2025 APCTP-IBS Focused Research Program: The origin and evolution of the Universe @ APCTP, Pohang

CGPQI
Center for Gravitational Physics and Quantum Information

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Hunting dark matter signature in low-frequency terrestrial magnetic fields: updates

Atsushi Taruya

(Yukawa Institute for Theoretical Physics)

June 17, 2025

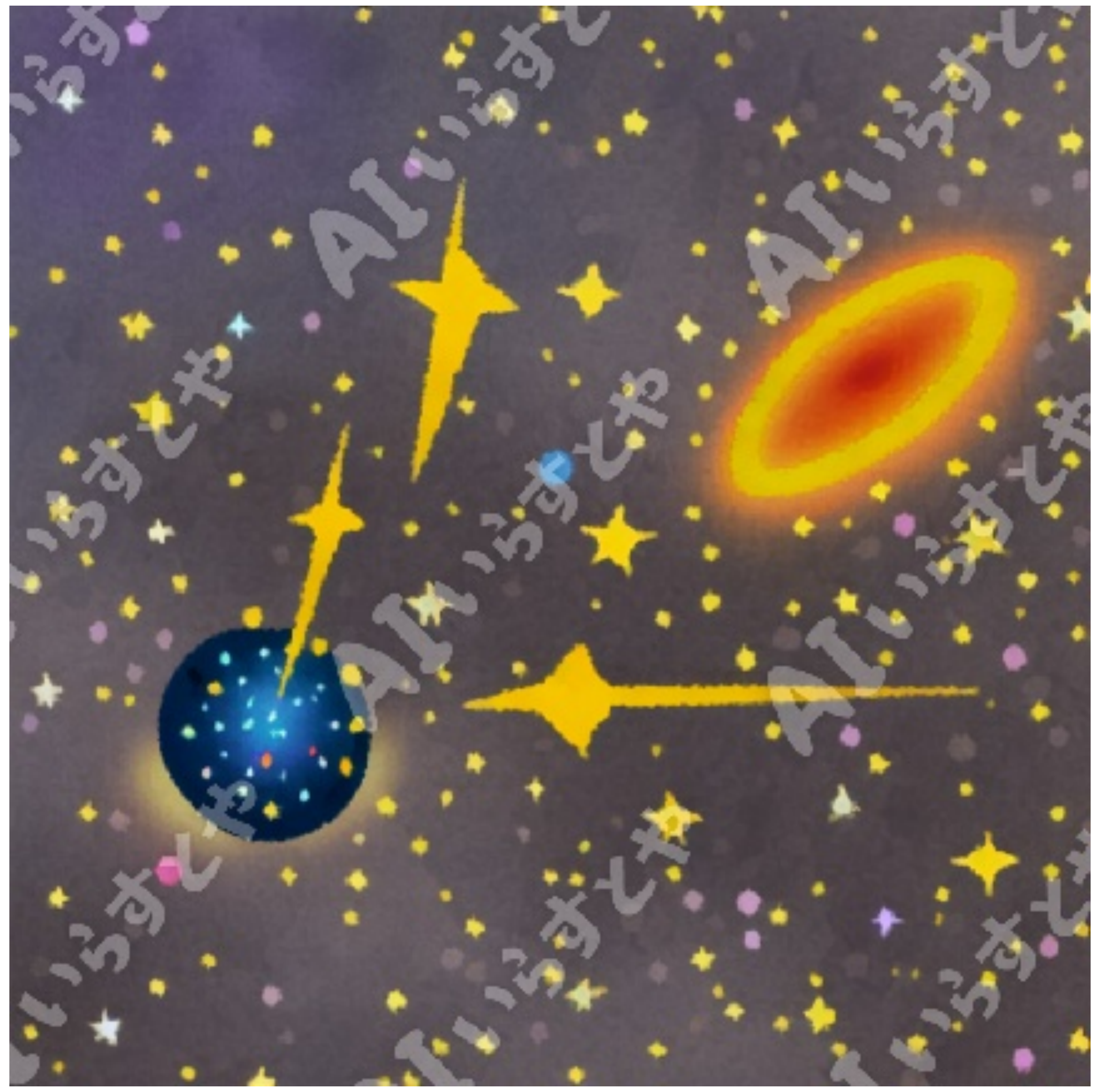
Contents

A novel search for dark matter signature using public geoscience data: progress & updated constraints on the coupling parameters

Introduction: cosmology and dark matter (DM)

DM search in the terrestrial environment
(axion & dark photon)

Summary & future prospects



Refs.

AT, A. Nishizawa, Y. Himemoto, arXiv:2504.06653

A. Nishizawa, AT, Y. Himemoto, arXiv:2504.07559

AT, A. Nishizawa, Y. Himemoto (in prep.)

K. Nomura, et al. (in prep)

Collaborators

Atsushi Nishizawa
(Hiroshima Univ.)

Yoshiaki Himemoto
(Nihon Univ.)

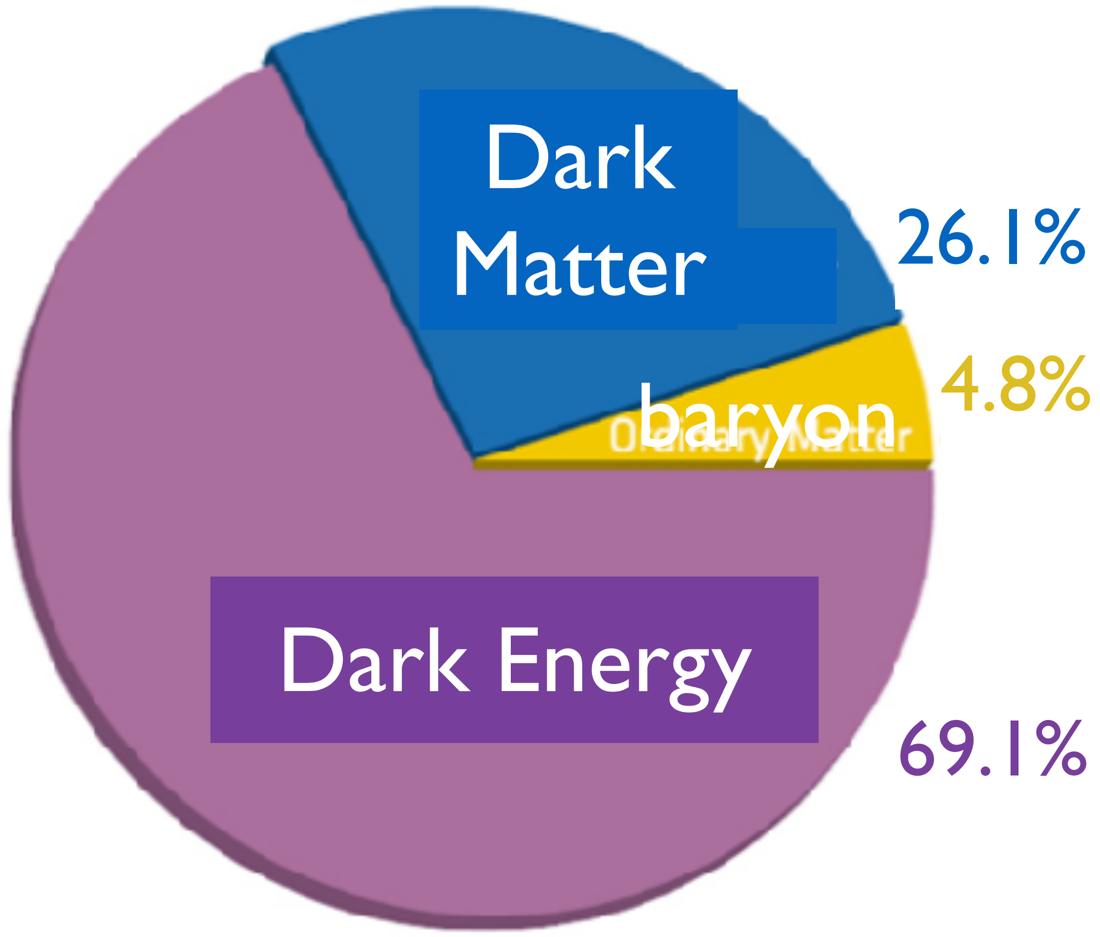
Kimihiro Nomura
(Kyoto Univ.)

Also, special thanks: KAGRA PEM group (Washimi & Yokozawa)
(Physical Environment Measurement)

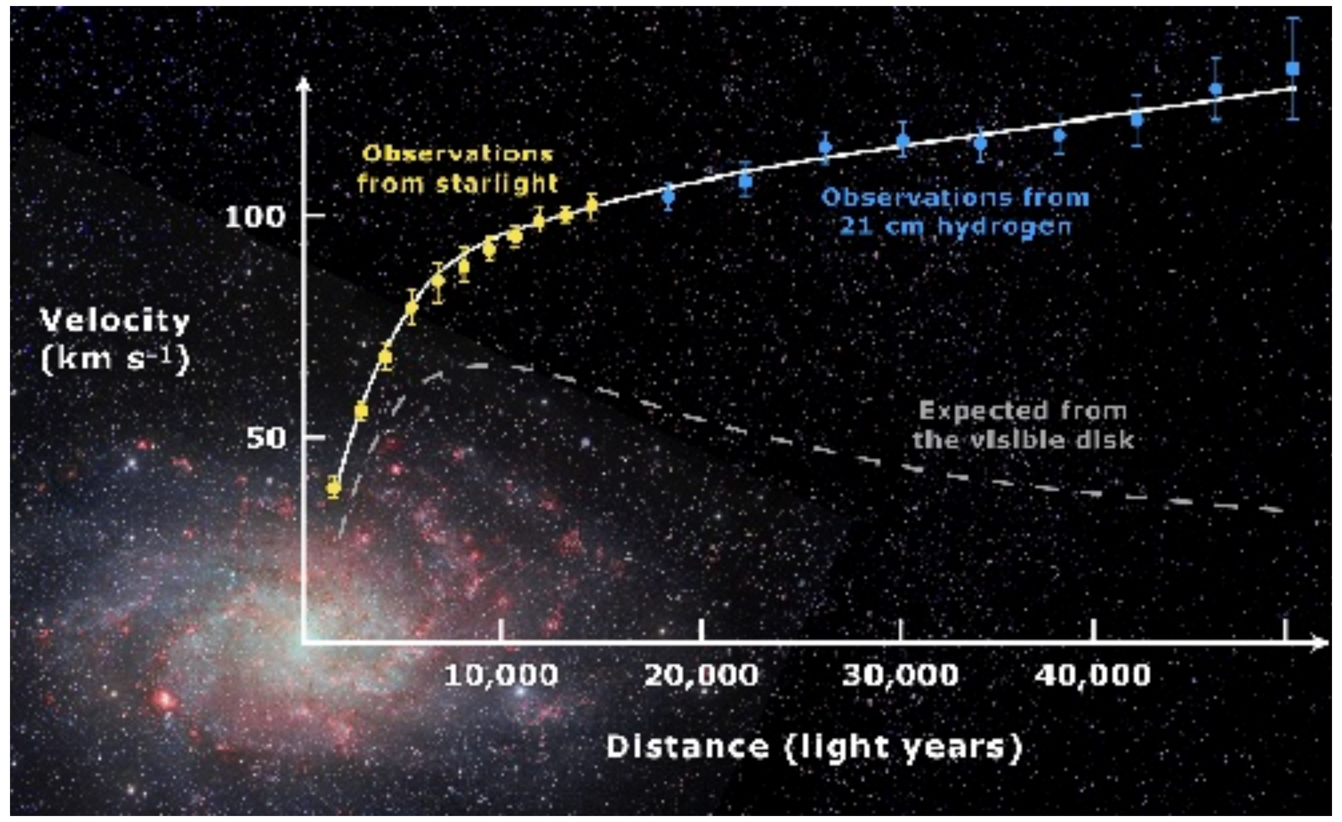
Introduction

Our universe is filled with dark matter (DM) !

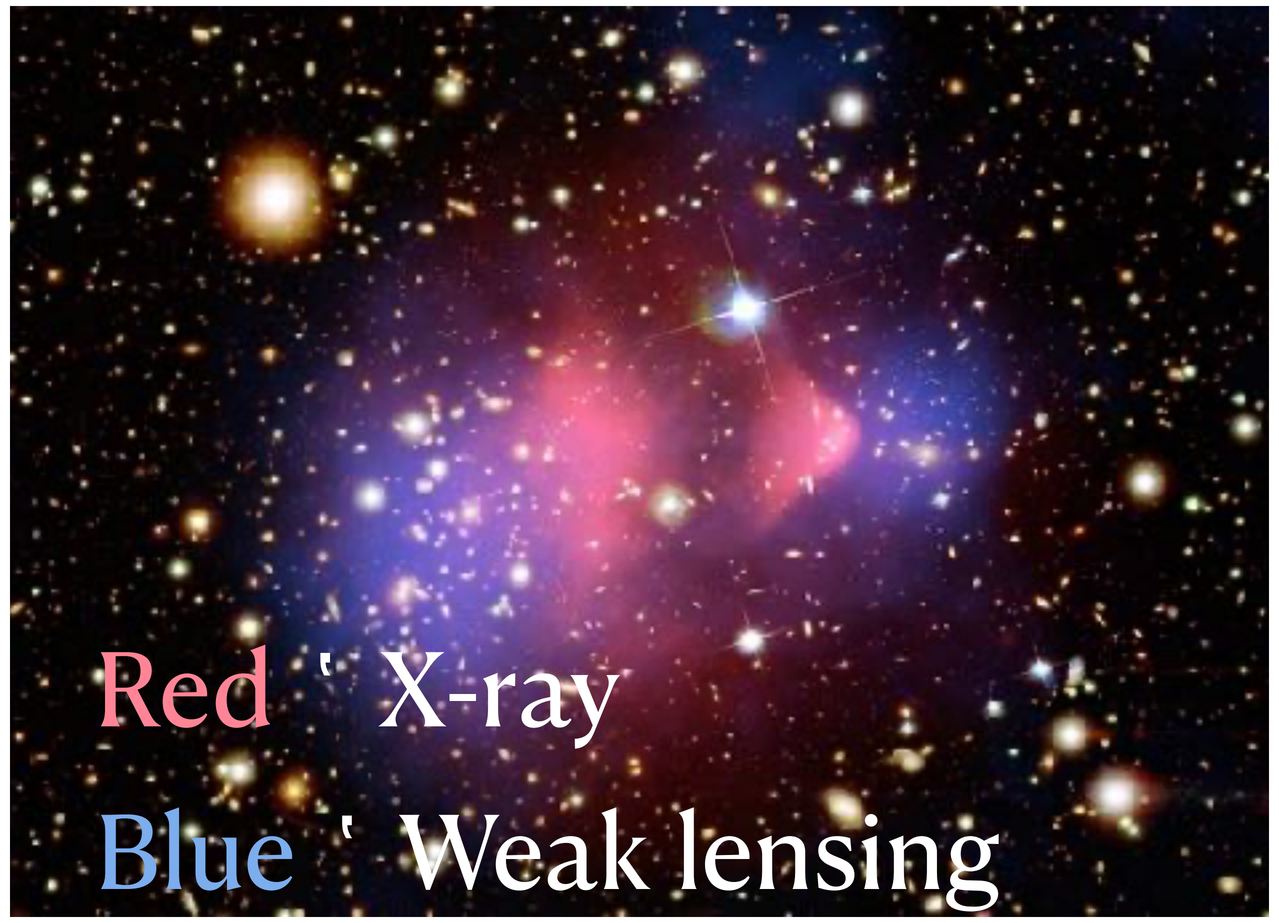
- An essential ingredient accounting for cosmic structure formation
- Much independent observational evidence



