

# Indirect search for Dark Matter : interpretation

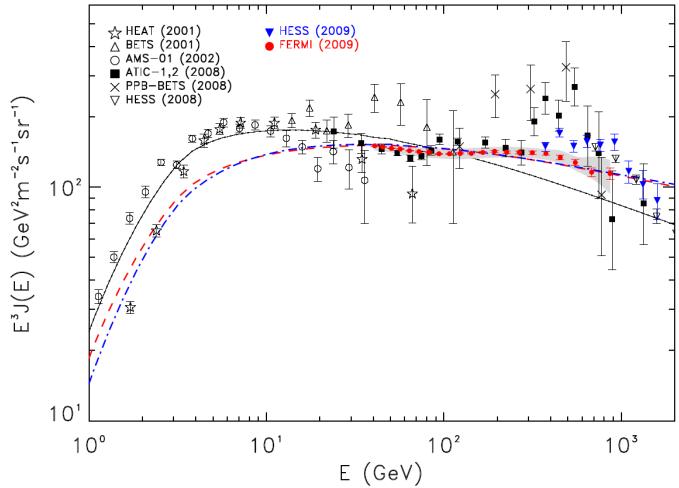
Pierre Salati – Université de Savoie & **LAPTH**

## Outline

- 1) Evidence for primary cosmic ray positrons
- 2) DM species with quite special properties
- 3) The effect of clumpiness on DM annihilation
- 4) Decaying dark matter
- 5) Perspectives more than conclusions

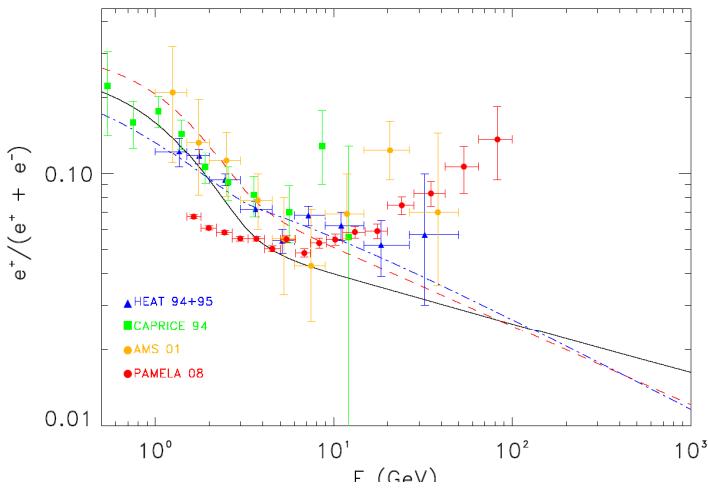


# 1) Evidence for primary cosmic ray positrons



- Primary  $e^-$  from SN driven shock waves
- Secondary  $e^-$  &  $e^+$  from CR spallations

$$\Phi_e \propto E^{-\alpha - 1/2 - \delta/2}$$

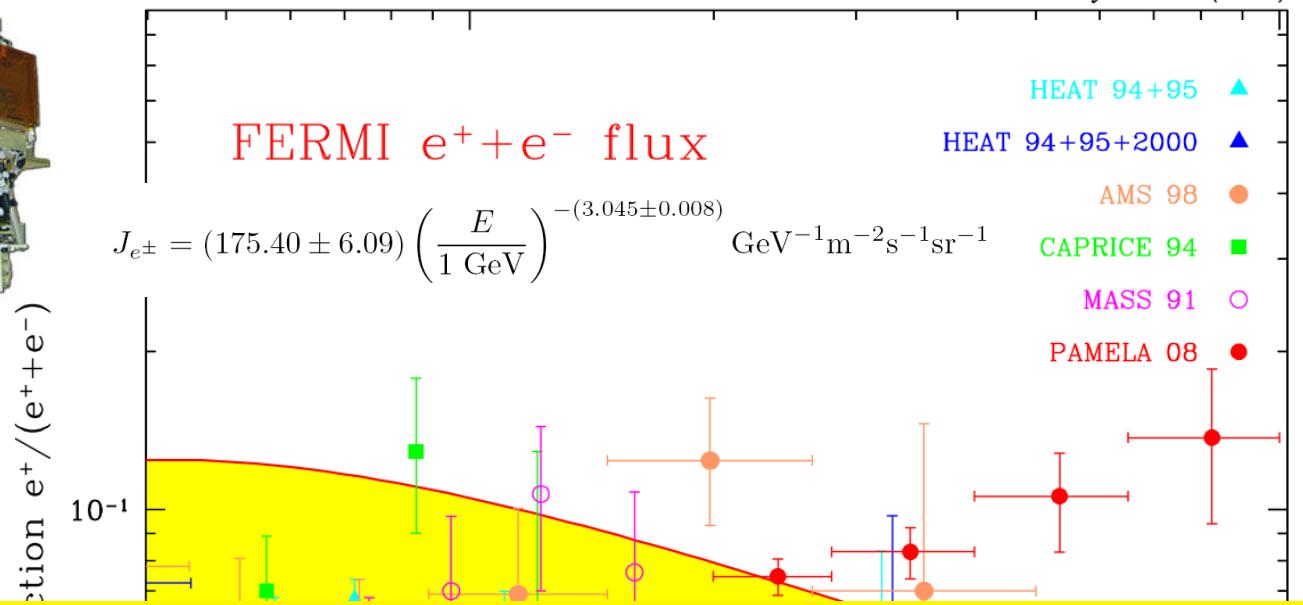


$$K(E) = K_0 \beta \mathcal{R}^\delta$$

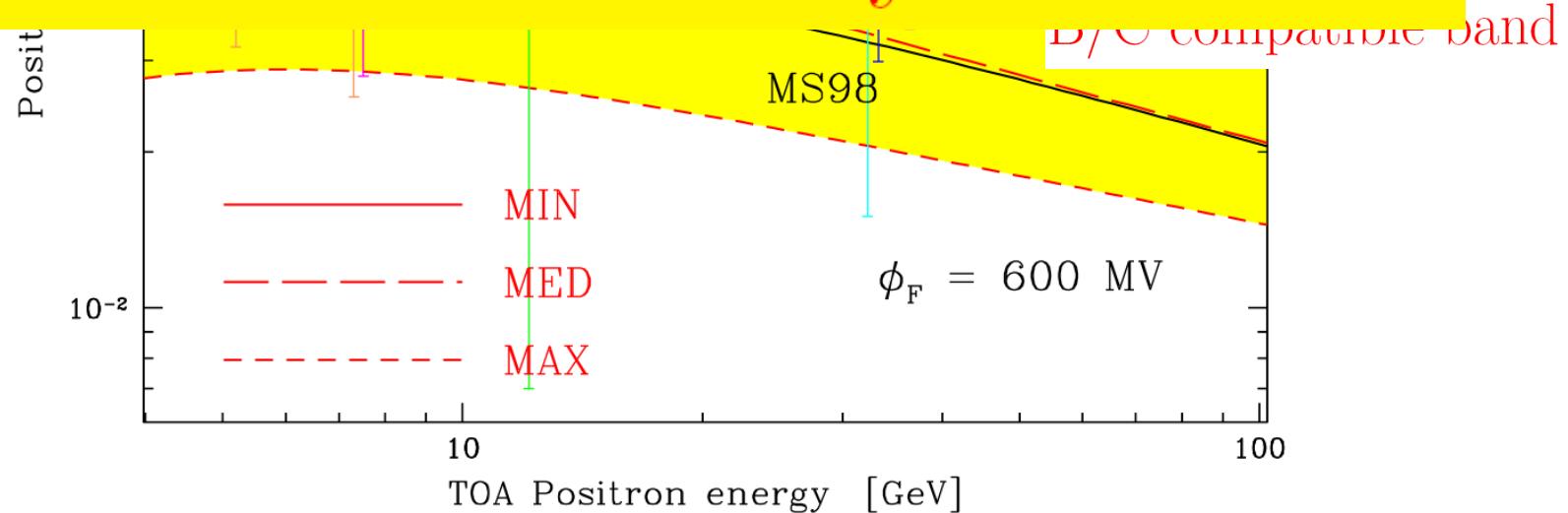
- $\Phi_{\text{primary } e^-} \propto E^{-3}$
- $\Phi_{\text{secondary } e^\pm} \propto E^{-3.5}$

Model #	$D_0$ ( $cm^2 s^{-1}$ )	$\delta$	$z_h$ (kpc)	$\gamma_0$	$N_{e^-}$ ( $m^{-2} s^{-1} sr^{-1} GeV^{-1}$ )	$\gamma_0^p$
0	$3.6 \times 10^{28}$	0.33	4	2.54	$1.3 \times 10^{-4}$	2.42
1	$3.6 \times 10^{28}$	0.33	4	2.42	$1.3 \times 10^{-4}$	2.42
2	$1.3 \times 10^{28}$	0.60	4	2.33	$1.3 \times 10^{-4}$	2.1

T. Delahaye et al. (2008)



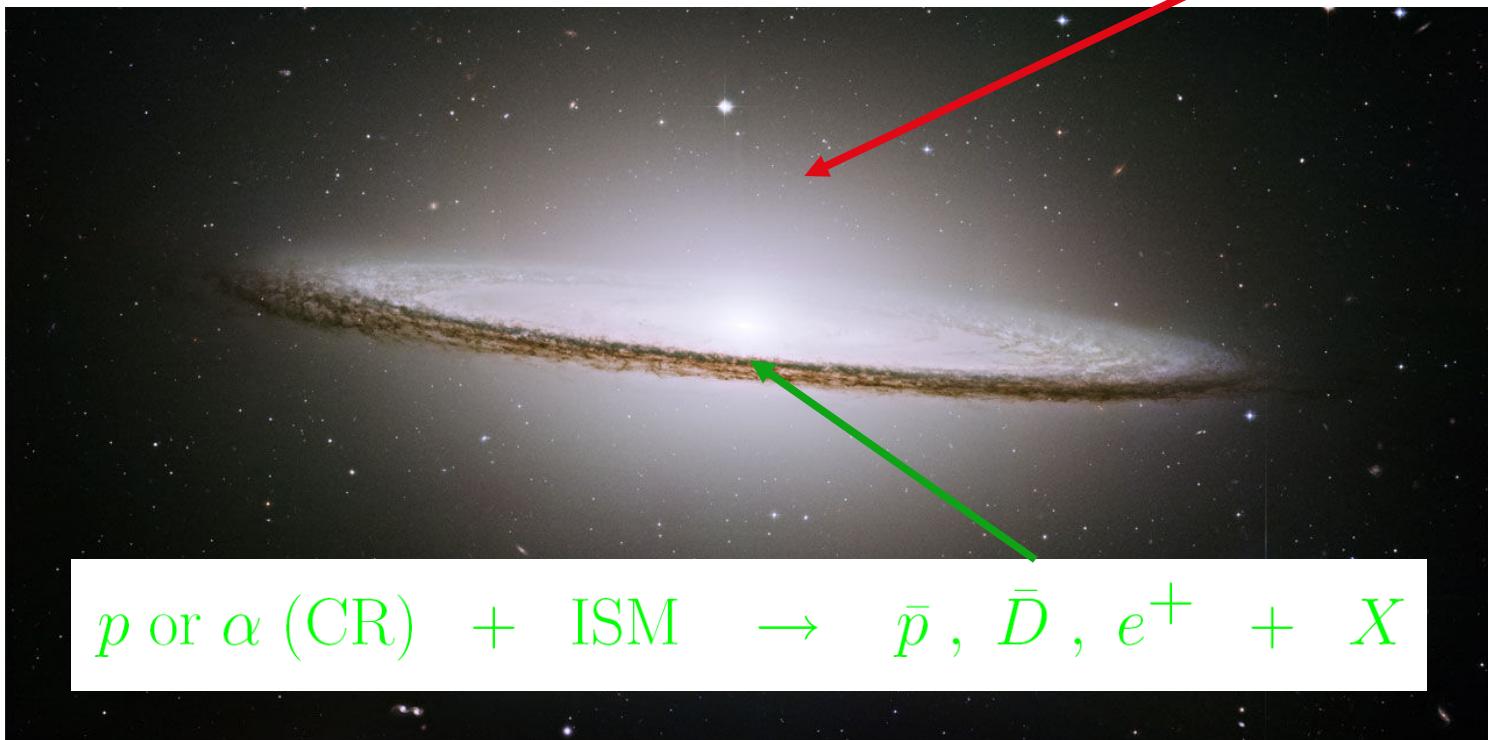
# Evidence for Primary Positrons



# Indirect signatures of DM species

Weakly Interacting Massive particles – WIMPs – may be the major component of the haloes of galaxies. Their mutual annihilations would produce an indirect signature of high-energy cosmic rays :

$$\chi + \chi \rightarrow q\bar{q}, W^+W^-, \dots \rightarrow \gamma, [\bar{p}, \bar{D}, e^+] \& \nu's$$



Antimatter is already manufactured inside the galactic disk

# PAMELA positron excess

May be the first indirect hint that DM species annihilate in the MW.

$$\Gamma_{\text{ann}} \equiv \langle \sigma v \rangle \times \frac{\rho_\chi^2}{m_\chi^2} \text{ needs to be enhanced}$$

$$\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}, \rho_\odot = 0.3 \text{ GeV cm}^{-3} \& m_\chi = 1 \text{ TeV} \Rightarrow \Gamma_{\text{ann}} \times 10^3$$

## 2) DM species with quite special properties

- Large  $\langle \sigma v \rangle$  but **different** thermal decoupling (quintessence).
- Large  $\langle \sigma v \rangle$  but **non-thermal** decoupling (gravitino decay).
- Sommerfeld effect : a non-perturbative enhancement of  $\langle \sigma v \rangle$  at low velocity.

Beware of the other messengers !

- Antiprotons are not produced  $\Rightarrow$  leptophilic WIMP.

$$\chi \chi \rightarrow l^+ l^-$$

OR

$$\chi \chi \rightarrow \phi \phi \rightarrow l^+ l^- l^+ l^- \text{ through } \phi \rightarrow l^+ l^-$$

# Sommerfeld effect – a non-perturbative enhancement of $\sigma_{\text{ann}}$ at low velocity

J. Hisano, S. Matsumoto and M. M. Nojiri

M. Pospelov & A. Ritz, Phys. Lett. **B671** (2009) 391

N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer & N. Weiner, Phys. Rev. **D79** (2009) 015014

