Indirect Evidence For Light WIMPs

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Dark Matter In The Galactic Center Region With Fermi

- The region surrounding the Galactic Center is complex; backgrounds present are not necessarily well understood.

- This does not, however, necessarily make searches for dark matter in this region intractable.

- The signal from dark matter annihilation is large in most benchmark models (for a typical 10 GeV WIMP, comparable to total flux observed in inner 1°).

- To separate dark matter annihilation products from backgrounds, we must focus on the distinct observational features of these components.
Dark Matter In The Galactic Center Region With Fermi

The characteristics of a signal from dark matter annihilations:

$$\Phi_\gamma(E_\gamma, \psi) = \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_X^2} \int_{\text{los}} \rho^2(r) dl$$

1) Distinctive “bump-like” spectral feature

2) Signal highly concentrated around the Galactic Center (but not entirely point-like); precise morphology determined by dark matter distribution
The Distribution of Dark Matter in the Inner Milky Way

- Dark matter only simulations (Via Lactea, etc.) yield halos which possess inner profiles of $\rho \propto r^{-\gamma}$ where $\gamma=1.0$ to $1.2$
- The inner volume (~10 kpc) of the Milky Way is dominated by baryons, not dark matter – significant departures from dark matter only results should be expected
- For years, an active debate has taken place in the literature over the question of how the baryons alter the profiles of dark matter halos
- Existing microlensing and dynamical data are not capable of determining the inner slope, although $\gamma \sim 1.3$ provides the best fit

![Graph showing constraints on the Dark Matter distribution parameters](Image from arXiv:1107.5810)
The Distribution of Dark Matter in the Inner Milky Way

- Recently, state-of-the-art hydrodynamical simulations carried out by several different groups, running different codes, have begun to converge in favor of a moderate degree of contraction in Milky Way-like halos, typically steepening the inner slope $\gamma$ from $\sim 1.0$ to $\sim 1.2-1.5$

- Such simulations include rapid supernova winds, cold accretion, galactic bars, inspiraling of dense baryonic clumps by dynamical friction, etc., but consistently find that baryonic contraction dominates over these effects

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(Gnedin, et al. arXiv:1108.5736)

Gottloeber et al. (2010)

Levine et al. (2008)
A Simple (but effective) Approach To The Galactic Center

1) Start with raw map (smeared over 0.5° circles)
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2) Subtract known point sources (Fermi 2nd point source catalog)
3) Subtract line-of-sight gas density template (empirical, good match to 21 cm)
This method removes ~90% of emission in the inner galaxy (outside of the innermost few degrees)

Typical residuals are ~5% or less as bright as the inner residual – spatial variations in backgrounds are of only modest importance

Hooper and Linden, PRD, arXiv:1110.0006
A Simple (but effective) Approach To The Galactic Center

- This method removes ~90% of emission in the inner galaxy (outside of the innermost few degrees)
- Typical residuals are ~5% or less as bright as the inner residual – spatial variations in backgrounds are of only modest importance
- Clearly isolates the emission associated with the inner source or sources (supermassive black hole? dark matter?), along with a subdominant component of “ridge” emission

Hooper and Linden, PRD, arXiv:1110.0006
Characteristics of the Observed Gamma ray Residual

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2) Clear spatial extension - only a small fraction of the emission above \(~300\) MeV is point-like

3) Good agreement is found between our analysis and those of other groups
How Much Of This Emission Could Be Coming From Dark Matter?

- If the inner profile is fairly steep (as is expected due to adiabatic contraction), the majority of the residual could originate from dark matter.
- Viable regions include $m_{\text{DM}} \sim 7$-$12$ GeV, annihilating (mostly) to leptons, with an annihilation cross section on the order of $\sigma v \sim 10^{-26}$ cm$^3$/s (uncertainties dominated by local density).

Parameter space in which the majority of the 0.3-10 GeV emission originates from dark matter.
The Dark Matter Interpretation

- The spectral shape of the excess can be well fit by a dark matter particle with a mass in the range of 7 to 12 GeV (similar to that required by CoGeNT, DAMA, and CRESST), annihilating primarily to $\overline{\nu}^+\overline{\nu}^-$ (possibly among other leptons)

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- The angular distribution of the signal is well fit by a halo profile with $\sqrt{\gamma}(r) \sim r^{-\alpha}$, with $\alpha \sim 1.25$ to 1.4 (in good agreement with expectations from simulations).

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- The angular distribution of the signal is well fit by a halo profile with $\rho(r) \sim r^{-\gamma}$, with $\gamma \sim 1.25$ to 1.4 (in good agreement with expectations from simulations).

- The normalization of the signal requires the dark matter to have an annihilation cross section within a factor of a few of the value predicted for a simple thermal relic ($\sqrt{s} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$).

Hooper and Linden, PRD, arXiv:1110.0006
Astrophysical Interpretations?

Unresolved Point Sources?

