NEWS-G
Light dark matter search with a Spherical Proportional Counter

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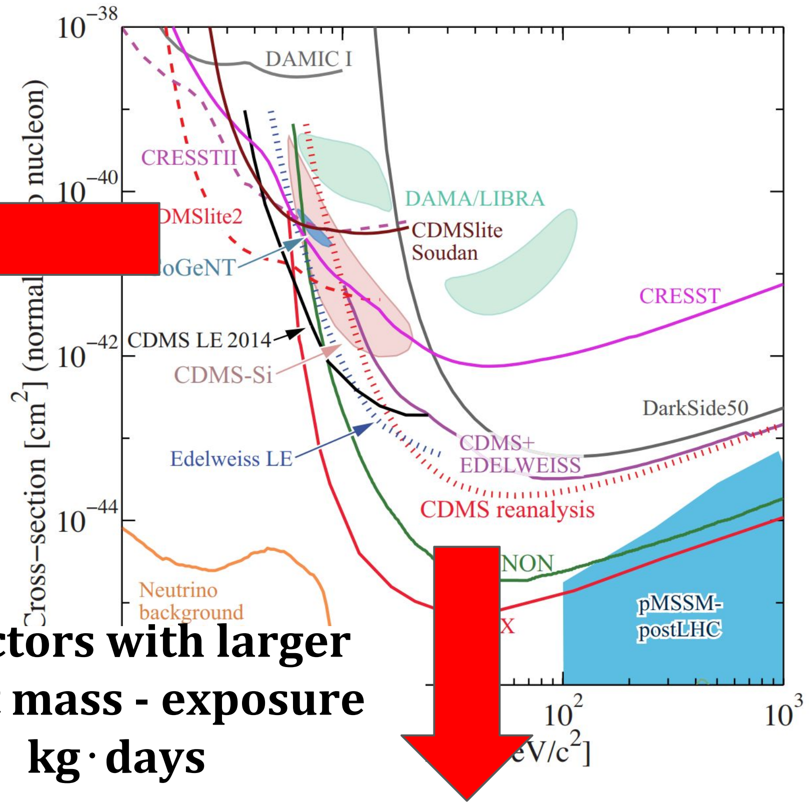
The Dark Matter conundrum

Status as of 2017

Detectors with lower threshold



Detectors with larger target mass - exposure kg · days

<u>Motivation</u>

1. Non-findings
2. Plethora of DM models

WIMP miracle era

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

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)

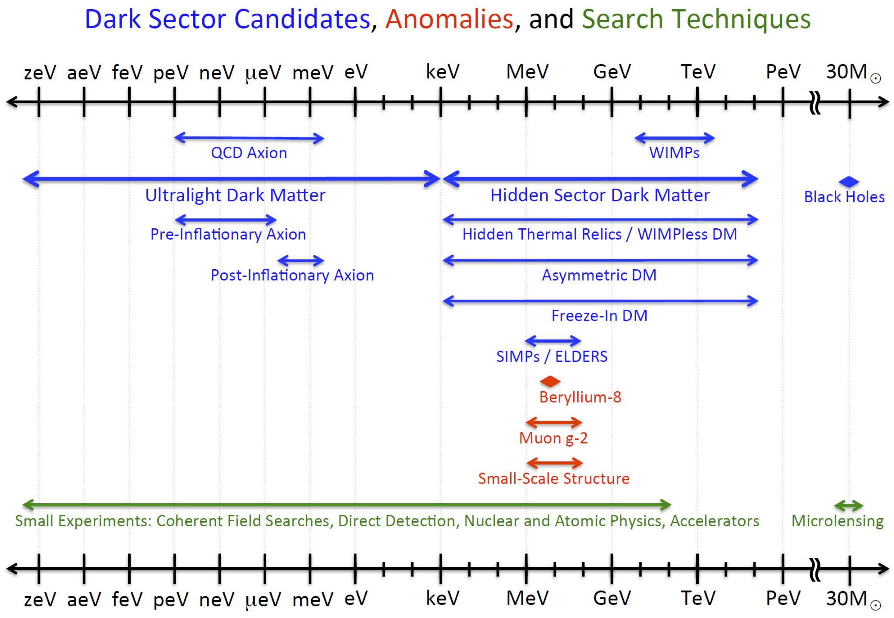
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

WIMP-less miracle era

PRL **101,** 231301 (2008) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2008

Dark-Matter Particles without Weak-Scale Masses or Weak Interactions

Jonathan L. Feng and Jason Kumar
Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
(Received 4 April 2008; published 1 December 2008)

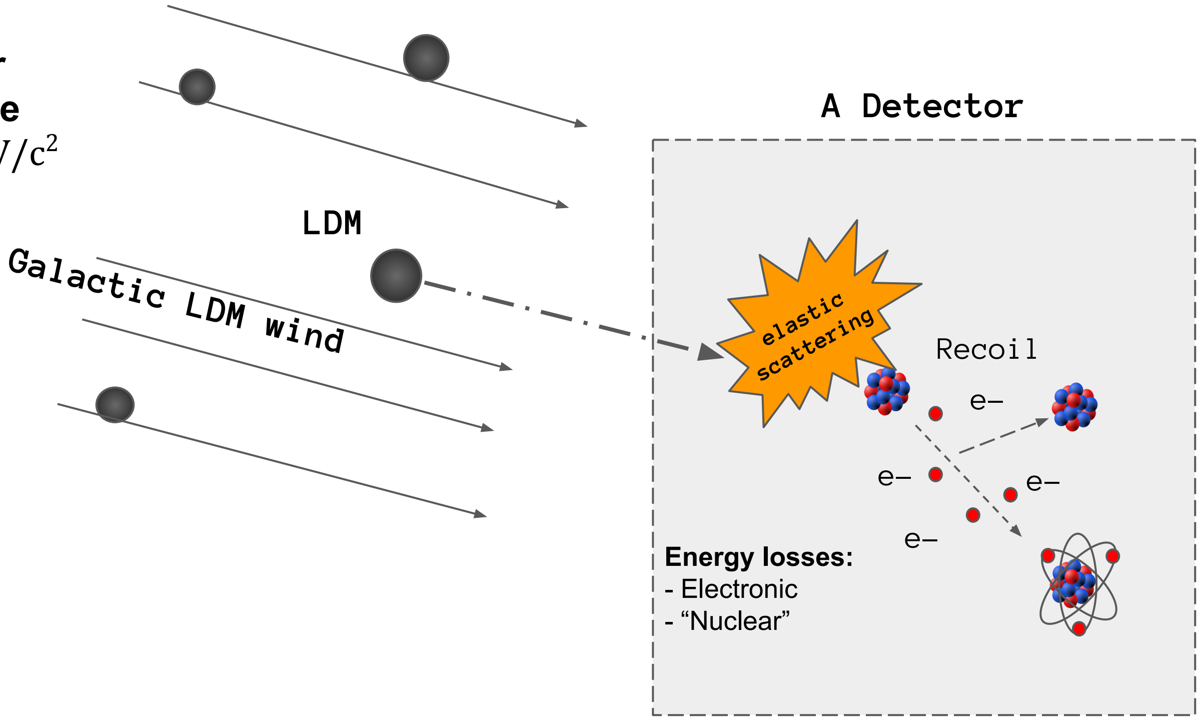


Cosmic visions 2017

Direct detection of light dark matter

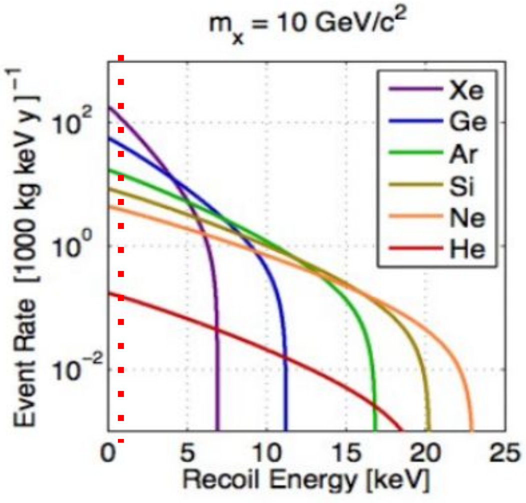
Detection through ionization

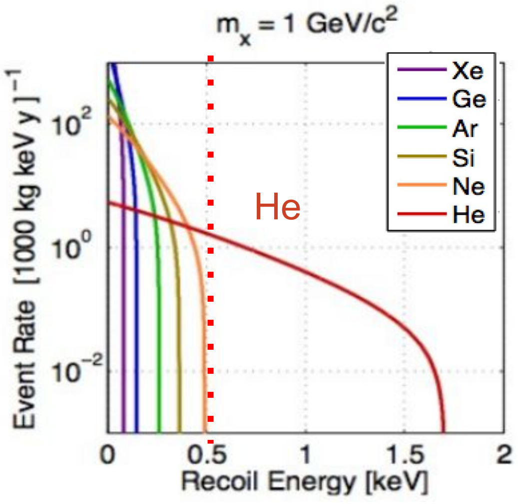
Light Dark Matter (LDM) Mass range
0.1GeV/c^2- few GeV/c^2



Comparison between heavy and light targets - A

Kinematics





500 eV . . . .

If we have E_R= 500 eV recoil induced by a DM particle of M_χ= 1 GeV/c²

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

Minimum relative WIMP velocity to produce a recoil of E_R

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

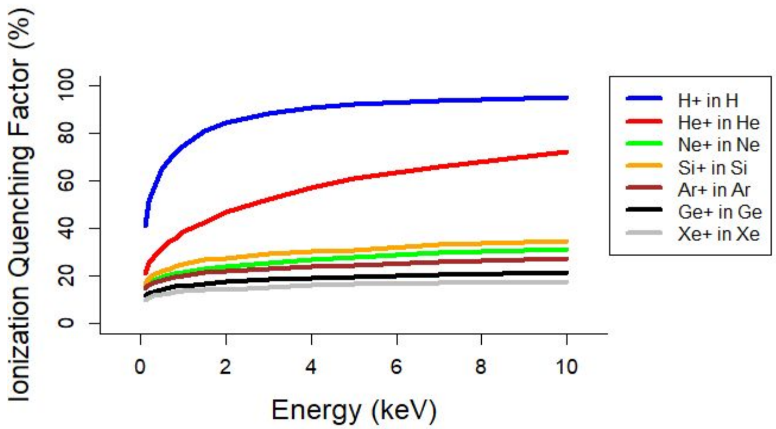
WIMP escape velocity ~540 km/s

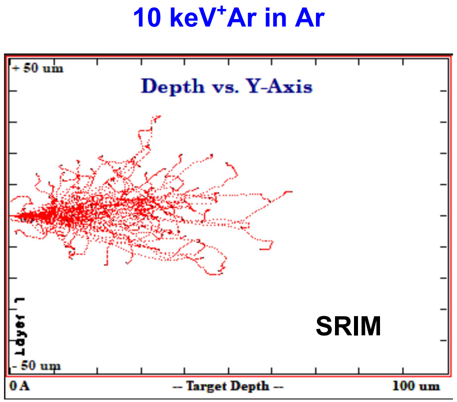
Light Projectile + Light target ⇒ Better kinematical match

Comparison between heavy and light targets - B

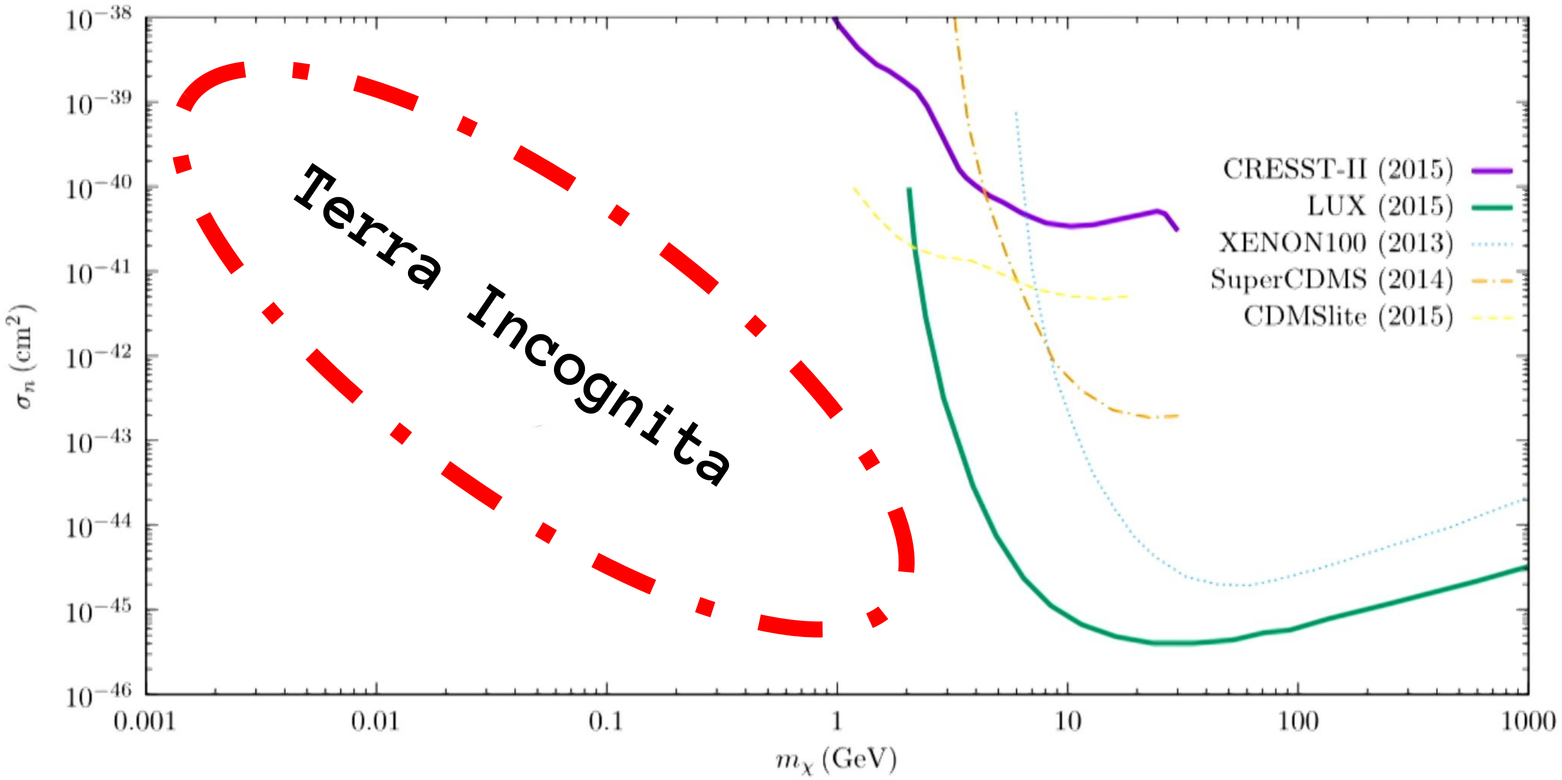
Ionization quenching

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.





