Cosmic Ray Signatures of Dark Matter Decay

Alejandro Ibarra
Technical University of Munich

Many thanks to Chiara Arina, Wilfried Buchmüller, Gianfranco Bertone, Laura Covi, Michael Grefe, Thomas Hambye, Koichi Hamaguchi, Tetsuo Shindou, Fumihiro Takayama, David Tran, Andreas Ringwald, Christoph Weniger and Tsutomu Yanagida.
Introduction

Dark matter exist
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Dark matter exists

What is the dark matter?
Observations indicate that the dark matter is a particle which the following properties:

- Non baryonic,
- Slow moving (“cold” or perhaps “warm”),
- Interactions with ordinary matter not stronger than the weak interaction,
- Long lived (not necessarily stable!)
All these evidences for dark matter are of gravitational origin.

Impossible to determine the nature and properties of the dark matter particle from these observations.

Independent (non-gravitational) evidences for dark matter are necessary.
Direct detection
DM nucleus $\rightarrow$ DM nucleus

Indirect detection
DM DM $\rightarrow \gamma X, e^+e^-...$ (annihilation)
DM $\rightarrow \gamma X, e^+X,...$ (decay)

Collider searches
pp $\rightarrow$ DM X
Collider searches

DM \rightarrow \gamma X, e^+ X, ... (decay)

Direct detection

DM nucleus \rightarrow DM nucleus

pp \rightarrow DM X
Collider searches

Indirect detection
$\text{DM DM} \rightarrow \gamma \gamma, e^+e^-, \ldots$ (annihilation)

$\text{pp} \rightarrow \text{DM X}$

Direct detection
$\text{DM nucleus} \rightarrow \text{DM nucleus}$

$\text{DM} \rightarrow \gamma X, e^+X, \ldots$ (decay)
Indirect detection

DM DM → γX, e^+e^−... (annihilation)
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Collider searches

pp → DM X
Direct detection
DM nucleus → DM nucleus

Indirect detection
DM DM → γX, e^+e^- ... (annihilation)
DM → γX, e^+X,... (decay)

Collider searches
pp → DM X
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani¹,², G. C. Barbarino³,⁴, G. A. Bazilevskaya⁵, R. Bellotti⁶,⁷, M. Boezio⁸, E. A. Bogomolov⁹, L. Bonechi¹,², M. Bongi², V. Bonvicini⁸, S. Bottai², A. Bruno⁶,⁷, F. Cafagna⁴, D. Campana⁴, P. Carlson¹⁰, M. Casolino¹¹, G. Castellini¹², M. P. De Pascale¹¹,¹³, G. De Rosa⁵, N. De Simone¹¹,¹³, V. Di Felice¹¹,¹³, A. M. Galper¹⁴, L. Grishantseva¹⁴, P. Hofverberg¹⁰, S. V. Koldashov¹⁴, S. Y. Krutkov⁹, A. N. Kvashnin⁵, A. Leonov¹⁴, V. Malvezzi¹¹, L. Marcelli¹¹, W. Menn¹⁵, V. V. Mikhailov¹⁴, E. Mocchiutti⁸, S. Orsi¹⁰,¹¹, G. Osteria⁴, P. Papini², M. Pearce¹⁶, P. Picozza¹¹,¹³, M. Ricci¹⁷, S. B. Ricciarini², M. Simon¹⁵, R. Sparvoli¹¹,¹³, P. Spillantini¹¹,², Y. I. Stozhkov⁵, A. Vacchi⁸, E. Vannuccini², G. Vasilyev⁹, S. A. Voronov¹⁴, Y. T. Yurkin¹⁴, G. Zampa⁸, N. Zampa⁸ & V. G. Zverev¹⁴