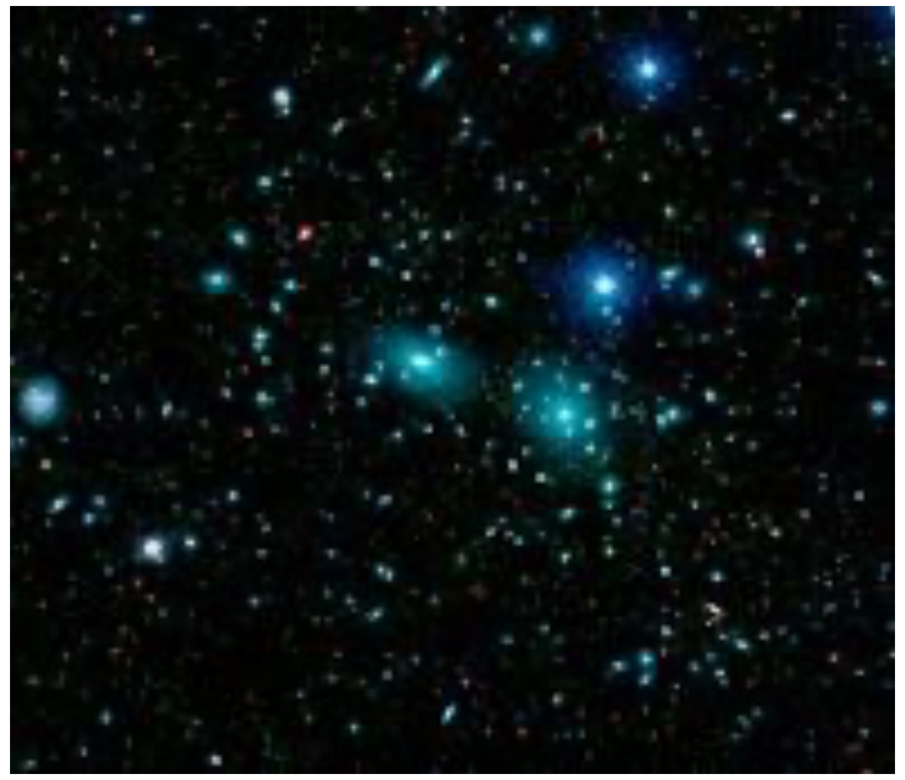
Galaxy rotation curve



Bullet cluster



Coma cluster



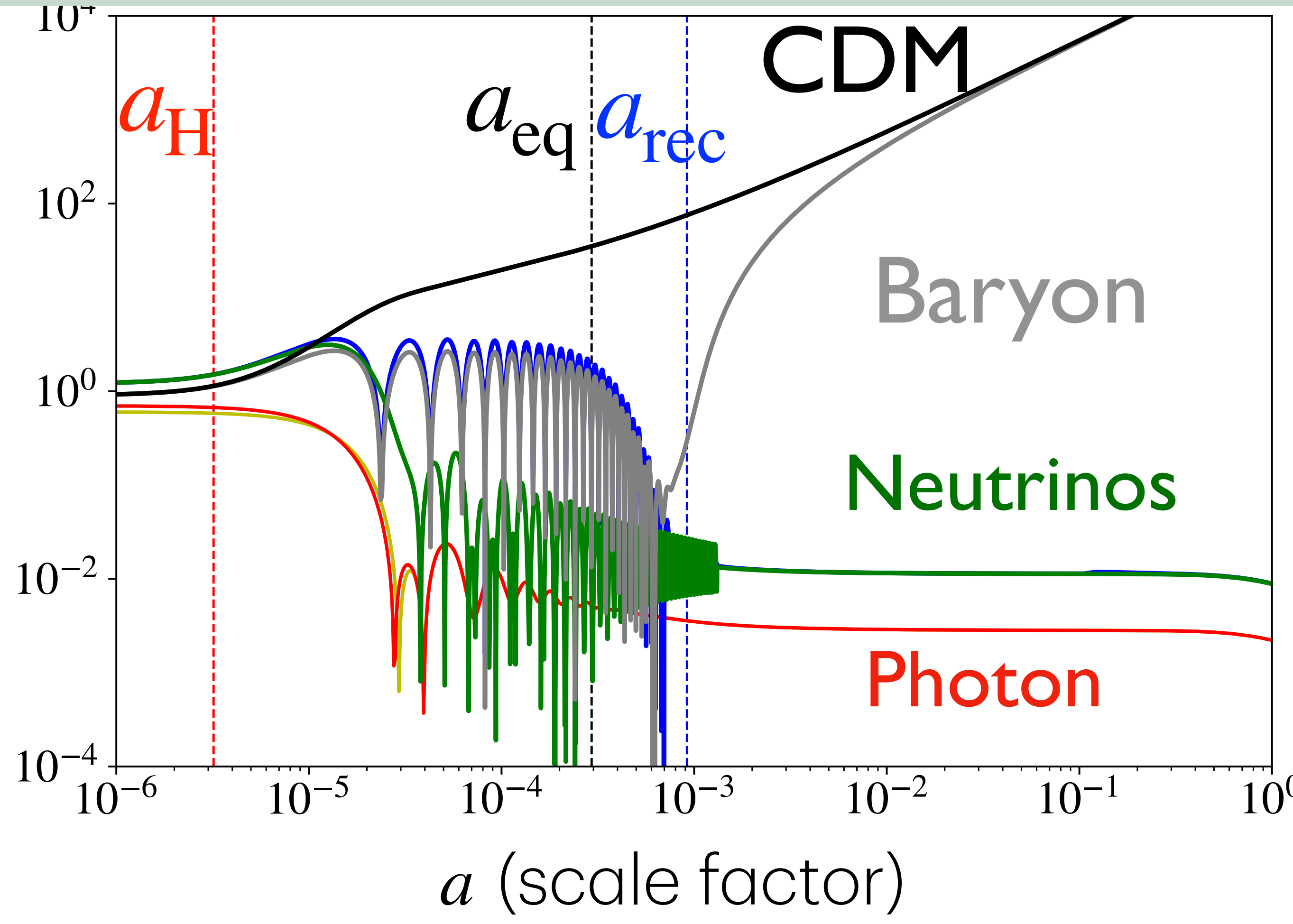
Cold dark matter paradigm

DM must be cold ($m_{\rm DM} \gg T_{\rm DM}$) and decoupled from thermal bath

- Early-time growth of matter inhomogeneity
- Late-time baryon catch-up (after recombination)

→DM halos as the primary sites for star/galaxy formation

Evolution of density fluctuations

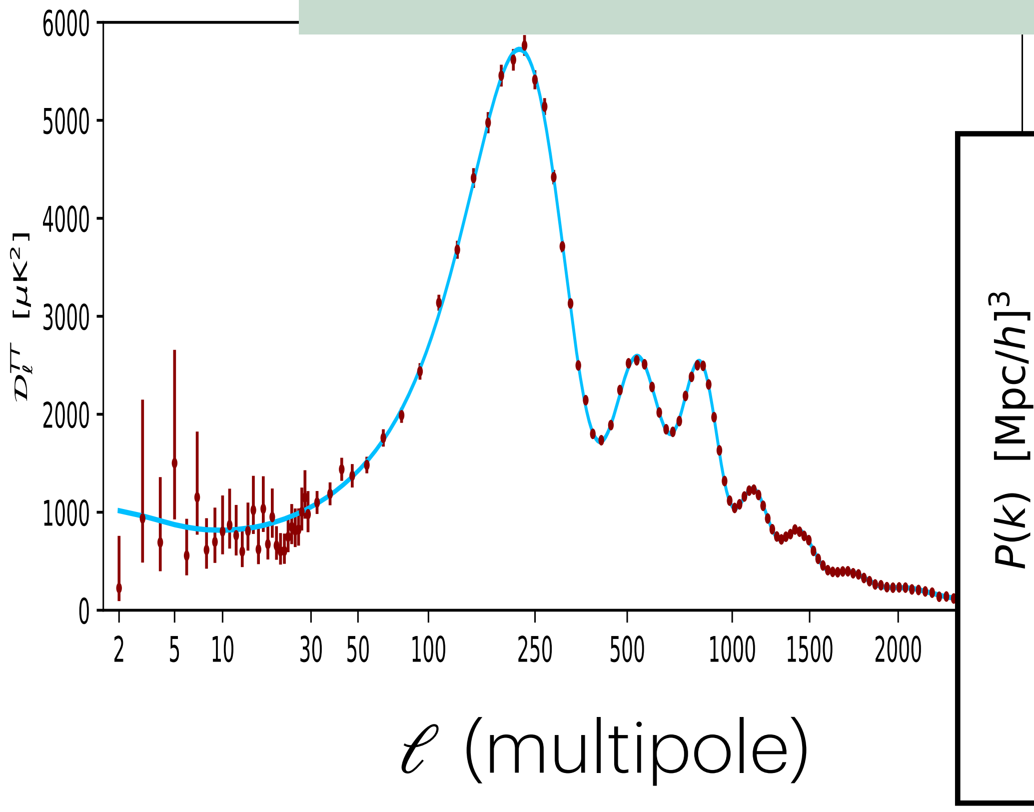


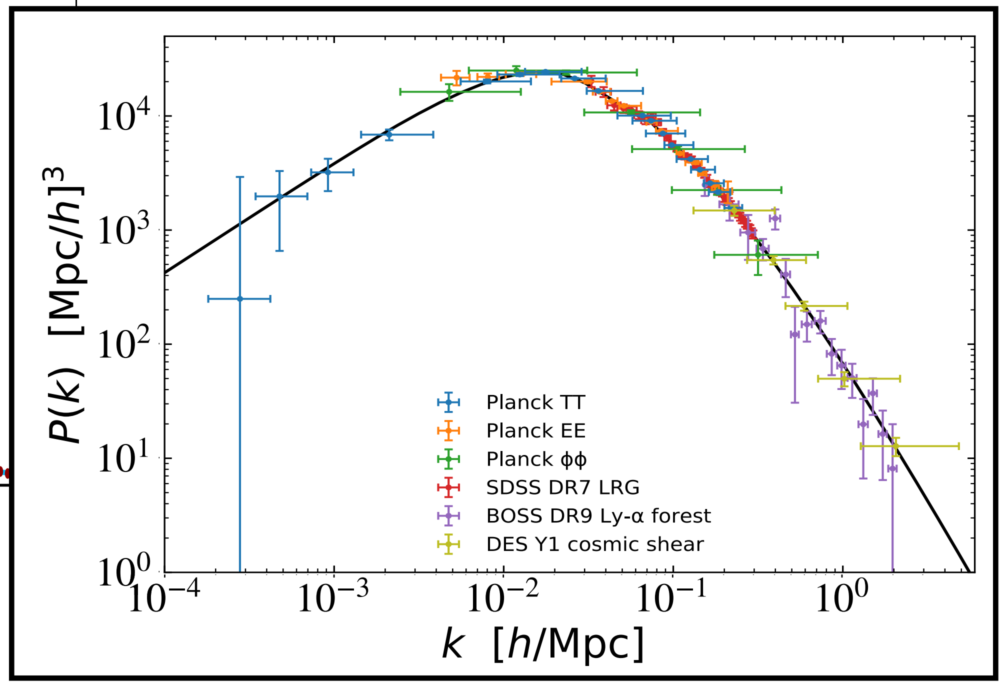
Matches with

Bottom-up picture of hierarchical clustering

(DM halos grow through mergers and accretion)

