Milli-charged particles and Dark Matter Indirect Detection

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Workshop on Particle Physics and Cosmology 2021 (Nov 26-28, 2021)

- **M.R. and Y. Farzan, "Pico-charged intermediate particles rescue dark matter interpretation of 511 keV signal"** JHEP (1712)(2017)083, arXiv:1708.01137.
- **M.R. and Y. Farzan, "Dark Matter Decaying into Millicharged Particles as a Solution to AMS-02 Positron Excess"** JCAP 1904(2019)040, arXiv:1901.11273v3.
- **M.R. and Y. Farzan, "Pico-charged particles explaining 511 keV line and XENON1T signal"** Phys. Rev. D **102** (2020) no.10, 103532 arXiv:2007.14421

- Dark Matter and Indirect Detection
- 511 keV Signal and DM explanation
- AMS-02 Positron Excess Signal and DM explanation
- 511 keV Signal and XENON1T signal (briefly)

Evidence

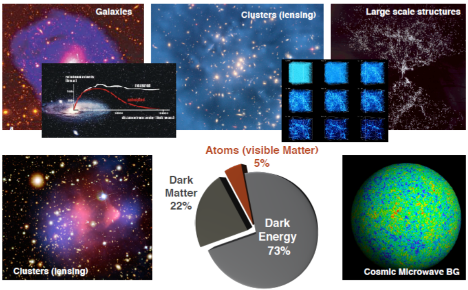
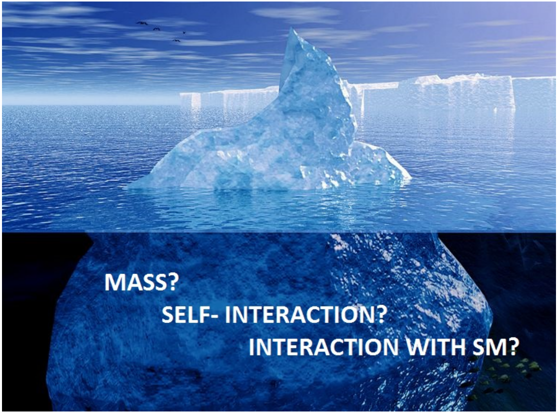


Figure : Courtesy of http://www.nicolascretton.ch/Astronomy, https://apod.nasa.gov/apod/ap060824.html and Laura Baudis slides on Dark matter lectures.

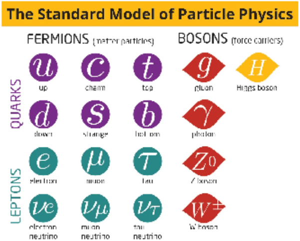
- Cluster Dark Matter
- Spiral Galaxies
- Bullet clusters
- CMB
- Large scale structures

- What we know about DM

- Nature of the dark matter is still unsolved

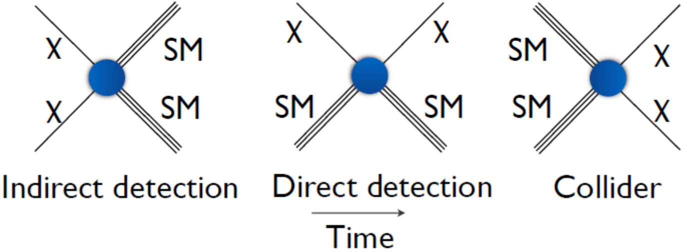


- No candidate in SM
- We need to go beyond the SM.



Interactions consistent with experimental bounds and Relic abundance observed today?

Dark Matter Searches



Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions.

Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.

Colliders: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new light dark-sector particles.

DM Indirect detection

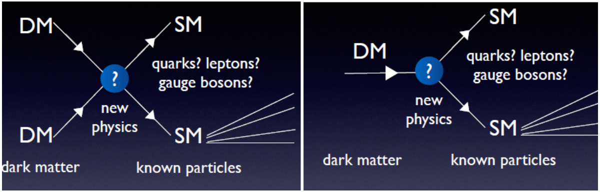


Figure : Courtesy of T. Slatyer lecture on cosmology summer school, ICTP summer school, Italy 2017.

Observable signatures are controlled by DM mass

Mechanisms for indirect detection

- Annihilating DM.
- If decaying DM (directly or through intermediate states) lifetime must be much larger than age of Universe
- Scattering on visible particles.
- DM production mechanisms and abundance of DM (For instance Thermal freeze out) provide a predictive target for indirect searches.)

