New Ideas: DNA and Nano-Explosions

Alejandro Lopez
University of Michigan

What is Dark Matter?
Stockholm, 2014

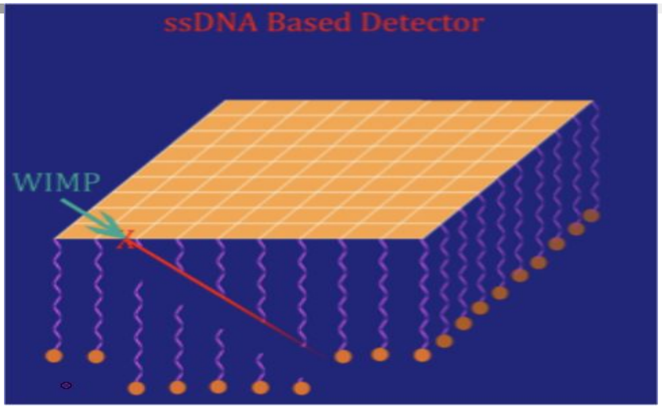
Outline

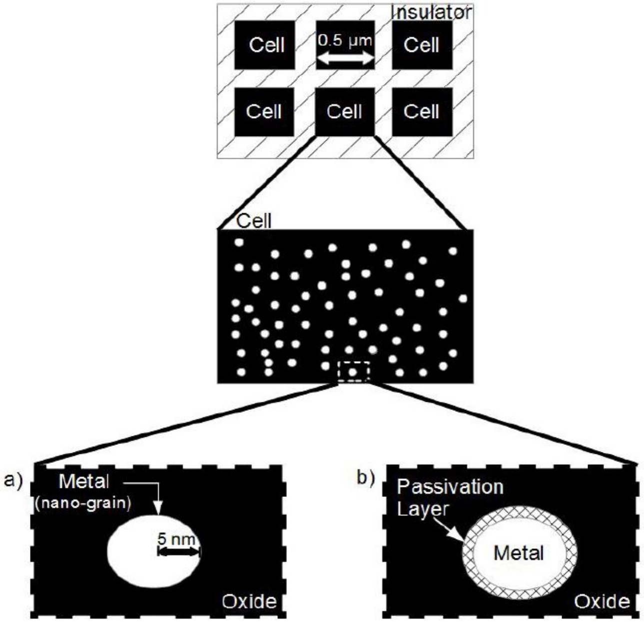
- DM Detector with nanometer resolution using ssDNA

  [arXiv:1206.6809]

- DM Detector using Nanoexplosives

  [arXiv:1403.8115]

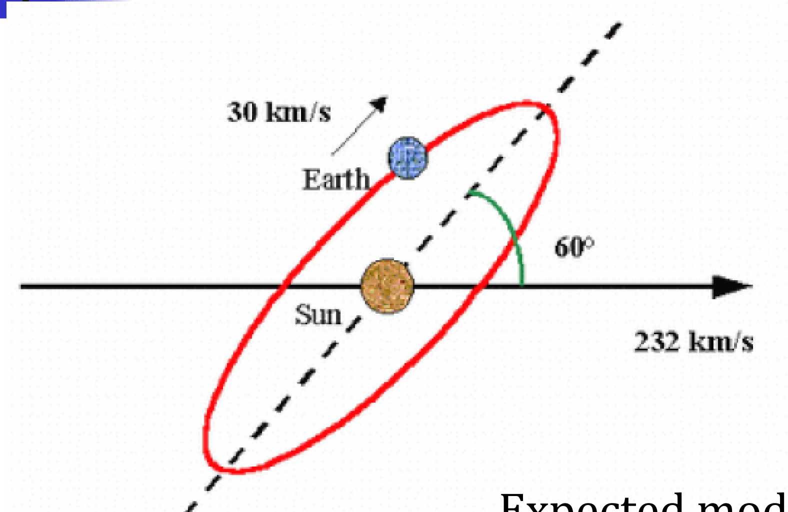




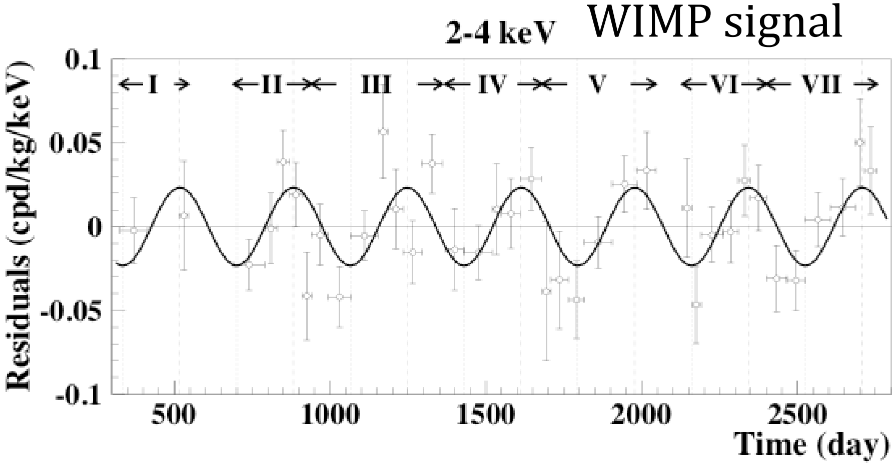
DNA Dark Matter Detector

Collaboration: A. Drukier, K. Freese, D. Spergel, C. Cantor, G. Church and T. Sano