CMB & matter power spectra





Origin and nature of CDM

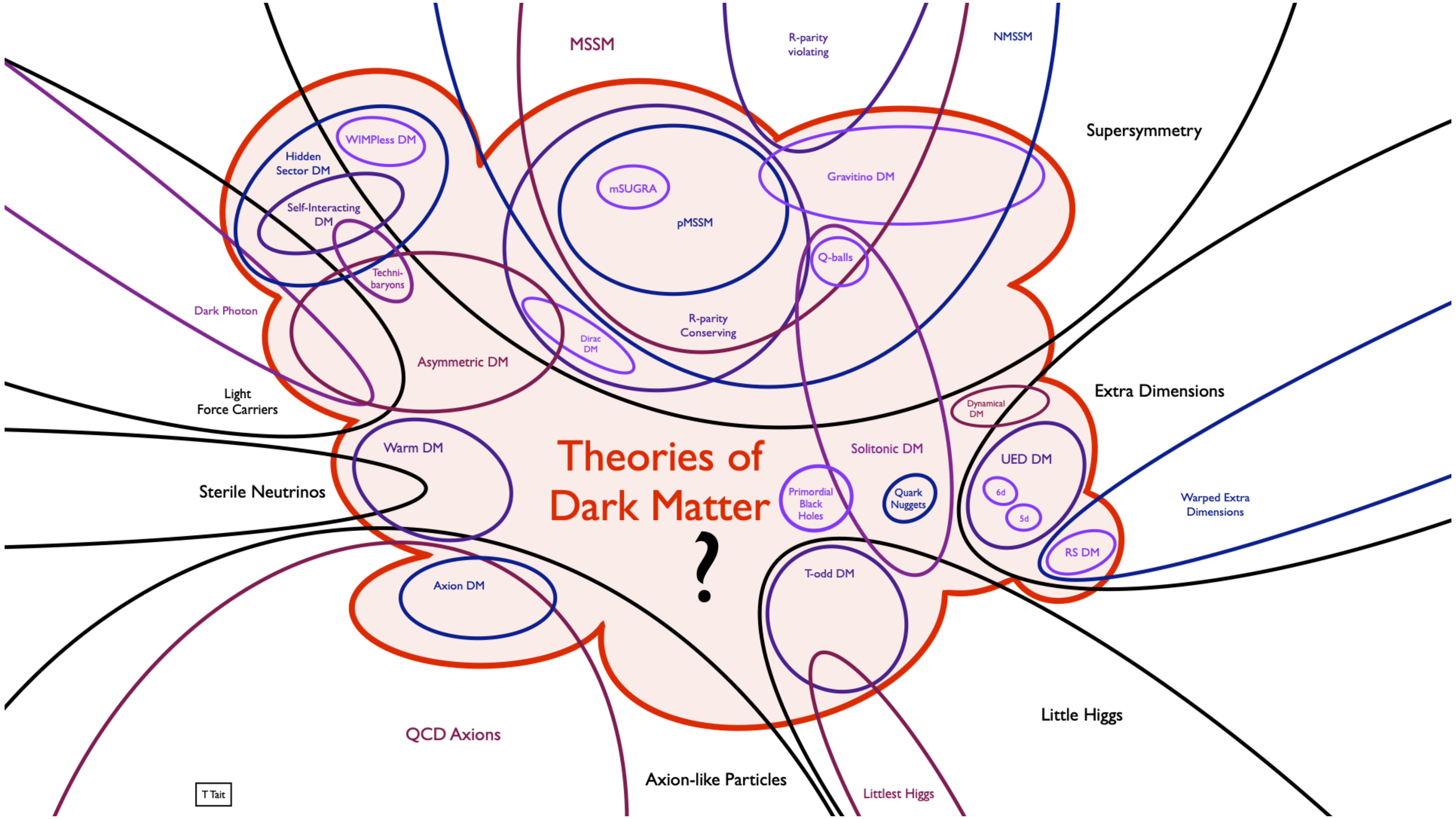
The cold nature of DM alone is not enough to specify its origin & properties

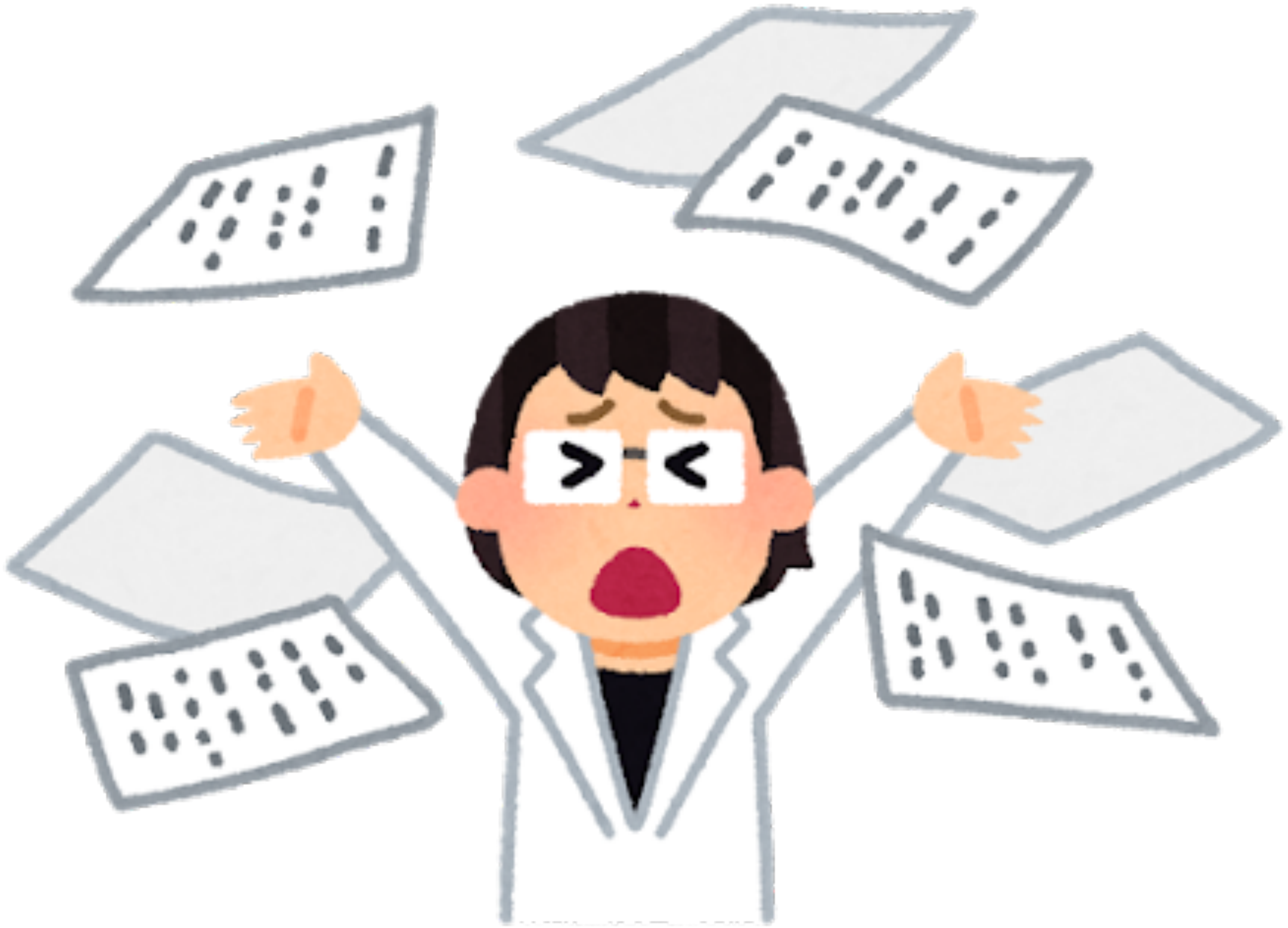
A thermally produced relic particle that interacts only very weakly with SM particles was long considered a strong candidate, however,...

(Most notably, a *supersymmetric* particle, called WIMP)

Particle physics theorist's view (?)

Theories of DM have developed too much, leading to many possibilities



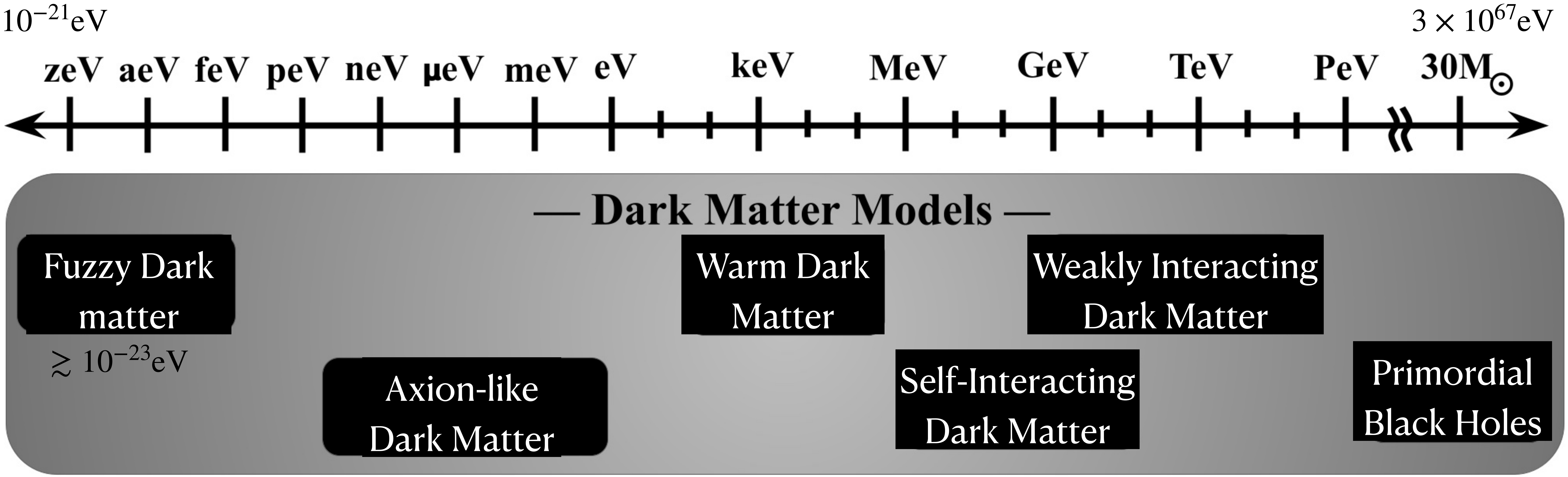


arXiv:2211.09978

DM masses

Viable DM models still permit a huge span of possible masses

(~90 order of magnitude !)



Huge discovery space !

arXiv:2209.08215

Be open-minded, and consider all possibilities

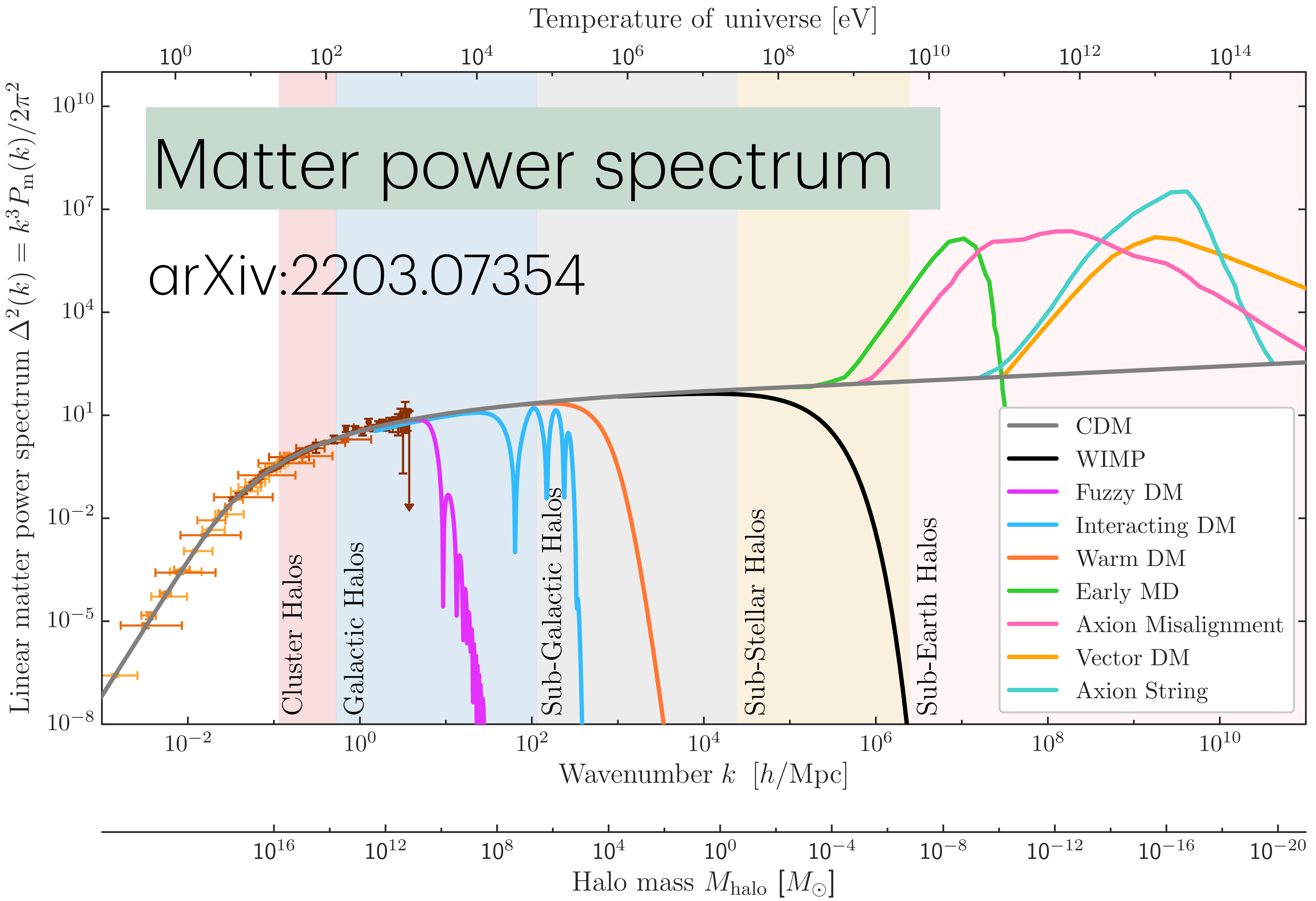
DM search

Indirect

*Through the **gravitational** interaction,*

small-scale cosmic structure formation provides a clue

- Small-scale matter power spectrum
- Density profile of halos
- Abundance of subhalos or substructures



→ Cosmological/astronomical observations are the key

$m_{\rm DM} \sim 100\,\mathrm{GeV}$

$m_{\rm DM} \sim \mathcal{O}(10)\,\mathrm{KeV}$

$\sigma/m_{\rm DM} \sim \mathcal{O}(1)\,\mathrm{cm}^2/\mathrm{g}$

$m_{\rm DM} \sim \mathcal{O}(10^{-22})\,\mathrm{eV}$

DM search

Direct & Indirect

(but very weak)

In the presence of ***electromagnetic (EM)*** *interaction,*

plenty of room to search for DM on the ground and in space using EM signals

Conversion between DM and EM fields (photons) through

Scalar DM
(axion or ALPs)

$$\mathcal{L}_{\rm int} = \frac{g_{a\gamma}}{4} \boxed{\phi} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad (F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\,\boldsymbol{E}\cdot\boldsymbol{B})$$