Going Beyond the WIMP Paradigm

- Interest in WIMPs comes from the fact that WIMPs in thermal equilibrium with the other particles in the early Universe naturally have the right abundance to be the cold dark matter ((but not the only option))

$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,\mathrm{pb}\left(\frac{200\,\mathrm{GeV}}{m}\right)^2$$

Not the only possibility!

- The WIMP parameter space is being actively explored.

- Several indiect experiments have found signals that might originate from DM but none of them has been so far conclusively established as DM discovery.
- Some of these alleged signals have disappeared altogether by collecting more data. However, there are examples that have stood the test of time and statistics
- Status of DM interpretation of these signals (simplest DM models)? DM scenario accounting for the observed signal also predicts other accompanying signals that have not been observed.
- One example of such accompanying signals is delayed recombination (and therefore impact on CMB)

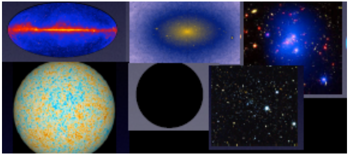


Figure: Subpictures taken from Wikipedia

The status of annihilating DM

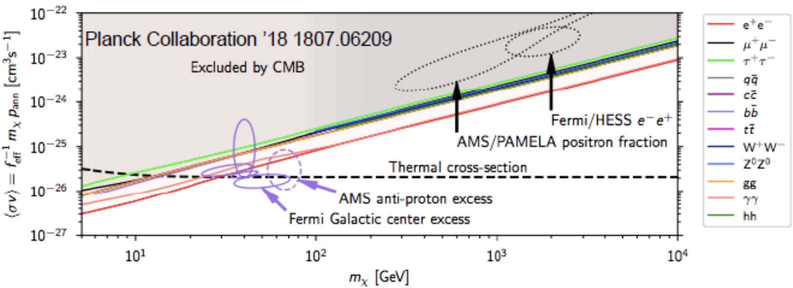


Figure: Taken from Tracy Slatyer slides, Cosmic Controversies Chicago, October 2019

- CMB limits: production of ionizing particles during cosmic dark ages modifies the CMB via late scattering of the photons on the extra free electrons.

- There are several statistically significant deviations between data and best background models that might be originating from DM signals are not yet fully resolved.
- For instance:
  - PAMELA/AMS-02 positron excess.
  - 511 keV photons from GC.
  - The GeV Galactic Center Excess (GCE).
  - etc.

511 keV photon line

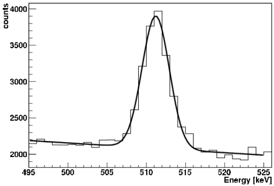


Figure: Courtesy of https://www.cosmos.esa.int/web/integral/science-nucleo

- The emission of a 511 keV gamma-ray line from a spherically symmetric region around the galactic centre has been observed by many experiments over more than four decades
- 2003: INTEGRAL/SPI observations comfirmed the 511 keV emission from the Milky Way center
- The decay of positronium atoms into two photons

511 keV photon line

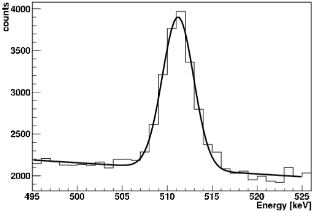


Figure: Courtesy of https://www.cosmos.esa.int/web/integral/science-nucleo

- arXiv:1512.00325: an analysis of the 11-year data from INTEGRAL/SPI was carried out and After a decade of exposure, the significance of the bulge signal has risen to 56 σ C.L..

- Nearly spherical morphology!
- Source of positrons are unkown.

Dark Matter annihilation can produce 511 keV signal

- The similarity between the spherically symmetric shape of the central bulge emission and the expected galactic DM distribution is highly suggestive of a DM origin.
- An interpretation in terms of self-annihilation of DM has been favoured for some time:
- 2003: C. Boehm, et al. : Light DM ($1 - 100$ MeV) annihilation to electron positron pairs. [astro-ph/0309686]
- $$\Phi \sim 10^{-4}(\frac{\langle \sigma v \rangle}{10^{-4}\text{pb}})(\frac{1\text{ MeV}}{m_{DM}})^2 \bar{J}(\Delta\Omega)\Delta\Omega \text{ cm}^{-2}\text{ s}^{-1}$$

Two main problems with this scenario:

