Hint of Ultra-Light Axionlike Dark Matter (ALPs)

and

Future Measurements with Diamond Quantum Sensors

Masashi Hazumi (NCU)

Collaborators

POLARBEAR collaboration

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(Only opt-in authors for today's topic are shown above)

Kyoto, Berkeley, SISSA, KEK, Tokyo, UCSD, Paris, Flatiron, Cardiff, Yokohama, Manchester, Melbourne

Ultra-light axion dark matter using NV-diamond quantum sensors

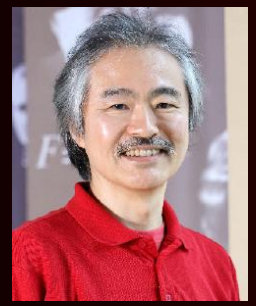
So Chigusa (MIT)

Kazunori Nakayama (Tohoku U.)

Yuichiro Matsuzaki (Chuo U.)

David Herbschleb (Kyoto U.)

Norikazu Mizuochi (Kyoto U.)



Masashi Hazumi (KEK, NCU)

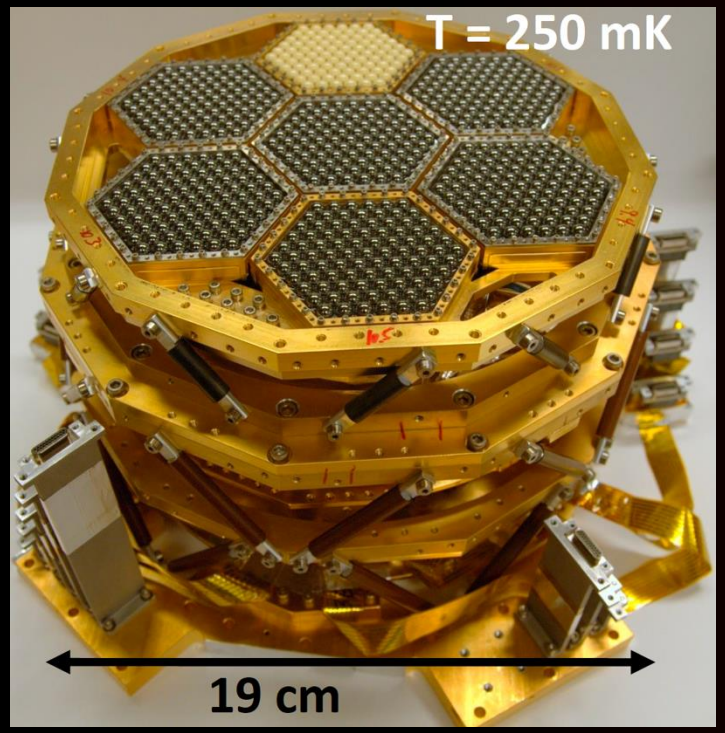
National Science Foundation
Gordon and Betty Moore Foundation
Simons Foundation
JSPS
JST
MEXT
WPI World Premier International Research Center Initiative
U.S. Department of Energy
Australian Government Australian Research Council
ASI Agenzia Spaziale Italiana
ERC European Research Council Established by the European Commission

Hint of ALPs at POLARBEAR

POLARBEAR Collaboration, Phys. Rev. D 110, 063013 (2024)

POLARBEAR

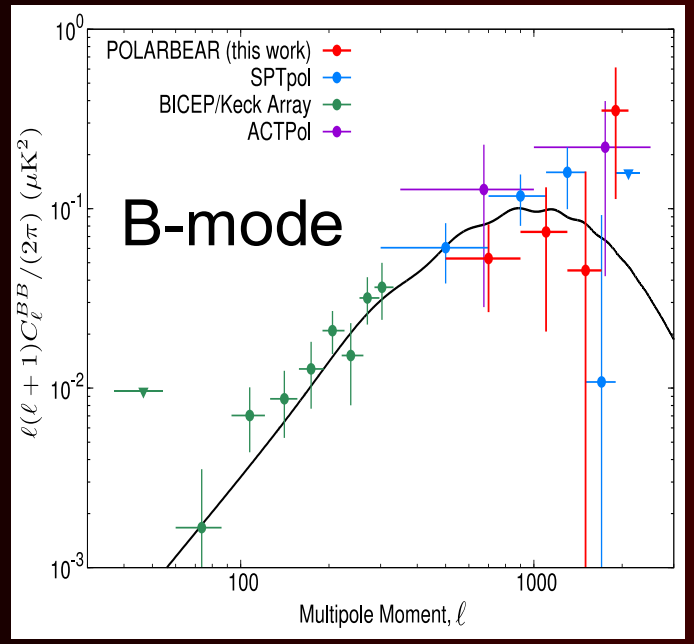
- Dedicated CMB polarization experiment
- Located at 5200 meters in Atacama, Chile
- First light Jan. 2012, expanded to Simons Array from 2018
- Powerful TES array with 3.5arcmin beam for 150GHz

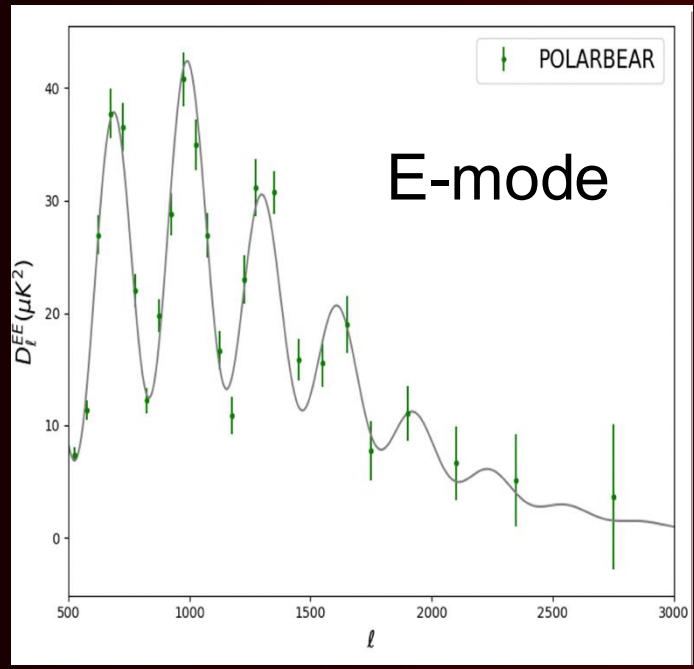


POLARBEAR

Many important cosmological publications, including

- First evidence for B-mode polarization lensing based on purely CMB information
- Constraints on Cosmic Birefringence and Primordial Magnetic Fields
- Primordial B-mode search: best result in Chile
- Cross correlation cosmology results
- Precise measurement of the Hubble parameter with E-mode observations

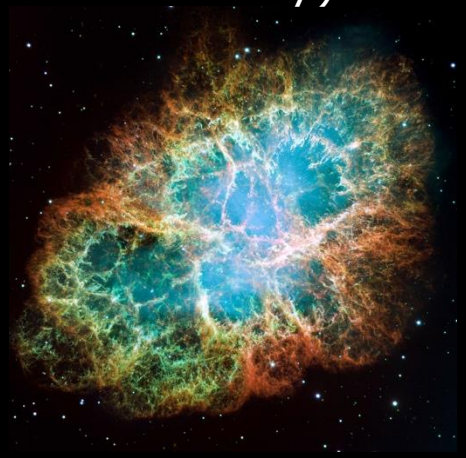




Ultra-Light ALPs Search with Tau A

- The Crab Nebula, also known as Tau A, is a polarized astronomical source at millimeter wavelengths.
- POLARBEAR observed Tau A periodically as a calibration tool.

