SATELLITE DATA AND DARK MATTER

-- 0906.4765 GK, Ran Lu, Watson + very recent data

[-- 0908.2430 Acharya, GK, Kumar, Watson -- Non-thermal Wimp Miracle]

[Earlier work with Grajek, Pierce, Phalen]

Show that conventional and well motivated wino LSP ($\sim$ 180 GeV), plus reasonable astrophysics, gives good description of PAMELA and Fermi data including antiprotons – no particle physics parameters, no “boost factors” – several recent and coming ***tests***

No virtuoso theory

Some other models – astrophysics, or new physics – may also describe data -- don’t discuss other models, just show wino LSP can work

- Introduction – wino LSP motivation – thermal and non-thermal cosmological histories – antiprotons?
- Data/tests/predictions
- Associated LHC phenomenology

WINO LSP VERY WELL MOTIVATED FOR DARK MATTER

$$W^+, W^0, W^- \rightarrow \tilde{W}^+, \tilde{W}^0, \tilde{W}^-$$

Wino LSP

- ***Models --*** mainstream ~ decade

-- anomaly mediated supersymmetry breaking (Randall, Sundrum…Moroi, Randall; Giudice,Luty,Murayama,Rattazzi; Gherghetta,Giudice,Wells) -- 1998

-- "split" supersymmetry (Arkani-Hamed, Dimopoulos, Giudice…)

-- Z' mediation (Wang, Langacker, Yavin, Paz, Verlinde …)

-- M theory compactified on G_2 manifold (Acharya, Kane, …)

-- MSSM scan – (Hewett, Rizzo …)

- ***Phenomenologically*** --*Wino* LSP DM annihilation provides the most positrons, most energetic positrons compared to other forms of LSP – normalized to local relic density (0.3 GeV/cm^3) gives reported PAMELA data with no "boost factors"

- ***Theoretically*** – non-thermal cosmological history generic in comprehensive theories, string theories – gives wimp miracle for relic density – wino LSP $\longleftrightarrow$ non-thermal history

❑ "non-thermal" cosmological history

-- comprehensive theories include many ways to generate entropy, other particles that decay to LSP –> non-thermal well motivated

-- generic in broader theories, string theories with moduli, very generic in UV completions of SM extensions

-- leads to "***non-thermal wimp miracle***"

$$n_{wimp} = H(\text{reheating temp} \approx \text{few MeV}) \Big/ \langle \sigma v \rangle_{wimp}$$

$$n_{wimp} = n_{wmap} \rightarrow \langle \sigma v \rangle_{wimp} \approx 3\times 10^{-24}\, cm^3\, \sec^{-1}$$

$$\rightarrow wimp \approx wino$$

-- concrete calculable example: M-theory on G_2 manifold has wino LSP – moduli decay generates entropy, winos – calculations before PAMELA

[Acharya, Bobkov, Kane, Kumar, Shao, Watson 0804.0863]

Little model dependence:

- Don't need to know number or details of moduli
- Moduli width is of order

$$\Gamma \sim M_{\varphi}^{3} / M_{pl}^{2}$$

and in generic supergravity theories no conflict with BBN etc if

$$M_{\varphi} \sim M_{3/2} \sim \text{ten(s) of TeV}$$

- BR of moduli to superpartners typically of order ¼
- Get many LSPs, solve Boltzman equations, number annihilates down to ***non-thermal wimp miracle***,

$$n_{LSP} \sim H\,(\text{reheating temp})/\langle \sigma \text{v} \rangle$$

- Reheating temperature comes out $\sim$ few MeV
- For $\langle\sigma v\rangle \sim 2\text{x}10^{-24}$ cm^3 sec^{-1} get WMAP relic density
- Wino annihilation cross section to W's via chargino exchange has no parameters but wino mass – for M_{wino} =180 GeV,

$$\langle\sigma v\rangle \sim 2\text{x}10^{-24} \text{ cm}^3 \text{ sec}^{-1}$$

OTHER ISSUES

- Use NFW profile of galaxy DM, normalize to local relic density (0.3 GeV/cm$^{3)}$

- Cosmic ray backgrounds poorly known. In region of interest for PAMELA positrons come from nearby, 1-2 kpc – antiprotons lose energy poorly so can come from further away , needed 1-150 GeV

- Run Galprop, vary 8 parameters and others, all relevant – ***not yet scan or fit*** since computing time for a given set of parameters few hours(!), few hundred simulations so far – treat signal and background in same way!!!

- Region below $\sim$ 10 GeV poorly described because of charge dependent solar modulation effects

Antiprotons?!

- Why do people think PAMELA did not see an antiproton excess?
- Experiments (BESS, HEAT,…) reported antiprotons $\sim$ decade ago
- People assumed was background, fitted analytic expressions, put in Galprop, Darksusy – used by papers after PAMELA data reported
- But get soft antiprotons from antiquarks – measured at LEP
- So original data contained both signal (if annihilation occurred) and background
- Must propagate background and signal same way, e. g. in galprop
- Galprop has degeneracies, flat directions in parameter space, so it allows antiproton backgrounds to vary a factor of a few
- It is ***incorrect*** to claim that PAMELA did not observe antiproton signal – have to explain how you know the background! – leptophilic NOT REQUIRED
- you can assume leptophilic if you want -- must then use consistent background to get observed amounts of antiprotons, e^+ etc

High energy astrophysics e^- , e^+ component – need assumptions:

Fermi sees energetic $e^+ + e^-$ up to a TeV – obviously an LSP of mass $\sim$ 180 GeV cannot generate those – but conventional astrophysics is expected to – PAMELA has shown electrons to over 200 GeV

Assume for higher energy component form suggested by old argument that ***interstellar medium electrons accelerated by supernova remnants and shock waves***, or pulsar spectra, (follow Zhang and Cheng) – ***this certainly happens, but numbers not clear***

