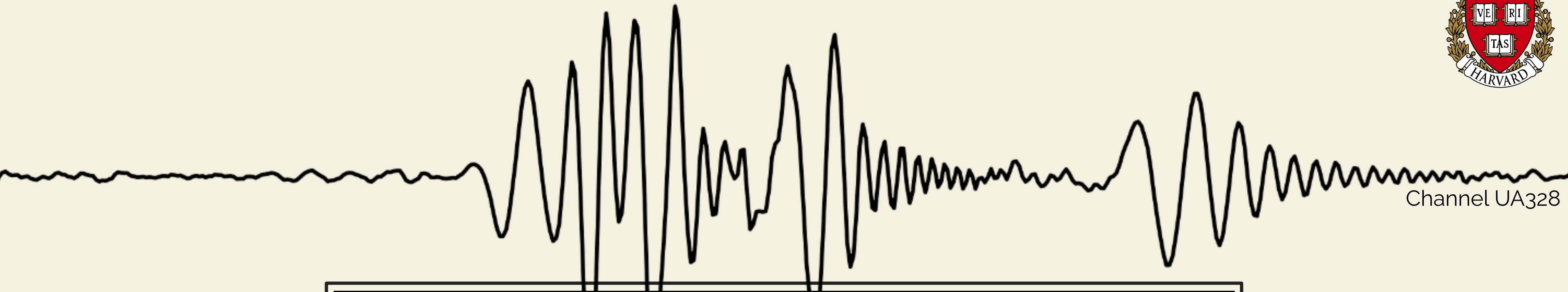


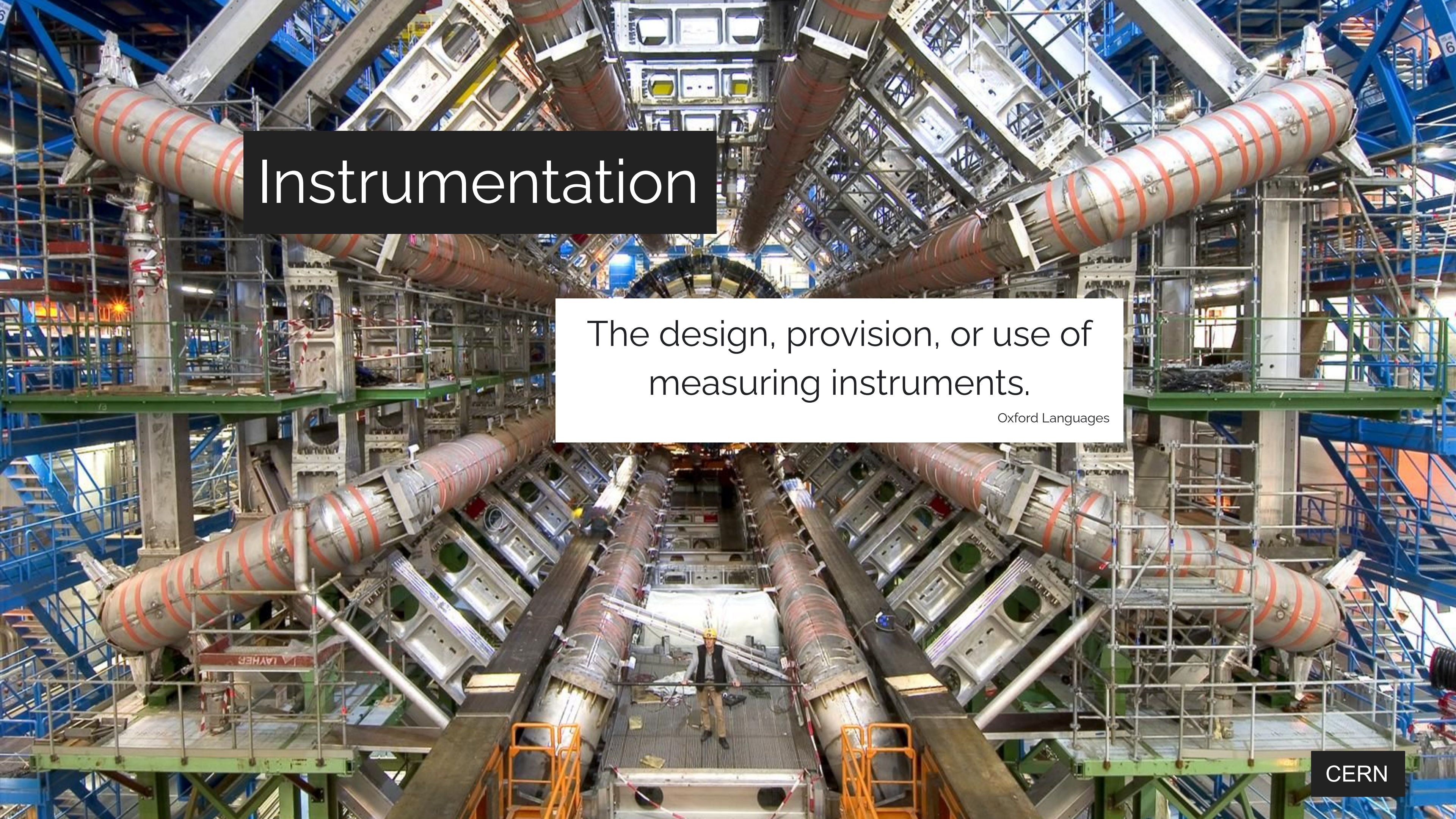
SECONDARY INSTRUMENTATION AND THE SEARCH FOR NEW PHYSICS

Chris Stanford
Harvard University
BNL Seminar

Instrumentation

The design, provision, or use of measuring instruments.

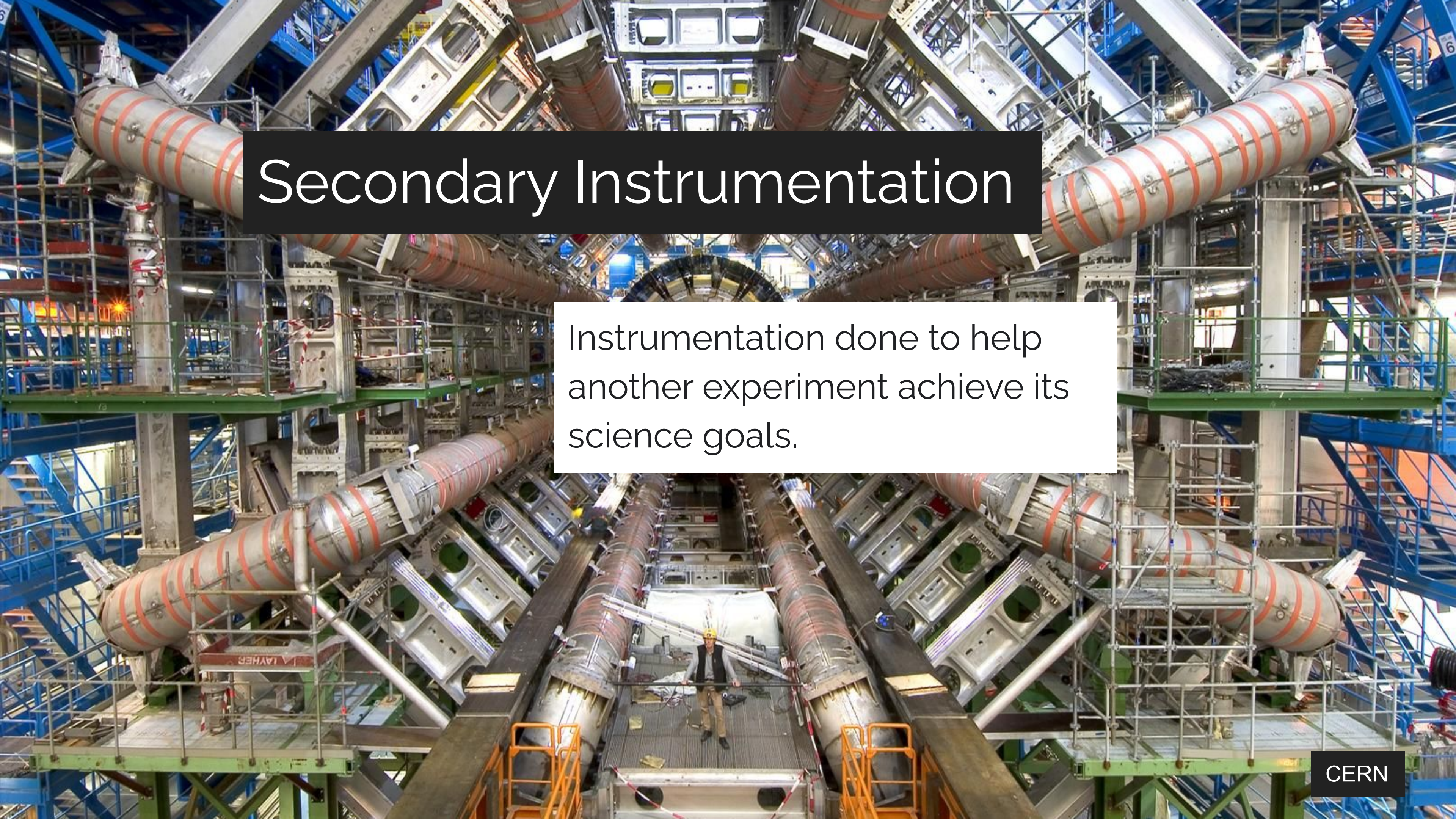
Oxford Languages



CERN

Secondary Instrumentation

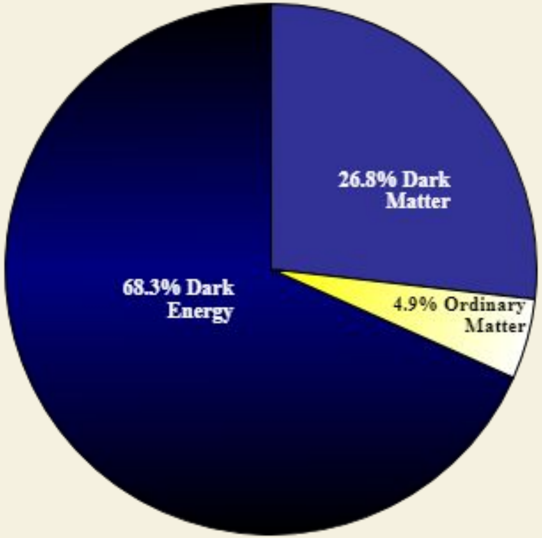
Instrumentation done to help another experiment achieve its science goals.

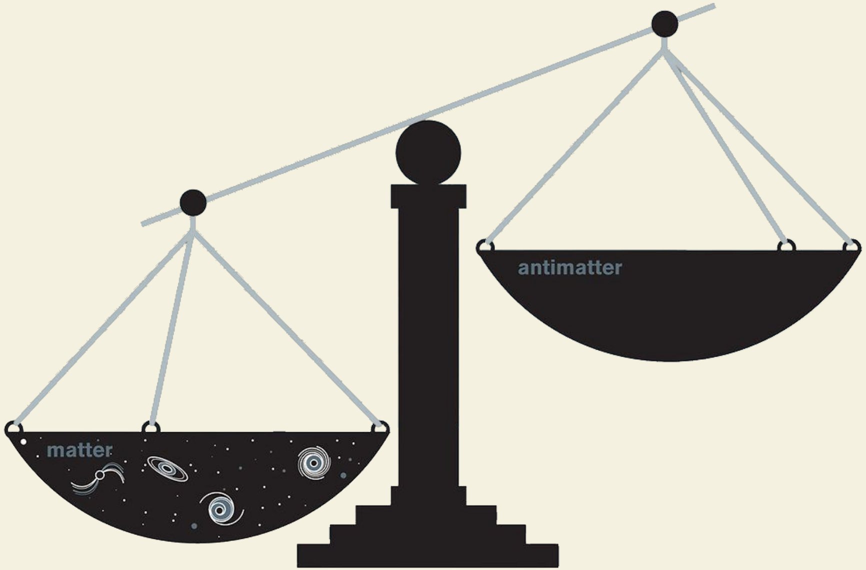


CERN

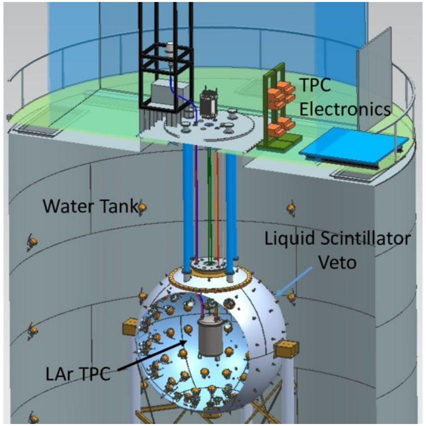
New Physics

Exploring the big questions



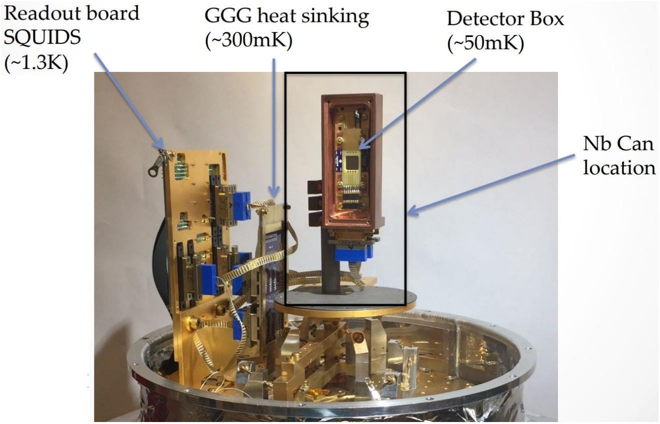


3 Experiments



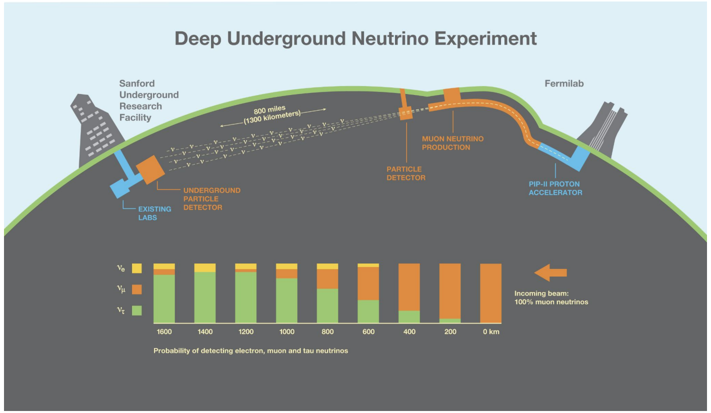
DARKSIDE 50

WIMP Dark Matter



SUPER CDMS Cryogenic Dark Matter Search

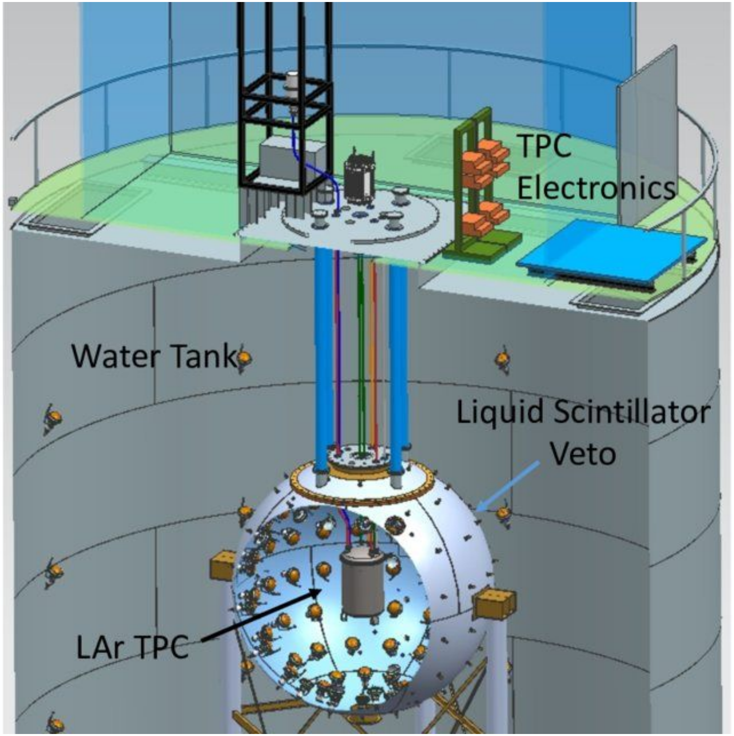
Low-mass Dark Matter



DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

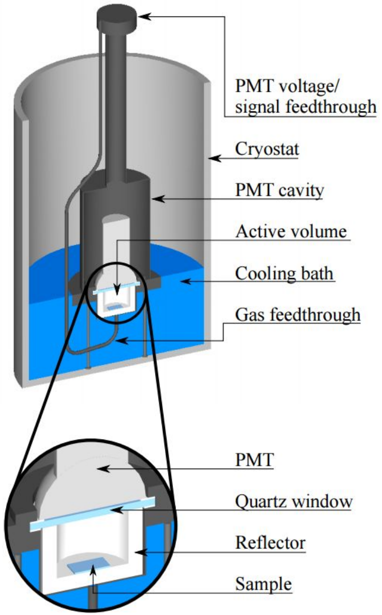
ν hierarchy, CP violation (matter-antimatter assym.), solar and supernova ν, dark matter, sterile ν, non-standard ν interactions, etc.

