Reevaluating the WIMP Miracle

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Acknowledgments:

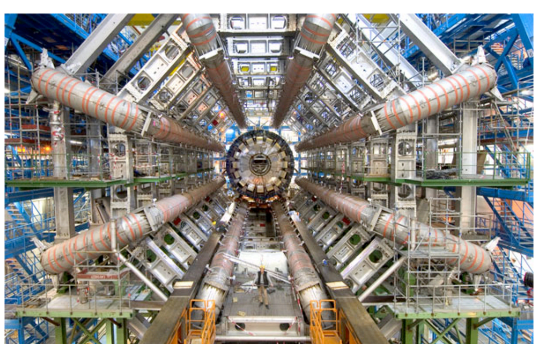
Bobby Acharya (ICTP)
Piyush Kumar (Berkeley)
Phill Grajek, Gordy Kane, Dan Phalen, and Aaron Pierce (Michigan)

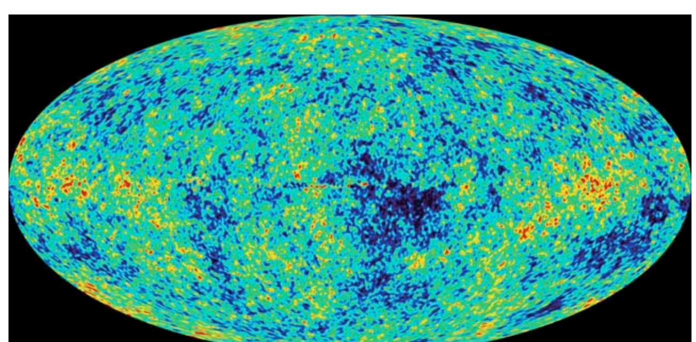
Conclusion

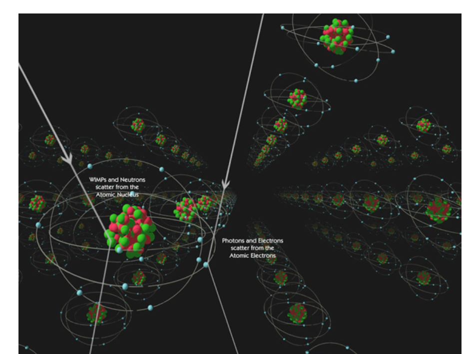
Thermal dark matter from “realistic” models of string phenomenology could prove challenging.

This is good news, because non-thermal dark matter (in contrast to thermal production) could provide a new window on probing string based models.

A complete understanding of dark matter requires a concordance approach (cosmology, particle experiment, and fundamental theory)



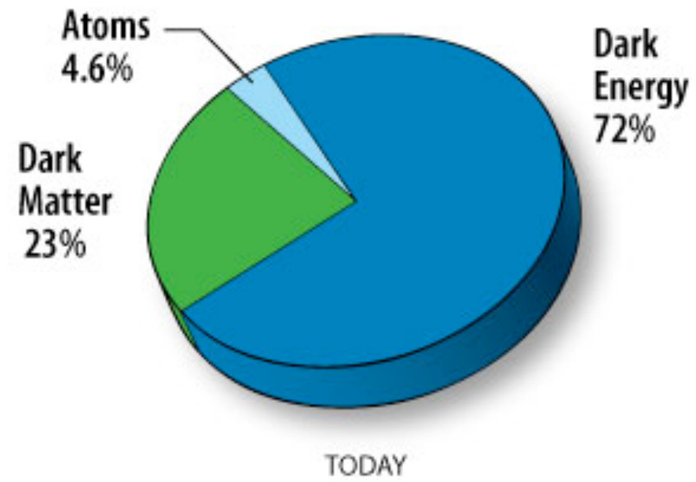




Precision Cosmology

Cosmic Energy Budget

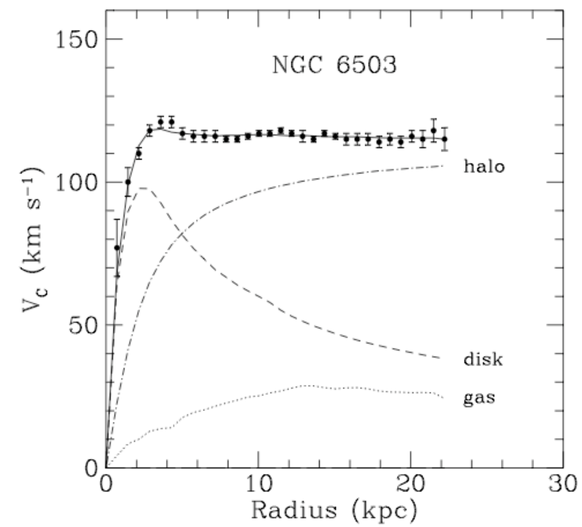
- Dark Energy 72%
- Dark Matter 23%
- Baryons 5%
- Early universe remarkably homogeneous
- Very small density contrast (1:100,000) at time of decoupling of CMB

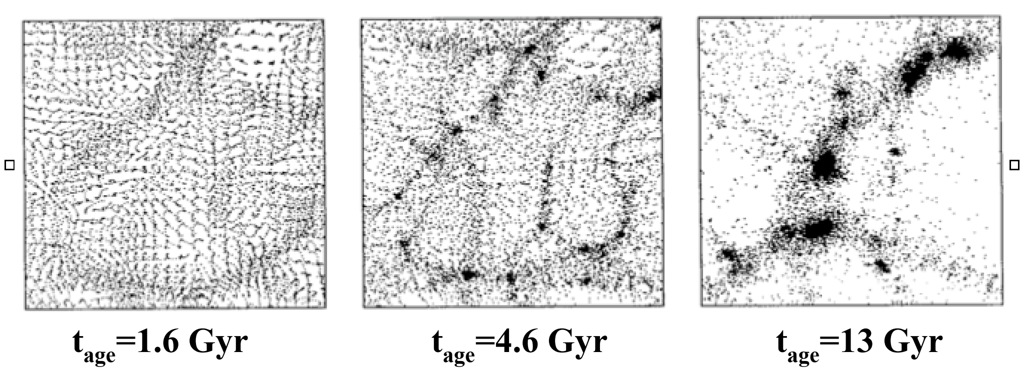


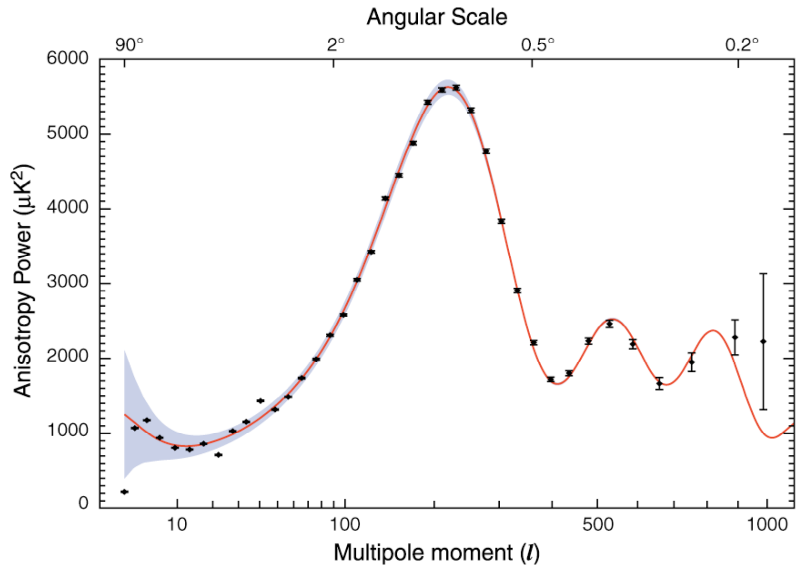
All suggest physics beyond the standard model.

Cosmological Dark Matter

- Rotation curves
- CMB / LSS / Supernovae
- Evolution of LSS
- Gravitational Lensing







Cosmological Dark Matter

Cosmological Properties:

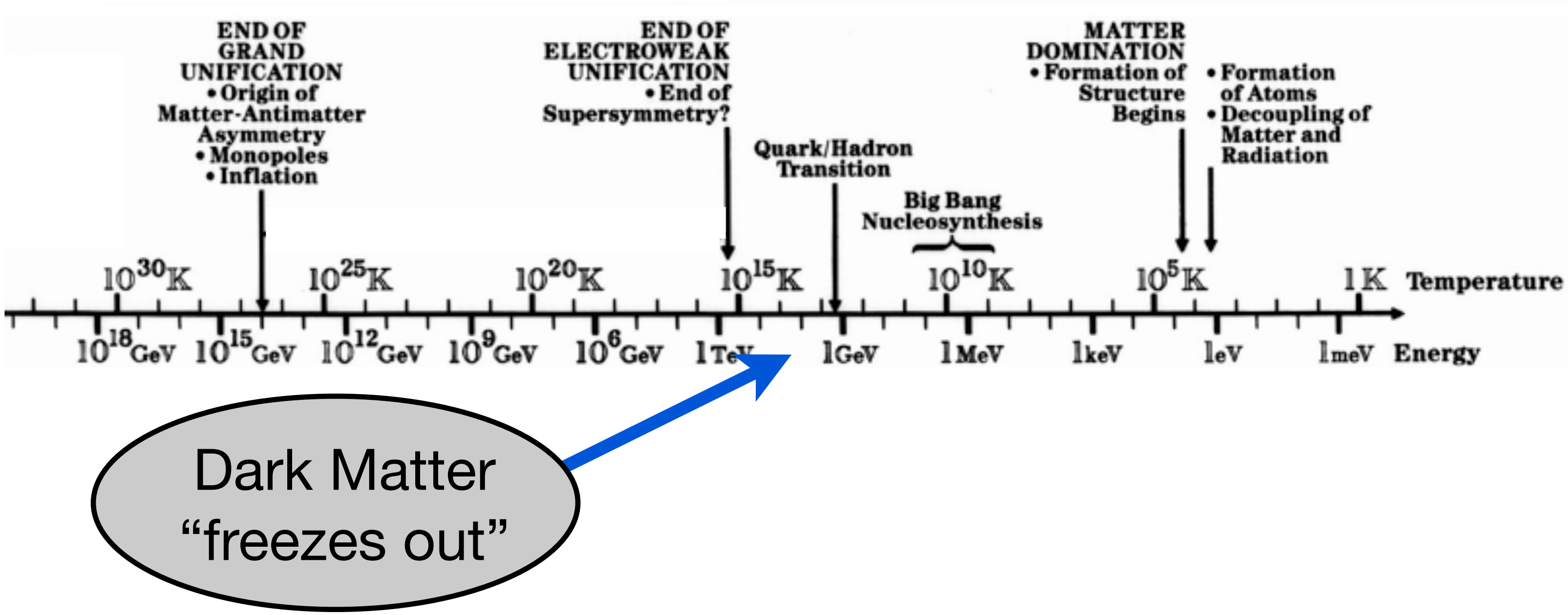
- Cold (Non-relativistic when structure forms)
- Dark (electrically neutral)
- Stable (or very long-lived)
- Weakly interacting with SM particles

"WIMPs"

$$\Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_{total}} = 0.233 \pm 0.013$$

How is dark matter produced?

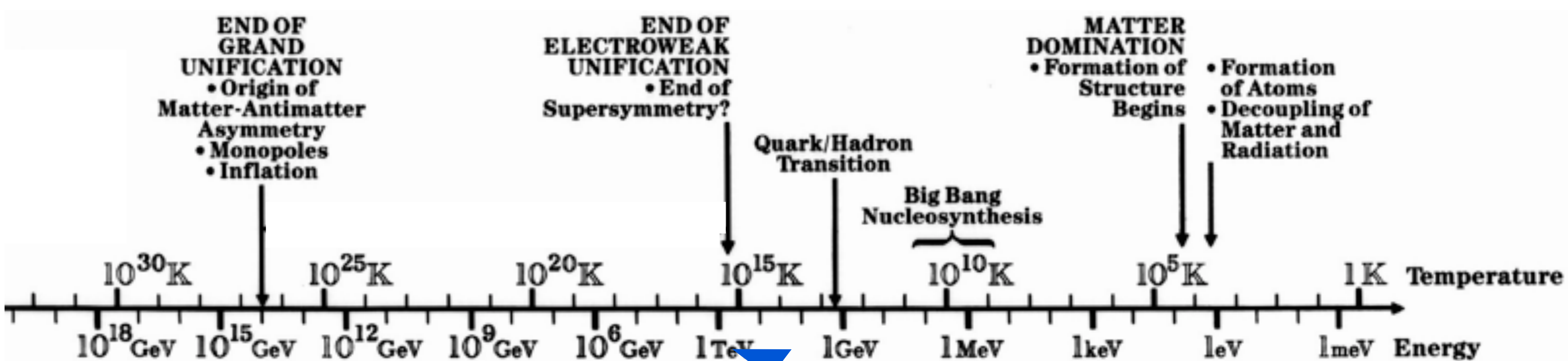
The “WIMP” Miracle



Dark Matter Abundance from Thermal Production

$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

The “WIMP” Miracle



Dark Matter “freezes out”

Dark Matter Abundance from Thermal Production

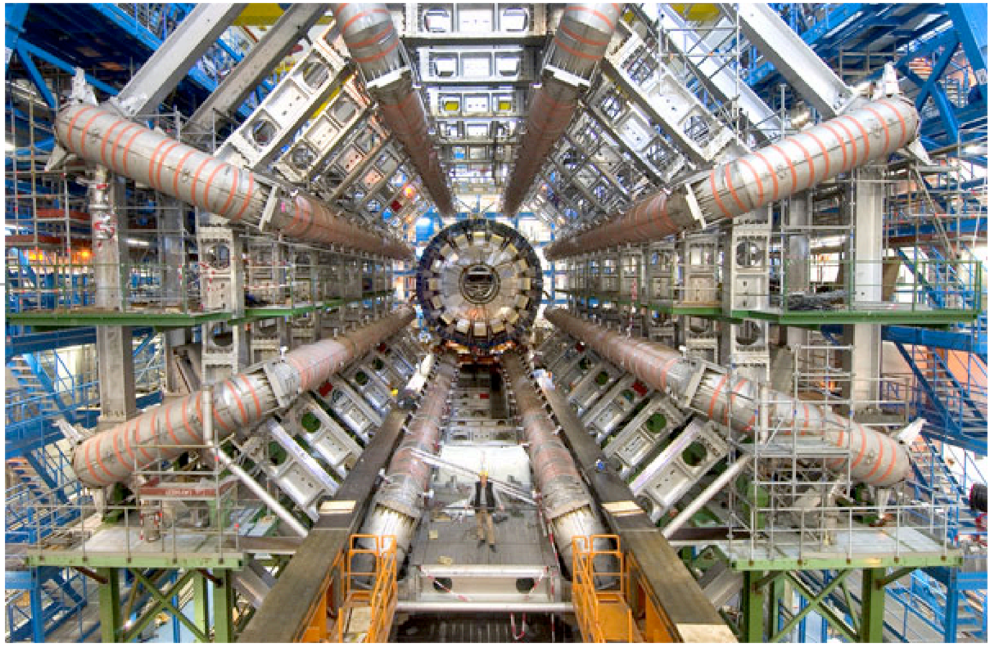
$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

Cosmological Measurement

Weak Scale Physics

As anticipated from particle theory

LHC and Dark Matter



LHC will probe our theories of EWSB.

$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

Measure dark matter mass/interaction

--> End game?

