Indirect dark matter detection using cosmic antideuterons: status and prospects

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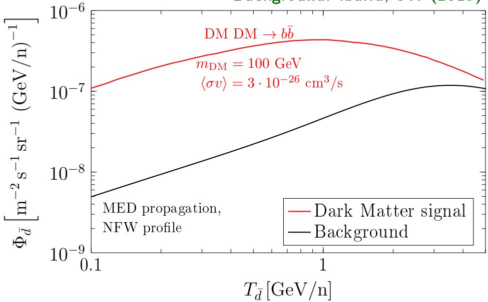
Based on 1209.5539 (JCAP '13) and 1301.3820 (PRD '13)
in collaboration with Alejandro Ibarra

Indirect DM detection with cosmic antideuterons

Background: Ibarra, SW (2013)

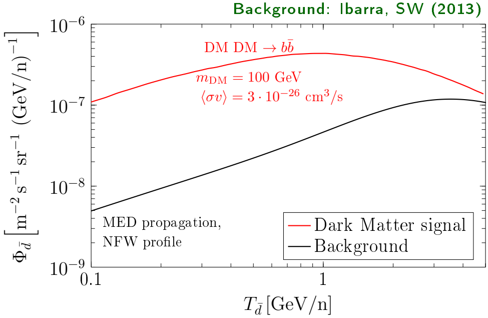


Motivation of using antideuterons:
DM signal $\gg$ cosmic ray backgnd.
[Donato, Fornengo, Salati 1999]

$\Downarrow$

Quite unique in indirect Dark Matter searches!

Indirect DM detection with cosmic antideuterons



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- Two basic ingredients from the theory side:
  - a) Sufficient understanding of the spallation background
  - b) Evaluation of the expected flux from Dark Matter annihilations/decays
- In view of the exciting prospects for **AMS-02** and **GAPS**, it is important to improve our understanding on both of these points!

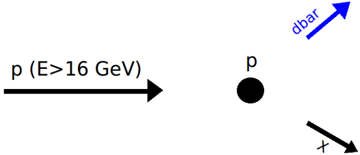
Outline

1. Reevaluation of the antideuteron background flux
2. Prospects for $\bar{d}$ detection in view of the PAMELA $\bar{p}/p$ data
3. Summary & Conclusions

Outline

Production of secondary $\bar{d}$'s by spallation processes

Chardonnet, Orloff, Salati 1999; Donato, Fornengo, Salati 1999
Duperray et. al. 2005; Donato, Fornengo, Maurin 2008
Ibarra, SW 2013



- Dominant production channel of **secondary** $\bar{d}$'s:
  $p_{\text{Cosmic Ray}} + H_{\text{Interstellar Matter}} \to \bar{d} + X$

- $E_p^{min} \simeq 16\,\text{GeV}$
  $\Rightarrow$ a) Suppression due to steeply falling cosmic ray proton flux
  b) System is highly boosted: additional suppression of low-energetic $\bar{d}$

Secondary antideuteron source spectrum

$\hookrightarrow$ Number of secondary antideuterons produced per unit volume, kin. energy per nucleon $T_{\bar{d}}$, and time:

$$Q^{\text{sec}}\left(T_{\bar{d}}\right) = \overbrace{\sum_{i \in \{p, \text{He}, \bar{p}\}}}^{\text{Cosmic rays}} \overbrace{\sum_{j \in \{p, \text{He}\}}}^{\text{ISM}} 4\pi \, n_j^{\text{ISM}} \int_{T_{\text{min}}^{(i,j)}}^{\infty} \text{d}T_i \;\; \Phi_i\left(T_i\right) \;\; \frac{\text{d}\sigma_{i,j}\left(T_i, T_{\bar{d}}\right)}{\text{d}T_{\bar{d}}}$$

- $\Phi_i\left(T_i\right)$: Incident flux of cosmic ray species i
  $\hookrightarrow$ Measured (precisely) by AMS-01, AMS-02, PAMELA
- $\frac{\text{d}\sigma_{i,j}\left(T_i, T_{\bar{d}}\right)}{\text{d}T_{\bar{d}}}$: antideuteron **production cross section** in the process $i + j$
  $\hookrightarrow$ crucial quantity for the evaluation of the secondary source spectrum!

