

# Indirect Detection of Wino Dark Matter: Multichannel Detection Study

## Work with:

**Andrzej Hryczuk, Roberto Iengo, Maryam Tavakoli, Piero Ullio**

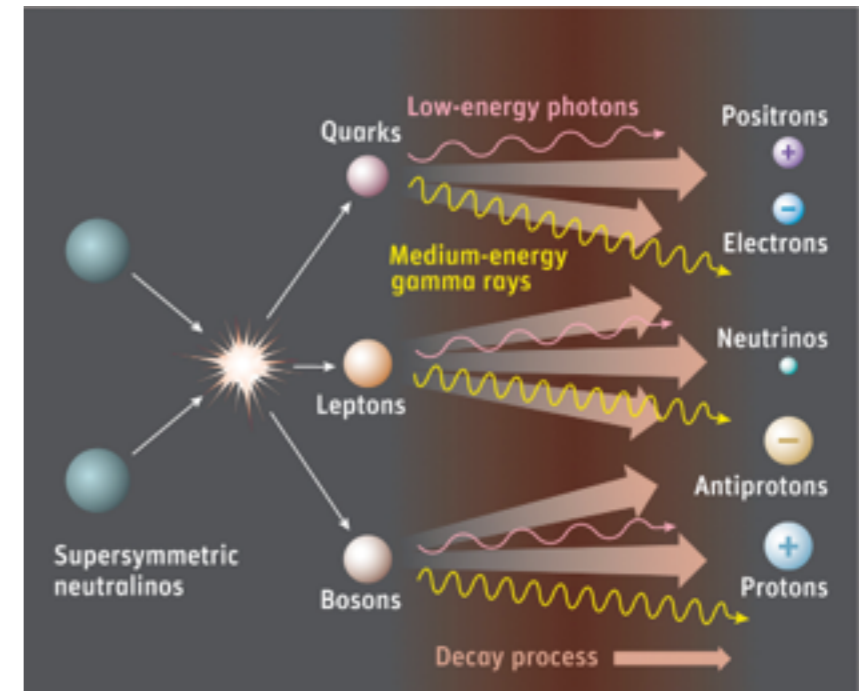
**arXiv:1401.6212(JCAP in prep.)**

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

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



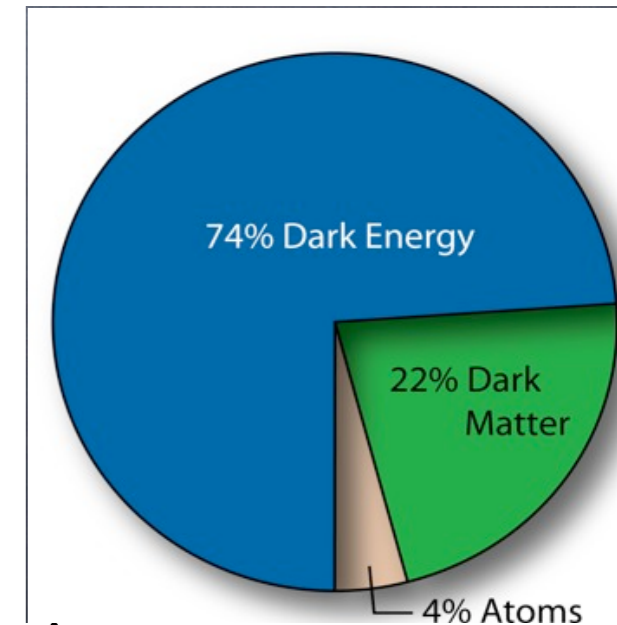
# Outline

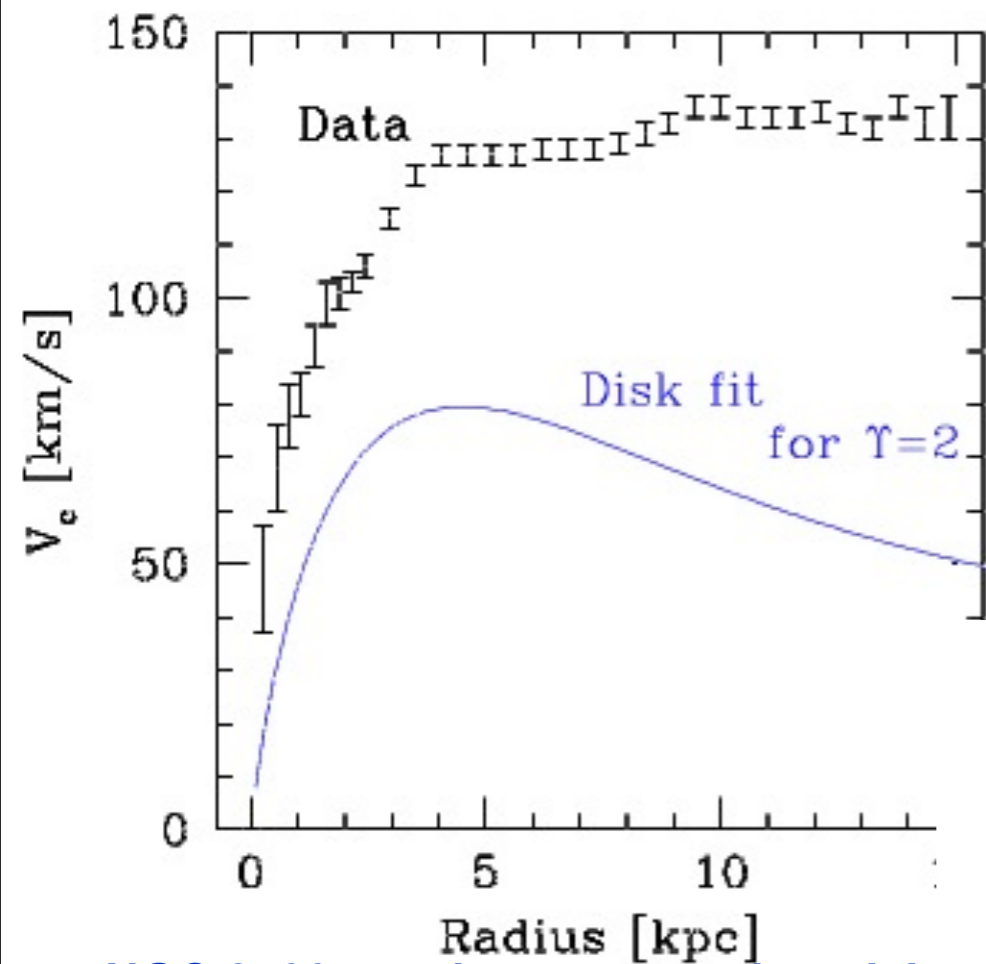


- Wino DM
- Cross-section and annihilation spectra
- General CRs
- Limits from Antiprotons, Positrons and future antideutrons probe. Include into the discussion all the important astrophysical uncertainties.
- Galactic Diffuse Gamma-rays, searching for a signal from the Milky Way in the continuum and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

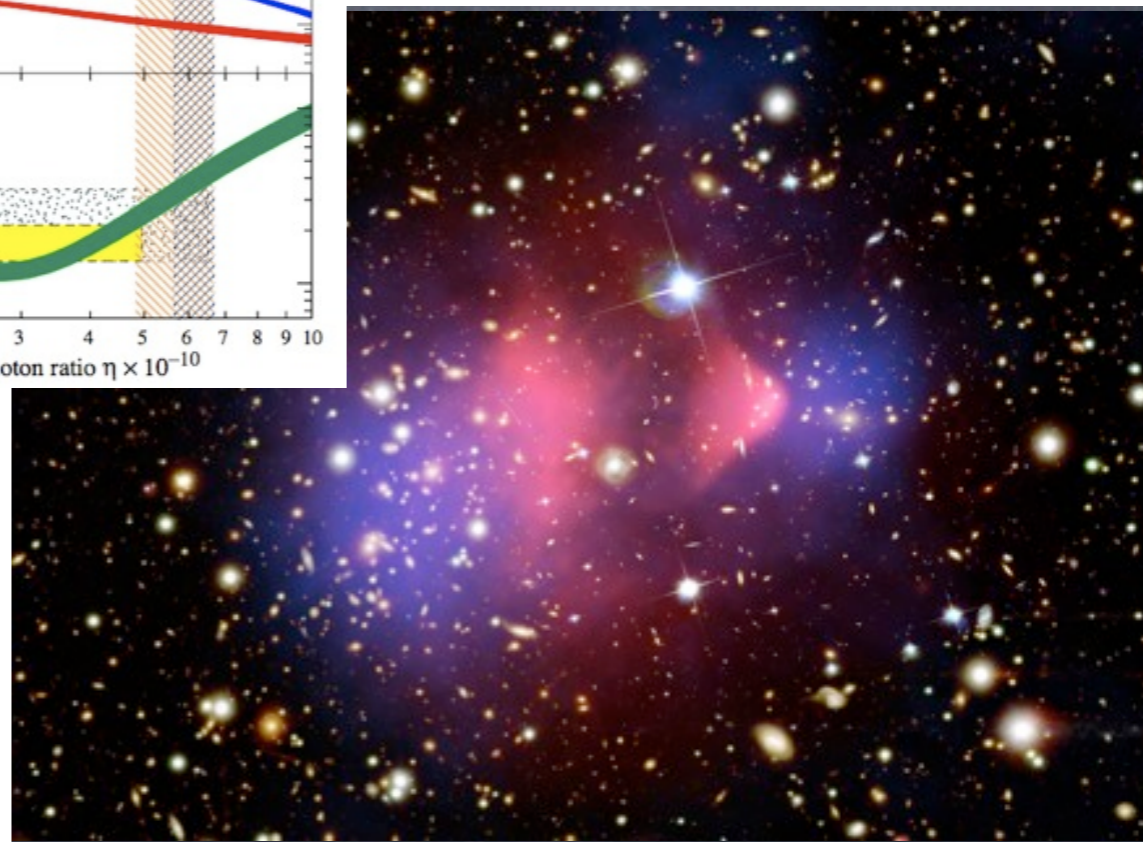
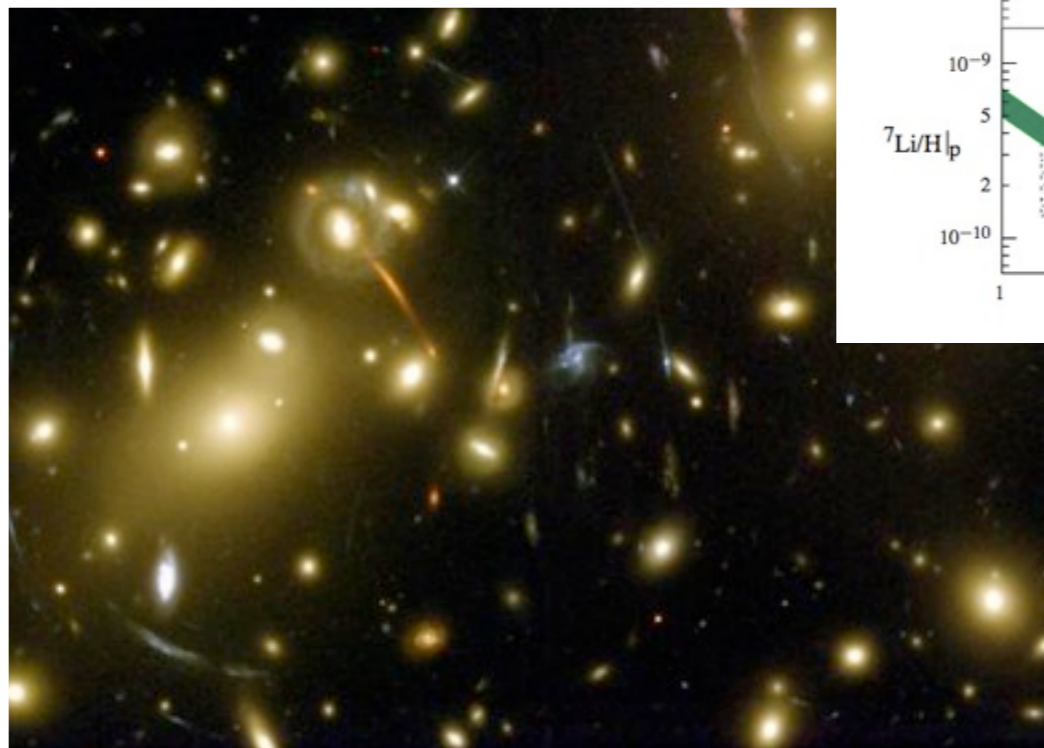
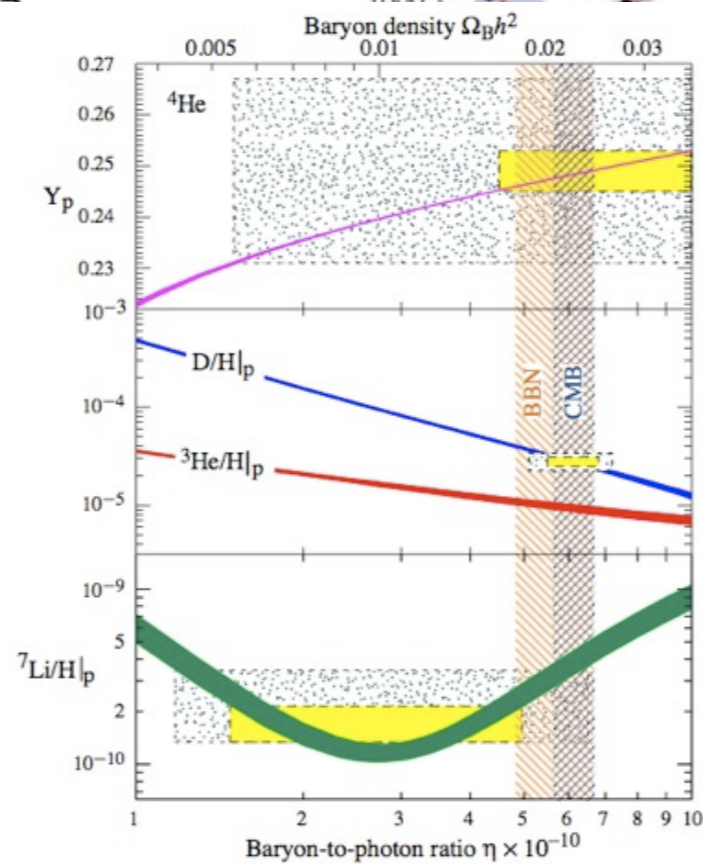
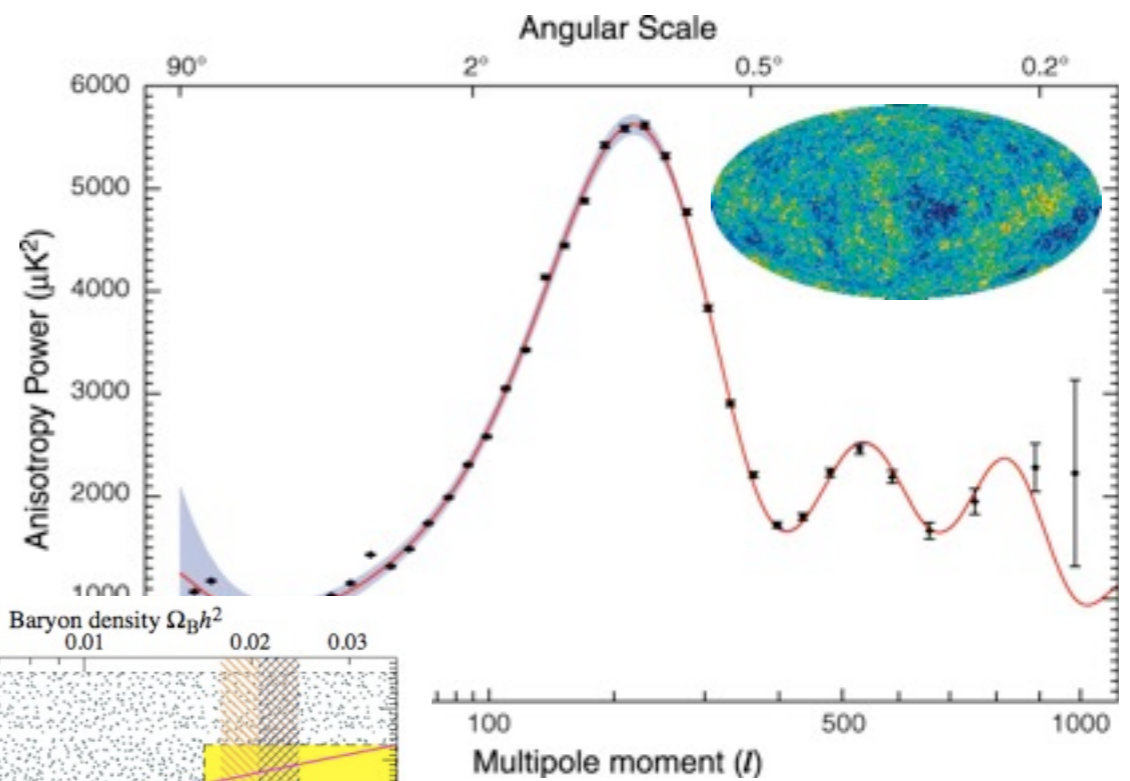
# evidence for CDM

- 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  $\sim 3$  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  $\sim 2-3$  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  $\sim 100$  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**.

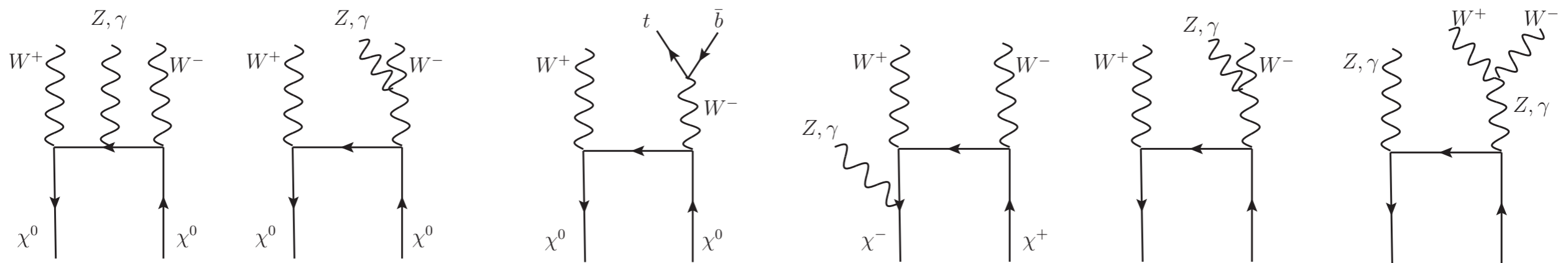
At tree level the indirect signals come from  $\chi\chi \longrightarrow W^+W^-$  where  $W^+W^-$  decay and hadronize giving protons, antiprotons, electrons, positrons, neutrinos and gamma-rays. With a (tree-level) cross-section:

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

$g_2$  the weak coupling const.,  $m_W$  the W mass  $m_\chi$  the Wino mass

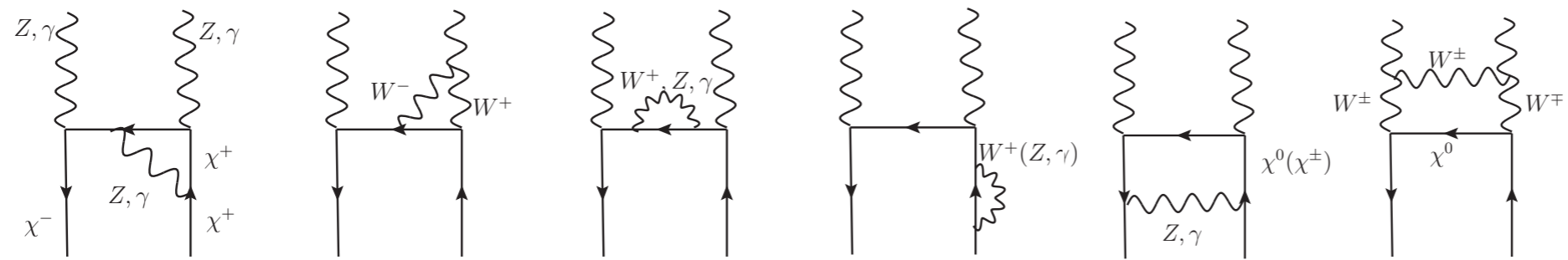
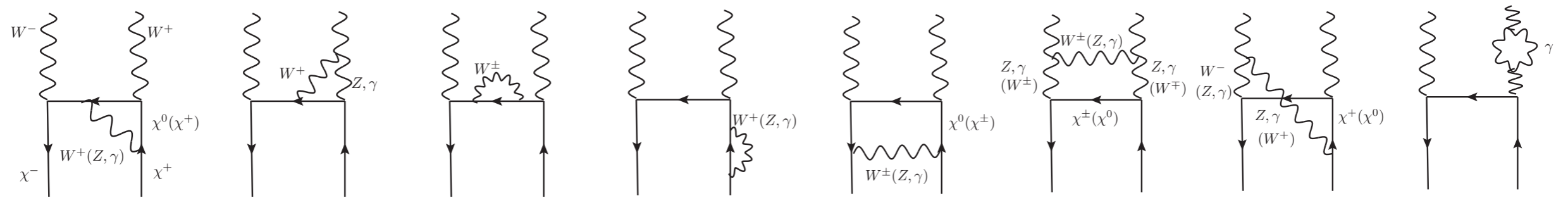
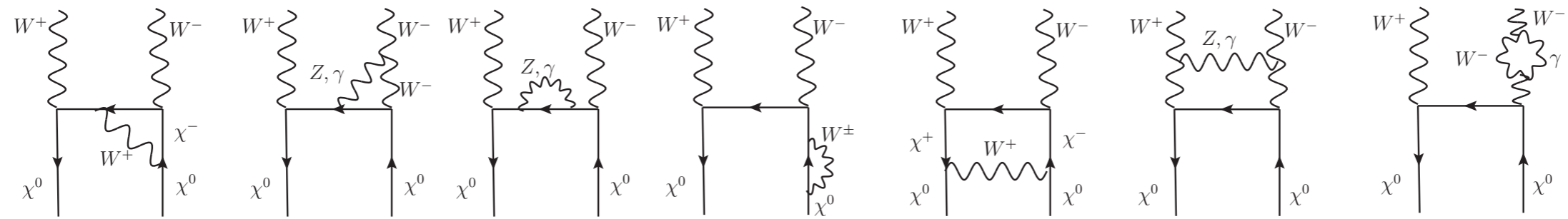
In addition we have three body processes:

$\chi\chi \longrightarrow W^+W^-\gamma$  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  $\sim 2.4$  TeV.

