A Galaxy and its Dark Matter Profile: a Story of Enhanced Annihilations

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with Takahiro Yamamoto & Kuver Sinha
arXiv:1701.00067
Milky Way Dark Matter

- **From observations**: compilation of rotation curve measurements, plus baryonic models indicates dark matter *inside the solar circle*.
Milky Way Dark Matter

- **From simulations:** State-of-the-art N-body + hydrodynamics simulations

Gammaldi et al., PRD 94 (2016)
A Dark Matter Spike?

- As SMBH forms, it dominates the potential in the inner galaxy.
- Dark matter particles are dragged into the deepening potential well.
- If the growth of the SMBH is slow enough, conservation of dark matter angular momentum and mass yields a “spike”.

Gondolo & Silk, PRL 83 1719 (1999)
Profile Form

- Roughly:

\[ \rho(r) = \begin{cases} 
\rho(r_{\text{core}}) & 10r_{\text{Sch.}} < r \leq r_{\text{core}} \\
\rho_0 (r/r_{sp})^{-\gamma_{sp}} & r_{\text{core}} < r \leq r_{sp} \\
\rho_0 (r/r_{sp})^{-\gamma_c} & r_{sp} < r 
\end{cases} \]

- Key features:
  - looks like initial (uncontracted) profile at large radii
  - density saturates at small radii:
    \[ \rho_{\text{sat}} = \frac{m_\chi}{\langle \sigma v \rangle \tau_{\text{spike}}} \]
  - “spike” between \( r_{\text{core}} \) and \( r_{sp} \)
Spike Details

• Roughly:
  \[ \rho(r) = \begin{cases} 
  \rho(r_{\text{core}}) & 10r_{\text{Sch.}} < r \leq r_{\text{core}} \\
  \rho_0 \left( \frac{r}{r_{sp}} \right)^{-\gamma_{sp}} & r_{\text{core}} < r \leq r_{sp} \\
  \rho_0 \left( \frac{r}{r_{sp}} \right)^{-\gamma_c} & r_{sp} < r 
  \end{cases} \]

• \( r_{sp} \) is related to sphere of influence of BH (~0.4 pc)

• \( r_{\text{core}} \) is the radius at which \( \rho(r) = \rho_{\text{sat}} \).
  
  • \( \rho(r_{\text{core}}) = \frac{m_\chi}{\langle \sigma v \rangle \tau_{\text{spike}}} \) and \( \langle \sigma v \rangle = c_0 + c_1 \left( \frac{v^2}{c^2} \right) = c_0 + c_1 \left( \frac{r_{\text{Sch.}}}{2r} \right) \)

• Note \( \langle \sigma v \rangle(r) \)

• For collisionless DM and adiabatic growth of the BH,
  \[ \gamma_{sp} = \frac{9 - 2\gamma_c}{4 - \gamma_c} \]
Dark Matter Spike

\[ \rho(r) = \rho_{\text{sat}} \]

\[ \rho(r) \propto r^{-\gamma_{sp}} \]

\[ \rho(r) \propto r^{-\gamma_C} \]

- \( m_\chi = 100 \text{ GeV} \)
- \( c_0 = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \)
- \( c_1 = 3 \times 10^{-30} \text{ cm}^3\text{s}^{-1} \)
- \( \gamma_C = 1.0 \)

\( r > r_{\text{core}} \)

\( r_{sp} \)

\( 10^{-5} \text{ } \text{\text{pc}} \)

\( 10^5 \text{ } \text{\text{pc}} \)
What is not included?

e.g. Fields, Shapiro, & Shelton, PRL 113 (2014)

• Gravitational interactions between DM and baryons

🌟 scattering of DM on stars → “heating” of DM

• invisible compact objects

• dramatic dynamical changes (mergers, etc.)

• DM self-interactions

• If growth is not adiabatic (BH appears suddenly)
  • even if seed is large and then growth is adiabatic

• BH off-center

⇒ all “flatten” the spike
Spike Details

• Rough form: 
\[ \rho(r) = \begin{cases} 
\rho(r_{\text{core}}) & 10r_{\text{Sch.}} < r \leq r_{\text{core}} \\
\rho_0 \left( \frac{r}{r_{\text{sp}}^{\gamma}} \right)^{-\gamma_{\text{sp}}} & r_{\text{core}} < r \leq r_{\text{sp}} \\
\rho_0 \left( \frac{r}{r_{\text{sp}}^{\gamma}} \right)^{-\gamma_{\text{c}}} & r_{\text{sp}} < r, 
\end{cases} \]

• Stars near the BH have much larger KE than DM, so tend to “heat up” the DM, which flattens the spike:

- \[ \rho(r, t) \approx \rho(r, 0) e^{-\tau/2} \quad \text{with} \quad \tau = \tau_{\text{spike}}/t_{\text{heat}} \]  

- \[ t_{\text{heat}} \approx \mathcal{O}(1) \text{ Gyr} \]  
  Bertone & Merritt (2005); Vasieliev & Zelnikov (2008)

