Model-Independent Constraints on Dark Matter Annihilation in Dwarf Spheroidal Galaxies

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with Kim Boddy (JHU); Stephen Hill, Jason Kumar, and Danny Marfatia (UH)

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and ongoing work

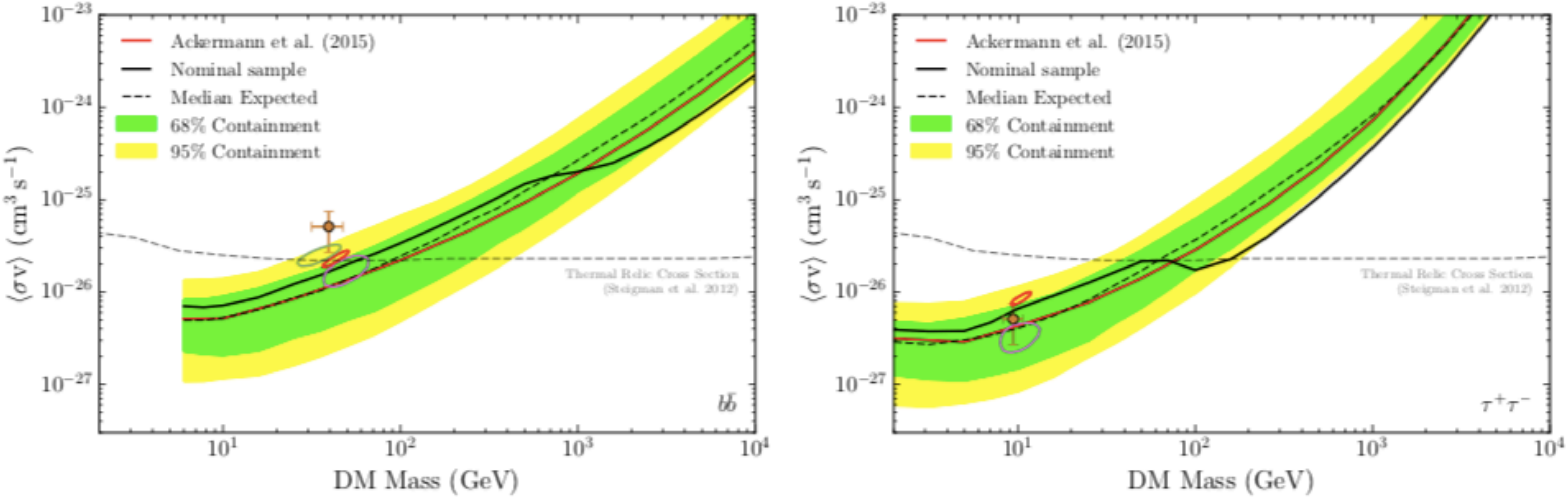
DM Indirect Detection

- Neutrinos
- Electrons/Positrons
- Protons/Antiprotons
- Nuclei/Antinuclei

- Photons:
  - Direct annihilation
  - Radiation (Internal Brem.)
  - Decays/Hadronization/Cascades
  - Synchrotron, Inverse Compton Scattering of e^+/e^-…

Annihilation in Dwarf Galaxies

Fermi-LAT+DES (2017)



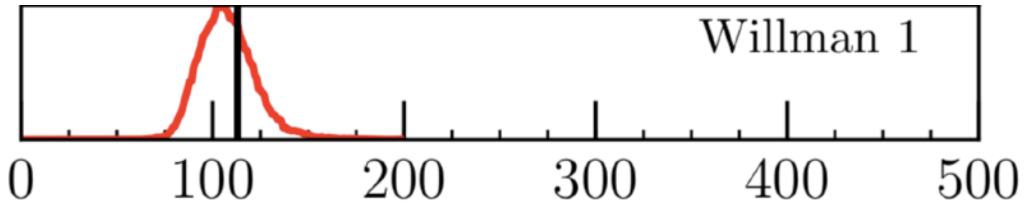
This analysis:

- **We constrain the number of DM annihilation photons, *completely independent of DM particle physics model or DM astrophysics.***
  - estimate the number of background (+foreground) photons empirically
  - constrain the number of DM annihilation photons statistically
- Similar to Geringer-Sameth and Koushiappas (2011):
  - background distribution determined empirically - *no modeling*
  - use only number of photon counts - *no spectral information*
- simple stacked analysis - *all photon events weighted equally*
  - separates observational data, J factor, and details of DM physics
- Fermi LAT Pass 8 data set and 3FGL point source catalog

Details of Analysis

- Choose an ROI (*i*), centered on a target dwarf, with radius 10 degrees.
- Define the signal region as area within 0.5 degrees of the target's location.
- Randomly choose 10^5 sample regions within the ROI of the same size as the signal region.
    - Reject any sample region whose boundary intersects the border of the ROI or the boundary of a known source region (within 0.8 degrees of a known point source).
- Histogram the number of counts for the surviving sample regions.

➡ Probability Mass Function: $P^i_{\mathrm{bgd}}(N^i_{\mathrm{bgd}})$



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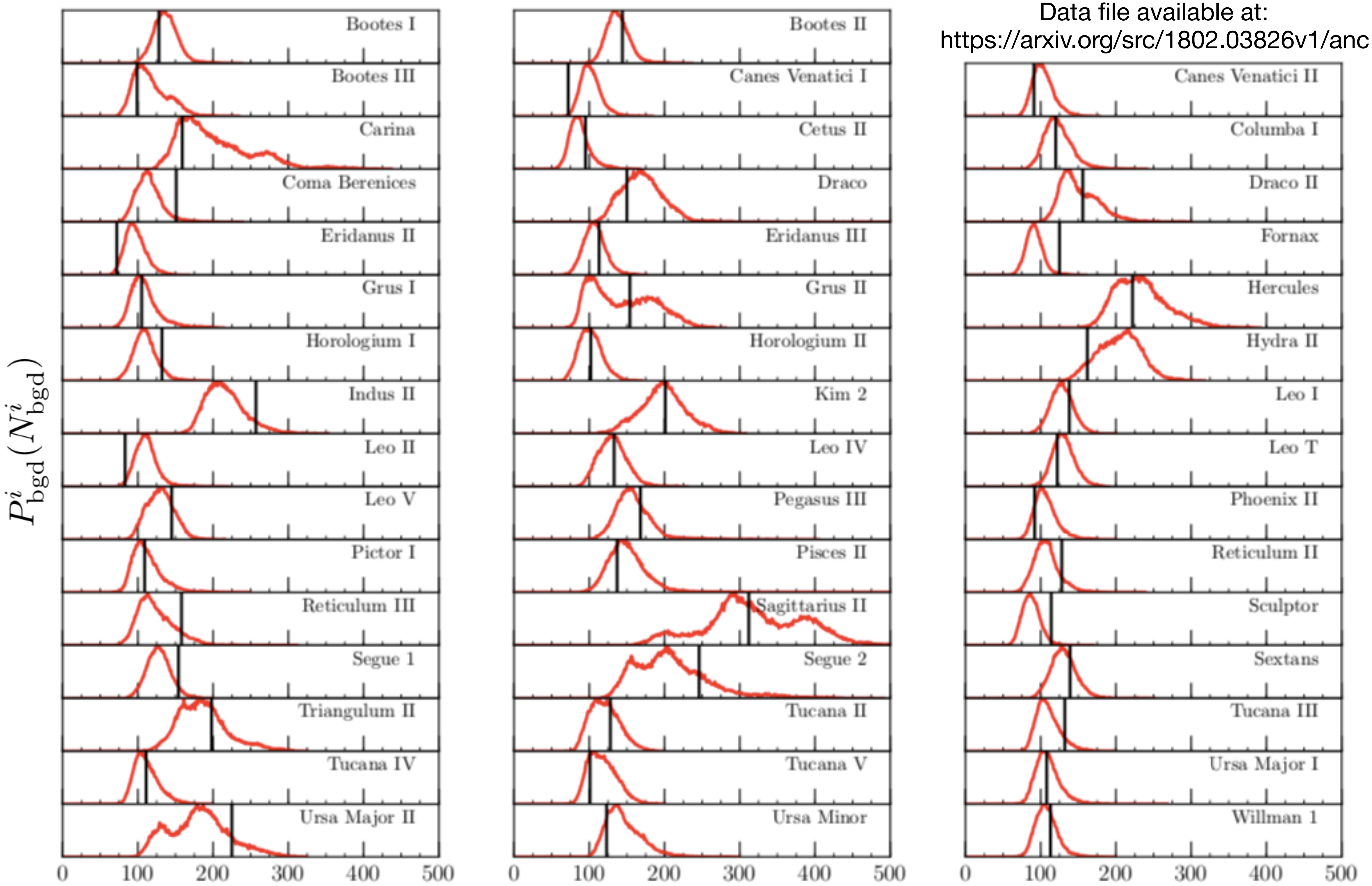

