \frac{\mathcal{N}}{2\pi}\sum_{k=0}^{\mathcal{N}-1}\frac{2\pi}{\mathcal{N}} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) = \boxed{\frac{\mathcal{N}}{2\pi}\int_0^{2\pi} V(x)dx} + \boxed{\mathcal{O}\left(\mathcal{N}^0\right)}$$



Does not depend on the axion!

$= \text{cte}$

The axion potential is contained in the subleading terms

Based on **2102.00012** and **2102.01082**

Why exp. suppressed?

$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{\mathcal{N}-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a} + \frac{\pi k}{\mathcal{N}}\right)}$$

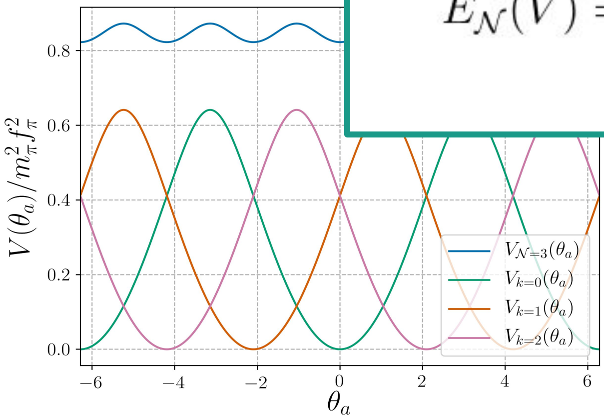
➔ One

➔ Let's

$V_{\mathcal{N}}\,(\theta$

The total Z_N axion potential is contained in the error committed in approximating the Riemann sum by an integral:

$$E_{\mathcal{N}}(V) = \int_0^{2\pi} V(x)dx - \frac{2\pi}{\mathcal{N}}\sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right)$$



on the axion!

$$= \text{cte}$$

The axion potential is contained in the subleading terms

Based on **2102.00012** and **2102.01082**

Why exponentially suppressed?

$$z \equiv m_u/m_d$$

$$E_{\mathcal{N}}(V) = \int_0^{2\pi} V(x)dx - \frac{2\pi}{\mathcal{N}} \sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right)$$

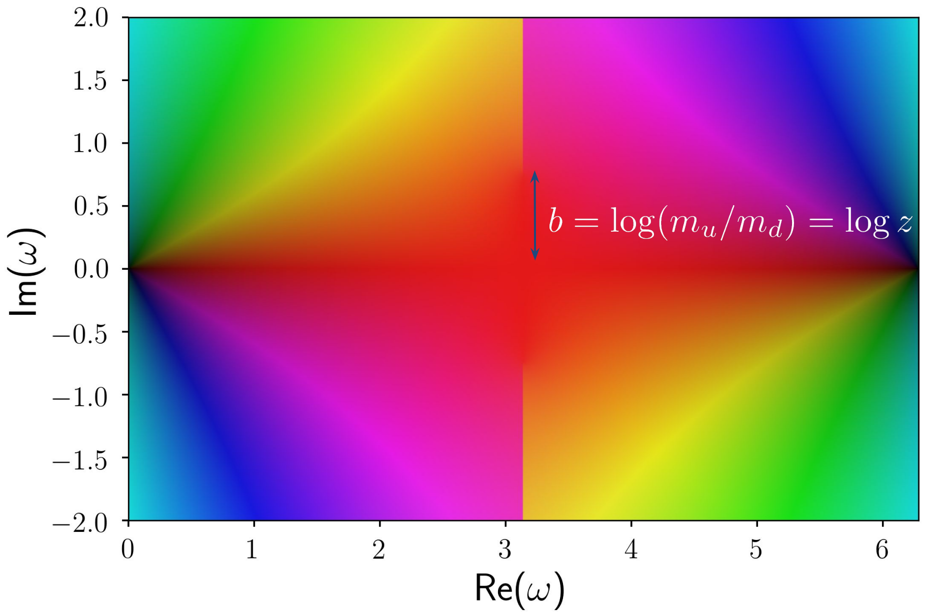
Theorem 9.28 *Let $f : \mathbb{R} \to \mathbb{R}$ be analytic and 2π-periodic. Then there exists a strip $D = \mathbb{R} \times (-b, b) \subset \mathbb{C}$ with $a > 0$ such that f can be extended to a holomorphic and 2π-periodic bounded function $f : D \to \mathbb{C}$. The error for the rectangular rule can be estimated by*

$$|E_{\mathcal{N}}(V)| \leq \frac{4\pi M}{e^{\mathcal{N}b} - 1},$$

where M denotes a bound for the holomorphic function f on D.

$$\frac{m_a^2 f_a^2}{m_\pi^2 f_\pi^2} \propto z^{\mathcal{N}} \sim 2^{-\mathcal{N}}$$

$$V(\omega) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\omega}{2}\right)}$$



Based on **2102.00012** and **2102.01082**

Why exponentially suppressed?

$$z \equiv m_u/m_d$$

$$E_{\mathcal{N}}(V) = \int_0^{2\pi} V(x) d$$

Theorem 9.28 *Let* $f : \mathbb{R} \to \mathbb{R}$
exists a strip $D = \mathbb{R} \times (-b, b) \subset$
to a holomorphic and 2π*-periodi*
for the rectangular rule can be es

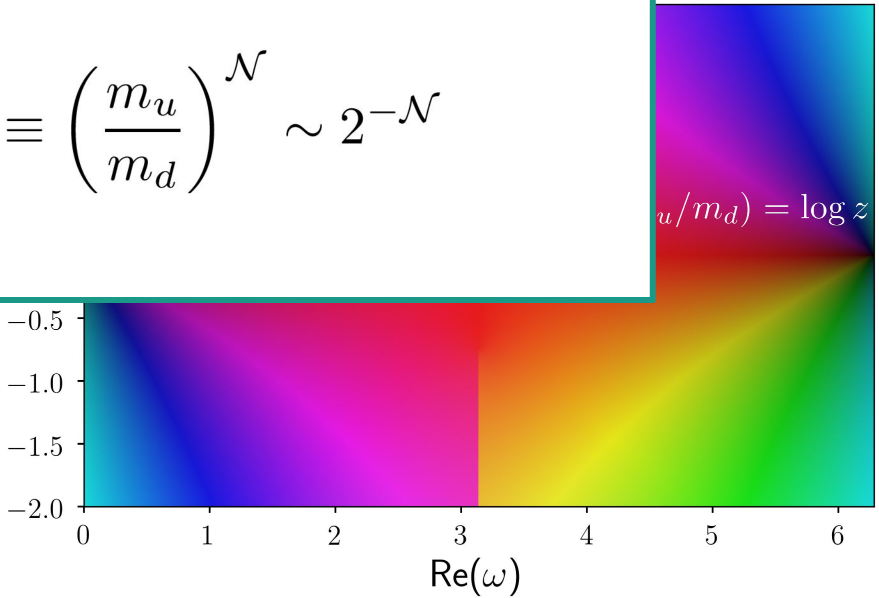
$$|E_{\mathcal{N}}(V$$

where M *denotes a bound for the*

The Z_N axion mass is exponentially suppressed:

$$\frac{m_a^2 f_a^2}{m_\pi^2 f_\pi^2} \propto z^{\mathcal{N}} \equiv \left(\frac{m_u}{m_d}\right)^{\mathcal{N}} \sim 2^{-\mathcal{N}}$$

$$\frac{m_a^2 f_a^2}{m_\pi^2 f_\pi^2} \propto z^{\mathcal{N}} \sim 2^{-\mathcal{N}}$$



Compact formula

$$V_{\mathcal{N}}(a) = -\sum_{k=0}^{N-1} m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a} + \frac{\pi k}{N}\right)}$$

➔ Using Fourier decomposition and Gauss hypergeometric functions we managed to show that:

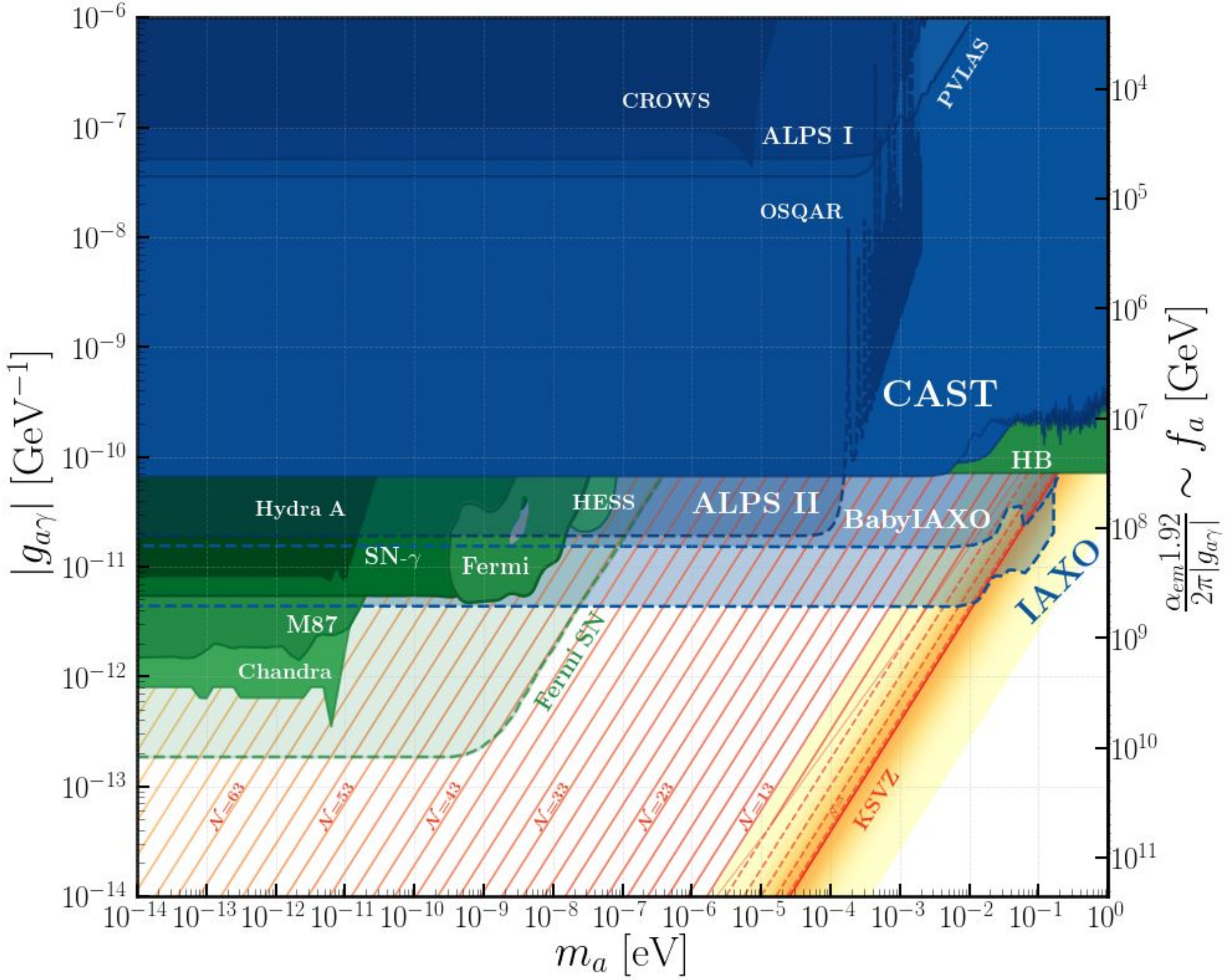
- The total Z_N axion potential approaches a cosine:

$$V_{\mathcal{N}}(\theta_a) \simeq -\frac{m_a^2 f_a^2}{\mathcal{N}^2} \cos(\mathcal{N}\theta_a)$$

