Dark Matter Annihilation in the Universe

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

Outline

1) DM production through annihilation

2) DM annihilation and big-bang nucleosynthesis

3) CMB constraints on DM annihilation

4) Indirect signatures of DM species

5) DM annihilation and stellar evolution

2nd International Workshop on Antimatter and Gravity
(WAG 2013)

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Europe/Zurich timezone

1) DM production through annihilation

• The entire field started when Zwicky measured the gravitational mass inside the Coma cluster of galaxies in 1933.

• Rotation curves of spiral galaxies are flatter than they should. This indicates the presence of unseen material inside galactic halos.

• The Cosmic Microwave Background anisotropies indicate the presence of dark matter on cosmological scales and allow to measure its abundance.

Dark-Matter is **not** baryonic – Exotic nature

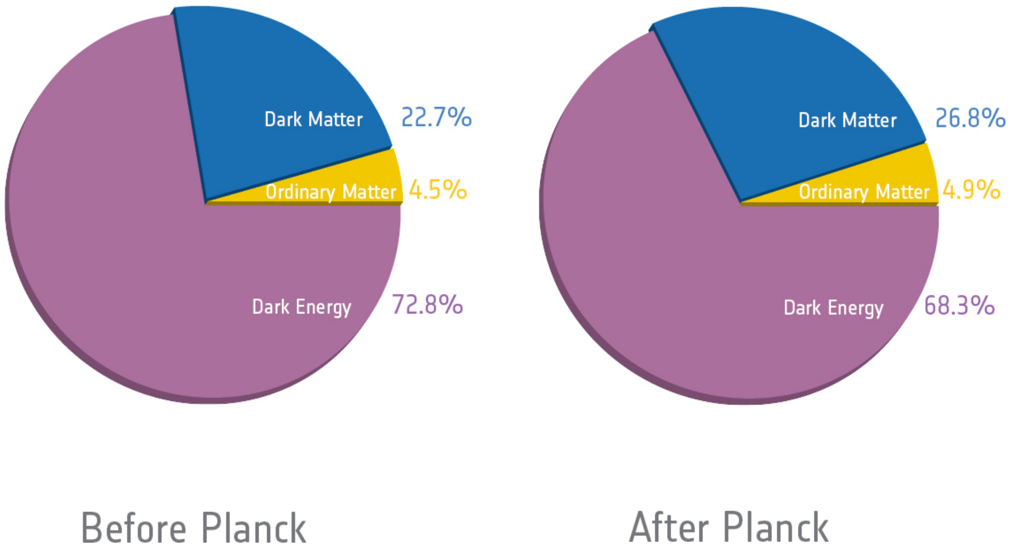
• Theoreticians have imagined for the last three decades a plethora of DM candidates. But very few are motivated by arguments independent from the DM problem.

Supersymmetric or Kaluza-Klein particles

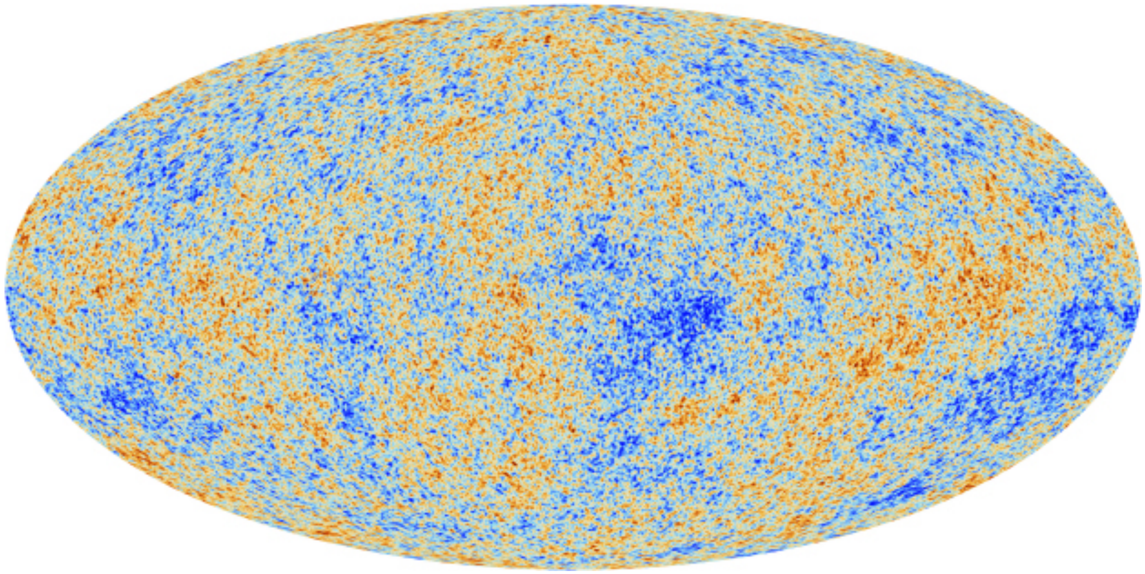
These candidates are predicted by the supersymmetric or extra-dimensional extensions of the standard model of particle physics. They are **electrically neutral**, **weakly interacting** and have a mass in the **GeV to TeV** range.

Weakly interacting massive particle – WIMP

Planck observations of the CMB



Confirmation of a flat universe with DE and DM



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PHYSICAL REVIEW LETTERS

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Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]

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and

Steven Weinberg[c]

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(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

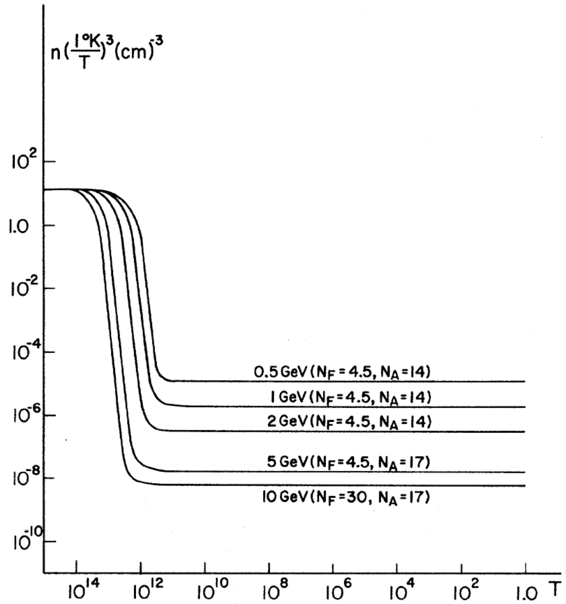


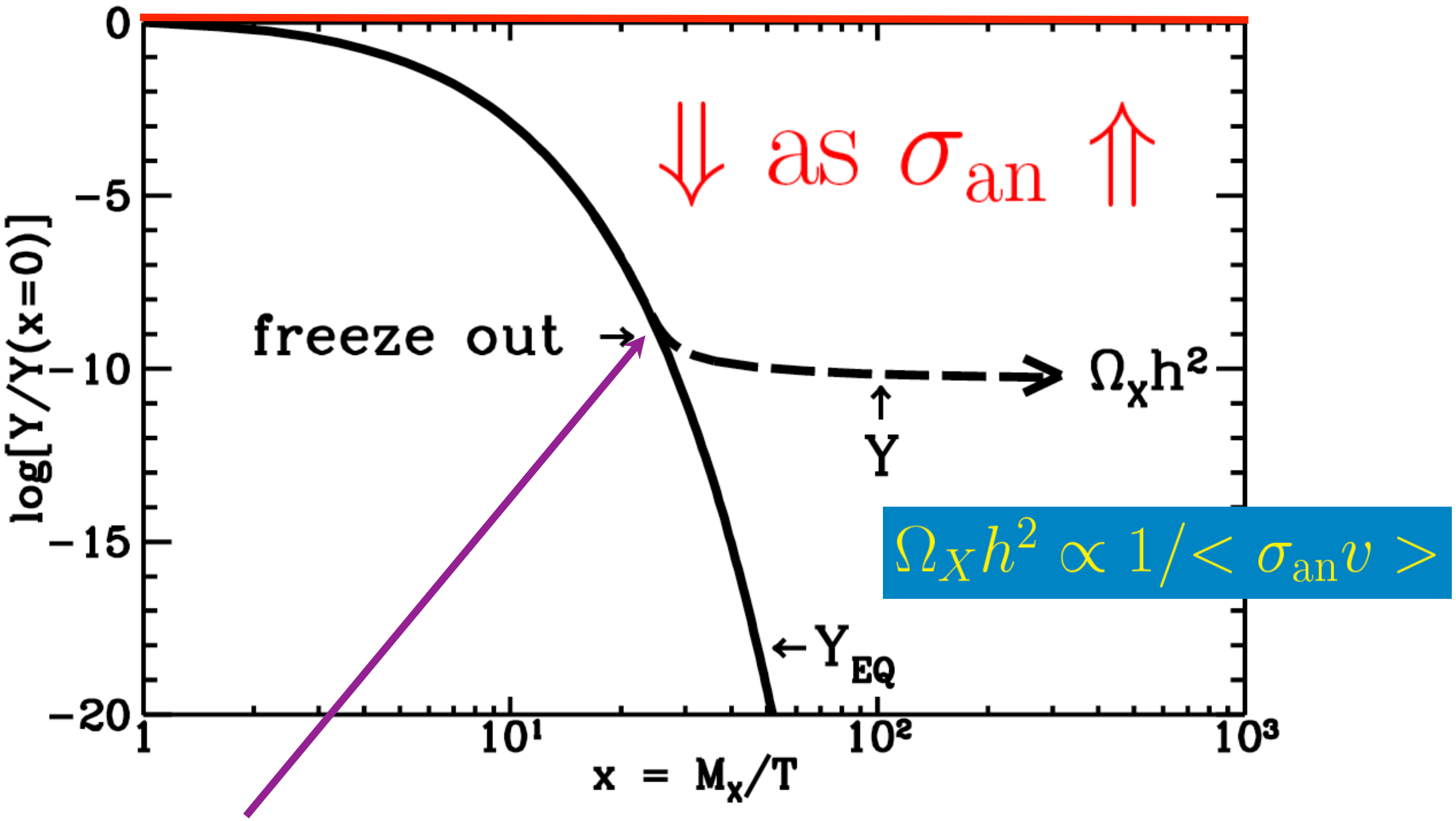
FIG. 1. n/T^3 vs T for a variety of special cases of m_L, N_F, and N_A.

Thermodynamical equilibrium production

$$X + \bar{X} \rightleftharpoons f + \bar{f}$$

$$\frac{dn_X}{dt} = -3Hn_X - <\sigma_{\rm an}v> {n_X}^2 + <\sigma_{\rm an}v> {n_X^0}^2$$

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



chemical decoupling when $<\sigma_{\rm an}v> n_X \sim H_F$ (NR)

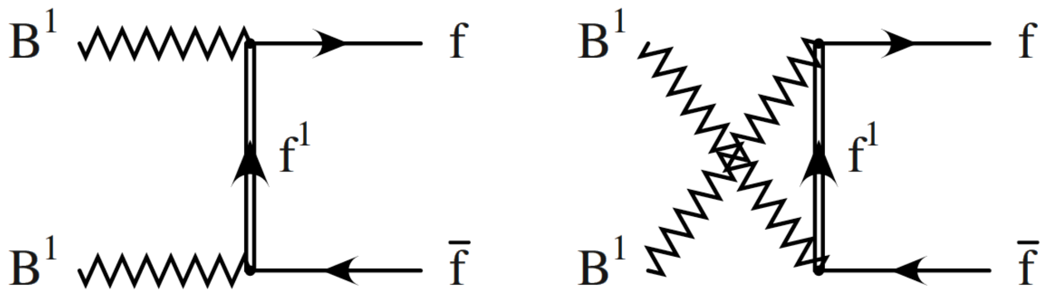


Figure 4: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into fermions.

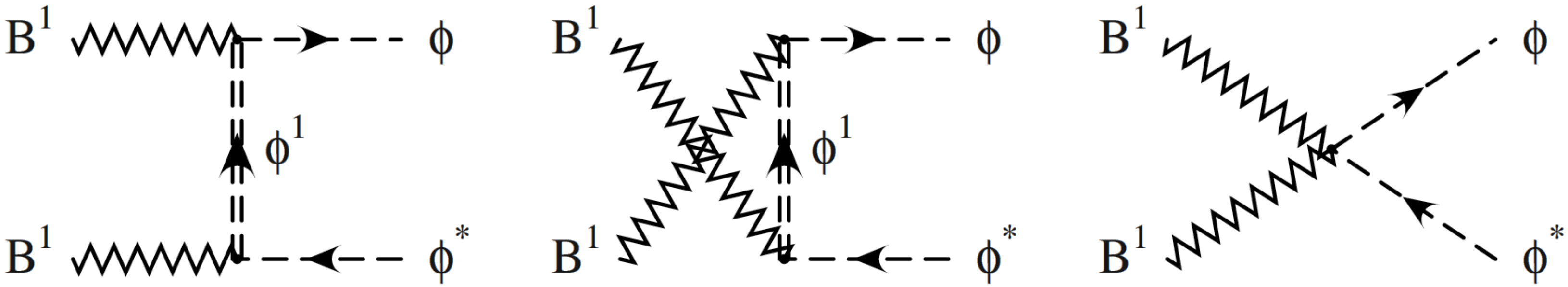
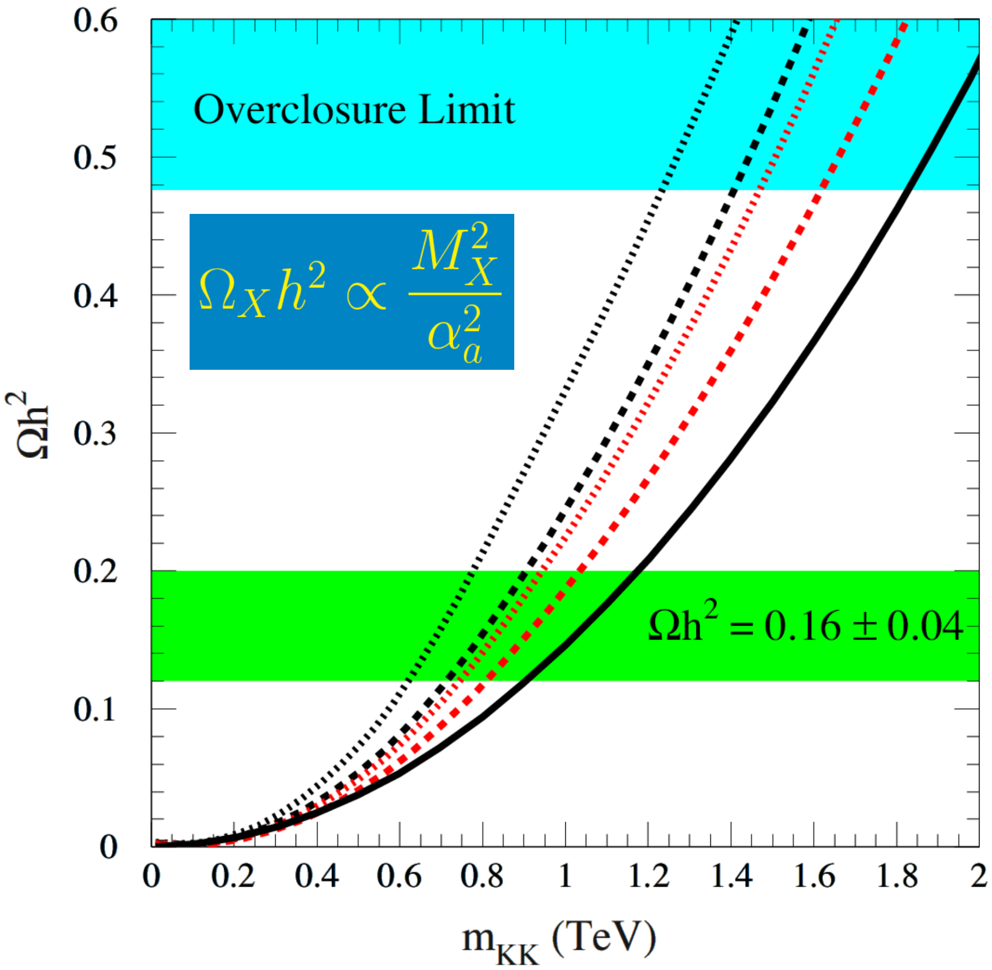


Figure 5: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into Higgs scalar bosons.

Géraldine Servant [a,b] and Tim M.P. Tait [a]

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) $\Delta = 0.05$.



