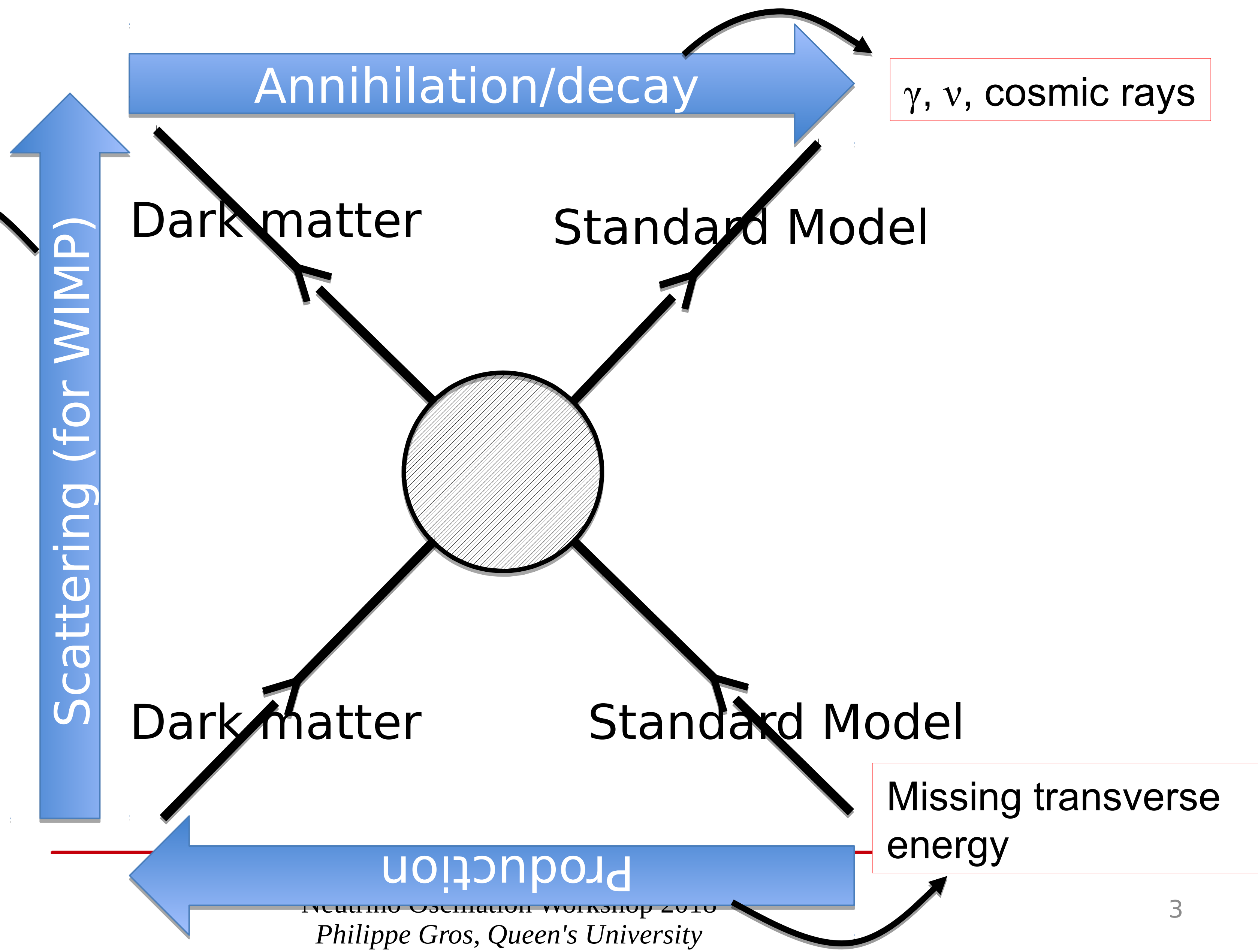
NEWS-G:
Direct detection of light WIMPs
with a
Spherical Proportional Counter

Philippe Gros, Queen's University

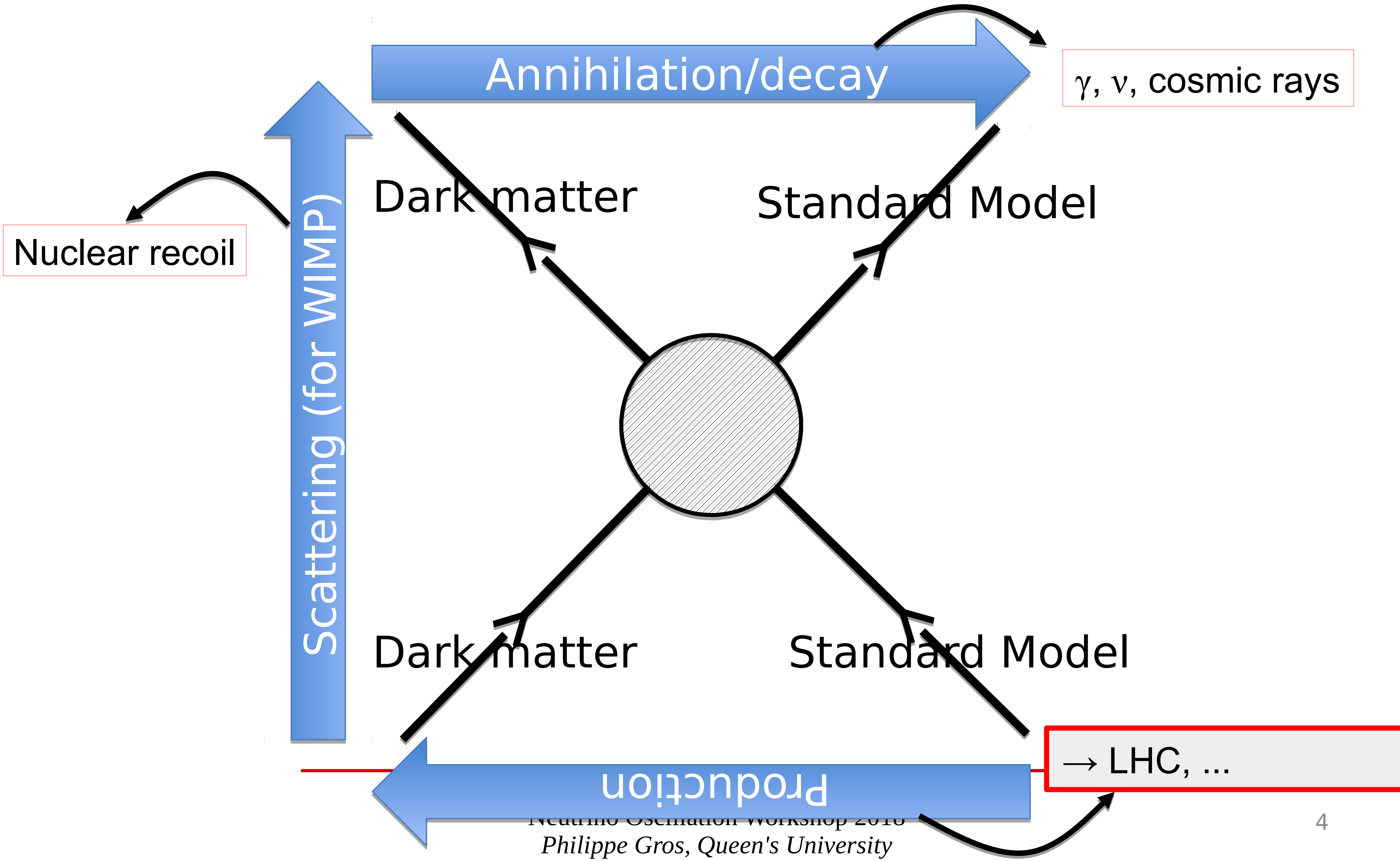
Séminaire LLR
2018-09-24

Dark matter detection

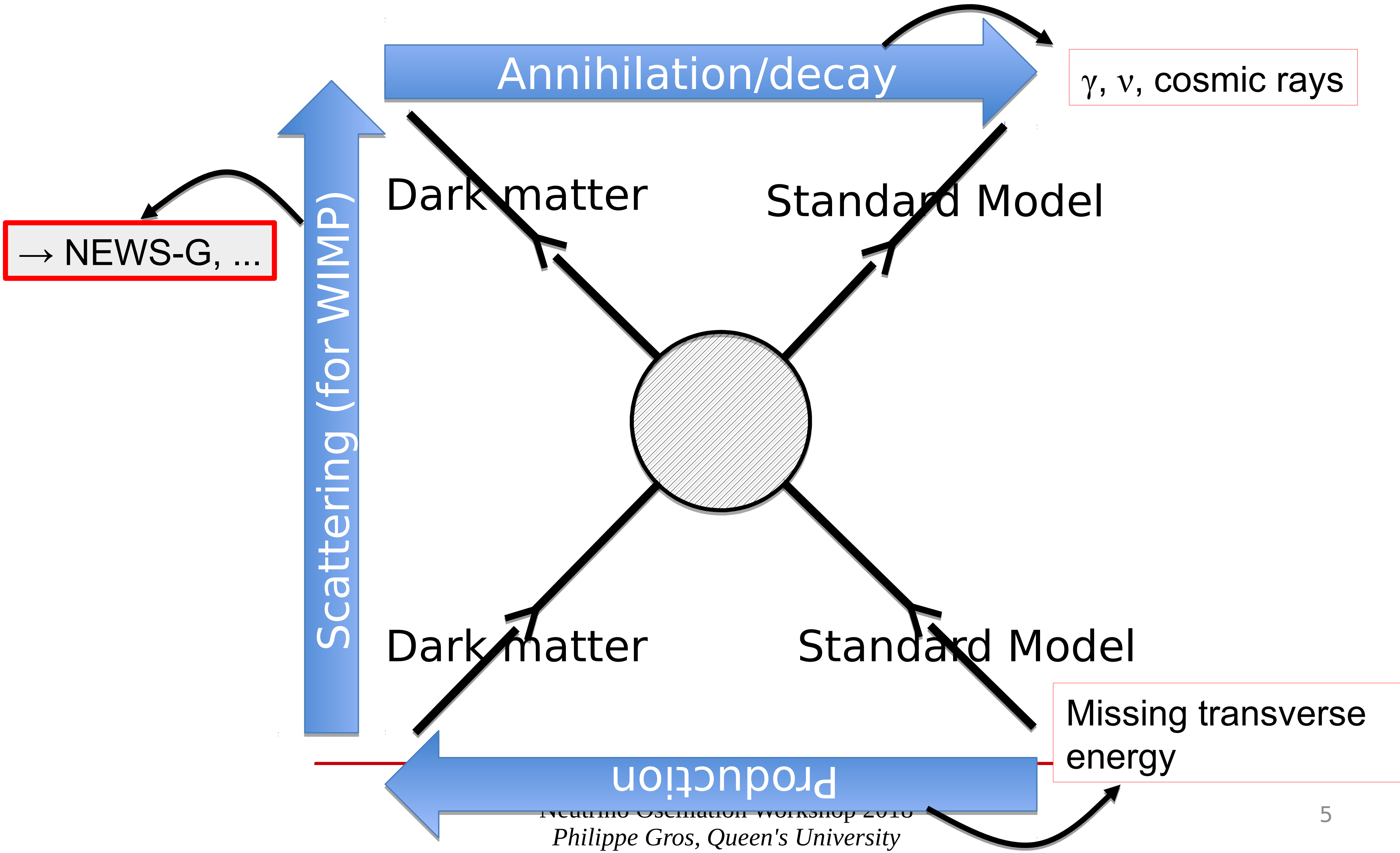
The multiple paths to dark matter



The multiple paths to dark matter

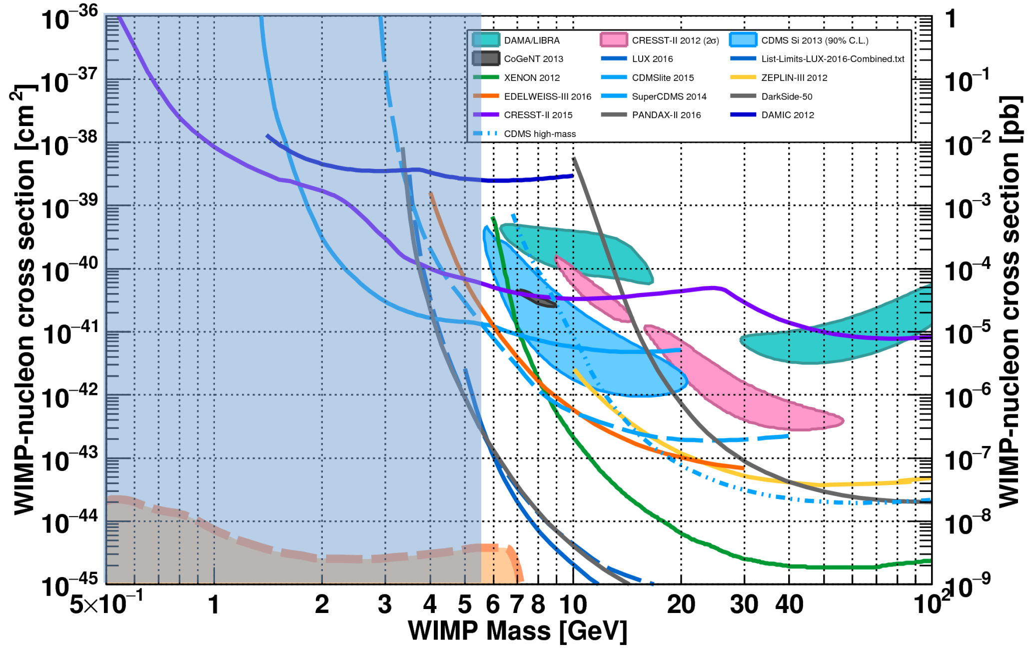


The multiple paths to dark matter



Motivation to search for low mass WIMPs

- Current Upper limits <5GeV orders of magnitude weaker than at higher mass
  - Wide region of the parameter space (σ_{SI},m_χ) can be probed without ton-scale absorbers
  - current main limitation = energy detection thresholds
- New theoretical approaches
  - e.g. asymetric dark matter, dark sector...
  - favorite SUSY candidates excluded by LHC

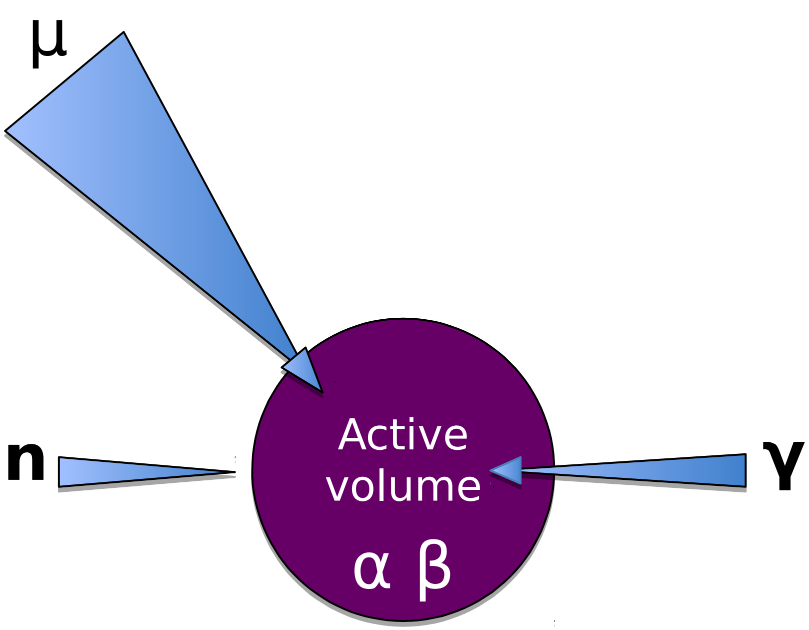


How to do it

- High sensitivity/Low threshold detector
  - low noise
  - light target material
- Low background
  - cosmic ray → underground
  - local radioactivity → material selection/purification
- (Large exposure)
  - not yet limiting for low mass

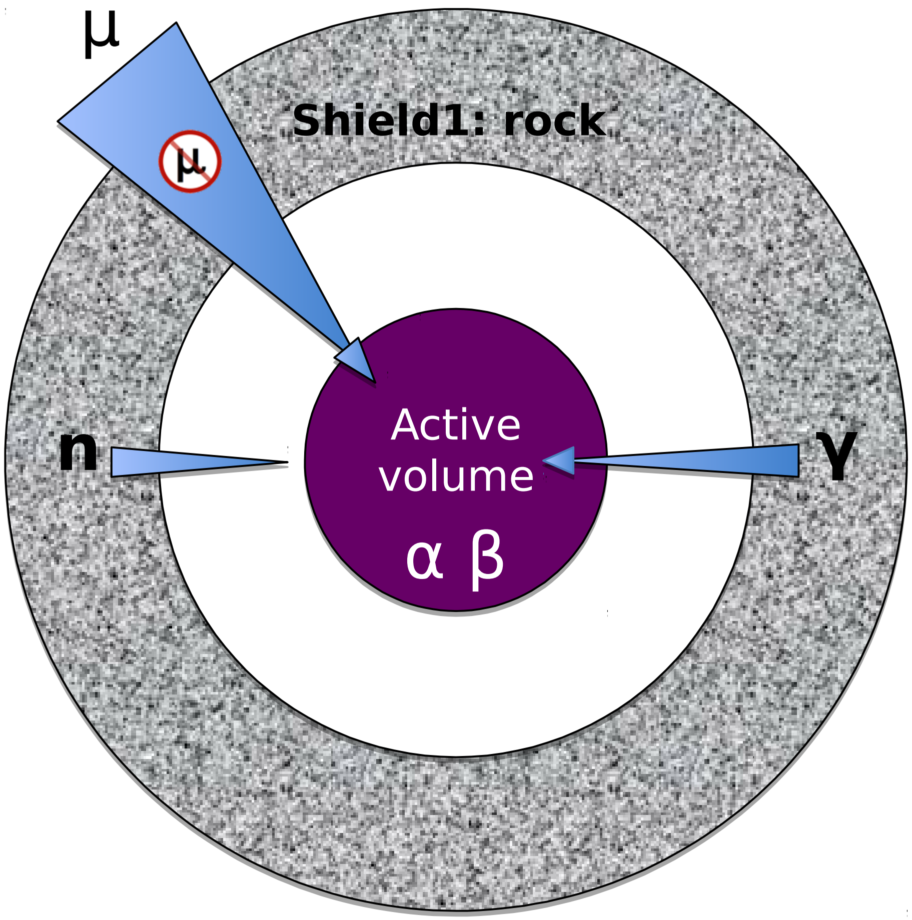
Low Background

Multiple background suppression strategies



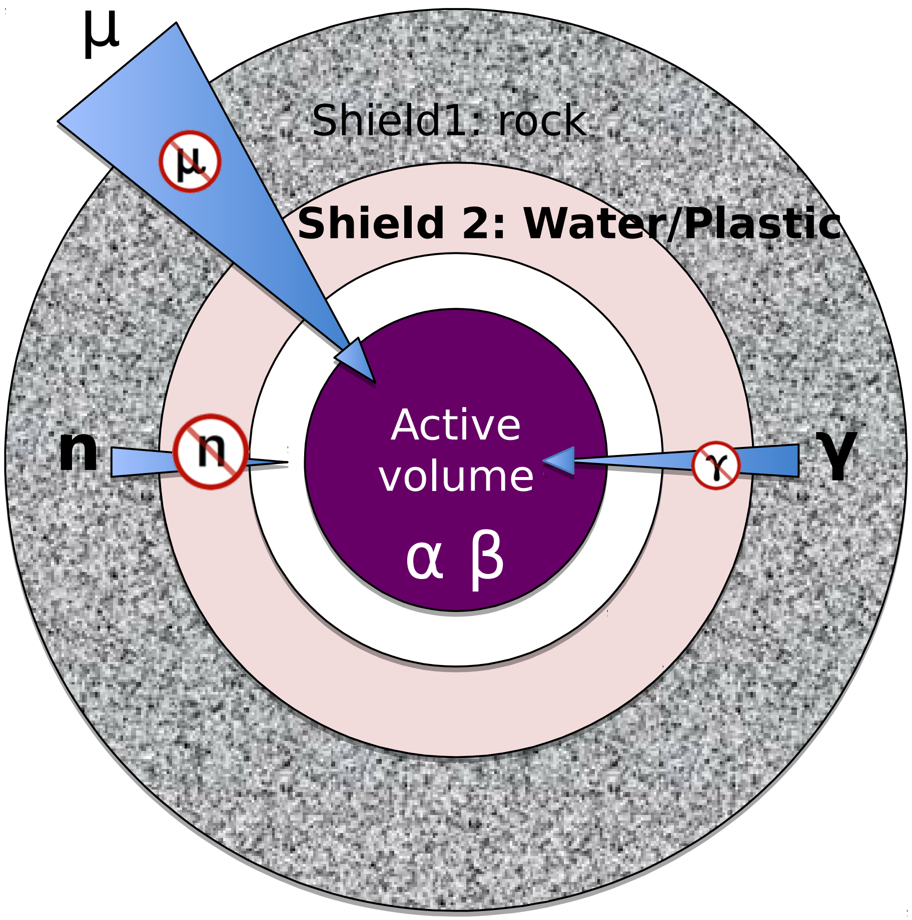
Multiple background suppression strategies

Passive shielding



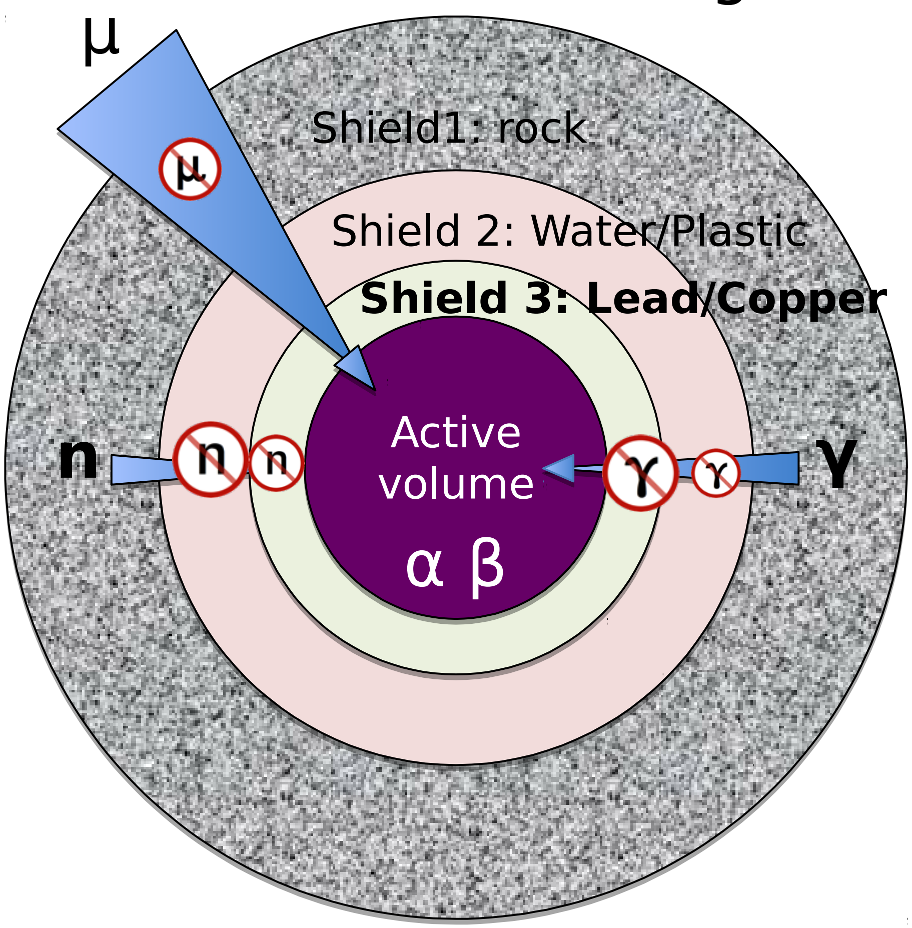
Multiple background suppression strategies

