11th KIAS workshop on Cosmology
& Structure Formation @ Gyeongju

CGPQI
Center for Gravitational Physics and Quantum Information

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Searching for Ultra-light axion in terrestrial electromagnetic waves

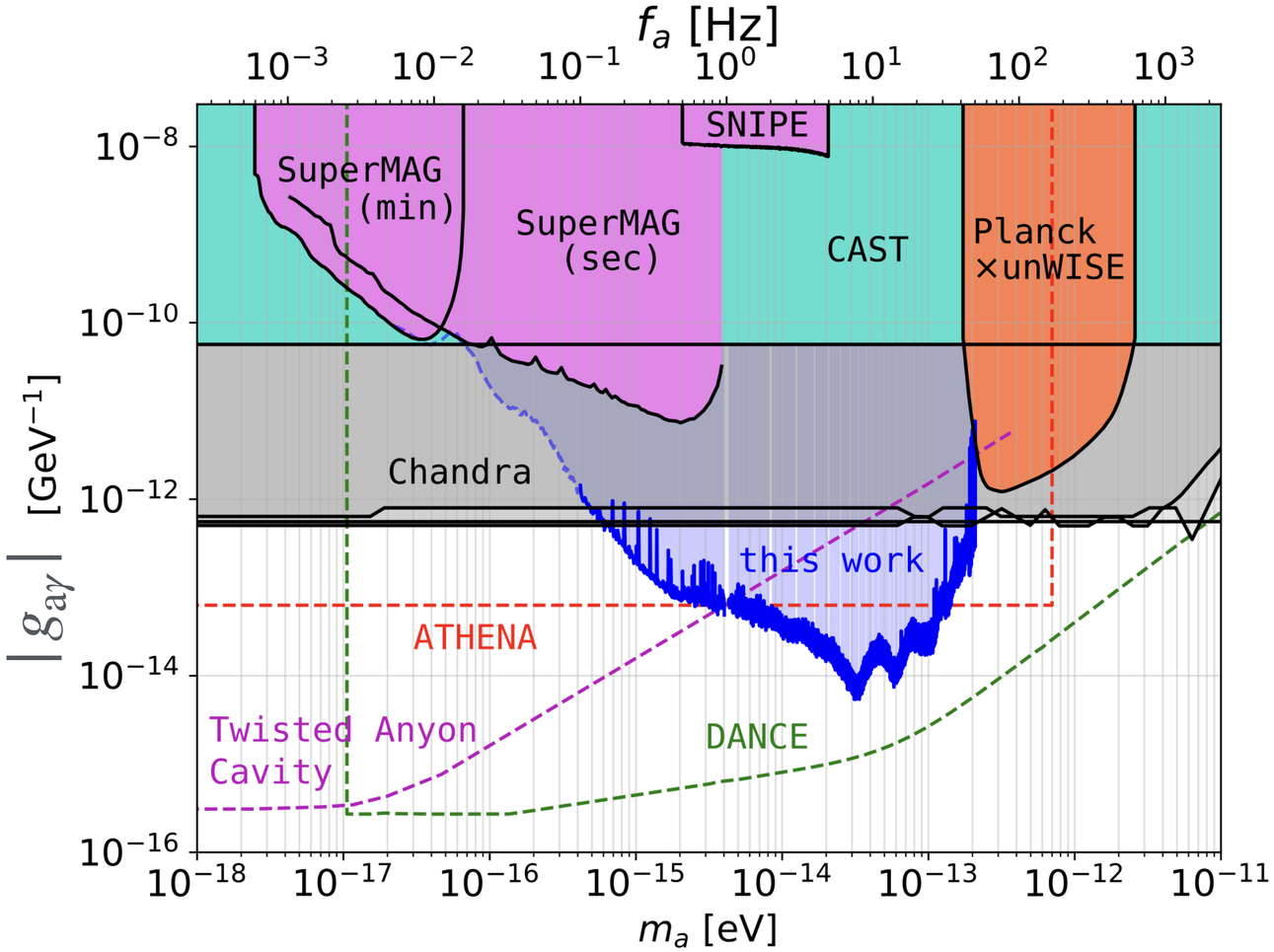
Atsushi Taruya

(Yukawa Institute for Theoretical Physics)

Oct 29, 2024

Short summary

Constraint on the ***axion-photon coupling parameter*** $g_{a\gamma}$ of the ultra-light axion from the long-term monitoring of terrestrial magnetic field at $10^{-2} - 10^{1}\,\mathrm{Hz}$



AT et al. ('24, in prep.)

In collaboration with



Atsushi Nishizawa
(Hiroshima Univ.)



Yoshiaki Himemoto
(Nihon Univ.)

Introduction

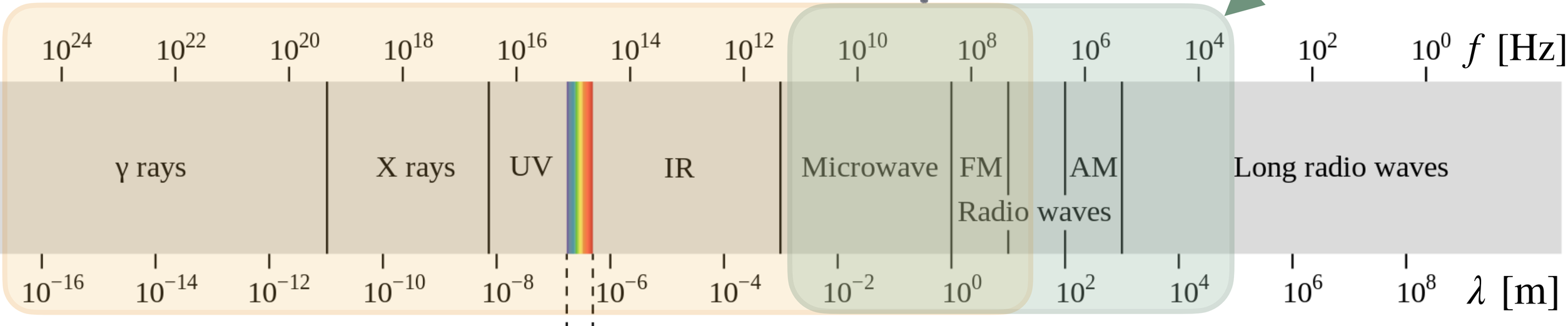
Electromagnetic (EM) waves *are ubiquitous & useful*

- Essential communication tools in our daily life (TV, radio, mobile phone, …)



