An even lighter QCD axion.

PHENO 21 - May 24th 2021

Pablo Quílez Lasanta - pablo.quilez@desy.de

Based on "*An even lighter QCD axion*" 2102.00012

"*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]

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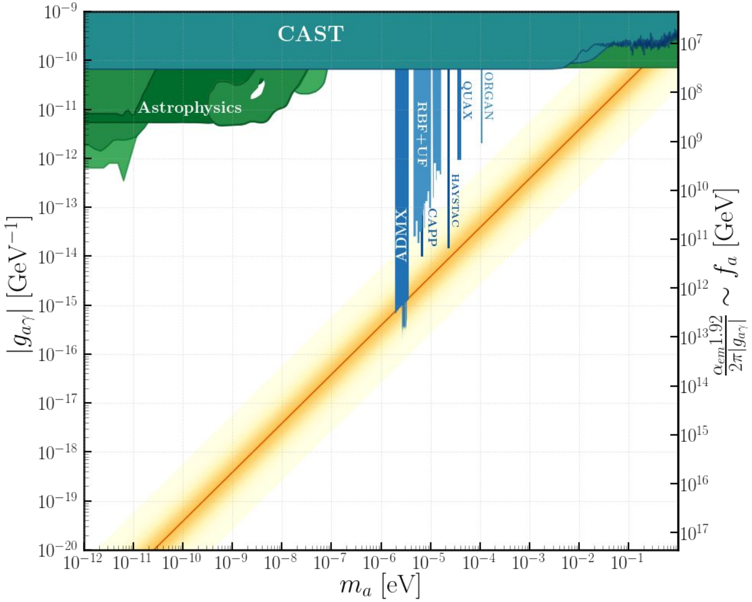

Based on **2102.00012** and **2102.01082**

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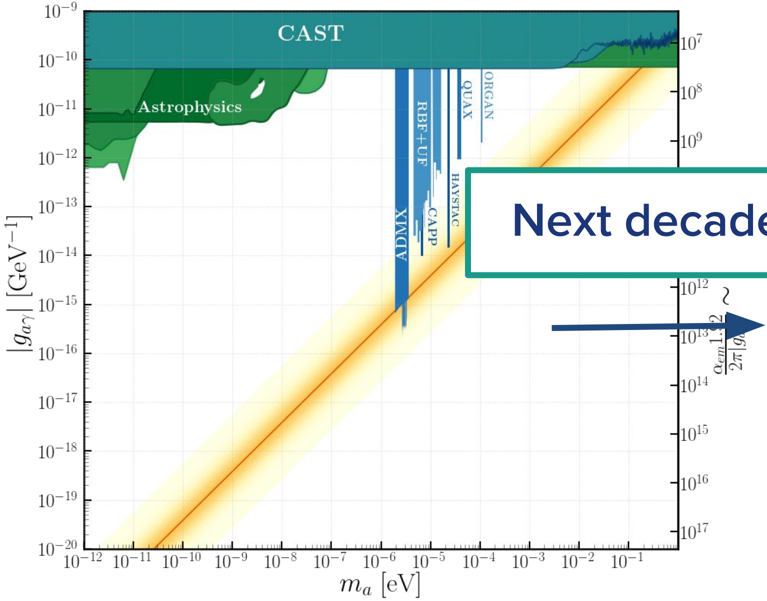
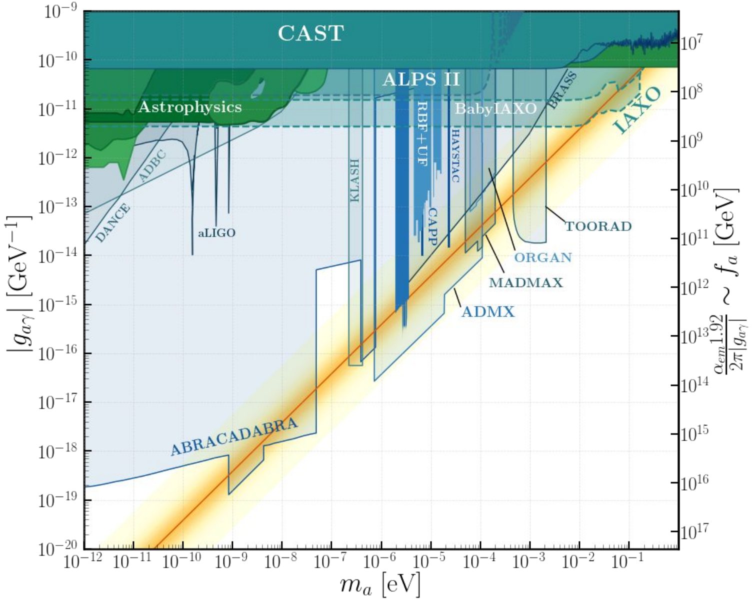
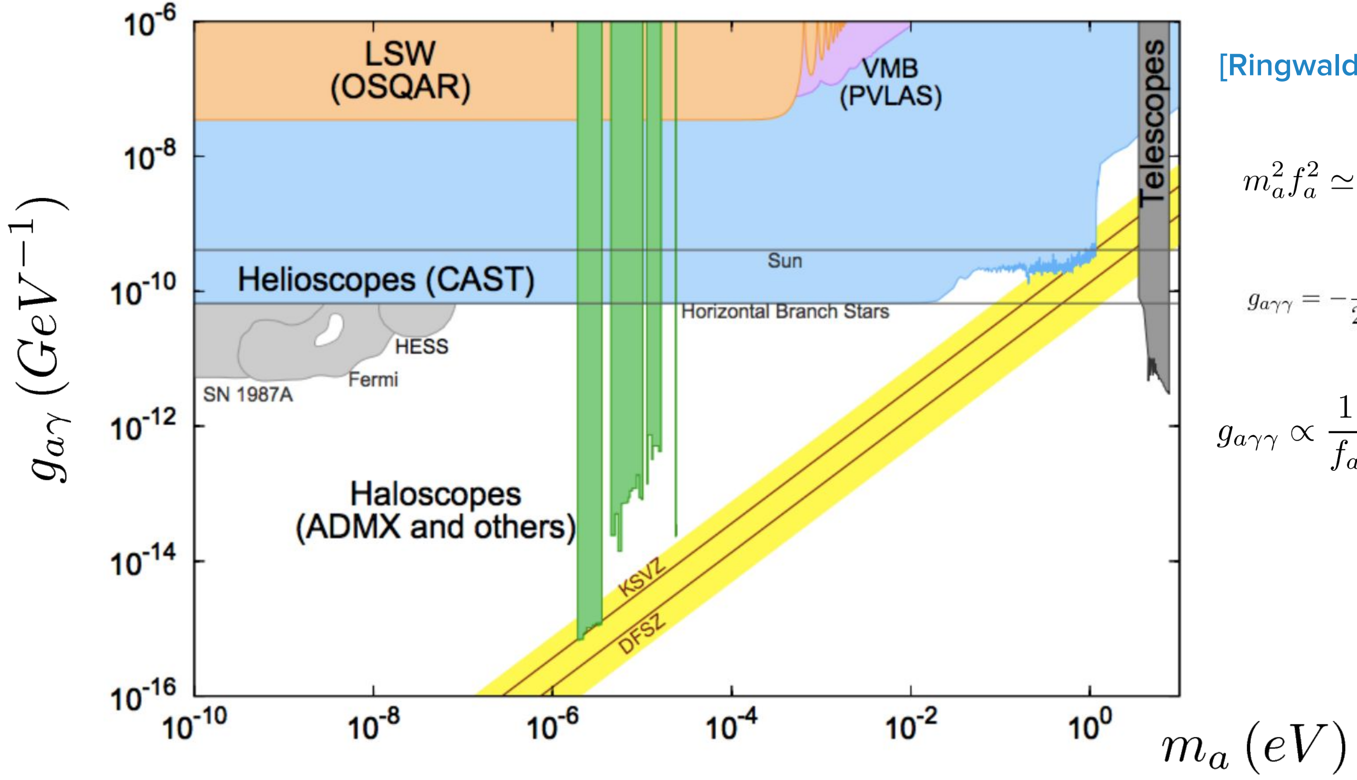


Next decades



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

Invisible axion parameter space



[Ringwald, PDG 17]

