Geomagnetic Signal of Millicharged Dark Matter and its Detection

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Main structure in one slide

Objective:

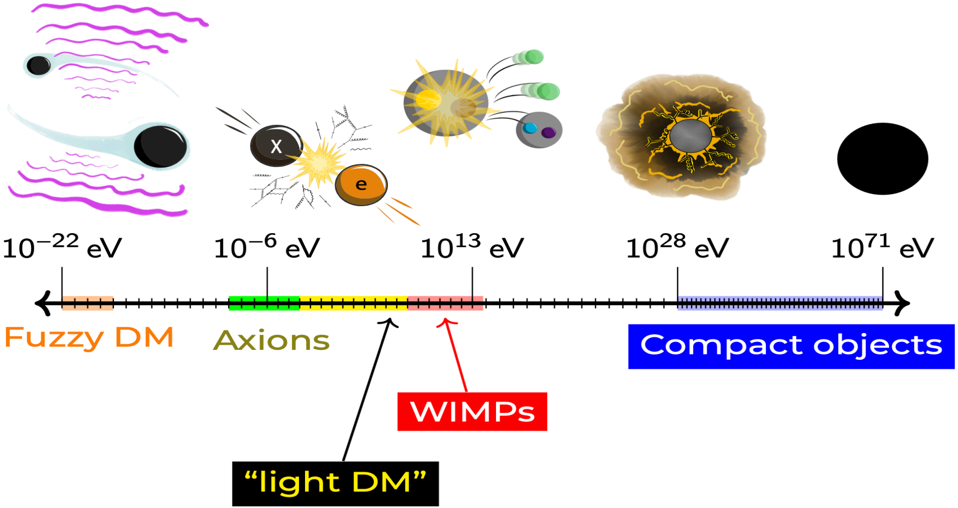
Demonstrate a novel mechanism (magnetic signal) to detect ultralight millicharged dark matter, leveraging the Earth as a transducer (atmospheric cavity) (2411.xxxxx) with Ariel Arza, Yuanlin Gong, Jing Shu and Lei Wu.





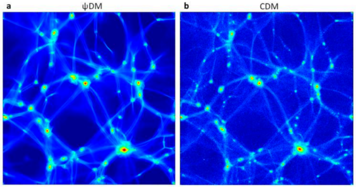
Dark Matter Landscape

From Benjamin V. Lehmann

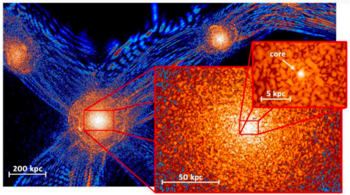


Why Ultralight Dark Matter

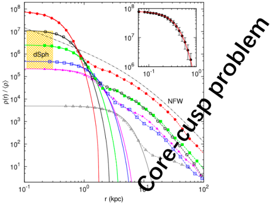
Small Scale Problem: Fuzzy Dark Matter Candidate



Comparison of cosmological large-scale structures formed by standard CDM and by wavelike DM



A slice of density field of wave DM simulation



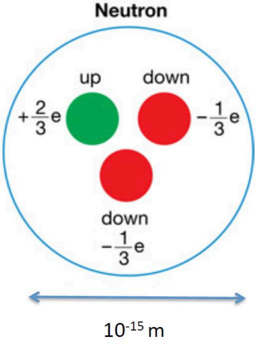
Radial density profiles of haloes formed in the wave DM model

Schive, Chiueh, Broadhurst, 1406.6586

Why Ultralight Dark Matter

Strong CP Problem

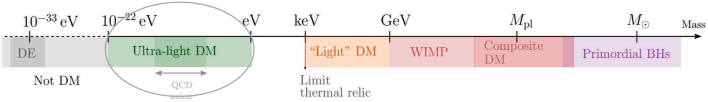
- Naive estimation: $10^{-16} e$ cm, Exp: $3 \times 10^{-26} e$ cm
- The best explanation: New U(1) axial symmetry, that when broken, cancels CP violation in the strong sector (Pecci, Quinn, 1977)
- Consequence: New particle, called the axion (Weinberg, Wilczek, 1978)

