Dark Matter in the Galactic Center

Tim Linden
University of Chicago

along with: Eric Carlson, Ilias Cholis, Dan Hooper, Manoj Kaplinghat, Stefano Profumo, Jennifer Siegal-Gaskins, Tracy Slatyer, Hai-Bo

The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
Goal of the Talk

- Overview of Dark Matter Physics
- A Gamma-Ray Signal at the Galactic Center !?
- Supporting Lower-Energy Observations
- Necessary Future Observations
Gravitational Effects of Dark Matter in the GC

There isn’t any:

Using the standard Navarro–Frenk–White Density profile for Dark Matter:

$$\rho_{NFW}(r) = \rho_c \left( \frac{R_c}{r} \right) \left( 1 + \frac{r}{R_c} \right)^{-2}$$

We obtain a mass within 0.1 kpc of the Galactic Center which

$$\left( 2.6 \times 10^7 \frac{M_\odot}{kpc^3} \right) 4\pi \int_0^{0.1kpc} r^2 \frac{22kpc}{r} \left( 1 + \frac{r}{22kpc} \right)^2 dr = 3.7 \times 10^7 M_\odot$$

Any detection of dark matter at the galactic center will depend on its particle nature.

Tuesday, October 22, 13
If this weak force interaction existed in the early universe, then it should still occur (at a suppressed rate) today.

We can look for these interactions.
Dark Matter Annihilation Rate is separable into astrophysical and particle physics components

$$\Phi_{DM} = \int \int \frac{dN}{dE} < \sigma v > \frac{\rho^2}{M_{DM}^2} dV dE = \left[ \int \frac{dN}{dE} < \sigma v > \frac{1}{M_{DM}^2} dE \right] \left[ \int \rho_r^2 dV \right]$$

The particle physics properties should be independent of the position in the universe – so we can compare different dark matter detection regimes without regard for a given dark matter particle physics model.
Dark Matter Annihilation at the Galactic Center

**Dwarfs**

<table>
<thead>
<tr>
<th>Name</th>
<th>l (deg.)</th>
<th>b (deg.)</th>
<th>d (kpc)</th>
<th>$\log_{10}(J)$</th>
<th>$\sigma$</th>
<th>ref.</th>
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<td>358.08</td>
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<td>0.13</td>
<td>[16]</td>
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<tr>
<td>Coma Berenices</td>
<td>241.9</td>
<td>83.6</td>
<td>44</td>
<td>19.0</td>
<td>0.37</td>
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<td>Draco</td>
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<td>34.72</td>
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<td>138</td>
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<td>Segue 1</td>
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<td>50.42</td>
<td>23</td>
<td>19.6</td>
<td>0.53</td>
<td>[18]</td>
</tr>
<tr>
<td>Sextans</td>
<td>243.4</td>
<td>42.2</td>
<td>86</td>
<td>17.8</td>
<td>0.23</td>
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<tr>
<td>Ursa Major II</td>
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<td>37.44</td>
<td>32</td>
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<tr>
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<td>104.95</td>
<td>44.80</td>
<td>66</td>
<td>18.5</td>
<td>0.18</td>
<td>[16]</td>
</tr>
</tbody>
</table>

- Corresponds to the relative annihilation rate of the region compared to other astrophysical sources

\[
\Phi_\gamma \propto J = \frac{1}{\Delta \Omega} \int d\Omega \int_{\text{l.o.s.}} \rho^2(l) dl(\psi)
\]

- The J-factor of the galactic center is

\[
\log_{10}(J) = 21.0
\]

for a region within 1° of the Galactic center and an NFW profile
**Completely Insignificant**

Using the NFW Profile and a standard 100 GeV dark matter particle annihilating to bb:

\[
2M_{DM} \frac{< \sigma v >}{2} \frac{\rho_0^2}{M_{DM}^2} 4\pi \int_0^{100\text{pc}} r^2 \rho_{r,NFW}^2 dr = 4.2 \times 10^{35} \text{erg/s}
\]
Dark Matter annihilation injects energy primarily in the GeV energy range, can produce a significant population of high energy particles.
Dark Matter annihilation can produce non-thermal emission on many energy scales.

Not a plot of the GC - don’t look too closely!
Total Gamma-Ray Flux from 1–3 GeV within 1° of Galactic Center is

\[ \sim 1 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \]

This is equivalent to the number of photons expected in this energy bin from a “vanilla” 100 GeV dark matter candidate annihilating to bb with a cross-section \( \langle \sigma v \rangle = 1.6 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1} \) (5 times our “magic” cross-section)

There’s no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the most naive prediction from dark matter
So you want to search for dark matter at the Galactic Center?

