Hooperon vs Antiproton constraints

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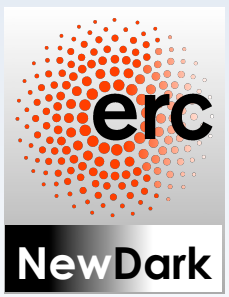
Work with Marco Cirelli, Daniele Gaggero, Marco Taoso and Alfredo Urbano- arxiv: 1407.2173



- There is a GeV γ-ray excess in Fermi-LAT data from the Galactic Center (GC)
- Computation of secondary emission from DM annihilation (Inverse Compton and Bremsstrahlung) $\Rightarrow$ determining the DM spectrum for hadronic and leptonic channels
- Constraints from antiprotons with a focus on solar modulation

The morphology of the GC excess allows to determine the DM density : **generalized Navarro-Frenk-White (gNFW)**

$$\rho_{\rm gNFW}(r) = \rho_\odot \left(\frac{r}{r_\odot}\right)^{-\gamma} \left[\frac{1+(r/R_s)^\alpha}{1+(r_\odot/R_s)^\alpha}\right]^{-\frac{(\beta-\gamma)}{\alpha}}$$

- $\rho_\odot = 0.3$ GeV/cm^3, $r_\odot = 8.5$ kpc, $R_s = 20$ kpc, $\alpha = 1$, $\beta = 3$.
- $\gamma =$ inner slope of the profile
- The GC excess is better fit by a profile with :

$$\gamma = 1.20 \text{ or } 1.26.$$

We consider three sources of γ-rays from DM :

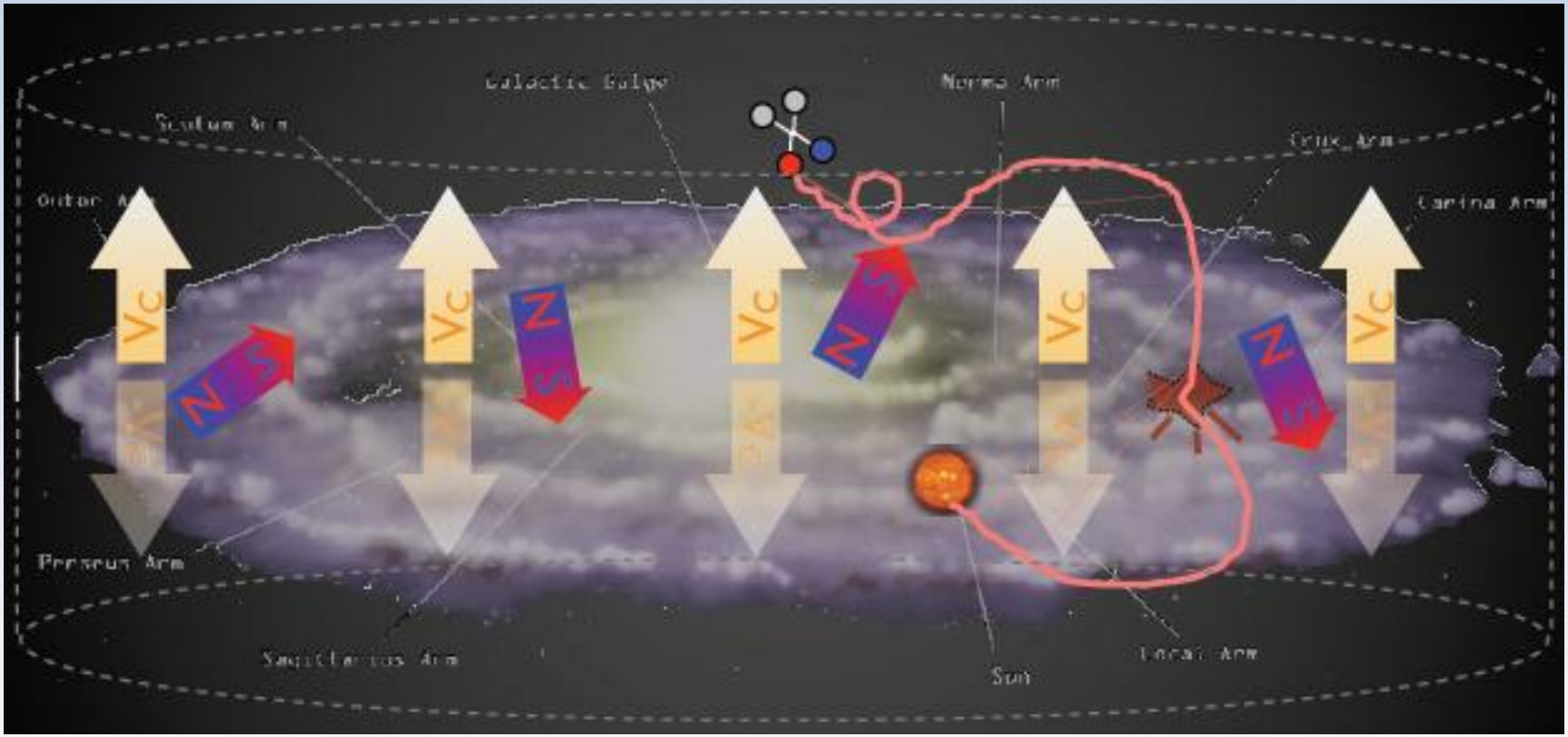
- **prompt** γ-ray flux

$$\frac{d\Phi}{dE_\gamma d\Omega} = \frac{r_\odot}{8\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left[\frac{\rho_{\rm gNFW}(r(s,\theta))}{\rho_\odot}\right]^2 \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE_\gamma}$$

  Input spectra dN_γ^f/dE_γ for a final state f (for instance $b\bar{b}$) from the PPPC4DMID

- **Inverse Compton** : e^+ and e^- from DM annihilation hit an ambiant photon (from CMB, IR or Opt galactic radiation fiel) and up-scatter it to γ-ray energies
- **Bremsstrahlung** : e^+ and e^- radiate soft γ-rays when slowed down by (neutral or ionized) interstellar gas

$\Rightarrow$ IC and Brems computed with GAMMASKY


Galactic Bulge
Norma Arm
Scutum Arm
Crux Arm
Outer Arm
Carina Arm
Perseus Arm
Sagittarius Arm
Sun
Local Arm

We solve the following equation :

$$\frac{\partial N^i(r,z,p)}{\partial t} = \frac{\partial}{\partial x_i} D_{ij} \frac{\partial N^i}{\partial x_j} + \boldsymbol{v}_c \cdot \boldsymbol{\nabla} N^i - \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\boldsymbol{\nabla}\cdot\boldsymbol{v}_c\right) N^i + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{N^i}{p^2} + Q(r,z,p)$$

