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New Classes of Detectors for WIMP's

"Three musketeers"

AKD /LS; EW/JG; AKD/KF/DS; F.T. Avignione *et al*.

"25 Years Later"

a) Classical (NaI) detectors

Good news: *high mass, ?annual modulation?*

Bad news: *high energy threshold*

b) Ultra-pure Ge-detectors

Good news: *best background*

Bad news: *low mass, mediocre energy threshold*

c) Cryogenic detectors

Good news: *works, great energy threshold, high Z elements*

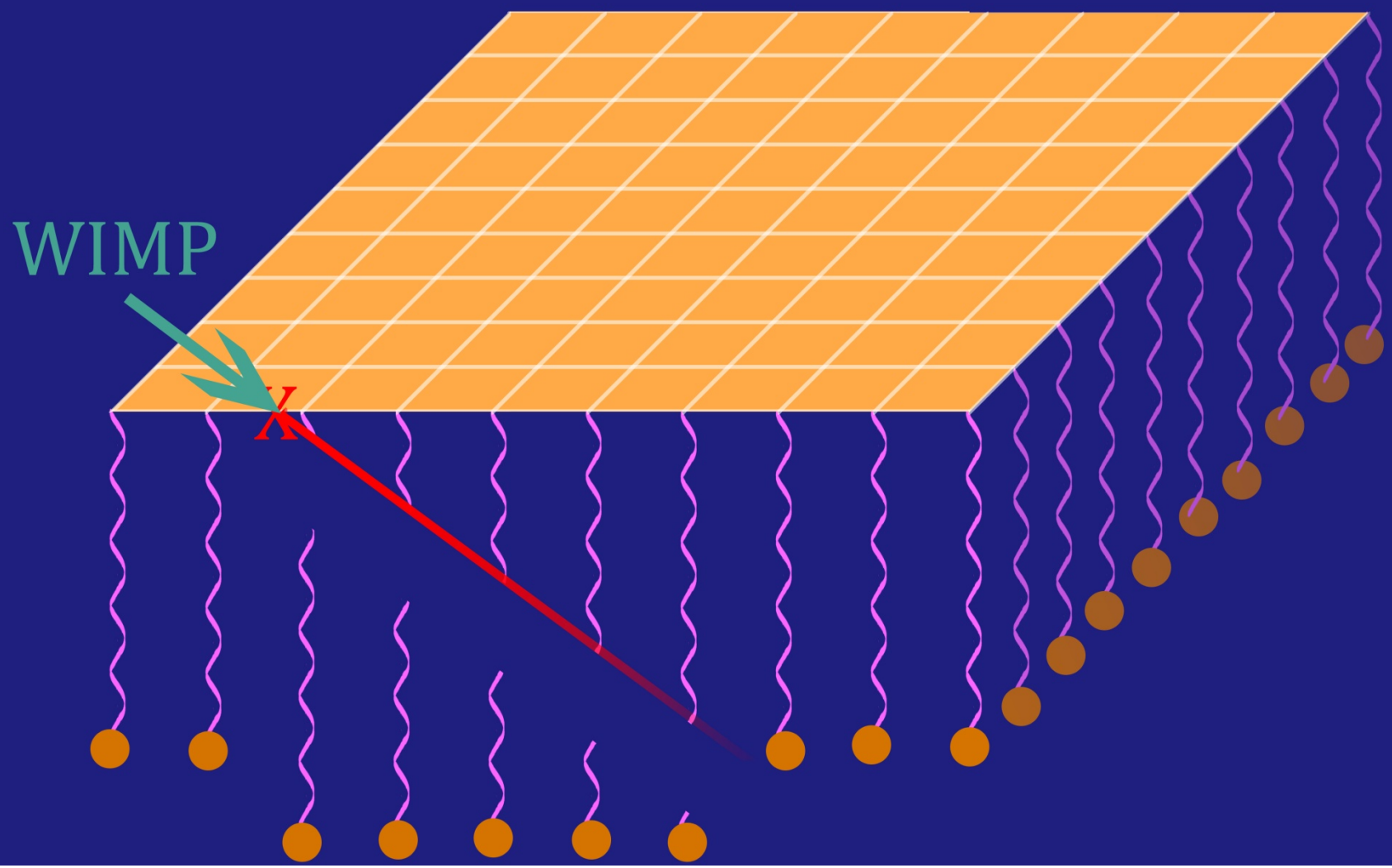
Bad news: *background???*

d) Liquid Xe et al.

