

# The cosmic ray positron excess : the revenge of orthodoxy

Pierre Salati – Université de Savoie & LAPTh

## Outline

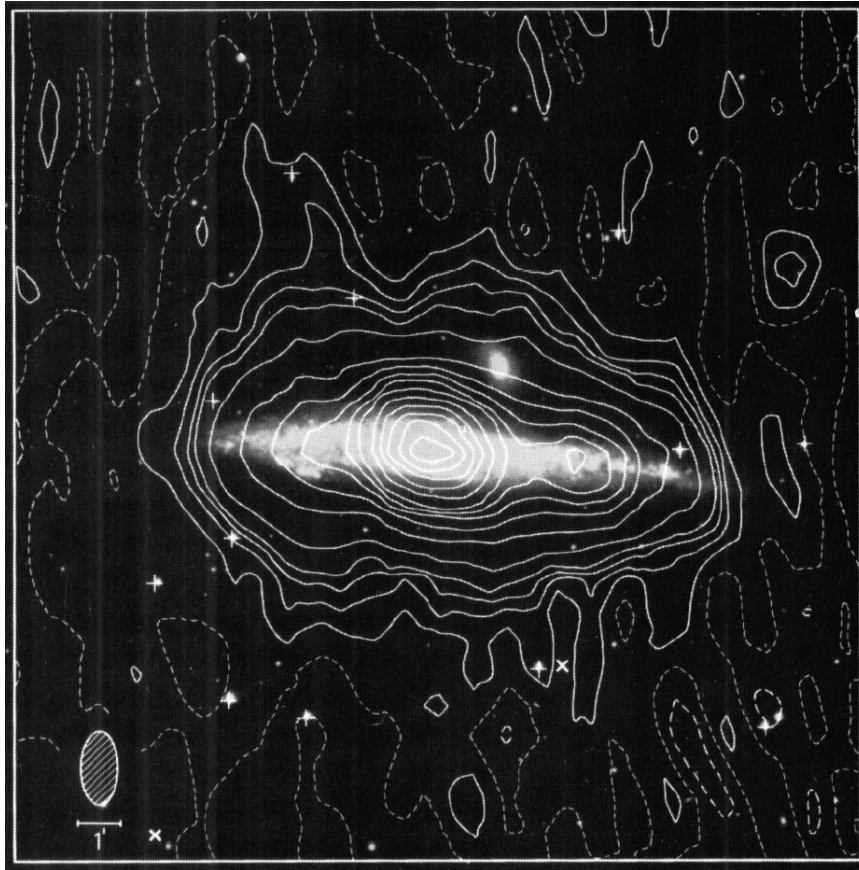
- 1) Observations – evidence for primary CR positrons
- 2) Is it the first hint for DM particles in space ?
- 3) Pulsars as potential sources of the positron excess
- 4) CR acceleration and spallation at the same time
- 5) The revenge of orthodoxy



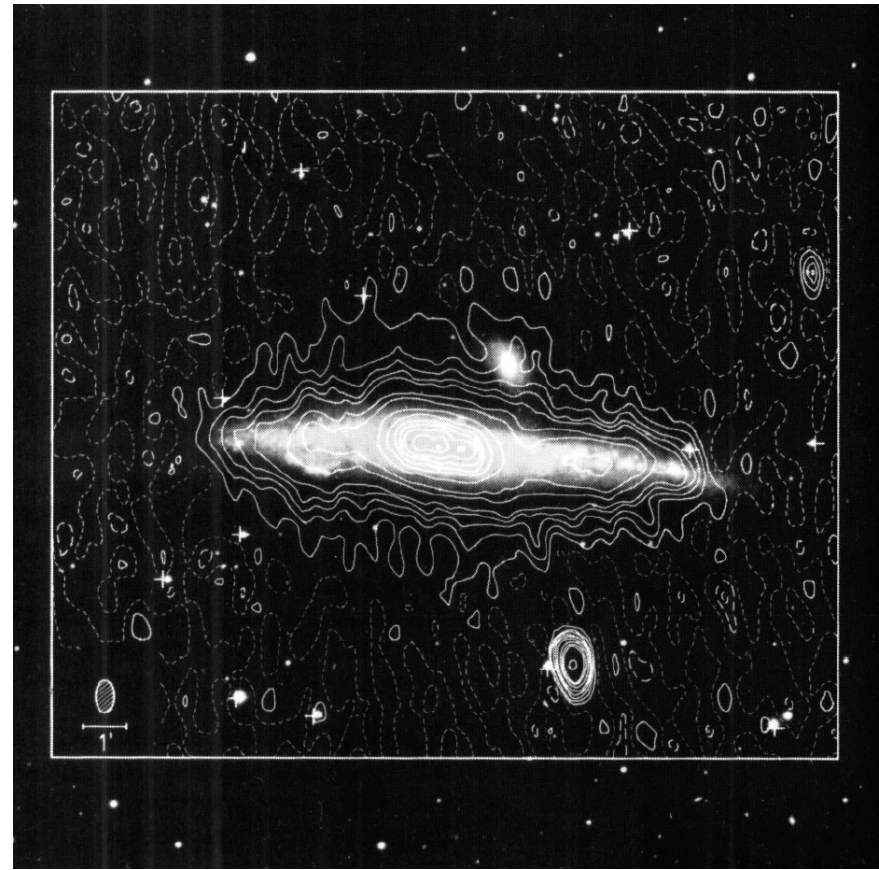
Séminaires de physique expérimentale LAPP – Annecy – January 31, 2014

# 1) Observations – evidence for primary CR positrons

610 MHz



1412 MHz



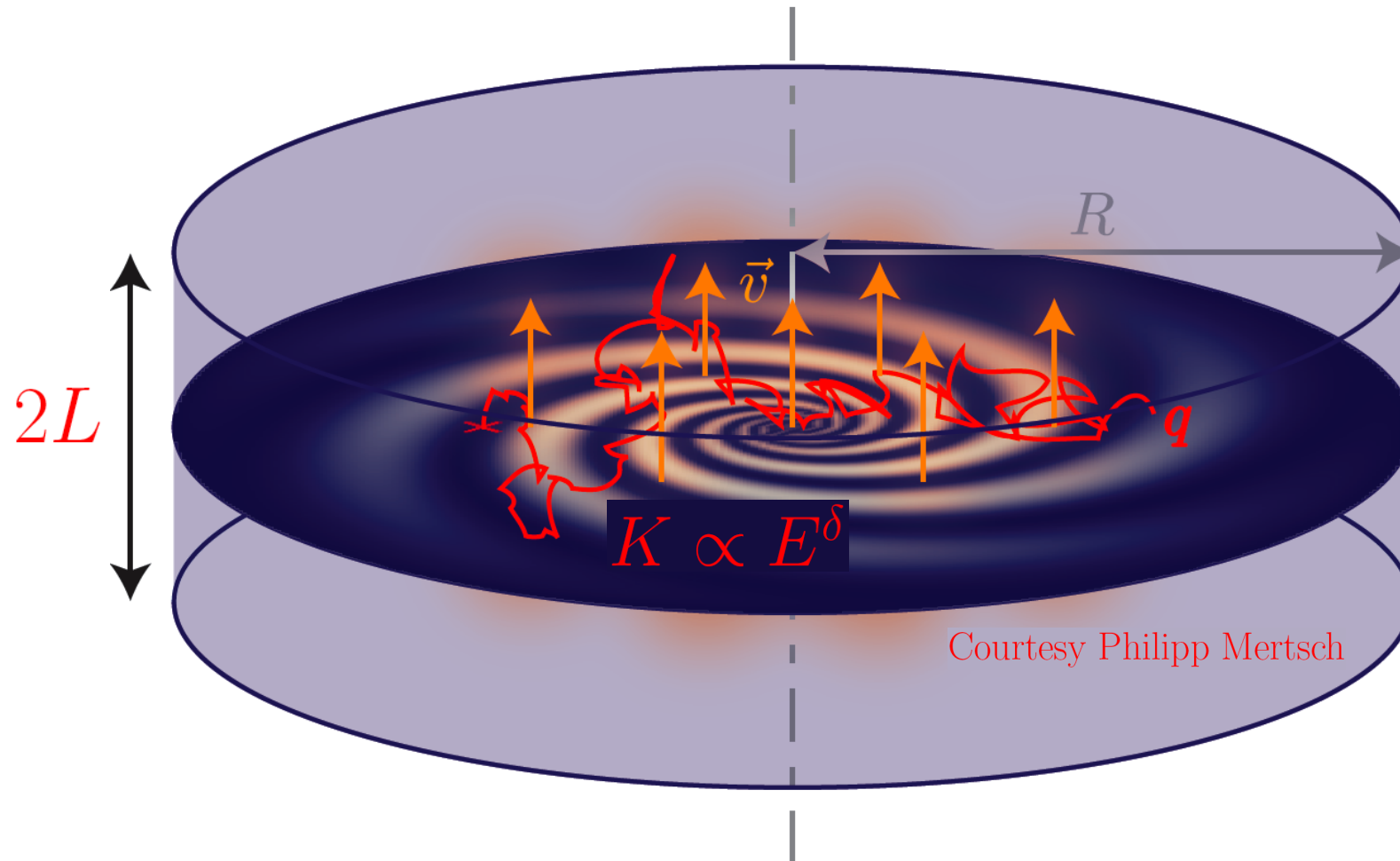
## **The Radio Continuum Halo in NGC 4631**

R. D. Ekers and R. Sancisi

*Astron. Astrophys.* 54, 973—974 (1977)

# Milky-Way seen by a cosmic-ray physicist

Cosmic rays propagate inside a diffusive halo



$$-K \Delta \psi + \partial_E \{ b^{\text{loss}}(E) \psi \} = q(\mathbf{x}, E) \text{ where } b^{\text{loss}}(E) = -\frac{E^2}{E_0 \tau_E} \text{ and } \tau_E \simeq 10^{16} \text{ s}$$



Mostly sensitive to the local region

$$\psi_{e^+}(\mathbf{x}, E) = \int_{E_S=E}^{E_S=+\infty} dE_S \int_{\text{DH}} d^3\mathbf{x}_S G_{e^+}(\mathbf{x}, E \leftarrow \mathbf{x}_S, E_S) q_{e^+}(\mathbf{x}_S, E_S)$$

IC on stellar light and CMB – synchrotron

Energy losses dominate

$$E_{\text{obs}} \leq E_S$$

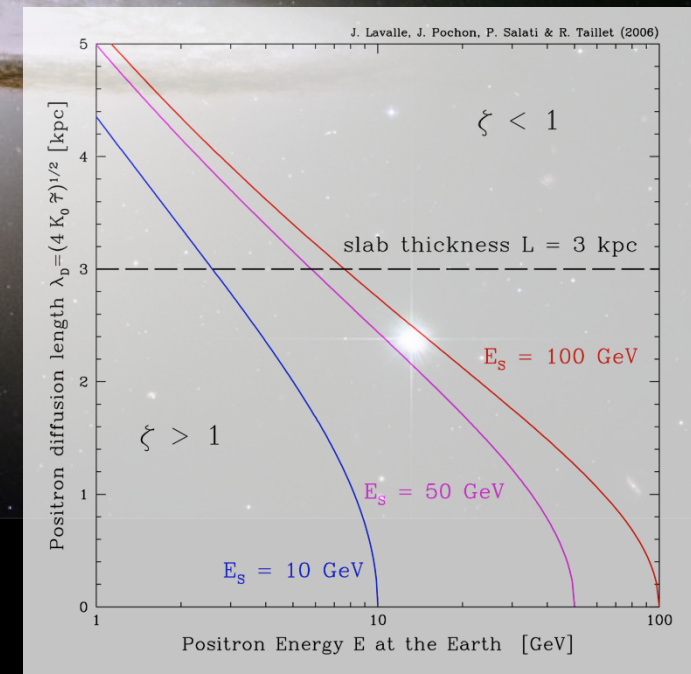


$$\tilde{t}(E) = \tau_E \left\{ v(E) = \frac{\epsilon^{\delta-1}}{1-\delta} \right\}$$

$$G_{e^+}(\vec{x}_\odot, E \leftarrow \vec{x}, E_S) = \frac{\tau_E}{E_0 \epsilon^2} \tilde{G}(\vec{x}_\odot, \tilde{t} \leftarrow \vec{x}, \tilde{t}_S)$$

$$\tilde{G}(\vec{x}_\odot, \tilde{t} \leftarrow \vec{x}, \tilde{t}_S) = \frac{\theta(r_S - r)}{V_S}$$

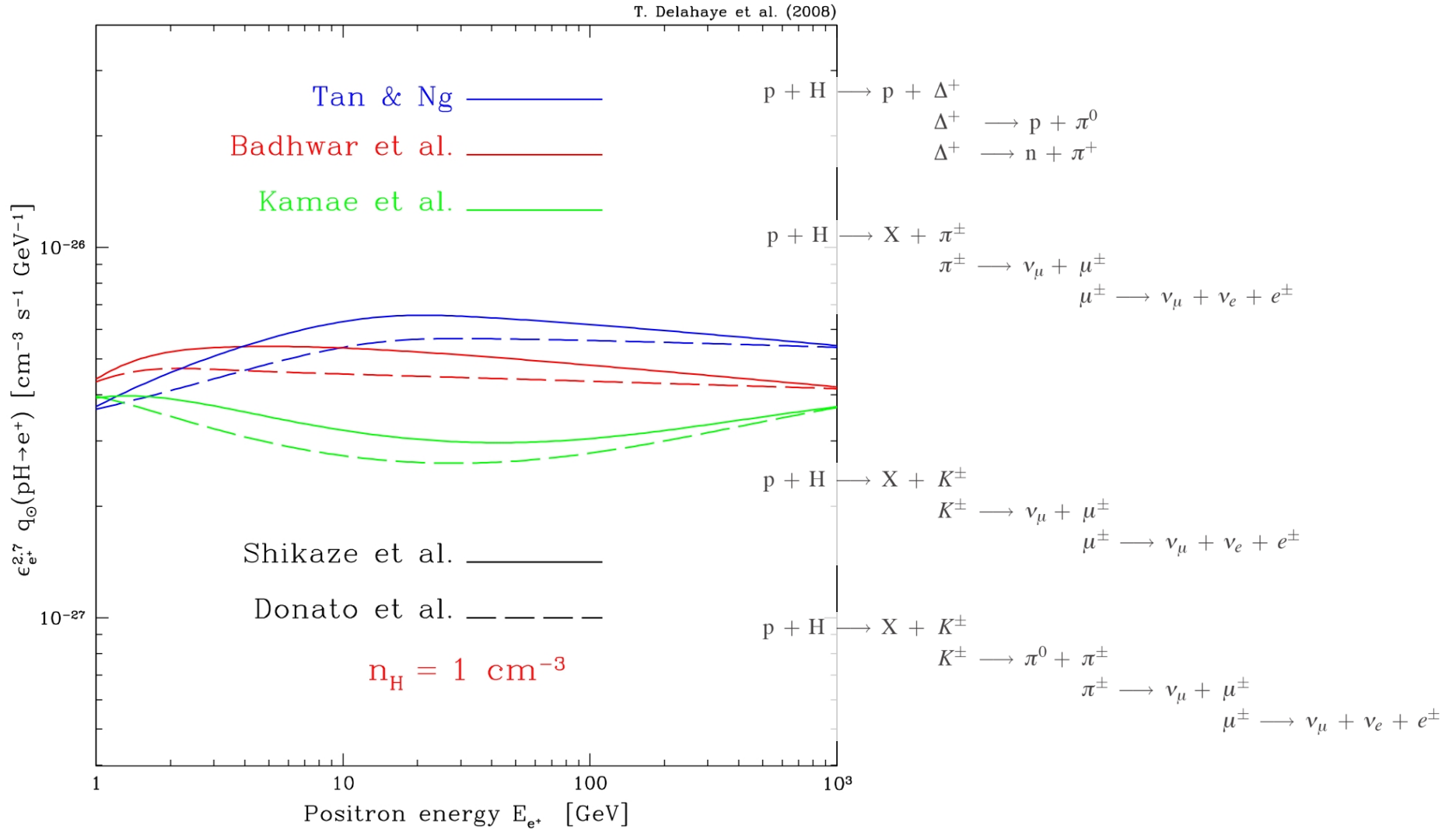
$$V_S = (\sqrt{2\pi} \lambda_D)^3$$





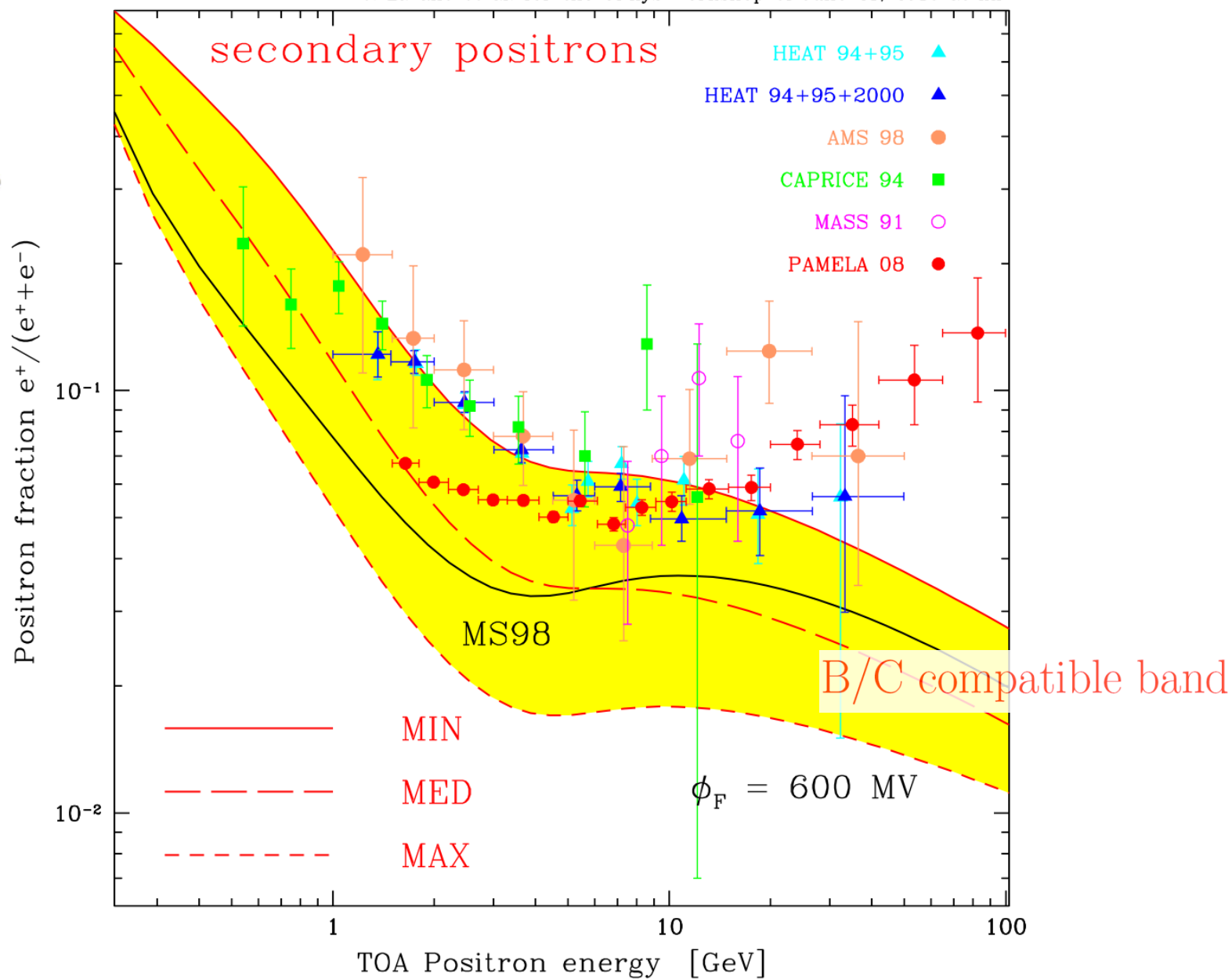
# Secondary positron source term

## Interactions of CR protons and He nuclei on the ISM



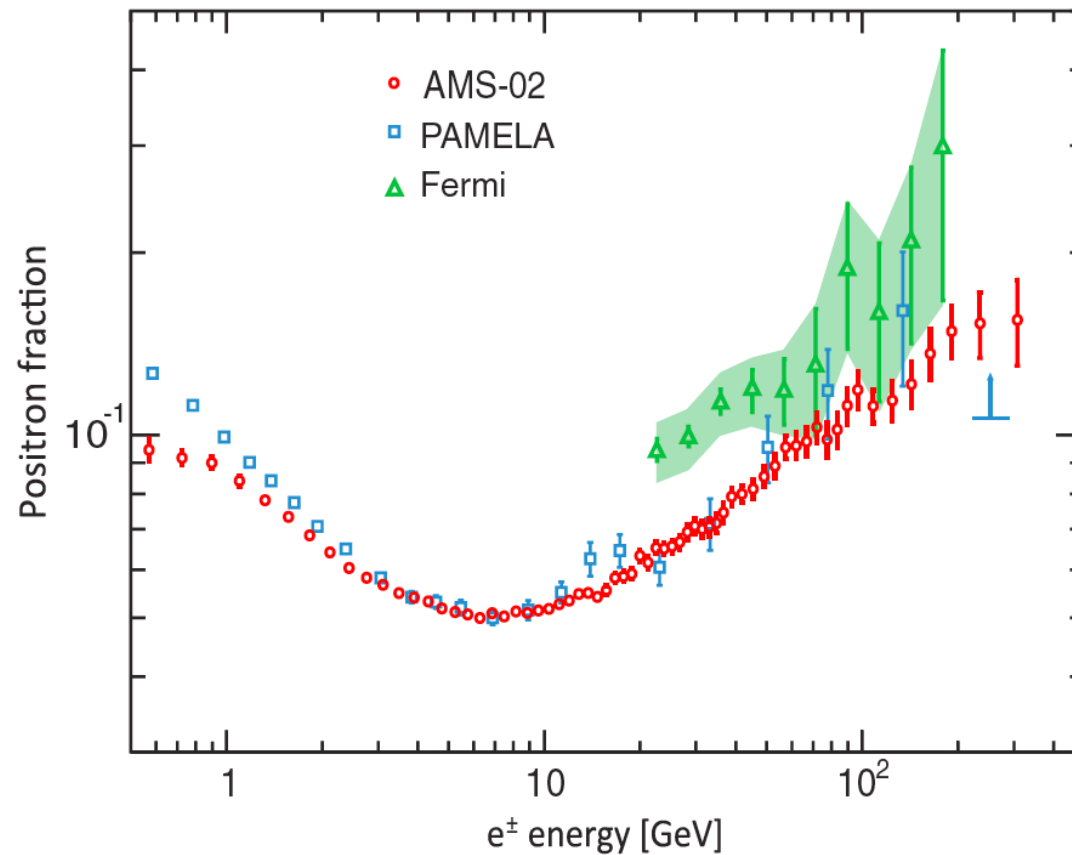


J. Lavalle et al. for the GPhyS workshop of June 21, 2010 at IAP



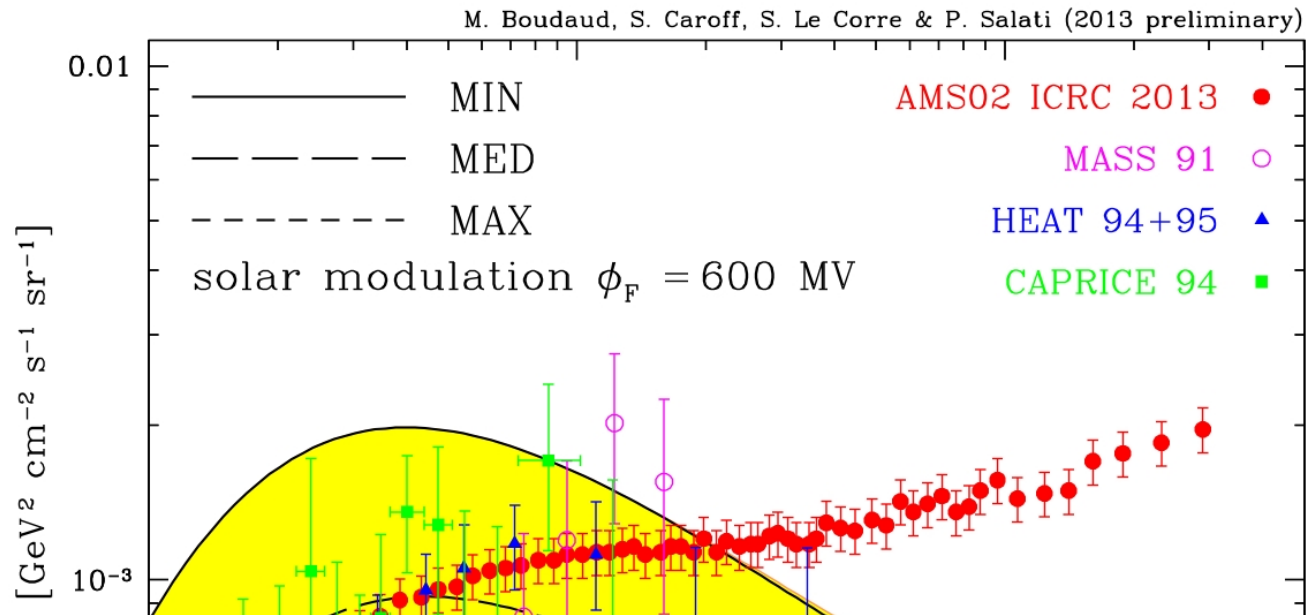
# Confirmation by AMS02 of the positron excess