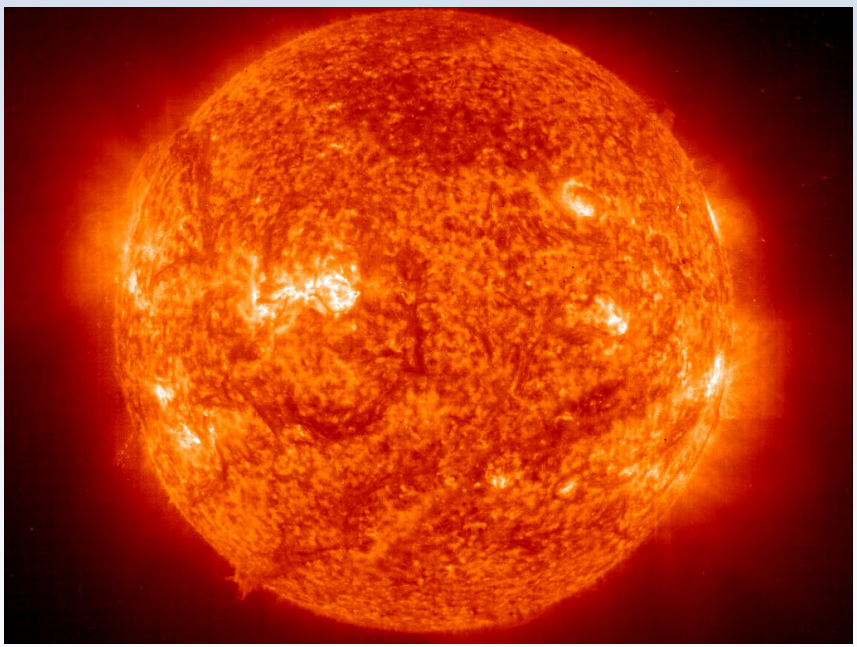
with $D = D_0\,\beta^\eta \left(\frac{R}{R_0}\right)^\delta e^{\frac{|z|}{z_t}}$

- D_0 : normalization of the diffusion coefficient ($R_0 = 3$ GeV)
- η : parametrizes our poor knowledge of the complicated physical effects that may play a major role at low energy
- δ : slope of the power law in rigidity and is constrained by light nuclei ratio
- z_t is the scale height of the diffusive halo of the Galaxy

- **Solar modulation** in the force-field approximation

$$J_{\oplus}(K) = J_{\mathrm{LIS}}(K + \phi\frac{Z}{A})\frac{K(K+2\,m)}{(K+m+\phi\frac{Z}{A})^2 - m^2},$$

ϕ is the Fisk potential, constraint using HelioProp



- **Benchmark** and **Thin** propagation models

	KRA	KOL	CON	THK	THN	THN2	THN3
z_t [kpc]	4	4	4	10	0.5	2	3
D_0 [10^{28} cm^2 s^{-1}]	2.64	4.46	0.97	4.75	0.31	1.35	1.98
δ	0.50	0.33	0.6	0.50	0.50	0.50	0.50
η	-0.39	1	1	-0.15	-0.27	-0.27	-0.27
v_A [km s^{-1}]	14.2	36	38.1	14.1	11.6	11.6	11.6
γ	2.35	1.78/2.45	1.62/2.35	2.35	2.35	2.35	2.35
dv_c/dz [km s^{-1} kpc^{-1}]	0	0	50	0	0	0	0
ϕ_F^p [GV]	0.650	0.335	0.282	0.687	0.704	0.626	0.623
$\chi^2_{\rm min}/{\rm dof}$ (p from PAMELA)	0.462	0.761	1.602	0.516	0.639	0.343	0.339

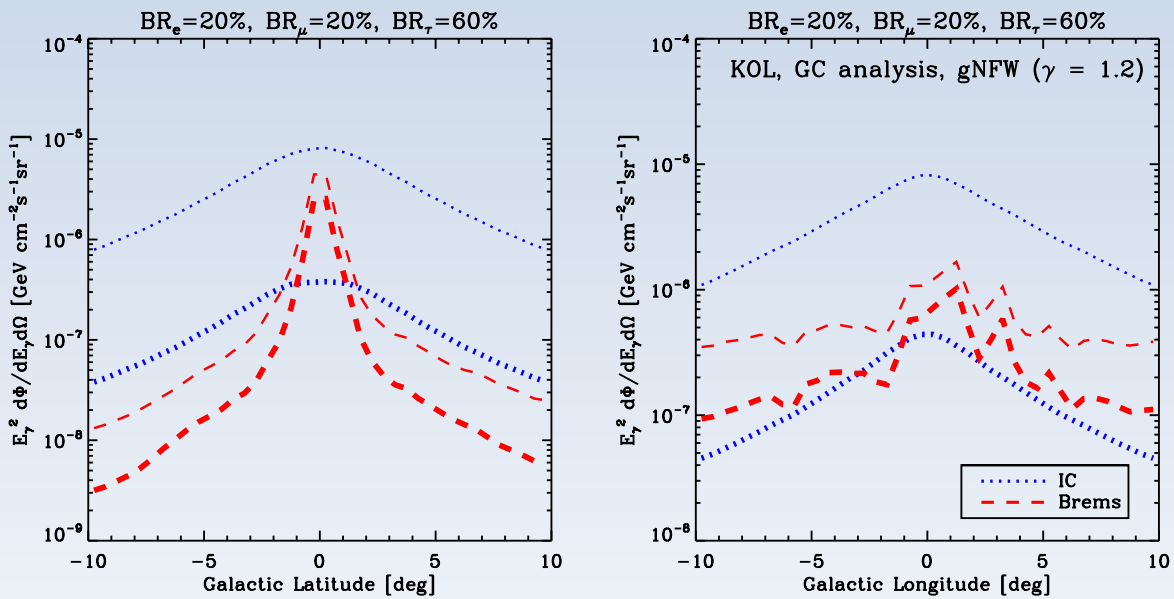
For the GC center γ-ray excess : two different sets of residual data

- **'Galactic Center'** analysis : $|b| < 5^\circ$, $|l| < 5^\circ \Rightarrow \gamma = 1.2$
- **'Inner Galaxy'** analysis : full-sky fit (masking 1° in latitude around the galactic plane) $\Rightarrow \gamma = 1.26$

