Antiproton constraints on Dark Matter

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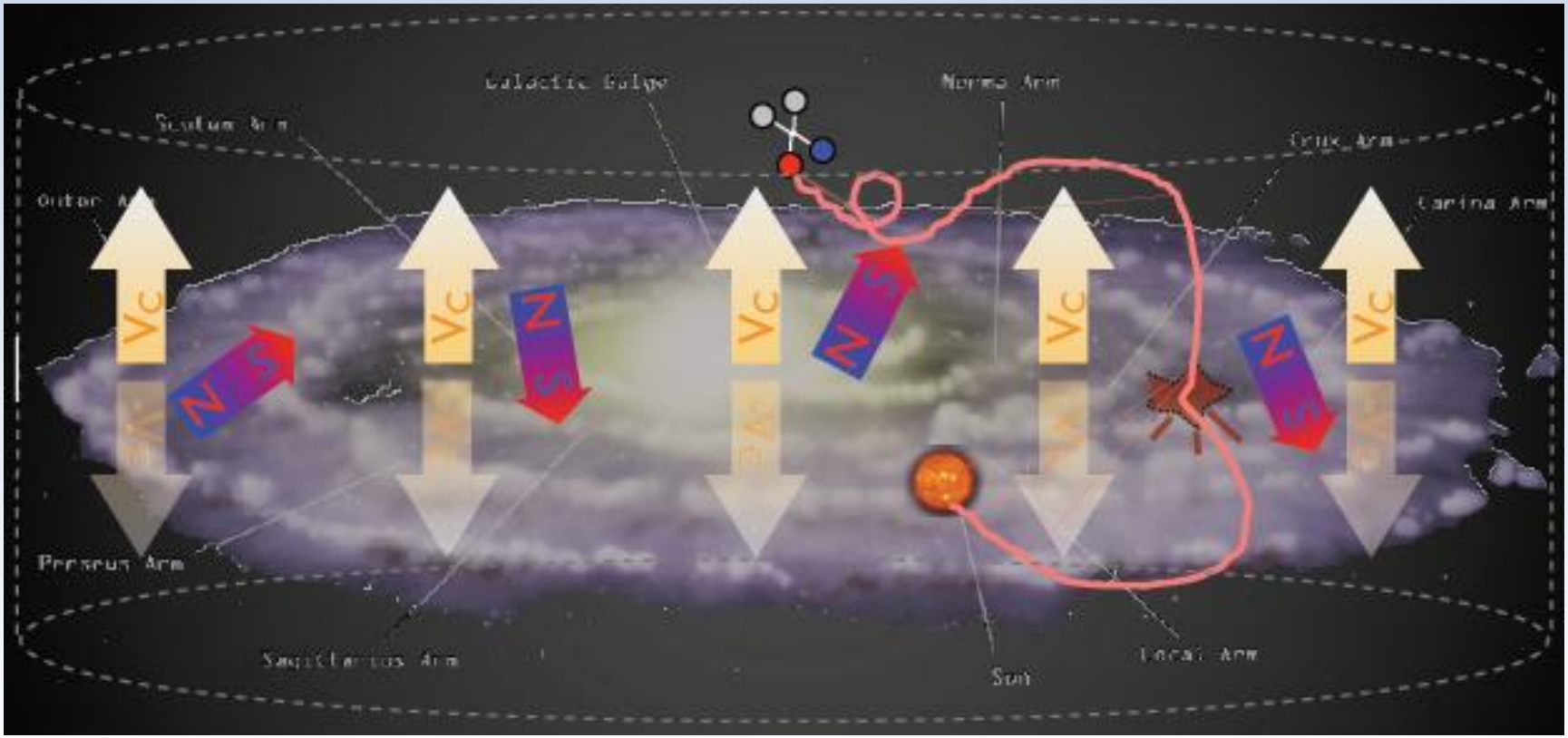
New Perspectives on Dark Matter

DM annihilation or decay in the halo of our Galaxy
⇒ Cosmic Ray propagation (convection, diffusion, etc...)
⇒ Detection at Earth



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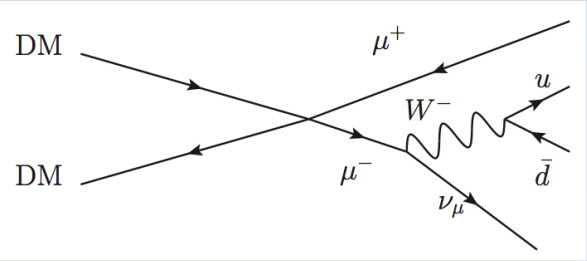

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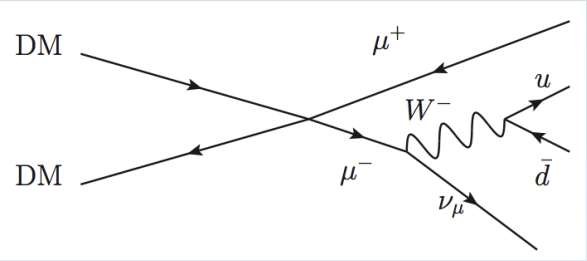

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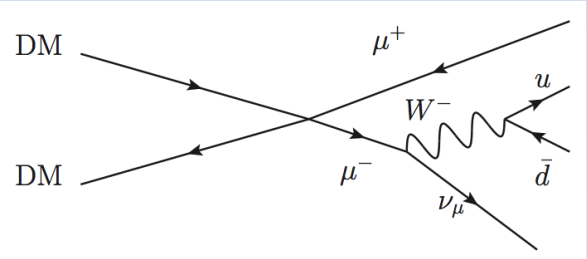

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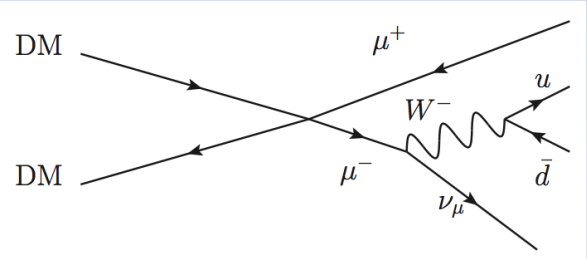

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- Upcoming AMS-02 data even more precise
  $\Rightarrow$ Forecast : sensitivities and reconstruction capabilities

- DM Annihilation/decay channels

$$\left.\begin{array}{rr} \text{annihilation} & \text{DM DM} \\ \text{decay} & \text{DM} \end{array}\right\} \rightarrow b\bar{b}, t\bar{t}, W^+W^-, ZZ, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma$$

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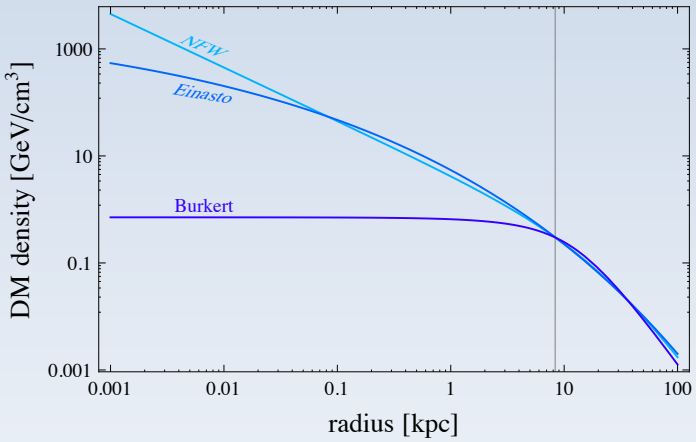

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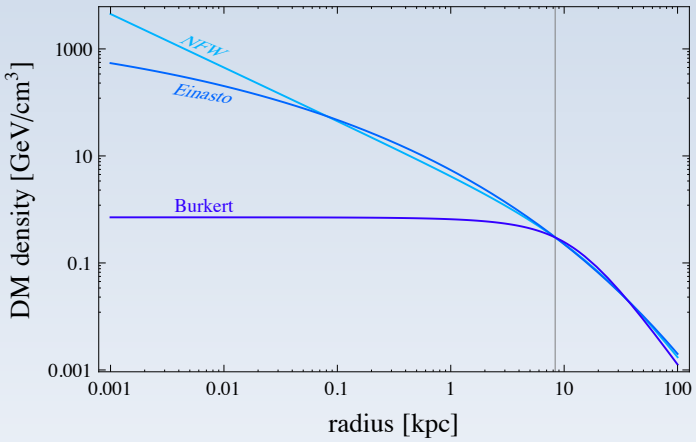
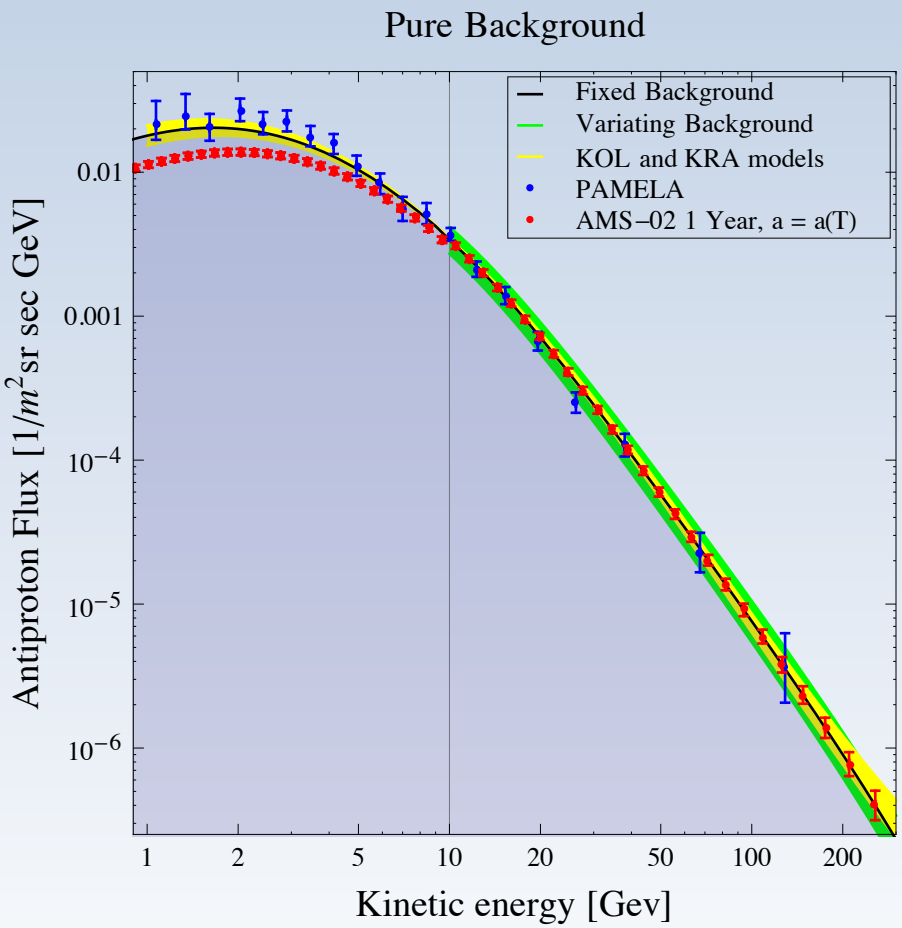


- Antiproton propagation in the galactic halo

Model	δ	$\mathcal{K}_0$ [kpc^2/Myr]	$V_{\rm conv}$ [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15



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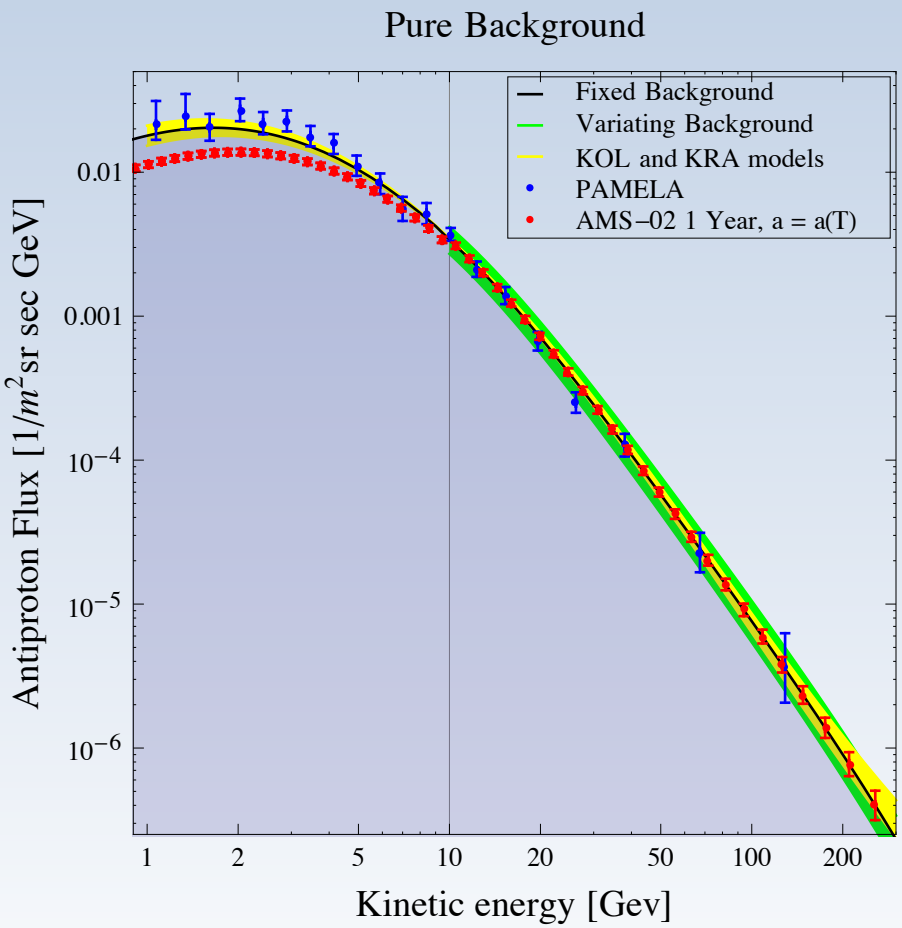
  $\phi_{\rm fixed}(T > 10\,{\rm GeV})$: power law