Light Projectile + Light target ⇒ Less demanding detector threshold



Terra Incognita
CRESST-II (2015)
LUX (2015)
XENON100 (2013)
SuperCDMS (2014)
CDMSlite (2015)
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
σ_n (cm^2)
0.001
0.01
0.1
1
10
100
1000
m_χ (GeV)

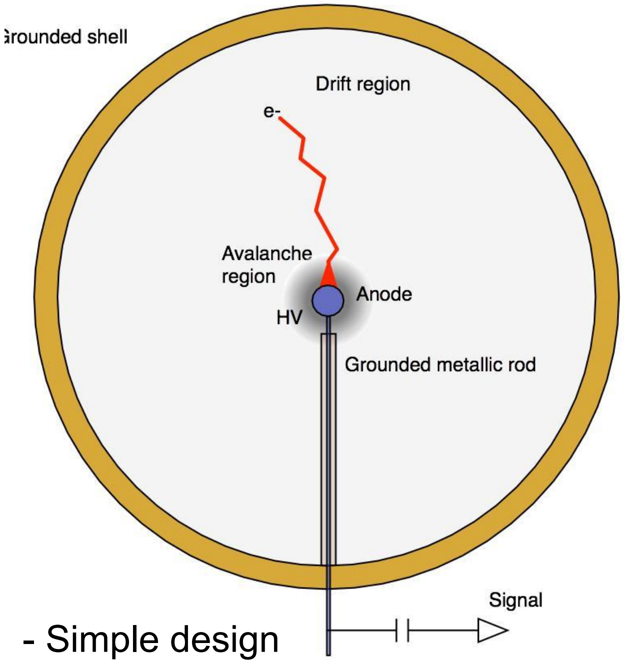
What about using light targets for dark matter searches?

Hydrogen and/or Helium

Gases (NTP)

Gaseous detector ???

The Spherical Proportional Counter



- Simple design
- Single readout

I.Giomataris et al ,JINST,2008, P09007

Electric field

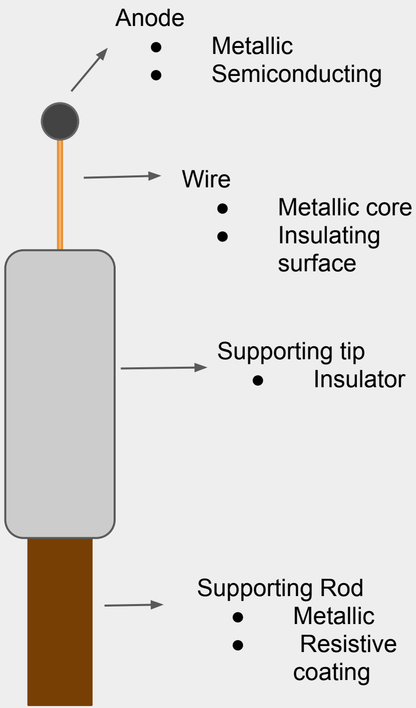
Strong dependence on the radius

$$E(r) = \frac{V_0}{r^2}\frac{r_A r_C}{r_C - r_A} \approx \frac{V_0}{r^2} r_A$$

r_A = anode radius
r_C = cathode radius

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

The sensor



Spherical Proportional Counter (SPC)

Fun fact

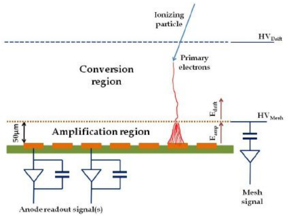
Old LEP RF cavities

Spherical gaseous detectors

In the picture:
I.Giomataris, G.Charpak

Advantage of spherical geometry - A

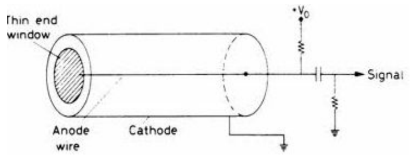
Large volume detector with low threshold



Parallel Plate

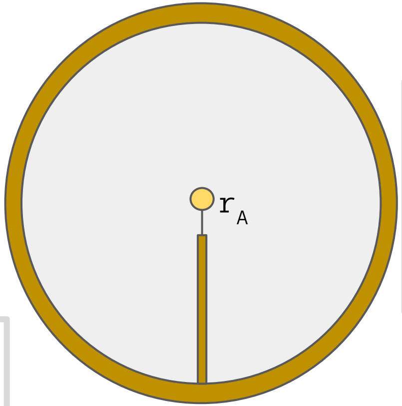
$$C = \varepsilon_0 \frac{S}{d} \approx 3500 \text{ pF}$$

Cylindrical



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

Spherical

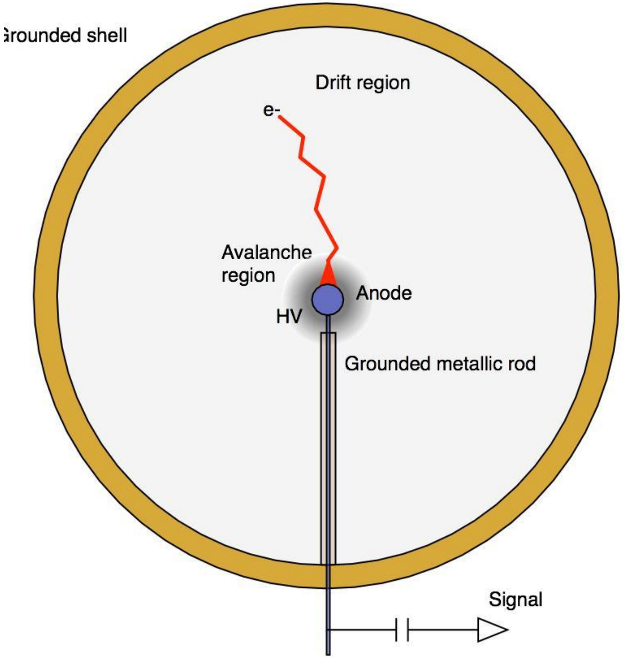


$$C \approx 4\pi\varepsilon r_A \approx 1.5 \text{ pF}$$

Capacitance ~ Electronic noise ~ Threshold

Advantage of spherical geometry - B

Construction with radiopure materials



Advantages of the spherical geometry

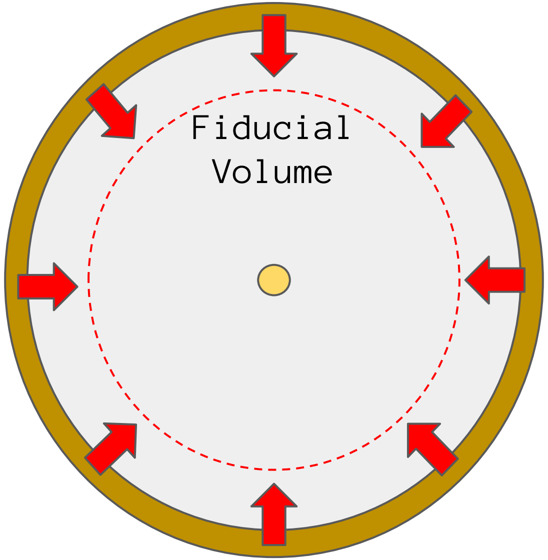
- Lowest surface to volume ratio
- Sustains higher pressure
- Robustness (anode Ø 1 mm - 6.3 mm)

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**

Background rejection capabilities-A

Fiducialization



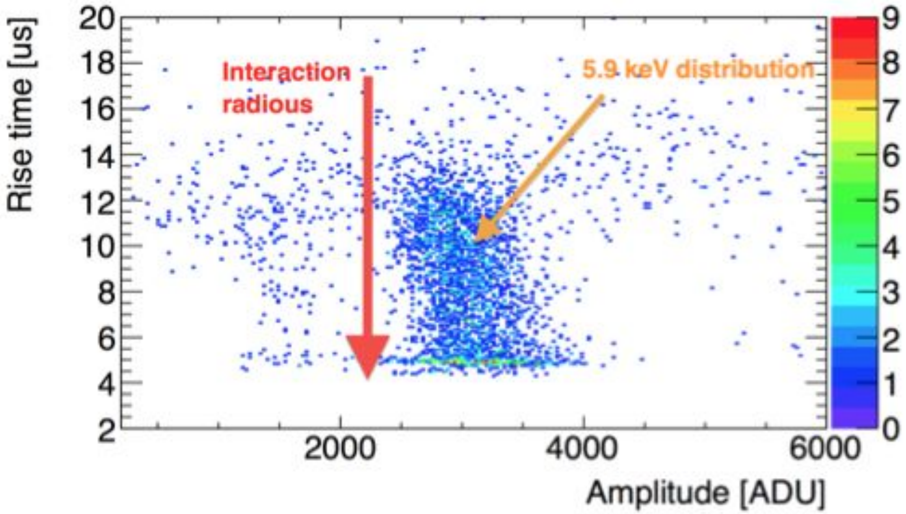
Background comes from the materials of the vessel

Surface

<u>Primary e- drift time dispersion</u>

$$\sigma(r) \propto (r/r_{sphere})^3$$

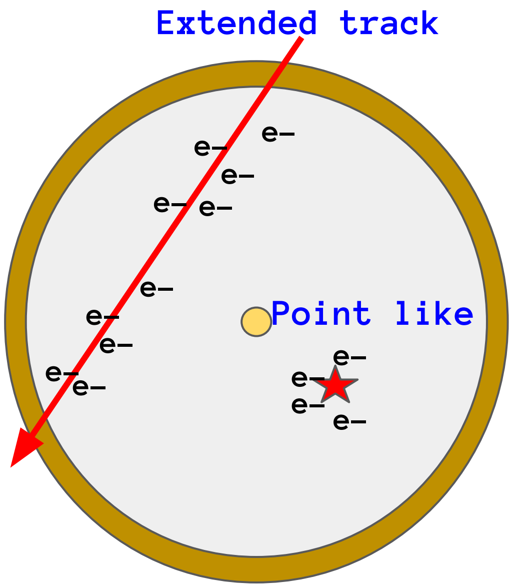
5.9 keV X-rays line

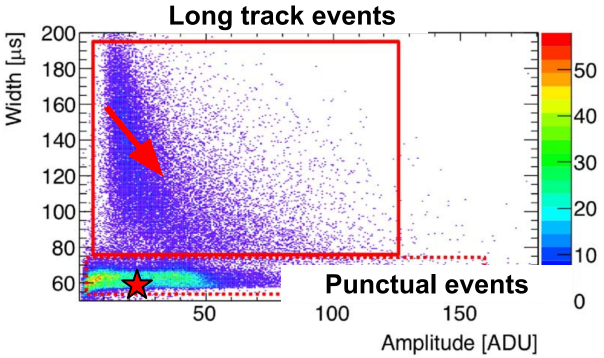


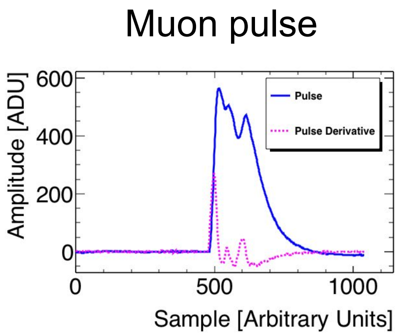
Rise time → Δt between 90% - 10% of pulse height

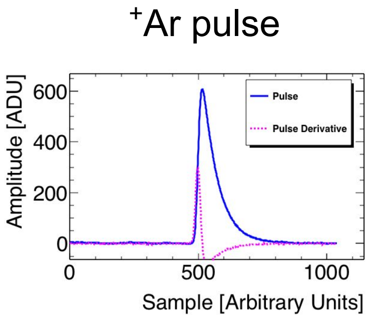
Background rejection capabilities-B

Event discrimination









Muon pulse:

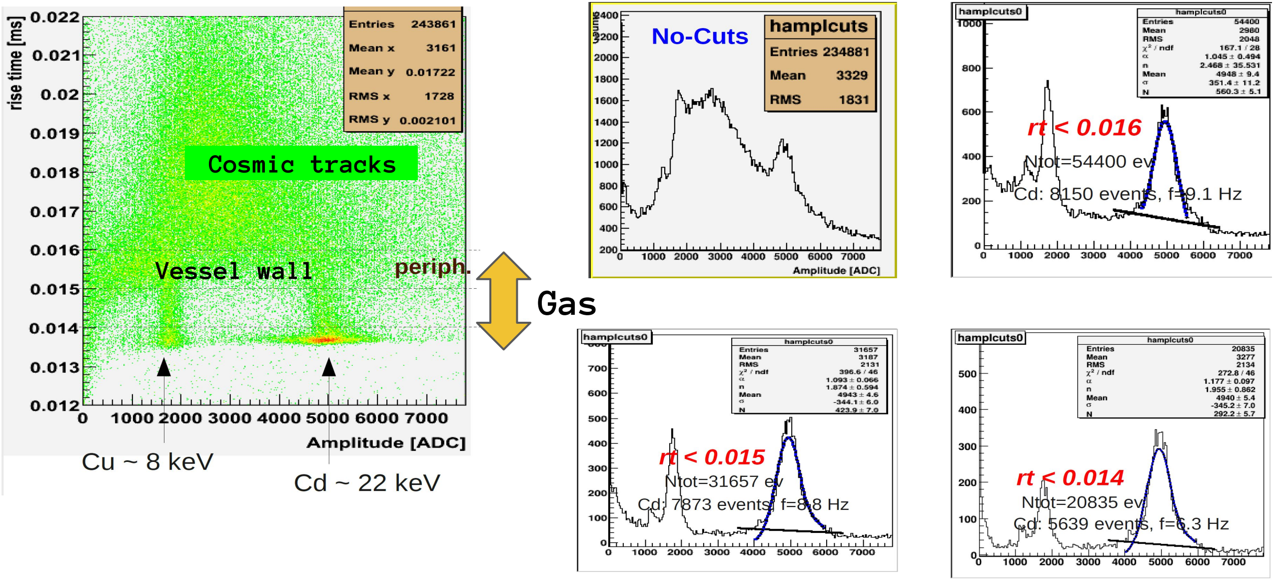
Amplitude = 575 ADU
Width (FWHM) = 155.5 µs
Rise time = 18.2 µs

$^{+}$Ar pulse:

Amplitude = 606 ADU
Width (FWHM) = 63.4 µs
Rise time = 16.3 µs

Illustration of particle identification – Background rejection

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

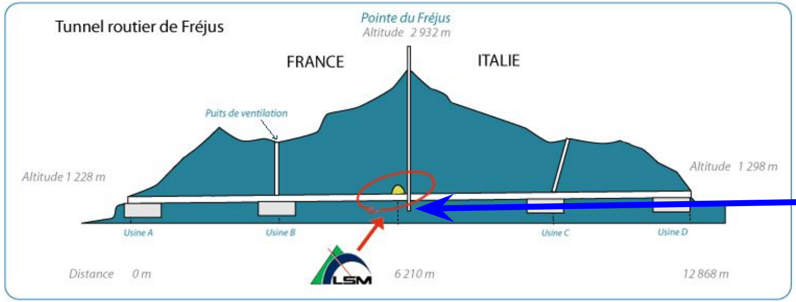


Efficiency of the cut in rt → ~ 70% signal (Cd line)
Significant background reduction

The SEDINE detector at LSM

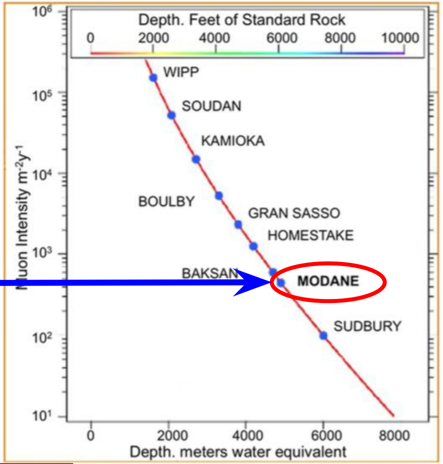
First exploration of light dark matter

Laboratoire Souterrain de Modane



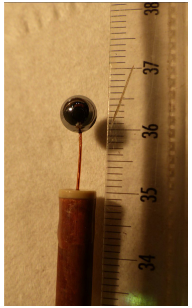
Laboratoire Souterrain de Modane

4800 wme
5 μ/m²/day

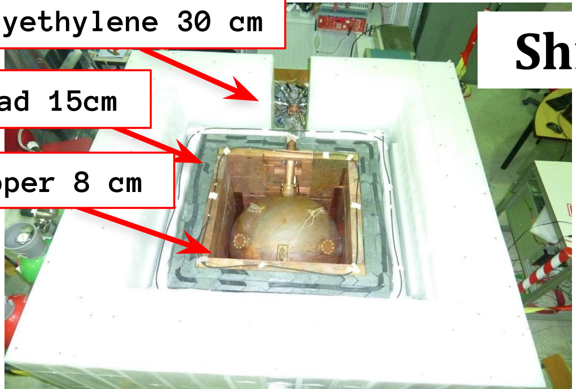


Vessel
Ø 60cm copper

Sensor
Ø 6.3mm Si



Polyethylene 30 cm
Lead 15cm
Copper 8 cm



Shielding

WIMP search run data

Target: Ne+0.7%CH_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)

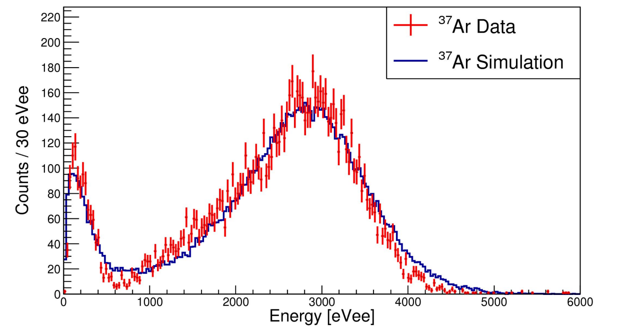
Analysis threshold: 150 eVee (~720 eVnr)

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

Calibrations

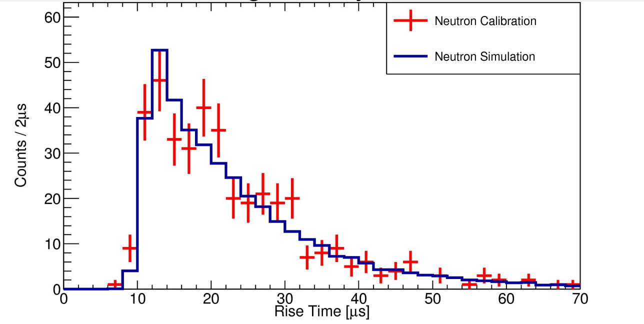
^{37}Ar gaseous source

2.82 keV and 270 eV X-rays (K and L shells)



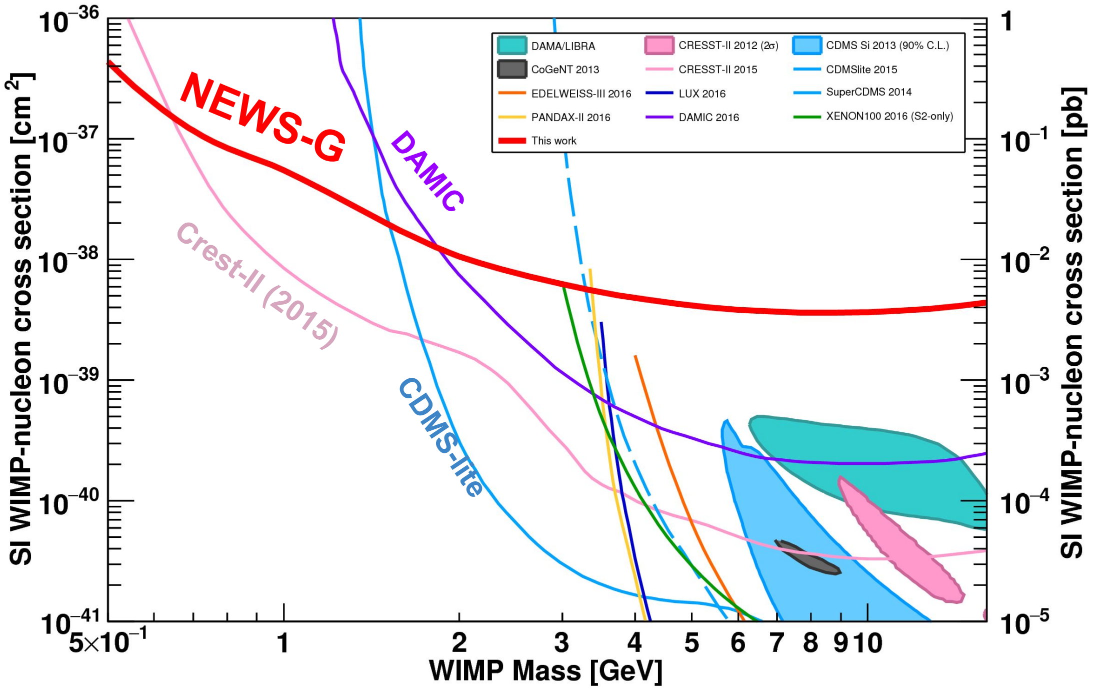
^{241}Am–^{9}Be neutron source

Nuclear recoils homogeneously distributed in the volume



First results of NEWS-G with SEDINE

[NEWS-G collaboration, Astropart. Phys. 97, 54 (2018), doi: 10.1016/j.astropartphys.2017.10.009]



Exclusion at 90% confidence level (C.L.) of cross-sections above $4.4 \cdot 10^{-37}$ cm^2 for a 500 MeV/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_4
- *High pressure operation (Penning)*
-*Hydrogen rich target*

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

Read-out modules R&D

Aims
- *High pressure operation*
- *High gain*
- *Increased stability*
- *Low radioactivity*

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

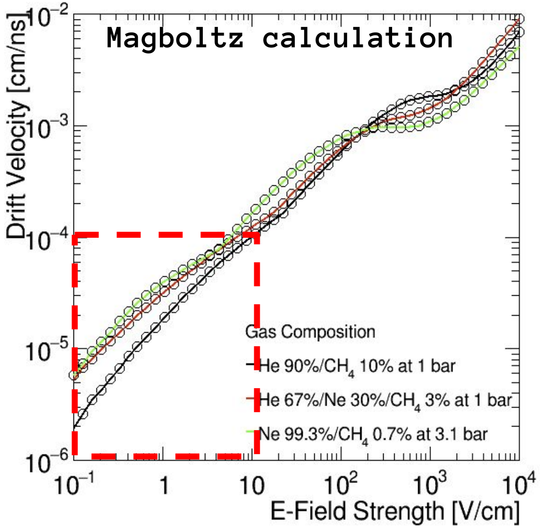
Quenching factor measurements
- *Ion / electron beam (LPSC, France)*
- *Neutron beam (TUNL, USA)*

Study of the detector response
Solid state laser (213 nm)
- *drift time measurements*
- *parametrization of the avalanche process*

Operating with a He mixture

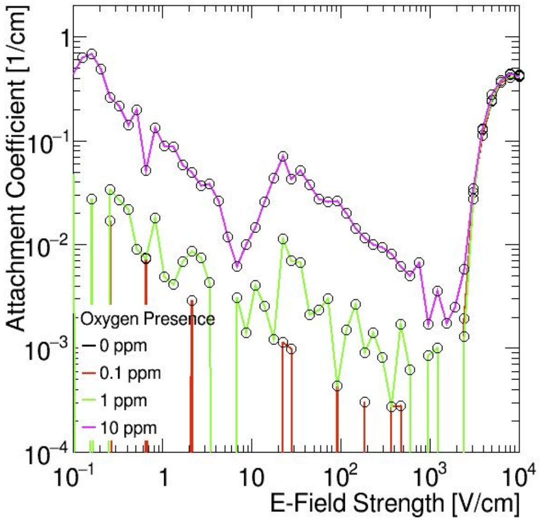
Sensitivity to contaminants - Attachment

Drift velocity of e⁻



Low E-field region

Attachment coefficient vs E-field magnitude



Lower O_2, H_2O levels

⇊

Purification (Getter, Oxysorb)

Increased E-field

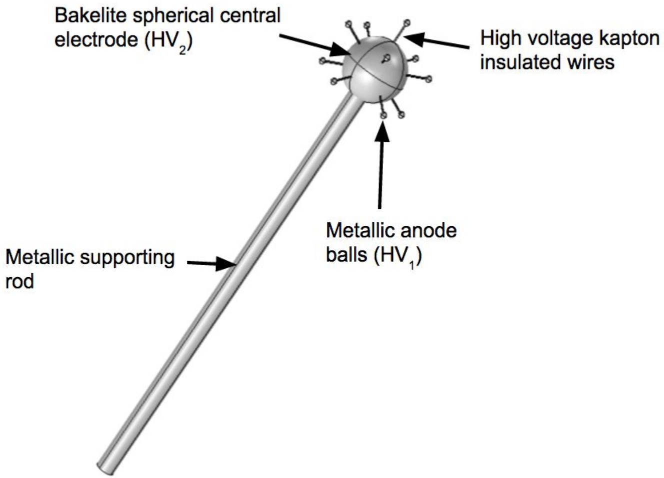
⇊

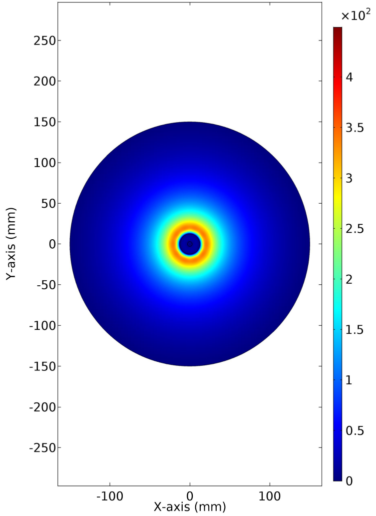
ACHINOS

The multi-anode sensor - ACHINOS

Dealing with the low electric field magnitude at large detectors → **Scalability**

