Light dark matter searches with the NEWS-G experiment

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The dark matter conundrum

Observations of Zwicky 85 years ago

"The Redshift of Extragalactic Nebulae", published in German in Helvetica Physica Acta in 1933

"In a spiral galaxy, the ratio of dark-to-light matter is about a factor of ten. That's probably a good number for the ratio of our ignorance-to-knowledge. We're out of kindergarten, but only in about third grade."

Vera Rubin

-What should it be from astrophysical constraints:

- Mostly “Cold”
- Non-Baryonic
- “Weakly” interacting
- $\Omega_X h^2 = 0.1186 \pm 0.002$
- Stable or $\tau_X \gg \tau_U$

No Standard Model particle matches the criteria
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^7$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

“WIMP miracle” ⇒ Relic abundance explained by a massive particle (10 GeV/c^2 - few TeV/c^2) interacting through weak scale interaction with baryonic matter
State of the art for dark matter detectors

Detector

- WIMP

Detector types:
- CDMS, EDELWEISS
- Ge, Si
- DRIFT, DM-TPC, PICO, DAMIC, NEWAGE, MIMAC

Materials:
- Ge, CS$_2$, C$_3$F$_8$, CF$_4$, He$^3$, Si

Light

- DAMA/LIBRA, COSINE, ANAIS, XMASS, DEAP
- NaI, CsI, LXe, LAr

Heat

- CRESST
- CaWO$_4$

Ionization
Status of dark matter searches

Detectors with a lower threshold

Larger target mass - exposure kg · days
J. Feng and J. Kumar, “The WIMPless Miracle: Dark Matter Particles without Weak-scale Masses or Weak Interactions.”
Direct detection of light dark matter

Light Dark Matter (LDM) Mass range
0.1GeV/c²- few GeV/c²

Galactic LDM wind

A Detector

Recoil

e-
e-
e-
e-
e-
e-

Energy losses:
- Electronic
- “Nuclear”

LDM
Comparison between heavy and light targets - A Kinematics

- If we have $E_R = 500$ eV recoil induced by LDM particle of $M_\chi = 1$ GeV/$c^2$

$$u_{\text{min}} = \sqrt{\frac{2 \cdot E_R}{r \cdot M_\chi}}$$  

Minimum relative WIMP velocity to produce a recoil of $E_R$

- $E_R \rightarrow u_{\text{min}}$
  - 1790 km/s for Xe target
  - 1340 km/s for Ge target
  - 1000 km/s for Ar target

WIMP escape velocity ~540 km/s

500 eV

Light Projectile + light target $\Rightarrow$ Better kinematical match
Quenching factor ($q_f$) is defined as the fraction of the kinetic energy of an ion that is dissipated in a medium in the form of ionization electrons and excitation of the atomic and quasi-molecular states.

**Comparison between heavy and light targets - B**

**Ionization quenching**

Quenching factor ($q_f$) is defined as the fraction of the kinetic energy of an ion that is dissipated in a medium in the form of ionization electrons and excitation of the atomic and quasi-molecular states.

**Detection energy threshold required due to quenching**

<table>
<thead>
<tr>
<th>Target</th>
<th>Threshold (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>50</td>
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<tr>
<td>Ge</td>
<td>58</td>
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<tr>
<td>Ar</td>
<td>74</td>
</tr>
<tr>
<td>He</td>
<td>105</td>
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</tbody>
</table>

**Light Projectile + light target $\Rightarrow$ Less demanding detector threshold**
Direct detection of light dark matter

No searches available in this region

![Graph showing the exclusion region for dark matter direct detection with the Terra Incognita region highlighted.](image-url)
Use light targets for dark matter searches?

Hydrogen, Helium $\Rightarrow$ Gases (NTP) $\Rightarrow$ Gaseous detector ???
Spherical Proportional Counter (SPC)

Fun fact

Old LEP RF cavities

Spherical gaseous detectors

*In the picture: I. Giomataris, G. Charpak*
The structure of the SPC

Electric field
Strong dependence on the radius

\[ E(r) = \frac{V_0}{r^2} \frac{r_A r_c}{r_c - r_A} \approx \frac{V_0}{r^2} r_A \]

- Simple design
- Single readout

Natural division of the volume in two
- Drift volume
- Multiplication volume

I. Giomataris et al., JINST, 2008, P09007
Advantage of spherical geometry - A

Capacities for a 1 m³ detector in different geometries

Parallel Plate

\[ C = \varepsilon_0 \frac{S}{d} \approx 3500 \text{ pF} \]

Cylindrical

\[ C = 2\pi\varepsilon_0 \frac{L}{\ln(b/a)} \approx 115 \text{ pF} \]

Spherical

\[ C \approx 4\pi\varepsilon r_A \approx 1.5 \text{ pF} \]
Advantage of spherical geometry - B

Advantages of the spherical geometry

- Lowest surface to volume ratio
- Sustains higher pressure
- Robustness (anode Ø 1 mm - 6.3 mm)

Built solely by radiopure materials

- Vessel made of Cu (~tens of kg)
- Rod made of Cu (~hundreds of gr)
- All the rest less than weigh < 1 g
Pulse production

- Primary ionization

Graph showing:
- Induced charge
- Induced current
- Integrated signal

Time [μs] from 0 to 100
Pulse production
Pulse production

Arrival to anode ...