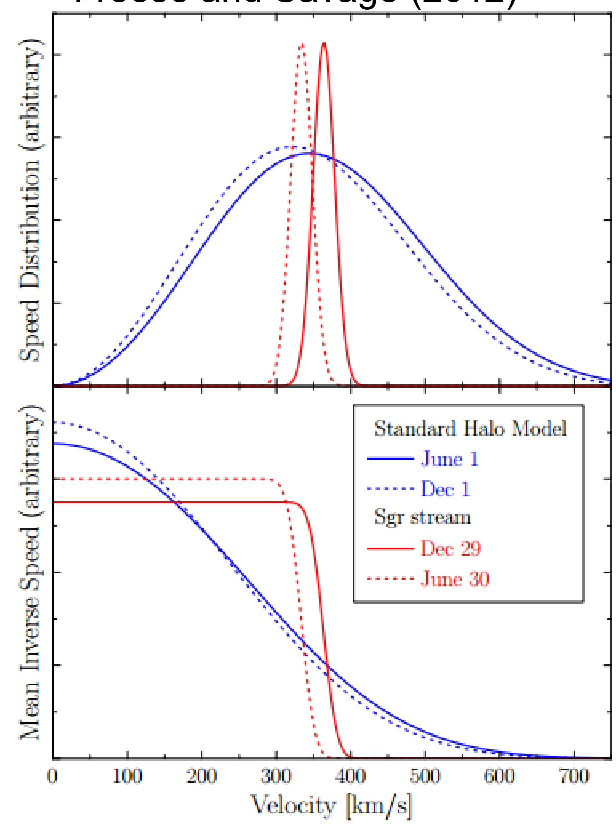
Dark Matter: Annual Modulation



Expected modulation in WIMP signal

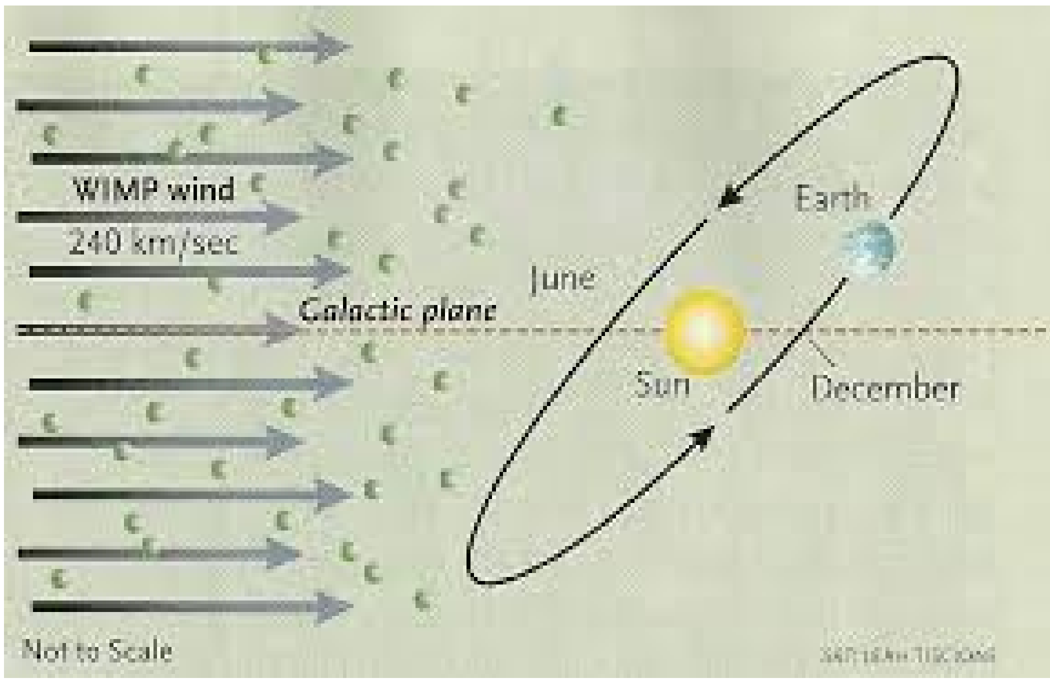


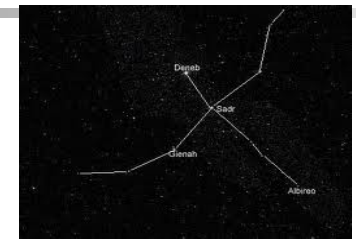
Freese and Savage (2012)

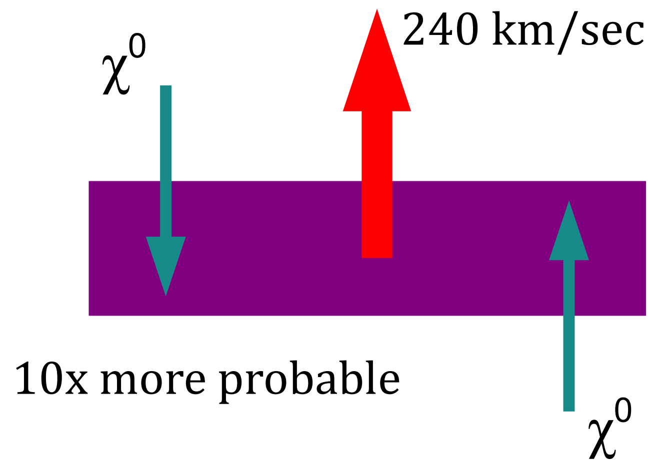


Drukier, Freese and Spergel (1986), Bernabei et al. (2003)

Dark Matter Detector: Directional Capability







Detector with head/tail asymmetry needs ~100 events for statistical significance.
[C. J. Copi, J. Heo and L. M. Krauss (1999)]