Géraldine Servant [a,b] and Tim M.P. Tait [a]

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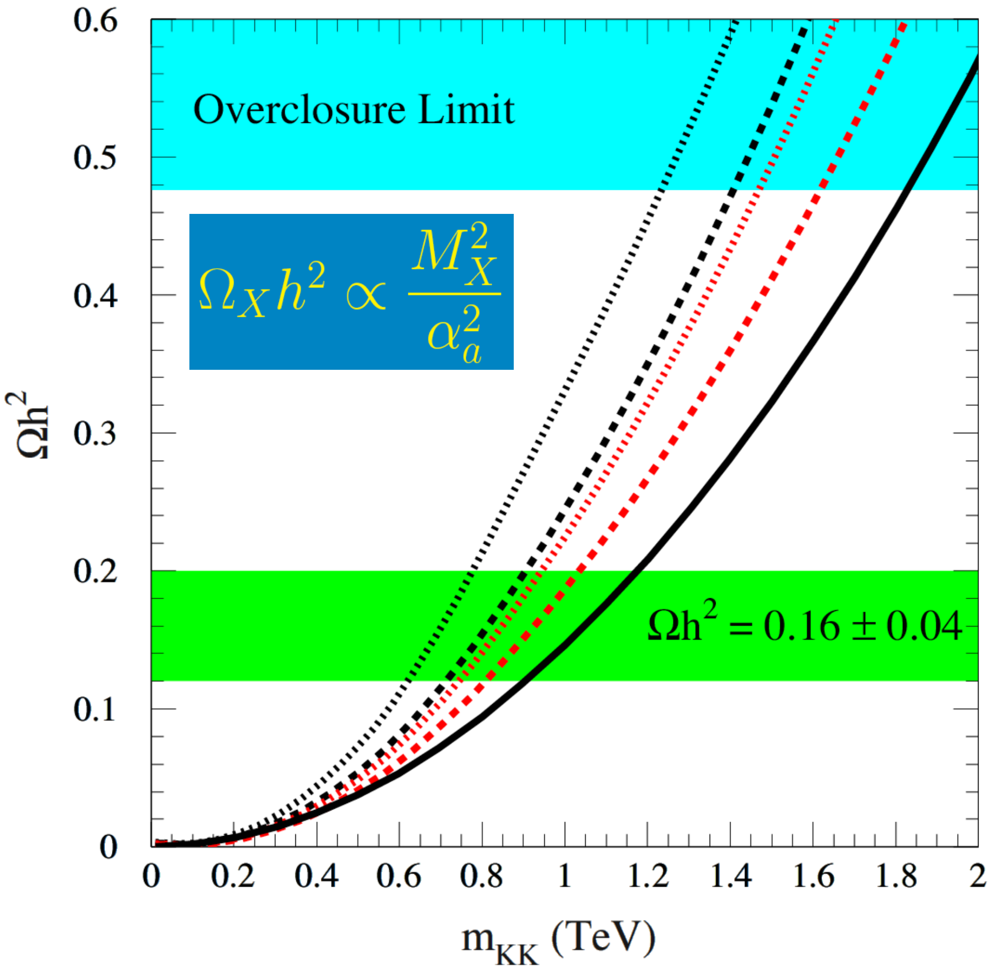
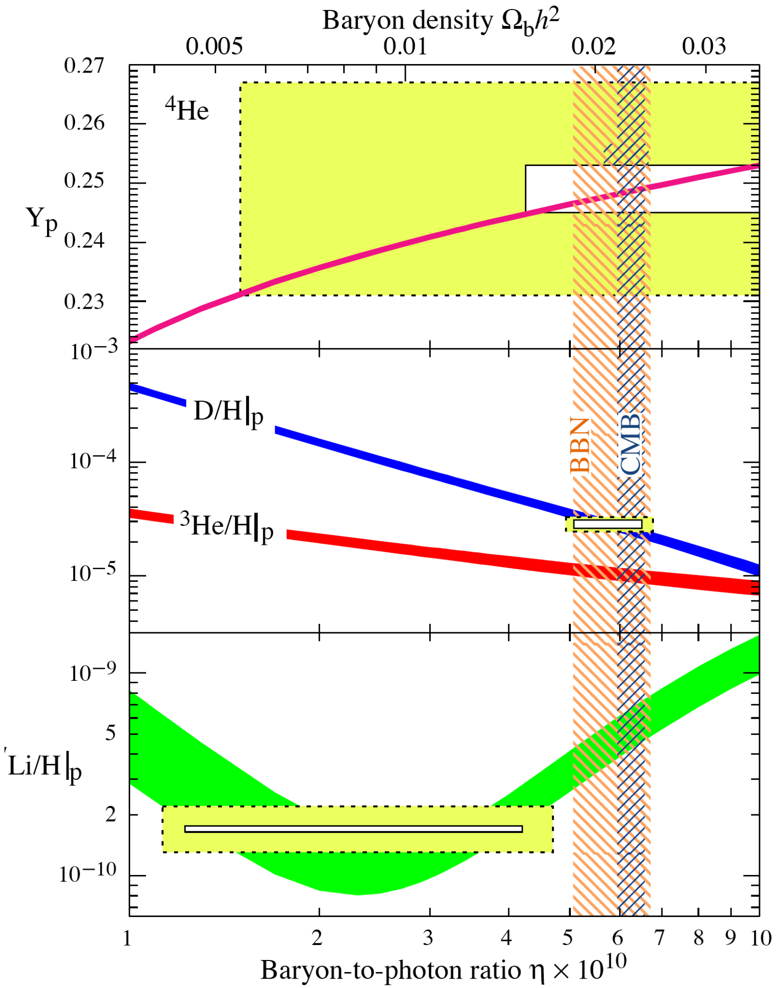


$$\Omega_X h^2 \sim 0.1 \;\Leftrightarrow\; \langle \sigma_{\rm an} v \rangle \sim 3 \times 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1}$$

2) DM annihilation and big-bang nucleosynthesis



• Big-bang nucleosynthesis is in remarkable agreement with observations of light element abudances although some tension exists for ^{7}Li.

$$^7\mathrm{Li/H}\big|_{\mathrm{th}} = 5.24\ {}^{+0.71}_{-0.67} \times 10^{-10} \text{ whereas } {}^7\mathrm{Li/H}\big|_{\mathrm{obs}} \simeq 1 - 2 \times 10^{-10}$$

The lithium problem

• Big-bang nucleosynthesis is in remarkable agreement with observations of light element abudances although some tension exists for ^{7}Li. That element is essentially produced through $^4\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ with subsequent electron capture of ^{7}Be into ^{7}Li. The reaction $^4\mathrm{He} + {}^3\mathrm{H} \rightarrow {}^7\mathrm{Li} + \gamma$ contributes also but in a lesser extent.

$$^7\mathrm{Li/H}\big|_{\mathrm{th}} = 5.24 \;{}^{+0.71}_{-0.67} \times 10^{-10} \text{ whereas } {}^7\mathrm{Li/H}\big|_{\mathrm{obs}} \simeq 1 - 2 \times 10^{-10}$$

• ^{6}Li is formed in the reaction $^4\mathrm{He} + \mathrm{D} \rightarrow {}^6\mathrm{Li} + \gamma$ which is extremely inefficient.

$$^6\mathrm{Li/H}\big|_{\mathrm{th}} \sim 10^{-14} \text{ whereas } {}^6\mathrm{Li}/{}^7\mathrm{Li}\big|_{\mathrm{HD\,84937}} = 0.052 \pm 0.019$$

DM species annihilations or decays inject SM particles

Injection of electromagnetic species in the primordial plasma

• Photons injected in the primordial plasma generate electromagnetic showers as long as $E_\gamma \geq E_C \simeq m_e^2/22\,T$. Interactions on CMB photons are dominant because η is so small.

• Shower photons with $E_\gamma \leq E_C$ can pair produce on protons and ^{4}He nuclei and Compton scatter off plasma electrons.

• A small fraction of photons with $E_\gamma \leq E_C$ may photodisintegrate D below 3 keV – D destruction – and then ^{4}He below 0.3 keV – D and ^{3}He production with ^{3}He/D overproduction.

DM species annihilations or decays inject SM particles

Injection of hadrons in the primordial plasma

- Injection of $\pi^\pm$ induces charge exchange reactions $\pi^- + \mathrm{p} \rightarrow \pi^0 + \mathrm{n}$ between 1 MeV and 300 keV. Creation of extra neutrons after n/p freeze-out implies an increase of the helium mass fraction Y_p.

- Antinucleons injected in the primordial plasma preferentially annihilate on protons so that Y_p also increases.

- Any extra neutrons injected at $T \sim 40$ keV may lead to an important depletion of ^{7}Be. This may solve the lithium problem.

- At lower temperatures, energetic neutrons and protons can destroy ^{4}He through $\mathrm{n} + {}^4\mathrm{He} \rightarrow {}^3\mathrm{H} + \mathrm{p} + \mathrm{n} + (\pi\text{'s})$ or $\mathrm{n} + {}^4\mathrm{He} \rightarrow \mathrm{D} + \mathrm{p} + 2\mathrm{n} + (\pi\text{'s})$. This may lead to the overproduction of D and the production of ^{6}Li.

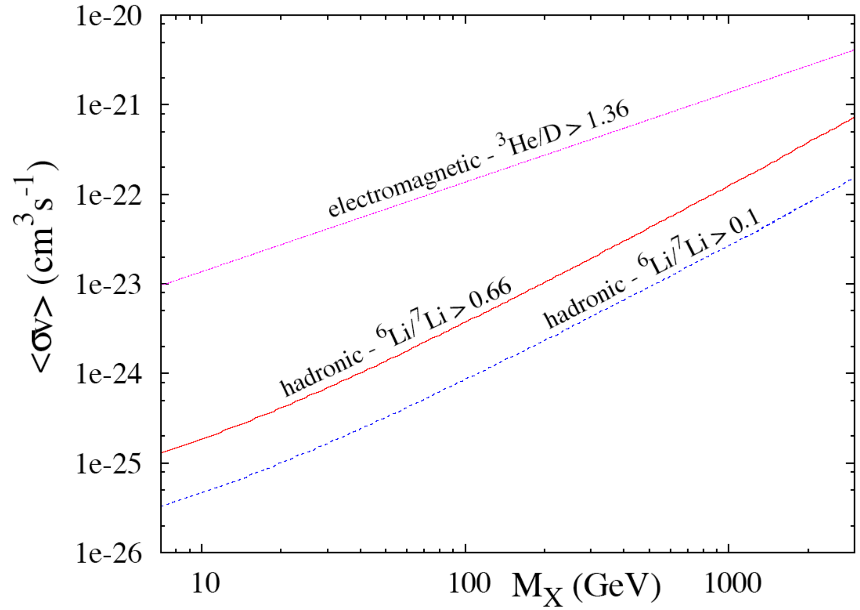
• Energetic ^{3}He and ^{3}H may be produced via spallation (hadronic) or photo-disintegration (electromagnetic) reactions so that efficient production of ^{6}Li is possible through

$$^3\mathrm{H} + {^4\mathrm{He}} \rightarrow {^6\mathrm{Li}} + \mathrm{n} - 4.78\ \mathrm{MeV}\ \text{whilst}\ {^3\mathrm{He}} + {^4\mathrm{He}} \rightarrow {^6\mathrm{Li}} + \mathrm{p} - 4.02\ \mathrm{MeV}$$

^{6}Li is a sensitive proble of DM annihilation

• If neutrons are injected between 60 and 30 keV – during or just after ^{7}Be synthesis – that element will be converted into ^{7}Li and destroyed via the reactions

$$\mathrm{n} + {^7\mathrm{Be}} \rightarrow \mathrm{p} + {^7\mathrm{Li}} \rightarrow {^4\mathrm{He}} + {^4\mathrm{He}}$$



Karsten Jedamzik[a] **and Maxim Pospelov**[b,c]

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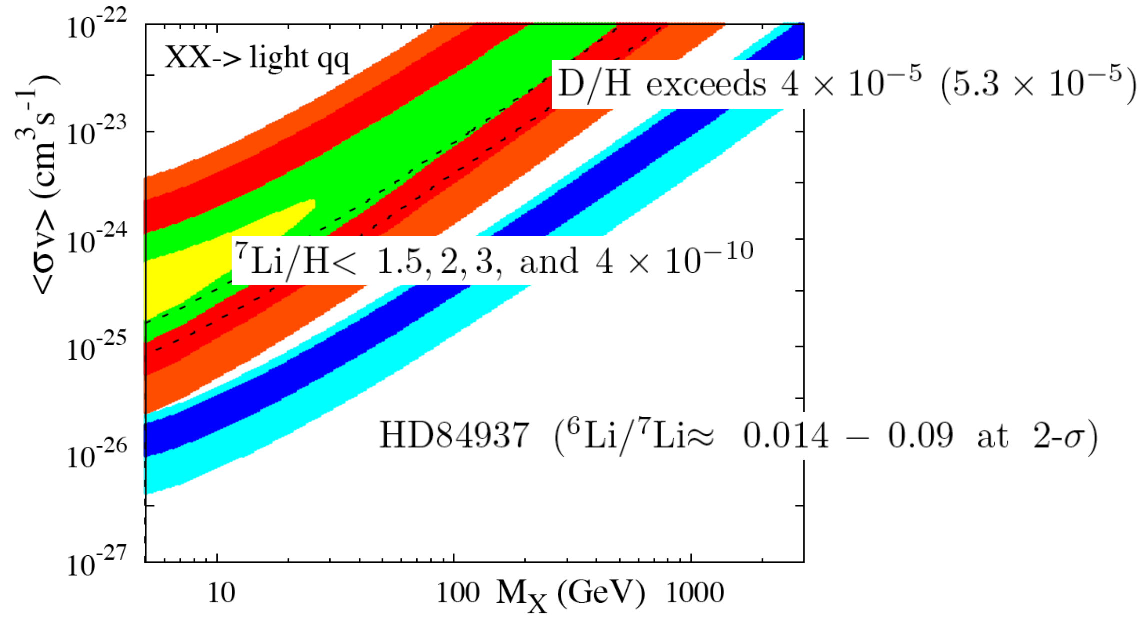
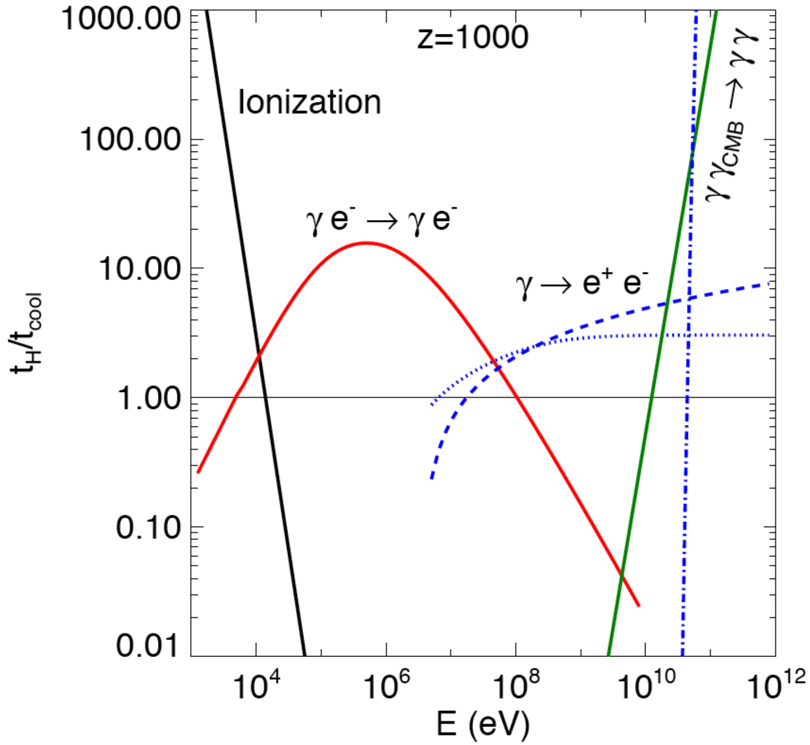


Karsten Jedamzik[(a)] **and Maxim Pospelov**[(b,c)]

3) CMB constraints on DM annihilation

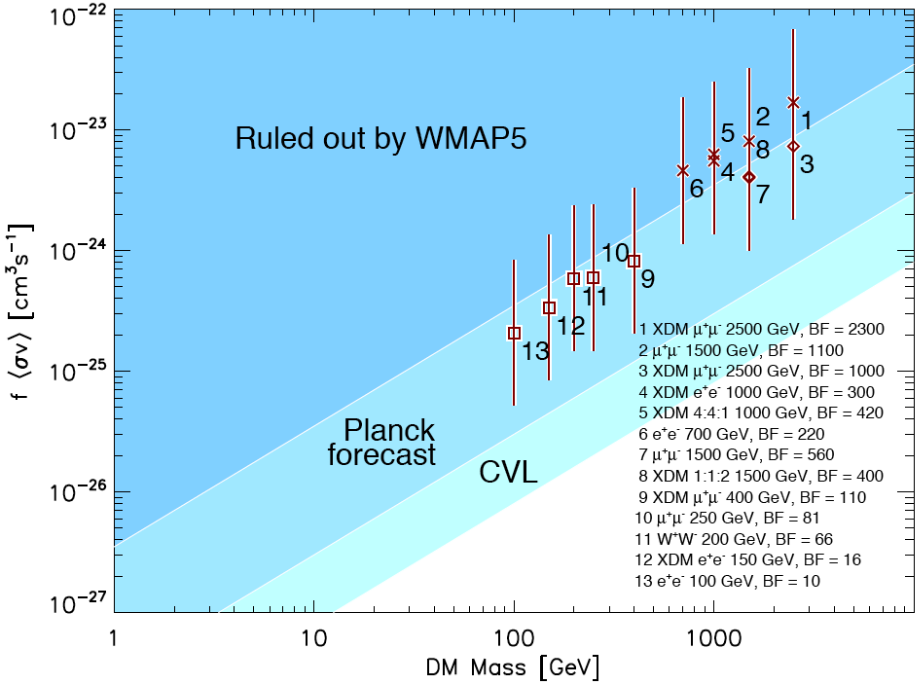
• Annihilation of DM species after recombination injects energy in the IGM which can be reionized more rapidly than in the conventional scenario.