Data file available at:
https://arxiv.org/src/1802.03826v1/anc

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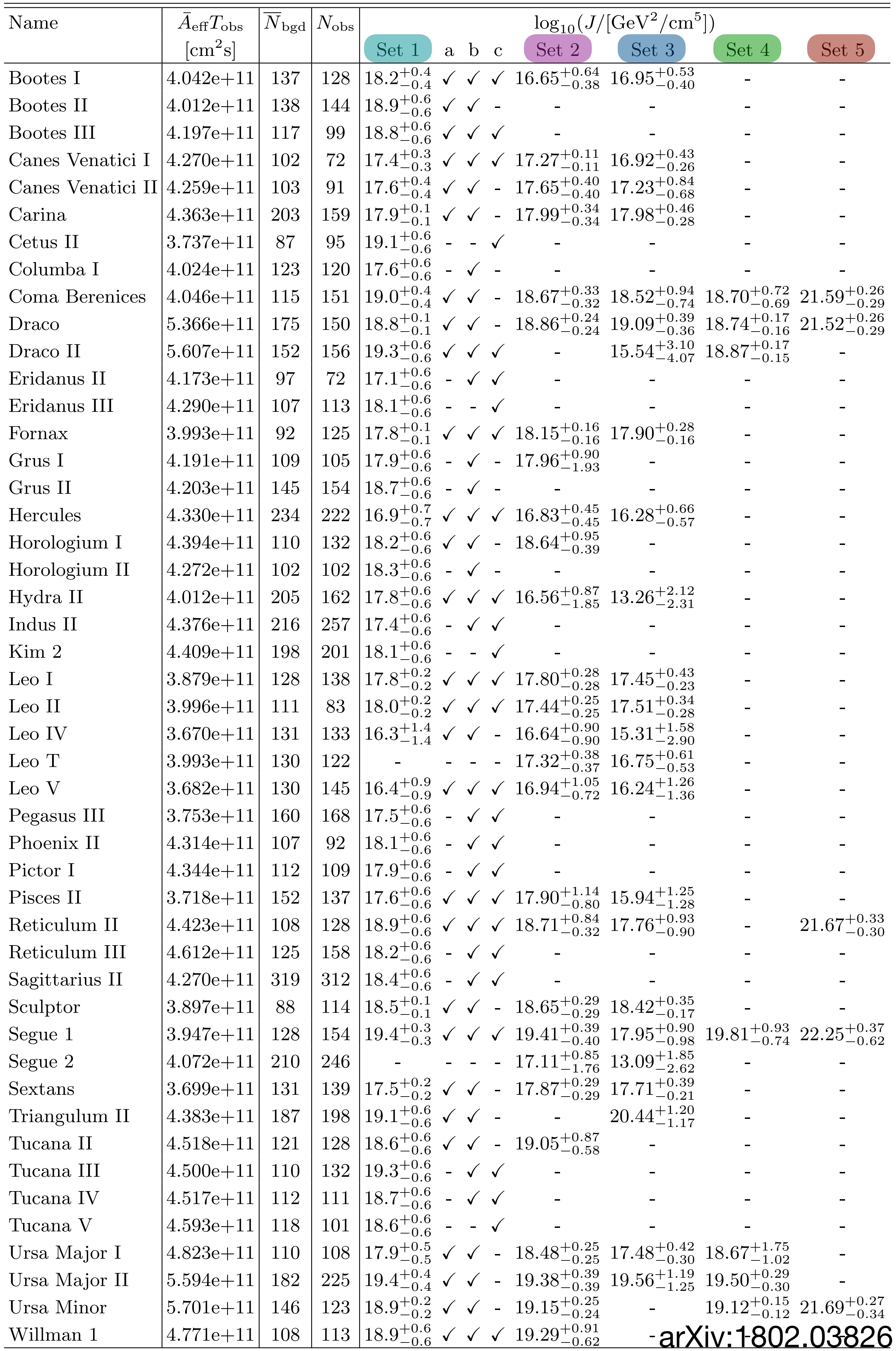
Targets

- Pre-defined sets:
  1. **45 objects** from 1611.03184
     - (a) 28 confirmed dwarfs
     - (b) 28 dwarfs + 13 likely galaxies
     - (c) 27 dwarfs w/out contamination
  2. **27 dwarfs** from 1604.05599
  3. **24 dwarfs** w/ J-factors assuming non-spherical halos from 1603.08046
  4. **7 dwarfs** w/ J-factors assuming modified foreground effects from 1608.01749 and 1706.05481
  5. **5 dwarfs** w/ Sommerfeld-enhanced J-factors (Coulomb limit) from 1702.00408
- Choose your own adventure!



Name	$\bar{A}_{\rm eff}T_{\rm obs}$ [cm^{2}s]	$\overline{N}_{\rm bgd}$	$N_{\rm obs}$	$\log_{10}(J/[\mathrm{GeV}^2/\mathrm{cm}^5])$							
				Set 1	a	b	c	Set 2	Set 3	Set 4	Set 5
Bootes I	4.042e+11	137	128	$18.2^{+0.4}_{-0.4}$	✓	✓	✓	$16.65^{+0.64}_{-0.38}$	$16.95^{+0.53}_{-0.40}$	-	-
Bootes II	4.012e+11	138	144	$18.9^{+0.6}_{-0.6}$	✓	✓	-	-	-	-	-
Bootes III	4.197e+11	117	99	$18.8^{+0.6}_{-0.6}$	✓	✓	✓	-	-	-	-
Canes Venatici I	4.270e+11	102	72	$17.4^{+0.3}_{-0.3}$	✓	✓	✓	$17.27^{+0.11}_{-0.11}$	$16.92^{+0.43}_{-0.26}$	-	-
Canes Venatici II	4.259e+11	103	91	$17.6^{+0.4}_{-0.4}$	✓	✓	-	$17.65^{+0.40}_{-0.40}$	$17.23^{+0.84}_{-0.68}$	-	-
Carina	4.363e+11	203	159	$17.9^{+0.1}_{-0.1}$	✓	✓	-	$17.99^{+0.34}_{-0.34}$	$17.98^{+0.46}_{-0.28}$	-	-
Cetus II	3.737e+11	87	95	$19.1^{+0.6}_{-0.6}$	-	-	✓	-	-	-	-
Columba I	4.024e+11	123	120	$17.6^{+0.6}_{-0.6}$	-	✓	-	-	-	-	-
Coma Berenices	4.046e+11	115	151	$19.0^{+0.4}_{-0.4}$	✓	✓	-	$18.67^{+0.33}_{-0.32}$	$18.52^{+0.94}_{-0.74}$	$18.70^{+0.72}_{-0.69}$	$21.59^{+0.26}_{-0.29}$
Draco	5.366e+11	175	150	$18.8^{+0.1}_{-0.1}$	✓	✓	-	$18.86^{+0.24}_{-0.24}$	$19.09^{+0.39}_{-0.36}$	$18.74^{+0.17}_{-0.16}$	$21.52^{+0.26}_{-0.29}$
Draco II	5.607e+11	152	156	$19.3^{+0.6}_{-0.6}$	✓	✓	✓	-	$15.54^{+3.10}_{-4.07}$	$18.87^{+0.17}_{-0.15}$	-
Eridanus II	4.173e+11	97	72	$17.1^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Eridanus III	4.290e+11	107	113	$18.1^{+0.6}_{-0.6}$	-	-	✓	-	-	-	-
Fornax	3.993e+11	92	125	$17.8^{+0.1}_{-0.1}$	✓	✓	✓	$18.15^{+0.16}_{-0.16}$	$17.90^{+0.28}_{-0.16}$	-	-
Grus I	4.191e+11	109	105	$17.9^{+0.6}_{-0.6}$	-	✓	-	$17.96^{+0.90}_{-1.93}$	-	-	-
Grus II	4.203e+11	145	154	$18.7^{+0.6}_{-0.6}$	-	✓	-	-	-	-	-
Hercules	4.330e+11	234	222	$16.9^{+0.7}_{-0.7}$	✓	✓	✓	$16.83^{+0.45}_{-0.45}$	$16.28^{+0.66}_{-0.57}$	-	-
Horologium I	4.394e+11	110	132	$18.2^{+0.6}_{-0.6}$	✓	✓	-	$18.64^{+0.95}_{-0.39}$	-	-	-
Horologium II	4.272e+11	102	102	$18.3^{+0.6}_{-0.6}$	-	✓	-	-	-	-	-
Hydra II	4.012e+11	205	162	$17.8^{+0.6}_{-0.6}$	✓	✓	✓	$16.56^{+0.87}_{-1.85}$	$13.26^{+2.12}_{-2.31}$	-	-
Indus II	4.376e+11	216	257	$17.4^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Kim 2	4.409e+11	198	201	$18.1^{+0.6}_{-0.6}$	-	-	✓	-	-	-	-
Leo I	3.879e+11	128	138	$17.8^{+0.2}_{-0.2}$	✓	✓	✓	$17.80^{+0.28}_{-0.28}$	$17.45^{+0.43}_{-0.23}$	-	-
Leo II	3.996e+11	111	83	$18.0^{+0.2}_{-0.2}$	✓	✓	✓	$17.44^{+0.25}_{-0.25}$	$17.51^{+0.34}_{-0.28}$	-	-
Leo IV	3.670e+11	131	133	$16.3^{+1.4}_{-1.4}$	✓	✓	-	$16.64^{+0.90}_{-0.90}$	$15.31^{+1.58}_{-2.90}$	-	-
Leo T	3.993e+11	130	122	-	-	-	-	$17.32^{+0.38}_{-0.37}$	$16.75^{+0.61}_{-0.53}$	-	-
Leo V	3.682e+11	130	145	$16.4^{+0.9}_{-0.9}$	✓	✓	✓	$16.94^{+1.05}_{-0.72}$	$16.24^{+1.26}_{-1.36}$	-	-
Pegasus III	3.753e+11	160	168	$17.5^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Phoenix II	4.314e+11	107	92	$18.1^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Pictor I	4.344e+11	112	109	$17.9^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Pisces II	3.718e+11	152	137	$17.6^{+0.6}_{-0.6}$	✓	✓	✓	$17.90^{+1.14}_{-0.80}$	$15.94^{+1.25}_{-1.28}$	-	-
Reticulum II	4.423e+11	108	128	$18.9^{+0.6}_{-0.6}$	✓	✓	✓	$18.71^{+0.84}_{-0.32}$	$17.76^{+0.93}_{-0.90}$	-	$21.67^{+0.33}_{-0.30}$
Reticulum III	4.612e+11	125	158	$18.2^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Sagittarius II	4.270e+11	319	312	$18.4^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Sculptor	3.897e+11	88	114	$18.5^{+0.1}_{-0.1}$	✓	✓	-	$18.65^{+0.29}_{-0.29}$	$18.42^{+0.35}_{-0.17}$	-	-
Segue 1	3.947e+11	128	154	$19.4^{+0.3}_{-0.3}$	✓	✓	✓	$19.41^{+0.39}_{-0.40}$	$17.95^{+0.90}_{-0.98}$	$19.81^{+0.93}_{-0.74}$	$22.25^{+0.37}_{-0.62}$
Segue 2	4.072e+11	210	246	-	-	-	-	$17.11^{+0.85}_{-1.76}$	$13.09^{+1.85}_{-2.62}$	-	-
Sextans	3.699e+11	131	139	$17.5^{+0.2}_{-0.2}$	✓	✓	-	$17.87^{+0.29}_{-0.29}$	$17.71^{+0.39}_{-0.21}$	-	-
Triangulum II	4.383e+11	187	198	$19.1^{+0.6}_{-0.6}$	✓	✓	-	-	$20.44^{+1.20}_{-1.17}$	-	-
Tucana II	4.518e+11	121	128	$18.6^{+0.6}_{-0.6}$	✓	✓	-	$19.05^{+0.87}_{-0.58}$	-	-	-
Tucana III	4.500e+11	110	132	$19.3^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Tucana IV	4.517e+11	112	111	$18.7^{+0.6}_{-0.6}$	-	✓	✓	-	-	-	-
Tucana V	4.593e+11	118	101	$18.6^{+0.6}_{-0.6}$	-	-	✓	-	-	-	-
Ursa Major I	4.823e+11	110	108	$17.9^{+0.5}_{-0.5}$	✓	✓	-	$18.48^{+0.25}_{-0.25}$	$17.48^{+0.42}_{-0.30}$	$18.67^{+1.75}_{-1.02}$	-
Ursa Major II	5.594e+11	182	225	$19.4^{+0.4}_{-0.4}$	✓	✓	-	$19.38^{+0.39}_{-0.39}$	$19.56^{+1.19}_{-1.25}$	$19.50^{+0.29}_{-0.30}$	-
Ursa Minor	5.701e+11	146	123	$18.9^{+0.2}_{-0.2}$	✓	✓	-	$19.15^{+0.25}_{-0.24}$	-	$19.12^{+0.15}_{-0.12}$	$21.69^{+0.27}_{-0.34}$
Willman 1	4.771e+11	108	113	$18.9^{+0.6}_{-0.6}$	✓	✓	✓	$19.29^{+0.91}_{-0.62}$	-		

