Fermilab

Indirect Detection of Wino Dark Matter: Multichannel Detection Study

Work with:

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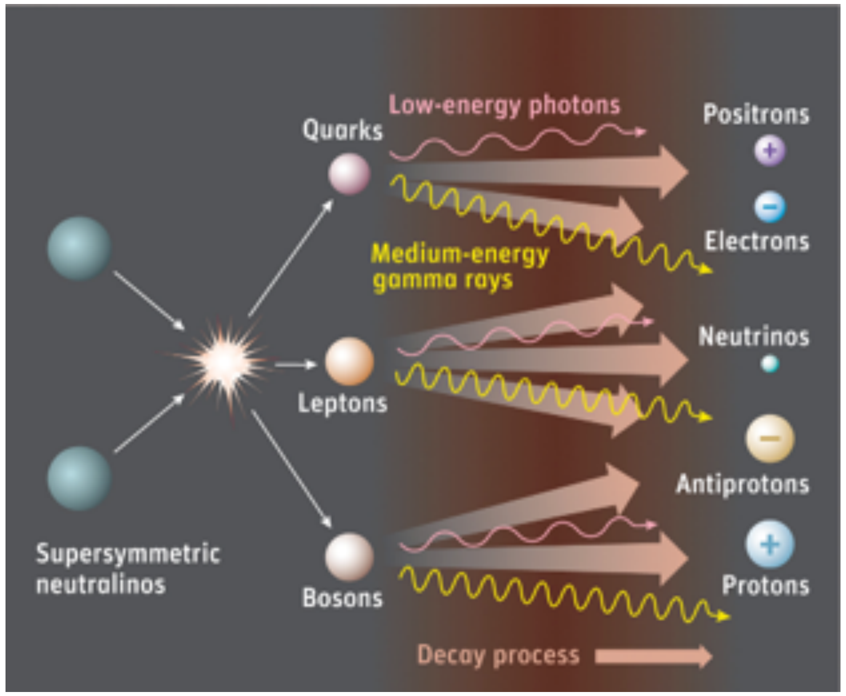
arXiv:1401.6212(JCAP in prep.)

Also work with Carmelo Evoli, Dan Hooper, Sam McDermott, Paolo Salucci

JCAP 1402 (2014), JCAP 1401 (2014), PRD 88 (2013), PRD 86 (2013)

Ilias Cholis, 03/17/2014

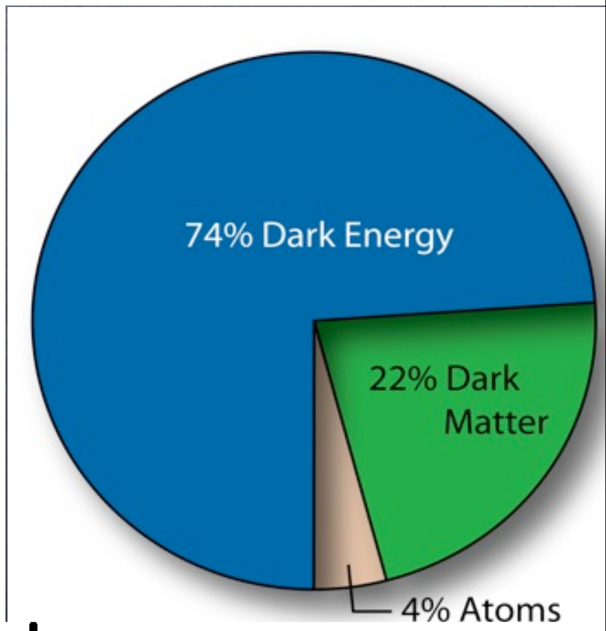
Outline

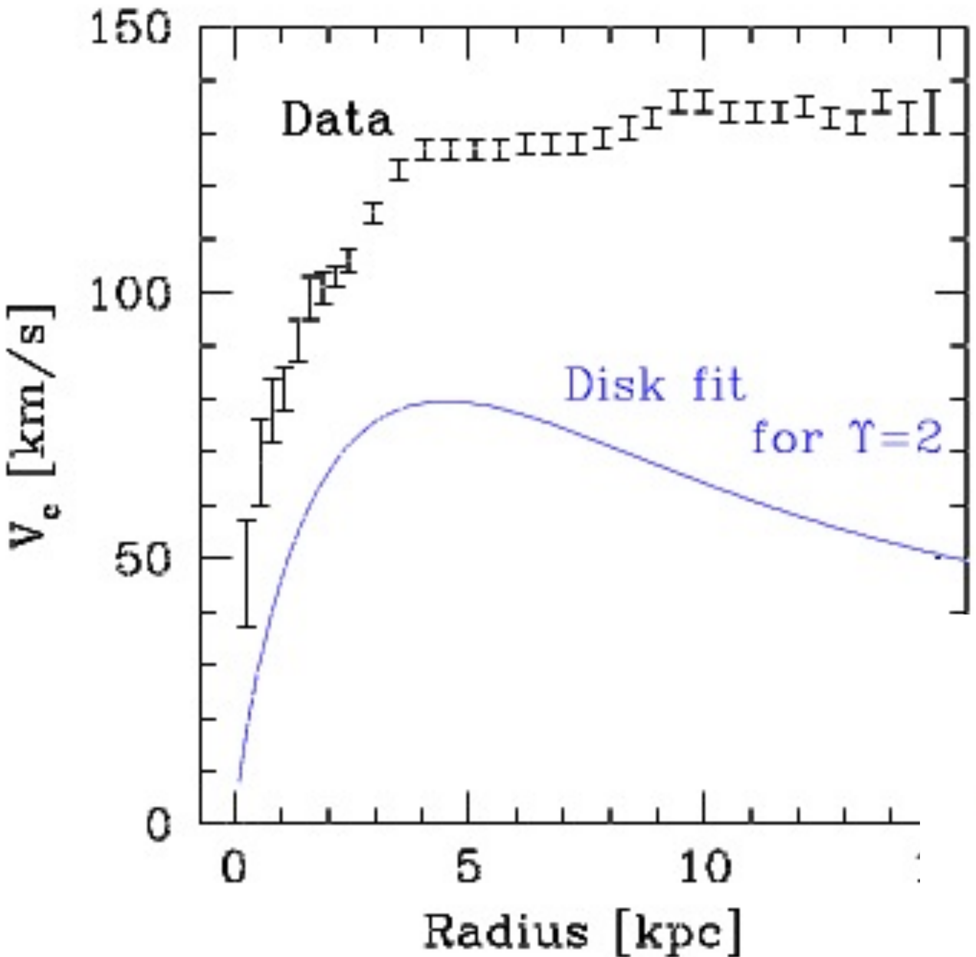


- Wino DM
- Cross-section and annihilation spectra
- General CRs
- Limits from Antiprotons, Positrons and future antideutrons probe. Include into the discussion all the important astrophysical uncertainties.
- Galactic Diffuse Gamma-rays, searching for a signal from the Milky Way in the continuum and from spectral features. Also discuss the impact of astrophysical assumptions.
- Dwarf Spheroidals and Extragalactic structures
- Neutrinos from the GC
- Overall Picture/Comparisons/Conclusions

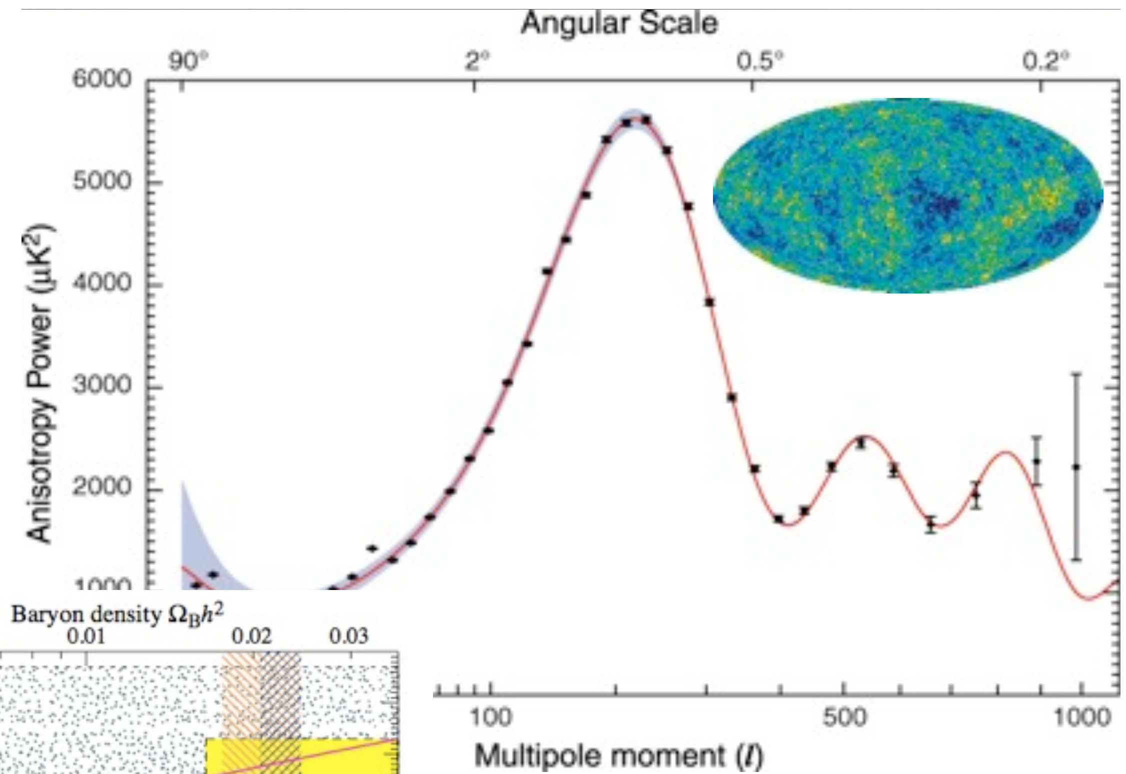
evidence for CDM

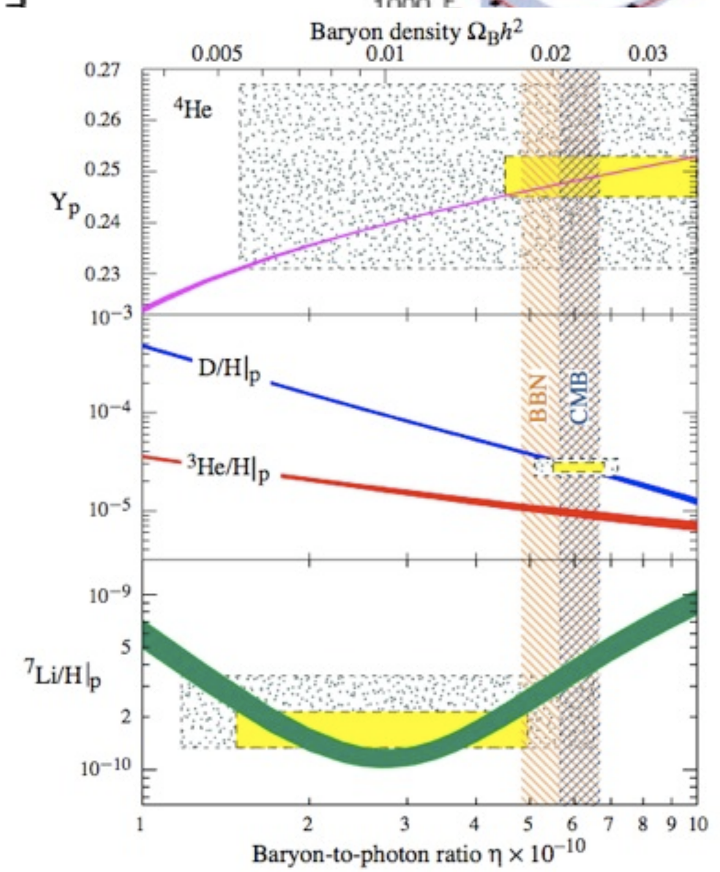
- galactic rotation curves
- velocity dispersion of galaxies in clusters
- CMB data and SN Ia data
- distribution of galaxies
- strong lensing measurements of background objects (usually galaxies)
- bullet cluster
- success of BBN (DM is non-baryonic)
- growth of structure (cold DM)

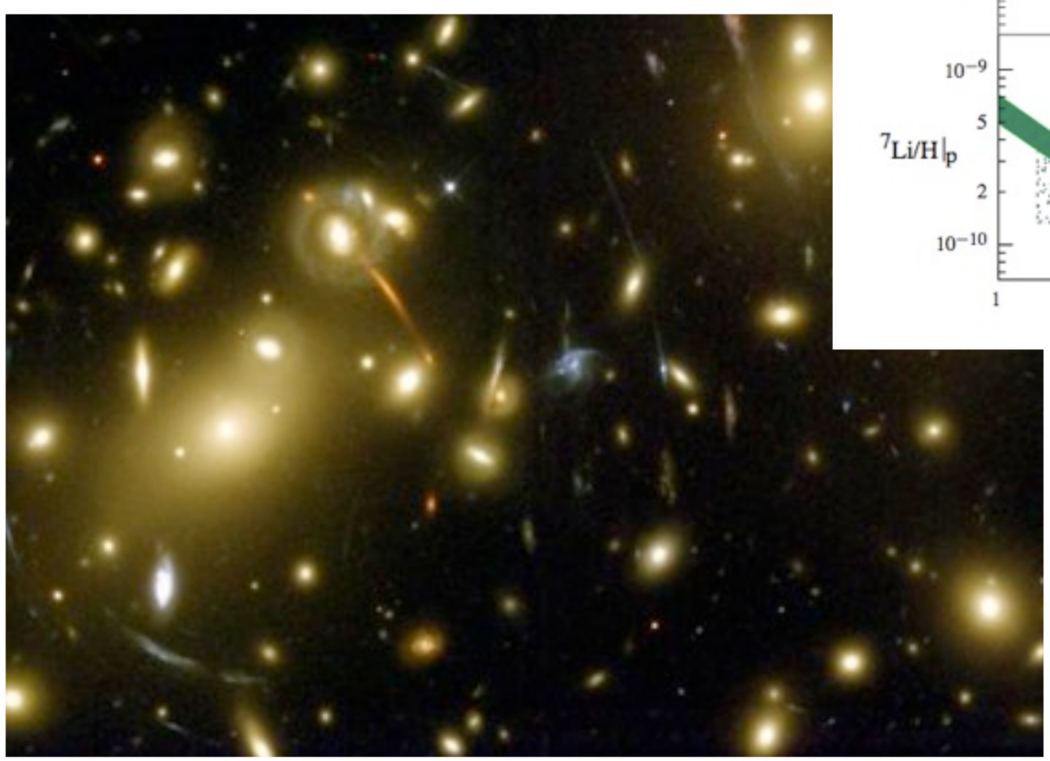


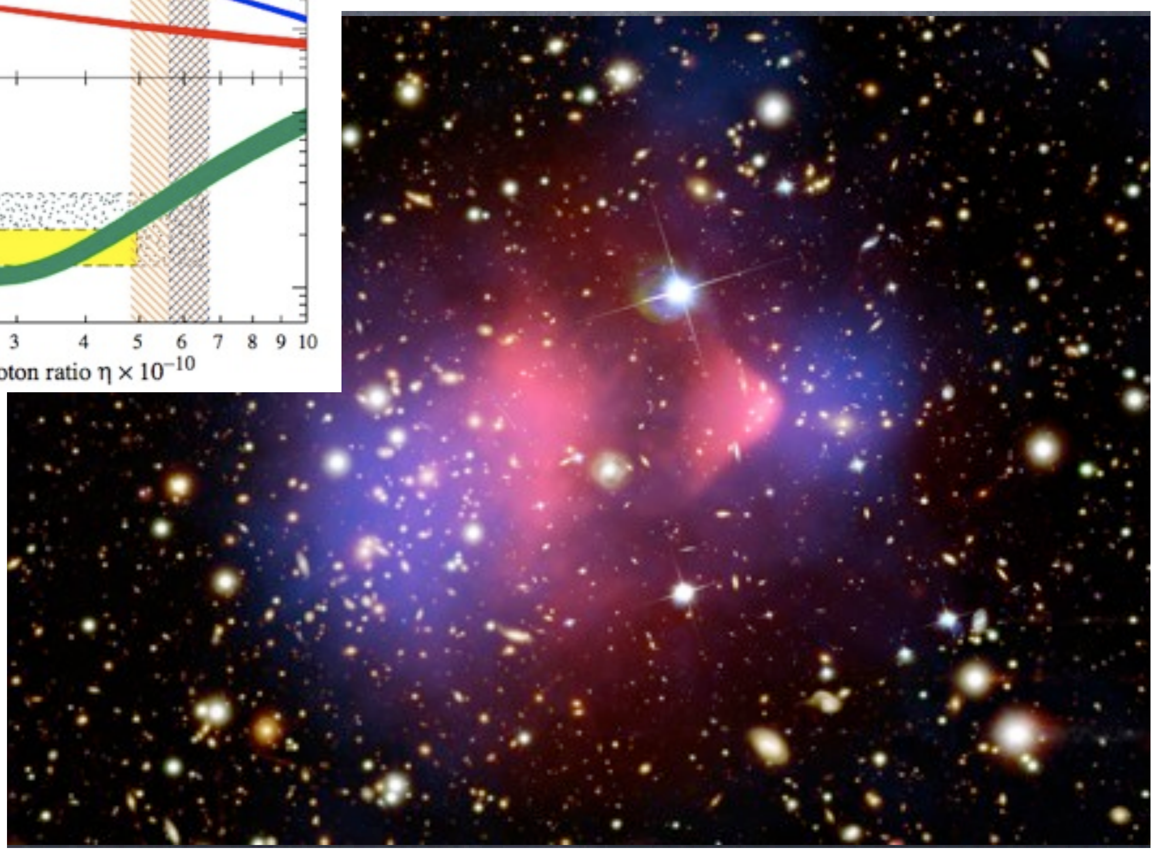


NGC 2403 rotation curve and model









Wino DM, cross-section and annihilation spectra

Supersymmetry provides a natural WIMP candidate for DM, the Lightest Supersymmetric Particle (LSP).
In the MSSM this is the lightest out of four neutralinos (linear combinations of R parity =-1 neutral Wino, Bino and Higgsinos).
We concentrate on the case of a pure Wino (the neutral member of an $SU(2)_L$ triplet)

Correct thermal relic density is achieved for Wino mass~3 TeV.
I will show results up to this mass scale. Lighter masses have higher cross-sections (larger indirect signals) and have to be produced non-thermally.
Heavier particles give too large relic abundance and no detectable signals.

In general we use 3 different probes to study DM: Collider production, Direct detection and Indirect detection.

For a ~2-3 TeV DM particle, Collider production at LHC has not enough energy, while direct detection suffers from low DM number density. (All direct detection experiments probe best ~100 GeV DM particles from a combination of kinematical and DM density reasons).

Indirect detection is the only probe for Wino DM that is currently accessible.

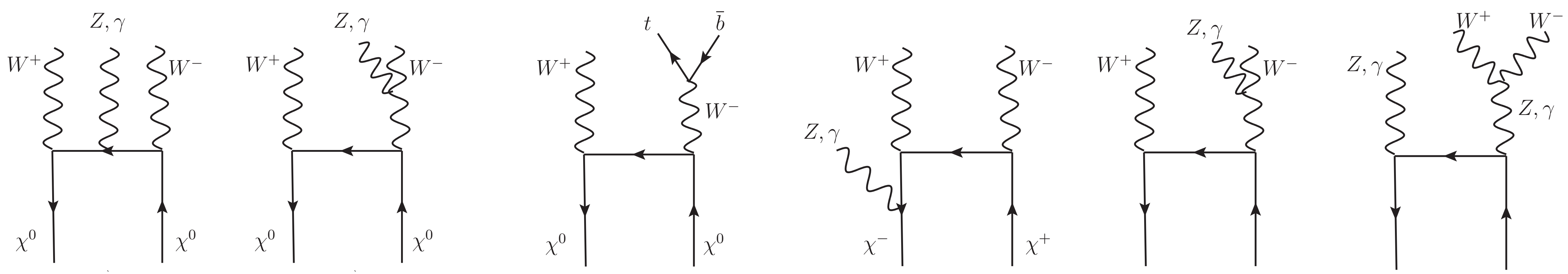
At tree level the indirect signals come from $\chi\chi \longrightarrow W^+W^-$ where W^+W^- decay and hadronize giving protons, antiprotons, electrons, positrons, neutrinos and gamma-rays. With a (tree-level) cross-section:

$$\sigma v|_{\chi\chi\to W^+W^-} = \frac{8\pi\alpha_2^2}{m_\chi^2}\frac{(1-m_W^2/m_\chi^2)^{3/2}}{(2-m_W^2/m_\chi^2)^2} \qquad \alpha_2 = g_2^2/(4\pi)$$

g_2 the weak coupling const., m_W the W mass m_χ the Wino mass

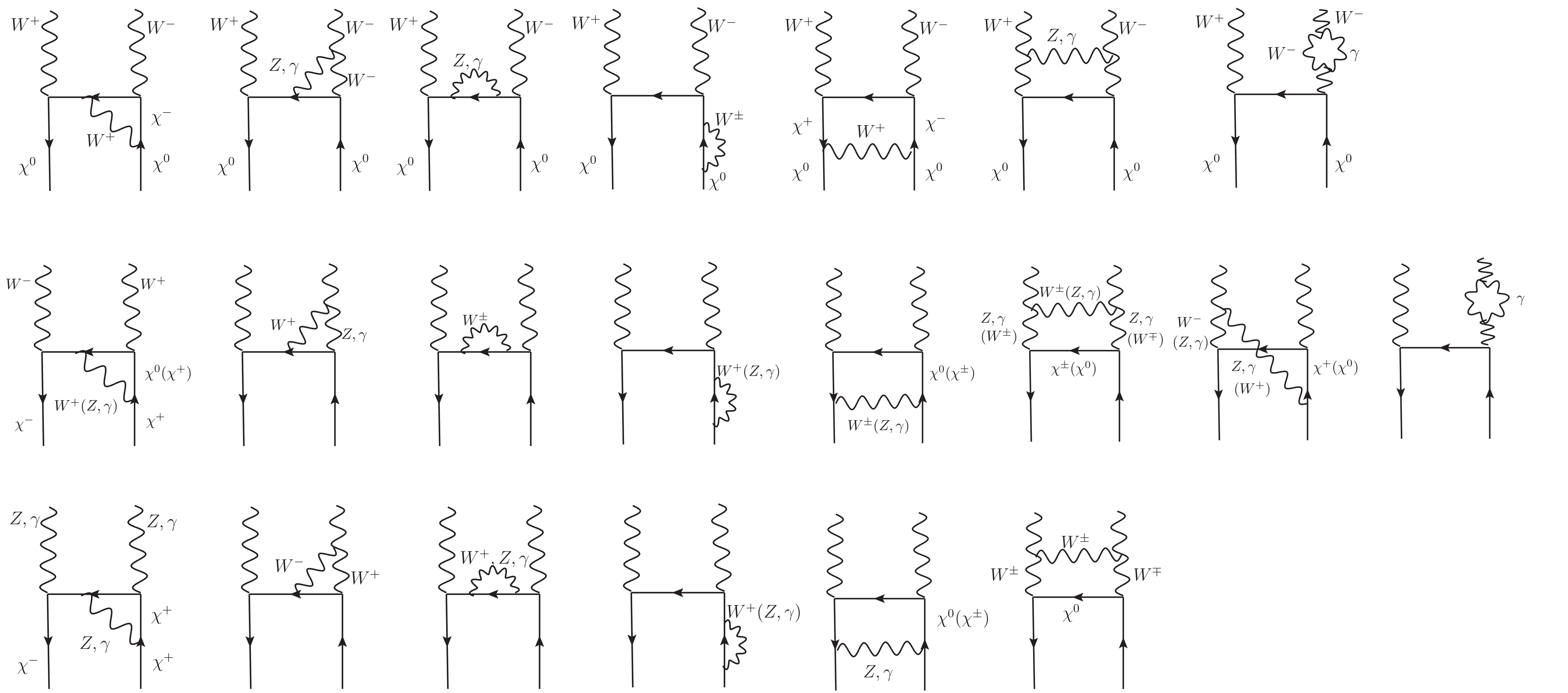
In addition we have three body processes:

$\chi\chi \longrightarrow W^+W^-\gamma$ or W^+W^-Z and $\chi\chi \longrightarrow \chi^+\chi^- \longrightarrow W^+W^-\gamma,\ W^+W^-Z$



A. Hryczuk and R. Iengo (2012)

and 1 loop calculations:



AND Sommerfeld corrections to the annihilation cross-section, important for $m_\chi \gg m_W$ due to a long range interaction between the Winos in the incoming state, with a resonance at ~2.4 TeV.

