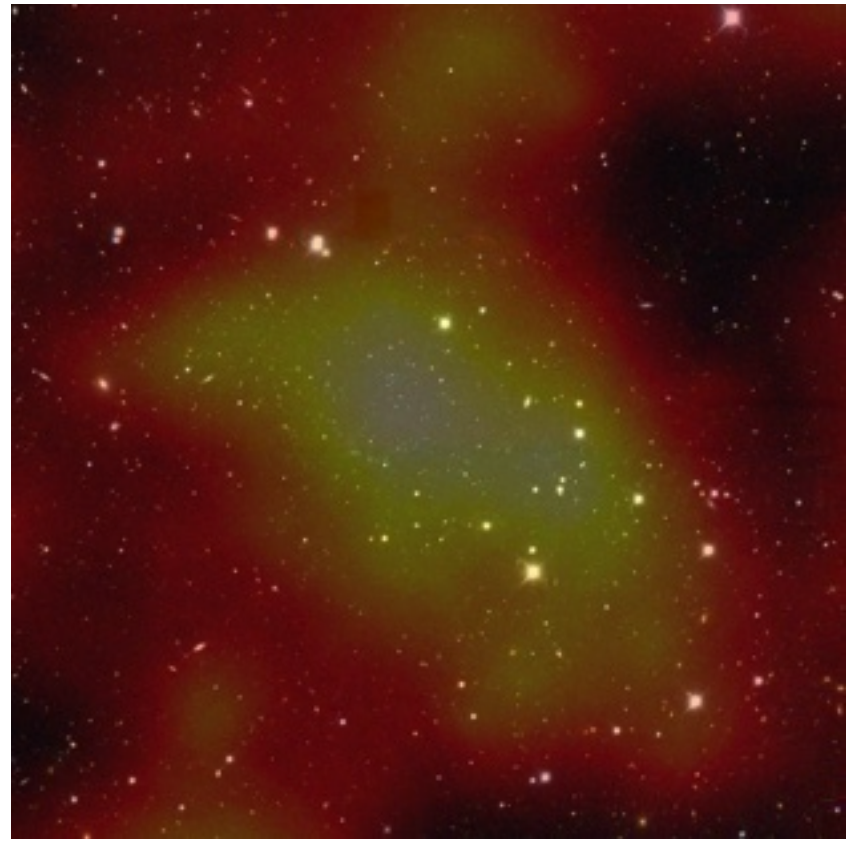
Dark Matter in the Cosmos

Savvas M. Koushiappas

BROWN



Dark matter in the Cosmos

Few facts:

1. If it annihilates in the early universe it can annihilate today.

2. Whatever is found in the laboratory (accelerator/direct detection) it must connect to the sky.

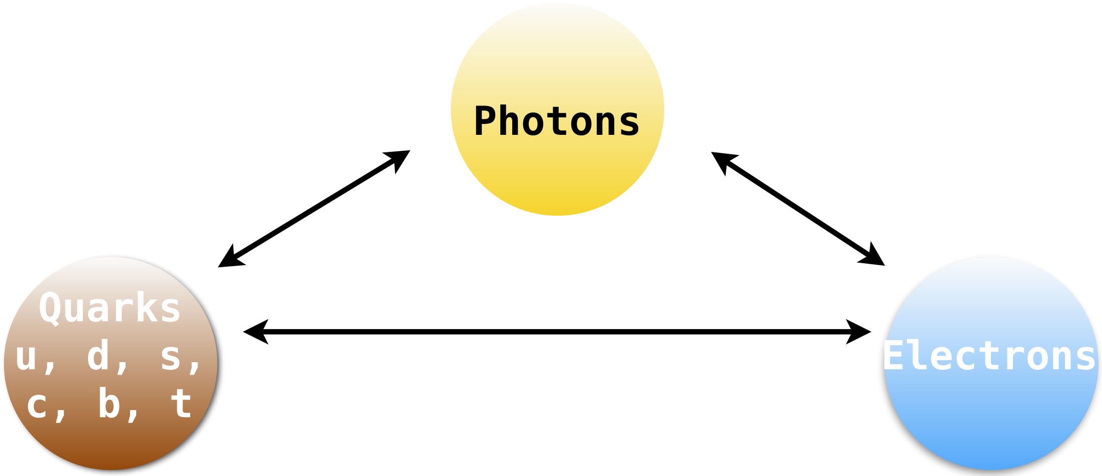
3. New experiments have results (AMS-02, Planck, IceCube, VERITAS, H.E.S.S., plus more from Fermi).

4. We are **now** sensitive to WIMPs with an annihilation cross section required to explain (naively) the observed relic abundance.

Dark matter in the Cosmos

In the early universe…

$$\hat{\mathbf{L}}[f] = \mathbf{C}[f]$$



Dark matter in the Cosmos

In the early universe⋯

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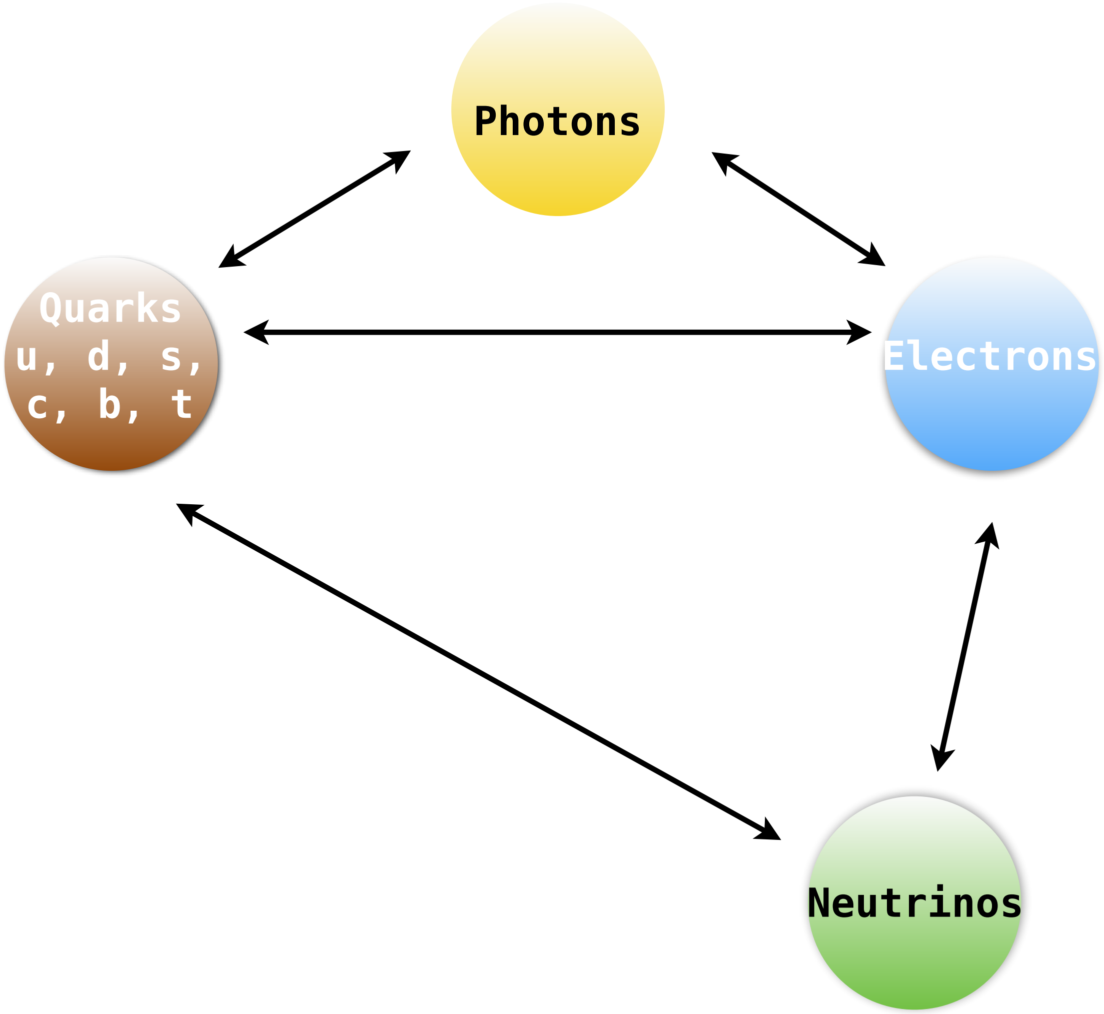

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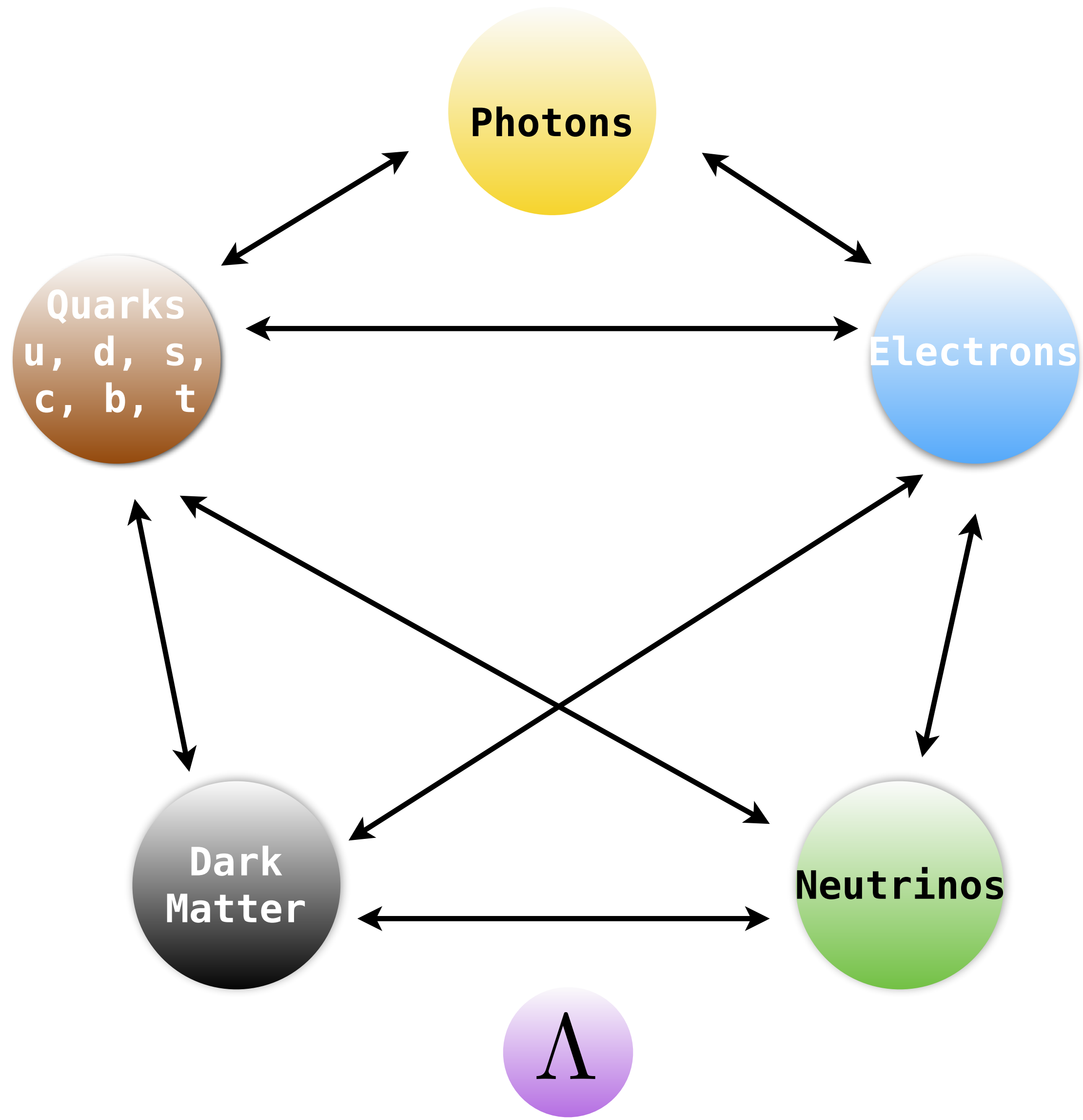

