Deviant Dark Matter:
Indirect Indicators of and Constraints on the Nature of Dark Matter

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SCIPP Seminar
March 6, 2012
Dark Matter Today

Cosmic Microwave Background:
WMAP, ACBAR, CBI, Boomerang

Large Scale Structure:
SDSS, 2dFGRS

\[ \Omega_{DM} = 0.227 \pm 0.007 \]

WMAP7 + SDSS BAO + H_0
(Komatsu et al. 2010)
The Cosmic Microwave Background: WMAP, Planck and the Future of LSS
Cosmic Microwave Background: Precision Cosmology

WMAP 7
Cosmic Microwave Background: Precision Cosmology

WMAP 7

$P(k) \rightarrow k \rightarrow \text{WMAP 7}$
Forecast Precision Cosmology: PLANCK

(Martin White)
The Primordial Spectrum: Precision Determination at Large Scales

\[ P(k) = A k^n \]

**WMAP 5 + BAO + SN:**  
\[ A = 2.445 \pm 0.096 \quad (3.4\%) \]
\[ n = 0.96 \pm 0.013 \quad (1.4\%) \]

**PLANCK + SDSS LRG:**  
\[ A = 2.4450 \pm 0.0085 \quad (0.35\%) \]
\[ n = 0.9600 \pm 0.0077 \quad (0.8\%) \]

forecast!
Large Scale Structure and $P(k)$

$P(k) \rightarrow k \rightarrow$

Tegmark & Zaldarriaga 2002
How far into the small-scale regime can we measure?
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The nature of dark matter...
How far into the small-scale regime can we measure?
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WIMP CDM

\( k_c \sim 10^6 \, h/\text{Mpc} \)

(Zaldarriaga & Loeb 2006)
Problems in Cold Dark Matter?

- Halo Substructure: satellite galaxies and sub-halos (Klypin et al. 1999; Moore et al. 1999)
- Halo Cores and Densities: (Gilmore et al. 2006; Kuzio de Naray 2008)
- Void Galaxy abundances (Peebles 2001)
- Angular Momentum Problem (Navarro & Benz 1991; Sommer-Larsen & Dolgov 2001)
- Disk Dominated Galaxy Formation (Governato et al. 2002)
Problems in Cold Dark Matter?

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Is the power spectrum different at small scales?
Measuring $P(k)$

- $P(k) \left[ \left( h^{-1} \text{Mpc} \right)^3 \right]$
- $k \left( h/\text{Mpc} \right)$
- CMB
- SDSS Ly-$\alpha$
- SDSS $w(p)$
- $\Sigma m_\nu = 0$
- $\Sigma m_\nu = 0.2 \text{ eV}$
- $\Sigma m_\nu = 0.7 \text{ eV}$
- $\Sigma m_\nu = 2 \text{ eV}$
Dwarf Spheroidal Density Profiles from Radial Stellar Velocity Dispersion

- All dwarf spheroidals studied are consistent with NFW and cored profiles, except for UMi, “only consistent with cored profile” [Gilmore et al., astro-ph/0608528]

- Constant core mass within stellar profile
Dark matter comes out of the cold

By Jonathan Amos
BBC News science reporter

Astronomers have for the first time put some real numbers on the physical characteristics of dark matter.

This strange material that dominates the Universe but which is invisible to current telescope technology is one of the great enigmas of modern science.

That it exists is one of the few things on which researchers have been certain.

But now an Institute of Astronomy, Cambridge, team has at last been able to place limits on how it is packed in space and measure its "temperature".

"It's the first clue of what this stuff might be," said Professor Gerry Gilmore. "For the first time ever, we're actually dealing with its physics," he told the BBC News website.

Science understands a great deal about what it terms baryonic matter - the "normal" matter which makes up the stars, planets and people - but it has struggled to comprehend the main material from which the cosmos is constructed.
Dark Matter $V_{\text{circ}}$ / Central Concentrations are Much Too Low...

Boylan-Kolchin, Bullock, Kaplinghat 2011
Central densities of Dwarfs are too low relative to latest high-res CDM simulations

(Parry, Eke, Frenk, Okamoto 2011)
Dwarf galaxies suggest dark matter theory may be wrong

By Leila Battison
Science reporter, Bradford

Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter.

Scientists' predictions about the mysterious dark matter purported to make up most of the mass of the Universe may have to be revised.

