Understanding High Energy Emission from the Galactic Center: 3 Convincing Stories

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with Dan Hooper, Elizabeth Lovegrove, Stefano Profumo and Farhad Yusef-Zadeh

4th International Fermi Symposium November 2, 2012
The Multi-wavelength Galactic Center

Extinction > 10
Fritz et al. 2011

Regis & Ullio 2009
The Galactic Center "Zoo"

O-star/Pulsar density peaks at 0.5 pc, and falls sharply for smaller radii (Buchholz et al. 2009)

Closest approach of 2013 gas cloud to Sgr A* (0.004 pc)

Ridge of TeV gamma-ray emission assumed to be from p-p collisions with gas in the galactic disk (up to 200 pc)

Accretion disk - Relatively dim now, but maybe not historically

Non-thermal Radio Filaments - Bright, polarized synchrotron sources

Synchrotron Emission within 20 light-minutes of Sgr A*, assumed to be at the Schwarzchild Radius (Gillessen et al. 2005)

Friday, November 2, 2012
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° x 10°

Hooper & Linden (2011)
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-LAT.
Abazajian & Kaplinghat employed a more sophisticated template-based regression analysis.

This also found an extremely significant improvement in the overall fit with the addition of a spherical profile with similar characteristics to that of Hooper & Goodenough and Hooper & Linden.

Abazajian & Kaplinghat (2012)
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This also found an extremely significant improvement in the overall fit with the addition of a spherical profile with similar characteristics to that of Hooper & Goodenough and Hooper & Linden.
Independent Confirmation!

- Note: Two different, and independent methods find strong evidence for a **bright, spatially extended, spherically symmetric residual** at the position of the galactic center.

- What can we learn from this?
The J-Factor of the Galactic Center

- 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 approximately:

\[ \log_{10}(J) = 23.91 \]

**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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</thead>
<tbody>
<tr>
<td>Bootes I</td>
<td>358.08</td>
<td>69.62</td>
<td>60</td>
<td>17.7</td>
<td>0.34</td>
<td>[15]</td>
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<tr>
<td>Carina</td>
<td>260.11</td>
<td>-22.22</td>
<td>101</td>
<td>18.0</td>
<td>0.13</td>
<td>[16]</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>241.9</td>
<td>83.6</td>
<td>44</td>
<td>19.0</td>
<td>0.37</td>
<td>[17]</td>
</tr>
<tr>
<td>Draco</td>
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<td>34.72</td>
<td>80</td>
<td>18.8</td>
<td>0.13</td>
<td>[16]</td>
</tr>
<tr>
<td>Fornax</td>
<td>237.1</td>
<td>-65.7</td>
<td>138</td>
<td>17.7</td>
<td>0.23</td>
<td>[16]</td>
</tr>
<tr>
<td>Sculptor</td>
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<td>-83.16</td>
<td>80</td>
<td>18.4</td>
<td>0.13</td>
<td>[16]</td>
</tr>
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<td>Segue 1</td>
<td>220.48</td>
<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>
<td>[16]</td>
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<td>Ursa Major II</td>
<td>152.46</td>
<td>37.44</td>
<td>32</td>
<td>19.6</td>
<td>0.40</td>
<td>[17]</td>
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<tr>
<td>Ursa Minor</td>
<td>104.95</td>
<td>44.80</td>
<td>66</td>
<td>18.5</td>
<td>0.18</td>
<td>[16]</td>
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</table>

**Clusters**

<table>
<thead>
<tr>
<th>Cluster</th>
<th>RA</th>
<th>Dec.</th>
<th>z</th>
<th>( J ) ((10^{17} \text{ GeV}^2 \text{ cm}^{-5}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWM 7</td>
<td>43.6229</td>
<td>41.5781</td>
<td>0.0172</td>
<td>( 1.4^{+0.1}_{-0.1} )</td>
</tr>
<tr>
<td>Fornax</td>
<td>54.6686</td>
<td>-35.3103</td>
<td>0.0046</td>
<td>( 6.8^{+1.0}_{-0.9} )</td>
</tr>
<tr>
<td>M49</td>
<td>187.4437</td>
<td>7.9956</td>
<td>0.0033</td>
<td>( 4.4^{+0.2}_{-0.1} )</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>190.7084</td>
<td>2.6880</td>
<td>0.0031</td>
<td>( 4.1^{+0.3}_{-0.3} )</td>
</tr>
<tr>
<td>Centaurus (A3526)</td>
<td>192.1995</td>
<td>-41.3087</td>
<td>0.0114</td>
<td>( 2.7^{+0.1}_{-0.1} )</td>
</tr>
<tr>
<td>Coma</td>
<td>194.9468</td>
<td>27.9388</td>
<td>0.0231</td>
<td>( 1.7^{+0.1}_{-0.1} )</td>
</tr>
</tbody>
</table>
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.