Passive shielding



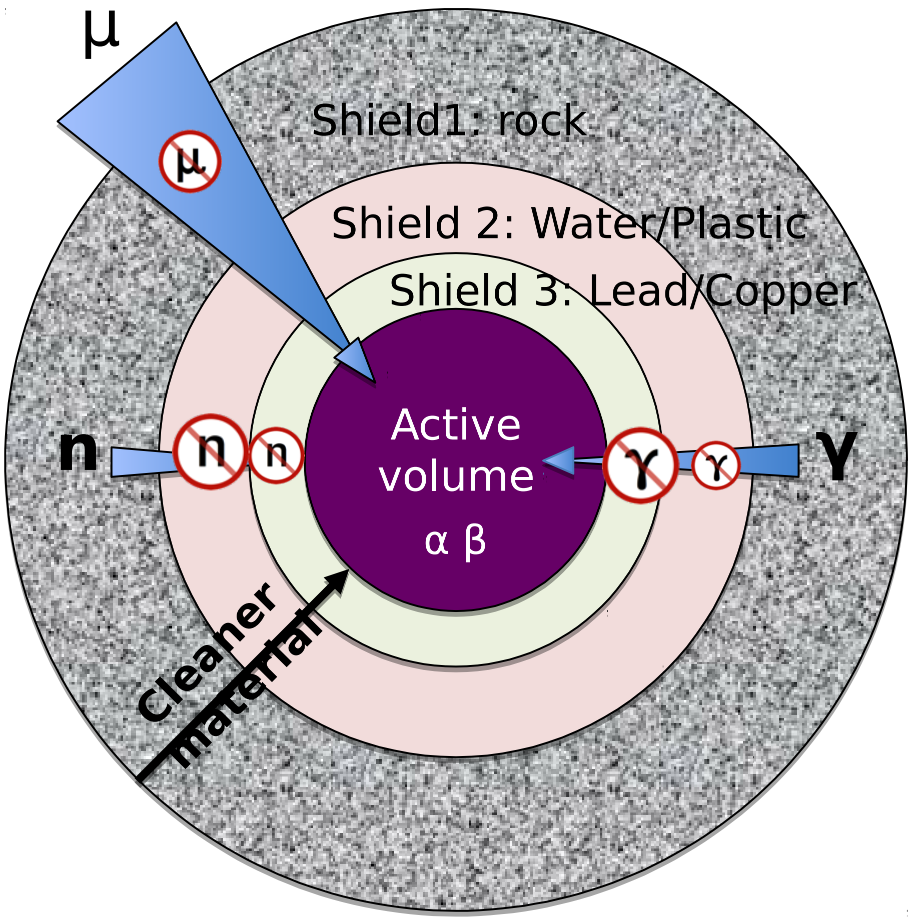
Multiple background suppression strategies

Passive shielding



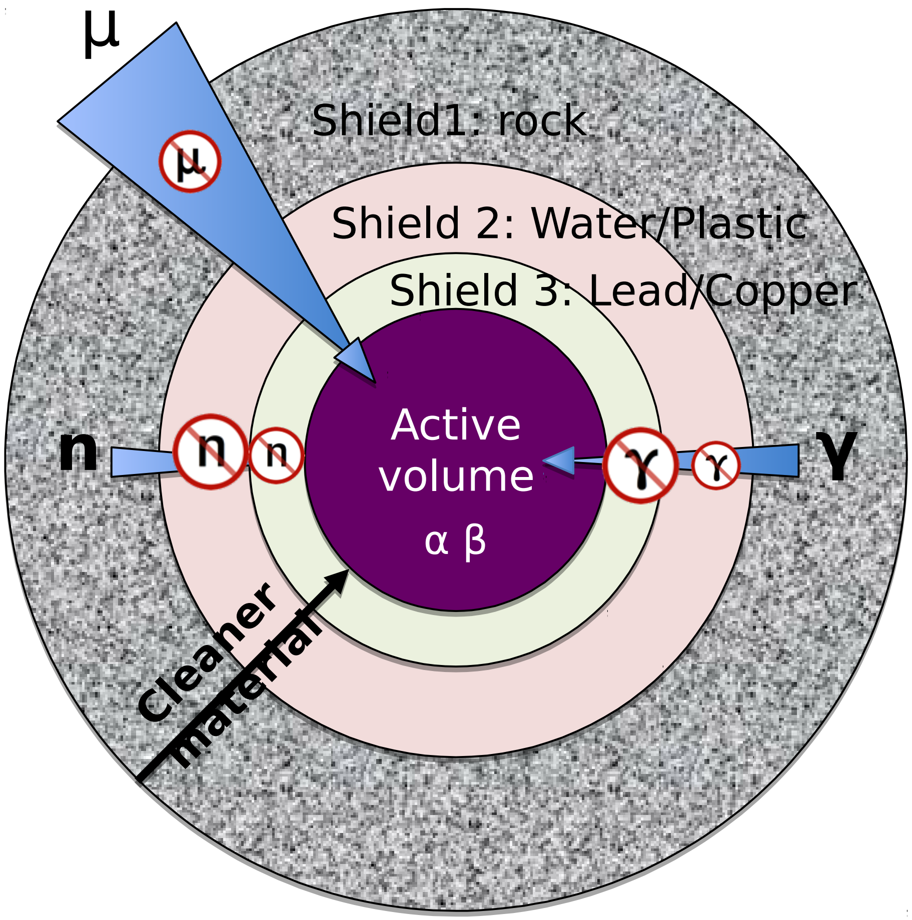
Multiple background suppression strategies

Passive shielding



Multiple background suppression strategies

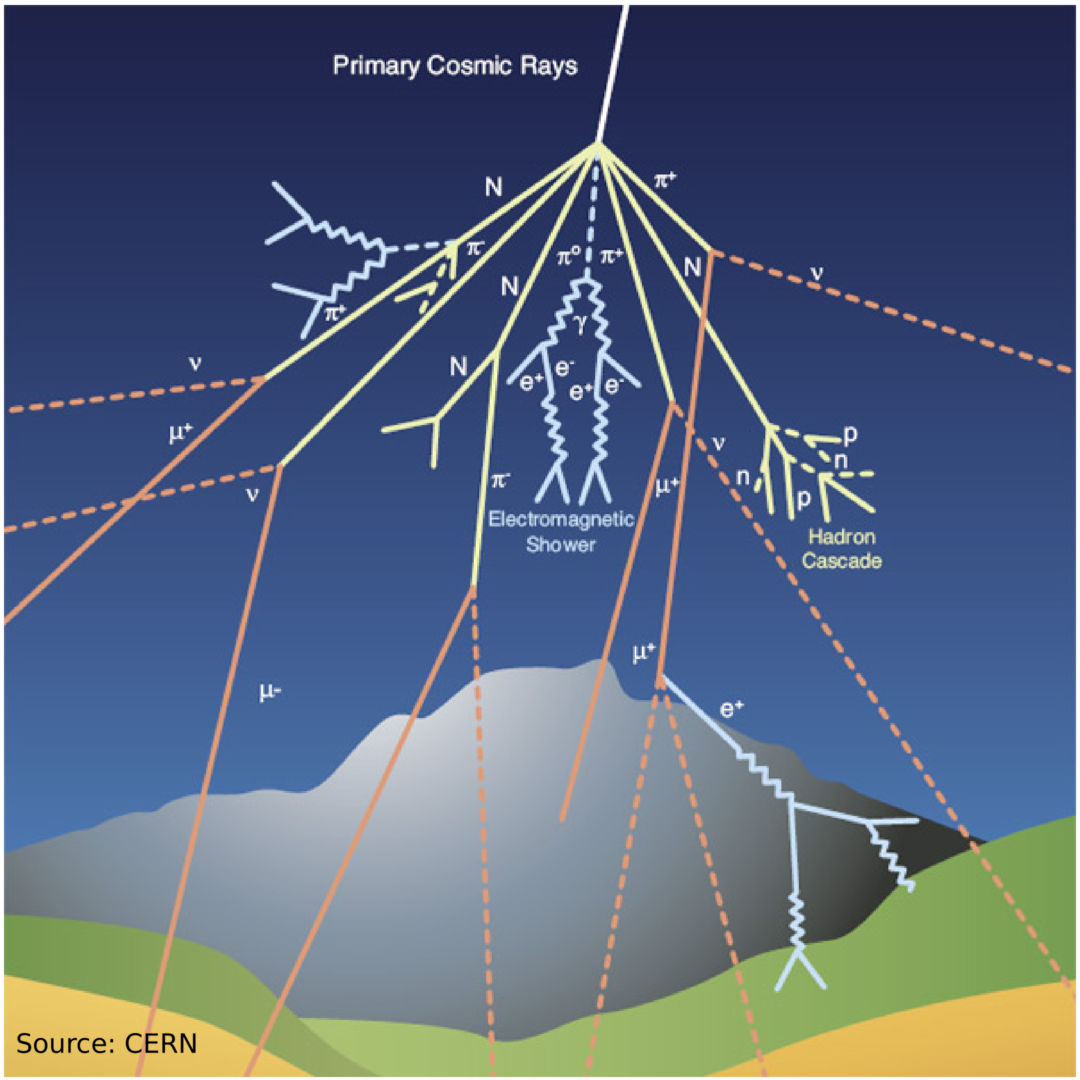
Passive shielding



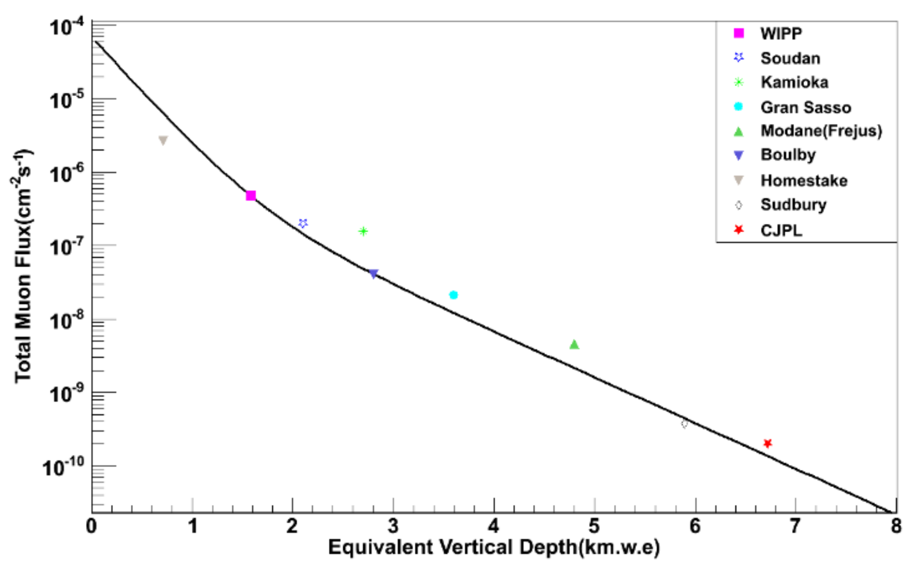
Discrimination

- Active veto
- Energy
- Position
- Pulse shape
- Multi signal
- …

The cosmic rays problem

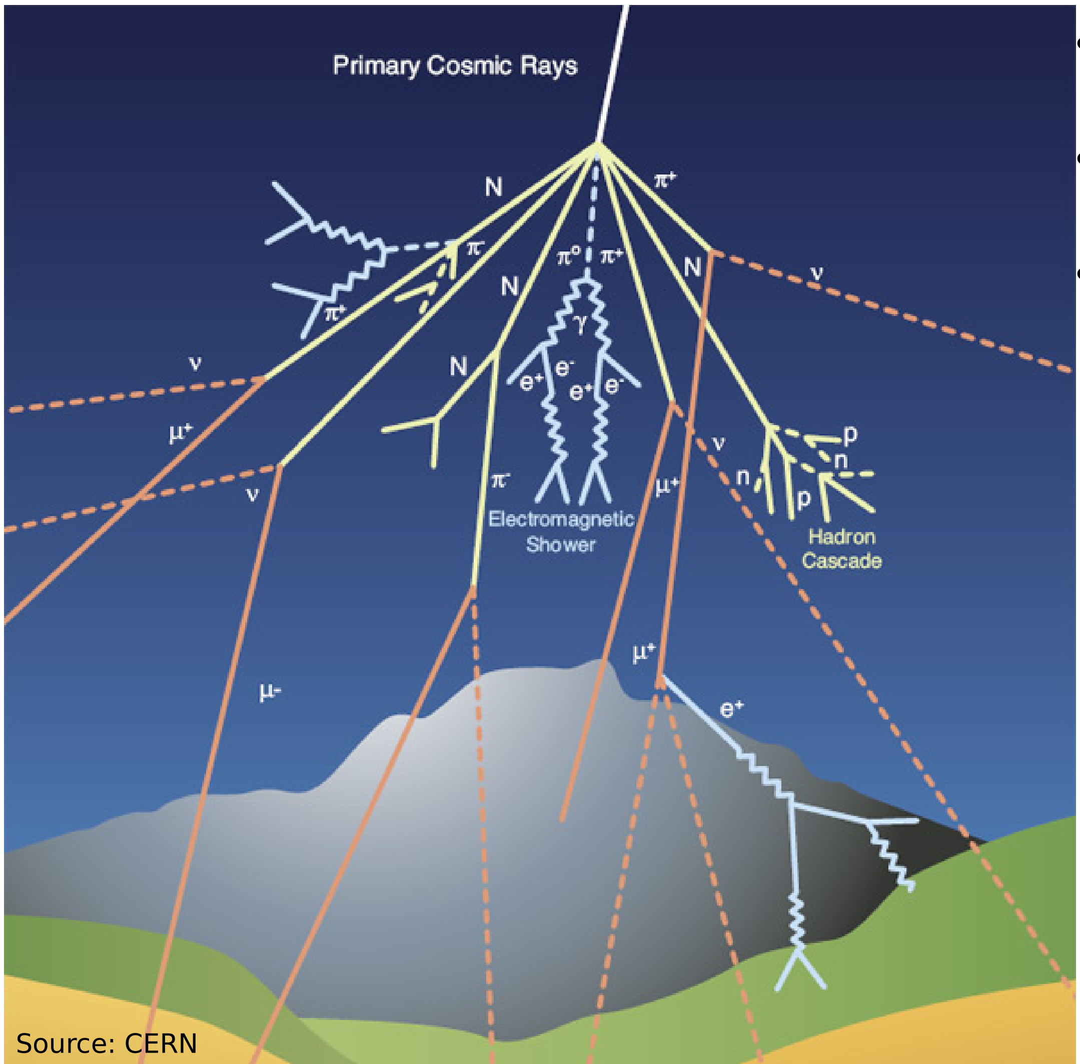


- High energy muons travel deep
- Production of unstable isotopes
- Muon-induced spallation=> neutrons



Measurement of Cosmic Ray Flux in China JinPing underground Laboratory
Arxiv:1305.0899

The cosmic rays problem



Source: CERN

- High energy muons travel deep
- Production of unstable isotopes
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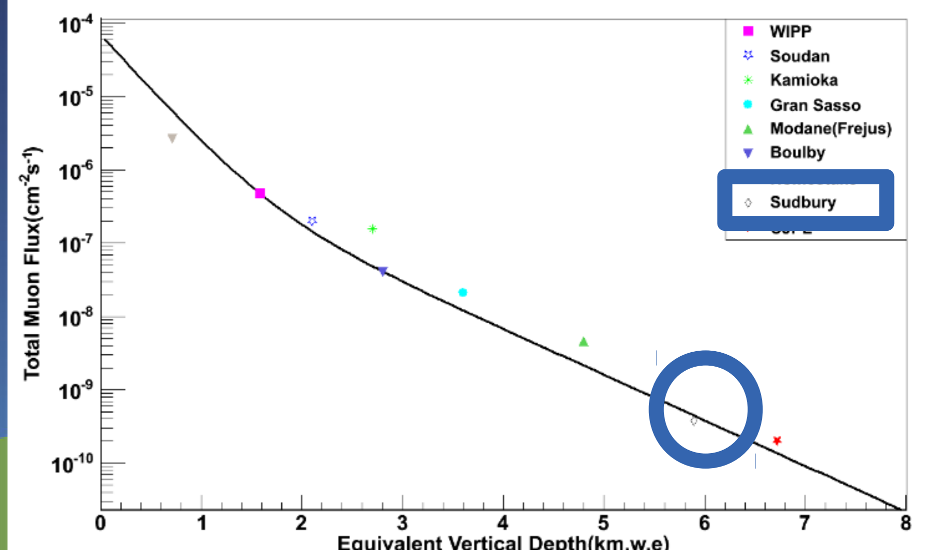
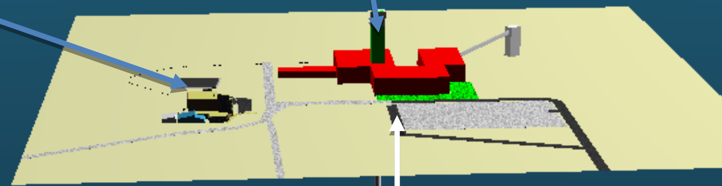


Measurement of Cosmic Ray Flux in China JinPing underground Laboratory
Arxiv:1305.0899

SNOLAB Surface facility
- Offices
- Clean laboratory
- Warehouse
- Machine shop

Shaft headframe



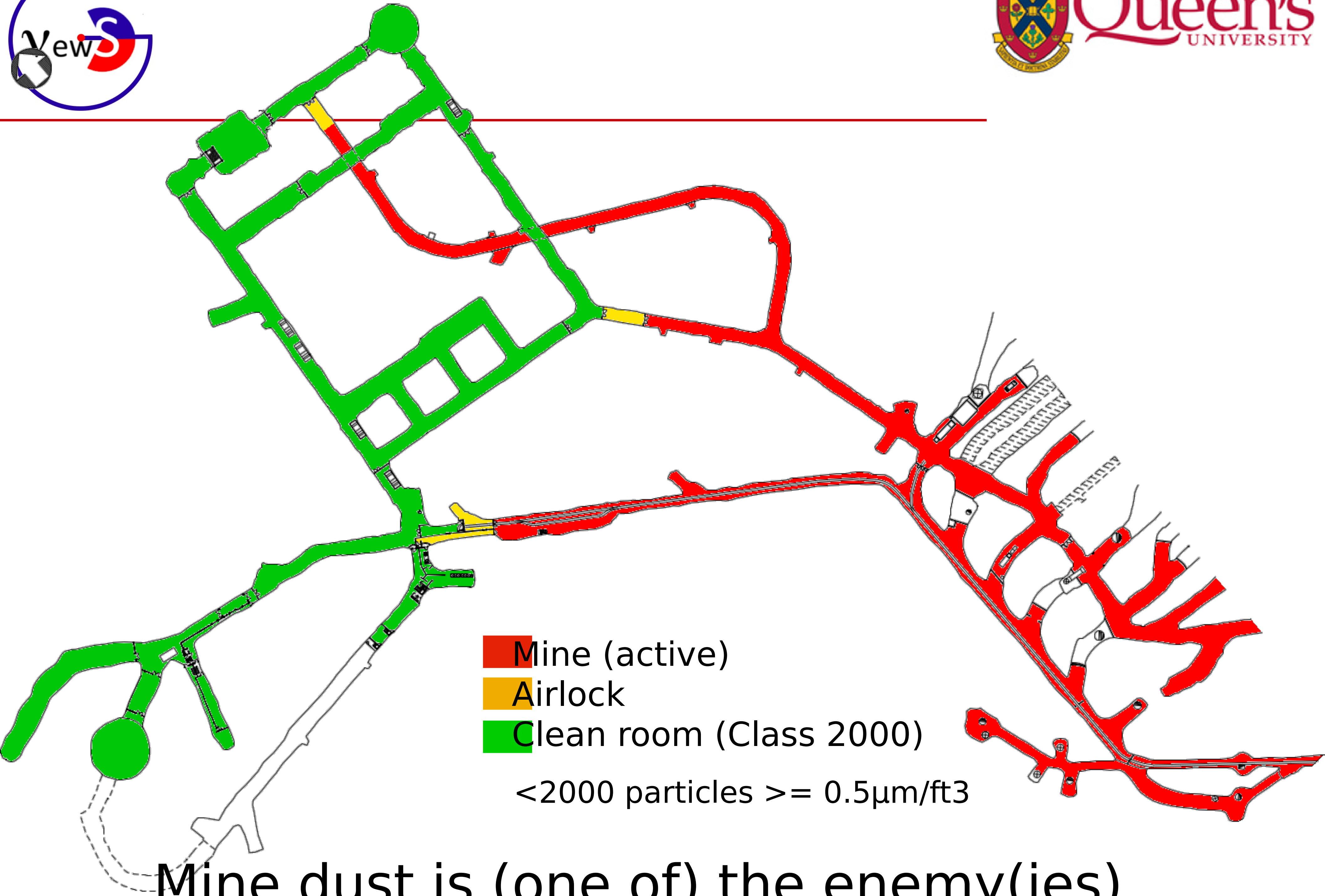
Greater Sudbury (Ontario)