- R. Wilkinson, et al. 2016: Delayed recombination $\rightarrow$ CMB constraints. (The light thermally-produced WIMP explanation of the 511 keV excess is strongly disfavoured by the latest cosmological data. This suggests a more exotic DM source of the signal.) [arXiv:1602.01114]
- C. Boehm et al. 2016: No such signal from dwarf galaxies. (among the 39 dwarf galaxies of milky way that were studied, only Reticulum II shows a 511 keV signal with a significance larger than 3σ) [arXiv:1608.00393]

Our scenario

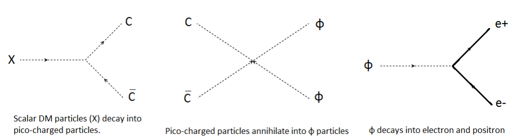
The scenario in a nutshell:

- Main component of DM: X particles decay with a lifetime larger than the age of universe to a pair of C and $\bar{C}$ particles which have an electric charge of 10^{-11}
- The magnetic field in galaxy will be enough to keep the C particles at a distance from galaxy center close to that at their production point. Thus, the profiles of C and $\bar{C}$ particles will follow the profile of the dark matter in galaxy:

$$n_C = n_{\bar{C}} = f \times n_X$$

- The $C\bar{C}$ annihilation leads to the positron production, the morphology of the 511 keV line will be similar to DM annihilation scenarios.

Our scenario



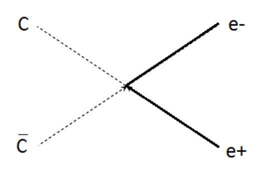
$$\mathrm{m_X} \sim 10 \text{ MeV}$$

Pico-charged particles (C) have charge of q $\sim 10^{-11} \rightarrow$ trapped in galactic center by galactic magnetic field

$$\sigma_{C\bar{C}} = 100\ pb \left(\frac{0.0001}{f}\right)^2 \left(\frac{m_X}{10 \text{ MeV}}\right)^2 \frac{1}{N_{pair}}$$

- $f = \Gamma_X t^0$ is the fraction of X particles that have decayed

Our scenario



Why not $C\bar{C}$ directly annihilate to e^-e^+?

Effective coupling $(\bar{e}e)(\bar{C}C)/\Lambda$

cross section of 100 pb requires $\Lambda \sim 100$ GeV

Must have been discovered at LEP!

Our scenario

- $C\bar{C} \to \phi\phi,$
- effective coupling of form $g_\phi \phi e \bar{e}$
- $\phi \to e^- e^+$
- $g_\phi < 10^{-11}$ No effect on supernova cooling
- $g_\phi > 10^{-15}$, ϕ can decay before traveling a distance 100 pc
- $g_\phi \in (10^{-15}, 10^{-11})$

Our scenario

How to keep C particles confined in the center?

- In the galactic center, there is a magnetic field with a magnitude of 10 μG.

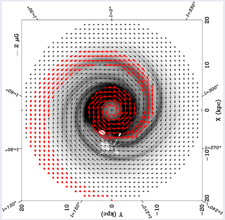


Figure: Courtesy of Sun et al., 2008; AA; 477; 573

Our scenario

- To reproduce the observed morphology of the 511 keV line:
  $r_L = 5\ pc \times (\frac{3\times10^{-11}}{q})(\frac{m_X}{10\ \text{MeV}})(\frac{10\ \mu\text{Gauss}}{B}) < 100$ pc.
- Magnetic field at dwarf galaxies $\sim 10^{-2}\ \mu$ Gauss

No signal is expected from dwarf galaxies!

Our scenario

How the C particles can acquire such small charge?

- $U(1)_X \times SU(2) \times U(1)_Y \to U(1)_{em}$
- Stueckelberg mechanism + kinetic mixing → small electric charge. (D. Feldman et al., Phys.Rev. D75(2007)115001)

$$-\frac{A_{\mu\nu}A^{\mu\nu}}{4} - \frac{B_{\mu\nu}B^{\mu\nu}}{4} - \frac{\delta}{2}A_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\left(\partial_\mu\sigma + M_1 A_\mu + \epsilon M_1 B_\mu\right)^2 \ , \quad (1)$$

- Particles charged under $U(1)_X$ obtain a tiny charge under $U(1)_{em}$, given by the mixing between $U(1)_X$ and $U(1)_Y$ gauge bosons
- W, Z bosons and the new gauge boson (γ') become massive