Crab Nebula (Tau A in radio astronomy)



(HST image)

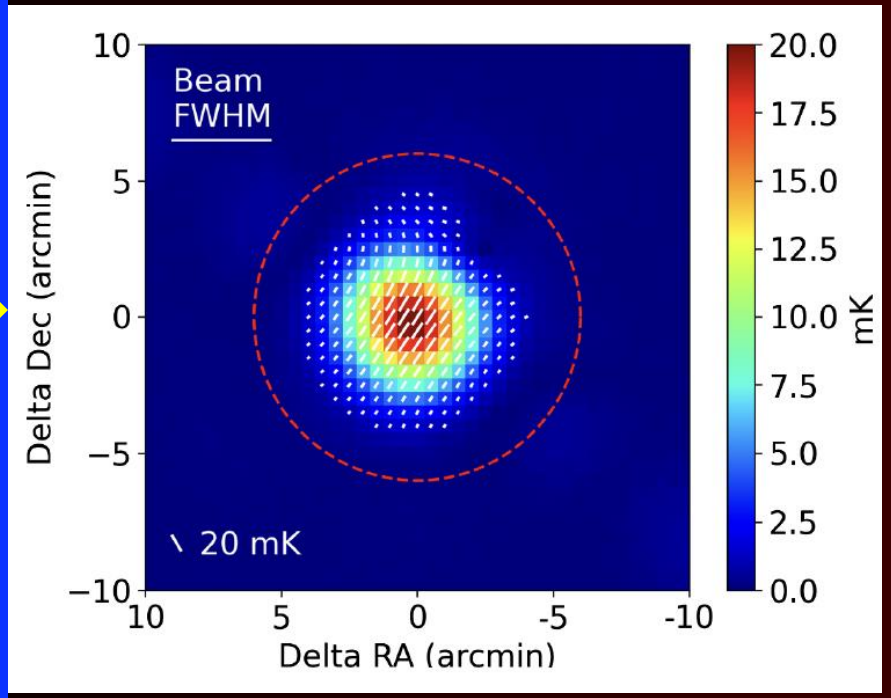
Axion field

as classical field with large number density

$$\psi = \frac{g_{a\gamma\gamma}}{2}\left(\phi_{\text{detected}} - \phi_{\text{emitted}}\right)$$