**First Result from the Alpha Magnetic Spectrometer on the International Space Station:  
Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV**

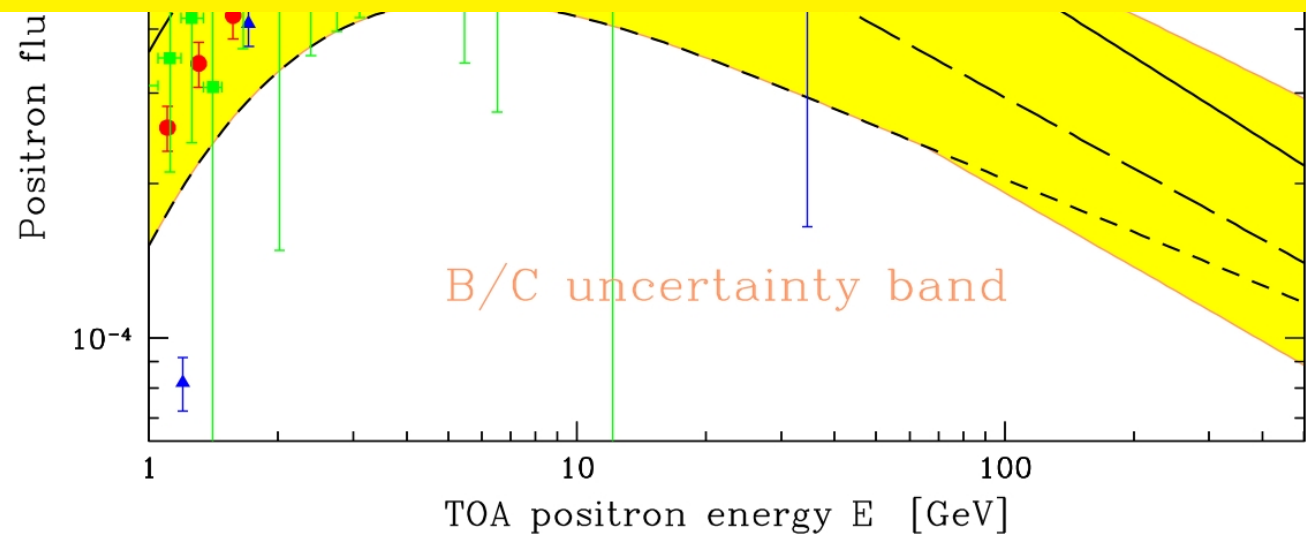


PRL **110**, 141102 (2013)





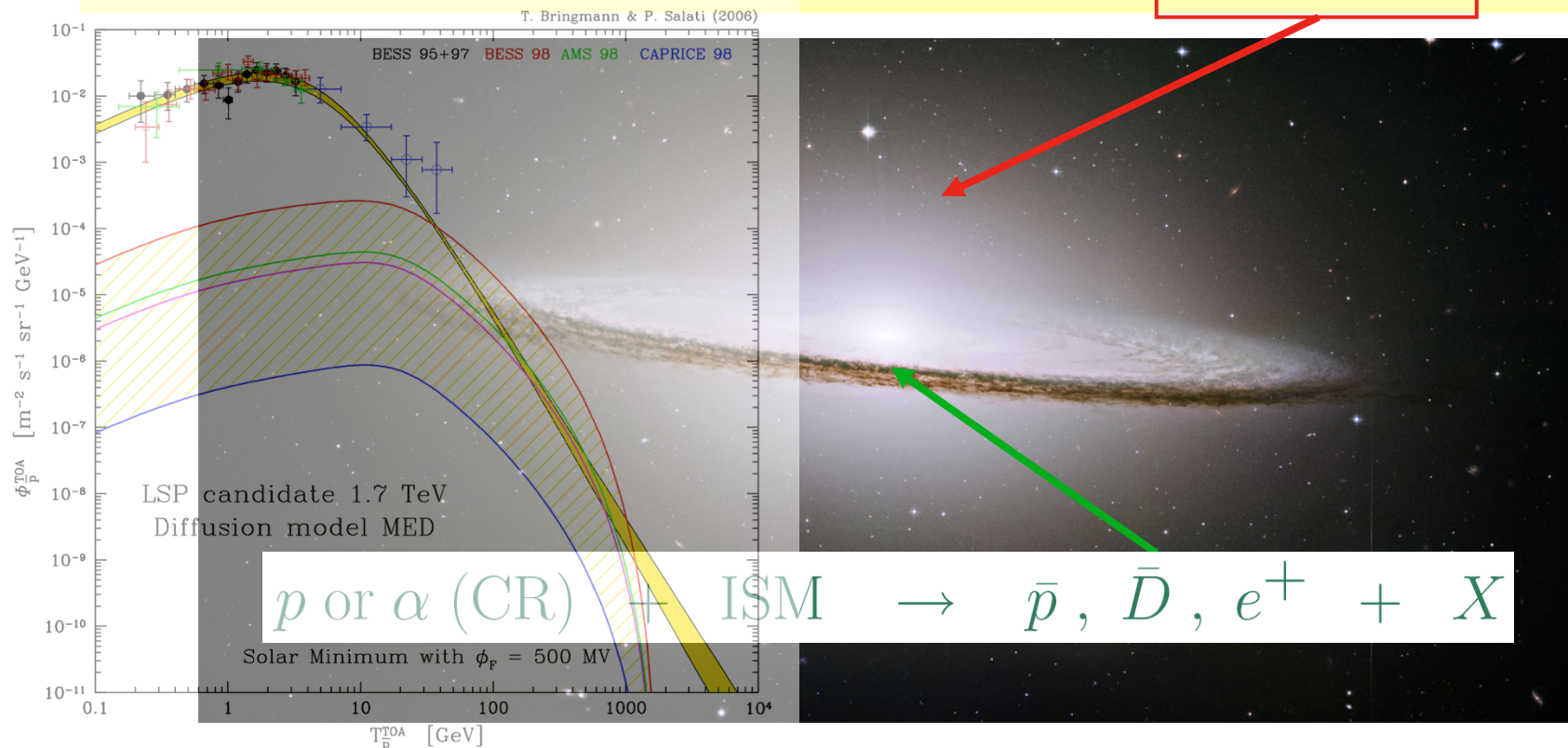
# Evidence for Primary Positrons



## 2) Is it the first hint for DM particles in space ?

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 :

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



Antimatter is already manufactured inside the galactic disk

## Annihilating DM particles and the positron excess

$$q_{e^+} = \frac{1}{2} \langle \sigma v \rangle \times \left\{ n_\chi \equiv \frac{\rho_\chi}{m_\chi} \right\}^2 \times \frac{dN_e}{dE_e}$$

A few remarks are in order

- (i) The WIMP mass  $m_\chi$  is expected to be of order 1 TeV – hence the excitement.
- (ii) But the annihilation rate needs to be considerably enhanced.
  - Thermal freeze-out cross section  $\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$
  - Local  $e^+$  production means DM density given by  $\rho_\odot = 0.3 \text{ GeV cm}^{-3}$

$$m_\chi = 1 \text{ TeV needs } \Gamma_{\text{ann}} \equiv \frac{1}{2} \langle \sigma v \rangle \times \frac{\rho_\chi^2}{m_\chi^2} \text{ boosted by } B = 10^3$$

- (iii) DM species are **leptophilic** and  $q$  channels are suppressed.

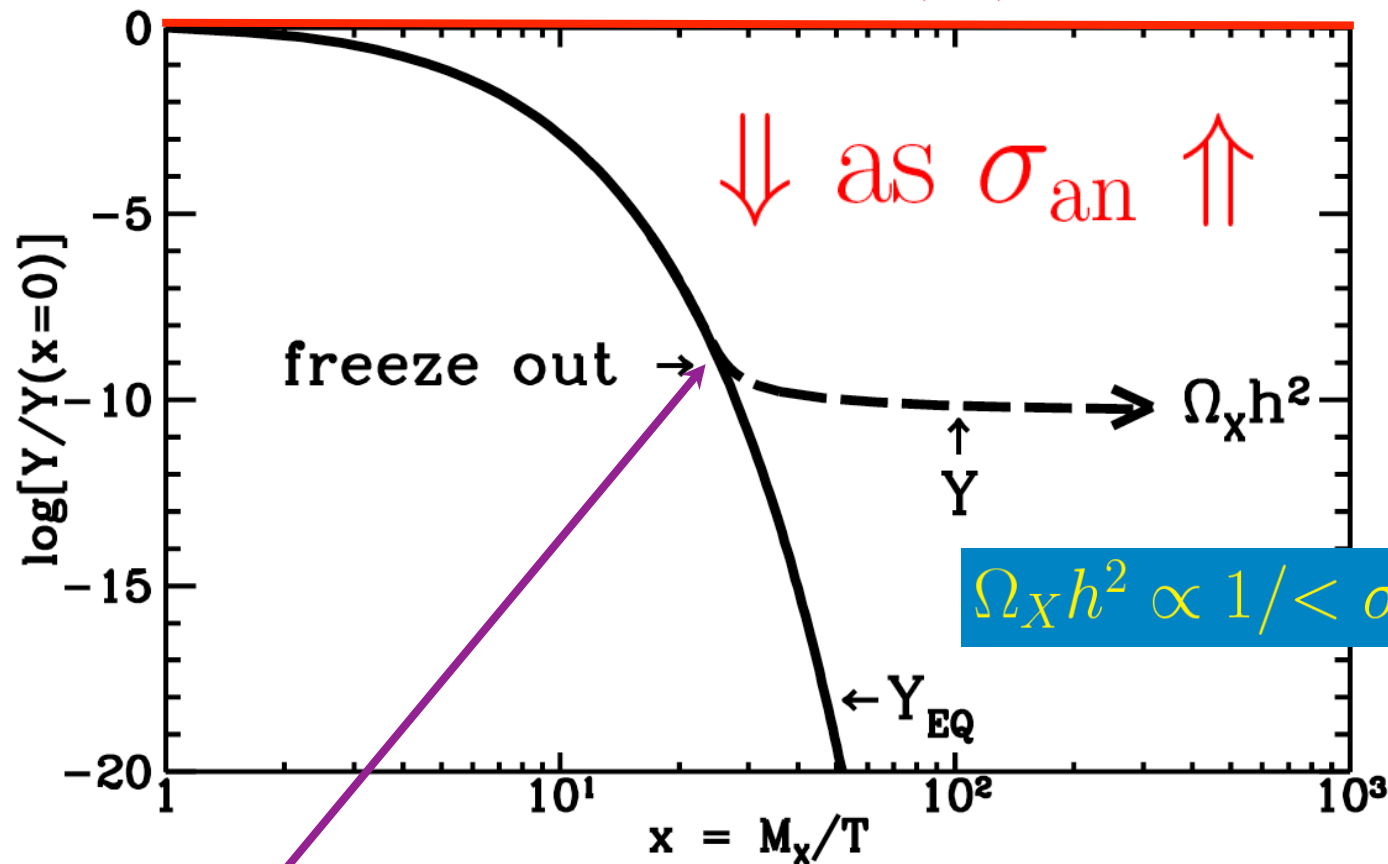


# Thermodynamical equilibrium production

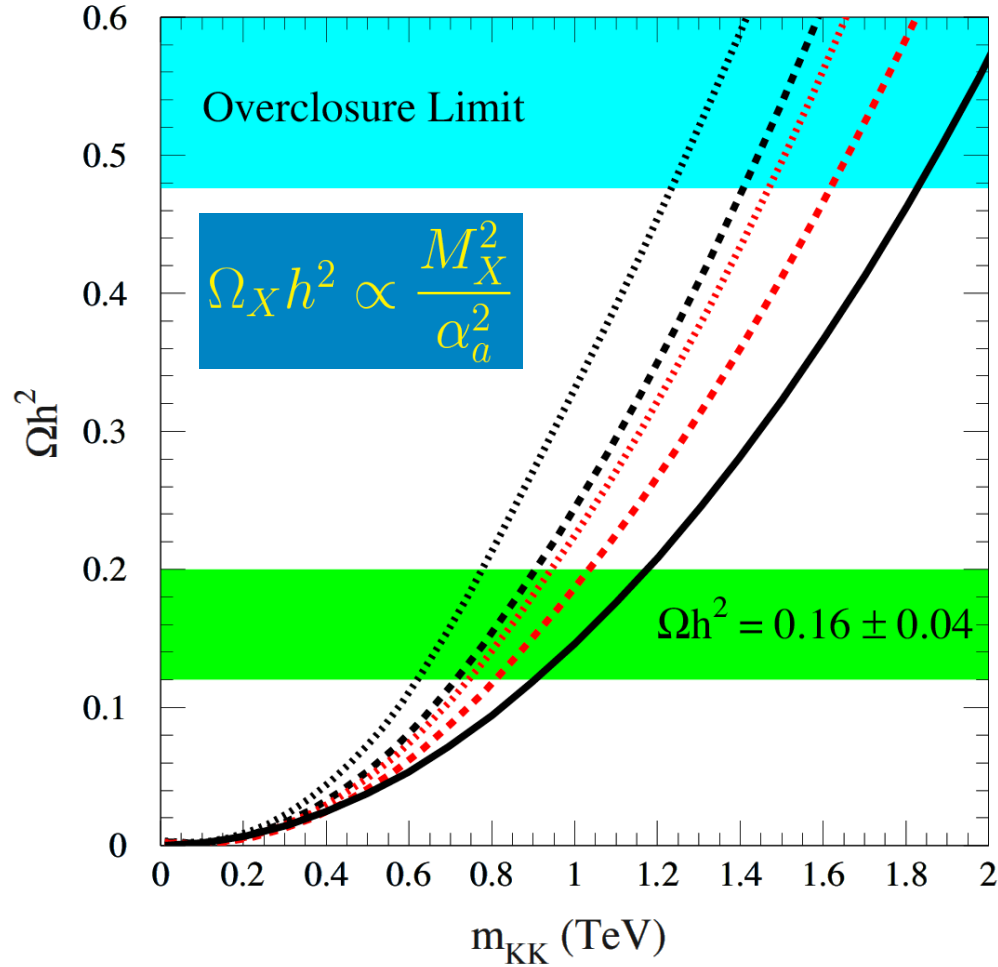


$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma_{\text{an}} v \rangle n_X^2 + \langle \sigma_{\text{an}} v \rangle n_X^0{}^2$$

thermal decoupling when  $\Gamma_{\text{coll}} \sim H_F$  (UR)



chemical decoupling when  $\langle \sigma_{\text{an}} v \rangle n_X \sim H_F$  (NR)



G  r  ldine Servant <sup>a,b</sup> and Tim M.P. Tait <sup>a</sup>

Figure 3: Prediction for  $\Omega_{B^{(1)}} h^2$  as in Figure 1. The solid line is the case for  $B^{(1)}$  alone, and the dashed and dotted lines correspond to the case in which there are one (three) flavors of nearly degenerate  $e_R^{(1)}$ . For each case, the black curves (upper of each pair) denote the case  $\Delta = 0.01$  and the red curves (lower of each pair)  $\Delta = 0.05$ .

## Annihilating DM particles and the positron excess

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M. Cirelli et al., Nucl. Phys. **B 813** (2009) 1

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

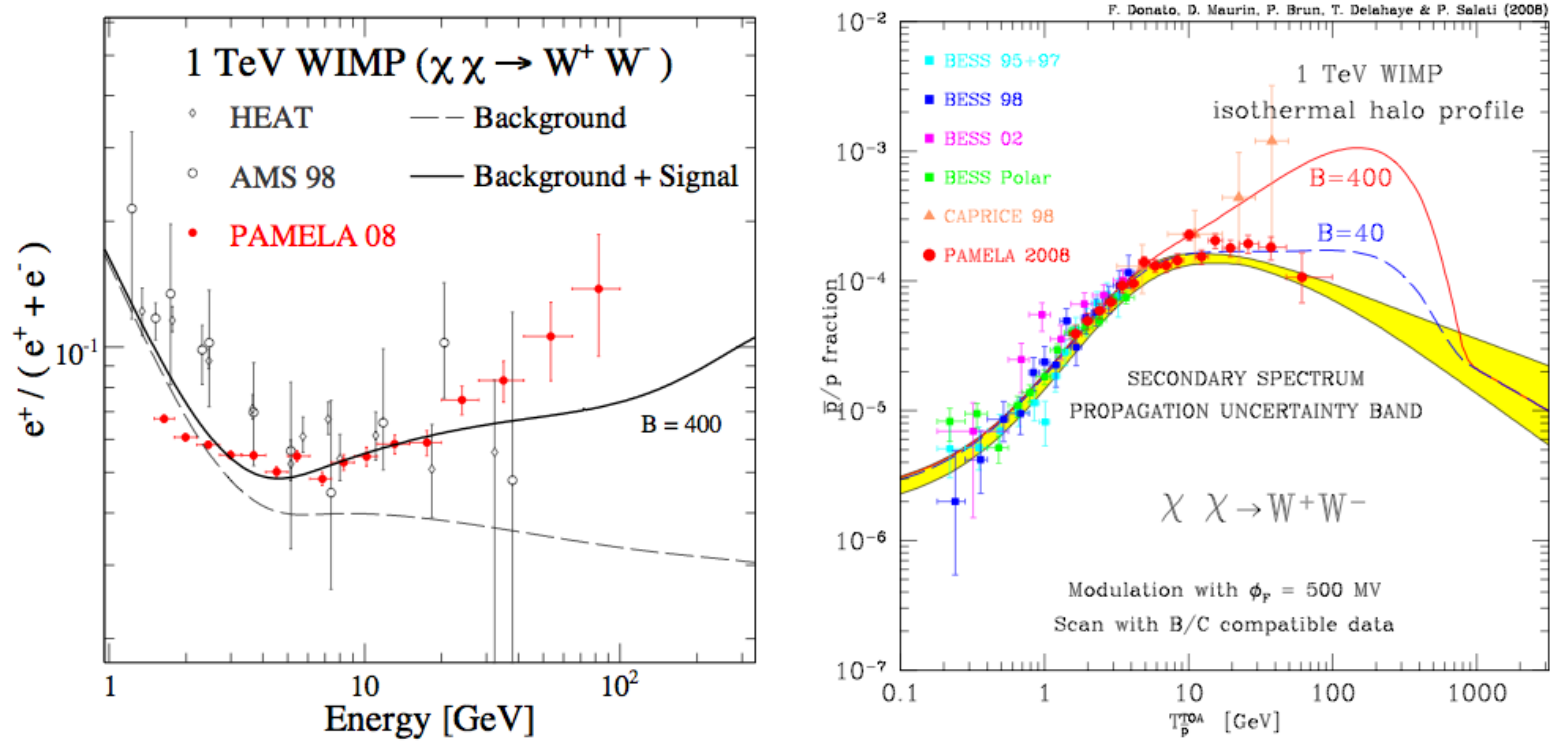


FIG. 3: The fiducial case of a 1 TeV LSP annihilating into a  $W^+W^-$  pair is featured. In the left panel, the positron signal which this DM species yields has been increased by a factor of 400, hence the solid curve and a marginal agreement with the PAMELA data. Positron fraction data are from HEAT [18], AMS-01 [5, 22] and PAMELA [2]. If the so-called Sommerfeld effect [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.

F. Donato et al. – PRL **102** (2009) 071301

- Peculiar and ad'hoc WIMP models

Leptophilic DM particles



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

or

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

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⇒ Abnormally large annihilation cross sections

- 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

⇒ A consequence of a clumpy DM distribution

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

- A statistical analysis is necessary to compute the signal enhancement

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

- How probable is a single nearby clump ?