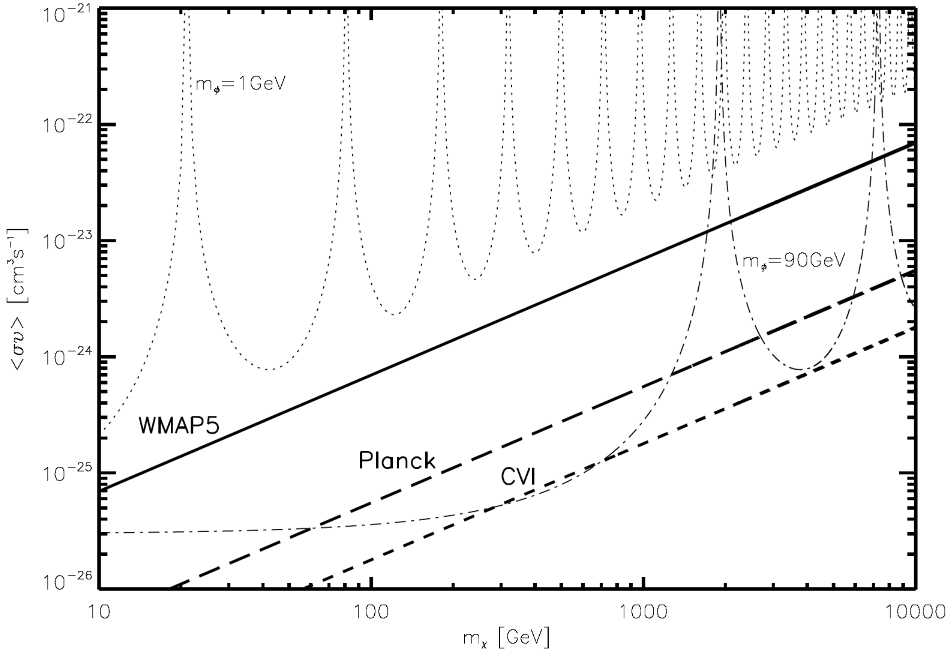
• Heating and ionization of the IGM occurs primarily through the electrons, positrons and photons injected as a result of DM annihilation.



Tracy R. Slatyer,[1,*] Nikhil Padmanabhan,[2,†] and Douglas P. Finkbeiner[1,3,‡]

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





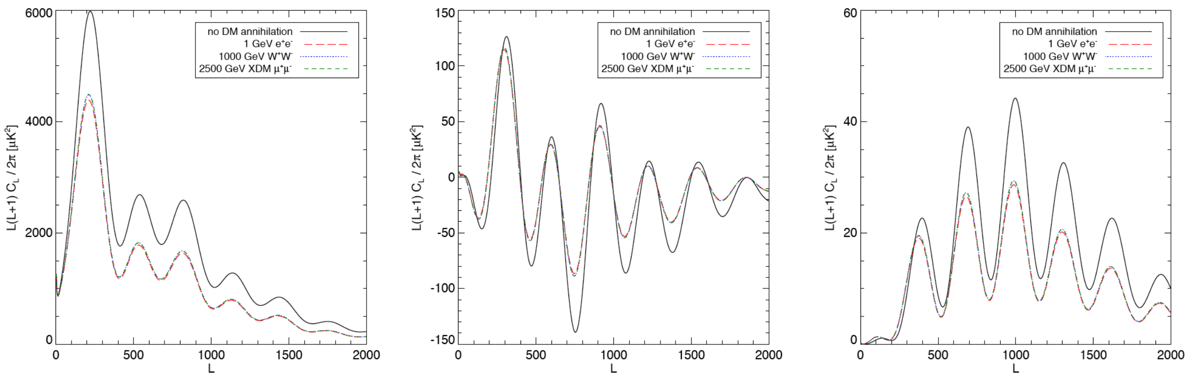
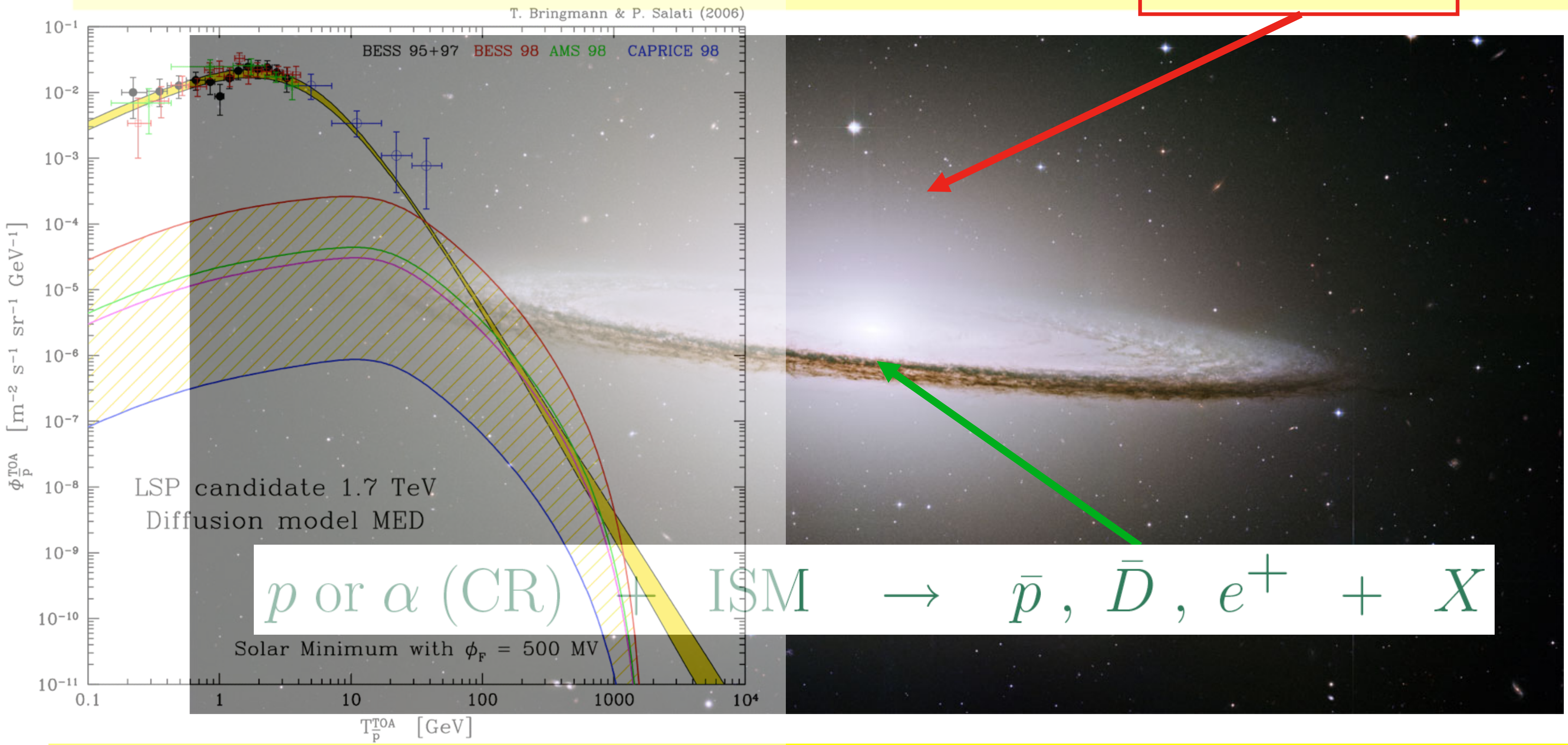


FIG. 5: CMB power spectra for three different DM annihilation models, with power injection normalized to that of a 1 GeV WIMP with thermal relic cross section and $f = 1$, compared to a baseline model with no DM annihilation. The models give similar results for the TT (*left*), TE (*middle*), and EE (*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 σ_8 [4].

4) 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 :

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



Antimatter is already manufactured inside the galactic disk

Antiproton Production in the Galaxy

- **Secondary** antiprotons are produced through the spallations of cosmic–ray protons on the interstellar material.

$$p\,(\mathrm{CR}) \;+\; H\,(\mathrm{ISM}) \;\longrightarrow\; \bar{\mathrm{p}} \;+\; X$$

$$\Downarrow$$

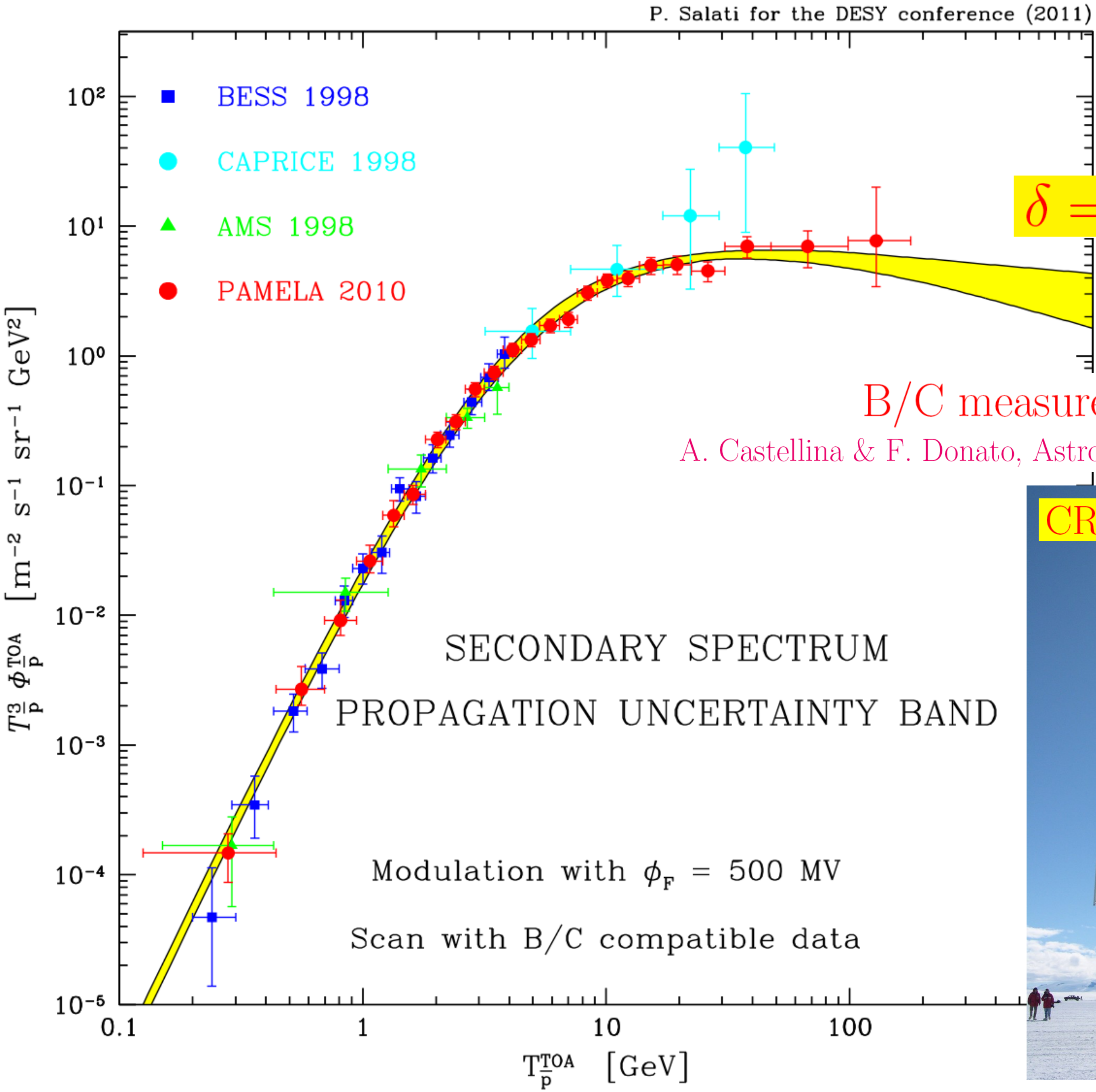
$$q_{\bar{\mathrm{p}}}^{\mathrm{sec}}(r, E_{\bar{\mathrm{p}}}) \;=\; \int_{E_{\mathrm{p}}^{0}}^{+\infty} \frac{d\sigma_{\mathrm{pH}\to\bar{\mathrm{p}}}}{dE_{\bar{\mathrm{p}}}} \left\{E_{\mathrm{p}} \to E_{\bar{\mathrm{p}}}\right\} \; n_{\mathrm{H}}\; v_{\mathrm{p}}\; \psi_{\mathrm{p}}(r, E_{\mathrm{p}})\; dE_{\mathrm{p}}$$

- **Primary** antiprotons originate from the annihilations of the dark matter particles – LKP and LZP species here – concealed inside the galactic halo.

$$\chi \;+\; \chi \;\longrightarrow\; q \;+\; \bar{q} \;\longrightarrow\; \bar{\mathrm{p}} \;+\; X$$

$$\Downarrow$$

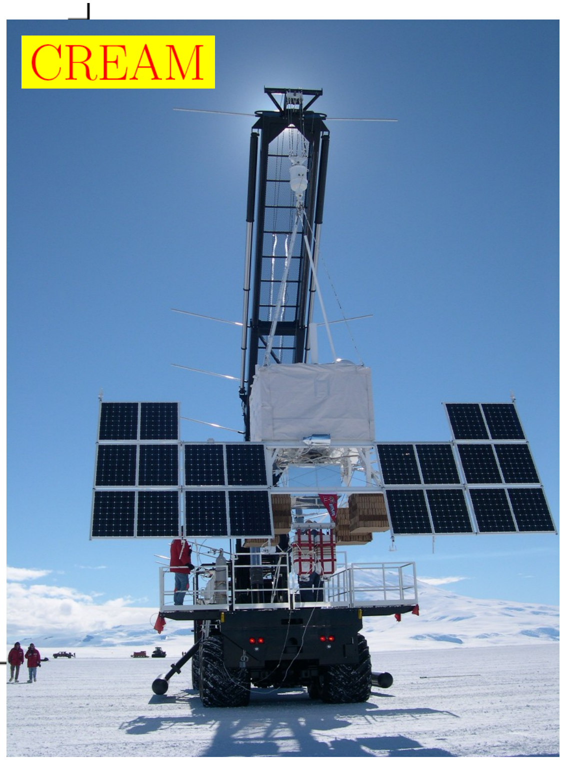
$$q_{\bar{\mathrm{p}}}^{\mathrm{susy}}(r, z, E_{\bar{\mathrm{p}}}) \;=\; \frac{1}{2}\,\langle\sigma_{\mathrm{ann}} v\rangle\; g\left(T_{\bar{\mathrm{p}}}\right)\; \left\{\frac{\rho_{\chi}(r, z)}{m_{\chi}}\right\}^{2}$$



$\delta = 0.46$ to 0.85

B/C measurements @ high E

A. Castellina & F. Donato, Astropart. Phys. **24** (2005) 146-159



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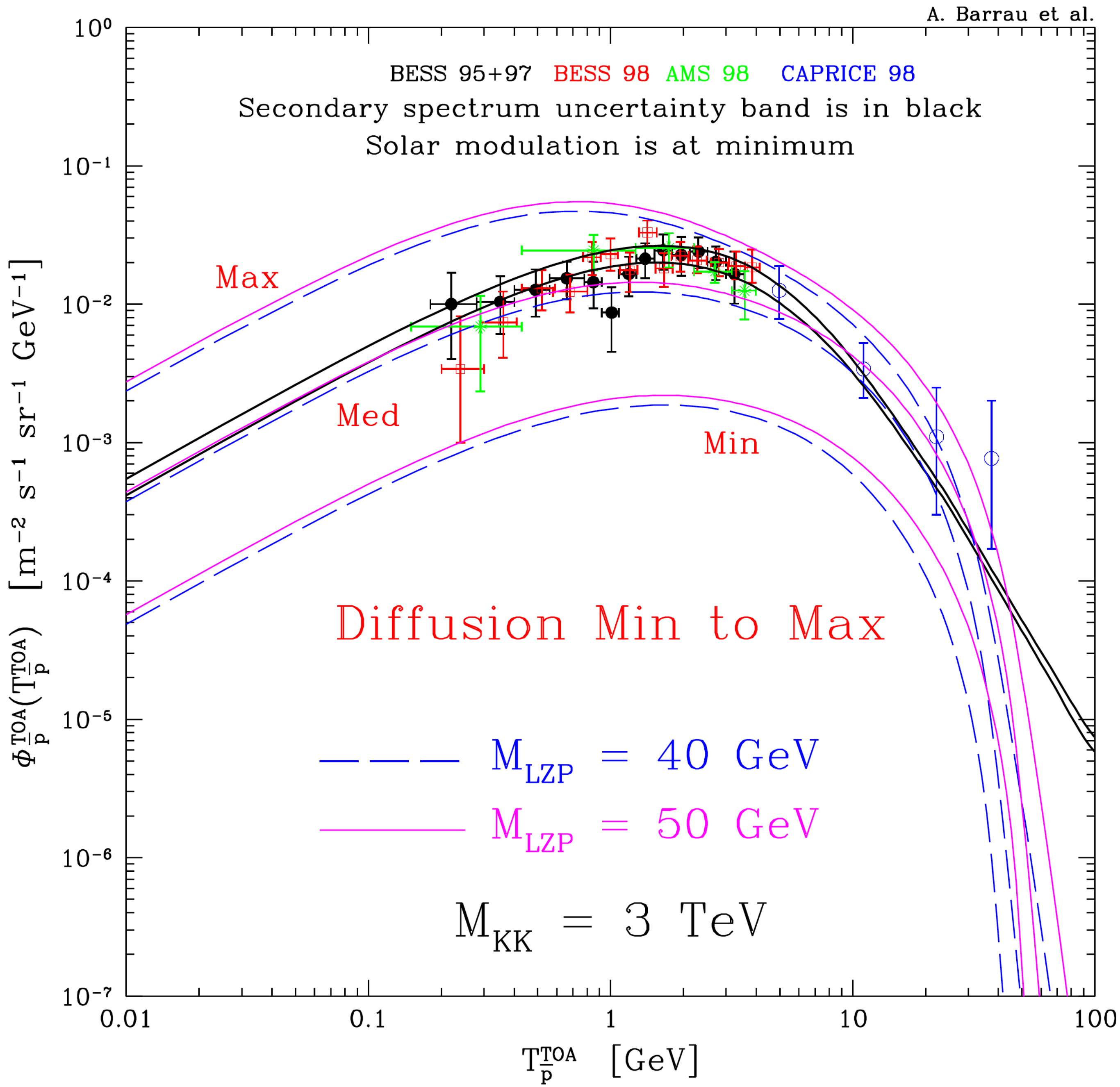
Galactic CR propagation is uncertain

case	δ	$K_0(\mathrm{kpc}^2/\mathrm{Myr})$	$L(\mathrm{kpc})$	$V_c(\mathrm{km/sec})$	$V_A(\mathrm{km/sec})$
max	0.46	0.0765	15	5	117.6
med	0.70	0.0112	4	12	52.9
min	0.85	0.0016	1	13.5	22.4