$$\psi(t) = \psi_0 + \frac{g_{a\gamma\gamma}}{2}\phi_{\text{local}}(t),$$

$$\phi_0 \sin\left(\frac{m_a c^2}{\hbar}t + \theta\right)$$

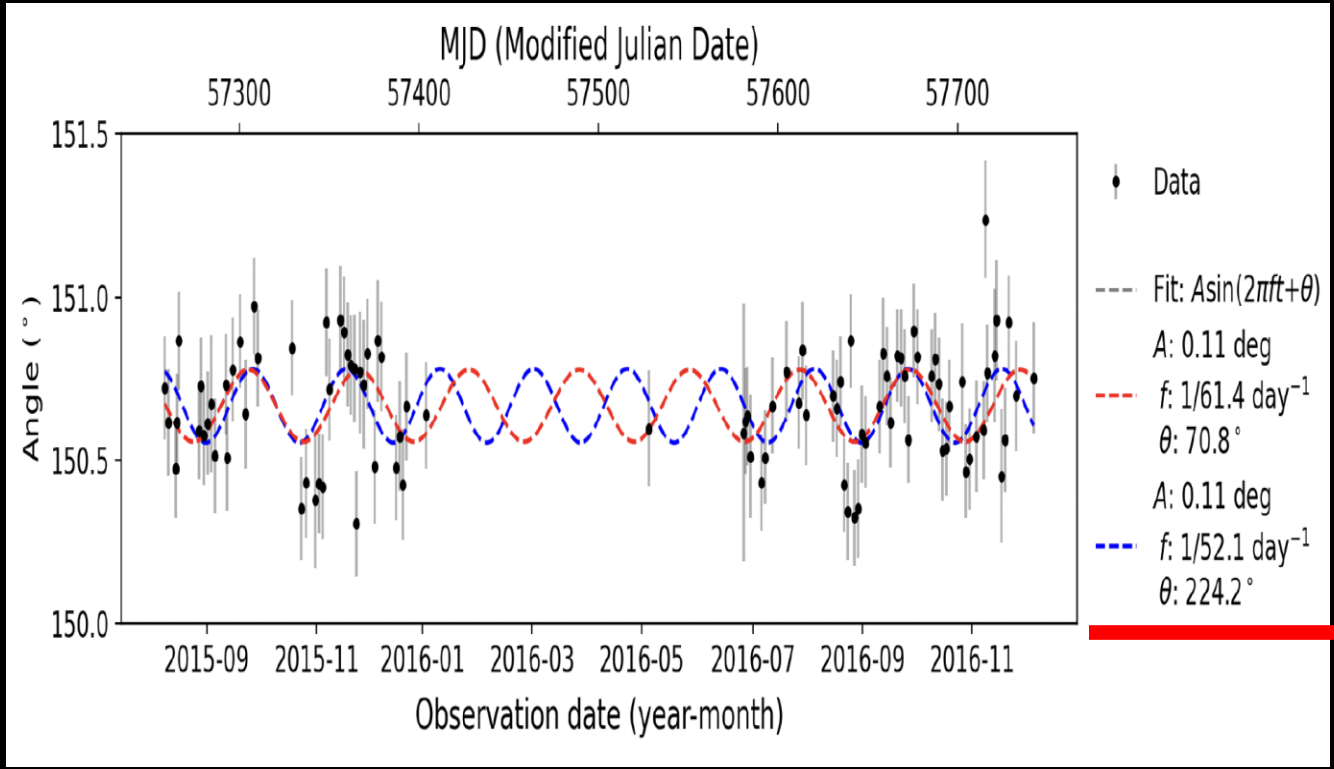


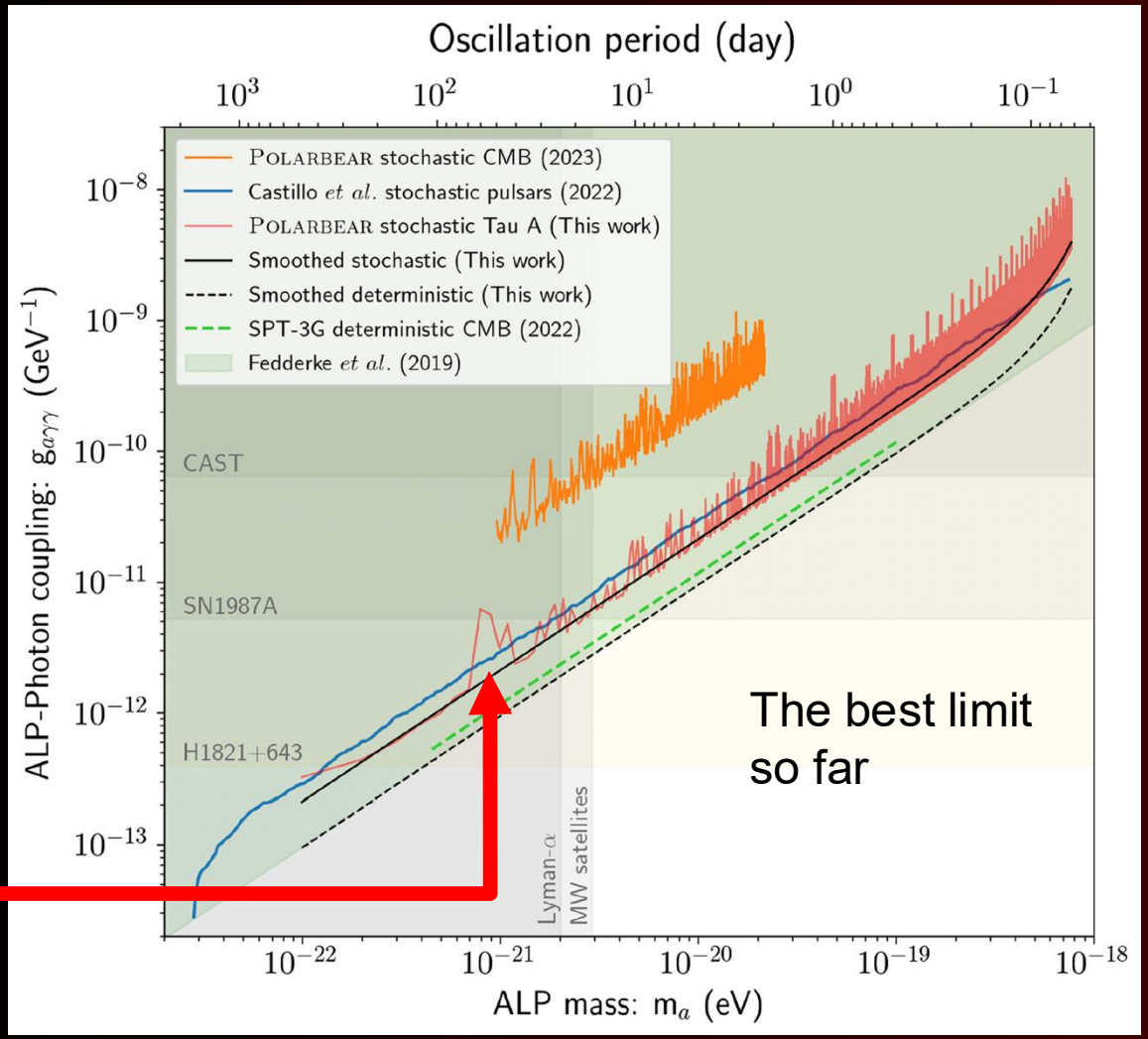
POLAREBAR image of Tau A

2.5σ Hint of Axions-like-Particles (ALPs) from POLARBEAR

POLARBEAR Collaboration, Phys. Rev. D 110, 063013 (2024)

2.5σ excess (incl. look-elsewhere-effect) at $m_a = 7.8\times10^{-22}$ eV





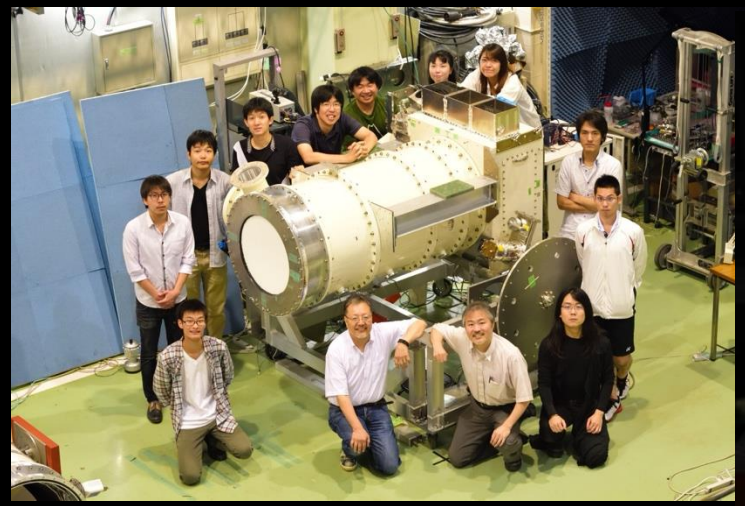

is this the real life?
is this just fantasy?

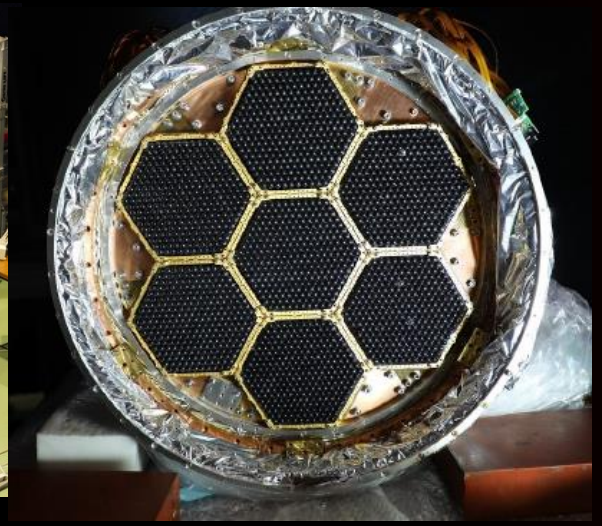
Discussion (1)

- Statistical uncertainties could explain the result

Simons Array data analysis in progress

→ Confirm or deny the hint





Discussion (2)

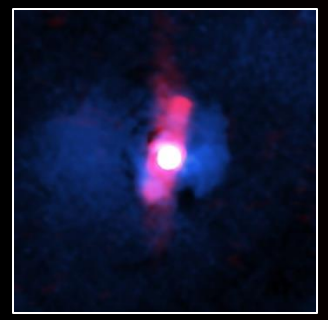
- Residual systematic errors
  - Unlikely, though not excluded completely.