6800 ft
2000 m
6060 m.w.e

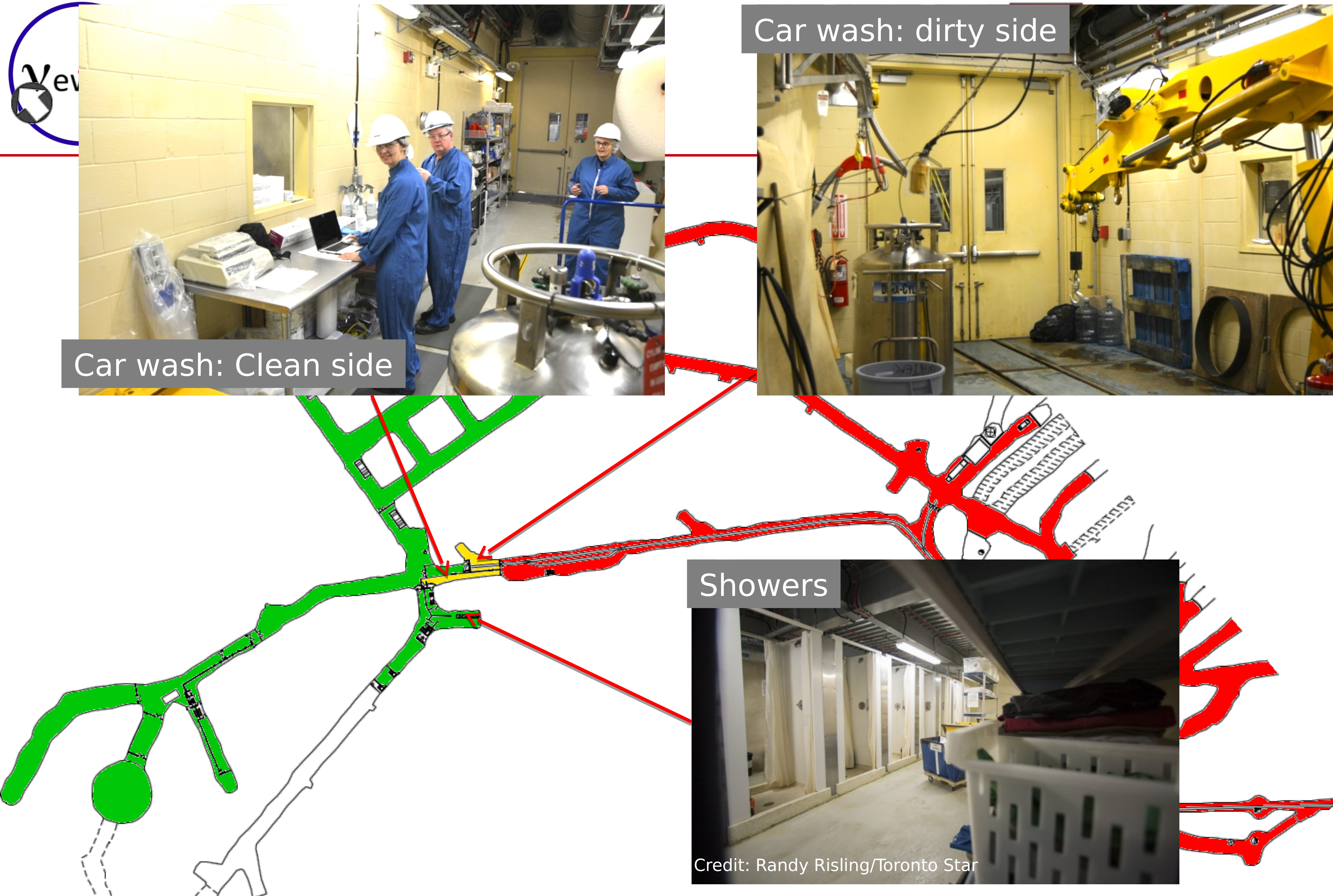
Lab entrance: boot wash

SNOLAB Underground facility

μ **0.27 muon/m²/day**



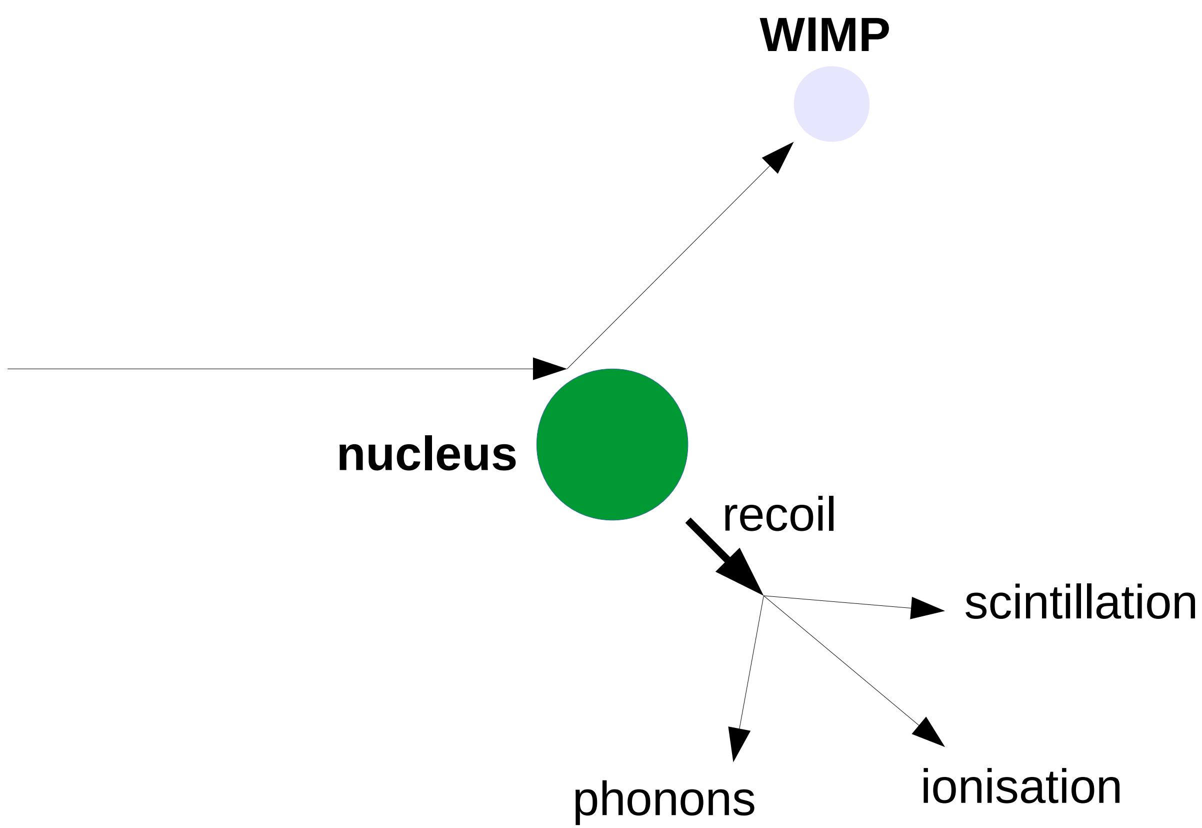
Mine dust is (one of) the enemy(ies)..



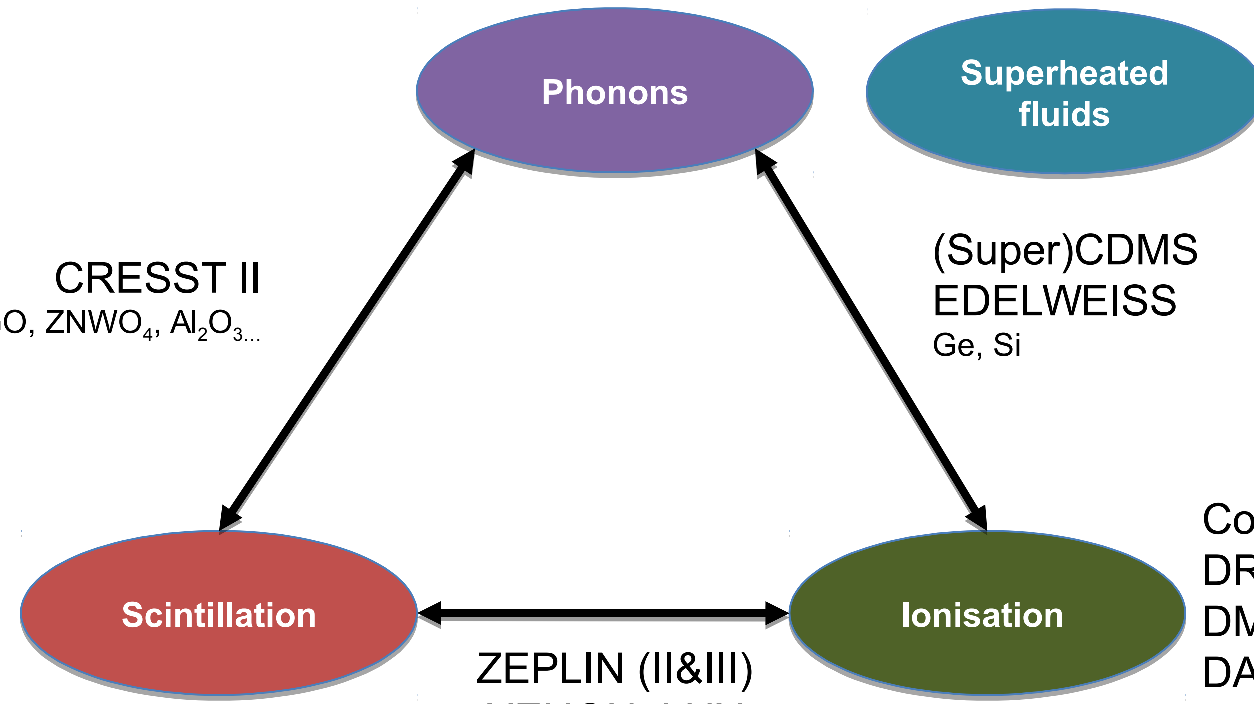
... everything/everyone must be clean !

A low threshold detector: Spherical Proportional Counter (SPC)

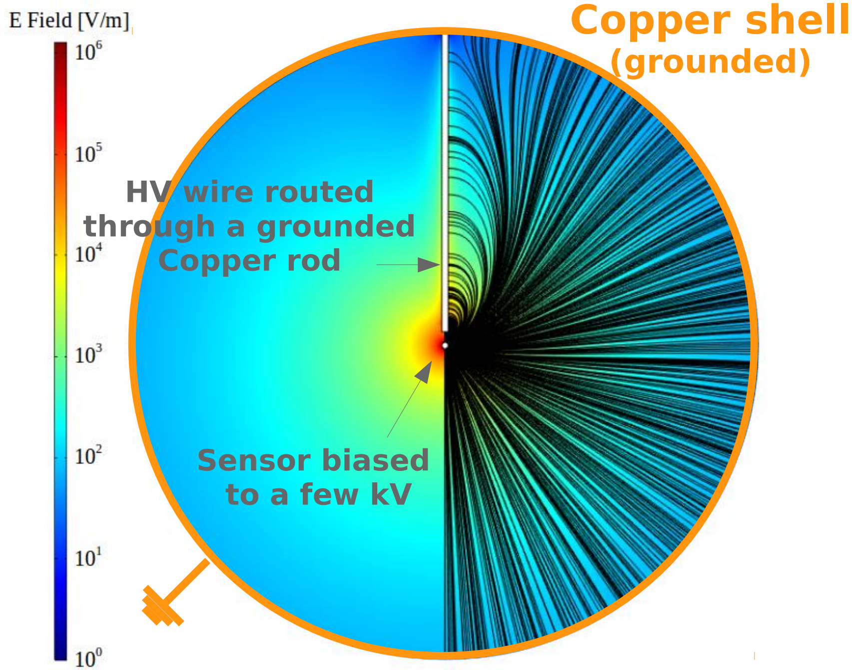
Detection principle



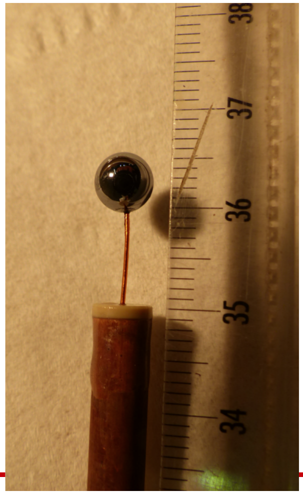
Direct detection techniques



SPC



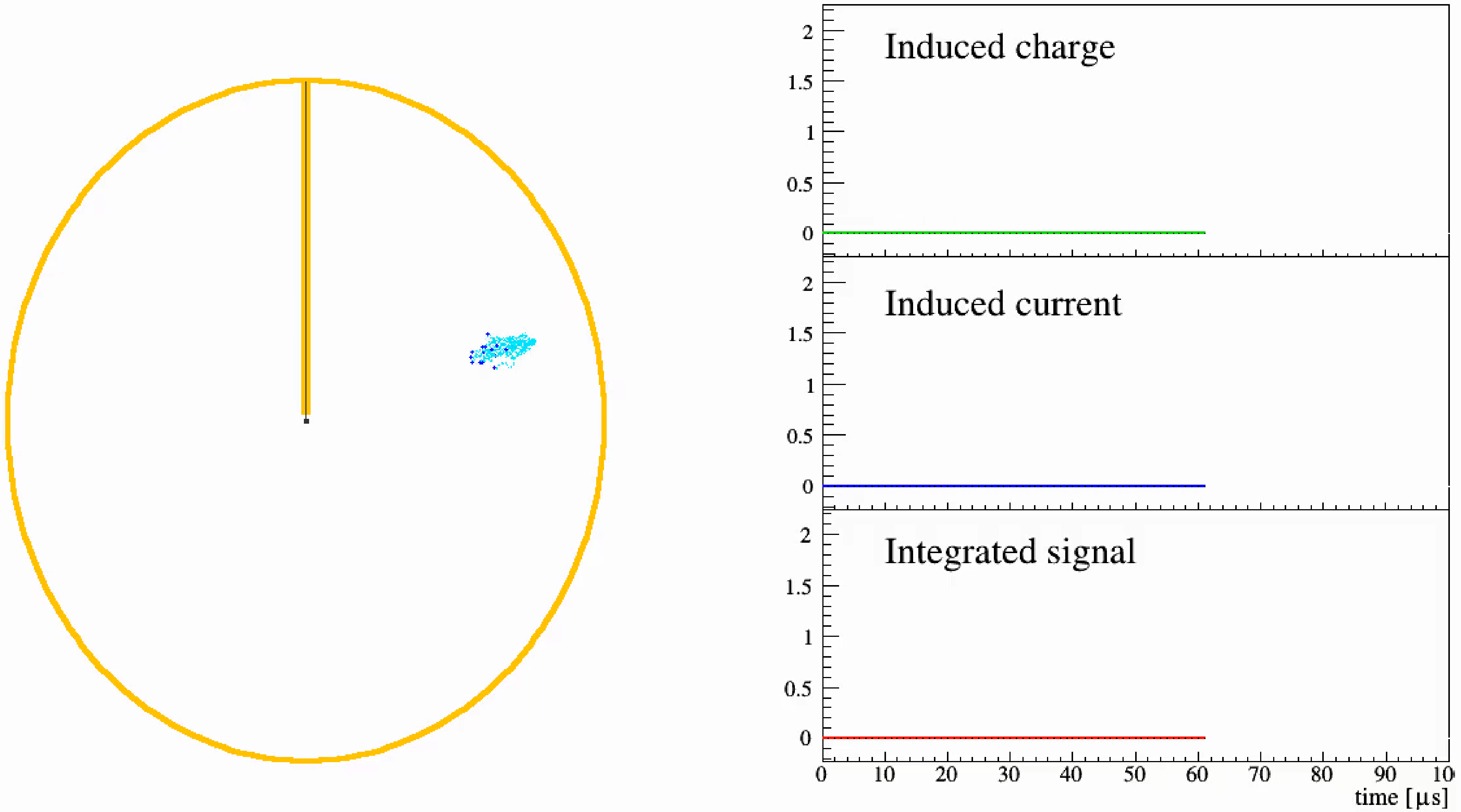
Vessel
60 cm ∅ NOSV Copper



Sensor
6.3 mm ∅

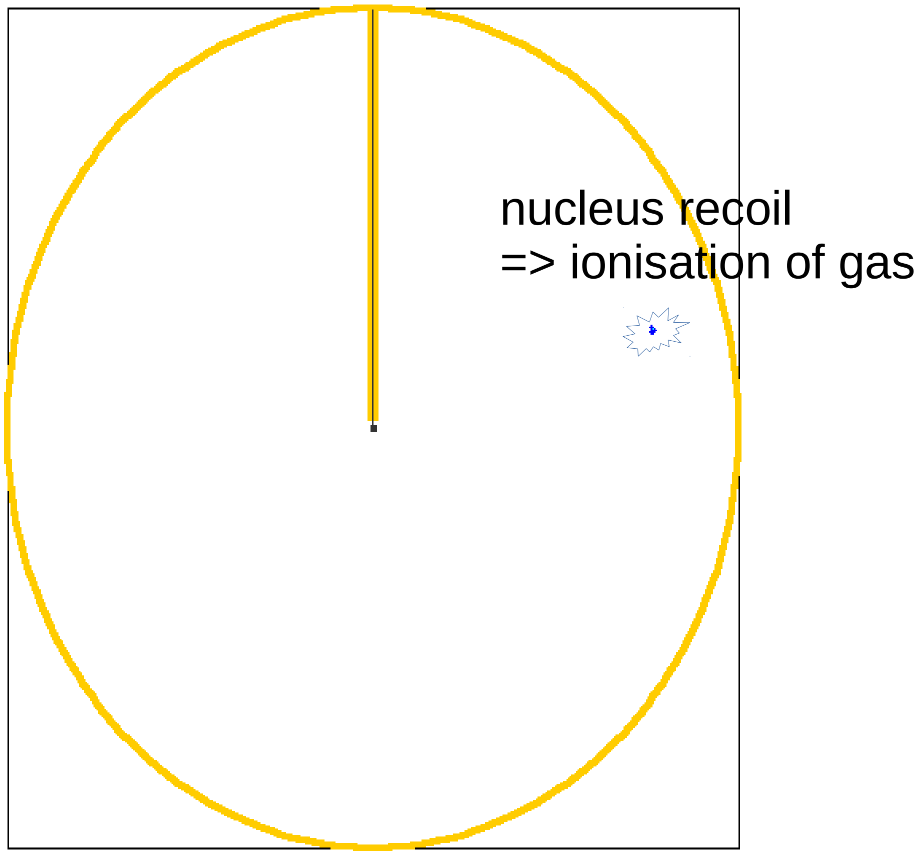
- Gaseous proportional counter
  - Copper sphere
  - Central ball with HV
- Very low capacitance
  - <1pF
- Drifting electrons from ionisation
- Light gas better for low mass WIMPs
  - elastic scattering energy transfer

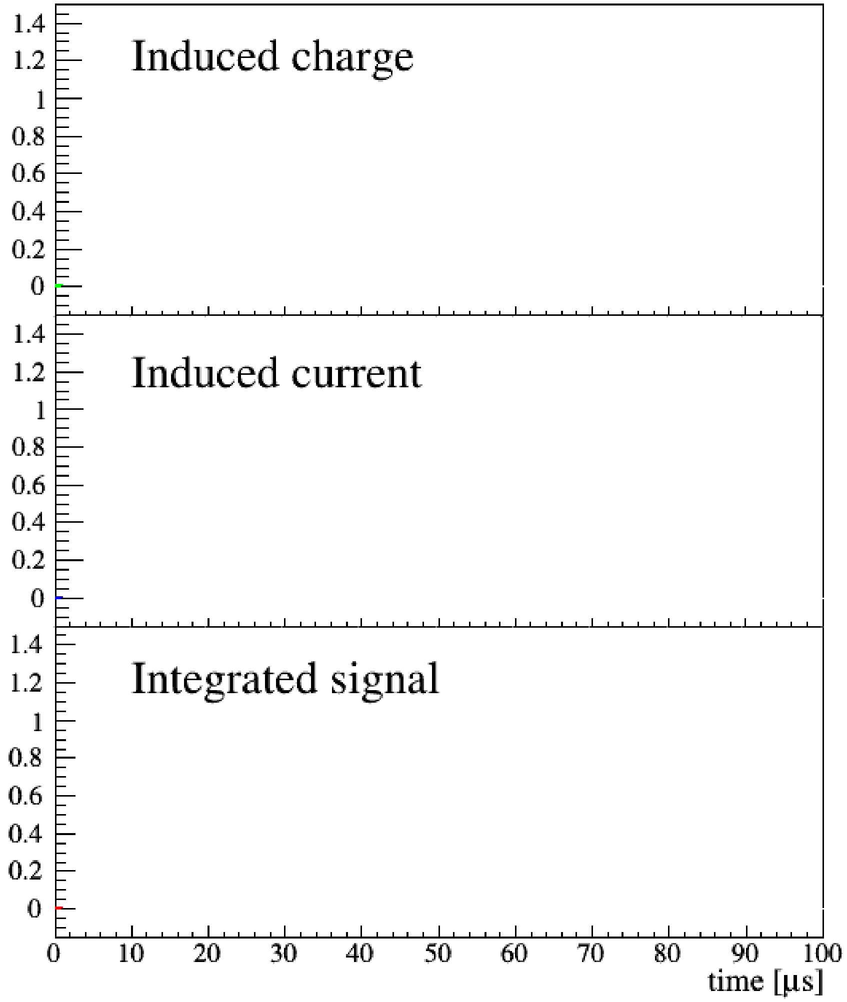
SPC signal



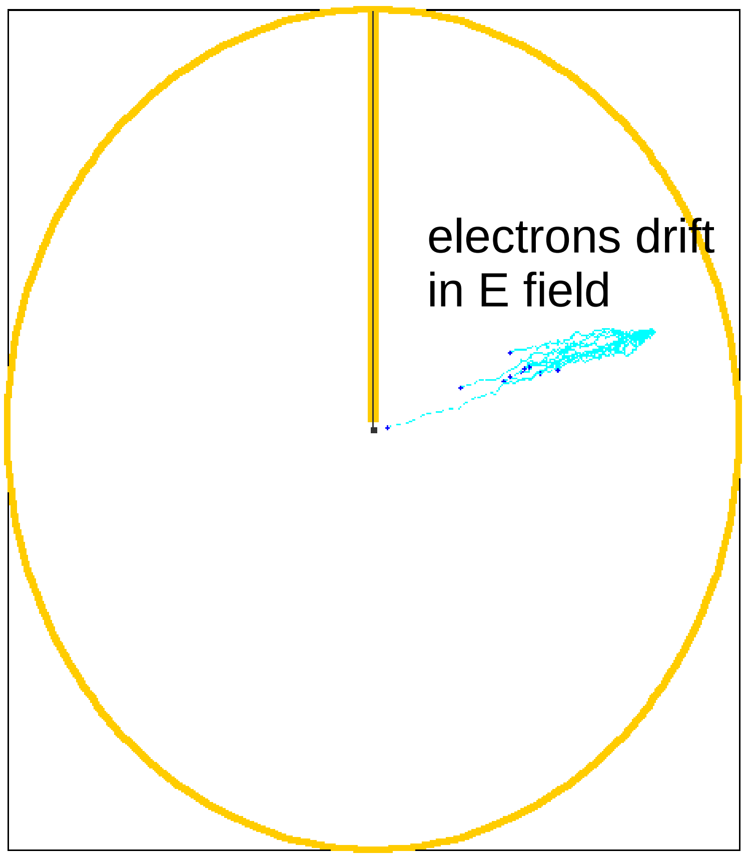
Induced charge
Induced current
Integrated signal
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
10
time [μs]

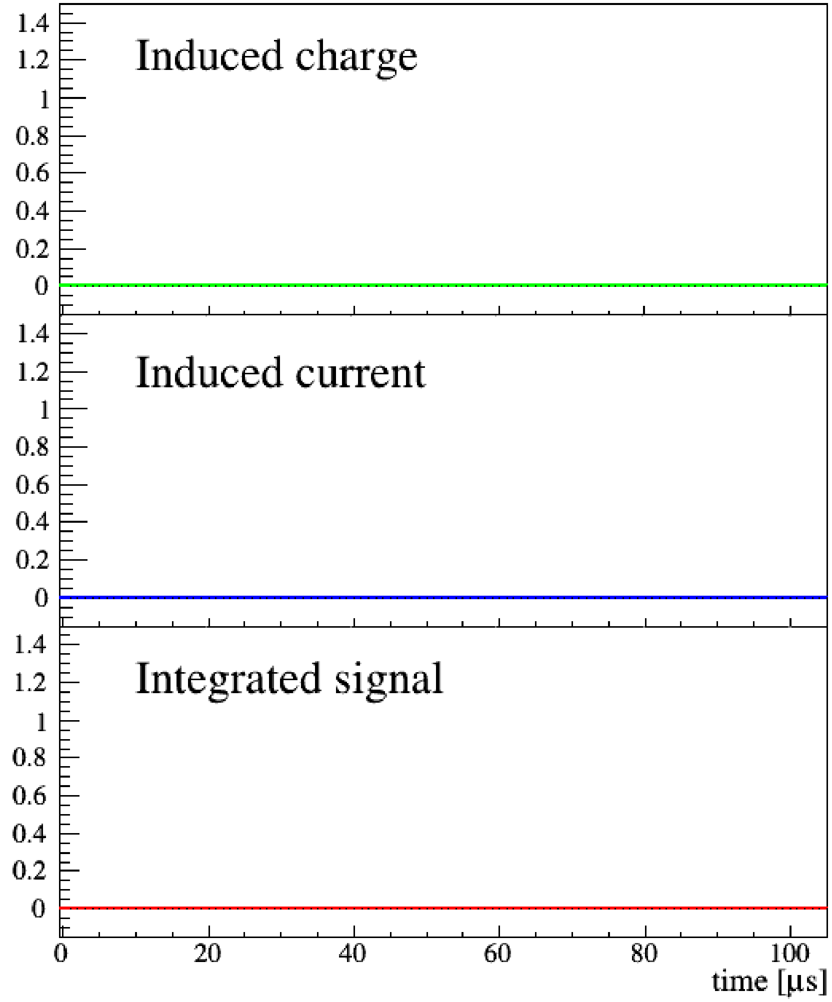
SPC signal


nucleus recoil
=> ionisation of gas

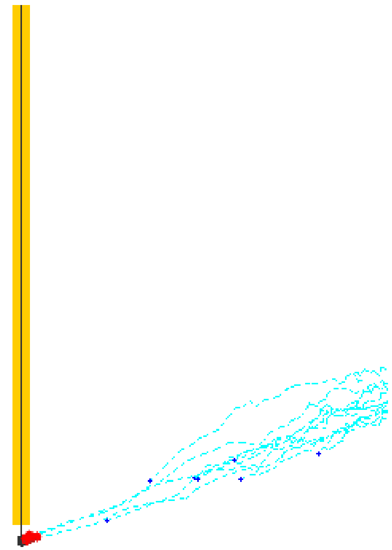

Induced charge
Induced current
Integrated signal
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 10 20 30 40 50 60 70 80 90 100
time [µs]

