Constraints on dark matter models from a Fermi LAT search for cosmic-ray electrons from the Sun

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Unexpected features in the cosmic-ray $e^\pm$ spectra?

- Rise in local positron fraction above $\sim 10$ GeV disagrees with conventional model for cosmic rays (secondary positron production only).

![PAMELA positron fraction graph](image)

**PAMELA positron fraction**

- Error bars show 1 s.d.; if not visible, they lie inside the data points.
- The PAMELA positron data presented here are insufficient to distinguish between astrophysical primary sources and dark matter annihilation.
- New important information will result from high energy behaviour of the positron fraction. Furthermore, the experiment is continuing.
- However, PAMELA will soon present results concerning the energy losses of electrons and positrons during their propagation.

**Graph Details**

- The solid line shows a propagation of cosmic rays in the Galaxy without reacceleration processes.
- The positron fraction is defined as $\frac{\phi(e^+)}{\phi(e^-) + \phi(e^+)}$.
- The PAMELA positron fraction with other experimental data and astrophysical primary components.
- As the energy rises, the positron fraction should exceed 0.3 above 50 GeV.
- The PAMELA positron data presented here are insufficient to distinguish between astrophysical primary sources and dark matter annihilation.
Unexpected features in the cosmic-ray e\(^{\pm}\) spectra?

- rise in local positron fraction above \(\sim 10\) GeV disagrees with conventional model for cosmic rays (secondary positron production only)
- unexpected bump in total electron + positron spectrum measured by ATIC

![ATIC electron + positron spectrum](image)
Unexpected features in the cosmic-ray e\(\pm\) spectra?

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- less prominent feature seen in Fermi cosmic ray electron/positron spectrum

Fermi electron + positron spectrum

![Graph showing Fermi electron + positron spectrum with data points and lines from various experiments.](image-url)

Ackermann et al. [Fermi LAT Collaboration] 2010
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- unexpected bump in total electron + positron spectrum measured by ATIC
- less prominent feature seen in Fermi cosmic ray electron/positron spectrum
- Fermi positron fraction agrees with PAMELA result, extends to higher energies
Hints of a dark matter signal?

sparked interest in DM explanations (e.g., Arkani-Hamed et al. 2009; Lattanzi & Silk 2009; Cirelli et al. 2009; Cholis et al. 2008; Grasso et al. 2009;...)

- leptophilic models
- large annihilation cross-sections; can arise in “secluded” or “intermediate state” models, in which DM interacts with SM via a new particle (typically a light scalar)

The Case for a 700+ GeV WIMP: Cosmic Ray Spectra from ATIC and PAMELA

Ilias Cholis,1 Gregory Dobler,2 Douglas P. Finkbeiner,3 Lisa Goodenough,1 and Neal Weiner1

The cosmic-ray signals from dark matter annihilations as the mediator decay modes and dashed lines), expected positron fraction vs energy due to secondary production only (dotted line), and PAMELA [77-124]-1

FIG. 3. The cosmic-ray signals from dark matter annihilations [47-133]-1

...
Meanwhile... in direct detection news

Elastic scattering

- CDMS limits exclude DAMA/LIBRA signal region for standard WIMP scenario

Inelastic scattering

- it was proposed that the experiments could be reconciled if dark matter scatters \textit{inelastically} (Tucker-Smith and Weiner, 2001)
Solar CREs from DM annihilation

the standard WIMP capture/annihilation scenario

- DM particles are captured by the Sun via elastic scattering with nucleons
- the DM particles lose energy with each scattering, and quickly sink to the core of the Sun where they annihilate into SM particles
- neutrinos are the only observable signal from DM annihilations in the Sun since they are the only SM particle that can escape from the Sun
Solar CREs from DM annihilation

Schuster, Toro, Weiner, Yavin 2010 discuss 2 scenarios in which dark matter annihilation leads to cosmic-ray electron and positron (CRE) fluxes from the Sun:

• **intermediate state scenario:** Dark matter annihilates in the center of the Sun into an intermediate state $\Phi$ which then decays to CREs outside the surface of the Sun.