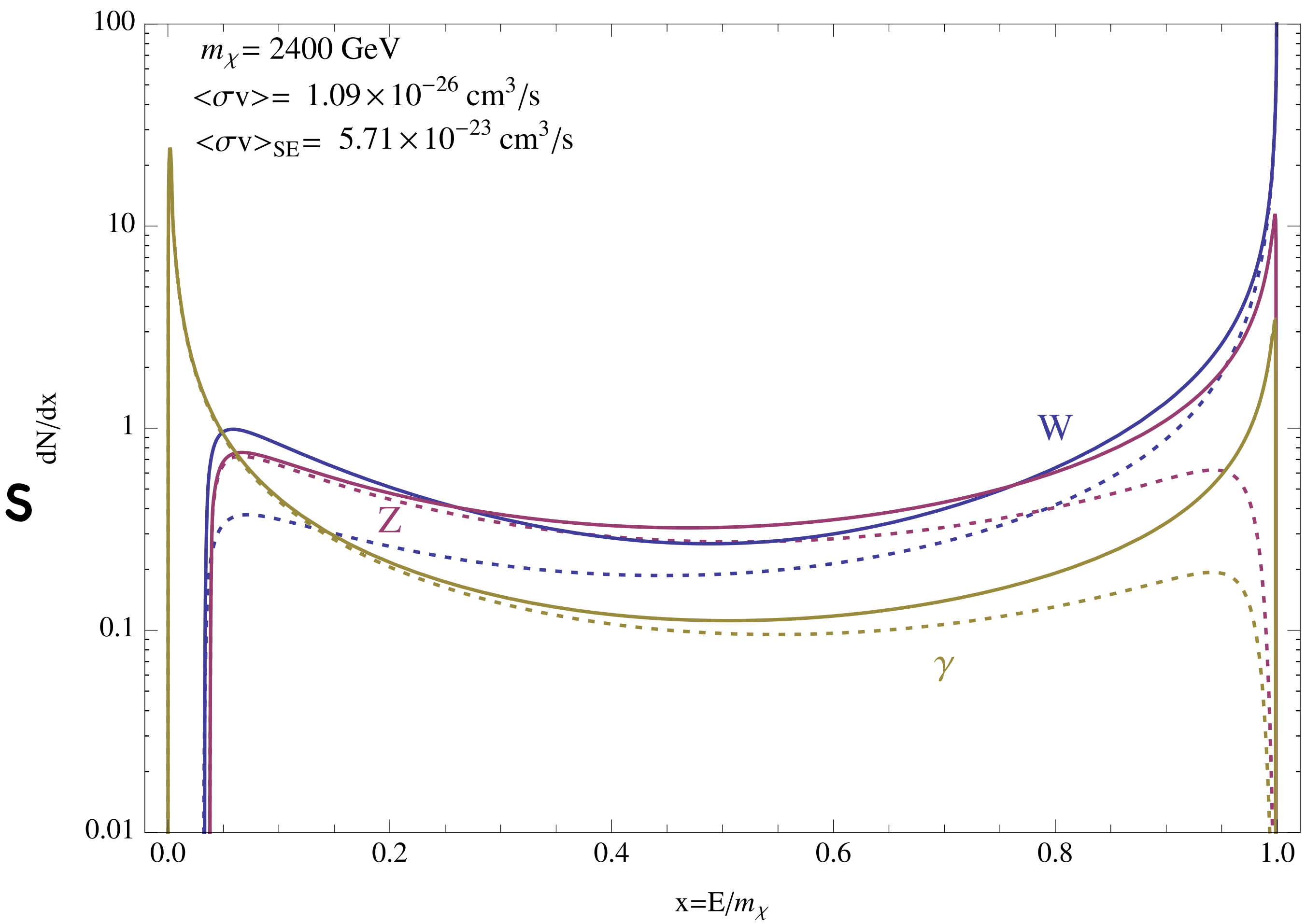
The amplitude of the enhancement is:

$$A^{\rm SE}_{\chi^0\chi^0\to{\rm SM}} = s_0 A_{\chi^0\chi^0\to{\rm SM}} + s_\pm A_{\chi^+\chi^-\to{\rm SM}}$$

Including all these effects. The initial annihilation spectra for Ws, Zs and gammas change significantly:

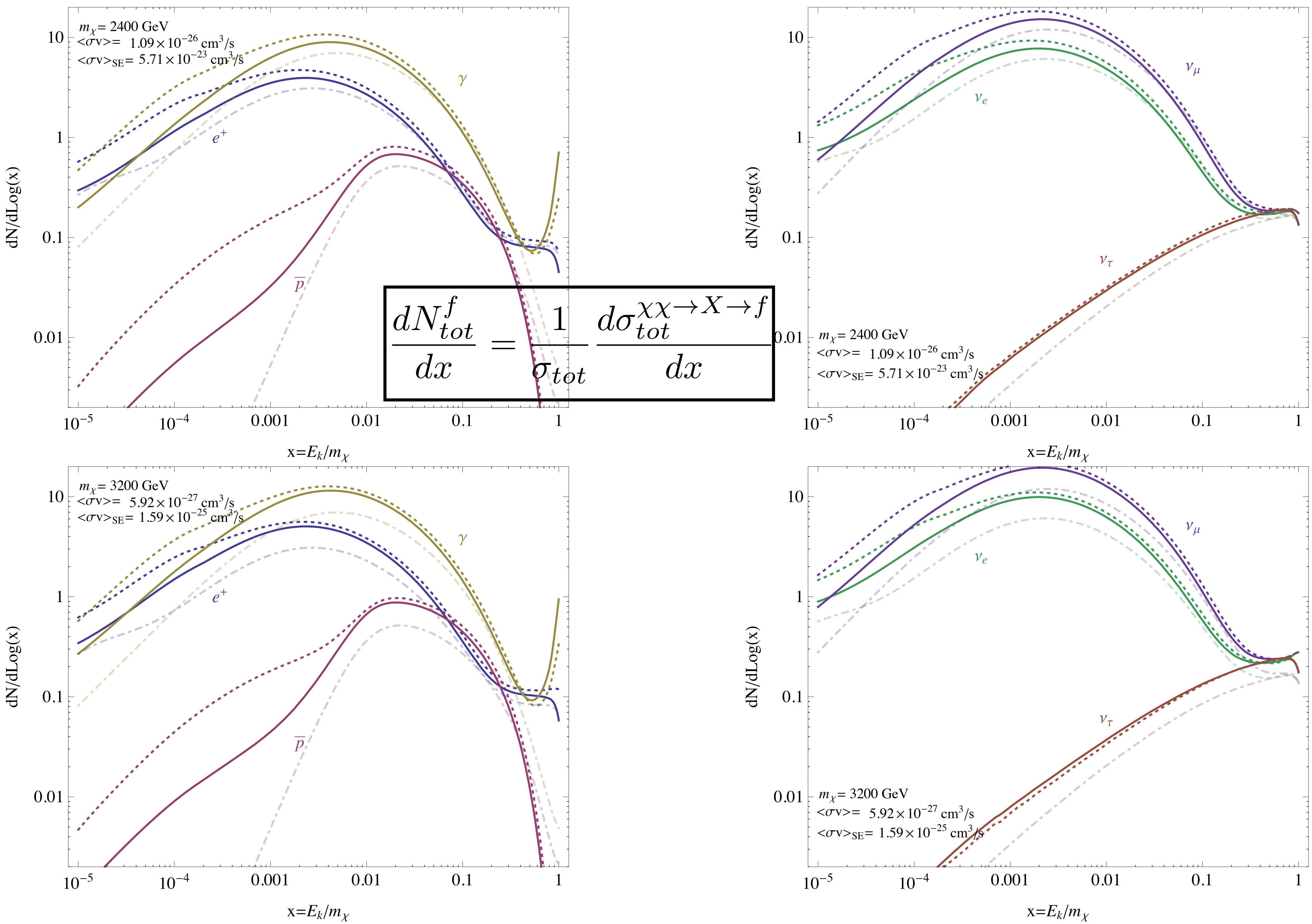
$$\frac{dN_{tot}}{dx} = \frac{1}{\sigma_{tot}}\frac{d\sigma_{tot}}{dx}$$

- Change in the cross-section
- ZZ, Zgamma and 2gamma channels open up.
- Modification of injection spectra



Final annihilation cosmic-ray gamma-ray and neutrino spectra

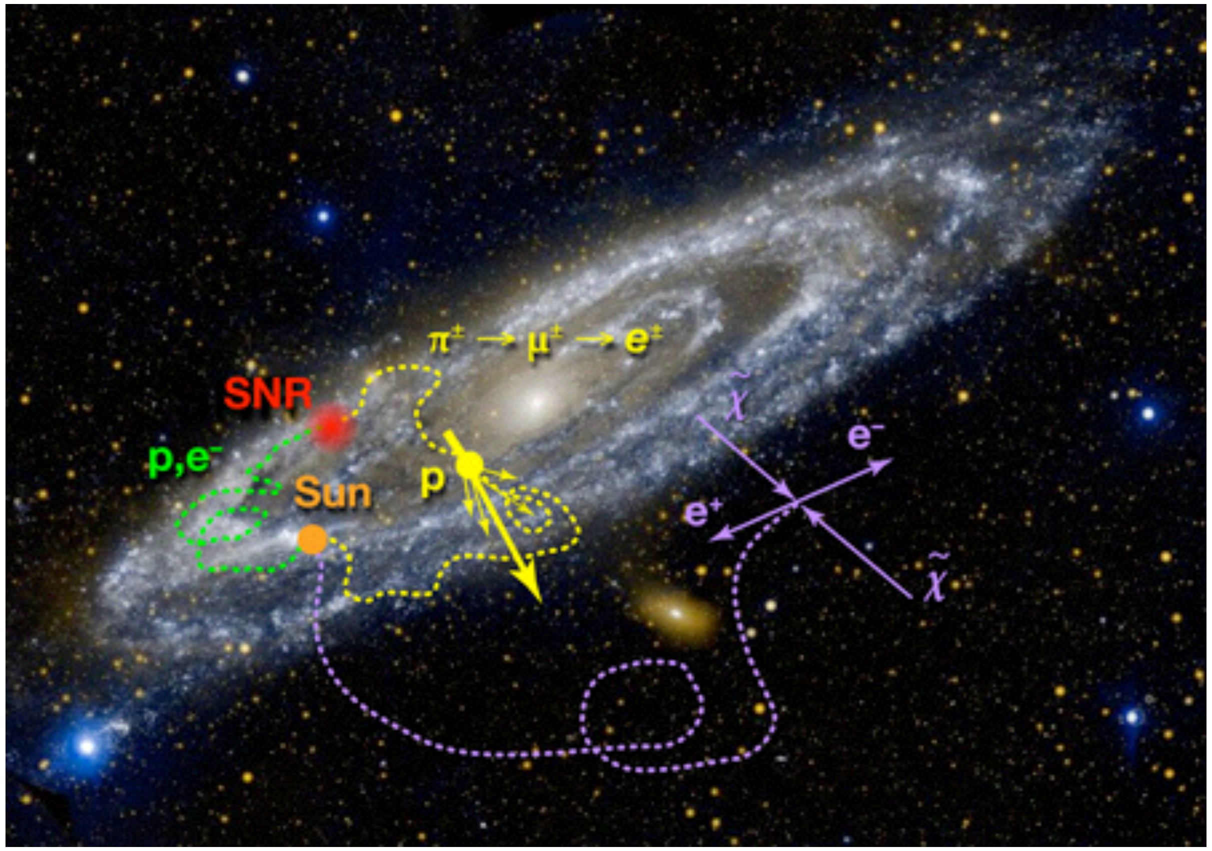
Chained lines: tree-level; Dotted: EW corrected; Solid: EW+Sommerfeld

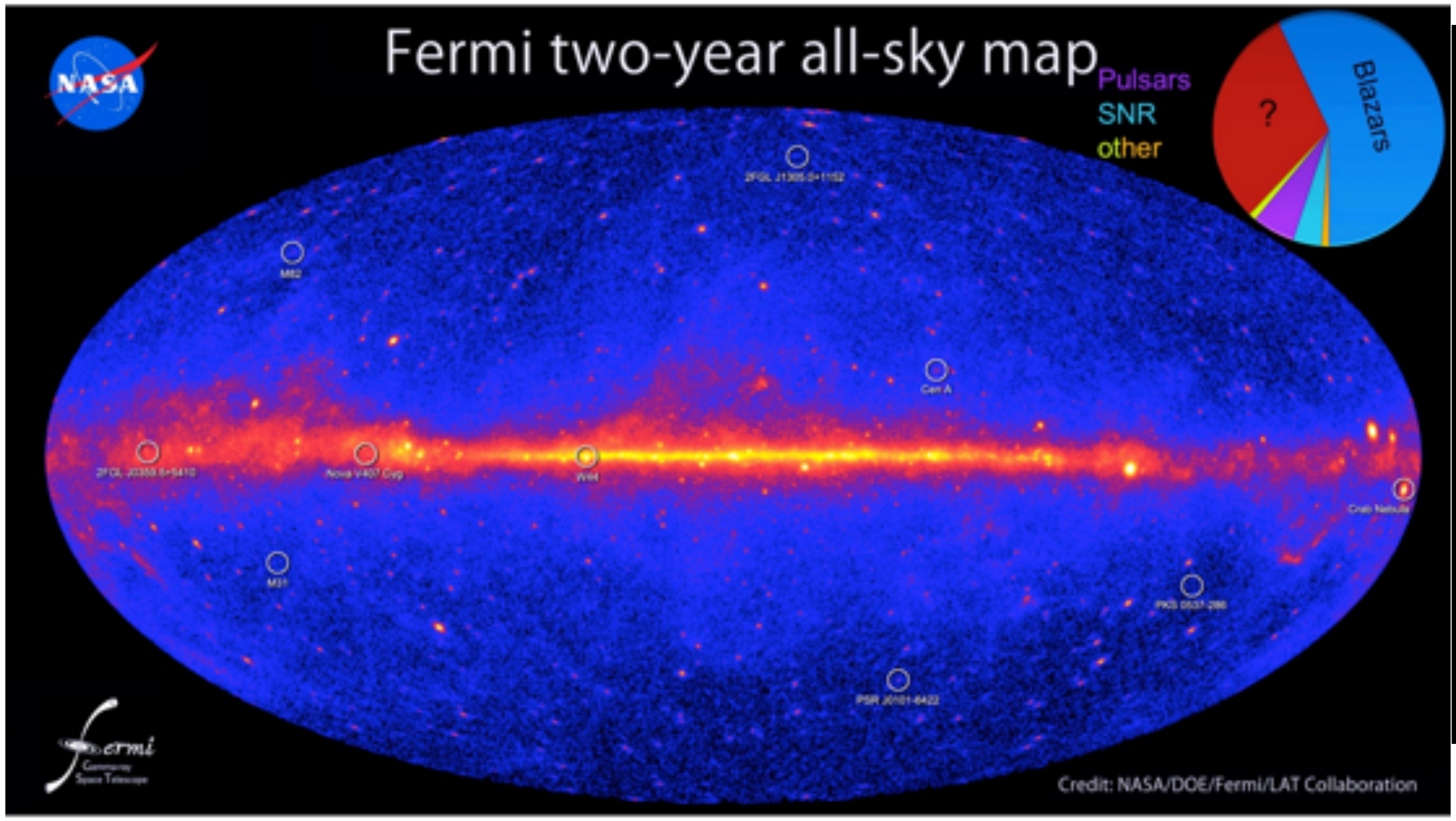


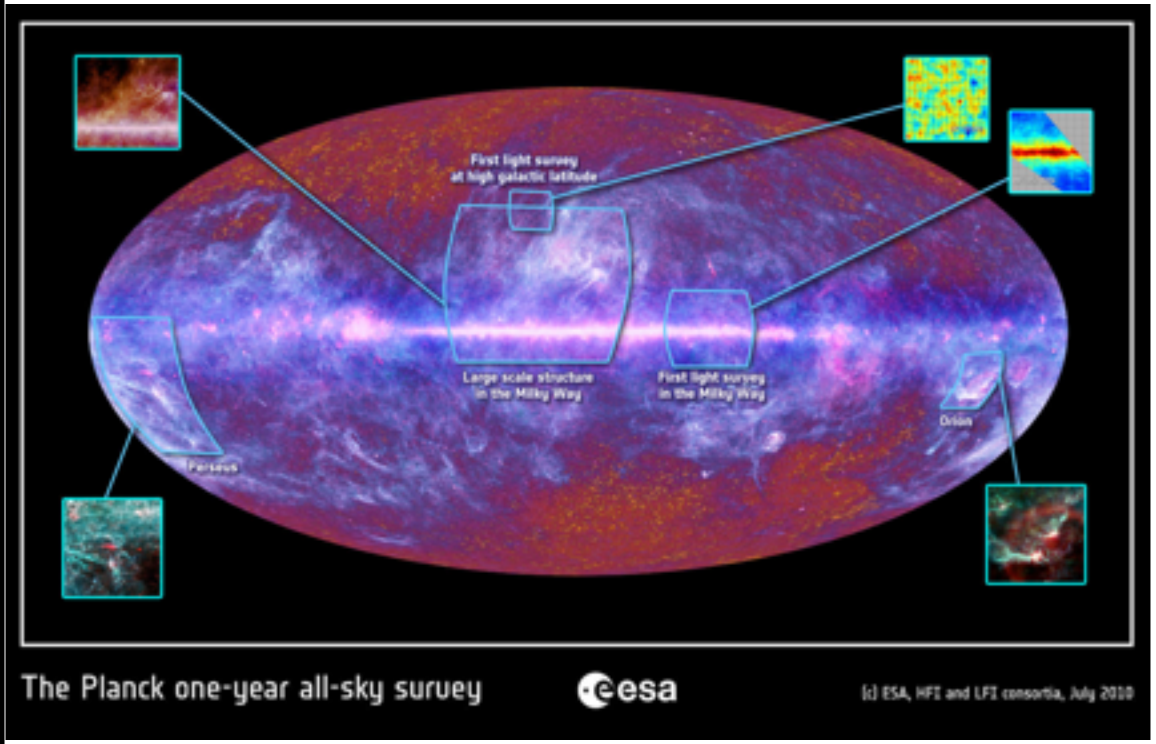
$$\frac{dN^f_{tot}}{dx} = \frac{1}{\sigma_{tot}} \frac{d\sigma^{\chi\chi\to X\to f}_{tot}}{dx}$$

Cosmic-rays and their relevance

With CR spectral measurements we can understand the properties of the ISM, and probe sources of high energy CRs. Antimatter CRs indirectly also probe DM. Combine with gamma-ray and radio observations.







