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Geomagnetic signal of millicharged dark matter

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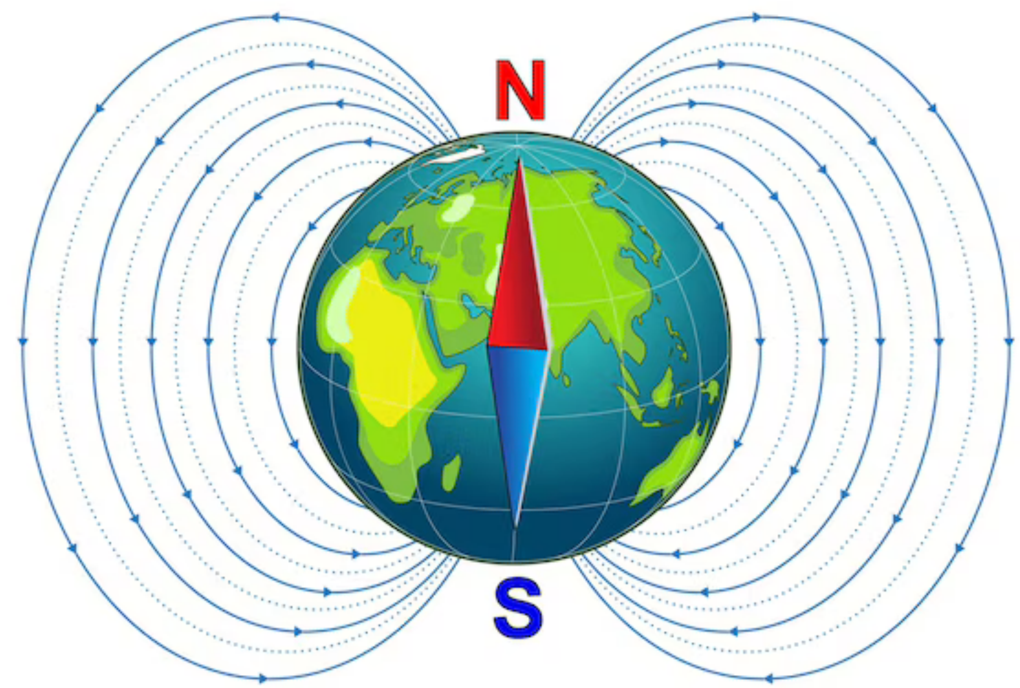
Outline

- Introduction of the ultralight geomagnetic field idea
- Review for the search of axions and dark photons
- Introduction to millicharged dark matter and its interaction with photons
- Model for the magnetic structure of the inner Earth, which is necessary for the signal calculation
- Signal calculation and constraints

