An Improved Model-Agnostic Dark Halo Analysis Tool: *MADHAT* v2

Pearl Sandick

THE UNIVERSITY OF UTAH®

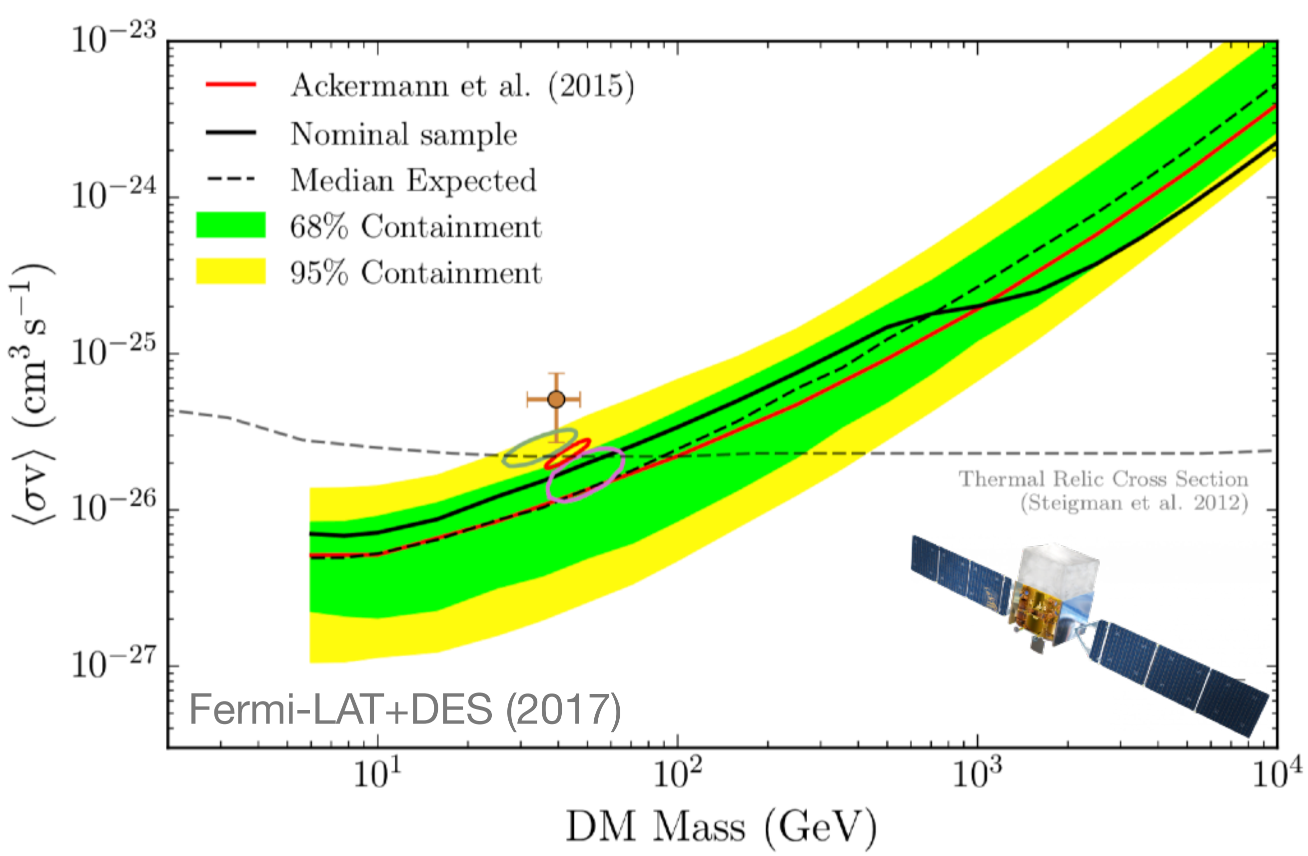
w/ Kim Boddy (UT Austin),
Zack Carter (UofU),
Jason Kumar (UH),
Luis Rufino (UofU → Syracuse)

Dark Matter Indirect Detection

- Dark matter annihilation flux (neutral):

$$\frac{d\Phi}{dE}_{\rm ann} \propto \frac{1}{m^2} \sum_f B_f \frac{dN_f}{dE}(E) \int d\Omega \int d\ell \, (\sigma_{\rm ann} v) \, \rho^2_{\rm DM}(r)$$

measure — assume — limit



<u>Key Assumptions</u>:

1. DM annihilates to b quark+antiquark
2. dark matter distribution
3. specific speed-dependence of annihilation

MADHAT: Model-Agnostic Dark Halo Analysis Tool

K. Boddy (JHU, UT Austin), S. Hill (UH), J. Kumar (UH),
P. Sandick (UofU), & B. Shams Es Haghi (UofU -> UT)

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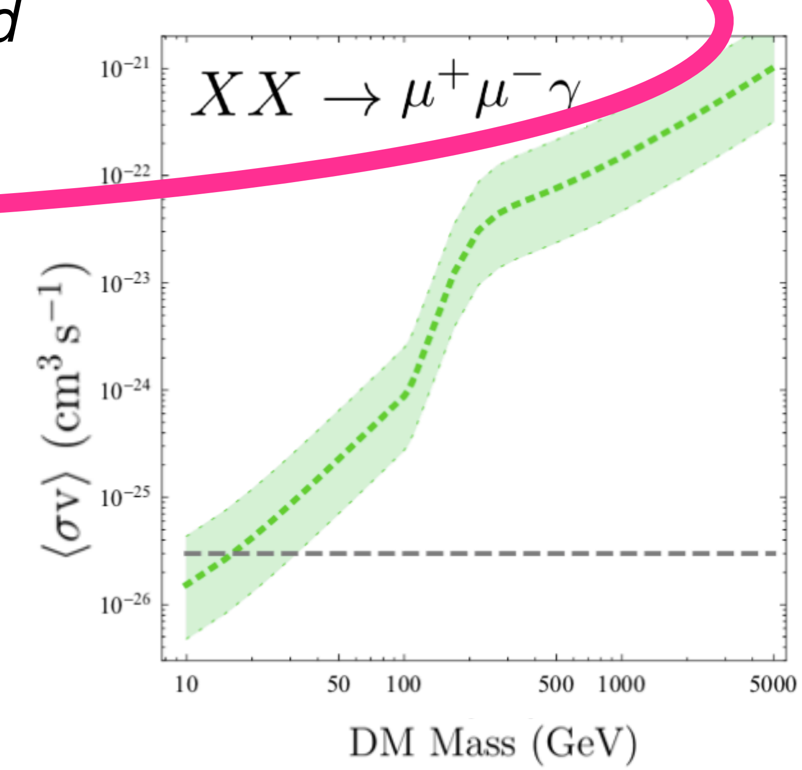
- **Goal: facilitate comparison of dark matter models with astrophysical data**
- **Goal: constrain the number of signal photons, *completely independent of dark matter particle physics model or dark matter astrophysics.***
    - determine the background (+foreground) distributions empirically- *no modeling*
    - use only number of photon counts - *no spectrum assumed*
    - simple stacking - *all photon events weighted equally*
- **Separation of observational data, dark matter distribution, and details of dark matter microphysics**
- ***MADHAT* v1.0 released September 12, 2019**

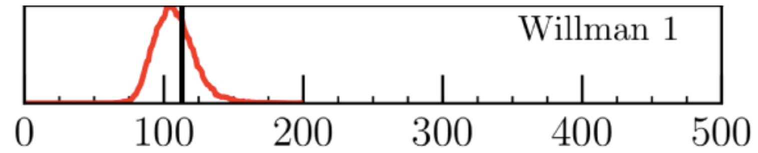


https://github.com/MADHATdm

How does it work?

- **determine the background (+foreground) distributions empirically- *no modeling***
- **use only number of photon counts - *no spectrum assumed***
- **simple stacking - *all photon events weighted equally***

  - *Choose an ROI with radius 10 deg., centered on a target signal region (0.5 deg. radius).*
  - *Construct background probability mass function (PMF) by randomly sampling regions within the ROI (staying away from known point sources and the target region). PMF is a normalized histogram of counts in sample regions.*



➡ *Count photons in range 1-100 GeV*

➡ *Constrain the number of photons from non-standard astrophysics statistically*

➡ *Extract limit for any new physics that predicts photons in that energy range*

Assume signal is Poisson-distributed. Expected total distribution is the convolution of the signal and the background. Bound on number of signal photons (N_{bound}) at CL β.

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

Constraining Dark Matter

- **For DM, the number of expected signal events depends on the particle physics, dark matter distribution, and exposure. *MADHAT* can constrain models that would have produced an unobserved excess.**

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

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

$$\sigma v = (\sigma v)_0 \times S(v)$$

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

- **Flexibility to choose target objects, input J-factors, specify DM model**

arXiv:1802.03826, 1910.02890

MADHAT v2

- **Two targets for improvement (for DM sensitivity):**

   1. *Binning energies* for increased sensitivity based on spectral features

      - 16 energy bins, 1 GeV to 100 GeV

   2. *Weighting photons* from target objects based on likelihood of DM origin

      - for *i* target objects (and *j* energy bins), define "optimal" weights:

$$w_{i,j} = \frac{N_{i,j}^{S(exp)}}{N_{i,j}^{B(exp)}}$$

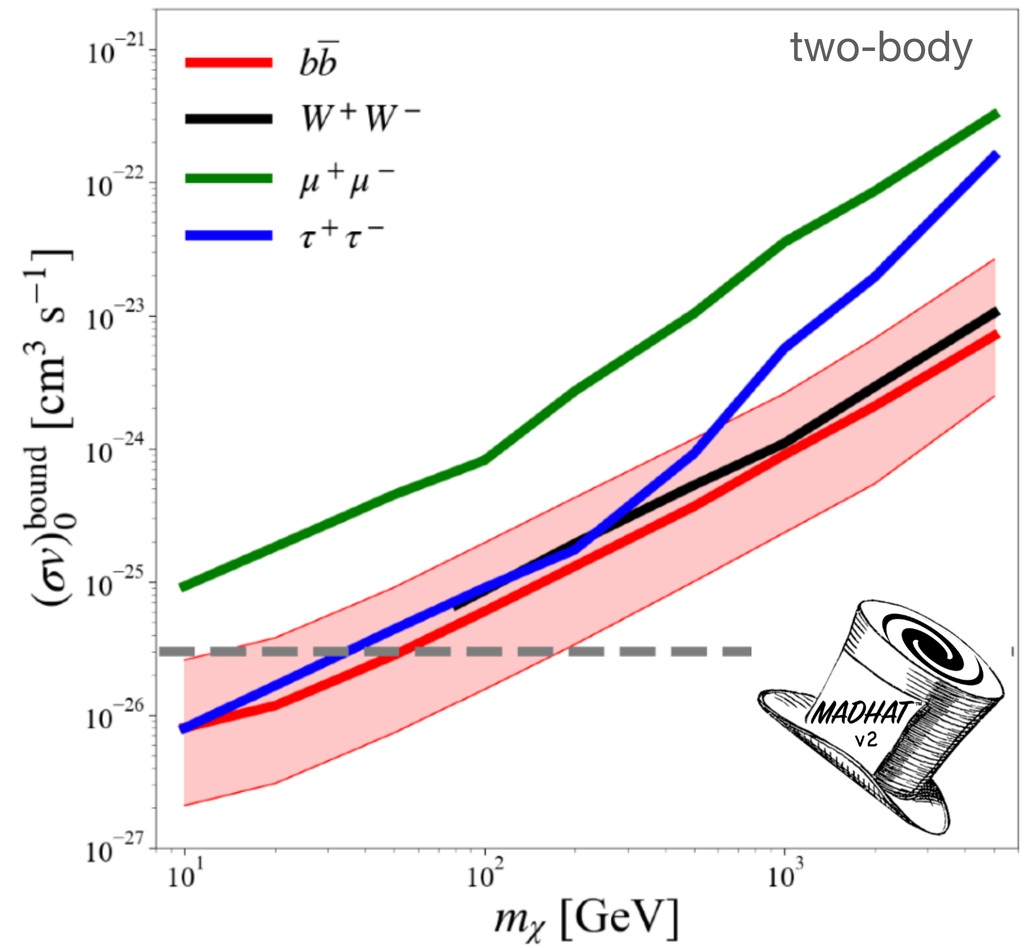
$N_{i,j}^{S(exp)}$ = expected signal count from target i in energy bin j

