Antihelium From Dark Matter

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arXiv:1401.2461

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d̄14 1st cosmic ray antideuteron workshop

Overview

- General picture for hadronic cosmic rays.
  - Motivations for heavy anti-nuclei searches
- Formation
  - The Coalescence Model for A>2 Nuclei
  - Production Channels
  - Guidelines for A=3 Coalescence Momenta
  - Injection Spectra
- Propagation
  - 2-Zone Diffusion + Force-Field (very briefly)
  - What's new for $\overline{^{3}He}$?
- Flux and Detection at AMS-02 and GAPS
  - Scaling Relations
  - Experimental Challenges
- Comparisons to "Antihelium from Dark Matter Annihilations"

  Cirelli, Fornengo, Taoso, Vittinio: 1401.4017

Astrophysical (Secondary) Production

Interstellar Propagation:
- Energy losses (radiative small, (NAR) inelastic small for A>1)
- Reacceleration (unclear for light nuclei)
- Annihilation (easy to include)
- Reasonable semi-analytic model

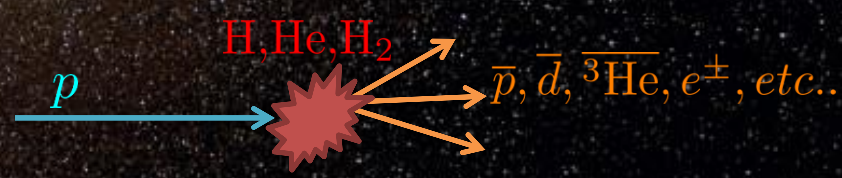
Interstellar Gas

Cosmic-ray Proton

Observation at TOA
(top of atmosphere)

Heliospheric Propagation
- Shifts spectrum to lower energy
- Depletes low energy population
- 22yr solar cycle (11yr + polarity flip)
- Reasonable analytic model

Cosmic-Ray Spallation



Dark matter (Primary) Production

Interstellar Propagation:
- Energy losses (radiative small, (NAR) inelastic small for A>1)
- Reacceleration (unclear for light nuclei)
- Annihilation (easy to include)
- Reasonable semi-analytic model

Observation at TOA
(top of atmosphere)

Heliospheric Propagation
- Shifts spectrum to lower energy
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- 22yr solar cycle (11yr + polarity flip)
- Reasonable analytic model

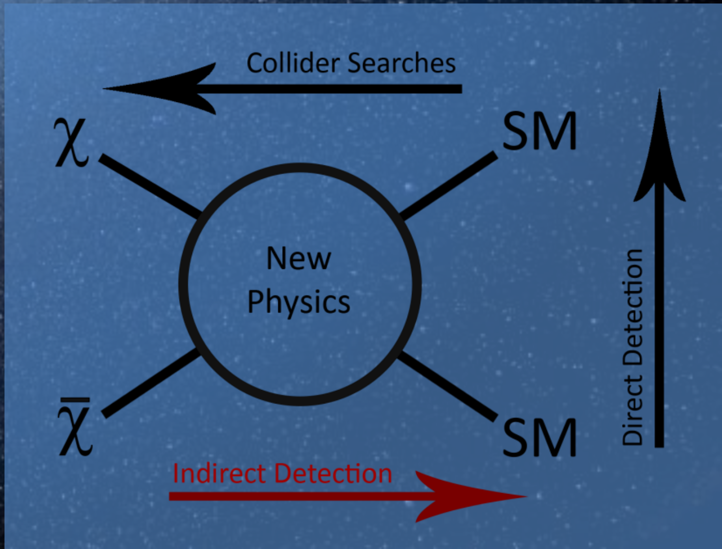
Dark Matter Annihilation
(or Decay) produces anti-nuclei

Source term is spatially and spectrally distinct from spallation.

Dominant uncertainty?

Propagation for $\bar{p}, \bar{d}$

Formation for $\overline{^3He}$



Why $\bar{d}$ and $\overline{^3He}$?

Secondary flux very rapidly decreasing!

Background uncertainties large for $\bar{p}$, small for $\bar{d}$, usually negligible for $\overline{^3He}$

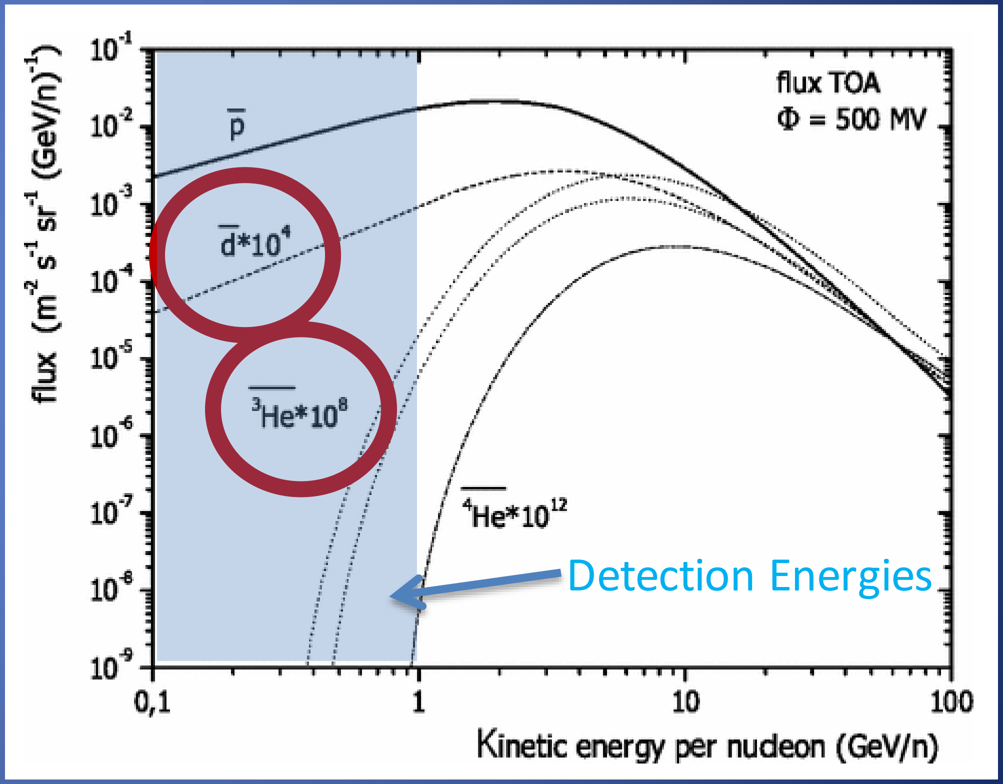
Cosmic-ray proton impacts interstellar gas

$p \longrightarrow H \Rightarrow \bar{p}, \bar{d}, \overline{^3He}$

(i) Quickly increasing production threshold $E_p \geq 7m_p, 17m_p, 31m_p$
+ Steep proton spectrum $\propto E_p^{-2.8}$

