AMS Days: Antideuterons, Enhanced Density Indirect Signal (DDDM)

Antideuteron: w/Cui, Mason
Double Disk Dark Matter: w/Fan, Katz, Reece
DDDM and Andromeda: w/Scholtz
Kinematic Bounds on DDDM: w/Kramer

Part I

- AMS days—
- Discuss less prominent indirect detection idea
- Antideuteron detection
- Way to look at likely dominant indirect signal
  - Assuming dark matter and normal matter interact
- Antiproton
  - But antideuteron—with much less background
- Antideuteron searches
  - Good: low background
  - Bad: low rate
- Worthwhile to complement antiproton searches

Part II

- Alternative dark matter model
  - Partially Interacting Dark Matter (PIDM)
  - Fraction of dark matter interats
- Double Disk Dark Matter
  - DDDM
  - Fraction of dark matter, but denser distribution
- Indirect detection: big boost factor
- Mention a few other ways to look

Antideuteron Searches for Dark Matter

LR
W/ Yanou Cui
John Mason

(WIMPy) Dark Matter Detection

- Direct Detection critical
- Indirect Detection important as well
  - Photons
  - Positrons
  - Antiprotons

Model-Dependent

- Rates for direct detection depend on coupling to protons and neutrons
- Rates for indirect detection depend on favored annihilation channels
- Good
  - Way of distinguishing models
- Bad
  - Unless multiple search strategies done at high sensitivity, dark matter could be missed

Early Paper

[redacted]

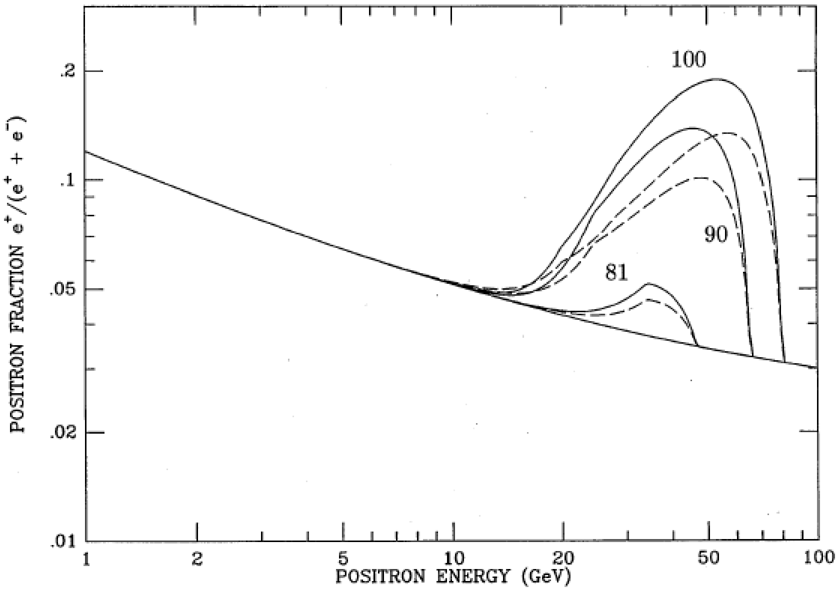

Fig. 2(a)

In computing the positron flux from neutralino annihilations we have computed $\langle\sigma\beta\rangle_8$ from Eqs. ((8),Zsection) and included positrons from both W^+ and Z^0 decays. To make things interesting we have increased the source amplitude a by a factor of 10 over the canonical value in Eqs. ((2),(4)) (which is equivalent to setting $\langle\rho^2_{0.4}\rangle = 10$). In Fig. 2 we show the cosmic-ray positron fraction for neutralino masses $m_{\tilde{\chi}} = 81\,\mathrm{GeV}$, $90\,\mathrm{GeV}$, $100\,\mathrm{GeV}$, $120\,\mathrm{GeV}$, $300\,\mathrm{GeV}$, and $500\,\mathrm{GeV}$, including a "background" from conventional sources, cf. Eq. (7). We show our

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A Distinctive Positron Feature from Heavy-WIMP Annihilations in the Galactic Halo

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ABSTRACT

If the dark matter in our galactic halo consists of weakly interacting massive particles (WIMPs) heavier than the $W^\pm$ boson which have a significant annihilation branch into $W^\pm$ and Z^0 pairs, e.g., a Higgsino-like neutralino, a feature in the cosmic-ray positron spectrum arises from W^+ and Z^0 decays which could provide a distinctive signature. Due to inherent astrophysical uncertainties such a signal is by no means guaranteed even if heavy WIMPs *do* comprise the galactic halo. However, the positron signature is virtually a "smoking gun" for particle dark matter in the halo and thus worthy of note.

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Slightly later paper

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Wino Cold Dark Matter from Anomaly-Mediated SUSY Breaking

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Abstract

The cosmological moduli problem is discussed in the framework of sequestered sector/anomaly-mediated supersymmetry (SUSY) breaking. In this scheme, the gravitino mass (corresponding to the moduli masses) is naturally $10 - 100$ TeV, and hence the lifetime of the moduli fields can be shorter than ~ 1 sec. As a result, the cosmological moduli fields should decay before big-bang nucleosynthesis starts. Furthermore, in the anomaly-mediated scenario, the lightest superparticle (LSP) is the Wino-like neutralino. Although the large annihilation cross section means the thermal relic density of the Wino LSP is too small to be the dominant component of cold dark matter (CDM), moduli decays can produce Winos in sufficient abundance to constitute CDM. If Winos are indeed the dark matter, it will be highly advantageous from the point of view of detection. If the halo density is dominated by the Wino-like LSP, the detection rate of Wino CDM in Ge detectors can be as large as $0.1 - 0.01$ event/kg/day, which is within the reach of the future CDM detection with Ge detector. Furthermore, there is a significant positron signal from pair annihilation of Winos in our galaxy which should give a spectacular signal at AMS.

It might be that the most promising method for searching for dark matter is to look for anti-matter, either anti-protons [25] or positrons [26, 27], produced by the pair annihilation of the LSP in our galaxy. The pair annihilation rate $\langle v_{\rm rel}\sigma\rangle$ for the Wino LSP is given in Eq. (2.4), and numerically is given by 3.8×10^{-24} cm^3/sec (for $m_\chi = 100$ GeV) – 0.9×10^{-24} cm^3/sec (for $m_\chi = 300$ GeV). Unlike standard SUSY dark matter, this rate is very large, and we expect a high flux of anti-particles. Furthermore, there are several

#7 In gravity-mediated SUSY breaking with the GUT relation among the gaugino mass parameters, a large Higgsino component in the LSP and/or a non-universal boundary condition for the scalar masses would be necessary for a detectable SUSY dark matter, unless $\tan\beta$ is large. It is very unlikely that conventional SUSY dark matter will be detected.

on-going projects for measuring the anti-matter flux in the cosmic ray. In particular, a very accurate measurement is expected by the AMS experiment [28], which is a search for anti-matters with "Alpha Magnetic Spectrometer" on the space shuttle and on the international space station. Since the experiment is not affected by the atmosphere, AMS will greatly improve the measurements of the anti-matter fluxes in the cosmic ray.

