Disentangling the gamma-ray emission from the Galactic bulge: Status and Prospects
The Galactic bulge

Some basics

- Central group of stars in spiral galaxies
- Radial extension 2-3 kpc
- Mass completely dominated by old stellar population
- Almost no molecular gas, except central few 100 pc (central molecular zone)
- No star formation, except in central region (CMZ, nuclear star cluster)
Instrumental panorama – Photons

Energy range

PeV
TeV
GeV
MeV
keV
XMM-Newton
EUVE
eV
VLT
Hubble Space Telescope

Low energy range

meV
µeV
neV

Years of operation


H.E.S.S.
and Veritas, Magic, ...
Fermi-LAT
NuSTAR
Hitomi
eROSITA
Hitomi 2
ATHENA
GAMMA-400
e-ASTROGAM
CTA
LHAASO
HAWC

C. Weniger
19 April 2018
Gamma-ray emission from the inner Galaxy

**INTEGRAL 511 keV positron annihilation line**
e.g. Leventhal+ 1978, Knödlseder+ 2003, see Prantzos for review

- Radiative decay
- Accreting binaries, jets
- Pulsars, curvature radiation
- Sgr A*
- Dark matter

**HESS Galactic ridge emission, PeVatron in center**

- Sgr A*
- Pulsar wind nebulae

HESS Collab. 2016

Siegert+ 2016
The Fermi GeV excess

Five years of Fermi LAT data
> 1 GeV

The Fermi GeV bulge emission

- Initial claims by Goodenough & Hooper (2009) [see also Vitale & Morselli (2009)]
- Controversial discussion in the community for six years
- In 2015, existence of “GeV excess” finally got the blessing from the Fermi LAT collaboration
- Is it a DM signal?

... Hooper & Linden 11; Boyarsky+ 11; Abazajian & Kalpinghat 12; Hooper & Slatyer 13; Gorden & Macias 13; Macias & Gorden 13; Huang+ 13; Abazajian+ 14; Daylan+ 14; Zhou+ 14; Calore+ 14; Huang+15; Cholis+ 15; Bartels+ 15; Lee+ 15, ...
For foreground / background subtraction, control regions are available!
Various groups found an “excess of GeV photons” that extends from the Galactic center up to mid-latitudes. (Goodenough & Hooper 2009; Vitale & Morselli 2009, ...)

... Hooper & Linden 11; Boyarsky+ 11; Abazajian & Kalpinghat 12; Hooper & Slatyer 13; Gorden & Macias 13; Macias & Gorden 13; Huang+ 13; Abazajian+ 14; Daylan+ 14; Zhou+ 14; Calore+ 14; Huang+15; Cholis+ 15; Bartels+ 15; Lee+ 15, ...)

**Characteristics**

- Extends up to ~15 (?) deg
- Morphology compatible with DM annihilation in contracted NFW
- Uniform spectrum with bump at ~2 GeV

**Different groups, different ROIs**

2 GeV

\[
\frac{dS}{dV} \sim r^{-2.5}
\]

14° × 14°

Daylan+ 14  
(GC analysis)

7° × 7°

Ajello+15  

Huang+ 15

Calore+14
Template regression

Neutral pion + Bremsstrahlung +
Inverse Compton +
Fermi bubbles, isotropic background, Loop I, Earth limb, Sun, ...

Point sources +

Bulge emission?

Data =

Free parameters: $N_{\text{params}} = N_{\text{ebins}} \times N_{\text{comp}}$
Hadronic production ("pi0")

Collision of relativistic cosmic-ray nuclei with the gas in the Milky Way

$\rho_{\text{CR}} \rightarrow \rho_{\text{ISM}} \rightarrow \pi^0 \rightarrow \gamma \rightarrow \ldots$

Spectrum has characteristic "pion bump":

$\pi^0 \rightarrow \gamma \gamma \quad m_{\pi^0}/2 \approx 70 \text{ MeV}$

Characteristics

- Pion bump at $\sim 1 \text{ GeV}$
- Traces interstellar medium

Adopted from J.A. Aguilar

Ackermann+13
Interstellar medium (ISM)

