multi-messenger constraints on annihilating dark matter

Miguel Pato

Universita' degli Studi di Padova / Institut d'Astrophysique de Paris

FCT
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[1] an exciting time for dark matter phenomenology?

:: the time for DM speculation is now coming to an end ::

present and upcoming data

+ LHC starting

+ GeV-TeV cosmic rays (PAMELA, AMS-02, ...)

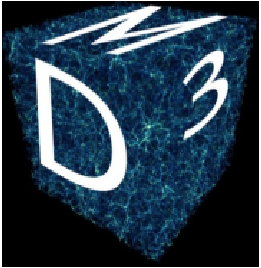
+ γ-rays (Fermi-LAT, HESS, MAGIC, ...)

+ direct detection (CDMS, Xenon, ...)

only way to convincingly reveal the nature of DM

multi-experiment

multi-wavelength



multi-messenger

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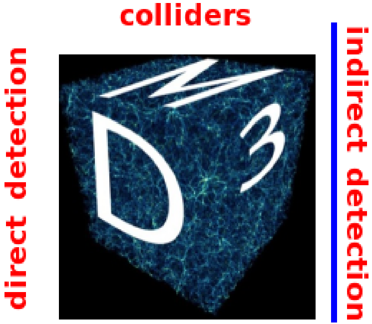
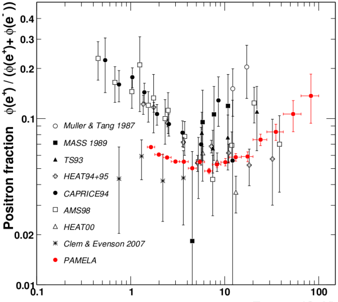
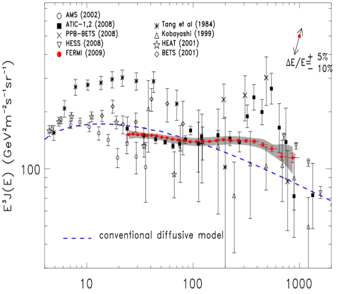


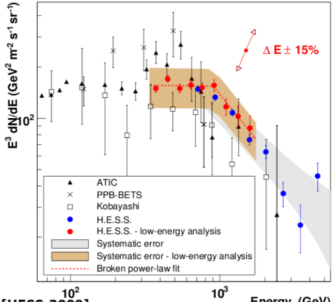
[1] the facts: cosmic-ray $e^{\pm}$



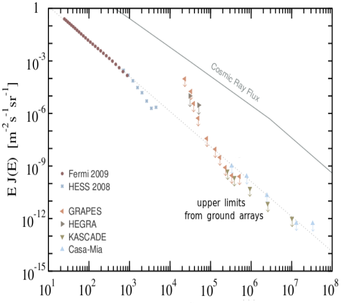
[PAMELA 2008]



[Fermi 2009]

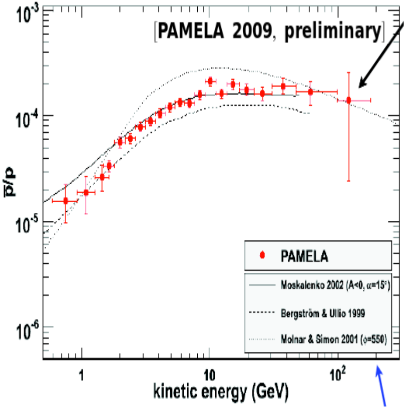


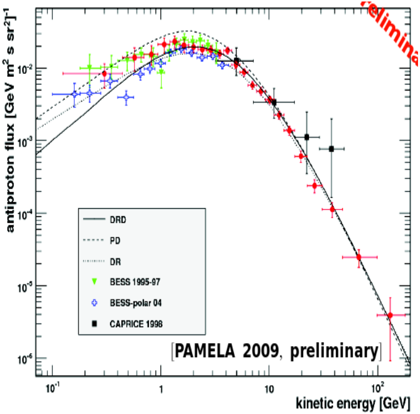
[HESS 2009]



Kistler & Yuksel 2009

[1] the facts: cosmic-ray antiprotons





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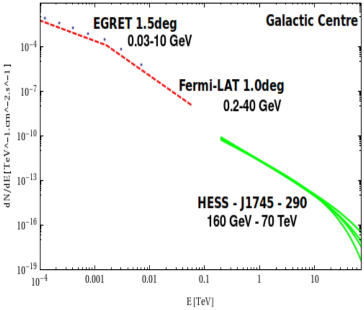

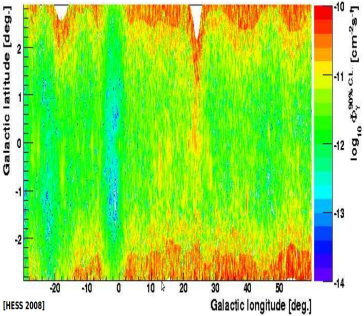

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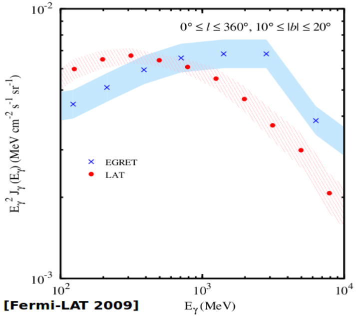
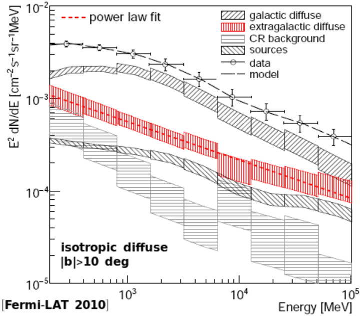


[Fermi-LAT 2009]



[Fermi-LAT 2010]

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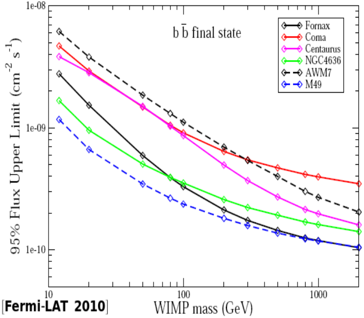
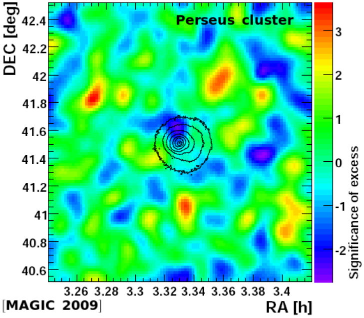
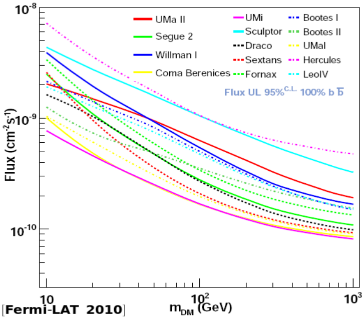


[**Fermi-LAT 2010**]



[**MAGIC 2009**]



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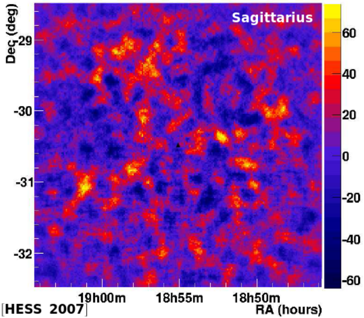
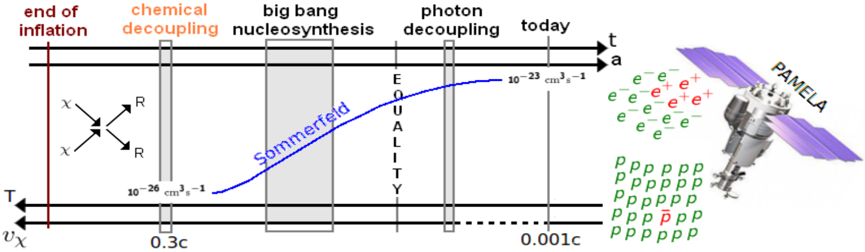


[**HESS 2007**]

[2] scrutinising Sommerfeld enhancements



Sommerfeld enhancement: a solution? [e.g. Arkani-Hamed et al. 2008]

exchange of low-mass particles ϕ
for low v, $\sigma_{ann} v \propto 1/v$ (until saturation at v_{sat})
resonances for certain combinations of masses and couplings