$\Rightarrow$ Computation of the differential flux from DM annihilation

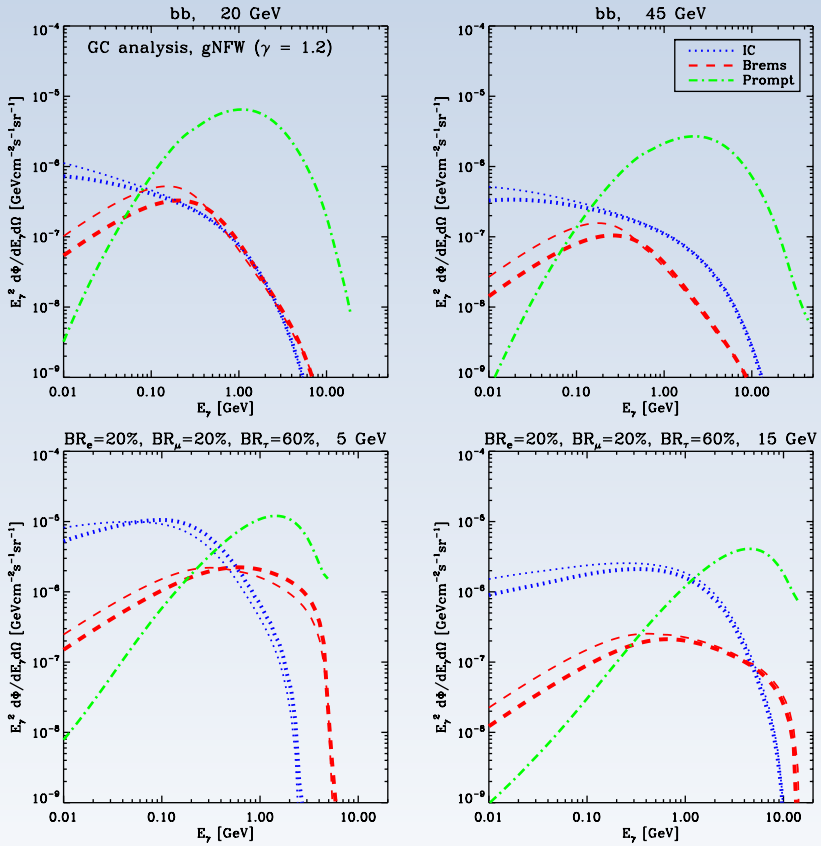
$\Rightarrow$ Gas and InterStellar Radiation Field (ISFR) maps, used in DRAGON, are the same as in the latest public version of GalProp

- Latitude- and longitude-dependence of **Brems** and **IC** emissions from DM annihilation into leptons with $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1} and with $E_\gamma = 3$ GeV (thicker lines) and $E_\gamma = 0.5$ GeV (thinner lines).



- IC is spherically symmetric (to a good approximation)
- Brems is correlated with the gas density in the Galactic Plane $\Rightarrow$ averaged value

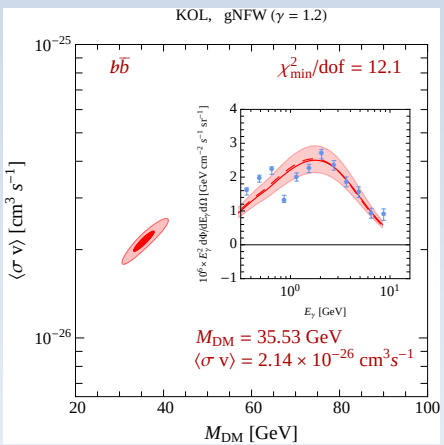
- **Gamma-ray spectrum** from DM annihilation in the Galactic center ($\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1})
  Thick lines $\rightarrow$ KOL, Thin lines $\rightarrow$ THN .

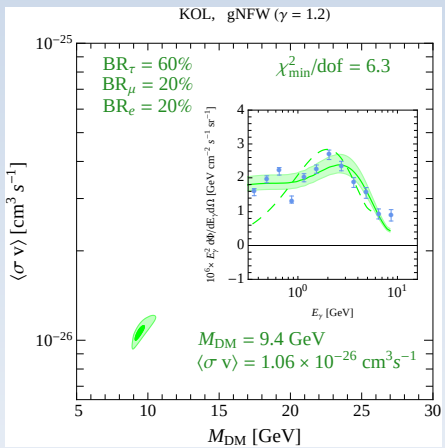


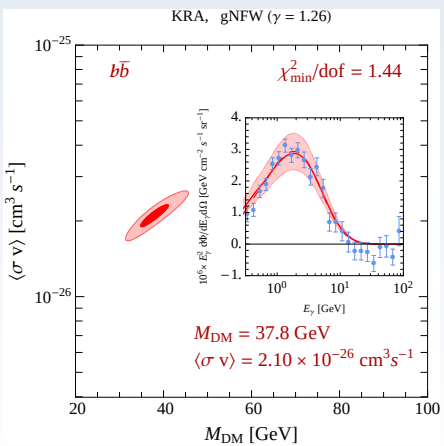
$\Rightarrow$ Secondary emissions relevant for leptonic channels already at an energy corresponding to a fraction of the DM mass

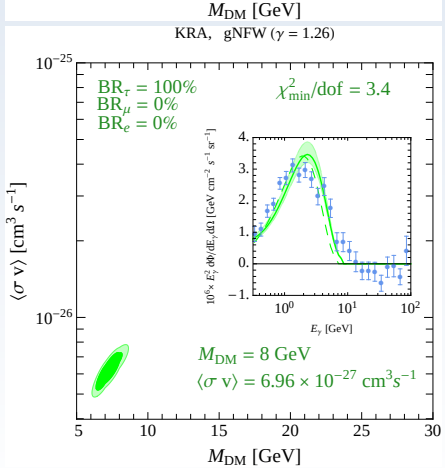
Analysis	Final State	Setup	$M_{\rm DM}$ [GeV]	$\langle\sigma v\rangle$ [cm^3 s^{-1}]	$\chi^2_{\rm min}$ /dof
'Gal Center', $\gamma = 1.2$	$b\bar{b}$	KOL	35.53	2.14×10^{-26}	12.1
	leptonic mix$^{(\star)}$	KOL	9.4	1.06×10^{-26}	6.3
'Inner Gal', $\gamma = 1.26$	$b\bar{b}$	KRA	37.8	2.10×10^{-26}	1.44
	$\tau^+\tau^-$	KRA	8	6.96×10^{-27}	3.4