Research on dwarf galaxies suggests they cannot form in the way they do if dark matter exists in the form that the most common model requires it to.

That may mean that the Large Hadron Collider will not be able to spot it.

Leading cosmologist Carlos Frenk spoke of the “disturbing” developments.
Weak Lensing Measures of the Nonlinear Regime

Markovic et al 2011

Great sensitivity to the effects of WDM

Markovic et al 2011
Modeling nonlinear clustering:
The full halo model in WDM

\[ P(k) = P_{1h}(k) + P_{2h}(k) + P_{ss}(k) + P_{sh}(k) \]
Modeling nonlinear clustering: The full halo model in WDM

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\[ P^{1h}(k) = \int dM \frac{dn}{dM} \left( \frac{M}{\bar{\rho}} \right)^2 |u(k|M)|^2 \]
Modeling nonlinear clustering: The full halo model in WDM

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\[ P_{2h}(k) = \int dM_1 \frac{dn}{dM_1} \frac{M_1}{\bar{\rho}} u(k | M_1) \times \int dM_2 \frac{dn}{dM_2} \frac{M_2}{\bar{\rho}} u(k | M_2) \times P_{hh}(k | M_1, M_2). \]

\[ P_{hh}(k | M_1, M_2) \approx b_1(M_1) b_2(M_2) P_{\text{lin}}(k) \]
Modeling nonlinear clustering: The full halo model in WDM

\[ P(k) = P_{1h}(k) + P_{2h}(k) + P_{ss}(k) + P_{sh}(k) \]

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Substructure within 1 halo:

\[ P_{1h} = P_{ss} + P_{sc} + P_{1c} + P_{2c} \]
Modeling nonlinear clustering:  
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Substructure within 1 halo:

\[ P_{1h} = P_{ss} + P_{sc} + P_{1c} + P_{2c} \]

Dunstan, Abazajian, Polisensky & Ricotti 2011
Halo and Subhalo Mass Functions

log\left( \frac{dn}{d\ln c} \right)

log\left( \frac{M}{M_f} \right)

Halo

Subhalo

Halo

Subhalo
Halo Profile Effects

- Left graph: Density profile $\rho [M_\odot h^2 \text{Mpc}^{-3}]$ as a function of radius $R [\text{kpc}]$ for different mass keV values.
- Right graph: Mass function $u [10^3 h^2 \text{Mpc}^{-1} M_\odot]$ as a function of mass $m [h^{-1} M_\odot]$ for different mass keV values.
- Bottom graph: Percentage difference from CDM as a function of wave number $k [h \text{Mpc}^{-1}]$ for different mass keV values.

Legend:
- CDM
- 10 keV
- 3 keV
- 1 keV
- 0.5 keV
Results on the Full Nonlinear Effects from the Halo Model
Particle Physics of Sterile Neutrinos
Sterile Neutrinos
Beyond the Standard Model of Particle Physics

- Phenomenological Insertion of Majorana & Dirac Mass Terms of Comparable Magnitude (atmos. & solar) (e.g. $\nu_{\text{MSM}}$ Asaka et al 2006)
- Left-Right Symmetric Models (Pati & Salam 1974; Mohapatra & Pati 1975)
- Higher Dimensional Operators in String-Inspired models (Langacker 1998)
- Bulk Fermions in Large Extra Dimensions (ADD; Dvali & Smirnov 2000)
- Axino in R-parity Violating Minimal Supersymmetric Models (Chun & Kim 1999)
The $\nu_{\text{MSM}}$ : a minimalist model

- The Neutrino Minimal Standard Model of Particle Physics [Asaka, Blanchet & Shaposhnikov 2005]
- Add Dirac & Majorana Neutrino Mass Terms to MSM

$$\delta \mathcal{L} = \bar{N}_I i \gamma^\mu \gamma^\nu N_I - f^\nu_{I\alpha} \Phi \bar{N}_I L_\alpha - \frac{M_I}{2} \bar{N}^c_I N_I + \text{h.c.}$$

- Two heavy sterile neutrinos provide atmospheric & solar mass scales
- Baryogenesis via Oscillation-based Leptogenesis in 2 more massive sterile neutrinos
- Light sterile neutrino is the (Warm) Dark Matter
- More involved models generally involve similar insertions for neutrino mass generation
Aguilar-Arevalo 2010 [MiniBooNE]
Akhmedov & Schwetz 2011
The choice of normalization is crucial for reactor experiments looking for \( \theta_{13} \) without near detector.