$$\rho(r) = N(r / r_\odot)\exp(-1.8(r - r_\odot)/r_\odot)\exp(-z/0.2kpc)$$

$$dN_{e^\pm}/dE = N' E^{-1.5}\exp(-E/950GeV)$$

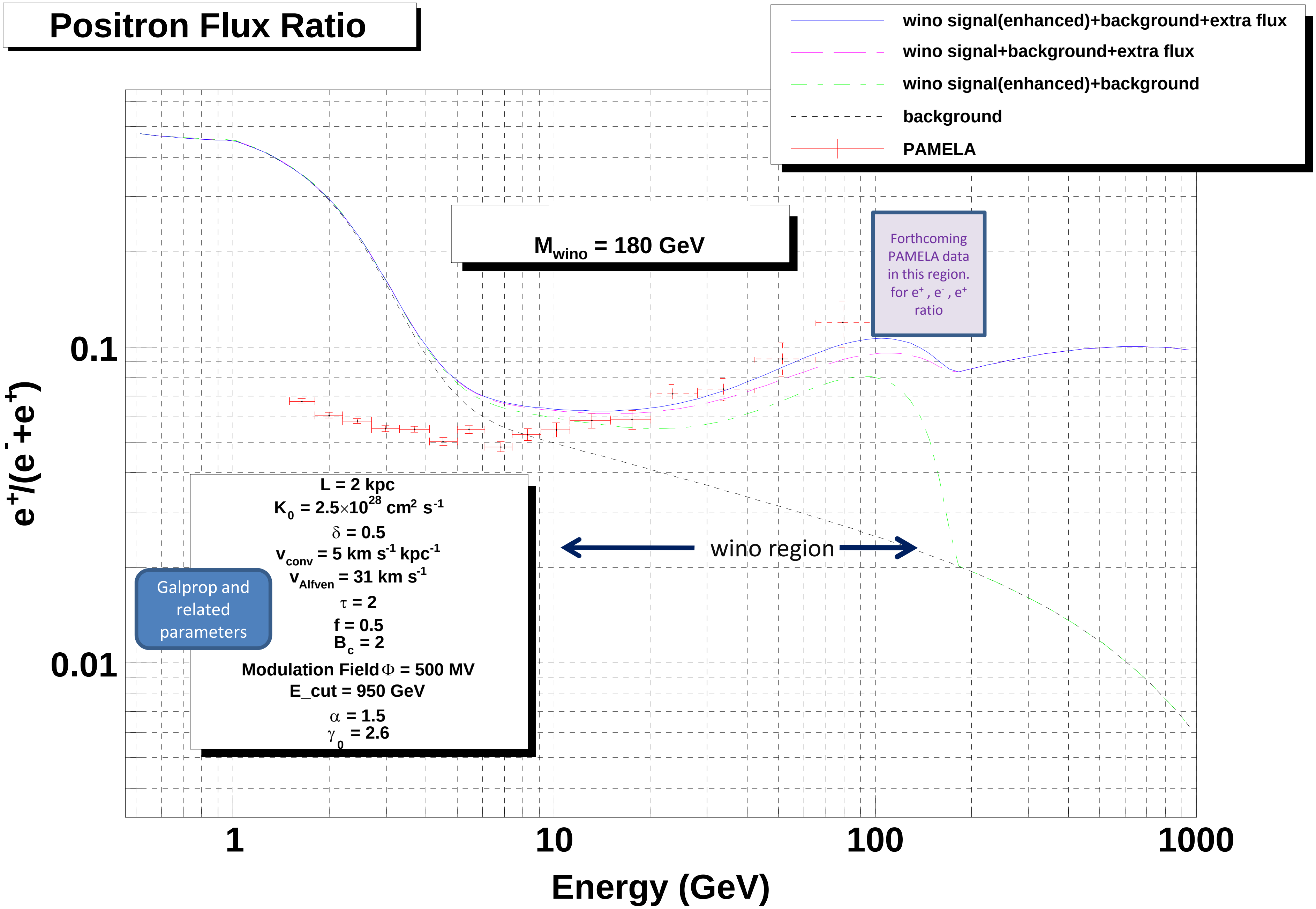
And assume e^+/e^- = 1/6

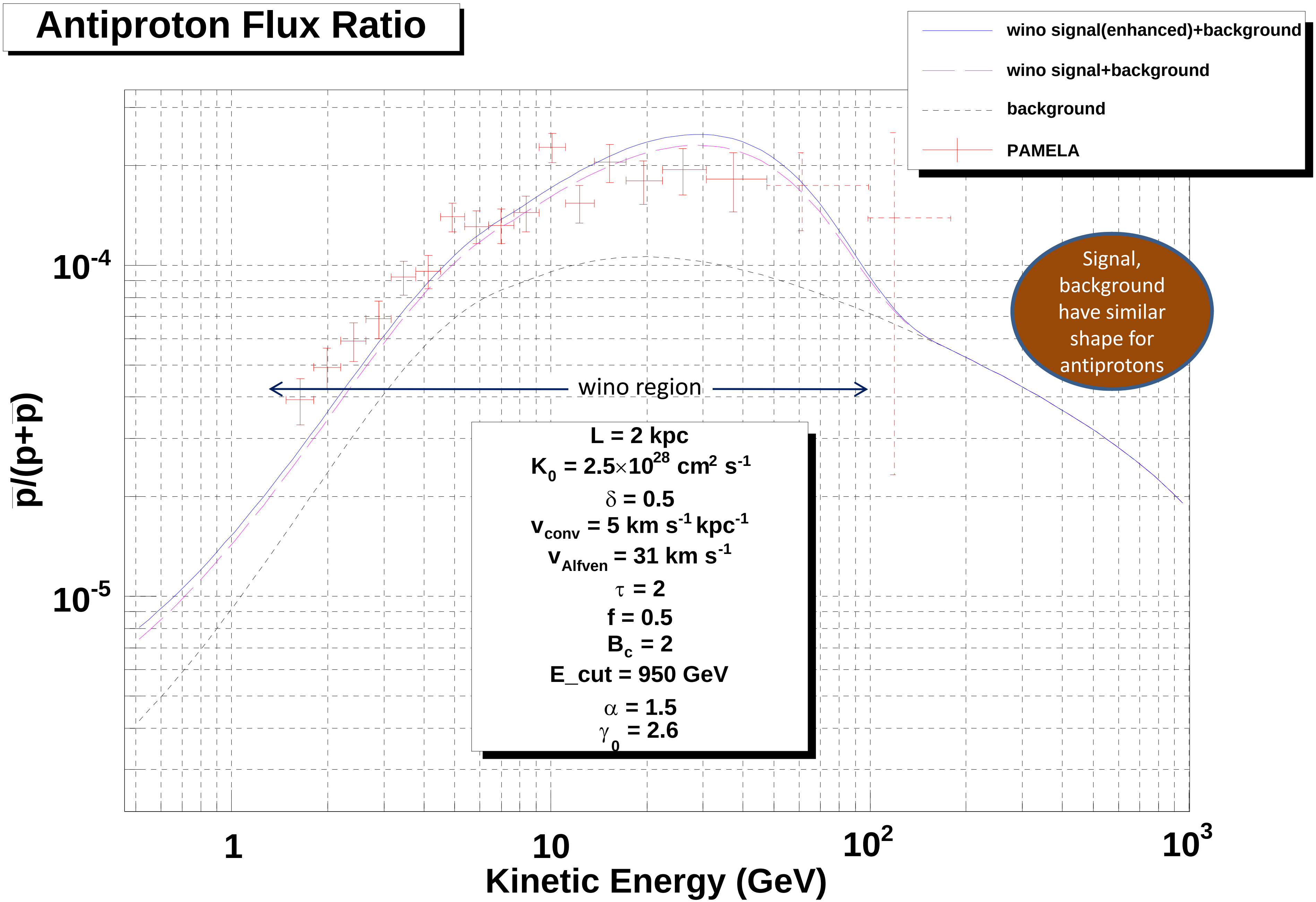
And normalize to Fermi data

Now show data and descriptions and predictions for one consistent set of propagation and injection parameters – M_{wino} =180 GeV

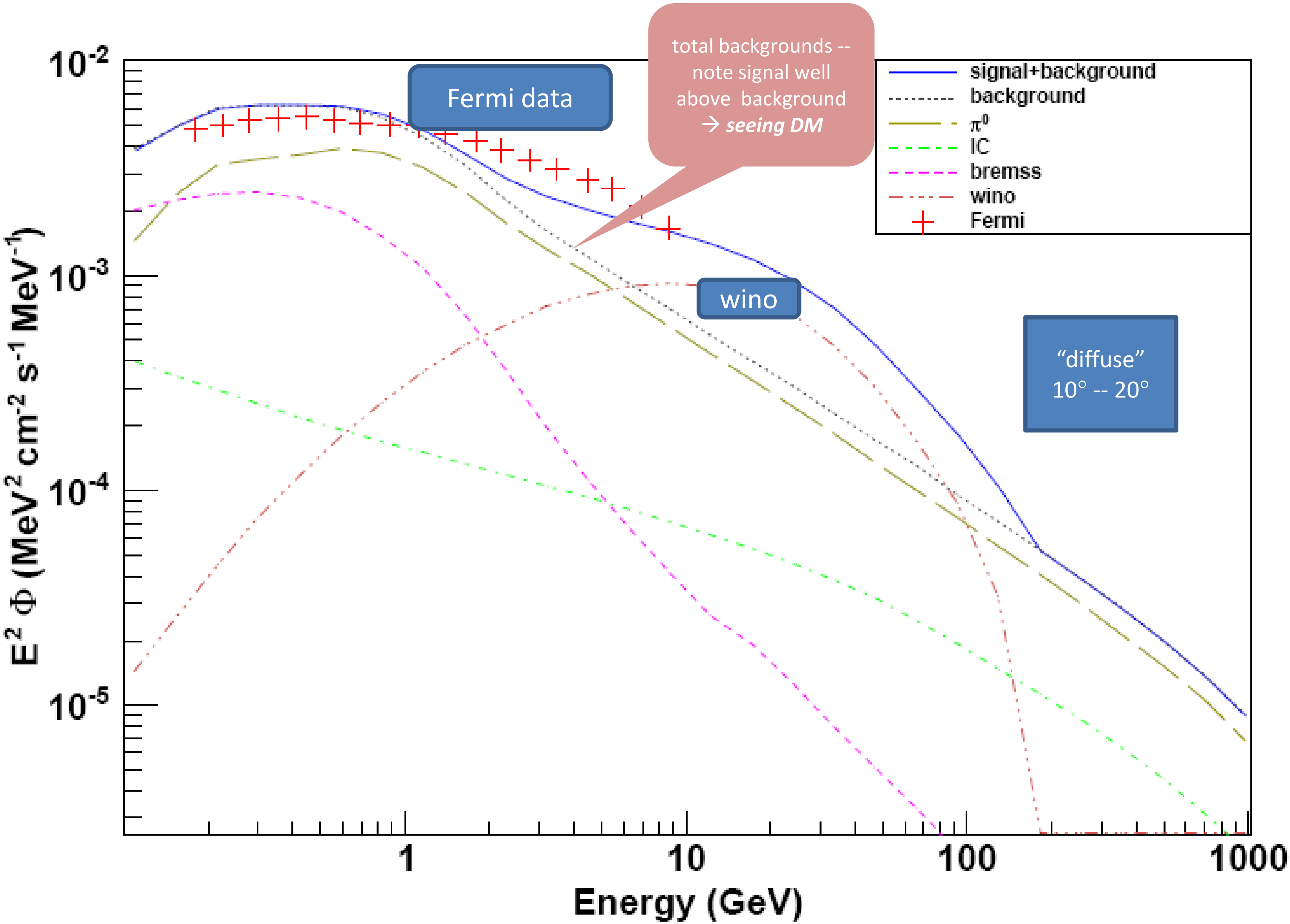
Not yet fit to data or scan of galprop parameter space, just educated guesses – agreement will be better.