Two* components: *neglecting dark gas, warm gas, hot gas

Cold neutral medium
- Atomic hydrogen, helium etc
- 50-100 K
- Density
  \[ n \sim 10 - 100 \text{ atoms/cm}^3 \]
- Scale height
  \[ z_s \sim 100 - 300 \text{ pc} \]
- Traced by 21 cm line (hyperfinesplitting)

Molecular clouds
- Molecular gas (H2, etc)
- 10-20 K
- Quite dense
  \[ n \sim 10^2 - 10^6 \text{ atoms/cm}^3 \]
- Very concentrated in disk
  \[ z_s \sim 80 \text{ pc} \]
- Traced by CO line
- This is were stars can form
Collisions of cosmic-ray electrons and positrons with photons in the radiation field

\[ e^{\pm}_{\text{CR}} \rightarrow \gamma_{\text{ISRF}} \rightarrow e^{\pm}_{\text{CR}} \gamma \]

Maximum final photon energy depends on CR Lorentz boost and target photon energy

\[ E_{\gamma} \sim 4 \frac{E_{e}^{2}}{m_{e}^{2}} E_{\text{ISRF}} \]

e.g.: 50 GeV CR hitting 1 eV photons → 20 GeV gamma-rays

\[ E_{\text{ISRF}} \sim 10^{-3} \ldots 1 \text{ eV} \]

**Characteristics**
- Featureless spectrum
- Traces interstellar radiation field
Interstellar radiation field (ISRF)

Since photons are emitted from a disk, the scale height of the ISRF is much higher than of the neutral and molecular gas (~kpc)

→ ICS emission extends much higher than pi0

Michael Hauser (Space Telescope Science Institute),
the COBE/DIRBE Science Team, and NASA

Strong+ 2000; Porter & Strong 2005; Moskalenko+ 2006; Porter+ 2008
Cosmic-ray sources

Sources of cosmic rays in the Galaxy

- Supernova remnants via shock acceleration
- Pulsars (mostly e+e-) via pulsar wind nebula
- Activity of central supermassive black hole?
- Dark matter annihilation or decay?
Cosmic-ray propagation in a nutshell

Lavalle & Salati 2012
Predictions from a CR propagation code

Hadronic production

- Traces gas
- Shows pion bump

Leptonic production

- Traces starlight
- Featureless spectrum

Predictions from the Galprop code
http://galprop.stanford.edu/

Ackermann+1

![Graph showing predictions from the Galprop code](image-url)
Fermi Bubbles

[Su+ 2010; Dobler+ 2010; Ackermann+ 2014]

Possible explanations

- Jets from the black hole
  [Guo & Mathews 2012, Yang+ 2012]

- Feedback from nuclear star formation
  [Crocker & Aharonian 2011, Carretti+ 2013; Lacki 2014]

- Shocks from accretion flows onto Sgr A*
  [Cheng+ 2011, Mou+ 2014]

- Spherical outflow from Sgr A*
  [Zubovas+ 2011]
Studying systematic uncertainties

Calore+14

ROI:
- "Inner Galaxy": $2^\circ \leq |b| \leq 20^\circ$ and $|\ell| \leq 20^\circ$
- We mask all point sources from the 2FGL

Components in the analysis:
- $\pi^0 +$Bremss
- ICS
- 2FGL
- Bubbles
- Isotropic
- Excess template

Simple standard template analysis:
minimize

$$-\ln \mathcal{L} = \sum_{ij} (\mu_{ij} - c_{ij} \ln \mu_{ij})$$

model

$$\mu_{ij} = \sum_{k=1}^{n_{\text{comp}}} T_i^{(k)} \theta_j^{(k)}$$

Fits independently in energy bins $\rightarrow$ Spectral information from Galprop models is neglected
Spectra from template fits

![Graph showing spectra from template fits.](image)