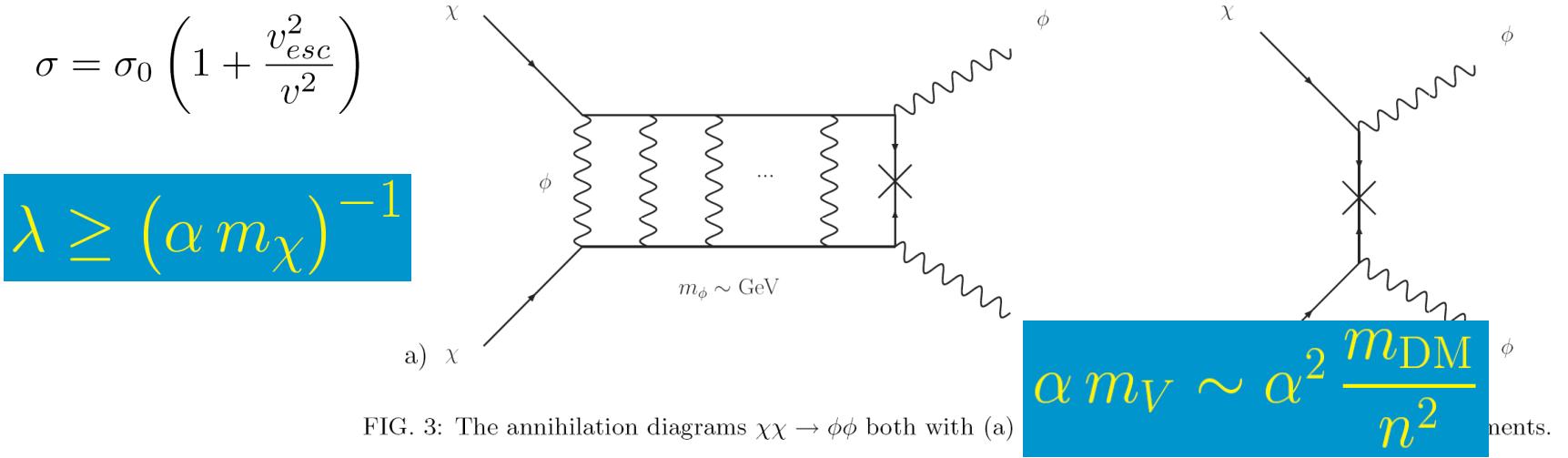
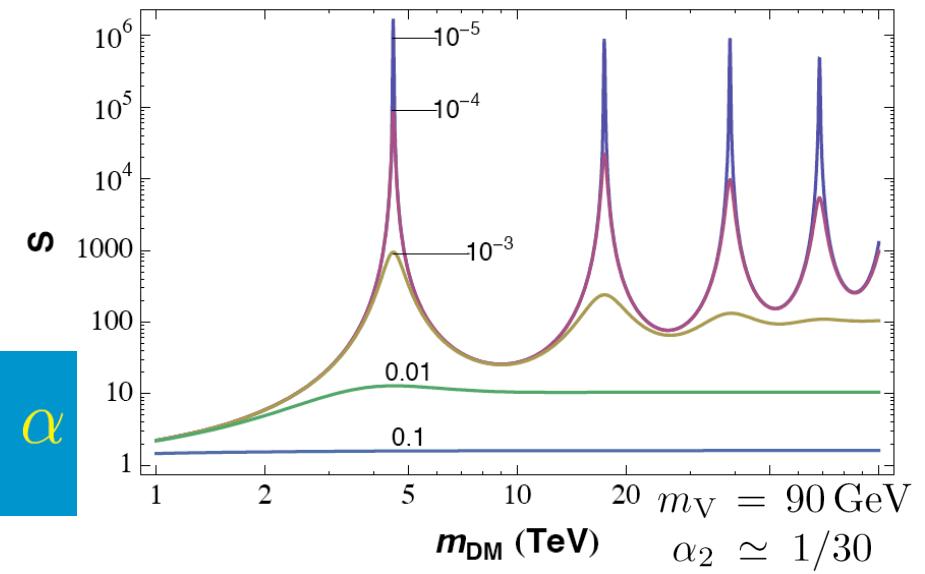
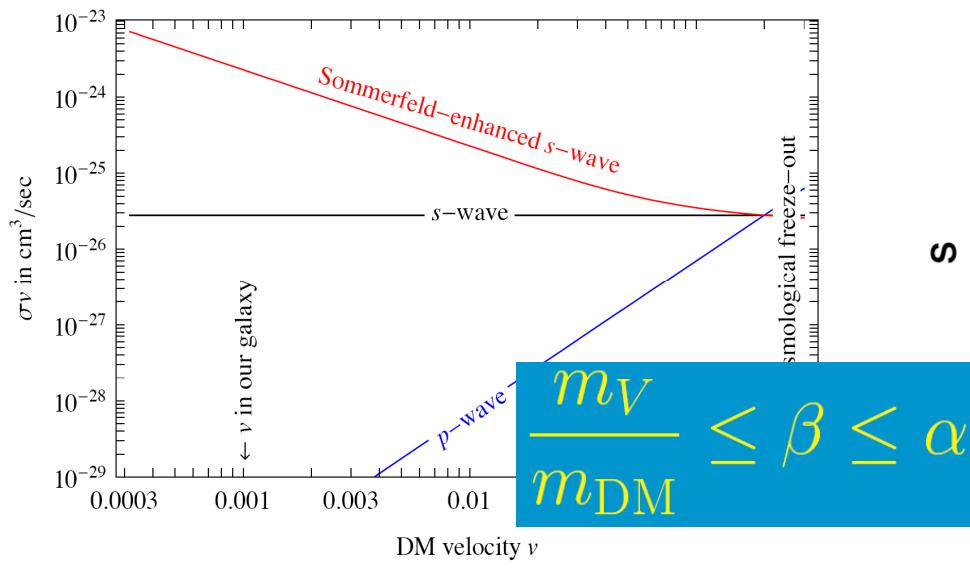


FIG. 3: The annihilation diagrams  $\chi\chi \rightarrow \phi\phi$  both with (a)



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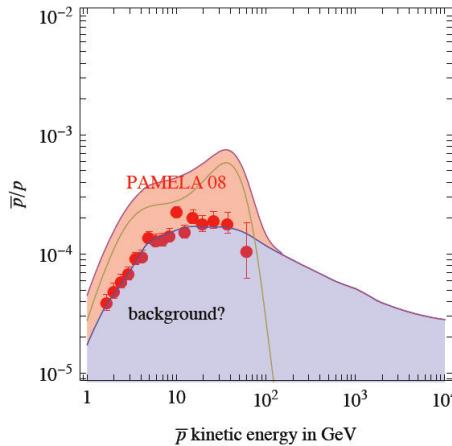
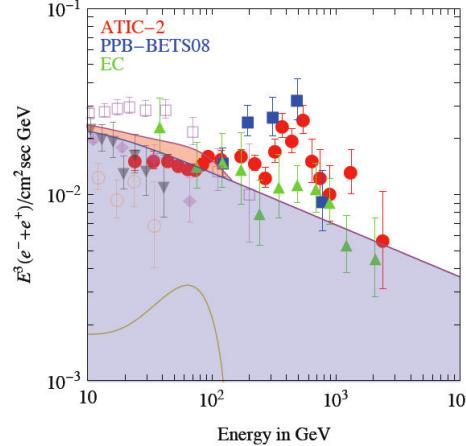
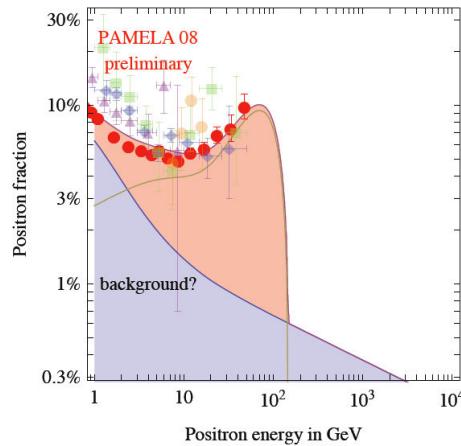
$$\chi \chi \rightarrow \phi \phi \rightarrow l^+ l^- l^+ l^- \text{ through } \phi \rightarrow l^+ l^-$$

# Antiprotons should not be overproduced

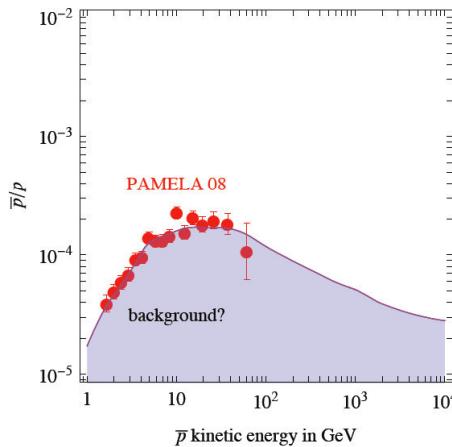
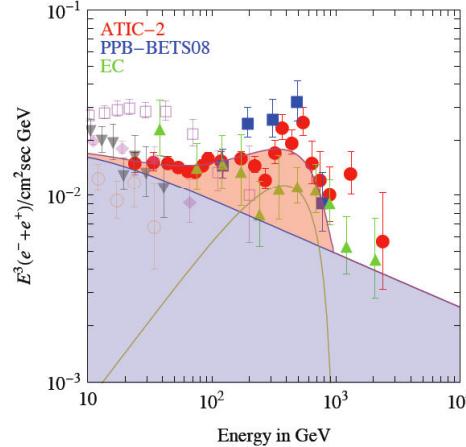
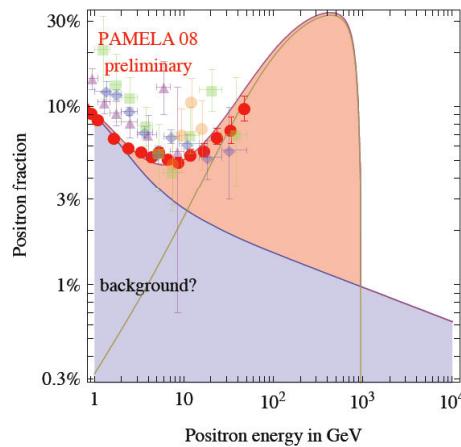
Quark channels are suppressed – purely leptophilic DM candidate

M. Cirelli<sup>a</sup>, M. Kadastik<sup>b</sup>, M. Raidal<sup>b</sup>, A. Strumia<sup>c</sup>

DM with  $M = 150$  GeV that annihilates into  $W^+ W^-$



DM with  $M = 1$  TeV that annihilates into  $\mu^+ \mu^-$



# Constraints on WIMP Dark Matter from the High Energy PAMELA $\bar{p}/p$ data

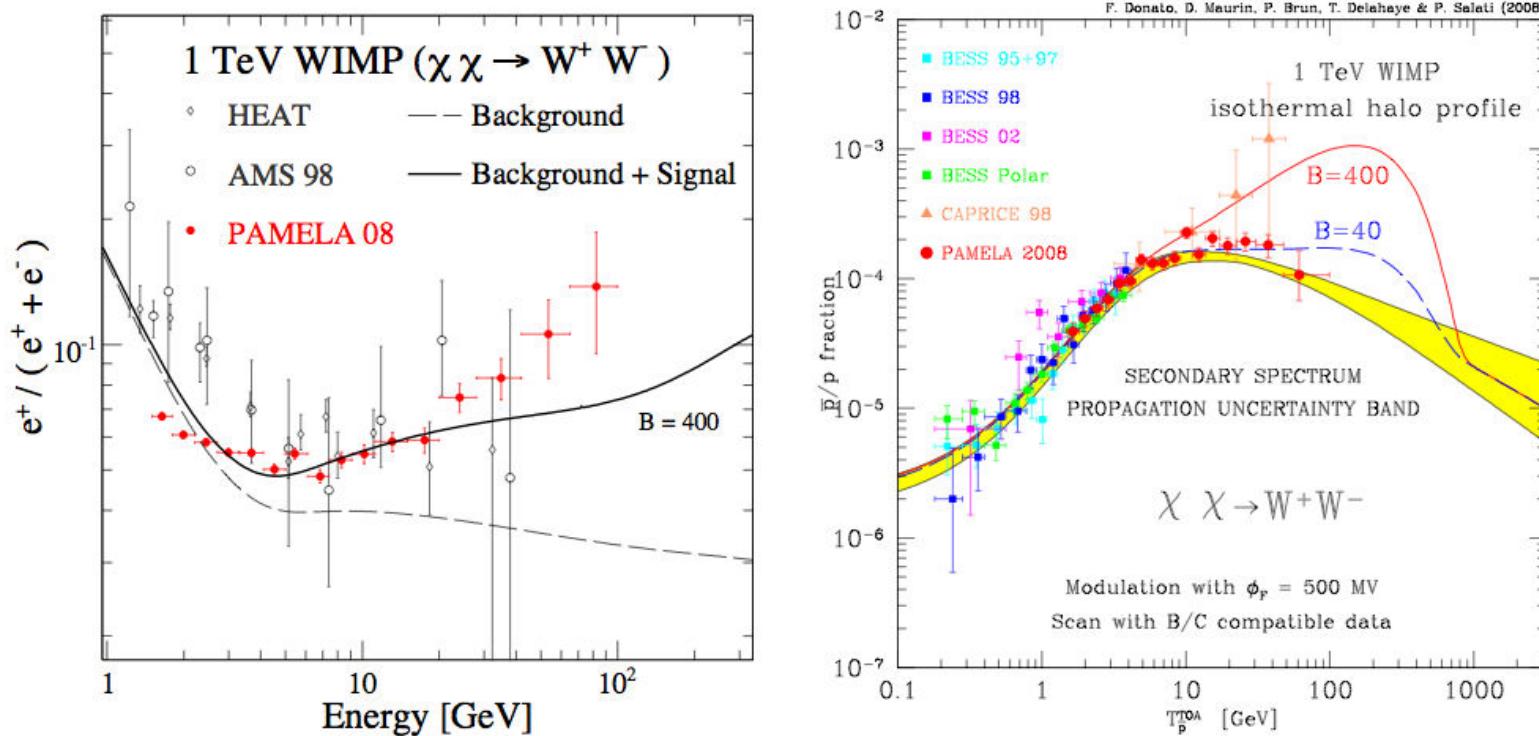
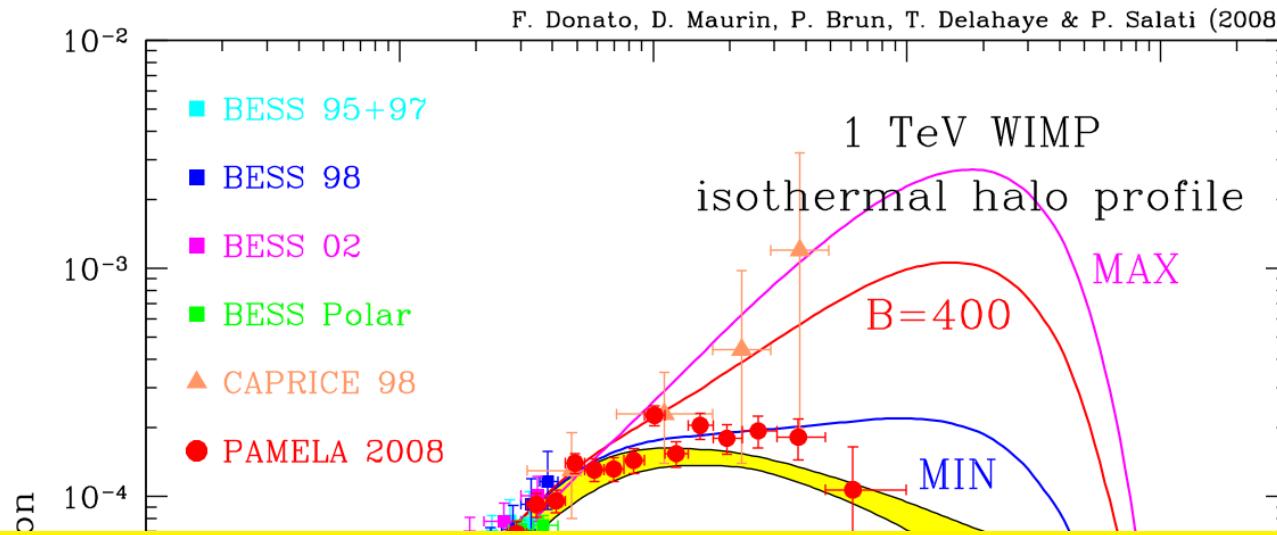
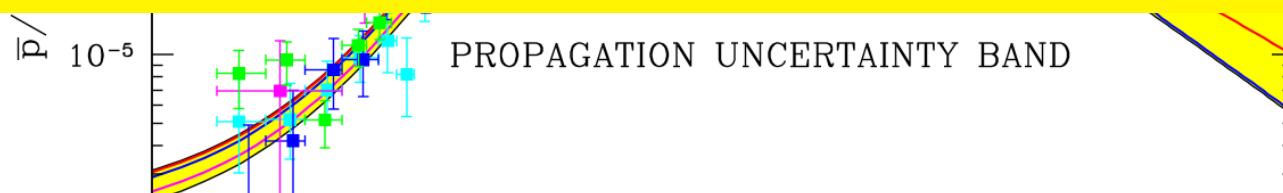


FIG. 3: The fiducial case of a 1 TeV LSP annihilating into a  $W^+W^-$  pair is featured. In the left panel, the positron signal which this DM species yields has been increased by a factor of 400, hence the solid curve and a marginal agreement with the PAMELA data. Positron fraction data are from HEAT [18], AMS-01 [5, 22] and PAMELA [2]. If the so-called Sommerfeld [7] is invoked to explain such a large enhancement of the annihilation cross section, the same boost applies to antiprotons and leads to an unacceptable distortion of their spectrum as indicated by the red solid line of the right panel.