(ii) CMS Frame boosted w.r.t. galaxy
→ boosted spectrum

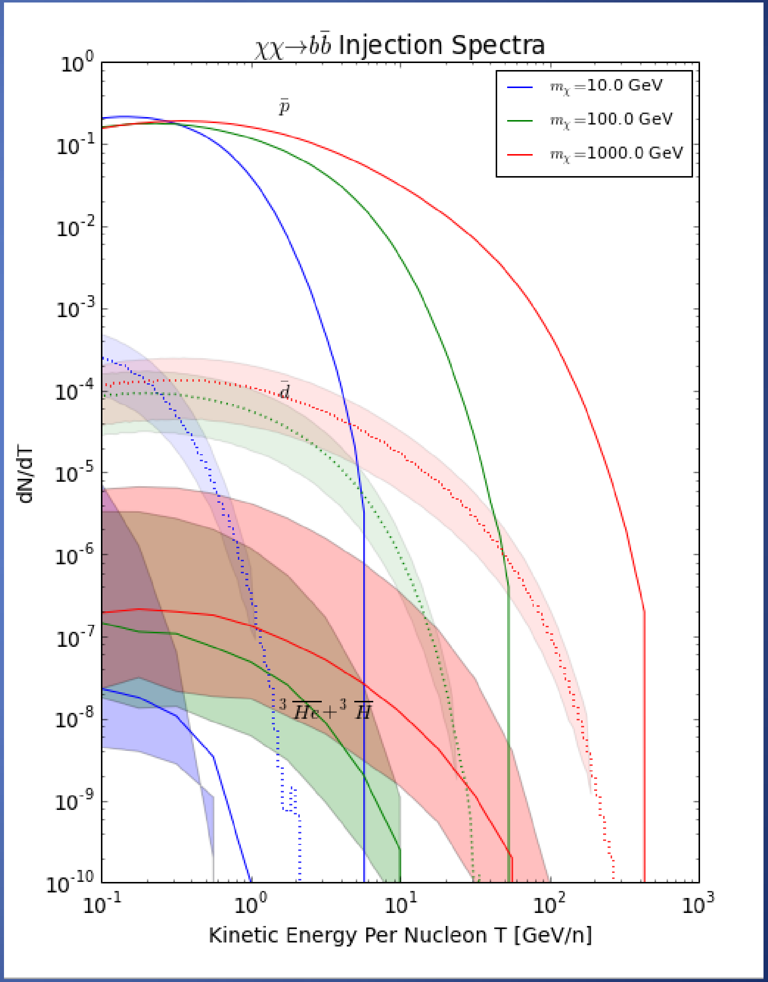
(iii) minimal energy loss during propagation → Stays boosted



Duperray et al (2005): astro-ph/0503544

Why $\overline{d}$ and $\overline{^3He}$?

- Naively, primary yield from dark matter reduced by 10^{-4} for each increase in atomic number A.
- May be some enhancements for antihelium (2 channels?, larger coalescence momentum?, propagation gains?)
- Dark matter is at rest w.r.t. galaxy, kinematics favor low energies unless heavy with e.g. hh or WW final states



Bottom Line: Sacrifice signal for *huge* gain in signal to noise ratio

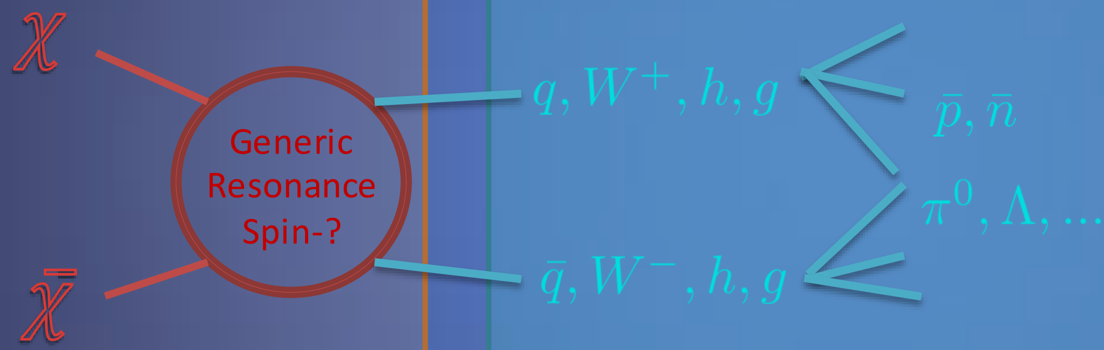
The Modern Coalescence Mechanism

New Physics

e.g. Neutralinos (Ann.), RPV Gravitinos

Standard Model Hadron Physics

Coalescence Algorithm



Applied event by event

For each $\overline{p}, \overline{n}$ pair in an event, $\overline{d}$ formed if

$$-(\Delta k^{\mu}_{\bar{p},\bar{n}})^2 < p_0^2$$

Generate hard process with PYTHIA, Herwig++, or MadGraph

Hadronization in PYTHIA or Herwig++

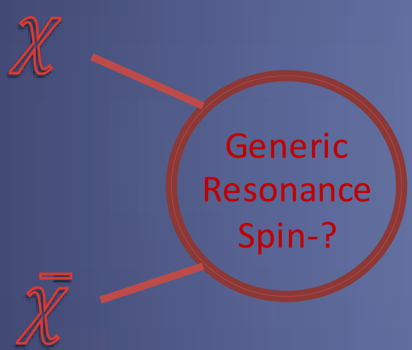
Stabilize weakly decaying hadrons τ>2 fm/c

p_0 fit to collider data

The Modern Coalescence Mechanism

New Physics

e.g. Neutralinos (Ann.), RPV Gravitinos

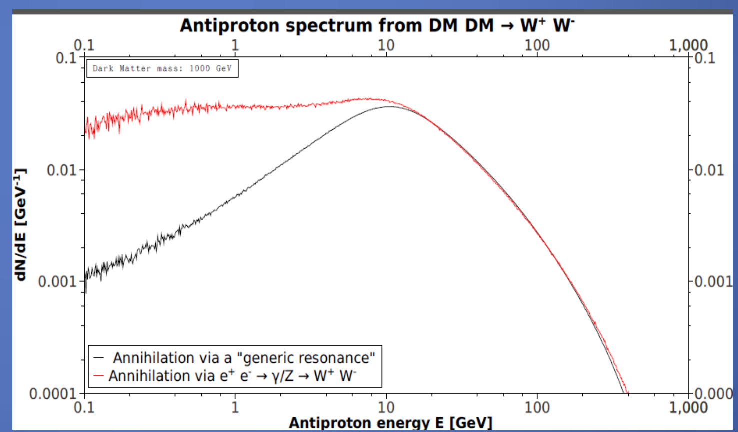


Generate hard process with PYTHIA, Herwig++, or MadGraph

Model Dependent! Some examples…

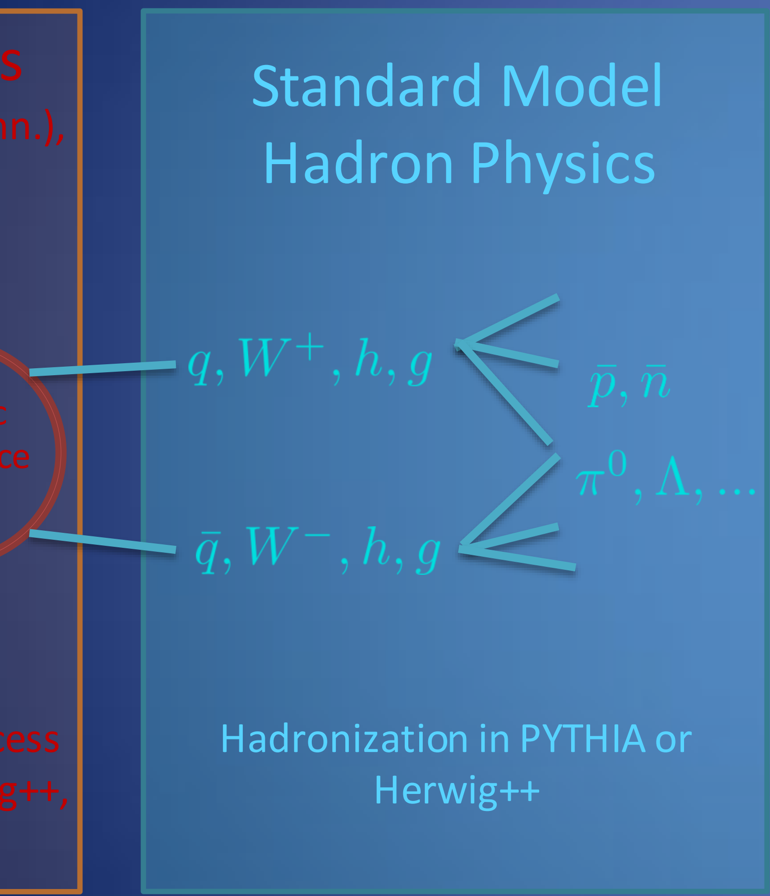
1.) Annihilation to light vs heavy quark channels