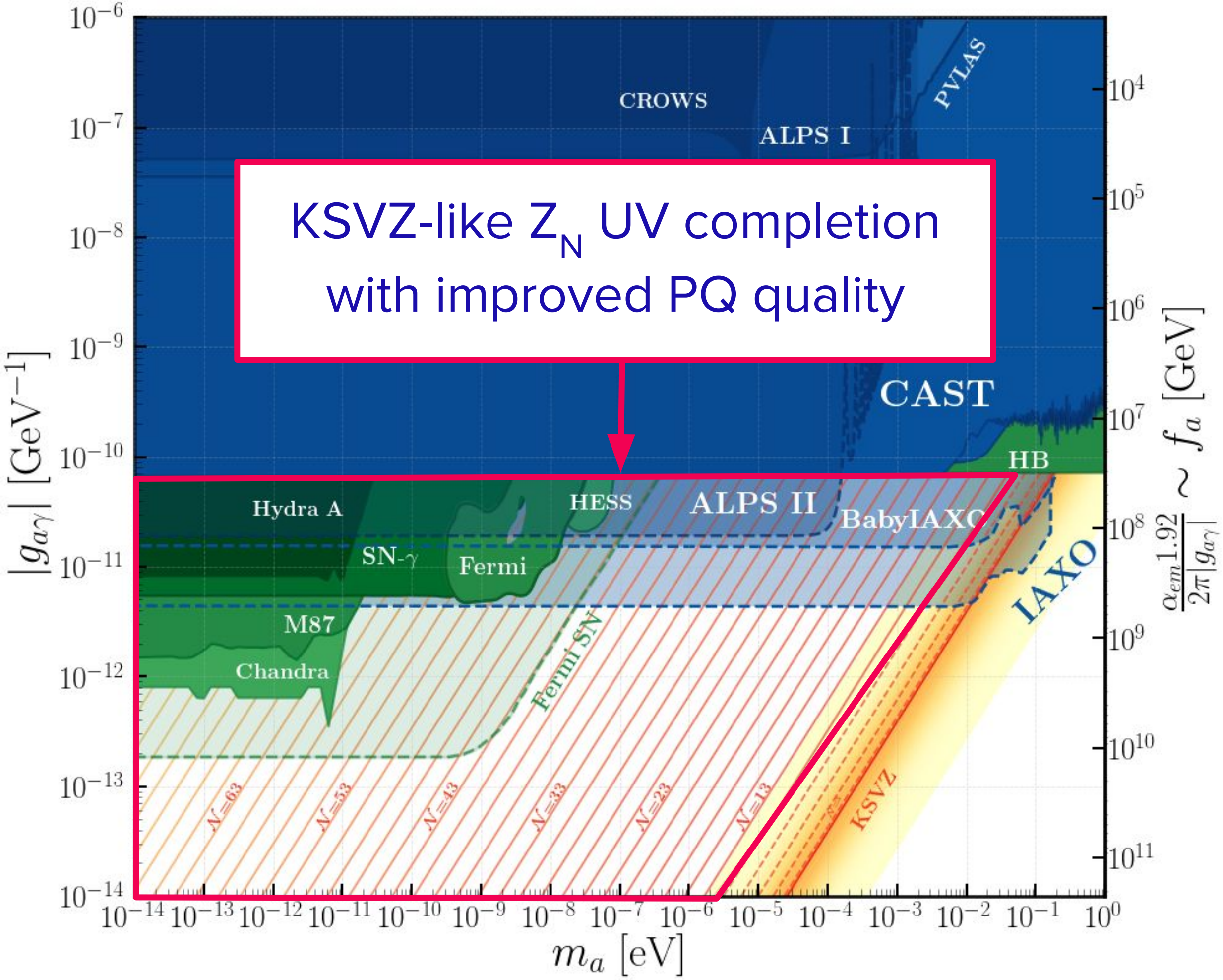
- Compact analytical formula for the Z_N axion mass

$$\boxed{m_a^2 f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{3/2} z^{\mathcal{N}}}$$

Based on **2102.00012** and **2102.01082**



Based on **2102.00012** and **2102.01082**



Based on **2102.00012** and **2102.01082**

Novel bounds from finite density effects

Vacuum: $$V_{\mathcal{N}}(\theta_a) = \sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) \sim m_\pi^2 f_\pi^2\, 2^{-\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

Exponentially small

Based on **2102.00012** and **2102.01082**

Novel bounds from finite density effects

Vacuum:

$$V_{\mathcal{N}}\left(\theta_a\right)=\sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a+\frac{2\pi k}{\mathcal{N}}\right) \sim m_\pi^2 f_\pi^2\, 2^{-\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

Exponentially small

High SM density:

$$V_{\mathcal{N}}^{f.d.}\left(\theta_a, n_N\right) \simeq \boxed{\left(1-\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2}\right) V\left(\theta_a\right)} + \sum_{k=1}^{\mathcal{N}-1} V\left(\theta_a+2\pi k/\mathcal{N}\right)$$

SM contribution is suppressed

Based on **2102.00012** and **2102.01082**

Novel bounds from finite density effects

Vacuum:

$$V_{\mathcal{N}}(\theta_a) = \sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) \sim m_\pi^2 f_\pi^2\, 2^{-\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

Exponentially small

High SM density:

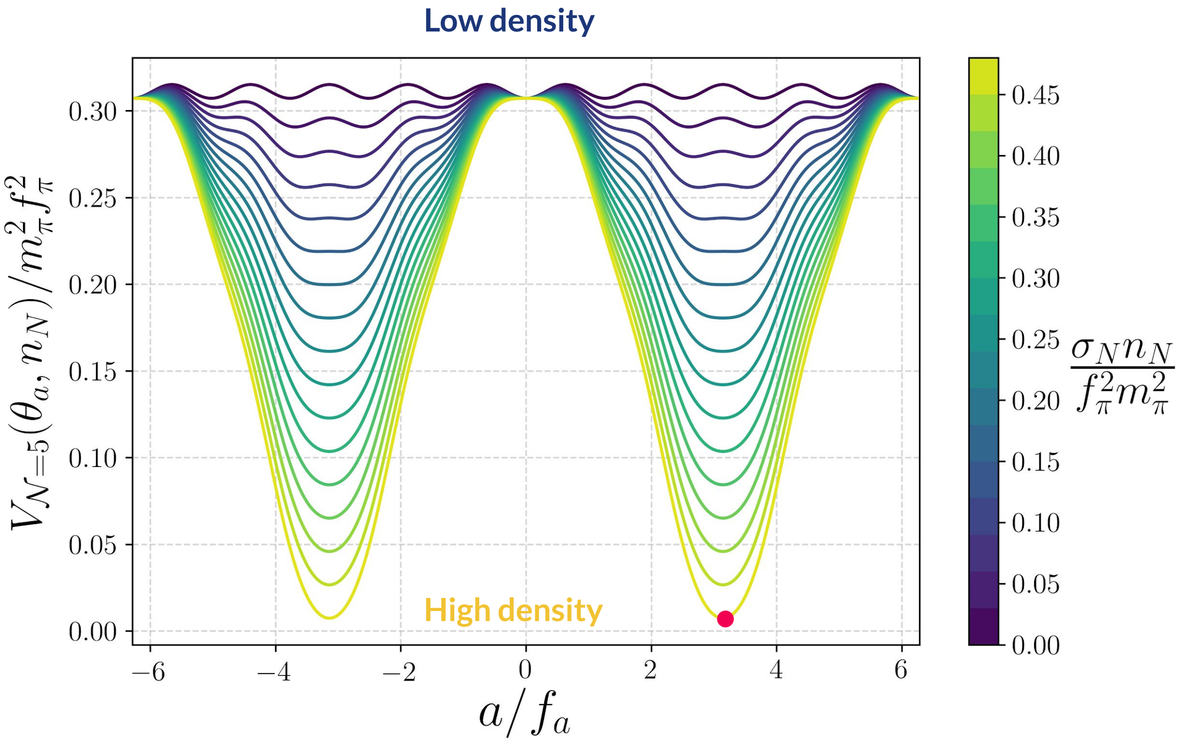
$$V_{\mathcal{N}}^{f.d.}(\theta_a, n_N) \simeq \boxed{\left(1-\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2}\right) V(\theta_a)} + \sum_{k=1}^{\mathcal{N}-1} V(\theta_a + 2\pi k/\mathcal{N})$$

SM contribution is suppressed

$$= -\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2} V(\theta_a) + \boxed{\sum_{k=0}^{\mathcal{N}-1} V(\theta_a + 2\pi k/\mathcal{N})} \xrightarrow{\mathcal{N}\gg 1} -\frac{\sigma_N n_N}{m_\pi^2 f_\pi^2} V(\theta_a)$$

