Indirect Search for Dark Matter

Da Huang
Physics Department, NTHU
@ Workshop on Dark Universe

PRD89, 055021(2014) [arXiv: 1312.0366]
In collaboration with C.-Q. Geng, L.-H. Tsai and C. Lai
Content

- Review of Experimental Status
- Motivation of Multi-Compent Dark Matter
- General Phenomenological Analysis–Two-Component Decaying DM
- Diffuse $\gamma$-ray Prediction
- Summary
There are already many established evidences for the existence of dark matter.

- Rotation Curves of Spiral Galaxies
  Babcock, 1939, Bosma, 1978; Rubin & Ford, 1980

- Gravitational Lensing

- CMB

- Bullet Clusters

But, they are all gravitational.
Dark Matter: Key Questions

- Is dark matter composed of particles?
- What kind of particle is dark matter?
- How does it interact with Standard Model particles?
- How is it distributed in our Universe? (Can it tell us its particle properties and dynamics?)
Dark Matter Particle Candidate

Assume dark matter is a WIMP (weakly-interacting massive particle):

- weak interactions with Standard Model
- GeV - TeV mass scale
- can pair annihilate or decay to produce Standard Model particles

Credit: Annika Peter

SUSY WIMP
Thermal Relic Dark Matter

- If DM is a WIMP produced thermally in the early universe, its pair annihilation cross-section is related to the relic abundance today.

- Measured DM abundance gives prediction for the annihilation cross-section: $\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

Jungman, Kamionkowski, and Griest 1996
How to detect particle DM?

Collider Searches

SM

Direct Detection

Complementarity: Related by cross symmetry

Indirect Detection + Relic Density
Indirect Search Signals

- Supersymmetric neutralinos
- Quarks
- Leptons
- Bosons
- Low-energy photons
- Medium-energy gamma rays
- Positrons
- Electrons
- Neutrinos
- Antiprotons
- Protons

Credit: Sky & Telescope / Gregg Dinderman
Current Experiments

Cherenkov Telescope Array [gamma rays and cosmic rays]

Fermi Gamma-ray Space Telescope [gamma rays and cosmic rays]

IceCube [neutrinos]

AMS-02 [cosmic rays]
Motivation

- Recently, AMS-02 published a series of new measurements of the positron fraction spectrum, showing an uprise above 10 GeV.

- Confirm the observation by many previous experiments, such as PAMELA, Fermi-LAT, AMS-01, et al..

- Different from usual astrophysical expectation: decreasing power law
Motivation

- The excess was also observed in the total $e^+ + e^-$ flux spectrum by PAMELA, Fermi-LAT and AMS-02.

- Conventional expectation: decreasing power law
Motivation

Moreover, both the AMS-02 positron fraction spectrum and the Femi-LAT total $e^+ + e^-$ flux spectrum showed some substructure around 100 GeV.
Motivation

- All the excesses indicate that there are additional positron and/or electron sources beyond our current knowledge, either in astrophysical or particle physical origin.

- In literature, there are two compelling candidate origin for these excesses: Pulsars and Dark Matter.

- In this talk, I concentrate on the decaying dark matter interpretation for this AMS-02/Fermi-LAT excess

Requirement

\[ \tau_{DM} \sim O(10^{26})s \gg \tau_{Universe} \sim O(10^{17})s \]
Decaying DM: Status

- Previous Studies concentrated on the Single-Component Decaying DM models with the dominant decay channels $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $W^+W^-$, $b^+b^-$, ... Their general conclusion is that such models cannot explain the AMS-02 positron fraction and Fermi-LAT total $e^+e^-$ flux simultaneously.

Further Constraints on Decaying DM

- The measured antiproton spectrum agrees with the prediction of the conventional astrophysical theory well.

---

Talk @ Workshop on Dark Physics of the Universe
Further Constraints on Decaying DM

➢ Recent analysis with the new AMS-02 data confirmed this conclusion.


Leptophilic DM
Decaying DM: General Formula

\[ \Phi_e^{(tot)} = \kappa_1 \Phi_e^{(primary)} + \kappa_2 \Phi_e^{(secondary)} + \Phi_e^{DM}, \]

\[ \Phi_p^{(tot)} = \kappa_2 \Phi_p^{(secondary)} + \Phi_p^{DM}, \]

Primary electron flux: assumed to be broken power law

\[ Br = 4.0 \times 10^3 \text{ MV}, \gamma_1 = 1.54, \gamma_2 = 2.6 \]

\[ \Phi_e^{(secondary)} = \Phi_p^{(secondary)} \]

Secondary \( e^- (e^+) \) produced in propagation, computed by GALPROP

\( \kappa_{1,2} \) denotes the uncertainty in normalization of backgrounds.
Two-Component Decaying DM

