

# Reticulum II: Evidence for gamma-ray emission, its dark matter content and implications for dark matter physics

Savvas M. Koushiappas



Based on

PRL 115, 081101 (2015) 1503.02320

ApJL 808 L36 (2015) 1504.03309



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**With:** Alex Geringer-Sameth & Matthew Walker (Carnegie-Mellon U.),  
Sergey Koposov, Vasily Belokurov, Gabriel Torrealba & Wyn Evans (Cambridge U.)  
Vincent Bonnavard, Celine Combet, David Maurin (U. Grenoble-Alpes),  
Mario Mateo, John Bailey (U. Michigan), Eduard Olszewski (U. Arizona)

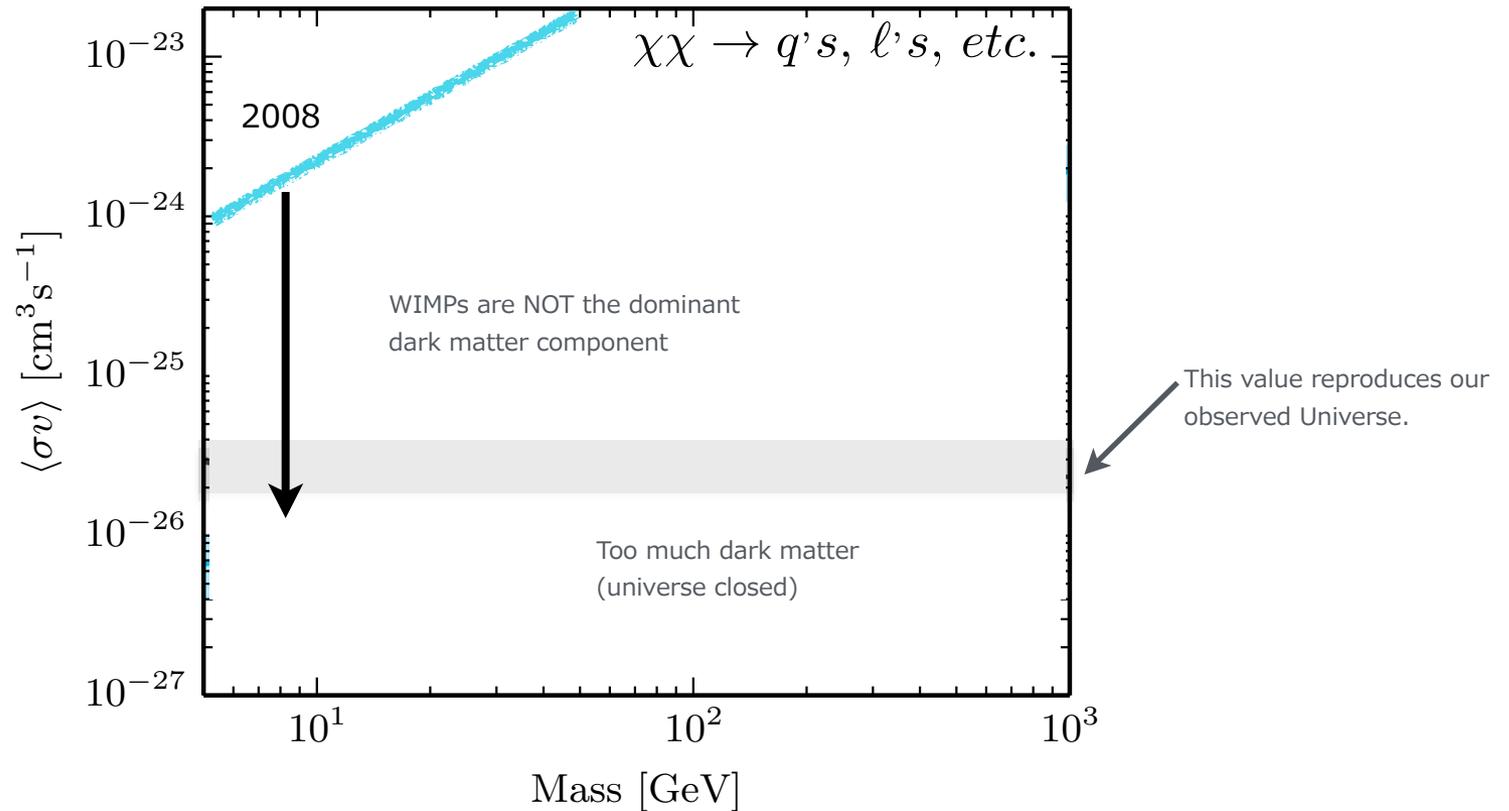


# Dwarf galaxies: The ideal targets in indirect detection

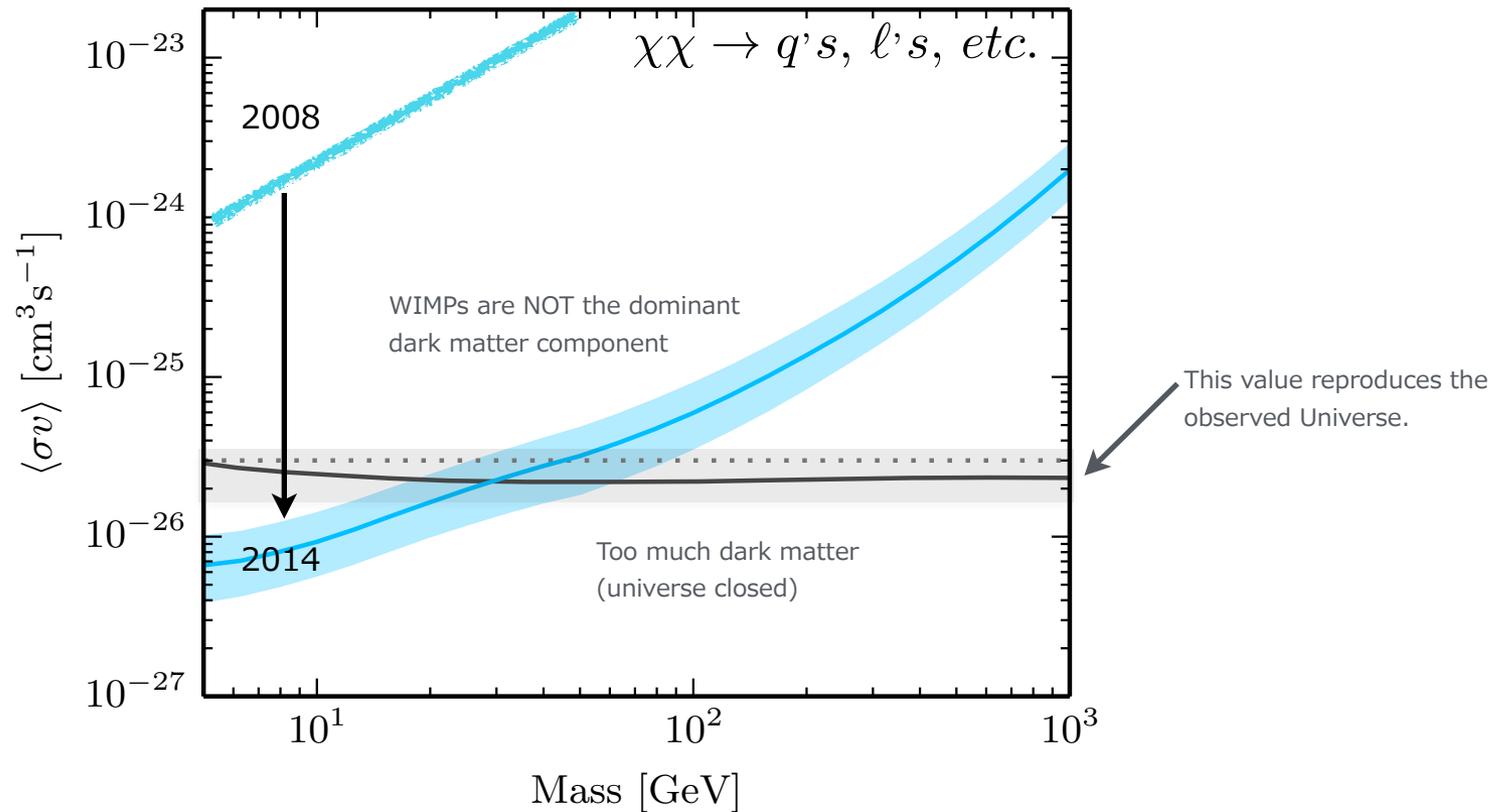
$$\chi\chi \xrightarrow{\langle\sigma_{Av}\rangle} q's, \ell's, \text{etc.} \quad \Gamma \propto \int n_{\chi}^2 d^3r$$



# Dwarf galaxies — state of constraints on $\langle\sigma v\rangle$



# Dwarf galaxies — state of constraints on $\langle\sigma v\rangle$



On March 8, 2015

[arXiv:1503.02079 \[pdf, ps, other\]](#)

**Beasts of the Southern Wild. Discovery of a large number of Ultra Faint satellites in the vicinity of the Magellanic Clouds**

[Sergey E. Koposov](#), [Vasily Belokurov](#), [Gabriel Torrealba](#), [N. Wyn Evans](#)

[arXiv:1503.02584 \[pdf, other\]](#)