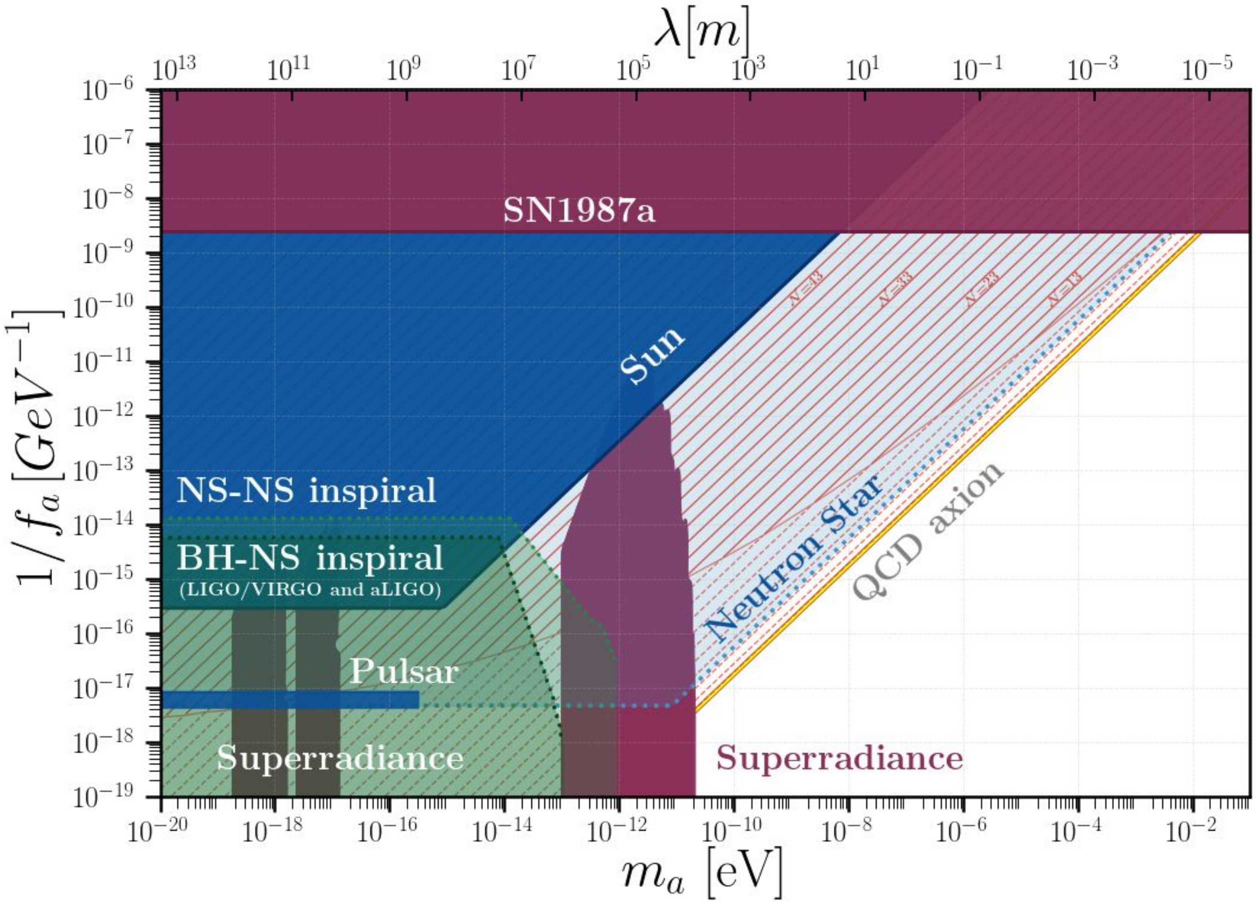
Based on **2102.00012** and **2102.01082**

Novel bounds from finite density effects



- A stellar object of high (SM) density is a background that breaks explicitly Z_N
- At high density the **minimum of the potential is in π**

Based on **2102.00012** and **2102.01082**



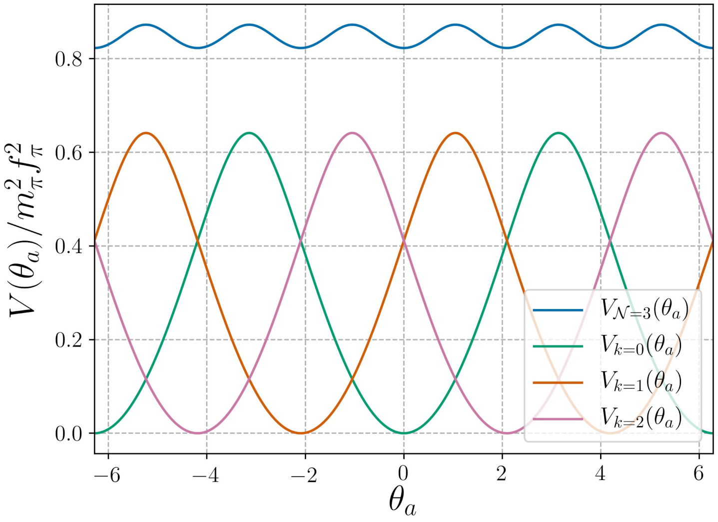
[Hook+Huang, 18]
[Huang et al 19]
[Di Luzio, PQ, Ringwald, Gavela, 21]
[Huang et al, 2105.13963]

Based on **2102.00012** and **2102.01082**

Caveat I

➔ There are N minima: we only solve the strong CP with 1/N prob

$$\theta_a = \{\pm 2\pi\ell/\mathcal{N}\} \qquad \text{for} \quad \ell = 0, 1, \ldots, \frac{\mathcal{N}-1}{2},$$



$$\bar{\theta} \lesssim 10^{-10}$$

$$\downarrow$$

$$1/\mathcal{N} \text{ probability}$$

Based on **2102.00012** and **2102.01082**

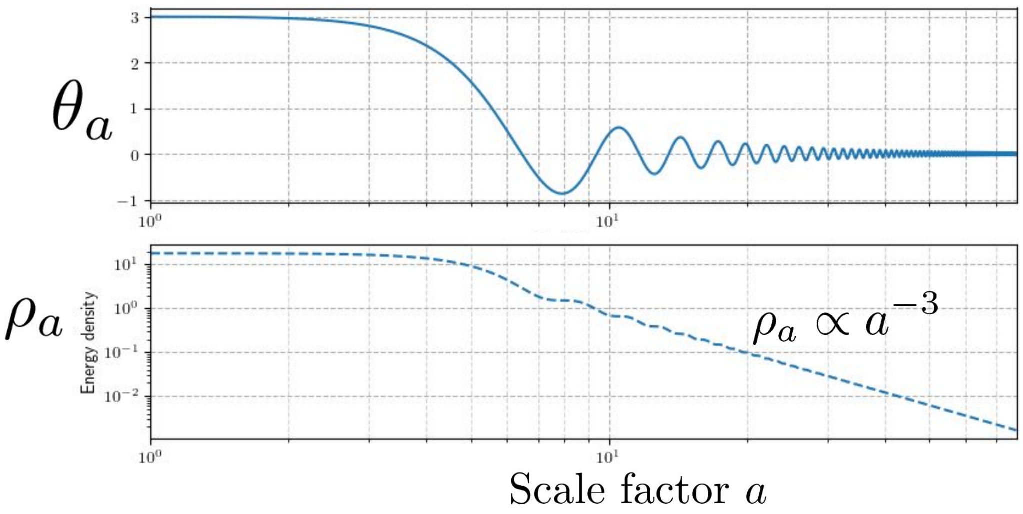
Dark matter from the Z_N axion

Trapped misalignment

Axion DM: Misalignment mech.

$$\ddot{\theta}_a + 3H\dot{\theta}_a + m_a^2 \sin(\theta_a) = 0$$

~Damped harmonic oscillator: $\left(\ddot{x} + \gamma\dot{x} + \omega^2 x = 0\right)$



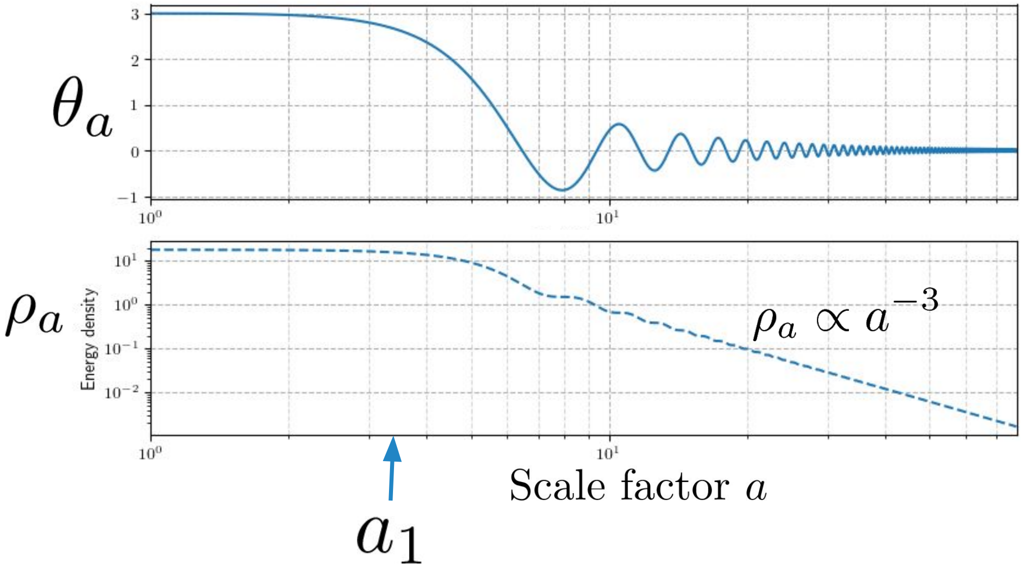
[Abbot+Sikivie, 83]
[Dine and W. Fischler, 83]
[Preskil et al, 91]

Based on **2102.00012** and **2102.01082**

Axion DM: Misalignment mech.

$$\ddot{\theta}_a + 3H\dot{\theta}_a + m_a^2 \sin(\theta_a) = 0$$

~Damped harmonic oscillator: $\left(\ddot{x} + \gamma\dot{x} + \omega^2 x = 0\right)$



Current axionic relic density:

$$\rho_{a,0} \simeq \frac{1}{2} m_a^2 (\theta_i f_a)^2 \boxed{\left(\frac{a_1}{a_0}\right)^3}$$

Dilution factor

[Abbot+Sikivie, 83]
[Dine and W. Fischler, 83]
[Preskil et al, 91]

Based on **2102.00012** and **2102.01082**

What about the Z_N axion?