Dark Matter Detector: Limitation of Existing Detectors

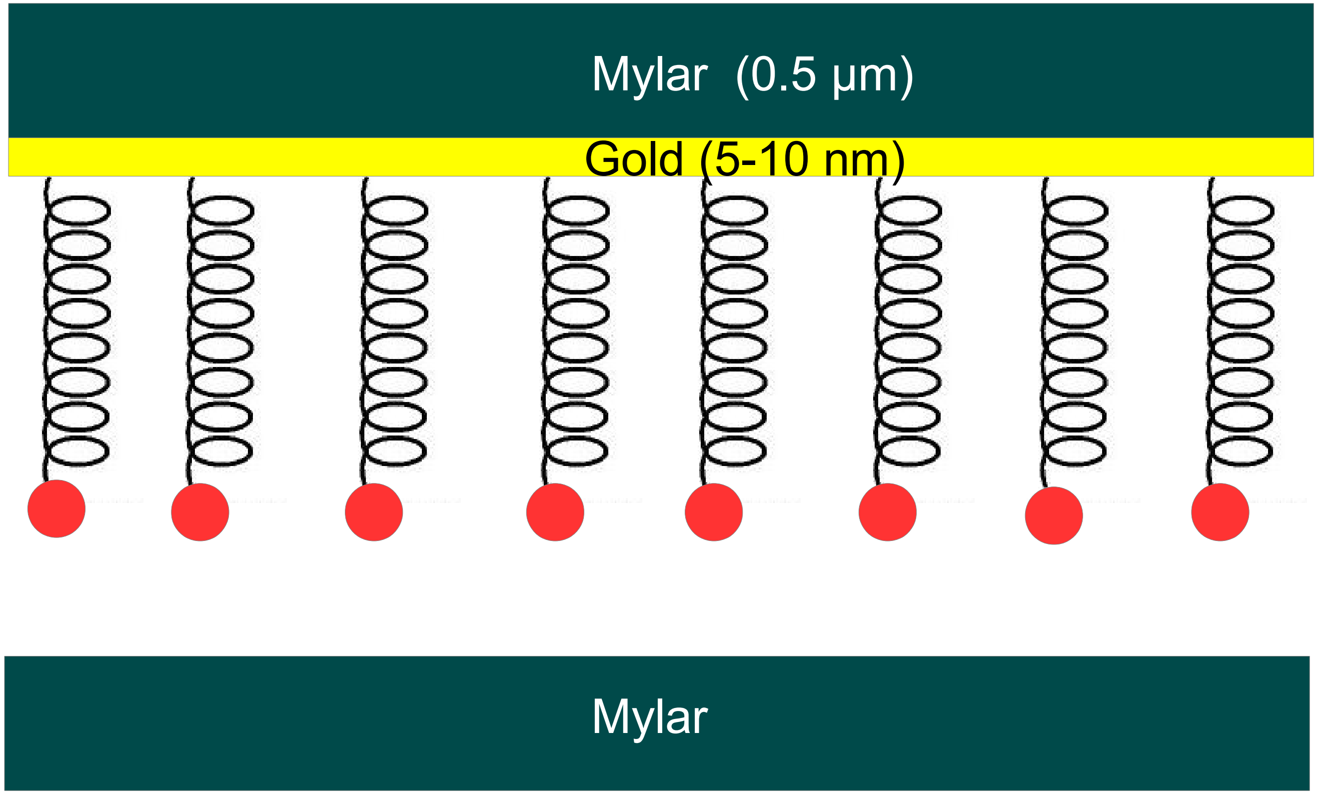
1)Track length of the recoiling nucleus (below 10 nm) is **shorter than spatial resolution** of the detector (microns).

2)Approach: **get detector to lower density**

Ex:CF_4 gas at 0.1 Atmosphere. Required volume 10^4 m^3, one tonne, \$150 million.

DNA DM Detector: Design

100 kg Gold, 1 kg ssDNA, sequence of bases with an order that is well known

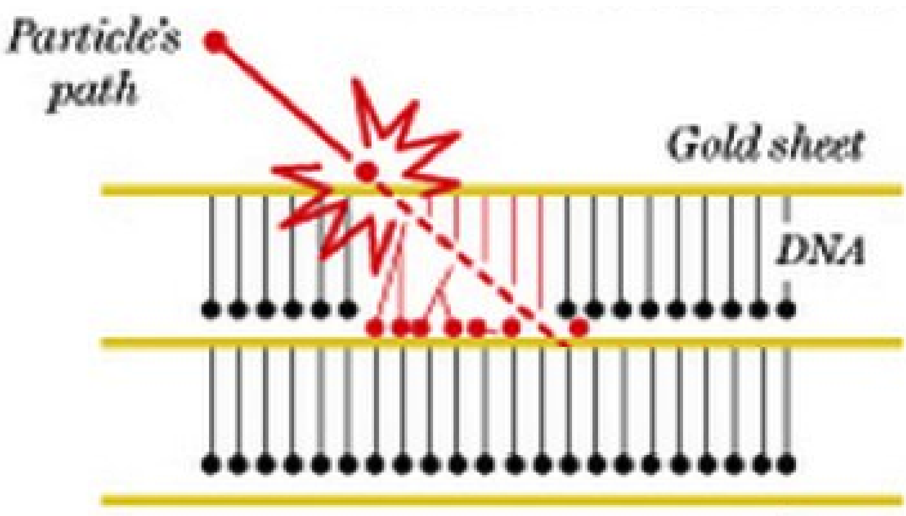


DNA DM Detector: Design

- Identical units stacked: 5000 such units.
- On top: 0.5 micron layer of mylar (inactive)
- Next: 5-10 nm layer of gold; WIMP interacts with Au nuclei.
- ssDNA strands: 0.7nm per base when stretched
- Strands differ only in “terminus pattern” of say 20-100 bases at the bottom.