2.) Majorana vs Dirac (scalar vs. vector resonance) enhances low energy $\bar{p}$ yield for W^+W^- final states at high-energy



3.) Gravitino LSP In baryonic R-parity violating SUSY, decays ($\tilde{G} \rightarrow \overline{U}_i \overline{D}_j \overline{D}_k$) can yield > 200% more $\bar{d}$ per event than usual $\chi\chi \rightarrow b\bar{b}$ (See Monteux, Carlson, Cornell 2014 arXiv:1404.5952)

The Modern Coalescence Mechanism



Domain of validity for Monte Carlo?

MC Tuned for multiplicity or angular distribution?
Seems to be order 1 correction
(See Dal & Raklev 2014 arXiv:1402.6259)

The Modern Coalescence Mechanism

Coalescence Algorithm

Applied event by event

For each $\overline{p},\overline{n}$ pair in an event, $\overline{d}$ formed if

$$(\Delta k^{\mu}_{\bar{p},\bar{n}})^2 < p_0^2$$

Stabilize weakly decaying hadrons τ>2 fm/c

p_0 fit to collider data

p_0 dependence on underlying process (pp vs e^+e^- collisions), not much data at multiple energies.

Most choose ALEPH e^+e^- at Z^0 pole giving p_0=192$\pm$30 MeV for $\overline{d}$

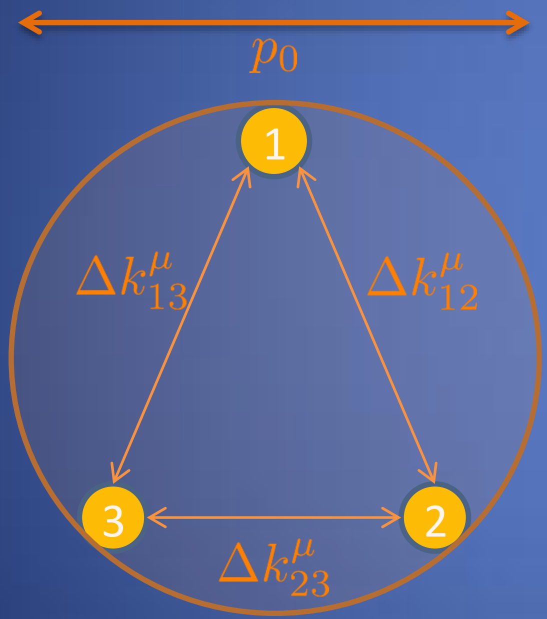
Still a factor ~3 uncertainty from p_0. Reduced by MC tuning to fit more data.

No antihelium data. Must use heavy-ion collisions and guiding principles. p_0 nearly free with dN/dT $\sim p_0^6$

What about for A>2 nuclei?

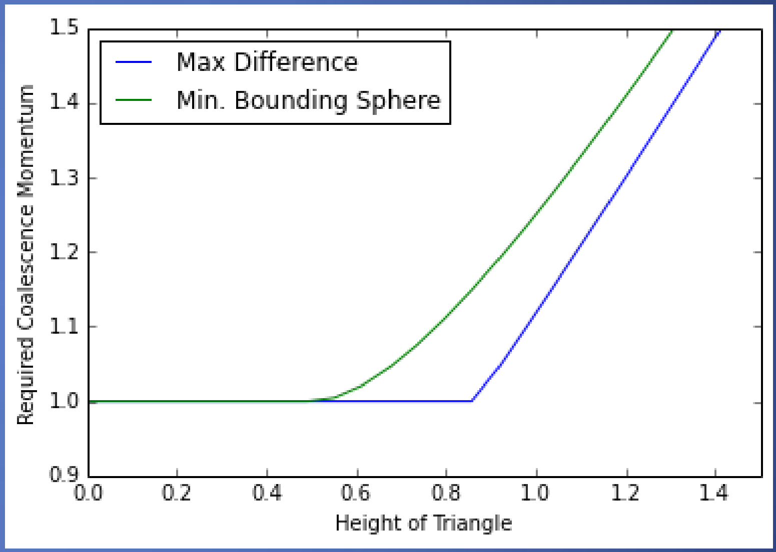
Two possibilities for coalescence prescription

Minimum Bounding Sphere



Maximum Difference

$$\max((\Delta k^\mu_{ij})^2) \leq p_0^2$$



- Neither is "more correct", and effect is small
- For fixed p_0, MBS produces ≈6% fewer A=3 nuclei
- dN/dE scales roughly as $p_0^{3(A-1)}$ => matters more for larger A

$\bar{p}\bar{n}\bar{n} + \bar{p}\bar{p}\bar{n}$?

2 Nucleon Case:

Exclusion principle forces di-proton to be spin-singlet

$$V_{\text{strong,s.d.}} \propto -\sigma_{p_1} \cdot \sigma_{p_2}$$

\+ Coulomb repulsion leads di-proton has positive binding energy.

$\overline{He}$ Case: Sum the yields?

$+ \overset{?}{\epsilon} \times$

Tritium

Antihelium-3

Allowed. Perhaps Coulomb suppressed.
Coulomb barrier is small:
10’s of MeV compared to $p_0 \approx 200 - 350$ MeV

Beta decays to antihelium-3
$\tau \approx 12$ yr. Provides main yield

$\bar{p}\bar{n}\bar{n} + \bar{p}\bar{p}\bar{n}$?

Suggestions from heavy-ion/fixed target collisions at $\sqrt{s} = 2$ GeV and target at $\sqrt{s} = 200$ GeV indicate Coulomb suppression between 0-100%.

p_0 (GeV/c)	Target	Lab momentum (GeV/c)	d/π^+ (10^{-4})	t/π^+ (10^{-7})	$^3He/\pi^+$ (10^{-7})	$\bar{d}/\pi^-$ (10^{-6})	$\bar{t}/\pi^-$ (10^{-10})	$^3\overline{He}/\pi^-$ (10^{-10})
200	Al	20	1.33±0.14	1.00±0.21	1.0±0.2	4.85±0.74		10±5
		22	1.41±0.18					
		30	1.72±0.18	0.90±0.20	0.90±0.15	6.36±0.80		≤4
		37	2.55±0.25			4.10±1.20		
	Be	12				3.16±0.63		
		16				4.11±0.78		
		20	0.88±0.09	0.31±0.06	0.80±0.15	4.60±0.92		7.0±3.5
		26				5.52±0.55		
		30	1.54±0.15	0.55±0.10	0.65±0.10	7.06±1.10	8±5	≤1.5
		37	1.92±0.19	0.56±0.12	0.65±0.10			
210		10.5						1.9±0.5
		23.7					12±2	3.1±0.4
		39.5				4.8±0.9		
240		23.4				5.2±1.0	8.0±1.5	4.2±0.4
		35.9					8.7±1.7	
		37.5						0.87±0.20

A. Bussière et al. / Search for long-lived particles

Gosset et al. Phys. Rev. C 1977, 16-2

We optimistically choose no suppression ($\epsilon = 1$).
≈Isospin invariance. Can simply rescale results by $(1+\epsilon)/2$

What about p_0 for A>2?