DM

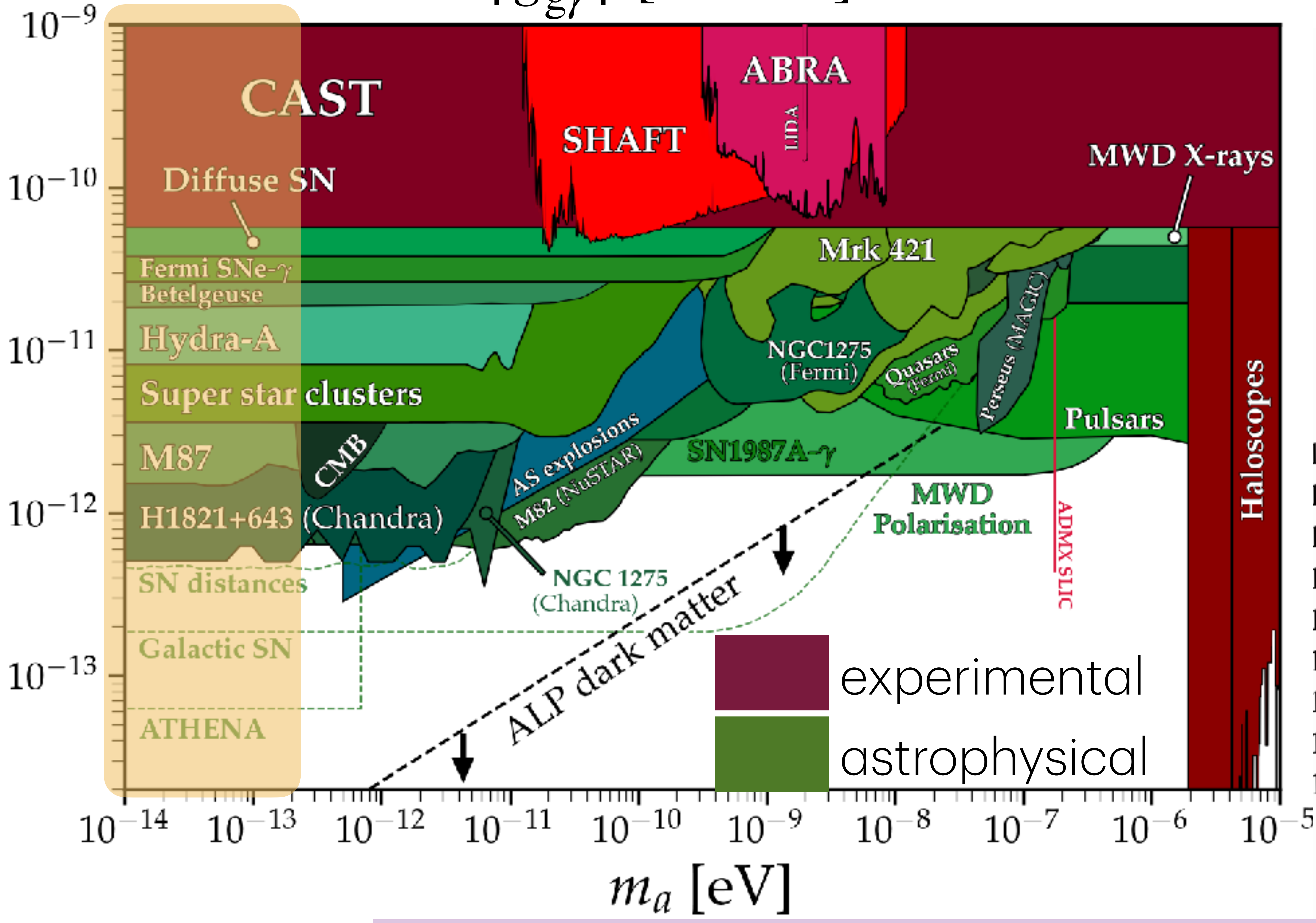
Vector DM
(dark photon)

$$\mathcal{L}_{\rm int} = \epsilon\, F^{\mu\nu} \boxed{F'_{\mu\nu}}$$

Constraints on coupling parameters

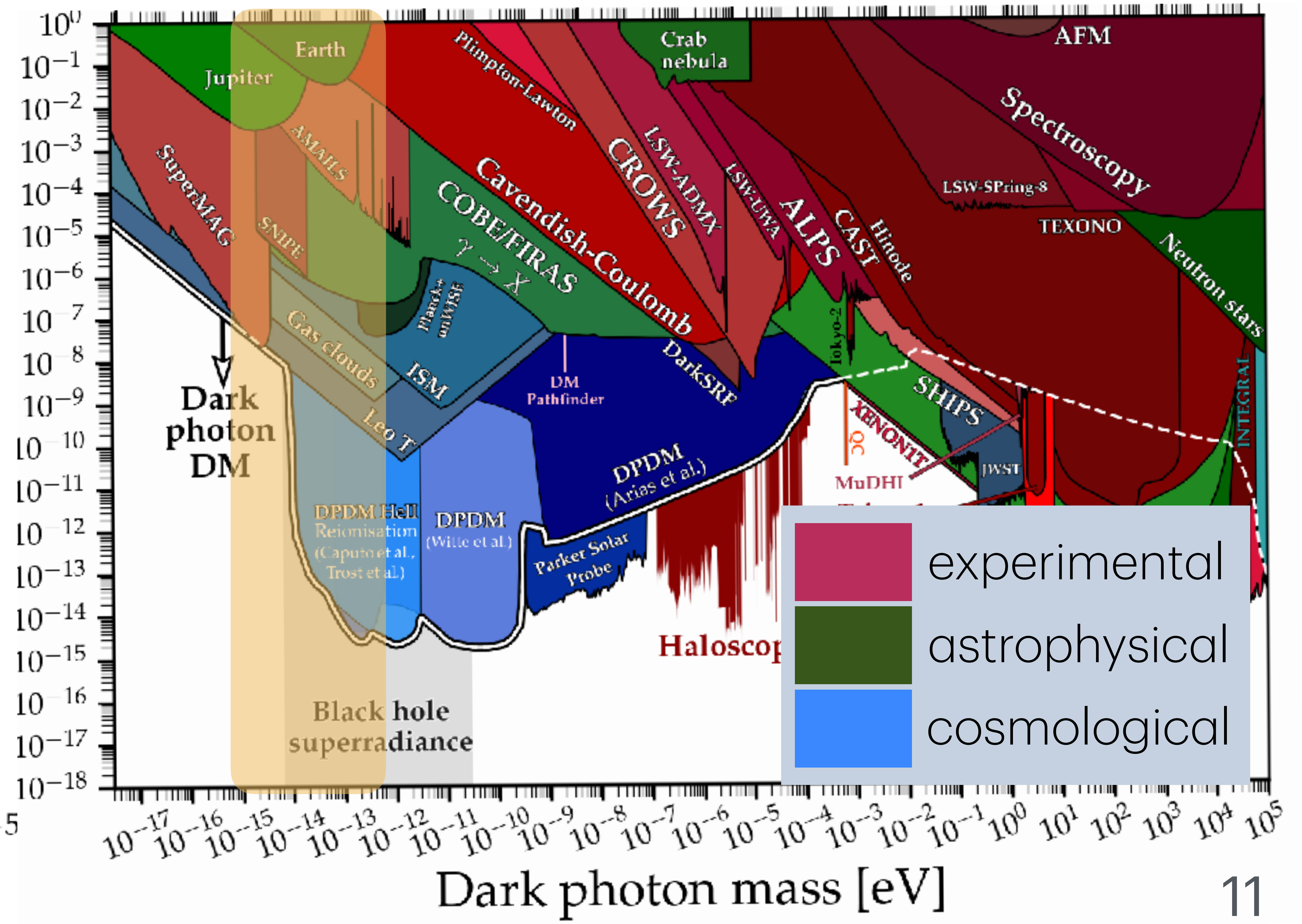
Axion Axon-photon coupling parameter

$|g_{g\gamma}|$ [GeV^{-1}]



Dark photon Kinetic-mixing parameter

ε



In this talk, we explore the search for DM in **terrestrial environments**

EM window

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

- Unique messengers to probe universe

EM window

- Essential communication tools in our daily life (TV, radio, mobile phone, ...)
- Unique messengers to probe universe

At $f \lesssim 10\,\mathrm{MHz}$ ($\lambda \gtrsim 30\,\mathrm{m}$),

EM waves cannot escape into space but are reflected by the ionosphere

EM window

Extremely low-frequency (ELF) band $(f \leq 30\,\mathrm{Hz})$

—-Unique & powerful window for DM search ?

Wavelength: $\lambda \gtrsim$ 10,000km $\sim$ Earth circumference

ne, ...)

At $f \lesssim 10\,\mathrm{MHz}\,(\lambda \gtrsim 30\,\mathrm{m})$,

EM waves cannot escape into space but are reflected by the ionosphere

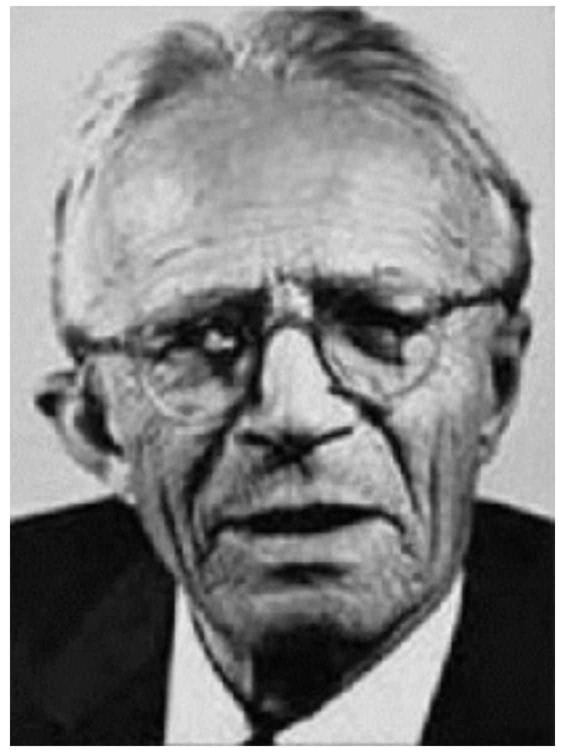
Schumann resonance

A potential noise source

- A set of spectrum peaks in the EM spectrum:

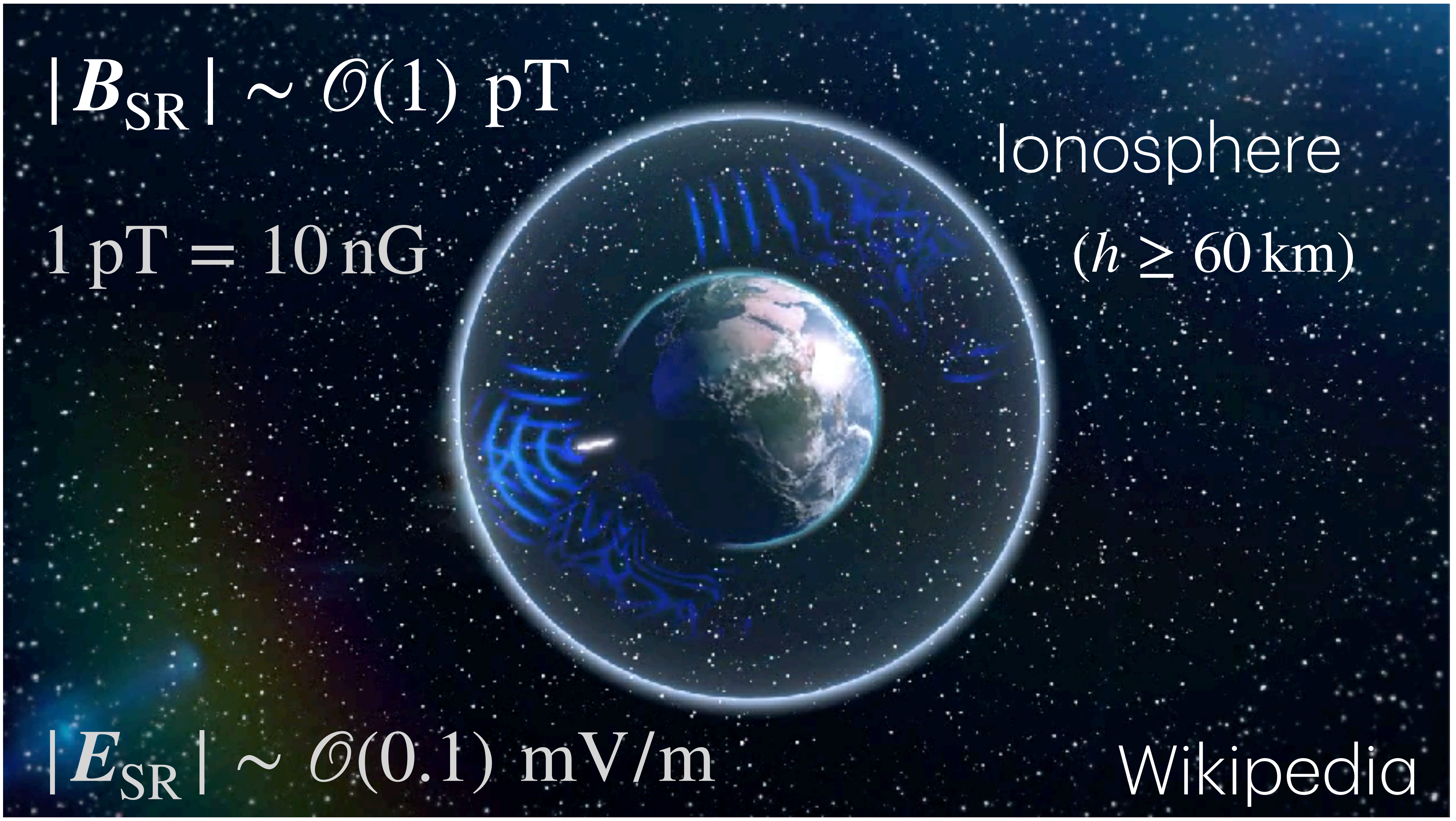
$$f = \frac{c}{2\pi R_\oplus}\sqrt{\ell(\ell+1)} \quad [\mathrm{Hz}] \quad (\ell = 1,2,\cdots)$$

Winfried Otto Schumann (1888-1974)

