Axions and Ultralight Dark Matter

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KITP Conference: Snowmass Theory Frontier

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Artwork by Sandbox Studio, Chicago

New Physics from Low to High Scales

- Axions are
  - Solutions to a theoretical puzzle of small numbers—the strong-CP problem
  - Approximately massless particle with mass and couplings fixed by a high scale f_a,

$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

  - Candidates for the dark matter of the universe

$$\frac{\Omega_a}{\Omega_{\rm DM}} \simeq \left(\frac{m_a}{\rm eV}\right)^{1/2}\left(\frac{f_a}{1.5\times 10^{11}\,\rm GeV}\right)^2\left(\frac{\theta_i}{\pi/\sqrt{3}}\right)^2 \quad *$$

  - Motivated by string theoretic constructions

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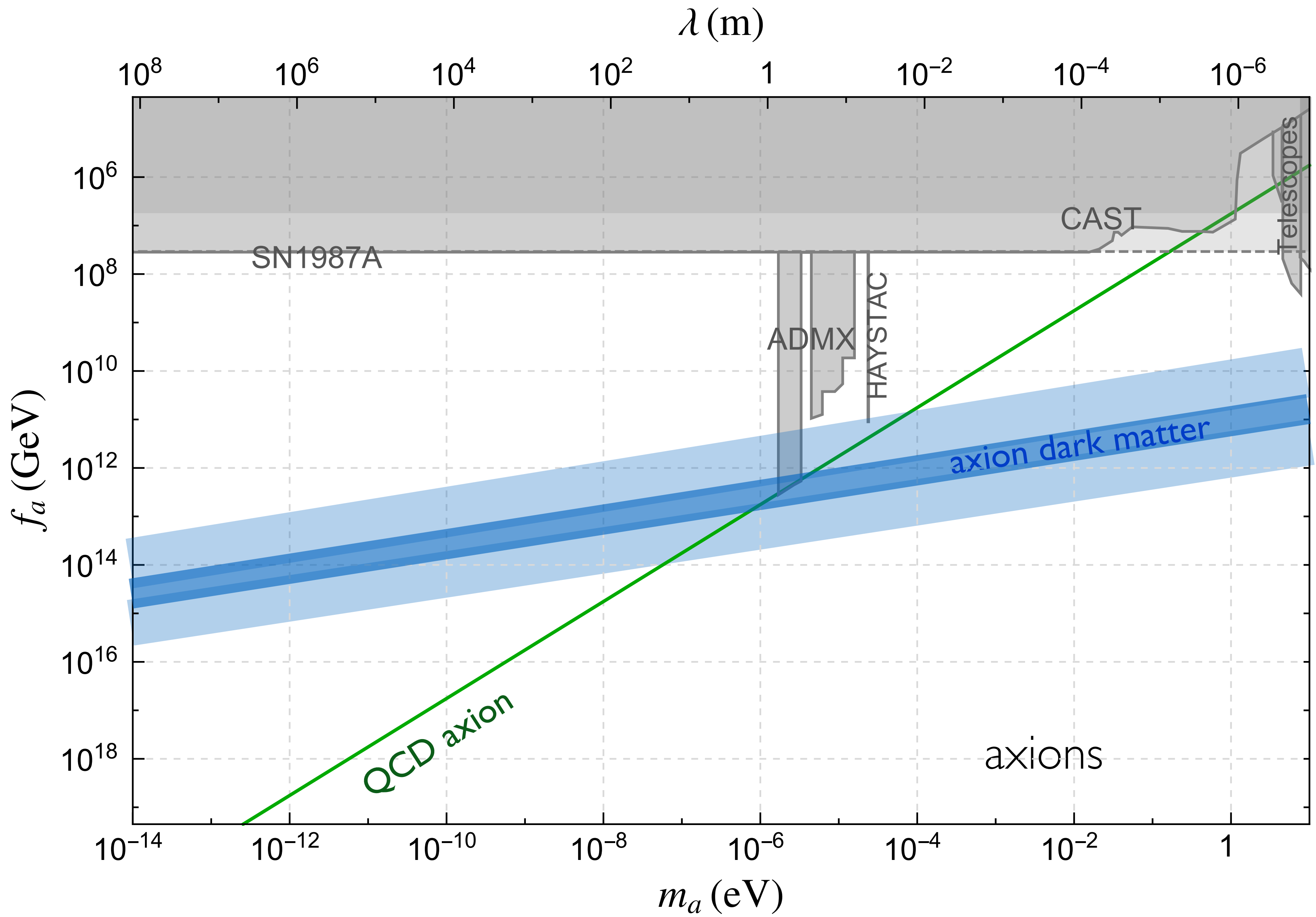
QCD axion

more general axion like particles, dark photons, dilatons,...

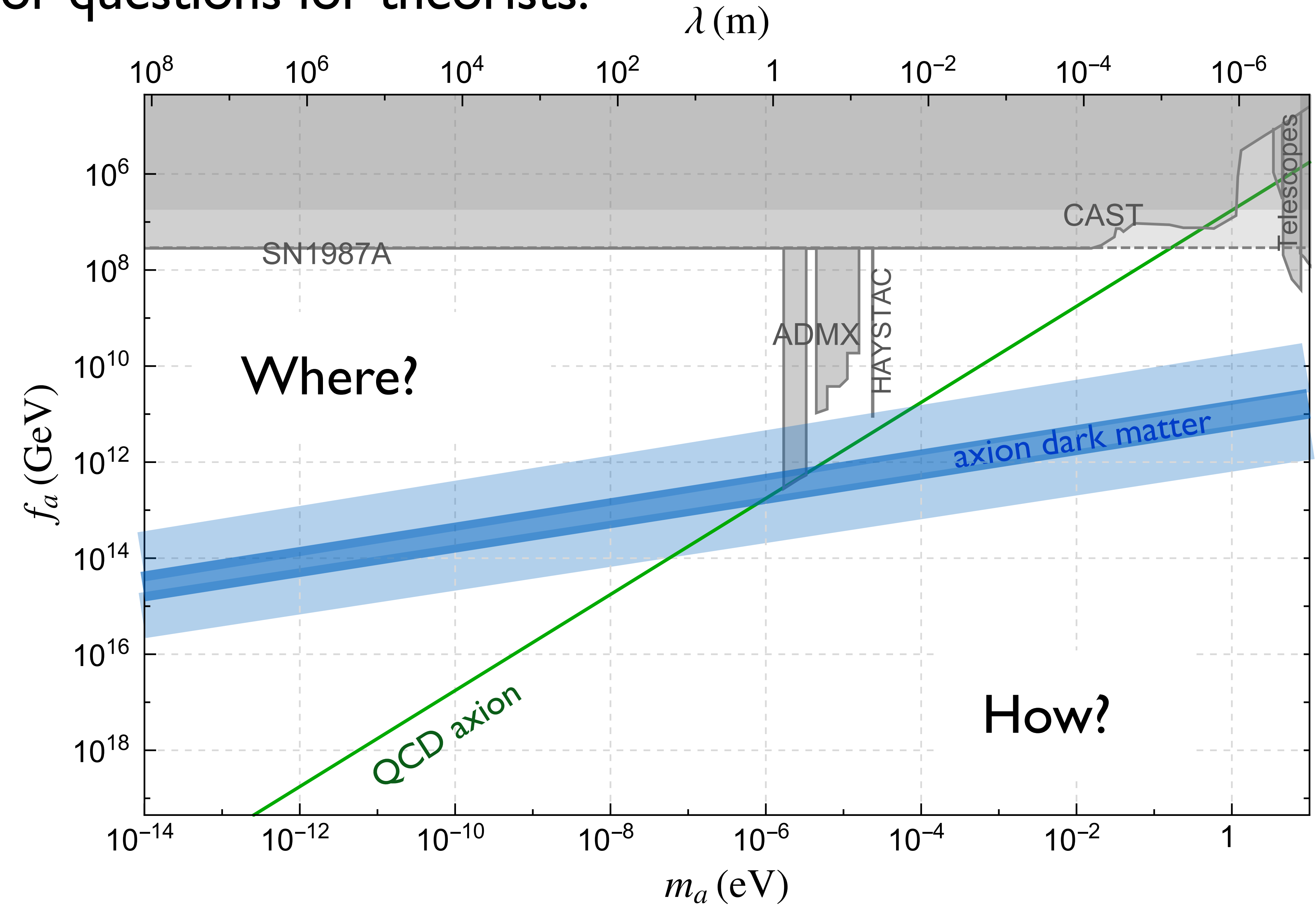
Axions and Ways to Find Them

- Axions are a window into the **highest scales**
- Macroscopic wavelengths call for **novel** and **distinct** approaches across mass scales



Axions and Ways to Find Them

- Since the last snomwass, there has been wide-ranging and accelerating progress in the field of axions and ultralight bosons
- **Two major questions for theorists:**



Where: which parts of this vast parameter space are theoretically motivated, or even plausible

- Model Building From String Theory to Experiment
  - String axiverse and stringy axion constructions: the expectations of many light axions, new ideas for axion potentials