Indirect Searches

- Positron, antiprotons searches interesting
- Many models favor annihilation into
  - Quark/antiquark pairs
  - W boson pairs
- Antiprotons produced in either case
- But ambiguity about signal versus background
- **Alternative ways to look for q qbar final state?**

Antideuterons

- Donato, Fornengo, Salati
- Antideuterons can dominate over background in low energy region
- $E_{threshold}=7m_p$ for antiprotons, $17m_p$ for antideuterons
  - p($\bar{p}$), pp($\bar{p}$)n($\bar{n}$)final states
  - Rest frame of p
  - Highly boosted
- Binding energy is 2.2MeV
  - Can't slow it down without dissociating
  - Implies very little background T<1GeV
- Dark matter can populate low energy region
- Better way in principle to search for many good dark matter candidates

DPS: Essentially Background Free

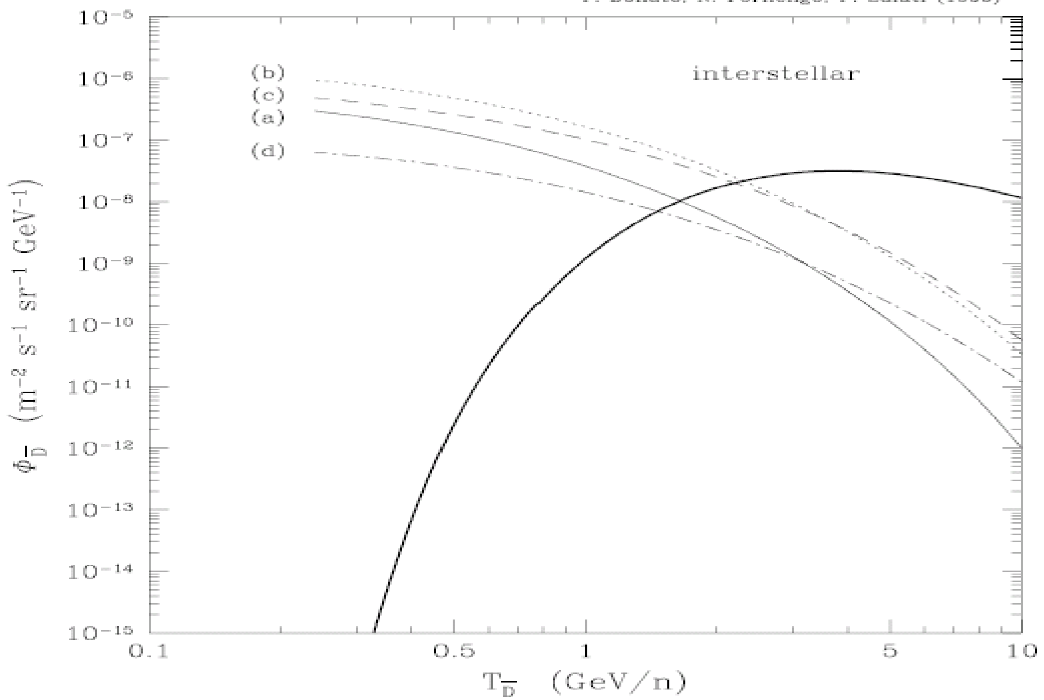

FIG. 3. The IS flux of secondary antideuterons (heavier solid curve) decreases at low energy whereas the energy spectrum of the antideuterons from supersymmetric origin tends to flatten. The four cases of table I are respectively featured by the solid (a), dotted (b), dashed (c) and dot-dashed (d) curves.

case	m_χ	$P_g(\%)$	$\Omega_\chi h^2$	$\Phi_{\overline{p}}^{min}$ (0.24 GeV)	$\Phi_{\overline{D}}^{min}$ (0.24 GeV/n)	$\Phi_{\overline{D}}^{max}$ (0.24 GeV/n)	$N_{\overline{D}}^{max}$
a	36.5	96.9	0.20	1.2×10^{-3}	1.0×10^{-7}	2.9×10^{-8}	0.6
b	61.2	95.3	0.13	3.9×10^{-3}	3.5×10^{-7}	1.1×10^{-7}	2.9
c	90.4	53.7	0.03	1.1×10^{-3}	1.8×10^{-7}	6.1×10^{-8}	2.0
d	120	98.9	0.53	2.9×10^{-4}	2.5×10^{-8}	8.6×10^{-9}	0.3

Good Sensitivity Planned New Experiments

- AMS : Anti-Matter Spectrometer
  - T/n<1 GeV and higher range
- GAPS: General/Gaseous Antiparticle Spectrometer
  - T/n<0.2 GeV

$$\Phi_{\bar{D}} < 0.95 \times 10^{-4}[m^2 \ s \ sr \ \mathrm{GeV}]^{-1} \quad 0.17 \leq T/n \leq 1.15 \ (\mathrm{GeV/n}) \quad \mathrm{BESS}$$

The sensitivites of the future AMS02 and GAPS experiments are:

$$\Phi_{\bar{D}} = 2.25 \times 10^{-7}[m^2 \ s \ sr \ \mathrm{GeV}]^{-1} \quad 0.2 \leq T/n \leq 0.8 \ (\mathrm{GeV/n}) \quad \mathrm{AMS02},$$

$$\Phi_{\bar{D}} = 2.25 \times 10^{-7}[m^2 \ s \ sr \ \mathrm{GeV}]^{-1} \quad 2.2 \leq T/n \leq 4.2 \ (\mathrm{GeV/n}) \quad \mathrm{AMS02},$$

$$\Phi_{\bar{D}} = 1.5 \times 10^{-7}[m^2 \ s \ sr \ \mathrm{GeV}]^{-1} \quad 0.1 \leq T/n \leq 0.2 \ (\mathrm{GeV/n}) \quad \mathrm{GAPS(LDB)}$$

$$\Phi_{\bar{D}} = 3.0 \times 10^{-8}[m^2 \ s \ sr \ \mathrm{GeV}]^{-1} \quad 0.05 \leq T/n \leq 0.25 \ (\mathrm{GeV/n}) \quad \mathrm{GAPS(ULDB)}$$

$$\Phi_{\bar{D}} \sim 2.6 \times 10^{-9}[m^2 \ s \ sr \ \mathrm{GeV}]^{-1} \quad 0.1 \leq T/n \leq 0.4 \ (\mathrm{GeV/n}) \quad \mathrm{GAPS(SAT)}.$$

GAPS: General/Gaseous Antiparticle Spectrometer

- Long duration balloon experiment
- Antideuterons captured and result in exotic atom in final state
- Decays into X-rays at well-defined energies
  - Plus a correlated pion signature
- Time of flight detection to tag events and particle velocities
  - Distinguish from eg antiprotons
- Si/Li detectors for X-ray resolution and particle tracking

GAPs and AMS can be sensitive

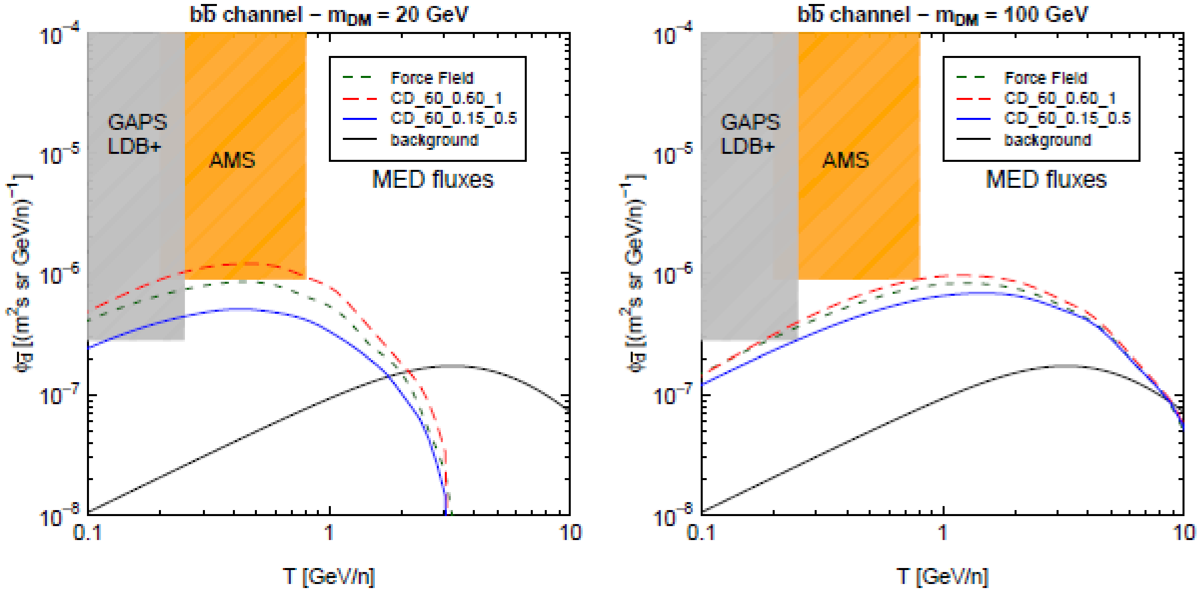

Figure 15. Top-of-atmosphere $\bar{d}$ flux as a function of the $\bar{d}$ kinetic energy, for dark matter signal production in the $b\bar{b}$ channel. The left panel refers to a dark matter mass of 20 GeV, the right panel to 100 GeV. Notations are as in Fig. 14. Annihilation cross sections are those reported in Fig. 12 for the $b\bar{b}$ channel.