**Calore+ 2015**

**Systematics from Galactic plane control regions**

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Parameters</th>
<th>$\chi^2$/dof</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>broken PL</td>
<td>$\alpha_1 = 1.42^{+0.22}<em>{-0.31}$, $\alpha_2 = 2.63^{+0.13}</em>{-0.095}$, $E_{\text{break}} = 2.06^{+0.23}_{-0.17}$ GeV</td>
<td>1.06</td>
<td>0.47</td>
</tr>
<tr>
<td>DM $\chi\chi \rightarrow \bar{b}b$</td>
<td>$\langle \sigma v \rangle = 1.76^{+0.28}<em>{-0.27} \times 10^{-26}$ cm$^3$ s$^{-1}$, $m</em>\chi = 49^{+6.4}_{-5.4}$ GeV</td>
<td>1.08</td>
<td>0.43</td>
</tr>
<tr>
<td>DM $\chi\chi \rightarrow \bar{c}c$</td>
<td>$\langle \sigma v \rangle = 1.25^{+0.2}<em>{-0.18} \times 10^{-26}$ cm$^3$ s$^{-1}$, $m</em>\chi = 38.2^{+4.6}_{-3.9}$ GeV</td>
<td>1.07</td>
<td>0.44</td>
</tr>
<tr>
<td>PL with exp. cutoff</td>
<td>$E_{\text{cut}} = 2.53^{+1.1}<em>{-0.77}$ GeV, $\alpha = 0.945^{+0.36}</em>{-0.5}$</td>
<td>1.37</td>
<td>0.16</td>
</tr>
<tr>
<td>DM $\chi\chi \rightarrow \tau^+\tau^-$</td>
<td>$\langle \sigma v \rangle = 0.337^{+0.047}<em>{-0.048} \times 10^{-26}$ cm$^3$ s$^{-1}$, $m</em>\chi = 9.96^{+1.1}_{-0.91}$ GeV</td>
<td>1.52</td>
<td>0.065</td>
</tr>
</tbody>
</table>
Residuals

Residuals all along the Galactic disk (using above analysis): similar strength, different spectrum.
Spectral uniformity

ρ_{DM} = \frac{1}{r^{\gamma}(r_s + r)^{2-\gamma}} \quad \gamma \approx 1.26

Consistent with DM annihilation in all ten regions!

(based on Calore+ 2014)
Contributions to the bulge emission

Star formation in central molecular zone
- Fermi GeV excess: $3 \times 10^{37}$ erg/s (e.g. Calore+ 2015)
- $\sim 5\%$ of star formation in CMZ (e.g. Kruijssen+ 2014)
  $\rightarrow O(1000)$ SN per Myr
- $10^{51}$ erg/SN $\& 10^{-3}$ lepton efficiency (e.g. Lemoine-Goumard 2012)
  $\rightarrow 3 \times 10^{37}$ erg/s injected by SN in the CMZ!
- Significant challenges: spectrum and morphology

Potentially, past activity of the central SMBH
- Cooling compresses electron spectrum
  $\rightarrow$ electrons peak at $\sim 30$ GeV
  $\rightarrow$ ICS peaks around 1-3 GeV
- But: Cooling timescale $\ll$ Diffusion timescale
  $\sim 1$ Myr $\quad 0.1-1$ kpc/√Myr
- Diffusion kernel is Gaussian, not inv. Power-law
- Significant challenges: spectrum and morphology

Petrovic+14; Cholis+15
Millisecond pulsars

Characteristics

- “Recycled” neutron stars (spun-up by accretion of matter from star companion)
- $P < 30 \text{ ms}, B < 10^9 \text{ G}$, can be billions of years old $\tau_c = \frac{P}{2\dot{P}}$
- Emission mostly in radio, often in gamma-rays, occasionally in X-rays

[Abdo+ 2013, 2nd Fermi Pulsar catalog]
Bulge MSPs from disrupted globular clusters

Possible formation history
- Field millisecond pulsars in the bulge could have been created in globular clusters that were tidally disrupted
- This scenario was suggested to explain both normalization and shape of the excess emission

Abazajian 2010: ~1000 MSPs in the Galactic bulge?
An observational challenge

A signal composed of point sources would appear more “speckled” than a purely diffuse signal (like from DM annihilation)

Find **peaks** on top of **Poisson noise**

(Credit: Lee+ 2014)
Wavelet kernel

Formal definition of wavelet transform:

\[ \mathcal{F}_W[C](\Omega) \equiv \int d\Omega \mathcal{W}(\Omega - \Omega') C(\Omega') \]

\[ \mathcal{S}(\Omega) = \frac{\mathcal{F}_W[C](\Omega)}{\sqrt{\mathcal{F}_{W^2}[C](\Omega)}} \]

We look at rescaled wavelet map (essentially signal to noise):

On sufficiently smooth data sets, and for a large number of photons, this behaves approximately like a normal distribution → Smoothed Gaussian random field.