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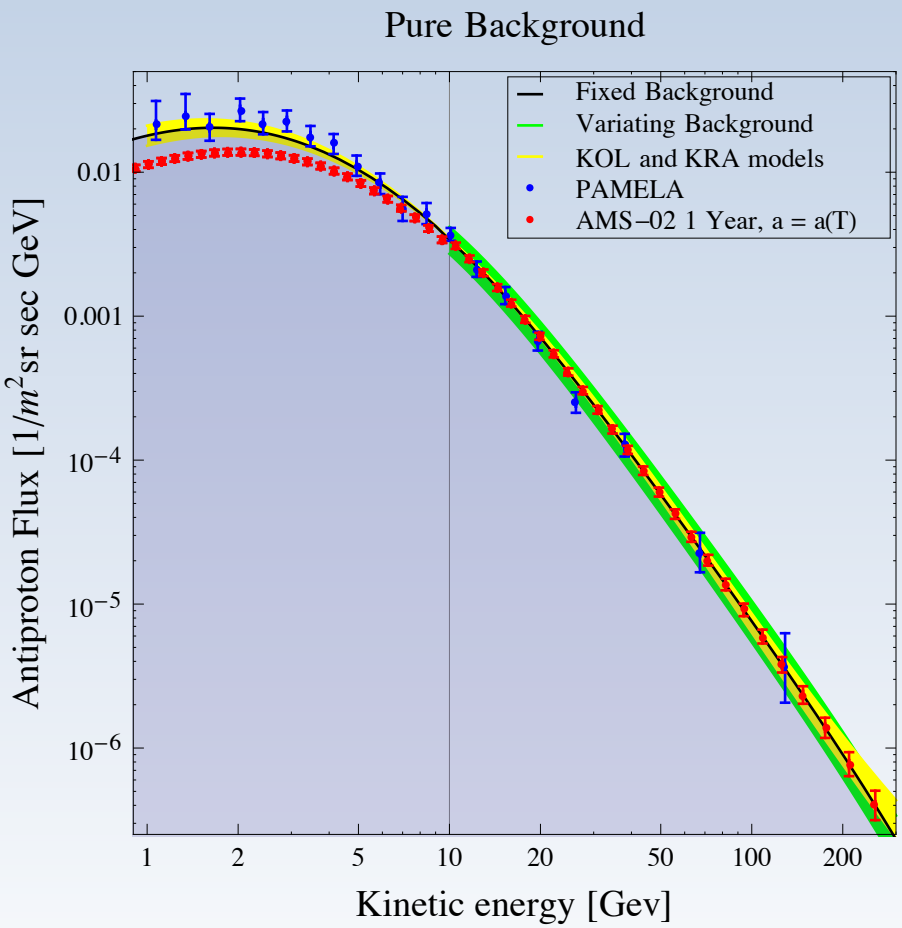
$A \in [0.9, 1.1]$ and $p \in [-0.05, 0.05]$



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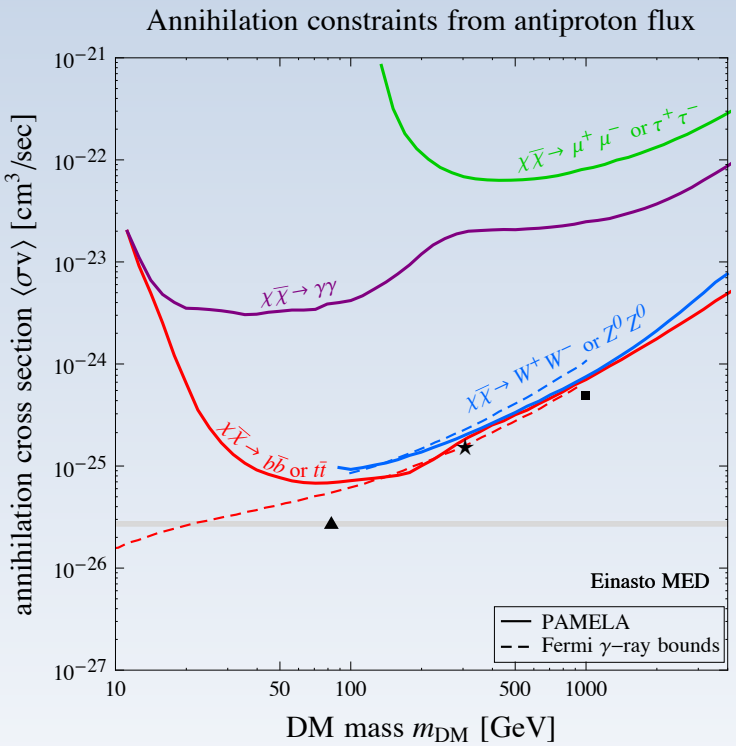
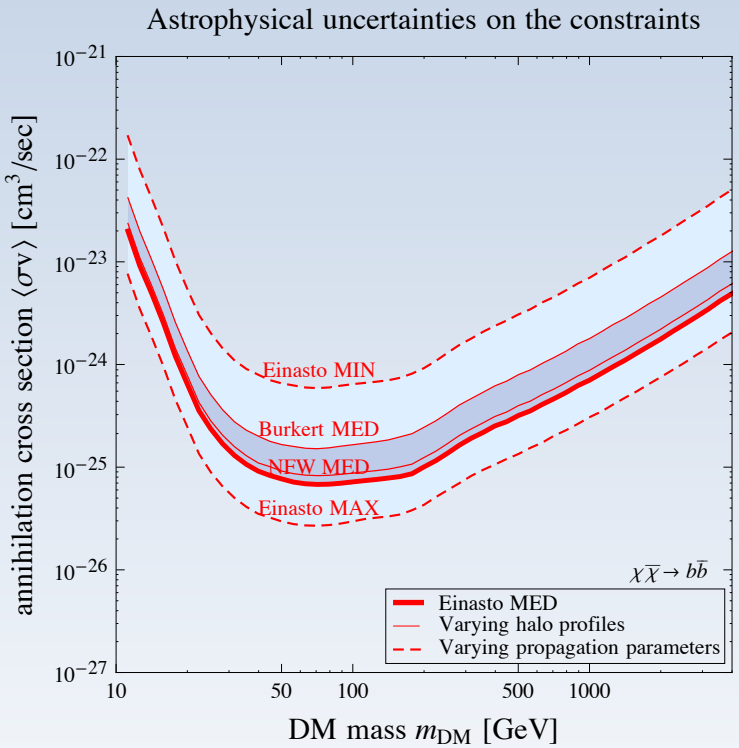
- Flux with DM signal

$$\phi_{\rm tot}(m_{\rm DM}, \langle\sigma v\rangle; A, p) = \phi_{\rm DM}(m_{\rm DM}, \langle\sigma v\rangle) + \phi_{\rm bkg}(A, p)$$

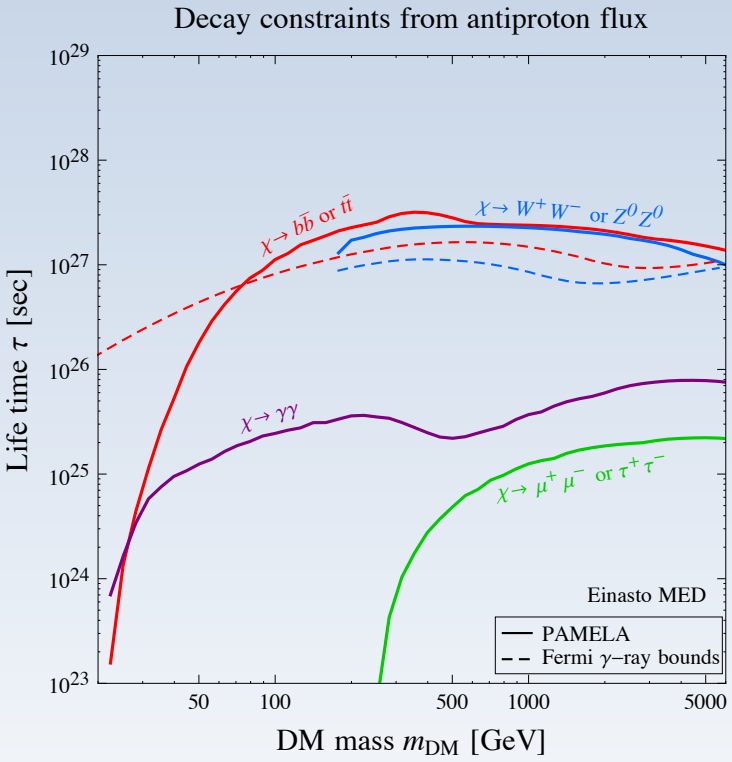
$\Rightarrow$ Marginalization over A and p

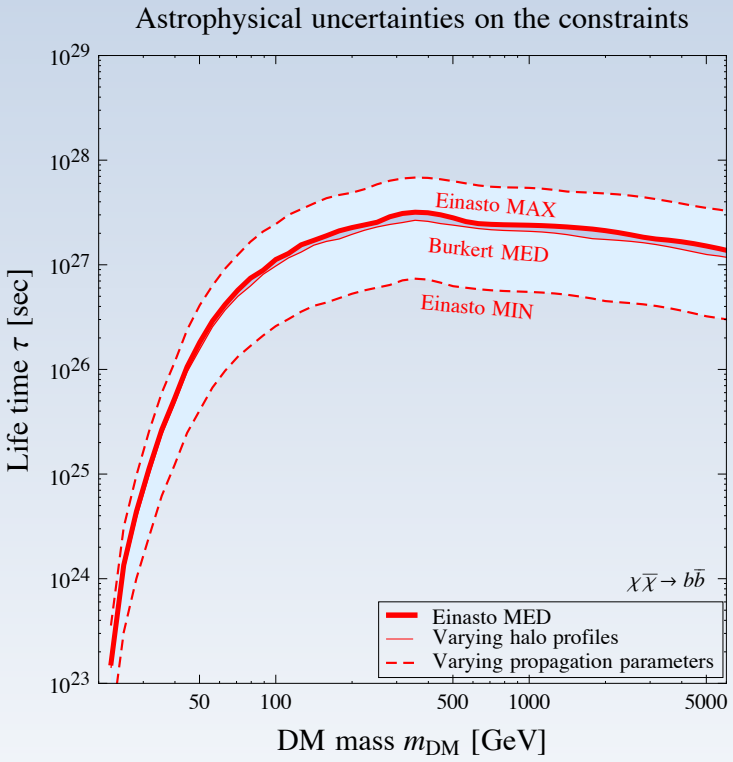
Current Antiproton constraints from PAMELA for annihilating DM



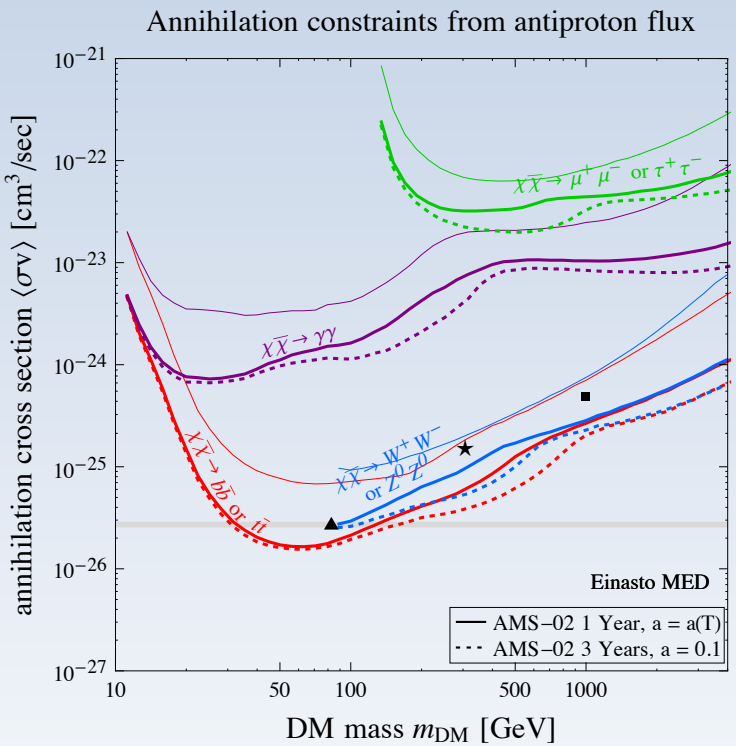


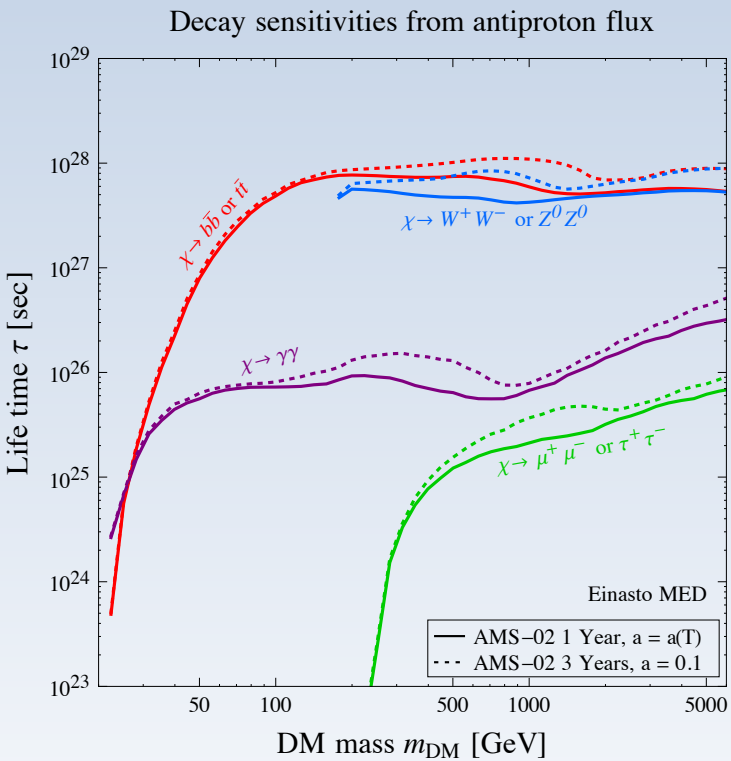
Current Antiproton constraints from PAMELA for decaying DM