No direct data from e^+e^-, pp, or $p\overline{p}$.

Reliant on theoretical and pheno evidence for increased $p_0^{A=3}$ compared to $p_0^{A=2}$

If extent of momentum wave function scales as square root of binding energy,

$$p_0^{A=3} = \sqrt{B_{^3\overline{He}}/B_{\bar{D}}}\; p_0^{A=2}$$

$$= 0.357 \pm 0.059 \text{ GeV/c}$$

Using $p_0^{A=3}/p_0^{A=2}$ averaged from heavy-ion production we obtain

$$p_0^{A=3} = 1.28\; p_0^{A=2}$$

$$= 0.246 \pm 0.038 \text{ GeV/c}$$

Really need some data to constrain p_0.
This is largest uncertainty in the problem!

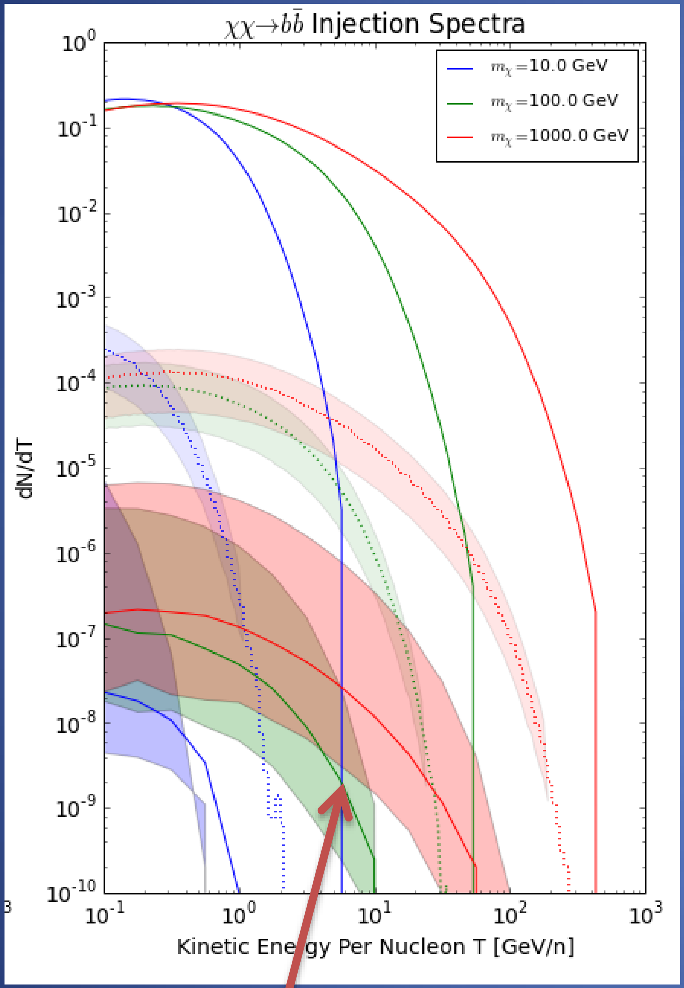
Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

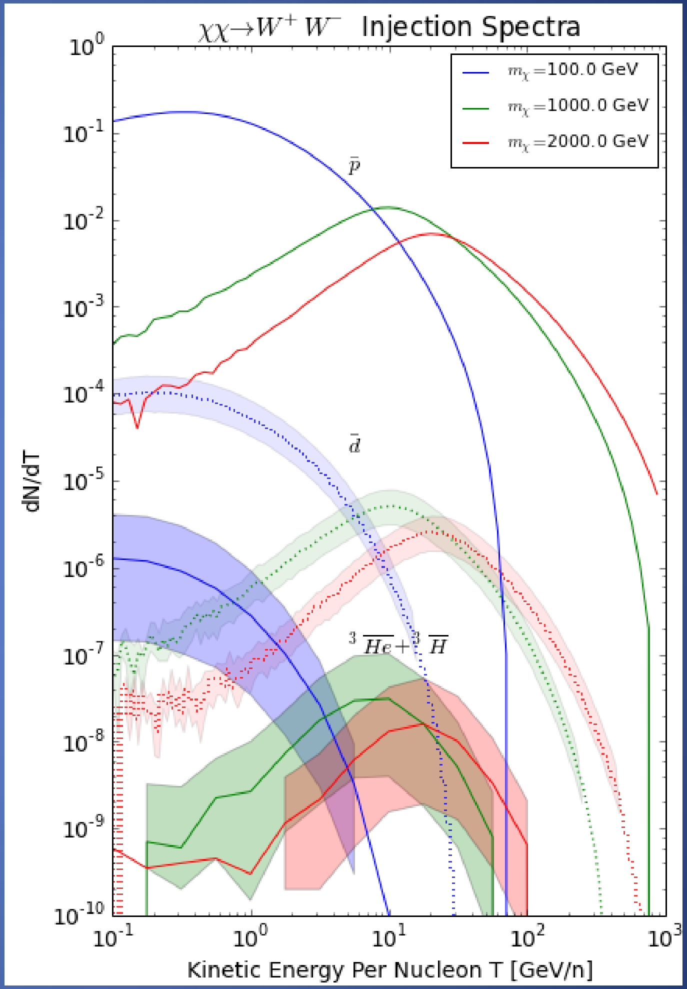
Table 1
C, p_0, $\bar{p}_0$, and R derived from the present data. Typical experimental errors are ± 30% for C and ± 10% for p_0, $\bar{p}_0$, and R. Unit of C is $(\text{mb/sr}(\text{GeV})^2)^{1-A}$

System	Energy (MeV/A)	σ_0 (mb)	Fragment	C	p_0 (MeV/c)	$\bar{p}_0$ (MeV/c)	R (fm)
C + C	800	939	d	3.33×10^{-5}	304	167	2.9
			t, ^{3}He	6×10^{-10}	280	204	2.6
C + Pb	800	2964	d	6×10^{-6}	221	122	3.9
			t	3×10^{-11}	219	159	3.4
			^{3}He	2.5×10^{-11}	226	164	3.3
Ne + NaF	400	1301	d	1.5×10^{-5}	259	142	3.4
			t, ^{3}He	8×10^{-11}	223	162	3.3
	800		d	1.5×10^{-5}	259	142	3.4
			t, ^{3}He	2×10^{-10}	260	189	2.8
	2100		d	1.5×10^{-5}	259	142	3.4
			t, ^{3}He	6×10^{-11}	212	154	3.5
Ne + Pb	400	3497	d	4×10^{-6}	205	113	4.2
			t	1.5×10^{-11}	207	150	3.6
			^{3}He	8×10^{-12}	198	144	3.7
	800		d	4×10^{-6}	205	113	4.2
			t	1.25×10^{-11}	199	145	3.7
			^{3}He	6×10^{-12}	189	137	3.9
	2100		d	4×10^{-6} a)	205	113	4.2
				2.4×10^{-6} b)	173	95	5.0
			t	9×10^{-12}	190	138	3.9
			^{3}He	8×10^{-12}	198	144	3.7
Ar + KCl	800	2445	d	8×10^{-6} a)	260	143	3.3
				6×10^{-6} b)	236	130	3.7
			t, ^{3}He	5×10^{-11} a)	254	185	2.9
				3.33×10^{-11} b)	238	173	3.1
Ar + Pb	800	4545	d	4×10^{-6} a)	223	123	3.9
				3×10^{-6} b)	203	112	4.3
			t	10^{-11} a)	211	153	3.5
				7×10^{-12} b)	199	144	3.7
			^{3}He	8×10^{-12} a)	216	157	3.4
				5×10^{-12} b)	200	145	3.7

1979, Physics Letters B, 85, 38

Injection Spectra





Uncertainty from p_0 using binding energy scaling.