# Are WIMPs really leptophilic ?



Case	$\delta$	$K_0$ [kpc $^2$ /Myr]	$L$ [kpc]	$V_C$ [km/s]	$V_a$ [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

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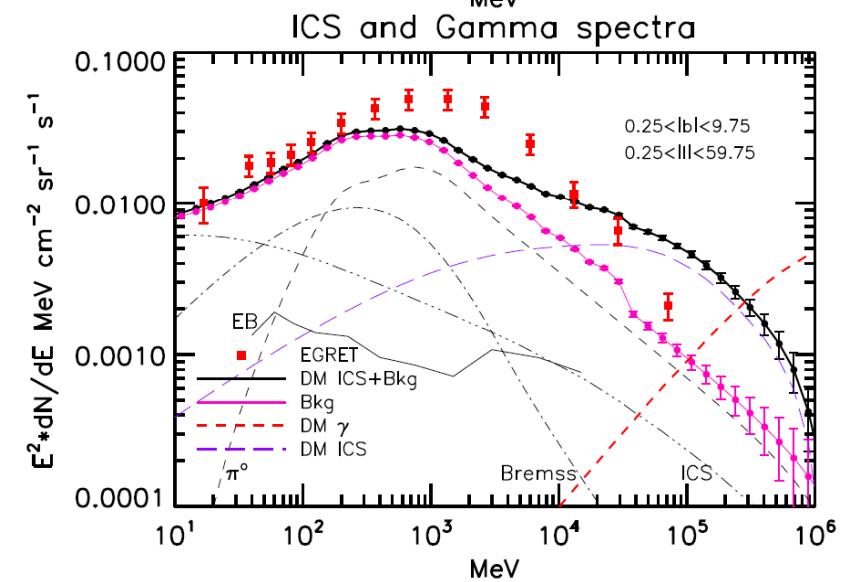
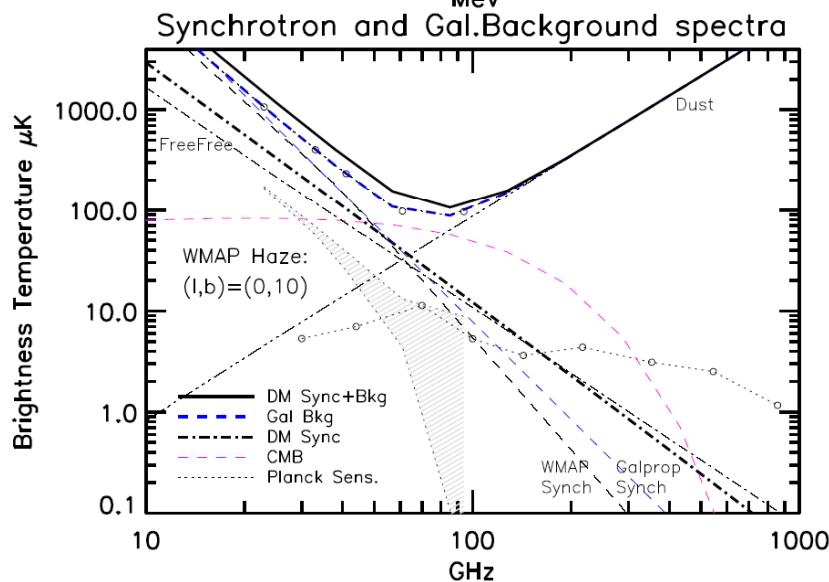
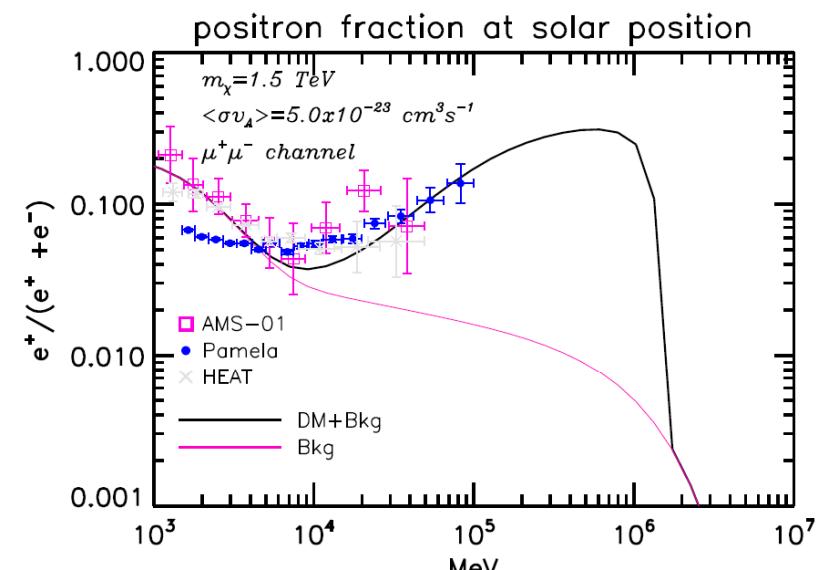
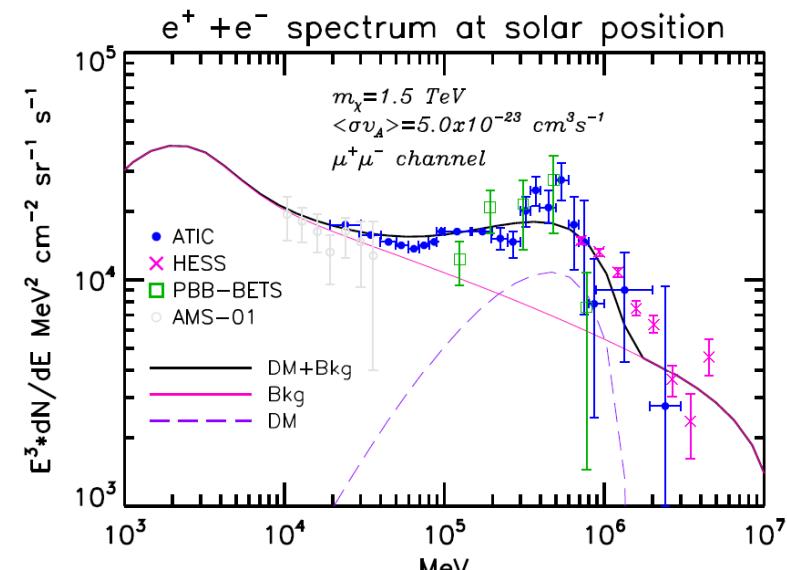
or

$$\chi \chi \rightarrow \phi \phi \rightarrow l^+ l^- l^+ l^- \text{ through } \phi \rightarrow l^+ l^-$$

- Even though, strong constraints from the other **messengers** :
  - ✓ Synchrotron radio emission from  $e^\pm$  spiraling in  $\mathbf{B}$ .
  - ✓ Inverse Compton Scattering on CMB and stellar light.
  - ✓ Final State Radiation  $\gamma$ -rays in the absence of quarks.

$$\chi \chi \rightarrow l^+ l^- \gamma \quad \text{or} \quad \phi \rightarrow l^+ l^- \gamma$$

SECONDARY RADIATION FROM THE PAMELA/ATIC EXCESS AND RELEVANCE FOR FERMI



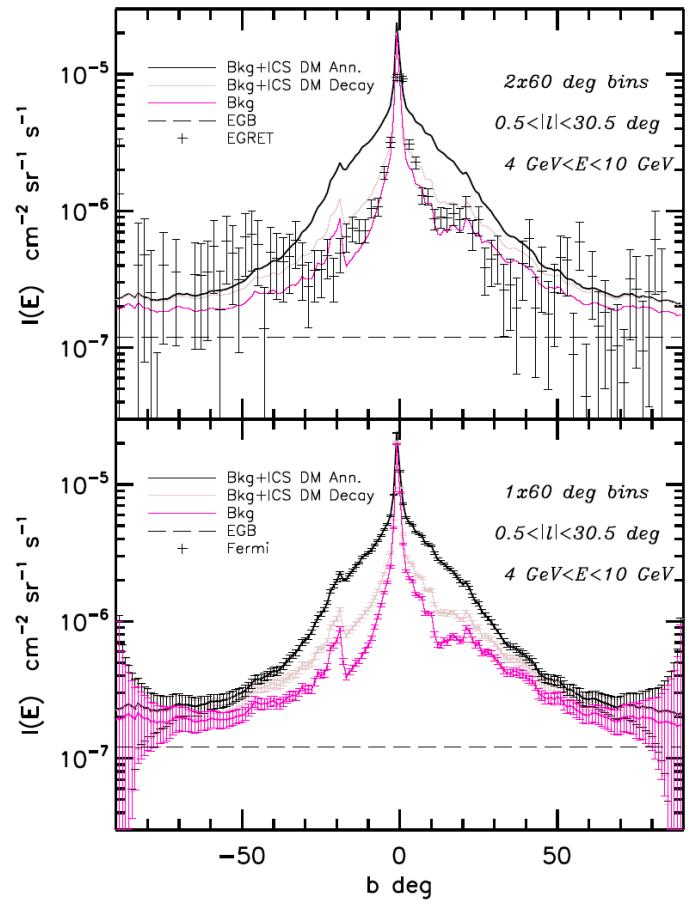
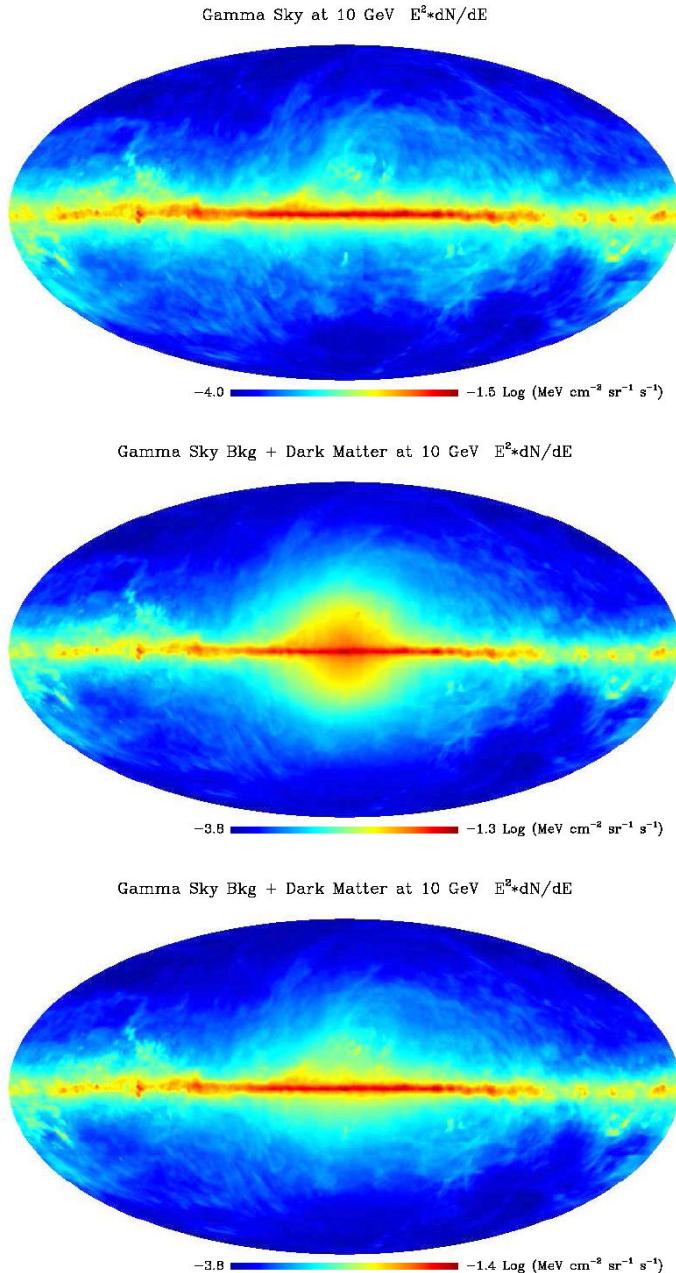
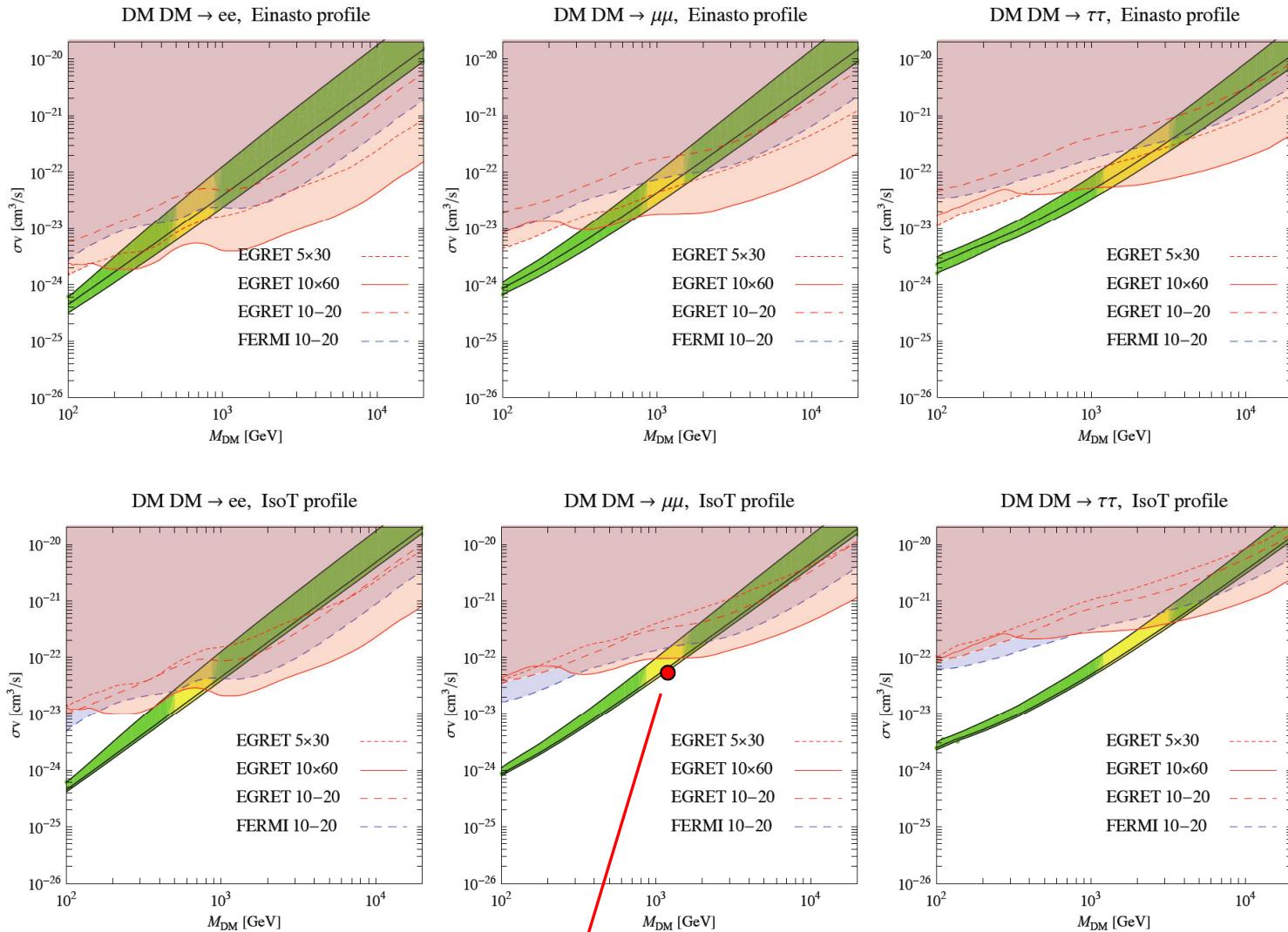


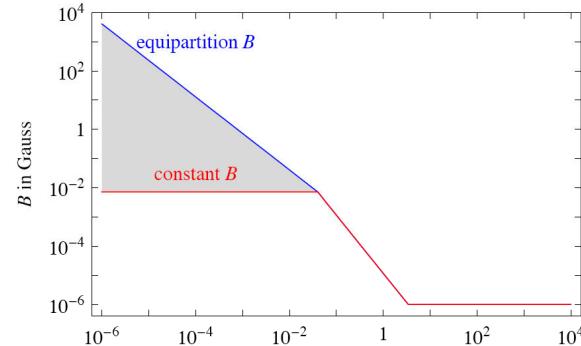
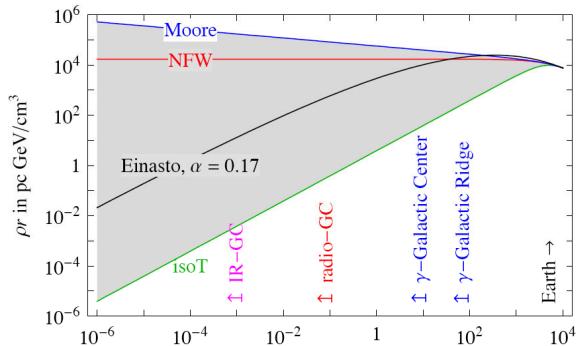
FIG. 3.— Top panel: Background and DM (either annihilating and decaying) latitude gamma profiles averaged in a strip of  $60^\circ$  along  $l = 0$  compared with the EGRET data. Bottom panel: same as above, but with the errors expected with a 1yr survey from Fermi. At high latitudes the error bars appear artificially to increase for the geometry of the  $0.5^\circ < |l| < 30.5^\circ$  strip (which is effectively shrinking along  $b$ ).



