What the Milky Way's Dwarfs have to tell us about the Galactic Center extended excess

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CIPANP

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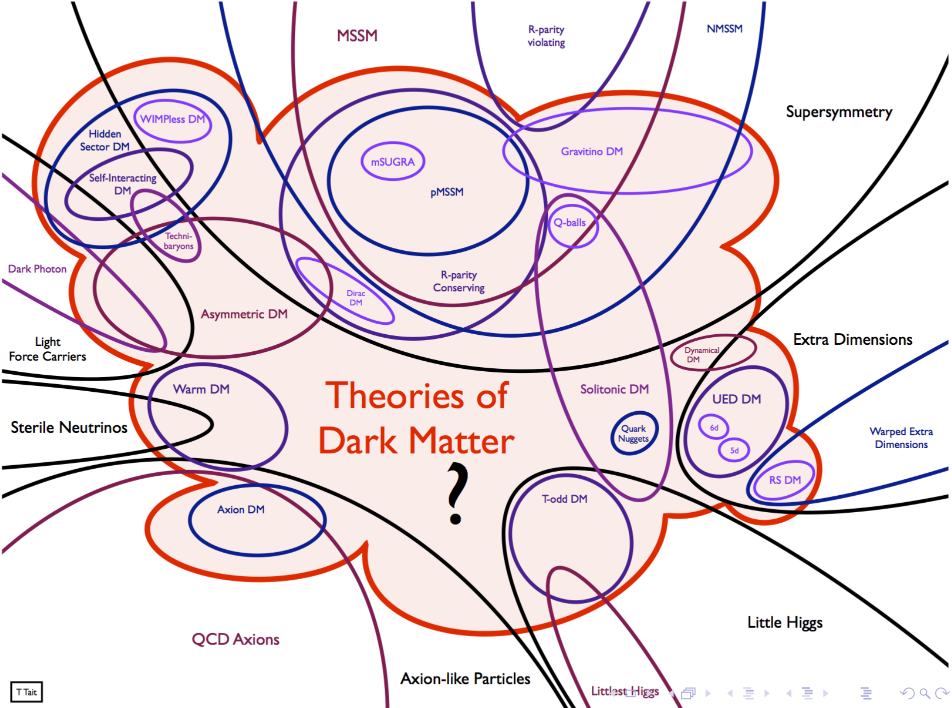
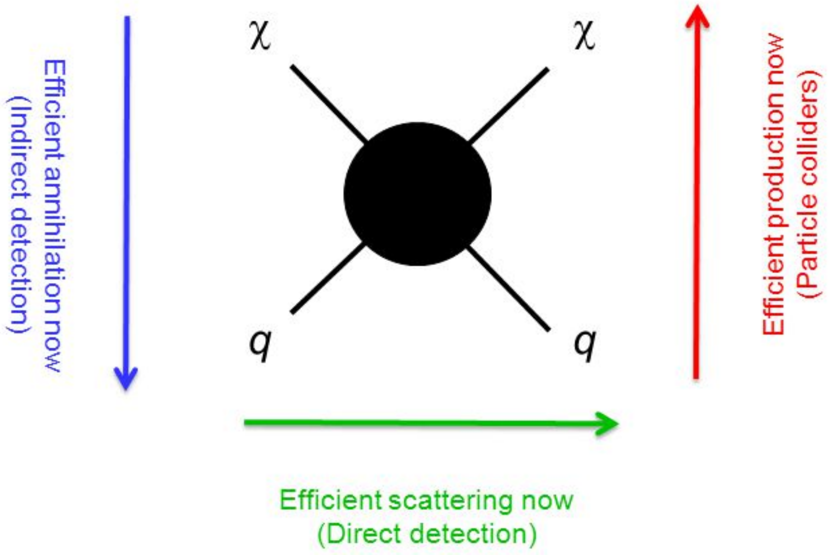
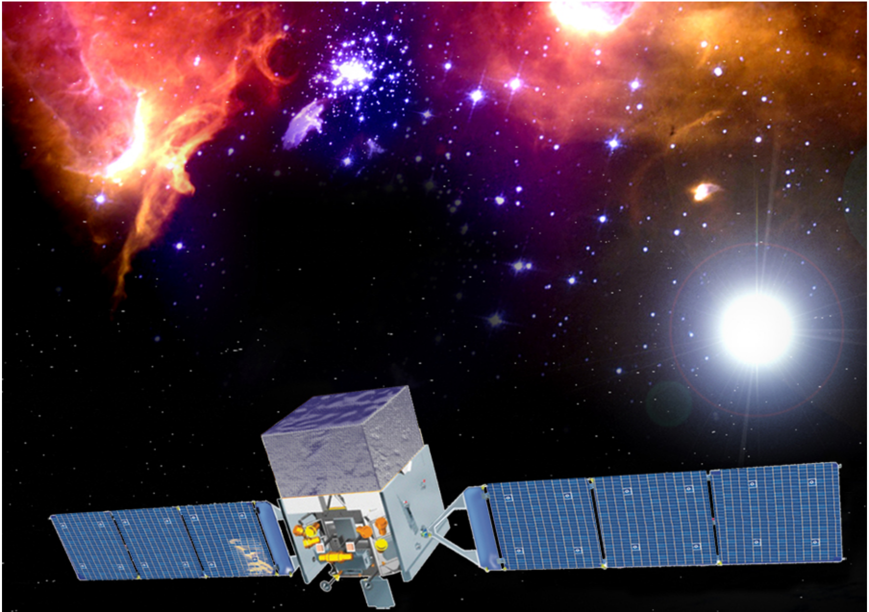
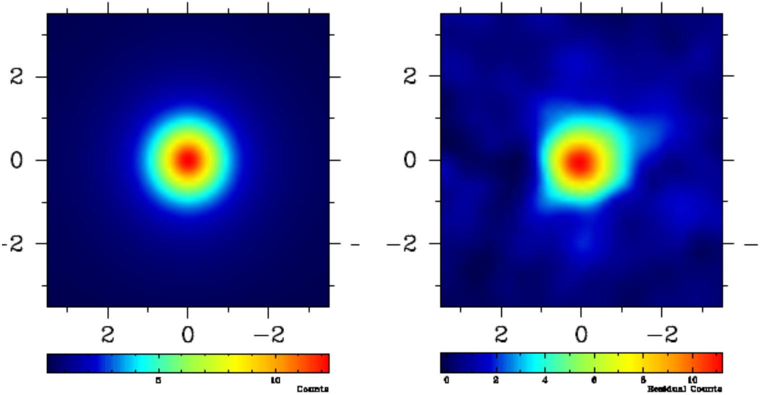

MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter ?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait


χ
χ
q
q
Efficient annihilation now
(Indirect detection)
Efficient production now
(Particle colliders)
Efficient scattering now
(Direct detection)

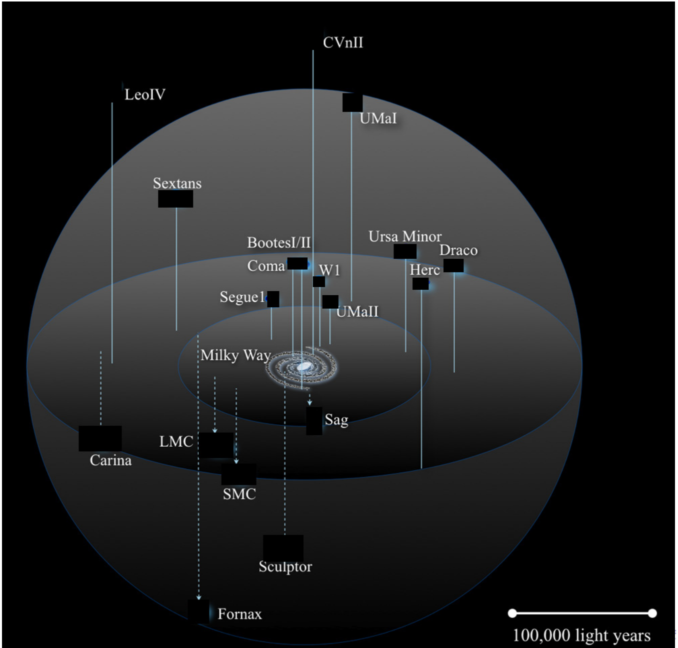
Fermi Gamma Ray Space Telescope



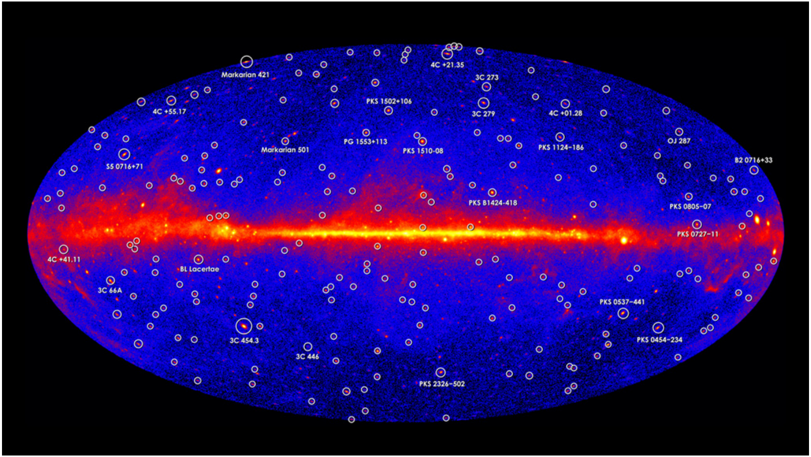
Dark Matter?



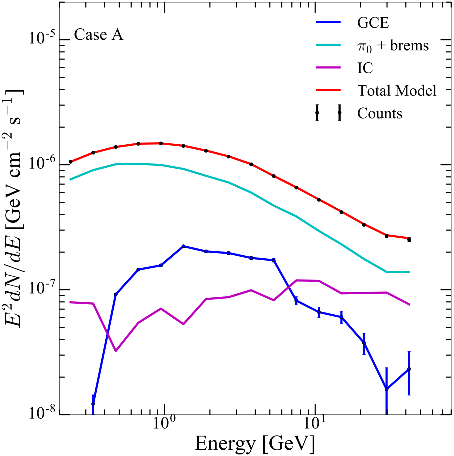
Dim Dwarf Galaxies



Complicated Gamma Ray Sky



An Accounting of the Fermi Gamma Rays

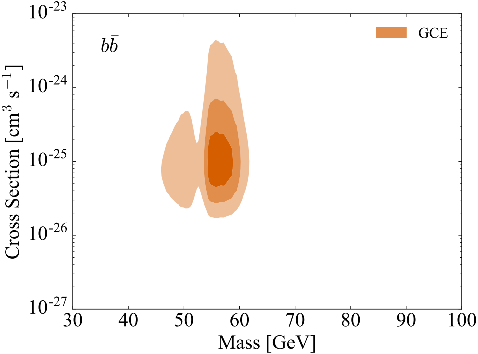


Templates for:

- Bremstrahlung
- π_0
- inverse Compton

In each energy bin the flux of each template is varied to minimize Poisson likelihood

Flux from Dark Matter Annihilation

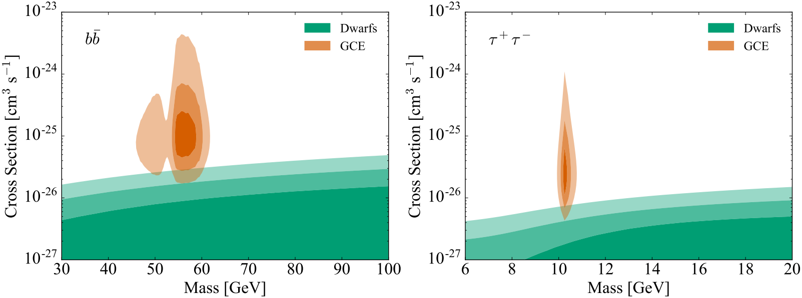


$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{J}{m_\chi^2}\frac{\langle \sigma v \rangle}{2}\frac{dN}{dE} \tag{1}$$

$$J = \int d\Omega \int dz \rho^2(z, \Omega) \tag{2}$$

$$\rho(r) = \frac{\rho_\odot}{\left(\frac{r}{R_\odot}\right)^\gamma \left(\frac{1+r/R_s}{1+R_\odot/R_s}\right)^{3-\gamma}} \tag{3}$$