Positron Flux Ratio



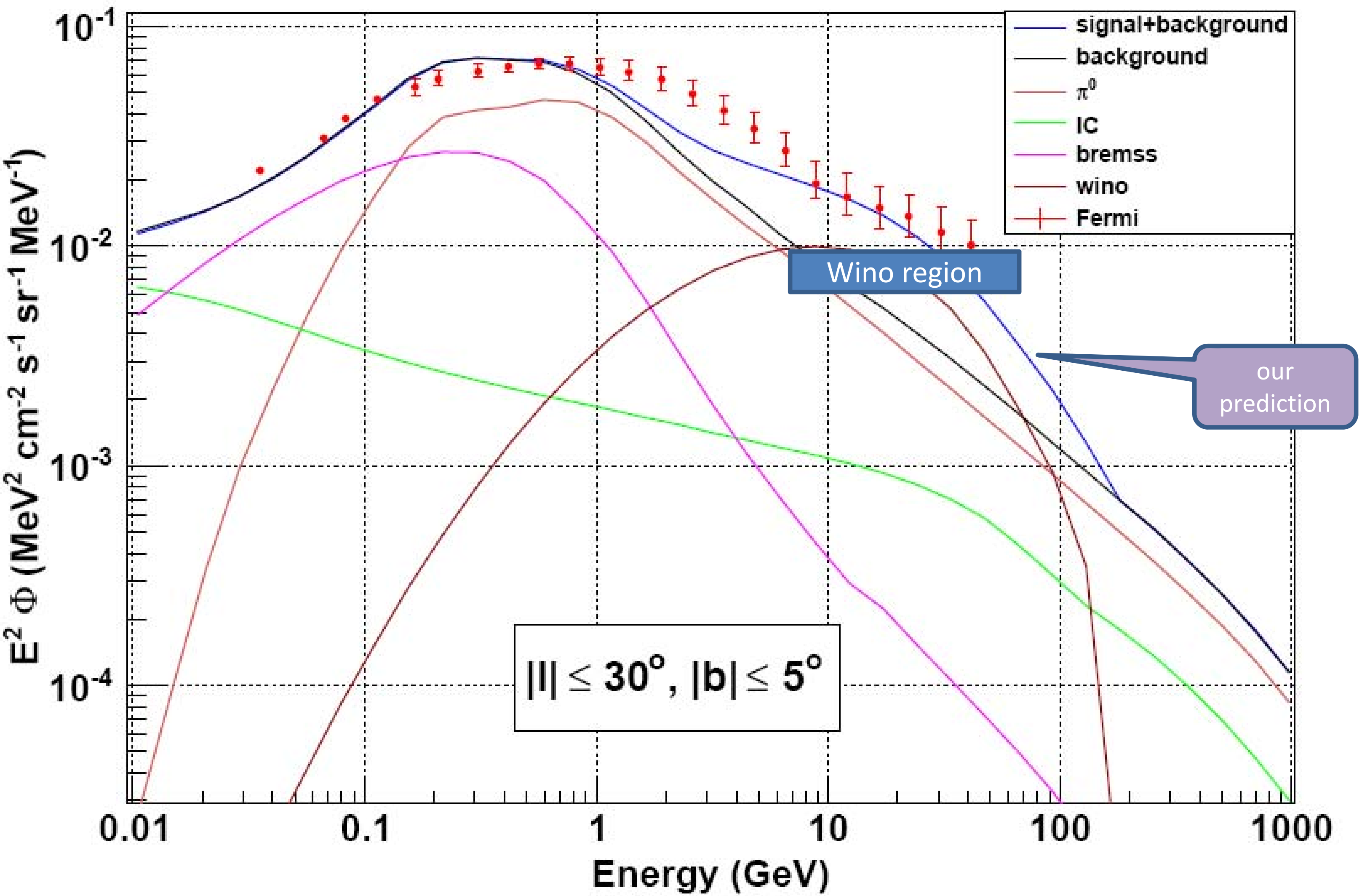


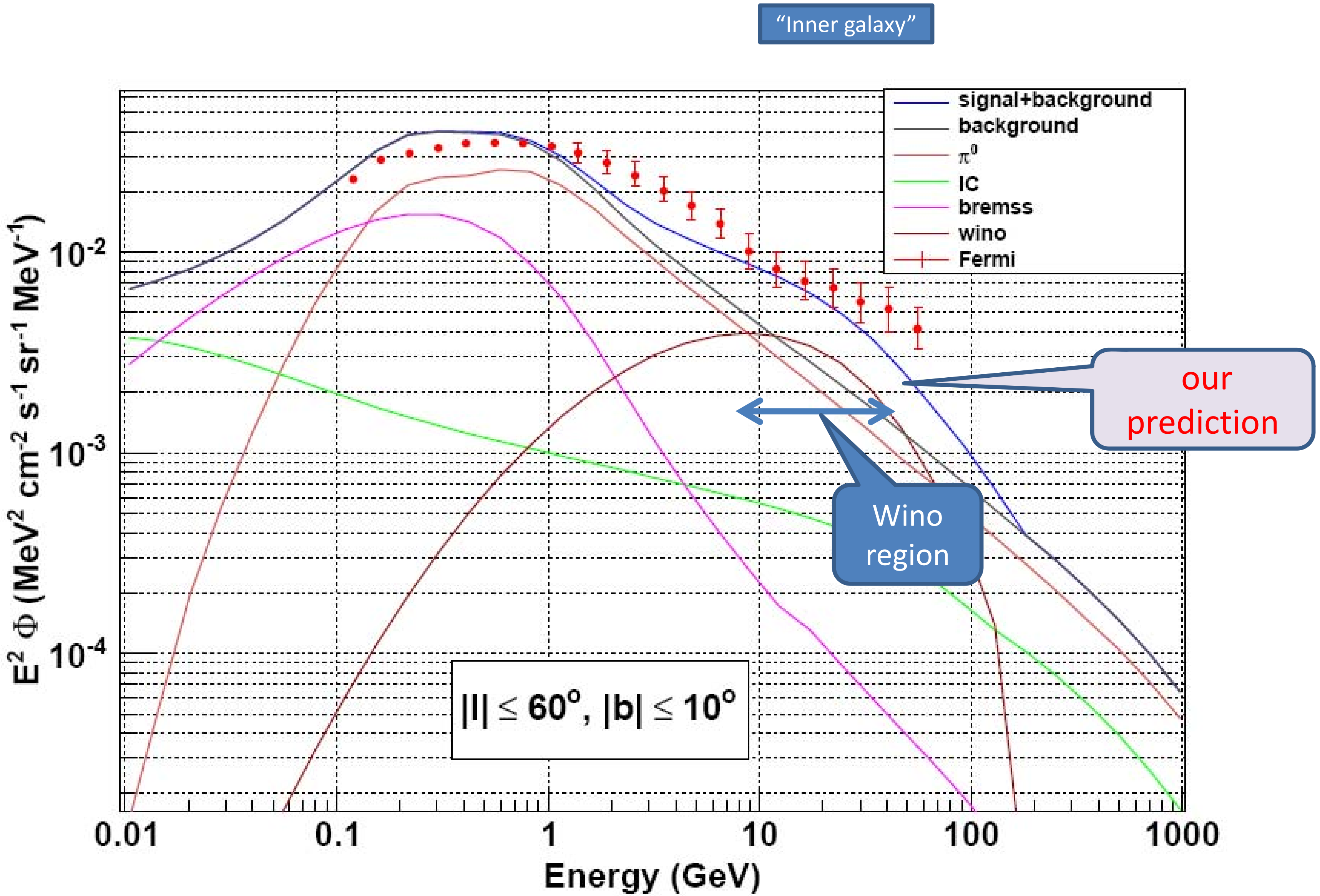
Antiproton Flux Ratio
wino signal(enhanced)+background
wino signal+background
background
PAMELA
Signal, background have similar shape for antiprotons
wino region
L = 2 kpc
$K_0 = 2.5\times10^{28}$ cm^2 s^{-1}
$\delta = 0.5$
v_{conv} = 5 km s^{-1} kpc^{-1}
v_{Alfven} = 31 km s^{-1}
$\tau = 2$
f = 0.5
$B_c = 2$
E_cut = 950 GeV
$\alpha = 1.5$
$\gamma_0 = 2.6$
10^{-4}
10^{-5}
$\bar{p}/(p+\bar{p})$
1
10
10^2
10^3
Kinetic Energy (GeV)

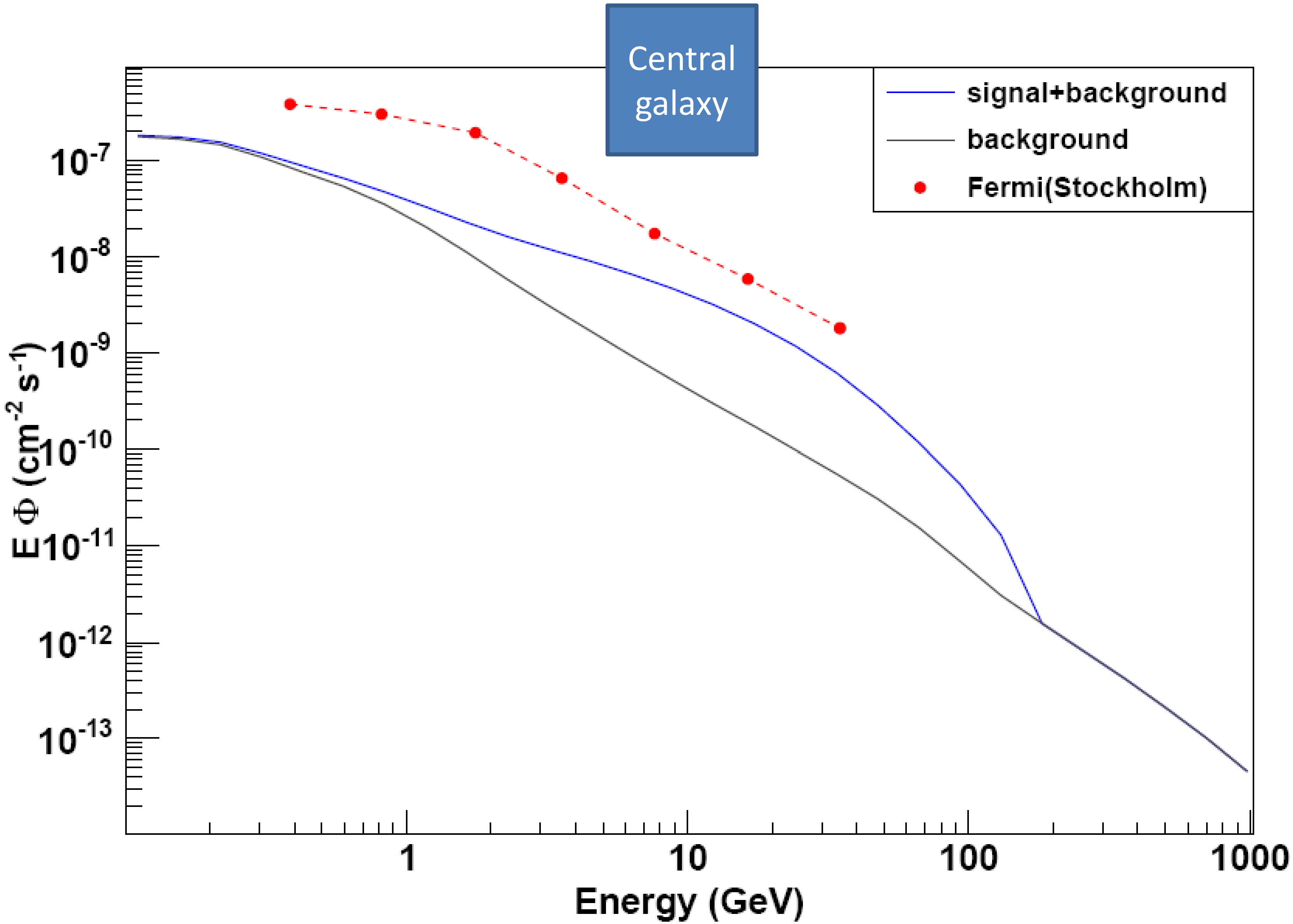


total backgrounds -- note signal well above background → seeing DM
Fermi data
wino
"diffuse" 10° -- 20°
signal+background
background
π^0
IC
bremss
wino
Fermi
$E^2\ \Phi\ (MeV^2\ cm^{-2}\ s^{-1}\ MeV^{-1})$
Energy (GeV)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
100
1000