SPC signal

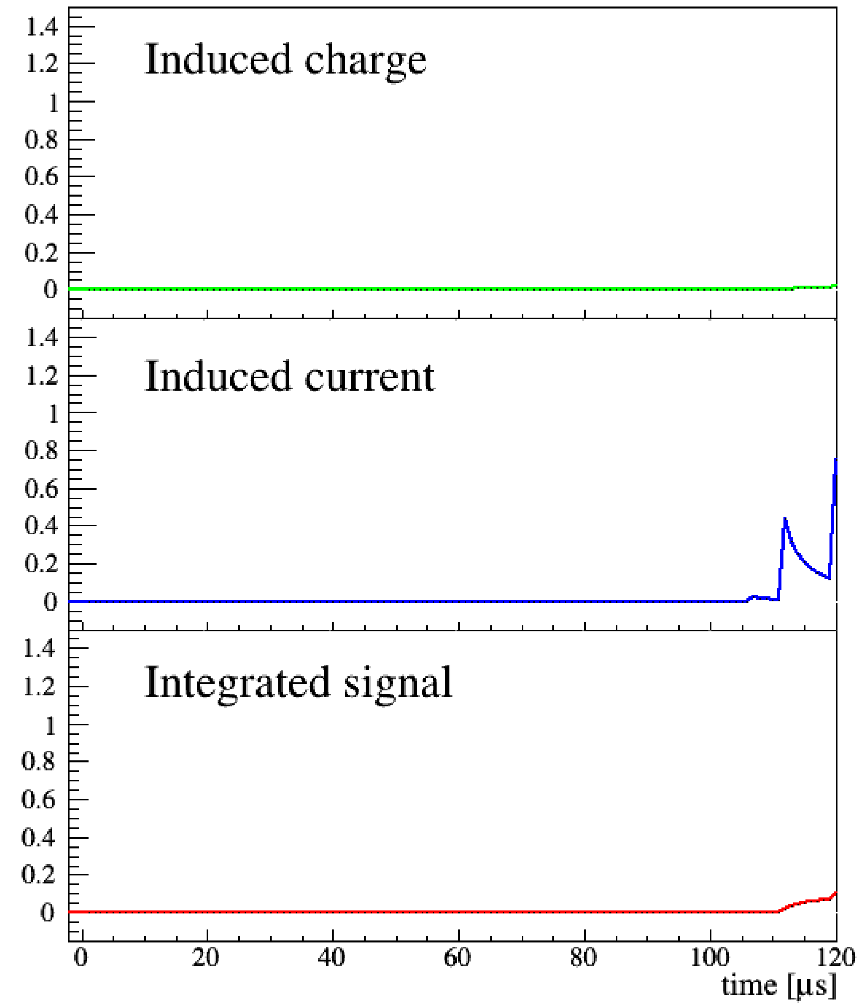

electrons drift
in E field


Induced charge
Induced current
Integrated signal
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
time [μs]

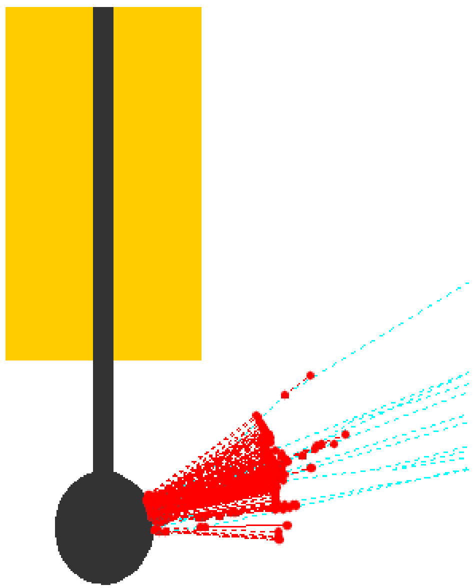
SPC signal



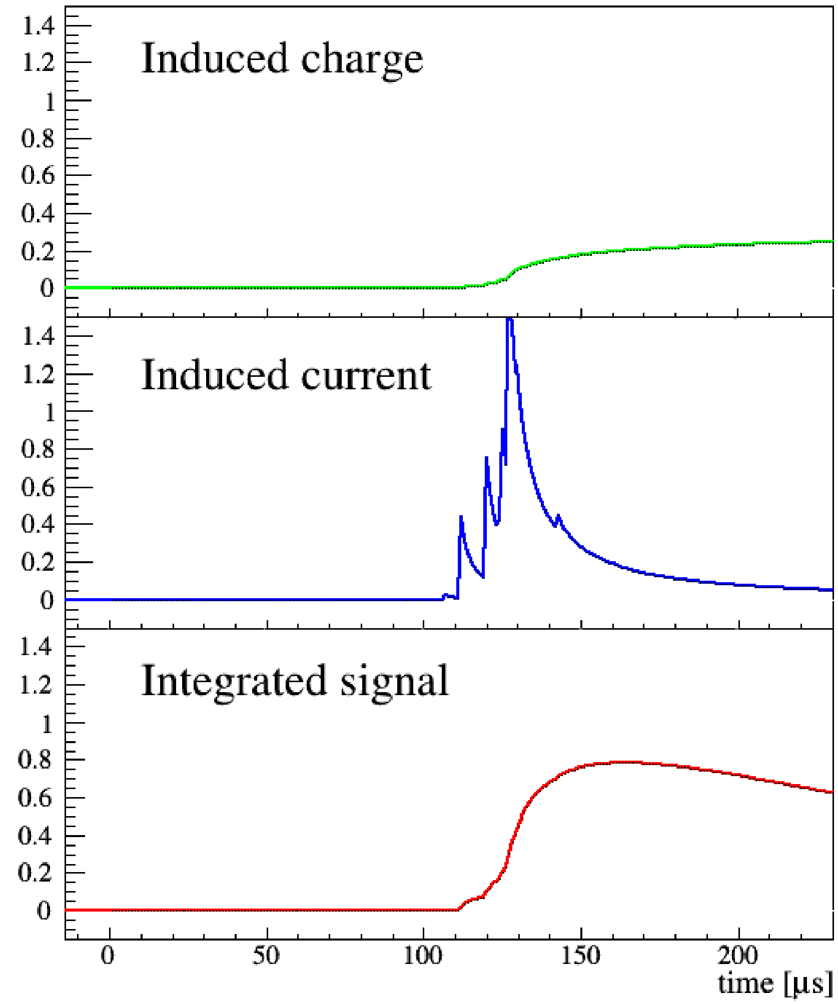
avalanche in high field near sensor



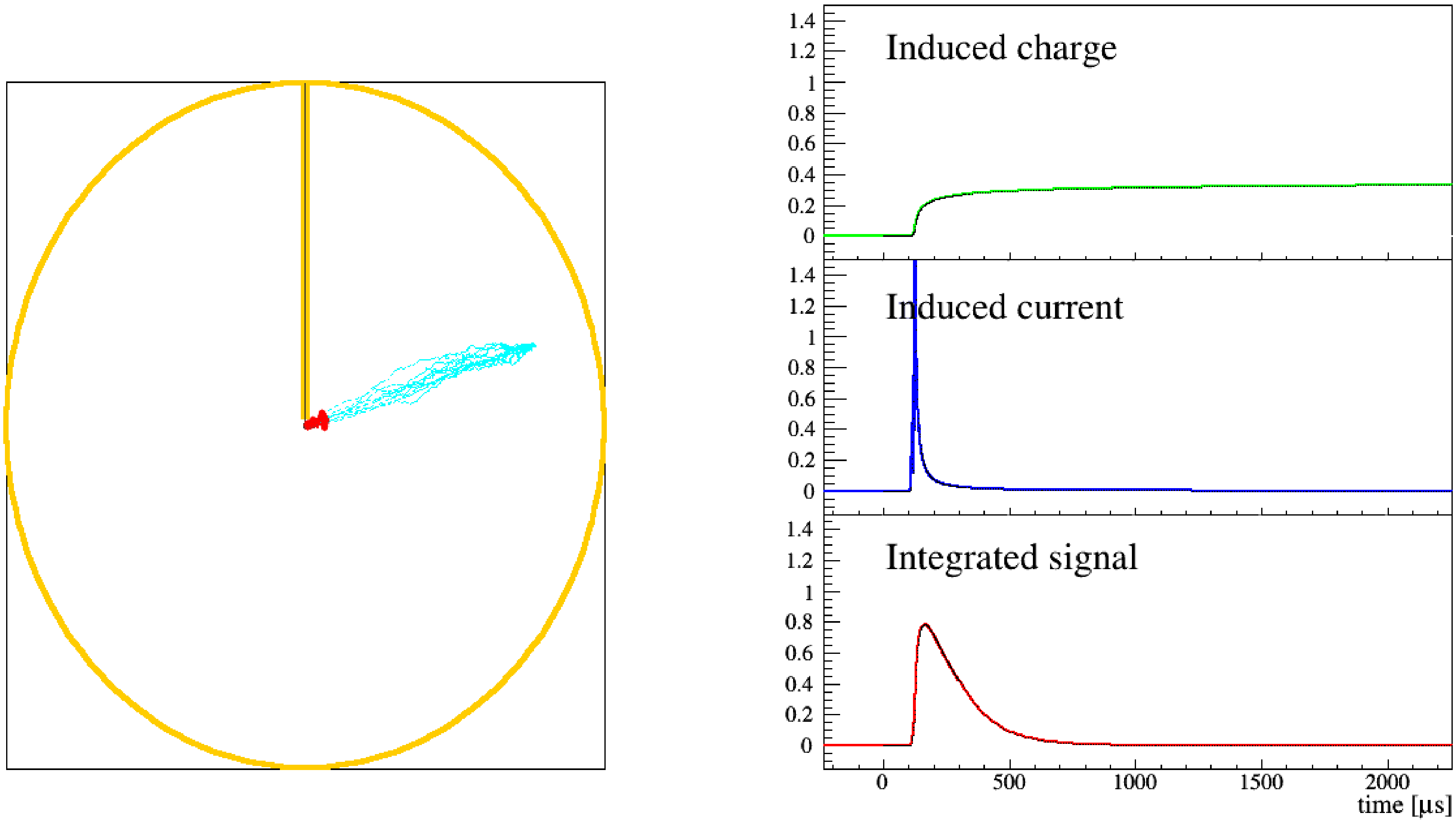
SPC signal



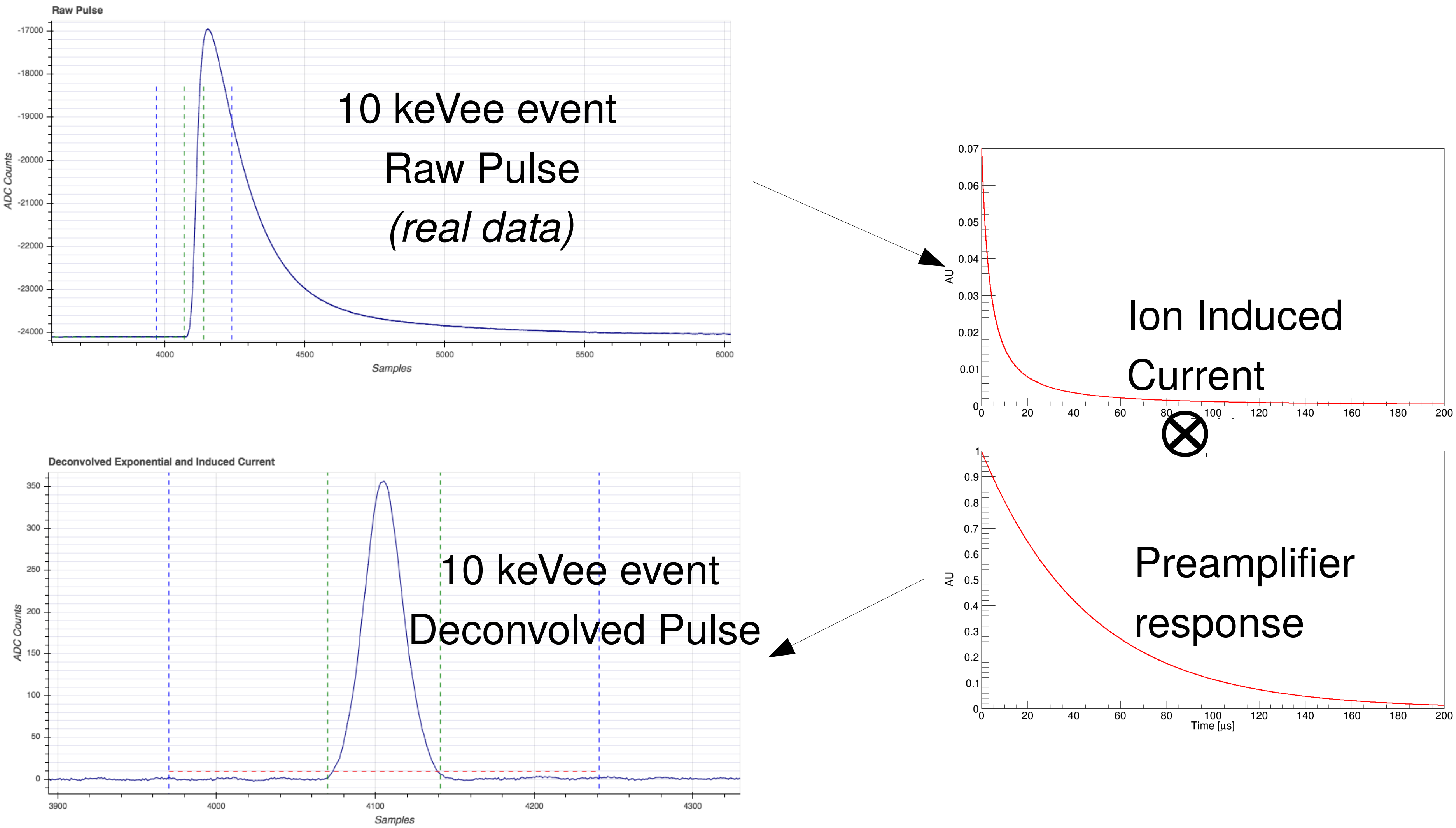
Signal induced by ions drifting back



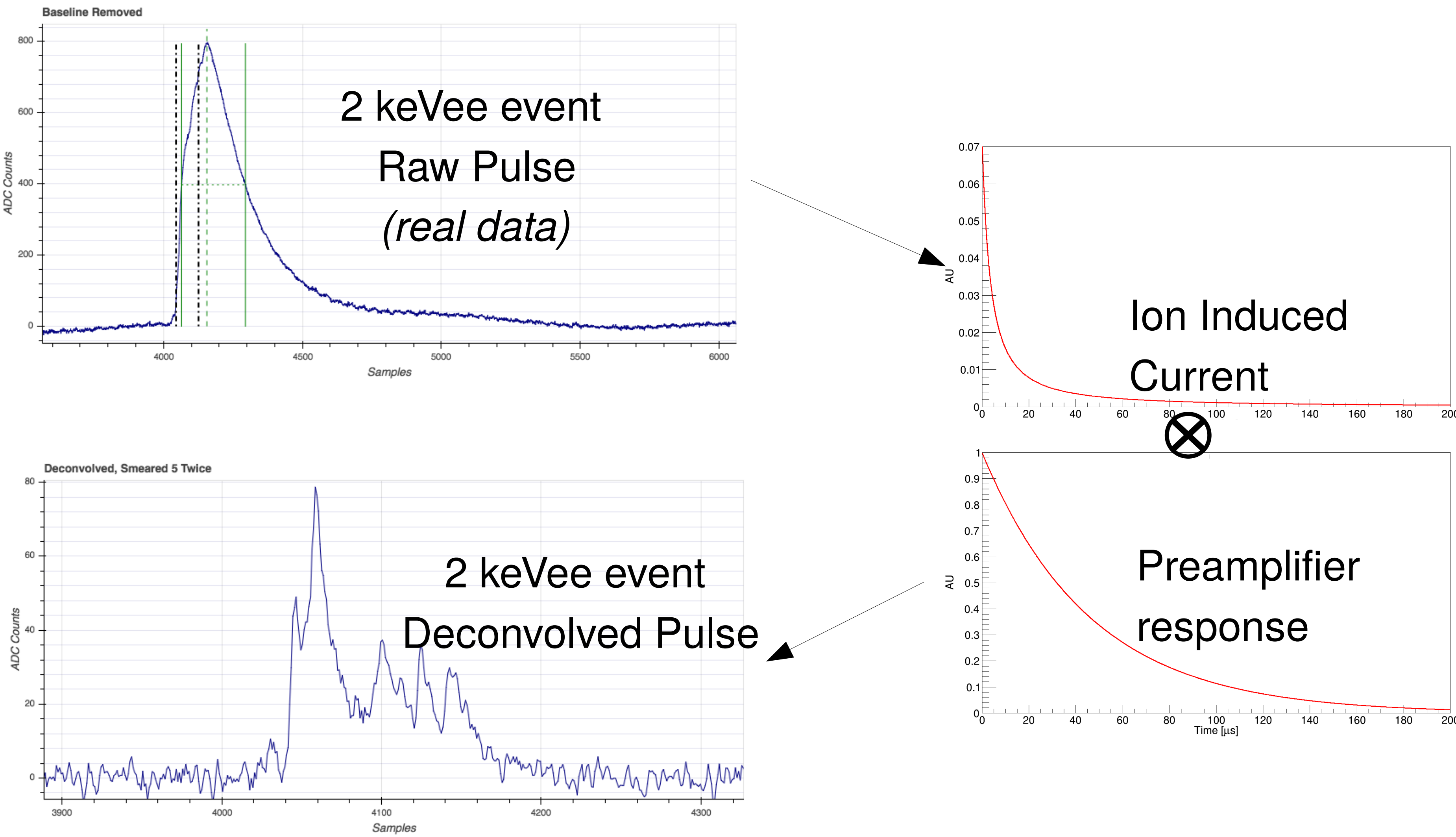
SPC signal


Induced charge
Induced current
Integrated signal
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
500
1000
1500
2000
time [μs]

Pulse treatment

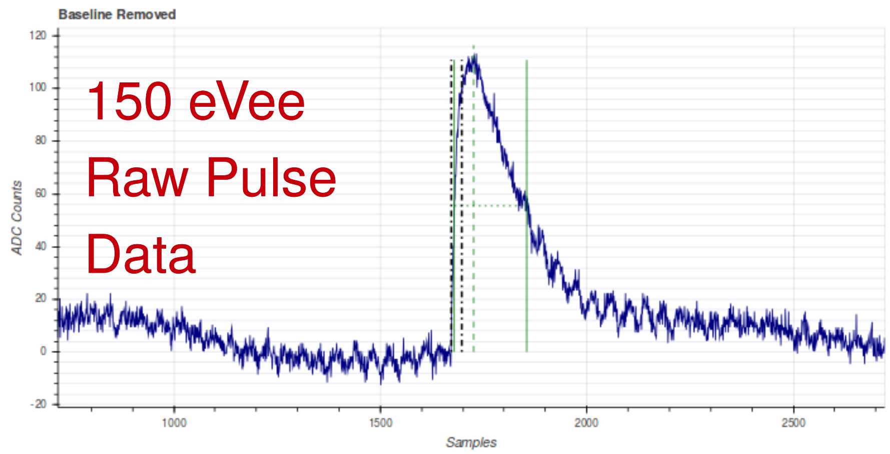


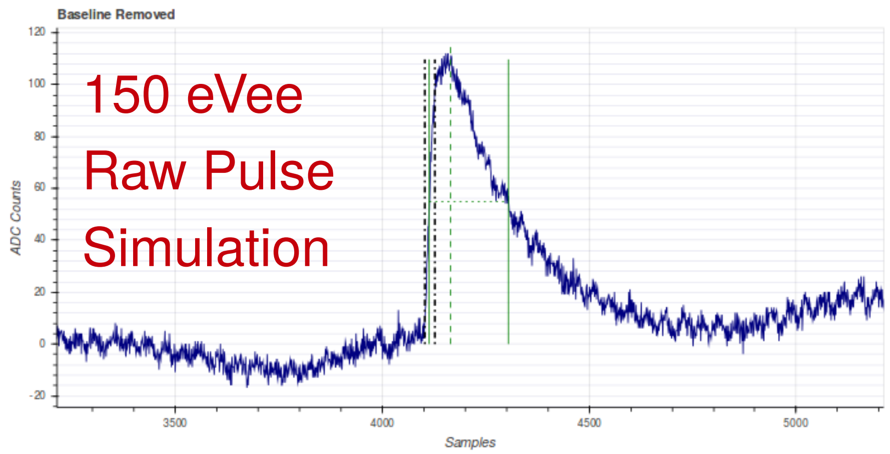
Pulse treatment



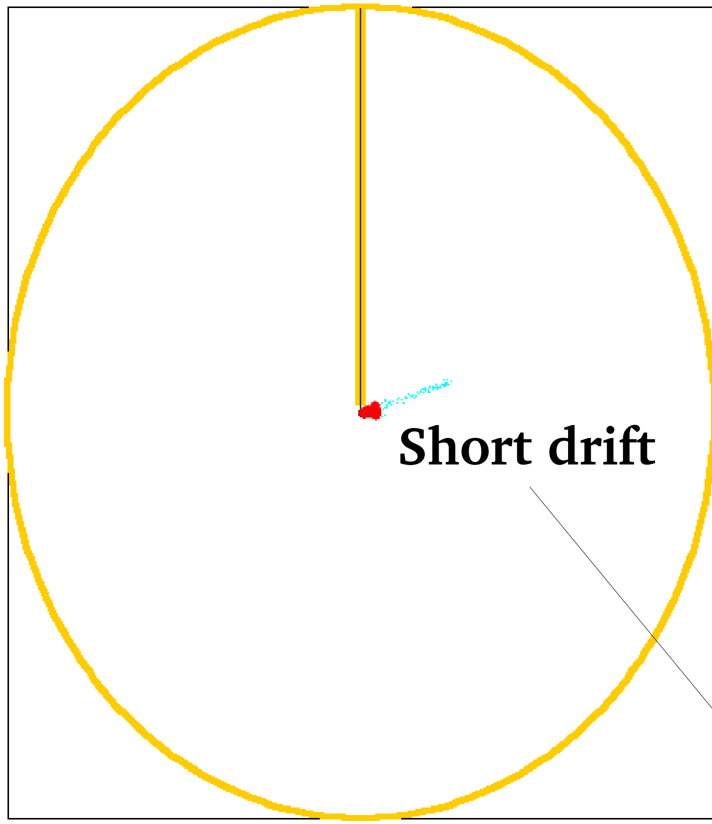
Simulation

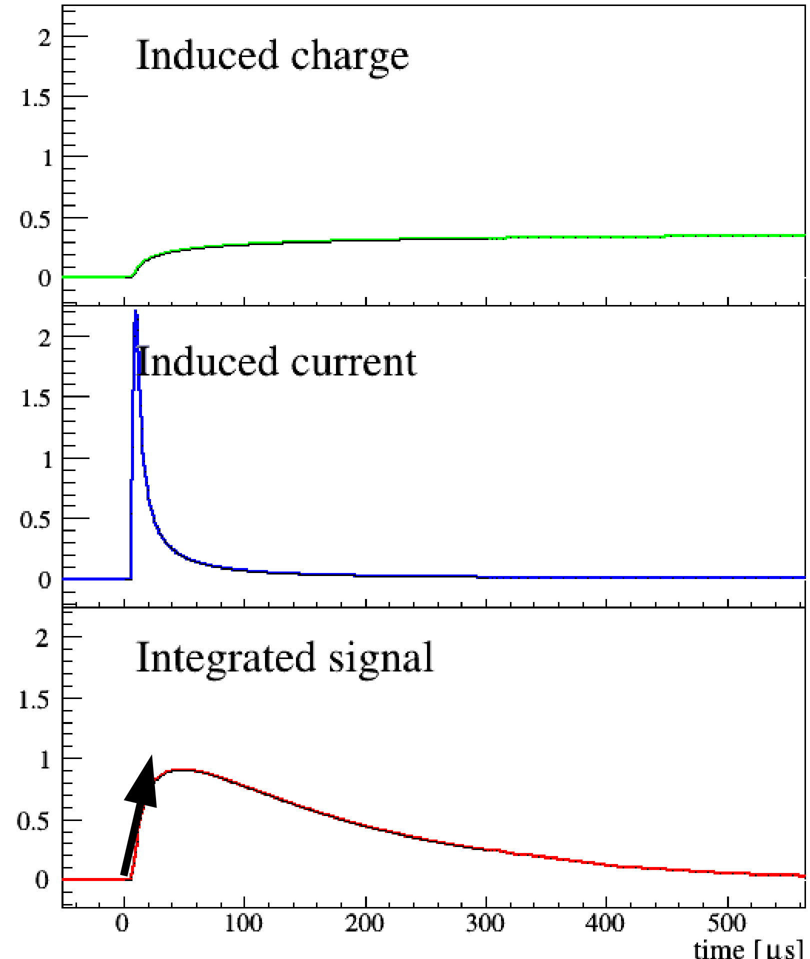
- Drift of individual electrons
  - COMSOL, Magboltz
- Quenching:
  - SRIM, parametrisation
- Avalanche
  - Polya distribution (Garfield++)
- Simulated amplifier pulses
- Noise from data templates
- Same processing as real pulses