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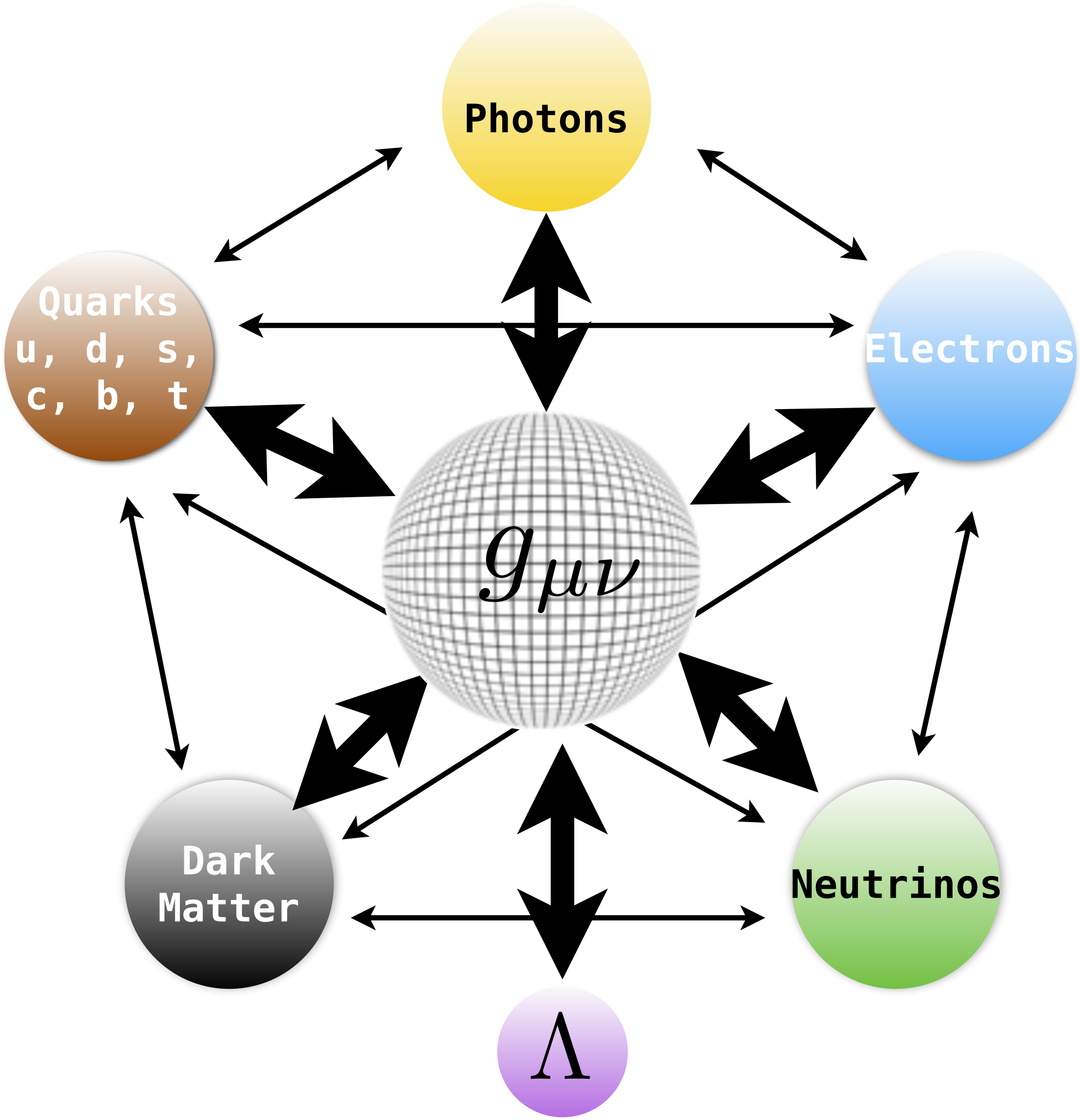
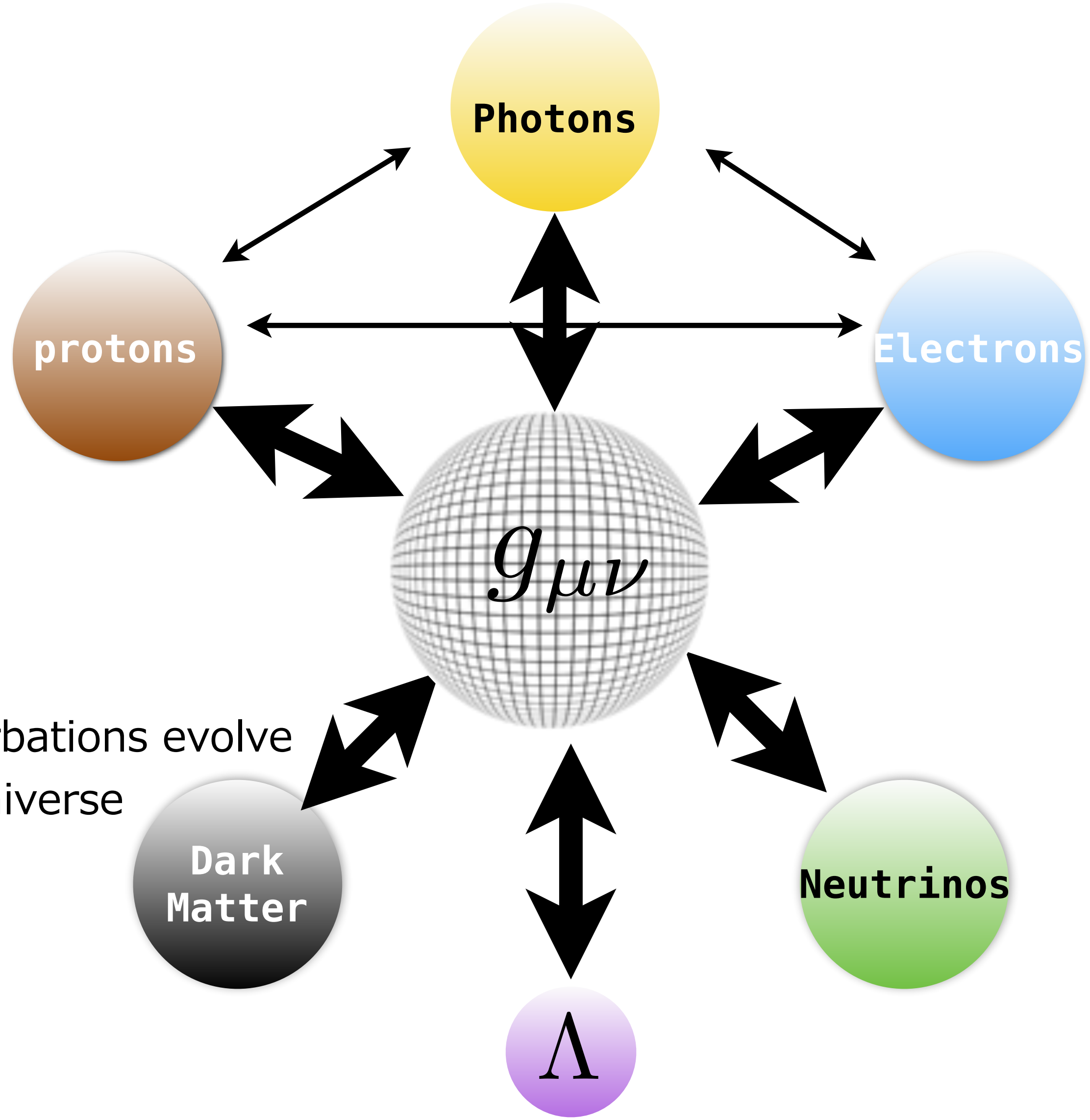


Dark matter in the Cosmos

After decoupling…

$$\hat{\mathbf{L}}[f] = 0$$

Dark matter perturbations evolve
in an expanding universe



Dark matter in the Cosmos

Two consequences:

Dark matter in the Cosmos

Two consequences:

1. $$\frac{\Omega_{\mathrm{DM}} h^2}{0.1} \approx \frac{3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma_A v \rangle}$$

$$\rho_{\mathrm{DM}} \approx 1\,\mathrm{GeV}/\mathrm{m}^3$$

Dark matter in the Cosmos

Two cons

1. $\frac{\Omega_{\mathrm{D}}}{0}$ $\frac{)^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma_A v\rangle}$

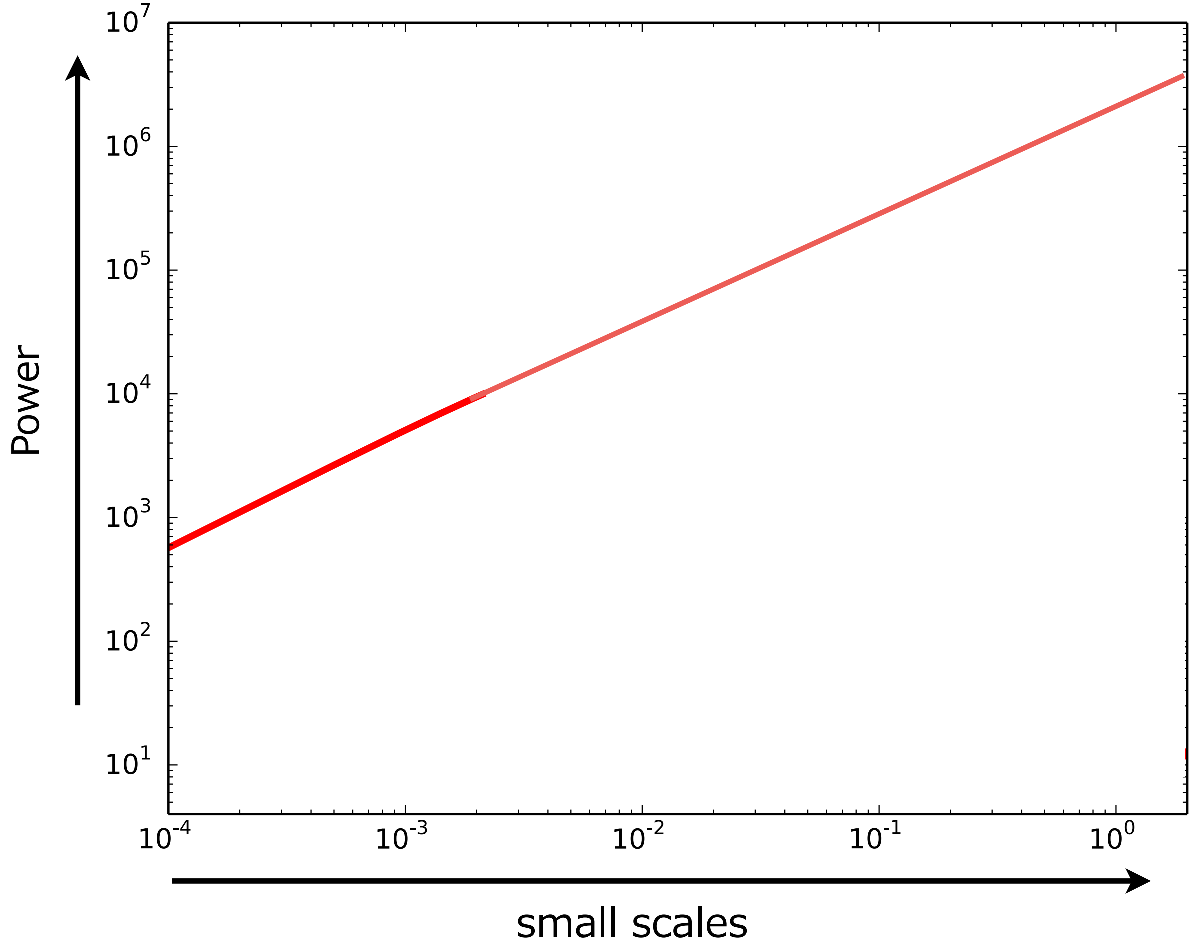
ρ_{D} n^3

per 100x

Dark matter in the Cosmos

Two consequences:

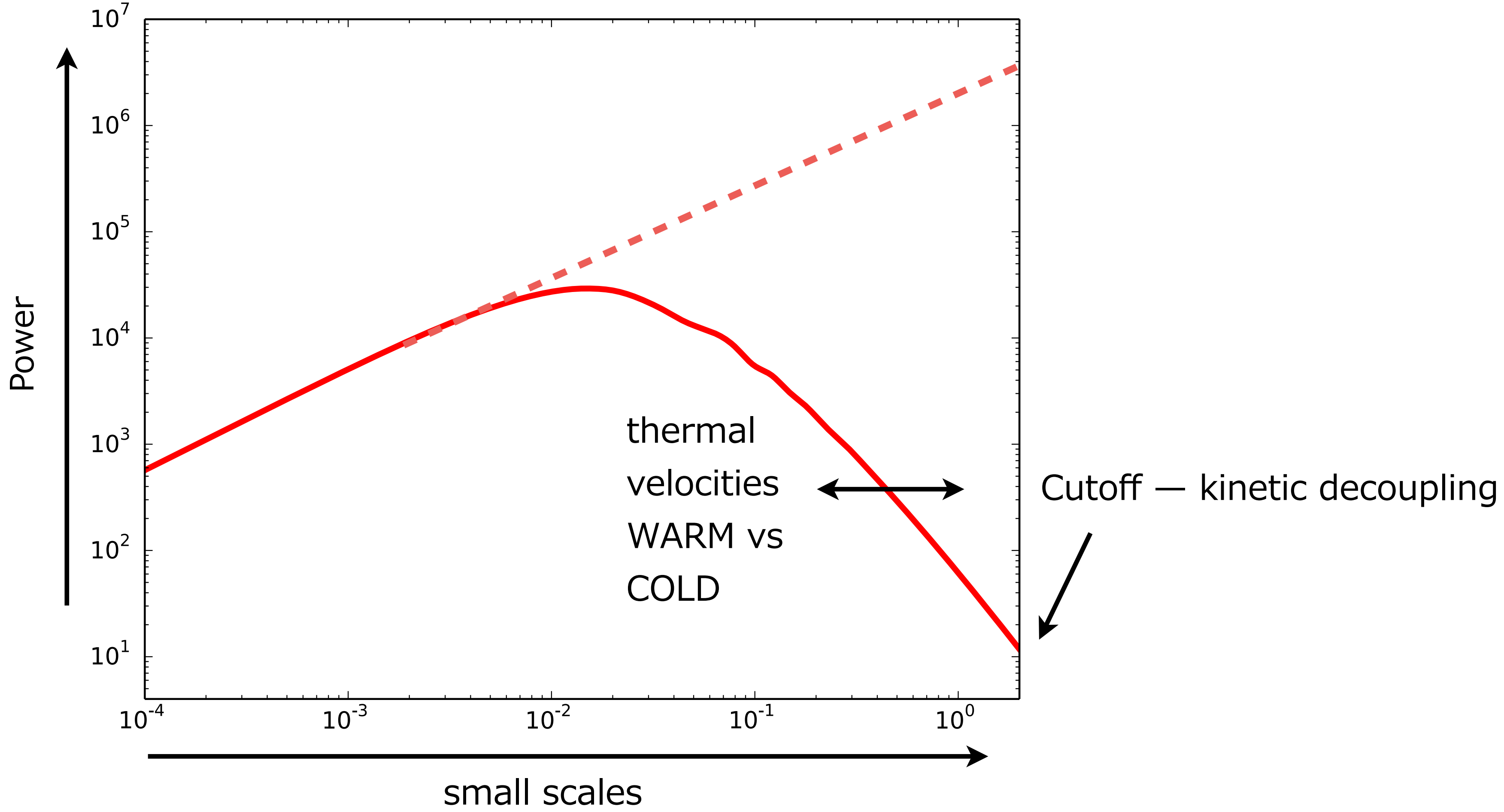
2.



Dark matter in the Cosmos

Two consequences:

2.



Dark matter in the Cosmos

The Universe is expanding with the dynamics determined by its constituents

+

The Horizon increases with time

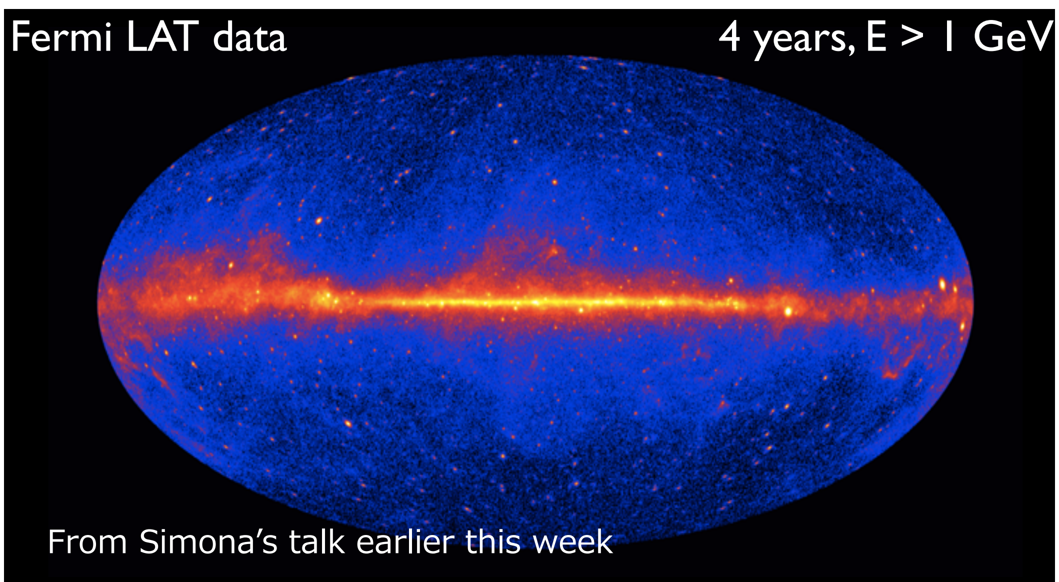
Small scales collapse first. The smaller the perturbation the earlier it collapses, the higher its density.

