DARK MATTER DETECTORS USING DNA

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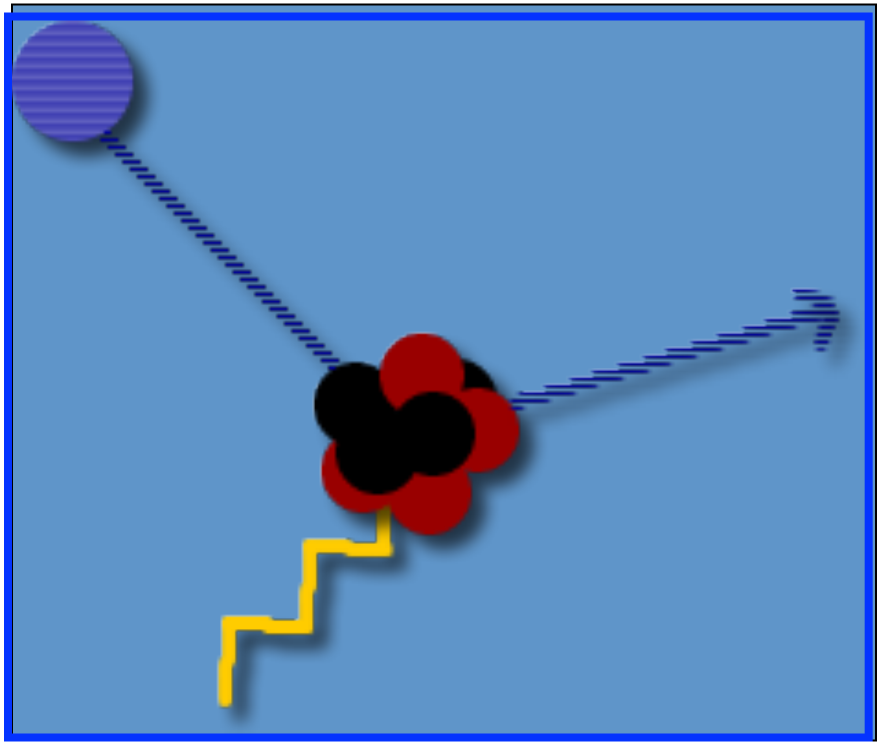
Direct Detection of WIMP dark matter

A WIMP in the Galaxy
travels through our
detectors. It hits a
nucleus, and deposits
a tiny amount of energy.
The nucleus recoils,
and we detect
this energy deposit.



Expected Rate: less than one count/kg/day

Event rate

(number of events)/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

$$= \frac{\rho\sigma_0 F^2(q)}{2m\mu^2} \int_{v>\sqrt{ME/2\mu^2}} \frac{f(v,t)}{v} d^3v$$

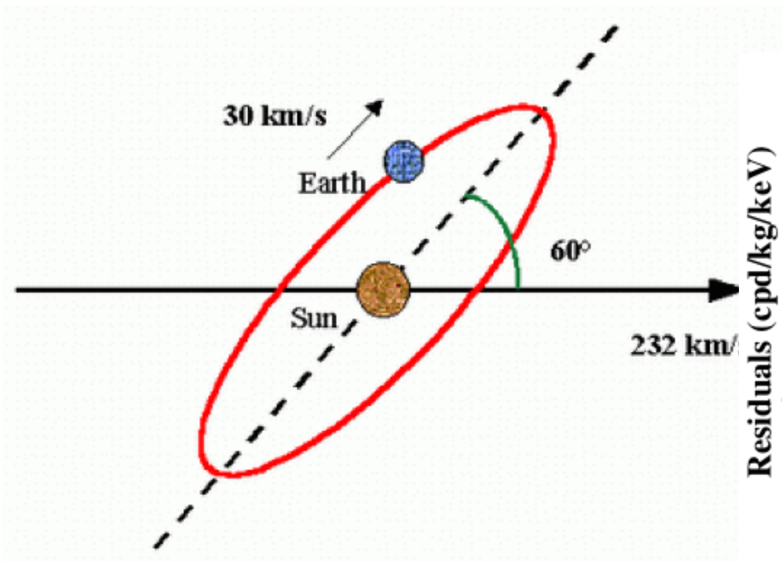
Spin-independent $\sigma_0 = \frac{A^2\mu^2}{\mu_p^2}\sigma_p$

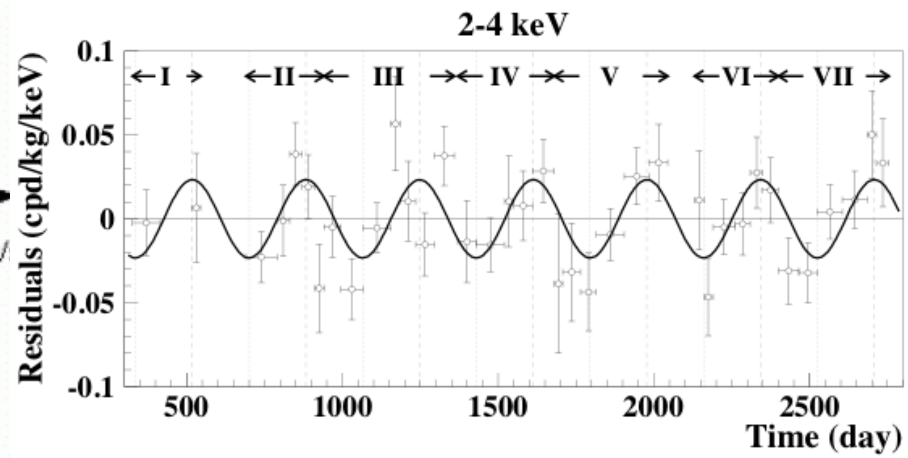
Spin-dependent $\sigma_0 = \frac{4\mu^2}{\pi} \left| \langle S_p \rangle G_p + \langle S_n \rangle G_n \right|^2$

DAMA annual modulation

Drukier, Freese, and Spergel (PRD 1986);
Freese, Frieman, and Gould (PRD 1988)

Bernabei et al 2003





250 kg of NaI crystals in Gran Sasso Tunnel under the Apennine Mountains in Italy.
Data do show a 9σ modulation
WIMP interpretation is controversial

Review of annual modulation:
Freese, Lisanti, Savage (2013 Rev Mod Phys)