The Mexican Hat Wavelet Family

Gonzales-Nuevo+ 2006
Wavelet transform of inner Galaxy data

1) Count peaks in different sky regions and bin them according to significance
2) Run MCs for different bulge population configurations
3) Compare using a Poisson likelihood
4) Study all kinds of systematics (foreground sources, gas fluctuations etc)
Strong support for MSP hypothesis

Results

- Can potentially account for ~100% of the GeV excess with MSP population with reasonable cutoff luminosity

- “Resolved” component of modeled emission accounts for ~10% of the GeV excess, 90% are extrapolated based on reasonable (?) luminosity function

Bartels+ 15
Similar results by other groups

Standard PSC search for pulsar candidates in Fermi data

- suggests ~2.7 times as many bulge pulsars as disk pulsars
- However, ~5x larger cutoff luminosity

(withdrawn, see Bartels+ 2017)

Non-Poissonian NFW template preferred over Poissonian one

- suggests that excess emission is due to unresolved sources
- However, ~5x lower cutoff luminosity
Spectral analyses: Molecular gas?

Huang+ 2015 (using D3PO)

"Cloud-like" component

"Bubble-like" component

"DM-like" component

Pixel-by-pixel spectral decomposition:

\[
\frac{dN}{dE} = \alpha_1 \left\{ \frac{dN}{dE} \right\}_{\text{Bu}} + \alpha_2 \left\{ \frac{dN}{dE} \right\}_{\text{Cl}} + \alpha_3 \left\{ \frac{dN}{dE} \right\}_{\bar{b}\bar{b}} + \text{PSC}
\]

But: other spectra lead to different results, and the claim that the "GeV excess" is actually correlated with molecular gas

De Boer, Gebauer, et al. 2016, 2017
New gas models: X-shaped bulge?

Discovery of Gamma-Ray Emission from the X-shaped Bulge of the Milky Way

Oscar Macias*, 1 Chris Gordon, 2 Roland M. Crocker, 3 Brendan Coleman, 2 Dylan Paterson, 2 Shunsaku Horiuchi, 1 & Martin Pohl 4 5

An anomalous signal has been found in Fermi Gamma-Ray Large Area Telescope data covering the center of the Galaxy. Given its morphological and spectral characteristics, this ‘Galactic Center Excess’ is ascribable to self-annihilation of dark matter particles. We report on an analysis that exploits hydrodynamical modeling to register the position of interstellar gas associated with diffuse Galactic γ-ray emission. Our improved analysis reveals that the excess γ-rays are spatially correlated with both the X-shaped stellar over-density in the Galactic bulge and the nuclear stellar bulge. Given these correlations, we argue that the Galactic Center gamma-ray excess is not a dark matter phenomenon but rather associated with the stellar population of the bulge and the nuclear bulge.

Published in Nature Astronomy with weaker title and conclusions: “Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess”
General caveats of template analyses

NONE of the diffuse emission models gives an acceptable fit to the data

1. Even the best models are excluded by many hundred sigmas
   
   Goodness-of-fit tests typically return p-value < $10^{-300}$

2. Many excess along the Galactic disk
   
   Some of the excesses have same size as Galactic center excess (Calore+15)

3. "Bracketing uncertainties" by looking at many wrong models does not give the right answer
   
   But everybody is doing it.