Fornengo, Maccione, Vittino

Antideuteron Production

- Poorly understood but estimated
  - Coalescence model
    - Background: pp->pppbar, ppnbar
  - Monte Carlo
    - Annihilation to quarks, gauge bosons
    - Subsequent hadronization and fragmentation
- P, n nearly at rest but ke<B, probably no antideuteron
- K_n- k_p<$(2m_pB)^{1/2}$~70MeV,~p_{coal} most likely form antideuteron

  Use data from Z decay

  p_{coal}~160MeV

Better estimate

Spectra of final states

- qqbar: Dominated by low kinetic energy antideuterons
- WW: peaked at higher energy

WW*->WW u dbar peaked at low energy

General Analysis of Antideuteron Searches for Dark Matter

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June 8, 2010

Abstract

Low energy cosmic ray antideuterons provide a unique low background channel for indirect detection of dark matter. We compute the cosmic ray flux of antideuterons from hadronic annihilations of dark matter for various Standard Model final states and determine the mass reach of two future experiments (AMS-02 and GAPS) designed to greatly increase the sensitivity of antideuteron detection over current bounds. We consider generic models of scalar, fermion, and massive vector bosons as thermal dark matter, describe their basic features relevant to direct and indirect detection, and discuss the implications of direct detection bounds on models of dark matter as a thermal relic. We also consider specific dark matter candidates and assess their potential for detection via antideuterons from their hadronic annihilation channels. Since the dark matter mass reach of the GAPS experiment can be well above 100 GeV, we find that antideuterons can be a good indirect detection channel for a variety of thermal relic electroweak scale dark matter candidates, even when the rate for direct detection is highly suppressed.

Injection Spectrum

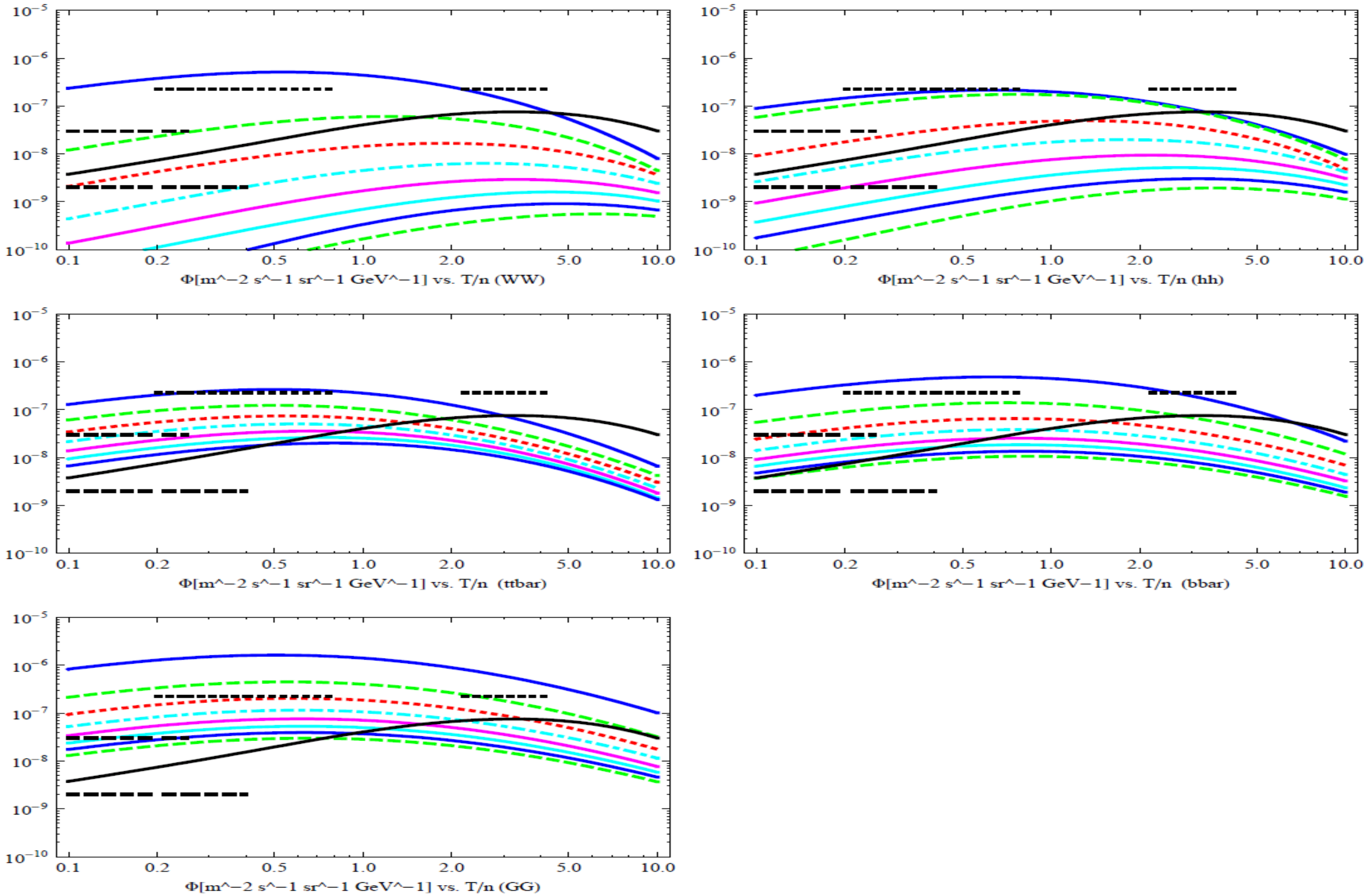

FIG. 2: The anti-deuteron reach of the AMS-02 (black dotted) and GAPS ULDB (black upper-Dashed) and satellite (black lower-dashed) experiment for Dark Matter annihilation to W^+W^-, hh (m_{higgs} = 115 GeV), $\bar{t}t$, $b\bar{b}$, and gg final states. In each case the Dark Matter present day annihilation is set to $< \sigma|v| >= 1$ pb. The Fluxes are plotted for different Dark Matter masses from m_{DM} = 100 − 800 GeV as in Fig. 1. The flux decreases as the mass increases. Also, the astrophysical background is given by the solid line. Propagation is done with "MED" parameters

Need to propagate

- Include effects of
  - Magnetic fields
  - Antideuteron annihilation
  - Energy losses
  - Solar modulation
- Introduces model dependence
  - Vary parameters to give range of predictions

