

# QCD Axion Dark Matter in Reach of Nucleon Electric Dipole Moment Experiments?

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Virtual LTP/PSI Thursday Colloquium  
Laboratory of Particle Physics  
Paul Scherrer Institute, Villigen, CH  
17 March 2022

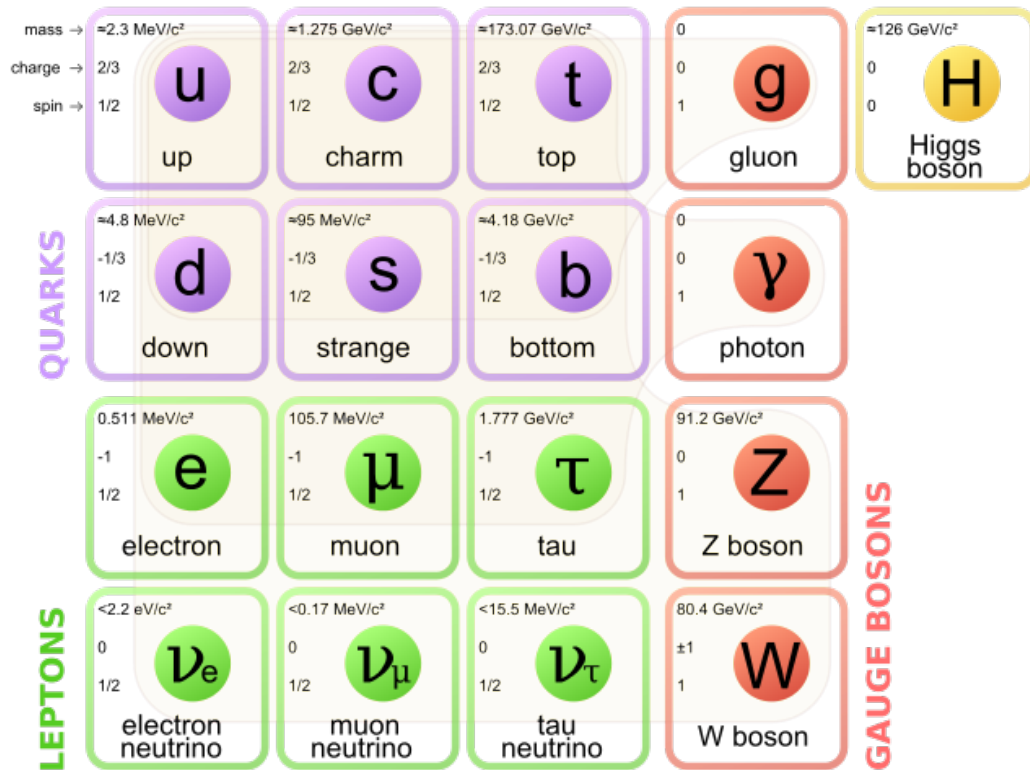
[Luca Di Luzio, Belen Gavela, Pablo Quilez, AR, [arXiv:2102.00012](https://arxiv.org/abs/2102.00012); [arXiv:2102.01082](https://arxiv.org/abs/2102.01082)]



# Introduction

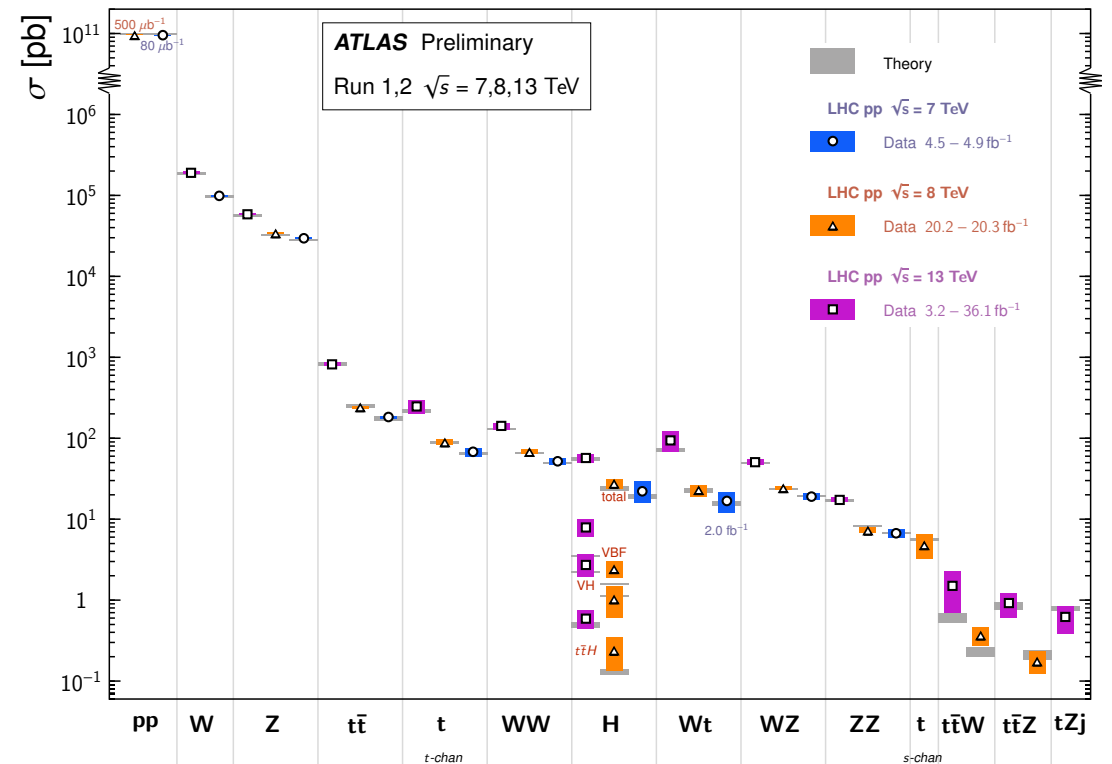
## The Quest for the Axion

- Standard Model (SM) extremely successful



[Wikipedia]

Standard Model Total Production Cross Section Measurements Status: March 2018



[twiki.cern.ch]

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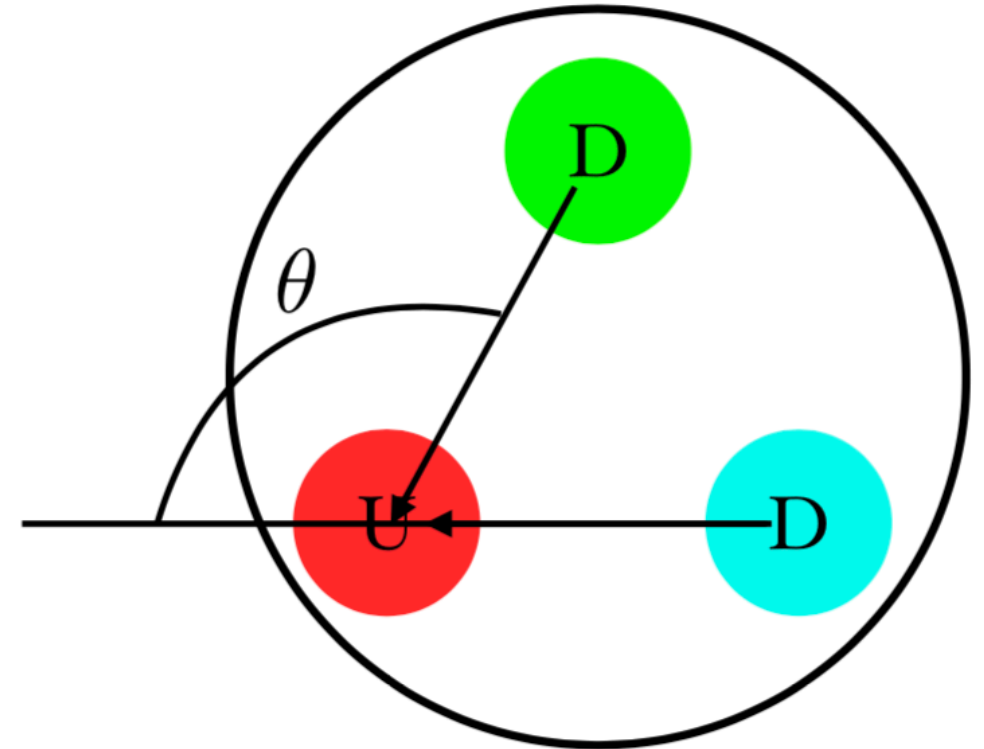
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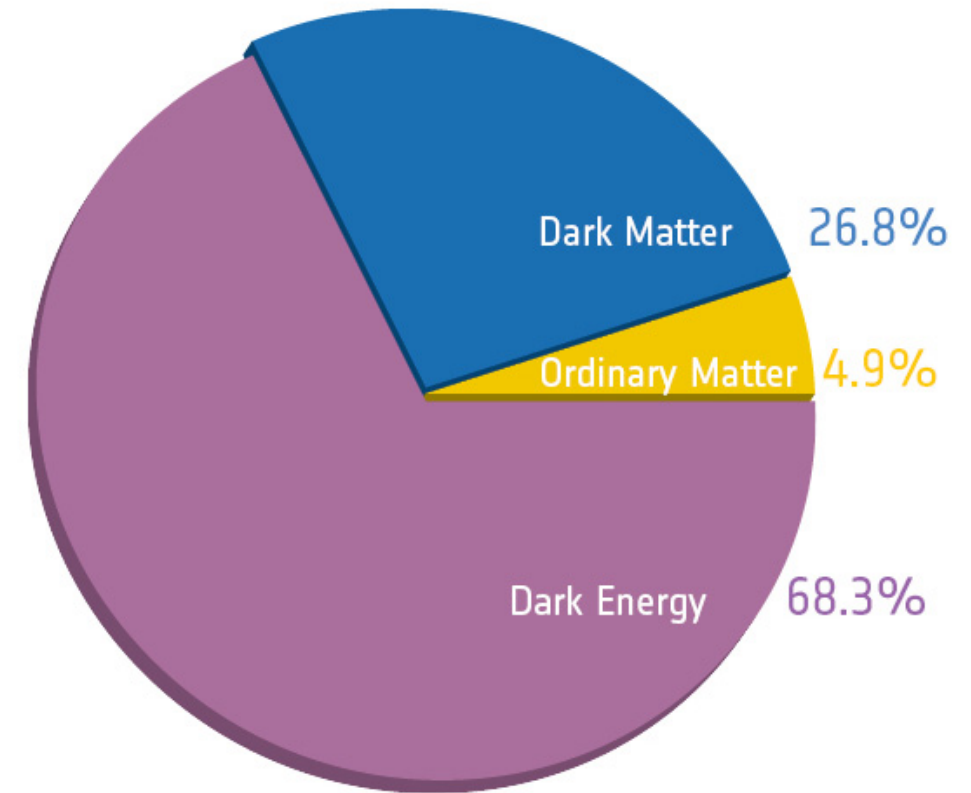


[Hook 18]

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[PLANCK]

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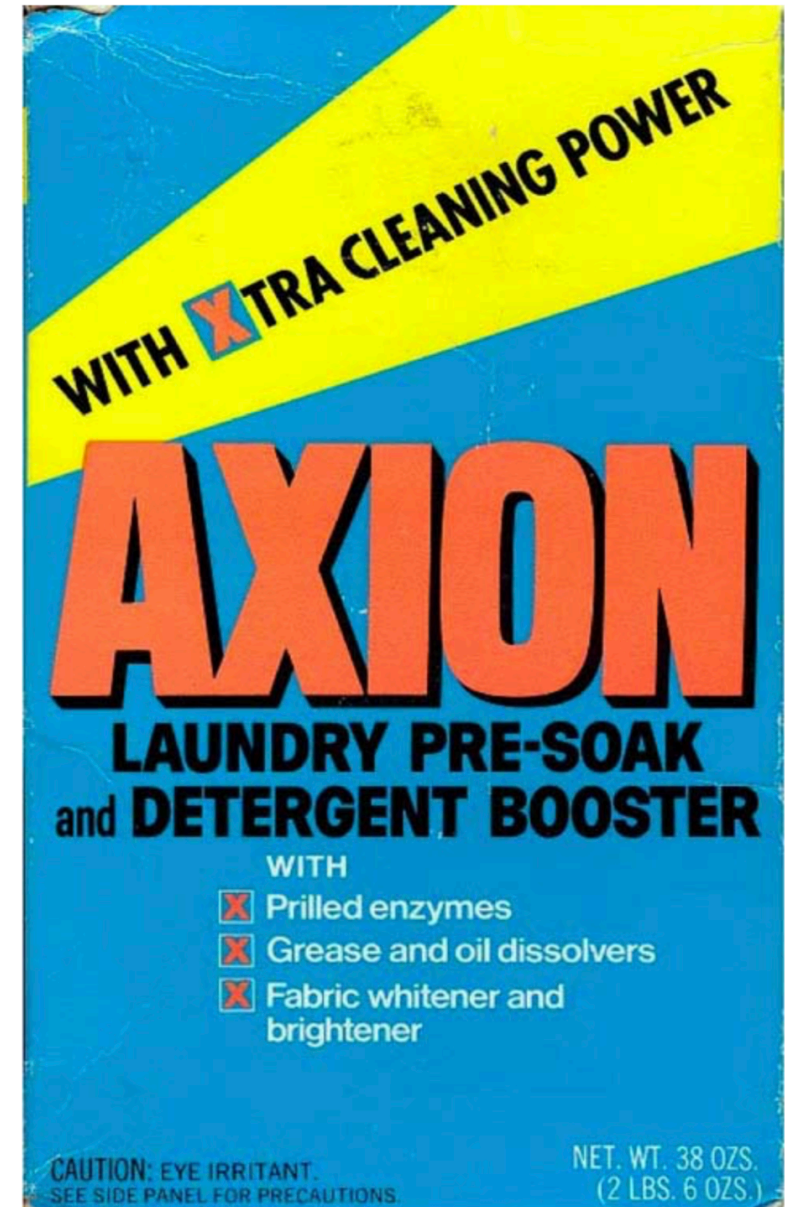
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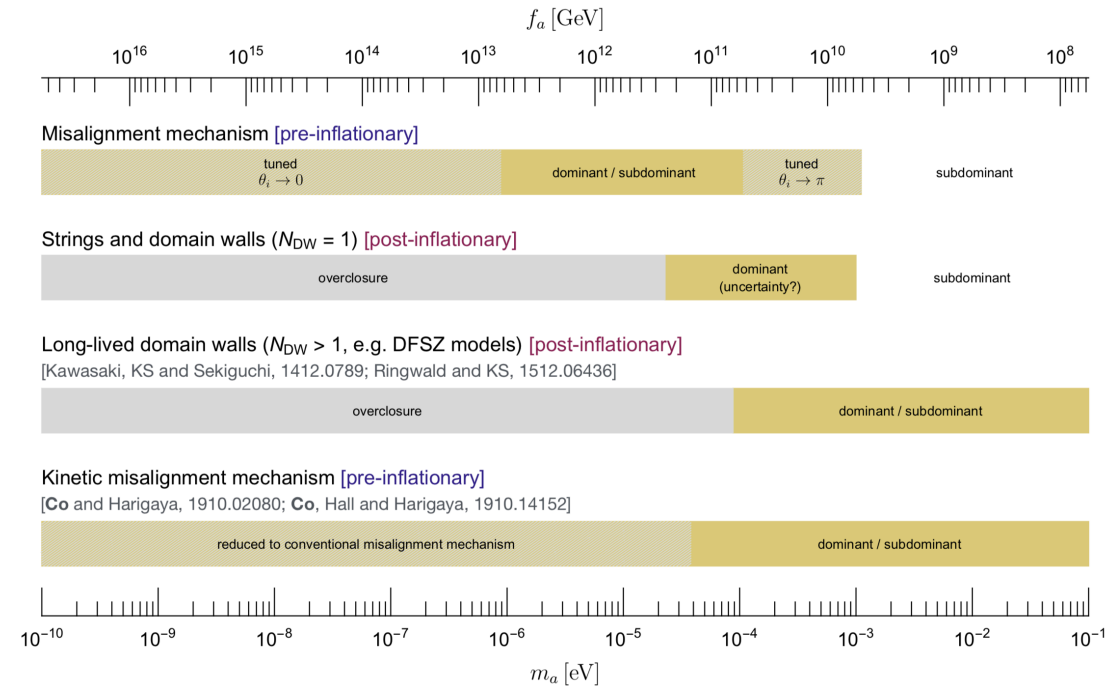
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[Peccei,Quinn `77; Weinberg `78; Wilczek `78]
  - Axion is excellent DM candidate  
[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]



[Saikawa]

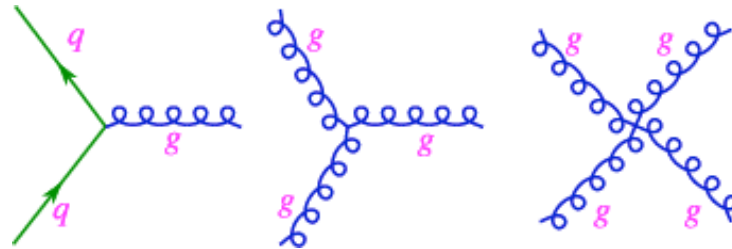
# Strong CP Puzzle

## Theta term in Quantum Chromodynamics

- Quantum Chromodynamics (QCD):

[Gross,Wilczek 73;Politzer 73; Fritzsche,Gell-Mann,Leutwyler 73]

