

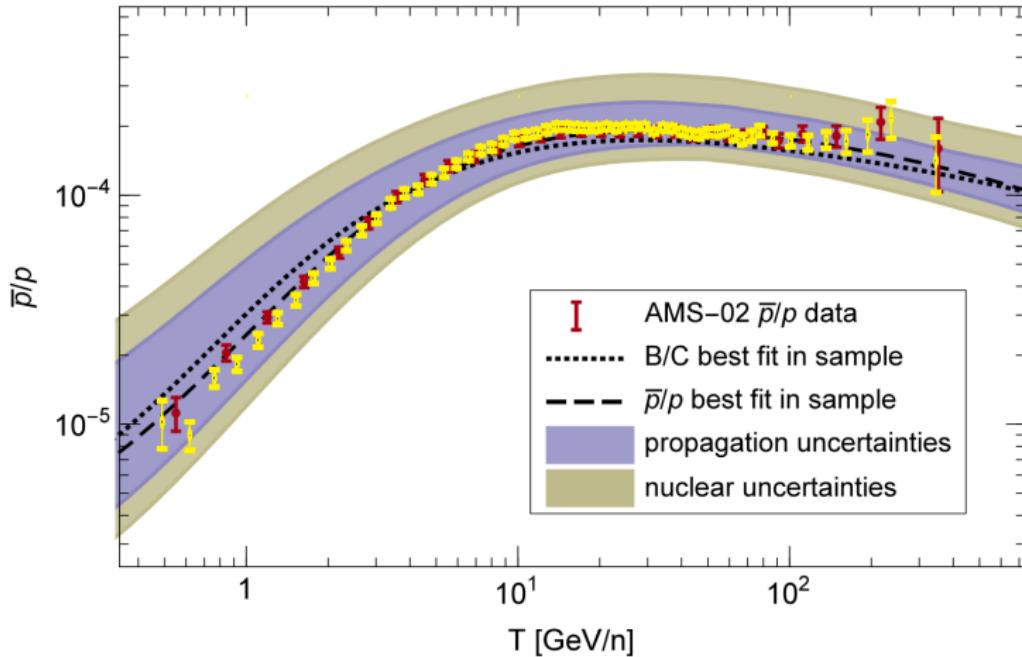
Antideuterons in Cosmic Rays: Sources and discovery potential

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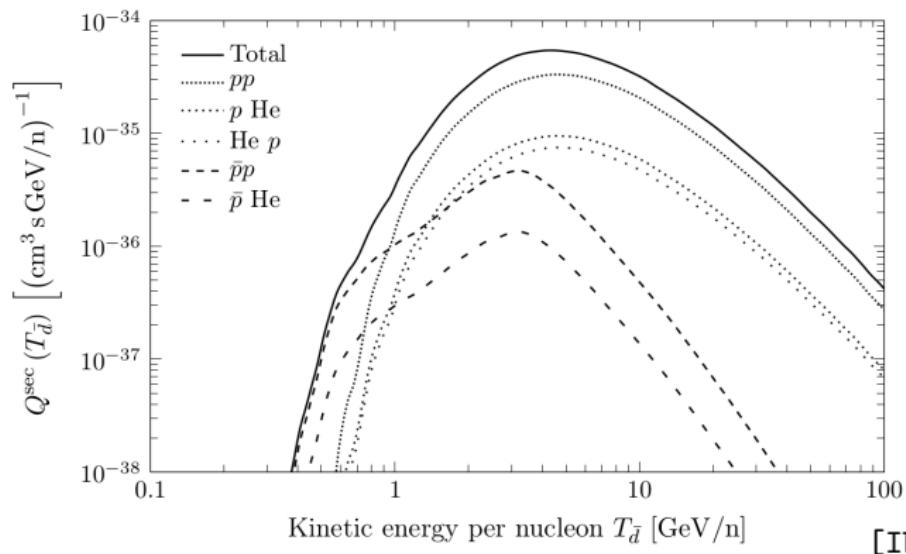
adapted from [Kappl+ '15] using [AMS Collaboration '16]



We have limits; but what about **signals?**

- Background suppression through baryon number conservation

$$\begin{cases} p + p \rightarrow \bar{p} + X & \sqrt{s}_{\text{thr}} = 4m_p & E_{\text{thr}} = 6m_p \\ \begin{matrix} 1 \\ 1 \end{matrix} \quad \begin{matrix} -1 \\ 3 \end{matrix} & & \\ p + p \rightarrow \bar{d} + Y & \sqrt{s}_{\text{thr}} = 6m_p & E_{\text{thr}} = 16m_p \\ \begin{matrix} 1 \\ 1 \end{matrix} \quad \begin{matrix} -2 \\ 4 \end{matrix} & & \end{cases}$$

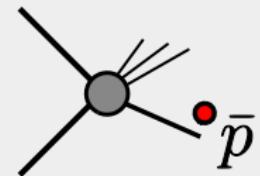


What can we see in \bar{d} that is hidden in \bar{p} ?