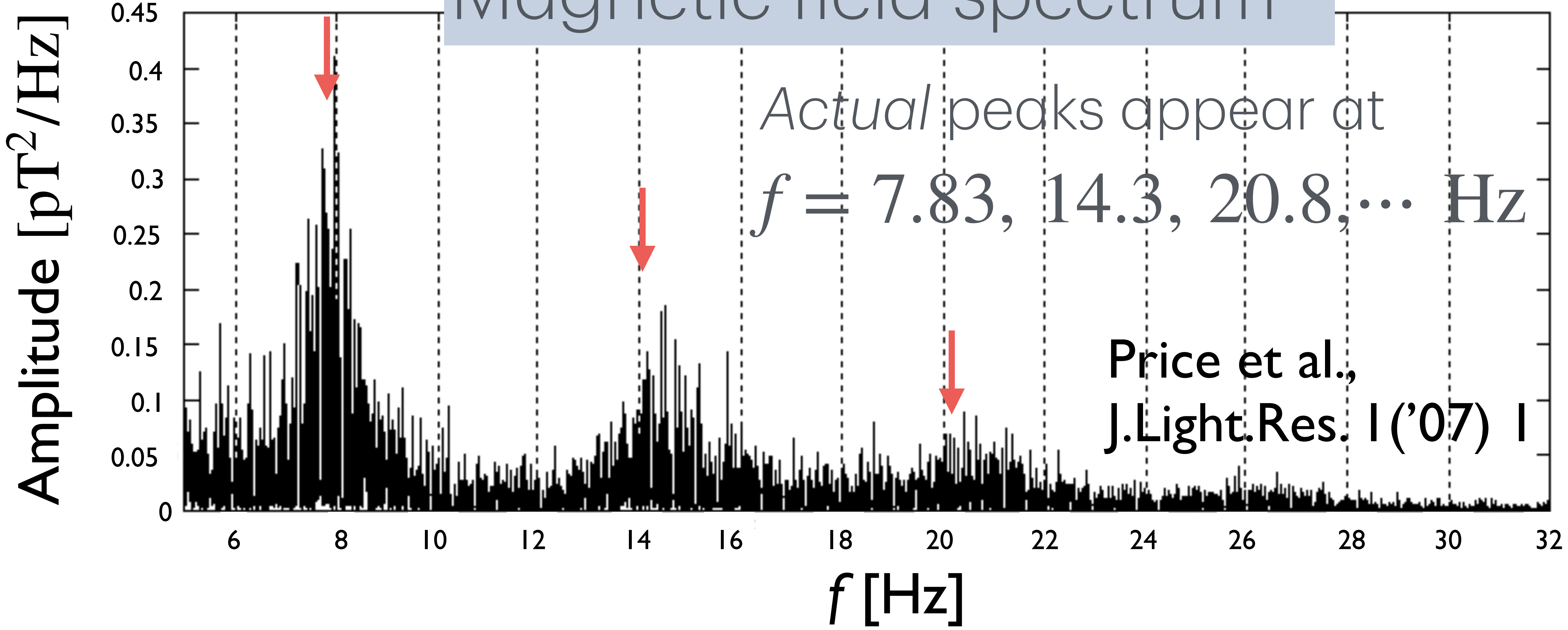


$R_\oplus = 6{,}371\mathrm{km}$

- Generated and excited by lightning discharges in the Earth-ionosphere cavity



Magnetic field spectrum



Actual peaks appear at

$f = 7.83,\ 14.3,\ 20.8, \cdots$ Hz

Price et al., J.Light.Res. 1('07) 1

Signature of axion DM

Axion-Maxwell system

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2 + \frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Maxwell equations coupled with axion

Vacuum

& coherent axion

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

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

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

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

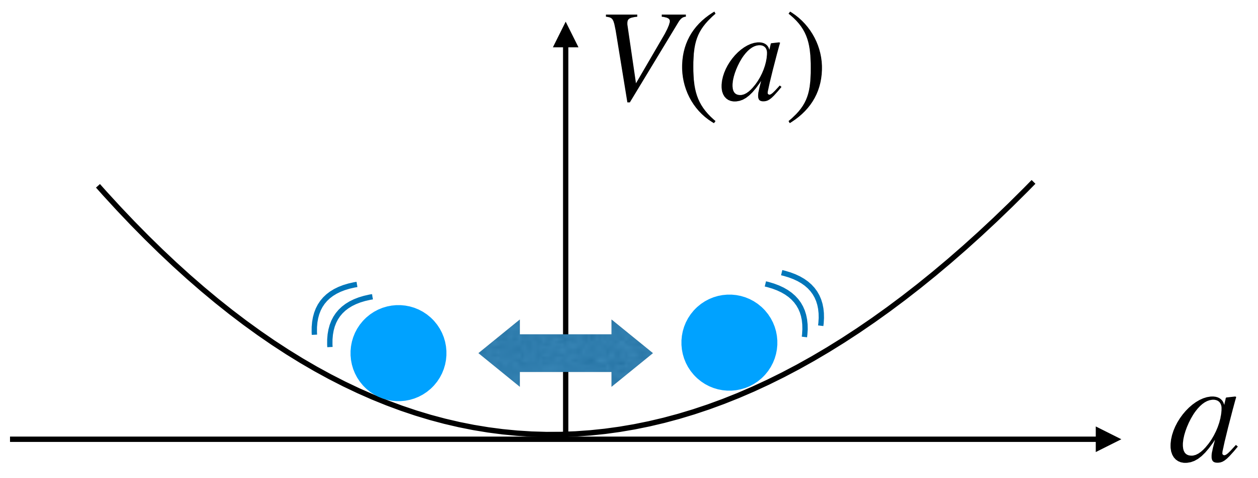
$$\ddot{a} + m_a^2\, a = g_{a\gamma}\, \boldsymbol{E} \cdot \boldsymbol{B}$$

For axion dark matter,

$$|\nabla a| \sim m_a v_{\mathrm{DM}}\, a \ll m_a a \sim |\dot{a}|$$

Signature of axion DM

Relevant equations to consider are:



$$\nabla \times \boldsymbol{B} - \dot{\boldsymbol{E}} = - g_{a\gamma}\, \boldsymbol{B}\, \dot{a} \equiv \boldsymbol{J}_{\mathrm{eff}}$$

$$\ddot{a} + m_{\mathrm{a}}^2\, a = g_{a\gamma}\, \boldsymbol{E} \cdot \boldsymbol{B} \approx 0 \longrightarrow a = a_0\, e^{-i\, m_{\mathrm{a}}\, t}$$

backreaction ignored

- Axion gives rise to non-zero *effective* alternating current (AC)
- In the presence of a static (external) magnetic field (i.e., $\boldsymbol{J}_{\mathrm{eff}} \propto e^{-i\, m_{\mathrm{a}} t}$), the first equation suggests that a monochromatic EM wave is produced

Characteristic frequency

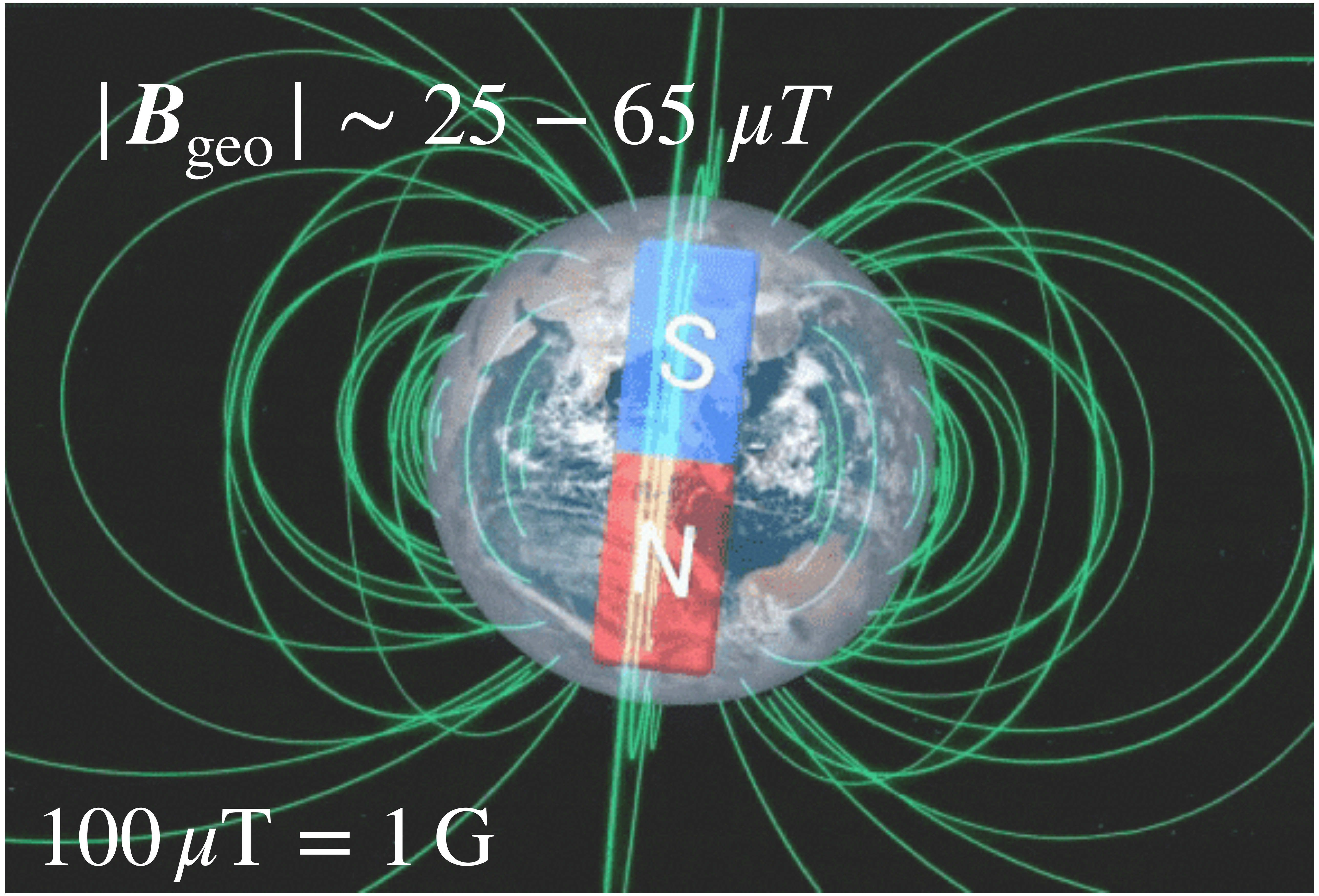
$$f_{\mathrm{a}} = \frac{m_{\mathrm{a}}}{2\pi} \simeq 2.4 \left(\frac{m_{\mathrm{a}}}{10^{-14}\, \mathrm{eV}} \right) \mathrm{Hz}$$

With very *narrow bandwidth*:

$$\Delta f / f_{\mathrm{a}} \sim (\sigma_{\mathrm{v}}/c)^2 \sim \mathcal{O}(10^{-6})$$