Previous WIMP example

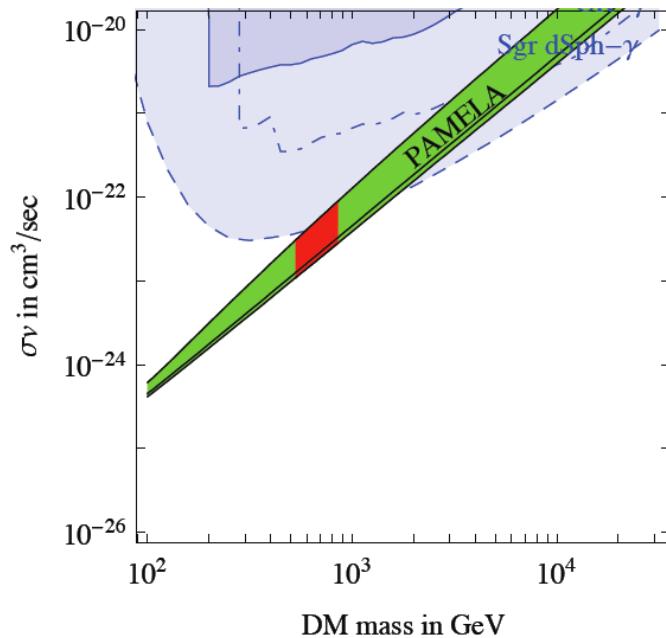
# Constraints from FSR $\gamma$ -rays and radio

G. Bertone, M. Cirelli, A. Strumia & M. Taoso, arXiv:0811.3744

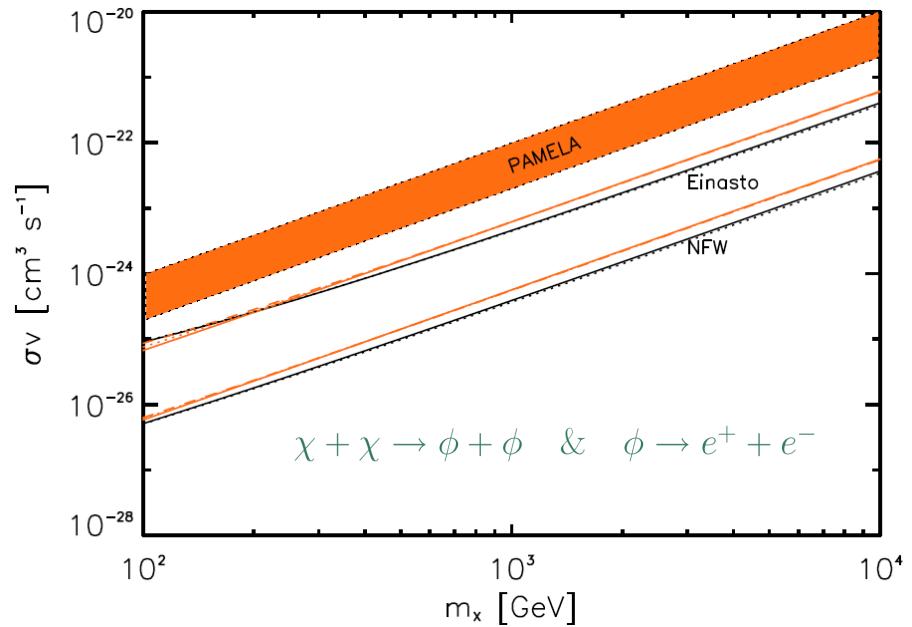


## Central DM profile flatter or $\Gamma_\odot > \Gamma_{\text{GC}}$

DM  $\text{DM} \rightarrow e^+e^-$ , isothermal profile



L. Bergström et al., arXiv:0812.3895



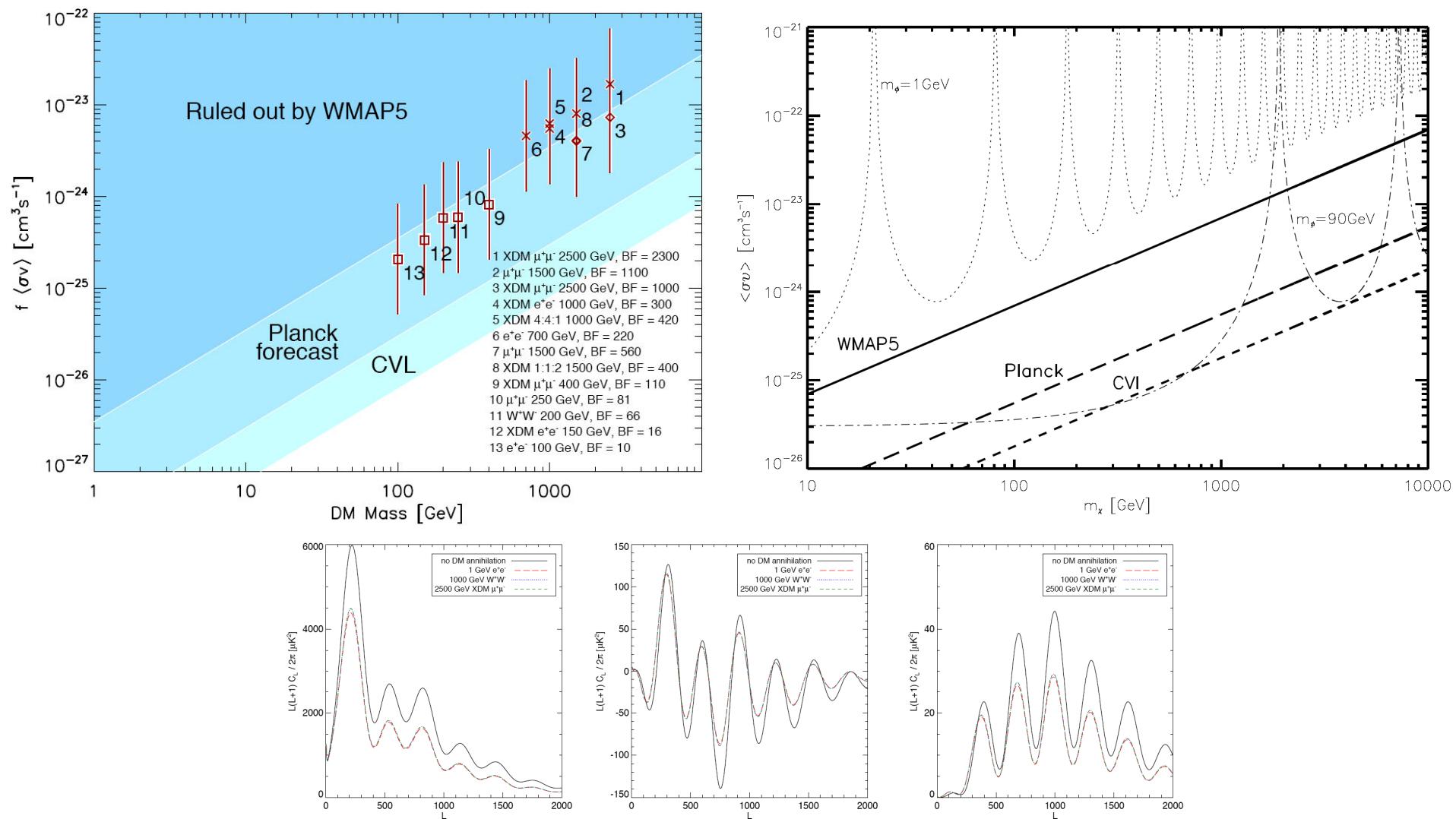


FIG. 5: CMB power spectra for three different DM annihilation models, with power injection normalized to that of a 1 GeV WIMP with thermal relic cross section and  $f = 1$ , compared to a baseline model with no DM annihilation. The models give similar results for the TT (*left*), TE (*middle*), and EE (*right*) power spectra. This suggests that the CMB is sensitive to only one parameter, the average power injected around recombination. All curves employ the WMAP5 fiducial cosmology: the effects of DM annihilation can be compensated to a large degree by adjusting  $n_s$  and  $\sigma_8$  [4].

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### 3) The effect of clumpiness on DM annihilation

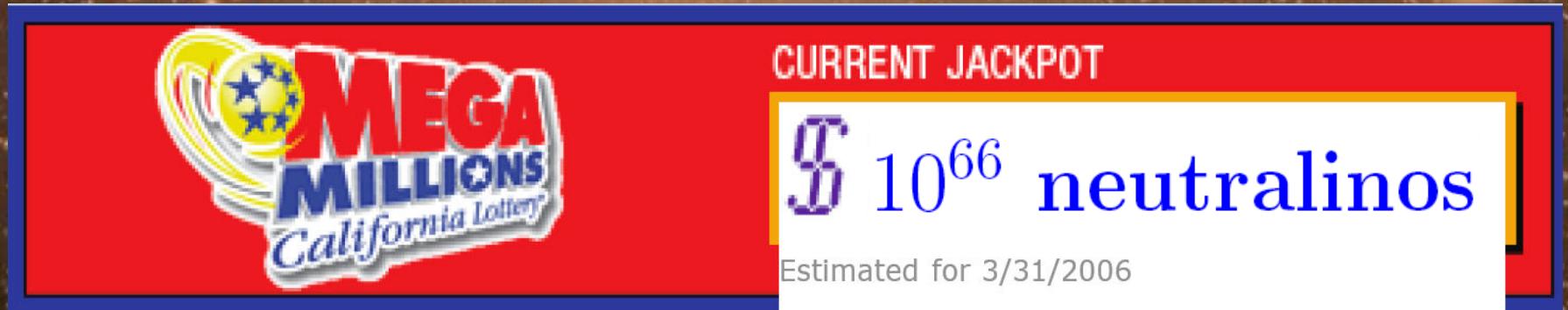
$$\text{DM substructures have } \langle \rho^2 \rangle \geq \langle \rho \rangle^2.$$

- A statistical analysis is necessary to compute the signal enhancement.

$$B_{\text{Milky Way}} \leq 20 \text{ in } \Lambda\text{CDM}$$

- A single nearby clump – how probable is it ?
- A single nearby clump – what about the other messengers ?
- Are minispikes about IMBHs a myth ?

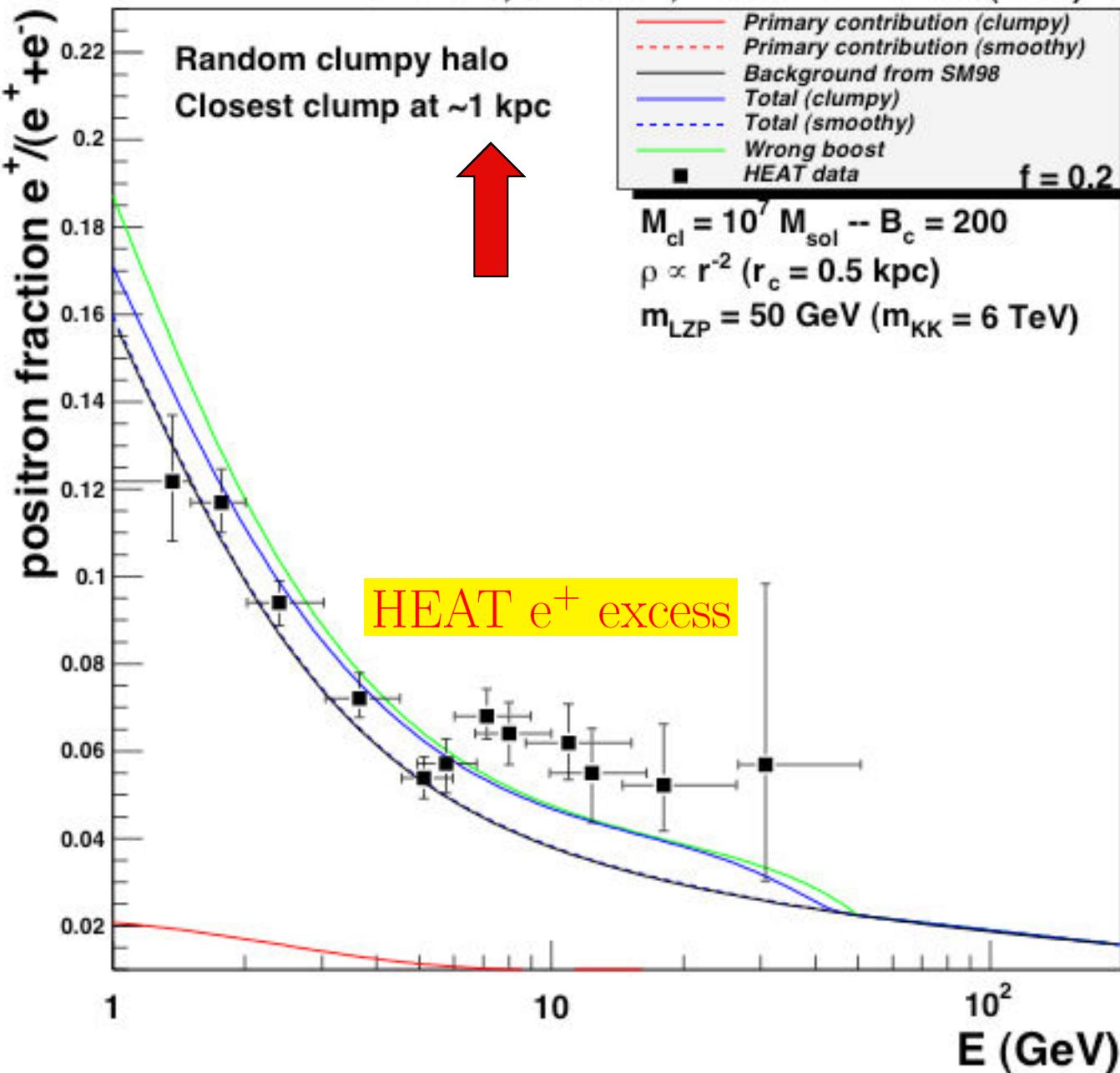
# Boost factors : a hazardous kind of magic



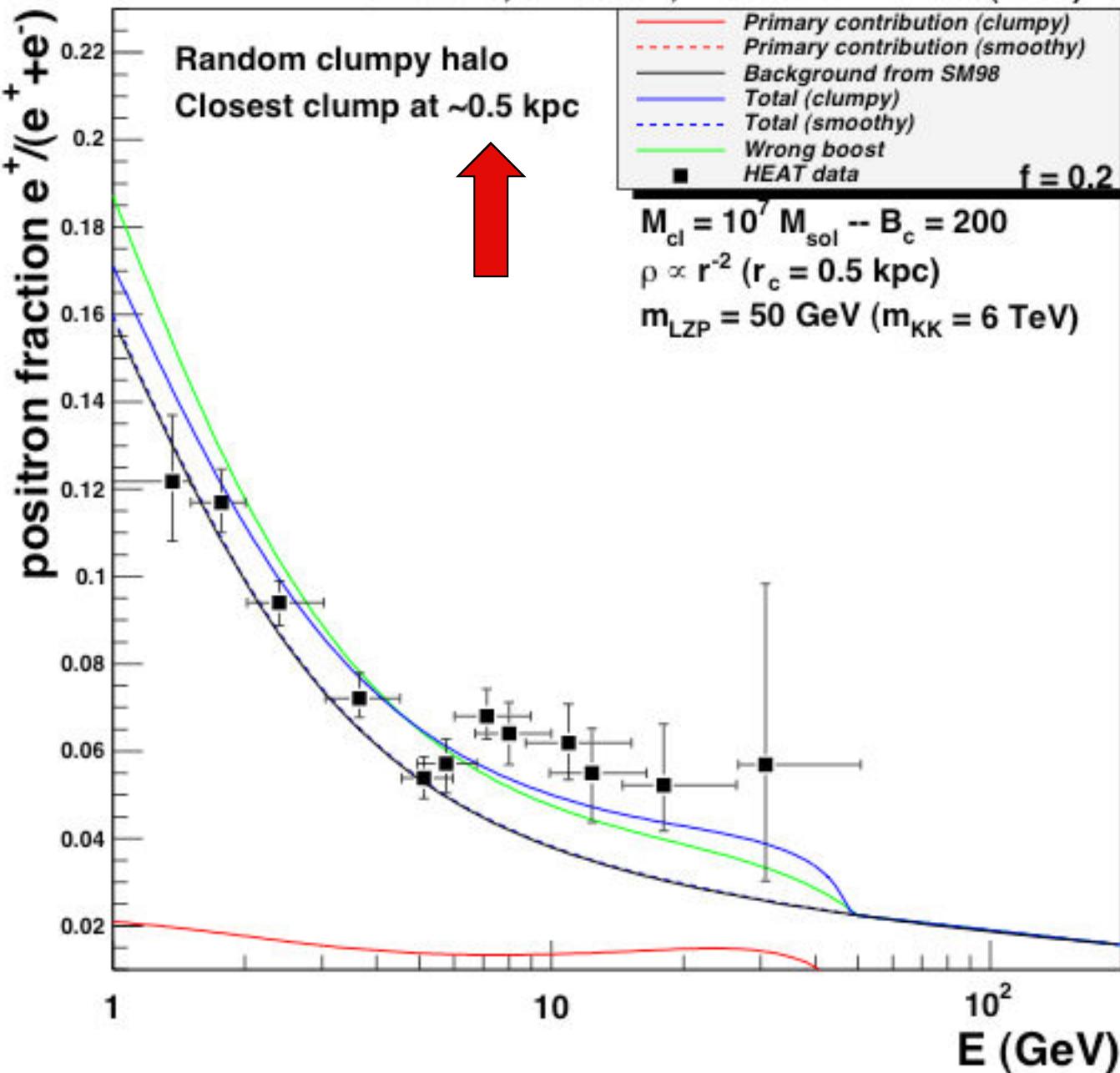
JÜRG DIEMAND<sup>1,2</sup>, MICHAEL KUHLEN<sup>1,3</sup>, & PIERO MADAU<sup>1,4</sup>

FIG. 2.— Projected dark matter density-squared map of our simulated Milky Way-size halo (“Via Lactea”) at the present epoch. The image covers an area of  $800 \times 600$  kpc, and the projection goes through a 600 kpc-deep cuboid containing a total of 110 million particles. The logarithmic color scale covers 20 decades in density-square.