- Unique messengers to probe universe



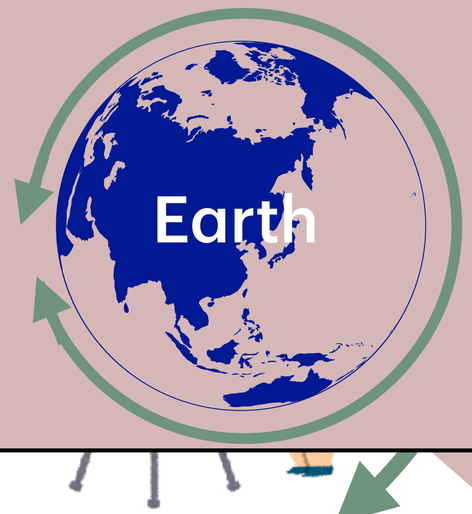


Introduction

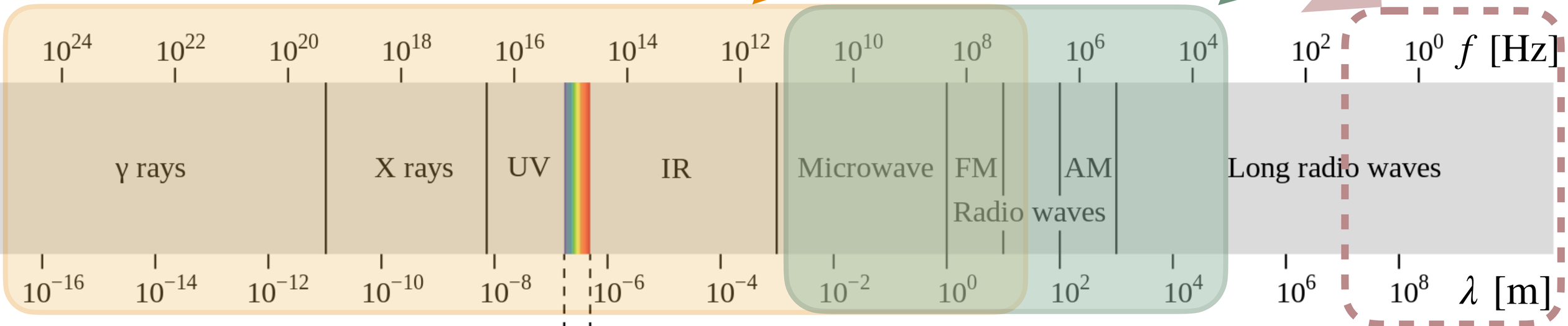
Extremely low-frequency (ELF) EM waves ($f \lesssim 30\,\mathrm{Hz}$)

Wavelength: $\lambda \gtrsim 10{,}000\mathrm{km}$ ~ Earth circumference

Q Is the ELF band useful for cosmology/ fundamental physics ? → ***Dark matter search***

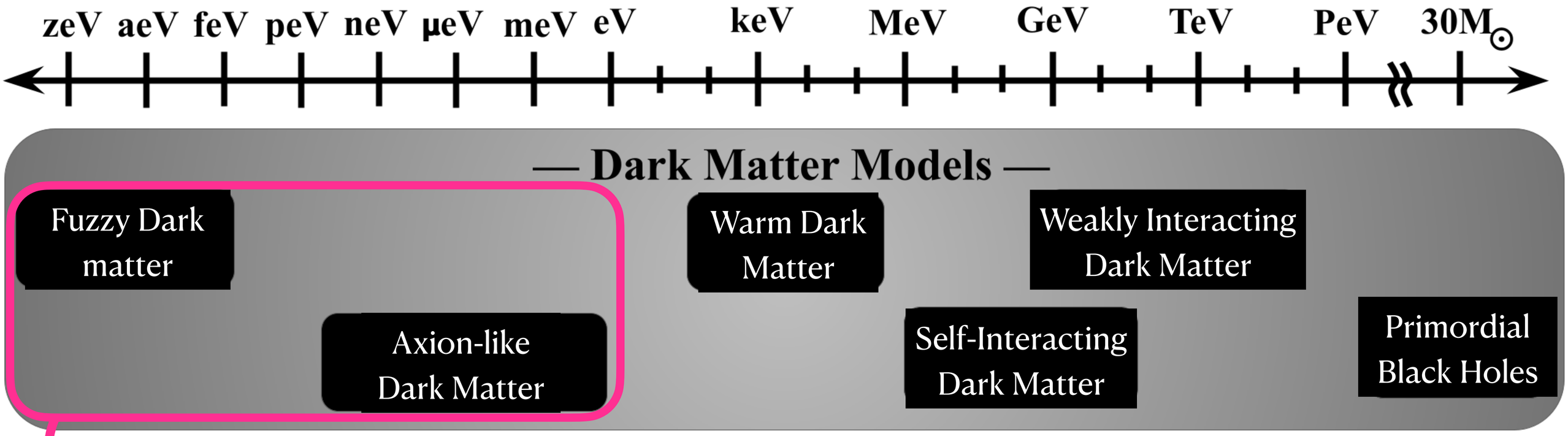






Dark matter candidates

arXiv:2209.08215



Axion

- Broad mass range: $10^{-23}\ \text{eV} \sim 1\,\text{eV}$
- Weakly interacting with EM fields : $\mathscr{L}_{\text{int}} = -g_{a\gamma}\, a\, \boldsymbol{E}\cdot\boldsymbol{B}$

(a : axion field)

Signature of axion dark matter

DM is supposed to be invisible → gravity is the only interaction with the SM particles

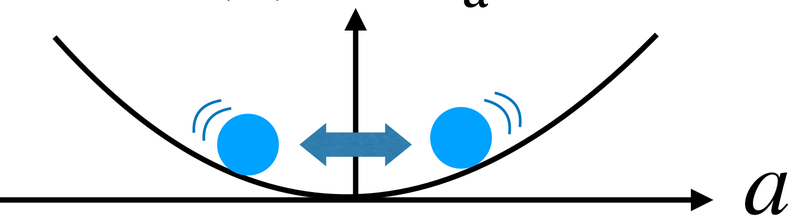
However, Axion-photon conversion

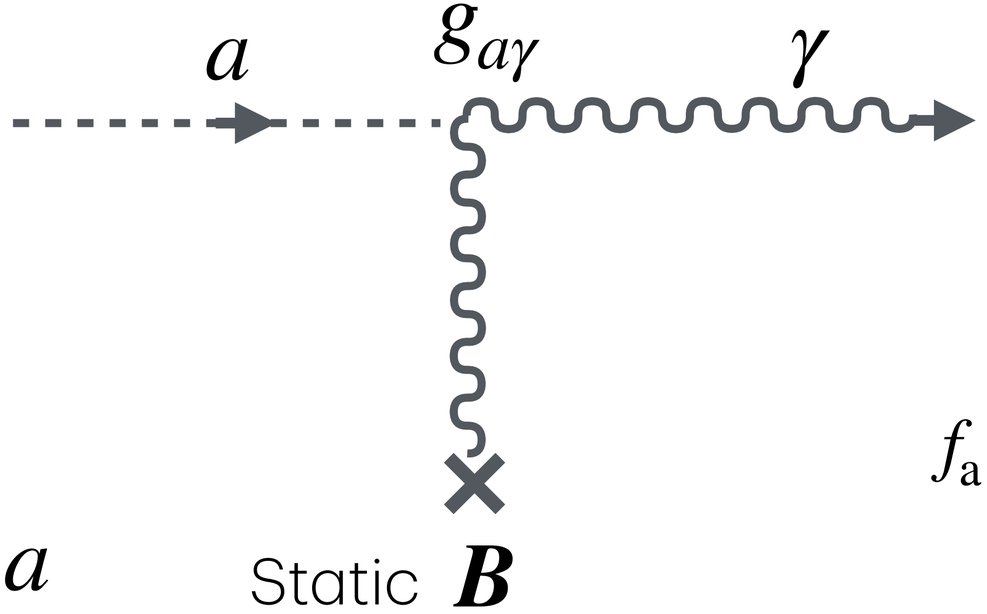
$$\mathscr{L}_{\rm int} = -\, g_{a\gamma}\, a\, \boldsymbol{E}\cdot\boldsymbol{B} \qquad (a: \text{axion field})$$