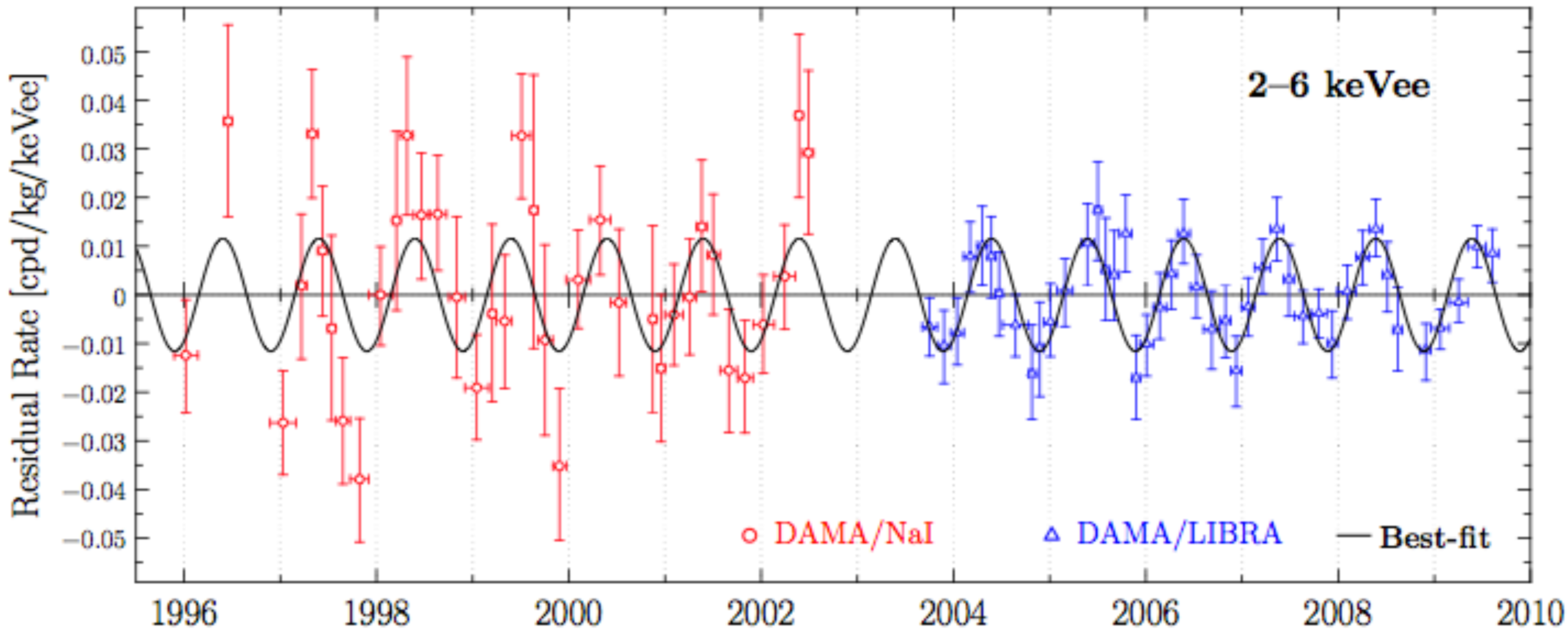
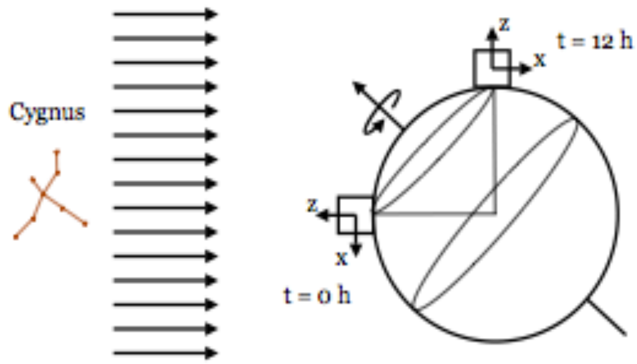


FIG. 5: The residual rate measured by DAMA/NaI (red circles, 0.29 ton-yr exposure over 1995–2002) and DAMA/LIBRA (blue triangles, 0.87 ton-yr exposure over 2003–2010) in the 2–6 keVee energy interval, as a function of time. Data is taken from Refs. [27, 29]. The solid black line is the best fit sinusoidal modulation $A\cos[\frac{2\pi}{T}(t-t_0)]$ with an amplitude $A = 0.0116 \pm 0.0013$ cpd/kg/keV, a phase $t_0 = 0.400 \pm 0.019$ yr (May 26 $\pm$ 7 days), and a period $T = 0.999 \pm 0.002$ yr [29]. The data are consistent with the SHM expected phase of June 1.

A major Step Forward: Directional Capability

- Nuclei typically get kicked forward by WIMP collision
- Goal: identify the track of the recoiling nucleus i.e. the direction the WIMP came from
- First, head/tail asymmetry: WIMP flux is peaked in direction of motion of Sun (towards constellation Cygnus). Recoil spectrum should be peaked in opposite direction with 10 times the event rate. Compare count rates 180 degrees apart. Only need 100 WIMPs to get statistical significance.

Diurnal Modulation
(due to Earth's rotation)



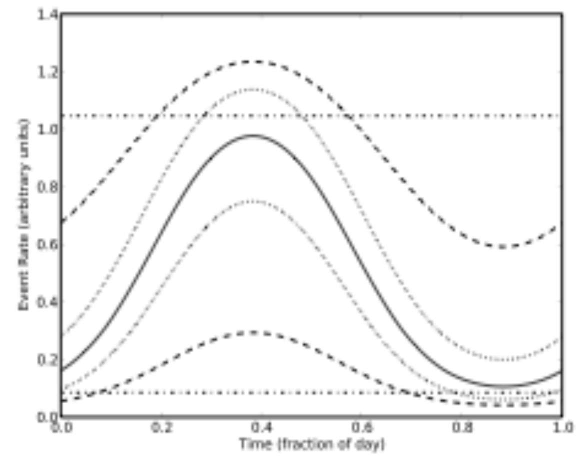


Fig. 2. (left) The daily rotation of the Earth introduces a modulation in recoil angle, as measured in the laboratory frame. (right) Magnitude of this daily modulation for seven lab-fixed directions, specified as angles with respect to the Earth's equatorial plane. The solid line corresponds to zero degrees, and the dotted, dashed, and dash-dot lines correspond to $\pm18°$, $\pm54°$ and $\pm90°$, with negative angles falling above the zero degree line and positive angles below. The $\pm90°$ directions are co-aligned with the Earth's rotation axis and therefore exhibit no daily modulation. This calculation assumes a WIMP mass of 100 GeV and CS_2 target gas. (from Ref. [13]).