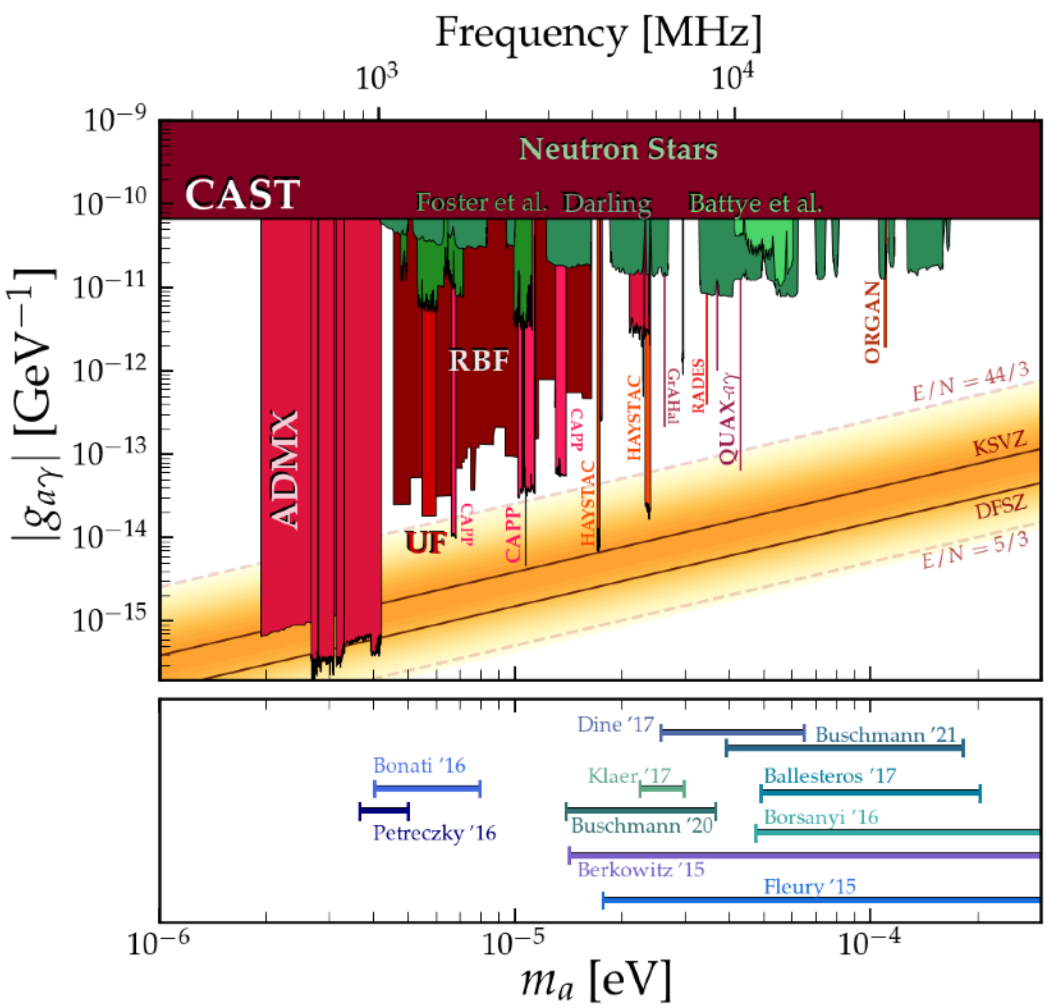
    Svrcek , Witten [0605206]
    Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell [0905.4720]

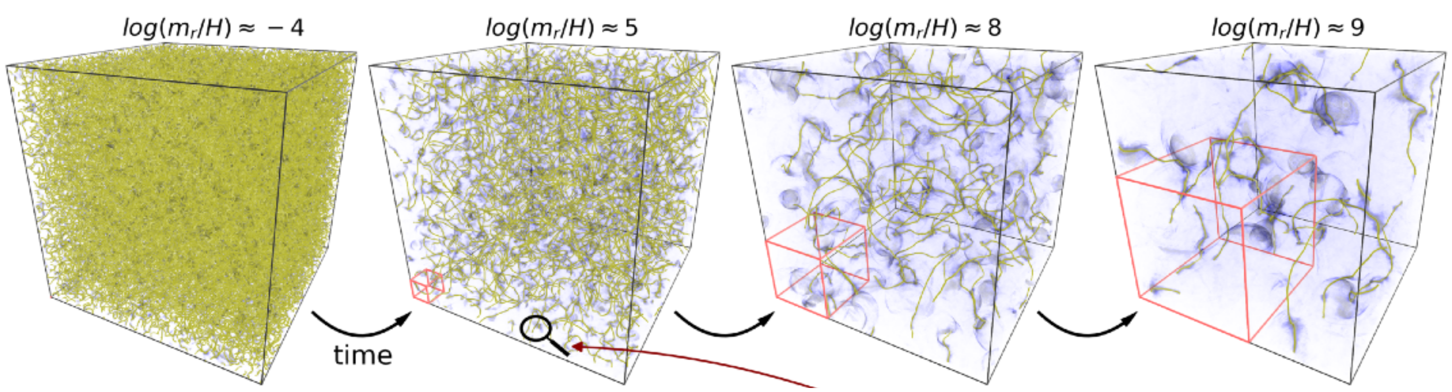
  - Enhanced couplings to matter, e.g. clockwork mechanism
    - See e.g. Experimental Targets for Photon Couplings of the QCD Axion, Agrawal, Fan, Reece, Wang1709.06085
  - Ultralight bosons and `fuzzy dark matter'

    Hu, Barkana, Gruzinov 2003; Hui, Ostriker, Tremaine, Witten 2016

Where: which parts of this vast parameter space are theoretically motivated, or even plausible

- If Peccei-Quinn Symmetry occurs **after** inflation, there is in principle a **unique QCD axion mass** that will give the correct dark matter abundance





Adaptive Mesh Largest Effective Grid:
M. Buschmann, J. W. Foster, A. Hook, A. Peterson, D. E. Willcox, W. Zhang et al. 2108.05368

Logarithmic Scaling of Strings:
Gorghetto Hardy Villadoro 1806.04677 & 2007.04990

https://github.com/cajohare/AxionLimits

Where: which parts of this vast parameter space are theoretically motivated, or even plausible

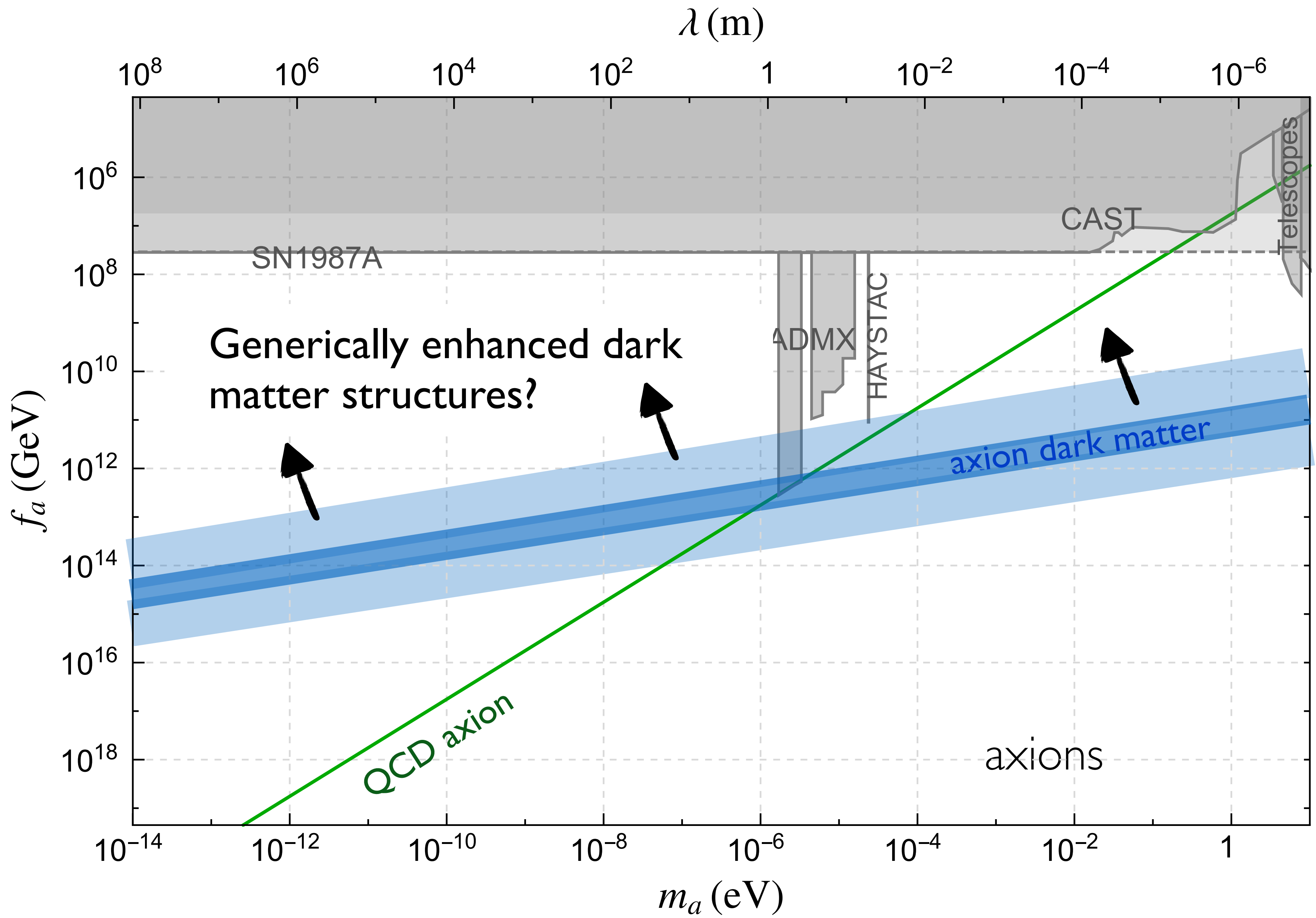
- If Peccei-Quinn Symmetry occurs **before** inflation… anything goes

- Enhanced axion abundance:
  - delaying the start of oscillations and red-shifting; large misalignment
  - non-zero kinetic energy at the start of oscillations as additional energy source
  - coupled axions can exchange energy: the friendly axion
  - cosmological history aside from the axion itself will affect the final axion abundance

- Suppressed axion abundance
  - small initial amplitude
  - decays to other particles, including parametric resonance
  - cosmological history aside from the axion itself will affect the final axion abundance