⇒ May be a combination of both effects

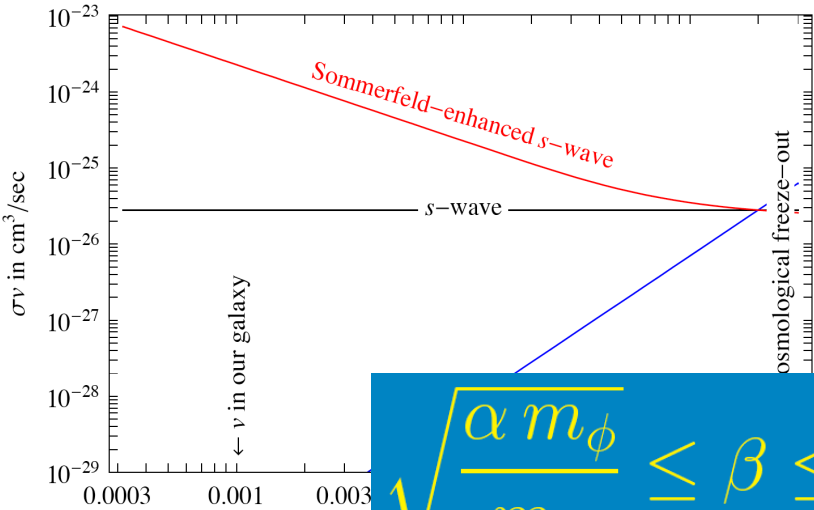
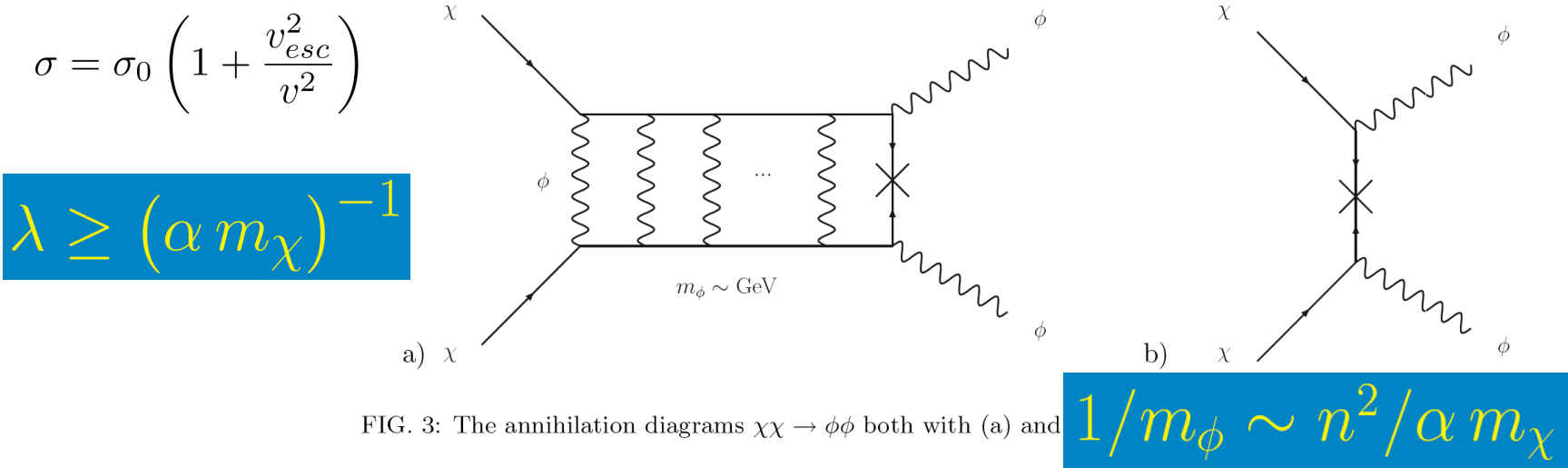


# Sommerfeld effect – a non-perturbative enhancement of $\sigma_{\text{ann}}$ at low velocity

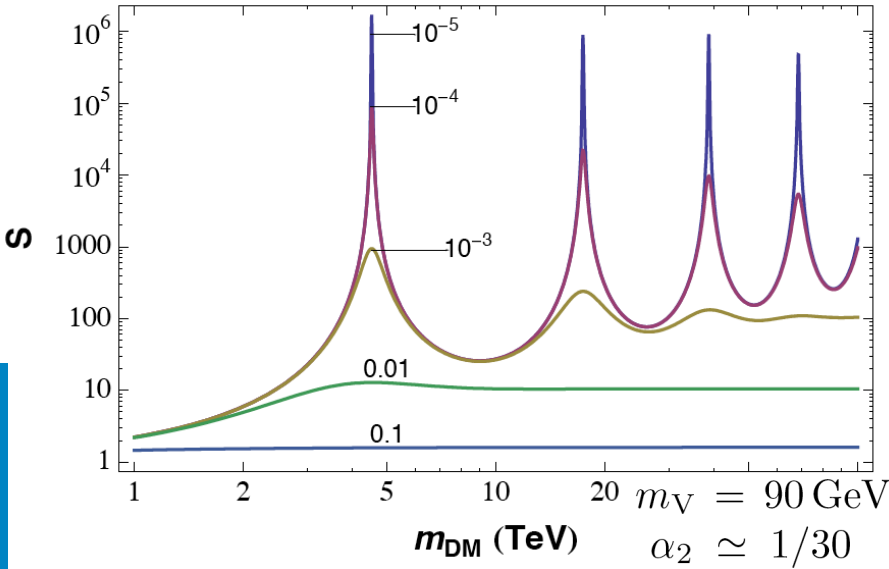
J. Hisano, S. Matsumoto and M. M. Nojiri

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



$$\sqrt{\frac{\alpha m_\phi}{m_\chi}} \leq \beta \leq \alpha$$



- Peculiar and ad'hoc WIMP models

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

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- But, strong constraints from the other **messengers** :

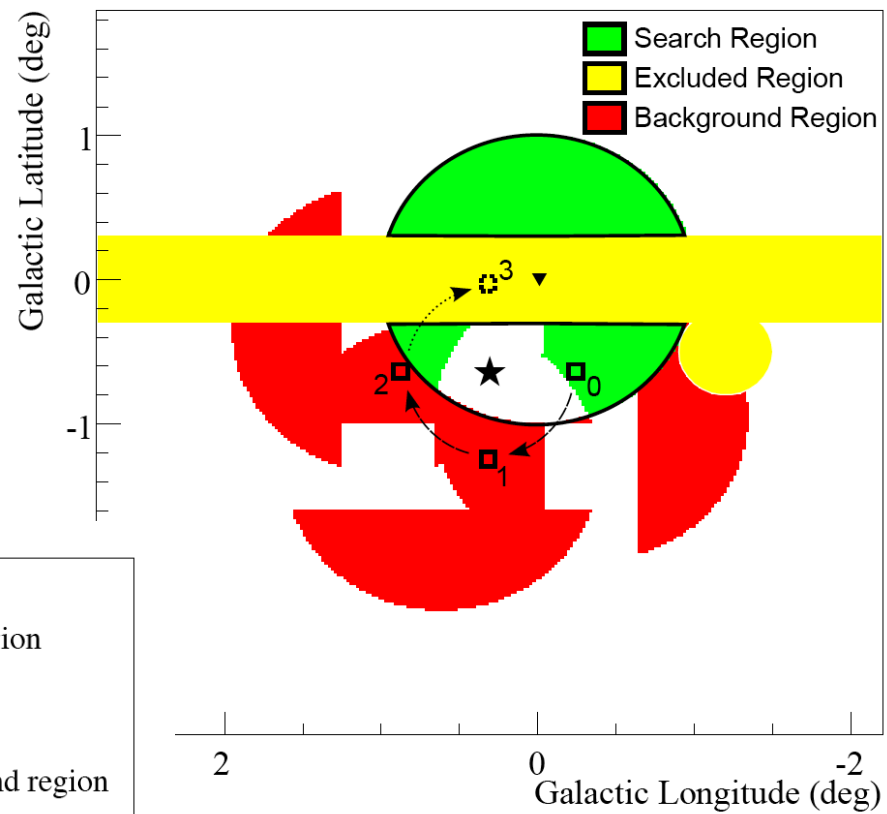
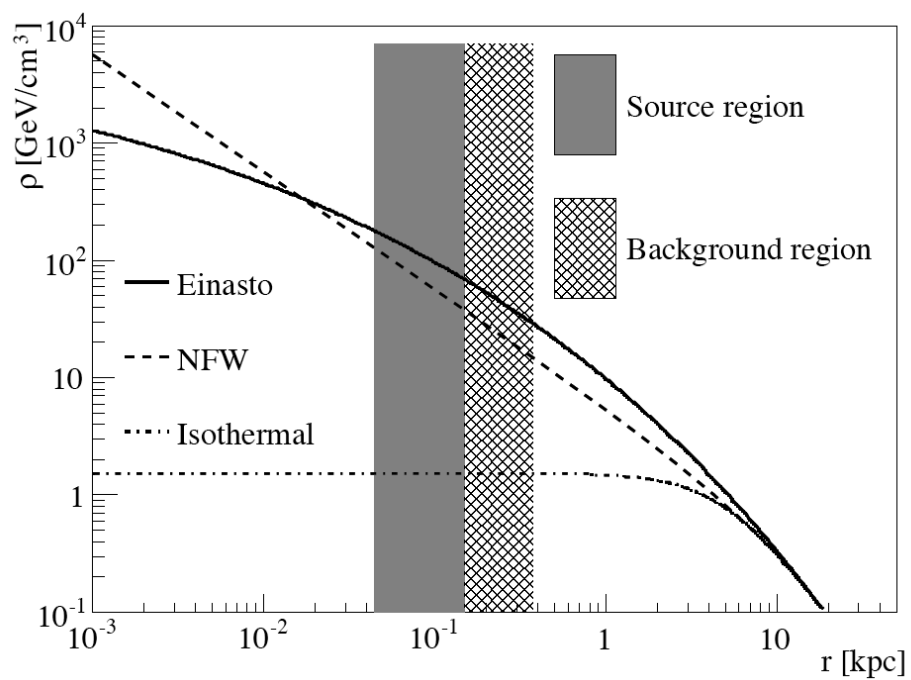
✓ Final State Radiation  $\gamma$ -rays in the absence of quarks.

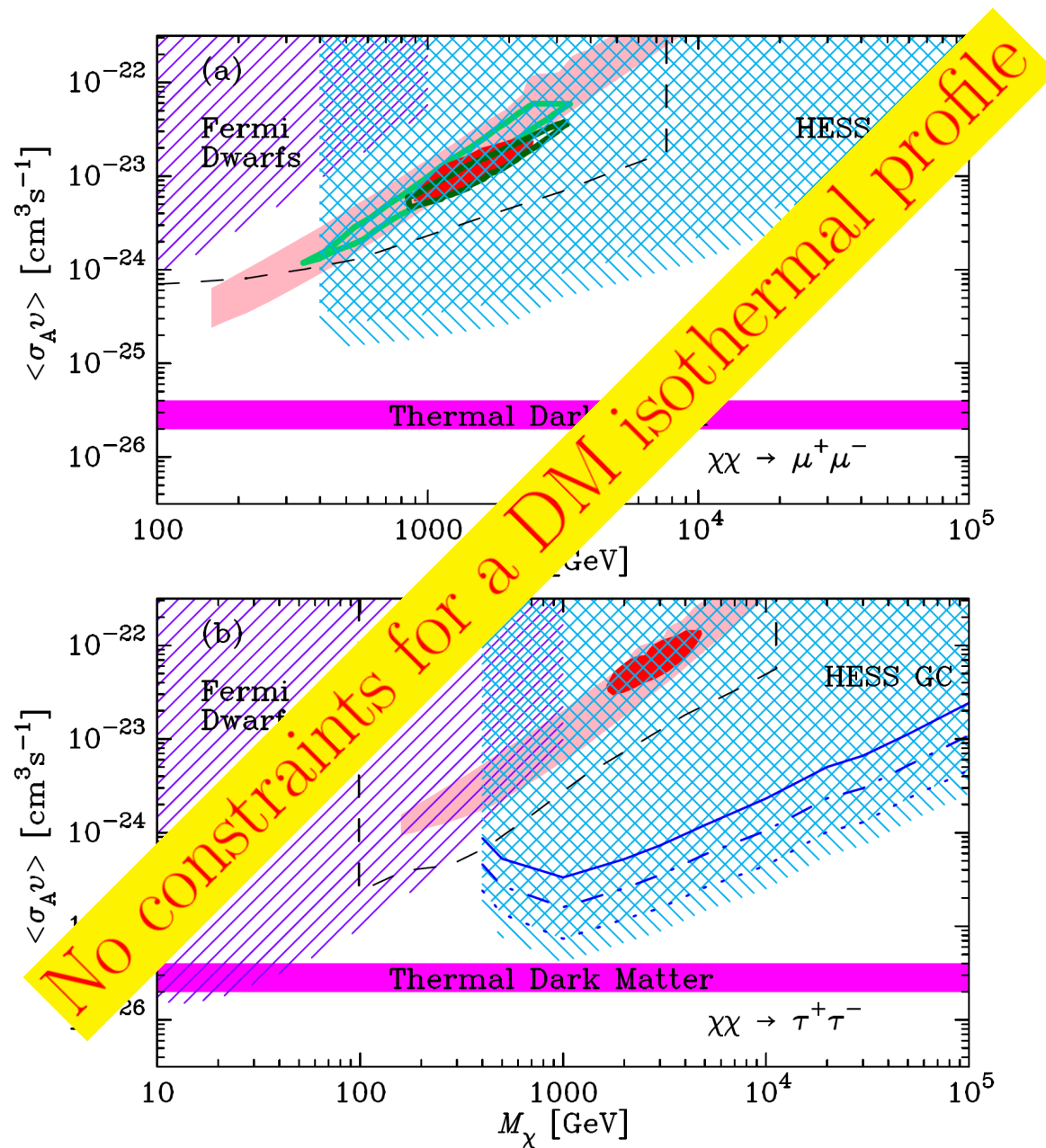
$$\chi \chi \rightarrow l^+ l^- \gamma \quad \text{or} \quad \phi \rightarrow l^+ l^- \gamma$$

✓ Inverse Compton Scattering of  $e^\pm$  on CMB and stellar light.

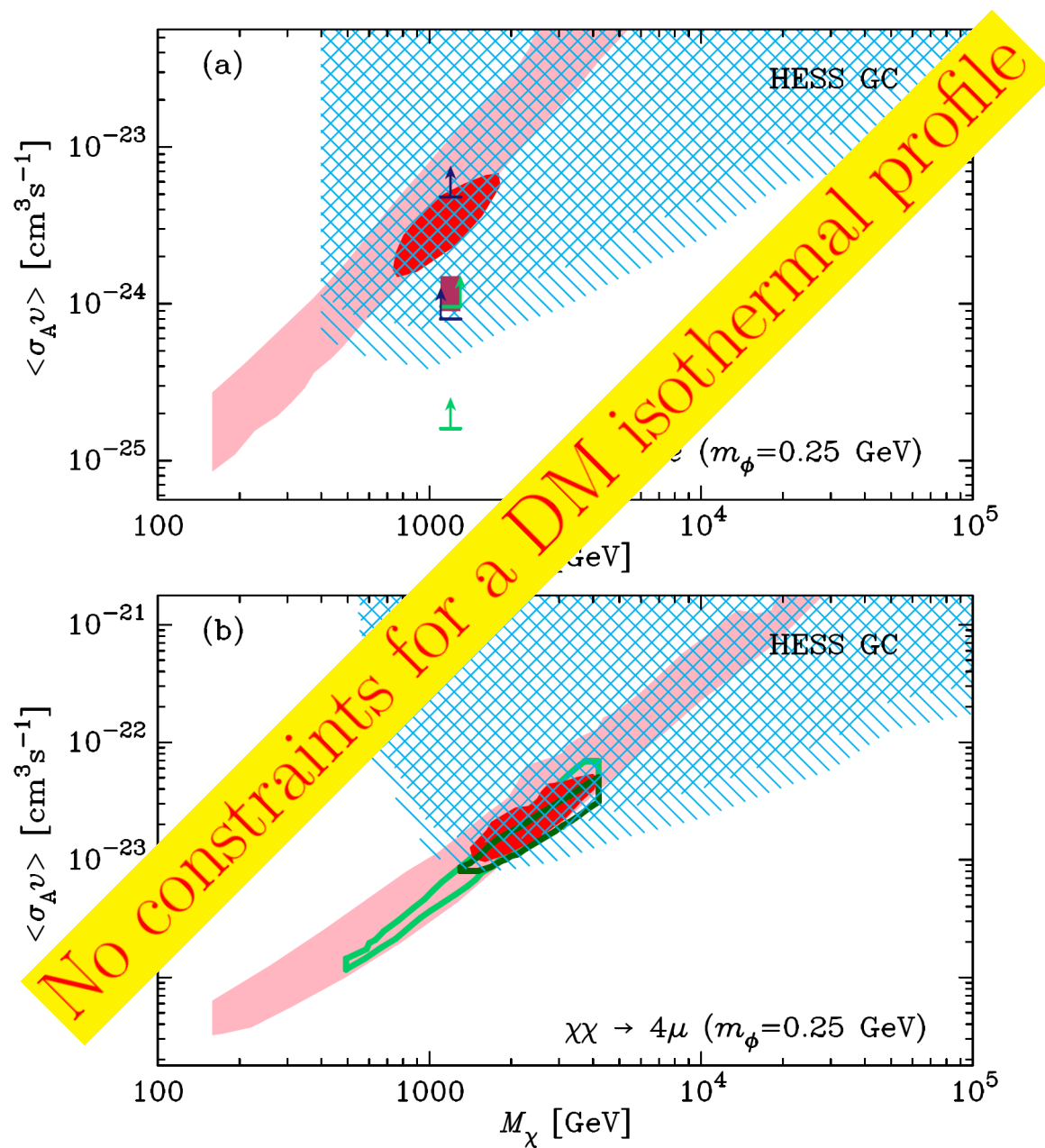
✓ Synchrotron radio emission from  $e^\pm$  spiraling in **B**.

✓ Energy release in the primordial plasma – constraints from CMB.