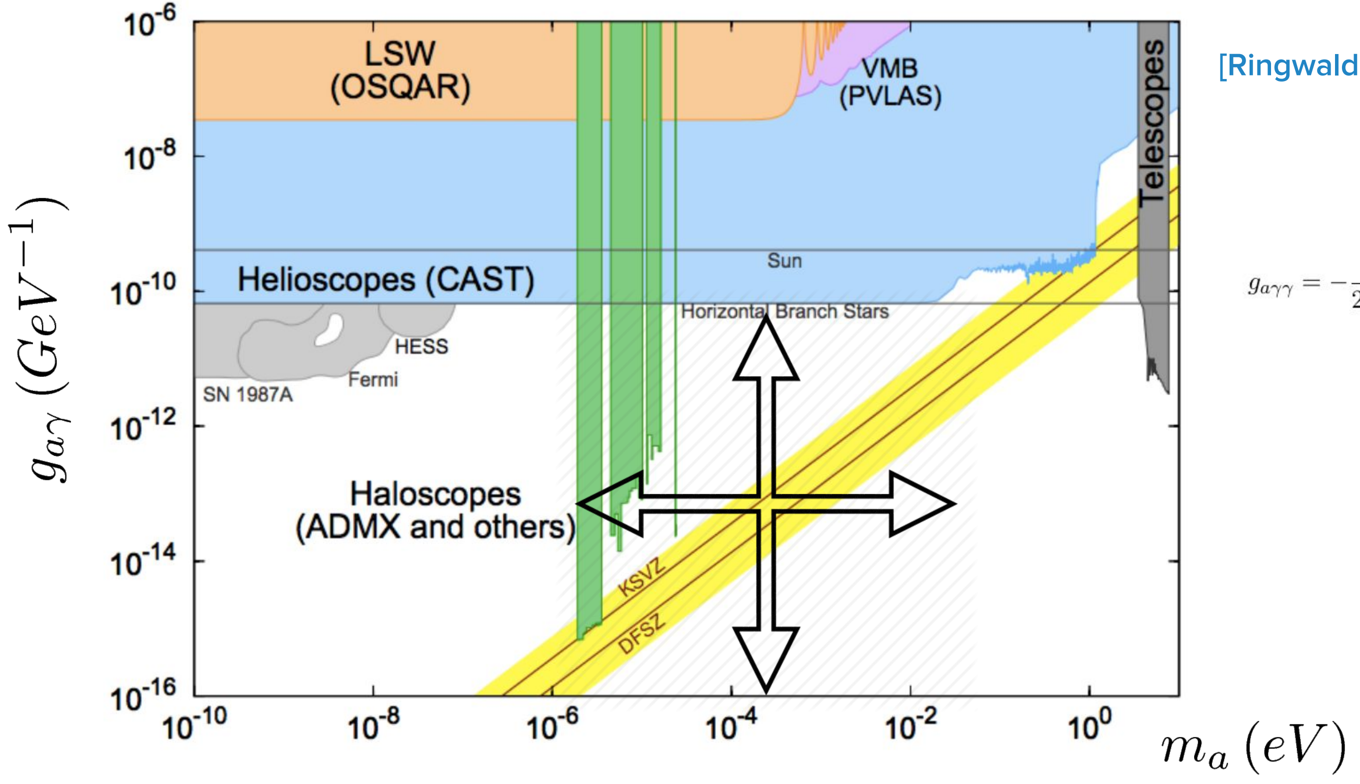
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

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

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

Are there other possibilities?



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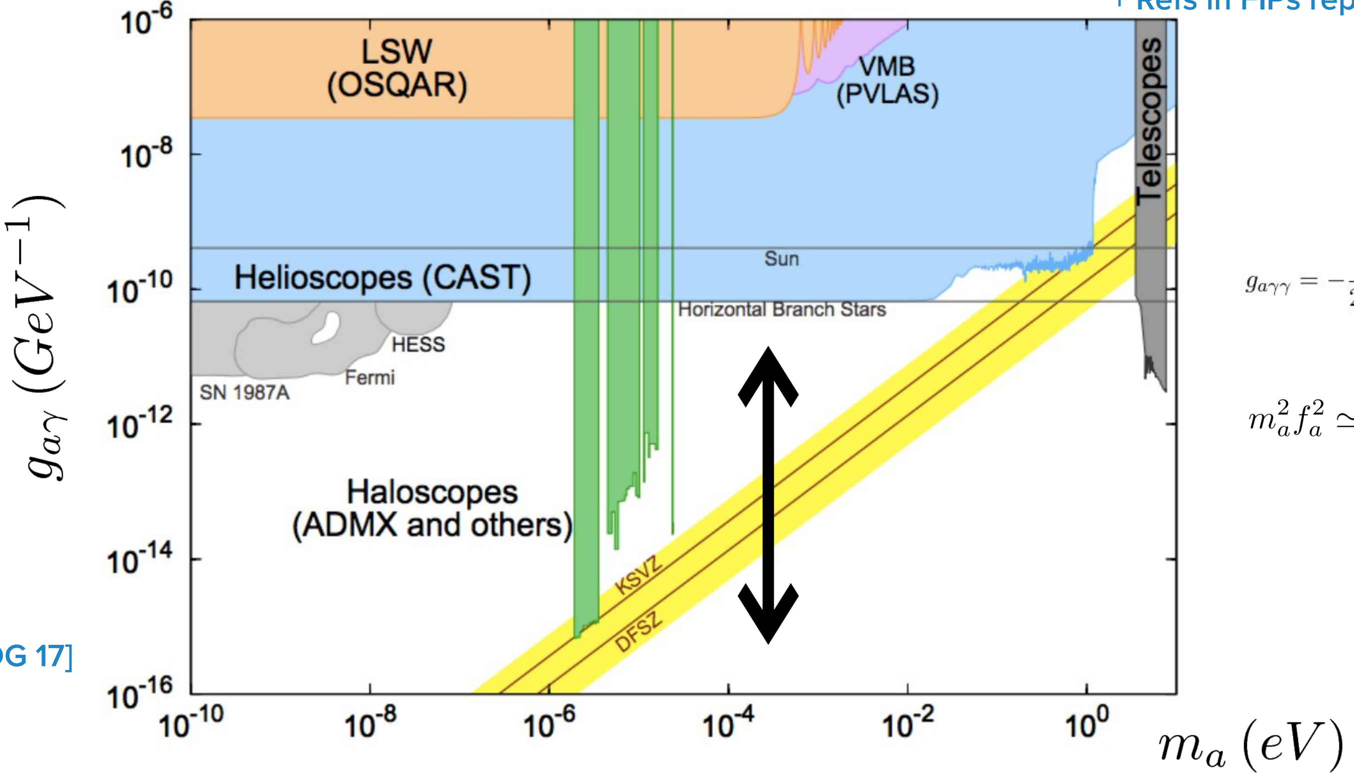
Based on **2102.00012** and **2102.01082**

Photophilic/photophobic

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



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$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\boxed{\left(\frac{E}{N} - 1.92(4)\right)}$$

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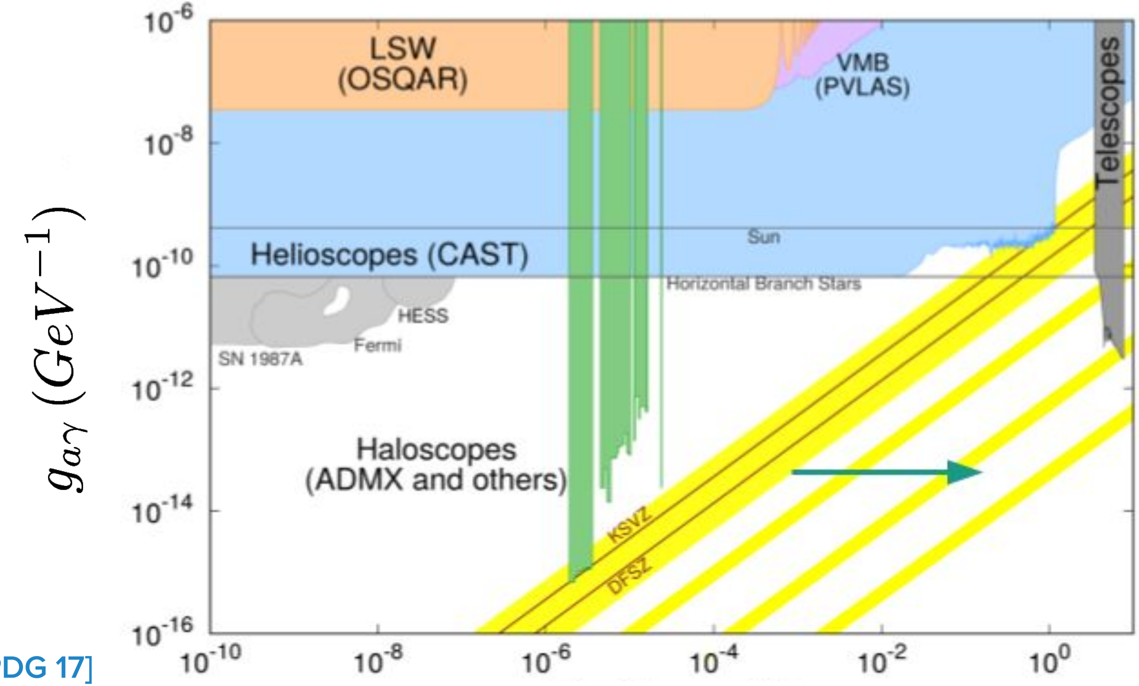
Based on **2102.00012** and **2102.01082**

Heavy axions



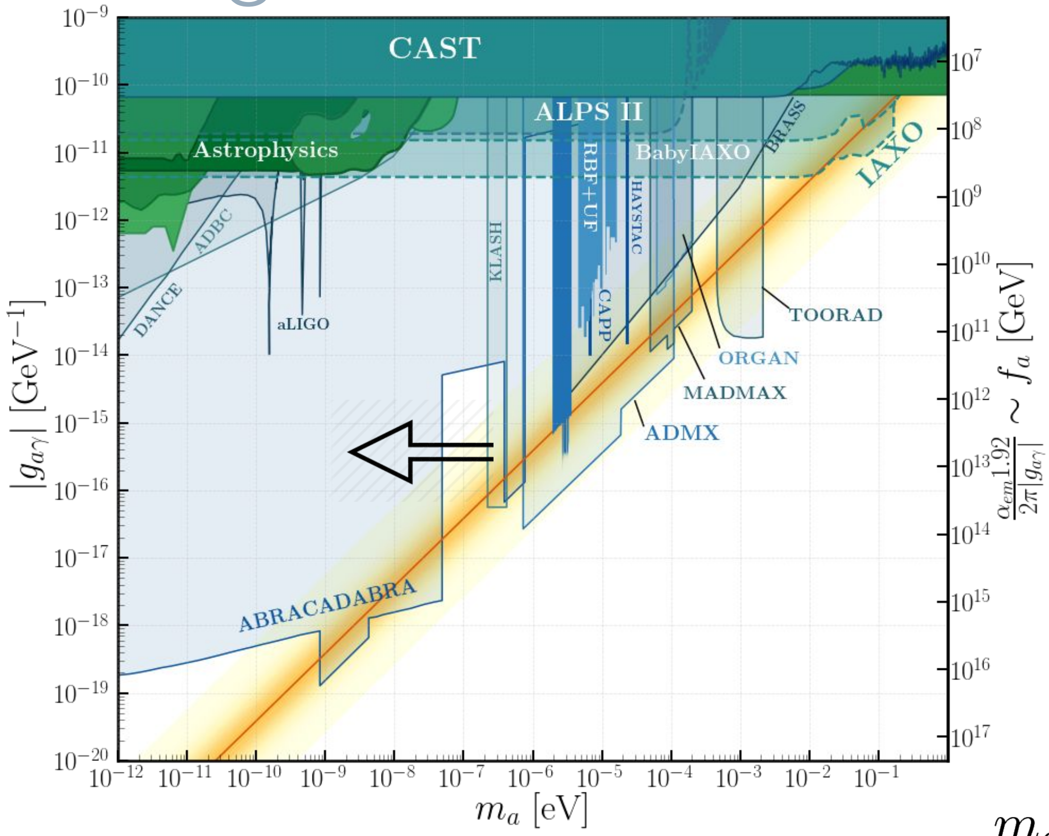
[Ringwald, PDG 17]

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

[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?