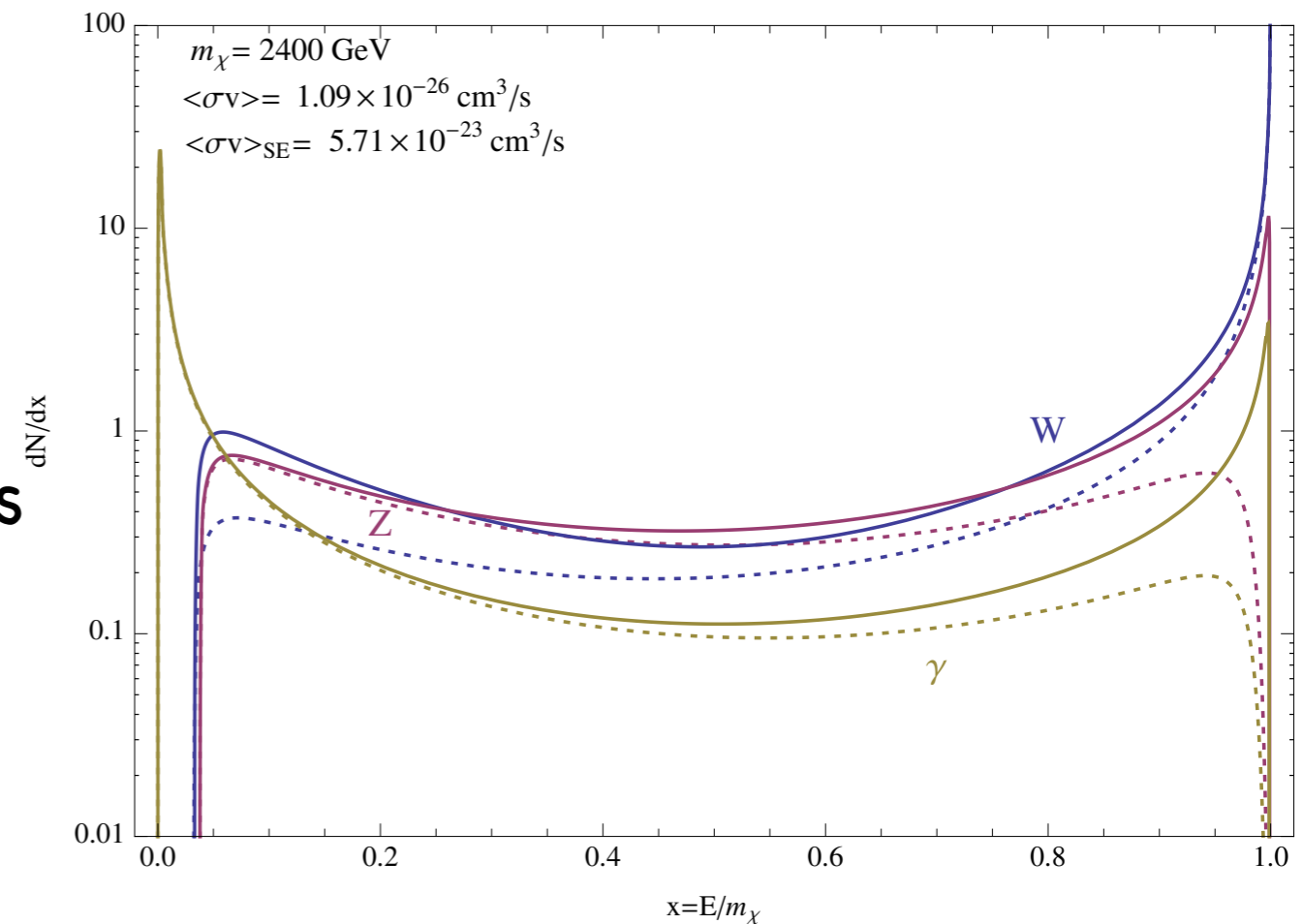
The amplitude of the enhancement is:

$$A_{\chi^0\chi^0\rightarrow\text{SM}}^{\text{SE}} = s_0 A_{\chi^0\chi^0\rightarrow\text{SM}} + s_\pm A_{\chi^+\chi^-\rightarrow\text{SM}}$$

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

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

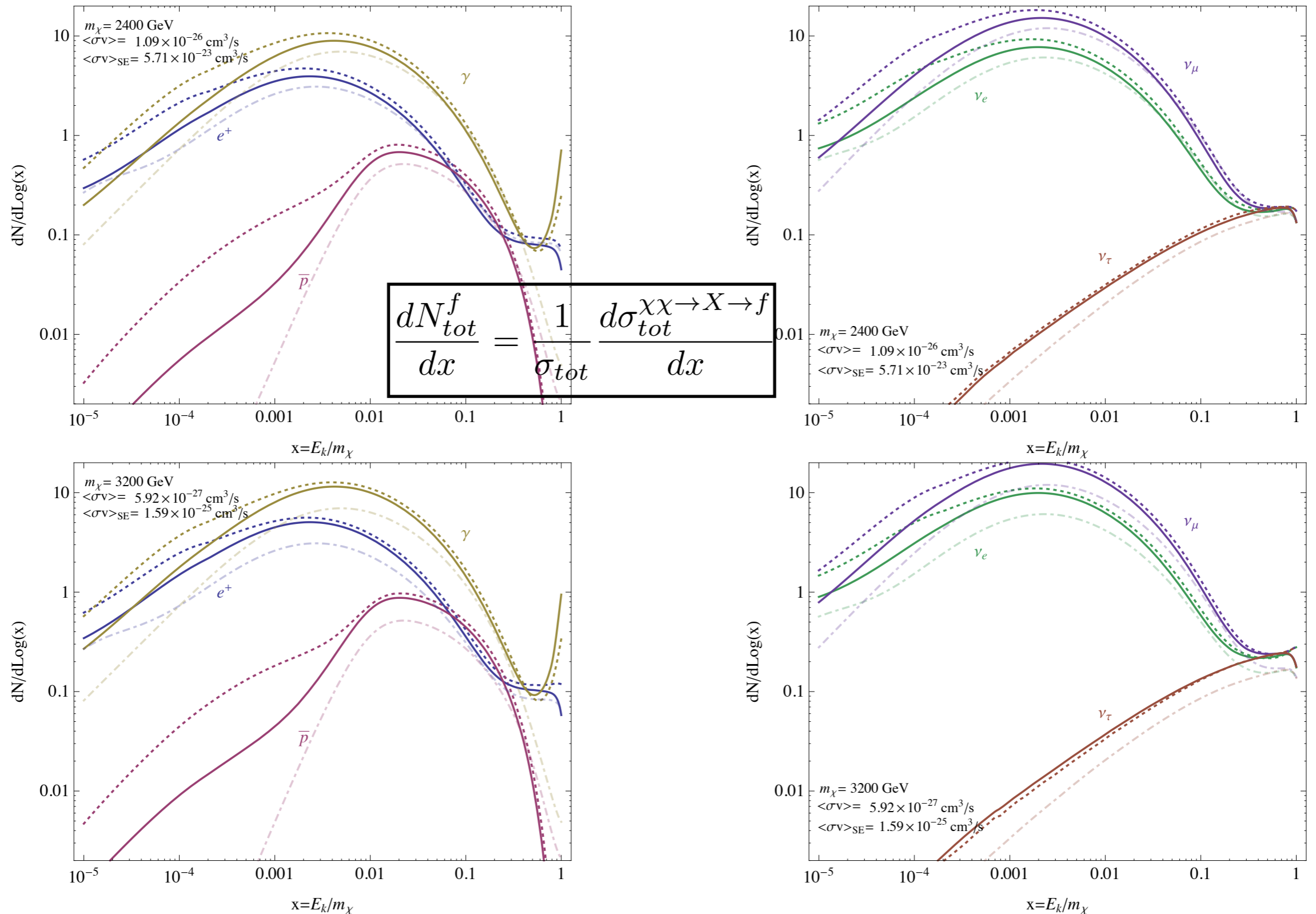
- Change in the cross-section
- ZZ, Zgamma and 2gamma channels open up.
- Modification of injection spectra





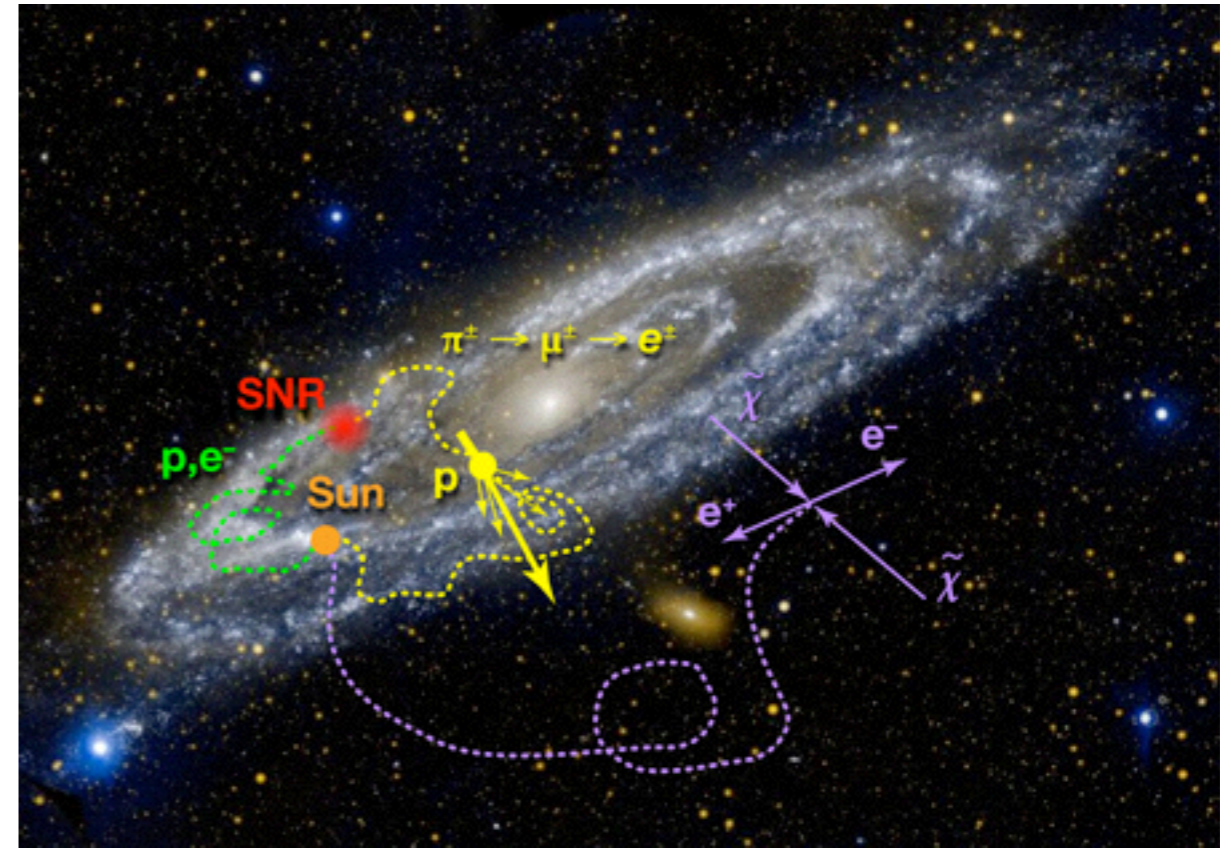
# Final annihilation cosmic-ray gamma-ray and neutrino spectra

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

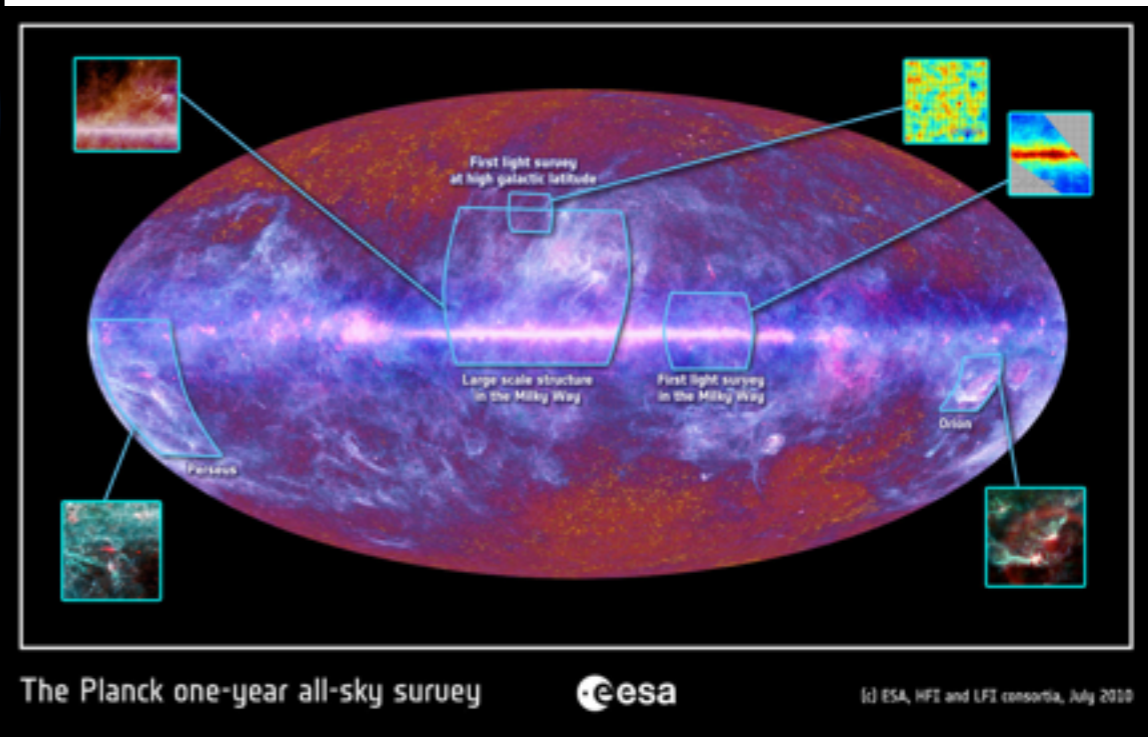
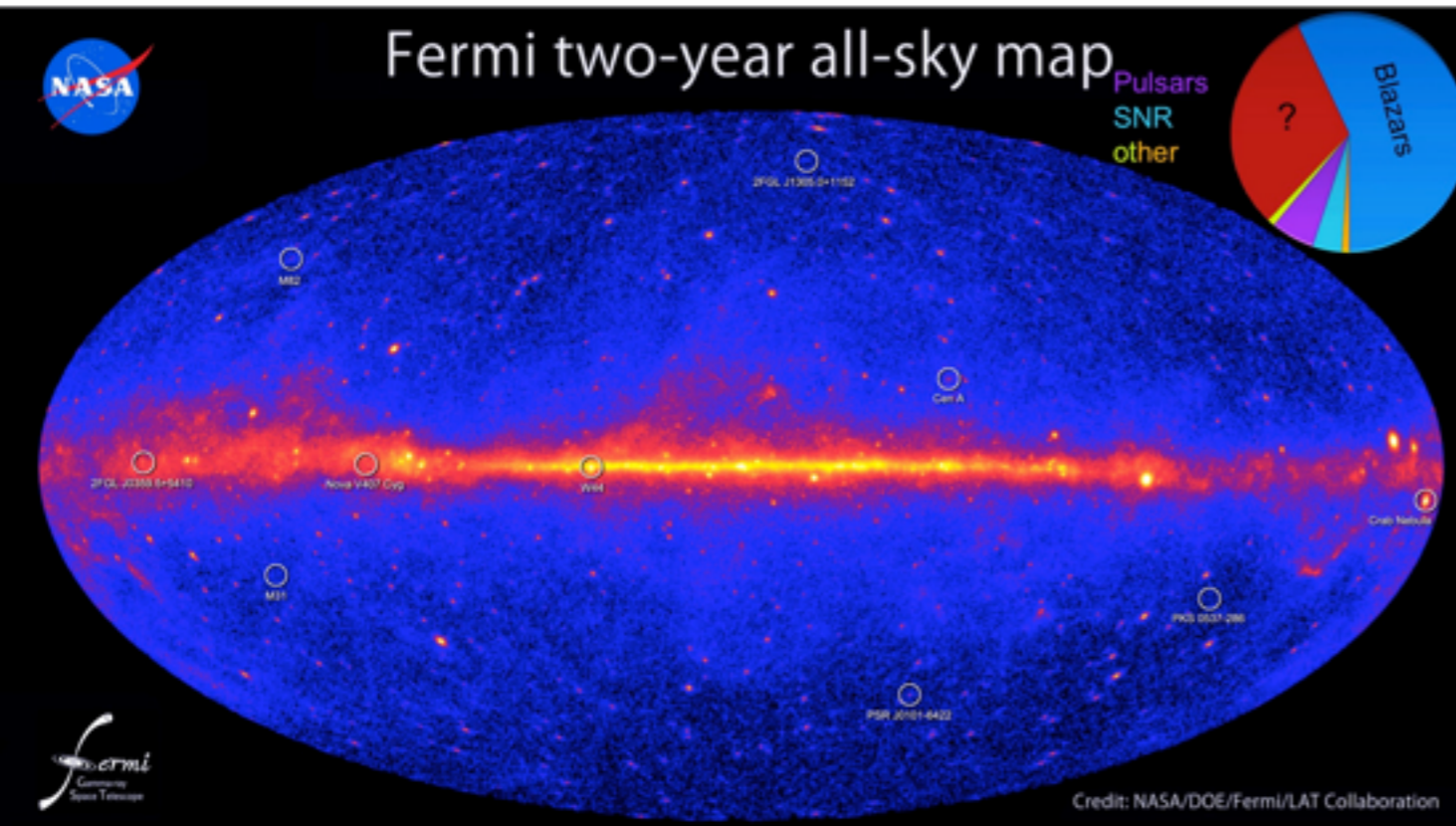


# Cosmic-rays and their relevance

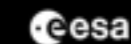
With CR spectral measurements we can understand the properties of the ISM, and probe sources of high energy CRs. Antimatter CRs indirectly also probe DM. Combine with gamma-ray and radio observations.



Fermi two-year all-sky map



The Planck one-year all-sky survey



[c] ESA, HFI and LFI consortia, July 2010



Credit: NASA/DOE/Fermi/LAT Collaboration

# A great new Era: The AMS-02 experiment

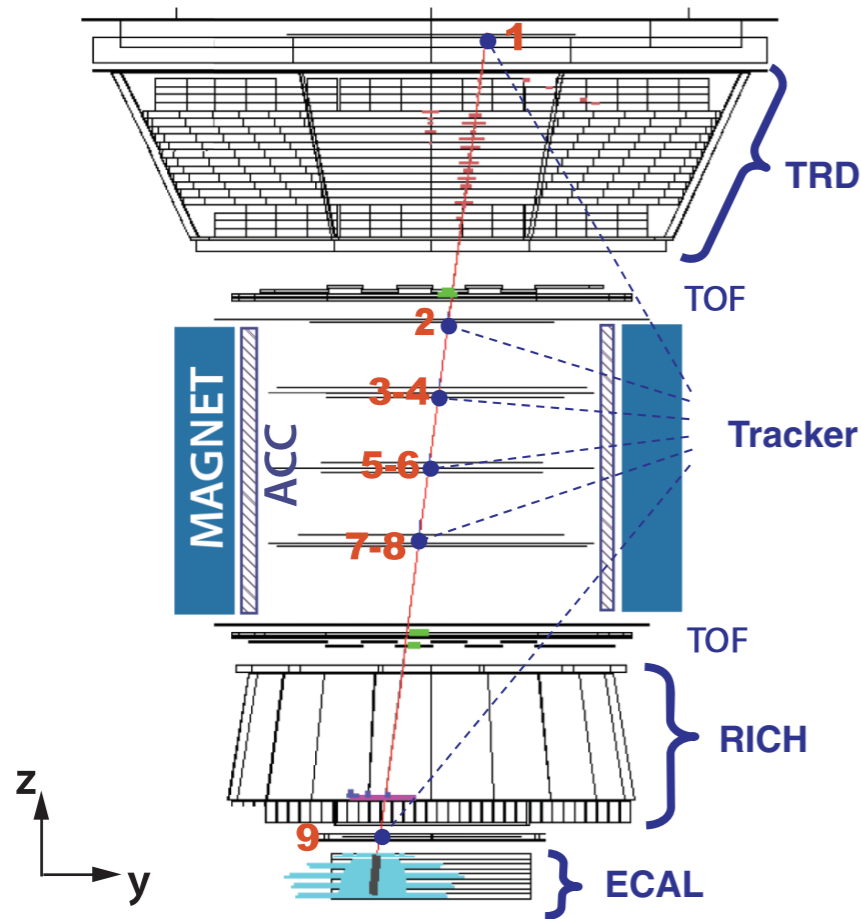
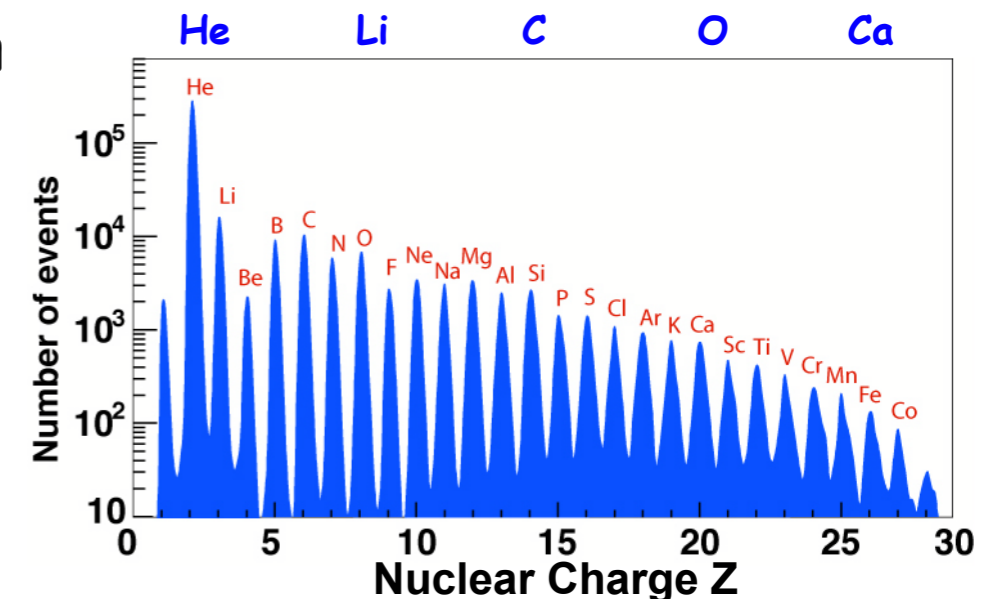
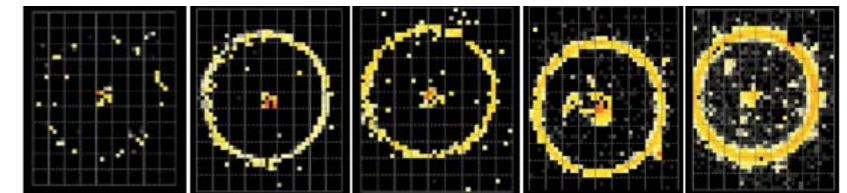


FIG. 1 (color). A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending ( $y$ - $z$ ) plane. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron. The TOF measures the charge and ensures that the particle is downward-going. 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:

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

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 :  $\frac{dN_p}{dR} \propto \left( \frac{R}{R_{0,j}^p} \right)^{-\gamma_j^p}$  (based on AMS, PAMELA and CREAM data)

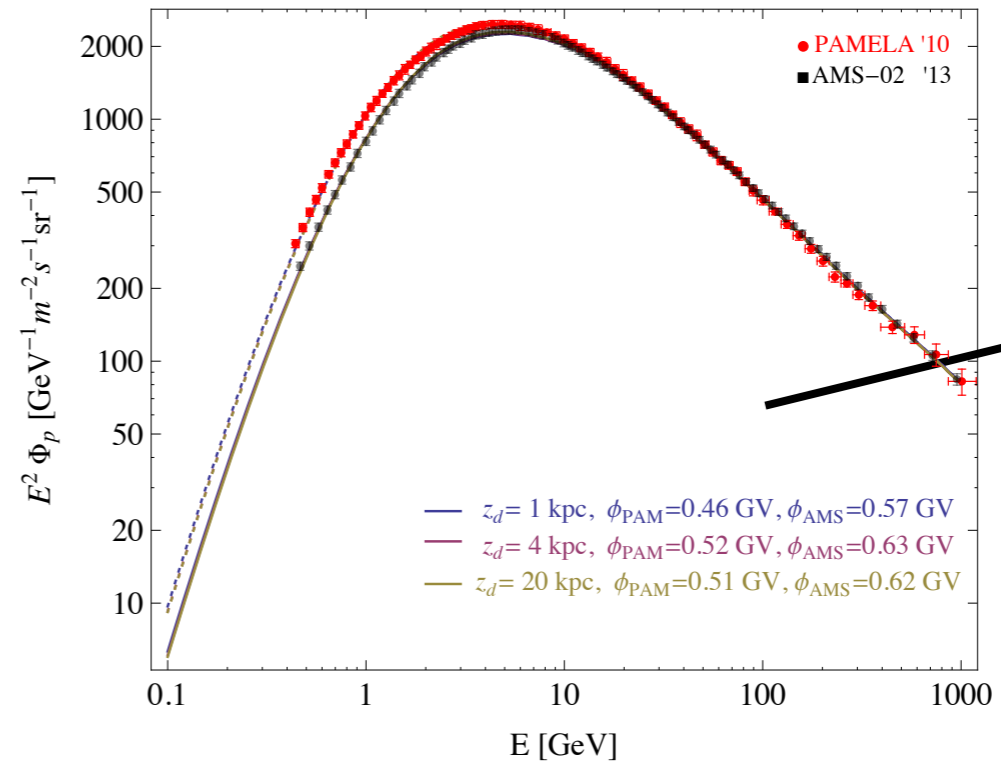
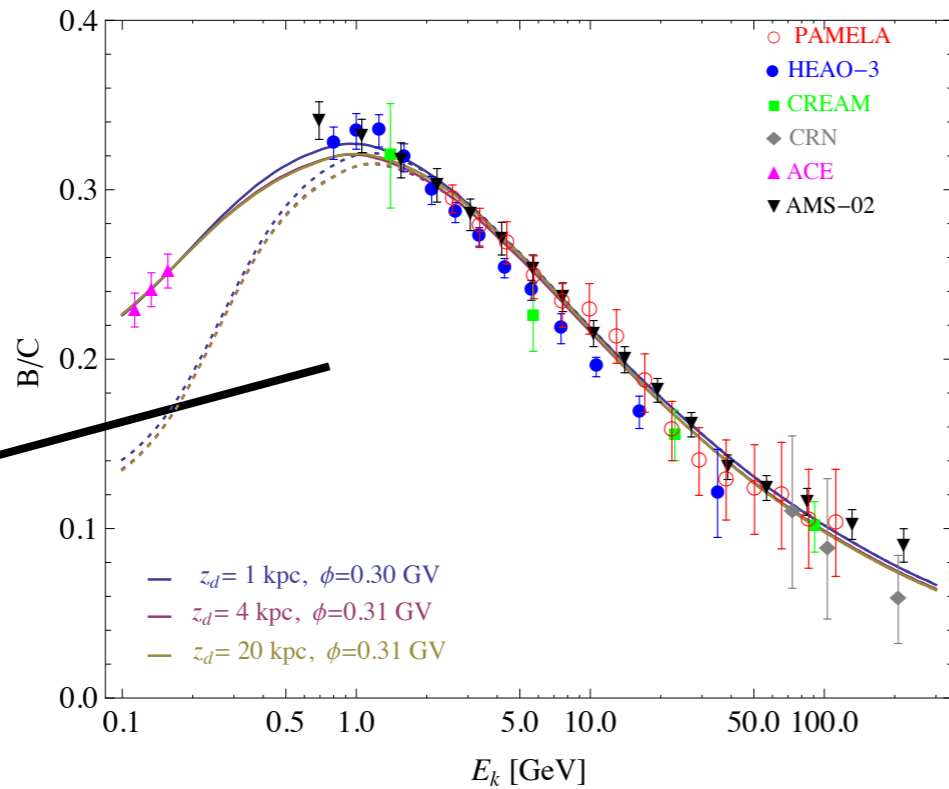
For diffusion in physical space:

