Dark Cosmic Rays

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Motivation

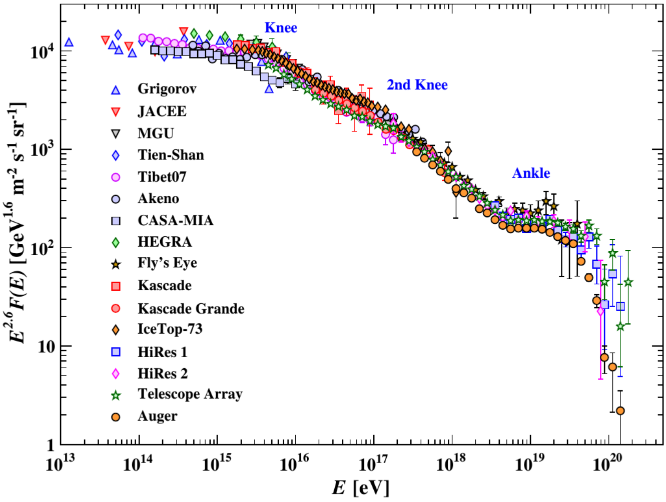


Figure : All particle cosmic rays spectrum (PDG review, 2014)

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 + Beyond SM**: Long-ranged force in the dark sector

  ex: $U(1)$ extension

Outline

- Motivation
- Model with $U(1)_D$ Extension
- Acceleration of Dark Cosmic Rays
- 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:

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

Dark sector:

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

Kinetic mixing:

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

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

Model

Dark fermions couple to both **dark photon** and **photon** fields

$\rightarrow$ carry a **millicharge** εe

SM fermions only couple to **photon**.

Free Parameters:

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

Model: Parameter Space

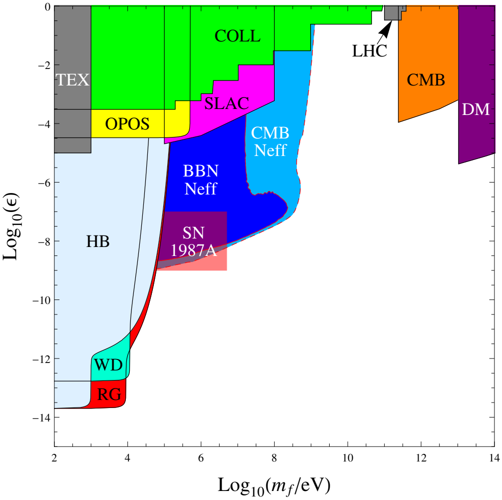


Figure : Constrained parameter space of millicharged particle by Vogel & Redondo (2014)

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

First-order Fermi acceleration (diffusive shock acceleration):

Acceleration driven by shock waves and magnetic mirrors.
Maximum energy:

$$E_{\max} \sim QBUL \quad \rightarrow \quad \varepsilon eBUL$$

Magnetic field: B
Speed of shock wave: U
Total distance of acceleration: L

For SNR,

$$E_{\max} \sim \varepsilon \left(\frac{B}{\mu \mathrm{G}}\right) \left(\frac{U}{0.1\mathrm{c}}\right) \left(\frac{L}{\mathrm{pc}}\right) \mathrm{PeV}$$

Acceleration of Dark Particles

Suppose dark cosmic rays and cosmic ray protons are both driven by **Fermi acceleration** and from the **same source**:

$\rightarrow$ SNR near Galactic Center

Dark cosmic ray flux (rigidity spectrum, $R = p/Q$):

$$\frac{dN_X}{dR} \bigg/ \frac{dN_p}{dR} \simeq \frac{(\rho_{\rm X}/m_{\rm X})}{(\rho_{\rm p}/m_{\rm p})} \times \frac{e^X_{\rm inj}}{e^p_{\rm inj}}$$

Number density of proton in interstellar medium: $(\rho_{\rm p}/m_{\rm p}) \sim 1/\text{cm}^3$

Number density of DM near Galactic Center: $(\rho_{\rm X}/m_{\rm X}) \sim 4.1\,({\rm GeV}/m_{\rm X})/\text{cm}^3$

Acceleration of Dark Particles

$(e^N_{\rm inj}/e^p_{\rm inj})$ increases with mass-to-charge ratio, i.e. (Z/A) or $(m_X/m_p)/\varepsilon$,and saturates at (Z/A), $(m_X/m_p)/\varepsilon \gtrsim 4$.