Mirror world cosmology

- ➔ Mirror worlds need to be colder than SM due to N_{eff} bounds:

$$\text{BBN: } N_{\text{eff}} = 2.89 \pm 0.57 \,, \qquad \text{CMB: } N_{\text{eff}} = 2.99^{+0.34}_{-0.33} \,. \qquad \frac{T'}{T} < \frac{0.51}{(\mathcal{N}-1)^{1/4}} \,,$$

Finite temperature Z_N axion potential

Vacuum:

$$V_{\mathcal{N}}(\theta_a) = \sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) \sim m_\pi^2 f_\pi^2\, 2^{-\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

Exponentially small

High SM temperatures:

$$T \geq \Lambda_{\rm QCD}$$

$$\begin{aligned} V_{\mathcal{N}}^{MT}(\theta_a, T) &\simeq \left(\frac{T_{\rm QCD}}{T}\right)^{\alpha} V(\theta_a) + \sum_{k=1}^{\mathcal{N}-1} V(\theta_a + 2\pi k/\mathcal{N}) \\ &= \left[\left(\frac{T_{\rm QCD}}{T}\right)^{\alpha} - 1\right] V(\theta_a) + \sum_{k=0}^{\mathcal{N}-1} V(\theta_a + 2\pi k/\mathcal{N}) \\ &\simeq \left[\left(\frac{T_{\rm QCD}}{T}\right)^{\alpha} - 1\right] V(\theta_a) - m_\pi^2 f_\pi^2 \frac{1}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{-1/2} (-1)^{\mathcal{N}} z^{\mathcal{N}} \cos(\mathcal{N}\theta_a) \\ &\xrightarrow{T \gg T_{\rm QCD}} -V(\theta_a)\,, \end{aligned} \tag{3.6}$$

[Di Luzio, PQ, Ringwald, Gavela, 21]

Based on **2102.00012** and **2102.01082**

Finite temperature Z_N axion potential

Vacuum:

$$V_{\mathcal{N}}(\theta_a) = \sum_{k=0}^{\mathcal{N}-1} V\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) \sim m_\pi^2 f_\pi^2 \, 2^{-\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

Exponentially small

High SM temperatures:

$$T \geq \Lambda_{\rm QCD}$$

$$\begin{aligned} V_{\mathcal{N}}^{MT}(\theta_a, T) &\simeq \left(\frac{T_{\rm QCD}}{T}\right)^\alpha V(\theta_a) + \sum_{k=1}^{\mathcal{N}-1} V(\theta_a + 2\pi k/\mathcal{N}) \\ &= \left[\left(\frac{T_{\rm QCD}}{T}\right)^\alpha - 1\right] V(\theta_a) + \sum_{k=0}^{\mathcal{N}-1} V(\theta_a + 2\pi k/\mathcal{N}) \\ &\simeq \left[\left(\frac{T_{\rm QCD}}{T}\right)^\alpha - 1\right] V(\theta_a) - m_\pi^2 f_\pi^2 \frac{1}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{-1/2} (-1)^{\mathcal{N}} z^{\mathcal{N}} \cos(\mathcal{N}\theta_a) \\ &\xrightarrow{T \gg T_{\rm QCD}} -V(\theta_a)\,, \end{aligned} \tag{3.6}$$

- **Unsuppressed potential**
- **Minimum in π**

$$V_{\mathcal{N}}(\theta_a) \simeq -V_{SM}(\theta_a)$$

[Di Luzio, PQ, Ringwald, Gavela, 21]

Based on **2102.00012** and **2102.01082**

Finite temperature Z_N axion potential

Vacuum: [redacted]

Exponentially small

High SM temperatures: [redacted]

$T \geq \Lambda_{\text{QCD}}$

- **Unsuppressed po**[redacted]
- **Minimum in π**

$V_{\mathcal{N}}(\theta_a) \simeq -V_{SM}($[redacted]

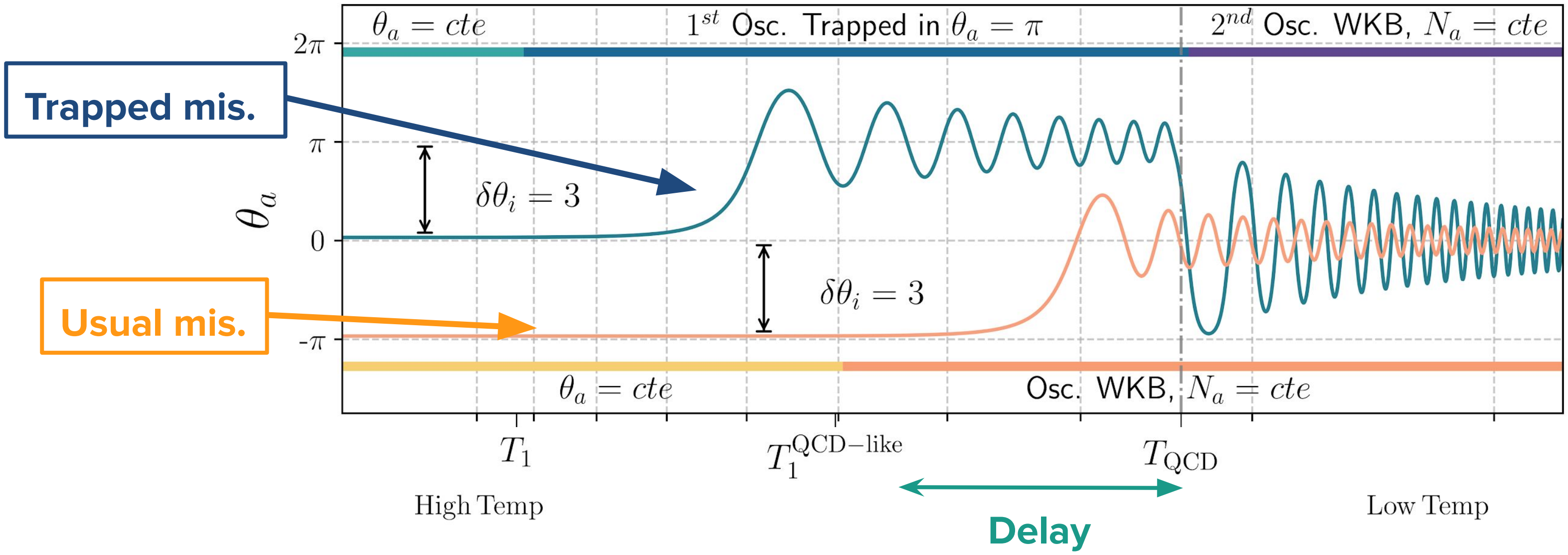
$\mathcal{N}^{-1/2}(-1)^{\mathcal{N}} z^{\mathcal{N}} \cos\left(\mathcal{N}\theta_a\right)$

(3.6)