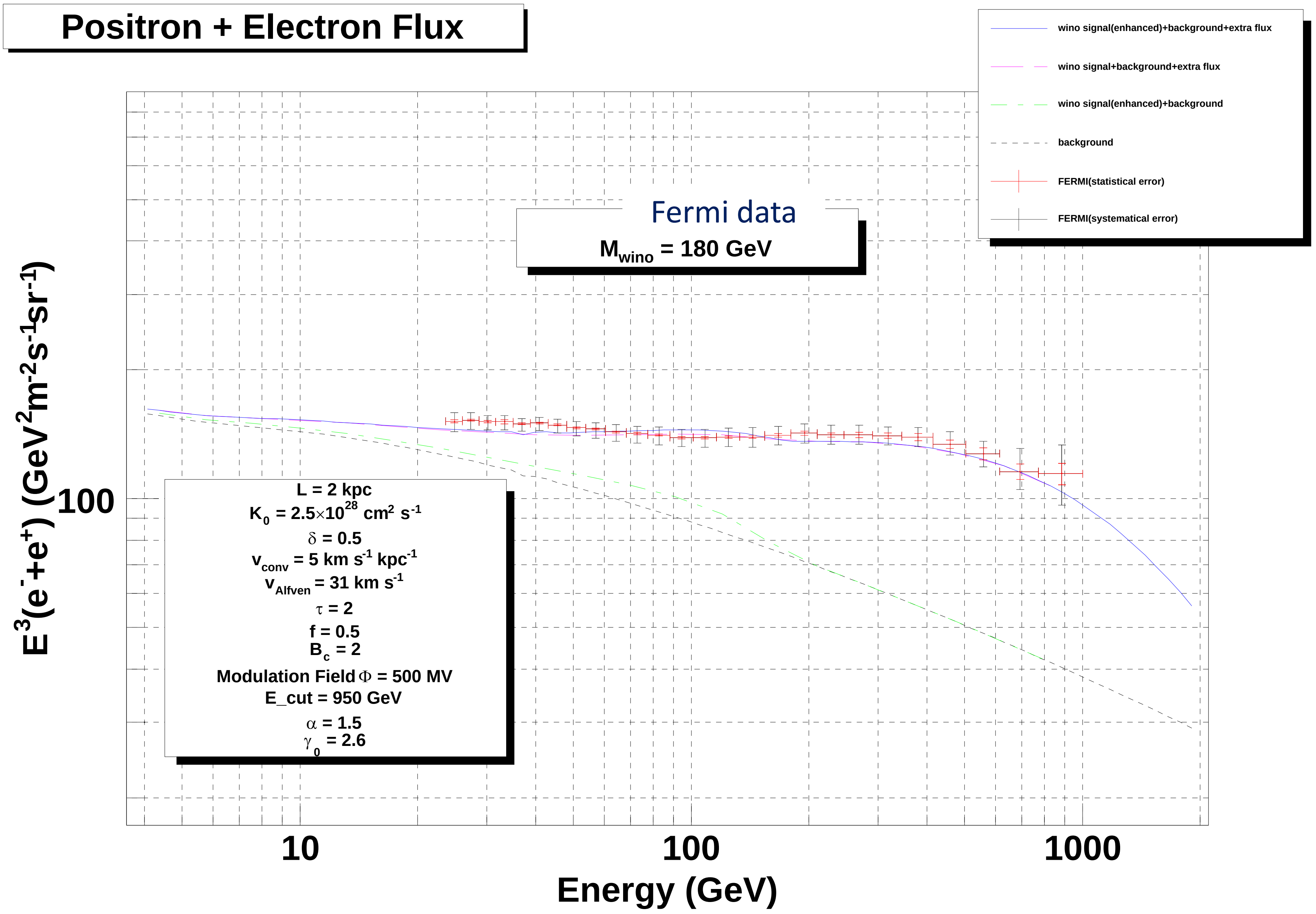
New Fermi data, normalized, high energy and point source gammas not removed– “Inner galaxy”



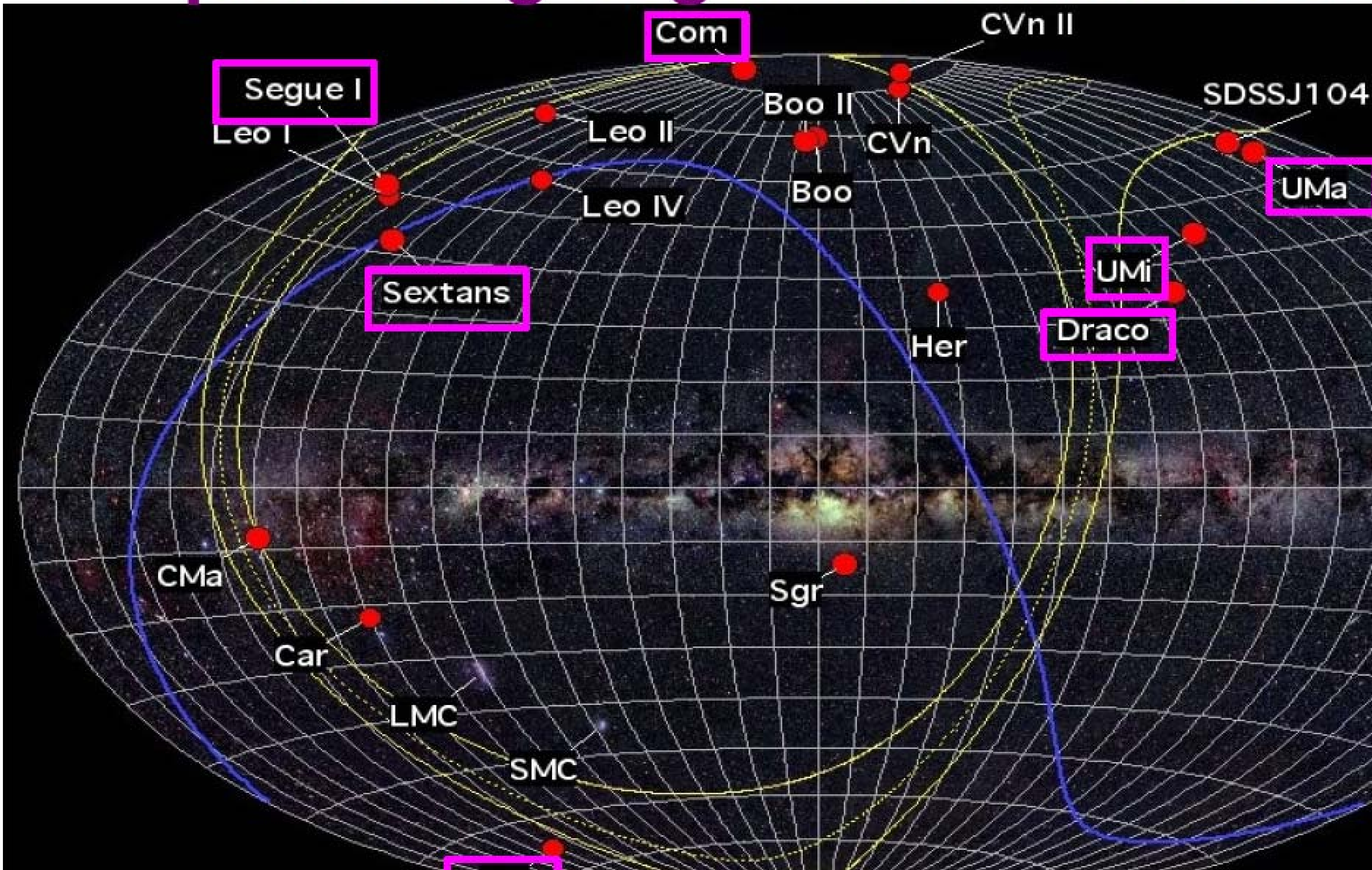

"Inner galaxy"
signal+background
background
π^0
IC
bremss
wino
Fermi
our prediction
Wino region
$|l| \leq 60^o, |b| \leq 10^o$
$E^2\ \Phi$ (MeV^2 cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Energy (GeV)
10^{-2}
10^{-3}
10^{-4}
0.01
0.1
1
10
100
1000



Central galaxy
signal+background
background
Fermi(Stockholm)
E Φ (cm-2 s-1)
10-7
10-8
10-9
10-10
10-11
10-12
10-13
1
10
100
1000
Energy (GeV)