Astrophysical parameters giving the maximal, medium and minimal LZP antiproton flux and compatible wih B/C analysis


A. Barrau et al.
BESS 95+97 BESS 98 AMS 98 CAPRICE 98
Secondary spectrum uncertainty band is in black
Solar modulation is at minimum
Max
Med
Min
Diffusion Min to Max
M_{LZP} = 40 GeV
M_{LZP} = 50 GeV
M_{KK} = 3 TeV
$\Phi_{\bar{p}}^{TOA}(T_{\bar{p}}^{TOA})$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
$T_{\bar{p}}^{TOA}$ [GeV]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.01
0.1
1
10
100

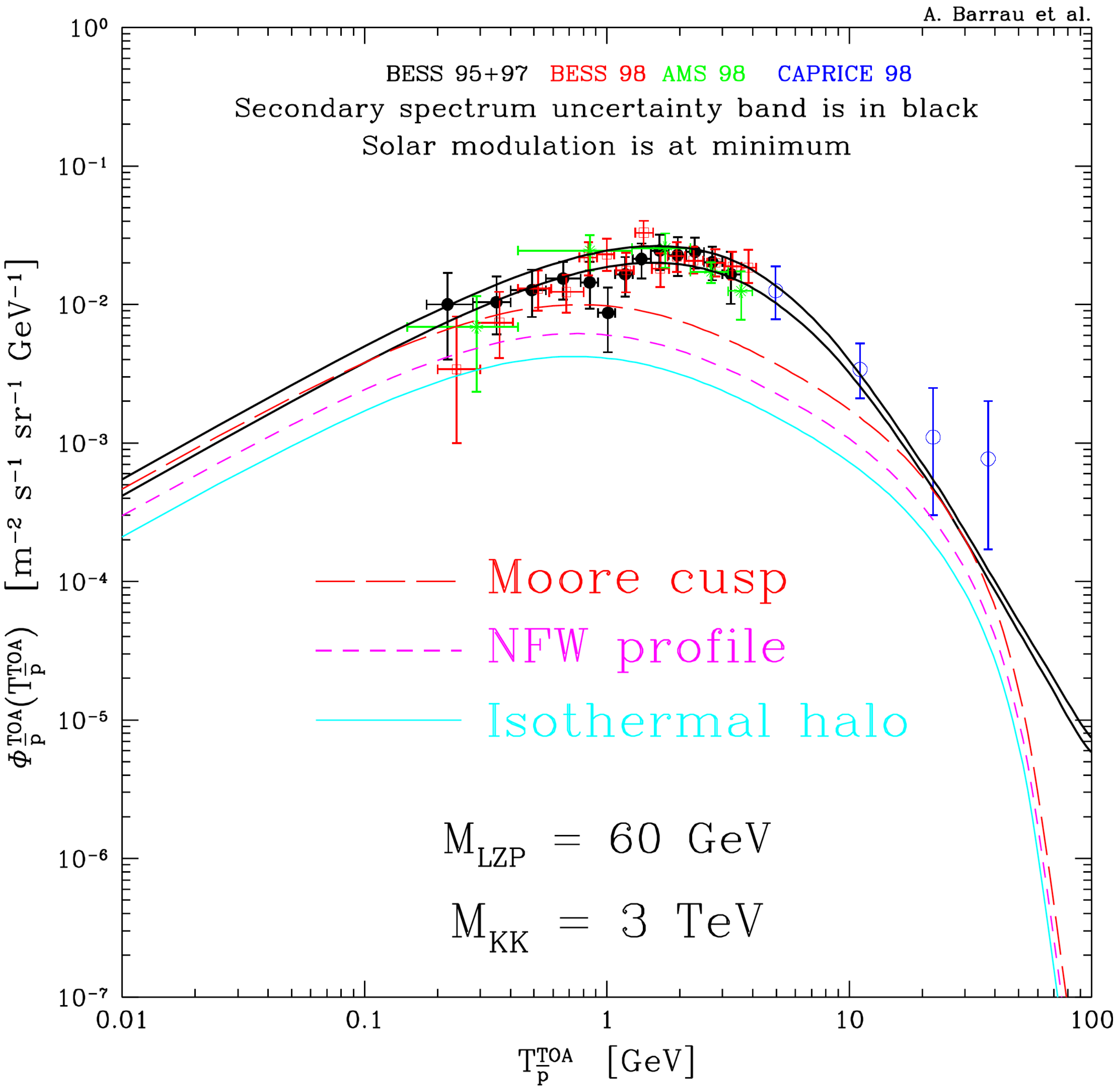
Halo profile is unknown

$$\rho_{\text{CDM}}(r) \;=\; \rho_{\text{CDM}\,\odot} \left\{\frac{r_\odot}{r}\right\}^\gamma \left\{\frac{1\,+\,(r_\odot/a)^\alpha}{1\,+\,(r/a)^\alpha}\right\}^{(\beta-\gamma)/\alpha}$$

$$\rho_{\text{CDM}\,\odot} = 0.3 \text{ GeV cm}^{-3}$$

Halo model	α	β	γ	a [kpc]
Cored isothermal [43]	2	2	0	4
Navarro, Frenk & White [32]	1	3	1	25
Moore [34]	1.5	3	1.3	30

Various models for the DM distribution within the Milky Way



A. Barrau et al.
BESS 95+97 BESS 98 AMS 98 CAPRICE 98
Secondary spectrum uncertainty band is in black
Solar modulation is at minimum
Moore cusp
NFW profile
Isothermal halo
M_{LZP} = 60 GeV
M_{KK} = 3 TeV
$\Phi_{\bar{p}}^{TOA}(T_{\bar{p}}^{TOA})$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
$T_{\bar{p}}^{TOA}$ [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.01
0.1
1
10
100

Antiprotons – a sensitive DM probe

Marco Cirelli [a †], **Gaëlle Giesen** [a ‡]

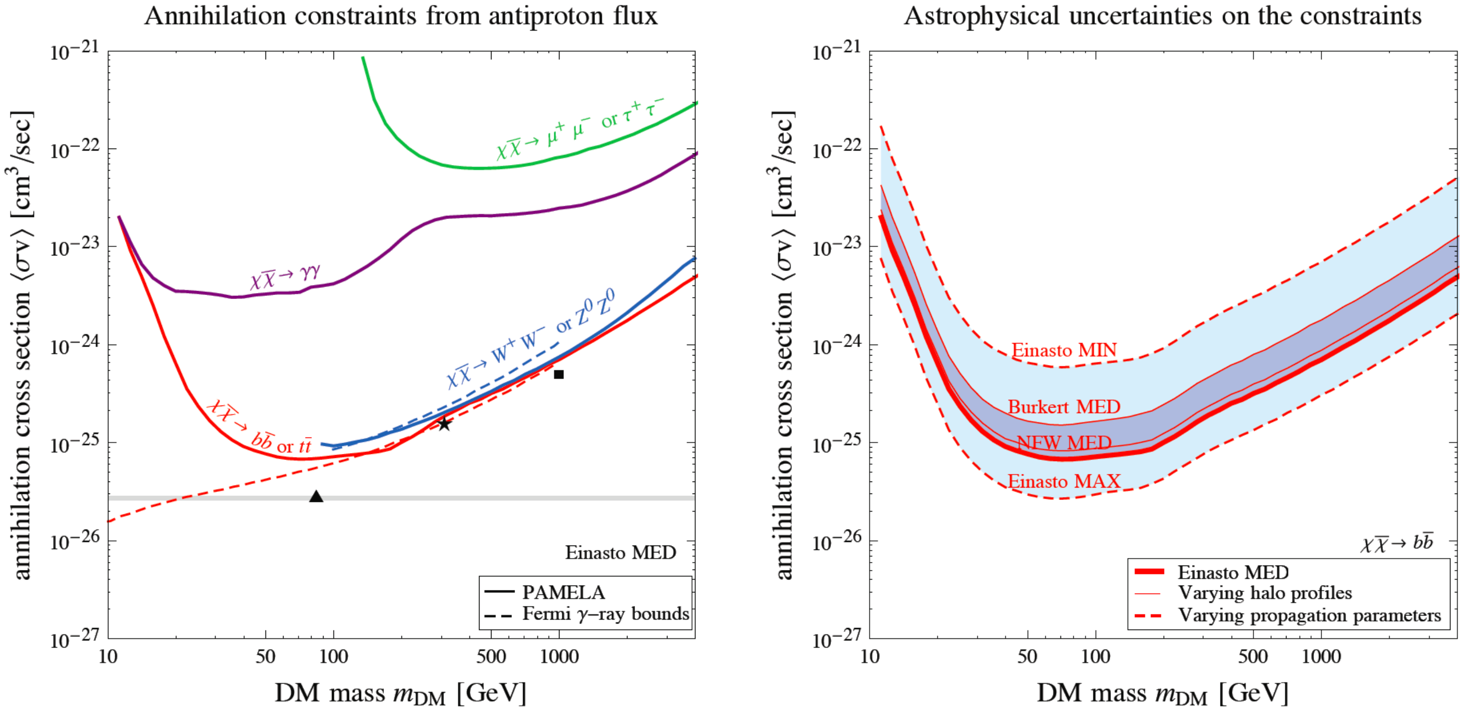
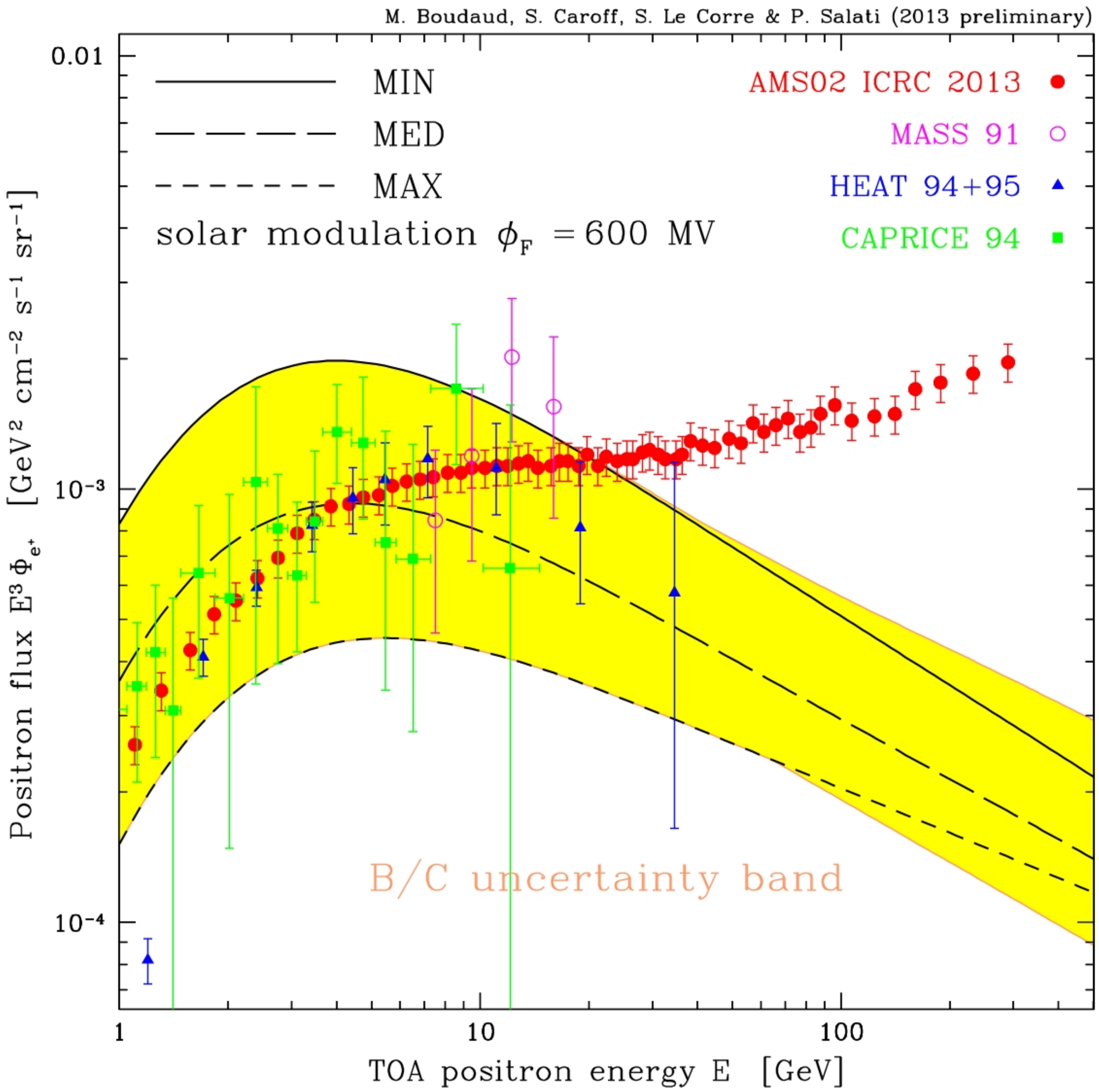


Figure 2: **Annihilating DM: current constraints.** Left Panel: *current constraints from the antiproton measurements by* PAMELA*, for different annihilation channels. The areas above the curves are excluded. The dashed lines reproduce the* γ*-ray constraints from [30], for the same channels. The symbols individuates the parameters used for the analyses in Sec. 3.2.2 while the horizontal band signals the thermal relic cross section.* Right Panel: *illustration of the impact of astrophysical uncertainties: the constraint for the* $b\bar{b}$ *channel spans the shaded band when varying the propagation parameters (dashed lines) or the halo profiles (solid lines).*

Positrons – the revenge of orthodoxy



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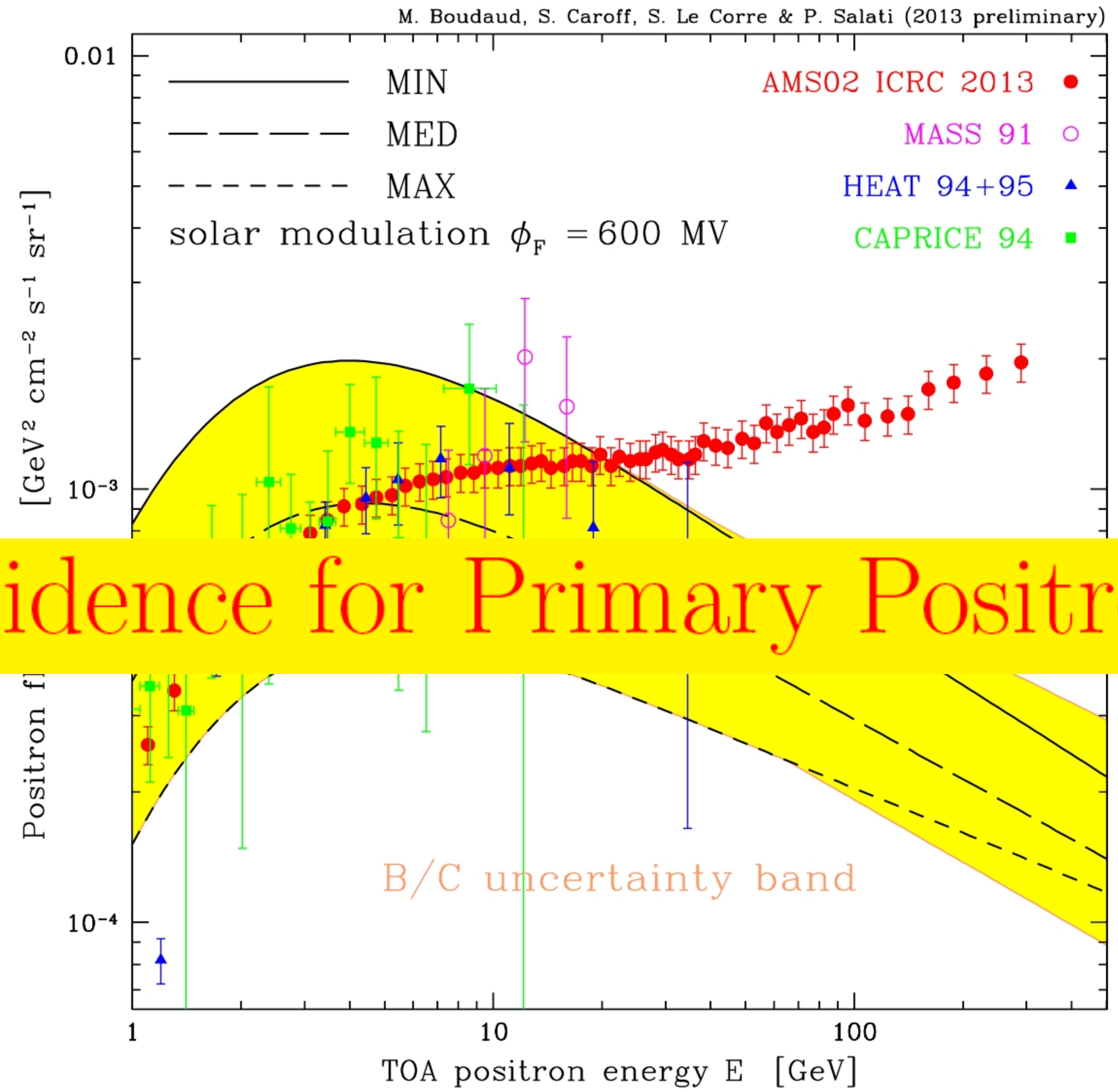


Evidence for Primary Positrons

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_χ 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 $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1}
- Local e$^+$ production means DM density given by $\rho_\odot = 0.3$ GeV cm^{-3}

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

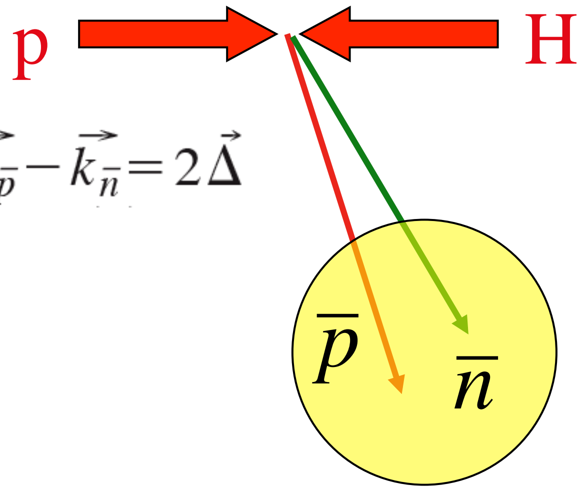
(iii) DM species are **leptophilic** and q channels are suppressed.