Good News: Highest mass, reasonable background

Bad news: No really high Z, high energy thresholds

ssDNA Based Detector



Physicist Vision:

a) Sensitivity

b) Few types of specific background sources

c) Pulse-by-pulse → Amplification ($\geq 10^6$)

d) Pulse-by-pulse → Background rejection

Biologist Vision:

a) Sensitivity

b) Specificity

c) Many types of non-specific background sources

d) Integrating detectors

Proteins – no amplification

DNA – amplification $\geq 10^6$ - 10^9

The WIMP's detection problem

The count-rate is so-low that it requires many years to acquire statistics necessary to understand background. Half way between physicist and biologist visions of "measurement challenge.

ergo

Importance of "annual modulation effect"

Hope for enhanced "modulation" effects

The need for directional detectors.

Main Experimental Trade-offs

High A *vs.* **Low A**

Mass *vs.* **Energy Threshold**

Mass *vs.* **Background**

Cryogenic *vs*. **Room Temperature**

Different Classes of WIMP's "direct" Detection

Scintillators/ L. Xe	Mass ≈ tons	E_{th} ≈ 5 keV
Ge	Mass – 100kg	E_{th} ≈ 0.5-5 keV
Cryogenic		
crystals	Mass – 100kg	E_{th} ≈ 0.1-1keV
"grains"	Mass – 10's kg	E_{th} (He-4) ≈ 0.5-5keV
		E_{th} (He-3) ≈ 0.1-1keV
"Rods"	Mass – 100 kg	E_{th} (He-3) < 0.05 keV

Biological

DNA (direct)	< 10 kg	E_{th} < 0.01 keV
"Rods" + DNA	> 100kg	E_{th} < 0.05 keV

!"Possible background problem" – need annual modulation (AME)!

Non – Standard Cosmologies

- WIMP's + Modified gravity (R. Juszkiewicz *et al*.)
- WIMP's + "modified initial conditions" → rings
- WIMPs + "directional detector"(D. Spergel *et al*, G. Gelmini *et al*…)

Standard	**Non-Standard**
$\rho_{Earth}=1$	$\rho_{Earth}=1.5 - 2$
$V_{max} = V_{Galaxy\ escape}$	$V_{max} \approx 0.5 – 0.75 \times V_{Galaxy\ escape}$
$E_{th} \geq 1$ keV	$E_{th} < 0.5$ keV
AME ≈ O(5%)	AME ≈ O(15%)
M* ≥ O(100kg)	M* ≥ O(10kg)!

M* = Mass ==> sufficient statistics to detect annual modulation effect

WE NEED DETECTOR WITH WELL UNDERSTOOD DIRECTIONALITY

“Head/Tail identification”

- WIMPs + “directional detector”(D. Spergel 1988)

X	Fraction	F/B	July/Jan	NF	NB	NAME
0.00	*1.0*	*4.0*	*1.04*	*80*	*20*	*10,000*
0.2	*0.97*	*4.2*	*1.045*	*78`*	*19*	*8,375*
0.4	*0.9*	*4.7*	*1.05*	*74*	*16*	*7,872*
0.6	*0.78*	*5.4*	*1.07*	*66*	*12*	*5,353*
0.8	*0.65*	*6.6*	*1.085*	*56*	*9*	*5,217*
1,0	*0.5*	*8.1*	*1.11*	*45*	*5*	*5,286*
1.2	*0.37*	*10.2*	*1.13*	*34*	*3*	*6,891*