**Eight New Milky Way Companions Discovered in First-Year Dark Energy Survey Data**

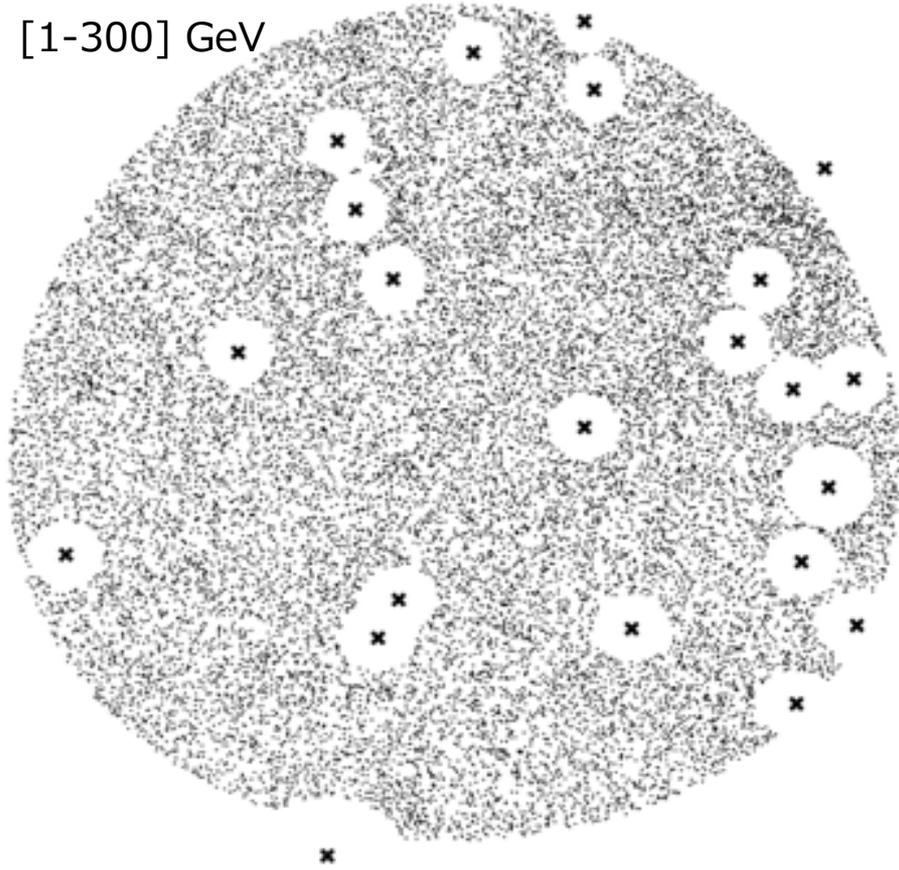
The DES Collaboration, [K. Bechtol](#), [A. Drlica-Wagner](#), [E. Balbinot](#), [A. Pieres](#), [J. D. Simon](#), [B. Yanny](#), [B. Santiago](#), [R. H. Wechsler](#), [J. Frieman](#), [A. R. Walker](#), [P. Williams](#), [E. Rozo](#), [E. S. Rykoff](#), [A. Queiroz](#), [E. Luque](#), [A. Benoit-Levy](#), [R. A. Bernstein](#), [D. Tucker](#), [I. Sevilla](#), [R. A. Gruendl](#), [L. N. da Costa](#), [A. Fausti Neto](#), [M. A. G. Maia](#), [T. Abbott](#), [S. Allam](#), [R. Armstrong](#), [A. H. Bauer](#), [G. M. Bernstein](#), [E. Bertin](#), [D. Brooks](#), [E. Buckley-Geer](#), [D. L. Burke](#), [A. Carnero Rosell](#), [F. J. Castander](#), [C. B. D'Andrea](#), [D. L. DePoy](#), [S. Desai](#), [H. T. Diehl](#), [T. F. Eifler](#), [J. Estrada](#), [A. E. Evrard](#), [E. Fernandez](#), [D. A. Finley](#), [B. Flaugher](#), [E. Gaztanaga](#), [D. Gerdes](#), [L. Girardi](#), [M. Gladders](#), [D. Gruen](#), [G. Gutierrez](#), [J. Hao](#), [K. Honscheid](#), [B. Jain](#), [D. James](#), [S. Kent](#), [R. Kron](#), [K. Kuehn](#), [N. Kuropatkin](#), [O. Lahav](#), [T. S. Li](#), et al. (32 additional authors not shown)

Name	$\alpha$ [deg]	$\delta$ [deg]	Signif	m-M [mag]	Dist $_{\odot}$ [kpc]
Reticulum 2	53.9256	-54.0492	48.5	17.4	30
Eridanus 2	50.9878	-42.5228	31.5	22.5	380
Horologium 1	43.8820	-54.1188	28.4	19.5	79
Pictoris 1	70.9475	-50.2830	17.3	20.3	114
Phoenix 2	354.9975	-54.4060	13.9	19.6	83
Indus 1	317.2044	-51.1656	13.7	20.0	100
Grus 1 <sup>a</sup>	344.1765	-50.1633	10.1	20.4	120
Eridanus 3	35.6897	-52.2837	10.1	19.7	87
Tucana 2	342.9664	-58.5683	8.3	19.2	69

# Reticulum II in gamma-rays

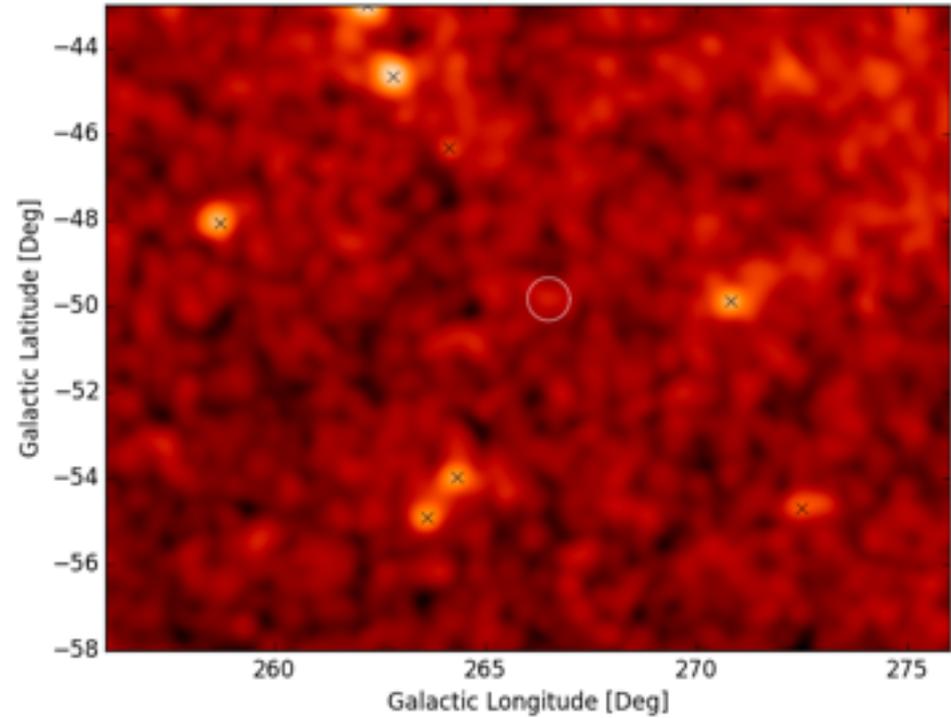
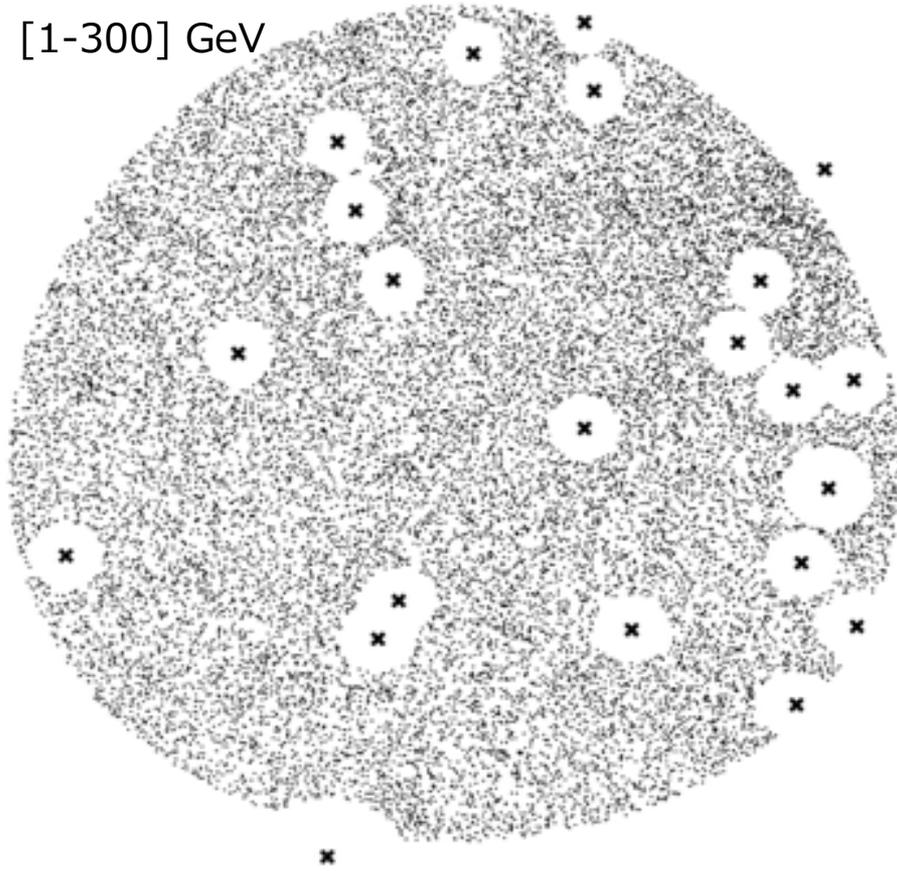
# Reticulum II in gamma-rays