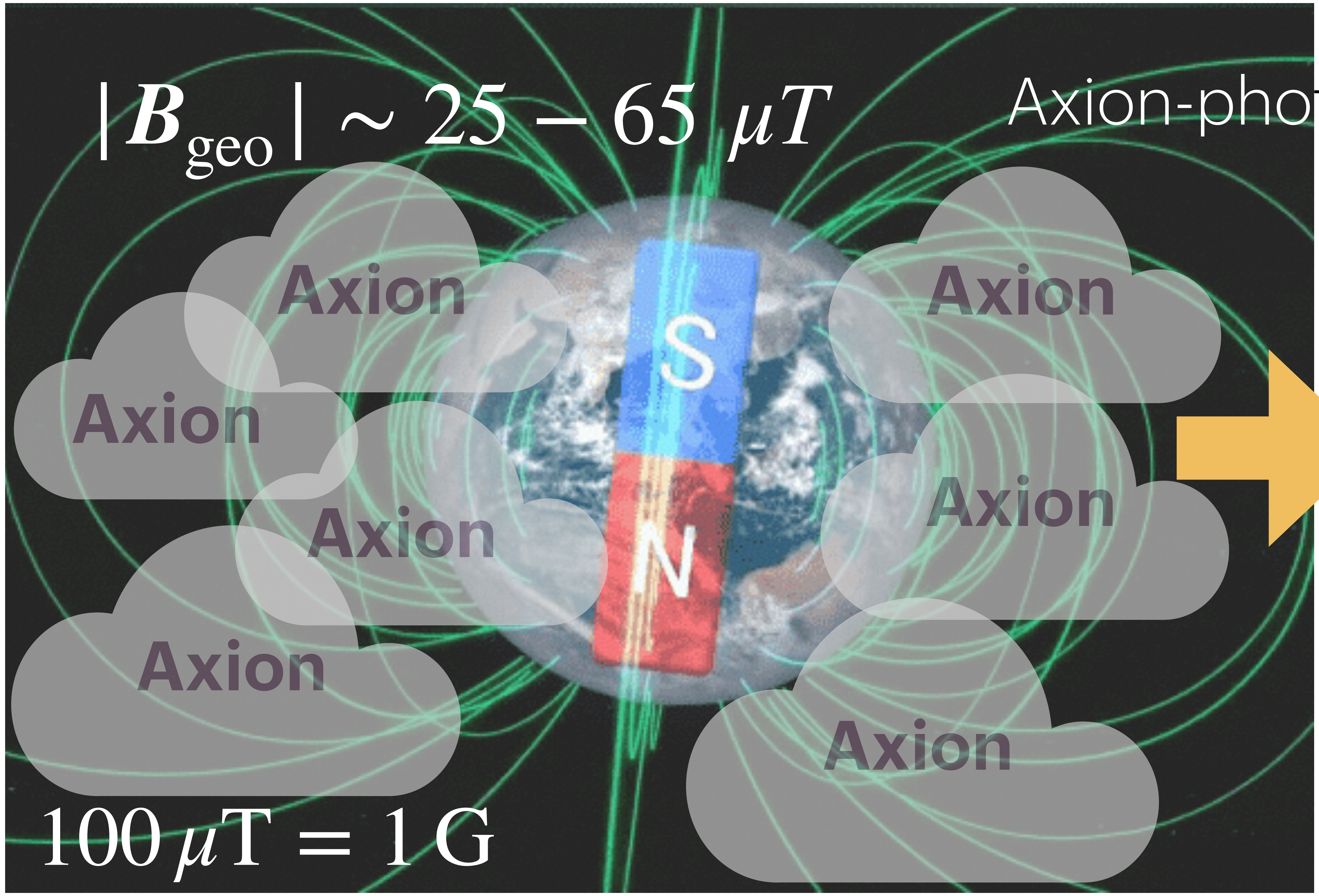
Signature of axion DM

Geomagnetic field as a global static B-field on Earth

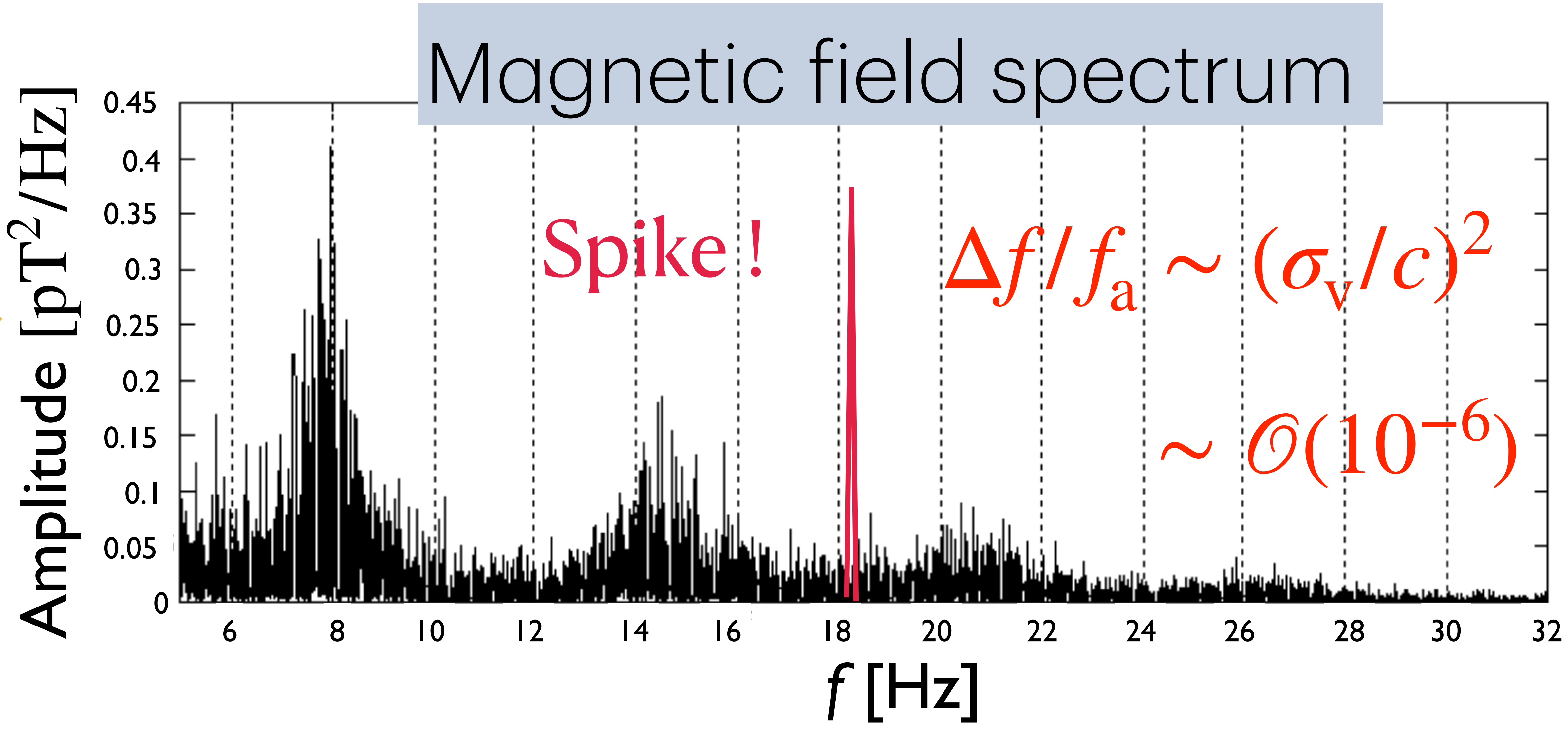


Signature of axion DM

Geomagnetic field as a global static B-field on Earth



Axion-photon coupling



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 B-field amplitude is

$$|\boldsymbol{B}_{\rm induced}| \sim \boxed{0.3\ \mathrm{pT}} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right) \left(\frac{\rho_{\rm DM}}{0.3\,\mathrm{GeV\,cm^{-3}}}\right)^{1/2} \left(\frac{|\boldsymbol{B}_{\rm geo}|}{50\,\mu\mathrm{T}}\right)$$

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

Quite small, but still measurable !

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

e.g., Metronix, MFS-06e (0.85 M JPY)

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

Commercial magnetometers

High-sensitivity detectors used at gravitational wave detector sites

Bartington Instruments

Mag-13MSL

https://www.bartington.com/products/mag-13/

metronix geophysics

MFS-06e

https://www.metronix.de/metronixweb/index.php?id=88&L=1

Sensitivity: $\sim 6\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at 1 Hz

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

Price: 10K USD

Price: 6.3K—7.4K USD (As of 2022)

Signature of dark photon DM (DPDM)

Dark photon-Maxwell system

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

(Massive) Dark EM Kinetic mixing

Maxwell equations coupled with DP

Vacuum & coherent dark photon

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

$$\nabla \times \boldsymbol{B} - \dot{\boldsymbol{E}} = \boxed{\varepsilon \dot{\boldsymbol{E}}' = -\varepsilon \ddot{\boldsymbol{A}}'}$$

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

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

$$(\partial_\nu \partial^\nu - m_{A'}^2) A'^\mu = \varepsilon A^\mu \qquad \partial_\mu A'^\mu = 0$$

Signature of dark photon DM

Relevant equations to consider are:

$$\nabla \times \boldsymbol{B} - \dot{\boldsymbol{E}} = -\varepsilon \ddot{\boldsymbol{A}}' \equiv \boldsymbol{J}_{\rm eff}$$

Spatially constant

$$\ddot{\boldsymbol{A}}' + m_{A'}^2 \boldsymbol{A}' = -\,\varepsilon \boldsymbol{A} \approx 0 \longrightarrow \boldsymbol{A}' = \hat{\boldsymbol{A}}' e^{-i m_{A'} t}$$

backreaction ignored

- ***Phenomenology similar to axion DM applies !***

Unlike axion, no need for geomagnetic field

- Dark photon induces a monochromatic EM wave via an alternating *dark current*

Back-of-envelope estimation

$$|\boldsymbol{B}_{\rm induced}| \sim 0.03\ \mathrm{pT} \left(\frac{\varepsilon}{10^{-8}}\right)\left(\frac{m_{A'}}{10^{-14}\,\mathrm{eV}}\right)\left(\frac{\rho_{\rm DM}}{\mathrm{GeV\,cm^{-3}}}\right)^{1/2}$$

at $f_{A'} \simeq 2.4\,(m_{A'}/10^{-14}\,\mathrm{eV})$ Hz

$$\rho_{\rm DM} = m_{\rm a}^2 \langle \hat{\boldsymbol{A}}^2 \rangle_\tau / 2$$

A more precise estimation

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

$$\nabla\left(n^2 \boldsymbol{E}\right) = 0$$

$$\nabla \times \boldsymbol{B} - n^2 \dot{\boldsymbol{E}} = \boldsymbol{J}_{\text{eff}} \propto e^{-i\, m_{\text{DM}}\, t}$$

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

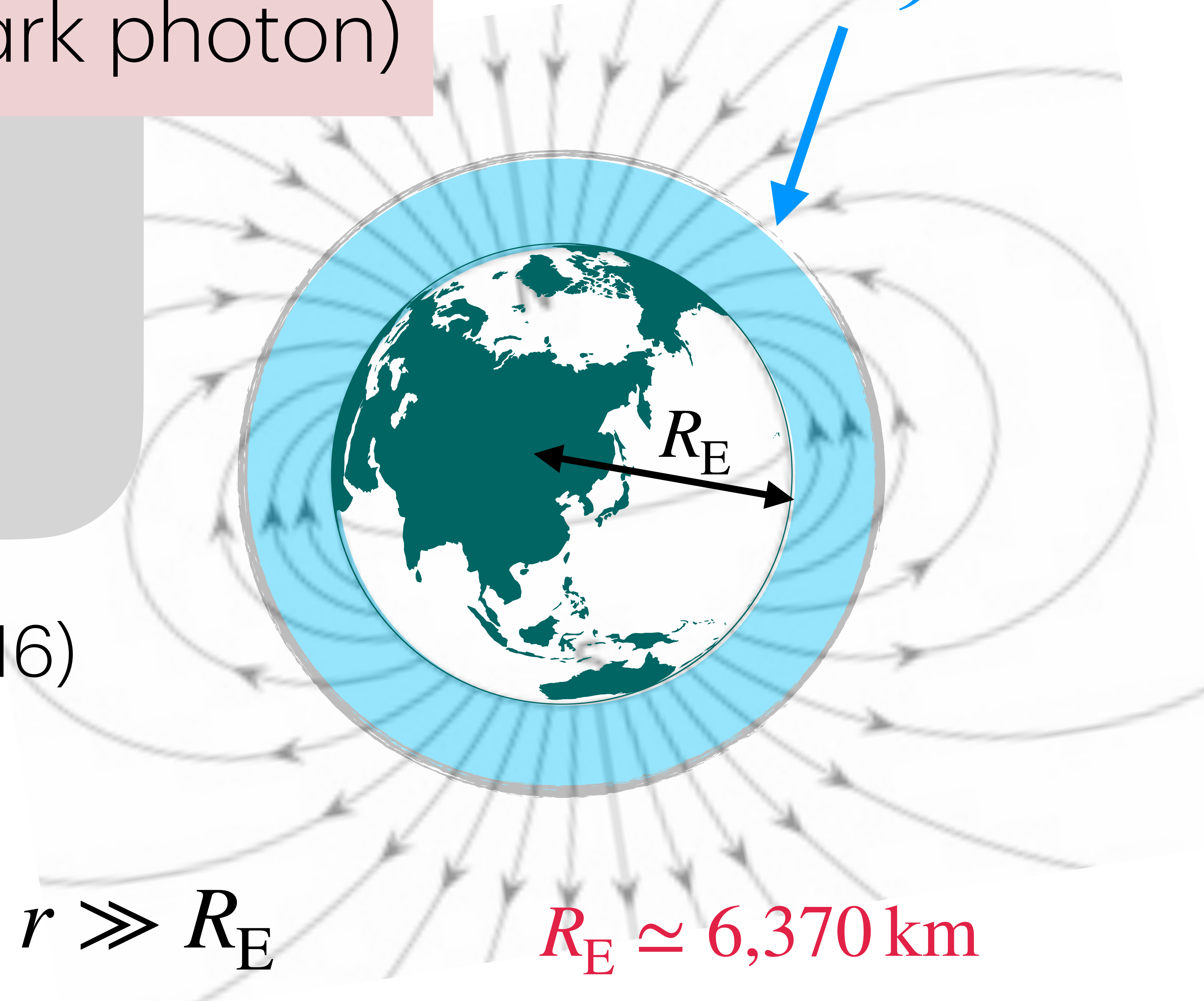
$$\nabla \times \boldsymbol{E} + \dot{\boldsymbol{B}} = 0$$

$$\boldsymbol{J}_{\text{eff}} = \begin{cases} -g_{a\gamma}\, \dot{a}\, \boldsymbol{B}_{\text{geo}} & \text{(axion)} \\ -\varepsilon \ddot{\boldsymbol{A}}' & \text{(dark photon)} \end{cases}$$

Refractive index

Conductivity

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



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

Results: axion DM

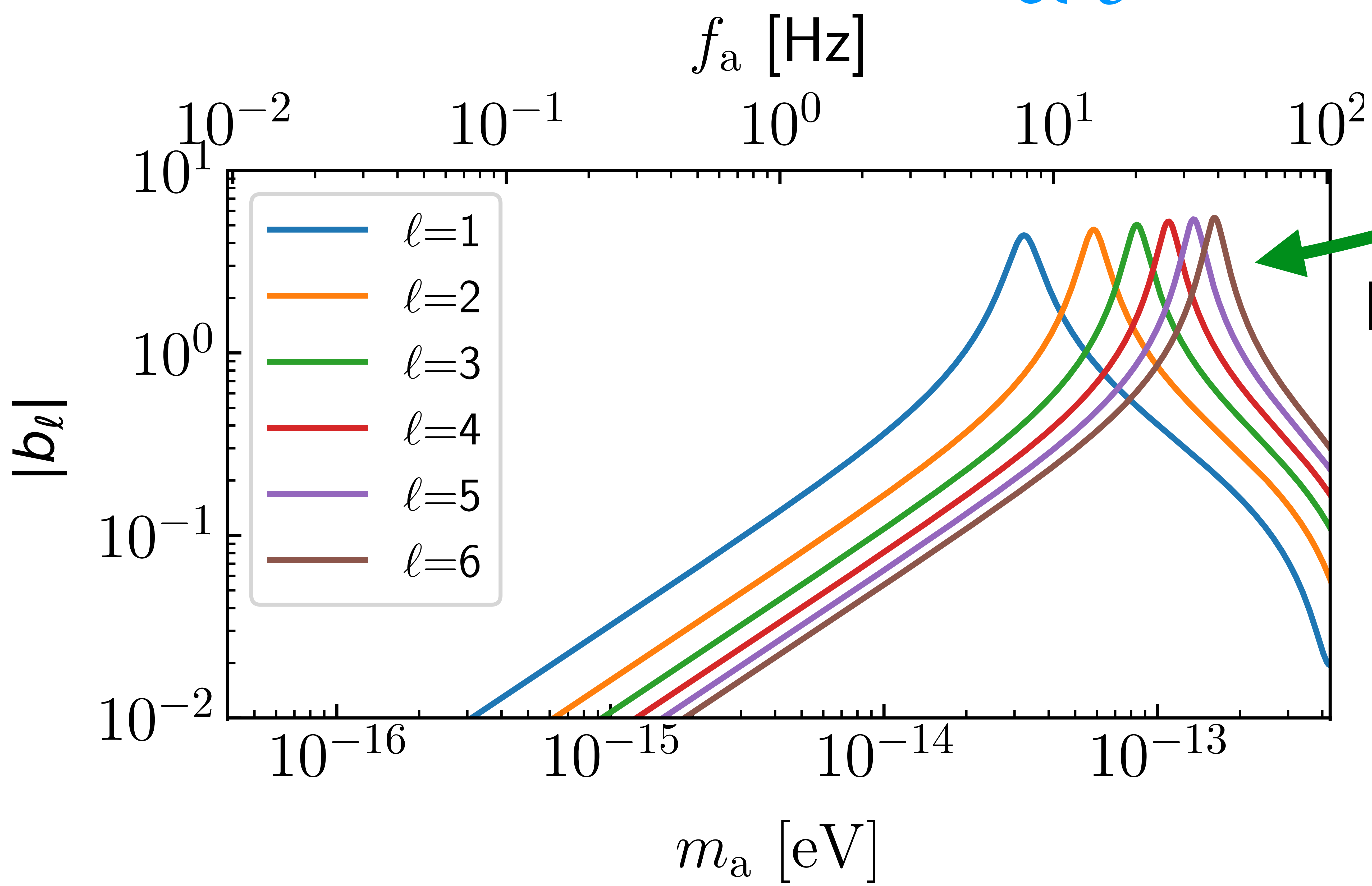
Geomagnetic field

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

Vector spherical harmonics

$\propto e^{-i m_a t}$

Radial mode function



Peak structures at $f_a \simeq 7.7\sqrt{\ell(\ell+1)}$ [Hz]