+ huge boost for $\sigma_{ann} v$ today without compromising thermal past
+ can motivate dominant leptonic channels
− tension with γ from GC and dSph and synchrotron [e.g. Bertone et al. 2008]

clumpiness

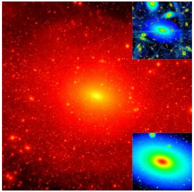
can galactic substructure alleviate the tension?
note: Sommerfeld overboosts subhalos

[2] modelling galactic dark matter

rely on simulations of Milky Way-like halos: Via Lactea II & Aquarius

Via Lactea II

[Diemand et al. 2008]



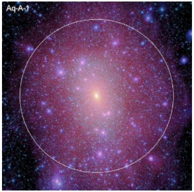
$$\rho_{sm} \sim \text{NFW}$$

$$\rho_{cl} \sim \text{NFW}$$

$$dN/dM \propto M^{-2}$$

Aquarius

[Springel et al. 2008]



$$\rho_{sm} \sim \text{Einasto}$$

$$\rho_{cl} \sim \text{Einasto}$$

$$dN/dM \propto M^{-1.9}$$

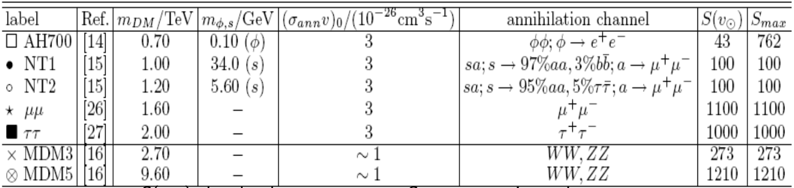
$$c(M, r) \propto r^{-\alpha_R} \left(C_1 M^{-\alpha_1} + C_2 M^{-\alpha_2} \right)$$

extrapolation down to $M_{min} = 10^{-6}\mathrm{M}_\odot$

many clumps + significant mass in clumps

$$\frac{d^2 N_{sh}}{dMdV} = N_{cl} \frac{dP_M}{dM} \frac{dP_V}{dV}$$

[2] the road map [MP, Pieri & Bertone 2009]



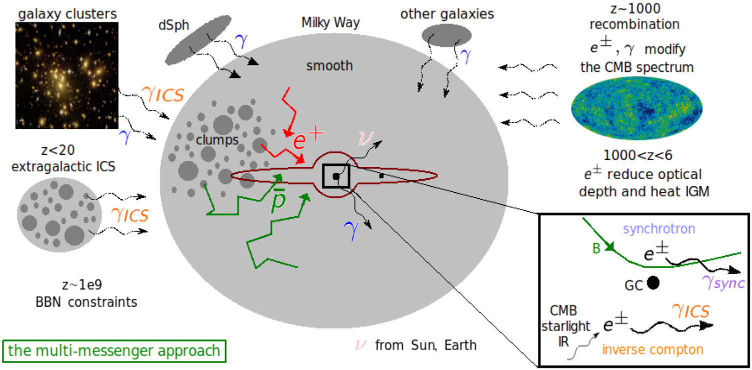
label	Ref.	m_{DM}/TeV	$m_{\phi,s}$/GeV	$(\sigma_{ann}v)_0/(10^{-26}\text{cm}^3\text{s}^{-1})$	annihilation channel	$S(v_\odot)$	S_{max}
☐ AH700	[14]	0.70	0.10 (ϕ)	3	$\phi\phi; \phi \to e^+e^-$	43	762
● NT1	[15]	1.00	34.0 (s)	3	$sa; s \to 97\% aa, 3\% b\bar{b}; a \to \mu^+\mu^-$	100	100
○ NT2	[15]	1.20	5.60 (s)	3	$sa; s \to 95\% aa, 5\% \tau\bar{\tau}; a \to \mu^+\mu^-$	100	100
⋆ $\mu\mu$	[26]	1.60	–	3	$\mu^+\mu^-$	1100	1100
■ $\tau\tau$	[27]	2.00	–	3	$\tau^+\tau^-$	1000	1000
× MDM3	[16]	2.70	–	~ 1	WW, ZZ	273	273
⊗ MDM5	[16]	9.60	–	~ 1	WW, ZZ	1210	1210

$S(v_\odot)$: local enhancement S_{max}: saturation enhancement

leptophilic: $\sim$ TeV masses, Sommerfeld boosts $\mathcal{O}(10^2 - 10^3)$

hadrophilic: $\sim$ multi-TeV masses, Sommerfeld boosts $\mathcal{O}(10^3 - 10^5)$

$$\chi\chi \to \ldots \to e^\pm, p, \bar{p}, \nu, \bar{\nu}, \gamma, \ldots$$



the multi-messenger approach

[2] the road map [MP, Pieri & Bertone 2009]

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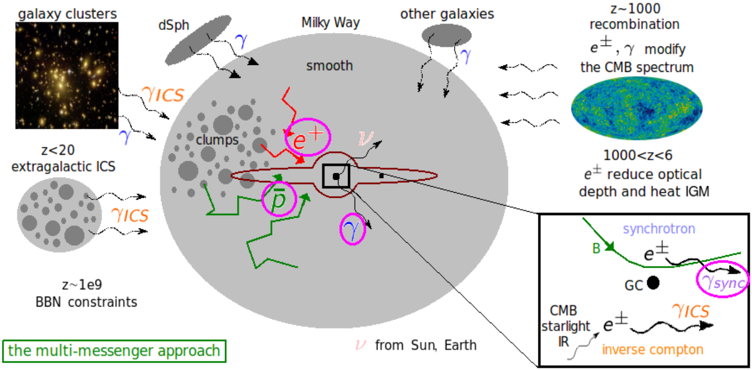


the multi-messenger approach

[2] positron and antiproton signals [MP, Pieri & Bertone 2009]

$e^+, \bar{p}$ smooth component

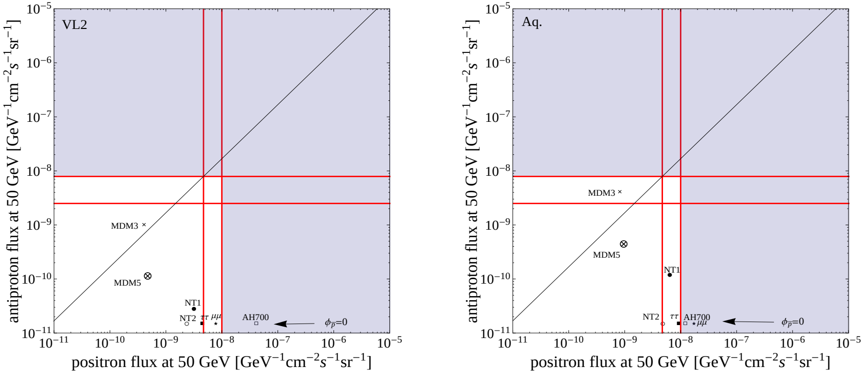
$$\phi^0_{sm} \rightarrow S(v_\odot)\phi^0_{sm}$$

$e^+, \bar{p}$ clumpy component

$$\langle\phi^0_{cl}\rangle \rightarrow S_{max}\langle\phi^0_{cl}\rangle$$

$$\phi = (1 - f_\odot)^2\, S(v_\odot)\, \phi^0_{\bar{p},sm} + S_{max}\, \langle\phi^0_{\bar{p},cl}\rangle$$

[approximation: all clumps in Sommerfeld saturation;
for $v_{sat} \gtrsim 10^{-4} c$, $M_{sh}(\text{in sat}) \lesssim 10^9\ \mathrm{M}_\odot$]



above diagonal line: cannot explain PAMELA positron excess without overproducing antiprotons

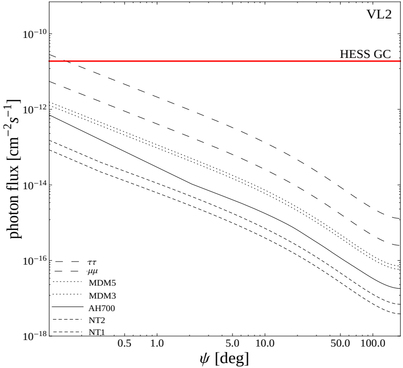
[2] the gamma signal [MP, Pieri & Bertone 2009]