$^{(\star)}$ leptonic mix = 20% e^+e^- + 20% $\mu^+\mu^-$ + 60% $\tau^+\tau^-$

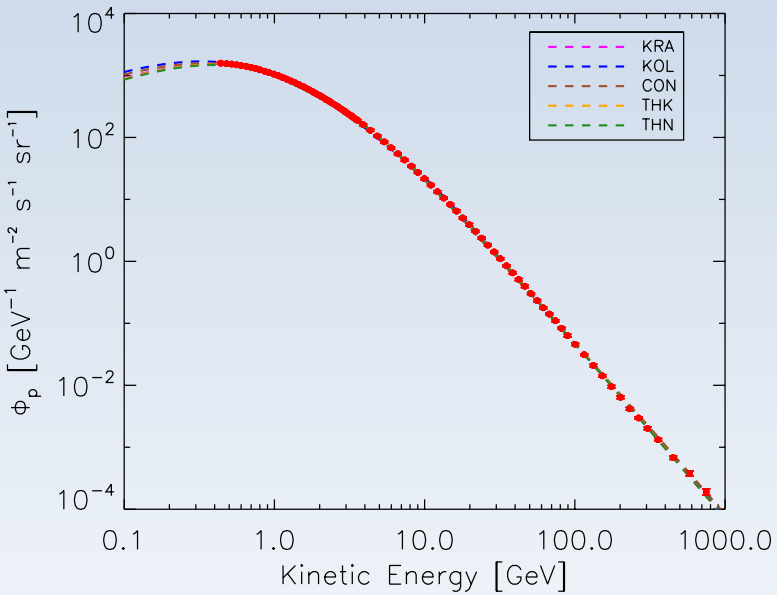


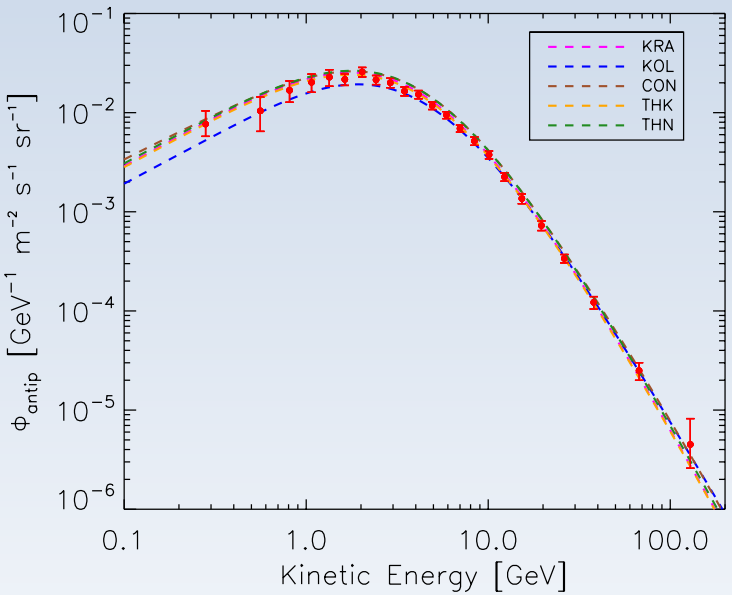




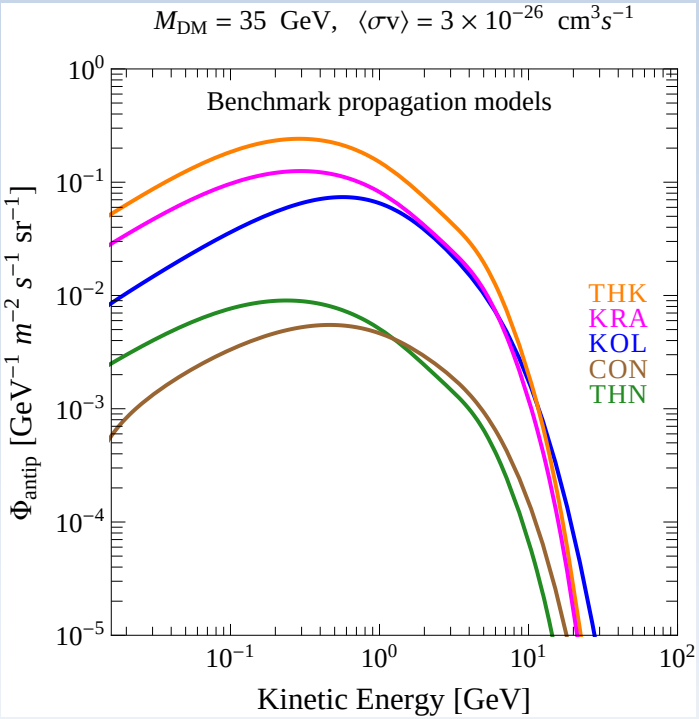


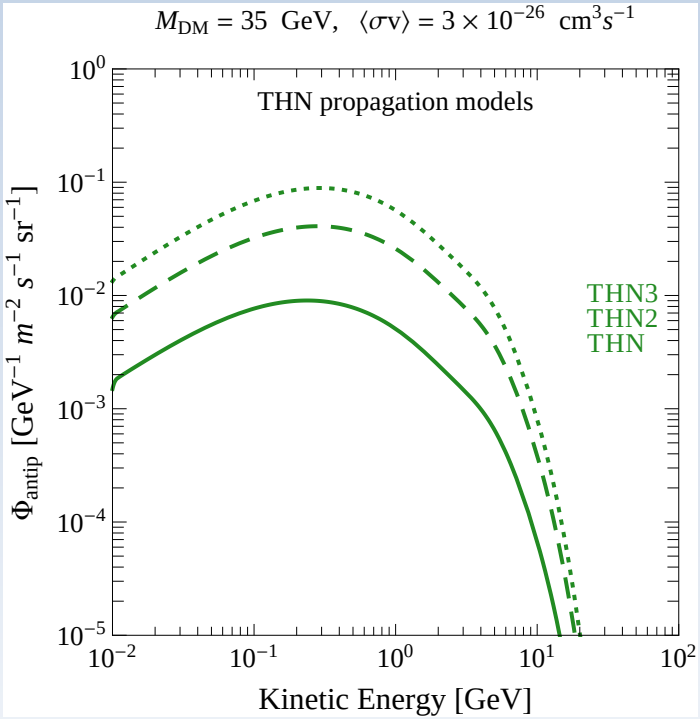
- **Proton** and **Antiproton** Fluxes from PAMELA





- **Antiproton flux** from DM annihilation into $b\bar{b}$ for a gNFW profile with $\gamma = 1.26$