Tension in Dark Matter Interpretation



Evidence Ratios

$$ER = \frac{p(D_1)p(D_2)}{p(D_1, D_2)}$$
$$= \frac{\int d\theta_1 p(D_1|\theta_1)p(\theta_1) \int d\theta_2 p(D_2|\theta_2)p(\theta_2)}{\int p(D_1, D_2|\theta)p(\theta)} \quad (4)$$

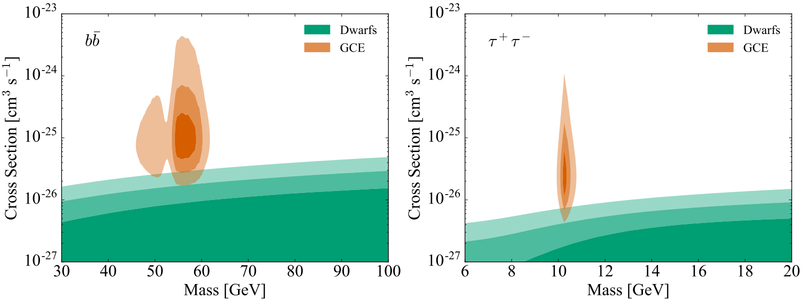
Bayes factor where the model for the numerator is the same as the one for the denominator but has an additional copy of the parameter space

$ER > 1 \rightarrow$ The data prefers to be described by two sets of parameters

$ER < 1 \rightarrow$ The data prefers to be described by one set of parameters

$ER = 1 \rightarrow$ No mutual information between the data sets

DM Tension



Model	
DM: $b\bar{b}$	3600
DM: $\tau^+\tau^-$	2300

Beyond DM Explanations

Log-parabola

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_s}\right)^{-\alpha-\beta\log(E/E_s)} \tag{5}$$

Exponential cutoff

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_s}\right)^{\gamma} e^{-E/E_c}\ , \tag{6}$$

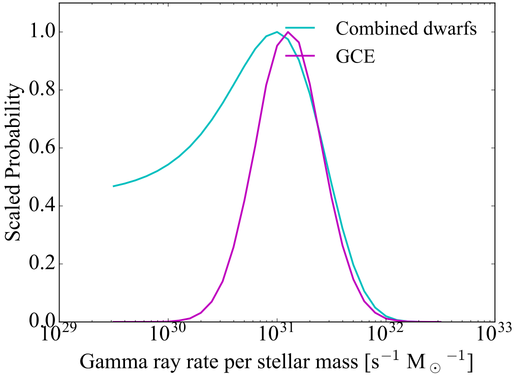
Flux Scalings

- Break any degeneracies between the normalization parameter and the spectral parameters
- Answer 'How well can these models fit the GCE?' and 'How well do these models address the difference in flux?' independently
- N_0 is set such that the integral of dN/dE over the energy is one.
- Allow the flux to scale as the stellar mass of the system.

$$\frac{d\Phi}{dE} = \frac{\dot{N}}{4\pi R^2} \frac{M_*}{M_0} \frac{dN}{dE}, \tag{7}$$

- $\dot{N}/M_0$, analogous to cross section
- M_*/R^2, analogous to the J-factor

Evidence Ratios: Astrophysics



Model	
Log-Parabola	0.69
Exponential Cutoff	0.73

- Both the GCE and the slight excesses in the Dwarfs pick out a scale of $\dot{N}/M_0^2 = 10^{31\pm1}$ sec^{-1} $M_\odot^{-1}$
- This explains why the ER is less than unity

Representative SIDM model

$$\frac{dn_\gamma}{dEdt} = \sigma_T c n_e n_{\rm ISRF} \frac{dN_\gamma}{dE} \,, \qquad (8)$$

GCE is produced by an IC process where high energy electrons from DM annihilation scatter off the interstellar radiation field

Representative SIDM model

$$\frac{dn_\gamma}{dEdt} = \sigma_T c n_e n_{\rm ISRF} \frac{dN_\gamma}{dE}\,, \tag{9}$$

$$\frac{dN_\gamma}{dE} = \int dE_e dE_{\rm ISRF}\, p(E_\gamma|E_e, E_{\rm ISRF}) p(E_e) p(E_{\rm ISRF})\,. \tag{10}$$

The energy distribution of the gamma rays is the convolution of the electron energy distribution and the energy distribution of the ISRF, with the IC process.