Kevork N. Abazajian<sup>a</sup> J. Patrick Harding<sup>a,b</sup>

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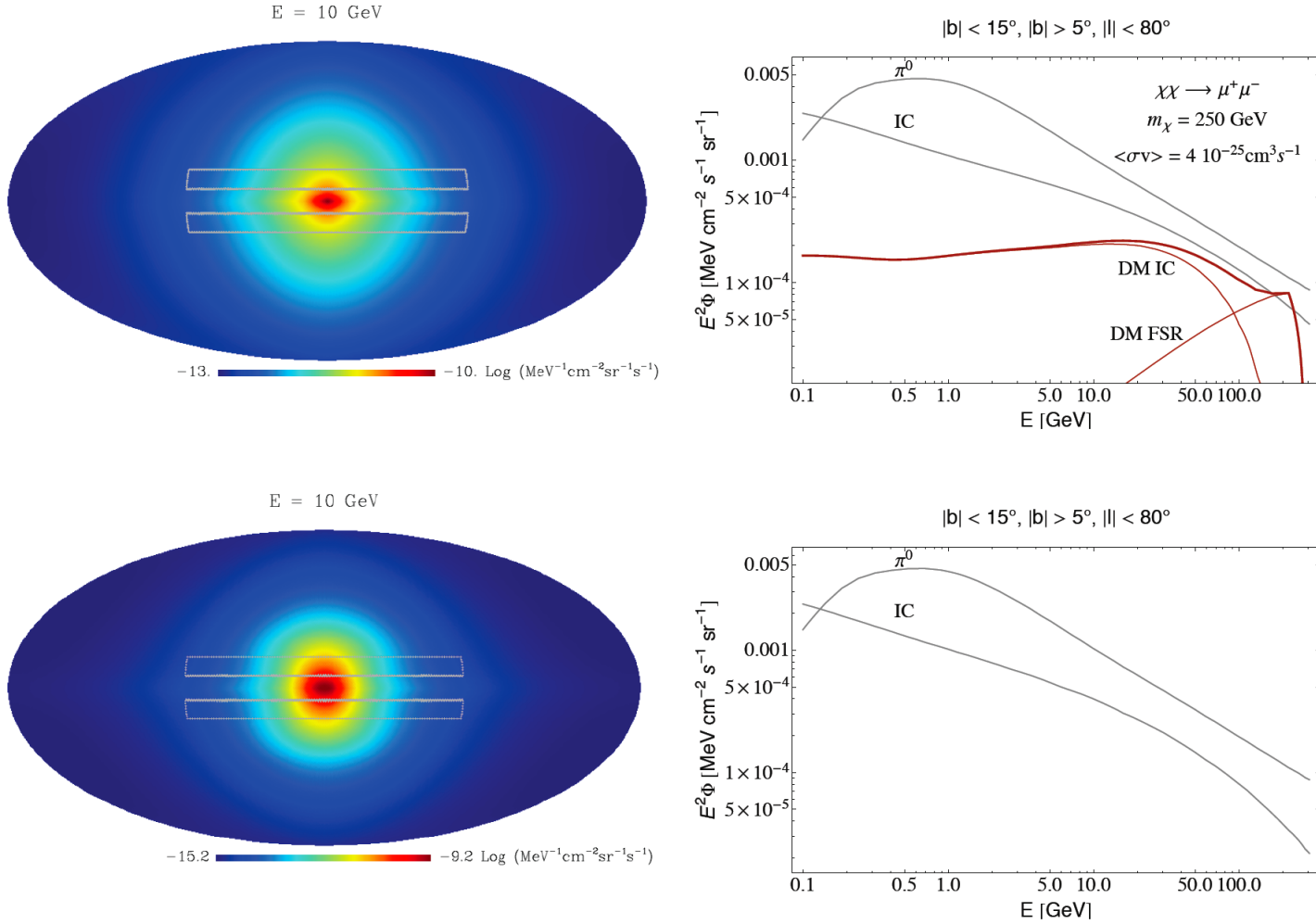
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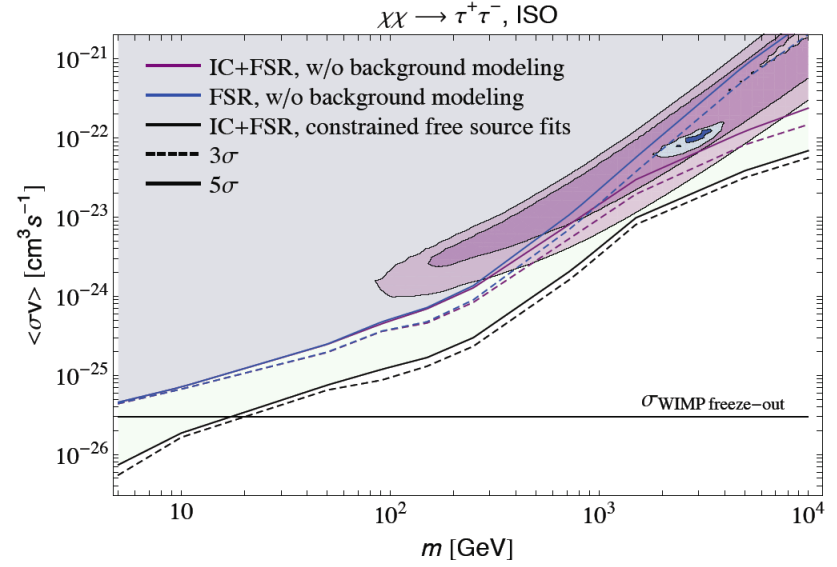
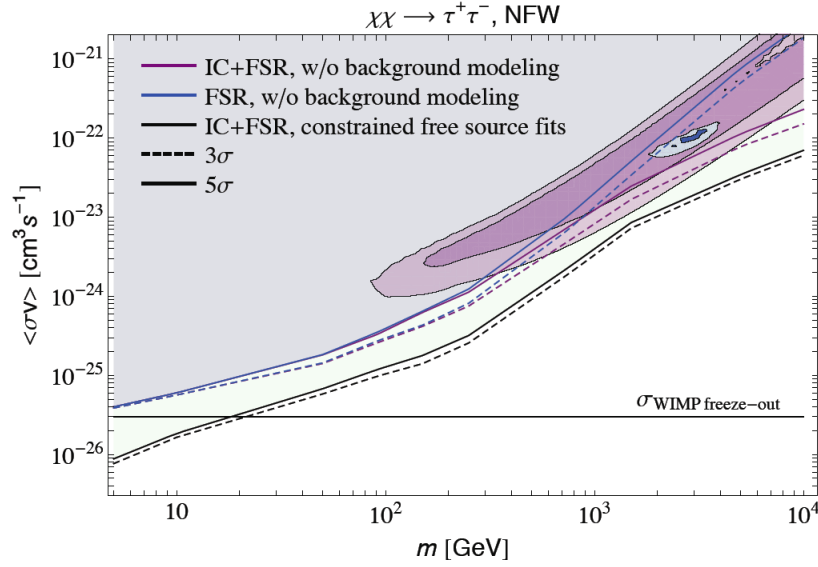
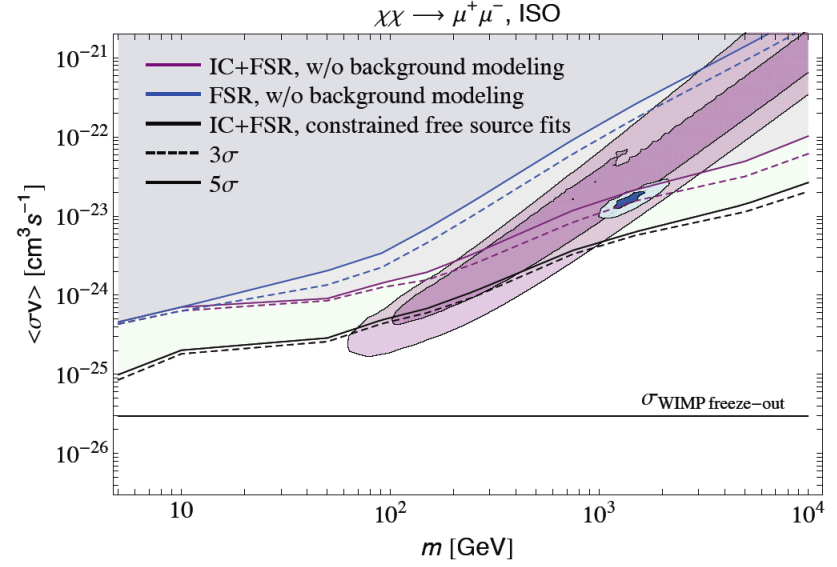
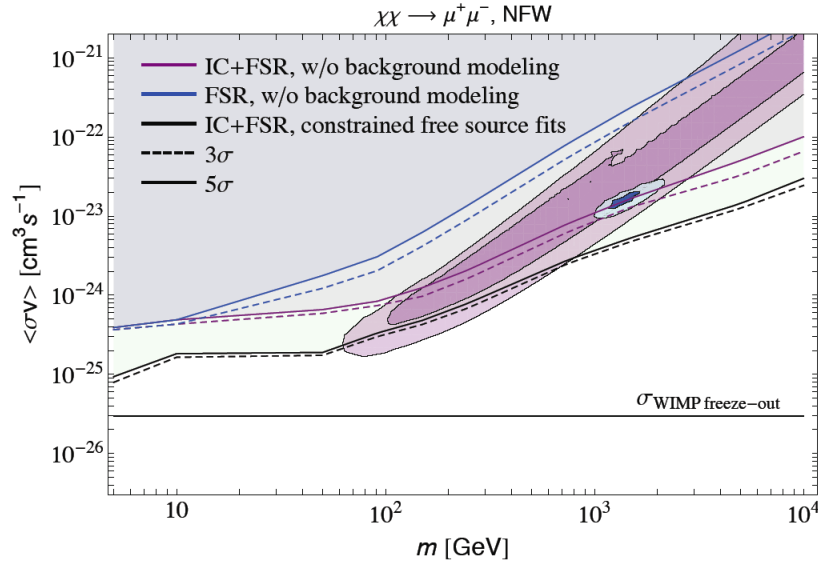
# CONSTRAINTS ON THE GALACTIC HALO DARK MATTER FROM FERMI-LAT DIFFUSE MEASUREMENTS

## 250 GeV WIMP annihilating into $\mu^+\mu^-$



astrophysical CR source population

# CONSTRAINTS ON THE GALACTIC HALO DARK MATTER FROM FERMI-LAT DIFFUSE MEASUREMENTS



S. Gallia, F. Iocco, G. Bertone & A. Melchiorri, arXiv:0905.0003  
T. Slatyer, N. Padmanabhan & D. Finkbeiner, arXiv:0906.1197

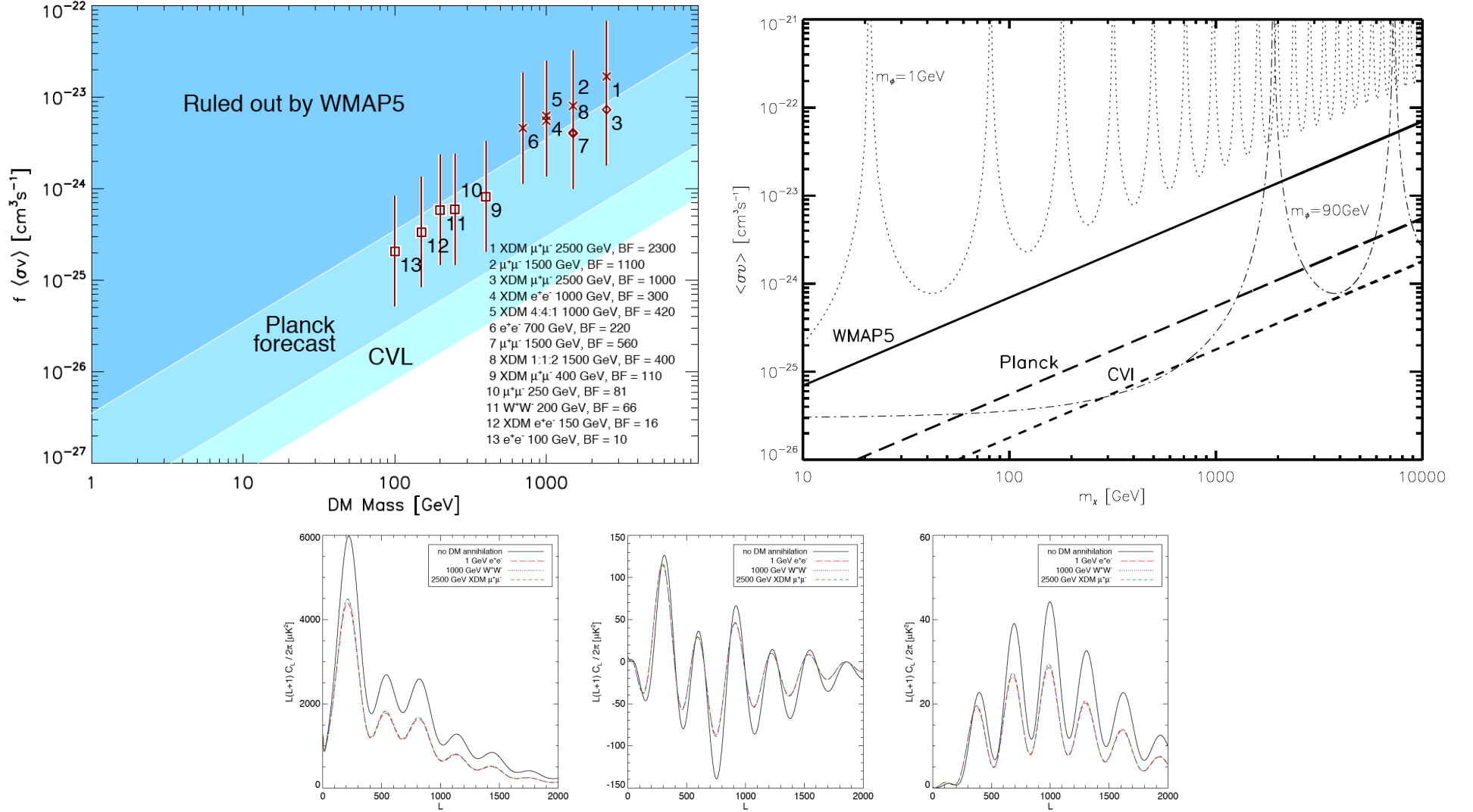


FIG. 5: CMB power spectra for three different DM annihilation models, with power injection normalized to that of a 1 GeV WIMP with thermal relic cross section and  $f = 1$ , compared to a baseline model with no DM annihilation. The models give similar results for the TT (left), TE (middle), and EE (right) 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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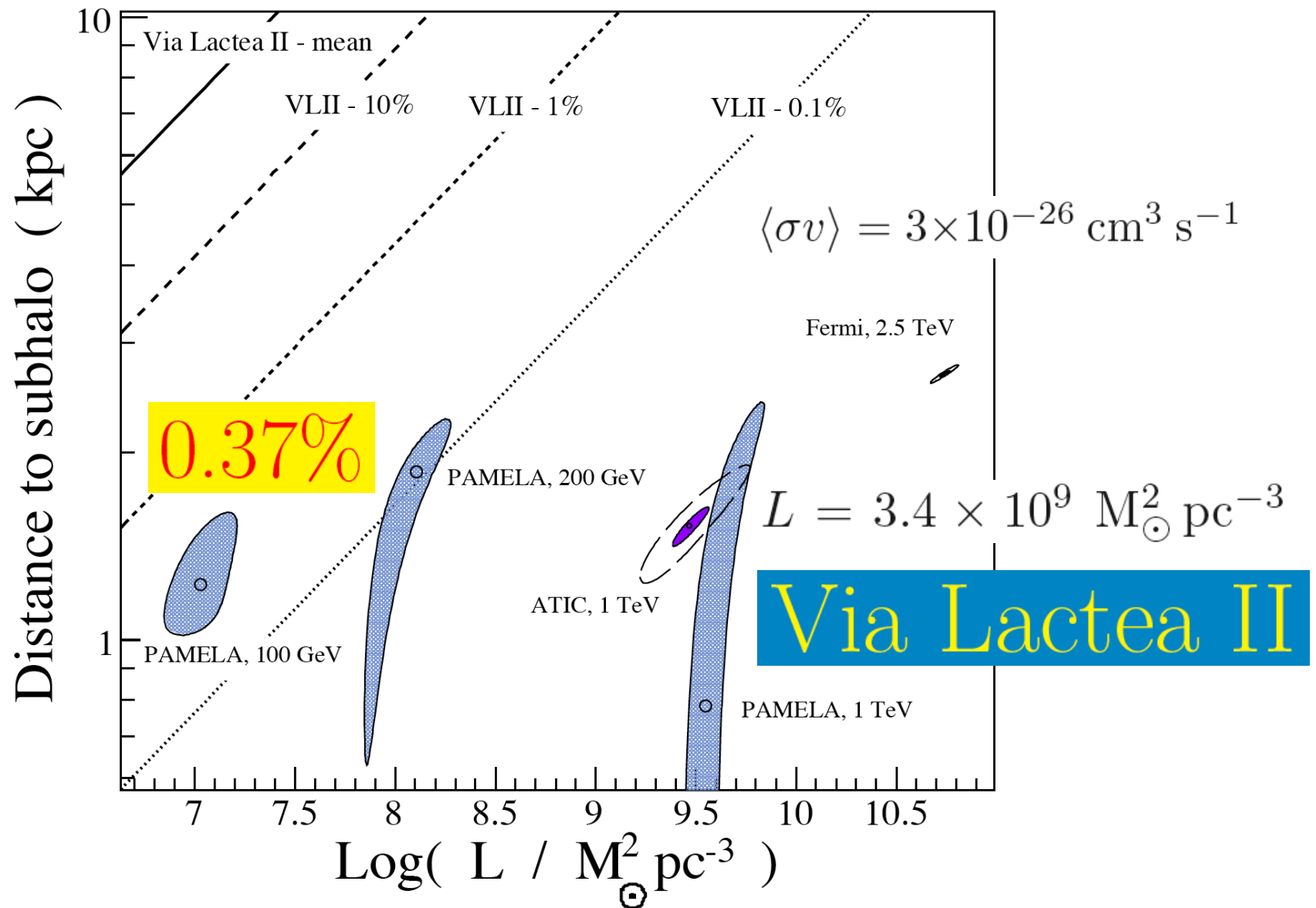
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# The cosmic ray lepton puzzle in the light of cosmological N-body simulations

P. Brun, T. Delahaye, J. Diemand, S. Profumo & P. Salati, [arXiv:0904.0812](#)



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- But, strong constraints from the other **messengers** :

✓ Final State Radiation  $\gamma$ -rays in the absence of quarks.

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

✓ Inverse Compton Scattering of  $e^\pm$  on CMB and stellar light.

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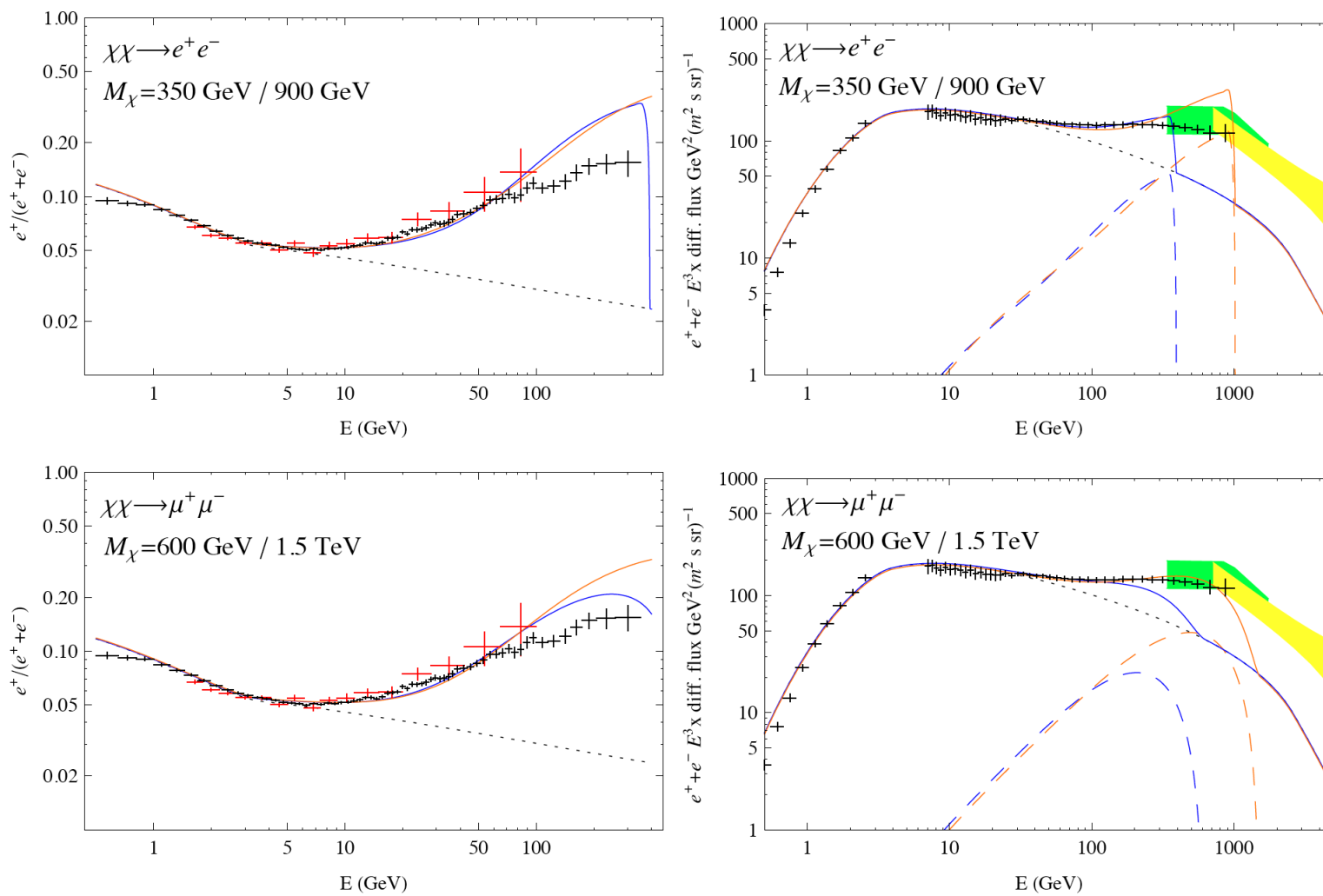
✓ Energy release in the primordial plasma – constraints from CMB.

- Precise measurements from AMS02.

$$\chi \chi \rightarrow l^+ l^- \text{ excluded}$$

# Dark matter and pulsar origins of the rising cosmic ray positron fraction in light of new data from AMS

Ilias Cholis<sup>1,\*</sup> and Dan Hooper<sup>1,2,†</sup>





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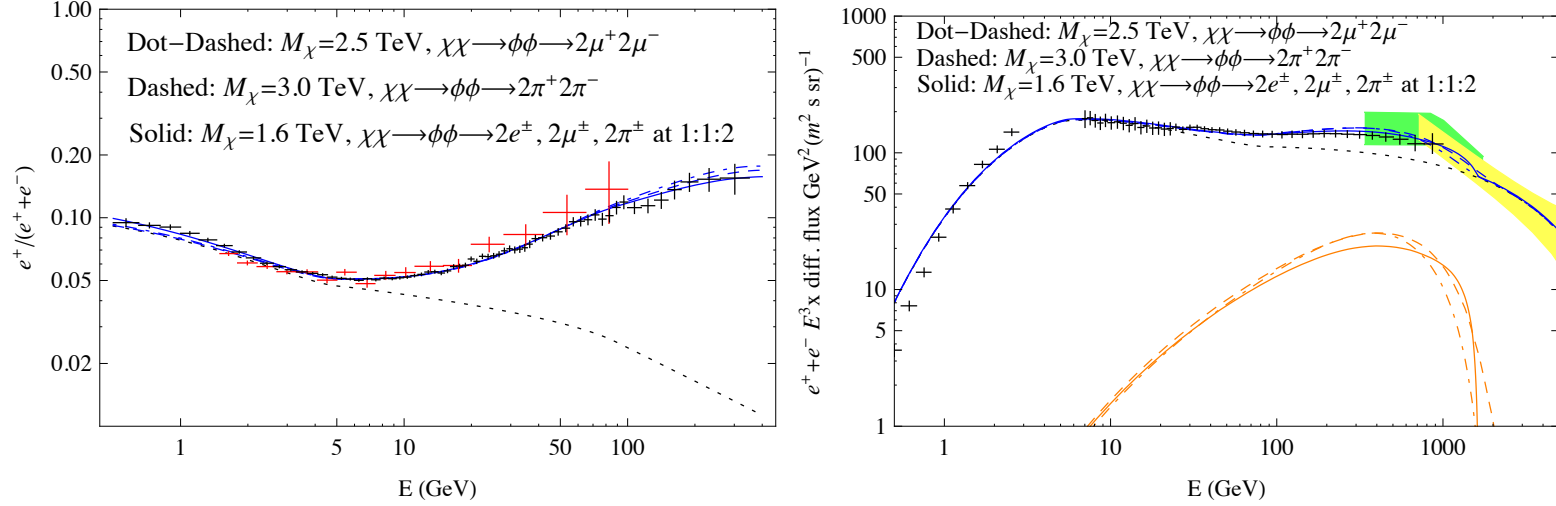


FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of  $L = 8$  kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ( $dN_{e^-}/dE_{e^-} \propto E_{e^-}^{-2.65}$  below 85 GeV and  $dN_{e^-}/dE_{e^-} \propto E_{e^-}^{-2.3}$  above 85 GeV). The cross sections are the same as given in the caption of Fig. 5. With this cosmic ray background, we show the dark matter models compared to the measurements of the cosmic ray positron fraction and the overall leptonic spectrum. Even with the presence of a break, there is a preference towards models with softer injection  $e^\pm$  spectra; with the 1.6 TeV to  $e^\pm, \mu^\pm, \pi^\pm$  case providing the best  $\chi^2/d.o.f.$  fit to the *AMS (Fermi)* lepton data of 0.82(0.51). The 2.5 TeV to  $2\mu^+ 2\mu^-$ , gives a  $\chi^2/d.o.f.$  fit of 1.32(1.07) and the 3.0 TeV to  $2\pi^+ 2\pi^-$  a fit of 1.00(1.03). We remind that in the *Fermi* error-bars we do not include an overall shift from the energy resolution uncertainty.