- Background
 - CR collisions with nuclei in the interstellar medium (ISM)
 - CR collisions with nuclei at CR sources (SNRs)
- Possible signals
 - Annihilating/decaying dark matter (DM)
 - Evaporating Primordial Black Holes (PBHs)
- Up-to-date detection prospects
 - realistic signal prospects from DM & PBHs, taking into account AMS-02 \bar{p} data

Antiprotons

- secondary production: expt. cross sects.
[Kappl+ '14]
- DM/PBH fragmentation functions: PYTHIA



Antideuterons

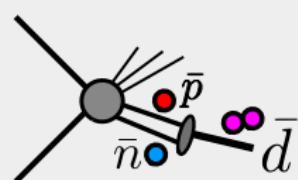
Event-by-event coalescence model:

[talk by A. Raklev, DM-ID 17:50]

- simulate process in event generator
- products $\bar{n} + \bar{p}$ coalesce into \bar{d} if

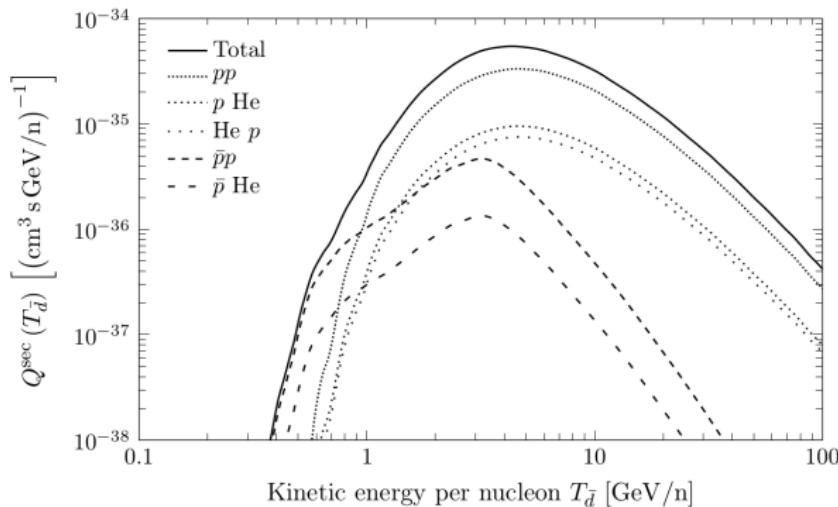
$$\begin{cases} \Delta p < p_0 \\ \Delta x < 2 \text{ fm} \end{cases}$$

- coalescence momentum p_0 from fit to experiment,
 $p_0^{pp} = 152 \text{ MeV}$, $p_0^{DM} = 192 \text{ MeV}$ [Aramaki+ '15]



$$Q_N^{\text{sec}}(T_{\bar{N}}) = \sum_i^{\text{cosmic rays}} \sum_j^{\text{ISM}} n_j \int_{T_{\text{thr}}^{(i,\bar{N})}}^{\infty} dT_i \frac{d\sigma_{ij \rightarrow \bar{N} + X}(T_i \rightarrow T_{\bar{N}})}{dT_{\bar{N}}} 4\pi \Phi_i(T_i)$$

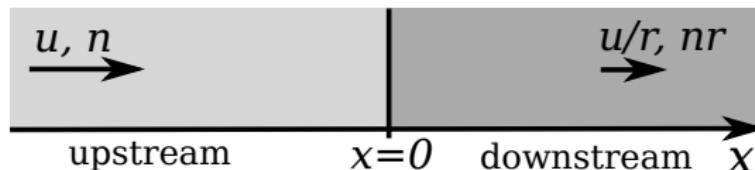
- Φ_i : primary CR fluxes from fit to AMS/CREAM [Kappl+ '15]
- $d\sigma_{ij \rightarrow \bar{d} + X} / dT_{\bar{d}}$ from event-by-event coalescence [Ibarra+ '13]



Diffusion-convection equation

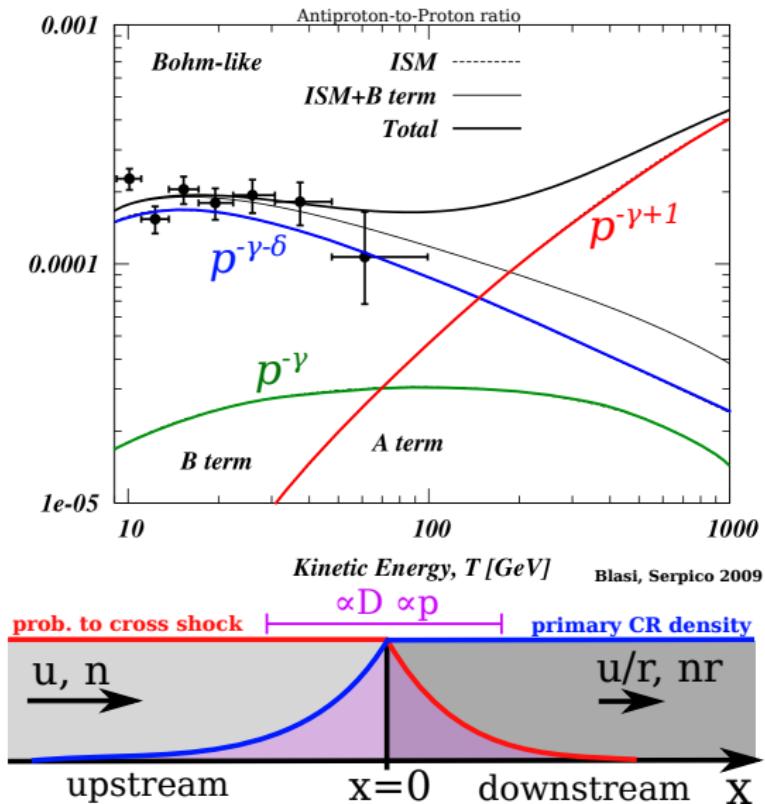
$$u \frac{\partial f}{\partial x} = D \frac{\partial^2 f}{\partial x^2} + \frac{1}{3} \frac{du}{dx} p \frac{\partial f}{\partial p} - \Gamma^{\text{inel.}} f + q$$