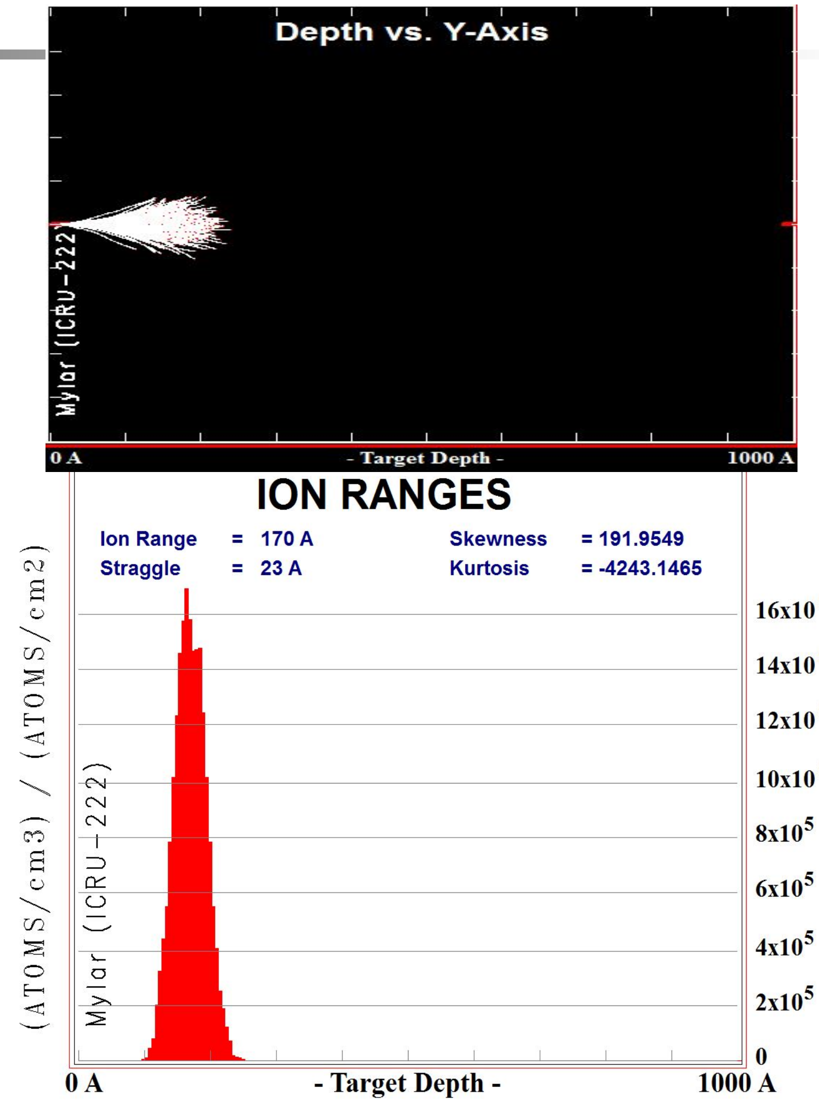
DNA DM Detector: Design

- Recoiling nucleus: **Enr ~10 keV** & **hundreds** of ssDNA breaks.
- **Cutoff segment of DNA falls &** periodically removed.
- Copies with **PCR (amplify the signal a billion fold)**
- DNA ladder: sequence with **single base accuracy**,(nm precision)



DNA DM Detector: Advantages

- Directional capability (nm resolution)
- High A (Au=197)
- Operates at Room Temperature
- Mylar gives detector head/tail asymmetry (100 events).
- Background Rejection due to directionality capability.