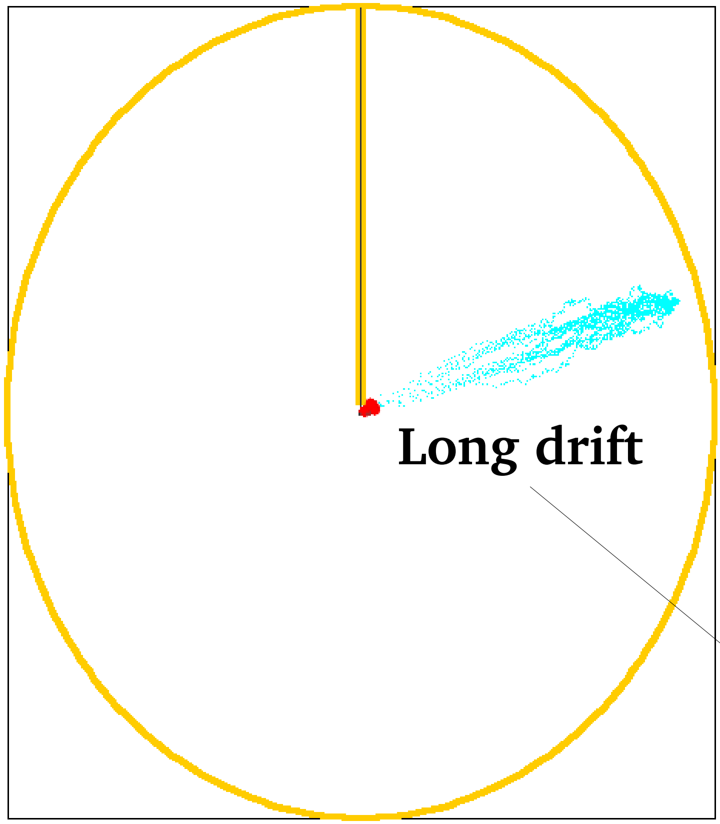
Event discrimination: Rise time

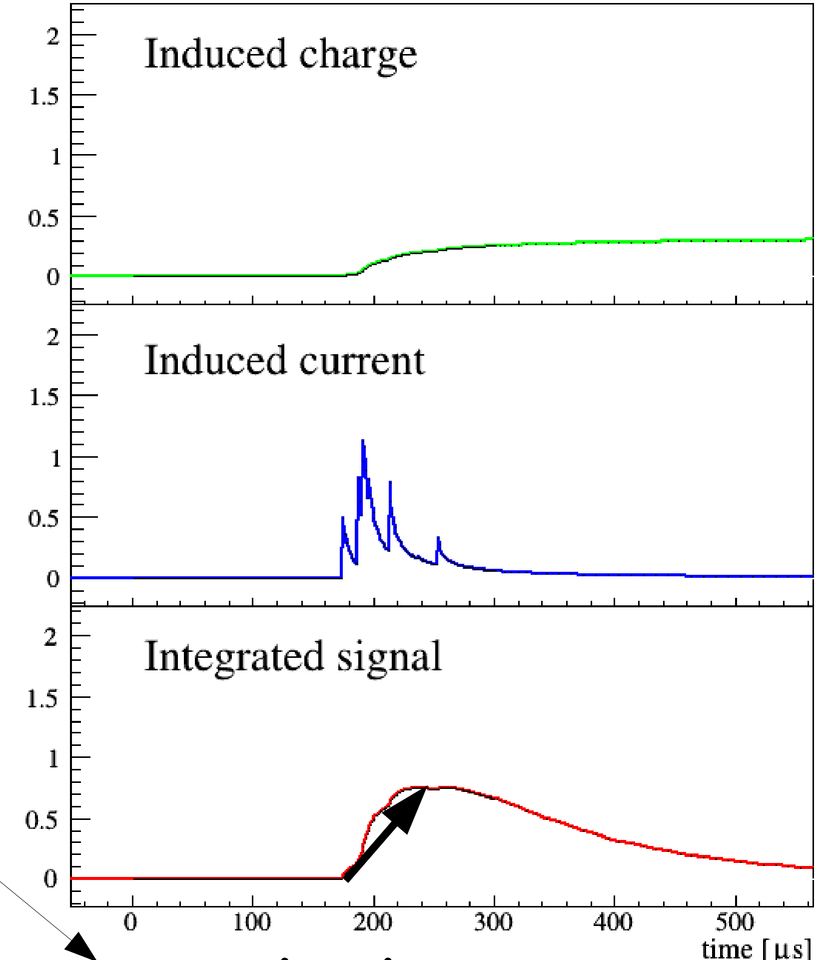




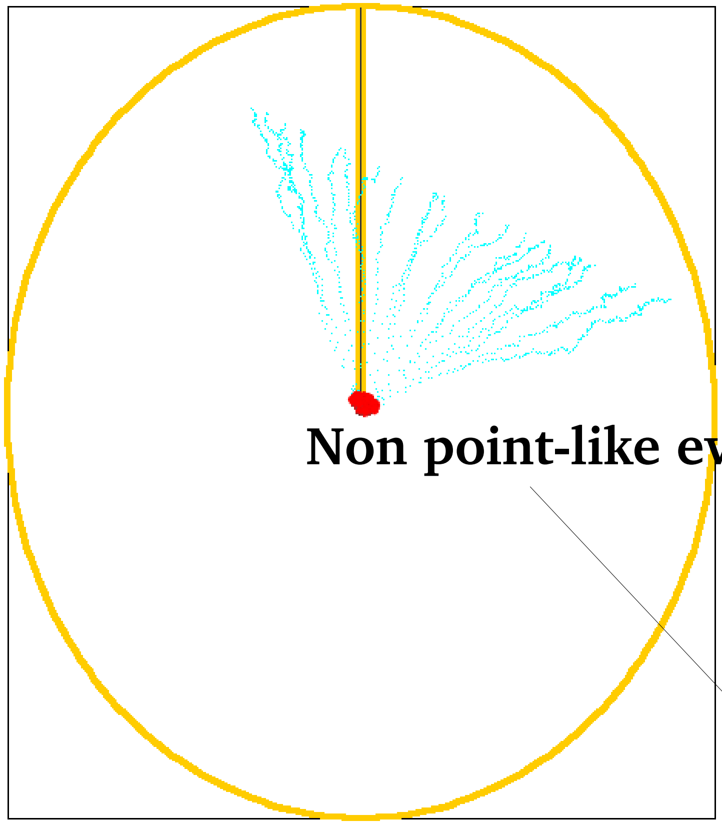
Short rise time

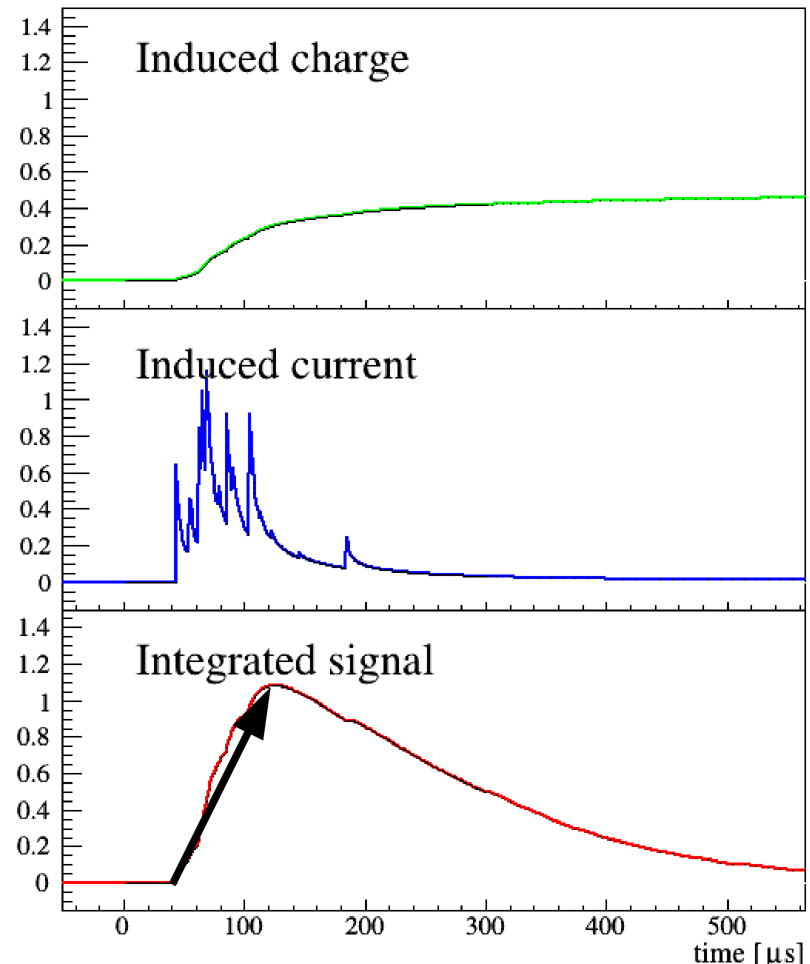
Event discrimination: Rise time





Event discrimination: Rise time





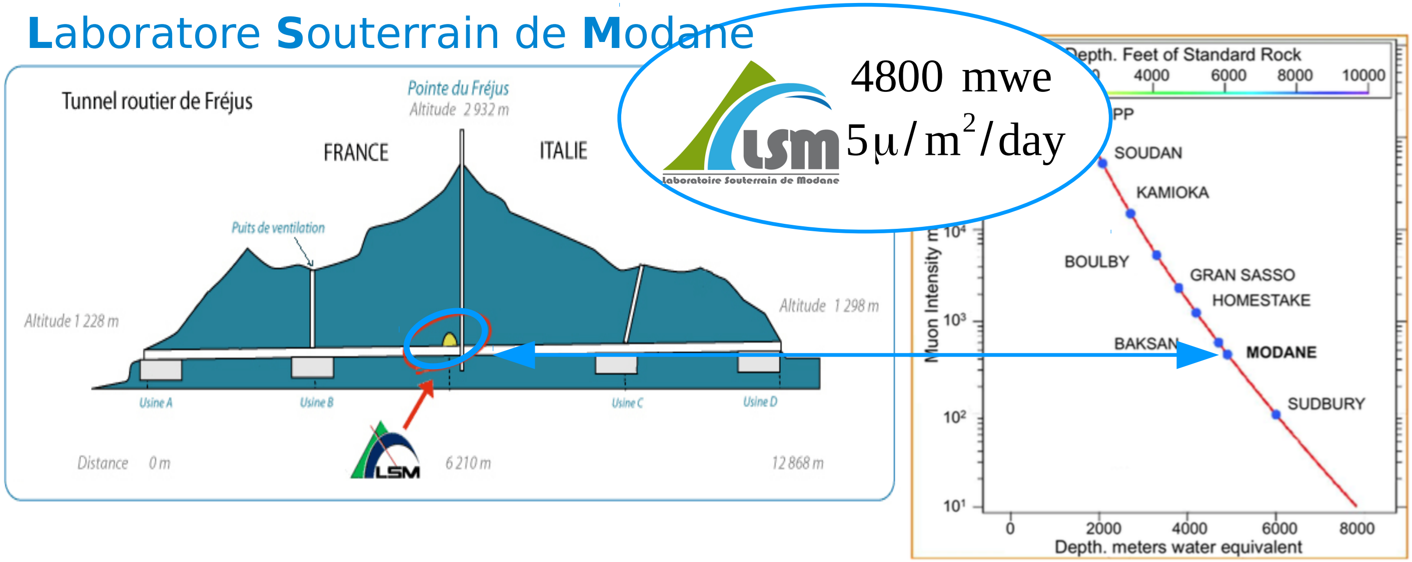
Loonng rise time

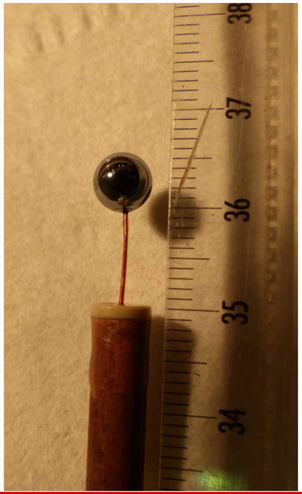
Results with SEDINE

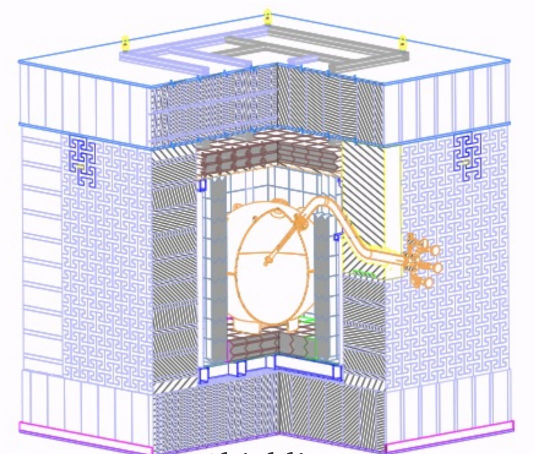
(NEWS-G at LSM)

SEDINE at LSM

Laboratore Souterrain de Modane





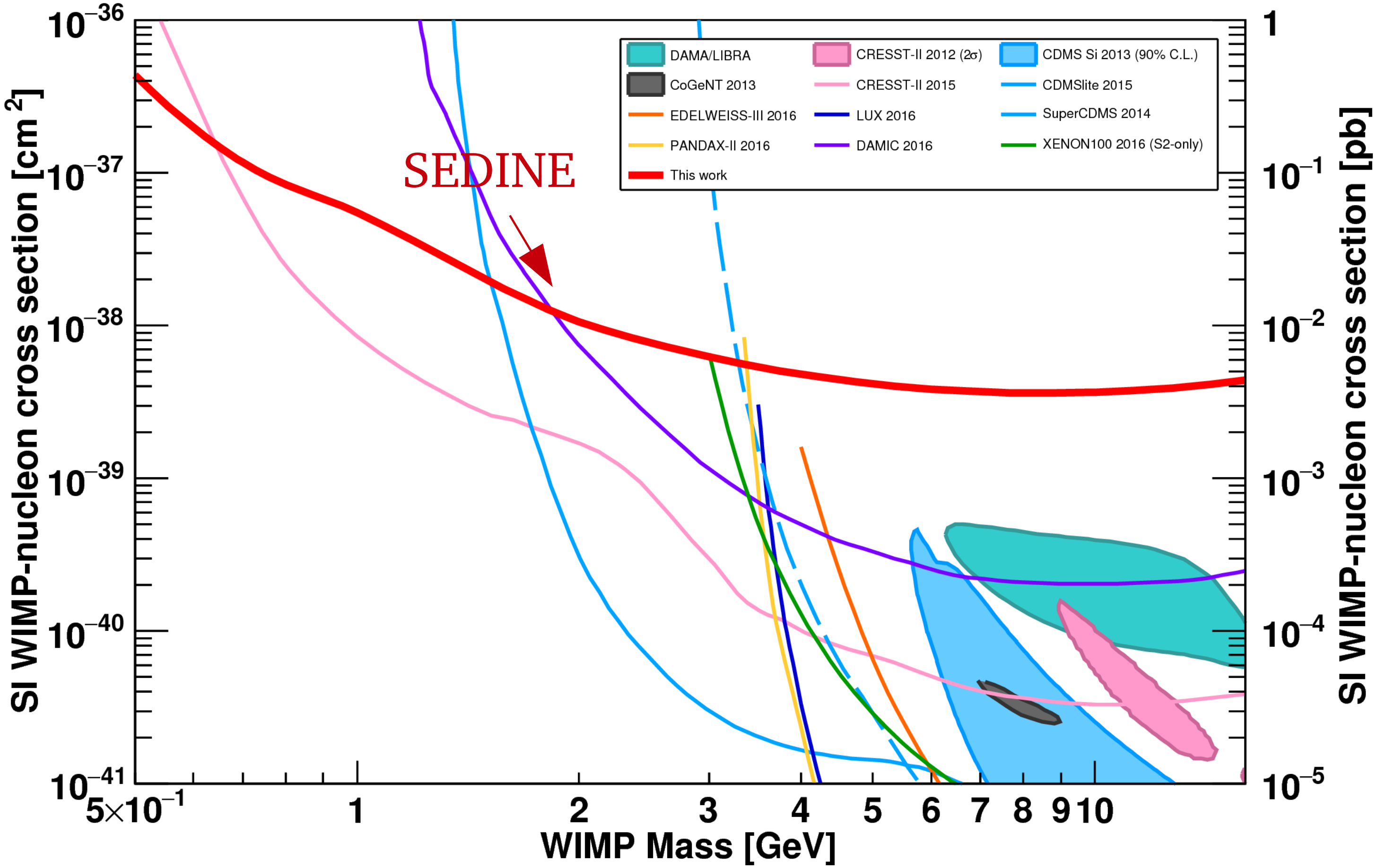


Shielding
30cm PE, 10-15cm Pb, [3-8]cm Cu

Vessel
60 cm ∅ NOSV Copper

Sensor
6.3 mm ∅

First results from NEWS-G at LSM

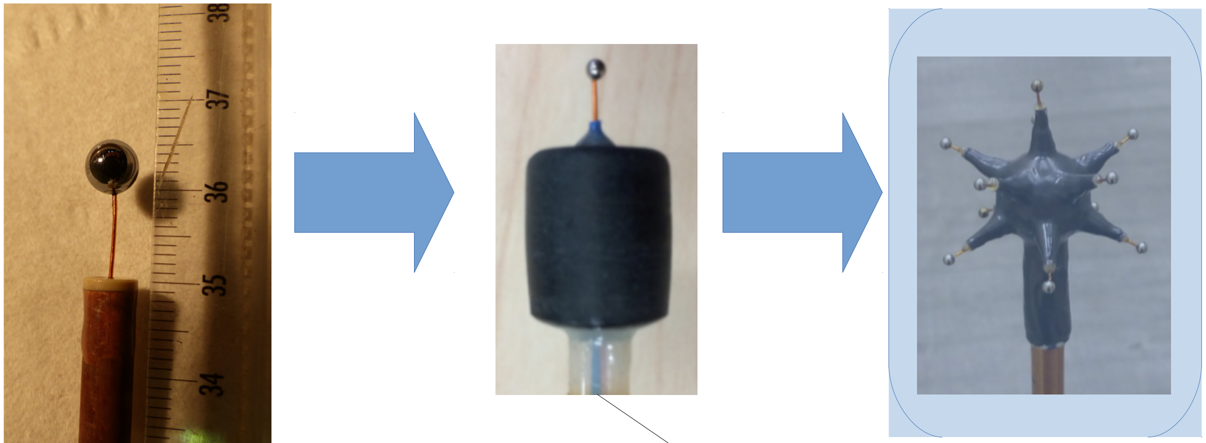


Q. Arnaud et al. (NEWS-G), Astropart. Phys. 97, 54 (2018)

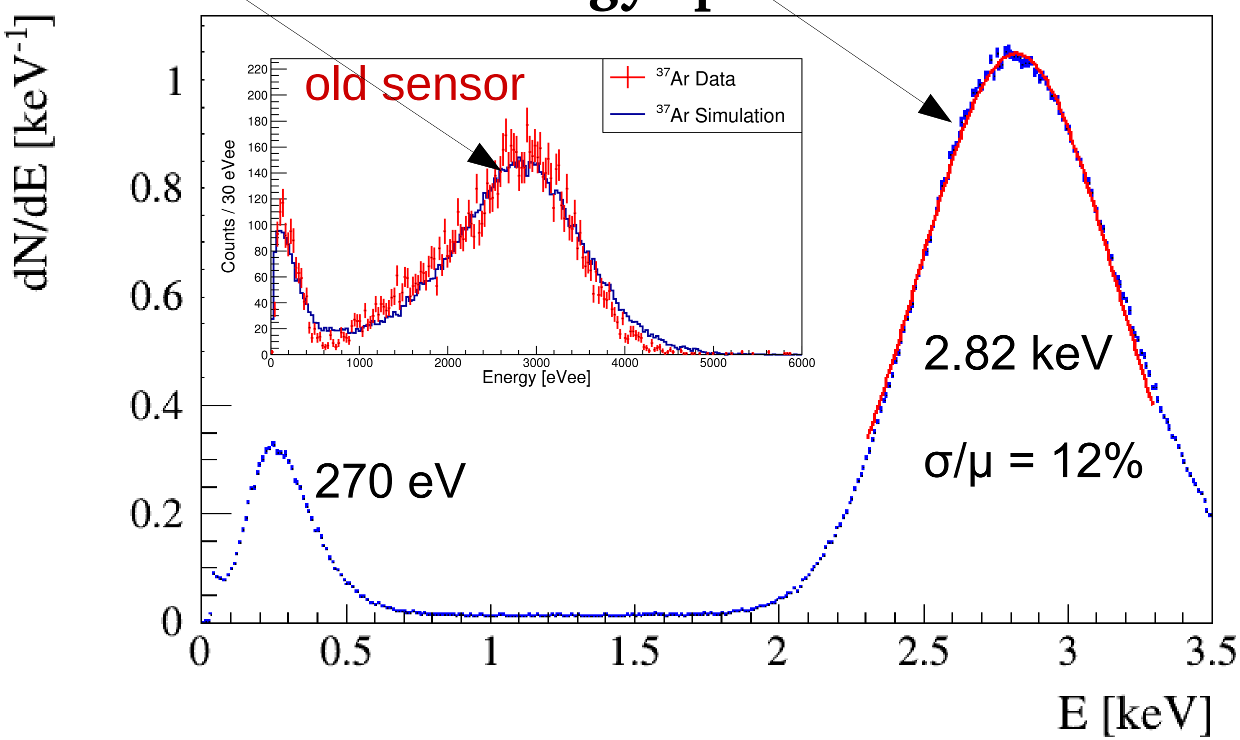
doi: 10.1016/j.astropartphys.2017.10.009