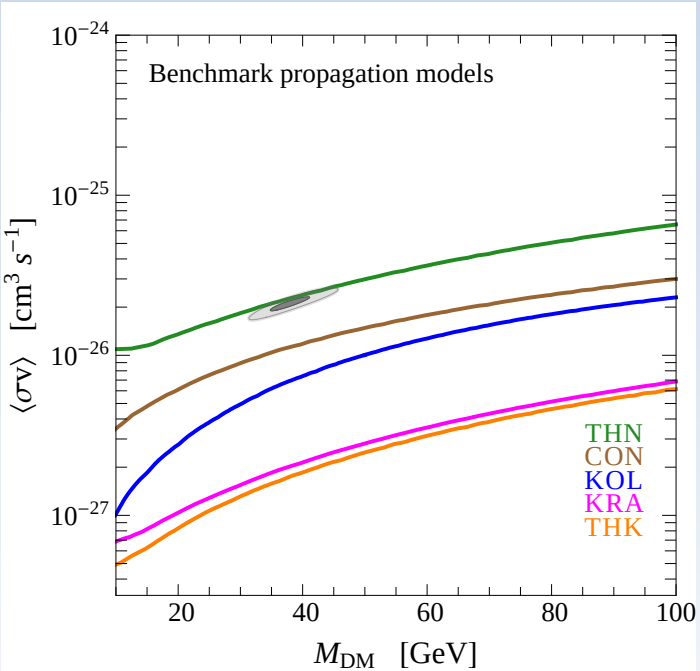


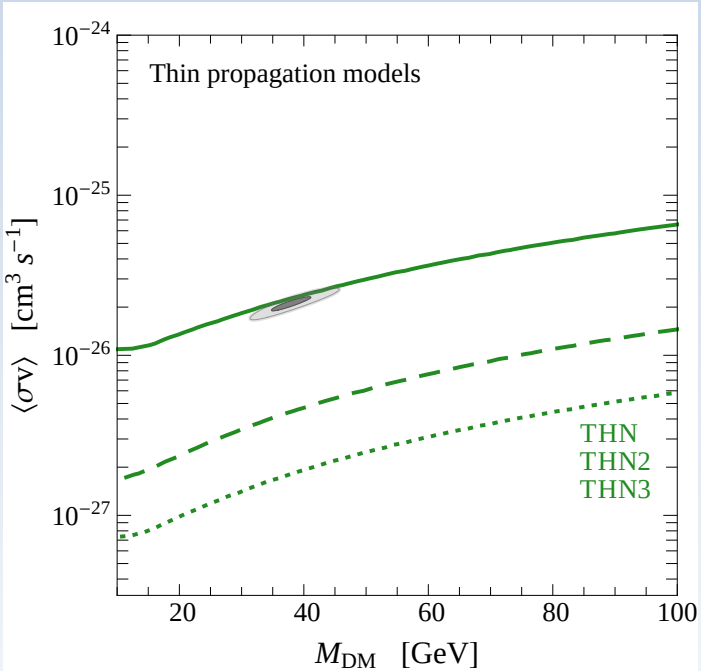


$\Rightarrow$ Total Antiproton flux :

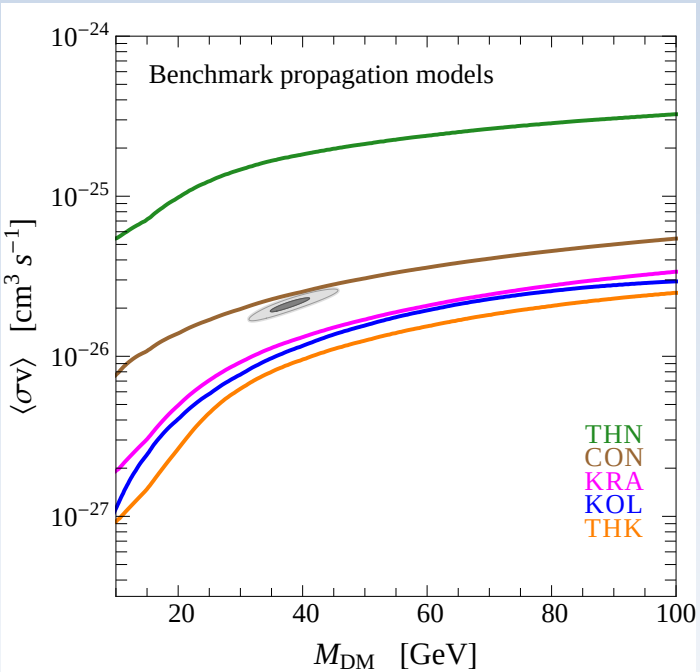
$$\Phi_{\bar{p}}(M_{\rm DM}, \langle\sigma v\rangle, \phi_F^{\bar{p}}) = \Phi_{\bar{p}}^{\rm BG}(\phi_F^{\bar{p}}) + \Phi_{\bar{p}}^{\rm DM}(M_{\rm DM}, \langle\sigma v\rangle, \phi_F^{\bar{p}})$$

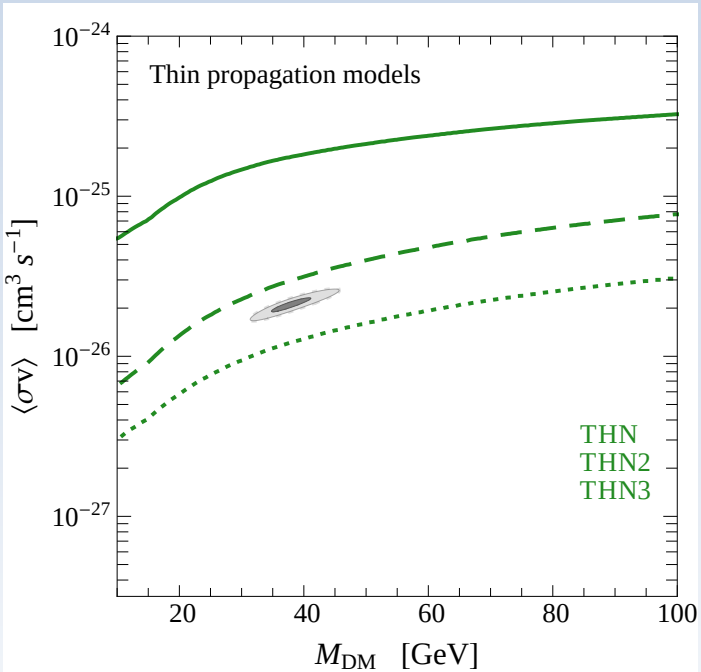
- **Antiproton bounds** : $\phi_F^{\bar{p}} = \phi_F^p$



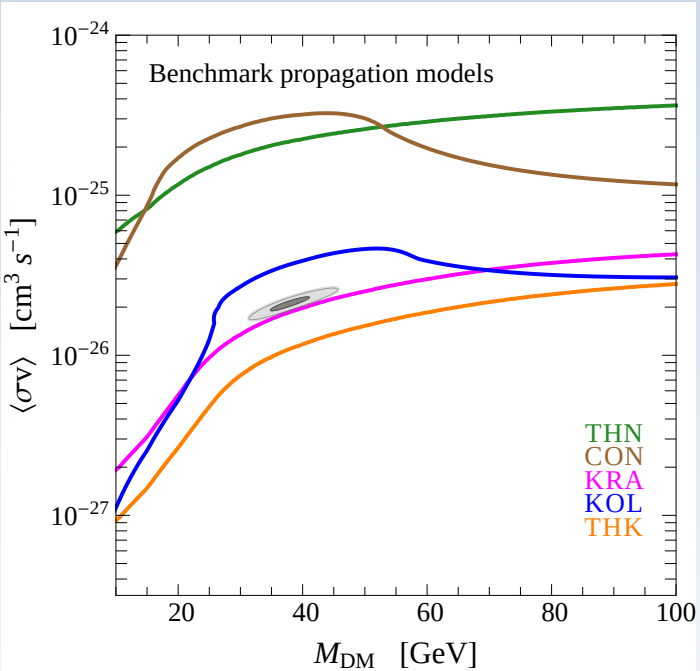


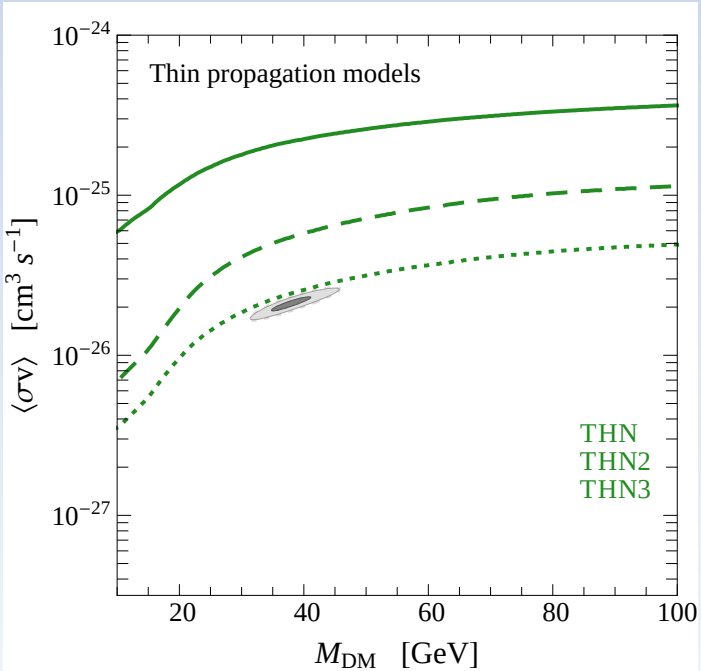
- **Antiproton bounds** : $\phi_F^{\bar{p}} = \phi_F^{p} \pm 50\%$





