Search for WIMP dark matter from dwarf spheroidal galaxies

Maja Llena Garde
maja.garde@fysik.su.se

Reference:

"Dark Matter Constraints from Observations of 25 Milky Way Satellite Galaxies with the Fermi Large Area Telescope"

Fermi-LAT Collaboration

arxiv:1310.0828

γ rays from Dark Matter

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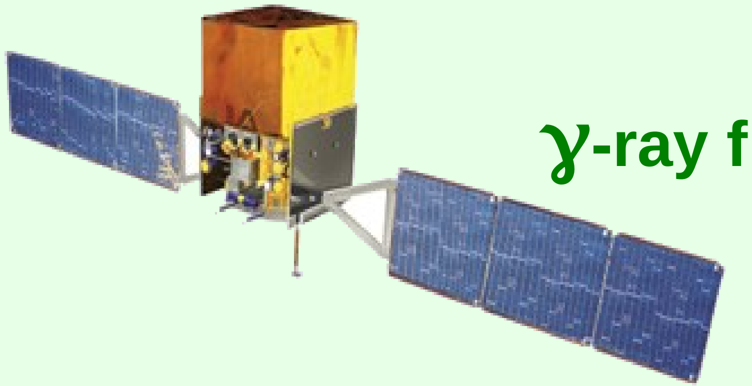
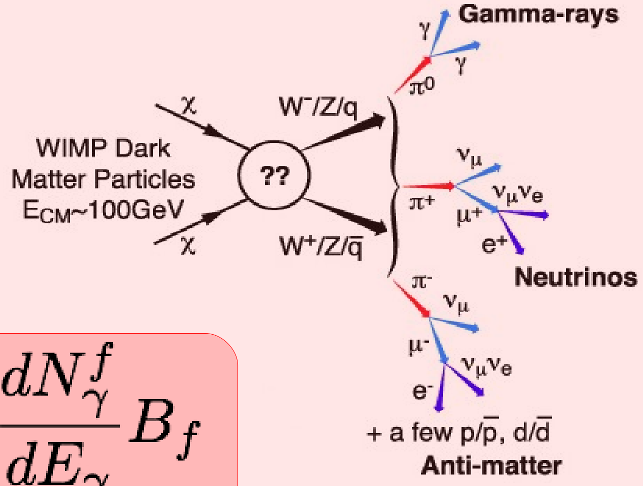


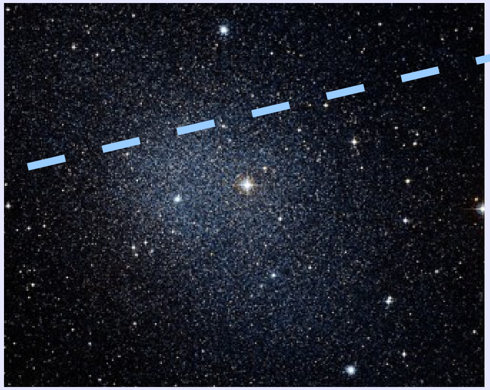
γ-ray flux

$$\Phi_{WIMP}(E_\gamma, \psi) = \frac{1}{4\pi} \frac{<\sigma_{ann} v>}{2\, m_{WIMP}^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f$$

Particle physics



$$\times \int_{l.o.s.} dl(\psi) \rho^2(l(\psi))$$



Dark Matter Distribution

"Astrophysical factor" or "J-factor"

