Cosmic Ray Anomalies from the MSSM?

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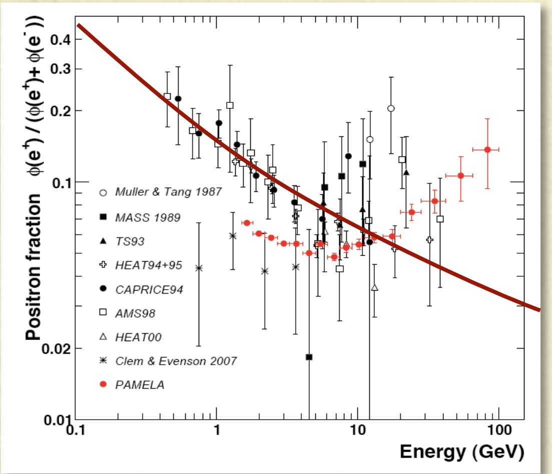
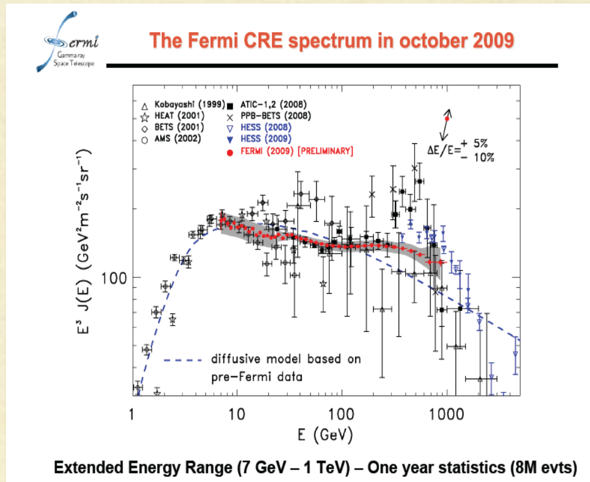
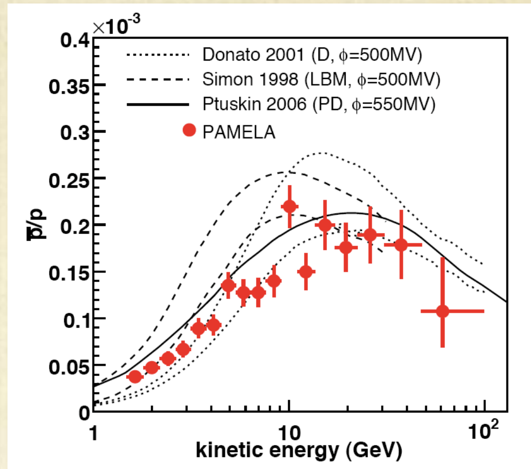
Based on:
0812.0980
0903.4409
1005.XXXX

Anomalous CRs... DM Or What?

Excess CR antimatter could be a signal of DM annihilation...
PAMELA Experiment ➔ Maybe we do see an excess:







BUT:

$$\Phi(\epsilon) = \int_{Halo} d^3x \cdot \rho^2(x) \cdot \int_{\epsilon}^{\infty} d\epsilon' \langle\sigma v\rangle_{tot} \frac{d\phi}{d\epsilon'} \cdot G(\epsilon, \epsilon')$$

? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?

Halo particle astrophysics

An MSSM WIMP? Lore: No.

Thermal Cosmology: <σv> ~ 10^{-26} cm^3 s^{-1}

Studied models: not particularly "leptophilic"

BUT:

The Goal for Today:

Is there anything to learn by:

i) venturing beyond mSUGRA and

ii) A more rigorous treatment of astrophysical uncertainties

$$\Phi(\epsilon) = \int_{Halo} d^3x \cdot \rho^2(x) \cdot \int_{\epsilon}^{\infty} d\epsilon' \langle \sigma v \rangle_{tot} \frac{d\phi}{d\epsilon'} \cdot G(\epsilon, \epsilon')$$

Halo ??? particle ??? astrophysics ???

Outline...

- Our Models the p(henomenological)MSSM (a larger subset of the MSSM)
- Gamma constraints from dwarf galaxy observation.
- Cosmic Rays, dealing with astrophysical uncertainties
- Astro+SUSY fitting of $(e^+ + e^-)$, $e+/(e^+ + e^-)$, pbar/p simultaneously
- An interesting place in pMSSM space.

SUSY Without Prejudice

0812.0980

C.F. Berger, J.S. Gainer, J.L. Hewett, T.G. Rizzo

- pMSSM = MSSM + CP-conservation, R-Parity, MFV, Two light gens. are Degenerate (by type), no light gen. yukawas…

- A 19 dim. Subspace of MSSM: m_{Q1},m_{Q3},m_{u1},m_{d1},m_{u3},m_{d3},m_{l1},m_{l3},m_{e1}, m_{e3},M_1,M_2,M_3,A_b,A_t,A_τ,μ,M_A,$\tan\beta$ (weak-scale pars.- no assumption of GUT or SUSY bkg. Mechanism)

- MC generation* of points in this space. Impose constraints from: Theory, Tevatron, LEP, EW Precision, WMAP, Direct Detection, g-2, rare decays, flavor.

- ➔ 10^7 scan points, ~ 68.4K survive (0.68%)

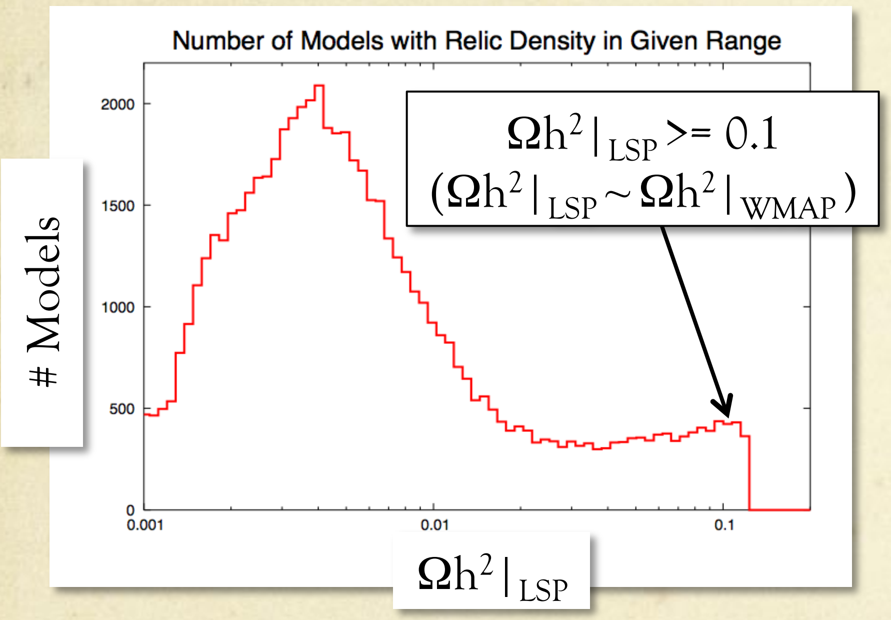
- The LSP is the lightest neutralino; thermal cosmology is assumed.

* With SuSpect, SUSY-HIT, PROSPINO, PYTHIA, PGS4 and MicrOMEGAs

DM Properties...

Fairly light WIMPs: $m_{LSP} \sim$ 100-400 GeV

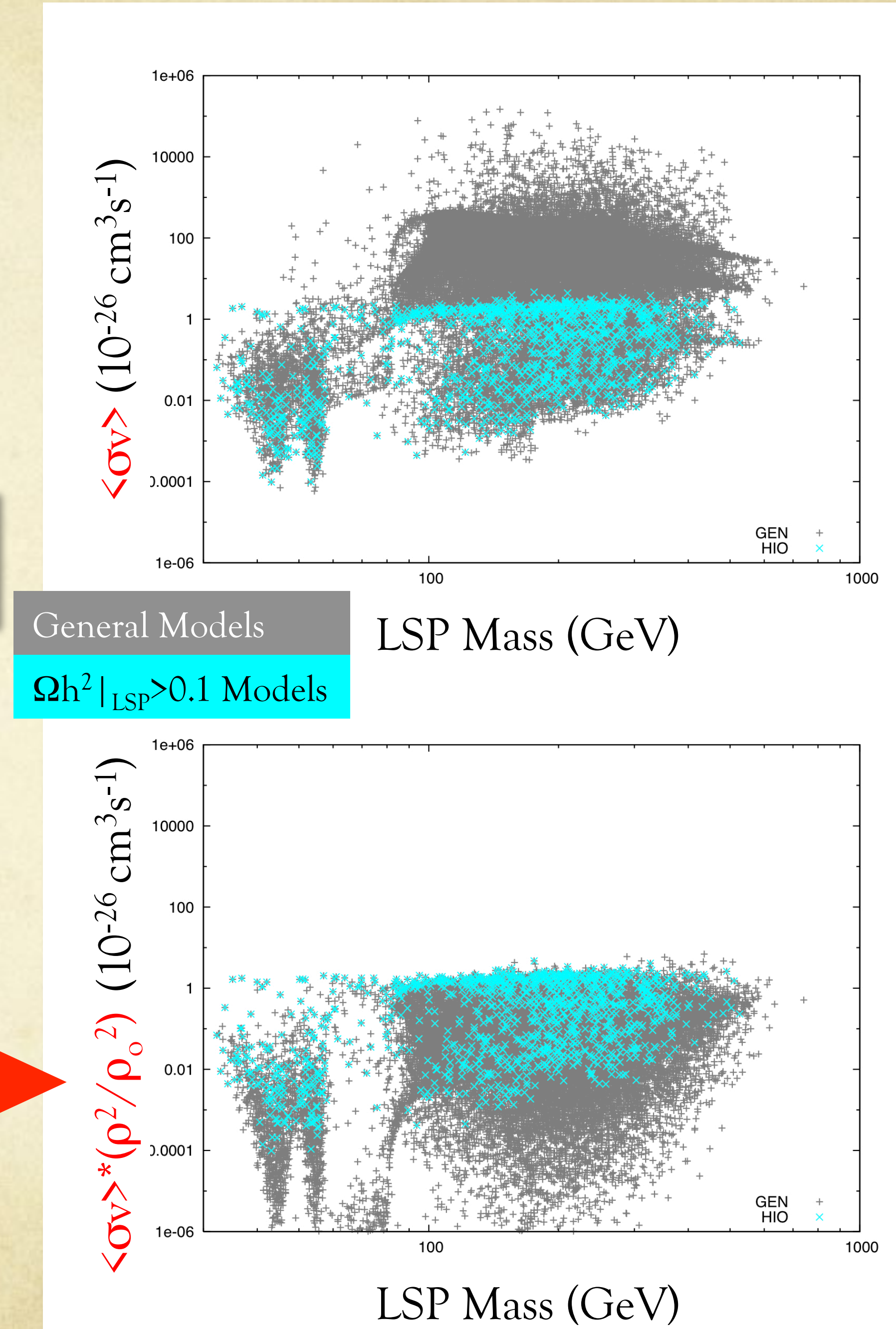
LSP: Not Necessarily ALL of DM...



Thermal Rescaling:

$$\rho^2 = \rho_o{}^2 * (\Omega h^2|_{LSP} / \Omega h^2_{WMAP})^2$$

$$\rho_o \sim 0.3 GeV/cm^3$$



Quarks vs. Leptons in Our Model Set...

Studies often take:

Br_b=80% ,

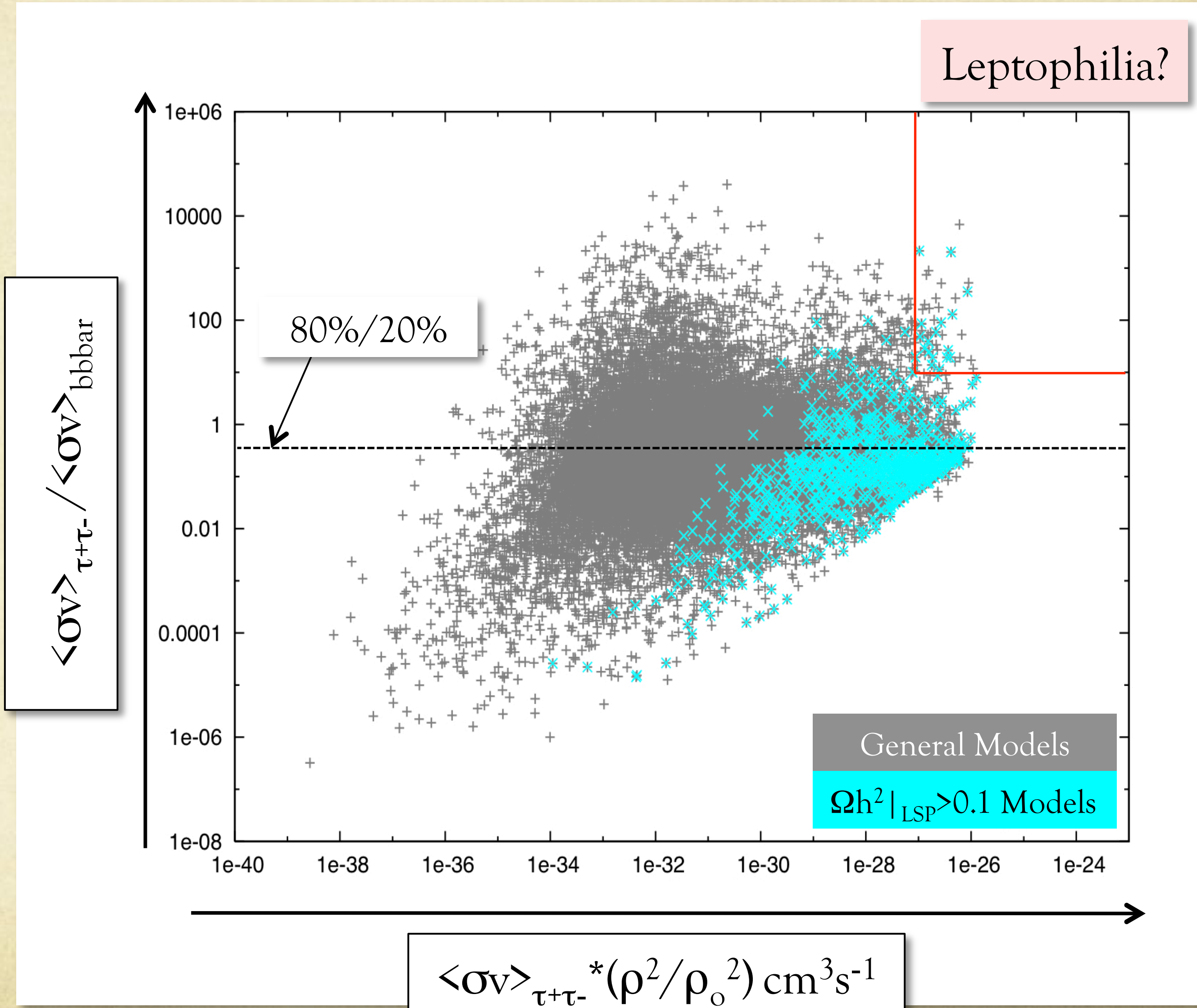
Br_τ=20%

Helicity suppression + color factor =>

$Br_\tau/Br_b \sim$

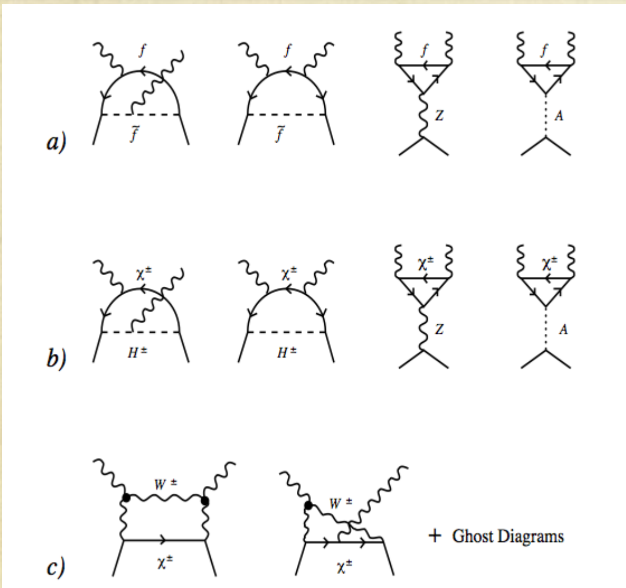
$(m_\tau/m_b)^2/3 \sim 0.25$

(If $m^{DR}{}_b(m_\chi) \sim 2$ GeV)



Continuum γ Signals (Not just Lines!)

