FERMI and Dark Matter

Savvas M. Koushiappas
“If there are more things in heaven and Earth that are dreamt of in our natural philosophy, it is partly because the standard model of particle physics is inadequate.”

\[
\Omega_M = \frac{\rho}{\rho_c} \sim \left( \frac{10^{-27} \text{cm}^3\text{s}^{-1}}{\langle\sigma v\rangle} \right) = 0.233 \pm 0.0013
\]

Komatsu et al. (2009)
FERMI and Dark Matter

1. Why dark matter is relevant to FERMI

2. How can FERMI search for the dark matter signal (targets and limitations)
The connection between the Early Universe and FERMI

\[ \chi \chi \leftrightarrow q \bar{q} \]

\[ f_i(k, t) d^3k = \frac{g_i}{(2\pi)^3} \frac{1}{e^{[E(k)-\mu_i]/T_i(t)} \pm 1} d^3k, \]

\[ \rho = \int E f(k) d^3k \quad \hat{L}[f] = C[f] \]

\[ \Omega_M \approx \left( 10^{-27} \text{ cm}^3\text{s}^{-1} / \langle \sigma v \rangle \right) = \text{Observed value if } M_\chi \sim \mathcal{O}(\text{GeV} - \text{TeV}) \]

Weakly Interacting Massive Particle (WIMP)
The connection between the Early Universe and FERMI

WIMP’s

Neutralinos
Axinos
Gravitinos
sneutrinos
Kaluza-Klein
Mirror matter
Heavy photons
...

Theorist

Theories that solve problems with the Standard Model can naturally provide a WIMP dark matter candidate (e.g., supersymmetry)
The connection between the Early Universe and FERMI

\[ \chi \chi \leftrightarrow q \bar{q} \]
The connection between the Early Universe and FERMI

\[ \chi \chi \rightarrow q \bar{q} \]
The connection between the Early Universe and FERMI

\[ \chi \chi \rightarrow q \bar{q} \quad \text{This results in photon final states} \]
The connection between the Early Universe and FERMI

\[ \chi \chi \rightarrow q \bar{q} \]

This results in photon final states

\[ E_\gamma < M_\chi \]

Continuum

Line emission

\[ E_\gamma = M_\chi \]
FERMI and Dark Matter

1. Why dark matter is relevant to FERMI

Because it can search for the photon emission from dark matter annihilation (a process we know must have taken place in the early universe).

Note: FERMI can also search for other annihilation by-products (e.g., antimatter)...no time to cover here but happy to discuss afterwards...
FERMI and Dark Matter

1. Why dark matter is relevant to FERMI

2. How can FERMI search for the dark matter signal (targets and limitations)
Photon searches

(An outcome of the requirement of proper relic abundance)

\[ \chi \chi \rightarrow q\bar{q} \]

\[ \Gamma \propto n^2_\chi \]
Photon searches

(An outcome of the requirement of proper relic abundance)

DANGER

It depends strongly on the distribution of dark matter

...and that’s where the difficulties are
Hierarchical structure formation in an evolving Universe

Courtesy A. V. Kravtsov

Stadel et al, arXiv:0808.2981
Photon searches

(An outcome of the requirement of proper relic abundance)

It depends strongly on the distribution of dark matter

...and that’s where the difficulties are

We can only discuss the distribution of dark matter in a statistical fashion (we do not know initial conditions)!
Photon searches

(An outcome of the requirement of proper relic abundance)

Individual objects

Along a line-of-sight

Objects along a line-of-sight
Photon searches

(An outcome of the requirement of proper relic abundance)

Individual objects

\[ \Gamma_{\gamma,e^+,\bar{p}} \sim \frac{1}{d} \int_V n^2(r) d^3r \]

Along a line-of-sight

\[ \Gamma_{\gamma,e^+,\bar{p}} \sim \int_{\text{LOS}} n^2(\ell) d\ell \]

Objects along a line-of-sight

\[ \Gamma_{\gamma,e^+,\bar{p}} \sim \int_{\text{LOS}} n(\ell) \mathcal{L}(\ell) d\ell \]

\[ \sim \int_V n^2(r) d^3r \]
### Photon searches

(An outcome of the requirement of proper relic abundance)

<table>
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<th>Individual objects</th>
<th>Dwarf spheroidals, Nearby galaxies/clusters</th>
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<td>Along a line-of-sight</td>
<td>Galactic center, Diffuse Galactic halo, Extragalactic</td>
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Distribution of dark matter unclear
A lot of astrophysical sources
Bottom line: Very difficult
They are ideal laboratories for studying the distribution of dark matter:

- High mass-to-light ratios
- Astrophysical backgrounds relatively not present
- High galactic latitude - better prospects for detection

\[
\sigma_t^2(R) = \frac{2}{\overline{I}(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\rho_\ast \sigma_r^2 r}{\sqrt{r^2 - R^2}} \, dr
\]

\[
r \frac{d(\rho_\ast \sigma_r^2)}{dr} = -\rho_\ast(r)V_c^2(r) - 2\beta(r)\rho_\ast \sigma_r^2
\]

Dwarf satellites of the local group

They are ideal laboratories for studying the distribution of dark matter:

- High mass-to-light ratios
- Astrophysical backgrounds relatively not present
- High galactic latitude - better prospects for detection

Dwarf satellites of the local group
Dwarf satellites of the local group

Abdo et al. 1001.4531 (2010)
Dwarf satellites of the local group

From Maja Llena Garde’s talk at the 2011 Fermi Symposium
Dwarf satellites of the local group

\[ \mathcal{L} \approx 10^{18} \text{GeV}^2 \text{cm}^{-5} \text{s}^{-1} \left( \frac{\text{Sensitivity}}{10^{-11} \text{cm}^{-2} \text{s}^{-1}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^3 \text{s}^{-1}} \right) \left( \frac{M_X}{50 \text{GeV}} \right)^2 \left( \frac{N_\gamma}{30} \right) \]
Dwarf satellites of the local group

$$\mathcal{L} \approx 10^{18}\text{GeV}^2\text{cm}^{-5}\text{s}^{-1} \left( \frac{\text{Sensitivity}}{10^{-11}\text{cm}^{-2}\text{s}^{-1}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26}\text{cm}^3\text{s}^{-1}} \right) \left( \frac{M_{\chi}}{50\text{GeV}} \right)^2 \left( \frac{N_\gamma}{30} \right)$$

Microhalos with proper motion:

$$10^{-8} \leq \frac{M}{M_\odot} \leq 10^{-2}$$

Sextans

Carina

Fornax

Sculptor

Draco

Ursa Minor

Milky Way dark substructure:

$$10^5 \leq \frac{M}{M_\odot} \leq 10^7$$

\[ \log_{10}[L/\text{GeV}^2\text{cm}^{-5}] \]
We need something like the Cerenkov Telescope Array

\[ \mathcal{L} \approx 10^{18} \text{GeV}^2 \text{cm}^{-5} \text{s}^{-1} \left( \frac{\text{Sensitivity}}{10^{-11} \text{cm}^{-2} \text{s}^{-1}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^3 \text{s}^{-1}} \right) \left( \frac{M_\chi}{50 \text{GeV}} \right)^2 \left( \frac{N_\gamma}{30} \right) \]
Individual Objects

\[ \Gamma_{\gamma,e^+,\bar{p}} \sim \int_V n^2 dV \]

The spectrum of dark matter subhalo properties originates from the host assembly history.

These two may have the same mass, but different history.

Individual Objects

\[ \Gamma_{\gamma, e^+, \bar{p}} \sim \int_V n^2 dV \]

The spectrum of dark matter subhalo properties originates from the host assembly history.

Individual Objects

\[ \Gamma_{\gamma,e^+,\bar{p}} \sim \int_V n^2 dV \]

The spectrum of dark matter subhalo properties originates from the host assembly history.

\[ M = [1-2] \times 10^6 \, M_\odot \]
\[ r = [50-60] \, \text{kpc} \]

Set by cosmology


Individual Objects

$$\Gamma_{\gamma,e^+,\bar{p}} \sim \int_V n^2 dV$$

The spectrum of dark matter subhalo properties originates from the host assembly history.


The Galactic gamma-ray background
The Galactic gamma-ray background

The Galactic gamma-ray background

Koushiappas, Zentner & Kravtsov, PRD 82 3504 (2010)
The Galactic gamma-ray background

Koushiappas, Zentner & Kravtsov, PRD 82 3504 (2010)


See also Lee, Ando & Kamionkowski, JCAP 07, 007 (2009)
The Galactic gamma-ray background

The Galactic gamma-ray background

The extragalactic gamma-ray background

\[ \Gamma_{\gamma,e^+,\bar{p}} \sim \int_{\text{LOS}} n(\ell) \mathcal{L}(\ell) d\ell \]

\[ \sim \int_V n^2(r) d^3r \]
The extragalactic gamma-ray background

\[ \Gamma_{\gamma,e^+,\bar{p}} \sim \int_{\text{LOS}} n(\ell) \mathcal{L}(\ell) d\ell \]

\[ \sim \int_{V} n^2(r) d^3r \]
The extragalactic gamma-ray background

Conclusions

A WIMP dark matter candidate results in photon final states.

Annihilation takes place in high density regions.

FERMI’s energy range is well within viable dark matter candidates.

Targets include dwarf spheroidals, the Galactic center, the diffuse Galactic halo emission as well as the extragalactic background.

All studies are affected severely by the level of our understanding of the distribution of dark matter.