Cosmic Rays from the U(1) Symmetry in the Dark Sector

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Motivation

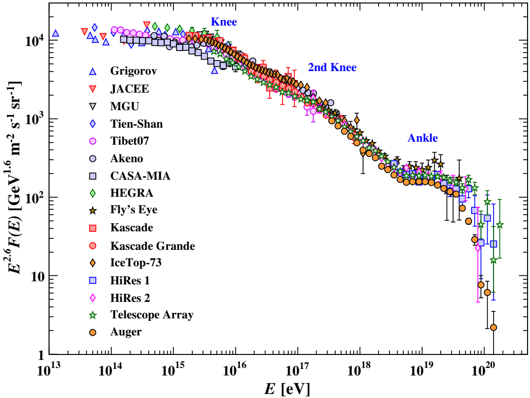


Figure : All Particle Cosmic Rays Spectrum (PDG, 2014)

Motivation

- **Bottom-up**: Boost charged particles to high energy scale by EM field. No need for beyond the Standard Model.

  ex: Fermi acceleration

- **Top-down**: Heavy particles decay or annihilation to create high-energy cosmic rays. Additional particles beyond the Standard model are needed.

  ex: SUSY, Majorana neutrino, ... etc

  Disadvantage: Fail to produce power law spectrum

- **Bottom-up + BSM**: Long-ranged force in the dark sector

  ex: $U(1)$ extension

Outline

- Motivation
- Model
- Acceleration of Dark Particles
- Detection
- Summary

Model

Model with $U(1)$ extension: Holdom (1986); Goldberg & Hall (1986); De Rujula *et al* (1990); Dimopoulos *et al* (1990), Feng *et al* (2009); Ackerman *et al* (2009) ...

Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm D} + \mathcal{L}_{\rm Mixing}$$

Hidden sector with dark fermion:

$$\mathcal{L}_{\rm D} = \bar{\psi}_{\rm D}(i\not{D} - m_{\rm D})\psi_{\rm D} - \frac{1}{4}\tilde{F}^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$\mathcal{L}_{\rm Mixing} = \frac{\tilde{\varepsilon}}{2}\tilde{F}^{\mu\nu}F_{\mu\nu}$$

where $\not{D} = \not{\partial} + iq\tilde{\not{A}}$ and $\tilde{F}_{\mu\nu} = (\partial_\mu \tilde{A}_\nu - \partial_\nu \tilde{A}_\mu)$.

Model

To decouple gauge fields, define

$$F'_{\mu\nu} = \tilde{F}_{\mu\nu} - \tilde{\varepsilon} F_{\mu\nu} = (\partial_\mu A'_\nu - \partial_\nu A'_\mu)$$

Decoupled gauge fields:

$$-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} \tilde{F}^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{\tilde{\varepsilon}}{2} \tilde{F}^{\mu\nu} F_{\mu\nu}$$

$$\rightarrow \quad -\frac{1}{4}(1 + \tilde{\varepsilon}^2) F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu}$$

Dark Photon: $A'_\mu = \tilde{A}_\mu - \varepsilon A_\mu$

Covariant: $\not{D} = \not{\partial} + iq\tilde{\not{A}} = \not{\partial} + iq\not{A}' + i\tilde{\varepsilon} q \not{B}$

Model

Atomic Dark Matter Model: Kaplan *et al* (2010, 2011); Cline *et al* (2012)

$$\mathcal{L}_{\rm D} = \bar{\psi}_e(i\not{D} - m_{{\rm D},e})\psi_e + \bar{\psi}_p(i\not{D} - m_{{\rm D},p})\psi_p - \frac{1}{4}\tilde{F}^{\mu\nu}\tilde{F}_{\mu\nu}$$

where $\not{D} = \not{\partial} \pm iq\tilde{\not{A}} = \not{\partial} \pm iq\not{A}' \pm i\tilde{\varepsilon}q\not{B}$.

Dark current:

$$J^\mu_{\rm D} = (\bar{\psi}_p\gamma^\mu\psi_p - \bar{\psi}_e\gamma^\mu\psi_e)$$

Interaction with ordinary matter with $\tilde{\varepsilon}q \equiv \varepsilon g'$:

$$\begin{aligned}\varepsilon g' J^\mu_{\rm D} B_\mu &= \varepsilon g' J^\mu_{\rm D}\left(\cos\theta_W A_\mu - \sin\theta_W Z^0_\mu\right)\\ &\equiv J^\mu_{\rm D}\left[\varepsilon e A_\mu + \varepsilon\frac{g_X}{2}\left(\frac{g}{\cos\theta_W}\right)Z^0_\mu\right]\end{aligned}$$