in stationary plane shock model

accelerates particles to power law spectrum $\propto p^{-\alpha}$

- simple
- describes main effect on CRs
- used extensively in context of positron excess

[Tomassetti+'11] [Mertsch+'09]



- principal motivation for \bar{d} search

Source Terms:

$$\mathcal{Q}_{\bar{N}}^{\text{DM,dec}}(\vec{r}, T) = \frac{\rho(\vec{r})}{m_{\text{DM}}} \Gamma_f \frac{dN_f^{\bar{N}}}{dT}$$

$$\mathcal{Q}_{\bar{N}}^{\text{DM,ann}}(\vec{r}, T) = \frac{1}{2} \left(\frac{\rho(\vec{r})}{m_{\text{DM}}} \right)^2 \langle \sigma v \rangle_f \frac{dN_f^{\bar{N}}}{dT}$$

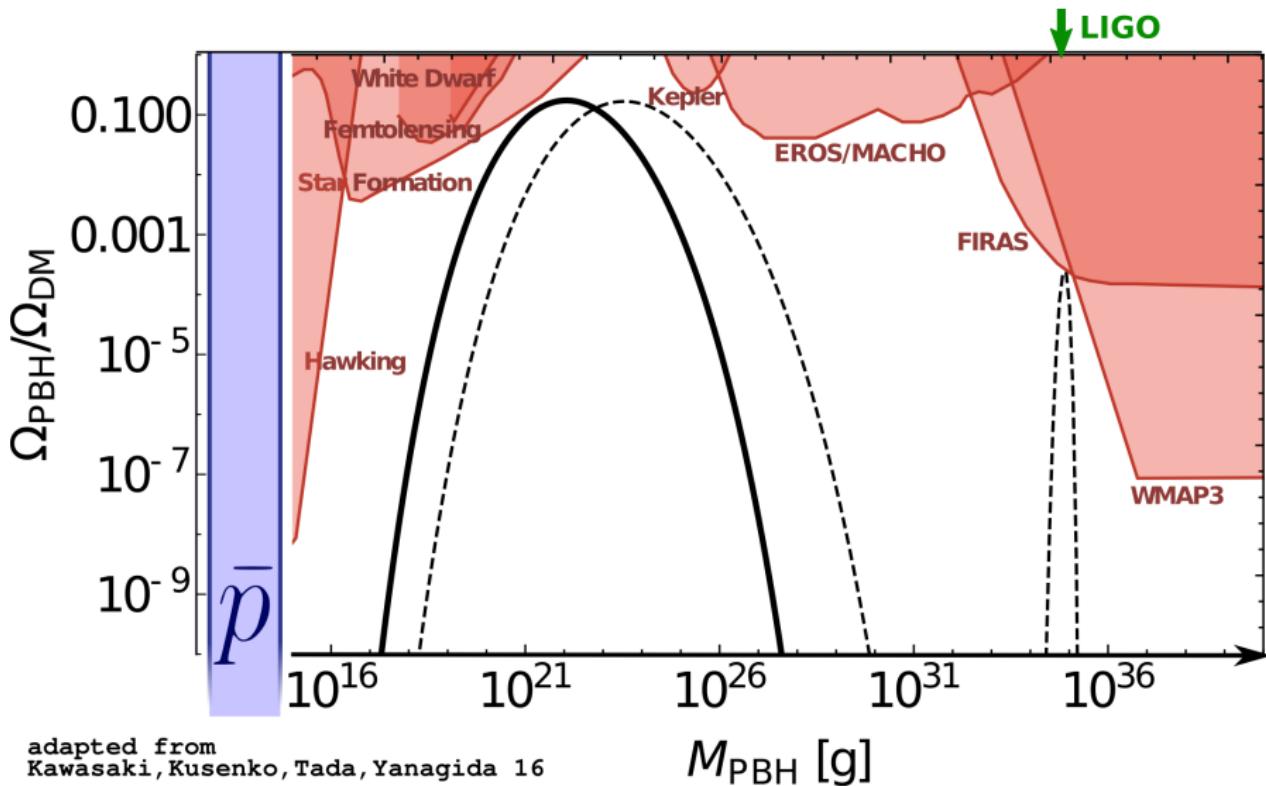
- $\rho(\vec{r}) \propto \rho_{\text{NFW}}(\vec{r})$
 - f : chose $b\bar{b}$ and W^+W^- as representative channels
 - $dN_f^{\bar{N}}/dT$ multiplicities from PYTHIA
- in the following: only ann. DM.