...and charge multiplication

Induced charge

Induced current

Integrated signal
Pulse production

Drift of slow moving ions

Induced charge

Induced current

Integrated signal
Pulse creation
Induced Pulses

Pulse Shape Analysis (PSA) parameters

**Long Tail Pulse**

- Baseline
- Noise
- Amplitude (Pulse Height)
- Rise time
- Width
- Integral
- Number of peaks

A lot of information hiding in the pulse shape

Rise time & Width $\propto$ Drift time dispersion
Fiducialization

Background comes from the materials of the vessel

Surface

Primary e- drift time dispersion
\[ \sigma(r) \propto \left( \frac{r}{r_{\text{sphere}}} \right)^3 \]

5.9 keV X-rays line

Rise time \( \Delta t \) between 90% - 10% of pulse height

Background rejection capabilities-A
Background rejection capabilities-B

Event discrimination

Extended track

Point like

Muon pulse

Amplitude = 575 ADU
Width (FWHM) = 155.5 μs
Rise time = 18.2 μs

Ar pulse

Amplitude = 606 ADU
Width (FWHM) = 63.4 μs
Rise time = 16.3 μs
Illustration of the basic analysis principle

$^{109}$Cd source
Irradiation through 200μm Al window
$P = 100$ mb, Ar–CH4 (2%)

Cosmic tracks
Vessel wall
Gas

Efficiency of the cut in $rt \rightarrow \sim 70\%$ signal (Cd line)
Significant background reduction
Low energy detection capabilities of a large volume SPC


SPC Ø 130 cm
Gas: Ar+2%CH₄

Detection of fluorescence X-rays

\(^{241}\text{Am} \rightarrow {^{237}\text{Np} + ^4\text{He}} \text{ 5.6 MeV}

Lines

\begin{align*}
\text{Al} & \rightarrow 1.45 \text{ keV} \\
\text{Cu} & \rightarrow 13.93 \text{ keV} \\
{^{237}\text{Np}} & \rightarrow 13.93 \text{ keV}(\text{L}_\alpha \text{ 17.60 keV}(\text{L}_\beta))
\end{align*}

-Energy threshold at the single electron level
The spherical detector around the globe

LSM, Modane

University of Saragoza

University of Thessaloniki

CEA Saclay

Queen's University

University of Tsinghua

Also joining University of Bordeaux and very soon University of Birmingham
The SEDINE detector at LSM - A
One of the deepest and “quietest” laboratories in the world

Laboratoire Souterrain de Modane

4800 wme
5 μ/m²/day
The SEDINE detector at LSM - B

A competitive detector and a testing ground for NEWS-G / SNO

- Copper vessel (Ø 60 cm)
- Equipped with a 6.3 mm Ø sensor
- Chemically cleaned several times for Radon deposit removal
Main background sources for LSM detector

$^{60}$Co Contamination of 1 mBq/kg
BG Rate = 0.3-0.5 keV$^{-1}$kg$^{-1}$day$^{-1}$

*Solution: Limit time exposure on ground for pure copper.*

$^{210}$Pb, $^{210}$Bi Contamination of 1 nBq/kg
BG Rate = 0.1 keV$^{-1}$kg$^{-1}$day$^{-1}$

*Competitive BG levels*

*Solution: Chemical cleaning*

*Effect of cleaning:*
- High energy events 180 mHz => ~2 mHz
- Low energy events 400 mHz => ~20 mHz
WIMP search run data

**Target:** Ne+0.7%CH\textsubscript{4} at 3.1 bar → 280 gr target mass

**Duration:** 42 days in sealed mode

**Dead time:** 20.1%

**Exposure:** 9.6 kg*days (34.1 live-days x 0.28 kg)

**Trigger threshold:** 35 eVee (~100% efficient at 150 eVee)

**Analysis threshold:** 150 eVee (~720 eVnr)

**Calibration:** \(^{37}\)Ar gaseous source, 8 keV Cu fluorescence, AmBe neutron source

Sideband region used together with simulations to determine the number and distribution of expected events in preliminary ROI
Simulating the detector response

Modeling the rise time vs energy response

**Electric field**
- Field map from COMSOL

**Drift of primary electrons**
- Magboltz drift parameters

**Quenching factor**
- Parametrization derived from SRIM

**Avalanche**
- Polya distribution estimation using Garfield++

**Simulated pulses**
- Ion induced current preamplifier response
- Noise templates taken from the pretraces of real pulses