Coalescence model for secondary antideuteron production

- **Coalescence model:**
  Given an $\bar{p}-\bar{n}$ pair, an antideuteron forms if $\left|\vec{k}_{\bar{p}}-\vec{k}_{\bar{n}}\right| < p_0$
  $\hookrightarrow$ More on that (incl. the question about the value of p_0) in the talks by Lars Dal and me tomorrow

- The coalescence model can be formulated as

$$\gamma_{\bar{d}}\frac{\mathrm{d}N_{\bar{d}}}{\mathrm{d}^3k_{\bar{d}}}\left(\vec{k}_{\bar{d}}\right)=\frac{1}{8}\cdot\frac{4}{3}\pi p_0^3\cdot\gamma_{\bar{p}}\gamma_{\bar{n}}\frac{\mathrm{d}N_{\bar{p}}\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3k_{\bar{p}}\mathrm{d}^3k_{\bar{n}}}\left(\frac{\vec{k}_{\bar{d}}}{2},\frac{\vec{k}_{\bar{d}}}{2}\right)$$

- Hence, we need to know the distribution of $\bar{p}-\bar{n}$ pairs in momentum space:

$$\frac{\mathrm{d}N_{\bar{p}}\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3k_{\bar{p}}\mathrm{d}^3k_{\bar{n}}}=?$$

Coalescence model for secondary antideuteron production

- *If* the production of $\bar{p}$ and $\bar{n}$ were statistically independent: **factorized coalescence model**

$$\frac{\mathrm{d}N_{\bar{p}}\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3k_{\bar{p}}\mathrm{d}^3k_{\bar{n}}} \longrightarrow \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}^3k_{\bar{p}}} \cdot \frac{\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3k_{\bar{n}}}$$

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- Dominant process for secondary $\bar{d}$ production: $p + p$ at $\sqrt{s} \simeq 10$ GeV

$$\Downarrow$$

Is the factorized coalescence model applicable for the secondary $\bar{d}$ production?

Coalescence model for secondary antideuteron production

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- Production of $\bar{d}$ is dominated by processes close to the production threshold of the "minimal process" $p\,p \to \bar{d}\,p\,p\,p\,n$
- Production of an antinucleon (plus one additional nucleon due to baryon number consevation) is **phase space suppressed**

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$$\Downarrow$$

Close to the threshold $E_{\rm min}^{(p)} \simeq 16$ GeV, there is a **strong anti-correlation** of $\bar{p}$ and $\bar{n}$ production

$$\Downarrow$$

Factorized coalescence model gives rise to too large $\bar{d}$ yields

Different versions of the coalescence model

"Modified factorized coalescence model" [Duperray et. al. 2002]

- In this approach, one adds an additional *phase space suppression factor* R_n:

$$\frac{\mathrm{d}N_{\bar{p}}\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3k_{\bar{p}}\mathrm{d}^3k_{\bar{n}}} \longrightarrow R_n\left(\sqrt{s}, E_{\bar{d}}\right) \cdot \frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}^3k_{\bar{p}}} \cdot \frac{\mathrm{d}N_{\bar{n}}}{\mathrm{d}^3k_{\bar{n}}}$$

with $R_n(x) \propto$ total phase space, typically being $\simeq 0.1 - 0.2$
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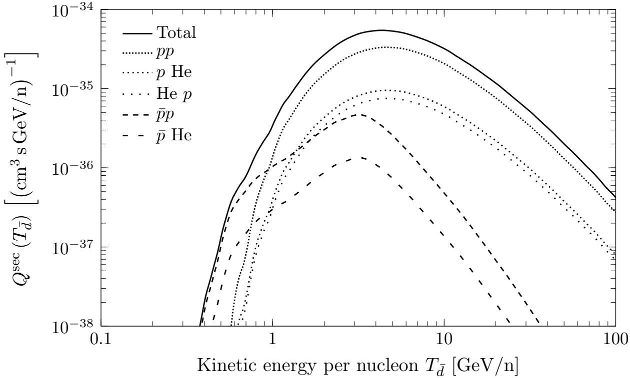
  [Duperray et. al. 2005; Donato, Fornengo, Maurin 2008]