Antiparticles account for a small fraction of cosmic rays and are known to be produced in interactions between cosmic-ray nuclei and atoms in the interstellar medium¹, which is referred to as a ‘secondary source’. Positrons might also originate in objects such as pulsars² and microquasars³ or through dark matter annihilation⁴, which would be ‘primary sources’. Previous statistically limited measurements⁵–⁷ of the ratio of positron and electron fluxes have calorimeter data. The proton-to-positron flux ratio increases from approximately 10³ at 1 GeV to approximately 10⁴ at 100 GeV. Robust positron identification is therefore required, and the residual proton background must be estimated accurately. The imaging calorimeter is 16.3 radiation lengths (0.6 nuclear interaction lengths) deep, so electrons and positrons develop well contained electromagnetic showers in the energy range of interest. In contrast, the majority of
Secondary positrons from spallation
Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope


(Fermi LAT Collaboration)

1National Research Council Research Associate
Probing the ATIC peak in the cosmic-ray electron spectrum with H.E.S.S.

Present situation:

Evidence for a primary component of positrons (possibly accompanied by electrons)

New astrophysics?
New particle physics?
Pulsars are sources of high energy electrons & positrons

Atoyan, Aharonian, Völk;
Chi, Cheng, Young;
Grimani
Pulsar explanation I: Geminga + Monogem

**Geminga**
- $T=370,000$ years
- $D=157$ pc

**Monogem (B0656+14)**
- $T=110,000$ years
- $D=290$ pc
Nice agreement. However, it is not a prediction!

- \( \frac{dN_e}{dE_e} \propto E_e^{-1.7} \exp(-E_e/1100 \text{ GeV}) \)
- Energy output in e+e- pairs: 40% of the spin-down rate (!)
\[ \frac{dN_e}{dE_e} \propto E_e^{-\alpha} \exp(-E_e/E_0), \ 1.5 < \alpha < 1.9, \ 800 \text{ GeV} < E_0 < 1400 \text{ GeV} \]

- Energy output in e+e- pairs: between 10-30% of the spin-down rate
Dark matter decay

- No fundamental objection to this possibility, provided $\tau_{\text{DM}} > 10^{17}$ s.
- Not as thoroughly studied as the case of the dark matter annihilation.

Possible reason: the most popular dark matter candidates are weakly interacting (can be detected in direct searches and can be produced in colliders). If the dark matter is a WIMP, absolute stability has to be normally imposed.
Beyond the SM

Sketch of a WIMP dark matter model:

$\tau_{\text{DM}} \sim 10^{-25}$ s
Sketch of a WIMP dark matter model:

Supersymmetry

\( \chi_1 \)

\( \tau \sim 10^{-25} \text{s} \)

SM
Supersymmetry

Requires a suppression of the coupling of at least 22 orders of magnitude!

Sketch of a WIMP dark matter model:

$\tau_\chi > 10^{17}$ s

SM
Supersymmetry

\[ \chi_1 \rightarrow \eta \rightarrow \tau = \infty \rightarrow SM \]

**Simplest solution**: forbid the dangerous couplings altogether by **imposing** exact R-parity conservation. The lightest neutralino is absolutely stable.

Sketch of a WIMP dark matter model:
WIMP dark matter is not the only possibility: the dark matter particle could also be superweakly interacting.
Sketch of a superWIMP dark matter model:
SuperWIMP DM particles are naturally very long lived. Their lifetimes can be larger than the age of the Universe, or perhaps a few orders of magnitude smaller.

Beyond the SM

It is enough a moderate suppression of the coupling to make the superWIMP a viable dark matter candidate.

\[ \tau_{DM} > 10^{17} \text{s} \]
SuperWIMP DM particles are naturally very long lived. Their lifetimes can be larger than the age of the Universe, or perhaps a few orders of magnitude smaller.

Beyond the SM

It is enough a moderate suppression of the coupling to make the superWIMP a viable dark matter candidate.

