511 keV γ-ray Emission from the Galactic Bulge by MeV Millicharged Dark Matter

Park, Jong-Chul

Seoul National University

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In collaboration with Ji-Haeng Huh, Jihn E. Kim, Seong Chan Park

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The Observation of 511keV γ-ray

- The first discovery

  γ-rays from the galactic center (GC) region was detected with a line center at 476 ± 26 keV.

  (Johnson et al., ApJ **172**, L1 (1972))

- More recent high resolution observations (cf. $m_e \simeq 510.99892$ keV)

instrument	year	flux $[10^{-3}\ ph\ cm^{-2}\ s^{-1}]$	centroid $[keV]$
HEAO-3	1979 – 1980	1.13 ± 0.13	510.92 ± 0.23
HEXAGONE	1989	1.00 ± 0.24	511.33 ± 0.41
TGRS	1995 – 1997	1.07 ± 0.05	510.98 ± 0.10
SPI/INTEGRAL	2003–	1.02 ± 0.10	$511.06^{+0.17}_{-0.19}$

- The shape of spatial distribution

  The morphology of the emission region is consistent with a 2-dimensional gaussian of a full width at half maximum (FWHM) of 6° with a 2σ uncertainty range covering $4^\circ - 9^\circ$.

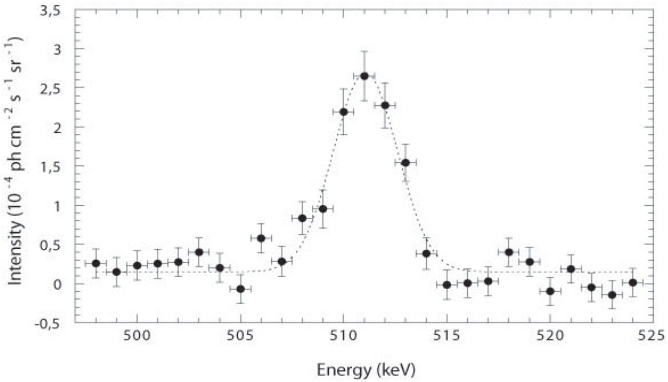


Figure: 511 keV γ-ray flux spectrum.

(Jean et al., Astron. Astrophys. **407**, L55 (2003))

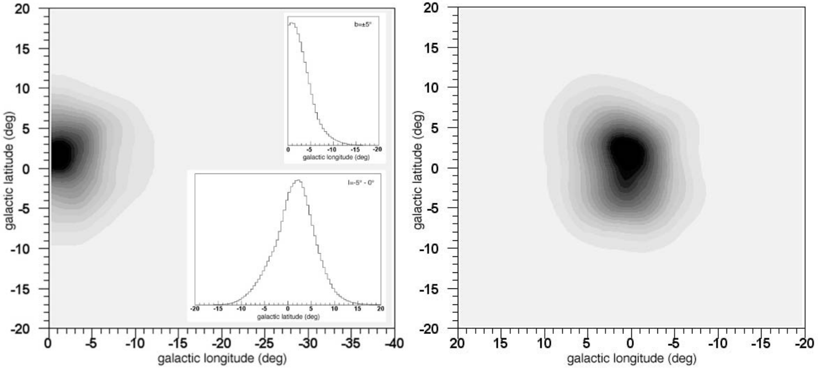


Figure: 511 keV γ-ray line intensity map of the GC region.

(Knodlseder et al., Astron. Astrophys. **411**, L457 (2003))

What is the origin of these positrons?

Various Possible Sources of e^+

- Astrophysical sources
  Massive stars, Hypernovae, Cosmic-ray interactions ($N + p \rightarrow \pi^+ \rightarrow e^+$), X-ray binaries (HMXB, LMXB), Classical novae, Thermonuclear Type Ia supernovae (SN Ia).

  (Knodlseder et al., Astron. Astrophys. **441**, 513 (2005))

- Particle physics
  $\star$ Light dark matter (DM) annihilation or decay
  $\longrightarrow$ Axino, Sterile neutrino, Light scalar, N=2 SUSY.
  $\star$ Others $\longrightarrow$ Exciting heavy DM with near-degenerate sates.

- The shape and flux of the emission impose severe constrains on the principal galactic e^+ sources.

Dark Matter

- Nature of DM
  DM is a hypothetical matter which is stable and neutral so that it has survived but has not been directly observed until now. $\Omega_{DM} \simeq 0.23$

- Only neutral DM?
  Only neutral particles are typically considered as DM candidates. However, charged particles also cannot be seen, i.e. could be a DM candidate, if their electric charge is sufficiently tiny.