\( \sigma_{T}^{\text{pred,new}} \): new prediction of the antineutrino fluxes.

\( \sigma_{T}^{\text{ano}} \): experimental cross section (best fitted mean averaged).

A deficit observed at 1-2 km can either be induced by \( \theta_{13} \) induced oscillation BUT also by other explanations (experimental, new \( \phi \), ...)

Aguilar-Arevalo 2010 [MiniBooNE]
Akhmedov & Schwetz 2011
A Phenomenological Model

Sterile Neutrino Dark Matter

\[ |\nu_6\rangle \]

\[ |\nu_\alpha\rangle = \cos \theta |\nu_a\rangle + \sin \theta |\nu_b\rangle \]

\[ |\nu_s\rangle = -\sin \theta |\nu_a\rangle + \cos \theta |\nu_b\rangle \]

\[ \sim 1 \text{ keV} \]

\[ \sin^2 2\theta \sim 10^{-7} \]

\[ \sim 1 \text{ eV} \]

\[ \sim 0.01 \text{ eV} \]
keV Sterile Neutrinos

- Could be the Dark Matter ($m_s \sim 1$ keV) 
  (Dodelson & Widrow 1994; Shi & Fuller 1999; 
  Abazajian, Fuller & Patel 2001)

- May Solve Several Potential Problems in the cold dark 
  matter paradigm of Galaxy and Small Scale Structure 
  Formation 
  (e.g., Bode, Ostriker & Turok 2001)

- Provides pulsar kicks 
  (Kusenko & Segre 1999)

- Enhances shock heating of the shock in Type II 
  supernovae 
  (Hidaka & Fuller 2006)
Sterile Neutrino Dark Matter Production

\[ \Gamma(\nu_\alpha \rightarrow \nu_s) \sim \frac{\Gamma_\alpha(p) \Delta^2(p) \sin^2 2\theta}{\Delta^2(p) \sin^2 2\theta + D^2(p) + [\Delta(p) \cos 2\theta - V^L(p) - V^T(p)]^2} \]
Sterile Neutrino Dark Matter Production

\[
\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5
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\[ D(p)^2 \sim T^{10} \]
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\[ \frac{\Gamma}{H} \sim \begin{cases} T^{-9} & \text{High } T \\ T^3 & \text{Low } T \end{cases} \]
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Never in Equilibrium!!
\[ \rho(\epsilon) = \frac{f_s(\epsilon)}{f_{\nu}(\epsilon)} \]

\[ f_{\nu}(\epsilon) = \frac{1}{e^\epsilon + 1} \]

\[ \epsilon = \frac{p}{T} \]

Abazajian 2005
Where does the CDM ansatz fail?

SDSS 3D P(k) Main Galaxies (Tegmark et al 2003)
SDSS Lyman-alpha forest (McDonald et al 2005)
High-Resolution Lyman-alpha forest (Viel, Haehnelt & Springel 2004)
CMB: WMAP, ACBAR, CBI, VSA, BooMERANG-2K2

Abazajian 2006
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\[ P_g(k) \]

Abazajian 2006

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Where does the CDM ansatz fail?

- SDSS galaxy $P_g(k)$
- SDSS Ly-α forest $P_F(k)$
- LUQAS (VLT) Ly-α forest $P_F(k)$
- Keck Ly-α forest $P_F(k)$

Abazajian 2006
Lyman-α forest: Powerful & Challenging

J. Shalf, Y. Zhang (UIUC) et al., GCCC
Lyman-α forest: Powerful & Challenging

![Diagram of Lyman-α forest with absorbing clouds and flux power spectrum graph.](image)

- Observer
- Absorber H clouds
- Source QSO

No absorbing clouds

- Flux (amount of light)
- Wavelength \( \lambda \rightarrow \)

One absorbing cloud close by

- Flux (amount)
- Emission

Left: the flux power spectrum

Diameter=0.62

\( \lambda \) (Å)
Lyman-alpha Forest Constraints on CDM

$m_s > 14$ keV \hspace{1cm} \text{Seljak et al 2006: WMAP1 + SDSS Pg(k) + Ly	extsc{a} + HR}

$\lambda_{FS} < 54$ kpc \hspace{1cm} M_{FS} < 10^7 M_{\text{sun}} \hspace{0.5cm} (\text{Abazajian & Koushiappas 2006})