$N_{i,j}^{B(exp)}$ = expected background count from target i in energy bin j

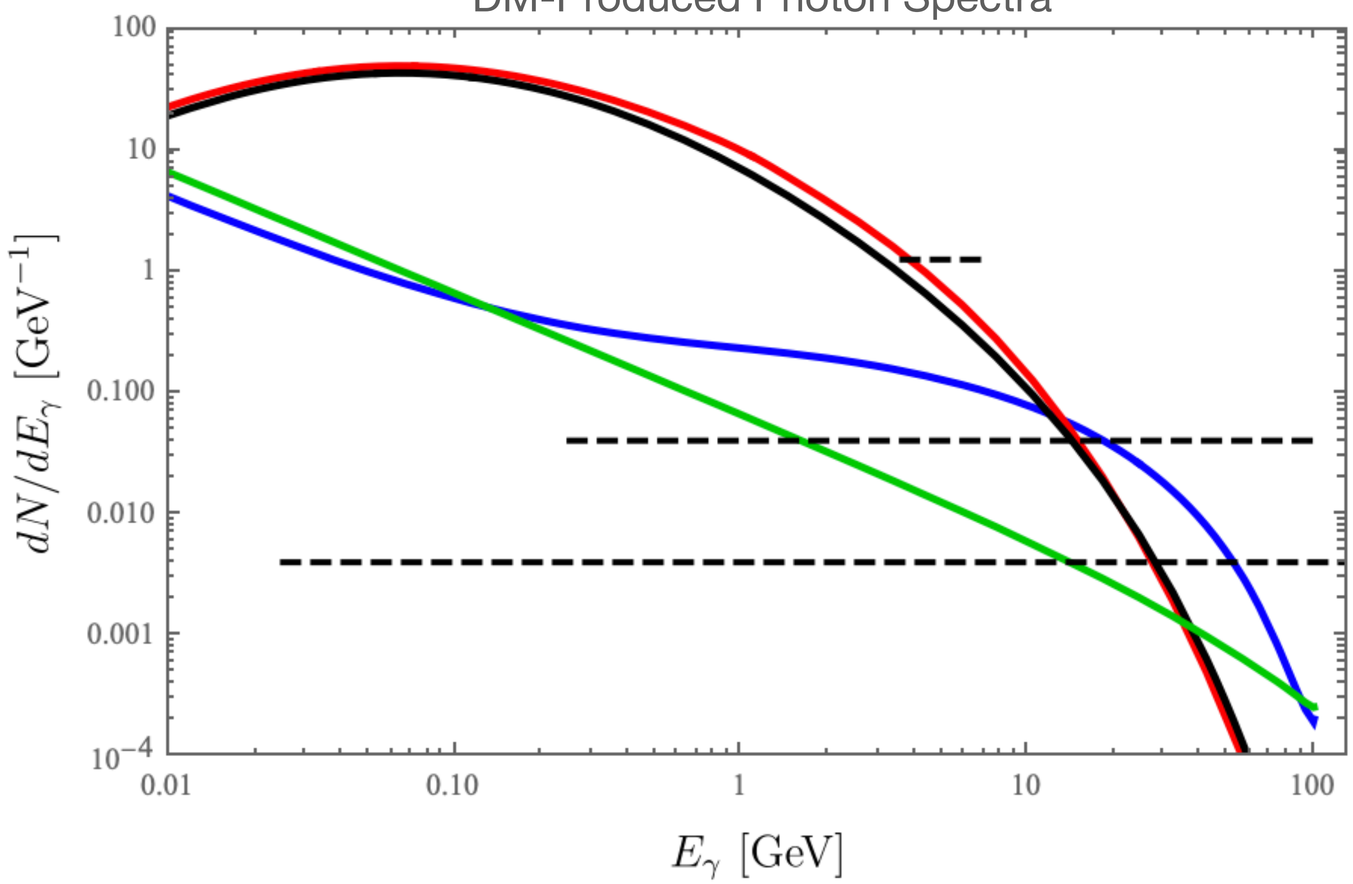
- Note: in *MADHAT* v2 there can't be a simple limit on the number of photons from all objects from non-standard astrophysics (no single N_{bound}). But one can obtain improved constraints for any specific model that produces excess photons.

