Astrophysical Signatures of Dark Matter Annihilation

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January 29th, 2009 - Ohio State University
Astrophysical Signatures of Dark Matter Annihilation

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Q&A with a hypothetical particle physicist

Q: What is the simplest model of DM you can come up with?

A: Let’s consider SUSY. Then the simplest possible particle would be the lightest stable SUSY particle. aka, the neutralino $\chi$
Q&A with a hypothetical particle physicist

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A: Let’s consider SUSY. Then the simplest possible particle would be the lightest stable SUSY particle. aka, the neutralino $\chi$

- own anti-particle (Majorana fermion)
- linear combination of higgsino, $B$-ino, $W$-ino
Q: What is the simplest model of DM you can come up with?

A: Let’s consider SUSY. Then the simplest possible particle would be the lightest stable SUSY particle. aka, the neutralino $\chi$
- own anti-particle (Majorana fermion)
- linear combination of higgsino, B-ino, W-ino

Lots of other candidates!
See comprehensive review by Bertone, Hooper, & Silk (2004)
The “WIMP Miracle”

Thermal equilibrium
The “WIMP Miracle”

Thermal equilibrium

Universe cools
The “WIMP Miracle”

Thermal equilibrium

Universe cools

Particles freeze out

The diagram illustrates the process where particles $\chi$ and $\bar{f}$ interact over time, leading to thermal equilibrium, universe cooling, and particles freezing out.
The “WIMP Miracle”

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

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Increasing \( <\sigma v> \)

J. Feng, FNAL, May 2007
The “WIMP Miracle”

\[ \Omega_\chi h^2 \sim \frac{3 \times 10^{-27} \text{ cm}^3\text{s}^{-1}}{\langle \sigma_A \nu \rangle} \]

Jungman et al. (1996)

\[ \langle \sigma_A \nu \rangle \propto \frac{1}{m^2_\chi} \sim 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]

for a neutralino of mass \( m_\chi \sim 0.1 - 1 \text{ TeV} \)
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Cosmology alone suggests that we consider weak-scale DM
Making $e^+e^-$ with DM

$\chi \rightarrow ? \rightarrow e^+$

$\chi \rightarrow ? \rightarrow e^-$
Making $e^+e^-$ with DM

$\chi \rightarrow ? \rightarrow e^+ e^-$

$bb, W^+W^-, ZZ, ... \rightarrow \mu^+\mu^- \rightarrow e^+e^-$
Making $e^+e^-$ with DM

$\chi \rightarrow e^+ e^- \rightarrow \mu^+ \mu^- \rightarrow e^+ e^-$

Multiple annihilation channels => large range of $e^+e^-$ energies $E_e \sim 50$ GeV up to $m_\chi$
Making $e^+e^-$ with DM

Multiple annihilation channels => large range of $e^+e^-$ energies $E_e \sim 50$ GeV up to $m_\chi$

Bottom line:
Injection of high energy $e^+e^-$ has observable astrophysical consequences
a signal in microwaves?
...CMB foregrounds
WIMP annihilations may produce gamma rays

WIMP annihilations also produce $e^+e^-$ (cosmic ray electrons)

Number density is high in the Galactic center (GC)
  $\Rightarrow$ many $e^+e^-$ injected

Significant B field in GC

B field + many electrons = synchrotron radiation

$\sim 10-100$ GHz $\Rightarrow$ WMAP
WMAP
Template Fitting

\[ s_{23} x + f_{23} x + d_{23} x = \text{23 GHz} - c_{23} x \]
Template Fitting

\[ s_{23} \times f_{23} \times d_{23} \times + c_{23} \times \]

\( s(\nu_i), f(\nu_i), d(\nu_i) \) represent estimates of the synchrotron, free-free, and dust spectra.
Template Fitting

\[ s_{23} \times + f_{23} \times + d_{23} \times = c_{23} \times \]

\[ 23 \text{ GHz} \]