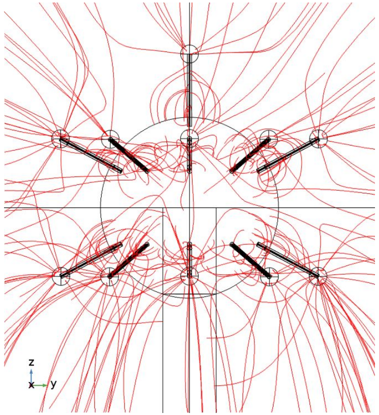
The idea: Use multiple anodes placed in the same potential instead





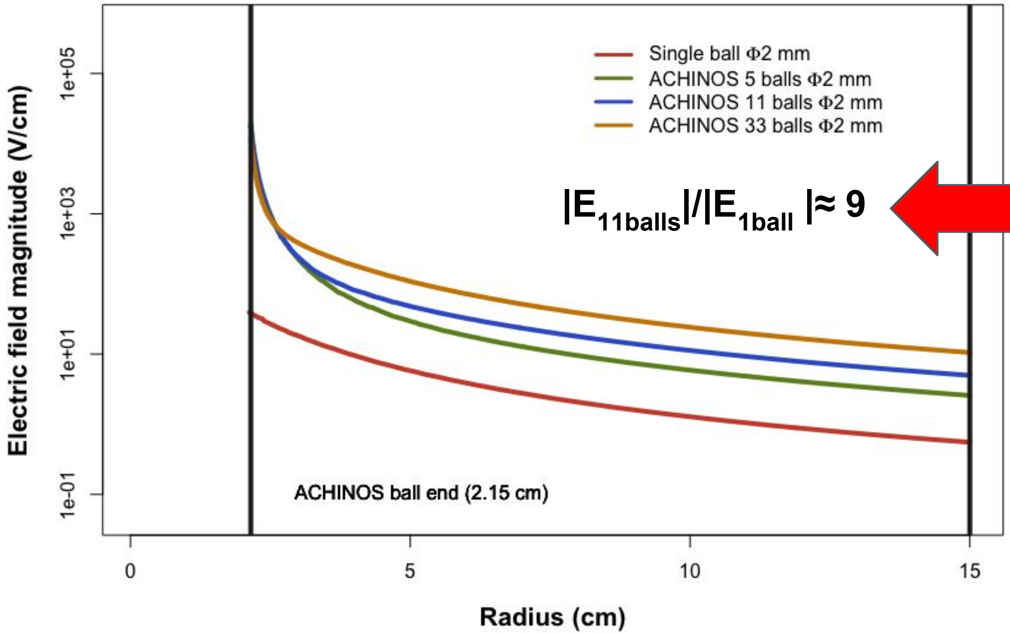
Creation of collective iso-potentials

Field lines close close to the central structure



$$E(r) = \frac{V_0}{r^2} r_1$$ *Electric field dependence on the radius*

Electric field magnitude with ACHINOS

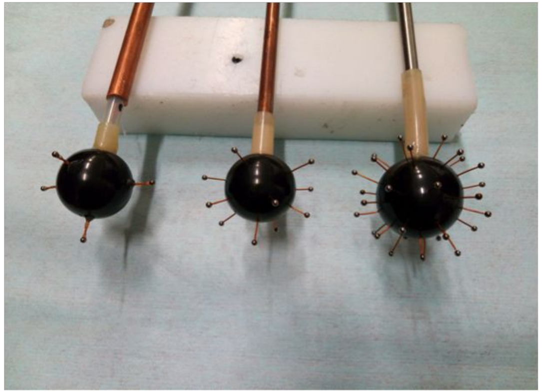


$|E_{11balls}|/|E_{1ball}| \approx 9$

Advantages

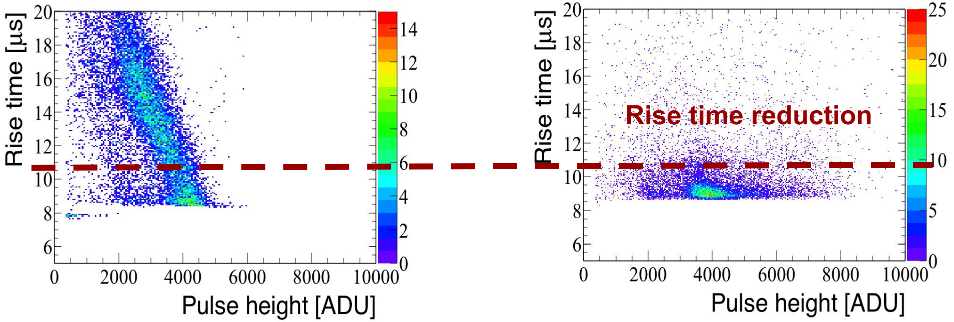
1. Amplification tuned by the anode ball size
2. Volume electric field tuned by the size and number of anodes of the ACHINOS structure
3. Individual readout - TPC like capabilities

Results with the first prototypes

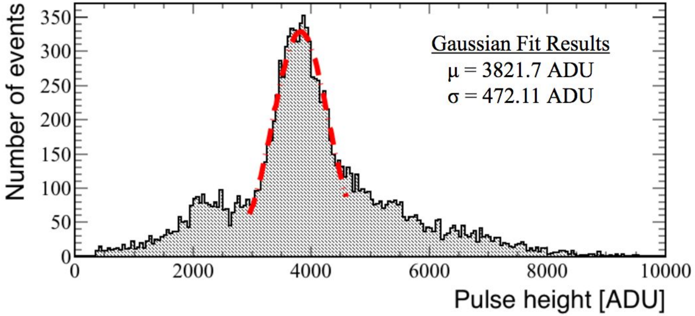


Rise time vs Pulse height Single ball

Rise time vs Pulse height 11-balls



Measurement of the Fe^{55} 5.9 keV line



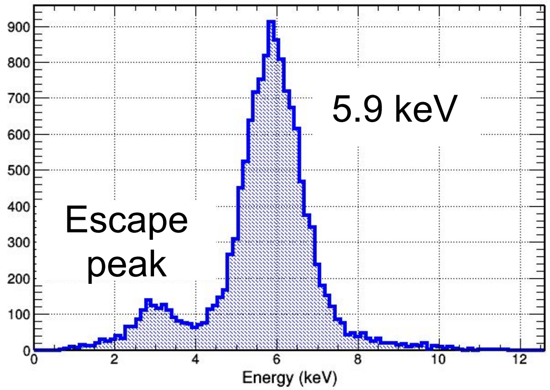
Conditions:

- Gas Mixture: $He:Ar:CH_4$ (80:11:9)
- Pressure: 640 mbar
- HV_1 = 2015 V, HV_2 = -200 V

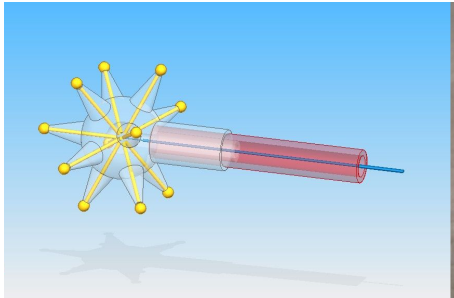
Improved results with the 2nd gen prototypes

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

Gain similar for every ball



3D printed design



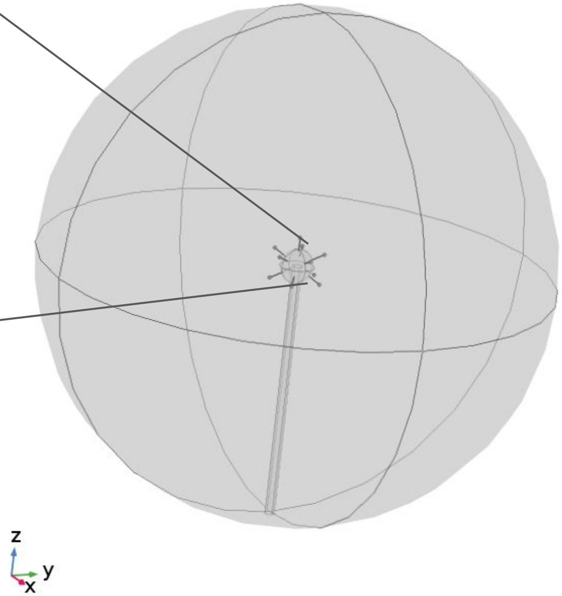
Modules covered with resistive coatings

Araldite+Graphite
Araldite+Copper

Conditions:

- *Gas Mixture: He:Ar:CH4 (56:37:7)*
- *Pressure: 455 mbar*
- *HV1 = 1100 V, HV2 = -100 V*

Why such a weird name?

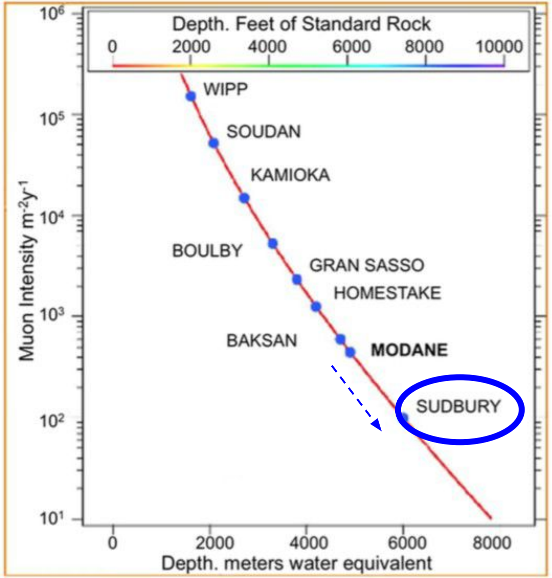


ACHINOS= ΑΧΙΝΟΣ = Sea urchin

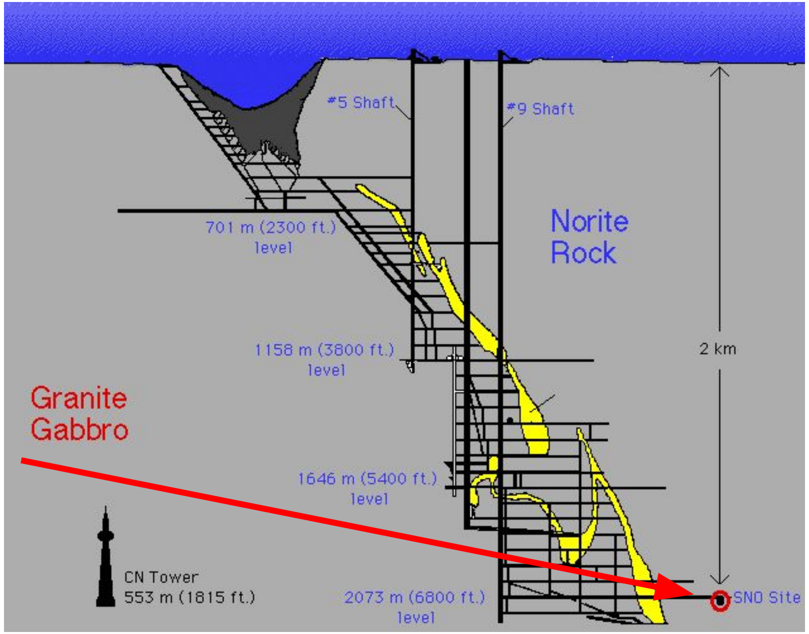
NEWS-G at SNOLAB

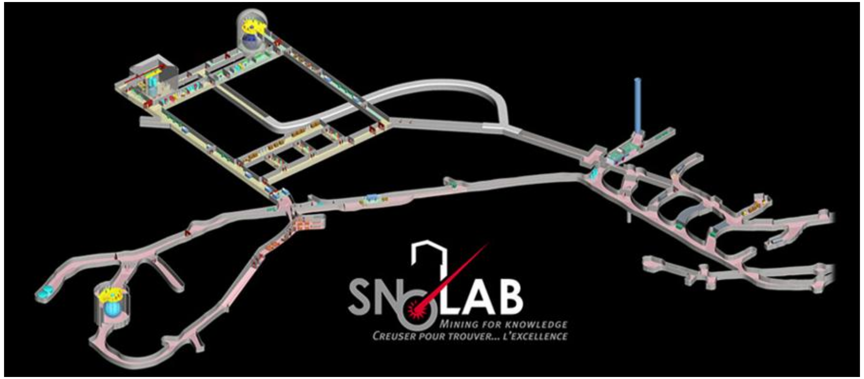
The underground laboratory in the Sudbury, Canada