Antideuterons – the next challenge

$$B_2 = \int \frac{E_{\bar{\mathrm{D}}}}{E_{\bar{\mathrm{p}}}\, E_{\bar{\mathrm{n}}}}\, d^3\vec{\Delta}\, \mathcal{C}(\vec{\Delta}) \simeq \left(\frac{m_{\bar{\mathrm{D}}}}{m_{\bar{\mathrm{p}}}\, m_{\bar{\mathrm{n}}}}\right) \left(\frac{4}{3}\pi\, {P_{\mathrm{coal}}}^3\right)$$

The coalescence factor B_2

$$\frac{E_{\bar{\mathrm{D}}}}{\sigma_{\mathrm{tot}}}\frac{d^3\sigma_{\bar{\mathrm{D}}}}{d^3\vec{K}} = B_2 \left\{\frac{E_{\bar{\mathrm{p}}}}{\sigma_{\mathrm{tot}}}\frac{d^3\sigma_{\bar{\mathrm{p}}}}{d^3\vec{k}_1}\right\} \left\{\frac{E_{\bar{\mathrm{n}}}}{\sigma_{\mathrm{tot}}}\frac{d^3\sigma_{\bar{\mathrm{n}}}}{d^3\vec{k}_2}\right\}$$



$$\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}} = 2\vec{\Delta}$$

$$B_2 = 4.4 \times 10^{-3}\ \mathrm{GeV}^2$$

$$P_{\mathrm{coal}} = 79\ \mathrm{MeV}$$

F. Donato, N. Fornengo & D. Maurin
Phys. Rev. **D78** (2008) 043506

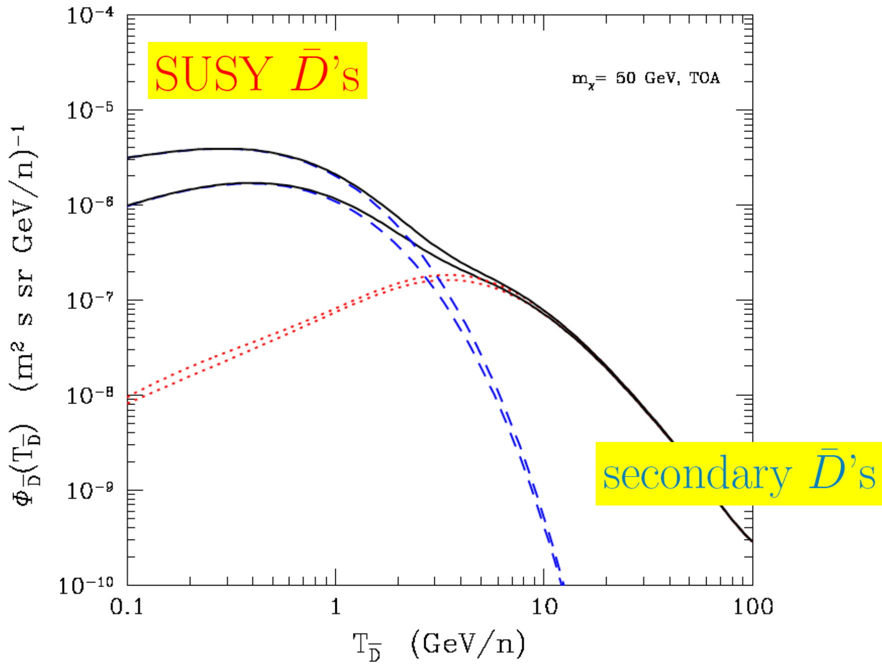
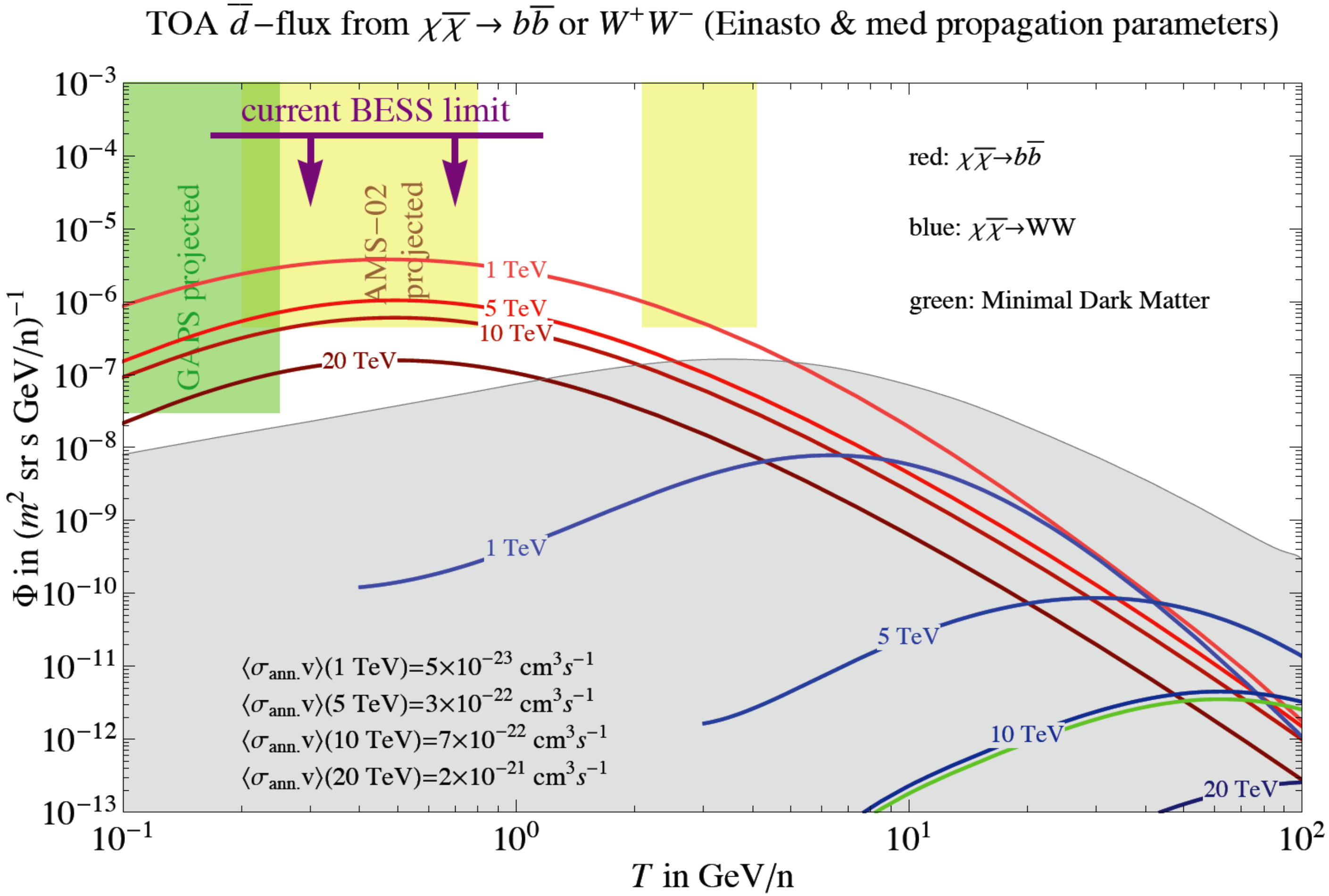


FIG. 7: Interstellar and Top–Of–Atmosphere (TOA) antideuteron fluxes. The dashed (blue) line shows the primary flux for m_χ=50 GeV and $\langle\sigma_{\mathrm{ann}} v\rangle_0 = 2.3 \cdot 10^{-26}$ cm^3 s^{-1}, the (red) dotted line denotes the secondary component and the (black) solid line stands for the total (signal+background) flux. Propagation model is the median one in Table I.

C. B. Bräuninger & M. Cirelli, arXiv:0904.1165



5) DM annihilation and stellar evolution

1978 – If DM species are trapped inside a star, they can transport heat from the center to the outskirts of the object – G. Steigman et al.

1985 – Accretion of WIMPs by the Sun is sufficient to induce a decrease of the central solar temperature and to solve the solar neutrino puzzle – B. Press and D. Spergel.

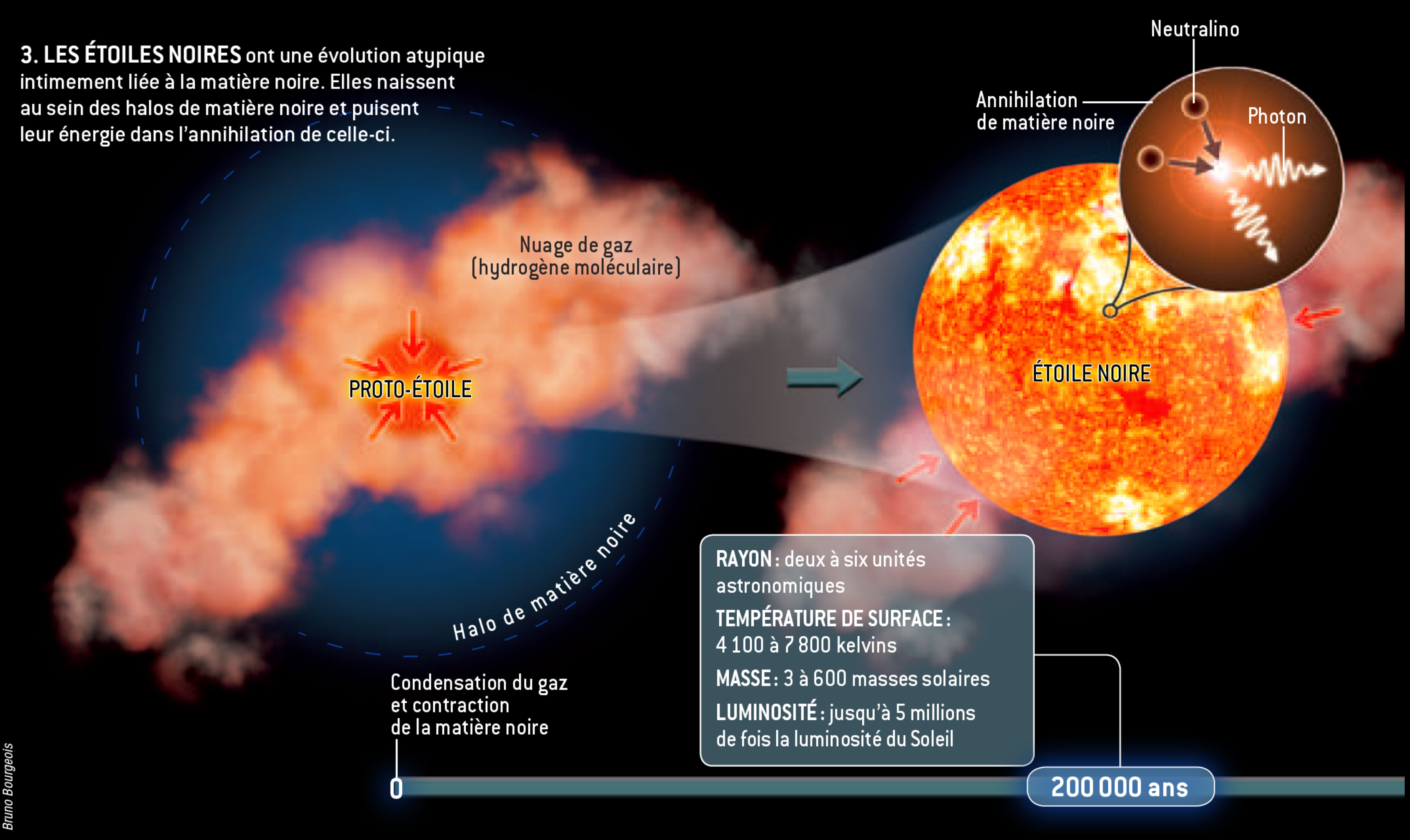
1985 – But DM species annihilate so that they cannot be numerous enough to solve the solar neutrino puzzle – K. Freese et al.

1989 – At the center of DM halos, WIMPs are so numerous that they can significantly alter a star inside which they have been captured – P. Salati and J. Silk.

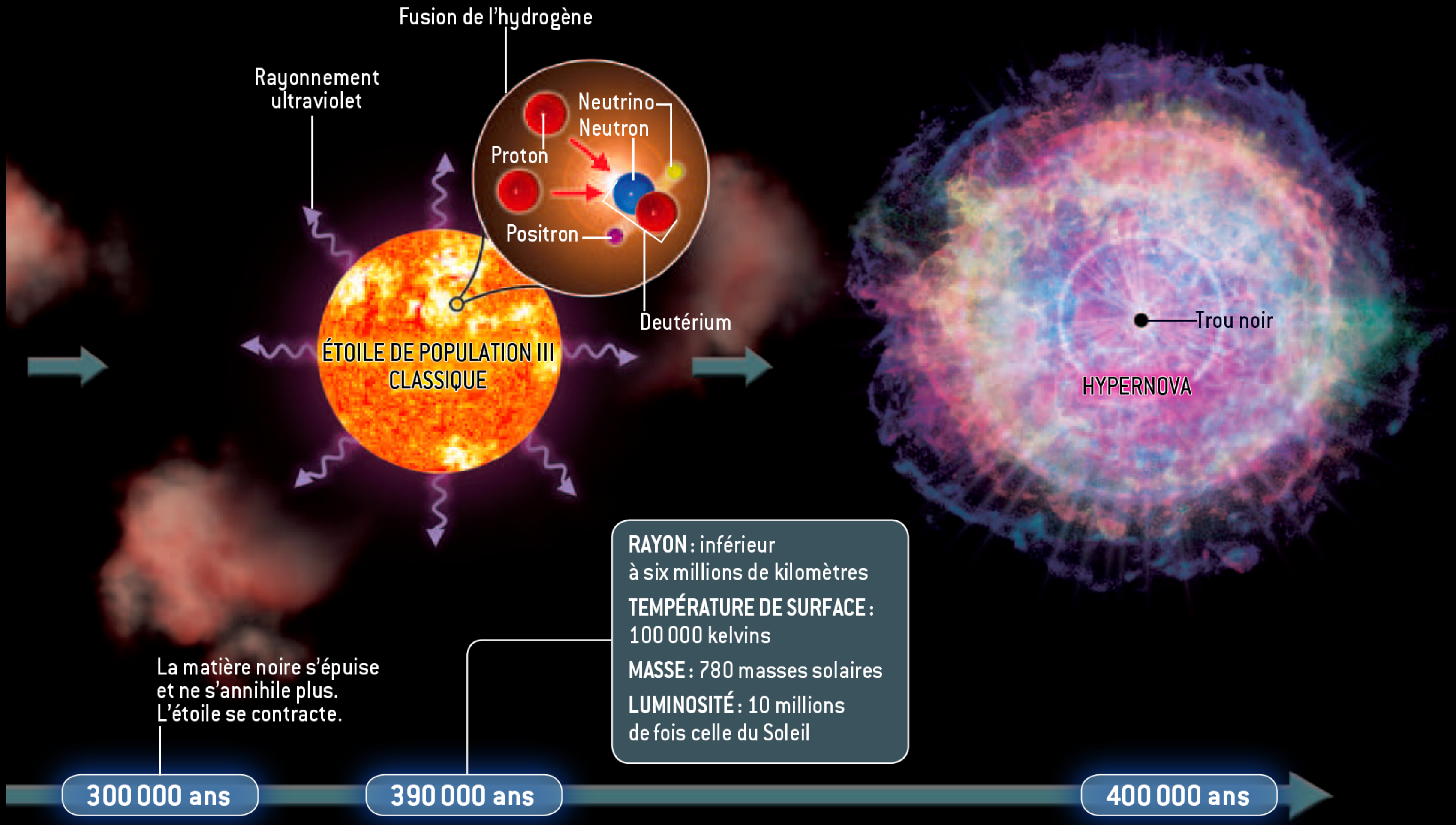
1990 to 2007 – The idea fades away because WIMPs interact so weakly...