arXiv:1802.03826

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Statistics

- Stacking of targets: $P^{\rm tot}_{\rm bgd}(N^{\rm tot}_{\rm bgd}) \equiv \sum_{\sum_i N^i_{\rm bgd} = N^{\rm tot}_{\rm bgd}} \prod_i P^i_{\rm bgd}(N^i_{\rm bgd})$
    - Total number of observed photons: $N^{\rm tot}_{\rm obs} = \sum_i N^i_{\rm obs}$
- Assume Poisson-distributed number of expected signal photons:

$$P^{\rm tot}_{\rm DM}(N^{\rm tot}_{\rm DM}; \overline{N}^{\rm tot}_{\rm DM}) = e^{-\overline{N}^{\rm tot}_{\rm DM}} \frac{(\overline{N}^{\rm tot}_{\rm DM})^{N^{\rm tot}_{\rm DM}}}{N^{\rm tot}_{\rm DM}!}$$

- Upper bound on the expected number of photons from DM annihilation (at confidence level β) is $N_{\rm bound}(\beta)$:

$$\sum_{N^{\rm tot}_{\rm bgd} + N^{\rm tot}_{\rm DM} > N^{\rm tot}_{\rm obs}} P^{\rm tot}_{\rm bgd}(N^{\rm tot}_{\rm bgd}) \times P^{\rm tot}_{\rm DM}(N^{\rm tot}_{\rm DM}; N_{\rm bound}(\beta)) = \beta$$

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- Stacking of targets: $P_{\mathrm{bgd}}^{\mathrm{tot}}(N_{\mathrm{bgd}}^{\mathrm{tot}}) \equiv \sum_{\sum_i N_{\mathrm{bgd}}^i = N_{\mathrm{bgd}}^{\mathrm{tot}}} \prod_i P_{\mathrm{bgd}}^i(N_{\mathrm{bgd}}^i)$
    - Total number of observed photons: $N_{\mathrm{obs}}^{\mathrm{tot}} = \sum_i N_{\mathrm{obs}}^i$
- Assume Poisson-distributed number of expected signal photons:

$$P_{\mathrm{DM}}^{\mathrm{tot}}(N_{\mathrm{DM}}^{\mathrm{tot}}; \overline{N}_{\mathrm{DM}}^{\mathrm{tot}}) = e^{-\overline{N}_{\mathrm{DM}}^{\mathrm{tot}}} \frac{(\overline{N}_{\mathrm{DM}}^{\mathrm{tot}})^{N_{\mathrm{DM}}^{\mathrm{tot}}}}{N_{\mathrm{DM}}^{\mathrm{tot}}!}$$

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$$\sum_{N_{\mathrm{bgd}}^{\mathrm{tot}} + N_{\mathrm{DM}}^{\mathrm{tot}} > N_{\mathrm{obs}}^{\mathrm{tot}}} P_{\mathrm{bgd}}^{\mathrm{tot}}(N_{\mathrm{bgd}}^{\mathrm{tot}}) \times P_{\mathrm{DM}}^{\mathrm{tot}}(N_{\mathrm{DM}}^{\mathrm{tot}}; N_{\mathrm{bound}}(\beta)) = \beta$$