$m_s > 12.1$ keV \hspace{1cm} (SDSS P_F(k) + VLT LUQAS data; Boyarsky et al 2008)

All Depend on the McDonald et al. (2006) SDSS P_F(k) Measurement
SDSS Ly-α Constraints: Viel et al 2006 (unpublished)

WDM analysis

Very high $T_0$ 
$\sim 35000 \text{ K}$
Turning an astrophysical signal into a constraint: The Dwarf galaxy count in the Milky Way

- Eventually, WDM is too much of a good thing, oversuppression of the dwarf galaxy scale
- SDSS has found a large population of new dwarf galaxies in the MW local group

Polisensky & Ricotti (2011)
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Polisensky & Ricotti (2011)
Radiative Decay in the X-ray

\[ \Gamma_\gamma = 6.8 \times 10^{-33} \text{ sec}^{-1} \left( \frac{\sin^2 2\theta}{10^{-10}} \right) \left( \frac{m_s}{1 \text{ keV}} \right)^5 \]

\[ E_\gamma = \frac{m_s}{2} \sim 1 \text{ keV} \]

"\(\nu_s\)" \(\rightarrow\) "\(\nu_\alpha\)" + \(\gamma\)

Pal & Wolfenstein 1981
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"$\nu_s$" → "$\nu_\alpha$" + $\gamma$

$E_\gamma = \frac{m_s}{2} \sim 1 \text{ keV}$

Virgo Cluster: $10^{70}$ DM particles

Pal & Wolfenstein 1981
Upper Mass Limit:
X-ray observations of Virgo

\[ m_s = 4 \text{ keV} \]

\[ m_s = 5 \text{ keV} \]

Abazajian, Fuller & Tucker 2001
Chandra Deep Field: Milky Way Halo Limits from the Unresolved X-ray Background

CDF-South

Source Removal

Hickox & Markevitch 2006, 2007
The (Unresolved) Cosmic X-ray Background

Abazajian et al. 2007
Hickox & Markevitch 2007

Channel Energy [keV]
X-ray Constraint Summary

XMM Newton: The Virgo Cluster

- Andromeda Galaxy: Watson et al. 2011
  \[ m_s < 2.2 \text{ keV} \]

- Ursa Minor: Lowenstein et al. 2008
  \[ m_s < 3.1 \text{ keV} \]

- Milky Way in CXB: Abazajian et al. 2006
  \[ m_s < 5.7 \text{ keV} \]

- Coma + Virgo Clusters: Boyarsky et al. 2006
  \[ m_s < 6.3 \text{ keV} \]

- X-Ray Background: Boyarsky et al. 2006
  \[ m_s < 8.9 \text{ keV} \]
The Detection of a WDM Sterile Neutrino?

Dark Matter Search Using *Chandra* Observations of Willman 1, and a Spectral Feature Consistent with a Decay Line of a 5 keV Sterile Neutrino

Michael Loewenstein\(^1,2\), Alexander Kusenko\(^3,4\)


Method of subtraction of the background could be revealing this line (Mirabel & Nieto, arXiv:1003.3745)
Claimed $\nu_s$ line: unaddressed problems...

- One should see a line in the noise in a 0.2 keV resolution spectrum from 1 - 7 keV at this level of statistical significance (2.8 $\sigma$)

- Sulfur K$\alpha$ and K$\beta$ lines present in this region

- Subtraction of the background can produce a similar feature (Mirabel & Nieto, arXiv: 1003.3745)

- Presence of feature is inconsistent at $> 14\sigma$ with limits from Andromeda (M31) observations, even when maximizing Willman I DM profile and minimizing that from M31
International X-ray Observatory
Sterile Neutrino Dark Matter Parameter Space Summary

Abazajian 2011
Sterile Neutrino Dark Matter Parameter Space Summary

Abazajian 2011
Not-So-Deviant Dark Matter Candidates
CDM to $\gamma$-ray: the potential dark matter sky

$X_{DM} + X_{DM} \rightarrow Y^+ + Y^- (\text{brems}), \quad X_{DM} \rightarrow \gamma + \gamma$

Springel et al 2008
The Observed Fermi-LAT Gamma-Ray
The Observed Isotropic Diffuse $\gamma$-ray Spectrum
DM Annihilation: Galactic and Extragalactic Contributions