- **DM Source Term:**
  \[ Q(x) = \frac{\rho(x)}{2} \left[ \frac{1}{\tau_1 M_1} \left( \frac{dN}{dE} \right)_1 + \frac{1}{\tau_1 M_2} \left( \frac{dN}{dE} \right)_2 \right] \]

  \( \rho(x) \): DM density distribution, here we use isothermal profile

  \( \tau_i \): DM lifetime

  \( M_i \): DM Mass

- **DM decay process:**

- **DM Injection Spectra:**
  \[ \left( \frac{dN}{dE} \right) = \epsilon_e \frac{dN_e}{dE} + \epsilon_\mu \frac{dN_\mu}{dE} + \epsilon_\tau \frac{dN_\tau}{dE} \]

  with condition:

  \[ \epsilon_e + \epsilon_\mu + \epsilon_\tau = 1 \]
Two-Component Decaying DM

- Normalized Injection Spectra for Electrons:

\[
\frac{dN_e}{dE} = \frac{1}{E_c} \delta(1 - x), \quad \text{where } x = \frac{E}{E_c}
\]

\[
\frac{dN_\mu}{dE} = \frac{1}{E_c} [3(1 - x^2) - \frac{4}{3}(1 - x)] \theta(1 - x),
\]

\[
\frac{dN_\tau}{dE} \quad \text{: obtained with the simulation by PYTHIA}
\]

- After $e^+/e^-$ are produced from DM decays, they would propagate in the Galaxy, which is solved numerically by GALPROP
Two-Component Decaying DM

Observations:

- The excess of total $e^+e^-$ flux by Fermi-LAT extends to 1 TeV, so at least one DM cutoff should be larger than 1 TeV;
- The substructure at around 100 GeV observed by both AMS-02 and Fermi-LAT.
Two-Component Decaying DM

- The observations above indicate that DM at least contains **two components**, with $E_{c1} > 1000$ GeV and $E_{c2} \approx 100$ GeV. For generic discussion, we take two DMs’ cutoffs $E_{ci}$ and masses $M_i$ as follows:

<table>
<thead>
<tr>
<th>$E_{c1}$</th>
<th>$M_1$</th>
<th>$E_{c2}$</th>
<th>$M_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 GeV</td>
<td>3030 GeV</td>
<td>100 GeV</td>
<td>416 GeV</td>
</tr>
</tbody>
</table>
Two-Component Decaying DM

Fitting Results:

<table>
<thead>
<tr>
<th>$\kappa$</th>
<th>$\epsilon_{e1}$</th>
<th>$\epsilon_{\mu1}$</th>
<th>$\epsilon_{\tau1}$</th>
<th>$\tau_1(10^{26}\text{s})$</th>
<th>$\epsilon_{e2}$</th>
<th>$\epsilon_{\mu2}$</th>
<th>$\epsilon_{\tau2}$</th>
<th>$\tau_2(10^{26}\text{s})$</th>
<th>$\chi^2$</th>
<th>$\chi^2/d.o.f.$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.844</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.92</td>
<td>0.018</td>
<td>0</td>
<td>0.982</td>
<td>0.81</td>
<td>62.3</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Conclusion: Double-Component DM decaying mainly via two-body leptonic decay CAN fit to AMS-02 positron fraction and Fermi-LAT total flux simultaneously.
New Data from AMS-02

- Last year, AMS-02 updated their result on positron fraction and provided the spectra of $e^+ (e^-)$ flux and total $(e^++e^-)$ flux.

- $e^+ (e^-)$ flux: Spectrum hardening above ~30 GeV
New Data from AMS-02

- Positron fraction: first evidence that positron fraction stops increasing with energy above ~200 GeV
- Total $e^+ + e^-$ flux: good fit with a single power law at high energy

![AMS-02 Positron Fraction Spectrum](image1)

![AMS-02 Spectrum of ($e^+ + e^-$) flux](image2)
Recently, we update our analysis of two-component decaying DM model with the **AMS-02 positron fraction and total \((e^+ + e^-)\) flux.** C. Lai, DH, C. Q. Geng, MPLA 30 (2015) 35, 1550188

- Advantage: reduce the systematic uncertainties of fit

### TABLE III. Parameters leading to the minimal values of \(\chi^2\) with the cutoffs of the heavy DM being 600, 800, 1200, and 1500 GeV, respectively.