Au[10 keV]/Mylar

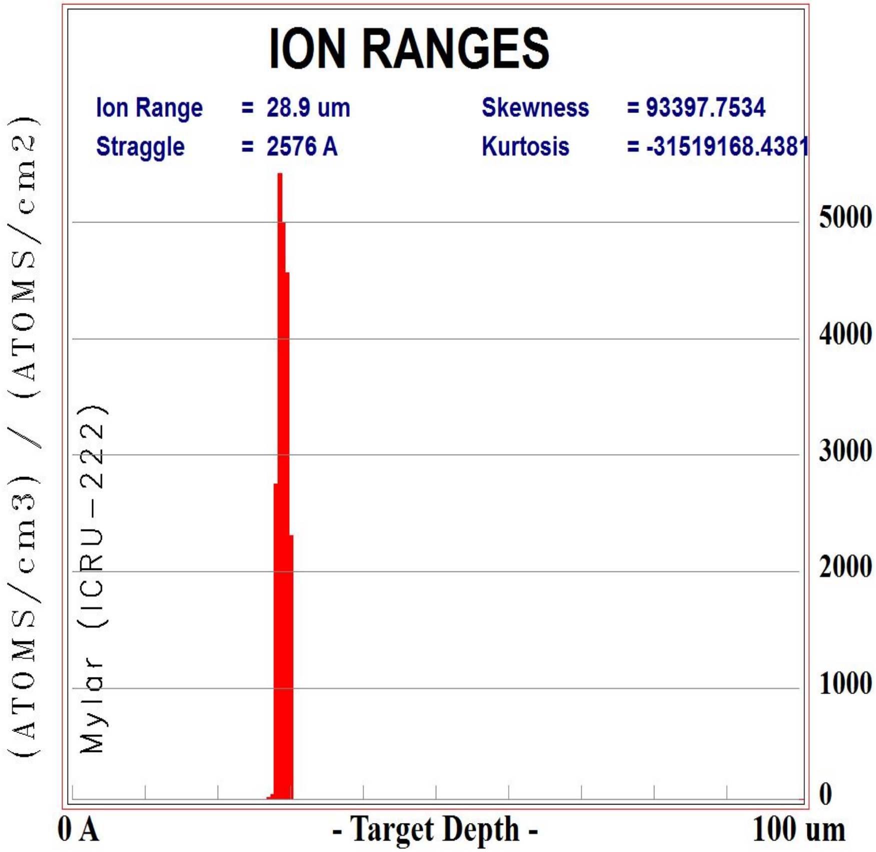
DNA DM Detector: Background

- DNA is radioactive: C^{14} and K^{40}.
- Must put detector underground (like all dark matter detectors)
- Biggest problem: fast neutrons. Do Monte Carlos. Put in Homestake mine, use water from LUX detector as shield.

DNA DM Detector: Background

- Backgrounds are isotropic.
- γ, α, e^{-}, CR: traverse ~50 foils (not just one)

α [5 MeV] moving through Mylar



DNA DM Detector: 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?
- Determine Interaction of ssDNA with heavy Ion (Cross-Section?, singular cut?)
- Off-Shelf DNA strands are about 250 bases (l~200nm), want thousand bases (l~μm)

DNA DM Detector: Summary

- Use of DNA gives directional capability with nano-meter resolution.
- Head/Tail Asymmetry allows for detection with ~100 events
- Excellent background rejection through multi-foil veto

Dark Matter Detector using Nanoexplosives

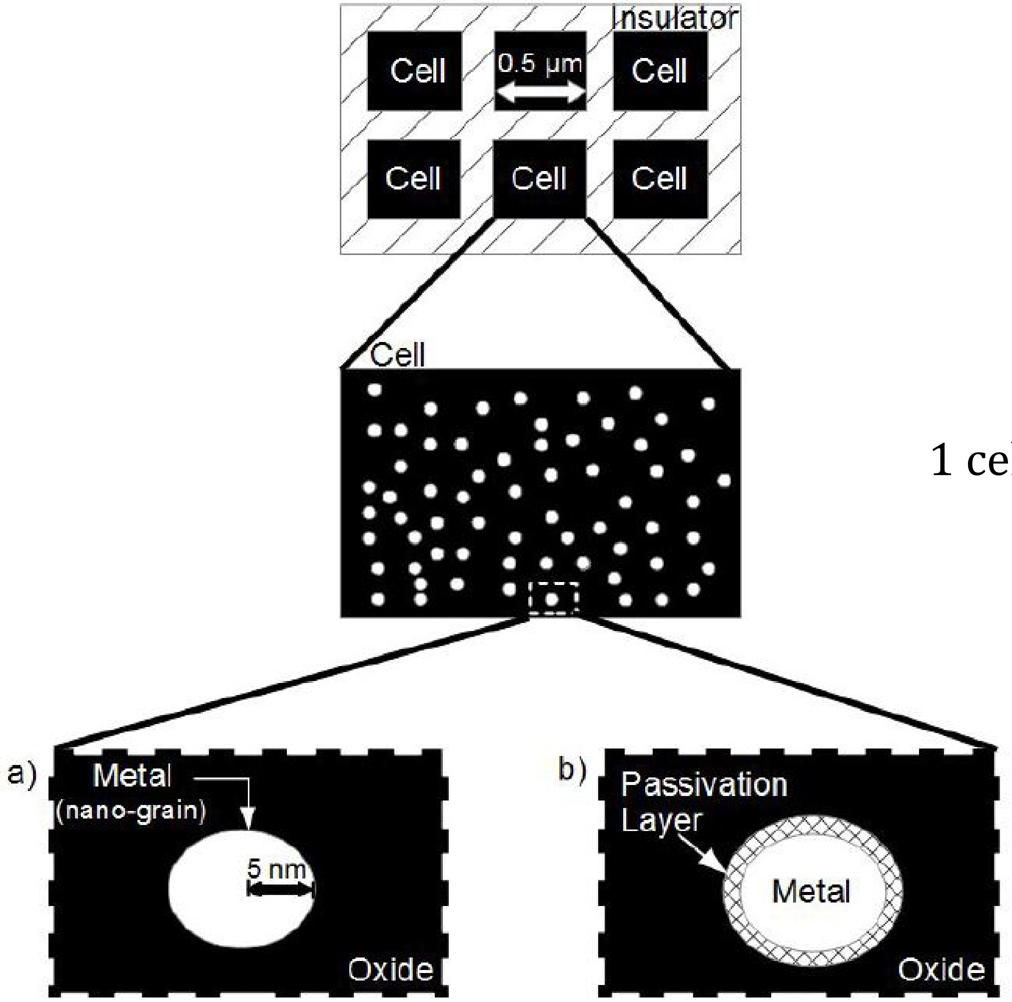
Collaboration: A. Drukier, K. Freese, C. Kurdak and G. Tarle

Nano-Thermite Detector: Thermites

- Thermite reaction is a chemical **exothermic** reaction between a metal fuel and a metal oxide.
- Metal fuel: Al, Zn, Mg and Si.
- Metal Oxide: Fe_2O_3, CuO and B_2O_3
- Common Ex:

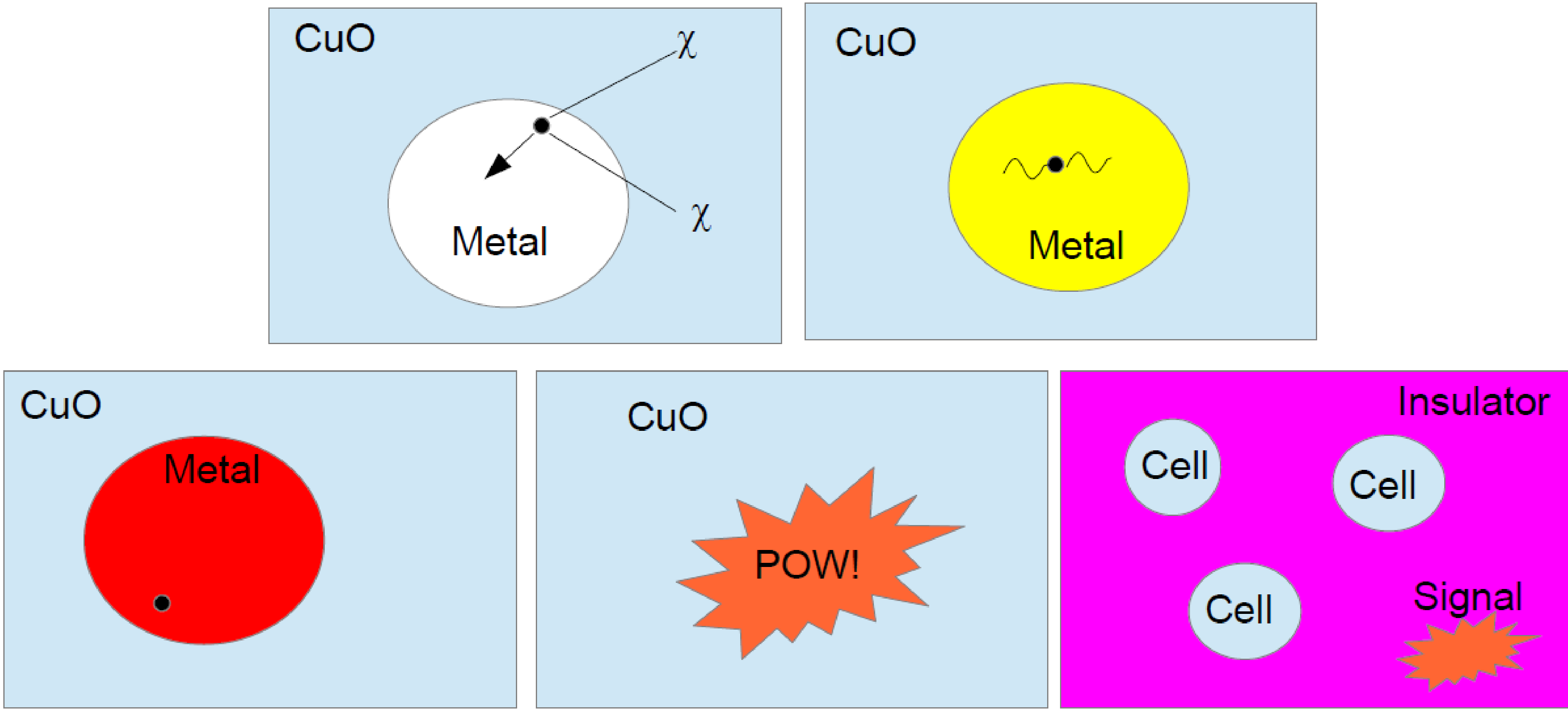
$$2Al + Fe_2O_3 \longrightarrow Al_2O_3 + 2Fe + 852\ kJ/mol$$

Nano-Thermite Detector: Design



1 cell = ~ 10^6 nano-grains

Nano-Thermite Detector: Design



Nano-Thermite Detector: Temperature Profile

Demand: Stable Detector at Room Temperature for 1 yr and signal for each WIMP interaction

Constrain: from Arrhenius Eq.

Activation Temperature: Ta > 3.1×10^4 K

Ignition Temperature: Ti > 3.5×10^3 K

Nano-Thermite Detector: Results

Element Name	Aluminum	Ytterbium	Thallium	Tantalum
ρ [g/cm^3]	2.7	6.9	11.85	16.69
M [amu]	26.98	173.05	204.38	180.95
k [W/(mK)]	237	38.5	46.1	57.5
$\Delta T_{300}(m_\chi = 10\ GeV)$ [K]	190	37	26	22
$\Delta T_{300}(m_\chi = 100\ GeV)$ [K]	483	1,605*	1,260*	992
$\Delta T_{300}(m_\chi = 1000\ GeV)$ [K]	510	2,155*	3,222*	3,272
$\Delta T_{700}(m_\chi = 10\ GeV)$ [K]	504	407	288	245
$\Delta T_{700}(m_\chi = 100\ GeV)$ [K]	749	2,282*	3,360*	3,465*
$\Delta T_{700}(m_\chi = 1000\ GeV)$ [K]	832	2,767*	4,078*	4,221*

Nano-Thermite Detector: Advantages/Disadvantages

- **Advantages:**
  - Easily scalable and relatively cheap
  - Background rejection due to granularity of cells