Our scenario

- (D. Feldman et al., Phys.Rev. D75(2007)115001)

$$-\frac{A_{\mu\nu}A^{\mu\nu}}{4}-\frac{B_{\mu\nu}B^{\mu\nu}}{4}-\frac{\delta}{2}A_{\mu\nu}B^{\mu\nu}-\frac{1}{2}\left(\partial_\mu\sigma+M_1A_\mu+\epsilon M_1B_\mu\right)^2\ , \quad (2)$$

- Going to the canonic kinetic and mass basis
  $q'\bar{f}\gamma^\mu f\gamma'_\mu$ where $q'=e\cos\theta_W(\epsilon-\delta)Q_f$
- the mass and couplings of the dark photon can have arbitrary values independent of the SM gauge boson masses.
- The intermediate C particles are charged under the new $U_X(1)$ symmetry. Their coupling to γ' is given by $g_X J^\mu_C\gamma'_\mu$ where J^μ_C is the current of the C particles.
- The electric charge of the C particles is $q_C=-g_X\epsilon\cos\theta_W$
- In order to keep the relativistic C particles produced by dark matter decay inside the galactic disk, the electric charge of these C particles, q_C, should be of order of or larger than $q_C\sim10^{-11}$.

- If we focus on the limit of equality of kinetic and mass mixings, $\delta = \epsilon$.
- In this limit, the coupling of γ' to the SM fermions vanishes.
  $q' = e \cos\theta_W (\epsilon - \delta) Q_f$

Our scenario

- $\mathrm{SM} + \mathrm{SM} \to C + \bar{C}$ (via s-channel photon exchange)
- Solving delayed recombination problem by introducing a new annihilation channel for $C\bar{C}$ pairs.
- Taking $m_{\gamma'} < m_C$, $C\bar{C} \to \gamma'\gamma'$ annihilation efficiently convert $C\bar{C}$ pairs to $\gamma'\gamma'$
- The ionizing energy dump at recombination too small to affect recombination and therefore CMB.

Positron excess

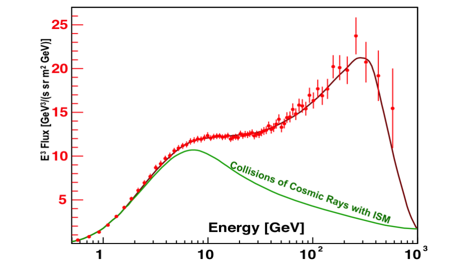


Figure: Courtesy of https://forum.nasaspaceflight.com/index.php?topic=25151.60

- In 2009 the PAMELA collaboration had discovered an increase of the positron fraction in cosmic rays at energies above 10 GeV.
- later confirmed by Fermi-LAT and AMS02

Positron excess

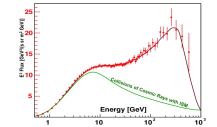


Figure: Courtesy of https://forum.nasaspaceflight.com/index.php?topic=25151.60

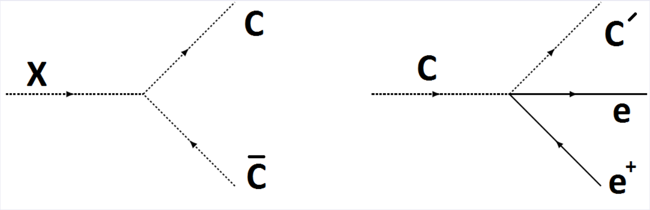
- Origin of the excess positrons is not certain.
- Contributions from pulsars, secondary cosmic ray from supernova remnants and decaying or annihilating Dark Matter are among possible explanations suggested in the literature. None of these solutions has been completely established as the prime origin.
    - Contributions from pulsars (Hooper, et al, JCAP 0901 (2009) 025)
    - secondary cosmic ray from supernova remnants (M. Di Mauro, et all, JCAP 1404 (2014) 006)

So, can dark matter annihilations (or decays) actually explain the AMS-02 positron data?

The typical annihilation cross section of the thermal relic DM and The local density leads to a much smaller flux than the observed.

