Is DM hidden in the $\bar{p}$ flux?

Pierre

Outline

1) Incorporating theoretical systematics in $\bar{p}$ fits

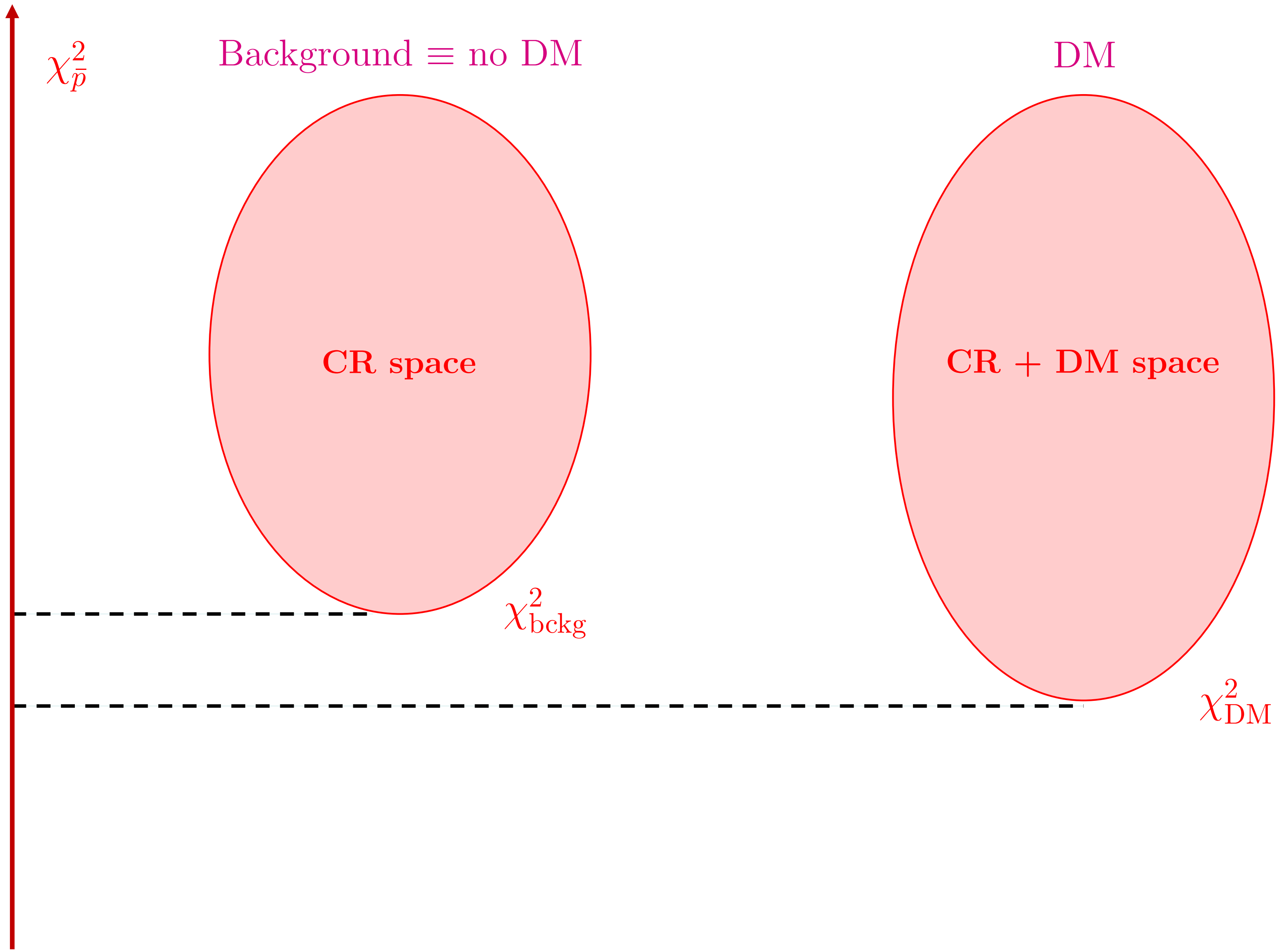
2) Spectral anomalies – Frequentist vs Bayesian