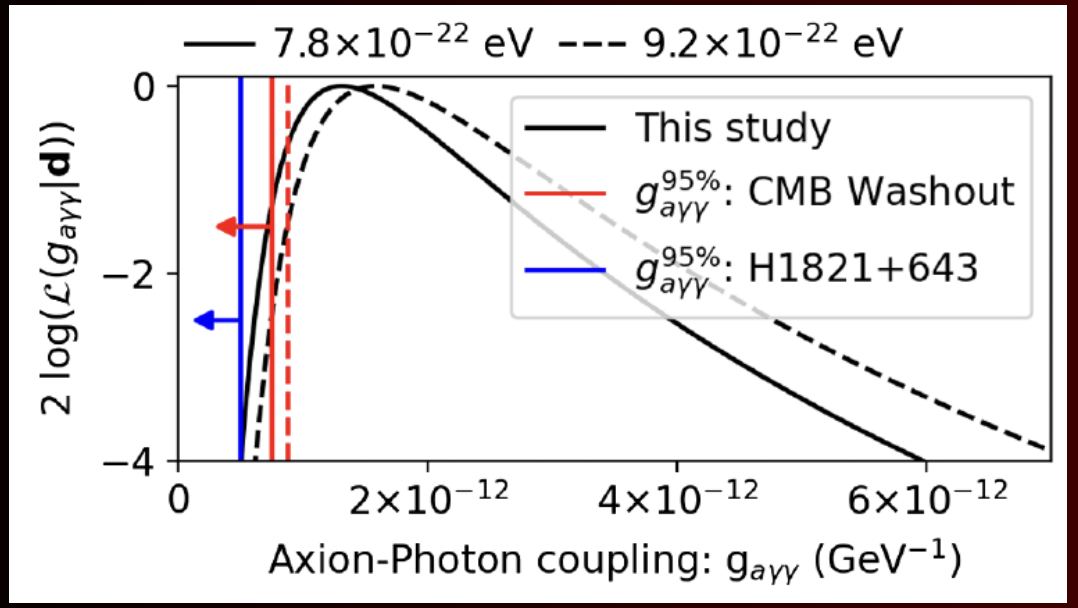
Type of statistical error	Median σ_t (deg)
Statistical error of Tau A	0.16
Polarization angle calibration by A_4	0.02

Type of systematic error	rms (deg)
I2P leakage	0.06
Ground	0.03
Residual $1/f$ noise	0.01
MD breaking	<0.01
Pointing	0.006
Time domain filter bias	0.005
Polarization angle of detectors	0.002

Discussion (3)

- Intrinsic variability of Tau A
  - Single-mode oscillation is unlikely for several-light-year-wide Crab Nebula
  - Crab Pulsar mm-wave signal is much darker than the amplitude observed
  - No intrinsic variability was observed in other measurements
- Consistency with other ALP bounds
  - Inconsistent with a bound from the x-ray spectrum of the quasar H1821+643
  - Some analyses claim a lower bound, $m_a > 2\text{-}3 \times 10^{-21}$ eV, but model-dependent

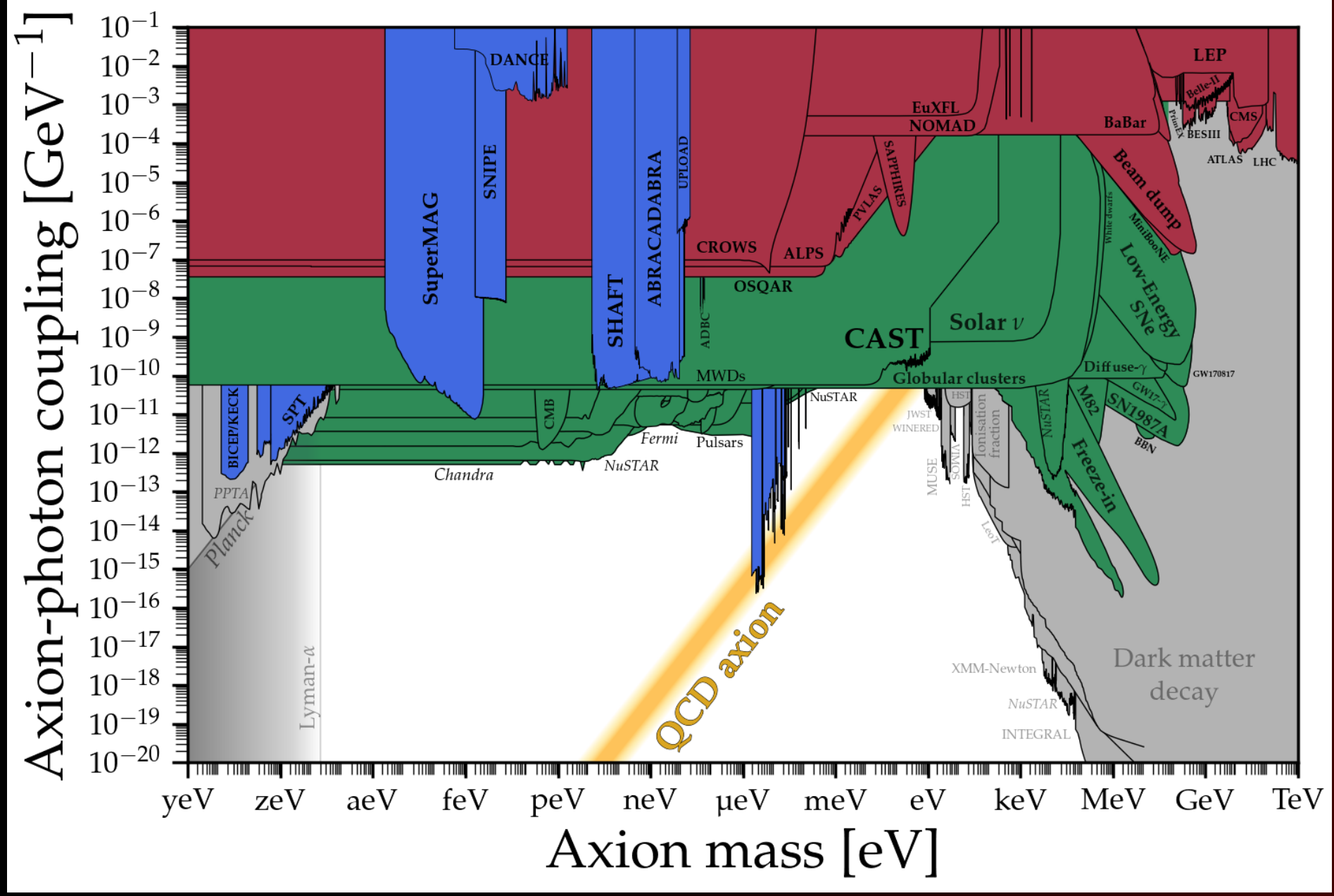




Axion-photon coupling

Full Panorama

AxionLimits, compiled by C.O'Hare



https://cajohare.github.io/AxionLimits/

What about Axion-electron coupling?