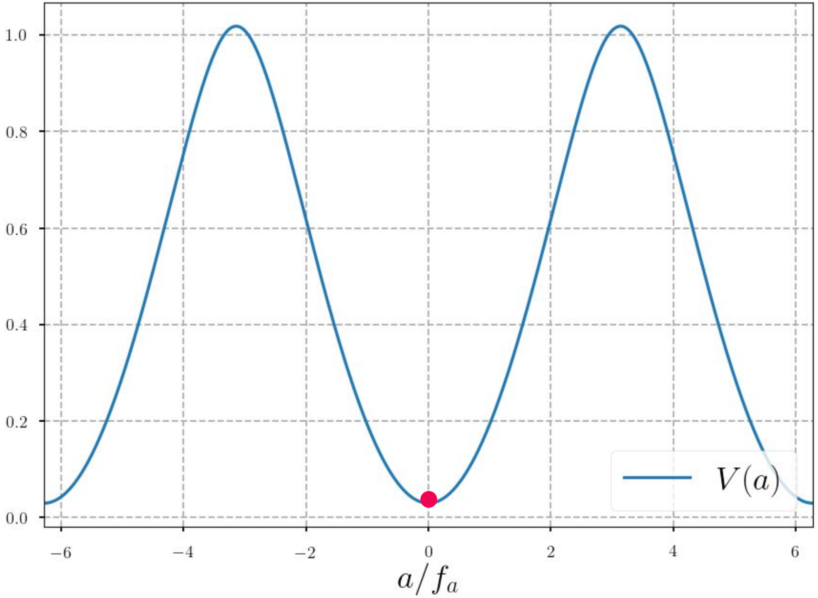


$m_a\,(eV)$

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

Axion potential

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



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

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

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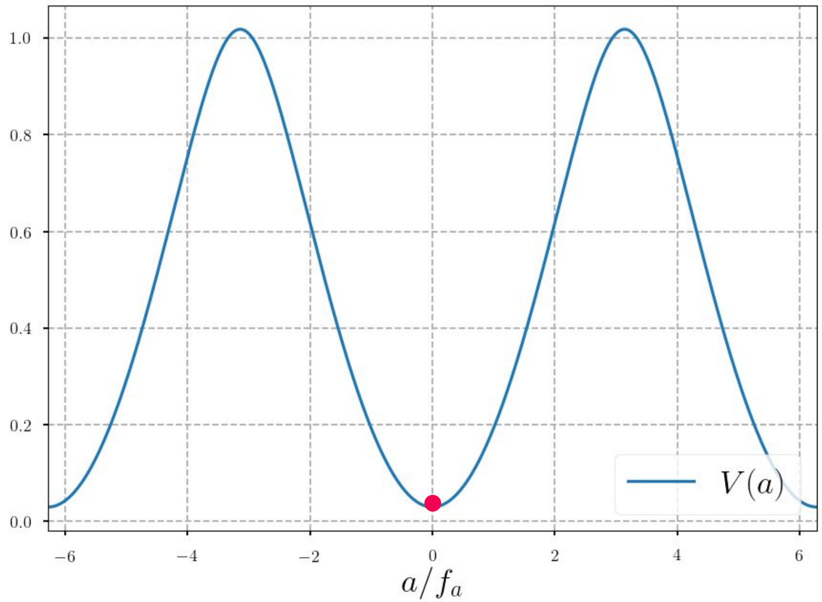

[Di Vecchia +Veneziano,80]
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- ➔ Alignment
- ➔ Cancelation

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

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

The Z_2 case: Mirror world

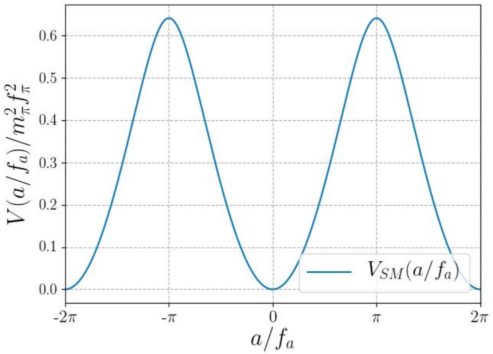
$$Z_2 : \quad \mathrm{SM} \longrightarrow \mathrm{SM}'$$
$$a \longrightarrow a + \pi f_a$$

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

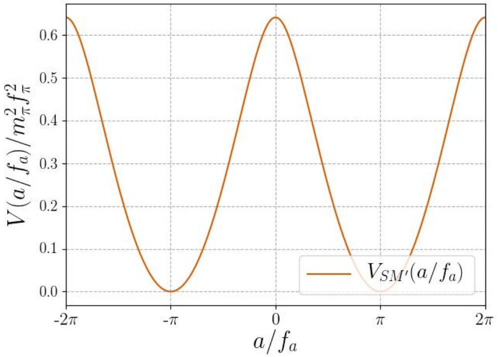
Based on **2102.00012** and **2102.01082**

What about lighter axions?

SM



SM'



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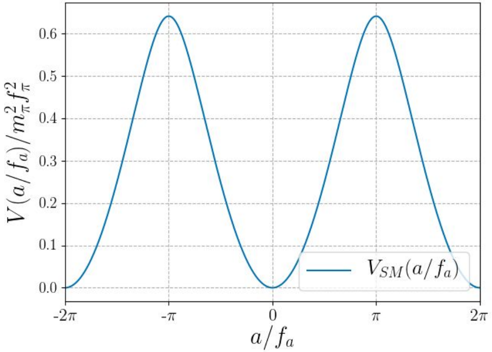

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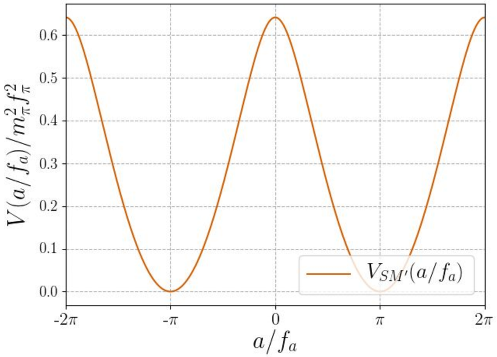

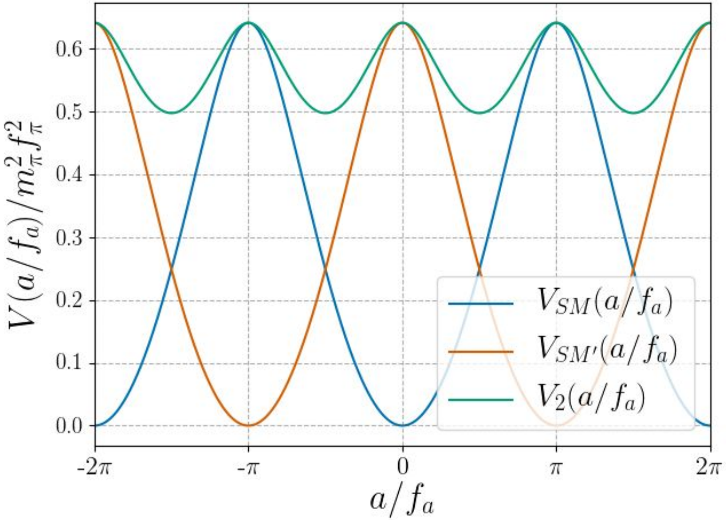

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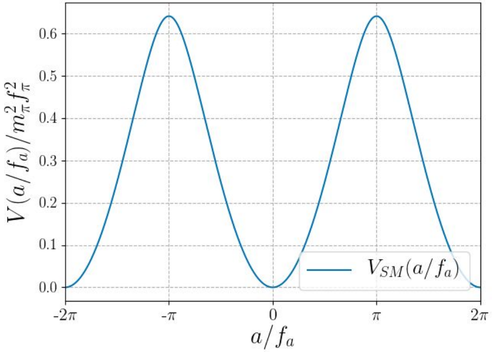

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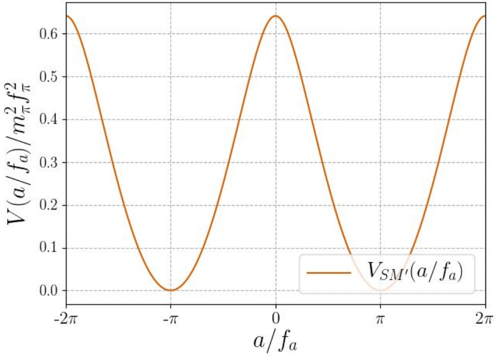
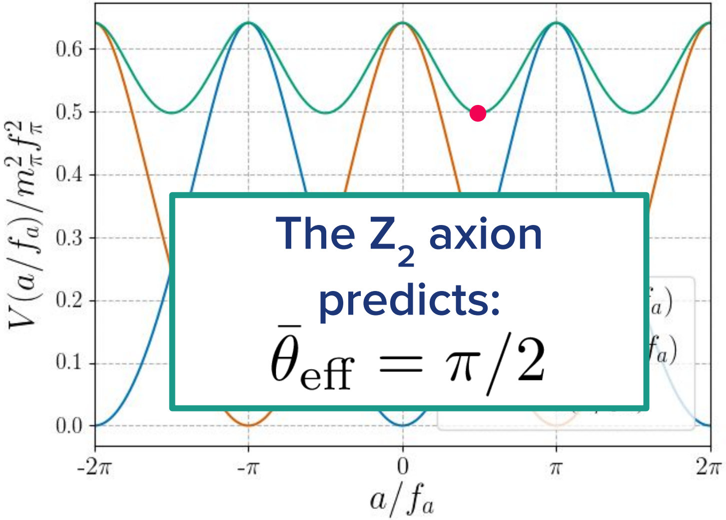




The Z_2 axion predicts:

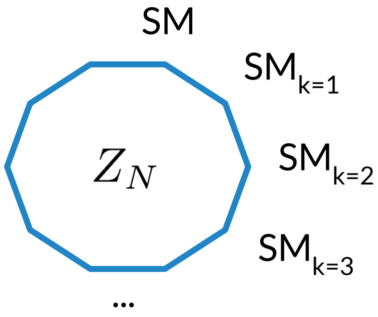
$$\bar{\theta}_{\text{eff}} = \pi/2$$

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.