F

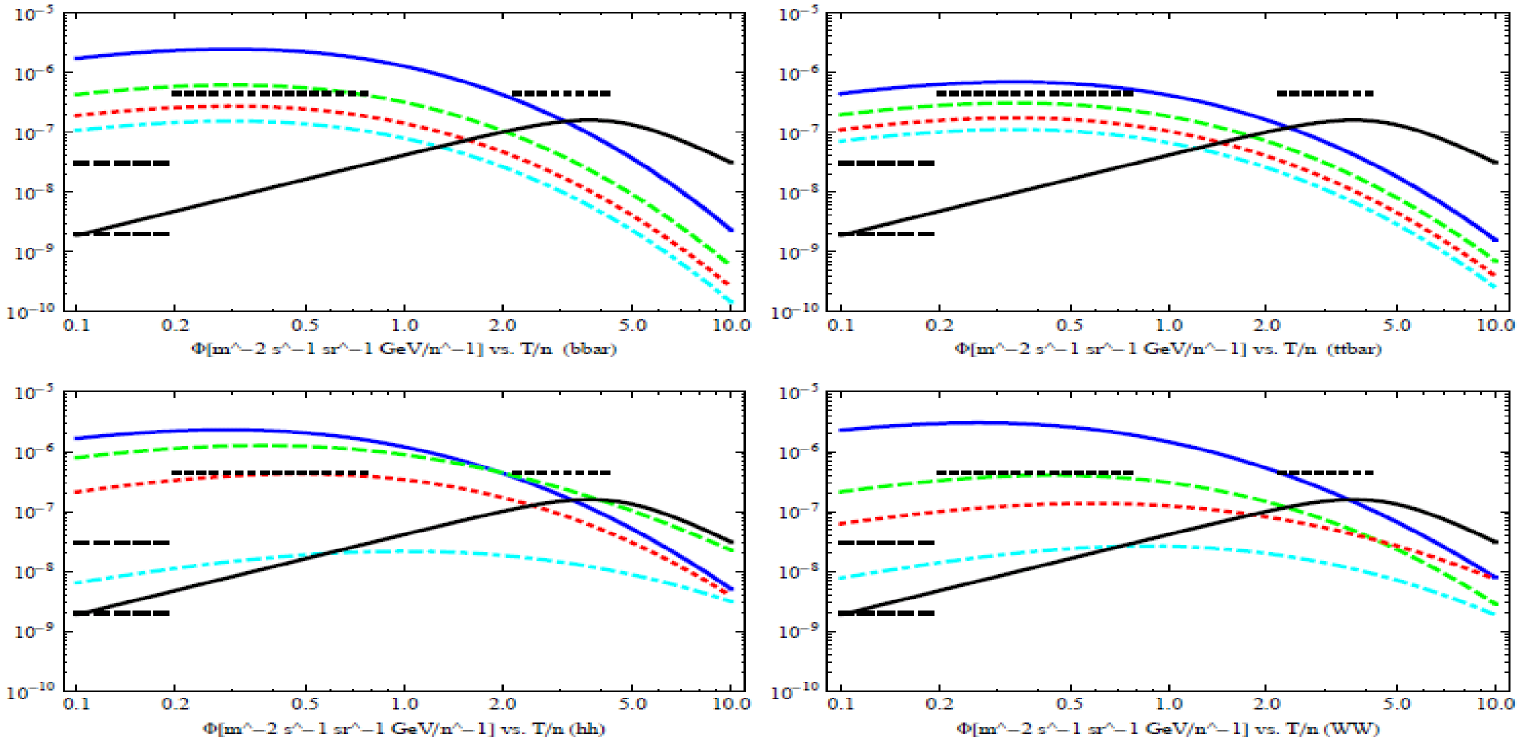

FIG. 2: The antideuteron reach of the AMS-02 (dotted) and GAPS ULDB (upper-Dashed) and satellite (lower-dashed) experiment for Dark Matter annihilation to $b\bar{b}$, $t\bar{t}$, h^0h^0 ($m_{h^0} = 115$ GeV), and W^+W^- final states. In each case the Dark Matter present day annihilation is set to $<\sigma|v|>= 3x10^{-26}\frac{cm^3}{s}$. For $b\bar{b}$: $m_{DM} = 100$ GeV, $m_{DM} = 200$ GeV, $m_{DM} = 300$ GeV, $m_{DM} = 400$ GeV, for $t\bar{t}$: $m_{DM} = 200$ GeV, $m_{DM} = 300$ GeV, $m_{DM} = 400$ GeV, $m_{DM} = 500$ GeV, for h^0h^0: $m_{DM} = 125$ GeV, $m_{DM} = 150$ GeV, $m_{DM} = 200$ GeV, $m_{DM} = 500$ GeV, for W^+W^-: $m_{DM} = 82.5$ GeV, $m_{DM} = 150$ GeV, $m_{DM} = 200$ GeV, $m_{DM} = 250$ GeV. The Flux decreases as the mass increases. Also note that the background is given by the solid line.

Mass reach for each mode? N necessary to exceed background?

of N satisfying the following inequalities:

$$\sum_{n=0}^{N-1} P(n,b) > 0.9545 \quad (2\sigma), \text{ or } \quad \sum_{n=0}^{N-1} P(n,b) > 0.9999994 \quad (5\sigma) \tag{19}$$

where $P(N,b) = (b^N e^{-b})/N!$ and b is the expected number of background events. In other words the probability of detecting the number of antideuterons listed in the N_{crit} column of Table II for each experiment is:

$$P_{2\sigma}(N \geq N_{crit}) < .0455, \quad \text{or} \quad P_{5\sigma}(N \geq N_{crit}) < 0.0000006 \tag{20}$$

In these cases a detection of N_{crit} anti-deuteron events implies that one is seeing and exotic contribution to anti-deuteron cosmic rays at a confidence level $> 95\%$ and $> 99.9999\%$,

Number vs. Mass

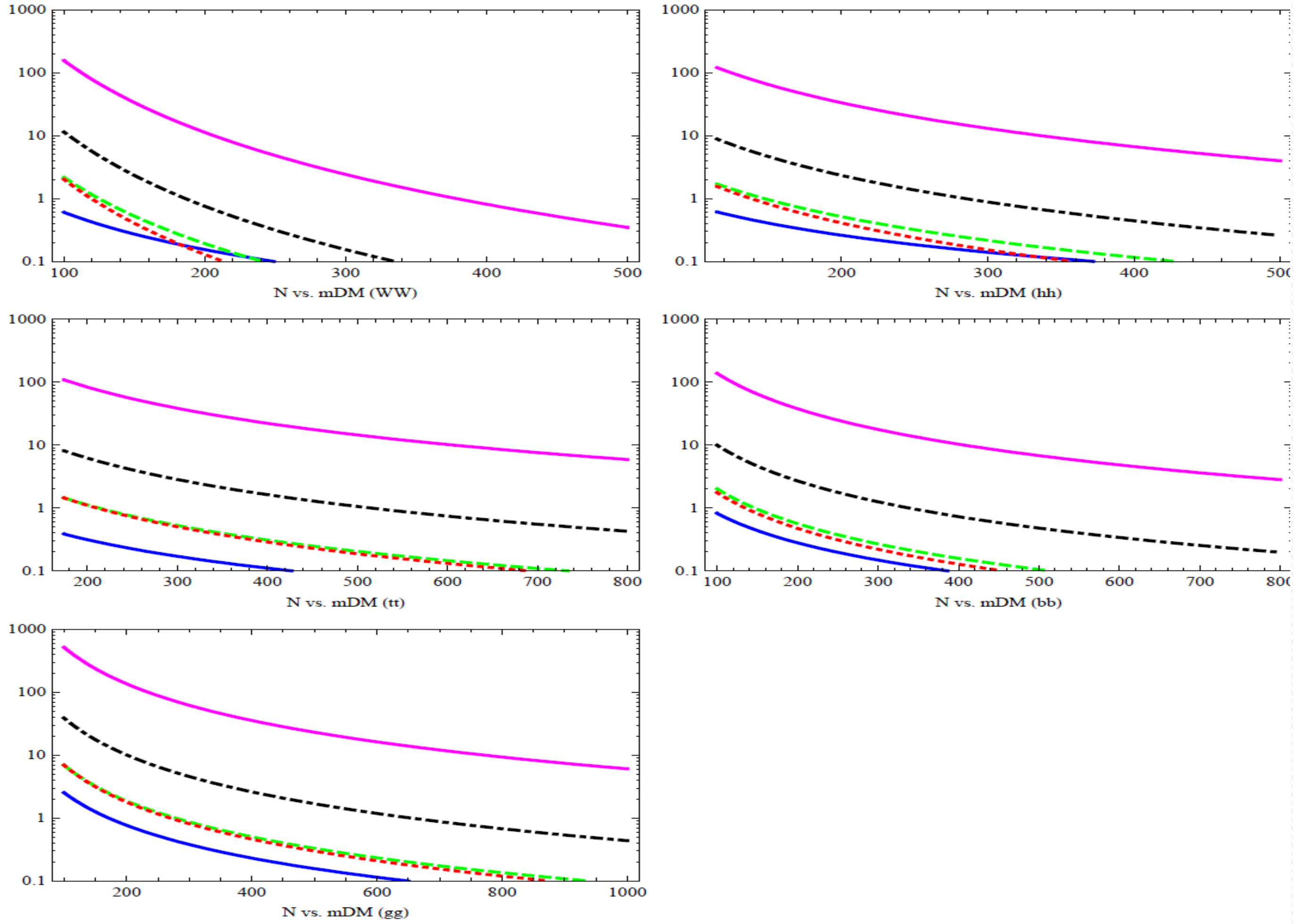

FIG. 3: The anti-deuteron reach of the AMS-02 (blue/solid), GAPS LDB (green/dahed), GAPS ULDB (red/dotted) and GAPS satellite (blue/dot-dashed) experiment for Dark Matter annihilation to W^+W^-, hh ($m_{higgs} = 115$ GeV), $\bar{t}t$, $b\bar{b}$, and gg final states. In each case the Dark Matter

Mass reach for modes

Experiment	$\bar{q}q$	$\bar{t}t$	h^0h^0	gg	W^+W^-	N_{crit}
AMS-02 high (2σ)	110	$< m_t$	$< m_h$	200	$< m_W$	1
AMS-02 low (2σ)	150	220	150	280	140	1
GAPS (LDB) (2σ)	150	220	150	280	120	1
GAPS (ULDB) (2σ)	360	560	300	720	200	1
GAPS (SAT) (2σ)	700	1000	550	1350	270	4
AMS-02 high (5σ)	50	$< m_t$	$< m_h$	60	$< m_W$	6
AMS-02 low (5σ)	70	$< m_t$	$< m_h$	140	$< m_W$	4
GAPS (LDB) (5σ)	75	$< m_t$	$< m_h$	150	$< m_W$	3
GAPS (ULDB) (5σ)	150	220	150	300	120	5
GAPS (SAT) (5σ)	360	550	300	670	200	14

TABLE II: Mass reach for various experiments (all masses in GeV units). Masses quoted denote the Dark Matter mass for which the signal + background flux predicts a number of events equal to N_{crit}. See text for a definition of N_{crit}. For each annihilation mode, 100% branching, $\langle \sigma v \rangle = 1$ pb, MED propagation parameters, and coalescence momentum of $p_0 = 160$ MeV is assumed.