- Enhancing the annihilation cross section today, (For example Sommerfeld enhancement (N. Arkani-Hamed, et al, Phys. Rev. D 79, 015014 (2009))
- BUT Models of annihilating DM $\rightarrow$ Delayed recombination problem (T. R. Slatyer, et al, Phys. Rev. D 80 (2009) 043526)
- Models of DM decay are constrained by gamma-ray observed by Fermi-LAT (C. Blanco and D. Hooper,).
- We need more exotic DM model,
- "Dark matter "transporting" mechanism explaining positron excesses," JHEP **04** (2018), 093,

- Y. Farzan and M. R, "Dark Matter Decaying into Millicharged Particles as a Solution to AMS 02 Positron Excess," JCAP **04** (2019), 040
- Instead of prompt decay into electron positron, if DM particles decay into meta-stable particles that diffuse out of the halo before decay, the constraint from Fermi-LAT is relaxed.
- On one hand, we want the intermediate particles produced in the halo to go out of the halo before decay and on the other hand, we want those produced in the disk to remain in our vicinity. This can be achieved by millicharged intermediate particles.
- Such particles become trapped by galactic magnetic field but they can escape the halo (where the magnetic filed is small) with a speed close to that of light.



- X particles should be heavier than TeV.
- C and $\bar{C}$ particles have small electric charge and therefore the magnetic field in galaxy can trap the C and $\bar{C}$ particles inside the disk.

$$q_C \sim 1.5 \times 10^{-6} \frac{500 \text{ pc}}{r_L} \frac{E_C}{4 \text{ TeV}} \frac{\mu\text{G}}{B} \; .$$

- Non-observation of the gamma ray signal from halo, the lifetime of the C particles has to be long enough to escape the halo:

$$\frac{m_C}{E_C}\Gamma(C \to e^- e^+ C') < \frac{1}{5} \times 10^{-5}\ \text{yr}^{-1}. \tag{3}$$

- Supernova shock waves can pump energy to the C particles driving them out of galaxy disk within a time scale of 100 Myr

$$\frac{m_C}{E_C}\Gamma(C \to e^- e^+ C') > 10^{-7}\ \text{yr}^{-1}, \tag{4}$$

which means the decay takes place before supernova shock waves can significantly accelerate the C particles.

We find

$$\Gamma(C \to e^- e^+ C') = \frac{m_C^3}{1536\pi^3\Lambda_C^2}.$$

$$5 \times 10^{15}\ \text{GeV} \left(\frac{8\ \text{TeV}}{m_X}\right)^{1/2} \left(\frac{m_C}{4\ \text{GeV}}\right)^2 < \Lambda_C$$

$$\Lambda_C < 1.5 \times 10^{17}\ \text{GeV} \left(\frac{8\ \text{TeV}}{m_X}\right)^{1/2} \left(\frac{m_C}{4\ \text{GeV}}\right)^2.$$

- We have to investigate the values of the parameters of the model that explain the AMS-02 positron excess
- Γ_X, m_X and m_C are free parameters to fit the data.

Table: Best fit point values to AMS-02 positron excess for different assumptions on the positron energy loss function.

dark matter halo Profile	χ^2	m_C (GeV)	m_X (GeV)	Γ (sec^{-1})
NFW	57.64	8	10000	3.7×10^{-27}
EinastoB	54.11	4	8000	3.1×10^{-27}

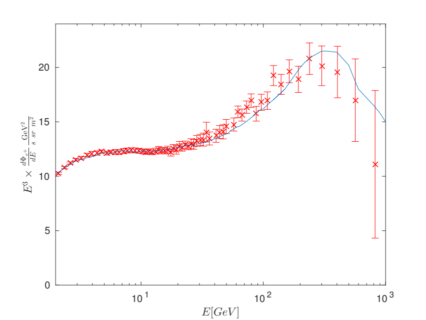


Figure: The AMS-02 positron flux compared with the prediction of our models. The red dots represent the AMS-02 data with their experimental errors shown by the vertical bars. The blue curve indicates expected positron spectrum plotted for our best fit point of $\Gamma_X = 3.1 \times 10^{-27}$ sec^{-1}, $m_X = 8$ TeV and $m_C = 4$ GeV plus cosmic ray positron background.

Y. Farzan and M. Rajaee, “Pico-charged particles explaining 511 keV line and XENON1T signal,” Phys. Rev. D **102** (2020) no.10, 103532 [arXiv:2007.14421 [hep-ph]].

Can the same scenario was originally proposed to account for the 511 keV line coming from the galactic center, explain the electron recoil excess reported by the XENON1T collaboration? (Electromagnetic interaction of relativistic pico-charged particles, produced in the decay of relatively light dark matter particles with a mass of about 10 MeV.)