Experiment #1



DarkSide-50

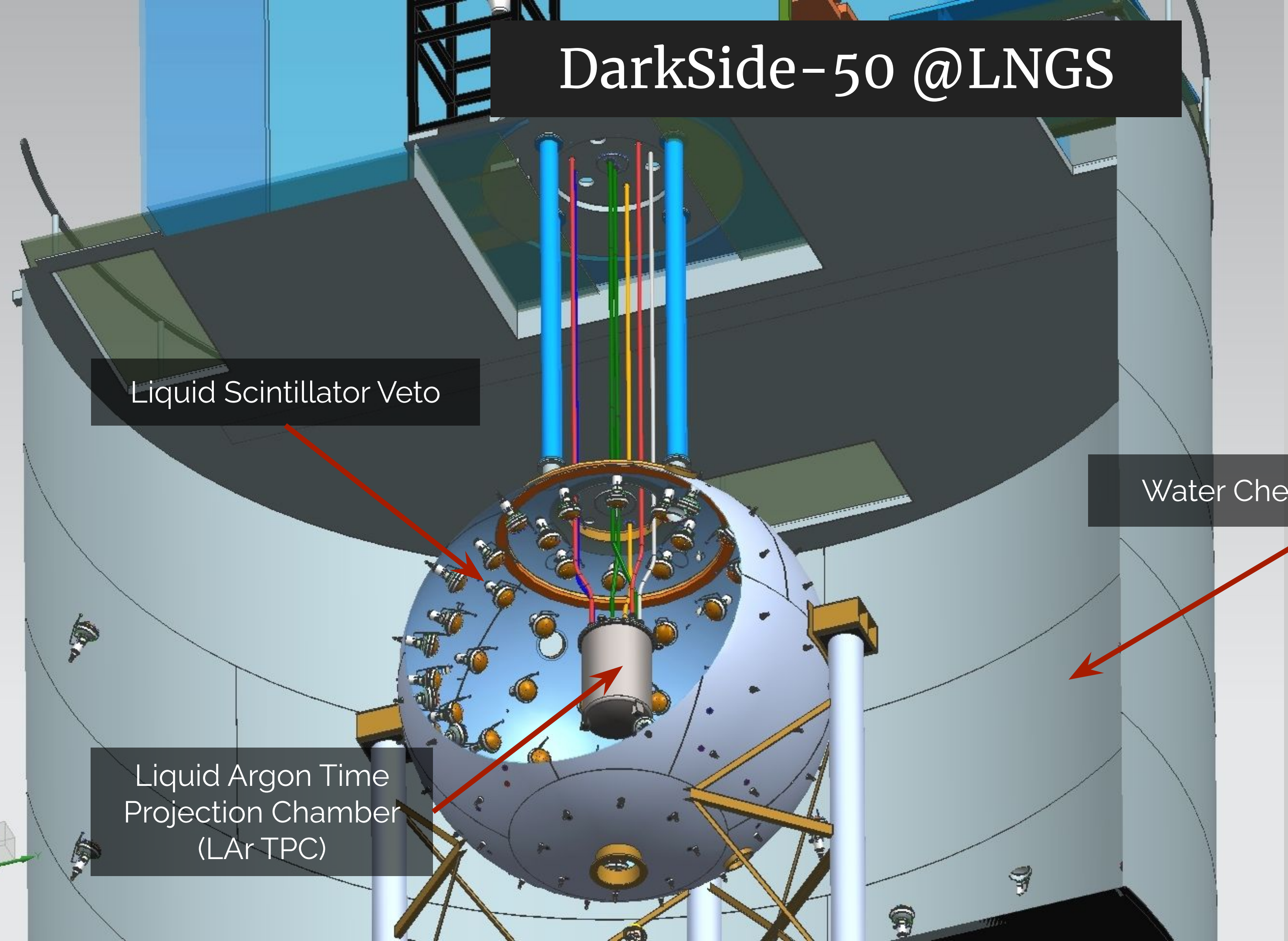
Secondary Instrumentation



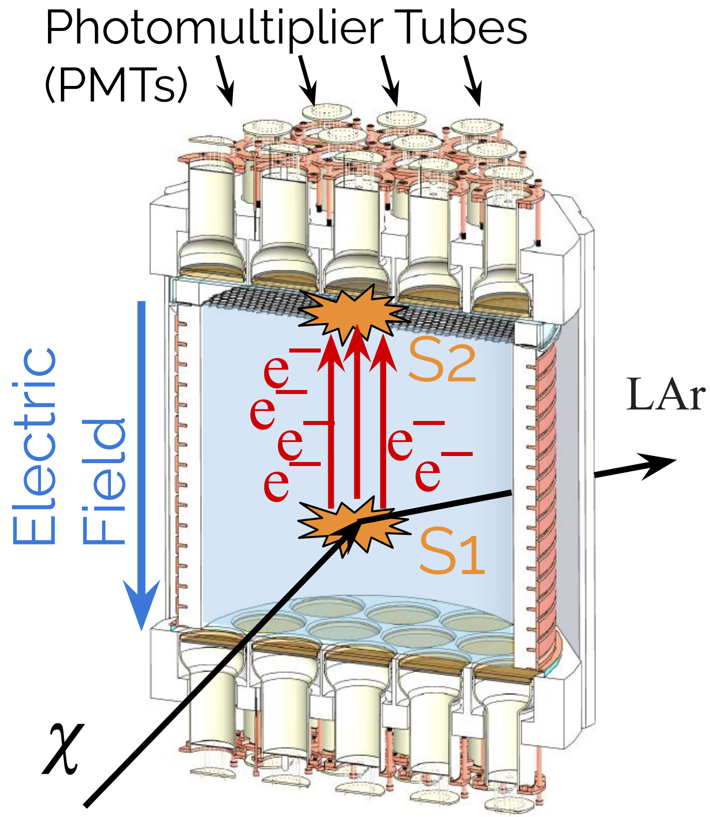
A tabletop radon daughter detector

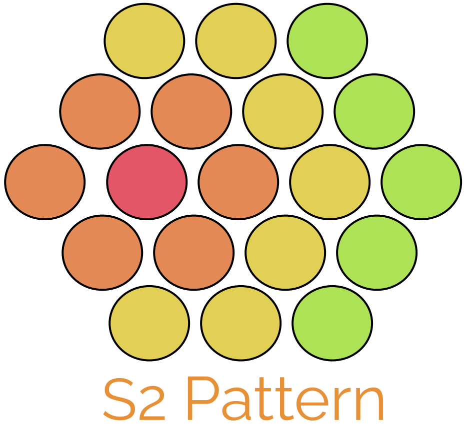
Science Goal: WIMP Dark Matter Search

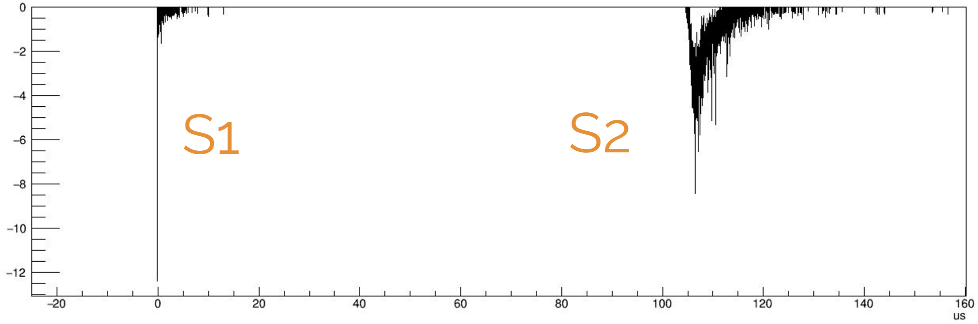
DarkSide-50 @LNGS



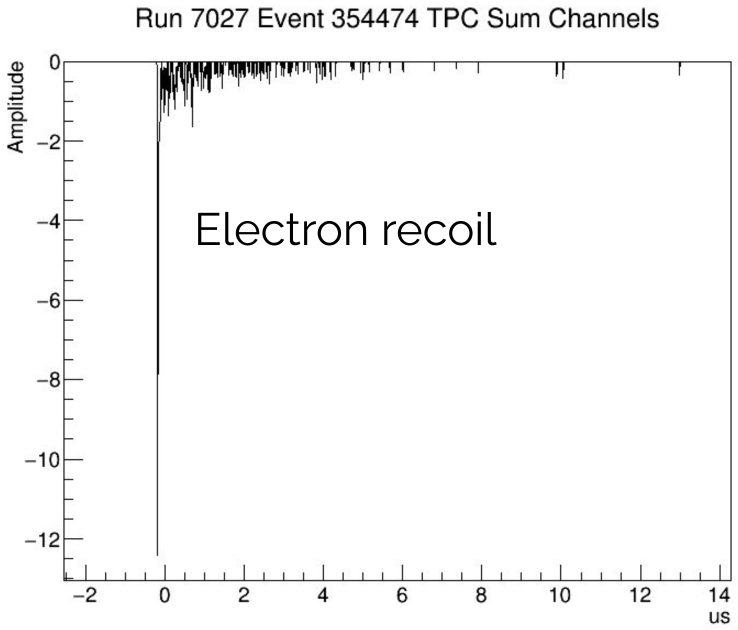
The TPC

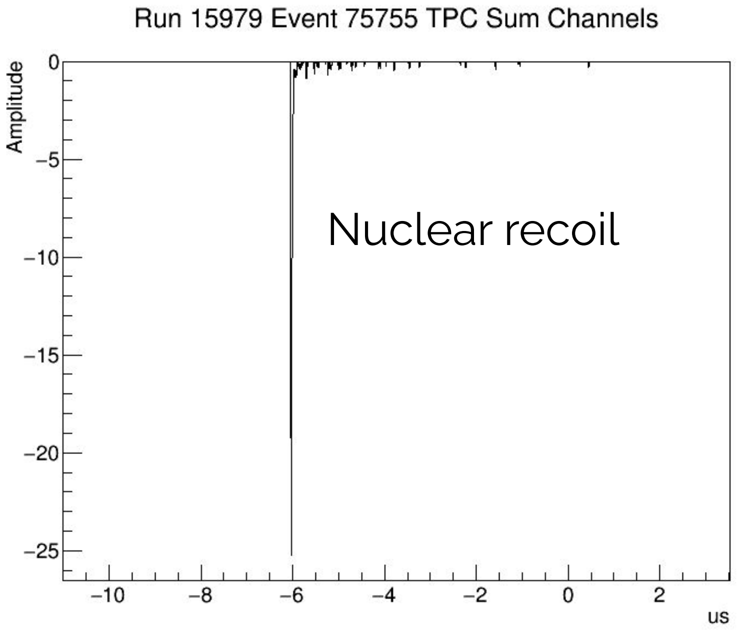

Photomultiplier Tubes
(PMTs)
Electric
Field
S2
S1
LAr
χ


S2 Pattern


0
−2
−4
−6
−8
−10
−12
−20
0
20
40
60
80
100
120
140
160
us
S1
S2

Pulse Shape Discrimination

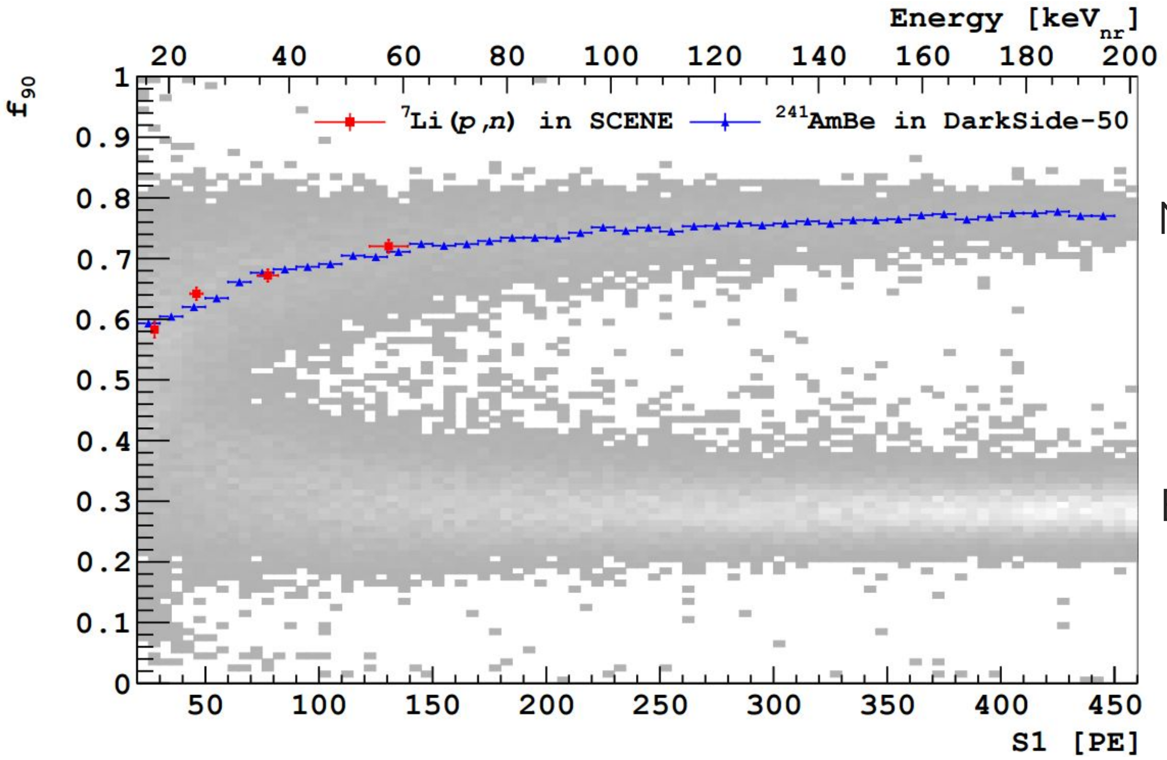




$$f_{90} \equiv \frac{\text{Integral of first 90ns}}{\text{Integral of first 7}\mu\text{s}}$$

ERs have a long tail, NRs don't

Pulse Shape Discrimination



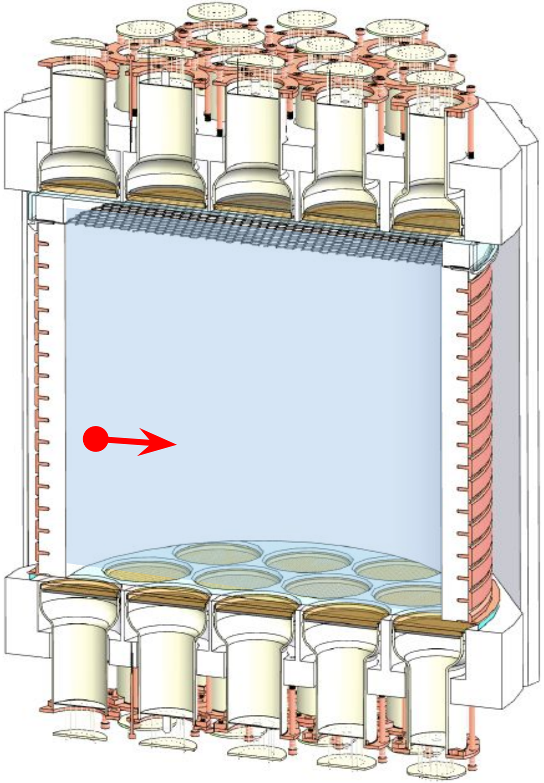
Nuclear recoils f_{90}~ 0.7

Electron recoils f_{90}~ 0.3

Background target: 0.1 events

Surface Backgrounds

Surface decays of radioisotopes were a big question mark



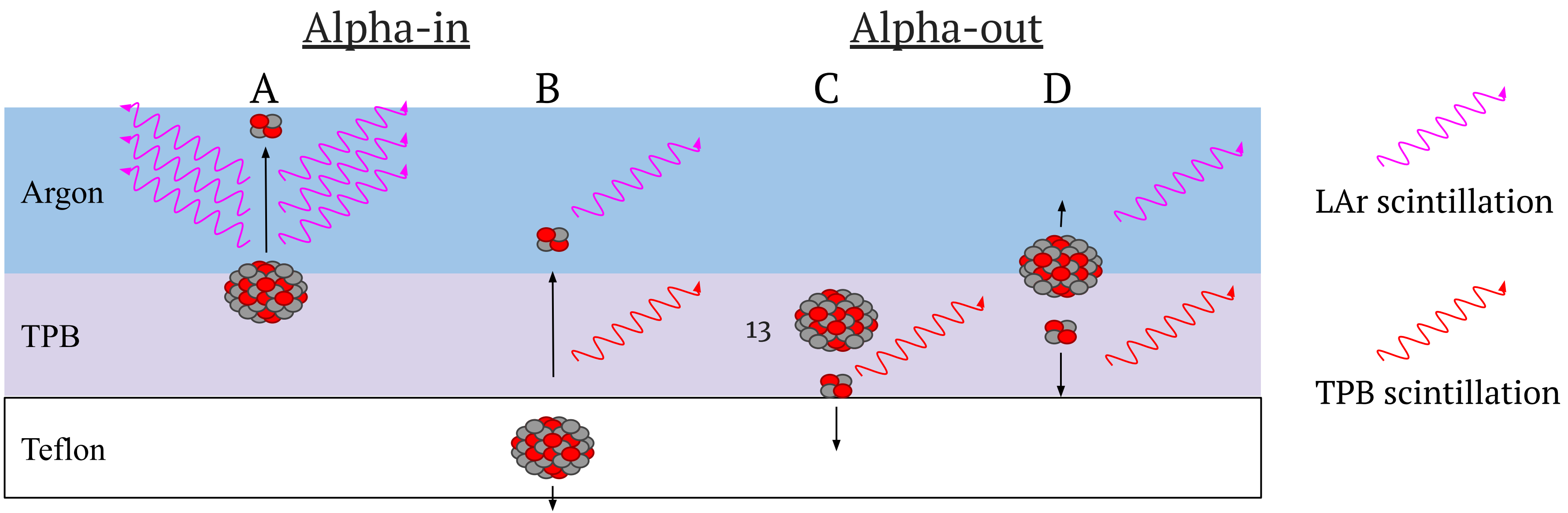
Surface Backgrounds

Argon

TPB

Teflon

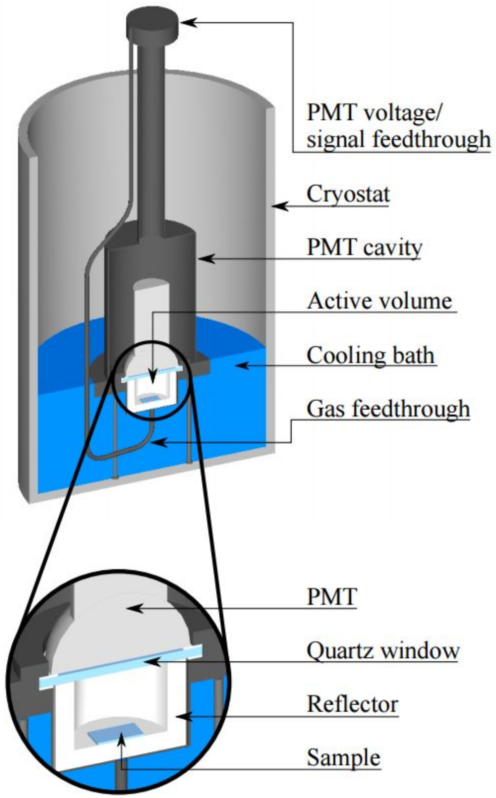
Surface Backgrounds



What do these signals look like?

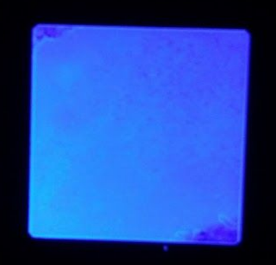
Secondary Instrumentation

Radon
Daughter and
Organic
Scintillator
Experiment



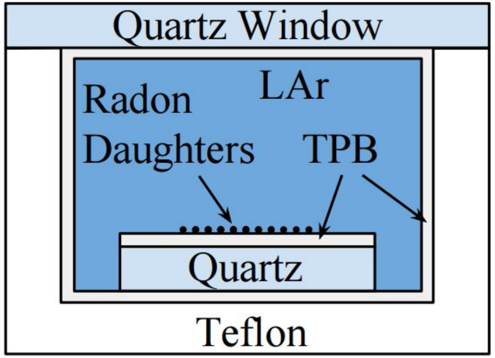
Evaporator

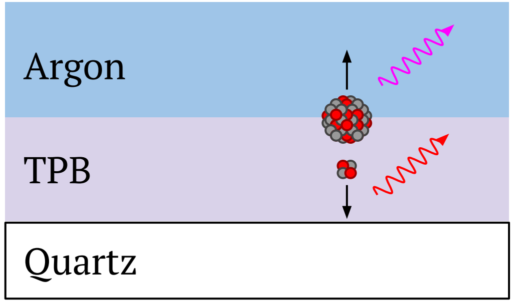
TPB Sample



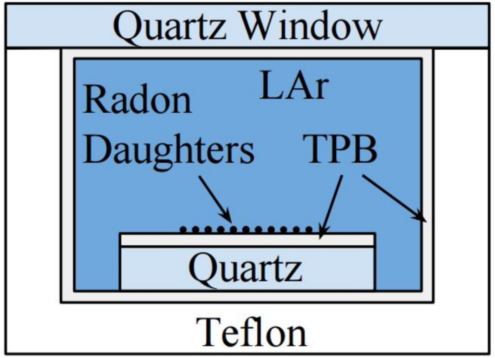
Radon Chamber

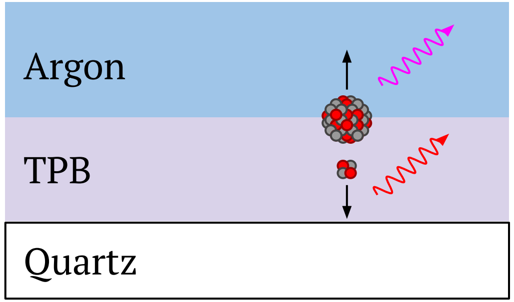
Background Confirmed

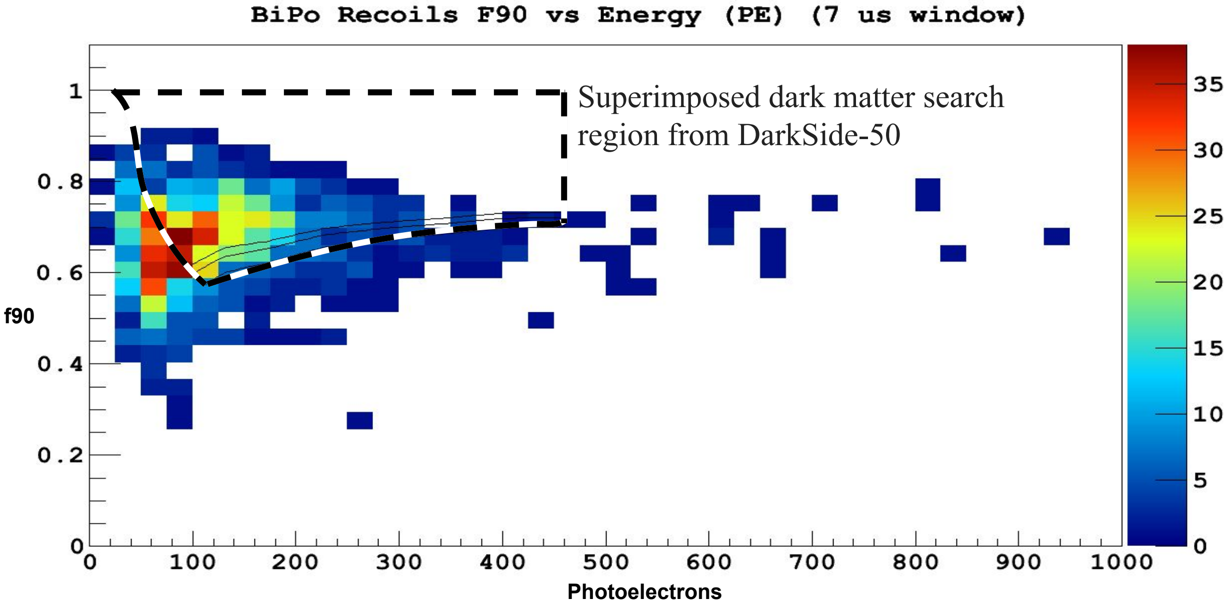




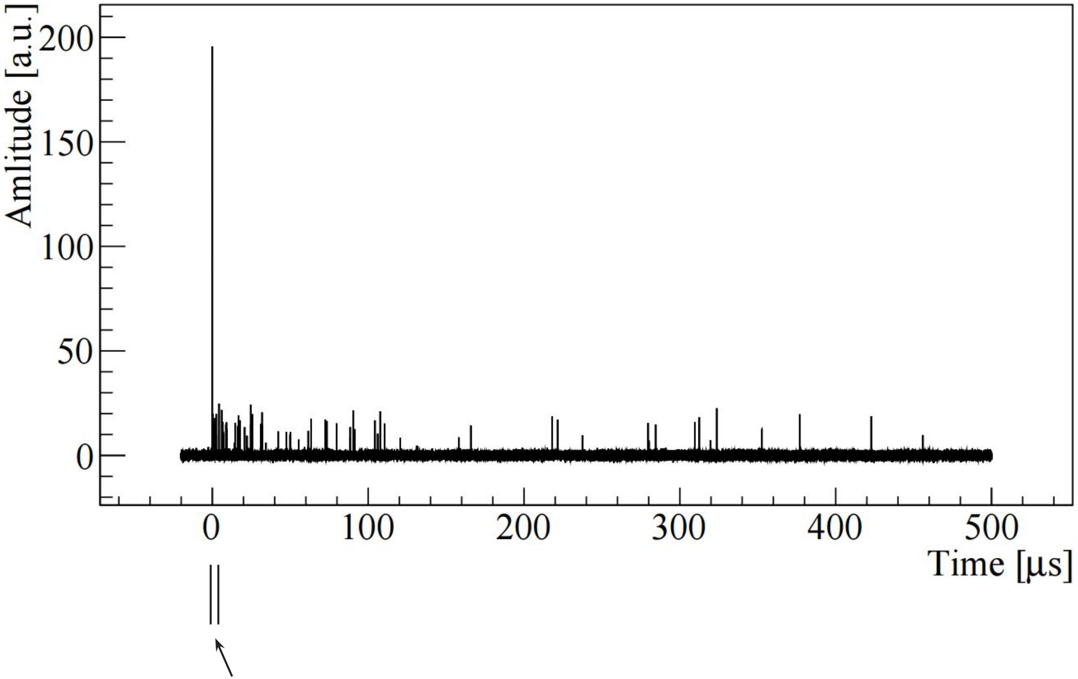
Background Confirmed







Long tail

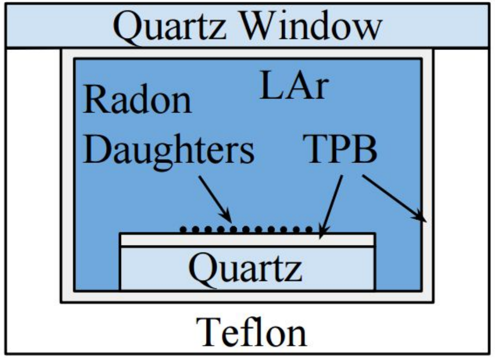


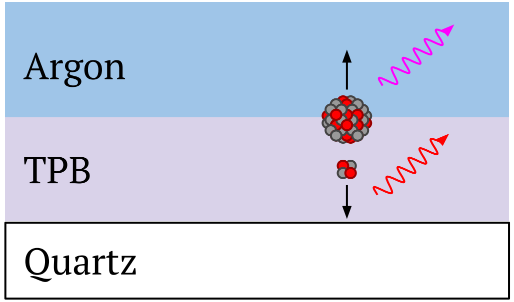
Original integration window

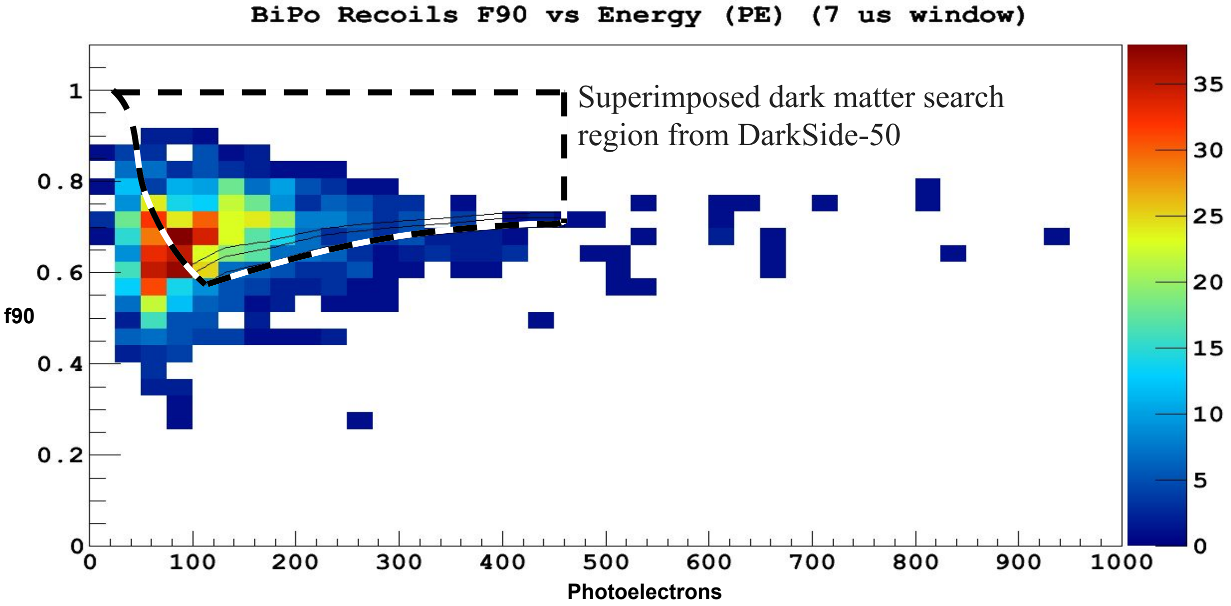
Millisecond-long scintillation lifetime, much longer than the LAr scintillation lifetimes.