Coherent axion

(Axion =dark matter)

$$V(a) = m_{\rm a} a^2/2$$





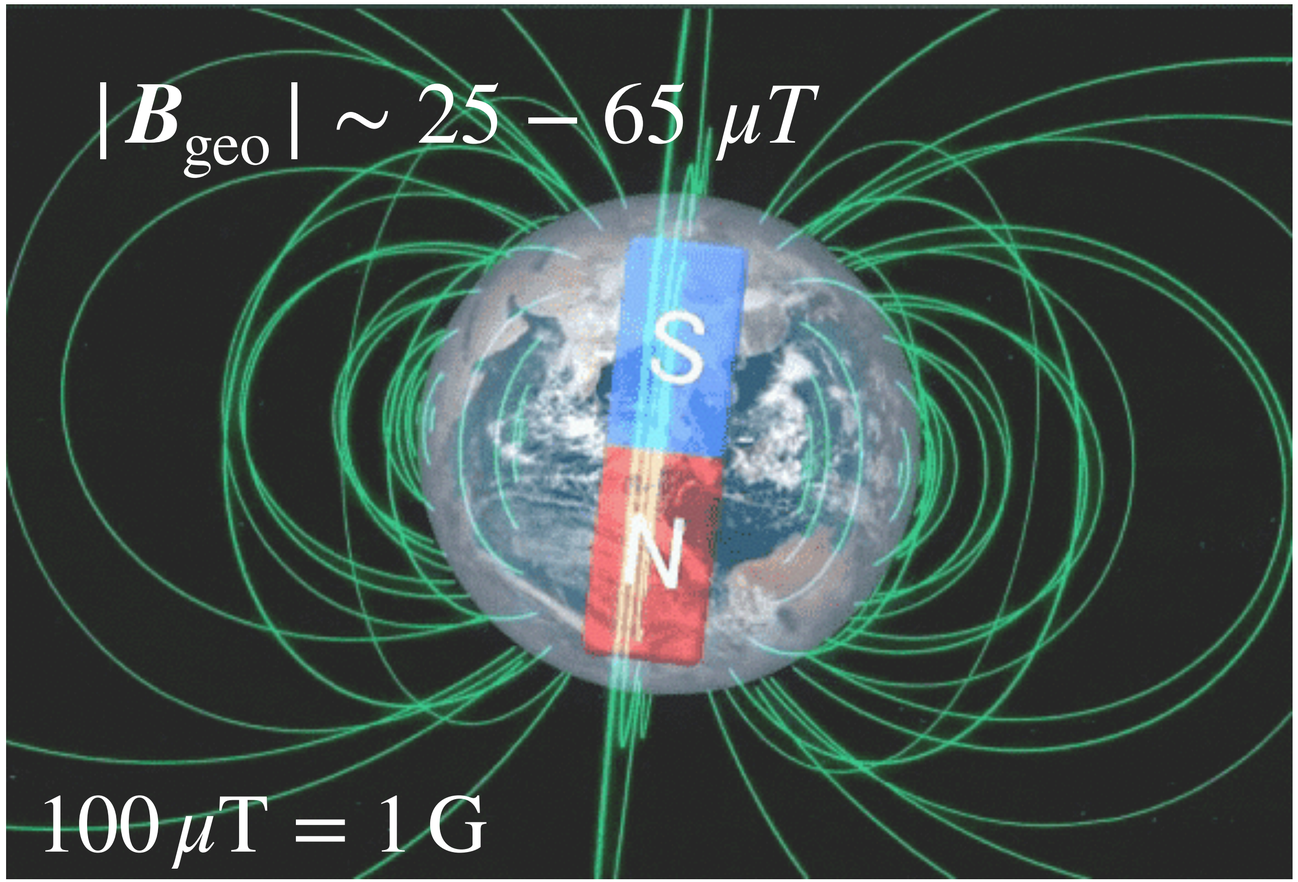
Monochromatic EM waves

Frequency:

$$f_{\rm a} = \frac{m_{\rm a}}{2\pi} \simeq 2.4 \left(\frac{m_{\rm a}}{10^{-14}\,\text{eV}}\right) \text{Hz}$$