Same trigger algorithm and processing as used for real pulses

**Validation**

**37Ar gaseous source**
2.82 keV and 270 eV X-rays (K and L shells)

**241Am–9Be neutron source**
Nuclear recoils homogeneously distributed in the volume
Analysis of the WIMP run data

Analysis methodology - BDT

Background modeling

1620 events recorded in the preliminary ROI

- Failed any of the BDT cuts
- pass the BDT cut for 0.5 GeV/c²: 15 events
- pass the BDT cut for 16 GeV/c²: 123 events
- pass the BDT cut for other masses

Trained with simulated WIMP and background events
First results of NEWS-G with SEDINE


Exclusion at 90% confidence level (C.L.) of cross-sections above $4.4 \cdot 10^{-37}$ cm$^2$ for a 0.5 GeV/c$^2$ WIMP

Limit set on spin independent WIMP coupling with standard assumptions on WIMP velocities, escape velocity and with quenching factor of Neon nuclear recoils in Neon calculated from SRIM
NEWS-G current status & developments

Preparing the He physics run

Gas quality
Testing gas mixtures of He/CH\textsubscript{4}
- High pressure operation (Penning)
- Hydrogen rich target

Upgrading gas system
- Tightness
- Filtering
- Gas recirculation
- Residual Gas Analyzer monitoring

Quenching factor measurements
- Ion / electron beam (LPSC, France)
- Neutron beam (TUNL, USA)

Study of the detector response
Solid state laser (213 nm)
- Drift time measurements
- Parametrization of the avalanche process

Sensor developments
Aims
- High pressure operation
- High gain
- Increased stability
- Low radioactivity

Techniques
- Resistive technologies
- 3D printing technologies
- FEM simulations

Major Issues
Reduced drift velocity
High probability of attachment
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<th>Component</th>
<th>Value</th>
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<tr>
<td>H₂O</td>
<td>&lt; 20 ppb</td>
</tr>
<tr>
<td>CO₂</td>
<td>&lt; 0.5 ppm</td>
</tr>
<tr>
<td>THC (as CH₄)</td>
<td>&lt; 100 ppb</td>
</tr>
<tr>
<td>N₂</td>
<td>&lt; 1 ppm</td>
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<tr>
<td>O₂</td>
<td>&lt; 10 ppb</td>
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<td>&lt; 100 ppb</td>
</tr>
<tr>
<td>N₂</td>
<td>&lt; 1 ppm</td>
</tr>
</tbody>
</table>
Gas quality

Gas filtering

He/CH4 (90/10) 600 mbar
HV1=1820 V
HV2=+225 V
Ball Φ2 mm
No OXISORB

He/CH4 (90/10) 600 mbar
HV1=1840 V
HV2=+300 V
Ball Φ2 mm
OXISORB

Improvements

Vacuum conditions
1.E-4 mbar→1.E-5 mbar→1.E-6 mbar
Leak Rate ≈ 1.4E-6 mbar*L/s
⇒ Not a dramatic effect

Gas quality

Contaminants ~ppm
↓
Oxisorb ~100 ppb
⇒ Big improvement

Increased drift velocity results in less attachment
Gas quality

Removing sources of outgassing

Result

- The whole signal is < 25 μs (before <35 μs)
- Resolution at 6 keV (σ) ~ 8% (instead ~10%)
- Resolution at 1.49 keV (σ) ~ 17.2% (instead ~22%)
- Clear separation between conversion e- events and volume events

P = 600 mbar, Oxisorb used, sensor Φ 2 mm, HV1= 1750 V, HV2= +200 V
Drift velocity increment

Addition of a third noble gas

Drift velocity vs |E-field|

Drift velocity [cm/ns]

He/CH4 (90/10)
He/CH4/Ne (85.5/9.5/5)
He/CH4/Ne (81.9/10)
He/CH4/Ne (76.5/8.5/15)
He/CH4/Ne (72.8/20)

Magboltz
Sensor influence on the E-field

Electric field magnitude dependence on the azimuthal angle ($\phi$) - Inhomogenous response

The ideal case

- A floating ball with a HV applied on its surface

The reality

- A ball connected to a wire through which the HV is applied on the ball.
- The wire - ball structure is supported by a grounded rod.

