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 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  - 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

Frampton and Kephart, arXiv:0503267, Bambi et al, arXiv:0801.2786, Cai et al, arXiv:2007.11804

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 $m_{BH} > 5 \times 10^{14}$ g, BH has a lifetime greater than age of universe

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

$$\frac{dm_{\mathrm{BH}}}{dt} = -\frac{\mathcal{G} g_{*,H}(m_{\mathrm{BH}}) M_{\mathrm{Pl}}^2}{30720\pi m_{\mathrm{BH}}^2}$$

$$\approx -8.2 \times 10^{-7}\,\mathrm{g/s}\left(\frac{g_{*,H}}{10.92}\right)\left(\frac{10^{16}\mathrm{g}}{m_{\mathrm{BH}}}\right)^2$$

Hawking Evaporation

- The spectrum of Hawking radiation from BHs looks like:

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

- Absorption cross section σ depends on the spin of the particle radiated

Identifying 511 keV Parameter Space

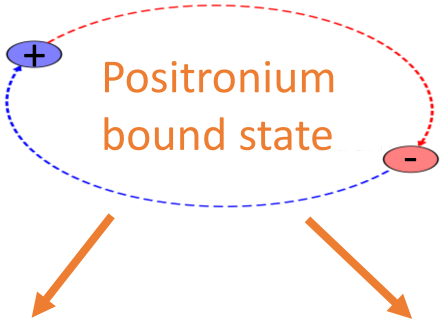
- Calculate the flux and spatial distribution of the injected positrons and compare to 511 keV data
- Not every positron emitted leads to a 511 keV photon
  - 0.55 photons per positron