Towards a 140cm Low background Sphere at SNOLAB

Improved electric field: new sensor rod



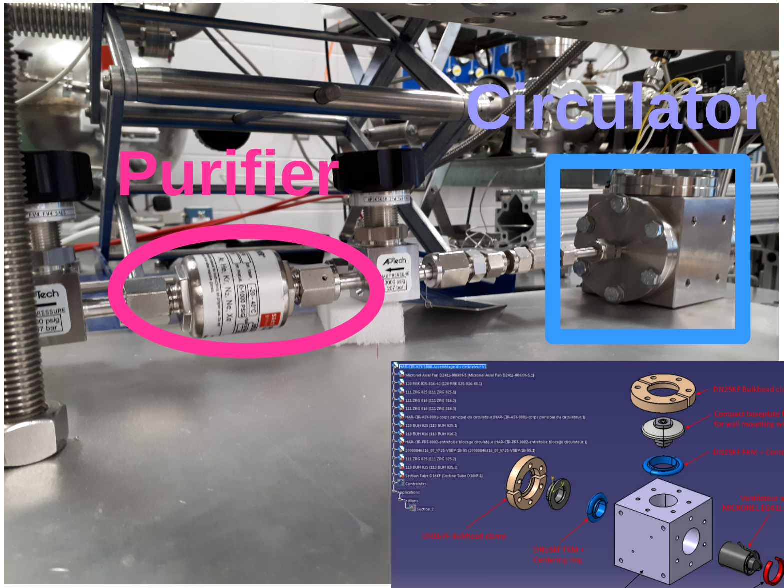
^{37}**Ar energy spectrum**

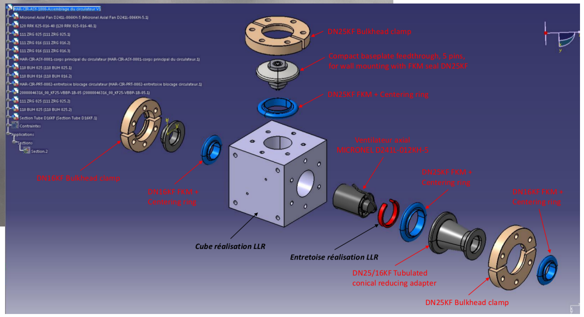


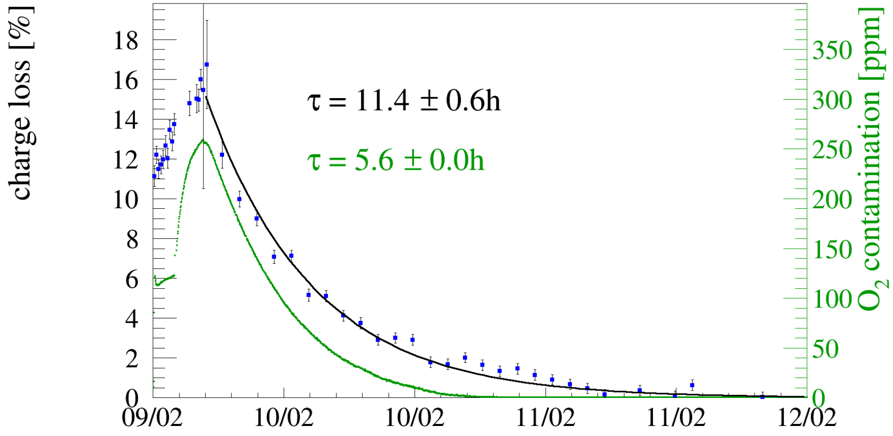
- Second electrode improves field uniformity
- Resistive material for spark protection
  - bakelyte
  - glass
- Significant resolution improvement
- Development of star shaped sensor
  - better for large detector
  - difficult to build

Gas purification

- O_2 contamination induces charge loss
- Simple circulator
  - **<u>Design J. Prudent</u>**
  - No noticeable contamination
- Purification with SAES getter
  - radon contamination
- Radon trap to be added

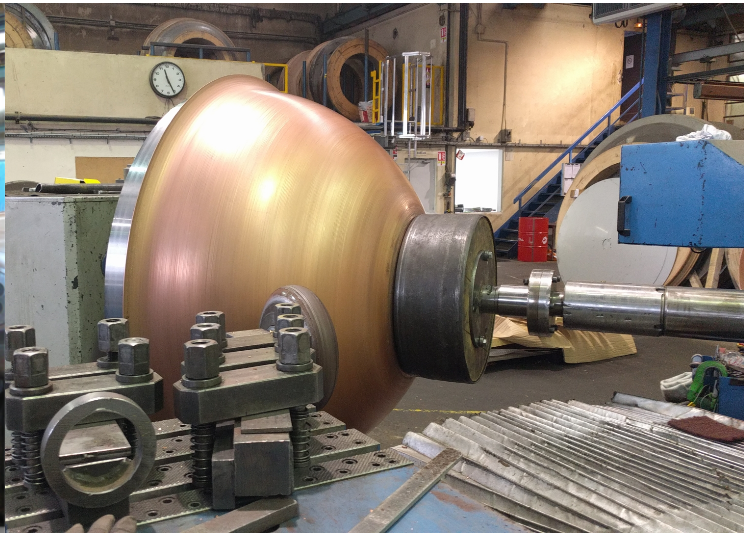


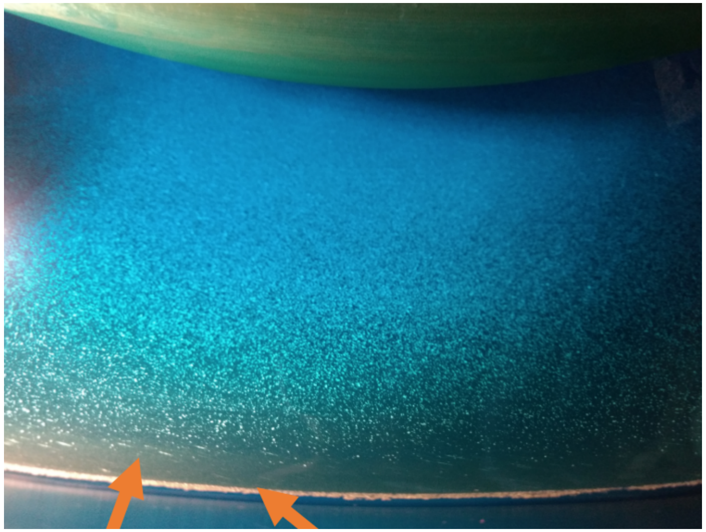




High purity copper sphere

- Low activity copper C10100
  - 7 to 25 μBq/kg Th
  - 1 to 5 μBq/kg U

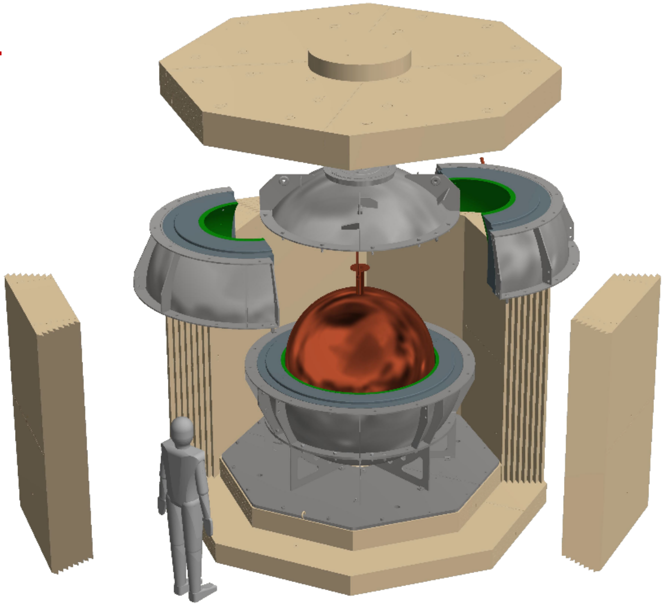




- Electropolished and Electroplated at LSM
  - 500μm pure Copper

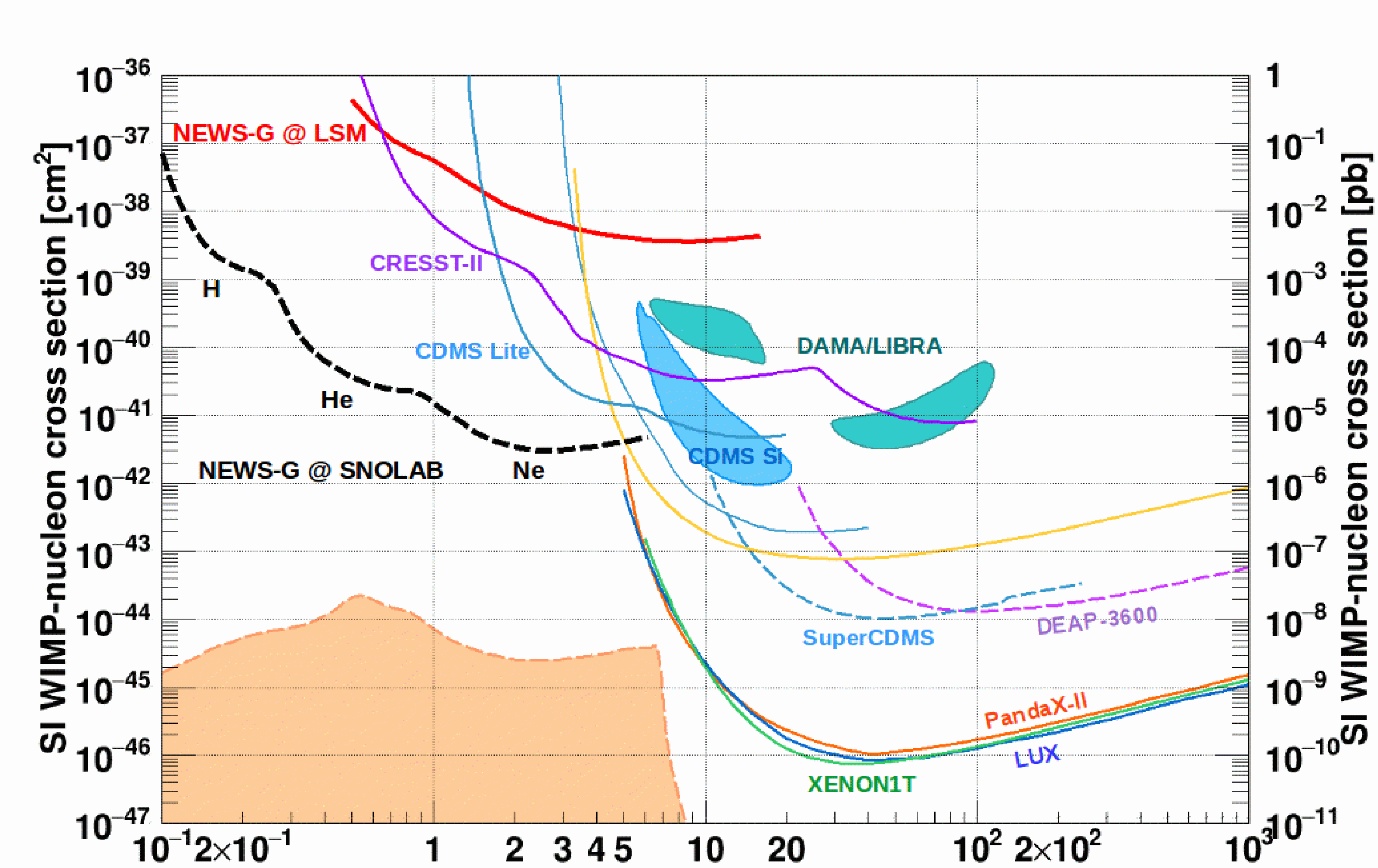
Shielding and others

- Compact shield
  - 3cm roman lead
  - 22cm VLA lead (1Bq/kg ^{210}Pb)
  - Air tight SS envelope with N_2 flushing
  - 40cm HDPE
  - *Under construction in France*
- Seismic platform *under construction at SNOLAB*
- Glove Box for rod change *built in Saclay*
- Gas purification system *tested in Kingston*
- Laser calibration *tested in Kingston*



Installation in Cube Hall at SNOLAB summer of 2019

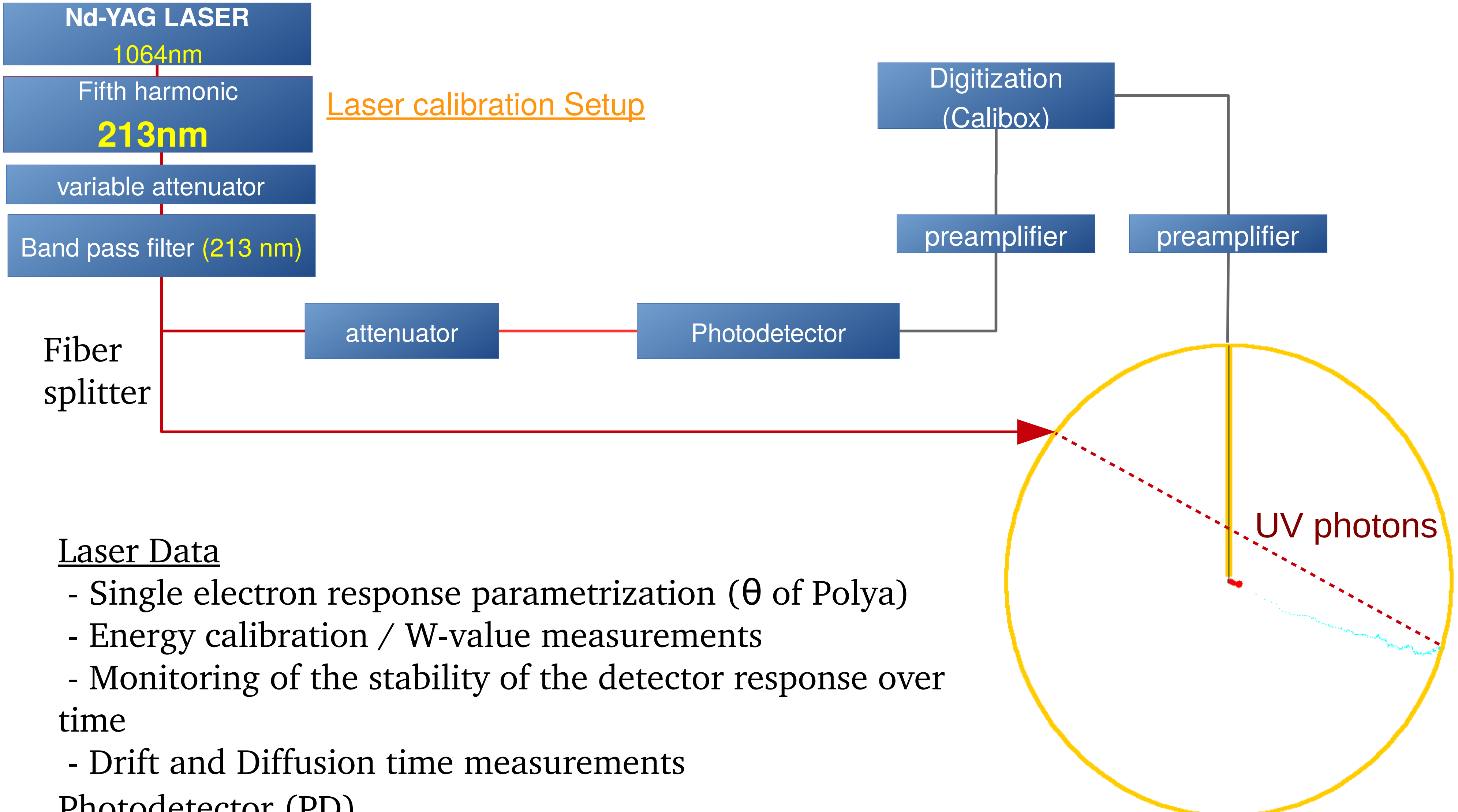
Sensitivity projection



100 kg.days, 200eVee ROI above threshold @ 1 electron.
(Not accounting for sensitivity improvement from resolution effects and RT cuts)

R&D and related activities

Single electron response with UV laser



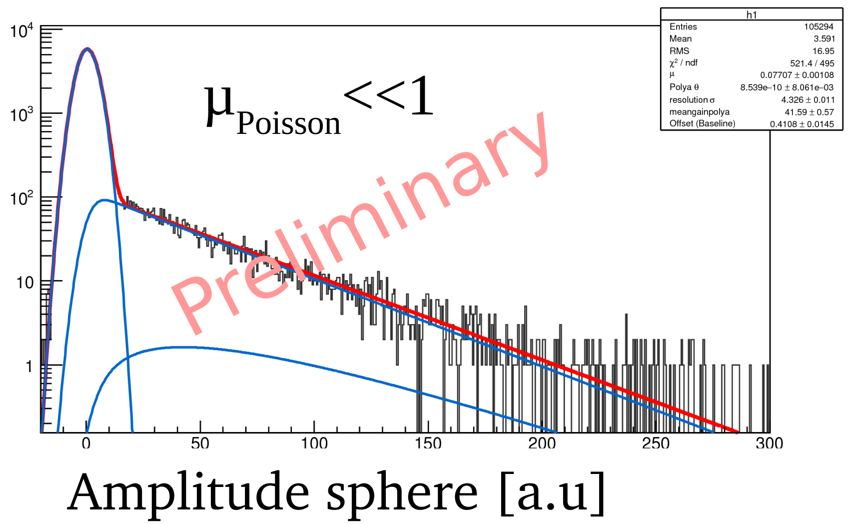
Laser Data

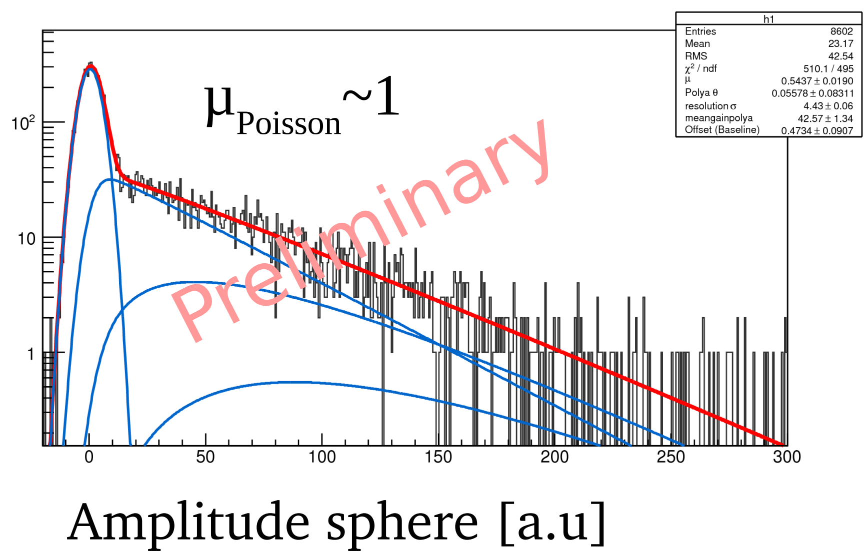
- Single electron response parametrization (θ of Polya)
- Energy calibration / W-value measurements
- Monitoring of the stability of the detector response over time
- Drift and Diffusion time measurements

Photodetector (PD)

- Monitoring of the stability of laser
- Start Time (in drift time measurements)

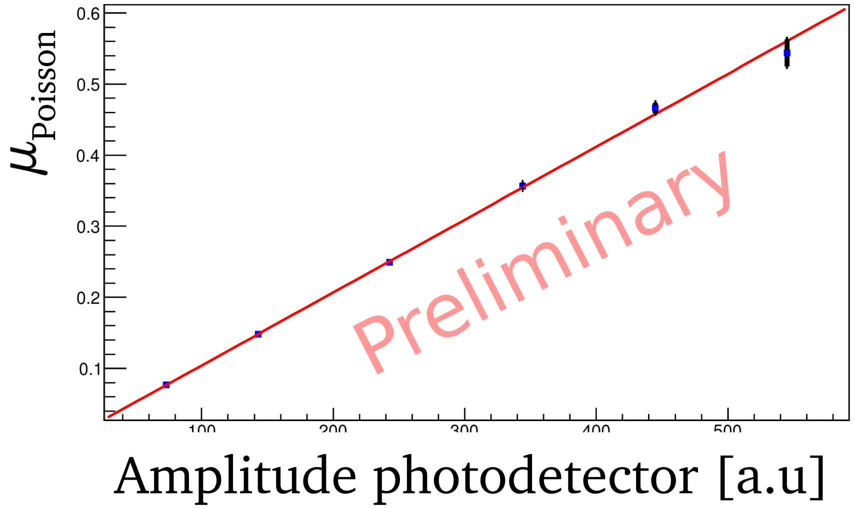
Single electron spectra

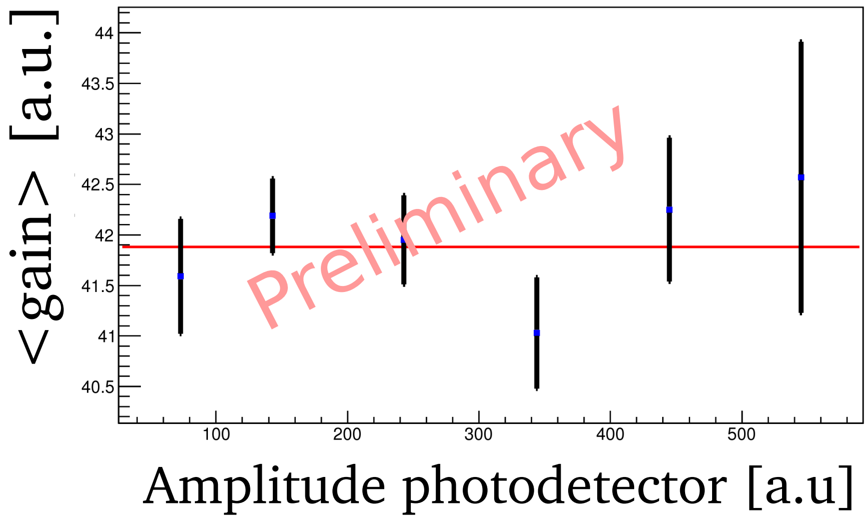




- Fitted with full model of the detector (4 parameters)
  - Poisson fluctuations: μ_{Poisson}
  - gain fluctuation: <gain>, θ
  - noise σ_{noise}
- <u>Fit valid for multiple electrons (Poisson)</u>
- only μ_{Poisson} depends on laser intensity