2007 – In the early Universe, DM is much denser than today, especially inside DM proto-halos which trigger the formation of Pop III stars. Baryons can drag DM with them during the proto-star formation. The annihilation of DM powers a new kind of object dubbed dark star – K. Freese, P. Gondolo and D. Spolyar.

Dark stars – Pop III stars powered by DM species



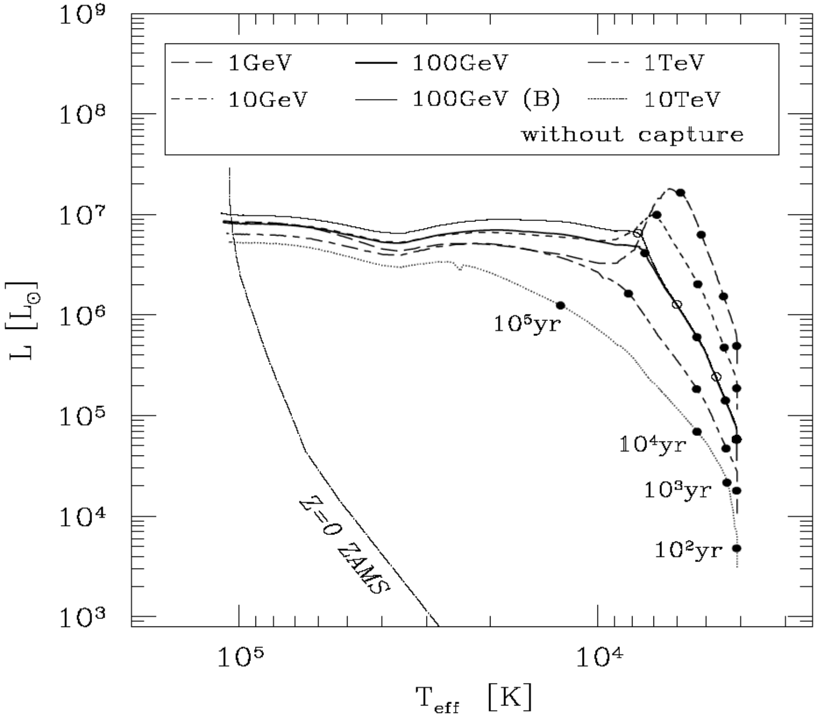
Dark stars – Pop III stars powered by DM species

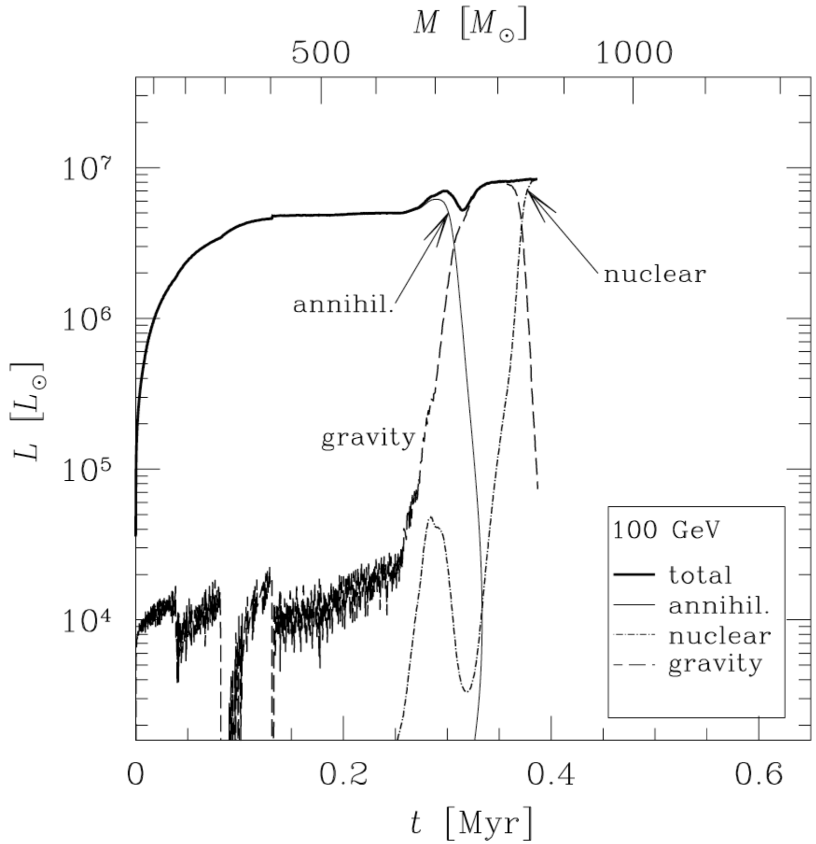


DARK STARS: A NEW LOOK AT THE FIRST STARS IN THE UNIVERSE

Douglas Spolyar[1], Peter Bodenheimer[2], Katherine Freese[3], and Paolo Gondolo[4]

The Astrophysical Journal, 705:1031–1042, 2009 November 1





- Adiabatic DM contraction is the key.
- Detection in the infrared with JWST through the magnified regions of clusters.

Conclusions and perspectives

• Dark matter annihilation has been occuring in many places and at various times since the big-bang. This process is of paramount importance since it generates the WIMP population provided that

$$\Omega_X h^2 \sim 0.1 \;\Leftrightarrow\; \langle \sigma_{\rm an} v \rangle \sim 3 \times 10^{-26} \,{\rm cm}^3 \,{\rm s}^{-1}$$

• DM annihilation during BBN could provide a possible explanation for a primordial lithium abundance smaller than the conventional nucleosynthesis yield.

• The CMB constraints on energy deposition at recombination will set stringent limits on XDM explanations of the PAMELA positron excess.

• Observation of anomalous Pop III stars by JWST could point towards the presence of DM inside these objects, with a completely new stellar evolution.

astro-particle physics !

• DM annihilation today inside the Galactic halo may be indirectly detected by the presence of distortions in the CR energy distributions.

Antimatter CR and DM relation

back-up slides

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

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

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

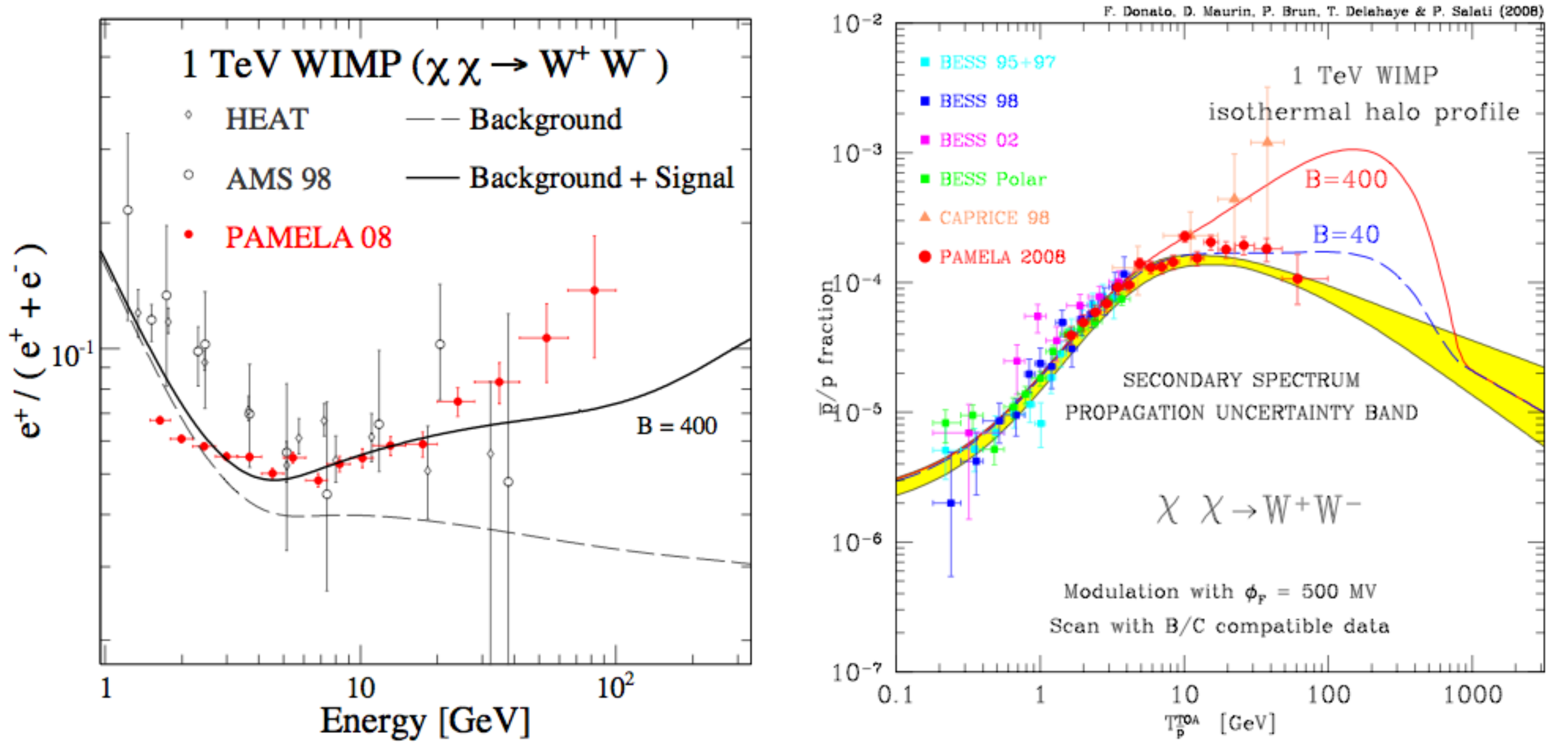


FIG. 3: The fiducial case of a 1 TeV LSP annihilating into a W^+W^- pair is featured. In the left panel, the positron signal which this DM species yields has been increased by a factor of 400, hence the solid curve and a marginal agreement with the PAMELA data. Positron fraction data are from HEAT [18],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

$$\Downarrow$$

$$\chi\,\chi \to l^+ l^-$$

or

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

(ii) But the annihilation rate needs to be considerably enhanced

$\Longrightarrow$ 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

$\Longrightarrow$ 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

$B_{\rm Milky\ Way} \leq 20$ in ΛCDM

– How probable is a single nearby clump ?

$\Longrightarrow$ May be a combination of both effects

Sommerfeld effect – a non–perturbative enhancement of $\sigma_{\rm ann}$ 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

$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2}\right)$$

$$\lambda \geq (\alpha\, m_\chi)^{-1}$$

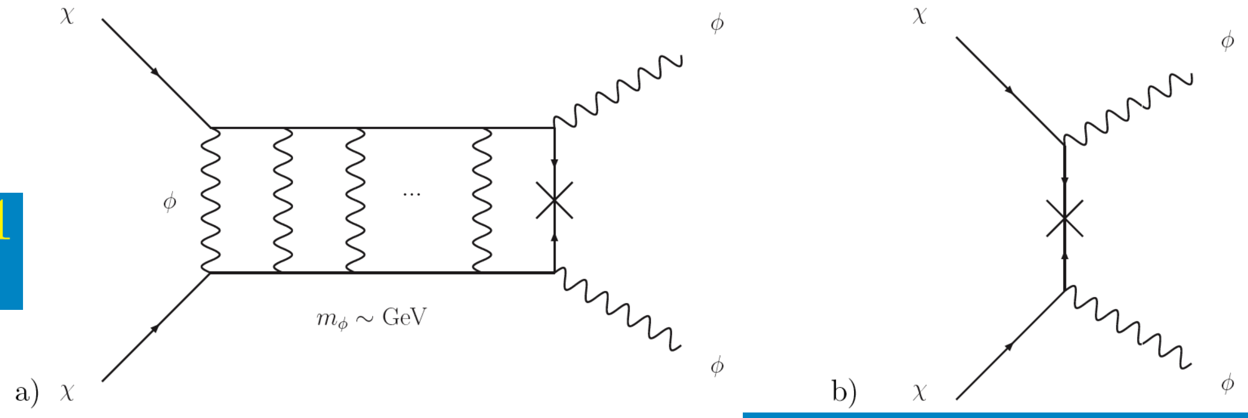
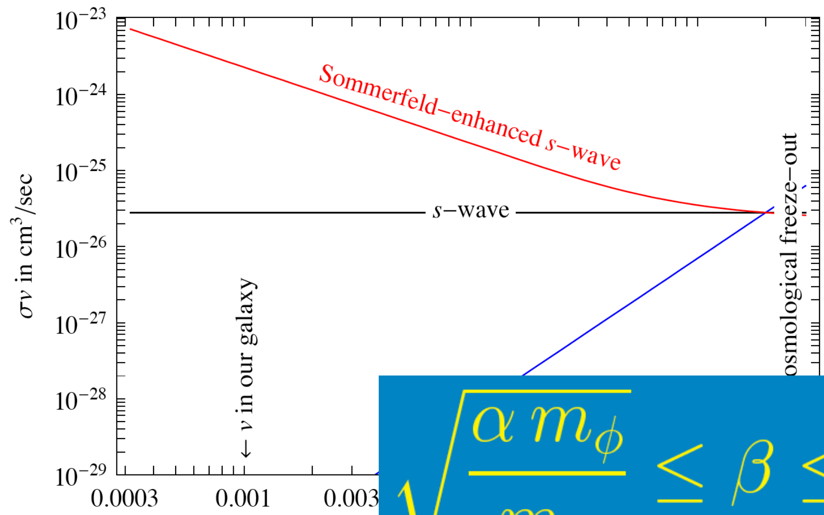
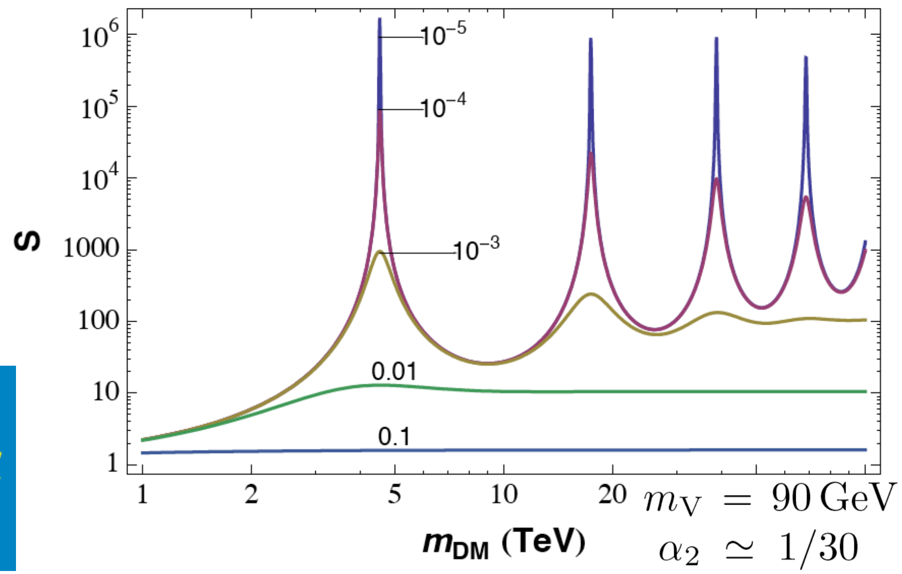


FIG. 3: The annihilation diagrams $\chi\chi \rightarrow \phi\phi$ both with (a) and

$$1/m_\phi \sim n^2/\alpha\, m_\chi$$



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



$m_V = 90$ GeV

$\alpha_2 \simeq 1/30$

- Peculiar and ad'hoc WIMP models

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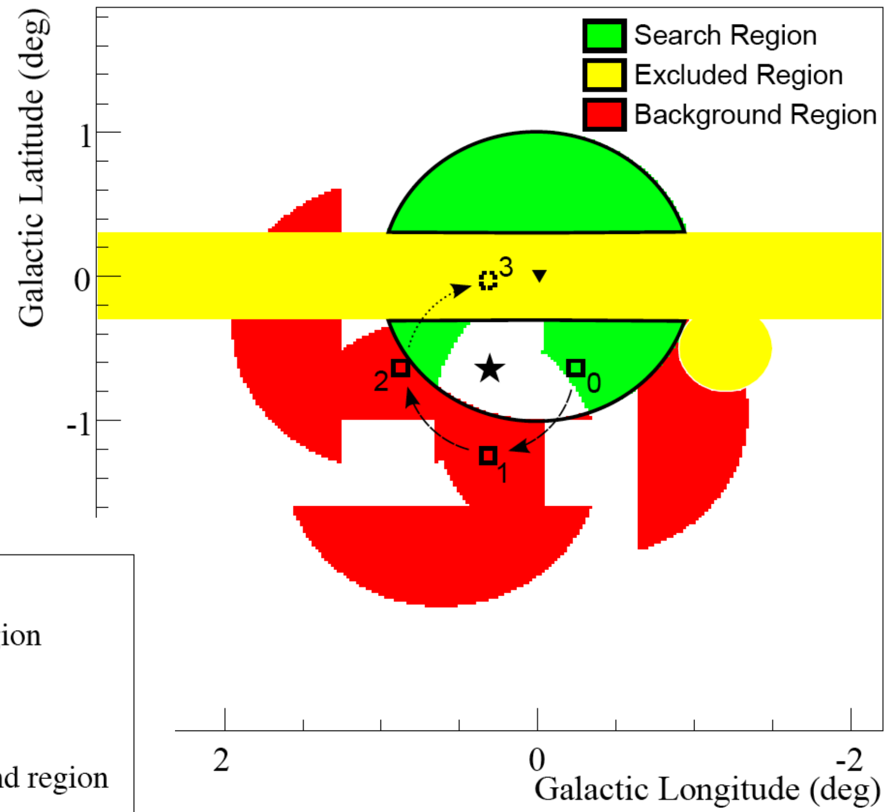
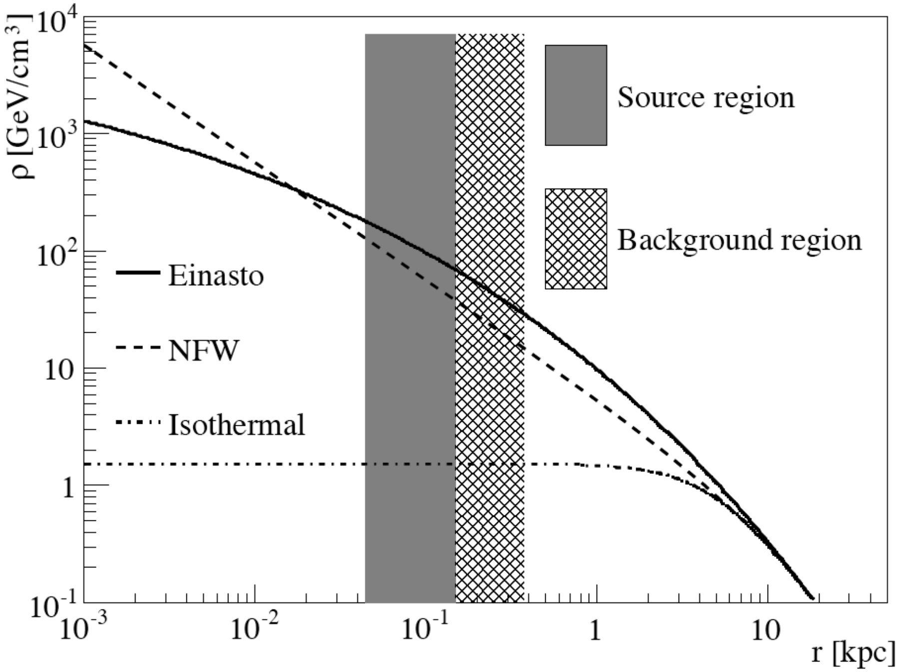
  - ✓ Final State Radiation γ-rays in the absence of quarks.