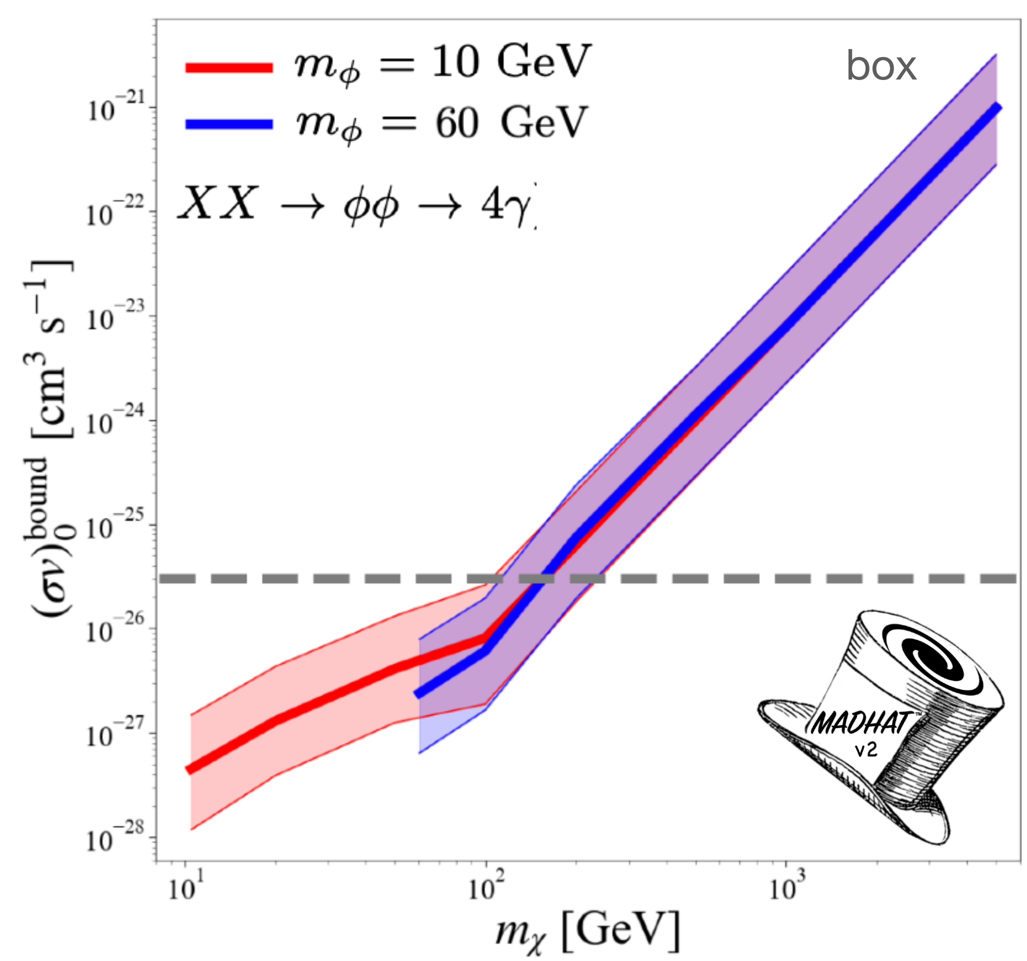
MADHAT v2 Results

- 14 years of Fermi-LAT data (Pass 8 Release 4 and 4FGL)
- 54 dwarfs (~100 objects now available for analysis)
- 16 energy bins, 1 - 100 GeV
- "optimal" target weighting
- Computational time: can run a model in ~1-2 hours on a single core (can check a model point in minutes)
- Note: these are not exceptionally strong bounds, but it is an extremely flexible tool.