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## Cosmic ray positron excess

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

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

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

$\Downarrow$

$$\Gamma_{\text{dec}} \sim 10^{-26} \text{ s}^{-1}$$

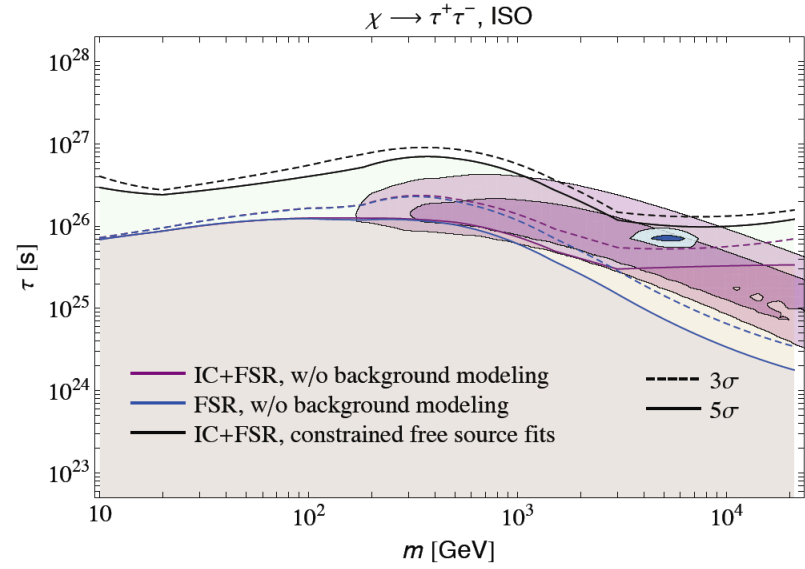
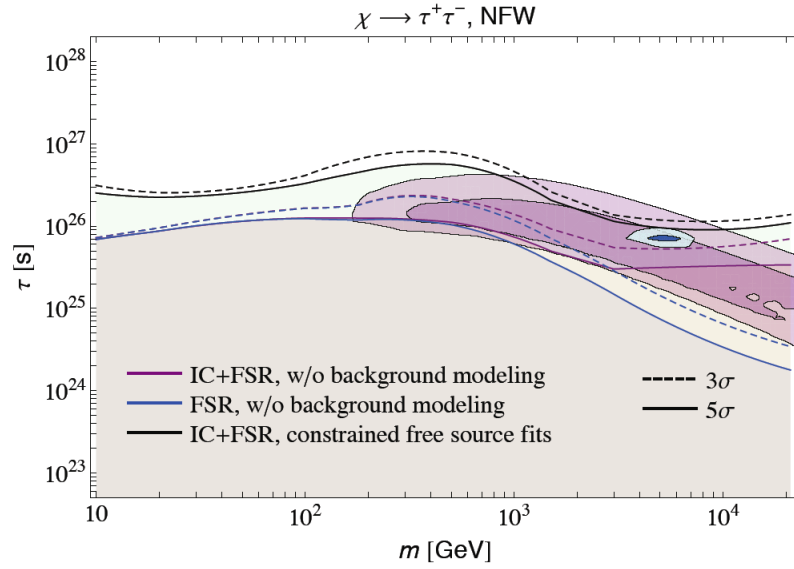
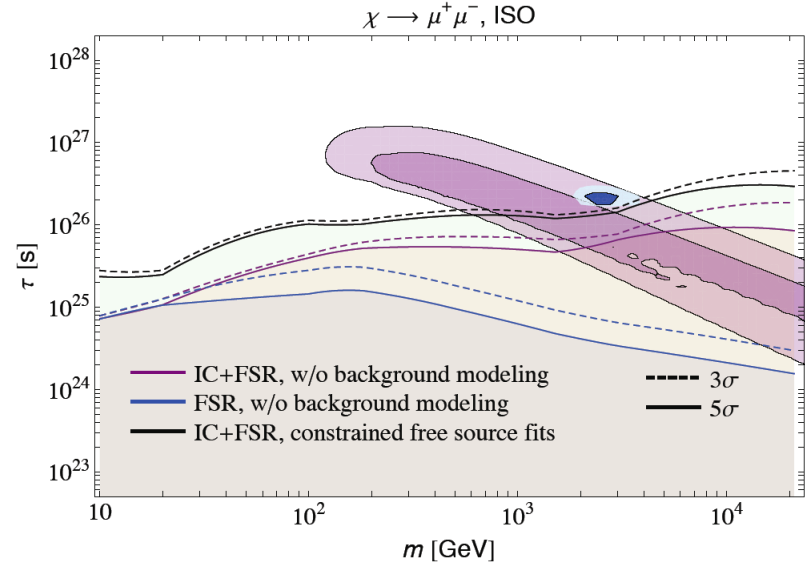
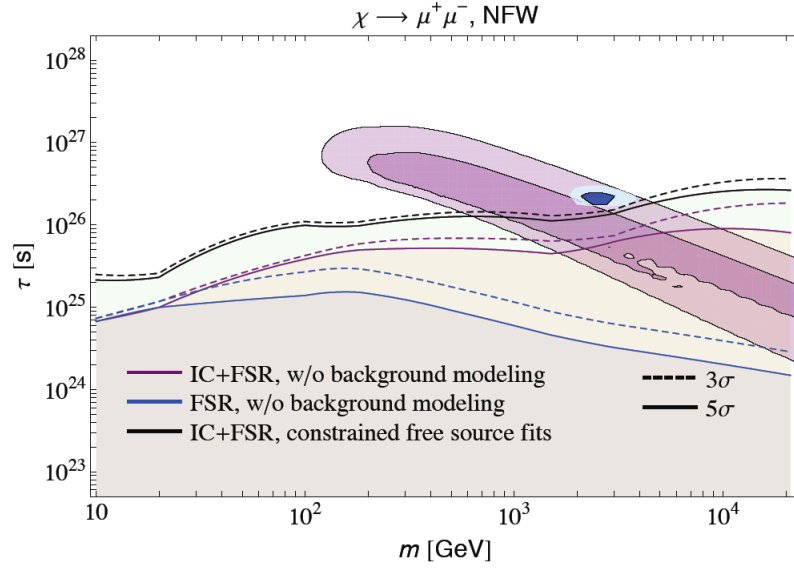
$\Uparrow$

$$\tau_{\text{dec}} \sim 10^{27} \text{ sec} \left\{ \frac{1 \text{ TeV}}{m_\chi} \right\}^5 \left\{ \frac{M_{\text{GUT}}}{10^{16} \text{ GeV}} \right\}^4$$

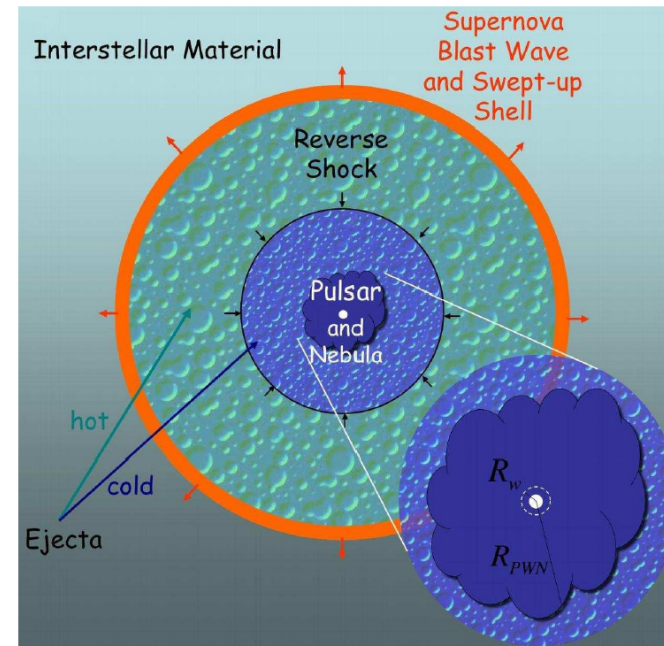
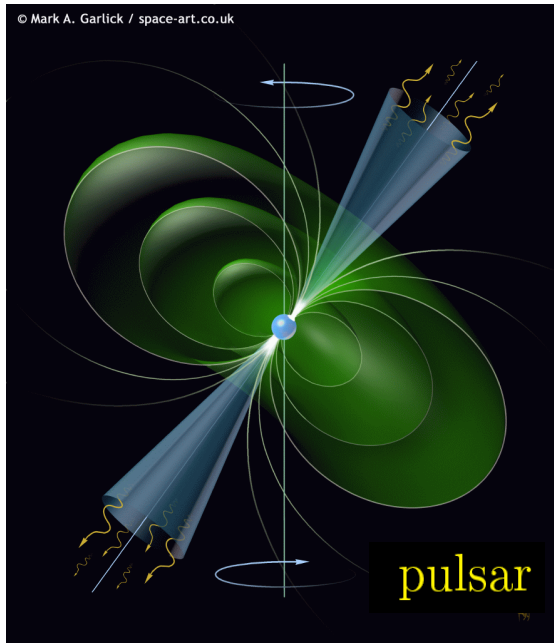
dim 6 operator in GUT theories for instance

- ✓ The lifetime needs to be fine-tuned though – a factor of 2 matters !
- ✓ Leptophilic DM species from antiproton measurements
- ✓ Decaying DM mildly passes the astrophysical tests as  $\Gamma_{\text{ann}} \propto \rho_\chi$

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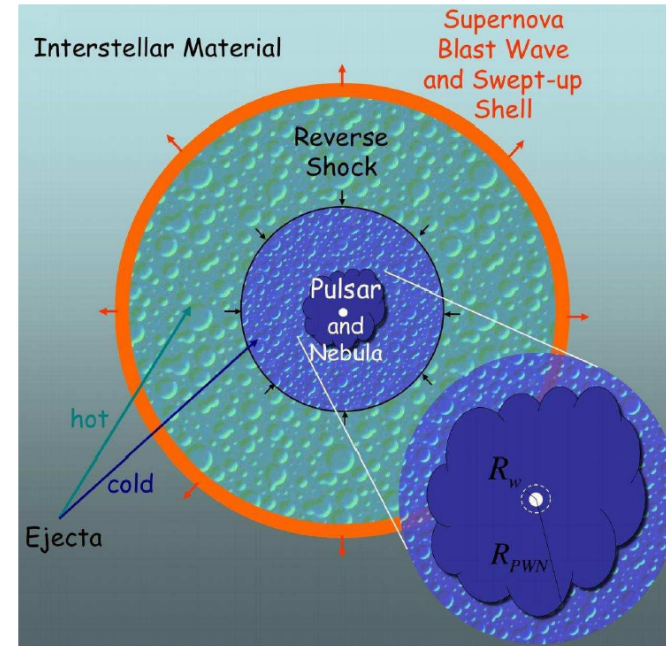
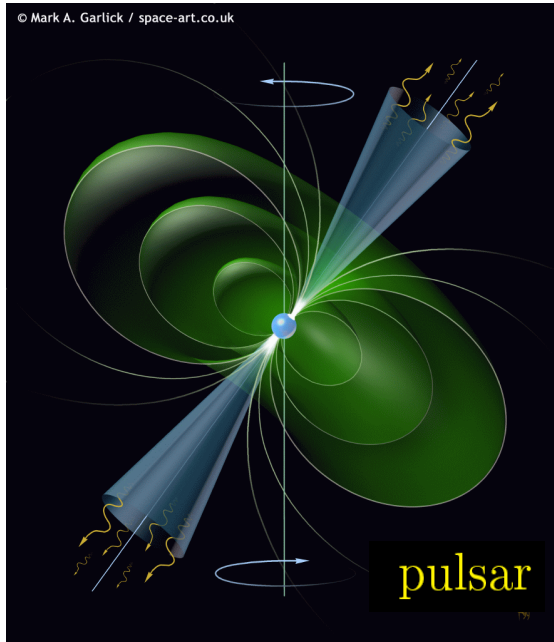
### 3) Pulsars as potential sources of the positron excess



courtesy Solène Le Corre

- Misaligned magnetized neutron stars accelerate electrons which interact with photons – light and magnetic field – to initiate an **electromagnetic cascade**. Pulsars inject electrons and positrons exclusively, not protons or nuclei.

### 3) Pulsars as potential sources of the positron excess



courtesy Solène Le Corre

$$q(E_s) = Q_0 \left( \frac{E_s}{E_0} \right)^{-\gamma} \exp \left( -\frac{E_s}{E_C} \right)$$

$E_K = \frac{1}{5} M R^2 \Omega^2$  translates into  $10^{50}$  ergs for a 10 ms pulsar

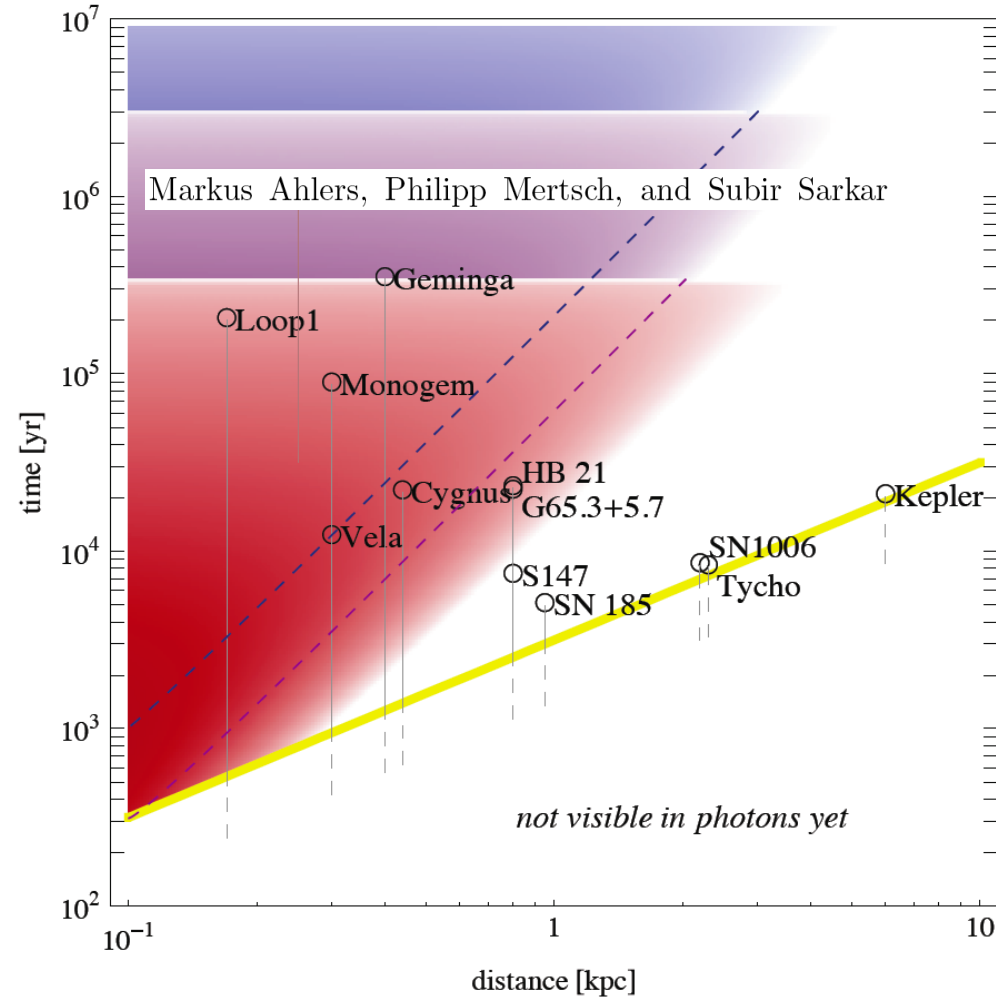
positron propagation for a transient source

$$G_{3D}^t(\vec{x}, E, t \leftarrow \vec{x}_s, E_s, t_s) = \delta(E_s - E_\star) b(E^\star) \times G_{3D}^{stat}(\vec{x}, E \leftarrow \vec{x}_s, E_s)$$

$$E_\star = \frac{E}{1 - E/E_{max}^{Th}}$$

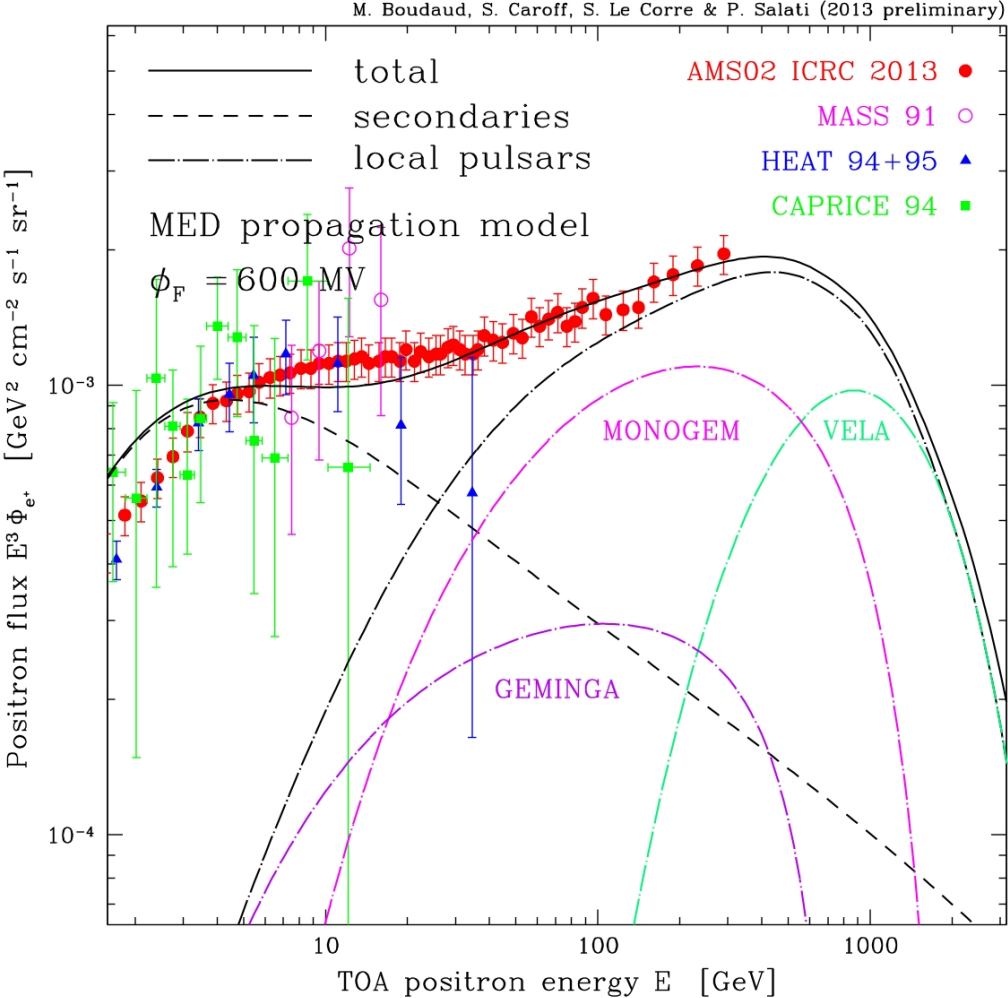
$$E_{max}^{Th} = (\tau_E / \Delta t) E_0$$

maximal positron energy for a source with age  $\Delta t$



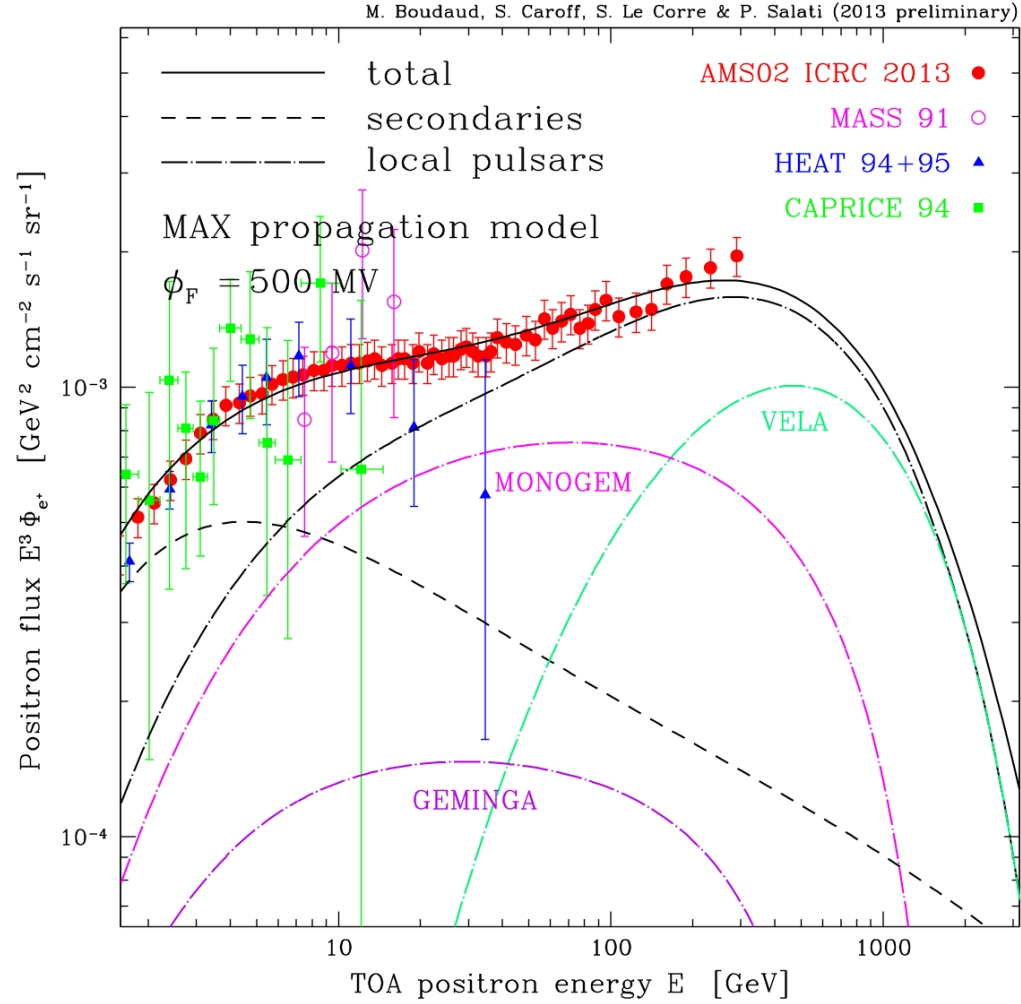


Pulsars provide a fit to the positron excess

$$q(E_s) = Q_0 \left( \frac{E_s}{E_0} \right)^{-\gamma} \exp \left( -\frac{E_s}{E_C} \right)$$


Pulsars	Modèle	$\chi^2$	$f W_0(\text{Geminga})$ ( $10^{50} \text{ GeV}$ )	$f W_0(\text{Monogem})$ ( $10^{50} \text{ GeV}$ )	$f W_0(\text{Vela})$ ( $10^{50} \text{ GeV}$ )	$\gamma$	$E_C$ (TeV)
Geminga + Monogem + Vela	med	0.66	7.755	4.265	0.59	1.9	1.0
	max	0.26	36.5	45.5	9.5	2.4	1.0