Loop Graphs => Line Signals:

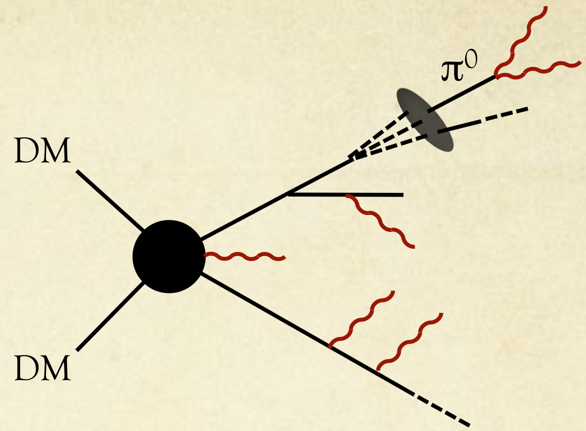


$$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \to \gamma + \gamma$$

$$E_\gamma = M_\chi.$$

$$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \to \gamma + Z^0$$

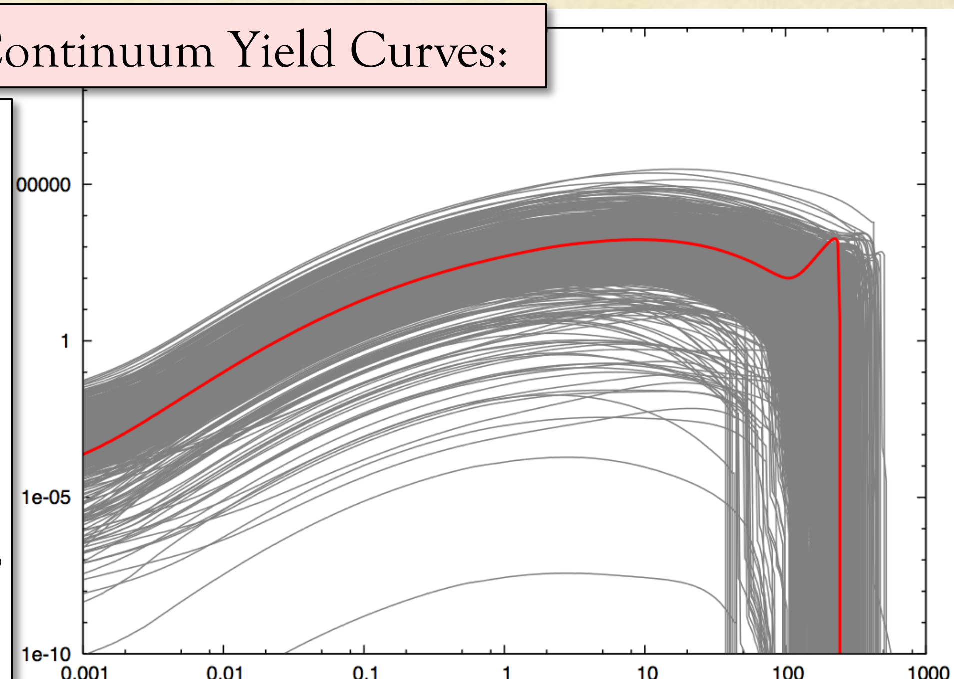
$$E_\gamma = M_\chi - \frac{m_Z^2}{4\,M_\chi}.$$



Radiation off of charged virtual and final state particles, decay products, Hadronization Prods. (π^0's)

=> Continuum Yield Curves:

$E_\gamma{}^{2*}dN_\gamma/dE_\gamma{}^*\Sigma_i\langle\sigma v\rangle_i{}^*$ $(\rho^2/\rho_o{}^2)$ $(10^{-29}cm^3s^{-1}GeV)$



E_γ (GeV)

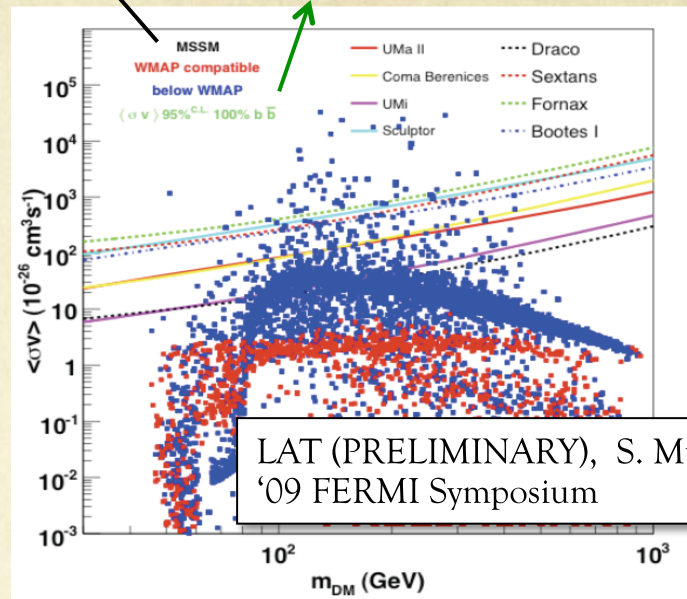
Continuum γ' s from Dwarf Galaxies...

Dwarfs: Extremely DM dominated,

Any γ's coming from dwarfs would be very conspicuous!

Ultra-Faint dwarf "Segue 1"

MSSM? 100% branching to bb-bar assumed



LAT (PRELIMINARY), S. Murgia '09 FERMI Symposium

Measured in Detector

$$\frac{dN_\gamma}{dAdt} = \frac{1}{8\pi}\mathcal{L}_{\rm ann}(\rho^2(\vec{r}), D)\frac{\langle\sigma v\rangle}{m_\chi^2}\int_{E_{th}}^{E_{max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma$$

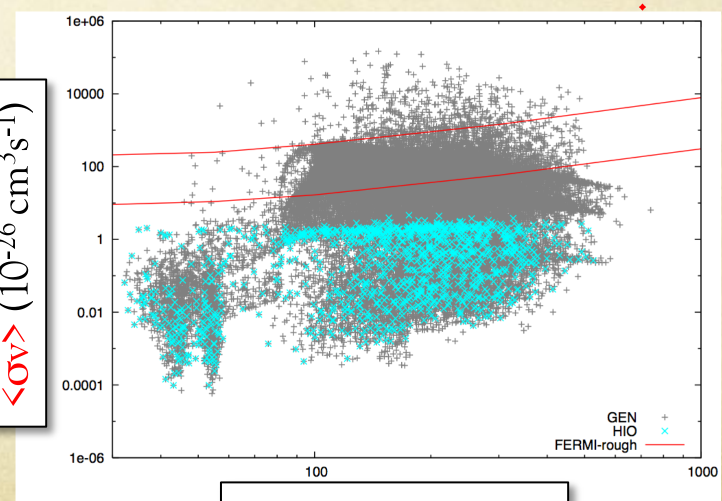
$$\mathcal{L}_{\rm ann} = \int_0^{\Delta\Omega}\left\{\int_{LOS}\rho^2(\vec{r})ds\right\}d\Omega$$

Particle Model Dependence

DM Halo Integral

(Est. for Segue 1: Essig etal. 0902.4750)

(NOT Thermal Rescaled) $\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm^3 s^{-1}})$

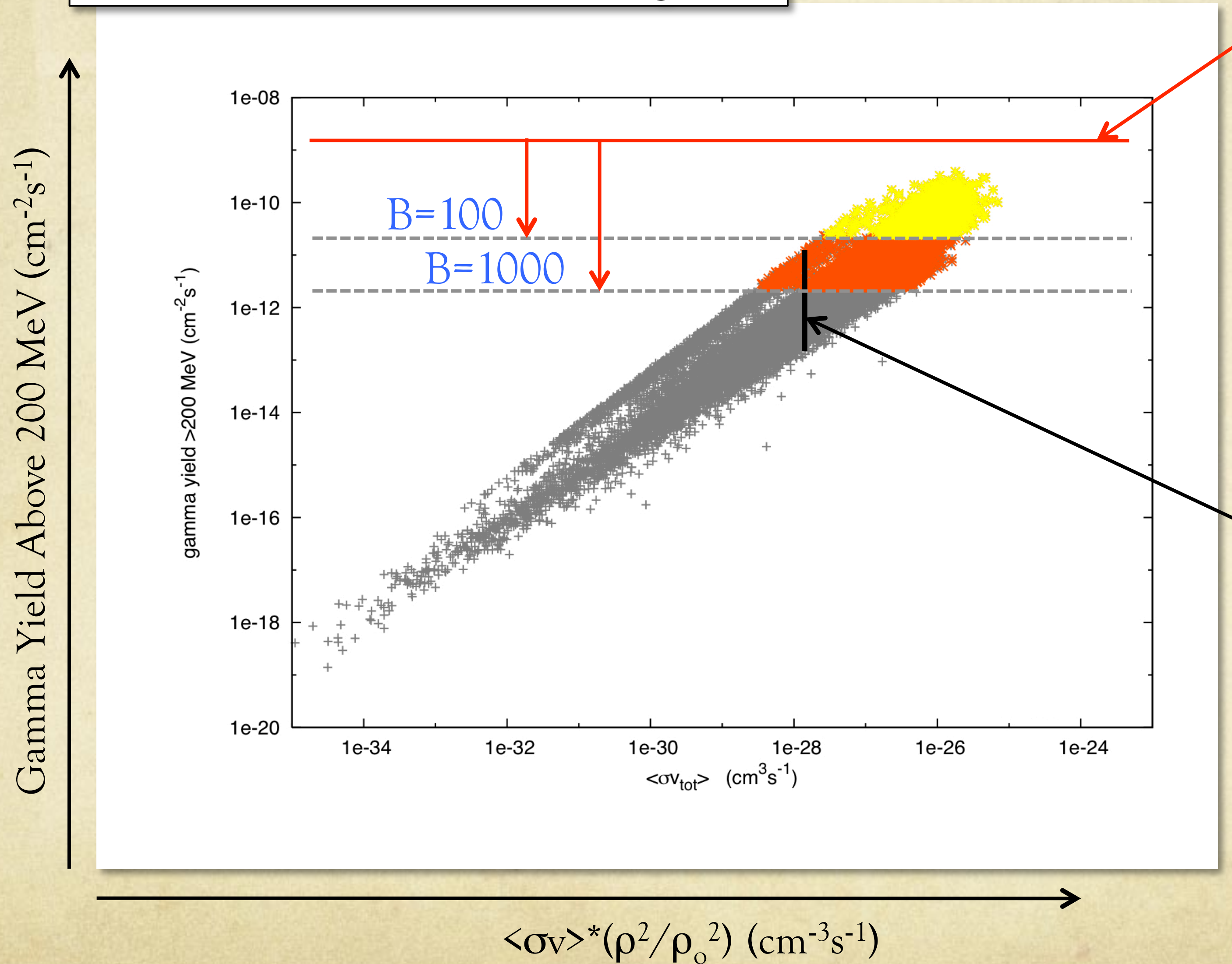


? ? ?

LSP Mass (GeV)

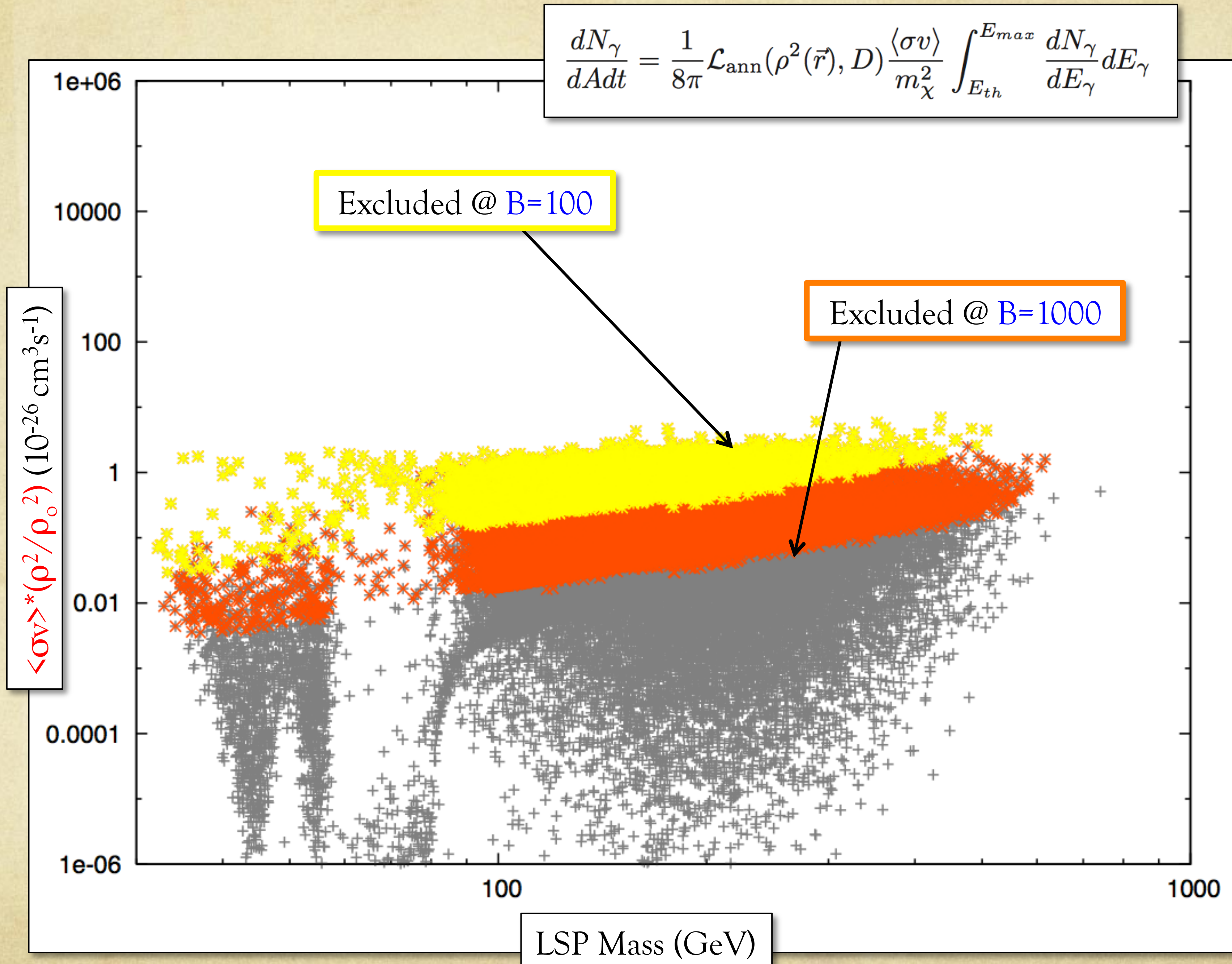
Continuum Gammas from Dwarfs...

For FERMI observations of Segue1...