Introduction

Monitoring the Earth geomagnetic field to hunt ultralight dark matter

$$\vec{B}_{\text{Earth}} = \vec{B}_{\text{geo}} + \vec{B}_{\text{DM}}$$

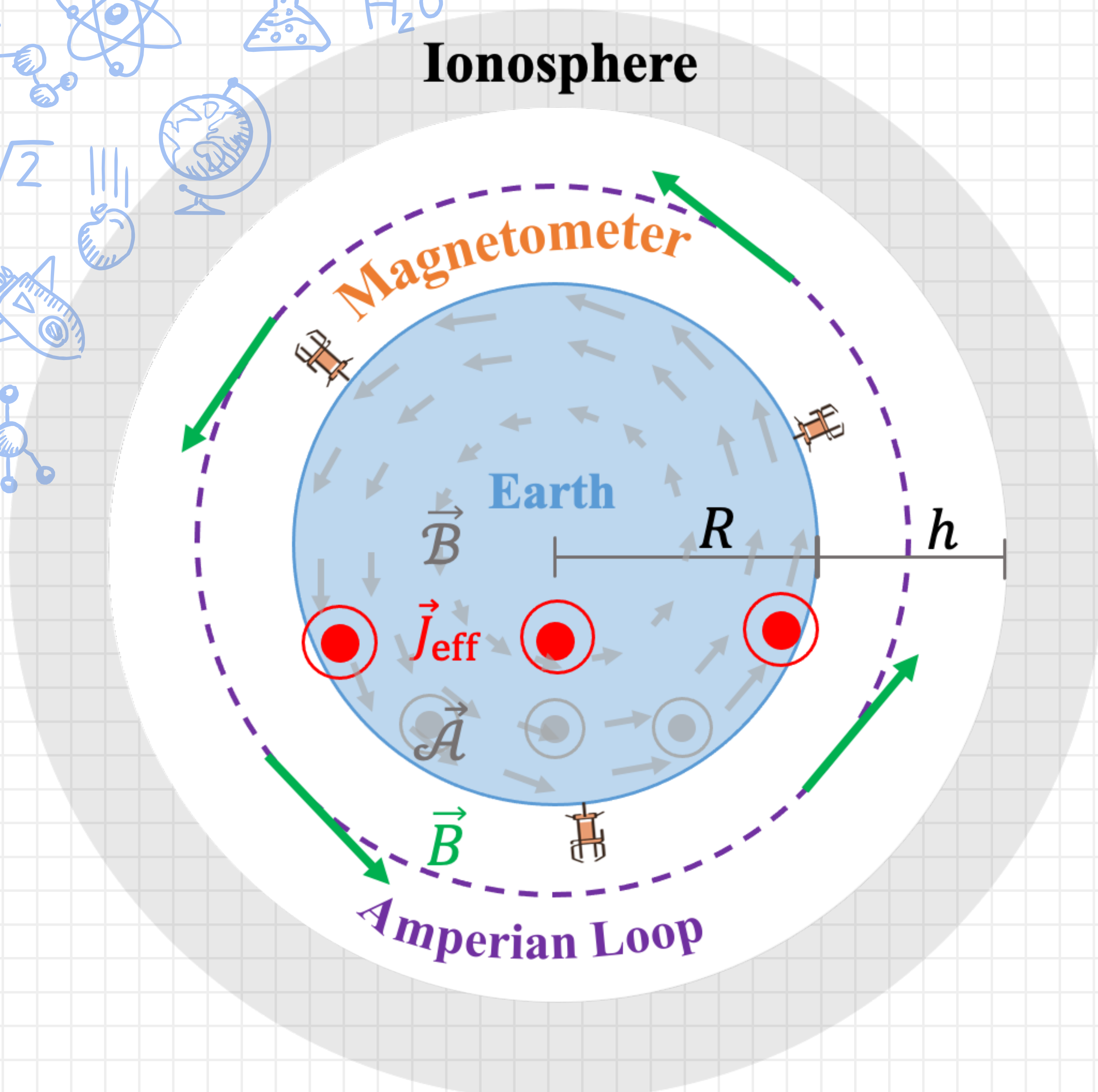


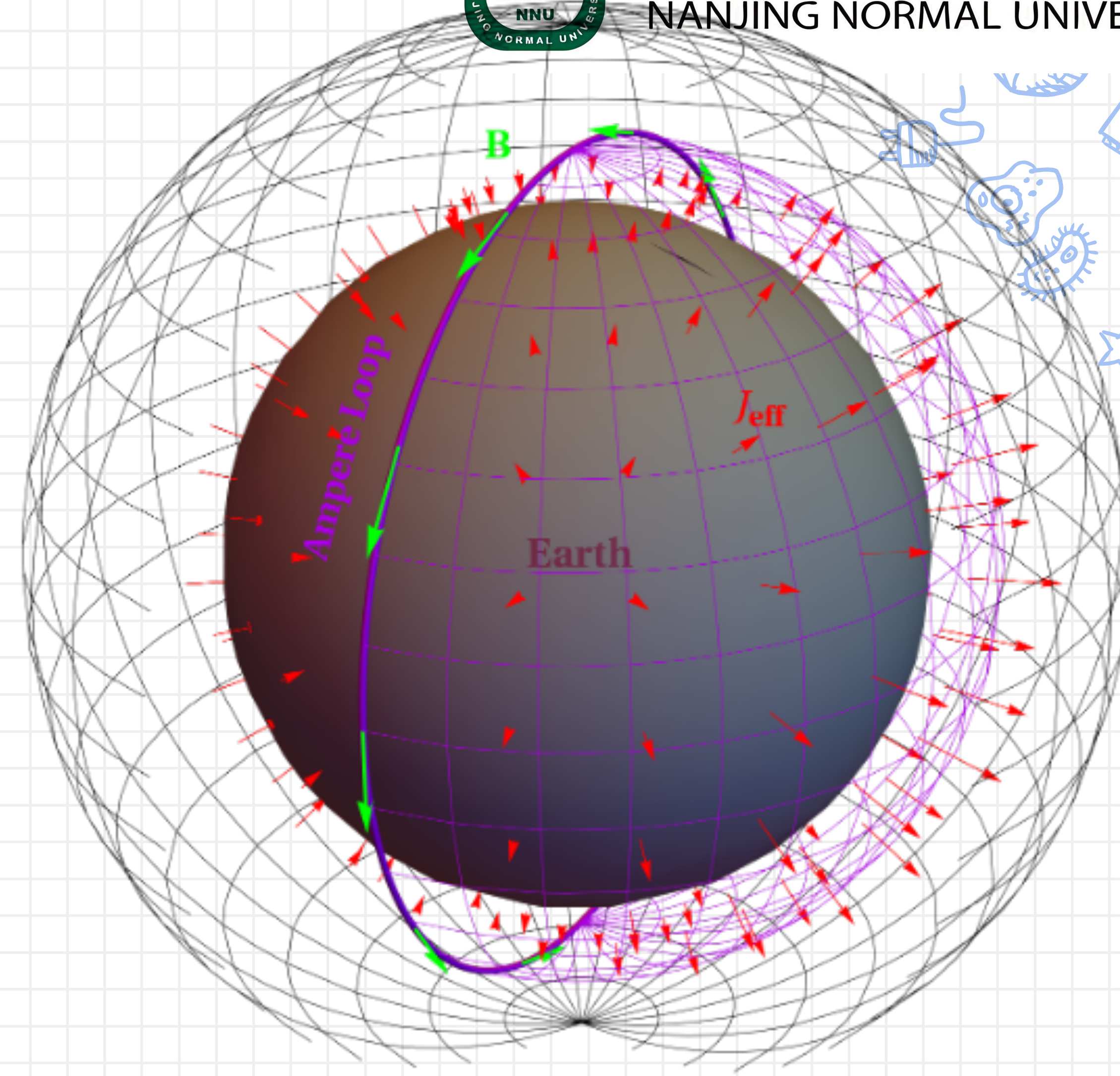
$\vec{B}_{\text{DM}}$ oscillates monochromatically at frequency $\omega = m_{\text{DM}}$

It is determined from $\vec{\nabla} \times \vec{B}_{\text{DM}} = \vec{J}_{\text{DM}}$

Quasi static limit if $m_{\text{DM}} \ll 1/R_{\text{Earth}}$

$\vec{J}_{\text{DM}}$ contains all the information of the dark matter field





$$\oint_c d\vec{\ell} \cdot \vec{B}_{\rm DM} = \int_S d\vec{S} \cdot \vec{J}_{\rm DM}$$

radial current component $\sim R\,B_{\rm DM} = \sim R^2 J_{\rm DM} \longrightarrow B_{\rm DM} \sim R\,J_{\rm DM}$

tangential current component $\sim R\,B_{\rm DM} = \sim R\,h J_{\rm DM} \longrightarrow B_{\rm DM} \sim h\,J_{\rm DM}$

Introduction

Axions [2112.09620]: $\vec{J}_{\rm DM} = -\, g_{a\gamma} \vec{B}_{\rm geo} \partial_t a$

$g_{a\gamma}$ axion to photon coupling

$a(t) = a_0 \cos(m_a t)$ axion dark matter field $a_0 = \dfrac{\sqrt{2\rho_{\rm DM}}}{m_a}$

for $\vec{B}_{\rm geo}$ the IGRF-13 model was used [Earth Planets Space 73 (2021) 49].

$$B_{\rm ave} = \sqrt{\frac{2}{3}} g_{a\gamma} B_0 R \sqrt{\rho_{\rm DM}} + \text{VSH corrections}$$

$B_0 = 2.94 \times 10^{-2}\,\mathrm{mT}$ representative value of the geomagnetic field at the equator

$$B_{\rm ave} \sim 0.1\,\mathrm{pT} \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} \right)$$

Introduction

Dark photons [2112.09620]: $\vec{J}_{\mathrm{DM}} = -\chi m_{\gamma'}^2 \vec{A}'$

χ kinetic mixing parameter

$\vec{A}'(t) = \vec{A}_0' \cos(m_{\gamma'} t)$ dark photon dark matter field

$$\left|\vec{A}_0'\right| = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}$$