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

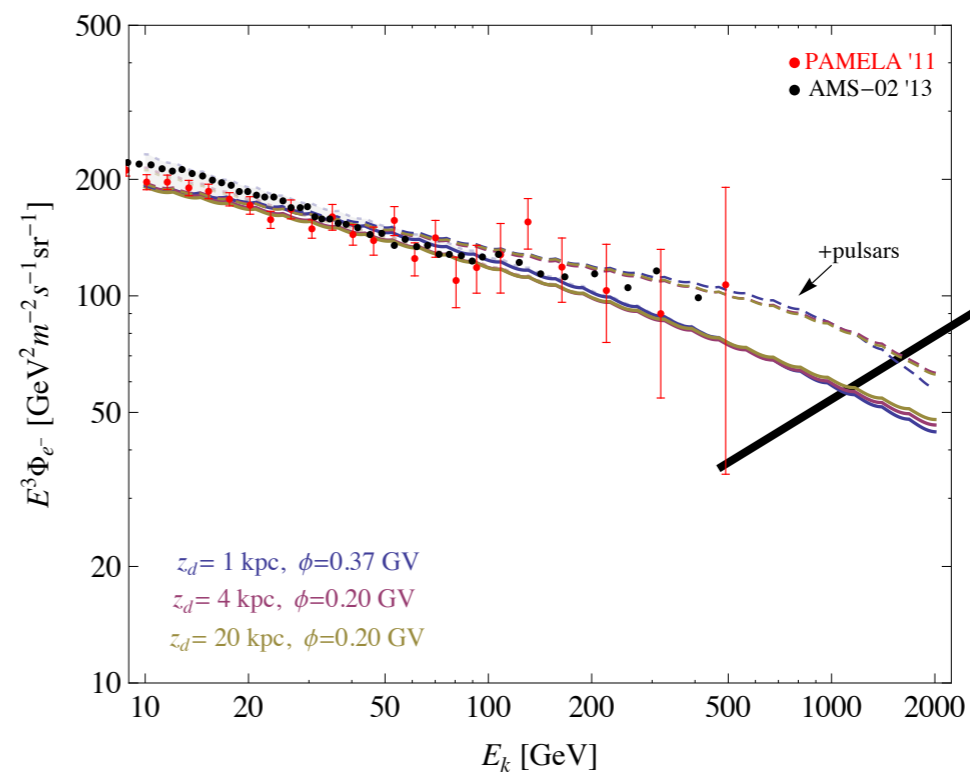
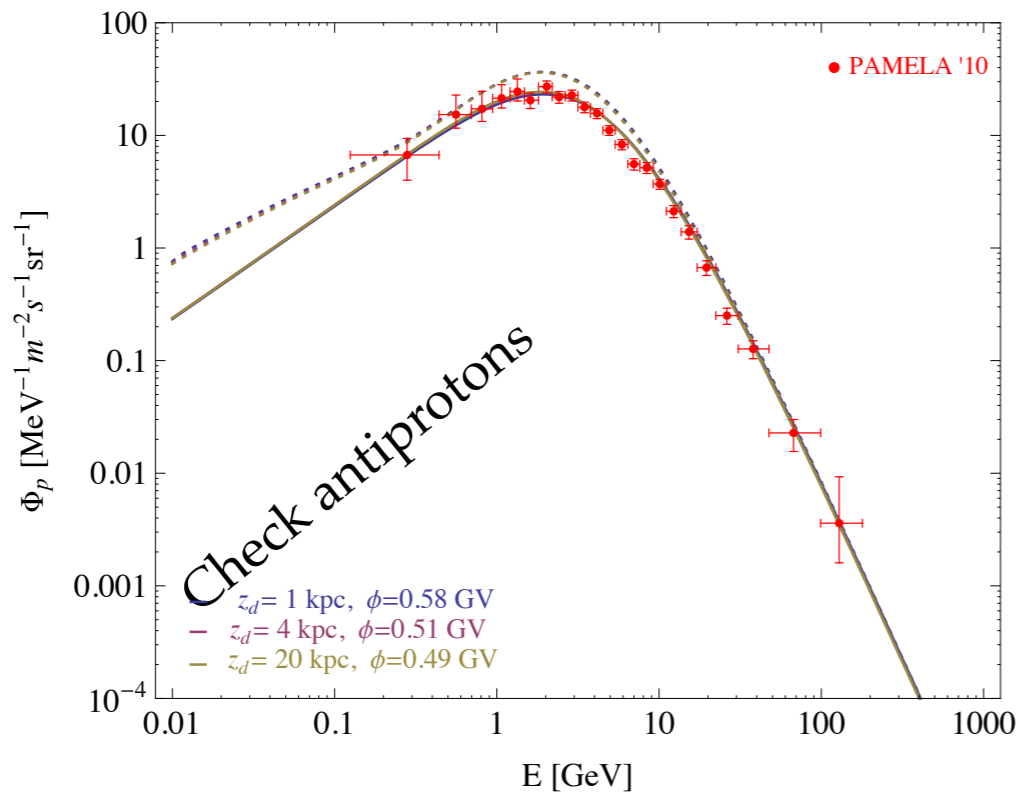
# Fit to the CR data

Choose:  $\delta, r_d, z_d$  and convection (also assume ISM gas and source distribution)

Fit  $D_0, \eta, v_A$

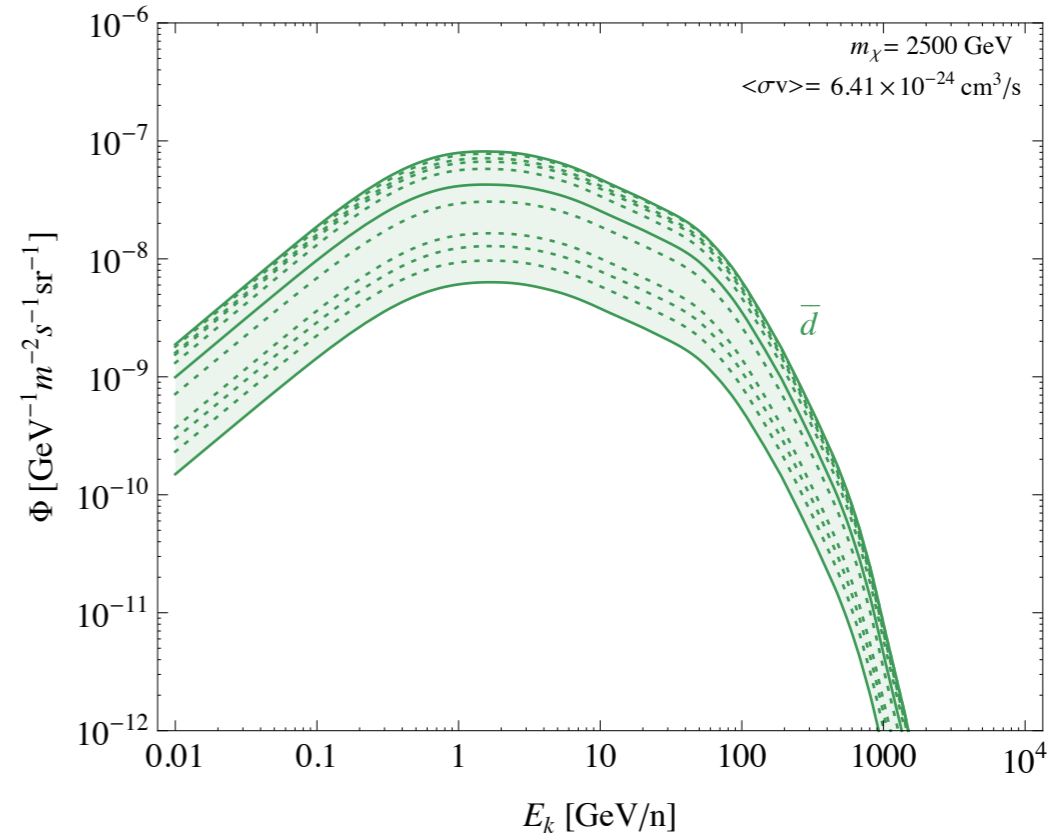
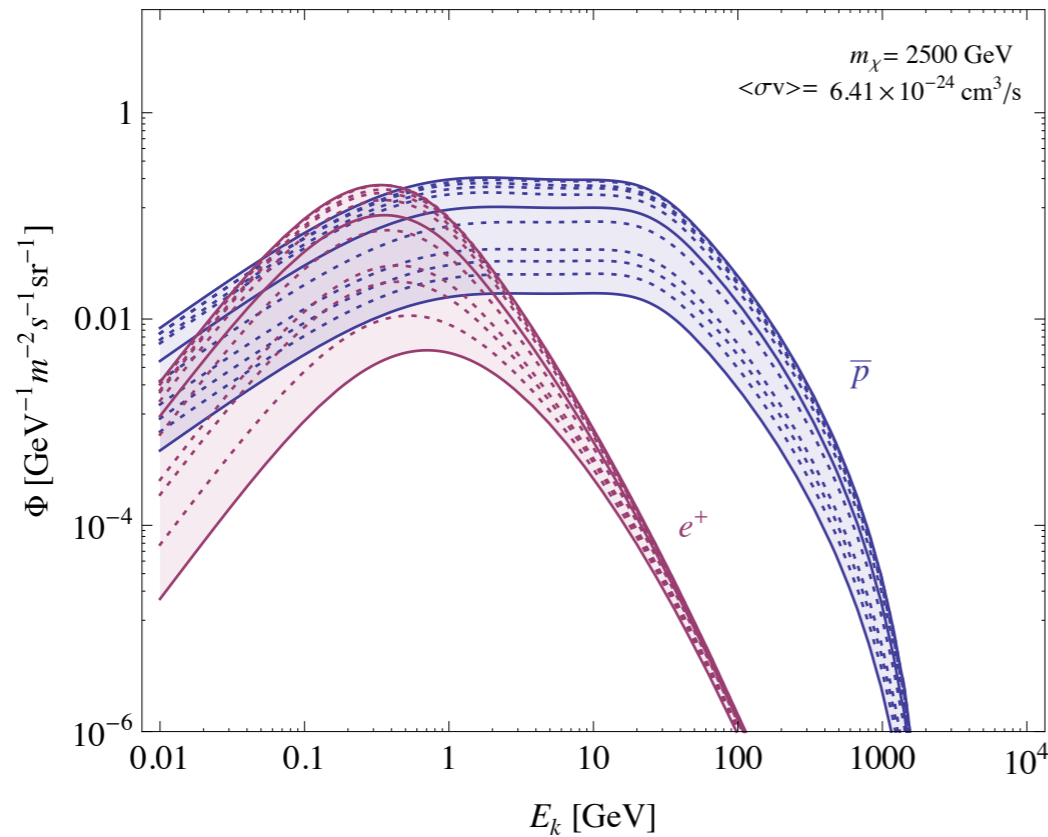


Get  
 $\gamma_j^p, R_{0,j}^p$



Assume middle aged pulsars  
and fit their *averaged* properties

# Effects of different CR Propagation assumptions

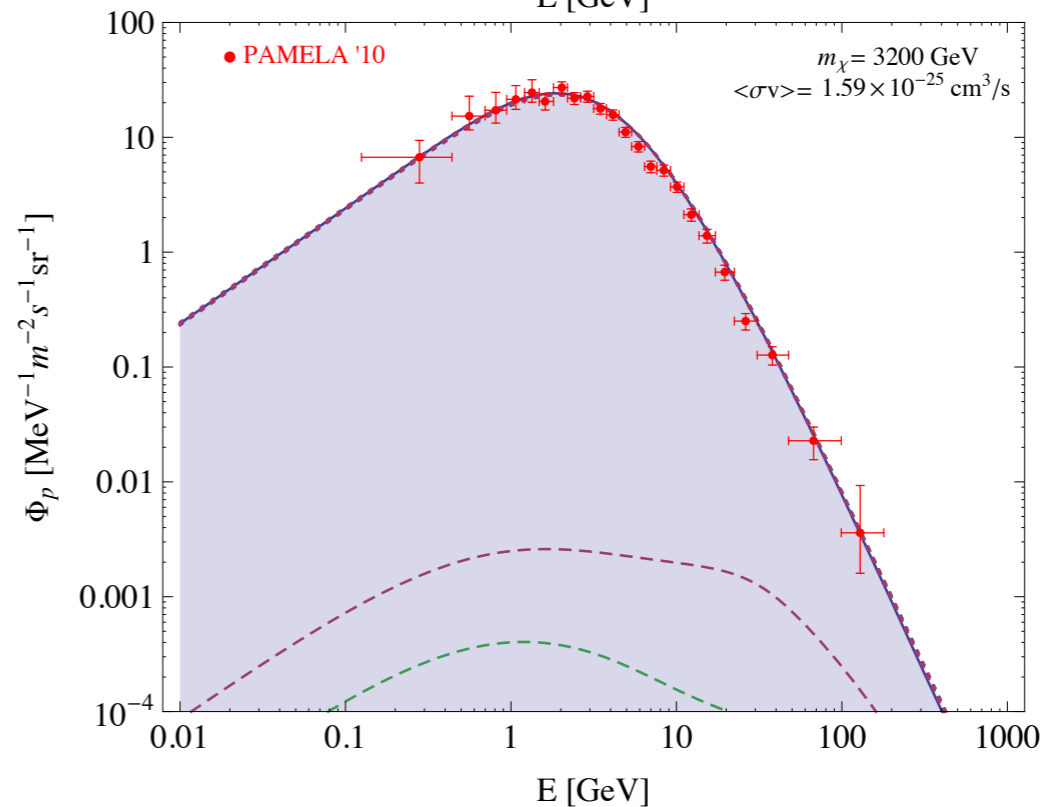
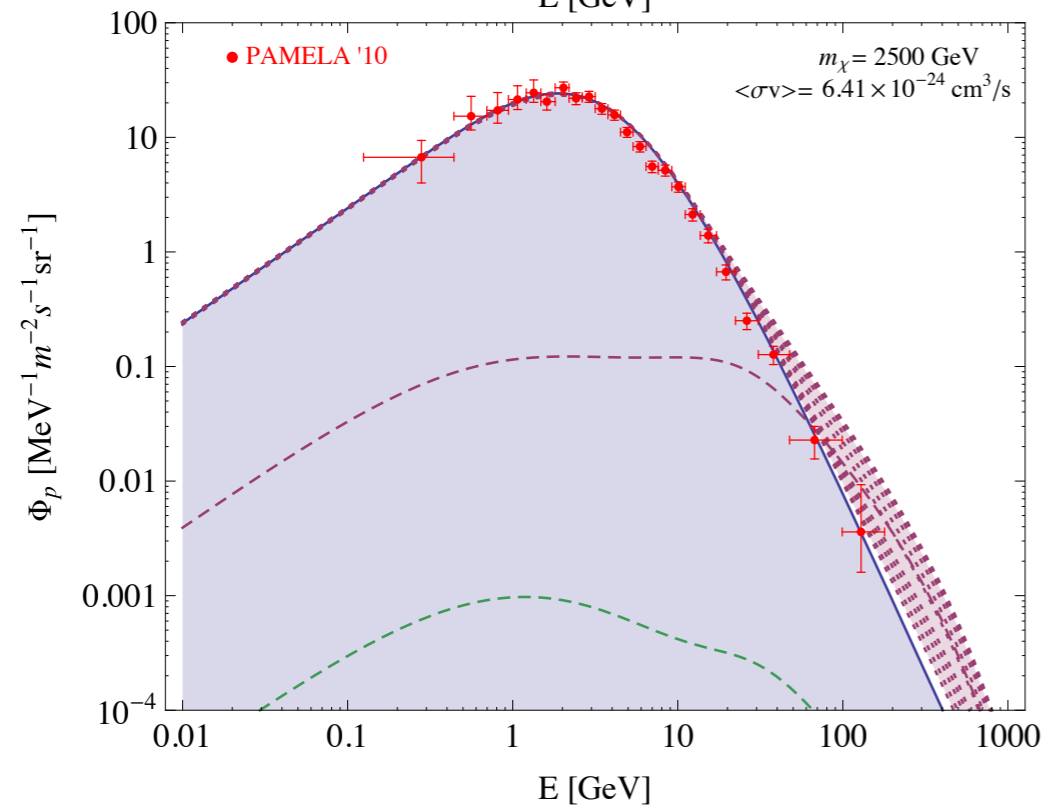
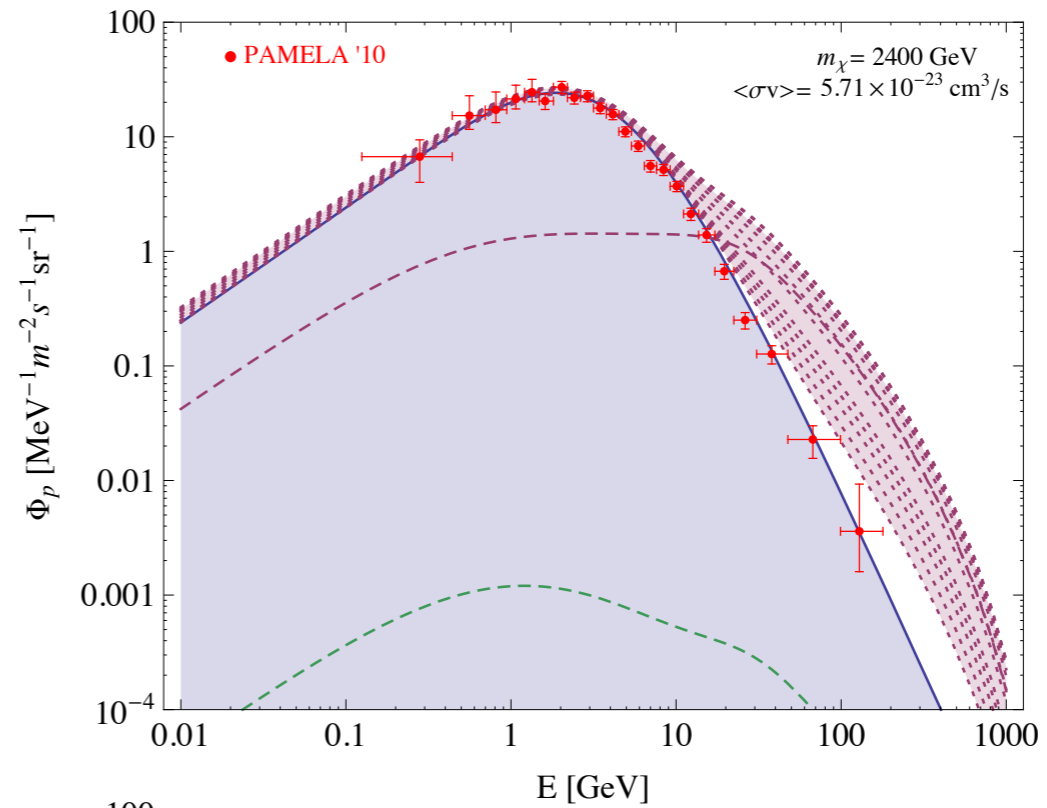
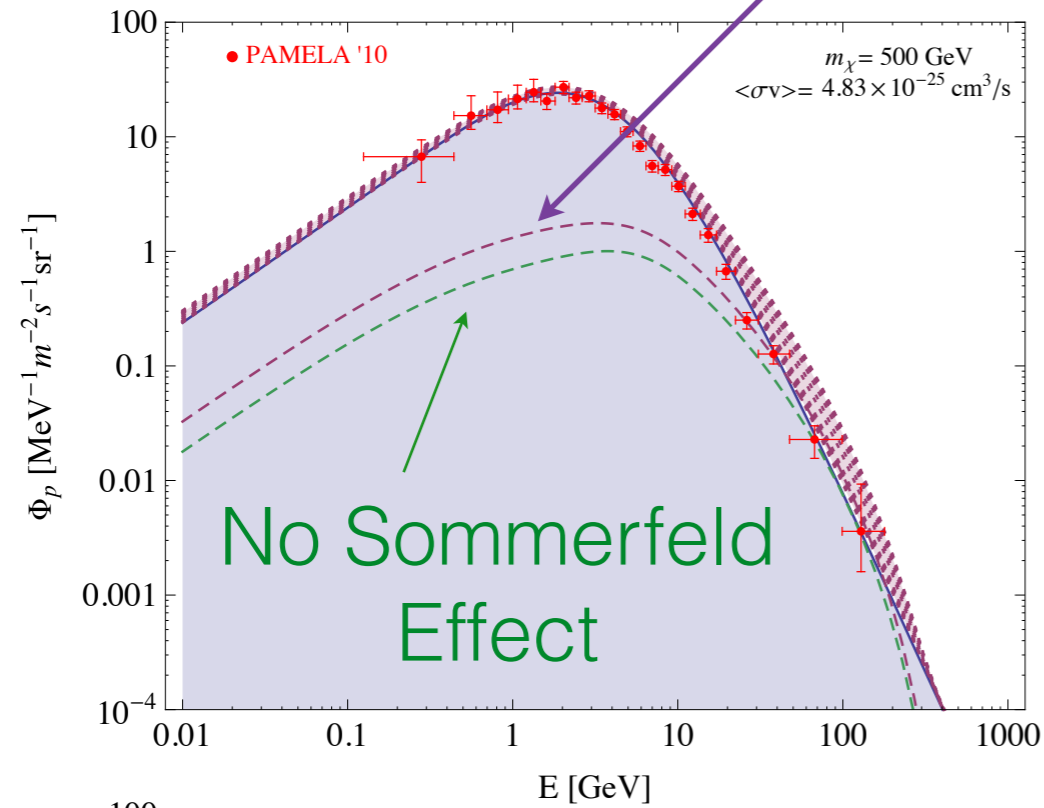


## 11 propagation Models:

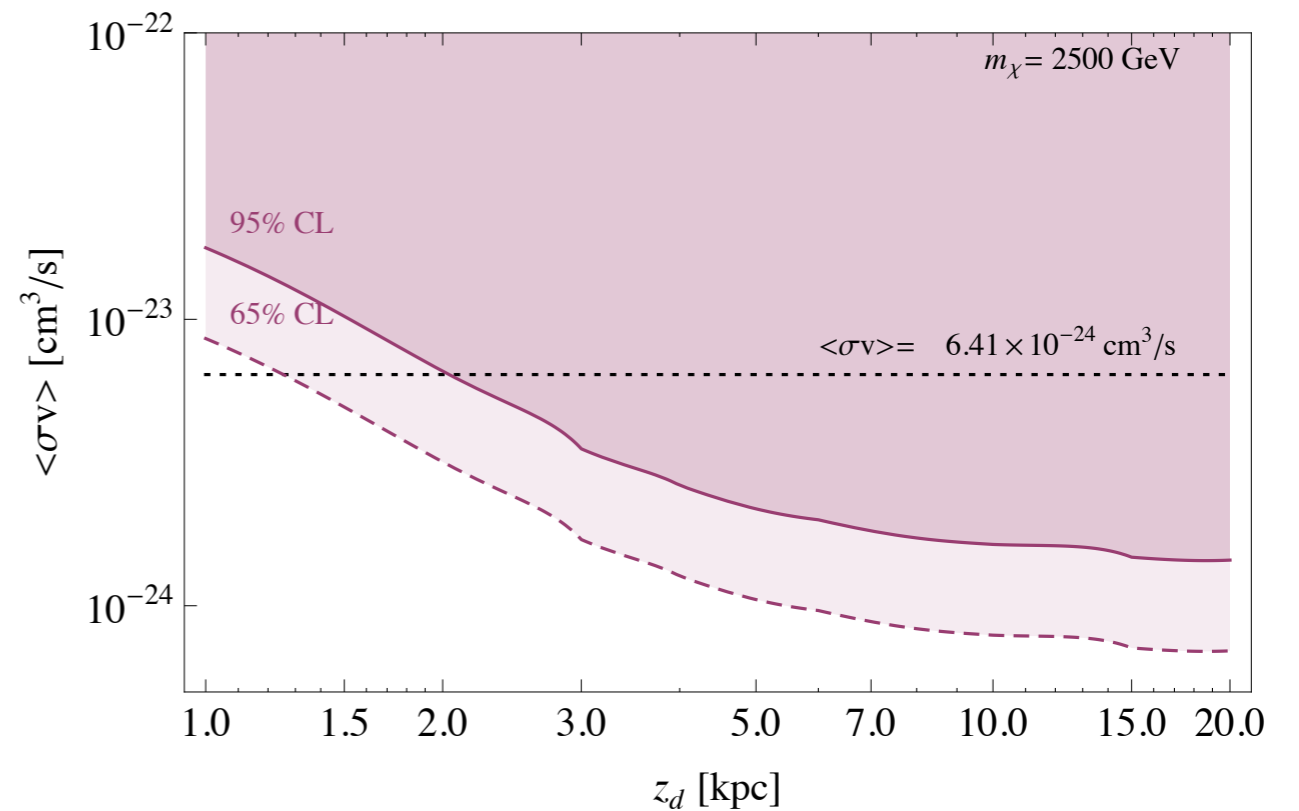
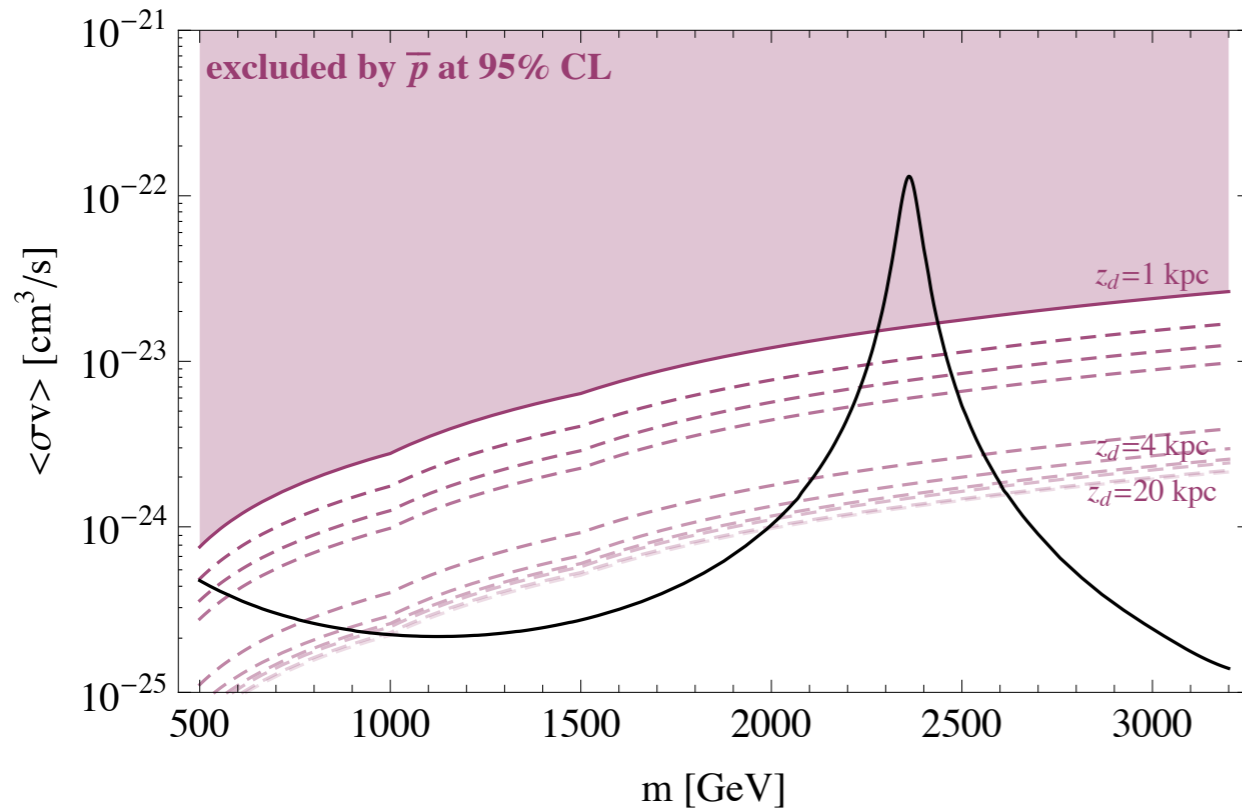
Benchmark			Fitted			Fitted		Goodness				
$z_d$	$\delta$	$r_d$	$D_0 \times 10^{28}$	$v_A$	$\eta$	$\gamma_1^p/\gamma_2^p/\gamma_3^p$	$R_{0,1}^p$	$\chi_{B/C}^2$	$\chi_p^2$	$\chi_{\bar{p}}^2$	$\chi_{\bar{p}/p}^2$	$\chi_{\text{tot}}^2$
[kpc]		[kpc]	[cm <sup>2</sup> s <sup>-1</sup> ]	[km s <sup>-1</sup> ]			GV					
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:

With Sommerfeld enhancement



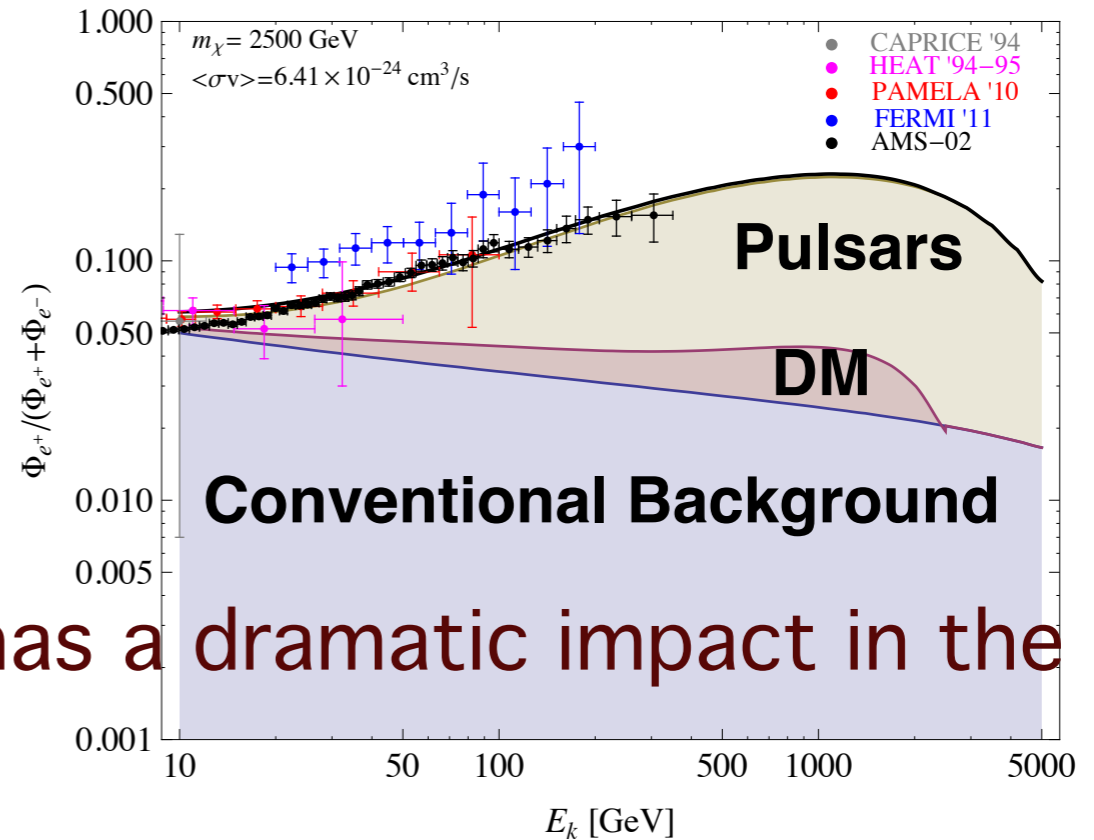
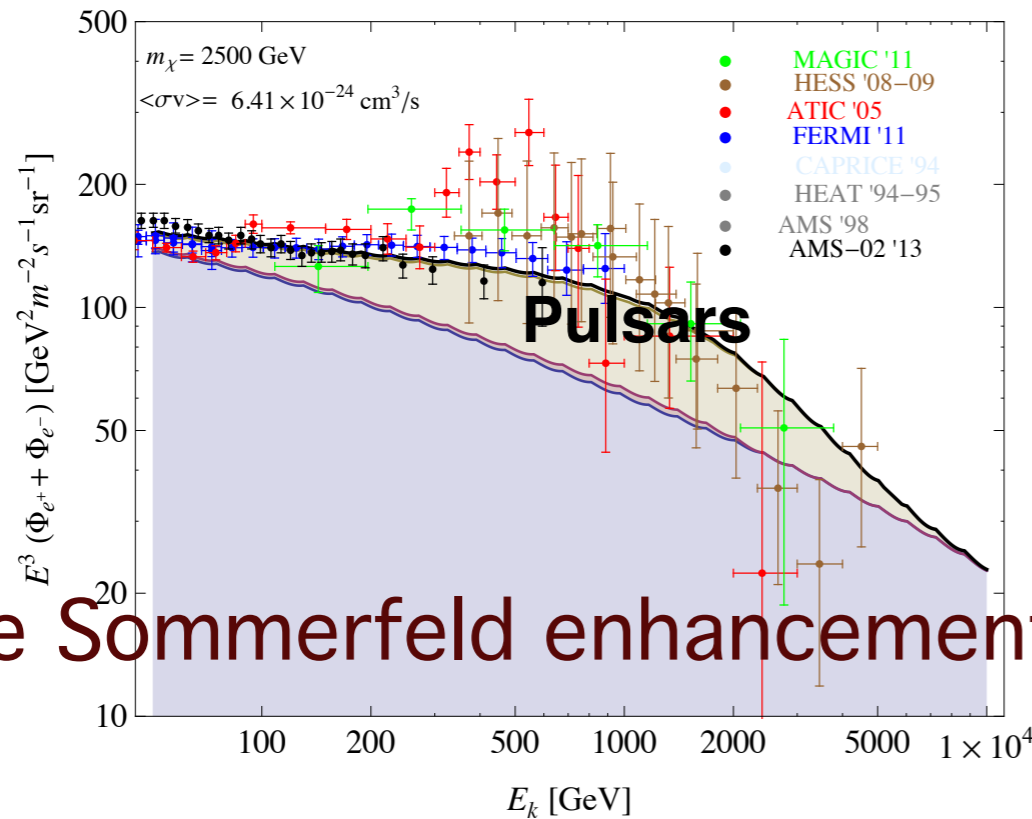
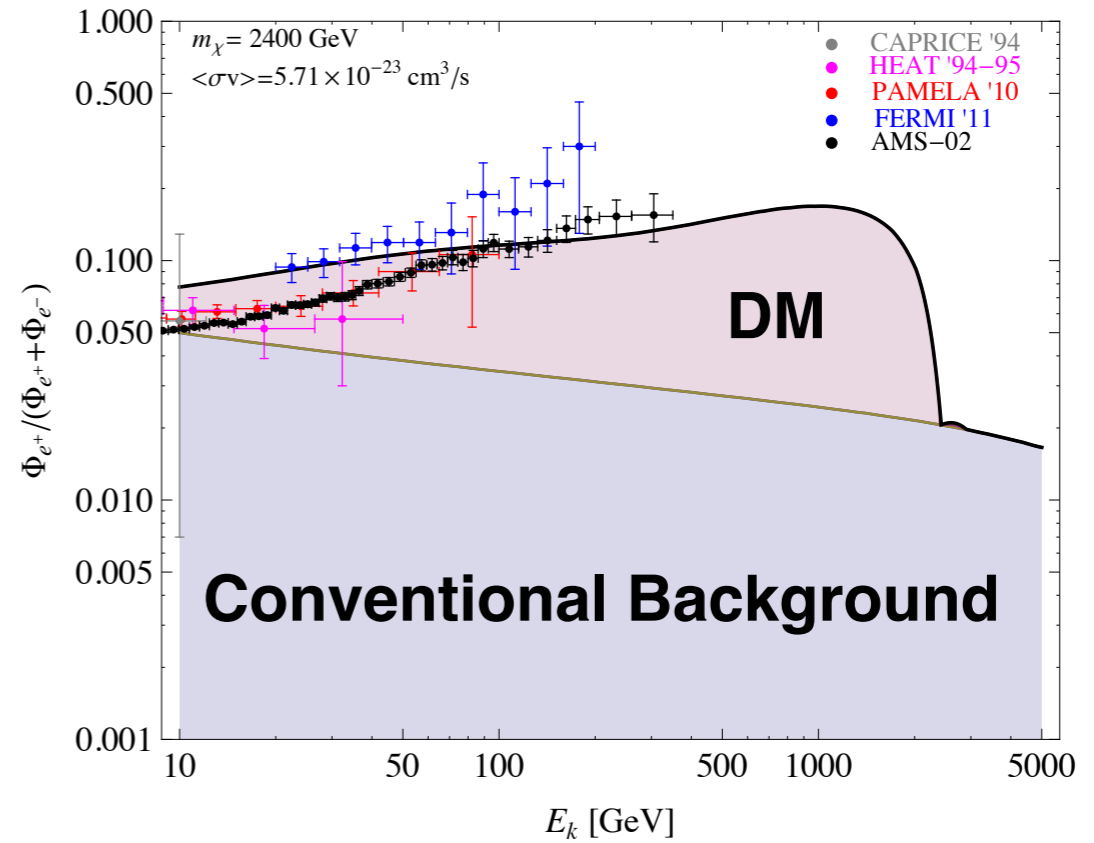
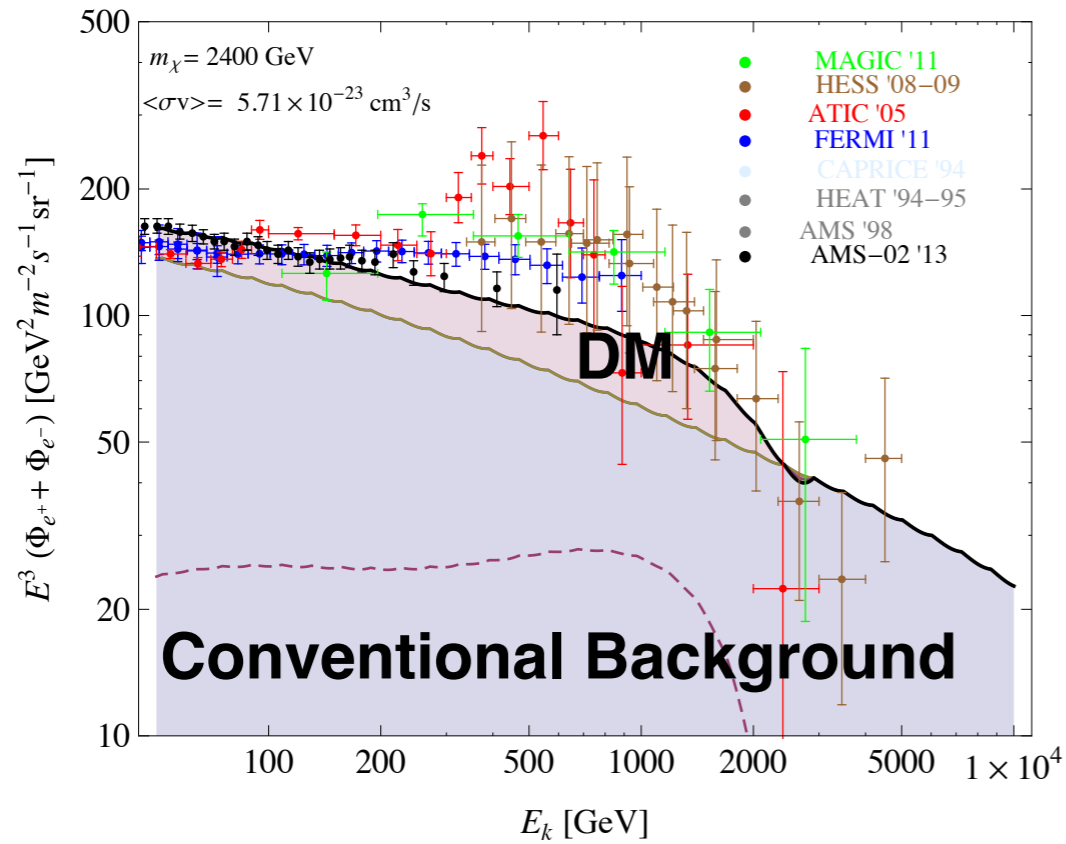
# Limits:



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.

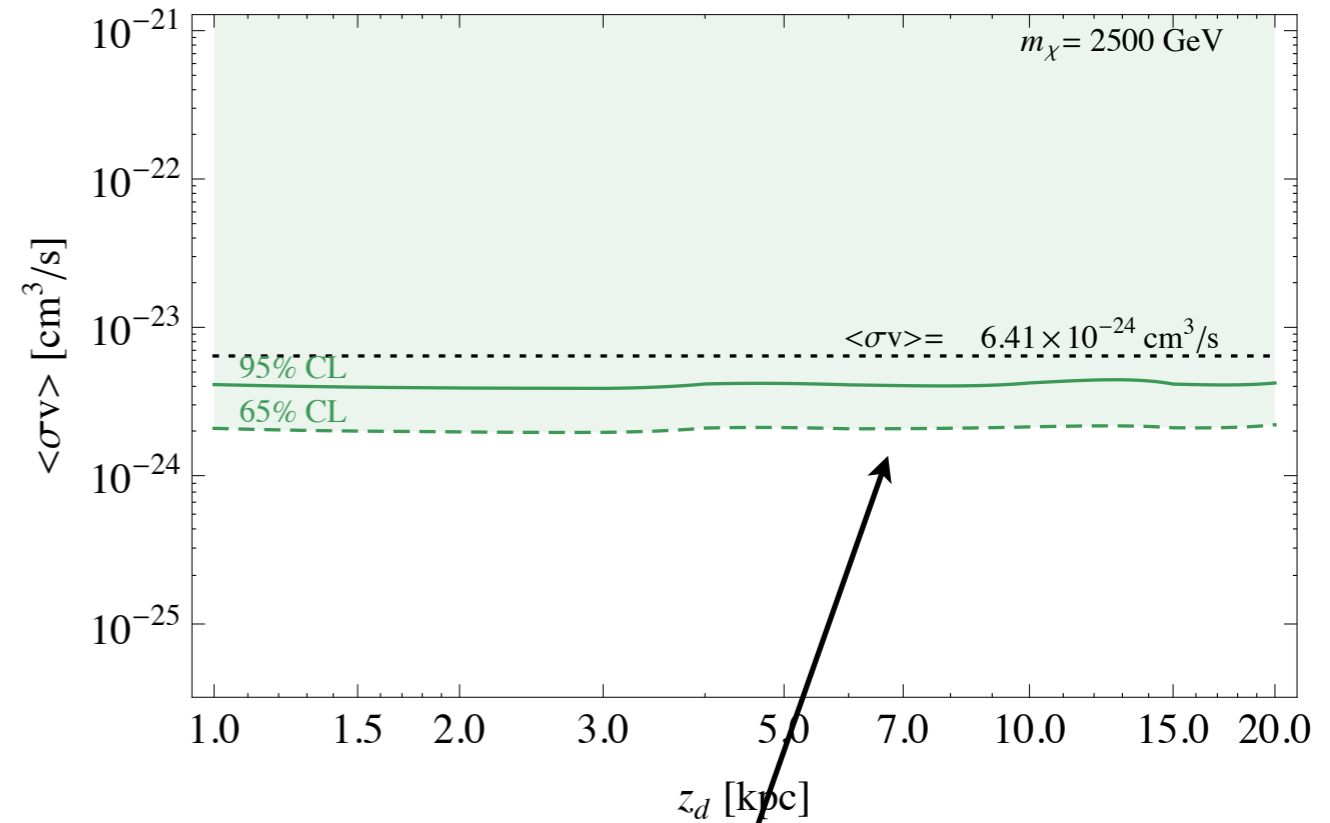
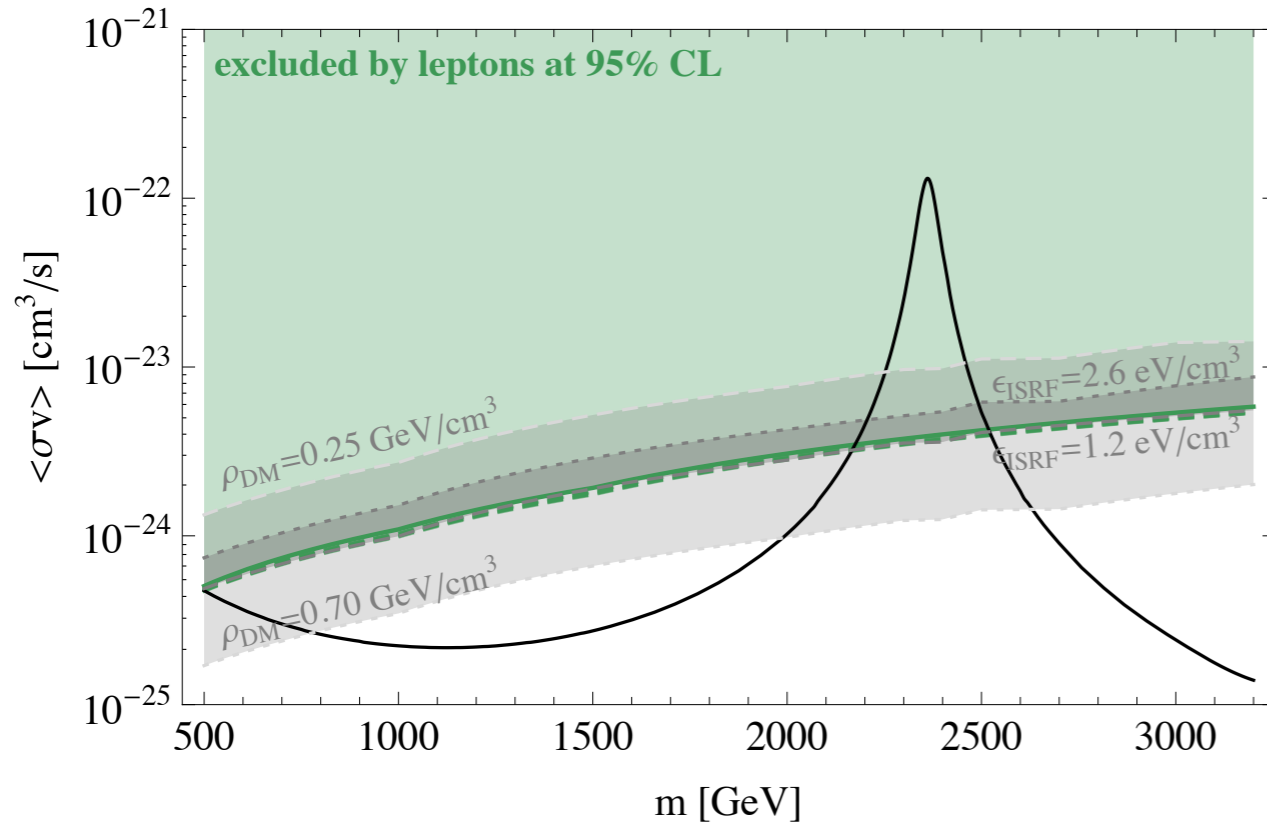


# Electrons, Positrons:



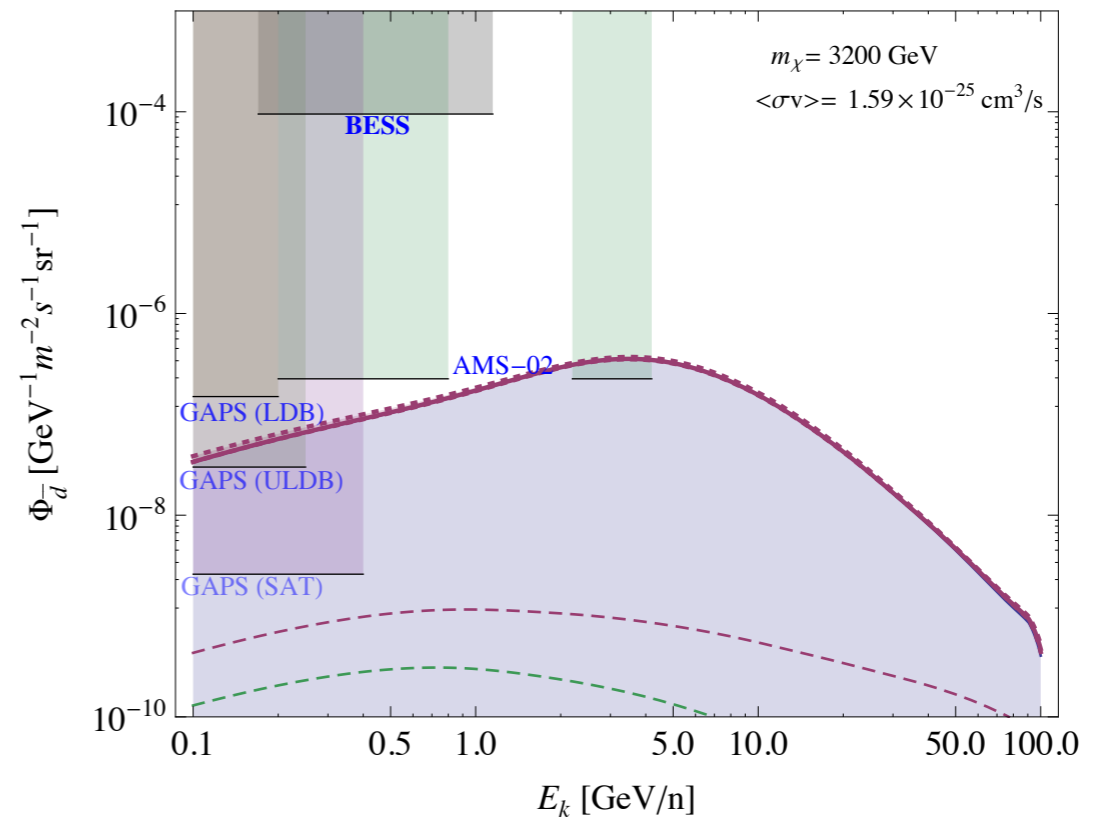
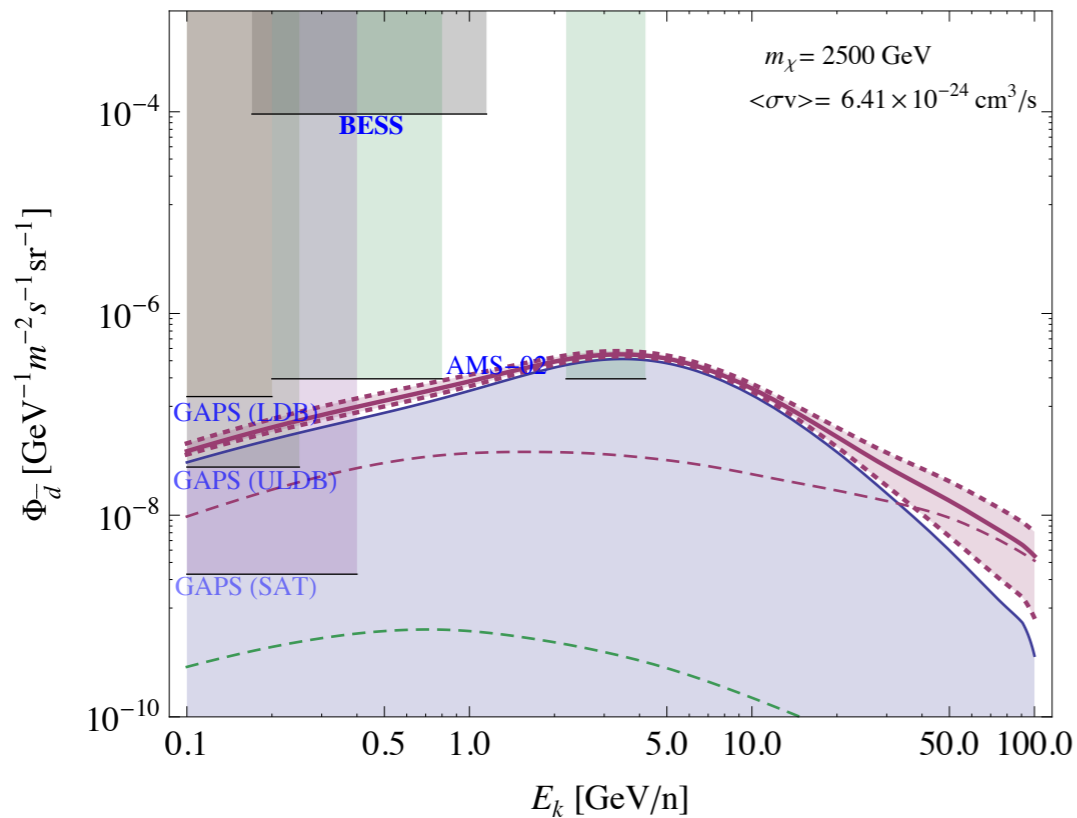
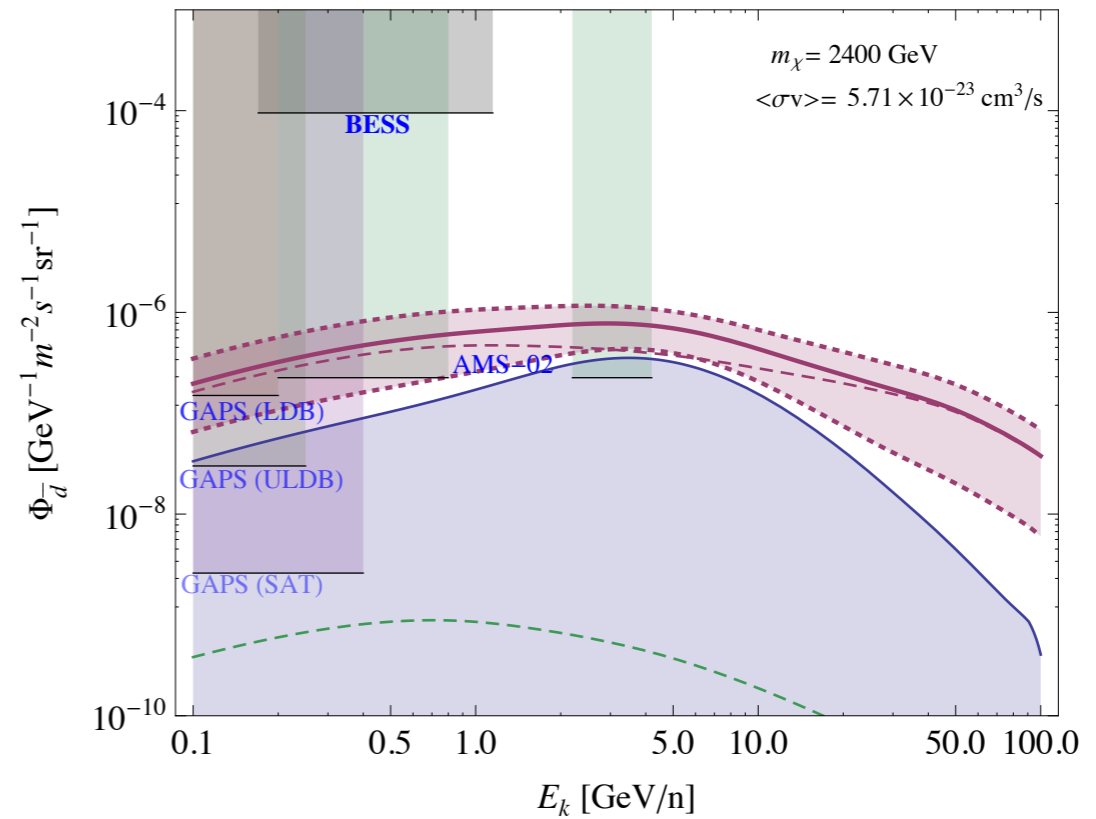
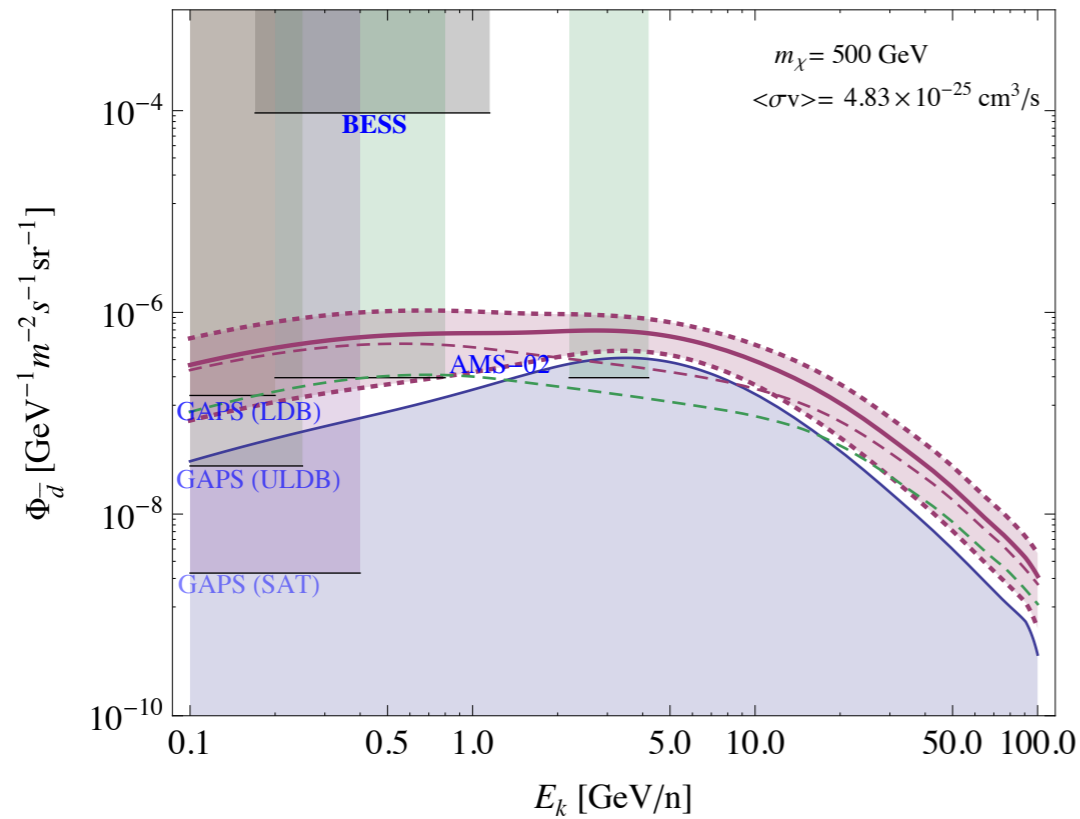
The Sommerfeld enhancement, has a dramatic impact in the flux