Dark matter halos contain **high density** substructure

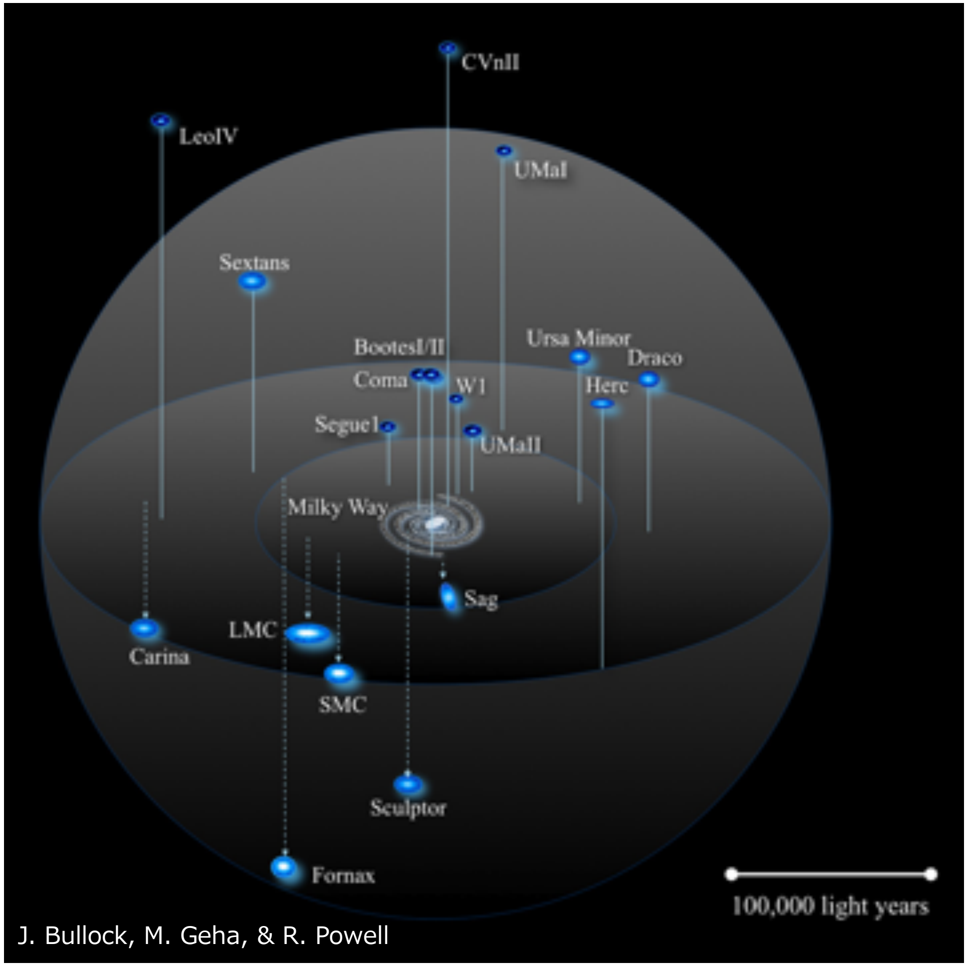
Dark matter in the Cosmos

$$\Gamma \propto \int n_\chi^2 d^3 r$$

Look for a signal in **dwarf galaxies** and dark substructure.

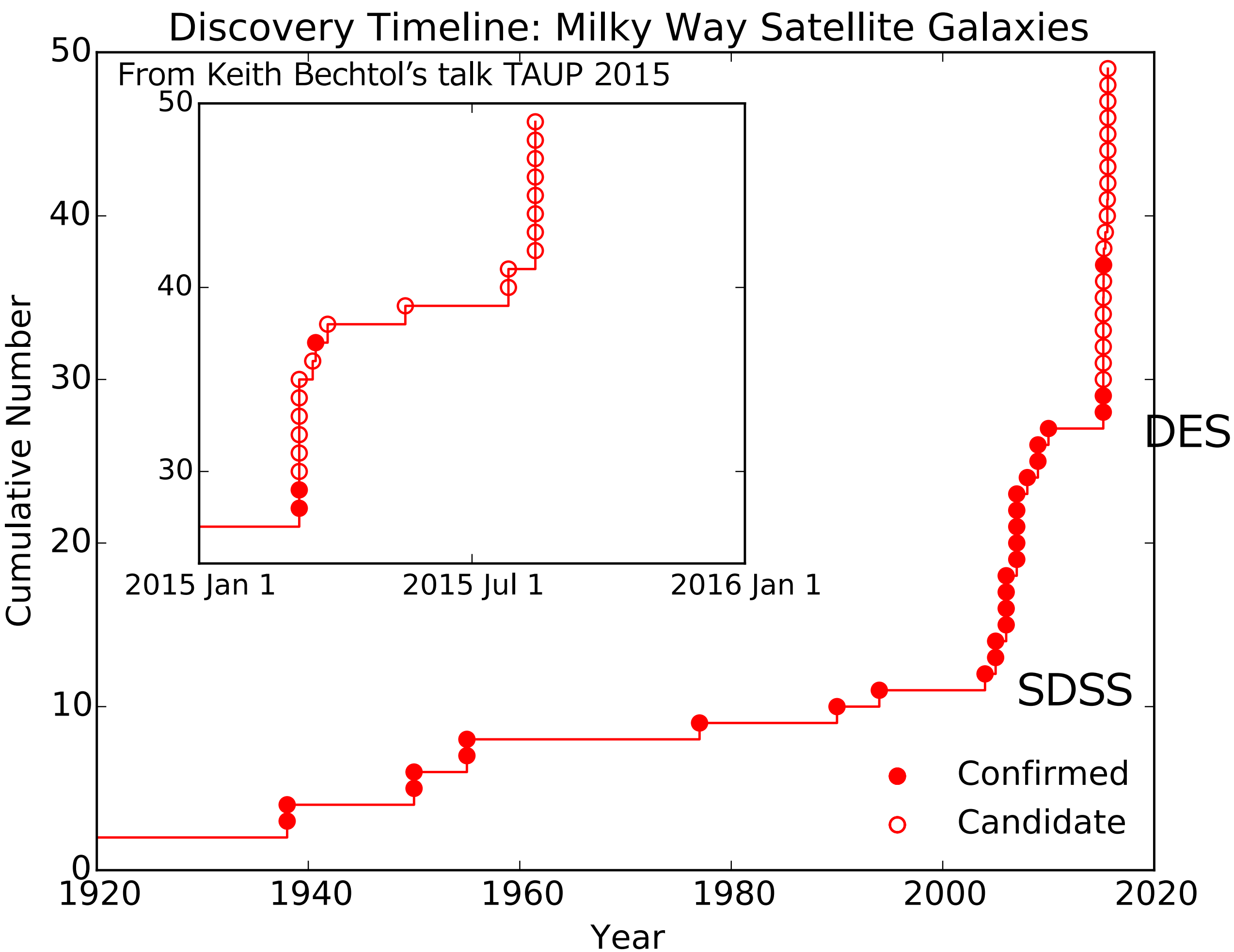


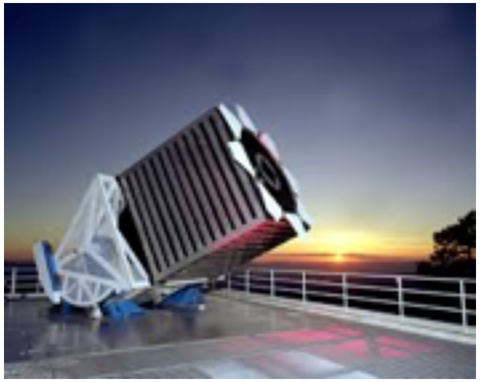
Dwarf galaxies



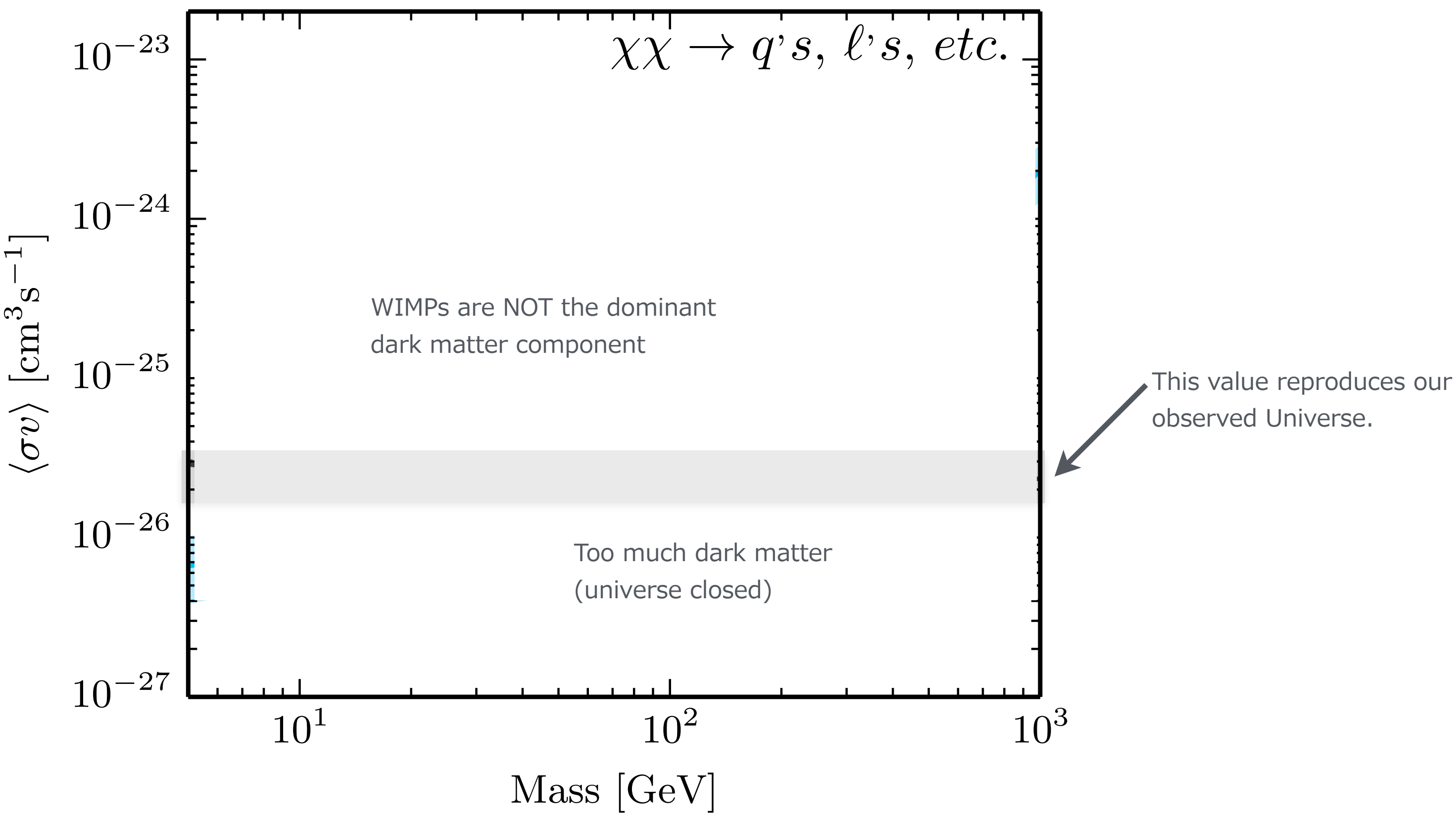
- High mass-to-light ratio (i.e., dark matter dominated, very few stars)
- No known astrophysical background (no gas, stars are old)

Dwarf galaxies





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



Geringer-Sameth, Koushiappas & Walker, PRD 91, 083535 (2015), see also ApJ 801, 74 (2014) & Ackermann et al., PRD 89, 042001 (2014) & 1503.02641

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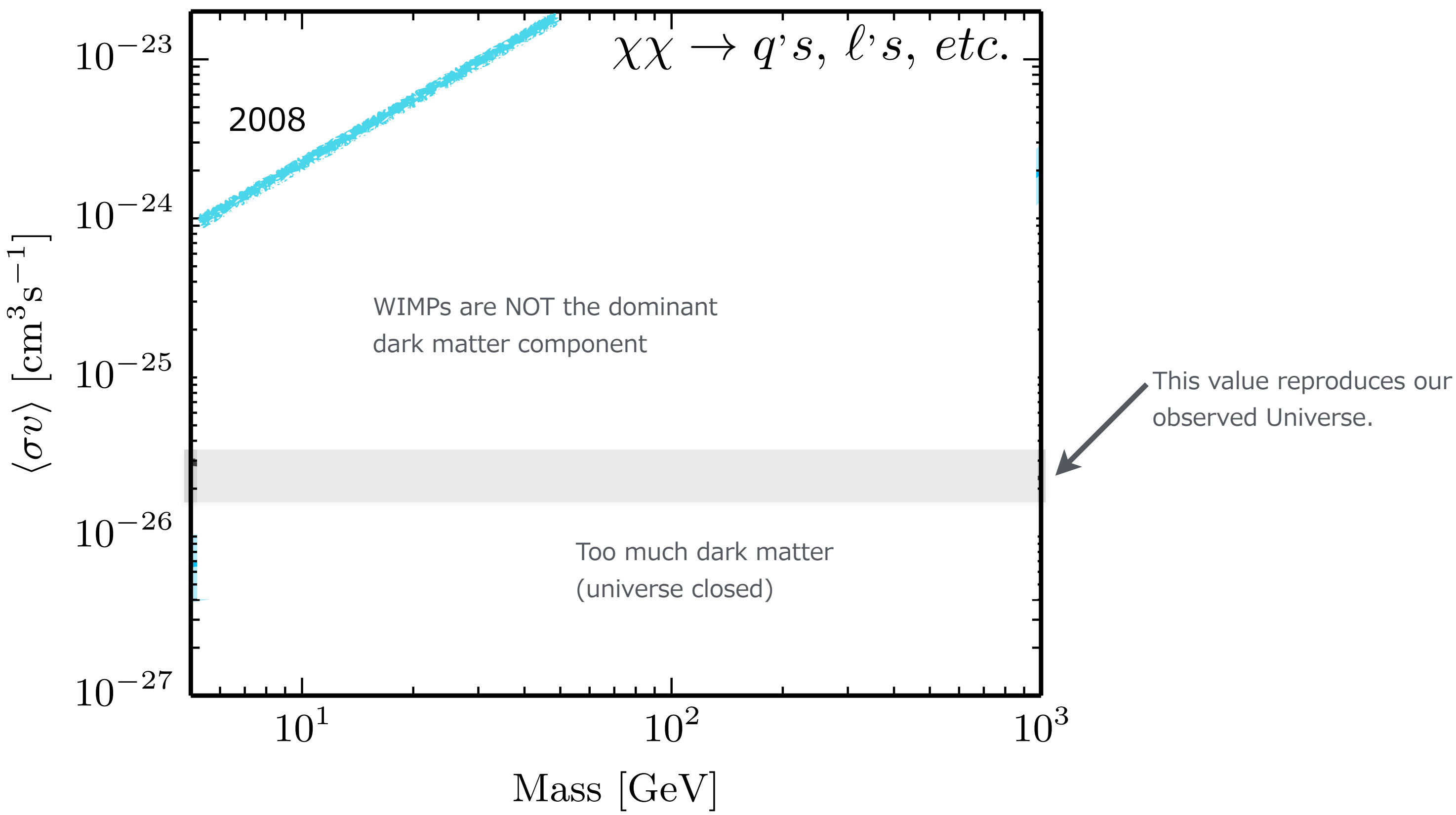