Patrick Knights PhD, University of Birmingham & University Paris-Saclay
The umbrella

Introduction of a secondary correction electrode

Goals:
- Homogeneous field
- Limited discharges
- Operation in high pressure
- Stability

Possible issues

Material used: Copper, Brass, Steel, Iron, PE, PEEK, Teflon, Kapton, Plexiglass, Si, Araldite

Inhomogeneous response

Instability
Sensor Design: Umbrella Voltage

$r_A = 1 \text{ mm}$

$r_C = 150 \text{ mm}$

$V_A = 2000 \text{ V}$

Separation = 3.5 mm
Sensor Design: Anode-Umbrella Separation

\[ r_A = 1 \text{ mm} \]
\[ r_C = 150 \text{ mm} \]
\[ V_A = 2000 \text{ V} \]
\[ V_U = 0 \text{ V} \]
Sensor Design: Measurements

- Fe55 Source – 5.9 keV x rays
- 30 cm diameter test sphere operating at 600 mbar of He + 10% CH$_4$
- Anode Diameter = 2 mm, Separation = 3.5 mm

\[ V_u = -200 \text{ V} \]
\[ V_1 = 0 \text{ V} \]
\[ V_1 = 200 \text{ V} \]

Gain reduced by presence of positive voltage on umbrella - electric field near anode reduced
The resistive umbrella

Advantages:
- Volume Resistivity $10^{10} \Omega \cdot \text{cm} - 10^{12} \Omega \cdot \text{cm}$
- Compact and homogeneous material
- Minimized insulating surface

Bakelite Prototypes

Glass Prototype

Bakelite
Chemical Formula: $(C_6H_6O.C-H_2-O)x$

Soda – lime glass
Chemical composition*:  
70% $\text{SiO}_2$ (glass) + 
15% $\text{Na}_2\text{O}$ (soda) + 
9% $\text{CaO}$ (lime) + 
Other 
*there are a lot different compounds
Performance of the resistives umbrellas - A

Homogeneous response

He+9%CH₄+7%Ar
730 mbar
Anode Φ 2 mm

The difference in gain between the two positions is close to the statistical error.
Performance of the resistives umbrellas - B

**Stability**

| Ball: Φ2 mm steel | Gas: He+30%Ar+7%CH4 | P = 715 mbar | HV1 = 1830 V | HV2 = 0 V
| Ball: Φ2 mm steel | Gas: He+10%Ar+2.5%CH4 | P = 1880 mbar | HV1 = 2300 V | HV2 = 0 V

**Resolution**

| Ball: Φ3 mm steel | Gas: He+30%Ar+3%CH4 | P = 1000 mbar | HV1 = 2300 V | HV2 = 0 V

**Iron fluorescence (~6.4 keV)**

Pulse Height (ADU) vs. Rise time (μs)
Evolution of the sensor “umbrellas”

- **Classic “umbrella”**
  - < 2016
  - ~Few cm

- **Bakelite Version 1**
  - 2017 first half
  - ~1-2 cm

- **Bakelite Version 2**
  - 2017 second half
  - <1 cm

- **Glass**
  - Present
  - ~1-5 mm

**Evolution targets:**
- Precision
- Easy construction
- Low mass
- Detector stability
- Homogeneous response
- Low radioactivity
The multiball sensor - ACHINOS

Dealing with the low electric field magnitude (~1 V/cm) at large detectors

The idea: Use multiple balls placed in the same potential instead

\[ E(r) = \frac{V_0}{r^2} \]  
Electric field dependence on the radius

Comparison of E-field strength for anode of different radii vs the radius

\[ \frac{E_{3\text{mm}}}{E_{2\text{mm}}} \approx 1.5 \]
\[ \frac{E_{6.3\text{mm}}}{E_{3\text{mm}}} \approx 2.1 \]

AIM:
1. Operation in high pressure
2. Build larger volume detectors

Conundrum:
Both Gain and Drift time are a function of E/P

The elegant solution - ACHINOS
- Decoupling Gain - Drift
- Tunes Volume electric field
- Anodes can be read out individually

\[ \ln M = \int \alpha(E/P) \frac{dE}{dV} \]
\[ v_{\text{drift}} = \frac{E}{P} \]
Study of the Electric field using FEM software

Field lines close close to the central structure

Creation of collective iso-potentials
Electric field magnitude with ACHINOS

\[ \frac{|E_{11\text{balls}}|}{|E_{1\text{ball}}|} \approx 9 \]
The first ACHINOS prototypes

Composition:
- 5, 11, or 33 balls
- Anode Ø 2 mm
- Placed in a virtual spherical surface
- Set in the same HV1
- Bias electrode made of bakelite (resistive) HV2
Positive results with the first prototypes

Stability in terms of sparking

Measurement of the 5.9 keV line

Rise time vs Pulse height

Single ball

11-balls

Conditions:
- Gas Mixture: He:Ar:CH4 (80:11:9)
- Pressure: 640 mbar
- HV1 = 2015 V, HV2 = -200 V
Preliminary results with the 2nd gen prototypes

On going study of the 2nd gen prototypes

Measurement of the 5.9 keV $^{55}$Fe X-ray line

Gain similar for every ball

Prospects

- Alternate coatings such as copper power/glue
- More compact design of the 3D printed support structure
- Anode balls of Ø1 mm
- Operation in higher pressure
- Operation in high gain