3) A few recent examples

CRAC meeting – Grenoble – July 5, 2019

1) Incorporating theoretical systematics in $\bar{p}$ fits

In general **systematics** $\equiv$ **CR** $+ \{\Phi_i = \Phi_p + \Phi_\alpha\} + \dfrac{d\sigma_{ij\to\bar{p}}}{dE_{\bar{p}}}$



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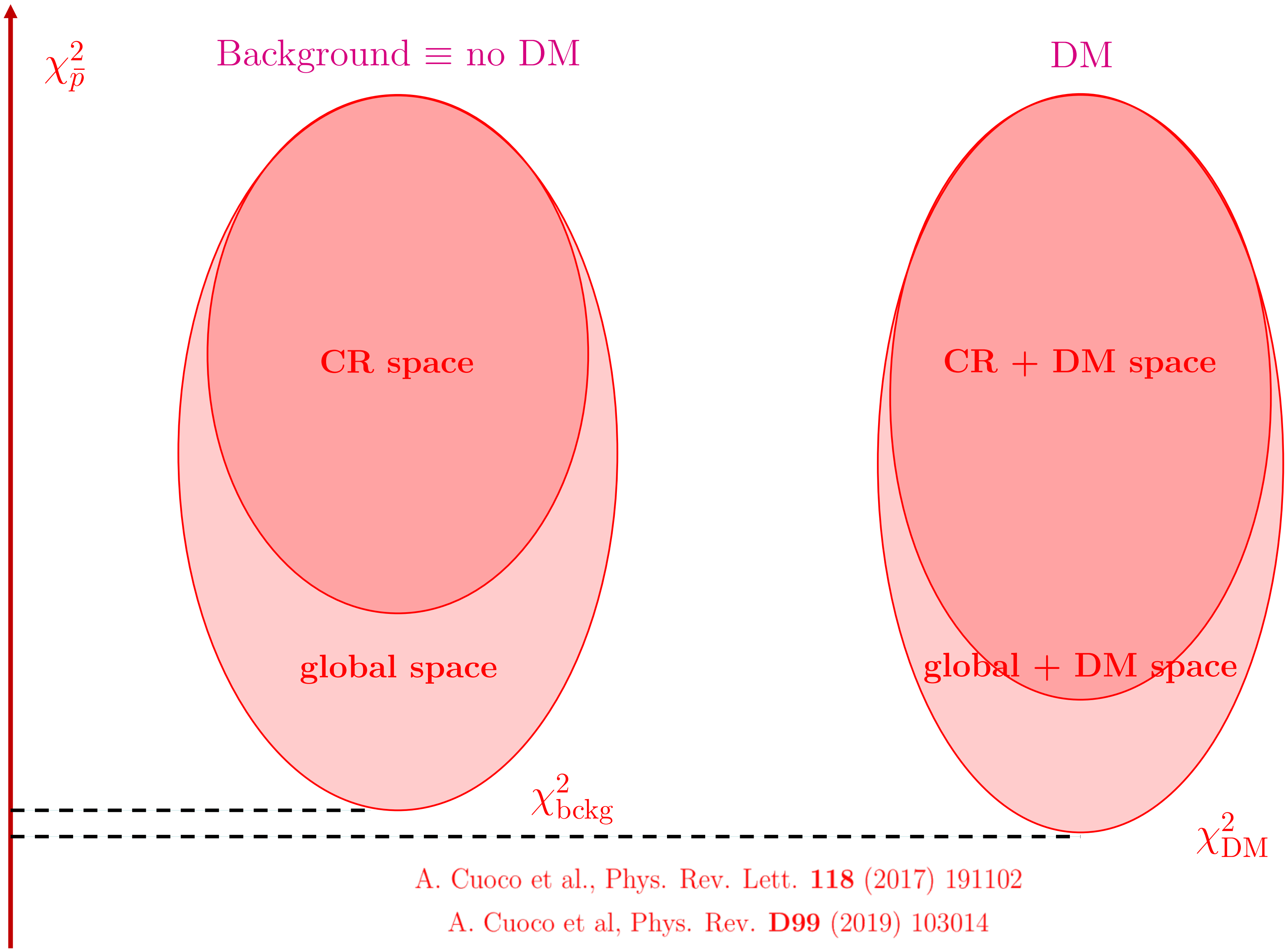

