New Dark Matter Detectors using DNA for Nanometer Tracking

Andrzej Drukier,1,∗ Katherine Freese,2,3,† David Spergel,4,‡
Charles Cantor,5,§ George Church,6,¶ and Takeshi Sano7,∗∗

1 Biotraces, Inc. Fairfax, VA
2 Michigan Center for Theoretical Physics, Department of Physics,
   University of Michigan, Ann Arbor, MI 48109
3 Physics Department, Caltech, Pasadena, CA 91101
4 Department of Astronomy Princeton University Princeton, NY 08544
5 SEQUENOM, Inc., 3595 John Hopkins Court, San Diego, CA 92121
6 Department of Genetics, Harvard University, Boston, MA 02115
7 DiThera, Inc., San Diego, CA 92121

(Dated: May 2, 2014)

Weakly Interacting Massive Particles (WIMPs) may constitute most of the matter in the Universe. While there are intriguing results from DAMA/LIBRA, CoGeNT and CRESST-II, there is not yet a compelling detection of dark matter. The ability to detect the directionality of recoil nuclei will considerably facilitate detection of WIMPs by means of ”annual modulation effect” and ”diurnal modulation effect”. Directional sensitivity requires either extremely large gas (TPC) detectors or detectors with a few nanometer spatial resolution.

In this paper we propose a novel type of dark matter detector: detectors made of DNA could provide nanometer resolution for tracking, an energy threshold of 0.5 keV, and can operate at room temperature. When a WIMP from the Galactic Halo elastically scatters off of a nucleus in the detector, the recoiling nucleus then traverses thousands of strings of single stranded DNA (ssDNA) (all with known base sequences) and severs those ssDNA strands it hits. The location of the break can be identified by amplifying and identifying the segments of cut ssDNA using techniques well known to biologists. Thus the path of the recoiling nucleus can be tracked to nanometer accuracy. In one such detector concept, the transducers are a few nanometer-thick Au-foils of 1m×1m, and the direction of recoiling nuclei is measured by ”DNA Tracking Chamber” consisting of ordered array of ssDNA strands. Polymerase Chain Reaction (PCR) and ssDNA sequencing are used to read-out the detector. The detector consists of ∼ 1 kg of gold and 0.1 kg of DNA packed into (1m)3. By leveraging advances in molecular biology, we aim to achieve about 1,000-fold better spatial resolution than in conventional WIMP detectors at reasonable cost.

∗ adrukier@gmail.com
† ktfreese@umich.edu
‡ dns@astro.princeton.edu
§ ccantor@sequenom.com
¶ gchurch@genetics.med.harvard.edu
∗∗ sanotakeshi@gmail.com
I. INTRODUCTION

The Milky Way, along with other galaxies, is well known to be encompassed in a massive dark matter halo of unknown composition. Only 5% of the Universe consists of ordinary atomic matter, while the remainder is 23% dark matter and 72% dark energy [1]. Identifying the nature of this dark matter is the longest outstanding problem in modern physics. Leading candidates for this dark matter are Weakly Interacting Massive Particles (WIMPs), a generic class of particles that includes the lightest supersymmetric particle. These particles undergo weak interactions and their expected masses range from 1 GeV to 10 TeV. These particles, if present in thermal equilibrium in the early universe, annihilate with one another so that a predictable number of them remain today. For a wide range of parameters, the relic density of these particles is found to be roughly in agreement with the value measured by WMAP.

Thirty years ago, Refs. [2, 3] first proposed that the most efficient laboratory mechanism for detecting weakly interacting particles, including WIMPs, is via coherent scattering with nuclei. Soon after [4] computed detection rates in the context of a Galactic Halo of WIMPs. Then development of ultra-pure Ge detectors permitted the first limits on WIMPs [5]. Since that time, a multitude of experimental efforts to detect WIMPs has been underway, with some of them currently claiming detection. The basic goal of direct detection experiments is to measure the energy deposited when weakly interacting particles scatter off of nuclei in the detector, depositing 1-10 keV in the nucleus. Numerous collaborations worldwide have been searching for WIMPs using a variety of techniques to detect the nuclear recoil. The most difficult aspect of these experiments is background rejection. To avoid cosmic rays (CR), the experiments are placed deep underground. Yet radioactive backgrounds persist; fast neutrons produced by CR are particularly difficult to differentiate from WIMPs. Important tools in isolating a WIMP signal are the annual and diurnal modulations (AME and DME) that would be expected for WIMPs but not for most backgrounds.