Hooper & Linden (2011)
Hooper et al. (2012) further tweaked the methods used to derive these limits, deriving rigorous constraints under a wide variety of assumptions.

These are the strongest gamma-ray limits on the cross-section for dark matter annihilation.
With some adiabatic contraction of the inner dark matter profile, these limits can become substantially stronger than any other indirect detection limit.

Hooper & Linden (2011)

Ackermann et al. (2011)
A Hadronic Scenario

- The HESS spectrum is well fit by the Fermi acceleration of protons and their subsequent interaction with galactic gas.

- Can the combined Fermi + HESS spectrum be described in the same way?

- **Problem 1:** The spectrum at GeV energies is significantly softer than at TeV energies - some modification is needed to control this transition.

- **Problem 2:** The H.E.S.S. spectrum is point-like, with a better angular resolution than Fermi-LAT.
Controlling the Emission Spectrum with Diffusion

- We can imagine two scenarios for cosmic-ray transport from the central black hole: rectilinear or diffusive transportation.

- In the regime where the diffusion stepsize exceeds the diffusion region, the emission intensity is energy independent, and an $E^{-2}$ proton injection spectrum corresponds directly to an $E^{-2}$ gamma-ray spectrum.

- In the regime where the diffusion step is small, then the emission intensity depends linearly on the time the particle spends within the diffusion region.

![Graph showing Fermi-LAT and HESS data](image.png)
By setting allowing the diffusion constant to float to a set of best fit values - a single hadronic emission model can fit the entirety of the Fermi/HESS data.

Several model parameters can also be adjusted, such as the duration of particle injection, the occurrence of recent flares, the maximum radius for diffusion etc.

Models are formed with a step-function gas density profile (1000 $n_H$/cm$^{-3}$ within 3 pc of the galactic center, and 0 $n_H$/cm$^{-3}$ outside).
Employing a Realistic Gas Model

• Detailed models of the galactic gas density exist in the literature

• We employ a spherically symmetric model for galactic gas, and use this to calculate the morphology of the gamma-ray emission as a function of energy

• By far the dominant feature is the Circumnuclear ring between 1-3 pc from the GC

Ferriere (2012)

Linden et al. (2012)
Employing a Realistic Gas Model

- 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
Understanding High Energy Emission from the Galactic Center: 2 Convincing Stories

Linden et al. (2012)
CTA and the Galactic Center

• By convolving our models of the gas and proton densities in the galactic center region with the PSF and effective area of each instrument, we can determine whether CTA can distinguish between these scenarios.

• CTA will conclusively determine whether the galactic center source stems from a hadronic emission channel.

Linden & Profumo (2012)
Story 2: Low-Mass Dark Matter

- For a best fitting profile $\gamma = 1.3$, we find an available parameter space for dark matter models which match the observed GC excess.
- These models are compatible with estimates for the relic density of dark matter.
- The models combine with best fitting astrophysical backgrounds such as the GC point source and the galactic ridge, to fit the total GC excess.

Hooper & Linden (2011)
Abazajian & Kaplinghat find a wider range of dark matter masses which provide improved fits to the data.

However, fits with low dark matter mass are much, much better.
Other Observations Fitting Light DM: Indirect

- The same dark matter model provides a reasonable explanation to the intensity and morphology of the WMAP haze.
- The magnetic field must be slightly stronger above the galactic plane than usually assumed.

- The same dark matter model also provides a fit to the spectrum and intensity of the filamentary arcs.
- Light DM annihilation naturally provides the near delta-function electron spectrum necessary to explain the synchrotron spectrum of the filaments.

