Dark Matter, Pulsar, and Diffuse Emission Models for the Galactic Center Excess

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The Central Molecular Zone

- 400 pc x 80 pc
- $10^7 \, M_\odot$ of gas in Molecular Clouds
- Conditions similar to nearby starburst galaxies

Molecular Gas clouds in the Central Molecular Zone are hot (~50-100K), which is indicative of heating by a significant cosmic-ray population. (Yusef-Zadeh et al. 2013)
What Generates these Cosmic-Rays?

The Galactic center region is known to contain nearly every known cosmic-ray acceleration mechanism.

1.) Supernovae
2.) Pulsars
3.) Sgr A*
4.) Dark Matter Annihilation?
The GC Powers Large Scale Excesses

Fermi Bubbles

GeV Excess

WMAP/PLANCK Haze

Integral 511 keV Excess
Non-Thermal Emission (Observables)

The photon excesses extend very far from the central molecular region!

This:

(a) Indicates the relative power of Galactic center accelerators, compared to the Galactic plane.
(b) Provides a large field of view for studies of GC emission.
(c) Implies that propagation is important!
Observational Results

These are the three resilient features of the GeV Excess:

1.) Hard Gamma-Ray Spectrum peaking at ~2 GeV
2.) Spherically Symmetric Emission Morphology
3.) Extension to >10° from the GC.
Astrophysical Models

How could we model this with:

1.) Dark Matter annihilation
2.) Millisecond Pulsars
3.) Diffuse Emission Modeling
Dark Matter Model Fitting?

**Spectrum**

- $E^2 \frac{dN}{dE}$ (GeV/cm$^2$/s/sr)
- $E_\gamma$ (GeV)

**Morphology**

- $E^2 \frac{dN}{dE}$ (GeV/cm$^2$/s/sr)
- $\psi$ (degrees)

**Sphericity**

- $\Delta \chi^2$
- Axis Ratio

**Intensity**

- $\sigma v$ (cm$^3$/s)
- $m_X$ (GeV)
- $\rho_{local}$ (GeV/cm$^3$)
- $\gamma = 1.26$
Particle Physics Models Exist...