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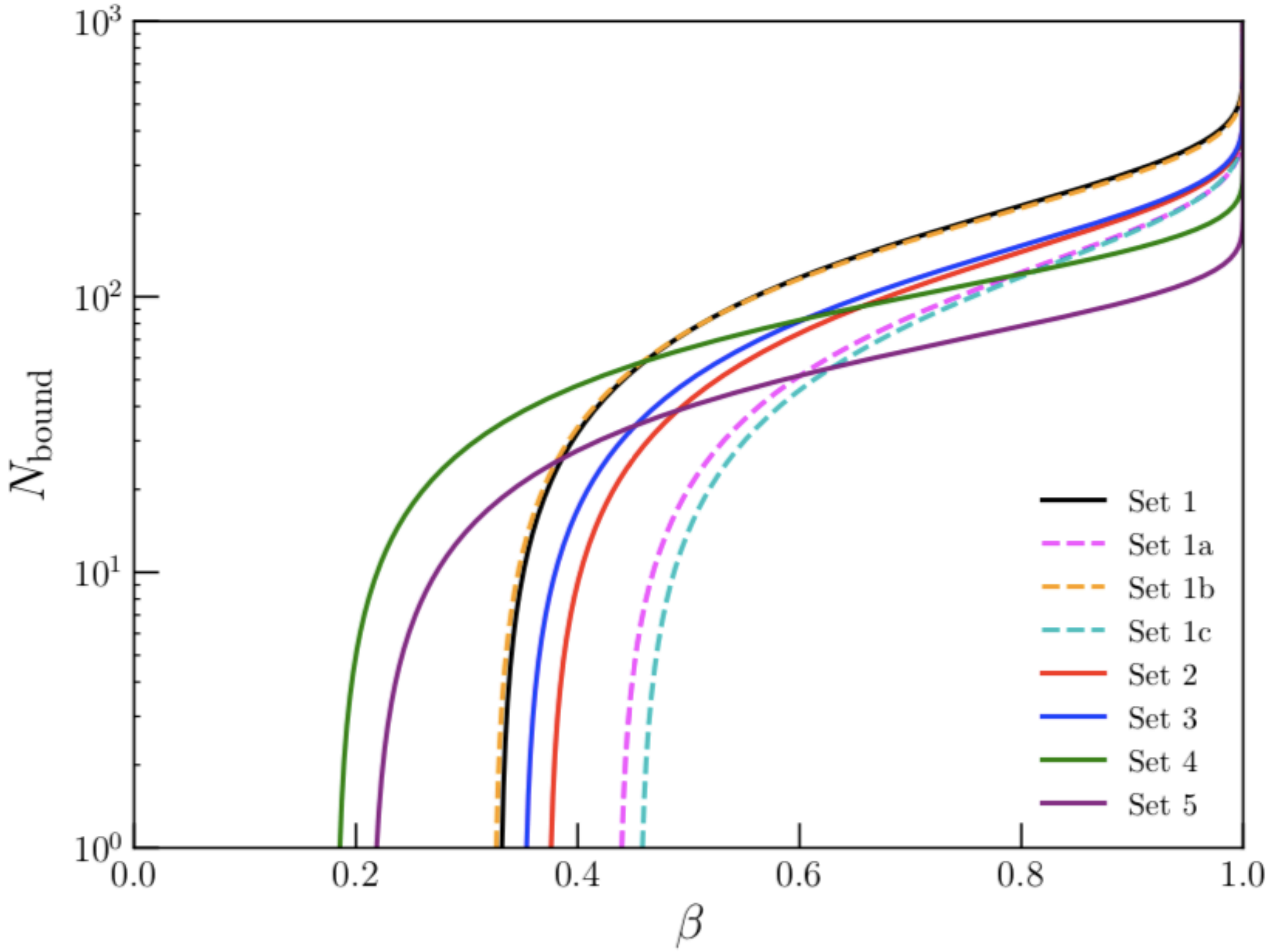
Results



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Constraining Dark Matter

- **Following Geringer-Sameth and Koushiappas (2011), we constrain models that could have produced an excess over background.**

$$\overline{N}_{\mathrm{DM}} = \Phi_{\mathrm{PP}} \times J(\Delta\Omega) \times (T_{\mathrm{obs}} \bar{A}_{\mathrm{eff}})$$

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$$\boxed{\Phi_{\mathrm{PP}} = \frac{(\sigma v)_0}{8\pi m_X^2} \int_{E_{\mathrm{th}}}^{E_{\mathrm{max}}} dE_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{A_{\mathrm{eff}}(E_\gamma)}{\bar{A}_{\mathrm{eff}}}}$$

$$\boxed{J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int d\ell \int d^3v_1 f(r(\ell,\Omega),\vec{v}_1) \int d^3v_2 f(r(\ell,\Omega),\vec{v}_2) \times S(|\vec{v}_1 - \vec{v}_2|)}$$

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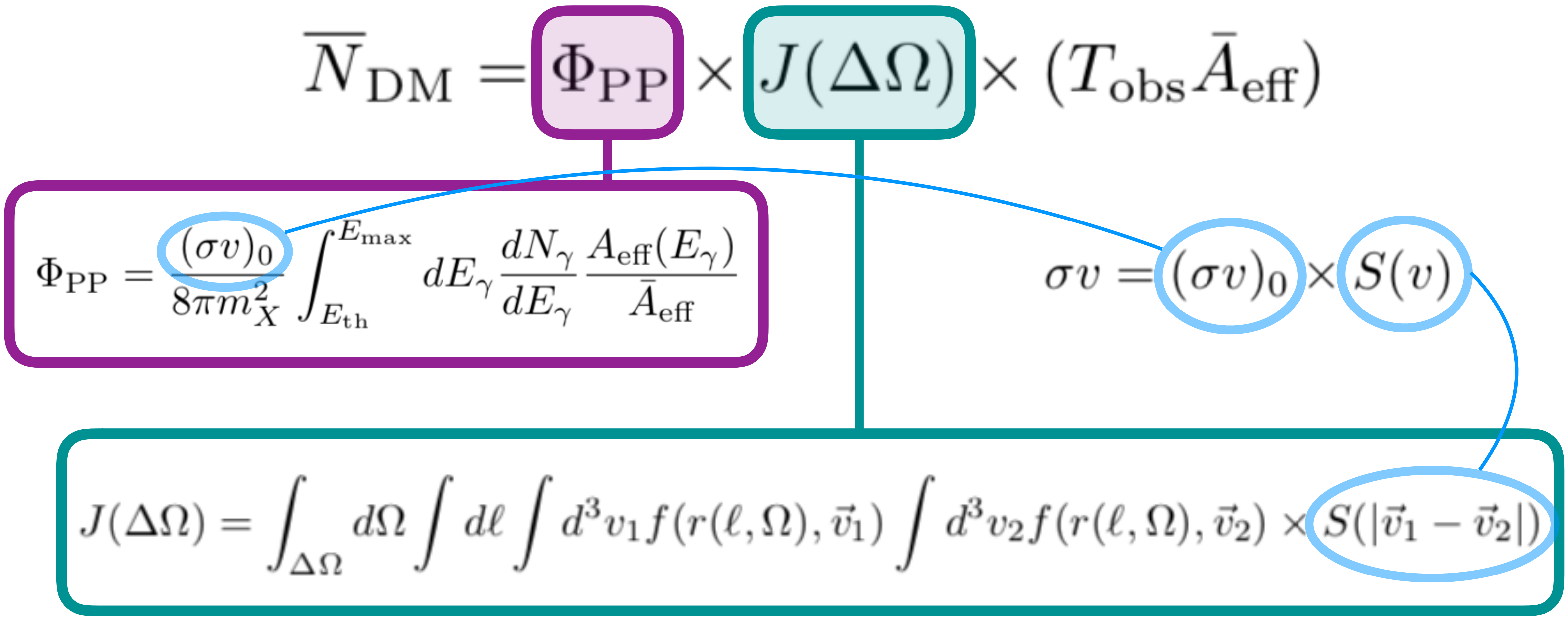

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Note: for decay, $(\sigma v)_0/2m_X \to \Gamma$ and $J \to J_D \equiv \int_{\Delta\Omega} d\Omega \int d\ell\, \rho$