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Hooper & Linden (2011)

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Linden et al. (2011)
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Linden et al. (2011)
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Letter to the Editor
Monoenergetic relativistic electrons in the galactic center

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Received March 29, accepted May 27, 1988

Summary
It is shown that the nonthermal radio spectra of the center, including Sgr A* and the extended component, is neither due to self-absorbed synchrotron radiation, nor due to thermal absorption. A model is proposed in which a central, axially symmetric source of electrons which propagate with a velocity of the order of the speed of light, is responsible for the observed radio emission. The self-absorbed source at a frequency of 10 GHz (Reich et al., 1986) and 10 GHz (Boson and Fujimoto, 1986) was

\[ \Theta_{\text{crit}} = \frac{2.6 \times 10^9}{S_{\text{m}}} \left( \frac{\nu}{3 \times 10^4} \right)^{1/2} \text{arcseconds} \]

The source is resolved with an uncertainty of 100 mas (Boson and Fujimoto, 1986) with typically small structures.
Other Observations Fitting Light DM: Direct

- Light Dark Matter (~10 GeV) provides a compelling fit to the excesses currently observed by DAMA, CoGeNT and CRESST.
- Light Dark Matter may also be compatible with observed signal/limits at CDMS.
- However, a recent error found in CoGeNT analysis may affect some early dark matter interpretations.

Hooper (2012)

Kelso et al. (2012)
Populations of Millisecond pulsars have been observed in multiple globular clusters (Terzan 5, Omega Cen, NGC 6388, M 28).

- GC source is ~200 brighter than Omega Cen - which correlates nicely with the 1000x larger mass of the GC region.

- Spectrum of MSP population is very similar to the observed gamma-ray excess.
Story 3: Milli-second Pulsars

- The galactic center residual spectrum ($\Gamma \approx 1.0$) is somewhat harder than the population of observed pulsars - though uncertainties in the astrophysical spectrum which is subtracted are uncertain

- Must explain the high density of pulsars near the Galactic Center ($\sim r^{-2.6}$)
  - Two body interactions in the densest clusters?
  - Mass segregation?
Conclusions

- There is strong evidence for an extended, spherically symmetric, excess in ~1 GeV gamma-ray emission surrounding the galactic center.

- This excess is not easily accounted for by any known astrophysical model - and the background subtraction models used indicate that it is not correlated with galactic gas.

- Dark Matter Annihilation and Pulsars both provide plausible models for this excess.

- New observations, and also novel models, are needed to separate these components.
Extra Slides
HESS Limits on TeV Dark Matter

- HESS observations of the Galactic center, and Galactic Halo provide the strongest indirect limits on TeV dark matter

- Limits are strongly profile dependent -- background subtraction weakens bounds on isothermal dark matter models as well

Abazajian & Harding (2011)

Abramowski et al. (2011)
Fermi Telescope (2008-Present)

- Fermi-LAT is a space-based gamma-ray detector with an effective energy range of 20 MeV-300 GeV
- Effective Area $\sim 0.8$ m$^2$
- Field of View $\sim 2.4$ sr
- Energy Resolution $\sim 10\%$
- Angular Resolution: Energy Dependent

In analyses of the Galactic Center, we will constrict ourselves to Front converting events
• HESS spectrum well matched by flat $E^{-2}$ spectrum, up to energies of $\sim 10$ TeV, where an exponential cutoff is observed

• HESS source is localized to within 13″ of Galactic center (solid white curve) - the 68% and 95% confidence levels on the source extension are at $\sim 1$ and 3 pc
CTA and the Galactic Center

- By convolving our models of the gas and proton densities in the galactic center region with the PSF and effective area of each instrument, we can determine whether CTA can distinguish between these scenarios.

- CTA will **conclusively** determine whether the galactic center source stems from a hadronic emission channel.

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Linden & Profumo (2012)
However, HESS shows no variability, even during outbursts observed by Chandra.

This implies that the source of the emission is spatially distinct from lower energy sources.
• HESS is an Atmospheric Cherenkov Telescope built in Namibia

• Effective over the energy range ~500 GeV - 100 TeV with an effective area on the order of $10^5$ m$^2$.

• Energy Resolution ~ 10%

• Angular Resolution (>1 TeV) ~ 0.075°.

• Total Observation of the Galactic Center: 93h/112h

Aharonian et al. 2006
And some surprises!

Fermi Bubbles? Do they extend to the galactic center?

Non-thermal Radio Filaments - Bright, polarized synchrotron sources shaped like “thin threads” and lying perpendicular to galactic plane (Yusef-Zadeh et al. 1984)

Friday, November 2, 2012
Under the assumption of an NFW profile, the 95% confidence limits are as good or better than those from dwarf-spheroidals.

They are especially stronger for leptophilic annihilation paths.

Hooper & Linden (2011)
Employing a Realistic Gas Model

But CTA may be able to probe this emission profile directly!