Kinetic Mixing and Millicharged Particle I

- If there exists another massless $U(1)$ gauge boson (*'exphoton'*) beyond the SM, most probably there can exist a kinetic mixing via loop effects between the photon and exphoton. After a proper diagonalization procedure of the kinetic energy terms, the hidden sector particles can be electromagnetically millicharged.

  (Okun, Sov. Phys. JETP **56**, 502 (1982); Holdom, Phys. Lett. **B166**, 196 (1986))

- Kinetic mixing
  The kinetic mixing between $U(1)_{\rm em}$ and $U(1)_{\rm ex}$ is parametrized as

$$\mathcal{L} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\xi}{2}\hat{F}_{\mu\nu}\hat{X}^{\mu\nu} \ .$$

Kinetic Mixing and Millicharged Particle II

- **Diagonalization of kinetic terms**

  By the following transformation of the gauge fields,

$$\begin{pmatrix} A_\mu \\ X_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{1-\xi^2} & 0 \\ \xi & 1 \end{pmatrix} \begin{pmatrix} \hat{A}_\mu \\ \hat{X}_\mu \end{pmatrix} ,$$

  we obtain

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} .$$

- **Interactions in the original basis**

  The interaction Lagrangian of a SM fermion:

$$\mathcal{L} = \bar{\psi} \left(\hat{e} Q \gamma^\mu \right) \psi \hat{A}_\mu .$$

  For a hidden sector fermion χ with a $U(1)_{\rm ex}$ charge Q_χ,

$$\mathcal{L} = \bar{\chi} \left(\hat{e}_{\rm ex} Q_\chi \gamma^\mu \right) \chi \hat{X}_\mu ,$$

  where $\hat{e}_{\rm ex} \neq \hat{e}$ in general.

Kinetic Mixing and Millicharged Particle III

- Interactions in the transformed basis
  The Lagrangian of a SM fermion:

$$\mathcal{L} = \bar{\psi}\left(\frac{\hat{e}}{\sqrt{1-\xi^2}} Q\gamma^\mu\right)\psi A_\mu \ .$$

  For a hidden sector fermion χ,

$$\mathcal{L} = \bar{\chi}\gamma^\mu\left(\hat{e}_{\rm ex} Q_\chi X_\mu - \hat{e}_{\rm ex}\frac{\xi}{\sqrt{1-\xi^2}} Q_\chi A_\mu\right)\chi \ .$$

- The physical hidden sector coupling: $e_{\rm ex} \equiv \hat{e}_{\rm ex}$.
  The coupling of the field χ to the photon A: $\varepsilon e \equiv -e_{\rm ex}\xi/\sqrt{1-\xi^2}$.

Annihilation Cross Sections

Needed cross sections for the cosmological study of χ

$$\chi\bar{\chi} \to 2\gamma_{\rm ex},\ \chi\bar{\chi} \to e^- e^+,\ \chi\bar{\chi} \to \gamma\gamma_{\rm ex},\ \text{and}\ \chi\bar{\chi} \to \gamma\gamma\ . \tag{1}$$

The ratio for these cross-sections

$$\sigma_{2\gamma_{\rm ex}} : \sigma_{e+e-} : \sigma_{\gamma\gamma_{\rm ex}} : \sigma_{2\gamma} \simeq \alpha_{\rm ex}^2 : \varepsilon^2\alpha^2 : \varepsilon^2\alpha\alpha_{\rm ex} : \varepsilon^4\alpha^2\ . \tag{2}$$

1. The first two channels mainly determine the relic density of the particle χ.
2. The process $\chi\bar{\chi} \to e^- e^+$ also determines the 511 keV photon flux.

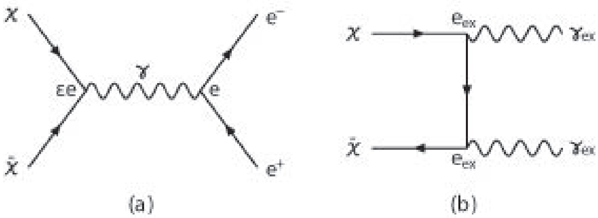


Figure: Annihilation diagrams of the millicharged particle χ to (a) e^+e^- and (b) $2\gamma_{\rm ex}$. The cross diagram in (b) is not shown.