A. Cuoco et al., Phys. Rev. Lett. **118** (2017) 191102

A. Cuoco et al, Phys. Rev. **D99** (2019) 103014

Incorporating CR systematics in the $\bar{p}$ fit

Background only vs DM hypotheses

(i) Old days agnostic scan of CR parameter space to find $\chi^2_{\bar{p},\,\mathrm{min}}$

$$P(\bar{p}\,|\,\text{flat }\theta_{\mathrm{CR}}) \Rightarrow \text{loss of information from B/C}$$

(ii) Fit together $\bar{p}$ and B/C to get best-fit CR parameters θ_{CR}

$$P(\bar{p} + \mathrm{B/C}\,|\,\theta_{\mathrm{CR}}) \Rightarrow \text{not the same question}$$

Fit could be dominated by B/C and not $\bar{p}$

A. Cuoco et al., Phys. Rev. Lett. **118** (2017) 191102

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(iii) Fit $\bar{p}$ and incorporate a theoretical CR uncertainty matrix such as

$$\mathcal{C}^{\bar{\mathrm{p}}\text{ source}}_{\mathrm{nm}} = \left\langle \left(\Phi^{\mathrm{th}}_{\bar{p}}\right)_{\mathrm{n}} \left(\Phi^{\mathrm{th}}_{\bar{p}}\right)_{\mathrm{m}} \right\rangle - \left\langle \Phi^{\mathrm{th}}_{\bar{p}} \right\rangle_{\mathrm{n}} \left\langle \Phi^{\mathrm{th}}_{\bar{p}} \right\rangle_{\mathrm{m}} \text{ with } \mathcal{C}_{\mathrm{B/C}} \text{ matrix}$$

$$\mathcal{C}^{\bar{\mathrm{p}}}_{\mathrm{nm}} = \mathcal{C}^{\mathrm{AMS}}_{\mathrm{nm}} + \mathcal{C}^{\bar{\mathrm{p}}\text{ source}}_{\mathrm{nm}}$$

A. Reinert & M.W. Winkler, JCAP **1801** (2018) 055

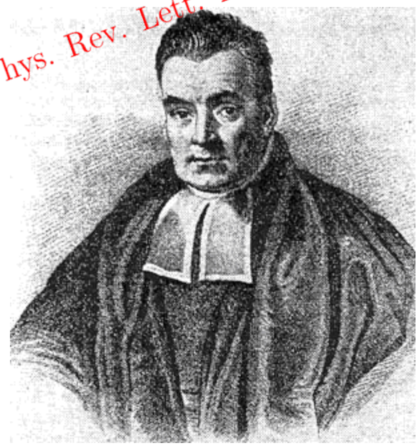
(iv) Use θ_{CR} as nuisance parameters when fitting $\bar{p}$ data

$$\chi^2 = \chi^2_{\bar{p}} + \left\{\chi^2_{\mathrm{CR}} \equiv (\theta_{\mathrm{p}} - \bar{\theta}_{\mathrm{p}})\,\mathcal{C}^{\mathrm{CR}}_{\mathrm{pq}}\,(\theta_{\mathrm{q}} - \bar{\theta}_{\mathrm{q}})\right\}$$

M.-Y. Cui et al., Phys. Rev. Lett. **118** (2017) 191101

How is $\mathcal{C}^{\mathrm{CR}}_{\mathrm{pq}}$ defined? If $\mathcal{C}^{\mathrm{CR}} \equiv \mathcal{C}_{\mathrm{B/C}} \Rightarrow$ back to (iii)

Bayesian with $P(\theta_{\mathrm{CR}}\,|\,\bar{p}) = \mathcal{L}(\bar{p}\,|\,\theta_{\mathrm{CR}}) \times \Pi(\theta_{\mathrm{CR}})$



2) Spectral anomalies – Frequentist vs Bayesian

(a) Model M_i is wright or wrong depending on its reduced χ^2 per d.o.f.