Positron + Electron Flux
wino signal(enhanced)+background+extra flux
wino signal+background+extra flux
wino signal(enhanced)+background
background
FERMI(statistical error)
FERMI(systematical error)
Fermi data
M_{wino} = 180 GeV
L = 2 kpc
$K_0 = 2.5\times10^{28}$ cm^2 s^{-1}
δ = 0.5
v_{conv} = 5 km s^{-1} kpc^{-1}
v_{Alfven} = 31 km s^{-1}
τ = 2
f = 0.5
B_c = 2
Modulation Field Φ = 500 MV
E_cut = 950 GeV
α = 1.5
γ_0 = 2.6
$E^3(e^-+e^+)$ (GeV^{2}m^{-2}s^{-1}sr^{-1})
100
10
100
1000
Energy (GeV)

Dwarf spheroidal galaxies (dSph) promising targets for DM detectio



Flux from 180 GeV wino annihilation in a dark matter dwarf galaxy
(based on luminosity from Essig, Sehgal, Strigari 0709.1510)

$$\frac{dN_\gamma}{dA\,dt} = \frac{1}{8\pi}\mathcal{L}_{\rm ann}\frac{\langle\sigma v\rangle}{M_{\widetilde{W}}^2}\int_{E_{\rm th}}^{E_{\rm max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma$$

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

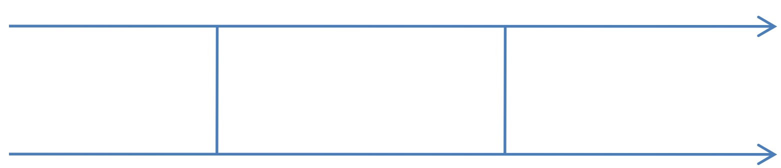
$$\langle\sigma v\rangle = 2.50\times10^{-24}\,{\rm cm^3 s^{-1}}$$

$$\int_{E_{\rm th}}^{E_{\rm max}}\frac{dN_\gamma}{dE_\gamma}dE_\gamma = 27.14$$

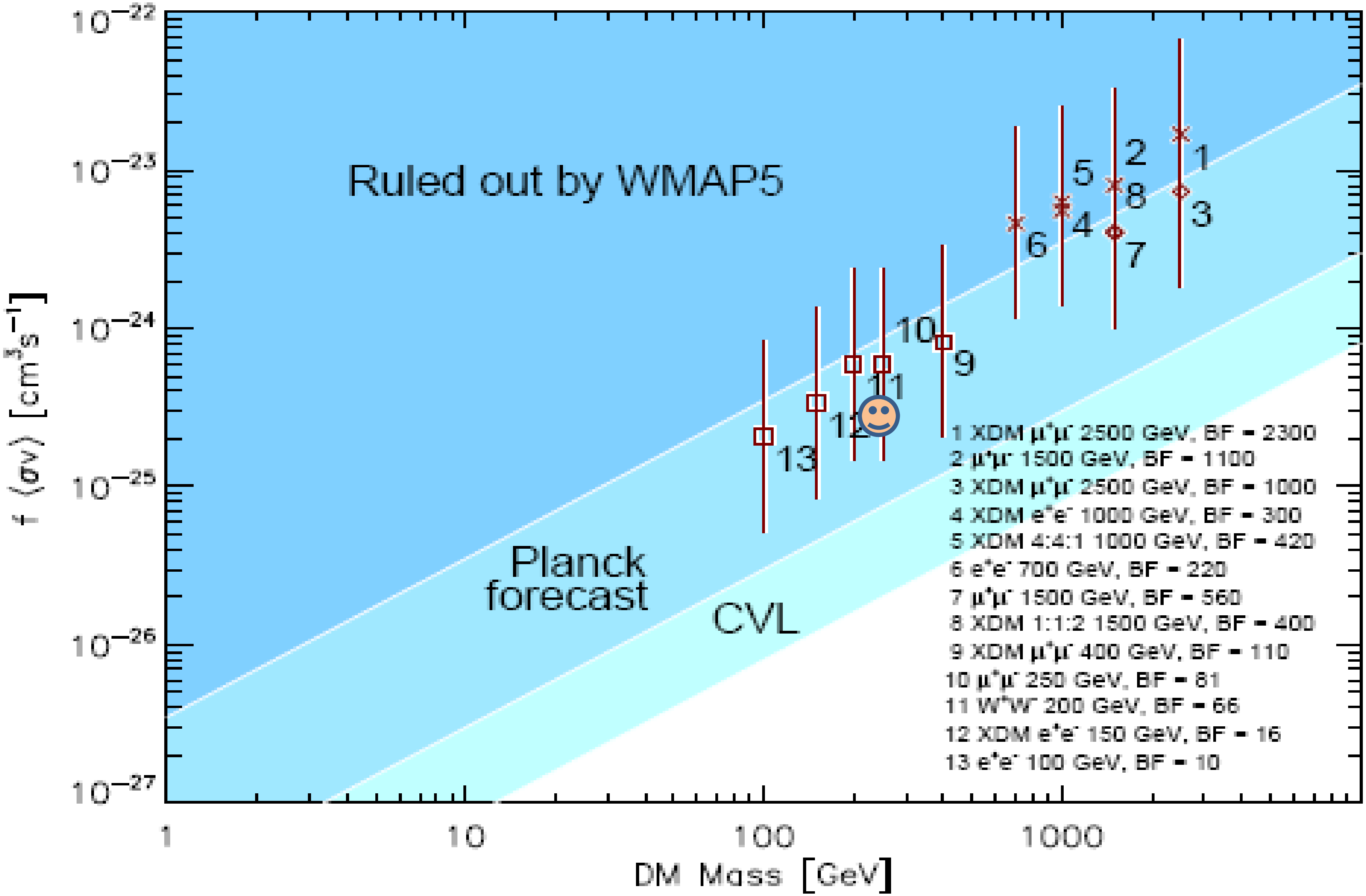
Dwarf Galaxy	Flux (E>100 MeV, 10^{-9} cm^{-2} sec^{-1})
Segue 1	0.5 – 350
Willman 1	0.3 – 30
Ursa Minor	0.03 – 9.6
Draco	0.09 – 1.5

Large flux uncertainty because of current large uncertainty in $\int\rho^2$

- gammas from dwarf galaxies – no backgrounds!
- distinguish DM annihilation from decay (rate, shape, lines)
- for wino annihilation, two monoenergetic lines from box diagrams!



Slatyer, Padmanabhan, Finkbeiner 0906.1197 recombination constraints



LHC phenomenology of light wino LSP well known

Early $\sim$ 1999, 2000

- Moroi-Randall
- Feng Moroi Randall Strassler
- Ghergetta, Giudice, Wells

Recent

- Moroi, Yanagida et al ph/0610277
- Acharya et al 0801.0478

Main early triggers are gluino production with decay chain giving LSP → H_T trigger, and monojet/missing energy+jets, then offline analysis for both

These are model dependent, e.g. gluino mass ranges from $\sim$ 2x wino mass (Ross, small fine tuning) to 9 from pure anomaly mediation – in G_2–MSSM about 4-5

Here – assume PAMELA → wino LSP is indeed DM

-- assume M-theory compactified on G_2 manifold is underlying theory since it gives such an LSP

[Acharya, Bobkov, Kane, Kumar, Shao 0801.0478]

-- pick particular spectrum from allowed ranges for the G_2 case

-- full analysis underway

Spectrum and notation – a G_2 benchmark model:

Gluino G, mass 900 GeV [note this mass could be smaller – very sensitive to it at 7 TeV]

Chargino C1, mass 173 GeV

LSP N1, mass 173 GeV

2nd neutralino N2, mass 253 GeV

[Stop ~ 8700 GeV, mainly RH, Higgs boson= 120 GeV, gravitino ~ 35 TeV)]

C1 and N1 mostly wino, N2 ~ bino

Production cross sections (at **7 TeV total energy**):

Dominant: gluino pair has $\sigma \sim$ 1/20 pb

Also C1 + C1 has $\sigma \sim$ 1/20 pb but hard to see

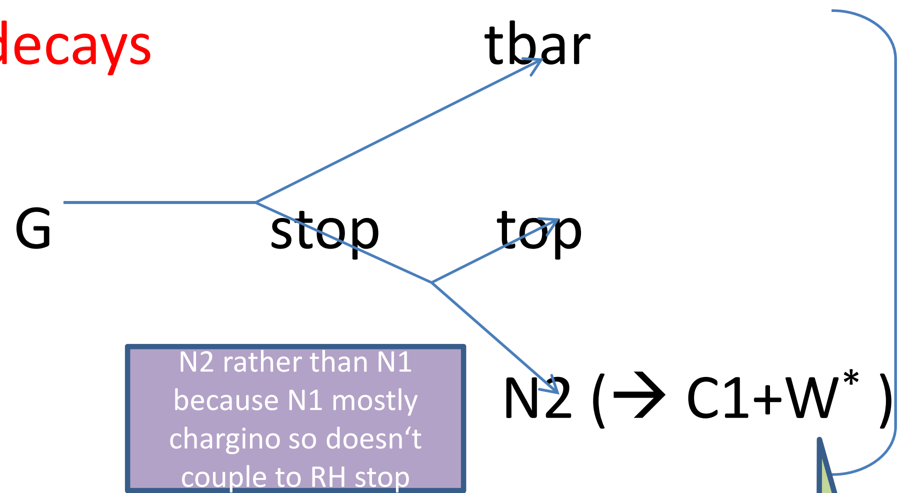
And C1 + N1 channel has large cross section but nearly unobservable

But C1 + N1 + jet has $\sigma \sim$ 1/60 pb, monojet or missing energy trigger

[C1 + N2 and N1 + N2 small since C1 – W – bino coupling small – but if N2 has significant wino mixture then C1 + N2 large and N2 has W* in its decay

C1 + G, N1 + G, N2 + G all small since need squark exchange]

Gluino decays



2 b’s, 3 W’s for each gluino!