Dwarf spheroidal galaxies

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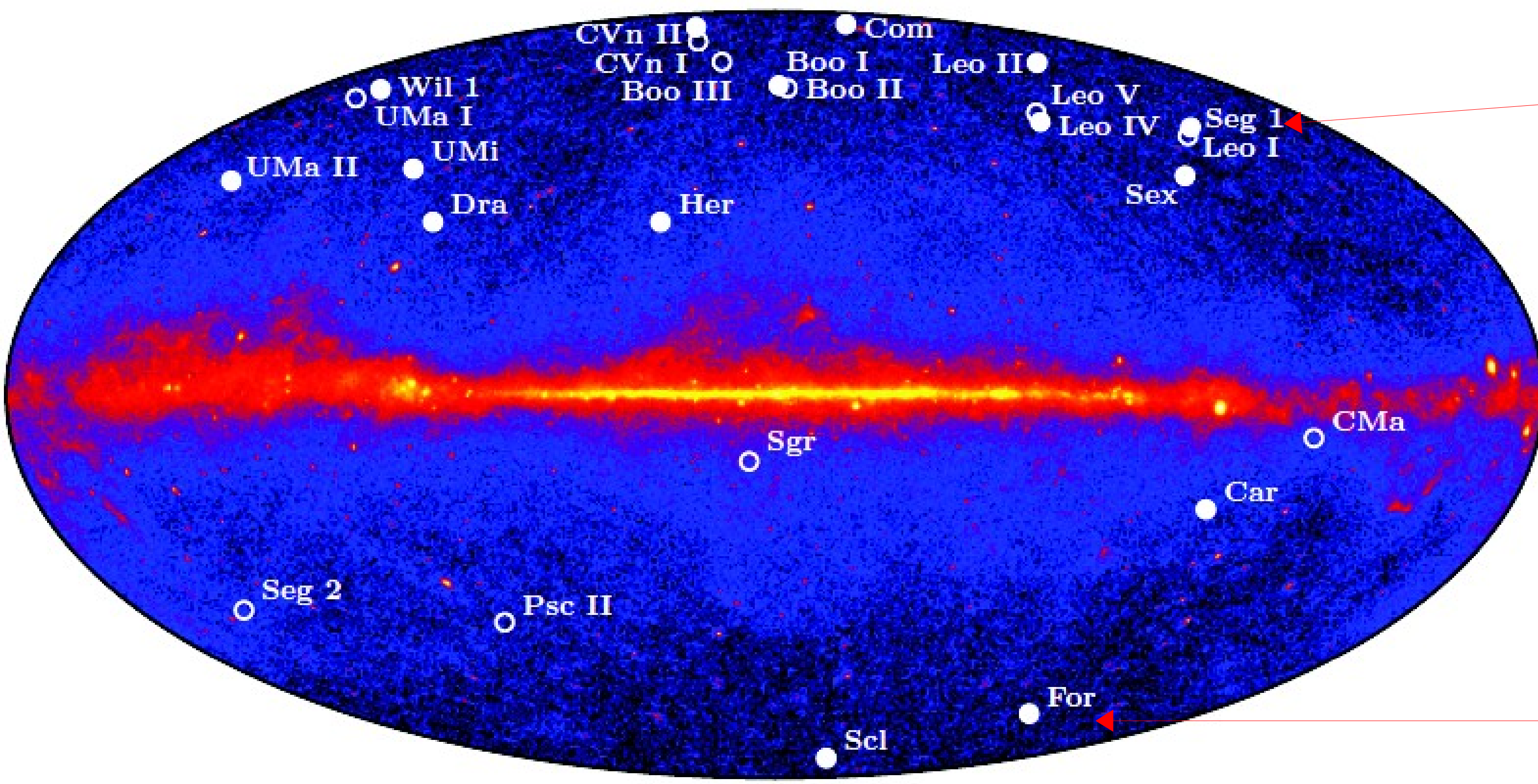
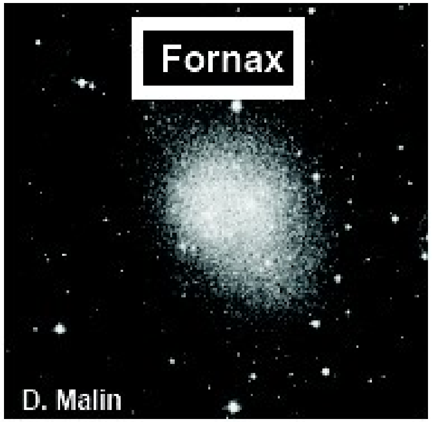
- ✔ dSphs are DM dominated systems (they have very high M/L ratios).
- ✔ Many dSphs are closer than 100 kpc to the Galactic Centre.
- ✔ Low background
  - Most dSphs are expected to be free from other astrophysical γ-ray sources.
  - Small content of gas and dust.





Joint Likelihood

- γ-ray spectrum is universal. J-factors individual.
- Joint likelihood (not data stacking) - add likelihood function of each spatially independent dSph, keep the dark matter cross section as common parameter across all likelihood functions:

Individual parameters (J-factors, backgrounds, near-by point sources)

$$\tilde{\mathcal{L}}(\mu, \{\alpha_i\} \mid \mathcal{D}) = \prod_i \mathcal{L}_i(\mu, \hat{\theta}_i \mid \mathcal{D}_i) \times \frac{1}{\ln(10) J_i \sqrt{2\pi}\sigma_i} e^{-(\log_{10}(J_i) - \overline{\log_{10}(J_i)})^2/2\sigma_i^2}$$