A great new Era:The AMS-02 experiment

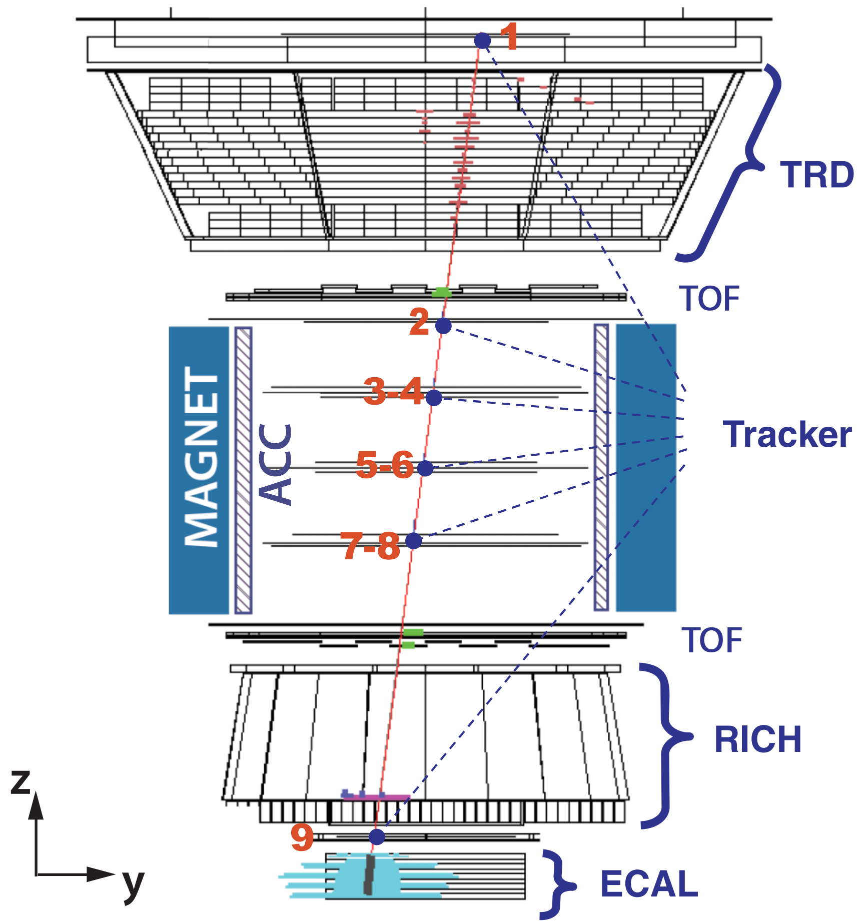
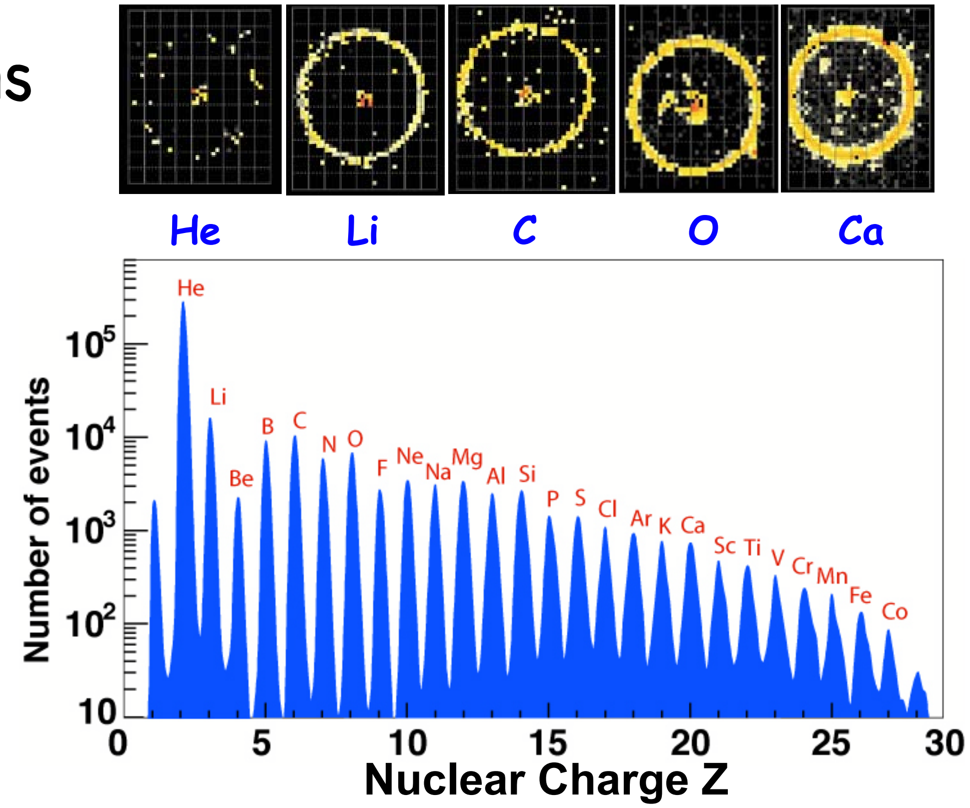


FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (*y*-*z*) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an electron, and measures its energy. An electron is identified by (i) an electron signal in the TRD, (ii) an electron signal in the ECAL, and (iii) the matching of the ECAL shower energy and the momentum measured with the tracker and magnet.

Lunched on May 2011, will collect data for 20 yrs.
Will measure all CR nuclei species up to Ni.

positron fraction,
positrons,electrons spectra,
antiproton/proton
B/C, Be10/Be9



Methodology

Using DRAGON to solve:

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

$$-\vec{\nabla}(\vec{V}\psi) + \frac{\partial}{\partial p}\left[\frac{p}{3}(\vec{\nabla}\vec{V})\psi\right] - \frac{\psi}{\tau_{frag}} - \frac{\psi}{\tau_{decay}}$$

Source term: $q_i(r,z,E) = f_s(r,z)q_{0,i}\left(\frac{R(E)}{R_0}\right)^{-\gamma^i}$

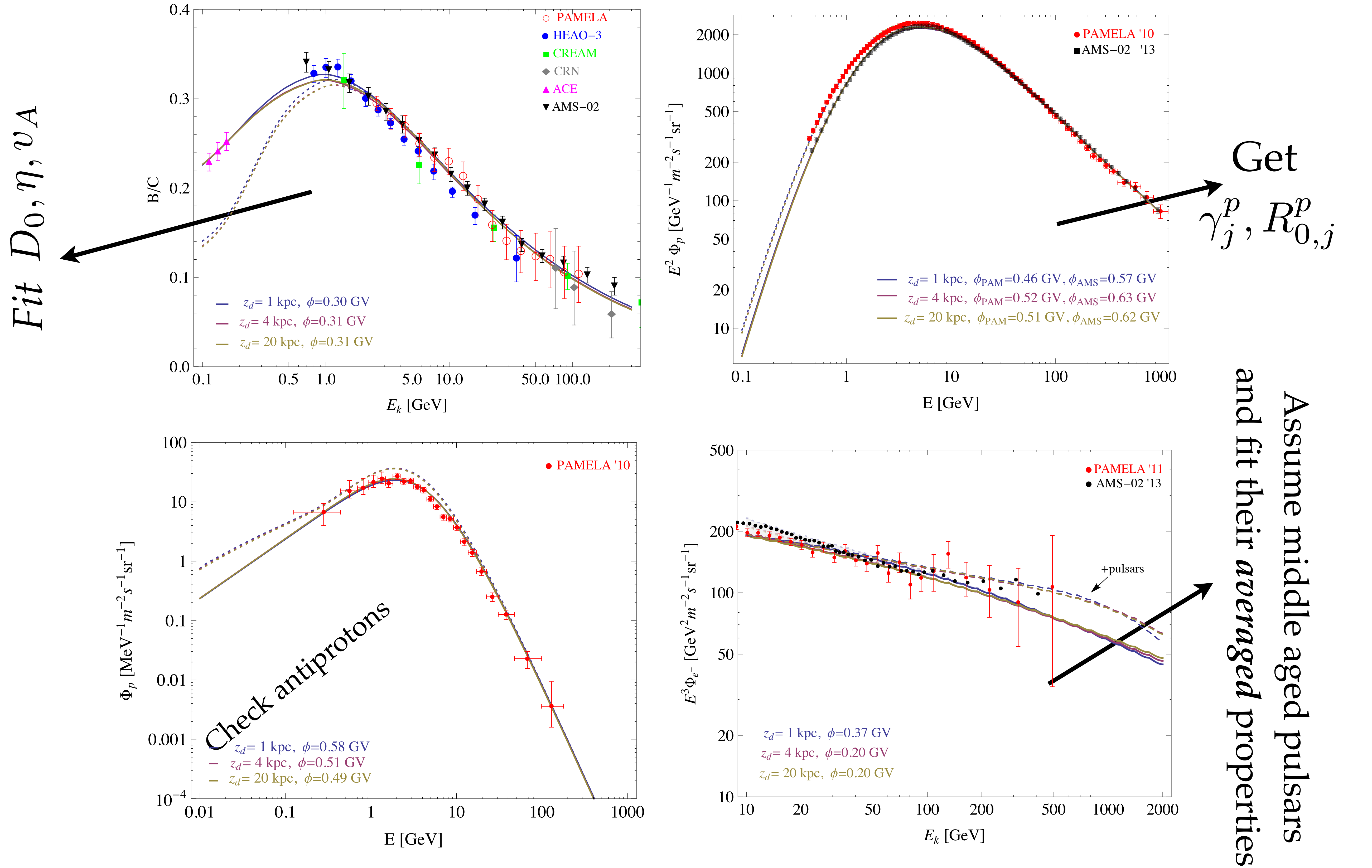
For protons : $\frac{dN_p}{dR} \propto \left(\frac{R}{R^p_{0,j}}\right)^{-\gamma^p_j}$ (based on AMS, PAMELA and CREAM data)

For diffusion in physical space:

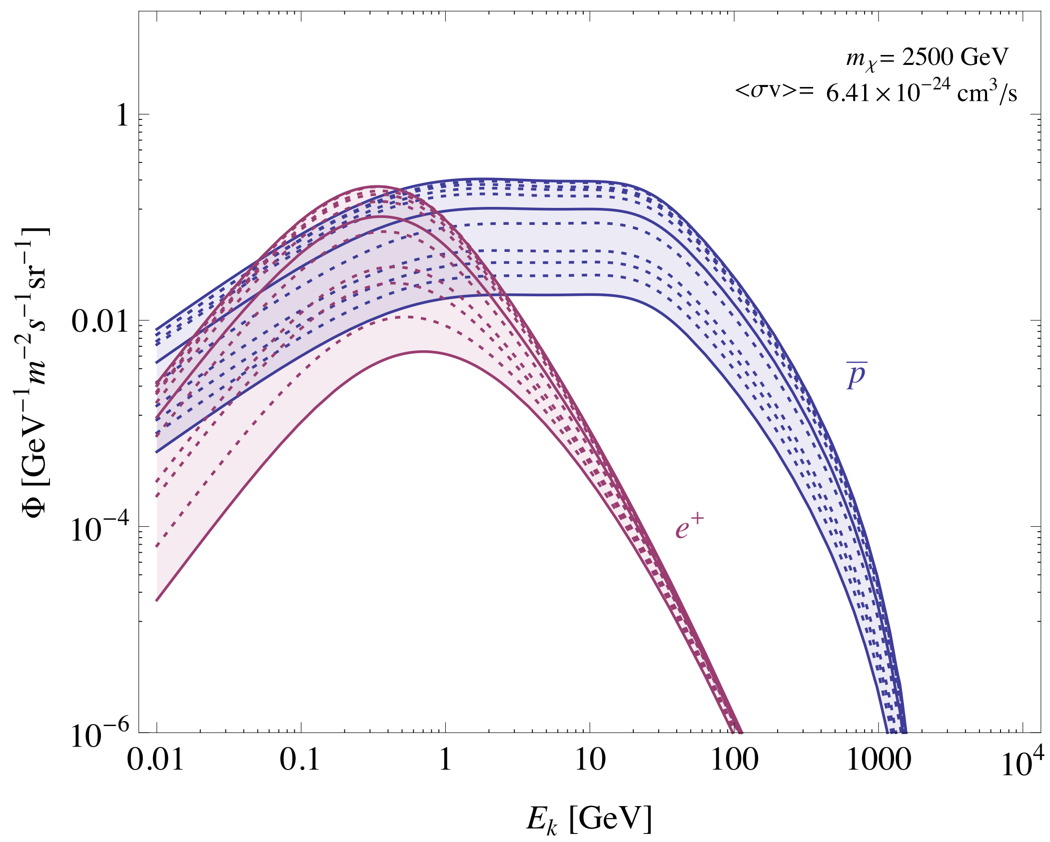
$$D(r,z,R) = D_0\beta^\eta(\frac{R}{R_0})^\delta \underbrace{\exp\left(\frac{r-r_\odot}{r_d}\right)}_{\text{new part}} \exp\left(\frac{|z|}{z_d}\right)$$

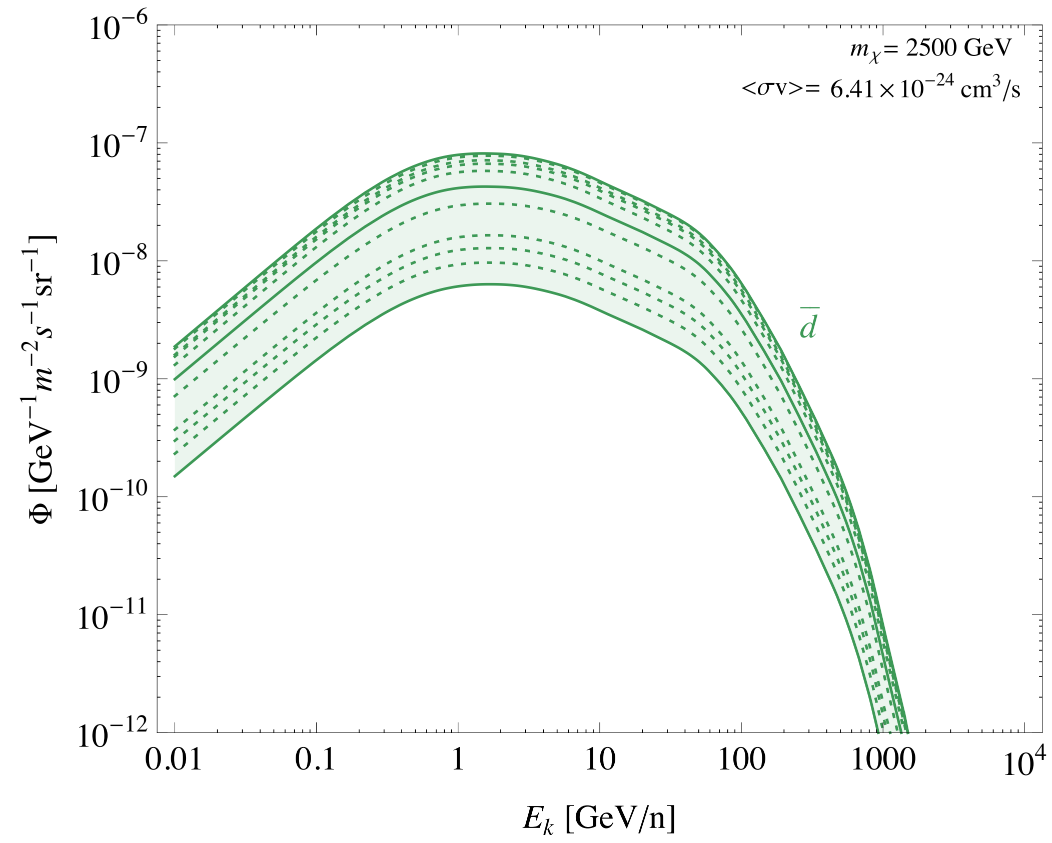
Fit to the CR data

Choose: δ, r_d, z_d and convection (also assume ISM gas and source distribution)



Effects of different CR Propagation assumptions

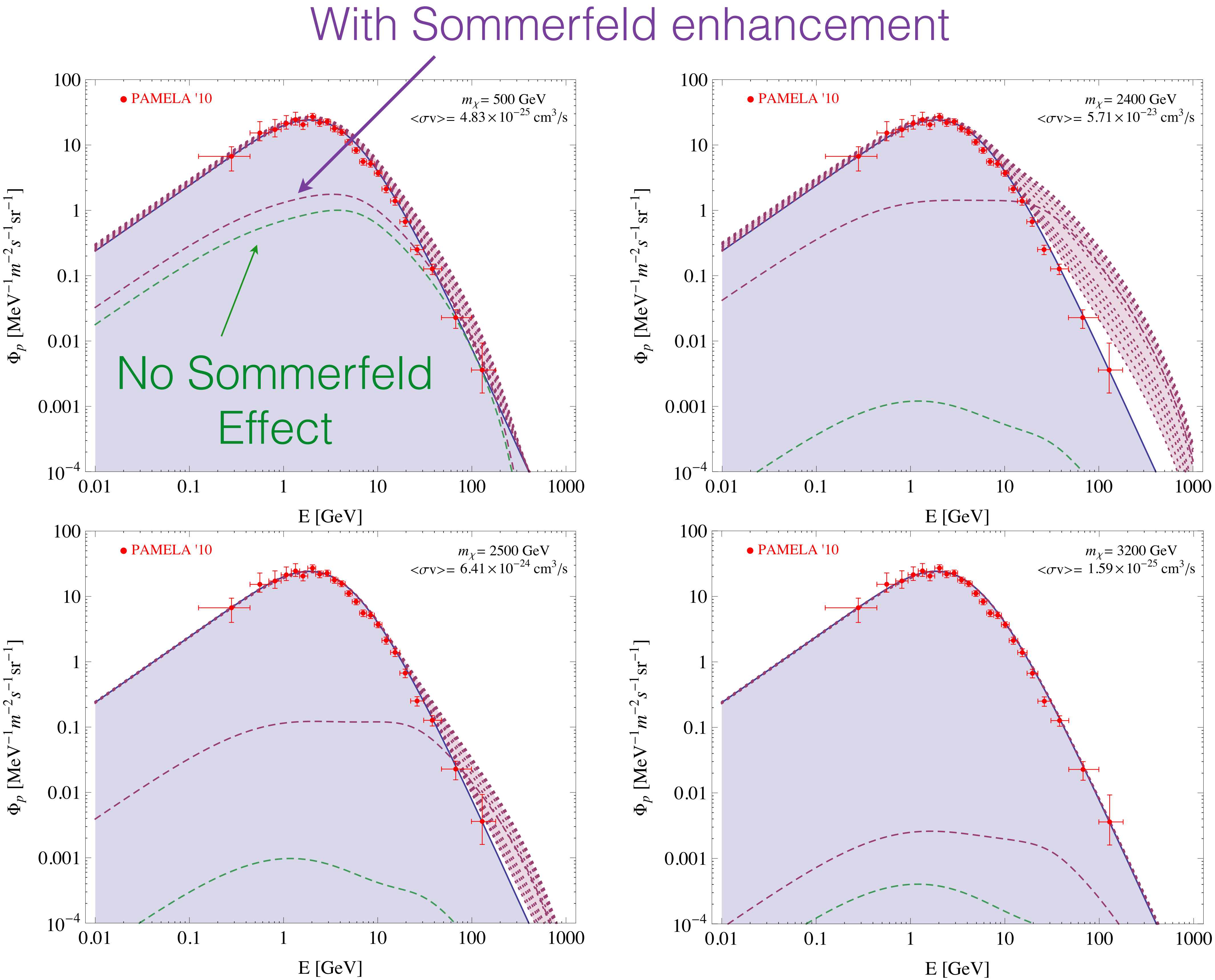




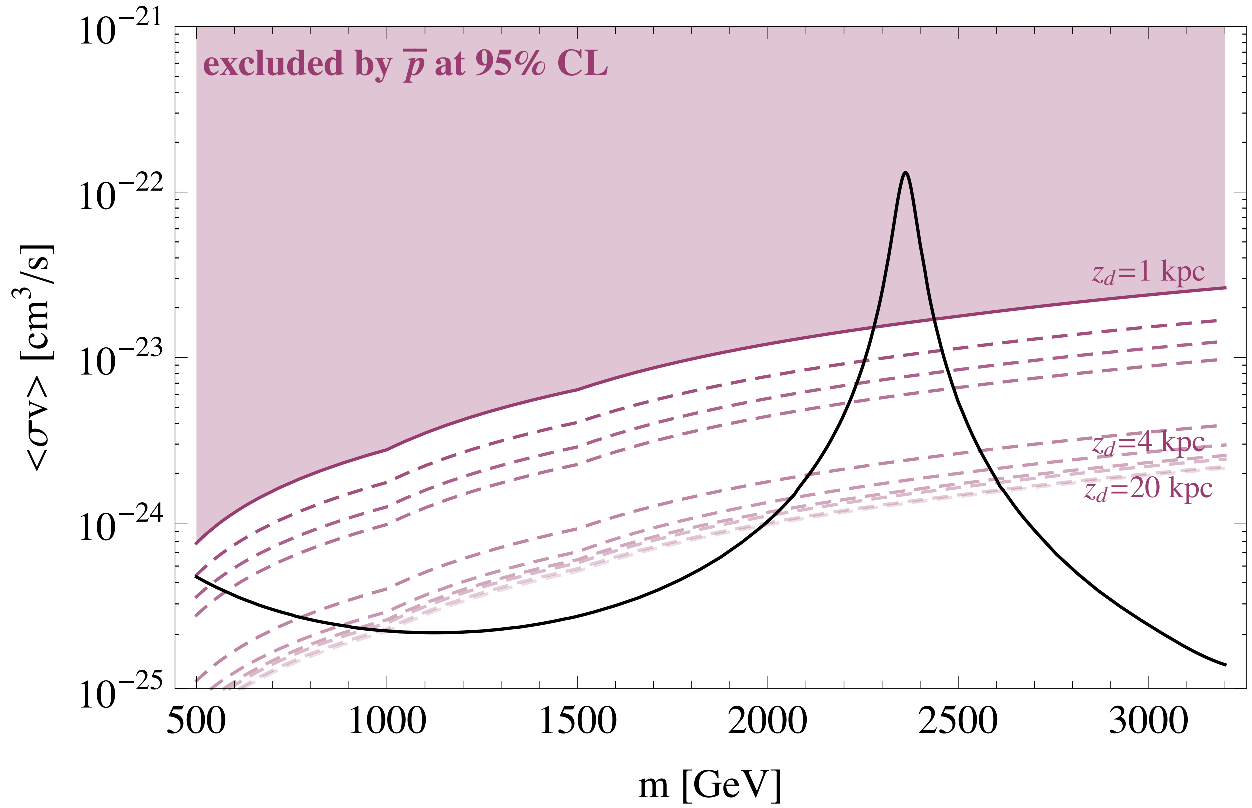
11 propagation Models:

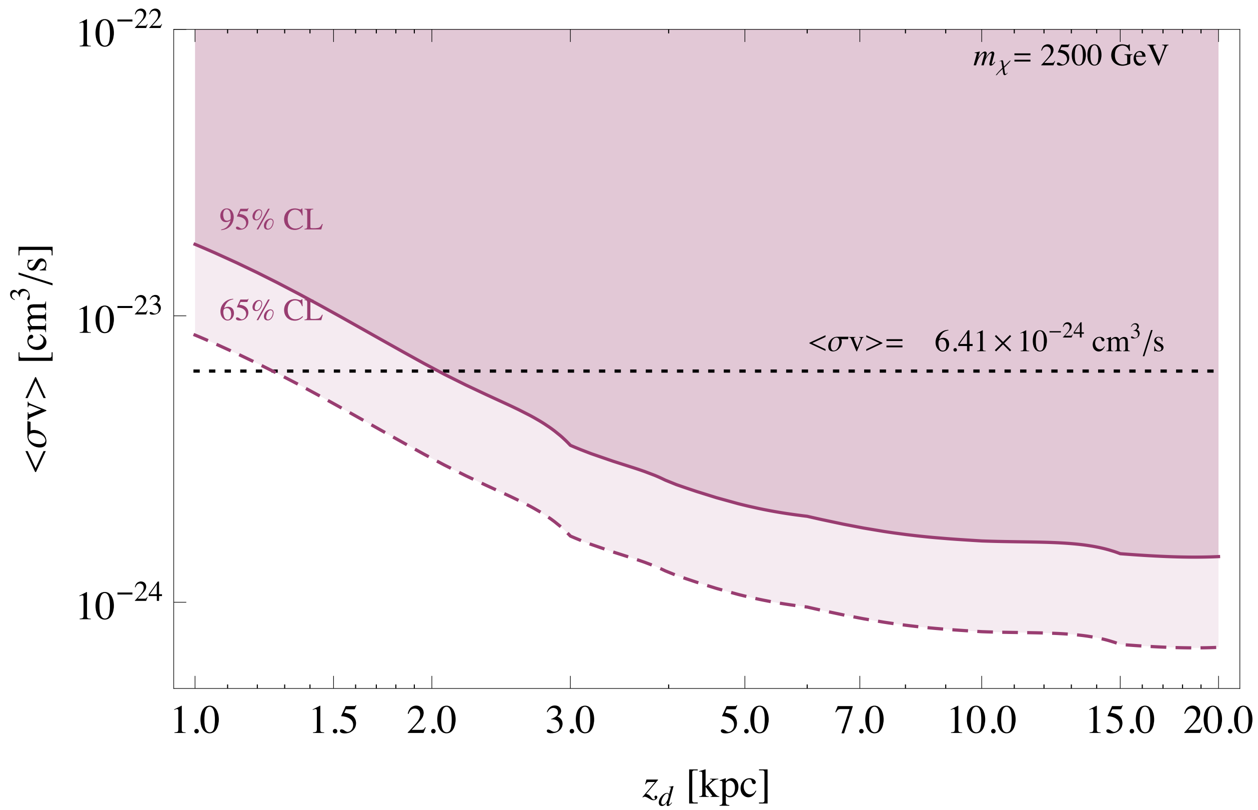
Benchmark			Fitted			Fitted		Goodness				
z_d [kpc]	δ	r_d [kpc]	$D_0 \times 10^{28}$ [cm^{2}s^{-1}]	v_A [km s^{-1}]	η	$\gamma_1^p/\gamma_2^p/\gamma_3^p$	$R_{0,1}^p$ GV	$\chi^2_{B/C}$	χ^2_p	$\chi^2_{\bar{p}}$	$\chi^2_{\bar{p}/p}$	$\chi^2_{\rm tot}$
1	0.45	20	0.47	15.0	-0.57	2.12/2.36/2.3	14.5	0.38	0.31	0.66	0.79	0.55
1.4	0.45	20	0.70	15.0	-0.57	2.12/2.36/2.3	14.5	0.39	0.26	0.59	0.94	0.63
1.7	0.45	20	0.89	16.8	-0.57	2.12/2.36/2.3	14.5	0.42	0.24	0.58	0.71	0.52
2	0.45	20	1.12	18.8	-0.57	2.12/2.36/2.3	14.5	0.57	0.4	0.57	0.54	0.53
3	0.45	20	1.65	18.0	-0.57	2.18/2.37/2.3	14.0	0.44	0.49	0.54	0.52	0.55
4	0.45	20	2.2	18.0	-0.57	2.20/2.37/2.3	14.0	0.54	0.41	0.47	0.47	0.52
6	0.45	20	3.08	19.0	-0.57	2.18/2.37/2.3	14.0	0.65	0.47	0.45	0.47	0.52
8	0.45	20	3.6	18.5	-0.57	2.18/2.37/2.3	14.0	0.51	0.50	0.48	0.47	0.53
10	0.45	20	4.1	19.5	-0.57	2.10/2.35/2.2	15.5	0.62	0.90	0.47	0.50	0.69
15	0.45	20	4.6	18.5	-0.57	2.10/2.35/2.2	15.5	0.56	0.95	0.50	0.51	0.72
20	0.45	20	5.0	17.5	-0.57	2.10/2.34/2.2	14.2	0.56	0.53	0.46	0.47	0.53

Antiprotons:



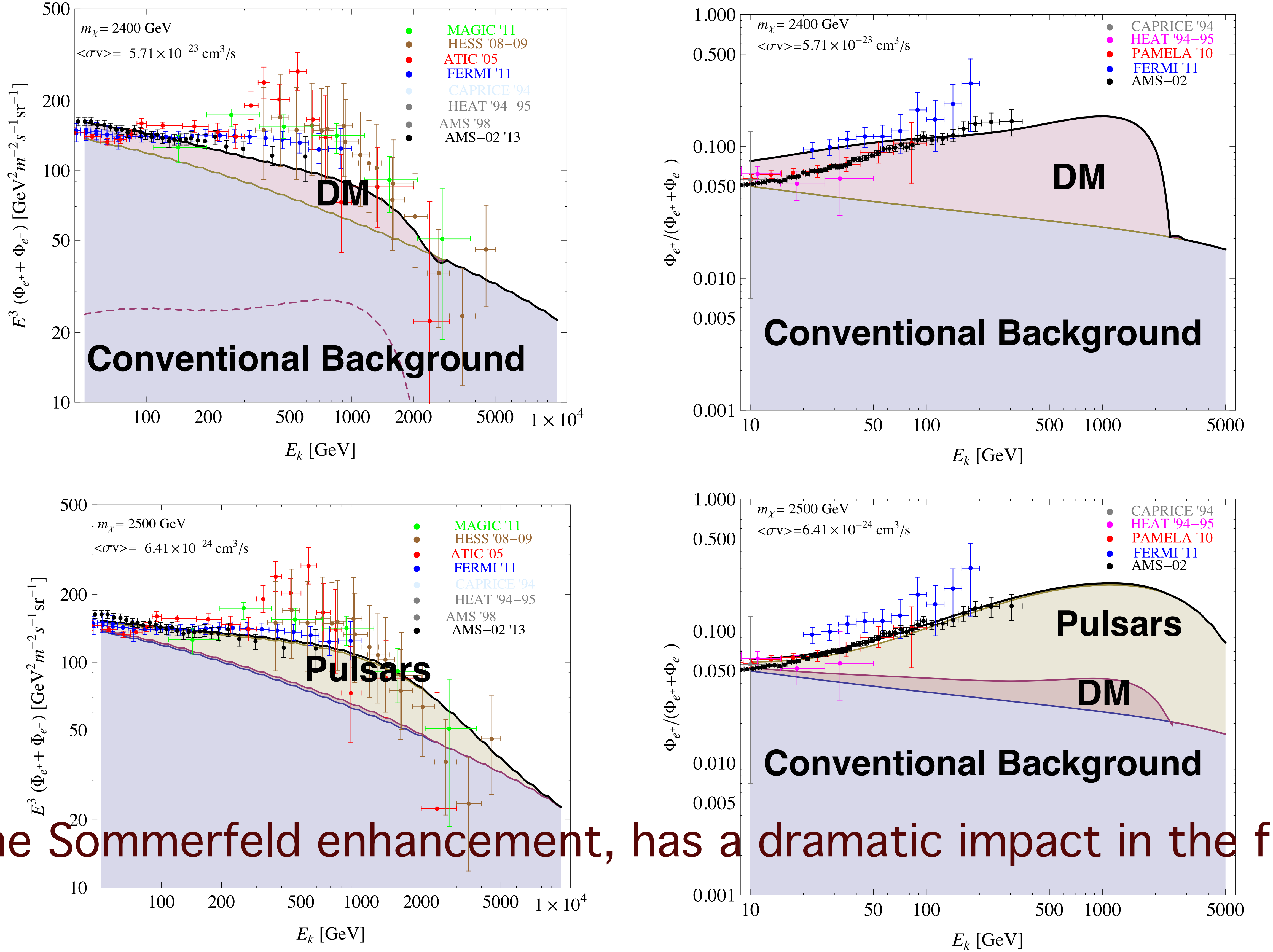
Limits:





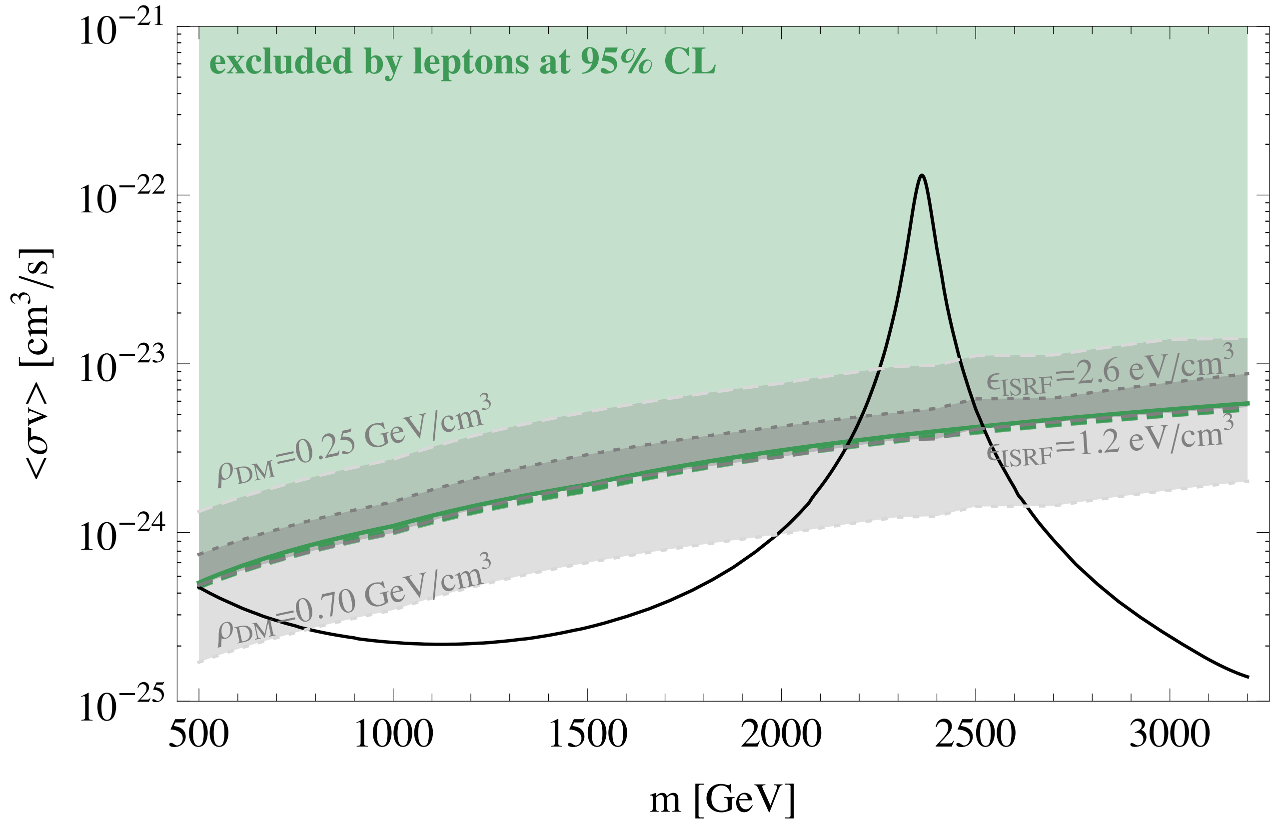
Sommerfeld enhancement corrections are important even at "light" Wino masses, Astrophysical Uncertainties, related to the diffusion properties of CR antiprotons are still significant. Yet, the resonance is always excluded.

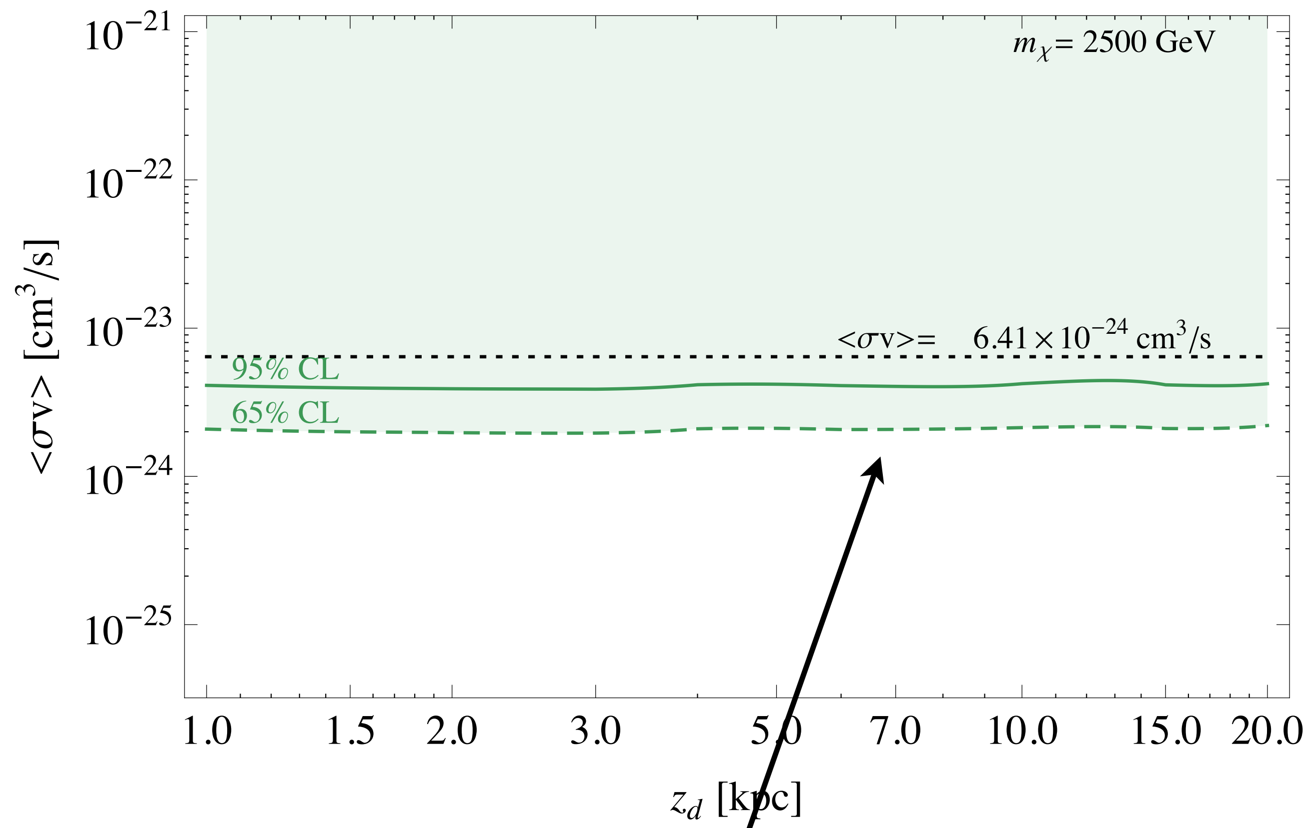
Electrons, Positrons:



The Sommerfeld enhancement, has a dramatic impact in the flux

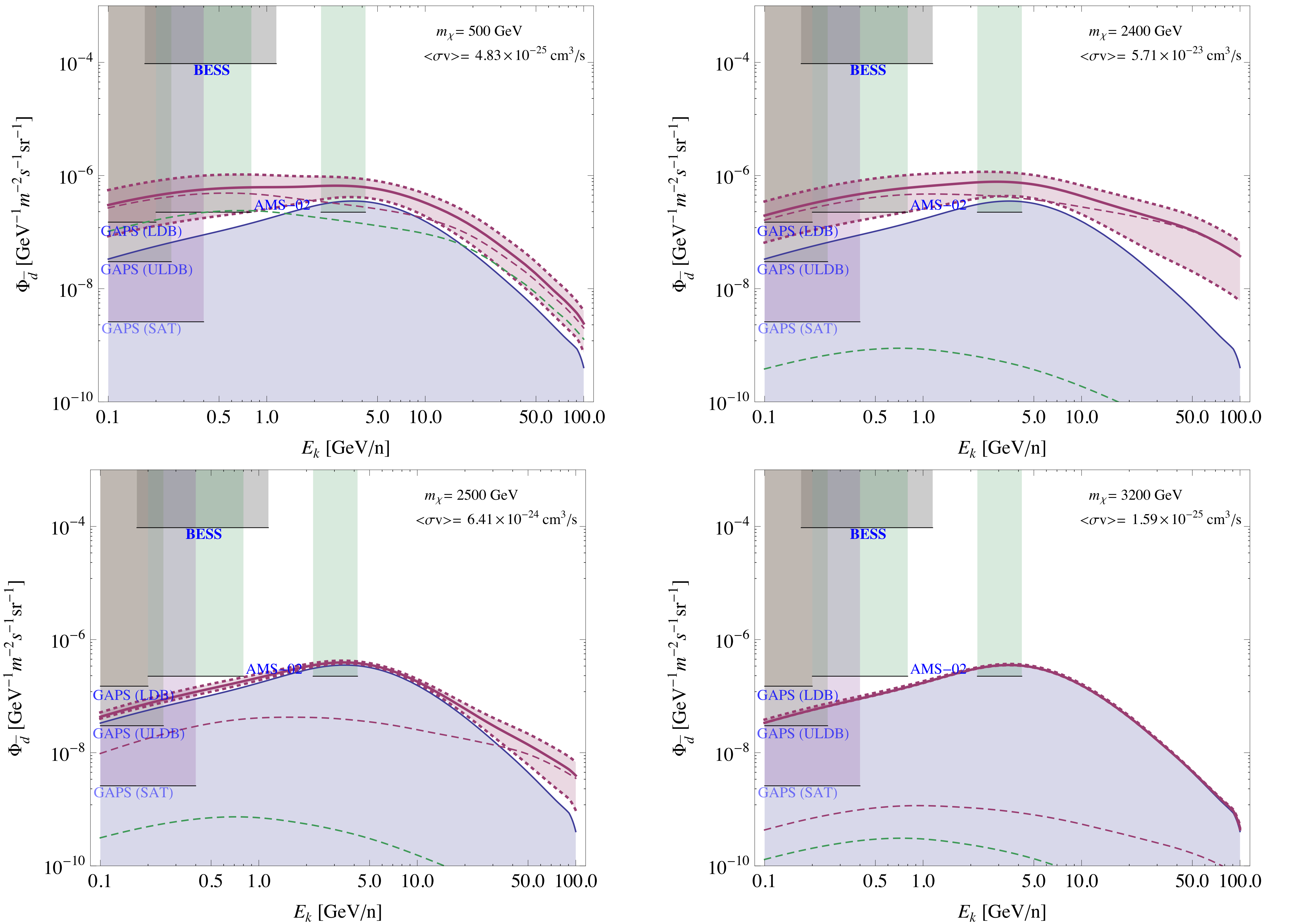
Limits:





Astrophysical Uncertainties, related to the diffusion properties of CR electrons, positrons are insignificant. Local energy losses and the local DM density are the most important astrophysical uncertainties in this probe. AGAIN, the resonance is always excluded.

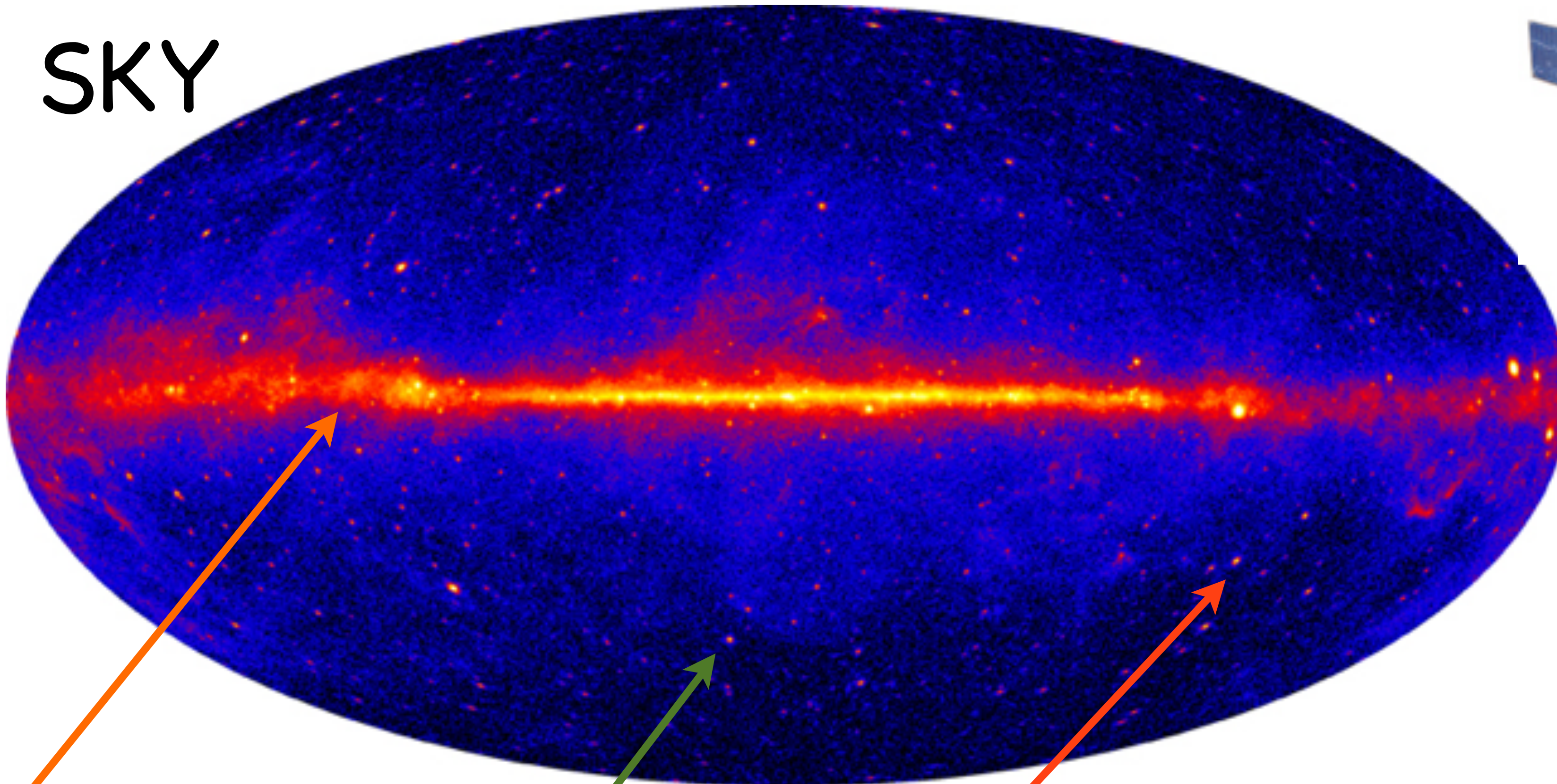
Anti-deutrons; a probe for the future

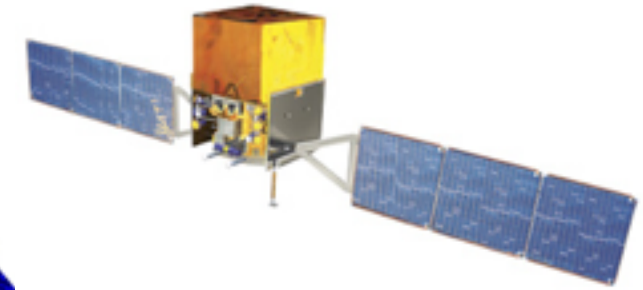


GAPS is the most sensitive experiment

Gamma-rays

Fermi SKY





Known sources for the observed gamma-rays are:

i)Galactic Diffuse: decay of pi0s (and other mesons) from pp (NN) collisions (CR nuclei inelastic collisions with ISM gas), bremsstrahlung radiation off CR e, Inverse Compton scattering (ICS): up-scattering of CMB and IR, optical photons from CR e