Annual Modulation Effect:

Three of us showed in 1986 that the count rate in WIMP direct detection experiments will experience an annual modulation [4, 6] as a result of the motion of the Earth around the Sun: the relative velocity of the detector with respect to the WIMPs depends on the time of year. Thus the count rate in detectors should change with a cosine dependence on time. For the past ten years the DAMA experiment [7] has been claiming detection of an annual modulation. This experiment consists of a large number of NaI crystals situated in the Gran Sasso Tunnel and currently reports a 9σ detection. Recently the CoGeNT experiment [8], made of germanium, also reported annual modulation, at the 2.8 sigma level. A third experiment, dilution-refrigerator based CRESST-II [9], has also announced anomalous results. There has been much discussion as to whether or not the three experiments may be consistent with the same WIMP parameter range, e.g. [10, 11]. Yet CDMS II sees no annual modulation [12], and both CDMS II [13] and XENON [14] find null results that appear to be in conflict with the other three experiments. The situation is perplexing.

Diurnal Modulation Effect:

A major step forward in the field of direct detection would be the development of detectors with directional capability [15], i.e., the capability to determine which direction the WIMP came from. As a result of the elastic scattering of WIMP off of a nucleus in the detector, the nucleus gets kicked in a particular direction (typically forward). Thus by determining the track of the nucleus one could identify the direction of the incoming WIMP (Figure 1). The WIMP flux in the lab frame is peaked in the direction of motion of the Sun (which happens to
be towards the constellation Cygnus). Hence the recoil spectrum for most energies should be peaked in the direction opposite to this. The event rate in the backward direction is expected to be $\sim 10$ times larger than that in the forward direction \[15, 16\]. A directional detector which could measure the direction of the recoiling nuclei from the interaction is required to detect this 'head-tail' asymmetry. Given the capability of ascertaining this asymmetry, the statistical requirements to show a WIMP detection would only require $\sim 10$-100 WIMPs \[17–19\]. In a second generation of directional detection experiments, the measurement of the diurnal variation of the count rate due to the daily rotation of the Earth could provide further information. Measurements of both the annual and diurnal modulations could then provide a "smoking gun" for the existence of WIMPs. In addition, any galactic substructure in the WIMP density, such as tidal streams, could show up as spikes coming from one particular direction in a directional detector.

**Limitations of existing detectors:**

The goal is to obtain the track of the recoiling nucleus after it has been hit by a WIMP. Yet in existing detectors the track length is shorter than the resolution of the detectors. Nuclei with high atomic number $A$ also have high atomic charge $Z$; the density is high, $> 10 \text{ g/cc}$; and the energy deposition is proportional to $Z^2$. Thus the range of recoiling nuclei is super-short, often below 10 nm, while existing detectors have spatial resolution of a few microns. In both typical solid state detectors as well as liquid detectors, the range is 100 times shorter than the spatial resolution. As a consequence, in prior designs of "directional detectors", the density of the detectors must be brought low enough to increase the recoil range. For example, it is proposed to use Xe gas pumped to 0.1 Atmosphere \[20–22\]. Such a huge volume of gas must be placed underground and shielded against radioactivity.

**DNA based detector:**

In this paper we describe a smaller and less expensive alternative: detectors made of DNA may provide nanometer resolution for tracking, energy threshold below 0.5 keV, and can operate at room temperature. One implementation consists of a large number of thin foils of gold (Au) with strings of single stranded DNA (ssDNA) hanging down from them as shown in Figure 2. The required amount of material is roughly 1kg of gold and 0.1kg of ssDNA. The DNA strands all consist of identical sequences of bases (combinations of A,C,G,T), with an order that is well known. An incoming WIMP from the Halo of our Galaxy strikes one of the gold nuclei and knocks it out of the plane with $\sim 10$ keV of energy. The Au nucleus traverses a few hundred DNA strands before stopping. Whenever it hits the DNA, it severs the ssDNA strand. The cutoff segment of DNA falls down onto a capture foil and is periodically removed. The locations of the breaks are easy to identify via a plurality of techniques: the broken segments can be copied using Polymerase Chain Reaction (PCR), thus amplifying the signal a billion fold; then the collection of amplified cut-off ssDNA becomes what biologists call a "DNA ladder". It can be sequenced with single base accuracy, i.e. $\sim \text{nm}$ precision. Thus the path of the recoiling nucleus can be tracked to nanometer accuracy. More details of this particular detector design are presented below. Alternative detector designs may be implemented instead, but the important new development is the idea of using DNA in lieu of more conventional detector materials to provide thousand-fold better tracking resolution, so that directionality of the WIMPs can be determined.

There are many advantages to this new technology of using DNA:

1. Nanometer spatial resolution enables directional detection with detector mass of 1 kg
(much lower than any alternative proposal);

2. Operates at room temperature;

3. Low energy threshold of 0.5 keV, allowing for study of low mass $< 10\text{GeV}$ WIMPs;

4. Flexibility of materials: One may choose from a variety of elements with high atomic mass (e.g. Au) to maximize the spin-independent scattering rate. Given a variety of materials one can also extract information about the mass and cross section of the WIMPs;

5. One can also select materials with high spin to maximize spin-dependent interaction rate;

6. Signal may be amplified by a factor of $10^9$ by using PCR;

7. Excellent background rejection, by using $\text{dE}/\text{dx}$ in vertex and $> 10^{16}$ physical granularity of the detector, i.e. there are $10^{16}$ voxels in a $(1\text{m})^3$ detector.