- abundant BHs may have formed in the early universe
[Hawking'71]
 - random density fluctuations
 - phase transitions
- Hawking radiation [Hawking'75]

$$T_{\text{PBH}} = \hbar c / 8\pi G M_{\text{PBH}} k_B \approx \frac{1 \text{ GeV}}{M/(1.06 \times 10^{13} \text{ g})}$$

- black holes smaller than $M_{\text{PBH}}^* = 5 \times 10^{14} \text{ g}$ have evaporated by now
- What are they good for?
 - constrain cosmology
 - *Dark Matter?*

review paper eg. [Green'1403.1198]



Formation mass spectrum

- from scale inv. fluctuations [Carr'75]

$$\frac{dn}{dM_{\text{PBH}}} \propto M_{\text{PBH}}^{-5/2}$$

- generally

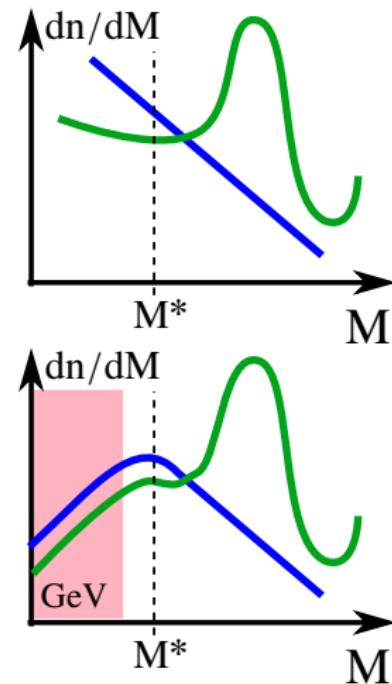
$$\frac{dn}{dM_{\text{PBH}}} \propto ?$$

Present mass spectrum: add mass loss

$$\frac{dM}{dt} = -\alpha M_{\text{PBH}}^2$$

→ a near-universal **low mass tail** evolves:

$$\frac{dn}{dM_{\text{PBH}}} \propto M_{\text{PBH}}^2$$



Standard emission model:

- BHs emit particles that are non-composite at T_{PBH}
- $T_{\text{PBH}} \gtrsim \Lambda_{\text{QCD}} \rightarrow$ emission of quarks and gluons

Elementary particle emission rate per internal dof.:

$$\frac{d^2N}{dQ dt} = \frac{\Gamma_s}{2\pi\hbar(\exp(Q/kT) - (-1)^{2s})}$$

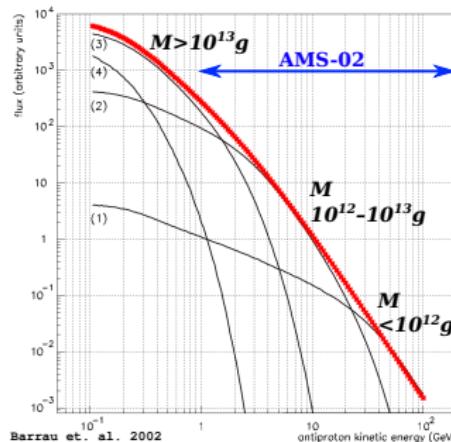
→ Thermal spectrum of a black body with absorption probability Γ_s
(from [Page '76])

Emission of antinuclei:

$$\frac{d^2N_{\bar{N}}}{dE dt} = \sum_j \int_{Q=E}^{\infty} \alpha_j \frac{d^2N_j(M_{\text{PBH}})}{dQ dt} \times \frac{dg_{\bar{N},j}(Q,E)}{dE} dQ$$

Total emission spectrum is the convolution of single BH emm. rate with PBH mass spectrum and local PBH number density

$$Q_N^{\text{PBH}}(\vec{r}, E) = \int dM_{\text{PBH}} \frac{d^2 N_{\bar{N}}}{dE dt} \times \frac{dn}{dM_{\text{PBH}}} \times \overbrace{\rho_{\text{PBH}}(\vec{r})}^{\propto \rho_{\text{DM}}} \frac{dn}{dM_{\text{PBH}} M_{\text{PBH}}}$$



$$\frac{d\psi_{\bar{N}}}{dt} = \underbrace{\mathcal{Q}_{\bar{N}}(r, z, T)}_{\text{sources}} + \underbrace{\nabla \left(D(T) \nabla \psi_{\bar{N}} - \vec{V}_c \psi_{\bar{N}} \right)}_{\text{diffusion \& convection}} - \underbrace{2h \delta(z) \Gamma_{\bar{N}} \psi_{\bar{N}}}_{\text{annihilation losses}} \\ - \underbrace{2h \delta(z) \frac{\partial}{\partial T} \left(b_{\text{tot}}(T) \psi_{\bar{N}} + K_E(T) \frac{\partial}{\partial T} \psi_{\bar{N}} \right)}_{\text{energy losses \& reacceleration}} + \underbrace{\mathcal{Q}_{\bar{N}, \text{tert}}}_{\text{tert. redist.}}$$