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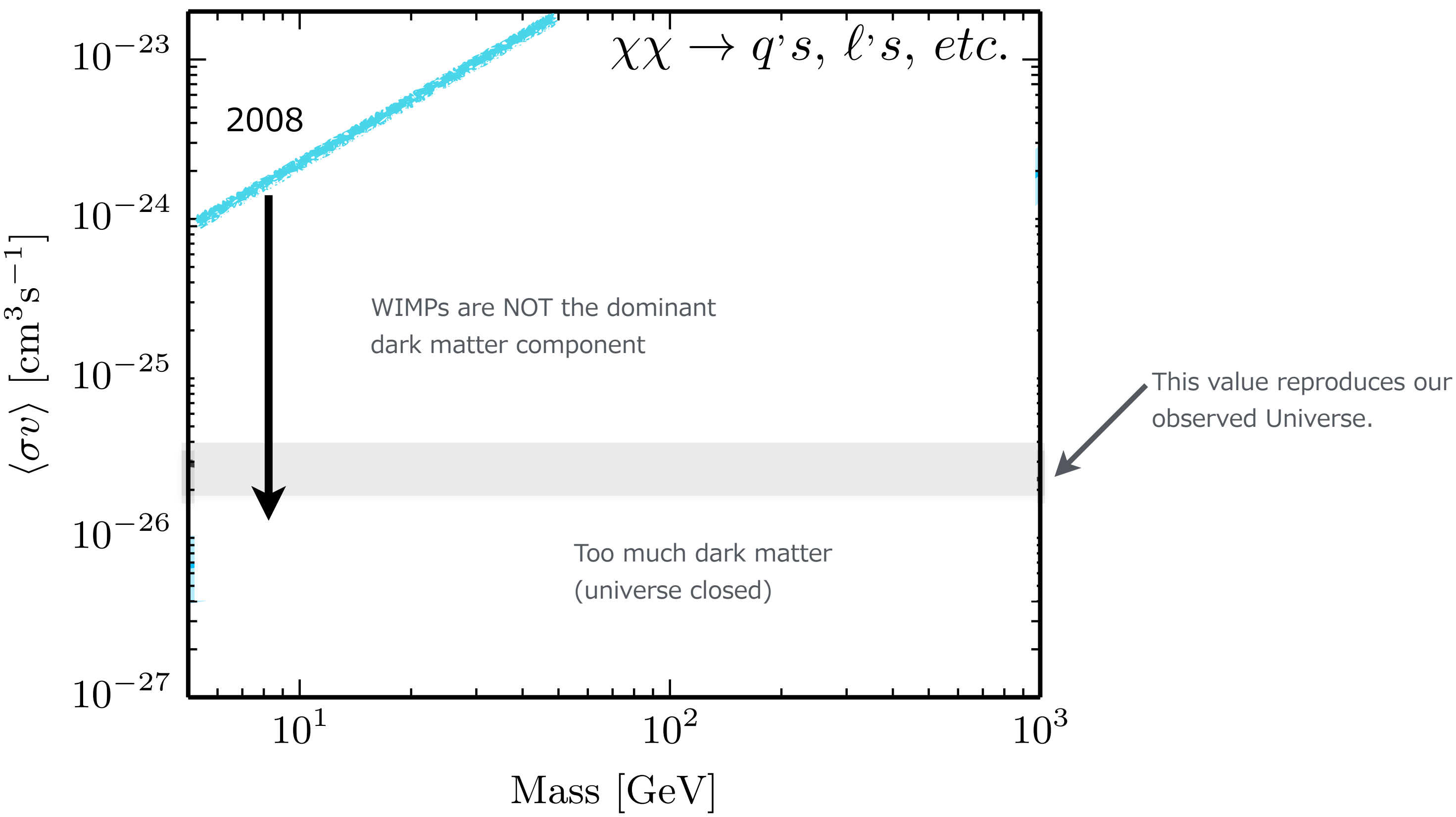

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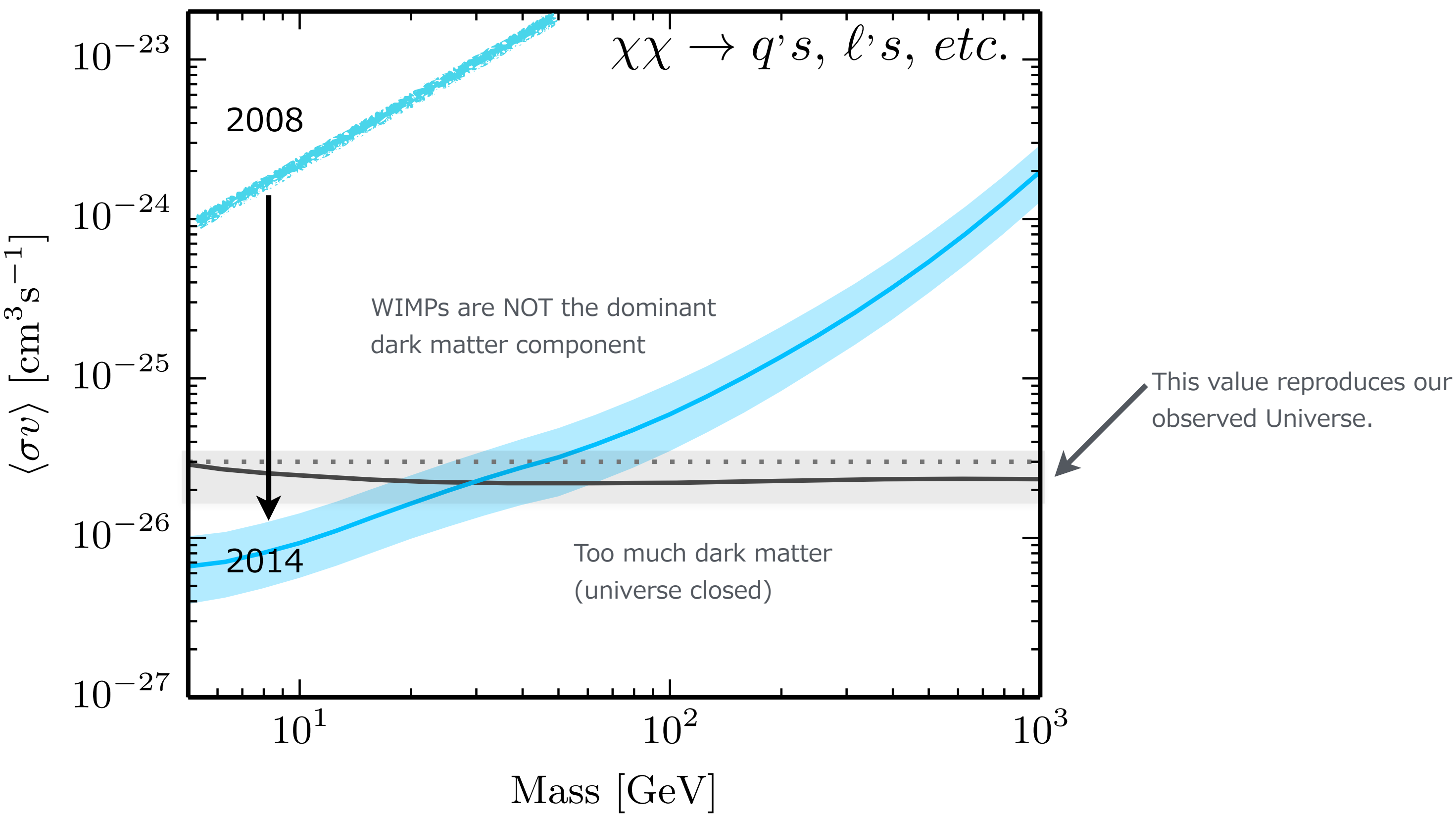

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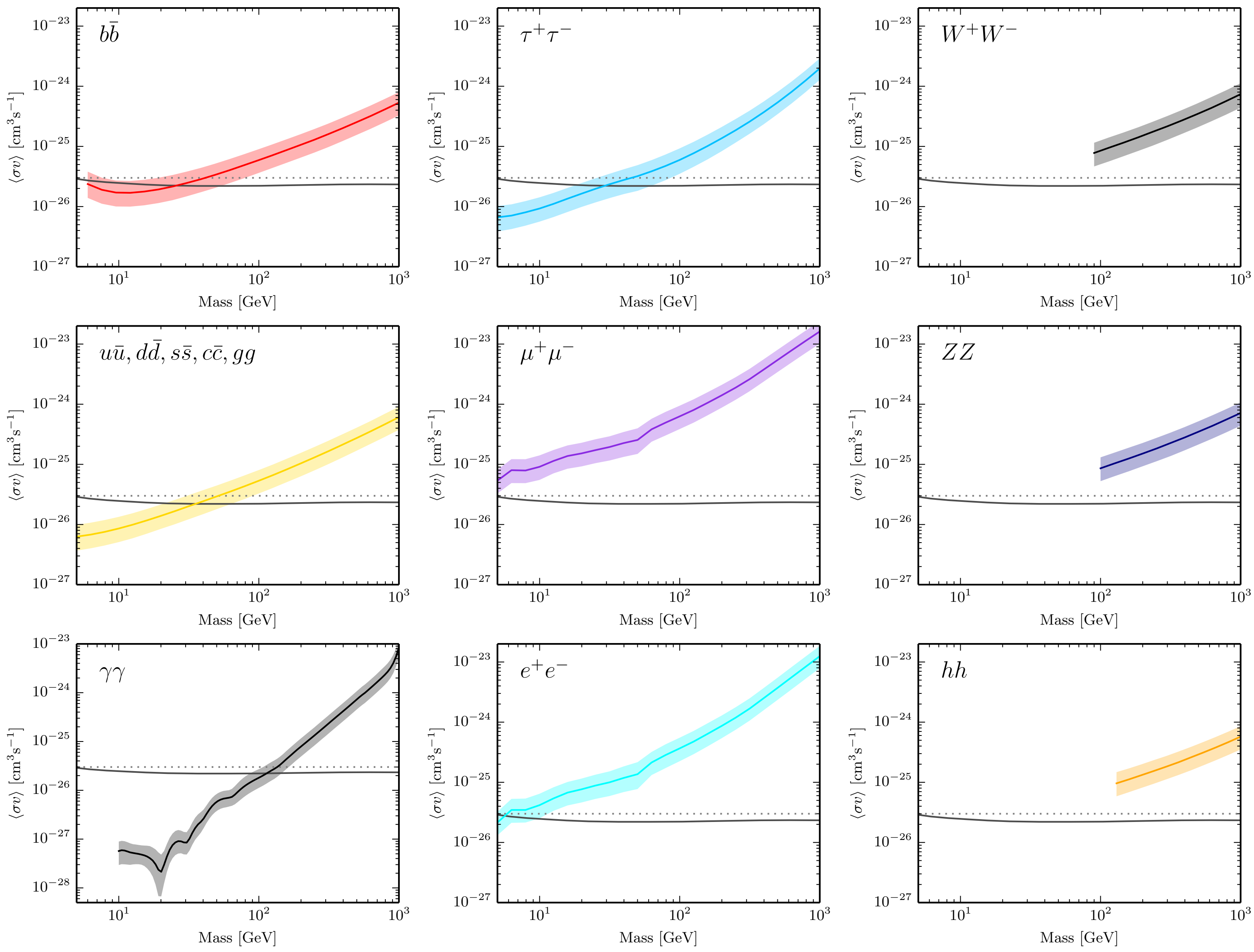

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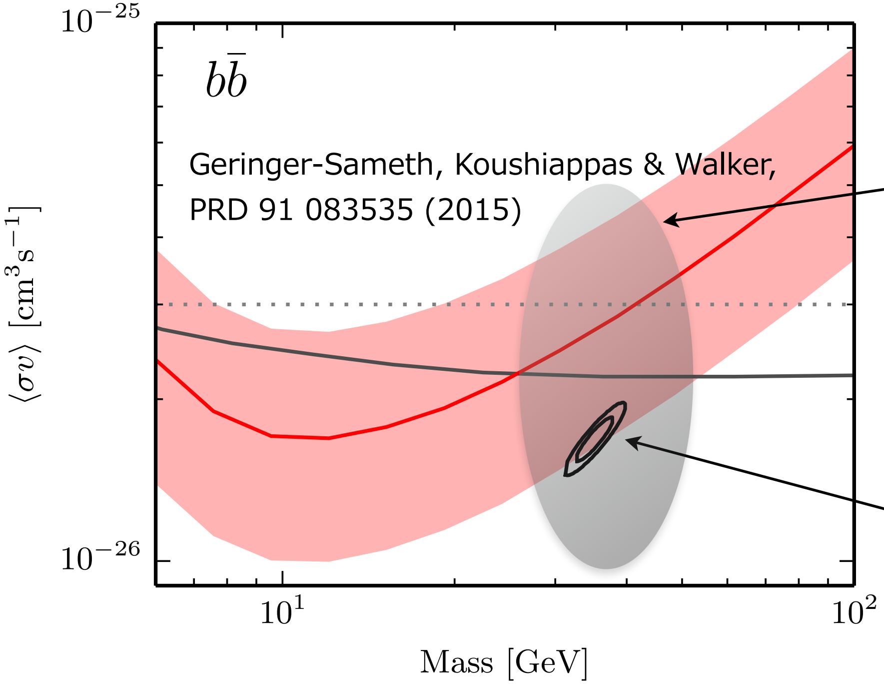

Systematic uncertainty in the interpretation of the signal (see Abazajian et al. PRD 90, 023526 (2014)).

Galactic center excess interpretation in the context of dark matter (Daylan et al., arXiv:1402.6703)

What about consistency checks with the Galactic center and other dwarfs? (see e.g., Abazajian & Keeley 1510.06424)

On March 8, 2015

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Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data
The Fermi-LAT Collaboration, The DES Collaboration: A. Drlica-Wagner, A. Albert, K. Bechtol, M. Wood, L. Strigari, M. Sanchez-Conde, L. Baldini, R. Essig, J. Cohen-Tanugi, B. Anderson, R. Bellazzini, E. D. Bloom, R. Caputo, C. Cecchi, E. Charles, J. Chiang, J. Conrad, A. de Angelis, S. Funk, P. Fusco, F. Gargano, N. Giglietto, F. Giordano, S. Guiriec, M. Gustafsson, M. Kuss, F. Loparco, P. Lubrano, N. Mirabal, T. Mizuno, A. Morselli, T. Ohsugi, E. Orlando, M. Persic, S. Raino, F. Spada, D. J. Suson, G. Zaharijas, S. Zimm
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arXiv:1503.02641 [pdf, other]
Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data
Fermi-LAT Collaboration

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Name	α [deg]	δ [deg]	Signif	m−M [mag]	$\mathrm{Dist}_\odot$ [kpc]
Reticulum 2	53.9256	−54.0492	48.5	17.4	30
Eridanus 2	56.0878	−43.5332	31.5	22.9	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[a]	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

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Phoenix 2	354.9975	−54.4060	13.9	19.6	83
Indus 1	317.2044	−51.1656	13.7	20.0	100
Grus 1[a]	344.1765	−50.1633	10.1	20.4	120
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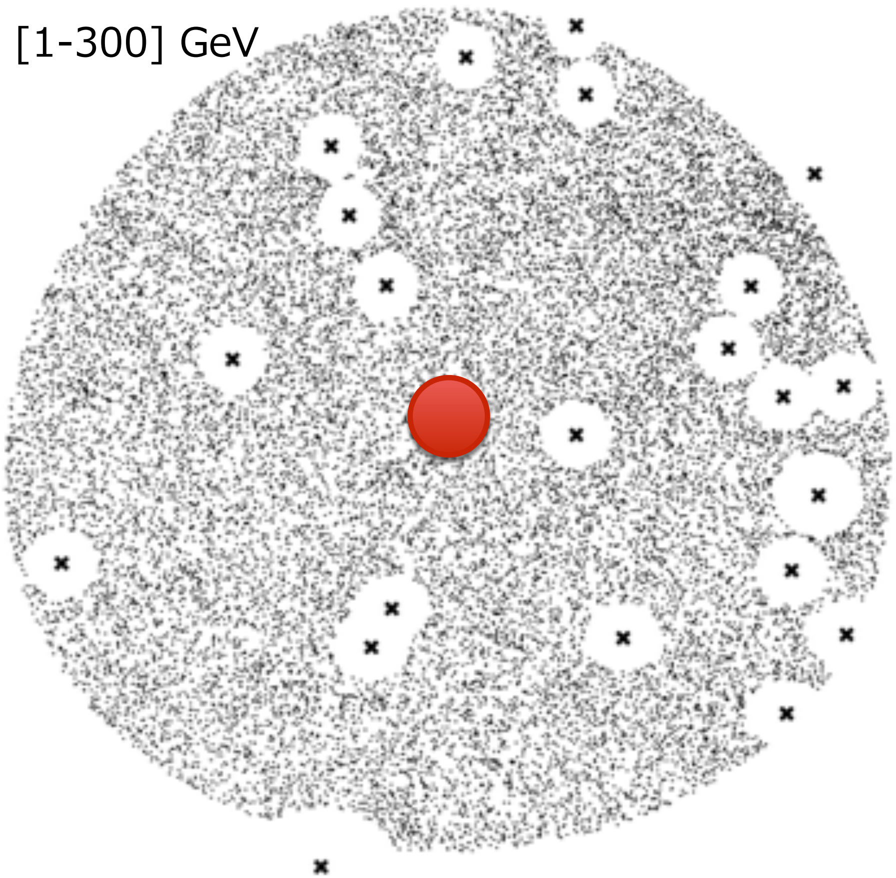
Reticulum II in gamma-rays

[1-300] GeV



Based on PRL 115, 081101 & ApJL 808 L36 (2015)