The nanometer tracking described in this paper may have many uses beyond dark matter detection as will be studied in future work.

II. DARK MATTER DETECTION

WIMP direct detection experiments seek to measure the energy deposited when a WIMP interacts with a nucleus in a detector. If a WIMP of mass $m_\chi$ scatters elastically from a nucleus of mass $M$, it will deposit a recoil energy $E_{nr} = (\mu^2 v^2 / M)(1 - \cos \theta)$, where $\mu \equiv m_\chi M / (m_\chi + M)$ is the reduced mass of the WIMP-nucleus system, $v$ is the speed of the WIMP relative to the nucleus, and $\theta$ is the scattering angle in the center of mass frame. The differential recoil rate per unit detector mass, typically given in units of $\text{cpd kg}^{-1}\text{keV}^{-1}$ (where $\text{cpd}$ is counts per day), can be written as:

$$\frac{dR}{dE_{nr}} = \frac{n_\chi}{M} \langle v \frac{d\sigma}{dE} \rangle = \frac{1}{2M\mu^2} \sigma(q) \rho_\chi \eta(v_{\text{min}}(E_{nr}), t),$$

(1)

where $n_\chi = \frac{\rho_\chi}{m_\chi}$ is the number density of WIMPs, with $\rho_\chi$ the local dark matter mass density; $q = \sqrt{2ME_{nr}}$ is the momentum exchange in the scatter; $\sigma(q)$ is an effective scattering cross-section; $\eta(v_{\text{min}}, t) = \int_{v>v_{\text{min}}} d^3v f(v, t)$ is the mean inverse velocity with $f(v, t)$ the (time-dependent) WIMP velocity distribution; and $v_{\text{min}} = \sqrt{\frac{ME_{nr}}{2\mu^2}}$ is the minimum WIMP velocity that can result in a recoil energy $E_{nr}$. More detailed reviews of the dark matter scattering process and direct detection can be found in Refs. [23–27].

The typical energy transferred to the nucleus in a scattering event is from 1 to 50 keV. Typical count rates in detectors are less than 1 count per kg of detector per day. Over the past twenty five years a variety of designs have been developed to detect WIMPs. They include detectors that measure scintillation; ionization; and dilution-refrigerator based calorimeters which measure the total energy deposed by means of a phonon spectrum. Current detector masses range in size up to 100 kg (e.g. XENON-100). The plan for the next generation of detectors is to reach one tonne.
A major concern in all WIMP detectors is backgrounds. To eliminate spurious events from CR, the detectors must be placed deep underground (> 2,000 m of water equivalent). Yet radioactive backgrounds remain and must be eliminated. Thus the experimental determination of annual and/or diurnal modulation is a crucial test of the WIMP origin of any events observed in the detector, as most backgrounds should not exhibit the same time dependence.

**Particle Physics: WIMP/nucleus cross sections:**

For a supersymmetric (SUSY) neutralino and many other WIMP candidates, the dominant WIMP-quark couplings in direct detection experiments are the scalar and axial-vector couplings, which give rise to spin-independent (SI) and spin-dependent (SD) cross-sections for elastic scattering of a WIMP with a nucleus, respectively. SI scattering is typically taken to be

\[
\sigma_{\text{SI}} = \frac{\mu^2}{m_p^2} A^2 \sigma_{p,\text{SI}},
\]

where \( A \) is the atomic mass of the nucleus, \( \mu \) is the WIMP-proton reduced mass and \( \sigma_{p,\text{SI}} \) is the SI scattering cross section of WIMPs with protons. For large momentum transfer, this relation is multiplied by a form factor correction to account for the sensitivity to the spatial structure of the nucleus. Since the SI cross-section grows rapidly with nuclear mass, direct detection experiments often use heavy nuclei to increase their sensitivity to WIMP scattering.

Spin-dependent (SD) WIMP-nucleus interactions depend on the spin of the nucleus. Most nuclei have equal numbers of neutrons and protons so that there is no SD contribution; specific nuclei must be chosen in experiments to search for nonzero SD couplings. SD scattering is often of lesser significance than SI scattering in direct detection experiments for the heavy elements used in most detectors due to the extra \( A^2 \) coherence factor in the cross section.