<table>
<thead>
<tr>
<th>(E_{cH}) (GeV)</th>
<th>(\kappa_1)</th>
<th>(\kappa_2)</th>
<th>(\epsilon_L^{e,\mu,\tau})</th>
<th>(\epsilon_H^{e,\mu})</th>
<th>(\tau_L(10^{26}\text{s}))</th>
<th>(\tau_H(10^{26}\text{s}))</th>
<th>(\chi^2_{\text{min}})</th>
<th>(\chi^2_{\text{min}}/\text{d.o.f.})</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0.94</td>
<td>1.51</td>
<td>0.02, 0, 0.98</td>
<td>0.18, 0.82</td>
<td>1.43</td>
<td>1.60</td>
<td>94</td>
<td>1.09</td>
</tr>
<tr>
<td>800</td>
<td>0.94</td>
<td>1.52</td>
<td>0.04, 0.08, 0.88, 0.05, 0.95</td>
<td>1.58</td>
<td>1.32</td>
<td>97</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>0.94</td>
<td>1.57</td>
<td>0.12, 0.48, 0.40</td>
<td>0, 1</td>
<td>2.58</td>
<td>1.06</td>
<td>107</td>
<td>1.24</td>
</tr>
<tr>
<td>1500</td>
<td>0.94</td>
<td>1.60</td>
<td>0.20, 0.80, 0</td>
<td>0, 1</td>
<td>3.41</td>
<td>0.93</td>
<td>119</td>
<td>1.38</td>
</tr>
</tbody>
</table>
Update with New AMS-02 Data

All the cases fit the AMS-02 dataset very well.
Diffuse $\gamma$-ray Constraint

- Previous studies showed that the diffuse $\gamma$-ray measured by Fermi-LAT could already give strong constraint to decaying DM

- **Question:** Does our two-component DM (or multi-component DM) scenario still survive after the consideration of diffuse $\gamma$-ray constraints?

- **Strategy:** We compute total various diffuse $\gamma$-ray spectrum, including the ones from two-component DM decays, which is compared with the Fermi-LAT data.

Cirelli et al PRD(2012); Essig et al. PRD (2009); Ibe et al(2013), 1305.0084; Cirelli & Panci, NPB (2009); ...

Talk @ Workshop on Dark Physics of the Universe
Model Prediction to Diffuse $\gamma$-ray

Conclusion: With the parameters fitted by AMS-02 and Fermi-LAT, the predicted $\gamma$ ray is still allowed by the Fermi-LAT measurement.
Summary

- In this talk we investigate the multi-component decaying Dark Matter model to explain AMS-02 and Fermi-LAT $e^+/e^-$ excesses, and show that two DM components are enough to explain the data.

- We also use the AMS-02 2014 data to update our analysis of two-component DM model, and show that it can also provide a good fit.

- We also show that the predicted diffuse $\gamma$-ray spectrum agrees with that observed by Fermi-LAT.
THANKS FOR YOUR ATTENTION!
Single-Component Decaying DM

$X^2$ Fitting Results:

<table>
<thead>
<tr>
<th>$E_c$(GeV)</th>
<th>$\kappa$</th>
<th>$\epsilon^e$</th>
<th>$\epsilon^\mu$</th>
<th>$\epsilon^\tau$</th>
<th>$\tau \times 10^{26}$s</th>
<th>$\chi^2_{\text{min}}$</th>
<th>$\chi^2_{\text{min}} / d.o.f.$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.73</td>
<td>0.09</td>
<td>0</td>
<td>0.91</td>
<td>0.66</td>
<td>463</td>
<td>7.35</td>
</tr>
<tr>
<td>1300</td>
<td>0.72</td>
<td>0.04</td>
<td>0</td>
<td>0.96</td>
<td>0.71</td>
<td>516</td>
<td>8.19</td>
</tr>
<tr>
<td>1500</td>
<td>0.71</td>
<td>0.02</td>
<td>0</td>
<td>0.98</td>
<td>0.74</td>
<td>541</td>
<td>8.46</td>
</tr>
</tbody>
</table>

(a) Total Flux

(b) Positron Fraction
All the cases fit the AMS-02 data very well $\rightarrow$ 2DM alive

Observation: if $E_{cH} < 1$ TeV, the positron fraction begins decreasing at $\sim 200$ GeV, as claimed by AMS-02, but it cannot explain the total $(e^+ + e^-)$ flux at high energies.
Propagation Parameters

TABLE I. The parameters for the diffuse propagation, primary electron, and primary proton.

<table>
<thead>
<tr>
<th>diffuse coefficient</th>
<th>primary electron</th>
<th>primary proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0$ (cm$^2$s$^{-1}$)</td>
<td>$\rho_r$ (MV)</td>
<td>$\rho_{br}^e$ (MV)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$v_A$ (km s$^{-1}$)</td>
<td>$\gamma_1^e$</td>
</tr>
<tr>
<td>$\gamma_2^e$</td>
<td>$\gamma_2^n$</td>
<td>$4.0 \times 10^3$</td>
</tr>
<tr>
<td>$5.3 \times 10^{28}$</td>
<td>$4.0 \times 10^3$</td>
<td>$0.33$</td>
</tr>
<tr>
<td>$33.5$</td>
<td>$2.6$</td>
<td>$1.88$</td>
</tr>
</tbody>
</table>