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

$e^- + e^+ \rightarrow \gamma + \gamma$

2 - 511 keV photons

OR



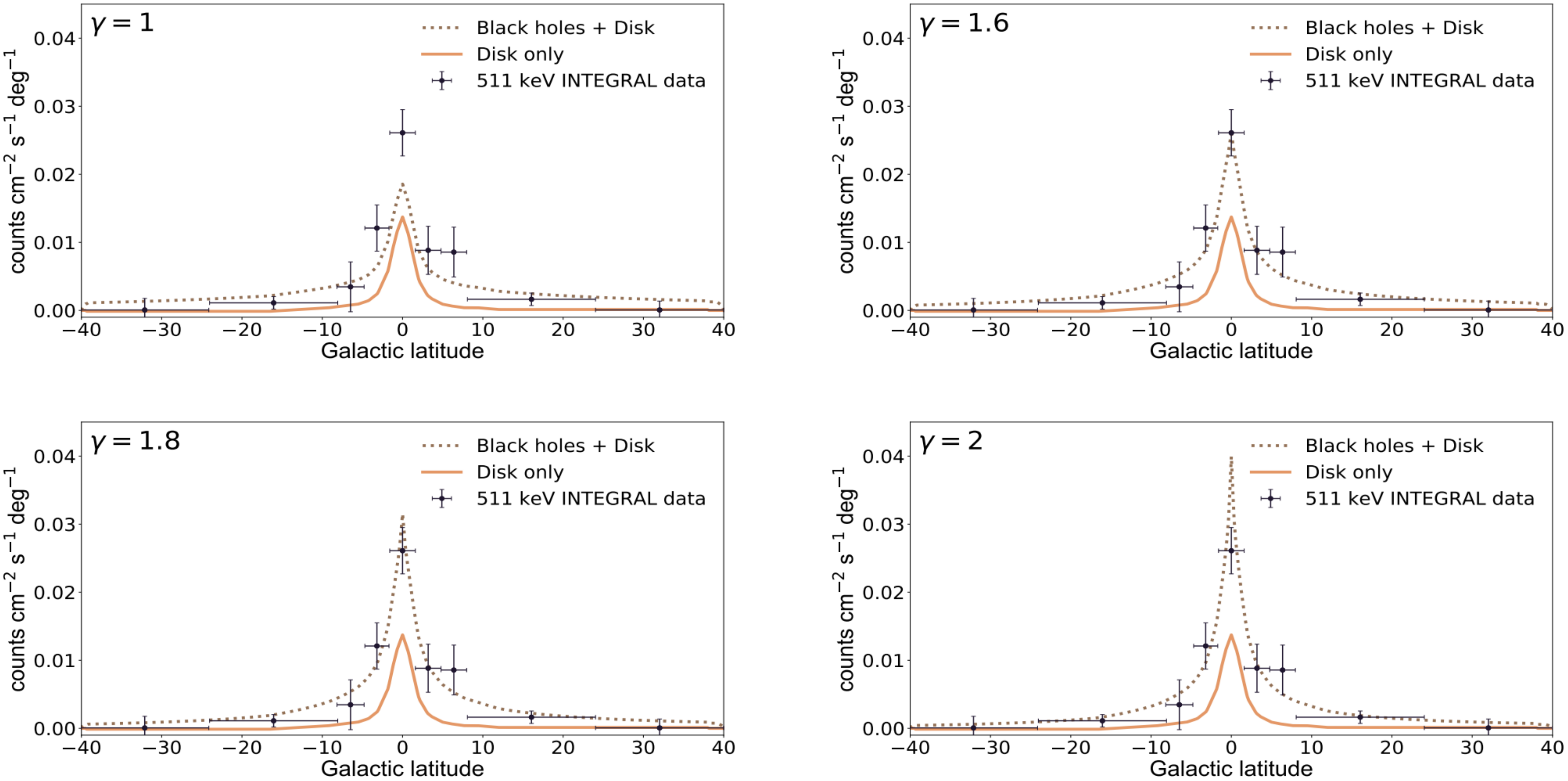
3 photons
$E_\gamma < 511$ keV

2 photons
$E_\gamma = 511$ keV

Identifying 511 keV Parameter Space

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