Relic Density

- $\langle \sigma v \rangle = a + b\langle v^2 \rangle + \mathcal{O}(\langle v^4 \rangle)$
- The relic density of a generic relic X

$$\Omega_X h^2 \approx \frac{1.07 \times 10^9\,\mathrm{GeV}^{-1}}{M_{Pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{(a + 3b/x_F)}$$
$$= 8.77 \times 10^{-17}\,\mathrm{MeV}^{-2} \frac{x_F}{\sqrt{g_*}} \frac{1}{(a + 3b/x_F)} \,.$$

(Bertone et al., Phys. Rep. **405**, 279 (2005))

- The relic density of the millicharged particle χ

$$\Omega_\chi h^2 \approx 1.6 \times 10^{-13} \frac{(11.6 + \ln \overline{m})\overline{m}^2}{\left(\frac{\alpha_{\rm ex}}{\alpha}\right)^2 + \varepsilon^2 \left(1 - \frac{m_e^2}{m_\chi^2}\right)^{1/2} \left(1 + \frac{m_e^2}{2m_\chi^2}\right)} \,,$$

where $\overline{m} \equiv m_\chi/\mathrm{MeV}$.

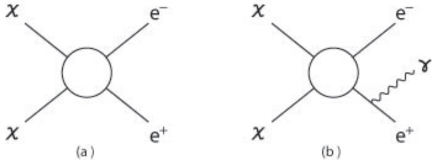
Note : In this step, we use $a = a_{e^-e^+} + a_{2\gamma_{\rm ex}}$ and $b = b_{e^-e^+} + b_{2\gamma_{\rm ex}}$.

Other Constraints

- Debye screening length
  The Debye screening length in the DM plasma, $\lambda_D = \sqrt{T_\chi/\varepsilon^2 e^2 n_\chi}$, is required to be larger than $1/m_\gamma^{\text{eff}}$.

  (Mitra, PRD **74**, 043532 (2006))

- Internal bremsstrahlung
  The process $\chi\chi \to e^+e^-$ is accompanied by the process $\chi\chi \to e^+e^-\gamma$.



- Comparing with COMPTEL and EGRET measurements of the diffuse γ-ray flux from the GC region, the internal bremsstrahlung contribution provides a constraint: $m_\chi \lesssim 20\mathrm{MeV}$

  (Beacom et al., PRL **94**, 171301 (2005))

- Recent analysis including the internal bremsstrahlung radiation and in-flight annihilation gives more stringent mass bound: $m_\chi \lesssim 3-4$ MeV.

  (Beacom et al., PRL **97**, 071102 (2006))

511keV γ-ray Flux I

1. If $m_\chi < m_\mu, m_\pi$, the low velocity annihilation of a pair of χ particles dominantly produce an $e^- e^+$ pair.
2. Most positrons lose energy through their interactions with the inter-stellar-medium (ISM) and bremsstrahlung radiation, and go rest and partly via the direct annihilation into two 511 keV gamma rays.
3. Positron annihilation mostly takes place via the positronium formation ($\sim 96.7 \pm 2.2\%$).

   (Jean et al., Astro. Astrophys. **445**, 579 (2006))

4. A singlet positronium state decays to two 511 keV photons (25%), whereas a triplet state decays to three continuum photons (75%).

511keV γ-ray Flux II

- The 511 keV γ-ray flux from the GC

$$\Phi_{\gamma,511} \simeq 0.275 \times 5.6 \left(\frac{\sigma v}{\mathrm{pb}}\right)\left(\frac{1\,\mathrm{MeV}}{m_\chi}\right)^2 \overline{J}(\Delta\Omega)\Delta\Omega\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \,,$$

where $\Delta\Omega$ is the observed solid angle toward the direction of the GC and $\overline{J}(\Delta\Omega)$ is defined as the average of $J(\psi)$ over a spherical region of solid angle $\Delta\Omega$ centered on $\psi = 0$.

(Bertone et al., Phys. Rep. **405**, 279 (2005))

- Halo profile depending factor

$$J(\psi) = \frac{1}{8.5\,\mathrm{kpc}}\left(\frac{1}{0.3\,\mathrm{GeV/cm}^3}\right)^2 \int_{\text{line of sight}} d\,s\,\rho^2\,(r(s,\psi)) \,,$$

where s is the coordinate running along the line of sight, in a direction making an angle ψ from the direction of the GC.