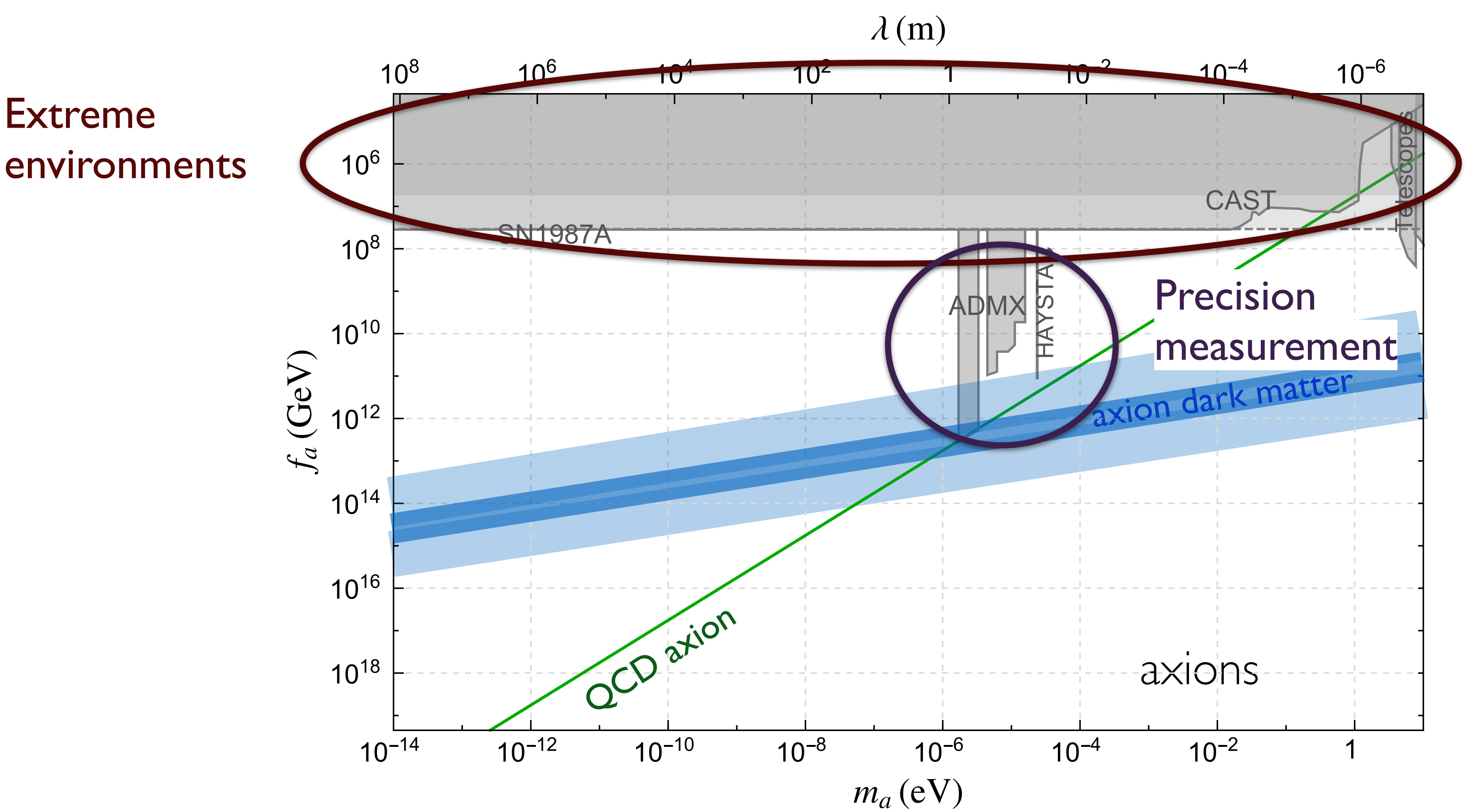
Axions and Ways to Find Them

- Axion cosmologies with enhanced abundance typically predict nonlinear axion structures: not all the DM is in a smooth halo
- Should we be modifying our search strategies?

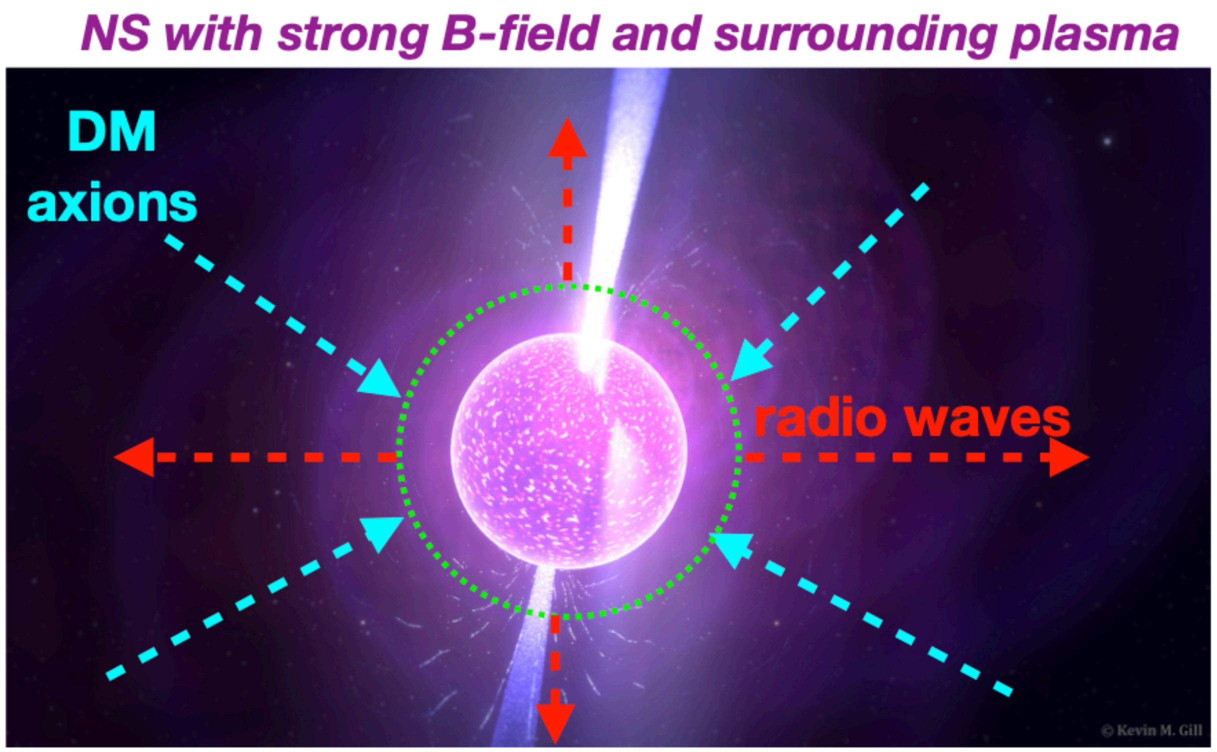


How: new ideas and tools for searches

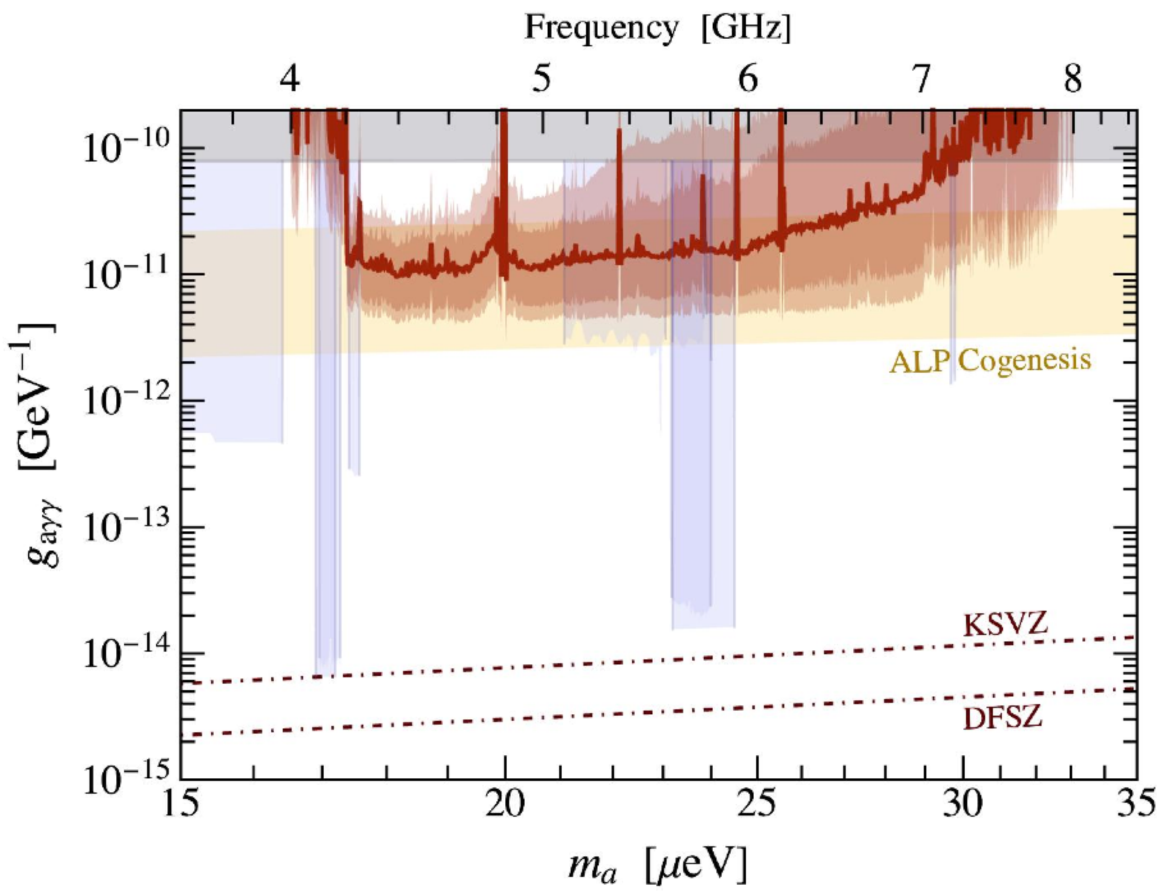
- Axions are very weakly coupled and difficult to produce in the lab
- High temperature, dense, large astrophysical objects can provide good testing grounds
- Weakly coupled, classical, coherent fields excellent targets for precision measurement techniques