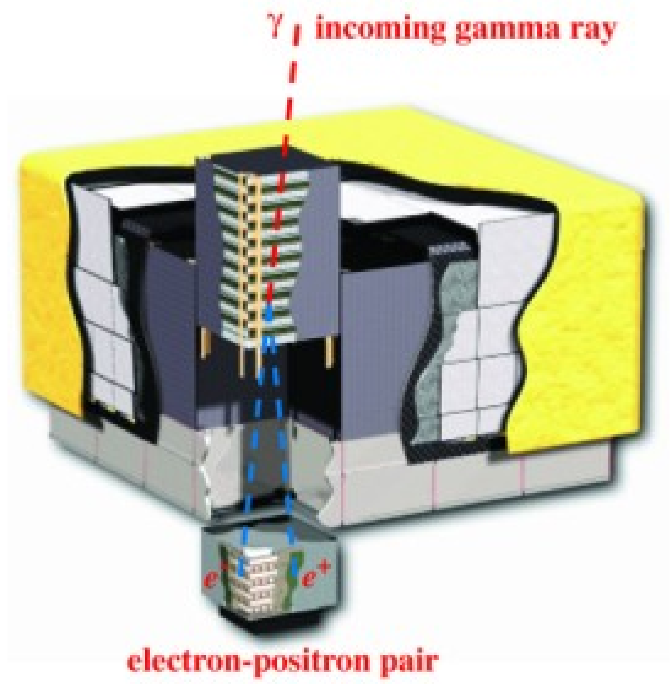
ii)from point sources (galactic or extra galactic) (1873 detected in the first 2 years)

iii)Extragalactic Isotropic

iv)"extended sources"

iv)misidentified CRs (isotropic dew to diffusion of CRs in the Galaxy)

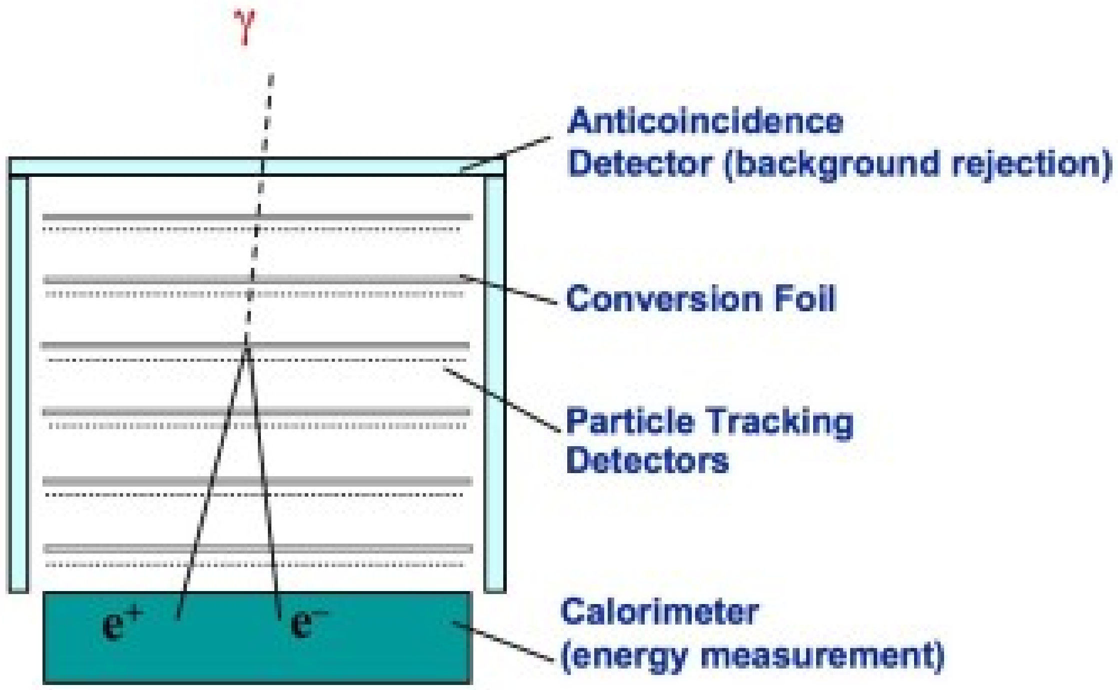
Fermi Large Area Telescope



The Fermi LAT is a pair conversion detector on board the Fermi Gamma-Ray Space Telescope.

Characteristics:

- Energy range: 20 MeV to above 300 GeV
- Field of view (FOV): 2.4 sr
- Energy resolution: <10% (above 10 GeV)
- Angular resolution: < 0.15º (above 10 GeV)
- Launched: 2008
- Will continue at least until 2014/2016



Main components:

Anti-coincidence shield (plastic scintillator) with photomultiplier tubes

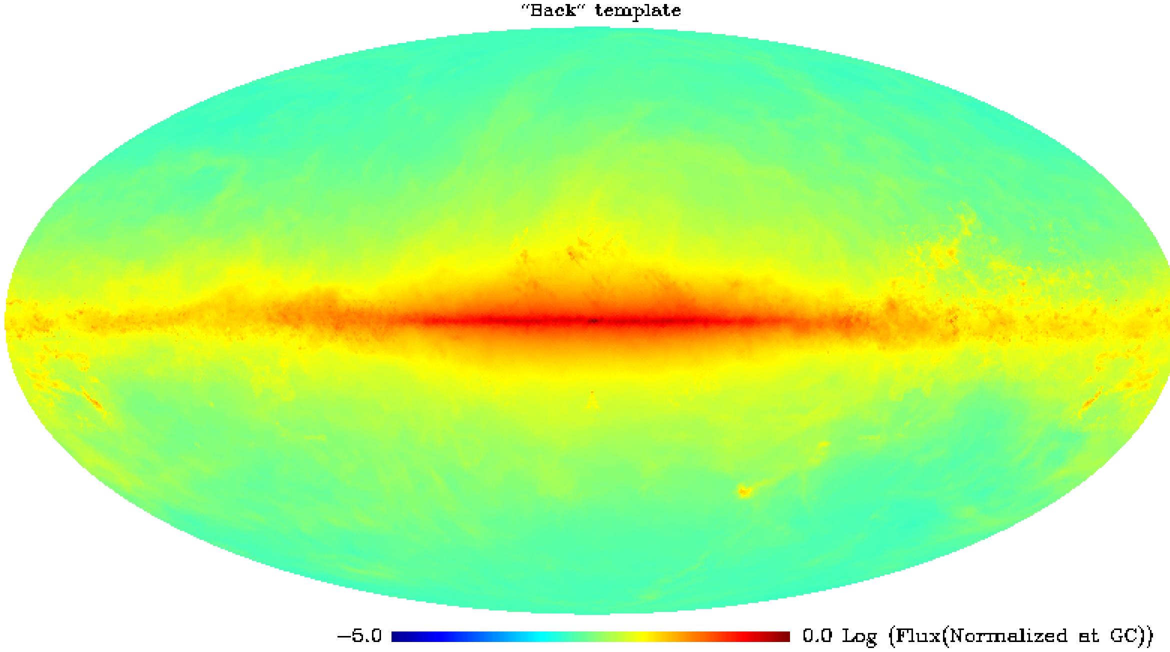
Tracker (silicon strip detectors) with conversion foils (tungsten)

Electromagnetic Calorimeter (CsI)

Diffuse Gamma-Ray maps, examples

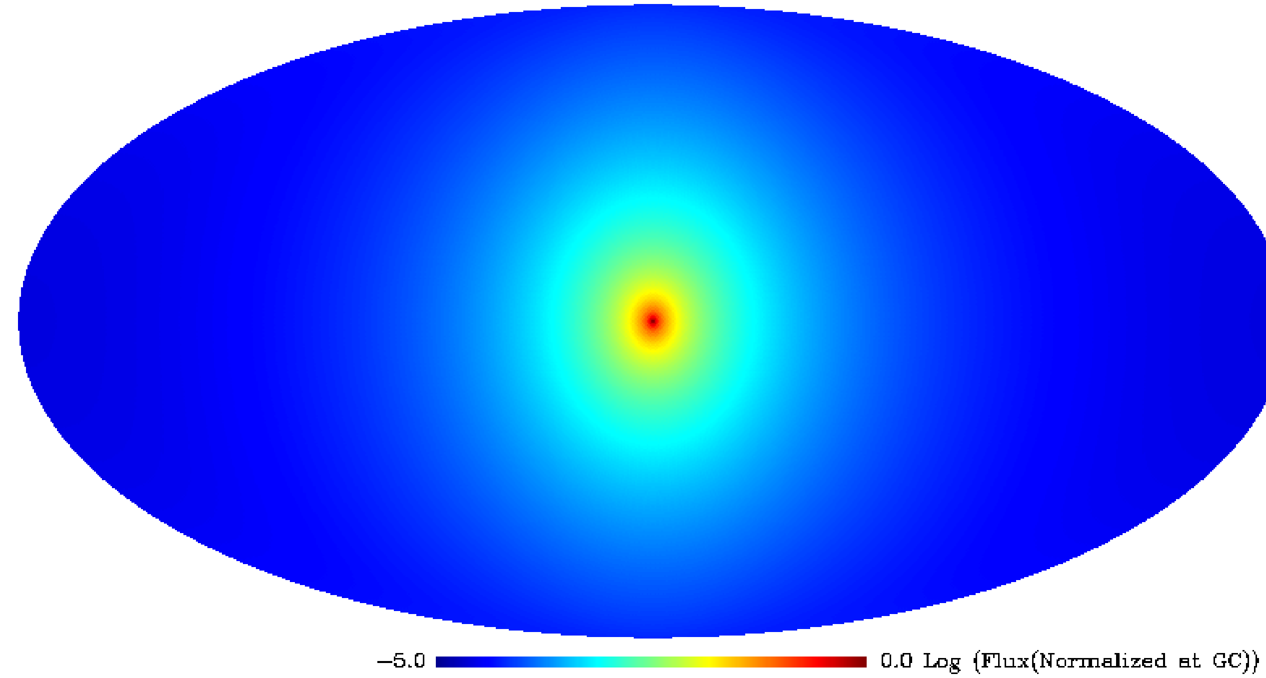
Galactic Diffuse Background at 106–116 & 123–135 GeV

"Back" template



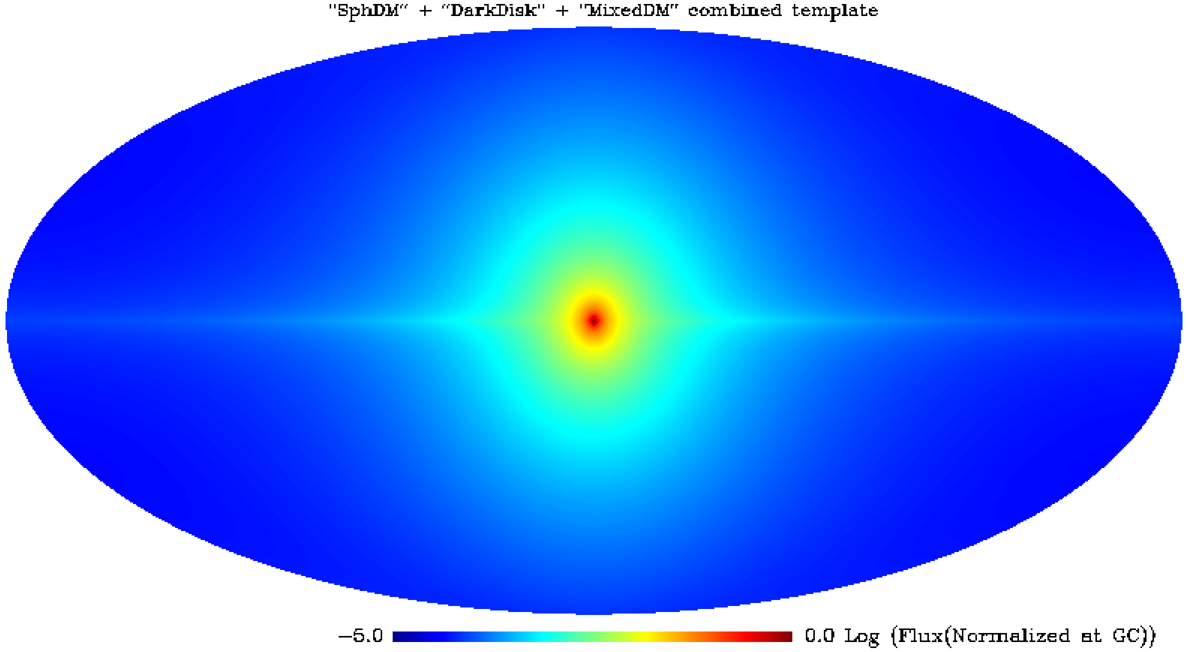
Spherical DM halo

"SphDM" template



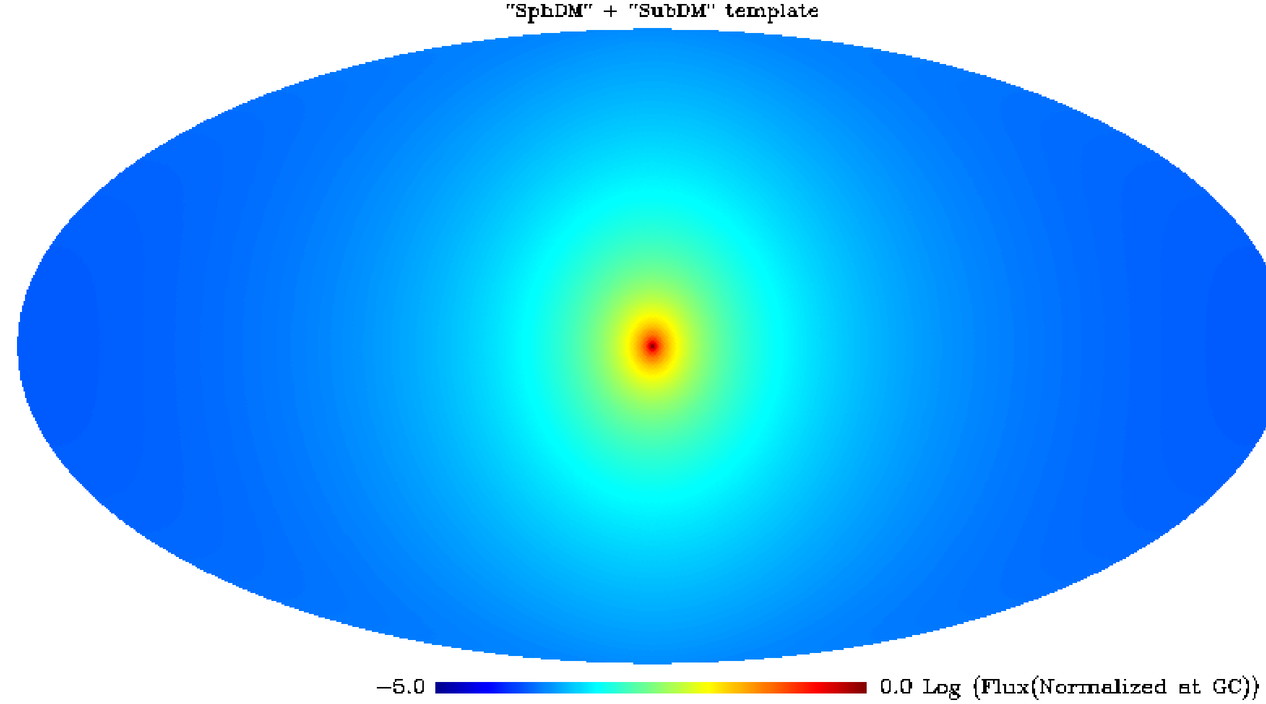
Spherical DM halo with a maximal dark disk Template

"SphDM" + "DarkDisk" + "MixedDM" combined template



Spherical DM halo & substructures

"SphDM" + "SubDM" template



$$\rho_{sph}(r) = \rho_{Ein} \exp\left\{-\frac{2}{\delta}\left[\left(\frac{r}{r_c}\right)^{\delta} - 1\right]\right\}$$

$$\rho_{DD}(R, z) = \rho_{0_{DD}} \exp\left[\frac{1.68\,(R_{\odot} - R)}{R_{1/2}}\right] \exp\left[-\frac{0.693\,|z|}{z_{1/2}}\right]$$

Looking for DM annihilation signals

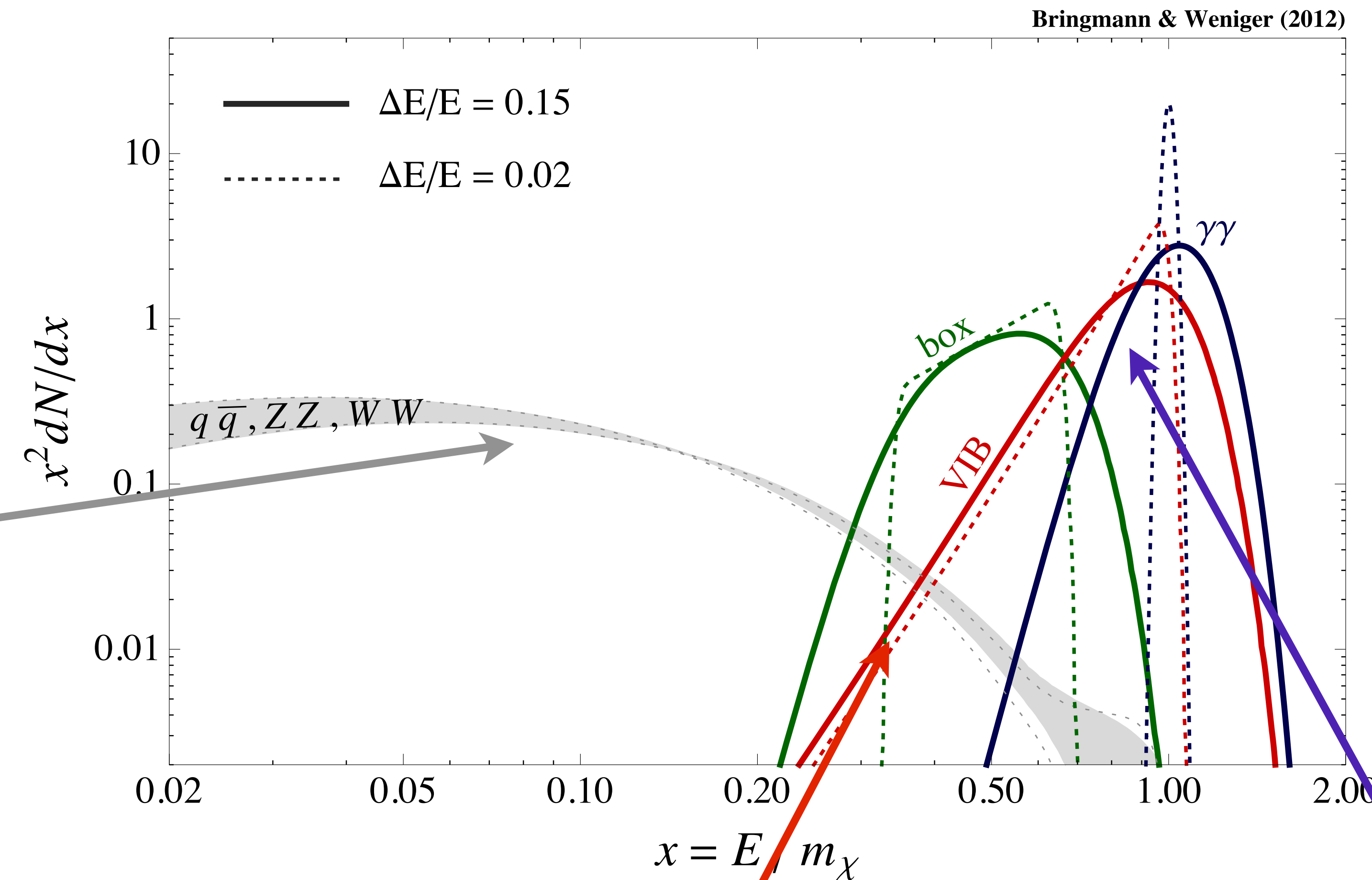
For a DM annihilation signal

We want to observe: $$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle\sigma v\rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho^2_{DM}(l,\Omega)}{2\, m^2_\chi} dl d\Omega$$

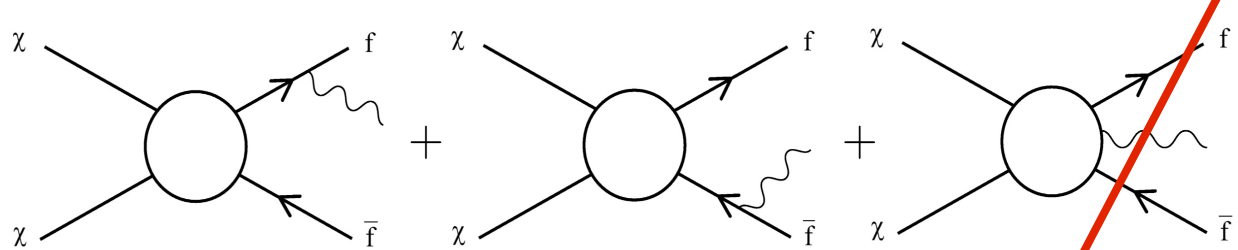
- Hardening of a spectrum without a clear cut-off localized in a certain region (Fermi haze->Fermi bubbles)
- Hardening of a spectrum with a clear cut-off: ~10 GeV DM claims towards the Galactic Center (GC) inner few degrees
- Line or lines
- One of the most likely targets is the GC (though backgrounds also peak), others are the known substructure (dSphs) or Galaxy clusters

DM annihilation spectra

Continuum emission, tree level, relatively hard spectrum, but featureless

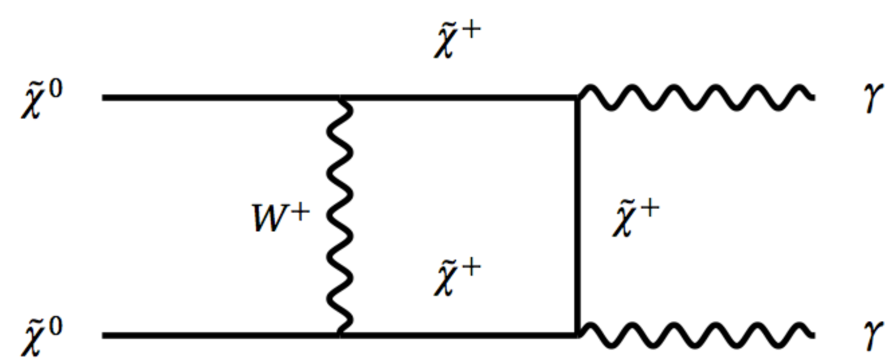


Two body annihilation to photons. Almost monochromatic Line, but suppressed at O(a^2).