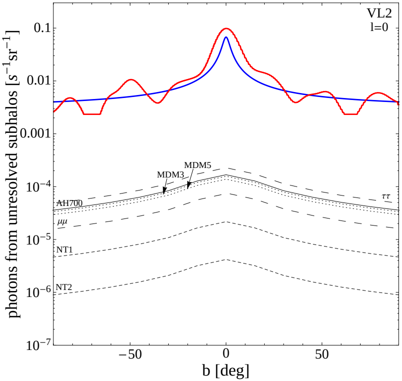
prompt γ from DM annihilations: π^0 decay, FSR, bremss.

$$\frac{d\Phi_\gamma}{dE_\gamma}(M, E_\gamma, \psi, \theta) = \frac{1}{4\pi}\frac{\sigma_{ann} v}{2m_\chi^2} \cdot \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f \int_V \frac{\rho_\chi^2(M,R)}{d^2} dV$$

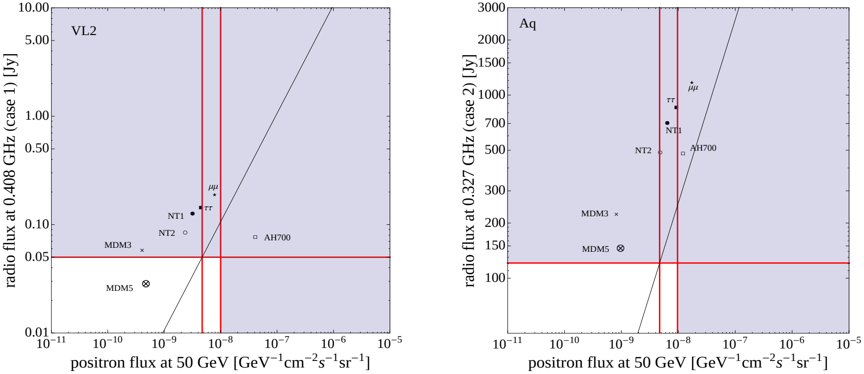
including Sommerfeld: $\Phi_S^{LOS} = \int \frac{S(M,R)\rho_\chi^2(M,c,R)}{d^2} dV$

DM annihilations in: **smooth galactic halo**, **galactic substructures**, extragalactic halos and subhalos





[2] the synchrotron signal [MP, Pieri & Bertone 2009]



above diagonal line: cannot explain PAMELA positron excess without overproducing radio fluxes

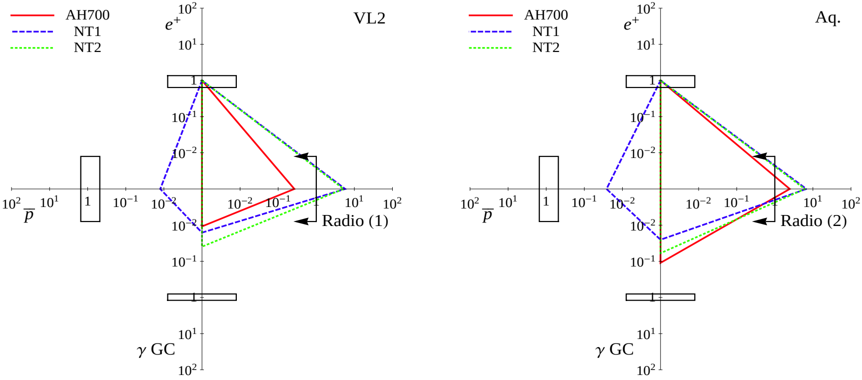
the most stringent bound depends on the DM density profile:
(1) for Via Lactea 2 (NFW) and **(2)** for Aquarius (Einasto)

[2] multi-messenger star plots! [MP, Pieri & Bertone 2009]

rescale fluxes to meet the PAMELA positron excess
(equivalent to rescaling $\langle \sigma_{ann} v \rangle_0$)

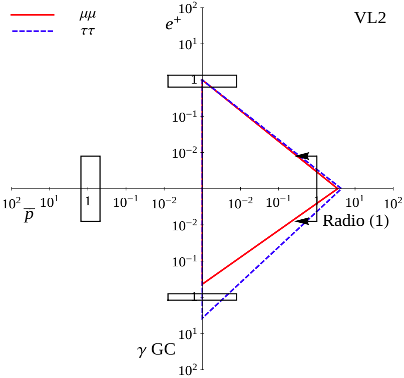
DM candidates exceeding the 'star' limits are excluded

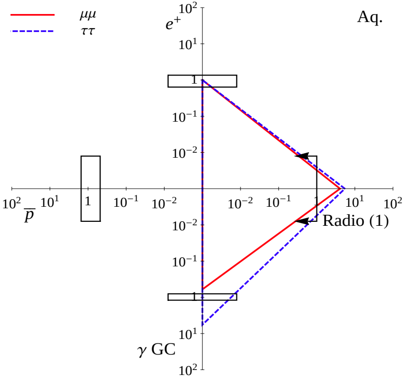
Arkani-Hamed et al, Nomura & Thaler



[2] multi-messenger star plots! [MP, Pieri & Bertone 2009]

$\mu\mu$ and $\tau\tau$





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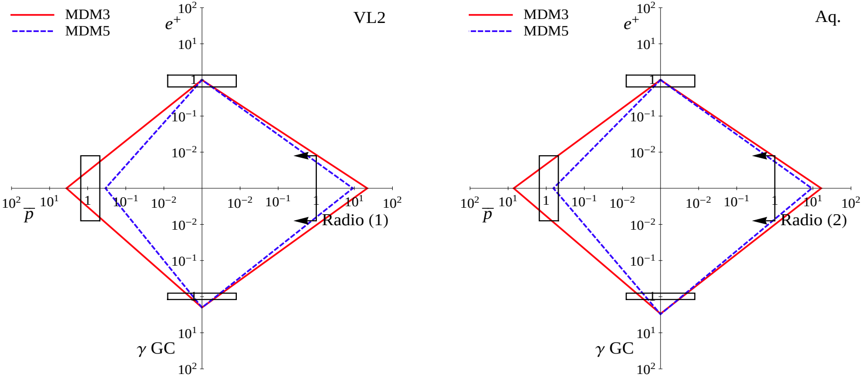
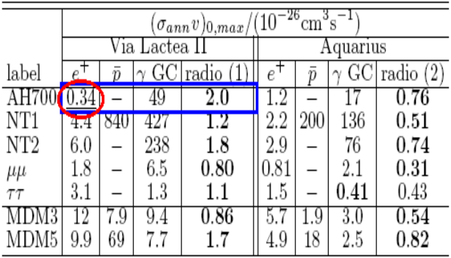
minimal dark matter



[2] multi-messenger analysis [MP, Pieri & Bertone 2009]



	$(\sigma_{ann}v)_{0,max}/(10^{-26}\mathrm{cm}^3\mathrm{s}^{-1})$							
	Via Lactea II				Aquarius			
label	e^+	$\bar{p}$	γ GC	radio (1)	e^+	$\bar{p}$	γ GC	radio (2)
AH700	0.34	–	49	2.0	1.2	–	17	0.76
NT1	4.4	840	427	1.2	2.2	200	136	0.51
NT2	6.0	–	238	1.8	2.9	–	76	0.74
$\mu\mu$	1.8	–	6.5	0.80	0.81	–	2.1	0.31
$\tau\tau$	3.1	–	1.3	1.1	1.5	–	0.41	0.43
MDM3	12	7.9	9.4	0.86	5.7	1.9	3.0	0.54
MDM5	9.9	69	7.7	1.7	4.9	18	2.5	0.82

allowed models with rather low $\langle\sigma_{ann}v\rangle_0$

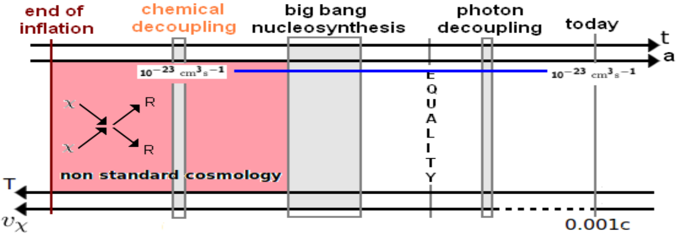
$\Downarrow$

overclose the universe if standard cosmology at DM freeze-out holds

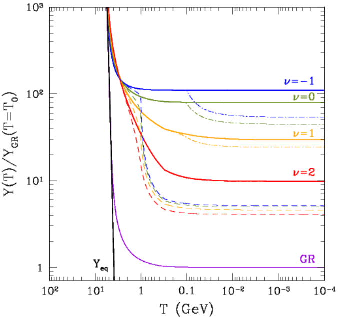
$\Downarrow$

need to invoke non-standard cosmologies to rescue these
Sommerfeld-enhanced candidates

[3] non-standard cosmologies and thermal relics



BBN is the deepest available probe of the early universe



freeze-out T_f: $\Gamma_{ann} \lesssim H \rightarrow \Omega_\chi h^2$

$H_{GR} \propto \sqrt{\rho_R} \propto T^2$

$H(T) = A(T) H_{GR}(T)$, $A(T) > 1$ [Schelke et al 2006]

examples: low T_{RH}, scalar-tensor theories, ...