Extreme Environments:
New Particles from Neutron Stars



Hook, Kahn Safdi 1804.03145



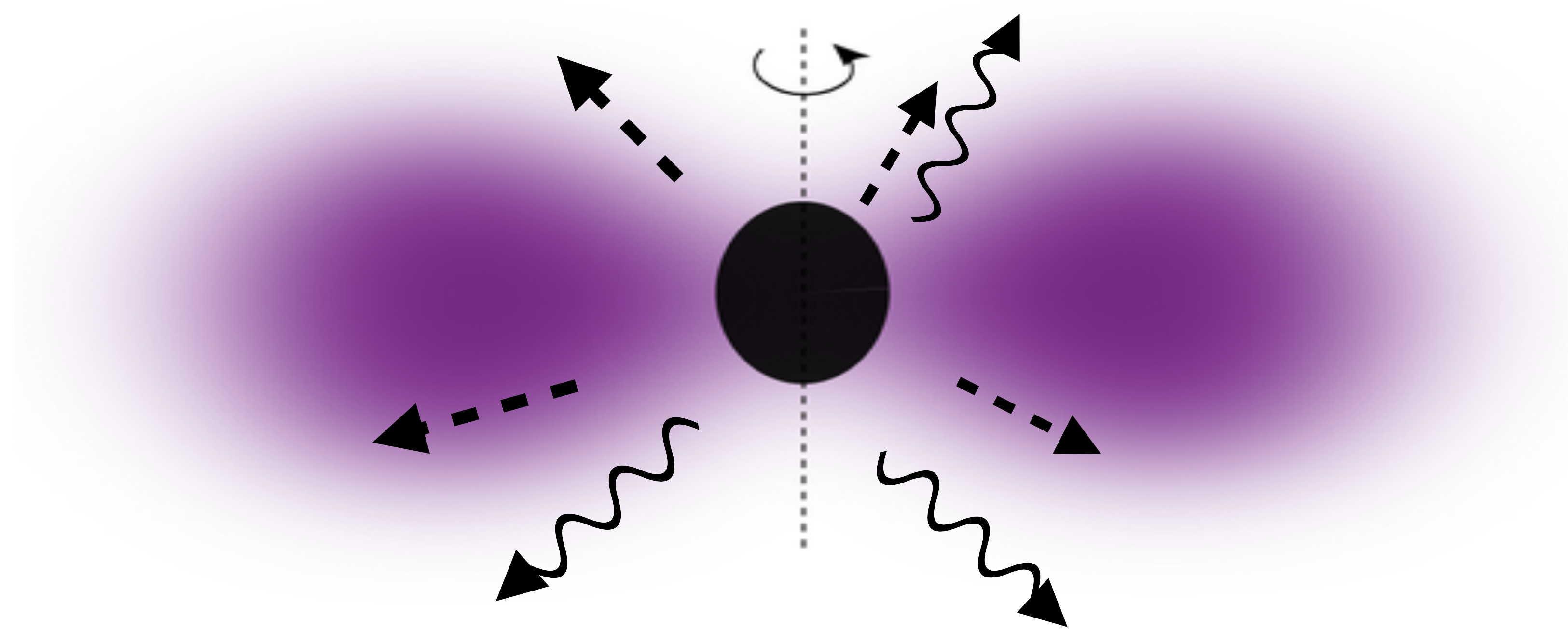
Foster, Witte, Lawson, Linden, Gajjar, Weniger, Safdi 2202.08274

Axion dark matter that couples to photons can convert to radio waves in neutron star magnetospheres with large magnetic fields and surrounding plasma of varying density

Follow-up searches can fall in the range of planned DM cavity experiments

Extreme Environments:

Black Hole Superradiance Searches for Ultralight Particles



Rotating black holes produce`clouds' of weakly coupled bosons through **superradiance,** allowing tests of ultralight, ultra-weakly interacting bosons

This spins down the black hole and the cloud sources gravitational and axion waves which are long-lasting and coherent

Black Hole Superradiance Searches for Ultralight Particles

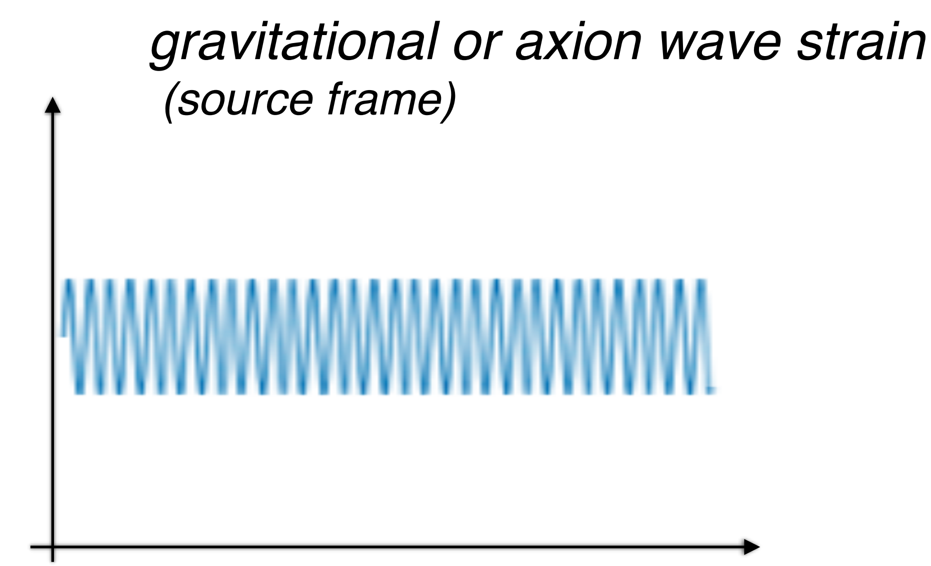
Signatures in Gravitational Wave observatories and Dark Matter Experiments

- Gravitational wave emission from the cloud: each BH sources a monochromatic signal

  Palomba, et al PRL 2019

  Zhu, Baryakhtar, Papa, Tsuna, Kawanaka, Eggenstein PRD 2020

  LVC Collaboration 2111.15507



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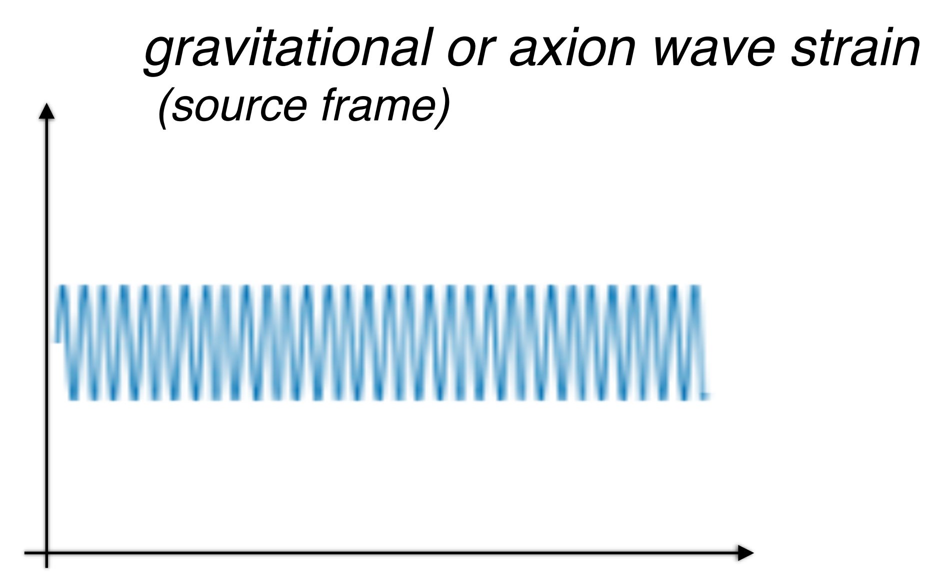
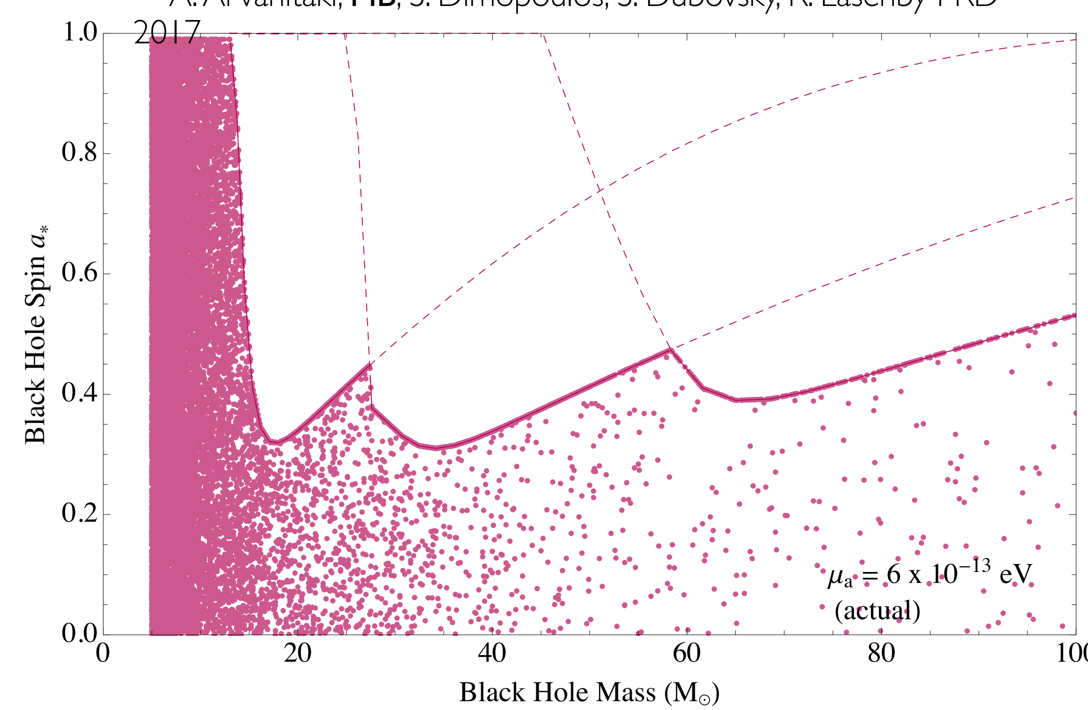
- Black hole spindown: exclusions from high spin BH measurements in X-ray binaries or LVC