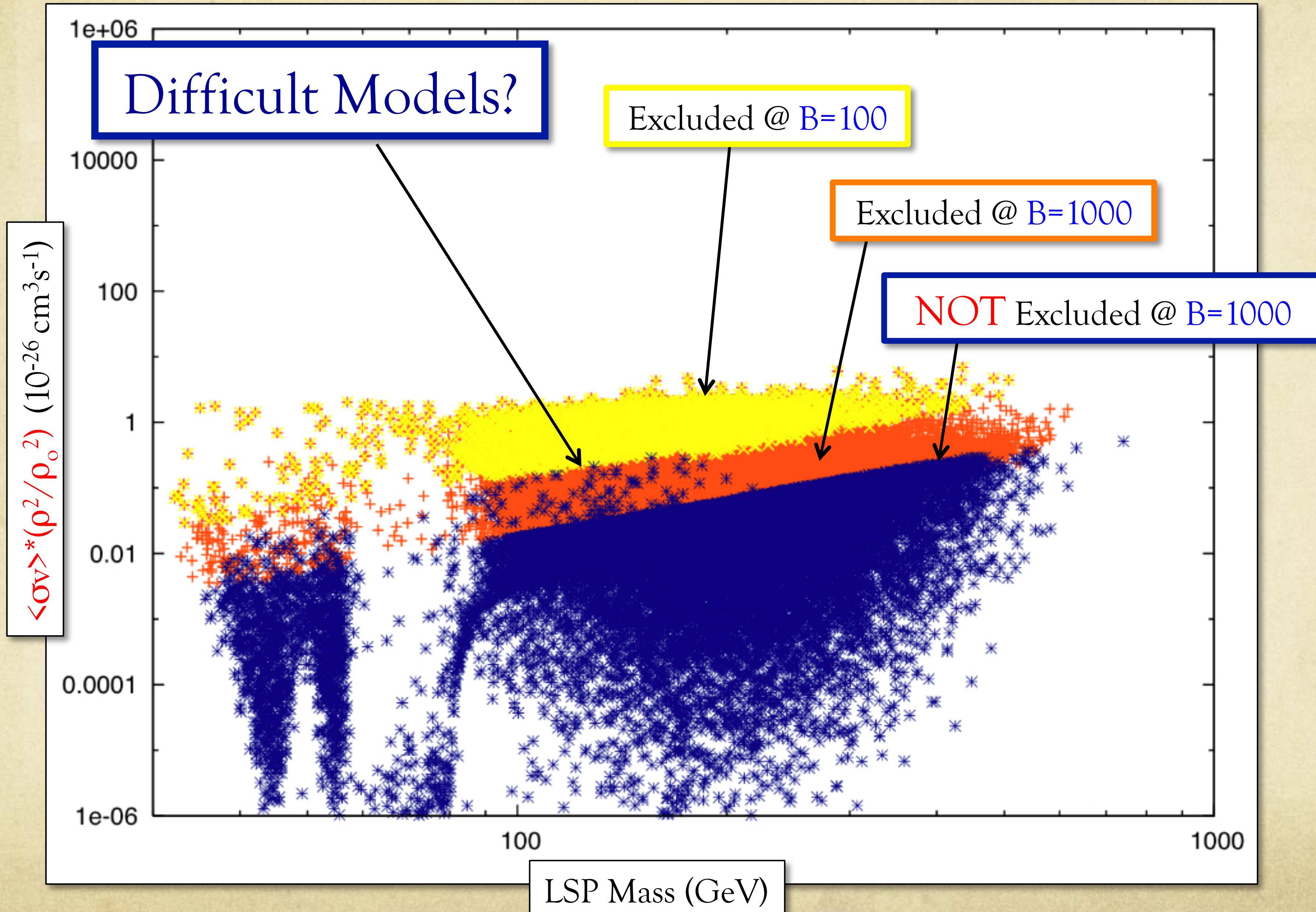


Estimated sensitivity (1 yr LAT, 3σ) Essig, etal. (0902.4750)

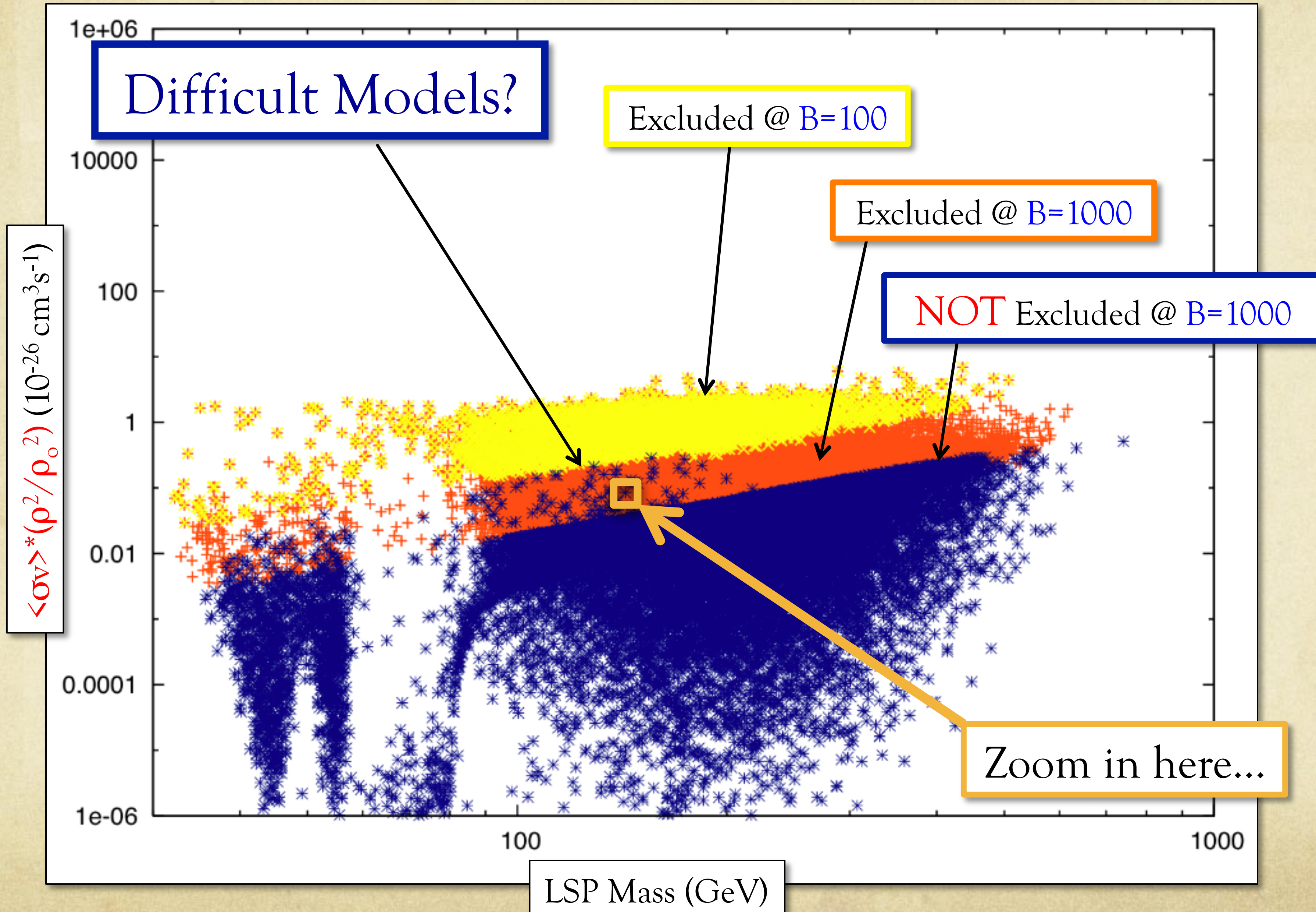
Couple of orders ambiguity in going from <σv> to the actual dwarf signal



$$\frac{dN_\gamma}{dAdt} = \frac{1}{8\pi}\mathcal{L}_{\rm ann}(\rho^2(\vec{r}), D)\frac{\langle\sigma v\rangle}{m_\chi^2}\int_{E_{th}}^{E_{max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma$$
Excluded @ B=100
Excluded @ B=1000
$\langle\sigma v\rangle * (\rho^2/\rho_o^2)$ (10^{-26} cm^{3}s^{-1})
1e+06
10000
100
1
0.01
0.0001
1e-06
100
1000
LSP Mass (GeV)



Difficult Models?
Excluded @ B=100
Excluded @ B=1000
NOT Excluded @ B=1000
<σv>*(ρ^2/ρ_o^2) (10^-26 cm^3s^-1)
1e+06
10000
100
1
0.01
0.0001
1e-06
100
1000
LSP Mass (GeV)

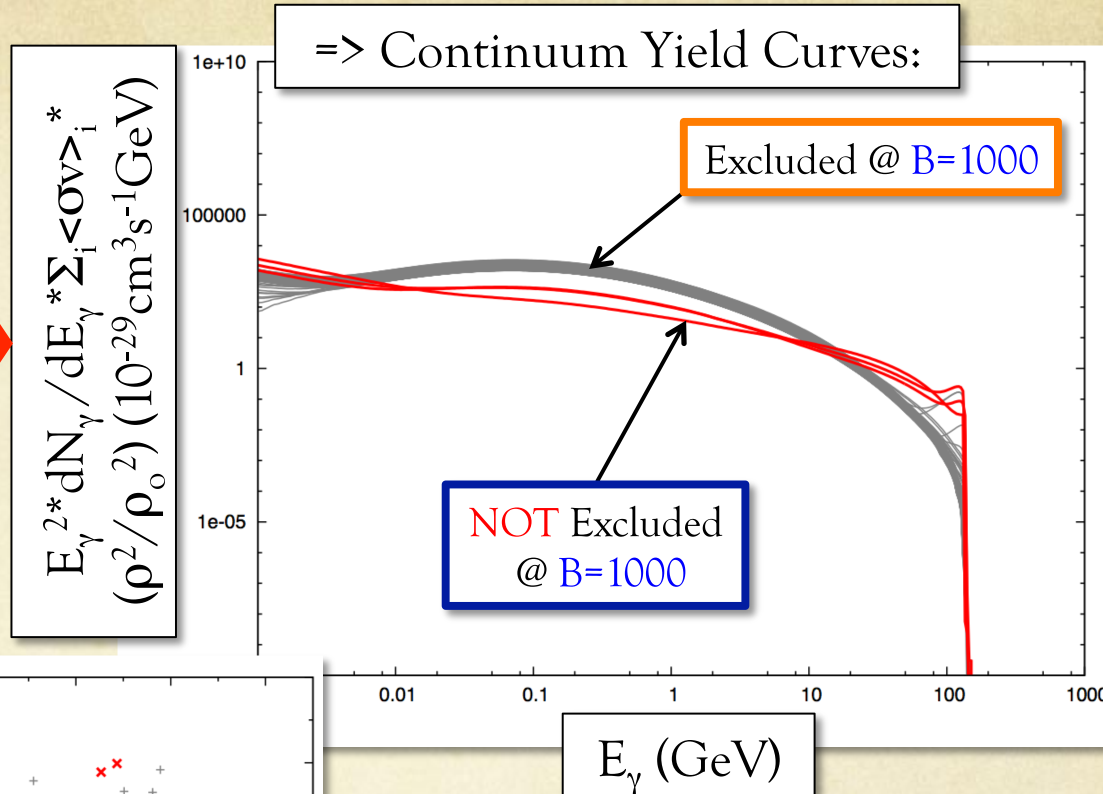


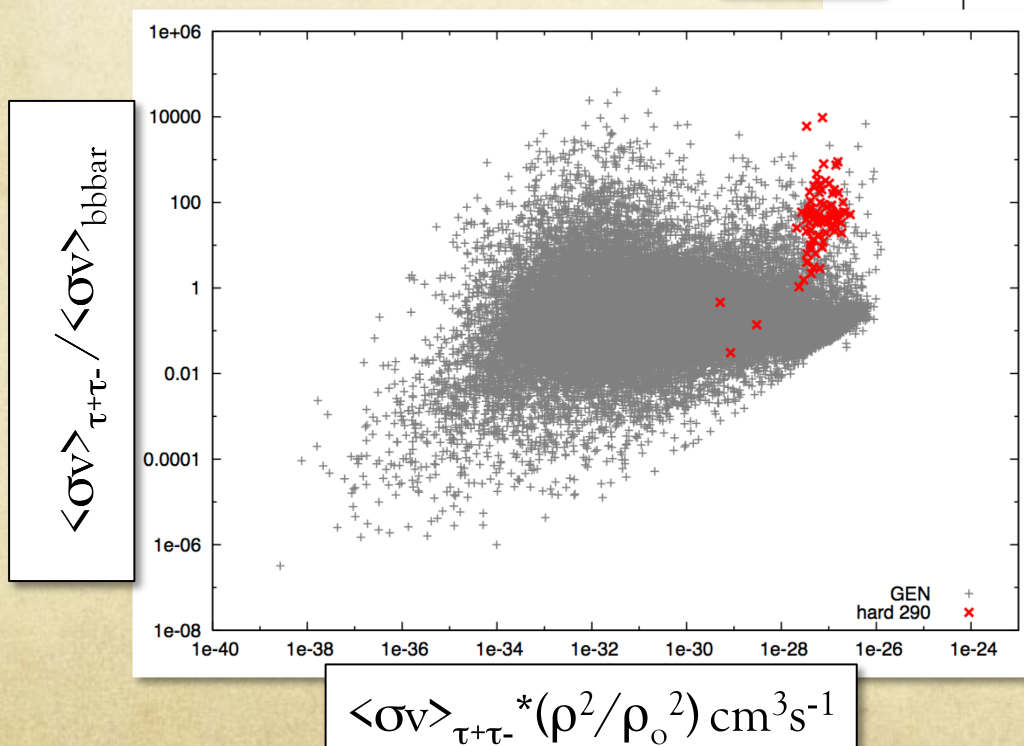
Difficult Models?
Excluded @ B=100
Excluded @ B=1000
NOT Excluded @ B=1000
Zoom in here...
1e+06
10000
100
1
0.01
0.0001
1e-06
100
1000
<σv>*(ρ²/ρo²) (10⁻²⁶ cm³s⁻¹)
LSP Mass (GeV)

What are they like?

This Plot: Models w/ $m_\chi \sim 135$ and $\langle\sigma v\rangle*(\rho^2/\rho_o^2) \sim 6*10^{-28}$

Stiffer (tau-ish) spectrum=> lower yield



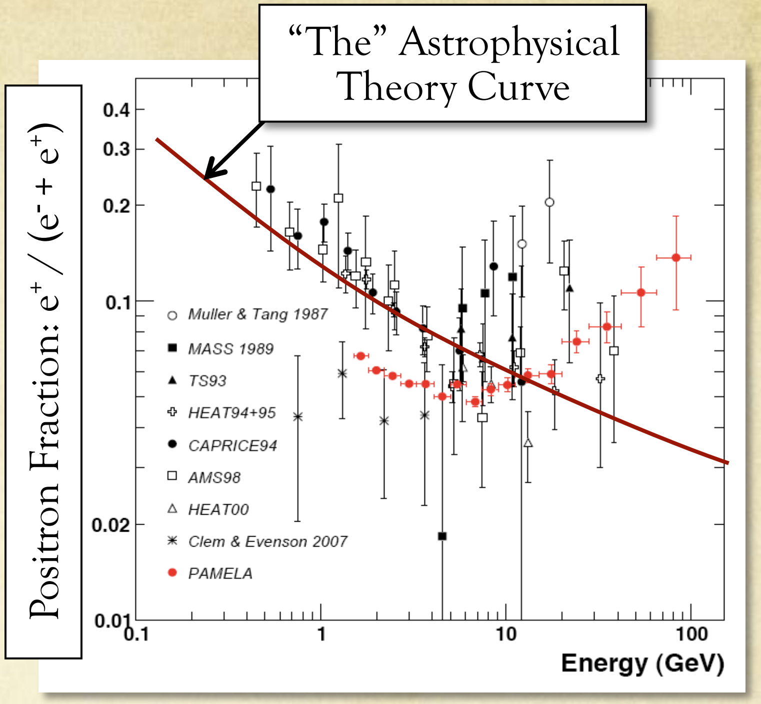


Typically $\tilde{\tau}$ or $\tilde{\nu}_\tau$ nLSP with small $\Delta(m_{nLSP} - m_{LSP})$

Now for Cosmic Rays...