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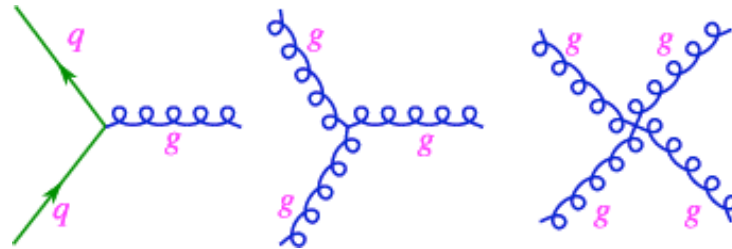
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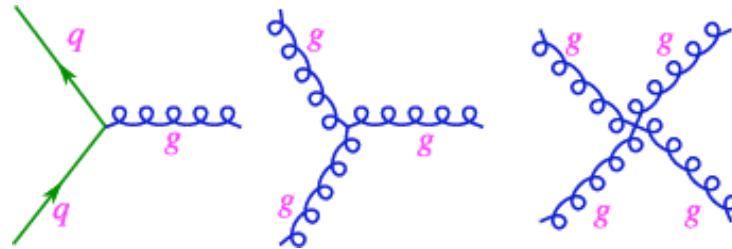
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$$\int d^4x \partial_\mu J_{\text{CS}}^\mu = 0, \pm 1, \pm 2, \dots$$

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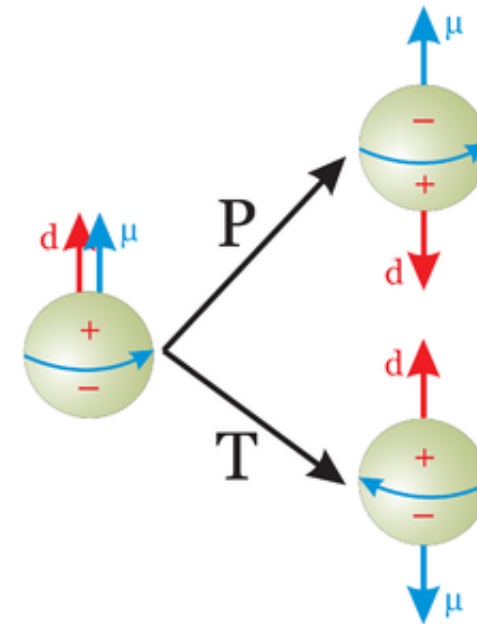
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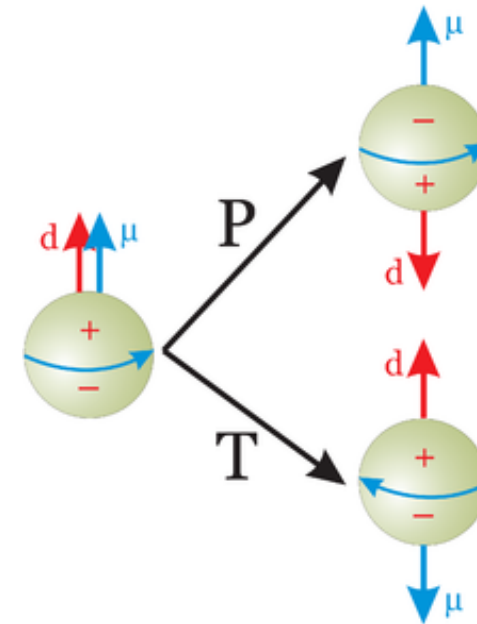
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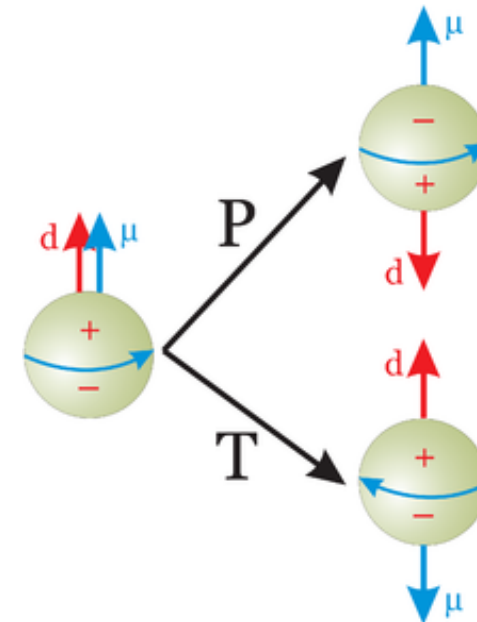
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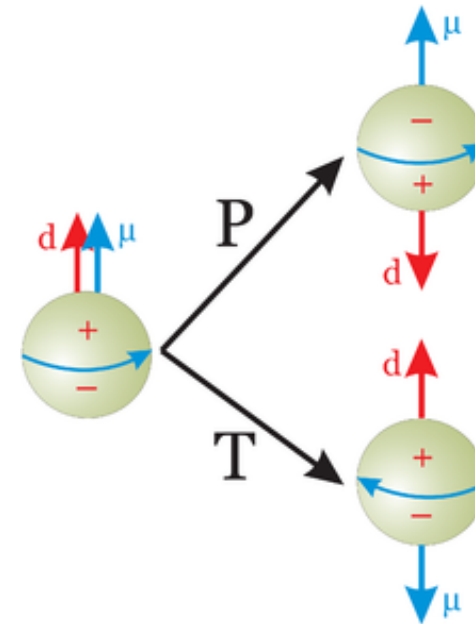
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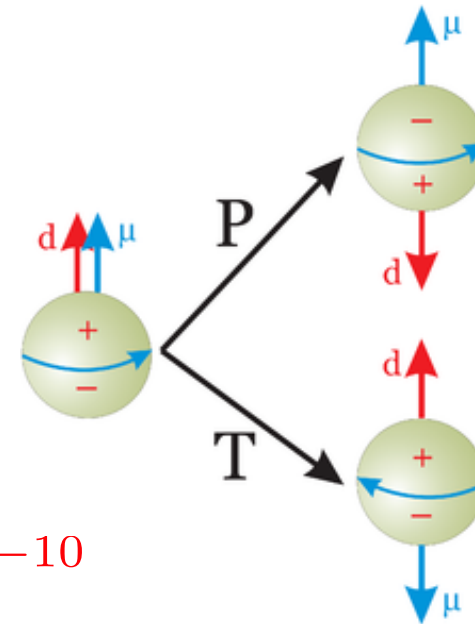
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$$\Rightarrow |\bar{\theta}| \lesssim 10^{-10}$$



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In a nutshell: Replace theta parameter by dynamical theta field

- Add to SM Nambu-Goldstone field,  $\theta(x) \equiv a(x)/f_a \in [-\pi, \pi]$

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$$V(\theta) = m_\pi^2 f_\pi^2 \left( 1 - \frac{\sqrt{1 + z^2 + 2z \cos \theta}}{1 + z} \right)$$

[Di Vecchia,Veneziano '80; Leutwyler,Smilga 92]

$$z \equiv m_u/m_d \approx 1/2$$

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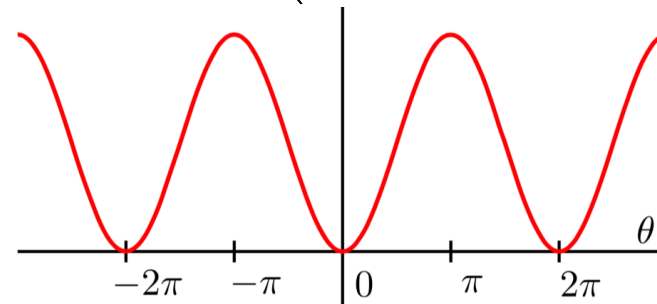
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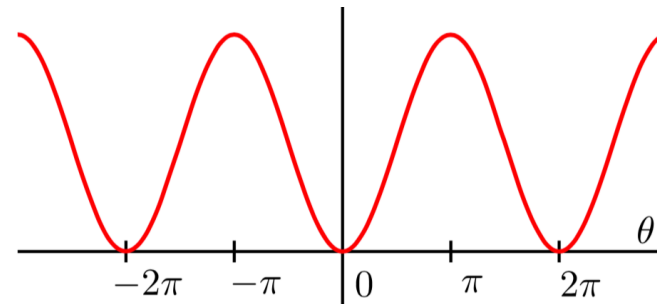
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- It is a pseudo Nambu-Goldstone boson with mass parametrically suppressed by inverse PQ scale:

$$m_a = \frac{\sqrt{V''(0)}}{f_a} = \frac{\sqrt{z}}{1+z} \frac{m_\pi f_\pi}{f_a} \approx 6 \mu\text{eV} \left( \frac{10^{12} \text{ GeV}}{f_a} \right)$$

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Axion couplings to SM at energies below QCD scale

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  - automatically produced in early universe by misalignment mechanism [Preskill, Wise, Wilczek 83; Abbott, Sikivie 83; Dine, Fischler 83, ...]

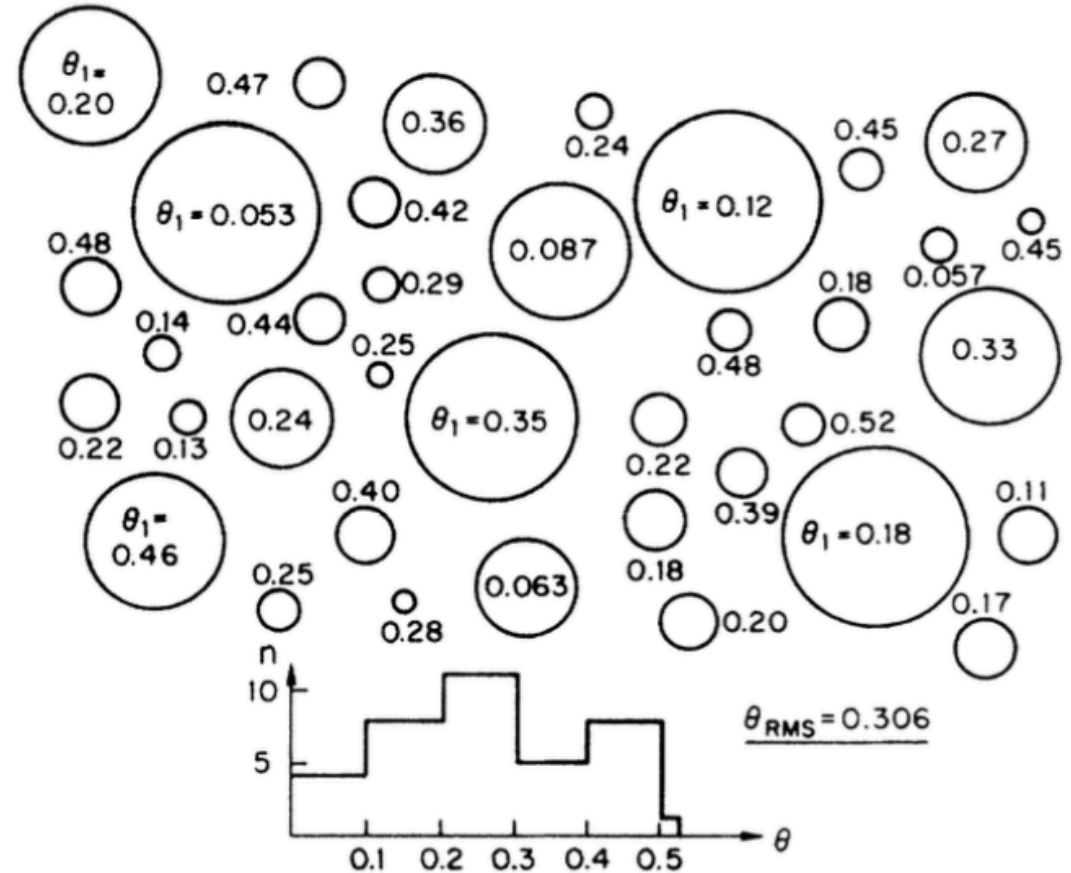
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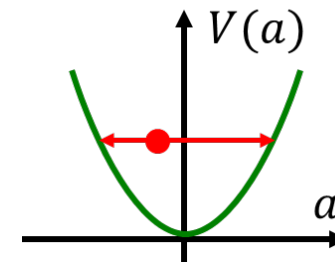
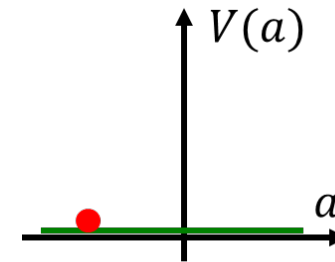
[Turner '86]

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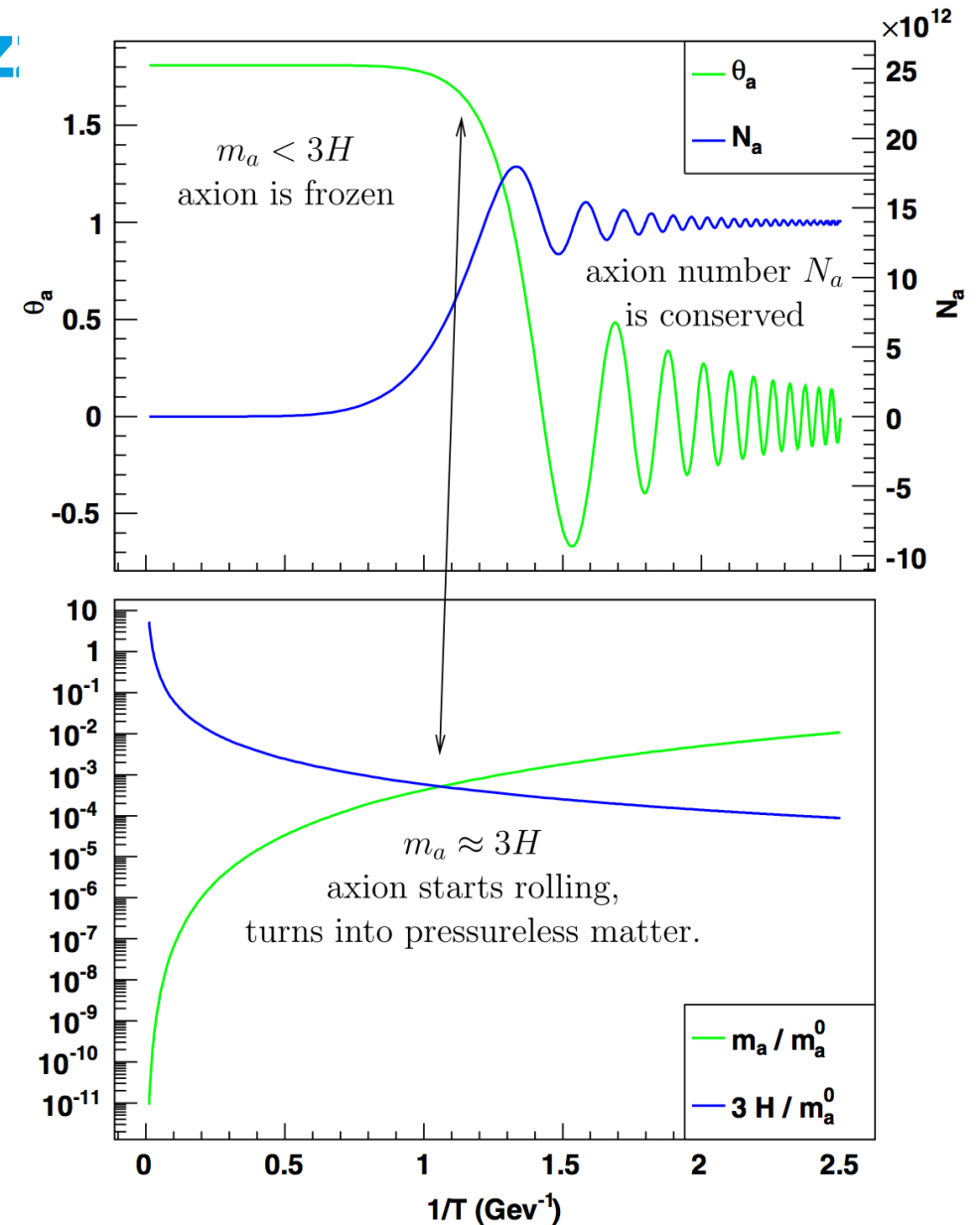


[Raffelt]