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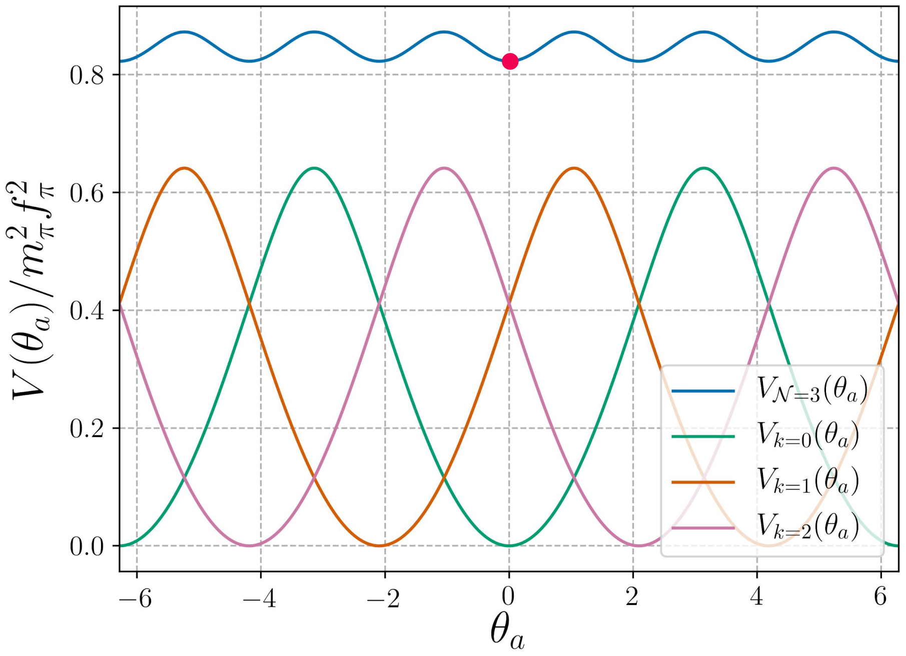
$$\frac{m_a(N)}{m_a(N=1)} \sim \frac{4}{2^{N/2}}$$

Example: Z_3



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

Z_N axion: N-mirror worlds

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Example: Z_3

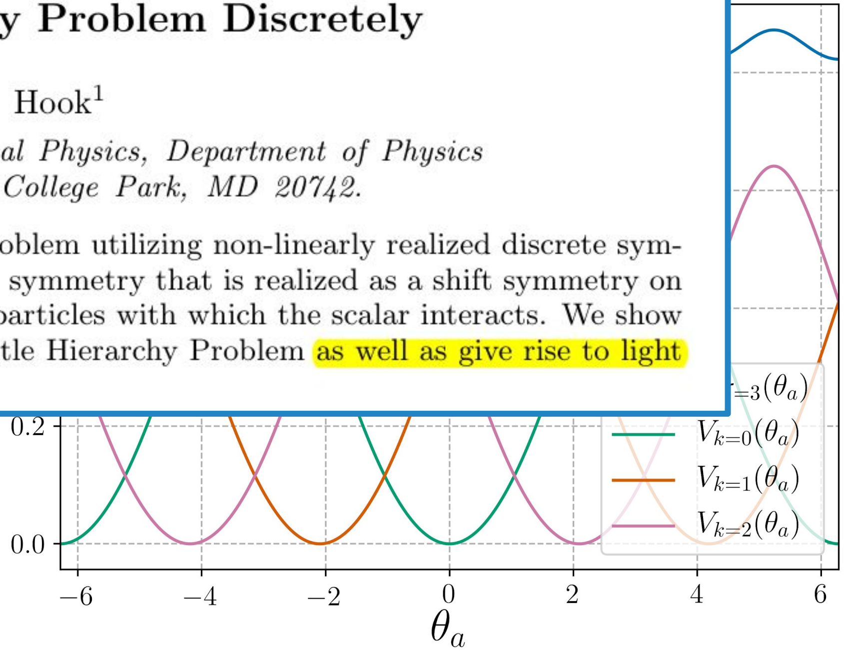
Solving the Hierarchy Problem Discretely

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.

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



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

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

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

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

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

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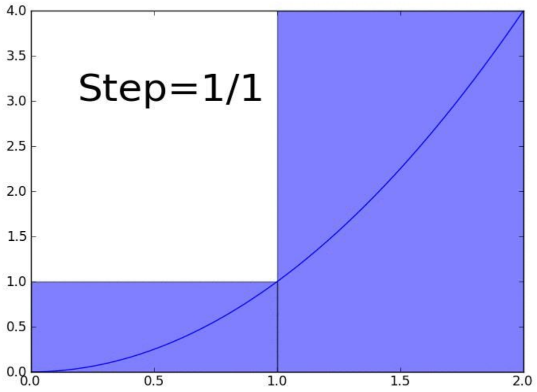
Source: Wikipedia



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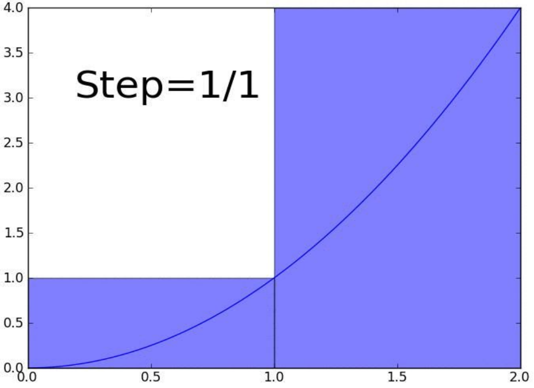
$$\theta_a \equiv \frac{a}{f_a}$$

Does not depend on the axion!

$$= \mathrm{cte}$$

Source: Wikipedia



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

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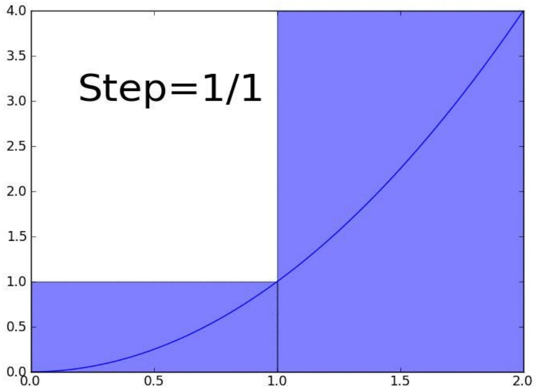
Does not depend on the axion!

$$= \text{cte}$$

The axion potential is contained in the subleading terms

Source: Wikipedia



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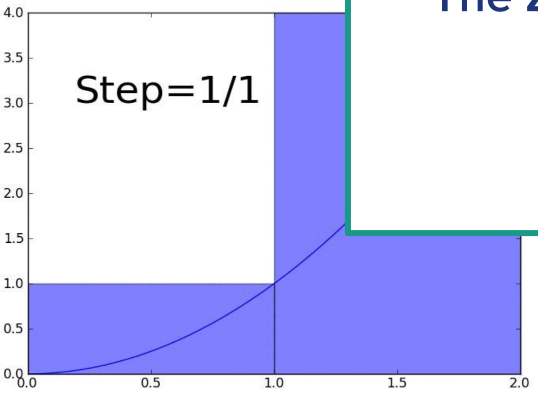
➔ One w

➔ Let's

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

Source: Wikipedia



potential is
in the
terms

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

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

The Z_N axion mass is exponentially suppressed:

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

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

Compact analytical formula

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

- The total Z_N axion potential approaches a cosine:

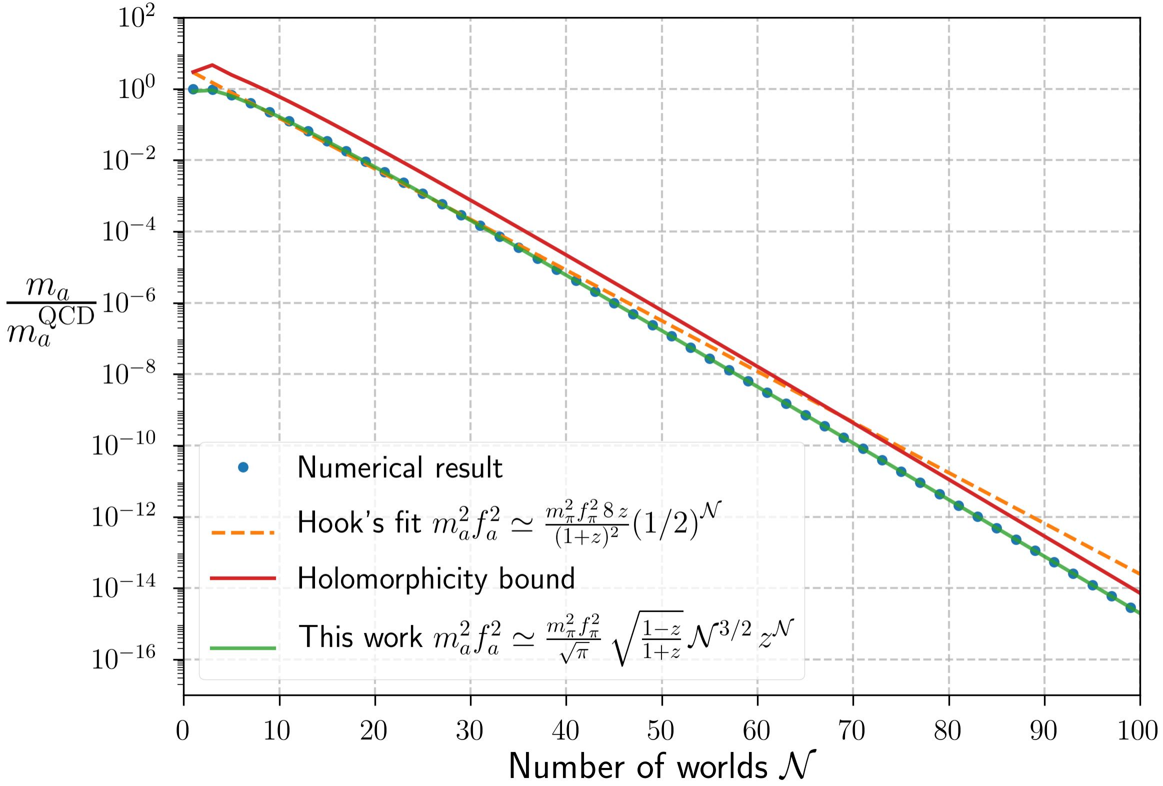
$$V_{\mathcal{N}}\left(\theta_a\right) \simeq -\frac{m_a^2 f_a^2}{\mathcal{N}^2} \cos(\mathcal{N}\theta_a)$$

- Compact analytical formula for the 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**

Z_N axion mass



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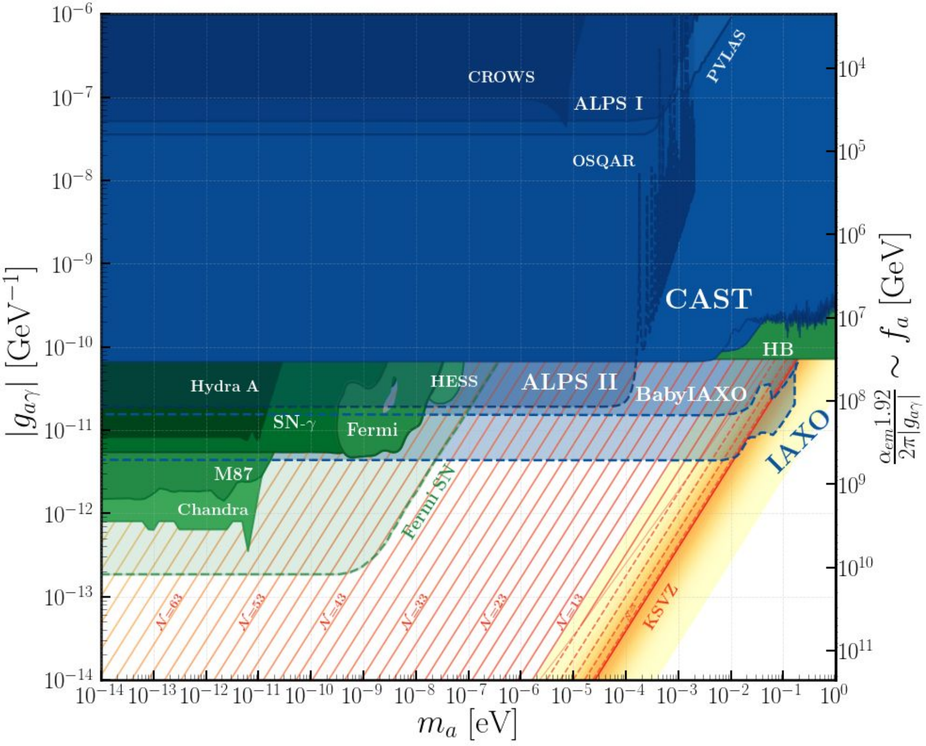

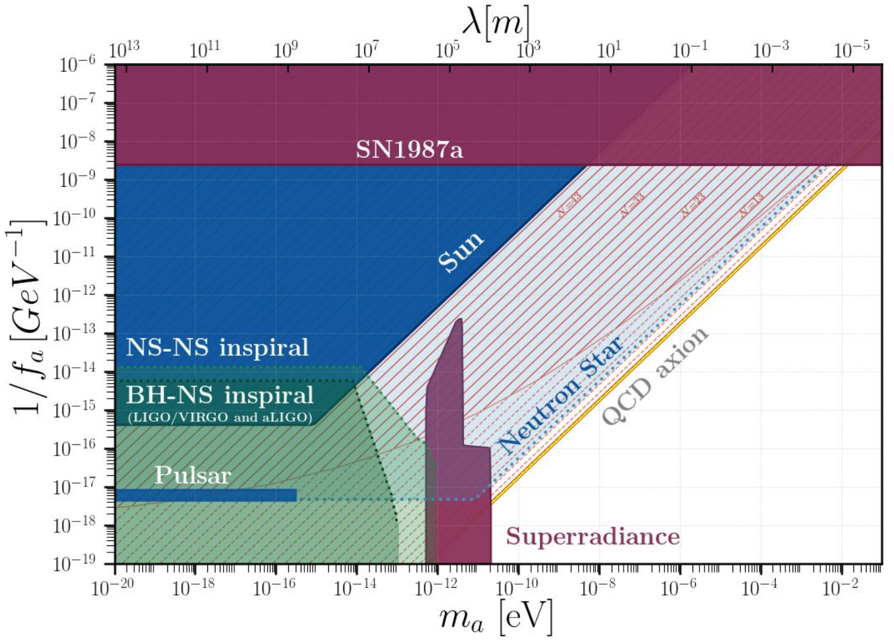

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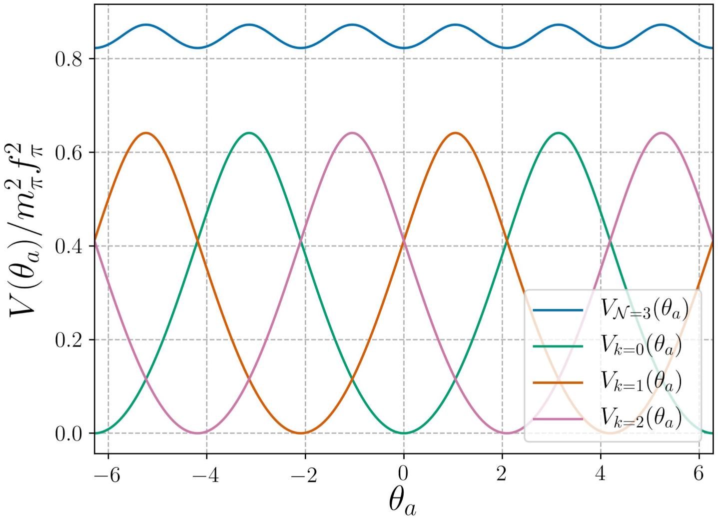
Caveat I

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

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



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

↓

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

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

Dark matter from the Z_N axion

Trapped misalignment

Mirror world cosmology

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

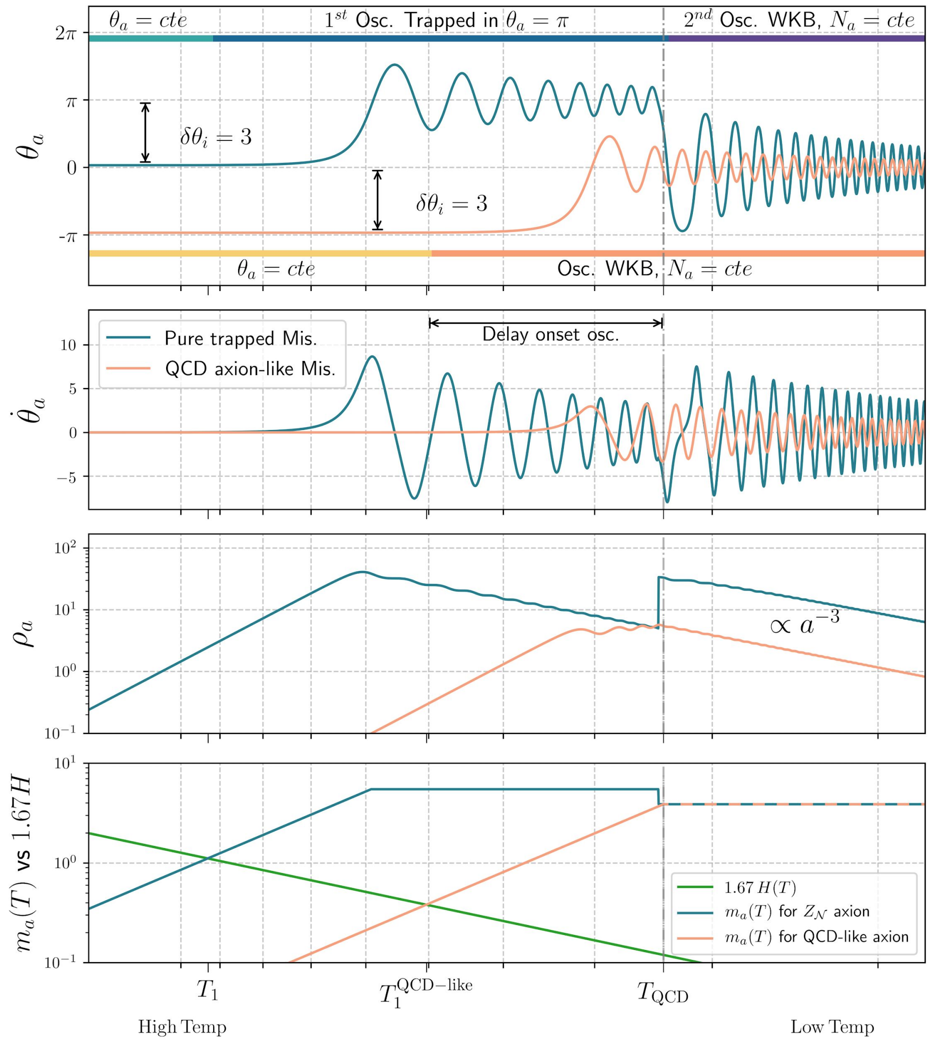
$$\text{BBN: } N_{\text{eff}} = 2.89 \pm 0.57\,, \qquad \text{CMB: } N_{\text{eff}} = 2.99^{+0.34}_{-0.33}\,. \qquad \frac{T'}{T} < \frac{0.51}{(\mathcal{N}-1)^{1/4}}\,,$$