- \[ t_{\text{heat}} \propto m^2_{\text{BH}} \sigma^{-3} \tilde{m}_{*}^{-1} [\ln(0.4 N_{*})]^{-1} \]  

• another way of thinking of this is that it changes $r_{\text{sp}}$

\[ r_{\text{sp}}(t) = r_{\text{sp}}(0) \times \exp \left( \frac{-\tau}{2(\gamma_{\text{sp}} - \gamma_{\text{c}})} \right) \]

“depleted”

“idealized”
Dark Matter Spike

\[ \rho(r) = \rho_{\text{sat}} \]

\[ \rho(r) \propto r^{-\gamma_{sp}} \]

\[ m_x = 100 \text{ GeV} \]
\[ c_0 = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]
\[ c_1 = 3 \times 10^{-30} \text{ cm}^3\text{s}^{-1} \]
\[ \gamma_c = 1.0 \]
Dark Matter Spike

\begin{align*}
\rho(r) &= \rho_{sat} \\
\rho(r) &\propto r^{-\gamma_{sp}} \\
\rho(r) &\propto r^{-\gamma_C}
\end{align*}

- $m_x = 100 \text{ GeV}$
- $c_0 = 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$
- $c_1 = 3 \times 10^{-30} \text{ cm}^3 \text{s}^{-1}$
- $\gamma_C = 1.0$

$r_{\text{core}}$, $r_{\text{sp}}$
Spike Radius

\[
\tau = 0 \text{ (idealized)}
\]

\[
\tau = 4 \quad \text{Vasiliev & Zelnikov, PRD 78 (2008)}
\]

\[
\tau = 10 \quad \text{Bertone & Merritt, PRD 72 (2005)}
\]
DM Annihilations in the Spike

\[ \frac{d\Phi_\gamma}{d\Omega \, dE} = \frac{1}{2 \, 4\pi} \frac{r_\odot}{M_{DM}} \left( \frac{\rho_\odot}{\rho_{DM}} \right)^2 \int_{\text{l.o.s.}} ds \frac{d\sigma}{dE} \left( \frac{\rho(r(s, \theta))}{\rho_\odot} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN_f}{dE} \]

\[ r(s, \theta) = \left( r_\odot^2 + s^2 - 2r_\odot s \cos \theta \right)^{1/2} \]

- Flux will contribute to GC point source
- Fermi-LAT GC point source is 3FGL source J1745.6-2859c (Sgr A*)
  - Integrated flux from 1 to 100 GeV is
    \[ \Phi_{\text{Fermi}} = 2.18 \times 10^{-8} \text{ photons/cm}^2\text{s} \]
  - Note: we take \( \int_{1 \text{ GeV}}^{100 \text{ GeV}} \frac{dN_f}{dE} \, dE = 1 \). Flux scales with integrated photon count.
  - Subnote: The spectrum may be important: Fermi’s PSF is highly energy-dependent below 10 GeV! This is not included.
• If there is depletion, it seems that you’re out of luck unless $\gamma_c$ is fairly large.

• Above holds for any DM model (final state).

• Velocity-dependence is minimal unless $c_1 \gg c_0$. 
Observational Reach

\[ c_0 = 3 \times 10^{-26} \text{ and } c_1 = 10^{-30} \text{ cm}^3\text{s}^{-1} \]

\[ \log_{10}(\Phi/\Phi_{\text{Fermi}}) \]

\[ m_\chi \text{ [GeV]} \]

\[ \gamma_C = 1.3 \]
\[ \gamma_C = 1.4 \]
\[ \gamma_C = 1.5 \]
Observational Reach

Depleted Spike

Idealized Spike

Factor of \(~200\) difference in flux depending on if ideal or depleted (!)
**An Interesting Example**

Fukushima, Kelso, Kumar, Sandick, & Yamamoto, (2014)

- singlet DM coupled to SM fermions via charged scalars
  - \( \rightarrow \text{bino DM} \)
  - \( \rightarrow \text{b quarks} \)
  - \( \rightarrow \text{b squarks} \)

- s-wave annihilation is chirality suppressed \( \sim \frac{m_f^2}{m_\chi^2} \)
- p-wave is velocity-suppressed \((v^2 \approx 0.1)\) at freeze-out
- Solution: L-R mixing eliminates chirality-suppression

\[
\mathcal{L}_{\text{int}} = \lambda_L e^{i\phi/2} \tilde{\chi} f_L + \lambda_R e^{-i\phi/2} \tilde{\chi} f_R + \text{c.c.}
\]

\[
\left( \begin{array}{c} f_1 \\ f_2 \end{array} \right) = \left( \begin{array}{cc} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{array} \right) \left( \begin{array}{c} \tilde{f}_L \\ \tilde{f}_R \end{array} \right)
\]

- Four mass parameters: \( m_\chi, m_{\tilde{f}_1}, m_{\tilde{f}_2}, m_f \)
- Yukawas, \(|\lambda_{L,R}|\), CPV phase, \( \phi \), scalar mixing angle, \( \alpha \)
An Interesting Example