Likelihood for each target

Common parameters, ie dark matter properties

Statistical uncertainty in J-factor

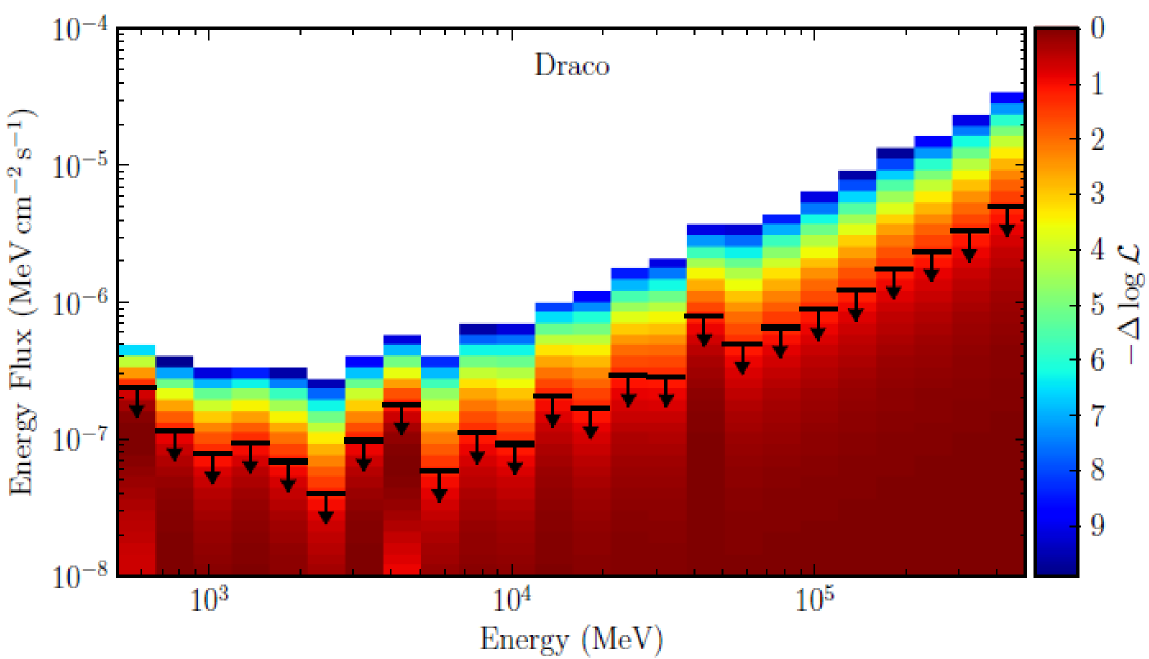
Maja Llena Garde
Fysikum, Stockholms Universitet

Analysis details

- 4 years of P7REP_CLEAN data (500 MeV - 500 GeV)
- Model galactic foreground, isotropic background and near-by point sources
- Make bin-by-bin analysis of 25 dSphs for flux upper limits
- Calculate dark matter content (J-factors) from stellar data for 18 dSphs
- Calculate dark matter upper limits for 18 dSphs for different annihilation channels
- Perform a joint likelihood analysis of 15 spatially independent dSphs
- Complementary Bayesian unfolding analysis

Bin-by-bin likelihood fit

- Analyze the data in a manner that is largely independent of source spectrum
- Set flux upper limits in each energy bin, but also retain the full likelihood profile in each bin.
- Fix background normalizations at best-fit value over all energy bins
- Keeping the full likelihoods in each energy bin allows us to recreate the full spectrally dependent likelihood
- Compare to expected sensitivity from simulations