Simulated 20 billion events for each model!

Injection Spectra

Shift injection spectrum by $\frac{e|Z|}{A}\varphi_F \approx$ 2/3 x 500 MeV for approx. solar modulation (only 250 MeV for $\overline{d}$)

Integrate dN/dT over GAPS energies for $\overline{d}$ and $\overline{{}^3He}$

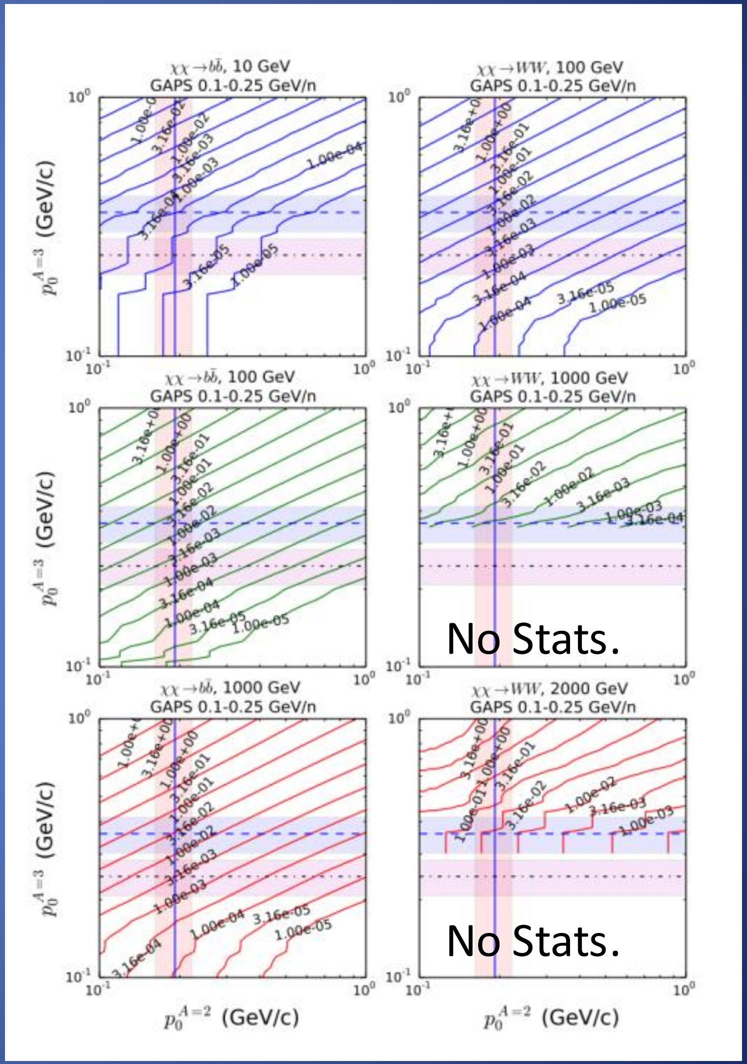
Take ratio as function of the A=2 and A=3 coalescence momenta.

Propagation effects only < 50% different from $\overline{d}$

$$\Phi^{\rm TOA}_{\overline{He3}}(T) \approx R_{\rm PP}\ \Phi^{\rm TOA}_{\overline{d}}(T + e\phi_{\rm f})$$

$$R_{\rm PP} \approx 10^{-3} - 10^{-2} \text{ Not likely } 10^{-4}$$

$$10^{-3} - 10^{-2}\ \overline{{}^3He} \text{ for each } \overline{d}!$$

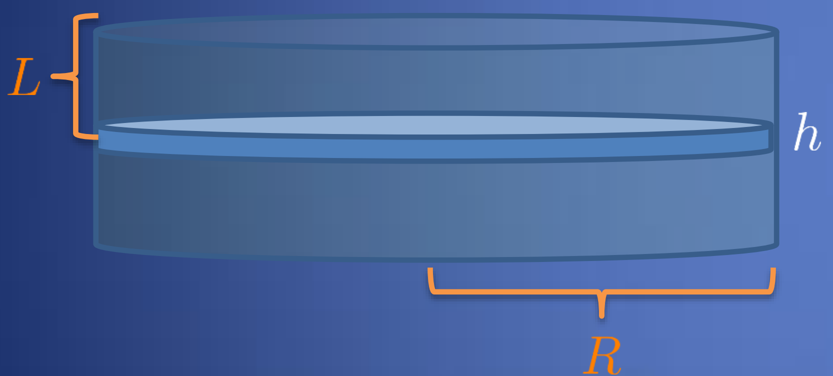


Propagation with 2-Zone Diffusion

Simplified Interstellar Propagation: neglect energy loss and diffusive reacceleration

$$0 = \frac{\partial n}{\partial t} = \nabla\cdot(K(T,\vec{r})\,\nabla n) - \nabla\cdot(V_c\,\mathrm{sign}(z)\,\vec{k}\,n) - 2\,h\,\delta(z)\,\Gamma_{\mathrm{int}}\,n + Q_{\overline{\mathrm{He}}}(T,\vec{r})$$

Diffusion | Convection (advection) | Thin Disk Interactions | Source Term



$$Q_{\overline{\mathrm{He}}}(T,\vec{r}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\vec{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN_{\overline{\mathrm{H3}}}}{dT}$$

$$\Gamma_{\mathrm{int}} = (n_{\mathrm{H}} + 4^{2/3}n_{\mathrm{He}})\;v\;\sigma_{\overline{\mathrm{He}},p}$$

$$K(\mathcal{R}) = \beta K_0 \mathcal{R}^{\delta}_{\mathrm{GV}}$$

Model	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Vary for B/C Compatibility

Assume NFW: $\rho_{\mathrm{DM}}(r) = \rho_0\left(\frac{r_s}{r}\right)^{\alpha}\frac{1}{(1+r/r_s)^{\alpha+1}}$

$$\Phi^{\mathrm{IS}}_{\overline{He}}(T) = \left(\frac{\rho_0}{0.39\ \mathrm{GeVcm}^{-3}}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2 \times\left(\frac{\langle\sigma v\rangle}{3\times10^{-26}\mathrm{cm}^3/\mathrm{s}}\right)\cdot P_{\mathrm{num}}(T)\cdot\frac{dN(T)}{dT}$$

Convolution of production and transport efficiency

Same as $\overline{d}$ propagation except for:

Gas interaction cross sections

$$\Gamma_{\rm int} = (n_{\rm H} + 4^{2/3} n_{\rm He})\ v\ \sigma_{\overline{\rm He},p}$$