**Galactic:**

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{J_{\Delta \Omega}}{J_0} \frac{1}{\Delta \Omega_{\text{obs}} m_\chi^2} \frac{dN_\gamma}{dE}
\]

\[
J(b, \ell) = J_0 \int_{x_{\min}}^{x_{\max}} \rho^2 (r_{\text{gal}}(b, \ell, x)) \, dx
\]

**Extragalactic:**

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{c}{\Delta \Omega_{\text{obs}} H_0} \frac{(f_{\text{DM}} \Omega_m)^2 \rho_{\text{crit}}^2}{m_\chi^2} \int_0^{z_{\text{up}}} f(z) (1 + z)^3 \frac{dN(E')}{dE'} e^{-\tau(z, E')} \, dz
\]
DM Annihilation: Galactic and Extragalactic Contributions

Galactic:

\[ \frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \cdot \frac{J_{\Delta \Omega}}{J_0} \cdot \frac{1}{\Delta \Omega_{\text{obs}} m_X^2} \cdot \frac{dN_\gamma}{dE} \]

\[ J(b, \ell) = J_0 \int_{x_{\text{min}}}^{x_{\text{max}}} \rho^2(r_{\text{gal}}(b, \ell, x)) \, dx \]

Extragalactic:

\[ \frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \cdot \frac{c}{\Delta \Omega_{\text{obs}} H_0} \cdot \frac{(f_{\text{DM}} \Omega_m)^2 \rho_{\text{crit}}^2}{m_X^2} \int_0^{z_{\text{up}}} f(z)(1 + z)^3 dN(E') \frac{dN(E')}{dE'} e^{-\tau(z, E')} \, dz \]
DM Annihilation: Galactic and Extragalactic Contributions

**Galactic:**

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{J_{\Delta \Omega}}{J_0} \frac{1}{\Delta \Omega_{\text{obs}} m_{\chi}^2} \frac{dN_\gamma}{dE} \\
J(b, \ell) = J_0 \int_{x_{\text{min}}}^{x_{\text{max}}} \rho^2 (r_{\text{gal}}(b, \ell, x)) \, dx
\]

**Extragalactic:**

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{c}{\Delta \Omega_{\text{obs}} H_0} \frac{(f_{\text{DM}} \Omega_m)^2}{m_{\chi}^2} \rho_{\text{crit}}^2 \int_{0}^{z_{\text{up}}} \frac{f(z)(1+z)^3}{h(z)} \frac{dN(E')}{dE'} e^{-\tau(z, E')} \, dz
\]
DM Annihilation: Galactic and Extragalactic Contributions

**Galactic:**

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{J_{\Delta\Omega}}{J_0} \frac{1}{\Delta\Omega_{\text{obs}} m^2_\chi} \frac{dN_\gamma}{dE}
\]

\[
J(b,\ell) = J_0 \int_{x_{\text{min}}}^{x_{\text{max}}} \rho^2 (r_{\text{gal}}(b,\ell, x)) \, dx
\]

**Extragalactic:**

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{c}{\Delta\Omega_{\text{obs}} H_0} \frac{(f_{\text{DM}} \Omega m)^2 \rho^2_{\text{crit}}}{m^2_\chi} \int_{0}^{z_{\text{up}}} \frac{f(z)(1+z)^3}{h(z)} \frac{dN(E')}{dE'} e^{-\tau(z,E')} \, dz
\]
DM Annihilation: Galactic and Extragalactic Contributions

Galactic:

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \cdot \frac{J_{\Delta \Omega}}{J_0} \cdot \frac{1}{\Delta \Omega_{\text{obs}} m_\chi^2} \cdot \frac{dN_\gamma}{dE}
\]

\[
J(b,\ell) = J_0 \int_{x_{\text{min}}}^{x_{\text{max}}} \rho^2 (r_{\text{gal}}(b,\ell,x)) \, dx
\]

Extragalactic:

\[
\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \cdot \frac{c}{\Delta \Omega_{\text{obs}} H_0} \cdot \frac{(f_{\text{DM}} \Omega_m)^2 \rho_{\text{crit}}^2}{m_\chi^2} \int_0^{z_{\text{up}}} \frac{f(z)(1+z)^3}{h(z)} \frac{dN(E')}{dE'} e^{-\tau(z,E')} \, dz
\]
Dark Matter in the Isotropic Diffuse Spectrum

\[ \langle \sigma_A v \rangle = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]