Antiproton Constraint

N. Fornengo[a,b] L. Maccione[c,d] A. Vittino[a,b]

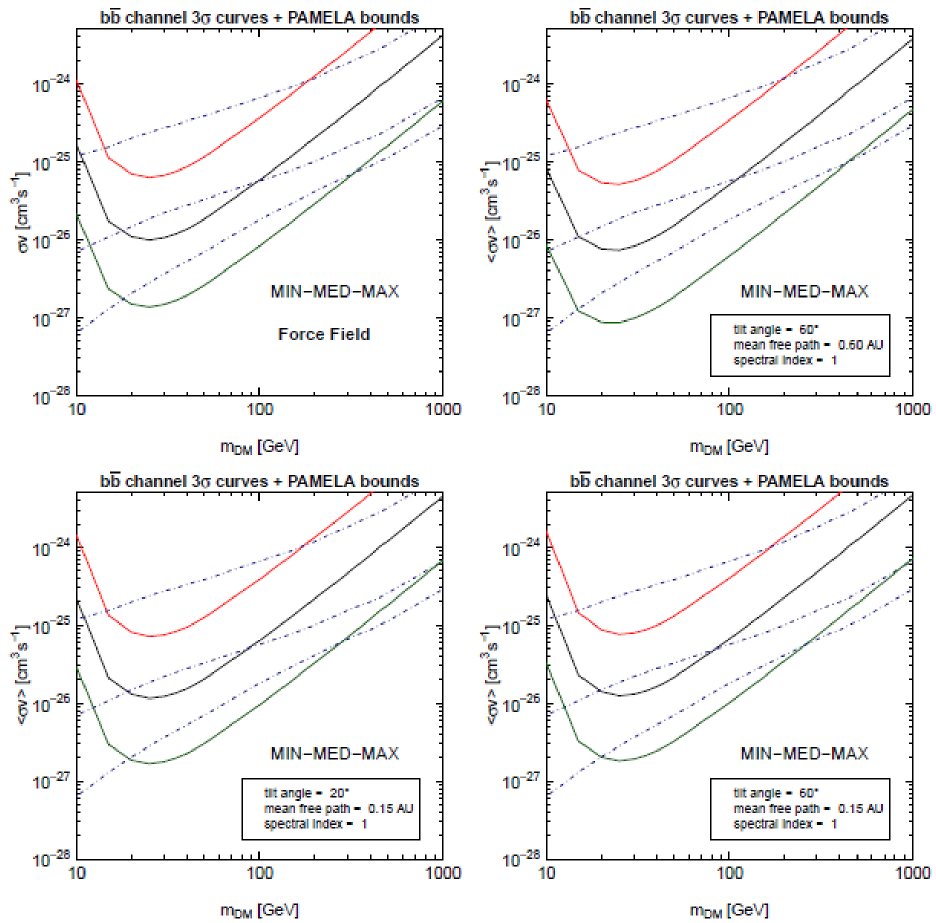

Figure 24. Prospects for a 3σ detection of a $\bar{d}$ signal with AMS-02, expressed in the plane annihilation cross-section $\langle \sigma v \rangle$ vs the dark matter mass m_{DM}, for the $b\bar{b}$ annihilation channel. Notations are as in Fig. 23. Solar modulation has been modeled with the standard force-field approximation in the first panel, and for solar modulation models as reported in the boxed insets, for the other panels.

Antideuteron Reach

- Clearly important potential improvement
- Antiproton bounds work only for very heavy dark matter
- Antideuteron can explore some interesting mass range
- Now: interesting to explore suggested models to see how well they work

Implications for Specific Models

- Many models don’t have exclusive branching ratios to a single state
- Many models tested through direct detection
- Given current bounds and future prospects, how well will antideuteron (or any indirect) detection do?
- Look at known models and more broadly weak scale models with thermal relics

Model Perspective: Direct Detection Implications

- Not having seen direct detection signal favors models where
  - Interaction with gauge bosons dominates
  - Spin-dependent interactions
  - Heavy fermions in final annihilation state (Higgs-like mediator)

- Such models have suppressed direct detection rate
- But conceivably sufficiently large indirect detection
- We do general search in terms of any final state, not assuming particular models
- Assume mass, thermal cross sections

Models to Consider (in progress)

- Of interest today
  - Models predicting GeV Fermi excess in galactic center
  - Dark matter annihilating to b bar
  - Antideuteron searches well set up
- To accommodate direct detection
  - Pseudoscalar intermediate state
  - Flavor dependent final state
  - Decay to Z’ Z’ then decays
    - Z’ can be light, coupling can be small
    - Important for antideuterons

Summary

- Antideuteron search excellent way to look for DM candidates with qqbar final states
- In some cases, can be best way to find DM
  - Will give complementary information about DM interactions
- Implications for models in progress

Double Disk Dark Matter

LR w/Fan, Katz, Reece
w/Reece
w/Kramer
w/Scholtz

Dark Matter

- What is dark matter?
- We know of gravitational interactions
  - Very little about possible others
  - Know weakly interacting, but that's about it
- How to learn about dark matter?
  - Direct Detection
  - Indirect Detection
    - In general requires unusual dark matter distribution
    - Or unusual dark matter model
      - To get visible signal

Status

- Dark matter searches to date always based on optimistic assumptions
  - Dark matter interacts with our matter at some level
- In principle could be purely gravity coupling
  - Or coupling only to its own sector
- Does dark matter have self-interactions?
- Or does at least some of it?
- Alternative to standard WIMP paradigm
  - Partially Interacting Dark Matter (PIDM)

Leads to Dark Disk (DDDM) Double Disk Dark Matter

- Can we imagine a bigger dark matter annihilation signal?
- Perhaps dark disk inside galactic plane
- But one with significant consequences
  - Leads to rethinking of implications of almost all dark matter, astronomical, cosmological measurements
  - Will be tested
- Since we don't know what dark matter is
  - Should keep an open mind
  - Especially in light of abundance of astronomical data

Provides Enormous Boost Factor

- Dark matter that condenses into a disk is much denser
- Net enhancement of density over ordinary matter

Indirect detection proportional to square of this factor

Can be enormous

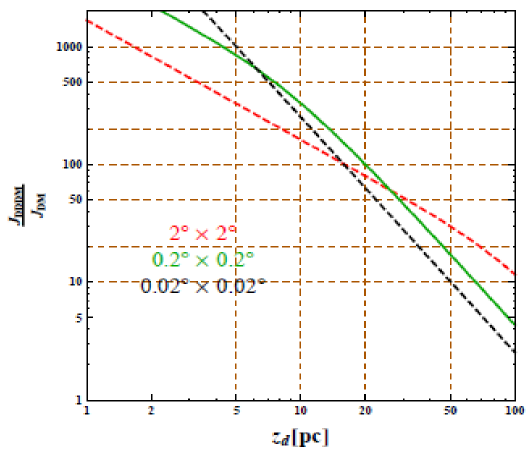

Figure 8: Local density enhancement in DDDM, as a function of disk scale height z_d, in a square region around the GC fixing $\epsilon = 0.05$ that DDDM is 5% of the total DM density. Red: region within $b \subset (-1°, 1°), l \subset (-1°, 1°)$. Green: region within $b \subset (-0.1°, 0.1°), l \subset (-0.1°, 0.1°)$ (current Fermi-LAT angular resolution). Black: region within $b \subset (-0.01°, 0.01°), l \subset (-0.01°, 0.01°)$.

