The 511 keV Excess and Primordial Black Holes in our Solar System

Celeste Keith
University of Chicago
Background

- INTEGRAL has detected an excess of 511 keV photons in the inner Milky Way
  - $[1.07 \pm 0.03] \times 10^{-3}$ photons cm$^{-2}$ s$^{-1}$
  - Translates to $\sim 2 \times 10^{43}$ positrons per second

- Proposed explanations
  - Type 1a supernovae
  - Gamma ray bursts
  - Microquasars
  - Low mass X ray binaries
  - Neutron star mergers
  - Annihilating, decaying, or upscattering dark matter
  - Other exotic scenarios
Our Proposal

• Excess positrons produced through Hawking evaporation of a population of primordial black holes
• We can explain this flux of positrons with these black holes, in a mass range $[1 - 4] \times 10^{16}$ grams
• Utilize constraints from INTEGRAL, COMPTEL and Voyager 1

Outline

• Identify the constraints from INTEGRAL, COMPTEL, and Voyager
• Calculate gamma ray signal from black holes
• Find the allowed parameter space
• Derive number density of black holes based on the allowed parameter space
• Explore possibility of the detection of this signal
Hawking Evaporation

• Black holes radiate all particle species lighter than or comparable to their temperature
• Radiation causes the black holes to evaporate at a rate
• For $m_{BH} > 5 \times 10^{14} \text{ g}$, BH has a lifetime greater than age of universe

\[
T_{BH} = \frac{M_{Pl}^2}{8\pi m_{BH}} \approx 1.05 \text{ MeV} \left( \frac{10^{16} \text{ g}}{m_{BH}} \right)
\]

\[
\frac{dm_{BH}}{dt} = -\frac{G g_{*,H}(m_{BH})M_{Pl}^2}{30720\pi m_{BH}^2} \approx -8.2 \times 10^{-7} \text{ g/s} \left( \frac{g_{*,H}}{10.92} \right) \left( \frac{10^{16} \text{ g}}{m_{BH}} \right)^2
\]
Hawking Evaporation

• The spectrum of Hawking radiation from BHs looks like:

\[
\frac{dN}{dE}(m_{\text{BH}}, E) = \frac{1}{2\pi^2} \frac{E^2 \sigma(m_{\text{BH}}, E)}{e^{E/T} \pm 1}
\]

• Absorption cross section \( \sigma \) depends on the spin of the particle radiated
Identifying 511 keV Parameter Space

- Calculate the flux and spatial distribution of the injected positrons and compare to 511 keV data
- Not every positron emitted leads to a 511 keV photon
  - 0.55 photons per positron

\[
F_{511}(\Delta \Omega) = \frac{L_{511}(m_{BH})}{4\pi} \int_{\Delta \Omega} \int_{\text{los}} n_{BH}(l, \Omega) \, dl \, d\Omega, \\
\approx \frac{0.55 L_{e^+}(m_{BH}) f_{BH}}{4\pi m_{BH}} \int_{\Delta \Omega} \int_{\text{los}} \rho_{DM}(l, \Omega) \, dl \, d\Omega
\]

\[e^- + e^+ \rightarrow \gamma + \gamma\]

OR

- 2 - 511 keV photons
- 3 photons \(E_\gamma < 511\) keV
- 2 photons \(E_\gamma = 511\) keV
Identifying 511 keV Parameter Space

• Adopt gNFW profile
• Local DM density is 0.4 GeV cm$^{-3}$

$$\rho_{DM} = \frac{\rho_0}{(r/R_s)^\gamma [1 + (r/R_s)]^{3-\gamma}}$$
\( \gamma = 1 \)  

\( \gamma = 1.6 \)  

\( \gamma = 1.8 \)  

\( \gamma = 2 \)  

Counts cm\(^{-2}\) s\(^{-1}\) deg\(^{-1}\)

Galactic latitude

Black holes + Disk
Disk only
511 keV INTEGRAL data

Bouchet et al, arXiv:1007.4753
Best fit to 511 keV data

- Our best fit of gamma corresponds to $2.2 \pm 0.6$ (at 2$\sigma$)
- We choose to focus on the lower end of this range
- Account for inflight annihilation and final state radiation

\[
F_\gamma(\Delta\Omega) = \frac{dN_\gamma^{\text{tot}}}{dE_\gamma} \frac{1}{4\pi} \int_{\Delta\Omega} \int_{los} n_{BH}(l, \Omega) \, dl \, d\Omega,
\]

\[
= \frac{dN_\gamma^{\text{tot}}}{dE_\gamma} \frac{f_{BH}}{4\pi m_{BH}} \int_{\Delta\Omega} \int_{los} \rho_{DM}(l, \Omega) \, dl \, d\Omega
\]
Final Constraints

- Vary $f_{BH}$ to minimize $\chi^2$ to find best fit to INTEGRAL data
  - For COMPTEL data, simply do not exceed COMPTEL error bars with choice of $f_{BH}$
  - Combine all energy bin constraints into strongest constraints over INTEGRAL and COMPTEL
Final Results

- $m_{BH} \sim [1 - 4] \times 10^{16}$ grams
- $\gamma \sim 1.6 - 1.8$
  - 2 is ruled out by INTEGRAL/COMPTEL/Voyager
  - Lower than 1.6 is disfavored by 511 keV signal
- $f_{DM} \sim 0.0001 - 0.004$
- Also apply constraints from Voyager 1 (Boudaud and Cirelli, arXiv: 1807.03075)
Implications of This Result

- Local DM density: 0.4 GeV/cm$^3$
- Closest black hole $\sim 10$ AU away
- Solar System has several hundred BHs in it at any moment
- Over 10 years, closest approach several AU

\[
n_{\text{local}}^{\text{BH}} = \frac{f_{\text{BH}} \rho_{\text{DM}}^{\text{local}}}{m_{\text{BH}}} \\
\simeq 1.0 \times 10^{12} \text{ pc}^{-3} \times \left( \frac{f_{\text{BH}}}{10^{-3}} \right) \left( \frac{2 \times 10^{16} \text{ g}}{m_{\text{BH}}} \right) \\
\simeq 1.2 \times 10^{-4} \text{ AU}^{-3} \times \left( \frac{f_{\text{BH}}}{10^{-3}} \right) \left( \frac{2 \times 10^{16} \text{ g}}{m_{\text{BH}}} \right)
\]
Prospects for Detection

• Future telescopes (AMEGO & e-Astrogam) can detect these?
  • To have enough flux to be detected, BH would have to be ~1AU away
  • High proper motion would complicate detection

• Possibly can use these telescopes to detect and characterize the diffuse gamma-ray emission generated by BHs in the Milky Way’s inner halo
Conclusion

• If a population of primordial black holes exist, they can explain the 511 keV excess from the GC within:
  • \( m_{BH} \sim [1 - 4] \times 10^{16} \) grams
  • \( f_{BH} \sim 0.0001 - 0.004 \)
  • \( n_{BH}^{local} \sim 10^{12} \text{ pc}^{-3} \)
  • \( \gamma \sim 1.6 - 1.8 \)
  • Difficulty testing due to the size and proper motion of local BHs
  • AMEGO and e-ASTROGAM are expected to be able to test this scenario