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- \( \rightarrow \) b quarks \( \rightarrow \) b squarks

- s-wave annihilation is chirality suppressed \( \sim \frac{m_f^2}{m_{\chi}^2} \)

- p-wave is velocity-suppressed \( (v^2 \approx 0.1) \) at freeze-out

- Solution: L-R mixing eliminates chirality-suppression

\[
\mathcal{L}_{\text{int}} = \lambda_L e^{i\phi/2} \bar{f}_L^* \chi P_L f + \lambda_R e^{-i\phi/2} \bar{f}_R^* \chi P_R f + \text{c.c}
\]

- Four mass parameters: \( m_\chi, m_{\tilde{f}_1}, m_{\tilde{f}_2}, m_f \)

- Yukawas, \( |\lambda_{L,R}| \), CPV phase, \( \phi \), scalar mixing angle, \( \alpha \)
An Interesting Example

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• singlet DM coupled to SM fermions via charged scalars
  \[ \rightarrow bino \text{ DM} \quad \rightarrow b \text{ quarks} \quad \rightarrow b \text{ squarks} \]

• DM abundance & lepton dipole moments (light sleptons), PRD (2014)

• Direct DM det. (light squark mediators) w/ Kelso, Kumar, & Stengel, PRD (2015)

• Direct DM det. (anapole moment) w/ Sinha & Teng, JHEP (2016)

• Indirect DM det. (dwarf galaxies) w/ Kumar, Teng, & Yamamoto, PRD (2016)

• LHC searches for nearly deg. charged mediator w/ Dutta et al. 1706.05339

• Direct DM det. in coannihilation regime w/ Davidson, Kelso, Kumar, & Stengel 1707.02460

See Also:

• Four mass parameters: \( m_\chi, m_{\tilde{f}_1}, m_{\tilde{f}_2}, m_f \)

• Yukawas, \( \lambda_{L,R} \), CPV phase, \( \phi \), scalar mixing angle, \( \alpha \)
An Interesting Example

Idealized Spike

$\Phi = \frac{\Phi_{Fermi}}{m_\chi = 100, \ m_{\tilde{b}} = 105, \ and \ m_{\tilde{\nu}} = 1000 \text{ GeV} \ and \ \gamma_C = 1.0}$

Flux exceeds GC point source flux
An Interesting Example

Idealized Spike

Depleted Spike

$m_\chi = 100$, $m_{\tilde{b}_1} = 105$, and $m_{\tilde{b}_2} = 1000$ GeV and $\gamma_C = 1.0$

$\Phi_{Fermi}$

$\Phi$

$log_{10}(c_0 [cm^3 s^{-1}])$

$log_{10}(c_0 [cm^3 s^{-1}])$
Mini Summary

• Constraints vary dramatically with the properties of the spike.
  • Depleted or idealized?
  • If depleted, how much?
  • Typical timescale for heating via scattering with stars?

Change Perspective

• What if we understand something about the dark matter?
Galactic Center $\gamma$-ray Excess

Brandon Anderson, Stockholm University | 5th Fermi Symposium

$L_3(D|\mu, \{\check{t}\}) = Y$ targets

$L_2(D|\mu, \check{t}) = \gamma$ targets

$\gamma$-ray Excess

Data Set & Technique


*see talk from Alex on Wednesday, also poster 2.01

Fermi-LAT Collaboration
Galactic Center $\gamma$-ray Excess

- The energy spectrum, morphology, and annihilation rate are all consistent with the expectations for DM annihilation, or at least suggest an underlying astrophysical component on top of a potential DM component. This is also consistent with the presence of similar fractional excesses along the Galactic plane where no DM signal is expected.

The spectrum and morphology of the excess are not obviously consistent with the expectations for 35 GeV WIMP $(\chi\chi \rightarrow b\bar{b})$.
Assuming a DM Model

Depleted Spike

• GC excess fit by

\[ \chi \chi \rightarrow \bar{b}b \]
\[ m_\chi = 49 \text{ GeV} \]
\[ c_0 = 1.76 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]

Calore, Cholis, & Weniger, JCAP 1503 (2015)

• Only a conflict if \( \gamma_C \) is large (even for LARGE \( \gamma_{sp} \))

• Contours are ~vertical!

➡ Heating timescale is critical…

\[ m_\chi = 49 \text{ GeV, } c_0 = 1.76 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \text{ and } c_1 = 10^{-30} \text{ cm}^3\text{s}^{-1} \]

\[ \frac{\Phi}{\Phi_{Fermi}} \]
Summary

• Is/was there a spike? **Maybe.**
• Depleted or not? **Can’t tell**
  • If spike is not depleted, pretty strong constraints can be placed on DM models, tension with dark matter explanation of GC excess (see also Fields Shapiro, & Shelton PRL 2014).
  • If spike is depleted, it may not be a “spike” at all anymore, and it really doesn’t help us say much about dark matter.

• Bottom line: Modeling of astrophysics near the Galactic Center is complicated, but really important.

• Future: Use dark matter to learn about our galaxy (?)