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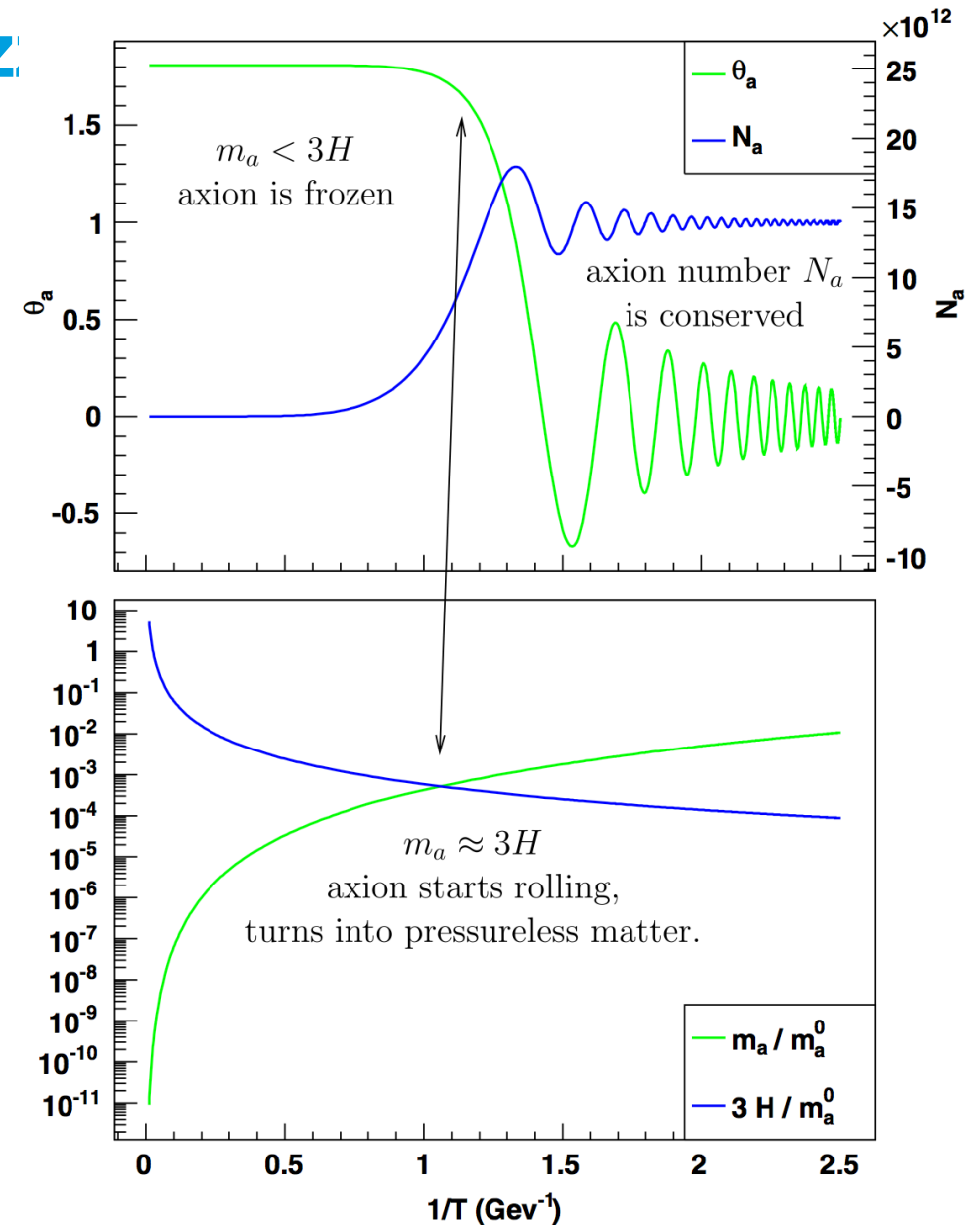
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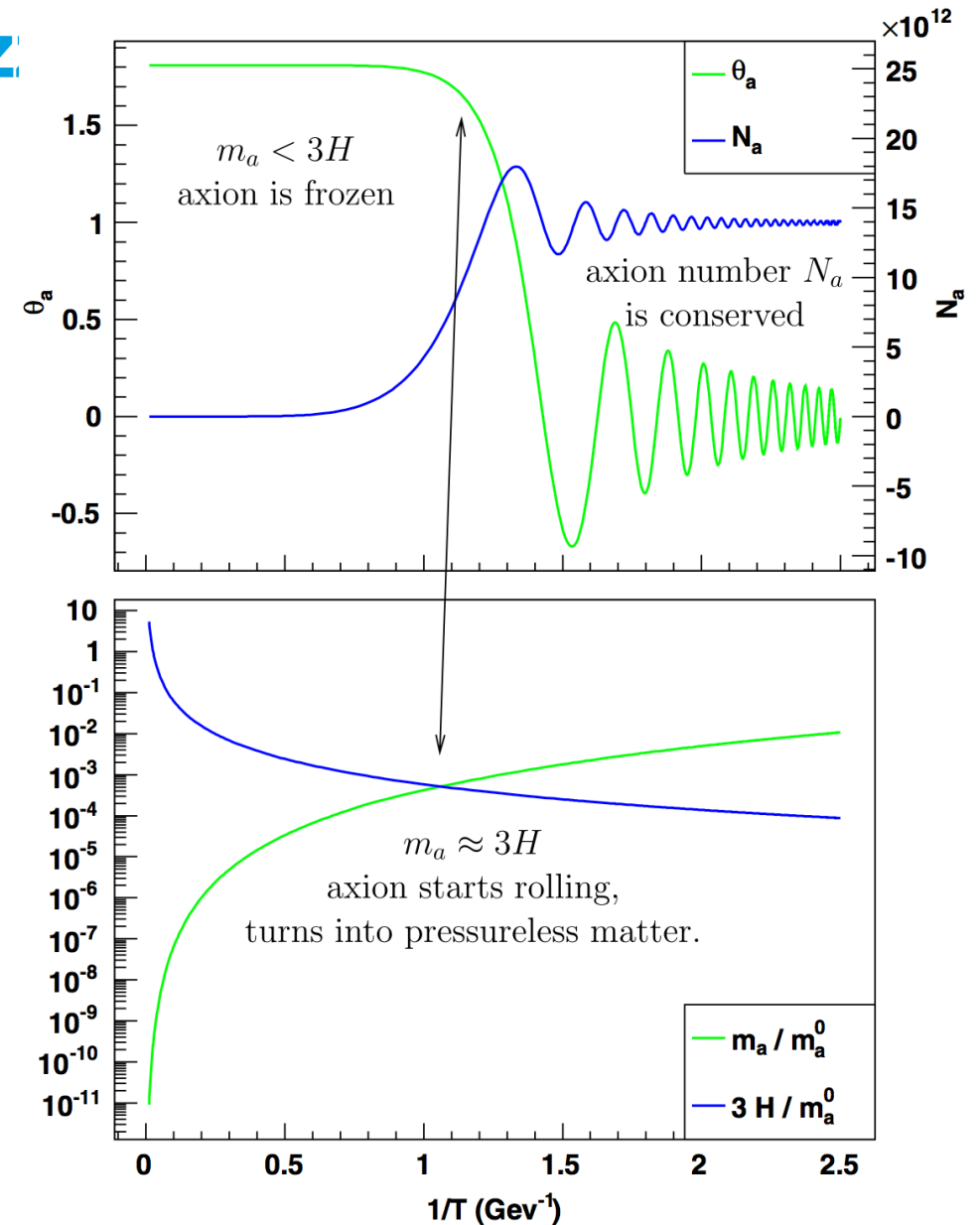
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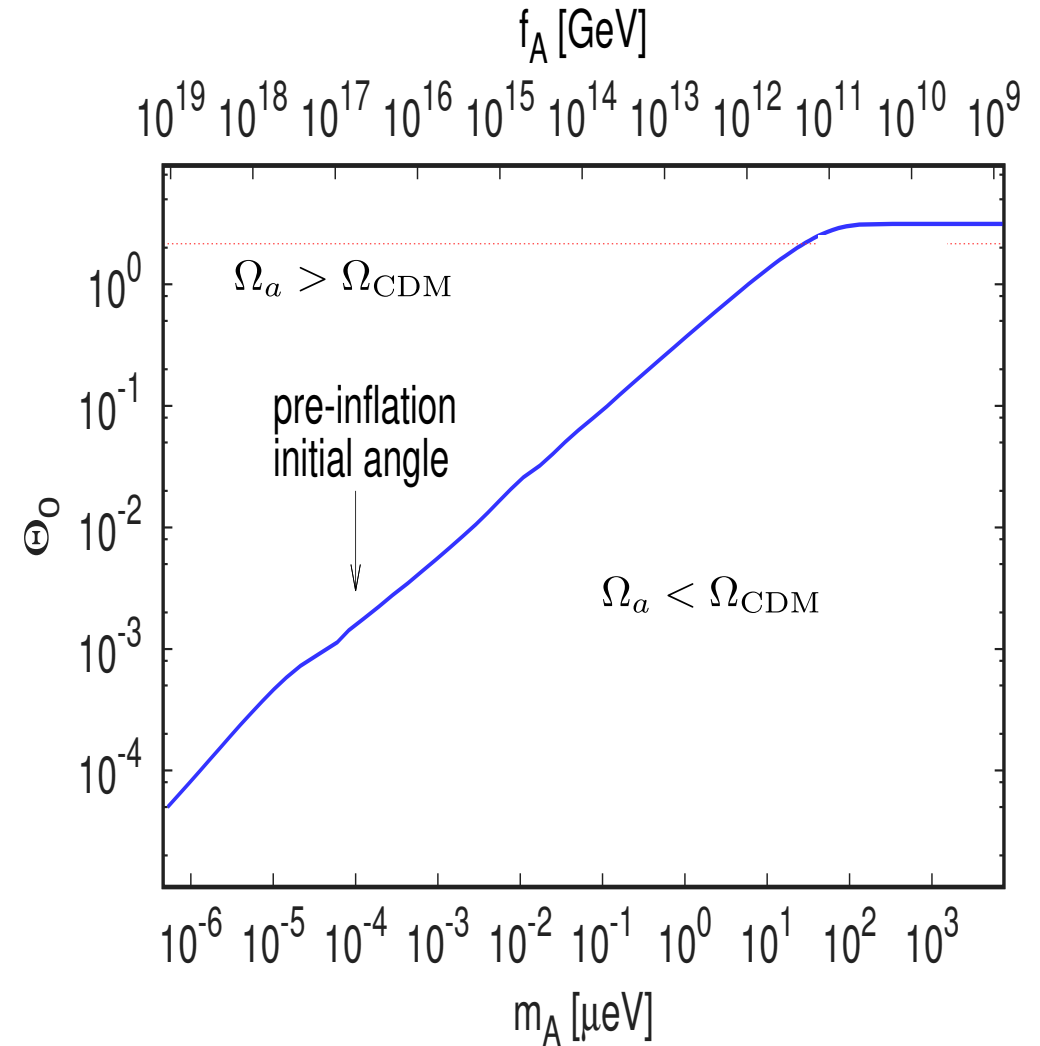
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[Borsanyi et al., Nature `16]

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- May search for axion DM by searching for oscillating NEDMs

[Graham, Rajendran '11; '13]

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Search in ILL and PSI nEDM experiment data

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## Search in ILL and PSI nEDM experiment data

- ALP dark matter has been searched for by analysing the ratio of the spin-precession frequencies of stored ultracold neutrons and  $^{199}\text{Hg}$  atoms for an oscillating nEDM

PHYSICAL REVIEW X 7, 041034 (2017)

### Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields

C. Abel,<sup>1</sup> N. J. Ayres,<sup>1,\*</sup> G. Ban,<sup>2</sup> G. Bison,<sup>3</sup> K. Bodek,<sup>4</sup> V. Bondar,<sup>5</sup> M. Daum,<sup>3</sup> M. Fairbairn,<sup>6</sup> V. V. Flambaum,<sup>7</sup> P. Geltenbort,<sup>8</sup> K. Green,<sup>9</sup> W. C. Griffith,<sup>1</sup> M. van der Grinten,<sup>9</sup> Z. D. Grujić,<sup>10</sup> P. G. Harris,<sup>1</sup> N. Hild,<sup>3</sup> P. Iaydjiev,<sup>9,‡</sup> S. N. Ivanov,<sup>9,§</sup> M. Kasprzak,<sup>5</sup> Y. Kermaidic,<sup>11</sup> K. Kirch,<sup>12,3</sup> H.-C. Koch,<sup>3</sup> S. Komposch,<sup>3,12</sup> P. A. Koss,<sup>5</sup> A. Kozela,<sup>1,3</sup> J. Krempel,<sup>12</sup> B. Lauss,<sup>3</sup> T. Lefort,<sup>2</sup> Y. Lemière,<sup>2</sup> D. J. E. Marsh,<sup>6</sup> P. Mohanmurthy,<sup>3,12</sup> A. Mtchedlishvili,<sup>3</sup> M. Musgrave,<sup>1,¶</sup> F. M. Piegsa,<sup>14</sup> G. Pignol,<sup>11</sup> M. Rawlik,<sup>12,†</sup> D. Rebreyend,<sup>11</sup> D. Ries,<sup>14,3,12</sup> S. Roccia,<sup>15</sup> D. Rozpedzik,<sup>4</sup> P. Schmidt-Wellenburg,<sup>3</sup> N. Severijns,<sup>5</sup> D. Shiers,<sup>1</sup> Y. V. Stadnik,<sup>7</sup> A. Weis,<sup>10</sup> E. Wursten,<sup>5</sup> J. Zejma,<sup>4</sup> and G. Zsigmond<sup>3</sup>

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<sup>15</sup>CSNSM, Université Paris Sud, CNRS/IN2P3, Université Paris Saclay,

Bat. 104&108, F91405 Orsay-Campus, France

(Received 29 August 2017; published 14 November 2017)

# Axion Dark Matter Search Based on NEDM Coupling

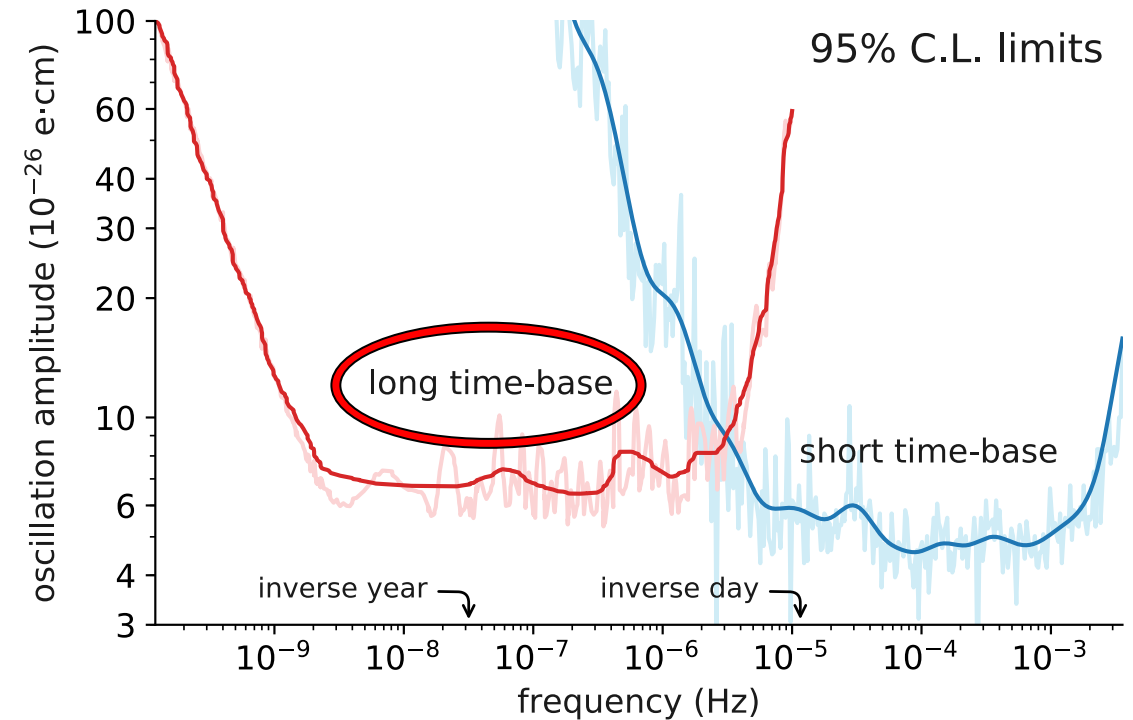
## Search in ILL and PSI nEDM experiment data