Perhaps a population of several/many unresolved points sources distributed throughout the inner tens of parsecs of the Milky Way could produce the observed signal - millisecond pulsars, for example
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-Much has been made of the qualitative similarity with the spectra of gamma ray pulsars, but in actuality very few of the pulsars observed by Fermi are compatible (the average spectrum is clearly incompatible); perhaps a somewhat different population or class of pulsars could be responsible?

-Why is the signal so concentrated (why so many in the inner 20 pc, and so few at 100 pc?); the signal \( F \propto r^{-2.5} \) is much more steeply cusped than the observed stellar distribution \( n_{\text{star}} \propto r^{-1.25} \)

-With typical pulsar kicks of 250-500 km/s, millisecond pulsars should escape the inner region of the galaxy, and be distributed no more steeply than \( r^{-2} \) (assuming that none are created outside of the inner tens of parsecs)

Abazajian, JCAP, arXiv:1011.4275,
Hooper, Goodenough PLB 2010,
Hooper, Linden PRD 2011
Astrophysical Interpretations?

Pion Decay Gamma Rays From Cosmic Rays Accelerated by the Supermassive Black Hole?

- The observed emission (above ~300 MeV) is spatially extended, and does not originate directly from the SMBH.

- But protons accelerated by or nearby the SMBH could propagate outward, leading to an extended gamma ray signal (Chernyakova et al., Ap. J, 2011).

- The spectrum of the extended emission, however, rises very rapidly between 100 MeV and 1 GeV; Much more so than the spectrum from proton collisions (for any proton spectrum).

- This is not what pion decay gamma rays should look like.

*Note: If only photons above 1 GeV are studied, much of this emission could be interpreted as pion decay gammas – sub-GeV emission is essential to distinguish between CR-gas and DM origins*
Other Signatures of Light WIMP Annihilation in the Inner Milky Way?

If dark matter annihilations are generating the gamma ray emission observed from the Galactic Center, where else in the sky, and in what other channels, might signals of this appear?
Other Signatures of Light WIMP Annihilation in the Inner Milky Way?

- For years, it has been argued that the WMAP data contains an excess of synchrotron emission from the inner ~20\degree around the Galactic Center, and that this cannot be explained by known astrophysical mechanisms – now “unambiguously” confirmed by Planck (expect a paper soon)

- Previous studies have shown that this emission could be accounted for electrons produced in dark matter annihilations

Dark Matter Annihilations and the Synchrotron Haze

- Using the halo profile, mass, annihilation cross section and annihilation channels determined by the Fermi GC data, we proceed to calculate the corresponding synchrotron spectrum and distribution.
- Set B-field model to obtain the spectrum and angular profile observed by WMAP (almost no additional freedom).
- The resulting synchrotron intensity is forced to be very close to that observed.

**A dark matter interpretation of the Galactic Center gamma rays (almost) automatically generates the WMAP Haze**

Annihilations to $e^+e^-$, $\bar{\nu}_e\nu_e$, $\bar{\nu}_\mu\nu_\mu$ B~10 $\mu$G in haze region

D. Hooper and Tim Linden, arXiv:1011.4520
Non-Thermal Radio Filaments

- Radio filaments are long (~40 pc) and thin (~1 pc) structures with extremely hard and polarized radio spectra, located 10-200 pc from the Galactic Center.
- Observations imply very strong (~100 µG) and highly ordered magnetic fields.
- It has been a long-standing challenge to explain the synchrotron spectra from these objects.

Linden, Hooper, and Yusef-Zadeh, arXiv:1106.5493
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- It has been a long-standing challenge to explain the synchrotron spectra from these objects.
- Since the late 1980’s, observations and modeling of NRFs has found that they must contain a nearly mono-energetic spectrum of electrons, with an energy of ~10 GeV.
- The highly ordered magnetic fields of these objects effectively confine the electrons they contain, and act as a magnetic mirror, preventing external electrons from entering (the ~10 GeV electrons responsible for the observed synchrotron emission must be produced within the volume of the filaments).

Linden, Hooper, and Yusef-Zadeh, arXiv:1106.5493
Non-Thermal Radio Filaments

- The roughly mono-energetic spectrum of electrons, found in every well measured filament, is very difficult to explain with astrophysics, but is an automatic prediction for a \( \sim 10 \) GeV WIMP annihilating to leptons.

- The intensity from a filament is determined by the dark matter density, the annihilation cross section, the volume of the filament, and the fraction of electrons’ energy lost before escaping filament (roughly proportional to length, on the order unity for most filaments).

- Spectrum is predictable, further depending only on the magnetic field strength (which can vary by a factor of a few from filament-to-filament).

Linden, Hooper, and Yusef-Zadeh, arXiv:1106.5493
We find that the handful of best-measured NRFs have spectra that can be easily explained by annihilating dark matter.