We want to add a DM annihilation signal to see if we can explain the anomaly...

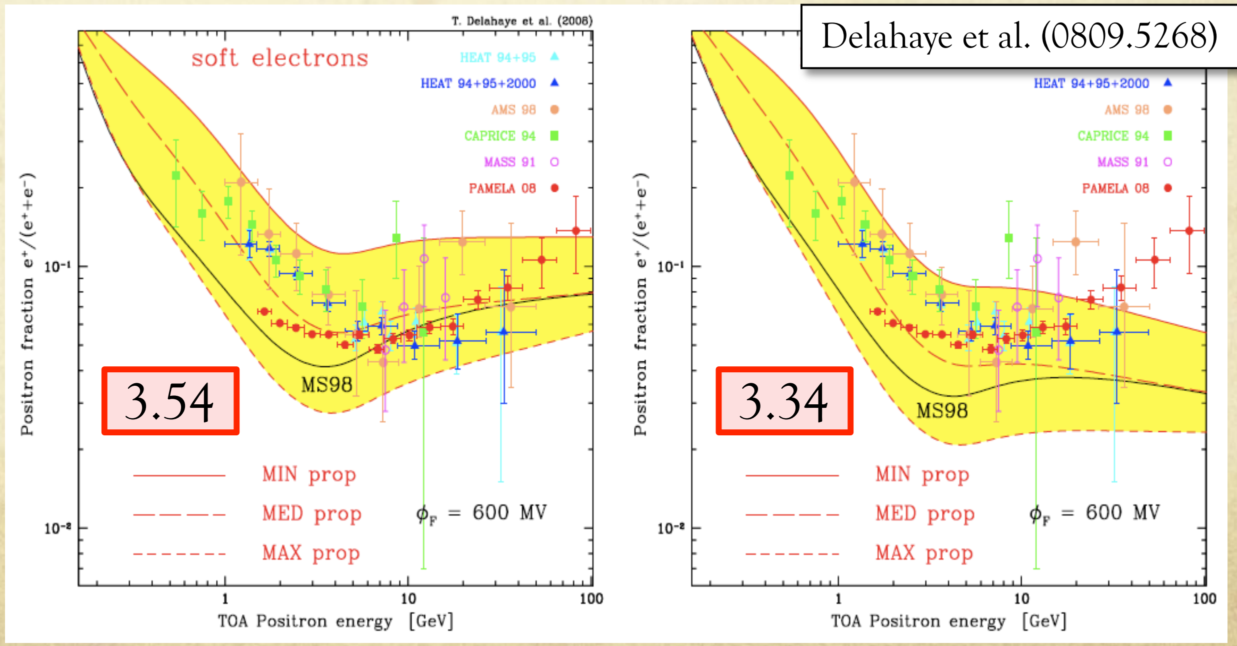
Do we know what to add our signals to? (What is the uncertainty on that curve?)



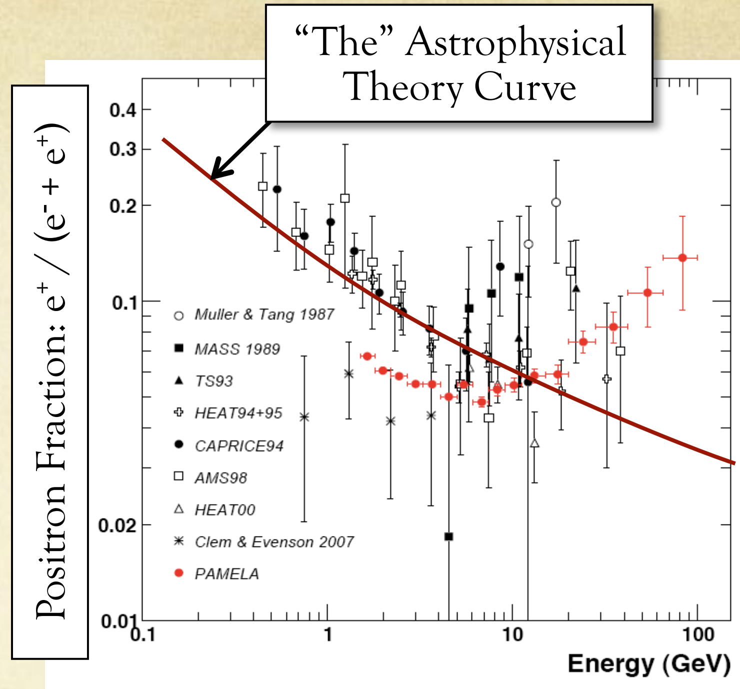
In Late 2008 one was doing well if they "knew" this:

$$(e\text{-}+e\text{+}) \sim E^{\gamma_{obs}}$$

$$\gamma_{obs} \sim \{3.34 - 3.54\}$$



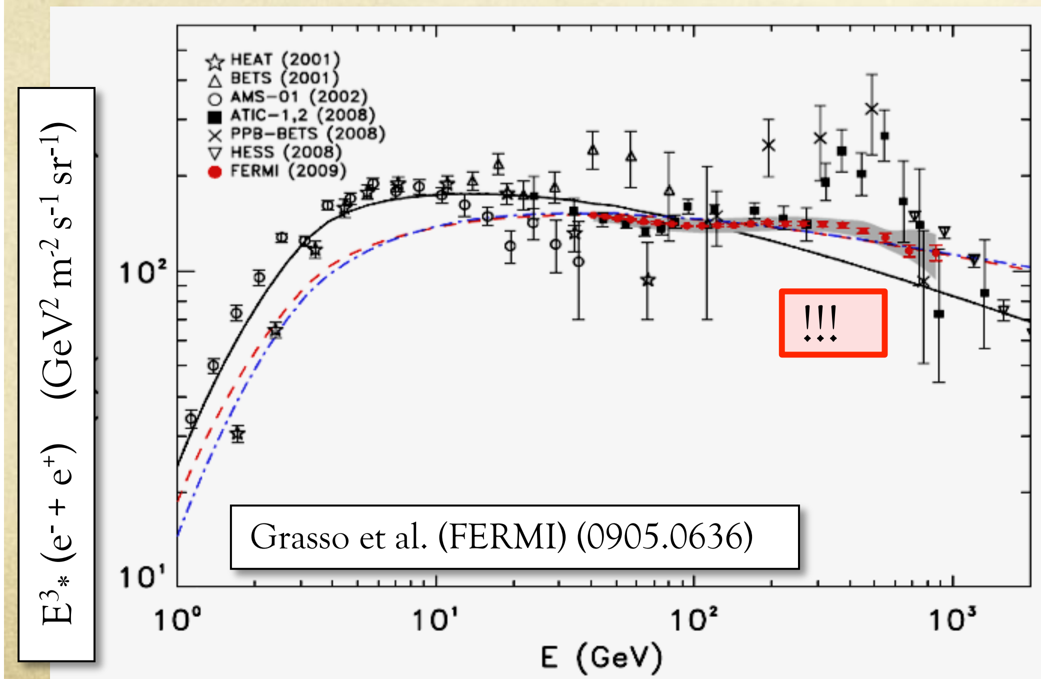
In Early 2009: the FERMI-LAT measurement of (e-+e+) sends us back to the drawing board...

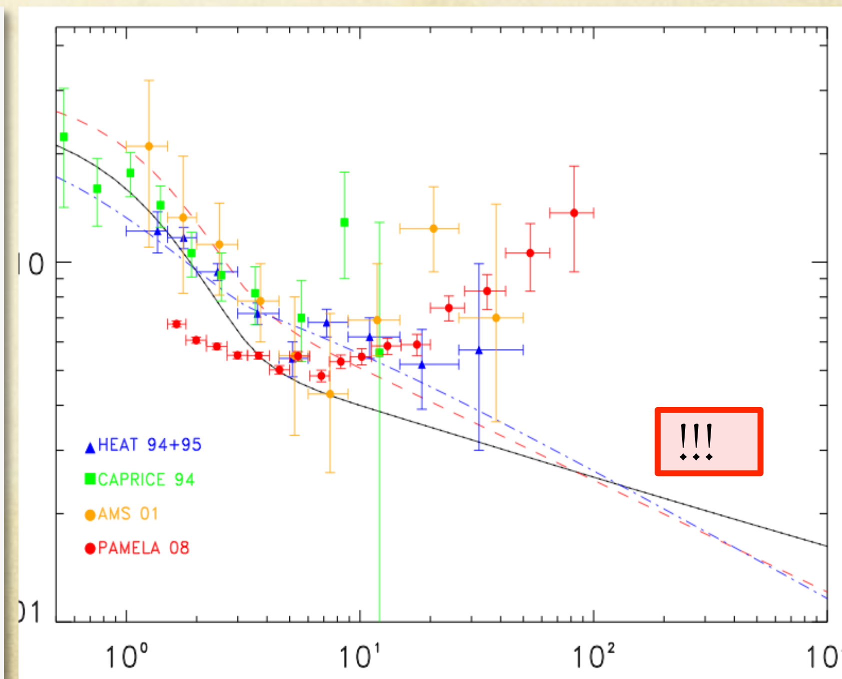


$$(e\text{-}+e+) \sim E^{\gamma_{obs}}$$

~~$\gamma_{obs} \sim \{3.34 - 3.54\}$~~

$$\Rightarrow \quad \gamma_{obs} = 3.045 \pm 0.008$$





The Plan:

Make "Astro-Scan" (just like SUSY scan). Combine (astro)X(SUSY) setups. Fit e+/(e^++e^-) , (e^++e^-) , pbar/p, simultaneously...

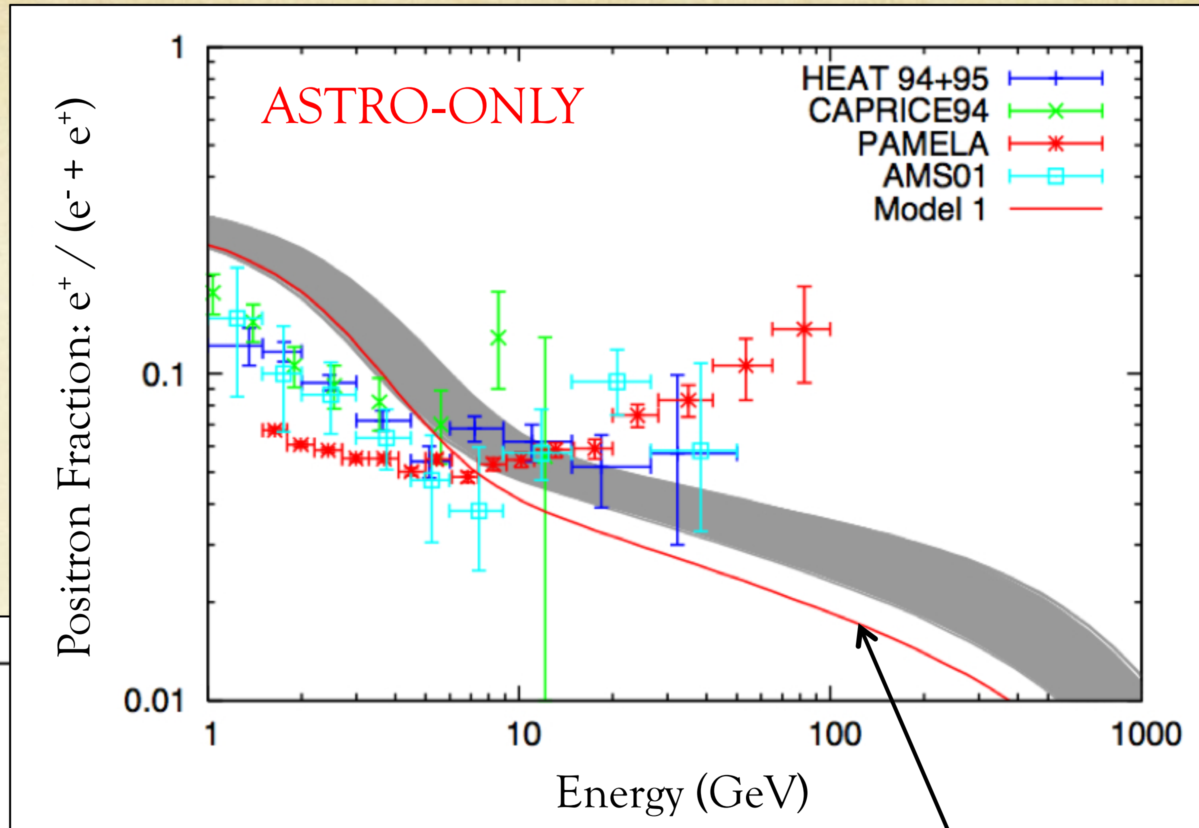
First...

Par. Type	Par. Names	Constrained By	Also Note...
Proton Source	N_n, γ_n	Proton Abs. Flux (AMS01,ATIC,BESS, CAPRICE)	These are fixed at the beginning and never floated thereafter
Diffusion	z_h, D_{0xx}, δ, V_A, V_c	B/C (HEAO-3, ATIC, CREAM)	z_h and D_{0xx} are "degenerate," we scan z_h. Radio clocks: z_h>~2Kpc. δ expected in ~ 0.3-0.8. Here δ=0.33
Electron Source	N_e, γ_e	e+/(e^++e^-), (e^++e^-)	
B-Field	N_B	e+/(e^++e^-), (e^++e^-) Diffuse γ's	N_B~ few μG
ISRF	(u_{FIR}+$u_{optical}$), $u_{optical}/u_{FIR}$	e+/(e^++e^-), (e^++e^-) Diffuse γ's	(u_{FIR},$u_{optical}$) ~ default, Scan similar to Blandford etal. (0908.1094)

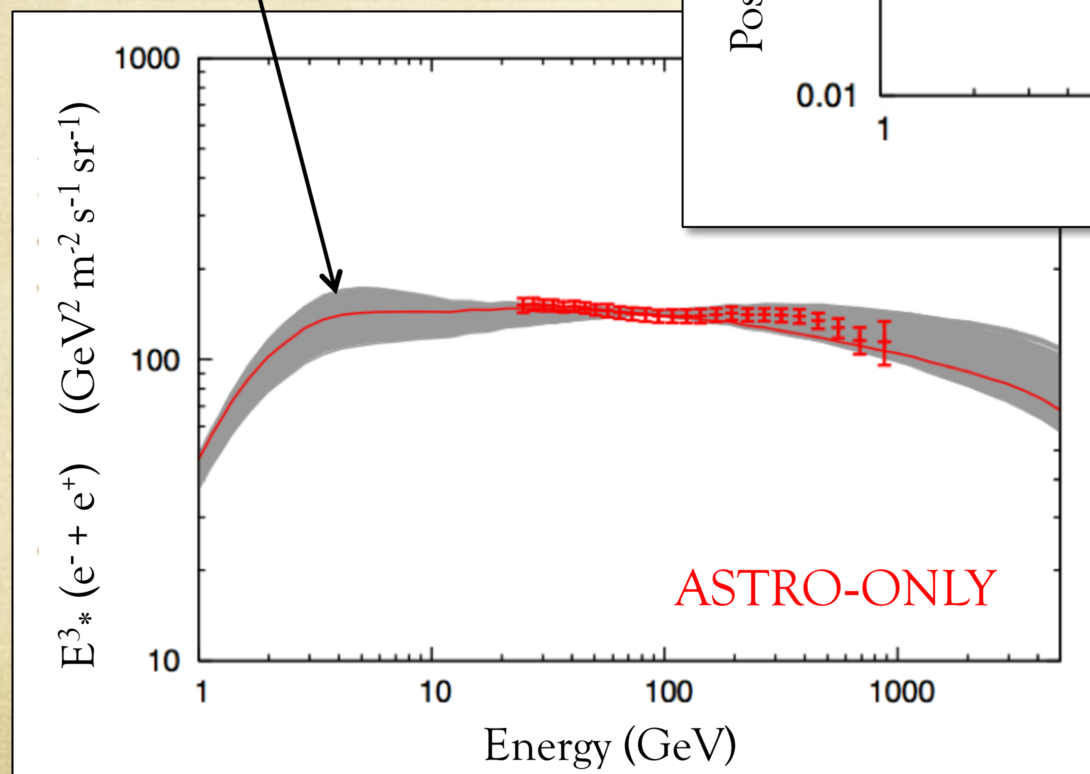
e+/(e^++e^-), (e^++e^-), pbar/p, fit above 10GeV