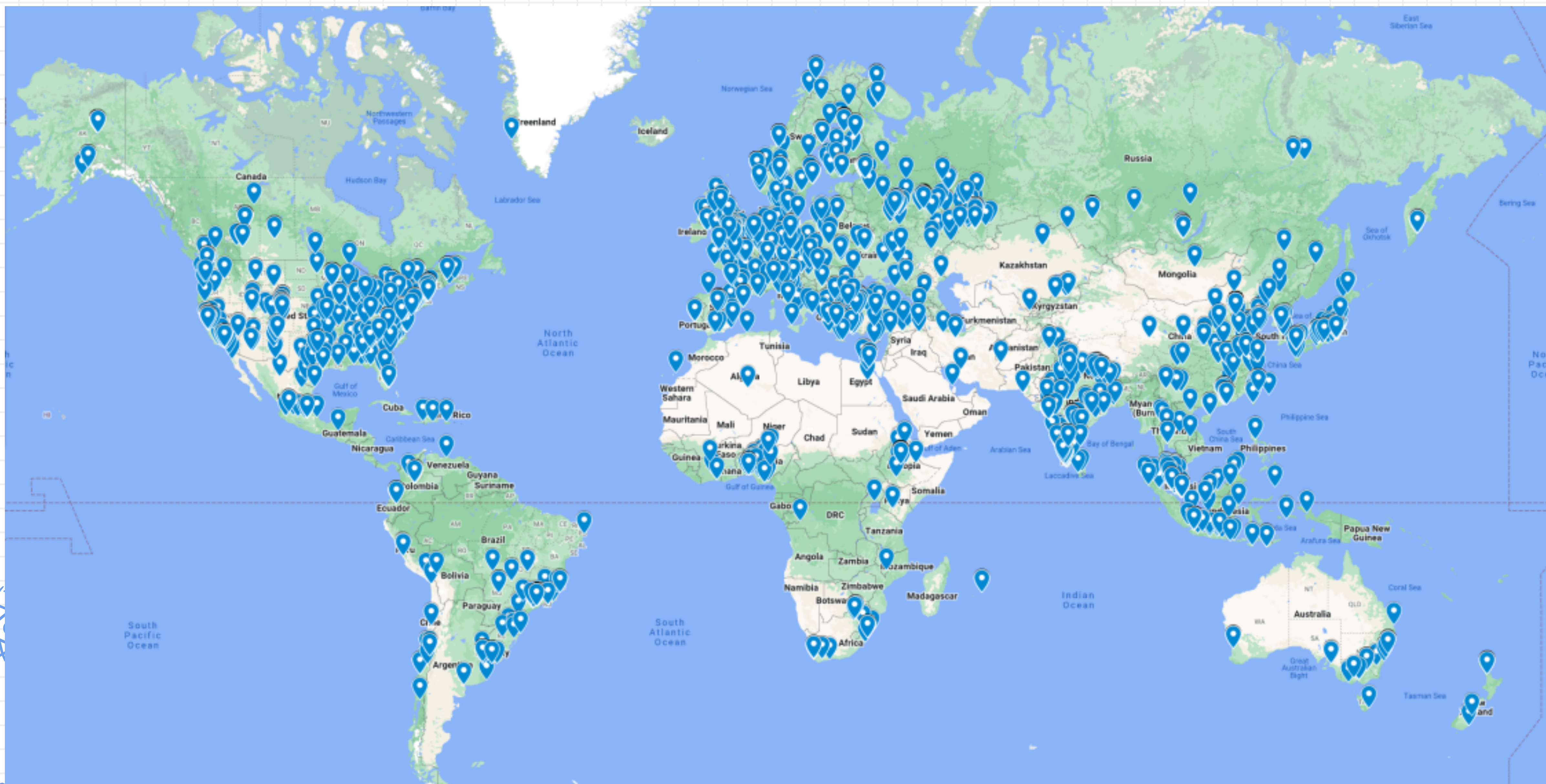
$$B_{\mathrm{ave}} = \frac{1}{\sqrt{6}} \chi\, m_{\gamma'} R \sqrt{\rho_{\mathrm{DM}}}$$

$$B_{\mathrm{ave}} \sim 0.1\,\mathrm{pT} \left(\frac{\chi}{10^{-5}}\right) \left(\frac{m_{\gamma'}}{10^{-16}\,\mathrm{eV}}\right)$$

Introduction

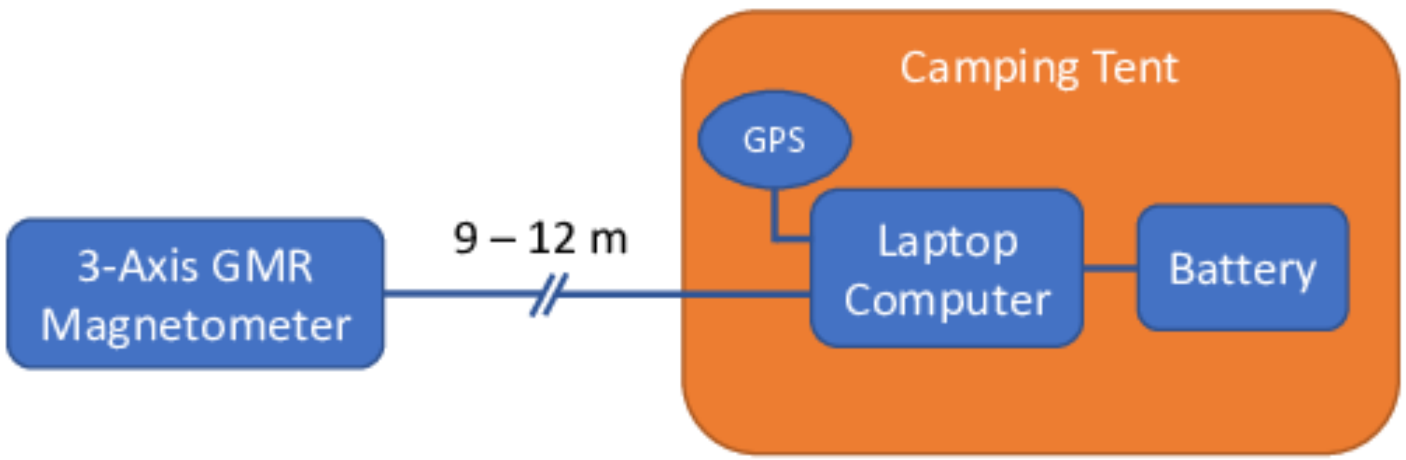
So far this idea has been employed using data from:

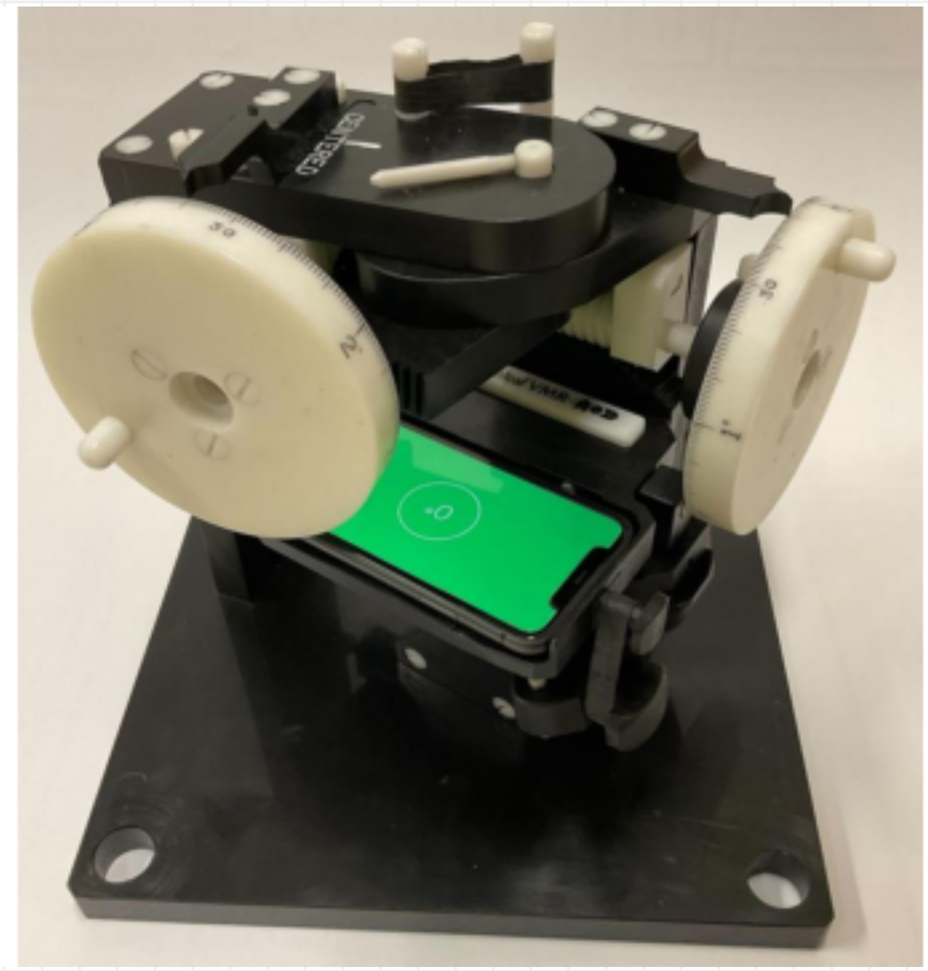
SuperMAG: network of near 600 ground based magnetometers monitoring the Earth magnetic field activity for 6 decades



Introduction

SNIPE Hunt: Emerging international collaboration aiming to perform dedicated measurements of the Earth magnetic field to search for ultralight dark matter





The first measurements were done with a $300\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$. More sensitive magnetometers are being implemented currently.

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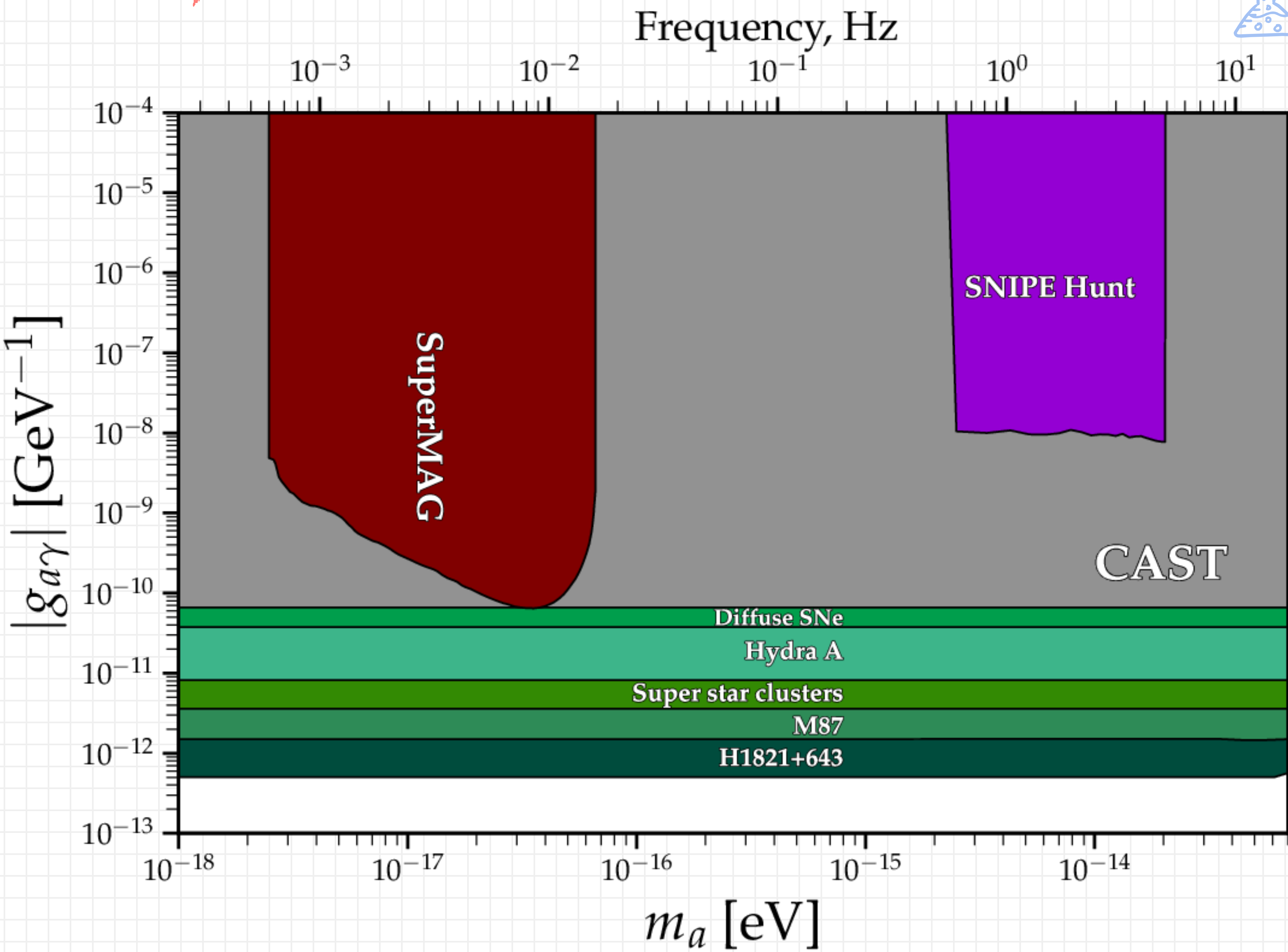
Introduction