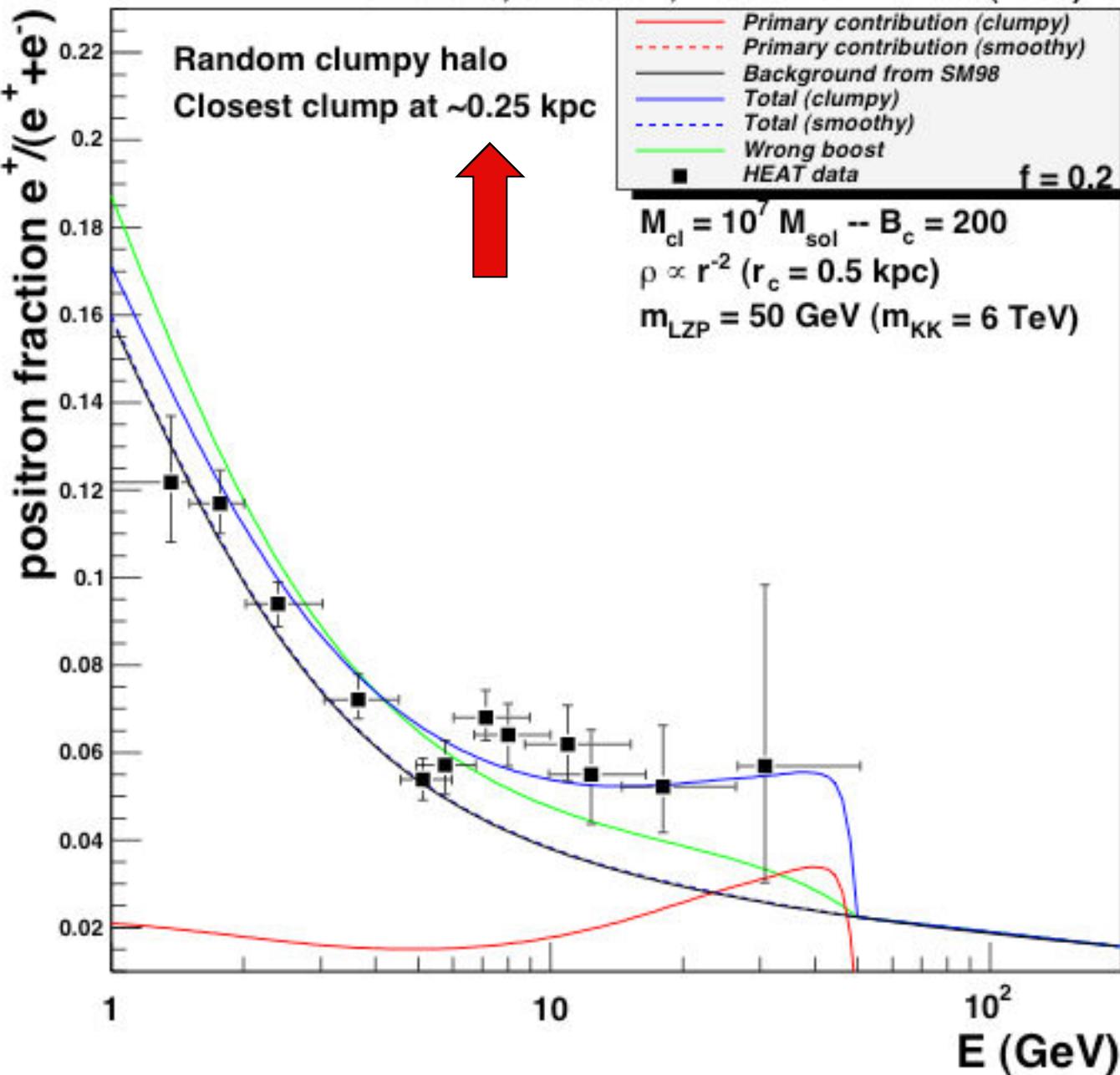
J.Lavalle, J.Pochon, P.Salati & R.Taillet (2006)



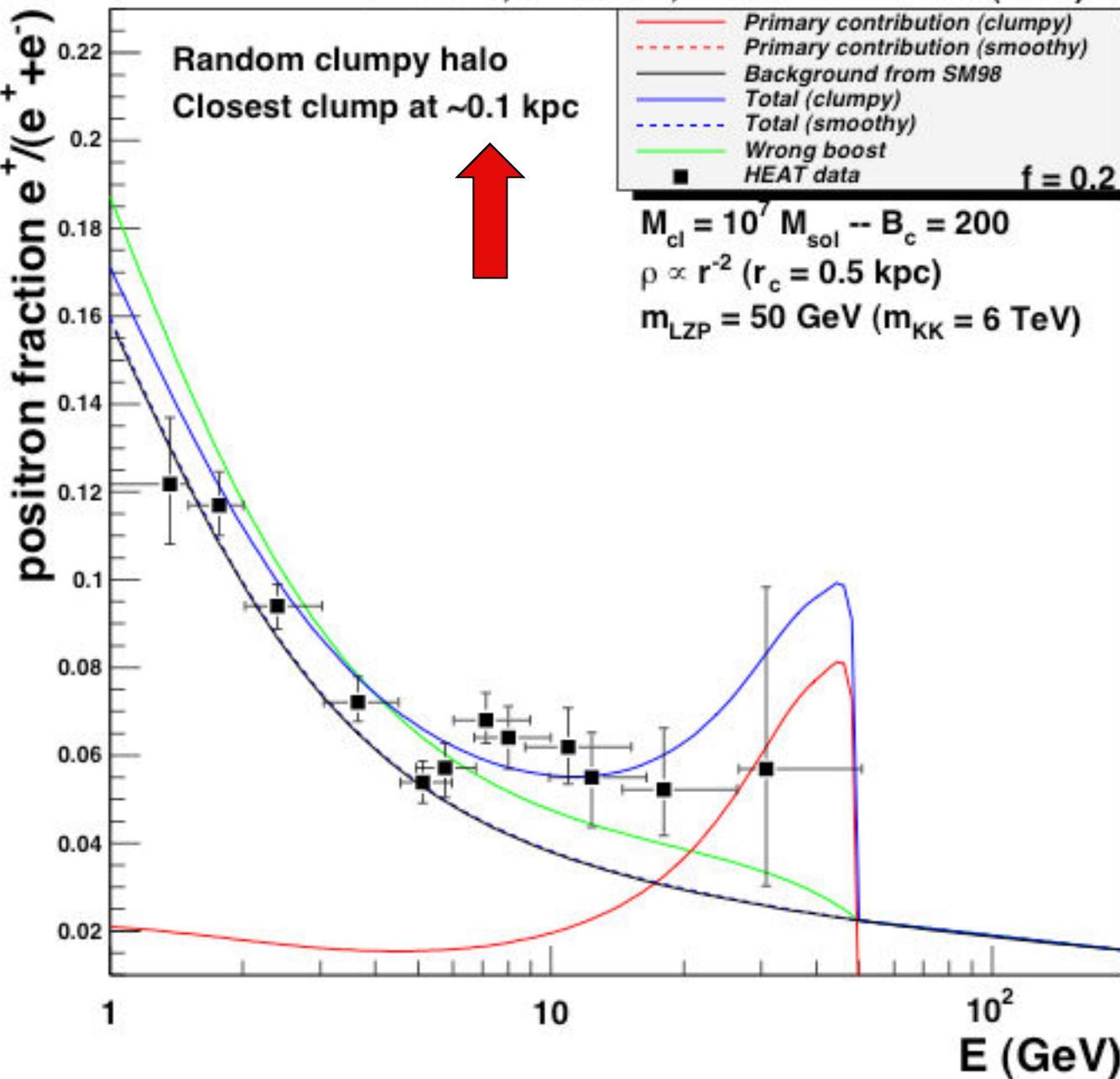
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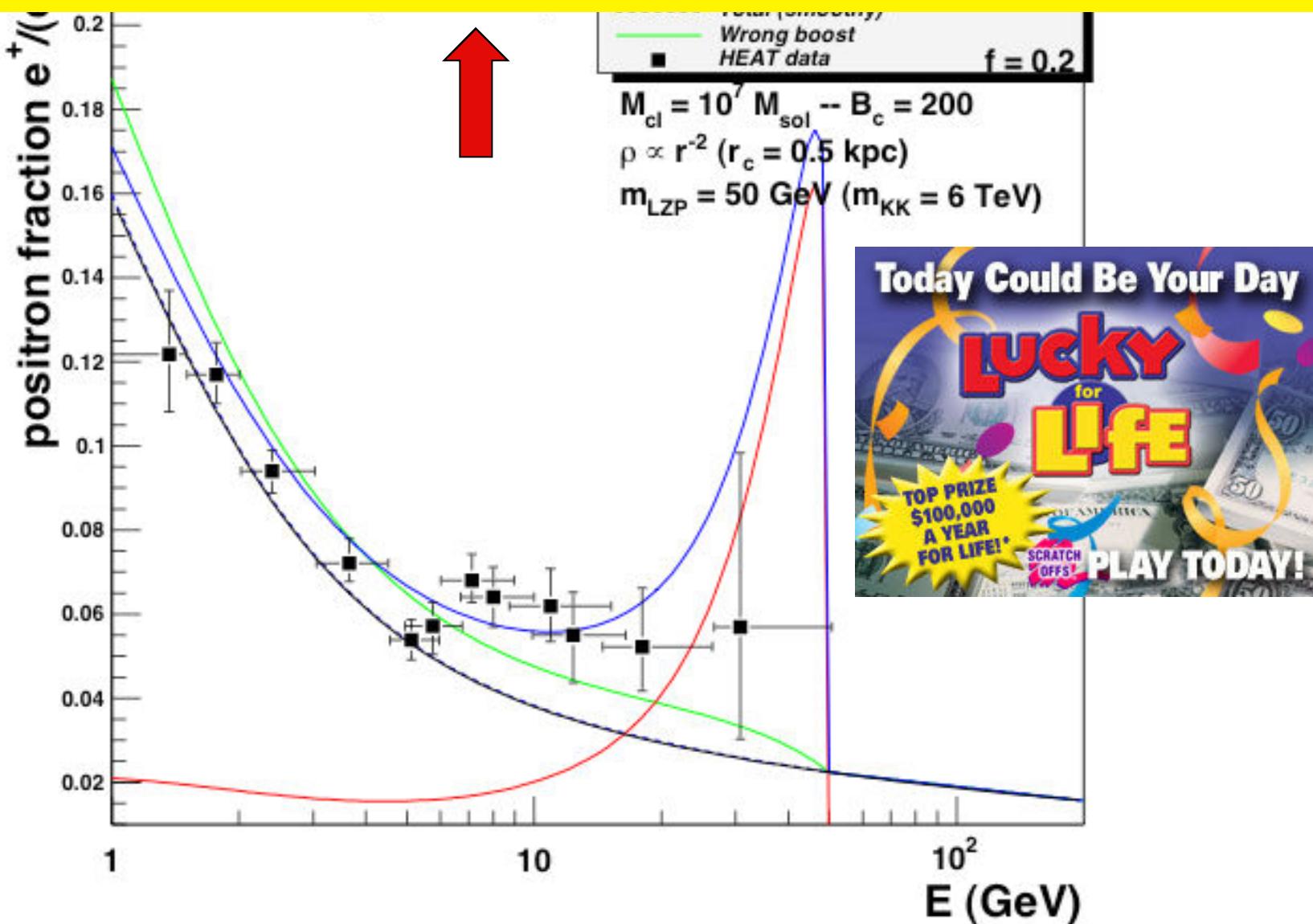
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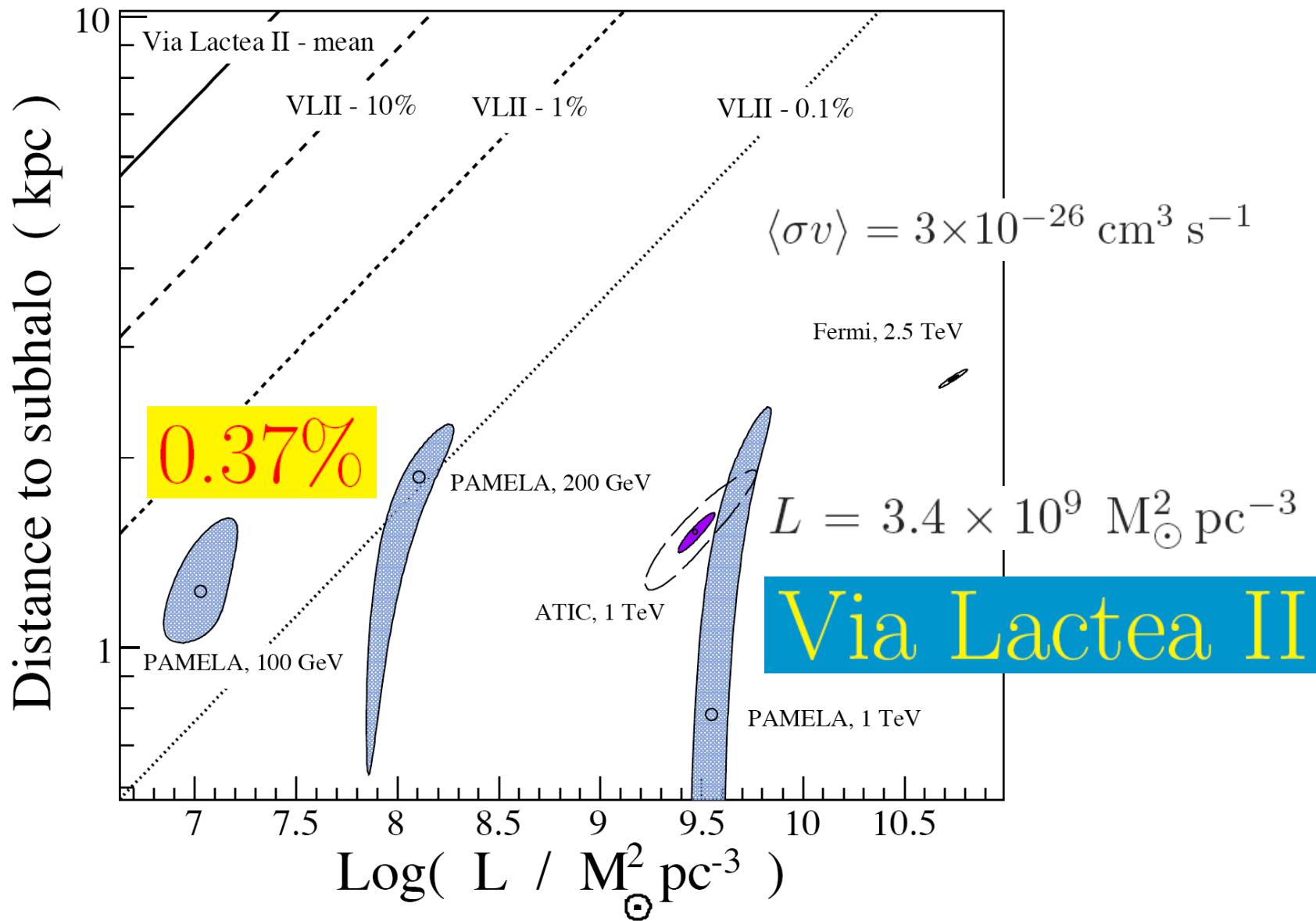