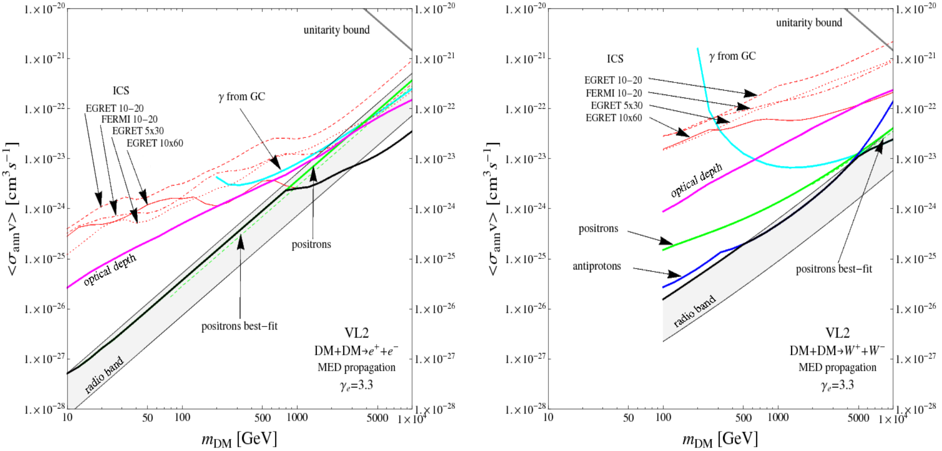
$\Omega_\chi h^2 \simeq 0.11$ is obtained for $\langle \sigma_{ann} v \rangle \gg 3 \cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$

indirect searches ↔ early universe expansion rate

[Catena, Fornengo, MP, Pieri & Masiero]

[3] the constrained WIMP scenario

strategy drop Sommerfeld specifics
model-independent constraints on $\langle \sigma_{ann} v \rangle$ vs. m_{DM}
different DM structure (VL2, Aq and smooth cored isothermal)
propagation models min/med/max



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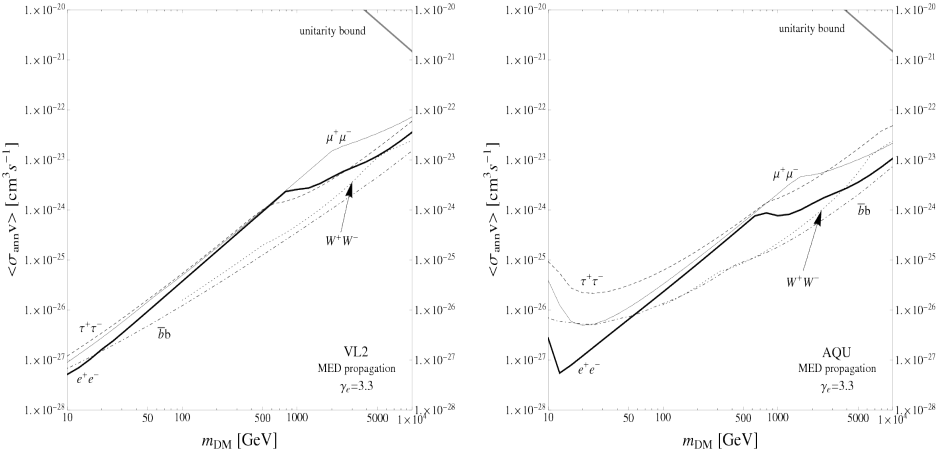

[Catena, Fornengo, MP, Pieri & Masiero]

[3] indirect searches and non-standard cosmologies

parametrisation $H(T) = A(T)H_{GR}(T)$ [Schelke et al 2006]

$$A(T) = 1 + \eta \left(\frac{T}{T_f}\right)^{\nu} tanh\left(\frac{T-T_{re}}{T_{re}}\right)$$

$\nu = -1, 0, 1, 2$ specifies cosmological model

key phenomenological parameter: $\eta \simeq A(T_f)$

fix $T_{re} = 1$ MeV

upper limits on $\langle \sigma_{ann} v \rangle$

$\downarrow \qquad \downarrow$

constrain non-standard cosmologies

assuming DM is an annihilating thermal relic, U.L. on $\langle \sigma_{ann} v \rangle$ imply U.L. on the expansion rate at freeze-out η

cosmological 'boost'

identify cosmological models where thermal relics have the $\langle \sigma_{ann} v \rangle$ needed by PAMELA positron data

[Catena, Fornengo, MP, Pieri & Masiero]

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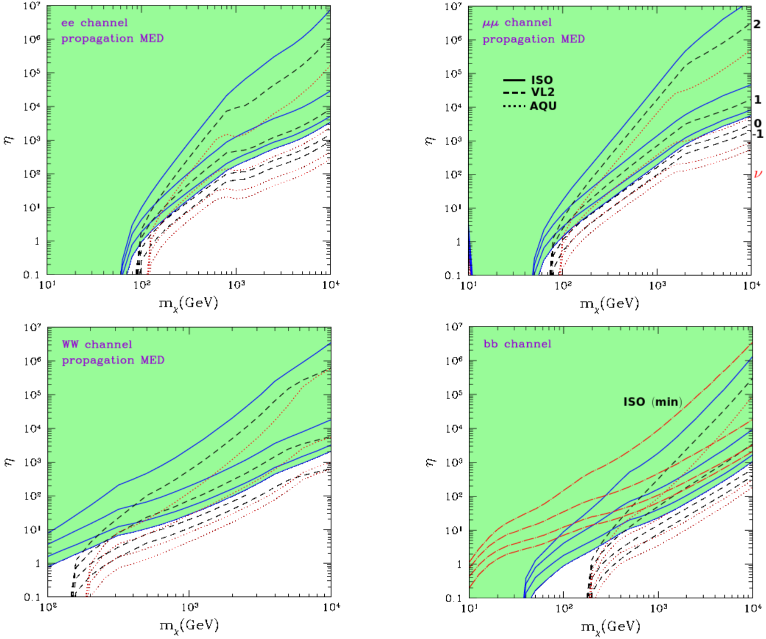

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[Catena, Fornengo, MP, Pieri & Masiero]

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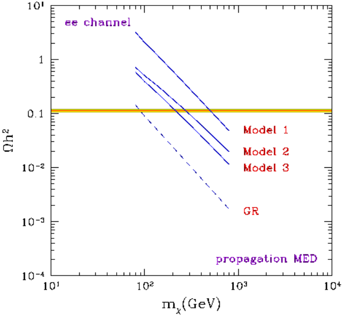
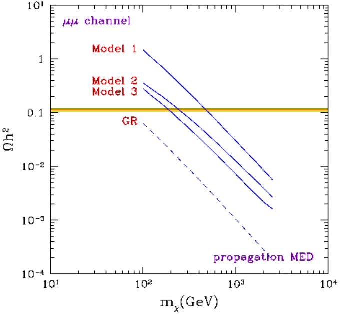
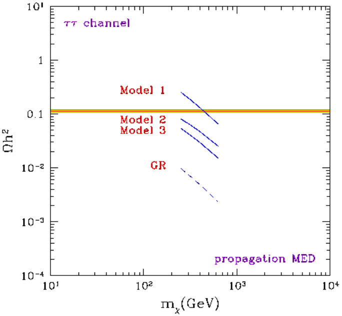






$\Omega_\chi h^2$ for $\langle \sigma_{ann} v \rangle_{PAMELA}$ in 3 specific scalar-tensor models

possible to find pre-BBN cosmological models in which thermal WIMPs are the dominant part of cold dark matter and easily 'fit' PAMELA positron data

[4] how robust are indirect DM constraints?