[1-300] GeV



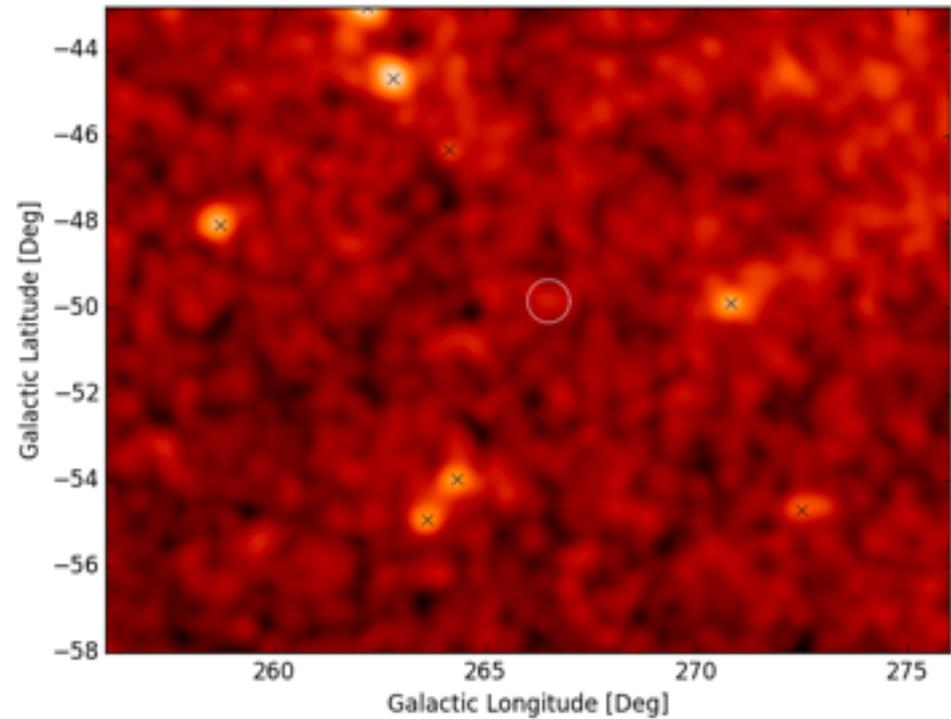
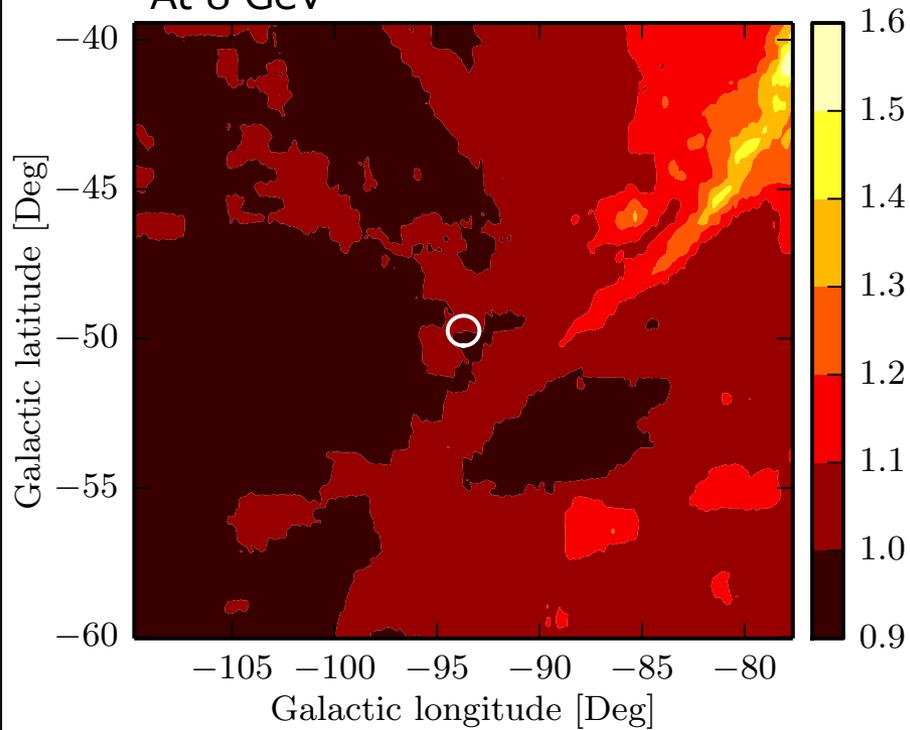
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[1-300] GeV



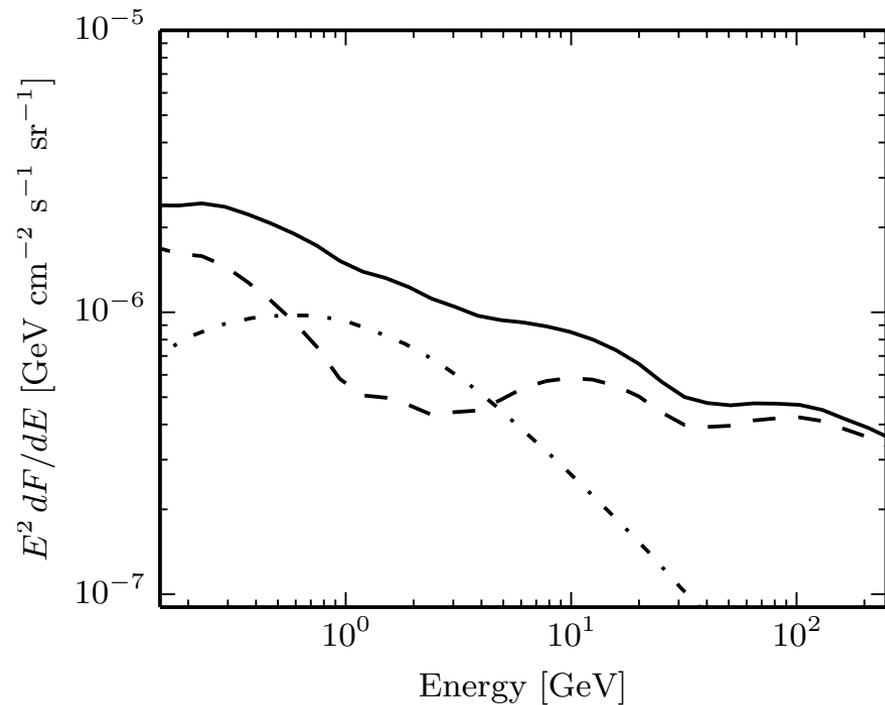
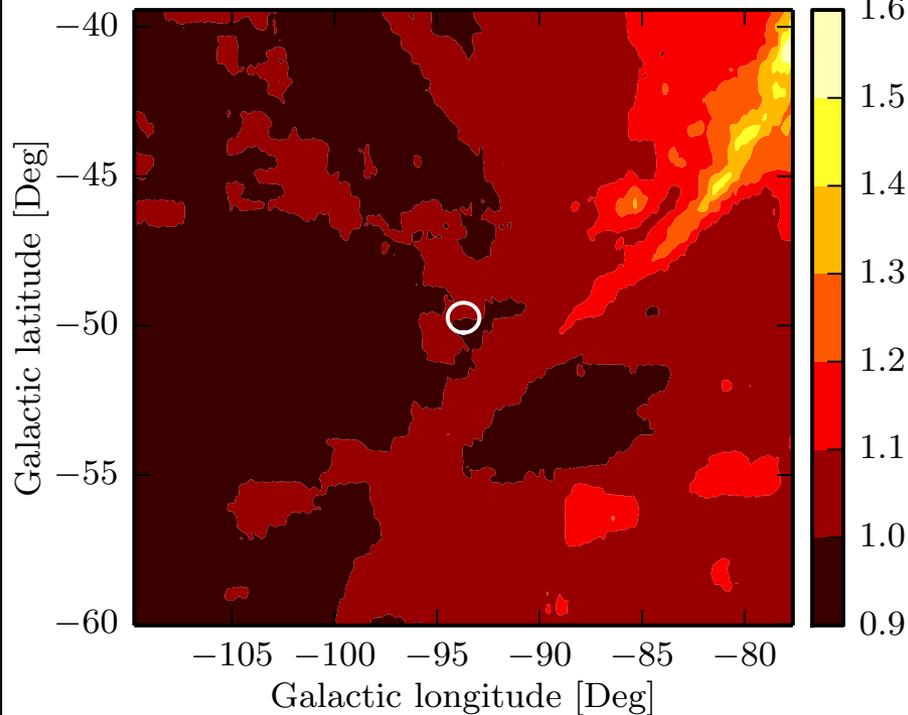
# Reticulum II in gamma-rays