Model

Free Parameters:

$$\begin{cases} \text{Dark Particle Mass} & : \quad m_X \\ \text{Coupling} & : \quad \alpha_{\mathrm{D}} = \dfrac{q^2}{4\pi} \\ \text{Mixing} & : \quad \tilde{\varepsilon} \;\to\; \varepsilon \end{cases}$$

Dark Atom Parameters:

$$\begin{cases} \text{Reduced Mass} & : \quad \mu = \dfrac{m_{\mathrm{D},e}\, m_{\mathrm{D},p}}{m_{\mathrm{D},e} + m_{\mathrm{D},p}} \\ \text{Bohr Radius} & : \quad 1/\mu\alpha_{\mathrm{D}} \\ \text{Binding Energy} & : \quad \frac{1}{2}\mu\alpha_{\mathrm{D}}^2 \end{cases}$$

Model: Parameter Space

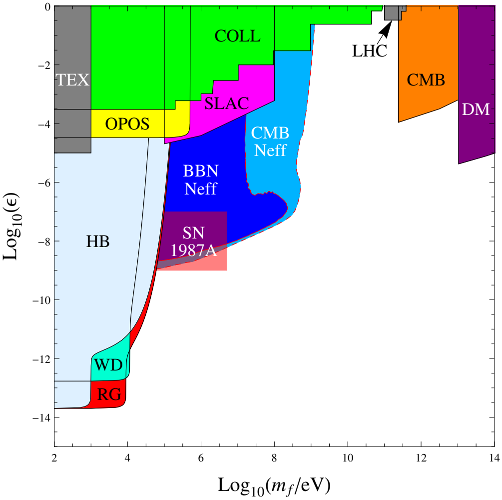


Figure : Constrained parameter space of millicharged particle by Vogel & Redondo (2014)

Acceleration of Dark Particles

With millicharge εe, dark particles can be accelerated as normal charged particles.

Mechanisms:

- Fermi Acceleration, Potential Drop, by Dark EM Field...

Sources:

- Galactic: Supernova Remnant (SNR), Pulsar, ...
- Extragalactic: Active Galactic Nucleus (AGN), Gamma Ray Burst, ...

Acceleration of Dark Particles - SNR

Fermi Acceleration driven by Supernova Shock:

$$\frac{dE}{dt} = \frac{UE}{\tau} + \left.\frac{dE}{dt}\right|_{\rm syn}$$

where $\tau \sim r_g/U = E/(\varepsilon e B_\perp U)$.

The upper limit of maximum energy:

$$E_{\rm max} = \varepsilon e B U L$$

If the radiation loss is significant,

$$\left.\frac{dE}{dt}\right|_{\rm syn} = -\frac{2\varepsilon^2 \alpha_{\rm EM}\alpha_{\rm D} B_\perp^2}{3m_X^4} E^2 \ \Rightarrow\ E_{\rm max}^{\rm syn} = \left[24\pi^2 \left(\frac{\alpha_{\rm EM}}{\alpha_{\rm D}}\right) \frac{U^2 m_X^4}{\varepsilon e^3 B_\perp}\right]^{1/2}$$

Acceleration of Dark Particles - Pulsar

Potential Drop of Pulsar:

$$\varepsilon e\,\Delta V \simeq \varepsilon e \frac{B\,\Omega\,R_p^2}{2}$$

$$= 5 \times 10^{18}\,\varepsilon\,\mathrm{eV}\left(\frac{B}{10^{12}\ \mathrm{G}}\right)\left(\frac{\Omega}{10^3/s}\right)\left(\frac{R_p}{10\,\mathrm{km}}\right)^2$$

Consider the curvature radiation:

$$\left.\frac{dE}{dt}\right|_{\mathrm{curve}} = -\frac{8\pi\alpha_{\mathrm{D}}}{3R_c^2}\left(\frac{E}{m_X}\right)^4$$

$$\Rightarrow\ E_{\mathrm{max}} \sim 2.5 \times 10^{17}\ \mathrm{eV}\ \left(\frac{m_X}{\mathrm{GeV}}\right)\varepsilon^{1/4}\left(\frac{\alpha_{\mathrm{EM}}}{\alpha_{\mathrm{D}}}\right)^{1/4}$$