So what?
An attempt to incorporate modeling systematics

SkyFACT (Sky Factorization with Adaptive Constrained Templates)

*Hybrid between template fitting & image reconstruction*

### Spatial template

\[
\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}
\]

### Spectral template

Poisson likelihood

\[
\ln \mathcal{L} = \ln \mathcal{L}_P + \ln \mathcal{L}_R
\]

Nuisance parameters

Regularization of nuisance parameters

\[
-2 \ln \mathcal{L}_R = \sum_k \lambda_k \mathcal{R}_X(\tau^{(k)}) + \lambda_k' \mathcal{R}_X(\nu^{(k)}) + \eta_k S_1(\tau^{(k)}) + \eta_k' S_2(\sigma^{(k)})
\]

\[
+ \sum_s \lambda_s \mathcal{R}_X(\sigma^{(s)}) + \lambda_s' \mathcal{R}_X(\nu^{(s)}) + \eta_s S_2(\sigma^{(s)}),
\]

### Notes

- Typically >10^5 parameters
- Problem typically convex → only one minimum

---

Storm, CW, Calore, 2017
Similar approach: D³PO

Selig+ 2014, 6.5 years of data, using D³PO algorithm
## Components in analysis runs

<table>
<thead>
<tr>
<th>Components</th>
<th>RUN1</th>
<th>RUN2</th>
<th>RUN3</th>
<th>RUN4</th>
<th>RUN5</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGRB</td>
<td>$\left[ \begin{array}{ccc} \infty &amp; 16 &amp; \infty \ 0 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} \infty &amp; 16 &amp; \infty \ 0 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} \infty &amp; 16 &amp; \infty \ 0 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} \infty &amp; 16 &amp; \infty \ 0 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} \infty &amp; 16 &amp; \infty \ 0 &amp; 0 &amp; 0 \end{array} \right]$</td>
</tr>
<tr>
<td>3FGL PSC</td>
<td>$\left[ \begin{array}{c} 0 \ 25 \ 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{c} 0 \ 25 \ 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{c} 0 \ 25 \ 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{c} 0 \ 25 \ 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{c} 0 \ 25 \ 0 \end{array} \right]$</td>
</tr>
<tr>
<td>Gas (0–19 kpc)</td>
<td>$\left[ \begin{array}{ccc} \infty &amp; 16 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 10 &amp; 16 &amp; 0 \ 0 &amp; 25 &amp; 0 \end{array} \right]$</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Gas ring I (0–3.5 kpc)</td>
<td>---</td>
<td>---</td>
<td>$\left[ \begin{array}{ccc} 10 &amp; 0 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 10 &amp; 0 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 10 &amp; 0 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
</tr>
<tr>
<td>Gas ring II (3.5–6.5 kpc)</td>
<td>---</td>
<td>---</td>
<td>$\left[ \begin{array}{ccc} 10 &amp; 16 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 10 &amp; 16 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 10 &amp; 16 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
</tr>
<tr>
<td>Gas ring III (6.5–19 kpc)</td>
<td>---</td>
<td>---</td>
<td>$\left[ \begin{array}{ccc} 4 &amp; 16 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 4 &amp; 16 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 4 &amp; 16 &amp; 0 \ 25 &amp; 0 &amp; 0 \end{array} \right]$</td>
</tr>
<tr>
<td>Extended sources</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>$\left[ \begin{array}{c} 0 \ 1 \ \infty \end{array} \right]$</td>
<td>$\left[ \begin{array}{c} 0 \ 1 \ \infty \end{array} \right]$</td>
</tr>
<tr>
<td>Inverse Compton</td>
<td>$\left[ \begin{array}{ccc} \infty &amp; 16 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 1 &amp; 16 &amp; 0 \ 100 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 1 &amp; 16 &amp; 0 \ 100 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 1 &amp; 16 &amp; 0 \ 100 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 1 &amp; 16 &amp; 0 \ 100 &amp; 0 &amp; 0 \end{array} \right]$</td>
</tr>
<tr>
<td>Fermi bubbles</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>$\left[ \begin{array}{ccc} 0 &amp; 400 &amp; \infty \ 4 &amp; 0 &amp; 0 \end{array} \right]$</td>
<td>$\left[ \begin{array}{ccc} 0 &amp; 400 &amp; \infty \ 4 &amp; 0 &amp; 0 \end{array} \right]$</td>
</tr>
<tr>
<td>511 keV template</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>$\left[ \begin{array}{c} 25 \ 0 \ \infty \end{array} \right]$</td>
</tr>
</tbody>
</table>