At 8 GeV



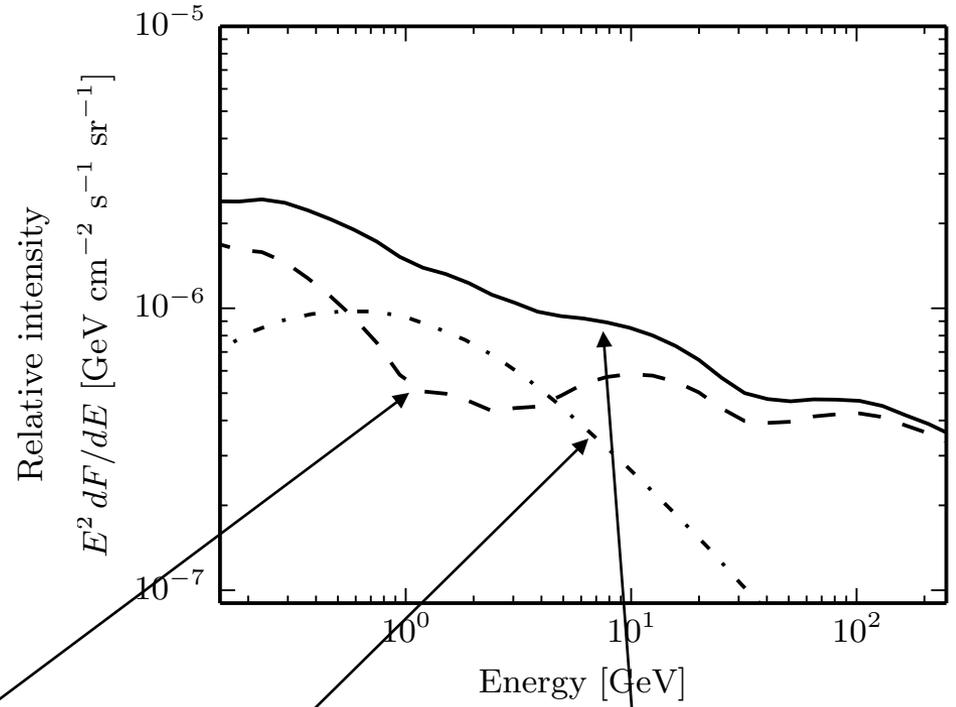
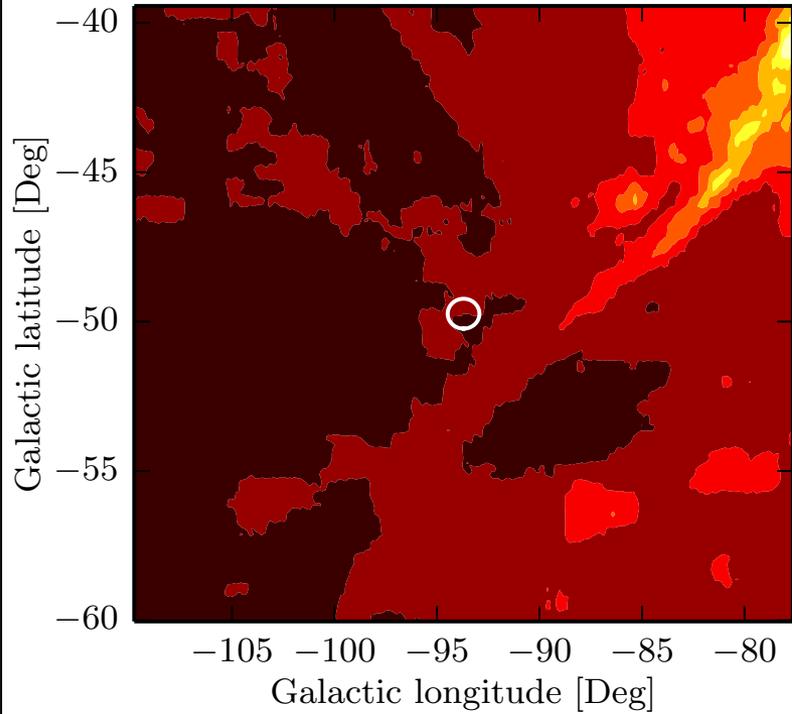
# Reticulum II in gamma-rays

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# Reticulum II in gamma-rays