Solar Modulation (Force Field)

$$\Phi^{\rm TOA}_{\rm A,Z}(T_{\rm TOA}) = \left(\frac{2m_A T_{\rm TOA} + T^2_{\rm TOA}}{2m_A T_{\rm IS} + T^2_{\rm IS}}\right) \times \Phi^{\rm IS}_{A,Z}(T_{\rm IS})$$

$$T_{\rm IS} = T_{\rm TOA} + e|Z|\phi_{\rm F}$$

Rigidity softer than antideuterons
---> more depletion at low T

Cross-Section Modifications for Antihelium

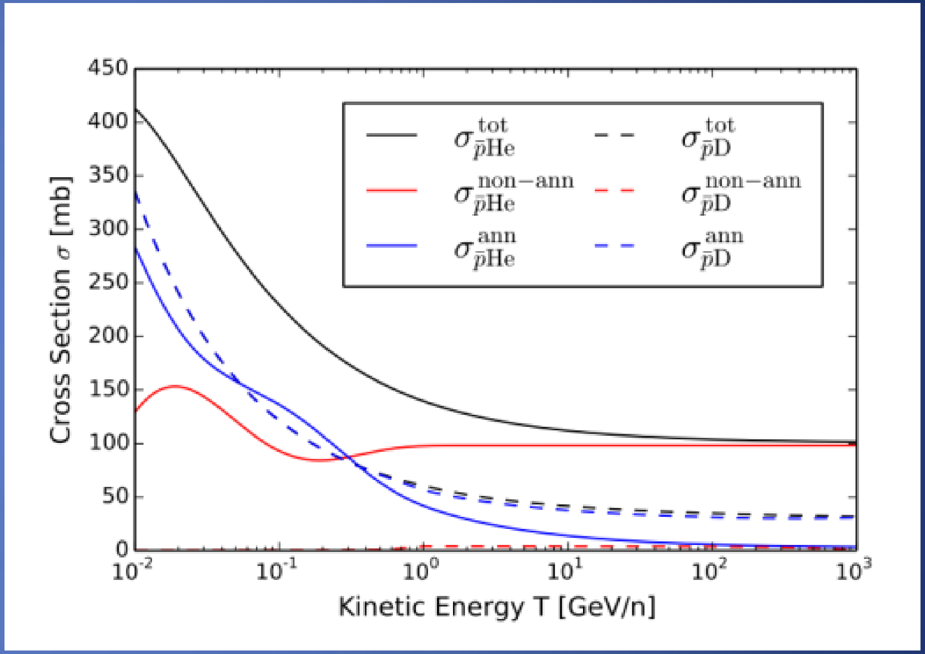
$$\Gamma_{\rm int} = (n_{\rm H} + 4^{2/3} n_{\rm He})\ v\ \sigma_{\overline{\rm He},p}$$

Binding energies

$$B_{\overline{\rm d}} = 2.2\ {\rm MeV} \quad B_{\overline{\rm He3}} = 7.71\ {\rm MeV}$$

Much larger non-annihilating inelastic (NAR) cross-section.

$$N_{\rm int} \approx c t_{\rm res}\ n_{\rm H}\ \sigma_{p,\overline{\rm He}}$$
$$\approx c \cdot 5 \times 10^6\ {\rm yr}\ 1\ {\rm cm}^{-3}\ 100\ {\rm mb}$$
$$\approx 0.5\ {\rm scatters\ during\ propagation}$$



He3 σ's from Strong et al 2002, Astrophys. J. , 565, 280

Only small momentum transfers allowed,
Ignore tertiary contribution for now

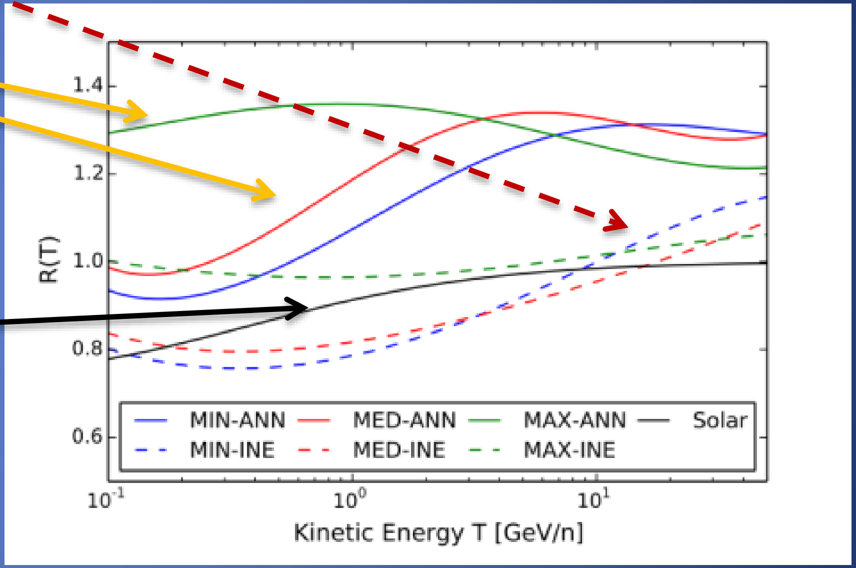
$$G(T,T') \propto \delta(T - T' + e|Z|\phi_{\rm F})$$

No spectral redistribution can just use ratios for injection spectra and propagation differences w.r.t. $\overline{d}$

Propagation Ratios

Bracket effect of total cross section
vs annihilation only

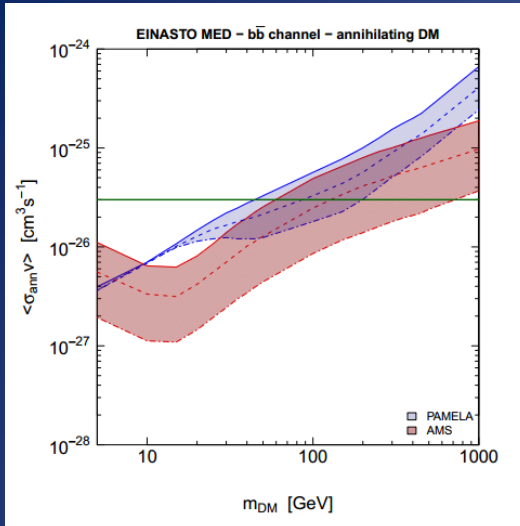
$\overline{{}^{3}He}$ has slightly lower rigidity than $\overline{d}$
→ more depletion during solar modulation