Two-zone diffusion model [Maurin+ '02]

parameters tuned to preliminary AMS-02 B/C data [Kappl+ '15]

L [kpc]	D_0 [kpc 2 Myr $^{-1}$]	δ	V_a [km s $^{-1}$]	V_c [km s $^{-1}$]
13.7	0.0967	0.408	31.9	0.2

Solar modulation in force field approx.:

$$\Phi_{\text{TOA}}(T_{\text{TOA}}) = \frac{T_{\text{TOA}}^2 + 2mT_{\text{TOA}}}{T_{\text{IS}}^2 + 2mT_{\text{IS}}} \cdot \Phi_{\text{IS}}(T_{\text{IS}})$$

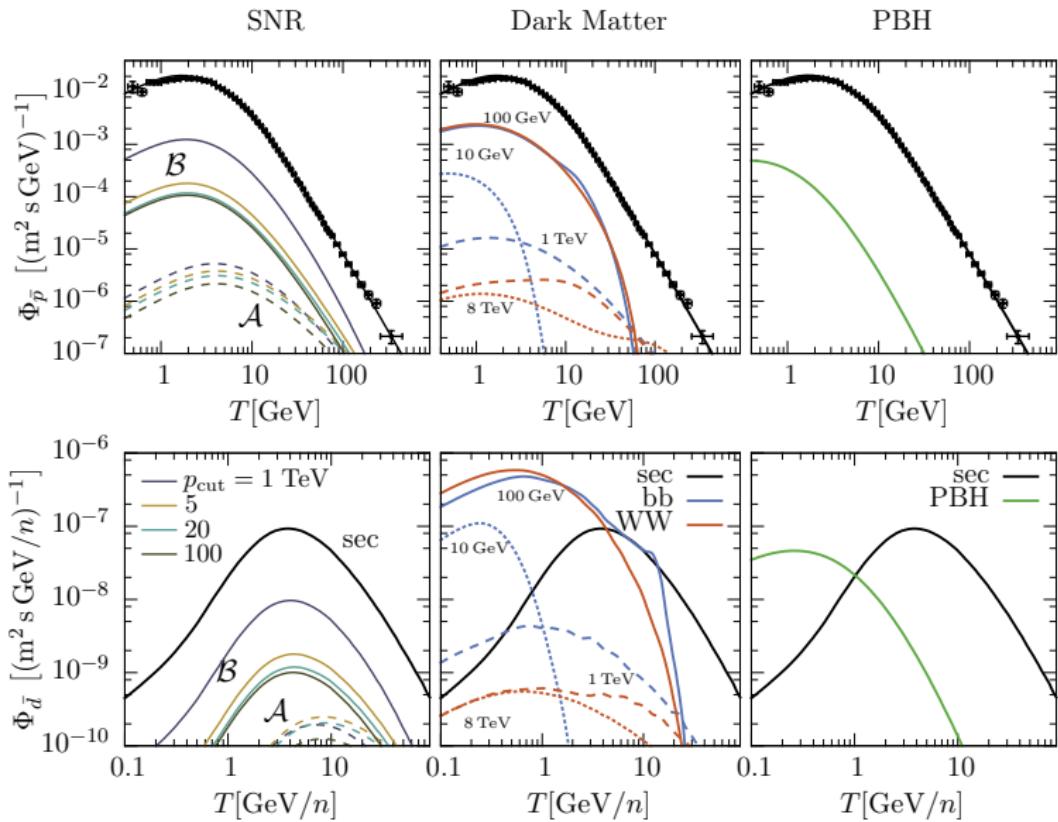
where $T_{\text{TOA}} = T_{\text{IS}} - \frac{Z e \varphi}{A}$ with $\varphi = 0.9$ GV for \bar{p} , $\varphi \in [0.5, 1.5]$ GV for \bar{d} .