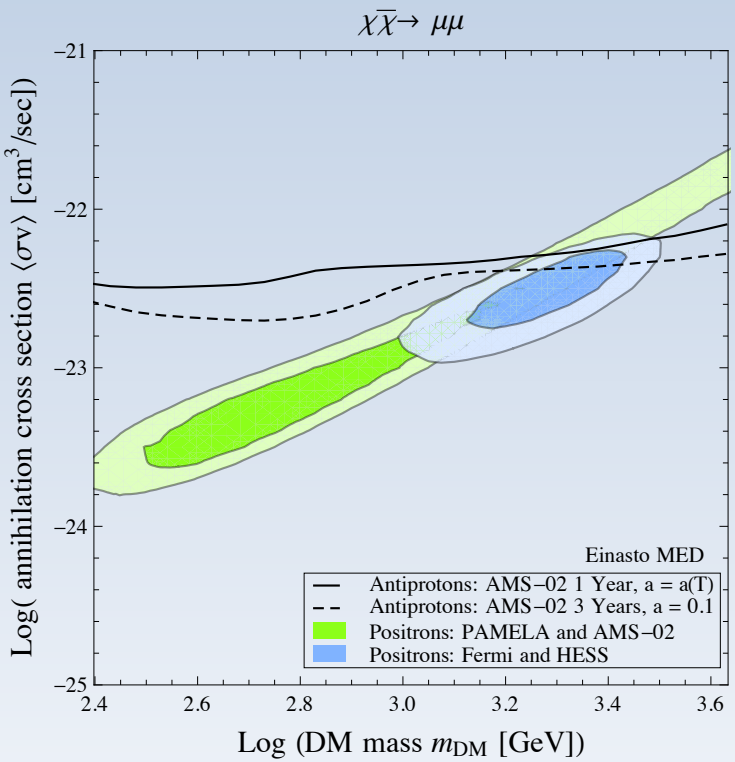




Future sensitivities of AMS-02



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Log (DM mass m_{DM} [GeV])
Einasto MED
Antiprotons: AMS−02 1 Year, a = a(T)
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Positrons: PAMELA and AMS−02
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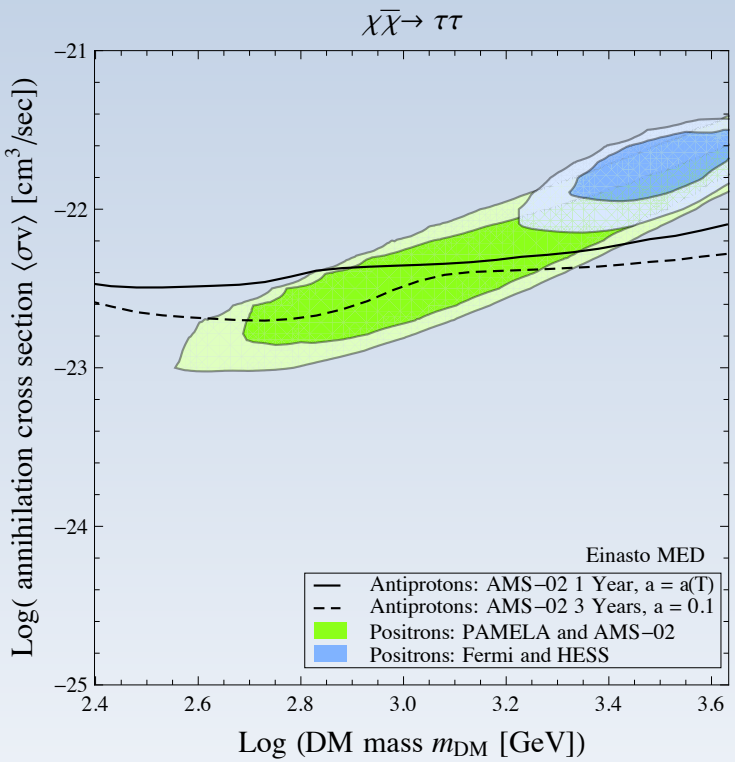
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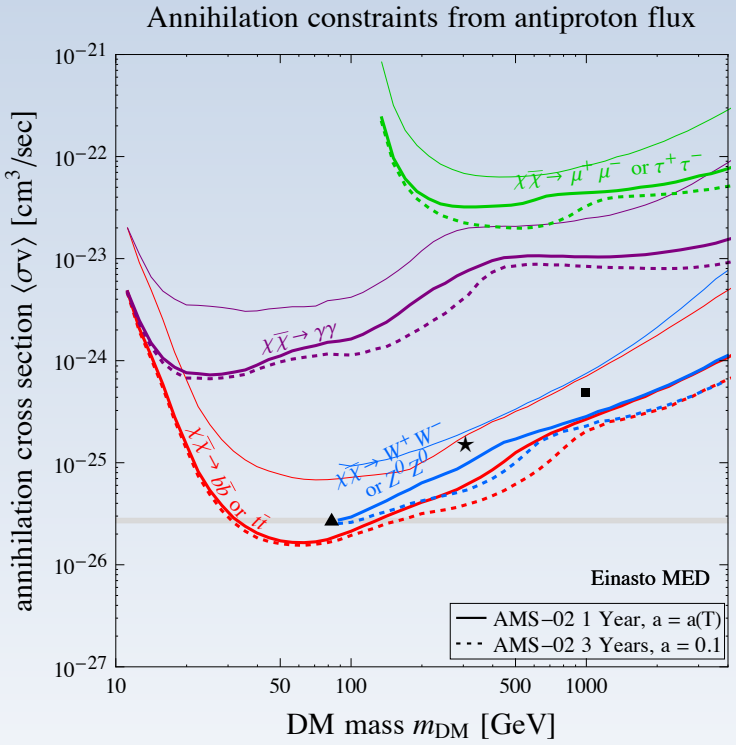

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Annihilation $\chi\chi \to b\bar{b}$, Einasto profile, MED propagation

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■ $m_{\mathrm{DM}} = 1\,\mathrm{TeV}$ $\langle \sigma v \rangle = 5 \times 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
DM signal at high energies
Data has big uncertainties

Current constraints

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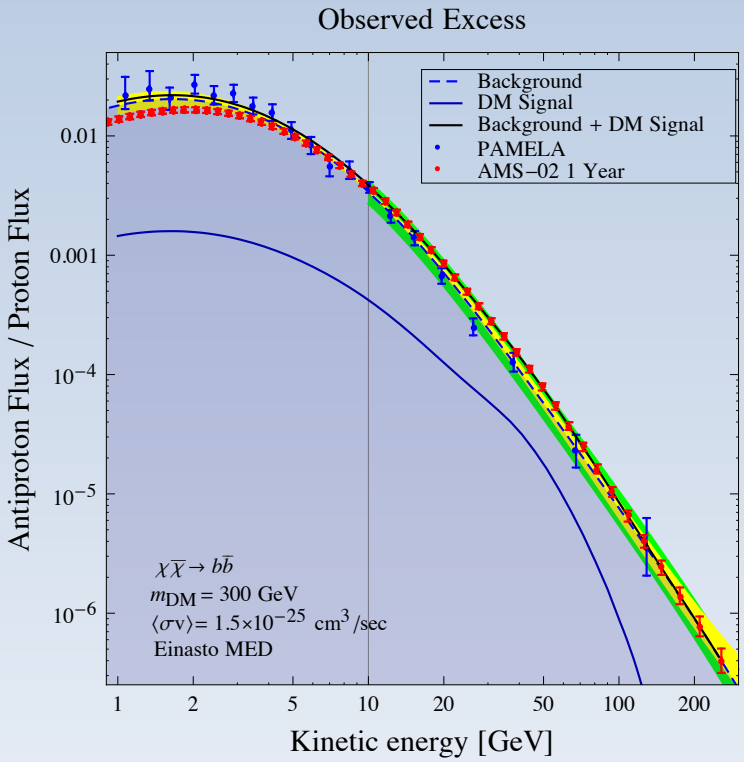

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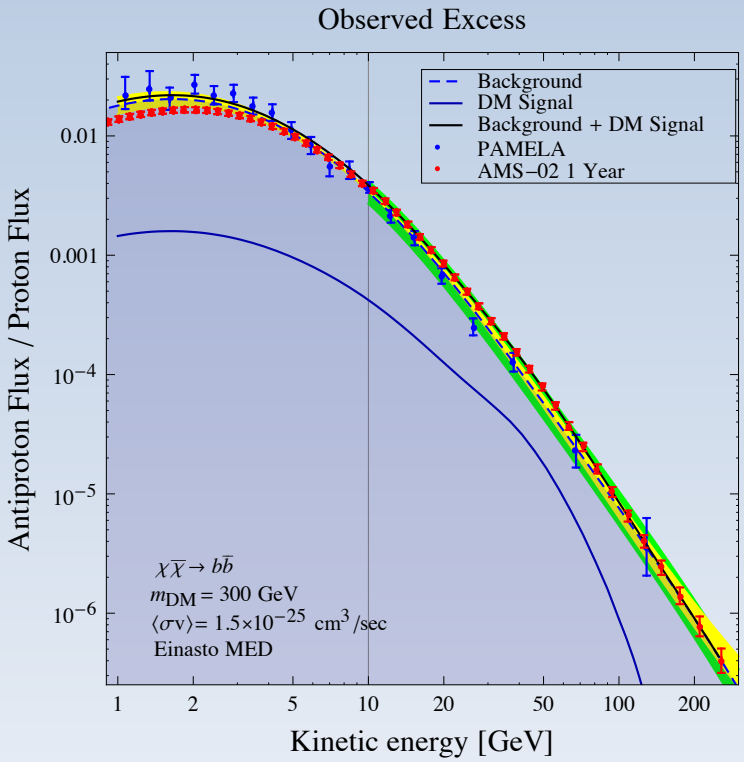

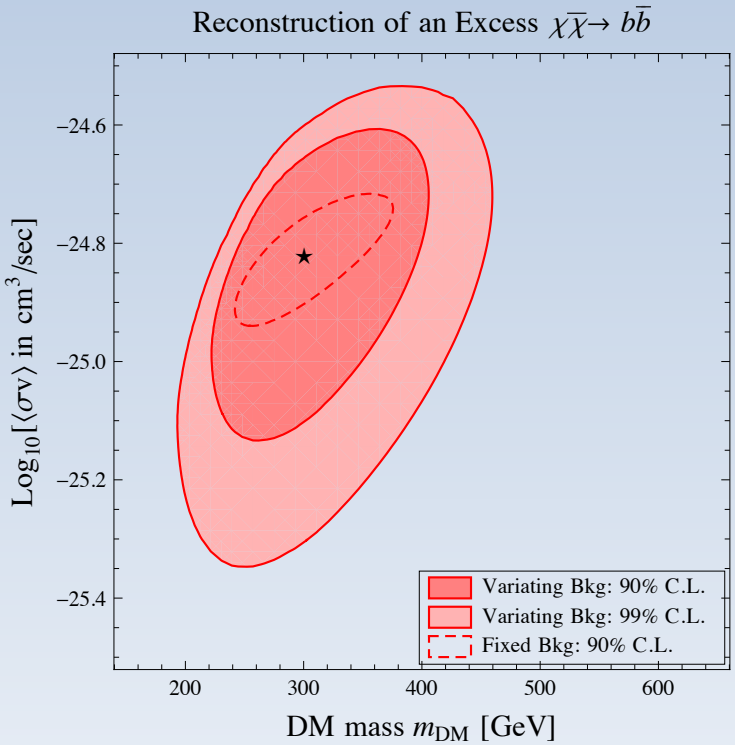

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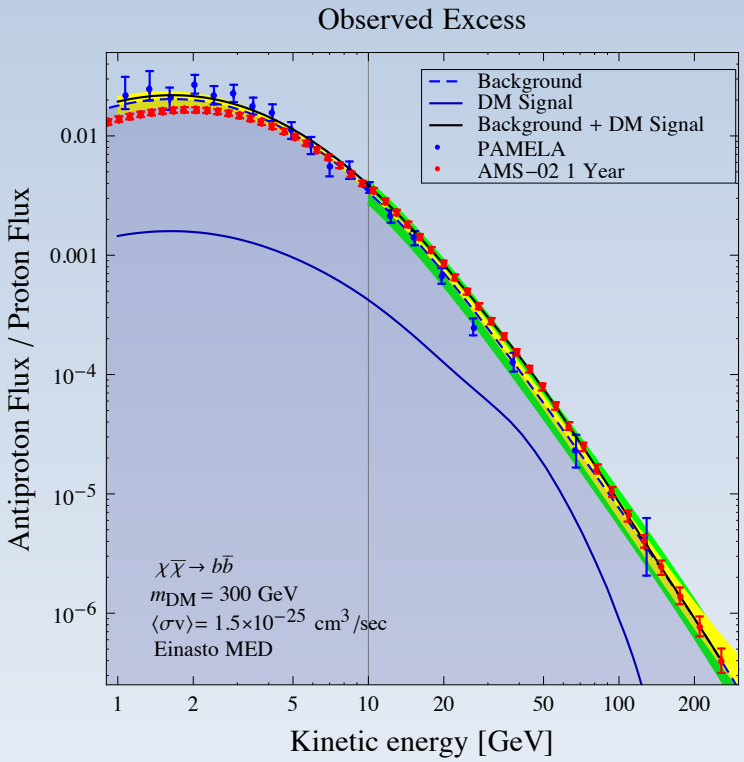

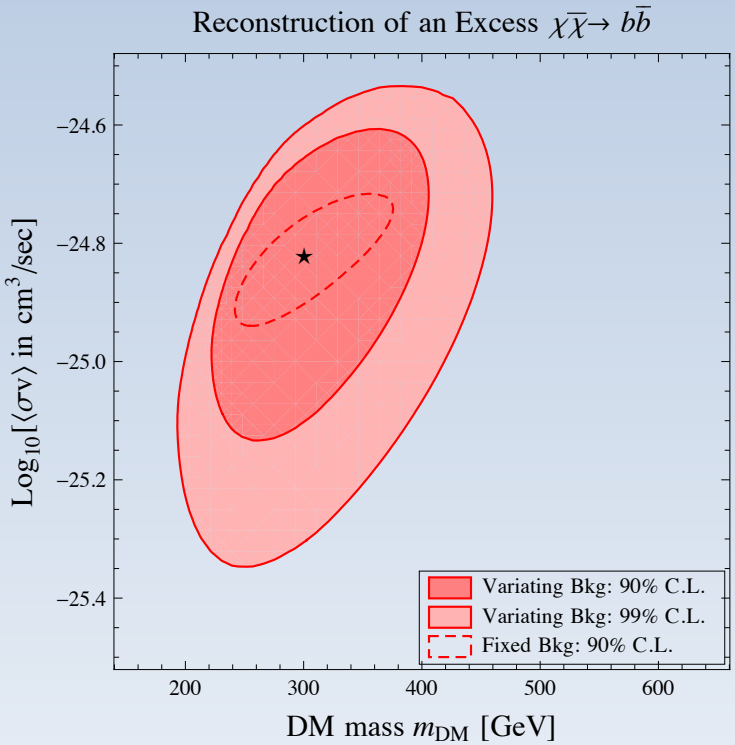

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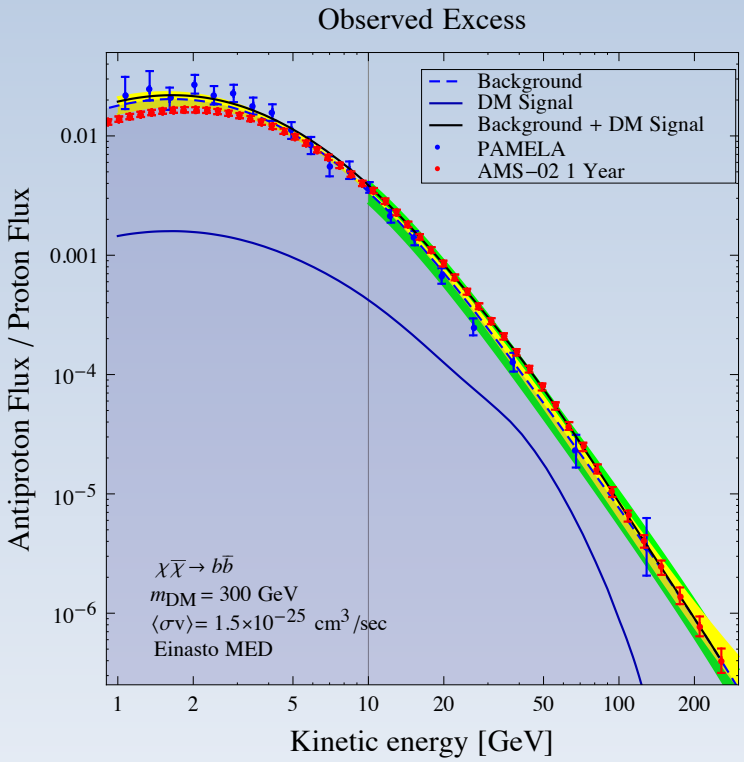