**Astrophysics: Velocity Structure of the Galactic Halo:**

The velocity distribution \( f(v) \) of dark matter particles in the Galactic Halo is crucial to their signals in dark matter detectors (as first stressed by [4]). The dark matter halo in the local neighbourhood is likely to be composed mainly of a smooth, well mixed (virialised) component with an average density \( \rho_\chi \approx 0.4 \text{ GeV}/\text{cm}^3 \). The simplest model of this smooth component is the Standard Halo Model (SHM), a spherically symmetric nonrotating isothermal sphere with an isotropic, Maxwellian velocity distribution characterized by an rms velocity dispersion \( \sigma_v \sim 290 \text{ km/sec} \); the distribution is truncated at escape velocity \( v_{\text{esc}} \sim 600 \text{ km/sec} \). The resultant count rates in direct detection experiments due to the SHM were first discussed in [4].

In addition to the smooth component of the Galaxy, the formation of the Milky Way via merger events throughout its history leads to significant structure in both the spatial and velocity distribution of the dark matter halo. The dark matter affiliated with any of these substructures (tidal streams of material, subhalos, clumps, caustics, or debris flow) located in the Solar neighborhood will affect count rates as well as the phase and amplitude of annual modulation in experiments\(^1\).

**Annual Modulation:**

---

\(^1\) For example the Sagittarius stream [28, 29] could give an increase in the count rate in detectors up to a cutoff energy, leading to an annually modulated steplike feature in the energy recoil spectrum. The stream...
The smooth component of the halo is essentially non-rotating, while the Sun moves with the disk and rotates about the center of the galaxy at a speed $v_{\text{rot}} \sim 245 \text{ km/sec}$ [30]. The halo thus exhibits a bulk motion relative to Earth. One can think of this phenomenon as the Earth moving into a "wind" of WIMPs. The relative velocity between the WIMPs and the detector plays an important role in detection rates.

This relative velocity experiences two types of modulation: annual and diurnal. These can be very important in proving that any detected signal is in fact due to WIMPs rather than background. Three of us predicted that, due to the motion of the Earth in orbit about the Sun, the dark matter velocity distribution as seen by a detector on Earth should undergo a yearly variation, leading to an annual variation in the recoil rate in the detector [4, 6]. In many cases, the annually modulating recoil rate can be approximated by

$$\frac{dR}{dE}(E, t) \approx S_0(E) + S_m(E) \cos \omega(t - t_0),$$

with $|S_m| \ll S_0$, where $S_0$ is the time-averaged rate, $S_m$ is referred to as the modulation amplitude (which may, in fact, be negative), $\omega = 2\pi/\text{year}$ and $t_0$ is the phase of the modulation. For the Standard Halo Model, the maximum count rate is on June 1 and the minimum on December 1. The modulation is only a few percent of the average count rate. Thus, a large number of events is required to observe a modulation of the rate in a detector. We note that, for low enough energy recoils, the typical WIMP is moving in the opposite direction and the phase of the modulation reverses (the signal is maximized in December); once the crossover energy of this phase reversal is measured it can be used to determine the WIMP mass$^2$.

The reason that annual and diurnal modulation are so powerful as a "smoking gun" for dark matter is that most background signals, e.g. from radioactivity in the surroundings, are expected to be isotropic and not modulating with the same time dependence as the WIMPs.

**Current Experimental Status for Direct Detection:**

In the past decade, a host of direct detection experiments using a variety of different detector materials and designs have reported unexplained nuclear recoil signals which could be due to WIMPs. Detection of annual modulation has now been claimed by the DAMA and, more recently, CoGenT experiments. The Italian Dark Matter Experiment, or DAMA [7], consists of 250 kg of radio pure NaI scintillator situated in the Gran Sasso Tunnel underneath the Apennine Mountains near Rome, and became the first direct detection experiment to observe a positive signal. The group now has accumulated 1 ton-yr of data over the past decade and finds an 8.9 $\sigma$ annual modulation with the correct phase and spectrum to be consistent with a dark matter signal. Recently CoGeNT [8], consisting of Germanium, also claim to see annual modulation of the signal with the correct phase to be consistent with WIMPs, and together with a third CRESST-II [9] experiment, could be seeing $\sim 10$ GeV WIMPs. Yet, other experiments, notably CDMS [12, 13] and XENON [14] have null results that appear to conflict with these positive signals. Many direct detection experiments are either currently running or gearing up to do so, and we can expect more data soon.

---

$^2$ $x_p = 0.89$ is the value of $x$ at which the phase of the modulation reverses, where $x \equiv v_{\min}/v_0$ with $v_{\min} \propto \sqrt{E})$.
In the past few years the cross-sections that have been reached by detectors have improved by two orders of magnitude; over the next few years another two orders of magnitude should be reached. The next generation of detectors after the current ones will be one tonne in mass or directional. A review of the theory and experimental status of annual modulation can be found in [31].