...Last

Our Astro-Background Scan... (NO SUSY added)

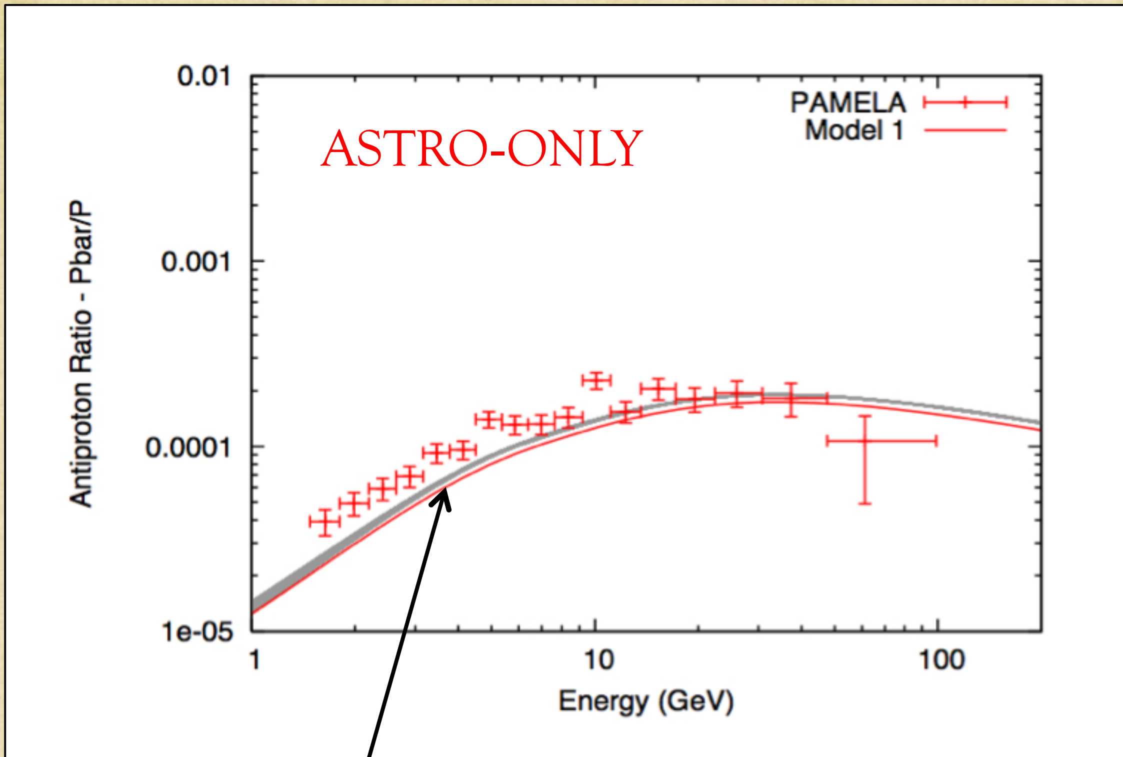


Our Models (qty. 524)



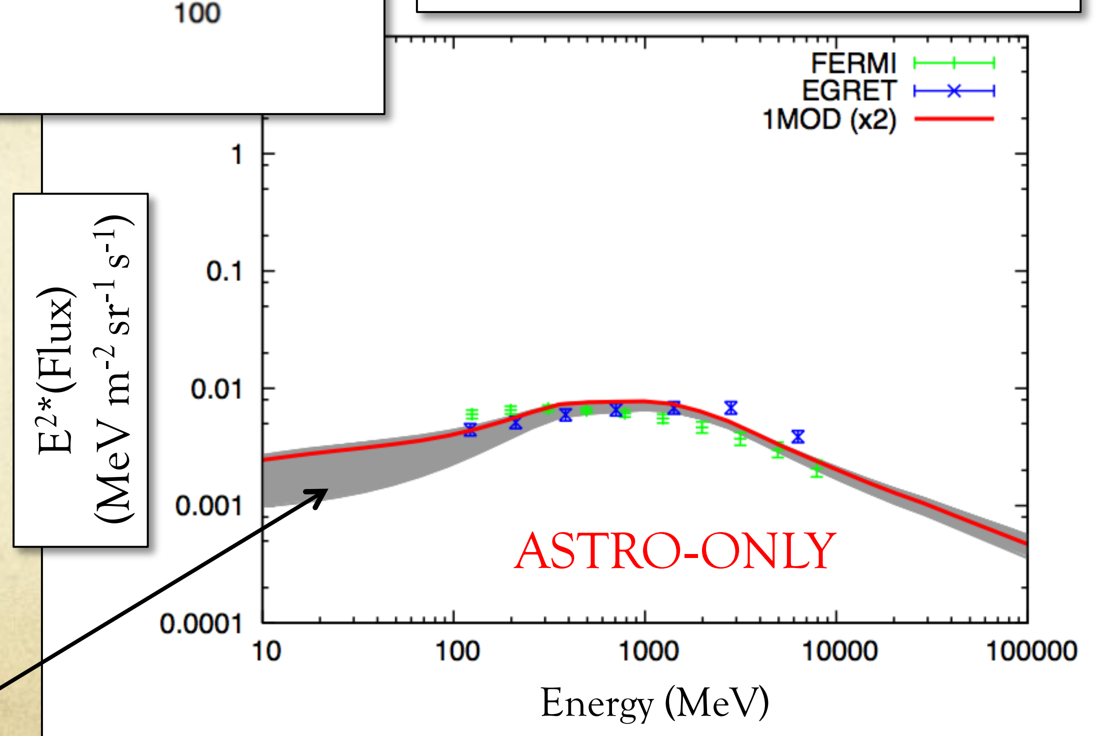
Benchmark "Model 1"
Grasso et al. (FERMI, 0905.0636)

Our Astro-Background Scan... (NO SUSY added)



Benchmark "Model 1" (0905.0636)

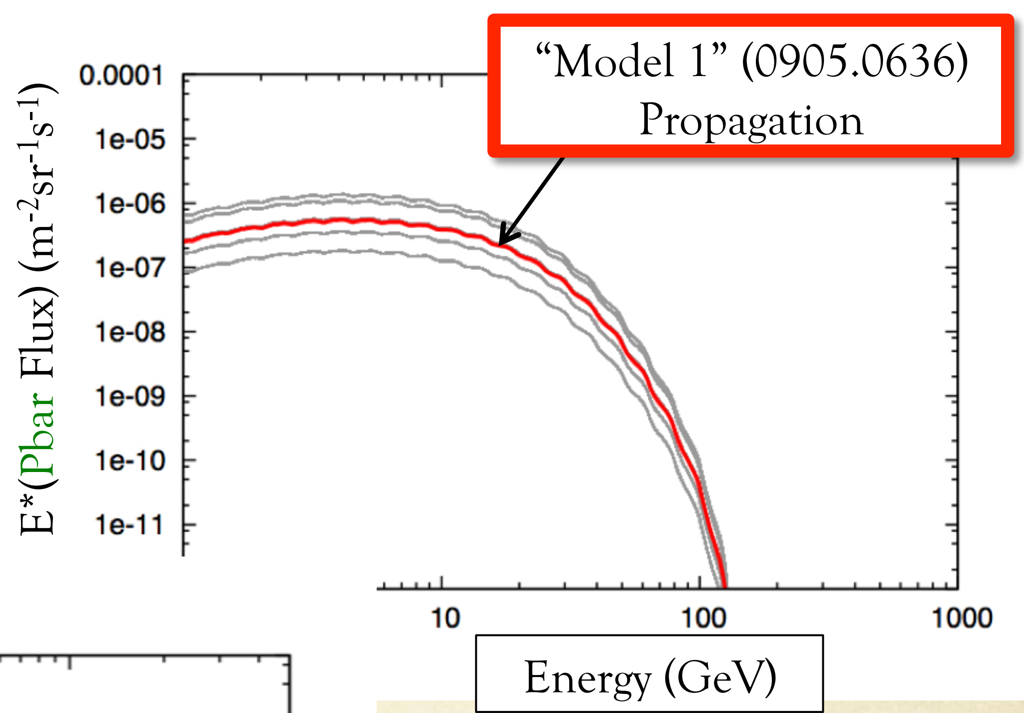
Diffuse Midlat. Gammas ($10^\circ<|b|<20^\circ$, $0^\circ<b<360^\circ$)

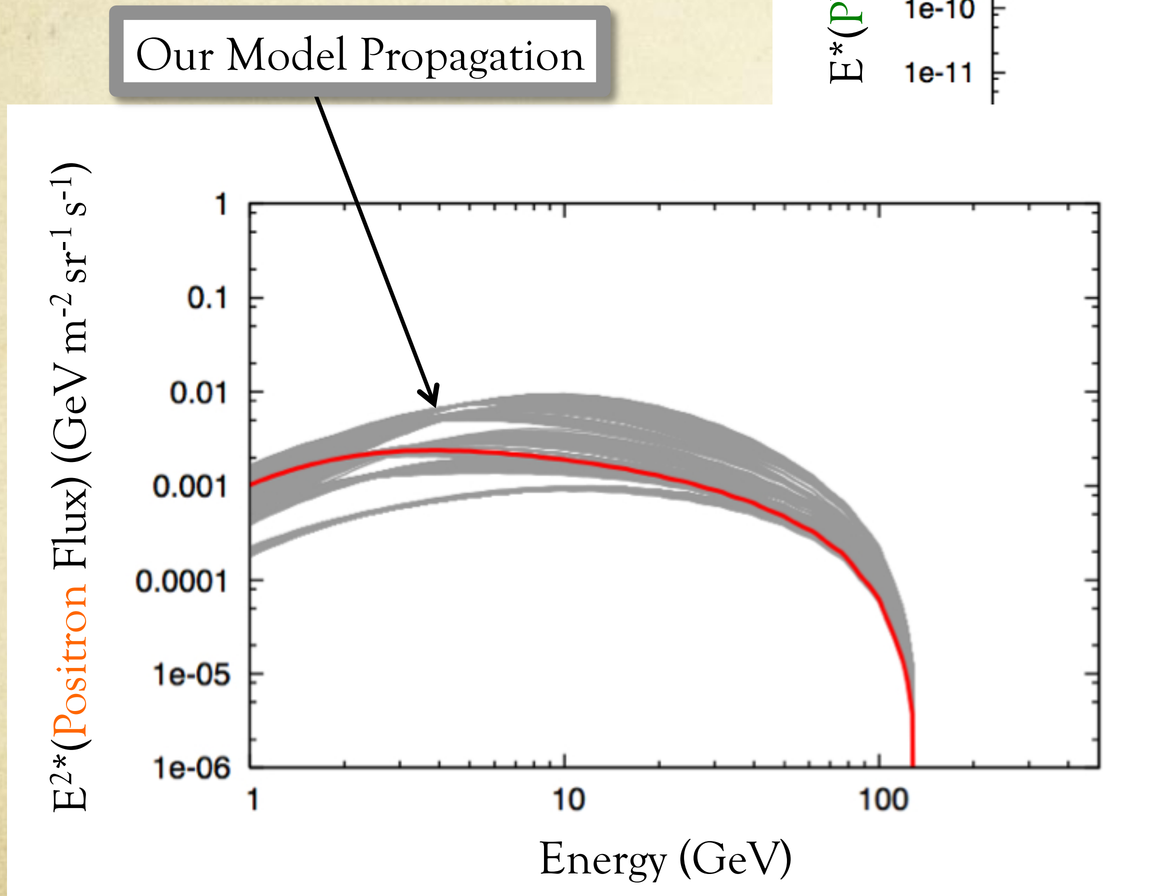


Our Models

SUSY ONLY Signals...

Shown: positron and antiproton fluxes from A SINGLE SUSY MODEL for each astro-model used



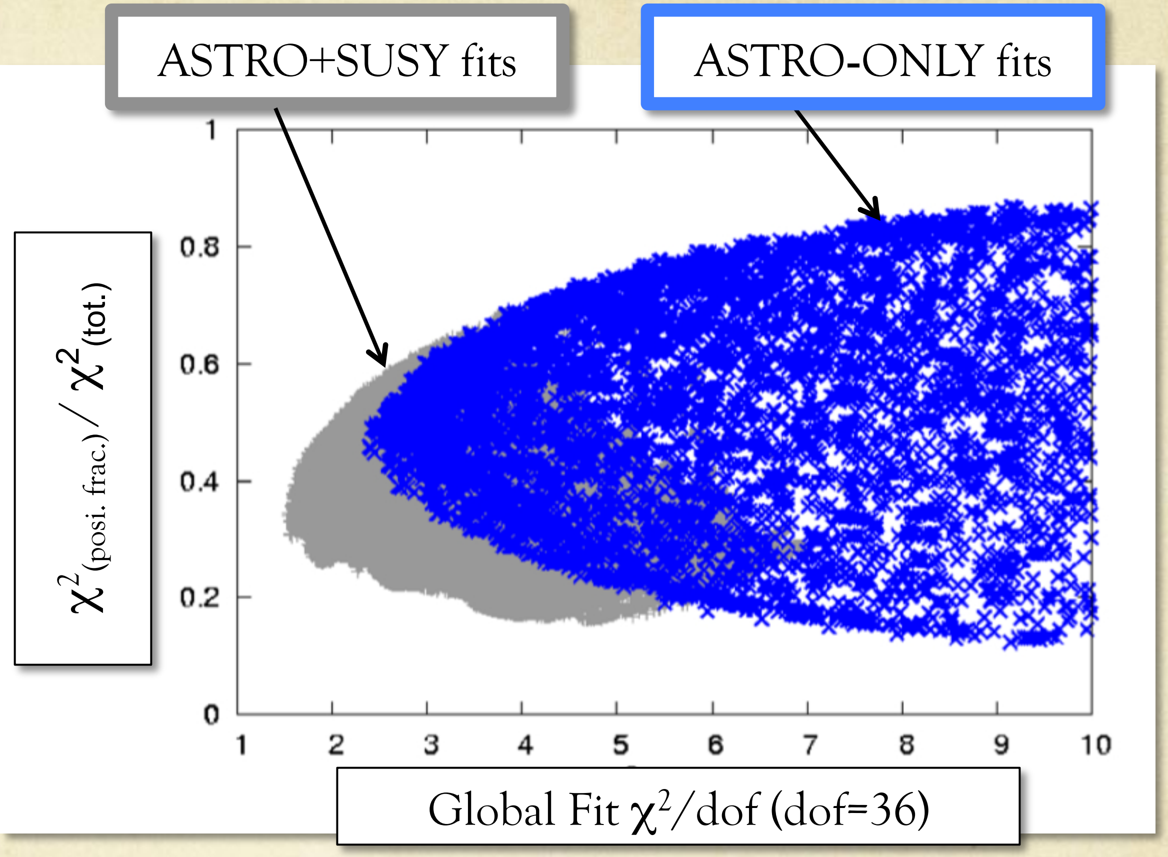


Green's functions appropriate to each custom astro-model are used to compute the SUSY signals (i.e. GALPROP -> DarkSUSY)

An Improvement ?

The SUSY-Added fits do significantly better than the ASTRO-ONLY fits.