f_{90} (7μs window) ~ 0.7 (nuclear recoil-like, bad)
f_{90} (2ms window) ~ 0.2 (good)

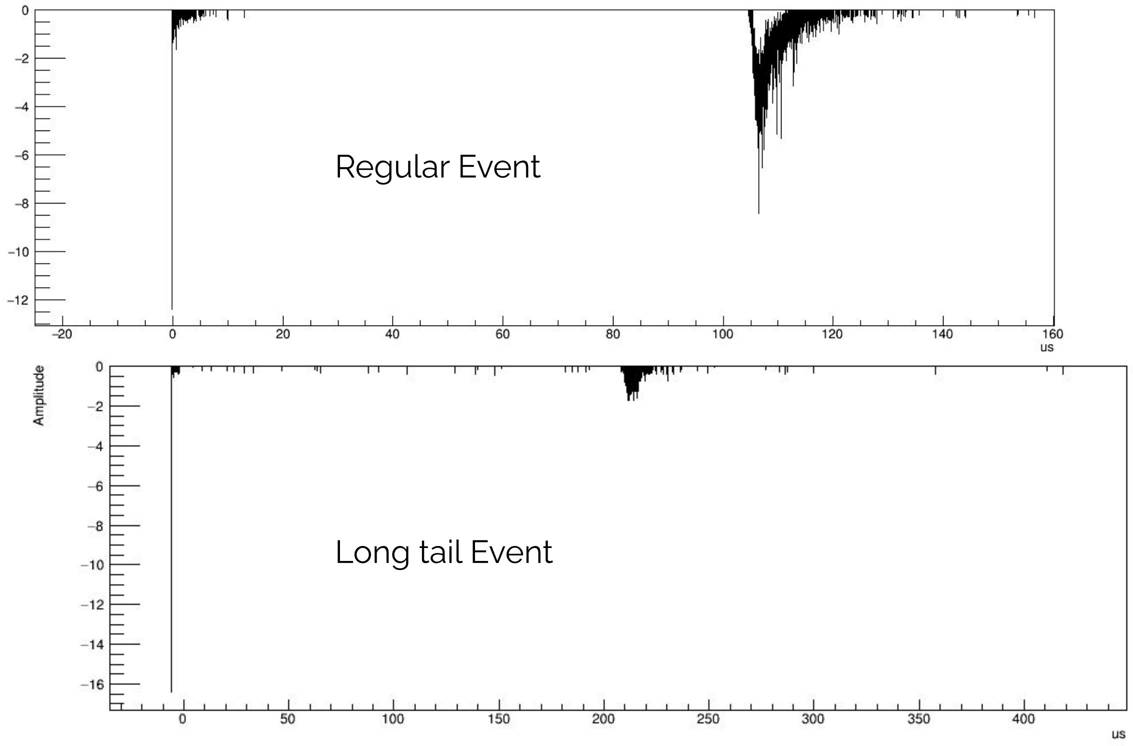
Background Confirmed



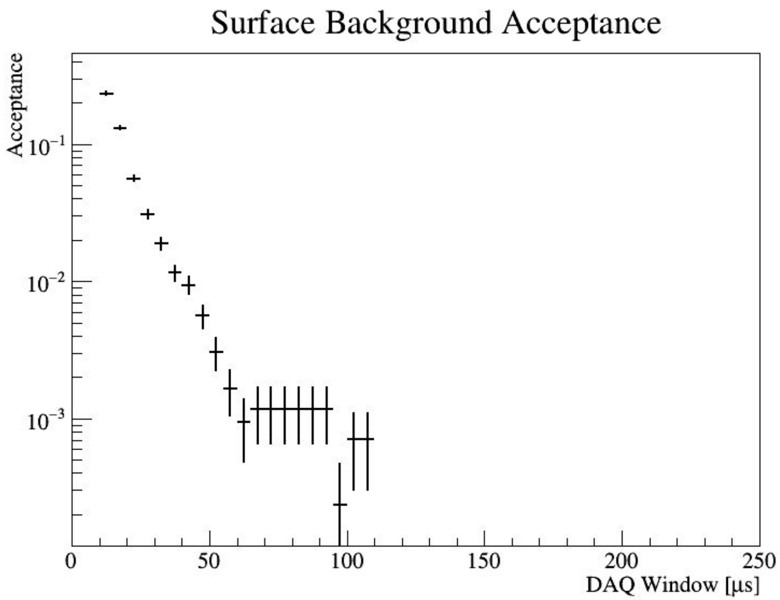




Seen in DarkSide-50 Data

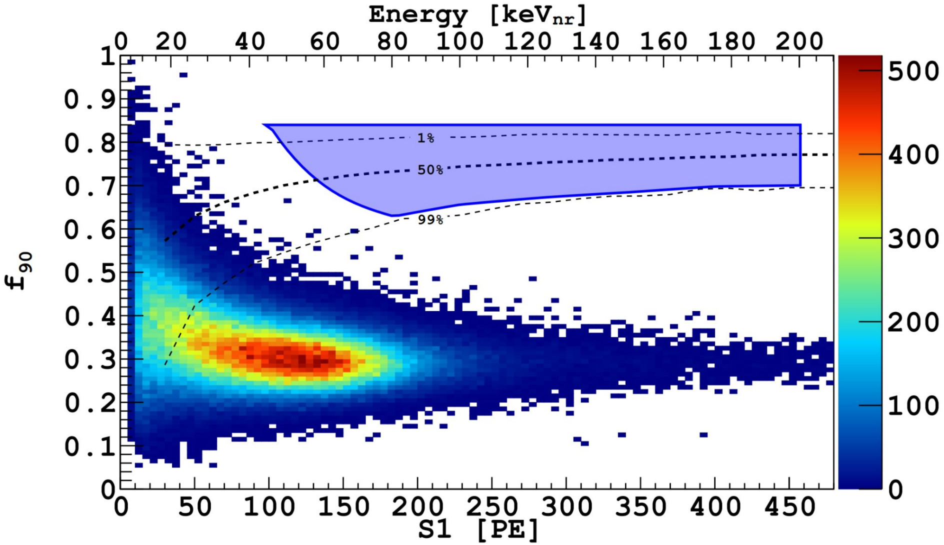


After Cuts



After developing a dedicated cut for this tail, we achieved greater than 10^3 rejection for surface background rejection while maintaining 99% nuclear recoil acceptance.

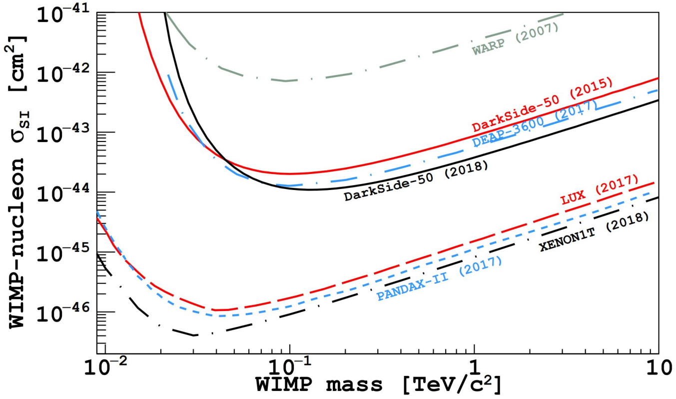
Result



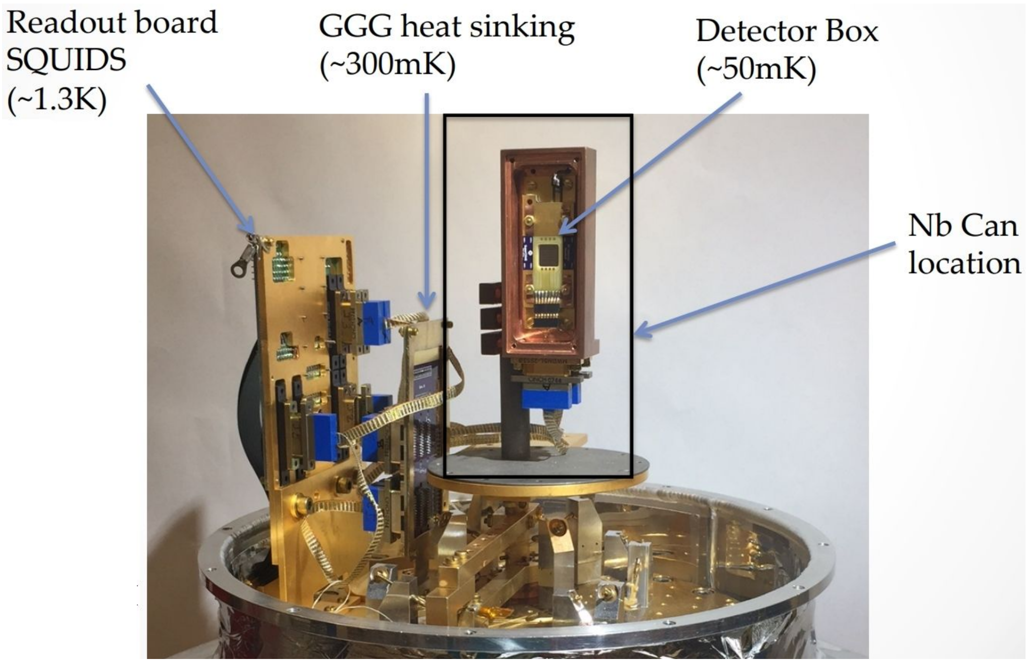
DarkSide-50 532-day dark matter search with low-radioactivity argon

P. Agnes *et al.* (DarkSide Collaboration)
Phys. Rev. D **98**, 102006 – Published 16 November 2018

As a result of this secondary instrumentation project, DarkSide-50 managed to succeed in its science goal of performing a background-free WIMP dark matter search.

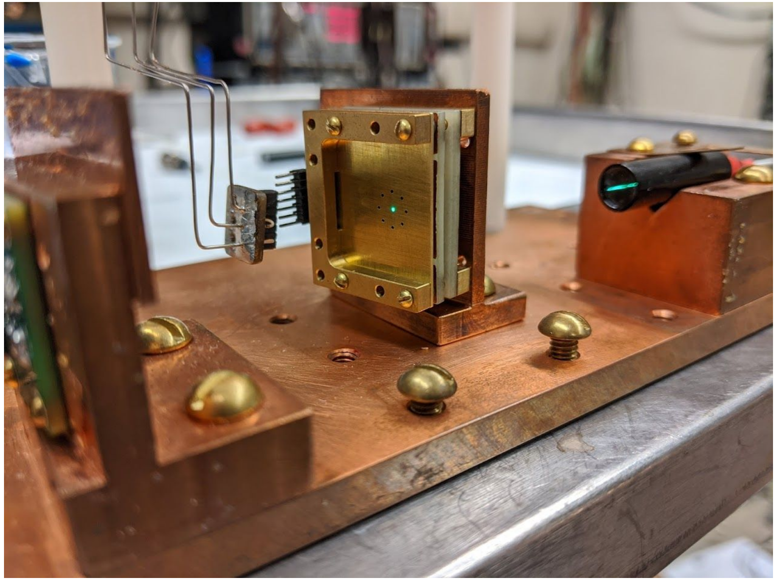


Experiment #2



SuperCDMS HVeV

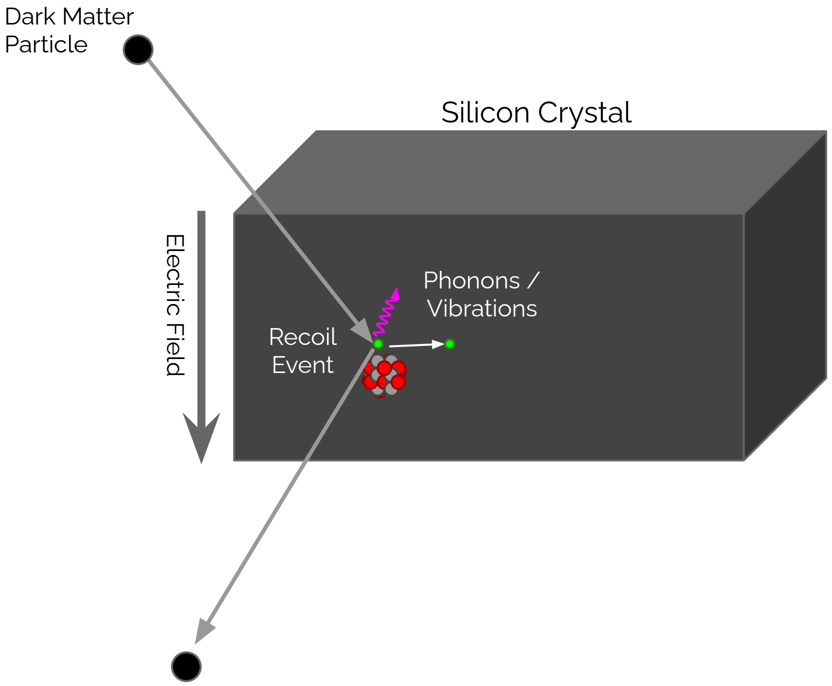
Secondary Instrumentation



A helium-3 fridge and optical system

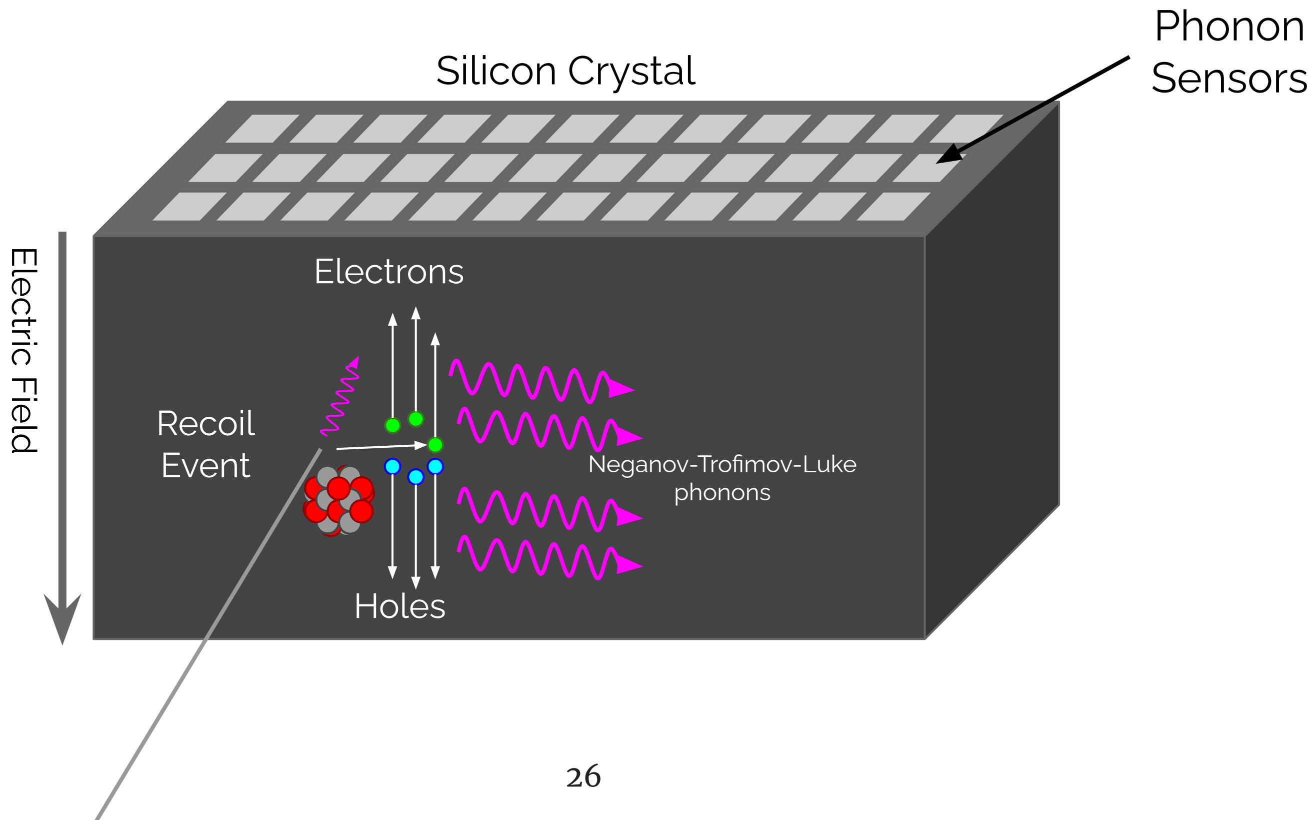
Science Goal: Low-mass Dark Matter Search

Result

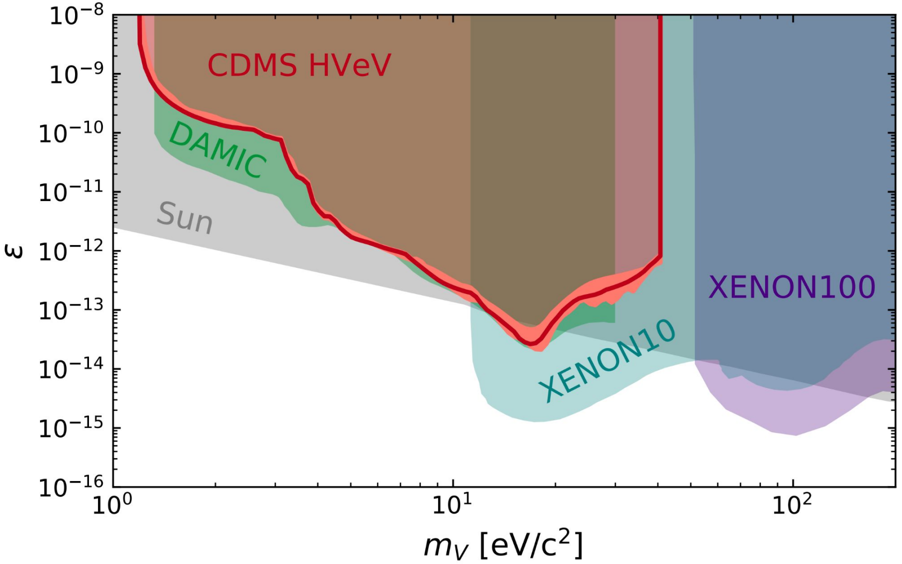


Dark Matter
Particle
Silicon Crystal
Electric Field
Phonons /
Vibrations
Recoil
Event

Result


Phonon
Sensors
Silicon Crystal
Electric Field
Electrons
Recoil
Event
Neganov-Trofimov-Luke
phonons
Holes

Dark Photon Search Results



First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector

R. Agnese *et al.*

Phys. Rev. Lett. **121**, 051301 – Published 3 August 2018; Erratum Phys. Rev. Lett. **122**, 069901 (2019)

In order to make a plot like this, you need to know the expected interaction rate of the dark photon for a given mass and cross-section.

Cross-sections

Dark photons

$$\sigma_{A'}(E_{A'}) = \frac{\varepsilon_{\text{eff}}^2}{v_{A'}} \sigma_{\text{p.e.}}(E_{A'}) n\hbar c$$

Axion-like particles

$$\sigma_a(m_a) = \sigma_{\text{p.e.}}(m_a c^2) \frac{g_{ae}^2}{\beta_a} \frac{3m_a^2}{16\pi\alpha m_e^2}$$

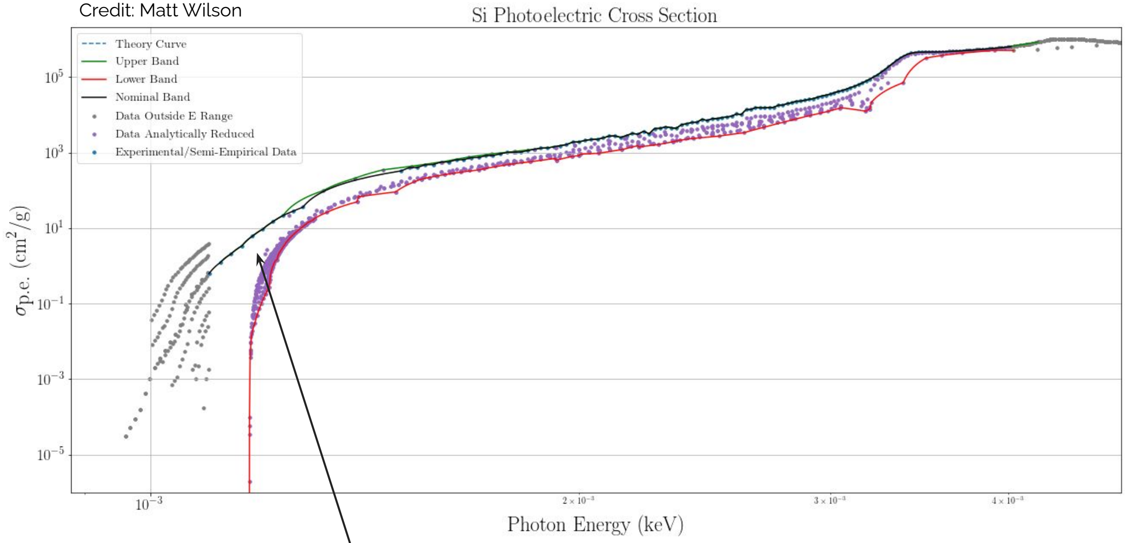
Also found in bremsstrahlung and Migdal effect searches.

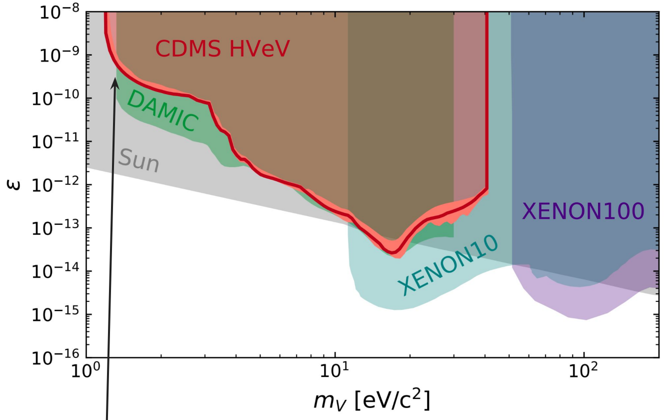
These searches are directly dependent upon σ_{PE}, the photoelectric absorption cross-section of the standard model photon with the target material.

But σ_{PE} was not well known at < 1 K temperatures.