- $$E_{max} = 2mv_f^2 \frac{m_C^2}{(m+m_C)^2} \qquad (3)$$
- Taking $m_C \sim 1-5$ MeV, $m = m_e$ and $v_f = 0.08$, we find $E_{max} = 3 - 5.5$ keV which is tantalizing in the range of electron recoil excess observed by XENON1T

- The differential cross section of scattering of the C and $\bar{C}$ particles with electric charge of q_C off the electrons

$$\frac{d\sigma}{dE_r} = \frac{e^2 q_C^2}{8\pi m_e v^2} \frac{1}{E_r^2} \quad \text{where} \quad E_r < E_{max} = 2 m_e v_f^2 \left(\frac{m_C}{m_C + m_e} \right)^2 . \tag{8}$$

- For general values of δ/ϵ, the coupling of the dark photon, γ', to the electron, q' is nonzero so the dark photon exchange between the electron and C also contributes to the scattering amplitude. Thus, $d\sigma/dE_r$ should be modified by an extra factor of

$$\left(1 + \frac{2 m_e E_r}{2 m_e E_r + m_{\gamma'}^2} \frac{\delta - \epsilon}{\epsilon} \right)^2 \tag{9}$$

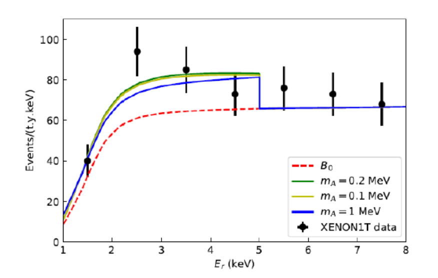


Figure : XENON1T electron recoil data compared with the prediction of our model without considering the contribution from the new gauge boson exchange. best fit values: $(\delta - \epsilon)/\epsilon = -13.9$ and $f = 6.6 \times 10^{-7}$ $((\delta - \epsilon)/\epsilon = -76$ and $f = 2 \times 10^{-7})$.

SUMMARY

- We have proposed a novel scenario for dark matter within which the chances for finding two indirect dark matter signals enhances despite the stringent bounds.
- In this scenario, dark matter is composed of scalar meta stable particles, X, that can decay to a pair of millicharged particles with a lifetime larger than age of the Universe.
- Using the idea of millicharged particles that are produced by the decay of dark matter particles in galaxy, and using the idea that depending on their mass they can be trapped in a distance from galaxy center, by the galactic magnetic field, we obtained the flux and morphology of two indirect dark matter signal: 511 keV signal from galactic center and signal of positron excess.
- We have explained how our scenario circumvent the stringent constraints that excluded previous dark matter models.

- However, an isotropic gamma ray signal is expected from cumulation of the photons produced by interaction of electron positrons off CMB all over the universe.
- Applying the scenario for Galactic GeV excess?