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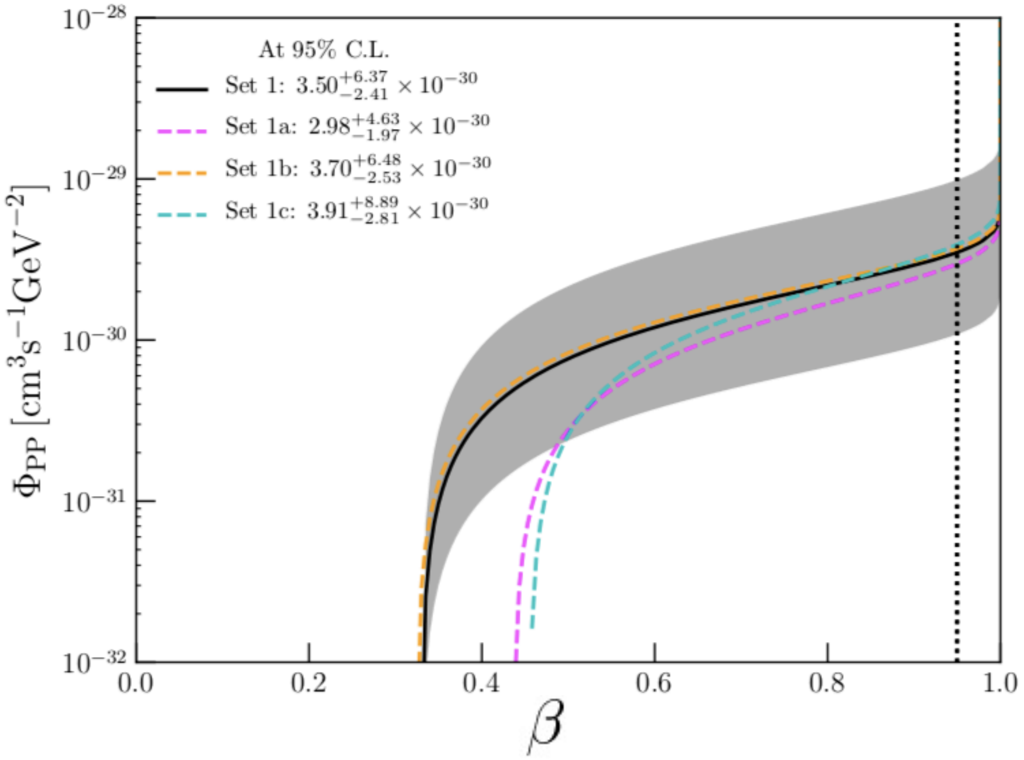
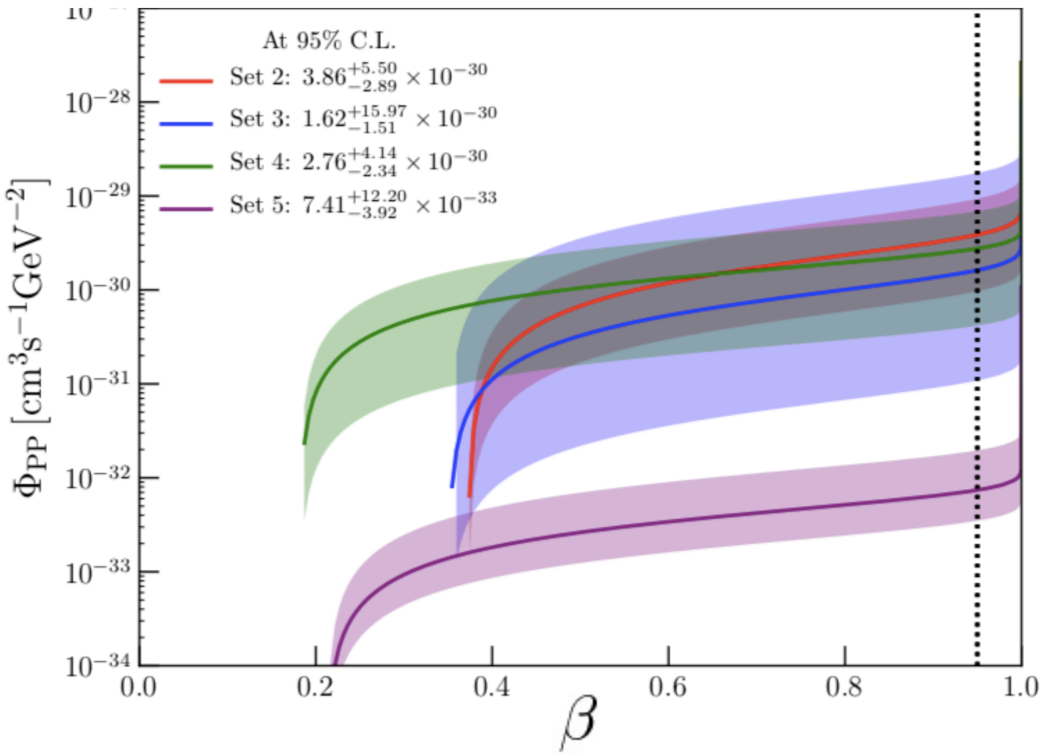
$$\Phi_{\rm PP}^{\rm bound}(\beta) \equiv N_{\rm bound}(\beta)\left[\sum_i J^i \times (T_{\rm obs}\bar{A}_{\rm eff})^i\right]^{-1}$$