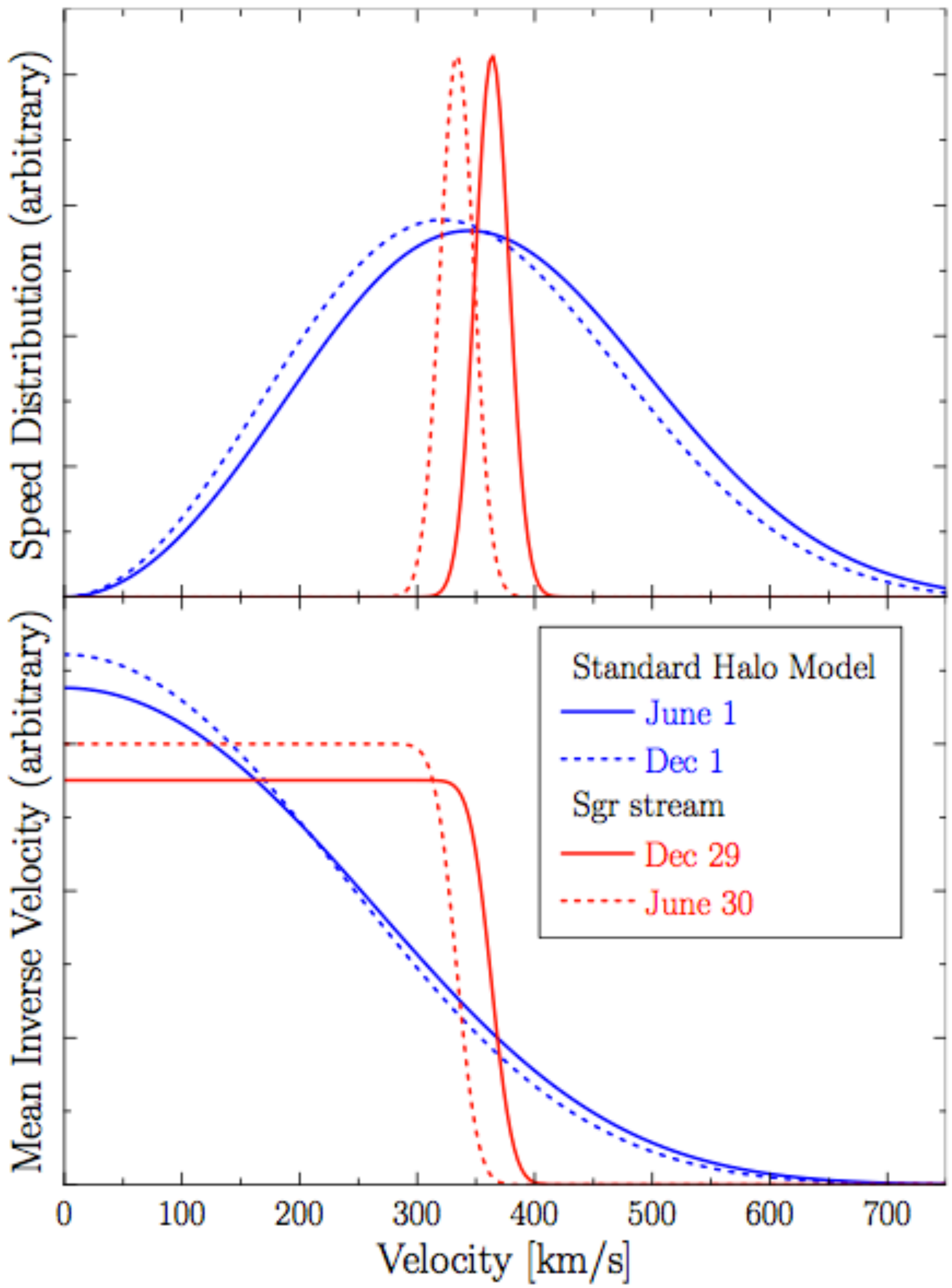
Powerful tools for DM searches

- Measure of annual plus diurnal modulation would be smoking gun for WIMPs
- Plus, any galactic substructure such as streams would show up as spikes in a directional detector

Streams of WIMPs

- For example, leading tidal stream of Sagittarius dwarf galaxy may pass through Solar System
  Majewski et al 2003, Newberg et al 2003
- Dark matter density in stream $\sim 0.01^{+0.20}_{-0.01}\ \rho_{local}$
  Freese, Gondolo, Newberg 2003
- New annual modulation of rate *and* endpoint energy; difficult to mimic with lab effects
  Freese, Gondolo, Newberg, Lewis 2003

See also Purcell, Zentner, and Wang 2012



Freese
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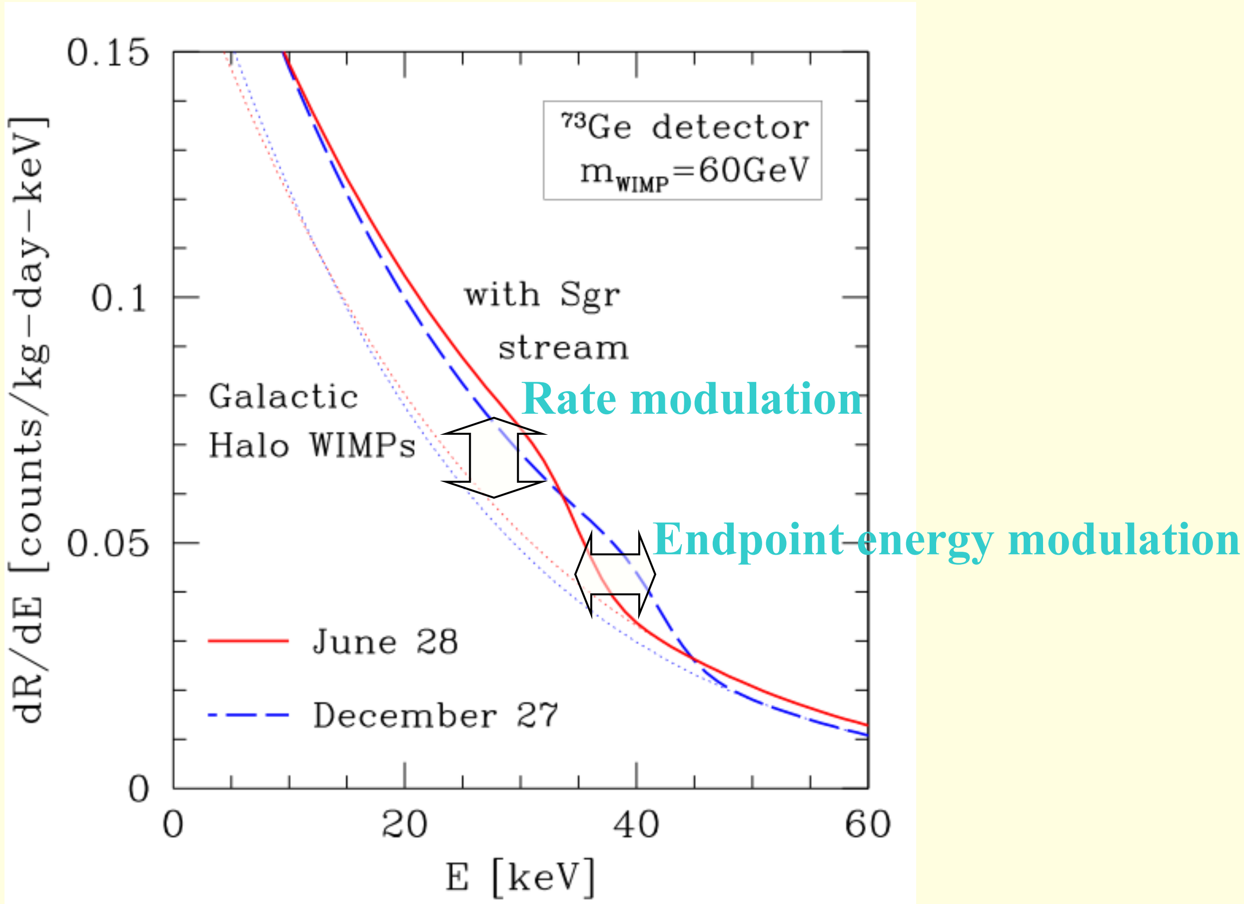
Annual Modulation of Dark Matter: A Review