Based on **2102.00012** and **2102.01082**

Trapped misalignment mechanism

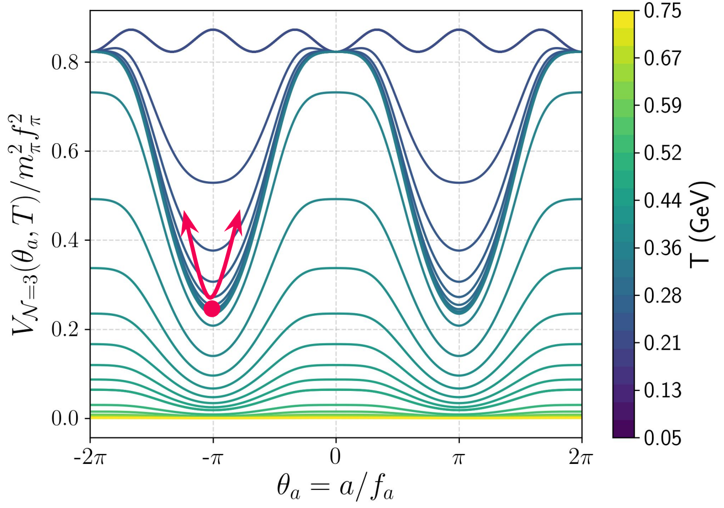
Trapped misalignment mechanism

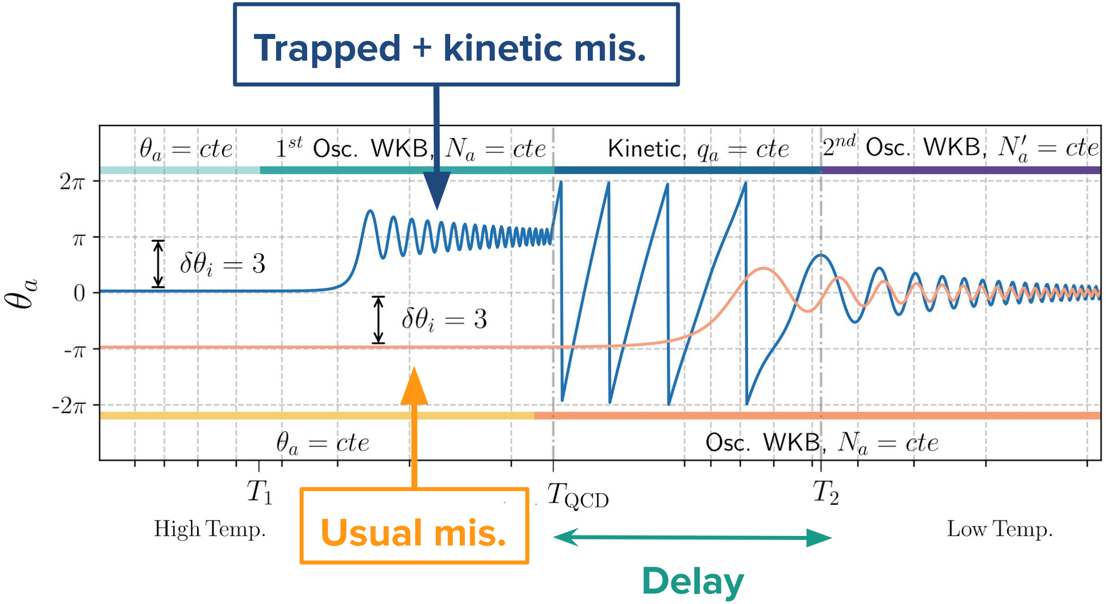


- Delayed onset of oscillations = Less dilution = More DM

Based on **2102.00012** and **2102.01082**

Trapped + kinetic misalignment



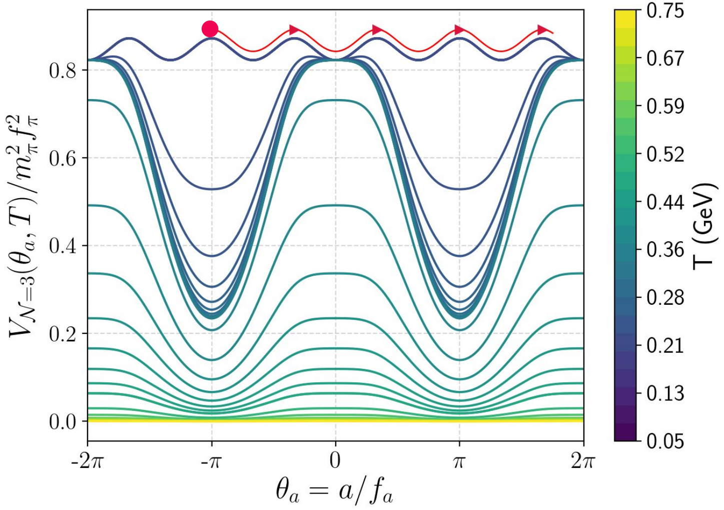


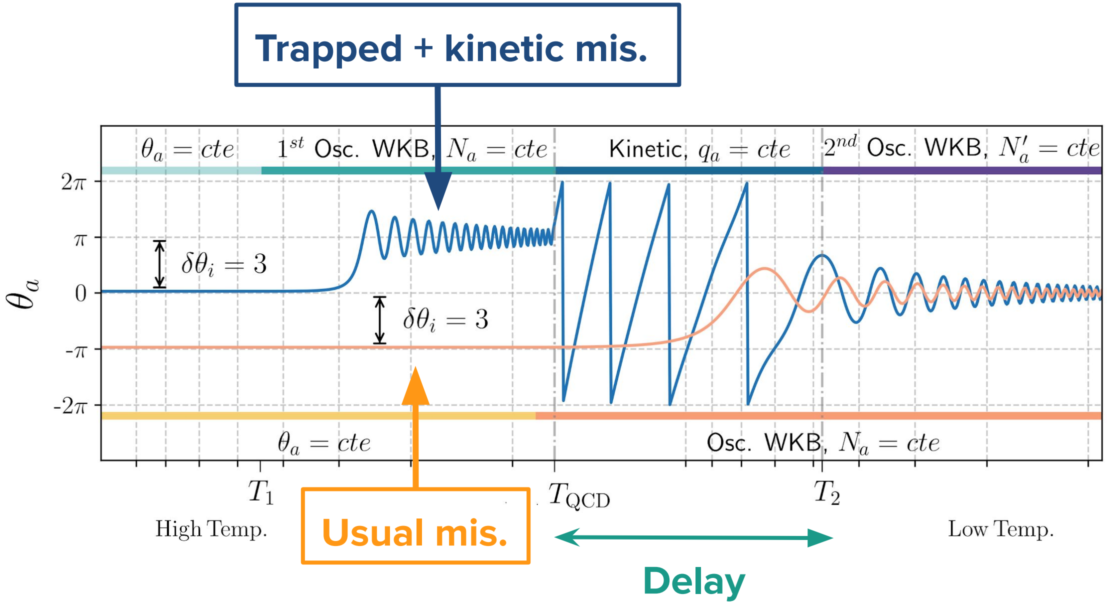
- Further delay of the onset of oscillations

[Co, Hall, Harigaya, 19]
[Di Luzio, Gavela, PQ, Ringwald, , 21]

Based on **2102.00012** and **2102.01082**

Trapped + kinetic misalignment

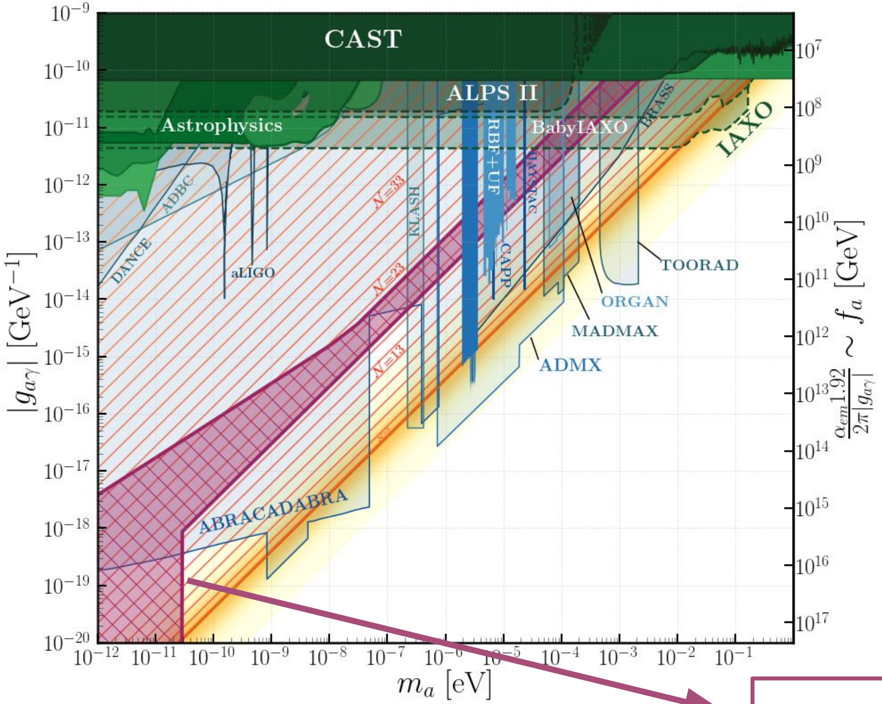


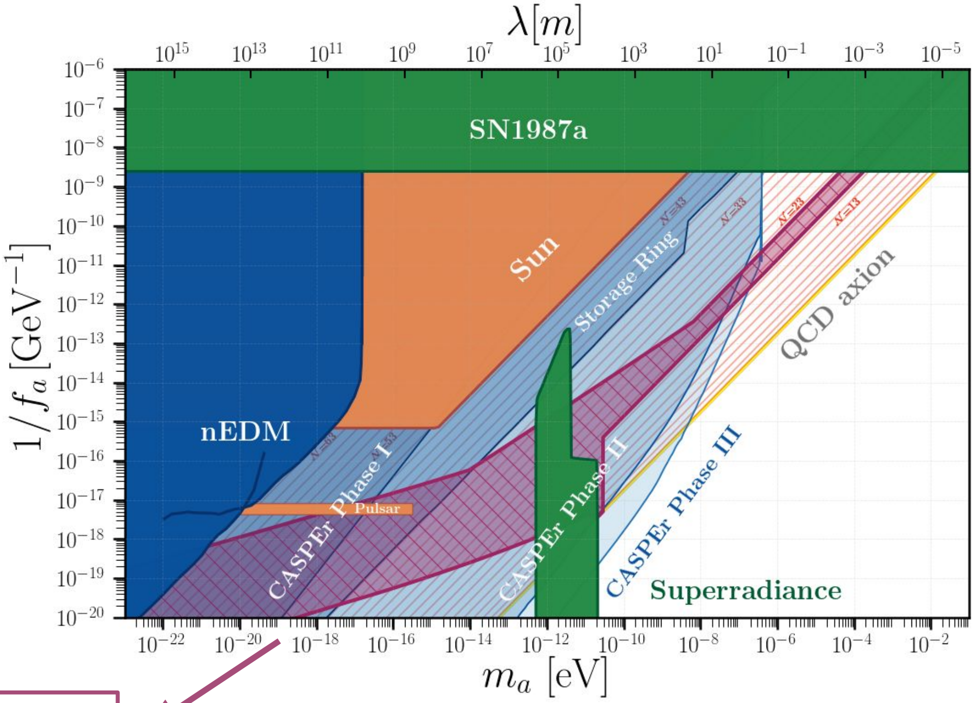


- Further delay of the onset of oscillations

[Co, Hall, Harigaya, 19]
[Di Luzio, Gavela, PQ, Ringwald, , 21]

Based on **2102.00012** and **2102.01082**





Z_N Axion DM

Based on **2102.00012** and **2102.01082**

Conclusions

$$m_a^2 f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{3/2} z^{\mathcal{N}}$$

- ➔ Proof of concept: the QCD axion can be even lighter
- ➔ UV completions: KSVZ is PQ protected
- ➔ Motivates regions accessible by ALPS II, BabyIAXO, IAXO...
- ➔ Both finite density and temperature effects are crucial
- ➔ The Z_N axion can explain DM in large regions of $\{m_a, f_a\}$ $\quad 3 \leq \mathcal{N} \leq 65.$
- ➔ Novel production mechanism: trapped misalignment
- ➔ It can source kinetic misalignment

Based on **2102.00012** and **2102.01082**

Caveats and outlook

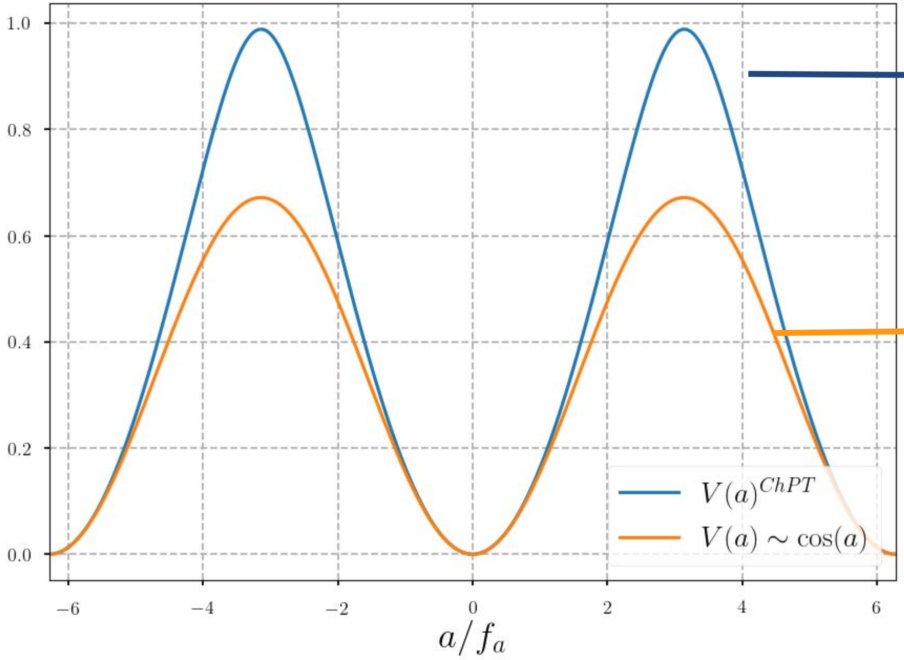
- ➔ N worlds is non-minimal: extra dimensions? strings?
- ➔ Solve the strong CP with 1/N prob.
- ➔ Trapped misalignment:
  - ◆ Only zero mode: Axion fragmentation?
  - ◆ Trapped in other scenarios

Thank you

Pablo Quílez Lasanta

Backup slides

True axion potential



$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a}\right)}$$

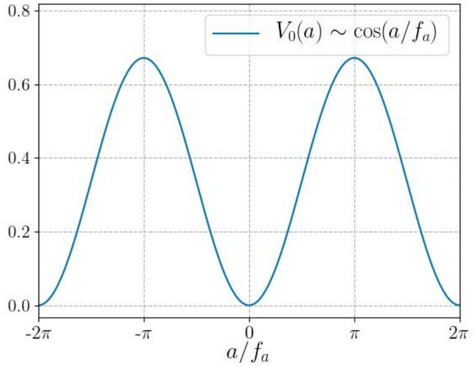
[Di Vecchia +Veneziano,80]
[Leutwyler+Smilga, 92]
[di Cortona et al, 15]

$$V(a) \sim -m_a^2 f_a^2 \cos(a/f_a)$$

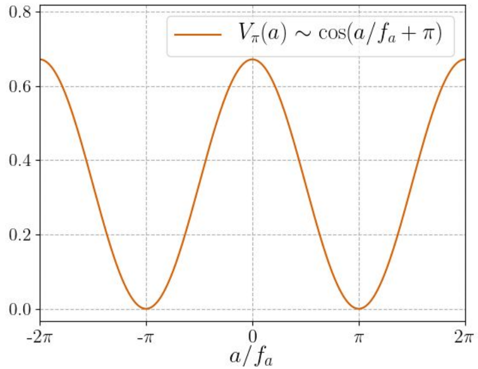
Based on **2102.00012** and **2102.01082**

What about lighter axions?