Representative SIDM model

$$\frac{dn_\gamma}{dEdt} = \sigma_T c n_e n_{\rm ISRF} \frac{dN_\gamma}{dE} \,, \tag{11}$$

$$\frac{dN_\gamma}{dE} = \int dE_e dE_{\rm ISRF}\, p(E_\gamma | E_e, E_{\rm ISRF}) p(E_e) p(E_{\rm ISRF}) \,. \tag{12}$$

$$\frac{d\Phi_\gamma}{dE} = \int dV' \frac{1}{4\pi(\vec{R} - \vec{R}')^2} \frac{dn_\gamma}{dEdt}(\vec{R}') \,. \tag{13}$$

Deriving how the flux scales...

Representative SIDM model

$$\frac{dn_\gamma}{dEdt} = \sigma_T c n_e n_{\rm ISRF} \frac{dN_\gamma}{dE} \,, \tag{14}$$

$$\frac{dN_\gamma}{dE} = \int dE_e dE_{\rm ISRF}\, p(E_\gamma|E_e, E_{\rm ISRF}) p(E_e) p(E_{\rm ISRF}) \,. \tag{15}$$

$$\frac{d\Phi_\gamma}{dE} = \int dV' \frac{1}{4\pi(\vec{R}-\vec{R}')^2} \frac{dn_\gamma}{dEdt}(\vec{R}') \,. \tag{16}$$

$$\frac{d\Phi_\gamma}{dE} \propto \int d\Omega dz \frac{1}{4\pi} n_{\rm ISRF} n_\chi^2 \frac{dN}{dE} \,. \tag{17}$$

...shows that the flux scales as a three-body process

Representative SIDM model

$$\frac{dn_\gamma}{dEdt} = \sigma_T c n_e n_{\rm ISRF} \frac{dN_\gamma}{dE} \,, \tag{18}$$

$$\frac{dN_\gamma}{dE} = \int dE_e dE_{\rm ISRF}\, p(E_\gamma | E_e, E_{\rm ISRF}) p(E_e) p(E_{\rm ISRF}) \,. \tag{19}$$

$$\frac{d\Phi_\gamma}{dE} = \int dV' \frac{1}{4\pi(\vec{R} - \vec{R}')^2} \frac{dn_\gamma}{dEdt}(\vec{R}') \,. \tag{20}$$

$$\frac{d\Phi_\gamma}{dE} \propto \int d\Omega dz \frac{1}{4\pi} n_{\rm ISRF}\, n_\chi^2 \frac{dN}{dE} \,. \tag{21}$$

$$\frac{d\Phi_\gamma}{dE} \propto \frac{J}{m_\chi^2} \frac{M_*}{M_{*,\rm GC}} \,. \tag{22}$$

Putting this into a useful form, take the flux to scale as the J-factor times the stellar mass of the system.

Evidence Ratios

Model	
DM: $b\bar{b}$	3600
DM: $\tau^+\tau^-$	2300
Log-Parabola	0.69
Exponential Cutoff	0.73
SIDM	1.1

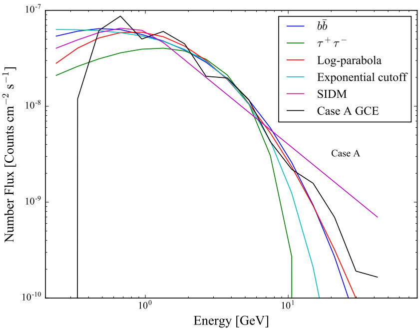
Bayes Factors

$$K_{12} = \frac{p(M_1|D)p(M_2)}{p(M_2|D)P(M_1)} = \frac{p(D|M_1)}{p(D|M_2)}\,. \tag{23}$$

Bayes factors for the considered models, relative to the $b\bar{b}$ model, for each of the different background cases. Values larger than one indicate the data prefer that model over $b\bar{b}$

Model	
DM: $\tau^+\tau^-$	4×10^{-24}
Log-Parabola	3×10^{12}
Exponential Cutoff	8×10^{7}
SIDM	5×10^{-20}