(for Reviews of Modern Physics)

Sagittarius stream

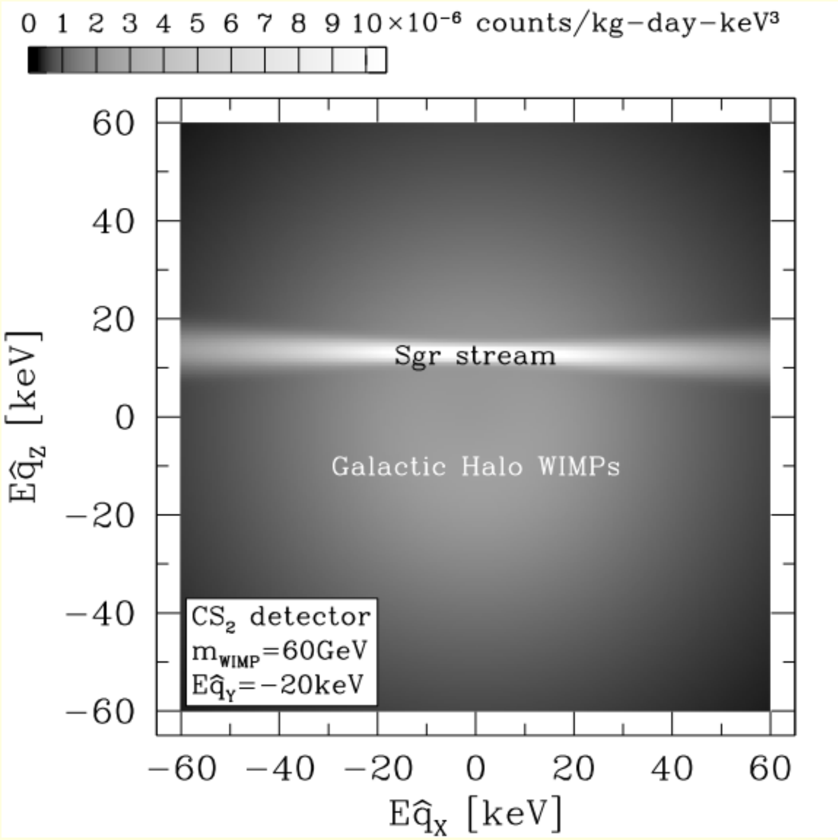


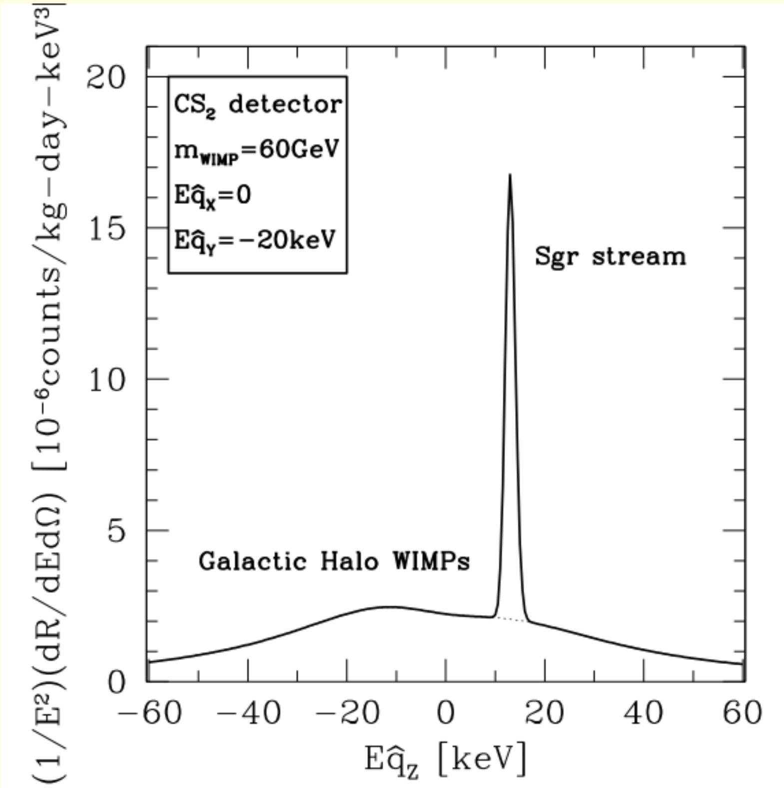
Plot for 20% Sgr stream density (to make effect visible); $\sigma_{\chi p}$=2.7x10^{-42}cm^2