- As this recipe is not confirmed (nor refuted) by data,
  we instead use the **event-by-event coalescence model**
  $\hookrightarrow$ this is already the standard for $\bar{d}$ production from DM
  $\hookrightarrow$ anti-correlation is directly taken from the Monte Carlo generator

- We use DPMJET-III with $p_0 = 152$ MeV
  $\hookrightarrow$ we have to (slightly) modify the Monte Carlo output
  in order to match its $\bar{p}$ yield to the data

Results for the secondary source spectrum Q^{sec}

Ibarra, SW (2013)

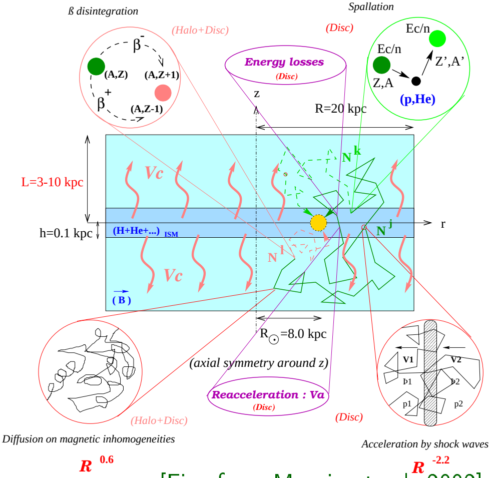


- $p\,p$ and p He are the most important channels
- $\bar{p}\,p$ has a lower threshold for $\bar{d}$ production
  $\hookrightarrow$ larger cross-section, and also the $\bar{d}$ are less boosted
  $\hookrightarrow$ dominates Q^{sec} for small $T_{\bar{d}}$, even though $\Phi_{\text{anti-}p} \ll \Phi_p$
  [Duperray et. al. 2005]

Propagation of antideuterons in the galaxy

↪ i.e. how to obtain a measurable flux $\Phi_{\bar{d}}(T_{\bar{d}})$ at earth for a given source spectrum $Q^{\text{sec}}(T_{\bar{d}})$

→ See talk by Fiorenza Donato tomorrow!



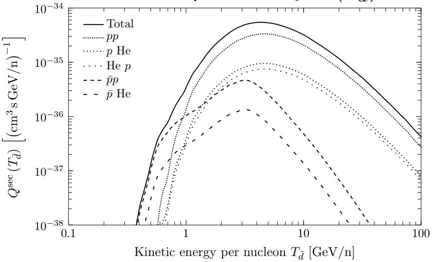
[Fig. from Maurin et al. 2002]

Relevant processes:

- diffusion, convection
- annihilations on the ISM
- **energy losses**

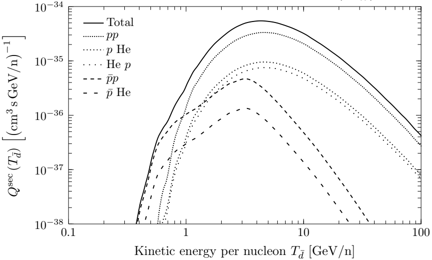
Importance of energy loss processes for the $\bar{d}$ background

Source spectrum $Q^{\text{sec}}\,(T_{\bar{d}})$



$\Rightarrow$ Zero background below $T_{\bar{d}} \simeq 0.5$ GeV/n ???

Importance of energy loss processes for the $\bar{d}$ background



$\Rightarrow$ Zero background below $T_{\bar{d}} \simeq 0.5$ GeV/n ???