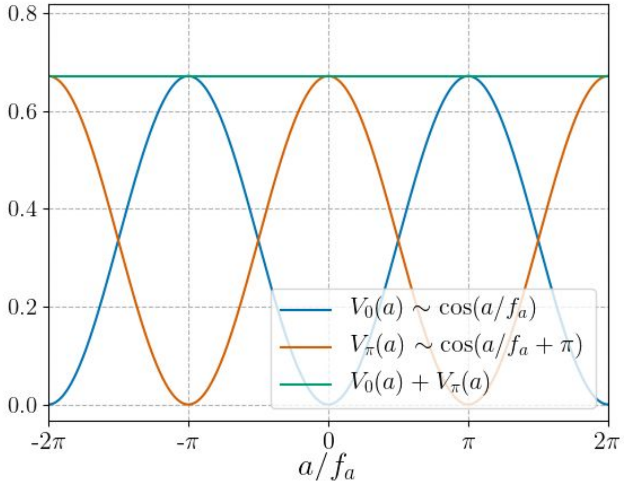
SM



SM'

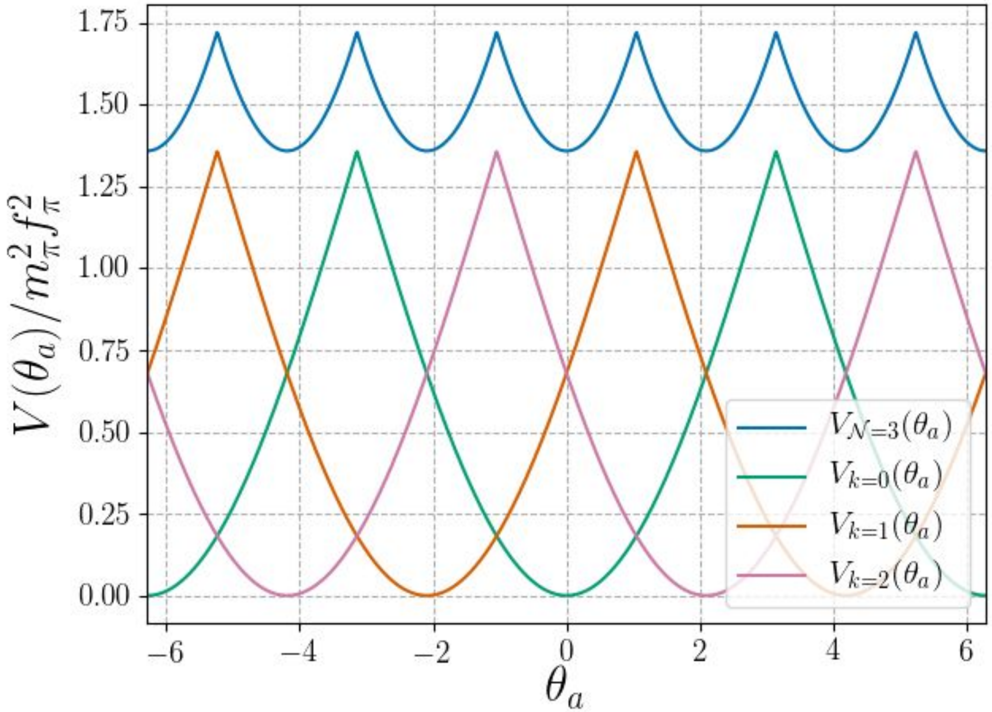


Completely massless axion?



Based on **2102.00012** and **2102.01082**

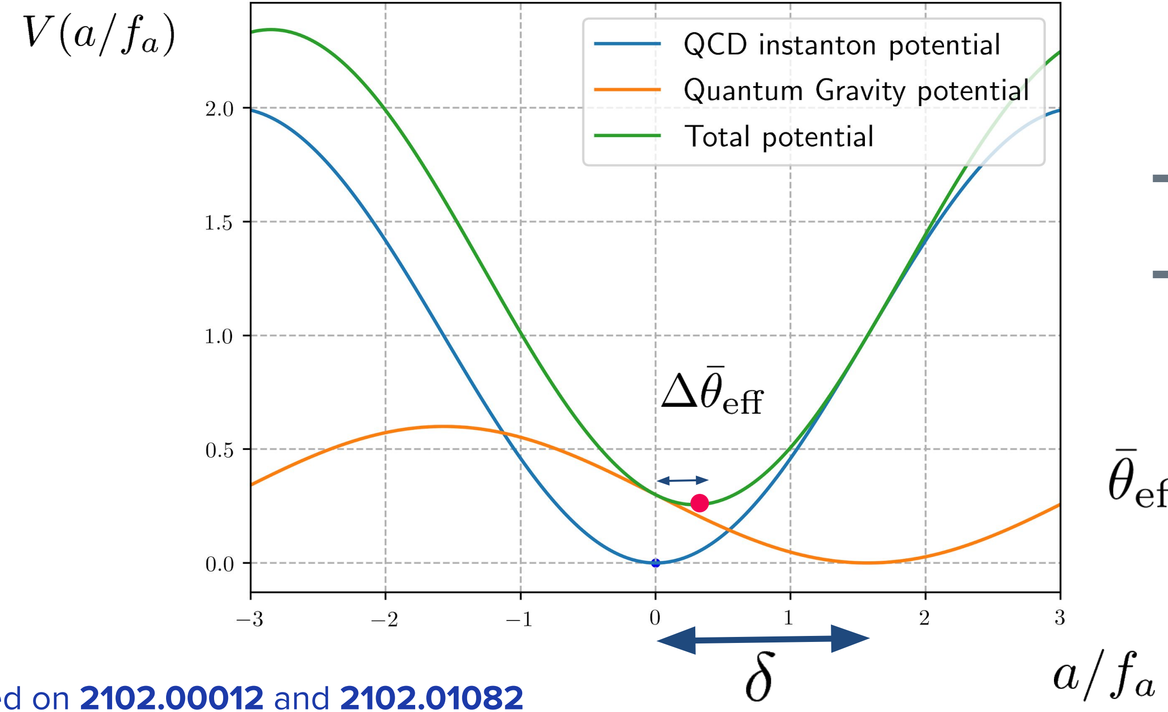
Potential for N=3, Z=1



Based on **2102.00012** and **2102.01082**

Axion potential

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} \longrightarrow V(a/f_a) \sim m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u+m_d)^2}\cos(a/f_a)$$

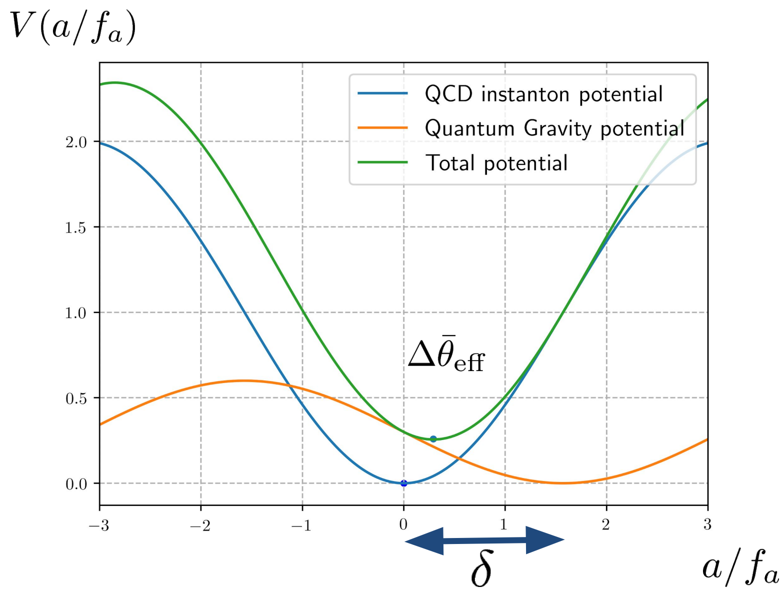


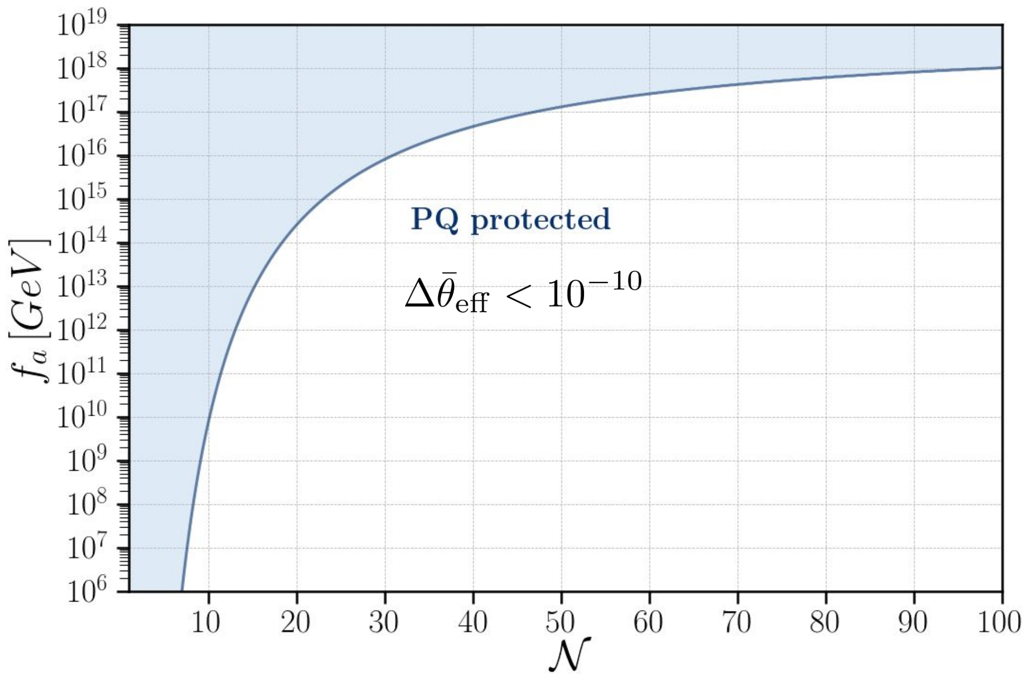
- Alignment
- Cancelation

$$\bar{\theta}_{\text{eff}} = \langle \bar{\theta} - \frac{a}{f_a} \rangle \neq 0$$