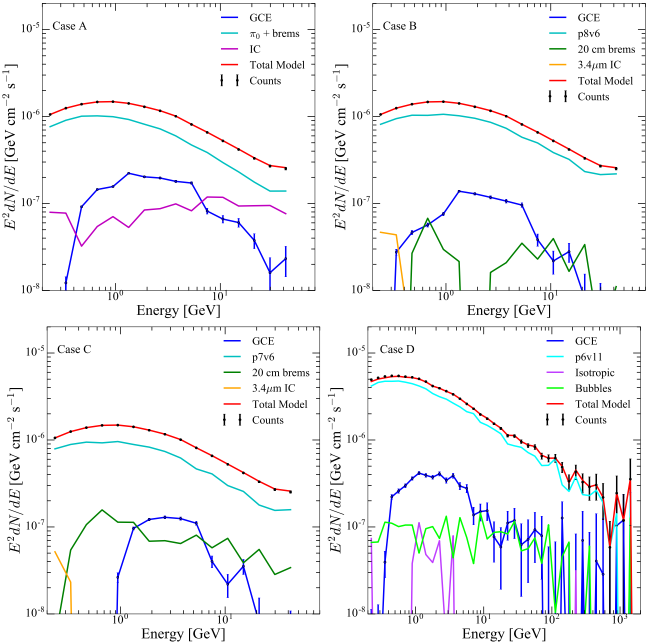
Best Fits



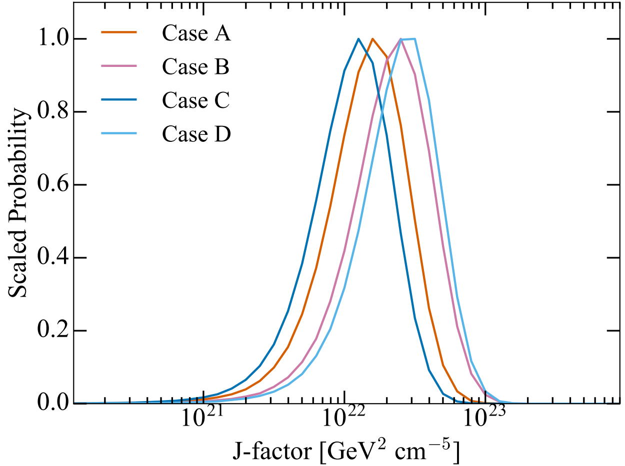
τ leptons cannot simultaneously explain the peak of the spectra and the high energy tail

Log-parabola can better explain the low energy data

Data Cases


Case A
GCE
π_0 + brems
IC
Total Model
Counts
Case B
GCE
p8v6
20 cm brems
3.4μm IC
Total Model
Counts
Case C
GCE
p7v6
20 cm brems
3.4μm IC
Total Model
Counts
Case D
GCE
p6v11
Isotropic
Bubbles
Total Model
Counts
$E^2 dN/dE$ [GeV cm^{-2} s^{-1}]
Energy [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^0
10^1
10^2
10^3

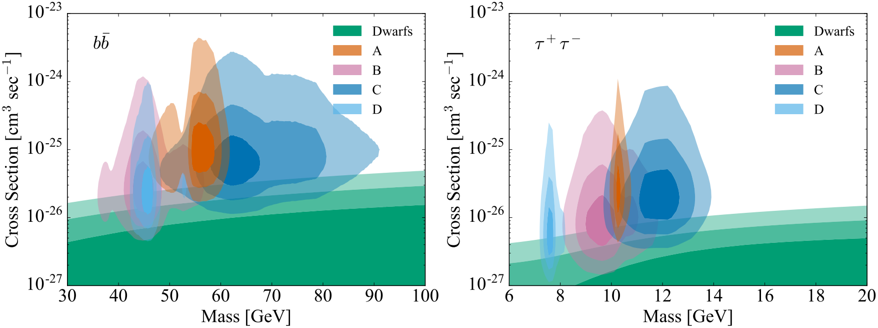
J-factors



$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{J}{m_\chi^2}\frac{\langle\sigma v\rangle}{2}\frac{dN}{dE} \tag{24}$$

$$J = \int d\Omega \int dz \rho^2(z,\Omega) \tag{25}$$

Tension



$b\bar{b}$
Dwarfs
A
B
C
D
Cross Section [cm^3 sec^{-1}]
Mass [GeV]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
30 40 50 60 70 80 90 100
$\tau^+\tau^-$
Dwarfs
A
B
C
D
Cross Section [cm^3 sec^{-1}]
Mass [GeV]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
6 8 10 12 14 16 18 20

Evidence Ratios

Evidence ratios for our five models using the diffuse templates for our various background cases.