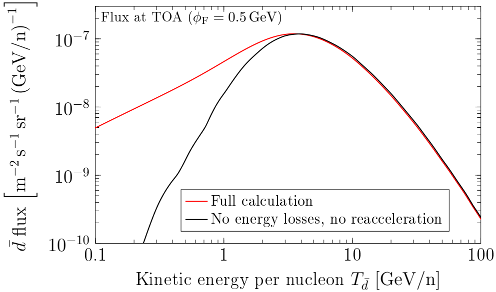
$\Downarrow$

Not after propagation!

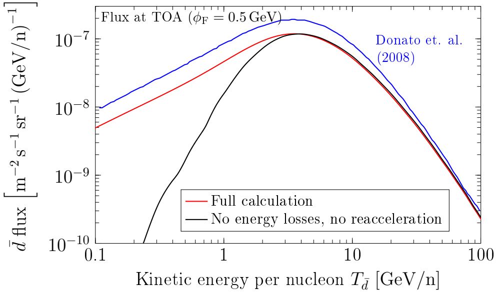
Energy loss effects are crucial for the $\bar{d}$ background for $T_{\bar{d}}^{\text{IS}} \lesssim 3$ GeV/n
$\hookrightarrow$ **redistribution** of $\bar{d}$ towards lowest $T_{\bar{d}}$

- Adiabatic energy loss $\propto \vec{\nabla} \cdot \vec{V}_c$ (dominant energy loss mechanism)
- "Tertiaries": $\bar{d} + p \rightarrow \bar{d} + X$
- Reacceleration

Result for the antideuteron background flux



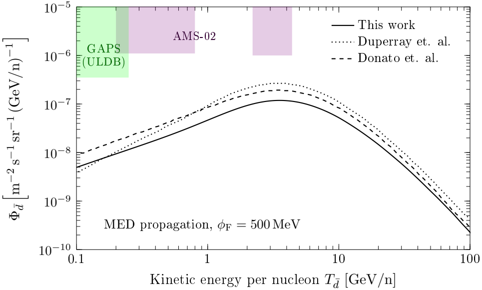
Result for the antideuteron background flux



- Within the uncertainties, our event-by-event calculation agrees with the calculations based on the "modified factorized coalescence model"
- Dominant sources of uncertainties:
  - $\bar{d}$ production cross section $\rightarrow$ coalescence model
  - energy loss mechanisms, in particular $\vec{\nabla} \cdot \vec{V}_c$

We estimate a total uncertainty of a factor $\simeq 3$, though it is very hard to quantify this reliably!

Implications for AMS-02 and GAPS



- Expected number of $\bar{d}$ **background events**:
  - $\simeq 0.1$ at AMS-02 ($\pm$ uncertainties!)
  - $\simeq 0.02$ at GAPS (ULDB) ($\pm$ uncertainties!)

The detection of **a few** ($\gtrsim 2-3$) $\bar{d}$ at AMS-02 or GAPS would be a strong indication for an exotic source

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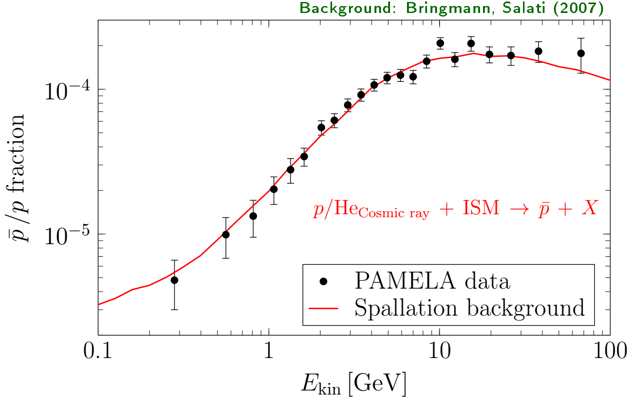
How many $\bar{d}$ events from DM can (at most) be expected at AMS-02 and GAPS?

How many $\bar{d}$ events from DM can (at most) be expected at AMS-02 and GAPS?