Acceleration of Dark Particles

Upper Limit of Accelerations by Galactic Sources

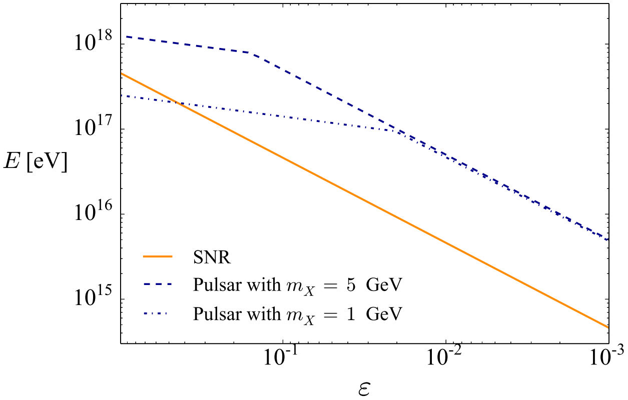


Figure : For SNR, $L \sim 10$ pc and $B = 5$ mG. For pulsars, $\sim R_c = 10^7$ m and $\alpha_{\rm D}/\alpha_{\rm EM} = 1$. The mass $m_X = 1$ GeV and 5 GeV are considered.

Acceleration of Dark Particles

Anisotropy

Compare the thickness of the galactic disk ~ 300 pc to gyroradius

$$r_{\rm g} = \frac{E}{\varepsilon e B} = 360 \ {\rm pc} \left(\frac{E/\varepsilon}{10^{18} \ {\rm eV}} \right) \left(\frac{3 \mu {\rm G}}{B} \right)$$

For electron/proton, anisotropy $\rightarrow \ E \gtrsim 10^{18}$ eV

For millicharged particle with $\varepsilon = 10^{-2}$, anisotropy $\rightarrow \ E \gtrsim 10^{16}$ eV

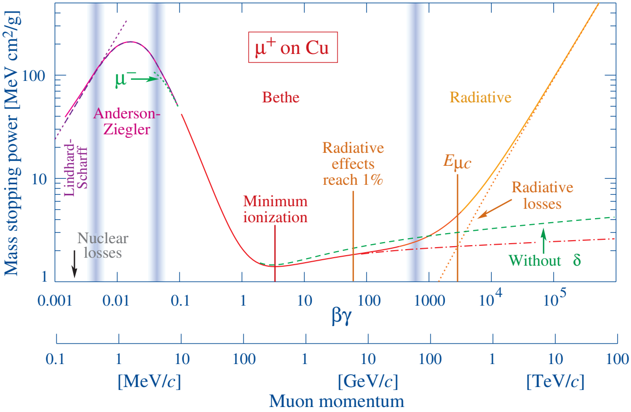
Detection

- No hadronic shower in the atmosphere
  $\rightarrow$ lepton search, ex: muon, neutrino
- Space-based detectors: PAMELA, AMS, ...
- Underground detectors: Super-Kamiokande, Icecube, ...
- Stopping power:

$$-\left\langle \frac{dE}{dx} \right\rangle = a_X(E) + b_X(E)E$$

Detection

Muon Stopping Power (PDG,2014)



Detection

In the **Intermediate Energy** scale ($1 \lesssim \beta\gamma \lesssim 1000$)

Bethe-Bloch Formula:

$$-\left\langle \frac{dE}{dx} \right\rangle = kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

which is proportional to the square of absolute charge z^2.

Space-based cosmic ray detector: **PAMELA**, **AMS**, ...

- Silicon tracker $\rightarrow$ Minimum Ionizing Particles (mip)

Detection

- Energy deposit in Super-Kamiokande
- Cherenkov radiation from the process

$$X + e^- \to X + e^-$$

which can be compared to background signal from atmospheric neutrinos.

Suppose the main sources of dark particles and proton are the same, and we propose the total flux

$$\frac{N_x}{N_p} = \left(\frac{\rho_x/m_x}{\rho_p/m_p}\right)\left(\frac{e_x}{e_p}\right) \sim 3.8\,\varepsilon^2 \left(\frac{\mathrm{GeV}}{m_X}\right)^2$$

Detection

Vertical dark particle intensity

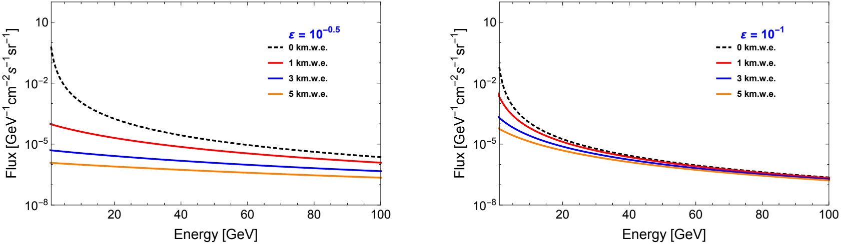


Figure : Energy spectrum of X after traversing 0, 1, 3 and 5 km.w.e. distance of standard rock, assuming $m_X = 1$ GeV. The cases of $\varepsilon = 10^{-0.5}$ (left) and $\varepsilon = 10^{-1}$ (right) are displayed.