At 8 GeV

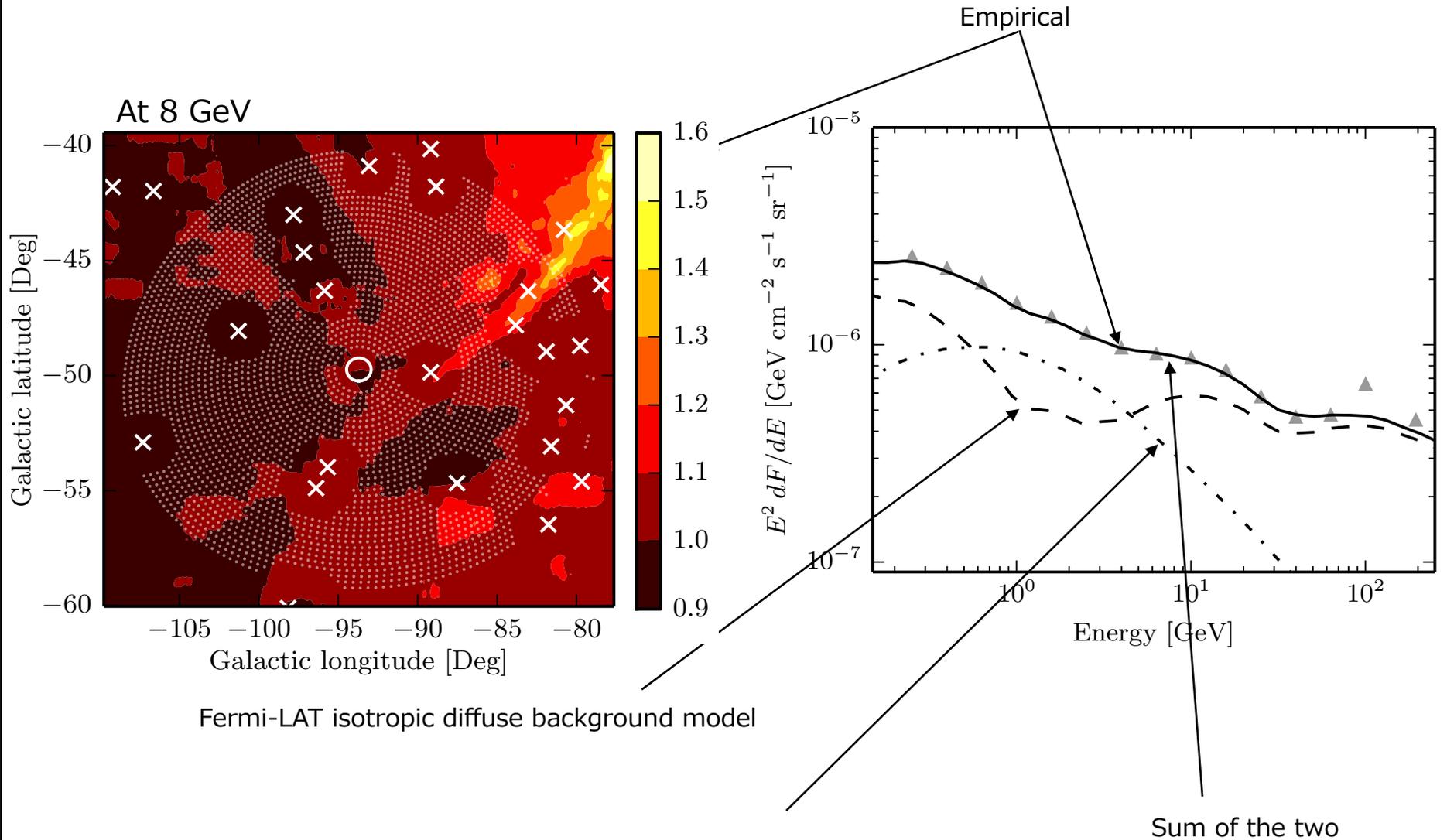


Fermi-LAT isotropic diffuse background model

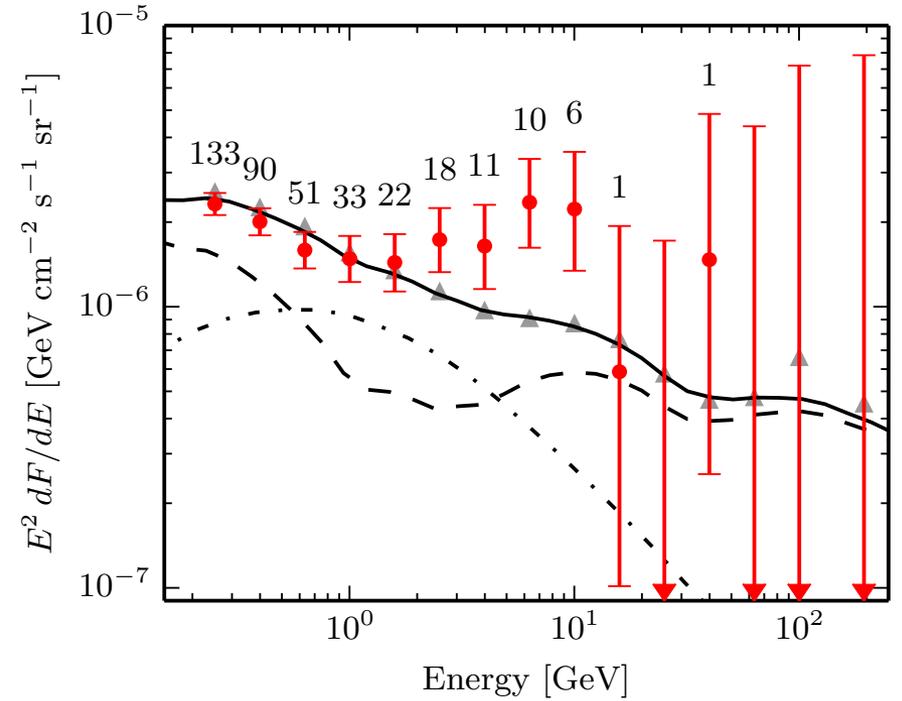
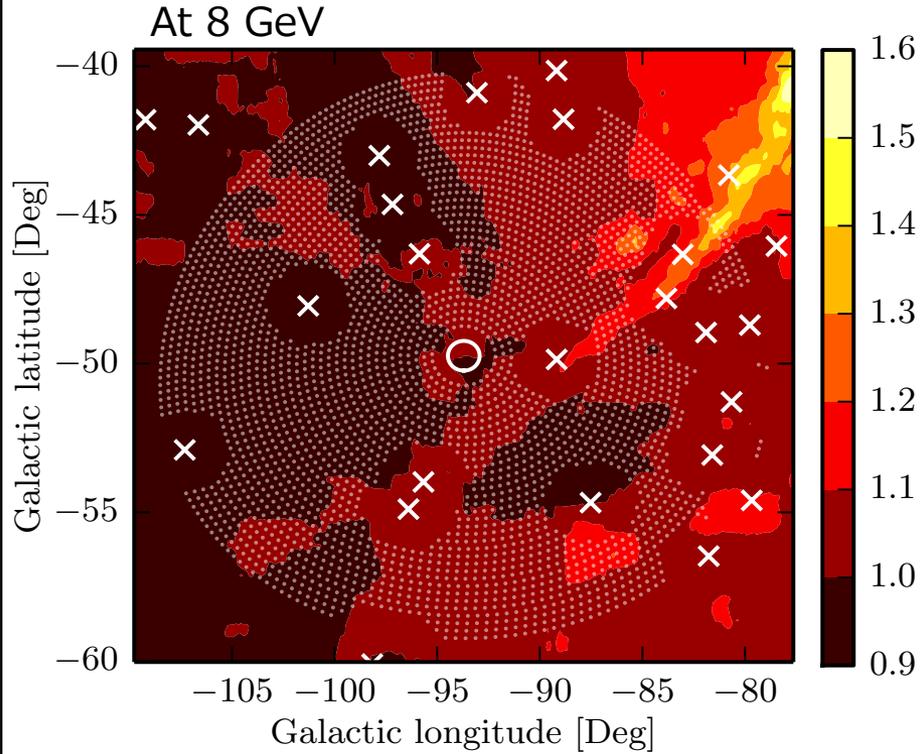
Sum of the two

Fermi-LAT Galactic diffuse background model

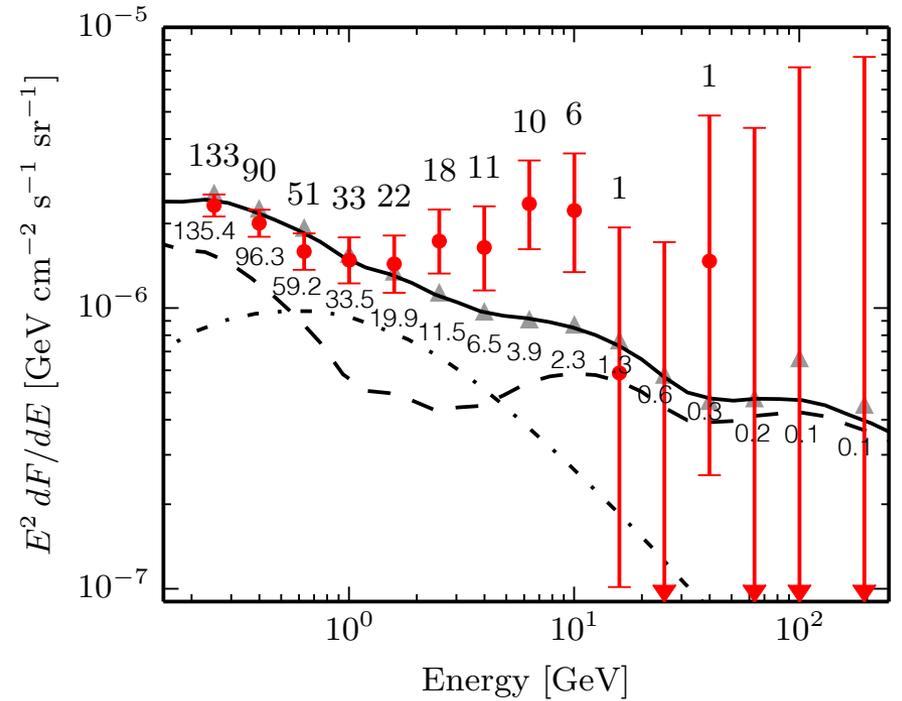
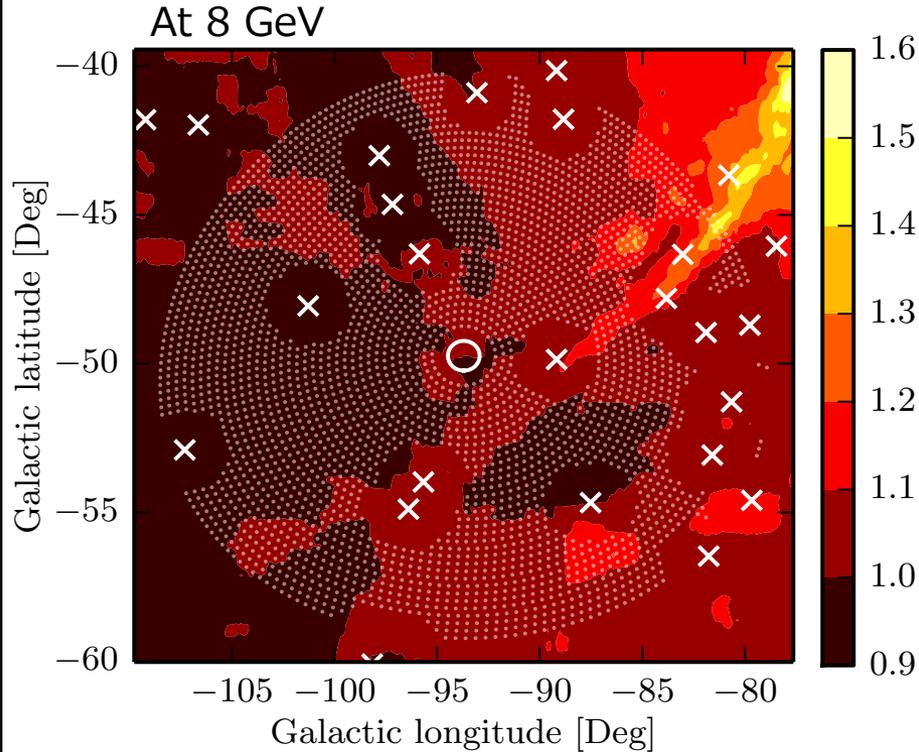
# Reticulum II in gamma-rays