감사합니다
Thank you
고맙습니다

Direct detection

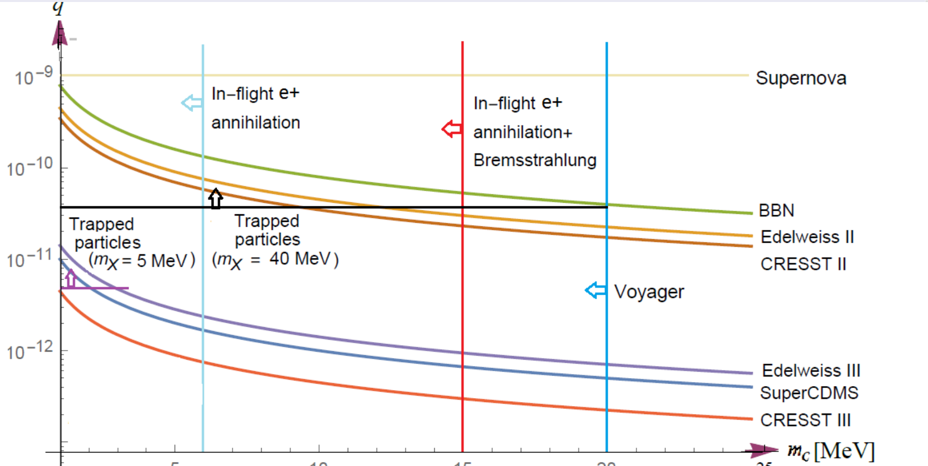


Fig 1-b

- In general for an arbitrary ratio of σ/ϵ , the coupling of the new gauge boson to the electrons does not vanish
- For A' lighter than a few MeV, A' can contribute as effective relativistic degrees of freedom
- BBN $q' < 10^{-9}(m_{A'}/\mathrm{MeV})^{1/2}$.
- For 100 eV $< m_{A'} <$ 100 keV, there are very strong bounds (as strong as 10^{-15}) on q' from stellar cooling which requires at least a partial cancellation between δ and ϵ.
- For $m_{A'}$ ~MeV, the strongest bound on q' is slightly below 10^{-10} which comes from supernova cooling. This bound can be relaxed if A' has an extra interaction that can trap it inside the supernova core or can result in a decay into the SM particles with a decay length smaller than ~ 10 m.

- In the range 100 keV $< m_{A'} <$ 1 MeV, the strongest upper bound on q' also comes from supernova cooling which is about $\sim 5 \times 10^{-11}$. Again by opening a fast decay mode, $A' \to \nu\bar{\nu}$ with a decay length smaller than ~ 10 m, the bound can be relaxed but the same coupling that leads to $A' \to \nu\bar{\nu}$ brings A' to thermal equilibrium with the plasma in the early universe so at BBN and at neutrino decoupling era, A' will contribute as three bosonic degrees of freedom which is ruled out by the bounds on N_{eff}.

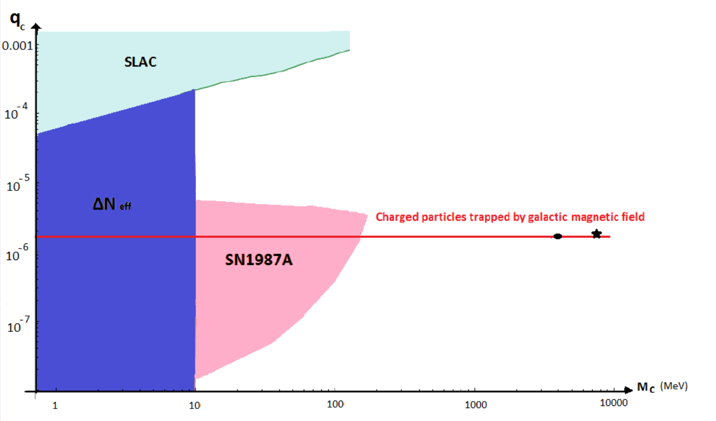


Figure: Bounds on the charge of C-particle versus its mass. The horizontal line shows lower limit on q_C above which C particles with energy $E_C = 4$ TeV have Larmour radius below 500 pc for galactic magnetic field of $B = 1\ \mu$G. The black dot and star indicate best fit point values to AMS-02 positron excess assuming EinastoB and NFW halo profiles as is shown in table 1.

Underlying model that gives rise to $(C')^\dagger Cee^+/\Lambda_C$

- We introduce a doublet scalar with the same quantum numbers as those of the standard model Higgs, $\Phi_D^T = (\Phi^+, \Phi^0)$.
- To explain the smallness of the effective coupling, we introduce a global $U_D(1)$ symmetry under which $\Phi_D \to e^{i\alpha_D}\Phi_D$ and $C' \to e^{i\alpha_D}C'$ along with a Z_2 symmetry under which $C' \to -C'$.
- The most general potential involving the scalars can then be written as

$$V = V_H + V_\Phi + V_{H\Phi} + V_{\Phi CH}$$

where V_H is the standard Higgs potential,

$$V_\Phi = m_D^2 \Phi_D^\dagger \Phi_D + \frac{\lambda_D}{2}(\Phi_D^\dagger \Phi_D)^2$$

and

$$V_{H\Phi} = \lambda_1(\Phi_D^\dagger \Phi_D)(H^\dagger H) + \lambda_2|\Phi_D^\dagger H|^2.$$

- $V_{C\Phi H}$ contains all electroweak, Z_2 and $U_D(1)$ invariant renormalizable combination of C, C', H and Φ_D.