Sagittarius stream

Freese, Gondolo, Newberg 2003

Directional detection

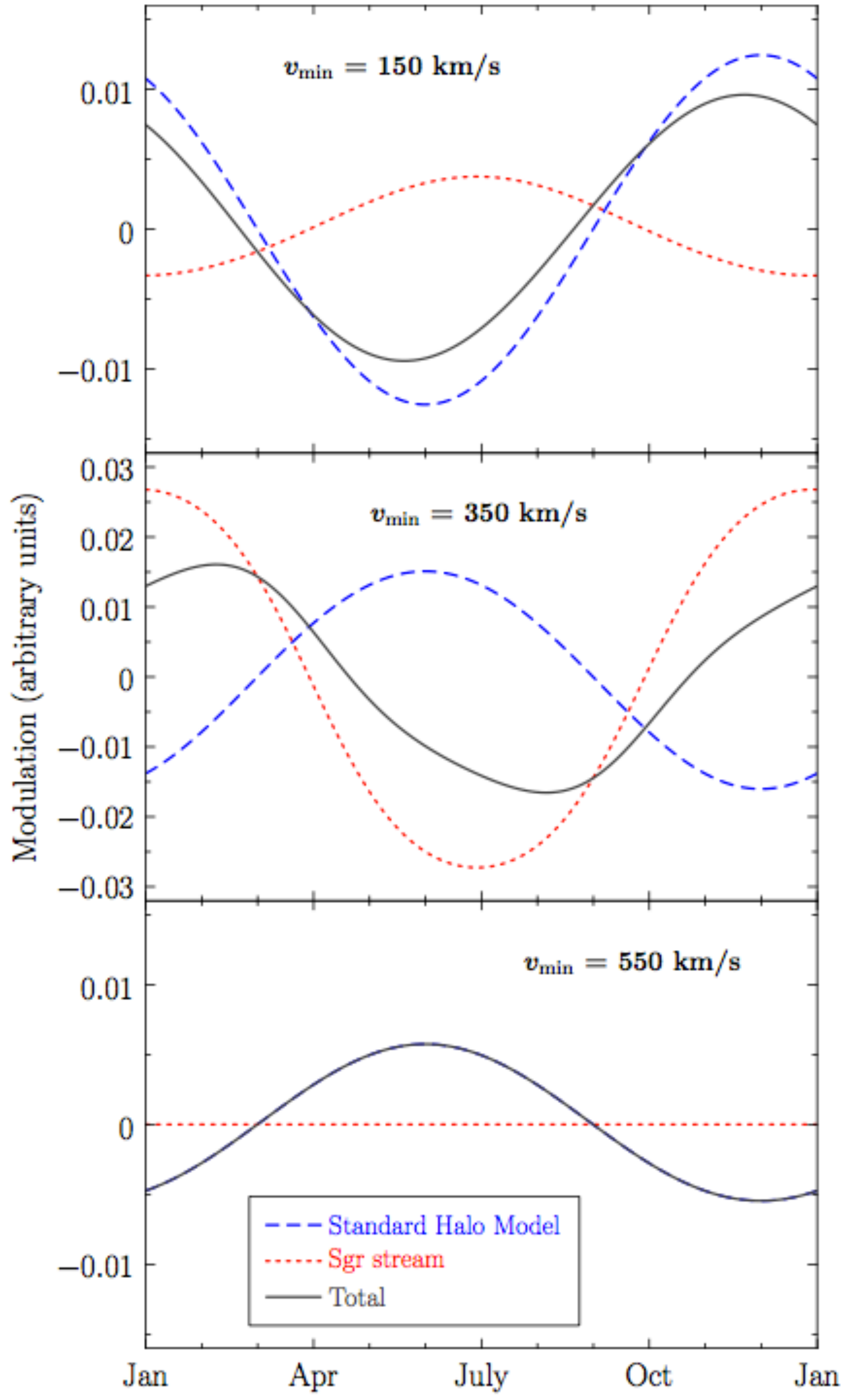




For 60 GeV WIMP and Ge target, 7 keV recoil energy

40 keV recoil energy

100 keV recoil energy



STREAM PLUS HALO

Shifts peak date of modulation.

Also, note phase reversal at different energy recoils: Can be used to determine WIMP mass (Freese and Lewis)

Chris Savage

Sagittarius stream

- Increases countrate in detectors up to cutoff in energy spectrum
- Cutoff location moves in time
- Sticks out like a sore thumb in directional detectors
- Changes date of peak in annual modulation
- Tool for WIMP detection
- Learn about halo

Limitations of Existing Detectors

- Track length of the recoiling nucleus (below 10 nm) is shorter than spatial resolution of the detector (microns).
- Approach: get detector to lower density to allow for longer recoil tracks, e.g. use CF4 gas pumped to 0.1 Atmosphere.. Required volume 10^4 m^3, one ton, $150 million.
- Existing prototypes: DRIFT 30gm(1m^3), DMTPC 3gm. Need to be scaled up.

Smaller, Cheaper Alternative: ssDNA Tracker

- Andrzej Drukier, Katherine Freese, David Spergel, Charles Cantor, George Church, Takeshi Sano

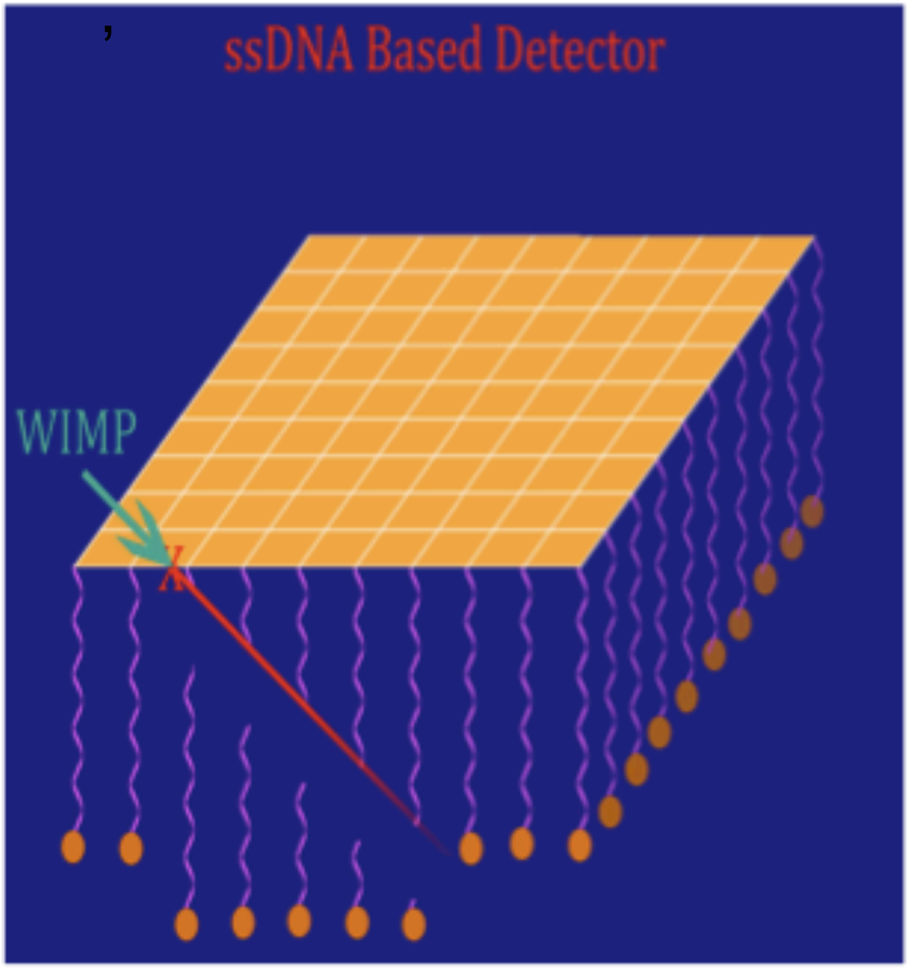
- MCUBED interdisciplinary funding at University of Michigan: Dave Gerdes, Rachel Goldman