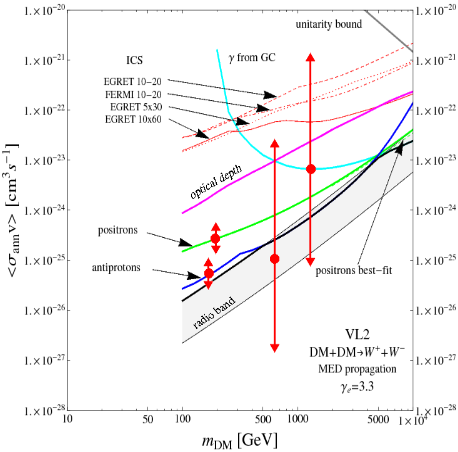
early universe constraints robust [Galli et al 09, Panci, Iocco & Cirelli 09]

DM structure in the MW (and beyond)

- local density?
- smooth halo profile: cored, cuspy?
- what happens below $r_{res}^{N-body} \sim 100\,\mathrm{pc}$?
- baryon infall? hot topic e.g. @ Zürich
- spherical halo?
- clumps: how to extrapolate $\frac{dN}{dM}$ and $c(M)$?
- how low is M_{min}?

crucial for GC radio, GC γ (e^+, $\bar{p}$)

can simulations improve this situation?



[4] how robust are indirect DM constraints?

cosmic ray propagation in the MW

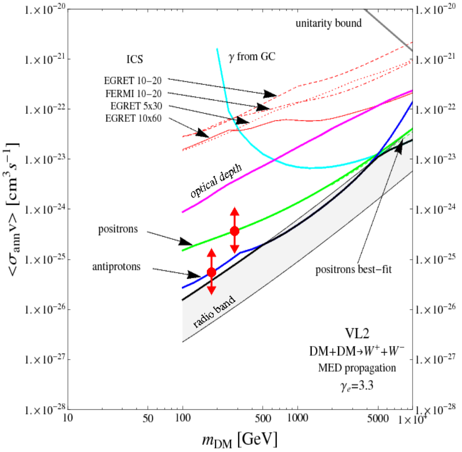
- factor 10 (within 'standard' propagation models)
- convection?
- diffusive reacceleration?
- inhomogeneous, anisotropic diffusion?
- stochasticity?

cosmic ray sources

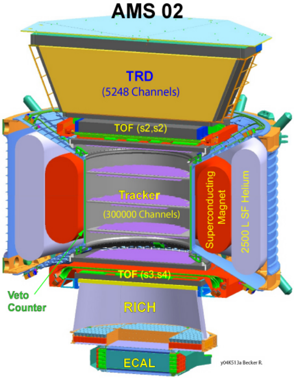
- composition?
- distribution?
- injected energy spectra?
- nature?

important for e^+, $\bar{p}$

can AMS-02 improve this situation?



[5] pinpointing cosmic ray propagation with AMS-02



AMS-02

- \# large acceptance cosmic ray detector
- \# to be launched in July 2010
- \# nuclei up to iron over 100 MeV – 1 TeV
- \# isotope separation up to $A = 10$ over 0.5–10 GeV/n
- \# superior precision, unprecendent statistics

[MP, Hooper & Simet]

use (conservative) projected capabilities of AMS-02 for B, C, ^{10}Be, ^{9}Be

$\Delta T/T \simeq 20\%$ 1-year data

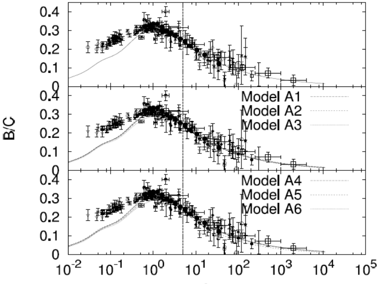
$$acc_B = acc_C = acc_{Be} = 0.45\ \mathrm{m}^2\mathrm{sr}$$

systematic misidentification of B and C: $\lesssim 1\%$

mass resolution of Be: $\Delta m/m \sim 2.5\%$

[5] pinpointing cosmic ray propagation with AMS-02

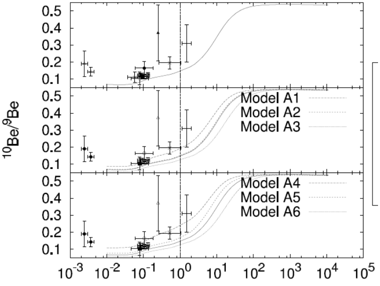
secondary-to-primary ratios



[Simet & Hooper 2009]

→ matter crossed by primaries

unstable ratios

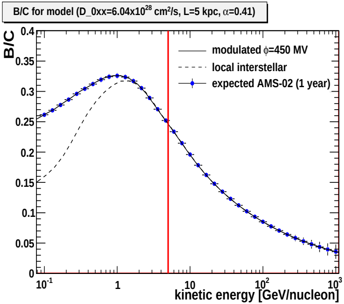


[Simet & Hooper 2009]

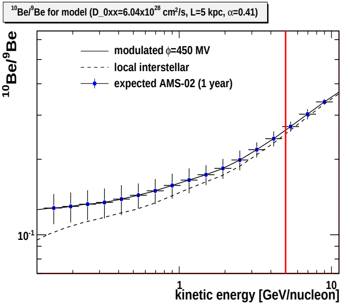
→ time since spallation

[5] pinpointing cosmic ray propagation with AMS-02

secondary-to-primary ratios



unstable ratios



→ matter crossed by primaries

→ time since spallation

after AMS-02 how much better can we constrain propagation?

[MP, Hooper & Simet]

[5] cosmic-ray propagation paradigm

$$\begin{aligned}\frac{\partial n_i}{\partial t} =& Q_{tot,i}(\mathbf{x}, p, t) + \vec{\nabla} \cdot \left(D_{xx}(\mathbf{x}, R)\vec{\nabla} n_i - \vec{V}_c(\mathbf{x}) n_i \right) \\ & + \frac{\partial}{\partial p} p^2 D_{pp}(\mathbf{x}, R) \frac{\partial}{\partial p} p^2 n_i - \frac{n_i}{\tau_{d,i}} - \frac{n_i}{\tau_{sp,i}} \\ & - \frac{\partial}{\partial p} \left(b_i(\mathbf{x}, p) n_i - \frac{p}{3} \vec{\nabla} \cdot \vec{V}_c(\mathbf{x})\, n_i \right)\end{aligned}$$

geometry: cylinder r_{max}, L

approximation: steady-state solution, $\frac{\partial n_i}{\partial t} = 0$

$$D_{xx}(R) = (v/c) D_{0xx} (R/R_0)^{\alpha}$$

$$\vec{V}_c(\mathbf{x}) = sgn(z)(V_{c,0} + |z| dV_c/dz)\vec{e}_z$$

$$D_{pp}(R) = \frac{4p^2 {v_A}^2}{3\alpha(4-\alpha^2)(4-\alpha)D_{xx}(R)}$$

(semi-)analytical vs numerical

e.g. Galprop (v50.1p)

[5] pinpointing cosmic ray propagation with AMS-02

strategy

assume true model from Simet & Hooper 2009

$D_{0xx} = 6.04 \cdot 10^{28}\mathrm{cm}^2/\mathrm{s}$ ($R_0 = 4$ GV), $L = 5$ kpc, $\alpha = 0.41$, $v_A = 36$ km/s, $dV_c/dz = 0$

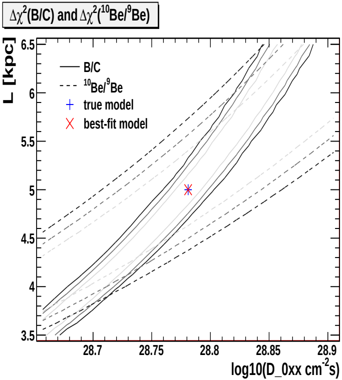
project AMS-02 B/C, ^{10}Be/^{9}Be data $T > 5$ GeV

scan over α, D_{0xx}, L

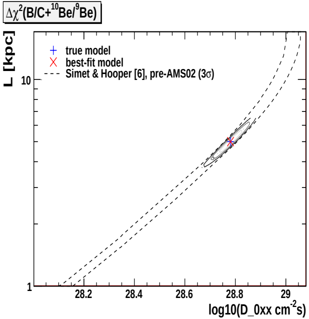
draw 1, 2, 3σ contours

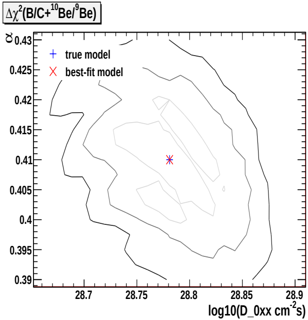
complementarity between B/C and ^{10}Be/^{9}Be