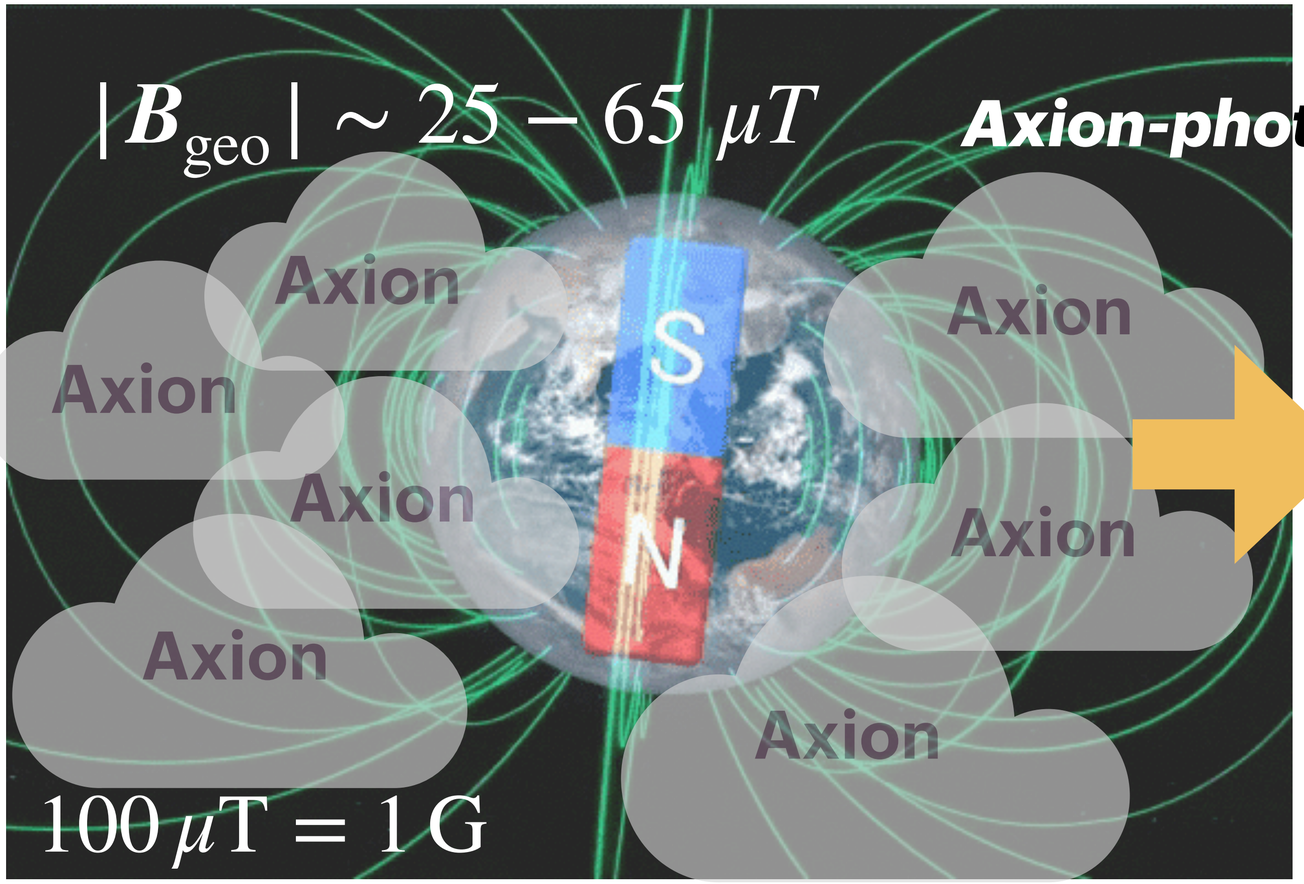
Signature of axion dark matter

Geomagnetic field as a global static B-field on Earth



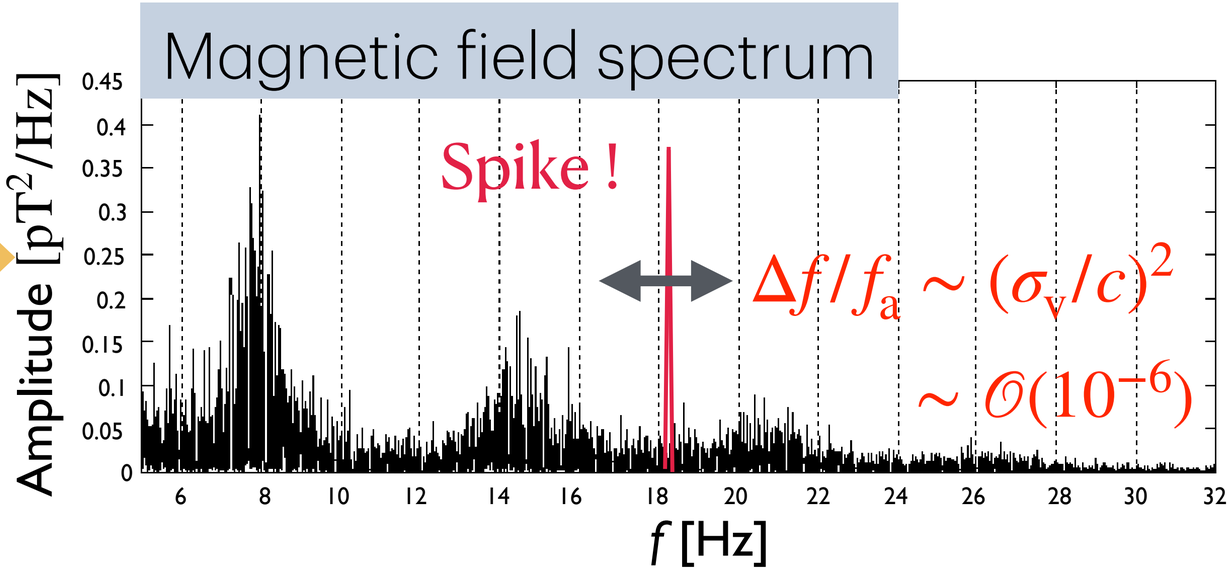
Signature of axion dark matter

Geomagnetic field as a global static B-field on Earth



Axion-photon coupling

$$f_{\rm a} = 2.4\,(m_{\rm a}/10^{-14}\,{\rm eV})\,{\rm Hz}$$



This signal exists ***permanently***
across the entire Earth

Back-of-envelope estimation

Axion-photon coupling induces effective current:

$$\nabla \times \boldsymbol{B} - \dot{\boldsymbol{E}} = - g_{a\gamma}\, \dot{a}\, \boldsymbol{B}_{\rm geo}$$

$\rho_{\rm DM}$: local DM density

$(\rho_{\rm DM} = m_{\rm a}^2 \langle a_0^2 \rangle_\tau / 2)$

Equating each term, the expected amplitude is

$$|\boldsymbol{B}_{\rm induced}| \sim 0.1\ {\rm pT} \left(\frac{g_{a\gamma}}{10^{-10}\,{\rm GeV}^{-1}}\right)\left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV\,cm}^{-3}}\right)^{1/2}\left(\frac{|\boldsymbol{B}_{\rm geo}|}{100\,\mu{\rm T}}\right)$$

$1\,{\rm pT} = 10\,{\rm nG}$

Quite small, but still measurable !

At the ELF band: $f_a \simeq 2.4\,(m_a/10^{-14}{\rm eV})\ {\rm Hz}$

e.g., Metronix, MFS-06e (~8,000 USD)

Sensitivity $\sim 0.1\,{\rm pT}/\sqrt{\rm Hz}$ at 1 Hz



A more precise estimation

Solving the ***Maxwell-axion system*** taking into account ***(i)*** atmospheric conductivity, ***(ii)*** geomagnetic field configuration (dipole & higher-ℓ)

$$\nabla \cdot \boldsymbol{D} = 0$$

$$\nabla \times \boldsymbol{B} - \dot{\boldsymbol{D}} = -\, g_{a\gamma}\, \dot{a}\, \boldsymbol{B}_{\rm geo}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} + \dot{\boldsymbol{B}} = 0$$

Coherently oscill. Axion

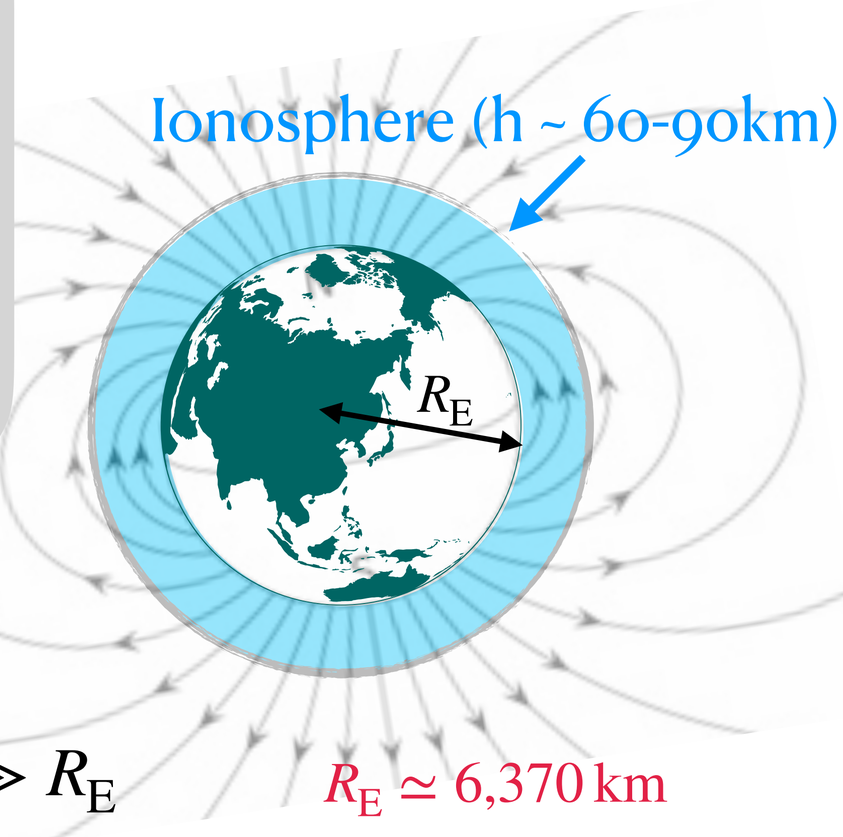
Displacement field

$$\boldsymbol{D} = \varepsilon_0\, n^2\, \boldsymbol{E}$$

Conductivity

Refractive index

$$n^2 \equiv 1 + i\, \frac{\sigma(r)}{m_{\rm a}}$$



- Atmospheric conductivity profile $\sigma(r)$ by Kudintseva et al. ('16)
- Geomagnetic field data by IGRF-13
- Boundary conditions : $\boldsymbol{E}_{\parallel} = 0$ at $r = R_{\rm E}$, upgoing waves at $r \gg R_{\rm E}$