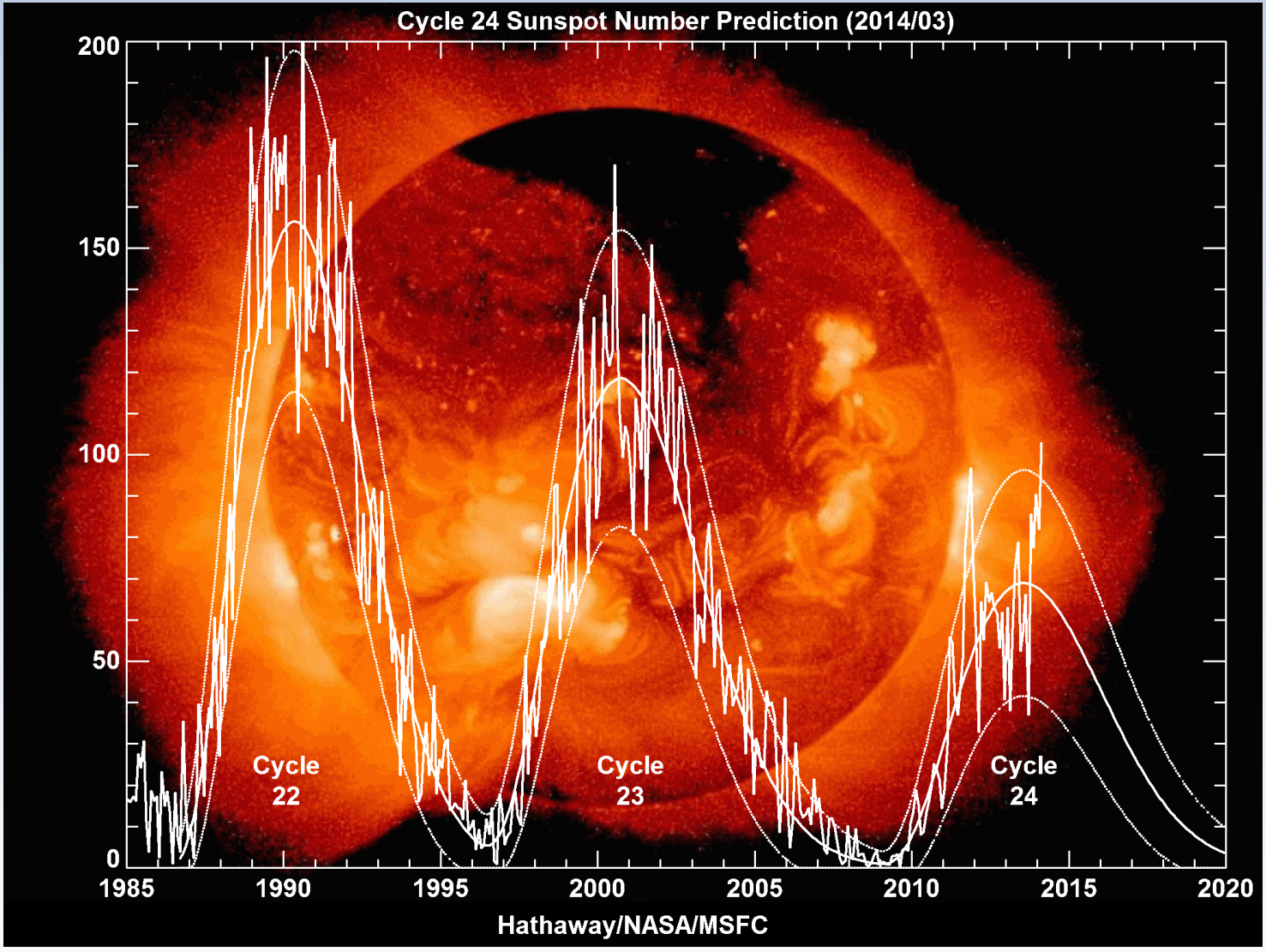
- **Antiproton bounds** : $\phi_F^{\bar{p}} \in [0.1, 1.1]$ GV