Schumann resonance Schumann ('52)

Resonant modes in Earth-ionosphere cavity

※ amplitude diverges if we ignore atmospheric conductivity (dotted curves)

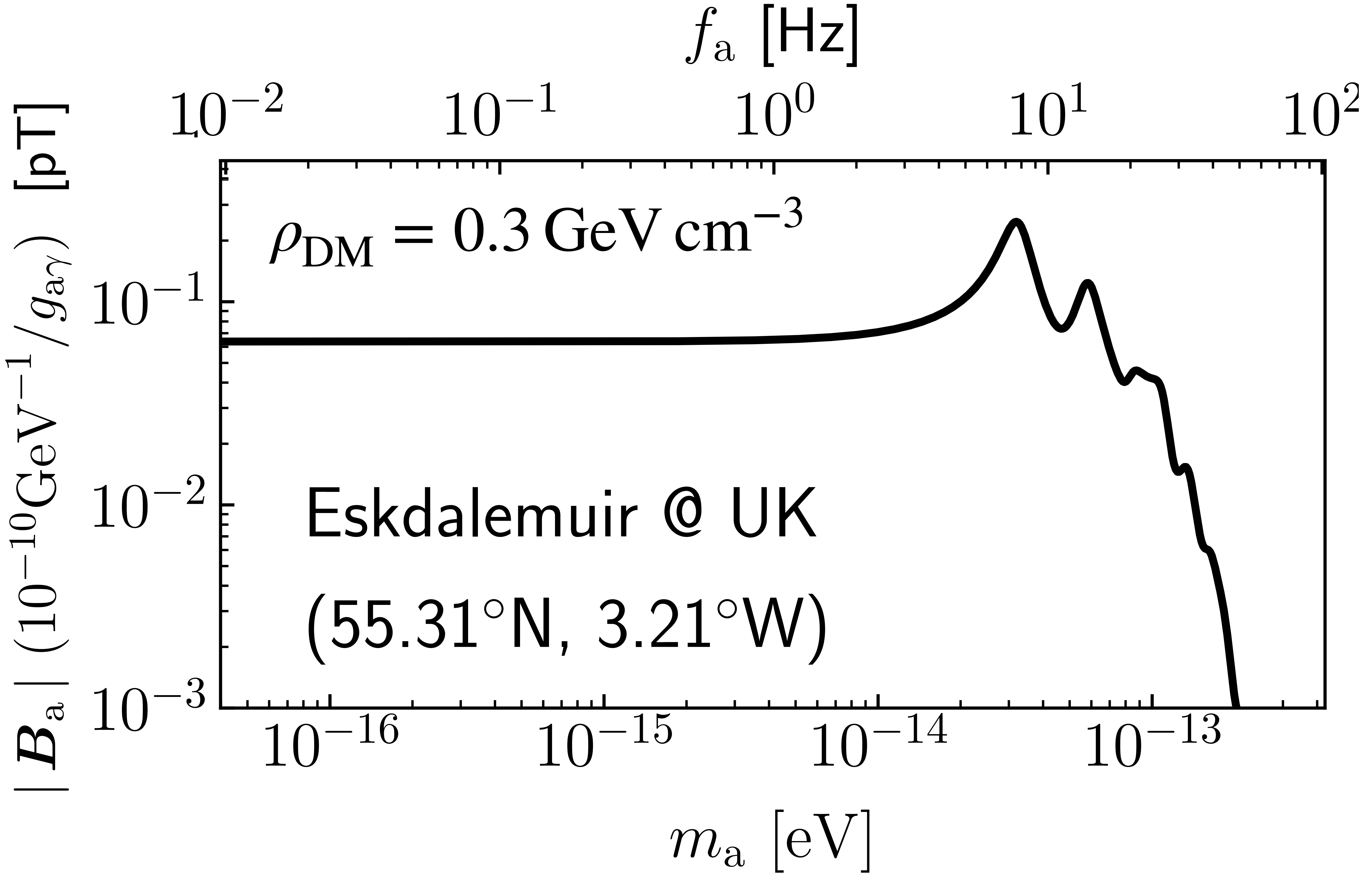
Results: axion DM

Vector spherical harmonics

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

$\propto e^{-i m_{\mathrm{a}} t}$

Radial mode function



Dominant dipole contribution for geomagnetic field

suppressed for higher multipoles)

∴ Indued B-field is suppressed at

$$f_{\mathrm{a}} \gtrsim 7.8\,\mathrm{Hz}$$

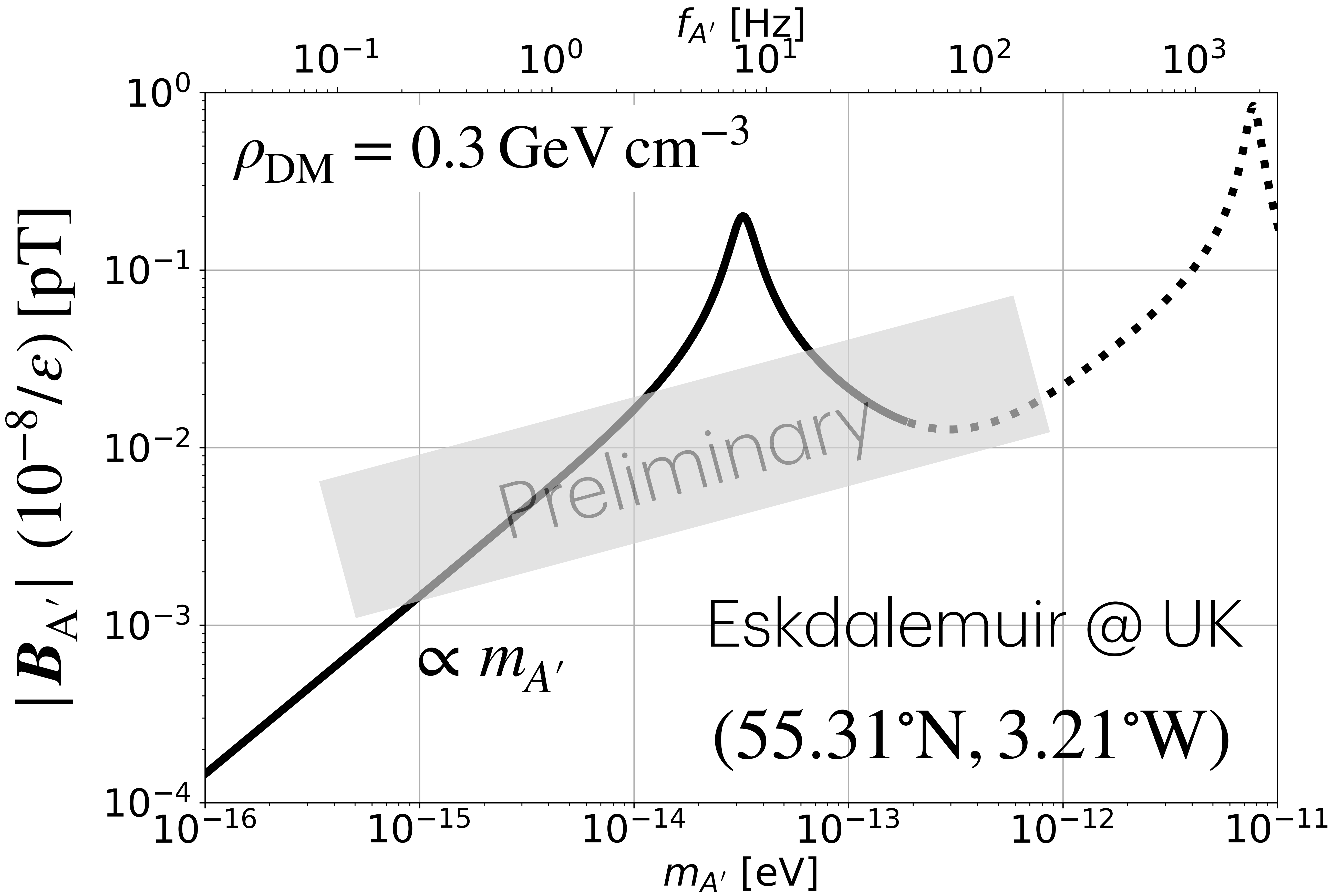
$$(m_{\mathrm{a}} \gtrsim 3\times 10^{-14}\,\mathrm{eV})$$

Results: dark photon DM

Vector spherical harmonics

$$\boldsymbol{B}_{\mathrm{induced}}(r,\boldsymbol{\theta}) = -\,i\,\varepsilon\,m_{A'}\,b_1(m_{A'}r)\,e^{-i\,m_{A'}t}\sum_{m=-1}\hat{A}'_m\,\boldsymbol{\Phi}_{1m}(\boldsymbol{\theta})$$

Radial mode function



Only the dipole contribution play a role due to the vectorial nature of DM

no higher multipoles)

∴ Even beyond the 1st resonance peak, the induced B field is not suppressed

Dark matter search from public B-field data

Public monitoring data for geoscience

SuperMAG https://supermag.jhuapl.edu/

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

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

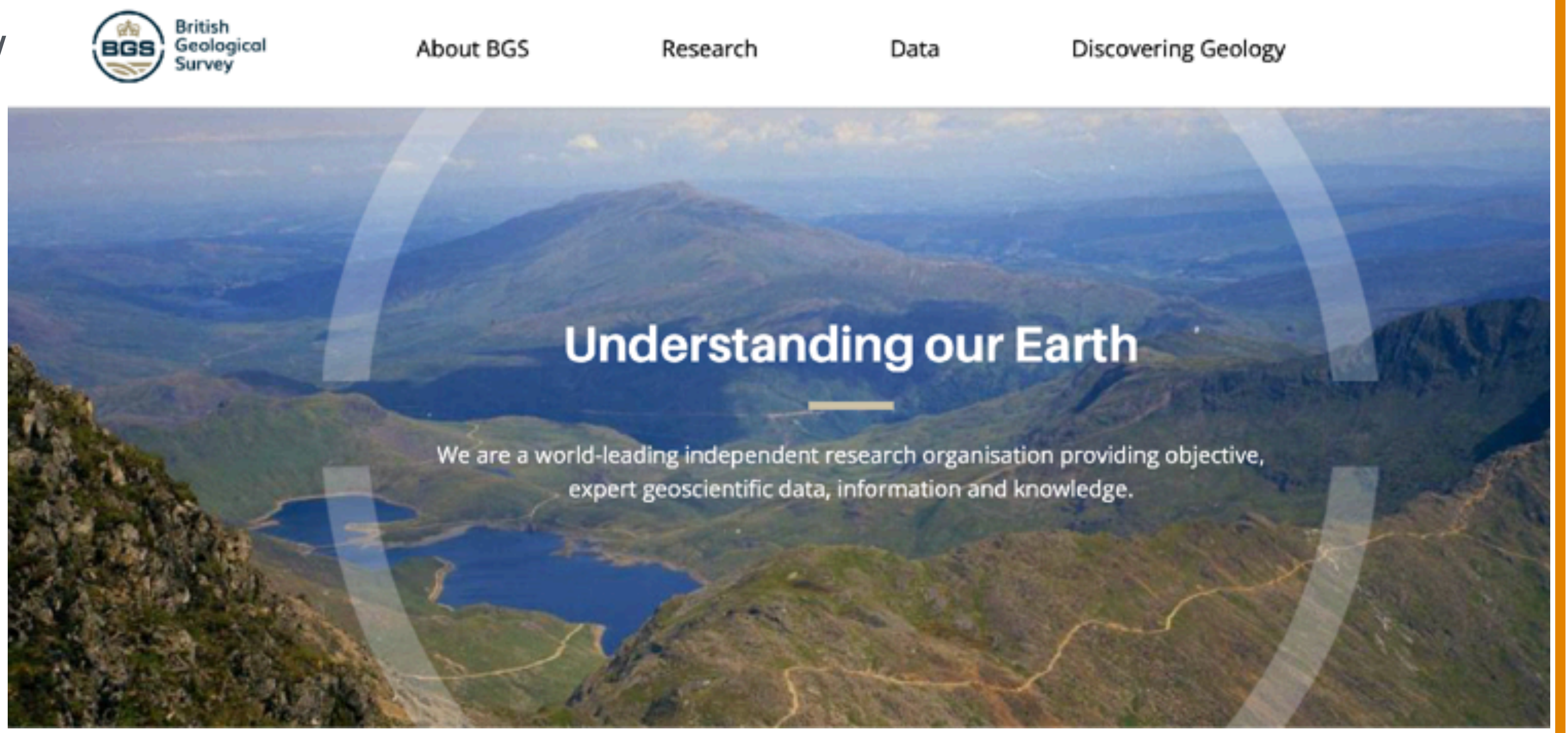
→Arza et al. ('22), Friel et al. ('24)

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

10 years, high sampling rate → ELF bands (0.01–10 Hz)