What do you do?
We employ a model of the galactic gas density (Kalberla & Kerp 2009) to subtract the contributions from the galactic plane.

This emission template provides a superb match to the total emission spectrum.

This large residual at the center of the galaxy is a factor of 10 brighter than anything else in the inner $20^\circ \times 10^\circ$.
After subtracting emission from known point sources, and an extrapolation of the line–of–sight gas density, the following “galactic center” emission is calculated.

This directly corresponds to a limit on the dark matter interaction cross–section which depends only on assumed dark matter density profile.
Is It A Point Source?

Several efforts have been made to fit the GC point source, using both best-fitting point-source tools from the Fermi collaboration (Boyarsky et al. Chernyakova et. al), as well as independent software packages (Hooper & Goodenough).

In all cases, the morphology of the observed emission cannot be fully accounted for by a single point source smeared out by the angular resolution of the Fermi-
Abazajian & Kaplinghat found a $20\sigma$ preference for models including an extended, spherically symmetric excess.

Including only a point source at the galactic center significantly oversubtracts the GC.
These observations have yielded strong evidence for a bright, extended, spherically symmetric gamma-ray residual around the galactic center.

What can we learn about physics from these observations?
Interpretations at this Point

1.) $\pi^0$ decay

2.) Dark Matter Annihilation

3.) A new astrophysical source
   - e.g. millisecond pulsars
   - Something else?
H.E.S.S. observations of TeV gamma-rays from the GC are very well fit by a scenario where high energy protons are emitted by Sgr A* and collide with the dense gas nearby.

Tuning the diffusion parameter can explain the different gamma-ray spectra observed at GeV and TeV energies.
The vast majority of emission stems from within 3 pc of the galactic center at all energies.

This lies below the PSF of all current gamma-ray instruments.

This effectively rules out hadronic interactions from Sgr A* as the source of the Fermi–LAT excess.

Linden et al. (2012)
• Dark Matter creates an excellent statistical fit to both the morphology and spectrum of the residual.

• Of course dark matter predictions are somewhat malleable.

See Next Talk by Chris Gordon

Abazajian & Kaplinghat

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Millisecond Pulsar Fits

- A population of undiscovered MSPs in the Galactic Center could fit the observed excess

- The spectrum of the MSP population is a reasonable fit

- I know there should be some

  \[ \Omega \text{ Cen: } \Gamma = 0.7^{+0.7+0.4}_{-0.6-0.4}, E_c = 1.2^{+0.7+0.2}_{-0.4-0.2}, \]
  \[ \text{NGC 6388: } \Gamma = 1.1^{+0.7+0.8}_{-0.5-0.8}, E_c = 1.8^{+1.2+1.8}_{-0.7-0.6}, \]
  \[ \text{M 28: } \Gamma = 1.1^{+0.7+0.6}_{-0.5-0.7}, E_c = 1.0^{+0.6+0.4}_{-0.3-0.2}, \]
  \[ \text{NGC 6652: } \Gamma = 1.0^{+0.6+0.3}_{-0.5-0.3}, E_c = 1.8^{+1.2+0.4}_{-0.6-0.3}. \]

See Next Talk by Chris Gordon

Abazajian (2011)
Personal Opinion: It’s not clear that new data from the GC will greatly improve our measurements of the GC excess – at least not in any way which can distinguish dark matter and MSPs.
Where Do We Go From Here?

- While dwarfs would provide a background free environment for the possible detection of a dark matter signal, it’s not clear that the limits will ever hit the cross-sections indicated by GC observations.

- Maybe DES will provide more “good” dwarfs.

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Geringer-Sameth & Koushiappas

Ackermann et al. (2013)

Tuesday, October 22, 13
The spectrum of millisecond pulsars does not fit the observed $\gamma$-ray spectrum of the Fermi bubbles.

Smaller background contamination = Small possibility that mis-subtraction of point sources can solve this.
Fermi Bubbles?