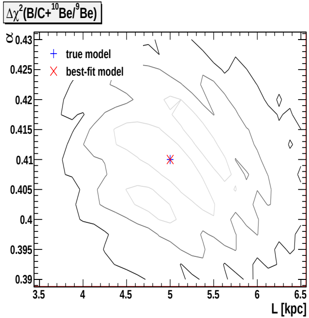
[MP, Hooper & Simet]



[5] the inverse problem







accuracy at 1σ

$$\Delta D_{0xx} \sim 1.4 \cdot 10^{28}\ \mathrm{cm}^2/\mathrm{s}$$
$$\Delta L \sim 1.0\ \mathrm{kpc}$$
$$\Delta\alpha \sim 0.02$$

much better than with present data

[MP, Hooper & Simet]

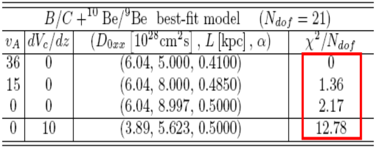
[5] varying reacceleration and convection

assume true model from Simet & Hooper 2009 for data projection

scan over α, D_{0xx}, L using different $(v_A, dV_z/dz)$

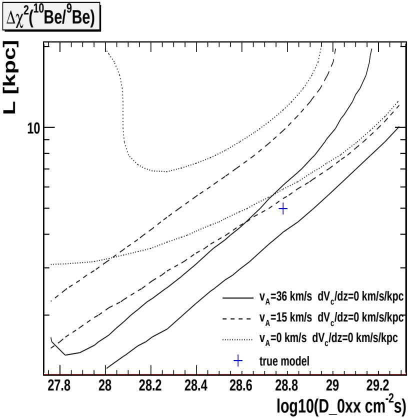
[lower v_A counterbalanced by higher L/D_{0xx}]

bottomline: AMS-02 fairly sensitive to details of reacceleration and convection



$B/C + {}^{10}\mathrm{Be}/{}^{9}\mathrm{Be}$ best-fit model $(N_{dof} = 21)$			
v_A	dV_c/dz	$(D_{0xx}\ [10^{28}\mathrm{cm}^2\mathrm{s}]\ , L\ [\mathrm{kpc}]\ , \alpha)$	χ^2/N_{dof}
36	0	(6.04, 5.000, 0.4100)	0
15	0	(6.04, 8.000, 0.4850)	1.36
0	0	(6.04, 8.997, 0.5000)	2.17
0	10	(3.89, 5.623, 0.5000)	12.78

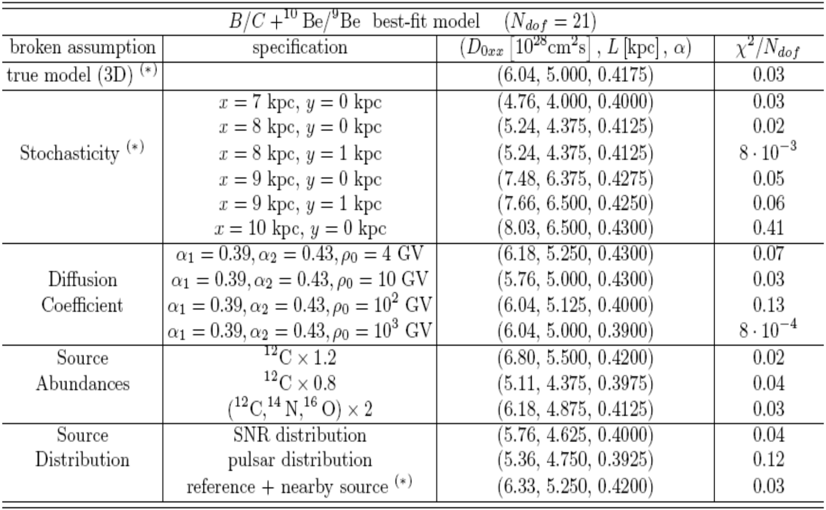
[MP, Hooper & Simet]



[5] breaking the assumptions

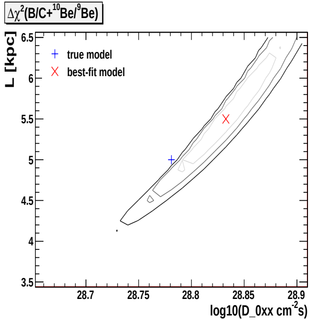
can we fit AMS-02 B/C + ^{10}Be/^{9}Be data even with wrong assumptions?

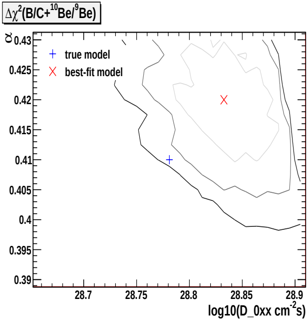
use different 'true' models and scan over α, D_{0xx}, L ($v_A = 36$ km/s, $\frac{dV_c}{dz} = 0$)

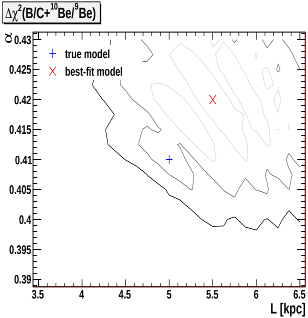


$B/C + {}^{10}\mathrm{Be}/{}^{9}\mathrm{Be}$ best-fit model ($N_{dof} = 21$)			
broken assumption	specification	(D_{0xx} $[10^{28}\mathrm{cm}^2\mathrm{s}]$, L [kpc] , α)	χ^2/N_{dof}
true model (3D) $^{(*)}$		(6.04, 5.000, 0.4175)	0.03
Stochasticity $^{(*)}$	$x = 7$ kpc, $y = 0$ kpc	(4.76, 4.000, 0.4000)	0.03
	$x = 8$ kpc, $y = 0$ kpc	(5.24, 4.375, 0.4125)	0.02
	$x = 8$ kpc, $y = 1$ kpc	(5.24, 4.375, 0.4125)	$8 \cdot 10^{-3}$
	$x = 9$ kpc, $y = 0$ kpc	(7.48, 6.375, 0.4275)	0.05
	$x = 9$ kpc, $y = 1$ kpc	(7.66, 6.500, 0.4250)	0.06
	$x = 10$ kpc, $y = 0$ kpc	(8.03, 6.500, 0.4300)	0.41
Diffusion Coefficient	$\alpha_1 = 0.39, \alpha_2 = 0.43, \rho_0 = 4$ GV	(6.18, 5.250, 0.4300)	0.07
	$\alpha_1 = 0.39, \alpha_2 = 0.43, \rho_0 = 10$ GV	(5.76, 5.000, 0.4300)	0.03
	$\alpha_1 = 0.39, \alpha_2 = 0.43, \rho_0 = 10^2$ GV	(6.04, 5.125, 0.4000)	0.13
	$\alpha_1 = 0.39, \alpha_2 = 0.43, \rho_0 = 10^3$ GV	(6.04, 5.000, 0.3900)	$8 \cdot 10^{-4}$
Source Abundances	$^{12}\mathrm{C} \times 1.2$	(6.80, 5.500, 0.4200)	0.02
	$^{12}\mathrm{C} \times 0.8$	(5.11, 4.375, 0.3975)	0.04
	$(^{12}\mathrm{C}, ^{14}\mathrm{N}, ^{16}\mathrm{O}) \times 2$	(6.18, 4.875, 0.4125)	0.03
Source Distribution	SNR distribution	(5.76, 4.625, 0.4000)	0.04
	pulsar distribution	(5.36, 4.750, 0.3925)	0.12
	reference + nearby source $^{(*)}$	(6.33, 5.250, 0.4200)	0.03

[5] source abundances: ^{12}C × 1.2







/ quality fits

/ wrong best-fit parameters

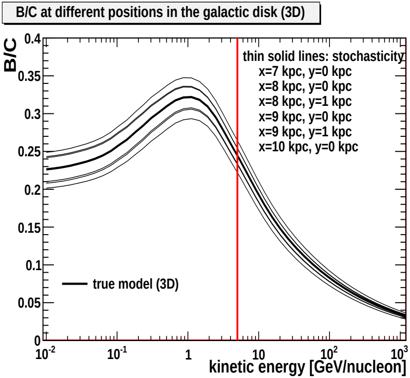
[MP, Hooper & Simet]