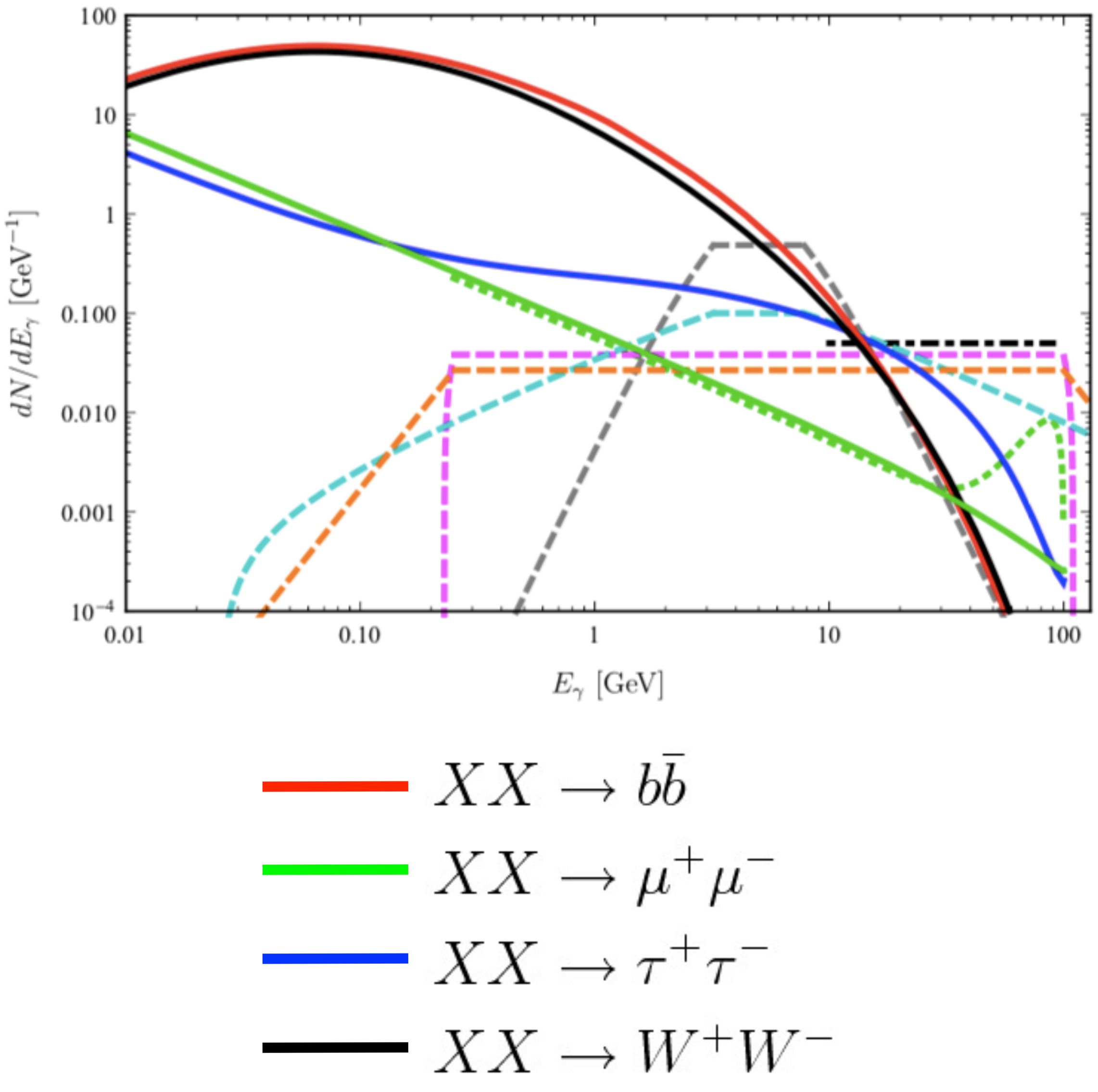




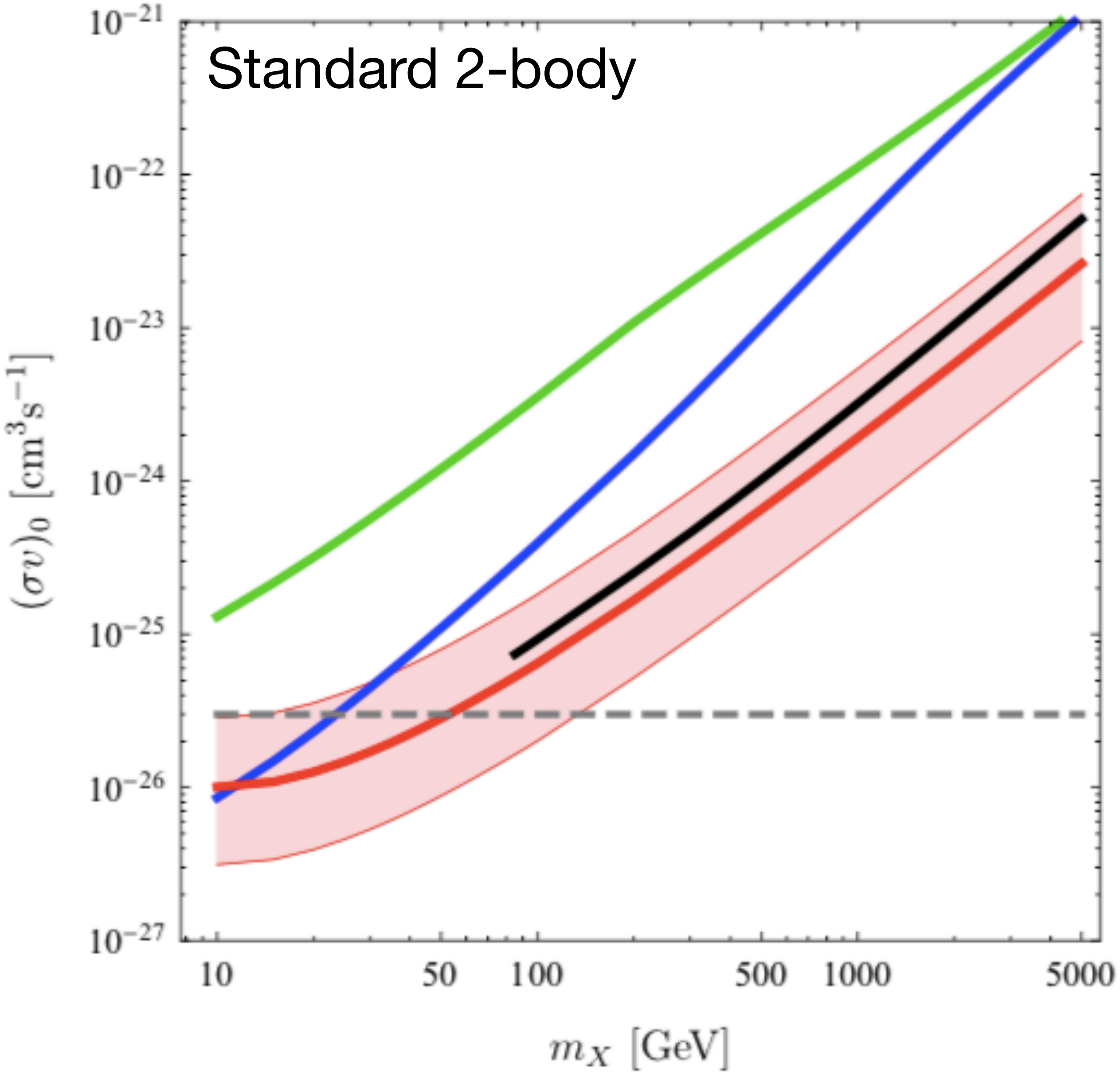
arXiv:1802.03826

Results

- Constrain DM properties: $\Phi_{\rm PP} = \frac{(\sigma v)_0}{8\pi m_X^2}\int_{E_{\rm th}}^{E_{\rm max}} dE_\gamma \frac{dN_\gamma}{dE_\gamma}\frac{A_{\rm eff}(E_\gamma)}{\bar{A}_{\rm eff}}$



arXiv:1012.4515



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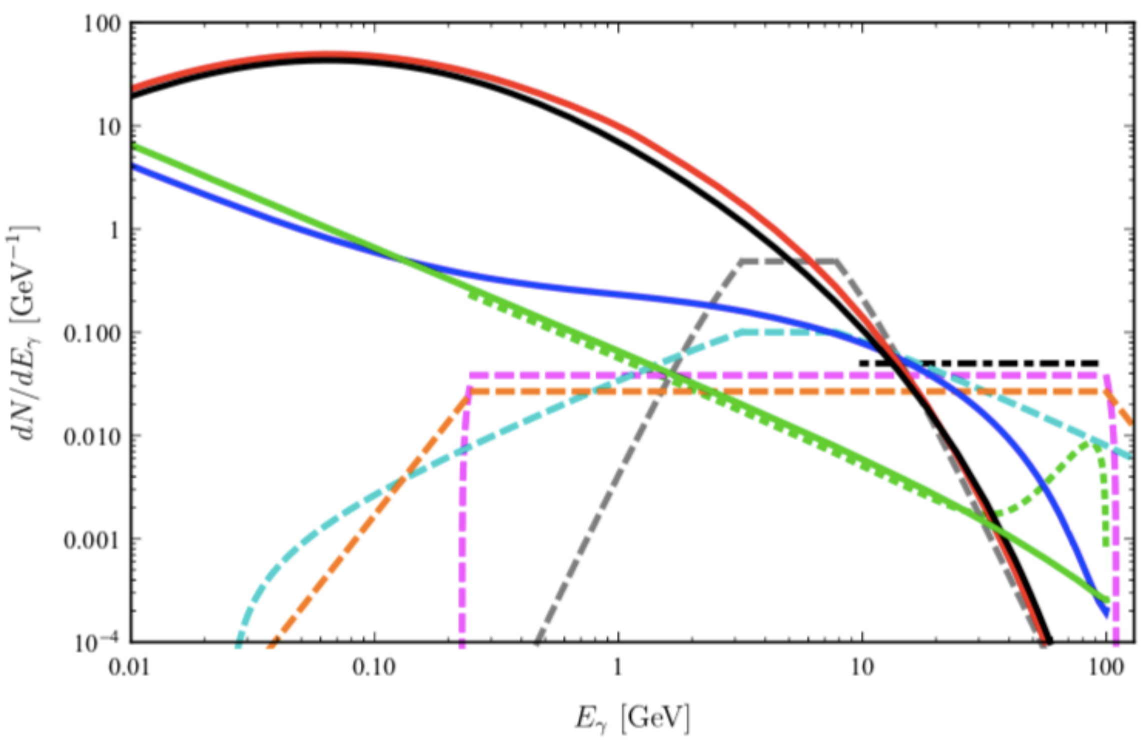
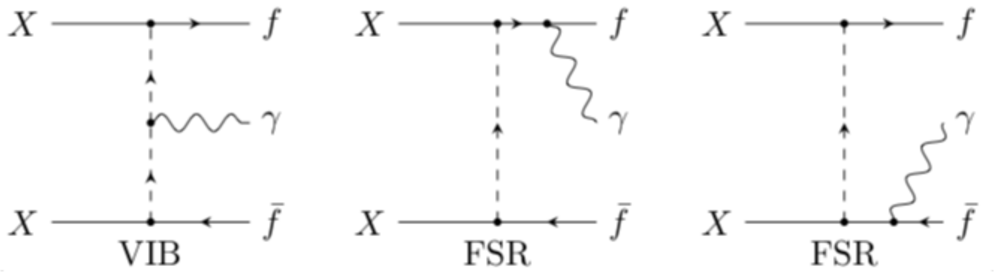
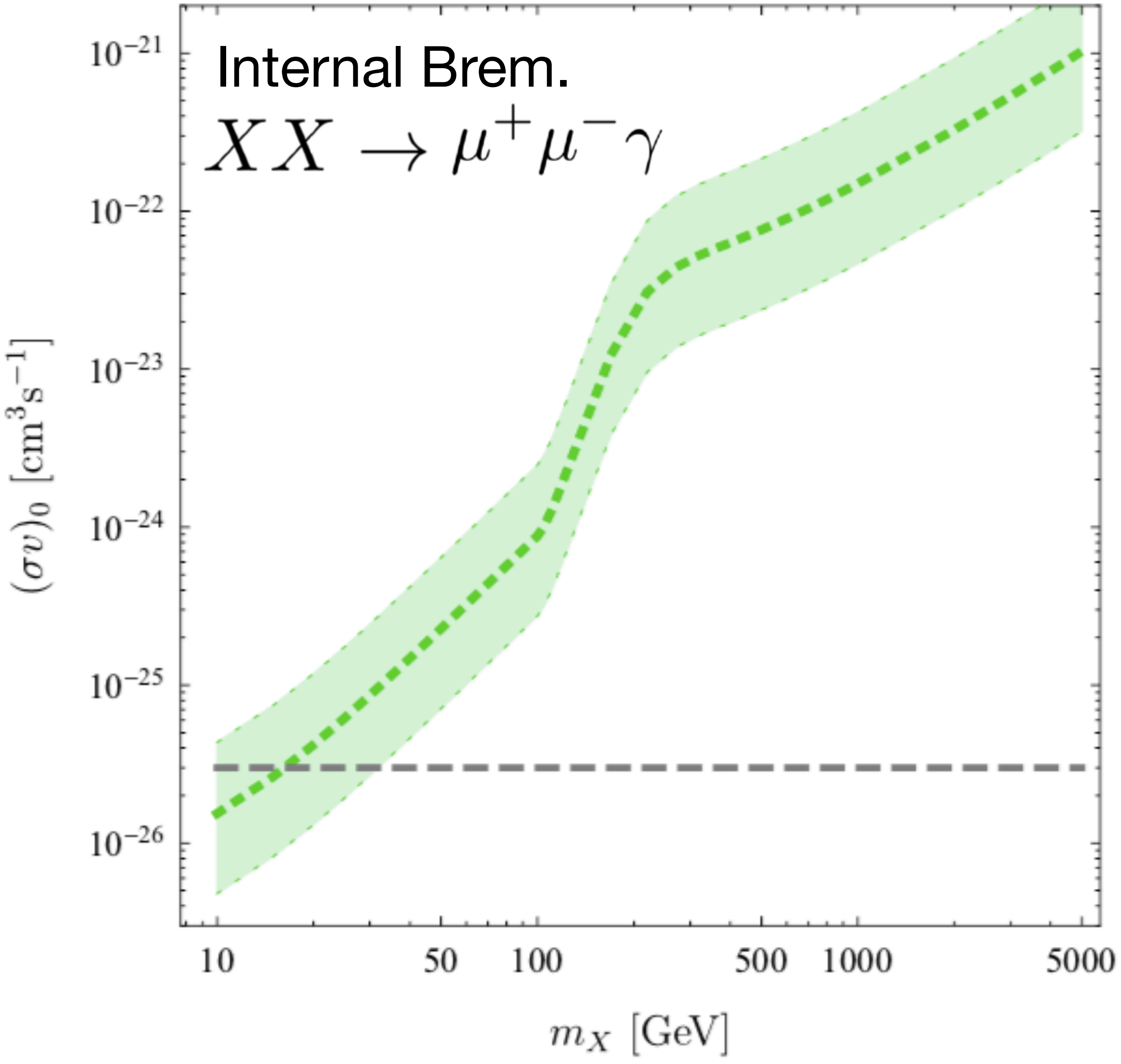