Frequentist approach – models M_1 and M_2 are both true

Maximum likelihood method if $M_1 \subset M_2$

A. Cuoco et al., Phys. Rev. Lett. **118** (2017) 191102
A. Cuoco et al, Phys. Rev. **D99** (2019) 103014
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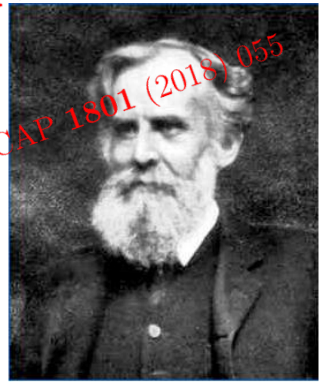


(b) Generate **Mock data sets** with best-fit model M_1, fit them and look for the Monte Carlo distribution of $\Delta\chi^2 = \chi_1^2 - \chi_2^2$.

Conclude from $P(\Delta\chi^2 \,|\, M_1)$

Mock data to be generated – lengthy procedure

Frequentist approach – may be the best one

(c) Use the **Akaike information criterion** (AIC) and compute the difference $\Delta\mathrm{AIC} = \mathrm{AIC}_2 - \mathrm{AIC}_1$.

$\mathrm{AIC} = 2\,p - 2\ln\mathcal{L}_{\max}$ with p parameters

$$\mathrm{AIC}_{\rm cor} = \mathrm{AIC} + \frac{2\,p^2 + 2\,p}{N - p - 1}$$ with N data points

In our example, N is large and $\Delta\mathrm{AIC} = 4 - \Delta\chi^2$

$$\boxed{\frac{P(M_1)}{P(M_2)} = e^{\Delta\mathrm{AIC}/2}}$$

In Cuoco et al. (2019) $P(\mathrm{no\,DM})/P(\mathrm{DM}) = 1.3 \times 10^{-2}$

(d) Bayesian approach in the spirit of method **iv** with nuisance parameters. In this example $\theta_1 = \{\theta_{\rm CR}\}$ while $\theta_2 = \{\theta_{\rm CR}, \langle\sigma_{\rm ann} v\rangle, m_\chi\}$. Compute the probability $P(\bar{p}\,|\,M_i)$ and use **Bayes factor** K.

M.-Y. Cui et al., Phys. Rev. Lett. **118** (2017) 191101

$$P(\theta_1\,|\,\bar{p}, M_1) = \frac{\mathcal{L}(\,\bar{p}\,|\,\theta_1, M_1)\,\Pi(\theta_1|M_1)}{P(\bar{p}\,|\,M_1)}$$

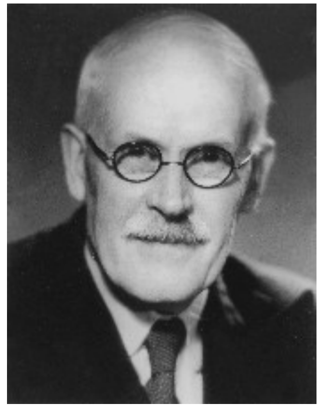
$$\boxed{P(\bar{p}\,|\,M_1) = \int \mathcal{L}(\,\bar{p}\,|\,\theta_1, M_1)\,\Pi(\theta_1|M_1)\,d\theta_1}$$

$$\frac{P(M_2\,|\,\bar{p})}{P(M_1\,|\,\bar{p})} = \left\{K \equiv \frac{P(\bar{p}\,|\,M_2)}{P(\bar{p}\,|\,M_1)}\right\}\left\{\frac{P(M_2)}{P(M_1)} \simeq 1\right\}$$