Conditions:

- Gas Mixture: He:Ar:CH4 (56:37:7)
- Pressure: 455 mbar
- HV1 = 1100 V, HV2 = -100 V
Why such a weird name

ACHINOS = Sea urchin = Αχινός
Development of detailed simulation methods to model the detector response

The power of combining state-of-the-art software

**Software for the simulation of particle passage through matter**
- Build geometry
- Transport of particles
- Particle interaction
- Generation-Transport of secondaries
- ...
- Energy deposition in the ROI

**Software for the simulation of gaseous detectors**
- Drift of charges
- Diffusion
- Avalanche
- Signal Induction
- Electronics

**Software based on FEM**
- Electric Field
- Magnetic Field
- Particle tracks

Garfield
Garfield++

Geant4

COMSOL

ANSYS
Simulated detector response

Examples of simulated pulses treated with the same analysis algorithm as real pulses

Surface e- extracted by a 5.9 keV X-ray

Atmospheric Muon

No pulse - only noise

He+10%CH4 @ 1 bar
Irradiation of the volume with an 5.9 keV $^{55}$Fe source
An illustration of the method

Assumed an $\tau=100\ \mu s$ for our preamp with $g=0.45\text{mV/fC}$ and 50 ADU/mV 2800 V applied on $\Phi$ 3mm anode.

From the initial interaction to the detector response
A qualitative comparison with the experiment

**Detector:** Spherical Proportional Counter (SPC)

**Source:** 55Fe X-ray (5.9 keV)

**Gas:** He/CH4 at 500 mbar
Quenching factor measurements at LPSC Grenoble

- "High" flux environment ($\sim 10^{10} \text{cm}^{-2}\text{s}^{-1}$)
- Very low energy threshold (<100 eV)

Electrons and ions are passing through a 1 $\mu$m in diameter hole to enter in the gaseous volume of the SPC!!!
LAST BUT NOT LEAST!!!
NEWS-G at SNOLAB

The underground laboratory in the Sudbury, Canada

**Deeper underground**

0.25 μ/m²/day

~8x lower μ flux than LSM

Practically, at 2 km is the deepest clean room in the world
NEWS-G at SNOLAB

The new and improved setup

**Copper vessel (140 cm $\phi$, 12 mm thick)**
- Low activity copper (C10100)
  - 7 to 25 $\mu$Bq/kg Th
  - 1 to 5 $\mu$Bq/kg of U
- Electropolishing & Electroplating

*Hemispheres built in France, stored at LSM before welding*

**Upgraded compact shielding (35t)**
- 40 cm PE + Boron sheet
- 22 cm VLA Pb (1 Bq/kg $^{210}$Pb)
- 3 cm archaeological lead
- Airtight envelope to flush pure N (against Rn)

*Glove box for Radon free rod installation*
Estimated background

<table>
<thead>
<tr>
<th>Source Position</th>
<th>Mass (kg) or Surface (cm²)</th>
<th>Source</th>
<th>evts/kg/day/[(µBq/kg) or (nBq/cm²)]</th>
<th>contamination units</th>
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<tbody>
<tr>
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<td>Co60</td>
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<tr>
<td>CopperSphere</td>
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<td>U238</td>
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Total 0.279
NEWS-G at SNOLAB

Projected sensitivity

100 kg.days, 200eVee ROI above threshold at 1 electron.
(Not accounting for sensitivity improvement from resolution effects and RT cuts)
The NEWS-G collaboration

- **Queen’s University Kingston** – G Gerbier, P di Stefano, R Martin, G Giroux, T Noble, D Durnford, S Crawford, M Vidal, A Brossard, F Vazquez de Sola, Q Arnaud, K Dering, J Mc Donald, M Clark, M Chapellier, A Ronceray, P Gros, J Morrison, C Neyron
  - Copper vessel and gas set-up specifications, calibration, project management
  - Gas characterization, laser calibration, on smaller scale prototype
  - Simulations/Data analysis
- **IRFU (Institut de Recherches sur les Lois fondamentales de l’Univers)/CEA Saclay** - I Giomataris, M Gros, C Nones, I Katsioulas, T Papaevangelou, JP Bard, JP Mols, XF Navick,
  - Sensor/rod (low activity, optimization with 2 electrodes)
  - Electronics (low noise preamps, digitization, stream mode)
  - DAQ/soft
- **LSM (Laboratoire Souterrain de Modane)**, IN2P3, U of Chambéry - F Piquemal, M Zampaolo, A DastgheibiFard
  - Low activity archeological lead
  - Coordination for lead/PE shielding and copper sphere
- **Thessaloniki University** – I Savvidis, A Leisos, S Tzamarias
  - Simulations, neutron calibration
  - Studies on sensor
- **LPSC (Laboratoire de Physique Subatomique et Cosmologie) Grenoble** - D Santos, JF Muraz, O Guillaudin
  - Quenching factor measurements at low energy with ion beams
- **Pacific National Northwest Lab** – E Hoppe, DM Asner
  - Low activity measurements, Copper electroforming
- **RMCC (Royal Military College Canada) Kingston** – D Kelly, E Corcoran
  - 37 Ar source production, sample analysis
- **SNOLAB –Sudbury** – P Gorel
  - Calibration system/slow control
- **University of Birmingham** – K Nikolopoulos, P Knight
  - Simulations, analysis, R&D