Relative propagation effects are <50% for all models. ≈Unity for MED/ANN model

Finally, The Local Flux

$b\bar{b} \leq 35\text{GeV}$ ruled out by PAMELA $\bar{p}$

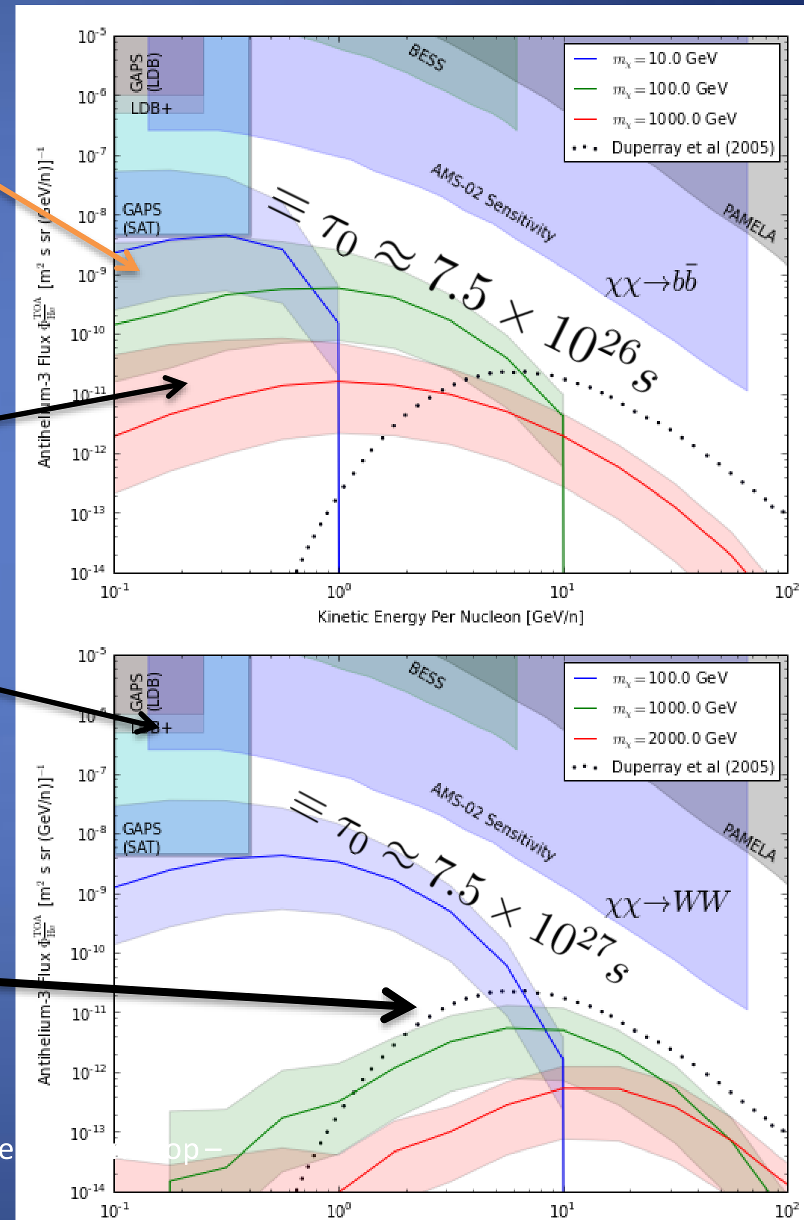


Fornengo, Maccione, Vittino 1312.3579

Uncertainties rep. propagation
MAX model constrained by $\bar{p}$

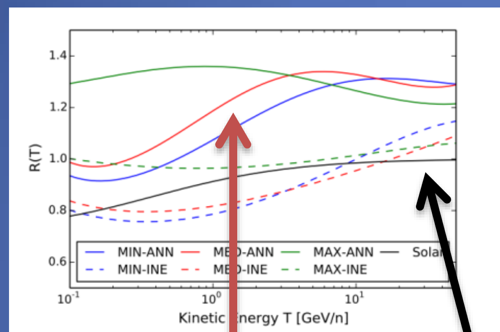
GAPS sensitivities are for $\bar{d}$! $\overline{^3He}$ available?
Satellite mission unlikely for now

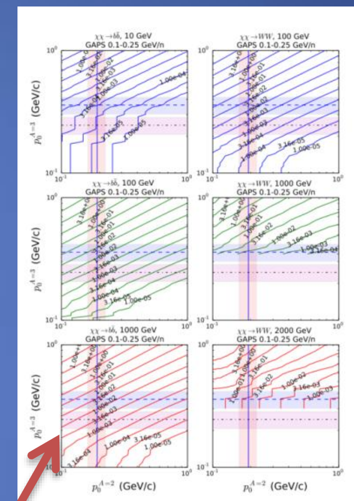
Need self-consistent secondary background for both $\bar{d}$ and $\overline{^3He}$ (using new coalescence model). Should be close at low energies



Scaling From $\overline{d}$ Results

Everything Presented in ratios to $\overline{d}$





$$\Phi_{\overline{He}}(T_{\mathrm{TOA}}) = R_{\mathrm{IS}}(T_{\mathrm{IS}}) \cdot R_{\mathrm{solar}}(T_{\mathrm{IS}}) \cdot R_{\mathrm{PP}}(T_{\mathrm{IS}}, m_\chi, f) \times \left(\frac{p_0^{A=3}}{\overline{p}_{A=3}}\right)^6 \left(\frac{\overline{p}_{A=2}}{p_0^{A=2}}\right)^3 \cdot \Phi_{\overline{D}}(T_{\mathrm{IS}} - e\phi_F/2)$$

DM Halo variations follow from antideuteron case
Charge dependent solar modulation should approx follow

Experimental Challenges for Satellite Missions

Must be close to poles for low-energy $\overline{^3He}$. Geomagnetic Cutoff Rigidity!

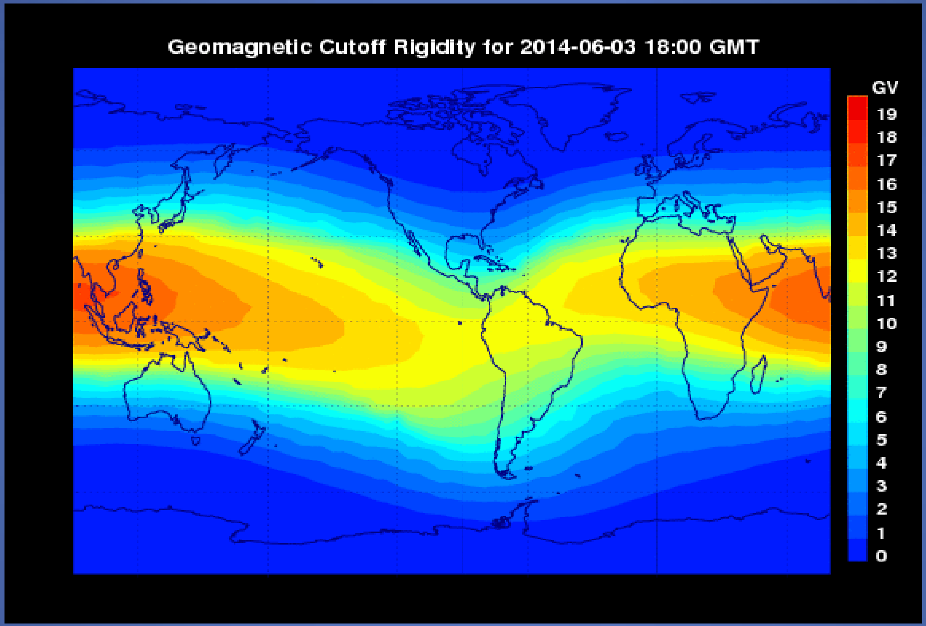


Image Credit:
http://terra2.spacenvironment.net/~raps_ops/current_files/Cutoff.html

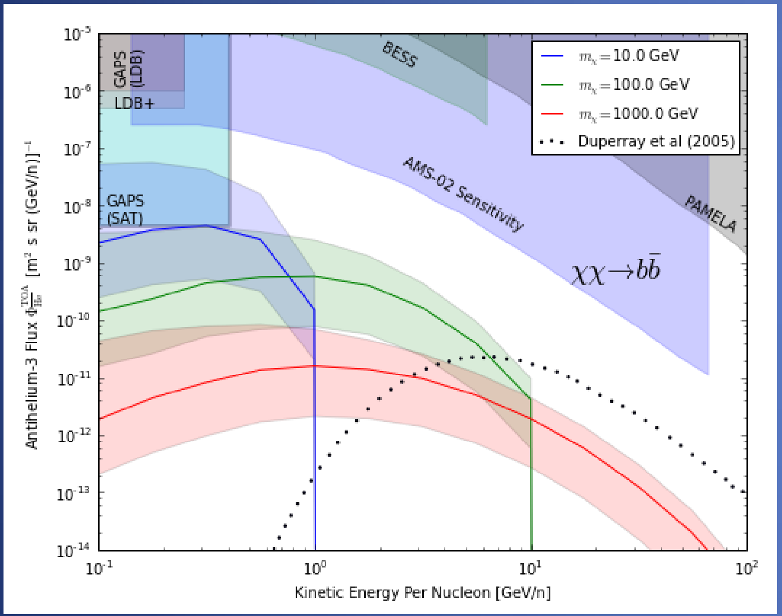
GAPS technology must stop nuclei in gas chamber to detect, Heavier nuclei require more stopping power --> Volume & payload limited sensitivity