Chan (1607.02246)  
Jia (1607.00737)  
Barrau et al. (1606.05327)  
Kumar et al. (1606.00611)  
Biswa et al. (1606.05566)  
Front et al. (1606.04589)  
Choquette et al. (1606.01039)  
Cuoco et al. (1605.08228)  
Chao et al. (1605.05192)  
Hektor et al. (1605.00714)  
Cai et al. (1605.08481)  
Duerr et al. (1605.07562)  
Droz et al. (1605.07053)  
Arcadi et al. (1605.02297)  
Williams (1605.00714)  
Cai & Spray (1605.00714)  
Freese et al. (1605.00714)  
Bhattacharya et al. (1605.03665)  
Algeri et al. (1605.01010)  
Fox & Tucker-Smith (1605.00499)  
Dutta et al. (1605.05989)  
Liu et al. (1605.05716)  
Berlin et al. (1605.05390)  
Fan et al. (1605.05699)  
Hektor et al. (1605.05096)  
Achterbeg et al. (1605.04644)  
Biswa et al. (1605.04543)  
Butter et al. (1507.02288)  
Mondal et al. (1507.01793)  
Cao et al. (1506.06471)  
Banik et al. (1506.05665)  
Ipek (1505.07826)  
Buchmuller et al. (1505.07826)  
Balazs et al. (1505.06758)  
Medina (1505.05565)  
Kim et al. (1505.04620)  
Ko et al. (1504.06944)  
Ko & Tang (1504.03908)  
Ghorbani & Ghorbani (1504.03610)  
Fortes et al. (1503.08220)  
Cline et al. (1503.08213)  
Rajaraman et al. (1503.05919)  
Bi et al. (1503.03749)  
Kopp et al. (1503.02669)  
Elor et al. (1503.01773)  
Ghergheita et al. (1502.07173)  
Berlin et al. (1502.06000)  
Achterberg et al. (1502.05703)  
Modak et al. (1502.05682)  
Guo et al. (1502.05058)  
Chen & Nomura (1501.07413)  
Kozaczuk & Martin (1501.07275)  
Berlin et al. (1501.03496)  
Kaplinghat et al. (1501.03507)  
Alves et al. (1501.03490)  
Biswa et al. (1501.02666)  
Biswa et al. (1501.02666)  
Ghorbani & Ghorbani (1501.00206)  
Mondal et al. (1410.6497)  
Heikinheimo & Spethmann (1410.4842)  
Freytsis et al. (1410.3818)  
Yu et al. (1410.3347)  
Cao et al. (1410.3239)  
Guo et al. (1409.7864)  
Yu (1409.3227)  
Cahill-Rowley et al. (1409.1573)  
Banik & Majumdar (1408.5795)  
Bell et al. (1408.5142)  
Ghorbani (1408.4929)  
Okada & Seto (1408.2583)  
Frank & Mondal (1408.2223)  
Baeck et al. (1407.6588)  
Tang (1407.5492)  
Balazs & Li (1407.0174)  
Huang et al. (1407.0038)  
McDermott (1406.6408)  
Cheung et al. (1406.6372)  
Arina et al. (1406.5542)  
Chang & Ng (1406.4601)  
Wang & Han (1406.3598)  
Cline et al. (1405.7691)  
Berlin et al. (1405.5204)  
Mondal & Basak (1405.4877)  
Martin et al. (1405.0272)  
Ghosh et al. (1405.0206)  
Abdullah et al. (1404.5503)  
Park & Tang (1404.5257)  
Cerdeno et al. (1404.2572)  
Izaguirre et al. (1404.2018)  
Agrawal et al. (1404.1373)  
Berlin et al. (1404.0022)  
Alves et al. (1403.5027)  
Finkbeiner & Weiner (1402.6671)  
Boehm et al. (1401.6458)  
Kopp et al. (1401.6457)  
Kopp et al. (1312.7488)  
Alves et al. (1312.5281)  
Fortes et al. (1312.2837)  
Banik et al. (1311.0126)  
Arhrib et al. (1310.0358)  
Kelso et al. (1308.6630)  
Kozaczuk et al. (1308.5705)  
Kumar (1308.4513)  
Demir et al. (1308.1203)  
Buckley et al. (1307.3561)  
Cline et al. (1306.4710)  
Cannoni et al. (1205.1709)  
An et al. (1110.1366)  
Buckley et al. (1106.3583)  
Boucenna et al. (1106.3368)  
Ellis et al. (1106.0768)  
Cheung et al. (1104.5329)  
Marshall et al. (1102.0492)  
Abada et al. (1101.0365)  
Tytgat (1012.0576)  
Logan (1010.4214)  
Barger et al. (1008.1796)  
Raklev et al. (0911.1986)
Testing the Dark Matter Interpretation

- Dwarfs: Hooper & Linden (2015)
- IGRB: Di Mauro & Donato (2015)
- Antiprotons: Cuoco et al. (2017)
- Bertoni et al. (2016)
Pulsar Fits

- The peak of the MSP energy spectrum matches the peak of the GeV excess

Abazajian (2010, 1011.4275)
Recent analyses of hot-spots and cold spots in the GC region find evidence for the presence of a population of sub-threshold point sources.

Bartels et al. (2015)

Lee et al. (2015)
The Life Cycle of a Galactic Center Pulsar

• Pulsars are initially formed during the collapse of a massive star in a supernova explosion.

• Pulsars can be “recycled” via angular momentum accretion from a binary companion.

• Recycled pulsars can be formed in Globular Clusters, and then disrupted during interactions with the GC.

• Pulsars from all three stages of evolution have been posited as the explanation for the Galactic center excess.
Young pulsar Models

- Young Pulsars trace star formation. Could trace the total density of the Galactic bulge and galactic plane.

- The pulsar morphology may be non-spherical, but the asphericity is hidden by the background subtraction of the Galactic plane (O’Leary et al. (2015), 1504.02477)

- However, many young radio pulsars observed in galactic center region. Gamma-Ray emission does not appear correlated with these systems (Linden 2016, 1509.02928)
Millisecond Pulsars

- Millisecond Pulsars are expected to be overabundant in the Galactic center due to the large stellar density.

- Since MSPs trace old star formation - they may have a significant abundance in the Galactic bulge.

- Bulge population may be spherically symmetric, or trace an X-shaped stellar distribution (Ploeg et al. 2017, 1705.00806)
Millisecond Pulsar Luminosities

- Can use observed pulsars (and their distances) to calculate the luminosity function of millisecond pulsars.