Eventually the dark matter decays!
Candidates of decaying dark matter

- **Gravitinos in general SUSY models**
  (without imposing R-parity conservation).
  Decay rate doubly suppressed by the SUSY breaking scale and by the small R-parity violation.
  Takayama, Yamaguchi; Buchmüller, et al.; AI, Tran; Ishiwata et al.; Choi et al.

- **Hidden sector gauge bosons/gauginos.**
  Decay rate suppressed by the small kinetic mixing between $U(1)_y$ and $U(1)_{hid}$
  Chen, Takahashi, Yanagida; AI, Ringwald, Weniger;

- **Right-handed sneutrinos in scenarios with Dirac neutrino masses.**
  Decay rate suppressed by the tiny Yukawa couplings.
  Pospelov, Trott

- **Hidden sector particles.**
  Decay rate suppressed by the GUT scale.
  Arvanitaki et al.; Hamaguchi, Shirai, Yanagida; Arina, Hambye, AI, Weniger

- **Bound states of strongly interacting particles.**
  Decay rate suppressed by the GUT scale.
  Hamaguchi et al.; Nardi et al.
Positron fraction from decaying dark matter: model independent analysis

Possible decay channels

- Fermionic DM
  - $\Psi \rightarrow Z^0 \nu$
  - $\Psi \rightarrow W^\pm \ell^\mp$
  - $\Psi \rightarrow \ell^+ \ell^- \nu$

- Scalar DM
  - $\Phi \rightarrow Z^0 Z^0$
  - $\Phi \rightarrow W^+ W^-$
  - $\Phi \rightarrow \ell^+ \ell^-$

AI, Tran, AI, Tran, Weniger
The injection spectrum of positrons depends just on two parameters: the dark matter mass and lifetime.

The positrons travel under the influence of the tangled magnetic field of the Galaxy and lose energy → complicated propagation equation
For “low” DM mass: conflict with PAMELA (spectrum too flat)
For “high” DM mass: agreement with PAMELA, but conflict with H.E.S.S.
\[ \psi \rightarrow e^+ e^- \nu \]
\[ m_{DM} = 2000 \text{ GeV} \]
\[ \tau_{DM} \sim 10^{26} \text{ s} \]

\[ \psi \rightarrow \mu^+ \mu^- \nu \]
\[ m_{DM} = 3500 \text{ GeV} \]
\[ \tau_{DM} \sim 10^{26} \text{ s} \]

\[ \psi \rightarrow \tau^+ \tau^- \nu \]
\[ m_{DM} = 5000 \text{ GeV} \]
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\[ m_{\text{DM}} = 5000 \text{ GeV} \]
\[ \tau_{\text{DM}} \sim 10^{26} \text{ s} \]
Democratic decay

\[ \psi \rightarrow \ell^+ \ell^- \nu \]

\[ m_{DM} = 2500 \text{ GeV} \]

\[ \tau_{DM} = 1.5 \times 10^{26} \text{ s} \]
Democratic decay

$$\Psi \rightarrow \ell^+ \ell^- \nu$$

$$m_{DM} = 2500 \text{ GeV}$$

$$\tau_{DM} = 1.5 \times 10^{26} \text{ s}$$
Some decay channels can explain simultaneously the PAMELA, Fermi LAT and H.E.S.S. observations

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>$M_{DM}$ [GeV]</th>
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<tr>
<td>$\psi_{DM} \rightarrow \mu^+ \mu^- \nu$</td>
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</tr>
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<tr>
<td>$\phi_{DM} \rightarrow \mu^+ \mu^-$</td>
<td>2500</td>
<td>1.8</td>
</tr>
<tr>
<td>$\phi_{DM} \rightarrow \tau^+ \tau^-$</td>
<td>5000</td>
<td>0.9</td>
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</table>
The lifetime of a TeV dark matter particle which decays via a dimension six operator suppressed by $M^2$ is

$$\tau \sim 2 \times 10^{26} \text{s} \left( \frac{\text{TeV}}{m_{\text{DM}}} \right)^5 \left( \frac{M}{10^{16} \text{GeV}} \right)^4$$

$M$ is remarkably close to the Grand Unification Scale ($M_{\text{GUT}} = 2 \times 10^{16} \text{ GeV}$).