**Diurnal Modulation:**

Our motion with respect to the Galactic rest frame also produces a diurnal modulation of the event rate. Due to the motion of the Sun around the Galactic Center we are moving into a “wind” of WIMPs. As shown in Figure 1, the daily rotation of the Earth then introduces a modulation in recoil angle as measured in the laboratory frame [15]. The WIMP count rate then is expected to modulate with the time of day. Measurement of the diurnal modulation would require directional detection capabilities discussed in this paper. An ideal detector could reject isotropy of WIMP recoils with only of order 10-100 events [17–19]. Most, but not all, backgrounds would produce an isotropic Galactic recoil distribution. An anisotropic Galactic recoil distribution would therefore provide strong, but not conclusive, evidence for a Galactic origin of the recoils. Roughly 30 events would be required for an ideal (no background) detector to confirm that the peak recoil direction coincides with the inverse of the direction of Solar motion, hence confirming the Galactic origin of the recoil events [32, 33]. Realistically about 100 events consistent with diurnal modulation will be required for WIMP detection (far less than without this modulation).

Measurement of the diurnal modulation would determine the direction of the WIMP wind, which could then be compared with an annual modulation signal found in a different experiment. If the annual modulation of the signal is dominated by the smooth halo, then the wind direction (obtained from the directional experiments) should predict the time of year when the event rate in direct detection experiments peaks; i.e. the time of year when the Earth moves the most quickly into the wind would be the time of peak signal. If, on the other hand, the phase of the modulation does not match up with the wind direction found by the directional detectors, then one would suspect that the WIMP interpretation of the experiments might be wrong³.

**III. DIRECTIONAL DETECTORS**

Ref. [21] reviews the status of one type of prototype directional detection experiments. Current designs require the detector material to be gaseous in order to produce long enough tracks compared to the spatial resolution of the detector and will thus require volumes $\sim \text{km}^3$.

In the paper we instead propose the use of DNA as a detector material that can provide nanometer resolution tracking. Figure 2 illustrates an example of a novel detector design, consisting of a thin (5-10 nanometer thick) plane of gold (Au) with strings of single stranded DNA (ssDNA) hanging down from it. The DNA strands are all identical in length, with an order of bases that is well known. The basic idea is the following: An incoming WIMP

---

³ Alternatively this discrepancy might be an indication of additional halo components such as streams, which could change the phase of the annual modulation. In principle comparison between the wind direction and the phase of the modulation could teach us about the structure of the dark matter in our halo.
from the Halo of our Galaxy strikes one of the gold nuclei and knocks it out of the plane with $\sim 10 \text{ keV}$ of energy. The Au nucleus moves forward into the strands of DNA, traverses thousands of these strands, and whenever it hits one, breaks the ssDNA. A segment of DNA falls down onto a “capture foil” below. Periodically (e.g. once an hour) the fallen segments are scooped up. The locations of the breaks can be identified: the strands can be copied using Polymerase Chain Reaction (PCR), thus amplifying the signal a billion fold; then DNA sequencing provides the location of the broken DNA. Since the DNA base units are at most $\sim 0.7 \text{ nm}$ apart (when fully stretched), the resulting detector resolution in the z-direction is nanometer. Thus the track of the recoiling nucleus may be obtained with nanometer accuracy.

”DNA Tracking Chamber”:

The detector is modular and consists of a series of identical units stacked on top of each other. It is like a book and the WIMP travels sequentially through the pages. Each module consists of the following layers. On the top is a $1 \mu\text{m}$ layer of mylar (which is inactive from the point of view of incoming WIMPs). Next is a 5-10 nanometer thick layer of gold, corresponding to roughly 10 atoms of Au in thickness. It is with these Au nuclei that the WIMPs will interact, giving the Au nuclei a kick of $\sim 10 \text{ keV}$ out of the plane. Hanging from the gold plane is an ordered periodic array of ssDNA strands, which can be thought of as a curtain of DNA through which the recoiling Au nuclei will travel. Whenever an Au nucleus strikes one of the ssDNA strands, it breaks the ssDNA. More accurate studies of this breaking will be required, e.g. by calibrating the response of the ssDNA to heavy ions of a given energy (such as 5, 10, 30 keV Ga ions that may be obtained from an ion implementation machine). The required amount of energy to break the strand $^4$ is estimated to be 10eV, but more accurate values must be obtained experimentally. Thus we estimate that it will take hundreds to thousands of direct hits of Au on ssDNA, corresponding to a comparable number of breaks of ssDNA strands, to stop a gold nucleus. Currently off the shelf technology consists of arrays containing ssDNA strands that are 250 bases in length (manufactured by Illumina Inc.). The average length of single-stranded DNA is up to about 0.7 nm per base when fully stretched. Thus this corresponds to $\sim 100–200 \text{ nm}$ length DNA strands. In 2nd generation detectors, ideally one would like to have ssDNA strands that are 10,000 bases in length, as this setup would then be optically thick to Au nuclei; i.e. all the Au nuclei would be stopped in the DNA Tracking Chamber and one could obtain the maximum information in reconstructing the particle’s track. More realistically we envision ssDNA strands consisting of $\sim 1000$ bases, or equivalently $\sim 0.3–0.7 \mu\text{m}$ in length.