🟩 $XX \to \mu^+\mu^-\gamma$



arXiv:1605.03224



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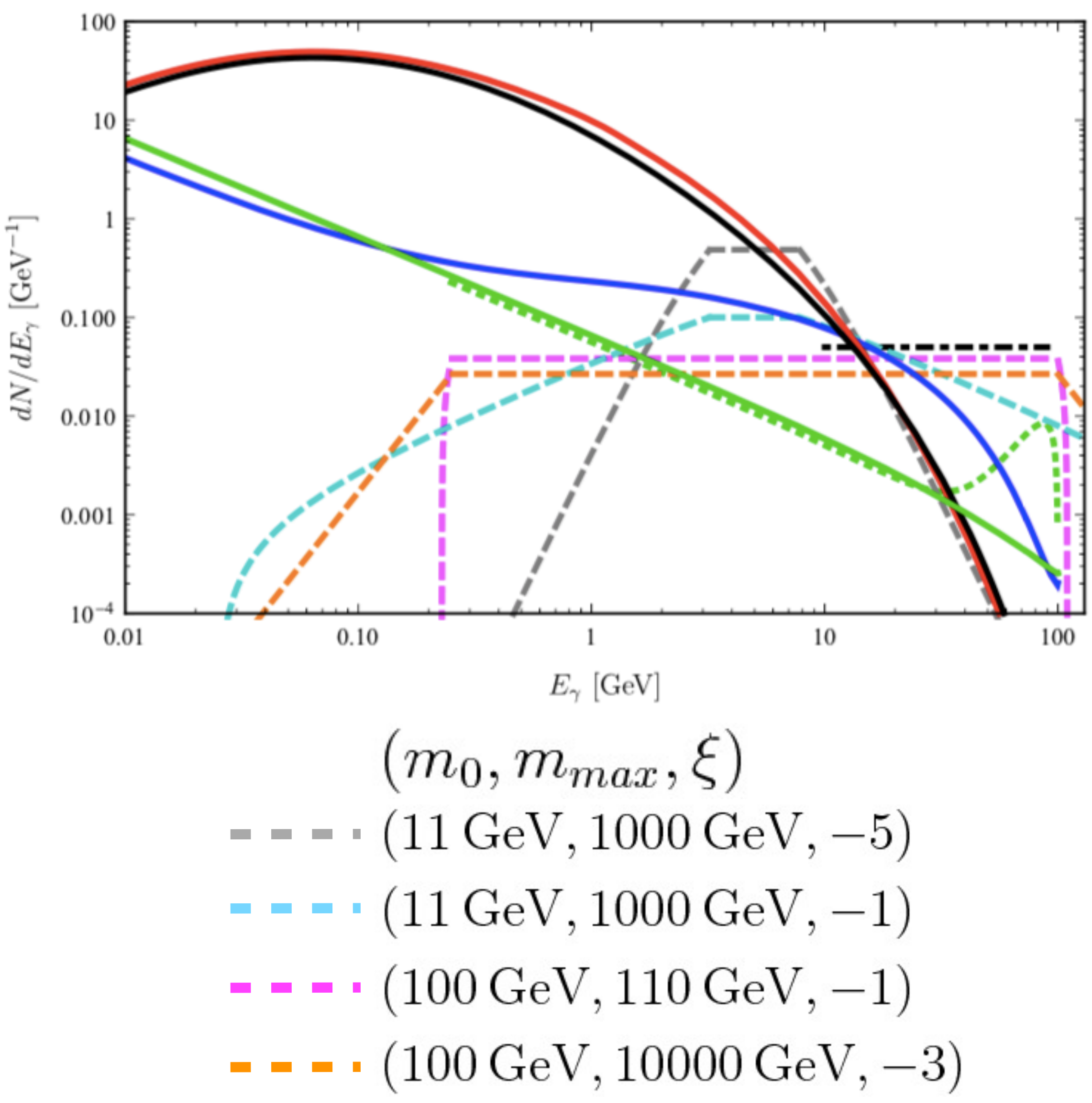
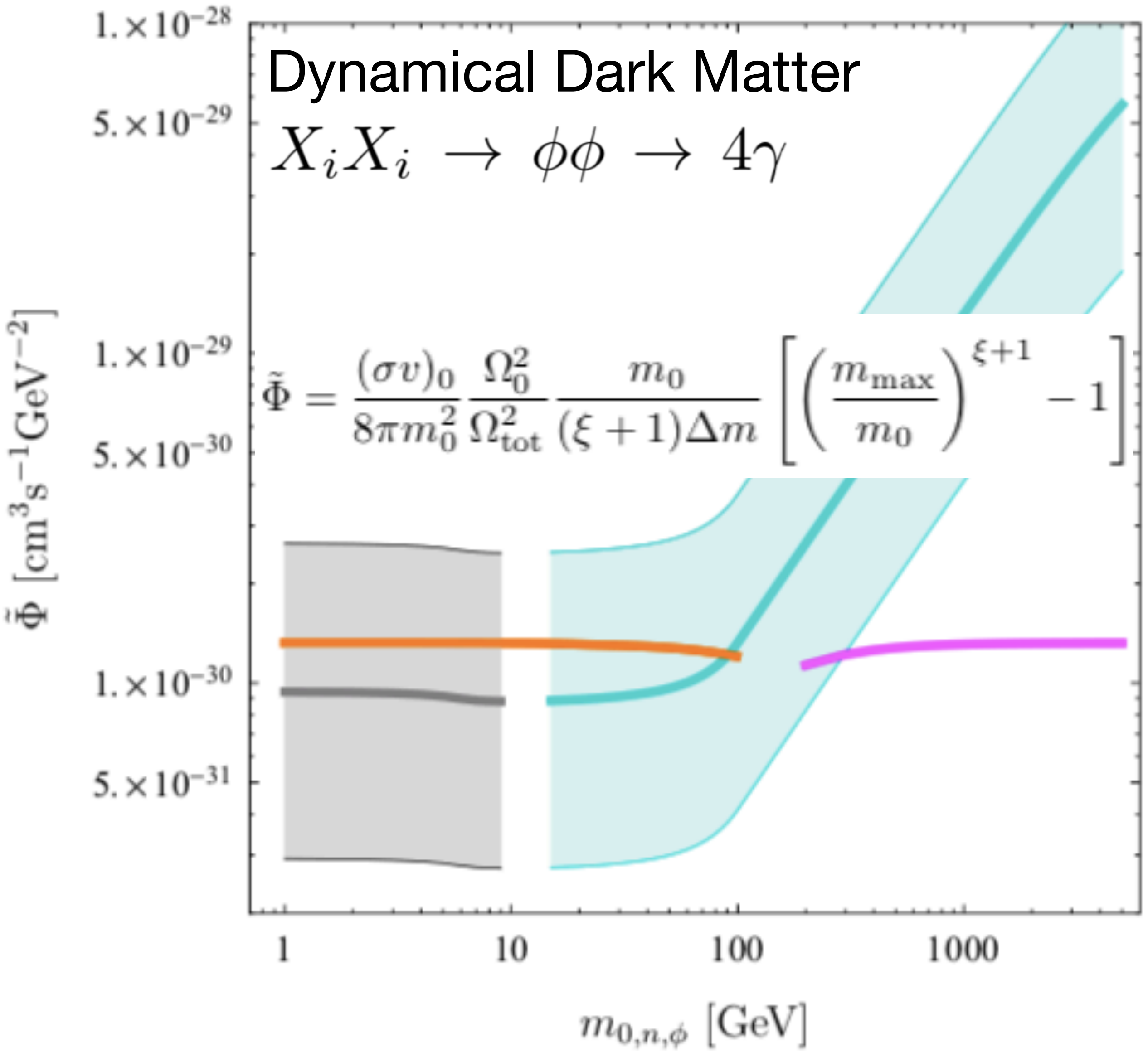


arXiv:1609.09104



Dynamical Dark Matter

$$X_i X_i \to \phi\phi \to 4\gamma$$

$$\tilde{\Phi} = \frac{(\sigma v)_0}{8\pi m_0^2} \frac{\Omega_0^2}{\Omega_{\mathrm{tot}}^2} \frac{m_0}{(\xi+1)\Delta m} \left[\left(\frac{m_{\mathrm{max}}}{m_0} \right)^{\xi+1} - 1 \right]$$