Indirect dark matter searches are starting to probe the Grand Unification Scale!
The electron/positron anomalies may be produced by a secondary component of dark matter.

The flux depends on $\rho_{\text{DM}}/\tau_{\text{DM}}$. Therefore, the same flux can be produced by the decay of a secondary component of dark matter, provided the density and lifetime are in that same ratio $\rho/\tau = \rho_{\text{DM}}/\tau_{\text{DM}}$:

$$\rho = \alpha \rho_{\text{DM}}$$
$$\tau \approx \alpha 10^{26} \text{ s}$$

The primary component of dark matter may even be stable. New possibilities for model building.

Example: hidden gaugino decay into DM neutralinos
Conclusion so far:
the electron/positron excesses can be naturally explained by the decay of dark matter particles.

Is this the first non-gravitational evidence of dark matter?

“Extraordinary claims require extraordinary evidence”
Carl Sagan
More tests needed!

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No free parameters from Particle Physics

Prediction for the fluxes of:
- Antiprotons
- Gamma rays
- Neutrinos
- Antideuterons
Good agreement of the theory with the experiments: no need for a sizable contribution to the primary antiproton flux. Purely leptonic decays (e.g. $\psi \rightarrow \mu^+\mu^-\nu$) are favoured over decays into weak gauge bosons.
Antiproton flux from dark matter decay

Propagation mechanism more complicated than for the positrons.

The predicted flux suffers from huge uncertainties due to degeneracies in the determination of the propagation parameters

\[ \psi \rightarrow W^{\pm} \mu^{\mp} \]
Antiproton flux from dark matter decay

Propagation mechanism more complicated than for the positrons.

The predicted flux suffers from huge uncertainties due to degeneracies in the determination of the propagation parameters $\Psi \rightarrow \mathcal{W}^\pm \mu^\mp$. 
Diffuse gamma ray flux from DM decay

The gamma ray flux from dark matter decay has two components:

- **Prompt radiation of gamma rays produced in the decay** (final state radiation, pion decay...)
- **Inverse Compton Scattering radiation of electrons/positrons produced in the decay**
Prompt radiation

\[
\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\text{halo}}}{dE_\gamma}(\Omega) + \frac{dJ_{\text{eg}}}{dE_\gamma}
\]

Halo component

- Depends on the dark matter profile. Strong dependence in the direction of the galactic center and mild at high latitudes (|b|>10°)
- Even if the profile is spherically symmetric, the flux at Earth is anisotropic (more later)

Extragalactic component

- Assumed to be isotropic
- It is attenuated at high energies due to scattering with the intergalactic background light.

Stecker et al.
Prompt radiation

\[
\frac{dJ}{dE_\gamma}(\Omega) = \frac{dJ_{\text{halo}}}{dE_\gamma}(\Omega) + \frac{dJ_{\text{eg}}}{dE_\gamma}
\]

\[
\psi \rightarrow \gamma \nu
\]

\( \alpha J [\text{ph cm}^{-2} \text{s}^{-1} \text{str}^{-1}] \)

\( \psi \) [degree]
Inverse Compton Scattering radiation

The inverse Compton scattering of electrons/positrons from dark matter decay with the interstellar and extragalactic radiation fields produces gamma rays.

\[ e^\pm + \gamma \rightarrow e^\pm + \gamma^* \]

- \( e^\pm \) from dark matter decay
- \( E_e \leq 1 \text{ TeV} \)
- Interstellar radiation field (Galactic)
- CMB (extragalactic)

Upscattered photon

\[ E_{\gamma^*} \leq 4 \left( \frac{E_e}{m_e} \right)^2 E_\gamma \]