(e) Use the **Schwarz/Bayes information criterion** (SBIC) and compute the difference ΔSBIC

Jeffreys' scale

2 ln *K*	***K***	**Strength of evidence**
0 to 2	1 to 3	not worth more than a bare mention
2 to 6	3 to 20	positive
6 to 10	20 to 150	strong
>10	>150	very strong



SBIC $= p\ln(N)$

In our example,

$$\frac{P(M_1\,|\,\bar{p})}{P(M_2\,|\,\bar{p})} = e^{\Delta}$$

In Cuoco et al.

tions of CRs [46]. The logarithmic Bayes factor value ($2\ln K$) of the DM component is found to be about $11-54$ for the three cross section parameterizations used. The best fit DM

(d) Bayesian approach in the spirit of method **iv** with nuisance parameters. In this example $\theta_1 = \{\theta_{\rm CR}\}$ while $\theta_2 = \{\theta_{\rm CR}, \langle\sigma_{\rm ann} v\rangle, m_\chi\}$. Compute the probability $P(\bar{p}\,|\,M_i)$ and use **Bayes factor** K.

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(e) Use the **Schwarz/Bayes information criterion** (SBIC) and compute the difference $\Delta{\rm SBIC} = {\rm SBIC}_2 - {\rm SBIC}_1$.

${\rm SBIC} = p\ln(N) \; - 2\ln\mathcal{L}_{\rm max}$ with p parameters

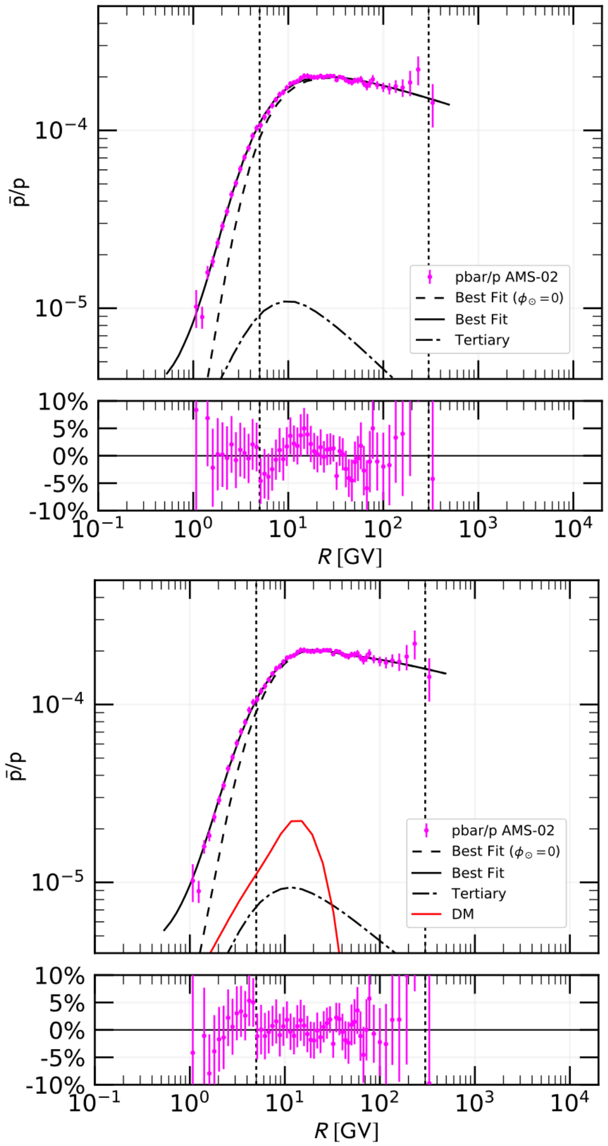
In our example, $N = 158$ and $\Delta{\rm SBIC} = 10.1 - \Delta\chi^2$

$$\boxed{\frac{P(M_1\,|\,\bar{p})}{P(M_2\,|\,\bar{p})} = e^{\Delta{\rm SBIC}/2}}$$