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

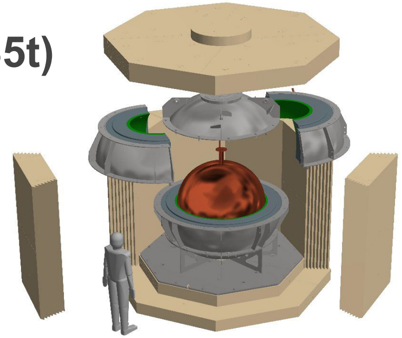
The new and improved setup

Copper vessel (140 cm ⌀, 12 mm thick)

- Low activity copper (C10100)
  - 7 to 25 μBq/kg Th
  - 1 to 5 μBq/kg of U
- Electropolishing & Electroplating

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)

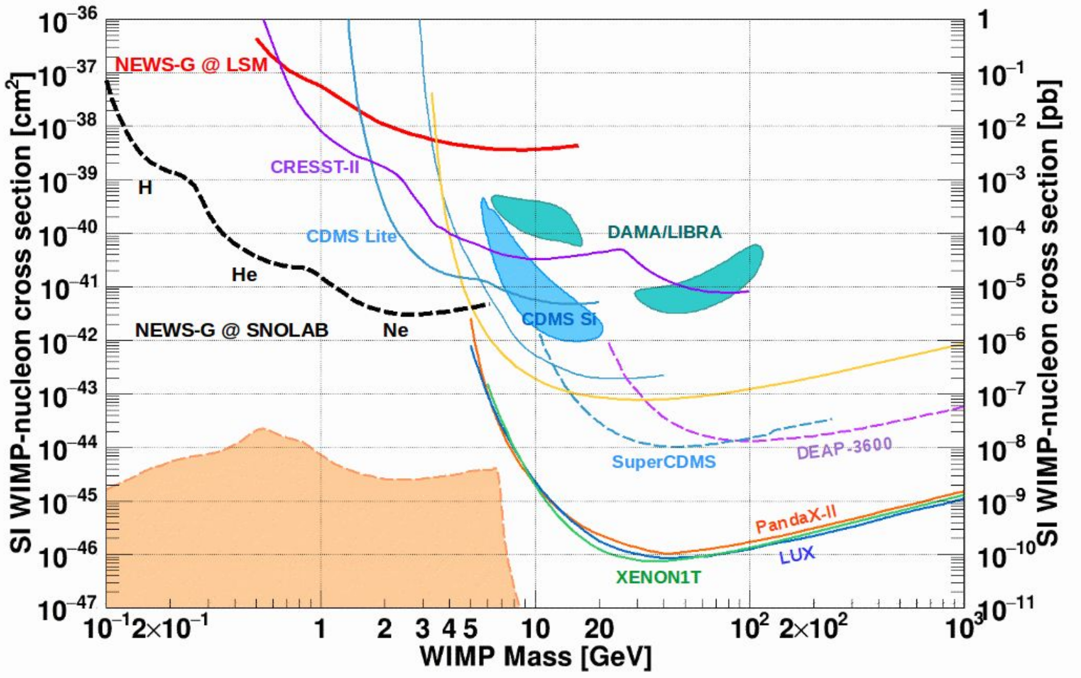


Hemispheres built in France, stored at LSM before welding
Electropolishing-Electroplating with PNNL colleagues

Glove box for Radon free rod installation

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)

- Simplicity of design
- Strong background rejection handles
- Scalability
- Lower backgrounds

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

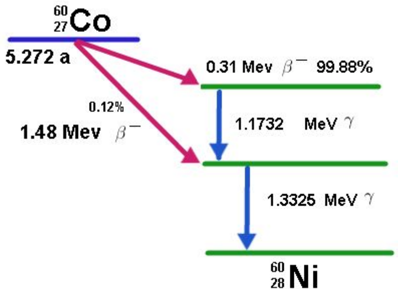
Associated lab : TRIUMF - F Retiere
- Future R&D on light detection, sensor

Thessaloniki, Greece 2018

Thank you very much for your attention

Additional material

Main background sources for LSM detector



^{60}Co Contamination of 1 mBq/kg

BG Rate = 0.3-0.5 evnt/keV/kg/day

Solution: Limit time exposure on ground for pure copper.

^{210}Pb, ^{210}Bi Contamination of 1 nBq/kg

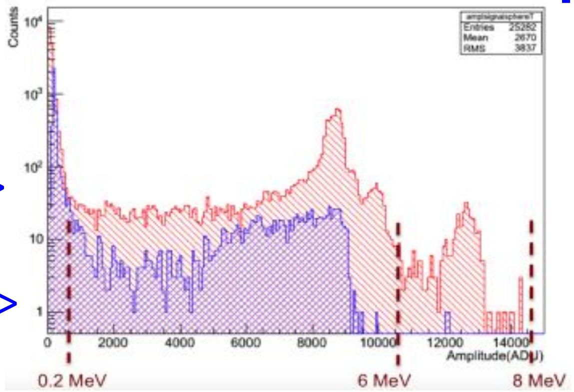
BG Rate = 0.1 evnt/keV/kg/day

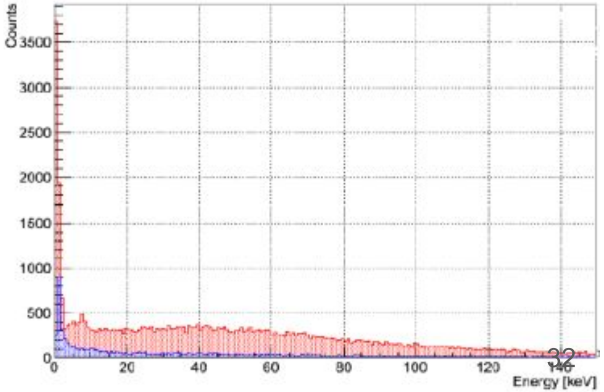
Competitive BG levels

Solution: Chemical cleaning

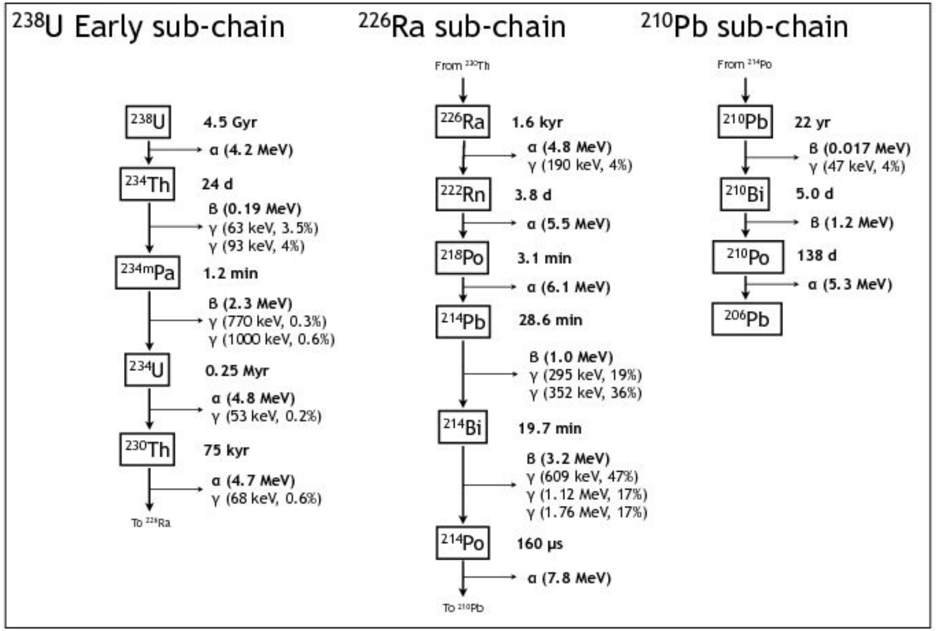
Effect of cleaning:

- High energy events 180 mHz => ~2 mHz
- Low energy events 400 mHz => ~20 mHz





^{238}U Chain



238U Early sub-chain
226Ra sub-chain
210Pb sub-chain
238U
4.5 Gyr
α (4.2 MeV)
234Th
24 d
β (0.19 MeV)
γ (63 keV, 3.5%)
γ (93 keV, 4%)
234mPa
1.2 min
β (2.3 MeV)
γ (770 keV, 0.3%)
γ (1000 keV, 0.6%)
234U
0.25 Myr
α (4.8 MeV)
γ (53 keV, 0.2%)
230Th
75 kyr
α (4.7 MeV)
γ (68 keV, 0.6%)
To 226Ra
From 230Th
226Ra
1.6 kyr
α (4.8 MeV)
γ (190 keV, 4%)
222Rn
3.8 d
α (5.5 MeV)
218Po
3.1 min
α (6.1 MeV)
214Pb
28.6 min
β (1.0 MeV)
γ (295 keV, 19%)
γ (352 keV, 36%)
214Bi
19.7 min
β (3.2 MeV)
γ (609 keV, 47%)
γ (1.12 MeV, 17%)
γ (1.76 MeV, 17%)
214Po
160 μs
α (7.8 MeV)
To 210Pb
From 214Po
210Pb
22 yr
β (0.017 MeV)
γ (47 keV, 4%)
210Bi
5.0 d
β (1.2 MeV)
210Po
138 d
α (5.3 MeV)
206Pb

Estimated background

Simulation done with 12mm thick 140cm diam copper sphere full with 99% Ne 1%CH4, 11.43 kg of gas

Source Position	Mass (kg) or Surface (cn		Source	evts/kg/day/[(µBq/kg) or (nBq/cm2)]	contamination	units	evts/kg/day < 1ke
CopperSphere	627.83 kg		Co60	0.0018	30	µBq/kg	0.054
CopperSphere	627.83 kg		U238	0.0036	3	µBq/kg	0.011
CopperSphere	627.83 kg		Th232	0.0049	12.9	µBq/kg	0.063
InnerSurface	57255 cm^2		Pb210	0.012	0.16	nBq/cm2	0.002
ArchLead	2108.95 kg		U238	0.001	61.8	µBq/kg	0.062
ArchLead	2108.95 kg		Th232	0.0011	9.13	µBq/kg	0.010
Rod	0.0931721 kg		Co60	2.95E-007	30	µBq/kg	0.000
Rod	0.0931721 kg		U238	1.81E-006	3	µBq/kg	0.000
Rod	0.0931721 kg		Th232	2.11E-006	12.9	µBq/kg	0.000
Wire	2.66005e-05	kg	Co60	1.48E-010	31000	µBq/kg	0.000
Wire	2.66005e-05	kg	U238	2.12E-009	300000	µBq/kg	0.001
Wire	2.66005e-05	kg	Th232	1.42E-009	50000	µBq/kg	0.000
Wire	2.66005e-05	kg	K40	5.41E-010	1660000	µBq/kg	0.001
LabArea			**Tl208/K40**				0.076

Total	0.279

Copper

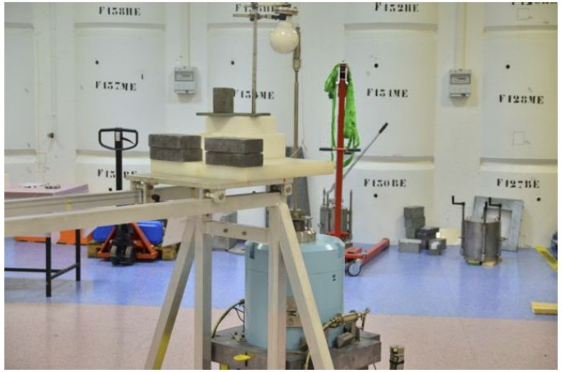
Internal surface

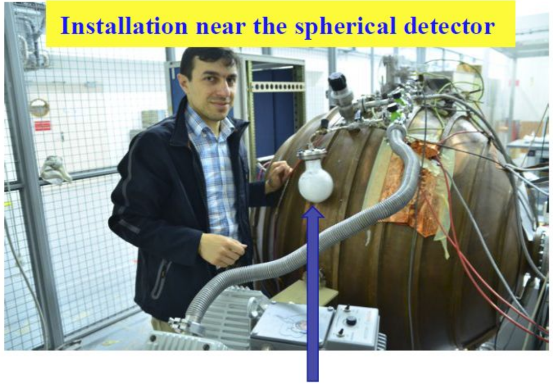
Lead shield

External BG with SNO Flux

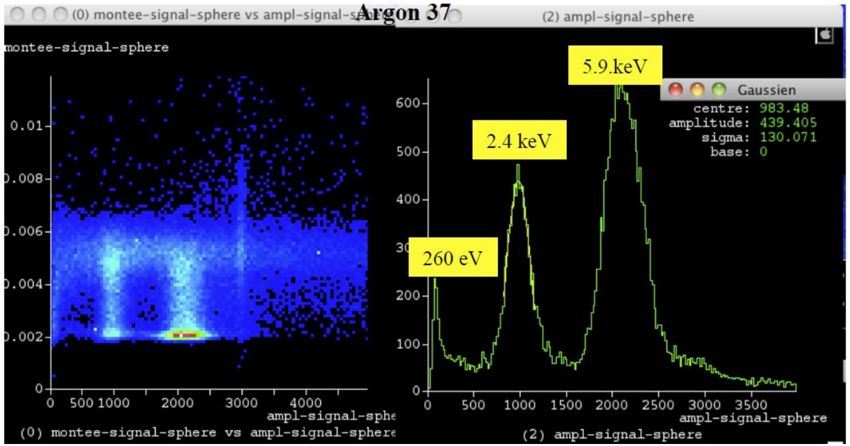
Low-energy calibration source *Argon-37*