Results: prediction

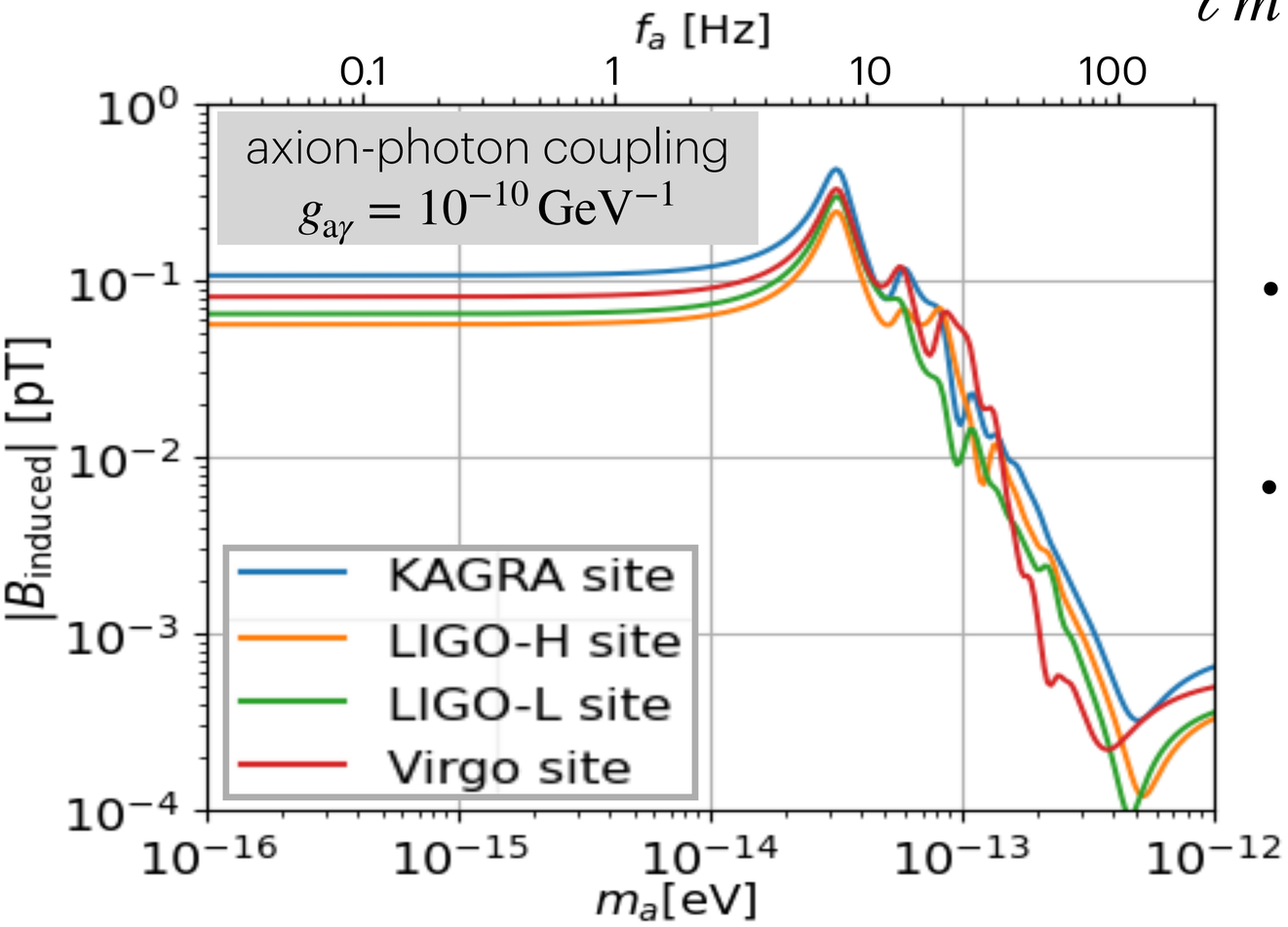
AT, Nishizwa & Himemoto ('24, in prep.)

Vector spherical harmonics

$$\boldsymbol{B}_{\rm induced}(r,\boldsymbol{\theta}) = g_{a\gamma}\, a(t) \sum_{\ell m} C_{\ell m}\, b_\ell(m_a r)\, \boldsymbol{\Phi}_{\ell m}(\boldsymbol{\theta})$$

Radial mode function

Geomagnetic field



- Resonant peaks from radial mode func.
  (= ***Schumann resonance, '52***)
- Dominant dipole contribution from geomagnetic field

∴ The induced B-field peaks at **7.7 Hz** and is suppressed at higher frequencies.

$(m_{\rm a} \gtrsim 3\times10^{-14}\,\mathrm{eV})$

Axion search from public B-field data

Public B-field monitoring data for geoscience

SuperMAG https://supermag.jhuapl.edu/

$>$40 years, # of detector sites: $\mathcal{O}(10^2)$

Low sampling rate: $\lesssim 1\,\mathrm{Hz}$

$\rightarrow$Arza et al. ('22), Friel et al. ('24)

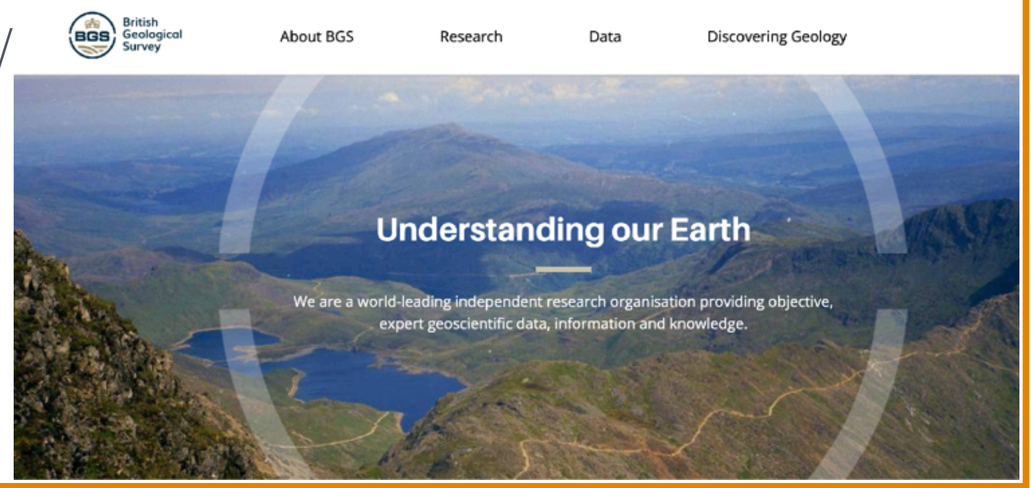


British Geology Survey Data https://www.bgs.ac.uk/

$\sim$10 years, high sampling rate $\rightarrow$ ELF bands (0.01–10 Hz)

In particular,

We use the data taken at *Eskdalemuir observatory*



Data analysis ~sketch~

AT, Nishizwa & Himemoto ('24, in prep.)
Nishizwa, AT & Himemoto ('24, in prep.)