Use DNA as nanometer tracker

- WIMP hits nucleus (transducer)
- Recoiling nucleus travels through ssDNA with known sequence of base pairs (0.7 nm apart)
- Breaks ssDNA
- Location of break can be amplified and sequenced
- Track of nucleus known to nanometer accuracy

One implementation:

- 1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known



BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

- Recoiling nucleus from WIMP interaction carries about 10 keV of energy.
- It takes about 10 eV to break ssDNA (will need experimental test).
- Cutoff segment of DNA falls down to a capture foil and is periodically removed.
- Errors in DNA are easy to replicate:
- Make copies of broken segment with PCR (amplify the signal a billion fold)
- DNA ladder: sequence with single base accuracy, i.e. nm precision

Advantages of DNA Detectors

- 1) Directional Detection with detector mass of 1 kg (vs DMTPC km^3):
- Spatial resolution of nm, track precision 10 degrees
- Low Energy threshold of 0.5 keV
- Any hi A material can be used
- Room Temperature
- Good signal to noise: background rejection and amplify signal by 10^9

Modular Detector

- Identical units stacked on top of each other (like a book): 5000 such units.
- On top: 1 micron layer of mylar (inactive)
- Next: 5-10 nm layer of gold (10 atoms thick); WIMP interacts with Au nuclei.
- ssDNA strands: 0.7nm per base when stretched, operate in helium or nitrogen gas
- Strands differ only in “terminus pattern” of say 20-100 bases at the bottom (actually members of a small bunch of DNA strands), like balls of different colors attached on the bottom.

Resolution of Detector

- In z direction, nm (distance between bases in DNA strand)
- In x-y direction, micron times micron (size of bunch of DNA strands with same base sequences).
- Location where DNA was severed is identified with nm resolution in z and micron resolution in x and y.
- Track of recoiling Au nucleus determined.

Head/Tail Asymmetry: use to discover dark matter with only about 100 events.

- Expect WIMPs from direction of Cygnus to be 10 times that from opposite direction, since we are moving into Galactic wind of WIMPs.
- WIMPs coming first through mylar then through Au and ssDNA can be detected. Those going the other way will not (interaction with Au will produce nuclei that get stuck in mylar).

Next Generation

- Actually track the path of the recoiling particle
- Nanometer resolution in z-direction
- Micron resolution in x,y directions: polka dot pattern on Au produces periodic array of ssDNA

Backgrounds

- DNA is radioactive (i.e. you are too). Must eliminate C14 and K40. Also need clean thin films of Au or other elements.
- Must put detector underground (like all dark matter detectors)
- Gammas, alphas, e, cosmic rays: their range is 100 times longer (energy deposition scales as Z^2); they will traverse hundreds of foils (not just one)

More on backgrounds

- Backgrounds are isotropic, whereas signal comes from a preferred direction. Thus tracking capability is important.
- Biggest problem: fast neutrons. Do Monte Carlos. Put in Homestake mine, use water from LUX detector as shield.

Experimental issues

- How to keep ssDNA strands straight? Electric or magnetic field (Church)
- How to get severed strands to fall down: use electric or magnetic field?
- How to scoop the severed ssDNA (e.g. once per hour): use magnetizable rod?

Goal: periodic array with 10 nm spacing

- Want single molecules attached to the Au plane on a well defined 2D “polka dot” pattern.
- DNA can be immobilized at one end, e.g. a Au-sulfur bond with DNA terminally labeled with a thiol group. OR Au coated with Streptavidin will hold DNA coated with biotin. OR simple positively charged dots.

Required Tests

- Test response of ssDNA to heavy ion hits e.g. 5,10,30 GeV Ga ions from an ion implementation machine. Best guess: it takes 10 eV to break a strand. Since nucleus carries about 10 keV energy from the WIMP, it takes 100s to 1000s of hits of Au on ssDNA to stop the Au.
- Currently off the shelf: arrays with 250 bases in length (Illumina Inc), 200 nm DNA strands
- Wanted: thousands of bases long, ie. micron length

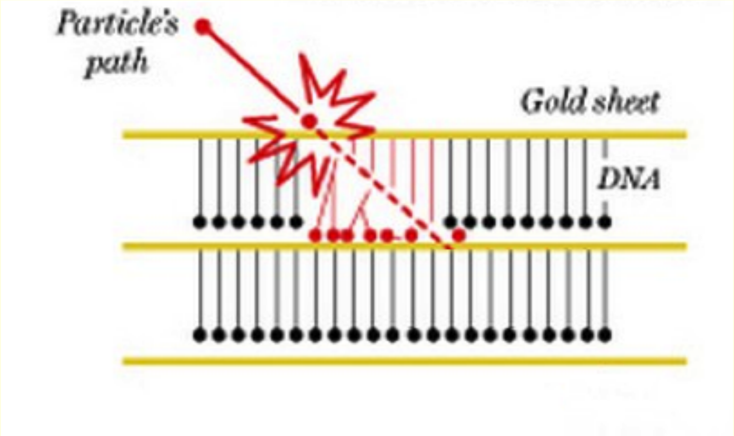
Experiments
Measuring the Ion-DNA Cross Section

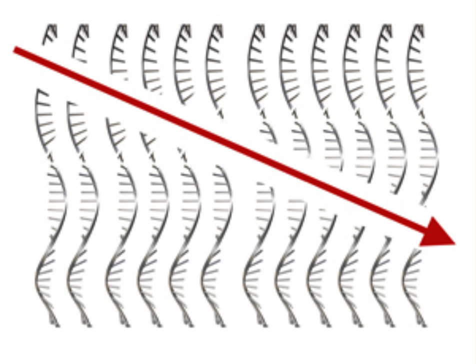
Students making the measurements:
Mykola Murskyj
Jordan Rowley
Theory aspects: Hai Bo Yu
Alejandro Lopez

Tests use Ion Implementation Machine at Michigan (costs 50 dollars an hour).
So far tested Argon and Gold ions

TO DO: Compare with SRIM Monte Carlo: “Stopping and Range of Ions in Matter”, input ions 10 eV – 2 GeV