Results for axions



Introduction

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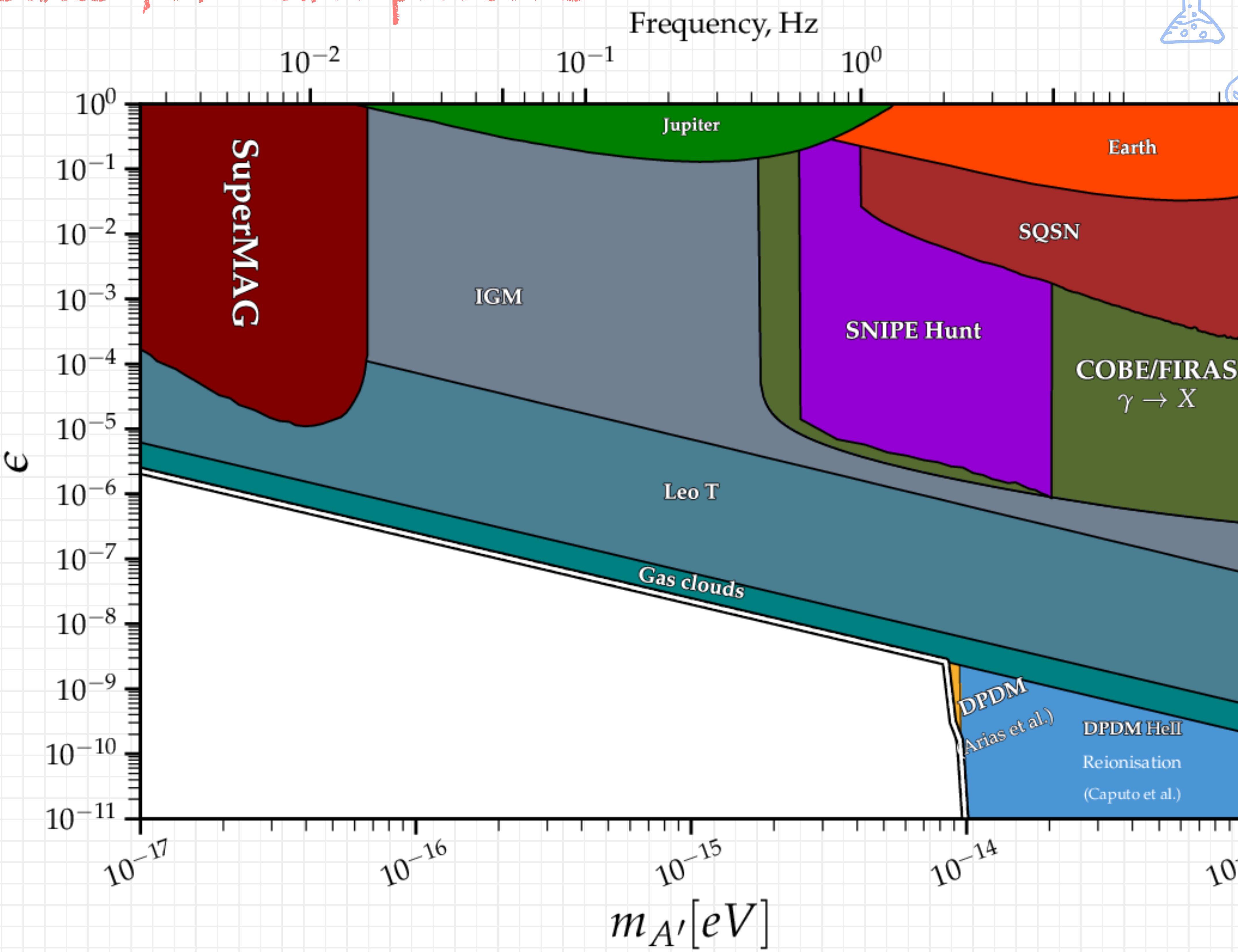
Results for dark photons



Millicharged dark matter

Ultralight millicharged dark matter can be produced by misalignment mechanism, similar to axion dark matter [2112.11476].

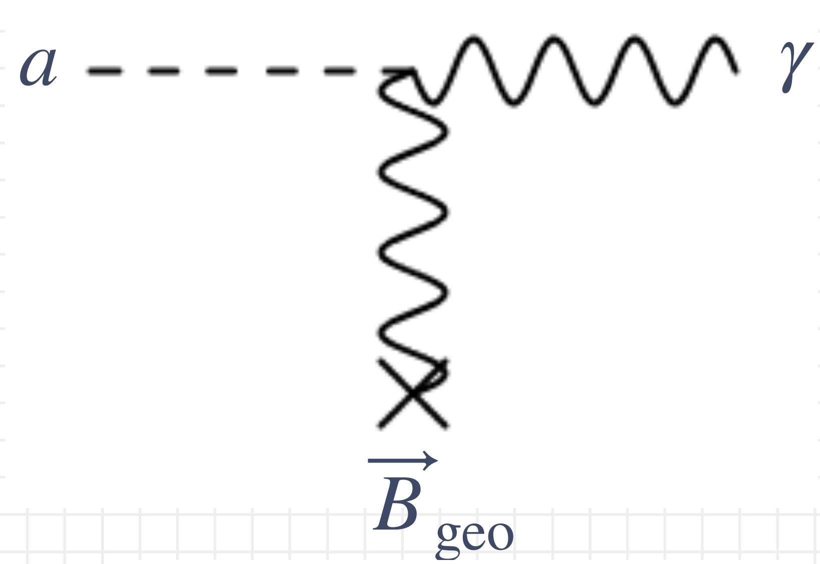
Millicharged dark matter interacting to photons (usual scalar QED):

$$\mathscr{L} = D_\mu \phi (D^\mu \phi)^* - m_\phi^2 |\phi|^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \qquad D_\mu = \partial_\mu + i e_m A_\mu$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

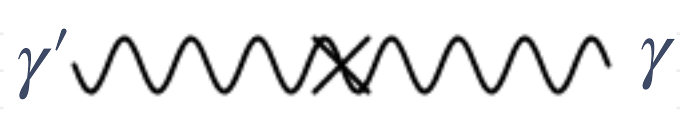
- A_μ → electromagnetic gauge field
- ϕ → millicharged field
- m_ϕ → mass of millicharged particles
- e_m → charge of millicharged particles

Millicharged dark matter

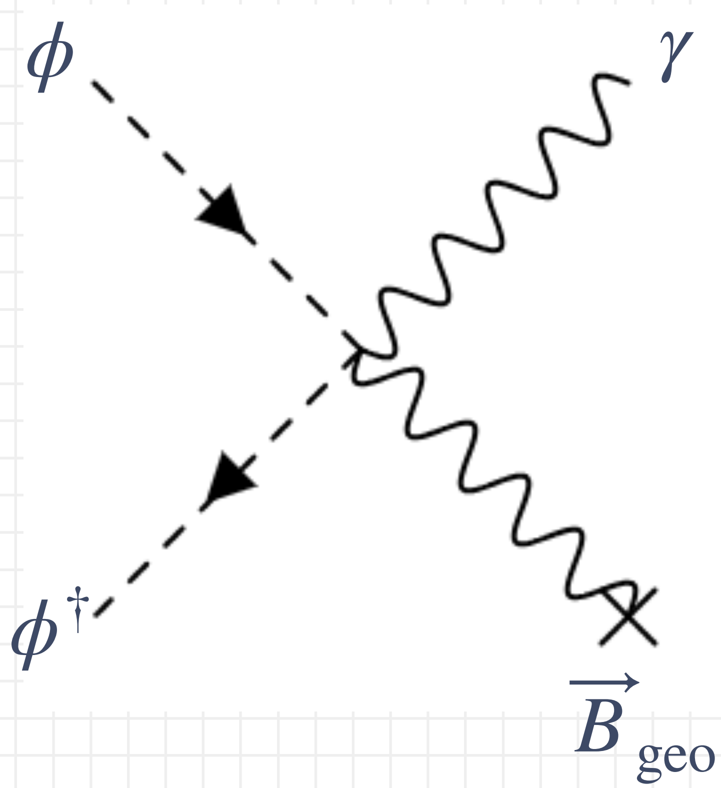


axions:

oscillation in the presence of the geomagnetic field background



Dark photon: oscillation



millicharged particles:

annihilation process in the presence of the geomagnetic field background

We assume the dark matter to be symmetric: $\rho_m = ie_m(\phi^* \partial_t \phi - \phi \partial_t \phi^*) = 0$