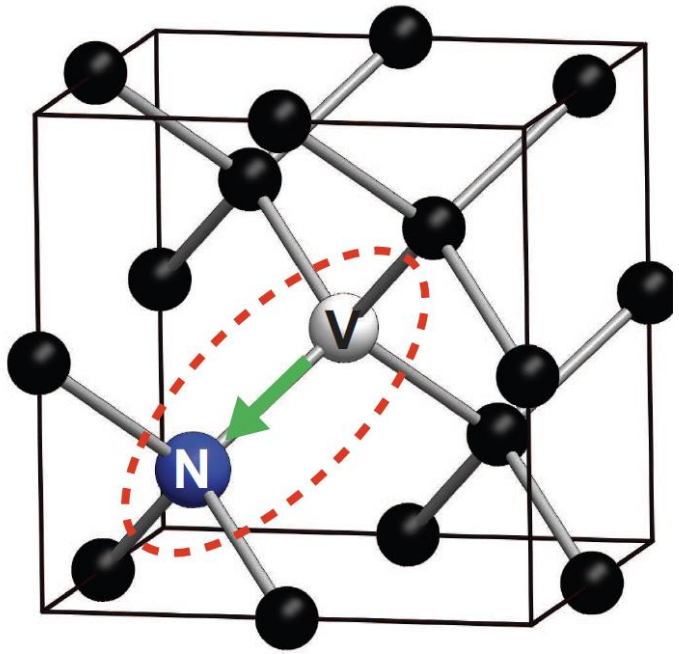
Future Measurements with Diamond Quantum Sensors

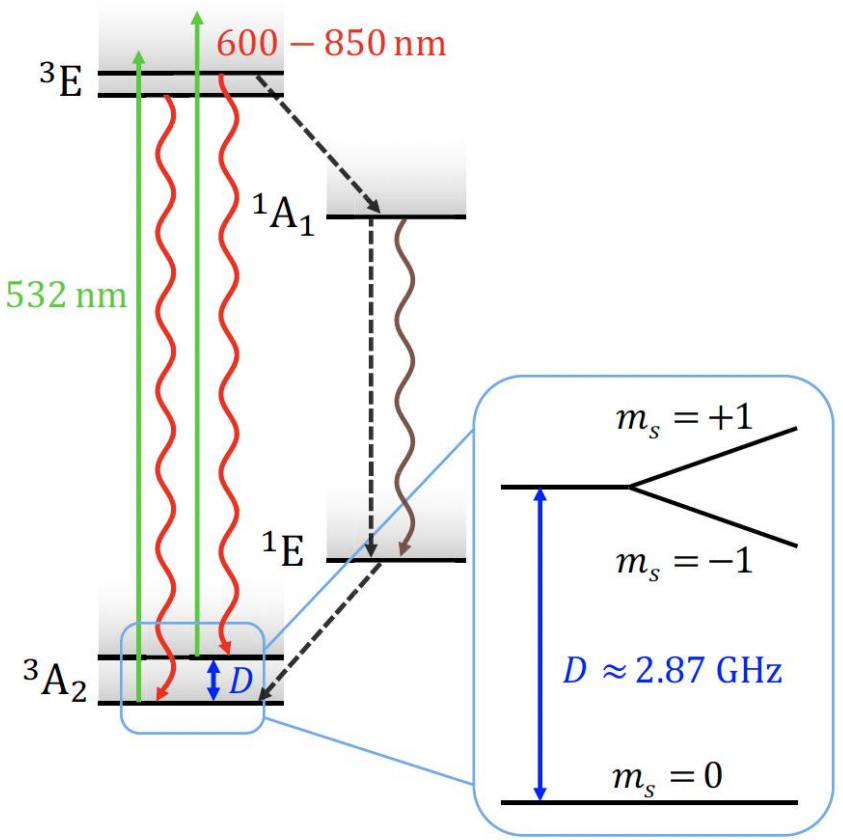
Nitrogen-Vacancy centers in diamond

[For reviews, see Doherty et al., 1302.3288; Barry et al. 1903.08176]

- In the ground state, e pair forms spin triplet at NV center
- Control/measure spin states

→ Quantum sensing





- Sensor as temperature, pressure, magnetic field, …

Many applications : quantum physics, engineering, bioscience,… particle physics!

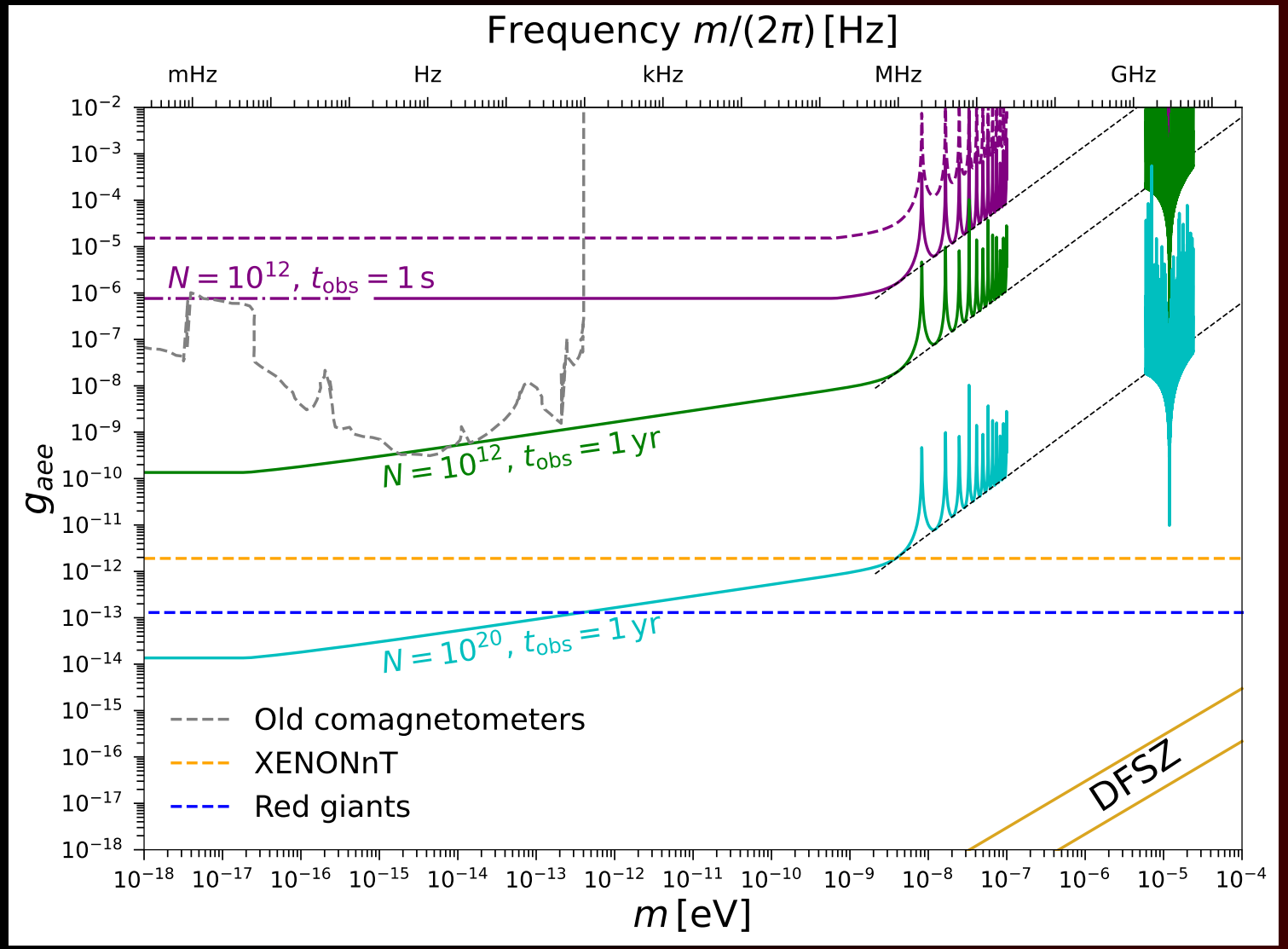
“Light Dark Matter Search with Nitrogen-Vacancy Centers in Diamonds”