Extraction of detector parameters





- Mean number of electrons measured is proportional to laser intensity
  - single photon photoelectric process
- Mean gain and θ consistent for all intensities
  - robust fit
- Simultaneous measurement of ^{37}Ar
  - measurement of mean number of ionisation electrons for the gas mixture (first results in argon consistent with literature)

Quenching factor measurement

- Definition
  - Energy(ionisation)/Energy(recoil)
- Crucial to measurement
  - Converts energy measured to energy deposited
  - No existing measurement for Neon or Helium
  - No reliable extrapolation
- Measurement with monochromatic neutron beam at TUNL
  - preliminary measurement down to 5keV Ne recoil
  - new beam campaign planned for Ne and He

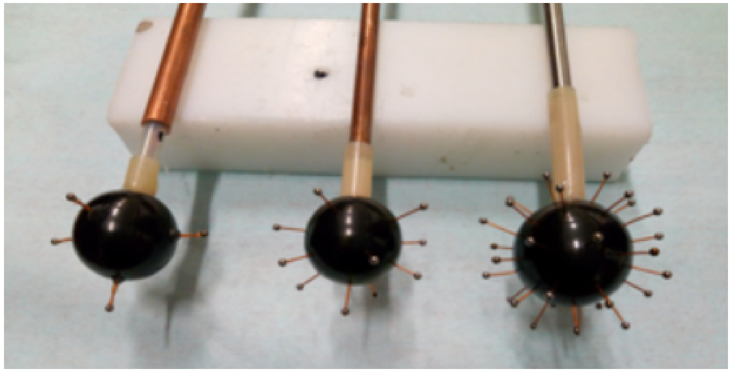
Future sensor: Achinos

- Amplification driven by the ball size
  - Smaller ball → higher amplification.

$$E(r) \approx \frac{V}{r^2} r_{anode}$$

- Drift field far from the sensor proportional to sensor radius
  - Smaller ball → lower drift field

→ Achinos structure: small balls, large sensor


Conclusions and outlook

- Low mass WIMPs are an interesting DM candidate
  - investigation only starting
- NEWS-G has an ambitious program of detection with SPCs
- SEDINE Prototype gave competitive results
- Intensive work provided great improvement in detector performance and understanding
  - improved electric field and gas purity
  - detailed measurement of amplification and drift parameters
- Construction under way for installation at SNOLAB in **summer 2019**
- And still more work to improve the future

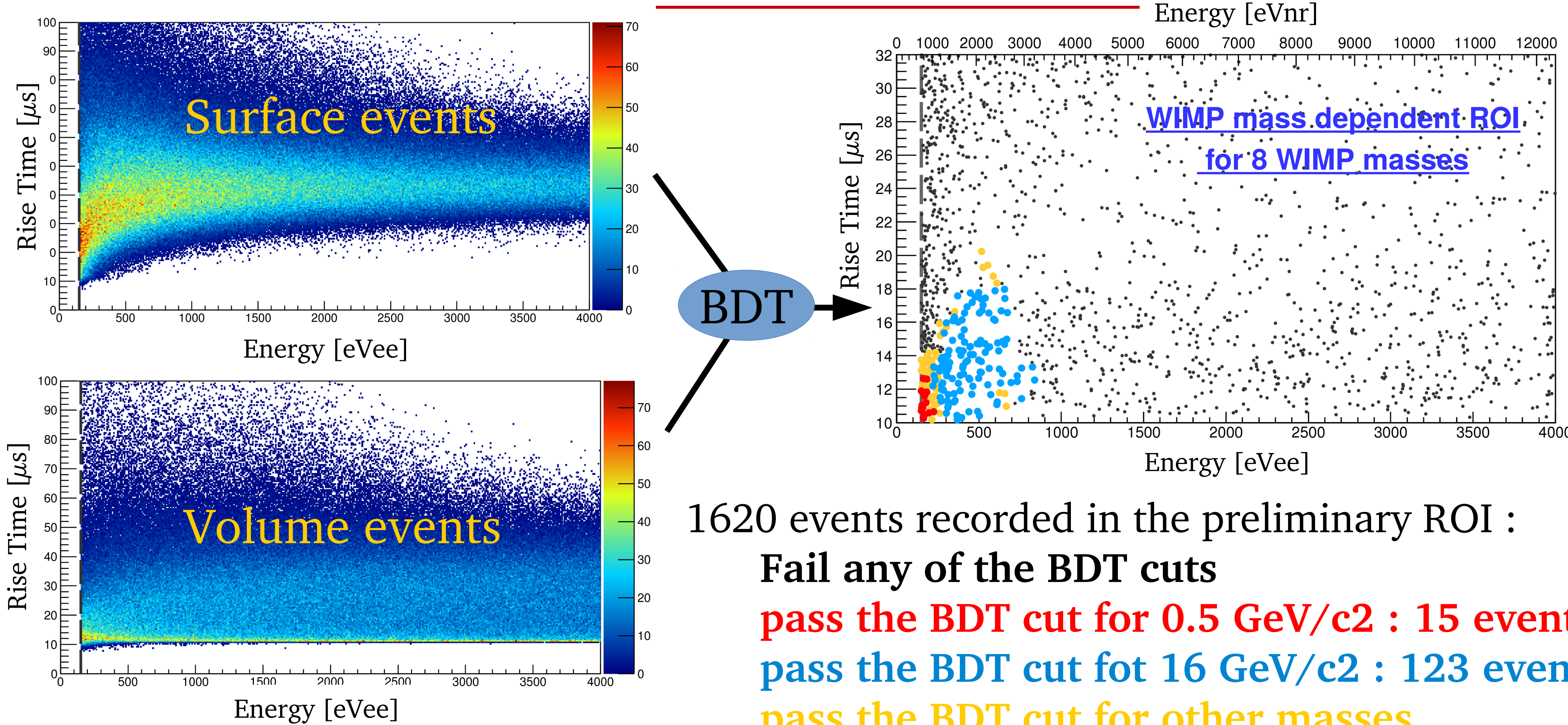
the NEWS-G Collaboration

- **Queen's University Kingston** – G. Gerbier, P. di Stefano, R. Martin, G. Giroux, T. Noble, D. Durnford, S. Crawford, M. Vidal, A. Brossard, P. Vasquez de Sola, Q. Arnaud, K. Dering, J. McDonald, M. Chapellier, A. Ronceray, P. Gros, C. Neron, A. Rolland
  - Copper vessel and gas set-up specifications, calibration, project management
  - Gas characterisation, laser calibration, on surface prototypes
  - Simulation/Data analysis
- **IRFU (Unstitut de Recherche sur les lois Fondamentales de l'Univers)/CEA Saclay** – I. Giomataris, M. Gros, C. Nones, I. Katsioulas, T. Papaevangelou, J.-P. Bard, J.-P. Mols, X.-F. Navick
  - Sensor/rod (low activity, optimisation of E field)
  - Electronics (low noise preamps, digitization, stream mode)
  - DAQ/soft
- **LSM (Laboratoire Souterrain de Modane), IN2P3, U. of Chambéry** – F. Piquemal, M. Zampaolo, A. Dastgheibi-Fard
  - Low activity archeological lead
  - Coordination for lead/HDPE shield and copper sphere
- **Thessaloniki University** – I. Savvidis, A. Leisos, S. Tzamarias
  - Simulation, neutron calibration
  - Studies on sensors
- **LPSC (Laboratoire de Physique Subatomique et Cosmologie) Grenoble** – D. Santos, J.-F. Muraz, O. Guillaudin
  - Quenching factor measurements, Copper electroforming
- **PNNL (Pacific Northwest National Lab)** – E. Hoppe, R. Bunker
  - Low activity measurements, Copper electroforming
- **RMCC (Royal Military College Canada) Kingston** – D. Kelly, E. Corcoran
  - 37Ar source production, sample analysis
- **SNOLAB, Sudbury** – P. Gorel
  - Calibration system, slow control
- **University of Birmingham** – K. Nikolopoulos, P. Knights
  - Simulation, analysis, R&D

- **Associated labs: TRIUMF** – F. Retiere

Back up

Data analysis



1620 events recorded in the preliminary ROI :

Fail any of the BDT cuts

pass the BDT cut for 0.5 GeV/c2 : 15 events

pass the BDT cut fot 16 GeV/c2 : 123 events

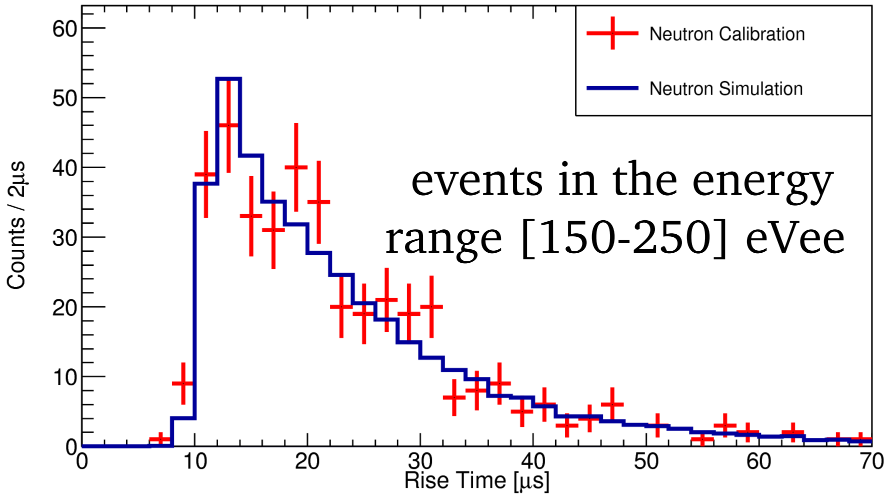
pass the BDT cut for other masses

Analysis methodology robust against background mis-modeling:
If BDT trained with inaccurate bkg models, ROI not optimized

Simulation Validation

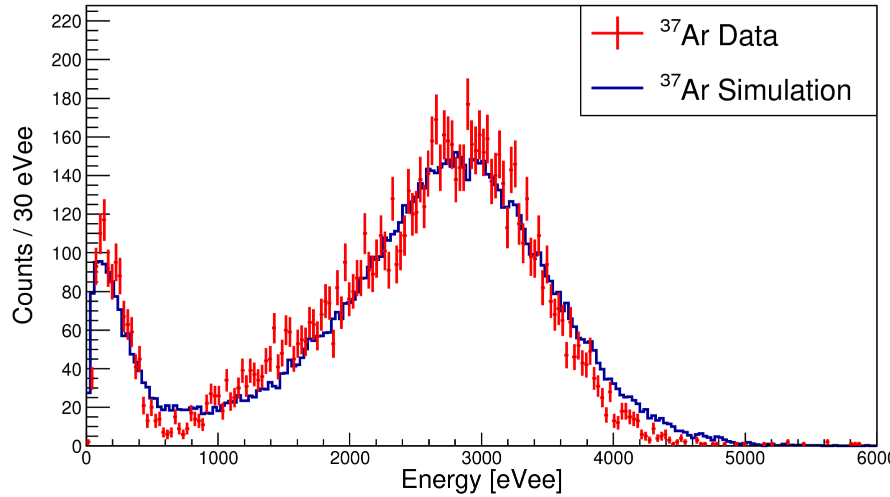
Am-Be neutron source

Nuclear recoils
homogeneously distributed
in the volume



^{37}Ar gas added to the mixture

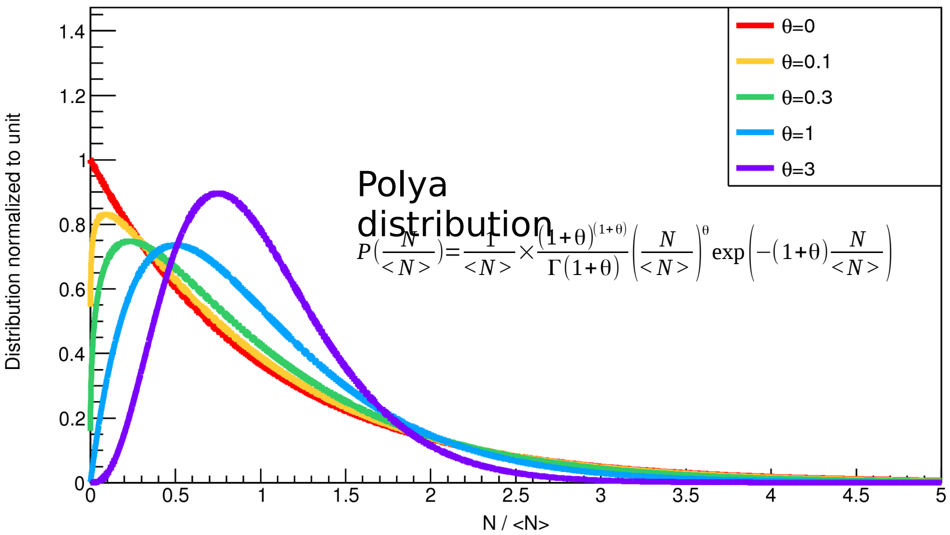
2.82 keV and 270 eV X-rays from
the electron capture
in the K- and L-shells respectively

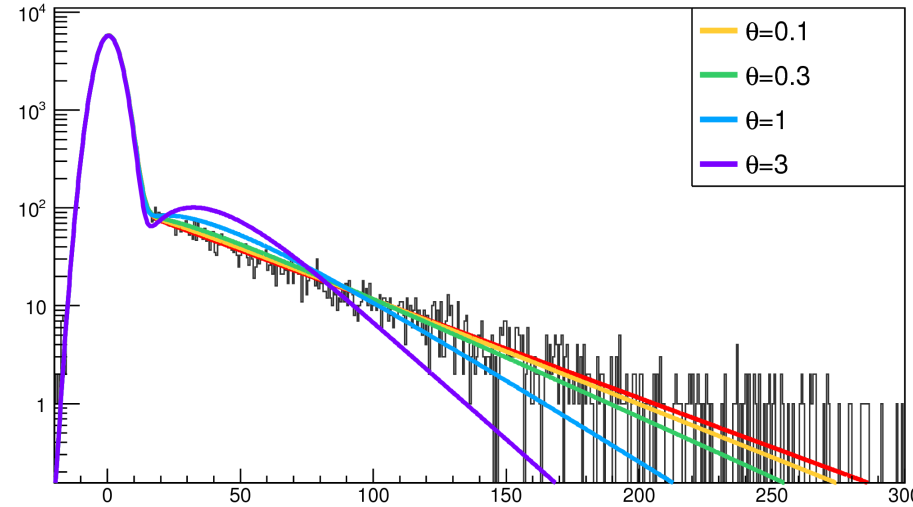


The overall agreement allows us to confidently derive our sensitivity from simulated WIMP events

Laser calibration measurements

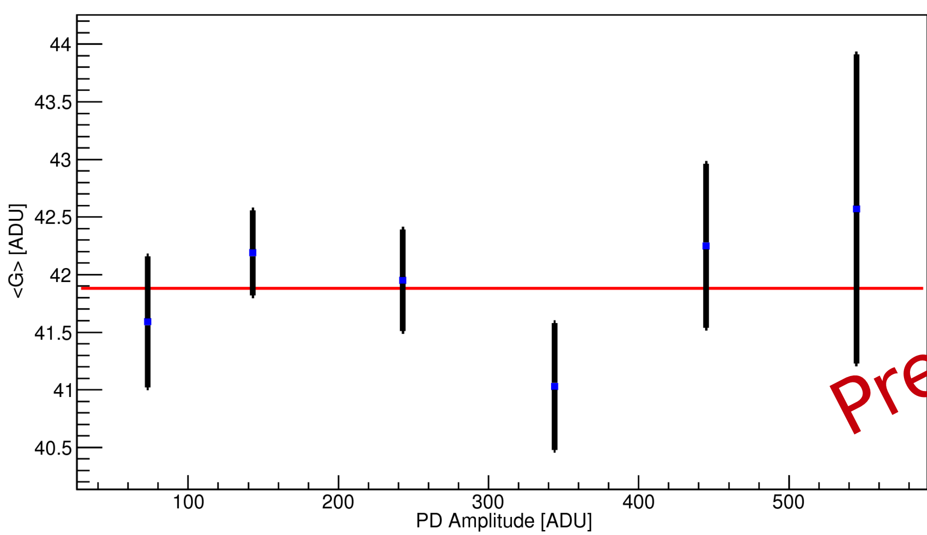
Parametrization of the Single Electron Response (SER)

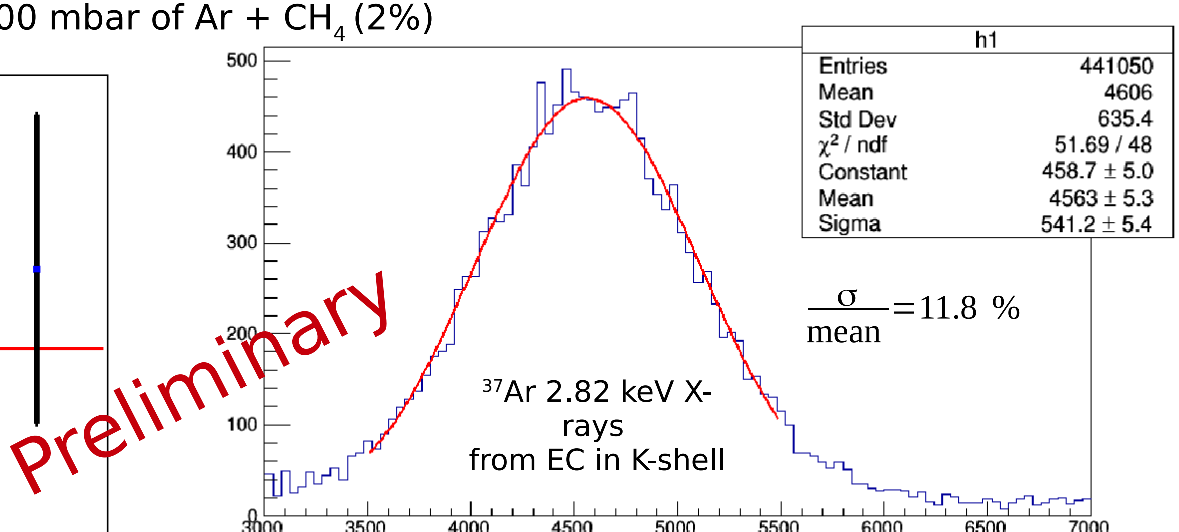




W-value measurement and upper limit on the Fano factor

in 500 mbar of Ar + CH_4 (2%)





⟨Gain⟩ ~ 41.9 ADU

&

2820 keV peak @ 4563 ADU

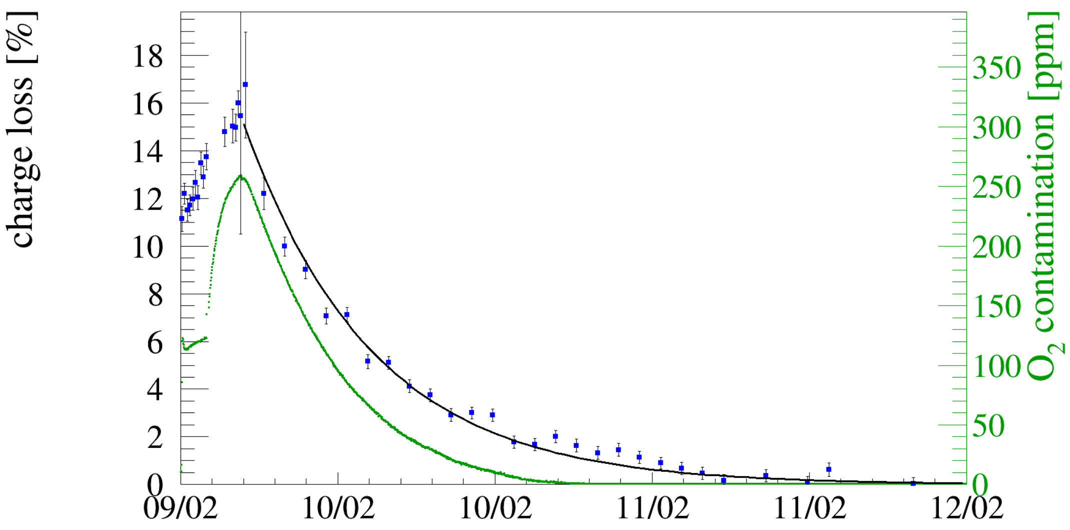
W ~ 25.9 eV

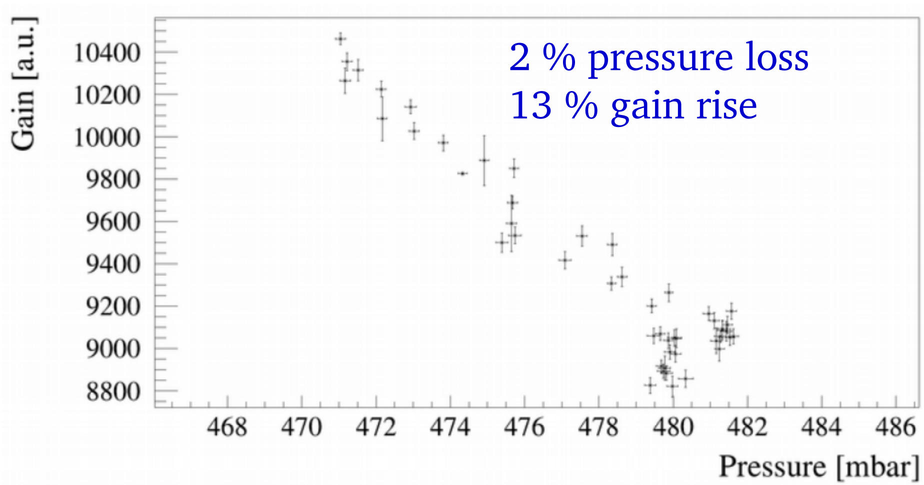
$$\boxed{\left(\frac{\sigma}{\text{mean}}\right)^2\times\frac{E_R}{W}=\left(F+\frac{1}{1+\theta}\right)}$$

F < 0.53

Gas quality

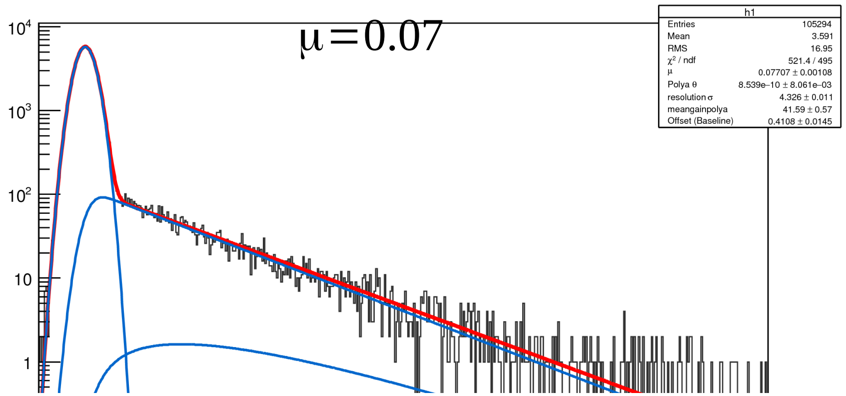
- Oxygen captures drifting electrons → signal loss
- RGA monitors oxygen contamination
- Gas purifier removes oxygen from gas mixture