Other probes of Dark Matter

Indirect Detection -- An Overview

Prior to BBN

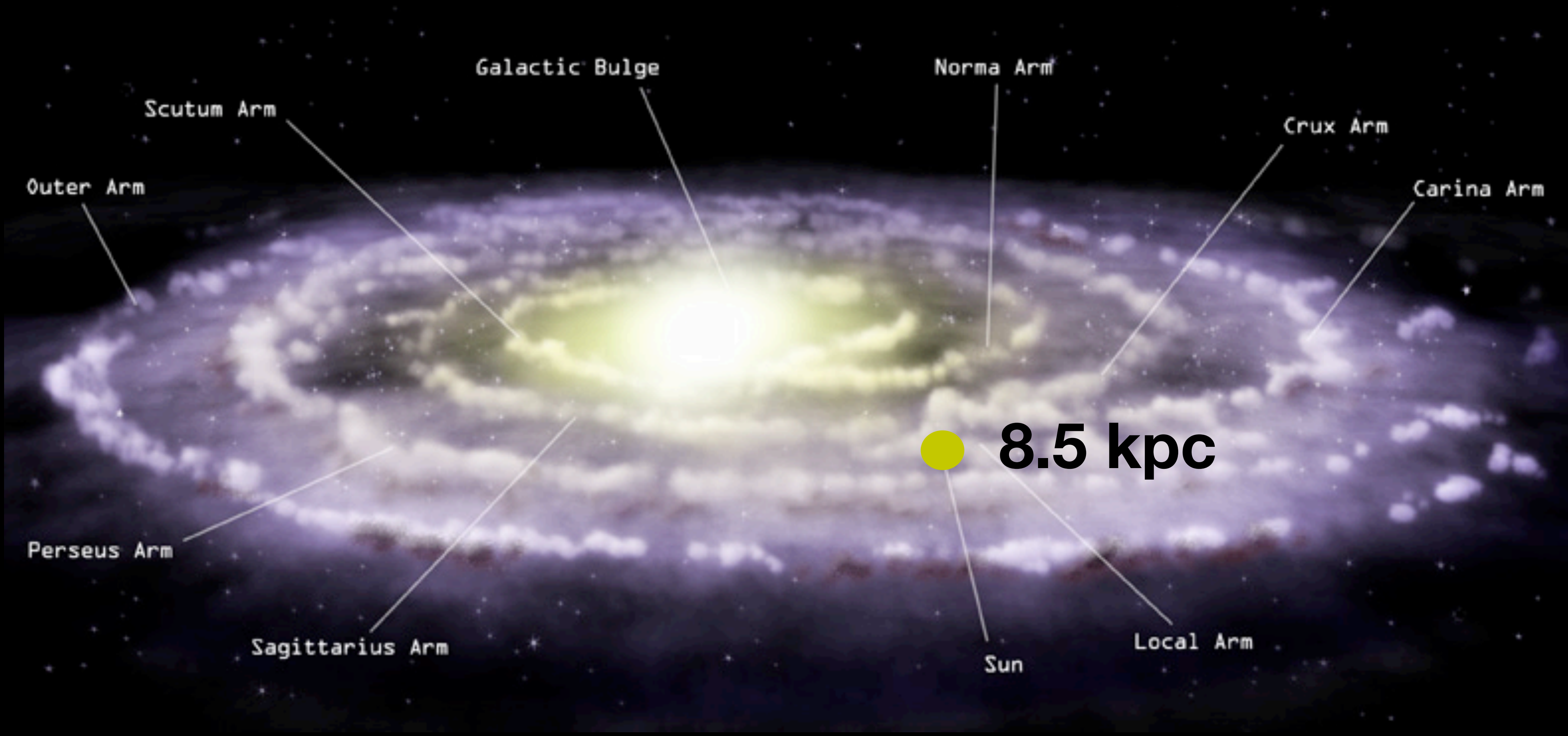
$$\Gamma_{ann} \sim n^2 \langle \sigma v \rangle \qquad \Gamma_{ann} < H$$

Inside our galaxy the density can again reach levels that lead to annihilations

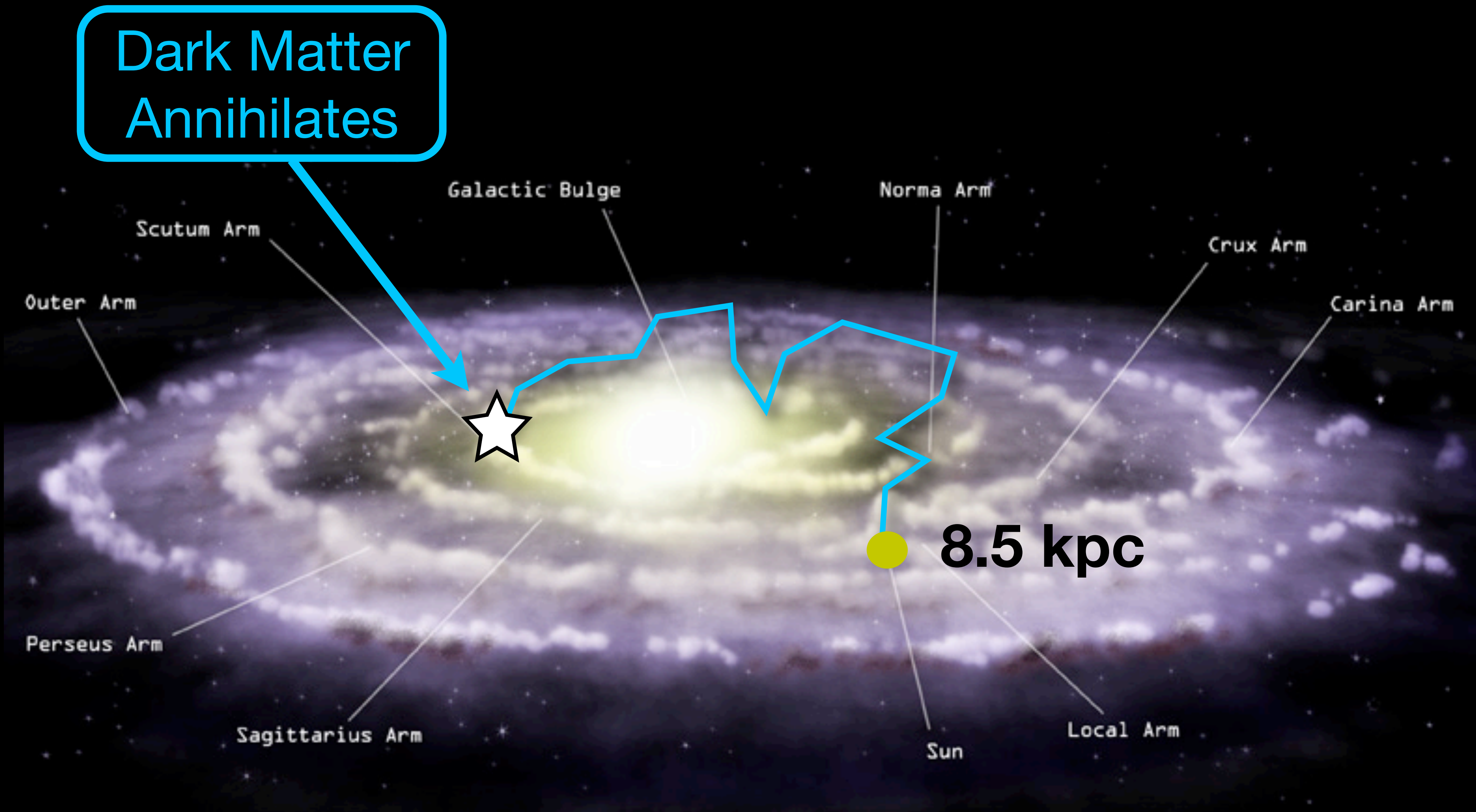
Many cosmic rays -- focus on anti-matter (rare)

$$e^+ \qquad \bar{p} \qquad \gamma \qquad \nu$$

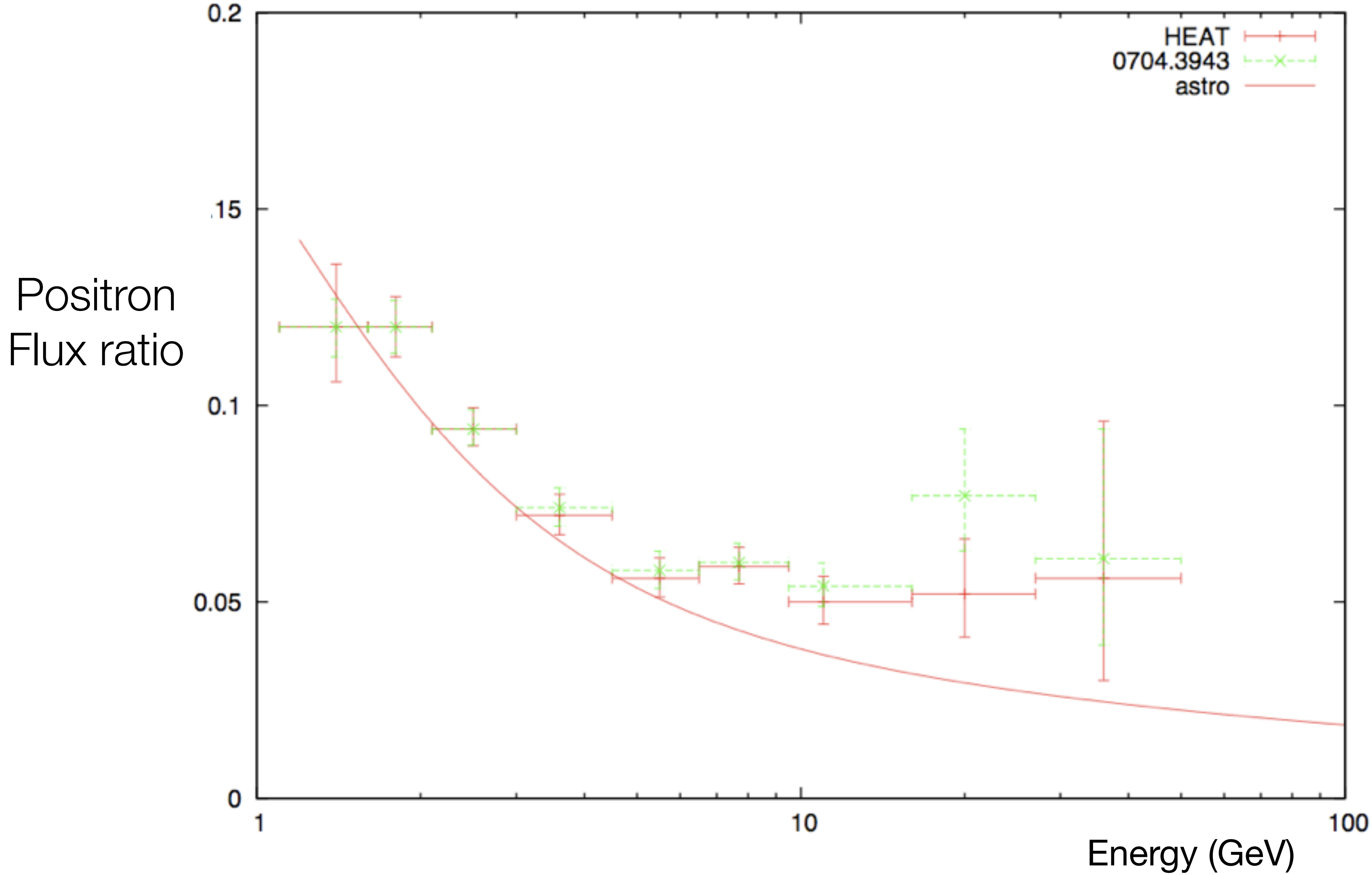
Indirect Detection of Dark Matter



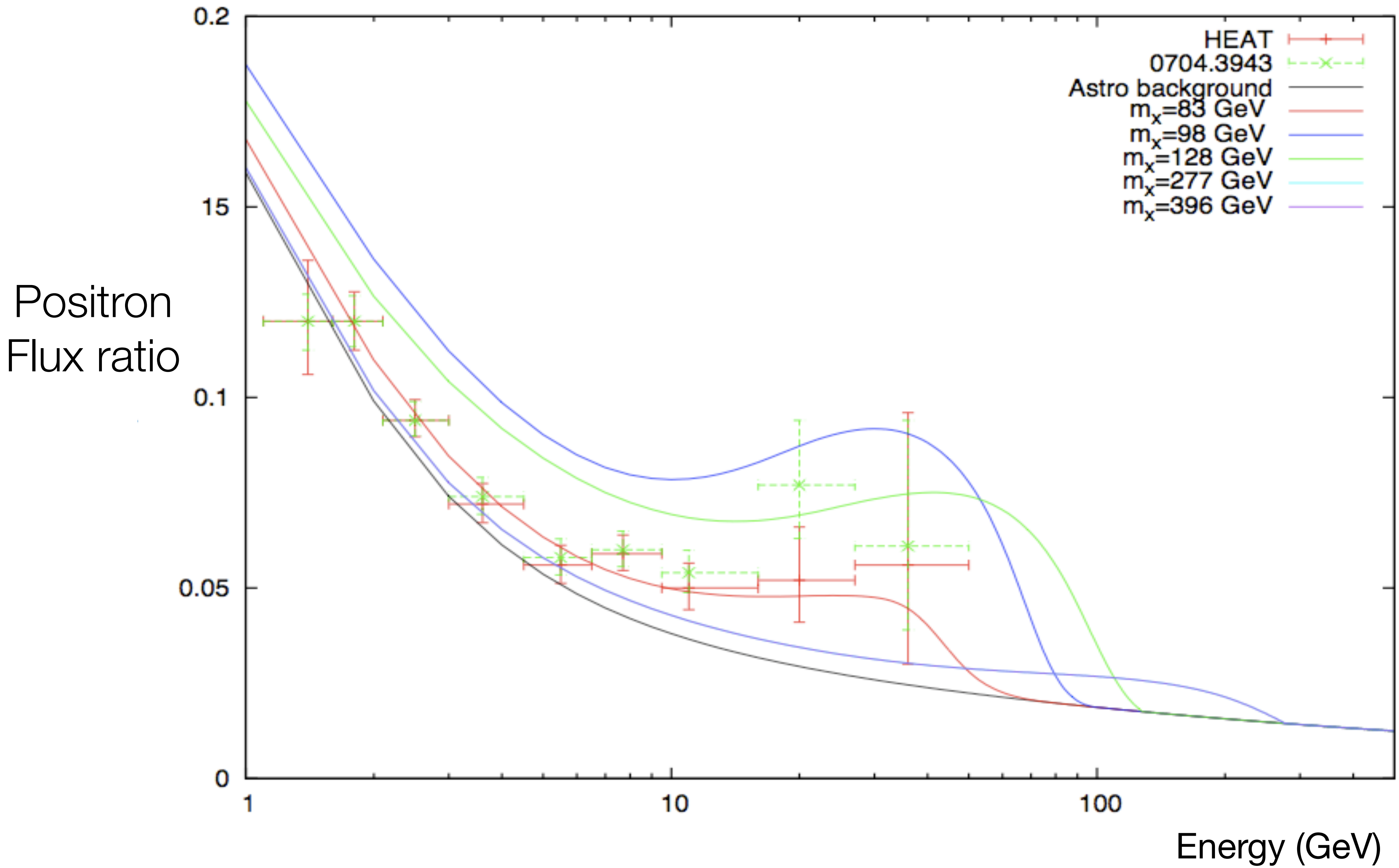
Indirect Detection of Dark Matter



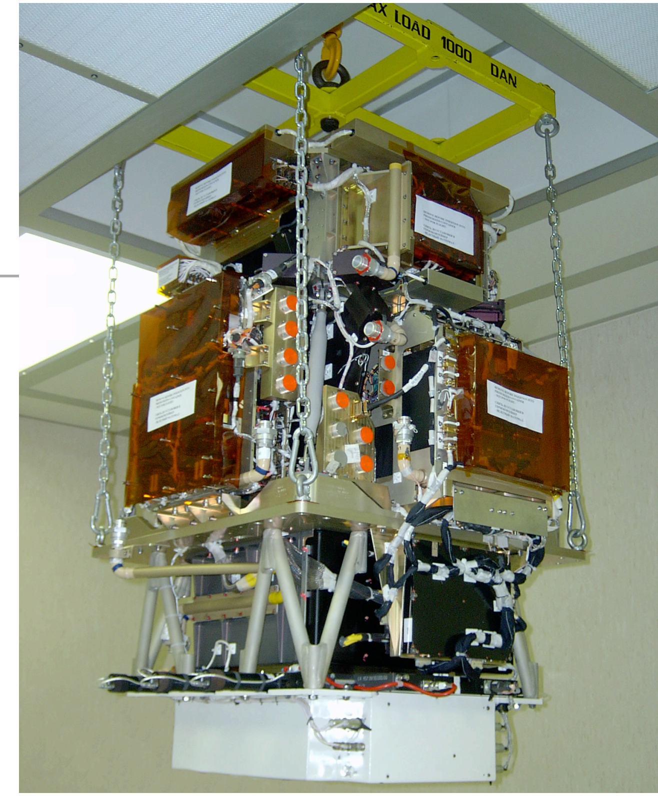
Cosmic-ray Flux in Positrons



Annihilating Dark Matter?