# 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.

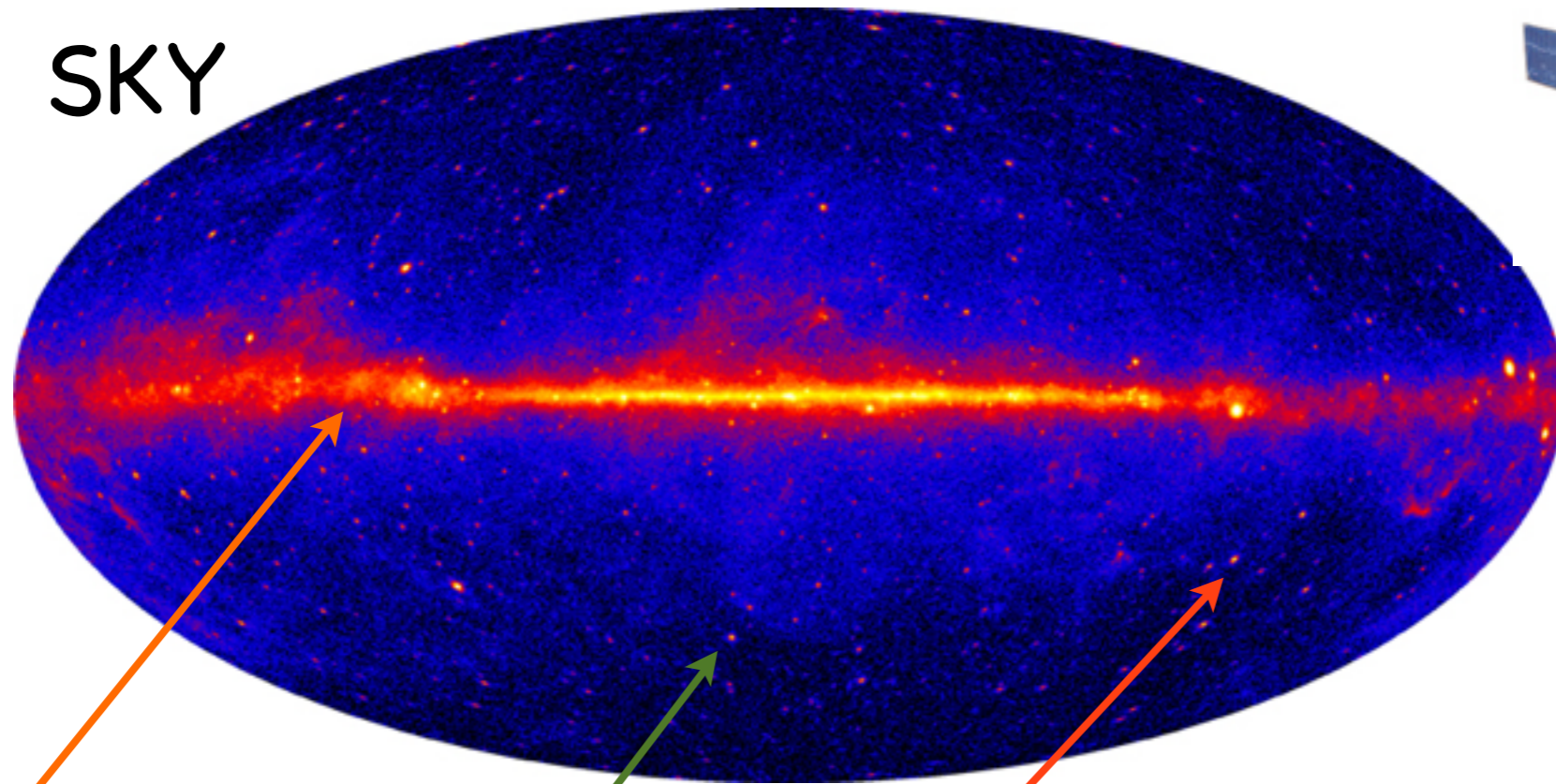
# Anti-deutrons; a probe for the future



**GAPS is the most sensitive experiment**

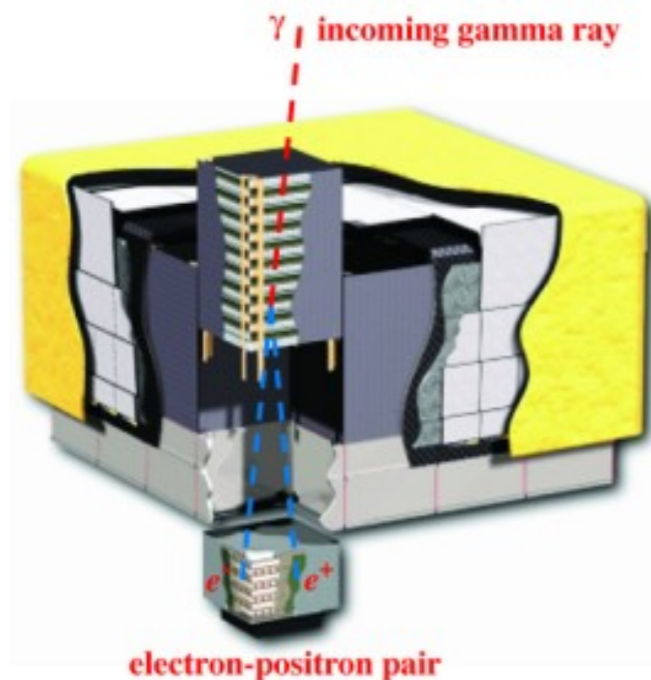
# Gamma-rays

Fermi SKY



- Known sources for the observed gamma-rays are:
- i) **Galactic Diffuse**: decay of  $\pi^0$ s (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 due to diffusion of CRs in the Galaxy)

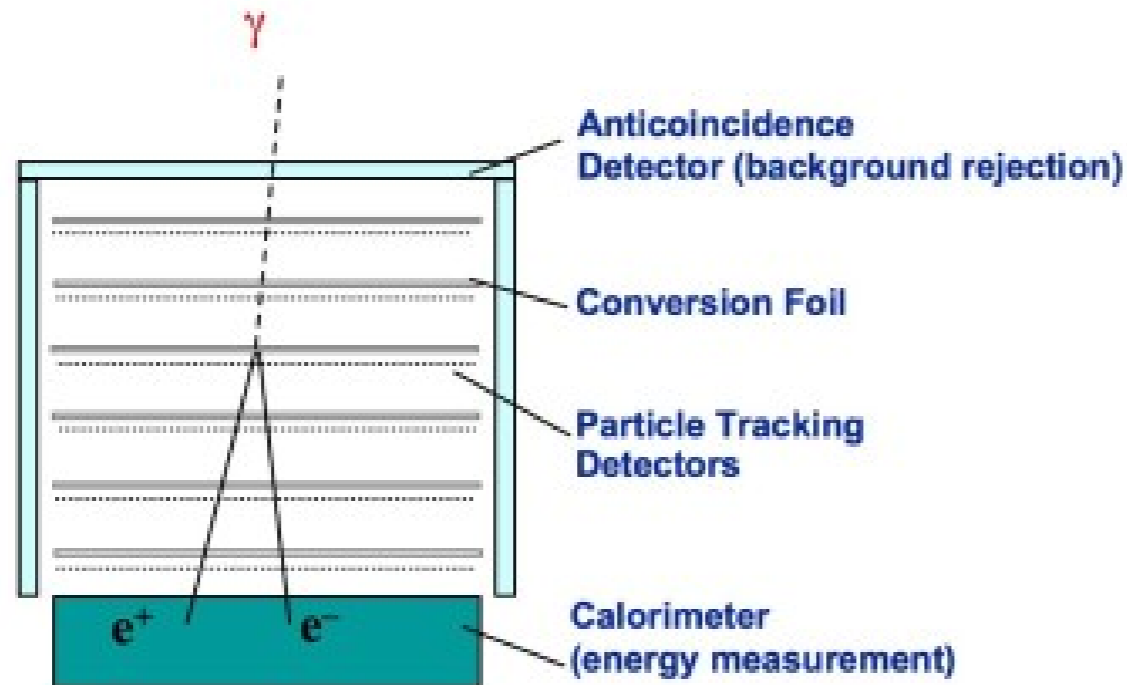
# Fermi Large Area Telescope



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: <  $0.15^\circ$  (above 10 GeV)
- Launched: 2008
- Will continue at least until 2014/2016



## Main components:

Anti-coincidence shield (plastic scintillator) with photomultiplier tubes

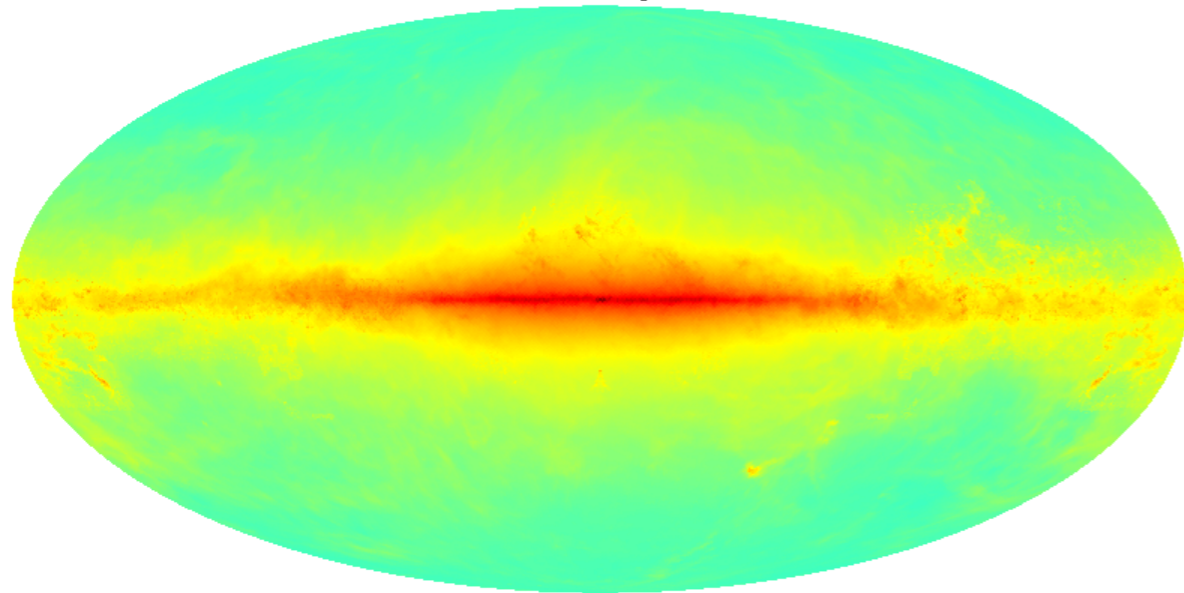
Tracker (silicon strip detectors) with conversion foils (tungsten)

Electromagnetic Calorimeter (CsI)

# Diffuse Gamma-Ray maps, examples

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

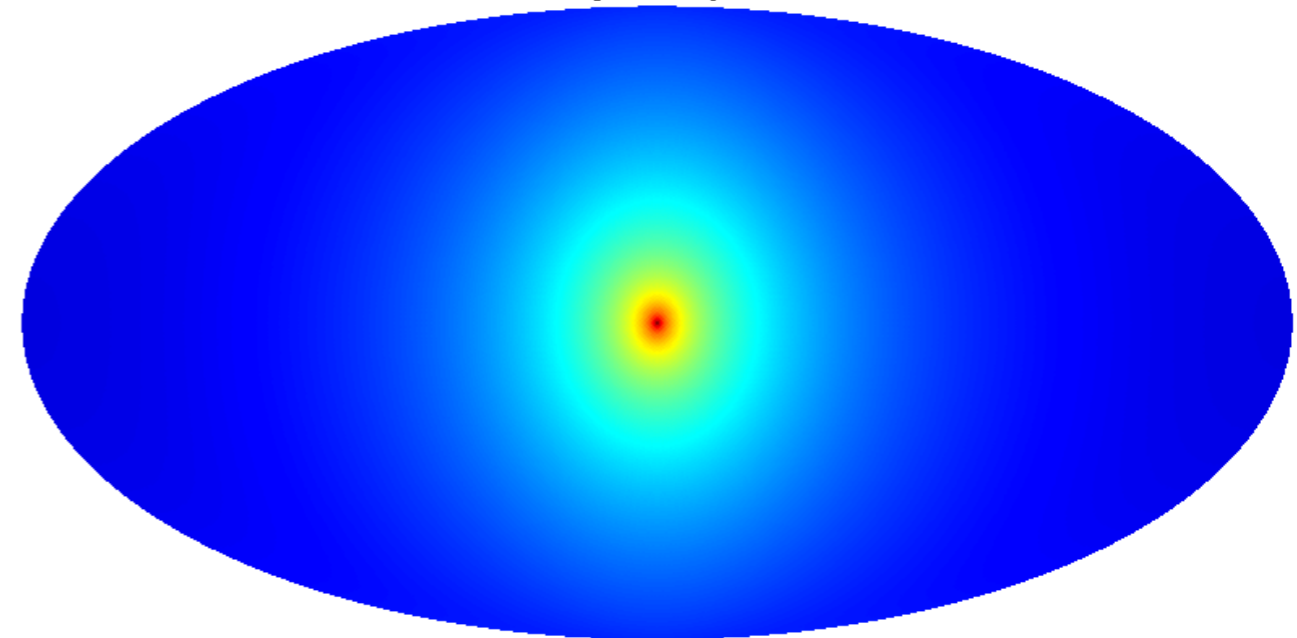
"BacK" template



-5.0  0.0 Log (Flux(Normalized at GC))

Spherical DM halo

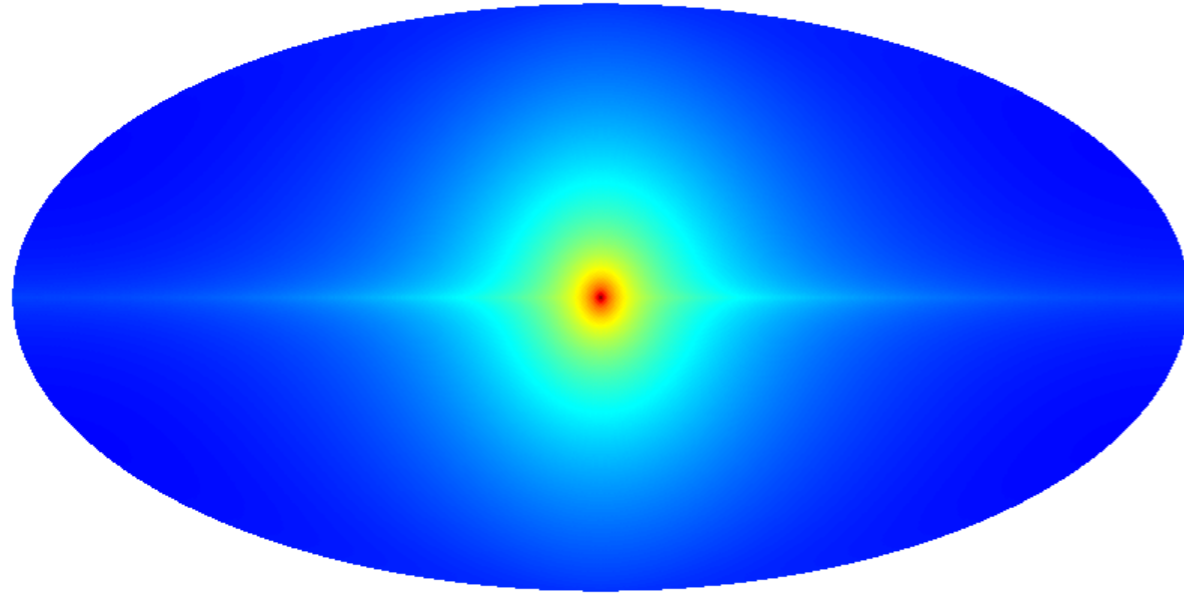
"SphDM" template



-5.0  0.0 Log (Flux(Normalized at GC))

Spherical DM halo with a maximal dark disk Template

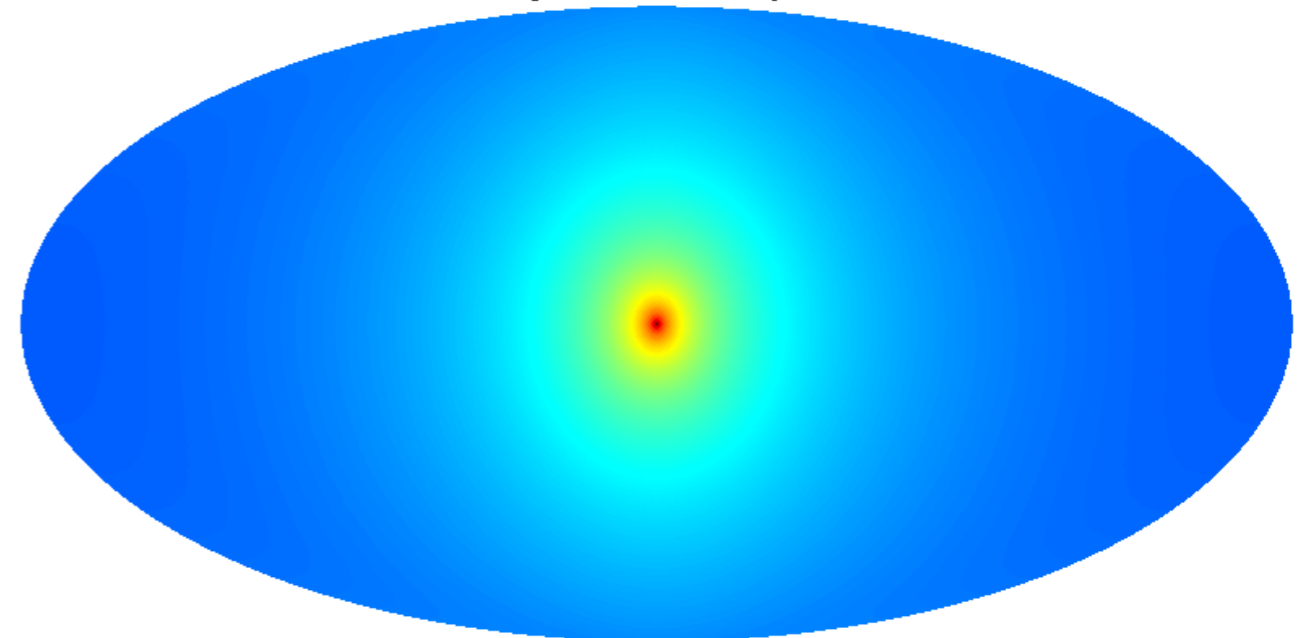
"SphDM" + "DarkDisk" + "MixedDM" combined template



-5.0  0.0 Log (Flux(Normalized at GC))

Spherical DM halo & substructures

"SphDM" + "SubDM" template



-5.0  0.0 Log (Flux(Normalized at GC))