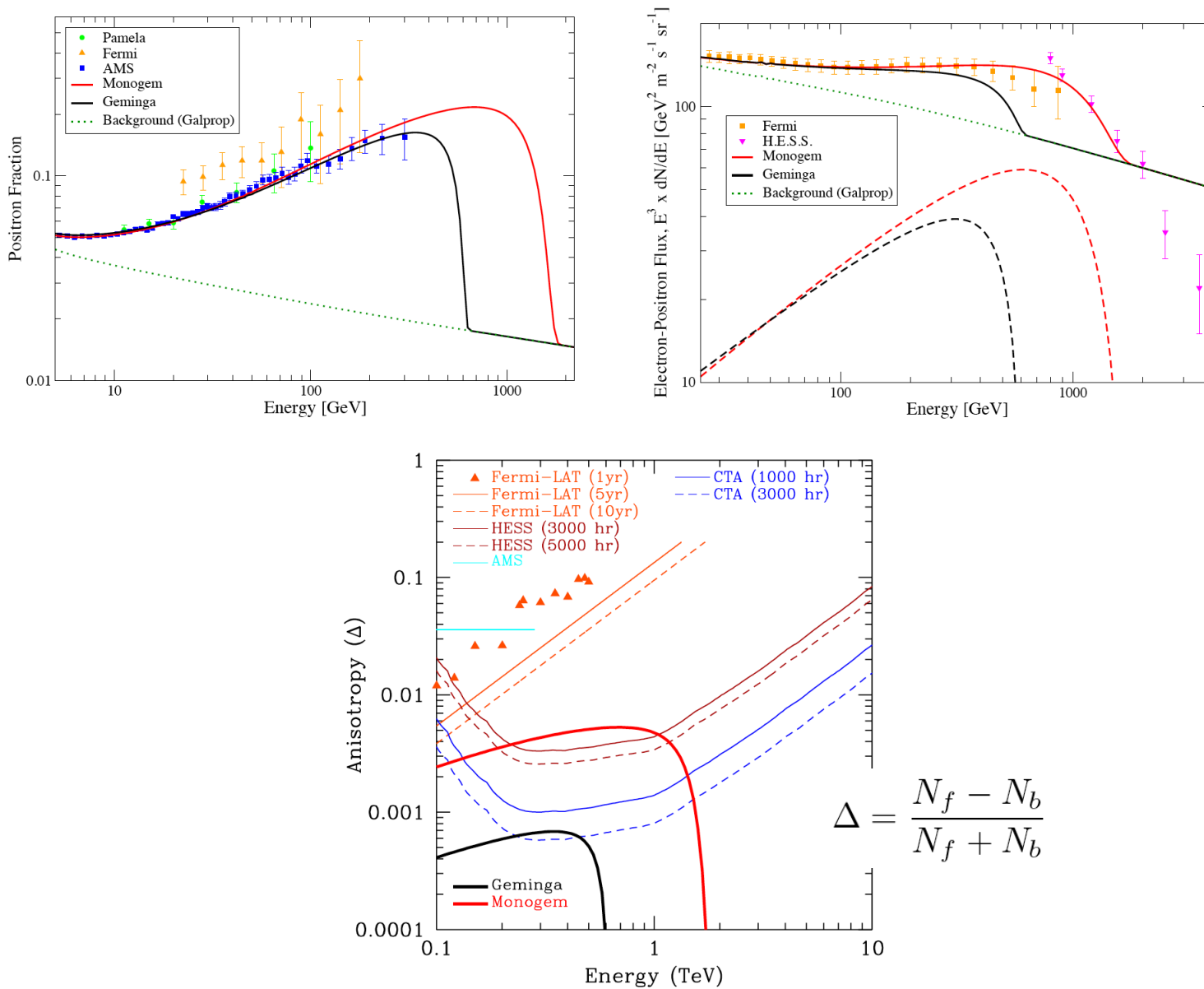
$$q(E_s) = Q_0 \left( \frac{E_s}{E_0} \right)^{-\gamma} \exp \left( -\frac{E_s}{E_C} \right)$$



Pulsars	Modèle	$\chi^2$	$f W_0(Geminga)$ ( $10^{50} GeV$ )	$f W_0(Monogem)$ ( $10^{50} GeV$ )	$f W_0(Vela)$ ( $10^{50} GeV$ )	$\gamma$	$E_C$ ( $TeV$ )
Geminga + Monogem + Vela	<i>med</i>	0.66	7.755	4.265	0.59	1.9	1.0
	<i>max</i>	0.26	36.5	45.5	9.5	2.4	1.0

# PROBING THE PULSAR ORIGIN OF THE ANOMALOUS POSITRON FRACTION WITH AMS-02 AND ATMOSPHERIC CHERENKOV TELESCOPES

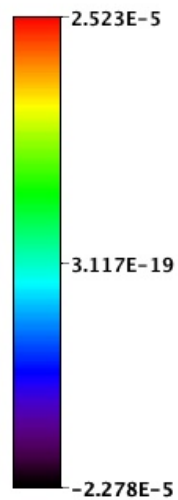
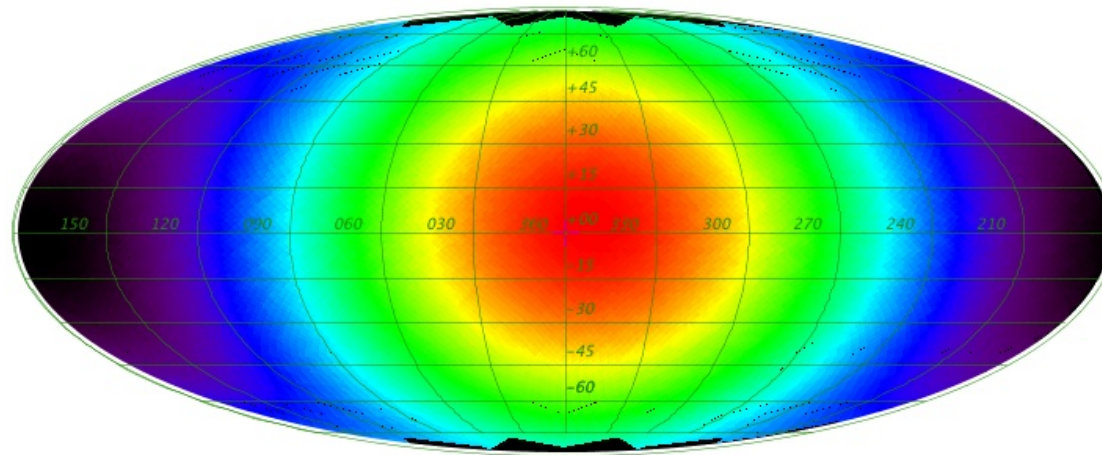
TIM LINDEN<sup>1</sup> AND STEFANO PROFUMO<sup>1,2</sup>



# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_1GeV

primary & secondary contributions

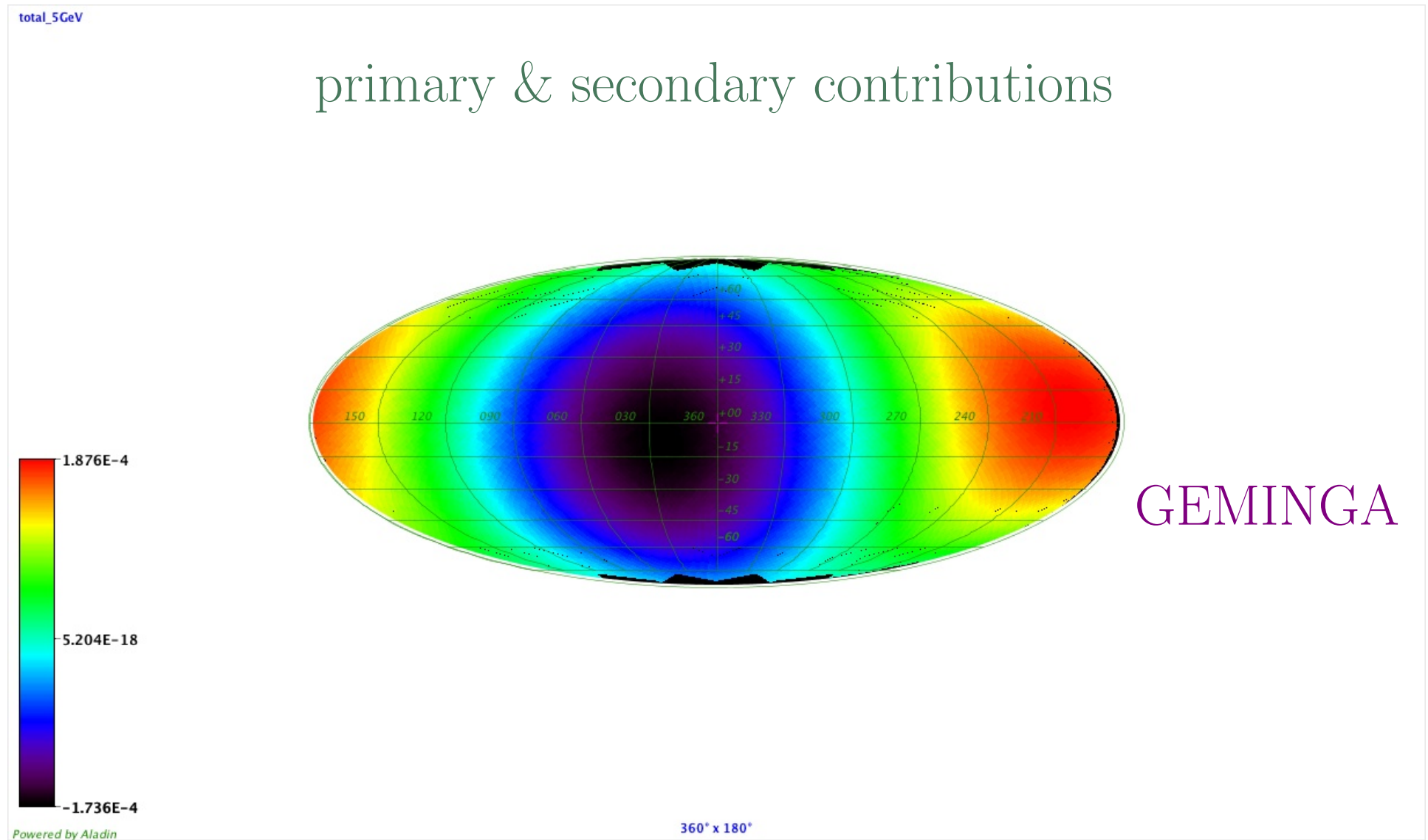


secondaries only

Powered by Aladin

360° x 180°

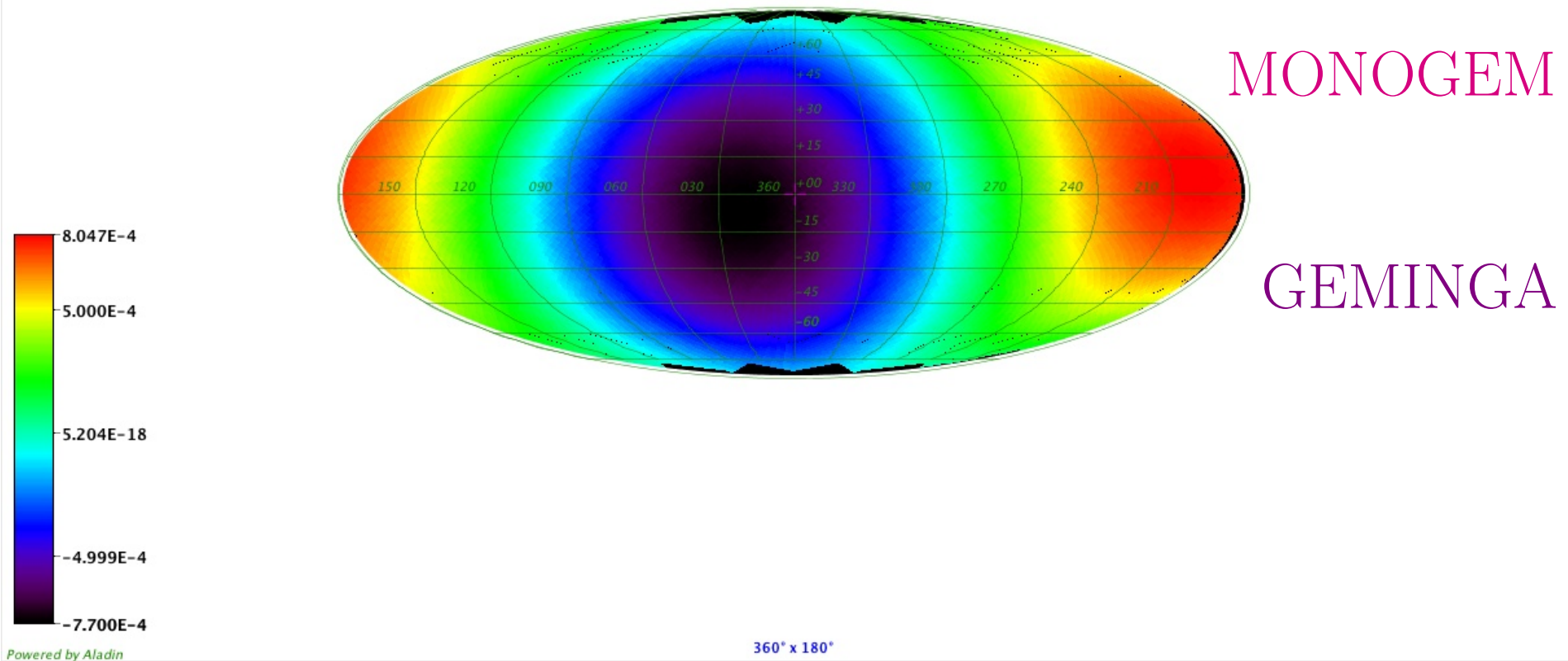
# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis



# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_10GeV

primary & secondary contributions

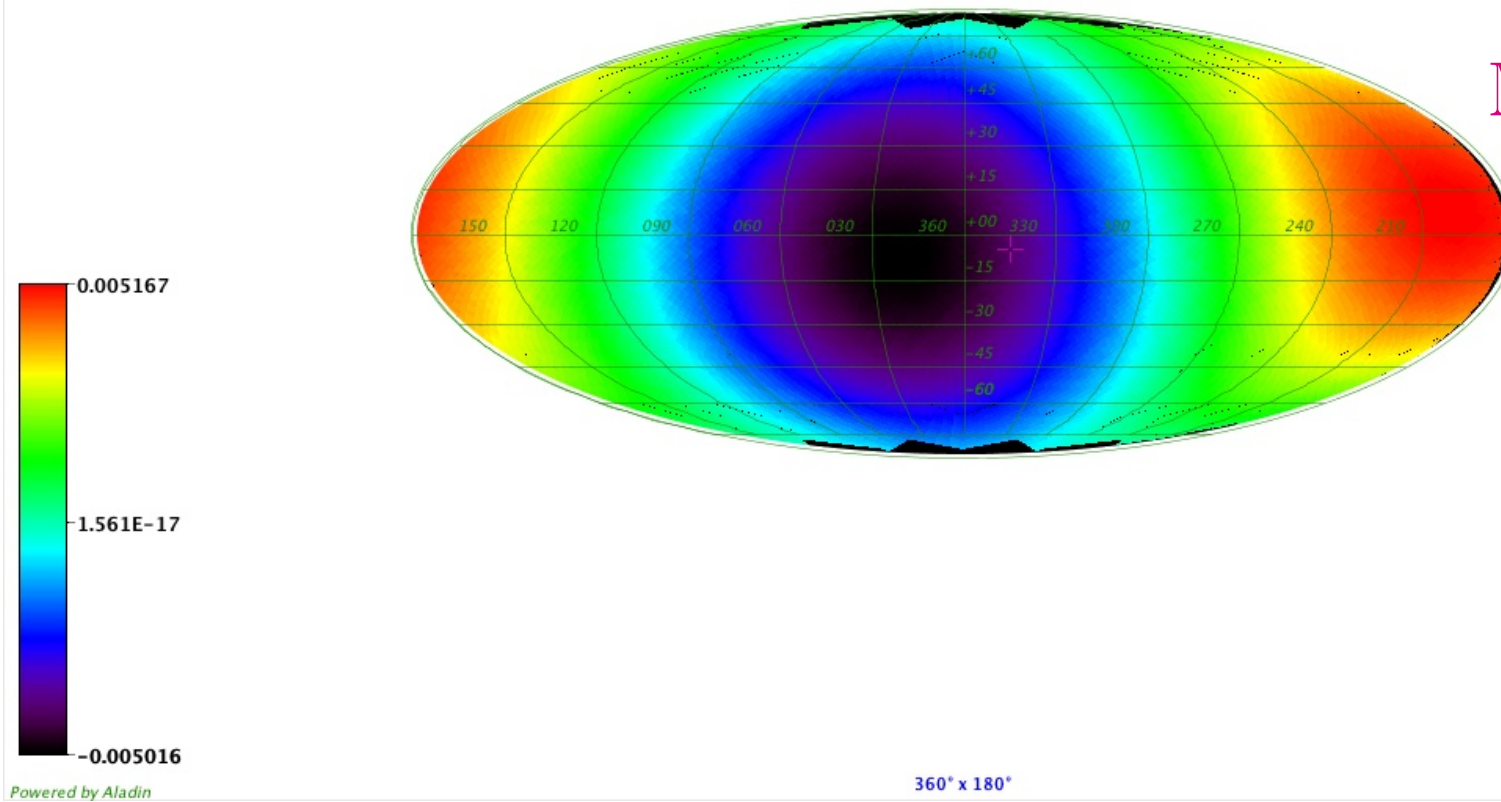


# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_50GeV

primary & secondary contributions

MONOGEM



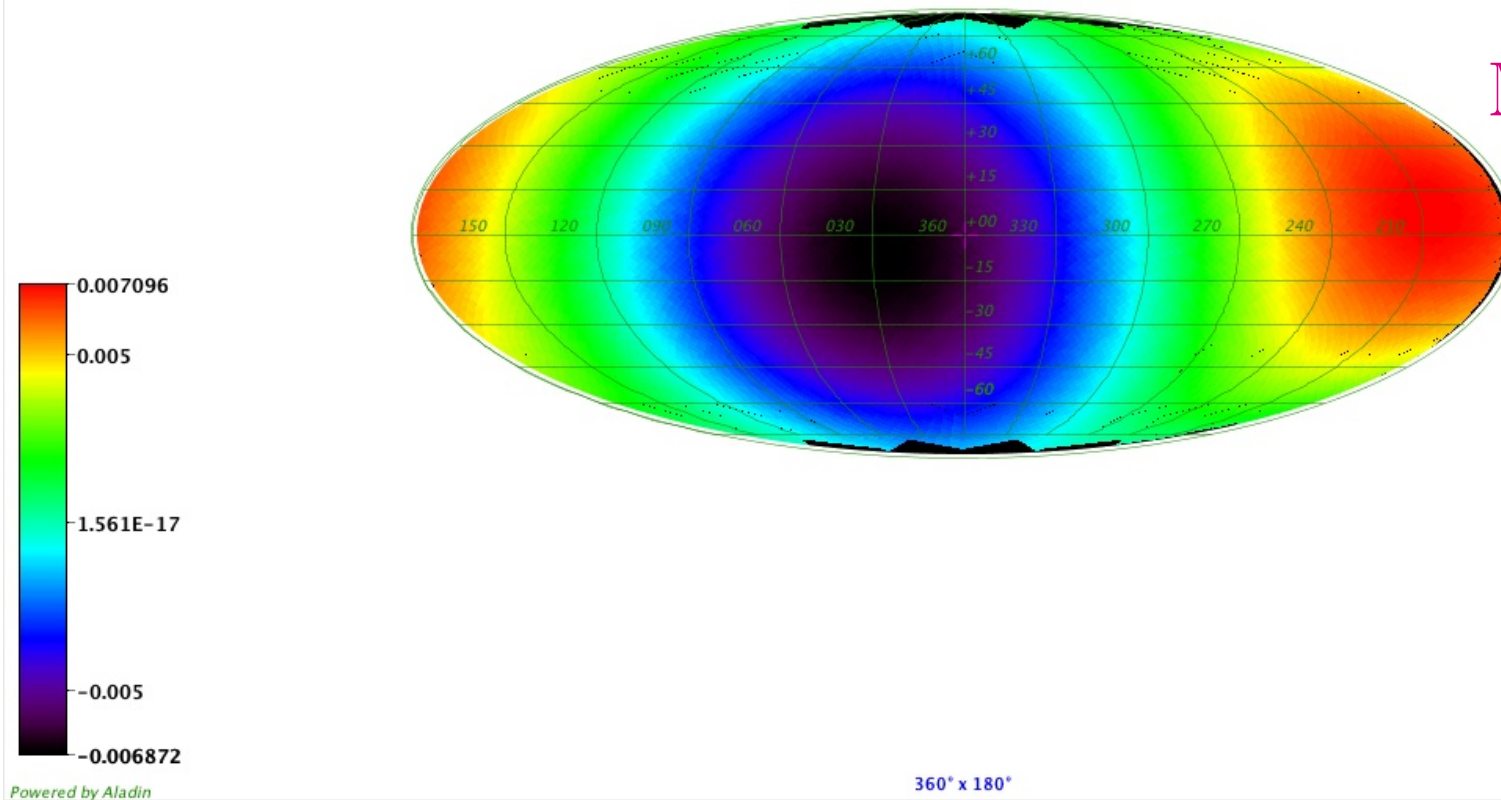


# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_100GeV

primary & secondary contributions

MONOGEM



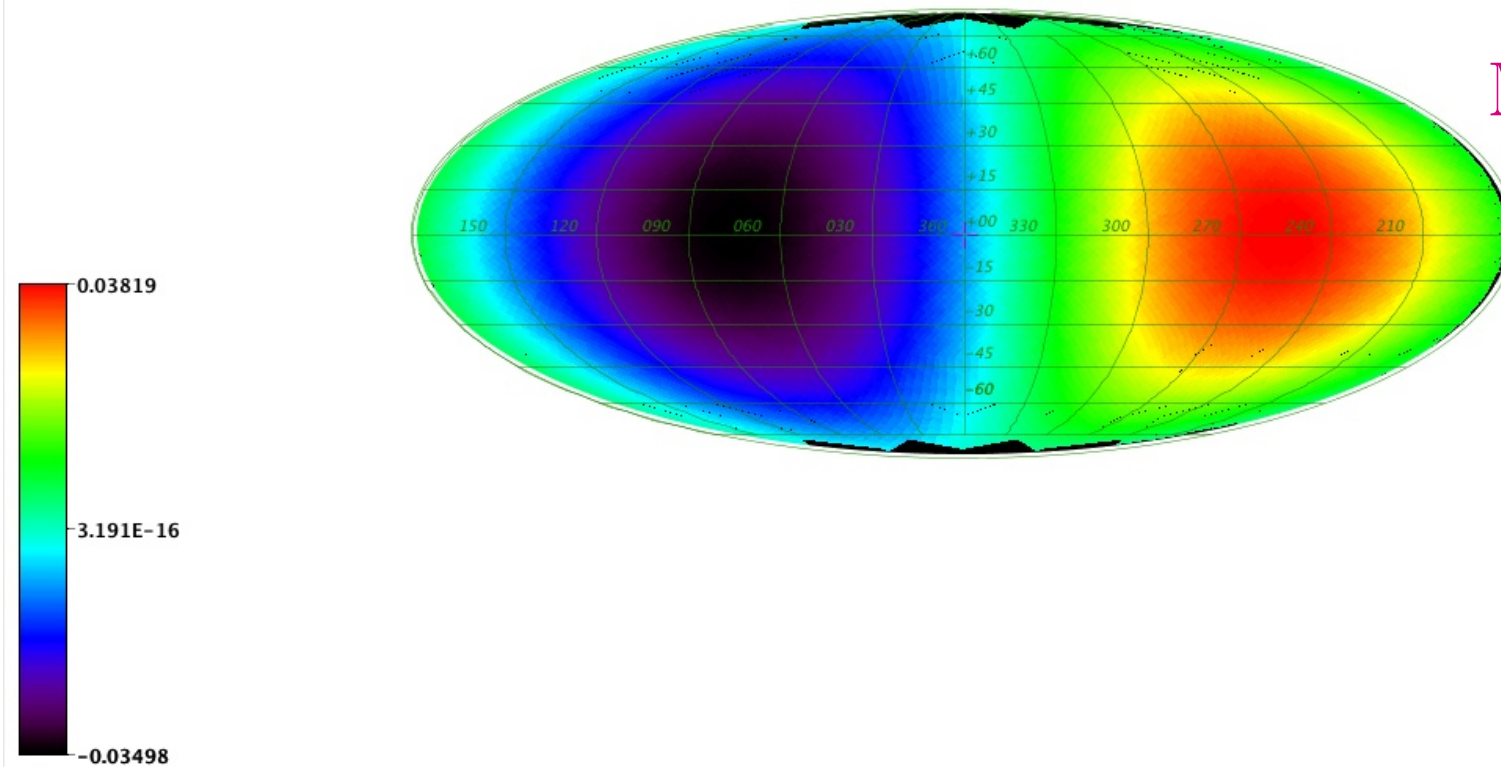
# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_500GeV

