Title: Millicharged Dark Matter Propagating in Space and Earth

Speakers: Itay Bloch

Series: Particle Physics

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Abstract: The possibility of having DM (or a fraction of it) charged under a dark U(1) which mixes with the U(1)EM has been of interest for many years. Many different experiments search for such a millicharged DM (MCDM), under the assumption that its velocity would be distributed according to MB. However, our galaxy and local environment have a variety of effects that make this assumption highly non trivial. In this talk, I will discuss the effects of galactic magnetic fields, collisions with Cosmic rays, acceleration from Supernovae remnants, and energy losses due collisions with particles in the interstellar medium on the velocity distribution of MCDM outside the solar system. Furthermore, to arrive at an underground detector, the MCDM would need to pass through the solar wind, not be deflected by earth's magnetic field, and pass through earth's crust to reach the underground lab. We will discuss these effects as well. I will end the talk by discussing the importance of these effects on Direct Detection experiments, and whether MCDM could explain the XENON excess.

Zoom Link: https://pitp.zoom.us/j/92701168758?pwd=UlY5Smlrd1MzWmI4ZkNyNVI5d3JIUT09

Tales of Millicharged Relics in our galaxy, solar system and DD experiments

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Outline

- Basics
- Millicharged relics in the galaxy
  - Galactic Magnetic Fields
  - Cosmic Rays acceleration
  - Supernova remnants acceleration
- Millicharged relics around us
  - Solar Wind
  - Earth's magnetic field
  - Overburden
- Preliminary estimates and future possible improvements.

MCDM 101

- Millicharged DM (mcDM/MCDM) is some relic ($f_\chi = \dfrac{\rho_{MC}}{\rho_{DM}} \sim 0.0001 - 1$), charged under a dark U(1).
- Through kinetic mixing ($F_{\mu\nu}F^{\mu\nu} + \epsilon(F')_{\mu\nu}F^{\mu\nu} + (F')_{\mu\nu}(F')^{\mu\nu}$) with our own photon, MCDM acquires an effective charge $\rightarrow q_{eff} = Q \propto \epsilon$.
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- We take a DP that is light enough for us not to worry about finite interaction length.
- For $f_\chi = 1$, strong CMB constraints $Q \leq (m_\chi/GeV)^{1/2}10^{-6}$, so we usually look at $f_\chi \leq 10^{-3}$, where these bounds disappear.
- Mass range we focus on $m_\chi \in [MeV, TeV]$.

MCDM and B fields

Lorentz force:

$$\frac{d\gamma m\vec{v}}{dt} = Qe\vec{v} \times \vec{B}$$

$ds = dt/|v|, \hat{s} = \hat{v}$

$$\frac{dR_\chi \hat{s}}{ds} = \hat{s} \times \vec{B}, R_\chi = \frac{m_\chi \gamma \beta_\chi}{Qe}$$

So for the most part, when only magnetic fields are involved, the rigidity tells you what you need to know, so we can use high momentum CRs to learn about low momentum MCDM with small charges.

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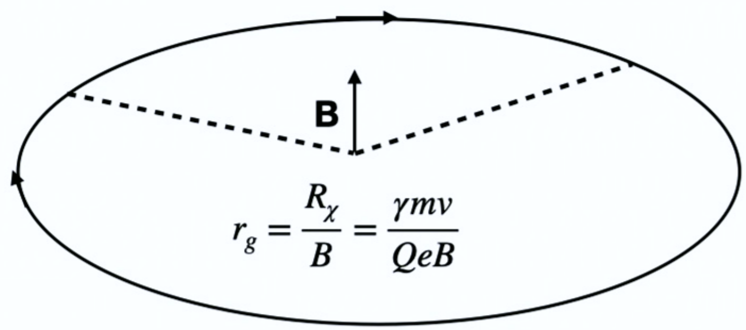
Gyroradius