The goal is to have the ssDNA strands completely periodically ordered, with $\sim 10 \text{ nm}$ distances between them. The DNA can be immobilized at one end by a variety of means. For example, a Au-sulfur bond with DNA terminally labeled with a thiol group[33]. Alternatively, Au coated with Streptavidin (a biotin-binding protein), will hold DNA labeled with biotin. Even simple positively-charged dots can be effective[34]. The challenge is to get single molecules attached to the gold plane on a well defined two-dimensional grid, ”polka dot”, pattern. Grid dots 5 nm in diameter can be microfabricated with a spacing of 10 nm in the x- and y-directions, but to guarantee close to a single DNA molecule per

$^4$ Whereas a recoiling Au nucleus will easily break ssDNA, it would only nick dsDNA. Thus in the current implementation we propose using ssDNA. However in future designs it may be useful to use a combination of the two.
dot requires a trick like steric hindrance (aka "Polony exclusion principle")[34] or designed 3D DNA-nanostructures[33]. These two methods can also help simplify manufacturing by dividing the plane into a 10nm grid from a 100 nm grid (the latter made by conventional photolithography or interference methods). If very non-repetitive DNA curtains of known positioning and sequence are sought, then these can be constructed from synthetic DNA selectively amplified from oligonucleotide DNA chips [35] and/or certain natural genomes.

The ssDNA Tracker will operate with helium or nitrogen gas in between the hanging ssDNA strands. Oxygen in air would react and water would absorb too much energy. The ssDNA strands are kept straight (rather than curling up) by either using an electric field or weighting the strands, e.g. with weights attached at fixed intervals along the strands.

Individual strands differ only in the "terminus pattern" of say 20-100 bases at the bottom that identify the individual strands (more accurately members of a small bunch of DNA strands). One may think of the Au plane as a grid of squares that are 1µm × 1µm in size. We will call the ssDNA hanging down from one grid square a "bundle" of DNA. All the ssDNA strands have the same base sequence ordering, except the last 20-100 at the bottom are different for each grid area — the same for all the ssDNA within one bundle. Thus one can localize the hit of the recoiling Au nucleus on the ssDNA to 1µm × 1µm in x-y. One can think of this as attaching balls of different colors to the bottoms of bunches of DNA strands that cover a square region that is 1µ by 1µ; thus the x-y resolution of the track will be micron-sized.

Once a ssDNA strand is severed, the segment falls to a collecting plate at the bottom. A magnetizable rod that is 3-4 nm in diameter and 50 nm long is attached to the bottom of the strand, provides the weight to pull it down, and is used to "scoop" the cut ssDNA. Roughly once an hour the ssDNA segments are scooped up. At that point they are amplified a billion fold using PCR, and then they are sequenced. The location where the DNA was severed is identified, with nm resolution in z and micron resolution in x and y. In this way the track of the recoiling Au nucleus from the WIMP interaction can be reconstructed.

**First Generation Implementation:**

The initial goal will be to identify a head/tail asymmetry of the WIMPs. As described above, the number of WIMPs coming from the direction of Cygnus should be ten times that from the opposite direction, since we are moving into the Galactic wind of WIMPs. Merely identifying this head/tail asymmetry may be enough to argue (together with annual modulation) that WIMPs have been discovered. The design described above automatically provides this distinction. WIMPs that come in the direction of first passing through the mylar, then into the Au plane, and then into the ssDNA strands will be detected. However, WIMPS that go the other way will not: these first go unnoticed through the DNA, then interact in the gold, producing recoiling gold nuclei that simply stop in the mylar. This is a simple implementation of head/tail differentiation. Then the entire detector may be flipped 180 degrees, so that it is sensitive to only WIMPs coming from the other direction. Once this simplest version works, the goal of the next generation detectors will be to look for the actual track of the recoiling nucleus with nanometer resolution, using longer ssDNA strands in a periodic array.

**Background rejection in the proposed Au/ssDNA detector:**

There are many sources of background that could mimic a WIMP signal. The improved granularity of our detector — nanoscale vs. micron length scale — should help with background rejection. In previous detector development, the background rejection has scaled
with the volume of the granularly, so one might hope that the background rejection improves a billion fold in these new detectors; but this must be verified.