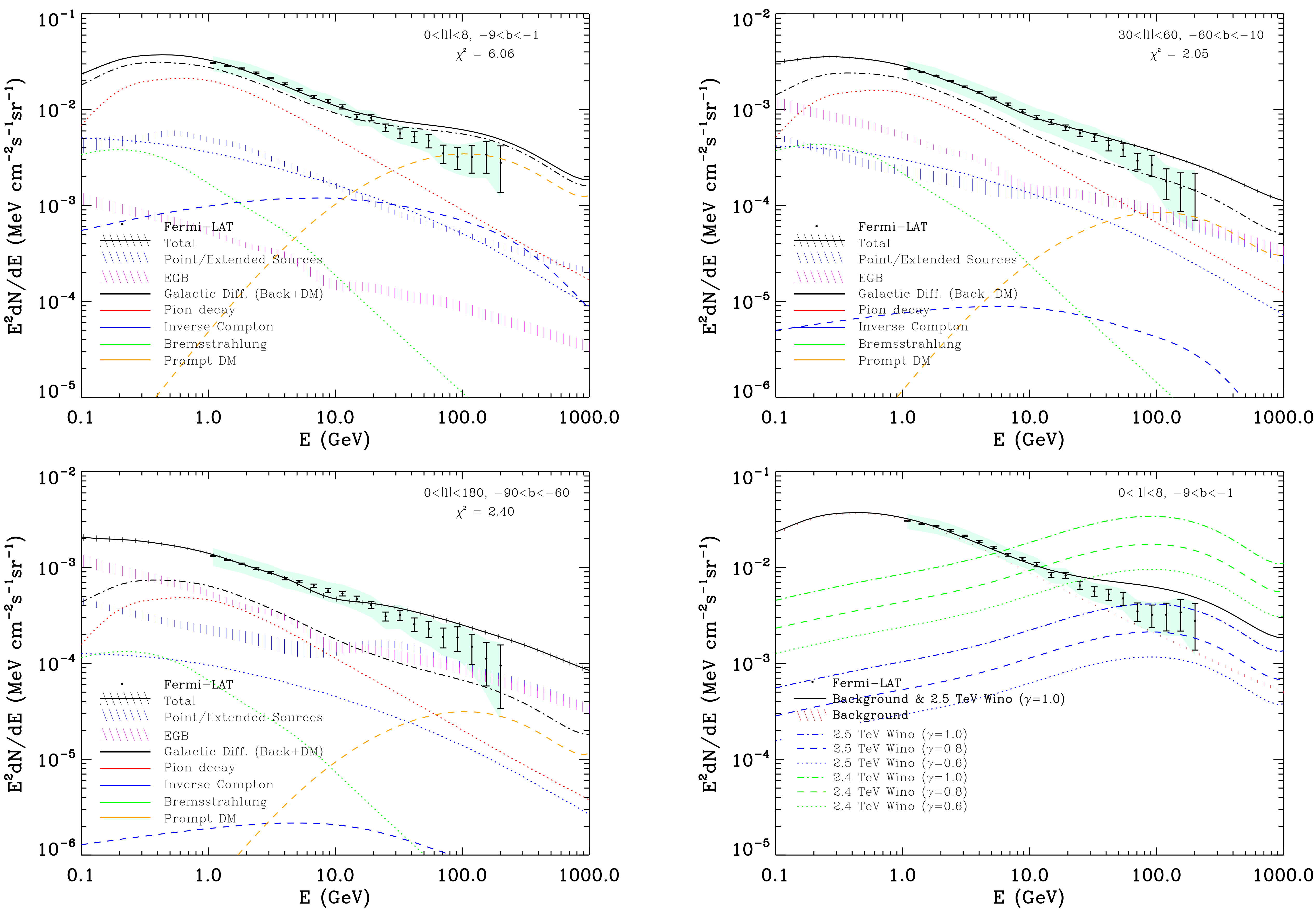


Final state radiation   Virtual Internal Bremss.

Comes from radiative corrections to processes with charged particles. Suppressed by O(a), but with a much harder spectrum; FSR has an additional suppression factor of (mf/Mchi)^2

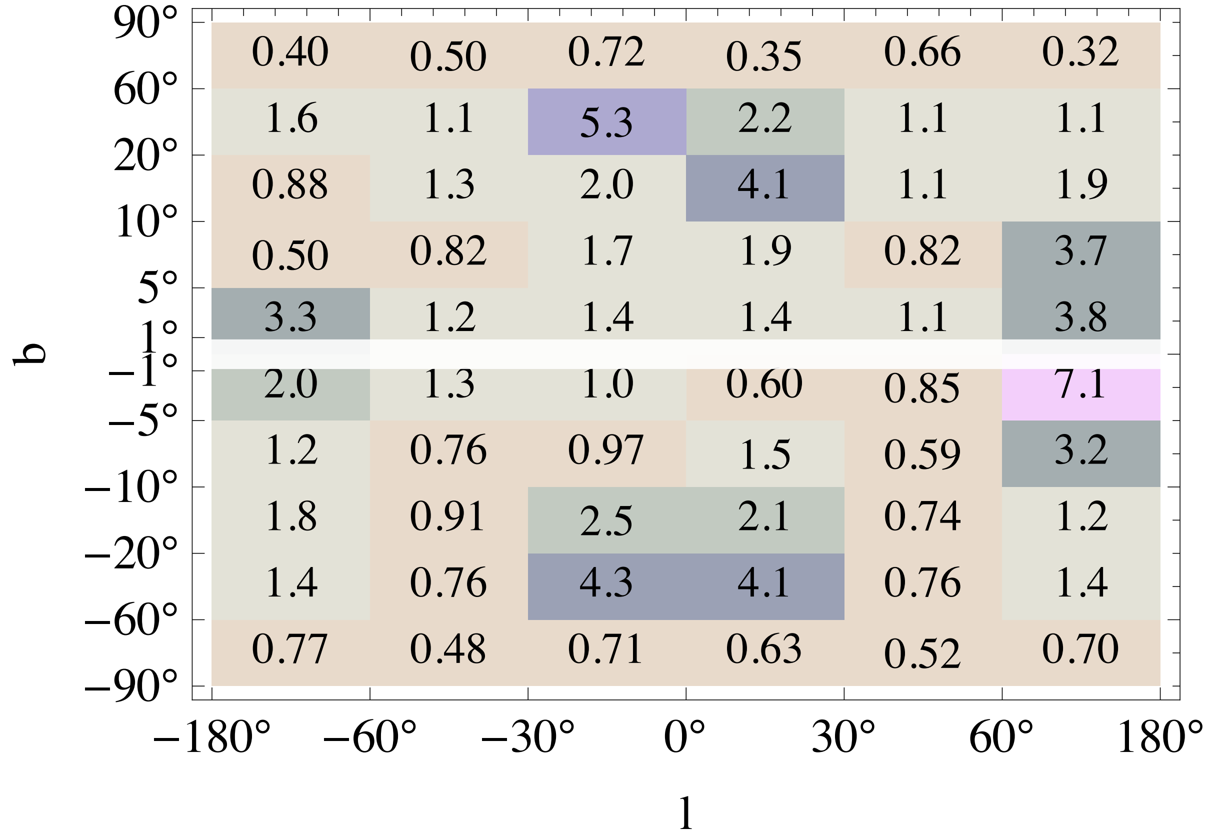


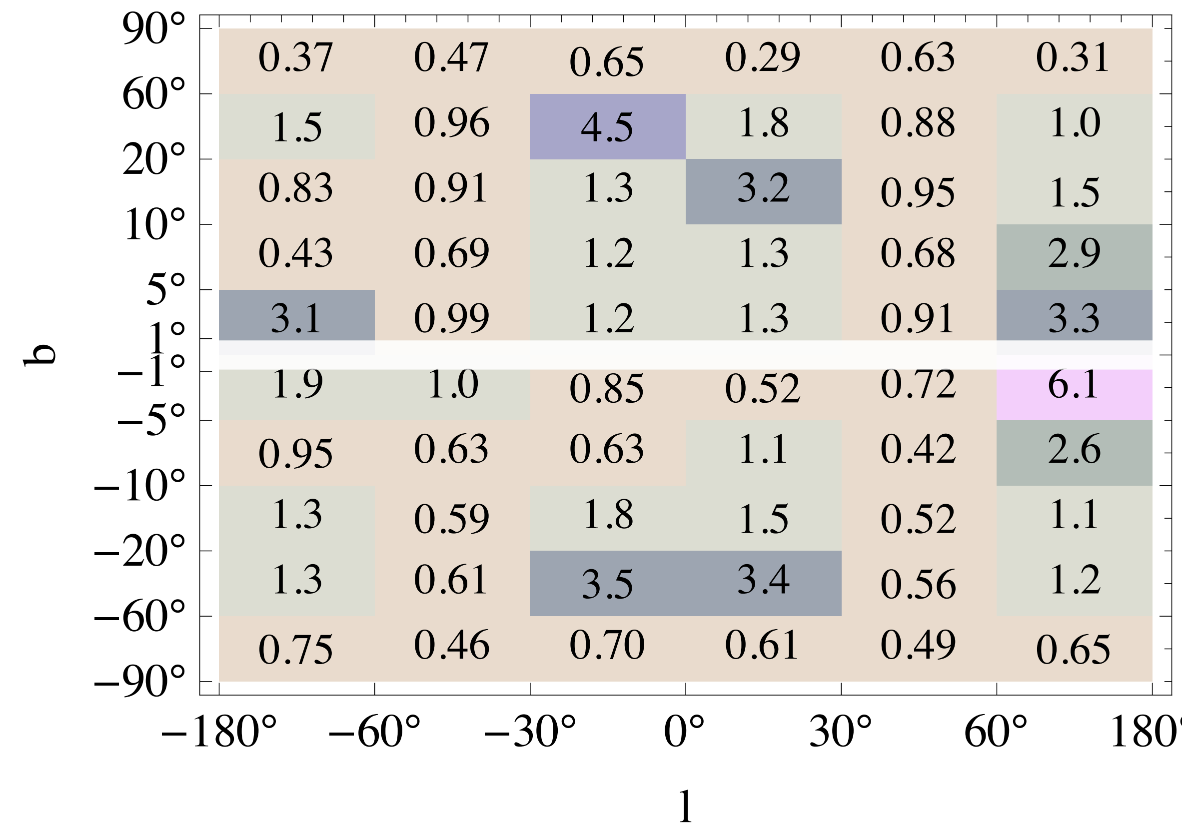
Calculating spectra in different patches of the sky

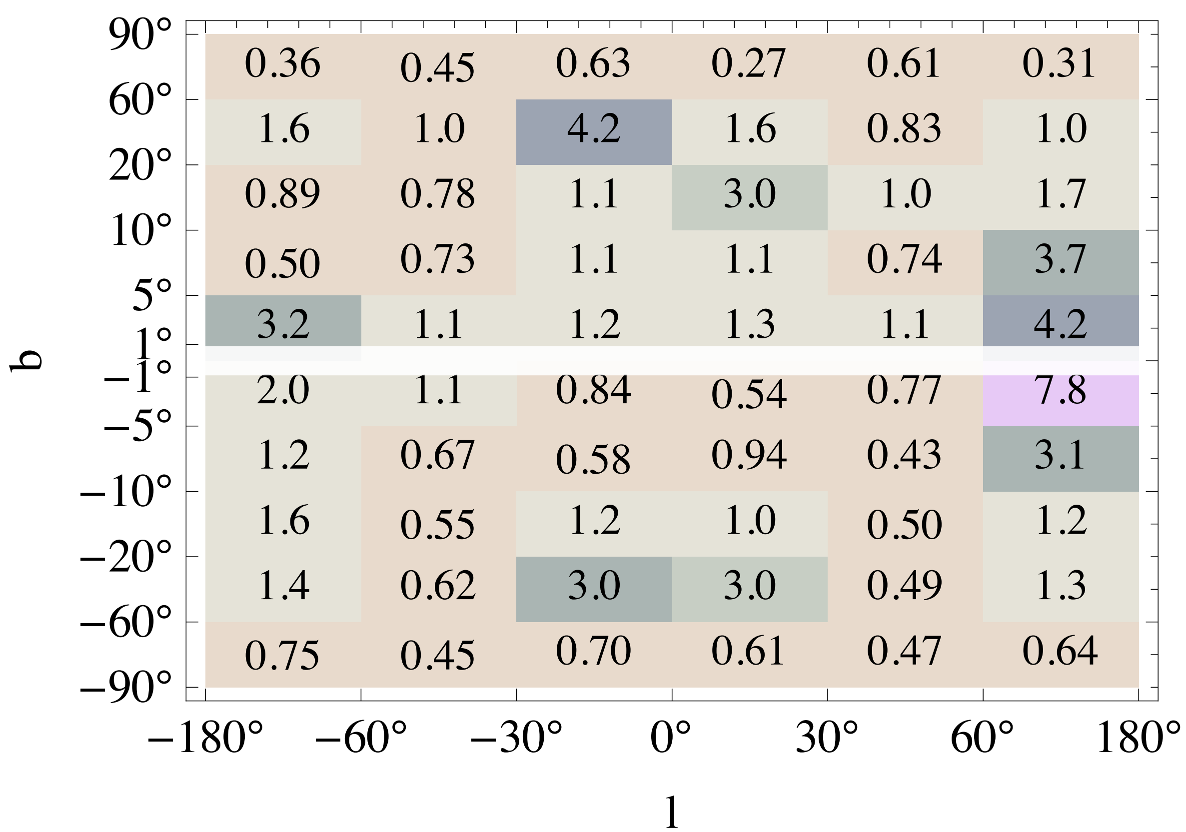


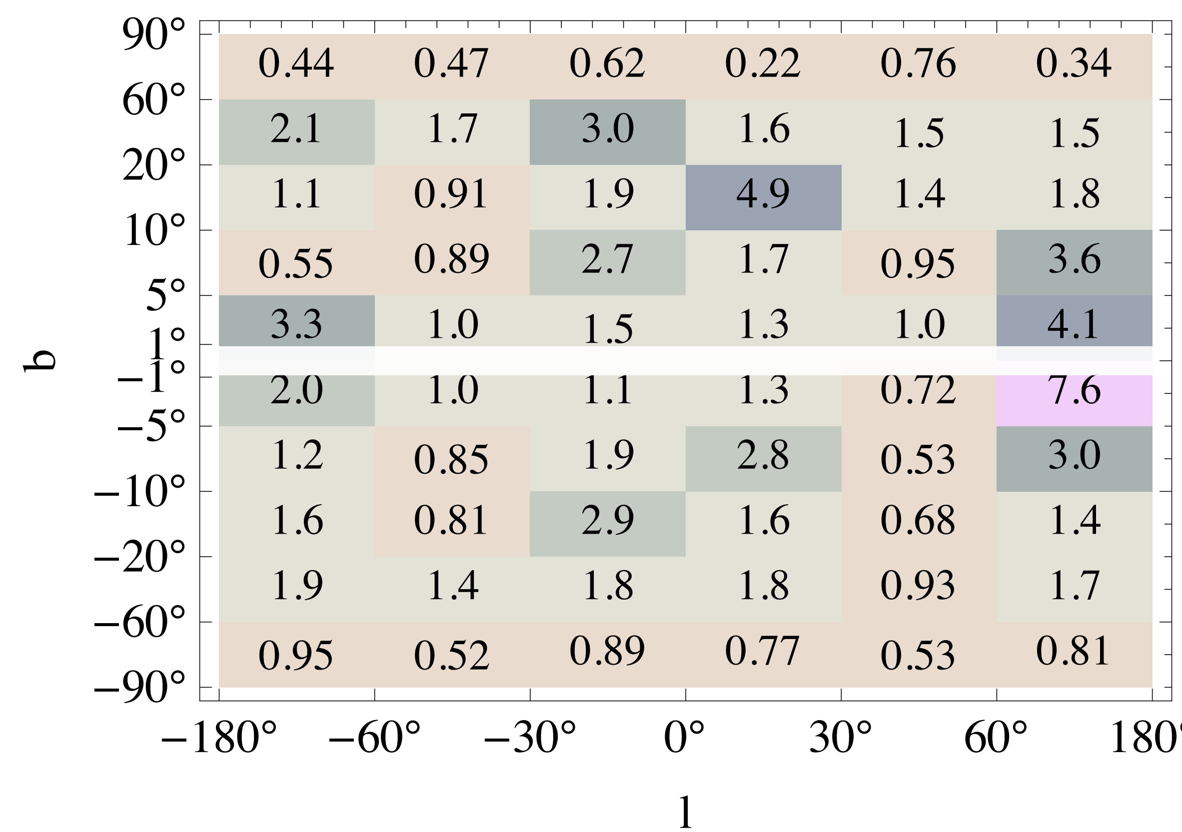
Comparison of models to Data

Different Choices of galactic CR diffusion:

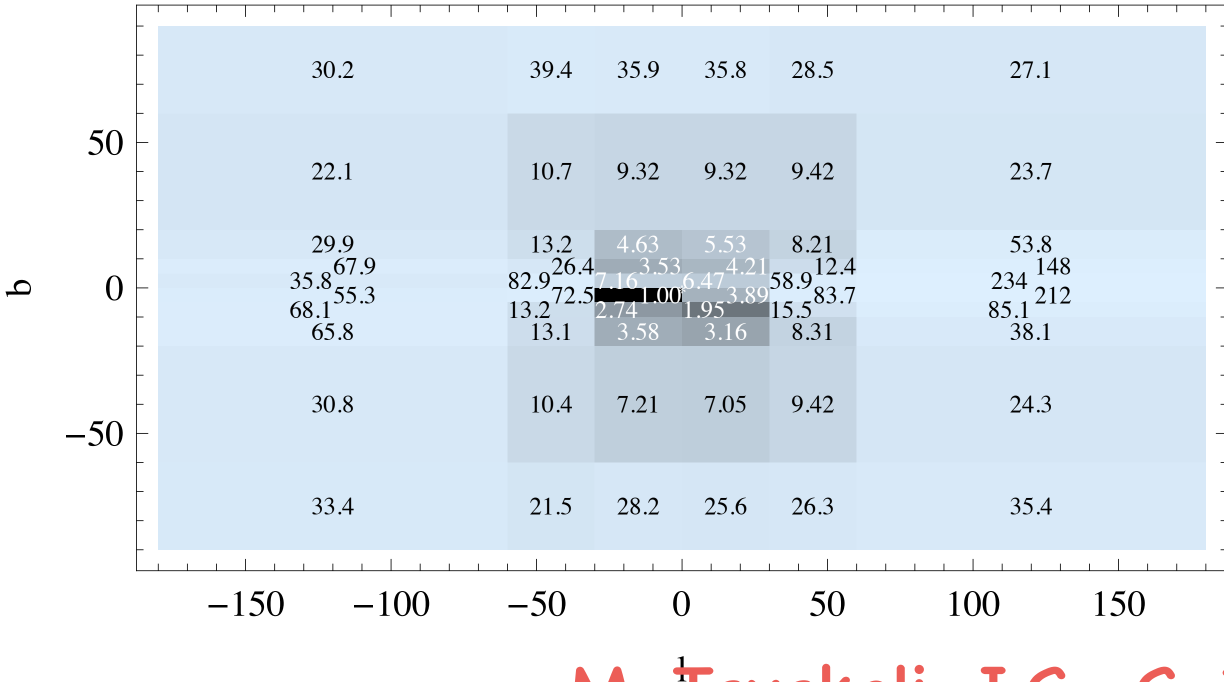


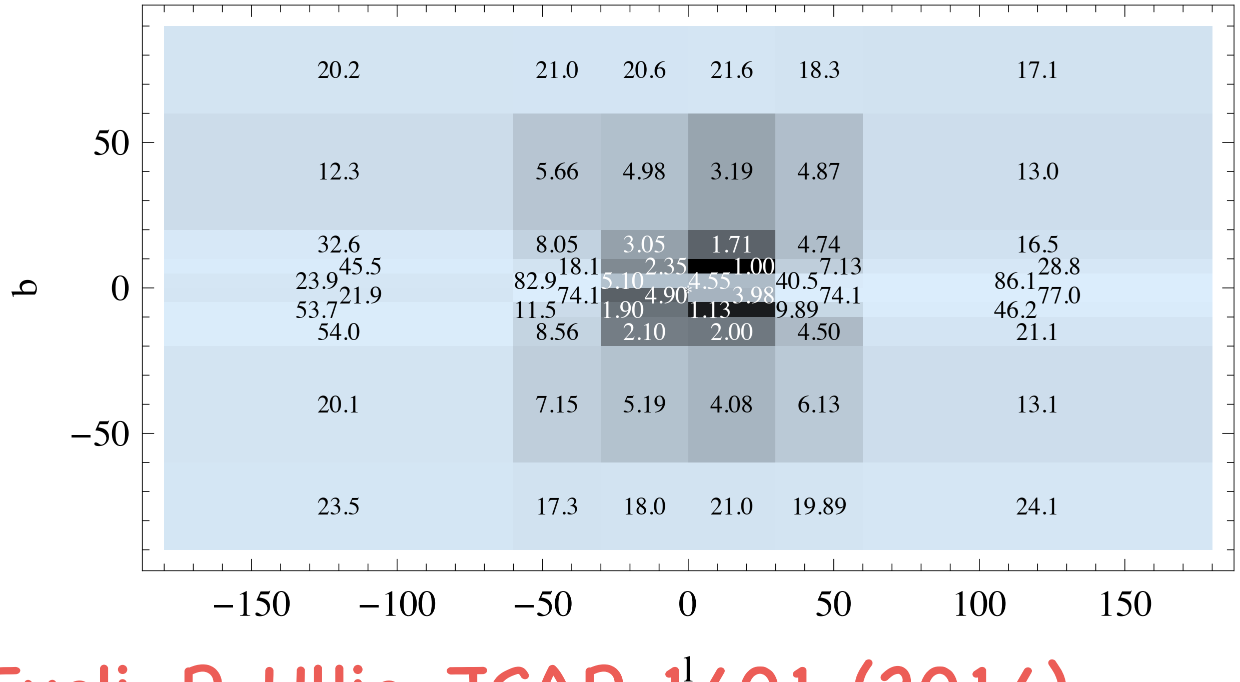






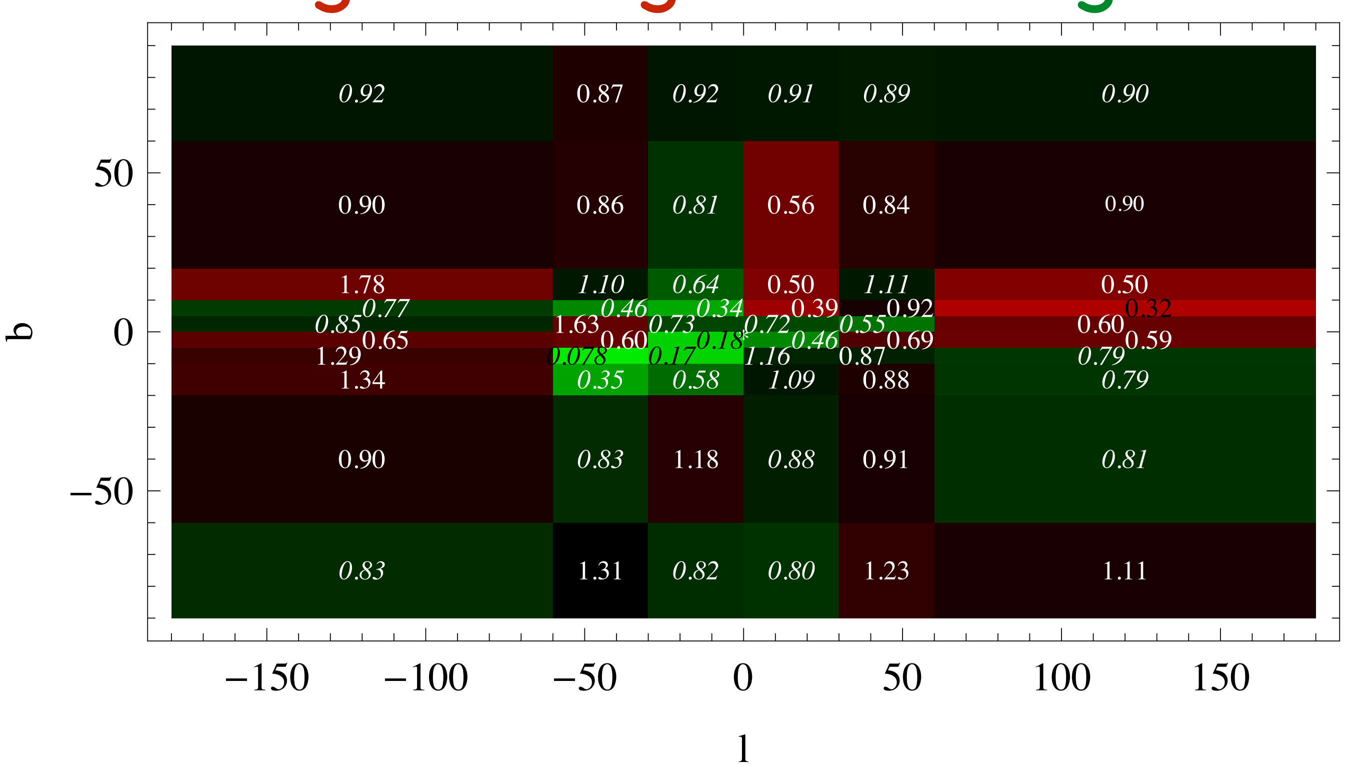
Limits on "light" Wino DM, in various patches of the sky (continuum emission)