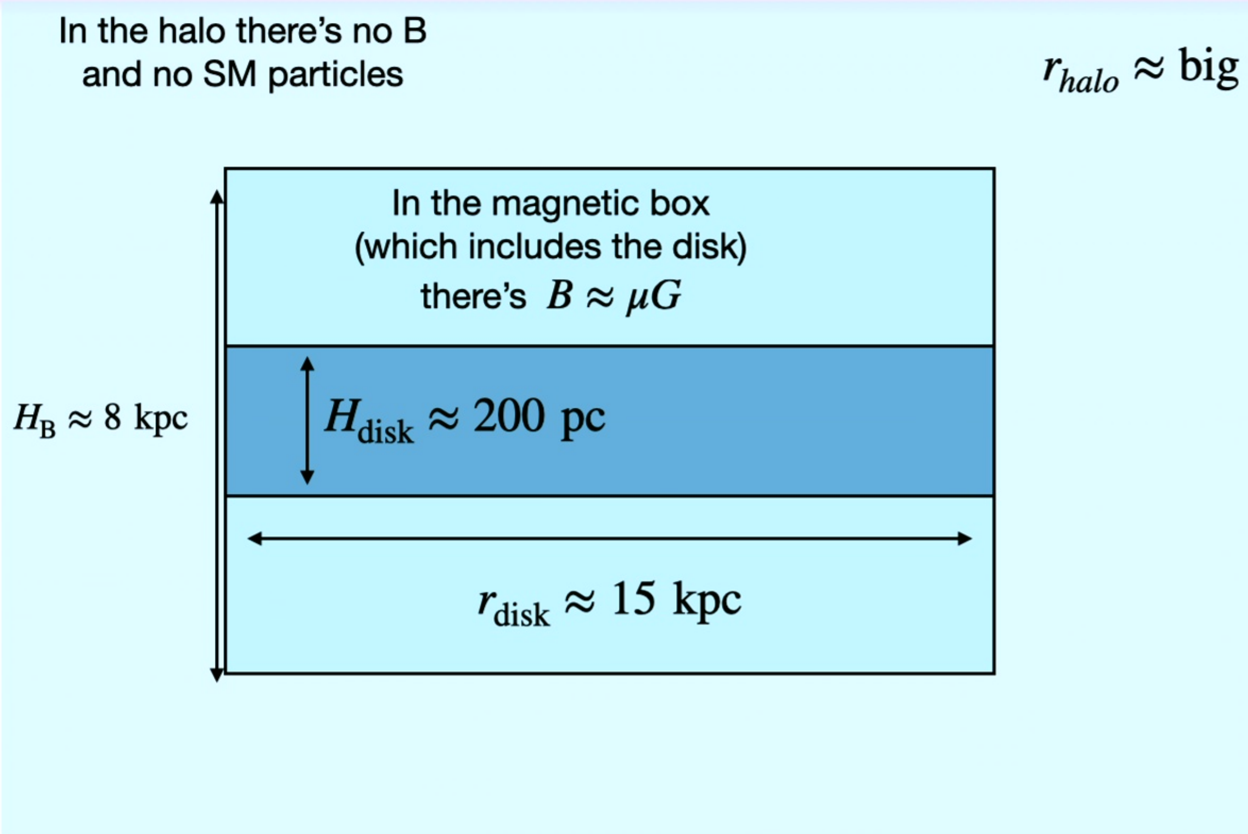
Under a constant magnetic field B, the curve would look like:



$$r_g = \left(\frac{p_\chi/eQ}{10^9 GV}\right)\left(\frac{\mu G}{B}\right) \text{kpc}$$

5

Simplified image for our galaxy



MCDM Evacuation

- If there are processes that remove MCDM from the disk, and **if we only had a constant magnetic field**, for $R_\chi \gtrsim 10^9$ GV, once they go out, they can't come back due to $r_g \sim$ kpc, so no MCDM in the galaxy.