# How probable is that ?

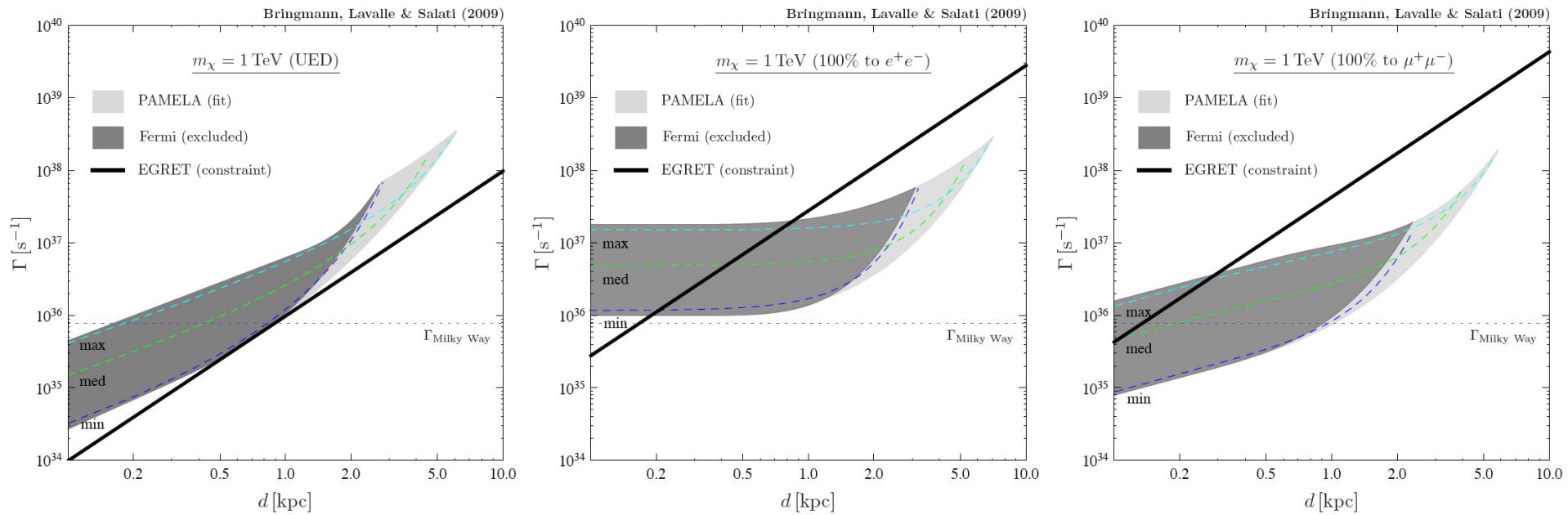


# The cosmic ray lepton puzzle in the light of cosmological N-body simulations

P. Brun, T. Delahaye, J. Diemand, S. Profumo & P. Salati, arXiv:0904.0812



$$\Gamma = \frac{1}{2} \langle \sigma v \rangle (\rho_0 / m_\chi)^2 \xi$$



$$\Phi_{\max}^{\text{EGRET}} = 2 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$$

	PAMELA		ATIC	Fermi
$m_\chi$ (GeV)	100	1 000	1 000	2500
$e^+/e^-$	$1.22 - 1.07 \cdot 10^7$	$0.78 - 3.56 \cdot 10^9$	$1.52 - 2.98 \cdot 10^9$	$2.68 - 5.53 \cdot 10^{10}$
$e^\pm + \mu^\pm + \tau^\pm$	$0.44 - 2.51 \cdot 10^7$	$0.27 - 9.84 \cdot 10^9$	$0.25 - 8.78 \cdot 10^9$	$2.81 - 2.17 \cdot 10^{11}$

TABLE I: Best fit values of the  $(D; L)$  couple in units of  $(\text{kpc}; M_\odot^2 \text{ pc}^{-3})$  for various DM particle masses and annihilation channels.

# Full Calculation of Cosmic Rays in

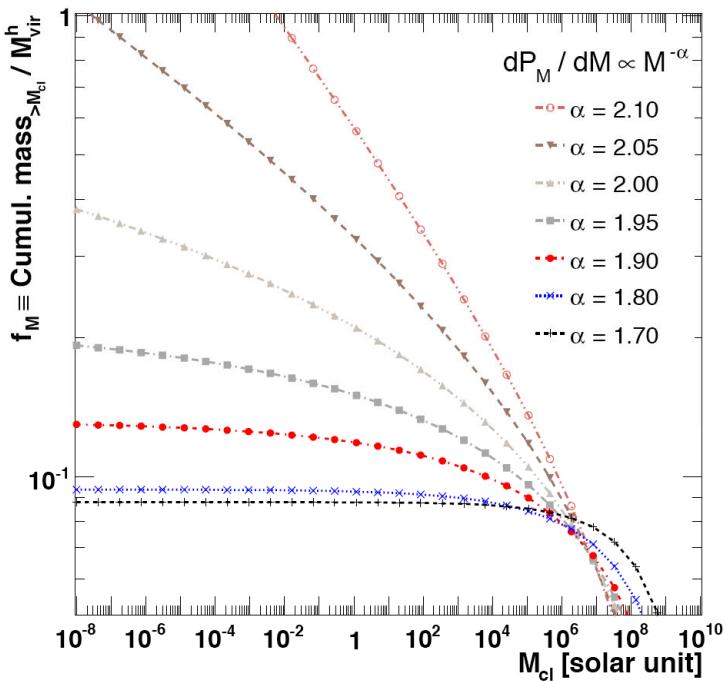
Ab.

for Antimatter Production results  
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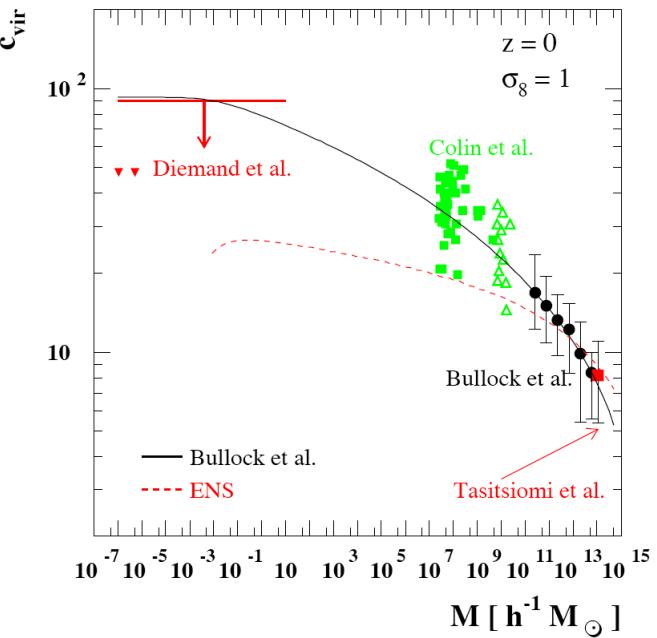
Clump description	Values
$dP_V(r)/dV$	Cored <sup>‡</sup> or NFW
Inner profile	NFW <sup>‡</sup> or Moore
$\alpha_m$	[1.8 – 1.9 <sup>‡</sup> – 2.0]
$M_{\min}$	$[10^{-6}{}^{\pm} - 1 - 10^6] M_\odot$
$c_{\text{vir}} - M_{\text{vir}}$	B01 <sup>‡</sup> or ENS01

<sup>‡</sup> Reference configuration.

**Table 2.** Description of the various configurations used in the paper for the sub-halo parameters.

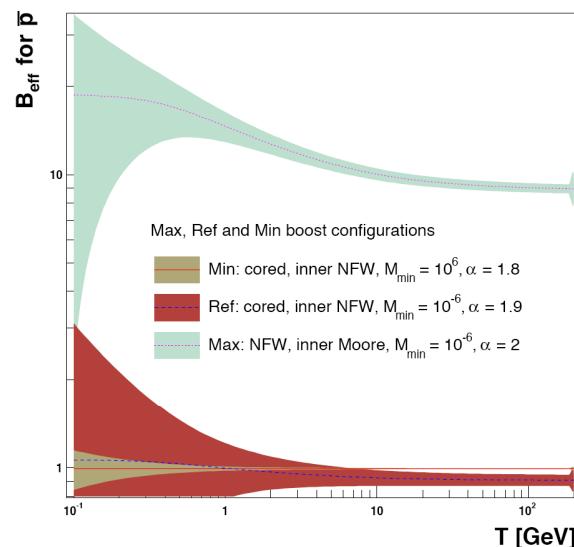
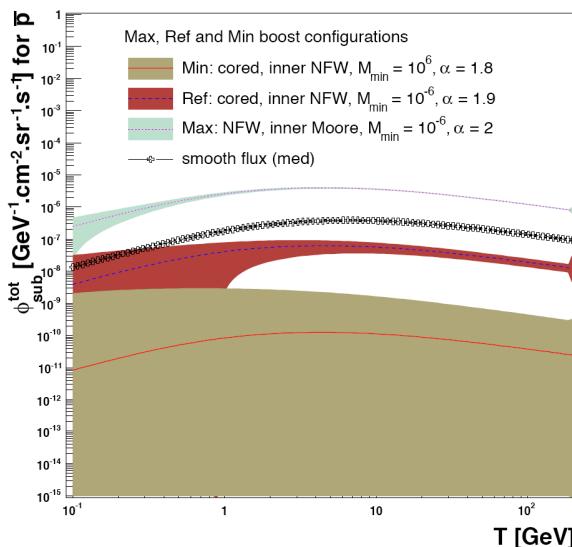
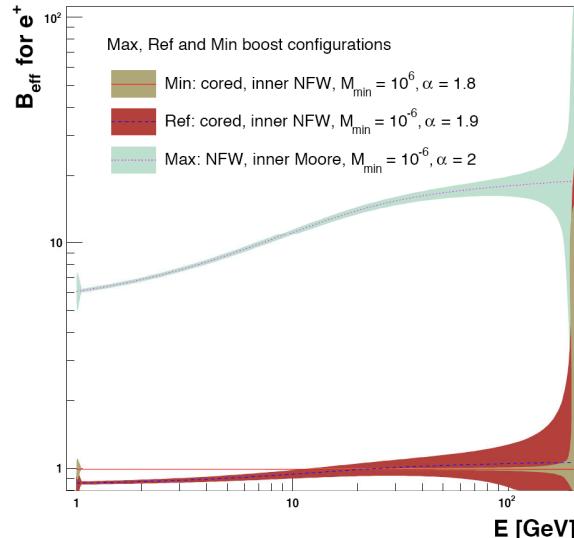
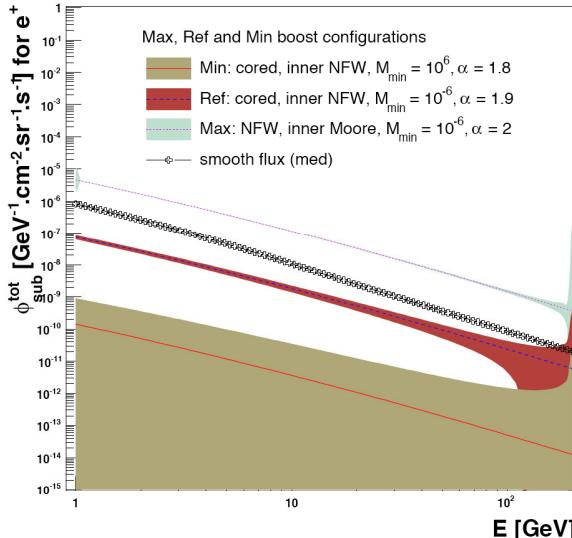


**Fig. 1.** The mass fraction  $f_M$  of DM in clumps is set once  $M_{\min}$  and  $\alpha_m$  are chosen. This fraction can be directly read off the graph for various  $\alpha_m$  (from 2.1 down to 1.7—top to bottom curves) and various  $M_{\min}$  (from  $10^8 M_\odot$  down to  $10^{-8} M_\odot$ , x-axis).



**Fig. 1.** The dependence of  $c_{\text{vir}}$  on the halo mass  $M$ , at  $z = 0$ , as in the Bullock et al. toy model (solid line) and in the ENS toy model (dashed line); predictions are compared to a few sets of simulation results in different mass ranges. A flat, vacuum-dominated cosmology with  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0.7$ ,  $h = 0.7$  and  $\sigma_8 = 1$  is assumed here.

# $B_{\text{Milky Way}} \leq 20$ in $\Lambda\text{CDM}$



**Fig. 6.** Extreme cases for the DM configurations: sub-halo antimatter fluxes associated with the maximal, reference and minimal DM configurations (medium set of propagation parameters). Left/right: fluxes/boosts and corresponding  $1-\sigma$  contours. Top/bottom: positrons/anti-protons. See details in the text.

# Dark matter mini-spikes around IMBHs

G. Bertone, A.R. Zentner & J. Silk, PRD **72** (2005) 103517

When the first DM halos form, gas cools and collapses as pressure supported disks

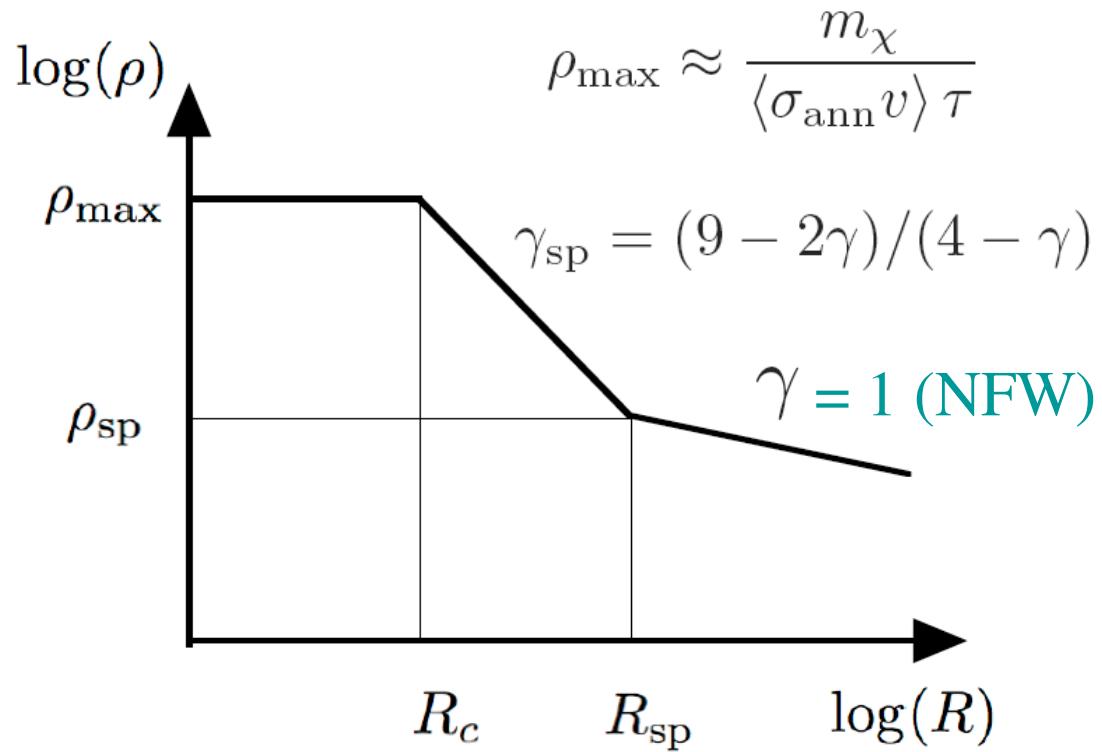
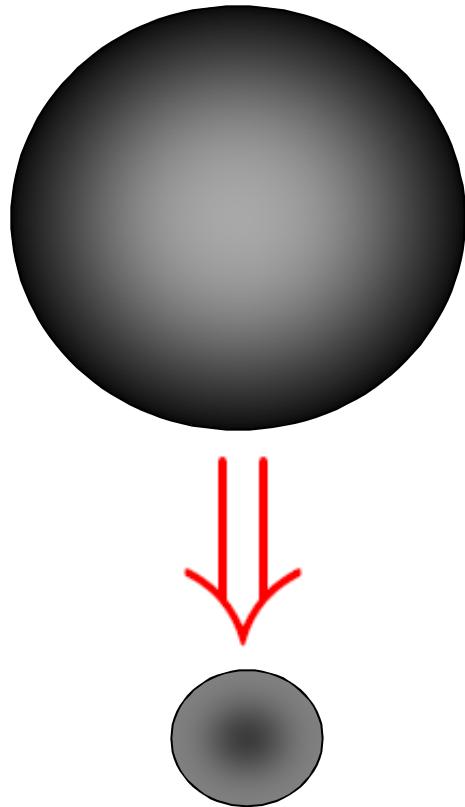