Annihilations to $e^+e^-$, $\chi^+\chi^-$, $\chi^+\chi^-$

$m_\chi=8$ GeV, $\sigma v=3\times10^{-26}$ cm$^3$/s

Linden, Hooper, and Yusef-Zadeh, arXiv:1106.5493
Non-Thermal Radio Filaments

- We find that the handful of best-measured NRFs have spectra that can be easily explained by annihilating dark matter.
- We also observe a correlation between brightness and distance from the Galactic Center; in a dark matter interpretation, this corresponds to roughly $\rho \sim r^{-1.25}$.

![Graph showing flux density vs. projected distance from Galactic Center](image)

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Extended Gamma Ray Emission From Galaxy Clusters

- The regions of the Virgo, Fornax, and Coma clusters were recently studied, using the first three years of Fermi data.
- In contrast to (hadronic) cosmic ray induced backgrounds, dark matter annihilations are predicted to produce a significantly extended pattern of emission.

Han, Frenk, Eke, Gao, White, arXiv:1201.1003
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- The regions of the Virgo, Fornax, and Coma clusters were recently studied, using the first three years of Fermi data.
- In contrast to (hadronic) cosmic ray induced backgrounds, dark matter annihilations are predicted to produce a significantly extended pattern of emission.
- Highest significance signal is found from Virgo (4.4σ); 2.3 and 2.1σ for others.
- Can be fit by dark matter annihilations with same mass, channels, and cross section required by the Galactic Center.
- Preferred over vanilla cosmic ray interpretation at ~3σ.

Han, Frenk, Eke, Gao, White, arXiv:1201.1003
An intriguing body of evidence has accumulated in support of dark matter in the form of ~10 GeV WIMPs.

In the first three years of publicly available FGST data, we have identified a component of gamma rays concentrated around the Galactic Center, with a spectrum peaked at GeV energies.

The spectrum and morphology of the observed emission can be easily accounted for with annihilating dark matter distributed with a halo profile similar to those inferred from simulations ($r^{-1.3}$), with a mass of 7-12 GeV, and an annihilation cross section consistent with a simple thermal relic ($v \sim 10^{-26} \text{ cm}^3/\text{s}$); this dark matter scenario also automatically leads to the observed WMAP Haze and to the peculiar signals from non-thermal radio filaments.

The mass range favored by these indirect signals is similar to that favored by the long standing claim of annual modulation from DAMA/LIBRA, and by the more recent results CoGeNT and CRESST-II.
IDM 2012 in Chicago!

- The Identification of Dark Matter Conference Series is coming to the US for the first time, hosted by the Kavli Institute for Cosmological Physics at the University of Chicago

- July 23-27\textsuperscript{th}, 2012 in beautiful/exciting/glorious downtown Chicago

- For more information, and to register:
  
  \texttt{kicp-workshops.uchicago.edu/IDM2012}

- Register early! Register often! (the way of Chicago politics)
Looking Forward

- The sensitivity of:
  - Fermi dwarfs
  - CMB power spectrum
  - LEP, mono-photon+missing energy
  - Super Kamiokande, neutrinos from Sun
  - PAMELA, low-energy positron fraction

Are each within a factor of a few needed to test this scenario

- Planck, AMS-02, LHC, and further Fermi data will each bring much information to bear on this topic

- Not to mention new information on the direct detection front:
  - CDMS modulation analysis (tomorrow?!)  
  - Much more data from CoGeNT (C4)
  - Southern hemisphere experiments (DM-Ice)
Gamma rays from dwarf spheroidal galaxies

- The gamma signal from the GC is dominated by annihilations to taus; to accommodate the observed flux we need roughly $\sigma v \sim 3 \times 10^{-27}$ cm$^3$/s to $\tau^+\tau^-$ (for canonical local density)

- Fermi’s study of dwarf galaxies places a constraint of $\sigma v < 1.5 \times 10^{-26}$ cm$^3$/s for a 10 GeV WIMP annihilating to taus

- Dwarfs are still a factor of a few away

*arXiv:1108.3546; see also Geringer-Sameth, Koushiappas arXiv:1108.2914*
**Constraints/Tests**

- Effects on the CMB from annihilations in the recombination epoch

- Energy injected by dark matter annihilations can heat and ionize the photon-baryon plasma at $z \sim 1000$, potentially altering the CMB power spectrum

- WMAP does not yet constrain this scenario, but Planck likely will

(f~0.45 in dem. lepton case)

Slatyer, Padmanabhan, Finkbeiner, PRD, arXiv:0906.1197; see also Finkbeiner, Galli, Lin, Slatyer, arXiv:1109.6322
Constraints/Tests

- Constraints from LEP

-The photon plus missing energy channel at LEP provides the strongest collider bound on light dark matter with sizeable couplings to electrons

- For heavy mediators (making use of effective field theory), and 1/3 of annihilations to electrons, constraints are near the $\sigma v \sim 10^{-26}$ cm$^3$/s level

- Once again, close, but not a problem

Dan Hooper - Indirect Evidence For Light WIMPs

Fox, Harnik, Kopp, Tsai, PRD, arXiv:1103.0240