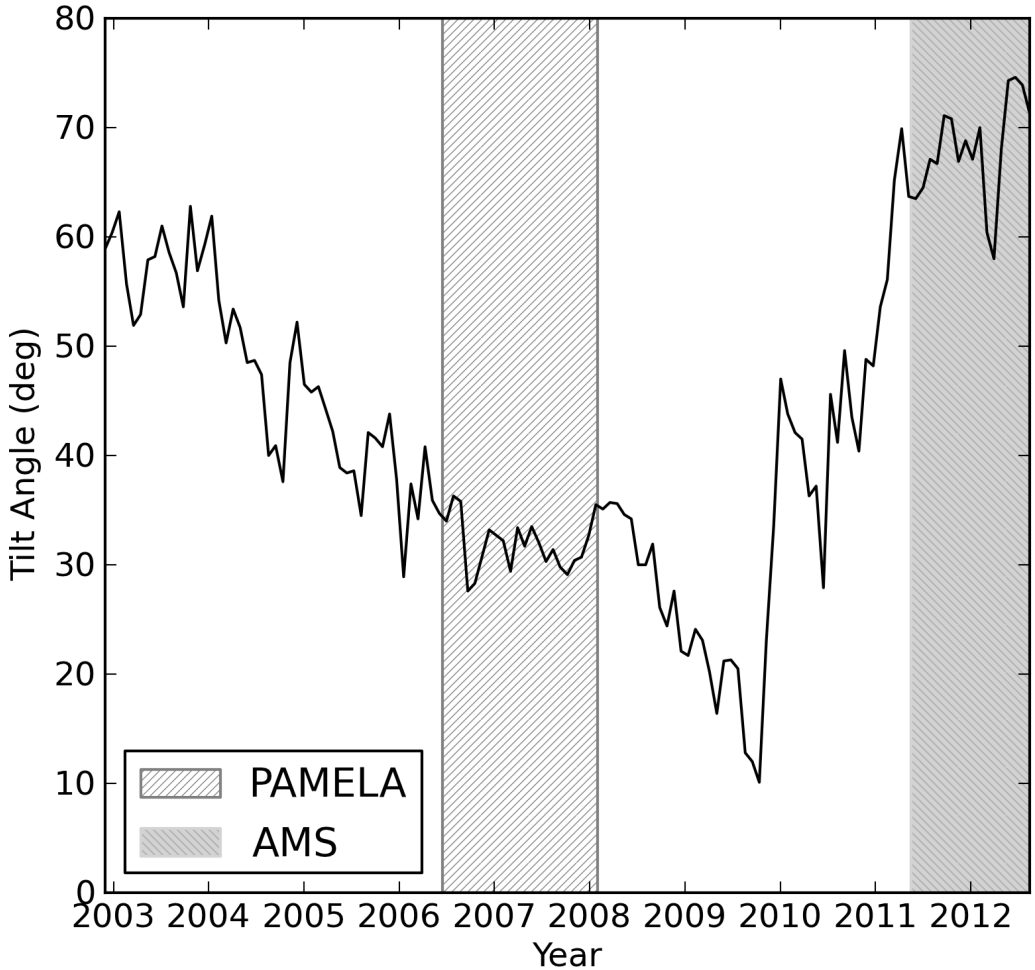




- **Secondary γ radiation** emitted by particles originating from DM annihilation, using DRAGON and GammaSky
  $\Rightarrow$ secondary emission relevant for leptonic channels
- **Antiproton constraints** with a special treatment of the solar modulation, using HelioProp
- With realistic propagation model and well motivated choices for solar modulation, the hadronic ($b\bar{b}$) DM interpretation for the GeV excess is in **strong tension** with antiproton data
- There are **conservative choices** (thin halo models and large solar modulation potentials) that do not exclude the DM interpretation of the excess
- To make a clear statement, we need a deeper understanding of CR propagation and modulation. Hopefully AMS-02 can help.

polarity	tilt angle	m.f.p. (AU)	δ	ϕ_p	$\phi_{\bar{p}}$	rel. diff.
-1.00	10.00	0.05	0.30	1.18	1.18	0.00%
-1.00	10.00	0.05	0.50	1.18	1.18	0.00%
-1.00	10.00	0.05	1.00	1.12	1.12	0.00%
-1.00	10.00	0.10	0.30	1.06	1.10	3.77%
-1.00	10.00	0.10	0.50	1.02	1.10	7.84%
-1.00	10.00	0.10	1.00	1.02	1.10	7.84%
-1.00	10.00	0.20	0.30	0.78	0.96	23.08%
-1.00	10.00	0.20	0.50	0.74	0.90	21.62%
-1.00	10.00	0.20	1.00	0.60	0.74	23.33%
-1.00	10.00	0.30	0.30	0.60	0.82	36.67%
-1.00	10.00	0.30	0.50	0.54	0.76	40.74%
-1.00	10.00	0.30	1.00	0.46	0.58	26.09%
-1.00	10.00	0.40	0.30	0.36	0.46	27.78%
-1.00	10.00	0.40	1.00	0.48	0.72	50.00%
-1.00	20.00	0.05	0.30	1.46	1.18	-19.18%
-1.00	20.00	0.05	1.00	1.28	1.12	-12.50%
-1.00	20.00	0.40	0.30	0.48	0.72	50.00%
-1.00	20.00	0.40	1.00	0.36	0.46	27.78%
-1.00	40.00	0.05	0.30	1.56	1.18	-24.36%
-1.00	40.00	0.40	0.30	0.50	0.70	40.00%
-1.00	40.00	0.40	1.00	0.38	0.44	15.79%
-1.00	60.00	0.05	0.30	1.50	1.86	24.00%
-1.00	60.00	0.05	1.00	1.18	1.34	13.56%
-1.00	60.00	0.40	0.30	0.50	0.66	32.00%
-1.00	60.00	0.40	1.00	0.40	0.42	5.00%


Cycle 24 Sunspot Number Prediction (2014/03)
200
150
100
50
0
1985
1990
1995
2000
2005
2010
2015
2020
Cycle 22
Cycle 23
Cycle 24
Hathaway/NASA/MSFC


80
70
60
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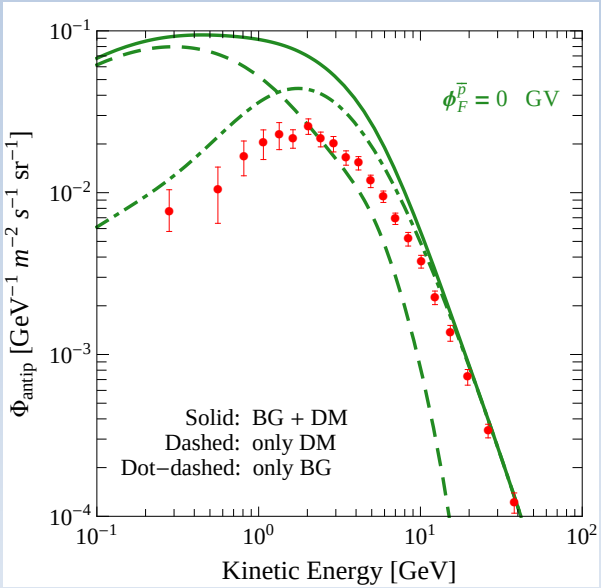
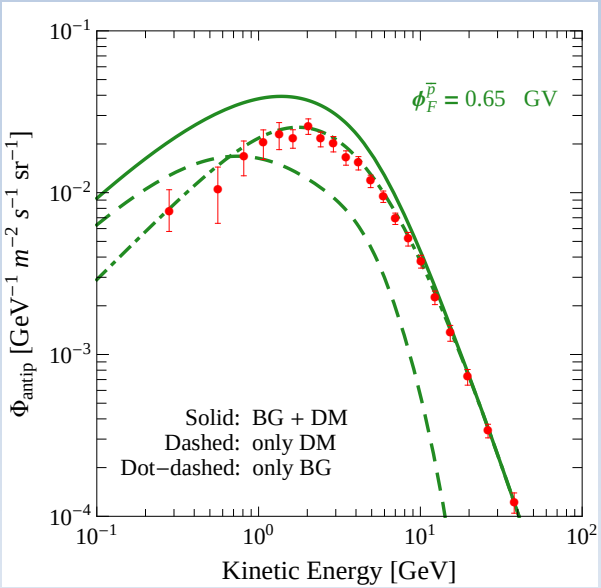
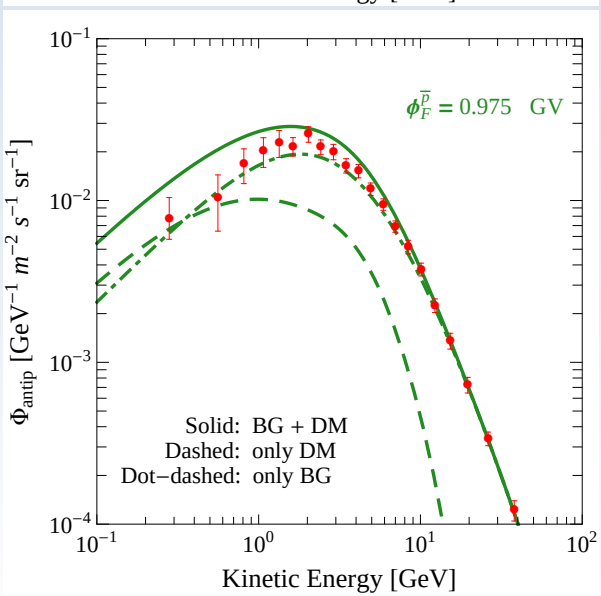
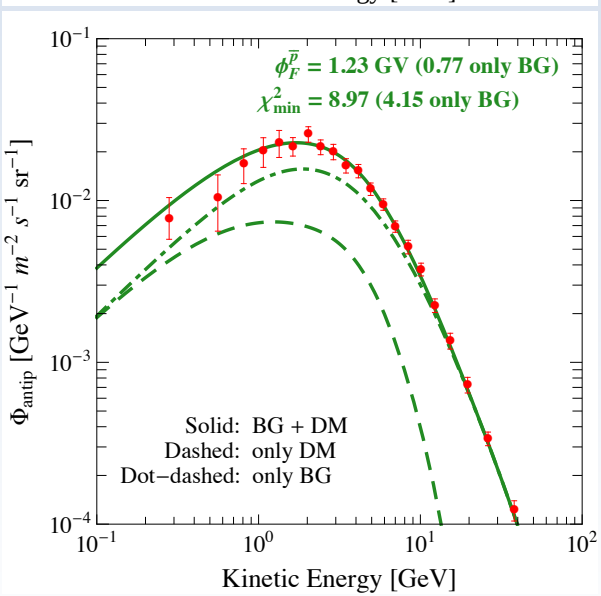
Tilt Angle (deg)
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
Year
PAMELA
AMS