Most cases: a significantly better fit to the PAMELA positron fraction data



Global Fit (Astro)X(SUSY) …

BEST FITS:

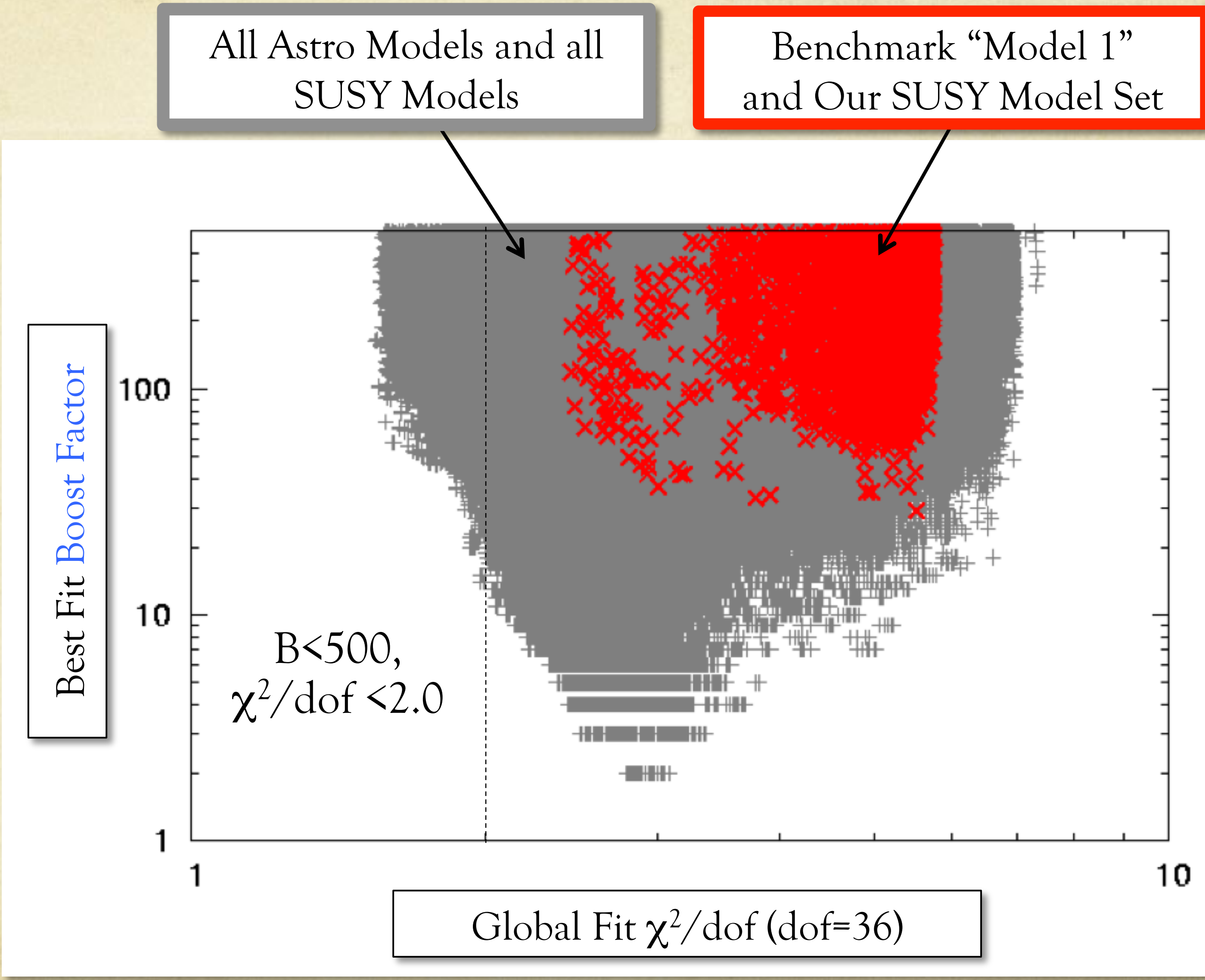
χ^2/dof = 1.54

With boosts in:

B ~ 70-150

Q: What are the best Astro-models like?

Q: What are the best SUSY models like?



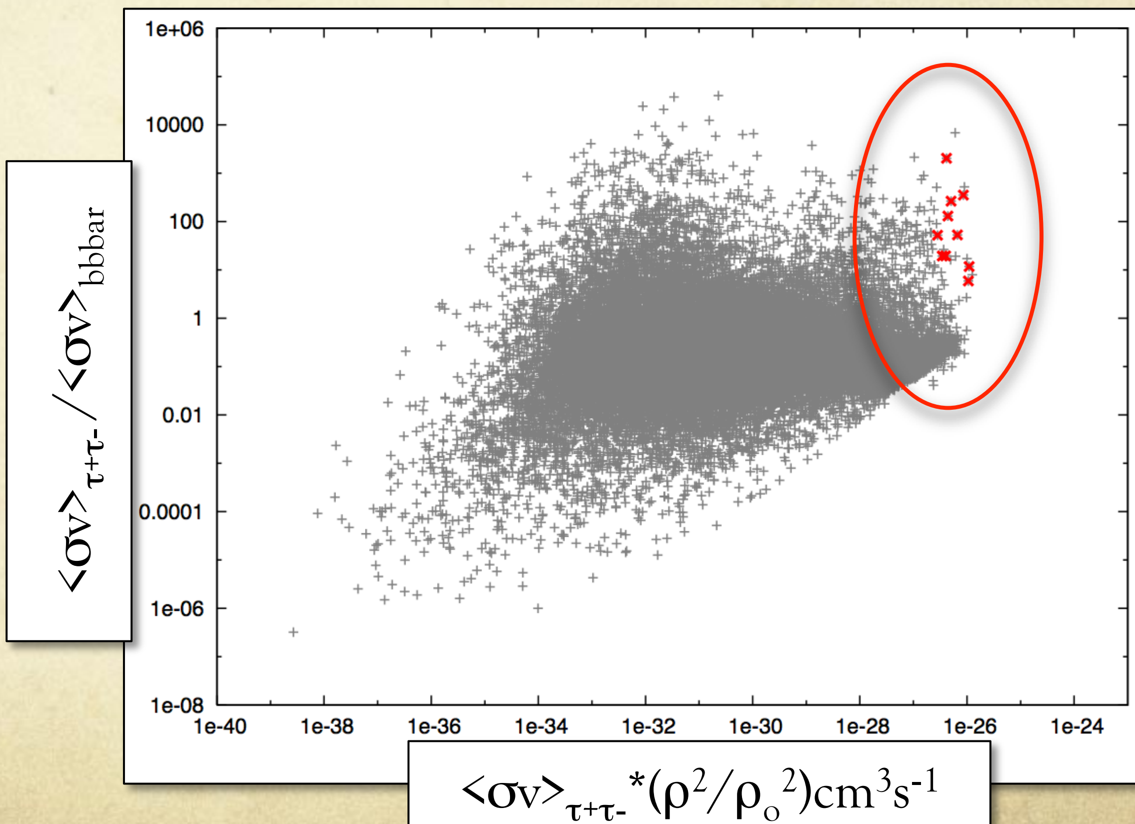
Answers…

Best Astro Models…

- Diffusion Zone Heights: 2-3Kpc, δ=0.33, relatively soft γ_e: 2.5-2.55
- Soft γ_e afforded by ($f_{optical}$,f_{FIR})=(1.8,0.2) (default, 1.0,1.0) "the KN bump"
- Bulk mag. field smaller than default (5μG), in 0.2-3 μG

Best SUSY Models…

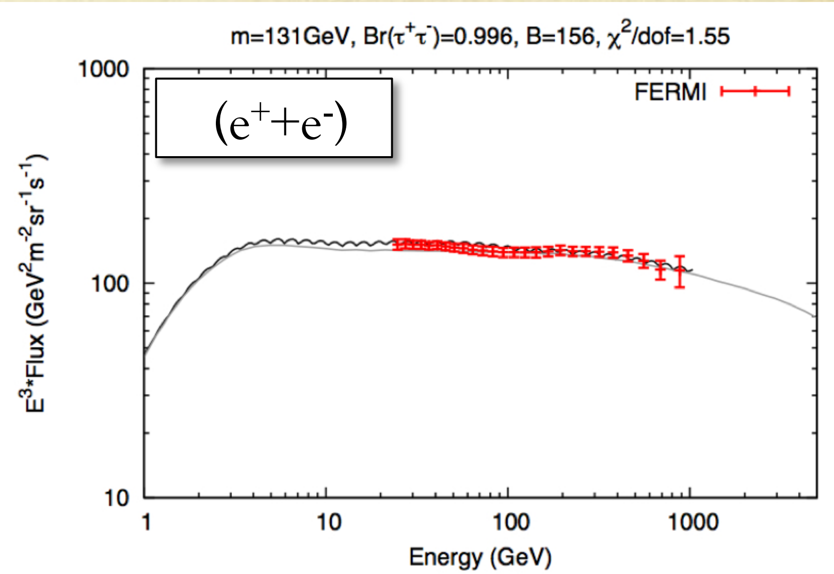
- Top 10 mods: all $\tilde{\tau}$ nLSP w/ m_{LSP}~120-160GeV
- 7/10 models annihilate with Br_τ > 95%, other 3/10 with Br_τ > 70%
- Best fit Boost Factors in 100-200
- The 7 tau-rich models PASS the LAT dwarf limit with their best-fit Boost!

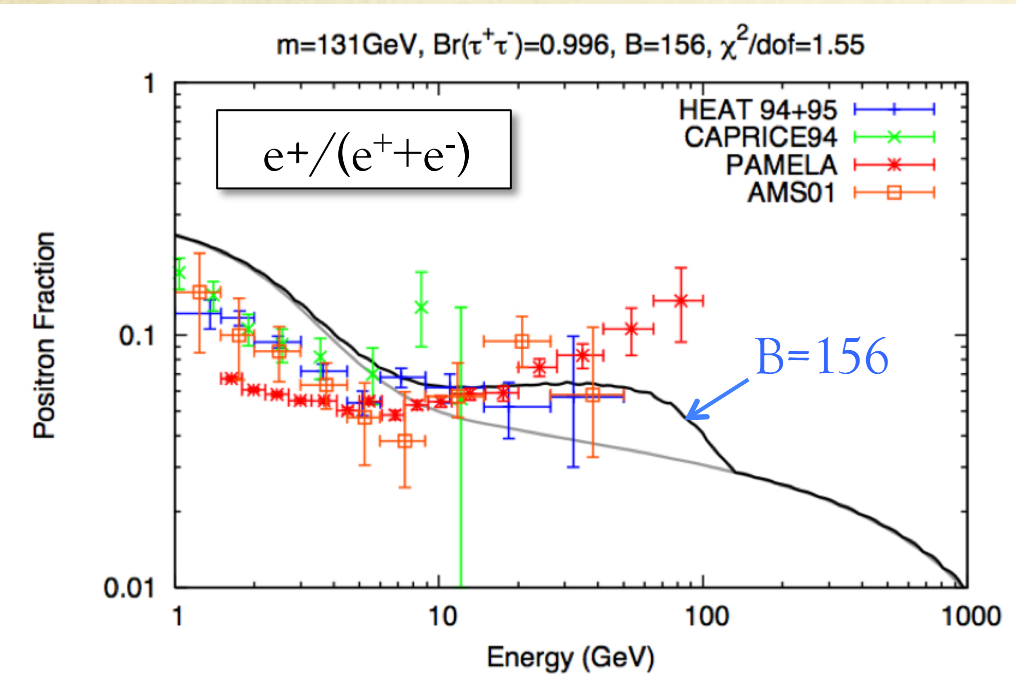


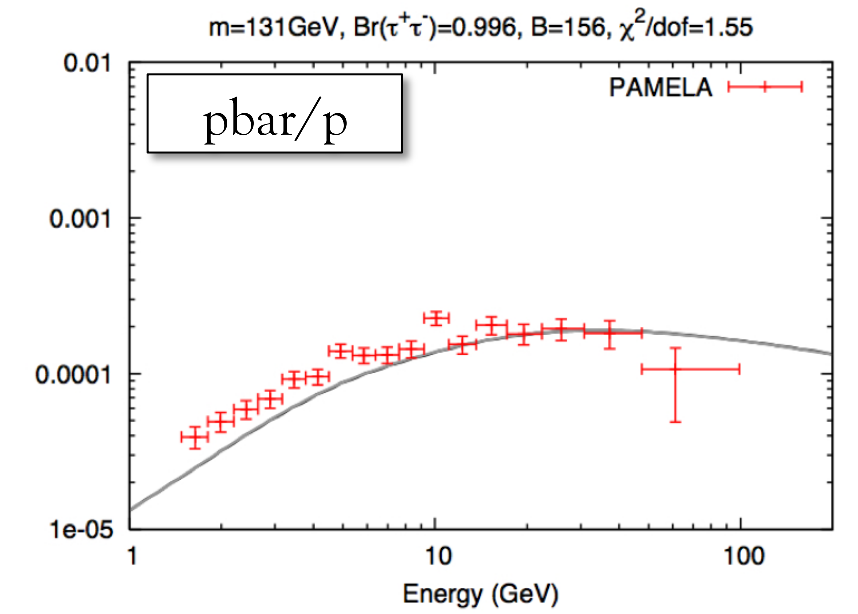
Astro AND SUSY, best fits…

Best Fit B<100:
Boost Factor = 72
χ^2/dof = 1.88 (36 dof)

Best Fit B<500:
Boost Factor = 163
χ^2/dof = 1.54 (36 dof)







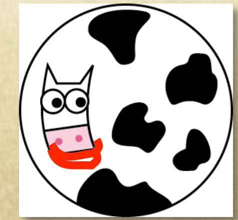
An Interesting Corner of MSSM Space?

- Tau-rich models are most likely candidates for leptophila in the MSSM.
- Spectra like stau-co-annihilation models but more general than mSUGRA
- $\Omega h^2|_{LSP} \sim \Omega h^2|_{WMAP}$ (for lowest Boosts) favors stau-LSP splitting ~15-20GeV
- Models relatively hard to exclude via FERMI dwarf observation.

Compelling Explanation of the Anomaly?

- No, Not Really.
- Boosts of ~ 100 are likely too large to be explained by halo uncertainties
- @ B~100, PAMELA positrons not fitted well. @ B ~1000 ruled out by LAT
- AMS-02 will be able to check PAMELA, LAT searches will continue to improve.
- So maybe... No, Not YET.

I'm Happy to discuss in more detail!!!



Backup Slides...