Home made Ar-37 source: irradiating Ca-40 powder with fast neutrons $7x10^6$neutrons/s
Irradiation time 14 days. Ar-37 emits K(2.6 keV) and L(260 eV) X-rays (35 d decay time)



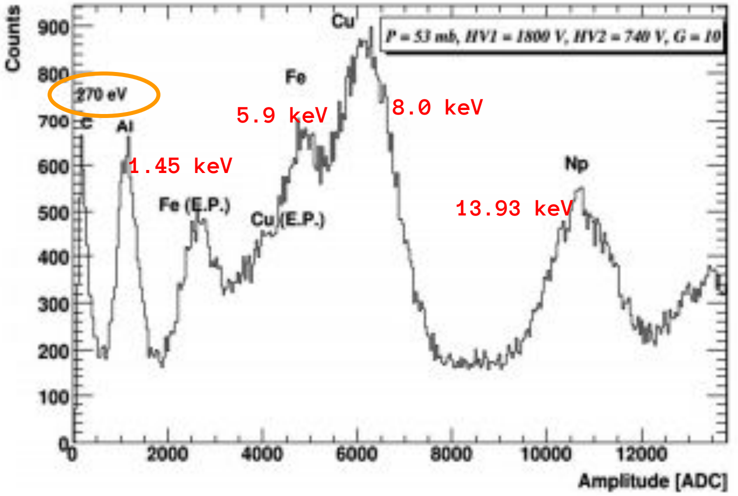


First measurement
with Ar-37 source
Total rate 40 hz
in 250 mbar gas, 8 mm ball
240 eV peak clearly seen
A key result for light dark matter search



Low energy capabilities

E. Bougamont et al, Journal of Modern Physics, Vol. 3 No. 1, 2012, pp. 57-63.



SPC Φ 130 cm

Gas: Ar+2%CH_4

Detection of fluorescence X-rays

^{241}Am -> ^{237}Np+^{4}He+ 5.6 MeV

Lines

Al -> 1.45 keV

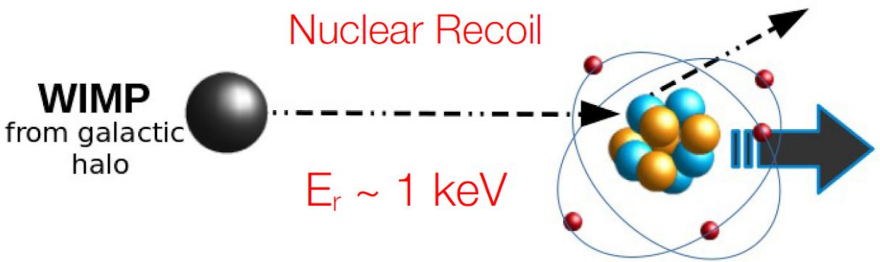
Cu -> 13.93 keV

^{237}Np -> 13.93 keV(L_α)

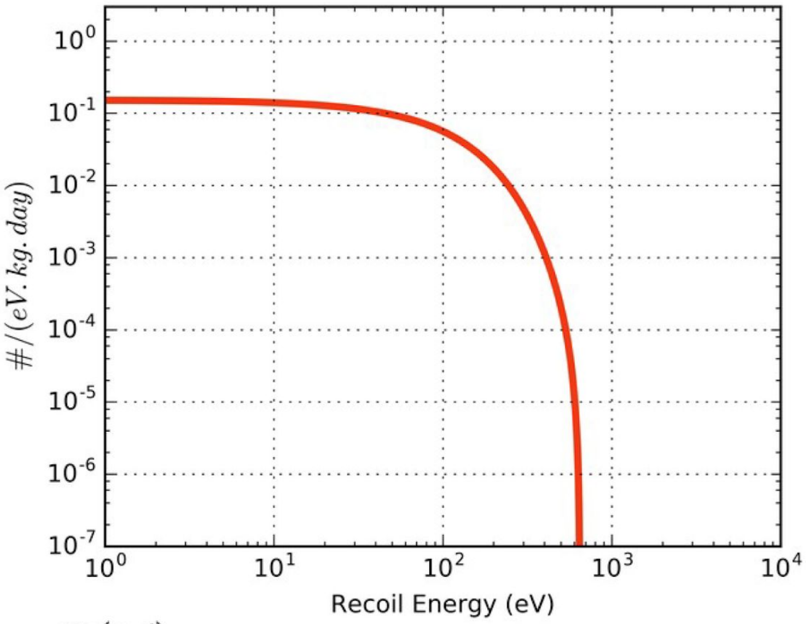
17.60 keV(L_β)

- **Single electron detection**
- **Energy threshold < 50 eV**

WIMP Recoil Spectrum



Neon, 1 kg.year, 1pb, 1 GeV WIMP

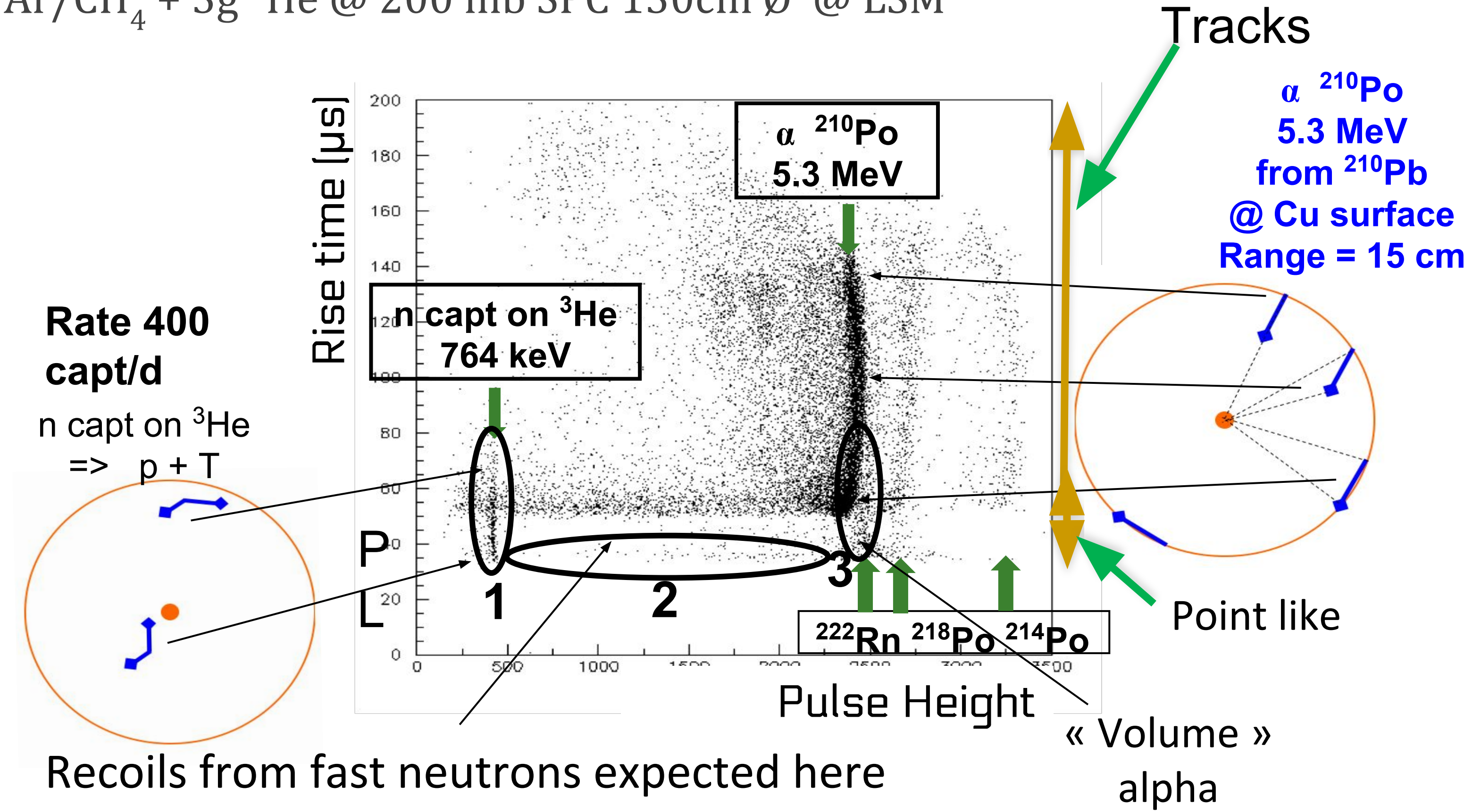


$$\frac{dR}{dE_r} = M_T \frac{\rho_0 \sigma_0}{2 m_\chi m_r^2} F^2(E_r) \int_{v_{min}} \frac{f(\vec{v})}{v} d^3v$$

Schnee, R. W. (2009). Introduction to Dark Matter Experiments. In Theoretical Advanced Study Institute in Elementary Particle Physics. Boulder, Colorado, USA.

Illustration of particle identification – Background rejection

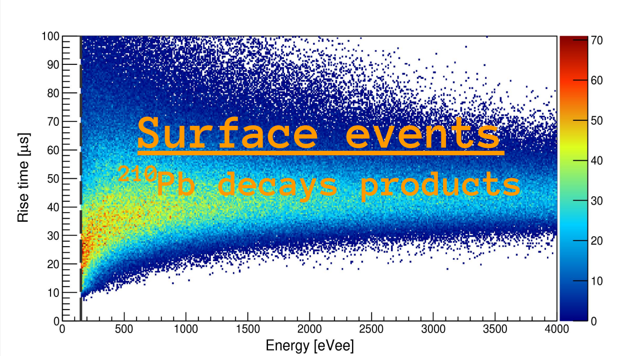
Run with Ar/CH_4 + 3g ^3He @ 200 mb SPC 130cm Ø @ LSM

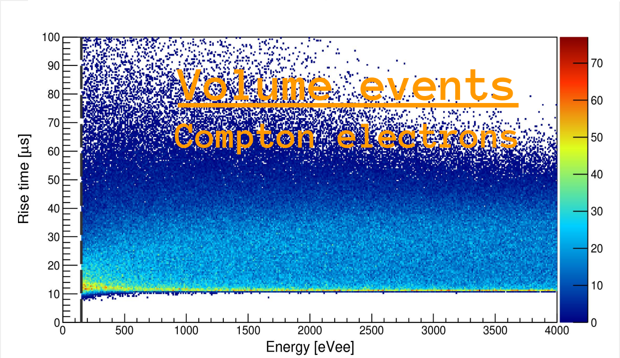


Analysis of the WIMP run data

Analysis methodology - BDT

Background modeling

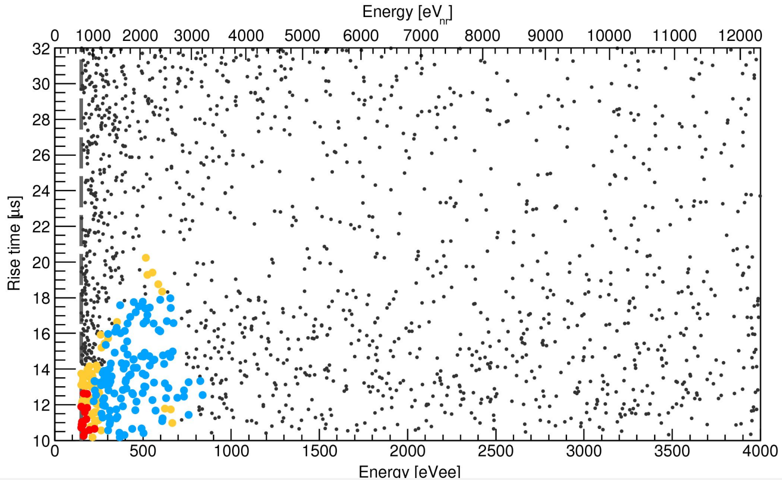




Trained with simulated WIMP and background events

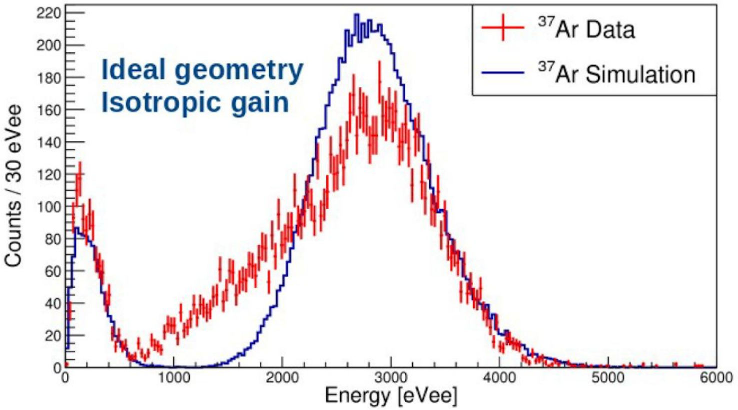
BDT

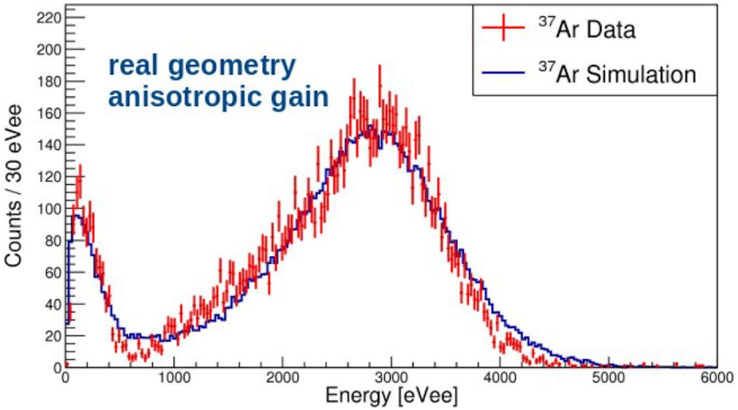
Mass dependent selection for 8 WIMP masses