PAMELA

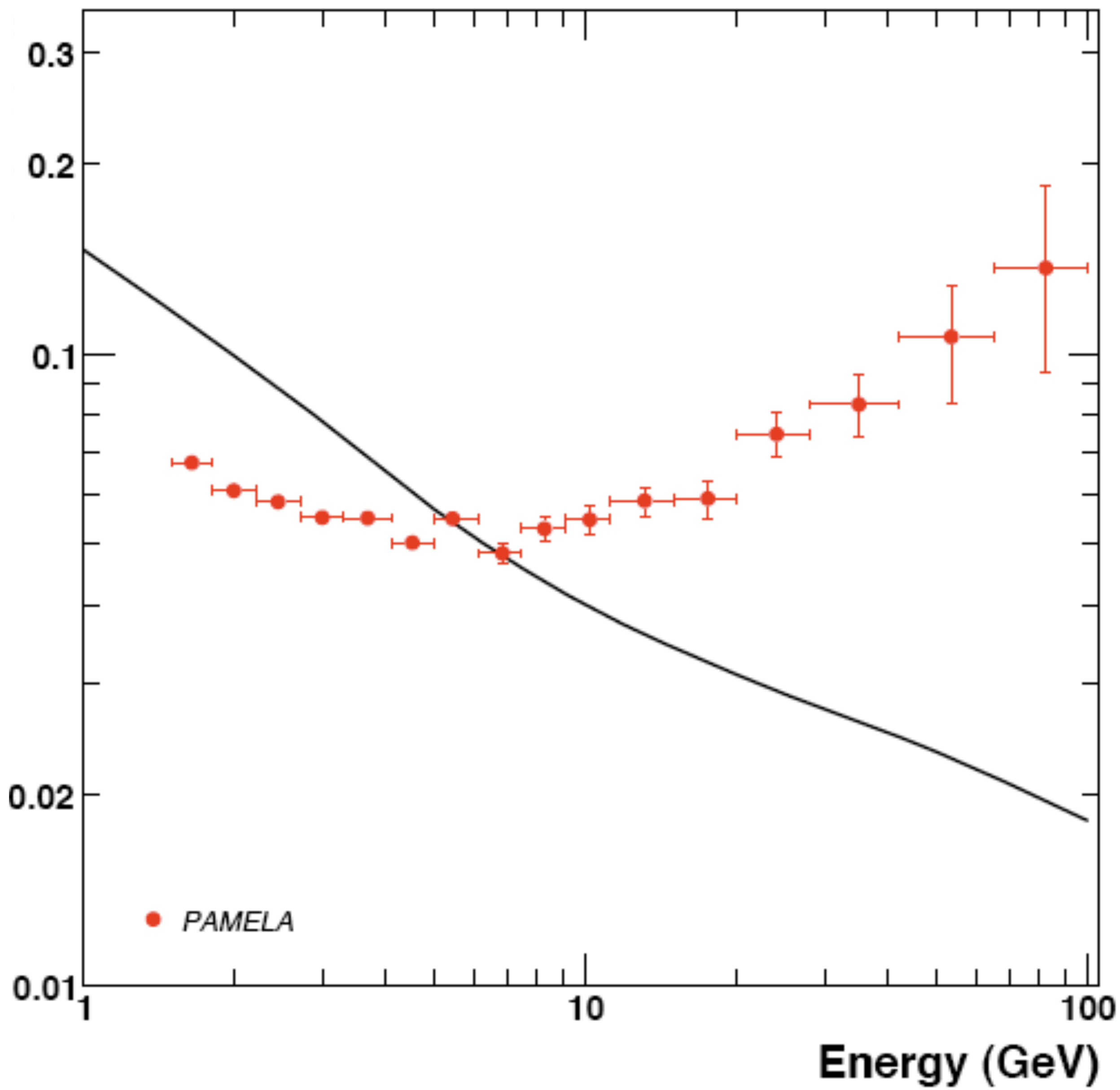


Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

- Satellite mission -- online as June 2008
- Positron data reported from 50 MeV - 100 GeV (will go to 270 GeV max)
- Anti-proton data from 80 MeV up to 190 GeV
  (consistent with existing data, e.g. BESS)

A Possible Positron Excess

Positron
Flux ratio



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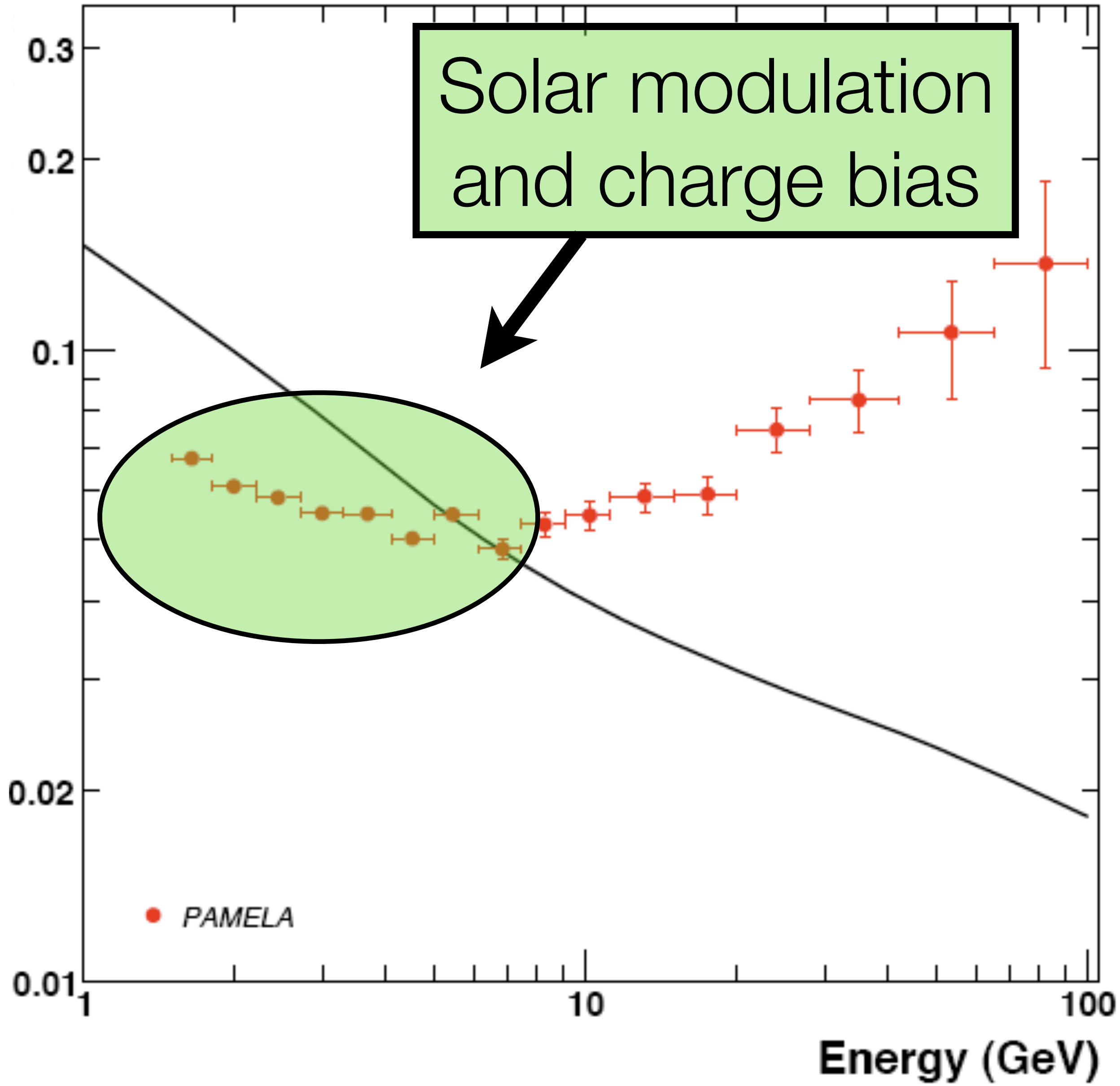

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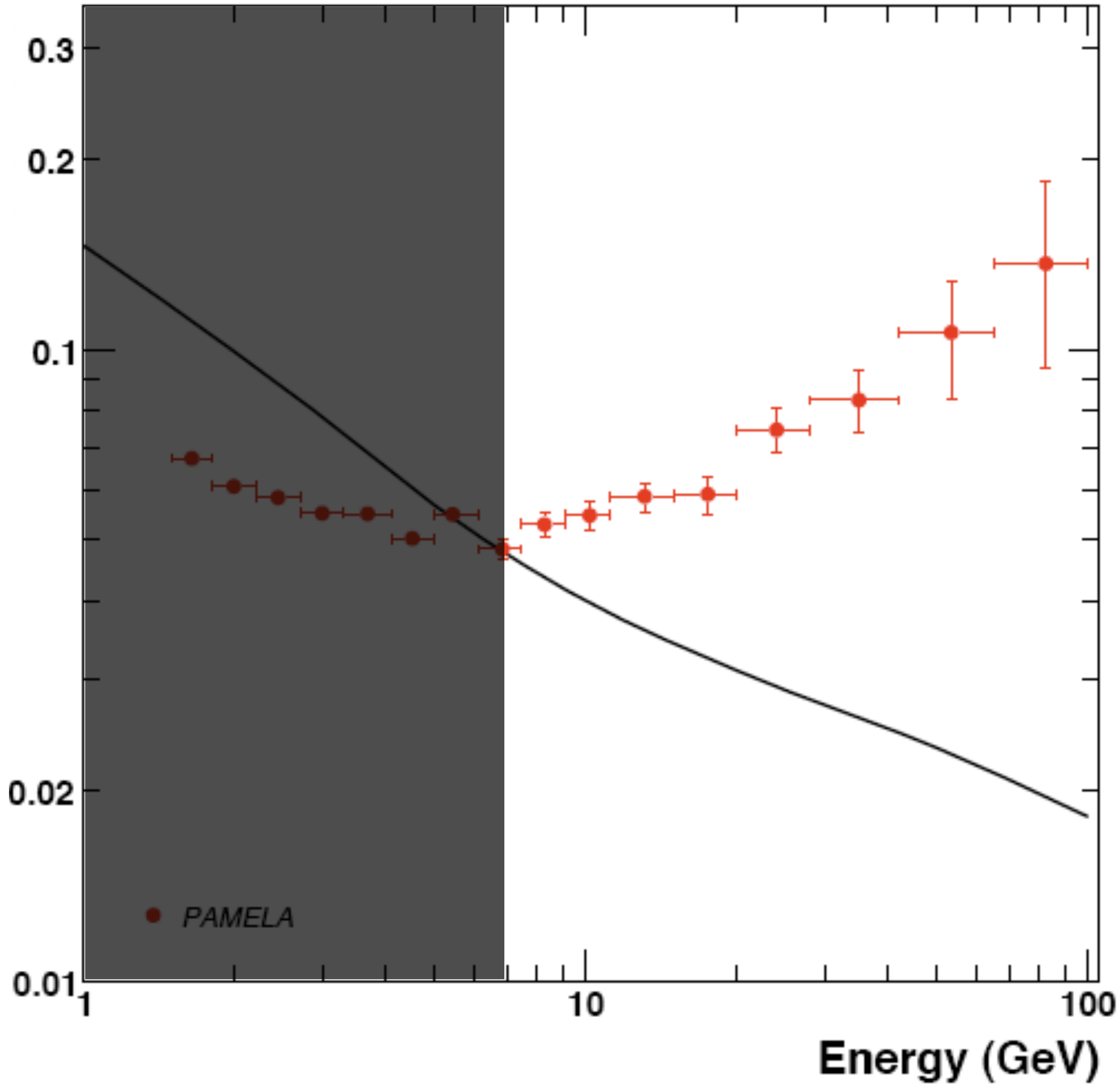


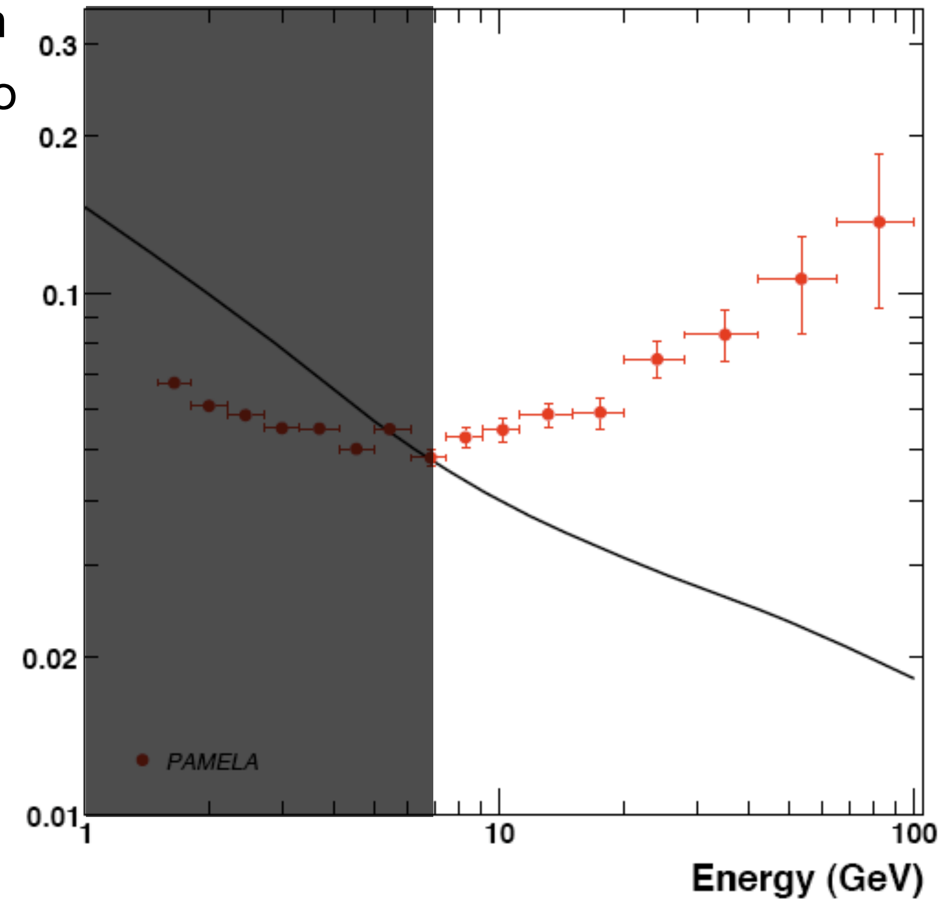
PAMELA -- Indirect Evidence for WIMPs?

Expected Positron Flux

$$\Phi \sim \frac{\langle \sigma v \rangle}{m_X^2} \times \rho^2(r)$$

Microphysics Astrophysics

Positron Flux ratio



Cosmological Constraint

$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

Flux many orders of magnitude too low

PAMELA -- Indirect Evidence for WIMPs?

Expected Positron Flux

$$\Phi \sim \frac{\langle \sigma v \rangle}{m_{\mathrm{X}}^2} \times \rho^2(r)$$

Microphysics Astrophysics

Important Considerations

- Astrophysical uncertainties: Halo profile, propagation, backgrounds
- Unknown astrophysical sources, e.g. Pulsars
- Proton contamination (10,000/1)

Taken alone probably not a compelling case for dark matter

Could another surprise be coming?