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

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

# Looking for DM annihilation signals

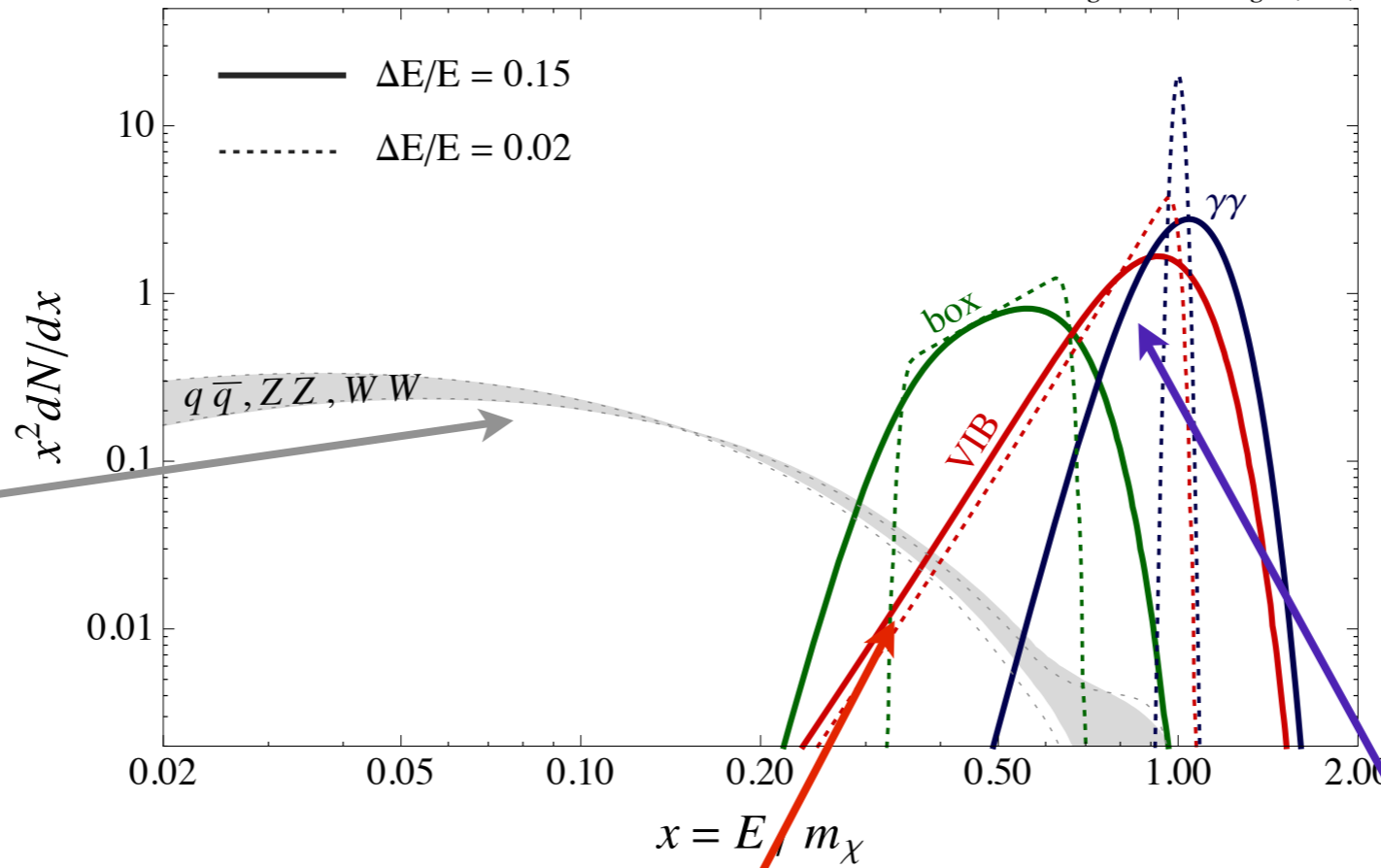
For a DM annihilation signal

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

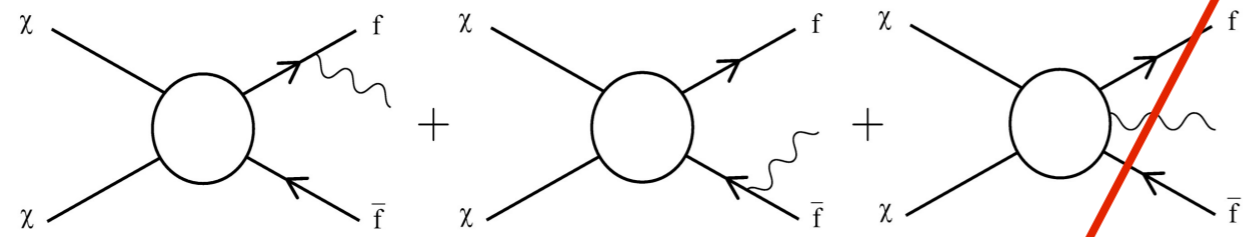
- Hardening of a spectrum without a clear cut-off localized in a certain region (Fermi haze  $\rightarrow$  Fermi bubbles)
- Hardening of a spectrum with a clear cut-off:  $\sim 10$  GeV DM claims towards the Galactic Center (GC) inner few degrees
- Line or lines
- One of the most likely targets is the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

# DM annihilation spectra

Bringmann & Weniger (2012)



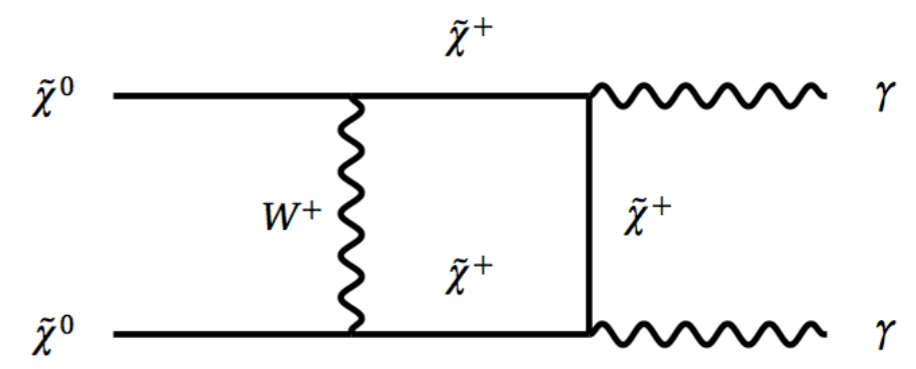
Continuum emission, tree level, relatively hard spectrum, but featureless



Final state radiation      Virtual Internal Bremss.

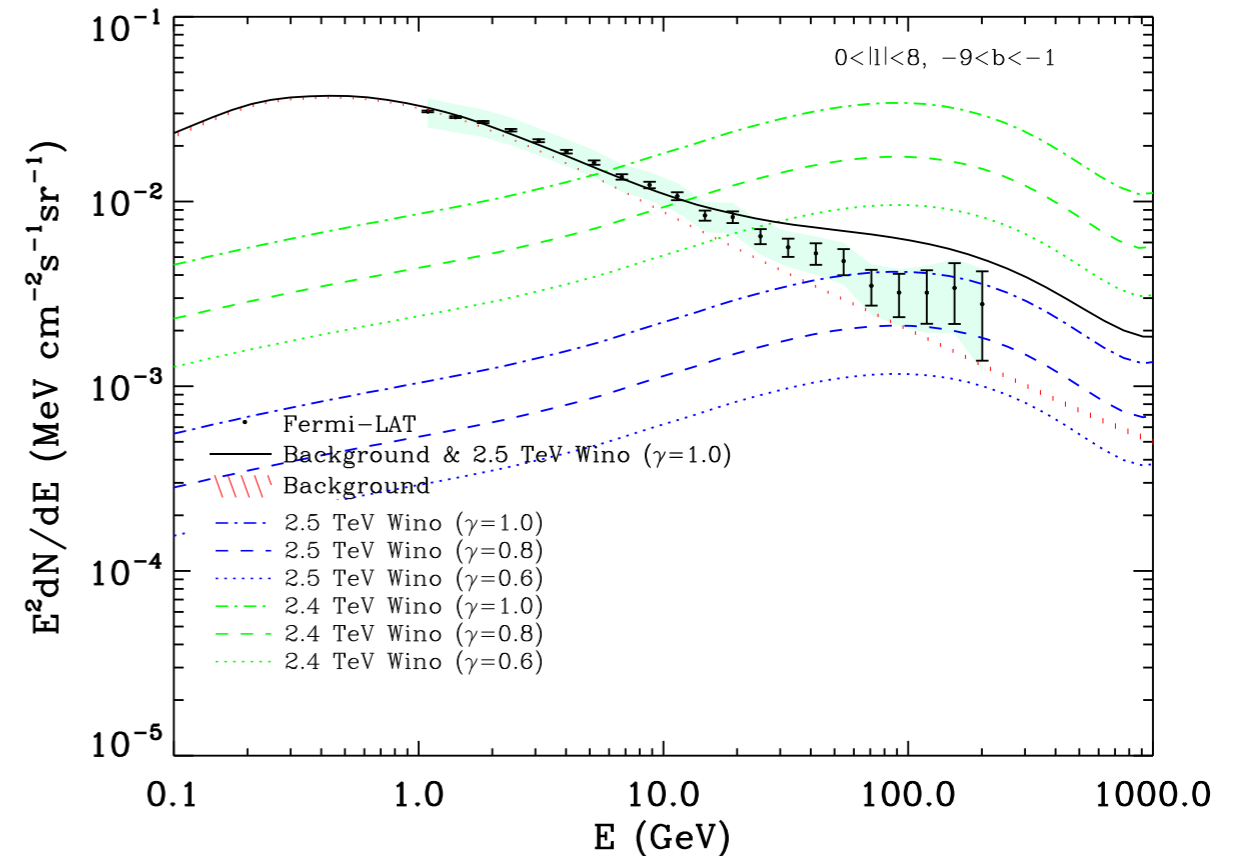
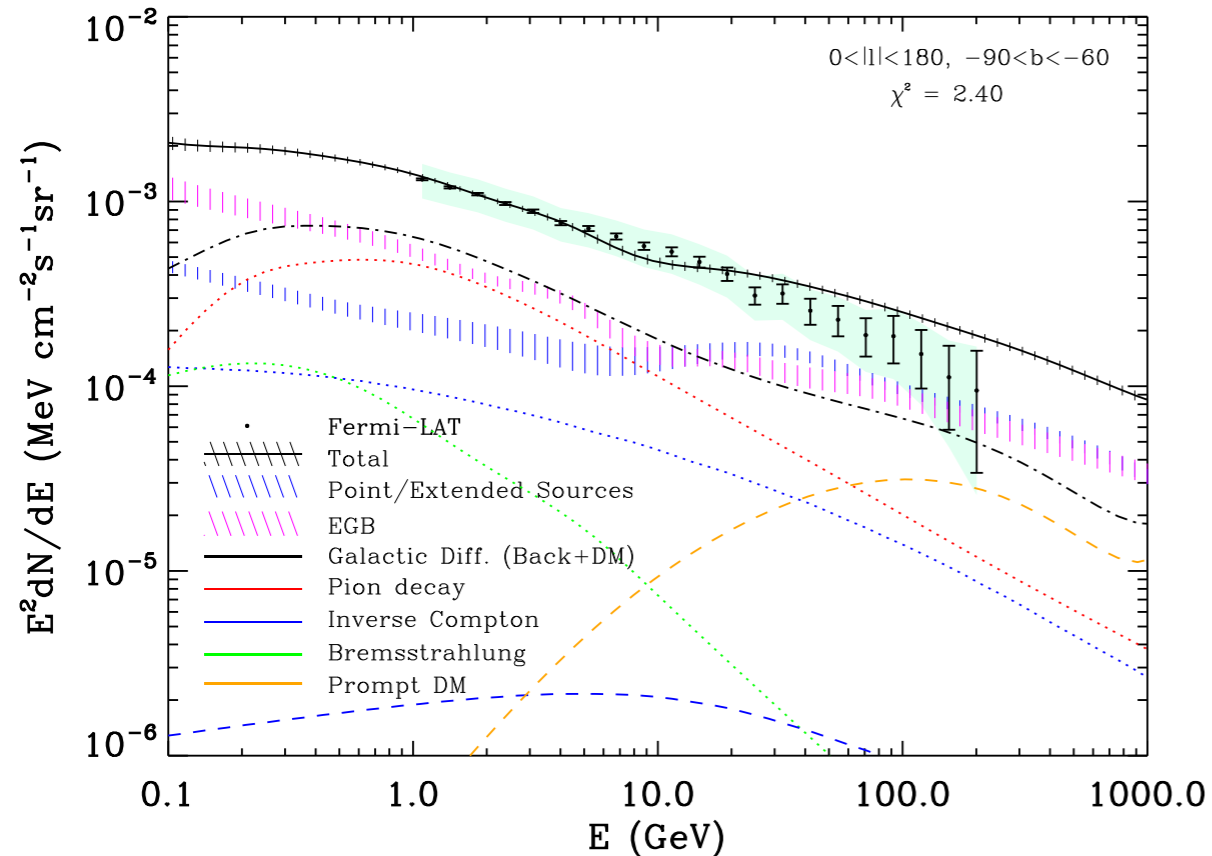
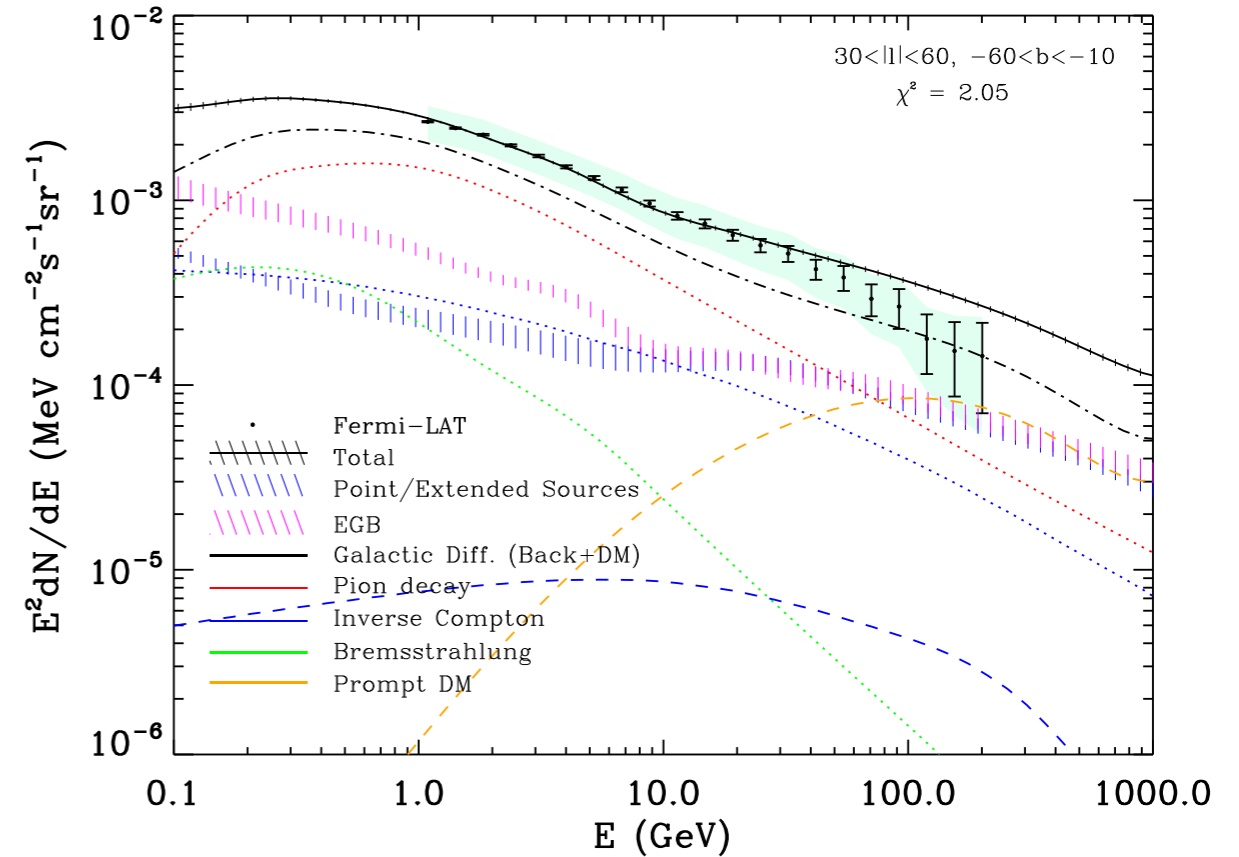
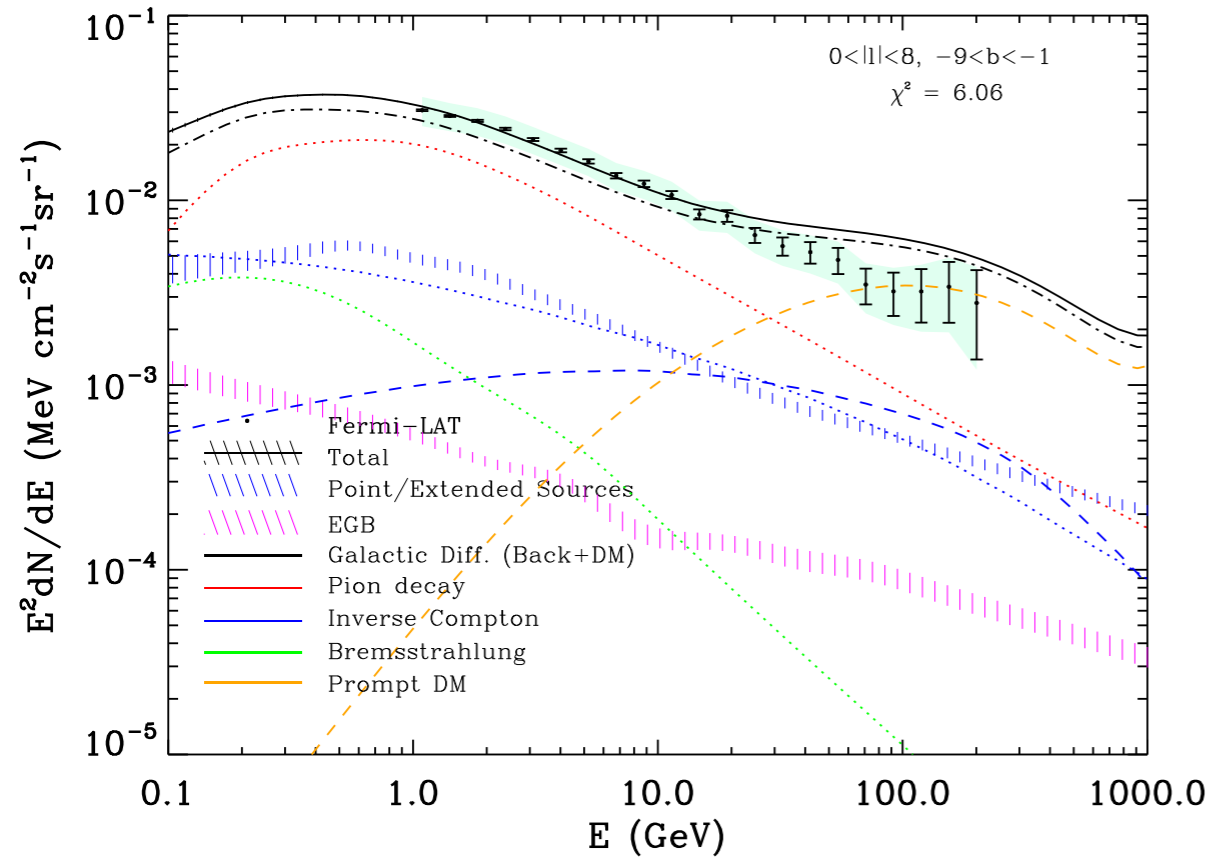
Comes from radiative corrections to processes with charged particles. Suppressed by  $O(\alpha)$ , but with a much harder spectrum; FSR has an additional suppression factor of  $(m_f/M_{\chi})^2$

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



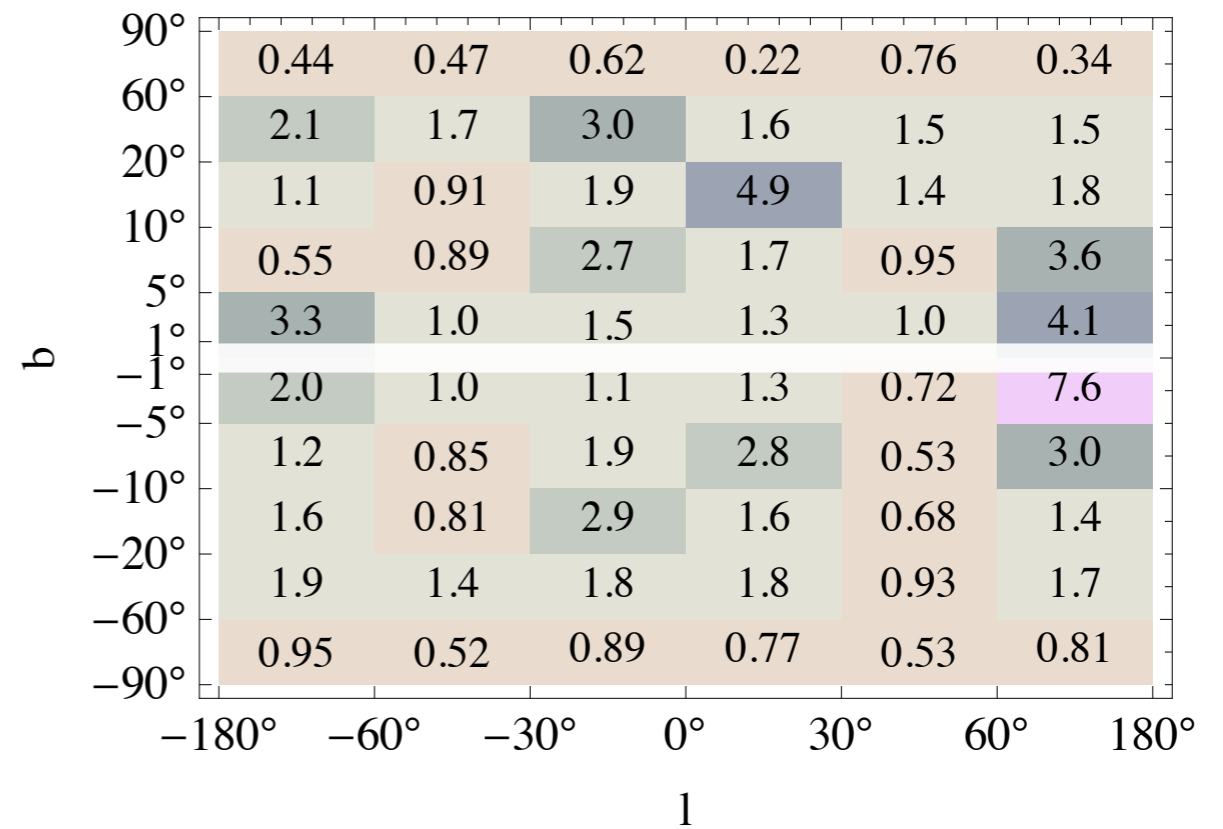
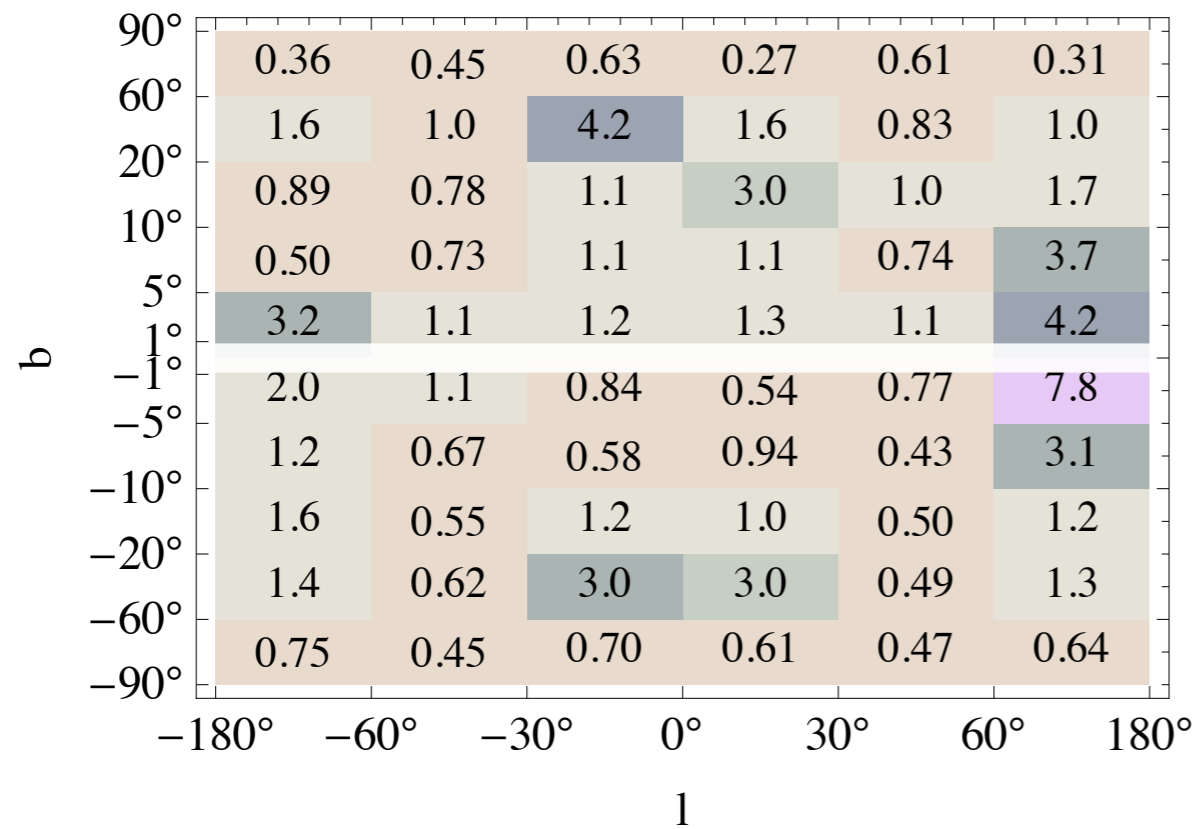
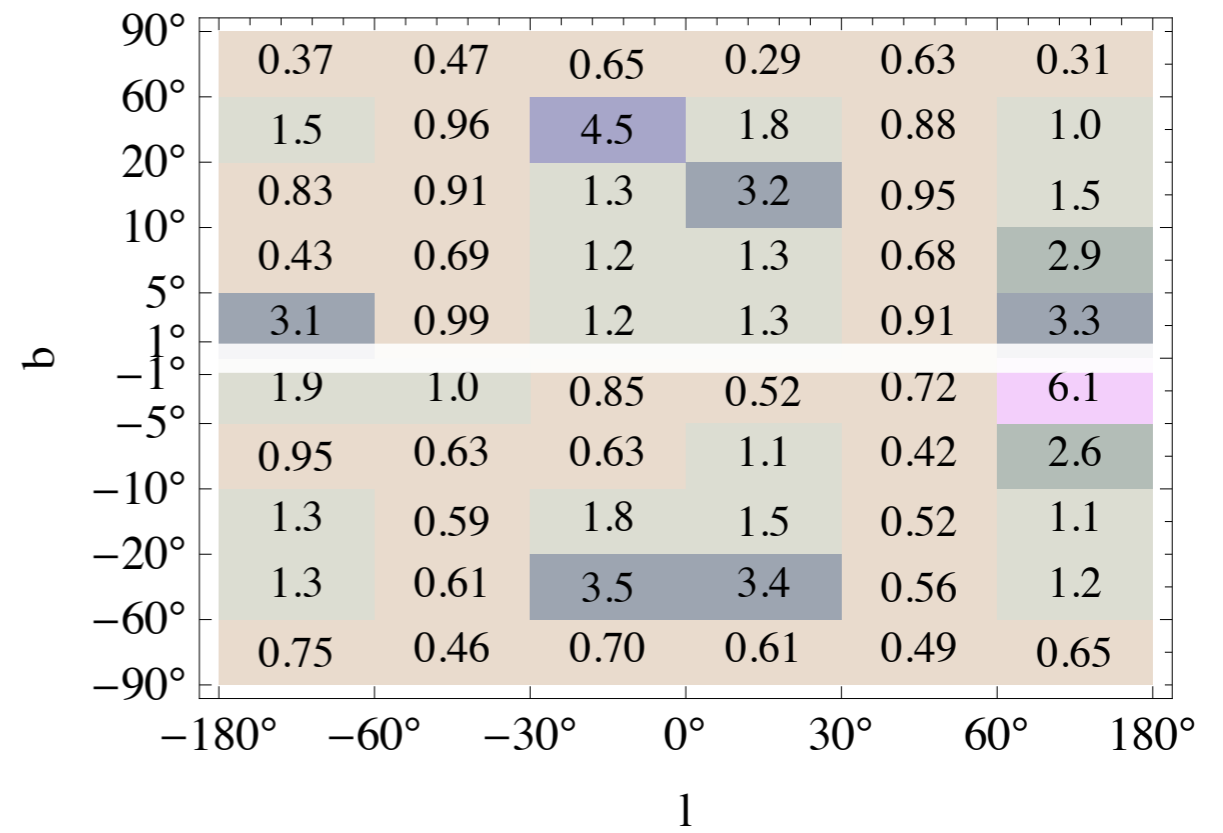
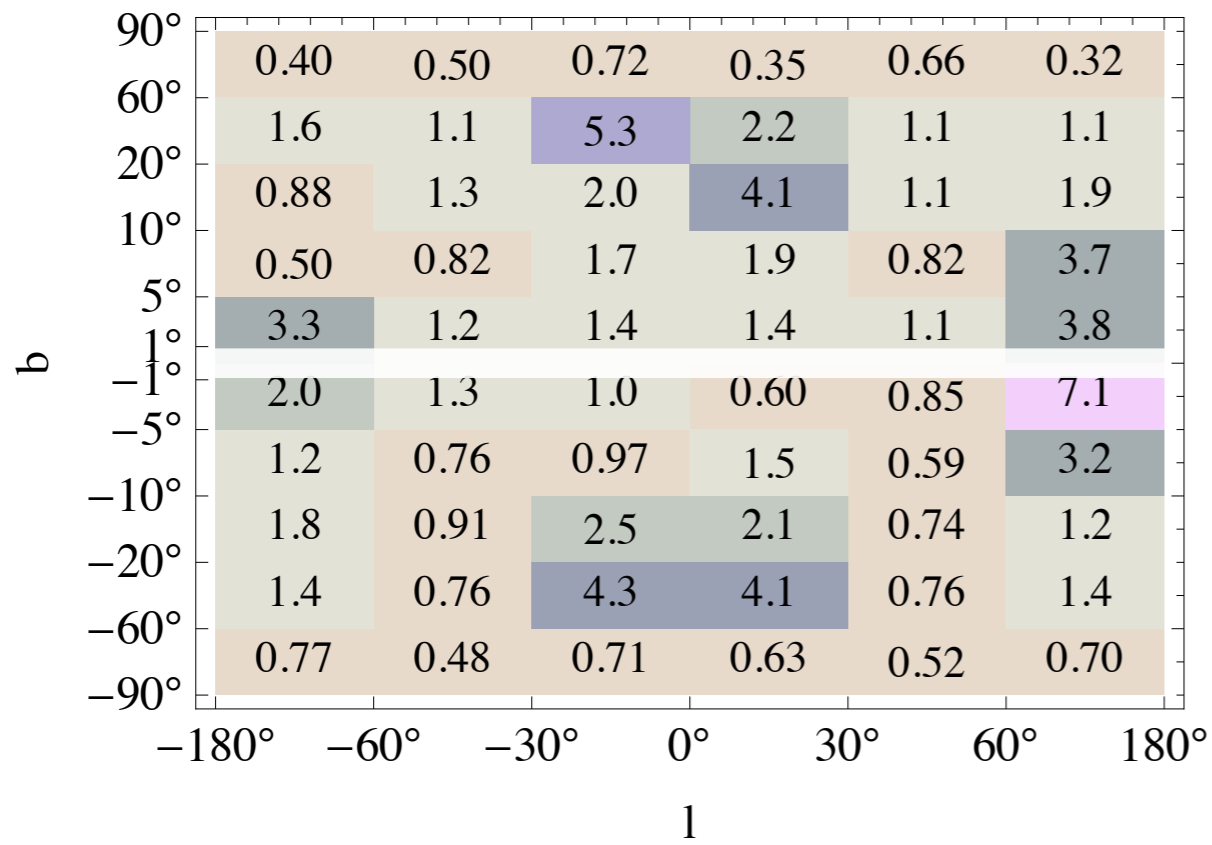