Distinctive Shape to Signal

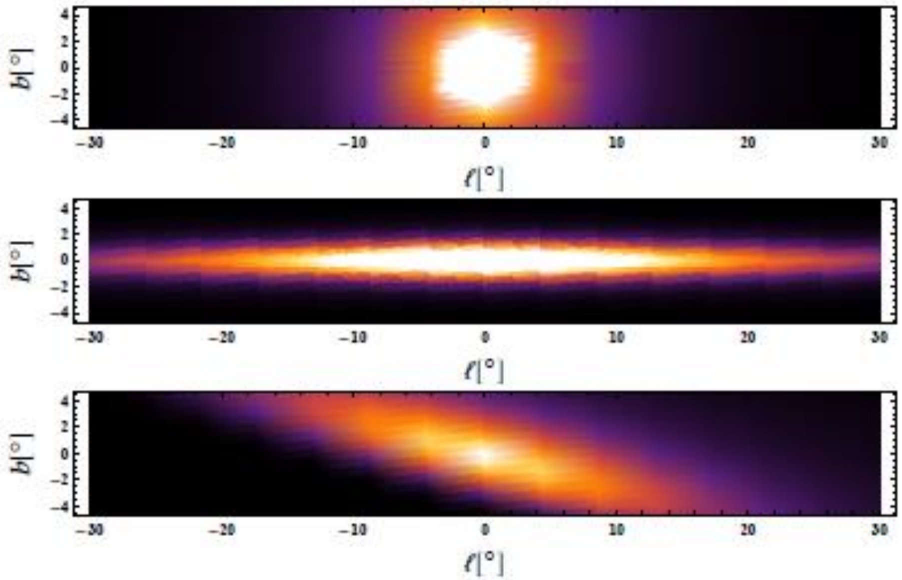

FIG. 10. Sky maps of the photon flux in A.U.s for different DM profiles. Upper: Normal DM with an Einasto profile. Middle: PDDM in a disk aligned with our disk. Lower: PDDM in a disk misaligned with our disk.

PIDM/DDDM changes everything

- Almost all constraints on interacting dark matter assume it is the dominant component
- If it's only a fraction, most bounds don't simply apply
  - Halo structure
  - Galaxy or cluster interactions
    - Eg Bullet Cluster
- If dark matter interacts, either
  - Reasonably strong constraints
    - Actually not all that strong…
  - Or it's not all the dark matter!
    - At most about baryonic energy density or fraction thereof

Why would we care?

- But if a fraction, you might expect even smaller signals
- However, not necessarily true…
- Can lead to a DARK DISK
- Implications of a subdominant component
  - Can be relevant for usual signals if it is denser
  - Can be relevant for structure and astronomy too
- Collapse of halo creates dense structure with different gravitational potential
  - PIDM can also be relevant to dwarf satellites, black holes, meteoroid flux

How a dark disk would be formed

- We know most dark matter in a halo
- Perhaps fraction that forms a disk
  - Self-interacting dark matter
  - Dark matter interacting via its own force
- Assume only a fraction
  - Rather than assume all dark matter
- Maybe like baryons—small fraction with unduly important role
  - Baryons matter because formed in a dense disk
  - Perhaps same for *component* of dark matter

Could interacting dark matter cool into a Dark Disk?

- To generate a disk, cooling required
- Baryons cool because they radiate
  - They thereby lower kinetic energy and velocity
  - Get confined to small vertical region
- Disk because angular momentum conserved

- Dark disk too requires a means of dissipating energy
- Assume interacting component has the requisite interaction
- Simplest option independent gauge symmetry
  - "Dark light"

Simple DDDM Model: Dark Light

- Could be U(1) or a nonabelian group
- $U(1)_D$, α_D
- Two matter fields: a heavy fermion X and a light fermion C
  - For "coolant" as we will see
- $q_X=1$, $q_C=-1$
- (In principle, X and C could also be scalars)
- (in principle nonconfining nonabelian group)

Thermal Abundance of X and C

- When X freezes out with weak scale mediators, could have half temp of SM particles
- If lighter mediator, could imagine comparable temps
- In any case, thermal abundance of weak scale particle naturally gives ride to fraction of dark matter abundance
- Not true however for light state, which annihilates too quickly
- Probably have both thermal and nonthermal components

Check Cooling:

- Bremsstrahlung
- Compton scattering off dark photons

  - We make assumption that cooling stops when recombination can occur
  - Approximately B/20

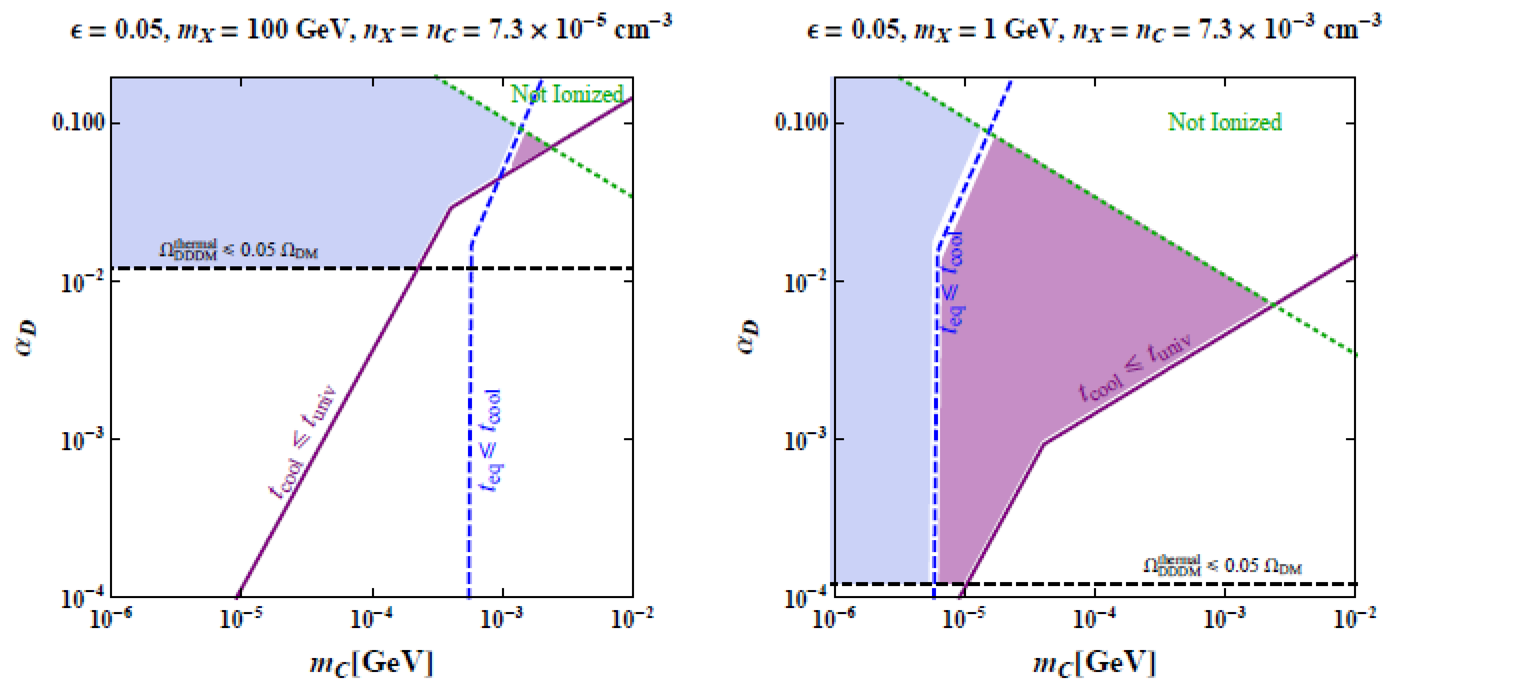

Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\mathrm{CMB}}/2$. The two plots on the left are for $m_X = 100$ GeV; on the right, $m_X = 1$ GeV. The upper plots are for a 110 kpc radius virial cluster; the lower plots, a 20 kpc NFW virial cluster. The solid purple curves show where the cooling time equals the age of the universe; they have a kink where Compton-dominated cooling (lower left) transitions to bremsstrahlung-dominated cooling (upper right). The dashed blue curve delineates fast equipartition of heavy and light particles. Below the dashed black curve, small α_D leads to a thermal relic $X, \bar{X}$ density in excess of the Oort limit. To the upper right of the dashed green curve, B_{XC} is high enough that dark atoms are not ionized and bremsstrahlung and Compton cooling do not apply (but atomic processes might lead to cooling).