The New York Times

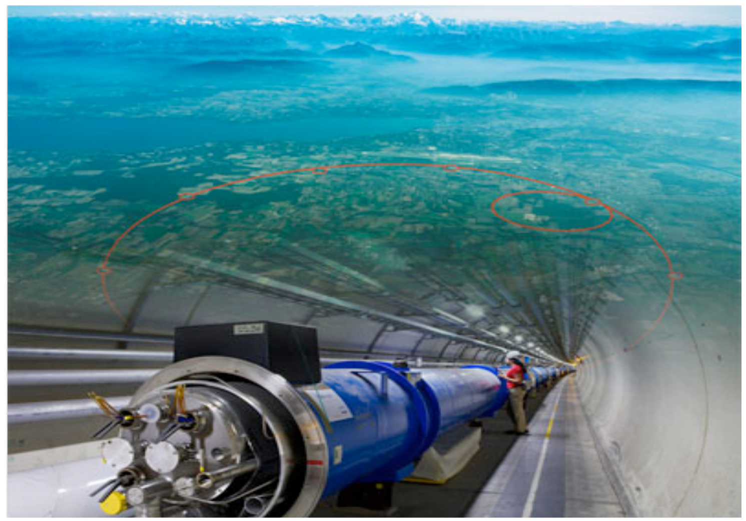
April 1, 2010 Last Update: 6:38 PM ET

New York Partly Cloudy 42°F

Obama Solves Global Financial Crisis and Brings World Peace

by Paul Krugman

President Obama addressed the nation today acknowledging that although his administration has successfully resolved the global financial crisis, restored the confidence of the American housing market, and brought world peace, that there is still much left to be accomplished. The president has promised to turn to more mundane issues such as establishing a legitimate college football playoff,



Experimental Result Leads to Excitement and Controversy

by Dennis Overbye

$$\Omega_{cdm} = 0.002$$

To the physicist, the above expression succinctly summarizes the recent surprising results coming from the Large Hadron Collider (LHC) located in Geneva, Switzerland. The equation symbolically represents the amount of dark matter in the universe, which from the initial findings of the experiment seem to fall short of expectations coming from cosmological observation.

OPINION »

Op-Ed: Restore the Senate's Treaty Power

America needs to maintain its sovereignty, write John R. Bolton and John Yoo.

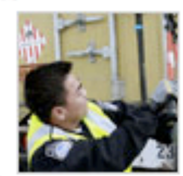
- Krugman: Stimulus Plan
  Comments (418)
- Kristol: Why Israel Fights
  Comments (368)
- Cohen: Penn's Dangers
  Comments (130)
- Editorial: Drug Money
  Comments (69)

ARTS »

A Leitmotif of Love, Memories and Secrets

Jayne Anne Phillips's novel fuses disparate influences into something utterly original.

Protecting Borders and Other Pursuits



A reality series about policing the borders is more homage than reportage.

MARKETS » At close 01/05/2009

S.&P. 500	Dow	Nasdaq
9927.45	19927.45	8927.45
−4.35	−81.80	−4.18
−0.47%	−0.91%	−0.26%

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Particle v.s. Cosmological Dark Matter

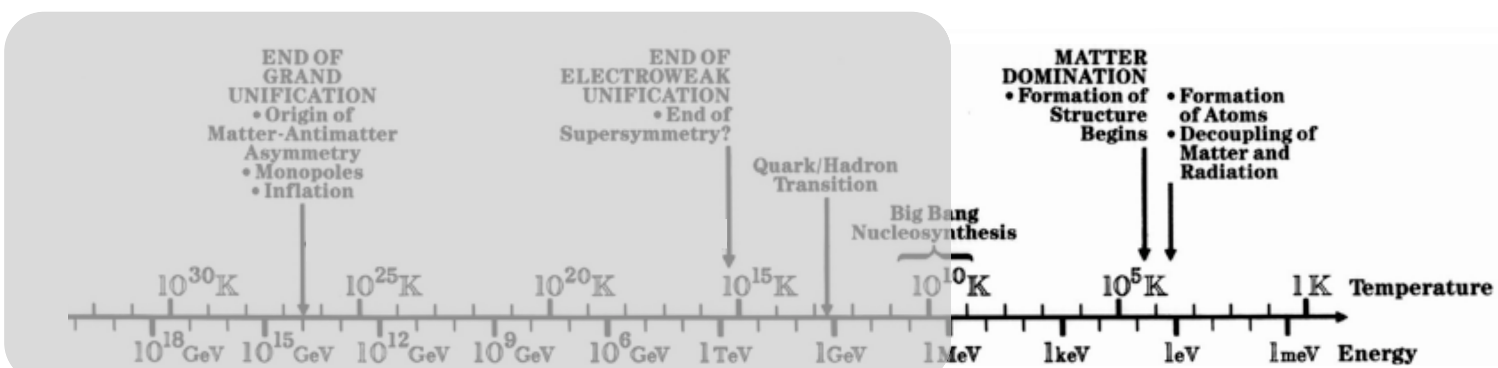
Review: G. Kane, S.W. arXiv:0807.2244

Many explanations for a low relic density:

- Many additional dark matter particles possible in addition to WIMPs (e.g. neutrinos / axions)

$$\Omega_{cdm}^{Total} = \sum_i \Omega_{cdm}^{(i)}$$

- Other light particles can result in a lower relic density (coannihilations)
- Thermal origin of dark matter may be too simplistic



Revisiting the WIMP Miracle

Dark Matter Abundance from Thermal Production

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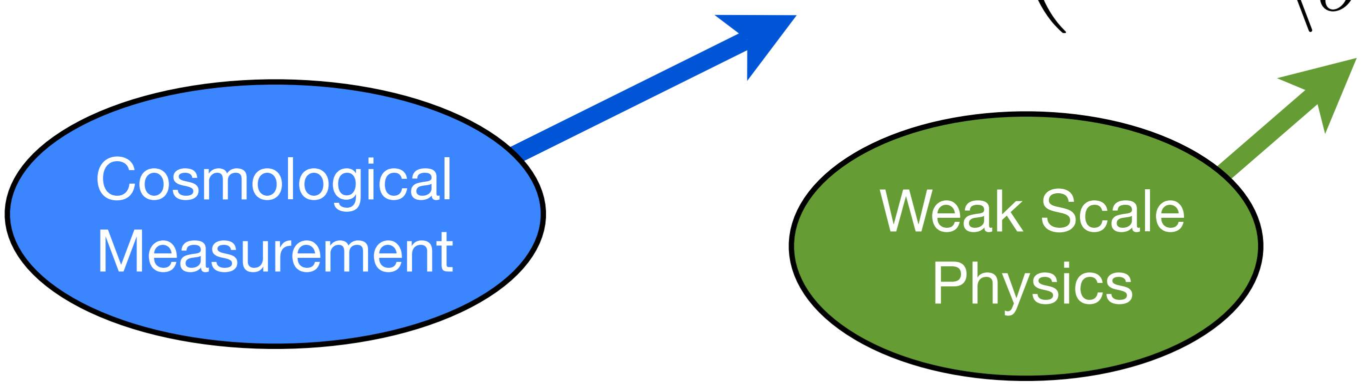
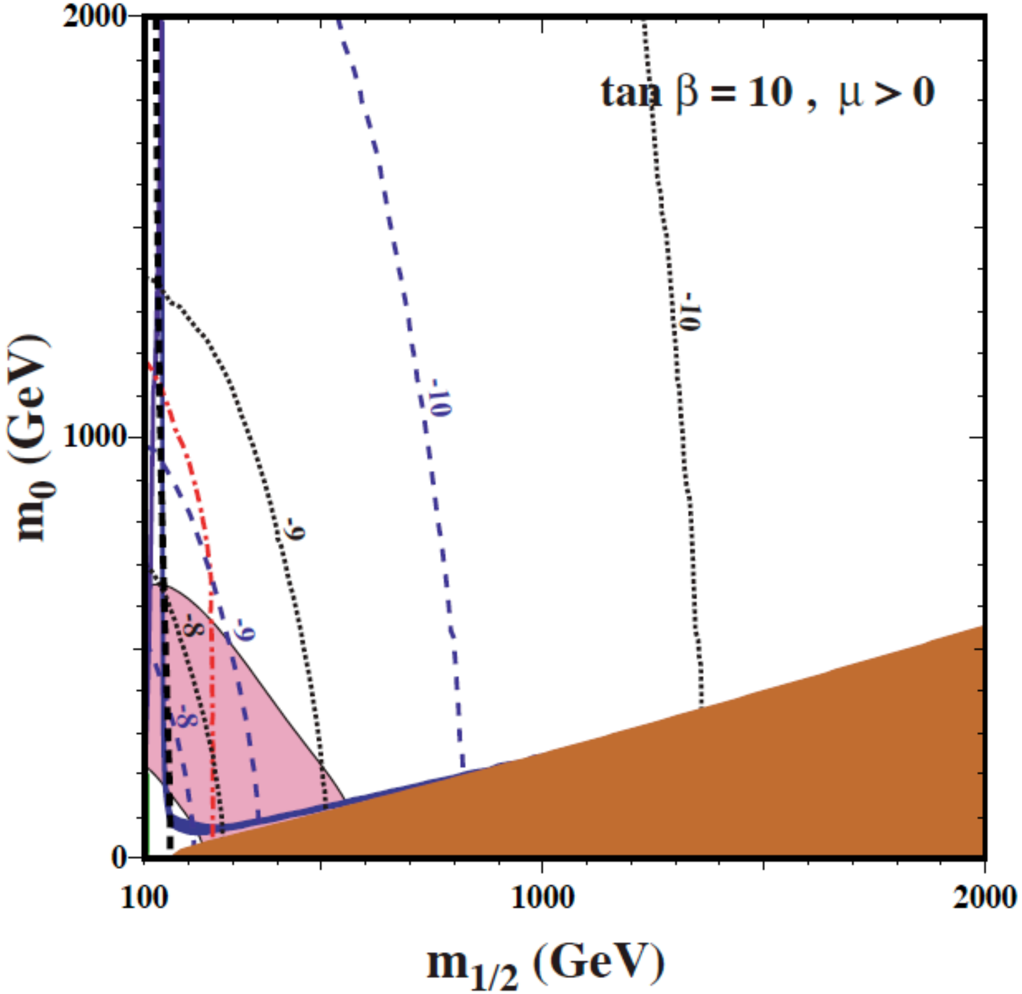
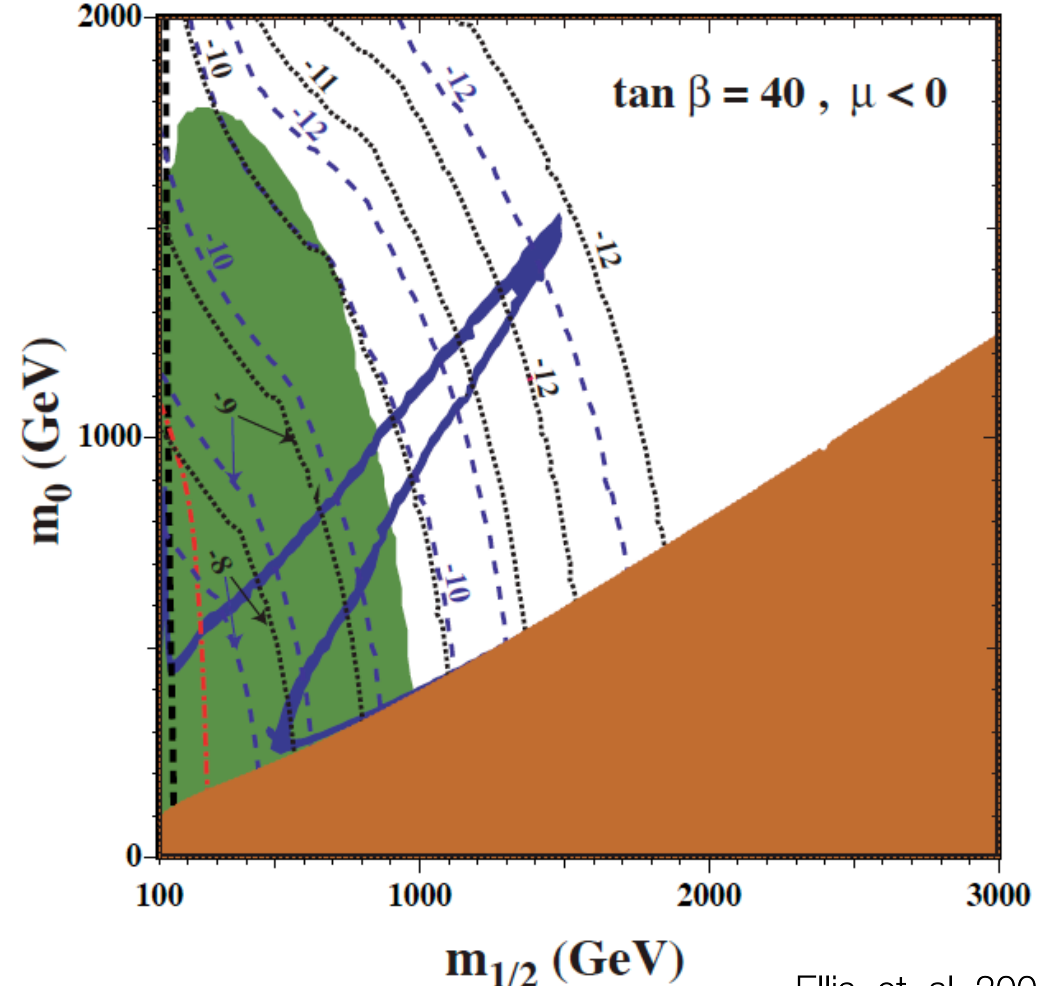


A larger cross-section would account for PAMELA and a surprise at LHC

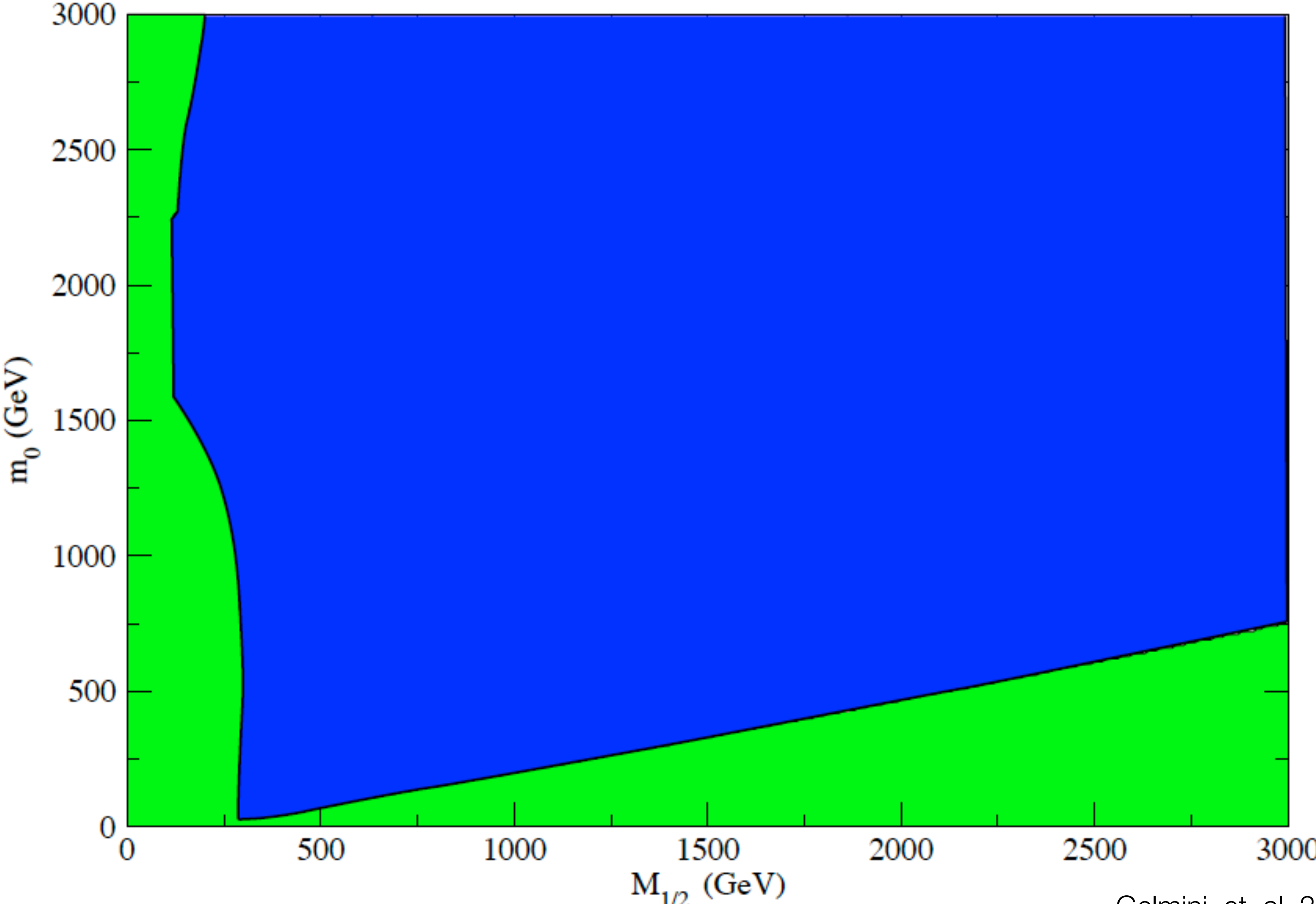
SUSY Model Constraints Enforcing WMAP (blue)