Linden et al. (2012)
CTA and the Galactic Center

• However, CTA may be able to distinguish between these models:

• The instrument specifications for CTA are not yet entirely known, so we employ the following:
  
  • An order of magnitude improvement in the effective area over HESS
  
  • A reduction in the PSF from 1-10 TeV from $0.075^\circ$ to $0.03^\circ$

CTA Consortium (2011)

Glicenstein (2011)
Sgr A* is highly variable (on multiple time scales) at both radio and X-Ray energies.
Motivating Question:

Why would the galactic center be an interesting place to look for Dark Matter?
The lack of variability indicates that the emission may be stemming from a region farther away from the GC itself.

A recent model examined the possibility that protons emitted from the galactic center produce gamma-rays through their subsequent interaction with galactic gas.

This has the potential to produce the vast majority of emission from TeV scales all the way down to radio energies.

Normalization depends sensitively on diffusion (stay tuned!)
A recent model examined the possibility that protons injected from the galactic center encountered the circumnuclear ring. This region of high density molecular gas would produce bright gamma-ray emission upon the interaction with energetic protons.

Ferriere (2012)
Assumptions for the slope of the inner dark matter profile can make orders of magnitude differences in the expected dark matter annihilation rate.

Dark Matter is not a dominant gravitational source near the galactic center, so there are few observational handles on the dark matter density in the GC region.
Simulations including the effects of baryonic contraction show a steepening of the spectral slope from $\gamma \approx 1.0$ to $\gamma \approx 1.2-1.5$

Much more work is required to understand the dark matter content of the GC region

This is imperative for understanding the signals from indirect detection
Sgr A* Discovered via radio observations in 1974

Measurements of stellar motion confirm the status of the central object as a black hole (Gillissen et al. 2009)

Majority of radio emission thought to stem from accretion disk, rather than at BH event horizon (Doeleman et al. 2008)
Dark Matter Indirect Detection

Particle Physics

Astrophysics

Instrumental Response

Diemand et al. 2008

Slides Courtesy of G. Zaharijas

Sum annihilations along the line of sight
What is the WMAP Haze?

- To determine the best-fit dark matter annihilation profile, Hooper & Goodenough bin the residuals as a function of radius.

- Then the residual as a function of radius can be compared with the dark matter injection profile convolved with the PSF of the Fermi-LAT.
What is the WMAP Haze?

- Discovered by Doug Finkbeiner in 2004
- Synchrotron origin determined by subsequent observations
- Hard spectrum difficult to fit with lepton injection spectra typical of astrophysical phenomena
- Well fit by dark matter models with typical annihilation cross-sections and spectra
- However, modifications are needed to magnetic fields in galactic halo

Dobler et al. (2008)

Linden et al. (2010)
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.
The Radial Dependence of the Filamentary Arcs

- The intensity of multiple filamentary arcs show a strong dependence on their distance from the galactic center.

- This is expected in dark matter models, but not in most astrophysical interpretations of the filaments.

Linden et al. (2011)
- Can use a Kolmogorov-Smirnov test after finding the CDF for the radial profile of dark matter annihilation

- Since the CDFs for dark matter and the background point-source can be compared linearly, strong limits can quickly be set on dark matter annihilation

- Limits on photon counts can then be translated to a limit on annihilation cross-section

- Of course, large uncertainties exist, stemming from models in the gas density, and in the ratio of background emission stemming from point-source vs. gas
Under the assumption that the proton source has a power-law spectrum and is in steady-state, then the slope of gamma-ray emission strongly constrains the diffusion constant in the galactic center region:

$$D_0 = 1.2 \times 10^{26} \ (E/1 \text{ GeV})^{0.91}$$

This adds additional constraints to the understanding of lepton diffusion and propagation in the galactic center region.
This is particularly interesting in light of recent models which have set a minimum strength of 50 \( \mu \text{G} \) on the magnetic fields in the galactic center (best fit range 100-300 \( \mu \text{G} \)).

This almost ensures that synchrotron is the dominant energy loss mechanism for high energy electrons.

In the hadronic scenario, the diffusion parameters are set by the fit to the gamma-ray data.
**Note:** Models of light dark matter and millisecond pulsars seek only to explain the bump in the Fermi GeV spectrum.

In both cases, another mechanism (such as proton emission from the galactic center) must be responsible for the TeV emission.
Conclusions - Galactic Center

- The galactic center is one of the most exciting places to search for a dark matter signal.

- Present observatories are capable of both making exciting discoveries, and setting stringent limits on the properties of WIMP dark matter.

- Upcoming instruments are likely to make exciting discoveries of both the astrophysical and dark matter properties of the galactic center region.