In Cuoco et al. (2019) $P({\rm no\,DM})/P({\rm DM}) = 0.28$ (no comment)

3) A few recent examples

A. Cuoco et al, Phys. Rev. **D99** (2019) 103014

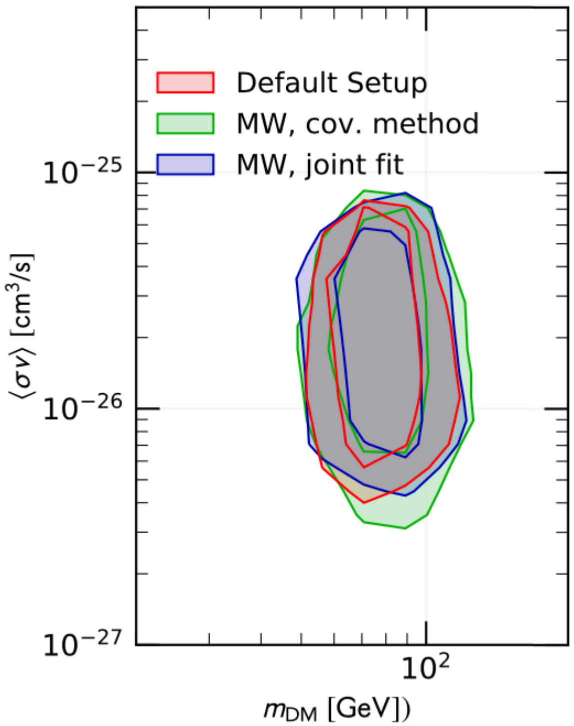


parameter	default setup	
XS parametrization	Param. MW	
DM	incl.	excl.
γ_1	$1.71^{+0.02}_{-0.25}$	$1.72^{+0.04}_{-0.12}$
$\gamma_{1,p}$	$1.78^{+0.003}_{-0.19}$	$1.75^{+0.03}_{-0.10}$
γ_2	$2.41^{+0.03}_{-0.002}$	$2.38^{+0.01}_{-0.02}$
$\gamma_{2,p}$	$2.45^{+0.03}_{-0.002}$	$2.42^{+0.01}_{-0.02}$
R_0, [MV]	6950^{+330}_{-1640}	7380^{+910}_{-1450}
s_0	$0.38^{+0.06}_{-0.04}$	$0.34^{+0.05}_{-0.04}$
D_0, $[10^{28}\ \mathrm{cm}^2/\mathrm{s}]$	$5.43^{+0.45}_{-3.17}$	$2.90^{+1.33}_{-1.21}$
δ	$0.38^{+0.01}_{-0.03}$	$0.42^{+0.02}_{-0.01}$
v_A, [km/h]	$18.0^{+2.1}_{-1.4}$	$16.2^{+1.0}_{-2.5}$
$v_{0,c}$, [km/h]	$0.08^{+9.09}_{-0.08}$	$0.52^{+2.32}_{-0.51}$
z_h, [kpc]	$6.45^{+0.30}_{-4.26}$	$3.58^{+2.36}_{-1.52}$
$\log(m_{\mathrm{DM}}/[\mathrm{GeV}])$	$1.89^{+0.03}_{-0.08}$	
$\log(\langle\sigma v\rangle/[\mathrm{s/cm}^3])$	$-26.16^{+0.78}_{-0.04}$	
δ_2		
R_1, [GV]		
$\varphi_{\mathrm{SM,AMS\text{-}02},p,\mathrm{He}}$, [MV]	616^{+71}_{-72}	625^{+55}_{-85}
$\varphi_{\mathrm{SM,AMS\text{-}02},\bar{p}}$, [MV]	604^{+112}_{-114}	561^{+135}_{-112}
$\chi^2_{\mathrm{AMS\text{-}02},p}$	3.2	2.6
$\chi^2_{\mathrm{AMS\text{-}02,He}}$	4.0	4.8
$\chi^2_{\mathrm{AMS\text{-}02},\bar{p}}$	11.1	22.1
$\chi^2_{\mathrm{Voager},p}$	3.2	3.8
$\chi^2_{\mathrm{Voager,He}}$	1.3	1.9
$\chi^2_{\mathrm{CREAM},p}$		
$\chi^2_{\mathrm{CREAM,He}}$		
$\chi^2_{\varphi_{\mathrm{SM}}}$	0.0	0.4
χ^2_{CR}	22.9	35.6
χ^2/dof	22.9/143	35.6/145
$\Delta\chi^2$	12.7	
DM significance	3.1σ	