(Bergstrom et al., Astropart. Phys. **9**, 137 (1998))

The DM Halo Density Profile

1. The usual parametrization of a DM halo density

$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma[1 + (r/R)^\gamma]^{(\beta-\gamma)/\alpha}} \ ,$$

where α, β, γ, and R are set by the choice of halo model and R is the distance from the GC at which the power law breaks. For the region we are concerned with, $r \ll R$:

$$\rho(r) \propto \frac{1}{r^\gamma} \ .$$

(Bertone et al., Phys. Rep. **405**, 279 (2005))

2. Comparing with the observed distribution
The modest slope of $\gamma \sim 0.6 - 1.2$ provides the best fit to the distribution observed by SPI.

Constraint from 511 keV $\gamma-$ray Flux I

- The observational result

  The γ-ray profile has 6° FWHM which varies between 4° and 9° (2σ limits) and the flux is $\Phi_{\gamma,511} \simeq (1.02 \pm 0.10) \times 10^{-3}$ ph cm^{-2} s^{-1}.

- The final relation for the charge ε

  $\Delta\Omega = 0.0086\ \mathrm{sr}$ corresponds to a 6° diameter circle.
  From $\langle \sigma v \rangle_{e^- e^+}$ and $\Phi_{\gamma,511}$,

$$\varepsilon \simeq 1.0 \times 10^{-6} \frac{\overline{m}^2}{\sqrt{\overline{J}}} \left[1 - \frac{m_e^2}{m_\chi^2}\right]^{-1/4} \left[1 + \frac{m_e^2}{2m_\chi^2}\right]^{-1/2} ,$$

  where $\overline{m} \equiv m_\chi / \mathrm{MeV}$.

- To estimate the required parameter space, we use the width of the observed distribution $\overline{J}(0.0086\ \mathrm{sr}) \sim 50 - 500$, approximately corresponding to $\gamma \simeq 0.6 - 1.2$.

Constraint from 511 keV $\gamma-$ray Flux II

- Bounds on millicharged particles

  Various bounds on millicharged particles from experimental and observational results are summarized in Davidson et al., JHEP **0005**, 003 (2000).

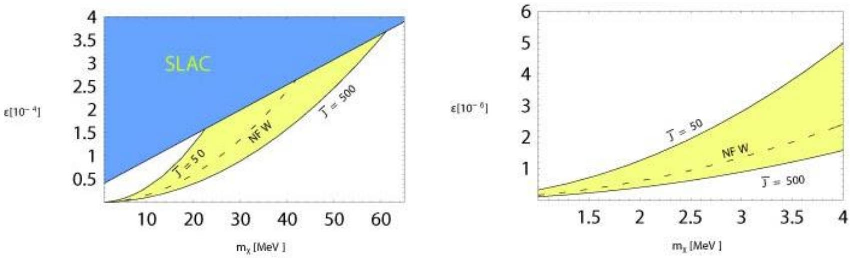


Figure: The plot for ε versus m_χ. The blue shaded region is excluded by the SLAC search of millicharged particles (Prinz et al., PRL **81**, 1175 (1998)). The yellow region is the allowed one for the value $\overline{J}(0.0086\ \mathrm{sr}) \sim 50 - 500$.

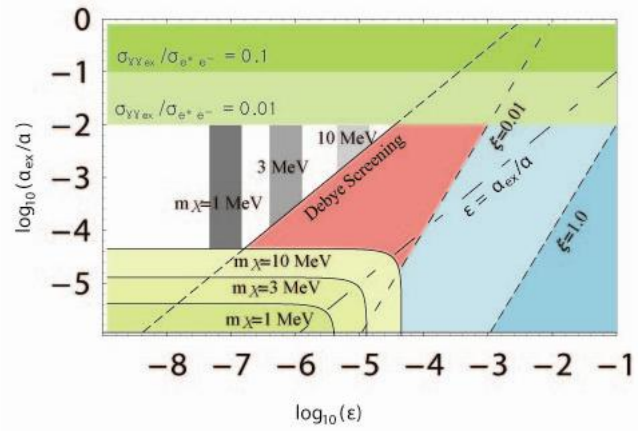


Figure: The plot for $\alpha_{\rm ex}/\alpha$ versus ε.

Conclusion

- 511 keV γ-ray emission from the galactic bulge may be an indirect signal of a new MeV millicharged DM candidate.
- We presented an allowed parameter range of this particle χ toward a possible solution to the recently observed 511 keV line.
- It couples to the photon with a 'milli' electric charge, εe, due to the kinetic mixing effect.
- It can constitute a sizable portion of the DM content of the Universe, but might have escaped detection so far basically because of its tiny electric charge.

Thank You!!