Measured proton flux:

$$\frac{dN_p}{dE} = 1.4 \left(\frac{E}{\text{GeV}}\right)^{-\alpha} / (\mathrm{GeV\,cm^2\,s\,sr})$$

with $\alpha = 2.7$.

Dark cosmic ray flux:

$$\frac{dN_{\rm X}}{dE} \simeq \frac{(\rho_{\rm X}/m_{\rm X})}{(\rho_{\rm p}/m_{\rm p})} \frac{e^X_{\rm inj}}{e^p_{\rm inj}} \varepsilon^{(\alpha-1)} \frac{dN_p}{dE}$$

$$= 30\,\varepsilon^{(\alpha-1)} \left(\frac{\text{GeV}}{m_{\rm X}}\right) \left(\frac{E}{\text{GeV}}\right)^{-\alpha} / (\mathrm{GeV\,cm^2\,s\,sr}),$$

Detection

How to detect dark cosmic rays?

- No hadronic shower in the atmosphere

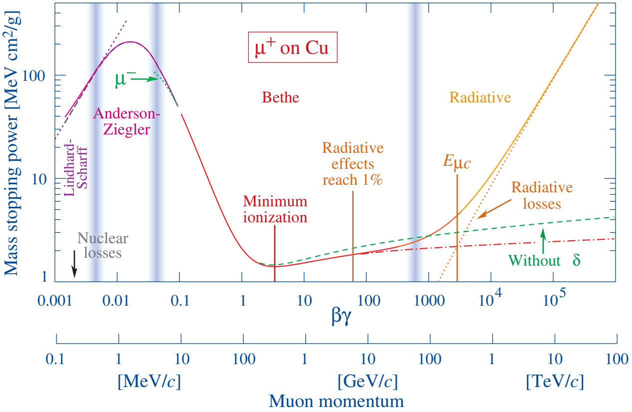
  $\rightarrow$ lepton search, ex: muon, neutrino

- 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

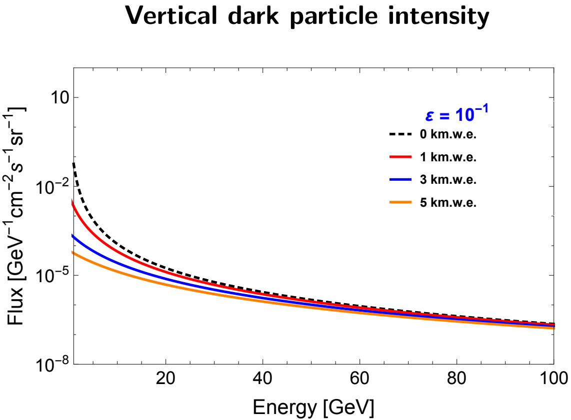


Figure : Energy spectrum of X after traversing 0, 1, 3 and 5 km.w.e. distance of standard rock, assuming $m_X = 1$ GeV.

Detection: Super-Kamiokande

Energy deposit in Super-Kamiokande

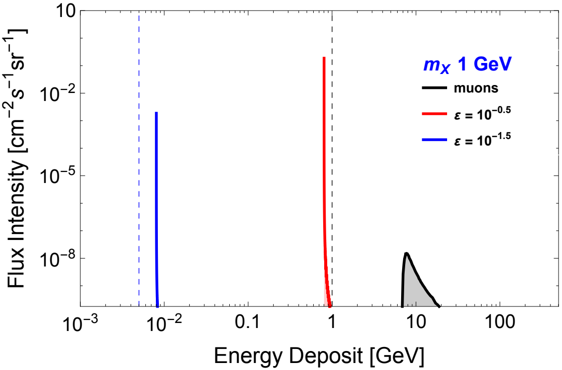


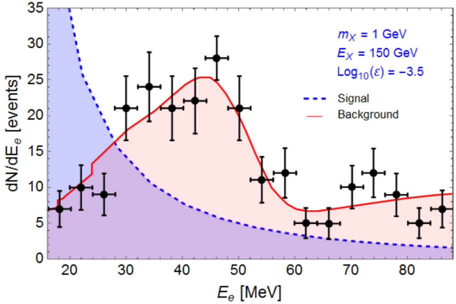
Figure : Energy deposit from a vertical through-going flux of millicharged dark matter particles. Vertical dashed lines denote the current SK through-going muon fitter capabilities ($\sim$ 1 GeV) as well as possible future improvement ($\sim$ 5 MeV).