# Calculating spectra in different patches of the sky

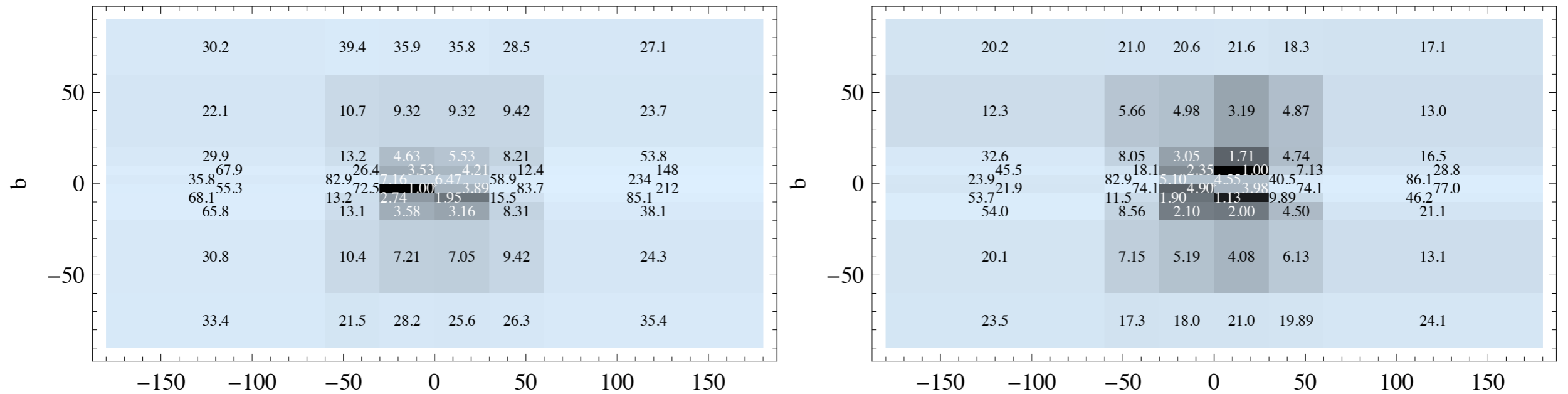


# Comparison of models to Data

Different Choices of galactic CR diffusion:

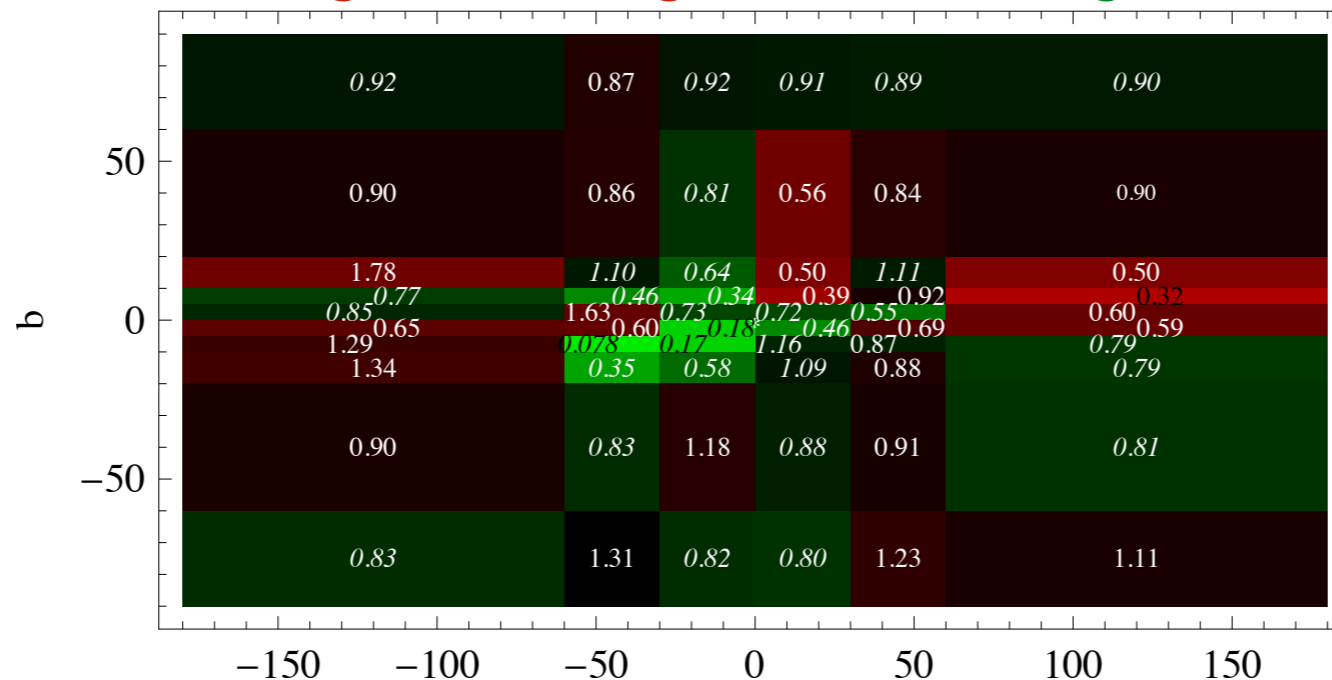


# Limits on "light" Wino DM, in various patches of the sky (continuum emission)



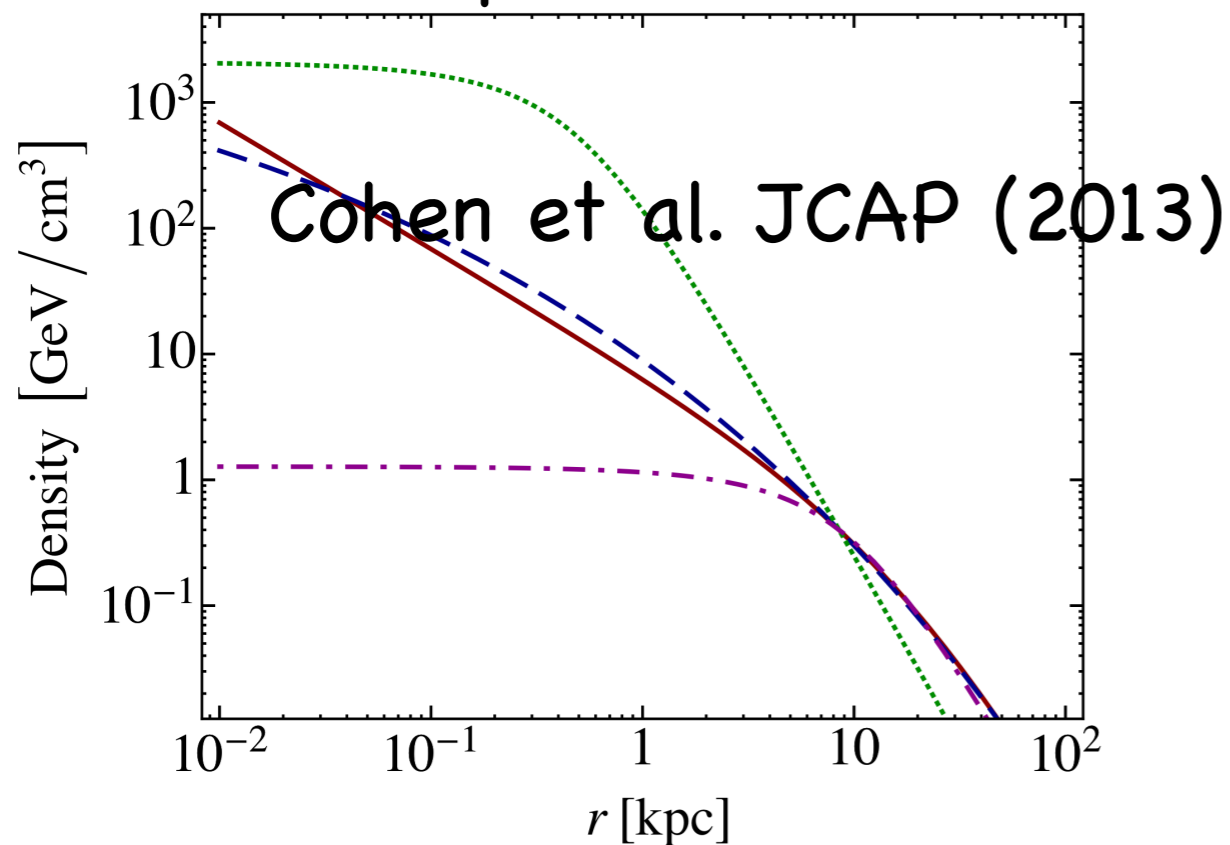
M. <sup>1</sup>Tavakoli, I.C., C. Evoli, P. Ullio, JCAP **1401** (2014)

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

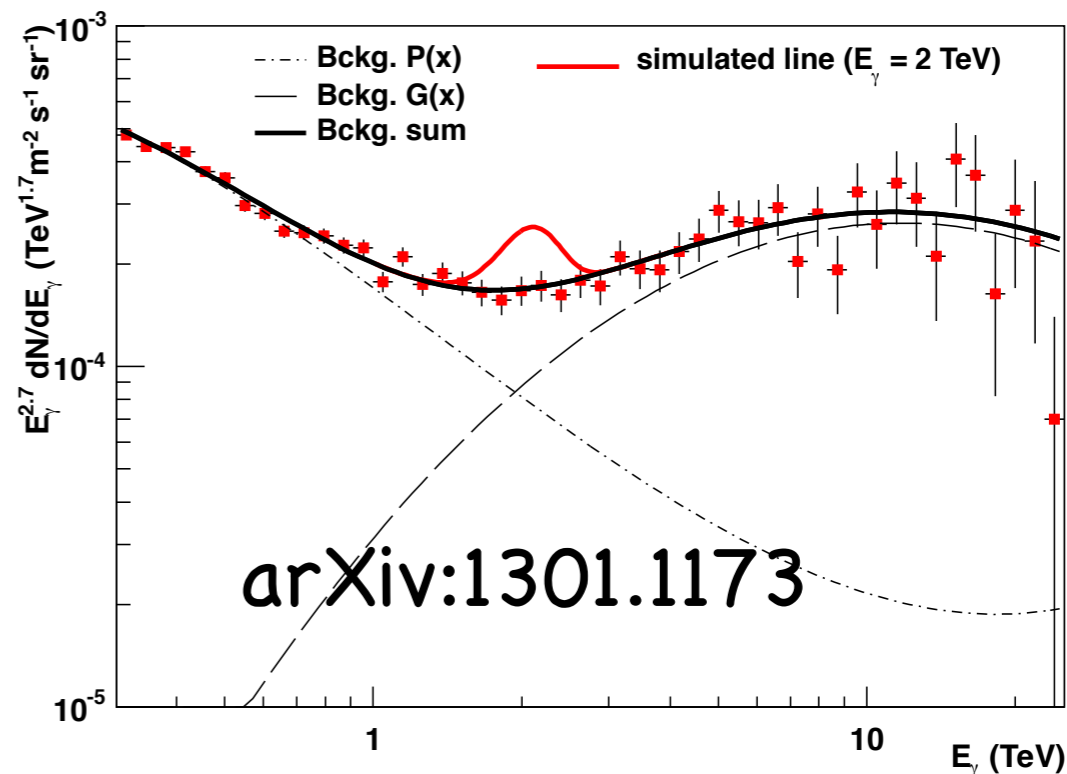


# The case of a gamma-ray line at the galactic center

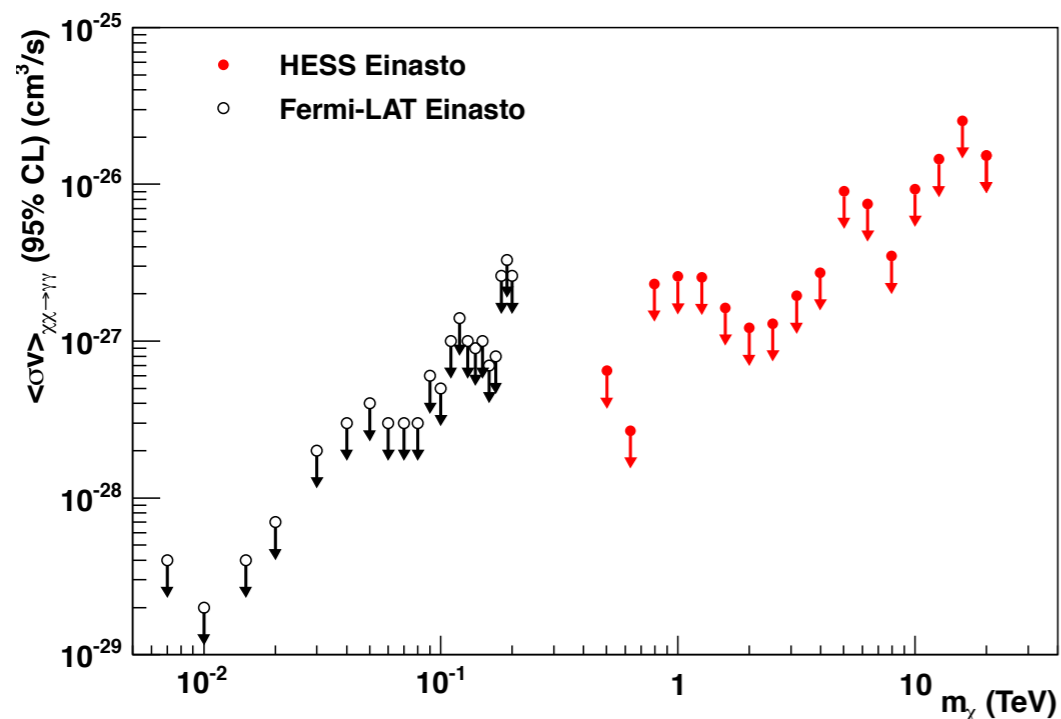
The DM profile:



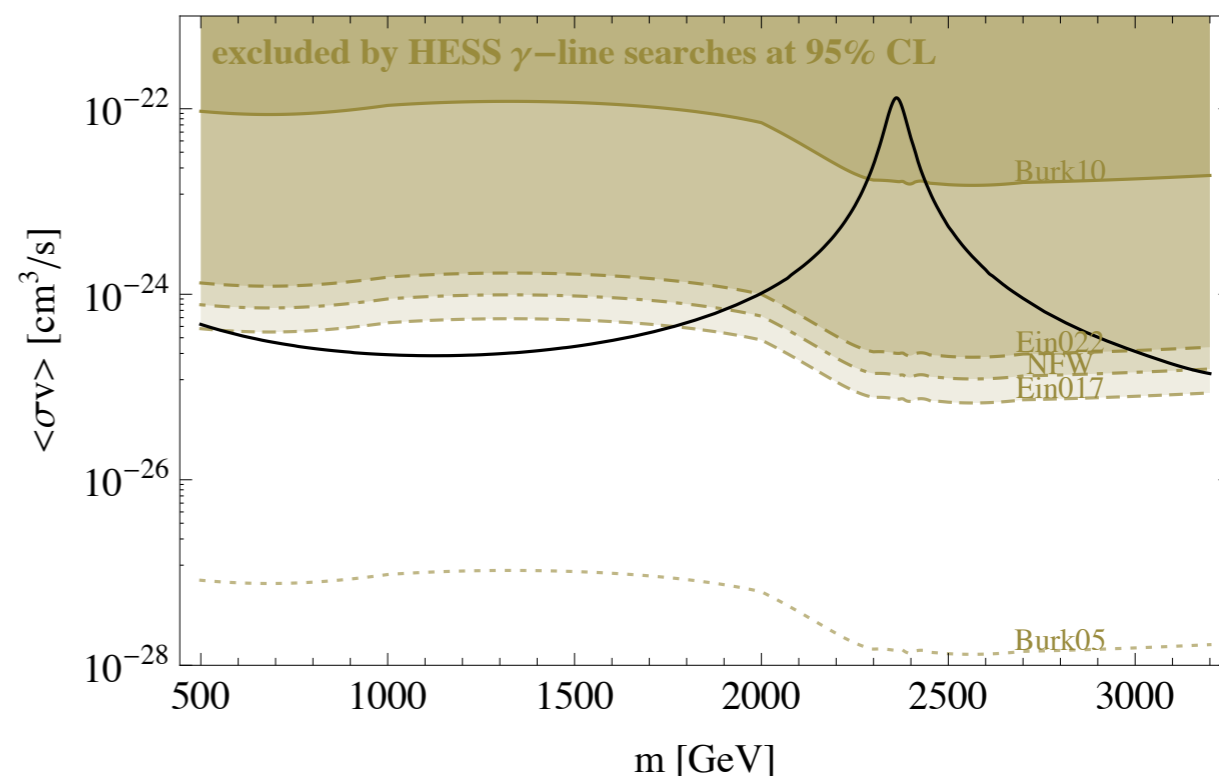
Looking for spectral features (HESS):



The Limits on spectral features:

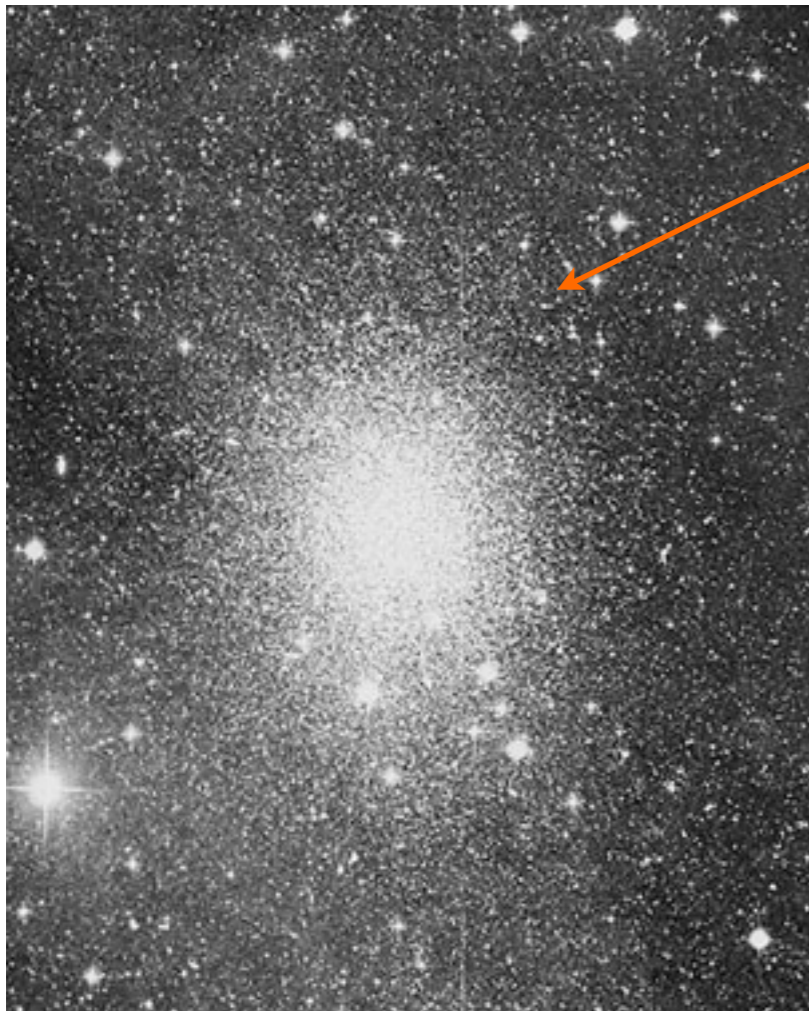


Wino Limits:



# Significance of dwarf spheroidal galaxies for Dark Matter annihilation signals

Sculptor



dwarf Spheroidal galaxies are low luminosity galaxies (**spheroidal in shape**) containing  $\sim 10$ – $100$  million stars with the observed ones being companions to our Galaxy or to Andromeda. Their typical mass is  $\sim 100$  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  $\rightarrow$