Ellis, et. al. 2005

SUSY Model Constraints Without Enforcing WMAP (blue)

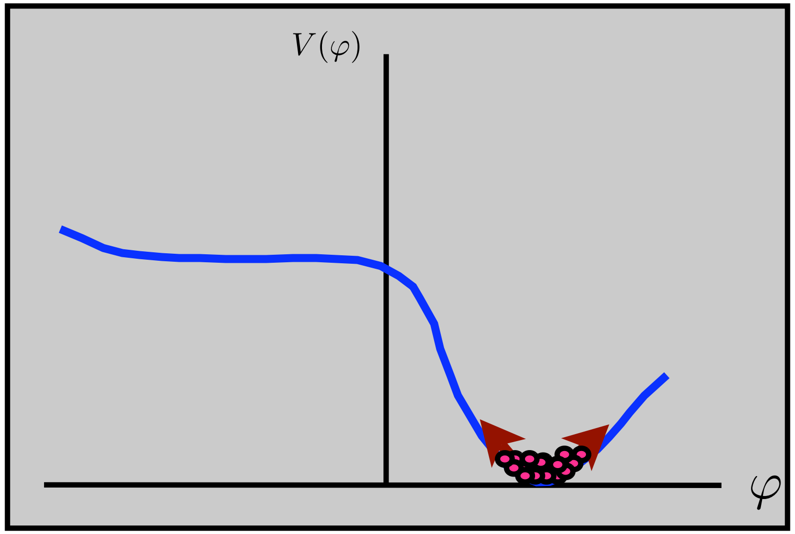


Gelmini, et. al. 2006

If dark matter is not produced thermally, how is it produced?

Example: Non-thermal Dark Matter from Light Scalars

Moroi and Randall -- hep-ph/9906527



Dark Matter from Scalar Decay:

- Moduli generically displaced in early universe
- Energy stored in scalar condensate

$$\Delta\Phi \to \Delta E$$

- Typically decays through gravitational coupling

$$T_r \simeq \left(\frac{m_\phi}{10\ \mathrm{TeV}}\right)^{3/2}\ \mathrm{MeV}$$

- Large entropy production dilutes existing dark matter of thermal origin

$$\Omega_{cdm} \to \Omega_{cdm}\left(\frac{T_r}{T_f}\right)^3$$

Thermal abundance diluted

Non-thermal Dark Matter

Review: G. Kane, S.W. arXiv:0807.2244

Non-thermal Dark Matter

Given $T_r < T_f$ then dark matter populated non-thermally

$$\Omega_{cdm} \sim \frac{m_x}{T} \left(\frac{H}{T^2 \langle \sigma v \rangle} \right)_{T=T_f}$$

$$\Omega_{cdm}^{NT} = \Omega_{cdm} \left(\frac{T_f}{T_r} \right)$$

Freeze-out temp (T_f)

Reheat temp (T_r)

$$T_f \sim \mathrm{GeV} \qquad T_r \sim MeV$$

Can vary over 3 orders of magnitude -- Allowed values still imply weak-scale physics “WIMP Miracle” survives

What do we expect from top-down model building?

What were the key ingredients?

1. "Light" Scalar

$$m_\phi \approx 10 \text{ TeV}$$

2. Gravitationally coupled

$$\Gamma_\phi \sim \frac{m_\phi^3}{M_p^2}$$

3. Stable dark matter particle

$$m_x \approx 100 \text{ GeV}$$

What were the key ingredients?

1

"Light" Scalar

$$m_\phi \approx 10 \text{ TeV}$$

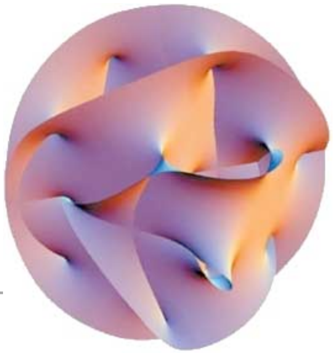
Light enough for decay after freeze-out,
Heavy enough to evade BBN bounds

3

Stable dark matter particle

$$m_x \approx 100 \text{ GeV}$$

Guidance from Fundamental Theory



What is needed from a top-down approach:

- 4D Effective theory (under parametric control)
- Spontaneously broken SUSY (or alternative)
- Explanation for how $M_{EWSB} \ll M_p$
- Small and Positive Vacuum Energy

In String theory, all these problems are related and are essentially a problem of stabilizing scalars.

String Models that adequately meet these goals

String Models that adequately meet these goals

(joke)

The Cosmological Moduli Problem

Coughlan, Fischler, Kolb, Raby, and Ross -- Phys. Lett. B131, 1983
Banks, Kaplan, and Nelson -- Phys. Rev. D49, 1994

“ Model Independent properties and cosmological implications of the dilaton and moduli sectors of 4-d strings ”
Carlos, Casas, and Quevedo -- Phys. Lett. B318, 1993

$$V = e^{\frac{K}{m_p^2}} |DW|^2 - 3m_{3/2}^2 m_p^2$$

Shift symmetry

$$\Phi = \phi + ia \longrightarrow W \neq W(\Phi)$$

Zero vacuum energy, stabilize scalar, break SUSY (spontaneously)

$$\Delta V(\Phi) = m_{3/2}^2 m_p^2 \, f\left(\frac{\Phi}{m_p}\right)$$

$$m_\phi \sim m_{3/2} \sim \text{ TeV}$$

Ex: Type IIB -- KKLT

$$W = W_0 + m_p^3 e^{-X} \qquad\qquad K = -n\, m_p^2 \log\left(X + \bar{X}\right)$$

$$V = e^{\frac{K}{m_p^2}}\left(|DW|^2 - 3m_{3/2}^2 m_p^2\right)$$

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SUSY Minimum

$$D_X W = 0 \rightarrow \langle X \rangle = \log\left(\frac{m_p}{n m_{3/2}}\right)$$

$$V_{AdS} = -3m_{3/2}^2 m_p^2$$

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Uplift and Break SUSY

$$\Delta V \sim m_{3/2}^2 m_p^2 \qquad \delta X \rightarrow \delta X_c = \frac{\sqrt{n}}{\langle ReX \rangle}\delta X$$

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Uplift and Break SUSY

$$\Delta V \sim m_{3/2}^2 m_p^2 \qquad \delta X \to \delta X_c = \frac{\sqrt{n}}{\langle ReX \rangle}\delta X$$

$$m_X = n^{-\frac{1}{2}} \log\left(\frac{m_p}{n m_{3/2}}\right) m_{3/2} \sim \text{“}4\pi^2\text{”} m_{3/2}$$

(Loaiza-Brito, Martin, Nilles , and Ratz)

Other models with possible non-thermal contribution:

- Large Volume Compactifications
  e.g. Conlon and Quevedo -- arXiv:0705.3460
- F-theory (Jonathan's talk)
  Heckman, Tavanfar, and Vafa-- arXiv:0812.3155
- M-theory on G2 manifolds (Gordy's talk)
  Acharya, et. al. -- arXiv:0804.0863

$$W = \cancel{W_0} + c_1 f(\phi) e^{-aX} + c_2 e^{-bX}$$

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Remarks

- Many open questions:
  Embedding visible sector, uplifting, path to 4d, SUSY breaking
- Scalar may be too light (then perhaps thermal inflation)
- Gaugino (dark matter) has three robust patterns

  "The Gaugino Code", Choi and Nilles -- arXiv:hep-ph/0702146

- Light scalar may be robust prediction
  (a.k.a. cosmological moduli "problem")

Moduli Stabilization Basics

If scalars stabilized without reintroducing electroweak hierarchy and accounting for small and positive vacuum energy this typically implies:

$$m_\phi \approx m_{3/2} \approx \mathrm{TeV}$$

A new "WIMP" miracle

Scalars are gravitationally coupled giving

$$T_r \simeq \left(\frac{m_\phi}{10\ \mathrm{TeV}}\right)^{3/2}\ \mathrm{MeV}$$

Non-thermal dark matter!!!!

Given hints from LHC (April 1, 2010)
and motivation from fundamental theory:

Can the well-motivated neutralino account for PAMELA?

Non-thermal SUSY Dark Matter

P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0812.4555 and arXiv:0807.1508

Neutralino WIMPs (light, stable (R-parity), neutral)

$$\tilde{\chi} = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0$$

Bino-like cross-section (P-wave suppression)

$$\langle \sigma v \rangle \sim 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \qquad \Omega_{lsp} \approx 0.23$$

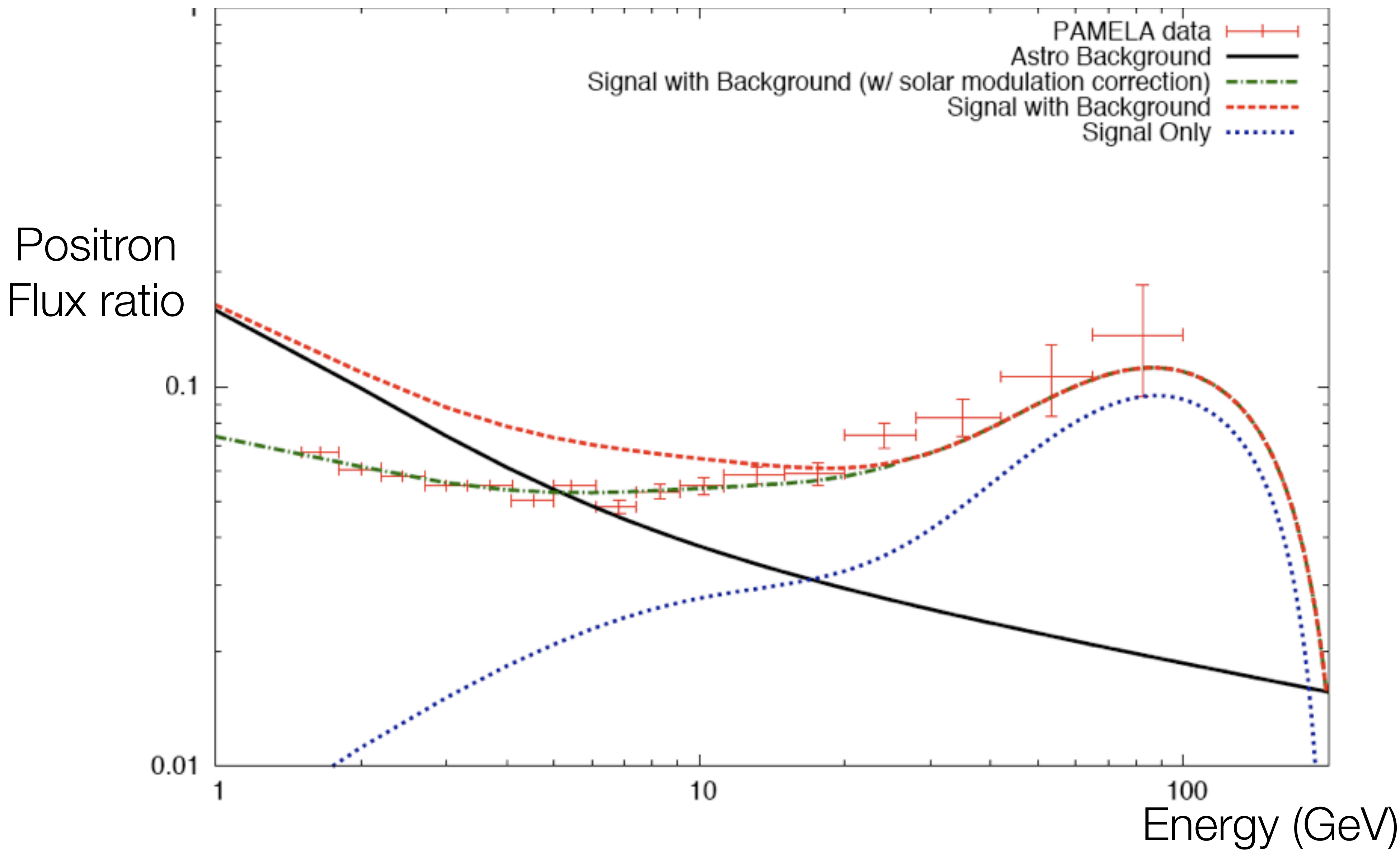
Wino-like cross-section (S-wave suppression)

$$\langle \sigma v \rangle \sim 10^{-24} \mathrm{cm}^3 \mathrm{s}^{-1} \qquad \Omega_{lsp} \approx 0.002$$

The PAMELA Excess from SUSY Dark Matter

P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0812.4555 and arXiv:0807.1508

Positron Flux for 200 GeV SUSY Dark Matter



PAMELA from Non-thermal SUSY Dark Matter

P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0812.4555 and arXiv:0807.1508

Light enough to explain PAMELA

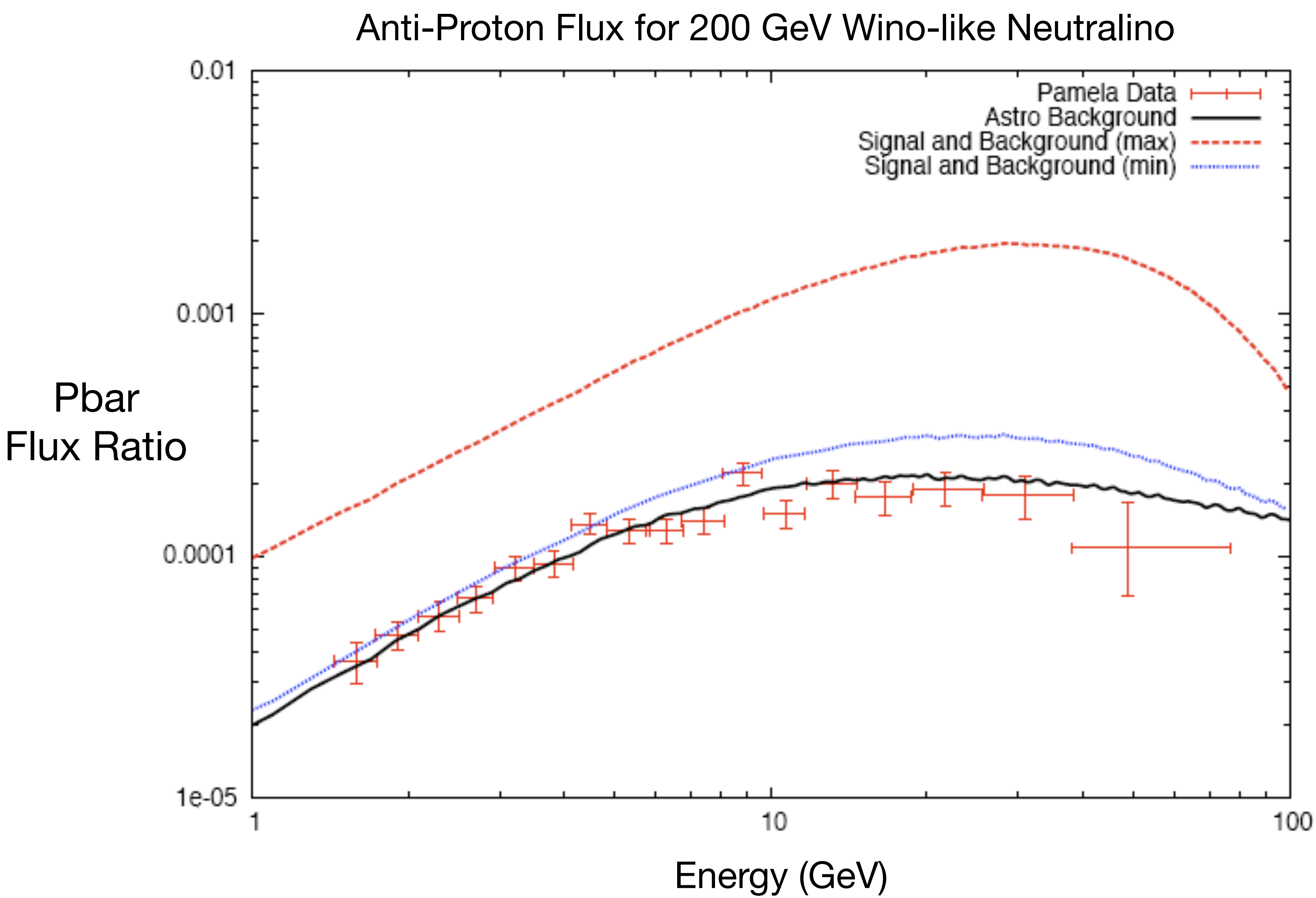
$$m_{\mathrm{X}} \lesssim 300\,\mathrm{GeV}$$