- This is (of course) a model-dependent question
- One way of assessing the prospects for detection: compare expected $\bar{d}$ signal with associated **PAMELA** $\bar{p}/p$ **data**
  $\hookrightarrow$ $\bar{d}$ and $\bar{p}$ production from DM is highly correlated for every model
  $\hookrightarrow$ uncertainties due to cosmic ray propagation "cancel out"

PAMELA data on $\bar{p}/p$ flux ratio



$\Rightarrow$ No need for an exotic component
$\Rightarrow$ **Antiproton constraints** on Dark Matter models:
Spallation background + DM induced flux $\leq$ PAMELA data

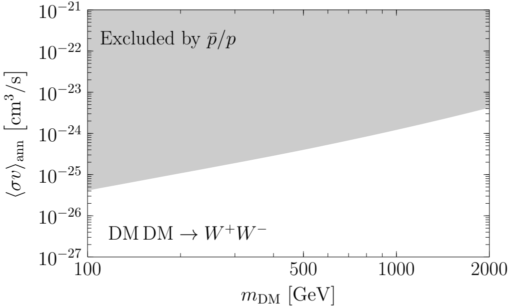
Production and propagation of primary $\bar{p}$ and $\bar{d}$

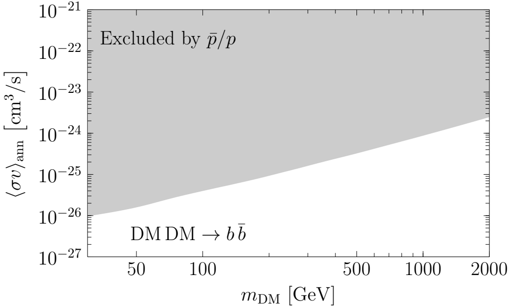
Production:

- $\bar{p}$ and $\bar{d}$ can be produced in DM annihilations or decays
  $\hookrightarrow$ We consider annihilation into W^+W^- and $b\bar{b}$
  $\hookrightarrow$ "representative", but of course not exhaustive
- $\bar{p}$ and $\bar{d}$ production is simulated with PYTHIA 8
  $\hookrightarrow$ $\bar{d}$ production uses the coalescence model with $p_0 = 192\,\mathrm{MeV}$
- We use three different **Halo profiles** (NFW, Einasto, Isothermal)

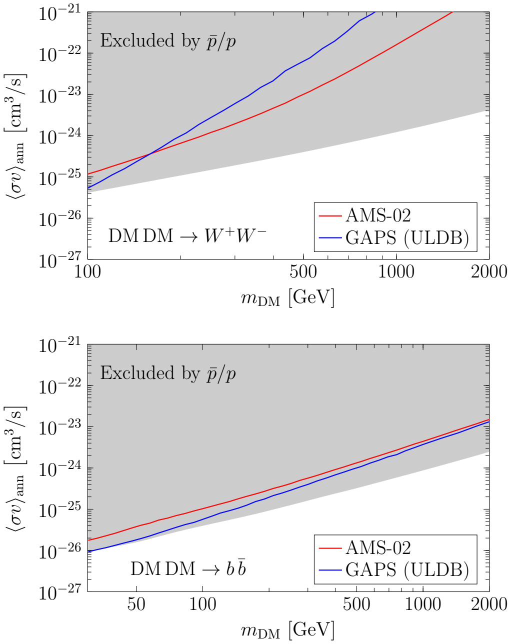
Propagation:

- Same diffusion model as for secondary $\bar{d}$
  $\hookrightarrow$ However, energy loss effects can be neglected for primary $\bar{d}$
  $\hookrightarrow$ see talk by Fiorenza Donato about the details
- We use three different sets of **propagation parameters**:
  MIN, MED and MAX [Donato et. al. 2004]