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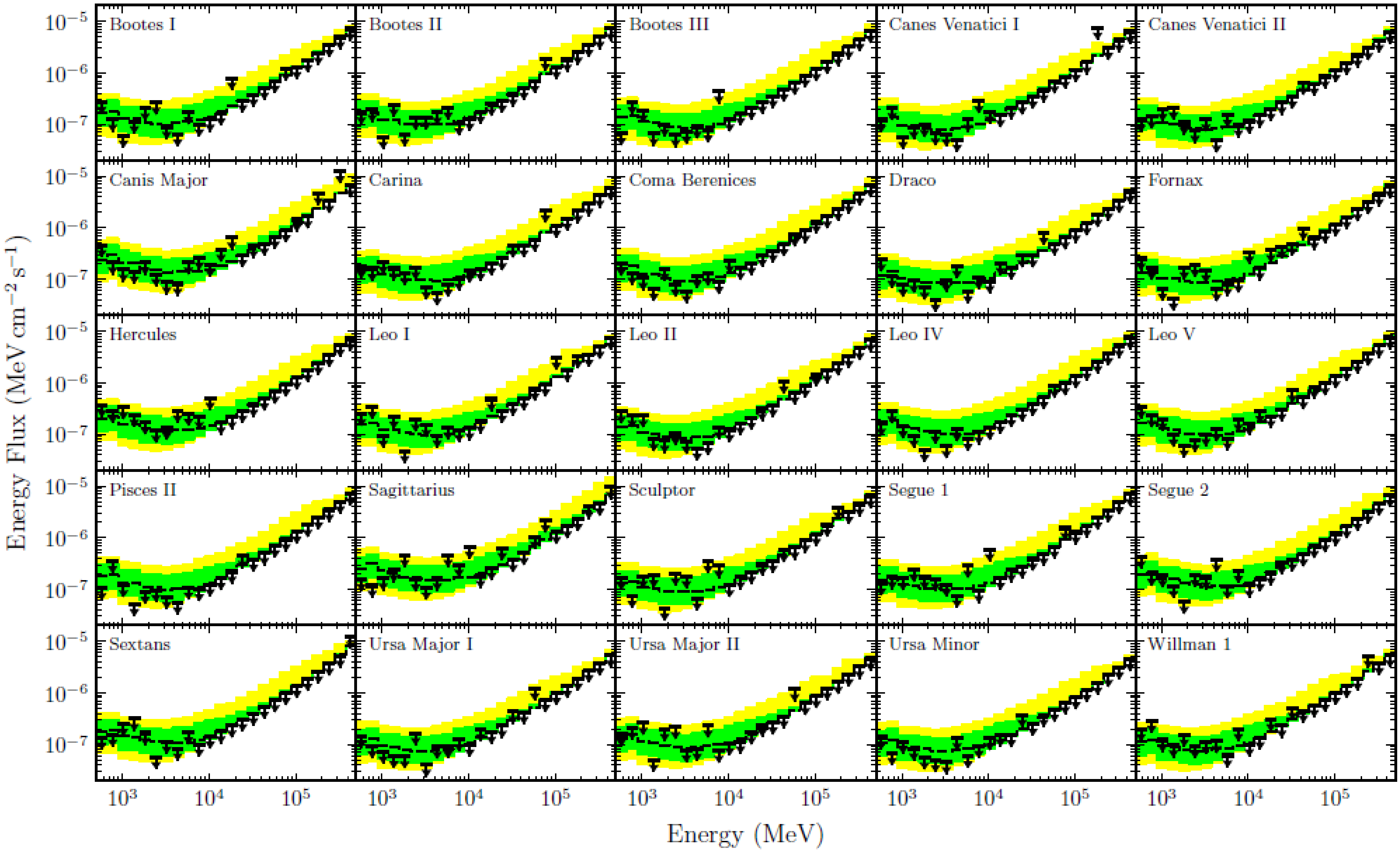
Bin-by-bin flux upper limits

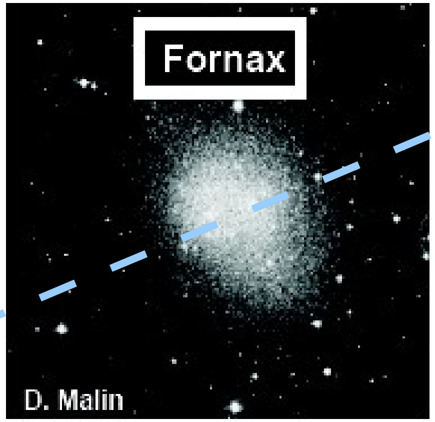
Sensitivities from 2000 realistic Monte Carlo simulations of the null hypothesis

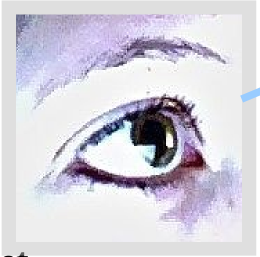


Dark matter content (J-factor)

