Understanding the Spherically Symmetric Gamma-Ray Residual at the Galactic Center

Tim Linden
UC - Santa Cruz

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

Closing in on Dark Matter - Aspen January 30, 2012
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:

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

for a region within 1° of the Galactic center and an NFW profile.
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 $20^\circ \times 10^\circ$
• 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

See talk by Kev Abazajian

Abazajian & Kaplinghat (2012)
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?
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.
Hadronic Emission Models for Fermi and HESS

• 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
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.
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.
Understanding High Energy Emission from the Galactic Center:

2 Convincing Stories

Linden et al. (2012)

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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)
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.

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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.
Comparison to Other Indirect Detection Regimes

- 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)
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.
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?
The expected gamma-ray signatures of MSPs and light dark matter annihilation in the galactic center are very similar

Fair Statement: Dark matter provides a slightly better statistical fit than MSPs. However our Bayesian prior (that MSPs emit in the GC) may be higher than for dark matter

Need new techniques or observations to differentiate these signals
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)

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

Non-thermal Radio Filaments - Bright, polarized synchrotron sources

Accretion disk - Relatively dim now, but maybe not historically

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• 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

Hooper & Linden (2011)

Dobler et al. (2007)
However, correlating the WMAP haze against the Fermi bubbles shows a clear edge.

Furthermore, multiple galaxies are underluminous in radio emission, compared to expectations from dark matter annihilation.
Filamentary Arcs

- Bright Radio Synchrotron sources near (<100 pc) the Galactic Center

- Polarization measurements imply the magnetic field is highly ordered

\[ B_{\text{tot}} \sim 50-1000 \mu \text{G} \]

\[ \frac{B_{\text{ord}}^2}{B_{\text{tot}}^2} > 0.6 \]

- Mechanism of filament creation and emission is unknown

Linden et al. (2011)

Yusef-Zadeh et al. (2004)
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.

Dark matter injection also naturally predicts an $r^{-2}$ trend for the flux of filaments which are farther from the GC, an implication not shared by local astrophysical sources.
\[ E_m = 7 \text{ GeV} \left( \frac{V_A}{2000 \text{ km s}^{-1}} \right)^2 \left( \frac{B^2/8\pi}{8 \times 10^{-6} \text{ erg cm}^{-3}} \right)^{-1} \left( \frac{K_{\parallel}}{10^{24} \text{ cm}^2 \text{ sec}^{-1}} \right)^{-1} \] (7a).

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

Summary

It is shown that the nonthermal radio spectra of the center, including Sgr A* and the extended component (Center and Arc) is neither due to self-absorbed nor due to thermal absorption. A solution which propagate with the format of (7a) function into the

\[ \delta \theta_{\text{crit}} = 2.6 \times 10^9 S_m^{1/2} \nu_m^{-5/4} B_m^{1/4} \text{ arcsec} \]

where \( S_m \) is the observed flux density of the self-absorbed source at a frequency of 10 GHz (Reich et al., 1988) and a 10^{-2} G (Sofue and Fujimoto, 1988) with the format of (7a).

The source is resolved with an approximately small structures
• Arcade-2 Collaboration noted a hard synchrotron residual in low frequency (<10 GHz radio data)

• Emission is hard to account for with known astrophysical sources

• Can be accounted for with light dark matter annihilation
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)
Diffuse Secondary Emission

- 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.
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
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.

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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
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.
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)
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 ~ 0.8 m²
- Field of View ~ 2.4 sr
- Energy Resolution ~ 10%
- Angular Resolution: Energy Dependent

- In analyses of the Galactic Center, we will constrict ourselves to Front converting events

Created on Tue Oct 18 16:51:21 2011
• HESS spectrum well matched by flat $E^{-2}$ spectrum, up to energies of ~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 ~1 and 3 pc.
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)
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!

Dark Matter??

Fermi (100 GeV) Fermi (1 GeV)

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

Fermi Bubbles? Do they extend to the galactic center?
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.

Comparison to Other Indirect Detection Regimes

Hooper & Linden (2011)
Employing a Realistic Gas Model

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

Linden et al. (2012)
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 $0.03^\circ$
Sgr A* is highly variable (on multiple time scales) at both radio and X-Ray energies.

Eckart et al. (2006)
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!**)
Fitting the Residual: Hadronic Processes

- 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)
Negative: The Profile Dependence

- 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 as reported in Gnedin et al. 2011.
History of Galactic Center Observations (in 60 seconds)

- 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

Slides Courtesy of G. Zaharijas

Diemand et al. 2008

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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
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.
Dark Matter at the Galactic Center

- 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.

Aharonian et al. (2009)

Linden et al.
• 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.