WE NEED DETECTOR WITH WELL UNDERSTOOD DIRECTIONALITY

Advantages of dE/Dx in vertex for background rejection

- One can use very high A material – A(Pb) = 207.2 => Cross-section =O(A^2);

- dE/dX is proportional to Z^2 => for Z=80

  (dE/dx)NR / (dE/dx)Z=1 = 6.4 x10^4;

- Other methods of rejection of charged background, *e.g.* gamma, electrons, alphas, CR (<x>)

  E_{tota}l (NR) /E_{total} (<x>) = O.1

  Range(<x> / (spatial resolution) = 10

  Fraction NR /Fraction <x> = 10 wherein $F_{fraction}$ = E_{total}/$E_{ionization}$

  Measurement of dE/dx in vertex permits much better background rejection.

Detecting WIMP's *via* Coherent Scattering on DNA

DNA = (A, T, C, G)

- Four sub-units (A, T, C, G)
- Complementary A < – > T and C <–> G
- A <–> T two hydrogen bonds; C <– > G three hydrogen bonds
- ssDNA + complementary *ssDNA* => dsDNA
- Circular DNA (plasmids)
- Your choice DNA (hairpins, partially collapsed circular DNA)

➔ Amplification + DNA repair + "coding capabilities"

⇒ PCR Amplification works when dsDNA was frozen for 10^4 years in permafrost

⇒ **No reasons why dsDNA frozen in L. helium should not be PCR Amplified**

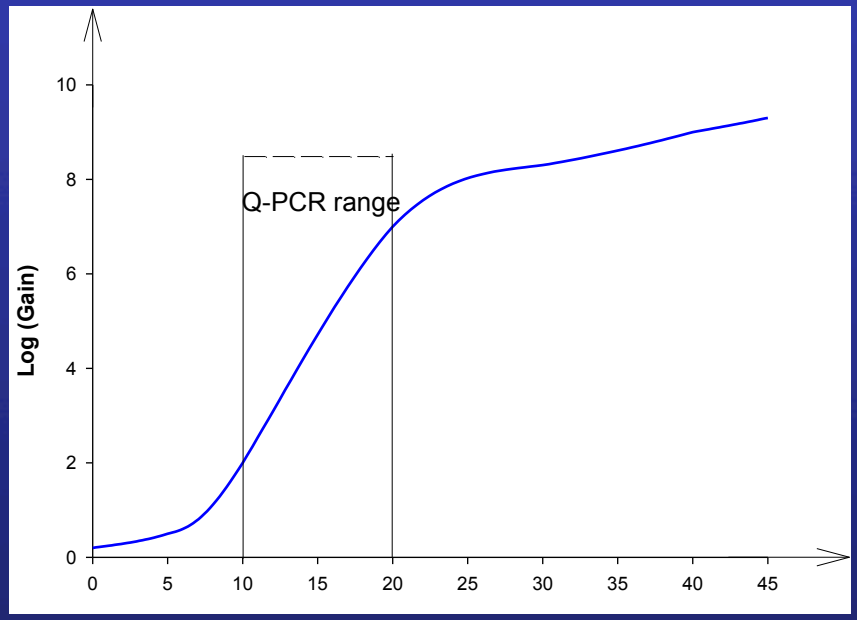
Nunc Hercules contra plures:

Cryogenic Detectors < 50 scientists/year in last 10 years
General Particle Detectors < 1,000 scientists/year in last 20 years
DNA based techniques 50,000 scientists/year in last 20 years

PCR – process

- Template dsDNA
- Excess of A, T, C, G
- Polymerase(s)
- Temperature cycling:

  $T_{min} = 0.5\ T_m$, $T_{max} = 1.0\ T_m$, $dT \approx 0.01°C$
- Control of "environment" (salts *etc*. …)



Natural dsDNA [$T_m \approx 25\text{-}35^{\circ}C$]