$\phi_F^{\bar{p}} = 0$ GV
Solid: BG + DM
Dashed: only DM
Dot−dashed: only BG
$\Phi_{\rm antip}$ [GeV^{-1} m^{-2} s^{-1} sr^{-1}]
Kinetic Energy [GeV]


$\phi_F^{\bar{p}} = 0.65$ GV
Solid: BG + DM
Dashed: only DM
Dot−dashed: only BG
$\Phi_{\rm antip}$ [GeV^{-1} m^{-2} s^{-1} sr^{-1}]
Kinetic Energy [GeV]


$\phi_F^{\bar{p}} = 0.975$ GV
Solid: BG + DM
Dashed: only DM
Dot−dashed: only BG
$\Phi_{\rm antip}$ [GeV^{-1} m^{-2} s^{-1} sr^{-1}]
Kinetic Energy [GeV]


$\phi_F^{\bar{p}} = 1.23$ GV (0.77 only BG)
$\chi^2_{\rm min} = 8.97$ (4.15 only BG)
Solid: BG + DM
Dashed: only DM
Dot−dashed: only BG
$\Phi_{\rm antip}$ [GeV^{-1} m^{-2} s^{-1} sr^{-1}]
Kinetic Energy [GeV]

GalProp parameters (used in DRAGON)

- Magnetic field

$$B_{tot} = B_0 e^{-(R-R_\odot)/R_B - |z|/z_B}$$

- InterStellar Radiation Field

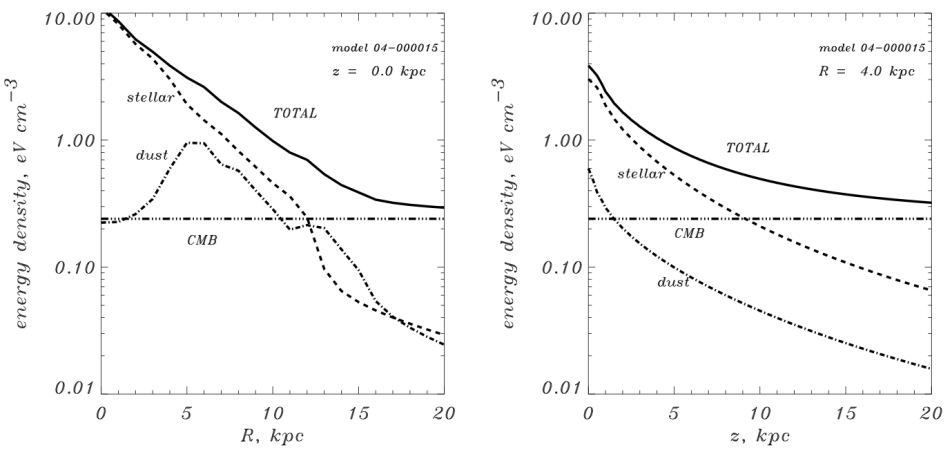
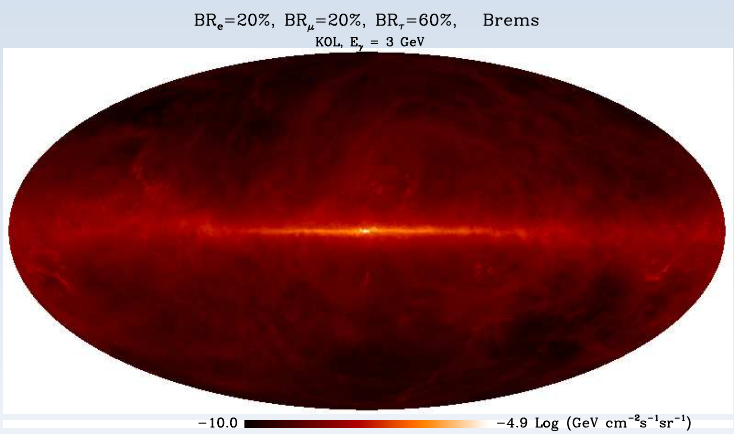
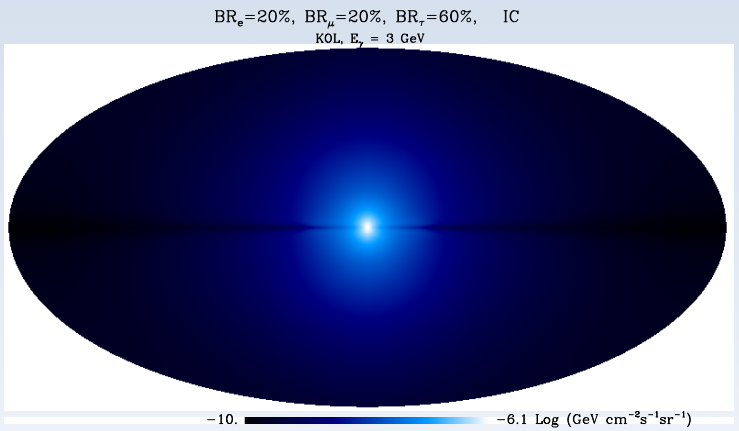


FIG. 1.— ISRF energy density as function of R at $z = 0$ (left), and of z at $R = 4$ kpc (right). Shown are the contributions of stars (dashed), dust (dash-dot), CMB (dash-3-dots), and total (full line).

- **Sky maps** for Brems and IC emission, considering democratic DM annihilation into leptons with $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1} and the KOL propagation model