Method **(ii)** used to look for DM with $P(p + \alpha + \bar{p}/p \,|\, \theta_{\mathrm{CR}})$

3) A few recent examples

A. Cuoco et al, Phys. Rev. **D99** (2019) 103014



	χ^2		$\Delta\chi^2$
	no DM	with DM	
Param. MD	34.2	22.2	12.0
Param. MW	**35.6**	**22.9**	**12.7**
Cov-mat (Param. MD)	34.2	22.0	12.2
Cov-mat (Param. MW)	33.9	23.0	10.9
Joint fit (Param. MW)	825.2	814.5	10.7

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3) A few recent examples

A. Cuoco et al, Phys. Rev. **D99** (2019) 103014

	χ^2/ndf			
rigidity cut [GV]	excl. DM	incl. DM	$\Delta\chi^2$	DM significance
5	$35.6/145 = 0.245$	$22.9/143 = 0.160$	12.7	3.1σ
3	$52.7/160 = 0.329$	$34.2/158 = 0.216$	18.5	3.9σ
2	$68.2/172 = 0.396$	$57.1/170 = 0.336$	11.1	2.9σ
1	$105.4/182 = 0.579$	$105.6/180 = 0.586$	-0.2	–

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Method **(e)**, i.e., Schwarz/Bayes information criterion, yields

$$\frac{P(\text{no DM}\,|\,\text{data})}{P(\text{DM}\,|\,\text{data})} = e^{\Delta\mathrm{SBIC}/2} = 0.28$$

	χ^2		$\Delta\chi^2$
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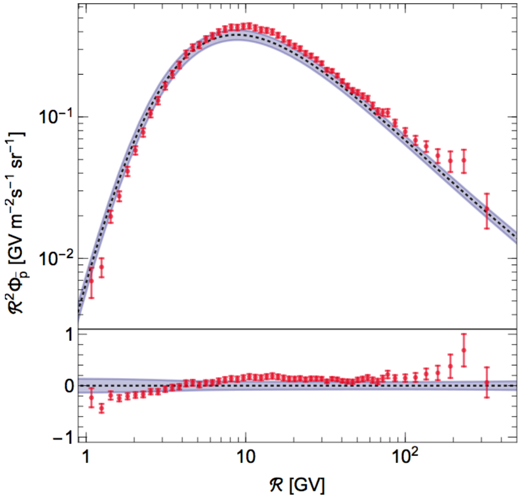
Method **(ii)** used to look for DM with $P(p+\alpha+\bar{p}/p\,|\,\theta_{\mathrm{CR}})$

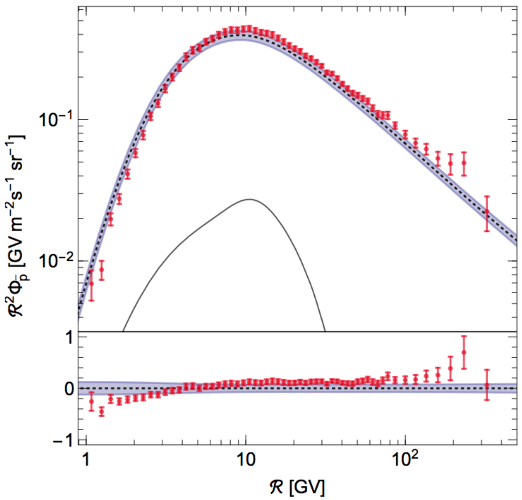
Mixed methods (ii) + (iii) used to look for DM