Chigusa, Hazumi, Herbschleb, Mizuochi, Nakayama, JHEP 03 (2025) 083

- Axion fields are similar to magnetic fields.

$$H_{\text{eff}} = \frac{g_{aee}}{m_e}\vec{\nabla}a \cdot \vec{S}_e,$$

- Future measurements with scalable NV diamond quantum sensors are promising.
- Broad mass coverage!
- Lots of experimental challenges, but no no-go theorem:

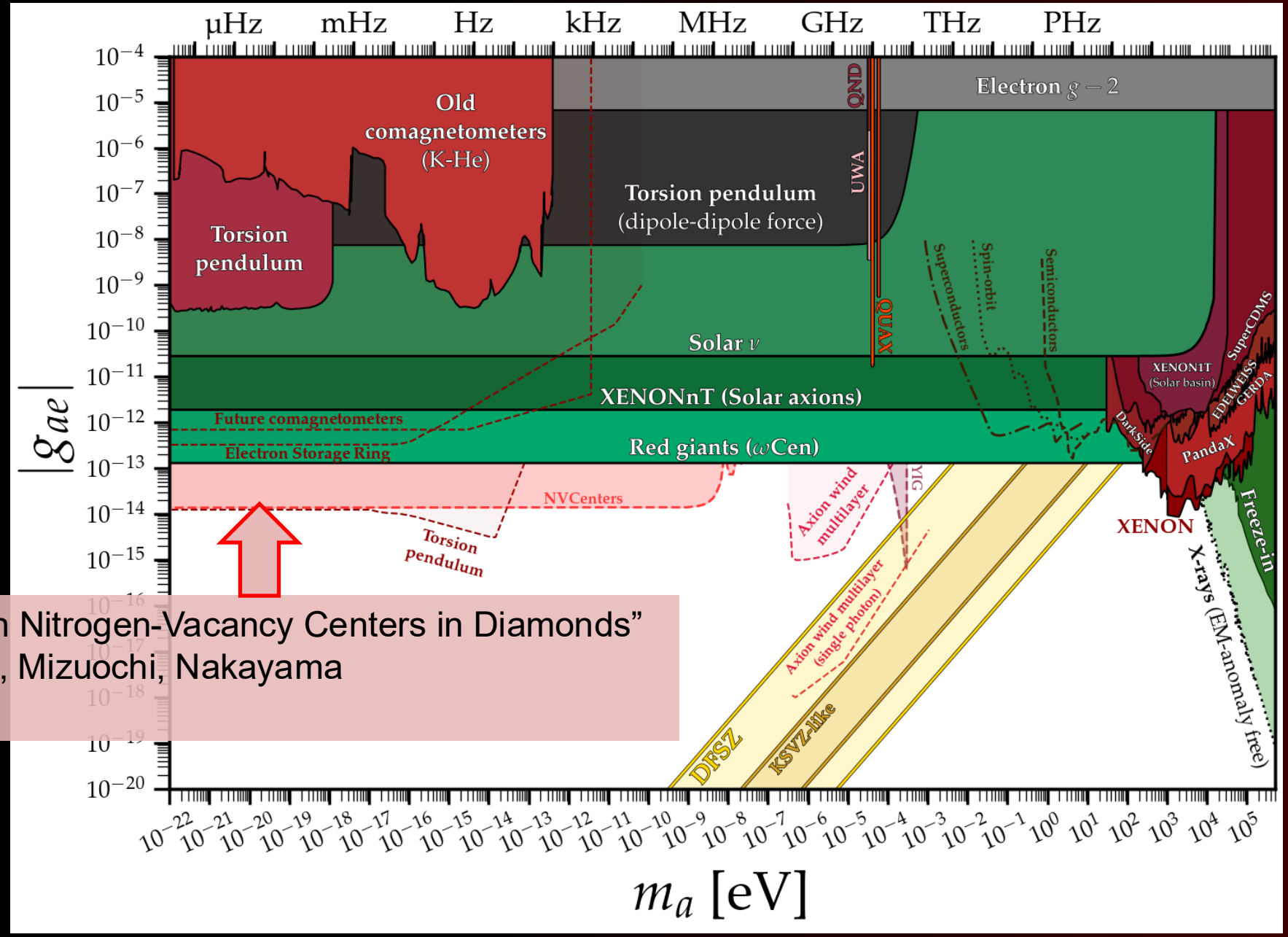


Axion-electron coupling

Results and future prospects

AxionLimits, compiled by C.O'Hare

"Light Dark Matter Search with Nitrogen-Vacancy Centers in Diamonds"
Chigusa, Hazumi, Herbschleb, Mizuochi, Nakayama
JHEP 03 (2025) 083



https://cajohare.github.io/AxionLimits/

Nuclear Spin Metrology with Nitrogen Vacancy Center in Diamond for Axion Dark Matter Detection

Chigusa, Hazumi, Herbschleb, Matsuzaki, Mizuochi, Nakayama, *Phys.Rev.D* 111 (2025) 7, 075028

New!

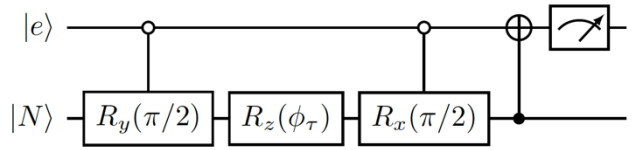
- Axion fields are similar to magnetic fields, but different.
  No mass suppression!
- Nuclear spin metrology was "abandoned" in QIS community, but very interesting for new physics search!
- Use of ^{14}N studied → next page

	axion	magnetic field
electron spin	$\mathcal{L} = \frac{1}{f}\vec{\nabla}a \cdot \vec{S}_e$	$H \sim \frac{eg_e}{2m_e}\vec{B} \cdot \vec{S}_e$
nuclear spin	$\mathcal{L} = \frac{1}{f}\vec{\nabla}a \cdot \vec{S}_N$	$H \sim \frac{eg_N}{2m_N}\vec{B} \cdot \vec{S}_N$
	Nuclear spin coupling is NOT suppressed	Nuclear spin coupling is suppressed

Nuclear Spin Metrology with Nitrogen Vacancy Center in Diamond for Axion Dark Matter Detection

Chigusa, Hazumi, Herbschleb, Matsuzaki, Mizuochi, Nakayama, *Phys.Rev.D* 111 (2025) 7, 075028

DC magnetometry (Ramsey sequence)



