Constraining dark matter signal from a combined analysis of Milky Way satellites with the Fermi-LAT

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On behalf of the Fermi-LAT collaboration
Outline

• Overview
  – dSphs

• Analysis
  – Combined Likelihood
  – Tests
  – Treating astrophysical uncertainties

• Results

• Conclusion
The $\gamma$-ray flux from self-annihilating dark matter can be expressed as:

$$\Phi_{\text{WIMP}}(E, \Psi) = J(\Psi) \times \Phi^{PP}(E)$$

Astrophysical factor

Particle physics factor

$$J(\Psi) = \int_{\text{l.o.s}} dl(\Psi) \rho^2(l)$$

$$\Phi^{PP}(E) = \frac{1}{2} \frac{\langle \sigma_{\text{ann}} v \rangle}{m_{\text{WIMP}}^2} \sum_f \frac{dN_f}{dE} B_f$$

"J-factor"
From now on defined as integrated over a cone of solid angle $2.4 \times 10^{-4}$ sr centered on the dwarf. (~size of PSF of LAT in our region)
Why dwarf Spheroidals?

✔ 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 $\gamma$-ray sources.
  - Small content of gas and dust.
✗ Predicted flux from DM is very low.
✗ Dependence on DM distribution.

But:
  fortunately estimates from stellar data
• For a given particle physics model (WIMP mass and branching ratio), the $\gamma$-ray yield per annihilation is the same for all the dwarfs. The J-factors of course are different.

• Combined likelihood (not data stacking) - we add the likelihood function of each dwarf ROI, and keep $\sigma v$ as one and the same parameter across all the likelihood functions:

$$L(\langle \sigma_{\text{ann}} v \rangle, m_{\text{WIMP}}; \Theta) = \prod_{i=1}^{N} L_i(\langle \sigma_{\text{ann}} v \rangle, m_{\text{WIMP}}, C, b_i; \Theta_i)$$

• We report profile likelihood intervals as implemented in MINUIT/MINOS
• The analysis can be individually optimised, and is more robust under background fluctuations and J-factor uncertainties.
• We have used Composite2 in Fermi ScienceTools

For other analyses using Combined Likelihood: see S. Zimmer's talk on Combined Analysis on Clusters of Galaxies, and the poster by B. Berenji and E. Bloom on Search for Large Extra Dimensions.
Behaviour of the combined limits

• For a Gaussian likelihood, the confidence interval is expected to scale as $1/\sqrt{N}$ where N is the number of samples, but what is the behaviour in our case?
• Test on identical background simulations using Fermi ScienceTools:
  – $\sigma \nu > 0$: better than $1/\sqrt{N}$
  – $\sigma \nu$ unconstrained: $1/\sqrt{N}$
• Test on different spectra using bootstrapped data:
  – Harder spectra: $1/N$
  – Softer spectra: $1/\sqrt{N}$
• Is the coverage still ok when constraining $\sigma \nu$ to be larger zero?
Coverage: the fraction of times the true value is contained in the confidence interval in a large number of repeated identical experiment

Here we have tested the coverage on a toy model: Poisson with known background

Coverage looks ok.

5 ROIs, Background=3

σv constrained to be larger than zero

σv unconstrained

PRELIMINARY
J-factor uncertainties

- Example: Bootes I has value $J = 0.16^{+0.35}_{-0.13} \, (e^{19} \text{GeV}^2 \text{cm}^{-5})$
- We include the uncertainties from the J-factors by including their distribution in the likelihood fit.

$$L(<\sigma_{\text{ann}}v>, m_{\text{WIMP}}; \Theta) = \prod_{i} L_{i}(<\sigma_{\text{ann}}v>, m_{\text{WIMP}}, J_{i}^{m}, C, b_{i}; \Theta_{i}) \frac{1}{J_{i}^{m} \sigma J_{i} \sqrt{2\pi}} e^{-(\ln(J_{i}^{m}) - J_{i}^{\text{true}})^{2}} \frac{2\sigma_{J,i}^{2}}{J_{i}^{m}}$$