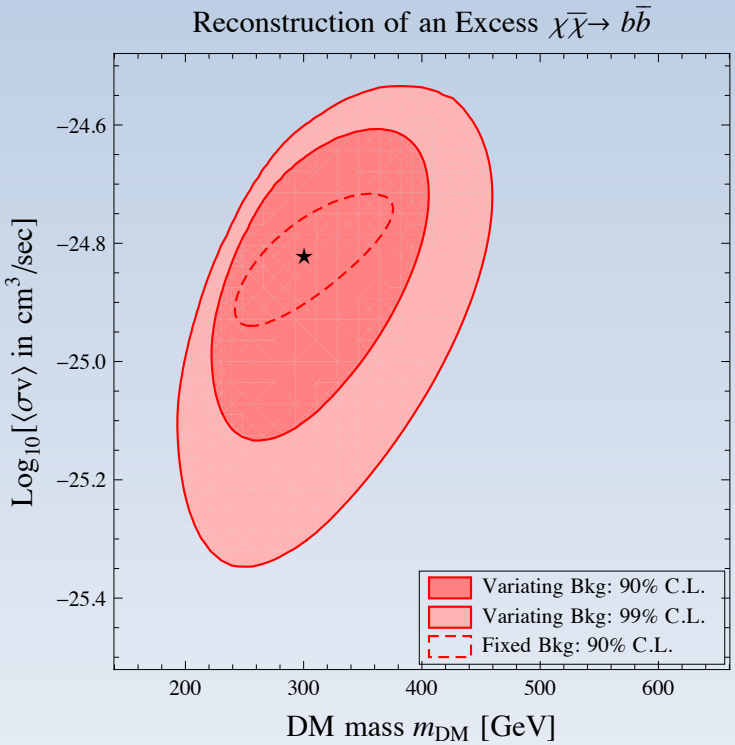

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- m_{DM} determined with 50% of its value
- $\langle\sigma v\rangle$ determined within an order of magnitude

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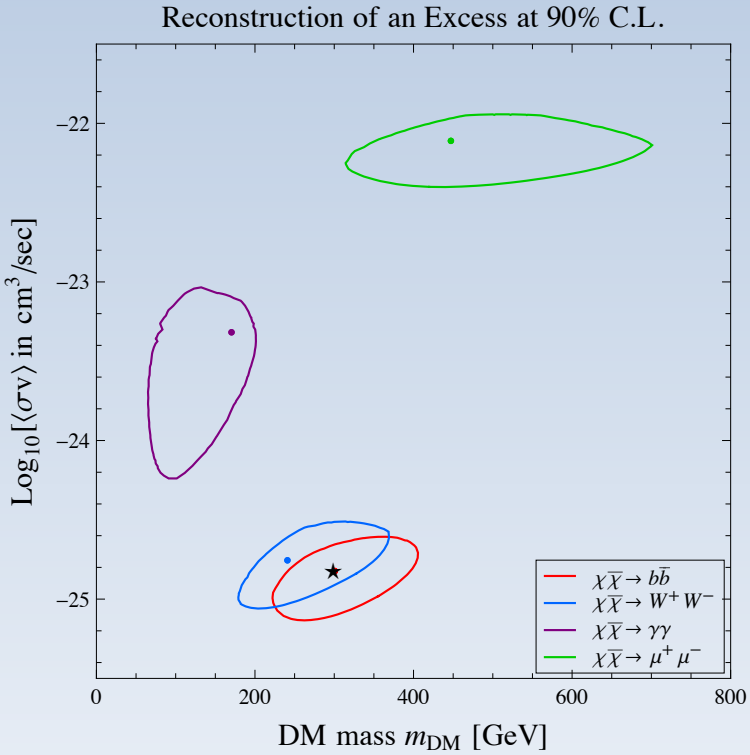

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$\chi\chi \to W^+W^-$	240	1.9×10^{-25}	-19.7
$\chi\chi \to \gamma\gamma$	169	4.8×10^{-24}	-9.8
$\chi\chi \to \mu^+\mu^-$	447	7.6×10^{-23}	-19.2

Current constraints

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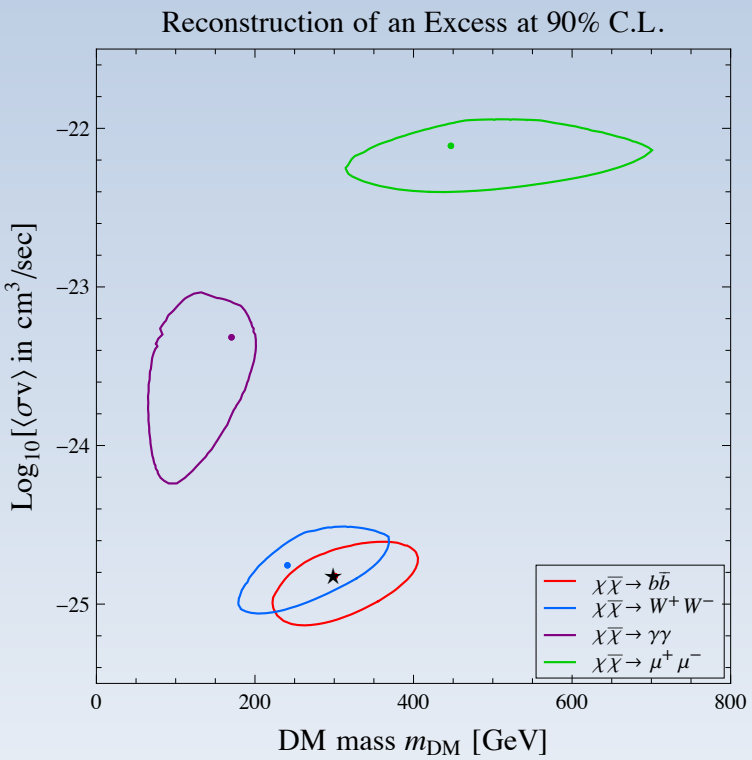

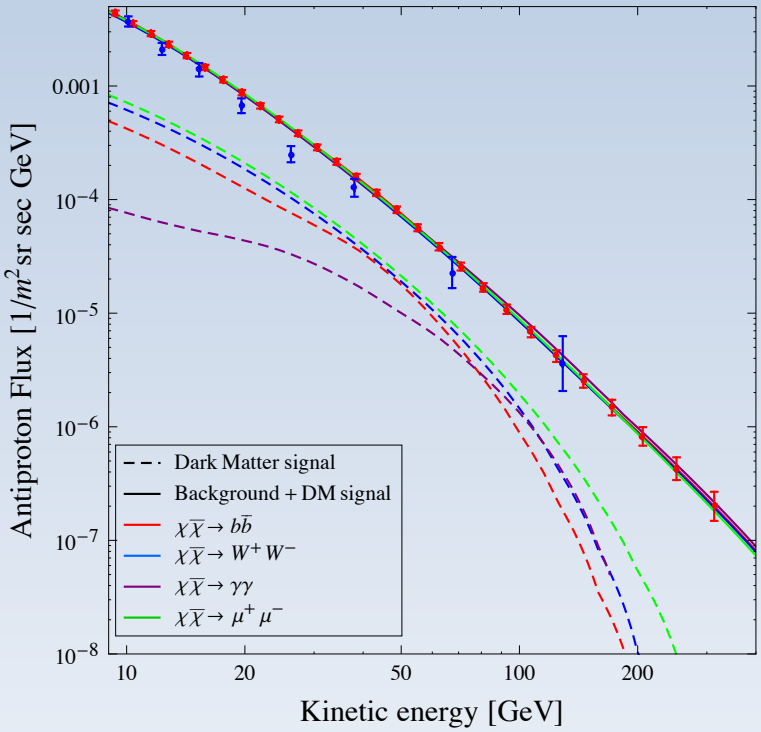

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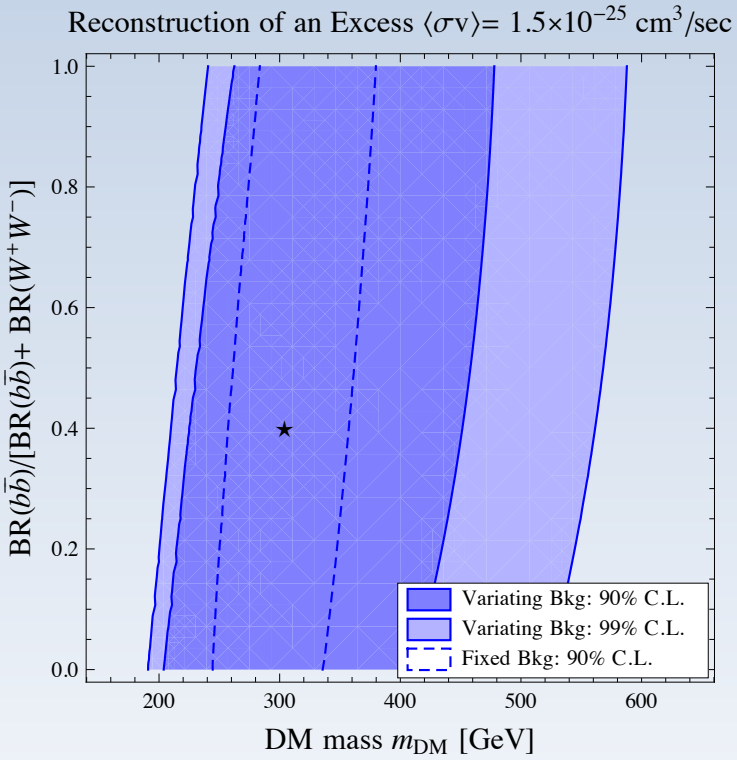
New annihilation signal : **40% $b\bar{b}$ + 60% W^+W^-**



Fixed cross-section $\langle\sigma v\rangle$ [cm^{3}s^{-1}] (true signal : **40% $b\bar{b}$ + 60% W^+W^-**)	mass $m_{\rm DM}$ [GeV]	relative branching ratio	$\Delta\chi^2$ with respect to a pure background
1.5×10^{-25}	300	0.4	-13.0

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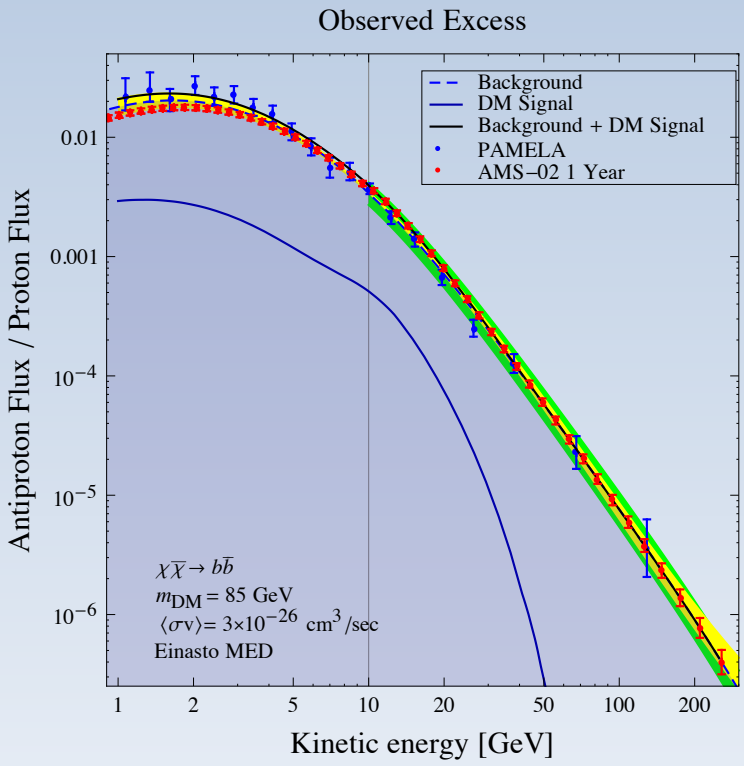

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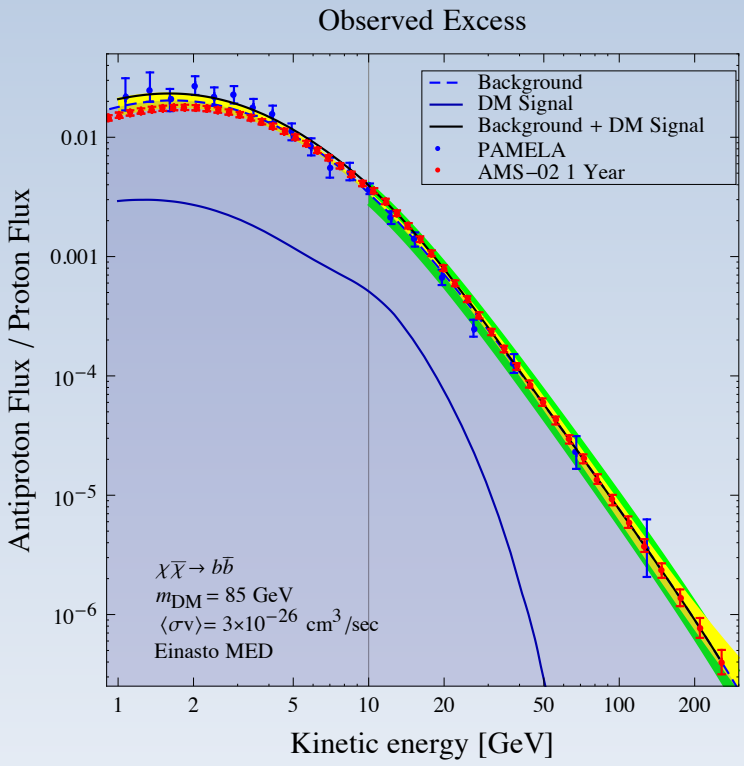