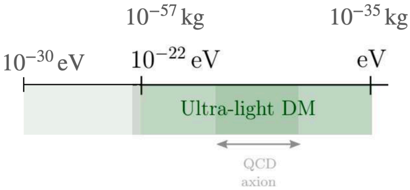


d = ~~10^{-16} e cm~~
< 3×10^{-26} e cm

What is Ultralight Dark Matter

We define ultralight dark matter (ULDM) as bosonic DM candidates with $m < \text{eV}$



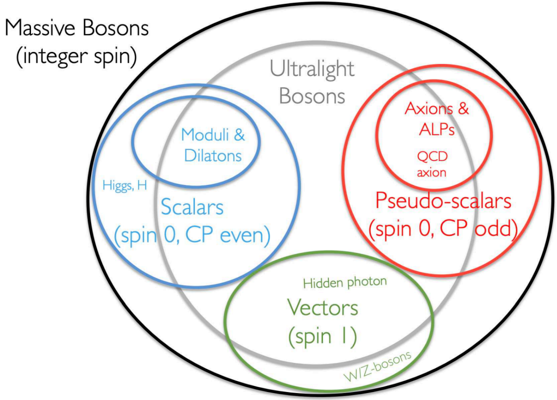


Bosons

Non-thermally produced

ULDM Candidates

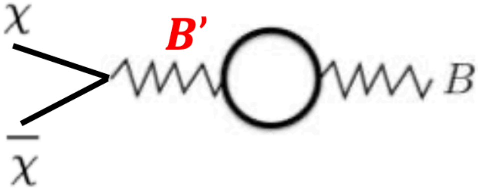
Many extensions of the Standard Model predict additional massive bosons, Ref.: Chadha-Day et al 2022



Why and What is millicharged scalar dark matter (MCDM)?

Why MCDM?

- Is electric charge quantized and why? A long-standing question!
  Testing whether or not $e/3$ is the minimal charge.
- MCP could have natural link to dark sector (massless dark photon, etc.)



- Used for the cooling of gas temperature to explain the EDGES anomaly

MCDM 101

- MCDM is some relic charged under a dark $U(1)$.

$$f_\chi = \frac{\rho_{\mathrm{MCDM}}}{\rho_{\mathrm{DM}}} \sim 0.0001 - 1$$

- Through kinetic mixing $\left(F_{\mu\nu}F^{\mu\nu} + \epsilon\left(F'\right)_{\mu\nu}F^{\mu\nu} + \left(F'\right)_{\mu\nu}\left(F'\right)^{\mu\nu}\right)$ with our own photon, MCDM acquires an effective charge

$$q_{\mathrm{eff}} = Q \propto \epsilon$$

- We are only probing MCDM here! Minimal assumptions. Most robust constraints.

$$\mathcal{L} = D_\mu\phi(D^\mu\phi)^* - m_\phi^2|\phi|^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

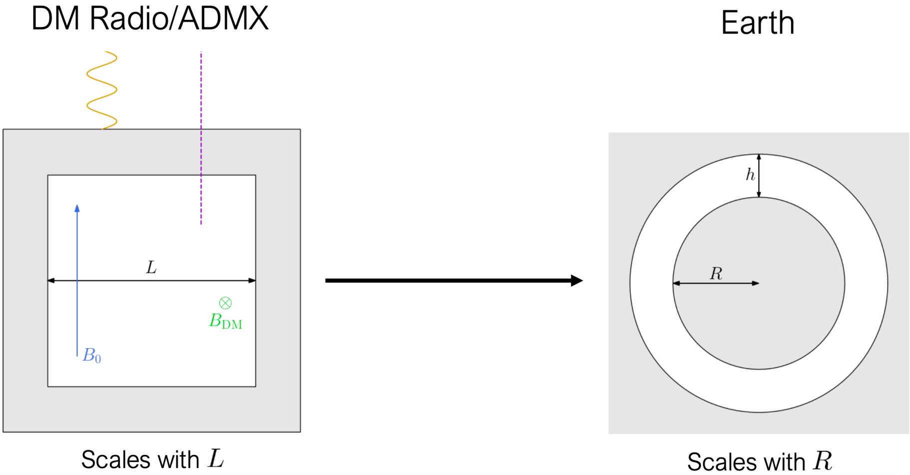
Production Mechanism

How to naturally generate ultralight MCDM in the cosmos

- Freeze-in works for keV to TeV-scale MCDM
  - X. Chu, T. Hambye and M.H.G. Tytgat, The Four Basic Ways of Creating Dark Matter Through a Portal, [arXiv:1112.0493]
  - W. Feng, Z. Zhang, K. Zhang, Sub-GeV millicharge dark matter from the $U(1)_X$ hidden sector, [2312.03837]
- Misalignment works for sub-eV MCDM
  Zachary Bogorada and Natalia Toro, arXiv:2112.11476