- ALP dark matter has been searched for by analysing the ratio of the spin-precession frequencies of stored ultracold neutrons and  $^{199}\text{Hg}$  atoms for an oscillating nEDM
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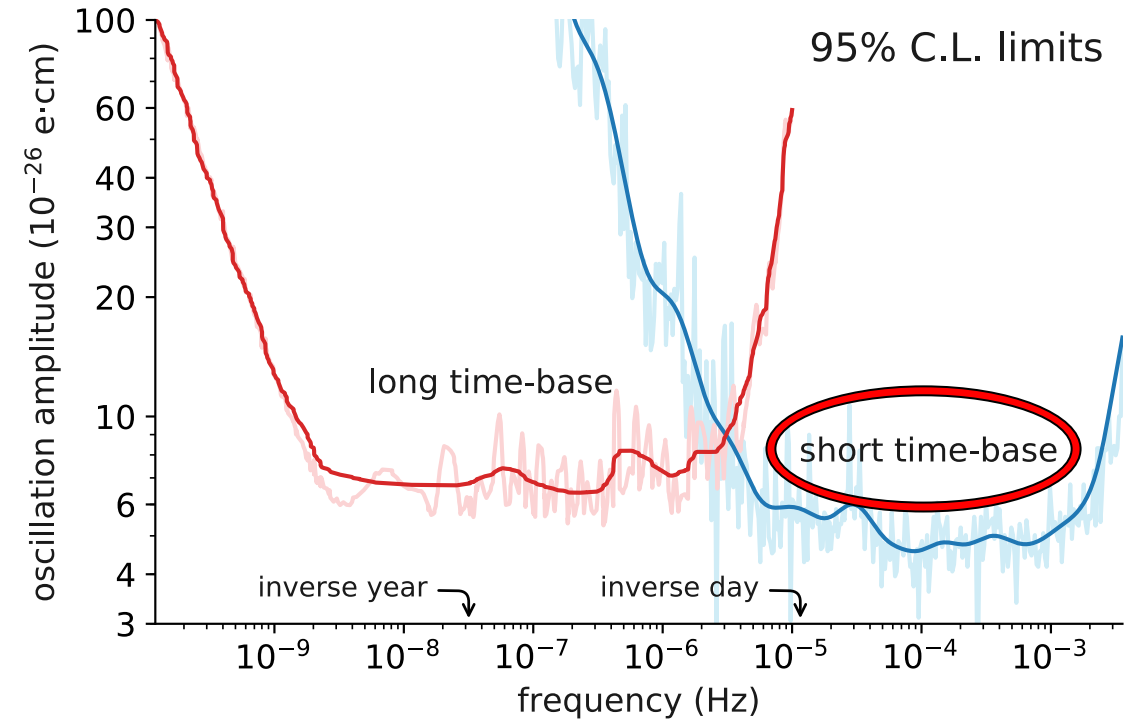
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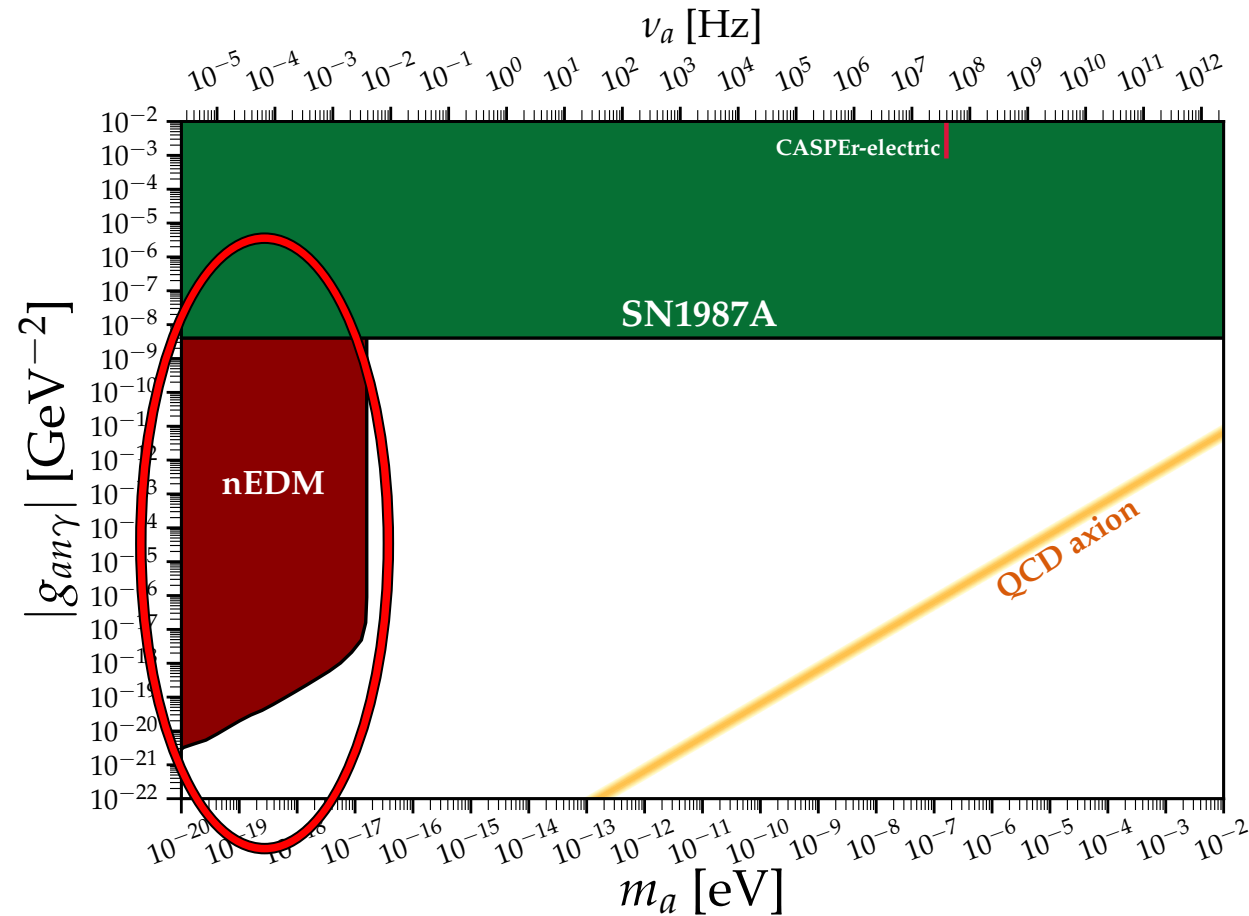
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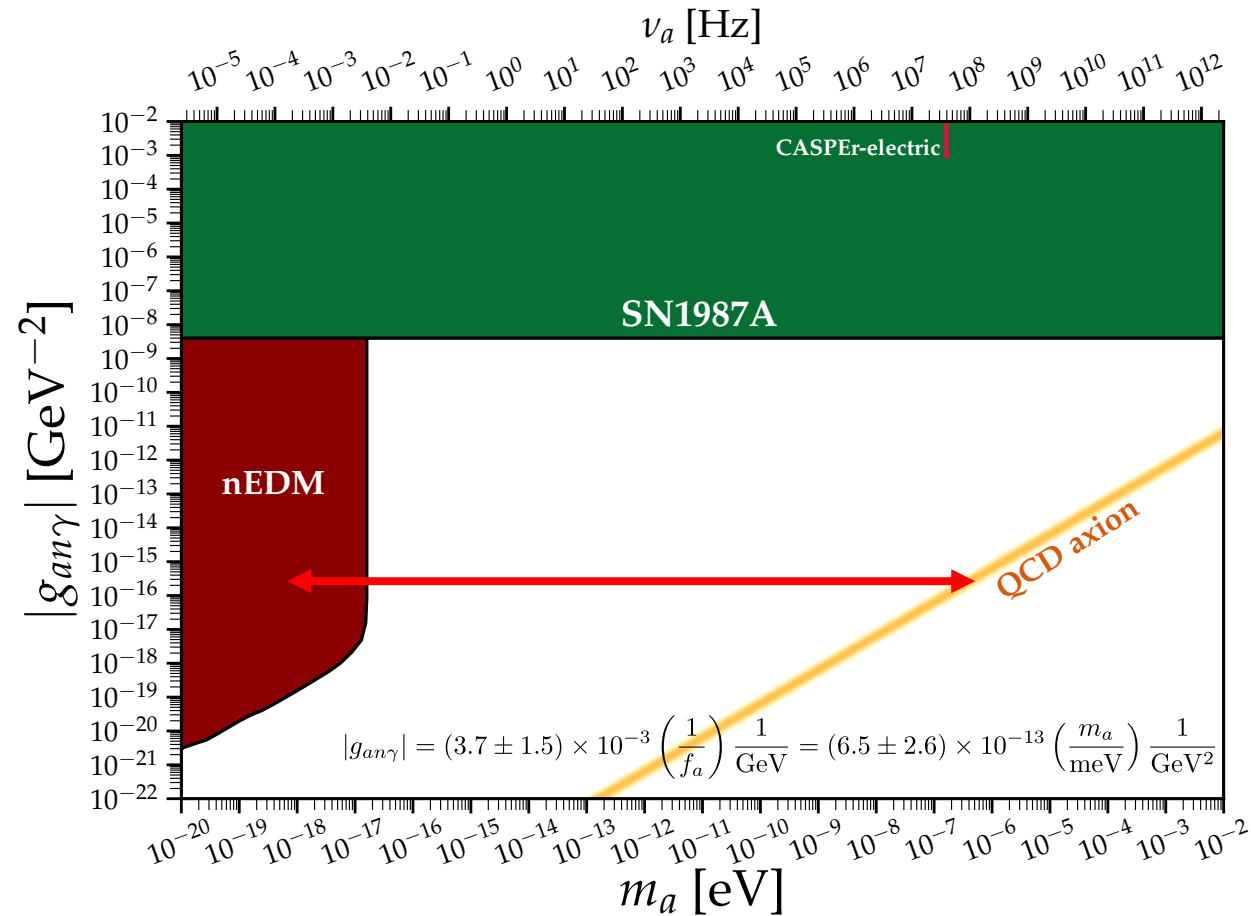
[AR,Rosenberg,Rybka in: 2021 Update of Review of Particle Physics]

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- An ALP with an nEDM coupling in the excluded region is much lighter than a canonical QCD axion with the same nEDM coupling strength



[AR,Rosenberg,Rybka in: 2021 Update of Review of Particle Physics]

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**Dedicated Nuclear Magnetic Resonance Searches** [Graham,Rajendran 13; Budker et al. 14]

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Dedicated Nuclear Magnetic Resonance Searches [Graham,Rajendran 13; Budker et al. 14]

- CASPER-Electric currently being set-up in Boston

PHYSICAL REVIEW X **4**, 021030 (2014)

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## Proposal for a Cosmic Axion Spin Precession Experiment (CASPER)

Dmitry Budker,<sup>1,5</sup> Peter W. Graham,<sup>2</sup> Micah Ledbetter,<sup>3</sup> Surjeet Rajendran,<sup>2</sup> and Alexander O. Sushkov<sup>4</sup>

<sup>1</sup>*Department of Physics, University of California, Berkeley, California 94720, USA*  
*and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

<sup>2</sup>*Department of Physics, Stanford Institute for Theoretical Physics, Stanford University,  
Stanford, California 94305, USA*

<sup>3</sup>*AOSense, 767 North Mary Avenue, Sunnyvale, California 94085-2909, USA*

<sup>4</sup>*Department of Physics and Department of Chemistry and Chemical Biology, Harvard University,  
Cambridge, Massachusetts 02138, USA*

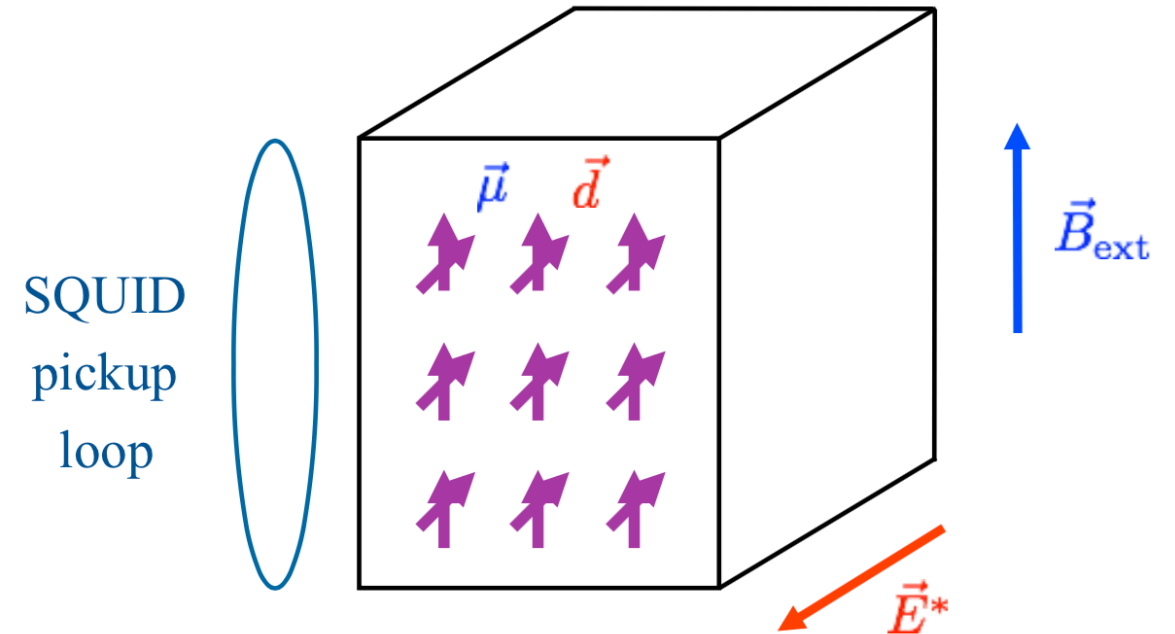
<sup>5</sup>*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*  
(Received 9 July 2013; published 19 May 2014)

We propose an experiment to search for QCD axion and axionlike-particle dark matter. Nuclei that are interacting with the background axion dark matter acquire time-varying  $CP$ -odd nuclear moments such as an electric dipole moment. In analogy with nuclear magnetic resonance, these moments cause precession of nuclear spins in a material sample in the presence of an electric field. Precision magnetometry can be used to search for such precession. An initial phase of this experiment could cover many orders of magnitude in axionlike-particle parameter space beyond the current astrophysical and laboratory limits. And with established techniques, the proposed experimental scheme has sensitivity to QCD axion masses  $m_a \lesssim 10^{-9}$  eV, corresponding to theoretically well-motivated axion decay constants  $f_a \gtrsim 10^{16}$  GeV. With further improvements, this experiment could ultimately cover the entire range of masses  $m_a \lesssim \mu$  eV, complementary to cavity searches.

# Axion Dark Matter Search Based on NEDM Coupling

Dedicated Nuclear Magnetic Resonance Searches [Graham,Rajendran 13; Budker et al. 14]

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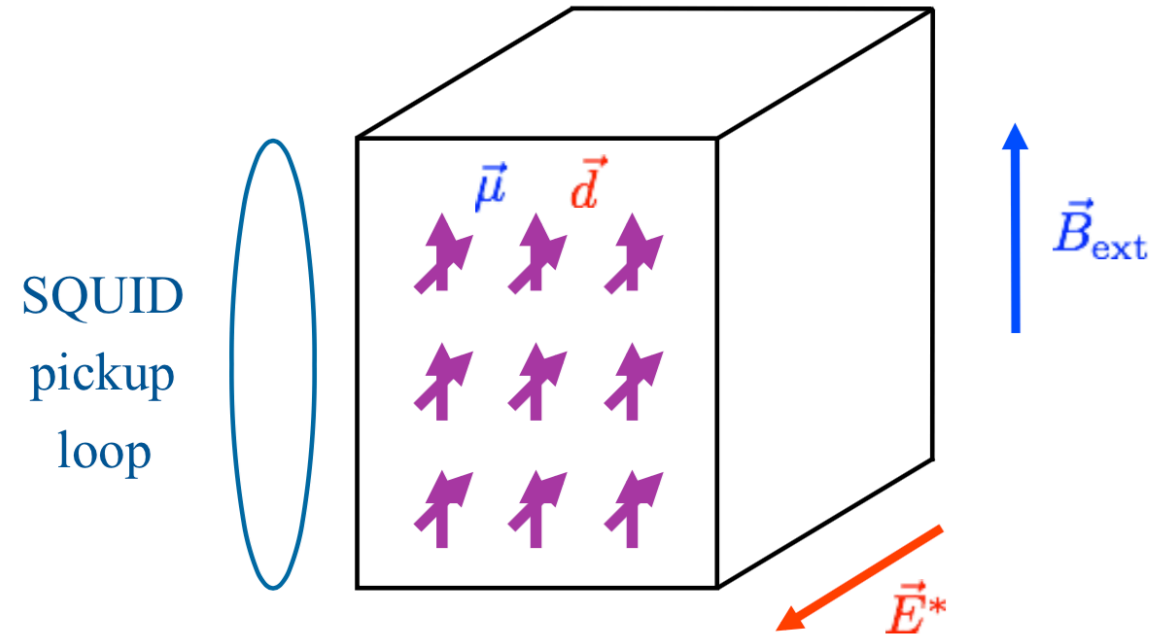


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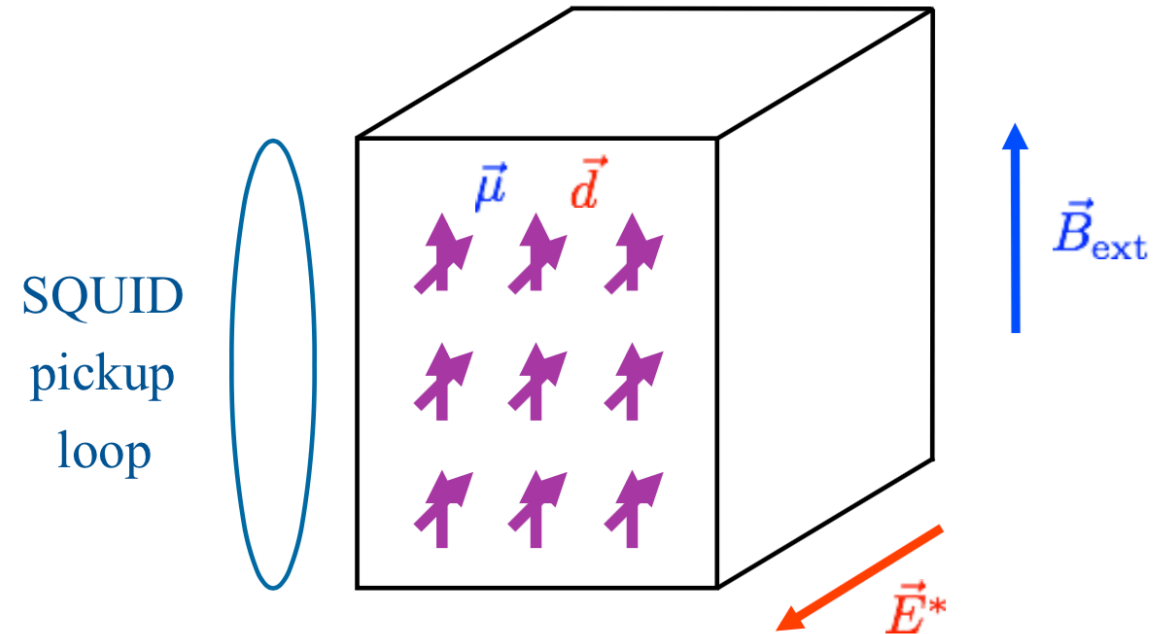