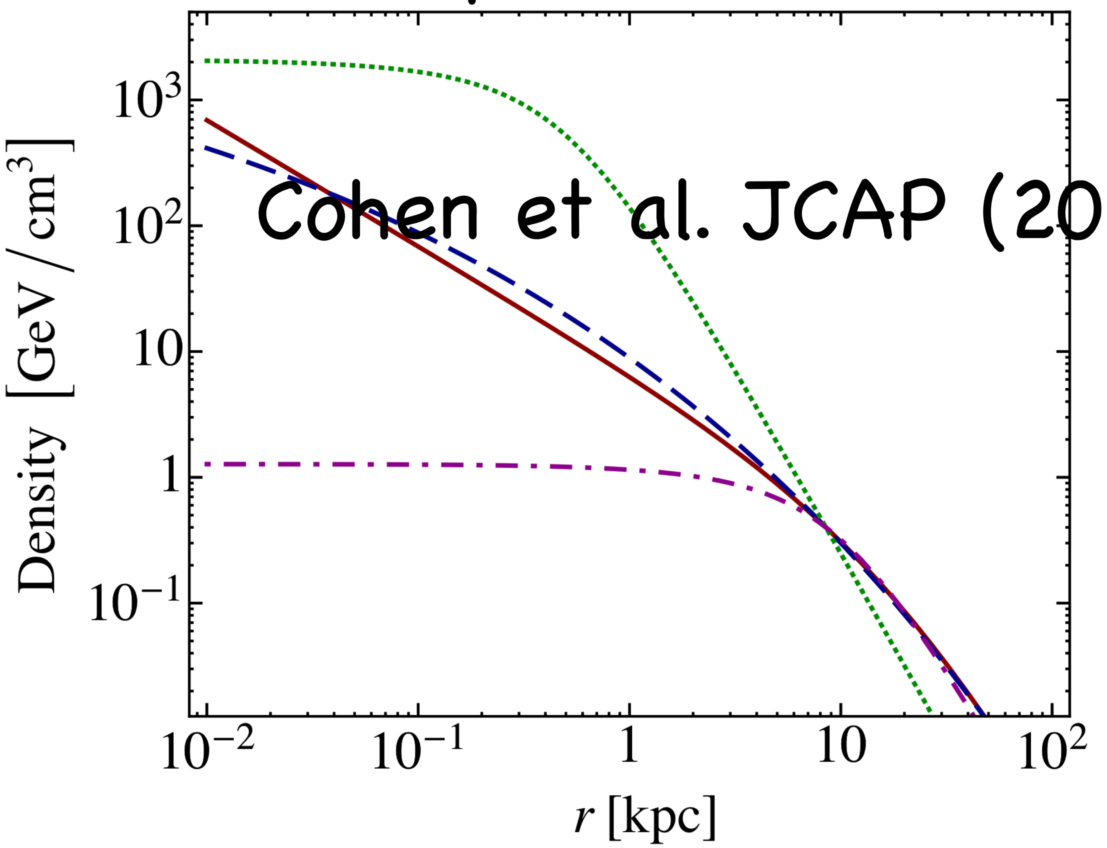
M. Tavakoli, I.C., C. Evoli, P. Ullio, JCAP 1401 (2014)

Impact of astrophysical uncertainties in Deriving Limits on DM, associated to the galactic gas or the galactic radiation field

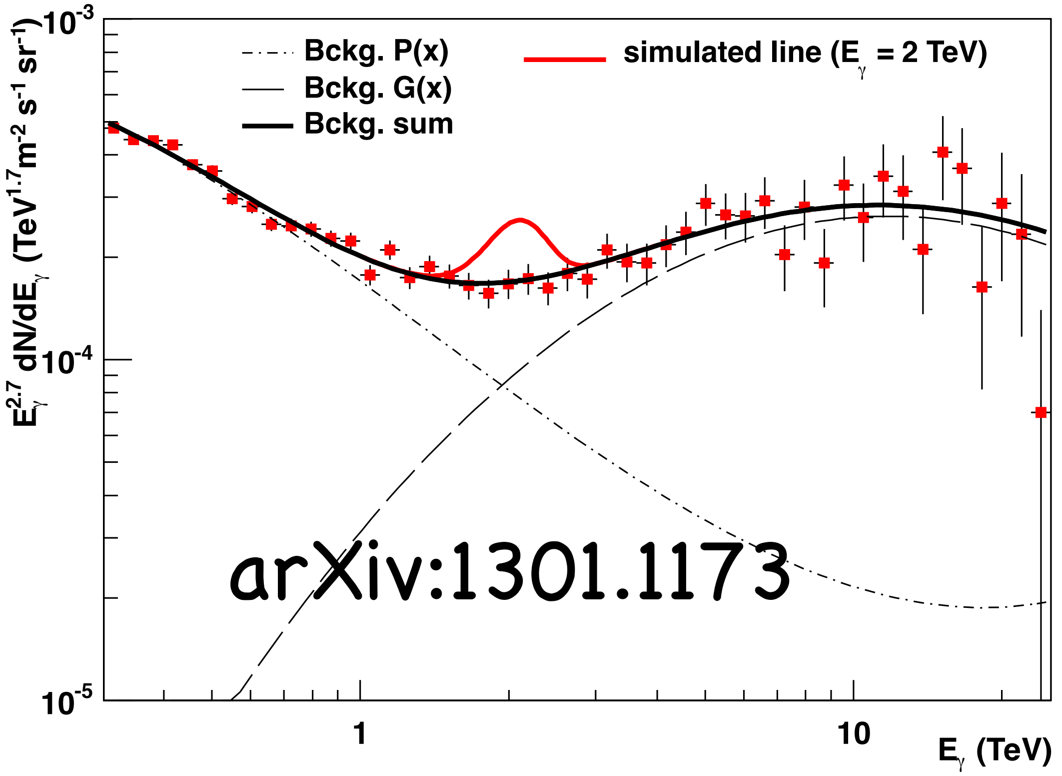


The case of a gamma-ray line at the galactic center

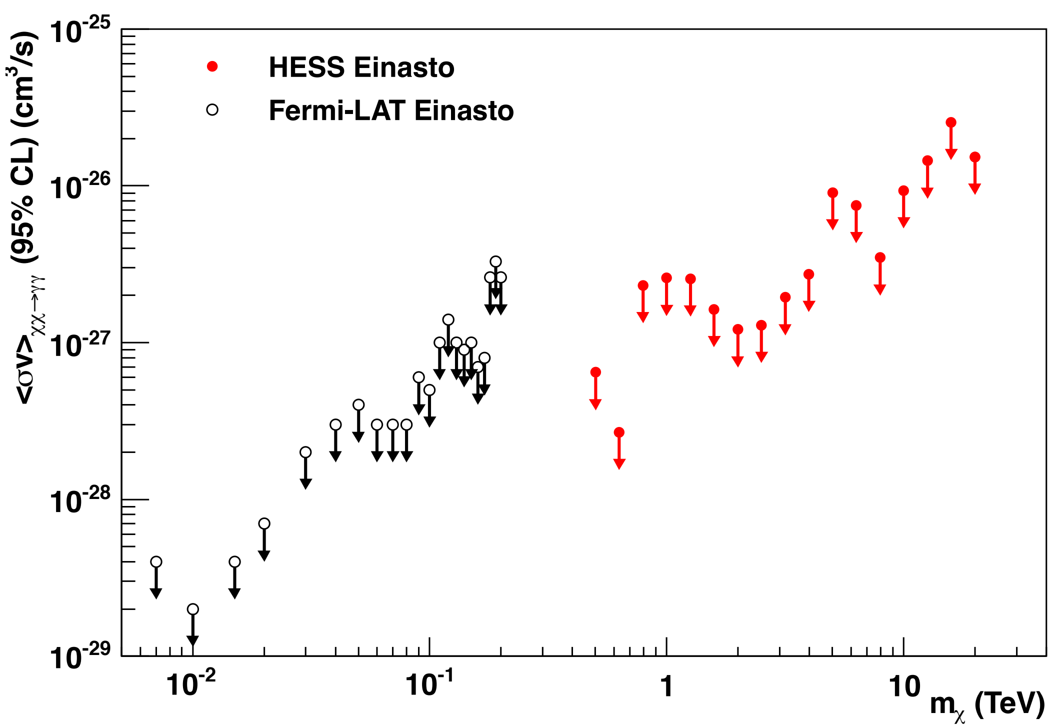
The DM profile:



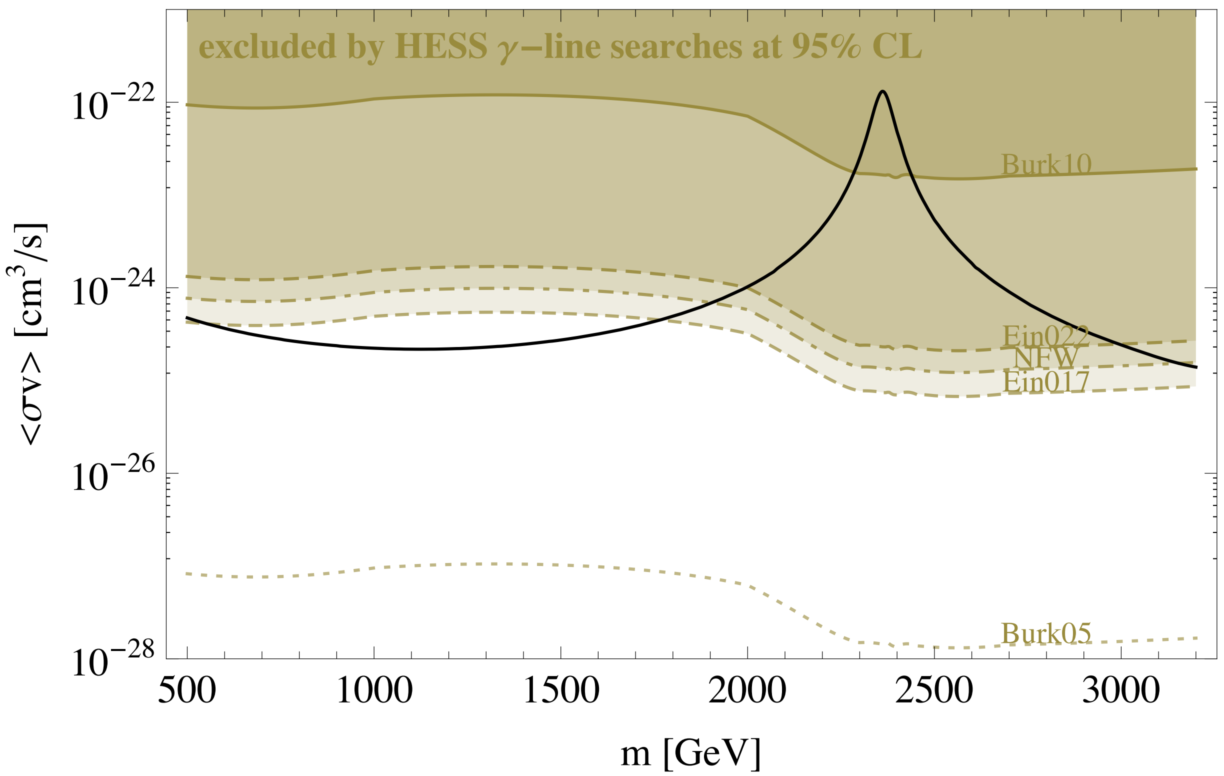
Looking for spectral features (HESS):



The Limits on spectral features:

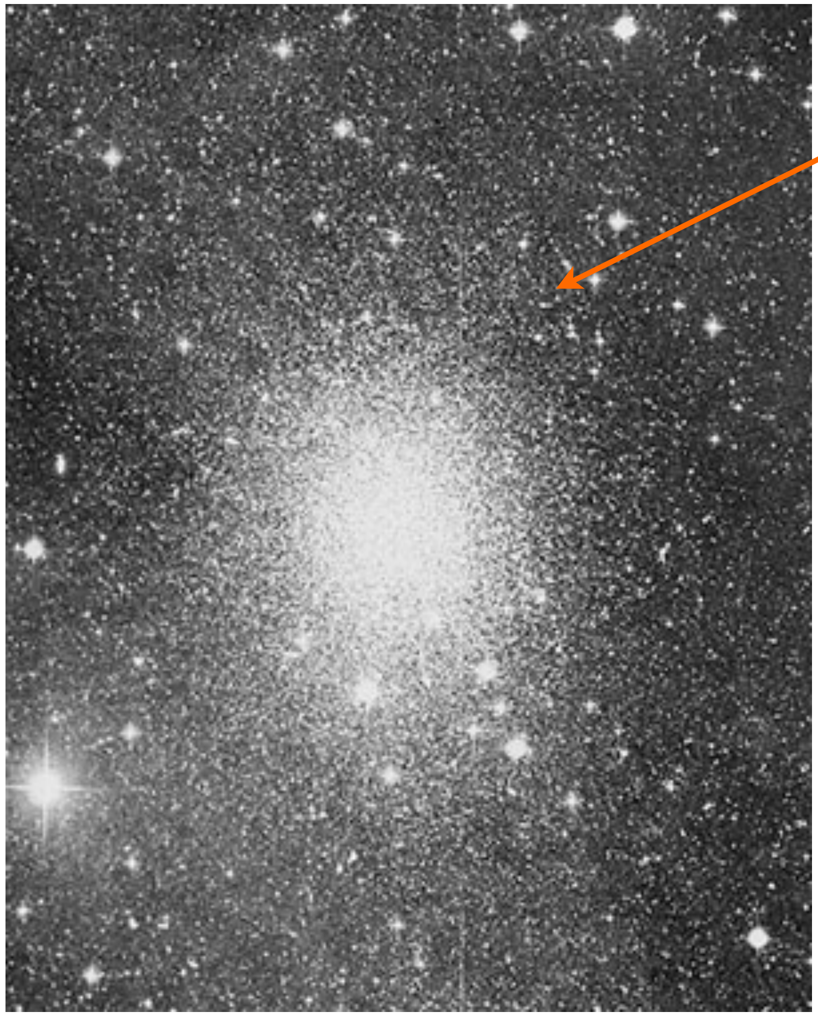


Wino Limits:



Significance of dwarf spheroidal galaxies for Dark Matter annihilation signals

Sculptor



dwarf Spheroidal galaxies are low luminosity galaxies (spheroidal in shape) containing ~10-100 million stars with the observed ones being companions to our Galaxy or to Andromeda. Their typical mass is ~ 100 times smaller than our galaxy.

Why we care:

among the most dark matter-dominated galaxies with very low baryonic gas densities, and suppressed star formation rates ->

flux of gamma-rays from individual sources and CRs interacting with local medium is low (small backgrounds in gammas),

thus a "good" target to look for a DM signal in gamma-rays, especially for detectors as the

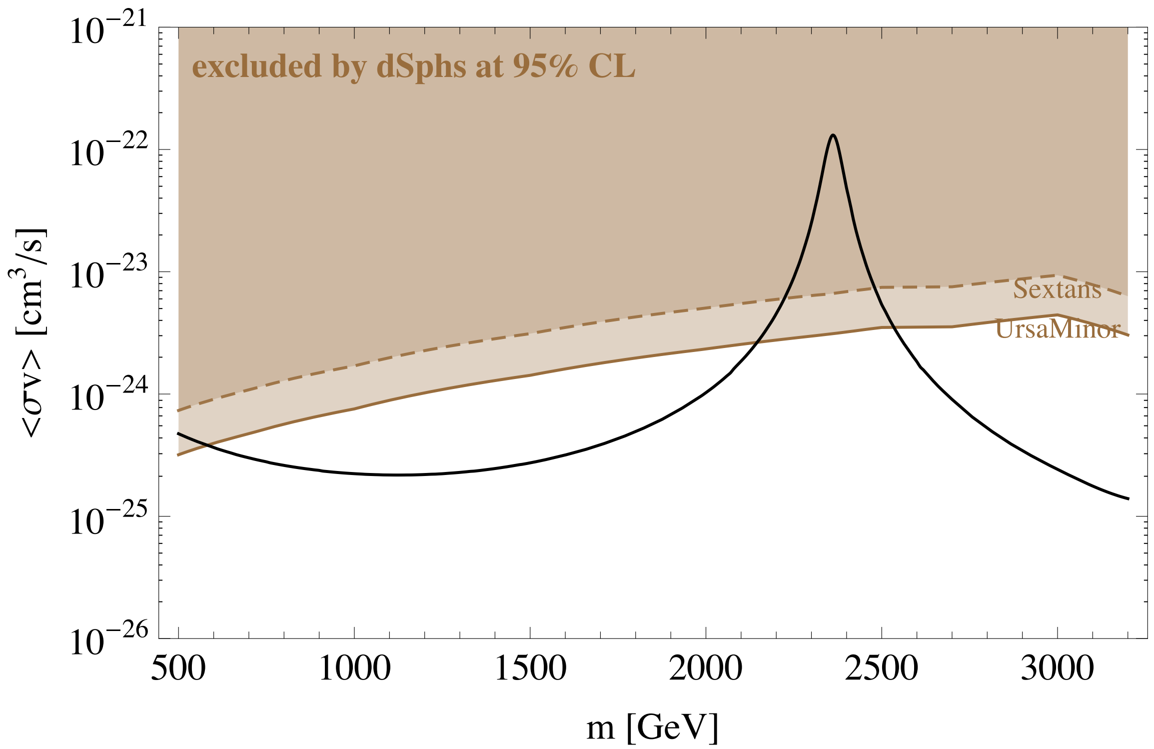
Fermi-LAT, Air-Cherenkov telescopes

(Evans,Ferrer&Sarkar 04, Colafrancesco,Profumo,Ullio 07, Strigari, Koushiappas, Bullok, Koplinghat 07, ...)