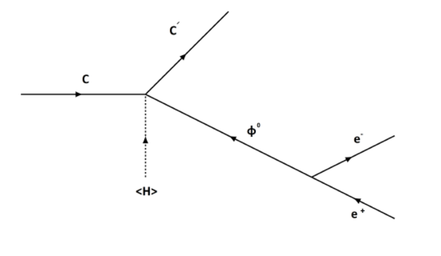
- The mass mixing term $C^\dagger C'$ as well as quartic terms such as $C^\dagger C'|H|^2$ and $C^\dagger C'|\Phi|^2$ are forbidden by $U_D(1)$ and the Z_2 symmetry.
- In the absence of these symmetries, $C^\dagger C'|H|^2$ along with the Higgs Yukawa couplings could lead to fast $C \to C'\bar{q}q$ or $C'\bar{\mu}\mu$.
- The effective Lagrangian breaks both the global $U_D(1)$ symmetry and the Z_2 symmetry under which $C' \to -C'$.
- In order to obtain the effective coupling we must add terms to the Lagrangian which break the $U_D(1)$ and Z_2 symmetries.

- We add the following four scalar coupling that breaks Z_2 but preserves $U_D(1)$

$$\lambda_{CC'}(C')^\dagger C H^\dagger \Phi_D + H.c.$$

along with the following Yukawa coupling for leptons of first generation that breaks the global $U(1)_D$ symmetry while maintaining the Z_2

$$Y_e \bar{e} \Phi_D^\dagger L_e + H.c.$$



- $Y_e \to 0$ or $\lambda_{CC'} \to 0$, the Z_2 and $U(1)_D$ symmetries are respectively maintained so their smallness of $1/\Lambda_C$ is explained in the framework of 't Hooft criterion.

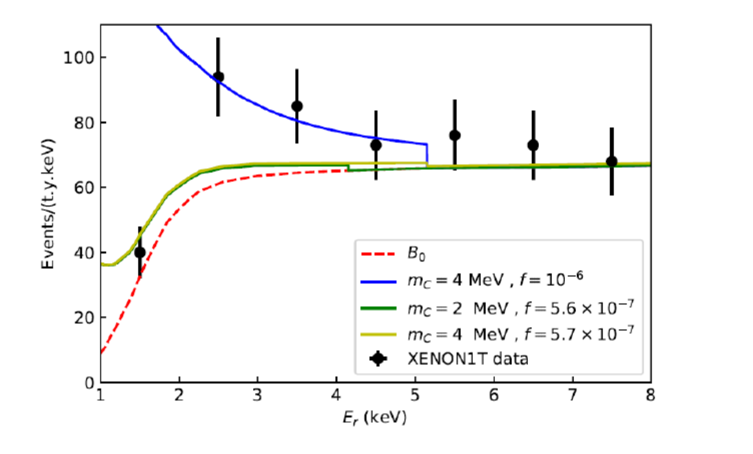


Figure: XENON1T electron recoil data compared with the prediction of our model without considering the contribution from the new gauge boson exchange.

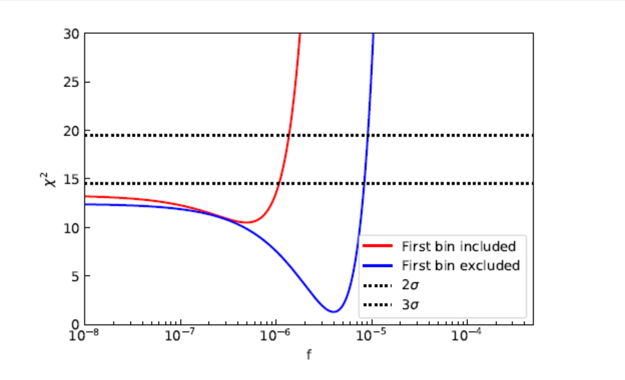


Figure: χ^2 vs. f. The red curve shows χ^2 for the first seven bins with $1 \text{ keV} < E_r < 8 \text{ keV}$ as a function of f. The minimum of χ^2 lies at at $f = 5.7 \times 10^{-7}$ and is aqual to 10.1. The blue curve demonstrates χ^2 computed excluding the first bin (*i.e.*, considering only the bins with $2 \text{ keV} < E_r < 8 \text{ keV}$). The best point fit is located at $f = 4 \times 10^{-6}$ and is aqual to 1.4.

We also searched for the best fit value for the $e^- + e^+$ flux from CALET and AMS-02 and found that the best fit can be achieved for

$$\Gamma_X = 2 \times 10^{-27}\ \text{sec}^{-1},\ m_X = 5.6\ \text{TeV and } m_C = 4\ \text{GeV} \tag{4}$$

with $\chi^2 = 128.2$ for $109 - 3 = 106$ degrees of freedom and a p-value equal to 0.0701 which indicates that they are consistent with each other.