➔ Above $T \geq \Lambda_{\text{QCD}}$ the SM contribution is suppressed which:

- Breaks the cancellation
- The minimum is in π

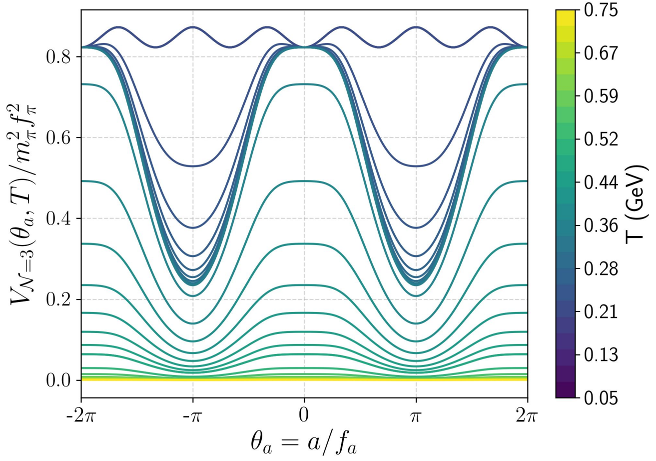
$$V_{\mathcal{N}}(\theta_a) \simeq -V_{SM}(\theta_a)$$

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



Trapped misalignment mechanism

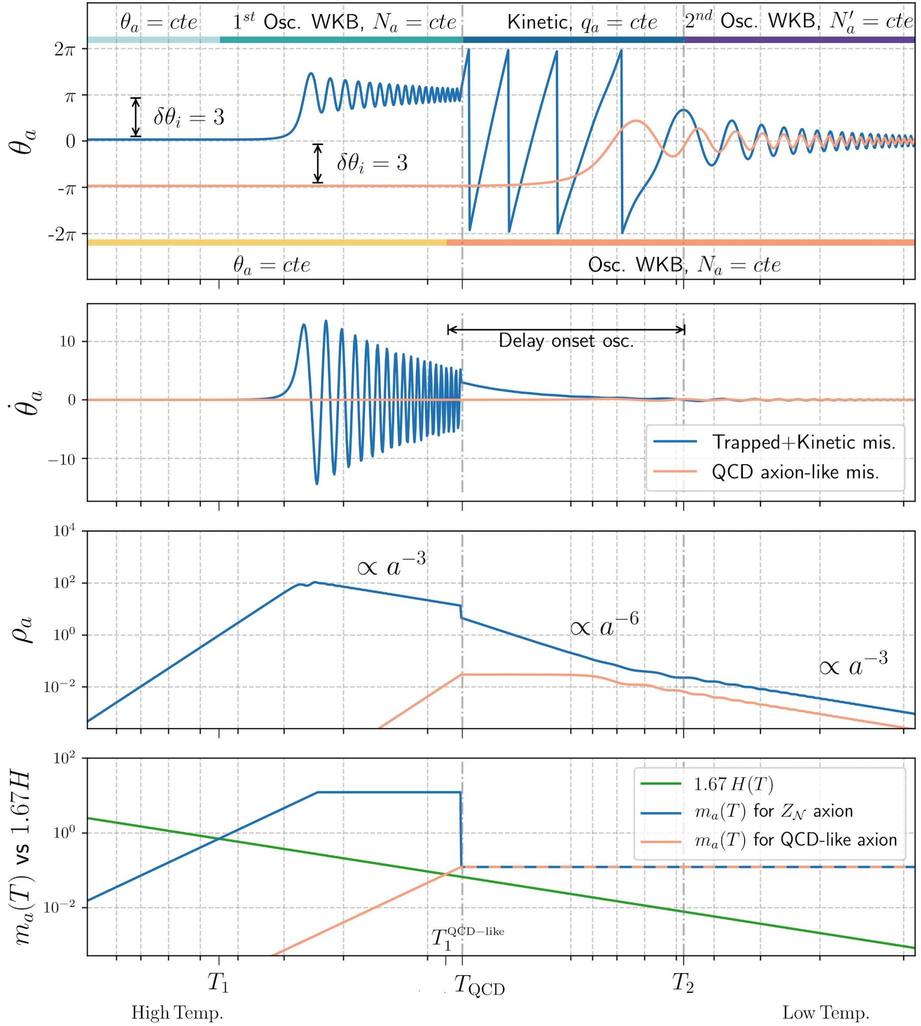
- Compare trapped (blue) with usual misalignment (orange)
- At high temperatures the axion is trapped in the wrong minimum
- The onset of oscillations is delayed
- Less dilution = more dark matter