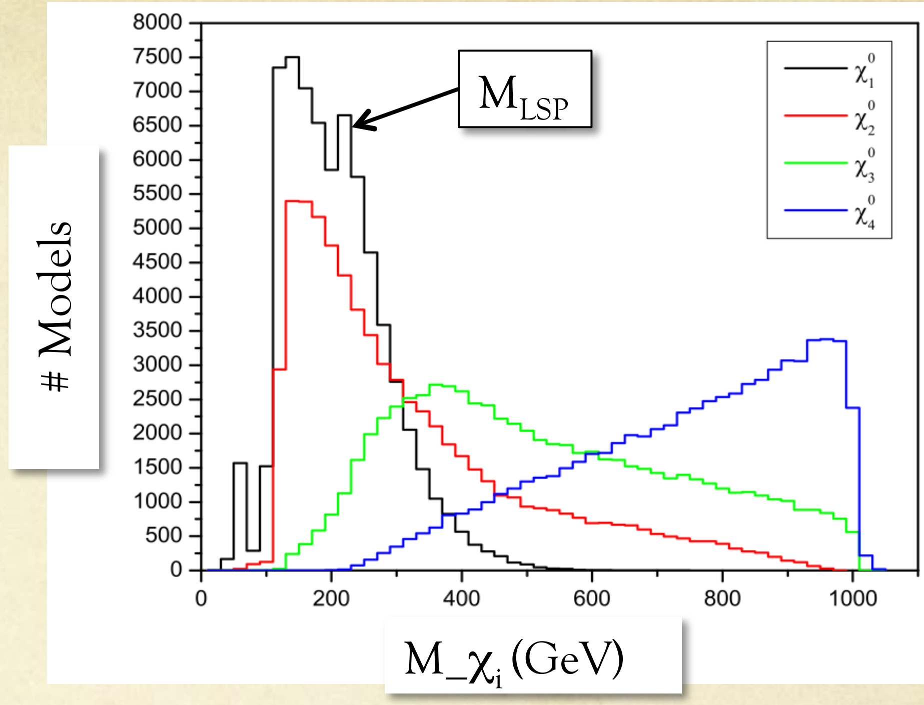
Model Characteristics

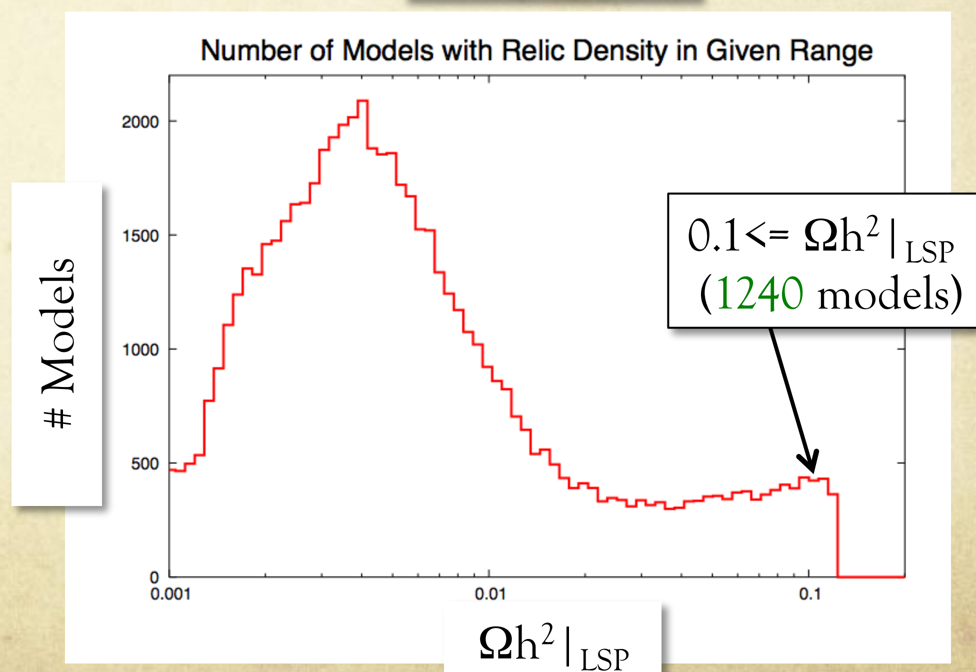
FLAT scan ranges

$$100\,\text{GeV} \leq m_{\tilde{f}} \leq 1\,\text{TeV}\,,$$
$$50\,\text{GeV} \leq |M_{1,2}, \mu| \leq 1\,\text{TeV}\,,$$
$$100\,\text{GeV} \leq M_3 \leq 1\,\text{TeV}\,,$$
$$|A_{b,t,\tau}| \leq 1\,\text{TeV}\,,$$
$$1 \leq \tan\beta \leq 50\,,$$
$$43.5\,\text{GeV} \leq m_A \leq 1\,\text{TeV}\,.$$

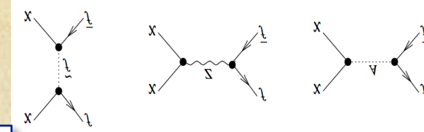
LSP Composition

LSP Type	Definition	Fraction of Models
Bino	$\|Z_{11}\|^2 > 0.95$	0.14
Mostly Bino	$0.8 < \|Z_{11}\|^2 \leq 0.95$	0.03
Wino	$\|Z_{12}\|^2 > 0.95$	0.14
Mostly Wino	$0.8 < \|Z_{12}\|^2 \leq 0.95$	0.09
Higgsino	$\|Z_{13}\|^2 + \|Z_{14}\|^2 > 0.95$	0.32
Mostly Higgsino	$0.8 < \|Z_{13}\|^2 + \|Z_{14}\|^2 \leq 0.95$	0.12
All other models		0.15

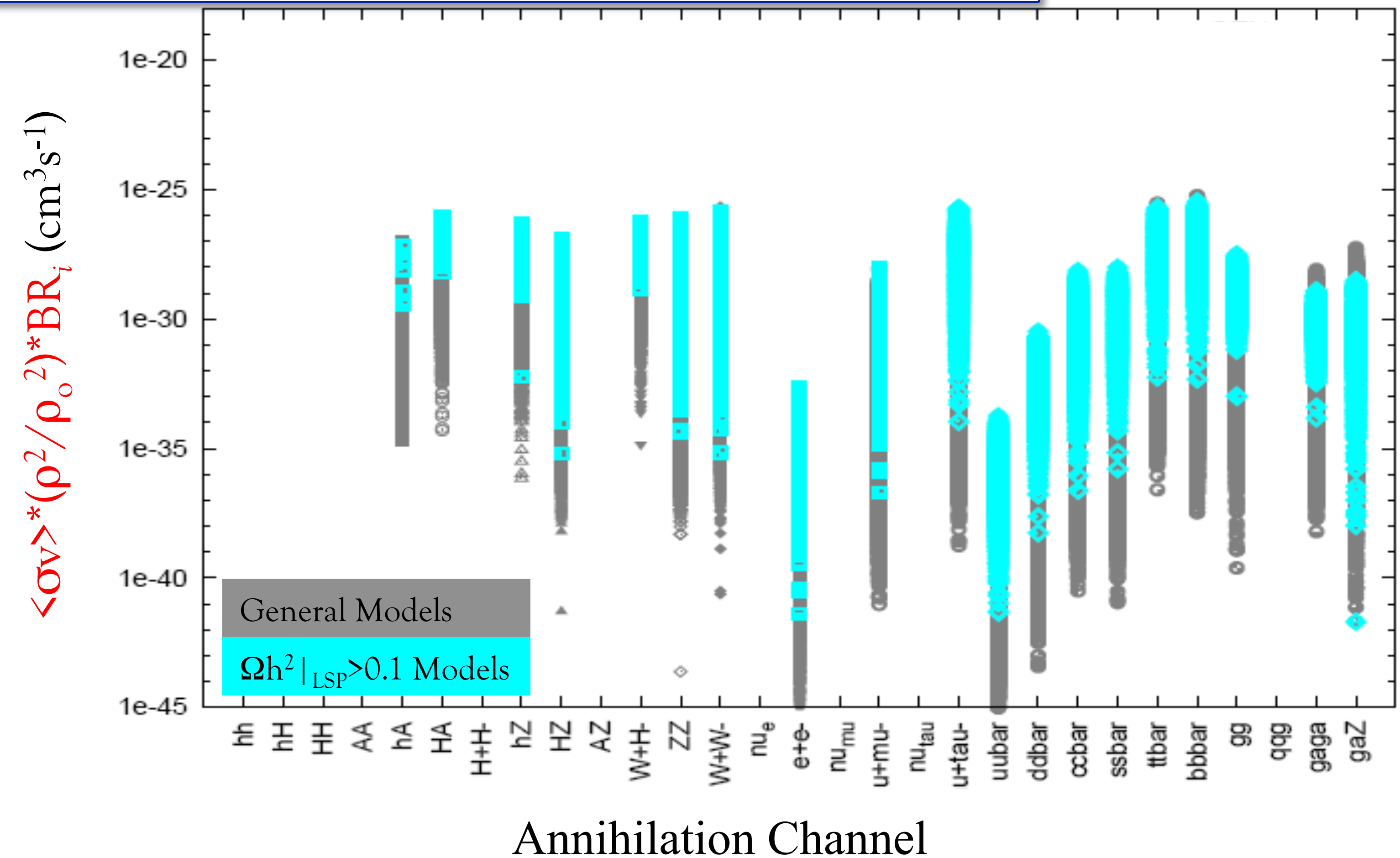


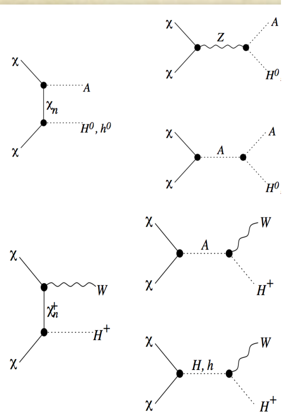


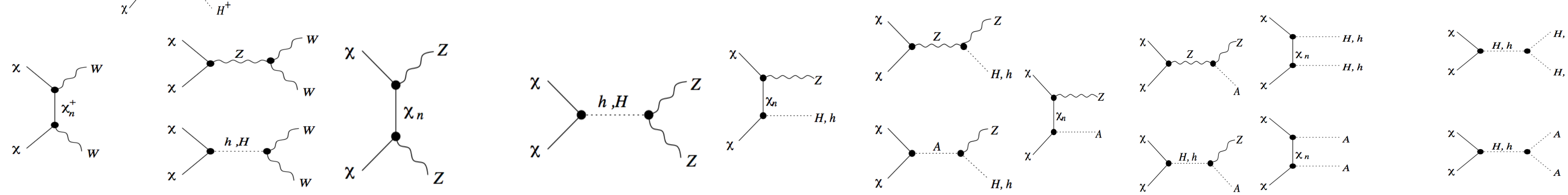
Channel-by-Channel...



~1.4M Annihilation cross sections from DarkSUSY







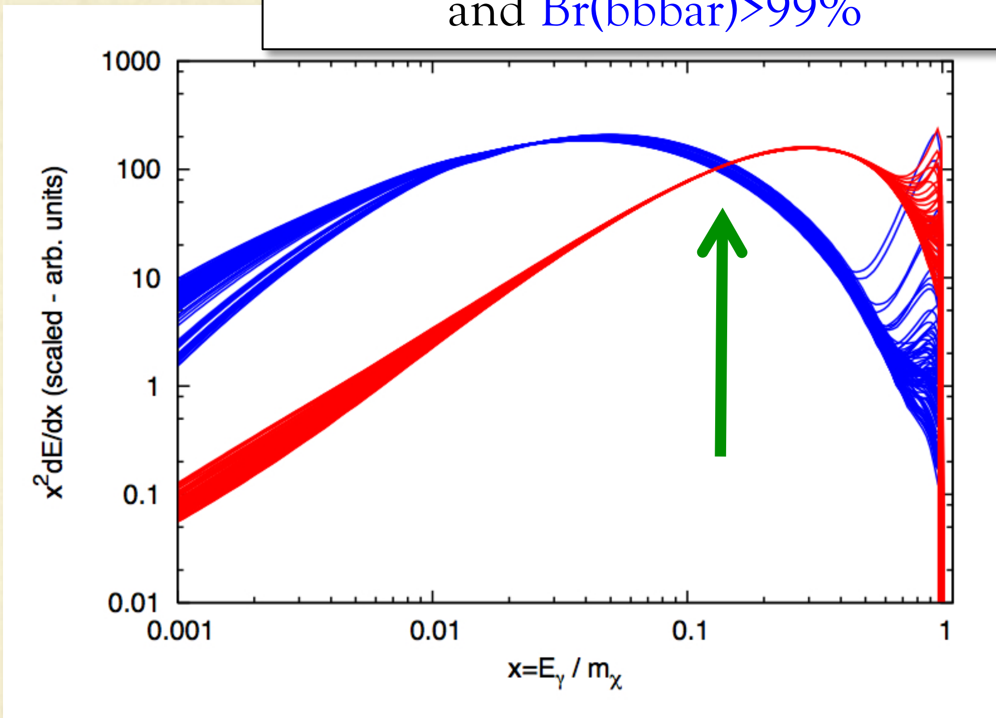
Q: Taus => Stiffer γ Spectra. Aren't they easier to see?
A: Depends what you are using to look ...

Take all pMSSM models that annihilate almost purely into τ or b-quark channels

Factor out trivial model dependence ($\langle\sigma v\rangle * (\rho^2/\rho_o^2)$, and m_χ)

Find a universal cross-over at $E_\gamma/m_\chi \sim 0.15$

All flat models with $Br(\tau^+\tau^-)>99\%$ and $Br(bbbar)>99\%$



Suppose $m_\chi \sim 100$ GeV => Cross-over @ ~ 15 GeV, then...

Cerenkov telescopes ($E_{th} \sim 100$ GeV) will see τ-like spectra more easily,
The FERMI-LAT ($E_{th} \sim 100$ MeV) will see b-like spectra more easily

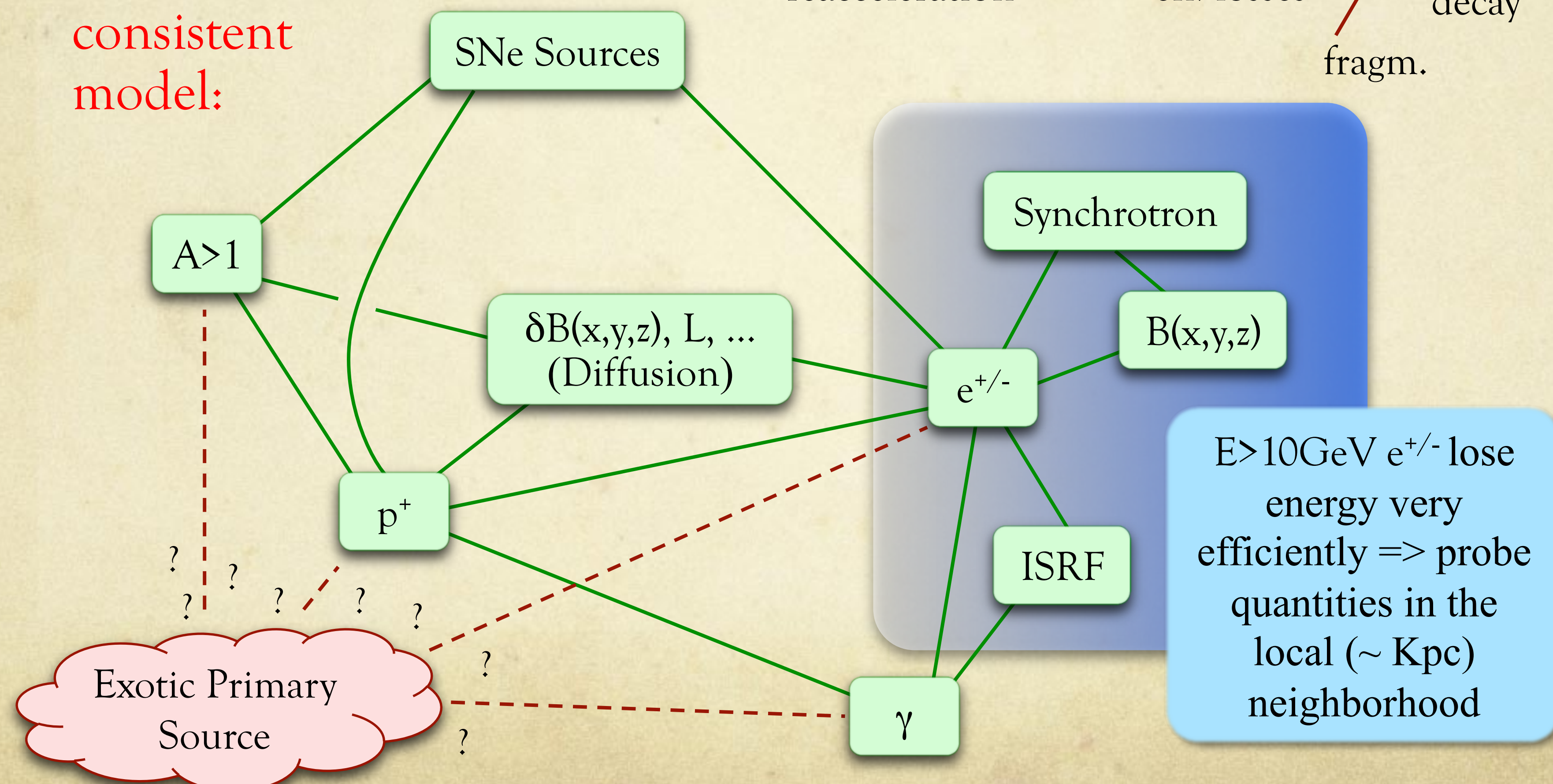
Cosmic Rays...