### Regularization hyper-parameters:

$\left[ \begin{array}{ccc} \lambda & \lambda' & \lambda'' \\ \eta & \eta' & \eta'' \end{array} \right]$

<table>
<thead>
<tr>
<th>Naive model parameters, $N_{\text{param}}$</th>
<th>RUN1</th>
<th>RUN2</th>
<th>RUN3</th>
<th>RUN4</th>
<th>RUN5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20253</td>
<td>78573</td>
<td>97838</td>
<td>104596</td>
<td>107639</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Naive DOF</th>
<th>RUN1</th>
<th>RUN2</th>
<th>RUN3</th>
<th>RUN4</th>
<th>RUN5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>708747</td>
<td>650427</td>
<td>631162</td>
<td>624404</td>
<td>621361</td>
</tr>
</tbody>
</table>

**Typical run time:** <50 core hours
Data vs diffuse emission components

Data

Data (0.34 - 228.65 GeV)

Gas ring I

Gas ring I (0.96 - 12.98 GeV)

Gas ring II

Gas ring II (0.96 - 12.98 GeV)

Gas ring III

Gas ring III (0.96 - 12.98 GeV)

Inverse Compton

Inverse Compton emission (0.96 - 12.98 GeV)
Residuals

Baseline model

+ Nuisance parameters

+ Multiple rings

+ Fermi bubbles
+ Extended sources

+ Galactic center excess

Nuisance parameters contain physics:

CR gradient, dark gas, extended sources, CMZ SF, ...
Dark gas corrections

- Fraction of gas neither emits CO (molecular gas) nor 21 cm line (atomic gas) → Not included in gas maps
- Correction factors are usually derived by considering dust reddening maps (assuming that dust is well mixed with ISM)

Dust corrections

Enhancement

Suppression

Acreo+ 2016
Modification of spectra

- Gas-related emission hardened w.r.t. naive Galprop predictions
- Indication for CR gradient (discussed before, e.g. Gaggero++, Aharonian++, Fermi coll++)
Extended source reconstruction “for free”

Extended sources (0.96 - 12.98 GeV)

Cyg X

PSC (0.96 - 12.98 GeV)
Inverse Compton emission
Low-latitude Fermi bubbles

- Low-latitude part of Fermi bubbles is not well studied
- However, a MSP component + bubble component (hard spectrum) decomposition is possible
- Suggests strongly enhanced HE emission in the inner few degrees
- **ICS from star formation?**
- However, *statistically not very significant*, hard to study

Ackermann+ 17
The morphology of the Fermi GeV excess

Red-clump giants
Cao+ 2013

Nuclear bulge

WISE template (X-shape)
Wright+ 2010, Ness & Lang 2016 (following Macias+ 2016)

Bartels+ 1711.04778 (results updated)

Simion+ 2017
VVV Survey
Residuals

\[ \rightarrow \text{add GCE} \rightarrow \]

0.34 GeV

1.24 GeV

4.57 GeV

16.85 GeV
Spectra are reasonably consistent with stacked MSP spectrum
Comparison with previous results
We find that a boxy + nuclear bulge model is preferred over (spherical) DM models with high statistical significance.

\[
\text{Fermi GeV excess emission is correlated with stellar mass in Galactic bulge.}
\]
Radio searches for MSPs in the bulge

**Radio searches:**
- Observations since 1980s (mostly Parkes, Arecibo), since 2002 GBT
- Today*: ~370 MSPs (~240 field, ~130 in globular clusters) [e.g., Stovall+13]
  - From surveys (e.g. Parkes HTRU)
  - From deep observations of globular clusters
  - *From radio follow-ups of Fermi LAT sources (~70 MSPs) [Ray+12]*
  - MSP searches at the Galactic center are very hard [Marcquart & Kanekar 15]