Using **10 years** public data at *Eskdalemuir observatory*

1. Taking the '*quiet*' data, and stacking their segments with consecutive 8 hours in the Fourier domain ($\Delta f/f \sim 3 \times 10^{-5}$)

2. Calculating the '***difference***' spectrum by applying a low-pass filter and subtracting the smoothed component

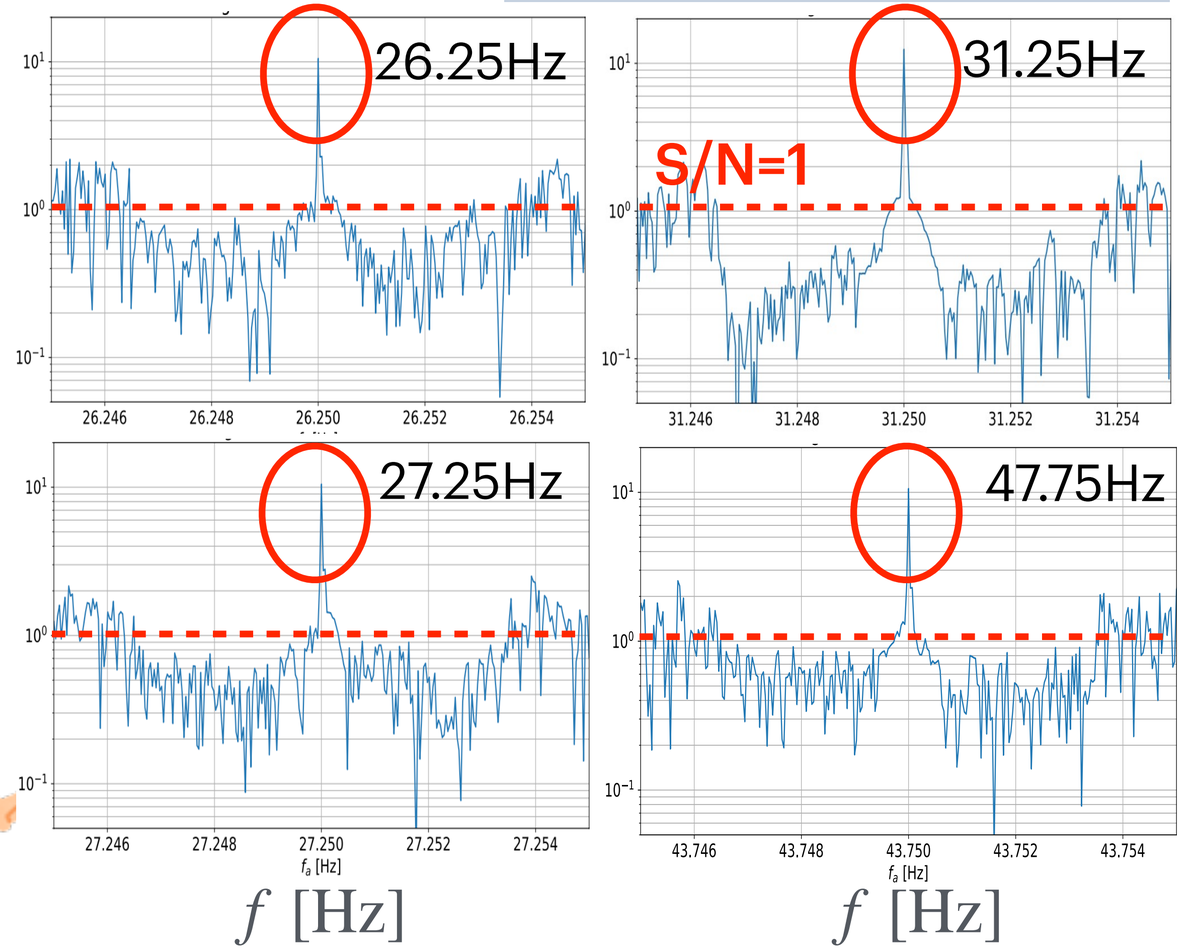
3. Identifying possible candidates of axion signals with $\mathrm{S/N} \geq 3$ for all years & $\mathrm{S/N} \geq 1$ for each year

   (noise = RMS of diff. spectrum)