• **iDM scenario:** Inelastic dark matter (iDM) captured by the Sun remains on large orbits, then annihilates directly to CREs outside the surface of the Sun.
The Fermi Gamma-ray Space Telescope

- pair-production detector: detects charged particle events as well as gamma rays
- can identify cosmic-ray electron and positron events; in general cannot determine charge on an event-by-event basis*

*position in the geomagnetic field can be used to select events by charge, as in Fermi positron spectrum measurement (Ackermann et al., 2011)
Data selection

- $\sim 10^6$ CRE events ($E > 60$ GeV), from 1st year of operation

- analysis performed in ecliptic coordinates, in reference frame centered on the Sun
Data analysis

3 approaches used to search for flux excesses:

• **flux asymmetry search**: compare flux from the Sun and from a “fake” Sun in the opposite sky direction

• **comparison with isotropic flux**: a sample of isotropic CRE events was simulated using an event-shuffling technique; the real flux from the Sun and the simulated isotropic flux is compared

• **spherical harmonics analysis**: tests for CRE flux variations correlated with any sky direction and on different angular scales
Flux asymmetry (real vs. fake Sun)

fluxes evaluated in a cone of 30° angular radius centered on the real or fake Sun

flux difference (real Sun - fake Sun)  flux upper limits (68%, 95%, 99% CL)

no flux excess detected in any energy bin at > 3σ
Comparison with isotropic flux

fluxes evaluated in a cone of 30° angular radius centered on the real Sun

flux difference (real Sun - simulated isotropic)  flux upper limits (68%, 95%, 99% CL)

no flux excess detected in any energy bin at > 3σ
Spherical harmonics analysis

fluctuation angular power spectrum of events $E > 60$ GeV

dotted and dashed lines show $3\sigma$ and $5\sigma$ limits on probability distribution of shot noise $C_N$

no significant angular power detected in this multipole range
Solar CRE fluxes from dark matter
Intermediate state scenario: overview

- DM is captured by the Sun via elastic scattering, continues to scatter and lose energy, and sinks to the core where it annihilates.

- Assume DM annihilates to a new light scalar $\Phi$ which then decays to an electron and positron pair:

$$\chi\chi \rightarrow \phi\phi \quad \phi \rightarrow e^+e^-$$

- The $\Phi$ are assumed to have mass less than a few GeV, while the DM has mass of ~100 GeV - few TeV, so the $\Phi$ are relativistic.

- Many $\Phi$ escape the Sun before decaying, so the CREs they produce are observable.

- The addition of the new light scalar is related to the mechanism used to generate Sommerfeld enhancement; this class of models is often considered as a possible explanation for the observed excesses in CREs by PAMELA and ATIC/Fermi.
Existing gamma-ray constraints

- **Observable gamma-rays** from the Sun (from FSR) are also produced in this scenario
- Solar gamma-ray measurements constrain decay rate of $\Phi$ outside sun

![Graph showing existing gamma-ray constraints](image)

- EGRET
- MILAGRO
- Fermi-LAT

Schuster, Toro, Yavin 2010

See also Batell, Pospelov, Ritz, Shang 2010; ...
CRE flux from intermediate state scenario

$$\frac{dN}{dt \, dA \, d\cos \theta_{\text{det}} \, dE_{\text{det}}} (\theta_{\text{det}}, E_{\text{det}}) = \int_0^\infty dR \frac{dN}{dV \, dt} \frac{d\Gamma}{d\cos \theta_{\text{det}}} \delta(E_{\text{det}} - E),$$

- decay rate of $\Phi$ per volume
- selects energy of observed CREs
- line-of-sight distance
- angular distribution of CREs
Φ decay rate per volume

\[ \frac{dN}{dV\, dt} (r (\theta_{\text{det}}, R)) = 2 \frac{C_\odot e^{-r/L}}{4\pi r^2 L} \]

- assume equilibrium (for every 2 particles that are captured, 2 annihilate)
- calculate solar capture rate with DarkSUSY
  - proportional to the elastic scattering cross-section
  - depends on DM particle mass
- L is decay length, set by lifetime of Φ and energy of Φ
Limits on elastic scattering cross-section
assuming annihilation to CREs via an intermediate state

spin-dependent scattering

spin-independent scattering

solar CRE flux limits correspond to constraints on the rate of decay to CREs outside the Sun that are ~ 2-4 orders of magnitude stronger than constraints on the associated FSR derived from solar gamma-ray data.
Inelastic dark matter scenario: overview