Earth as a transducer

A natural vacuum cavity: Formed between the inner conducting sphere of the Earth and the conducting ionospheric layer



Effective Current

Just a EM problem with a background current!

In non-relativistic limit, effects of ultralight DM given by

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\text{eff}}, \quad \partial_\mu F^{\mu\nu} = J^\mu_{\text{eff}}$$

- For dark-photon dark matter,

$$\mathbf{J}_{\text{eff}} = -\varepsilon m^2_{A'} \mathbf{A}'$$

- For axion-like dark matter,

$$\mathbf{J}_{\text{eff}} = i g_{a\gamma} m_a a \mathbf{B}_0$$

- For MCDM, originated from the interaction between the MCDM and the geomagnetic filed

$$J^\mu_{\text{eff}} = 2e^2_m \mathcal{A}^\mu |\phi|^2, \quad \mathcal{A}_\mu = (\mathcal{A}_0, -\vec{\mathcal{A}})$$

The current depends on $\mathcal{A}^\mu$ rather than B, thus the gauge choice, giving us infinite possible solutions!

Gauge Invariance

- The correct way is to include the MCDM current

$$J_m^\nu = ie_m \left(\phi^* \partial^\nu \phi - \phi \partial^\nu \phi^*\right).$$

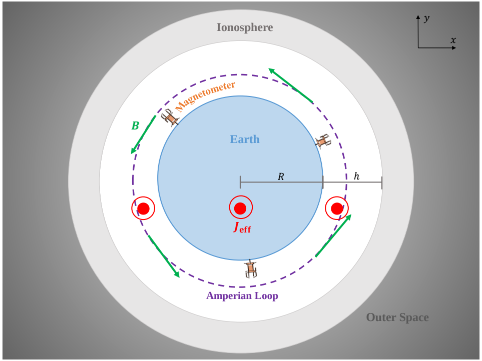
- The MCDM can be solved via equation of motion

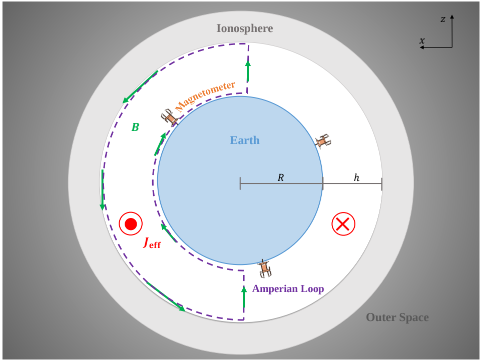
$$\Box \phi = -ie_m \partial_\mu \mathcal{A}^\mu \phi - 2ie_m \partial_\mu \phi \mathcal{A}^\mu + e_m^2 \mathcal{A}_\mu \mathcal{A}^\mu \phi$$

- For a different gauge choice $\mathcal{A}'_\mu = \mathcal{A}_\mu + \partial_\mu \Lambda$, correspondingly $\phi' = \phi\, e^{-ie_m \Lambda}$, so that

$$J_m^{\mu\prime} + J_{\text{eff}}^{\mu\prime} = J_m^\mu + J_{\text{eff}}^\mu$$

How to probe MCDM





a monochromatic magnetic signal with spatial dependence of a particular vector spherical harmonics

Rough Estimate

Why MCDM has much better sensitivity than dark photon and axion

- Ampere law

$$\int \mathbf{B} \cdot \mathbf{d}\ell = \iint \mathbf{dA} \cdot \mathbf{J}$$

- Simple dimensional analysis

$$BR \approx R^2 e_m^2 (B_0 R) \phi_0^2 \rightarrow B \sim 100 \text{ pT}$$

- Rough sensitivity for Vector Magnetoresistive (VMR) sensors

$$300\text{pT}/\sqrt{\text{Hz}} \quad \text{over the frequency } 0.1 - 100 \text{ Hz}$$