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- However, if there's inhomogeneities of B on scales smaller than rg, this breaks down

Galactic Magnetic Field (GMF)

The GMF has a coherent component and an incoherent one.
Both of order μG

Coherent→deflection

Incoherent→diffusion

$$\frac{\partial f}{\partial t} = D(p)\frac{\partial^2 f}{\partial z^2}$$

CR collisions

The magnetic box has CRs inside it, which may collide with our DM.
To describe that, it makes sense to split our f into "low momentum" and "high momentum":

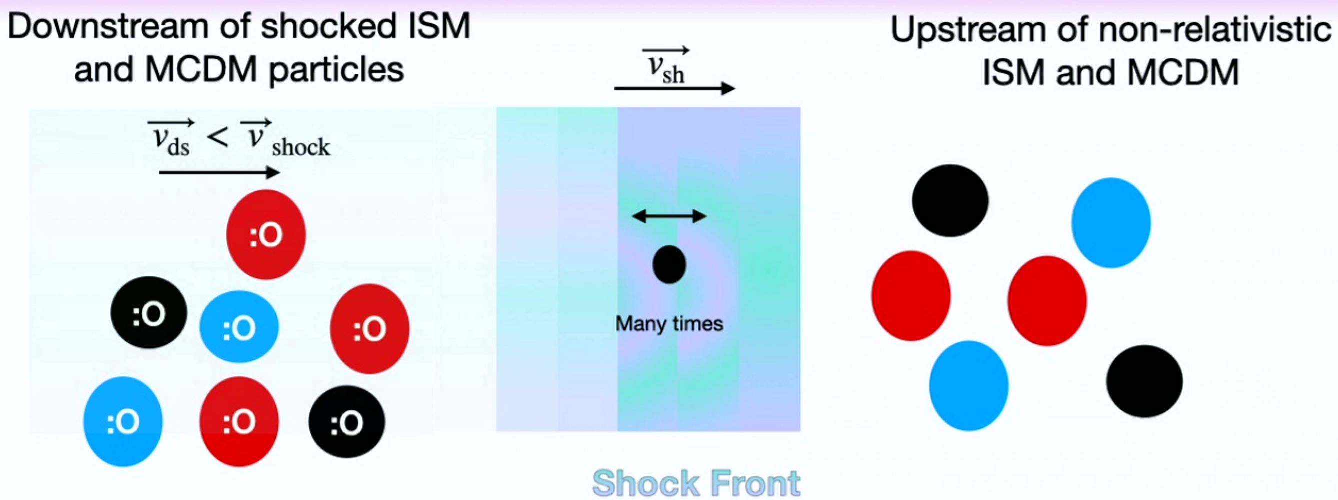
For low momenta:
scattering=disappears

$$\frac{\partial f_l}{\partial t} = D(p)\frac{\partial^2 f_l}{\partial z^2} - \frac{1}{t_{\rm CR}} f_l$$

For high momenta:
Scattering= a new fast dude appears!

$$\frac{\partial f_h}{\partial t} = D(p)\frac{\partial^2 f_h}{\partial z^2} + \frac{n_l(z,t)}{t_{\rm CR}} F_{\rm CR}(p)$$

Supernova Remnants (SNR)



SNRs can accelerate cosmic rays via Fermi Acceleration → they can do the same for mCDM

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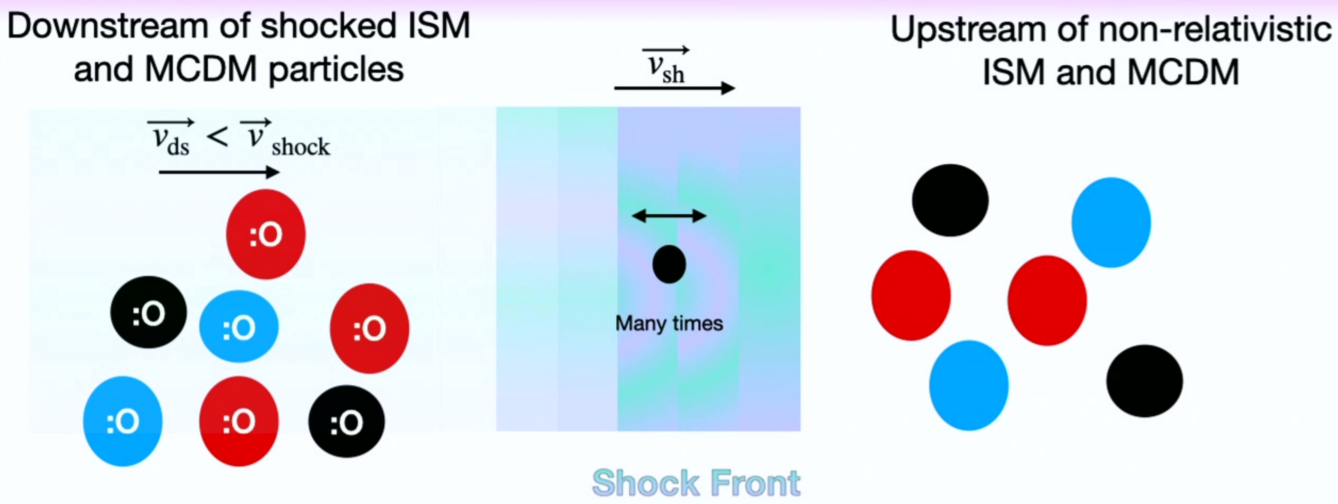