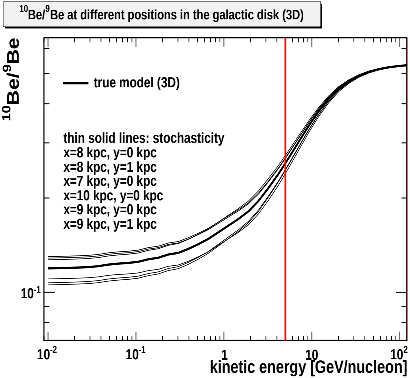
[5] stochasticity

cosmic ray injection proceeds through stochastic events

temporal and spatial variations are expected in cosmic-ray fluxes

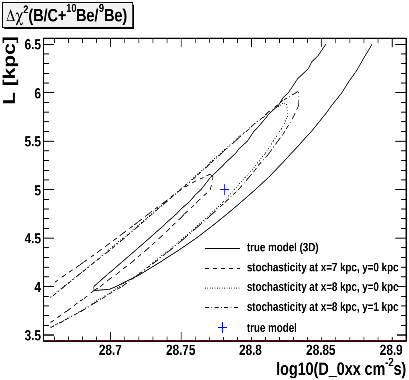
will AMS-02 be sensitive to such fluctuations?

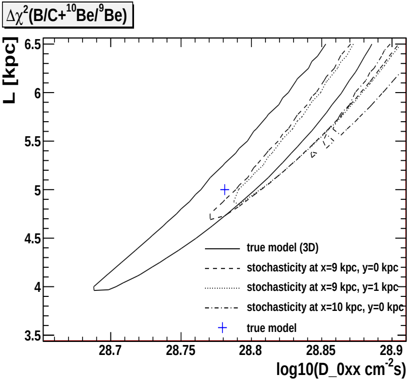




[MP, Hooper & Simet]

[5] stochasticity

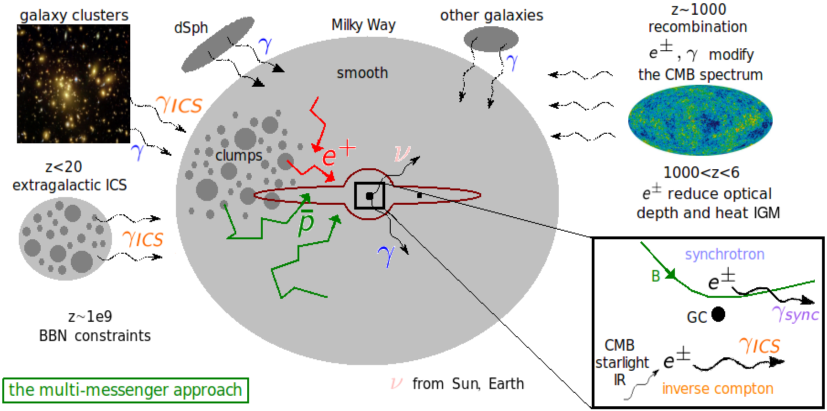




short conclusions for AMS-02

within simple propagation models, the propagation parameters can be inferred
some degree of sensitivity to reaccelearation/convection is expected
inaccurate assumptions produce good fits but wrong best-fit parameters

… last words …



galaxy clusters

dSph

Milky Way

other galaxies

z~1000
recombination
$e^{\pm}, \gamma$ modify
the CMB spectrum

smooth

γ

γ_{ICS}

clumps

e^{+}

ν

$\bar{p}$

z<20
extragalactic ICS

γ_{ICS}

1000<z<6
$e^{\pm}$ reduce optical
depth and heat IGM

synchrotron

B

$e^{\pm}$

GC

γ_{sync}

CMB
starlight
IR

$e^{\pm}$

γ_{ICS}

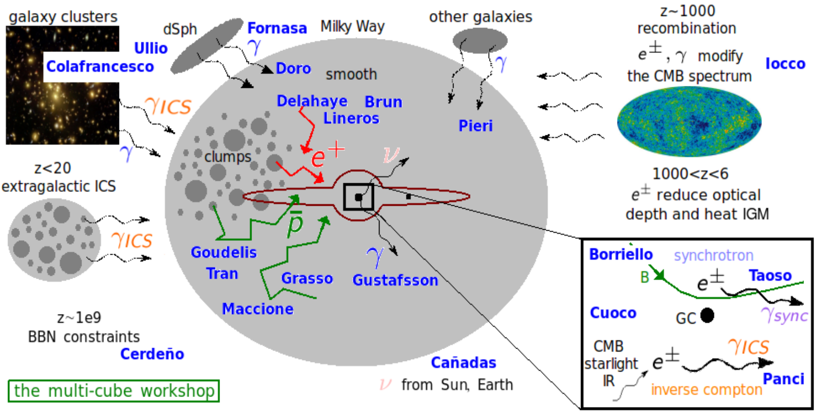
inverse compton

z~1e9
BBN constraints

the multi-messenger approach

ν from Sun, Earth

… last words …


galaxy clusters
dSph
Fornasa
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z~1000
recombination
$e^{\pm}, \gamma$ modify
the CMB spectrum
Iocco
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Colafrancesco
γ
Doro
smooth
γ
γ_{ICS}
Delahaye
Brun
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Pieri
γ
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e^+
ν
z<20
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γ_{ICS}
Goudelis
Tran
Grasso
γ
Gustafsson
Maccione
Borriello
synchrotron
B
$e^{\pm}$
Taoso
Cuoco
GC
γ_{sync}
z~1e9
BBN constraints
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starlight
IR
$e^{\pm}$
γ_{ICS}
Panci
inverse compton
Cañadas
ν from Sun, Earth
the multi-cube workshop

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[-] backup slides

[-] the positron signal

[Delahaye et al. 2008, ...]

$$\frac{\partial n_{e^+}}{\partial t} - K_{e^+}(E_{e^+})\nabla^2 n_{e^+} - \frac{\partial}{\partial E_{e^+}}\left(b(E_{e^+})n_{e^+}\right) = Q_{e^+}(\mathbf{x}, E_{e^+})$$

diffusion

$K_{e^+}(E_{e^+}) \simeq K_0\,(E_{e^+}/\mathrm{GeV})^{\delta}$

diffusive cylinder $R_{gal} = 20$ kpc L

propagation (K_0, δ, L): use M2, MED, MAX

diffusion length $\lambda_D \lesssim \mathcal{O}(1)$ kpc: multi-GeV e^+ should be local

energy losses (ICS + synchrotron) $b(E_{e^+}) \simeq E^2_{e^+}/(\mathrm{GeV}\cdot\tau_E)$ $\tau_E \sim 10^{16}$ s

injection dark matter annihilations $Q_{e^+} \propto \rho^2_{DM}$

smooth component

[Lavalle et al. 2008]

$$\phi^0_{e^+,sm}(E) \propto \langle\sigma_{ann}v\rangle_0 \int_E^\infty dE_S\,\frac{dN_{e^+}}{dE}\int_{DZ} d^3\mathbf{x}\left(\frac{\rho_{sm}(\mathbf{x})}{\rho_\odot}\right)^2 G^{e^+}_\odot(\mathbf{x},\lambda_D)$$

clumpy component

$$\langle\phi^0_{e^+,cl}\rangle(E) \propto \langle\sigma_{ann}v\rangle_0\, N_{cl}\,\langle\xi\rangle_M \int_E^\infty dE_S\,\frac{dN_{e^+}}{dE}\int_{DZ} d^3\mathbf{x}\, G^{e^+}_\odot(\mathbf{x},\lambda_D)\,\frac{dP_V}{dV}(\mathbf{x})$$

[-] the antiproton signal

[Donato et al. 2001, ...]