50-mer

WIMP

ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGAT
TAGCTAGCTAGCTAGCTAGCTAGCTAGCTAGCTAGCTAGCTAGCTAGCTAGCTA – xx

xx – linker

WIMP interacts with C (Carbon) or O or P

$$\sigma\,(\text{WIMP, C}) \approx \sigma\,(\text{WIMP, O}) > \sigma\,(\text{WIMP, P}) >> \sigma\,(\text{WIMP, H})$$

$$\sigma\,(\text{WIMP, A}) \approx \sigma\,(\text{WIMP, T}) \approx \sigma\,(\text{WIMP, C}) \approx \sigma\,(\text{WIMP, G})$$

The random interaction at any place of dsDNA!

The WIMP kick's off the base and creates a nick.

The T_m of nicked (dsDNA) lower than for dsDNA.

Assymmetric PCR: $T_{min} \approx 20°C$ T_{max} (nick)$\leq T_{max} \leq T_m$ (whole)

Result: We do not know what we do! MESS!

Engineered <dsDNA>

50-mer

Hg Hg WIMP

CTGACTCAGTCAGTCAGTCAGCCAGTCAGTCAGTCAGTCAGTCAGTCAGTCAG
GACTGAGTCAGTCAGTCAGTCGGTCAGTCAGTCAGTCAGTCAGTCAGTCAGTC

Each C is derivatized with Hg

WIMP's interacts preferably with Hg

RESULT 1: Nick is created in middle of <dsDNA>

=> T_m (dsDNA, nick) ≤ T_m (dsDNA, no nick)

Challenge: T_m (dsDNA, nick) - T_m (dsdNA, no-nick) ≈ $dT_{instrument}$ ≈ 0.05°C

RESULT 2: dsDNA is broken into dsDNA1 + dsdNA2
=> PCR enables sequencing => reliable detection

Circular DNA

The Circular DNA is like “soap bubble”, if you pinch it will collapse

WIMP + CiDNA → ssDNA

1) $(T_m\,(\text{CiDNA}) - T_m\,(\text{ssDNA})) \geq 10°C$

2) You can put many Hg – substituted bases in C:
the final result is always the same ssDNA

3) The ssDNA and CiDNA have very different properties:
one can purify collection of CiDNA

Intercalators can be used as WIMP's target

ATATATATATATATATATATATATATATATATATATATATATATATATATAT
XXXX XXXX
TATATATATATATATATATATATATATATATATATATATATATATATATATA

XXXX = intercalator

Typical intercalator is cis-platinum), it cross-link dsDNA and stops PCR

WIMP interacts with Pt =>breaks cis-platinum=> dsDNA may be amplified

$[T_m$ (with cross-link) - T_m (without cross-link)$] \geq 15°C$

There are many known intercalators based on heavy metals

The Main Challenges of Direct DNA method

- C^{14} will also break a base; need to use carbon from 1 mln years old petroleum
- Need to "perfectly control" nicks, *i. e*. every week or so the DNA have to be mixed with "DNA repair" enzymes, which are after fished-out and/or denaturated
- To diminish fast neutrons / Cosmic Rays => underground

Backgrounds, backgrounds, backgrounds…

but

a) It's a new class of detectors;

b) They have the lowest energy threshold;

c) It's "elegant";

d) Nunc Hercules contra plures.

The best of Two Worlds

Mixing Nanotechnology and Molecular Biology

Principle:

=> WIMPS interact in high A material
=> recoiling nuclei escapes due to nano-size;
=> after escape , recoiling nuclei crosses and breaks hundreds of ssDNA
=> molecular biology permits "ordered arrays" of ssDNA;
=> ladder of cut ssdNA is created;
=> The geometruy gives angle.

Implementation:

⇒ Amplified dsDNA is sequenced for QC
⇒ Cut ssDNA is removed and PCR amplified, e.g. 10^6 X
⇒ Ladder of cut ssDNA permits reconstruction of "angle";
⇒ One and only one class of ssDNA permits background rejection.