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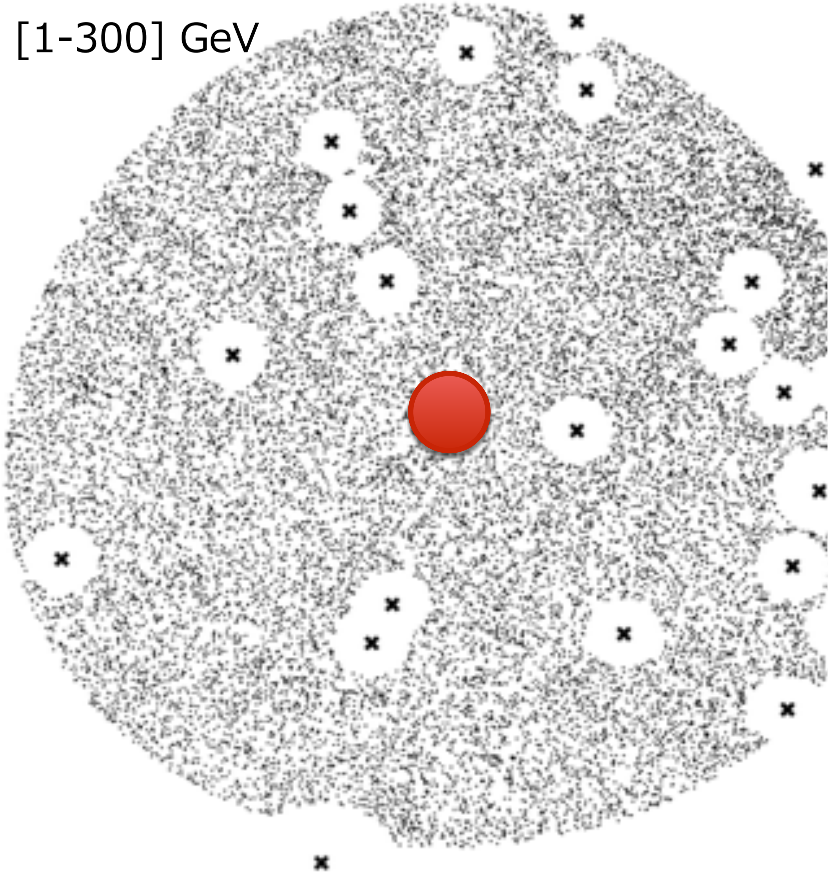
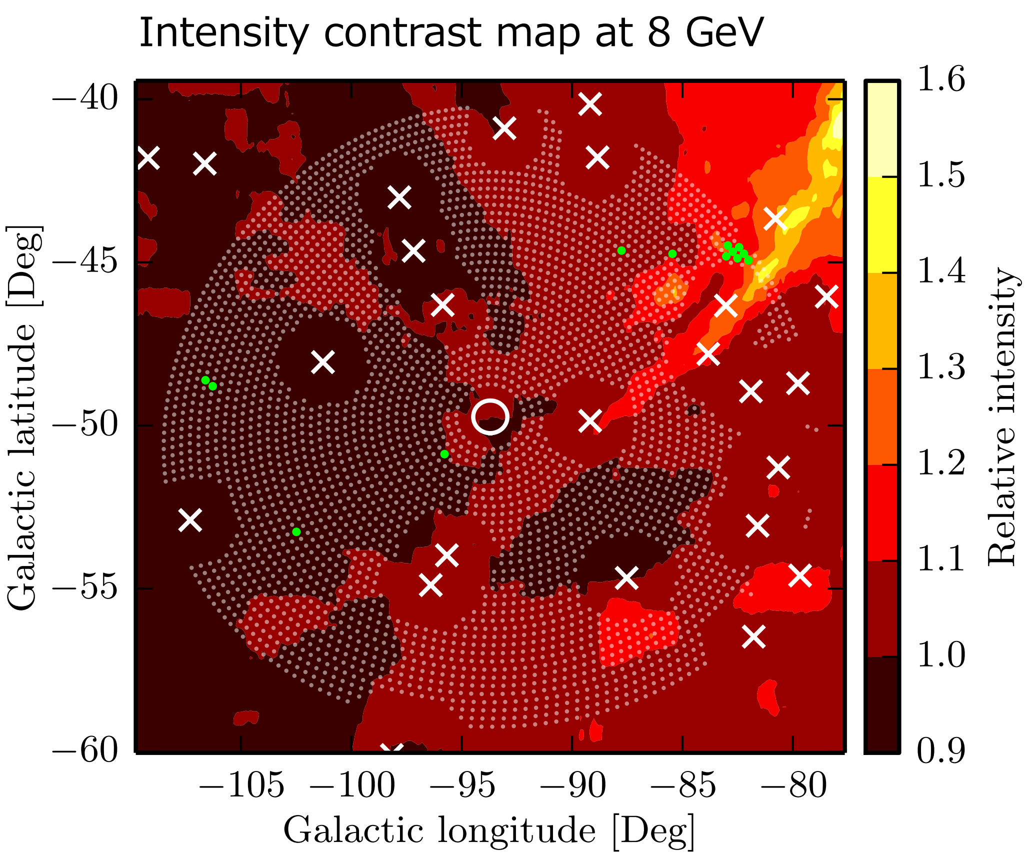
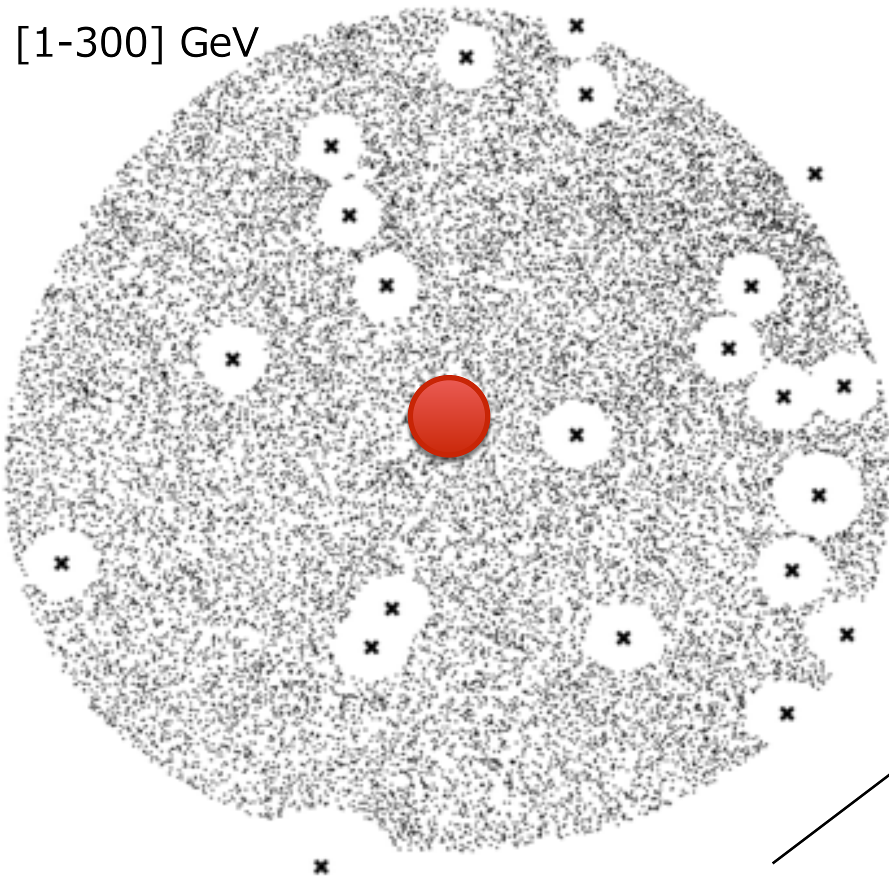
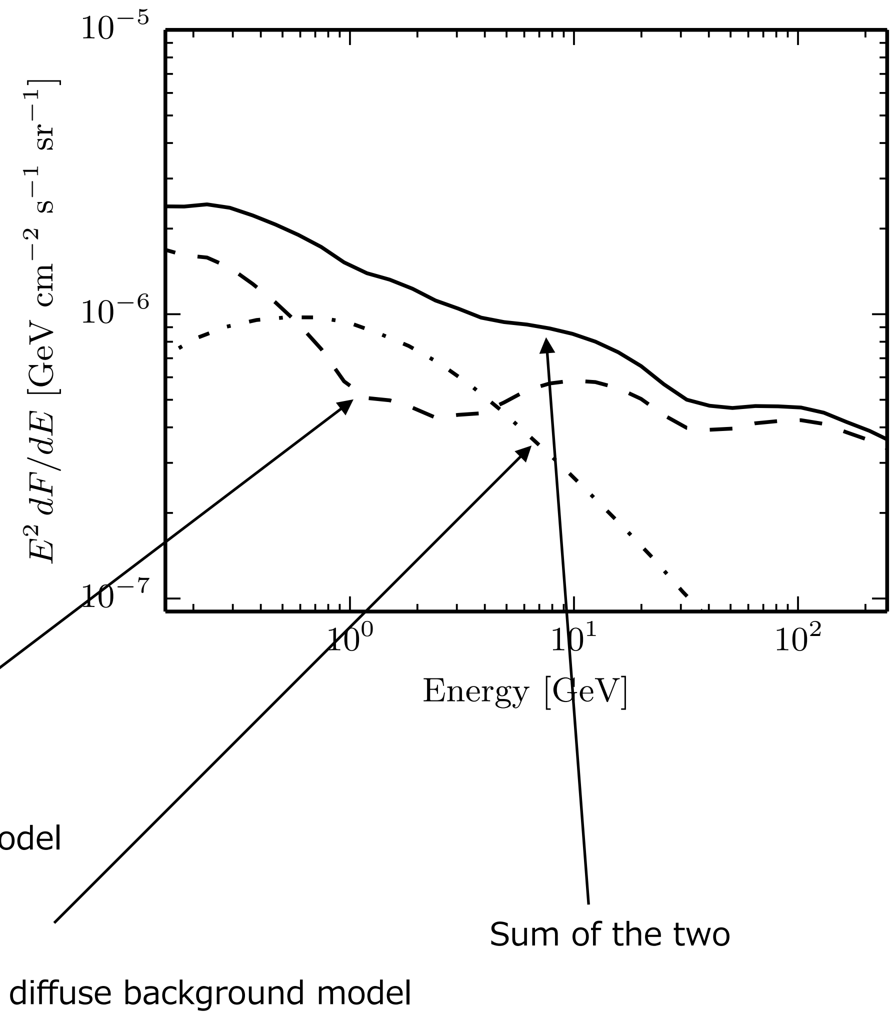




Based on PRL 115, 081101 & ApJL 808 L36 (2015)

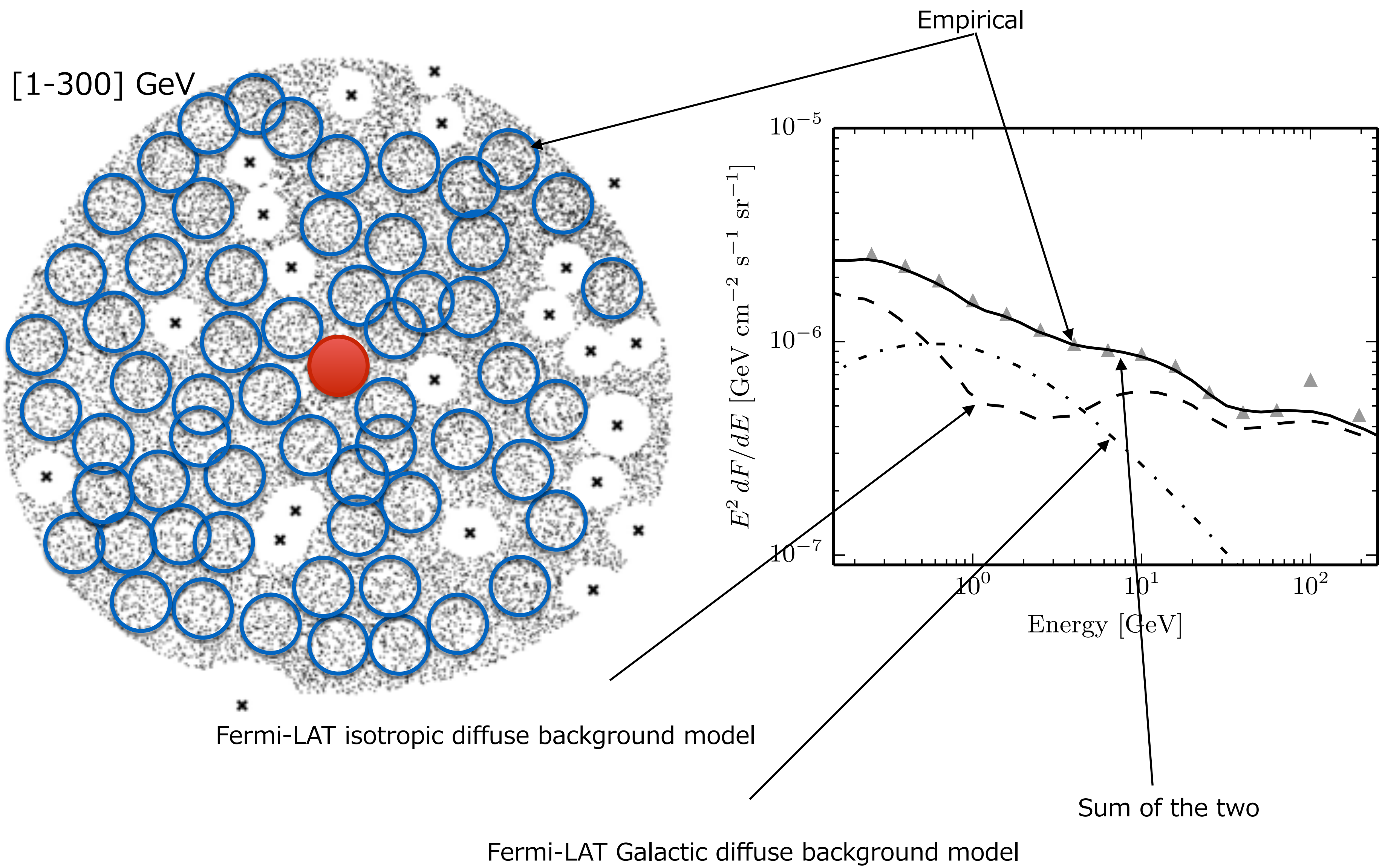
Reticulum II in gamma-rays





Based on PRL 115, 081101 & ApJL 808 L36 (2015)