In particular,

We use the data taken at *Eskdalemuir observatory*

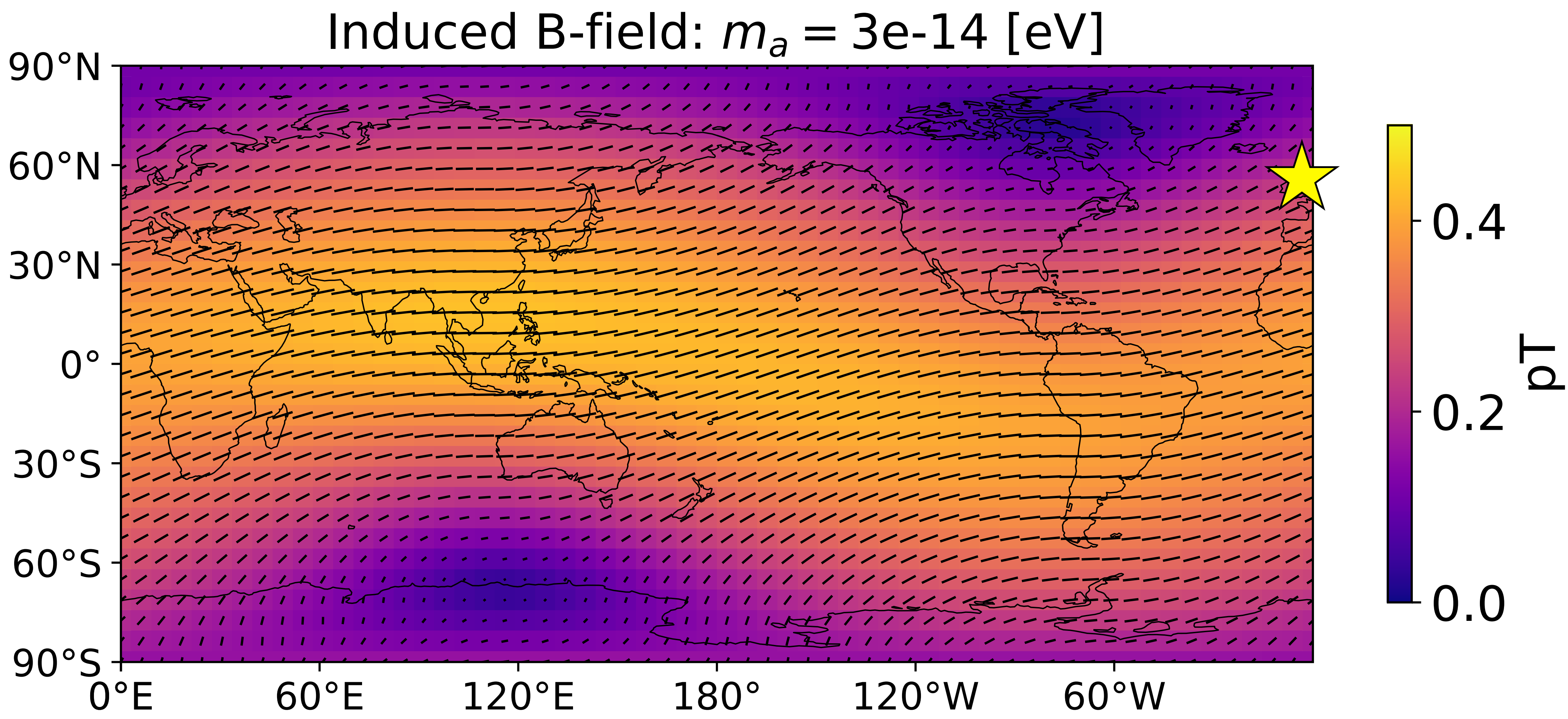


Data analysis ~sketch~

AT, Nishizwa & Himemoto ('25)
Nishizwa, AT & Himemoto ('25)
Nomura, Nishizawa, AT & Himemoto ('25, in prep)

Using **11 years** public data at ***Eskdalemuir observatory***

World map of the predicted amplitude of axion-induced B-field at 7.2 Hz



Data analysis ~sketch~

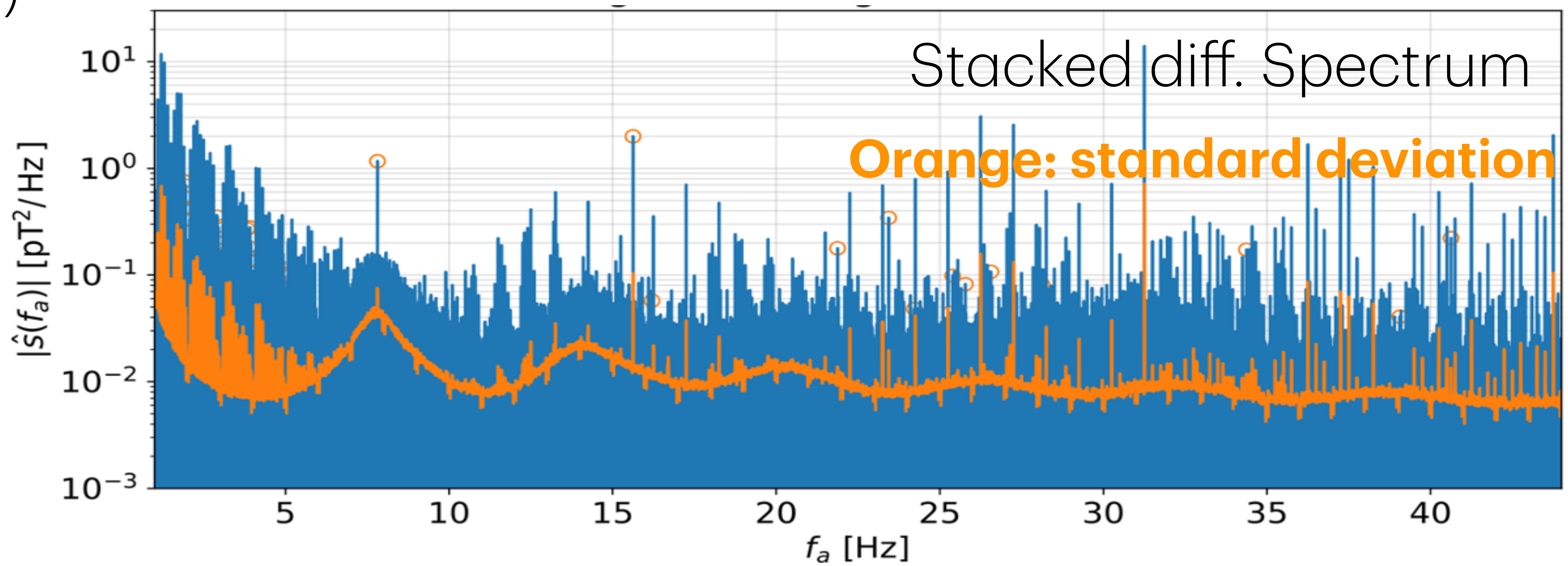
AT, Nishizwa & Himemoto ('25)
Nishizwa, AT & Himemoto ('25)

Using **11 years** public data at ***Eskdalemuir observatory***

1. Stacking their segments with consecutive 8 hours in the Fourier domain $(\Delta f/f \sim 3 \times 10^{-5})$
2. Calculating the '*differential*' spectrum by applying a low-pass filter & subtracting the smoothed component (Butterworth)
3. Identifying possible candidates of axion signals with $\mathrm{S/N} \geq 2$ for both each and all years (noise is RMS of diff. spectrum)

342 candidates at 0.4—43 Hz

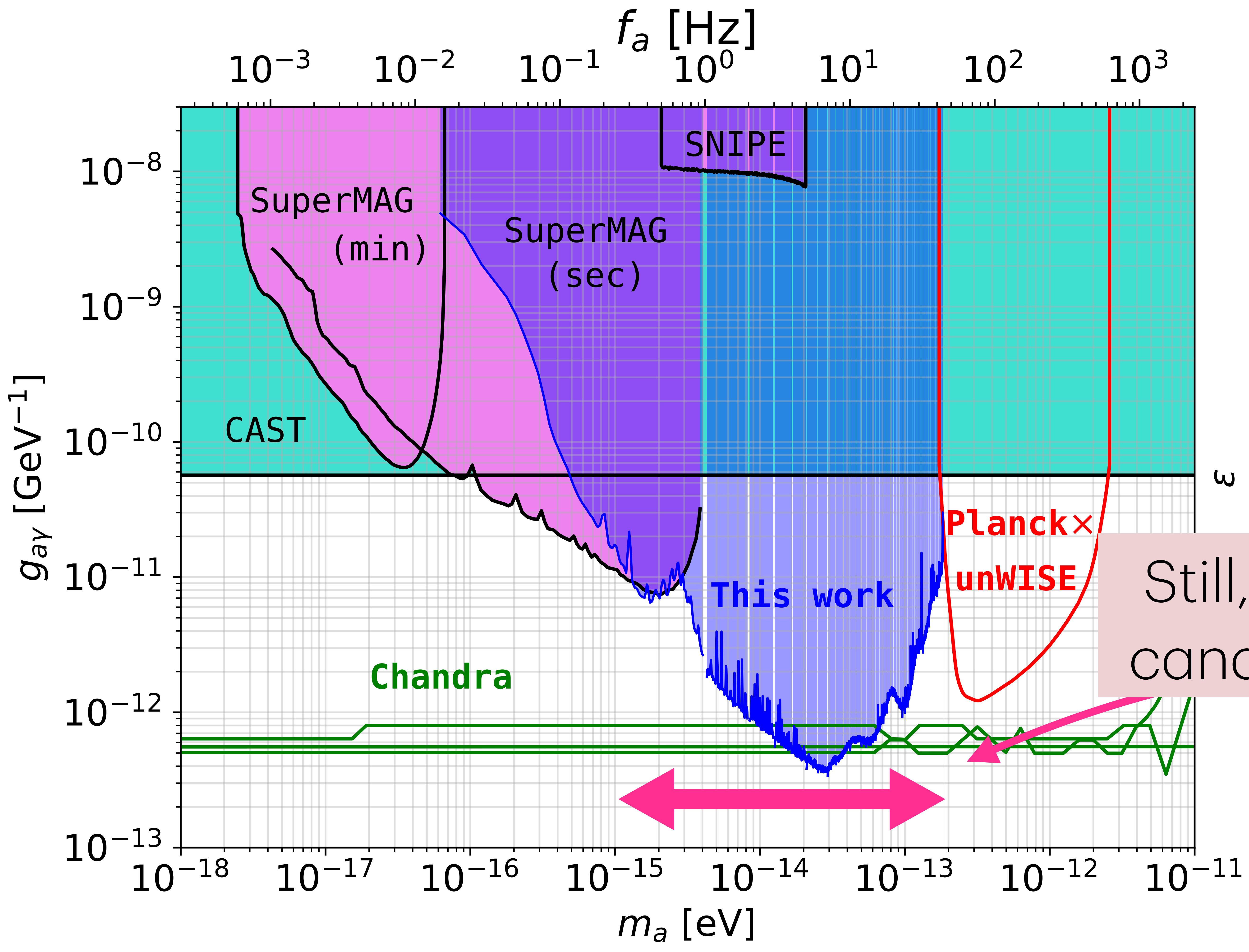
(31 candidates for $\mathrm{S/N} \geq 5$)



Candidates with high S/N

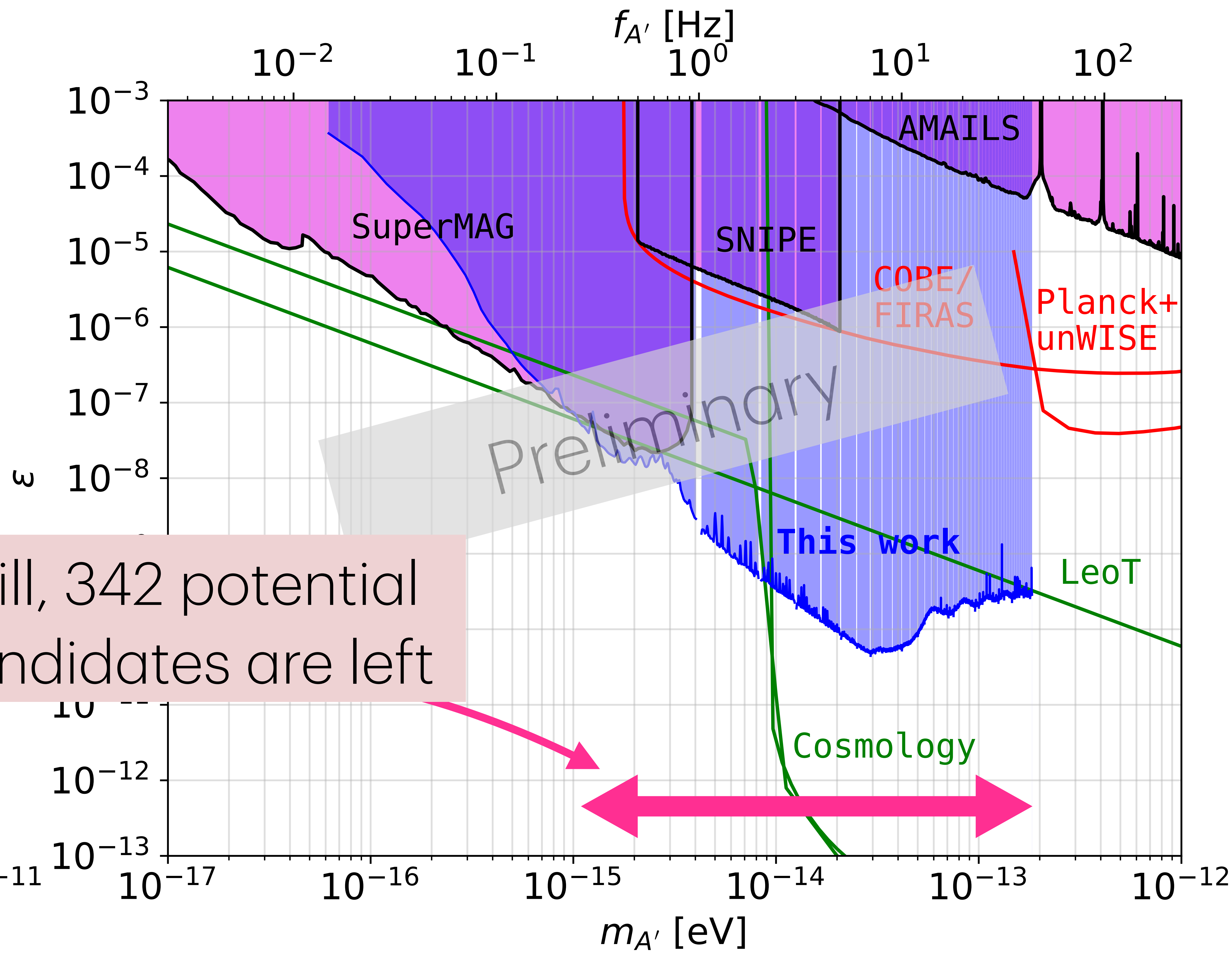
Constraints on coupling parameters

Axion Axon-photon coupling parameter



AT et al. ('25) & Nishizawa et al. ('25)

Dark photon Kinetic-mixing parameter



Still, 342 potential candidates are left

Nomura et al. (in prep).

Summary & future prospects

A novel dark matter search in the terrestrial EM fields

at extremely low-frequency bands (0.3–30Hz)

DM weakly coupled with EM produces a persistent EM wave having a sharp spectrum

A new theoretical calculation & search for DM signature using geoscience data

(axion & dark photon)

Future prospects

- Follow-up measurements by environment monitoring data at GW sites
- Induced EM waves at ELF band are also expected from
  - **Dark matter having other types of EM coupling**
  - **Gravitational waves** $\mathscr{L}_{\rm EM} = -(1/4)g^{\mu\alpha}g^{\beta\nu}F_{\mu\nu}F^{\alpha\beta}_{\rho\sigma}$ via graviton-photon conversion

Your suggestions are welcome !

- Jupiter may offer an opportunity to expand discovery space