- The spectrum of millisecond pulsars does not fit the observed $\gamma$-ray spectrum of the Fermi bubbles

- Smaller background contamination = Small possibility that mis-subtraction of point sources can solve this

Hooper & Slatyer

Hooper et al.
Radio Observations of the Galactic Center

<table>
<thead>
<tr>
<th>Name</th>
<th>Alternative Name</th>
<th>$\alpha_{1.4 GHz}^{0.33 GHz}$</th>
<th>$\alpha_{1.4 GHz}^{4.8 GHz}$</th>
<th>$\alpha_{4.8 GHz}^{8.33 GHz}$</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>G0.08+0.15</td>
<td>Northern Thread</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-2.0</td>
<td>Lang et al. (1999b); LaRosa et al. (2000)</td>
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<tr>
<td>G358.85+0.47</td>
<td>The Pelican</td>
<td>-0.6</td>
<td>-0.8 ± 0.2</td>
<td>-1.5 ± 0.3</td>
<td>Kassim et al. (1999); Lang et al. (1999a)</td>
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<tr>
<td>G359.1-0.02</td>
<td>The Snake</td>
<td>-1.1</td>
<td>~0.0</td>
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<td>Nicholls &amp; Gray (1993); Gray et al. (1995)</td>
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<tr>
<td>G359.32-0.16</td>
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<td>-0.1</td>
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<td>RF-N8</td>
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<td>-0.9 to -1.3</td>
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<td>Law et al. (2008a)</td>
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<td>G359.85+0.39</td>
<td>RF-N10</td>
<td>0.15 to -1.1* *</td>
<td>-0.6 to -1.5* *</td>
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<td>LaRosa et al. (2001); Law et al. (2008a)</td>
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<td>G359.96+0.09</td>
<td>Southern Thread</td>
<td>-0.5</td>
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<td>LaRosa et al. (2000)</td>
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<tr>
<td>G359.45-0.040</td>
<td>Sgr C Filament</td>
<td>-0.5</td>
<td></td>
<td>-0.46 ± 0.32</td>
<td>Liszt &amp; Spiker (1995); Law et al. (2008a)</td>
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<tr>
<td>G359.54+0.18</td>
<td>Ripple</td>
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<td>-0.5 to -0.8</td>
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<td>Law et al. (2008a)</td>
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<td>Law et al. (2008a)</td>
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<td>G0.15+0.23</td>
<td>RF-N1 (in Radio Arc)</td>
<td></td>
<td>+0.2 to -0.5</td>
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<td>Law et al. (2008a)</td>
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<td>G0.09-0.09</td>
<td></td>
<td></td>
<td></td>
<td>0.15</td>
<td>Reich (2003)</td>
</tr>
</tbody>
</table>

*Two very different values exist in the literature for the high frequency spectrum of the Snake. Gray et al. (1995) cites a value of -0.2 ± 0.2, while a more recent analysis by Law et al. (2008b) yields $\alpha_{4.8 GHz}^{8.33 GHz} = -1.86 ± 0.64$.

*Spectrum is highly position dependent, but shows a clear trend towards steeper spectral slopes at high frequencies for any given position.

Linden et al. (2011)
Radio Observations of the Galactic Center

Linden et al. (2011)


Letter to the Editor

Monoenergetic relativistic electrons in the galactic center

H. Lesch*, R. Schlickeiser, and A. Crusius

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn 1, Federal Republic of Germany

Received March 29, accepted May 27, 1988

Linden et al.
Radio Observations of the Galactic Center

Linden et al. (2011)

- Dark Matter can easily produce such a spectrum!
Radio Observations of the Galactic Center

- The radial profile of radio filaments may suggest a dark matter injection morphology.

- Hard spectrum, non-thermal radio filaments can be fit with dark matter annihilation.

Linden et al. (2011)
X-Ray observations find a total of 2347 point sources within 40 pc of the GC – this could include a large population of MSPs.

MSPs exist in a particular location on the luminosity-color diagram in 47 Tuc.

Can this information be used to determine the statistical distribution of MSPs?

Heinke et al. (2006)
Another method for distinguishing between gamma-ray emission models is to investigate the production of electron and positron pairs.

These charged leptons will lose considerable energy to synchrotron radiation, producing a bright radio signal in the galactic center.

Positive: The angular resolution of radio telescopes is significantly greater than gamma-ray observatories.

Negative: The diffusion and energy loss time of charged electrons adds additional uncertainties to the model.
• What future measurements are most likely to constrain, or provide convincing evidence for a dark matter signal?

• What new missions, pointing strategies, analyses are most likely to elucidate current dark matter models?

• Comments?

• Opinions?

• Criticism?