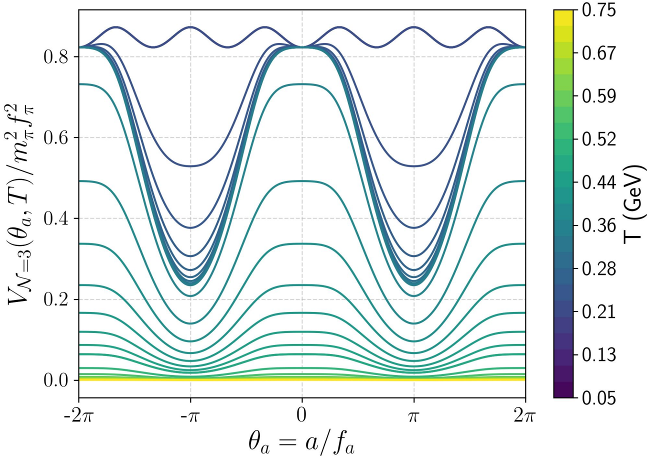


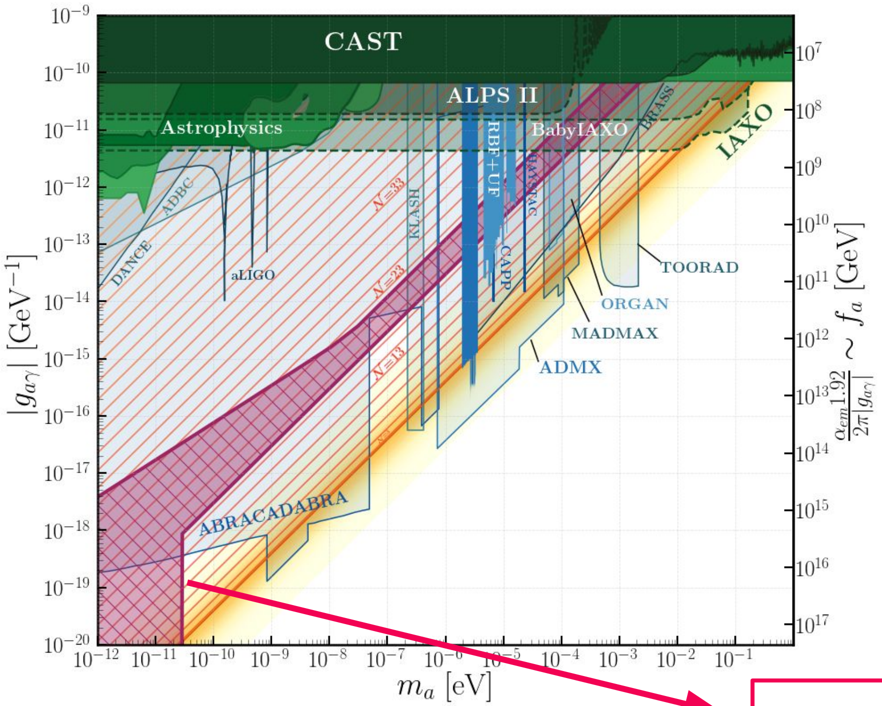
Trapped+kinetic mechanism

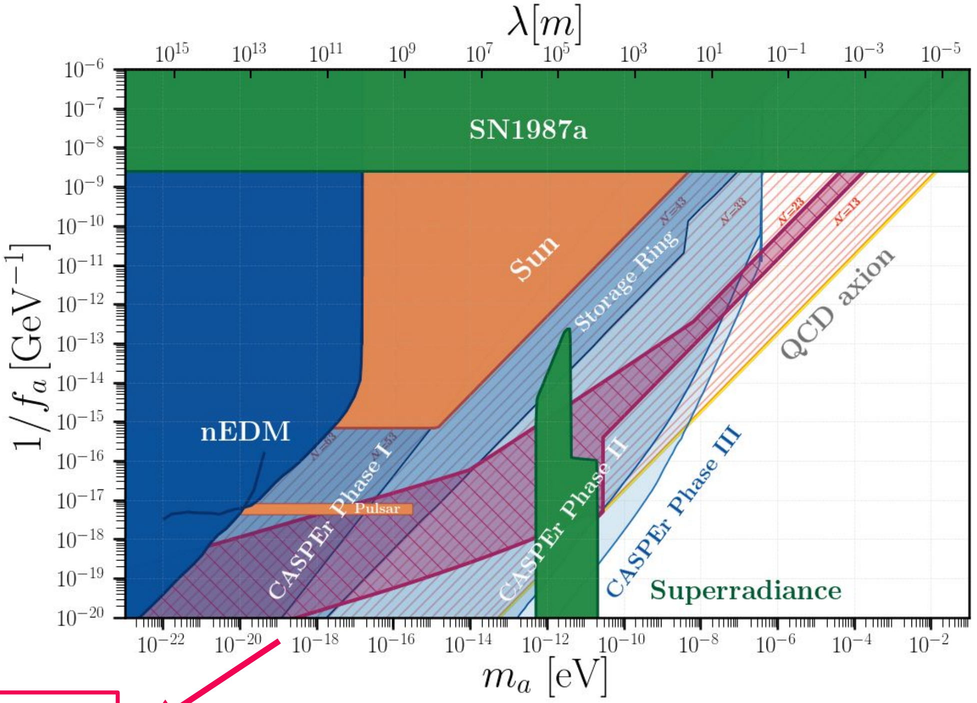
[Co+Hall+Harigaya, 19]
[Di Luzio+ PQ+Ringwald +Gavela, 21]

- 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



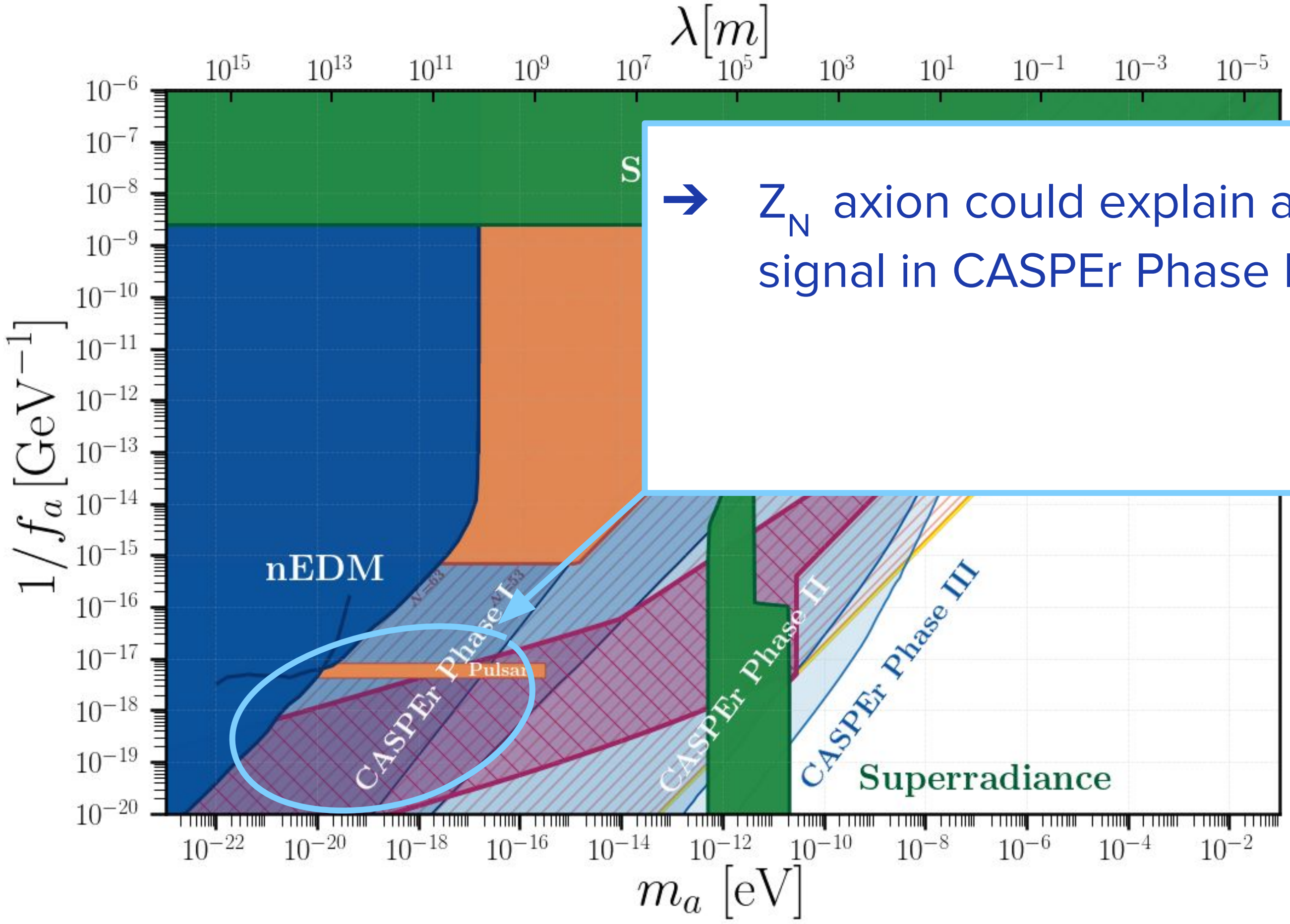






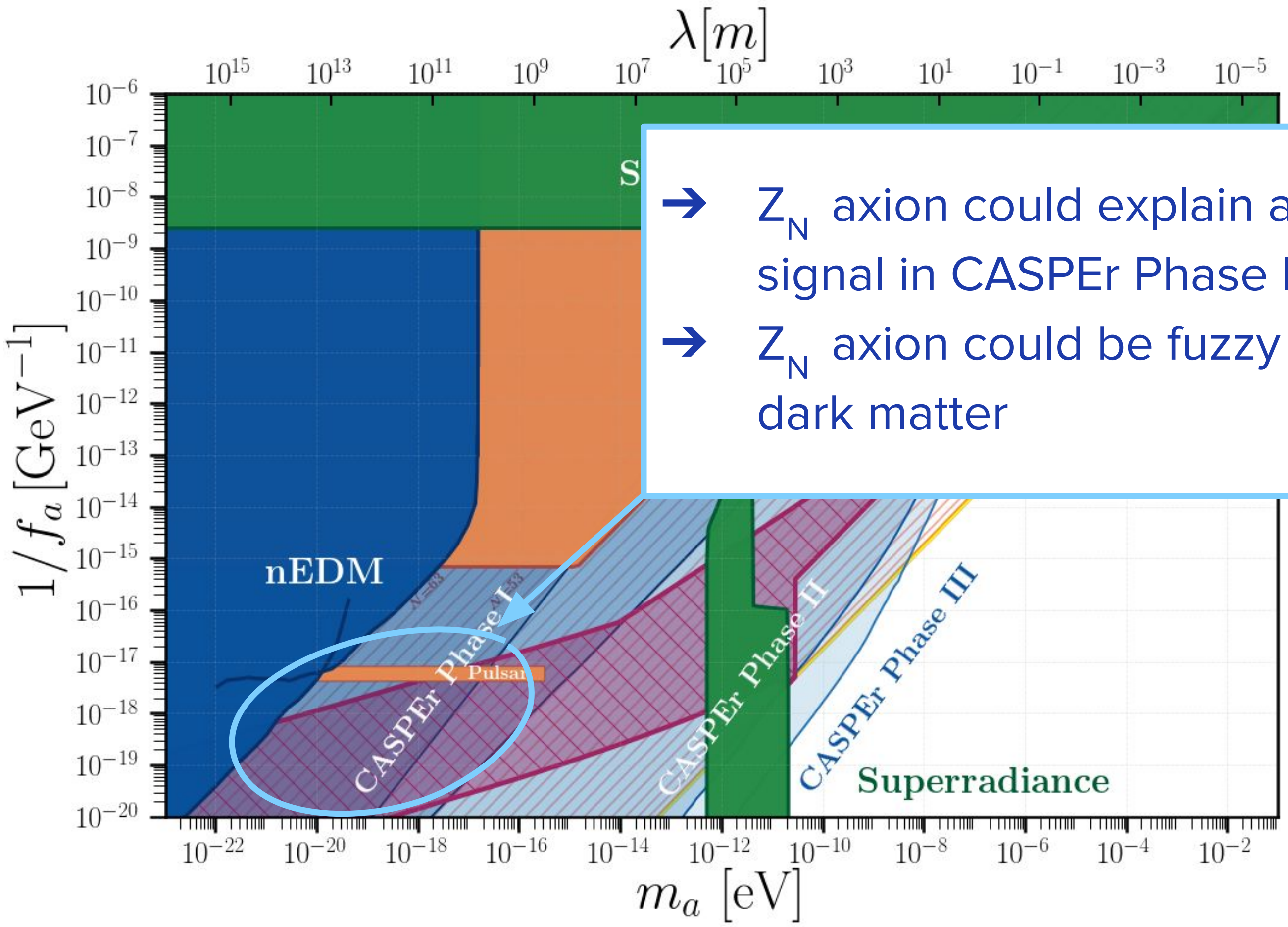
Z_N Axion DM

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



➔ Z_N axion could explain a signal in CASPEr Phase I

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



- ➔ Z_N axion could explain a signal in CASPEr Phase I
- ➔ Z_N axion could be fuzzy dark matter

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

Conclusions I

- Z_N axion as strong CP solution:
  - The QCD axion can be even lighter
  - UV completions: KSVZ is PQ protected
  - Motivates interesting regions accessible by ALPS II, BabyIAXO, IAXO...