Millicharged dark matter

EoM:

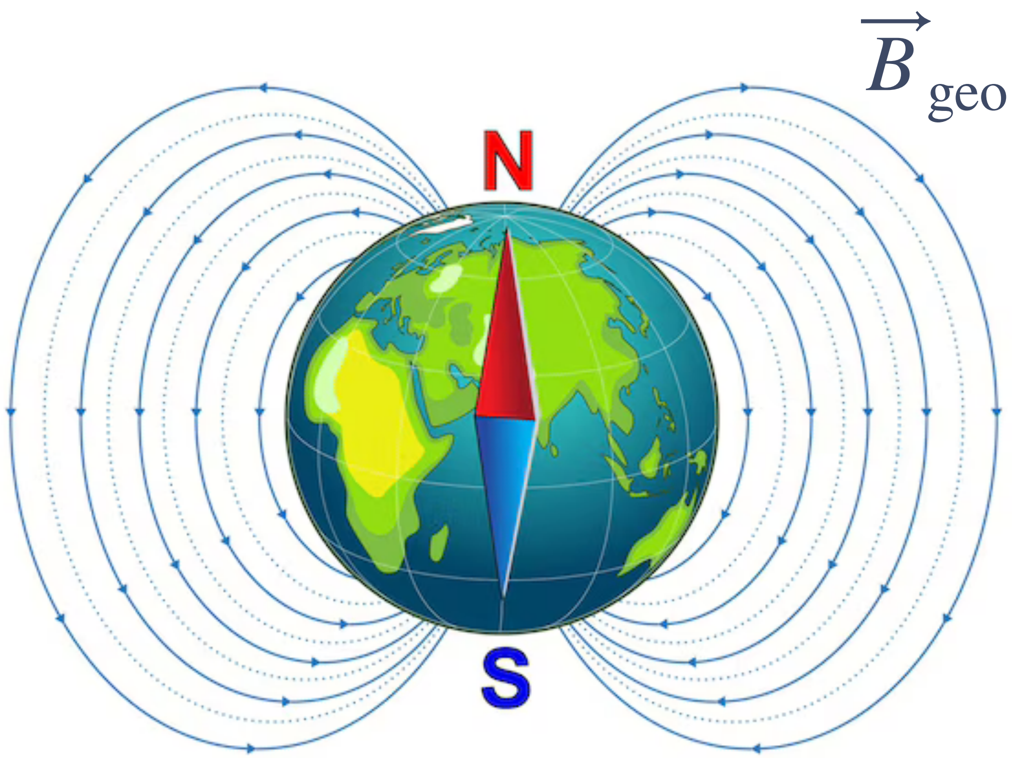
$$\vec{\nabla} \cdot \vec{B} = 0,$$

$$\vec{\nabla} \times \vec{B} = -ie_m\left(\phi^* \vec{\nabla}\phi - \phi\vec{\nabla}\phi^*\right) - 2e_m^2 \vec{A}_{\rm geo} |\phi|^2$$

$$(\Box + m_\phi^2)\,\phi = -2ie_m \vec{A}_{\rm geo} \cdot \vec{\nabla}\phi - e_m^2 |\vec{A}_{\rm geo}|^2 \phi$$

Millicharged dark matter

We include the Earth geomagnetic field $\vec{B}_{\rm geo}$ field as a background



$$\vec{B}_{\rm geo} = \vec{\nabla} \times \vec{A}_{\rm geo}$$

$\vec{A}_{\rm geo}$: geomagnetic vector potential

Coulomb gauge:

$$\vec{\nabla} \cdot \vec{A}_{\rm geo} = 0, \qquad A^0_{\rm geo} = 0$$

We determine $\vec{A}_{\rm geo}$ from:

$$\vec{\nabla} \times \vec{A}_{\rm geo} = \vec{B}_{\rm geo}$$

Vector geopotential

$$\vec{\nabla} \times \vec{\nabla} \times \vec{A}_{\rm geo} = \vec{\nabla} \times \vec{B}_{\rm geo} = \vec{J}_{\rm geo}$$

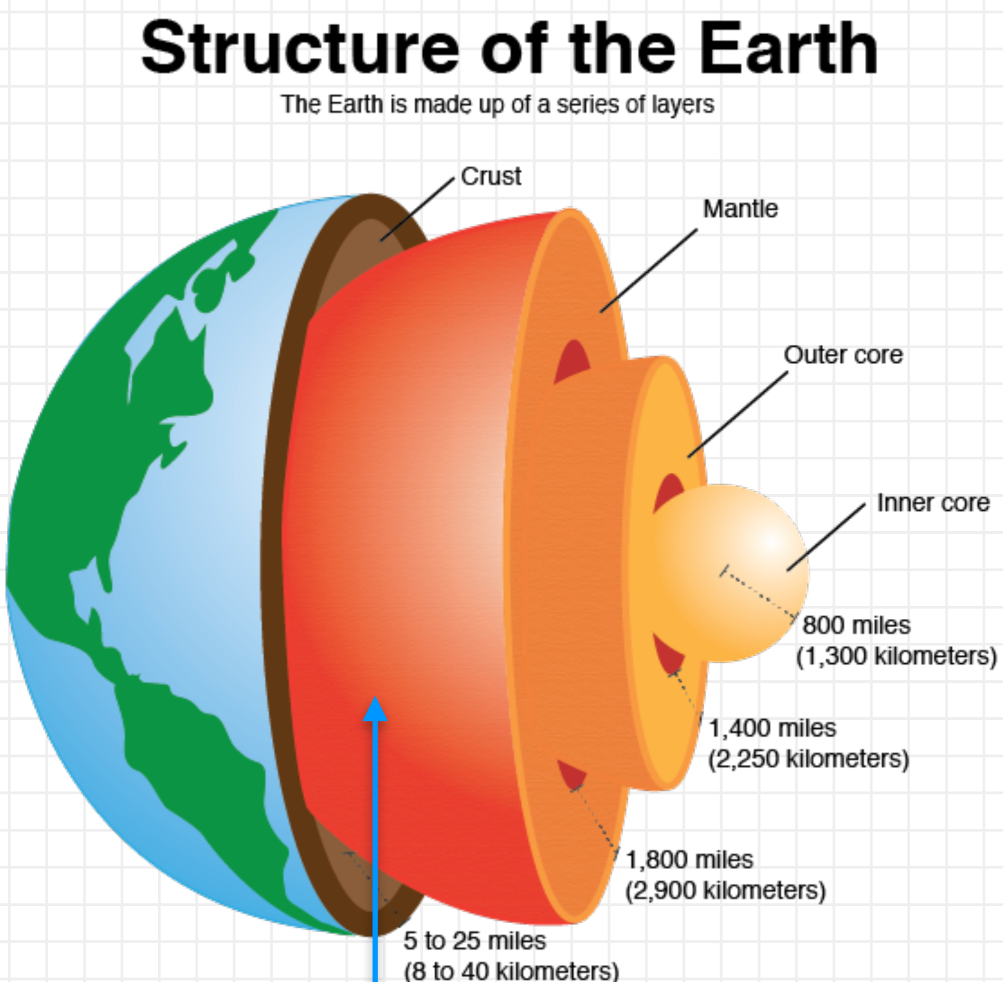
$$\nabla^2 \vec{A}_{\rm geo} = -\vec{J}_{\rm geo}$$