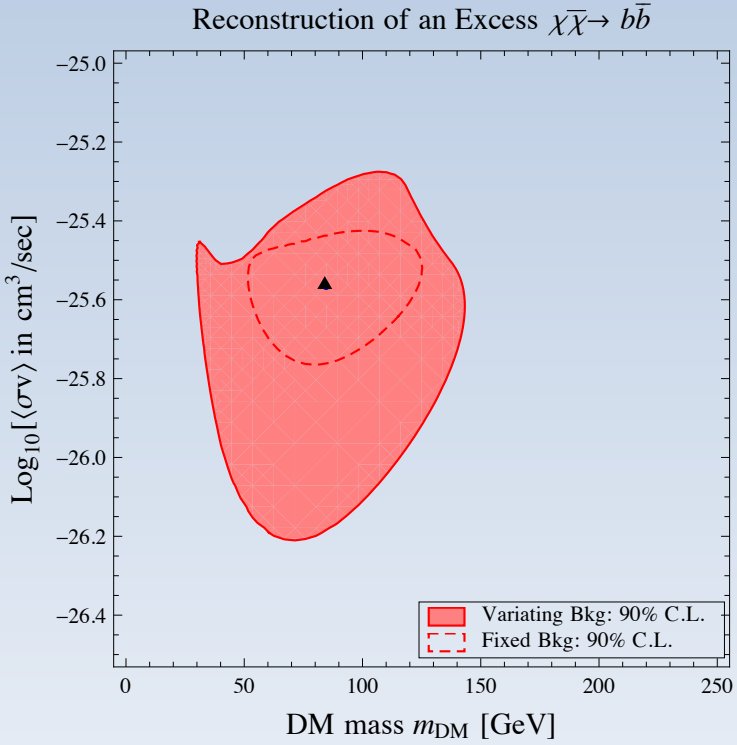

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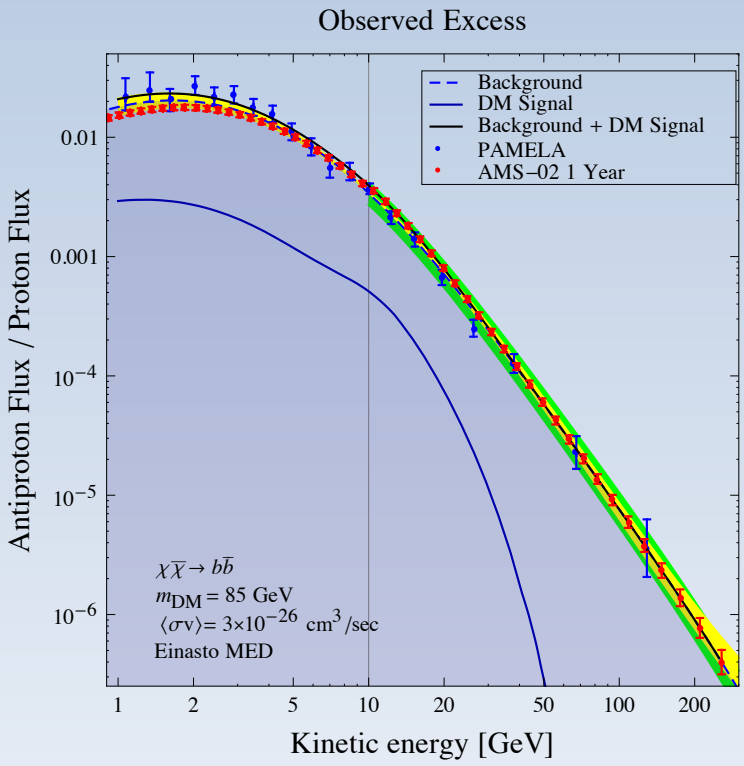

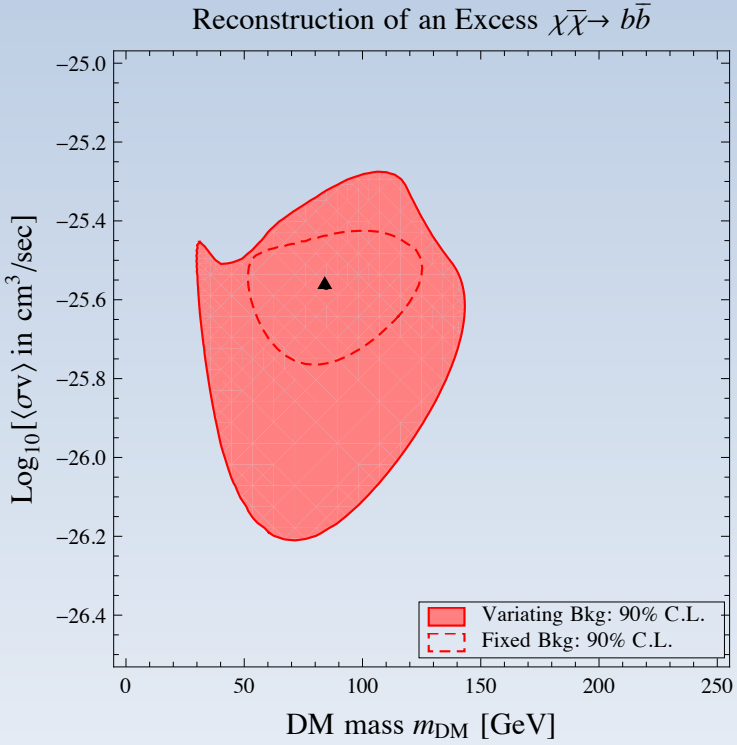

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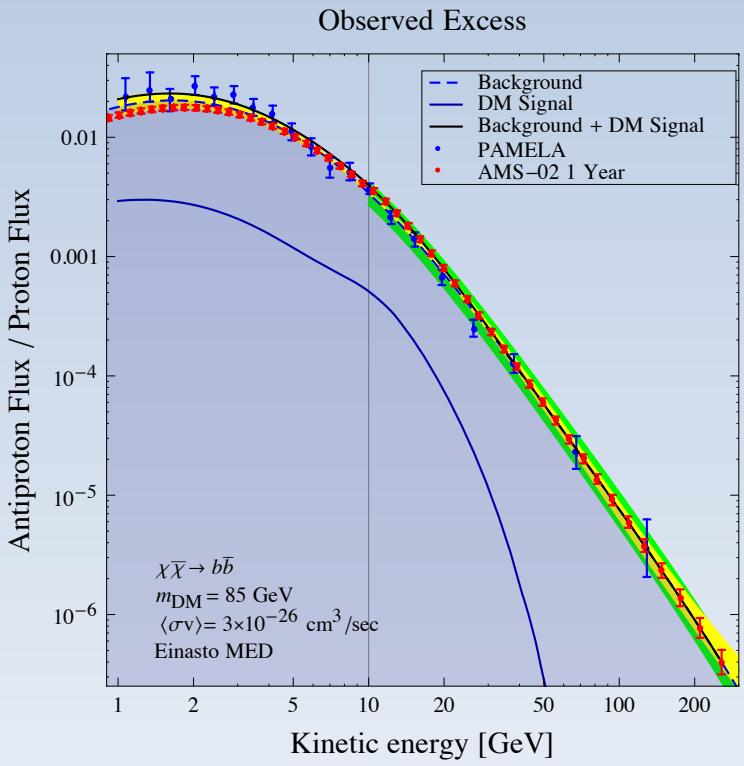

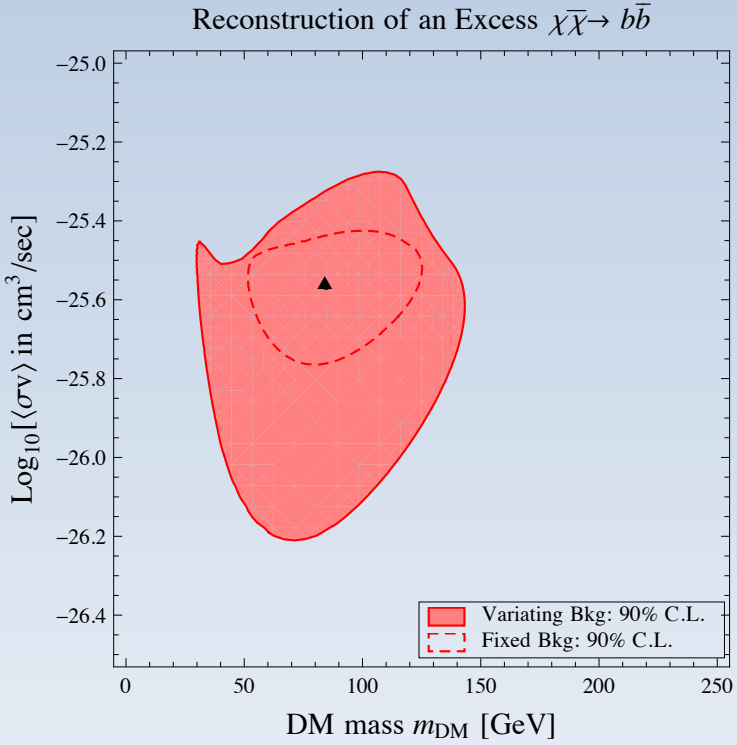

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- 99% C.L. contour would extend artificially to low masses
- Points in the 99% C.L. contour prefer a pure background

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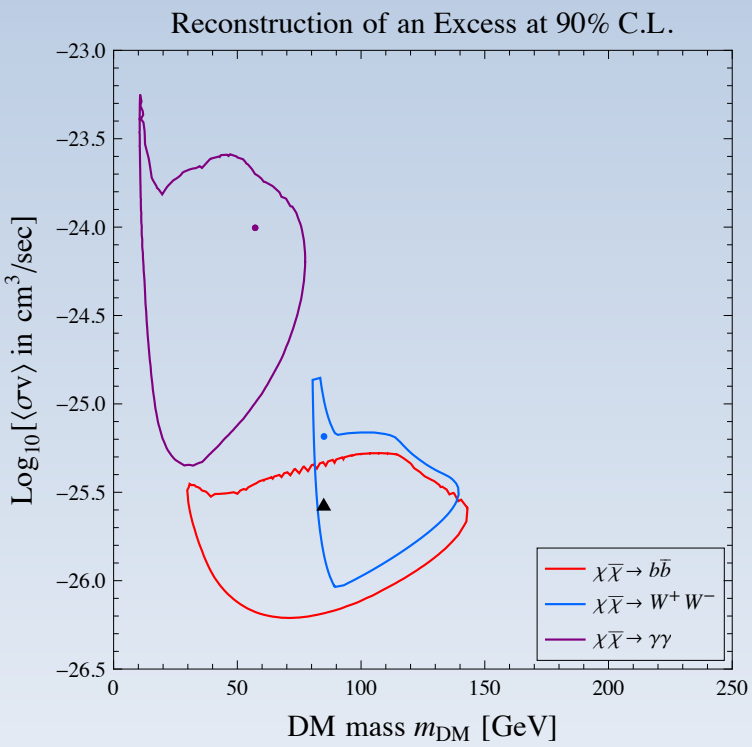

Fixed annihilation channel (true signal : **100% $b\bar{b}$**)	mass m_{DM} [GeV]	cross-section $\langle \sigma v \rangle$ [$\mathrm{cm}^3\mathrm{s}^{-1}$]	$\Delta\chi^2$ with respect to a pure background
$\chi\chi \to b\bar{b}$	84.9	2.7×10^{-26}	-10.5
$\chi\chi \to W^+W^-$	84.8	6.6×10^{-26}	-10.3
$\chi\chi \to \gamma\gamma$	57.4	1.0×10^{-24}	-5.7

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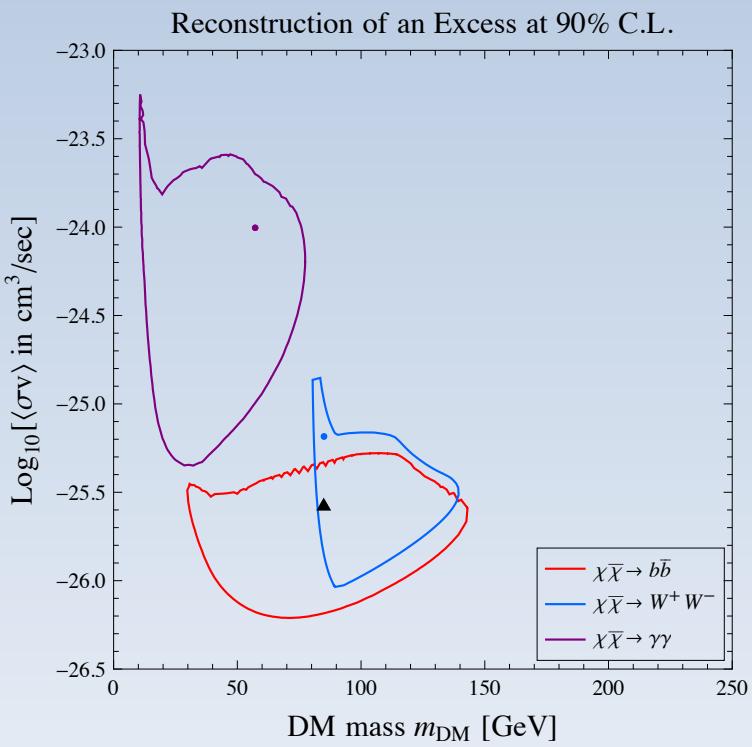

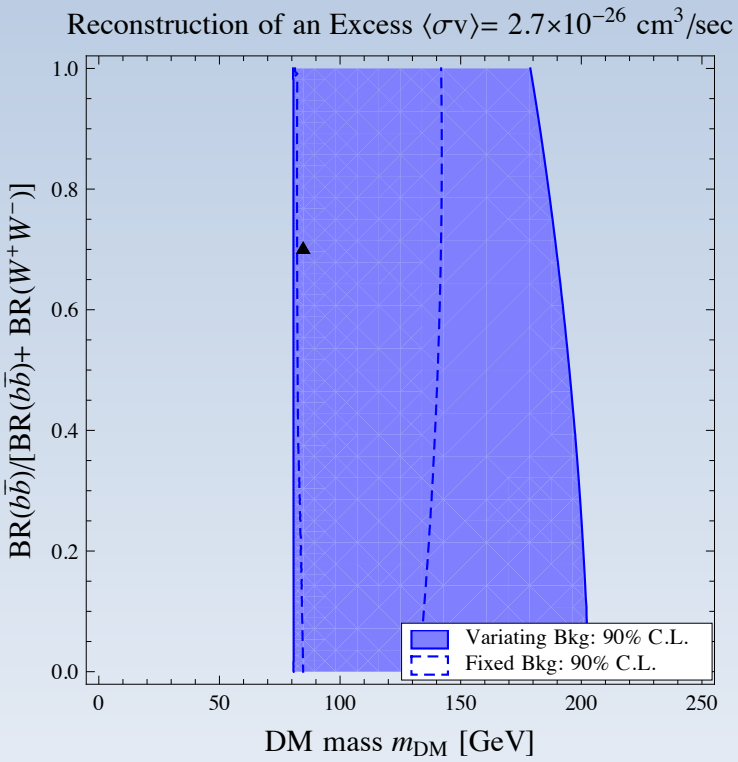

Fixed annihilation channel (true signal : **100% $b\bar{b}$**)	mass $m_{\rm DM}$ [GeV]	cross-section $\langle\sigma v\rangle$ [cm^{3}s^{-1}]	$\Delta\chi^2$ with respect to a pure background
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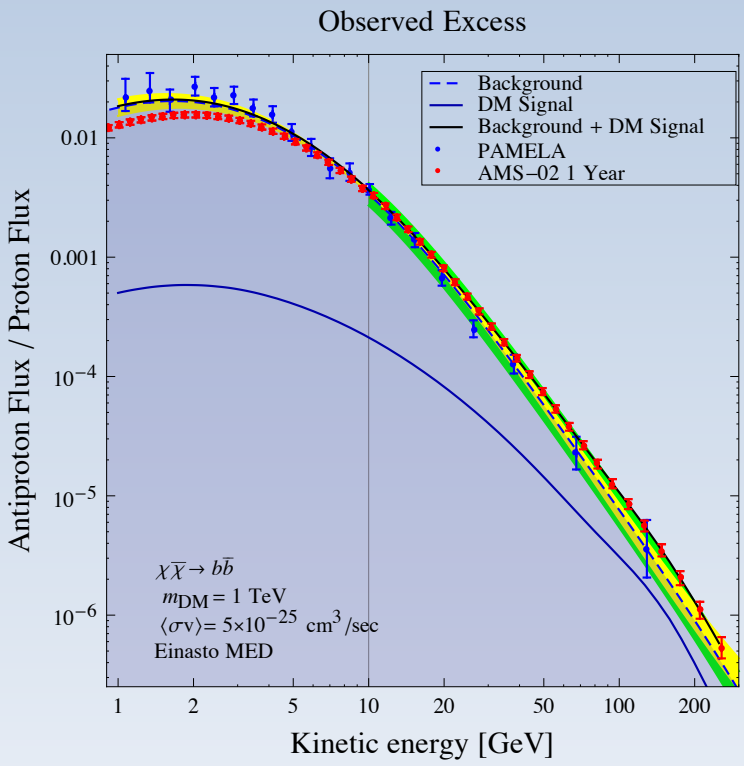
$\chi\chi \to \gamma\gamma$	57.4	1.0×10^{-24}	-5.7