- DM is captured by the Sun via inelastic scattering
  \[ \chi + N \rightarrow \chi^* + N \]

- Inelastic scattering can only occur if the DM has sufficient energy:
  \[ E \geq \delta (1 + m_\chi / m_N) \quad \delta = m_{\chi^*} - m_\chi \]

- The mass splitting (delta) is typically assumed to be \( \sim 100 \) KeV

- After only a few scatterings the DM doesn’t have enough energy to continue scattering and so, rather than sink to the core, it remains on large orbits which take it outside the surface of the Sun

- A non-negligible fraction of DM can be accumulated outside the surface of the Sun in this scenario, and annihilations outside the Sun can produce an observable CRE flux

- iDM models could potentially explain the inconsistent results of DAMA/LIBRA and CDMS (and other direct-detection experiments), e.g. Smith & Weiner 2001; Chang, Kribs, Tucker-Smith, Weiner 2009
Flux from iDM outside the Sun

• isotropic flux (but observable flux is a factor of 2 smaller b/c CREs produced on the opposite side of Sun can’t reach us)

\[ F = 2 \frac{\Gamma_{A,\text{out}}}{4\pi D_*^2} \]

• annihilation rate is proportional to fraction of captured dark matter particles outside the Sun at a given time; assume capture/annihilation are in equilibrium

\[ \Gamma_{A,\text{out}} = f_{\text{out}} \Gamma_A = \frac{1}{2} f_{\text{out}} C_* \]

• \( f_{\text{out}} \) has been calculated by Schuster et al. 2010, iDM capture rate calculated by Nussinov et al. 2009 and Menon et al. 2010

• dark matter assumed to annihilate at rest so CRE flux is mono-energetic with \( E = \text{mass of the dark matter particle} \)

• in this scenario we account for the energy resolution of the LAT since the limits for masses near the energy bin edges are weakened by spreading the signal over more than one bin
Limits on inelastic scattering cross-section

DAMA/LIBRA allowed regions and CDMS exclusion curves

![Graph showing DAMA/LIBRA allowed regions and CDMS exclusion curves.](image)

only parameter space compatible with DAMA/LIBRA and CDMS:

\[ m_\chi \leq 100 \text{ GeV} \]

\[ \sigma_{SI} \sim 10^{-39} - 10^{-40} \text{ cm}^2 \]
Limits on inelastic scattering cross-section

Parameter space above curves excluded at 95% CL for CRE final state

only parameter space compatible with DAMA/LIBRA and CDMS:
\( m_\chi \leq 100 \text{ GeV} \)
\( \sigma_{SI} \sim 10^{-39} - 10^{-40} \text{ cm}^2 \)

solar CRE constraints exclude by \( \sim 1-2 \) orders of magnitude all of the parameter space compatible with an inelastic DM explanation of DAMA/LIBRA and CDMS for DM masses greater than \( \sim 70 \text{ GeV} \), assuming DM annihilates to CREs
Complementarity with direct searches

Signal and exclusion regions for direct detection experiments at 90% CL (for delta = 120 keV)

Parameter space above curves excluded at 95% CL for CRE final state by Fermi LAT CRE analysis

Fermi solar CRE constraints are competitive with and complementary to direct detection results

- tests for a unique astrophysical signal arising from specific dark matter models
- different sources of uncertainties make solar CRE limits a valuable cross-check
Summary

- for models in which dark matter annihilates to CREs via an intermediate state:

  solar CRE constraints on the DM-nucleon elastic scattering cross-section correspond to significantly stronger bounds on the rate of CRE decay outside the Sun than existing constraints on associated FSR emission from solar gamma-ray data

- for inelastic dark matter models:

  the CRE constraints exclude all of the parameter space for DM masses above ~ 70 GeV that can reconcile the results of DAMA/LIBRA and CDMS, assuming DM annihilates to CREs; constraints are complementary to results from direct detection experiments