59 candidates at 2—45 Hz

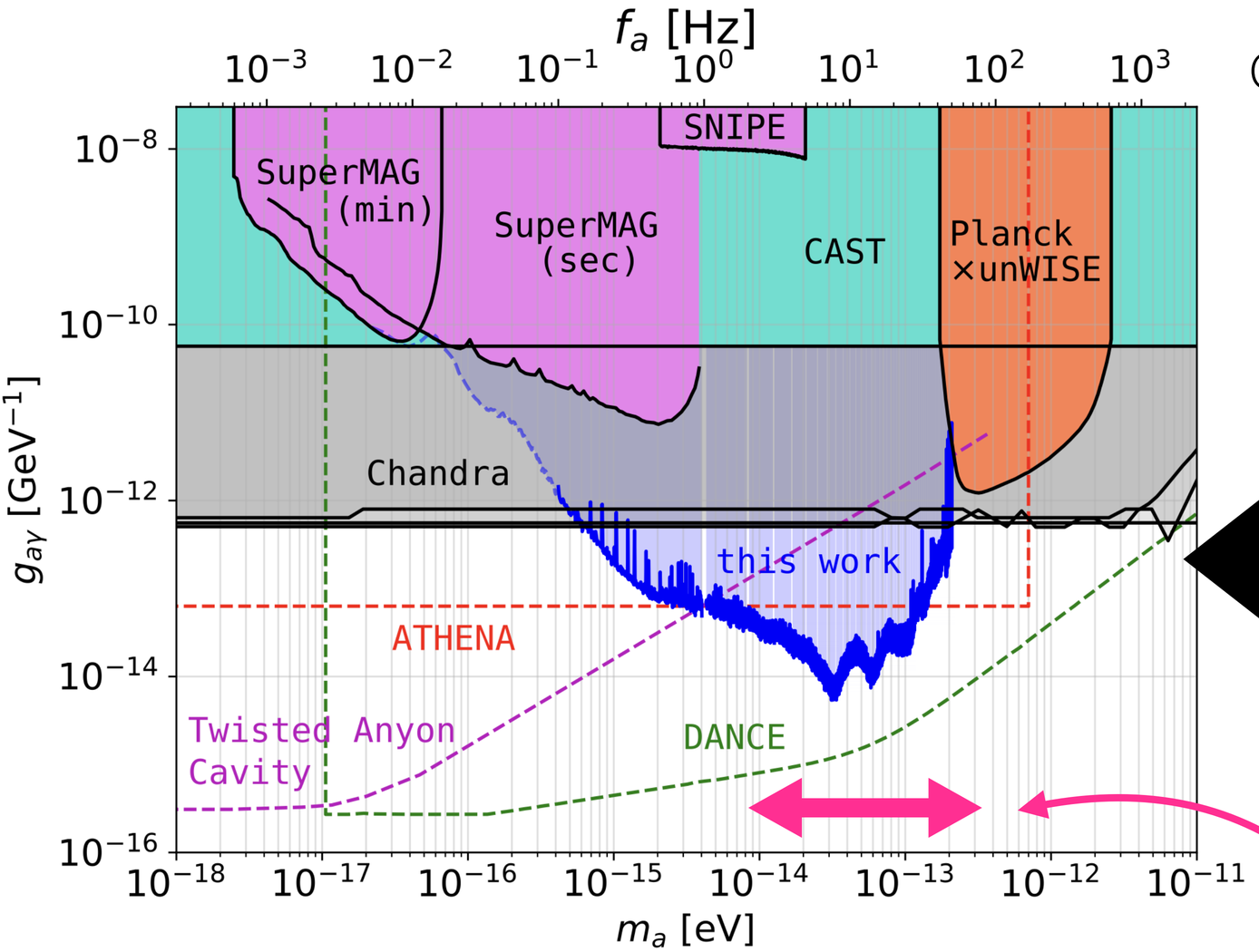


Candidates exceeding $\mathrm{S/N} = 10$ for all years



Summary & discussions

A novel axion dark matter search in the terrestrial EM fields



Coupled with geomagnetic field,
axion-induced EM waves across the Earth:

$$|\boldsymbol{B}_{\rm induced}| \sim 0.1\ {\rm pT}\left(g_{a\gamma}/10^{-10}\,{\rm GeV}^{-1}\right)$$

$$\text{at } f_{\rm a} \simeq 2.4\,{\rm Hz}\left(m_{\rm a}/10^{-14}\,{\rm eV}\right)$$

Constraint on axion-photon coupling from public B-field data

Tightest bound in the mass range of

$$m_{\rm a} = 10^{-15} - 10^{-13}\,{\rm eV}$$

59 potential candidates are still left

Summary & discussions

Follow-up measurements

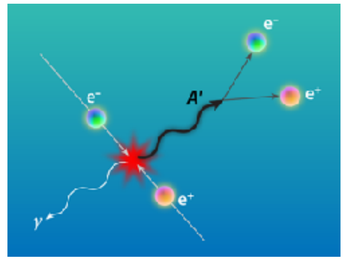
- Ground-based experiment by DANCE, Astronomical obs. by ATHENA
- Environment monitoring data at gravitational-wave detector sites

Possible extentions

Induced EM waves at ELF band are also expected from

- **Dark photon DM** $\mathscr{L}_{\rm int} = (\varepsilon/2) F_{\mu\nu} F'^{\mu\nu}$
- **Gravitational waves** $\mathscr{L}_{\rm int} = -(1/4) g^{\mu\alpha} g^{\beta\nu} F_{\mu\nu} F^{\alpha\beta}_{\rho\sigma}$