A. Reinert & M.W. Winkler, JCAP **1801** (2018) 055

Uncertainties on XS treated with $\Sigma_{\rm nm}^{\bar{p}\ \rm source} + \Sigma_{\rm nm}^{\rm B/C\ source}$

$P(\bar{p} + \mathrm{B/C} + \mathrm{AMS/PAMELA}\,|\,\theta_{\rm CR} + \phi_{\bar{p}}^{\rm F})$





Best Fit	B/C (w/o break)	B/C (w/ break)	$\bar{p}$ (w/ break)	B/C + $\bar{p}$ (w/ break)
K_0 $[\frac{\rm kpc^2}{\rm Gyr}]$	$39.6 \cdot L_{4.1}$	$34.3 \cdot L_{4.1}$	$39.5 \cdot L_{4.1}$	$32.5 \cdot L_{4.1}$
δ	0.479	0.507	0.446	0.506
V_a $[\frac{\rm km}{\rm s}]$	0	0	$59.7 \cdot \sqrt{L_{4.1}}$	$15.6 \cdot \sqrt{L_{4.1}}$
V_c $[\frac{\rm km}{\rm s}]$	0	1.3	0	0
$\Delta\delta$	no break	0.157	0.157	0.157
$\mathcal{R}_b$ [GV]		275	275	275
s		0.074	0.074	0.074
ϕ_0 [GV]	0.72	0.72	0.72	0.72
ϕ_1 [GV]			0.66	0.84
$\chi^2_{\rm B/C}$ (67 bins)	64.2	48.0		55.1
$\chi^2_{\bar{p}}$ (57 bins)			21.3	47.9
$\chi^2_{\rm AMS/PAM}$ (17 bins)			10.9	12.6

Channel	$\bar{b}b$	WW
$m_{\rm DM}$	78.7 GeV	85.2 GeV
$\langle\sigma v\rangle$ $[\frac{\rm cm^3}{\rm s}]$	$0.91 \cdot 10^{-26}$	$1.0 \cdot 10^{-26}$
K_0 $[\frac{\rm kpc^2}{\rm Gyr}]$	34.0	33.7
L [kpc]	4.1	4.1
δ	0.499	0.500
V_a $[\frac{\rm km}{\rm s}]$	15.0	15.1
V_c $[\frac{\rm km}{\rm s}]$	0	0
$\Delta\delta$	0.157	0.157
$\mathcal{R}_b$ [GV]	275	275
s	0.074	0.074
ϕ_0 [GV]	0.72	0.72
ϕ_1 [GV]	0.95	0.96
$\chi^2_{\rm B/C}$	53.2	53.6
$\chi^2_{\bar{p}}$	43.2	45.0
$\chi^2_{\rm AMS/PAM}$	14.5	14.6
$\Delta\chi^2$	4.7	2.4
$p_{\rm local}$	0.015 $(2.2\,\sigma)$	0.061 $(1.6\,\sigma)$
$p_{\rm global}$	0.14 $(1.1\,\sigma)$	0.25 $(0.7\,\sigma)$

Method **(b)** used

Mock data $\Rightarrow$ $\Delta\chi^2$ & $P(\Delta\chi^2\,|\,M_1)$

$$\frac{P(\text{no DM}\,|\,\text{data})}{P(\text{DM}\,|\,\text{data})} = e^{\Delta\rm SBIC/2} = 13.5 \text{ \& } 42.5$$

Method **(e)**, i.e., Schwarz/Bayes information criterion, yields $\Delta\mathrm{SBIC} = 2\ln(N) - 2\,\Delta\ln\mathcal{L}_{\rm max} = 9.9 - \Delta\chi^2$

DM is 7.4% ($\bar{b}b$) and 2.4% (WW) as probable as no DM!