This produces \( E_{\gamma^*} \leq 100 \text{ GeV} \)

Porter et al.
Diffuse gamma ray flux from DM decay

(Data taken from M. Ackermann, talk given at TeV Particle Astrophysics 2009)

$\psi \rightarrow \mu^+ \mu^- \nu$

$\psi \rightarrow \ell^+ \ell^- \nu$
Diffuse gamma ray flux from DM decay

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AI, Tran, Weniger
arXiv: 0909.3514
Diffuse gamma ray flux from DM decay

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Galactic foreground
(GALPROP)

Total flux
(measured)

DM decay

Diffuse EG
(extracted)

$\psi \rightarrow \mu^+ \mu^- \nu$

$\psi \rightarrow l^+ l^- \nu$
**Diffuse gamma ray flux from DM decay**

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Galactic foreground
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**Crucial test:** The contribution from DM decay to the total flux should not exceed the measured one.
Diffuse gamma ray flux from DM decay

(Data taken from M. Ackermann, talk given at TeV Particle Astrophysics 2009)

• **Crucial test**: the contribution from DM decay to the total flux should not exceed the measured one.
• In some channels, there starts to be a deviation from the power law in the diffuse EG flux at higher energies.
Diffuse gamma ray flux from DM decay

(Data taken from M. Ackermann, talk given at TeV Particle Astrophysics 2009)

AI, Tran, Weniger
arXiv: 0909.3514
More indications for or against the decaying dark matter scenario arise from the **angular distribution** of gamma-rays. 

**Gamma rays do not diffuse and point directly to the source!**
More indications for or against the decaying dark matter scenario arise from the angular distribution of gamma-rays. Gamma rays do not diffuse and point directly to the source!

It will be possible to distinguish between annihilating dark matter and decaying dark matter.

Annihilation signal $\propto \rho^2$

Decay signal $\propto \rho$

From B. Moore
More indications for or against the decaying dark matter scenario arise from the angular distribution of gamma-rays. Gamma rays do not diffuse and point directly to the source!

It will be possible to distinguish between annihilating dark matter and decaying dark matter.
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

(but no North-South anisotropy)
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

Strategy: 1) For a certain energy, take the map of the total diffuse gamma ray flux

Bertone et al.
AI, Tran, Weniger
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

Strategy: 2) Remove the galactic disk

Bertone et al.
AI, Tran, Weniger
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic. Bertone et al. AI, Tran, Weniger

Strategy: 3) Take the total fluxes coming from the direction of the galactic center ($J_{GC}$) and the galactic anticenter ($J_{AC}$).
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic. Bertone et al. AI, Tran, Weniger

Strategy: 4) Calculate the anisotropy, defined as:

\[ A(E) = \frac{J_{GC} - J_{GA}}{J_{GC} + J_{GA}} \]
A crucial test: since the Earth is not in the center of the Milky Way halo, the contribution from dark matter decay to the diffuse gamma ray flux is anisotropic.

Strategy: 4) Calculate the anisotropy, defined as:

$$A(E) = \frac{J_{GC} - J_{GA}}{J_{GC} + J_{GA}}$$

DM decay prediction: 15-20% at high energies!

“conventional” diffusive model
The same conclusion holds for all decaying DM scenarios that explain the electron/positron excesses.
Galactic center

Galactic anticenter

Asymmetry GC-GA

Our estimate

Fermi coll.
Neutrino flux

- Difficult to see due to large atmospheric backgrounds.

More details in Michael Grefe's talk.
Neutrino flux

- Difficult to see due to large atmospheric backgrounds.

Covi et al.
Neutrino flux

- Difficult to see due to large atmospheric backgrounds.
- But not impossible: it may be observed by IceCube (+ DeepCore)

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Covi et al.