Fixed cross-section $\langle\sigma v\rangle$ [cm^{3}s^{-1}] (true signal : **70% $b\bar{b}$ + 30% W^+W^-**)	mass $m_{\rm DM}$ [GeV]	relative branching ratio	$\Delta\chi^2$ with respect to a pure background
2.7×10^{-26}	84.9	0.7	-5.4

Current constraints

- $m_{\mathrm{DM}} = 1\,\mathrm{TeV}$ and $\langle \sigma v \rangle = 5 \times 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$



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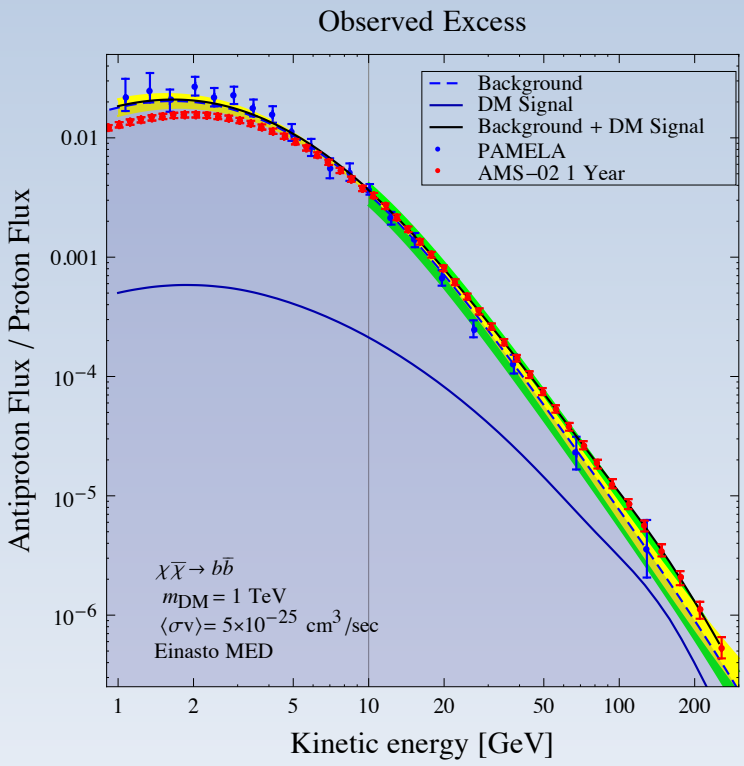
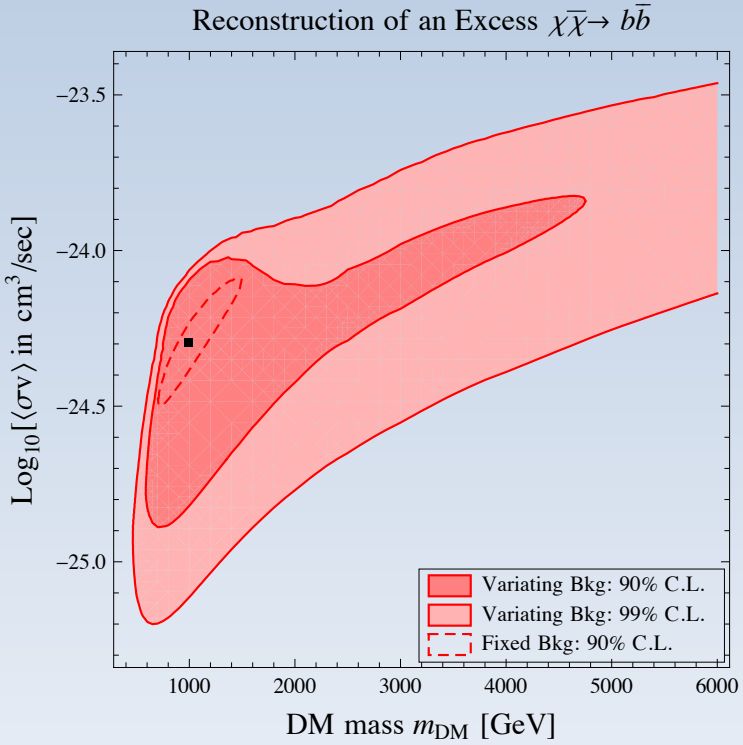
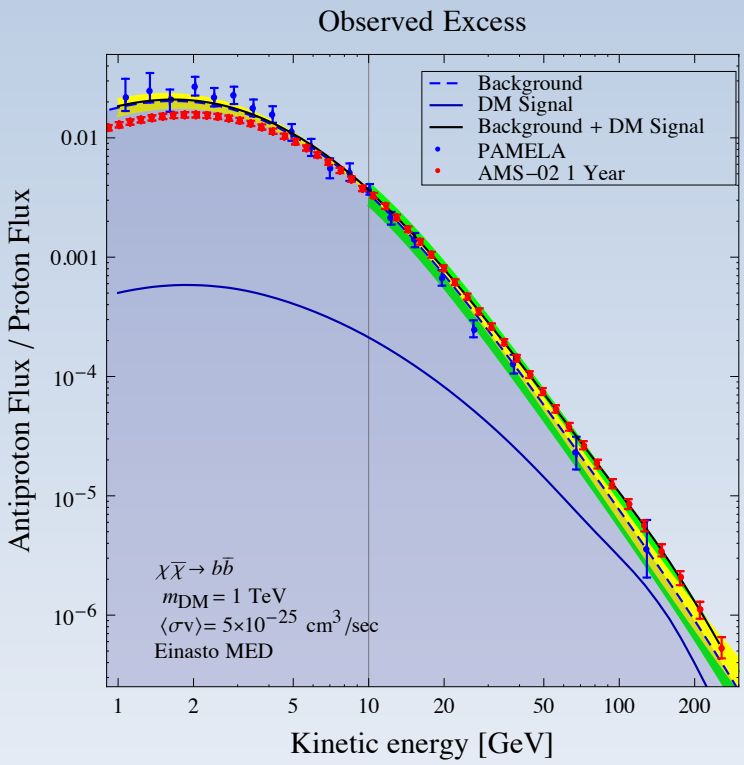
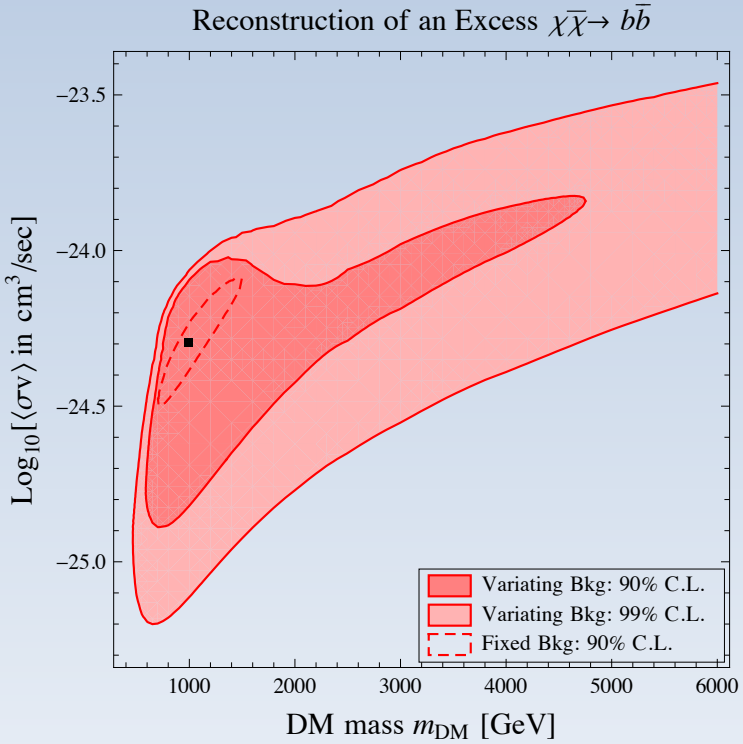




Current constraints

- $m_{\rm DM} = 1\,{\rm TeV}$ and $\langle \sigma v \rangle = 5 \times 10^{-25}\,{\rm cm}^3\,{\rm s}^{-1}$





- 99% C.L. contour extends to high masses
- Any contribution with $m_{DM} > 1\,{\rm TeV}$ can fit the data at 99% C.L. with a cross-section large enough

Current constraints

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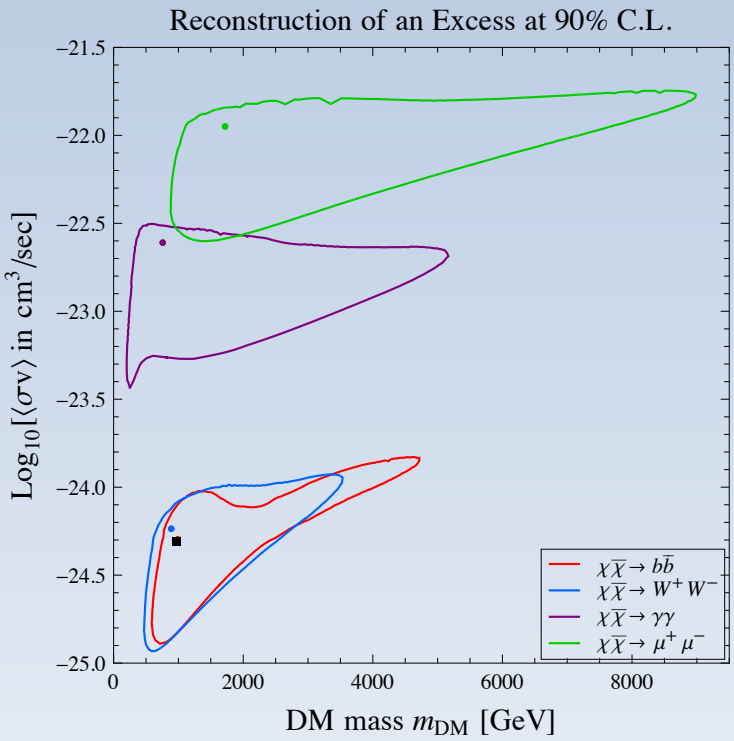

Fixed annihilation channel (true signal : **100% $b\bar{b}$**)	mass $m_{\rm DM}$ [GeV]	cross-section $\langle \sigma v \rangle$ [cm^{3}s^{-1}]	$\Delta\chi^2$ with respect to a pure background
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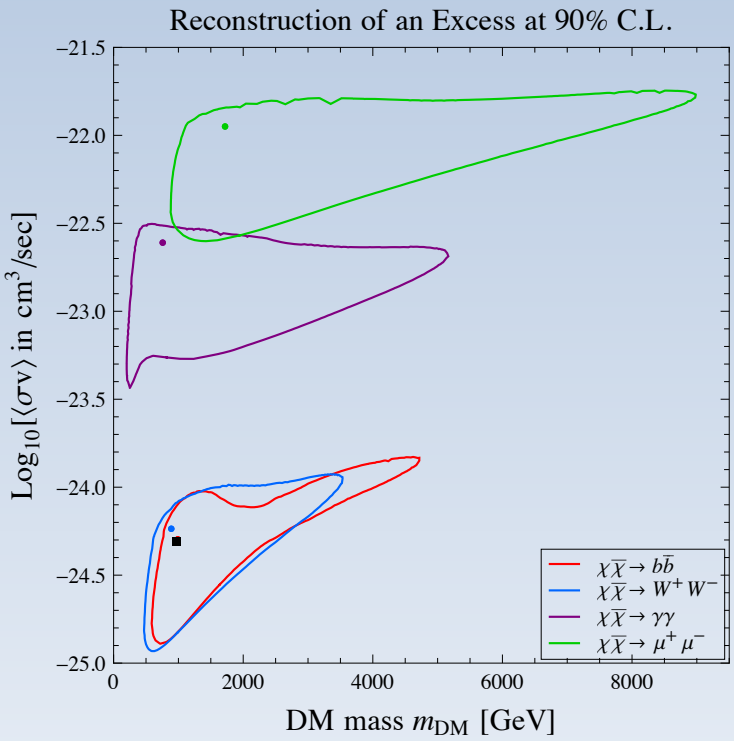

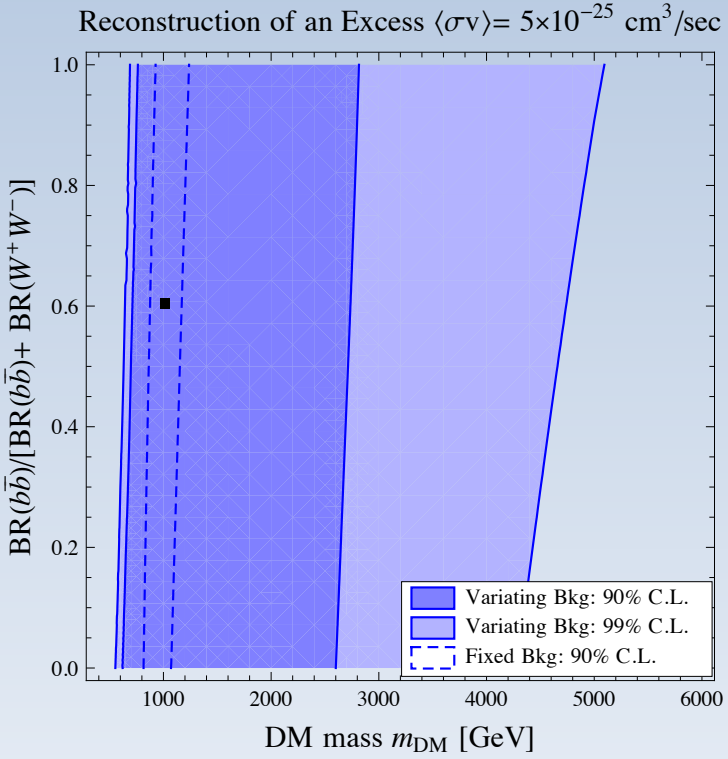

Fixed annihilation channel (true signal : **100% $b\bar{b}$**)	mass $m_{\rm DM}$ [GeV]	cross-section $\langle\sigma v\rangle$ [cm^{3}s^{-1}]	$\Delta\chi^2$ with respect to a pure background
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Fixed cross-section $\langle\sigma v\rangle$ [cm^{3}s^{-1}] (true signal : **60% $b\bar{b}$ + 40% W^+W^-**)	mass $m_{\rm DM}$ [GeV]	relative branching ratio	$\Delta\chi^2$ with respect to a pure background
5×10^{-25}	999	0.6	-15.3