Cooling temp determines disk height

- And therefore density of new component

The disk scale height could be estimated as follows. In an axisymmetric gravitational system with height z,

$$\frac{\partial(\rho \bar{v_z^2})}{\partial z} + \rho \frac{\partial(\Phi)}{\partial z} = 0 \tag{9}$$

$$4\pi G_N \rho = \frac{\partial^2(\Phi)}{\partial z^2}, \tag{10}$$

where the first equation is the Jeans equation neglecting the radial derivative (see Eq. (4.222b) in [2]) and the second is the Poisson equation. Solving these two equations, one find the scale height is [3]

$$z_d = \sqrt{\frac{v_z^2}{8\pi G_N \rho}} = \sqrt{\frac{k_B T}{m_p 24\pi G_N \rho}}, \tag{11}$$

where in the second step, the thermal relation $m_p \bar{v_z^2} = k_B T/3$ is used. Numerically,

$$z_d \approx 2.5\,\mathrm{pc} \left(\frac{\alpha_D}{0.02}\right)^2 \frac{m_Y}{10^{-3}\ \mathrm{GeV}} \frac{100\ \mathrm{GeV}}{m_X} \tag{12}$$

where T is in unit of K and ρ is unit of GeV/cm^3. Interstellar gas (and young stars) have velocity $v \sim 10$ km/s which corresponds to $T \sim 10^4$ K. Plugging it in, we get the disk height is about 300 pc. For old stars, the velocity is about $20 - 30$ km/s and the local disk height is estimated to be 600 pc - 1 kpc, which agrees with the observations (see numbers in [2]).

Disk Height

- In reality, gravitational heating can occur
- Reasonable to assume disk height between
- m_P/m_X---1 times baryonic disk height
- Can be very narrow disk
- For 100 GeV particle, can get boost factor of 10,000!

Disks at least approximately align

- Alignment time:
- R~10 kpc
- M~10[12] M_{sun}

$$t \approx \left(\frac{R^3}{GM}\right)^{1/2} \sqrt{\theta}$$

$$10^{12} M_{Sun} = 1.99 \times 10^{45} \text{ gr}$$

$$G = 6.67 \times 10^{-8} \text{ cm}^3 \text{gr}^{-1} \text{sec}^{-2}$$

$$t \sim \left(\frac{R^3}{GM}\right)^{1/2} \sim \sqrt{2.2 \times 10^{29}} \text{ sec} \sim 4.7 \times 10^{14} \text{ sec} \sim 1.5 \times 10^{7} \text{ years}$$

Summary of model

- A heavy component
  - Was initially motivated by Fermi signal
- For disk to form, require light component
  - Can't be thermal (density would be too low)
  - Constraint on density vs mass
    - Aside: anthropic bound on electron mass!
- With these conditions, expect a dark disk
  - Might even be narrower than the gaseous disk

Consequence

- Dark disk
- Could be much denser and possibly titled with respect to plane of our galaxy
- Very significant implications
  - Even though subdominant component
- Expect interesting signals
  - And bounds
- Velocity distributions in or near galactic plane constrain fraction to be comparable or less to that of baryons
- But because it is in disk and dense signals can be rich

Traditional Methods

- Smaller direct detection, small velocity
  - Very interesting: below threshold even with big mass
  - Possibly other noncanonical possibilities
- Indirect detection
  - Possible if mediation between visible, invisible sectors
  - As earlier, could have enhancement and distinctive shape
    - Essential for thermal component to survive

Other methods, constraints

- Number of degrees of freedom
  - BBN, CMBR : not a problem
- CMBR
  - New acoustic peak
  - Suppression of structure on small scales
  - PIDM<5% total dark matter

Bound from Structure w/Kramer

- Recall bound from shapes not so bad
  - But bound from from matter accounting
  - And detailed shape of galaxy
- Gravitational potential measured
  - Both in and out of plane of galaxy
  - Star velocities
- Baryonic matter independently constrained
- Dominant component of dark matter constrained
  - Extrapolate halo
- Total constraint on any new form of matter
- Constrains any new (nonhalo) component in galactic plane

Various effects

- Add new component
- Has different thickness
- Pinches other components
- Surface density and thickness ultimately constrained

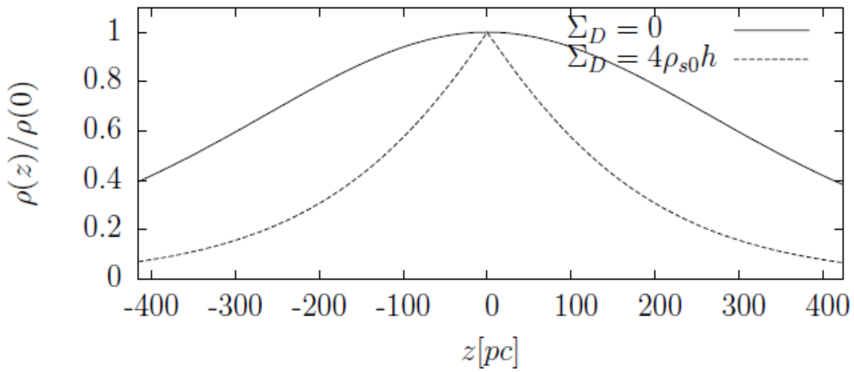

Figure 1: A plot of the exact solutions without and with a dark disk of $Q = 1$. The density is 'pinched' by the disk, in accordance with Eq. 31.

This will improve dramatically

- Hipparcos now
- Gaia survey measuring position and velocity of stars in solar neighborhood
- Will significantly constrain properties of our galaxy
- In particular, new disk component will give measurable signal if surface density sufficiently height
- Don't know how much gas measurements will improve but they should too

w/Scholtz

Satellites of Andromeda Galaxy

- About half the satellites are approximately in a (big plane)
  - 14kpc thick, 400 kpc wide
- Hard to explain
- Proposed explanation: tidal force of two merging galaxies
- Fine except of excessive dark matter content
- Tidal force would usually pull out only baryonic matter from disk
- Not true if dark disk

- We worked out consequence with dark disk
  - Two important effects-
    - Dark matter in disk
    - Low velocity: more readily bound
- Assume pull out patch on order of size of Toomre instability

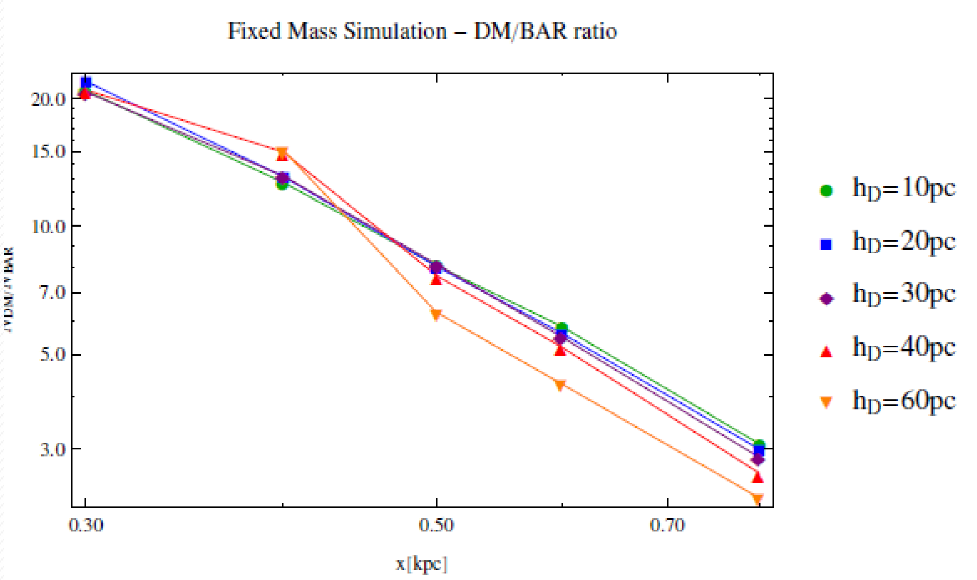

Figure 9: Dependence of the final DM to baryon ratio on the size of the initial patch.