Cross-sections

Credit: Matt Wilson

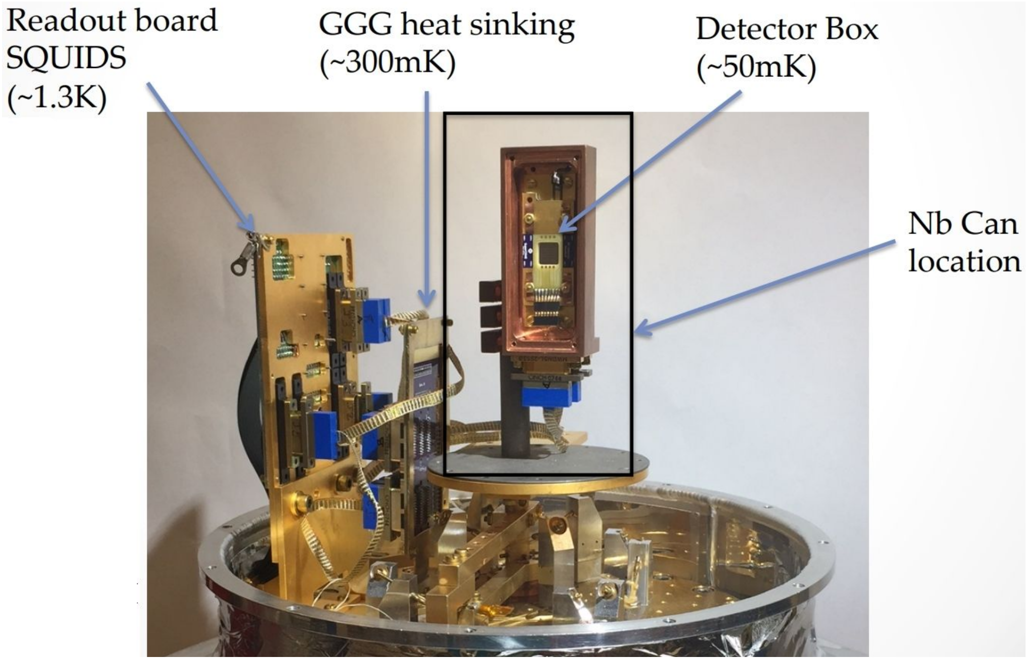




Order of magnitude discrepancy here…

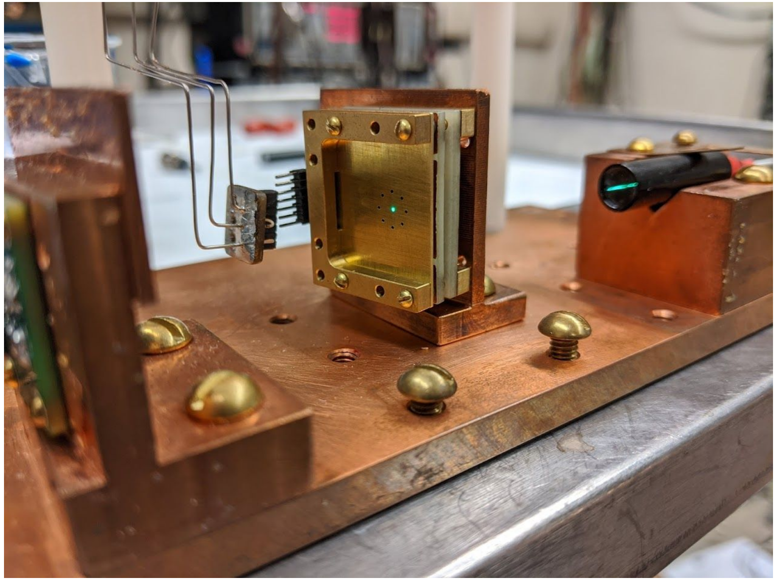
…leads to order of magnitude uncertainty here

Experiment #2



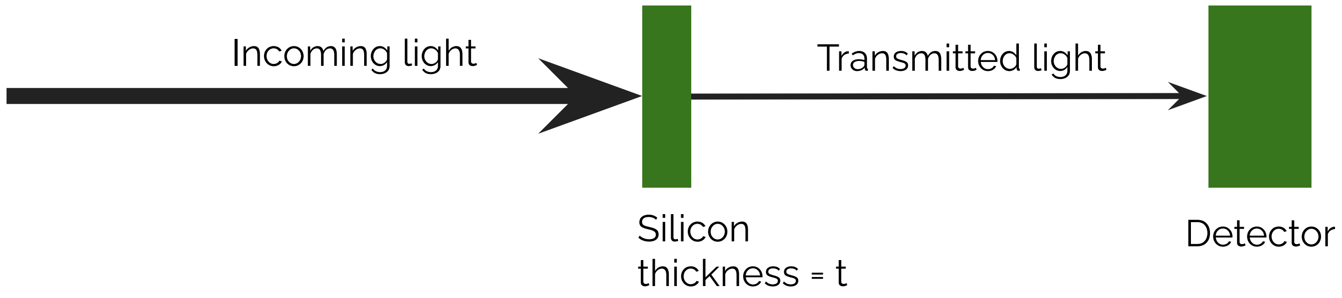
SuperCDMS HVeV

Secondary Instrumentation



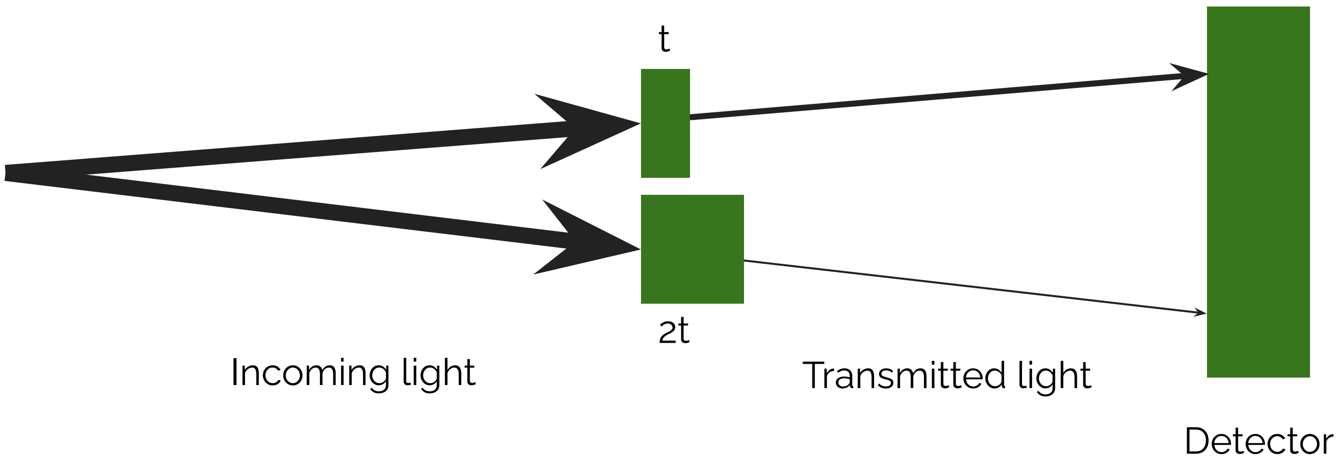
A helium-3 fridge and optical system

Measuring σ_{PE}(E) at <1 K



Absolute measurements of σ_{PE} are difficult. They require knowing things like the precise amount of incoming light, the amount of reflected light, the quantum efficiency of the detector, etc.

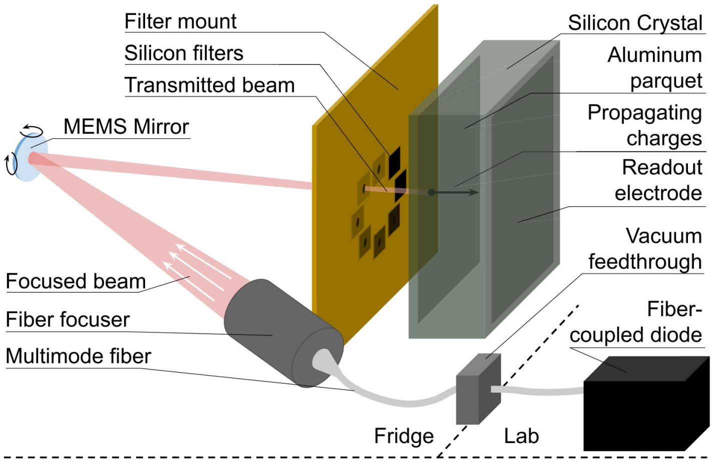
Relative Measurement

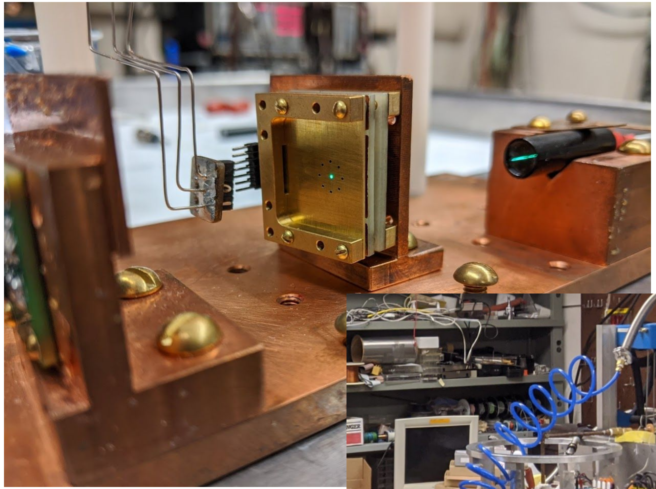


Our solution was to perform a relative measurement, which eliminated all these systematics.

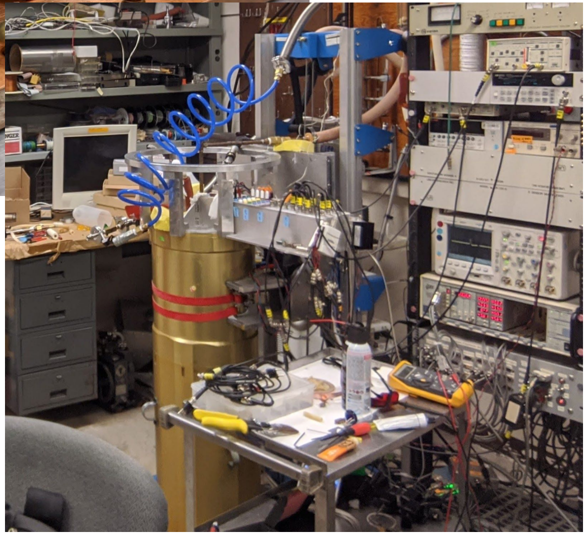
Secondary Instrumentation

We built a dedicated experiment to perform this measurement at <1K



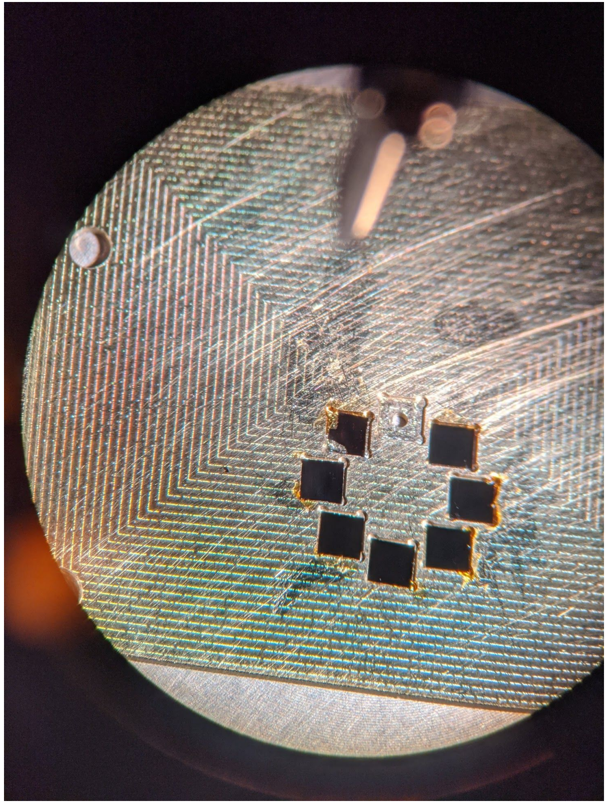


Cold stage

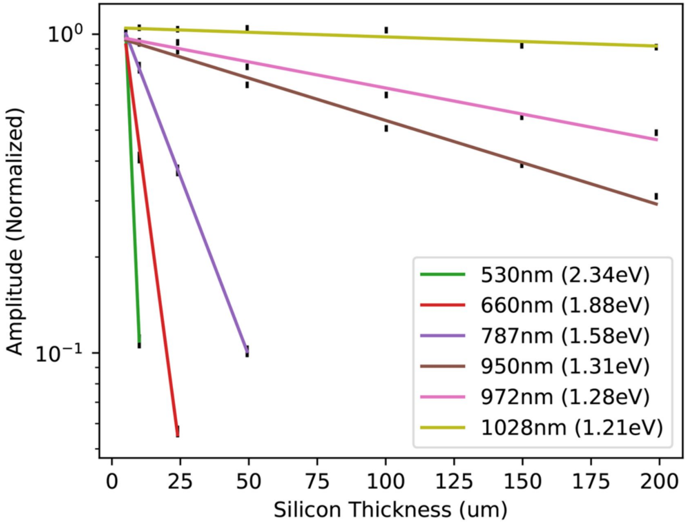


Fridge

Si Wafers



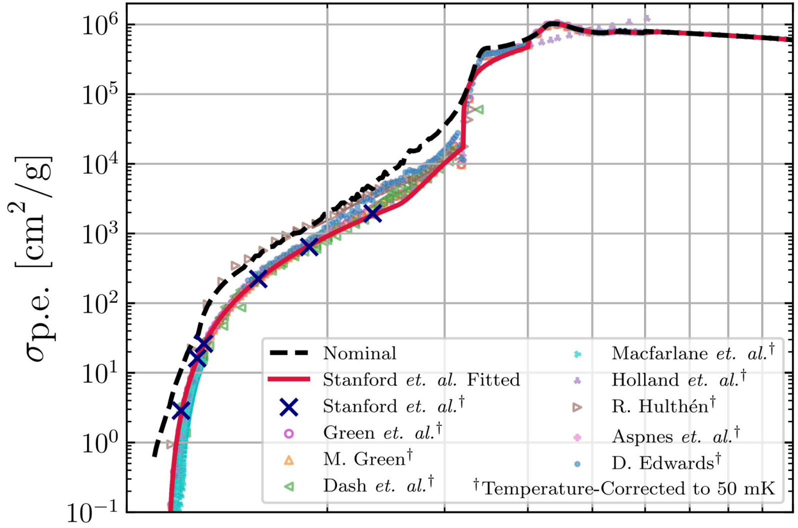
Results



Photoelectric absorption cross section of silicon near the bandgap from room temperature to sub-Kelvin temperature

AIP Advances 11, 025120 (2021); https://doi.org/10.1063/5.0038392

C. Stanford[1,2,a], M. J. Wilson[3,4], B. Cabrera[1,5,b], M. Diamond[3], N. A. Kurinsky[6,7], R. A. Moffatt[1], F. Ponce[1], B. von Krosigk[4], *and* B. A. Young[8]



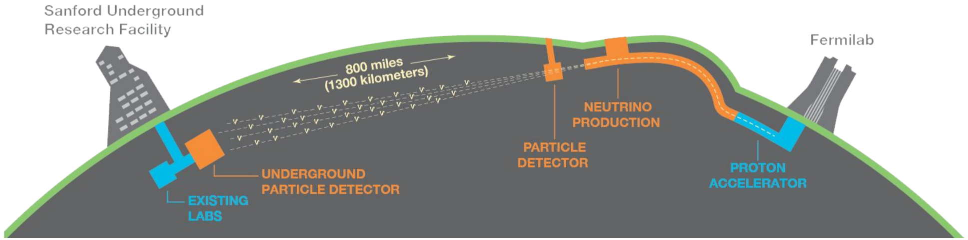
Effect on dark matter exclusion limits from new silicon photoelectric absorption measurements

B. von Krosigk, M. J. Wilson, C. Stanford, B. Cabrera, R. Calkins, D. Jardin, N. A. Kurinsky, F. Ponce, and C.-P. Wu
Phys. Rev. D **104**, 063002 – Published 8 September 2021

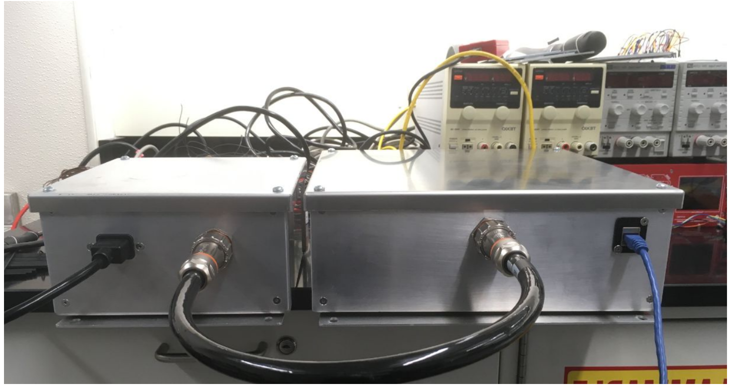
As a result of this instrumentation project, the SuperCDMS HVeV detectors (and all other Si-based dark matter detectors) are now able to accurately state their science results.

Experiment #3

Secondary Instrumentation



DUNE

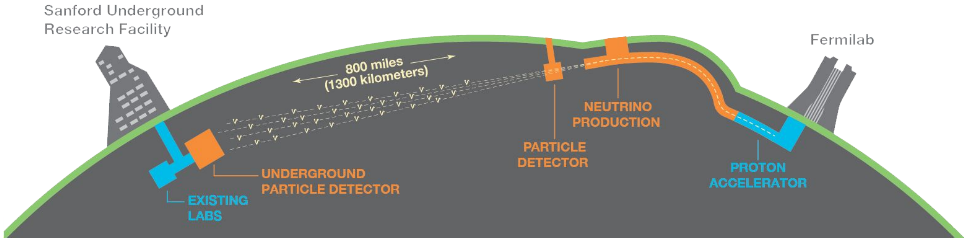


The Digital Wire Analyzer

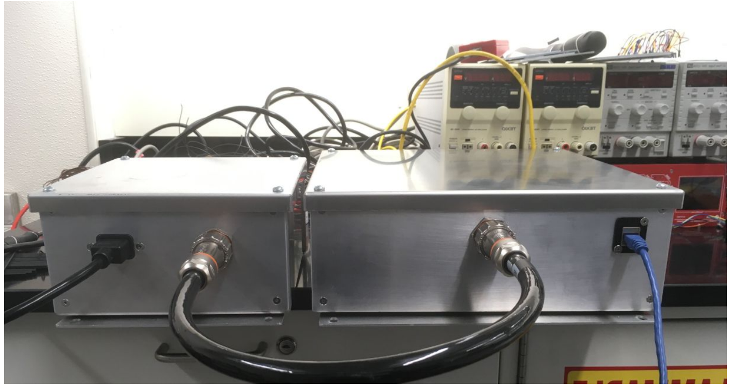
Primary science goals: neutrino mass hierarchy and CP violating phase angle

Experiment #3

Secondary Instrumentation



DUNE

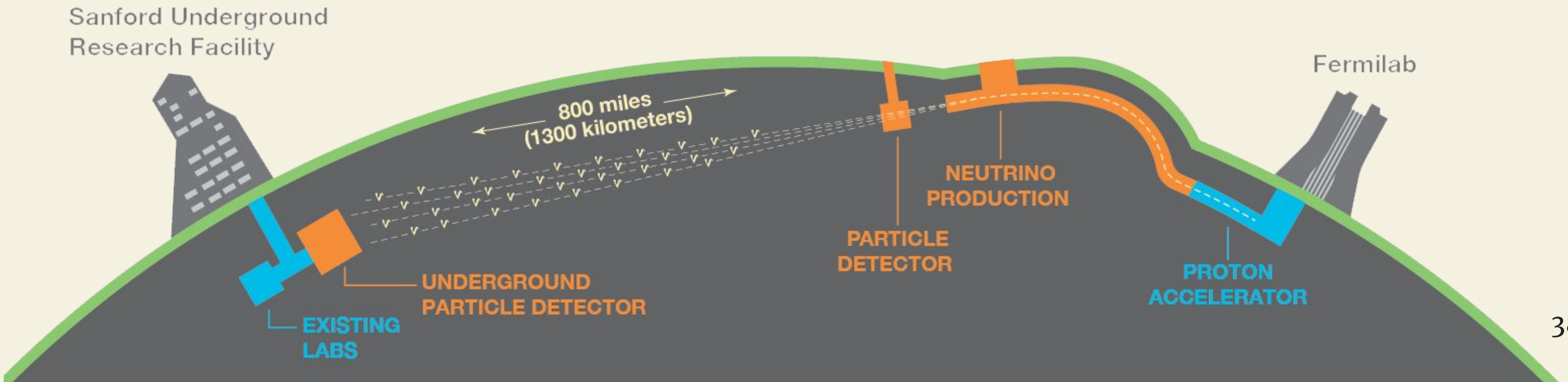


The Digital Wire Analyzer

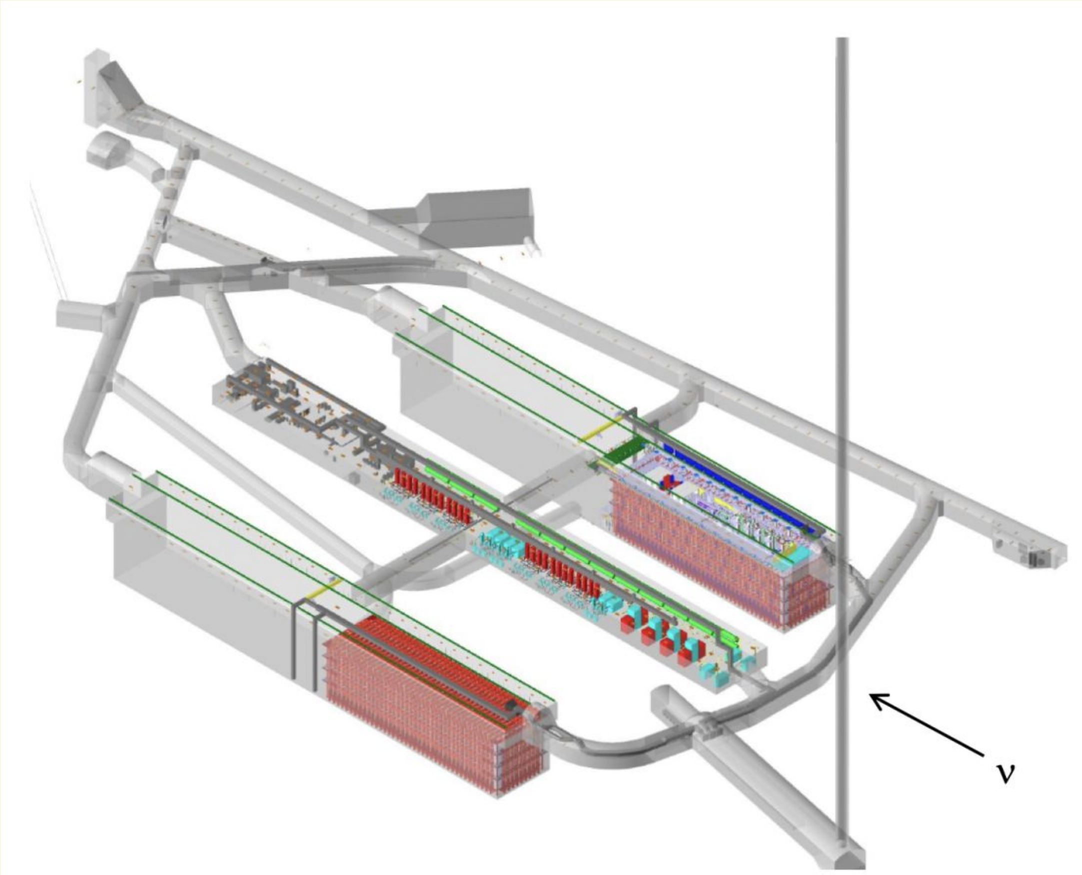
Primary science goals: neutrino mass hierarchy and CP violating phase angle