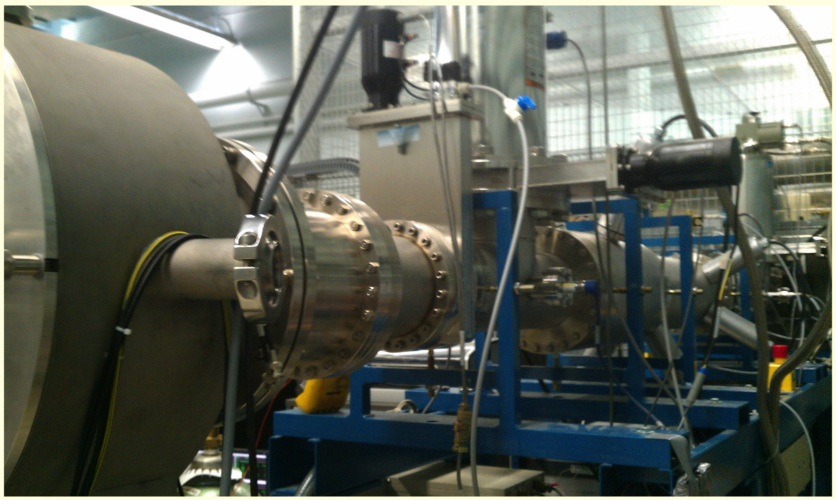
- Need to be measured
  - Ejection efficiency for ions
  - Angular recoil spectrum
  - DNA fragment collection efficiency
  - Cross section for breaking single strand of DNA
- What is the probability that a gold ion will cut ssDNA?

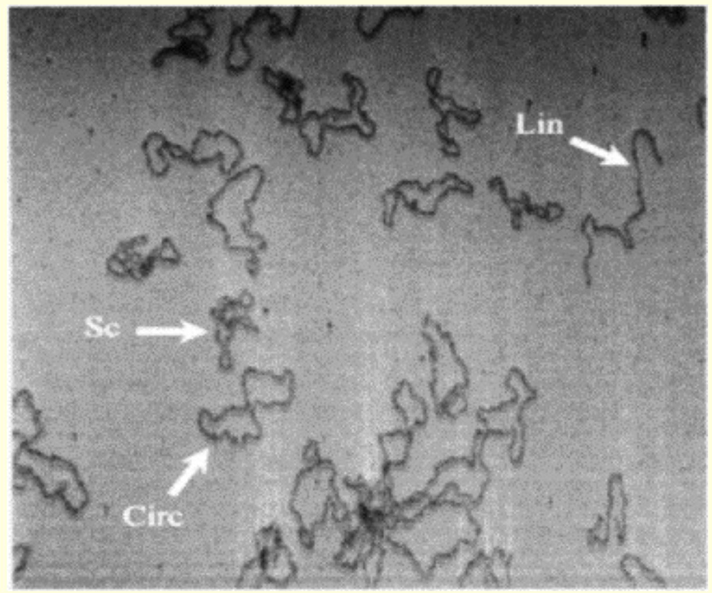




Setup

- Circular DNA (called *plasmid*) is irradiated with low energy ions at various fluxes.

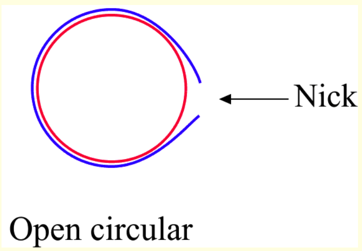




- The plasmid is naturally very tangled, or *supercoiled*.
- One strand nicked: structure untangles, becomes *circular*.
- Both strands cut in same place: structure becomes *linear*.

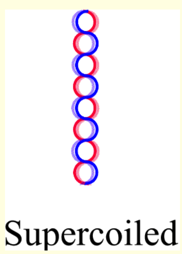
Results

Finding the SSB Fraction

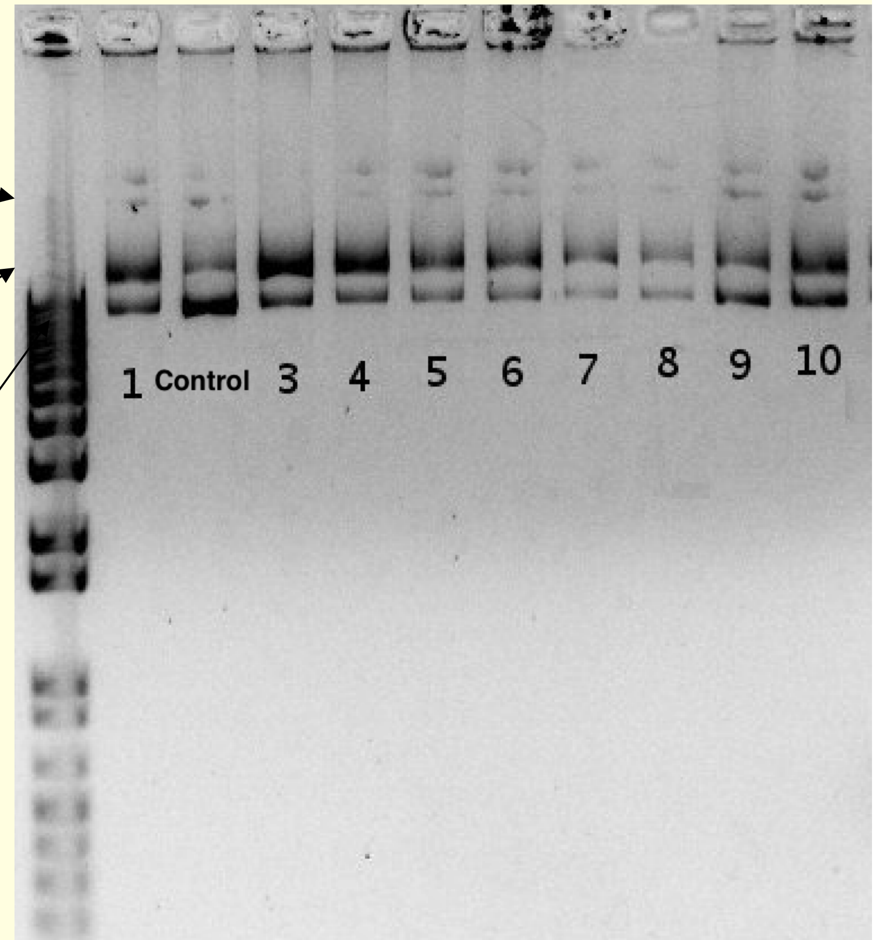


Circular DNA (SSB)

Linear DNA (DSB)