→ very good H_T trigger, then look offline for leptons, b’s

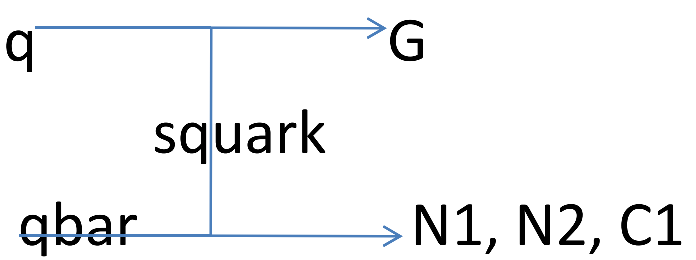
MODE	BR
G→t tbar N2	**~ ½**
→t bbar C1	~ 1/5
→b bbar N1	~ 1/5
→q qbar N1	~1/10
→g N1 (or N2)	~ 1%

$M_{N2} – M_{C1}$ = 80 GeV for this model so essentially real W

Gluino lifetime ~ 10^{-19} sec

General features of signatures:

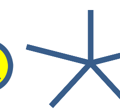
- lots of leptons but always with jets – no "trileptons"
- ALL prompt leptons are from W decay! → no flavor correlations for leptons
- Leptons from gluino production so no charge asymmetries (compared to squarks…)
- Assuming the model is right, distributions can measure three mass differences, G-N2, G-N1, G → can solve for three masses
- N2 –> C1 + W^* but not C1 + Z^*
- Should not see squarks, or virtual squarks such as

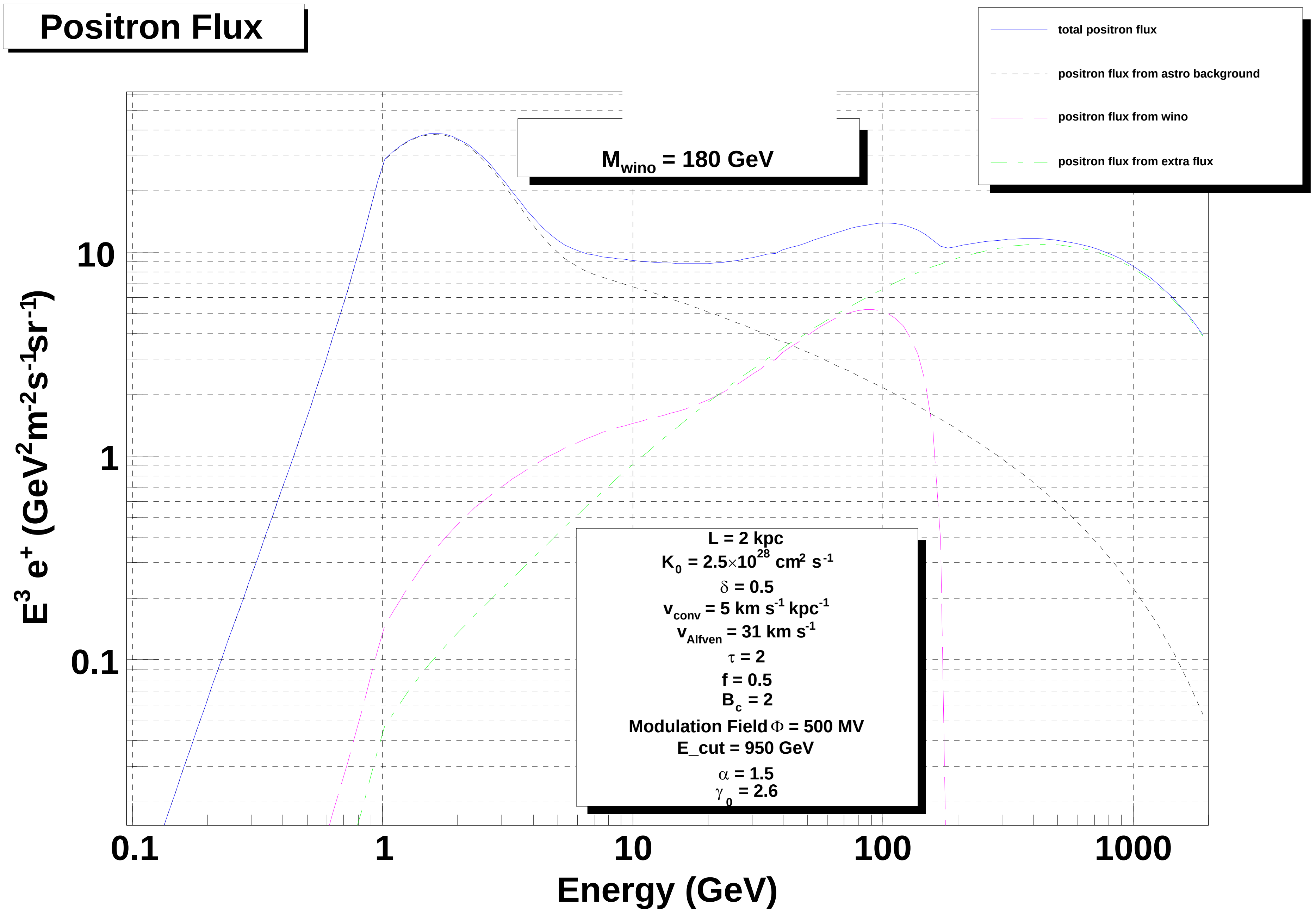


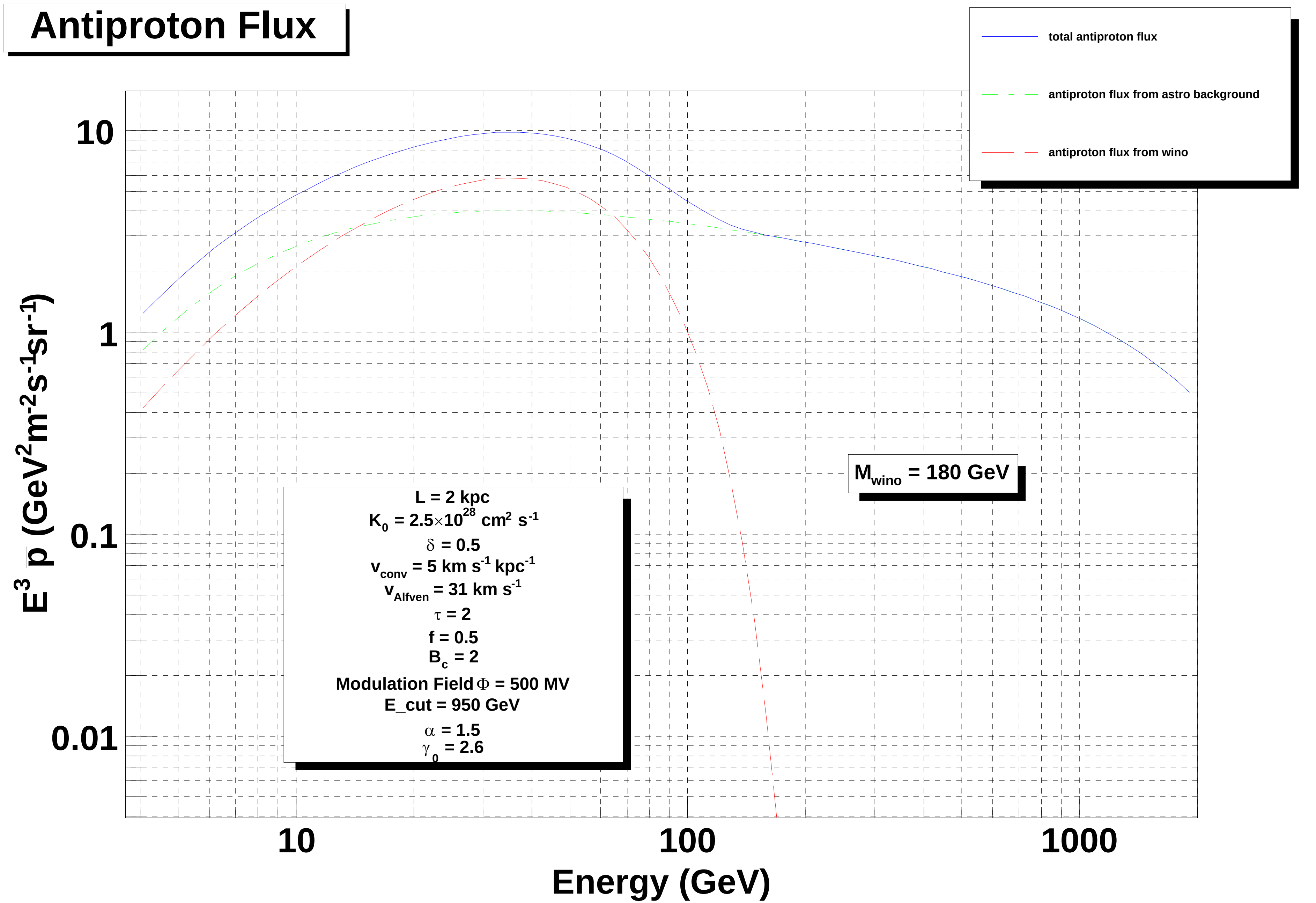
Wino LSP dark matter observed THREE ways already!