Motion of Sun: Crater Periodicity

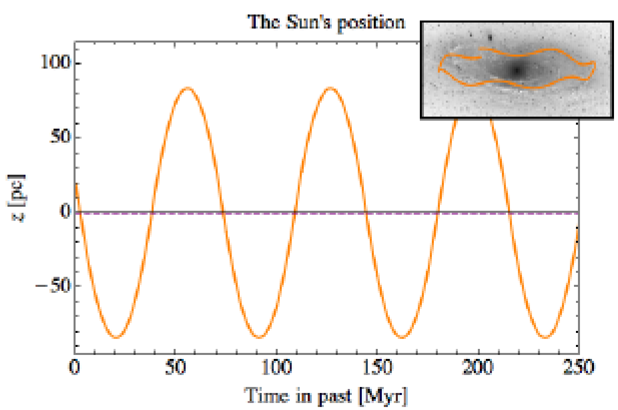

FIG. 1. The Sun's height above the galactic plane as a function of time, extrapolated backward via Eq. 2. The corresponding cratering probability is shown in Fig. 3. Inset: an illustration of how the Sun moves around the galactic center while also oscillating vertically; the vertical oscillation is exaggerated for visibility.

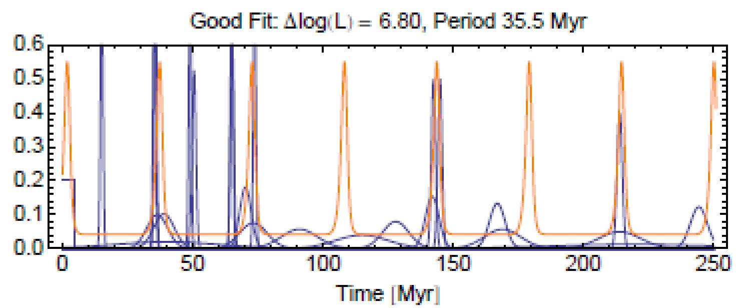

FIG. 3. An example of a model that provides a good fit. The parameters of the dark disk are $\Sigma_D = 13 M_\odot/\mathrm{pc}^2$ and $z_d^D = 5.4$ pc. The baryonic disk is 350 pc thick with total surface density 58 $M_\odot/\mathrm{pc}^2$. The local dark halo density is 0.037 $\mathrm{GeV/cm}^3$. $Z_\odot = 20$ pc and $W_\odot = 7.8$ km/s. In this case, the period between disk crossings is about 35 Myr. In orange is the rate $r(t)$ of comet impacts (with arbitrary normalization). This is approximately proportional to the local density, but convolved with the shower profile from Fig. 2. The various blue curves each correspond to one recorded crater impact.

Meteorite Periodicity?

- Meteorite database gives 21 craters bigger than 20 km in circumference in last 250 years
- Evidence for about 32 million year periodicity
- Evidence however goes away when look elsewhere effect incorporated
- This will change with a model and measured priors
- We assume a dark disk take into account constraints on measured parameters, and determine whether likelihood ratio prefers model to flat distribution
- And what a posteriori distribution is favored

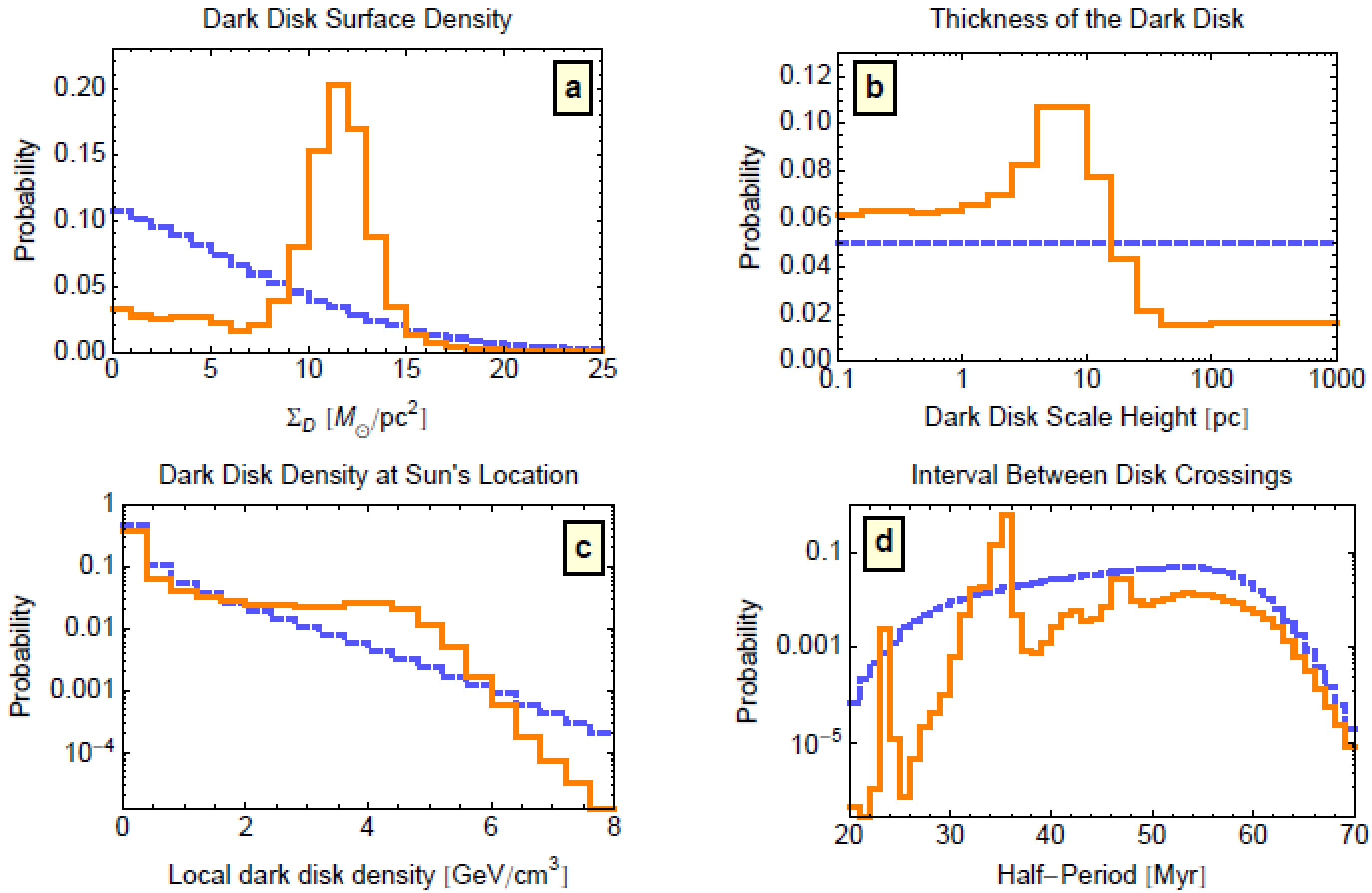

Figure 2: One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\text{pc}^2$. (b) The dark disk thickness, which fits best at about 10 parsec scale height but extends to thinner disks. (c) The local density of disk dark matter (relevant for solar capture or direct detection), which has significant weight up to several GeV/cm^3. (d) The interval between times when the Sun passes through the dark disk, which fits best at values of about 35 Myr.

Many Consequences to think about

- Can explain dwarf satellite galaxies
  - More general
  - No other explanation
- Possibly formation big black holes
- Cluster mergers
- New results on dark disk constraints
  - Ways to discover
- Results on planar dwarf galaxy satellites
- Ultimate anthropic☺ Killing dinosaurs

Conclusions

- Whether or not annihilation “signals” survive,
- Very interesting new possibility for dark matter
  - That one might expect to see signals from
- Since in some sense only minor modification (just a fraction of dark matter)
- hard to know whether or not it’s likely
- But presumably would affect structure
  - Just like baryons do
  - Research area
- Rich arena: lots of questions to answer
- In any case all methods of searching for dark matter important
  - Indirect detection: antideuteron useful complement
  - Detailed probes of gravitational potential