- While for dark photon (proportional to mass) and axion (independent to mass)

The lower mass, the better sensitivity for MCDM

Our basic motivation for MCDM

Computational Framework

Vector potential in the vector spherical harmonics bases

- Expand geomagnetic field in terms of VSH
$$\vec{B}_0(\vec{x}) = \sum_{\ell,m} \left(B^{(r)}_{\ell,m}(r)\vec{Y}_{\ell m}(\theta,\varphi) + B^{(1)}_{\ell,m}(r)\vec{\Psi}_{\ell m}(\theta,\varphi) + B^{(2)}_{\ell,m}(r)\vec{\Phi}_{\ell m}(\theta,\varphi) \right).$$
- The curl of the background vector potential is expressed as
$$\vec{\nabla} \times \vec{A}^{(0)} = \sum_{\ell,m} \left(-\frac{\ell(\ell+1)}{r} A^{(2)}_{\ell m}\, \vec{Y}_{\ell m} - \left(\frac{dA^{(2)}_{\ell m}}{dr} + \frac{A^{(2)}_{\ell m}}{r} \right) \vec{\Psi}_{\ell m} + \left(-\frac{A^{(r)}_{\ell m}}{r} + \frac{dA^{(1)}_{\ell m}}{dr} + \frac{A^{(1)}_{\ell m}}{r} \right) \vec{\Phi} \right).$$
- Identifying both terms yields (The last equation comes from the gauge condition $\nabla \cdot \vec{A}^{(0)} = 0$)
$$-\frac{\ell(\ell+1)}{r} A^{(2)}_{\ell m} = B^{(r)}_{\ell m}(r),$$
$$\frac{dA^{(2)}_{\ell m}}{dr} + \frac{A^{(2)}_{\ell m}}{r} = B^{(1)}_{\ell m}(r), \quad \text{redundant from} \quad \nabla \cdot \vec{B}^{(0)} = 0$$
$$\frac{dA^{(1)}_{\ell m}}{dr} + \frac{A^{(1)}_{\ell m}}{r} - \frac{A^{(r)}_{\ell m}}{r} = B^{(2)}_{\ell m}(r);$$
$$\frac{dA^{(r)}_{\ell m}}{dr} + \frac{2A^{(r)}_{\ell m}}{r} - \ell(\ell+1)\frac{A^{(1)}_{\ell m}}{r} = 0.$$

Computational Framework

Solving for the vector potential

- The first equation is easy to solve

$$A^{(2)}_{\ell m} = -\frac{r}{\ell(\ell+1)} B^{(r)}_{\ell m}(r)$$

- For the last two equations

$$\frac{\left(r^2 (r A^{(1)}_{\ell m})'\right)'}{r^3} - \frac{\ell(\ell+1)}{r^2} A^{(1)}_{\ell m} = \frac{1}{r^3}\left(r^3 B^{(2)}_{\ell m}\right)'$$

- Due to Green function

$$A^{(1)}_{\ell m} = \int dr' G_\ell(r,r') \frac{1}{r'^3}\left(r'^3 B^{(2)}_{\ell m}(r')\right)'$$

with

$$G_\ell(r,r') = -\frac{1}{2\ell+1}\begin{cases} \frac{r^{\ell-1}}{r'^{\ell-2}}, & r < r' \\ \frac{r'^{\ell+3}}{r^{\ell+2}}, & r > r' \end{cases}$$

Geomagnetic Signal

In the cavity range of $R < r < R + h$:

- Effective current

$$\vec{J}_{\text{eff}} = \left(J_{10}^{(r)}(r)\mathbf{Y}_{10} + J_{10}^{(1)}(r)\mathbf{\Psi}_{\ell m} + \sum_{\ell m} J_{\ell m}^{(2)}(r)\mathbf{\Phi}_{\ell m} \right) 2e_m^2\phi_0^2 e^{-i\omega t}$$