# Reticulum II in gamma-rays



# Reticulum II in gamma-rays



# Photon weighting and statistical significance of a dark matter interpretation

See Geringer-Sameth, Koushiappas & Walker, PRD 91, 083535 (2015) for details

# Photon weighting and statistical significance of a dark matter interpretation

$$T = \sum_{i=1}^N w(Q_i) \quad Q = \{E, \theta\}$$

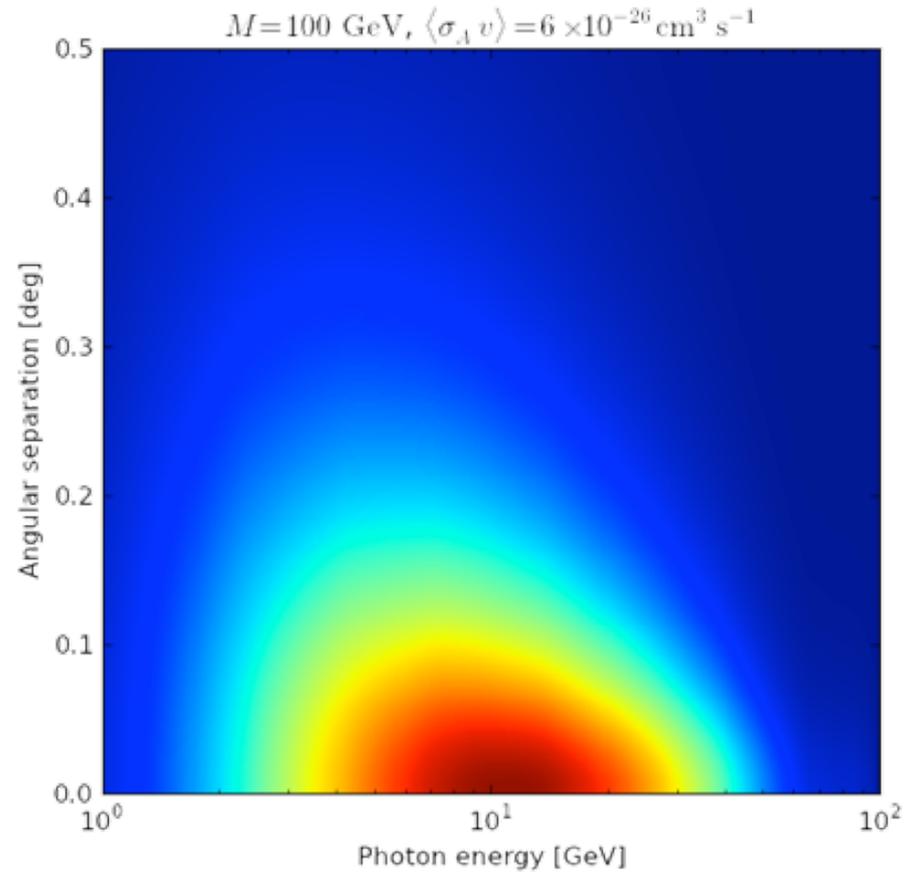
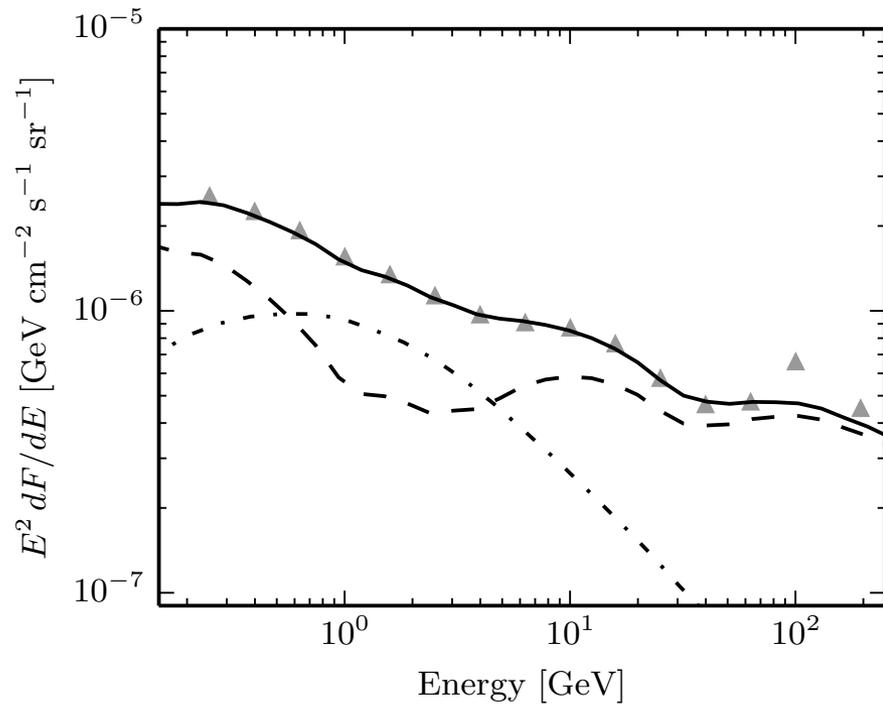
$$w(Q) = \log \left( 1 + \frac{s_Q}{b_Q} \right)$$

$$s_Q = \frac{dN(E, \theta)}{dE d\Omega} = \frac{\langle \sigma v \rangle}{8\pi M^2} \frac{dN_\gamma(E)}{dE} [(J * \text{PSF})(E, \theta)] \epsilon(E)$$

$b_Q$  represents a description of the background



# Photon weighting and statistical significance of a dark matter interpretation



See Geringer-Sameth, Koushiappas & Walker, PRD 91, 083535 (2015) for details

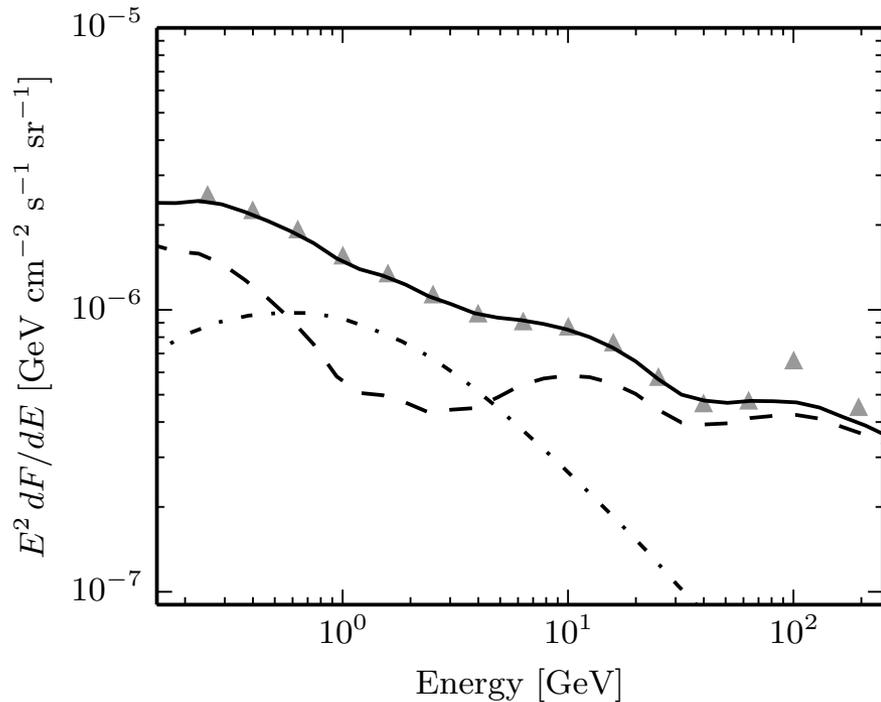
# Photon weighting and statistical significance of a dark matter interpretation

## **Background modeling**

- Background in the central 0.5 degree ROI is a Poisson random variable
- Background is isotropic
- Energies are drawn from a given spectrum

Test statistic is a compound Poisson variate whose PDF can be obtained for any weight function and any adopted background spectrum (no asymptotic assumptions).

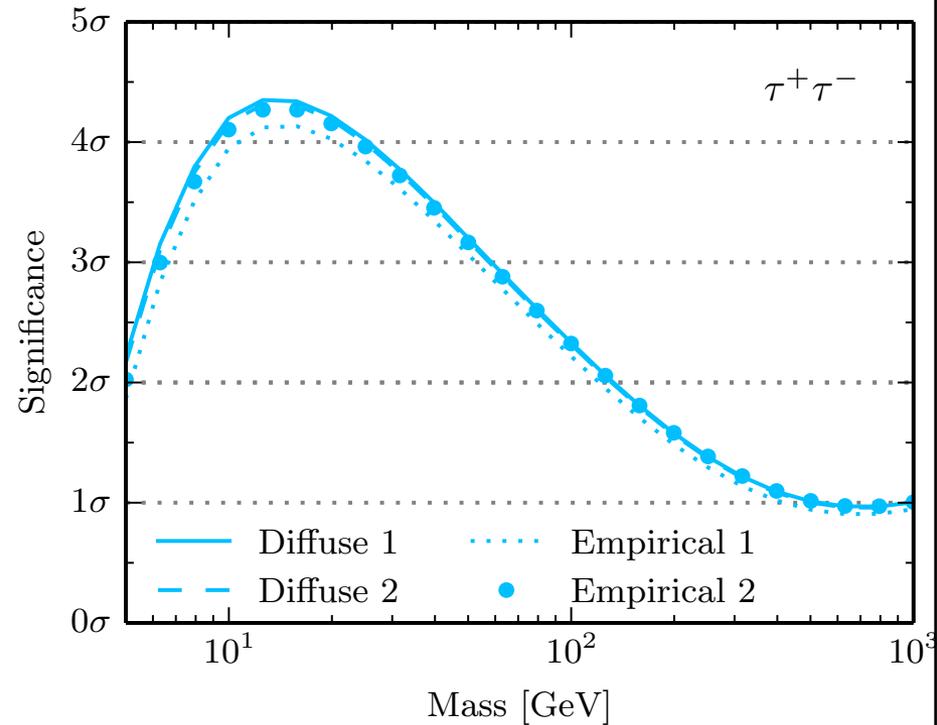
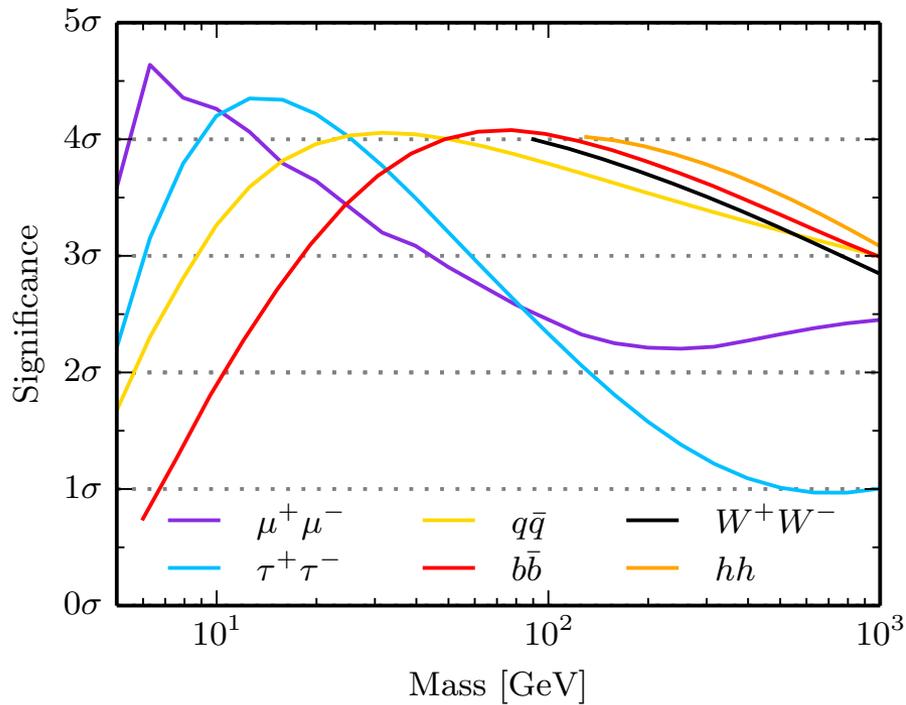
# Photon weighting and statistical significance of a dark matter interpretation