primary & secondary contributions

VELA

MONOGEM



Powered by Aladin

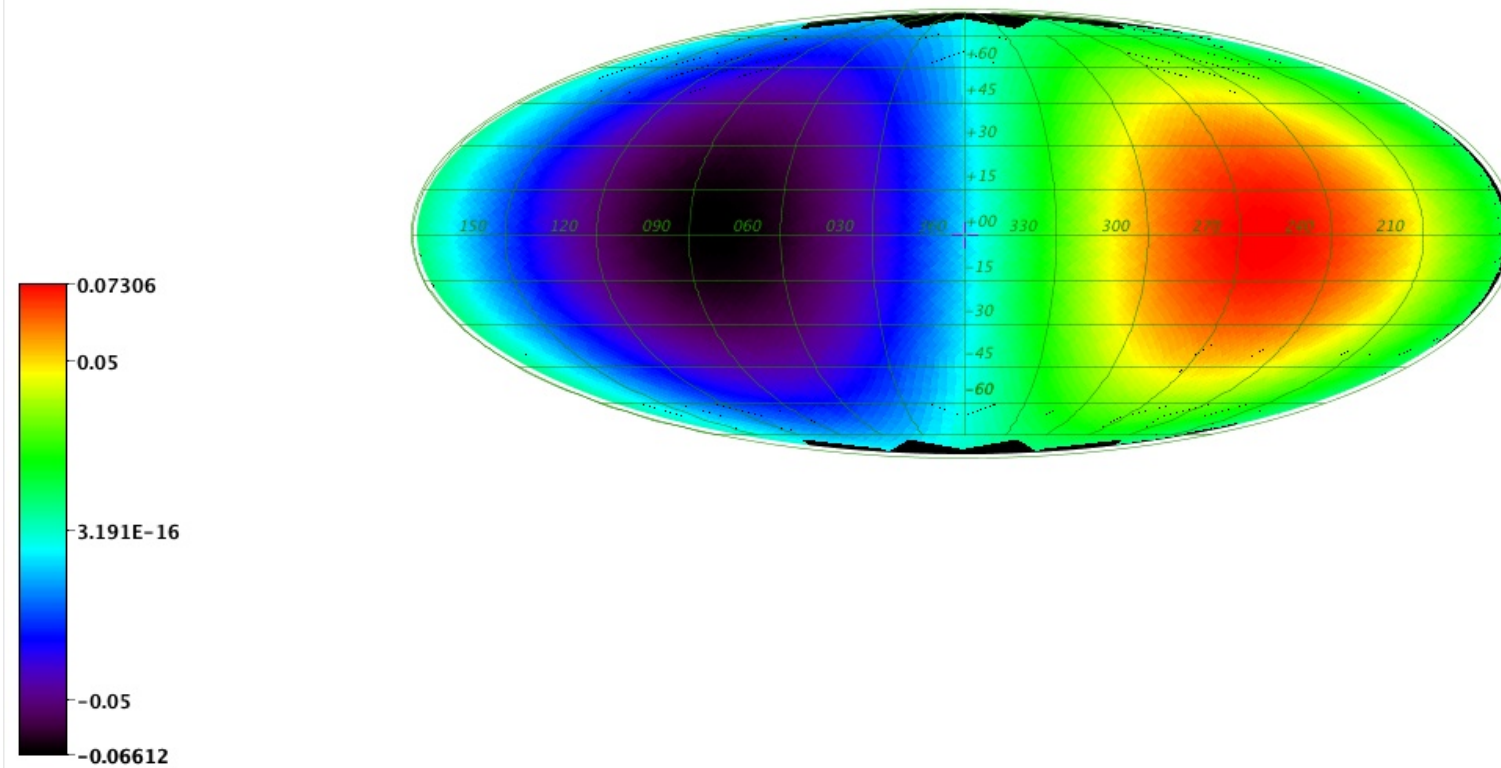
360° x 180°

# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_1000GeV

primary & secondary contributions

VELA



Powered by Aladin

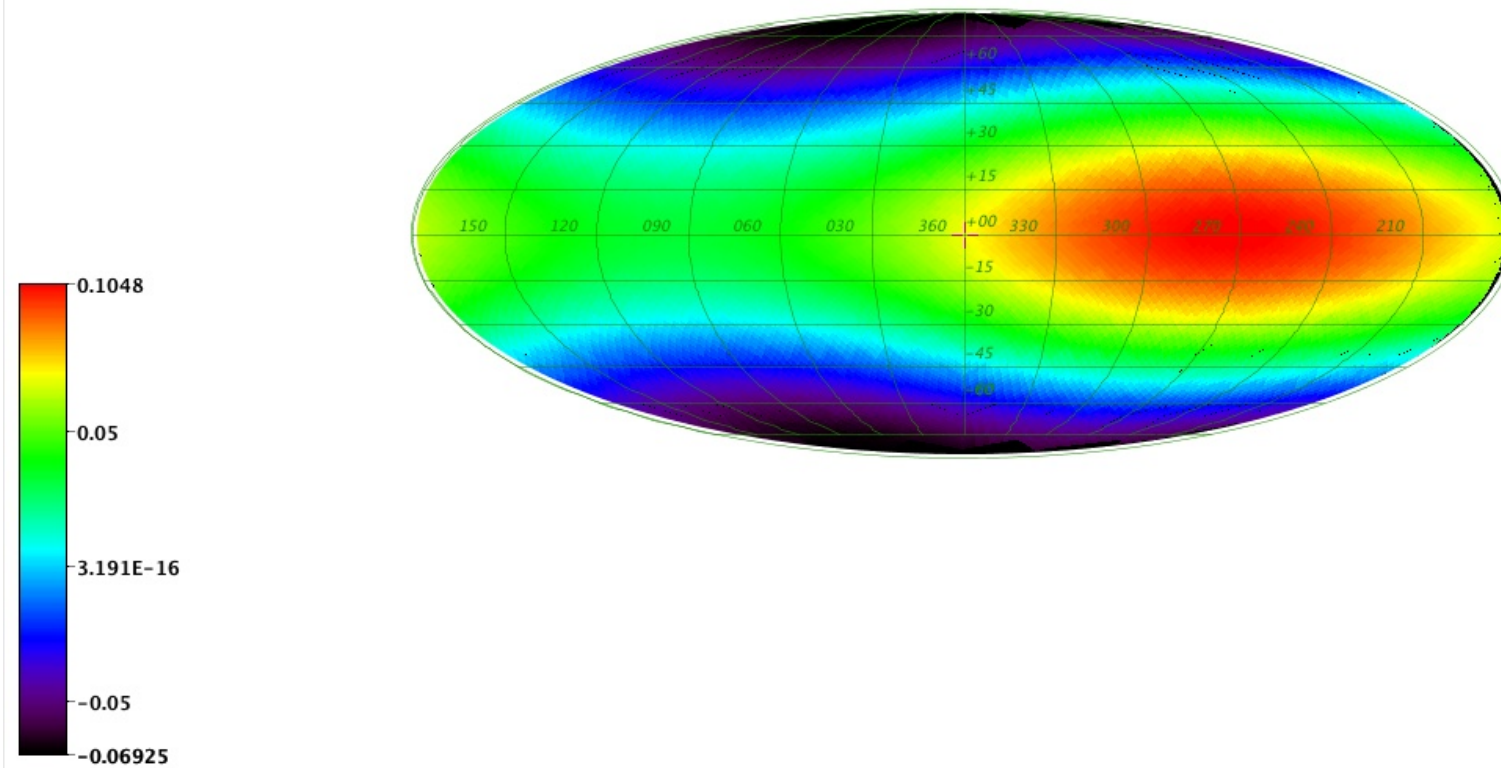
360° x 180°

# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_5000GeV

primary & secondary contributions

VELA



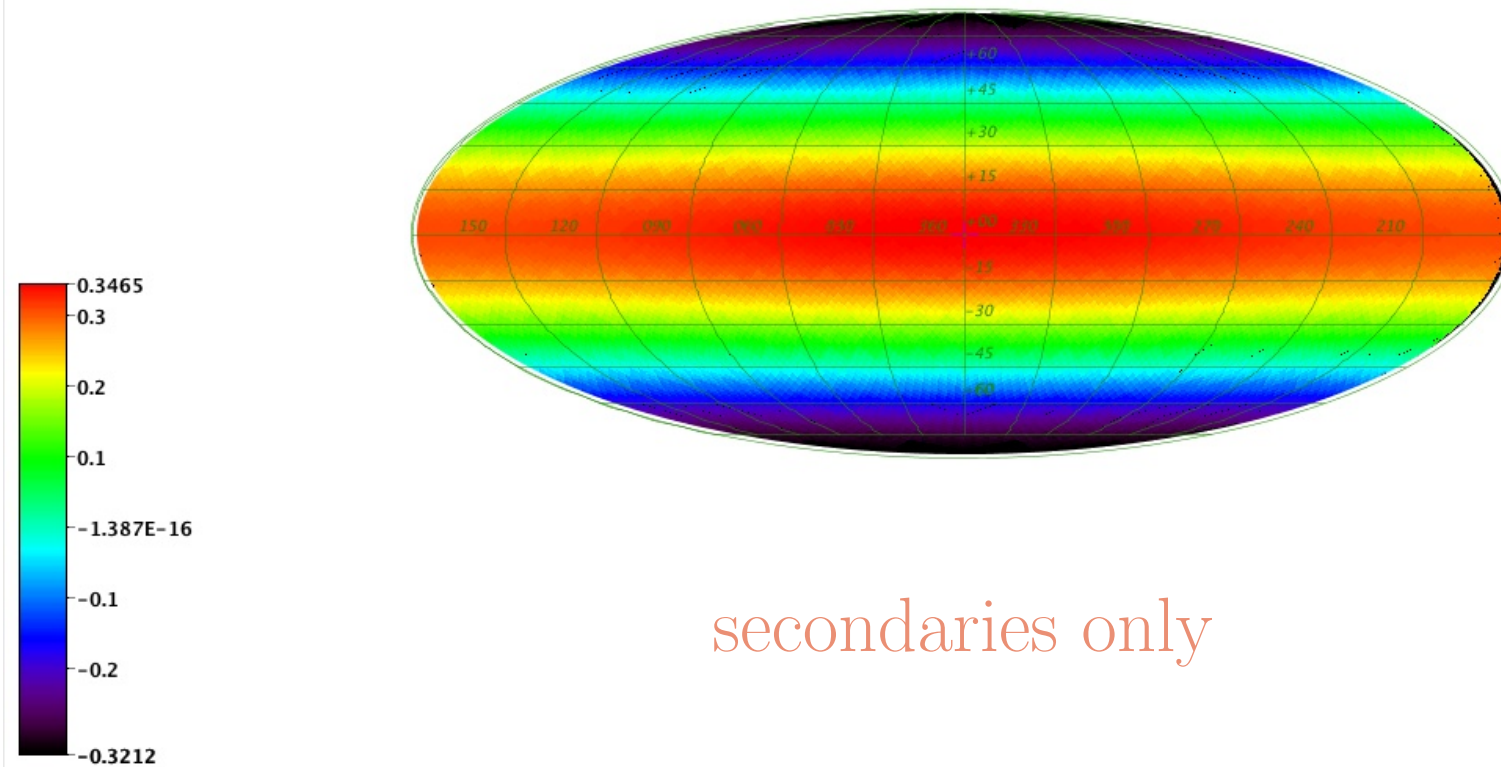
Powered by Aladin

360° x 180°

# Positron sky map @ different energies – Mathieu Boudaud Ph.D. thesis

total\_10000GeV

primary & secondary contributions



secondaries only

Powered by Aladin

360° x 180°



#### 4) CR acceleration and spallation at the same time

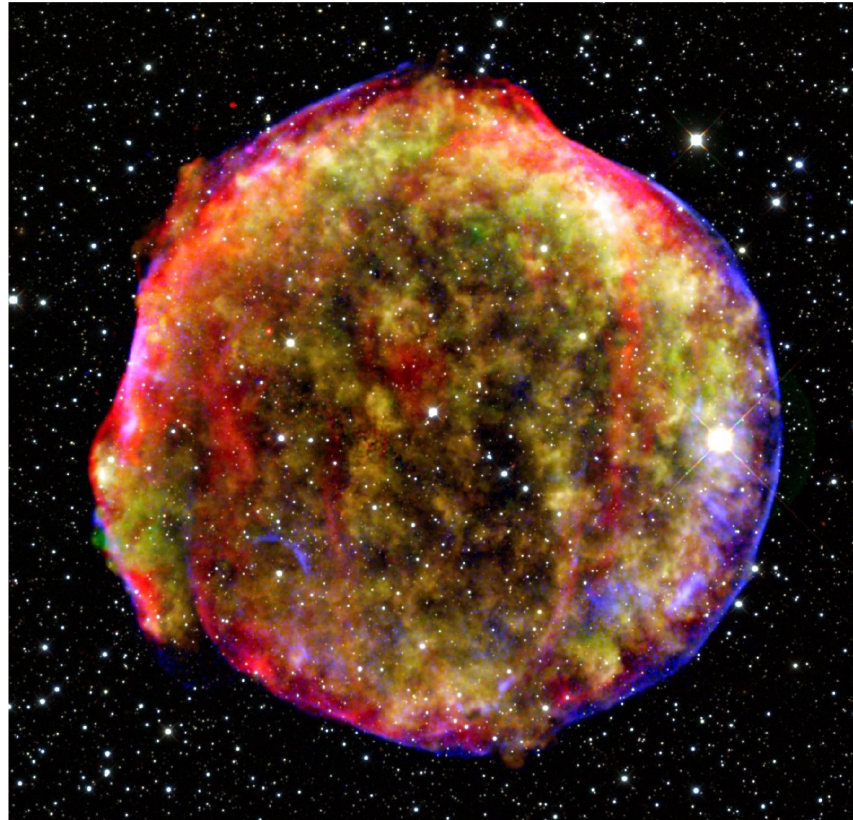
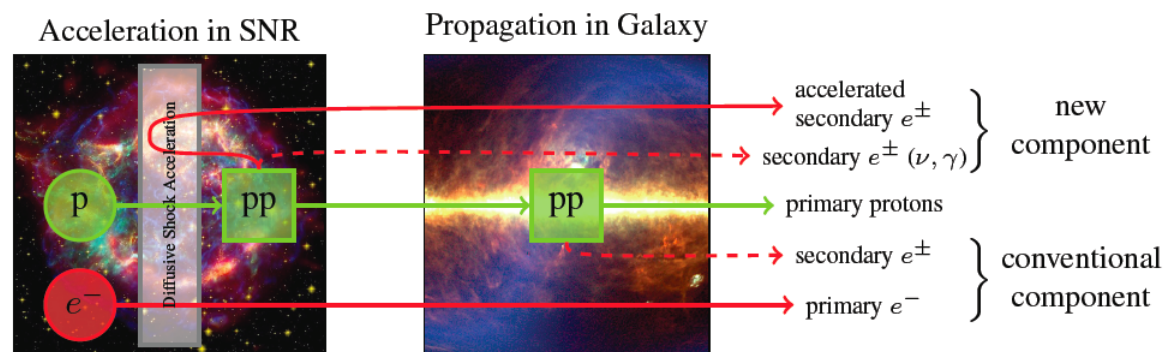


FIGURE 3.11: Restes de la SN de Tycho (1572)

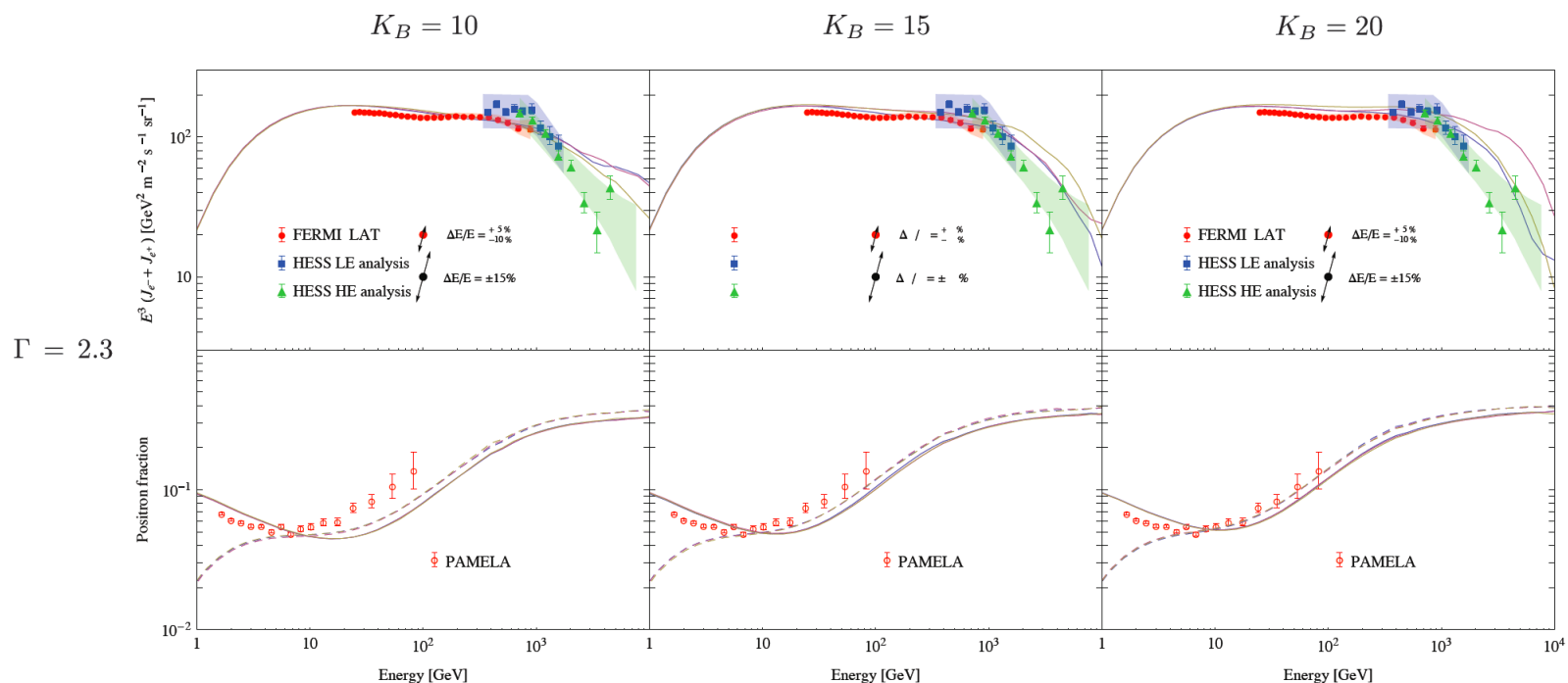
- Supernova driven shock waves accelerate the elements of the interstellar medium through a **first order Fermi mechanism**. Nuclei and electrons are injected.