SNRs can accelerate cosmic rays via Fermi Acceleration → they can do the same for mCDM

Many **Many** theoretical uncertainties. Efficiency of the process is taken as a free parameter.

SNR acceleration

- The acceleration spectrum assuming one shock per particle is: $f_{\mathrm{SN}} = \dfrac{p^{-2}}{p_{\mathrm{min}}^{-1} - p_{\mathrm{max}}^{-1}}$

- We assume that a fraction $1/\kappa$ of the particles are accelerated. We assume single shock acceleration.

SNR acceleration

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- We assume that a fraction $1/\kappa$ of the particles are accelerated. We assume single shock acceleration.

- We also ensure that the total energy deposited in MCDM is $< 10^{51}{\rm erg} = E_{\rm SN}$.

New evolution equations

$$\frac{\partial f_l}{\partial t} = D(p)\frac{\partial^2 f_l}{\partial z^2} - \frac{1}{t_{\rm CR}} f_l - \frac{1}{t_{\rm SNR}} f_l \Theta(H_{\rm disk}/2 - |z|)$$

$$\frac{\partial f_h}{\partial t} = D(p)\frac{\partial^2 f_h}{\partial z^2} + \frac{n_l(z,t)}{t_{\rm CR}} F_{\rm CR}(p) + \frac{n_l(z,t)}{t_{\rm SNR}} F_{\rm SNR}(p)\Theta(H_{\rm disk}/2 - |z|)$$

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Things I didn't mention

Boundary Conditions:

$$D\partial_z f_l(t, \pm H_B/2, p) = \pm v(f_{\rm MB}(p) - f_l(t, \pm H_B/2, p))$$

$$D\partial_z f_h(t, \pm H_B/2, p) = \mp v f_h(t, \pm H_B/2, p)$$

Energy loss:

$$\frac{\partial f_h}{\partial t} = \ldots - \frac{\partial(b(p) f_h)}{\partial p}\Theta(H_{\rm disk}/2 - |z|)$$

(We will discuss this later, but don't worry too much because energy loss is weak for relativistic particles)

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    - ER
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- Preliminary guesses and hopes

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Millicharged particles have a small effective charge, and can be a component or all of our DM.
They diffuse through the GMFs of our galaxy, and are accelerated from collisions with cosmic rays, and from supernovae remanents' shocks

Solar Wind

- Our solar system (and 100AU around it) has streams of charged particles that deflect cosmic rays through magnetic fields.

- We use the force field approximation:

$$\frac{dn_{\text{Earth region}}}{dT}(T) = \frac{(T+m)^2 - m^2}{\left(T+m+e|Q|\Phi\right)^2 - m^2} \frac{dn_{\text{ISM}}}{dT}\left(T+|Q|e\Phi\right),$$