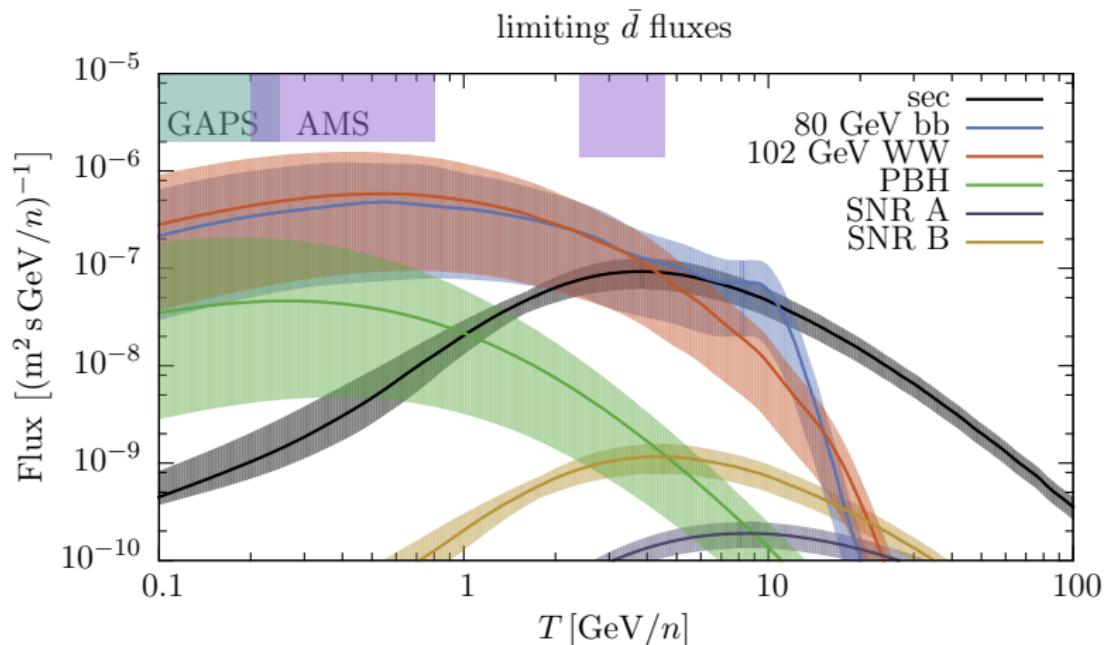


We set limits (95% C.L.) on the various contributions in a profile likelihood approach:

$$\chi^2 = \sum_i \frac{(R_{i,\text{th}}(\theta, N_{\text{sec}}) - R_{i,\text{exp}})^2}{\sigma_{i,\text{exp}}^2} < \chi^2_{\min} + 4$$

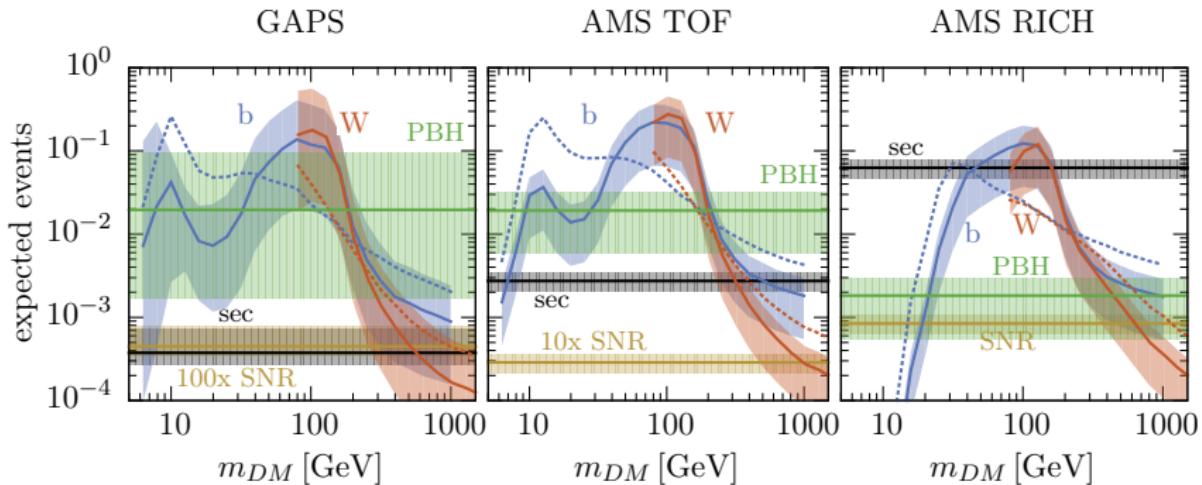
- $R_{i,\text{exp}}$ is the \bar{p} flux in bin i measured by AMS [AMS Collaboration'16]
- $R_{i,\text{th}}(\theta, N_{\text{sec}})$ is the theoretical prediction for the spallation background plus one signal contributing
 - θ is the source parameter to be constrained, $\theta = \langle \sigma v \rangle$ for dark matter, $N_{\mathcal{A}}, N_{\mathcal{B}}$ for SNR \mathcal{A} and \mathcal{B} terms, ρ_{PBH} for PBHs.
 - N_{sec} is the normalization of the spallation background $\in [0.9, 1.3]$ from uncertainty in the cross section