- How many MSPs are needed to explain the excess - how many of these are bright enough to be detectable?

- Most of the luminosity is generated by relatively bright pulsars. Many of these are likely to be detectable.

  - Pro: And we’re finding sub-threshold sources.
  - Con: This luminosity function predicts we should see hundreds of bright sources, not tens.
Comparison with LMXBs

- The angular momentum of MSPs is produced during an LMXB phase.
- LMXBs are extremely X-ray bright, and are detectable throughout the galaxy.

- In Andromeda, an overabundance of LMXBs is observed in the galactic bulge. (Voss & Gilfanov 2007, astro-ph/0610649)
Comparison with LMXBs

- LMXBs and MSPs are overabundant in globular clusters.

- Can correlate number of observed LMXBs with total gamma-ray luminosity to determine ratio of MSP to LMXB emission.

- Number of observed LMXBs in the Galactic center indicates that only \(~5\%\) of the galactic center excess is due to MSPs.

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*Haggard et al. 2017, 1701.0272*
Disrupted Globular Clusters

- Can avoid this if excess is produced via disrupted globular clusters.
  - LMXB formation stops, affecting the LMXB/MSP ratio.
  - MSPs spin-down, decreasing the number of bright sources.

- Model is approximately spherically symmetric, because globular clusters are spherically concentrated around the Galactic center.
Disrupted Globular Clusters

• However, the spin-down of the MSP luminosity is fast.

• For many models this spin-down is faster than the evolution of LMXBs (~1 Gyr).
  (Fragos & McClintock 2015 1408.2661)

• Means more MSPs are needed to explain the intensity of the excess. Necessary mass can exceed the total mass of the Galactic bulge.

\[
\tau \equiv \frac{\dot{E}}{\dot{E}} = \frac{P}{2 \dot{P}} \simeq 0.46 \text{ Gyr} \times \left( \frac{3 \times 10^{34} \text{ erg/s}}{L_\gamma} \right) \left( \frac{\eta_\gamma}{0.2} \right) \left( \frac{3 \text{ ms}}{P} \right)^2
\]
Too Bright or Too Many or Just Right?

- Utilizing the luminosity distribution of pulsars in the field produces too many bright (detectable) pulsars, compared to observations. (Hooper et al. 2013, 2015)

- This is also true when normalizing the number of detected pulsars against intermediate sources, such as LMXBs – which avoids many binary evolution uncertainties.

- Evolving the pulsars (compared to the replenished field population) decreases the number of bright pulsars, but requires too many systems to explain the total luminosity. (Hooper & TL 2016)
Fortunately the Pulsar Hypothesis is Testable

- Radio Observations with GBT targeted at gamma-ray hotspots would be expected to find ~5-10 MSPs with a 200 hr commitment.

- Fortunately, SKA observations are likely to conclusively find MSPs in the GC, or rule out this scenario.
Proving the Pulsar Interpretation
Can this be proven in the negative?
A More Ominous Problem...

Multiwavelength observations indicate that the Galactic Center is a dense star-forming environment.

3-20% of the total Galactic Star Formation Rate is contained within the Central Molecular Zone.

2-4% - ISOGAL Survey Immer et al. (2012)
2.5-5% - Young Stellar Objects Yusef-Zadeh et al. (2009)
5-10% - Infrared Flux Longmore et al. (2013)
10-20% - Wolf-Rayet Stars Rosslowe & Crowther (2014)
2% - Far-IR Flux Thompson et al. (2007)
2.5-6% - SN1a Schanne et al. (2007)
The Solution

Solution: Add a new cosmic-ray injection morphology tracing the molecular gas density.

Observationally Resilient: Several tracers of molecular gas are sensitive to the galactic center region.

Theoretically Motivated: Molecular Gas is the seed of star formation, the Schmidt Law gives

\[
\Sigma_{\text{SFR}} \propto \Sigma_{\text{Gas}}^{1.4 \pm 0.15}
\]

Specifically we inject a fraction of cosmic-rays \((0 < f_{\text{H}_2} < 1)\) following:

\[
Q_{\text{CR}}(\vec{r}) \propto \begin{cases} 
    0 & \rho_{\text{H}_2} \leq \rho_s \\
    \rho_{\text{H}_2}^{-n_s} & \rho_{\text{H}_2} > \rho_s 
\end{cases}
\]
Two features leap out immediately:

1.) Spiral Arms

2.) A bright bar in the Galactic Center
The Solution

Adds a new, and significant, cosmic-ray injection component, in particular near the Galactic Center.