A baryonic mass of  $\sim 10^5 M_{\odot}$  loses its angular momentum

It is transferred at the center to form an Intermediate Mass Black Hole

During the process, DM is adiabatically compressed onto this central object

# Adiabatic DM compression around the IMBH



Large annihilation volume  $1.84 \text{ pc}^3$

$$\text{DM mini-spike} \propto \left\{ \langle \sigma_{\text{ann}} v \rangle^{2/7} m_\chi^{-9/7} \right\}^{3/7} \equiv \frac{\rho_{\max}}{\rho_{\text{sp}}} \left( \frac{\rho_{\text{sp}}}{\rho_\odot} \right)^{(9-2\gamma)/(4-\gamma)} \left( \frac{R_c}{R_\odot} \right)^{3/7}$$

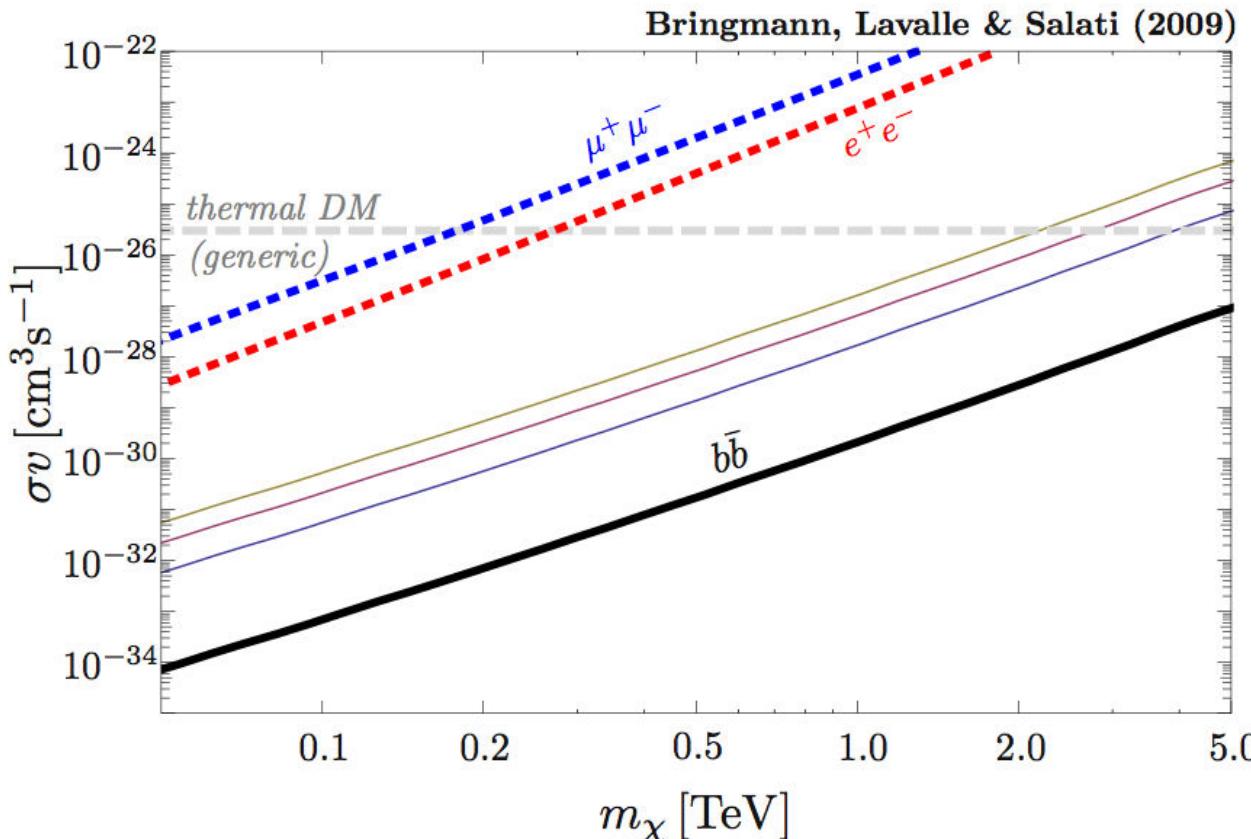
Compensation between  $\rho_{\max}$  &  $\langle \sigma_{\text{ann}} v \rangle$

gamma ray flux at the Earth from a single mini-spike

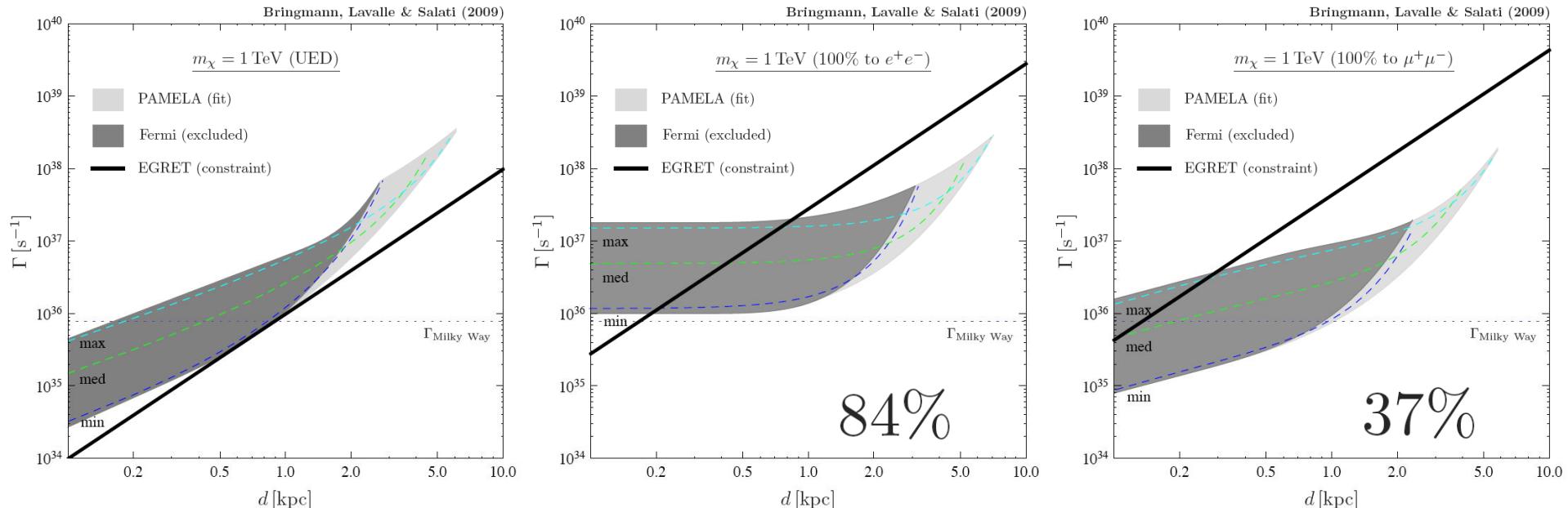
$$\Phi_\gamma \simeq 3.315 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \times \frac{\tilde{\xi}/d^2}{10^4 \text{ kpc}} \times \mathcal{F}(m_\chi, <\sigma v>)$$

$$\mathcal{F}(m_\chi, <\sigma v>) = \left\{ \frac{N_\gamma}{100} \right\} \times \left\{ \frac{m_\chi}{1 \text{ TeV}} \right\}^{-9/7} \times \left\{ \frac{<\sigma v>}{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right\}^{2/7}$$

$$\Phi_{\max}^{\text{EGRET}} = 2 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$$



# DM mini-spike around an IMBH



$$\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

FIG. 2: The solid lines give the EGRET constraints on the DM annihilation rate  $\Gamma = \frac{1}{2}\sigma v(\rho_0/m_\chi)^2 \xi$  of a nearby, generic DM point-source at a distance  $d$  from the Earth; from left to right, we show the case of KK DM and a fiducial DM candidate annihilating to  $e^+e^-$  and  $\mu^+\mu^-$ , respectively. The dashed lines show the  $\Gamma$  needed to fit the PAMELA data, for sets of propagation parameters as defined in [23]; in the dark shaded area this would produce an  $e^\pm$  flux in conflict with the Fermi data at higher energies. For comparison, the dotted line indicates  $\Gamma$  for the *whole Milky Way*, assuming  $\langle \sigma v \rangle \sim 3 \cdot 10^{-26} \text{ cm}^{-3} \text{ s}^{-1}$ .

## PAMELA positron excess

May be the first indirect hint that DM species annihilate in the MW.

$$\Gamma_{\text{ann}} \equiv \langle \sigma v \rangle \times \frac{\rho_\chi^2}{m_\chi^2} \text{ needs to be enhanced}$$

### 3) The effect of clumpiness on DM annihilation

$$\text{DM substructures have } \langle \rho^2 \rangle \geq \langle \rho \rangle^2.$$

- A statistical analysis is necessary to compute the signal enhancement.

$$B_{\text{Milky Way}} \leq 20 \text{ in } \Lambda\text{CDM}$$

- A single nearby  $\Lambda$ CDM clump is very improbable.
- Moreover, EGRET constrains the WIMP to be leptophilic.
- If so, IMBH could be a solution although future strong limits from FERMI.

## PAMELA positron excess

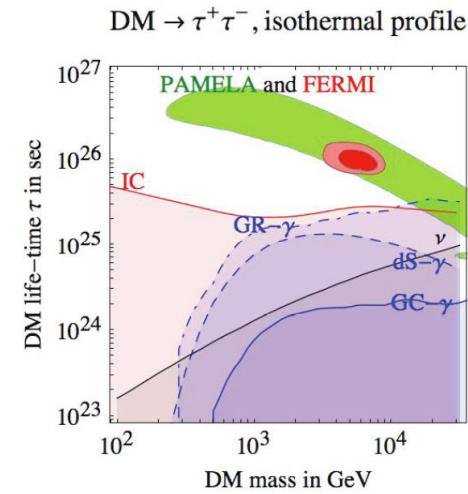
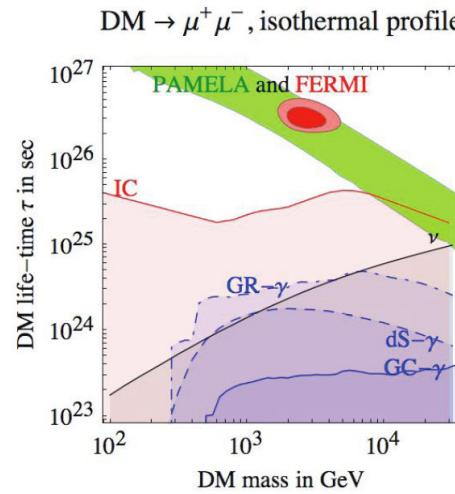
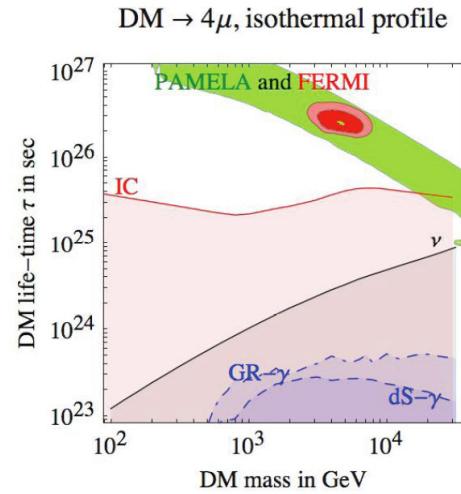
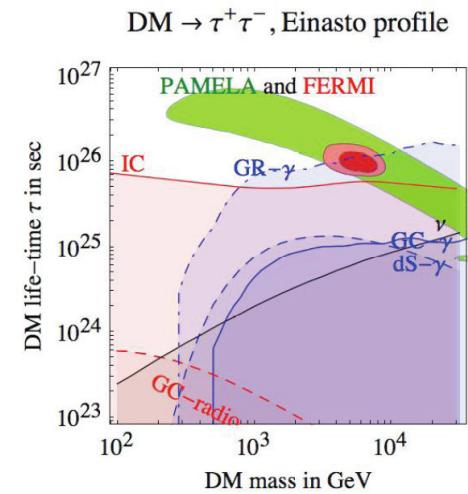
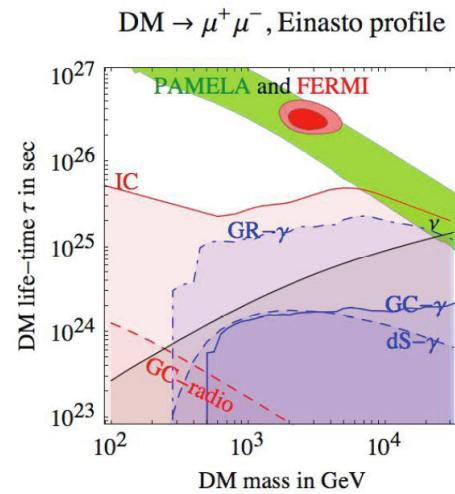
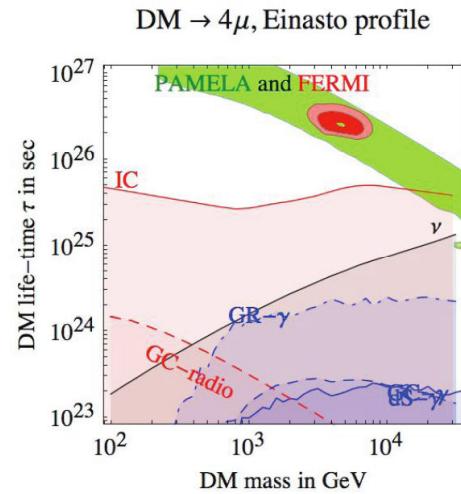
May also be an indication that DM species **decay** in the MW.

$$\Gamma_{\text{ann}} \equiv \langle \sigma v \rangle \times \frac{\rho_\chi^2}{m_\chi^2} \Rightarrow \Gamma_{\text{ann}} \equiv \Gamma_{\text{dec}} \times \frac{\rho_\chi}{m_\chi}$$

$$\langle \sigma v \rangle = 3 \times 10^{-23} \text{ cm}^3 \text{ s}^{-1}, \rho_\odot = 0.3 \text{ GeV cm}^{-3} \& m_\chi = 1 \text{ TeV}$$
$$\Downarrow$$
$$\Gamma_{\text{dec}} \sim 10^{-26} \text{ s}^{-1}$$

## 4) Decaying dark matter

- Decaying DM species still pass the astrophysical tests since  $\Gamma_{\text{ann}} \propto \rho_\chi$ .
- The lifetime needs to be fine-tuned though.
- Why is it so large – dimension 5 or 6 operators ?
- FERMI should be able to detect the ICS WIMP signal.