*As of Jan 2016

**Gamma-ray searches:**
- Discovery of numerous gamma-ray MSPs came as surprise, but now well established (Abdo+10)
- MSPs usually appear as unassociated sources in Fermi LAT data (spectral curvature, non-variable)
- Follow-up searches required to (1) discover associated radio pulsation and (2) fold ephemerides back into gamma rays
- At least one MSP found by blind search for gamma-ray pulsation alone

For a review see Grenier & Harding 15
We use MSP population in globular clusters as proxy

<table>
<thead>
<tr>
<th>Globular cluster</th>
<th>$\ell$ [deg]</th>
<th>$b$ [deg]</th>
<th>$d$ [kpc]</th>
<th>$L_\gamma$ [$10^{34}$ erg s$^{-1}$]</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{rad}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ter 5</td>
<td>3.8</td>
<td>1.7</td>
<td>5.5</td>
<td>26.5 ± 9.0</td>
<td>25</td>
<td>82 ± 16</td>
</tr>
<tr>
<td>47 Tuc</td>
<td>305.9</td>
<td>-44.9</td>
<td>4.0</td>
<td>5.1 ± 1.1</td>
<td>14</td>
<td>37 ± 10</td>
</tr>
<tr>
<td>M 28</td>
<td>7.8</td>
<td>-5.6</td>
<td>5.7</td>
<td>6.4 ± 2.0</td>
<td>9</td>
<td>63 ± 21</td>
</tr>
<tr>
<td>NGC 6440</td>
<td>7.7</td>
<td>3.8</td>
<td>8.5</td>
<td>35.4 ± 8.0</td>
<td>6</td>
<td>48 ± 21</td>
</tr>
<tr>
<td>NGC 6752</td>
<td>336.5</td>
<td>-25.6</td>
<td>4.4</td>
<td>1.3 ± 0.7</td>
<td>5</td>
<td>21 ± 10</td>
</tr>
<tr>
<td>M 5</td>
<td>3.9</td>
<td>46.8</td>
<td>7.8</td>
<td>2.4 ± 0.5</td>
<td>5</td>
<td>13 ± 6</td>
</tr>
<tr>
<td>Stacked</td>
<td></td>
<td></td>
<td></td>
<td>77.1 ± 12.3</td>
<td>64</td>
<td>264 ± 37</td>
</tr>
</tbody>
</table>

Simple rescaling to get number of radio bright ($S_{1400} > 10 \mu$Jy) MSPs in bulge

\[
\frac{\langle L_\gamma^{\text{bulge}} \rangle}{\langle N_{rb}^{\text{bulge}} \rangle} \approx \frac{L_\gamma^{\text{stacked}}}{N_{rb}^{\text{stacked}}} = (1.0 \pm 0.3) \times 10^{34} \text{ erg s}^{-1}
\]

\[
L_\gamma^{\text{bulge}} = (2.7 \pm 0.2) \times 10^{37} \text{ erg s}^{-1}
\]

\[
N_{rb}^{\text{bulge}} = (2.7 \pm 0.9) \times 10^3
\]
Modeling the radio properties of bulge MSPs

**Modeled pulsars in x-y plane**
- Predict enhancement of MSP density by several orders of magnitude in the Galactic bulge w.r.t disk

**Surface density of radio-bright bulge MSPs**
- Varies from ~100 deg$^{-2}$ to ~1 deg$^{-2}$, depending on the distance from the GC.

Comparison with globular clusters suggests

\[ N_{rb}^{\text{bulge}} = (2.7 \pm 0.9) \times 10^3 \]
Prospects for radio searches for bulge MSPs

Radio detection prospects (Calore+ ’15)
(Bulge population is just below sensitivity of Parkes HTRU mid-lat survey)

- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT mid-lat survey ~300h: ~30 bulge MSPs

Good news! Our plans for the near future

- We teamed up with MeerKAT TRAPUM → hopefully dedicated survey in early 2019 (~100h)
Connections between 511 keV signal and GeV excess?