The cosmic-ray injection rate now matches observational constraints.
A Better fit to the Gamma-Ray Sky

1.) Adding a cosmic-ray injection component tracing $f_{H2}$ improves the full-sky fit to the gamma-ray data.

2.) The best fit value over the full sky is $f_{H2} = 0.25$

3.) Technique will become more powerful with the introduction of 3D gas and dust maps in the near future.
Effect on the GC Excess

Increasing the value of $f_{H^2}$ decreases the intensity of the gamma-ray excess.

However, the best global fit is $f_{H^2} = 0.1$, with a GC excess intensity that decreases by only $\sim 30\%$. 
Effect on the Excess Morphology

The morphology of the excess is also degenerate with $f_{\text{H}2}$.

As $f_{\text{H}2}$ is increased, the best-fit morphology becomes stretched perpendicular to the galactic plane.

However, marginalized over all values of $f_{\text{H}2}$, the standard NFW template is still consistent with the data.
A Similar Result with Different Techniques

Gaggero et al. (2015)

Ajello et al. (2015)

Fermi-LAT Collaboration (2016)
Models of point source contributions to the Galactic center excess contend with a significant diffuse component that must be subtracted.
Effect on the Point Source Population

Changing the diffuse model changes the point source population significantly.

This is important for our interpretation of pulsar contributions to the excess.

Fermi-LAT Collaboration (2015, 1511.02938)

Fermi-LAT Collaboration (2017, 1705.00009)
TeVPA 2017

tevpa2017.osu.edu

- August 7–11, Columbus, OH
- Registration and abstract submission are open
- Pre-meeting mini-workshops on Sunday, August 7
Conclusions

The galactic center excess is bright, and resilient to systematic uncertainties.

Dark Matter and pulsar models of the Galactic center excess remain reasonable.

Understanding galactic diffusion emission is critical for disentangling emission sources.
Extra Slides
Cosmic-Ray Propagation Codes (e.g. Galprop), generally utilize a cosmic-ray injection rate at the Galactic center that is identically 0. These models were not produced to study the very center of the Galaxy!

Results from these cosmic-ray propagation codes are used in many analyses of the Galactic center region.

Carlson et al. (2016a, 2016b)  
1510.04698  
1603.06584
The lack of cosmic-ray injection in the GC should still be slightly disturbing. Especially when we try to answer the question: “excess compared to what?”

Our models indicate a degeneracy between cosmic-ray injection and the existence of a Galactic center excess template tracing an NFW profile. However, at present the best fit models still include a significant NFW component.
The Galactic Center Deficit?

Models which reproduce the SN rate at the Galactic center generally predict a negative gamma-ray excess!
Crocker et al. (2011) demonstrated that the break in the GC synchrotron spectrum is best fit in the regime with:

a.) Large Magnetic Fields  
b.) Large Convective Winds

Very different from typical Galprop diffusion scenario.
Applying strong convective winds to the diffuse emission model fixes the low-energy over subtraction.

The intensity of the excess near the spectral peak also increases, up to ~50% of its nominal value.

The model produces a significantly better fit to the gamma-ray sky dataset - and also coincides better with multi wavelength data.
Testing the GCE with Dwarfs

Ackermann et al. (2015)

Constraints from dSphs are statistically in 1-2σ tension with the GC excess.

However, uncertainties in the dark matter density profile can easily resolve this tension.

credit: Kev Abazajian (2015)
DES, Pan-Starrs (and later LSST) are likely to greatly improve the detection of dwarf spheroidal galaxies in the Southern Hemisphere. Future limits may improve drastically if nearby dwarfs are discovered.
The addition of more dwarfs (in particular, several nearby dwarfs) can significantly strengthen the limits from the Fermi-LAT joint-likelihood analysis.

The Fermi-LAT has already observed all dwarfs in the sky, now we just need to know where they are.
Cosmic-Ray Outbursts are Well-Motivated

Fermi Bubbles

GeV Excess

WMAP/PLANCK Haze

Integral 511 keV Excess
Cosmic-Ray Outbursts

So far, we have only considered steady-state diffuse emission scenarios - but the Galactic center is unlikely to be in steady state (e.g. Fermi bubbles).