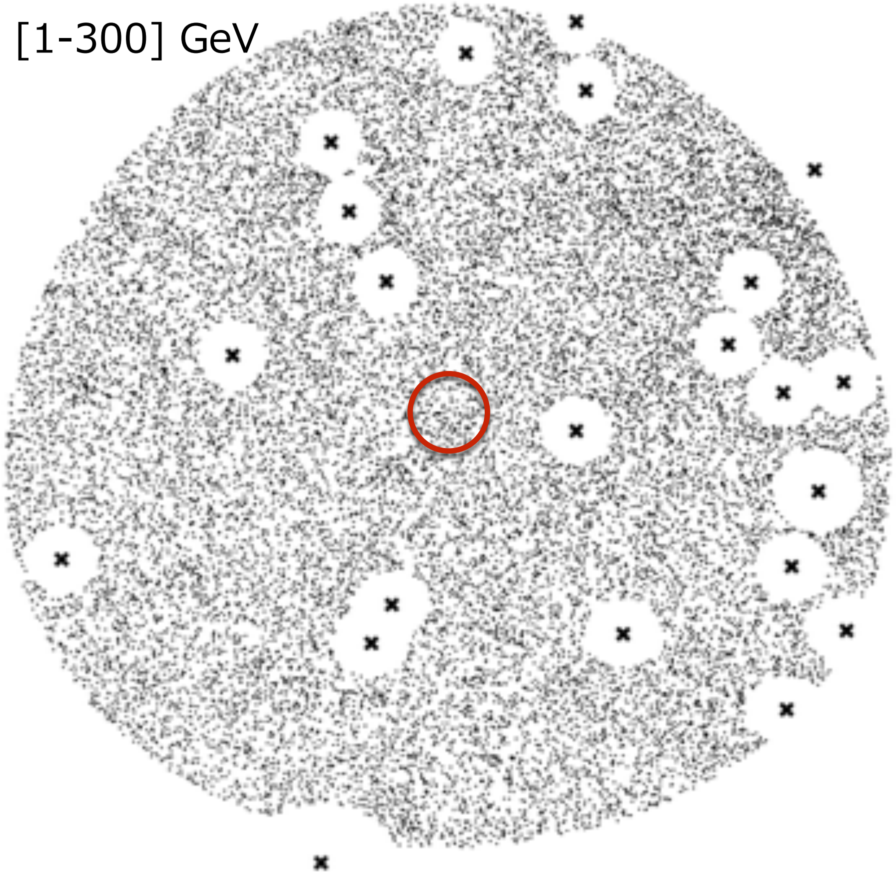
Reticulum II in gamma-rays

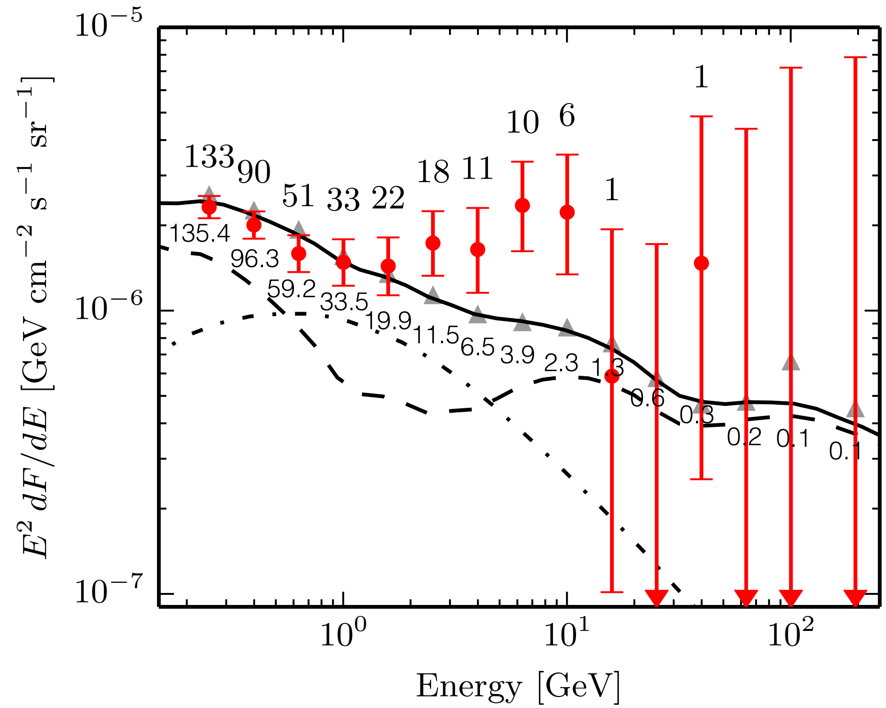


Based on PRL 115, 081101 & ApJL 808 L36 (2015)

Reticulum II in gamma-rays

[1-300] GeV



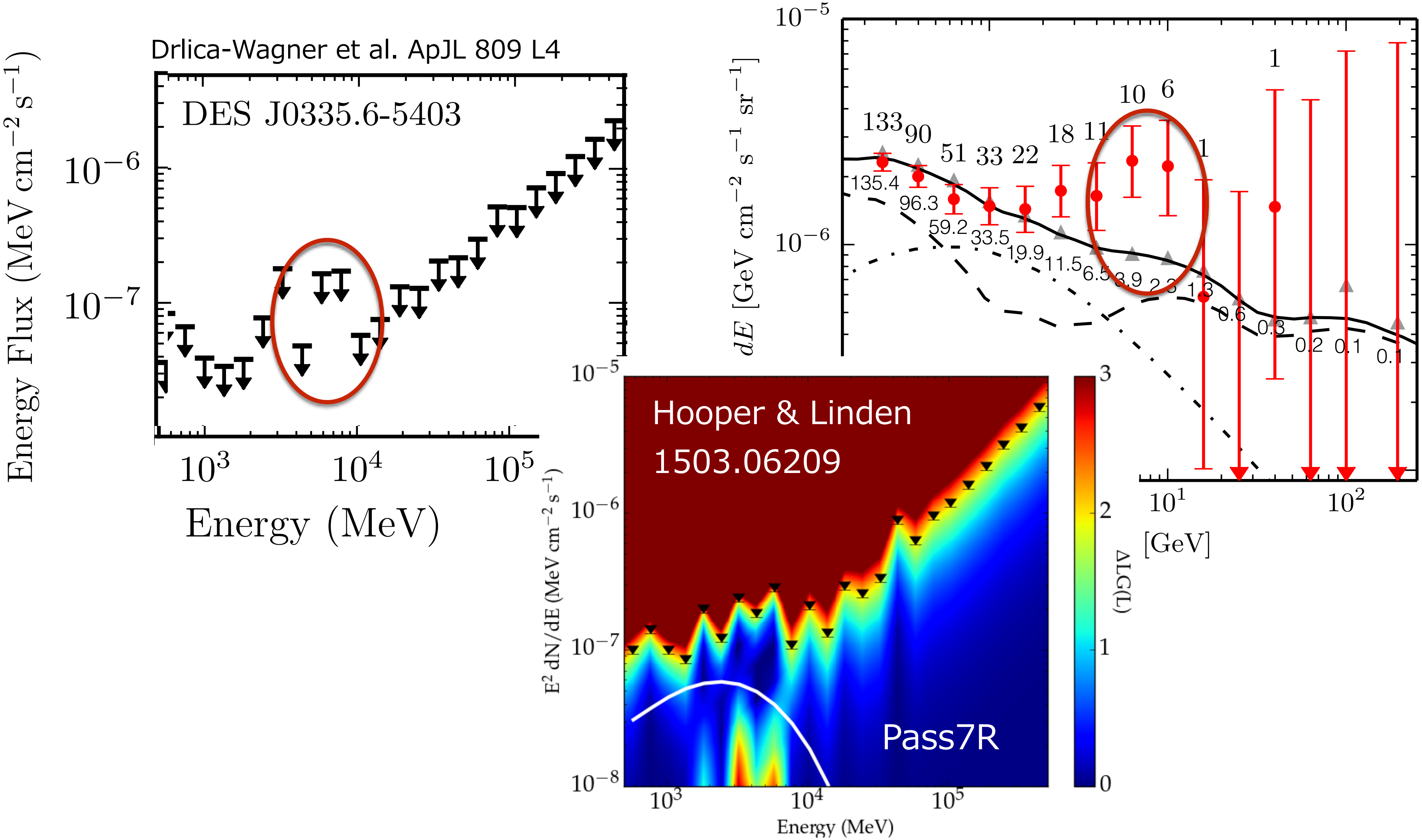


Based on PRL 115, 081101 & ApJL 808 L36 (2015)

Reticulum II in gamma-rays

Pass8 Fermi-LAT w/hybrid Pass8/7 background

Pass7R



Questions

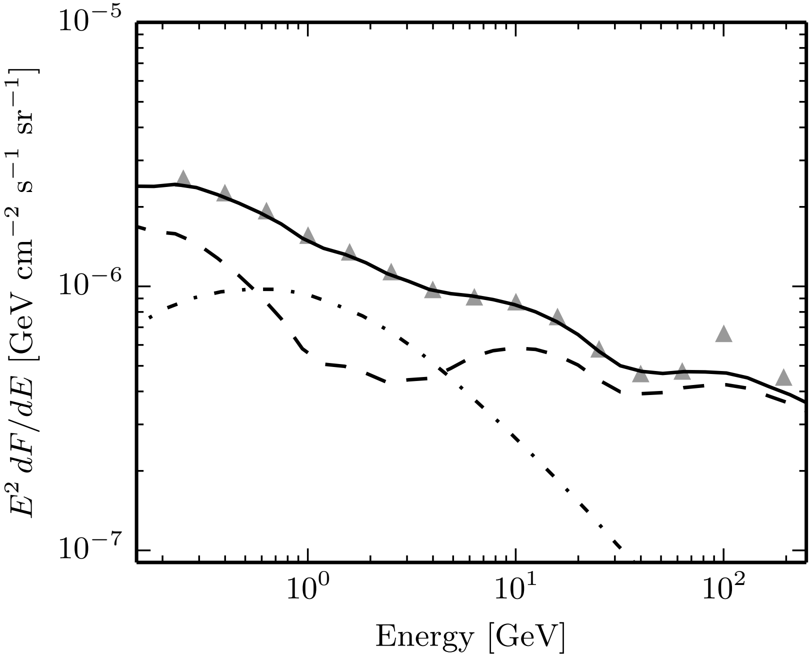
1. Is it consistent with background?

2. Is it consistent with dark matter annihilation?

3. Is it consistent with any other source?

4. Is it something else? (e.g., instrumental/data set systematics?) (P7R vs P8)

Statistical significance of a dark matter interpretation



Background modeling

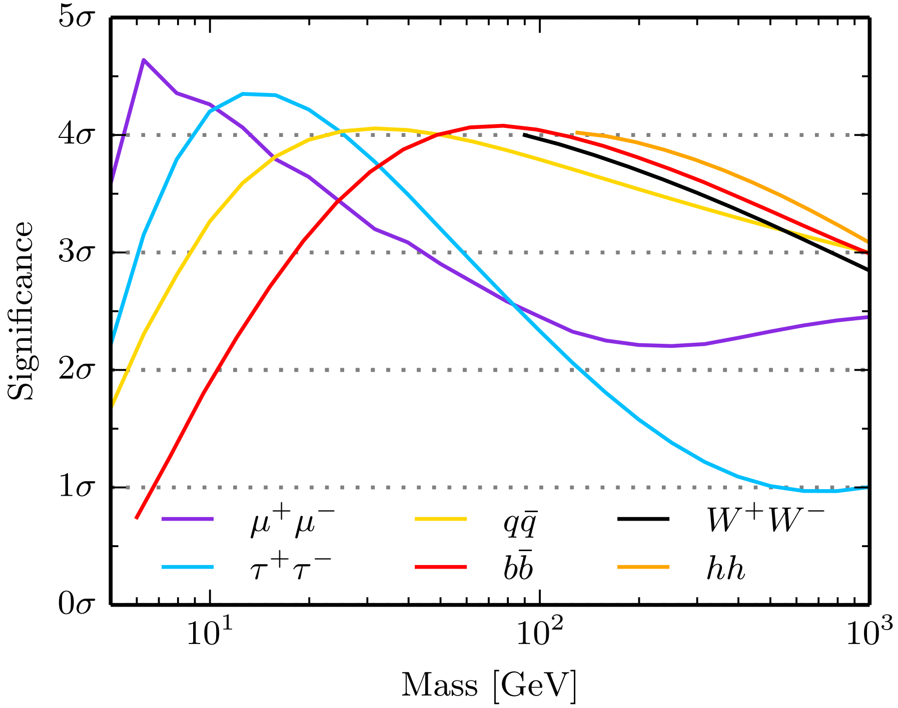
- ***Diffuse 1***: Fermi-LAT background averaged over 1 degree.
- ***Diffuse 2***: Fermi-LAT background averaged over 2 degrees.
- ***Empirical 1***: Events in an [1-5] degree annulus from central ROI with 20% gaussian width on energy.
- ***Empirical 2***: Bin *Empirical 1* events in energy.

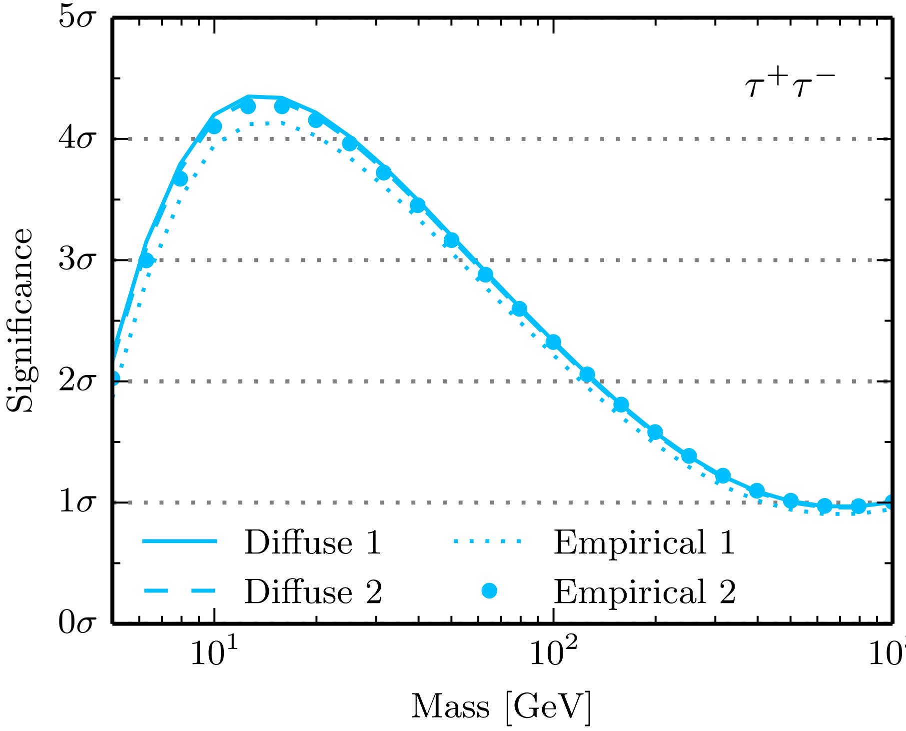
- Background in the central 0.5 degree ROI is a Poisson random variable
- Background is isotropic
- Energies are drawn from a given spectrum

Based on PRL 115, 081101 & ApJL 808 L36 (2015)

Statistical significance of a dark matter interpretation

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





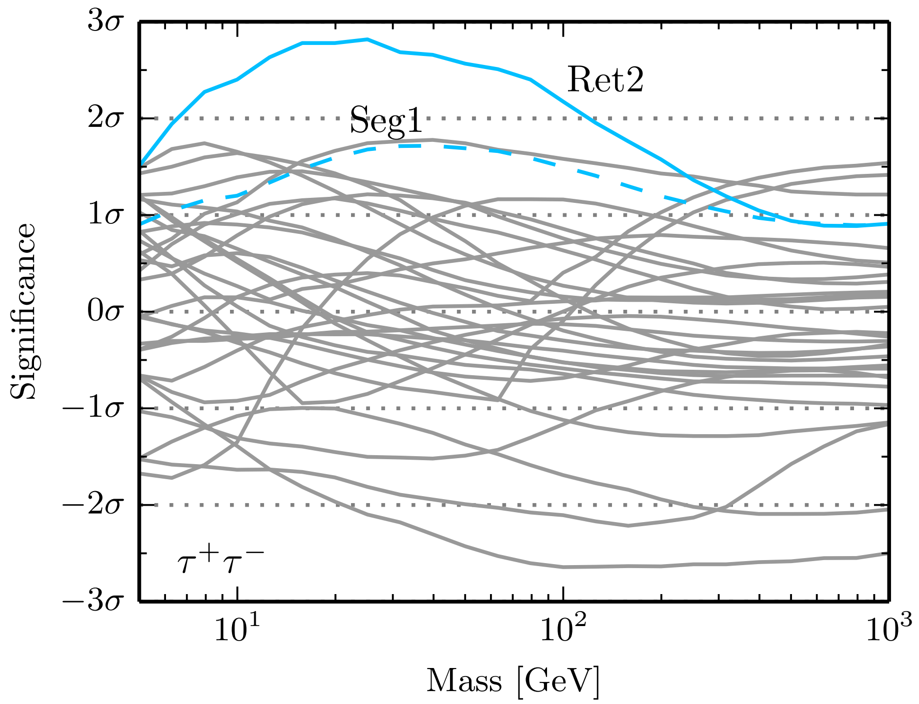
Local p-value = 0.0000068 (4.4 sigma)