- LMXB are progenitors of MSPs
- LMXB (jets) → 511 keV signal & MSPs (curvature radiation) → GeV emission
- Proof-of-concept in context of specific population synthesis scenario with UCXB

Bartels, Calore, Storm, CW 2018
Star formation in the inner Galaxy

Star formation in CMZ

- For the last few mio years, can be observationally well constrained (within factor ~two)
- Potentially asymmetry in CR injection
- To be confronted with gamma-ray observations

Kruijssen+ 2014
Conclusions

- Gamma ray emission from the Galactic bulge
  - 511 keV line, GeV excess (+ other components?), ridge & PeVatron
  - Possible contributions from compact sources (jets, curvature radiation), star formation (stellar winds, SNRs, radioactive elements), Sgr A* (accretion)

- The Fermi Galactic center/bulge GeV excess
  - Remains hard difficult to study (since bright disk along line-of-sight)
  - Relative consensus about properties, but other interpretations have been proposed (molecular clouds, X-shaped emission)
  - SkyFACT approach: Hybrid of template fit and image reconstruction
    → GeV excess traces stellar mass; asymmetric high-energy component at bottom of Fermi bubbles; nuisance parameters consistent with known shortcomings of a-priori Galactic diffuse emission models

- Some future directions
  - Bulge MSP searches with MeerKAT promising, hopefully happen in 2019!
  - Finding corroborating evidence for 511 keV – GeV excess connection
  - Understanding role of star formation in CMZ and nuclear star cluster

Thank you!
Backup slides
Wavelet fluctuation analysis supports MSPs

Search for non-Poissonian noise after background subtraction:

\[
\text{Data} - \text{Background} = \text{Residuals}
\]

Potential fake “peaks"

Similar to Lee+15 (PRL)

Wavelet fluctuation analysis (Bartels+15 PRL):

\[
\text{Data} \times \text{Kernel} = \text{Wavelet transform}
\]

Wavelet approach is robust and simple

- Straightforward background subtraction can be very powerful, but you have to get backgrounds right
- No background modeling required for wavelet analysis (separation of scales!!!)
- Build-in source localization
- Extremely fast (allowed careful Monte Carlo tests of the results)
Gas fluctuations etc unlikely to cause signal

Small scale feature in gas

- Even assuming that all diffuse emission comes from gas, we predict a non-detection (Schlegel+97 with ~0.1 deg resolution; Planck optical depth map)

Check out extensive appendix of Bartels+16 for more details.
Data and (some of the) fit components

Data (0.34 - 228.65 GeV)

Gas ring I

Gas ring II

Gas ring III

Inverse Compton

19 April 2018

C. Weniger
Repeat fit in each energy bin → Energy spectra
Fits have 5 parameters (x24 energy bins)

Calore, Cholis, CW 2014
Relevant gamma-ray source classes

**Extragalactic sources**
- Unlikely (at >5sigma level) that extragalactic source density is peaked sufficiently towards inner Galaxy

**Supernova remnants and PWN**
- Very rare at |b|>2 deg
- Not peaked towards inner Galaxy (usually more closeby)
- Usually detected at other frequencies first

**Young pulsars and MSPs**
- Peak in selected energy range (by design)
- Detected (radio) pulsars do not peak towards the inner galaxy

**Globular clusters**
- Emission will be approximately the combined emission of many pulsars

**Unassociated sources**
- At higher latitudes, large fraction is expected to be young and millisecond pulsars

We expect that wavelet signal is dominated by whatever source class (except EG) is responsible for the majority of the unassociated sources in the inner galaxy. Spherical distribution more plausible for MSPs than for young pulsars → MSPs the (by far?) most likely interpretation
**Residuals ~2 GeV**

- Regular template fit
- Templates with 10%-30% uncertainty
- + GeV excess
Residuals ~ 6 GeV

Regular template fit

Templates with 10%-30% uncertainty

+ GeV excess
Longitude profile

- Bubble component is clearly displaced from center
- Shape quite different from contracted NFW, but hard to determine within disk
Comparison with dwarf limits

Future possible improvements

• More data: Up to 15 years (until 2023)
• 3x more dwarfs
• → would lead to factor ~4 improvement of limits
• → strong enough to probe GC excess even for pessimistic DM profiles