An outburst of leptonic (or possibly hadronic) origin can also produce the gamma-ray excess, but only if the injected electron spectrum is extremely hard (compared to observed blazar spectra).

Cholis et al. (2015, 1506.05119)
Proving an Outburst Interpretation

The origin of the WMAP haze was determined due to cross-correlation with the Fermi bubbles.

Is a similar cross-correlation (e.g. with X-Ray data) possible?
Can Outbursts be Ruled Out?

Leptonic Outbursts at high latitude produce an associated synchrotron flux given by the ratio of the magnetic field and ISRF energy densities.

\[
\frac{F_{\text{radio}}}{F_{\gamma}} \bigg|_{\text{DM}} = \frac{B_e \left( \frac{\rho_B}{\rho_B + \rho_{\text{rad}}} \right)}{B_e \left( \frac{\rho_{\text{rad}}}{\rho_B + \rho_{\text{rad}}} \right) + B_\gamma}
\]

Enhanced measurements of the low-energy synchrotron signal at the Galactic center may rule out any associated synchrotron flux.
The GeV Excess
How To Find an Excess

Data
750 — 950 MeV
Best Angular Resolution Cut
10° x 10° ROI

pion-decay
bremsstrahlung
ICS
ICS-CMB
Point Sources
Excess? (NFW)
Observational Results

These are the three resilient features of the GeV Excess:

1.) Hard Gamma-Ray Spectrum peaking at $\sim$2 GeV
2.) Spherically Symmetric Emission Morphology
3.) Extension to $>10^\circ$ from the GC.
Two Analyses of the Gamma-Ray Excess

**INNER GALAXY**
- Mask galactic plane (e.g. $|b| > 1^\circ$), and consider $40^\circ \times 40^\circ$ box
- Bright point sources masked at $2^\circ$
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
- Background systematics controlled

**GALACTIC CENTER**
- Box around the GC ($10^\circ \times 10^\circ$)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source
- Bright Signal
Leptonic Outbursts

The Galactic center is unlikely to be in steady state (e.g. Fermi bubbles).

An outburst of leptonic origin can produce the gamma-ray excess, but only if the injected electron spectrum is extremely hard (compared to observed blazar spectra).

Cholis et al. (2015, 1506.05119)
Petrovic et al. (2014, 1405.7928)
Cholis et al. (2015, 1506.05119)
The Sgr A* Source

HESS has detected diffuse gamma-ray emission at energies ~100 TeV.

This is not observed in even the youngest supernova remnants.

The emission profile is indicative of diffusion from the central BH.
• However, these residuals are found once an extremely smooth diffuse emission model is subtracted - it remains to be seen whether the residuals are resilient to diffuse model changes.

see slides by Christoph Weniger
Recently, observations by Iocco, Pato & Bertone (2015) have used stellar velocity measurements to directly measure the dark matter density in the Milky Way (to within 3 kpc of the GC).

Future measurements (employing Gaia data) will have the ability to significantly improve these measurements.

Iocco, Pato & Bertone (2015)
Simulations!

Add the new cosmic-ray injection models into Galprop to produce a new steady-state cosmic-ray distribution.
Galactic center excess is resilient....
Changing the point source catalog from the 3FGL to the 1FIG has only a negligible effect on the gamma-ray excess.
Fits are significantly improved, in particular in regions near the Galactic Center where there is significant kinematic gas information.
Application to the Galactic Center

Data
750 — 950 MeV
Best Angular Resolution Cut
10° x 10° ROI

+ pion-decay
+ bremsstrahlung
= ICS
+ ICS-CMB
+ Point Sources
+ Excess? (NFW)
This increases the best fit value of $f_{\text{H}_2}$ for the GC data, bringing this value into agreement with the global best fit value.

Models with a GCE component still prefer slightly lower values of $f_{\text{H}_2}$, but these have increased to 0.2 as well.
For the Galactic Center analysis, the morphology of the excess component remains relatively robust.
Analysis regions far from the GC also show an excess — not much star formation occurs a few degrees above the Galactic plane.

Calore et al. (2014, 1409.0042)
Comparison to Cygnus-X

Uncovering a gamma-ray excess at the galactic center