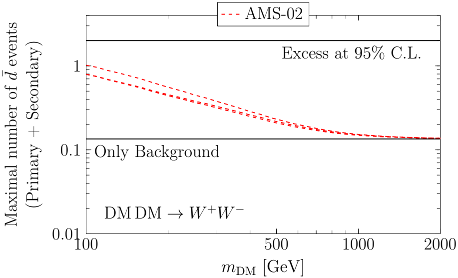


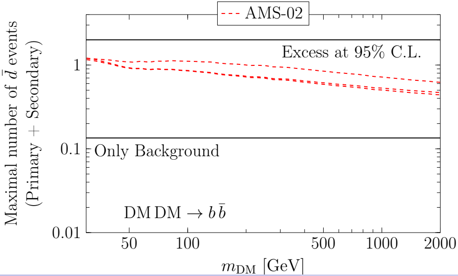
- Shaded regions: 95% C.L. exclusion from PAMELA $\bar{p}/p$
  ↪ using NFW profile, MED propagation parameters



- Shaded regions: 95% C.L. exclusion from PAMELA $\bar{p}/p$
  $\hookrightarrow$ using NFW profile, MED propagation parameters
- Red and blue: cross sections necessary for an expectation of a primary $\bar{d}$ signal at 95% C.L.
  $\hookrightarrow$ 2 events for AMS,
  1 event for GAPS (ULDB)

Maximimal number of $\bar{d}$ events at AMS-02



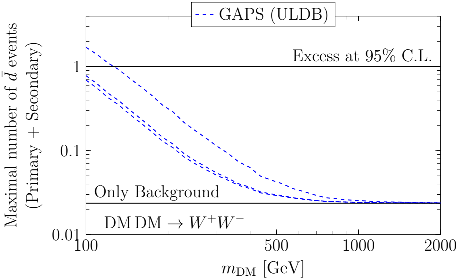


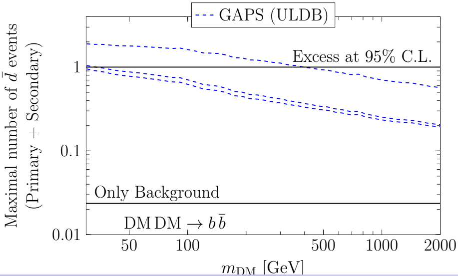
- Red curves:
  Maximal number of $\bar{d}$ at AMS-02 compatible with $\bar{p}/p$ constraints (MIN, MED, MAX)
- Propagation uncertainties largely cancel out for the **maximal** number of events

↓

Detection of one event with AMS-02 is (marginally) viable for $m_\chi < 100$ GeV, if $p_0 = 192$ MeV

Maximimal number of $\bar{d}$ events at GAPS (ULDB)

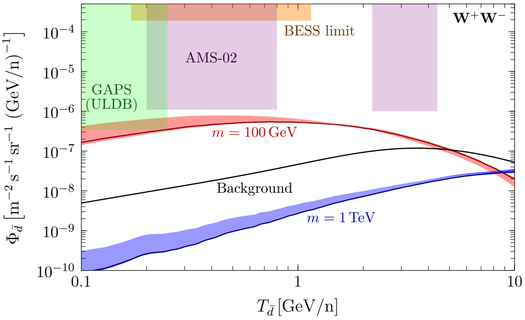


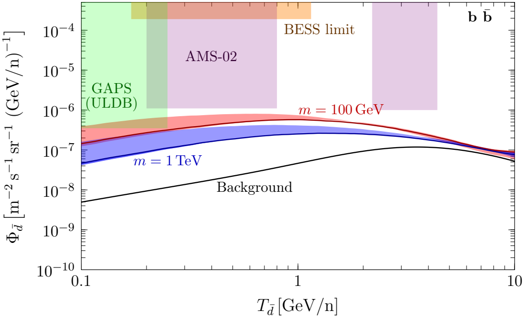


- Blue curves:
  Maximal number of $\bar{d}$ at GAPS (ULDB) compatible with $\bar{p}/p$ constraints (MIN, MED, MAX)

↓

Depending on the prop. model, we can hope for one event for
$m_{\rm DM} \lesssim 100 - 130\,\text{GeV}\,(W^+W^-)$
$m_{\rm DM} \lesssim 30 - 300\,\text{GeV}\,(b\bar{b})$,
if $p_0 = 192$ MeV





- Red and blue curves: Maximally allowed $\bar{d}$ fluxes $(m_{\mathrm{DM}} = 0.1/1\mathrm{TeV})$

$\Downarrow$

Maximally allowed $\bar{d}$ fluxes are still well above the background

$\Downarrow$

There is room left for a DM induced $\bar{d}$ flux above the background

Prospects for AMS and GAPS: caveats?