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

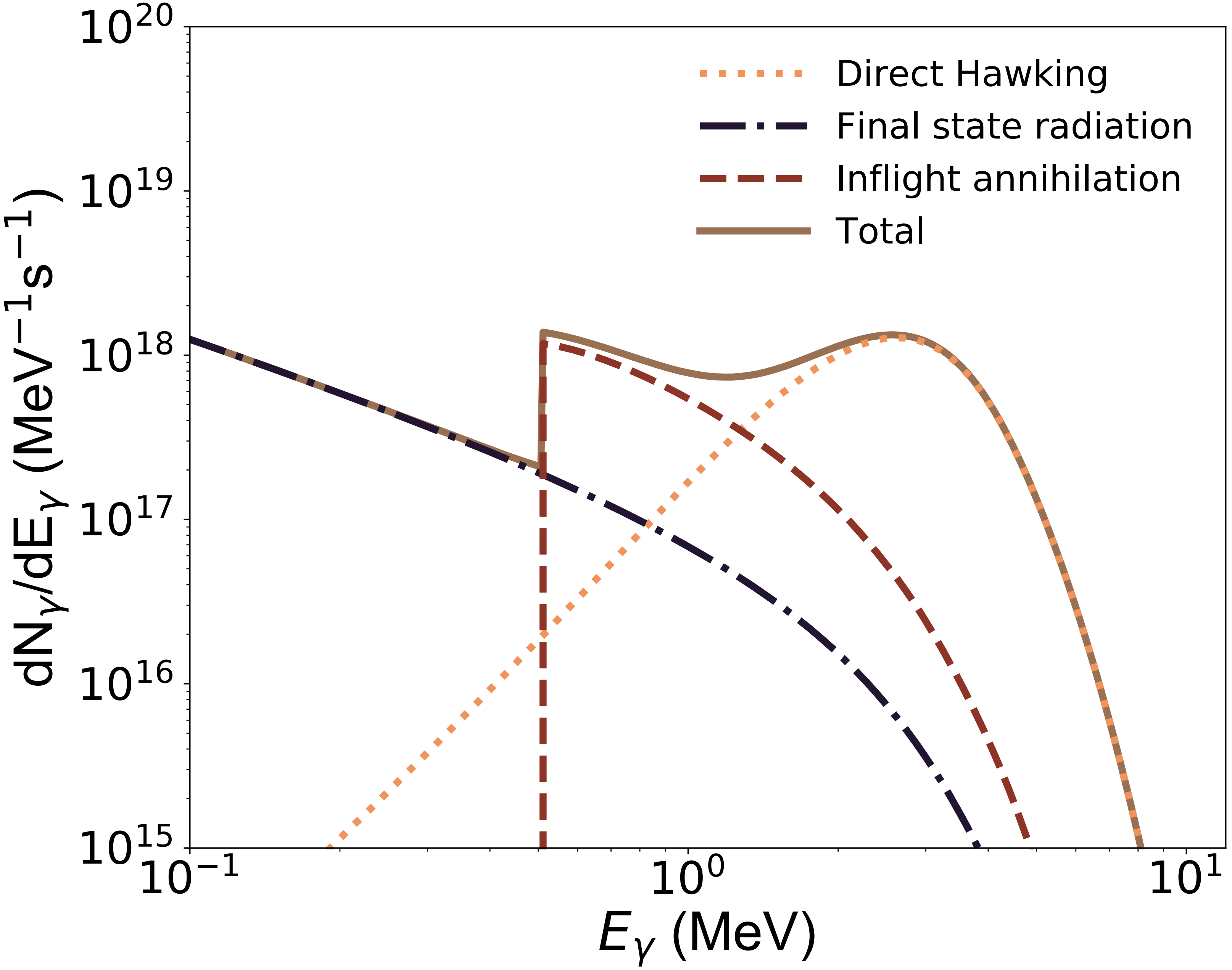


Bouchet et al, arXiv:1007.4753

Best fit to 511 keV data

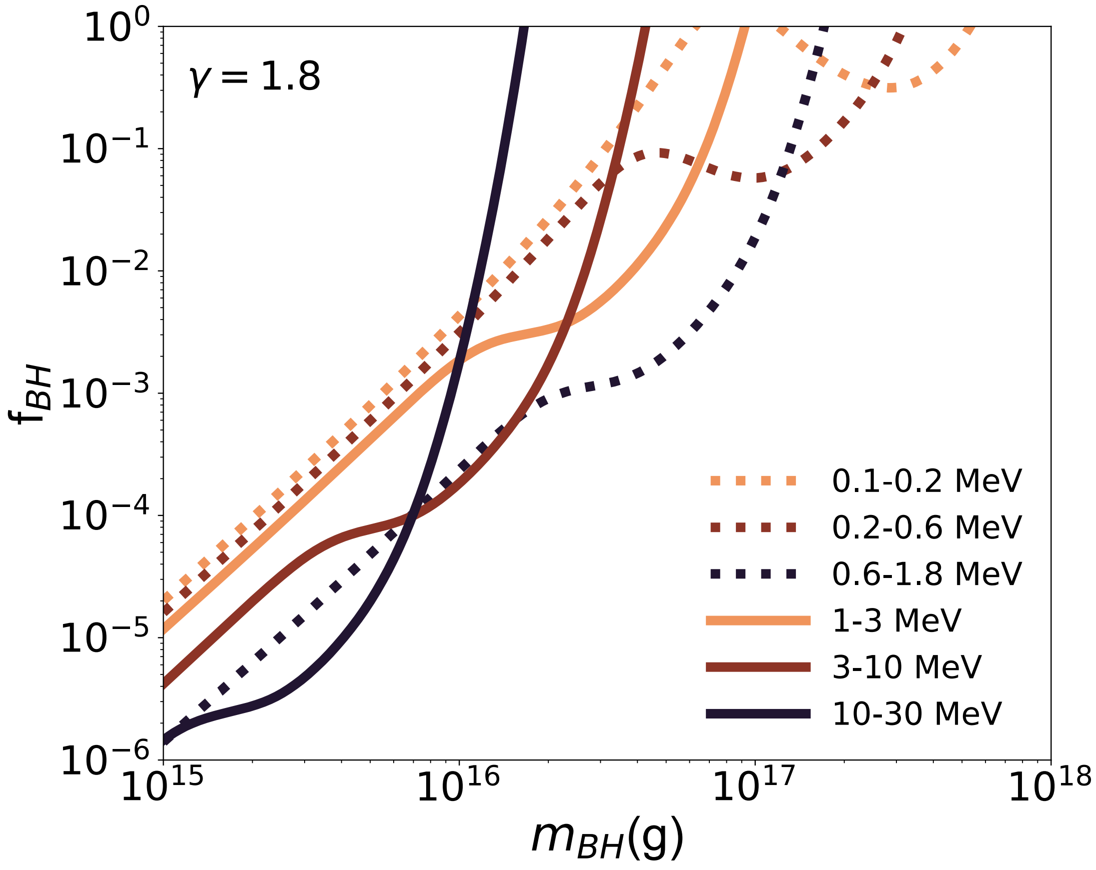
- Our best fit of gamma corresponds to 2.2 ± 0.6 (at 2σ)
- We choose to focus on the lower end of this range
- Account for inflight annihilation and final state radiation