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

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

Conclusions II

- Z_N axion as Dark matter
  - It can explain DM in large regions of $\{m_a, f_a\}$ $3 \leq \mathcal{N} \leq 65.$
  - Novel production mechanism: trapped mis.
  - It can source kinetic mis.
  - First fuzzy dark matter that solves the strong CP
  - First axion model that could explain potential signal in CASPEr Electric Phase I

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

Caveats and outlook

- Caveats and outlook
    - N worlds is non-minimal: extra dimensions? strings?
    - Solve the strong CP with 1/N prob.
    - Trapped misalignment: only zero mode
        - Non-linearities?
        - Axion fragmentation?
        - Trapped in other scenarios...

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

Thank you

Pablo Quílez Lasanta

Why exponentially suppressed?

$$z \equiv m_u/m_d$$

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

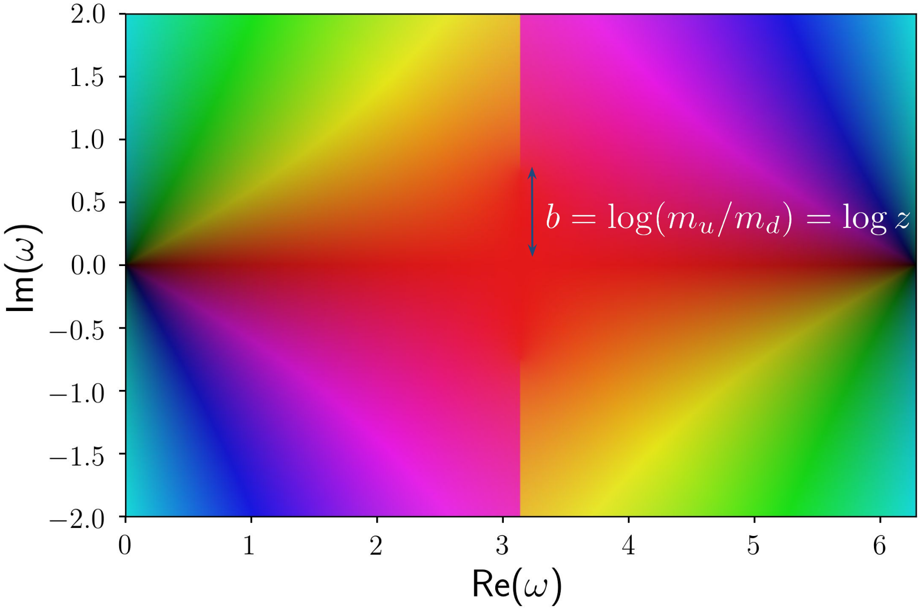
Theorem 9.28 *Let $f : \mathbb{R} \to \mathbb{R}$ be analytic and 2π-periodic. Then there exists a strip $D = \mathbb{R} \times (-b, b) \subset \mathbb{C}$ with $a > 0$ such that f can be extended to a holomorphic and 2π-periodic bounded function $f : D \to \mathbb{C}$. The error for the rectangular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

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

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



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

Can the QCD axion be fuzzy Dark Matter?

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

White paper [1904.09003]

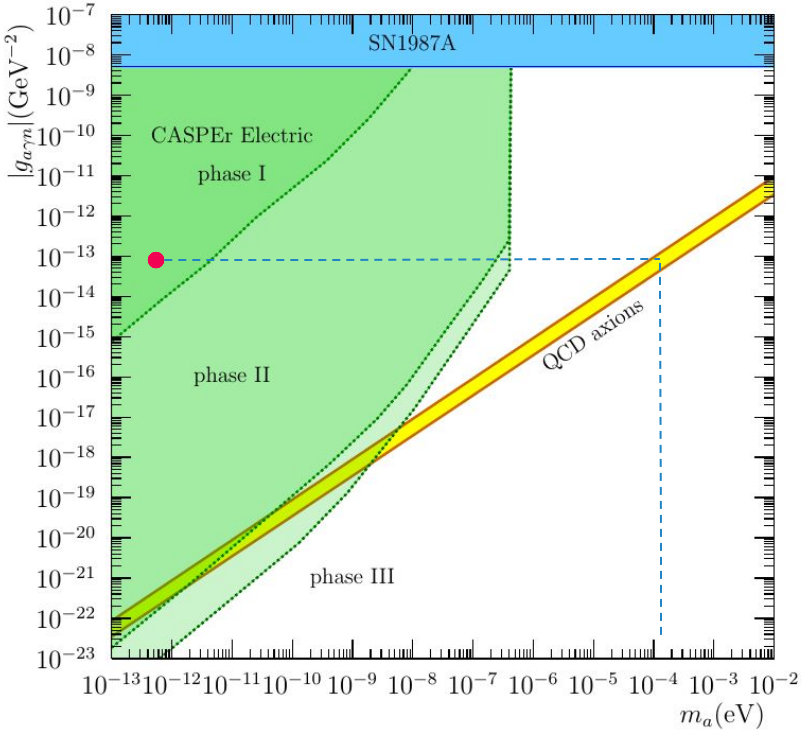
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

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

NO, a canonical axion would have transplanckian decay constant

Could CASPEr Phase I detect an axion?

$g_{a\gamma n}$



[Irastorza+Redondo, 18]

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

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

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

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

Coupling to the nEDM

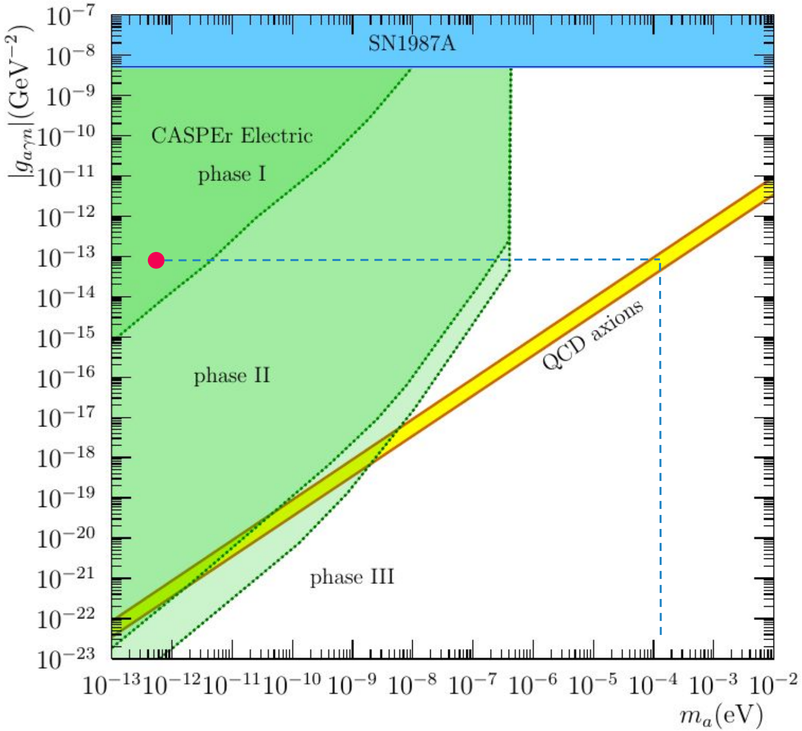
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

Axion mass

$m_a\,(eV)$

Could CASPEr Phase I detect an axion?

$g_{a\gamma n}$



[Irastorza+Redondo, 18]

$m_a\ (eV)$

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

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

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

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

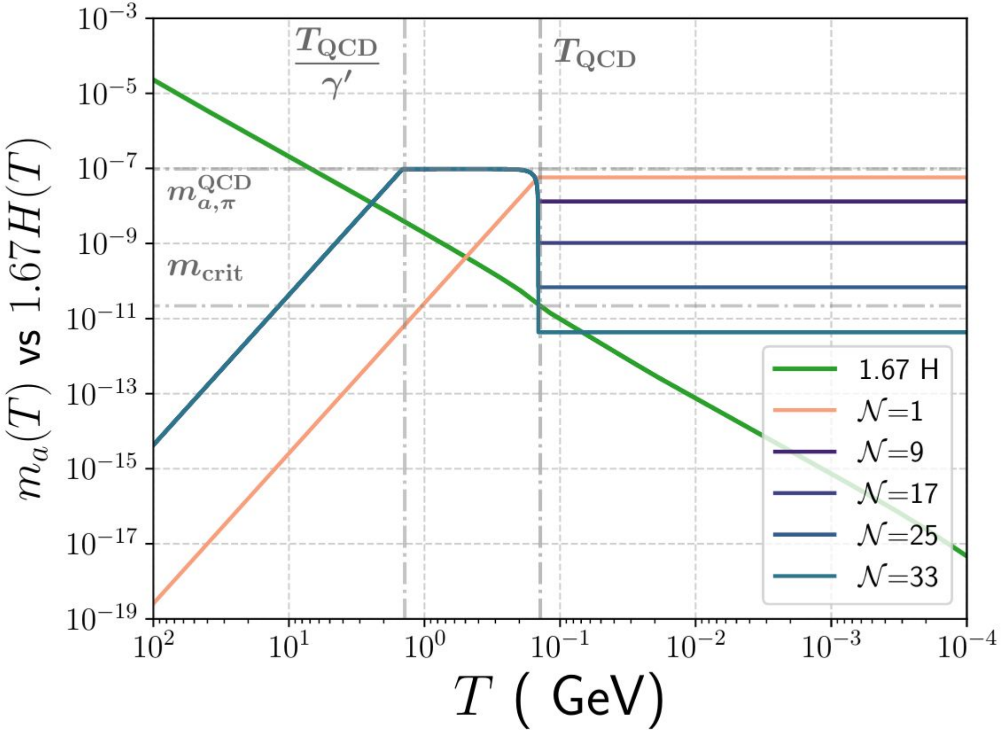
$$\boxed{m_a^2\, f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}}\sqrt{\frac{1-z}{1+z}}\mathcal{N}^{3/2}\, z^{\mathcal{N}}}$$

Coupling to the nEDM

Axion mass

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

Temperature dependence



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