$$\frac{\partial n_{\bar{p}}}{\partial t} - K_{\bar{p}}(T_{\bar{p}})\nabla^2 n_{\bar{p}} + \frac{\partial}{\partial z}\left(\mathrm{sgn}(z) V_c n_{\bar{p}}\right) = Q_{\bar{p}}(\mathbf{x}, T_{\bar{p}}) - 2h\delta_D(z)\Gamma^{p\bar{p}}_{ann}(T_{\bar{p}}) n_{\bar{p}}$$

diffusion

$$K_{\bar{p}}(T_{\bar{p}}) = K_0 \beta_{\bar{p}} \left(\frac{p_{\bar{p}}}{\mathrm{GeV}}\right)^{\delta}$$

diffusive cylinder $R_{gal} = 20$ kpc L

propagation (K_0, δ, L): use MIN, MED, MAX

galactic wind $\vec{V}_c(\mathbf{x}) = sgn(z) V_c \vec{e}_z$

injection dark matter annihilations $Q_{\bar{p}} \propto \rho^2_{DM}$

destruction in the disk $p\bar{p}$ annihilations

$$\sigma^{p\bar{p}}_{ann}(T_{\bar{p}}) = \begin{cases} 661 \text{ mb } (1 + 0.0115\,\tilde{T}_{\bar{p}}^{-0.774} - 0.948\,\tilde{T}_{\bar{p}}^{0.0151}) & \tilde{T}_{\bar{p}} = T_{\bar{p}}/\mathrm{GeV} < 15.5 \\ 36 \text{ mb } \tilde{T}_{\bar{p}}^{-0.5} & \tilde{T}_{\bar{p}} = T_{\bar{p}}/\mathrm{GeV} \geq 15.5 \end{cases}$$

smooth component [Lavalle et al. 2008]

$$\phi^0_{\bar{p},sm}(T) \propto \langle \sigma_{ann} v \rangle_0 \frac{dN_{\bar{p}}}{dE} \int_{DZ} d^3\mathbf{x} \left(\frac{\rho_{sm}(\mathbf{x})}{\rho_\odot}\right)^2 G^{\bar{p}}_\odot(\mathbf{x}, T, L, K_o, \delta, V_c)$$

clumpy component

$$\langle \phi^0_{\bar{p},cl} \rangle(T) \propto \langle \sigma_{ann} v \rangle_0 \, N_{cl} \, \langle \xi \rangle_M \frac{dN_{\bar{p}}}{dE} \int_{DZ} d^3\mathbf{x} \, G^{\bar{p}}_\odot(\mathbf{x}, T, L, K_0, \delta, V_c) \frac{dP_V}{dV}(\mathbf{x})$$

[-] the synchrotron signal

[Bertone et al. 2008, ...]

under the galactic magnetic field DM-induced relativistic $e^{\pm}$ emit synchrotron radiation

$e^{\pm}$ population $n_{e^{\pm}}(\mathbf{x}, E) = \frac{\langle \sigma_{ann} v \rangle}{2m_{DM}^2} \rho_{DM}^2(\mathbf{x}) \frac{N_{e^{\pm}}(>E)}{b_{syn}(\mathbf{x}, E)}$

(neglect advection, diffusion and losses other than synchrotron)

magnetic field profile $B = \begin{cases} 7.2 \text{ mG} & r \leq 0.04 \text{ pc} \\ 7.2 \text{ mG}(r/0.04 \text{ pc})^{-2} & 0.04 \text{ pc} < r < 3.38 \text{ pc} \\ 1\,\mu\text{G} & r \geq 3.38 \text{ pc} \end{cases}$

total synchrotron power

$$\nu \frac{dW_{syn}}{d\nu} = \frac{\langle \sigma_{ann} v \rangle}{2m_{DM}^2} \int_{\Delta\Omega} d\Omega \int_{los} dl\, \rho_{DM}^2(\mathbf{x})\, E_p(\mathbf{x}, \nu)\, \frac{N_{e^{\pm}}(>E_p)}{2}$$

constrain Sommerfeld: $\langle \sigma_{ann} v \rangle \longrightarrow S(v_{\odot}) \langle \sigma_{ann} v \rangle_0$ (conservative)

radio observations

(1) $\nu = 408$ MHz, cone half-aperture 4" from GC
(2) $\nu = 327$ MHz, 5' to 10' from GC
(3) $\nu = 327$ MHz, cone half-aperture 13.5' from GC

[-] cmb constraints

DM annihilations produce high-energy secondaries at $z_{rec} \sim 1000$

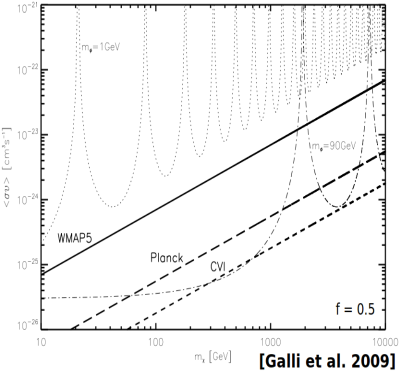
$e^{\pm}, \gamma$ ionise, excite and heat the photon-baryon plasma

bottomline CMB angular power spectrum constrain $f \langle \sigma_{ann} v \rangle / m_\chi$
+ Sommerfeld: $v(z_{rec}) \sim 10^{-8} c \ll v_\odot \sim 10^{-3} c$ $\langle \sigma_{ann} v \rangle_{rec} \geq \langle \sigma_{ann} v \rangle_\odot$

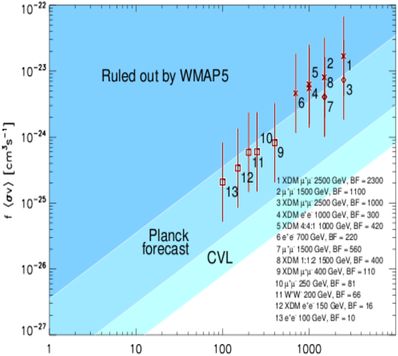
$\langle \sigma_{ann} v \rangle$ required by PAMELA are in tension with WMAP

reminder very solid bound: no astrophysical uncertainties (SF, DM profile)

$f(z)$: fraction of energy deposited in the plasma by DM annihilations



[Galli et al. 2009]



[Galli et al. 2009]+[Slatyer et al. 2009]

[-] cmb optical depth

[Belikov & Hooper 2009, Cirelli, Iocco & Panci 2009]

reionisation after recombination the gas was ionised, probably at $20 > z > 6$

the observable

$$\tau = -\int_0^\infty n_e(z)\,\sigma_T\,\frac{dt}{dz}\,dz \simeq 0.087 \pm 0.017 \quad \text{(WMAP 5yr)}$$

$\int_0^3 + \int_3^6 \sim 0.04$: ionised H and He

hypothesis dark matter reionised the universe

1) dark matter annihilations produce prompt γ, and $e^\pm$ up-scatter γ_{CMB}
2) low-energy γ ionise H and He atoms
3) released and subsequent e^- reduce optical depth τ

bottomline if $\langle \sigma_{ann} v \rangle / m_{DM}^2$ is large, the universe is too opaque to CMB
(constraint independent of DM profile)

+ other effects of DM annihilations: heat of intergalactic medium

[-] inverse compton scattering (from small/mid galactic latitudes)

[Cirelli & Panci 2009]

DM-induced relativistic $e^{\pm}$ up-scatter CMB, infrared and starlight photons

$e^{\pm}$ population $\quad n_{e^{\pm}}(\mathbf{x}, E) = \frac{\langle \sigma_{ann} v \rangle}{2 m_{DM}^2} \rho_{DM}^2(\mathbf{x}) \frac{N_{e^{\pm}}(>E)}{b_{ics}(\mathbf{x}, E)}$

(neglect advection, diffusion and losses other than inverse compton scattering)

low-energy photons $\quad T_{CMB} \sim 2.7^\circ \ \mathrm{K} \quad T_{IR} \sim 3.5 \ \mathrm{meV} \quad T_{SL} \sim 0.3 \ \mathrm{eV}$

inverse compton scattering flux

$$\frac{dF_{ics}}{dE_\gamma} = \frac{1}{E_\gamma} \int_{\Delta\Omega} d\Omega \int_{los} dl \int_{m_e}^{m_{DM}} dE \, n_{e^{\pm}}(\mathbf{x}, E) \, P_{ics}(\mathbf{x}, E, E_\gamma)$$

γ-ray observations

(1) $|b| \lesssim 5^\circ$, $330^\circ \lesssim l \lesssim 30^\circ$ (EGRET)
(2) $|b| \lesssim 10^\circ$, $300^\circ \lesssim l \lesssim 60^\circ$ (EGRET)
(3) $10^\circ \lesssim |b| \lesssim 20^\circ$, $0^\circ \lesssim l \lesssim 360^\circ$ (EGRET, Fermi-LAT)

\+ new Fermi-LAT data [Cirelli, Panci & Serpico 0912.0663]