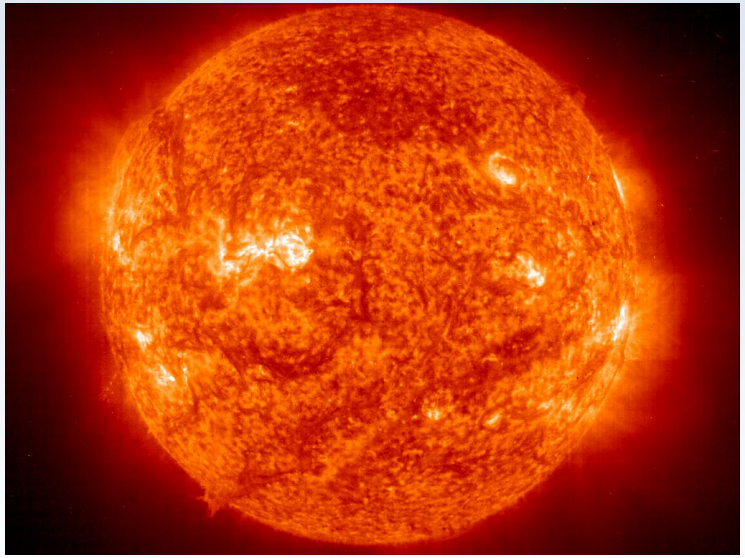
- Force-field approximation

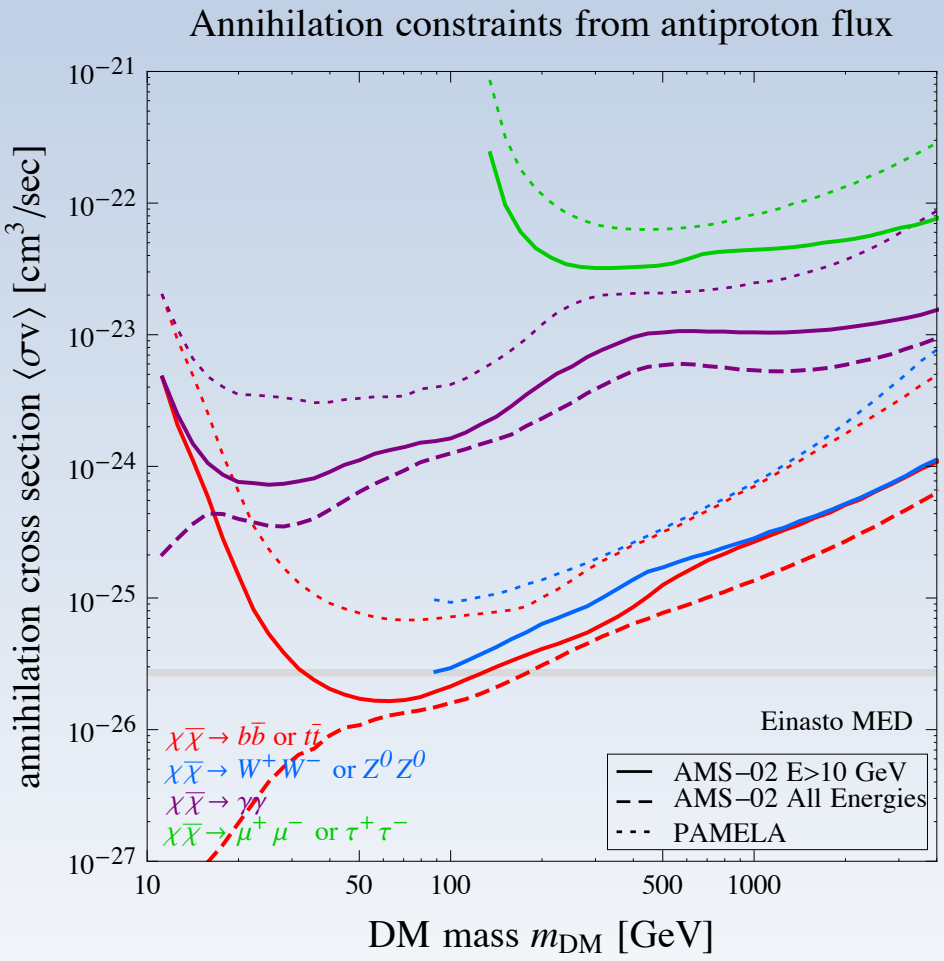
$$J_{\oplus}(K) = J_{\mathrm{LIS}}(K + \phi\frac{Z}{A})\frac{K(K+2\,m)}{(K+m+\phi\frac{Z}{A})^2 - m^2}$$

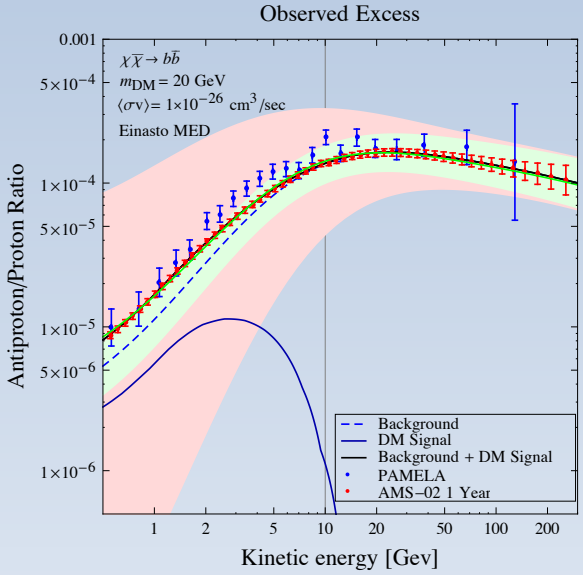
- Total $\bar{p}/p$ ratio

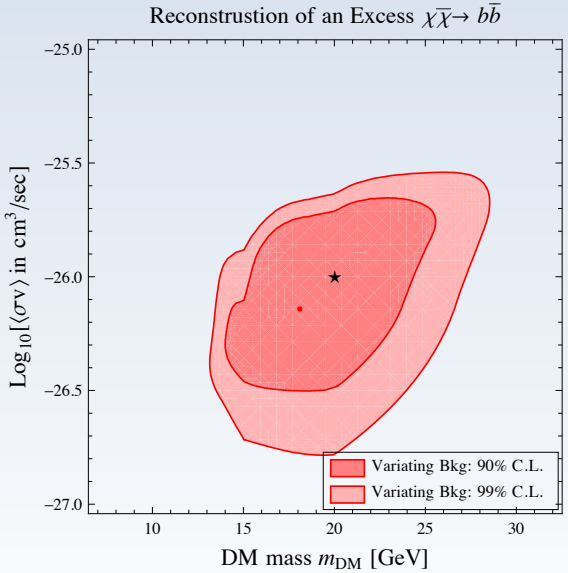
$$\phi_{\mathrm{tot}}(m_{\mathrm{DM}}, \langle\sigma v\rangle; A, p; \phi^+\phi^-)$$
$$= \phi_{\mathrm{DM}}(m_{\mathrm{DM}}, \langle\sigma v\rangle; \phi^+, \phi^-) + \phi_{\mathrm{bkg}}(A, p; \phi^+, \phi^-)$$

with $\phi^+, \phi^- \in [0.3, 1.7]$ GeV




Annihilation constraints from antiproton flux
annihilation cross section ⟨σv⟩ [cm³/sec]
DM mass m_{DM} [GeV]
$\chi\bar{\chi} \to b\bar{b}$ or $t\bar{t}$
$\chi\bar{\chi} \to W^+W^-$ or Z^0Z^0
$\chi\bar{\chi} \to \gamma\gamma$
$\chi\bar{\chi} \to \mu^+\mu^-$ or $\tau^+\tau^-$
Einasto MED
AMS−02 E>10 GeV
AMS−02 All Energies
PAMELA


Observed Excess
$\chi\bar{\chi} \to b\bar{b}$
m_{DM} = 20 GeV
⟨σv⟩= 1×10⁻²⁶ cm³/sec
Einasto MED
Antiproton/Proton Ratio
Kinetic energy [Gev]
Background
DM Signal
Background + DM Signal
PAMELA
AMS−02 1 Year


Reconstrustion of an Excess $\chi\bar{\chi} \to b\bar{b}$
Log₁₀[⟨σv⟩ in cm³/sec]
DM mass m_{DM} [GeV]
Variating Bkg: 90% C.L.
Variating Bkg: 99% C.L.

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- If an excess is measured :
  - Restricting to "traditional" hadronic channels :
    - m_{DM} reconstructed within 50% for $m_{DM} \sim$ few hundred GeV (most favorable case)
    - $\langle \sigma v \rangle$ reconstructed within an order of magnitude
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  - If "exotic" annihilation channels open, no discrimination
- Solar Modulation effects can be added : AMS-02 can probe the thermal cross-section for $m_{DM} < 300$ GeV

Linear approximation of the rigidity resolution

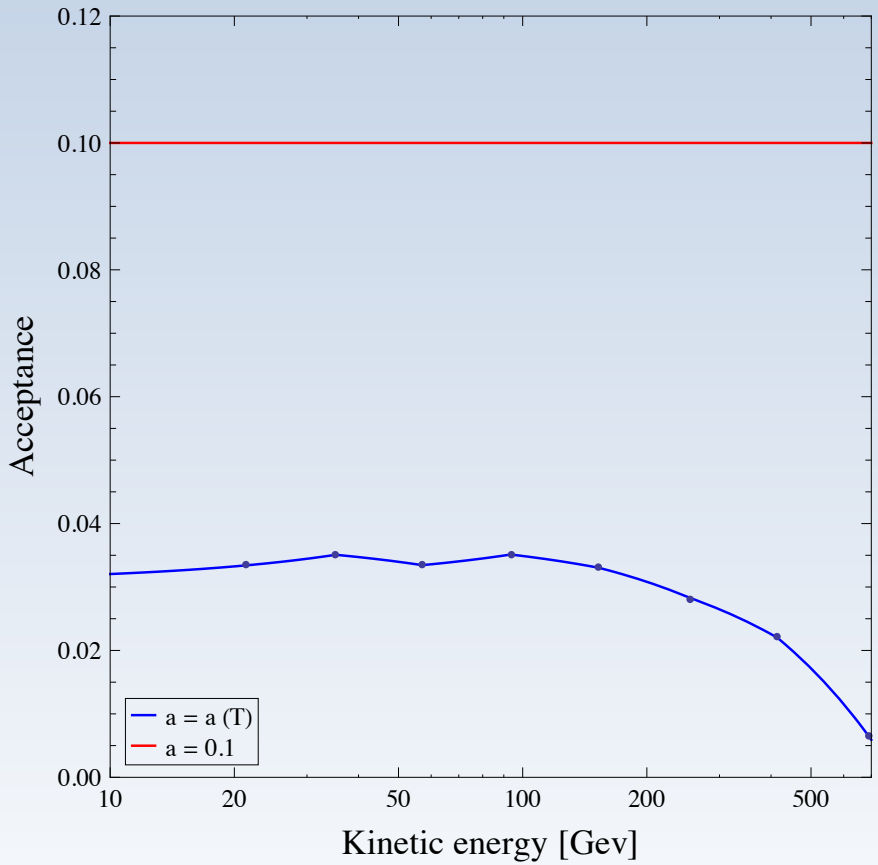
$$r(T) = \frac{\Delta T}{T} = 0.0042 \times T + 0.1$$

The number of collected and reconstructed antiprotons in a bin i centered around a kinetic energy T_i

$$N_i = \epsilon\, a(T_i)\, \phi(T_i)\, \Delta T_i\, \Delta t$$

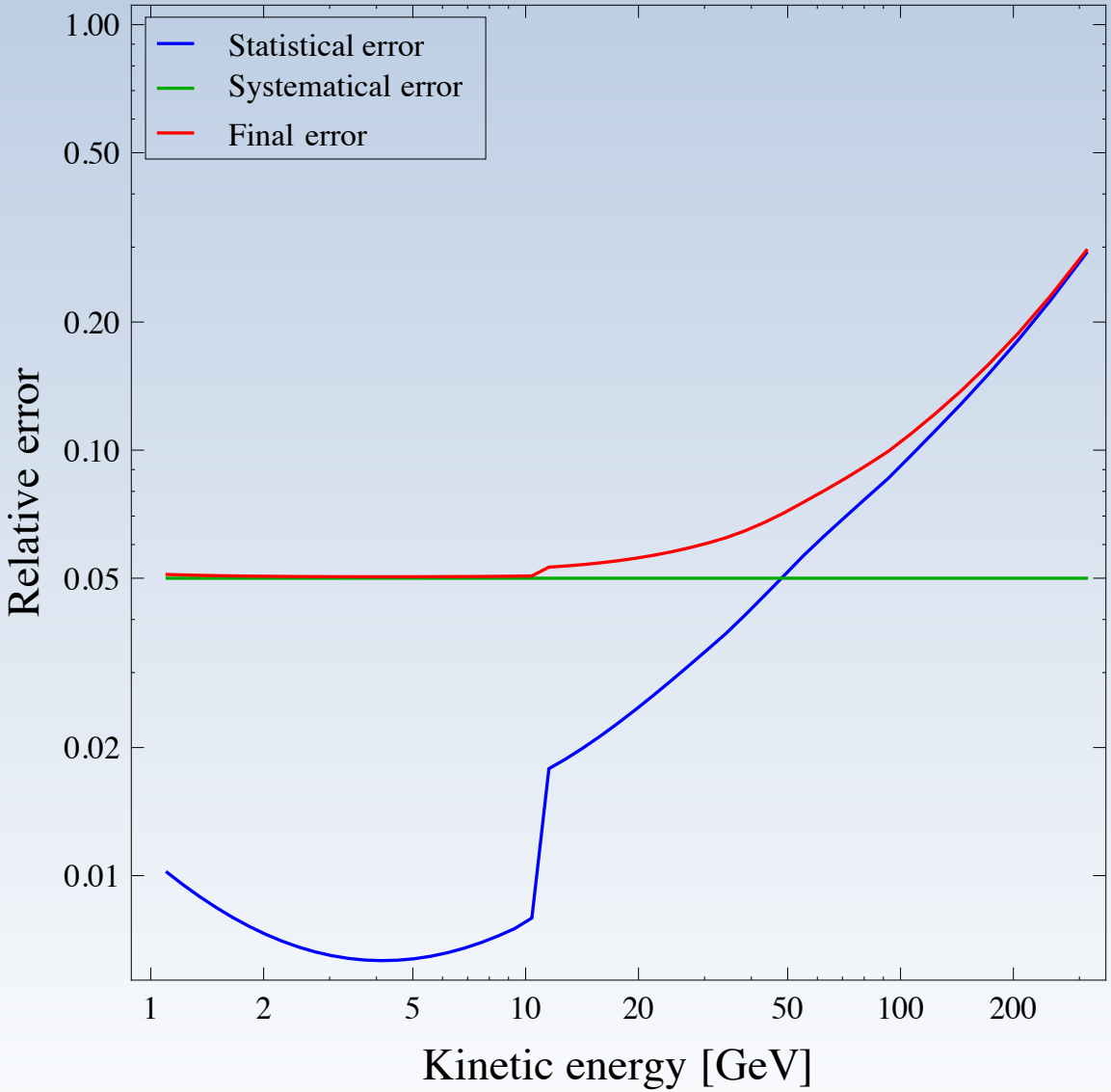
ϵ	the efficiency ($\epsilon = 1$ for protons),
a	the geometrical acceptance of the apparatus,
ϕ	the antiproton flux,
ΔT	the width of the kinetic energy bin and
Δt	the exposure time.