Naturally occuring DNA itself contains radioactive $^{14}C$ and $^{41}K$. The DNA in the detector must be made of old carbon, and potassium can be replaced by other moieties. Studies must be performed of the radioactivity of thin films of Au or other elements. Backgrounds that could be confused with WIMPs include $\gamma$, $\alpha$, electrons, and cosmic rays (CR). Yet the ranges of these particles in our detector will be at least 100 times as long as the range of a recoiling nucleus from a WIMP, so that the differentiation between them should easily be possible. The energy deposition in the detector scales as $Z^2$, where $Z$ is the electric charge of the particle. For example, for a recoiling Au ion($Z=80$), the energy deposition is 6400 times as large as for an electron ($Z=1$). Whereas recoiling Au nuclei will be stopped in a single module of Au foil + ssDNA, the background particles will travel much farther as they traverse and interact with many of the sequential modules. We have described our detector design as a book with many pages. The recoiling nuclei from WIMP interactions will never make it past the first page, whereas the $\gamma$, $\alpha$, electrons, and cosmic rays (CR) will go through multiple pages. Cosmic Rays will have enough energy to traverse hundreds, say 500 foils, and will be rejected due to the extraordinary granularity of our detector. Thus the signature of a WIMP is that there is an interaction in ”one and only one” gold plane. As discussed, the background signals are expected to be isotropic whereas the WIMPs are expected to exhibit head/tail as well as temporal asymmetries.

Even more accurate determinations can be made by measuring the values of $dE/dx$ of the various particles traveling through the detector, as this will allow differentiating between them. Such a measurement requires the spatial resolution to be shorter than the range of the particle. Previous to the use of DNA, the spatial resolution of detectors wasn’t good enough to make this determination, so that the best that could be done was the measurement of the integrated value of $dE/dx$ over the spatial resolution of the detector. The DNA tracking chamber provides for the first time the capability of obtaining this quantity.

As in all WIMP direct detection experiments, once these backgrounds are removed, the chief remaining troublesome particles that can mimic a WIMP signal are fast neutrons. Further studies, both experimental tests and Monte Carlos, will be required to deal with these neutrons. The capability of tracking particles as they move through the ssDNA should assist with this distinction.

IV. SUMMARY

A major step forward in the field of direct detection would be the development of detectors with directional capability. By contrasting the count rates in a detector in the direction toward and away from the Galactic WIMP ”wind” that the Sun is moving into, the statistical requirements on the number of detected WIMPs drops to $\sim 100$ rather than thousands without the directional sensitivity. In the paper we proposed using DNA as a detector material that can provide nanometer resolution tracking. We presented a particular design consisting of modules of thin gold planes with single stranded DNA hanging down from each plane. The required amount of material is $\sim 1$kg of gold and 0.1kg of ssDNA. The DNA strands all consist of (almost) identical sequences of bases (combinations of A,C,G,T), with an order that is well known. An incoming WIMP from the Halo of our Galaxy strikes one of the gold nuclei and knocks it out of the plane with $\sim 10$ keV of energy. The Au nucleus moves forward into the strands of DNA, traverses thousands of these strands, and whenever
it hits one, breaks the ssDNA. The locations of the breaks are easy to identify, using PCR to amplify the broken segments a billion fold followed by DNA sequencing to locate the break. In this way the path of the recoiling nucleus can be tracked to nanometer accuracy.

We note that this design is not restricted to the use of Au nuclei, which can be interchanged with many different nuclei with high atomic number (so as to maximize the SI interaction rate). By using a variety of different materials, it should be possible to identify the mass and cross-section of the interacting WIMP. In addition, although the specific detector design may be modified, the important new development is the idea of using DNA in lieu of other detector materials to provide better tracking resolution so that directionality of the WIMPs can be determined. More generally, it is easy to imagine multiple applications for nanometer tracking beyond that of WIMP detection.

Acknowledgments

K.F. acknowledges the support of the DOE and the Michigan Center for Theoretical Physics via the University of Michigan. K.F. thanks the Caltech Physics Dept for hospitality during her visit. We are grateful to Dave Gerdes, Rachel Goldman, Sharon Glotzer, Caglayan Kurdak, Chris Meiners, Joanna Millinchuk, Neelima Sehgal, and Greg Tarle for useful conversations.