Directional DNA detectors

- The single base is 3.5 A => 0.35 nm
- Range of 20 keV recoiling Pt => 330 nm
- For DNA in vaccum = > range = O(1,000) bases
- For DNA in H_2O => range = O(500 bases)

<u>Another "back of envelope" calculation:</u>

- Energy necessary to break ssDNA = O(20 eV)
- 50 % of energy lost in DNA
  = > 0.5 x (20keV)/(20 eV) = O(500 bases broken)

Counting number of broken ssDNA
=> spatial resolution of 0.5 nm

The DNA bundle Implementation

- **Imagine dsDNA bundle:**
- ***Length = 100,000 bases => 35 microns***
- ***Diameter = 50 layers***

Thin bundle approximation (Diameter < Range)

- ***Direction = along the bundle => N_{max} = 500 bases broken***
- ***Direction = 45 ^{o} = N = 50xsqrt(2) = 70.5 bases broken***
- ***Direction = 90 ^{o}=> N = 50 bases broken***

Thick bundle approximation (Diameter > Range)

- ***N_{broken} = Range / cos(alpha)***

Uncertainty with dsDNA : Do we nick? Do we break?:

Modified dsDNA + ssDNA Bundle

ATCGATCGATCGATCG XXXXXXXXX.....XXXXXXXXXXXXXATCGATCGATCG
ATCGATCGATCGATCG YYYYYYYYY.....YYYYYYYYYYYYYATCGATCGATCG
ATCGATCGATCGATCG ZZZZZZZZZZ.....ZZZZZZZZZZZZZZATCGATCGATCG
CGCGCGCGCGCGCGCGCGCGCGCGCGCG.....CGCGCGCGCGCGCGCGCGCGCGCG
GCGCGCGCGCGCGCGCGCGCGCGCGCGC.....GCGCGCGCGCGCGCGCGCGCGCGC
ATCGATCGATCGATCGZZZZZZZZZZZ.....ZZZZZZZZZZZZZZATCGATCGATC
ATCGATCGATCGATCGYYYYYYYYYY.....YYYYYYYYYYYYYATCGATCGATC
ATCGATCGATCGATCGXXXXXXXXXX.....XXXXXXXXXXXXXATCGATCGATC