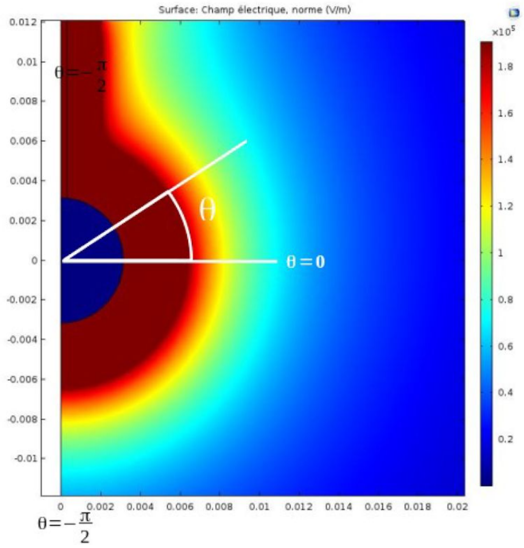


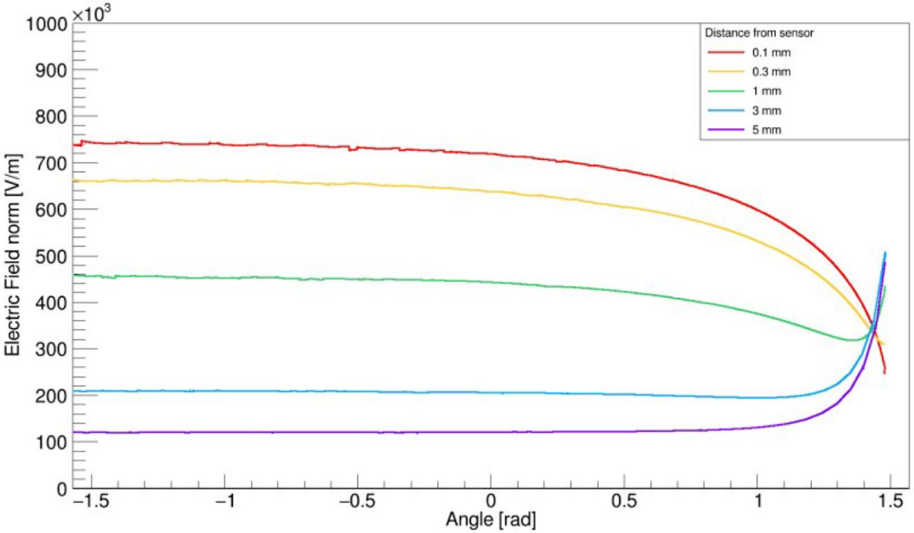
1620 events recorded in the preliminary ROI

- Failed any of the BDT cuts
- pass the BDT cut for 0.5 GeV/c^2 : 15 events
- pass the BDT cut for 16 GeV/c^2 : 123 events
- pass the BDT cut for other masses


Ideal geometry
Isotropic gain
^{37}Ar Data
^{37}Ar Simulation
Counts / 30 eVee
Energy [eVee]


real geometry
anisotropic gain
^{37}Ar Data
^{37}Ar Simulation
Counts / 30 eVee
Energy [eVee]


Surface: Champ électrique, norme (V/m)
$\theta = -\frac{\pi}{2}$
θ
$\theta = 0$
$\theta = -\frac{\pi}{2}$

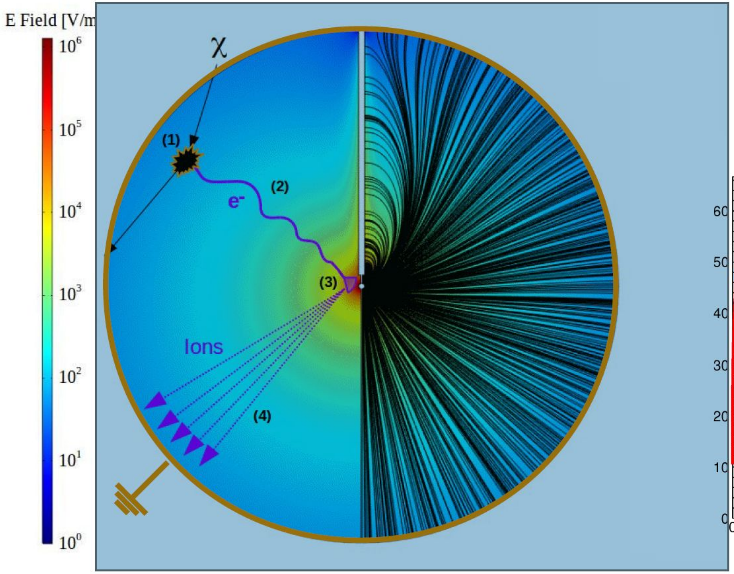

Distance from sensor
0.1 mm
0.3 mm
1 mm
3 mm
5 mm
Electric Field norm [V/m]
Angle [rad]

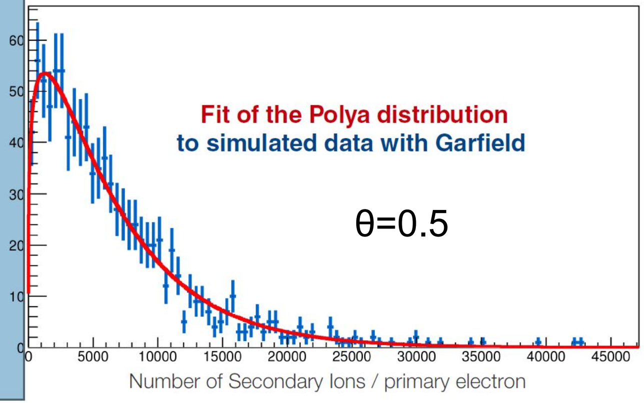
Avalanche process

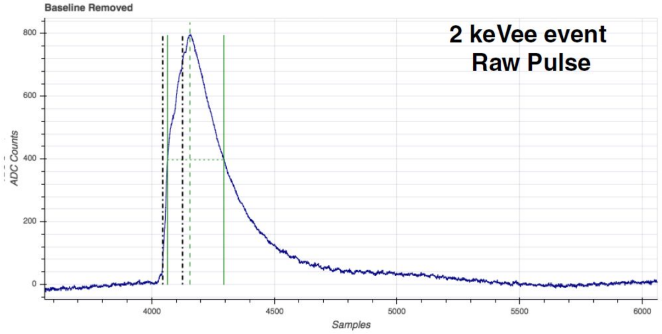
<Gain> ~ **7000** secondary ions / primary electron