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

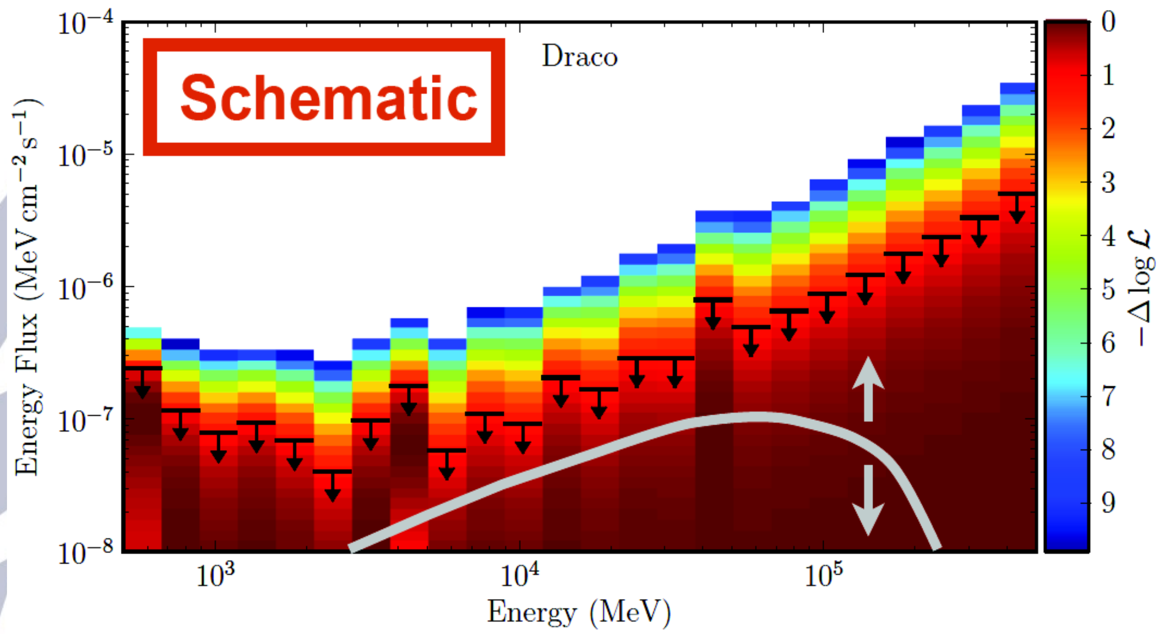
- Determine the dark matter content from stellar data
  - Classical dSphs: several thousand stars
  - Ultra-faint dSphs: fewer than 100 stars
- J-factors are determined by using a Bayesian hierarchical modeling
  - Use the population of dSphs to constrain priors on dark matter parameters
  - Reduce dependence on N-body simulations
- Calculate the integrated J-factor within 0.5 deg.





Global likelihood analysis

- Make a global likelihood by assuming a spectral model
- Include statistical uncertainty in the J-factor as a nuissance parameter
- Model the Spatial distribution of the putative γ-ray source according to the dark matter profile in the dSphs
- Constrain the maximum cross section allowed by the data



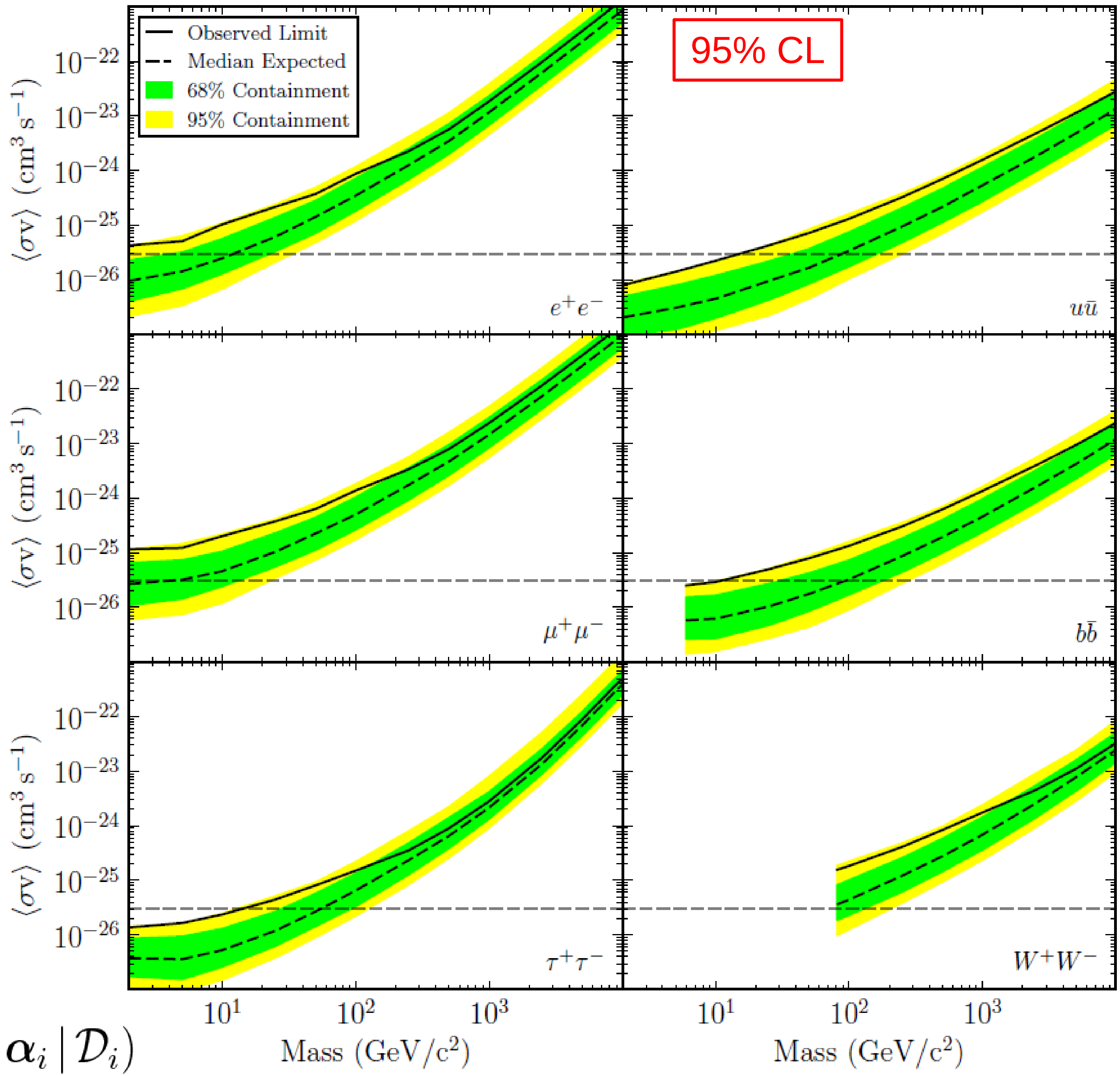
$$\tilde{\mathcal{L}}_i(\mu, \alpha_i \,|\, \mathcal{D}_i) = \mathcal{L}_i(\mu, \hat{\theta}_i \,|\, \mathcal{D}_i) \times \frac{1}{\ln(10) J_i \sqrt{2\pi}\sigma_i} e^{-(\log_{10}(J_i) - \overline{\log_{10}(J_i)})^2 / 2\sigma_i^2}$$