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

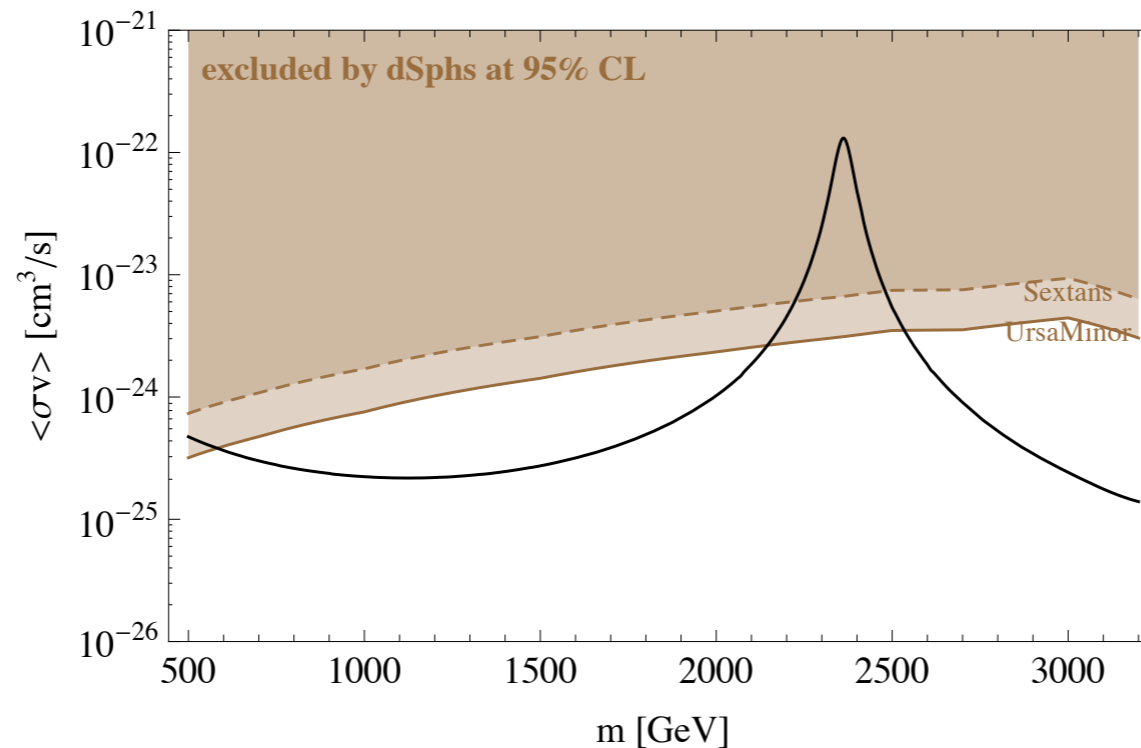
thus a "**good**" target to look for a DM signal in gamma-rays, especially for detectors as the Fermi-LAT, Air-Cherenkov telescopes

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

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

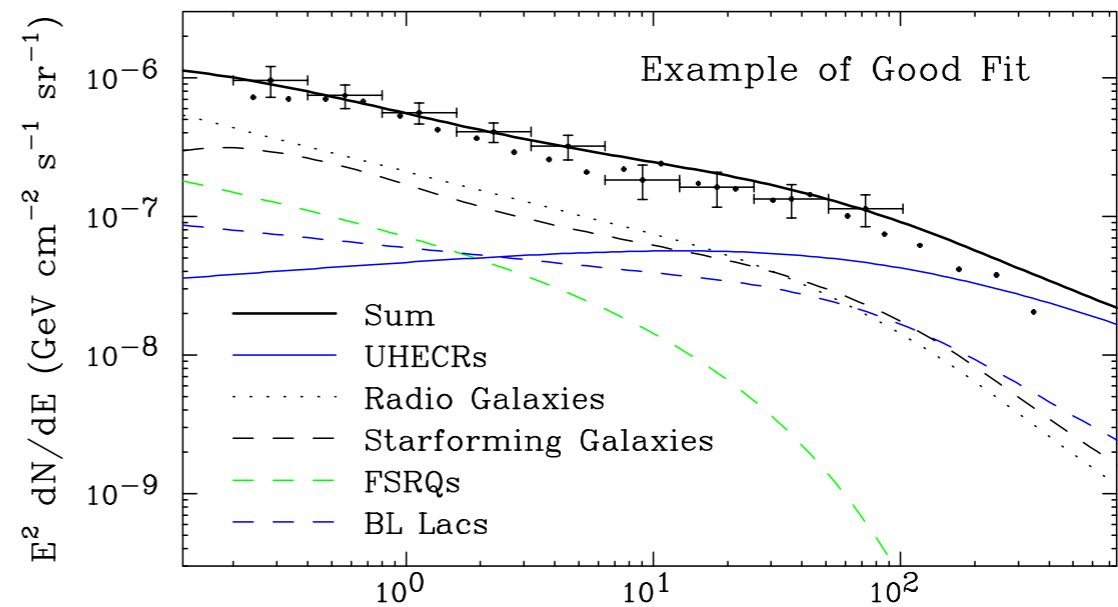
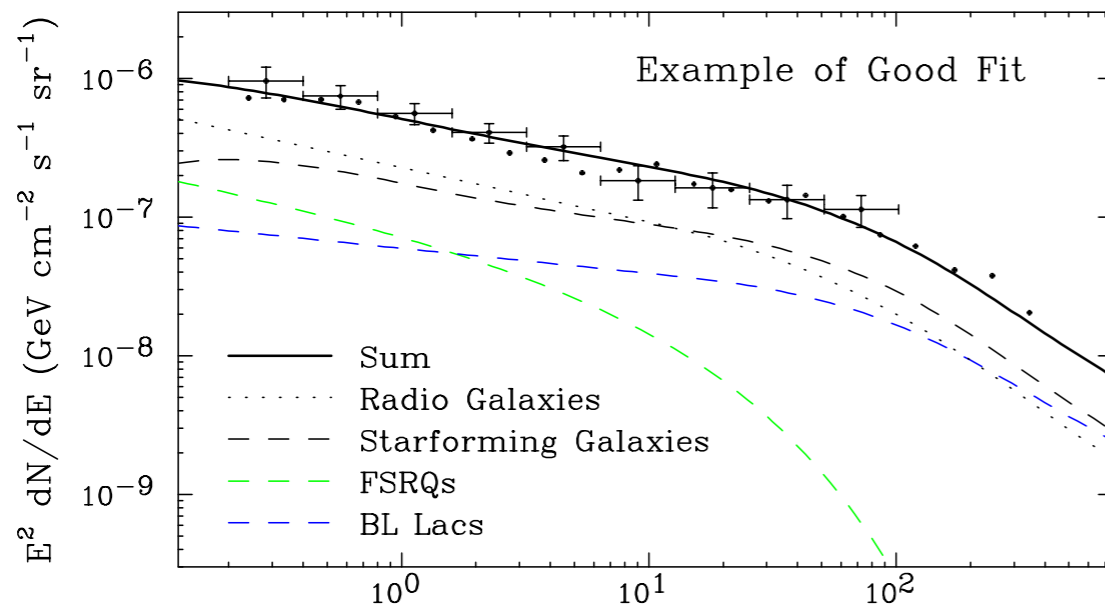
Mass [GeV]	Ursa Minor			Sextans		
	90% CL	95% CL	99.9% CL	90% CL	95% CL	99.9% CL
500	0.66	0.94	2.13	1.52	2.02	4.02
1000	3.19	4.77	11.8	7.17	9.67	19.7
2360	0.020	0.031	0.079	0.043	0.059	0.123
2400	0.033	0.051	0.132	0.071	0.097	0.203
2500	0.55	0.83	2.14	1.16	1.59	3.31
2700	3.69	5.61	14.46	7.84	10.7	22.4
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 BF's smaller than one suggest the model is excluded.



# Constraints from High Latitudes (mainly extragalactic)

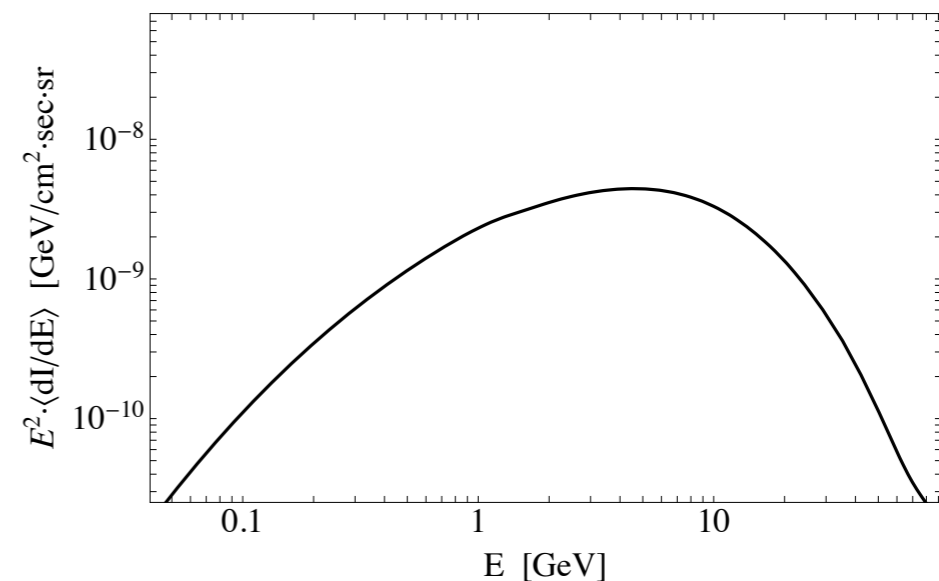
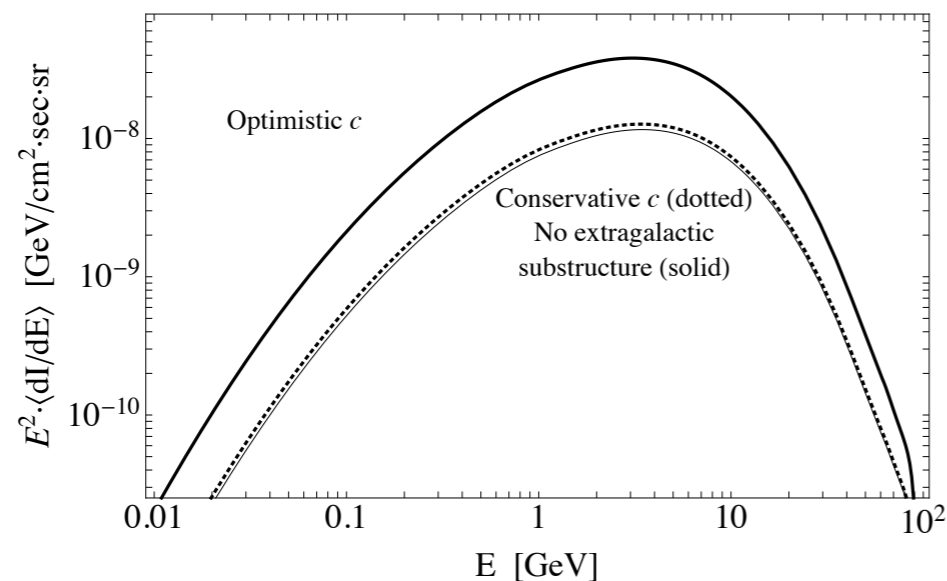
Extragalactic diffuse gamma-rays are isotropically distributed. There are many astrophysical sources that suffer from relatively large uncertainties. Correlating to radio we can extract some of their properties and model them out. → Build models for the non-DM contribution and derive limits on DM.



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

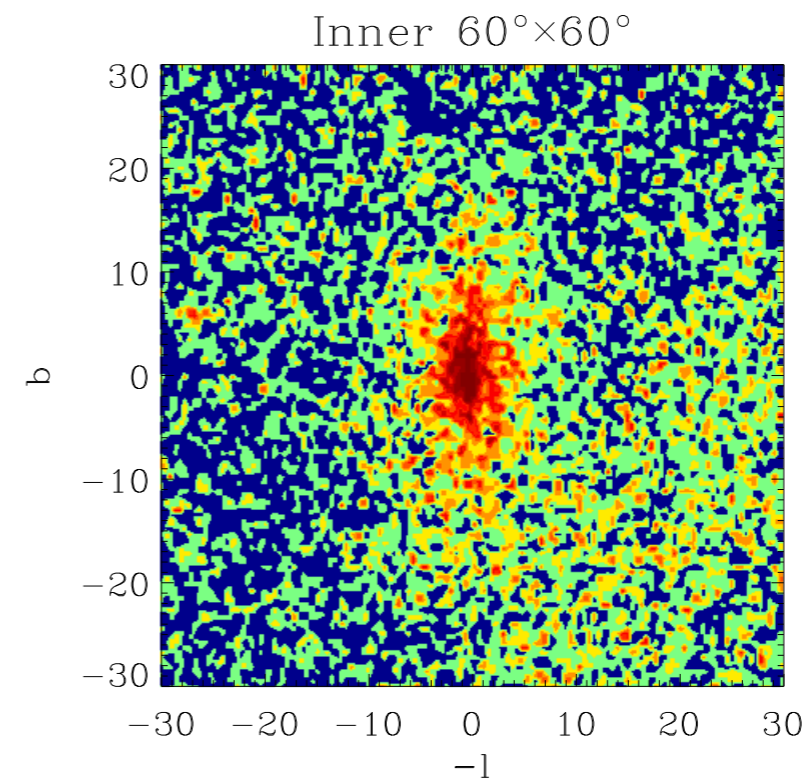
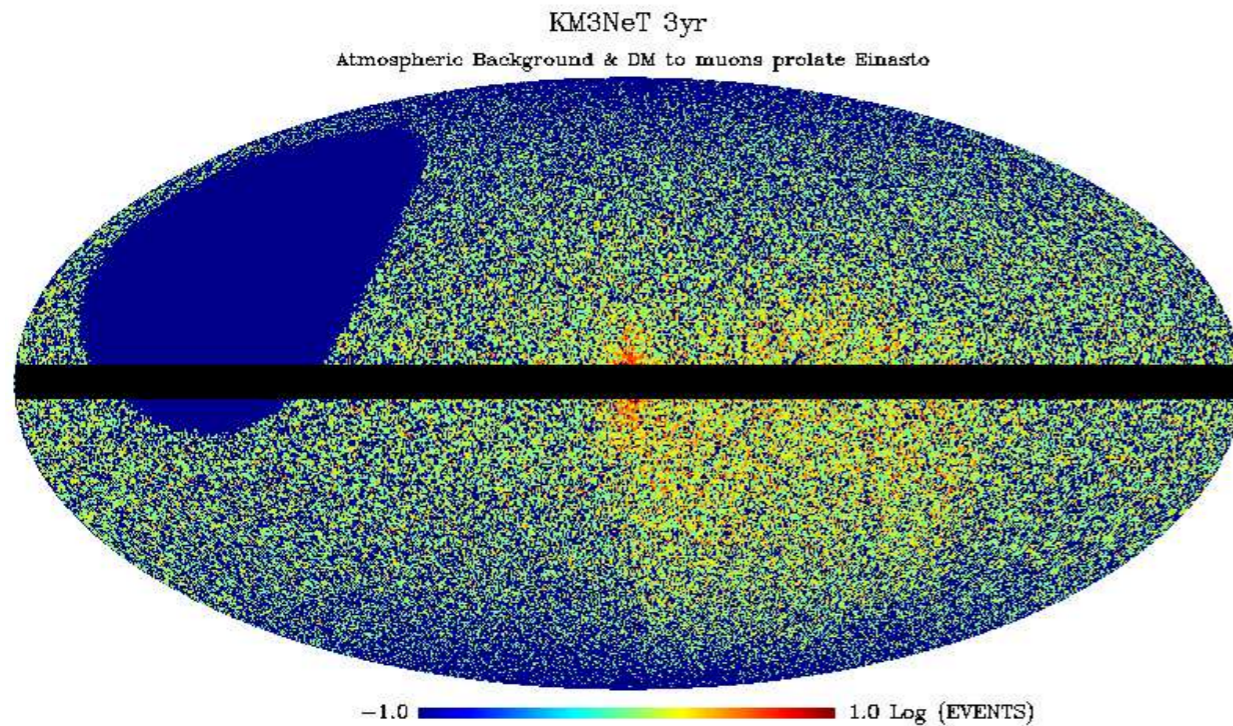
Extragalactic Structure

MW Smooth



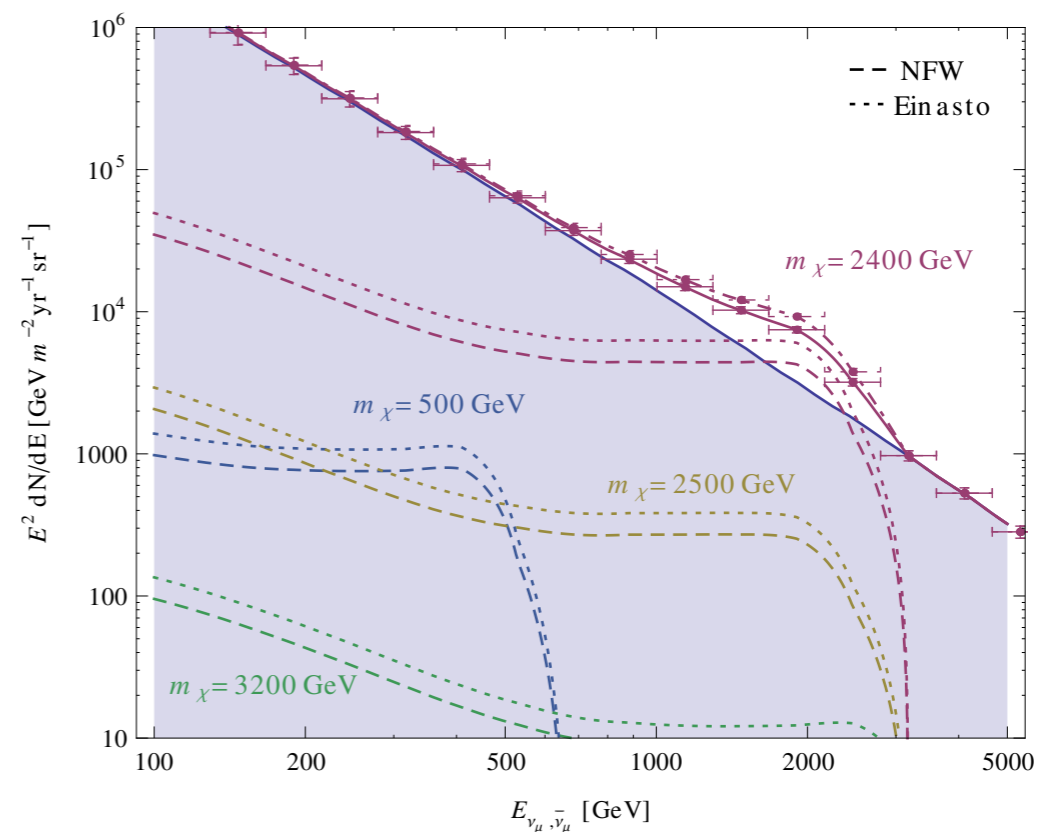
# Neutrinos from the GC (future projections)

A possible **enhanced signal** of SM annihilation in the Milky Way



I.C. PRD 88 (2013)

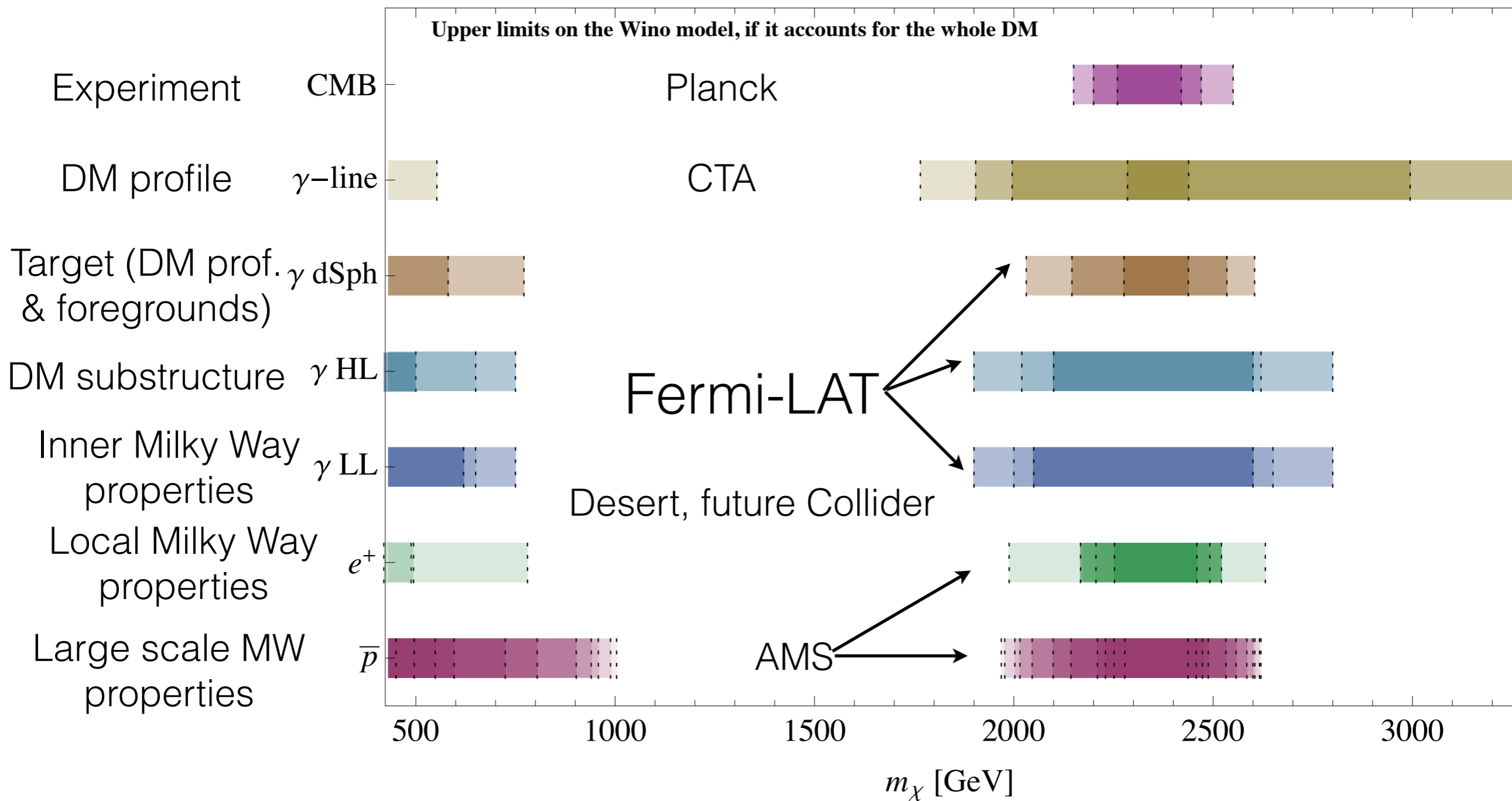
Only close to the resonance will we be able to observe such a signal. But **the resonance has already been excluded by other indirect probes:**





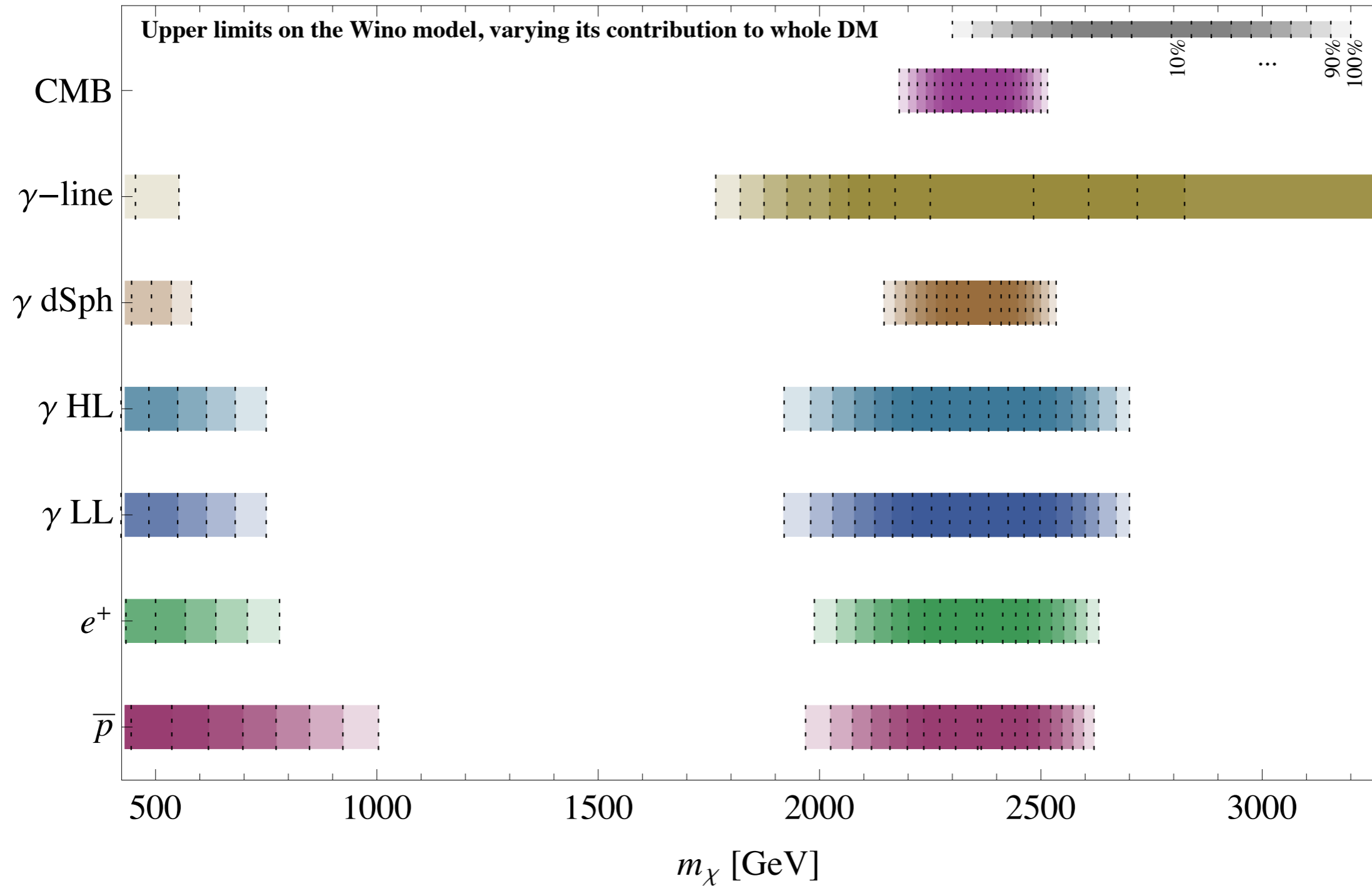
# Comparisons and Conclusions

95% CL upper limits:



95% CL upper limits.

RELAXING the Wino relic density condition:



**Thank you**