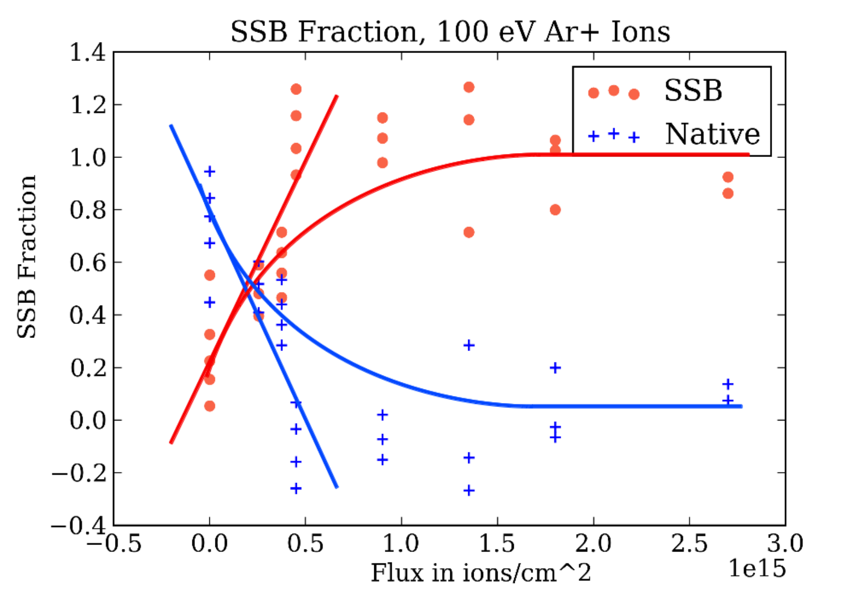
Native conformation



The fraction of the plasmid that's *circularized* tells us the probability of producing breaking a single strand of DNA.

Results

Cross section per unit length DNA:
~ 10^(-11) m
which is 1% of the width of a single strand of DNA.



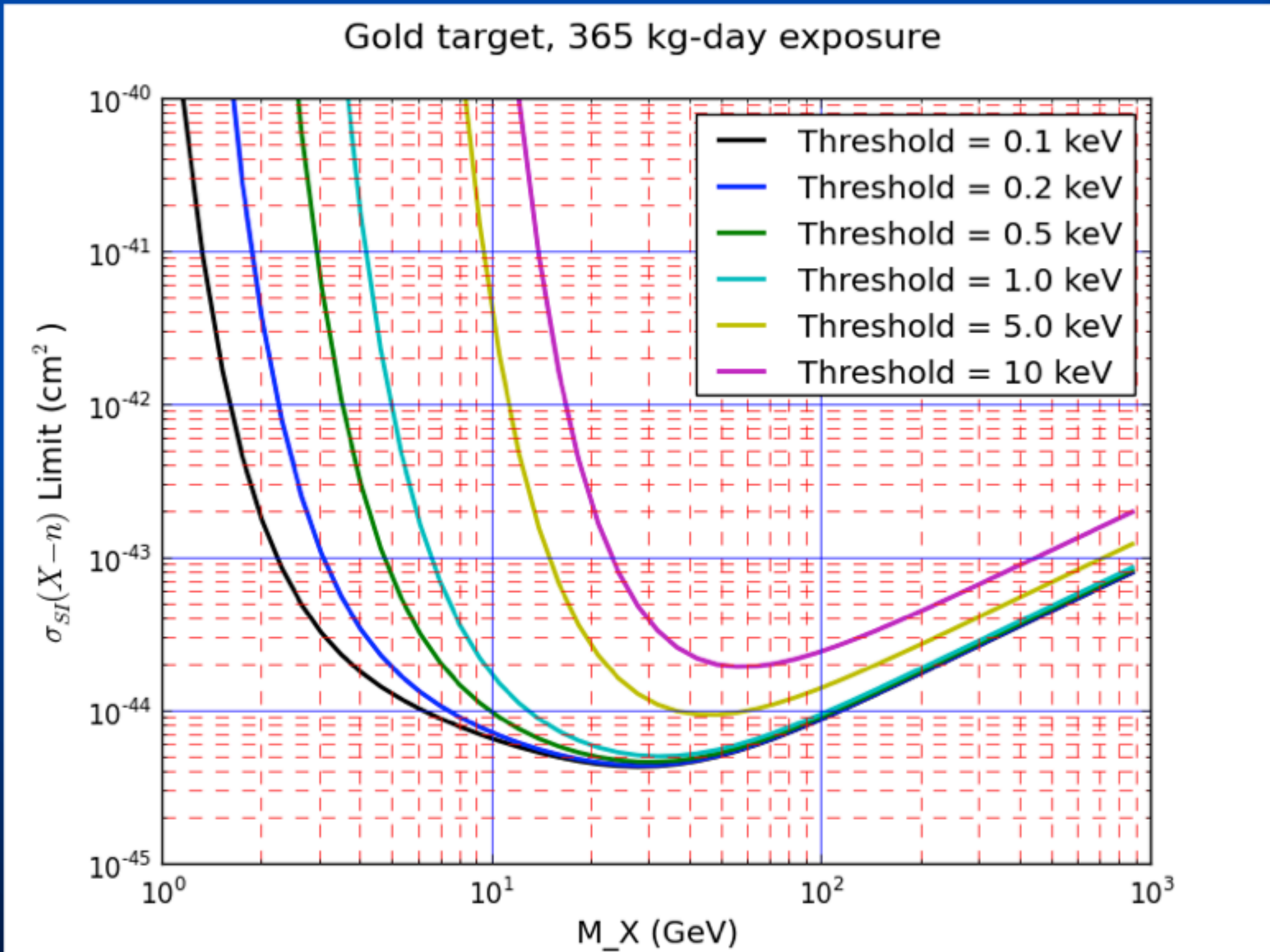
Thus, if DNA of length 1 micron (1500 bases) is spaced ~10 nm apart, a typical recoiling argon nucleus will cut *O*(5) strands.

Same flux in gold cut everything, must redo.

Why is 1 kilogram enough?

- We can go to low threshold to look for 10 GeV WIMPs, where 1 kg is enough (XENON and CDMS have poor sensitivity there)
- Also, gold is very heavy and rates scale as atomic mass squared for SI interactions
- 1m^2 plates of gold, 5000 of them, micron length of mylar plus a micron length of DNA, totals to 0.01 meter^3 in volume

  n.b. 100 kilograms would be 1m^3 to 100 GeV WIMPs



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Spin-independent cross sections scale as atomic mass squared

- Au: 197
- Xe: 130
- I: 127
- Ge: 73
- Na: 23

Summary: ssDNA Tracker

- By identifying the track of the recoiling nucleus from a WIMP interaction, obtain directional sensitivity i.e. identify where the WIMP came from.
- This allows dark matter discovery with much lower statistics (100 events).
- This allows for background rejection using annual and diurnal modulation.