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

Abazajian, Agrawal, Chacko & Kilic, arXiv: 1002.3820
Lessons from the Cosmic X-ray Background
Chandra Deep Field: Milky Way Halo Limits from the Unresolved X-ray Background

CDF-South

Source Removal

Hickox & Markevitch 2006, 2007
The Observed Fermi-LAT Gamma-Ray

15% of extragalactic flux is already found to be from resolved blazars
Blazars in the Unified Model of AGN

- Blazars
- FSRQ
- BL Lac
- SSRQ
- FR I (NLRG)
- FR II (NLRG)
- Seyfert 2
- Seyfert 1
- QSO
- radio-loud
- radio-quiet
Allows for Forecasts for Fermi-LAT’s DGRB

Abazajian, Blanchet & Harding, 1012.1247
Annihilation Channel Forecasts

\[ \langle \sigma v \rangle \text{ [cm}^3\text{s}^{-1} \rangle \]

\( \chi \chi \rightarrow b \bar{b} \)

Fermi–LAT DGRB Current

Forecast

MSSM/mSUGRA

Abazajian, Blanchet & Harding 2012
Annihilation Channel Forecasts

\[ \langle \sigma v \rangle [\text{cm}^3\text{s}^{-1}] \]

\[ (c) \ \chi \chi \rightarrow t\bar{t} \]

Fermi-LAT DGRB Current

Forecast

MSSM/mSUGRA

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

Abazajian, Blanchet & Harding 2012
Annihilation Channel Forecasts

\[ \langle \sigma_A \nu \rangle \text{ [cm}^3\text{s}^{-1}] \]

- \( \chi \chi \rightarrow W^+ W^- \)
- Fermi-LAT DGRB Current
- Forecast
- Wind
- MSSM/mSUGRA

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

Abazajian, Blanchet & Harding 2012
Annihilation Channel Forecasts

\[ \langle \sigma v \rangle [\text{cm}^3 \text{s}^{-1}] \]

(d) \[ \chi \chi \rightarrow \tau^+ \tau^- \]

Fermi–LAT
DGRB Current

Forecast

MSSM/mSUGRA

Abazajian, Blanchet & Harding 2012
Dark Matter in the Galactic Center?

Hooper & Goodenough, arXiv:1010.2752
Dark Matter in the Galactic Center?
Dark Matter in the Galactic Center?

Gal. Center
Dark Matter in the Galactic Center?
Dark Matter in the Galactic Center?

![Graph showing energy vs. number of events in GeV cm$^{-2}$ s$^{-1}$ for different regions: Galactic Center, Omega Cen, and Geminga Pulsar.](image-url)
Dark Matter in the Galactic Center?

Gal. Center

Omega Cen
NGC 6388

Geminga Pulsar

Energy [GeV]
Dark Matter in the Galactic Center?

Gal. Center

Omega Cen

NGC 6388

M 28

Geminga Pulsar

Energy [GeV]
Light DM: Morphological Case?

Hooper & Linden 2011
Morphological Evidence Non-...
High Energy Spectroscopic Survey (HESS) 
Gamma-Ray Telescope in Namibia

Would detect gamma-rays from annihilation products in 
PAMELA Dark Matter Models
Residual Spectrum Toward the Galactic Center
HESS Galactic Center Constraints on PAMELA Dark Matter Interpretations

Abazajian & Harding 2011
Summary

Sterile Neutrino Dark Matter

- Warm Dark Matter has become the “standard alternate” cosmological structure formation scenario, as it may resolve many problems in structure formation, though stringent limits exist.
- Sterile Neutrino Dark Matter is a natural, minimal WDM and CDM candidate.
- Upcoming weak lensing and galaxy surveys can be sensitive to WDM effects in the mild to strongly nonlinear regime.
- Lower-limits mass from the Lyman-alpha Forest are dependent on the thermal history of the universe, uncorrected noise in the SDSS spectrograph and uncertain.
- Sterile Neutrino Dark Matter, in the standard production scenarios, is detectable or potentially excludable with the IXO satellite.

WIMP Dark Matter

- The diffuse gamma-ray background is the most conservative and, when including the MW Galactic contribution, a stringent constraint.
- The DGRB constraints are dwarfed by Fermi-LAT dwarf galaxy constraints and HESS GC Constraints.
- Claims for DM signals from the GC based on both spectral & morphological information do not survive quantitative scrutiny.