\( s(\nu_i), f(\nu_i), d(\nu_i) \) represent estimates of the synchrotron, free-free, and dust spectra

(...actually, Haslam-, H\( \alpha \)-, and FDS99-correlated spectra)
Determining Foreground Spectra

Multi-Linear Regression Template Fit
- Bands are completely decoupled
- Spectral shapes are unconstrained
- Constant across the sky

\[ P\tilde{a} = w \]
\[ \tilde{a} = (P / \sigma)^* (w / \sigma) \]
\[ \left| \frac{P}{\sigma} \tilde{a} - \frac{w}{\sigma} \right|^2 = \frac{\|P\tilde{a} - w\|^2}{\sigma^2} \equiv \chi^2 \]

Dobler & Finkbeiner, 2008

TEMPLATES
- Dust: FDS99 (Finkbeiner et al 1999)
- Free-free: H\alpha Map (WHAM, SHASSA, VTSS; assembled and corrected for dust by Finkbeiner 2003)

CMB ESTIMATORS
- 6 different types
- introduces a cross-correlation bias
- mean zero
- largest source of uncertainty
CMB “Cross-Correlation” Bias
CMB “Cross-Correlation” Bias

\[ s_{23} x + f_{23} x + d_{23} x = 23 \text{ GHz} - c_{23} x \]
CMB “Cross-Correlation” Bias

\[ \rightarrow + b_s x \]
CMB “Cross-Correlation” Bias

\[ s_{23} \times f_{23} \times d_{23} = 23 \text{ GHz} - c_{23} \times \left( b_{s} \times \right) \]
CMB “Cross-Correlation” Bias

\[ s_{23} x + f_{23} x + d_{23} x = c_{23} x ( + b_s x ) \]

\[ s_v \rightarrow s_v - c_v x b_s \quad f_v \rightarrow f_v - c_v x b_f \quad d_{23} \rightarrow d_v - c_v x b_d \]
$s_{23} \times$

$\pm$

$f_{23} \times$

$\pm$

$d_{23} \times$

$\pm$

$c_{23} \times$

$\pm$

WMAP
A 5th Foreground: the Haze

Dobler & Finkbeiner (2008)
A 5th Foreground: the Haze

- Multi-linear regression fit
- Excess towards the GC

Dobler & Finkbeiner (2008)
Synchrotron Spectra
This ambiguity will be **eliminated** with *Planck*.
A 5th Foreground: the Haze

- Multi-linear regression fit
- Excess towards the GC

Separate, *hard* synchrotron component

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K: 23 GHz
Ka: 33 GHz
Q: 41 GHz

Dobler & Finkbeiner (2008)
A 5th Foreground: the Haze

- Multi-linear regression fit
- Excess towards the GC

Separate, hard synchrotron component

Upcoming surveys at 5 GHz (CBASS), 15 GHz, and especially Planck will provide A LOT more information!

Dobler & Finkbeiner (2008)
23 GHz Synchrotron
33 GHz Synchrotron
41 GHz Synchrotron
61 GHz Synchrotron
The Haze Spectrum

- Looks like synchrotron with,
  \[ E^2 dN/dE \propto E^\alpha \quad -0.1 \leq \alpha \leq 0.2 \]

- If it is synchrotron, it requires
  - hard $e^+e^-$ spectrum
  - extended emission

- Very difficult to produce astrophysically

Dobler & Finkbeiner (2008)
The Haze Spectrum

- Looks like synchrotron with,
  \[ E^2 dN/dE \propto E^\alpha \quad -0.1 \leq \alpha \leq 0.2 \]

Can be confirmed by ICS signal in Fermi!