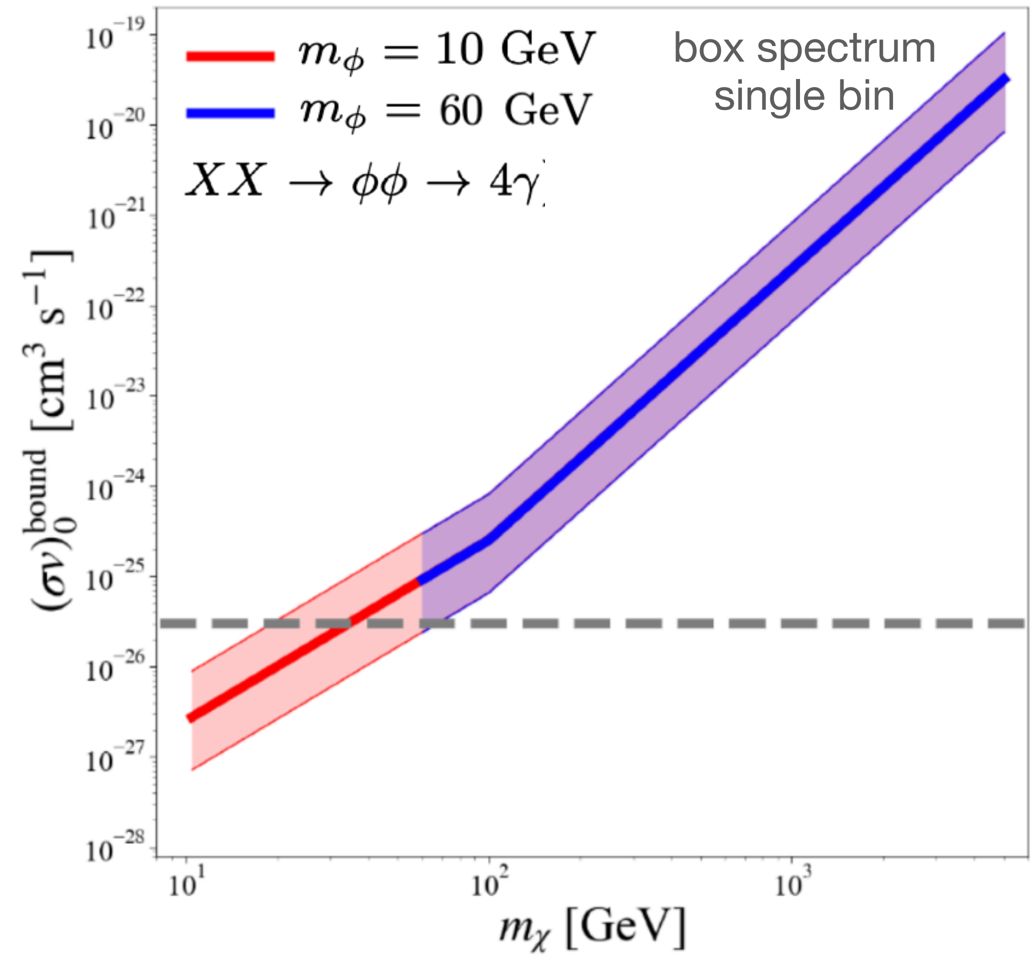
DM-Produced Photon Spectra

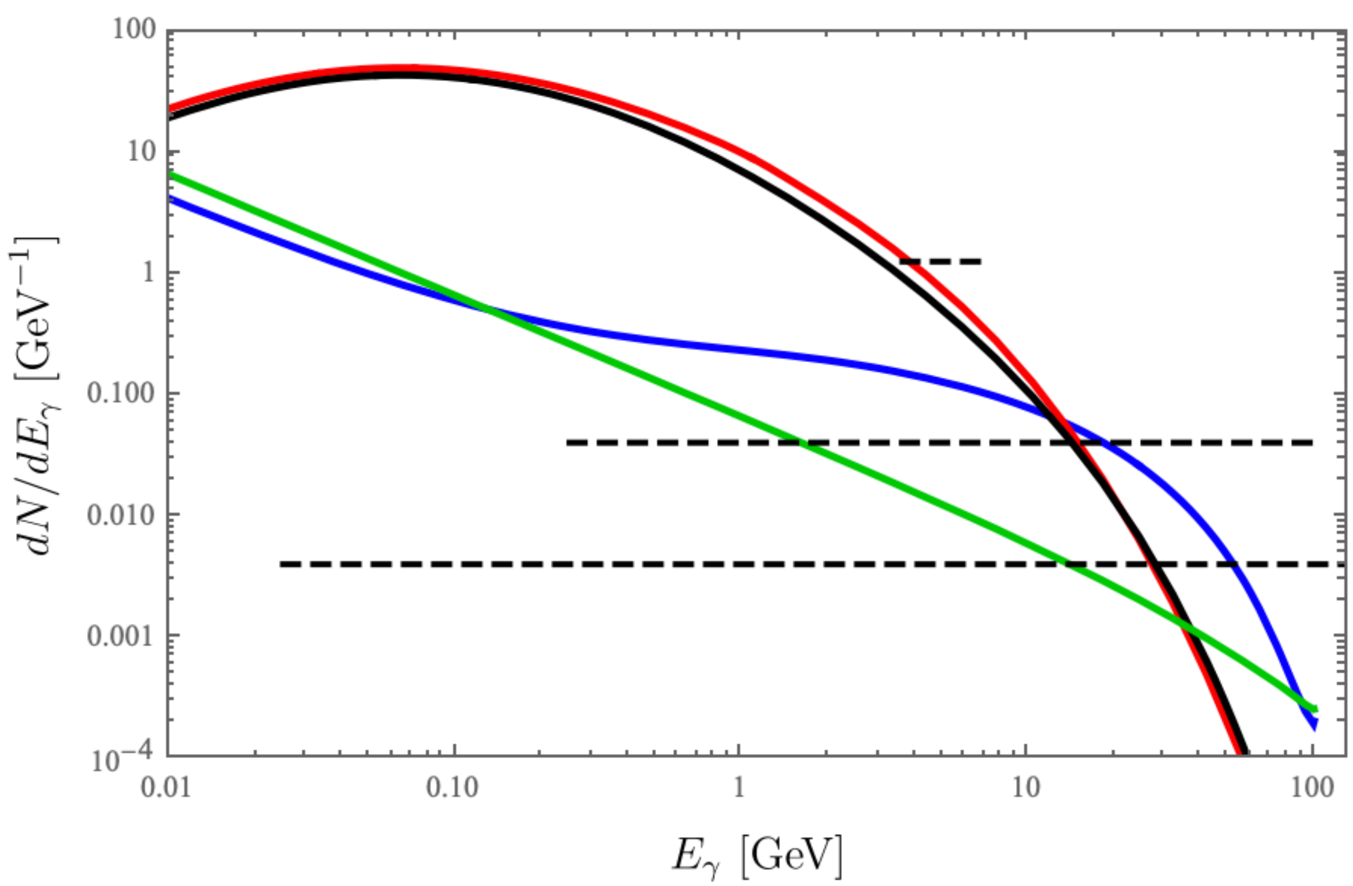


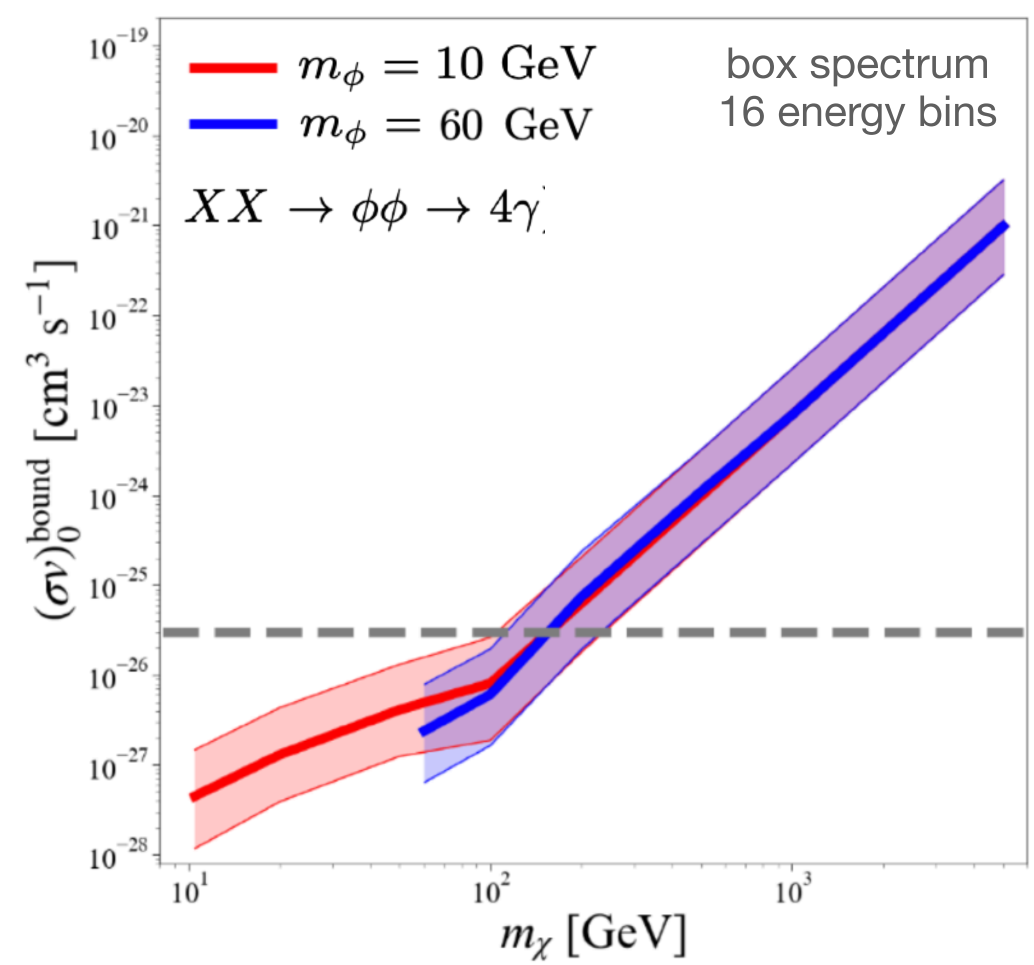


Energy Binning

- Enhanced sensitivity to distinct* spectral shapes.
  - ✳ "distinct" from a typical falling power law
- A new capability of *MADHAT*:
  - user can include model-specific spectra
  - user chooses set of target objects
  - MADHAT v2 will produce limits based on Fermi data from chosen objects