Detection

Energy deposit in Super-Kamiokande

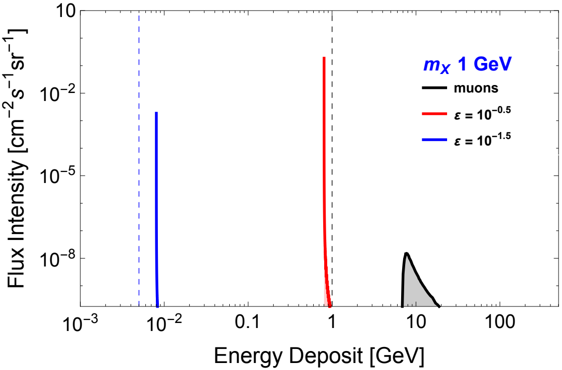


Figure : Energy deposit from a vertical through-going flux of millicharged dark matter particles. Vertical dashed lines denote the current SK through-going muon fitter capabilities ($\sim$ 1 GeV) as well as possible future improvement ($\sim$ 5 MeV).

Detection

In the **High Energy** scale

The stopping power

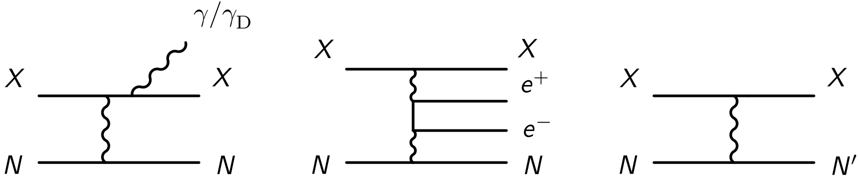
$$-\left\langle \frac{dE}{dx} \right\rangle = a_X(E) + b_X(E)E$$

The radiative contribution includes **Bremsstrahlung**, **Pair Production**, and **Photonuclear Interaction**:

$$b_X = b_{\mathrm{brem}} + b_{\mathrm{pair}} + b_{\mathrm{nucl}}$$

$\rightarrow$ **Cherenkov Radiation**

Detection



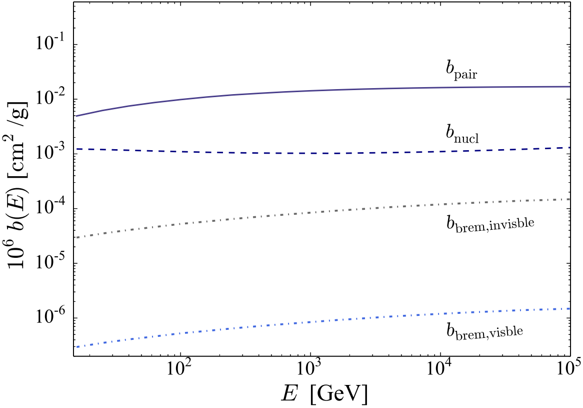
$$
\begin{cases}
\text{Bremsstrahlung (visible)} & \propto \quad \varepsilon^4/m_x^2 \\
\text{Bremsstrahlung (invisible)} & \propto \quad \varepsilon^2\,(\alpha_{\rm D}/\alpha_{\rm EM})/m_x^2 \\
\text{Pair Producation} & \propto \quad \varepsilon^2/m_x \\
\text{Photonuclear Interaction} & \propto \quad \varepsilon^2
\end{cases}
$$

Compared to muons:

$$b_X/b_{\rm muon} \sim (m_\mu/m_x)\,\varepsilon^2/2$$

Detection

The Radiative Energy Loss of Millicharged Particles

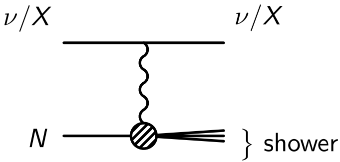


The parameters $m_X = 1$ GeV, $\varepsilon = 0.1$, and $\alpha_{\text{D}} = \alpha_{\text{EM}}$ are chosen.

Detection

Produce IceCube Shower Events?