Model	Case A	Case B	Case C	Case D
DM: $b\bar{b}$	3600	21	220	15
DM: $\tau^+\tau^-$	2300	25	230	29
Log-Parabola	0.69	0.58	0.71	0.54
Exponential Cutoff	0.73	0.59	0.78	0.54
SIDM	1.1	1.2	1.2	1.1

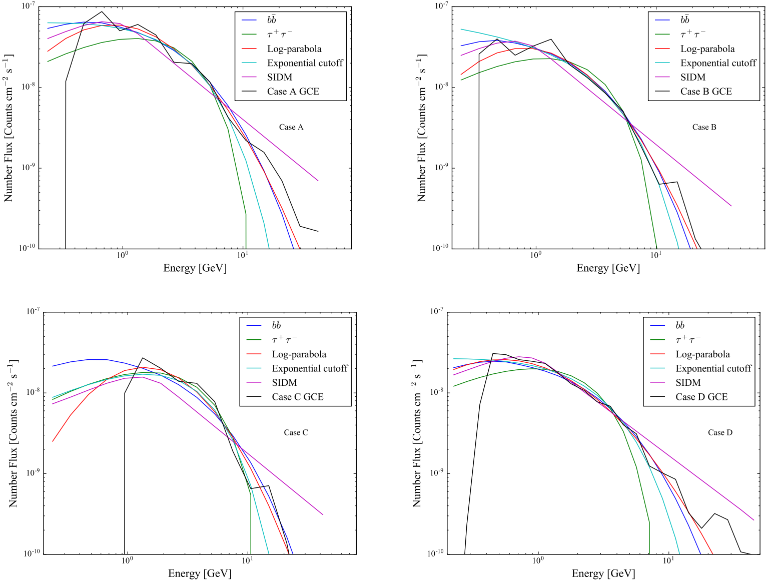
Bayes Factors

$$K_{12} = \frac{p(M_1|D)p(M_2)}{p(M_2|D)P(M_1)} = \frac{p(D|M_1)}{p(D|M_2)} . \qquad (26)$$

Bayes factors for the considered models, relative to the $b\bar{b}$ model, for each of the different background cases. Values larger than one indicate the data prefer that model over $b\bar{b}$

Model	Case A	Case B	Case C	Case D
DM: $\tau^+\tau^-$	4×10^{-24}	1×10^{-5}	7×10^{4}	1×10^{-22}
Log-Parabola	3×10^{12}	9×10^{6}	2×10^{12}	5×10^{9}
Exponential Cutoff	8×10^{7}	2×10^{4}	4×10^{10}	0.1
SIDM	5×10^{-20}	8×10^{-19}	6×10^{-2}	0.1

Best Fits



$b\bar{b}$
$\tau^+\tau^-$
Log-parabola
Exponential cutoff
SIDM
Case A GCE
Case A
Number Flux [Counts cm^{-2} s^{-1}]
Energy [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{0}
10^{1}
$b\bar{b}$
$\tau^+\tau^-$
Log-parabola
Exponential cutoff
SIDM
Case B GCE
Case B
Number Flux [Counts cm^{-2} s^{-1}]
Energy [GeV]
$b\bar{b}$
$\tau^+\tau^-$
Log-parabola
Exponential cutoff
SIDM
Case C GCE
Case C
Number Flux [Counts cm^{-2} s^{-1}]
Energy [GeV]
$b\bar{b}$
$\tau^+\tau^-$
Log-parabola
Exponential cutoff
SIDM
Case D GCE
Case D
Number Flux [Counts cm^{-2} s^{-1}]
Energy [GeV]

Concluding Remarks

- DM interprations display a strong to definitive tension between the bright GCE and the dim dwarfs
- Astrophysical interpretations pick out a consistent scale between the GCE and the low significance excesses.
- The GCE is precise enough to prefer (in all data cases) the log-parabola spectrum over any DM spectrum