Statistical error : $\Delta N = \sqrt{N} \Rightarrow \Delta\phi_i\,|_{stat} = \sqrt{\frac{\phi(T_i)}{\epsilon\, a(T_i)\, \Delta T_i\, \Delta t}}$
Systematic errors :$\Delta\phi_i\,|_{syst} = 0.05 \times \phi_i(T_i)$



Two cases :

- Realistic
  $\Delta t = 1$ Year and $a = a(T)$,
- Idealistic
  $\Delta t = 3$ Years and $a = 0.1$


Statistical error
Systematical error
Final error
Relative error
1.00
0.50
0.20
0.10
0.05
0.02
0.01
1
2
5
10
20
50
100
200
Kinetic energy [GeV]

Real signal : $\chi\chi \to b\bar{b}$, $m_{\rm DM} = 1\,{\rm TeV}$ and $\langle\sigma v\rangle = 5 \times 10^{-25}$ cm^{3}s^{-1}

Fixed annihilation channel (true signal : **100% $b\bar{b}$**)	mass $m_{\rm DM}$ [GeV]	cross-section $\langle\sigma v\rangle$ [cm^{3}s^{-1}]	$\Delta\chi^2$ with respect to a pure background
$\chi\chi \to b\bar{b}$	999	5×10^{-25}	-15.7
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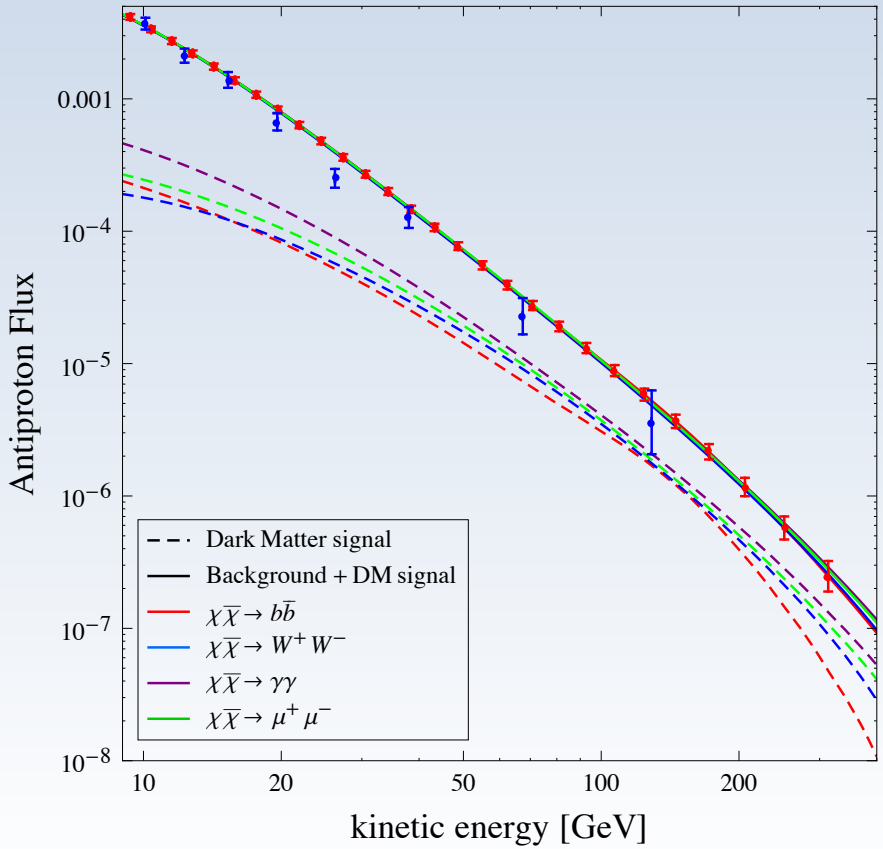
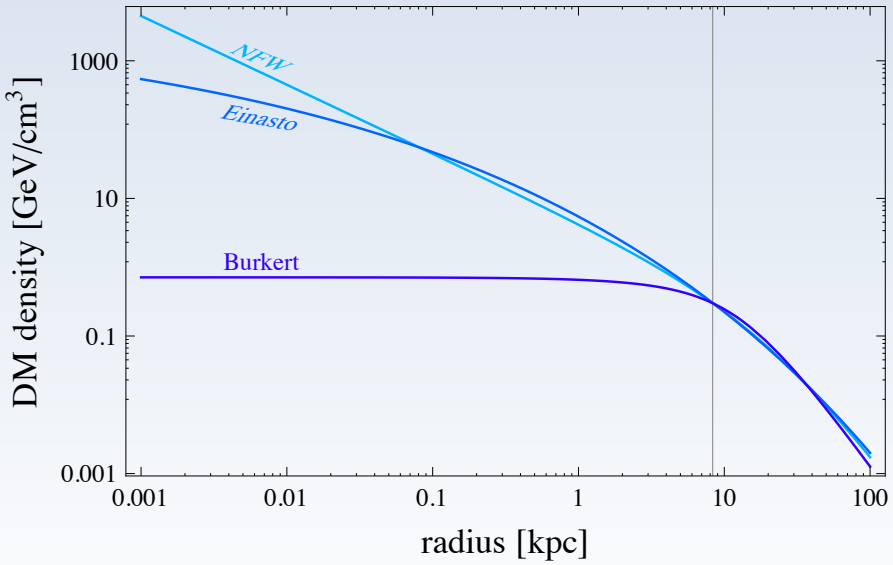


$$\rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2} \qquad r_s = 24.42 \quad \rho_s = 0.184$$

$$\rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\} \qquad \alpha = 0.17 \quad r_s = 28.44 \quad \rho_s = 0.033$$

$$\rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)} \qquad 1r_s = 2.67 \quad \rho_s = 0.712$$



Diffusion equation for the number density of antiprotons per unit energy $f(t, \vec{x}, T)$:

$$\frac{\partial f}{\partial t} - \mathcal{K} \cdot \nabla^2 f + \frac{\partial}{\partial z}(\text{sign}(z) f V_{conv}) = Q - 2h\delta(z)(\Gamma_{\text{ann}} + \Gamma_{\text{non-ann}}) f$$

diffusion term	$\mathcal{K}(T) = \mathcal{K}_0 \beta \left(\frac{p}{\text{GeV}}\right)^{\delta}$
convective wind	V_{conv}
DM ann/decay source term	Q
annihilation rate of $\bar{p}$ on p	Γ_{ann}
interaction rate of $\bar{p}$	$\Gamma_{\text{non-ann}}$

Model	δ	$\mathcal{K}_0$ [kpc^2/Myr]	V_{conv} [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15

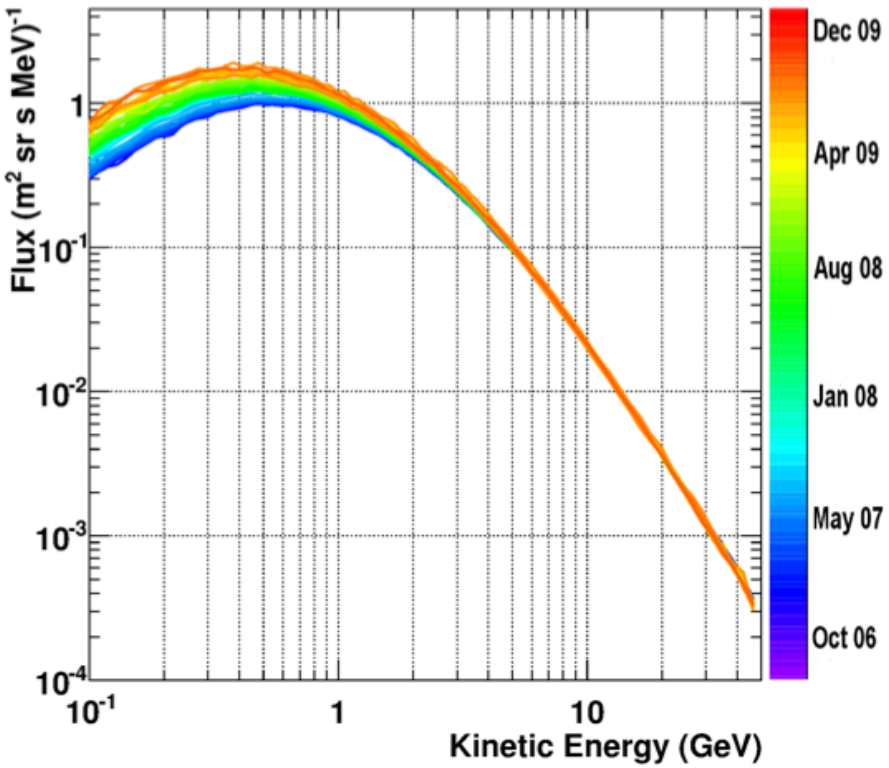
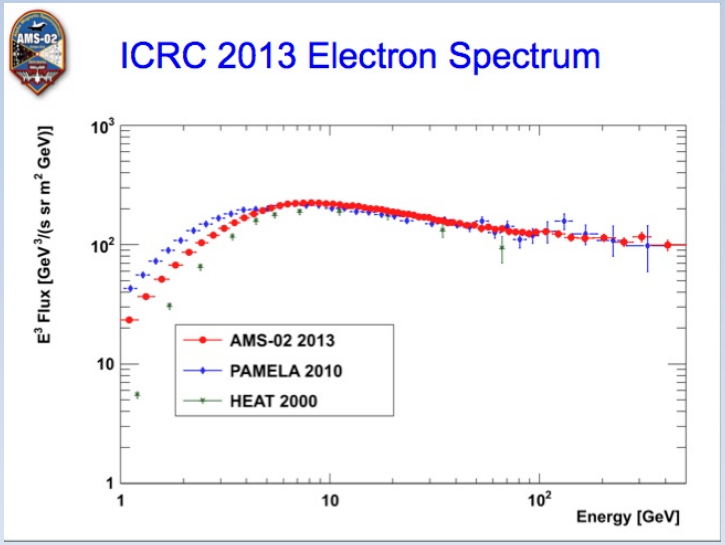
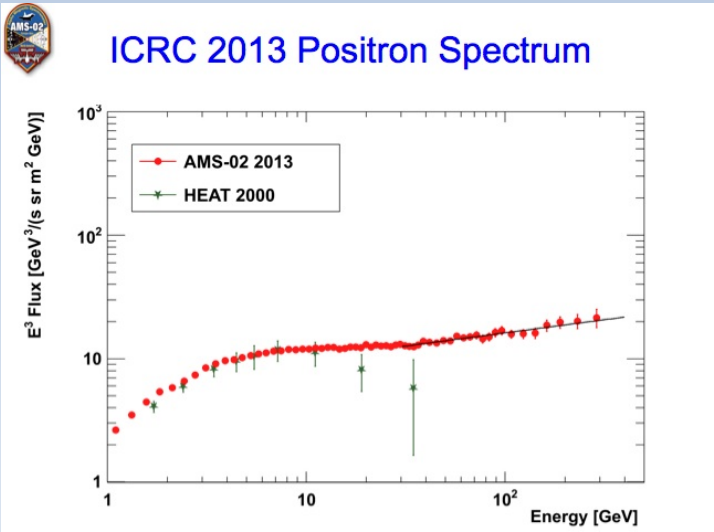
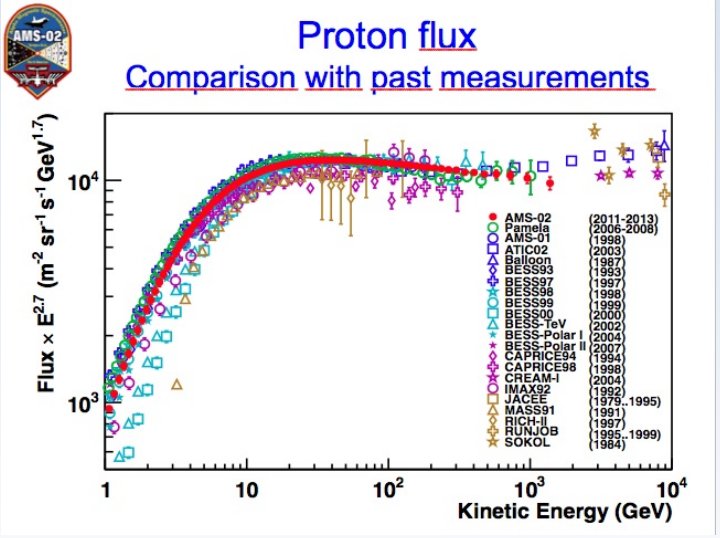


Fig. 4.— The evolution of the proton energy spectrum as particle intensities approached the period of minimum solar activity, from July 2006 (violet), to December 2009 (red). The region between the blue and red curves indicates the spread in proton fluxes during this time.


ICRC 2013 Electron Spectrum
E³ Flux [GeV³/(s sr m² GeV)]
Energy [GeV]
AMS-02 2013
PAMELA 2010
HEAT 2000


ICRC 2013 Positron Spectrum
E³ Flux [GeV³/(s sr m² GeV)]
Energy [GeV]
AMS-02 2013
HEAT 2000


Proton flux
Comparison with past measurements
Flux × E^2.7 (m⁻² sr⁻¹ s⁻¹ GeV^1.7)
Kinetic Energy (GeV)
AMS-02 (2011-2013)
Pamela (2006-2008)
AMS-01 (1998)
ATIC02 (2003)
Balloon (1987)
BESS93 (1993)
BESS97 (1997)
BESS98 (1998)
BESS99 (1999)
BESS00 (2000)
BESS-TeV (2002)
BESS-Polar I (2004)
BESS-Polar II (2007)
CAPRICE94 (1994)
CAPRICE98 (1998)
CREAM-I (2004)
IMAX92 (1992)
JACEE (1979..1995)
MASS91 (1991)
RICH-II (1997)
RUNJOB (1995..1999)
SOKOL (1984)