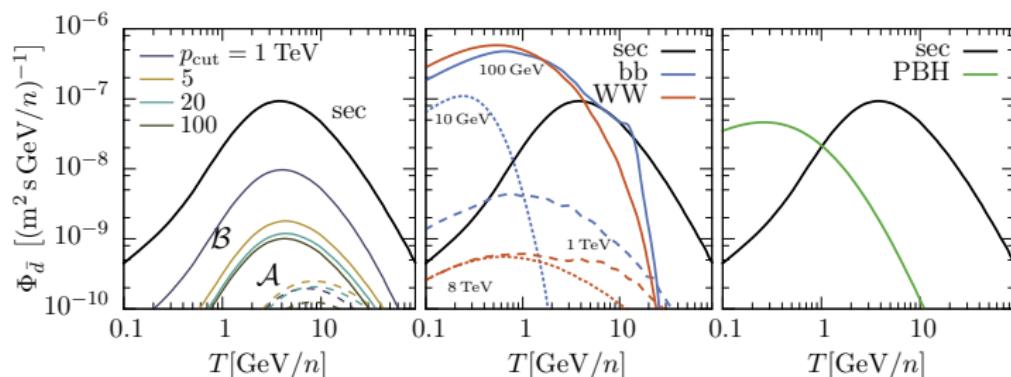
shaded regions reflect uncertainty in p_0 and possible values of φ

[GAPS: talk by P.v.Doetinchem, DM ID 17:30]

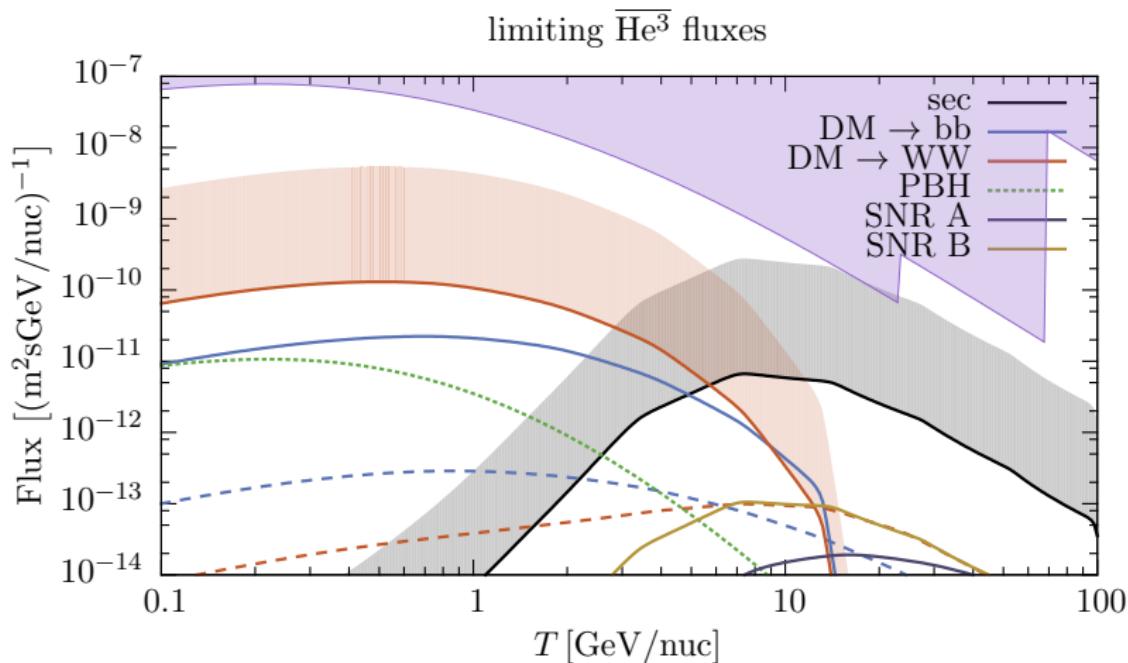


GAPS refers to 3×35 day balloon flights; AMS-02: 5 year reach [Aramaki+’15]

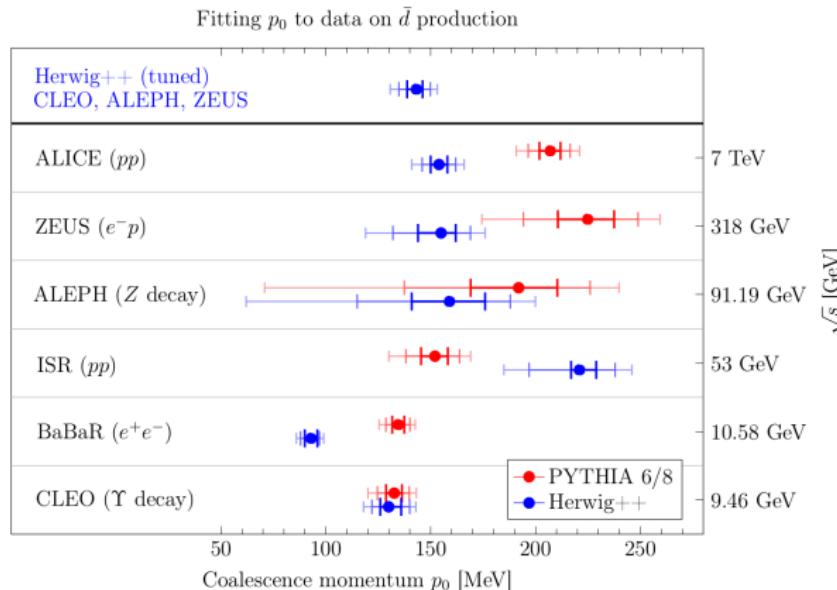
- even with nothing visible in \bar{p} , low-energy \bar{d} may harbor signals orders of magnitude larger than the spallation background
- spallation background enhancement by SNRs is negligible
- PBH/DM detection prospects for currently operating/planned detectors limited, but lots of room to the ‘secondary floor’