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- First demonstrator

PHYSICAL REVIEW LETTERS **126**, 141802 (2021)

## Search for Axionlike Dark Matter Using Solid-State Nuclear Magnetic Resonance

Deniz Aybas<sup>1,2</sup>, Janos Adam,<sup>1</sup> Emmy Blumenthal,<sup>1</sup> Alexander V. Gramolin,<sup>1</sup> Dorian Johnson,<sup>1</sup> Annalies Kleyheeg,<sup>1</sup> Samer Afach,<sup>3,4</sup> John W. Blanchard,<sup>3</sup> Gary P. Centers,<sup>3,4</sup> Antoine Garcon,<sup>3,4</sup> Martin Engler,<sup>3,4</sup> Nataniel L. Figueroa,<sup>3,4</sup> Marina Gil Sendra,<sup>3,4</sup> Arne Wickenbrock,<sup>3,4</sup> Matthew Lawson,<sup>5,6</sup> Tao Wang,<sup>7</sup> Teng Wu,<sup>8</sup> Haosu Luo,<sup>9</sup> Hamdi Mani,<sup>10</sup> Philip Mauskopf,<sup>10</sup> Peter W. Graham,<sup>11</sup> Surjeet Rajendran,<sup>12</sup> Derek F. Jackson Kimball,<sup>13</sup> Dmitry Budker,<sup>3,4,14</sup> and Alexander O. Sushkov<sup>1,2,15,\*</sup>

<sup>1</sup>Department of Physics, Boston University, Boston, Massachusetts 02215, USA

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<sup>4</sup>Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

<sup>5</sup>The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, 10691 Stockholm, Sweden

<sup>6</sup>Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 10691 Stockholm, Sweden

<sup>7</sup>Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

<sup>8</sup>State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronics, and Center for Quantum Information Technology, Peking University, Beijing 100871, China

<sup>9</sup>Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, China

<sup>10</sup>School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287, USA

<sup>11</sup>Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA

<sup>12</sup>Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218, USA

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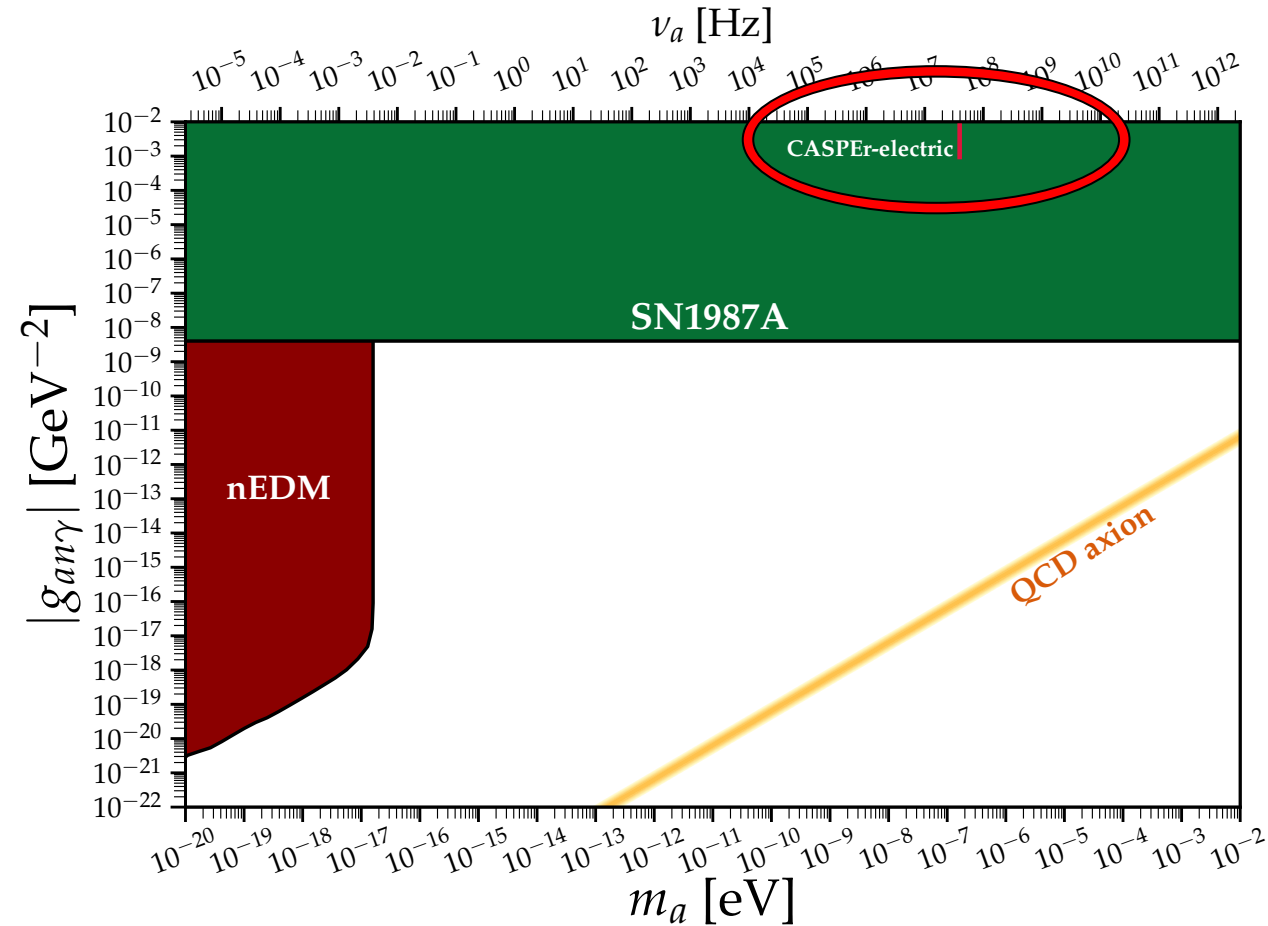
<sup>14</sup>Department of Physics, University of California, Berkeley, California 94720-7300, USA

<sup>15</sup>Photonics Center, Boston University, Boston, Massachusetts 02215, USA

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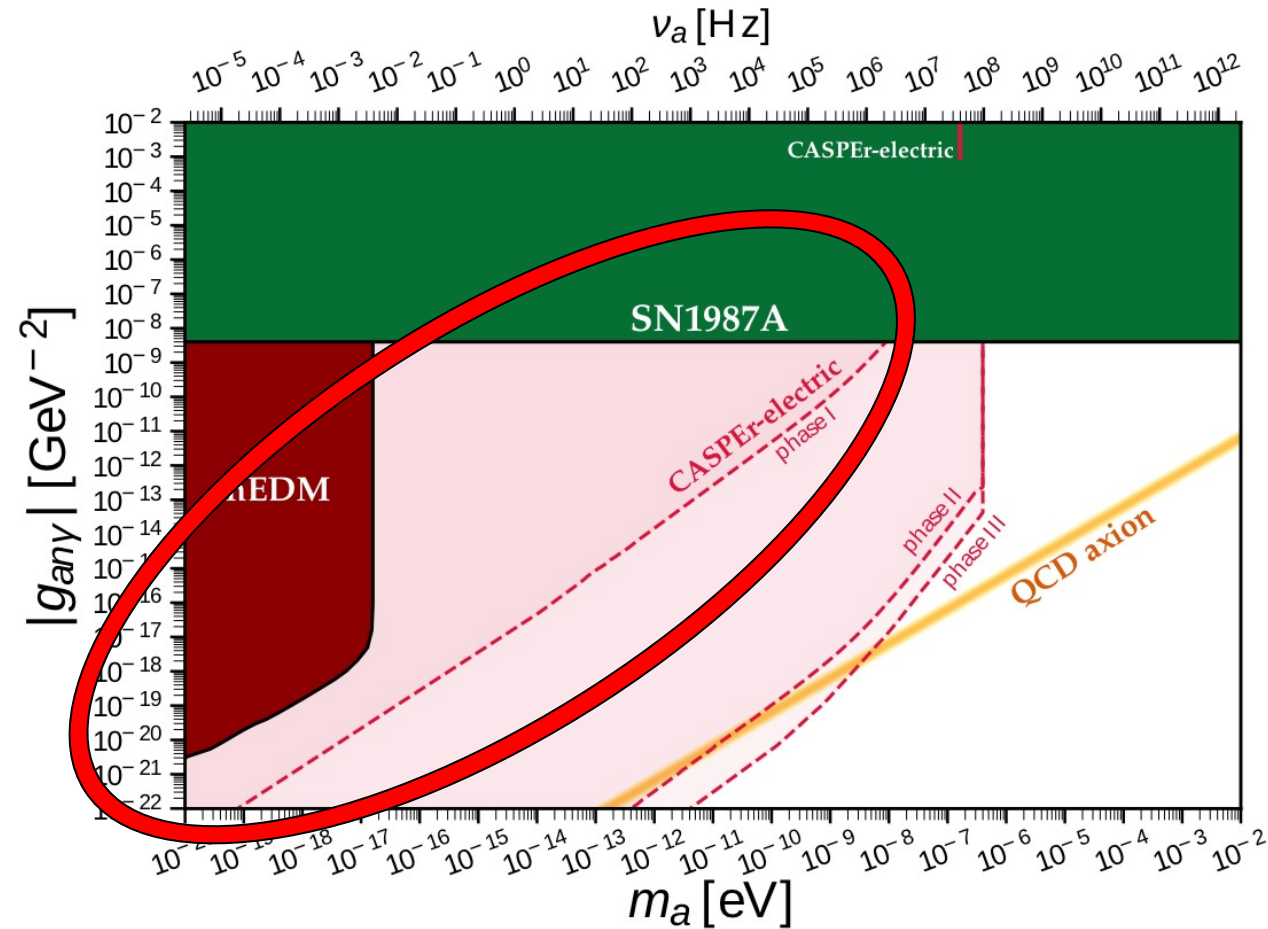
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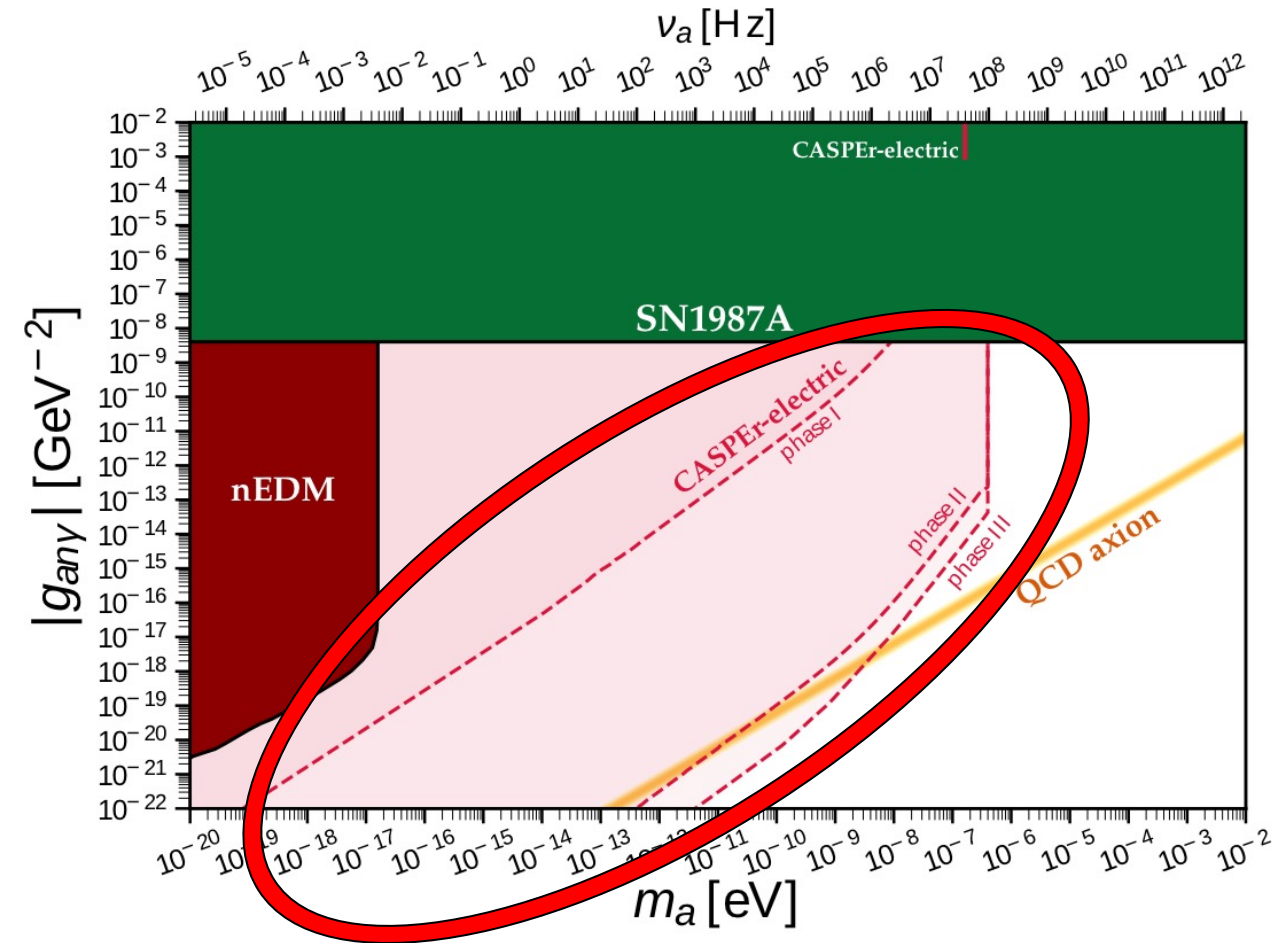


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- Phase II and III will reach canonical QCD axion sensitivity, if axions are 100% of DM



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# Axion Dark Matter Search Based on NEDM Coupling

Storage ring EDM method

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PHYSICAL REVIEW D **99**, 083002 (2019)

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## Axionlike dark matter search using the storage ring EDM method

Seung Pyo Chang,<sup>1,2</sup> Selçuk Hacıömeroğlu,<sup>2</sup> On Kim,<sup>1,2</sup> Soohyung Lee,<sup>2</sup> Seongtae Park,<sup>2,\*</sup> and Yannis K. Semertzidis<sup>1,2</sup>

<sup>1</sup>*Department of Physics, KAIST, Daejeon 34141, Republic of Korea*

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(Received 20 June 2018; revised manuscript received 28 January 2019; published 8 April 2019)

We propose using the storage ring electric dipole moment (EDM) method to search for the axion dark matter induced EDM oscillation in nucleons. The method uses a combination of  $B$  and  $E$  fields to produce a resonance between the  $g - 2$  spin precession frequency and the background axion field oscillation to greatly enhance sensitivity to it. An axion frequency range from  $10^{-9}$  Hz to 100 MHz can, in principle, be scanned with high sensitivity, corresponding to an  $f_a$  range of  $10^{13}$  GeV  $\leq f_a \leq 10^{30}$  GeV, the breakdown scale of the global symmetry generating the axion or axionlike particles.

DOI: [10.1103/PhysRevD.99.083002](https://doi.org/10.1103/PhysRevD.99.083002)

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## Storage ring EDM method

12th Int. Particle Acc. Conf.  
ISBN: 978-3-95450-214-1

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ISSN: 2673-5490

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doi:10.18429/JACoW-IPAC2021-WEPAB188

### NEW METHOD TO SEARCH FOR AXION-LIKE PARTICLES DEMONSTRATED WITH POLARIZED BEAM AT THE COSY STORAGE RING

S. Karanth\*, Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland  
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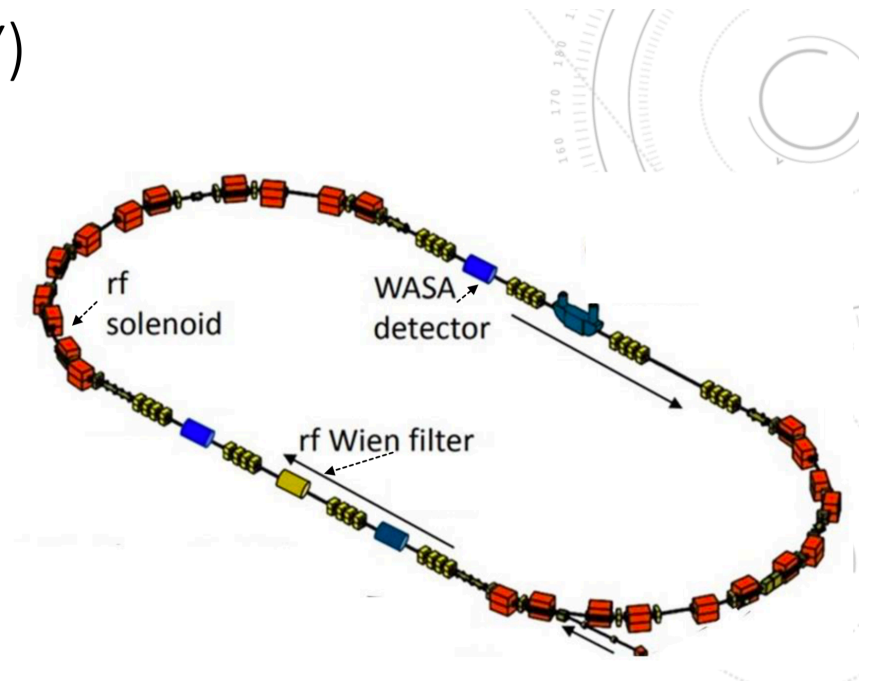
First demonstrator experiment at COSY

#### Abstract

The axion was originally proposed to explain the absence size of CP violation in quantum chromodynamics. Axions or axion-like particles (ALPs), when coupled to gluons, induce an oscillating Electric Dipole Moment (EDM) along the nucleon's spin direction. At the Cooler Synchrotron COSY in Jülich, this principle was used to perform a first test experiment to search for ALPs using an in-plane polarized deuteron beam. In COSY, the beam polarization vector precesses in the horizontal plane due to the presence of magnetic fields. If the spin precession frequency equals the EDM oscillation frequency, a resonance occurs that accumulates the rotation of the polarization out of the ring plane. Such a resonance is searched for by scanning beam revolution frequency, which is directly related to the spin precession frequency. At COSY, four beam bunches with different polarization directions were used to make sure that no resonance was missed because of the unknown relative phase between the polarization precession and the EDM oscillations. We scanned a frequency window of about 1.5 kHz width around the spin precession frequency of 121 kHz. This paper describes the experiment.