Low-energy: Solar and supernova ν sensitivity
BSM: dark matter, sterile ν, non-standard ν interactions, CPT violation, and other new physics

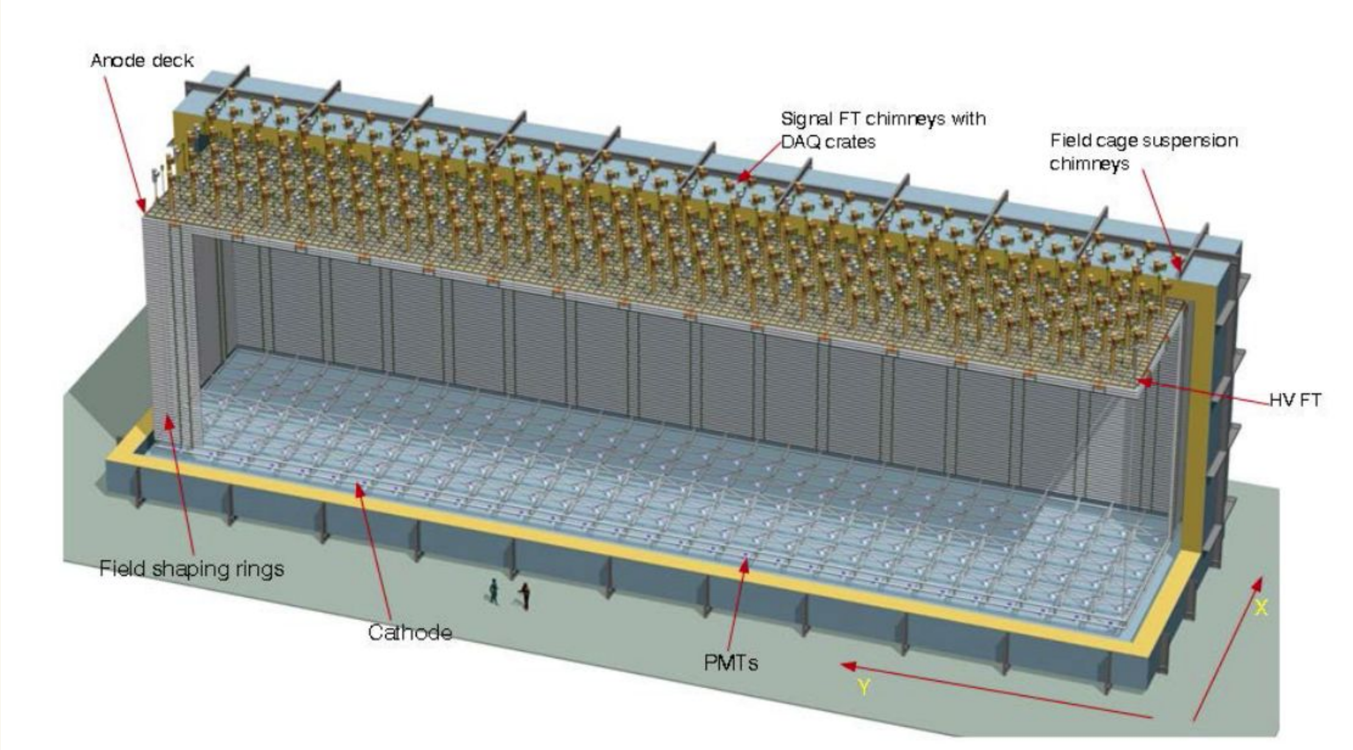
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



Sanford
Underground
Research
Facility

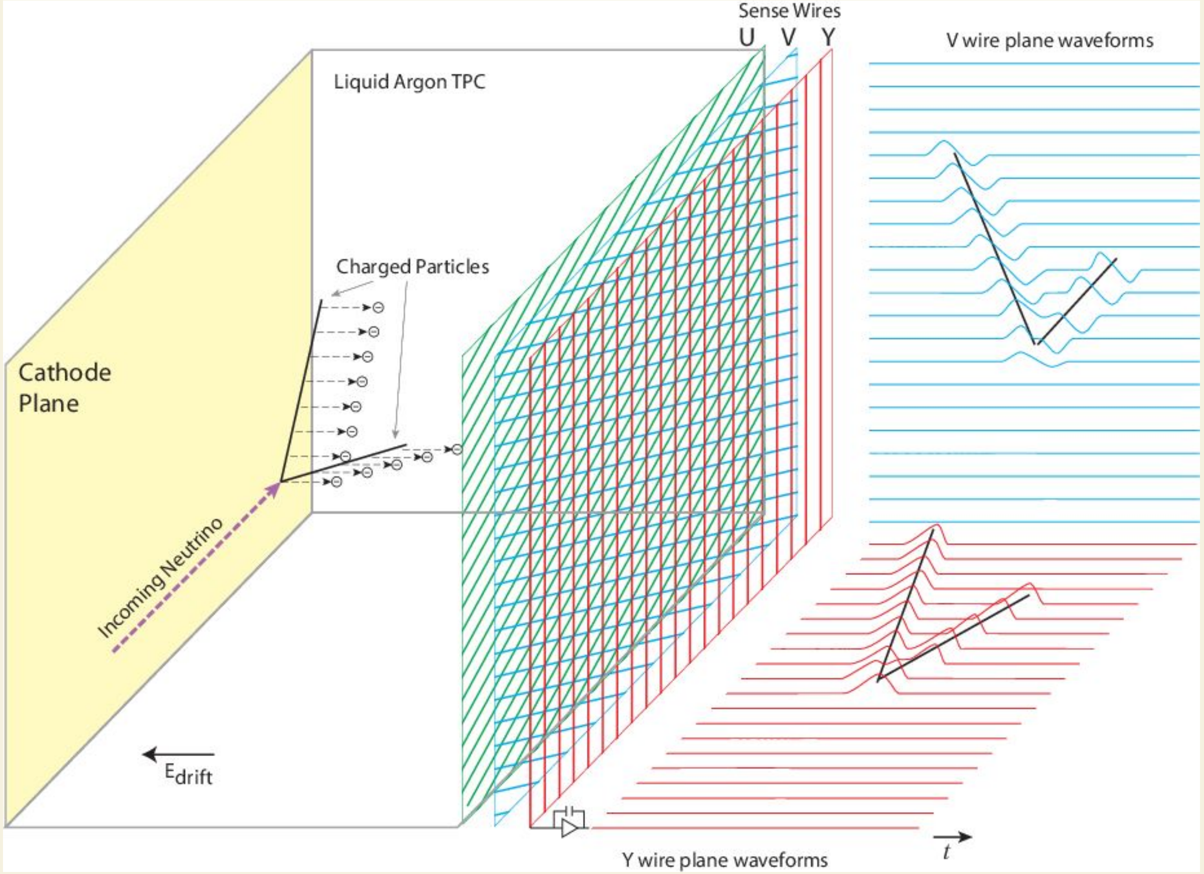


Far Detector Module

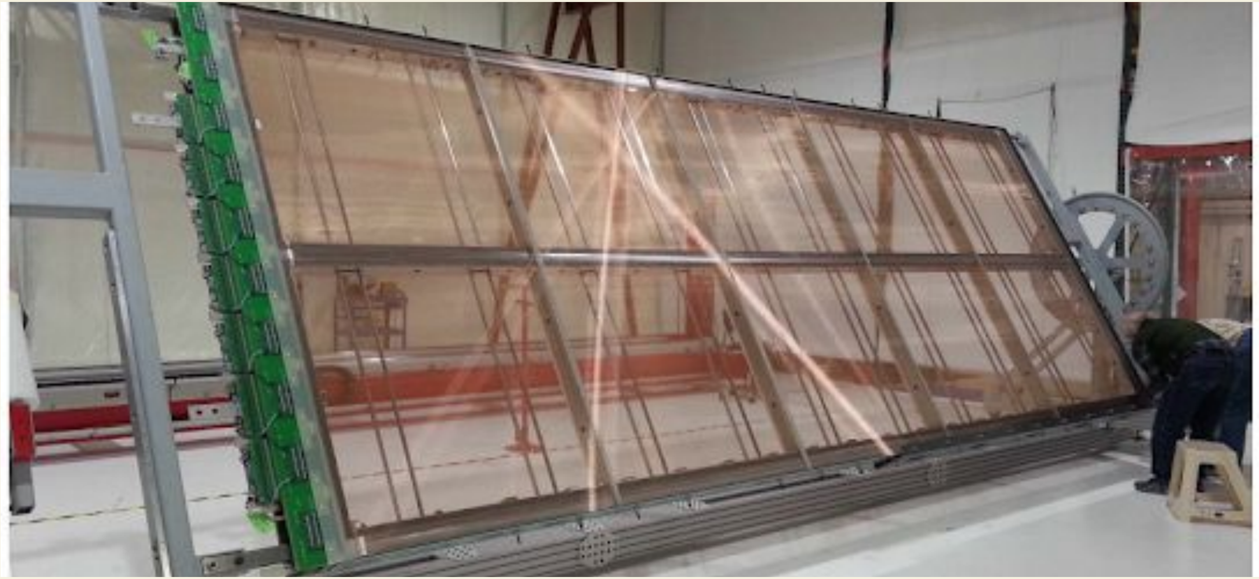


Liquid
Argon

Time
Projection
Chamber



Anode
Plane
Assembly

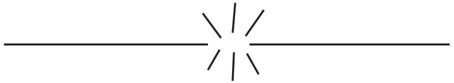


Wire Tensions

Wires in an plane assemblies have tension tolerances

Too loose: 

Might touch neighboring wire or pick up too much noise

Too tight: 

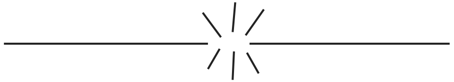
Might snap after cooling, shorting wires and ruining detector

Wire Tensions

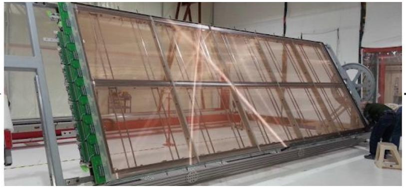
Wires in an plane assemblies have tension tolerances

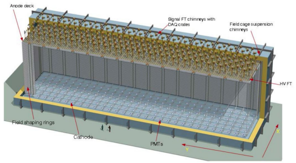
Too loose: 

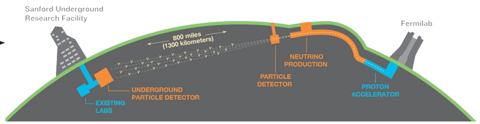
Might touch neighboring wire or pick up too much noise

Too tight: 

Might snap after cooling, shorting wires and ruining detector

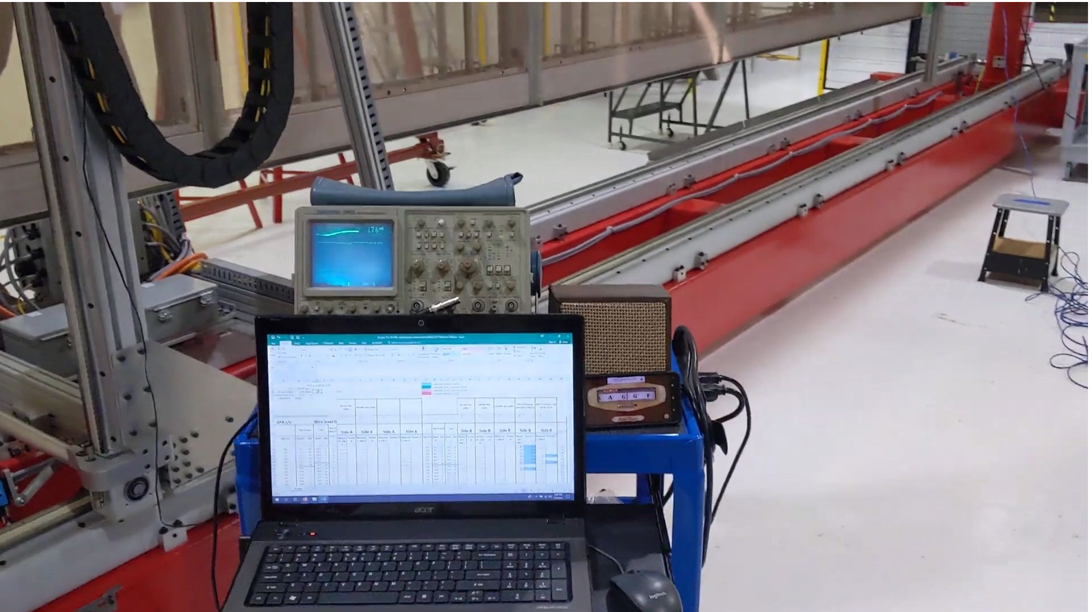




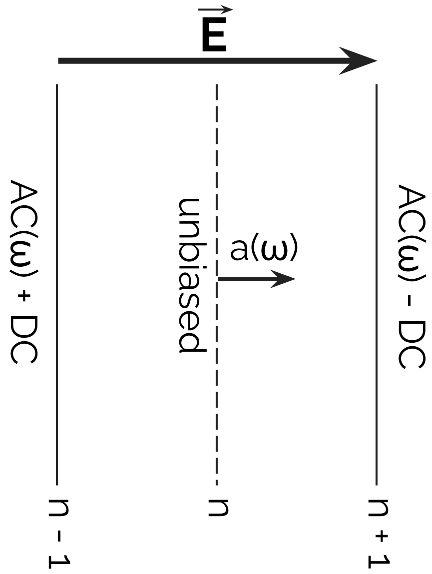


Wire Tensions: Laser Method

Wires tensions in APAs are traditionally measured individually and are time consuming to measure. Each APA has over 5000 wires and takes 2 people ~80 hours.



The Electrical Method



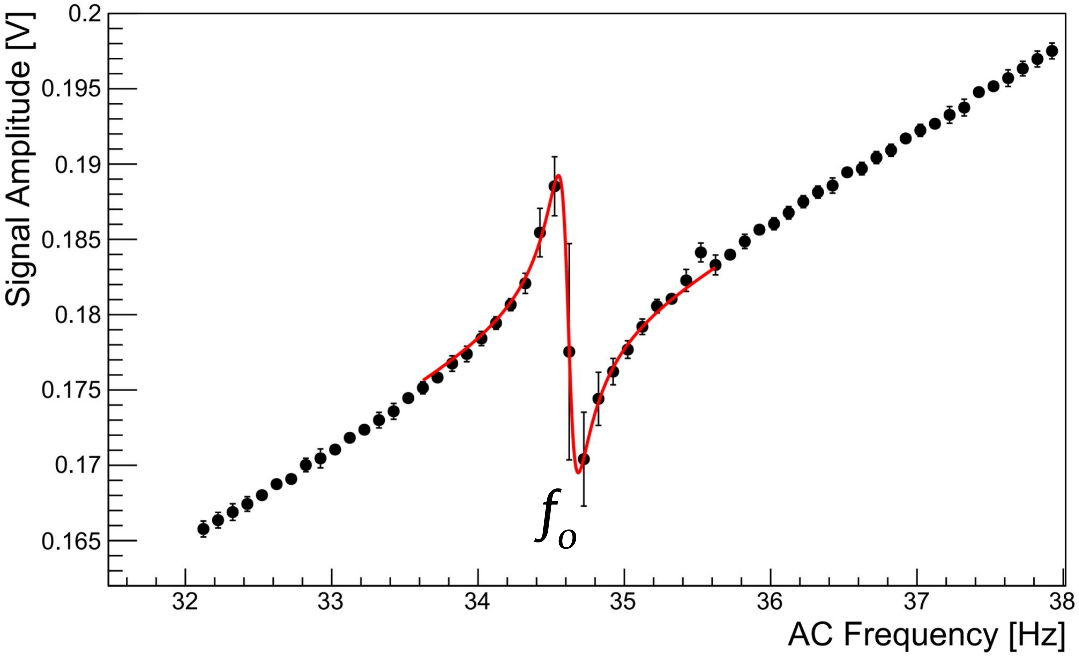
Channels n-1 and n+1 biased with AC(ω) and DC.

The frequency ω is varied, while the voltage of channel n is read out.

The frequency at which the wire resonates determines the tension.

Based on concept outlined in D. Garcia-Gamez et al. (2019): https://doi.org/10.1016/j.nima.2018.09.031