Associated lab : **TRIUMF** - F Retiere
- Future R&D on light detection, sensor

Thessaloniki, Greece 2018
Thank you very much for your attention
Additional material
Operation with different targets: Ne, He, H

Operation with different pressures: Tenths mbar - 10 bar

Operation with High Z medium (Xenon) to better determine the background

Resistive sensors: High Gain

ACHINOS sensor: Tuning volume electric field - High gain - Multichannel readout

“Penning” Mixtures Ne/CH4 or He/CH4 (99.3/0.7): High pressure - High Gain - Minimized voltages applied

Regular Mixtures Ne/CH4 or He/CH4 (90/10): Hydrogen rich gases
**Illustration of the basic analysis principle**

109\(^{\text{Cd}}\) source
Irradiation through 200\(\mu\text{m}\) Al window
P = 100 mb, Ar–CH4 (2%)

Efficiency of the cut in rt → ~ 70% signal (Cd line)
Significant background reduction
Table 1. Radiocarbon results. Material codes and protocols are described in Crann et al. (2017).

<table>
<thead>
<tr>
<th>Lab ID</th>
<th>Submitter ID</th>
<th>Material</th>
<th>Mat. Code</th>
<th>$^{14}$C yr BP</th>
<th>±</th>
<th>$F^{14}$C</th>
<th>±</th>
<th>A (Bq/kg)</th>
<th>±</th>
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<tbody>
<tr>
<td>UOC-6176</td>
<td>Bakelite_NewsG</td>
<td>Bakelite</td>
<td>D</td>
<td>9334</td>
<td>35</td>
<td>0.3129</td>
<td>0.0014</td>
<td>69.52</td>
<td>0.47</td>
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<table>
<thead>
<tr>
<th>Material</th>
<th>$^{14}$C (Bq/kg)</th>
<th>$^{14}$C (mBq)</th>
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<tbody>
<tr>
<td>Bakelite</td>
<td>69,52 Bq/kg</td>
<td>69,52 mBq</td>
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</table>
### Glass tube

<table>
<thead>
<tr>
<th></th>
<th>Bq/kg</th>
<th>Bq/m</th>
<th>Bq/tube</th>
<th>Bq/umbrella</th>
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</thead>
<tbody>
<tr>
<td>226Ra</td>
<td>4.06</td>
<td>± 0.223</td>
<td>1.70E-04</td>
<td>1.54E-03</td>
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<tr>
<td>228Th</td>
<td>1.46</td>
<td>± 0.081</td>
<td>6.11E-05</td>
<td>5.55E-04</td>
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<tr>
<td>210Pb</td>
<td>3.28</td>
<td>± 0.467</td>
<td>1.38E-04</td>
<td>1.25E-03</td>
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<tr>
<td>238U</td>
<td>3.02</td>
<td>± 0.371</td>
<td>1.27E-04</td>
<td>1.15E-03</td>
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<tr>
<td>40K</td>
<td>1.3</td>
<td>± 0.410</td>
<td>5.48E-05</td>
<td>4.94E-04</td>
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<tr>
<td>228Ra</td>
<td>1.36</td>
<td>± 0.225</td>
<td>5.70E-05</td>
<td>5.17E-04</td>
</tr>
</tbody>
</table>

### Bakelite

- **Glass tube dimension:**
  - High: 100 mm
  - Radius$_{ext}$: 2 mm
  - Thickness: 0.5 mm
  - Weight: 0.38 g

- **Bakelite conic umbrella:**
  - Weight: ≈ 1 g
Illustration of particle identification – Background rejection

Run with Ar/CH$_4$ + 3g $^3$He @ 200 mb SPC 130cm Ø @ LSM

- Rise time ($\mu$s)

- Pulse Height

- $^{210}$Po 5.3 MeV

- $^{3}$He 764 keV

- $^{210}$Po from $^{210}$Pb @ Cu surface

- Range = 15 cm

- Rate 400 capt/d

- n capt on $^3$He $\Rightarrow$ p + T

- Recoils from fast neutrons expected here

- Tracks

- $^{210}$Po 5.3 MeV from $^{210}$Pb @ Cu surface

- Range = 15 cm

- Point like

- « Volume » alpha
Ne-CH4(93-7), P = 100 mb, lamp with 3 attenuator

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>P1</td>
<td>2385</td>
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<tr>
<td>P2</td>
<td>0.4114</td>
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<tr>
<td>P3</td>
<td>62.69</td>
</tr>
<tr>
<td>P4</td>
<td>20.95</td>
</tr>
</tbody>
</table>