  Ng, Vitale, Hannuksela, Li PRD&PRL 2021



A. Arvanitaki, **MB**, S. Dimopoulos, S. Dubovsky, R. Lasenby PRD 2017



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- Black hole spindown: exclusions from high spin BH measurements in X-ray binaries or LVC

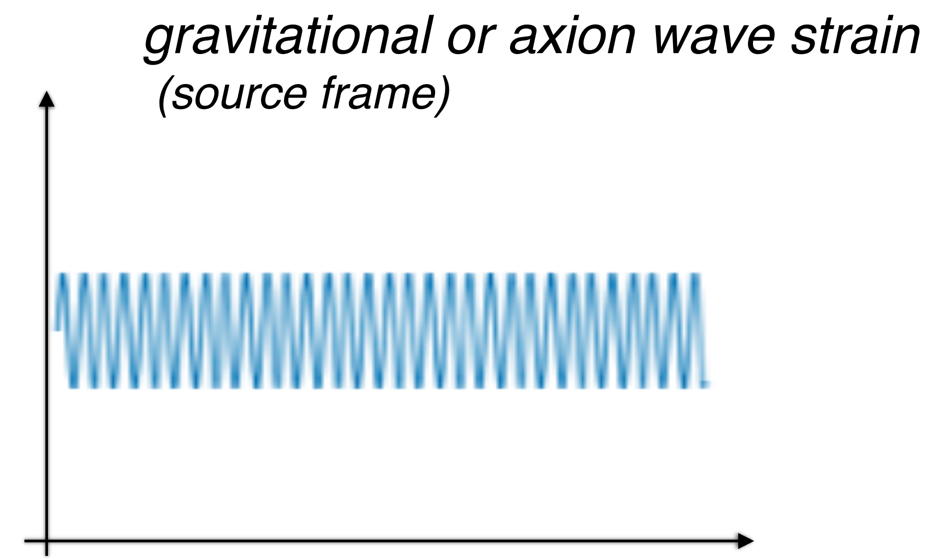
  Ng, Vitale, Hannuksela, Li PRD&PRL 2021

- In the presence of self-interactions, monochromatic axion emission occurs

  Baryakhtar, Galanis, Lasenby, Simon, *PRD 2021*

- Future searches for clouds in binaries

  Baumann, Chia, Porto, Stout, et al



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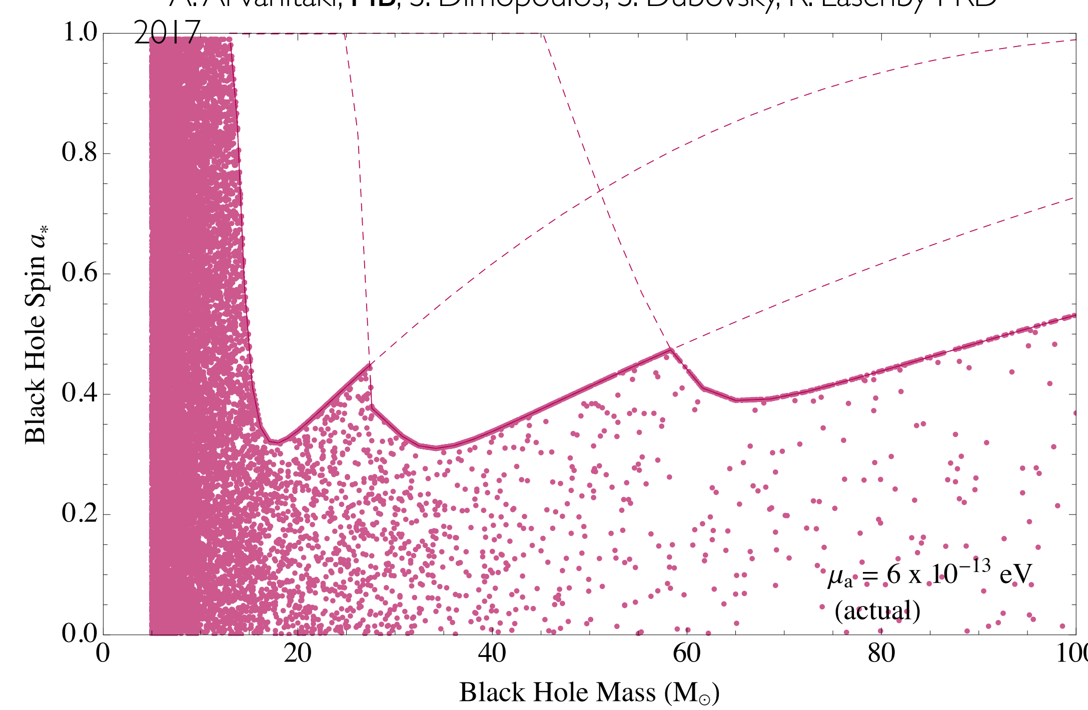

Precision Searches

Sikivie: *Experimental Tests of the "Invisible" Axion (1983)*

Krauss, Moody, Wilczek, Morris: *Calculations for Cosmic Axion Detection (1985)*

Adapted from K. Irwin

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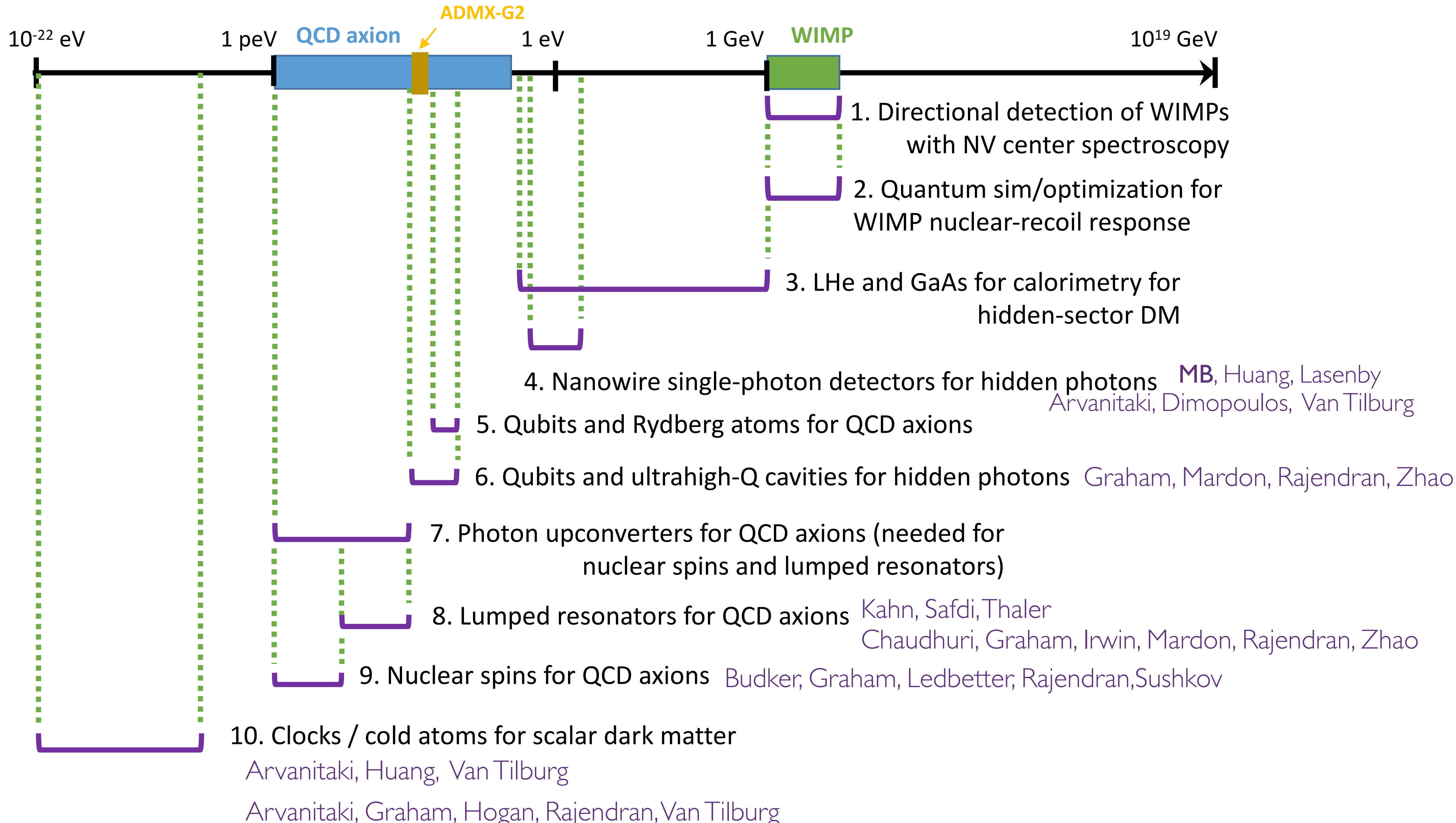
Seaches for axion and ultralight boson dark matter are accelerating with new ideas and technologies with crucial input from theory