## Cooler Synchrotron (COSY)

- A proof-of-principle experiment to search for ALPs
- Polarized deuterons
- WASA detector as the polarimeter



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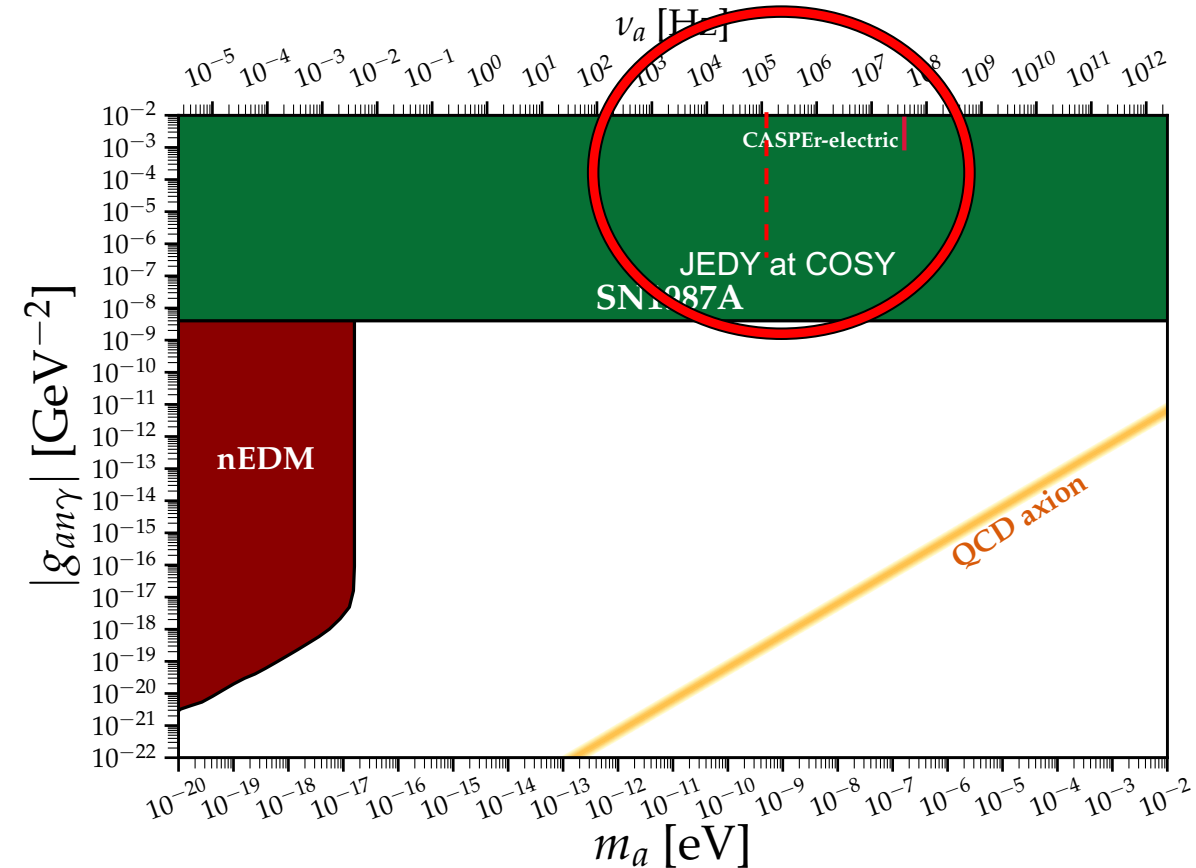
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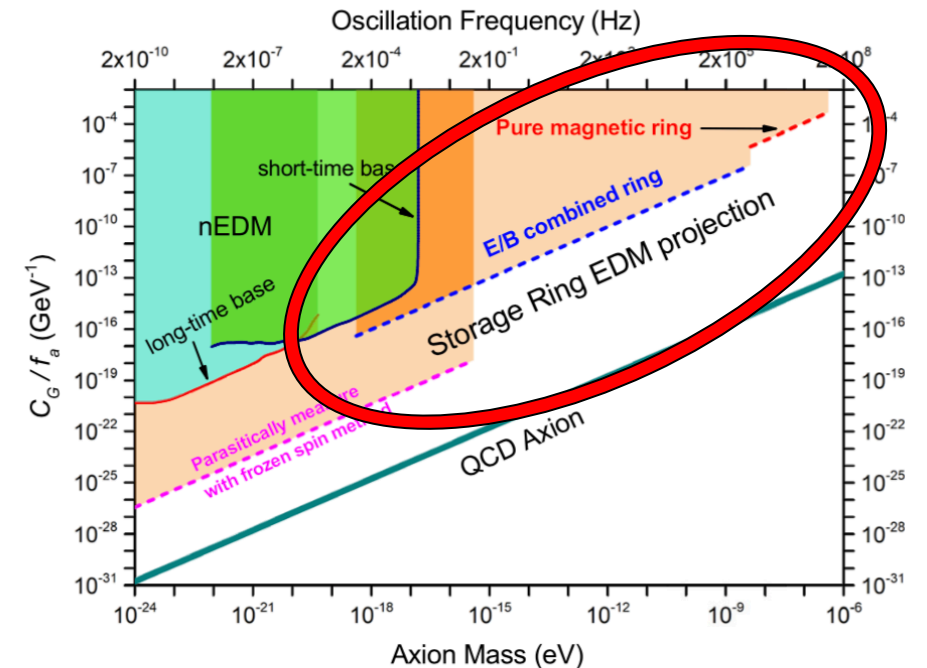


FIG. 7. Experimental limits for the frequency scan with deuterons. The measurement time is assumed to be 3 s for each frequency with an  $E + B$  ring and axion coherence time with a  $B$ -field ring. See Table III for details.

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[Hook, arXiv:1802.10093]

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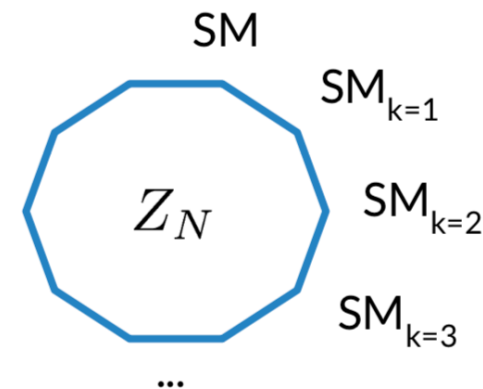
- $Z_{\mathcal{N}}$  axion in mirror world extension of SM allows to achieve this in technically naturally manner

[Hook, arXiv:1802.10093]

- Extension of the SM by adding  $\mathcal{N} - 1$  copies of the SM that are interchanged under a  $Z_{\mathcal{N}}$  symmetry which is non-linearly realized by the axion field:

$$Z_{\mathcal{N}} : \text{SM}_k \longrightarrow \text{SM}_{k+1} \pmod{\mathcal{N}}$$

$$a \longrightarrow a + \frac{2\pi k}{\mathcal{N}} f_a$$



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$Z_N$  axion in mirror world extension of SM

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$$Z_N : \text{SM}_k \longrightarrow \text{SM}_{k+1 \pmod{\mathcal{N}}}, \quad a \longrightarrow a + \frac{2\pi k}{\mathcal{N}} f_a \quad [\text{Hook, arXiv:1802.10093}]$$

- The most general Lagrangian implementing this symmetry describes  $\mathcal{N}$  mirror worlds whose couplings take exactly the same values as in the SM, with the exception of the effective  $\theta$ -parameter: for each copy the effective  $\theta$  value is shifted by  $2\pi/\mathcal{N}$  with respect to that in the neighbour  $k$  sector,

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# An Even Lighter QCD Axion

## $Z_N$ axion in mirror world extension of SM

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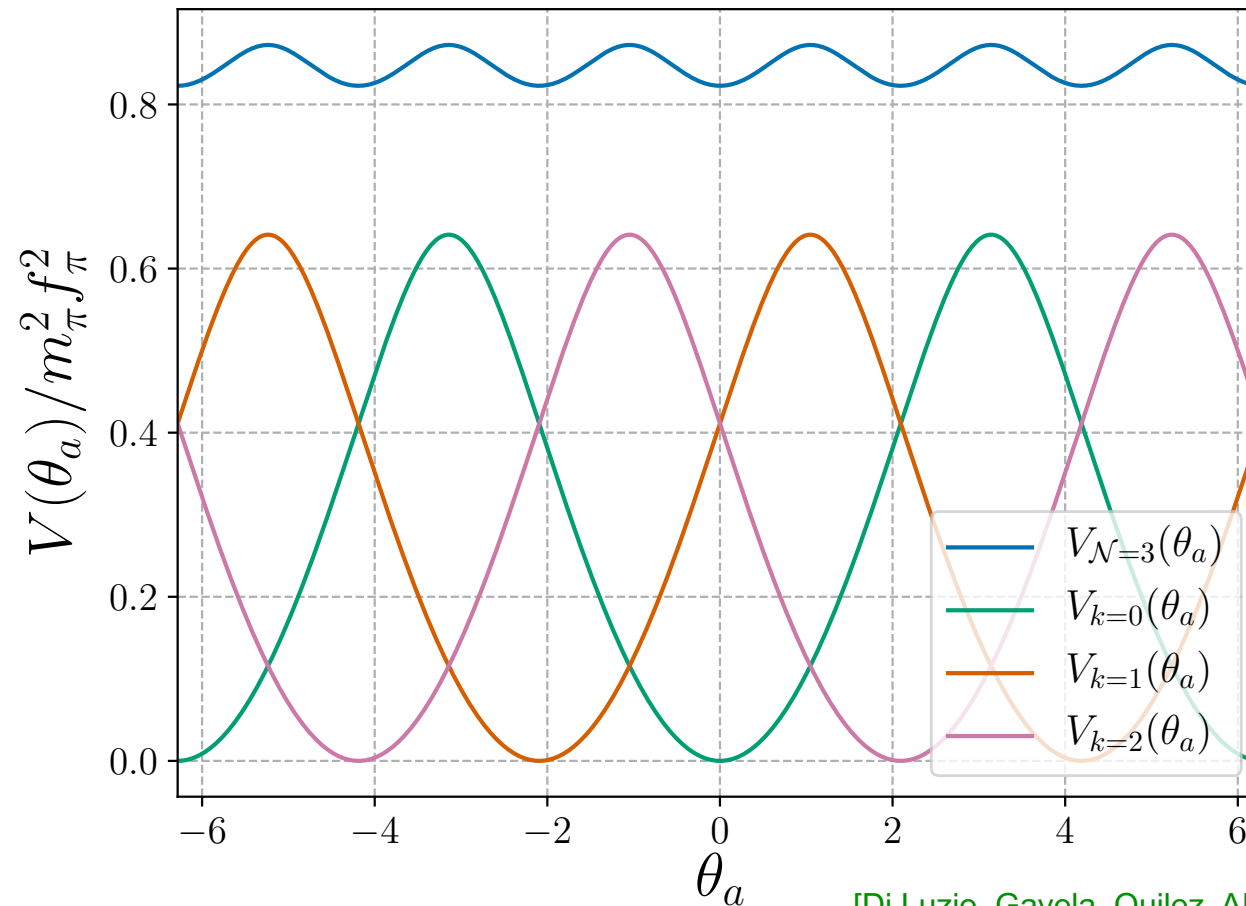
- Each  $\text{QCD}_k$  sector contributes to the axion potential, which in leading order chiral expansion reads

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

# An Even Lighter QCD Axion

## $Z_N$ axion in mirror world extension of SM

- For  $\mathcal{N}$  odd, strong CP problem solved: potential has  $\mathcal{N}$  minima located at  $a = \{\pm 2\pi\ell/\mathcal{N}\}f_a$ , for  $\ell = 0, 1, \dots, (\mathcal{N} - 1)/2$ , including the origin,  $a = 0$



[Di Luzio, Gavela, Quilez, AR, arXiv:2102.00012]

# An Even Lighter QCD Axion

## $Z_N$ axion in mirror world extension of SM

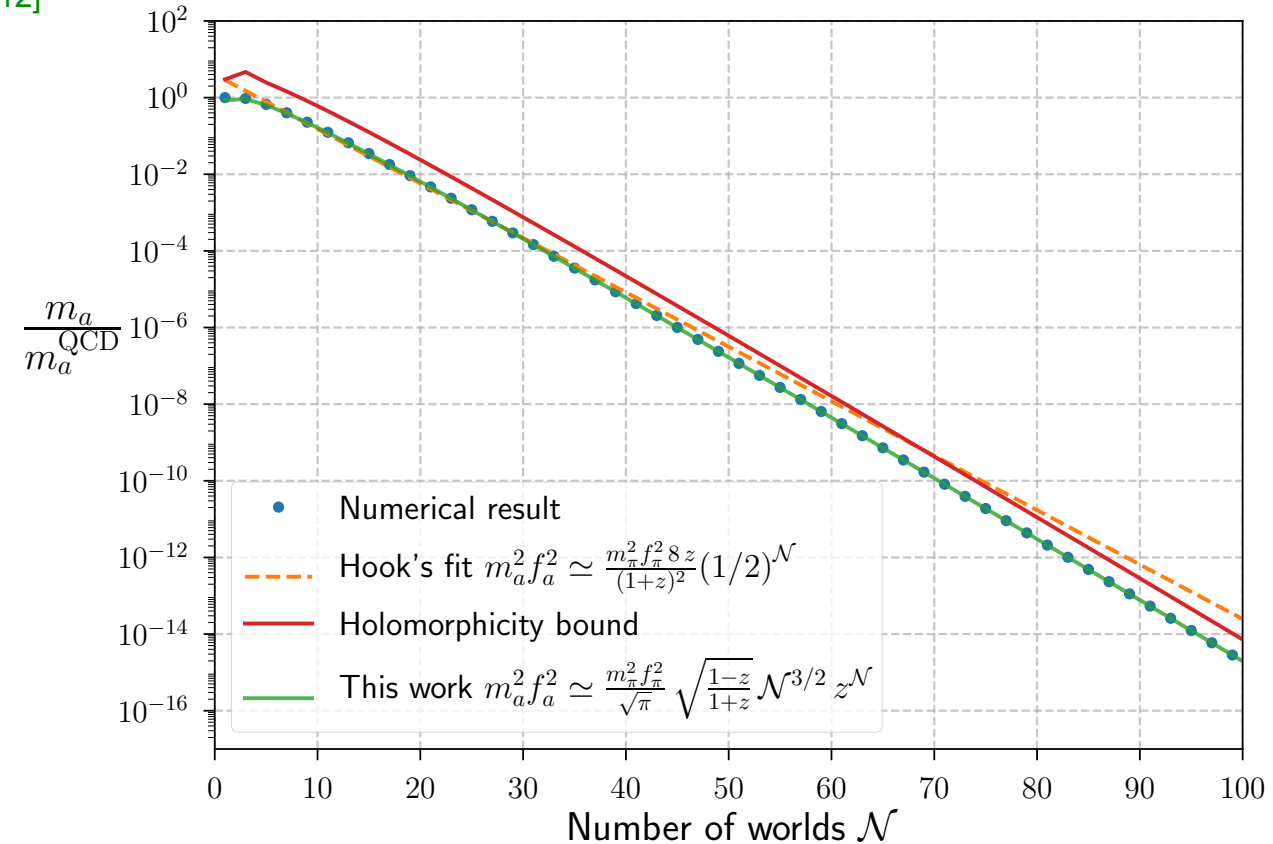
- In the large  $\mathcal{N}$  limit: [Di Luzio, Gavela, Quilez, AR, arXiv:2102.00012]

$$V_{\mathcal{N}}(a) \simeq -\frac{m_{\pi}^2 f_{\pi}^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{-1/2} z^{\mathcal{N}} \cos\left(\mathcal{N} \frac{a}{f_a}\right)$$

- In particular:

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

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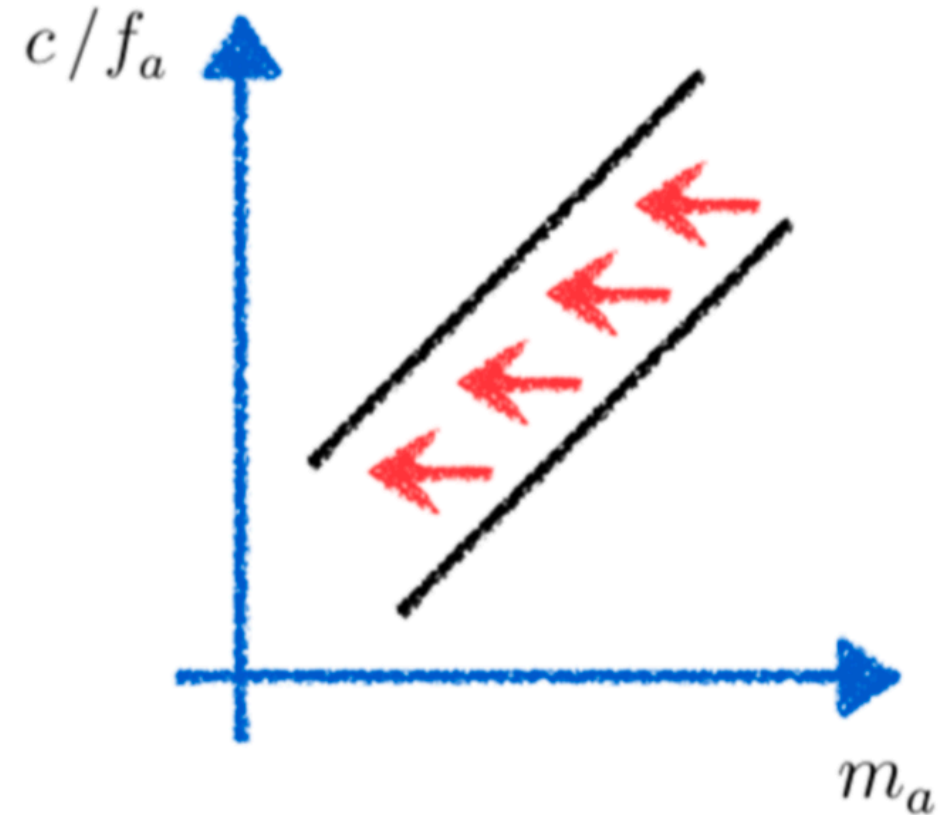
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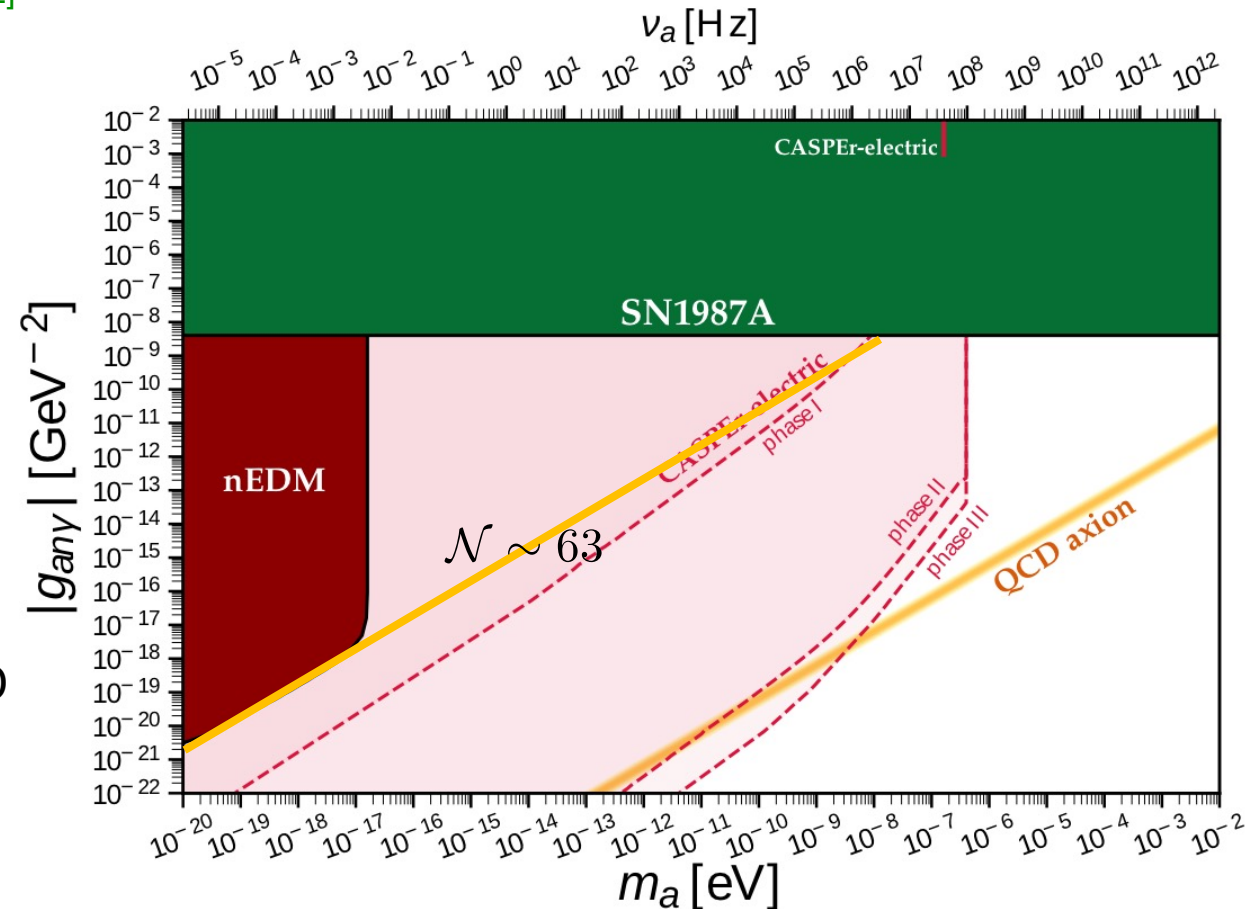
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- May be in reach of CASPER-electric Phase I if it can be 100% of dark matter



[adapted from <https://github.com/cajohare/AxionLimits>]

# DM from an Even Lighter QCD Axion

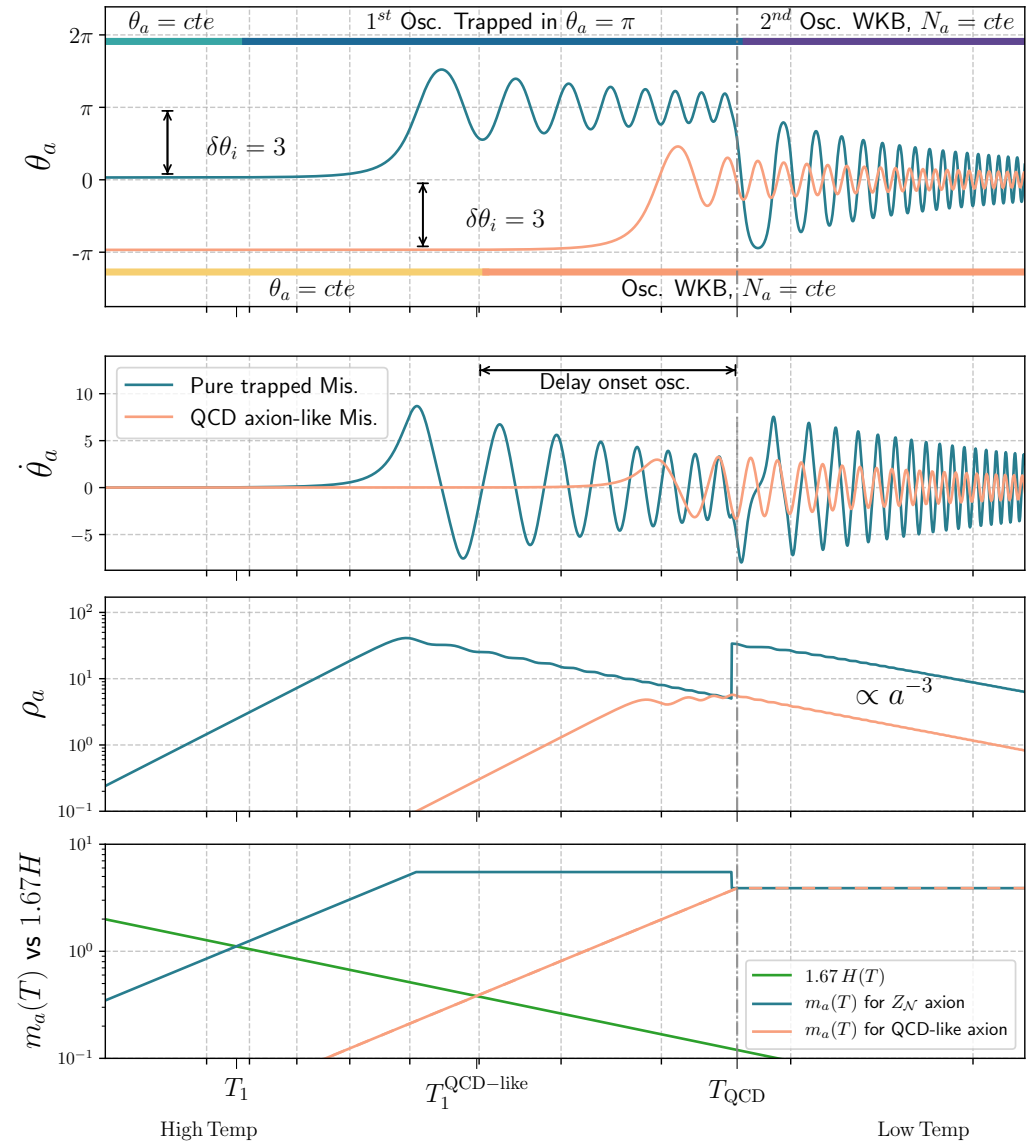
**Dark matter production** [Di Luzio, Gavela, Quilez, AR, arXiv:2102.01082]

- Peculiar temperature dependence of axion potential: DM produced by different types of misalignment

# DM from an Even Lighter QCD Axion

**Dark matter production** [Di Luzio, Gavela, Quilez, AR, arXiv:2102.01082]

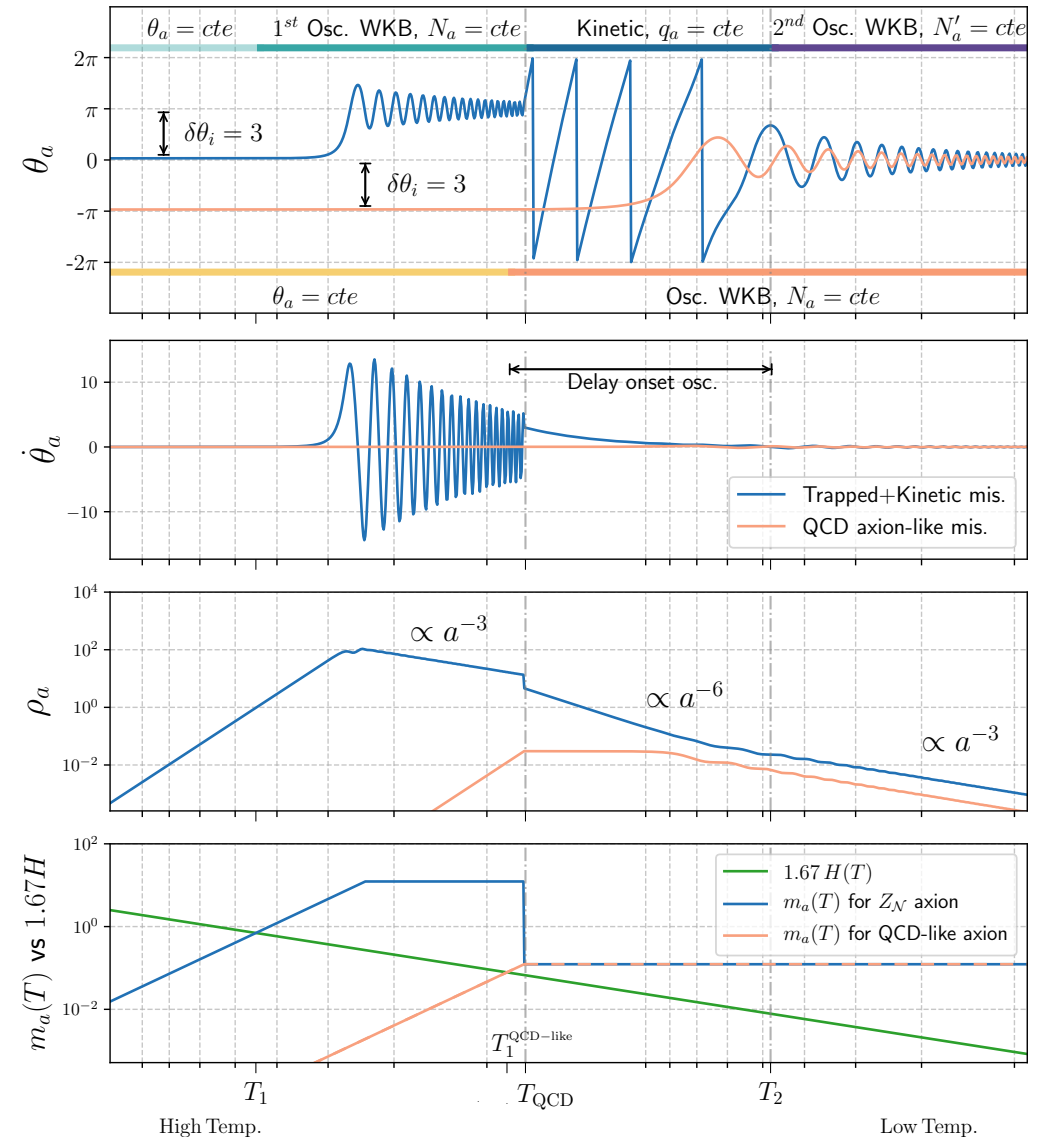
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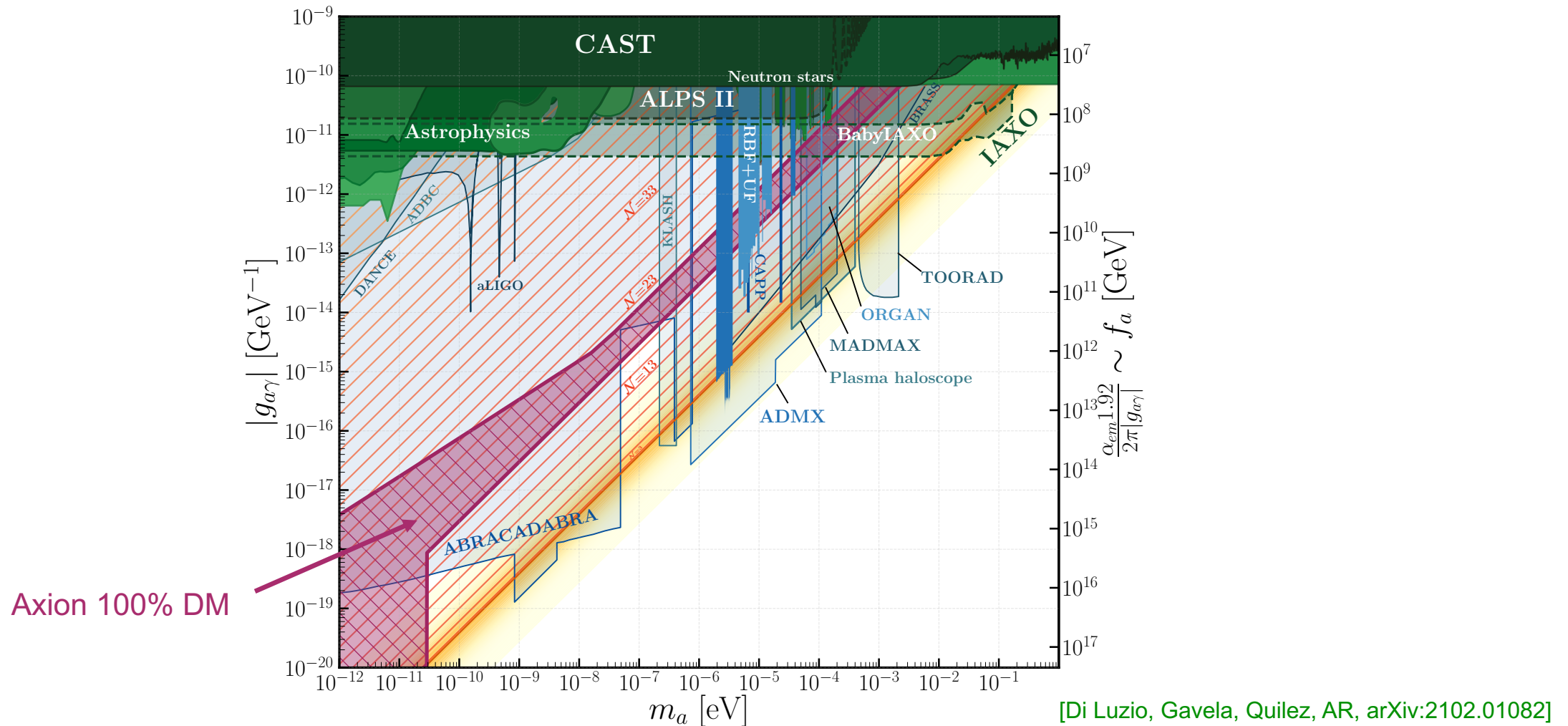
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  - simple ALP ( $f_a \gtrsim 10^{17}$  GeV)