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

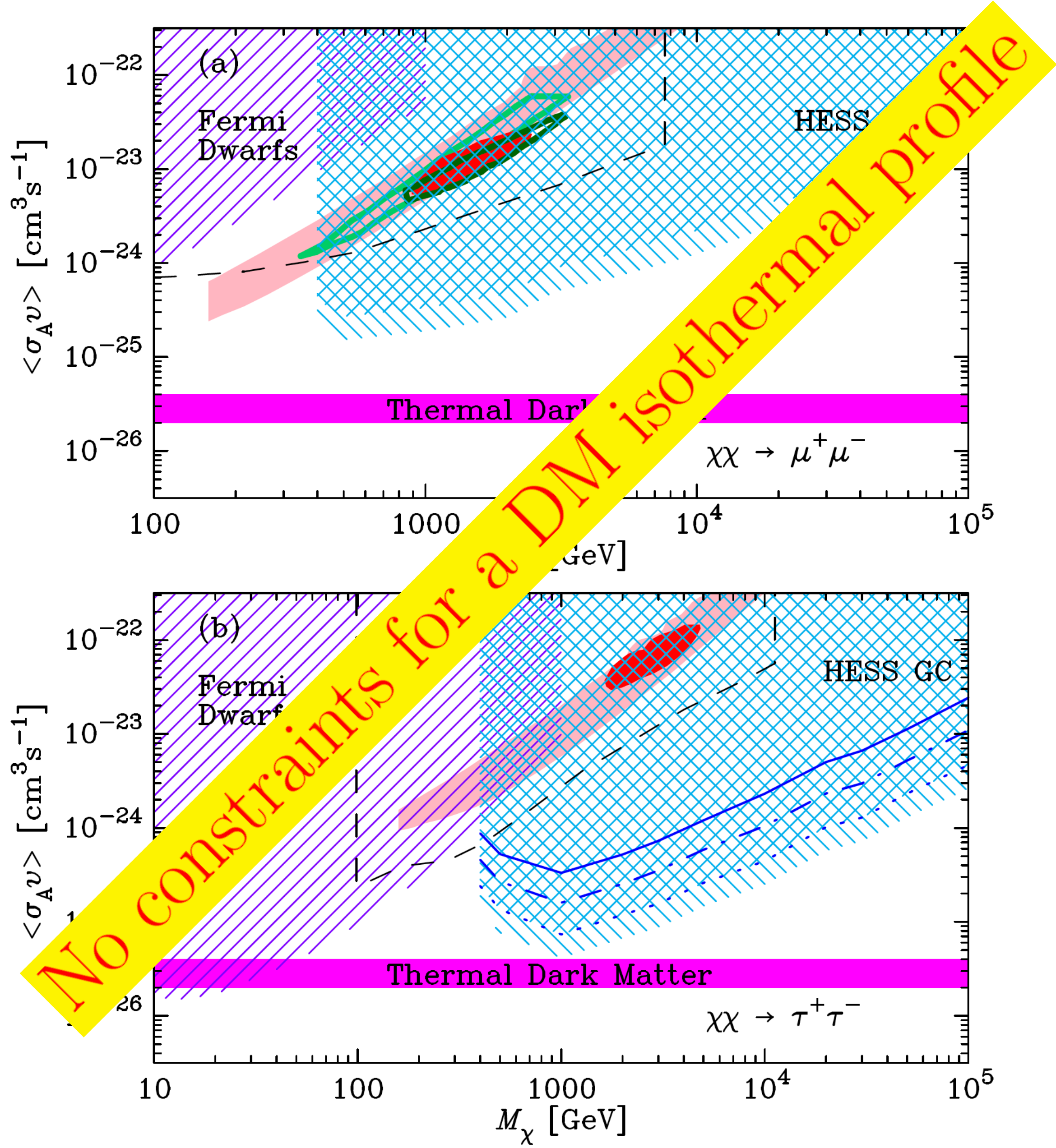
  - ✓ Inverse Compton Scattering of $e^{\pm}$ on CMB and stellar light.
  - ✓ Synchrotron radio emission from $e^{\pm}$ spiraling in **B**.
  - ✓ Energy release in the primordial plasma – constraints from CMB.

Kevork N. Abazajian[a] J. Patrick Harding[a,b]

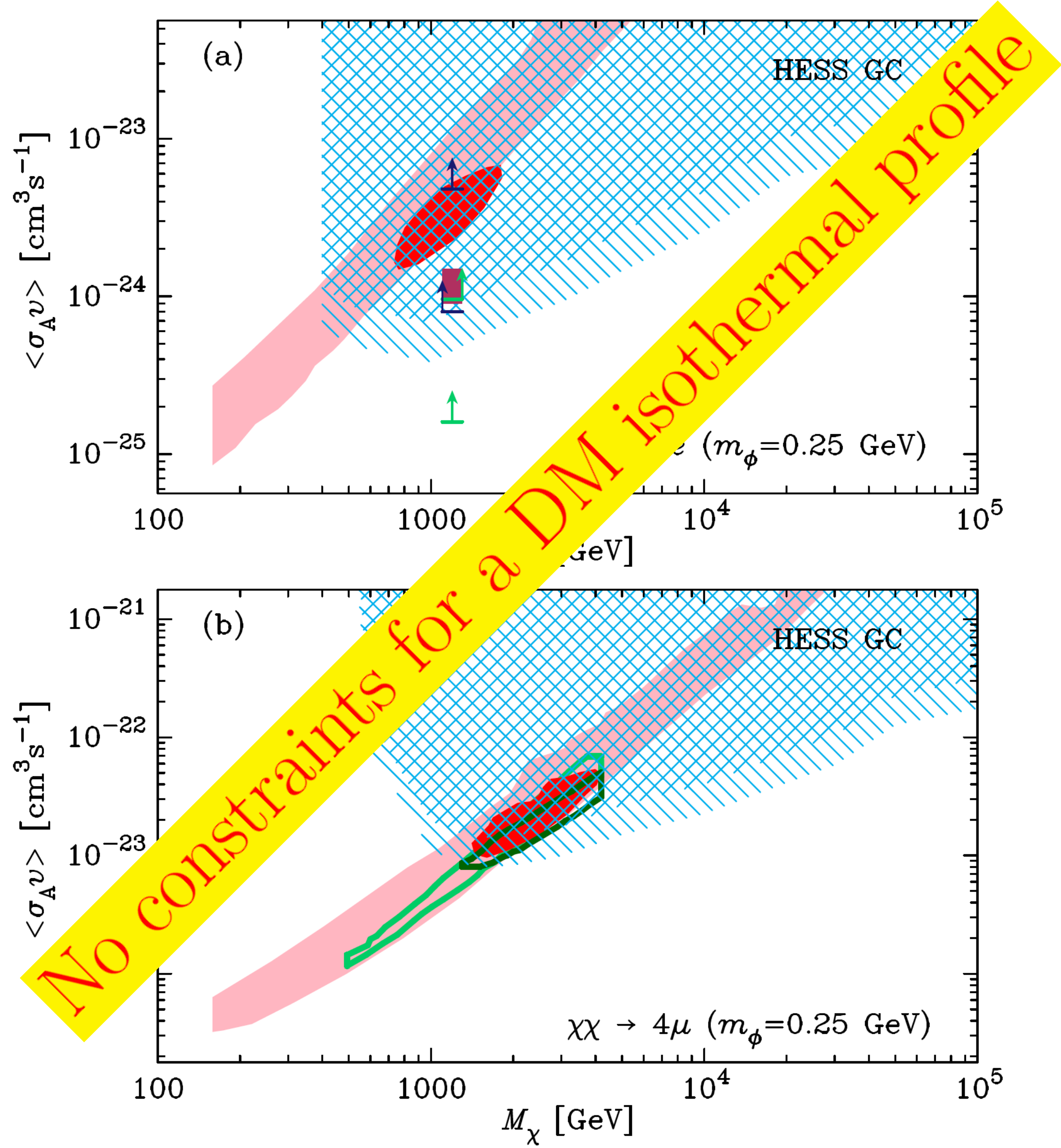




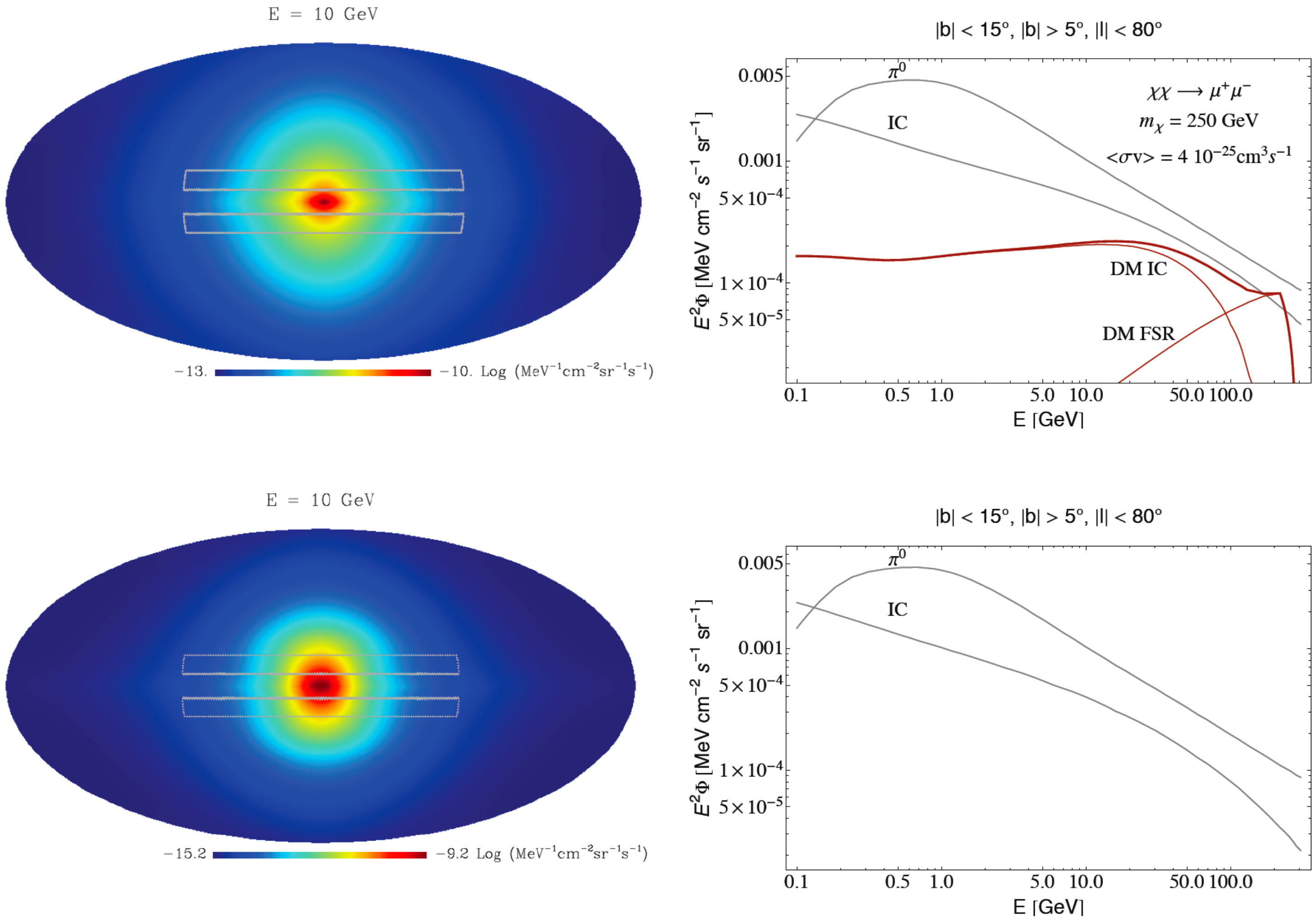
Kevork N. Abazajian[a] **J. Patrick Harding**[a,b]



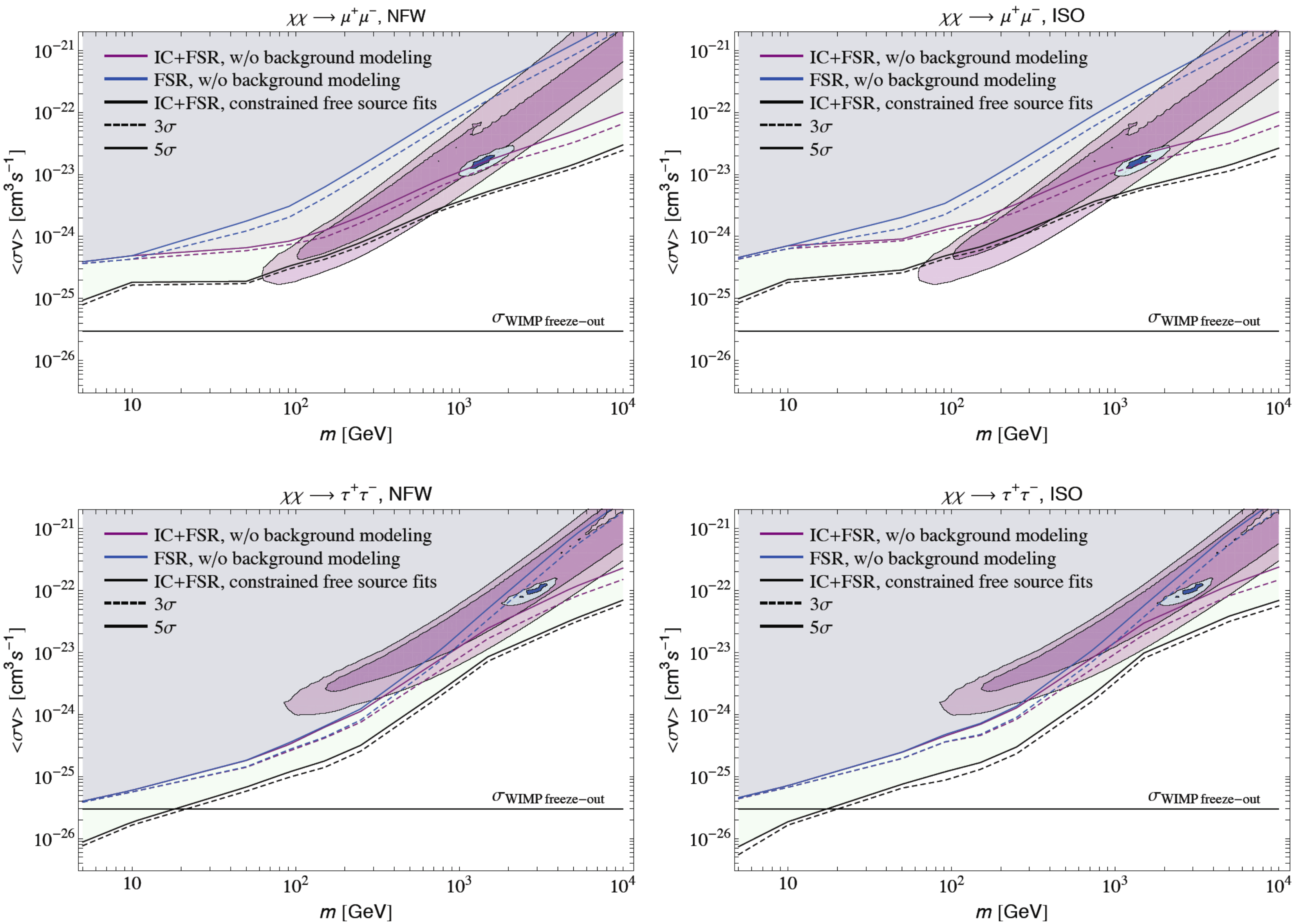
Kevork N. Abazajian[a] J. Patrick Harding[a,b]