## Background modeling

- ***Diffuse 1***: Fermi-LAT background averaged over 1 degree.
- ***Diffuse 2***: Fermi-LAT background averaged over 2 degrees.
- ***Empirical 1***: Events in an [1-5] degree annulus from central ROI with 20% gaussian width on energy.
- ***Empirical 2***: Bin *Empirical 1* events in energy.

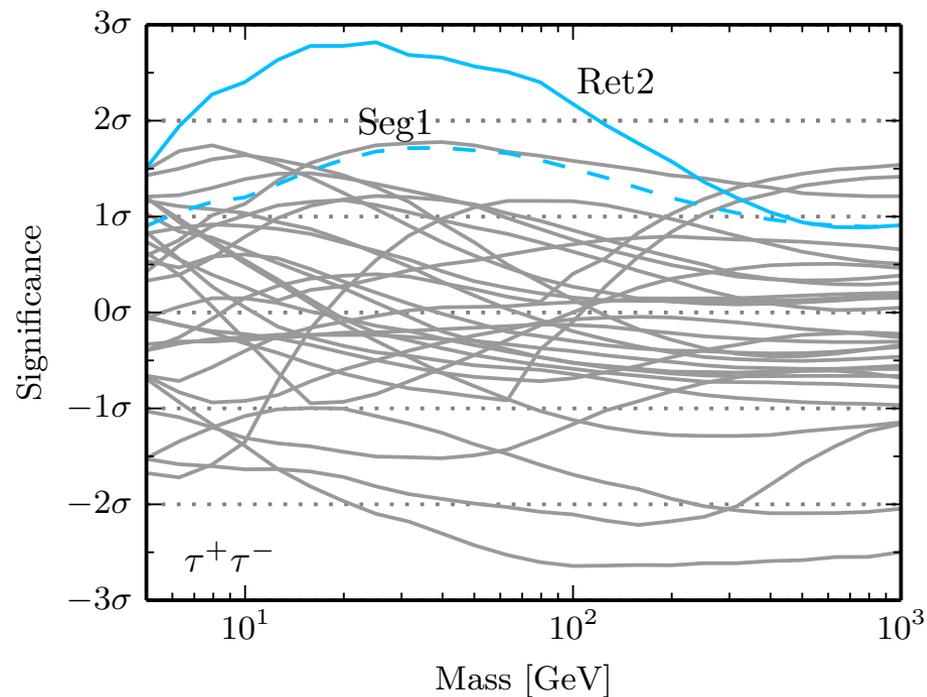
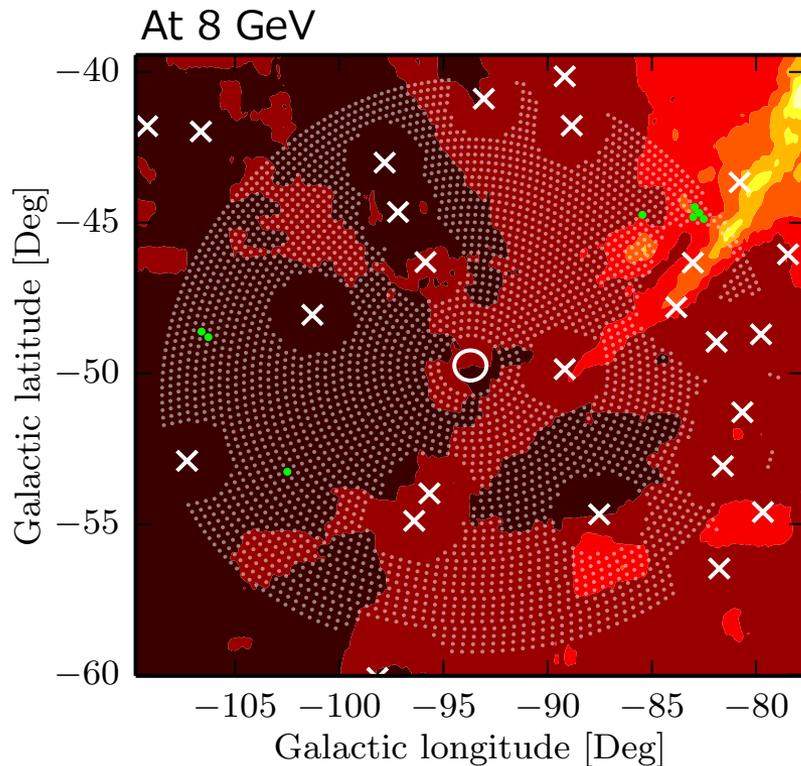
# Photon weighting and statistical significance of a dark matter interpretation



Local p-value  $< 3 \times 10^{-5}$

Global p-value  $< 9.8 \times 10^{-5}$

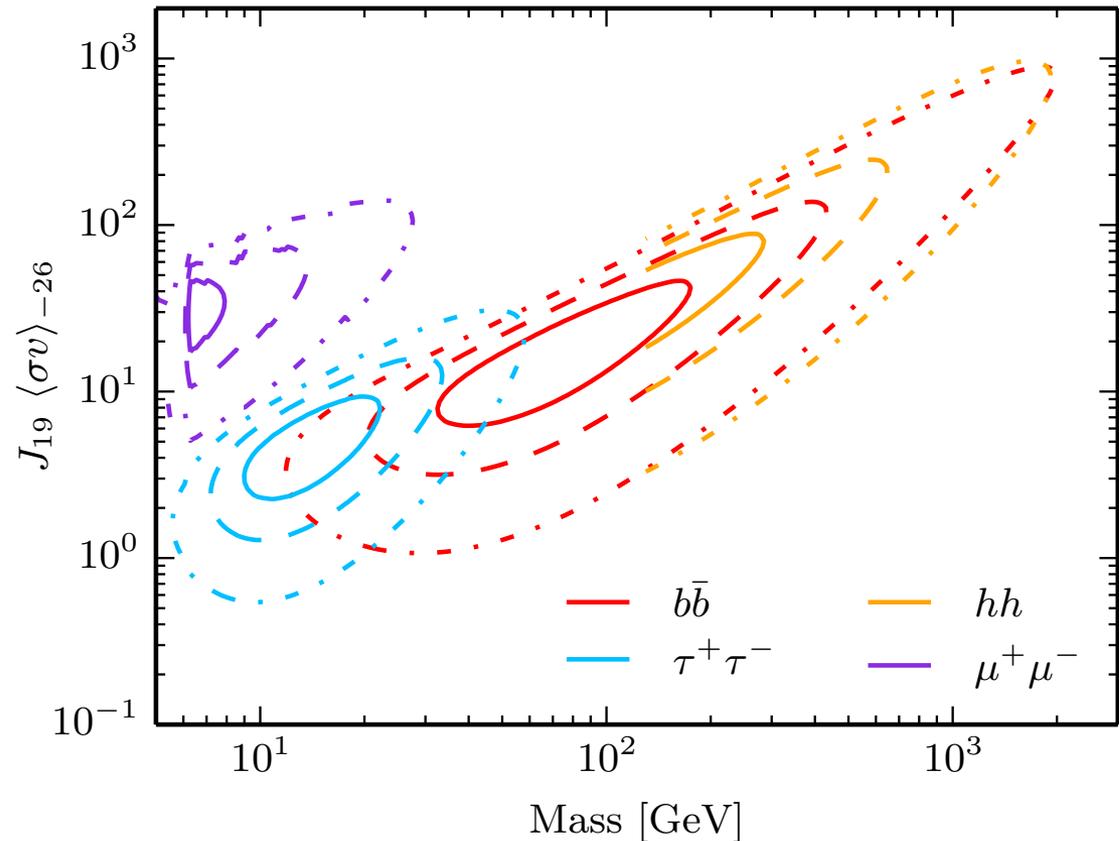
# Photon weighting and statistical significance of a dark matter interpretation