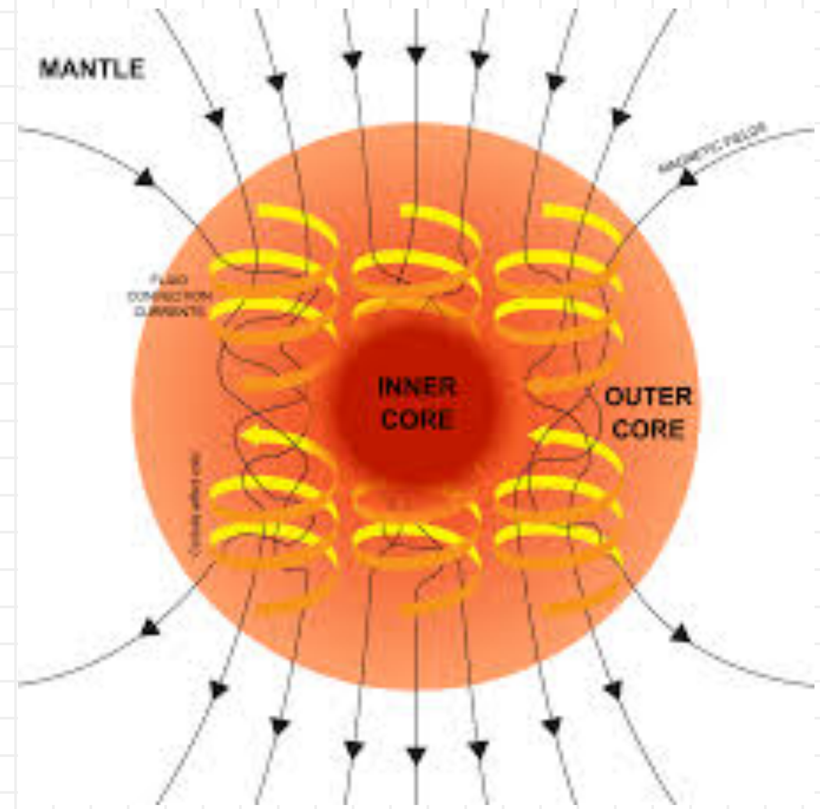
$$\vec{A}_{\rm geo}(\vec{x}) = -\int d^3x' \, G(\vec{x}, \vec{x}') \, \vec{J}_{\rm geo}(\vec{x}')$$

$G(\vec{x}, \vec{x}')$: Green's function associated to ∇^2 with vanishing boundary conditions

How is $\vec{J}_{\rm geo}$?

Vector geopotential





Geodynamo

IGRF model works well

$$\vec{J}_{\text{geo}}^{\text{mantle}} = \vec{J}_{\text{geo}}^{\text{inner core}} = 0$$

$$\vec{J}_{\text{geo}}^{\text{outer core}} = \text{something complicated}$$

Vector geopotential

Model building for the outer core current

- We know that the rms value of the magnetic field varies between:

$$B_{\mathrm{oc}}^{\mathrm{rms}} = \sqrt{\frac{1}{V_{\mathrm{oc}}}\int_{V_{\mathrm{oc}}} dV\, B_{\mathrm{oc}}^{2}} = 2.5 - 10\,\mathrm{mT}$$

[C. G. Provatidis, Physica Scripta 99, 025006 (2024)]

- The value of the magnetic field in the inner core is uniform and given by:

$$B_{\mathrm{ic}} = 6\,\mathrm{mT}$$

- The magnetic field at the mantle is descried by the IGRF model:

- The currents vanish smoothly on the outer core boundaries:

Vector geopotential

Model building for the outer core current

$$\vec{J}_{oc}(\vec{x}) = J_r(r)\,\overrightarrow{Y}_{1,0}(\theta,\varphi) + J_1(r)\,\overrightarrow{\Psi}_{1,0}(\theta,\varphi) + J_2(r)\overrightarrow{\Phi}_{1,0}(\theta,\varphi)$$

$$\overrightarrow{B}_{geo}(\vec{x}) = B_r(r)\,\overrightarrow{Y}_{1,0}(\theta,\varphi) + B_1(r)\,\overrightarrow{\Psi}_{1,0}(\theta,\varphi) + B_2(r)\overrightarrow{\Phi}_{1,0}(\theta,\varphi)$$

$$\overrightarrow{\nabla} \times \overrightarrow{B}_{geo} = \vec{J}_{geo}, \qquad \overrightarrow{\nabla} \cdot \overrightarrow{B}_{geo} = 0$$

$$\overrightarrow{B}_{IGRF} = -\sqrt{\frac{4\pi}{3}}B_0\left(\frac{R}{r}\right)^3\left(2\,\overrightarrow{Y}_{1,0} - \overrightarrow{\Psi}_{1,0}\right)$$

$$B_2 = -\frac{r}{2}J_r$$

No contribution to IGRF

$$B_1 = \int dr'\,G_1(r,r')\frac{1}{r'^3}\frac{d}{dr'}\left(r'^3 J_2(r')\right)$$

contribution to IGRF

$$B_r = r\frac{dB_1}{dr} + B_1 - r\,J_2$$

Vector geopotential

Model building for the outer core current

$$J_2 = a_0 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + a_5 r^5$$

$$J_r = -2\tilde{\beta}\,(r - R_{\mathrm{icb}})^4\,(r - R_{\mathrm{cmb}})^3$$

This form ensure smoothly vanishing for J_r and J_1

$$J_2\,(R_{\mathrm{icb}}) = J_2\,(R_{\mathrm{cmb}}) = 0, \qquad J_2'\,(R_{\mathrm{icb}}) = J_2'\,(R_{\mathrm{cmb}}) = 0$$

$$B_1(R_{\mathrm{icb}}) = B_1^{\mathrm{ic}}, \qquad B_1(R_{\mathrm{cmb}}) = B_1^{\mathrm{IGRF}}$$