This has never been done before!
(to our knowledge)

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<th>$J$</th>
<th>Error +</th>
<th>Error -</th>
<th>$\sigma_{J}$</th>
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Analysis details

- 10 dSphs
- 24 month data
- **Diffuse event class** (only events with the highest $\gamma$-like confidence)
- Region of interest: 10° radius centred on dSph location
- Energy range from 200MeV to 100GeV
- Standard cuts removing Earth albedo (zenith angle < 100°)
- Instrument response function: P6_V3_DIFFUSE
- Models:
  - dSphs modelled as DM point sources (DMFIT)
  - Galactic and Isotropic diffuse models recommended by the Fermi-LAT collaboration
  - Point-like sources from the 1FGL point source catalogue (A. A. Abdo et al 2010 ApJS 188 405) with some additions
- **Binned Likelihood** (using energy and spatial information)
- **Parameter of interest**: DM cross-section
- **Nuisance parameters**: J-factors, normalisations of the Diffuse Backgrounds, and the normalisation of nearby sources (<5°)
Including J-factor uncertainties

Nominal J-factor used, no uncertainties included

Example:
For $M=150\text{GeV}$, the combined limit using nominal J is $6.1\times10^{-26}\ \text{cm}^3/\text{s}$, and the combined limit with J-factor uncertainties included is $8.9\times10^{-26}\ \text{cm}^3/\text{s}$
In the following slides, all limits include the uncertainty on the J-factor.
Results $b\bar{b}$ and $W^+W^-$ Channels

Evaluated at $M = 10, 15, 50, 100, 150, 300, 600$ and $1000$ GeV

Evaluated at $M = 100, 150, 300, 600$ and $1000$ GeV

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Results $\tau^+\tau^-$ and $\mu^+\mu^-$ Channel

Evaluated at M = 5, 6, 7, 8, 9, 50, 100, 150, 300, 600 and 1000 GeV

Evaluated at M = 10, 15, 50, 100, 150, 300, 600 and 1000 GeV
Upper limits, Combined Likelihood limits of 10 dSphs

PRELIMINARY

- Thermal WIMP cross-section
- $\mu^+\mu^-$ Channel
- $b\bar{b}$ Channel
- $W^+W^-$ Channel
- $\tau^+\tau^-$ Channel
Summary

• We have presented robust constraints including J-factor uncertainties on dark matter annihilation cross-sections from a combined likelihood analysis of 10 dSph galaxies for different annihilation channels.
• The limits start to cut into parameter space below the thermal WIMP cross-section for low masses!
• Various tests and cross-checks have been made to verify the method.
• A paper is in preparation within the collaboration.
TeVPA 2011
Stockholm Aug 1-5
Abstract submission deadline: 31 May

http://tevpa2011.albanova.se/
Results all channels

Upper limits, Combined Likelihood limits of 10 dSphs

- Thermal WIMP cross-section
- $b\bar{b}$ Channel, nominal J
- Typical $\tau^+\tau^-$ Channel, J prior
- Typical $\mu^+\mu^-$ Channel, nominal J
- Typical $W^+W^-$ Channel, nominal J

PRELIMINARY

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Combined Likelihood limits plotted with the same model scans as in the 11 month dSph paper


Model scans
Likelihood curves when including priors

100GeV bbbar channel
J(x1.e19), log10(sigmaJ) :
Carina : 0.063, 0.1
UrsaMajorII : 0.58, 0.4
The Fermi-LAT

- Launched on June 11, 2008
- 16 identical modules in a 4x4 array, where each module is made up by a tracker for direction determination and a calorimeter for energy measurements
- Field of view is ~2.4 sr
- Energy range 20MeV to >300GeV
- LAT observes the entire sky every ~3 h (2 orbits)

خلاف: LAT is a great instrument for DM searches!