Based on **2102.00012** and **2102.01082**

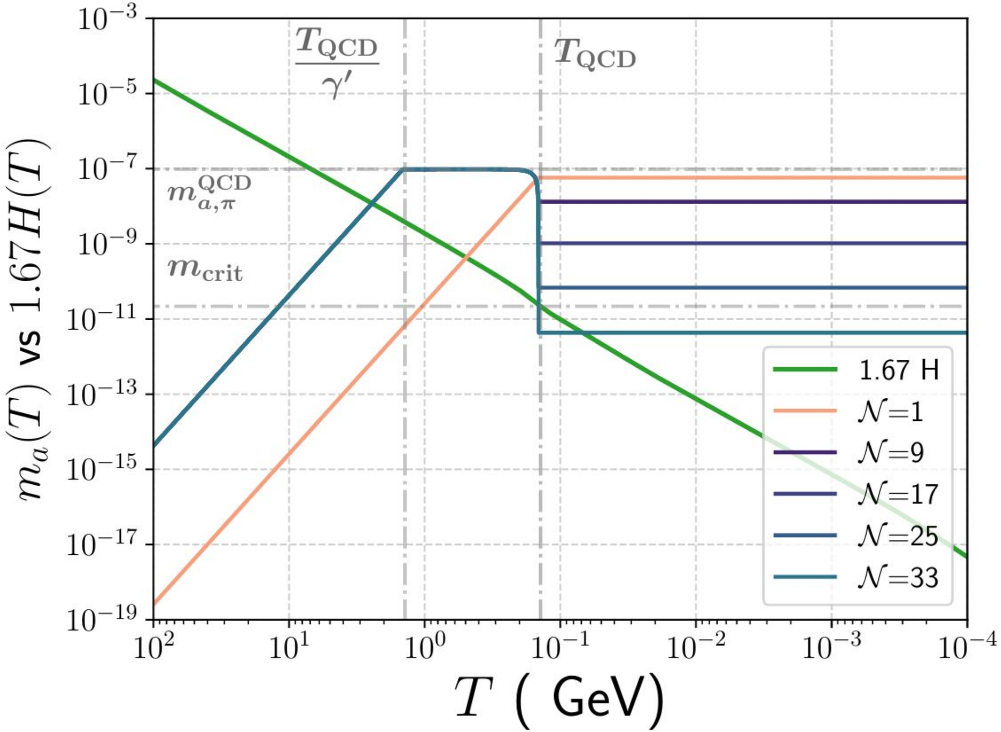
PQ quality: KSVZ-like Z_N



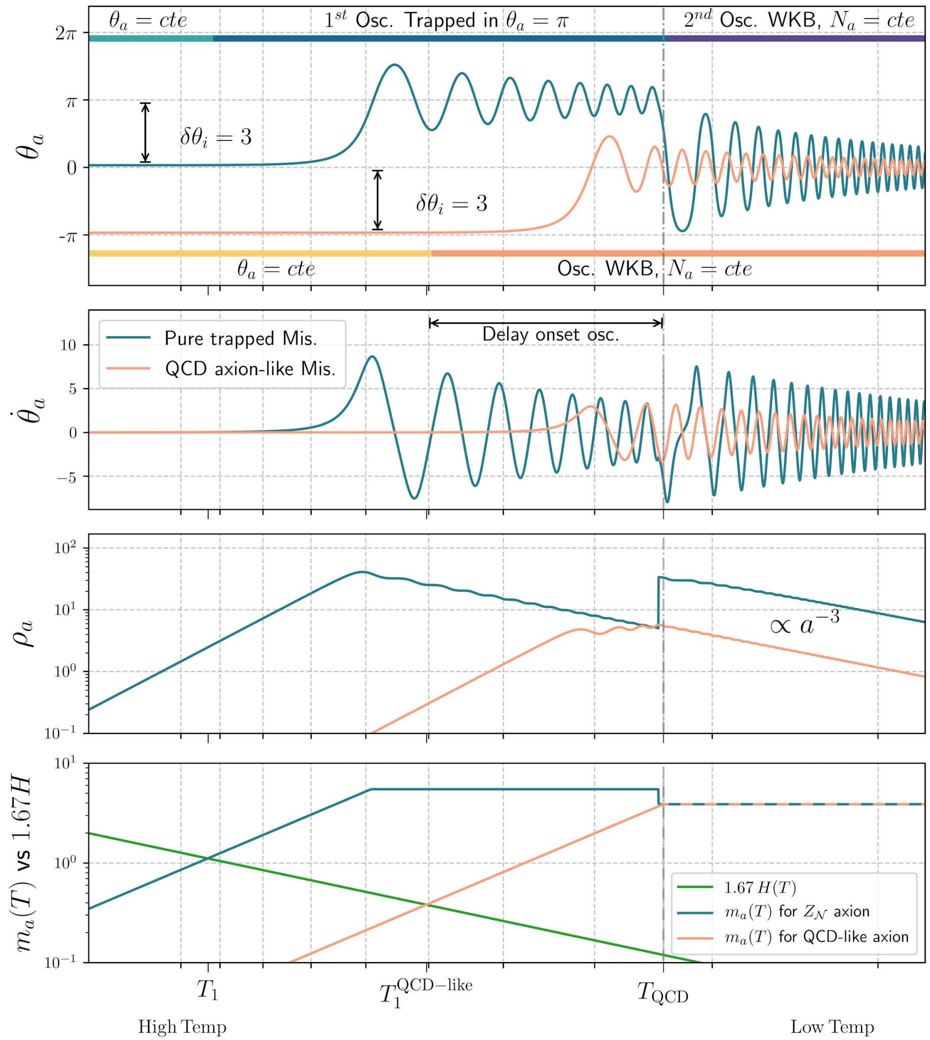


Based on **2102.00012** and **2102.01082**

Temperature dependence

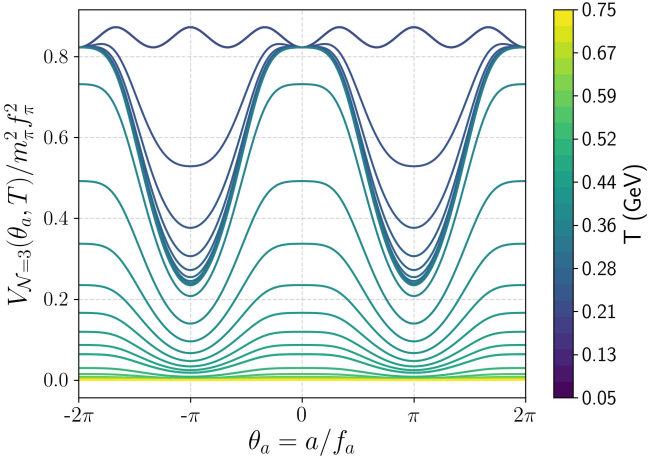


Based on **2102.00012** and **2102.01082**



Trapped misalignment mechanism

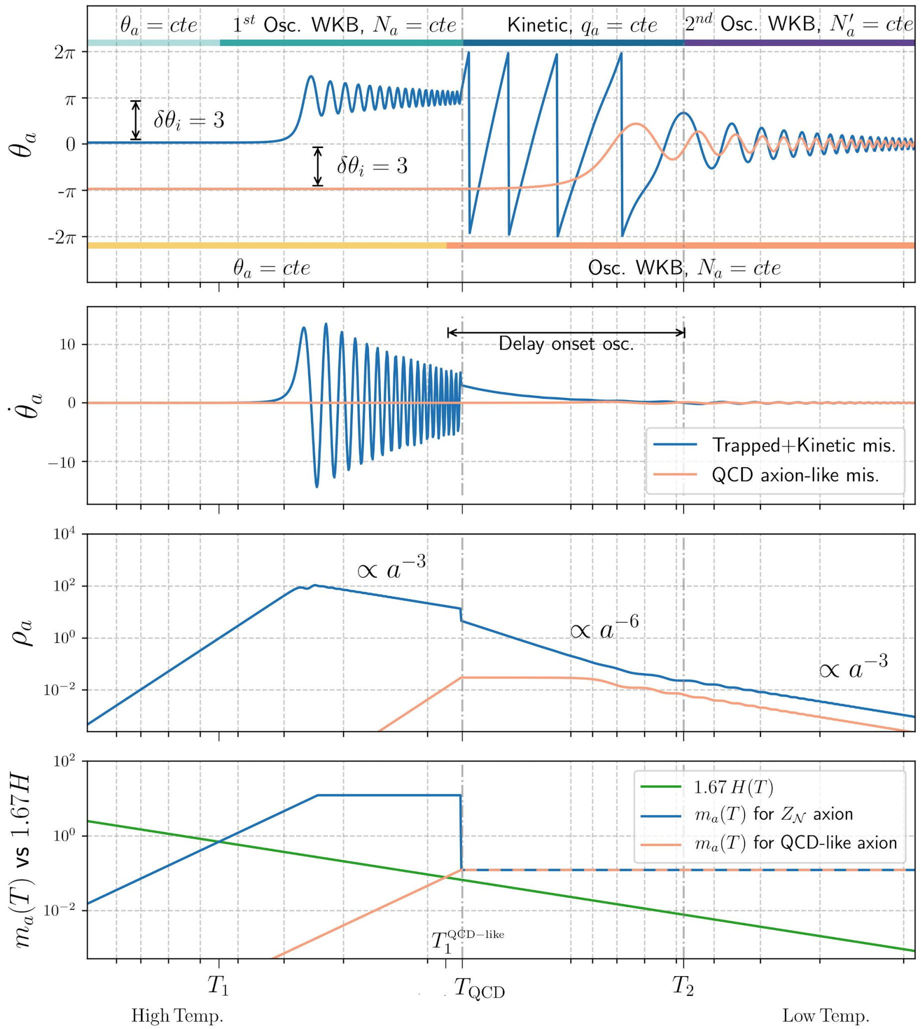
- Compare trapped (blue) with usual misalignment (orange)
- At high temperatures the axion is trapped in the wrong minimum
- The onset of oscillations is delayed
- Less dilution = more dark matter