# Experimental Probes of the $Z_N$ Axion

## Searches based on photon coupling

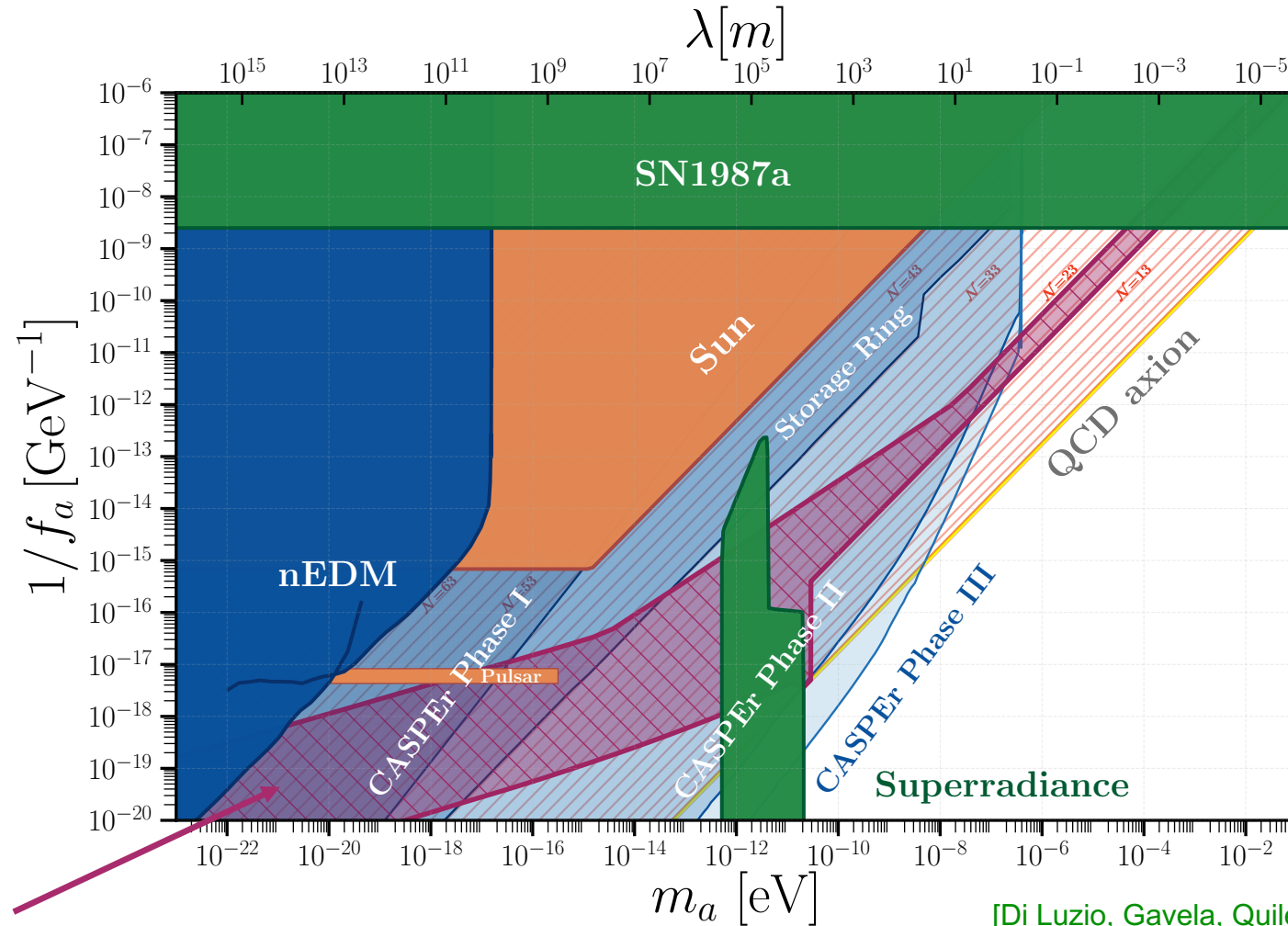
- Huge discovery potential for light-shining through wall (ALPS II), helioscope (IAXO) and haloscope searches:



# Experimental Probes of the $Z_N$ Axion

## Searches based on NEDM coupling

- Large discovery potential for searches for oscillating NEDMs:



[Di Luzio, Gavela, Quilez, AR, arXiv:2102.01082]

# Conclusions

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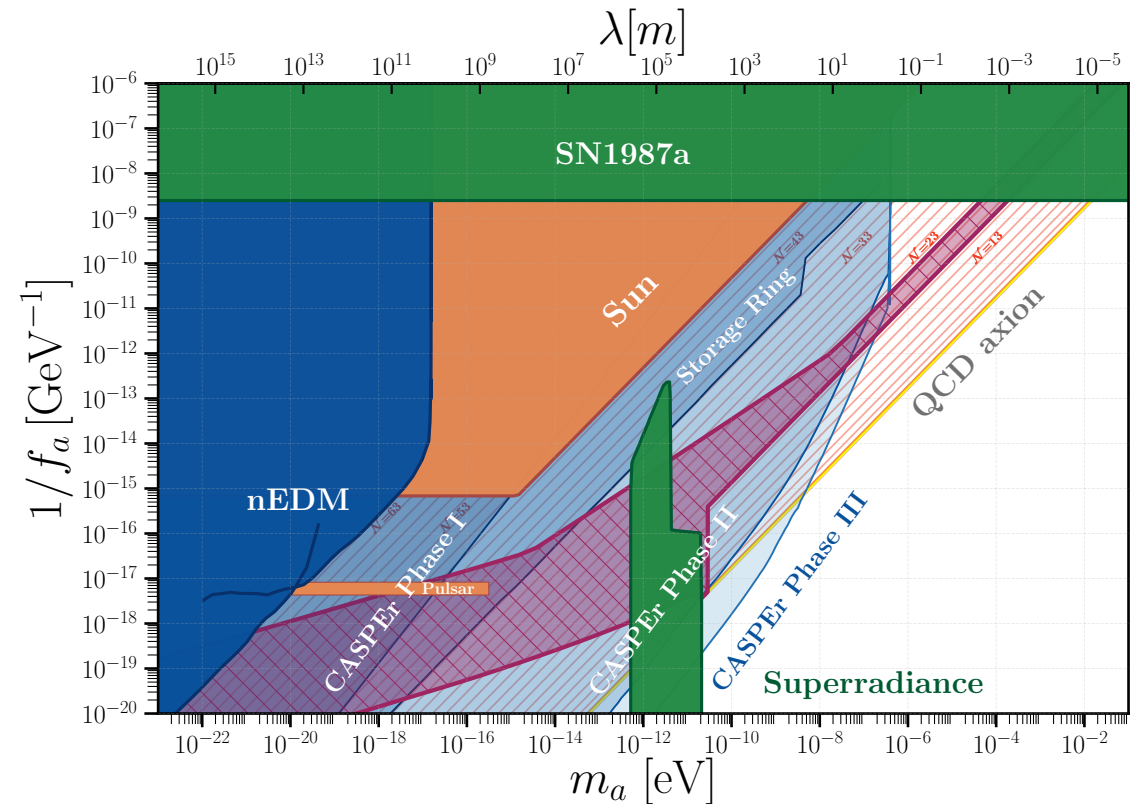
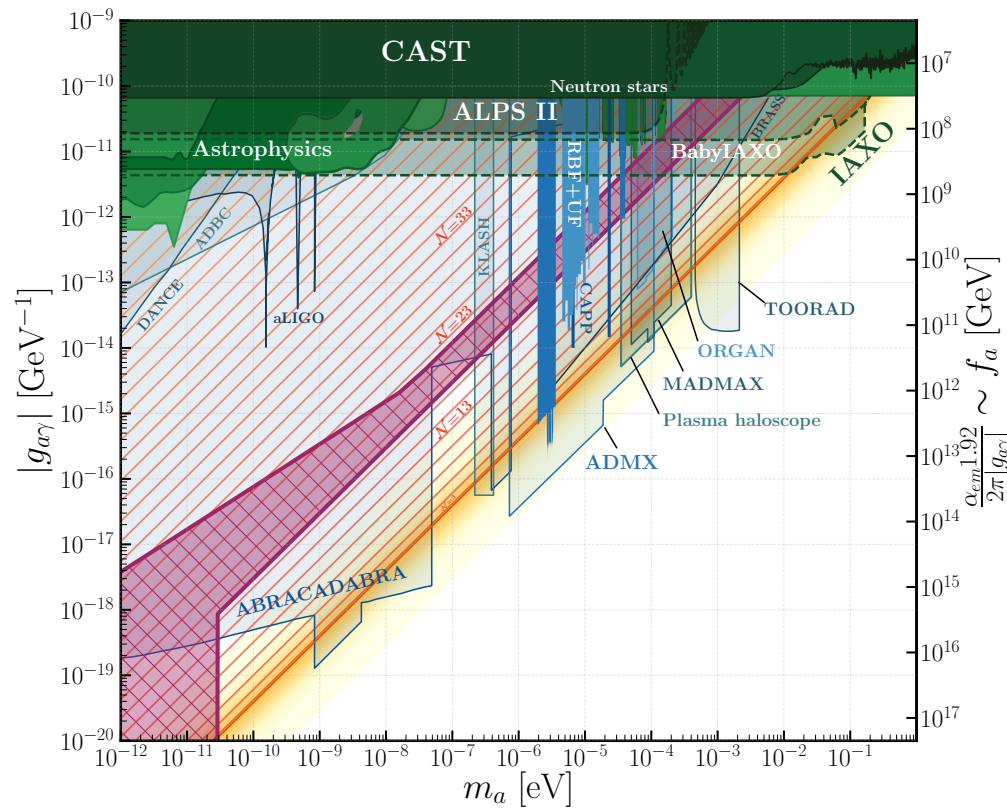
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- QCD axion can be even lighter than canonical one
- All interactions of QCD axion are then universally enhanced relative to the canonical one with the same mass
- Experiments which were aiming to search for generic ALPs may in fact discover a true QCD axion candidate



# Backup: Astrophysical Probes of the $Z_N$ Axion

## Stellar constraints

- Duration of neutrino signal from Supernova 1987A [Raffelt, hep-ph/0611350]

- Superradiance [Arvanitaki et al., 1004.3558; 1411.2263]

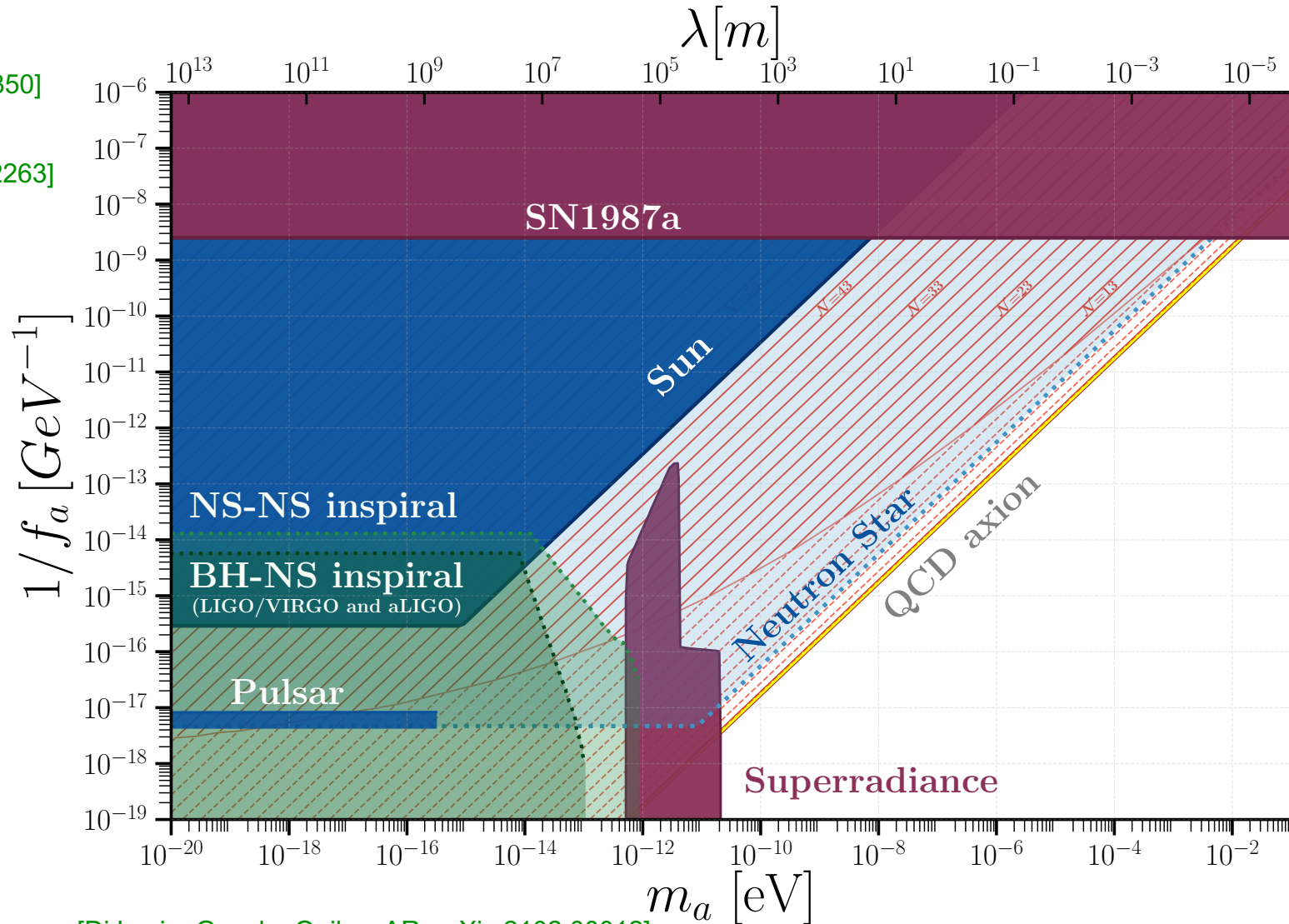
- In stellar cores minimum of axion potential may be shifted to  $\pi$ , leading to modifications

- of nuclear processes in

- Sun
- Neutron stars
- Pulsars

- in the orbital decay of binary systems (NS-NS or BH-NS) and subsequently in the emitted gravitational waves

[Hook, Huang, 1708.08464; Huang et al., 1807.02133]

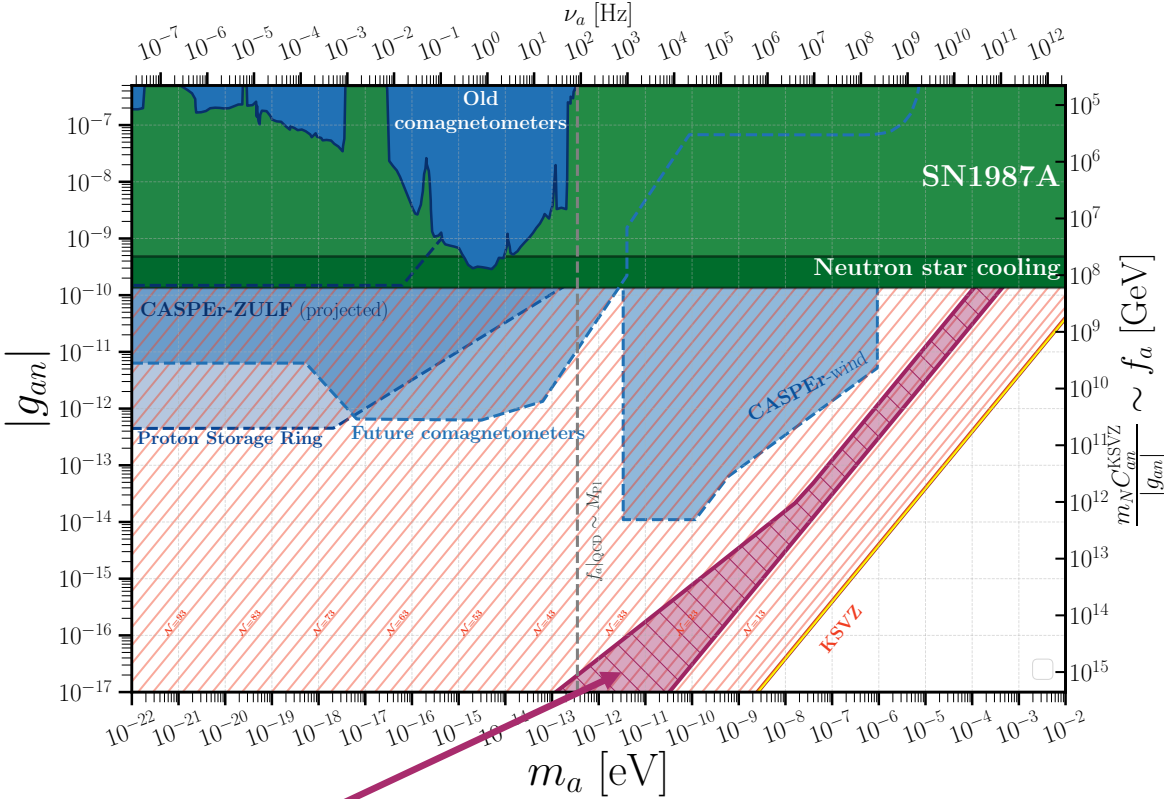


[Di Luzio, Gavela, Quilez, AR, arXiv:2102.00012]

# Backup: Experimental Probes of the $Z_N$ Axion

## Searches based on nucleon coupling

- Prospected sensitivity for searches for dark matter wind:



Axion 100% DM

[Di Luzio, Gavela, Quilez, AR, arXiv:2102.01082]