Global Fermi-LAT likelihood

Statistical uncertainty in J-factor

Dark Matter Upper Limits

- Combined limits from 15 dSphs
- 4 years of data
- Expected sensitivity from data (300 sets of 15 random sky positions)
- Slight discrepancy for soft dark matter spectra



$$\tilde{\mathcal{L}}(\boldsymbol{\mu}, \{\boldsymbol{\alpha}_i\} \mid \mathcal{D}) = \prod_i \tilde{\mathcal{L}}_i(\boldsymbol{\mu}, \boldsymbol{\alpha}_i \mid \mathcal{D}_i)$$

Conclusions

- No significant γ-ray signal coincident with any of the 25 dSphs for any of the spectral models tested.
- We present a combined analysis of 15 dSphs to constrain the dark matter annihillation cross section.
- We find the largest excess for models with 10 GeV to 25 GeV WIMPs annihilating through the b-bbar channel.
- This excess corresponds to a Gaussian significance of ~1.4σ (obtained through studies of random blank fields).
- The systematic uncertainties arising from the LAT IRFs, diffuse modeling and modeling of the dark matter distribution individually impact the limits on the ~15% level.

Back-up slides

Maja Llena Garde
Fysikum, Stockholms Universitet

Significant excess?

- Largest excess at 25 GeV b-bbar
- Significance of ~1.4σ
- Distribution of TS values in the data does not follow asymptotic theorems