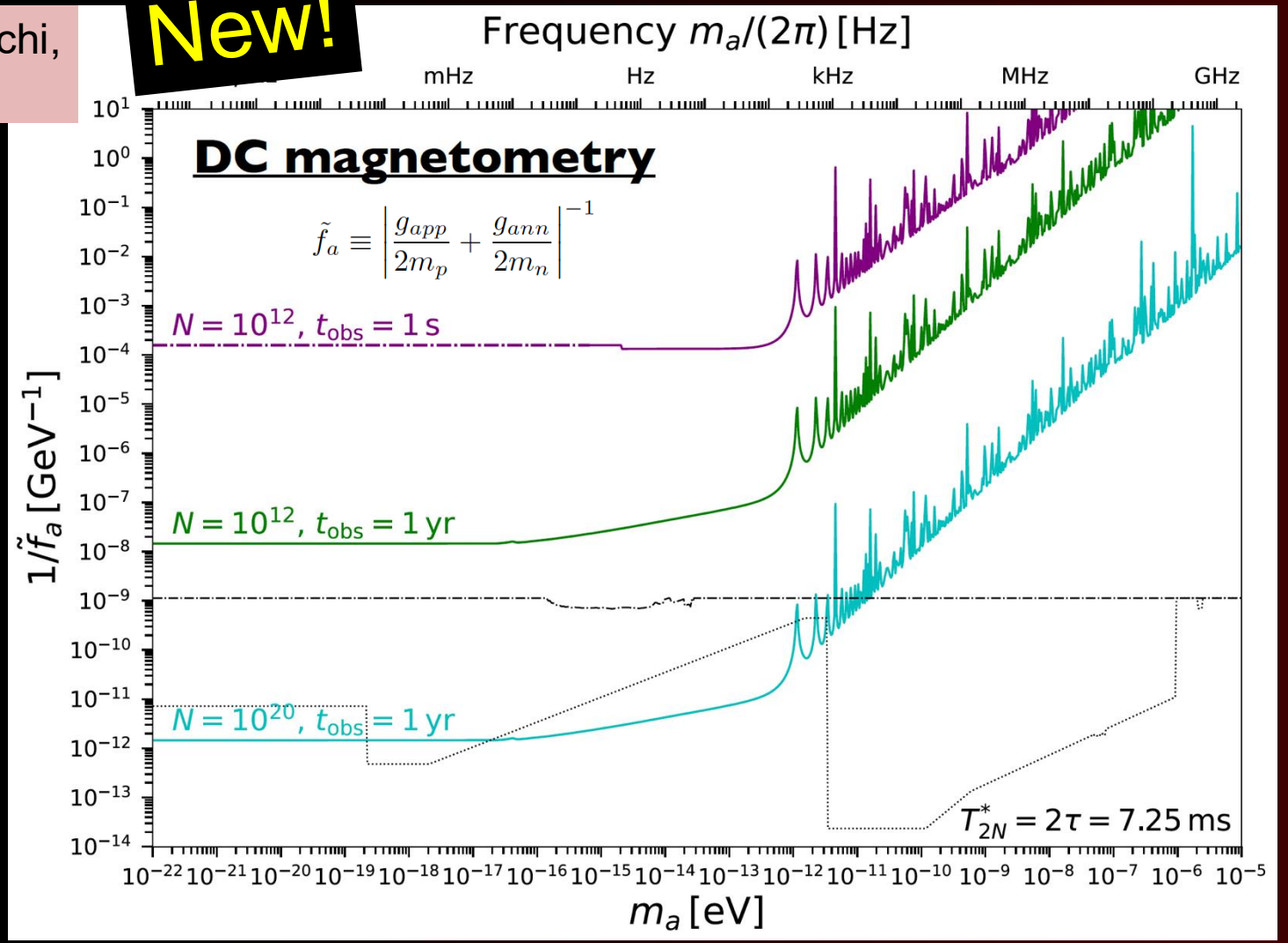
- Effective B field proportional to

$\frac{g_{app}}{m_p} + \frac{g_{ann}}{m_n}$ for ^{14}N

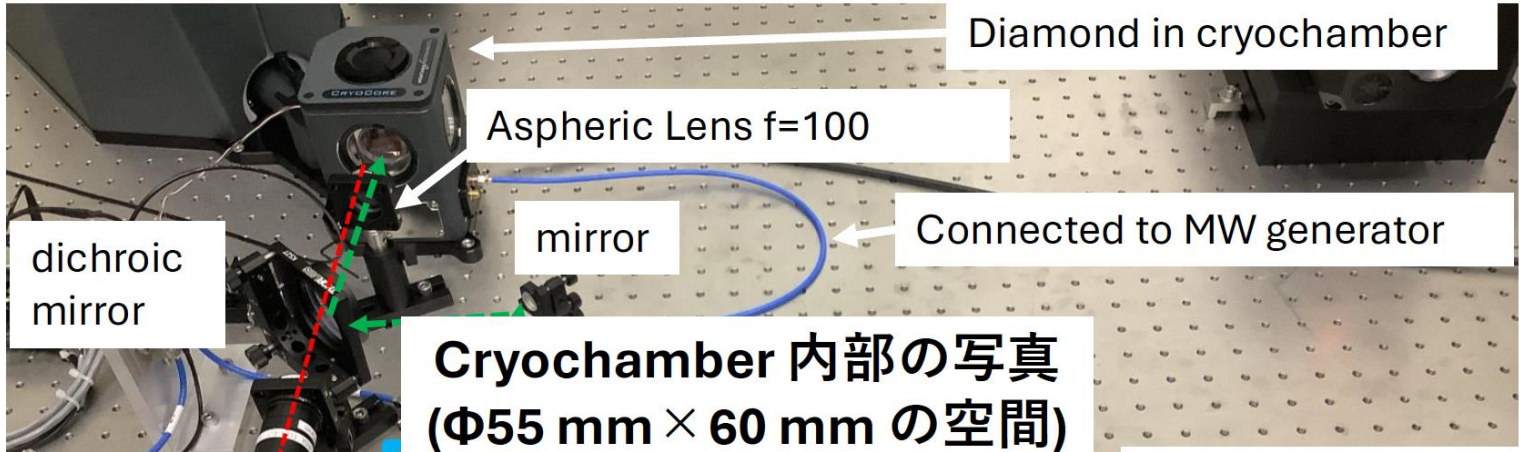
$\frac{g_{app}}{m_p}$ for ^{15}N

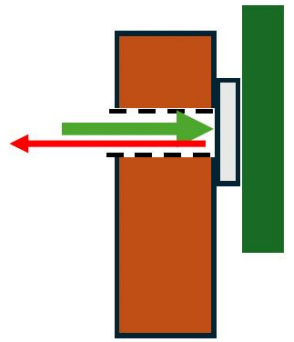
- ^{15}N-rich samples give constraints on g_{app} alone.
- Broad mass coverage!

New!