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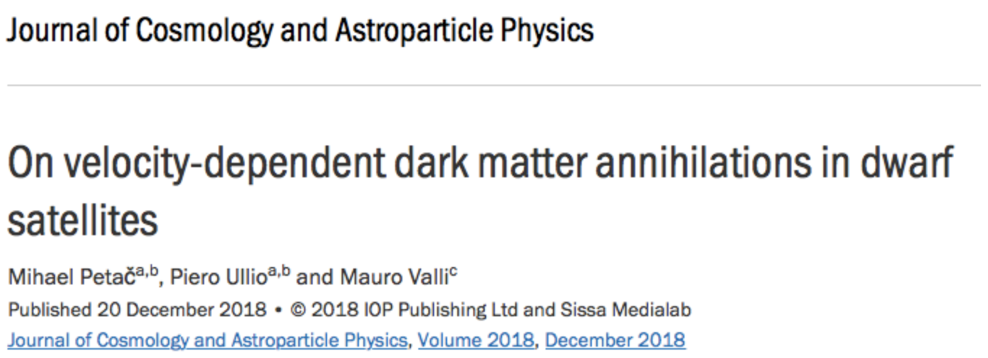
MADHAT: Model-Agnostic Dark Halo Analysis Tool

Jason Kumar (UH), Kim Boddy (JHU)
Stephen Hill (UH)

- Everyone should be able to do this analysis!
    - Stand-alone code
    - Interface with GAMBIT and others
- Inputs: dwarf set and J factors; integrated spectrum of photons in relevant energy range, DM mass
- Outputs: Nbound, PhiPP, cross section limit (if relevant)
- Status: code works, release soon (~1 month)

MADHAT: Model-Agnostic Dark Halo Analysis Tool

Jason Kumar (UH), Kim Boddy (JHU)
Stephen Hill (UH)



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On velocity-dependent dark matter annihilations in dwarf satellites

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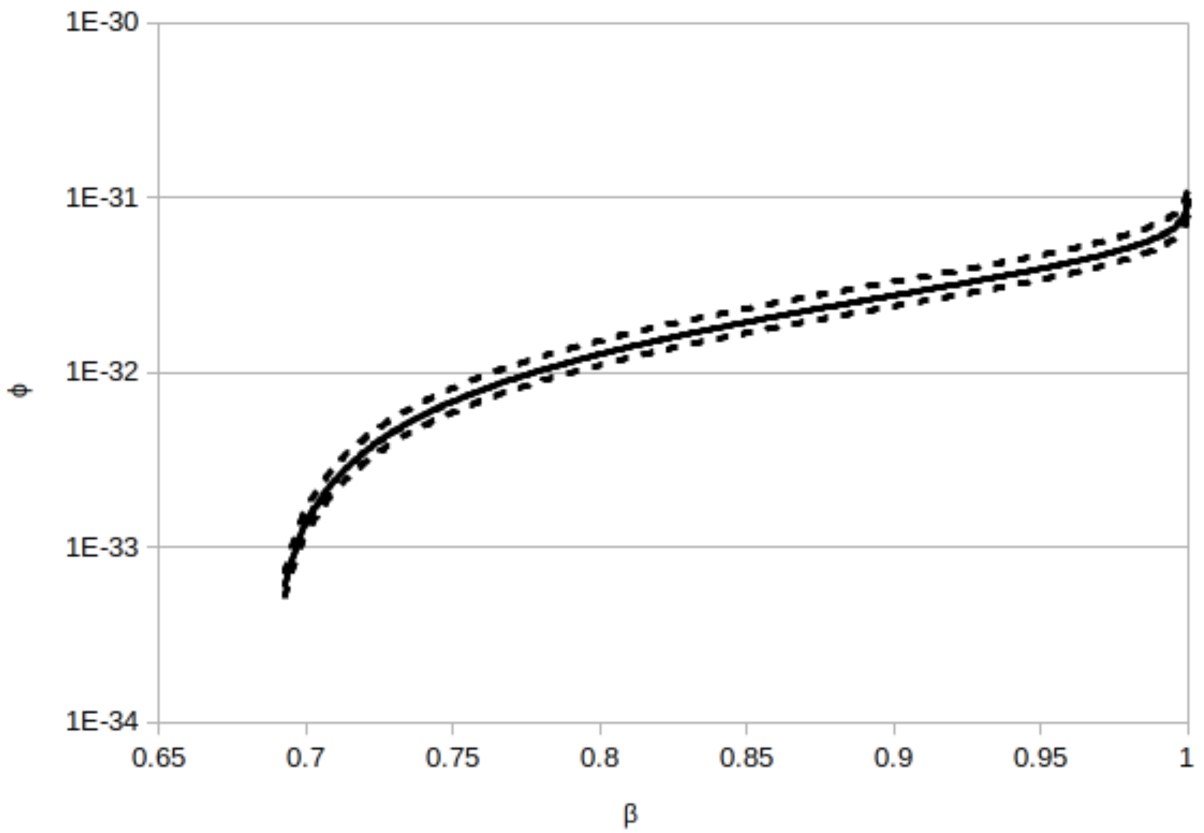

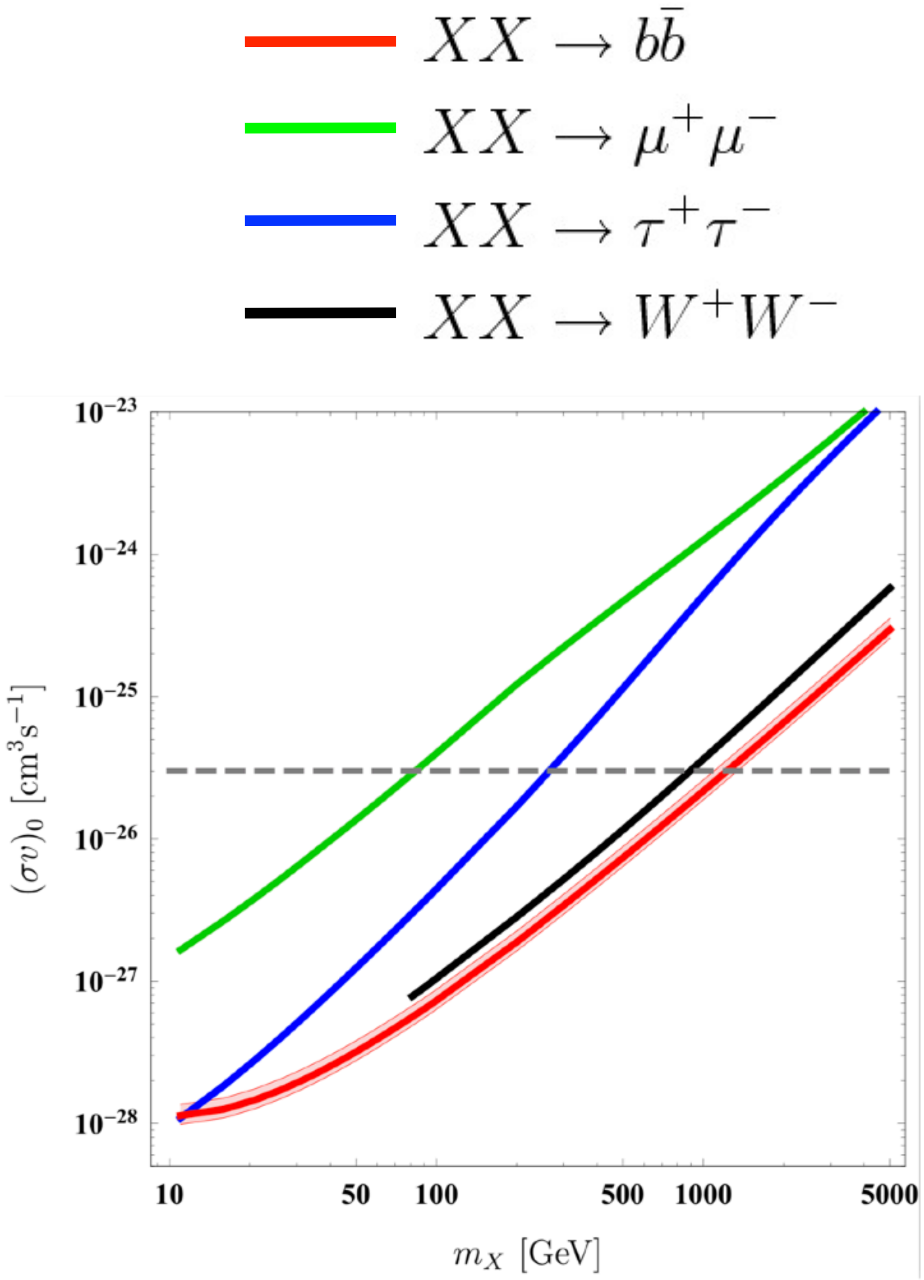

Summary

- **We constrain the number of DM annihilation photons, *completely independent of DM particle physics model or DM astrophysics.***
    - estimate the number of background (+foreground) photons empirically
    - constrain the number of DM signal photons statistically
- There is a minor loss of sensitivity relative to model-dependent searches, but this is an **important tool in light of new J-factor determinations and for DM models for which standard analyses are not applicable.**
    - eg. multi-body annihilation final states, final-state cascades, multi-component DM, nontrivial velocity dependence, etc.
- **MADHAT and GAMBIT-integrated version coming soon!**