Local p-value = 0.0024 (8/3306)

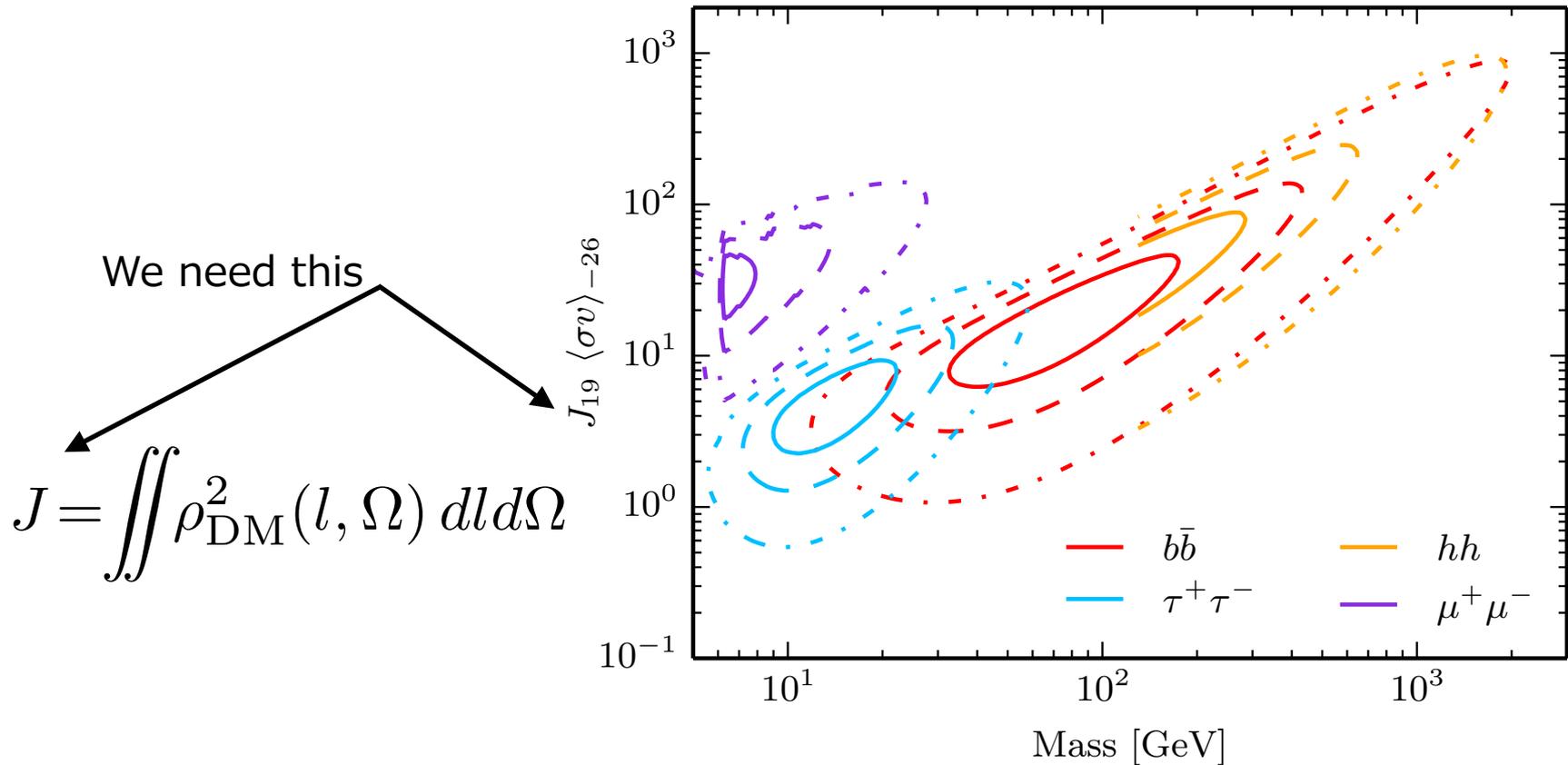
Global p-value = 0.0097

# Photon weighting and statistical significance of a dark matter interpretation



Does the data prefer one explanation (channel) over something else? What can the LHC tell us? (see Fan, Koushiappas & Landsberg, in preparation)

# Photon weighting and statistical significance of a dark matter interpretation



Does the data prefer one explanation (channel) over something else? What can the LHC tell us? (see Fan, Koushiappas & Landsberg, 1507.06993)

# The dark matter content of Reticulum II

Bonnivard et al. ApJL 808 L36

Simon et al. 1504.02889

$\alpha_{\text{int}}$	$\log_{10}(J(\alpha_{\text{int}}))$
[deg]	$[J/\text{GeV}^2 \text{ cm}^{-5}]^{\text{a}}$
0.01	$16.9^{+0.5(+1.1)}_{-0.4(-0.8)}$
0.05	$18.2^{+0.5(+1.0)}_{-0.4(-0.7)}$
0.1	$18.6^{+0.6(+1.1)}_{-0.4(-0.8)}$
0.5	$19.5^{+1.0(+1.6)}_{-0.6(-1.3)}$
1	$19.7^{+1.2(+2.0)}_{-0.9(-1.5)}$

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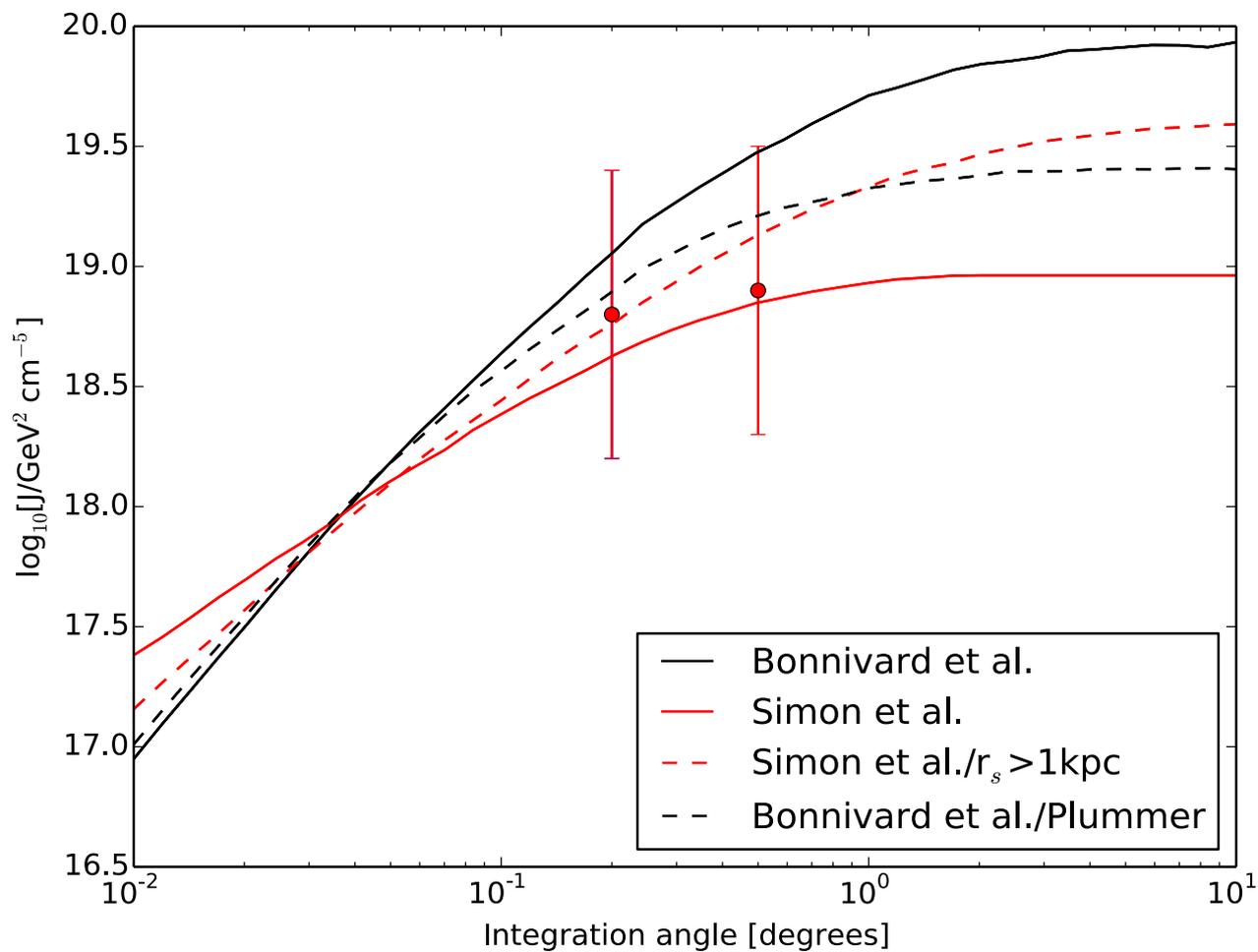
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# The dark matter content of Reticulum II



## Where do we go from here

1. Is what we see consistent with background?
2. Is it consistent with any other possible source (pulsars, AGNs, ?)
3. Is it consistent with dark matter annihilation?
4. Is it something else? (e.g., instrumental/data set systematics?)

Given that this is the very first time of a detection of gamma-rays along the line of sight to a dwarf galaxy it is important we understand Reticulum II as much as the data allows.