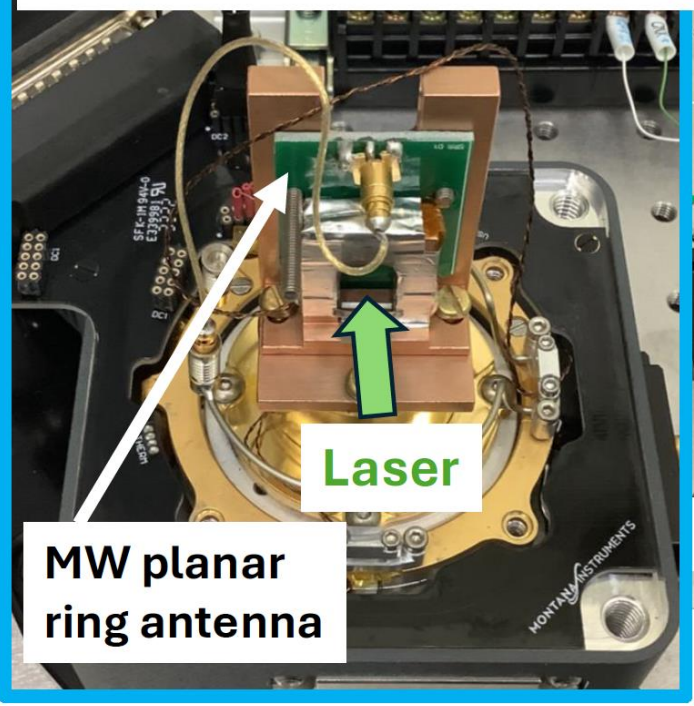


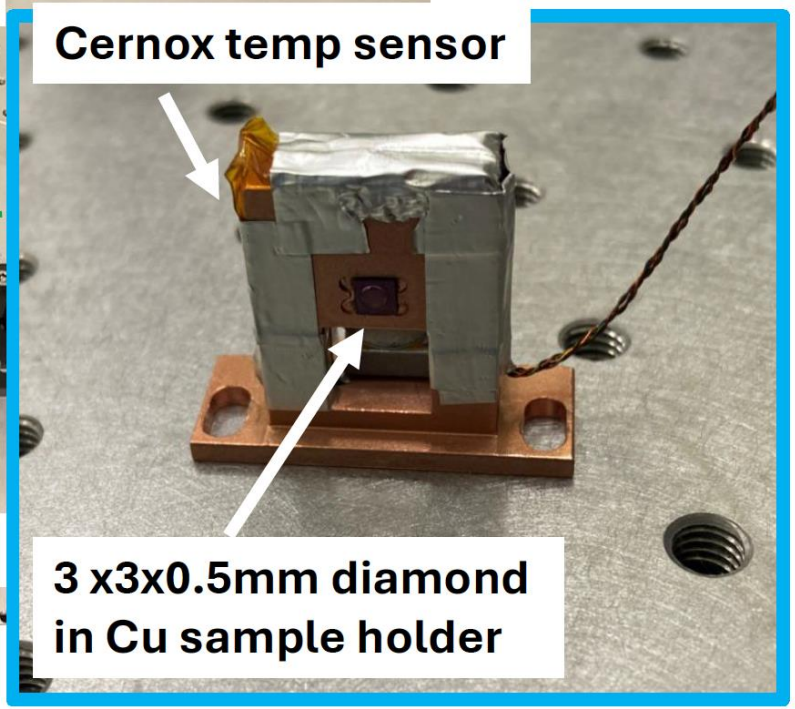
Measurement system in preparation at KEK



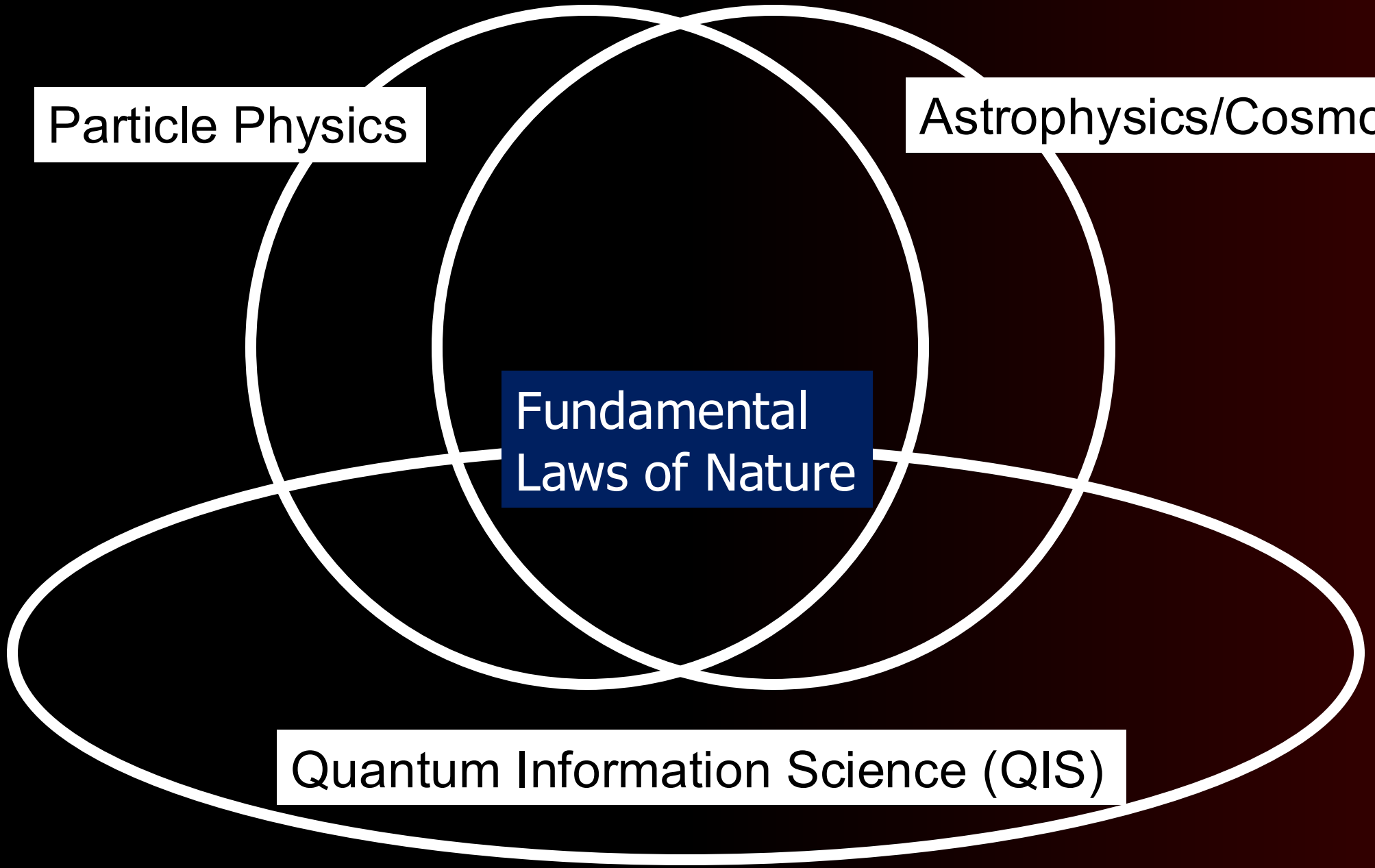


Cryochamber 内部の写真 (Φ55 mm × 60 mm の空間)





Atsuhiro Umemoto


Particle Physics
Astrophysics/Cosmology
Fundamental
Laws of Nature
Quantum Information Science (QIS)

Summary

- POLARBEAR's measurements on the Crab Nebula polarization angle show 2.5σ modulation, which might be a hint of ultra-light ALPs.
- More data from the Simons Array will confirm or deny the result.
- The results prompted consideration of other methods and couplings, leading to a new idea: using quantum sensing technology.
- Use of the diamond sensor is just an example. We have a vast, new, exciting, uncharted territory to explore in the overlap of particle physics, cosmology, and QIS.