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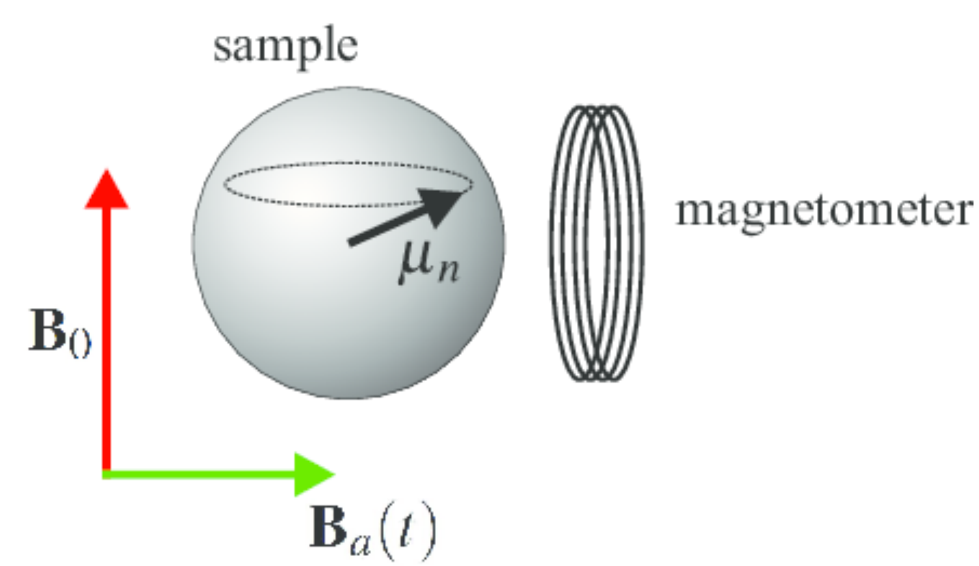
Precision Searches

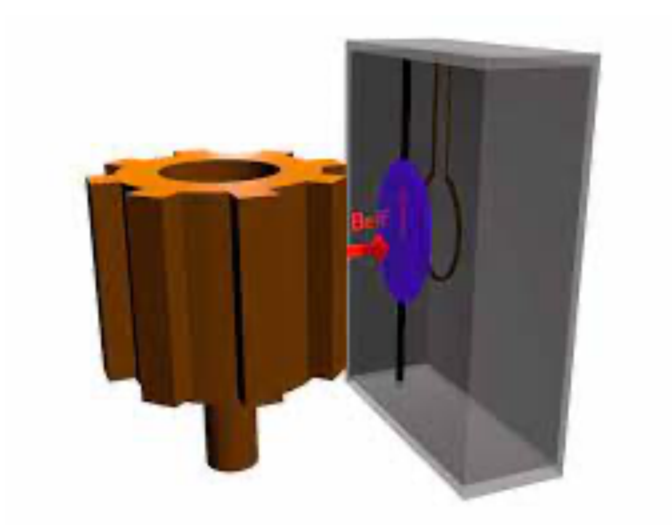
New Observables to Explore

- Axion field gradient acts like a magnetic field on particle spins in the background of axion dark matter or sources by a source mass in the presence of background CP violation

$$H_n \supset g_n \sigma \cdot (\nabla a + \dot{a} v_n)$$
$$\simeq B_a \cdot \mu_n$$



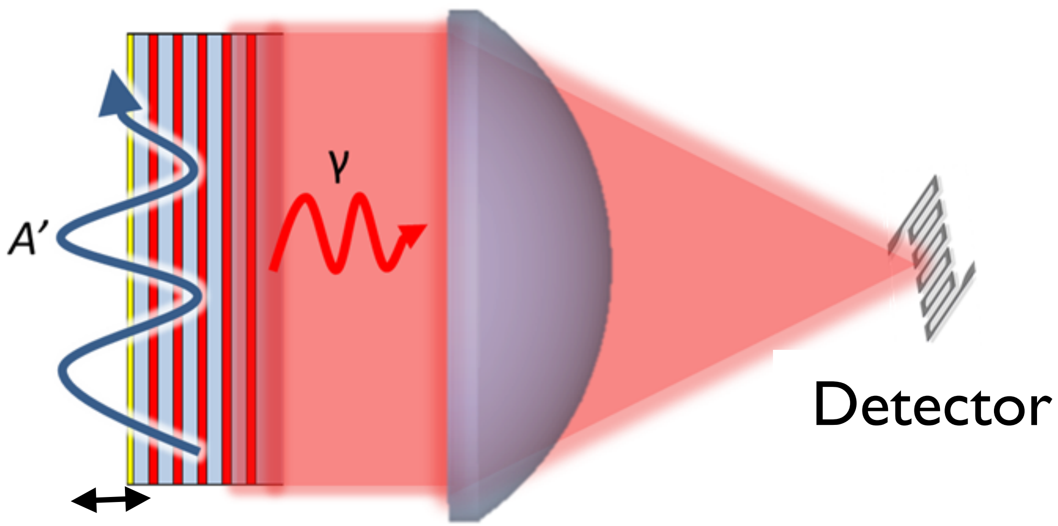
CASPEr collaboration
Budker, Graham, Ledbetter, Rajendran, Sushkov (2014)
Kimball et al (2017)



ARIADNE collaboration
Arvanitaki and Geraci 2014

Precision Searches

From Idea to New Parameter Space in Three Years



$$m_{dm} \simeq \frac{\pi}{nd}$$

- Impossible to conserve both energy and momentum: **photons** relativistic while **dark matter** is massive with a small velocity in our galaxy

- Use material lattice to introduce momentum scale in the problem

MADMAX collaboration
MB, J. Huang, R. Lasenby, PRD 2018
Chiles, Charaev, Lasenby, **MB**, Huang, Roshko, Burton, Colangelo, Van Tilburg, Arvanitaki, Nam, Berggren 2110.01582
Manenti, Mishra, Bruno, Di Giovanni, Millar, Morå, Roberts, Oikonomou, Sarnoff, Arneodo 2110.10497

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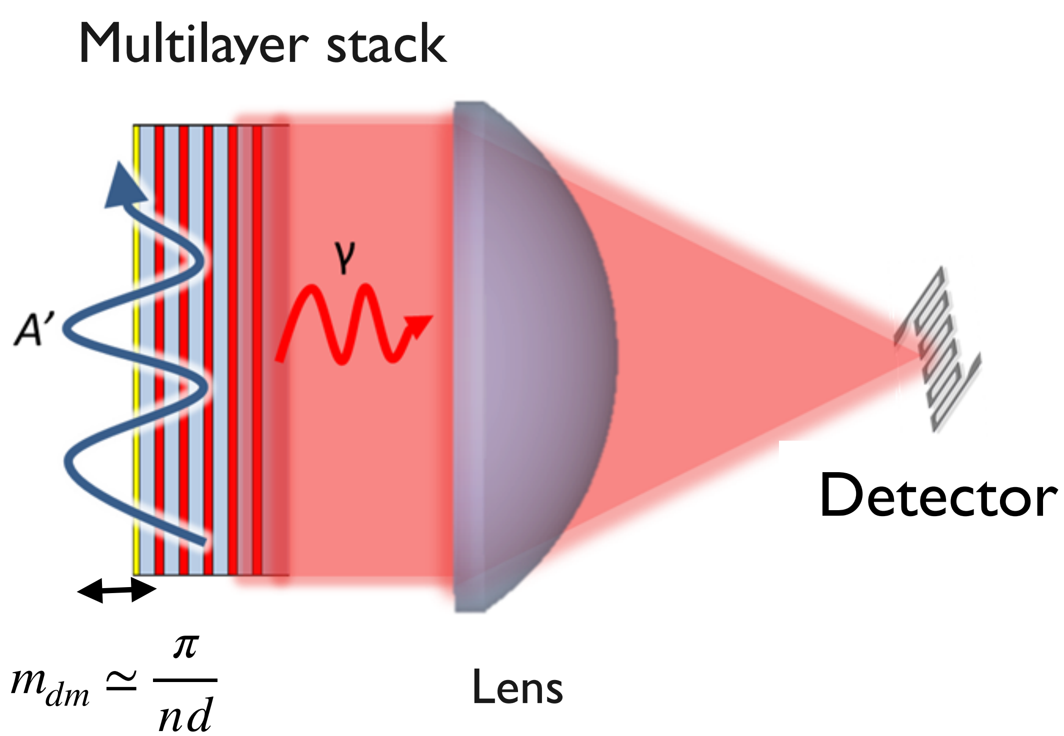

