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.) Cosmic-Ray Outbursts
4.) Diffuse Emission Modeling
Dark Matter Model Fitting?

Spectrum

Morphology

Sphericity

Intensity

Spectrum

Morphology

Sphericity

Intensity
Particle Physics Models Exist...
Testing the Dark Matter Interpretation

- Dwarfs
  Hooper & Linden (2015)

- IGRB
  Di Mauro & Donato (2015)

- Antiprotons
  Hooper et al. (2015)

- J2212.5+0703
  Bertoni et al. (2016)
Testing the GCE with Dwarfs

Constraints from dSphs are statistically in 1-2\(\sigma\) tension with the GC excess.

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

credit: Kev Abazajian (2015)
Testing the GCE with Dwarfs

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.
Millisecond Pulsar Fits

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

- MSPs are thought to be overabundant in dense star-forming regions like the Galactic Center
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.
Too Bright or Too Many?

- 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 \(~5\text{-}10\) 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?
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.

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

Enhanced measurements of the low-energy synchrotron signal at the Galactic center may rule out any associated synchrotron flux.
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 Rossowe & Crowther (2014)
2% - Far-IR Flux Thompson et al. (2007)
2.5-6% - SN1a Schanne et al. (2007)
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 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:

\[ Q_{\text{CR}}(r) \propto \begin{cases} 0 & \rho_{\text{H}_2} \leq \rho_s \\ \rho_{\text{H}_2}^{n_s} & \rho_{\text{H}_2} > \rho_s \end{cases} \]
The Solution

Two features leap out immediately:

1.) Spiral Arms

2.) A bright bar in the Galactic Center
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.
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

Excess? (NFW)
Effect on the GC Excess

Increasing the value of $f_{\text{H}_2}$ decreases the intensity of the gamma-ray excess.

However, the best global fit is $f_{\text{H}_2} = 0.1$, with a GC excess intensity that decreases by only $\sim 30\%$. 
The morphology of the excess is also degenerate with $f_{H2}$.

As $f_{H2}$ is increased, the best-fit morphology becomes stretched perpendicular to the galactic plane.

However, marginalized over all values of $f_{H2}$, the standard NFW template is still consistent with the data.
The Galactic Center Deficit?

Models which reproduce the SN rate at the Galactic center generally predict a negative gamma-ray excess!
Advection and Convection in the Galactic Center

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.
The Low Energy Spectrum

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.
A Similar Result with Different Techniques

Gaggero et al. (2015)

Ajello et al. (2015)

Preliminary

Fermi-LAT Collaboration (2016)
Cosmic-Ray Outbursts are Well-Motivated

Fermi Bubbles

GeV Excess

WMAP/PLANCK Haze

Integral 511 keV Excess
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.
Extra Slides
The GeV Excess
How To Find an Excess

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

pion-decay + bremsstrahlung = ICS

Point Sources + Excess? (NFW) = ICS-CMB
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°), and consider 40° x 40° box
- Bright point sources masked at 2°
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
- Background systematics controlled

GALACTIC CENTER
- Box around the GC (10° x 10°)
- 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).

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.
This increases the best fit value of $f_{H2}$ 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 $f_{H2}$, 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

Unprocessed map of 1.0 to 3.16 GeV gamma rays
Known sources removed