- PAMELA positron excess
- PAMELA antiprotons
- Fermi diffuse gammas and inner galaxy

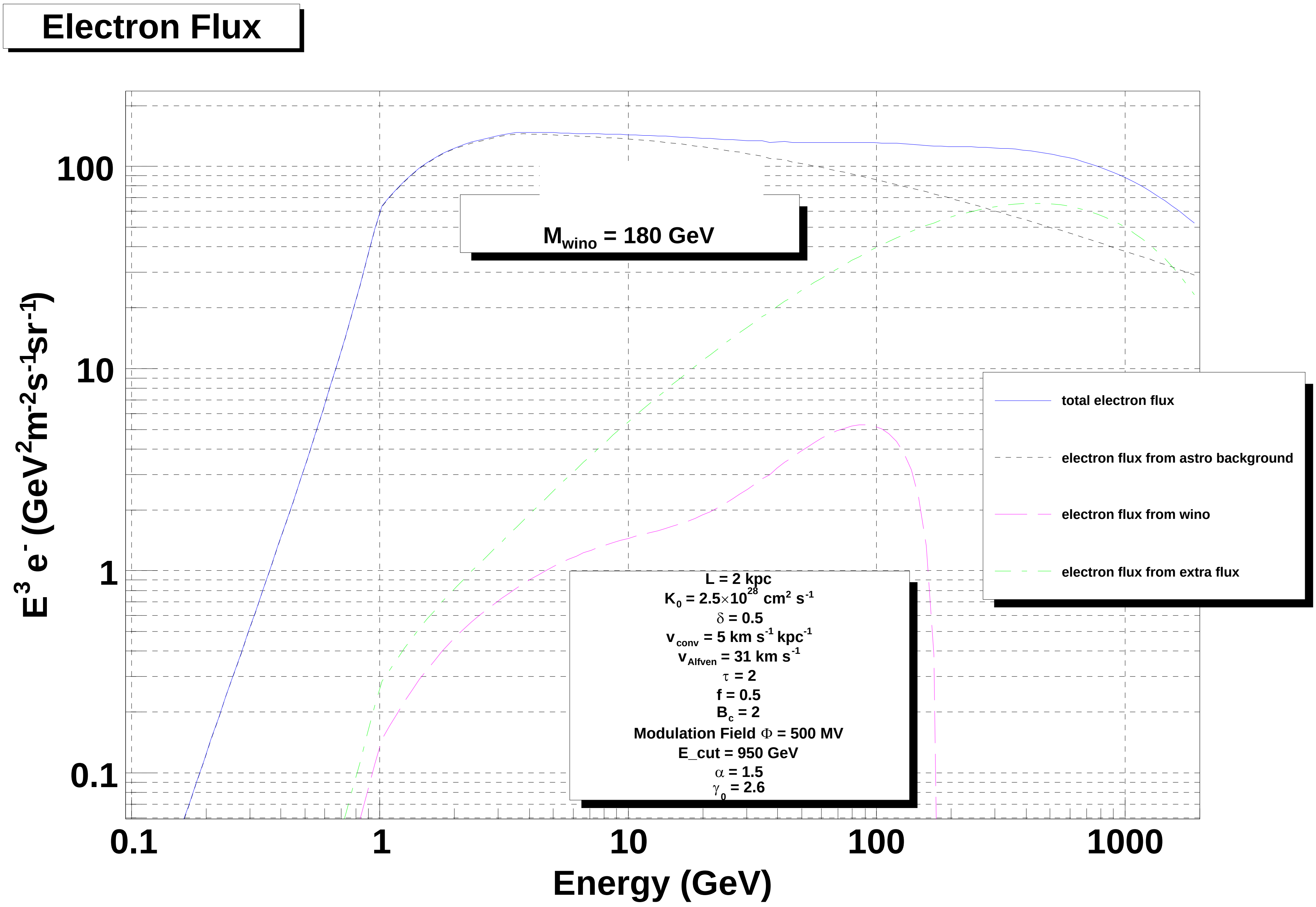
Tests already or soon: LHC + AMS2 +

- ☺ Rise in positron excess not due to decrease in electrons
- o Turnover of PAMELA positron excess at higher energies (☺ )
- ☺ Turnover of PAMELA antiproton excess at higher energies
- ☺ Diffuse Fermi spectrum at 10 GeV
- ☺ Inner galaxy and galactic center Fermi spectrum
- o ***Annihilation signal from dwarf galaxies – continuum and two discrete gamma lines (wino+wino → $\gamma\,\gamma$, γ Z)***
- o WMAP haze, recombination constraints OK, maybe observable (PLANCK)

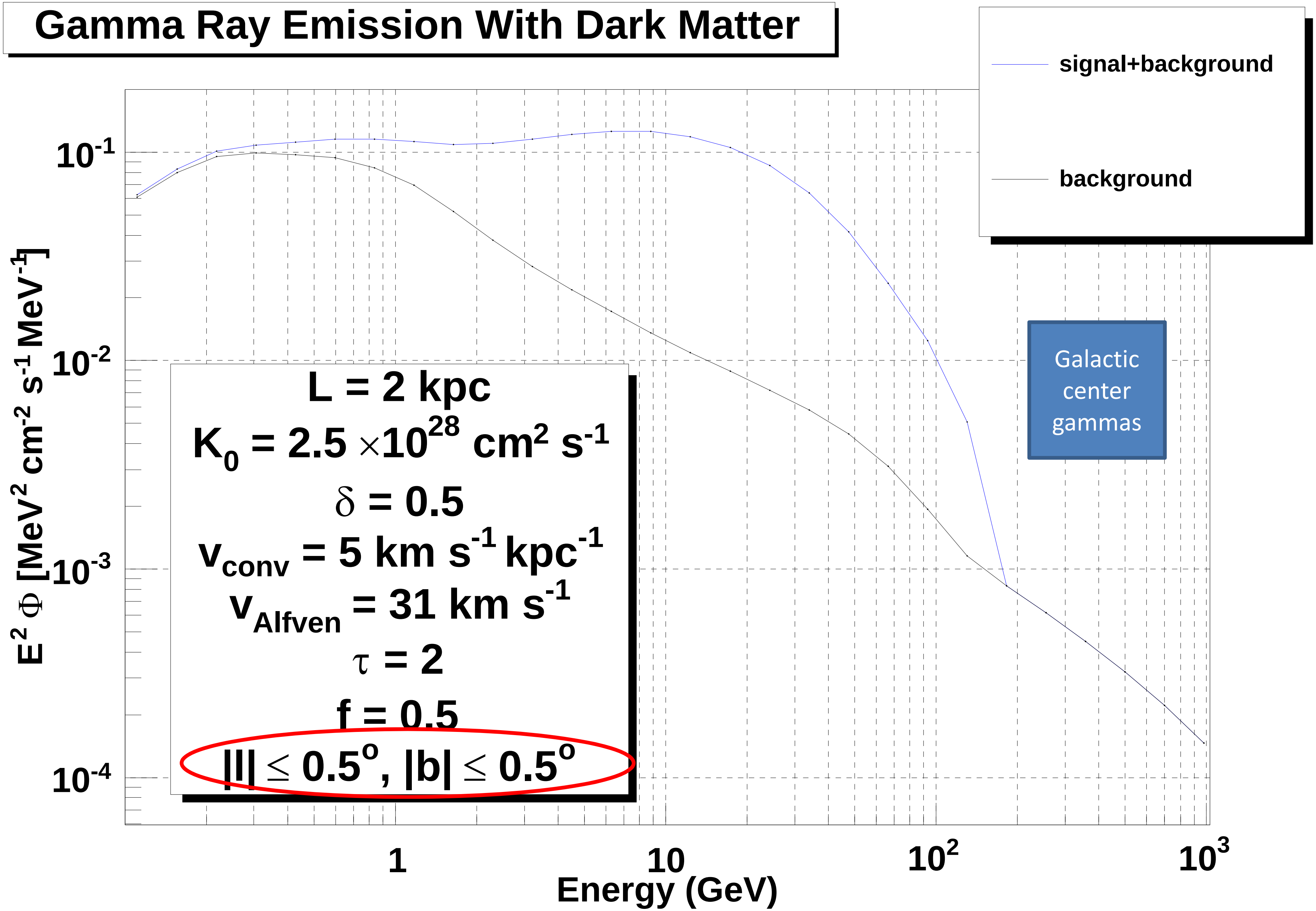

Positron Flux
total positron flux
positron flux from astro background
positron flux from wino
positron flux from extra flux
M_wino = 180 GeV
L = 2 kpc
K_0 = 2.5×10^28 cm^2 s^-1
δ = 0.5
v_conv = 5 km s^-1 kpc^-1
v_Alfven = 31 km s^-1
τ = 2
f = 0.5
B_c = 2
Modulation Field Φ = 500 MV
E_cut = 950 GeV
α = 1.5
γ_0 = 2.6
E^3 e^+ (GeV^2m^-2s^-1sr^-1)
10
1
0.1
0.1
1
10
100
1000
Energy (GeV)