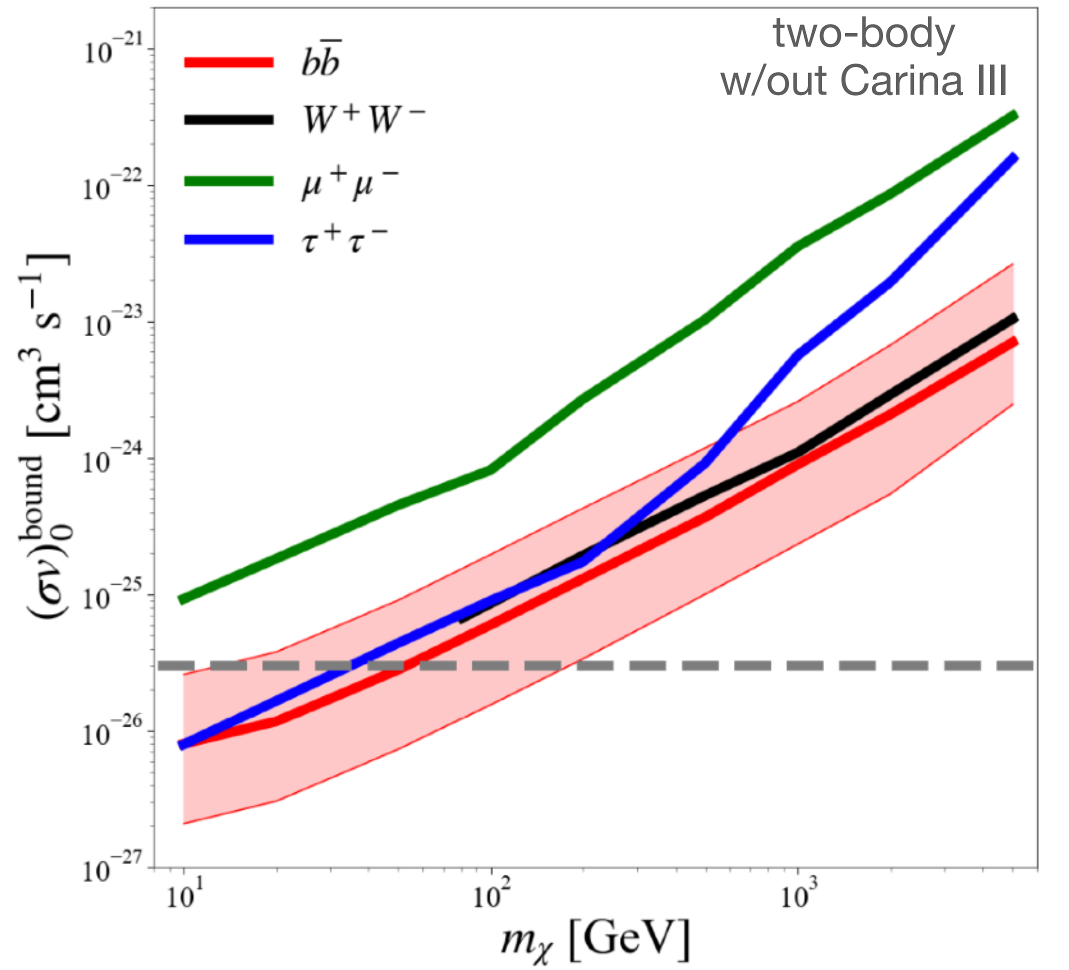


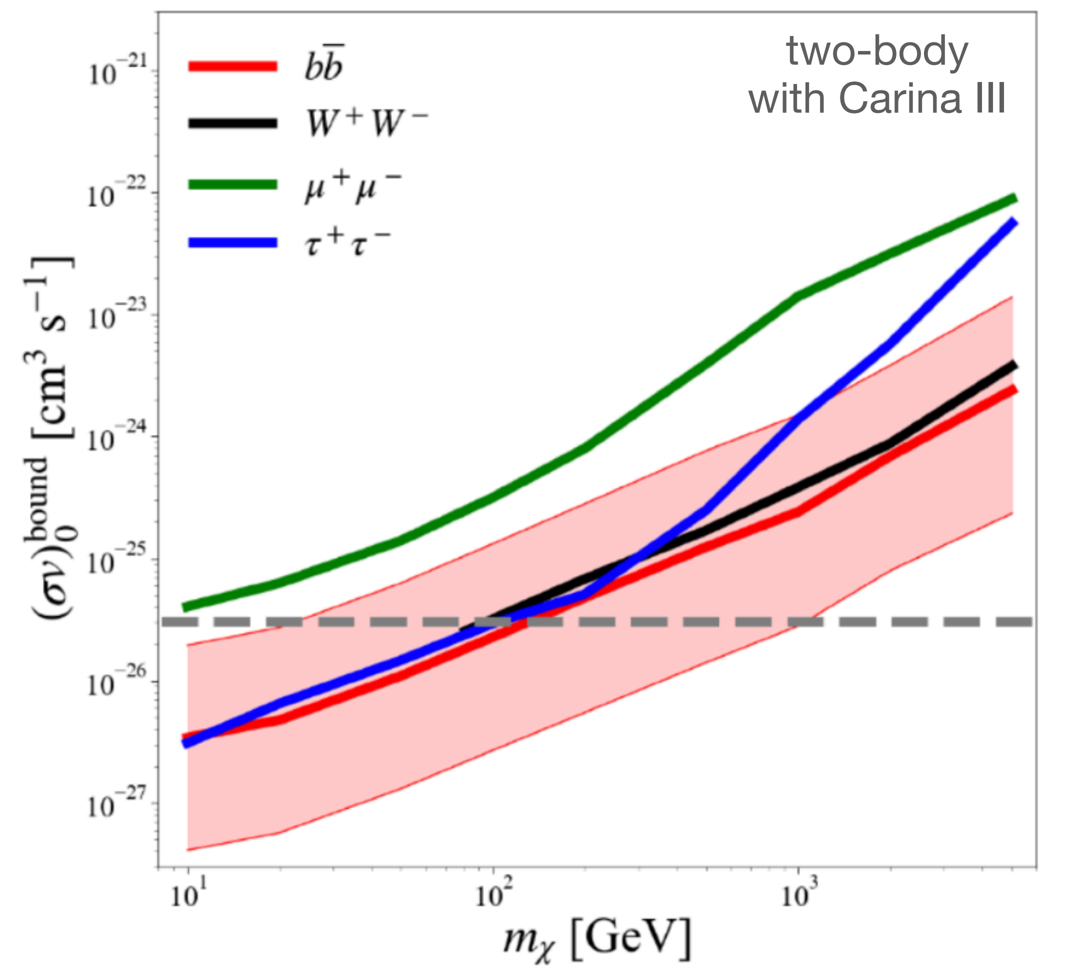




New targets? (Carina III, for example)

- Adding Carina III to the set of 53 target objects can substantially alter results! (Carina III's DM distribution is very uncertain, so don't take this too seriously.)
- Demonstrates importance of further study of Carina III and the ultrafaint dwarfs.
    - Ultrafaint dwarfs with smaller stellar populations that we find in the future may have a huge effect on dark matter constraints.
- This is a virtue of *MADHAT* - can appropriately include new objects in your analysis as you wish!





Summary

- *MADHAT* is a portable and flexible computational tool that can provide constraints on the number of gamma-ray photons from known Milky Way dwarf satellite galaxies, and can be used for *any model of dark matter particle physics or astrophysics*.

- *MADHAT* v2 incorporates spectral information via energy binning, and weights photons from different target objects based on the likelihood that the signal is due to dark matter, providing improved constraints on dark matter scenarios.

- New dwarf satellite galaxies and similar targets of interest (as will likely be discovered by Vera Rubin and other observatories) can be easily incorporated, with weighted impact, to an analysis. *MADHAT* can be updated rapidly with new data and/or new targets.

https://github.com/MADHATdm