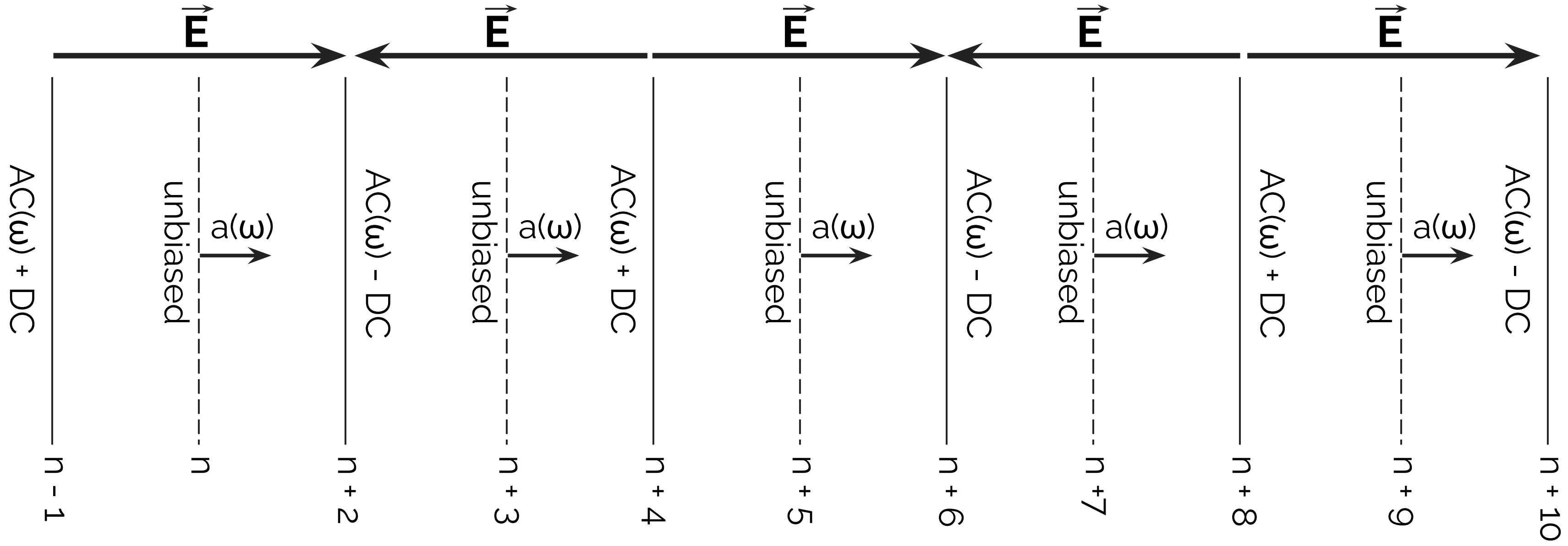
Proof of concept



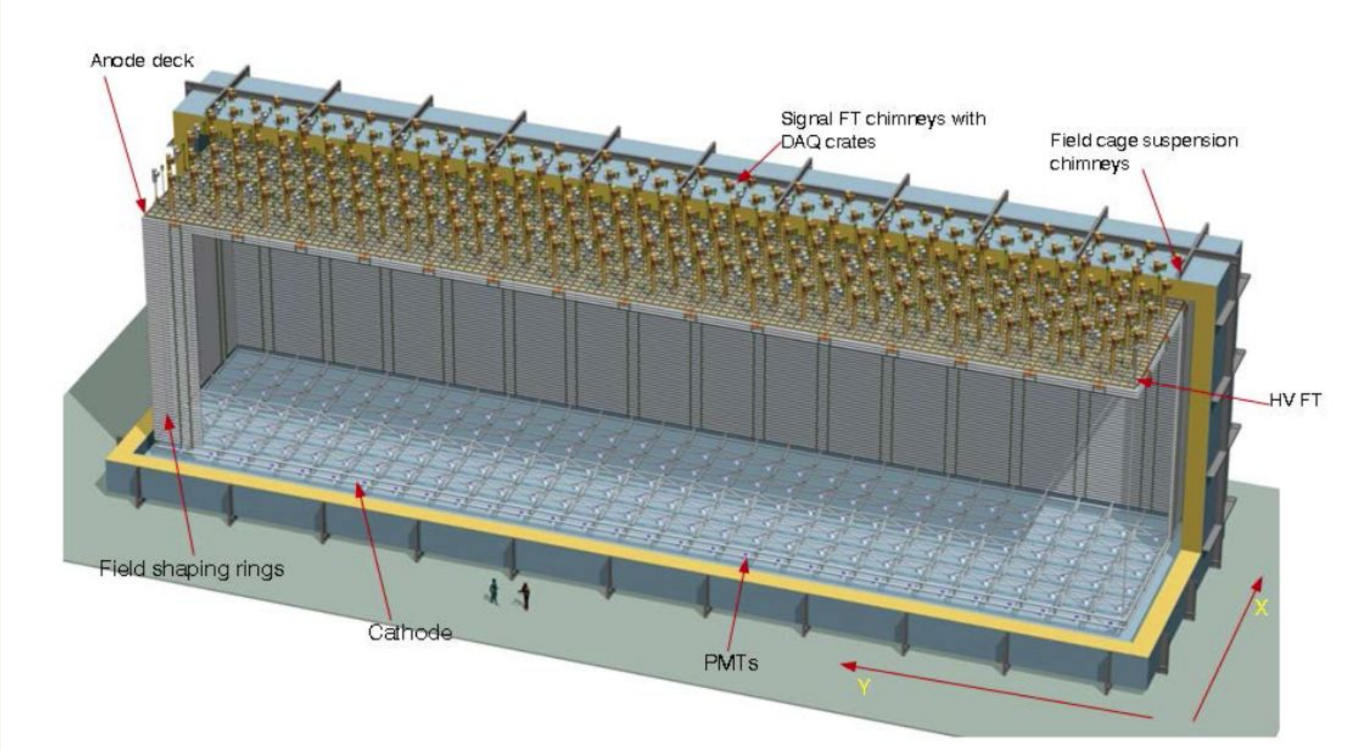
$$T = 4\mu L^2 f_o^{\,2}$$

D. Garcia-Gamez et al. (2019): https://doi.org/10.1016/j.nima.2018.09.031

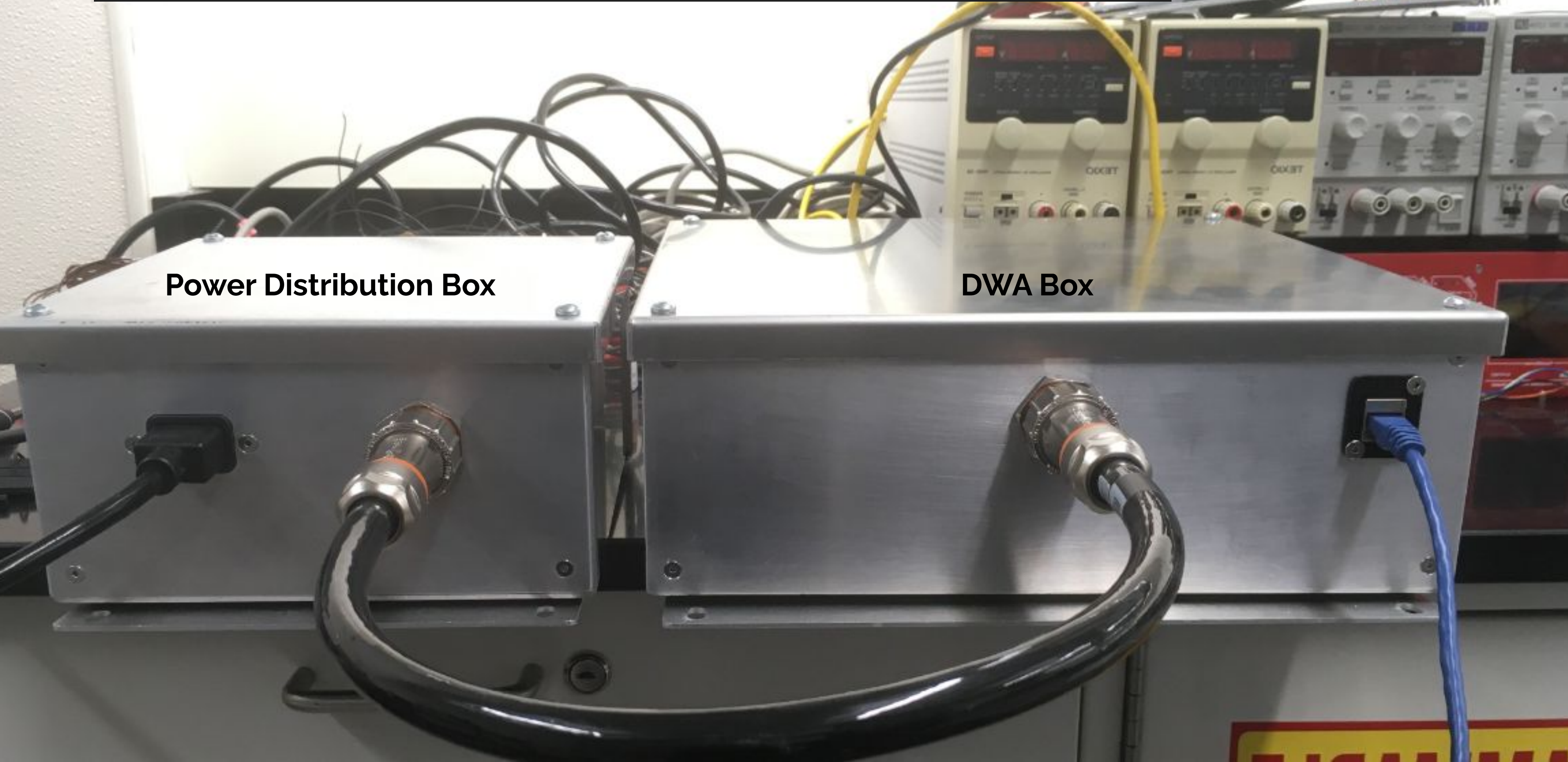
The Electrical Method

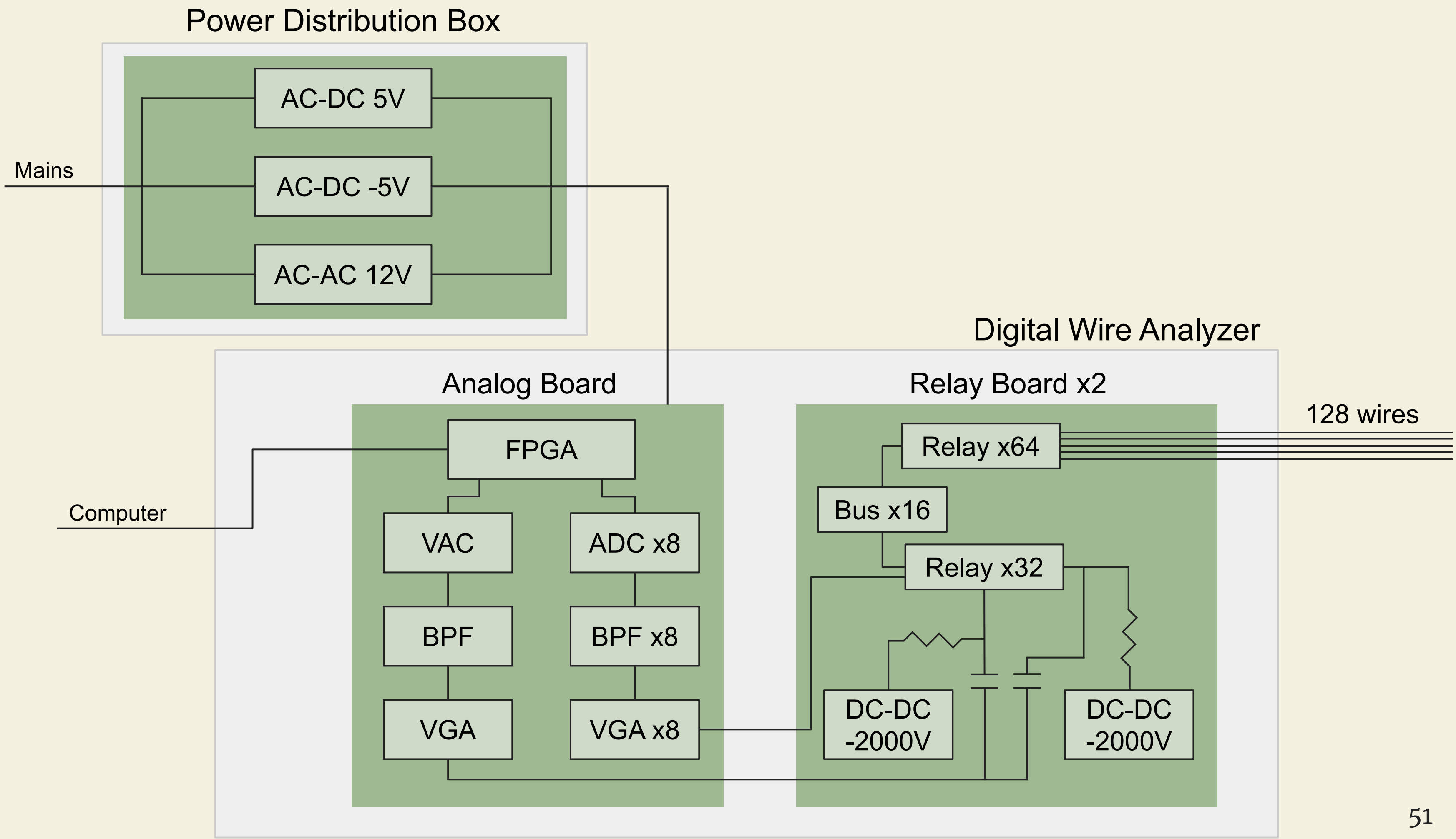


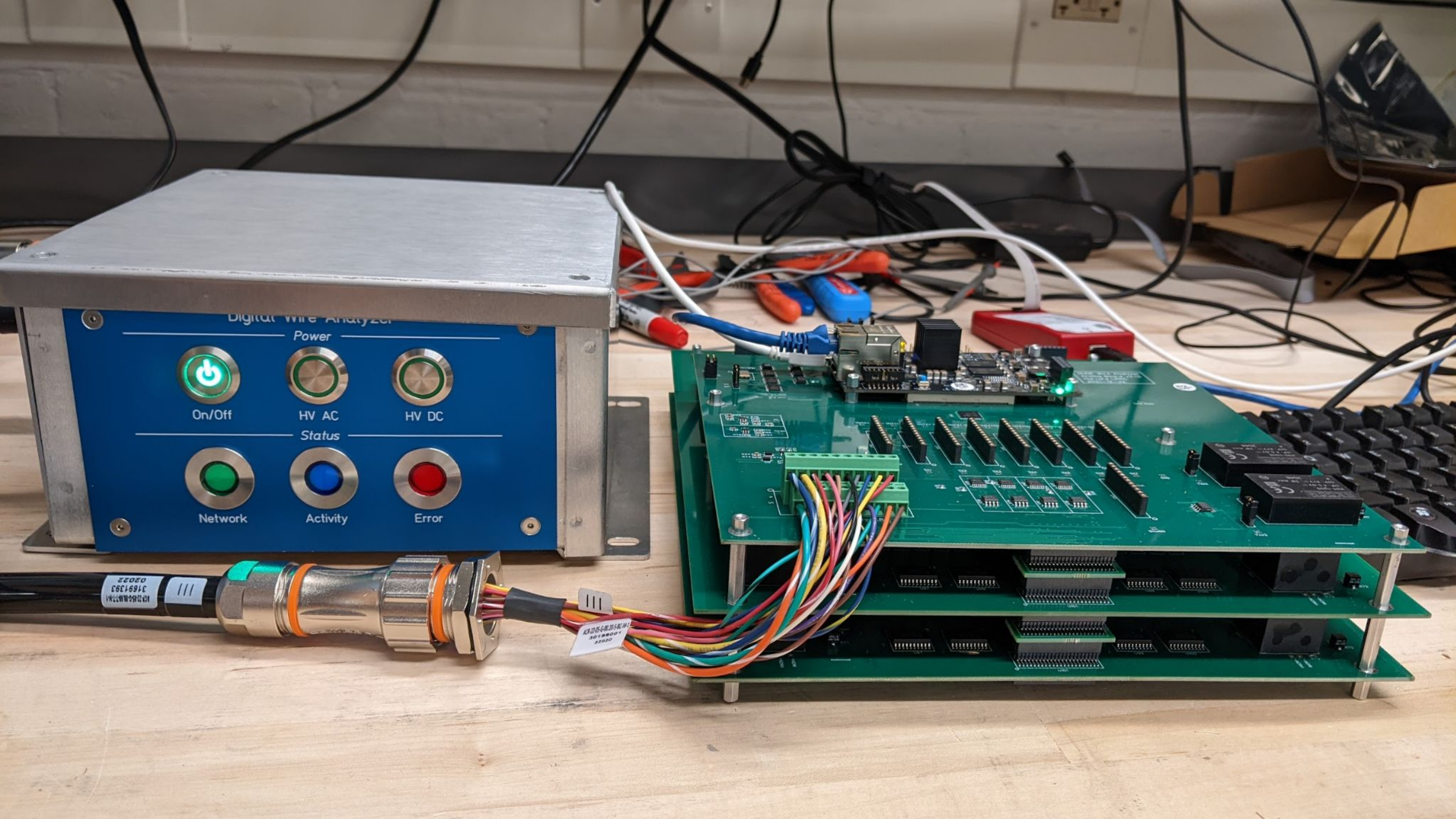
Also, the wires are not always physically accessible.



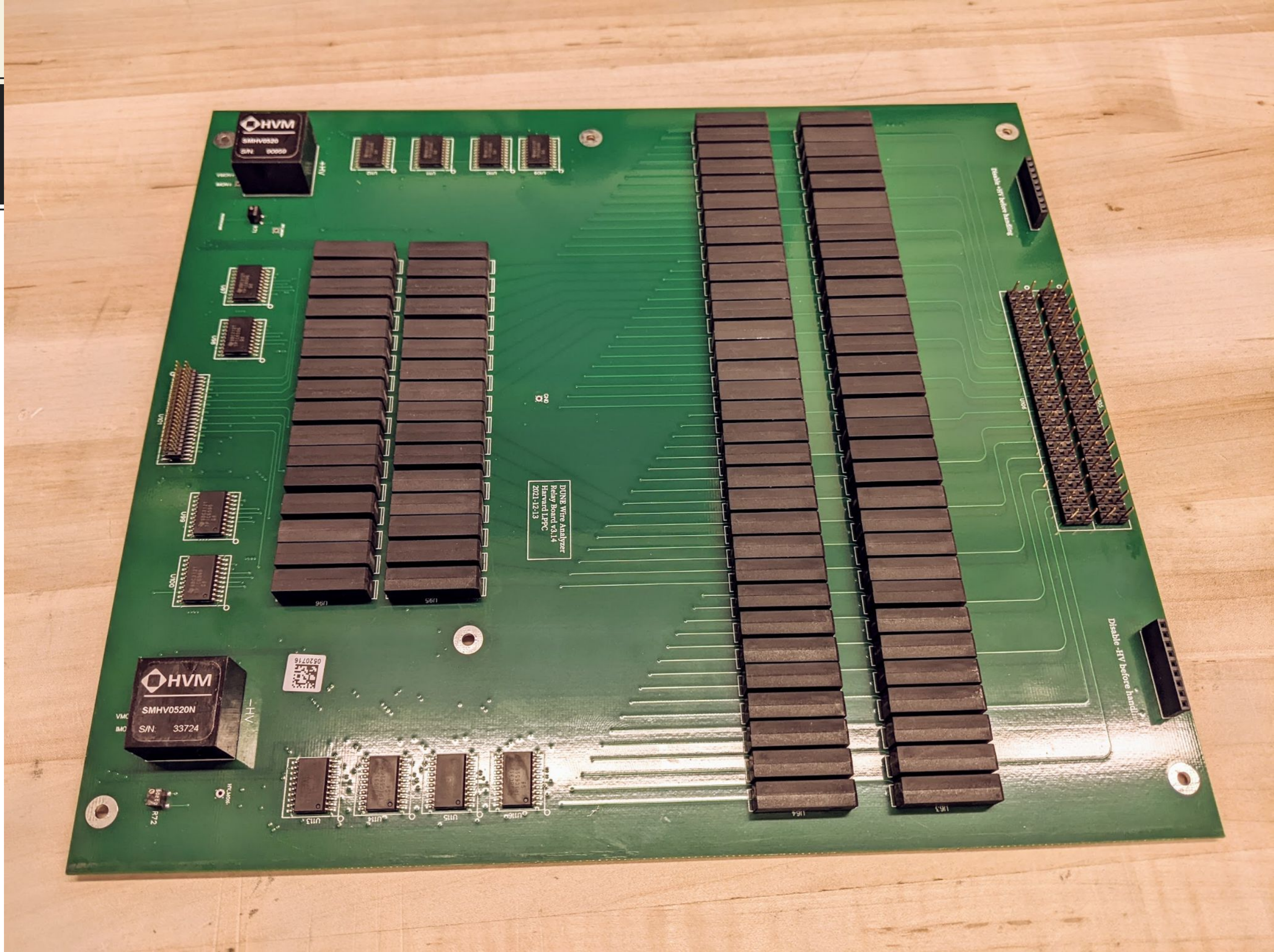
Secondary Instrumentation: Digital Wire Analyzer (DWA)



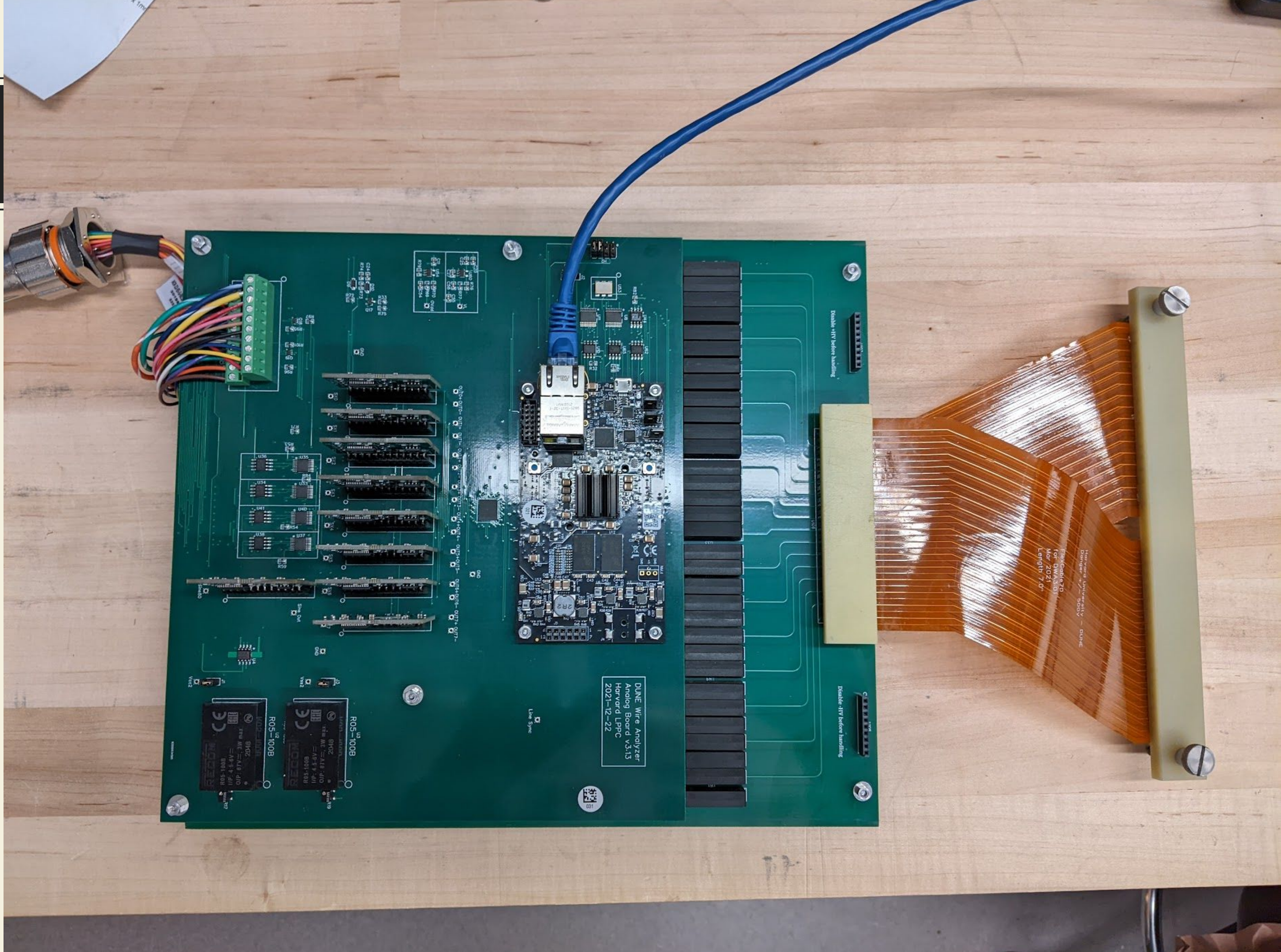

Power Distribution Box
AC-DC 5V
AC-DC -5V
AC-AC 12V
Mains
Digital Wire Analyzer
Analog Board
Relay Board x2
128 wires
FPGA
Computer
VAC
ADC x8
BPF
BPF x8
VGA
VGA x8
Relay x64
Bus x16
Relay x32
DC-DC
-2000V
DC-DC
-2000V


Power
On/Off
HV AC
HV DC
Status
Network
Activity
Error

Relay Board (x2)



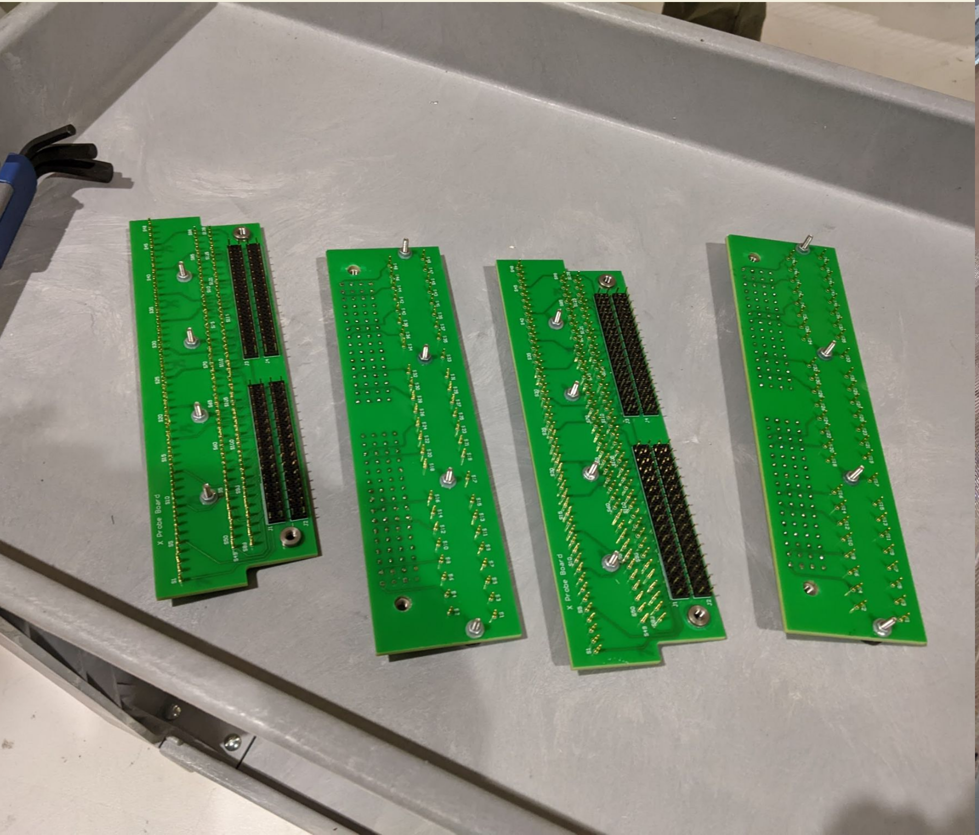
Flex Cable



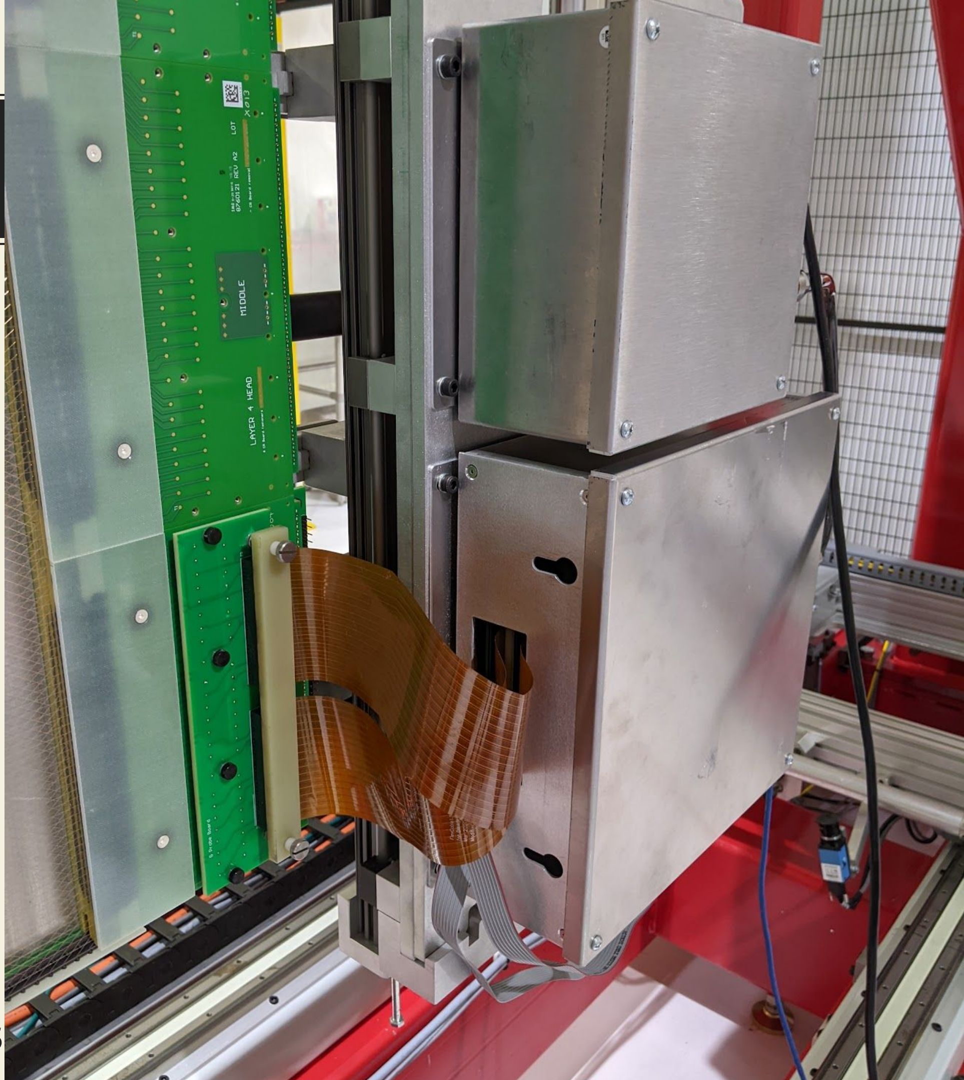
DUNE Wire Analyzer
Analog Board v3.13
Harvard LPPC
2021-12-22
R05-100B
R05-100B
Disable +HV before handling
Disable +HV before handling

Connecting to an APA

Probe Boards



Connecting to an APA



Support

Software

Connect | 300100002-0001-US200-01-00-00 | Start

DWA Info

Not Connected

DWA MAC N/A

DWA IP N/A

Client IP N/A

Serial # N/A

Firmware N/A

Period N/A

State N/A

HV AC HV DC

Error state N/A

Heartbeat *

Run Status

Scan freqs [Hz]

Min ....