$$F_\gamma(\Delta\Omega) = \frac{dN_\gamma^{\rm tot}}{dE_\gamma}\frac{1}{4\pi}\int_{\Delta\Omega}\int_{los} n_{\rm BH}(l,\Omega)\,dl\,d\Omega,$$
$$= \frac{dN_\gamma^{\rm tot}}{dE_\gamma}\frac{f_{\rm BH}}{4\pi m_{\rm BH}}\int_{\Delta\Omega}\int_{los} \rho_{\rm DM}(l,\Omega)\,dl\,d\Omega$$

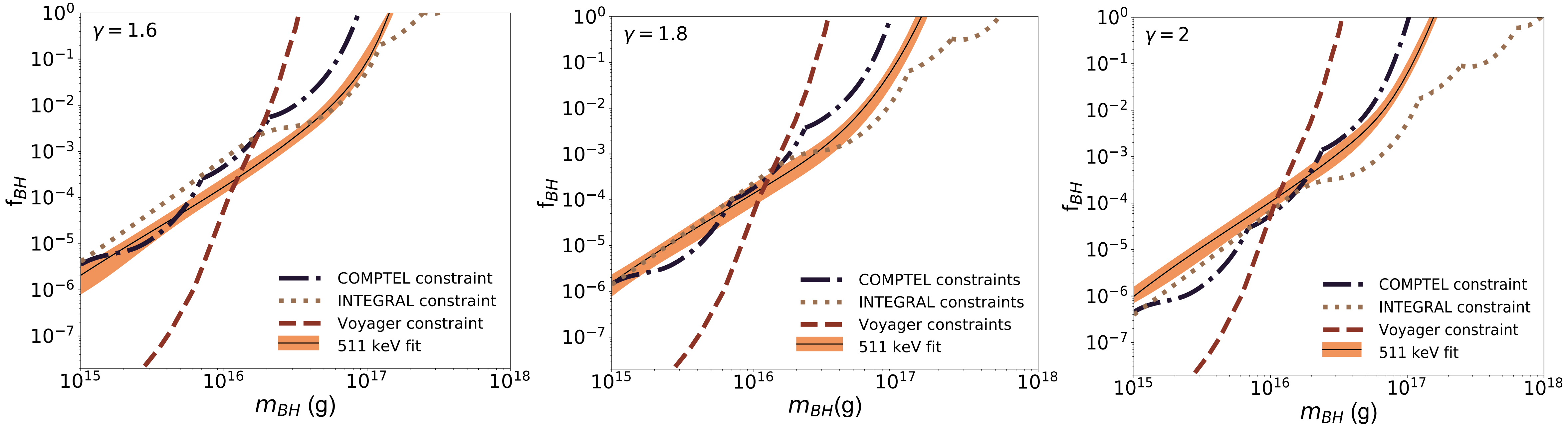


Direct Hawking
Final state radiation
Inflight annihilation
Total
dN_γ/dE_γ (MeV^{-1}s^{-1})
E_γ (MeV)
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{-1}
10^{0}
10^{1}

Final Constraints



- Vary f_{BH} to minimize χ^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
- γ ~ 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 $\mathrm{GeV/cm^3}$
- 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

$$
\begin{aligned}
n_{\rm BH}^{\rm local} &= \frac{f_{\rm BH}\rho_{\rm DM}^{\rm local}}{m_{\rm BH}} \\
&\simeq 1.0\times 10^{12}\,{\rm pc}^{-3}\times\left(\frac{f_{\rm BH}}{10^{-3}}\right)\left(\frac{2\times10^{16}\,{\rm g}}{m_{\rm BH}}\right) \\
&\simeq 1.2\times 10^{-4}\,{\rm AU}^{-3}\times\left(\frac{f_{\rm BH}}{10^{-3}}\right)\left(\frac{2\times10^{16}\,{\rm g}}{m_{\rm BH}}\right)
\end{aligned}
$$

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
  - $f_{BH} \sim 0.0001 - 0.004$
  - $n_{BH}^{local} \sim 10^{12}\ \mathrm{pc}^{-3}$
  - $\gamma \sim 1.6 - 1.8$
  - 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