Molecular clouds as the origin of the Fermi Gamma-ray GeV excess

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THE FERMI GEV EXCESS

Spectral shape of excess compatible with 35 GeV DM particle annihilating into $b\bar{b}$.

Spatial distribution in latitude compatible with generalized NFW profile.

Daylan et al., 1402.6703

Calore et al., 1411.4647
USUAL APPROACH: SPATIAL TEMPLATES

- Calculate diffuse emission ($\pi^0$, bremsstrahlung, inverse Compton) from spatial templates using models like Galprop or Dragon
- Based on astronomical data on gas distributions/ISRF
  \[\rightarrow\] models do not describe galactic center well

THIS STUDY: SPECTRAL TEMPLATES

- Calculate diffuse emission from spectral templates of known physical processes ($\pi^0$, bremsstrahlung, inverse Compton), use local cosmic ray measurements and gamma-rays to determine interstellar cosmic ray spectra.
- Derive spatial distribution of fit components from Fermi data.
  \[\rightarrow\] allows to determine if new physical processes are required
  \[\rightarrow\] fit is over-constrained
PROPGATED COSMIC RAYS (PCR)

Simplest possible approach: assume local cosmic ray spectra are representative for Galaxy → independent of transport model.

Propagated cosmic rays (PCR): $\pi^0$ production by propagated cosmic ray protons in the diffuse interstellar medium, following an $E^{-2.85}$ spectrum consistent with the AMS-02 data above 20 GV.
Bremsstrahlung (BR): cosmic ray electrons emit bremsstrahlung in the interstellar gas. The interstellar electron spectrum follows $E^{-3.21}$, consistent with the AMS-02 data. Below 1 GeV, where ionization losses dominate, a harder spectrum of $E^{-0.81}$ is required by the gamma-ray data.
Inverse Compton scattering (IC): photons from the interstellar radiation field (starlight, dust emission, CMB) scatter off cosmic ray electrons.
SOURCE COSMIC RAYS (SCR)

CRs accelerated in sources see high density gas in shock wave and surrounding ISM

→ expect copious $\pi^0$ production with a spectrum from $1/E^{2.1}$ protons

Source cosmic rays (SCR): $\pi^0$ production by freshly accelerated protons in the vicinity of cosmic ray sources, following a hard $E^{-2.1}$ spectrum. The SCR template agrees with the Fermi bubbles shown as the blue band.
MOLECULAR CLOUDS

Size CMZ:
-1.5° < l < 2°
-0.5° < b < 0.5°

Mass CMZ: $5 \times 10^7 M_\odot$
(Black hole GC: $4 \times 10^6 M_\odot$)

Total mass fraction in MCs: ~ 40%

Molecular clouds are accompanied by strong magnetic fields
Earth's magnetic field leads to position dependent cutoff of low rigidity cosmic rays.

Geomagnetic cutoff in AMS-01 data.
Earth's magnetic field leads to position dependent cutoff of low rigidity cosmic rays.

A similar effect is expected for molecular clouds: the magnetic moment of the cloudlets will prevent low rigidity cosmic rays from entering the dense cores. Only over-cutoff protons can enter the dense cores and produce $\pi^0$. 
MOLECULAR CLOUD COSMIC RAYS (MCR)

Molecular cloud cosmic rays (MCR): π⁰ production by propagated cosmic ray protons in the dense cores of molecular clouds.
Alternatively, to test the Dark Matter (DM) hypothesis an additional gamma-ray template expected for a DM candidate with a mass of 45 GeV annihilating into $b\bar{b}$ quark pairs is used instead of the MCR template.
RESULTS

CMZ

Halo

Scutum-Centaurus arm

best fit for 45 GeV → bb
RESULTS: DARK MATTER HYPOTHESIS vs MOLECULAR CLOUDS

**Molecular clouds**
- 5 templates
- + isotropic background
- + variable MC cutoff value

**DM: 45 GeV → b\bar{b}**
- 5 templates
- + isotropic background
THE MCR TEMPLATE DISTRIBUTION

"GeV-excess" is longitudinally extended, tracing the rectangular shape of the Galactic bar.
CORRELATION BETWEEN MCR AND CO ROTATION LINES

CO surveys are the primary way of identifying molecular clouds (low J transitions). We use the Planck measurements on the CO J 2 →1 emission.


The MCR template traces molecular clouds.

Along latitude the GeV-excess shows indeed the morphology of a generalized NFW profile.

Calore et al., 1411.4647
THE DM TEMPLATE DISTRIBUTION

rectangular shape is incompatible with the expected spherical morphology of DM
The DM sky map does not resemble the expected spherical DM halo profile but has a morphology similar to the CO sky map.
THE SCR TEMPLATE DISTRIBUTION
THE SCR TEMPLATE DISTRIBUTION

SCR traces
Fermi bubbles, bar and spiral arms

Bar [40...-30deg]
Spiral arms
Cygnus
Centaurus arm
CONCLUSION

Using a fit based on energy templates we find that the GeV excess is compatible with the emission of $\pi^0$ decay from molecular clouds.

We compared the dark matter hypothesis and the molecular cloud hypothesis to explain Fermi GeV excess.

The molecular cloud hypothesis is preferred for the following reasons:

- it provides better fits if the whole sky and all energies are considered
- both hypotheses follow the CO profile instead of a NFW profile
- the CMZ shows a strong excess in the Galactic Center in a longitudinal extended rectangular profile of $l \times b=4^\circ \times 1^\circ$ instead of a spherical DM profile
ADDITIONAL MATERIAL
CORRELATION BETWEEN SCR AND AL26 EMISSION

Sources are expected to reside inside molecular clouds → correlation between MCR and SCR template.

AI26 synthesized by proton capture of Mg25 in heavy, magnesium rich sources, 1.8 MeV line emitted in decay [SPI/Integral].

Source cosmic rays trace AI26 emission
FIT WITH 5 COMPONENTS

The total flux in a given direction can be described by a linear combination of the gamma-ray fluxes from the various processes:

\[
|\Phi_{tot} > = n_1 |\Phi_{PCR} > + n_2 |\Phi_{BR} > + n_3 |\Phi_{IC} > + n_4 |\Phi_{SCR} > + n_5 |\Phi_{MCR} > + n_6 |\Phi_{ISO} > ,
\]

- Propagated cosmic rays
- Bremsstrahlung
- Inverse Compton
- Source cosmic rays
- Molecular cloud cosmic rays (or DM)
- Isotropic background (fixed normalization)
SPECTRAL TEMPLATE FIT

Total: 797 cones binning adapted to structures

Data: Fermi-LAT data between 0.1 and 100 GeV using the diffuse class of the public P7REP SOURCE V15 data collected from August, 2008 till July 2014 (72 months).

For each cone in the sky the normalization of 5 components is optimized and the optimal cutoff position for the MCR template is chosen.

Each cone has 21 energy bins with only $N_i \leq 6$ free parameters $\rightarrow$ fit is overconstrained.

$$\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{21} \left[ \frac{\langle data(i, j) \rangle - \sum_{k=1}^{5} n(i, k) \times tem(i, j, k)\rangle^2}{\sigma(i, j)^2} \right] ,$$

total error on data(i, j)

Template contribution
ISOTROPIC BACKGROUND

Isotropic background is redetermined by comparing observed and fitted flux for each energy bin in regions outside the bubbles and the disk.

Offset determines misestimate of EB for each energy bin → iterative process

Final template deviates from template provided by Fermi by around 10%, 40% at highest energies.