Detection: Super-Kamiokande

Cherenkov radiation from the process

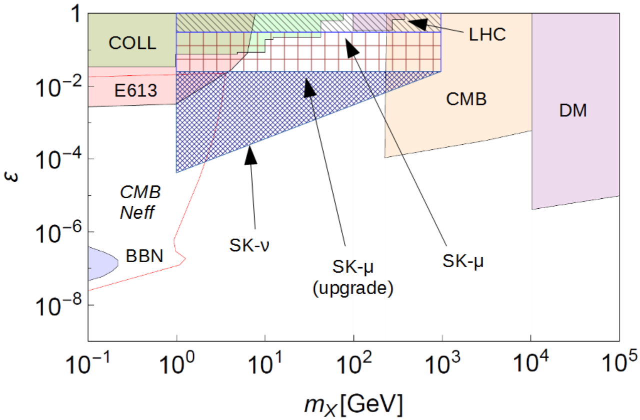
$$X + e^- \to X + e^-$$

which can be compared to background signal from atmospheric neutrinos.



Detection: Super-Kamiokande

Parameter space revisited



Detection

In the **High Energy** scale

The stopping power

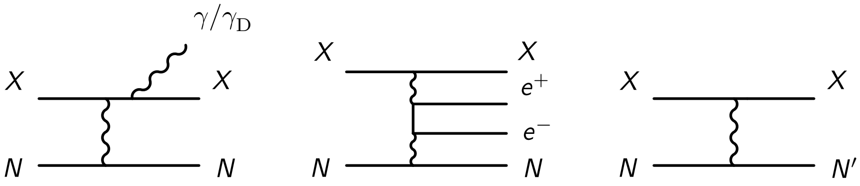
$$-\left\langle \frac{dE}{dx} \right\rangle = a_X(E) + b_X(E)E$$

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

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

$\rightarrow$ **Cherenkov Radiation**

Detection



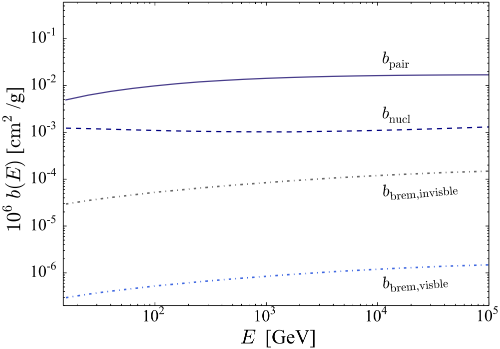
$$\begin{cases} \text{Bremsstrahlung (visible)} & \propto \quad \varepsilon^4/m_x^2 \\ \text{Bremsstrahlung (invisible)} & \propto \quad \varepsilon^2\,(\alpha_{\mathrm{D}}/\alpha_{\mathrm{EM}})/m_x^2 \\ \text{Pair Producation} & \propto \quad \varepsilon^2/m_x \\ \text{Photonuclear Interaction} & \propto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

Compared to muons:

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

Detection

Radiative energy loss of millicharged particles

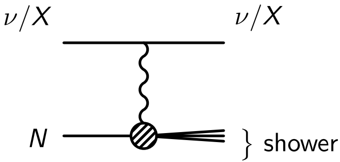


The parameters $m_X = 1$ GeV, $\varepsilon = 0.1$, and $\alpha_{\rm D} = \alpha_{\rm EM}$ are chosen.

Detection: IceCube

Produce IceCube Shower Events?

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



Summary

- Kinetic mixing $\rightarrow$ εe charge $\rightarrow$ **Dark Cosmic Rays**
- Predict dark cosmic rays flux from proton flux measurement
- Cosmic rays detection:

  Indirect Search $\rightarrow$ **Direct Search**
- **SNR** serves as a potential Galactic sources
- Detection in **SuperK** explores DM mass region 1 - 200 GeV
- Possibly resemble the **IceCube Shower Events**