Heavy enough to avoid other indirect detection

$$m_{\mathrm{X}} \gtrsim 200\,\mathrm{GeV}$$

Anti-Proton Bounds and Uncertainties

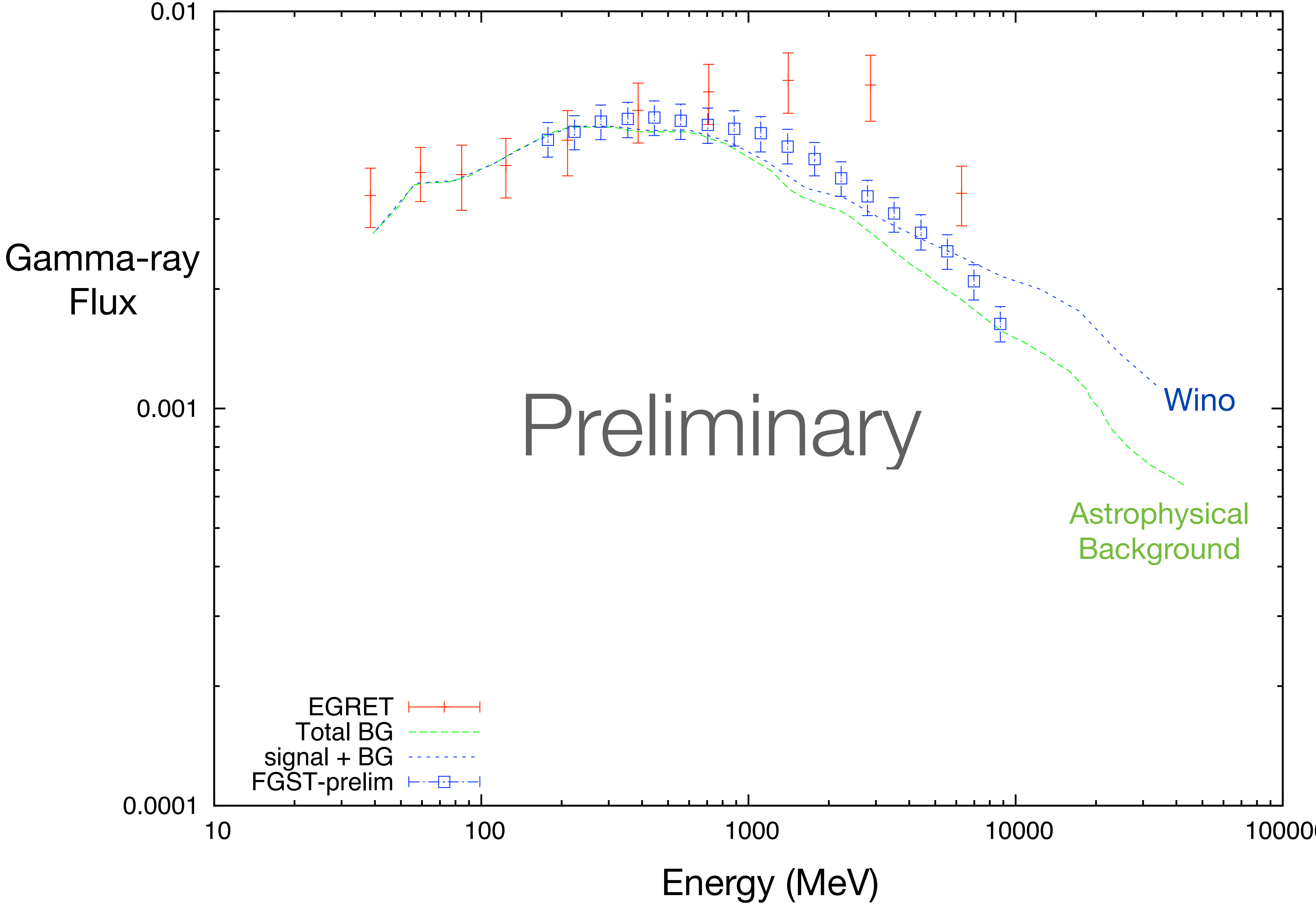
P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0812.4555 and arXiv:0807.1508



What about Gamma-rays and FERMI?

Gamma-ray fluxes and FERMI

Data taken from talk at Michigan workshop (MCTP) on LHC/CDM



Conclusion

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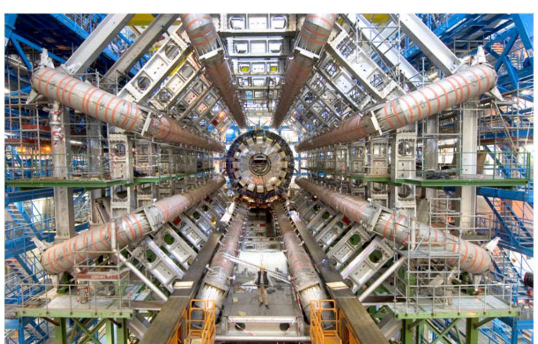
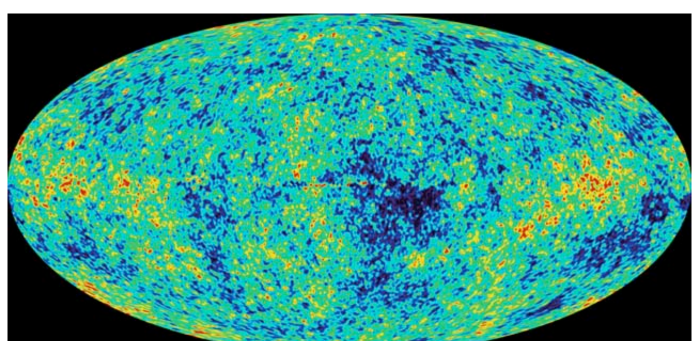
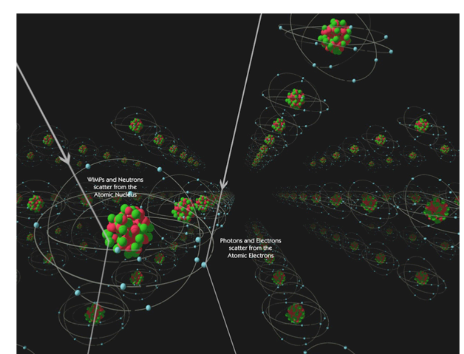
A complete understanding of dark matter requires a concordance approach (cosmology, particle experiment, and fundamental theory)







Thank You

Backups

Wino-like Neutralinos - Positron Excess

P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0812.4555 (PRD)
P. Grajek, G. Kane, D. Phalen, A. Pierce, S.W. arXiv:0807.1508 (PRD)

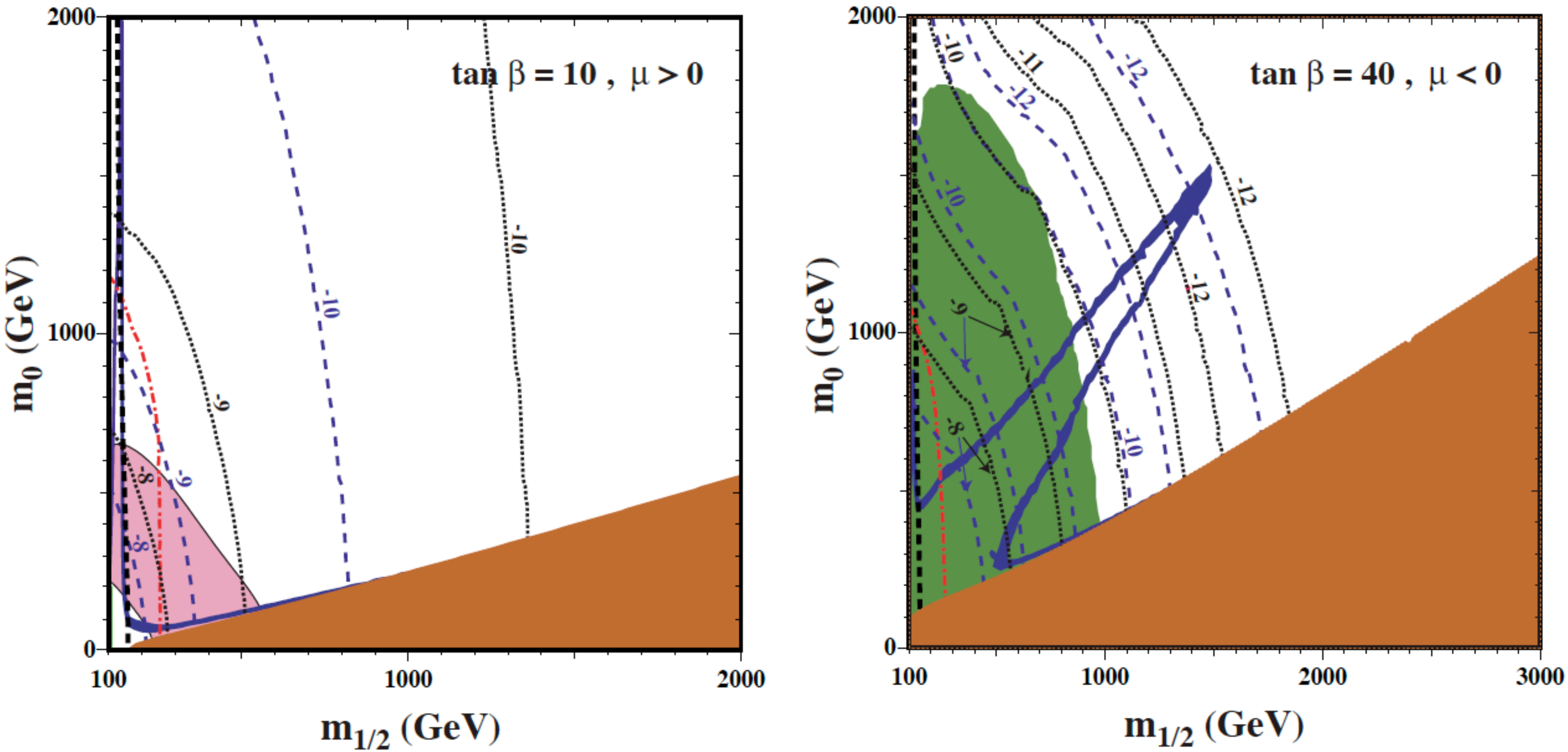
Could excess be due to annihilating SUSY dark matter?

Bino-like requires large "boost" factor

$$Flux \sim \langle \sigma v \rangle \times \left(\frac{\rho_\chi^{halo}}{m_\chi} \right)^2$$

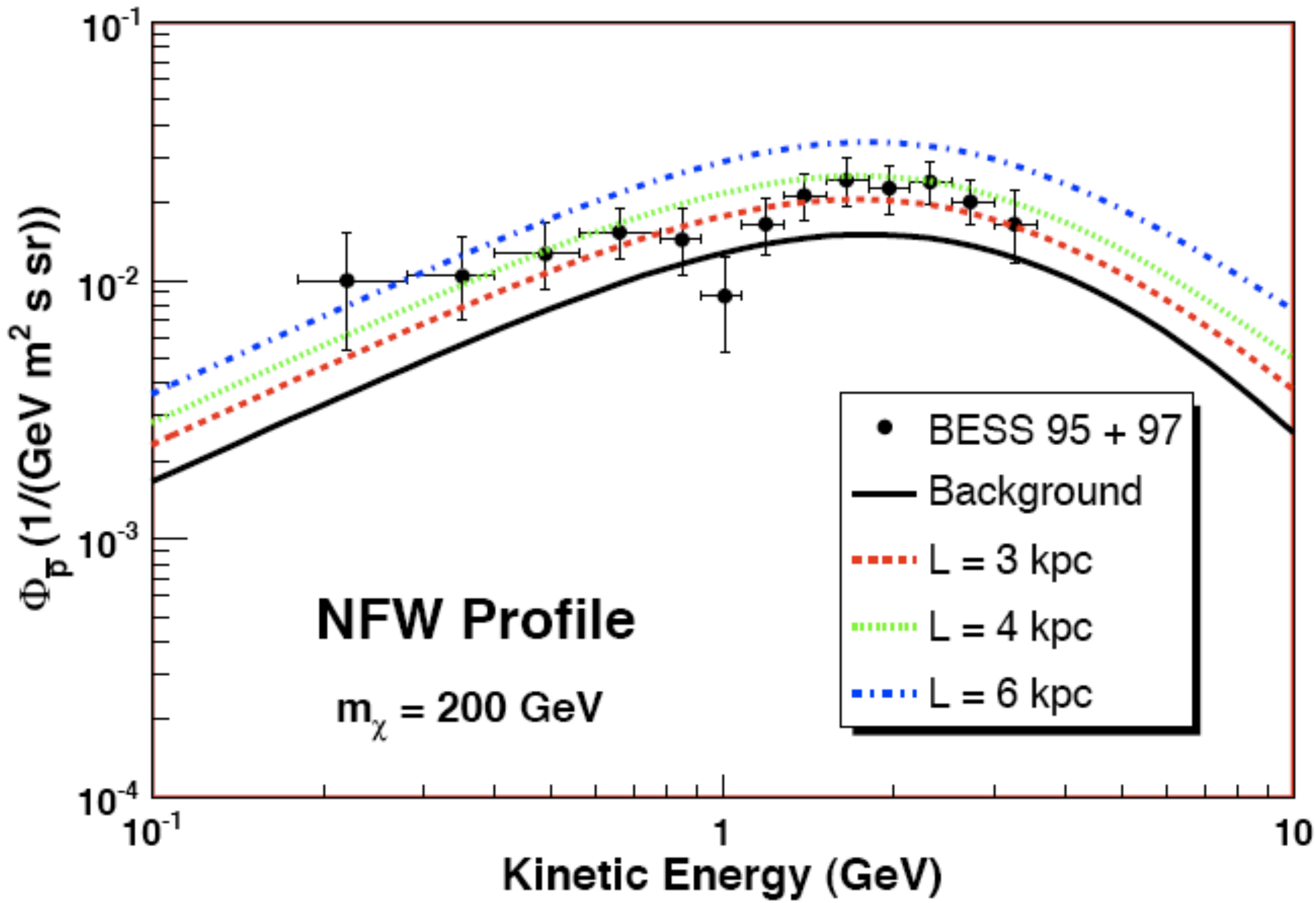
Wino leading decay channel:

$$\chi + \chi \to W + W \to e^+ + X$$

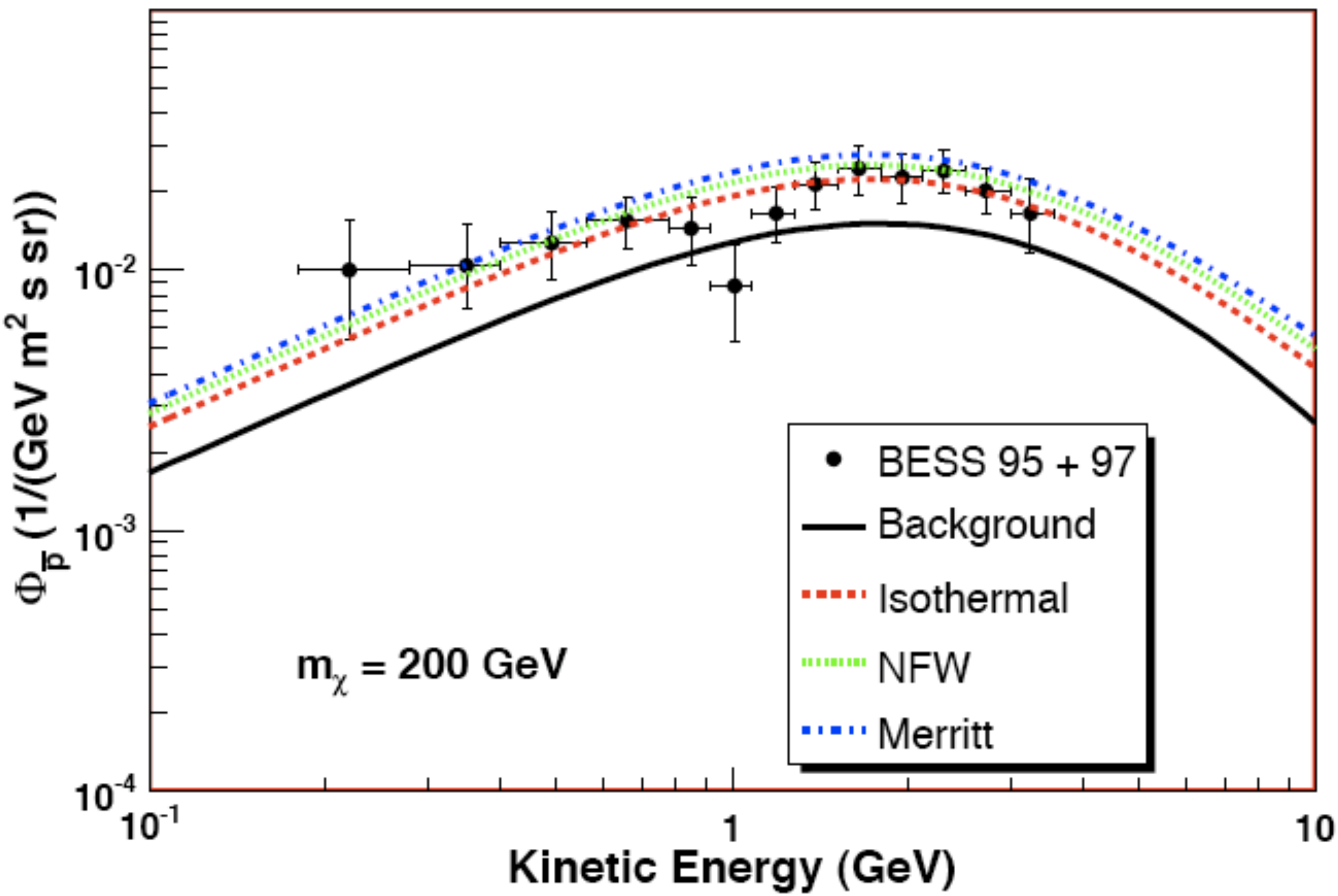


The $(m_{1/2}, m_0)$ planes in the CMSSM for (a) tan = 10, $\mu < 0$, (b) tan = 10, $\mu > 0$, (c) tan = 40, $\mu < 0$ and (d) tan = 57, $\mu > 0$, all assuming $A_0 = 0$. We display the WMAP relic-density constraint, the experimental constraints due to m_h, $m_{\chi^\pm}$, $b \to s$ and $g_\mu - 2$, and contours of the spin-independent elastic-scattering cross section calculated for = 45 and 64 MeV (lighter, blue and black dotted contours, respectively), labelled by their exponents in units of picobarns.

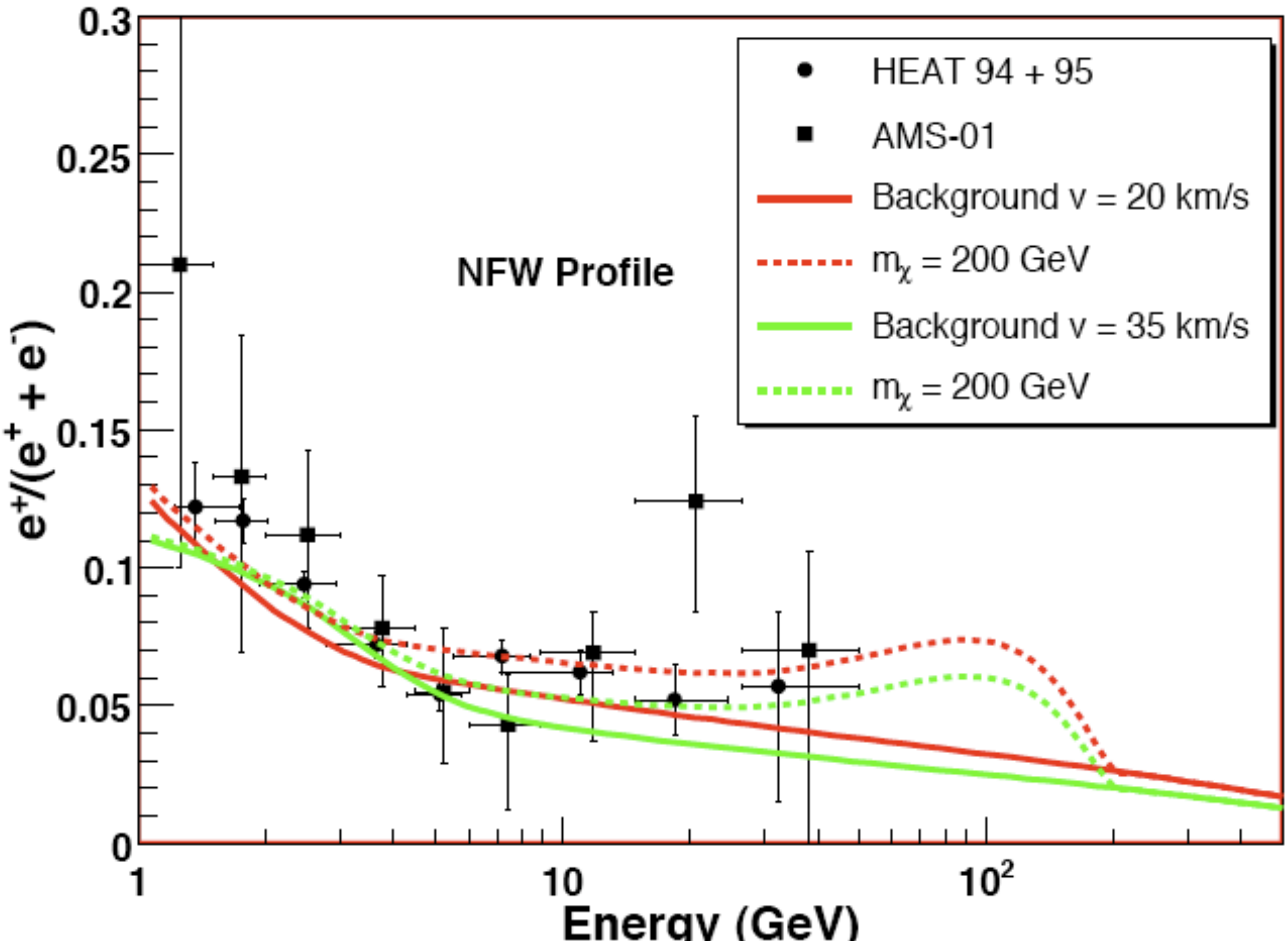
Anti-proton flux for changing cylinder height



Anti-proton flux for changing halo profile



Anti-proton flux for changing Alfven Velocity

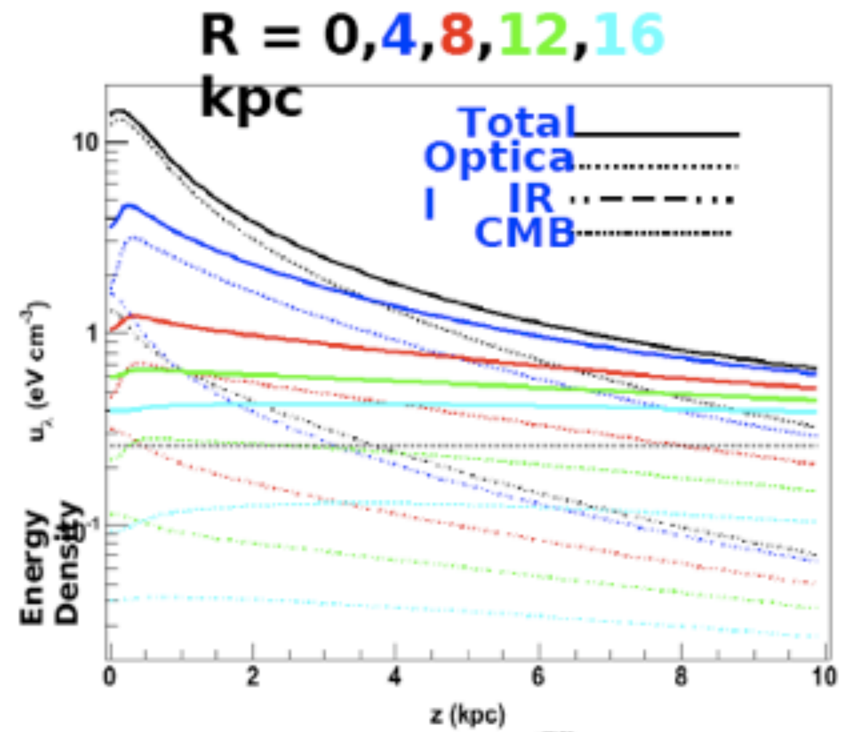


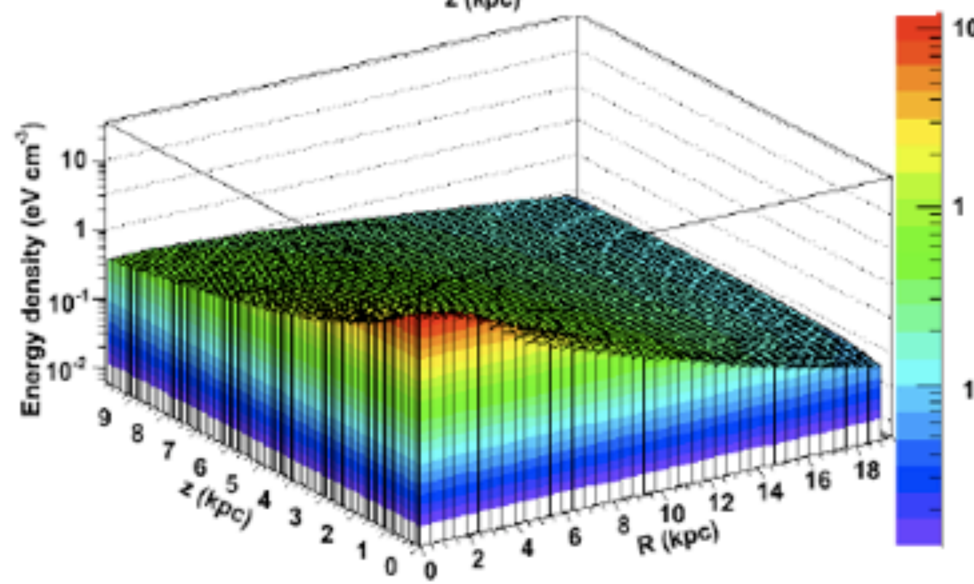
Large Scale Distribution

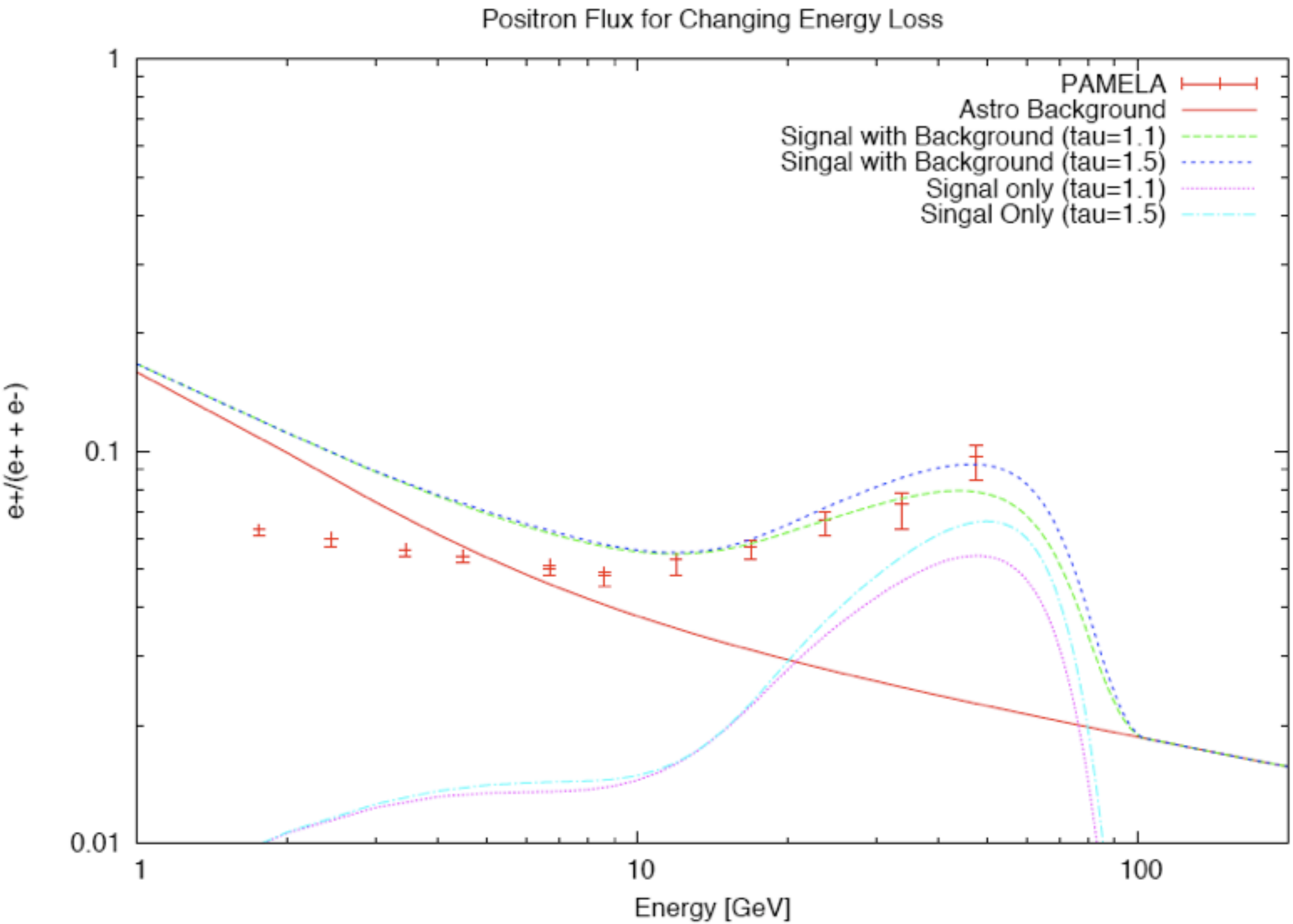
ISRF extends for significant distance above GP