[1] E. Komatsu et al. [WMAP Collaboration], Astrophys. J. Suppl. 192, 18 (2011) [arXiv:1001.4538 [astro-ph.CO]].
[2] A. Drukier and L. Stodolsky, Phys. Rev. D 30, 2295 (1984).
[3] M. W. Goodman and E. Witten, Phys. Rev. D 31, 3059 (1985).
[4] A. K. Drukier, K. Freese, D. N. Spergel, Phys. Rev. D33, 3495-3508 (1986)
[5] S. P. Ahlen, F. T. Avignone, R. L. Brodzinski, A. K. Drukier, G. Gelmini and D. N. Spergel, Phys. Lett. B 195, 603 (1987).
[6] K. Freese, J. A. Frieman and A. Gould, Phys. Rev. D 37, 3388 (1988).
[7] R. Bernabei, P. Belli, F. Cappella et al., Eur. Phys. J. C67, 39-49 (2010). [arXiv:1002.1028 [astro-ph.GA]].
[8] C. E. Aalseth, P. S. Barbeau, J. Colaresi, J. I. Collar, J. Diaz Leon, J. E. Fast, N. Fields, T. W. Hosebach et al., Phys. Rev. Lett. 107, 141301 (2011). [arXiv:1106.0650 [astro-ph.CO]].
[9] G. Angloher, M. Bauer, I. Bavykina, A. Bento, C. Bucci, C. Ciemniak, G. Deuter, F. von Feilitzsch et al., [arXiv:1109.0702 [astro-ph.CO]].
[10] C. Kelso, D. Hooper and M. R. Buckley, Phys. Rev. D 85, 043515 (2012) [arXiv:1110.5338 [astro-ph.CO]].
[11] P. J. Fox, J. Kopp, M. Lisanti and N. Weiner, Phys. Rev. D 85, 036008 (2012) [arXiv:1107.0717 [hep-ph]].
[12] Z. Ahmed et al. [CDMS Collaboration], arXiv:1203.1309 [astro-ph.CO].
[13] Z. Ahmed et al. [CDMS-II Collaboration], Phys. Rev. Lett. 106, 131302 (2011) [arXiv:1011.2482 [astro-ph.CO]].
[14] J. Angle et al. [XENON10 Collaboration], Phys. Rev. Lett. 107, 051301 (2011) [arXiv:1104.3088 [astro-ph.CO]].
[15] D. N. Spergel, Phys. Rev. D 37, 1353 (1998).
[16] P. Gondolo, *Phys. Rev. D* **66**, 103513 (2002), *astro-ph/0209110*.
[17] C. J. Copi and L. M. Krauss, *Phys. Rev. D* **63**, 043508 (2001), *astro-ph/0009467*.
[18] C. J. Copi, J. Heo and L. M. Krauss, *Phys. Lett. B* **461**, 43 (1999), *astro-ph/990449*.
[19] B. Morgan, A. M. Green and N. J. C. Spooner, *Phys. Rev. D* **71**, 103507 (2005), *astro-ph/0408047*.
[20] G. J. Alner *et al.*, Nucl. Instrum. Meth. A **555**, 173 (2005).
[21] S. Ahlen *et al.*, *Int. J. Mod. Phys. A.* **25**, 1 (2010), *arXiv:0911.0323*.
[22] J. B. R. Battat, S. Ahlen, T. Caldwell, C. Deaconu, D. Dujmic, W. Fedus, P. Fisher and F. Golub *et al.*, PoS IDM **2010**, 042 (2011) [arXiv:1012.3912 [astro-ph.IM]].
[23] J. R. Primack, D. Seckel and B. Sadoulet, Ann. Rev. Nucl. Part. Sci. **38**, 751 (1988).
[24] P. F. Smith and J. D. Lewin, Phys. Rept. **187**, 203 (1990).
[25] J. D. Lewin and P. F. Smith, Astropart. Phys. **6**, 87 (1996).
[26] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267**, 195 (1996) [arXiv:hep-ph/9506380].
[27] G. Bertone, D. Hooper and J. Silk, Phys. Rept. **405**, 279 (2005) [arXiv:hep-ph/0404175].
[28] K. Freese, P. Gondolo, H. J. Newberg and M. Lewis, Phys. Rev. Lett. **92**, 111301 (2004) [arXiv:astro-ph/0310334].
[29] K. Freese, P. Gondolo and H. J. Newberg, Phys. Rev. D **71**, 043516 (2005) [arXiv:astro-ph/0309279].
[30] J. Bovy, D.W. Hogg and H.-W. Rix, ApJ, 704, 1704.
[31] K. Freese, M. Lisanti, and C.M. Savage, Review of Annual Modulation”, to be published in Reviews of Modern Physics
[32] J. Billard, F. Mayet, J. F. Macias-Perez and D. Santos, *Phys. Lett. B* **691**, 156 (2010), *arXiv:0911.04086*.
[33] A. M. Green and B. Morgan, *Phys. Rev. D* **81**, 061301(R) (2010), *arXiv:1002.2717*.
[34] S.M. Douglas, I. Bachelet, and G.M. Church Science 335, 831-834. (2012)
[35] R. Drmanac R, et al. Science 327, 78-81 (2009).
[36] S. Kosuri, N. Eroshenko, E. LeProust, M. Super, J. Way, J.B. Li, G.M. Church Nature Biotech. 28, 1295-9 (2010)
FIG. 1: Diurnal modulation of WIMPs: the Sun orbits around the Galactic Center (in a direction that happens to be towards the constellation Cygnus), therefore experiencing a WIMP wind, for which the orientation relative to the laboratory frame depends on the rotation of the earth, and hence time of day.

FIG. 2: ssDNA/Au Tracking Chamber: A WIMP from the Galaxy scatters elastically with a gold nucleus situated in a thin gold foil. The recoiling Au nucleus traverses hanging strings of single stranded DNA, and severs any ssDNA it hits. The location of the breaks can be found by amplifying and sequencing the fallen ssDNA segment, thereby allowing reconstruction of the track of the recoiling Au nucleus with nanometer accuracy.