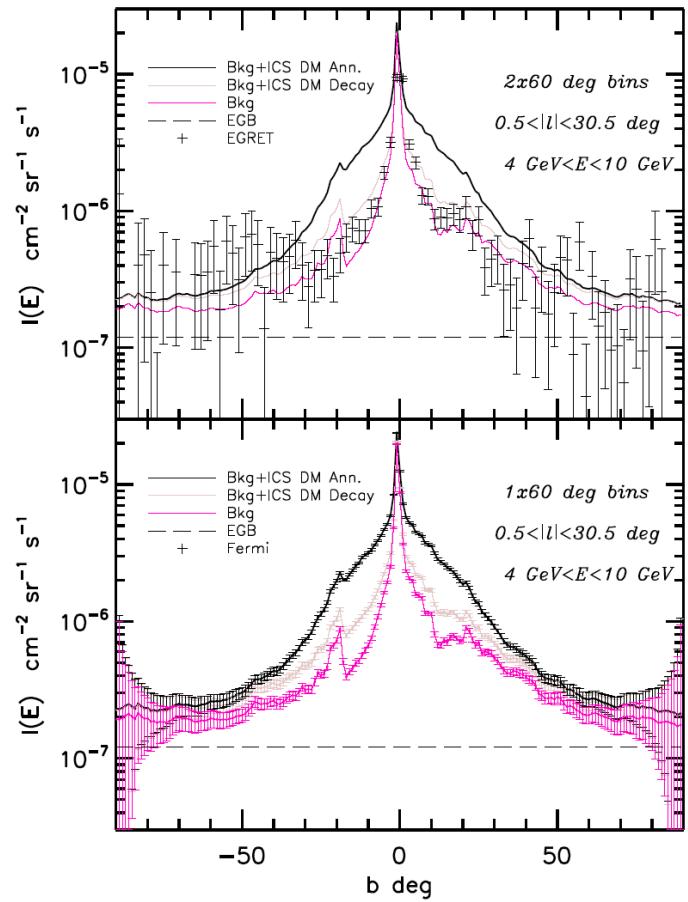
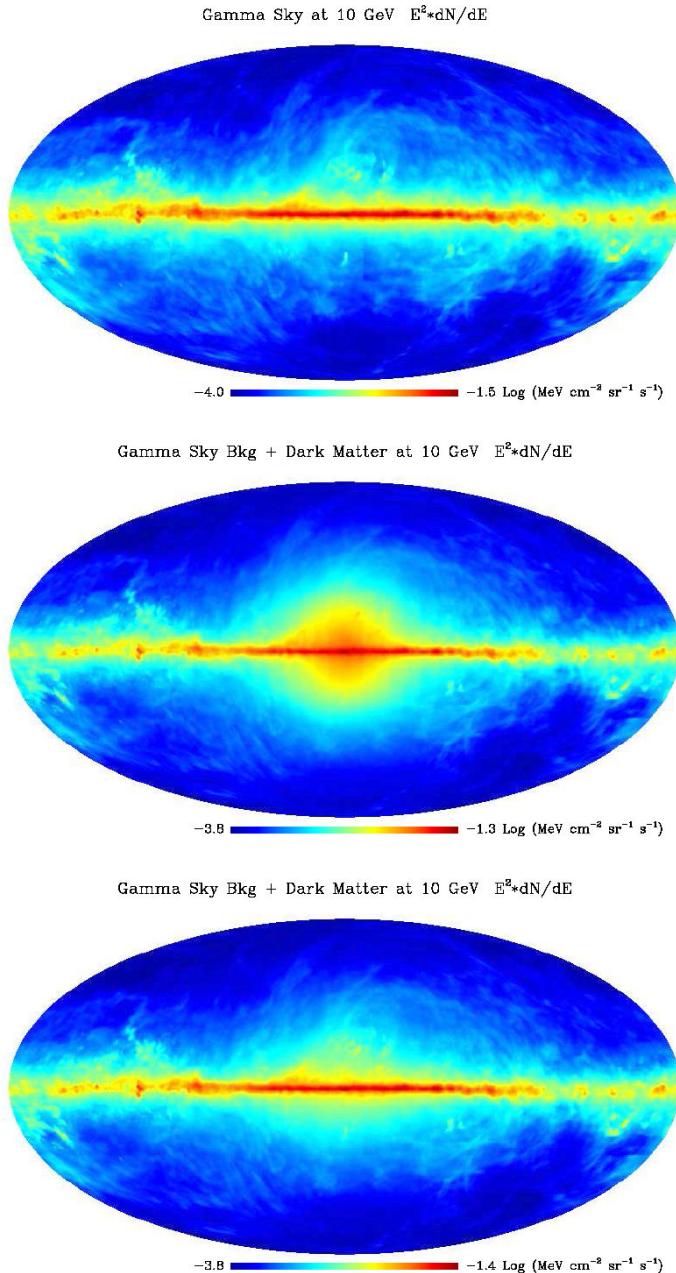


FIG. 3.— Top panel: Background and DM (either annihilating and decaying) latitude gamma profiles averaged in a strip of  $60^\circ$  along  $l = 0$  compared with the EGRET data. Bottom panel: same as above, but with the errors expected with a 1yr survey from Fermi. At high latitudes the error bars appear artificially to increase for the geometry of the  $0.5^\circ < |l| < 30.5^\circ$  strip (which is effectively shrinking along  $b$ ).

## 5) Perspectives more than conclusions

No coherent picture yet !

- Leptophilic vs CR propagation : are normal WIMPs really excluded ?
- DM clumpiness alleviates the tension from GC constraints.
- Sommerfeld effect combined with DM clumps & CR propagation.
- WIMP decay is OK although fine-tuned.



FERMI will soon explore these possibilities



Astrophysical explanations of the  $e^+$  excess

- Local pulsars with an injection spectral index of 1.5 ?
- Spallation & reacceleration in SN shock waves ?

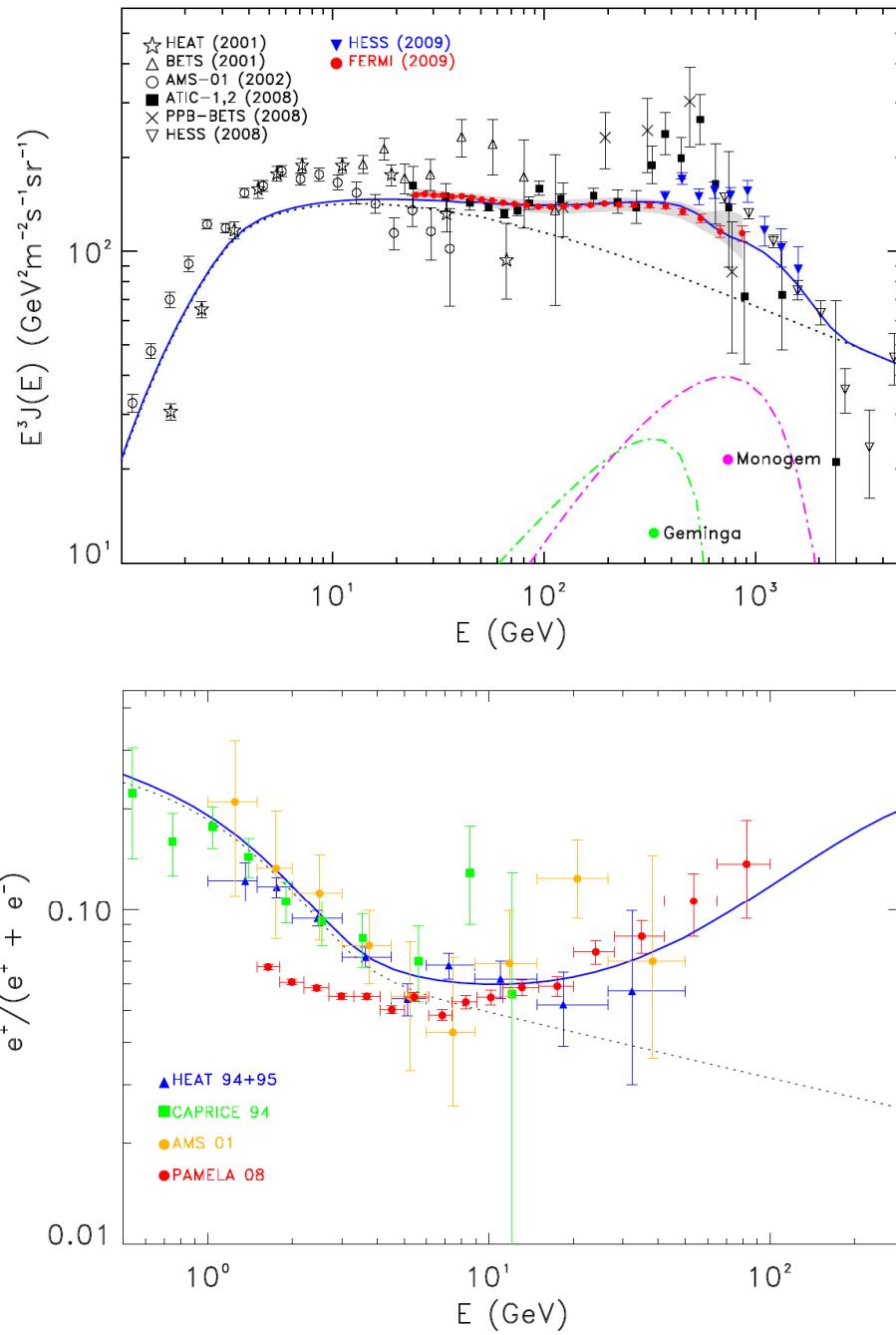
The diagram illustrates the internal structure and emission regions of a pulsar. A central black sphere represents the pulsar's core, with a red vertical axis labeled 'Rotation axis' and a blue curved arrow indicating rotation. A grey cylinder represents the 'Light Cylinder'. Inside, green lines form 'Region of closed magnetic field lines' around the rotation axis. A pink cone labeled 'Cone of radio emission' points outwards. A blue slot gap at the bottom emits 'Gamma rays'. Red lines represent 'Open magnetic field lines' that connect the pulsar's poles to the light cylinder. An 'outer gap' is shown where these lines meet the cylinder. A purple 'Radio beam' is directed upwards from the top. A scale bar indicates a distance of 1000 km. The bottom right corner of the diagram area contains the text 'D. Page'.

$\phi_0 = \Omega B a^2 / c$

Formation of pulsar wind

Faraday disk: unipolar induction

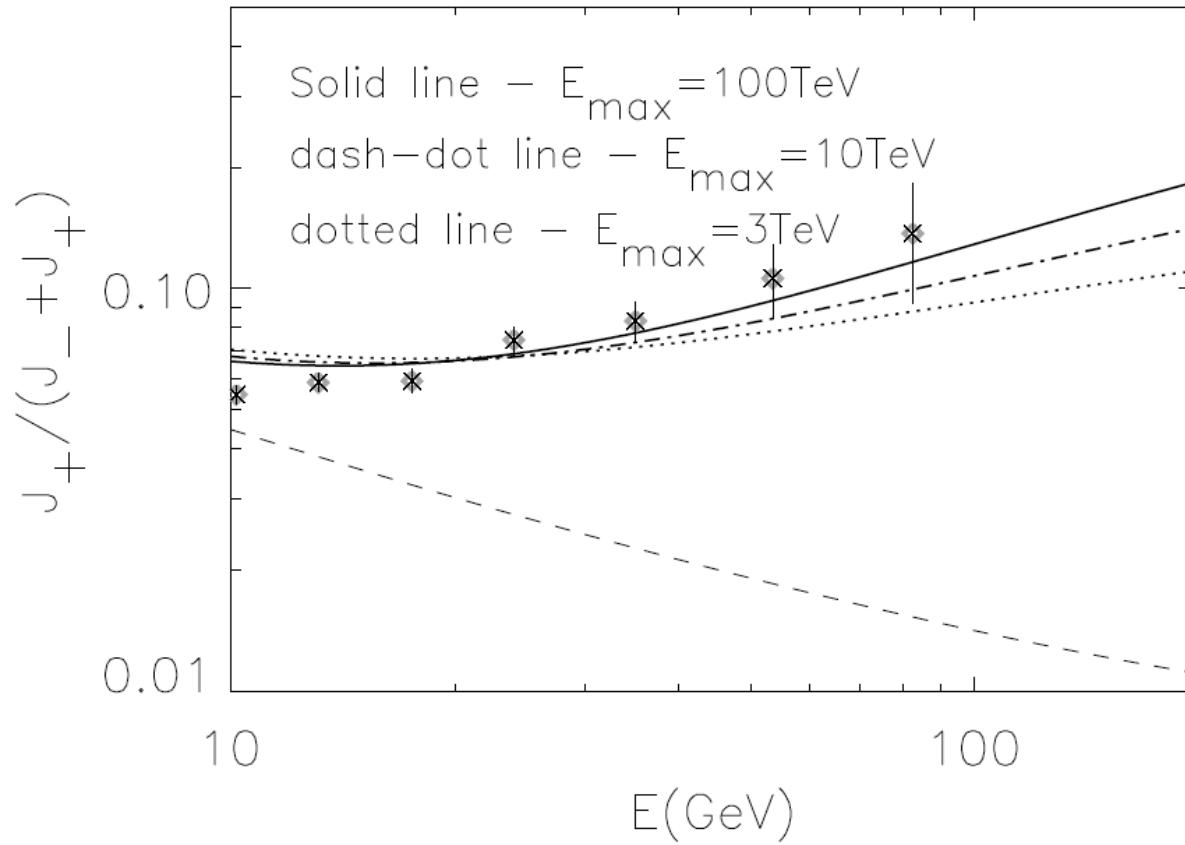
- but pulsars are not in vacuum!
- Equator-pole potential difference ( $10^{15}$  V for Crab)
- Charge extraction from the surface ( $E$  field  $\gg$  gravity)
- Currents, strong magnetization
- Corotating zone; Light cylinder
- Throwing away toroidal field – energy loss (Poynting flux)
- Plasma currents modify field. How can we model this?



# The origin of the positron excess in cosmic rays

Pasquale Blasi

Acceleration and spallation in SN shock waves



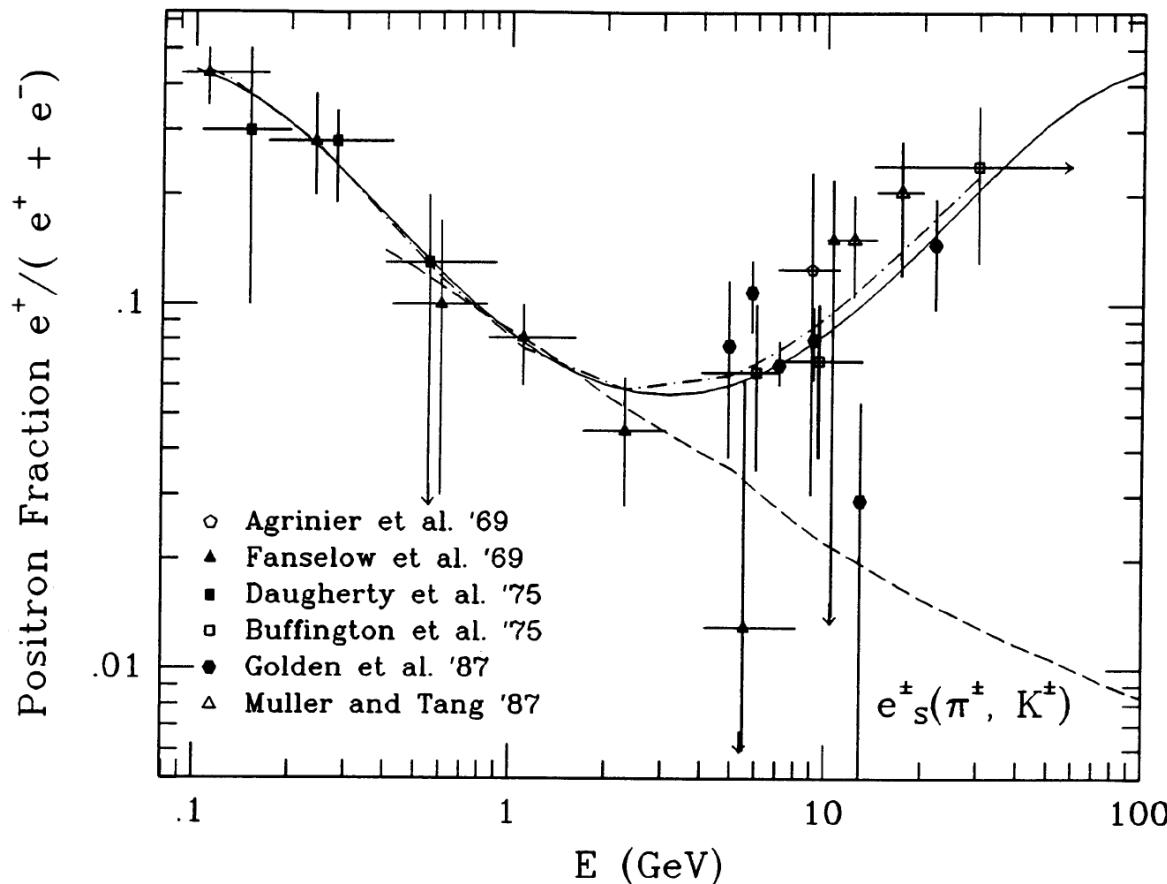
B/C and  $\bar{p}/p$  should increase at high E

# THE NATURE OF THE COSMIC-RAY ELECTRON SPECTRUM, AND SUPERNOVA REMNANT CONTRIBUTIONS

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# Galactic CR propagation