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PAMELA/Fermi

exclusion from through-going muons after 1 year at IceCube

exclusion from through-going muons after 1 year at IceCube + DeepCore
Conclusions

• Recent experiments have confirmed the existence of an excess of positrons at energies larger than \(~7\)GeV. Evidence for a primary component:
  
  New astrophysics?
  New particle physics?

• Some well motivated candidates for dark matter are predicted to decay with very long lifetimes. Their decay products could be detected in indirect search experiments.

• **Decaying dark matter** could explain the electron/positron excesses observed by PAMELA and Fermi. Furthermore, these scenarios make predictions for future gamma-ray and neutrino observations, providing tests for this interpretation of the e+/e- excesses.
POSITRON TO ELECTRON FRACTION: new data

Data: July 2006 → December 2008

Two different analysis methods

Factor 2.5 increase in statistics (factor 3 in the highest energy bin)


From Roberta Sparvoli
Les Rencontres de Physique de la Vallée d’Aoste 2010
PAMELA ELECTRON ($e^-$) SPECTRUM

From Roberta Sparvoli
Les Rencontres de Physique
de la Vallée d'Aoste 2010
PAMELA ELECTRON ($e^-$) SPECTRUM

From Roberta Sparvoli
Les Rencontres de Physique
de la Vallée d'Aoste 2010
Asymmetry N-S

Fermi coll.

North hemisphere

South hemisphere

Asymmetry N-S

preliminary
Diffuse gamma ray flux

Fermi coll.
For the dominant high-latitude components, bremsstrahlung and $\pi^0$-decay emission from H\textsc{ii} and H\textsc{lt} in the local Galaxy ($7.5 \text{ kpc} < R < 9.5 \text{ kpc}$) and IC emission, the intensities are fit to the LAT data via scale factors. We use the GALPROP sky maps as templates with the component normalizations per energy bin as fit parameters. The subdo-

<table>
<thead>
<tr>
<th>Energy in GeV</th>
<th>0.2–0.4</th>
<th>0.4–0.8</th>
<th>0.8–1.6</th>
<th>1.6–3.2</th>
<th>3.2–6.4</th>
<th>6.4–12.8</th>
<th>12.8–25.6</th>
<th>25.6–51.2</th>
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<td>Intensity scale factor</td>
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<td>$\times 10^{-7}$</td>
<td>$\times 10^{-7}$</td>
<td>$\times 10^{-8}$</td>
<td>$\times 10^{-8}$</td>
<td>$\times 10^{-9}$</td>
<td>$\times 10^{-9}$</td>
<td>$\times 10^{-10}$</td>
<td>$\times 10^{-10}$</td>
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<td>EGB</td>
<td>2.4 ± 0.6</td>
<td>9.3 ± 1.8</td>
<td>3.5 ± 0.6</td>
<td>12.7 ± 2.1</td>
<td>5.0 ± 1.0</td>
<td>14.3 ± 4.0</td>
<td>63 ± 1.5</td>
<td>2.6 ± 0.7</td>
<td>11.1 ± 2.9</td>
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<tr>
<td>Galactic diffuse (fit)</td>
<td>4.9 ± 0.4</td>
<td>25.9 ± 1.8</td>
<td>12.6 ± 1.3</td>
<td>50.7 ± 7.2</td>
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<td>IC (fit)</td>
<td>1.5 ± 0.1</td>
<td>6.8 ± 0.5</td>
<td>3.5 ± 0.4</td>
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<td>6.6 ± 1.2</td>
<td>23.3 ± 4.9</td>
<td>9.3 ± 2.1</td>
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<td>IC (model)</td>
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<td>16.2</td>
<td>6.3</td>
<td>2.4</td>
<td>8.7</td>
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<tr>
<td>local H\textsc{ii} (fit)</td>
<td>2.7 ± 0.2</td>
<td>15.4 ± 1.1</td>
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<td>28.3 ± 4.0</td>
<td>8.3 ± 1.5</td>
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<td>local H\textsc{ii} (model)</td>
<td>3.1</td>
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<td>Sources</td>
<td>0.8 ± 0.1</td>
<td>3.8 ± 0.2</td>
<td>1.7 ± 0.1</td>
<td>7.2 ± 0.8</td>
<td>2.7 ± 0.4</td>
<td>9.0 ± 1.3</td>
<td>3.4 ± 0.5</td>
<td>1.5 ± 0.2</td>
<td>6.3 ± 1.0</td>
</tr>
<tr>
<td>CR background</td>
<td>1.4 ± 0.6</td>
<td>4.2 ± 1.7</td>
<td>1.0 ± 0.4</td>
<td>2.8 ± 1.2</td>
<td>0.8 ± 0.4</td>
<td>6.3 ± 3.0</td>
<td>14.8 ± 0.8</td>
<td>0.6 ± 0.4</td>
<td>0.9 ± 0.9</td>
</tr>
<tr>
<td>Solar</td>
<td>0.1 ± 0.01</td>
<td>0.4 ± 0.04</td>
<td>0.2 ± 0.02</td>
<td>1.0 ± 0.2</td>
<td>0.4 ± 0.2</td>
<td>1.7 ± 0.4</td>
<td>0.7 ± 1.6</td>
<td>0.1 ± 0.04</td>
<td>0.8 ± 0.5</td>
</tr>
<tr>
<td>LAT</td>
<td>9.6 ± 0.8</td>
<td>44.0 ± 3.0</td>
<td>18.8 ± 2.0</td>
<td>72.9 ± 10</td>
<td>25.3 ± 4.5</td>
<td>81.3 ± 16</td>
<td>283 ± 5.7</td>
<td>10.6 ± 2.1</td>
<td>37.9 ± 7.7</td>
</tr>
</tbody>
</table>