C = C-base derivatized with Hg, I or Br

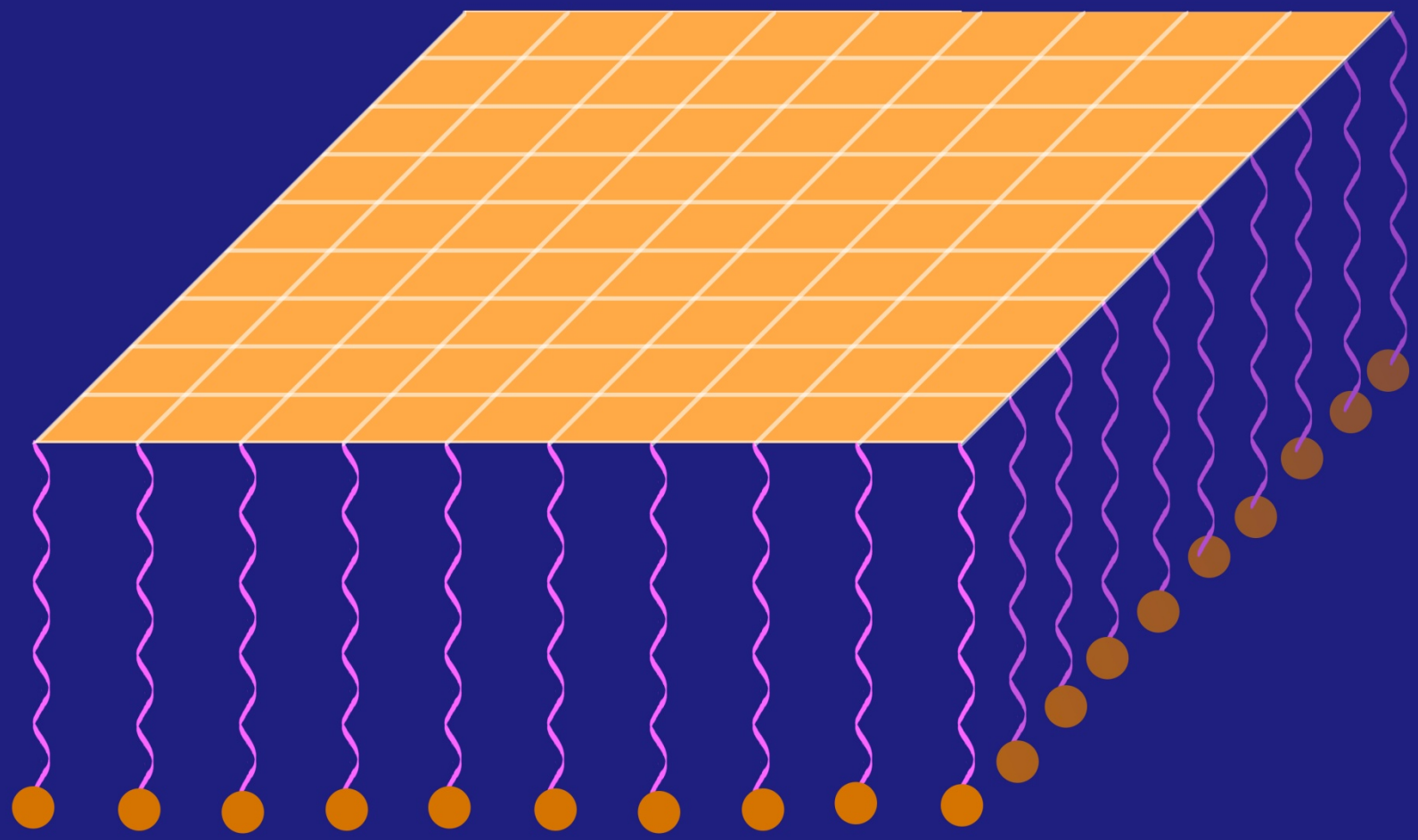
ATCGATCGATCGATCG - primers ..... more of the same

XXXX, YYYY, ZZZZ… the forensic regions of DNA (encodes 10^{10} different ssDNA)