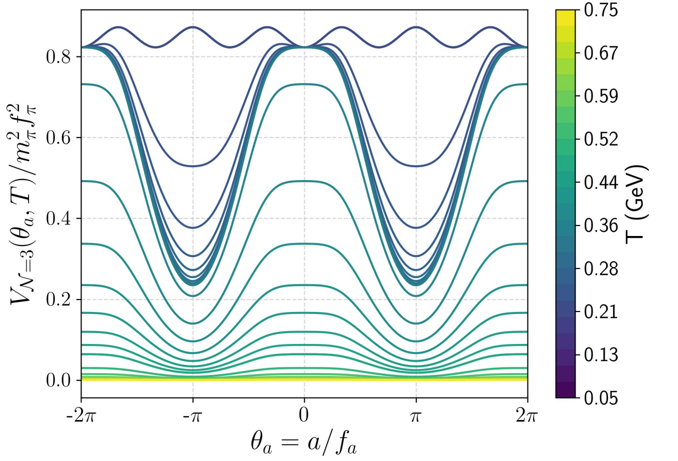


Trapped+kinetic mechanism

[Co+Hall+Harigaya, 19]
[Di Luzio+ PQ+Ringwald +Gavela, 21]

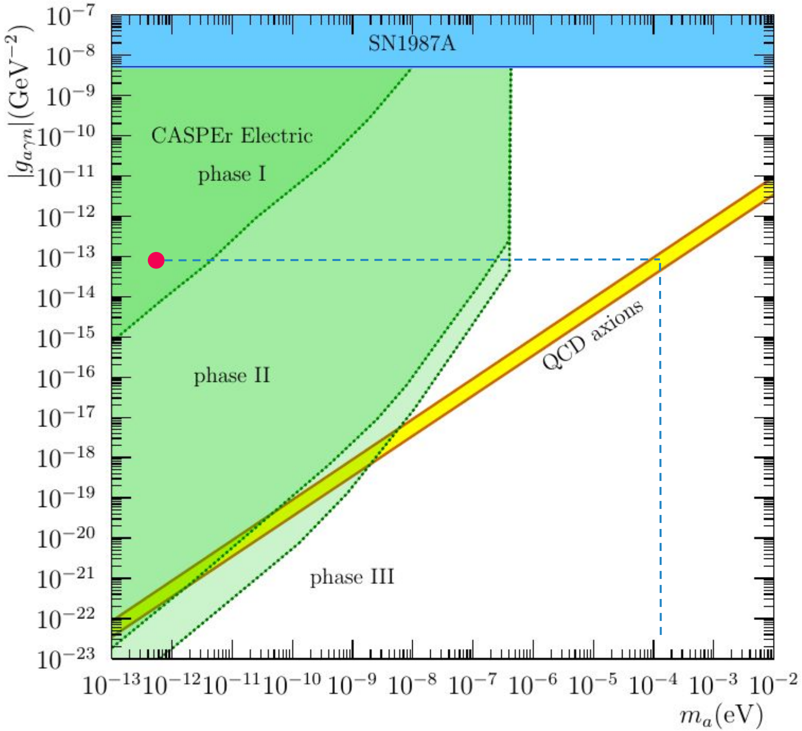
- Compare trapped+kinetic (blue) with usual misalignment (orange)
- After trapping the axion has enough kinetic energy to overcome the barriers
- The onset of oscillations is delayed even further
- Less dilution = more dark matter





Could CASPEr Phase I detect an axion?

$g_{a\gamma n}$



[Irastorza+Redondo, 18]

Based on **2102.00012** and **2102.01082**

$m_a\,(eV)$

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

$$\delta\mathcal{L} \equiv -\frac{i}{2}\frac{0.011\,e}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

$$\equiv g_{a\gamma n}$$

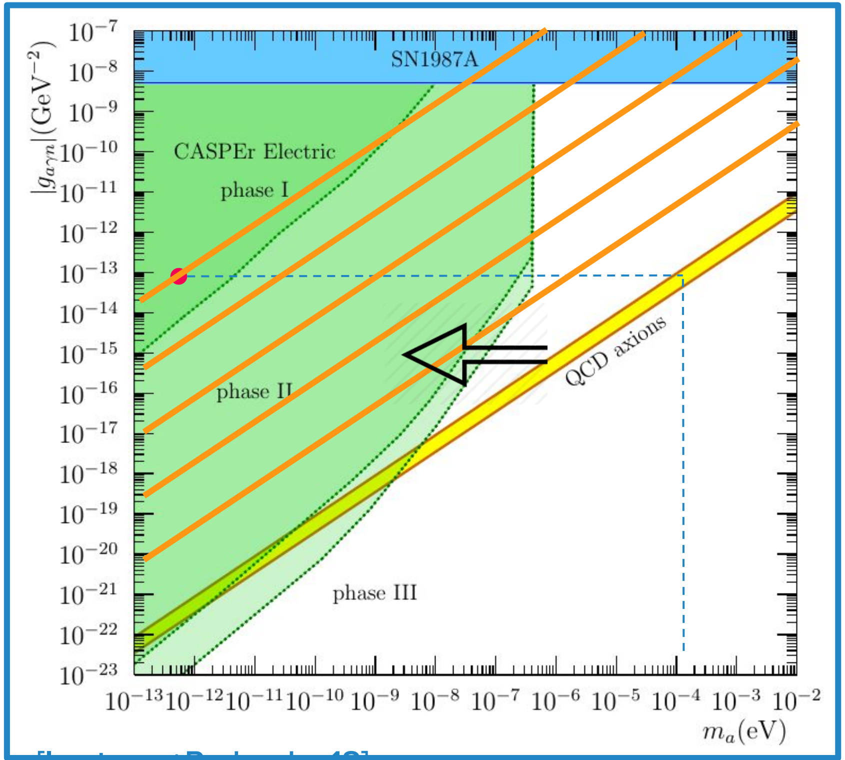
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u+m_d)^2}$$

Coupling to the nEDM

Axion mass

Could CASPEr Phase I detect an axion?

$g_{a\gamma n}$



[Irastorza+Redondo, 18]

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G} + \dots$$

$$\delta\mathcal{L} \equiv -\frac{i}{2}\frac{0.011\, e}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

$$\equiv g_{a\gamma n}$$

$$\cancel{m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}}$$

$$\boxed{m_a^2\, f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{3/2}\, z^{\mathcal{N}}}$$

Coupling to the nEDM

Axion mass

$m_a\,(eV)$

Based on **2102.00012** and **2102.01082**

Can the QCD axion be fuzzy Dark Matter?

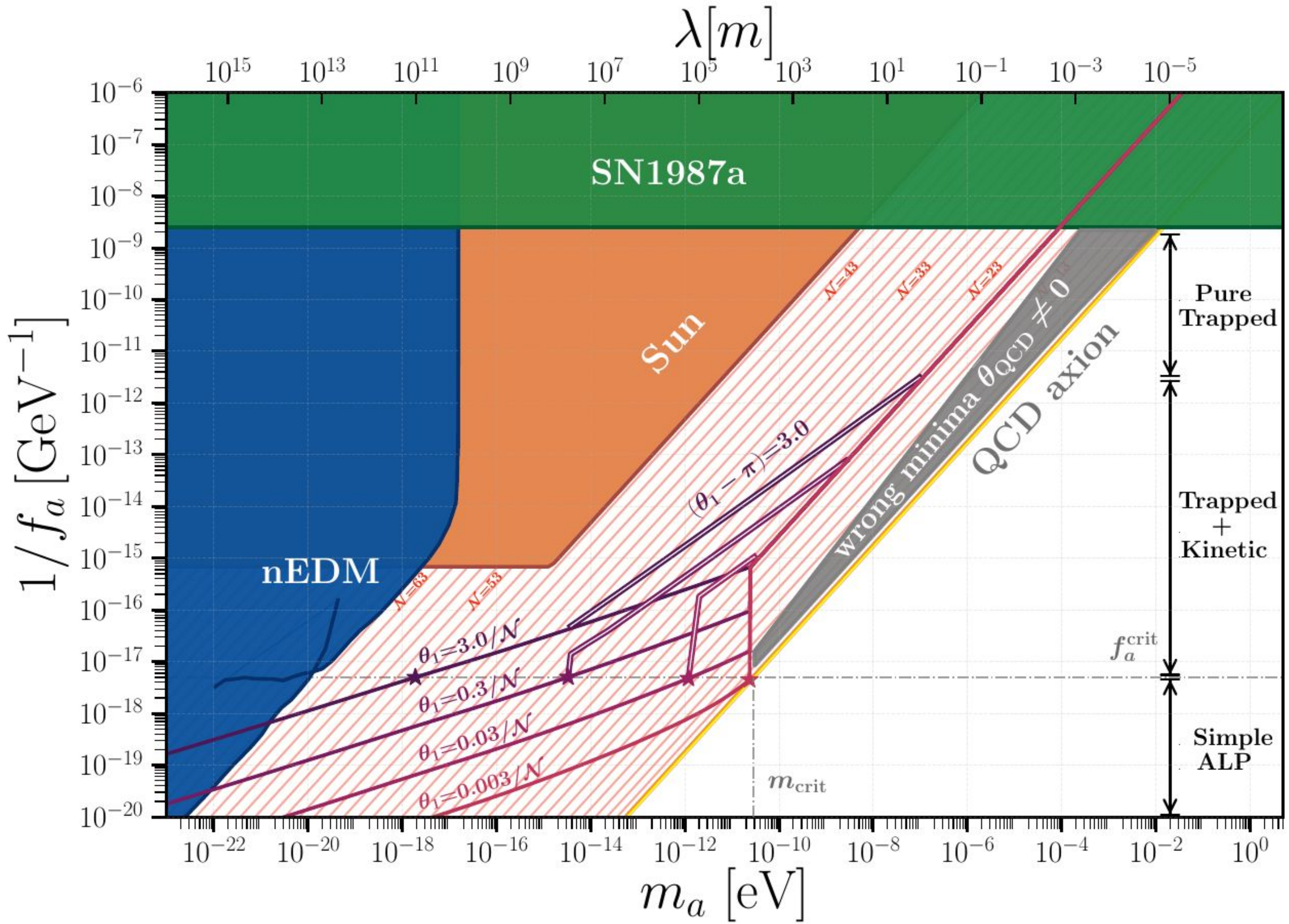
➔ Fuzzy dark matter: light boson with $m_a \sim 10^{-22} - 10^{-20}\,\mathrm{eV}\,, \quad \lambda_c \sim kpc$

White paper [1904.09003]

$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

$$m_a \sim 10^{-22}\,\mathrm{eV} \implies f_a \sim 10^{28}\,\mathrm{GeV} \gg M_{\mathrm{Pl}}$$

NO, a canonical axion would have transplanckian decay constant



λ[m]
10^15
10^13
10^11
10^9
10^7
10^5
10^3
10^1
10^−1
10^−3
10^−5
SN1987a
Sun
nEDM
N=63
N=53
N=43
N=33
N=23
wrong minima θQCD ≠ 0
QCD axion
(θ1 − π)=3.0
θ1=3.0/N
θ1=0.3/N
θ1=0.03/N
θ1=0.003/N
f_a^crit
m_crit
Pure Trapped
Trapped + Kinetic
Simple ALP
1/f_a [GeV^−1]
m_a [eV]