Dobler & Finkbeiner (2008)
an explanation...

particle dark matter
The Haze: an explanation

- WIMP annihilation produces very energetic electrons (>50 GeV)

- Halo annihilation towards the GC is extended injection (i.e., not a point source)

- Can it explain the haze data towards the south Galactic center?
The Haze: an explanation

• Galactic/baryon parameters:
  – Magnetic field, $B = 10 \, \mu G$
  – Diffusion constant, $K(E) \approx 10^{28} \, \text{cm}^2/\text{s}$

• Dark matter parameters
  – DM halo profile, $\rho = \rho(r)$
  – WIMP mass, $M \approx 100\text{-}800 \, \text{GeV}$
  – Annihilation cross section, $<\sigma v> \approx 3 \times 10^{-26} \, \text{cm}^3/\text{s}$
  – Annihilation mechanisms ($W^+W^-, ZZ, b\bar{b}$, etc.)
Diffusion Equation

\[
\frac{d}{dt}n(E, x) = \nabla \cdot (K(E, x)\nabla n) + \frac{\partial}{\partial E} [b(E, x)n] + Q(E, x)
\]

\(K(E, x) = \) diffusion coefficient

\(b(E, x) = \) energy loss coefficient

\(Q(E, x) = \) source term

Assuming steady state and isotropic diffusion and energy loss =>

\[-K(E)\nabla^2 n - \frac{\partial}{\partial E} [b(E)n] = Q(E, x).\]
The Haze: an explanation

\[ \rho(r) \sim r^{-1.2} \] favored

Hooper, Finkbeiner, & Dobler, 2007
$\rho(r) \sim r^{-1.2}$ favored

Hooper, Finkbeiner, & Dobler, 2007
• $\rho(r) \sim r^{-1.2}$ favored

Hooper, Finkbeiner, & Dobler, 2007
The Haze: an explanation

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- Multiple annihilation channels are consistent with 23-33 GHz spectrum

Hooper, Finkbeiner, & Dobler, 2007
The Haze: an explanation

- $\rho(r) \sim r^{-1.2}$ favored
- Multiple annihilation channels are consistent with 23-33 GHz spectrum
- Prompt gammas possibly observable by *Fermi*

*Hooper, Zaharijas, Finkbeiner, & Dobler, 2008*
new evidence...?

*cosmic rays*
PAMELA

ATIC
PAMELA

ATIC
PAMELA

ATIC

Adriani et al. (2008)

Chang et al. (2008)
PAMELA

pulsars?

Hooper et al. (2008)

ATIC

Chang et al. (2008)
PAMELA

ATIC

Cholis, Dobler, et al. (2008)
8.5 kpc
\[ \ln(\rho/\rho_{-2}) = -(2/\alpha) (x^\alpha - 1) \]

\[ d\ln \rho / d\ln r = -2 (r/r_{-2})^\alpha \]

Cholis, Dobler, et al. (2008)
$\ln(\rho/\rho_{-2}) = -(2/\alpha)(x^\alpha - 1)$

$\frac{d\ln\rho}{d\ln r} = -2(r/r_{-2})^\alpha$
\[
\ln(\rho/\rho_2) = -(2/\alpha)(x^\alpha - 1)
\]

\[
d\ln\rho/d\ln r = -2(r/r_2)\alpha
\]

Cholis, Dobler, et al. (2008)
Conclusions

• Excess microwaves towards the GC are consistent with synchrotron radiation from a hard spectrum cosmic ray electron population.
  \[ E^2 dN/dE \propto E^\alpha \quad -0.1 \leq \alpha \leq 0.2 \]

• A simple WIMP annihilation model fits the data reasonably well
  \[ M \sim 500 \text{ GeV} \]
  \[ <\sigma v> \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \]
  \[ \rho(r) \sim r^{-1.2} \text{ favored} \]

• Particle DM models which reproduce the haze naturally explain the observed local positron (PAMELA) and total electron (ATIC) excesses and *vice-versa*
the present...
the present... ...the future
the present...

Fermi (fall-ish 2009)
ICS gammas from $e^+e^-$, possible prompt gammas

Planck (late 2010-???)
reduce systematics in the haze spectrum by an order of magnitude