Selecting Optimal search targets (IC & Paolo Salucci PRD 86 (2013))

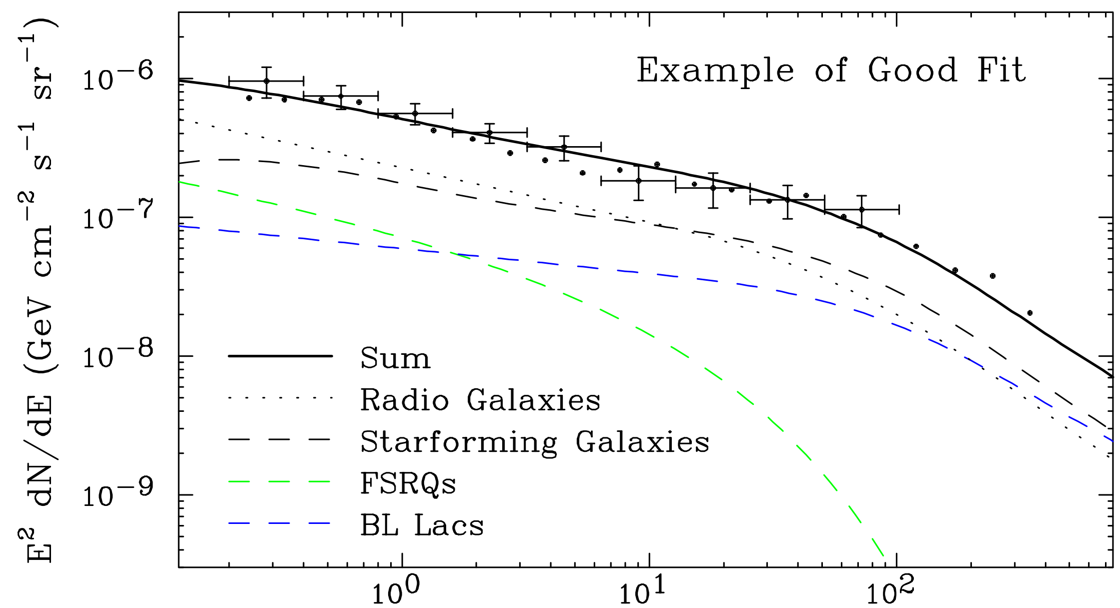
	Ursa Minor			Sextans		
Mass [GeV]	90% CL	95% CL	99.9% CL	90% CL	95% CL	99.9% CL
500	0.66	0.94	2.13	1.52	2.02	4.02
1000	3.19	4.77	11.8	7.17	9.67	19.7
2360	0.020	0.031	0.079	0.043	0.059	0.123
2400	0.033	0.051	0.132	0.071	0.097	0.203
2500	0.55	0.83	2.14	1.16	1.59	3.31
2700	3.69	5.61	14.46	7.84	10.7	22.4
3200	14.7	22.4	58.0	30.4	41.9	87.9

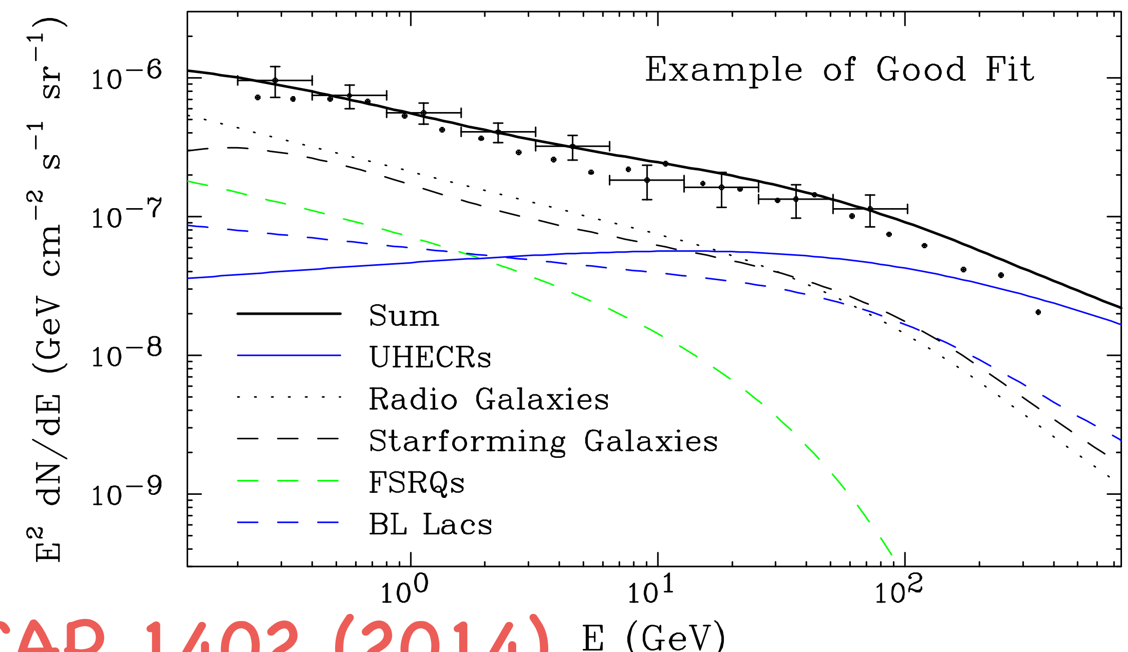
Table 3. The upper limits on the boost factors coming from two dSphs: Ursa Minor and Sextans. Values of BFs smaller than one suggest the model is excluded.



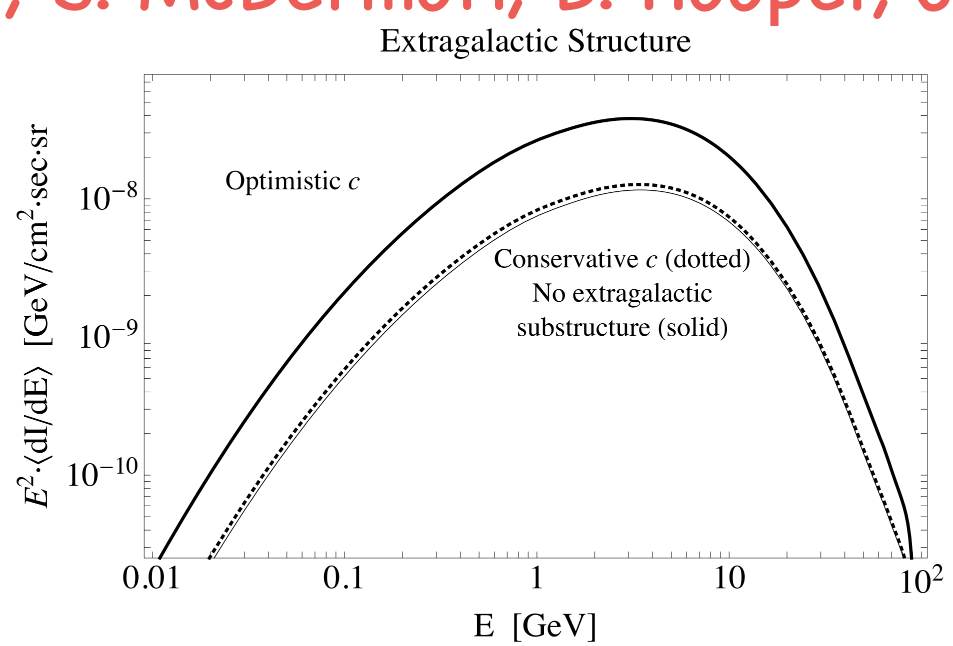
Constraints from High Latitudes (mainly extragalactic)

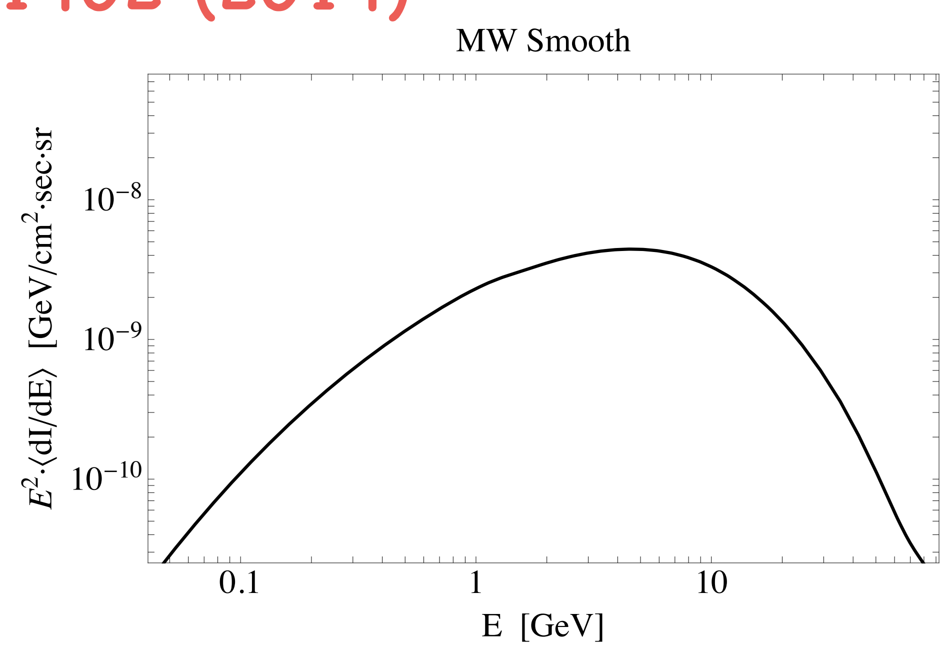
Extragalactic diffuse gamma-rays are isotropically distributed.There are many astrophysical sources that suffer from relatively large uncertainties. Correlating to radio we can extract some of their properties and model them out. —> Build models for the non-DM contribution and derive limits on DM.





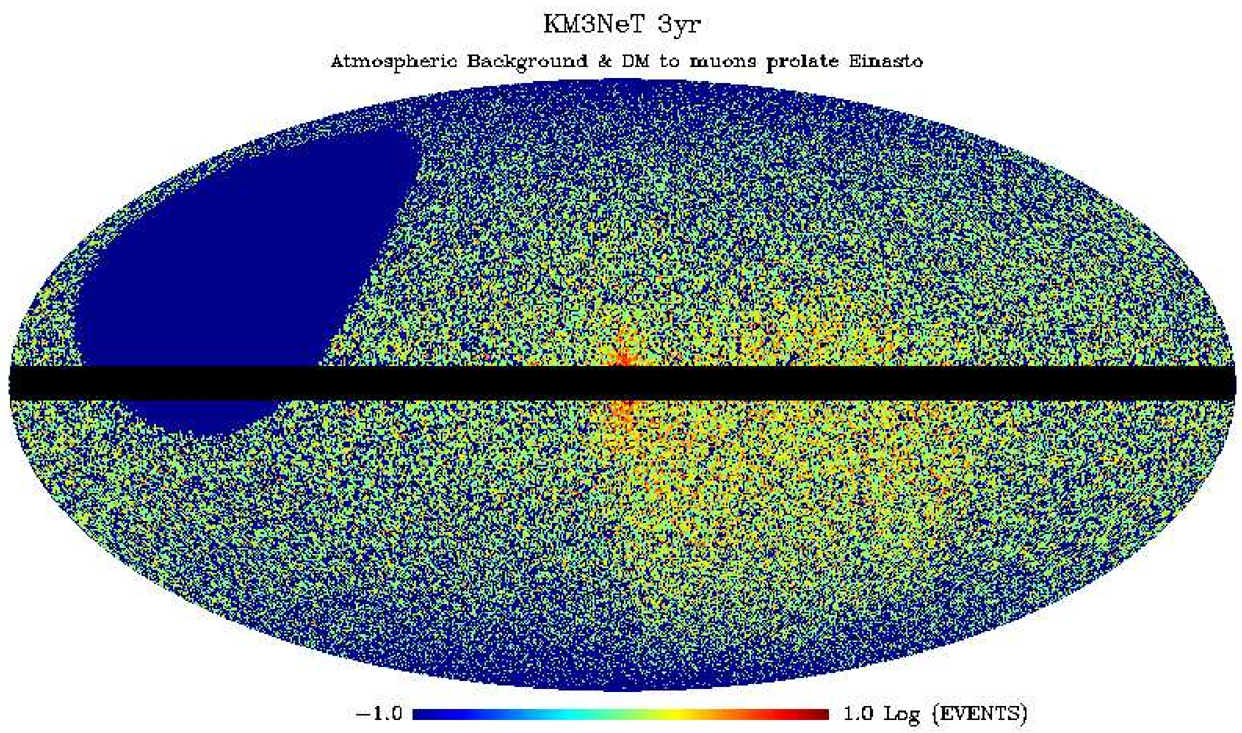
I.C., S. McDermott, D. Hooper, JCAP 1402 (2014)

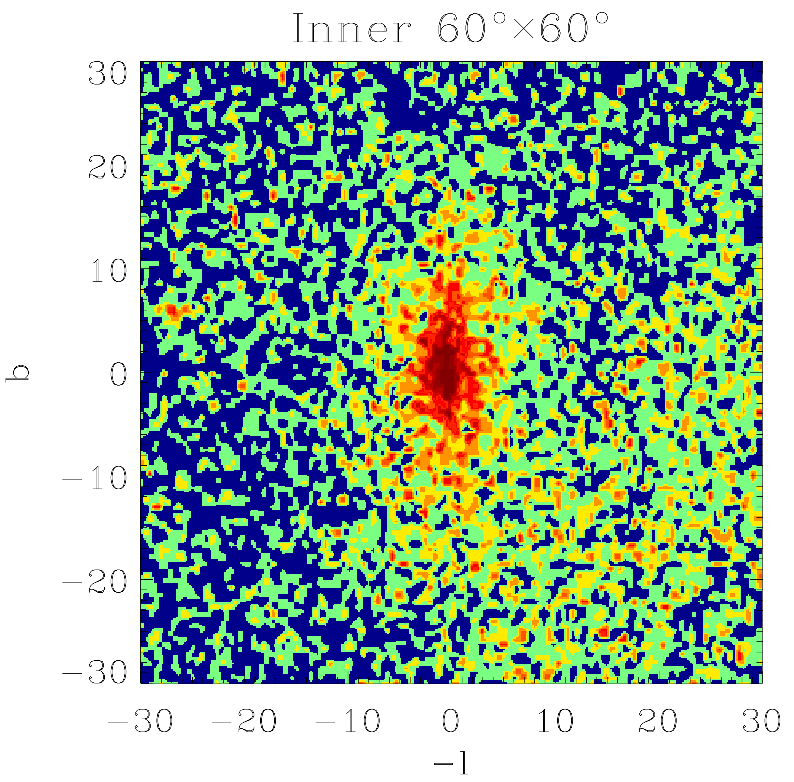




Neutrinos from the GC (future projections)

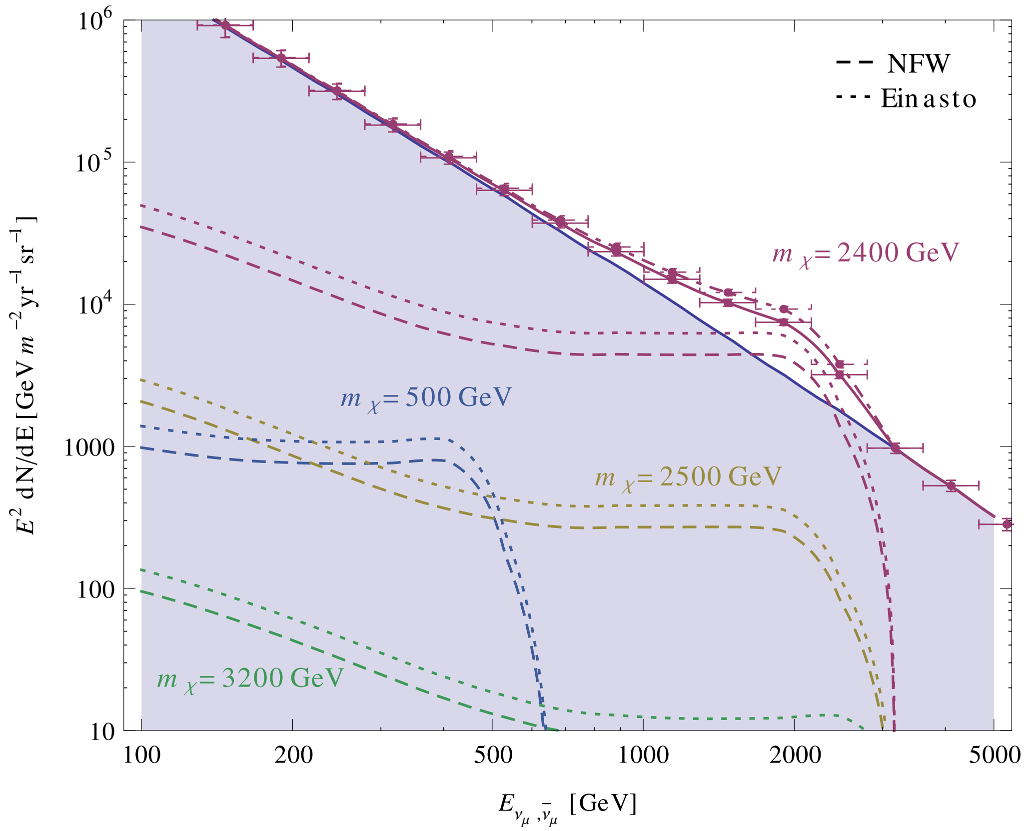
A possible enhanced signal of SM annihilation in the Milky Way





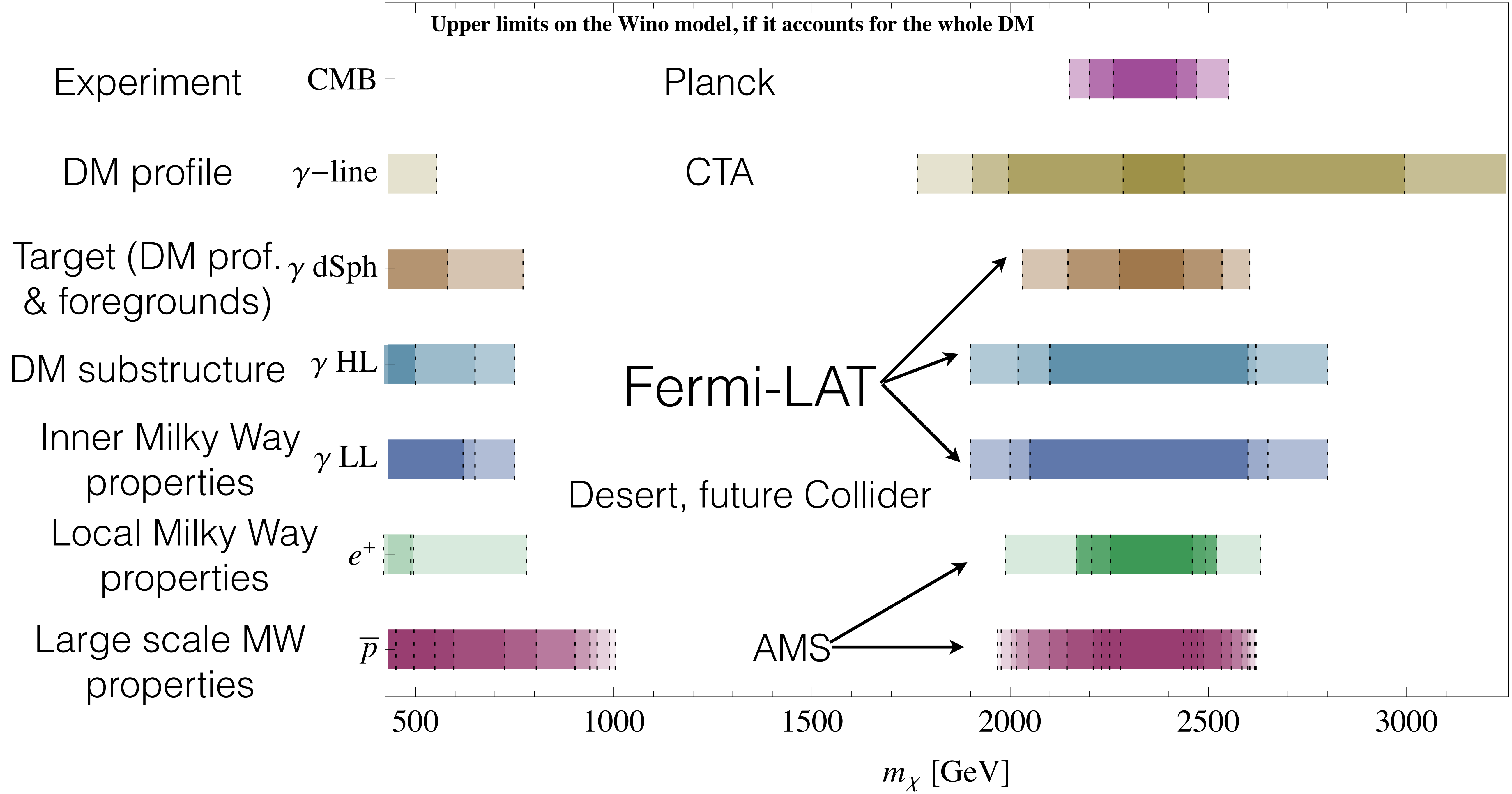
I.C. PRD 88 (2013)

Only close to the resonance will we be able to observe such a signal. But the resonance has already been excluded by other indirect probes:



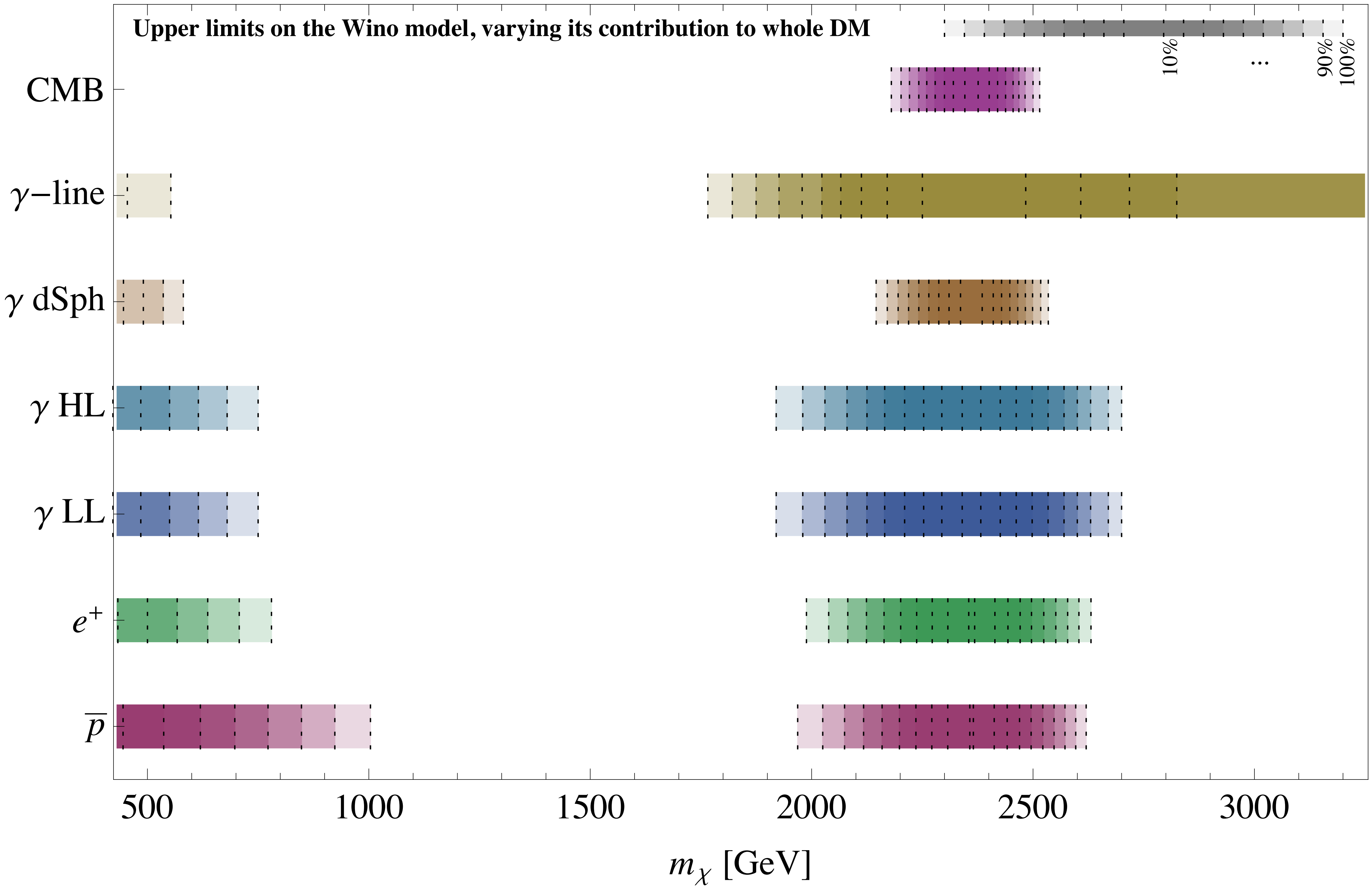
Comparisons and Conclusions

95% CL upper limits:



95% CL upper limits.

RELAXING the Wino relic density condition:



Thank you