Comparison to 1401.4017

Only days apart and very similar analyses! Overall very good agreement

Antihelium from Dark Matter

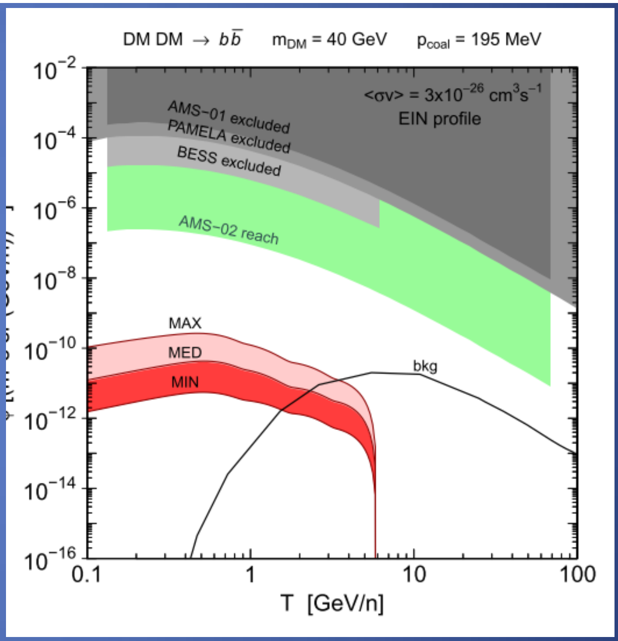
Eric Carlson,[1,2] Adam Coogan,[1,2,*] Tim Linden,[1,2,3,4,†] Stefano Profumo,[1,2,‡] Alejandro Ibarra,[5,§] and Sebastian Wild[5,¶]



- Less conservative, more optimistic
- Gas interaction cross-section
- Includes scaling relations

Anti-helium from Dark Matter annihilations

Marco Cirelli [a], Nicolao Fornengo [b,c], Marco Taoso [a], Andrea Vittino [a,b,c]



- Uses $p_0 = 192$ MeV as default
- Assumes no $\bar{p}\bar{p}\bar{n}$ channel
- Includes antiproton constraints!

Better experimental comparison before we copied it here ☺

Summary and Outlook

- Experimental challenges exist, but $\overline{^3He}$ provides a near zero background probe for large volume of dark matter parameter space (not sensitive to high mass DM -> gauge boson)
- $\overline{^3He}$ TOA Flux is likely to be around 1000 times smaller than $\bar{d}$
- Uncertainty dominated by nuclear physics, propagation secondarily
  Need collider measurements more than anything else
- Not detectable by foreseeable experiments, optimistically detectable by next generation.
- Could be necessary to rule out background following $\bar{d}$ detection.
- Results are consistent between independent groups other than p_0

Shameless Plugs

Gravitino Dark Matter and Flavor Symmetries

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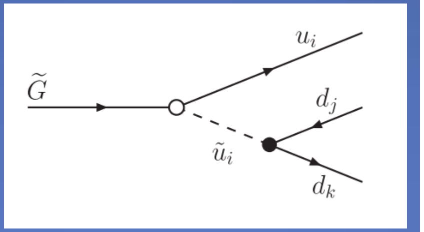
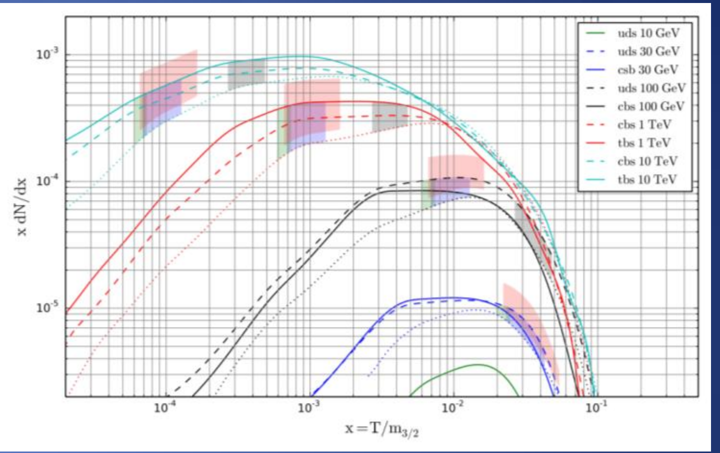
ABSTRACT: In supersymmetric theories without R-parity, the gravitino can play the role of a decaying Dark Matter candidate without the problem of late NLSP decays affecting Big Bang Nucleosynthesis. In this work, we elaborate on recently discussed limits on R-parity violating couplings from decays to antideuterons and discuss the implications for two classes of flavor symmetries: horizontal symmetries, and Minimal Flavor Violation. In a large portion of the parameter space the antideuteron constraints are stronger than low-energy baryon-number-violating processes. For TeV scale superpartners, we find that the allowed MFV parameter space is a corner with gravitino masses smaller than $\mathcal{O}(10)$ GeV and small $\tan\beta$.

$$W_{RPV} = \mu_i L_i \phi_u + \lambda_{ijk} L_i L_j \bar{\ell}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k \,,$$



arXiv: 1404.5952



Cosmic Ray Protons in the Inner Galaxy and the Galactic Center Gamma-Ray Excess

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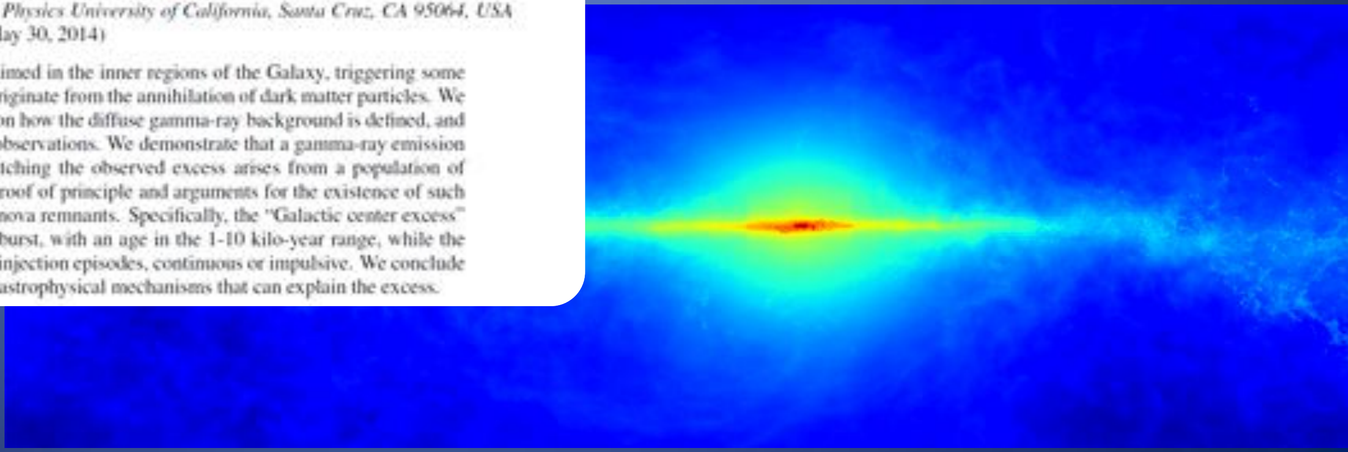
A gamma-ray excess over background has been claimed in the inner regions of the Galaxy, triggering some excitement about the possibility that the gamma rays originate from the annihilation of dark matter particles. We point out that the existence of such an excess depends on how the diffuse gamma-ray background is defined, and on the procedure employed to fit such background to observations. We demonstrate that a gamma-ray emission with spectral and morphological features closely matching the observed excess arises from a population of cosmic ray protons in the inner Galaxy, and provide proof of principle and arguments for the existence of such a population, most likely originating from local supernova remnants. Specifically, the "Galactic center excess" is readily explained by a recent cosmic-ray injection burst, with an age in the 1-10 kilo-year range, while the extended inner Galaxy excess points to mega-year old injection episodes, continuous or impulsive. We conclude that it is premature to argue that there are no standard astrophysical mechanisms that can explain the excess.



arXiv: 1405.7685