- **Summary of the prospects for $b\bar{b}$ and W^+W^-:**
  PAMELA $\bar{p}/p$ data allows for one event at...
  ... AMS-02, if $m_\chi \lesssim 100$ GeV
  $\hookrightarrow$ however, one event would not be conclusive in view of ~ 0.1 expected background events
  ... GAPS, if $m_\chi \lesssim 30 - 300$ GeV, depending on the propagation model and the annihilation channel

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Possible and impossible caveats

- These numbers are for $p_0 = 192$ MeV!
  $\hookrightarrow N_{\bar{d}} \propto p_0^3$
  $\hookrightarrow$ this can boost (or decrease) the $\bar{d}$ signal, **without affecting the $\bar{p}/p$ bounds**
- Different propagation models or parameters?
  $\hookrightarrow$ unlikely, as the strong correlation of the $\bar{p}$ and $\bar{d}$ is (almost) independent of the propagation model
- $u\bar{u}$ channel is more promising for low m_χ (see talk by Nicolao Fornengo)

Outline

Summary & Conclusions

Event-by-event calculation of the $\bar{d}$ spallation background

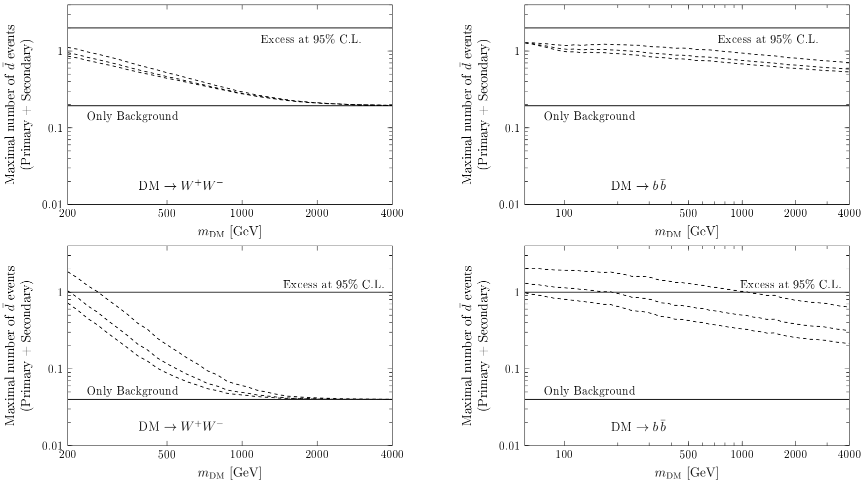
- The event-by-event approach is important due to the anti-correlation of $\bar{p}$ and $\bar{n}$ production in spallation processes
- Our final result is a factor of 2 smaller than previous calculations
  $\hookrightarrow$ agreement within the uncertainties
- $N_{\bar{d}}^{\text{background}}$: $\simeq 0.1$ at AMS-02, $\simeq 0.02$ at GAPS (ULDB)

Dark Matter signal in cosmic antideuterons

- The PAMELA $\bar{p}/p$ data constrains the maximally allowed $\bar{d}$ flux quite significantly
  $\hookrightarrow$ this conclusion is pretty robust against propagation uncertainties
- For the **benchmark choice** $p_0 = 192$ MeV, $\lesssim 2$ events are still possible, if m_χ is small enough
- **However:** $N_{\bar{d}} \propto p_0^3$
  $\Rightarrow$ This can boost (but also decrease) the potential $\bar{d}$ yield, without being in conflict with the $\bar{p}/p$ constraints

Backup slides

Maximal number of events for decaying Dark Matter



Upper panel: AMS-02, lower panel: GAPS (ULDB)