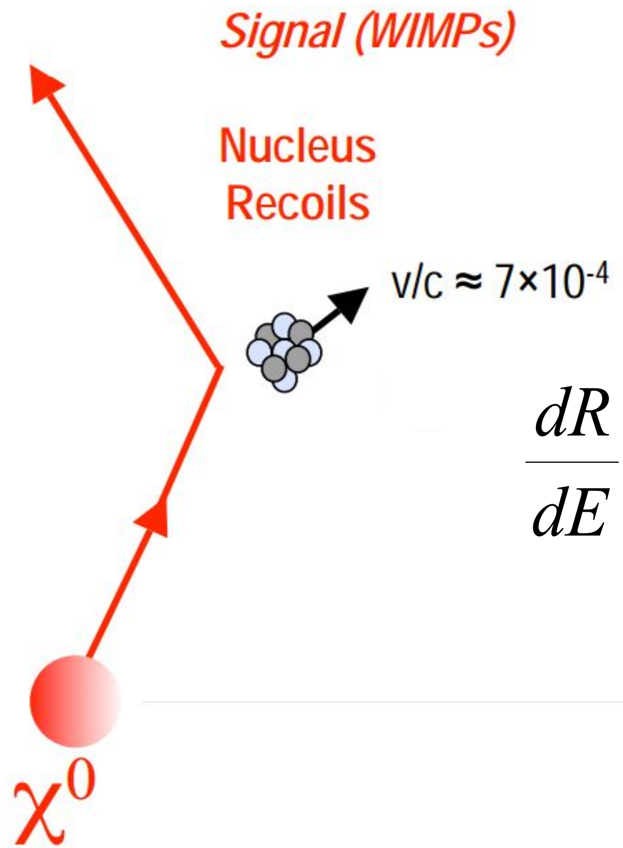
    (0.5 μm)
  - Cryogenic Temperature: lower the energy threshold to 0.5 keV (useful for low mass WIMP detection)
  - Multiple targets are plausible
  - WMD Grant $$$
- **Disadvantages:**
  - No directionality with current design
  - Synthesis of nano-thermites at cryogenic temperatures is non-trivial

Summary

- DNA DM Detector:
  - Head/Tail Asymmetry: lowers statistics ~100 events
  - DNA provides directionality at nm resolution
  - Background rejection due to physical granularity
- Nano-Thermite DM Detector:
  - Easily Scalable and cheap
  - Potentially low energy threshold at cryogenic temperatures: 0.5 keV
  - Background rejection due to physical granularity

THANK YOU

Dark Matter: Direct Detection SI



$$E_{nr} = \frac{2\mu^2}{M} v^2$$

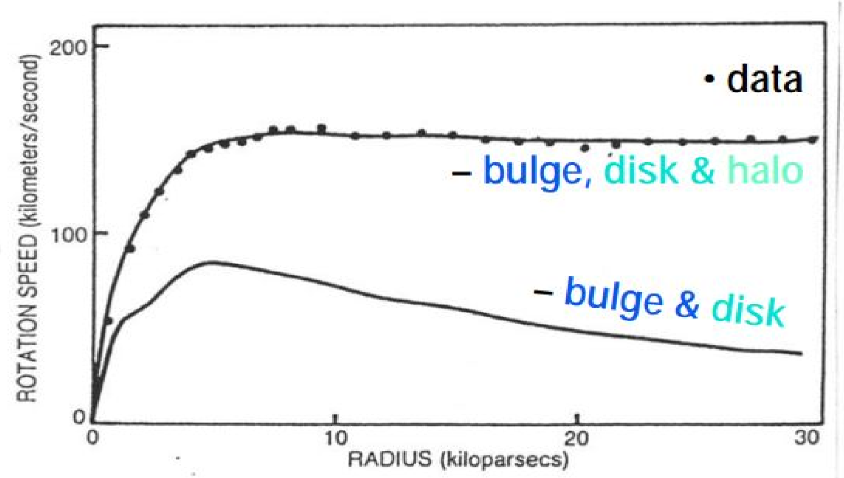
where $\mu = \frac{m_\chi M}{m_\chi + M}$

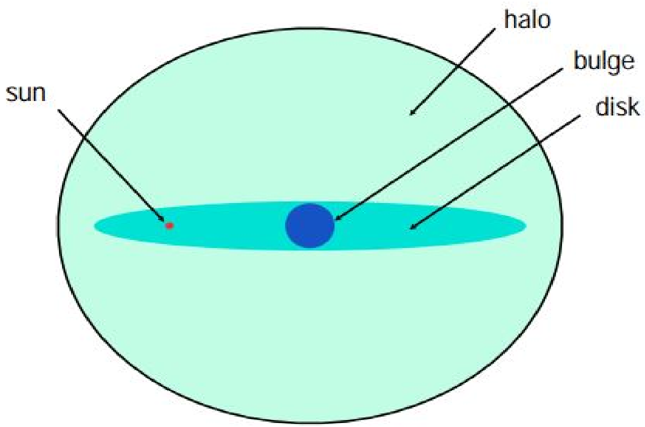
$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