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



astrophysical CR source population


χχ ⟶ μ⁺μ⁻, NFW
χχ ⟶ μ⁺μ⁻, ISO
χχ ⟶ τ⁺τ⁻, NFW
χχ ⟶ τ⁺τ⁻, ISO
IC+FSR, w/o background modeling
FSR, w/o background modeling
IC+FSR, constrained free source fits
3σ
5σ
σ WIMP freeze−out
<σv> [cm³s⁻¹]
m [GeV]
10
10²
10³
10⁴
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶

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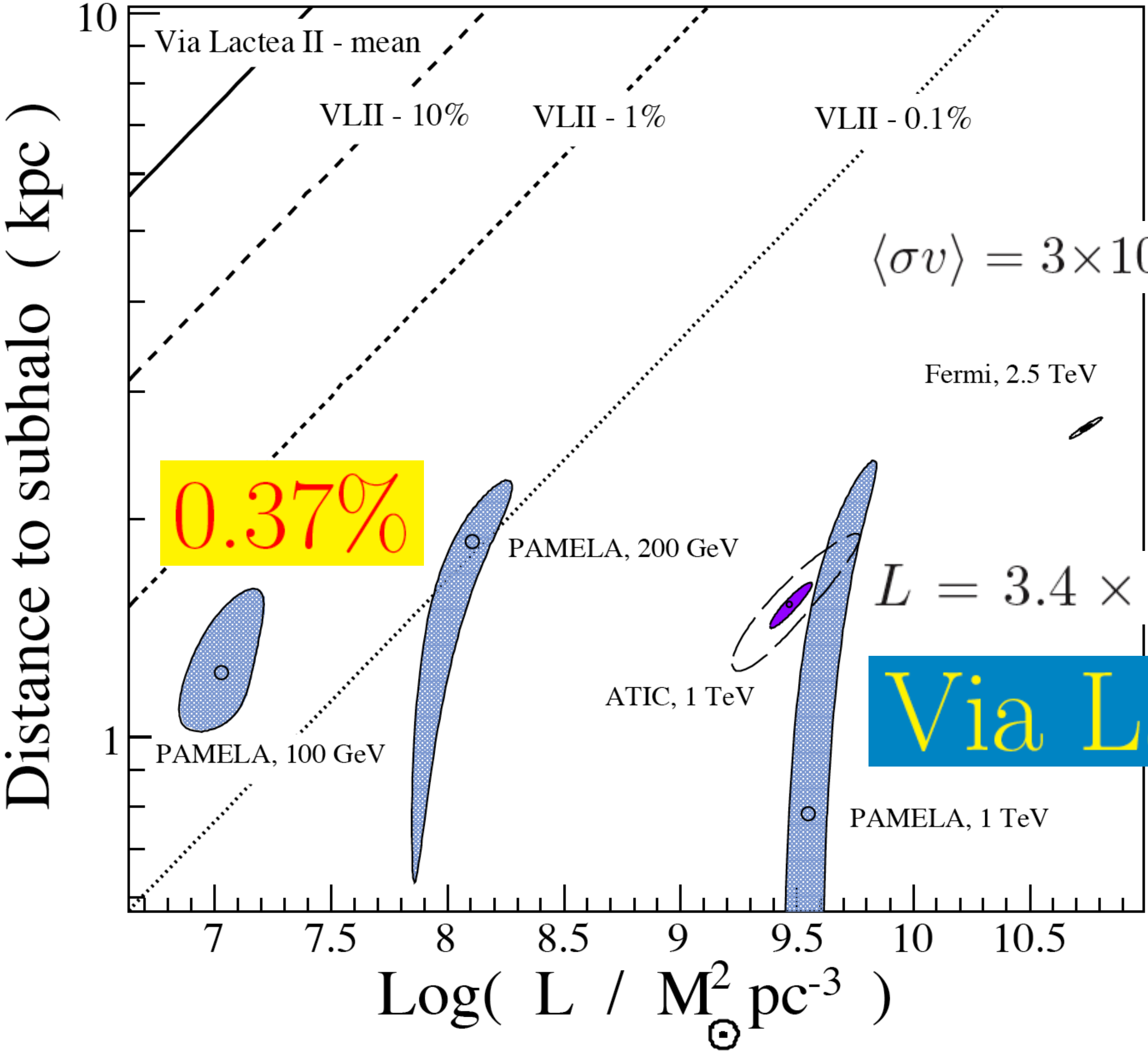
The cosmic ray lepton puzzle in the light of cosmological N-body simulations

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



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

$L = 3.4 \times 10^9$ $M_\odot^2$ pc^{-3}

Via Lactea II

- Peculiar and ad'hoc WIMP models

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

or

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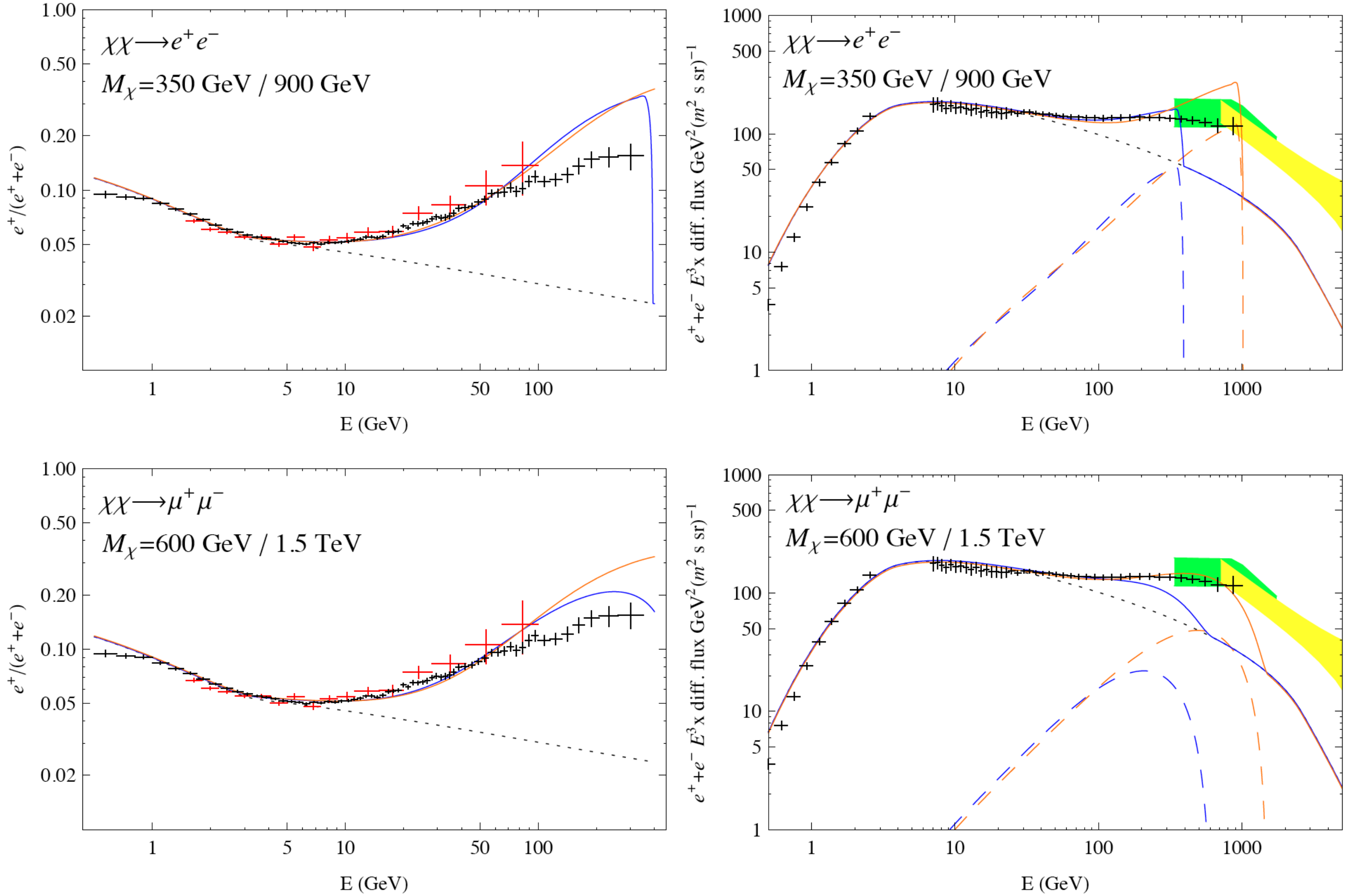
  - ✓ Inverse Compton Scattering of $e^{\pm}$ on CMB and stellar light.
  - ✓ Synchrotron radio emission from $e^{\pm}$ spiraling in $\mathbf{B}$.
  - ✓ Energy release in the primordial plasma – constraints from CMB.
- Precise measurements from AMS02.

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

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

Ilias Cholis[1,*] and Dan Hooper[1,2,†]



(ii) But the annihilation rate needs to be considerably enhanced

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– How probable is a single nearby clump ?

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Cosmic ray positron excess

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

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

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

$$\Downarrow$$

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

$$\Uparrow$$

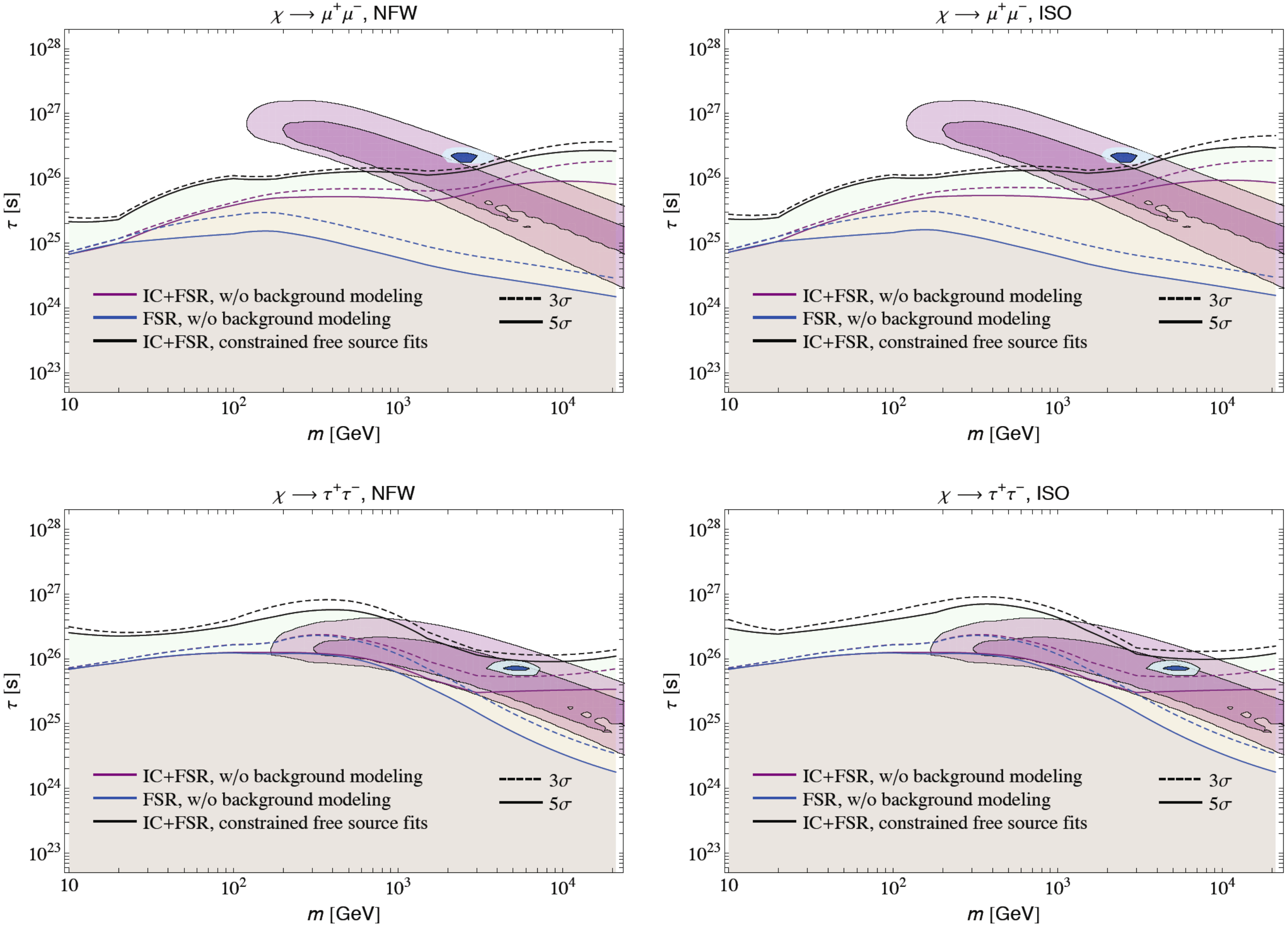
$$\tau_{\rm dec} \sim 10^{27} \text{ sec} \left\{ \frac{1 \text{ TeV}}{m_\chi} \right\}^5 \left\{ \frac{M_{\rm GUT}}{10^{16} \text{ GeV}} \right\}^4$$

dim 6 operator in GUT theories for instance

✓ The lifetime needs to be fine–tuned though – a factor of 2 matters !

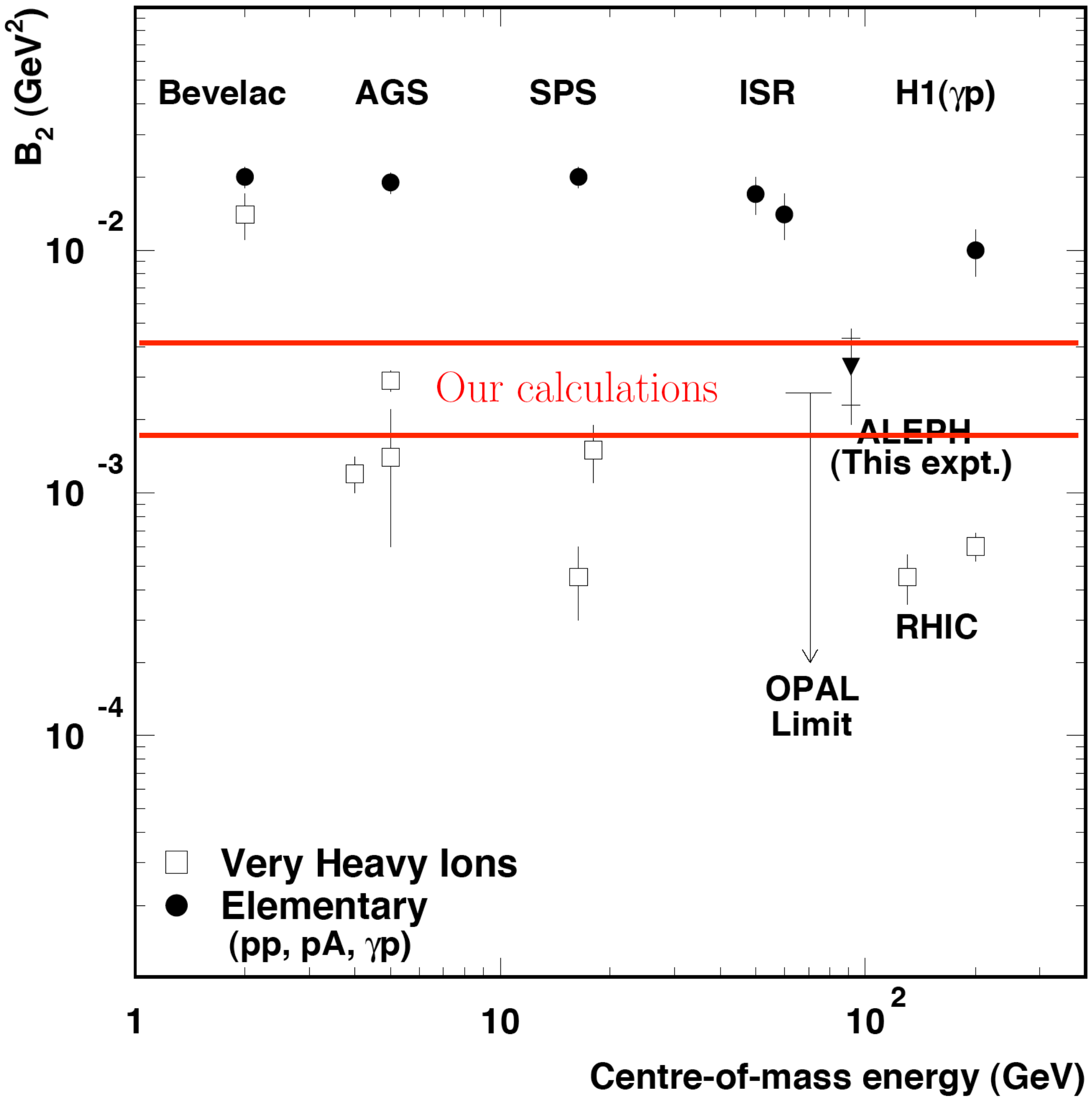
✓ Leptophilic DM species from antiproton measurements

✓ Decaying DM mildly passes the astrophysical tests as $\Gamma_{\rm ann} \propto \rho_\chi$



$\chi \longrightarrow \mu^+\mu^-$, NFW
$\chi \longrightarrow \mu^+\mu^-$, ISO
$\chi \longrightarrow \tau^+\tau^-$, NFW
$\chi \longrightarrow \tau^+\tau^-$, ISO
τ [s]
m [GeV]
IC+FSR, w/o background modeling
FSR, w/o background modeling
IC+FSR, constrained free source fits
3σ
5σ

Deuteron and Anti-deuteron Production in e^+e^- Collisions at the Z Resonance



C. B. Bräuninger & M. Cirelli, arXiv:0904.1165