# On cosmic ray acceleration in supernova remnants and the FERMI/PAMELA data

Markus Ahlers, Philipp Mertsch, and Subir Sarkar



$$D(E) = 3.3 \times 10^{22} K_B \left( \frac{B}{\mu\text{G}} \right)^{-1} \left( \frac{E}{\text{GeV}} \right) \text{cm}^2\text{s}^{-1}$$

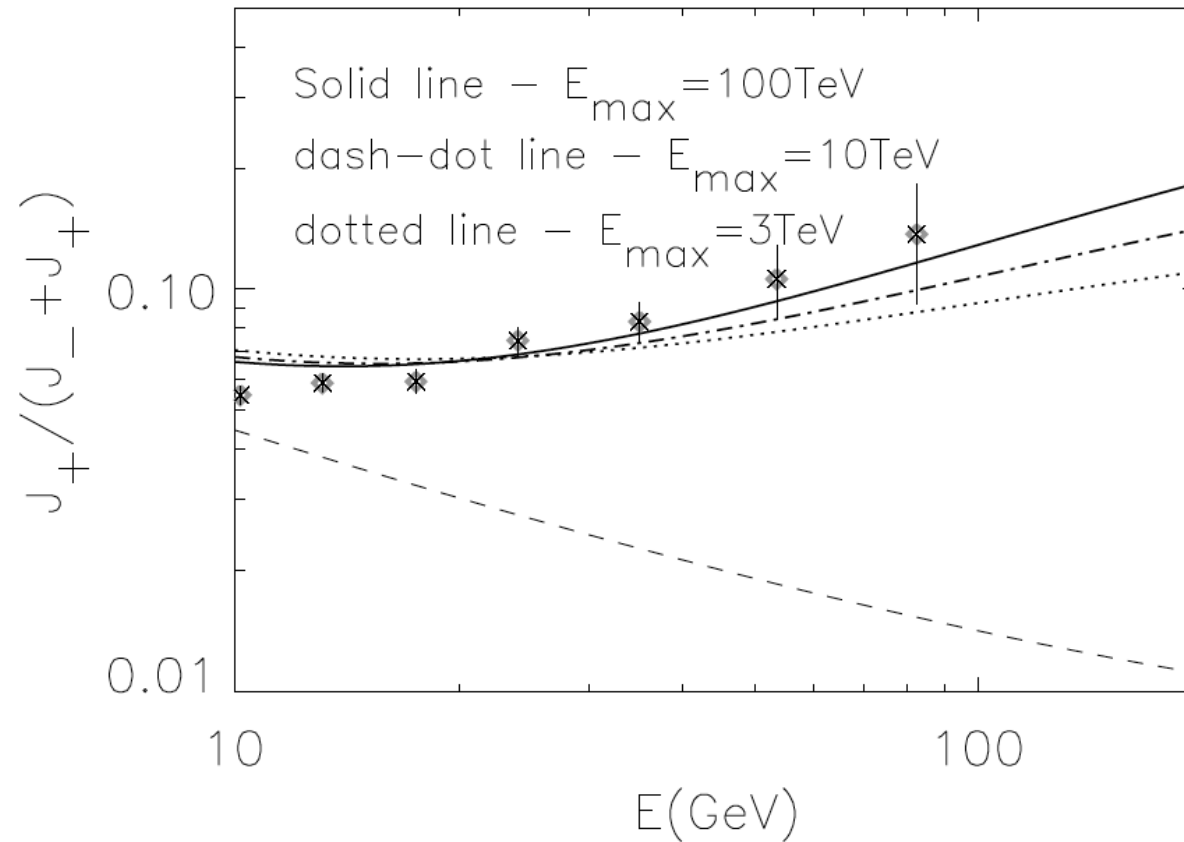




# The origin of the positron excess in cosmic rays

Pasquale Blasi

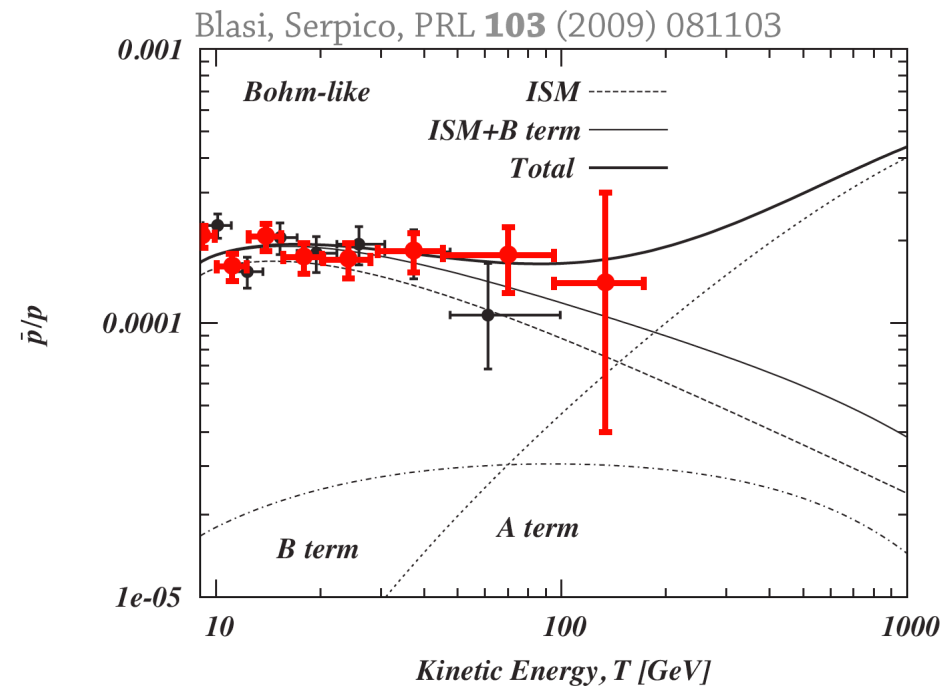
Acceleration **and** spallation in SN shock waves



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

# Antiproton-to-proton Ratio

rise in...	$\bar{p}/p$
DM	(✓)
Pulsars	✗
Acceleration of Secondaries	✓



✗ *Phys. Rev. Lett.* 102, 051101 (2009)

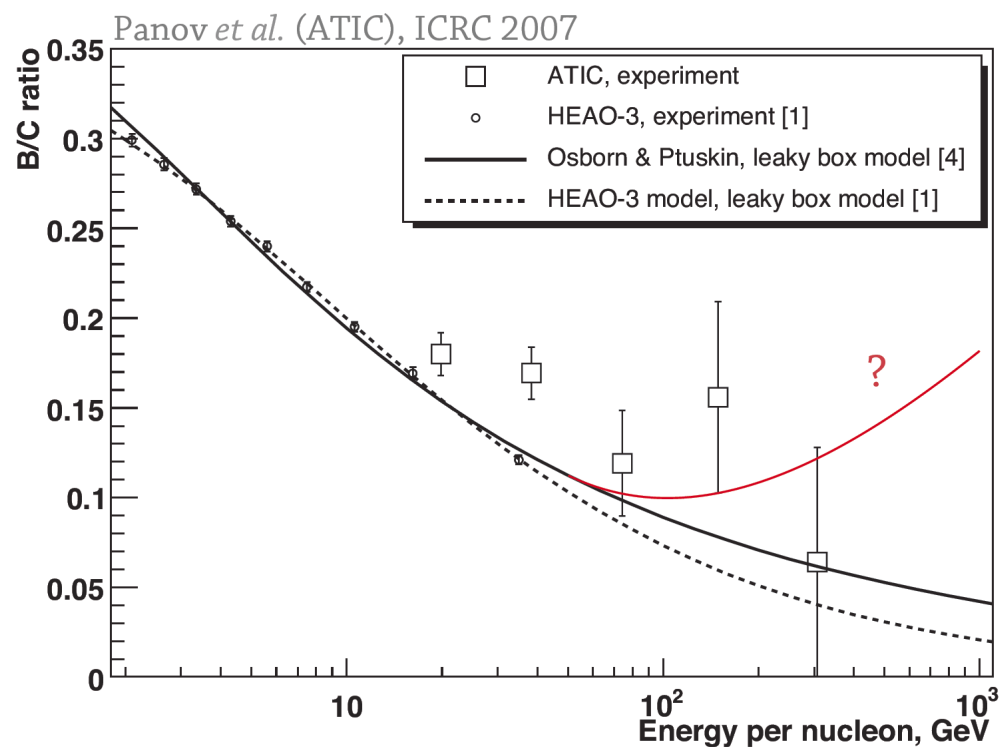
✗ *arXiv:1007.0821*

# Nuclear Secondary-to-Primary Ratios

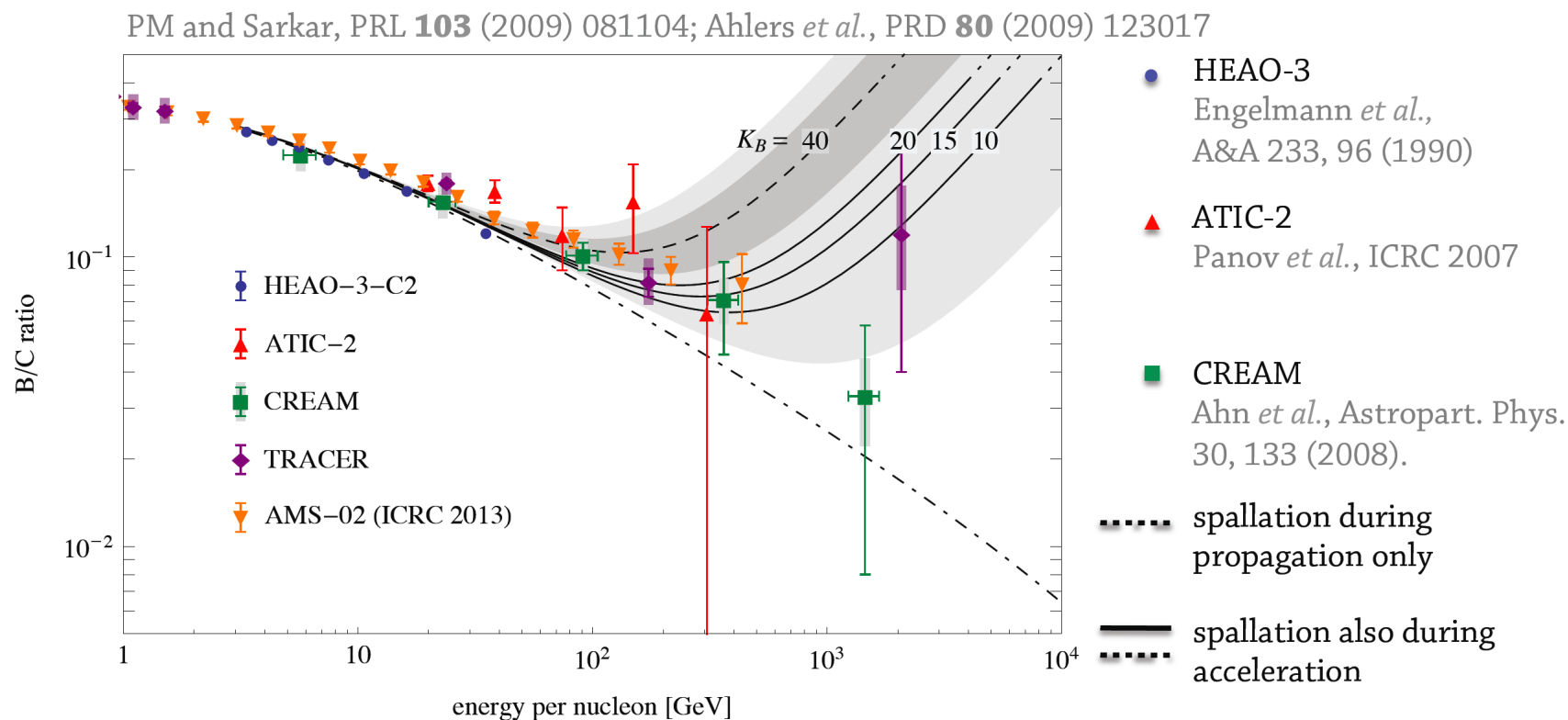
rise in...	nuclei
DM	X
Pulsars	X
Acceleration of Secondaries	✓

This would be a clear indication for acceleration of secondaries!

If nuclei are accelerated in the same sources as electrons and positrons, nuclear ratios *must* rise eventually



# Boron-to-Carbon Ratio



AMS02 is currently measuring the B/C ratio

A rise would rule out the DM and pulsar explanations

## 5) The revenge of orthodoxy

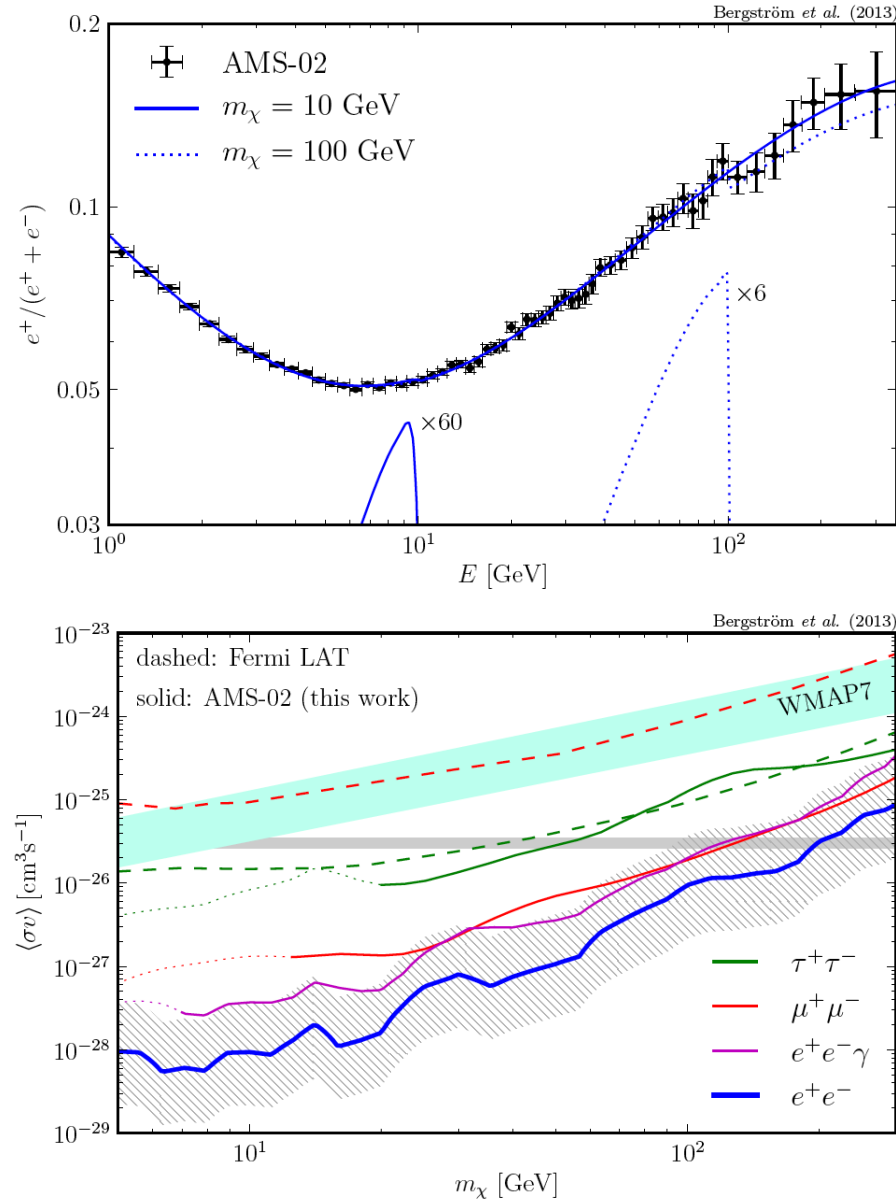
**New limits on dark matter annihilation from AMS cosmic ray positron data**

Lars Bergström,<sup>1,\*</sup> Torsten Bringmann,<sup>2,†</sup> Ilias Cholis,<sup>3,‡</sup> Dan Hooper,<sup>3,4,§</sup> and Christoph Weniger<sup>5,¶</sup>

In this study, we do not make any attempt to explain the origin of the rise in the positron fraction. Instead, we focus on using the AMS data to derive limits on subdominant exotic contributions to the observed CR positron spectrum, in particular from DM with masses below  $\sim 300$  GeV. While positrons have been used in the past to probe DM annihilation or decay [28–33], we exploit here for the first time the extremely high quality of the AMS data to search for pronounced *spectral features* in the positron flux predicted in some DM models

# New limits on dark matter annihilation from AMS cosmic ray positron data

Lars Bergström,<sup>1,\*</sup> Torsten Bringmann,<sup>2,†</sup> Ilias Cholis,<sup>3,‡</sup> Dan Hooper,<sup>3,4,§</sup> and Christoph Weniger<sup>5,¶</sup>



## Conclusions and perspectives

- Annihilating DM species can still explain the CR positron excess. But a quite ad hoc model with Sommerfeld enhancement and possibly substructure effects are needed.

### Beware of the EGGR background

- Decaying DM is also an option but  $\tau$  exceedingly large. The existence of dim 6 operators would make it natural though.
- Pulsars provide a natural explanation but it is difficult to define which sources are responsible for the CR positron excess. Interesting framework.
- Spallations in the acceleration sites are also an appealing possibility.

### Several probes are needed

- A rise of B/C and  $\bar{p}/p$  would rule out the pulsar and DM explanations.
- Otherwise, anisotropies in the positron sky would help make the difference between DM and pulsars.

Is that really true ?

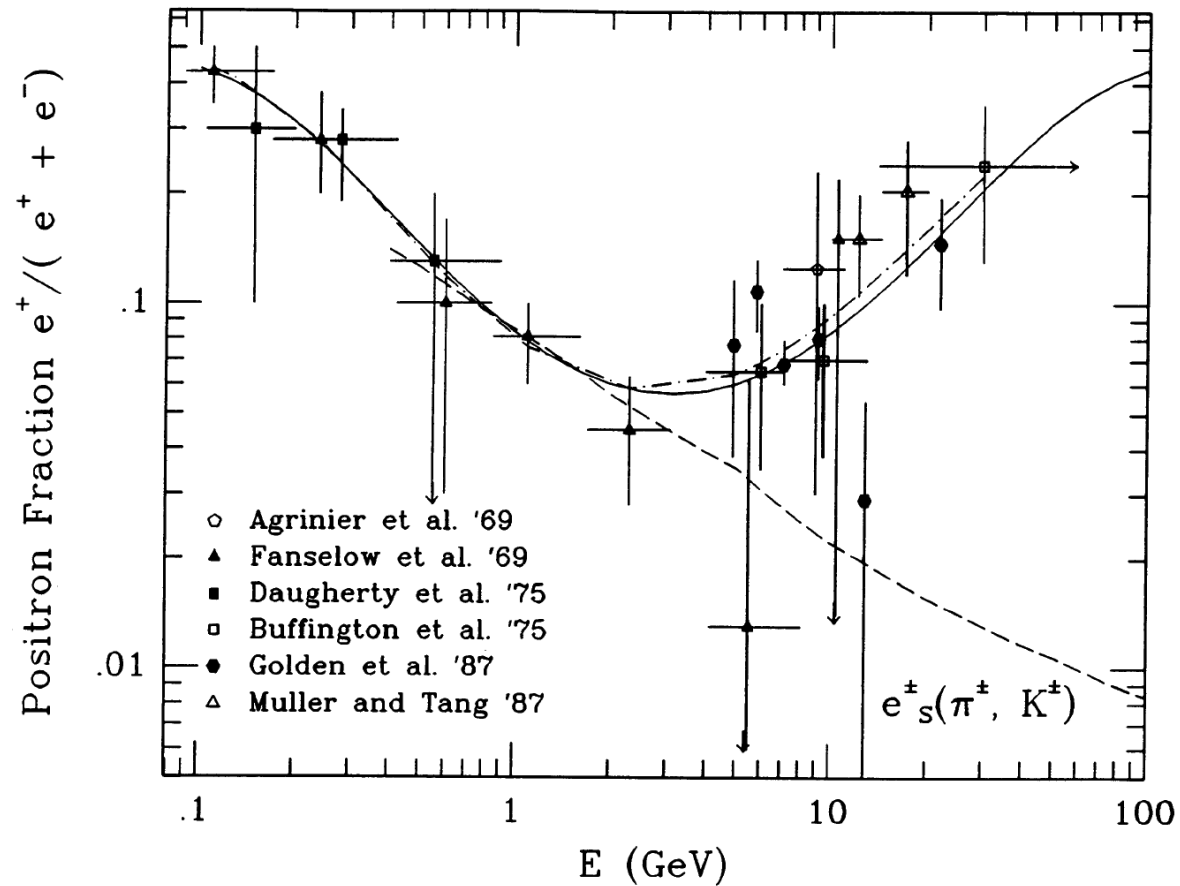


# THE NATURE OF THE COSMIC-RAY ELECTRON SPECTRUM, AND SUPERNOVA REMNANT CONTRIBUTIONS

AHMED BOULARES

Physics Department, Space Physics Laboratory, University of Wisconsin-Madison

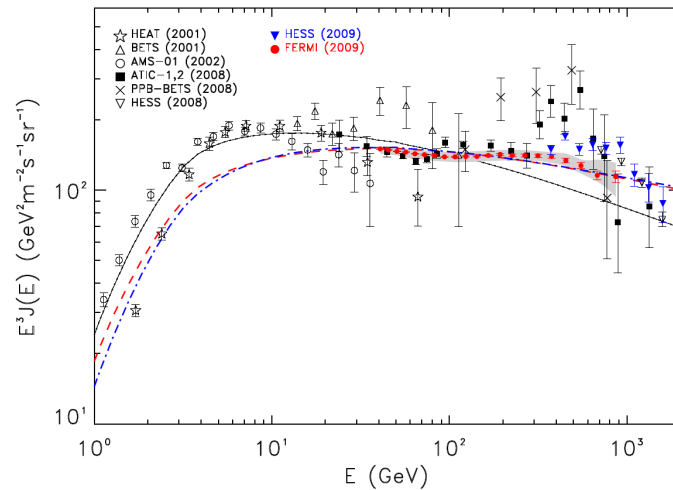
*Received 1988 October 24; accepted 1988 December 29*





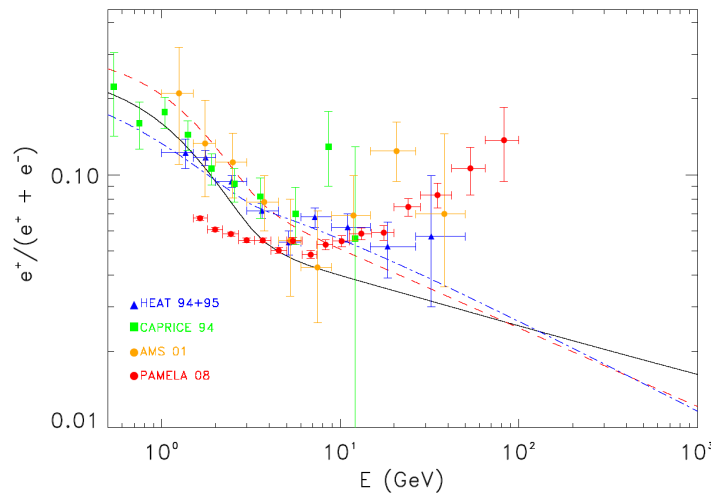
back-up slides

# The situation before the PAMELA measurements



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

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



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

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

$$J_{e^\pm} = (175.40 \pm 6.09) \left( \frac{E}{1 \text{ GeV}} \right)^{-(3.045 \pm 0.008)} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$