83 eV
1.7 p.e.
15597 evts
The umbrella

Introduction of a secondary correction electrode

Material used: Copper, Brass, Steel, Iron, PE, PEEK, Teflon, Kapton, Plexiglass, Si, Araldite

Goals:
- Homogeneous field
- Limited discharges
- Operation in high pressure
- Stability
The resistive umbrella

Advantages:
- Bakelite resistivity $\sim 10^{12} \, \Omega \cdot \text{cm}$
- Compact and homogeneous material
- Very good conduct between the steel (conducting) layer and the bakelite layer
- Minimized insulating surface

Bakelite
Chemical Formula:
$(C_6H_6-O.C-H_2-O)_x$

Thermosetting phenol formaldehyde resin, formed from a condensation reaction of phenol with formaldehyde.

First Prototypes
“Glass” sensor prototype performance

**Stability**

- Ball: Φ2 mm steel
  - Gas: He+30%Ar+7%CH4
  - P = 715 mbar
  - HV1 = 1830 V
  - HV2 = 0 V

- Ball: Φ2 mm steel
  - Gas: He+10%Ar+2.5%CH4
  - P = 1880 mbar
  - HV1 = 2300 V
  - HV2 = 0 V

- Ball: Φ3 mm steel
  - Gas: He+30%Ar+3%CH4
  - P = 1000 mbar
  - HV1 = 2300 V
  - HV2 = 0 V

**Resolution**

- Iron fluorescence (~6.4 keV)

**Anode micro-soldering**

*Picture from digital microscope (x 45.9)*
The μ-soldered ball

Motivation

- Better sphericity
- Avoidance of ball deformations
- Field homogeneity
Control of ball quality

Checking diameter and surface smoothness

2 mm Inox ball  3 mm steel ball

A closer look on a 3 mm ball
Metallized glass umbrella

\[ R = \frac{\rho L}{\pi (b^2 - a^2)} \]

\[ R = \frac{\rho}{2\pi L} \ln\left(\frac{b}{a}\right) \]

E_{\text{wire}} = 0 on metallic layer
Properties of “Soda”-glass

Resistivity - Activity - Density

Measurement result
\( \rho = 5.05 \times 10^{10} \ \Omega \cdot \text{cm} \pm 26.6\% \)

Activity: 14.48 mBq/g

Density: 2.1-2.25 g/cm³
Second generation of prototypes under investigation

The new 11-ball ACHINOS modules based on 3D-printed supporting structures, coated with graphite-glue layer (resistivities in the $10^6 \, \Omega \cdot \text{cm}$-$10^{12} \, \Omega \cdot \text{cm}$) and glass tubes to extend the bias electrodes
A new idea

Improvement of the electric field in the far region of the detector

Figures from P.Knights recent presentation at IOP
A sensor upgrade

Sensor development - ACHINOS

If instead of one ball we use a number of them placed at equal distance on a sphere you can have the same gain but increased field at the outer region of the detector.

**AIM:**
1. Operation in high pressure
2. Build larger volume detectors

**Conundrum:**
Both Gain and Drift time are a function of $E/P$

**The elegant solution - ACHINOS**
- Decoupling Gain –Drift
- Tunes Volume electric field
- Anodes can be read out individually

\[
\ln M = \int \alpha \left(\frac{E}{P}\right) \frac{dE}{d\phi} \\
\nu_{\text{drift}} = \frac{E}{P}^2
\]
Possible improvements

- Construction method
- Testing of different geometries
  - Simulations
  - Prototypes
- Looking for the optimal number of anodes
  - Performance
  - Complexity
  - Noise
- Material for the bias electrode
  - Resistive coating
  - Bakelite
  - Thin layer of deposited carbon (<50 nm)
WIMP Recoil Spectrum

Nuclear Recoil

\[ E_r \sim 1 \text{ keV} \]

\[
\frac{dR}{dE_r} = M_T \frac{\rho_0 \sigma_0}{2 m_\chi m_r^2} F^2 (E_r) \int_{v_{\text{min}}}^{\frac{f(\vec{v})}{v}} d^3 \vec{v}
\]

\( \theta = 0.5 \)

**Avalanche process**

\[ \langle \text{Gain} \rangle \approx 7000 \text{ secondary ions / primary electron} \]

large statistical fluctuations

**Fit of the Polya distribution to simulated data with Garfield**

\( W_{Ne} = 36 \text{eV} \)

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**2 keVee event**

*Baseline Removed*

*Raw Pulse*

*Deconvolved, Smearred 5 Twice*

*Deconvolved Pulse*
The image contains a series of histograms showing the distribution of counts over rise time for different energy slices.