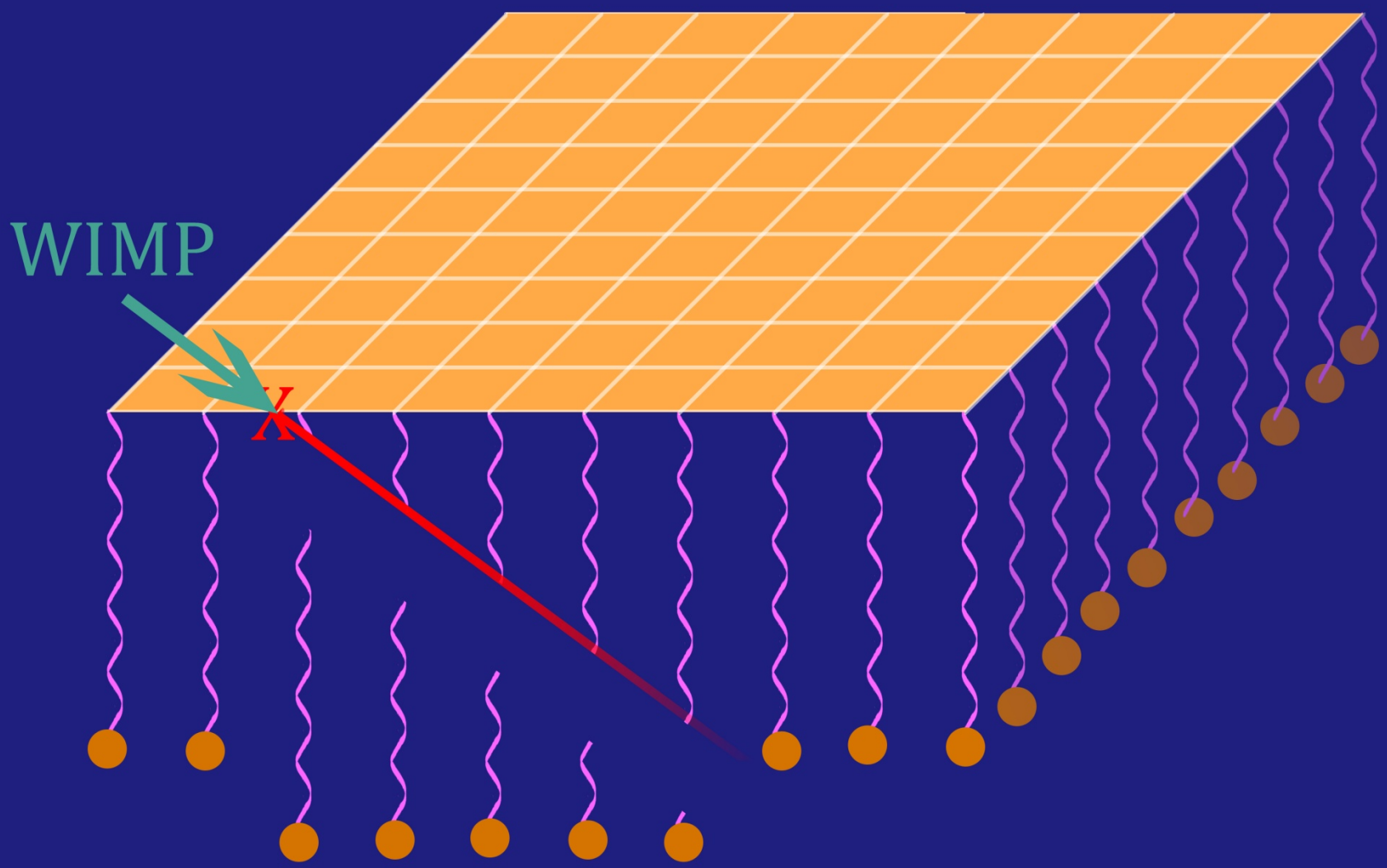
Use of ssdNA means that any interaction with recoiling nuclei leads to broken ssDNA and can be PCR amplified and sequenced to identify.

Two independent measurements of range/direction of recoiling nuclei-number of broken ssDNA and maximal range of recoiling nuclei from DNA forensics.

ssDNA Based Detector



ssDNA Based Detector



DNA Strings Detector

➔ **Gravity**

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG

HHX

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG

HHX

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG

HHX

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCHATCGATCGATCGATCGATCG

HHX

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG

HHX

HHX-ATCGATCGATCGATCGATCGATCGHATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG

-> **Gravity**

HH = plastic (500 nm) X = Au(5 nm) ATCG….ATCG = 10,000 long ssDNA

DNA Strings Detector

➔ **Gravity**

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCHATCGATCGATCGATCGATCGATCG
HHX
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX
HHX-ATCGATCGATCGATCGATCGATCGHATCGATCGATCGATCGATCGATCGATCGATCGATCG

-> **Gravity**

WIMP under 45 degree => high probability of detection
=> high number of ssdNA broken
=> characteristic cut-off pattern (ssDNA ladder)