Max .....

Step .....

Active .....

Stimulus / Results / Tensions / Log / Event Viewer

Config | Advanced | V(t) grid | V(t) chan | A(f) grid | A(f) chan

Measured By: Chris Stanford

Stage: DWA Development

Layer: G

Side: A

Headboard: 1

Type: ☑ Continuity ☑ Tension

Configure Scan List

DWA is not connected

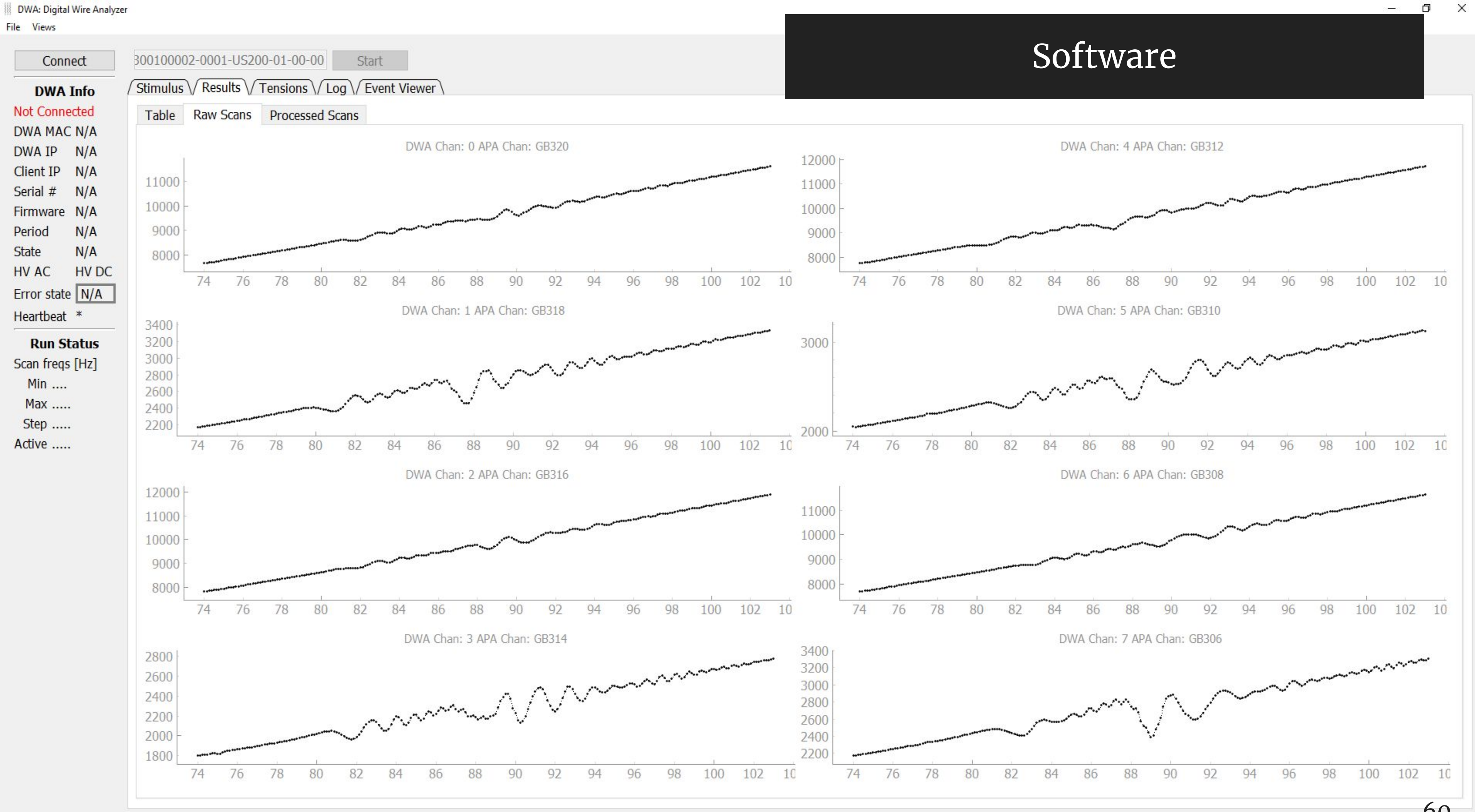
	Type	Status	Wires	Freq Min (Hz)	Freq Max (Hz)	Step Size (Hz)
1	Continuity	Pending	[2, 4, 6, 8, 10, 12, 14, 16]	100	950	50
2	Tension	Pending	[2, 4, 6, 8, 10, 12, 14, 16]	74	102	0.125
3	Continuity	Pending	[3, 5, 7, 9, 11, 13, 15, 17]	100	950	50
4	Tension	Pending	[3, 5, 7, 9, 11, 13, 15, 17]	74	102	0.125
5	Continuity	Pending	[18, 20, 22, 24, 26, 28, 30, 32]	100	950	50
6	Tension	Pending	[18, 20, 22, 24, 26, 28, 30, 32]	74	102	0.125
7	Continuity	Pending	[19, 21, 23, 25, 27, 29, 31, 33]	100	950	50
8	Tension	Pending	[19, 21, 23, 25, 27, 29, 31, 33]	74	102	0.125
9	Continuity	Pending	[34, 36, 38, 40, 42, 44, 46, 48]	100	950	50
10	Tension	Pending	[34, 36, 38, 40, 42, 44, 46, 48]	74	102	0.125
11	Continuity	Pending	[35, 37, 39, 41, 43, 45, 47, 49]	100	950	50
12	Tension	Pending	[35, 37, 39, 41, 43, 45, 47, 49]	74	102	0.125
13	Continuity	Pending	[1]	100	950	50
14	Tension	Pending	[1]	74	102	0.125

Start selected scan

☐ Automate scanning

errorBits N/A buttonStatus N/A

Software


DWA: Digital Wire Analyzer
File
Views
Connect
300100002-0001-US200-01-00-00
Start
Stimulus
Results
Tensions
Log
Event Viewer
Table
Raw Scans
Processed Scans
DWA Info
Not Connected
DWA MAC N/A
DWA IP N/A
Client IP N/A
Serial # N/A
Firmware N/A
Period N/A
State N/A
HV AC HV DC
Error state N/A
Heartbeat *
Run Status
Scan freqs [Hz]
Min ....
Max .....
Step .....
Active .....
DWA Chan: 0 APA Chan: GB320
DWA Chan: 4 APA Chan: GB312
DWA Chan: 1 APA Chan: GB318
DWA Chan: 5 APA Chan: GB310
DWA Chan: 2 APA Chan: GB316
DWA Chan: 6 APA Chan: GB308
DWA Chan: 3 APA Chan: GB314
DWA Chan: 7 APA Chan: GB306

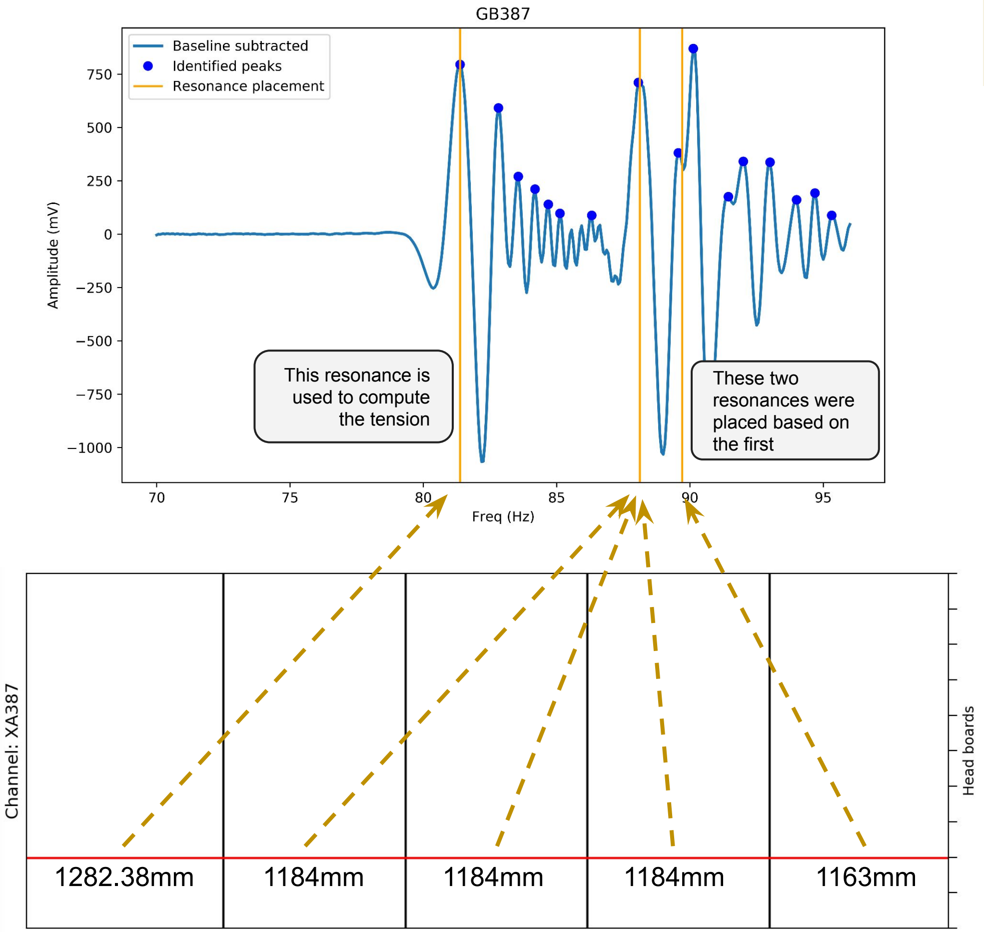
Software

DWA: Digital Wire Analyzer
File
Views
Connect
300100002-0001-US200-01-00-00
Start
Stimulus
Results
Tensions
Log
Event Viewer
Table
Raw Scans
Processed Scans
Submission note...
Submit All Tensions to DB
Tensions have not been submitted
DWA Info
Not Connected
DWA MAC N/A
DWA IP N/A
Client IP N/A
Serial # N/A
Firmware N/A
Period N/A
State N/A
HV AC HV DC
Error state N/A
Heartbeat *
Run Status
Scan freqs [Hz]
Min ....
Max .....
Step .....
Active .....
DWA Chan: 0 APA Chan: GB320
DWA Chan: 4 APA Chan: GB312
DWA Chan: 1 APA Chan: GB318
DWA Chan: 5 APA Chan: GB310
DWA Chan: 2 APA Chan: GB316
DWA Chan: 6 APA Chan: GB308
DWA Chan: 3 APA Chan: GB314
DWA Chan: 7 APA Chan: GB306
GB320 None None Submit
GB312 None None Submit
GB318 None None Submit
GB310 None None Submit
GB316 None None Submit
GB308 None None Submit
GB314 None None Submit
GB306 None None Submit

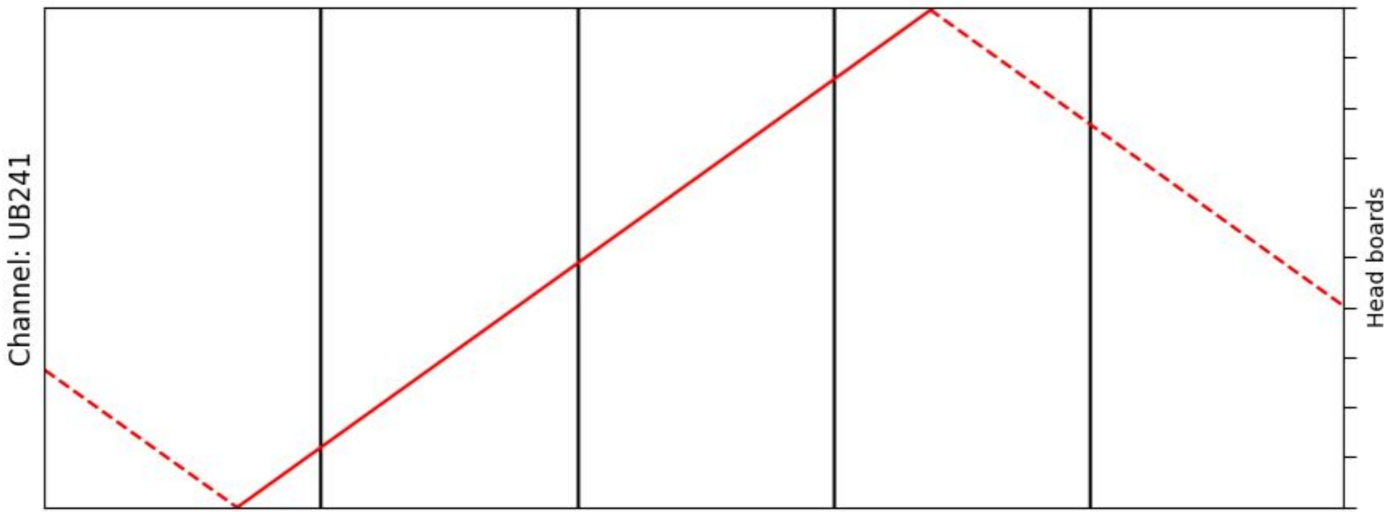
Resonance Identification

We expect multiple resonances per wire.

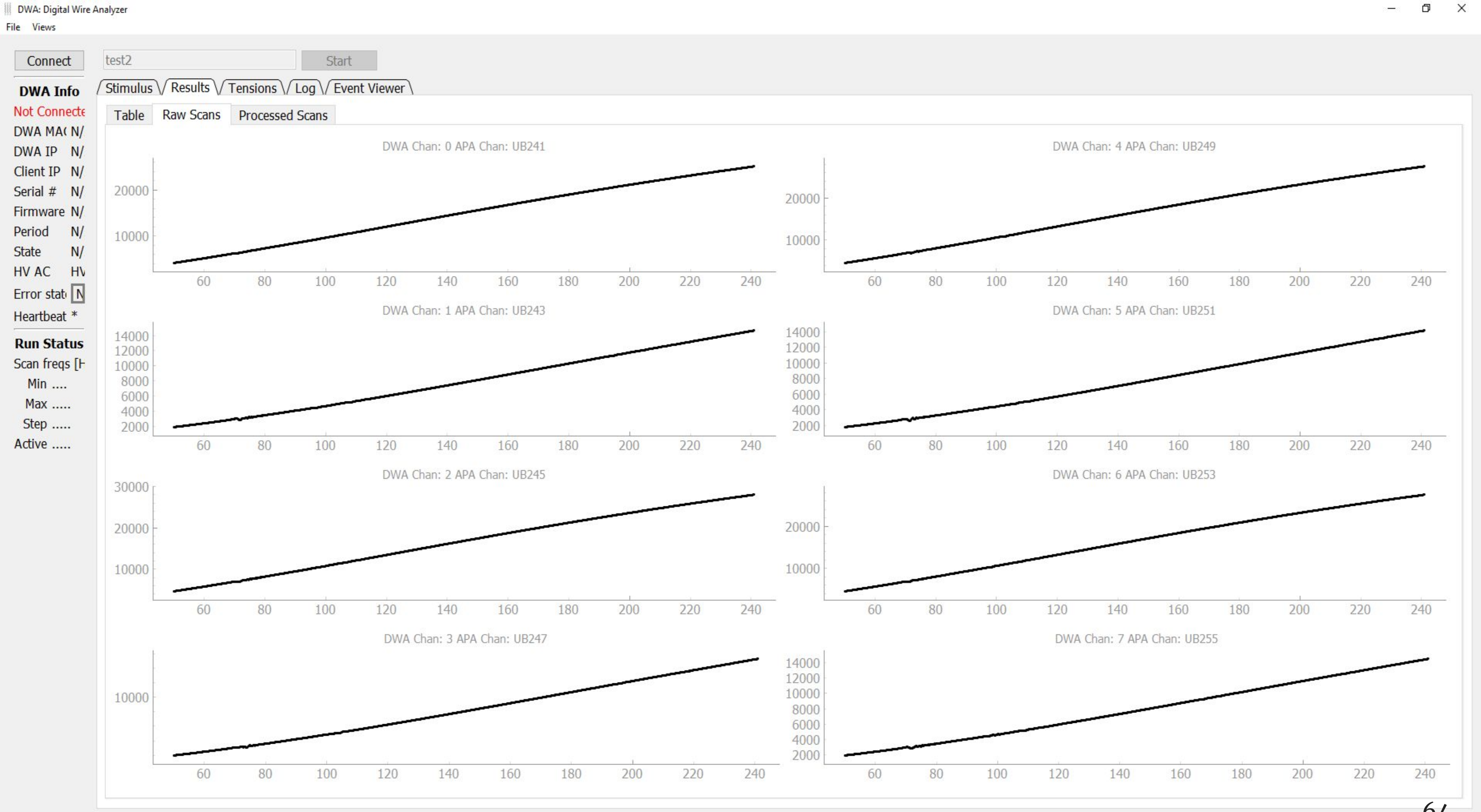
We get a “ringing” effect due to the speed of the frequency sweep.