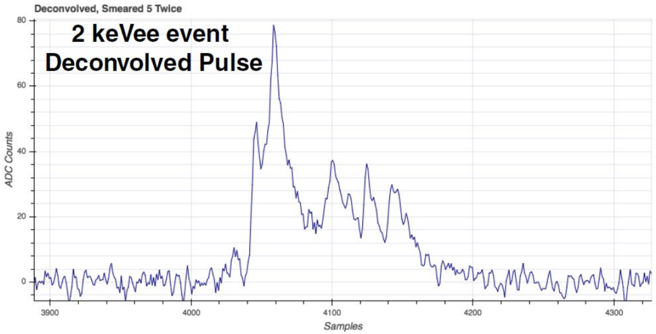
large statistical fluctuations

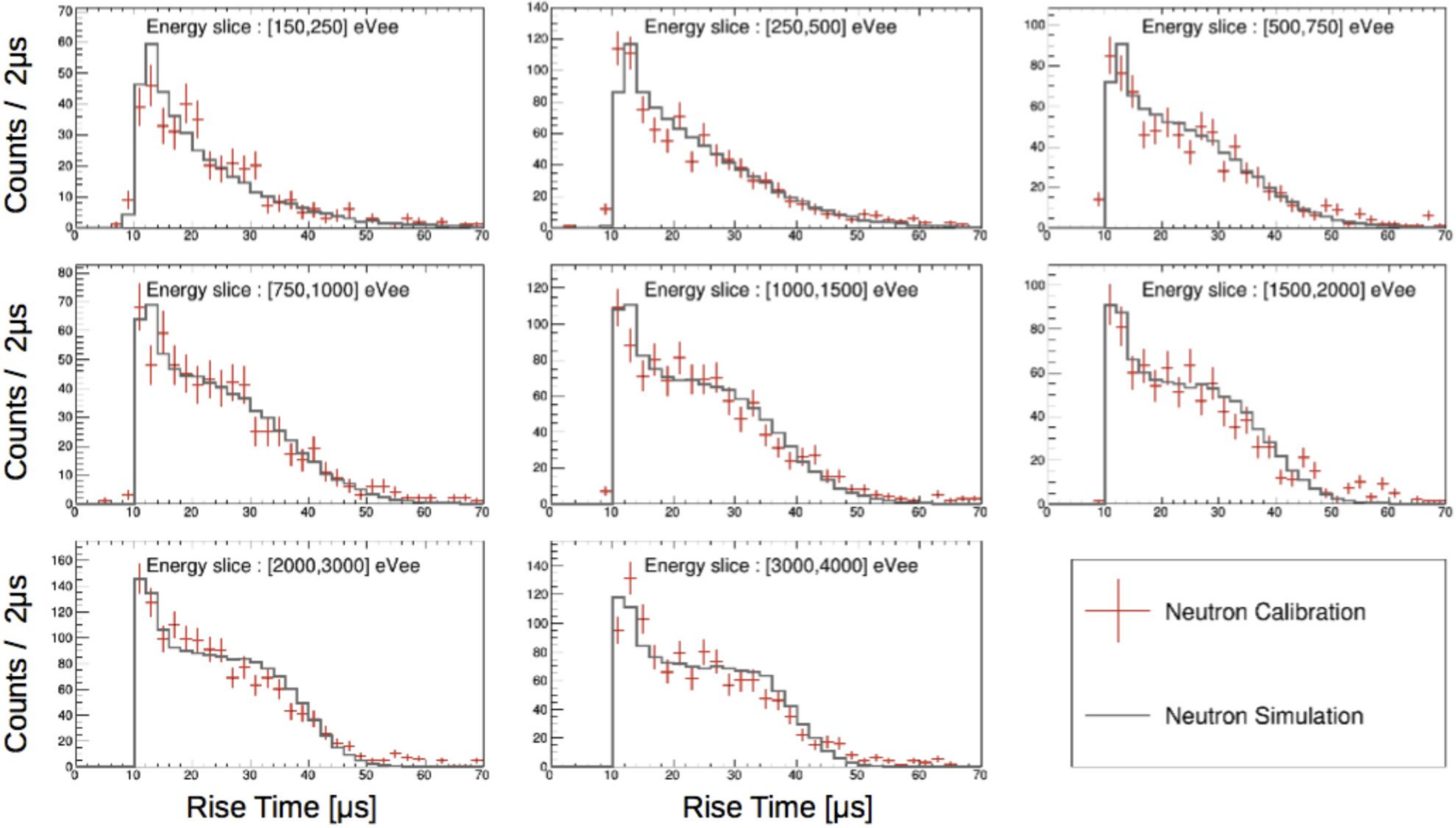
W_{Ne}=36eV





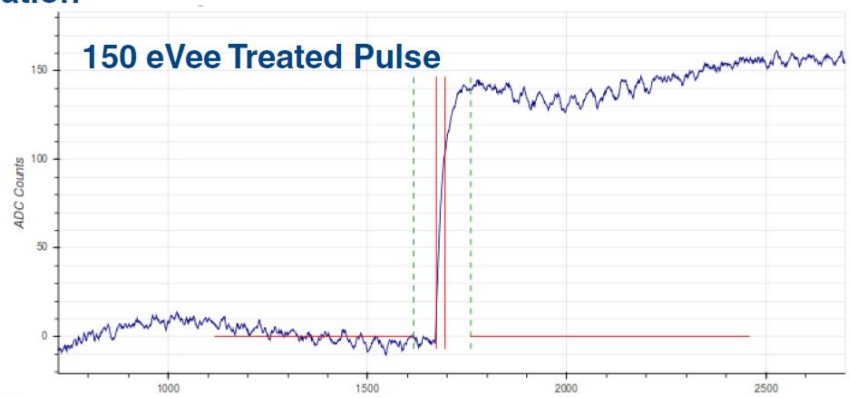




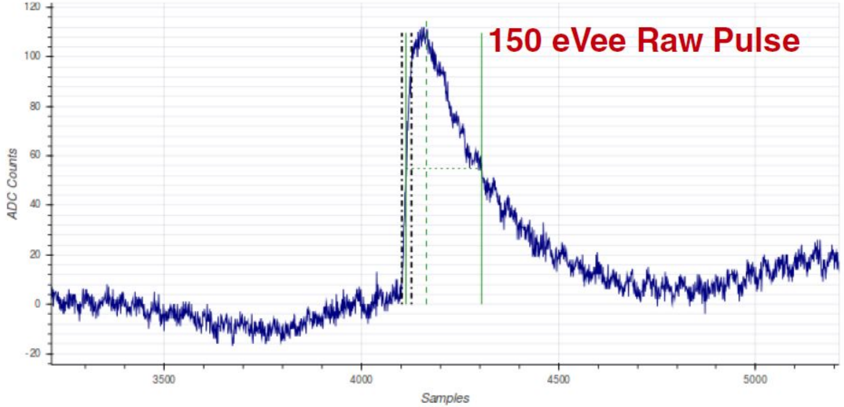


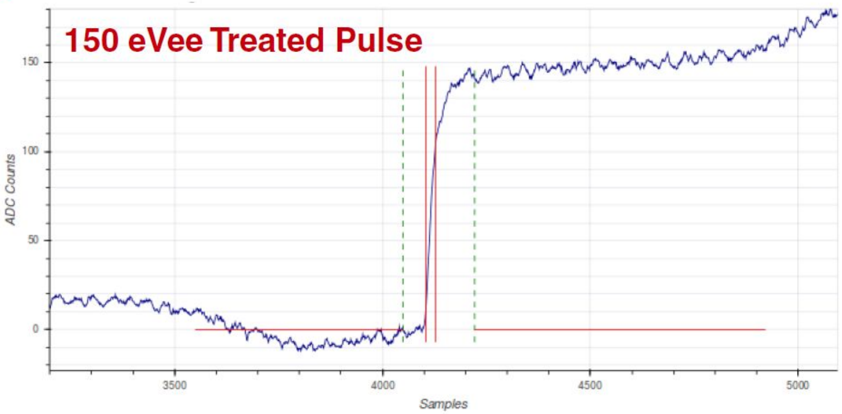
Energy slice : [150,250] eVee
Energy slice : [250,500] eVee
Energy slice : [500,750] eVee
Energy slice : [750,1000] eVee
Energy slice : [1000,1500] eVee
Energy slice : [1500,2000] eVee
Energy slice : [2000,3000] eVee
Energy slice : [3000,4000] eVee
Counts / 2µs
Rise Time [µs]
Neutron Calibration
Neutron Simulation

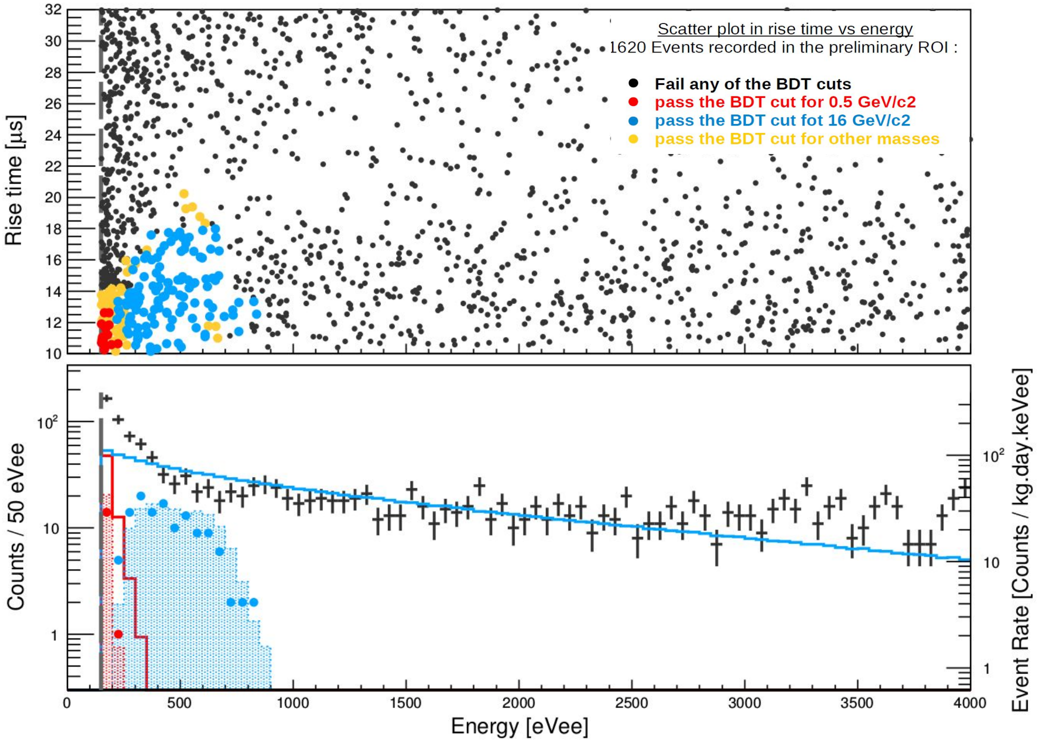
Simulation



Data



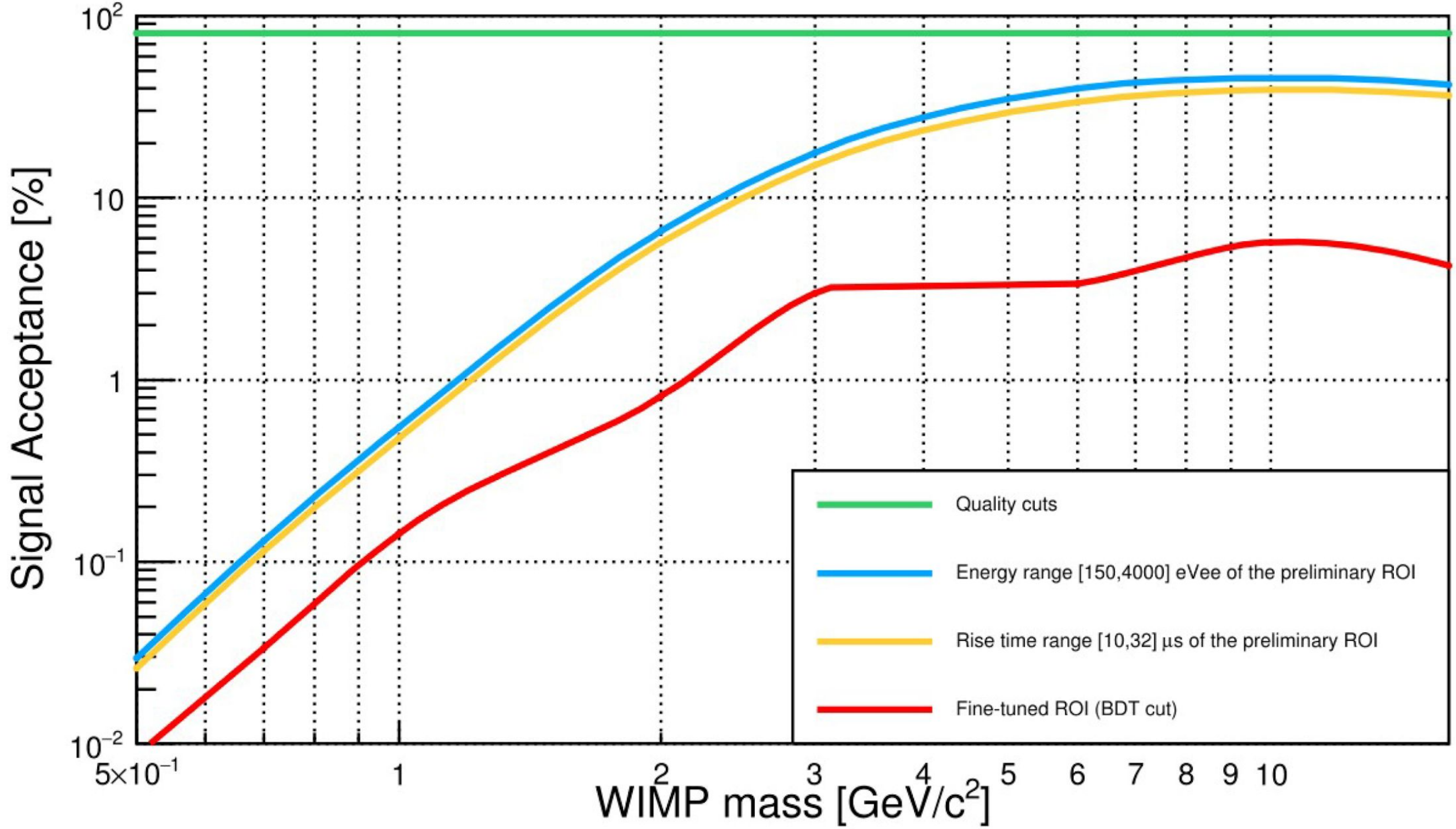




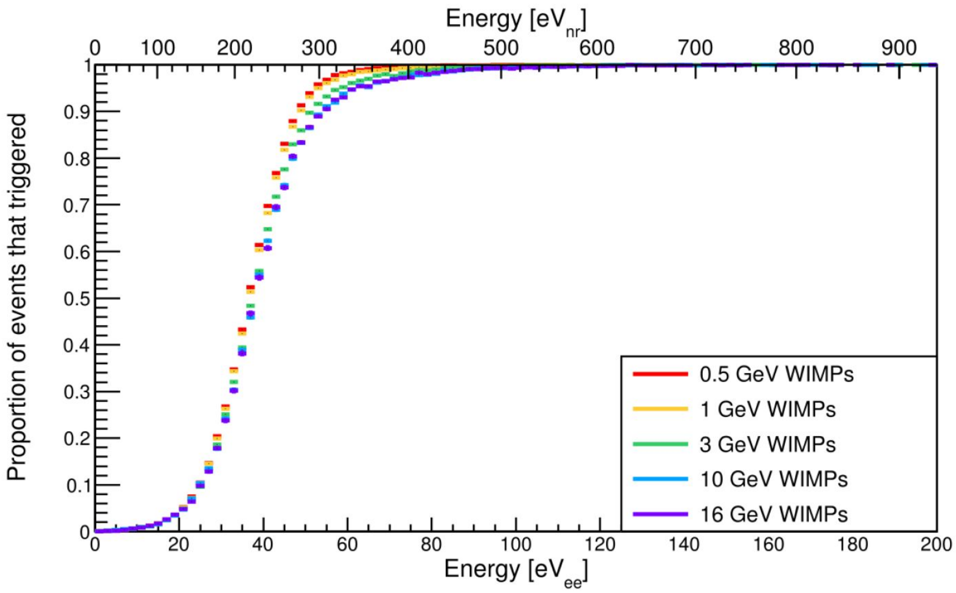
Top panel: distribution of the 1620 events recorded during the physics run in the preliminary ROI. Events that fail (resp. pass) the BDT cut for any of the WIMP masses are shown in black (resp. colour) dots. Events accepted as candidates for 0.5 GeV/c2 and 16 GeV/c2 WIMP masses are shown in red and blue, 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/c2 and 16 GeV/c2 WIMP candidates are shown in red and blue dots. The energy spectra before and after the BDT cut of simulated 0.5 GeV/c2(resp. 16 GeV/c2) WIMPs of cross section σexcl=4.4×10−37cm2 (resp. σexcl=4.4×10−39cm2) 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



Analysis threshold set @ 150 eVee far above the trigger threshold of ~35 eVee (100% trigger efficiency @ 150 eVee)

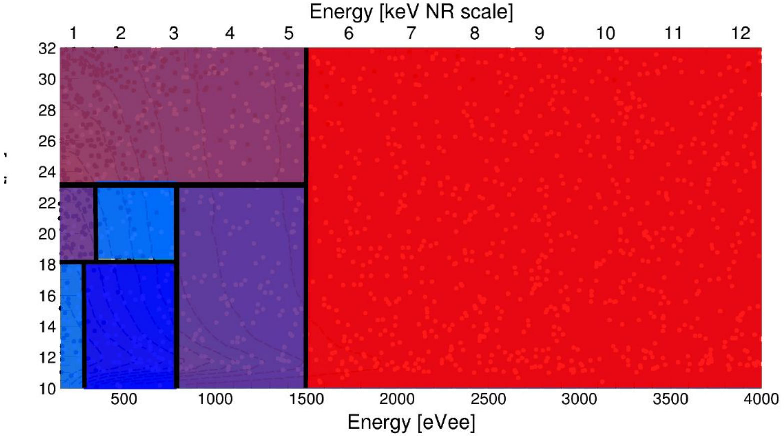


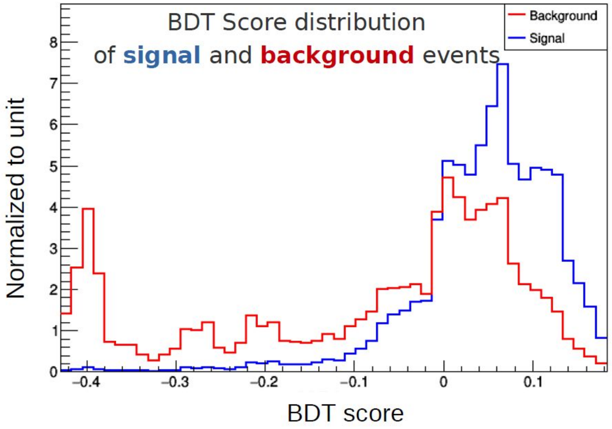
Proportion of events that trigger when pulses are added on top of a baseline vs the energy of the pulse alone

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

The trigger algorithm performs slighlty better for single PE events

For 0.5 GeV WIMPs : mostly single PE events VS For higher WIMP masses : single & multiple PE events





Background like
low BDT Score

Signal like
high BDT Score