CR spectra can be modeled as solutions to the diffusion/loss equation:

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi,$$

diffusion, convection, reacceleration, en. losses, fragm., decay

A more consistent model:



Energy-Dependent Diffusion Constant...

Scattering of CRs off of mag. turbulence: resonant process (Max. for δB's with size ~ the CR's gyroradius).

D(E) ~ E^{δ} (i.e. δ=0.33 Kolmogorov, δ=0.5 Kraichnan)

diffusion

convection

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi,$$

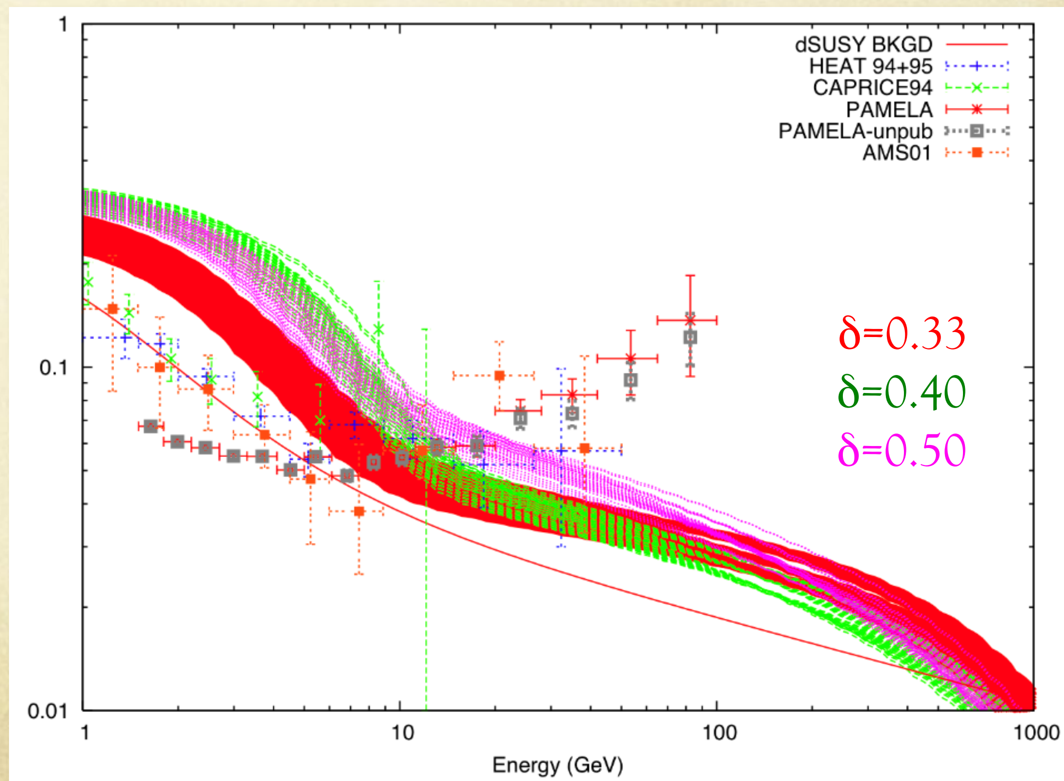
reacceleration energy losses fragm. decay

Fluxes of primary species: ~ $E^{-\delta}$ (protons, electrons, etc.)

Fluxes of secondary species: ~ $E^{-2\delta}$

So: B/C, e+/(e^++e^-) : ~ $E^{-\delta}$

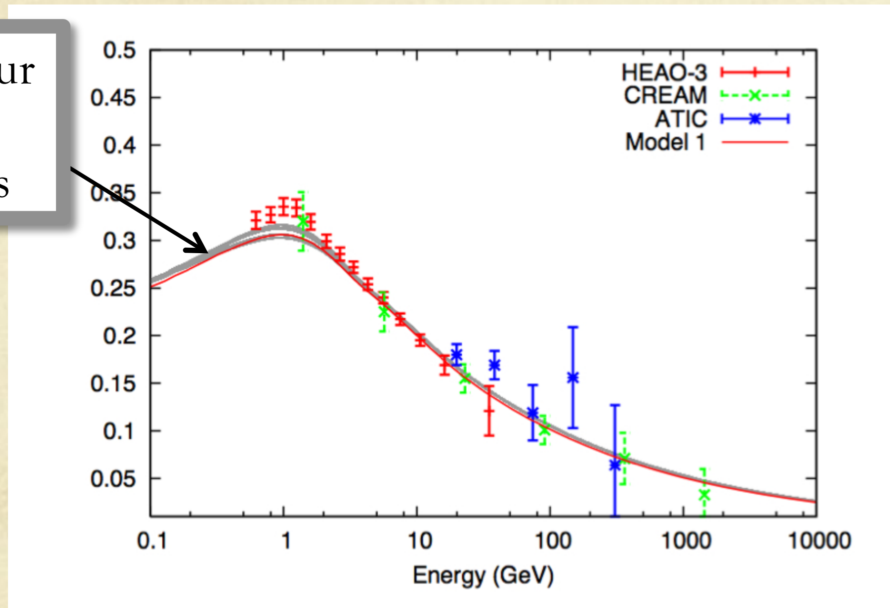
Thus, small δ is desirable for SUSY visibility in e+/(e^++e^-) with lower Boosts. We use δ=0.33.

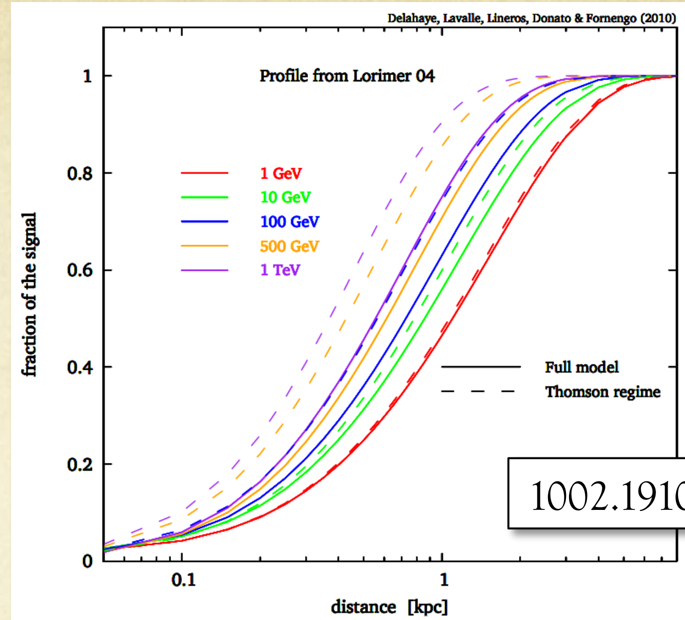


Is δ=0.33 OK ??

Many B/C measurements. Many authors working to constrain δ given this data. May be a consensus forming: δ >~ 0.5

B/C, Our Astro. Models





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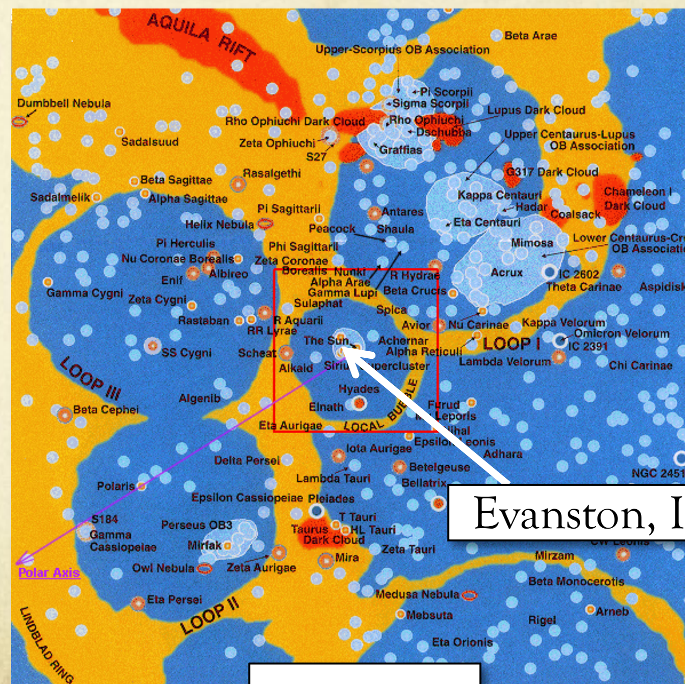


Evanston, Il.

~ 0.5Kpc

Still...

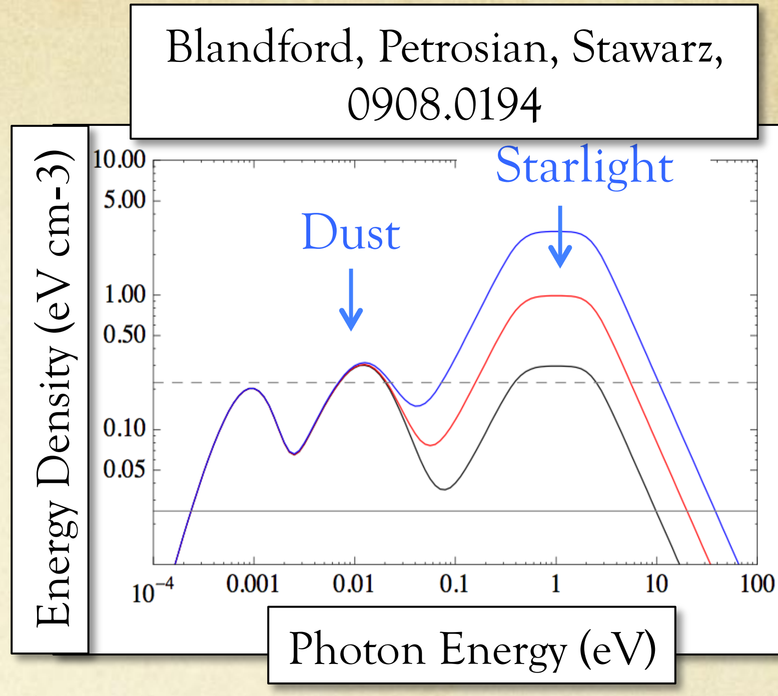
E>10GeV $e^{+/-}$ are cooled very efficiently by synchrotron, IC and brem. => $e^{+/-}$ come from the local ~ kpc. (NOT true of nuclei CRs)

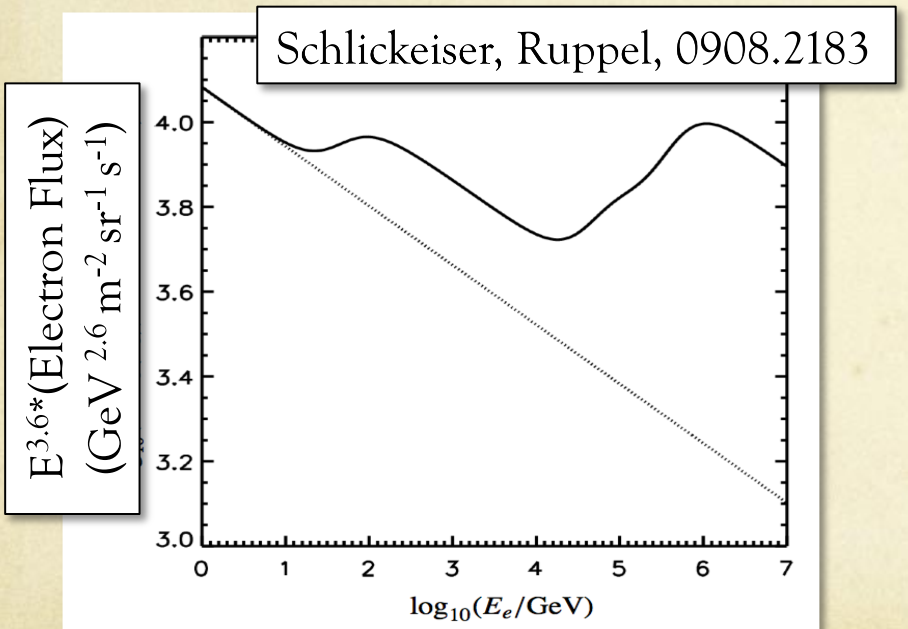
Very tricky to associate the "δ" describing B/C with the "δ" that should be used to propagate local CR $e^{+/-}$

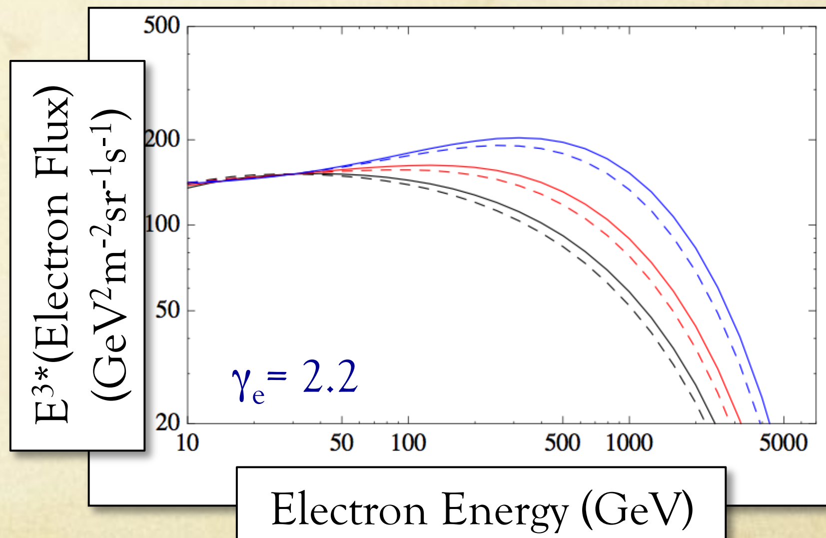
Electron Energy Losses...

$e^{+/-}$ lose energy dominantly via Inverse Compton and Synchrotron

IC losses are Thomson-like ($\dot{E} \sim E^2$) or Klein-Nishina-like ($\dot{E} \sim \log(E)$) depending on both the electron energy and the energy of the incident photon.







The Ratio of dust (FIR) and starlight (optical) photon densities in the local ISRF is just as important as their sum.

Astro-Parameters in Detail...

Diffusion Parameters...

δ		0.33	0.33	0.33	0.33	0.33
L	Kpc	2.0	3.0	4.0	7.0	10.0
D_{0xx}	$*10^{28}$ cm^2/s (@ $\mathcal{R} = 4$GV)	2.83	4.20	5.40	8.25	9.97
V_a	km/s	33.67	34.33	33.67	32.83	32.00
$\partial V_c/\partial z$	km/s/ Kpc	0.5	0.5	0.1	0.1	0.1

Table 1: Best fit parameter configurations in the diffusion sector.

Loss Parameters... (**bold**: default values)

γ_e	**2.42**,2.45,2.48,2.51,2.54,2.57,2.60
B_n (μG)	0.2,0.4,0.6,0.8,1.0,2.0,3.0,4.0,**5.0**
$\mathcal{F}_{op} + \mathcal{F}_{FIR}$	0.5,1.0,**2.0**
$\mathcal{F}_{op}/\mathcal{F}_{FIR}$	0.1,0.25,0.5,**1.0**,2.0,4.0,10.0