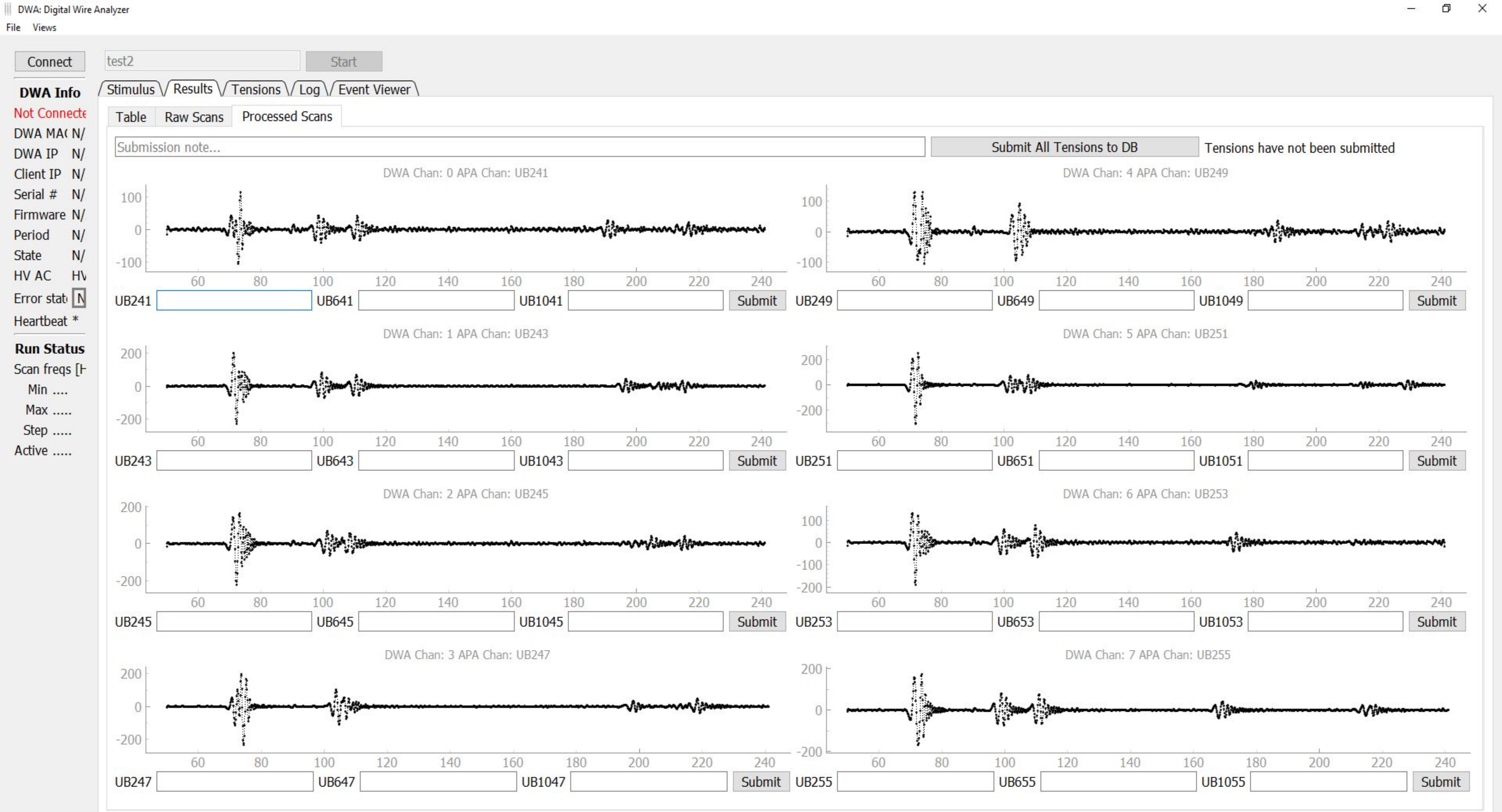


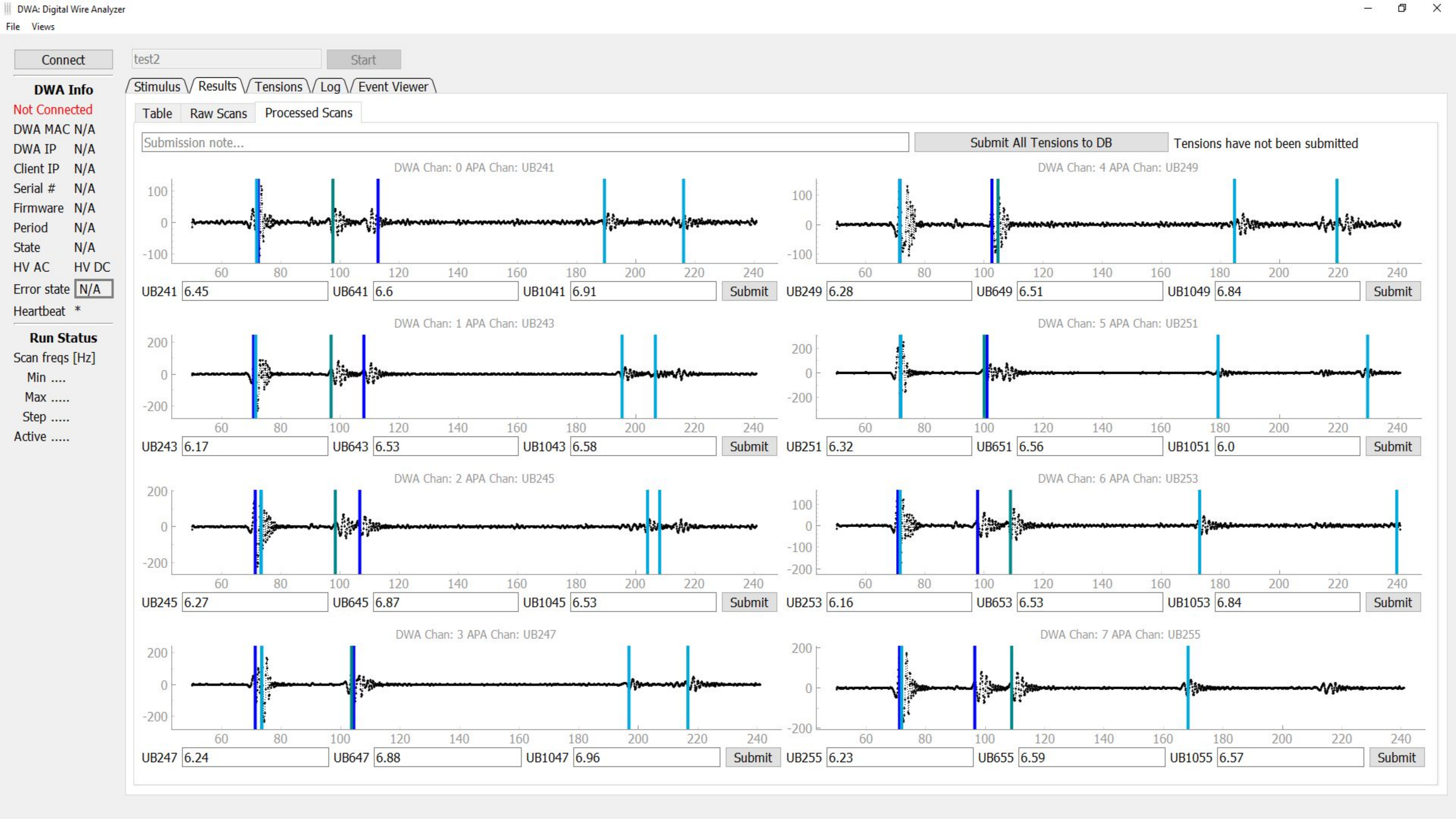
Resonance Identification



Some channels are more complex and are made up of separate segments.

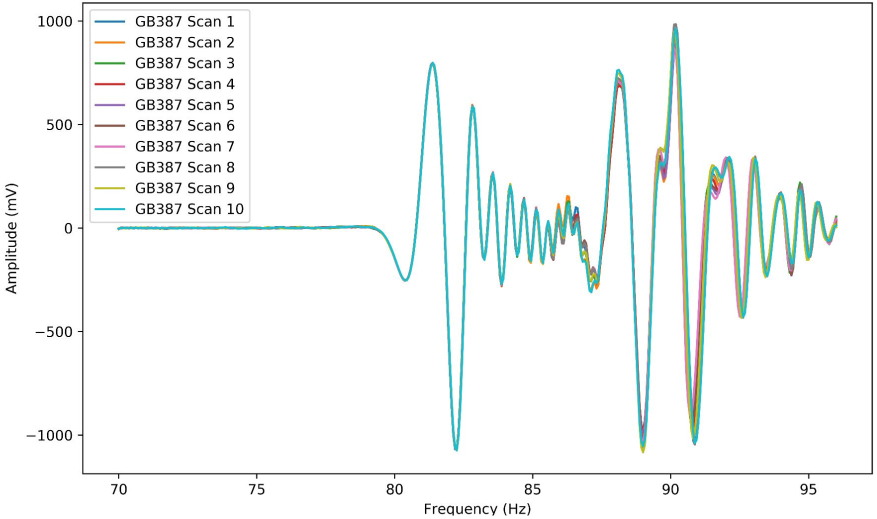

DWA: Digital Wire Analyzer
File
Views
Connect
test2
Start
Stimulus
Results
Tensions
Log
Event Viewer
Table
Raw Scans
Processed Scans
DWA Info
Not Connecte
DWA MA(N/
DWA IP N/
Client IP N/
Serial # N/
Firmware N/
Period N/
State N/
HV AC HV
Error stat N
Heartbeat *
Run Status
Scan freqs [H
Min ....
Max .....
Step .....
Active .....
DWA Chan: 0 APA Chan: UB241
DWA Chan: 4 APA Chan: UB249
DWA Chan: 1 APA Chan: UB243
DWA Chan: 5 APA Chan: UB251
DWA Chan: 2 APA Chan: UB245
DWA Chan: 6 APA Chan: UB253
DWA Chan: 3 APA Chan: UB247
DWA Chan: 7 APA Chan: UB255

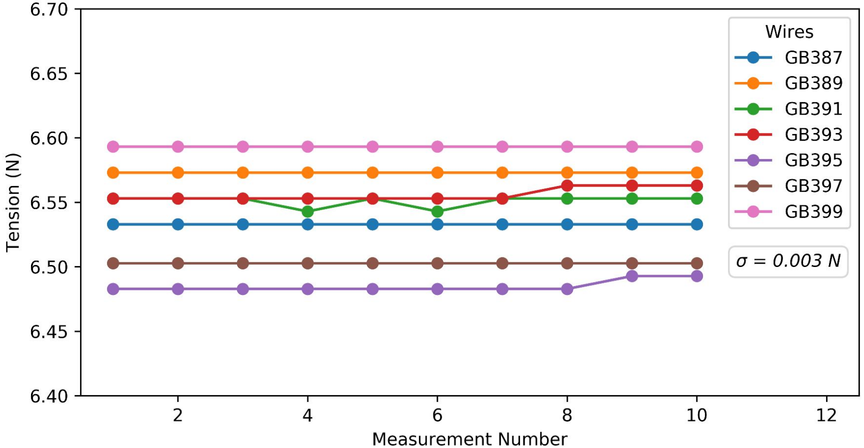

DWA: Digital Wire Analyzer
File Views
Connect
test2
Start
Stimulus
Results
Tensions
Log
Event Viewer
DWA Info
Not Connecte
DWA MA(N/
DWA IP N/
Client IP N/
Serial # N/
Firmware N/
Period N/
State N/
HV AC HV
Error stat N
Heartbeat *
Run Status
Scan freqs [H
Min ....
Max .....
Step .....
Active .....
Table
Raw Scans
Processed Scans
Submission note...
Submit All Tensions to DB
Tensions have not been submitted
DWA Chan: 0 APA Chan: UB241
UB241 UB641 UB1041 Submit
DWA Chan: 4 APA Chan: UB249
UB249 UB649 UB1049 Submit
DWA Chan: 1 APA Chan: UB243
UB243 UB643 UB1043 Submit
DWA Chan: 5 APA Chan: UB251
UB251 UB651 UB1051 Submit
DWA Chan: 2 APA Chan: UB245
UB245 UB645 UB1045 Submit
DWA Chan: 6 APA Chan: UB253
UB253 UB653 UB1053 Submit
DWA Chan: 3 APA Chan: UB247
UB247 UB647 UB1047 Submit
DWA Chan: 7 APA Chan: UB255
UB255 UB655 UB1055 Submit


DWA: Digital Wire Analyzer
File
Views
Connect
test2
Start
DWA Info
Not Connected
DWA MAC N/A
DWA IP N/A
Client IP N/A
Serial # N/A
Firmware N/A
Period N/A
State N/A
HV AC HV DC
Error state N/A
Heartbeat *
Run Status
Scan freqs [Hz]
Min ....
Max .....
Step .....
Active .....
Stimulus
Results
Tensions
Log
Event Viewer
Table
Raw Scans
Processed Scans
Submission note...
Submit All Tensions to DB
Tensions have not been submitted
DWA Chan: 0 APA Chan: UB241
UB241 6.45
UB641 6.6
UB1041 6.91
Submit
DWA Chan: 4 APA Chan: UB249
UB249 6.28
UB649 6.51
UB1049 6.84
Submit
DWA Chan: 1 APA Chan: UB243
UB243 6.17
UB643 6.53
UB1043 6.58
Submit
DWA Chan: 5 APA Chan: UB251
UB251 6.32
UB651 6.56
UB1051 6.0
Submit
DWA Chan: 2 APA Chan: UB245
UB245 6.27
UB645 6.87
UB1045 6.53
Submit
DWA Chan: 6 APA Chan: UB253
UB253 6.16
UB653 6.53
UB1053 6.84
Submit
DWA Chan: 3 APA Chan: UB247
UB247 6.24
UB647 6.88
UB1047 6.96
Submit
DWA Chan: 7 APA Chan: UB255
UB255 6.23
UB655 6.59
UB1055 6.57
Submit

Consistency Check

Measurements with the DWA are highly repeatable.



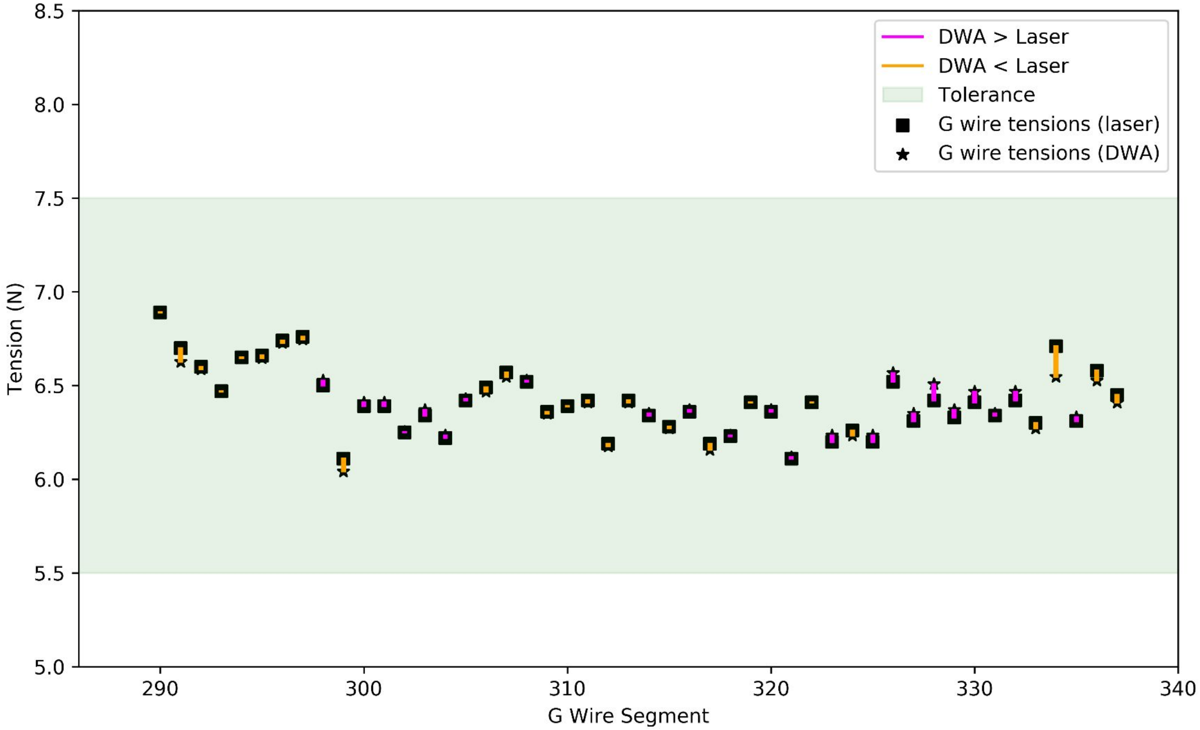


Results

Real APA tensions.

Highly consistent with the laser method.

5x faster than laser, and only 1 operator.

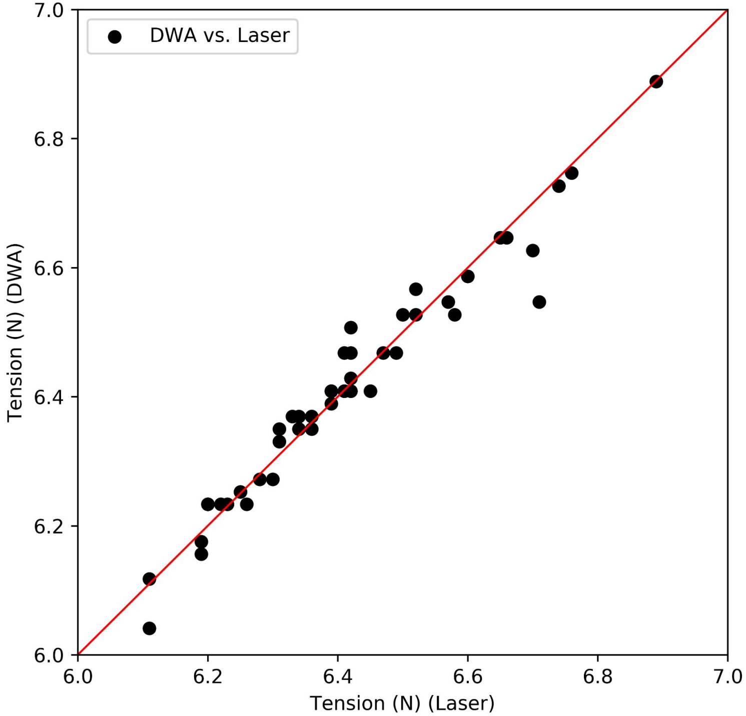


Results

Real APA tensions.

Highly consistent with the laser method.

5x faster than laser, and only 1 operator.



Results

The electrical method:

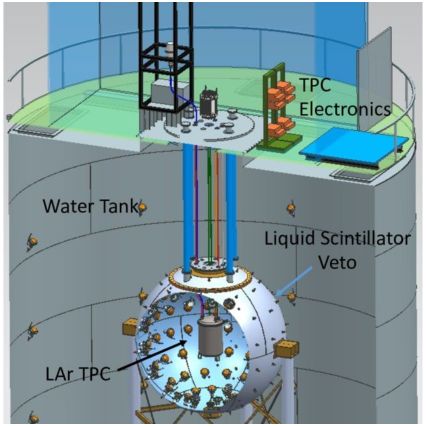
- High speed
- High accessibility

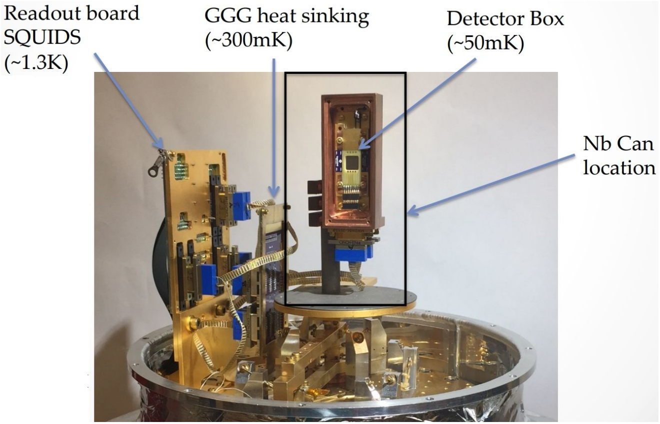
The DWA:

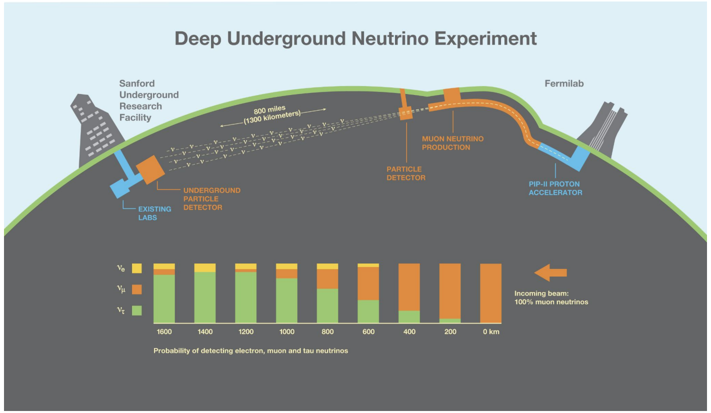
- High accuracy
- High precision

The DWA will be used to ensure we produce a functional experiment that can meet its science goals.

Summary





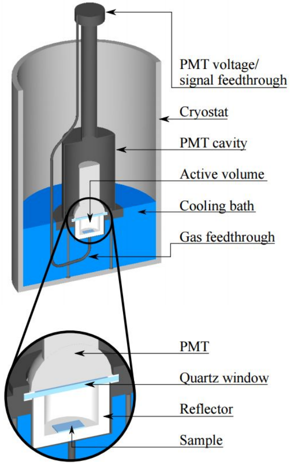


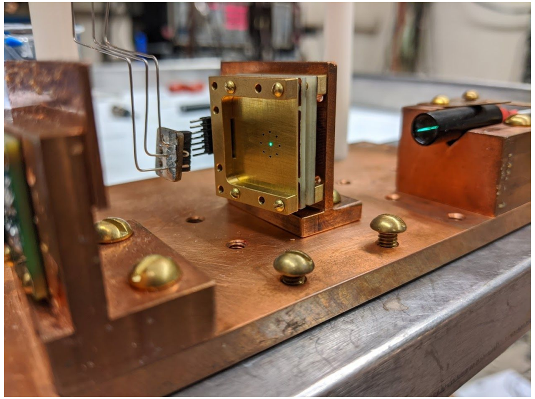
DARKSIDE 50

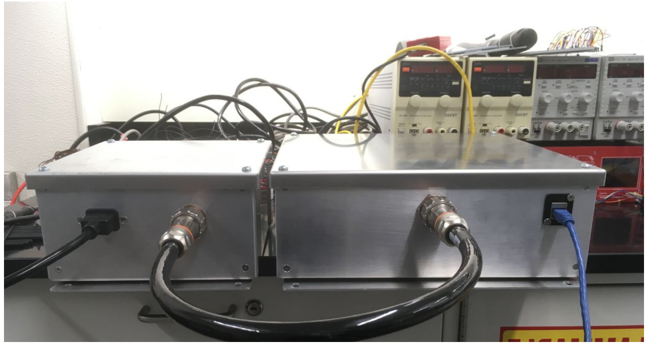
SUPER CDMS
Cryogenic Dark Matter Search

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Summary







DARKSIDE 50

SUPER CDMS Cryogenic Dark Matter Search

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Secondary instrumentation can be just as important to the success of an experiment as primary instrumentation.

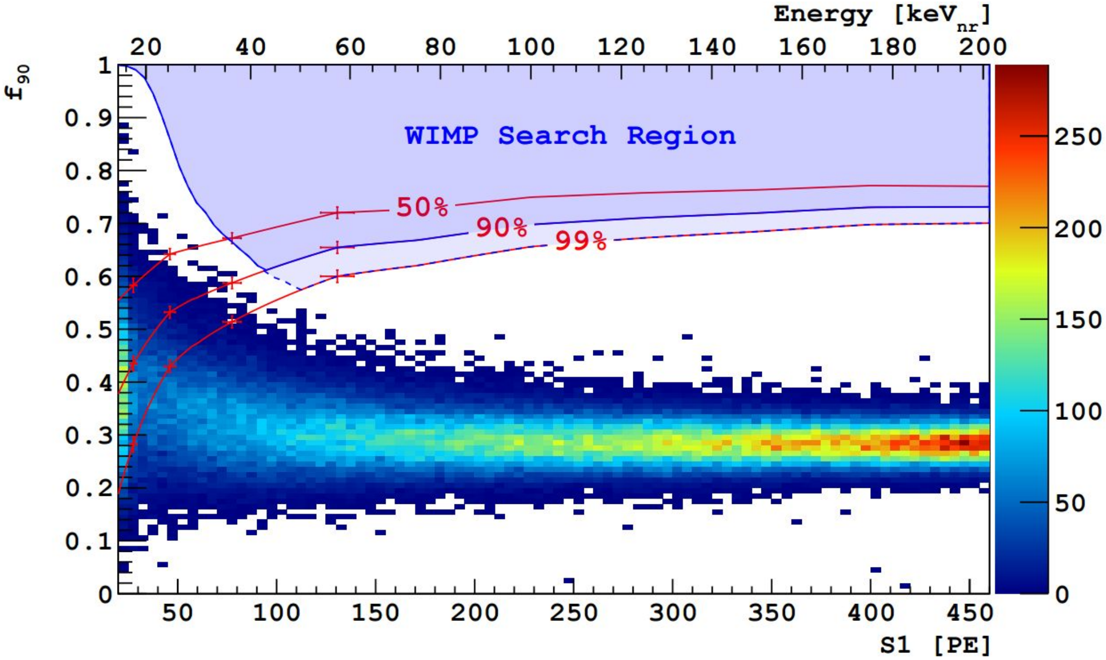

CERN

Thank You

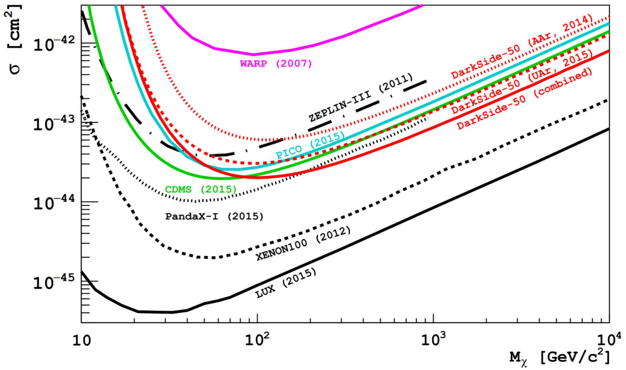
Extra

Support

Result



As a result of this secondary instrumentation project, DarkSide-50 managed to succeed in its science goal of performing a background-free WIMP dark matter search.



Results from the first use of low radioactivity argon in a dark matter search

P. Agnes *et al.* (DarkSide Collaboration)
Phys. Rev. D **93**, 081101(R) – Published 8 April 2016; Erratum Phys. Rev. D **95**, 069901 (2017)