- **Energy slice:** [150,250] eVee
- **Energy slice:** [250,500] eVee
- **Energy slice:** [500,750] eVee
- **Energy slice:** [750,1000] eVee
- **Energy slice:** [1000,1500] eVee
- **Energy slice:** [1500,2000] eVee
- **Energy slice:** [2000,3000] eVee
- **Energy slice:** [3000,4000] eVee

Each histogram is labeled with the corresponding energy slice and includes a legend indicating that the solid line represents the neutron calibration and the red crosses represent the neutron simulation.

The x-axis represents the rise time in microseconds, and the y-axis represents the counts per 2 microseconds.
Top panel: distribution of the 1620 events recorded during the physics run in the preliminary ROI. Events that fail (resp. pass) the BDT cut for any of the WIMP masses are shown in black (resp. colour) dots. Events accepted as candidates for 0.5 GeV/c$^2$ and 16 GeV/c$^2$ WIMP masses are shown in red and blue, respectively, while for intermediate WIMP masses, candidates are shown in yellow.

Bottom panel: the energy spectrum of events recorded during the physics run in the preliminary ROI is indicated by the black markers. Energy spectra of 0.5 GeV/c$^2$ and 16 GeV/c$^2$ WIMP candidates are shown in red and blue dots. The energy spectra before and after the BDT cut of simulated 0.5 GeV/c$^2$ (resp. 16 GeV/c$^2$) WIMPs of cross section $\sigma_{\text{excl}} = 4.4 \times 10^{-37}$cm$^2$ (resp. $\sigma_{\text{excl}} = 4.4 \times 10^{-39}$cm$^2$) excluded at 90% (C.L.) are shown in unshaded and shaded red (resp. blue) histograms, respectively.
Proportion of simulated WIMPs that pass a successive set of cuts vs the WIMP mass

- Quality cuts
- Energy range [150,4000] eVee of the preliminary ROI
- Rise time range [10,32] μs of the preliminary ROI
- Fine-tuned ROI (BDT cut)
Analysis threshold set @ 150 eVee far above the trigger threshold of ~35 eVee (100% trigger efficiency @ 150 eVee)

Proportion of events that trigger when pulses are added on top of a baseline vs the energy of the pulse alone

Trigger efficiency derived from simulated WIMP events of various masses to point out its dependence with the WIMP mass.

The trigger algorithm performs slightly better for single PE events

For 0.5 GeV WIMPs: mostly single PE events VS For higher WIMP masses: single & multiple PE events
Energy [keV NR scale]

BDT Score distribution of **signal** and **background** events

Background like low BDT Score

Signal like high BDT Score

Find the optimal cut

Efficiency
The weak electric field

Comparison of E-field magnitude for different anode diameters (HV=2000 V)

\[ \frac{E_{3\text{mm}}}{E_{2\text{mm}}} \approx 1.5 \]
\[ \frac{E_{6.3\text{mm}}}{E_{3\text{mm}}} \approx 2.1 \]

AIM:
1. Operation in high pressure
2. Build larger volume detectors

Conundrum:
Both Gain and Drift time are a function of E/P

\[ \ln M = \int_{E_1}^{E_2} \frac{\mu(E/P) \, dE}{dE} \]

\[ v_{\text{drift}} = \frac{\mu E}{P} \]
Quenching factor measurements at TUNL
Why a spherical detector?

Answer:

- It is a geometry that permits the construction of robust, large volume detectors that can sustain high pressure with minimal material.
- The simplicity of the design permit a construction solely by radiopure materials.
- The configuration of the electric field provide a handle for background rejection, through event discrimination and volume fiducialization.
- The low capacitance even for large volumes provides single electron detection threshold.
An illustration of the method

The Geant4 simulation

The setup
- SPC Φ 30cm
- Anode Φ 3 mm
- Gas Mixture He+10%CH4 at 1 bar
- Copper rod include along with the wire
- Fe55 X-ray source inside the detector (shielded)

Low energy electromagnetic interactions enabled along with fluorescence models
Metallized glass umbrella

First results - Stability in high gain - Grounded umbrella

He + 29.7% Ar + 2.0% CH4  700 mbar
HV1=1650 V, HV2= 0 V
An illustration of the method

Assumed an $\tau=100\,\mu\text{s}$ for our preamp with $g=0.45\text{mV/fC}$ and 50 ADU/mV 2800 V applied on $\Phi$ 3mm anode.
Background rejection capabilities-A

Fiducialization

X-ray source

Interaction points

Primary e- drift time dispersion

$$\sigma(r) \propto \left(\frac{r}{r_{\text{sphere}}}\right)^3$$

5.9 keV X-rays line

Rise time $\rightarrow \Delta t$ between 90% - 10% of pulse height