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

Spin Independent: $\sigma_0 = \frac{A^2 \mu^2}{\mu_p^2} \sigma_p$

Dark Matter: Our Galaxy





The Milky Way

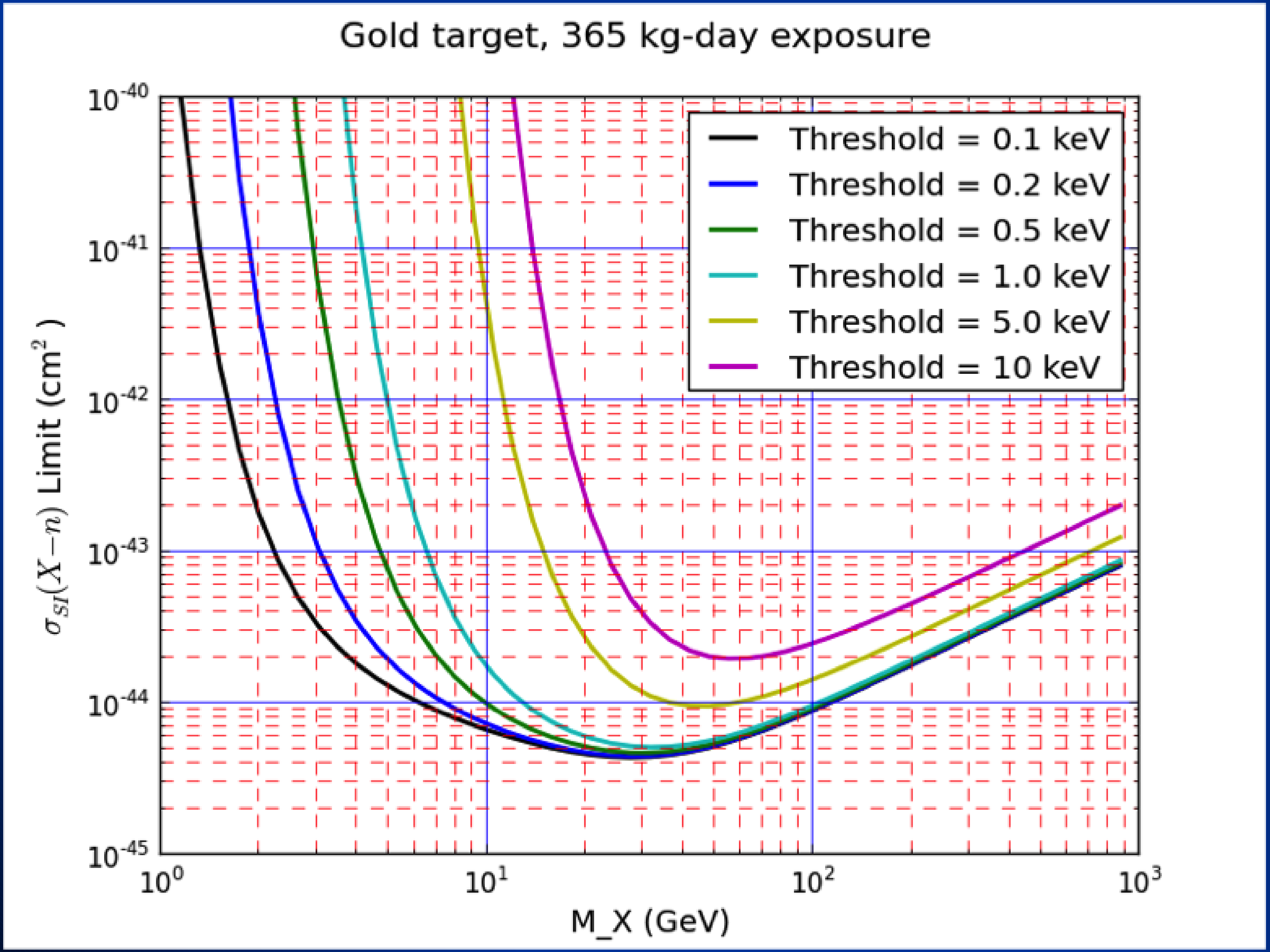
Dark Matter Halo exists
in our Galaxy

Local Dark Matter density is:
ρ=0.4 GeV/cm^3

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


Gold target, 365 kg-day exposure
Threshold = 0.1 keV
Threshold = 0.2 keV
Threshold = 0.5 keV
Threshold = 1.0 keV
Threshold = 5.0 keV
Threshold = 10 keV
$\sigma_{SI}(X-n)$ Limit (cm^2)
M_X (GeV)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^0
10^1
10^2
10^3

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.

Dark Matter Detector: Directional Capability

Nuclei typically get kicked forward by WIMP collision

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.**

Goal: identify the track of the recoiling nucleus i.e. the direction the WIMP came from

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

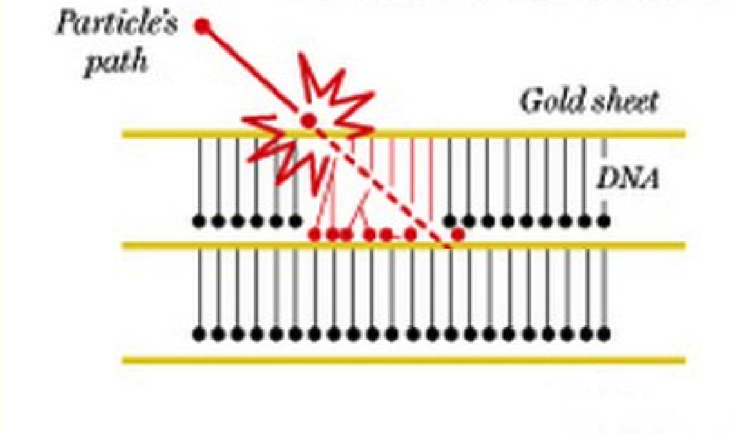
Experiments
Measuring the Ion-DNA Cross Section

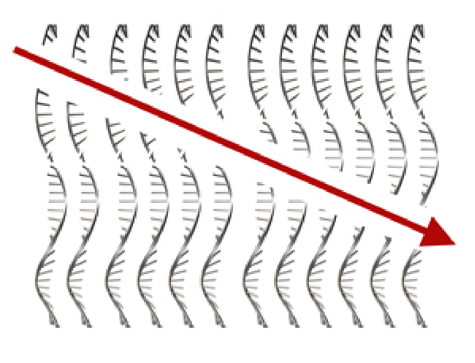
Students making the measurements:
Mykola Murskyj
Jordan Rowley
Theory aspects: Hai Bo Yu
Alejandro Lopez

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?





- Don't use annual modulation; because things in nature have modulation as well.
- Be careful with higher derivative operators