Many thanks to collaborators A.Ibarra, A.Vittino, S.Wild

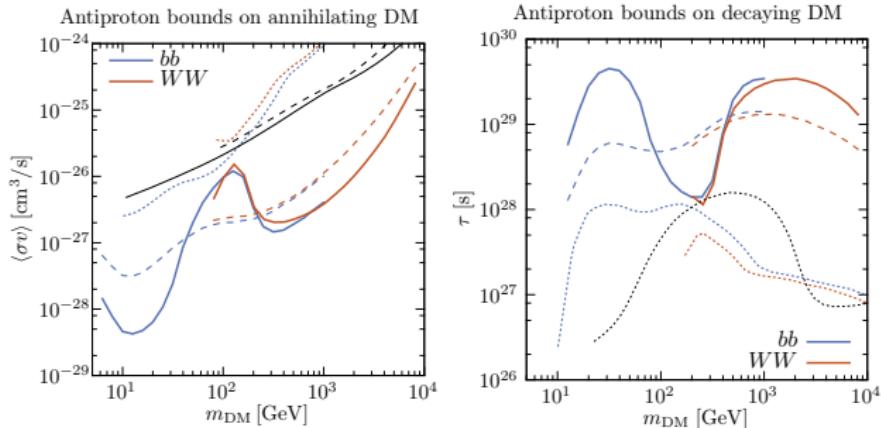


no value of p_0 can fit all the data: [Aramaki+’15]



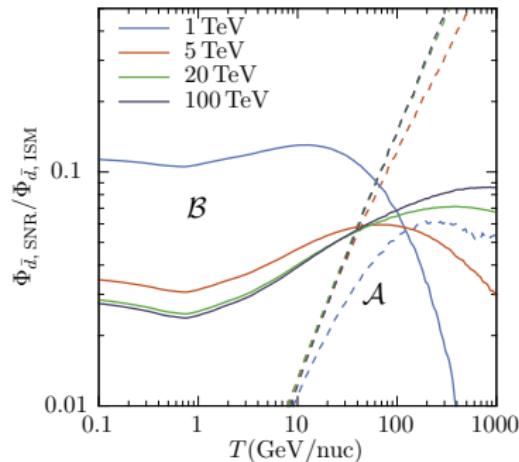
- $p_0^{\text{DM}} = 192^{+34}_{-63} \text{ MeV}$ (envelope 2σ ALEPH & BaBar)
- $p_0^{pp} = 152^{+12}_{-14} \text{ MeV}$ (2σ ISR)

Dark Matter: limits lines, secondary hypothesis dashed, previous \bar{p} dotted
 [Giesen+ '15], Gamma rays black [Ahnen+ '16], [Ando+ '15]



PBHs:

- $\rho_{\text{PBH}, \odot} \lesssim 4.0 \cdot 10^{-35} \text{ g/cm}^3$
- $\Omega_{\text{PBH}} / \Omega_{\text{DM}} \lesssim 6 \cdot 10^{-11}$
- $\mathcal{R}_{\text{PBH}} \lesssim 2.4 \cdot 10^{-4} \text{ pc}^{-3} \text{ yr}^{-1}$ (cf. GRB sensitivity $\sim 3 \cdot 10^3$ [Abdo+ '15])

Enhancement of \bar{d} spallation background

- at low energies, the enhancement of the \bar{d} spallation background is at most 10%

We use as benchmark SNR parameters:

$n_1 = 2 \text{ cm}^{-3}$, $u_1 = 5 \times 10^7 \text{ cm/s}$, $B/K_B = 1/20 \mu\text{G}$ and $\tau_{\text{SNR}} = 20 \text{ kyr}$;
 $r = 3.2$ to match primary CR slopes, p_{cut} is varied manually.

Up to loss effects, changes in these parameters can be absorbed into normalization of fluxes:

$$\mathcal{P} \propto \mathcal{R}_{\text{SNR}} Y_{\text{proton}} \tau_{\text{SNR}}^3 u_1^3$$

$$\mathcal{A} \propto \mathcal{P} \cdot u_1^{-2} n_1 D_0 =: \mathcal{P} \cdot F_{\mathcal{A}}$$

$$\mathcal{B} \propto \mathcal{P} \cdot \tau_{\text{SNR}} n_1 =: \mathcal{P} \cdot F_{\mathcal{B}}$$

Scaling $\mathcal{N} = F/F_{\text{benchmark}}$ instead of recalculating spectra for different SNR parameters is accurate up to 1(5)% for $\mathcal{B}(\mathcal{A})$ term.