- Suppressed rediative loss $\rightarrow$ behaves like a muon with lower energy
- Event selection
- Deep inelastic scattering (DIS) $\rightarrow$ shower events



Detection

Deep inelastic scattering (DIS) of millicharged particles:

$$\frac{d\sigma^X}{dxdy} = \varepsilon^2 \, \frac{4\pi\alpha_{\rm EM}^2 ME}{Q^4} \left\{ \left(1 - y - \frac{Mxy}{2E}\right) \left[F_2^\gamma - g_X \eta_{\gamma Z} F_2^{\gamma Z} + g_X^2 \eta_Z F_2^Z\right] \right. \\ \left. + \frac{y^2}{2} 2x \left[F_1^\gamma - g_X \eta_{\gamma Z} F_1^{\gamma Z} + g_X^2 \eta_Z F_1^Z\right] \right\}$$

Compared to inelastic scattering of neutrino,

$$\frac{d\sigma^X}{dxdy} \bigg/ \frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} = 4\varepsilon^2 \sin^4\theta_W \, \frac{4\cos^4\theta_W F_2^\gamma + 2\cos^2\theta_W F_2^{\gamma Z} + F_2^Z}{F_2^Z + \cos^4\theta_W F_2^W} \\ \sim \varepsilon^2$$

Cosmic Ray Abundance to Explain Icecube Data

The best fit of neutrino flux spectrum in the range 30 – 2000 TeV:

$$1.5 \times 10^{-18} \left(\frac{100 \text{ TeV}}{E} \right)^{2.3} \text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

The spectrum of millicharged cosmic rays:

$$\frac{dN^X}{dE} = 4.7 \times 10^{-7} \varepsilon^{-2} \left(\frac{E}{\text{GeV}} \right)^{-2.3} \text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Cosmic Ray Abundance

Cosmic Rays from Point Sources

Diffusion equation:

$$\frac{\partial n}{\partial t} = \nabla \cdot (D \nabla n) - \frac{\partial}{\partial E}(bn) + \mathcal{Q}$$

with $\mathcal{Q}(\mathbf{r}, E) = \delta(\mathbf{r})\, Q_0\, (E/\mathrm{GeV})^{-\gamma}$.

The generated spectrum:

$$\frac{dN^X}{dE} = \frac{Q_0}{16\pi^2 R D(E)} \left(\frac{E}{\mathrm{GeV}}\right)^{-\gamma}$$

Cosmic Ray Abundance

In order to explain IceCube signals:

$$Q_0 = 2 \times 10^{39}\, \varepsilon^{-2} \left(\frac{R}{8\,\mathrm{kpc}} \right) \mathrm{GeV}^{-1}\mathrm{s}^{-1}$$

Power Needed:

$$\mathcal{P} = 2 \times 10^{39}\, \varepsilon^{-2} \left(\frac{R}{8\,\mathrm{kpc}} \right) \frac{1}{\gamma - 2} \left(\frac{E_{\mathrm{min}}}{\mathrm{GeV}} \right)^{-\gamma+2} \mathrm{GeV}\,\mathrm{s}^{-1}$$

Power of Supernovae:

$$\mathcal{P}_{\mathrm{sn}} = 10^{51}\,\mathrm{erg}/\,100\,\mathrm{yr} = 2 \times 10^{44}\,\mathrm{GeV}\,\mathrm{s}^{-1}$$

Cosmic Ray Abundance

Total Flux Needed:

$$\mathcal{F} = 2 \times 10^{39}\,\varepsilon^{-2}\left(\frac{R}{8\,\mathrm{kpc}}\right)\frac{1}{\gamma-1}\left(\frac{E_{\mathrm{min}}}{\mathrm{GeV}}\right)^{-\gamma+1}\mathrm{s}^{-1}$$

Total Flux of Supernovae:

$$\mathcal{F}_{\mathrm{sn}} = 5.4 \times 10^{54}\left(\frac{R_{\mathrm{sh}}}{100\,\mathrm{pc}}\right)^{3}\left(\frac{\mathrm{GeV}}{M_{\mathrm{D}}}\right)\left(\frac{\Gamma}{1/30\,\mathrm{yr}}\right)\mathrm{s}^{-1}$$

Total Flux of Pulsars

$$\mathcal{F}_{\mathrm{pulsar}} = \left(\frac{\rho_{\mathrm{D}}}{M_{\mathrm{D}}}\right) c\, R_p^2 \pi = 2.8 \times 10^{20}\left(\frac{\mathrm{GeV}}{M_{\mathrm{D}}}\right)\mathrm{s}^{-1}$$

Summary

- Dark Cosmic Rays from U(1) charge
- Cosmic rays detection:

  Indirect Search $\rightarrow$ **Direct Search**
- **SNR** serves as a potential Galactic sources
- Detection in **SuperK**
- Possibly resemble the **IceCube Shower Events**