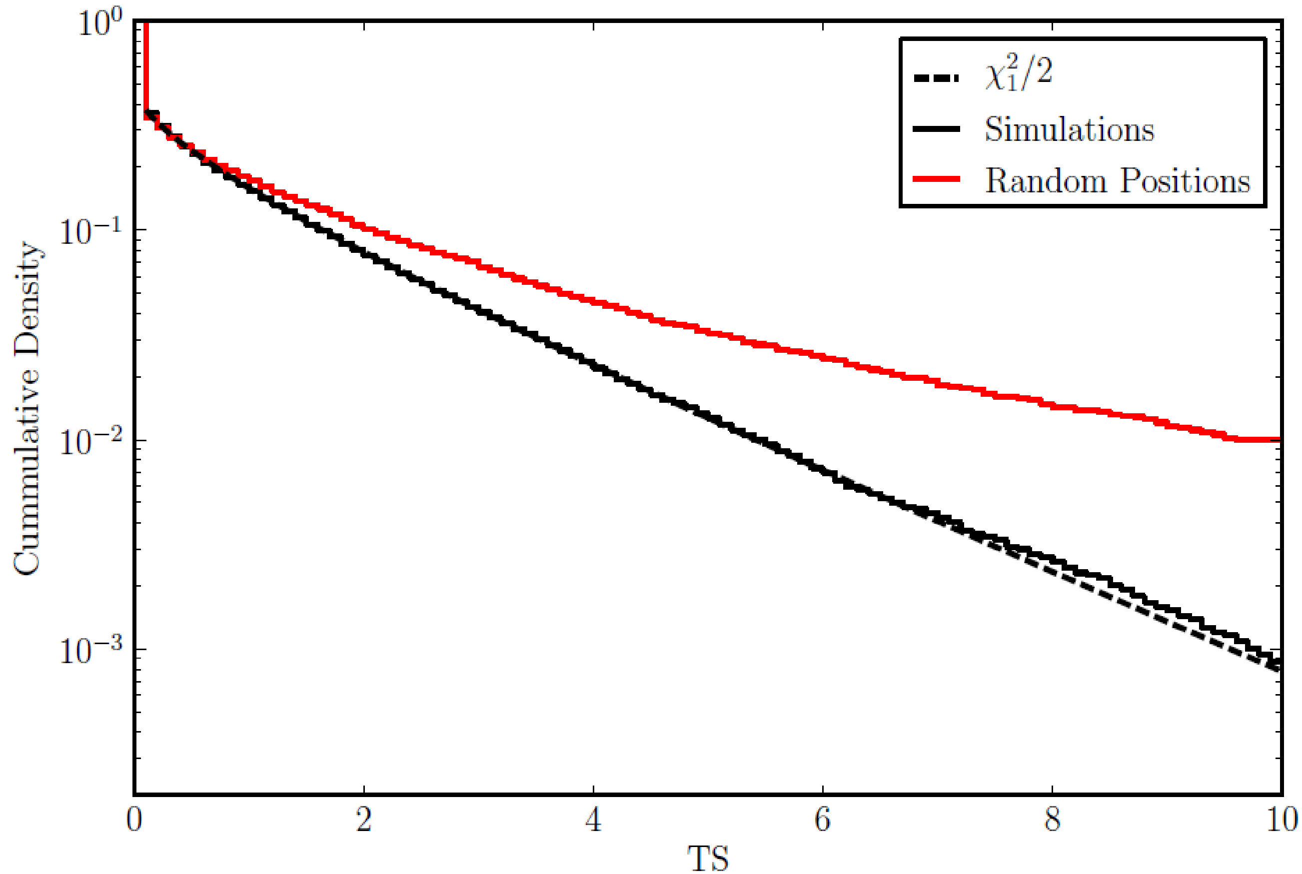


FIG. 4. Distribution of TS values from individual fits of a 25 GeV $b\bar{b}$ annihilation spectrum to the null hypothesis generated from 50000 realistic Monte Carlo simulations and 7500 random blank-sky locations at high latitude in the LAT data. The distribution of TS values derived from simulations of individual ROIs is well matched to the expectations from the asymptotic theorem of Chernoff [70], while the distribution derived from random sky positions shows an excess at high TS values.