TABLE I.  Fit results and uncertainties for the EGB and other components for $|b| \geq 10^\circ$.  

| Foreground modeling related uncertainty in cm$^{-2}$ s$^{-1}$ sr$^{-1}$ |
|---------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| H\textsc{ii} column density | +0.1/−0.3 | +0.1/−1.7 | +0.1/−0.9 | +0.1/−3.6 | +0.1/−1.1 | +0.1/−2.4 | +0.1/−0.9 | +0.1/−0.2 | +0.1/−1.1 |
| IC + halo size | +0.1/−0.2 | +0.1/−0.8 | +0.1/−0.5 | +0.1/−1.8 | +0.1/−0.5 | +0.1/−0.7 | +0.3/−0.3 | +0.4/−0.1 | +2.9/−0.5 |
| CR propagation model | +0.1/−0.3 | +0.1/−1.1 | +0.1/−0.6 | +0.1/−0.8 | +0.1/−0.3 | +0.1/−1.2 | +1.4/−0.1 | +0.4/−0.1 | +3.0/−0.1 |
| Subregions of $|b| > 10^\circ$ sky | +0.2/−0.3 | +0.8/−1.5 | +0.4/−0.9 | +1.9/−2.1 | +0.7/−0.5 | +2.5/−1.9 | +1.0/−1.5 | +0.5/−0.3 | +2.7/−0.9 |
Acceleration in nearby sources

\[ \Gamma = 2.4 \]
FIG. 1: The titanium-to-iron ratio in cosmic rays along with model predictions — the ‘leaky box’ model with production of secondaries during propagation only (dashed line), and including production and acceleration of secondaries in a nearby source (solid line - dotted beyond the validity of our calculation). The data points are from ATIC-2 (triangles) [27] and HEAO-3-C3 (circles) [34].

FIG. 2: The boron-to-carbon ratio in cosmic rays along with model predictions — the ‘leaky box’ model with production of secondaries during propagation only (dashed line), and including production and acceleration of secondaries in a nearby source (solid line). The data points are from HEAO-3-C2 (circles) [31], ATIC-2 (triangles) [35] and CREAM (squares) [36].