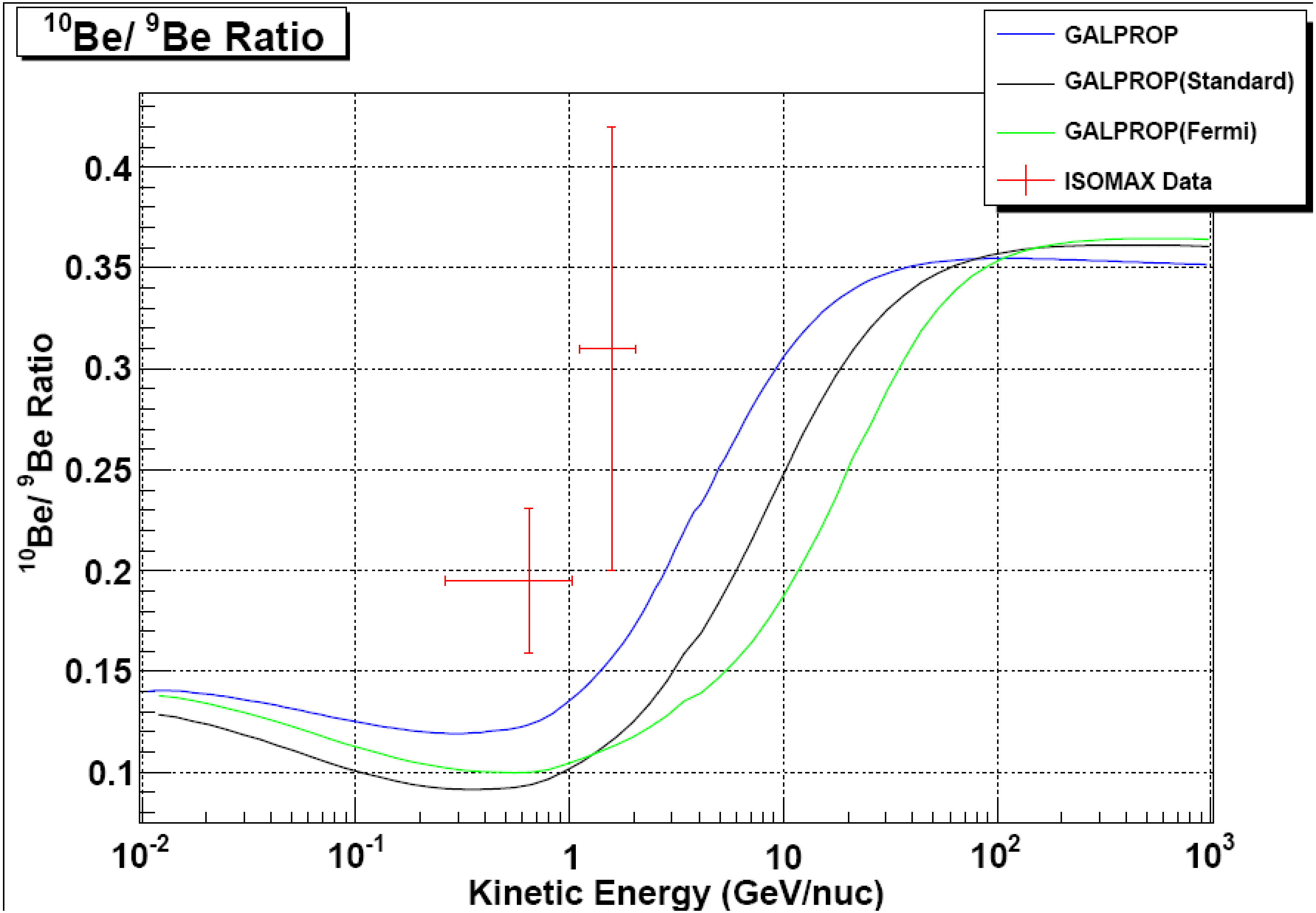
Antiproton Flux
total antiproton flux
antiproton flux from astro background
antiproton flux from wino
M_{wino} = 180 GeV
L = 2 kpc
$K_0 = 2.5\times10^{28}$ cm^2 s^{-1}
δ = 0.5
v_{conv} = 5 km s^{-1} kpc^{-1}
v_{Alfven} = 31 km s^{-1}
τ = 2
f = 0.5
B_c = 2
Modulation Field Φ = 500 MV
E_cut = 950 GeV
α = 1.5
γ_0 = 2.6
10
1
0.1
0.01
$E^3\ \bar{p}$ (GeV^{2}m^{-2}s^{-1}sr^{-1})
10
100
1000
Energy (GeV)



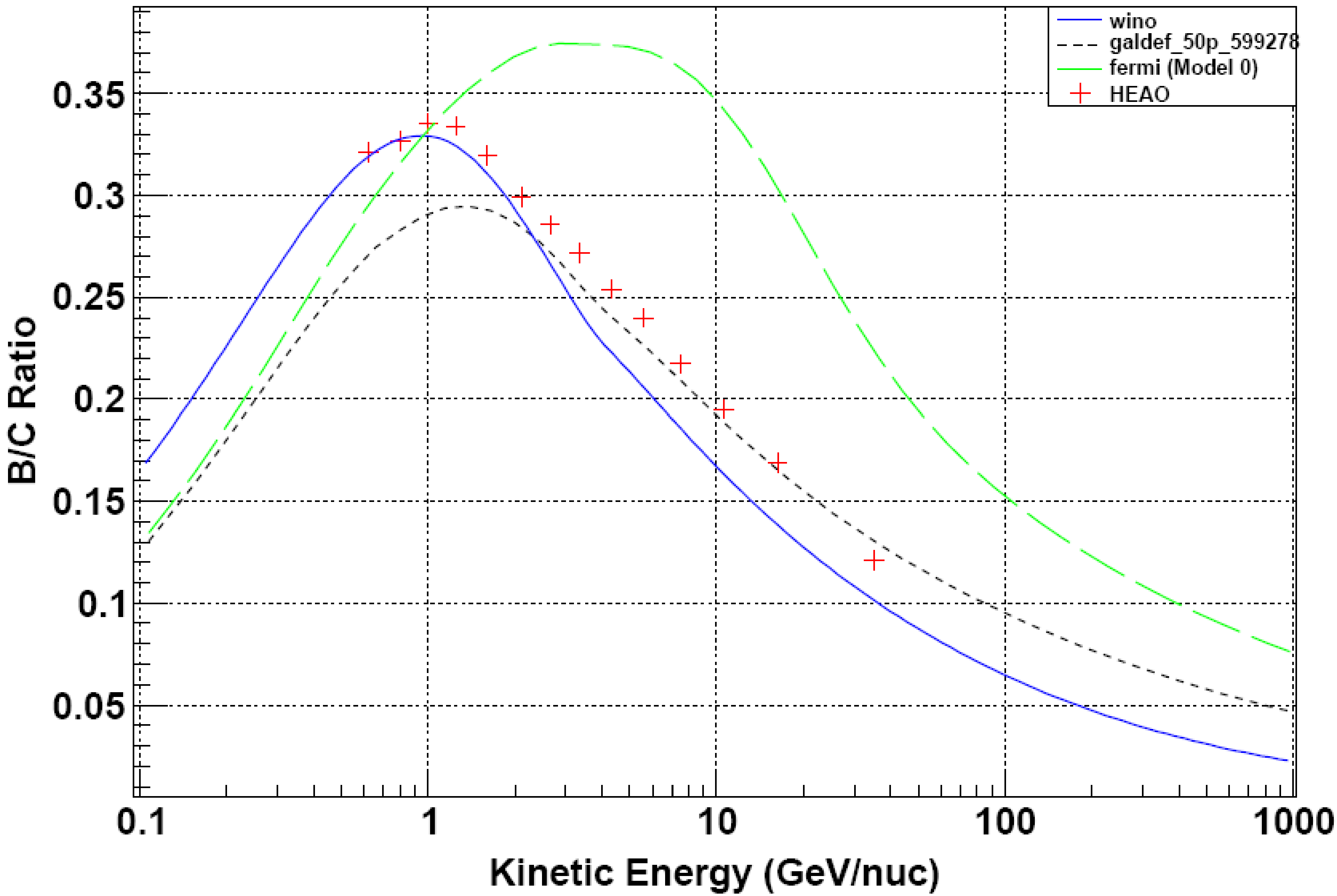
Electron Flux
M_{wino} = 180 GeV
L = 2 kpc
$K_0 = 2.5\times10^{28}$ cm^2 s^{-1}
δ = 0.5
v_{conv} = 5 km s^{-1} kpc^{-1}
v_{Alfven} = 31 km s^{-1}
τ = 2
f = 0.5
B_c = 2
Modulation Field Φ = 500 MV
E_cut = 950 GeV
α = 1.5
γ_0 = 2.6
total electron flux
electron flux from astro background
electron flux from wino
electron flux from extra flux
$E^3\,e^-$ (GeV^{2}m^{-2}s^{-1}sr^{-1})
Energy (GeV)
0.1
1
10
100
1000
100
10
1
0.1



Gamma Ray Emission With Dark Matter
signal+background
background
Galactic center gammas
L = 2 kpc
$K_0 = 2.5 \times 10^{28}$ cm^2 s^{-1}
$\delta = 0.5$
v_{conv} = 5 km s^{-1} kpc^{-1}
v_{Alfven} = 31 km s^{-1}
$\tau = 2$
f = 0.5
$|l| \leq 0.5^o$, $|b| \leq 0.5^o$
$E^2\,\Phi$ [MeV^2 cm^{-2} s^{-1} MeV^{-1}]
Energy (GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3



^{10}Be/ ^{9}Be Ratio
GALPROP
GALPROP(Standard)
GALPROP(Fermi)
ISOMAX Data
0.4
0.35
0.3
0.25
0.2
0.15
0.1
^{10}Be/ ^{9}Be Ratio
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
Kinetic Energy (GeV/nuc)



wino
galdef_50p_599278
fermi (Model 0)
HEAO
0.35
0.3
0.25
0.2
0.15
0.1
0.05
B/C Ratio
0.1
1
10
100
1000
Kinetic Energy (GeV/nuc)

Two physically different approaches to the origin of the dark matter relic density, even assuming wimps – *every analysis picks one of these*

- "Thermal" cosmological history – at the BB, SM particles and superpartners created – since then no additional particles created and no entropy added – theoretically *poorly motivated, but widely used*

--Leads to "thermal wimp miracle"

$$n_{wimp} = H(\, freezeout \text{ temp} \approx \text{few GeV}) \Big/ \langle \sigma \upsilon \rangle_{wimp}$$

$$n_{wimp} = n_{wmap} \to \langle \sigma \upsilon \rangle_{wimp} \approx 3 \times 10^{-26} cm^3 \sec^{-1}$$

$$\to wimp \approx bino$$

--Bino annihilates via heavy squark exchange or neutral Z to quarks and leptons, helicity suppressed, so small rate to positrons (and softer ones), so poor description of PAMELA positron excess