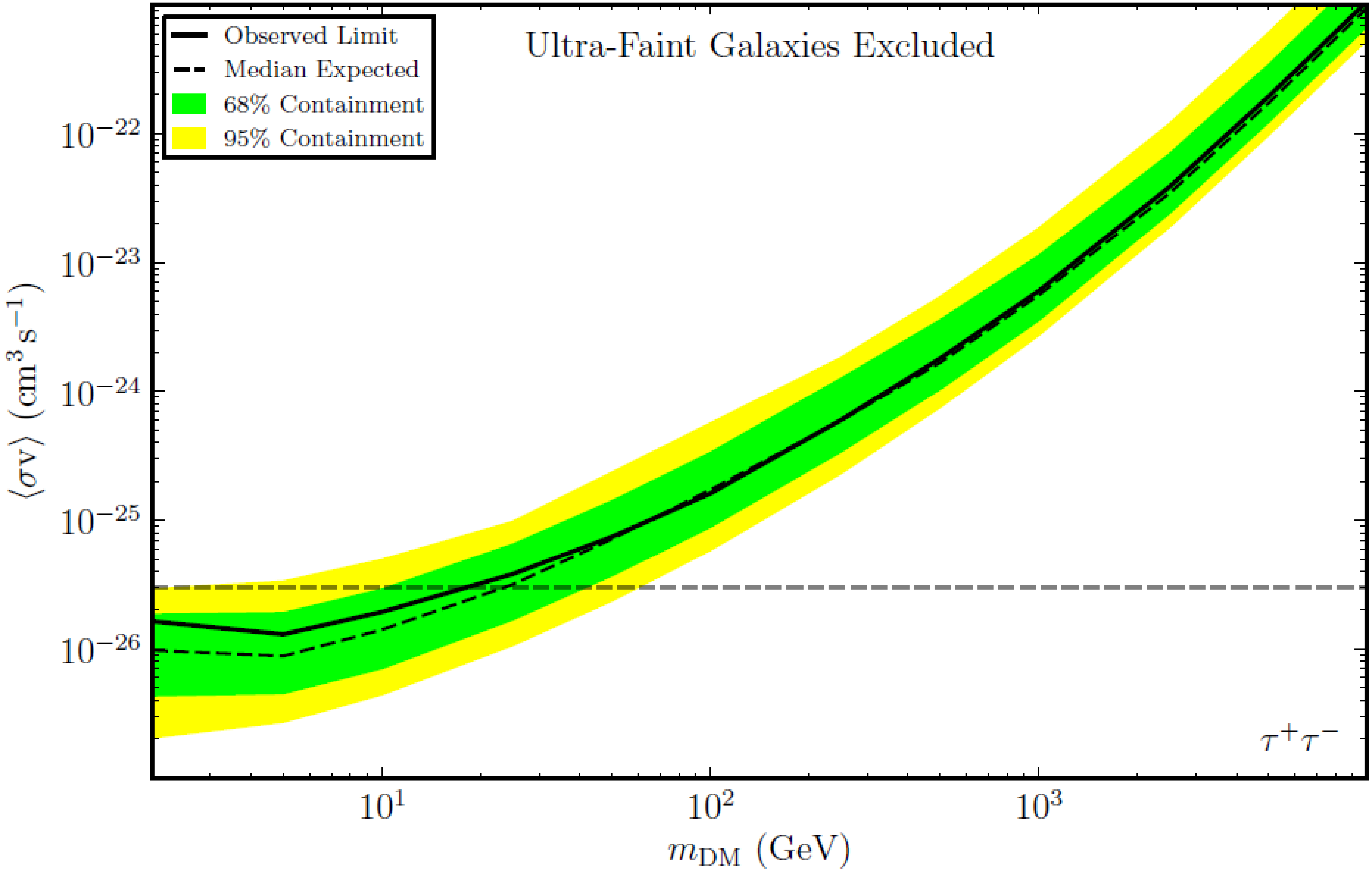


FIG. 6. Constraints on the dark matter annihilation cross section ($\tau^+\tau^-$ channel) at 95% CL derived from a combined analysis excluding three ultra-faint dwarf galaxies: Segue 1, Ursa Major II, and Willman 1 (solid line). The expected sensitivity is similarly calculated excluding these three ultra-faint dwarf galaxies and is represented in the same manner as in Figure 5.

TABLE VIII. Systematic uncertainties on the maximum likelihood analysis decomposed into contributions from the IRFs, the diffuse modeling, and the spatial extension of the dark matter profile. Entries represent the percentage change to the combined upper limits on the dark matter annihilation cross section from varying each component individually.

		10 GeV	100 GeV	1000 GeV	10000 GeV
e^+e^-	IRFs	+14%/-12%	+12%/-10%	+11%/-9%	+11%/-9%
	Diffuse	+3%/-4%	+3%/-3%	+1%/-1%	+1%/-1%
	Extension	+7%/-5%	+17%/-11%	+11%/-6%	+10%/-6%
$\mu^+\mu^-$	IRFs	+15%/-12%	+12%/-10%	+11%/-9%	+11%/-9%
	Diffuse	+4%/-5%	+3%/-4%	+2%/-1%	+1%/-1%
	Extension	+7%/-5%	+15%/-10%	+11%/-6%	+10%/-6%
$\tau^+\tau^-$	IRFs	+15%/-13%	+12%/-10%	+13%/-11%	+12%/-10%
	Diffuse	+5%/-5%	+1%/-5%	+1%/-1%	+0%/-1%
	Extension	+6%/-4%	+14%/-9%	+13%/-7%	+6%/-3%
$u\bar{u}$	IRFs	+15%/-14%	+14%/-12%	+12%/-10%	+11%/-9%
	Diffuse	+9%/-4%	+3%/-4%	+3%/-4%	+2%/-3%
	Extension	+4%/-3%	+9%/-7%	+12%/-8%	+12%/-7%
$b\bar{b}$	IRFs	+15%/-13%	+14%/-12%	+12%/-10%	+11%/-9%
	Diffuse	+10%/-3%	+4%/-5%	+2%/-4%	+2%/-3%
	Extension	+3%/-2%	+8%/-6%	+12%/-8%	+12%/-7%
W^+W^-	IRFs	–	+14%/-12%	+12%/-10%	+13%/-11%
	Diffuse	–	+4%/-4%	+2%/-4%	+1%/-1%
	Extension	–	+8%/-6%	+13%/-8%	+14%/-8%