- **Significant ICS at high lats.**

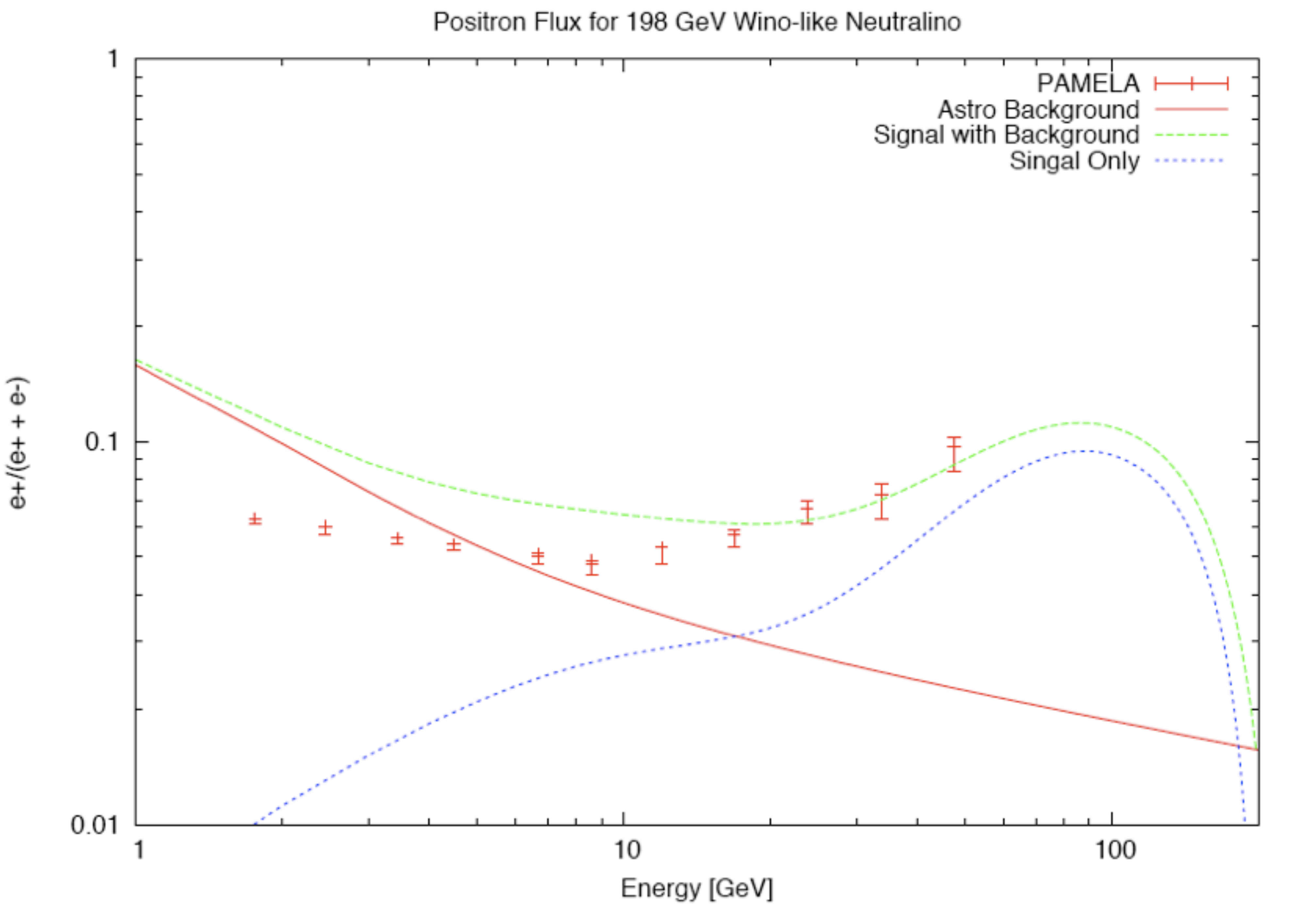
Not so much in plane because of dust and star density decreases with R



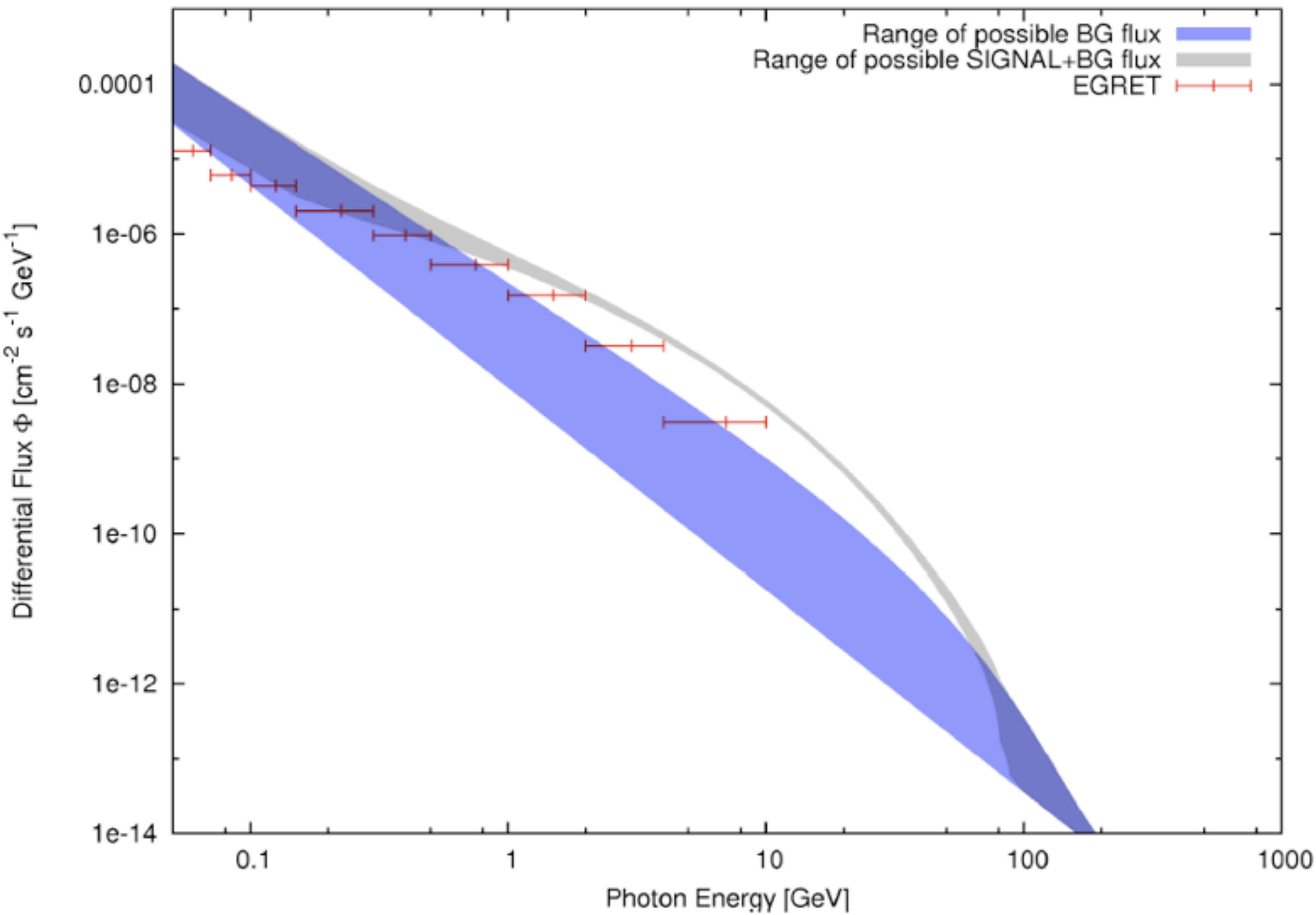




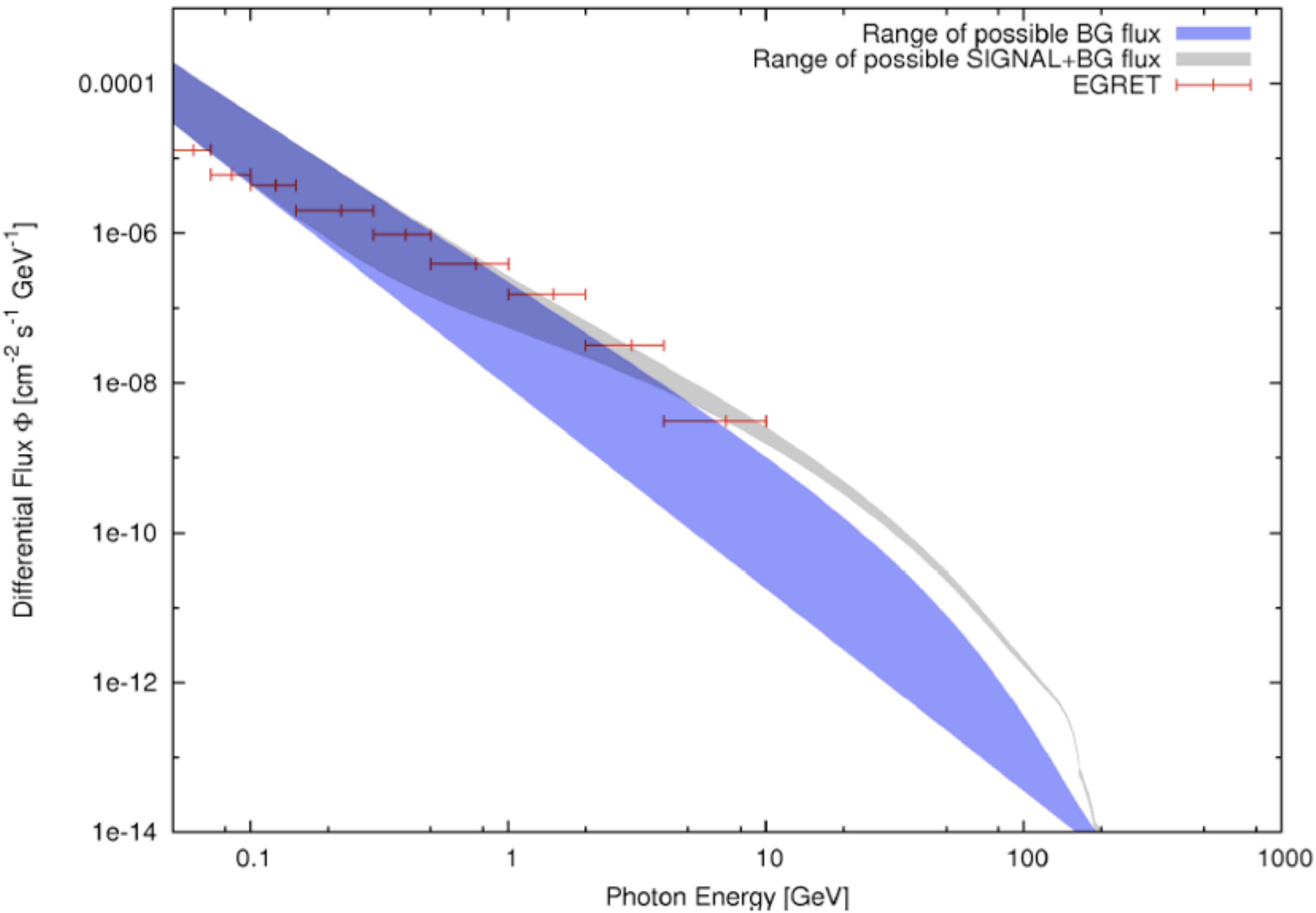
Positron Flux for Changing Energy Loss
PAMELA
Astro Background
Signal with Background (tau=1.1)
Singal with Background (tau=1.5)
Signal only (tau=1.1)
Singal Only (tau=1.5)
e+/(e+ + e-)
Energy [GeV]
1
0.1
0.01
1
10
100



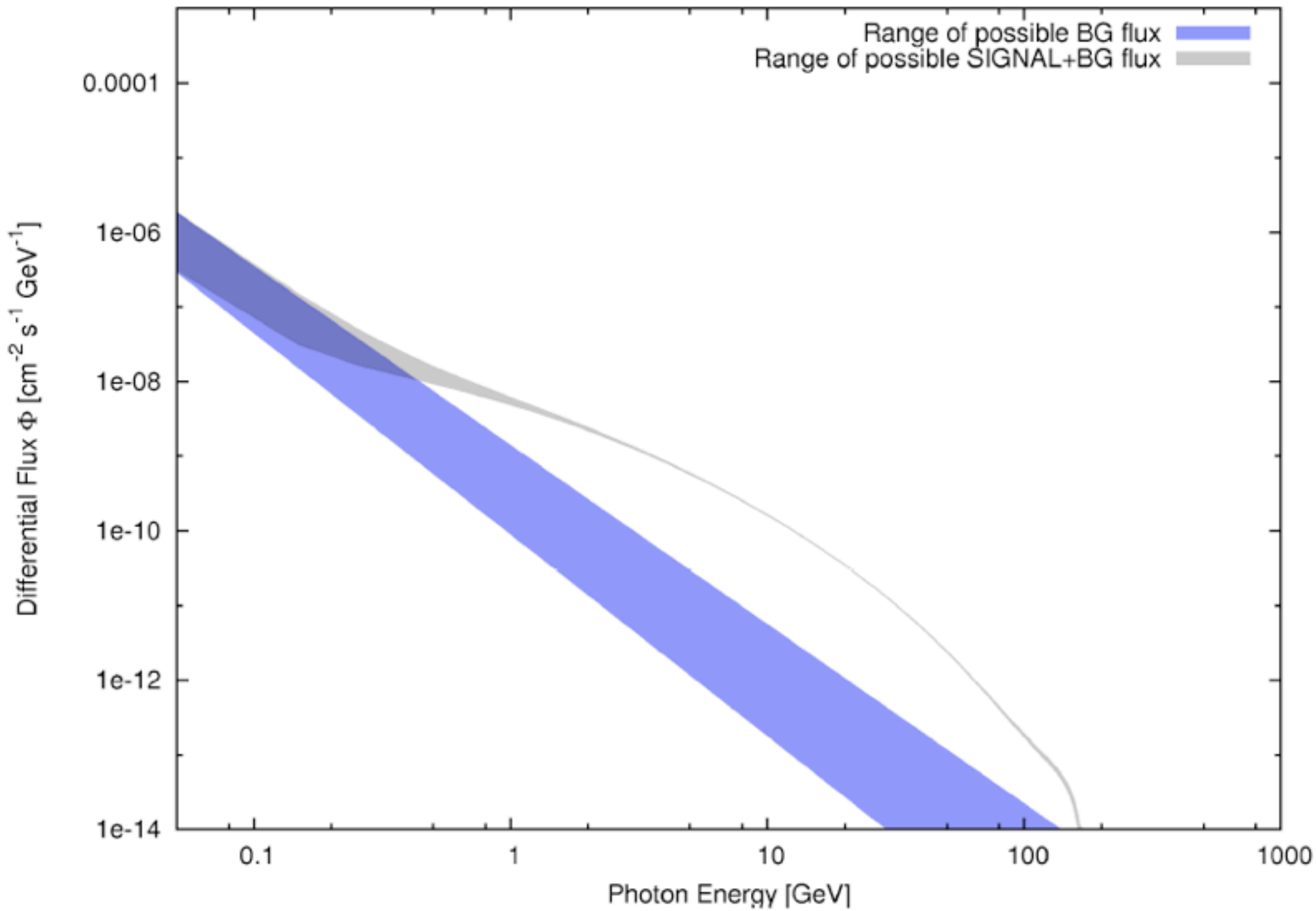
Positron Flux for 198 GeV Wino-like Neutralino
PAMELA
Astro Background
Signal with Background
Singal Only
e+/(e+ + e-)
Energy [GeV]
1
0.1
0.01
1
10
100



Range of possible BG flux
Range of possible SIGNAL+BG flux
EGRET
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
0.1
1
10
100
1000
Differential Flux Φ [cm^-2 s^-1 GeV^-1]
Photon Energy [GeV]



Range of possible BG flux
Range of possible SIGNAL+BG flux
EGRET
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
Differential Flux Φ [cm⁻² s⁻¹ GeV⁻¹]
0.1
1
10
100
1000
Photon Energy [GeV]



Range of possible BG flux
Range of possible SIGNAL+BG flux
Differential Flux Φ [cm^-2 s^-1 GeV^-1]
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
0.1
1
10
100
1000
Photon Energy [GeV]

Dark Matter Self Annihilations

Source term for dark matter annihilations

$$Q = \frac{1}{2} \left[\frac{\langle \sigma v \rangle}{m_{\mathrm{X}}^2} \sum_i \frac{dN_i}{dE} B_i(\mathrm{xx} \rightarrow i) \right] \times \rho(\vec{r})^2$$

Microphysics

Astrophysics