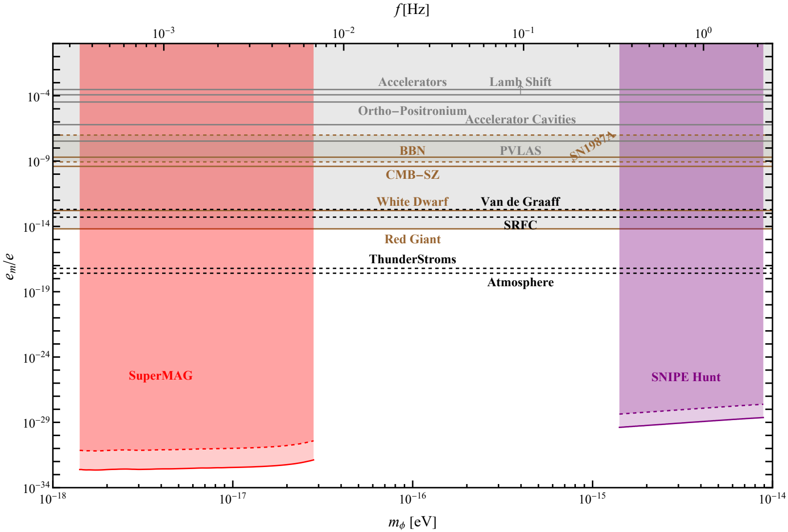
- Geomagnetic signal

$$\vec{B}_{\ell m}^{(2)}(R) = -2e_m^2\phi_0^2 R^2 b_{\text{oc}}\Phi_{10} e^{-i\omega t}$$

- For SuperMAG and SNIPE experiment, the exclusion limits become

$$e_m \lesssim \left(\frac{6372.1\ \text{km}}{R}\right)^{\frac{3}{2}} \cdot \left(\frac{0.3\text{GeV/cm}^3}{\rho}\right)^{\frac{1}{2}} \cdot \begin{cases} 10^{-29} \cdot \left(\frac{m_\phi}{10^{-17}\text{eV}}\right)^{\frac{1}{2}}, & \text{SuperMAG} \\ 10^{-27} \cdot \left(\frac{m_\phi}{5\times 10^{-15}\text{eV}}\right)^{\frac{1}{2}}, & \text{SNIPE} \end{cases}$$

Result



f[Hz]
10^−3
10^−2
10^−1
10^0
Accelerators
Lamb Shift
Ortho−Positronium
Accelerator Cavities
BBN
PVLAS
SN1987A
CMB−SZ
White Dwarf
Van de Graaff
SRFC
Red Giant
ThunderStroms
Atmosphere
SuperMAG
SNIPE Hunt
10^−4
10^−9
10^−14
10^−19
10^−24
10^−29
10^−34
e_m/e
10^−18
10^−17
10^−16
10^−15
10^−14
m_ϕ [eV]

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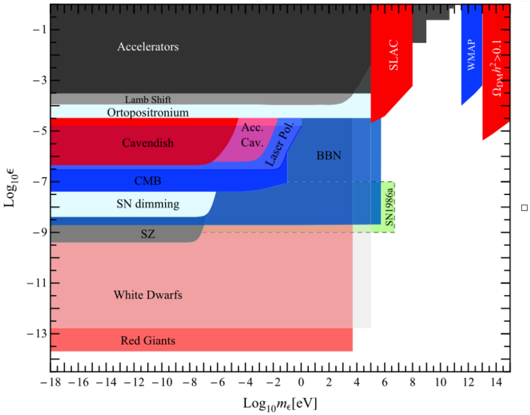

- **Big-bang nucleosynthesis**
  Particles with small electric charge will interact with the plasma in the early universe contributing to $\Delta N_{\rm eff}$
- **Stellar evolution of Red Giant**
  Plasma decay process affect the Stellar evolution
- **Territorial Experiment**
  Lamb Shift, Coulomb's Law, invisible decay of ortho-positronium

Background Geomagnetic field

- IGRF model

$$\vec{B}_0(\vec{x}) = \sum_{\ell,m} C_{\ell m} \left(\frac{R}{r}\right)^{\ell+2} \Big((\ell+1)\vec{Y}_{\ell m}(\theta,\varphi) - \vec{\Psi}_{\ell m}(\theta,\varphi)\Big)$$

- It actually determines $A^{(2)}_{\ell m}$. However, the other two requires integrating over the whole earth, thus inner geomagnetic field becomes relevant