$\tilde{\beta}$ is determined by $B_{\mathrm{oc}}^{\mathrm{rms}} = \sqrt{\frac{1}{V_{\mathrm{oc}}}\int_{V_{\mathrm{oc}}} dV\,B_{\mathrm{oc}}^2} = 2.5 - 10\,\mathrm{mT}$

Geomagnetic signal

$$\vec{A}_{\rm geo} = -B_0 R\left(1.01\beta\left(\frac{R}{r}\right)^3\left(2\vec{Y}_{1,0}-\vec{\Psi}_{1,0}\right)-\sqrt{\frac{4\pi}{3}}\left(\frac{R}{r}\right)^2\vec{\Phi}_{1,0}\right)$$

$\beta = 1 - 4.6$ accounts for the uncertainty of the magnetic field in the outer core

Now we can finally calculate the magnetic field signal:

$$\vec{\nabla}\cdot\vec{B} = 0,$$

$$\vec{\nabla}\times\vec{B} = \vec{J}_{\rm eff}$$

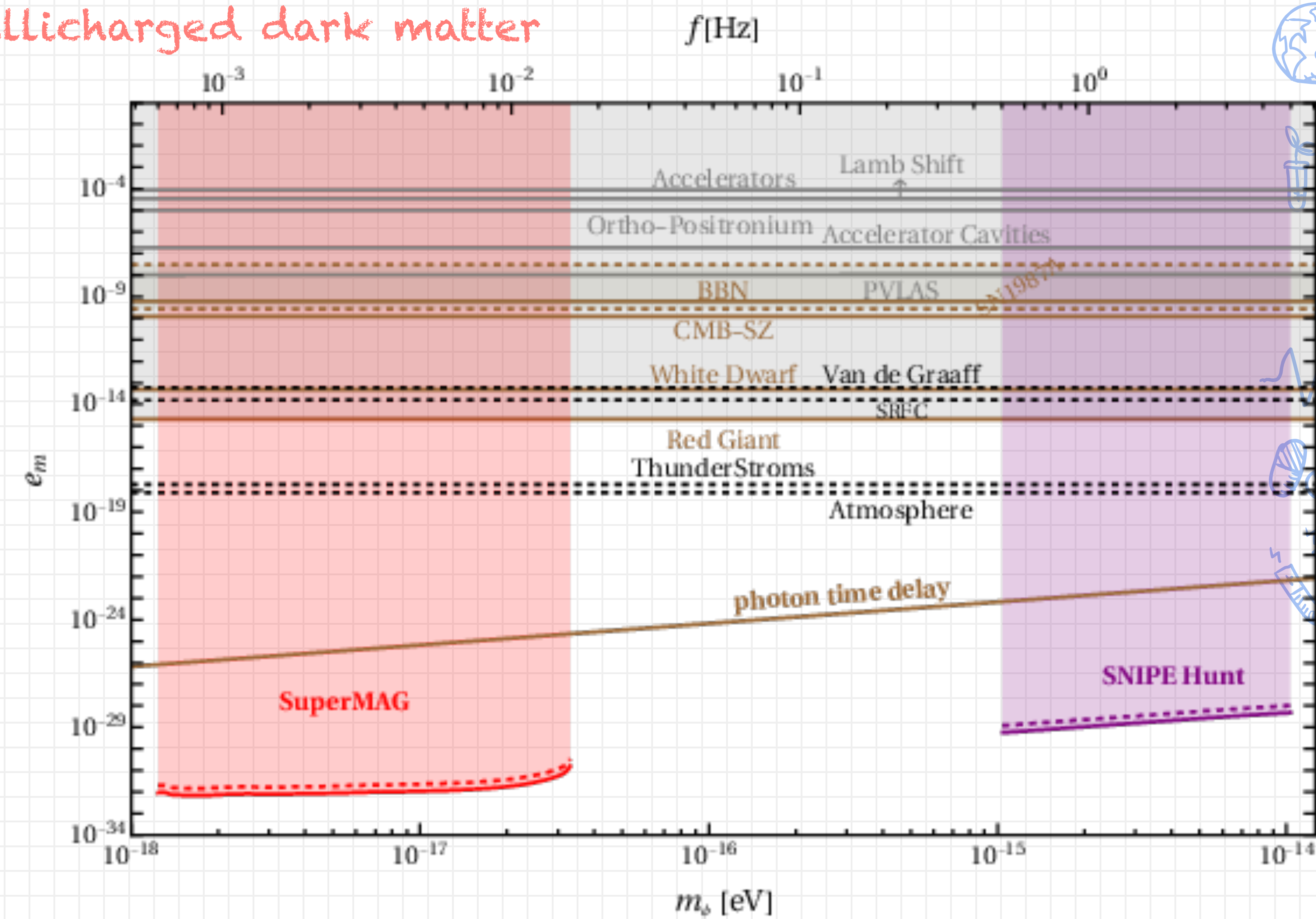
$$\vec{J}_{\rm eff} = \frac{2e_m^2\rho_{\rm DM}B_0 R}{m_\phi^2}\left(1.01\beta\left(\frac{R}{r}\right)^3\left(2\vec{Y}_{1,0}-\vec{\Psi}_{1,0}\right)-\sqrt{\frac{4\pi}{3}}\left(\frac{R}{r}\right)^2\vec{\Phi}_{1,0}\right)$$

The fact that $J_{\rm eff}\sim 1/m_\phi^2$ is a clear advantage with respect to axions and dark photons where $J_{\rm eff}\sim m_a^0$ and $J_{\rm eff}\sim m_{\gamma'}$, respectively.

Geomagnetic signal

$$\vec{B}(t) = \frac{2e_m^2 \rho_{\rm DM} B_0 R^2}{m_\phi^2} \left(\sqrt{\frac{4\pi}{3}} \frac{h}{R} \vec{\Psi}_{1,0} - 2.02\beta \vec{\Phi}_{1,0} \right) e^{-2im_\phi t}$$

We take the results from SuperMAG and SNIPE Hunt and put constraints on millicharged dark matter



Conclusions

- We considered millicharged dark matter and their effect on the Earth's geomagnetic field

- We calculated the magnetic field signal for frequencies below Hz

- For millicharged dark matter the signal is enhanced by a $1/m_\phi^2$ behavior of the effective current

- Using axion search bounds we were able to put constraints on millicharged dark matter up to 17 orders of magnitude stronger than stellar evolution bounds