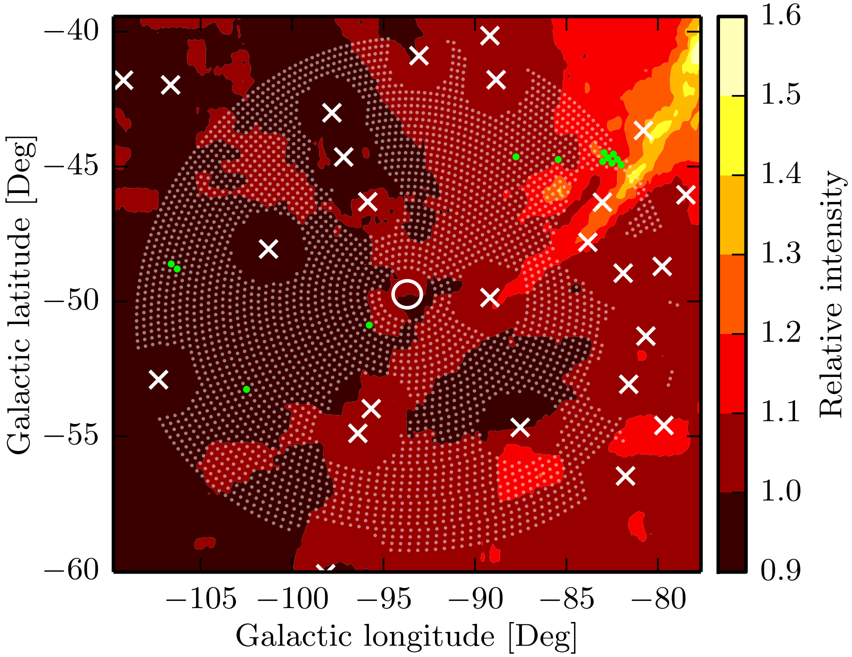
Global p-value = 0.000042 (**3.7 sigma**)

Based on PRL 115, 081101 & ApJL 808 L36 (2015)

Statistical significance of a dark matter interpretation

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





Local p-value = 0.0024 (2.8 sigma)

Global p-value = 0.0097 (**2.3 sigma**)

Based on PRL 115, 081101 & ApJL 808 L36 (2015)

Statistical significance of a dark matter interpretation

Pass7

Empirical background

Local p-value = 0.0024 (2.8 sigma)

Global p-value = 0.0097 (**2.3 sigma**)

Poisson background

Local p-value = 0.0000068 (4.4 sigma)

Global p-value = 0.000042 (**3.7 sigma**)

Pass8

p-values comparable with what found in Drlica-Wagner et al. ApJL 809 L4.

Based on PRL 115, 081101 & ApJL 808 L36 (2015)

Statistical significance of a dark matter interpretation

Pass7

Empirical background

Local p-value = 0.0024 (2.8 sigma)

Global p-value = 0.0097 (**2.3 sigma**)

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Pass8

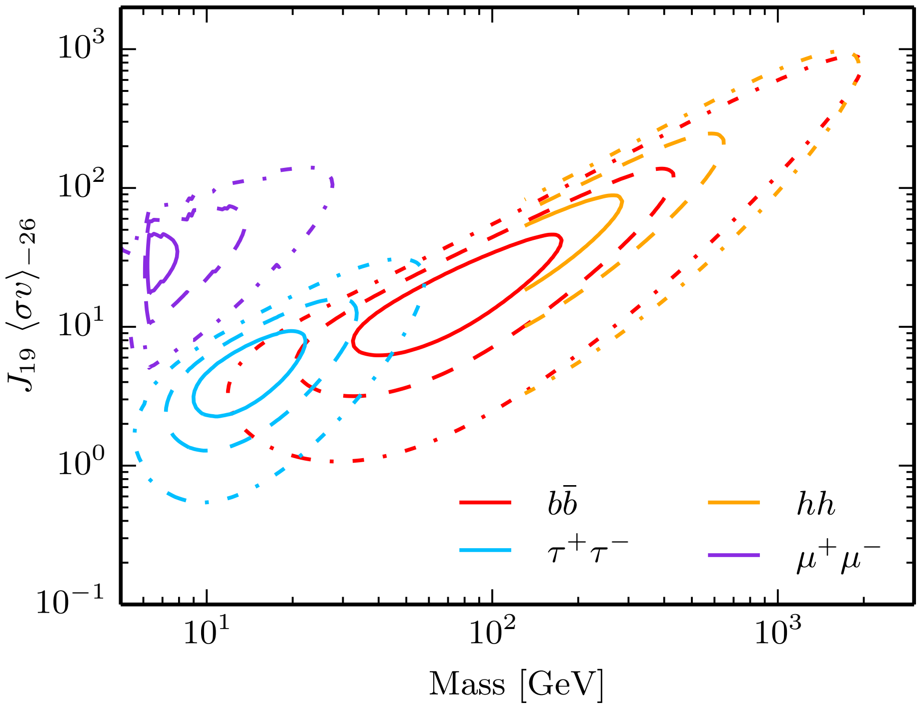
p-values comparable with what found in Drlica-Wagner et al. ApJL 809 L4.

Reticulum II is the brightest dwarf galaxy among all known dwarfs in both data sets

Based on PRL 115, 081101 & ApJL 808 L36 (2015)

Statistical significance of a dark matter interpretation

Based on PRL 115, 081101 & ApJL 808 L36 (2015)



$$\Gamma \sim J\,\frac{\langle \sigma v \rangle}{M^2}$$

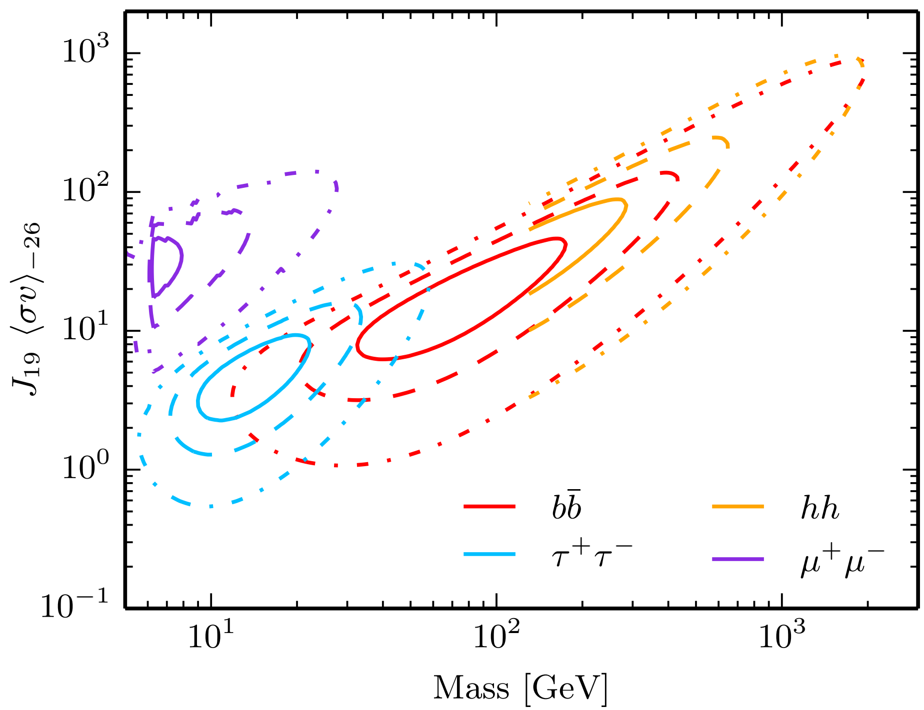
$$J = \iint \rho^2_{\rm DM}(l,\Omega)\,dl\,d\Omega$$

What about consistency checks with the Galactic center and other dwarfs?
(see e.g., Abazajian & Keeley 1510.06424)

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

Statistical significance of a dark matter interpretation

Based on PRL 115, 081101 & ApJL 808 L36 (2015)



$$\Gamma \sim J\,\frac{\langle\sigma v\rangle}{M^2}$$

$$J = \iint \rho^2_{\rm DM}(l,\Omega)\,dl\,d\Omega$$

Prediction: J should have a certain value if it is dark matter.

What about consistency checks with the Galactic center and other dwarfs? (see e.g., Abazajian & Keeley 1510.06424)

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

The dark matter content of Reticulum II

The dark matter content of Reticulum II

$$\Gamma \sim J \, \frac{\langle \sigma v \rangle}{M^2}$$

$$J = \iint \rho_{\mathrm{DM}}^2(l, \Omega) \, dl d\Omega$$

The dark matter content of Reticulum II

$$\Gamma \sim J\,\frac{\langle \sigma v \rangle}{M^2} \qquad\qquad J = \iint \rho^2_{\mathrm{DM}}(l,\Omega)\, dl d\Omega$$

Use stellar kinematics to reconstruct the gravitational potential.

PHYSICAL REVIEW D **75,** 083526 (2007)

Precise constraints on the dark matter content of Milky Way dwarf galaxies for gamma-ray experiments

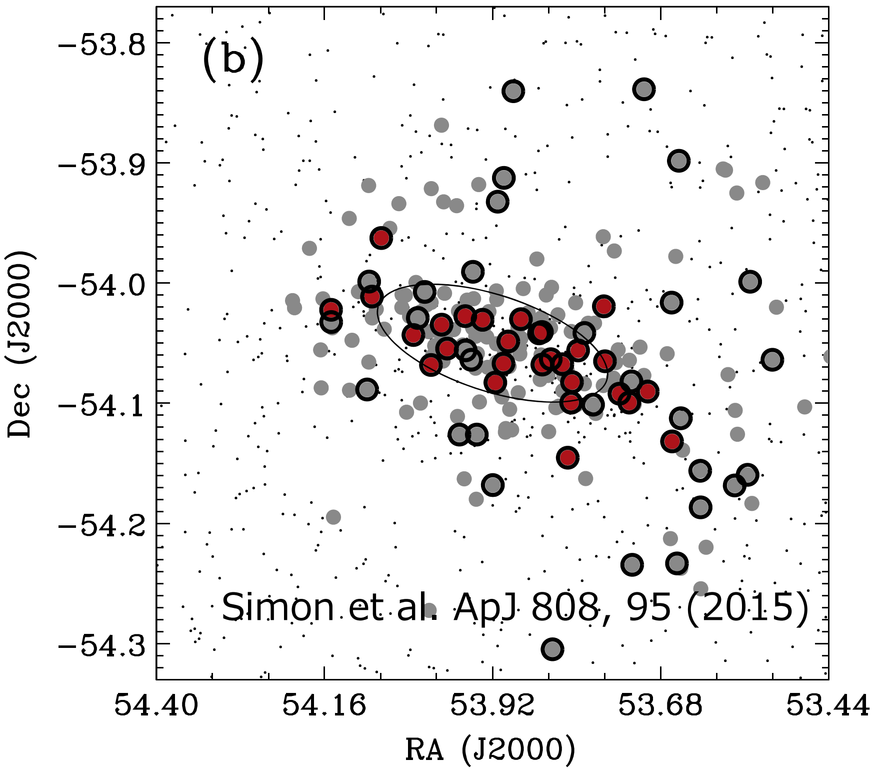
Louis E. Strigari,[1,*] Savvas M. Koushiappas,[2,†] James S. Bullock,[1,‡] and Manoj Kaplinghat[1,§]

The Astrophysical Journal, 678:614–620, 2008 May 10

THE MOST DARK-MATTER–DOMINATED GALAXIES: PREDICTED GAMMA-RAY SIGNALS FROM THE FAINTEST MILKY WAY DWARFS

Louis E. Strigari,[1] Savvas M. Koushiappas,[2] James S. Bullock,[1] Manoj Kaplinghat,[1]
Joshua D. Simon,[3] Marla Geha,[4] and Beth Willman[5]
Received 2007 October 12; accepted 2008 January 7

The dark matter content of Reticulum II



Recall, we need $\Gamma \propto \int n_\chi^2 d^3 r$

$n(r) \propto f(\mathbf{v})$ (Newton)

$\mathbf{v} \propto f'(\sigma_\perp)$ (Jeans)

Stellar kinematics

The dark matter content of Reticulum II

The Astrophysical Journal, 808:108 (14pp), 2015 August 1 doi:10.1088/0004-637X/808/2/108

MAGELLAN/M2FS SPECTROSCOPY OF THE RETICULUM 2 DWARF SPHEROIDAL GALAXY*

Matthew G. Walker[1], Mario Mateo[2], Edward W. Olszewski[3], John I. Bailey III[2], Sergey E. Koposov[4], Vasily Belokurov[4], and N. Wyn Evans[4]

The Astrophysical Journal, 808:95 (14pp), 2015 July 20 doi:10.1088/0004-637X/808/1/95

STELLAR KINEMATICS AND METALLICITIES IN THE ULTRA-FAINT DWARF GALAXY RETICULUM II*†‡

J. D. Simon[1], A. Drlica-Wagner[2], T. S. Li[3], B. Nord[2], M. Geha[4], K. Bechtol[5], E. Balbinot[6,7], E. Buckley-Geer[2], H. Lin[2], J. Marshall[3], B. Santiago[7,8], L. Strigari[3], M. Wang[3], R. H. Wechsler[9,10,11], B. Yanny[2], T. Abbott[12], A. H. Bauer[13], G. M. Bernstein[14], E. Bertin[15,16], D. Brooks[17], D. L. Burke[10,11], D. Capozzi[18], A. Carnero Rosell[7,19], M. Carrasco Kind[20,21], C. B. D'Andrea[18], L. N. da Costa[7,19], D. L. DePoy[3], S. Desai[22], H. T. Diehl[2], S. Dodelson[2,5], C. E. Cunha[10], J. Estrada[2], A. E. Evrard[23], A. Fausti Neto[7], E. Fernandez[24], D. A. Finley[2], B. Flaugher[2], J. Frieman[2,5], E. Gaztanaga[13], D. Gerdes[23], D. Gruen[25,26], R. A. Gruendl[20,21], K. Honscheid[27,28], D. James[12], S. Kent[2], K. Kuehn[29], N. Kuropatkin[2], O. Lahav[17], M. A. G. Maia[7,19], M. March[17], P. Martini[27,30], C. J. Miller[23,31], R. Miquel[24], R. Ogando[7,19], A. K. Romer[32], A. Roodman[10,11], E. S. Rykoff[10,11], M. Sako[14], E. Sanchez[33], M. Schubnell[23], I. Sevilla[20,33], R. C. Smith[12], M. Soares-Santos[2], F. Sobreira[2,7], E. Suchyta[27,28], M. E. C. Swanson[21], G. Tarle[23], J. Thaler[34], D. Tucker[2], V. Vikram[35], A. R. Walker[12], and W. Wester[2]
(The DES Collaboration)