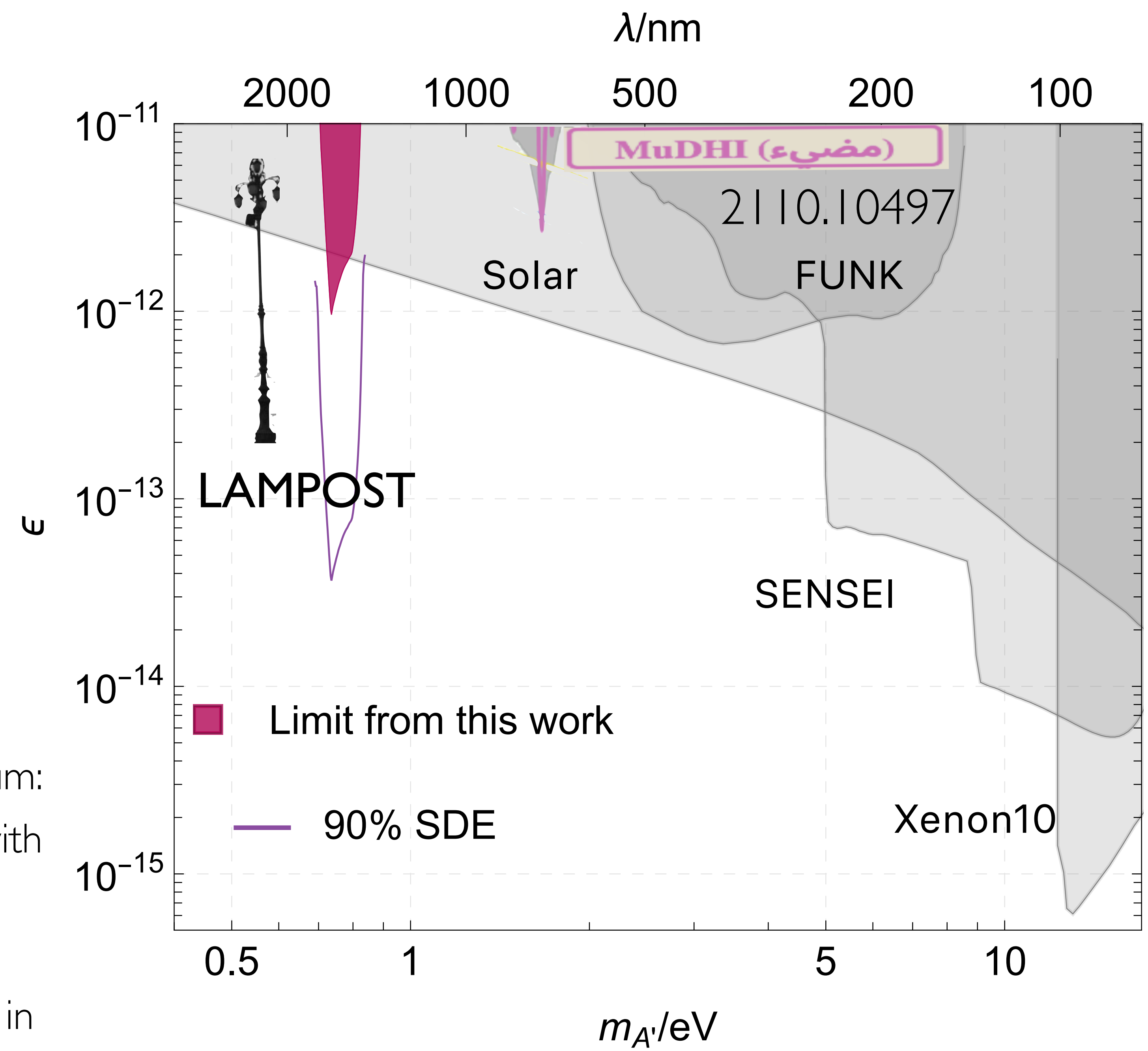

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Few days of runtime already interesting due to ultrasensitive detectors

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Axions and Ultralight Dark Matter in the Last Decade

Snowmass2021 White Paper:
Stellar signatures of feebly interacting light particles

Maurizio Giannotti[1] and Edoardo Vitagliano[2]

[1]Physical Sciences, Barry University, 11300 NE 2nd Ave., Miami Shores, FL 33161, USA
[2]Department of Physics and Astronomy, University of California, Los Angeles, California 90095-1547, USA

Snowmass2021 CF2 Wavelike Dark Matter Axion White Paper

Gray Rybka[1], Add Your Name[5], Derek F. Jackson Kimball[6], Chen Sun[7], Edoardo Vitagliano[8], Yevgeny V. Stadnik[9], and Yu-Dai Tsai[10]

[1]University of Washington

Snowmass2021 Theory Frontier White Paper:
Astrophysical Probes of Dark Matter

Kimberly K. Boddy[1], Mariangela Lisanti[2,3], Samuel D. McDermott[1], Nicholas L. Rodd[4], Christoph Weniger[9], Djuna Croon[5], Rebecca K. Leane[10,11], Siddharth Mishra-Sharma[6,7,8], Samuel J. Witte[9], and Additional authors[1]

Early universe model building

Editors:Asher Berlin, David Curtin, Keisuke Harigaya, Yonit Hochberg, Eric Kuflik, and Neal Weiner

Snowmass2021 Cosmic Frontier White Paper:
Dark Matter In Extreme Astrophysical Environments

Add your name[1], Masha Baryakhtar[1], Emanuele Berti[23], Joseph Bramante[21,22], Malte Buschmann[13], Richard Brito[12], Regina Caputo[2], Adam Coogan[14,15], Djuna Croon[3,4], William E. East[22], Joshua Foster[32], Marios Galanis[31], Bradley J. Kavanagh[17], Ranjan Laha[27], Rebecca K. Leane[9,10], Gustavo Marques-Tavares[30], Jamie McDonald[4,7], Kerstin Perez[5], Nirmal Raj[16], Laura Sagunski[28], Nils Siemonsen[22,25,26], Olivier Simon[31], Kuver Sinha[11], Chen Sun[19], Volodymyr Takhistov[18], Yu-Dai Tsai[20], Edoardo Vitagliano[8], Salvatore Vitale[5,29], and Jun Zhang[23,24]

Theory meets the lab: A snowmass white paper

Rouven Essig[a] , Peter Graham[b] , Yonatan Kahn[c,d,e] , Simon Knapen[f,g] , Andreas Ringwald[i] and Natalia Toro[j]

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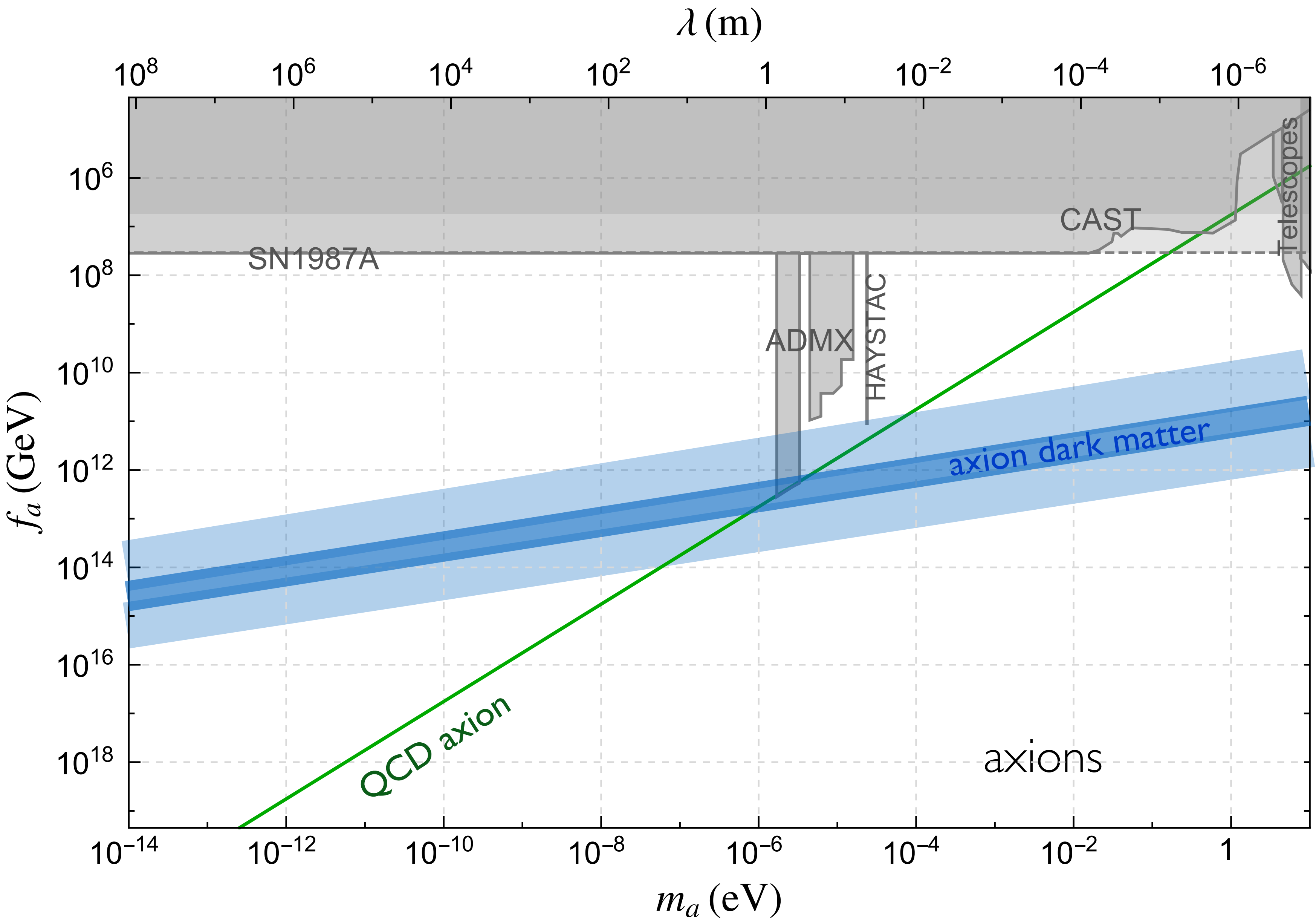
- Macroscopic wavelengths call for **novel** and **distinct** approaches across mass scales



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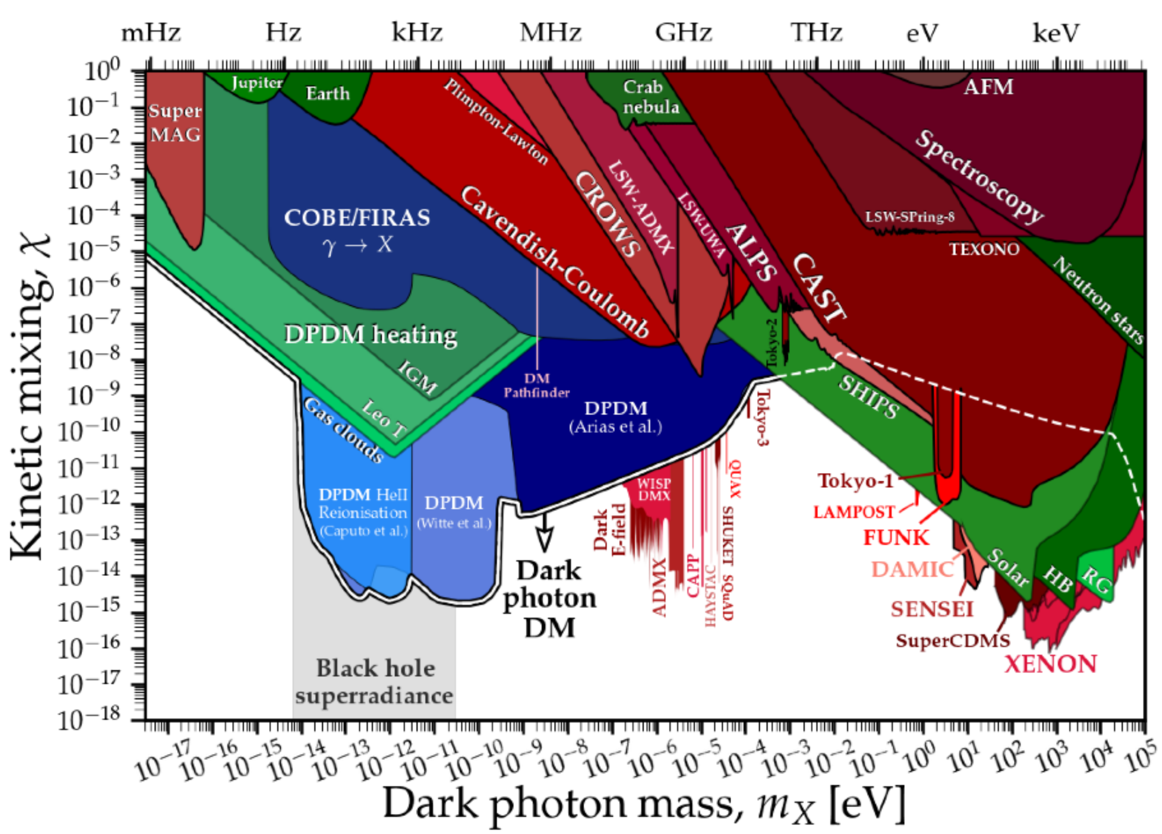