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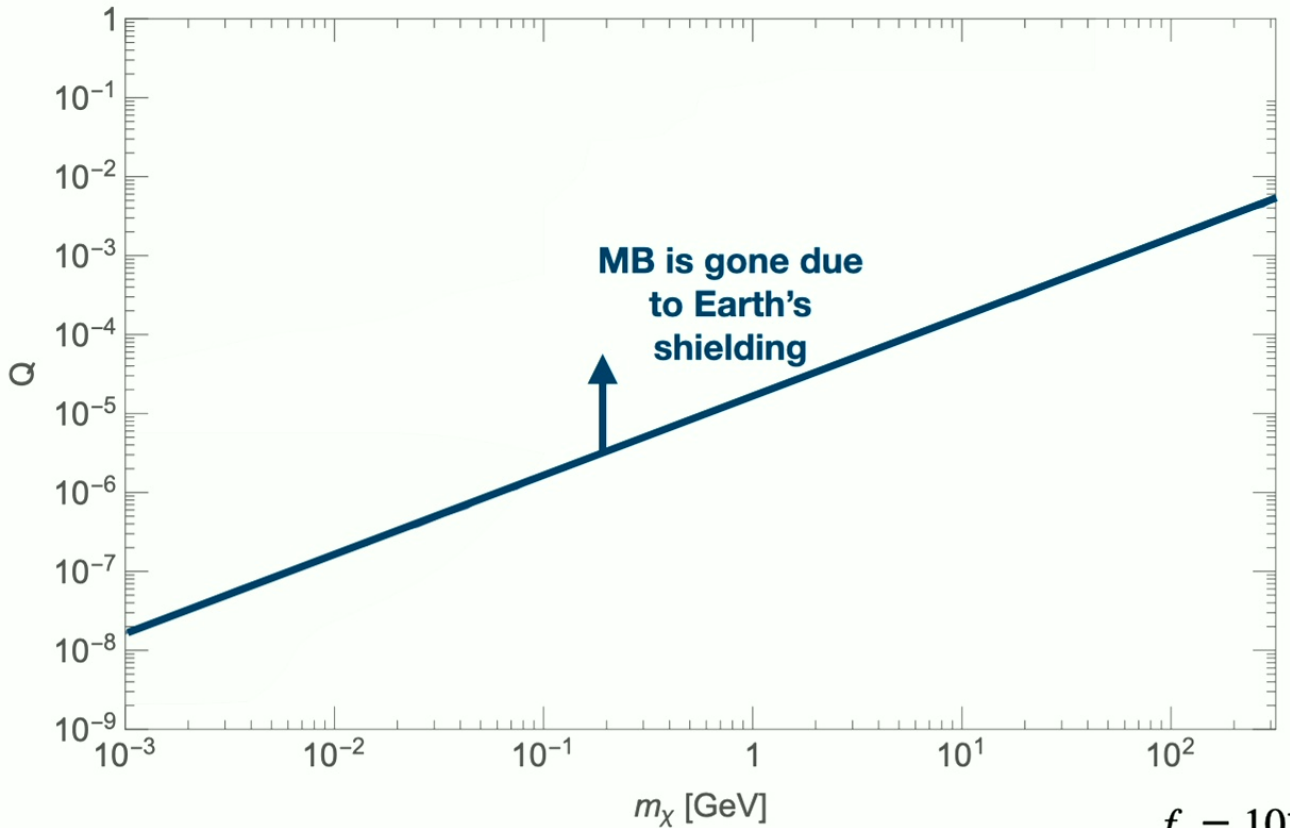
- Using [1511.01507], we have an effective $\Phi(R, \beta, t, \text{sign}(Q))$ that is phenomenologically fitted.

- The potential is very strongly dependent on the sign of the charge, so that one kind of charges can pass very easily compared to the other.

Earth's magnetic field

- To a fairly good approximation, when $r_g(R_{\rm earth})(\approx \dfrac{R_\chi}{0.3 \text{ Gauss}}) = R_{\rm earth}$, MCDM starts being deflected, with almost no MCDM arriving when it is much smaller.

- Therefore, a cut around: $R_\chi \gtrsim (5 - 50)$ GV



1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Q
MB is gone due to Earth's shielding
10^{-3}
10^{-2}
10^{-1}
1
10^{1}
10^{2}
m_χ [GeV]

$f_\chi = 10^{-3}$

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Overburden

- Our MCDM interacts fairly strongly with regular particles, so it can be stopped by earth's crust for underground experiments.

Overburden