The dark matter content of Reticulum II

Quantity	Value
R.A. at center	$\alpha_{J2000} = 03{:}35{:}42$
Decl. at center	$\delta_{J2000} = -54{:}02{:}57$
Galactic longitude	$l = 266.2958$ deg
Galactic latitude	$b = -49.7357$ deg
Distance modulus	$m - M = 17.4 \pm 0.2$
Distance from Sun	$D \sim 30$ kpc
Absolute magnitude	$M_V = -2.7 \pm 0.1$ (-3.6 ± 0.1)
Exponential scale length	$R_e = 3.37^{+0.23}_{-0.13}$ arcmin
Ellipticity	$e = 1 - (b/a) = 0.59^{+0.02}_{-0.03}$
Position angle	PA $= 71 \pm 1$ deg
Projected halflight radius	$R_h = 3.64^{+0.21}_{-0.12}$ arcmin
Projected halflight radius	$R_h = 32^{+1.9}_{-1.1}$ pc
Systemic line of sight velocity	$v_{los} = 64.3^{+1.2}_{-1.2}$ km s^{-1}
Systemic line of sight velocity	$v_{los} = -90.9$ km s^{-1}
Internal velocity dispersion	$\sigma_{v_{los}} = 3.6^{+1.0}_{-0.7}$ km s^{-1}
Velocity gradient	$k_{v_{los}} = 0.5^{+0.4}_{-0.3}$ km s^{-1} arcmin^{-1}
PA of velocity gradient	$\theta_{v_{los}} = -92^{+217}_{-65}$ deg
Mean metallicity	$\langle[Fe/H]\rangle = -2.58^{+0.34}_{-0.33}$ dex
Metallicity dispersion	$\sigma_{[Fe/H]} = 0.49^{+0.19}_{-0.14}$ dex
Metallicity gradient	$k_{[Fe/H]} = 0.01^{+0.06}_{-0.06}$ dex arcmin^{-1}
Mass enclosed within R_h	$M(R_h) = 2.4^{+1.4}_{-0.8} \times 10^5 M_\odot$
Mass-to-light raio	$\Upsilon = 467^{+286}_{-168} M_\odot/L_\odot$

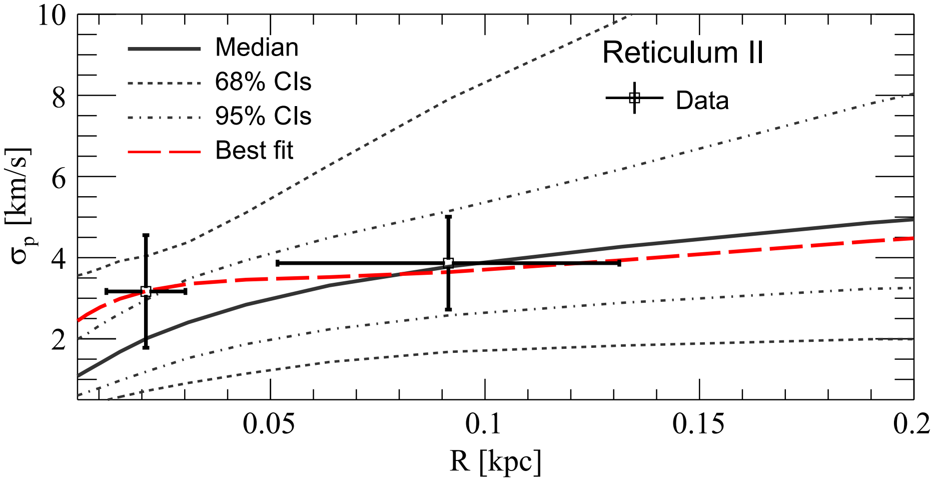
Quantity	Value
R.A. (J2000)	03:35:41
Decl. (J2000)	–54:03:00
Distance (kpc)	32
$M_{V,0}$	-3.6 ± 0.1
$L_{V,0}$ $(L_\odot)$	2360 ± 200
ϵ	$0.60^{+0.10}_{-0.20}$
$r_{1/2}$ (pc)	55 ± 5
V_{hel} (km s^{-1})	62.8 ± 0.5
V_{GSR} (km s^{-1})	-92.5 ± 0.5
σ (km s^{-1})	3.3 ± 0.7
Mass within the half-light radius $(M_\odot)$	$5.6 \pm 2.4 \times 10^5$
$M_{1/2}/L_V$ $(M_\odot/L_\odot)$	470 ± 210
Mean [Fe/H]	-2.65 ± 0.07
Metallicity dispersion (dex)	0.28 ± 0.09
$\log_{10} J(0.^\circ2)$ (GeV^2 cm^{-5})	18.8 ± 0.6
$\log_{10} J(0.^\circ5)$ (GeV^2 cm^{-5})	18.9 ± 0.6

The dark matter content of Reticulum II

The Astrophysical Journal Letters, 808:L36 (5pp), 2015 August 1
doi:10.1088/2041-8205/808/2/L36

DARK MATTER ANNIHILATION AND DECAY PROFILES FOR THE RETICULUM II DWARF SPHEROIDAL GALAXY

Vincent Bonnivard[1], Céline Combet[1], David Maurin[1], Alex Geringer-Sameth[2], Savvas M. Koushiappas[3], Matthew G. Walker[2], Mario Mateo[4], Edward W. Olszewski[5], and John I. Bailey III[4]



$$\sigma_p^2(R) = \frac{2}{\Sigma(R)} \int_R^\infty \left(1 - \beta_{\rm ani}(r)\frac{R^2}{r^2}\right) \frac{\nu(r)\,\overline{v_r^2}(r)\,r}{\sqrt{r^2 - R^2}} dr,$$

$$\mathcal{L} = \prod_{i=1}^{N_{\rm stars}} \frac{(2\pi)^{-1/2}}{\sqrt{\sigma_p^2(R_i) + \Delta_{v_i}^2}} \exp\left[-\frac{1}{2}\left(\frac{(v_{\rm i} - \bar{v})^2}{\sigma_p^2(R_i) + \Delta_{v_i}^2}\right)\right],$$

The dark matter content of Reticulum II

Bonnivard et al. ApJL 808 L36 (2015)

$\alpha_{\rm int}$ [deg]	$\log_{10}(J(\alpha_{\rm int}))$ $[J/\mathrm{GeV}^2\,\mathrm{cm}^{-5}]^{\rm a}$
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	$19.7^{+1.2(+2.0)}_{-0.9(-1.5)}$

Simon et al. ApJ 808, 95 (2015)

$\alpha_{\rm int}$ [deg]	$\log_{10}(J(\alpha_{\rm int}))$ $[J/\mathrm{GeV}^2\,\mathrm{cm}^{-5}]^{\rm a}$
0.2	18.8 ± 0.6
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The dark matter content of Reticulum II

Bonnivard et al. ApJL 808 L36 (2015)

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Flexible profile
No artificial truncation
No assumption on the distribution
J is the peak of the distribution
Error is percentiles

Simon et al. ApJ 808, 95 (2015)

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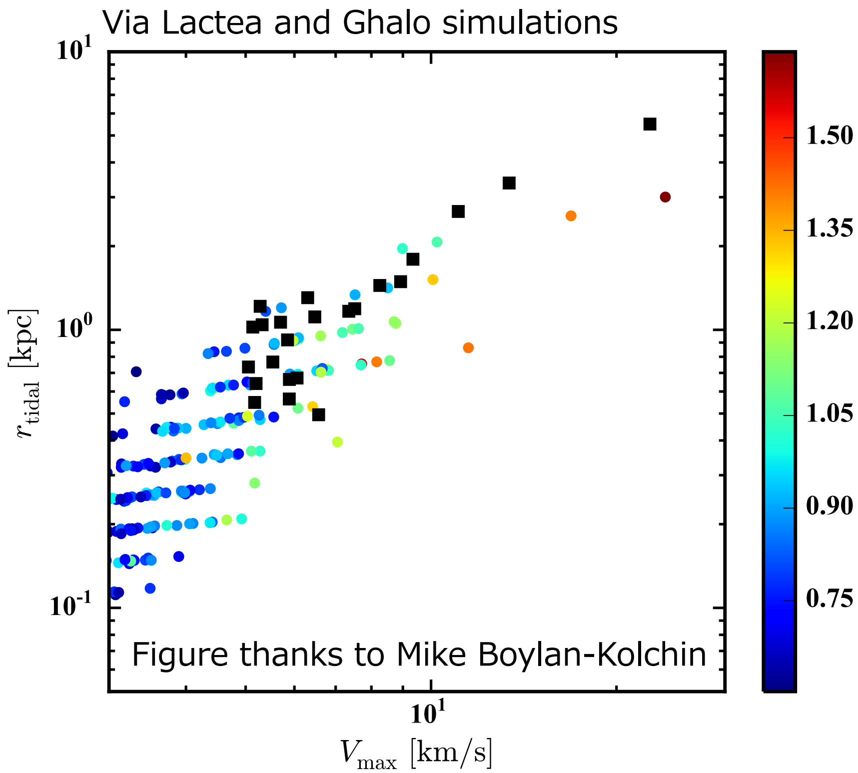
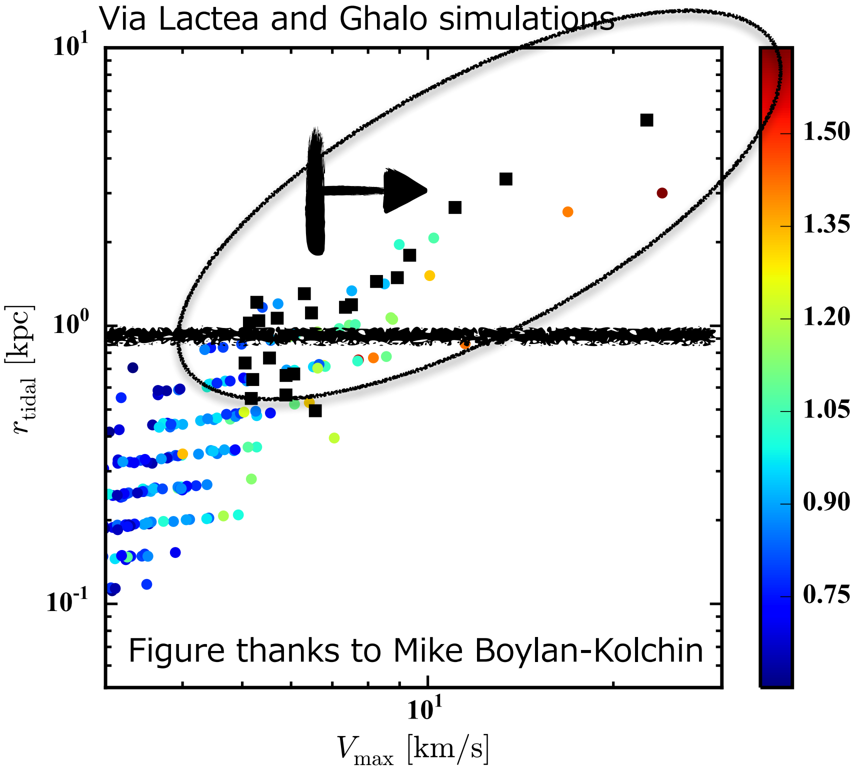
Plummer profile
Truncation at 1 kpc
Gaussian approximation
J is the peak of the Gaussian
Error is standard deviation

The dark matter content of Reticulum II



Flexible profile	Plummer profile
No artificial truncation	***Truncation at 1 kpc***
No assumption on the distribution	Gaussian approximation
J is the peak of the distribution	J is the peak of the Gaussian
Error is percentiles	Error is standard deviation

The dark matter content of Reticulum II



Flexible profile	Plummer profile
No artificial truncation	***<u>Truncation at 1 kpc</u>***
No assumption on the distribution	Gaussian approximation
J is the peak of the distribution	J is the peak of the Gaussian
Error is percentiles	Error is standard deviation

Questions

1. Is it consistent with background?

2. Is it consistent with dark matter annihilation?

3. Is it consistent with any other source?

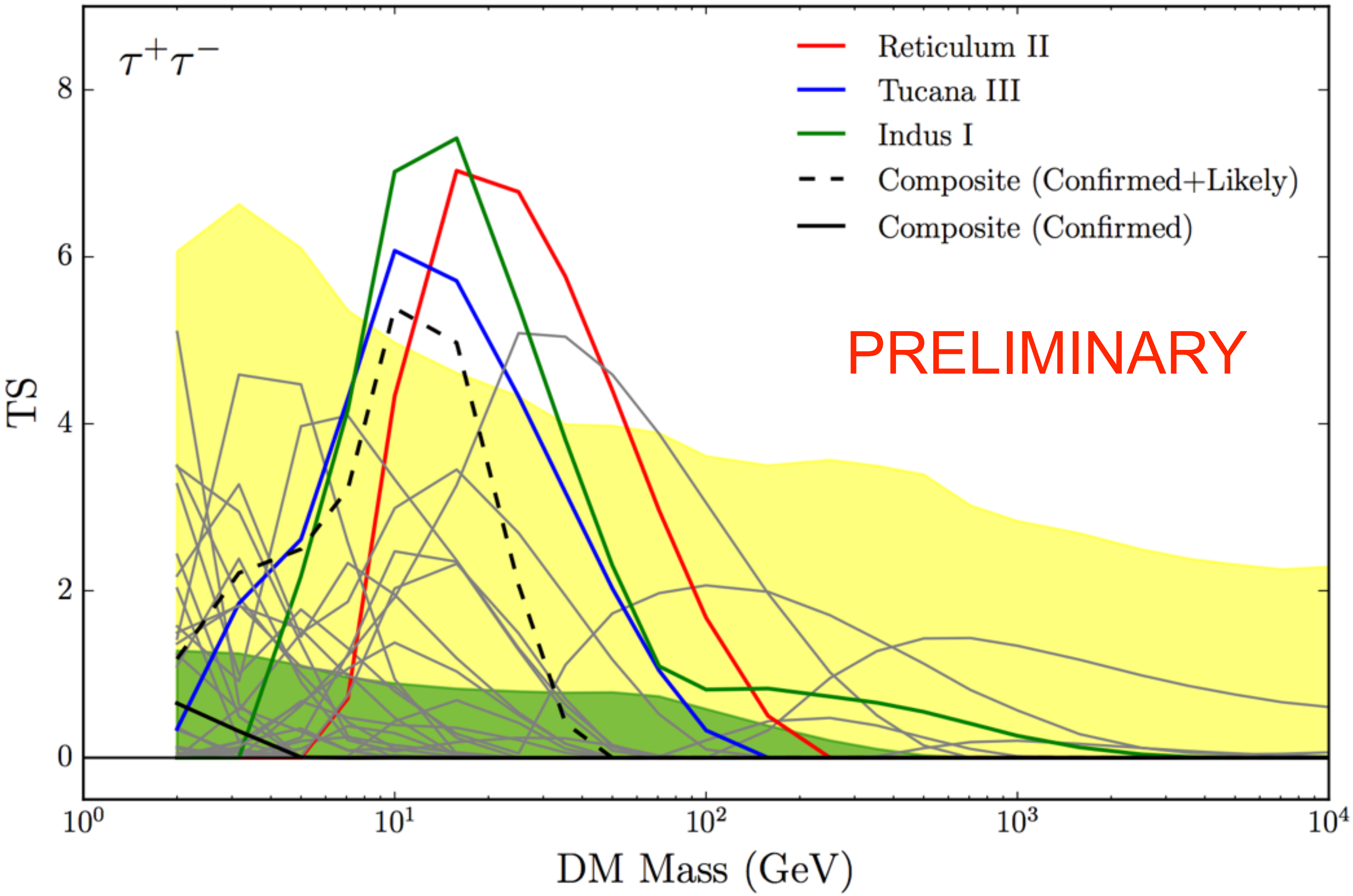
4. Is it something else? (e.g., instrumental/data set systematics?)

Question: Why don’t we see it in other dwarfs:

- -Uncertainty in J is large
- -Joint analysis is dominated by the dwarfs with the highest
- -Not all dwarfs have ***consistent*** J estimates!

Questions

From Keith Bechtol's talk TAUP 2015



Realities

- At this point any dark matter discovery will come at the detection threshold.

- We only have one dataset to work with (no possibility of independent cross-check).

- Each and every photon counts (this is important for any source at the threshold).

In conclusion

Given that this is the very first time we have a [fill in your favorite word] 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 as it is a massive nearby dwarf galaxy — a prime target in the search for a non-gravitational signature of dark matter.

In conclusion

Given that this is the very first time we have a [fill in your favorite word] 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 as it is a massive nearby dwarf galaxy — a prime target in the search for a non-gravitational signature of dark matter.

Bottom line: We need more data