via kinetic coupling & graviton-photon conversion



Speculation

Measuring EM data at Jupiter will expand the discovery space

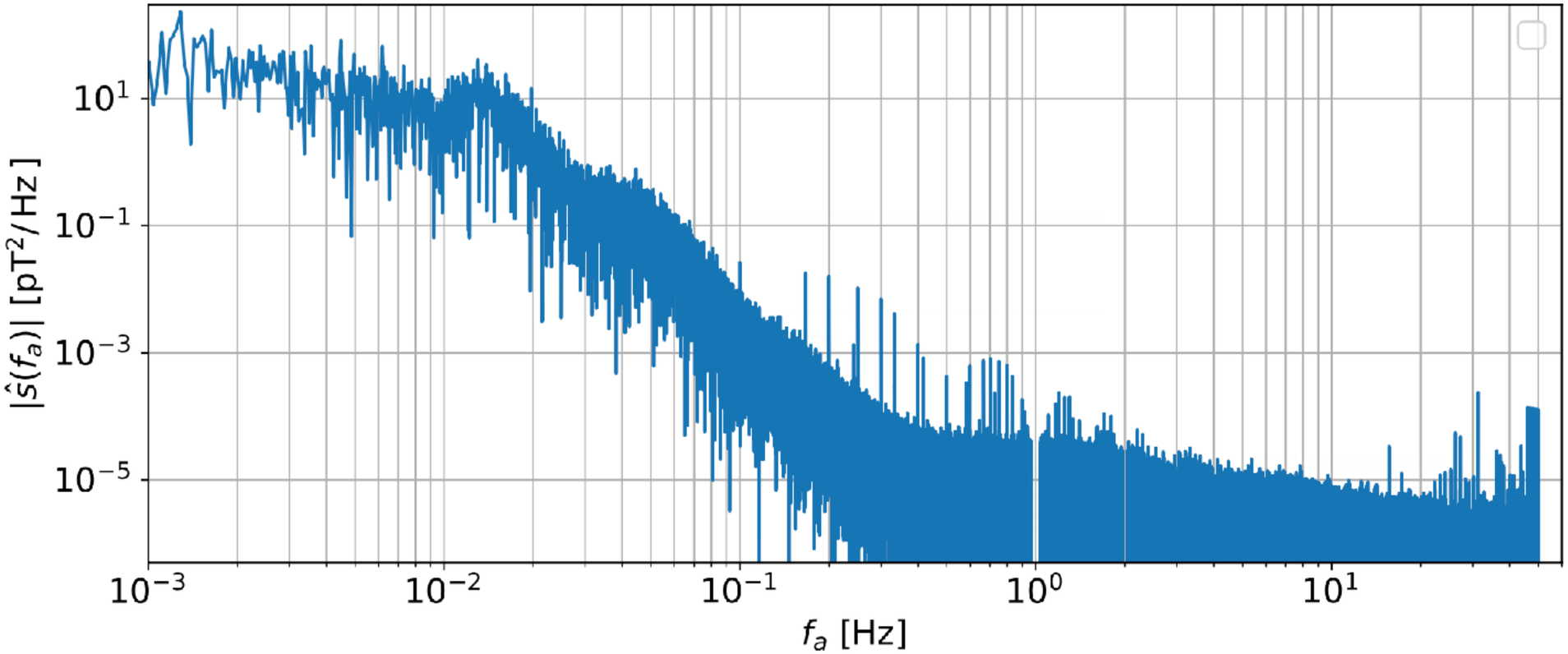


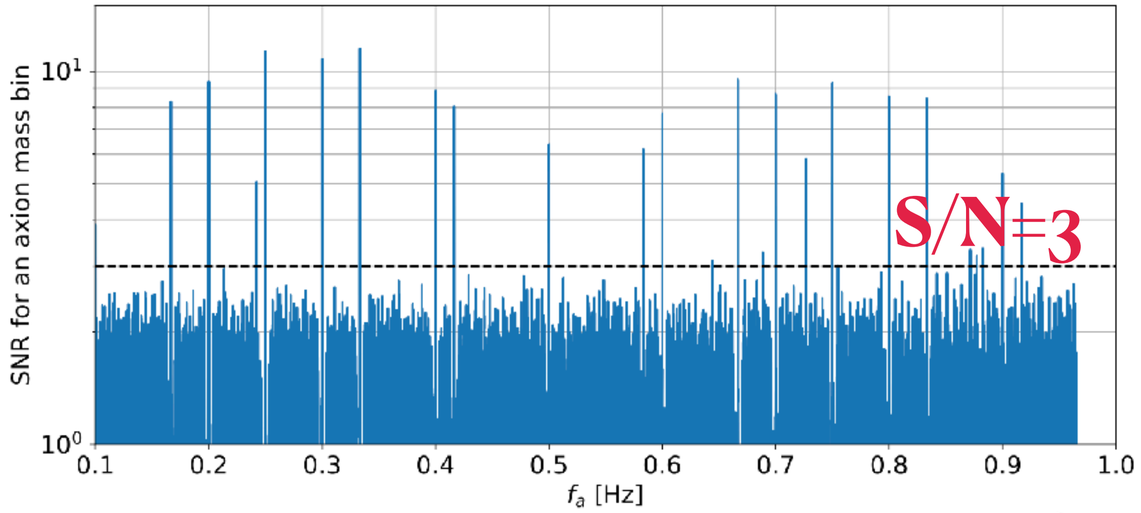
Backup

Difference spectrum

Results stacked over all 8-hour segments

(1753 segments for all year)

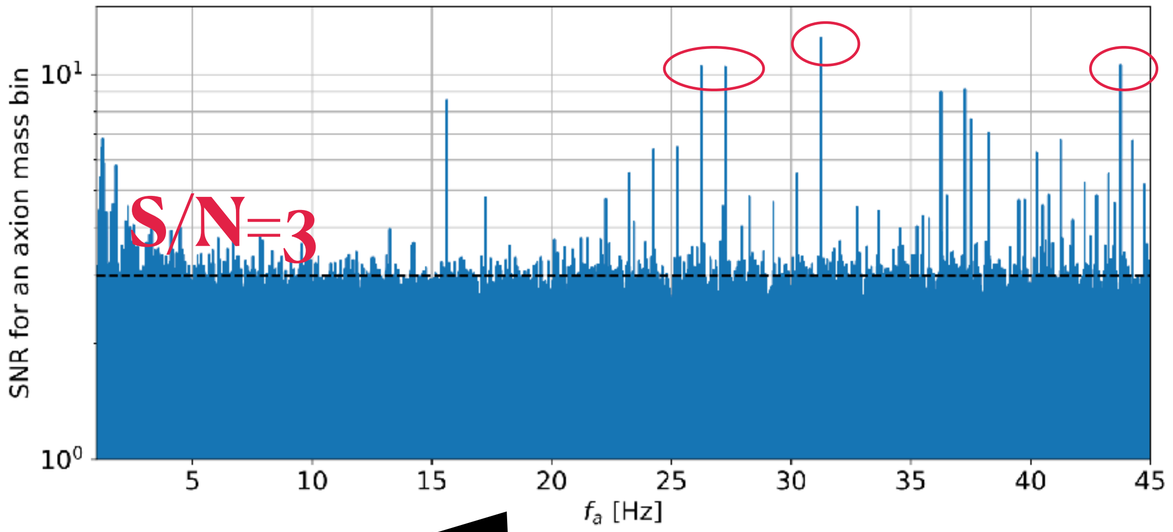


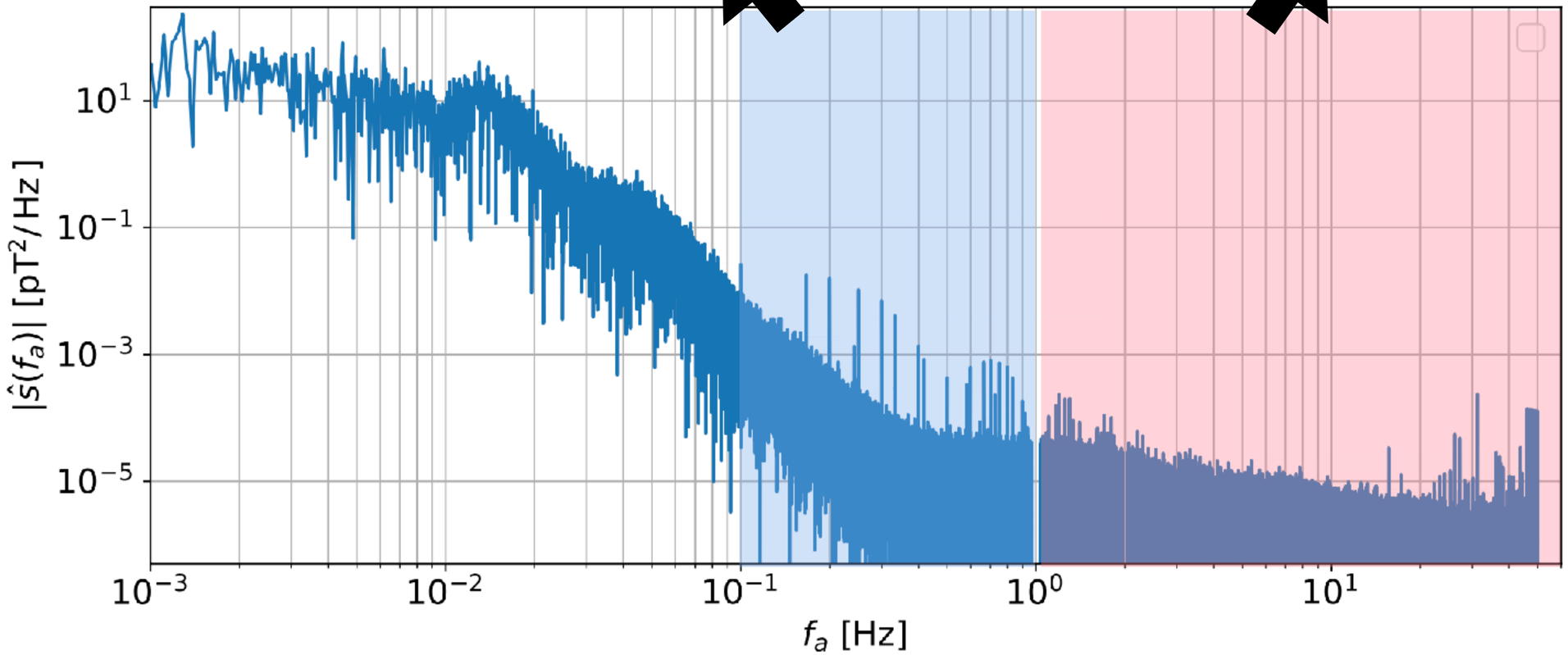

SNR for an axion mass bin
10^1
10^0
S/N=3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
f_a [Hz]

ur

all

seq


SNR for an axion mass bin
10^1
10^0
S/N=3
5
10
15
20
25
30
35
40
45
f_a [Hz]


$|\hat{s}(f_a)|$ [pT^2/Hz]
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
f_a [Hz]