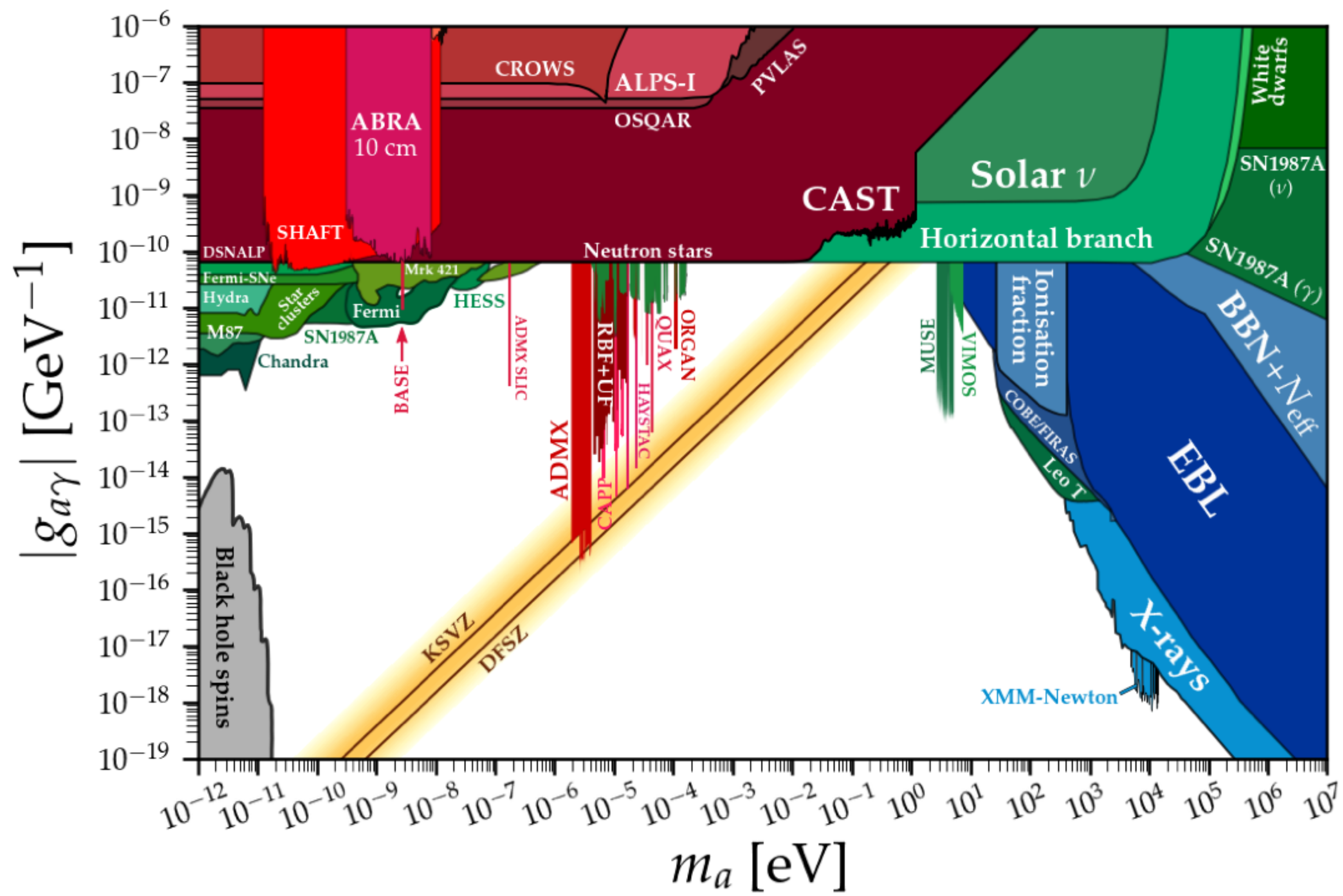

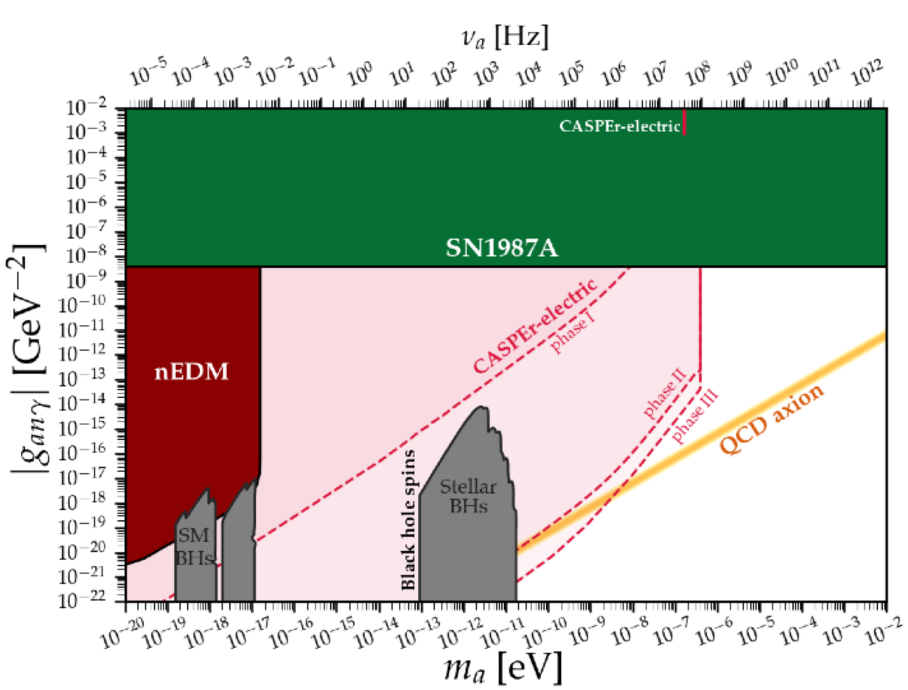

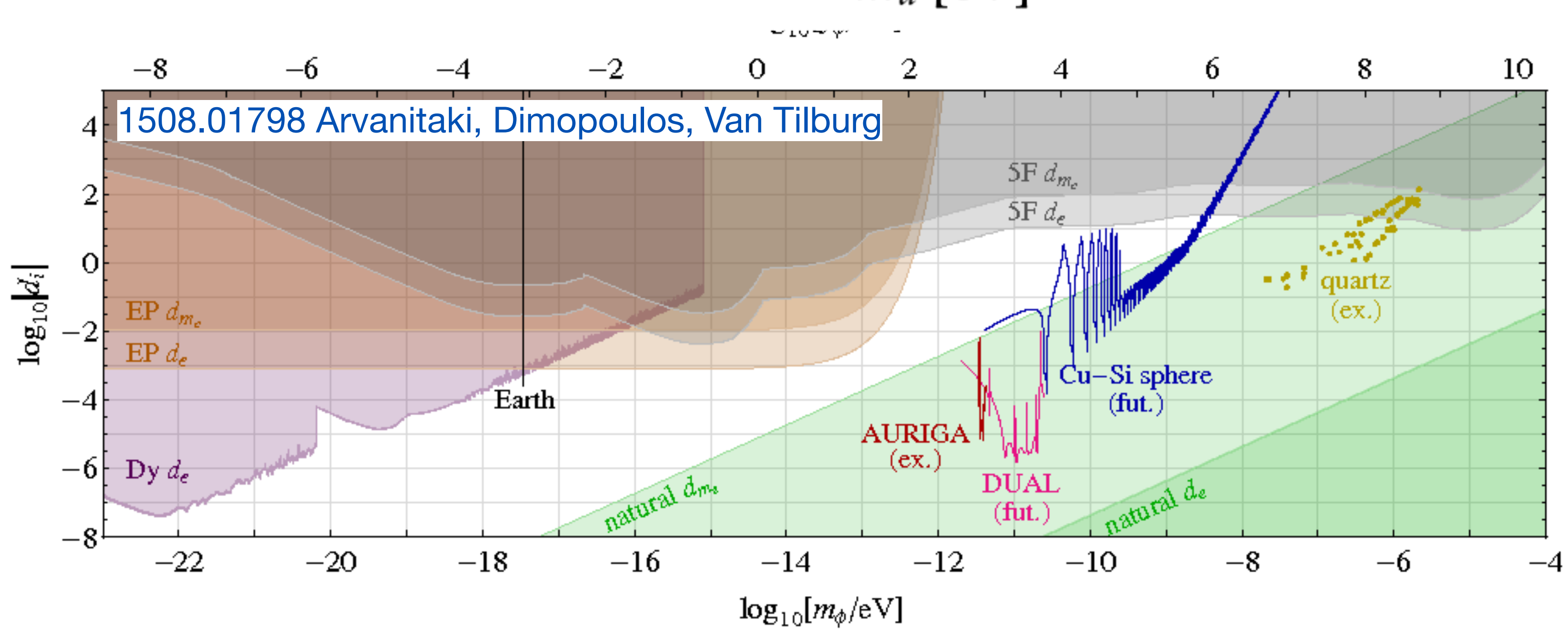

https://github.com/cajohare/AxionLimits