ssDNA Strings Detector - Production

HHHH

ssDNA Strings Detector – “frame” production

- 1st – step – make ordered array of “frame ssDNA”

```
CGCGCGCGCGCGCGCGCGCGCGCGCGCGCGCGCGC...........GCGCGCGCGCGCGCGCGCGCGCGCGCGCGCGCGC
      GCGCGC                CGCGC                CGCGC                GCGCGC
           GC                    GC                    GC                    GC
           CG                    CG                    CG                    CG
           GC                    GC                    GC                    GC
           CG                    CG                    CG                    CG
            X                     X                     X                     X
            X                     X                     X                     X
            X                     X                     X                     X
            o                     o                     o                     o
            X                     X                     X                     X
            X                     X                     X                     X
            X                     X                     X                     X
           CG                    CG                    CG                    CG
           G C                   GC                    G C                   GC
           C G                   CG                    C G                   CG
           G C                   GC                    G C                   G C
    GCGCGC                GCGCGC                GCGCGC                GCGCGC
    CGCGCCGCGCGCGCGCGCGCGHCGCGCGCGC............GCGCGCGCGCGCGCGCGCGCGCGCGCGCGCGCGCGC
```

Actually :

G = GGGG C = CCCC X = any nucleoside o = more of the same

DNA Strings Detector + Au Rods

➔ **Gravity**

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX xxxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX xxxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCHATCGATCGATCGATCGATCGATCG
HHX xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx
HHX-ATCGATCGATCGATCGATCGATCGHATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG

-> **Gravity**

Planes : HH = plastic (500 nm), X = Au(5 nm)
Strings : ATCG….ATCG = 3,000 long ssDNA = 1,050 nm = O(1 micron)

Coupling (ssdNA to Au-rods) : each C biotinylated, Au-rod coated with streptavidin.

Adding nano-technology to molecular biology

Au plane + DNA strings is “simple” but not efficient mass-wise

Nanotechnology permits production of nano-clusters and nano wires , either gold of platinum. They can be “attached “ to certain bases by molecular biology tricks.

Table: Fcc- Pt nano-particles.

Shell	*$N(Pt)_{core}$*	*$N(PT)_{surface}$*	*N(PT)total*	*D(nm)*
3	*55*	*92*	*147*	*1.21*
4	*147*	*162*	*309*	*2.32*
4	*309*	*252*	*561*	*2.84*
6	*561*	*362*	*923*	*3.35*
7	*923*	*492*	*1415*	*3.87*
8	*1415*	*642*	*2057*	*4.39*

DNA Strings Detector + Pt nano-clusters

➔ **Gravity**

HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX o o o o o o o o
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX o o o o o o o o
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX o o o o o o o o
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCHATCGATCGATCGATCGATCGATCG
HHX o o o o o o o o
HHX-ATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG
HHX o o o o o o o o
HHX-ATCGATCGATCGATCGATCGATCGHATCGATCGATCGATCGATCGATCGATCGATCGATCGATCG

-> **Gravity**

Each C is biotinylated, each Pt-nano cluster is coated with streptavidin
=> with proper stechiometry to every second C is attached 2057 atoms of Pt

0.5 m x 0.5 m x 0.5 m ➔ 1 kg of Pt + 1 kg ssDNA , E_{th} = 0.2-0.5 keV

BACKGROUND REJECTION

- ***We replace old "one and only one grain" with "one and only one ssDNA bundle".***
- ***Electrons*** *etc…* ***cross hundreds of bundles;***
- ***Recoiling nucleons stays inside of bundle;***
- ***Recoiling nuclei always starts from middle of the bundle, but recoiling neutrons starts wherever;***
- ***DNA permits encoding billions of bundles;***
- ***This is "room temperature detector".***

Hybrid ssDNA-based detectors

- The ss-DNA is stable in gas, *e.g.* He atmosphere
- Detector is Z-direction modular, *e.g*. the gas-filled spacing of O(1mm) can be induced
- This will facilitate ssDNA sweeping but also may permit hybrid detectors
- Presence of 1 mm of He permits use of TPC –type gas detector to obtain
  - event timing
  - rough spatial resolution of O(1 mm)

Assumes that 50% energy is lost in ssDNA and 50% in He.

Alternative hybrid detector can be implemented with “explosive nano-grains” incorporated in plastic and read-out by sonic boum (see Part 3 of my talk).

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Ad memoria

Ron Brodzinsky and Roman Juszkiewicz