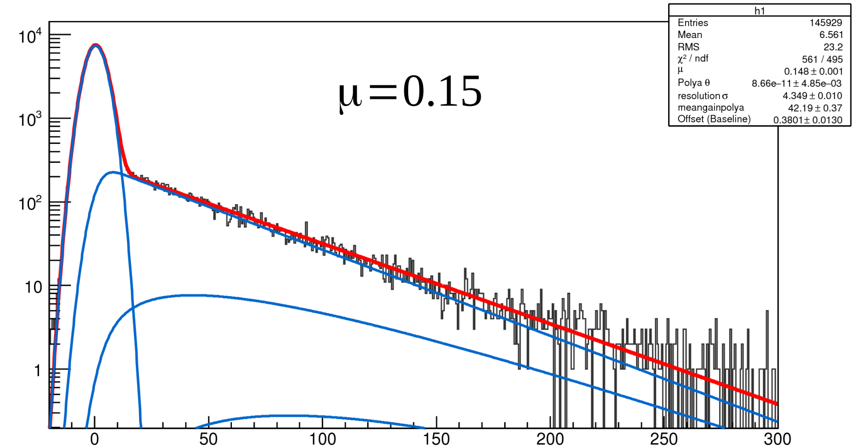


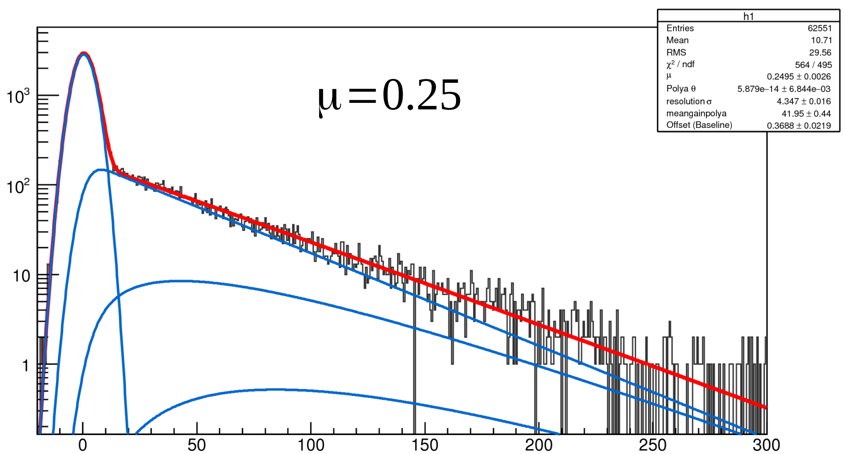


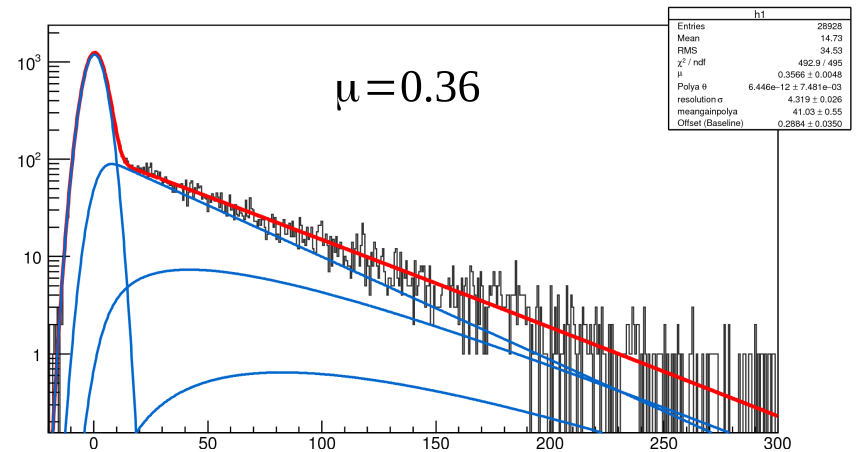
- Gain very sensitive to gas pressure
- Continuous monitoring of pressure
- measurement of dependence

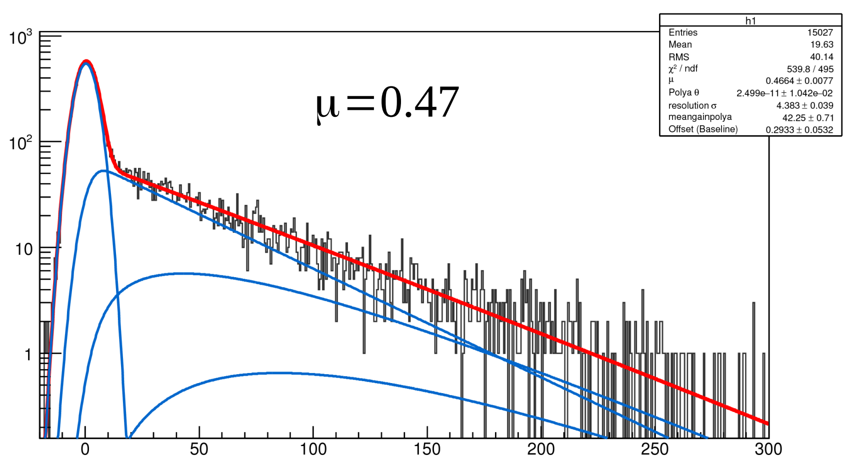
Fit of our model to Real data

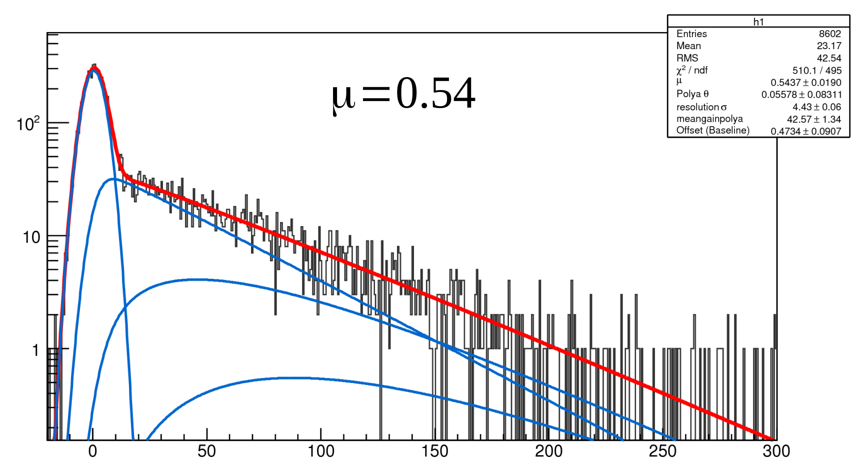




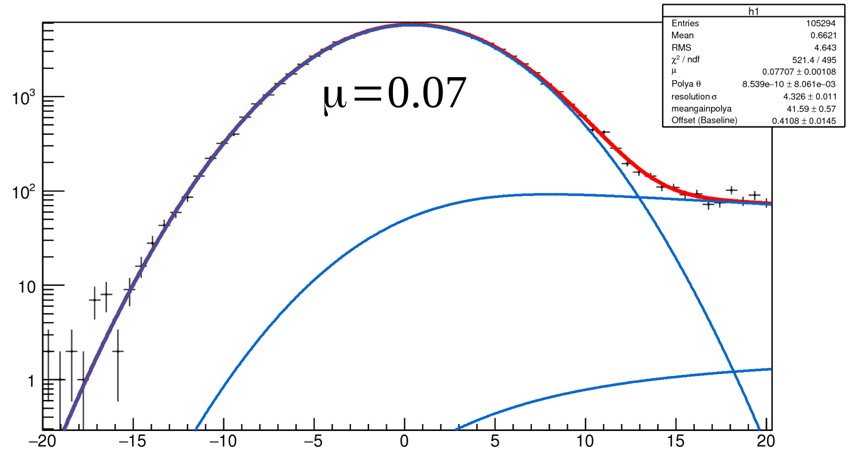


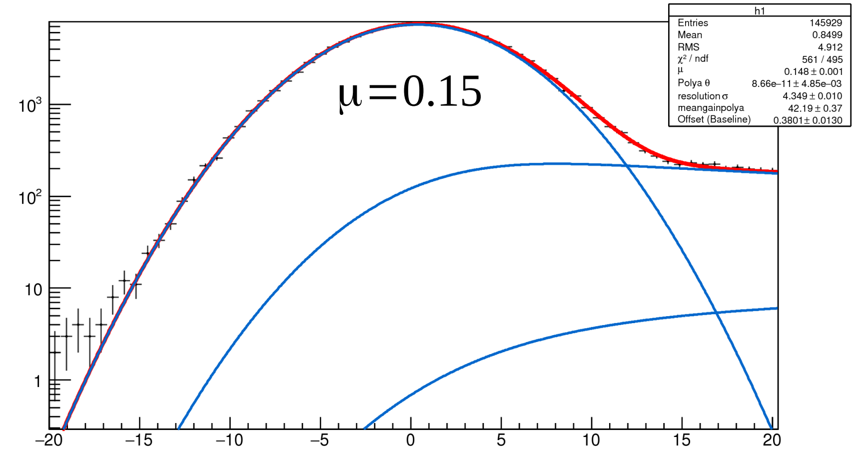


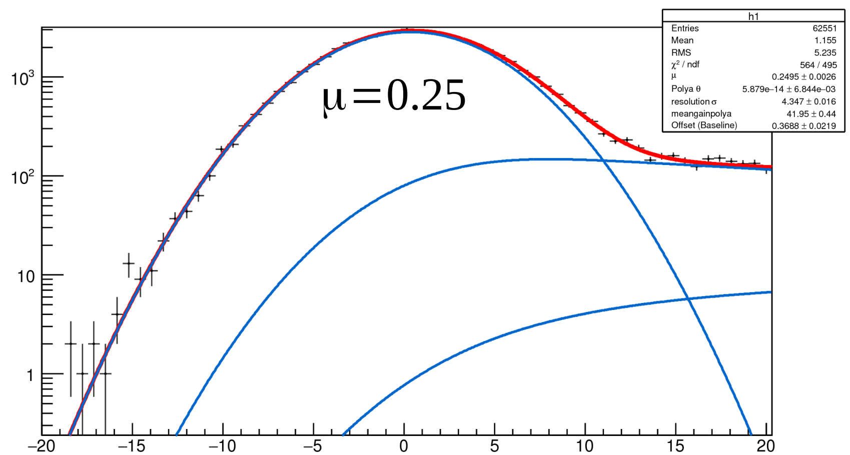


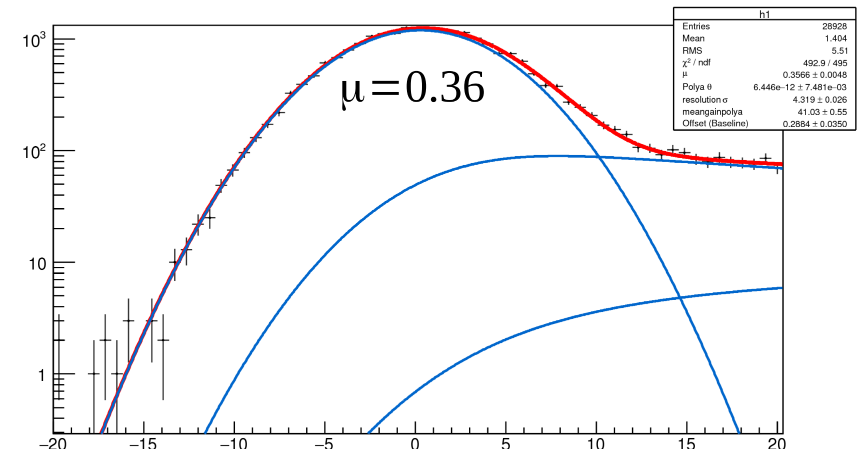


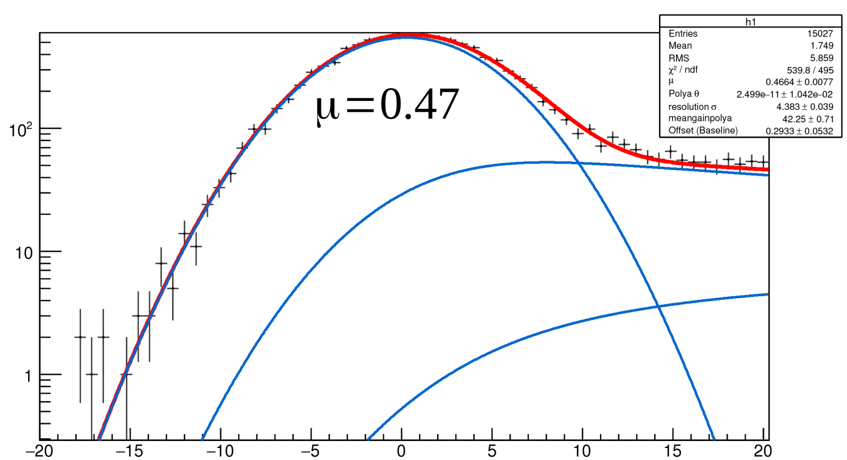
Fit of our model to Real data (zoom in the low energy region)

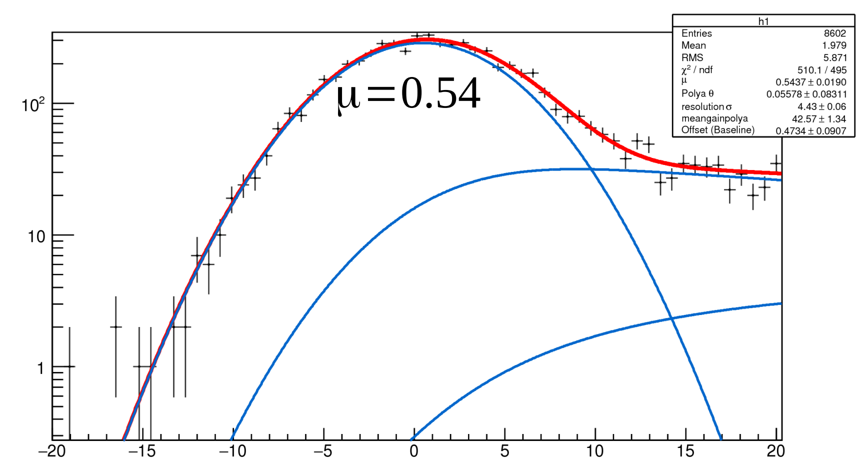




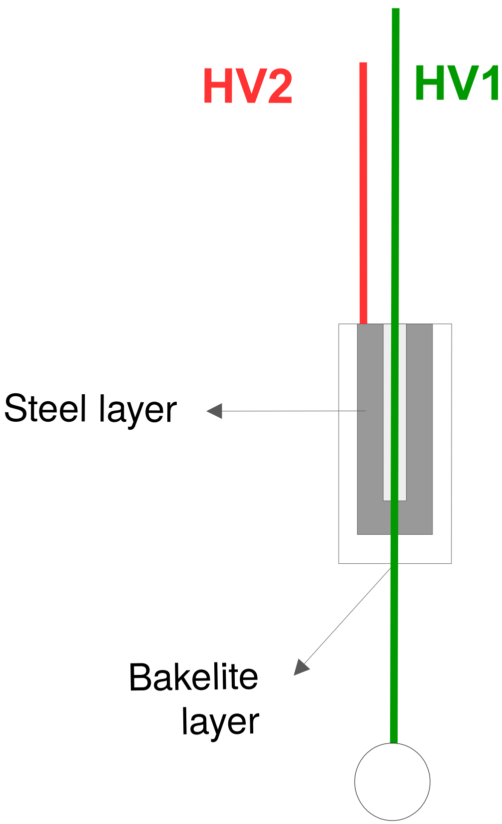


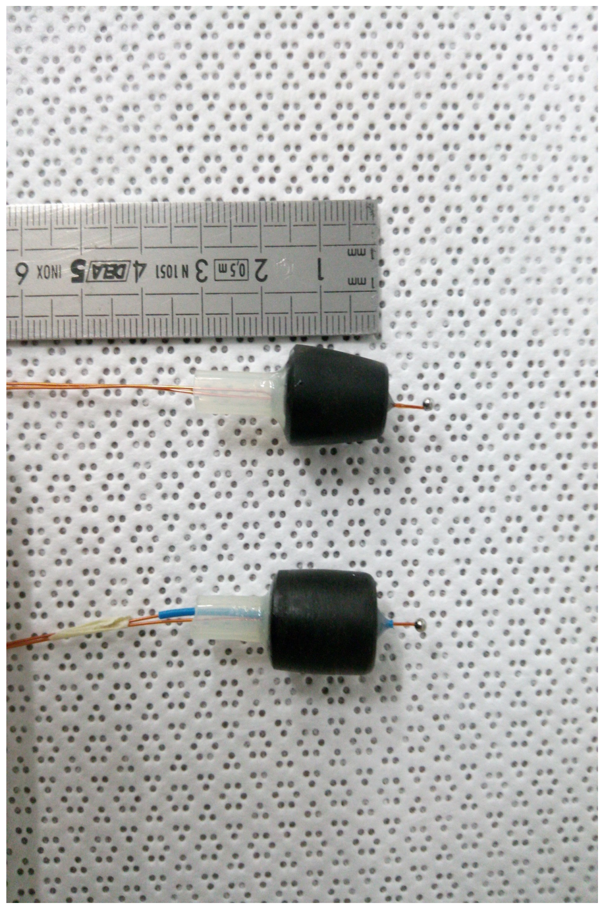






The bakelite resistive umbrella





Bakelite
Chemical Formula:
(C6-H6-O.C-H2-O)x

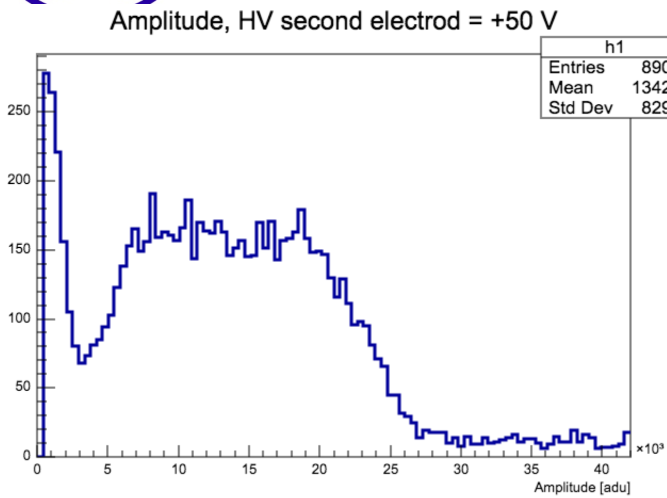
Thermosetting phenol formaldehyde resin, formed from a condensation reaction of phenol with formaldehyde.

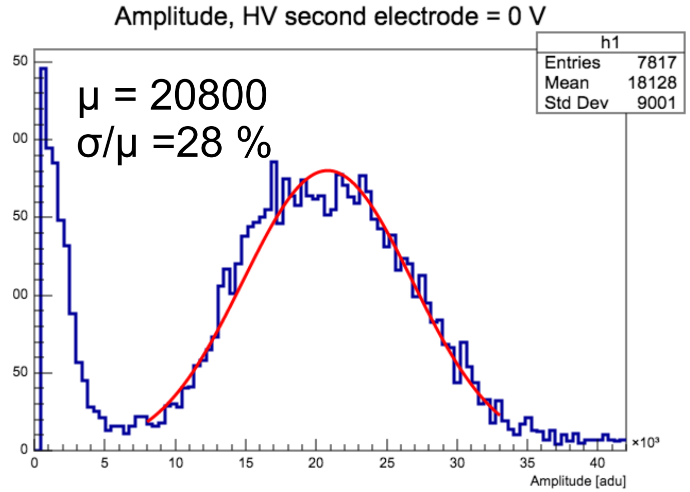
Advantages:

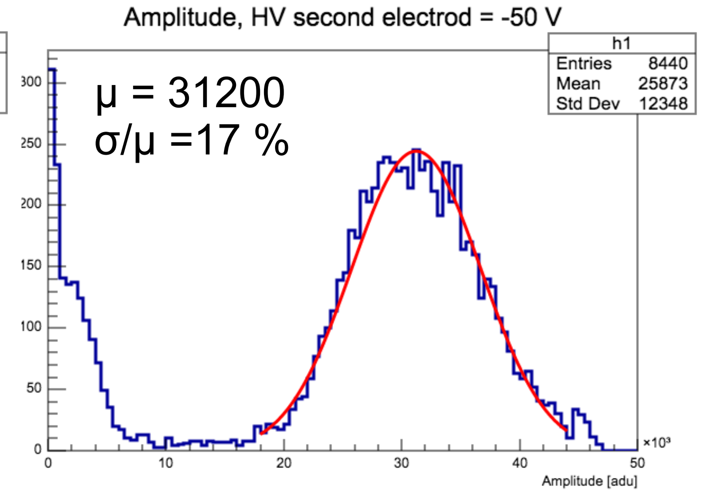
- Bakelite resistivity up to ~ 10^12 Ω.cm
- Compact and homogenous material

30 cm diameter sphere / Gas mixture: Ar + 2% CH_4 @ 500 mbar

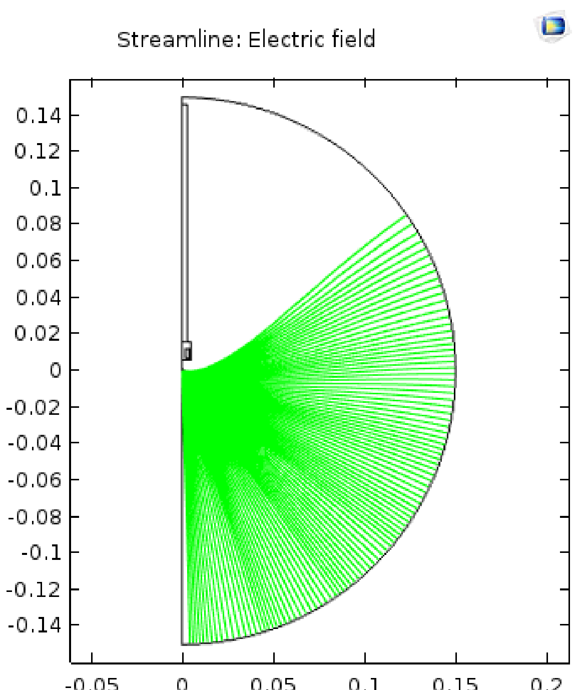
Source: ^{37}Ar Electronic capture released 0.27 or 2.8 keV



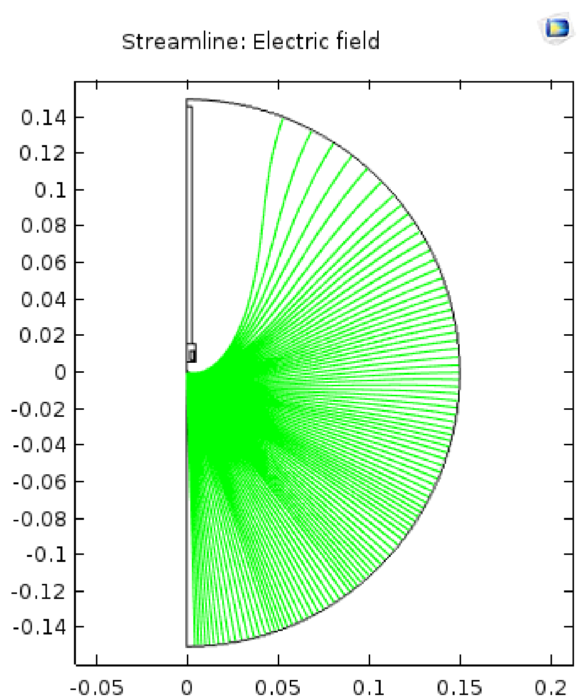




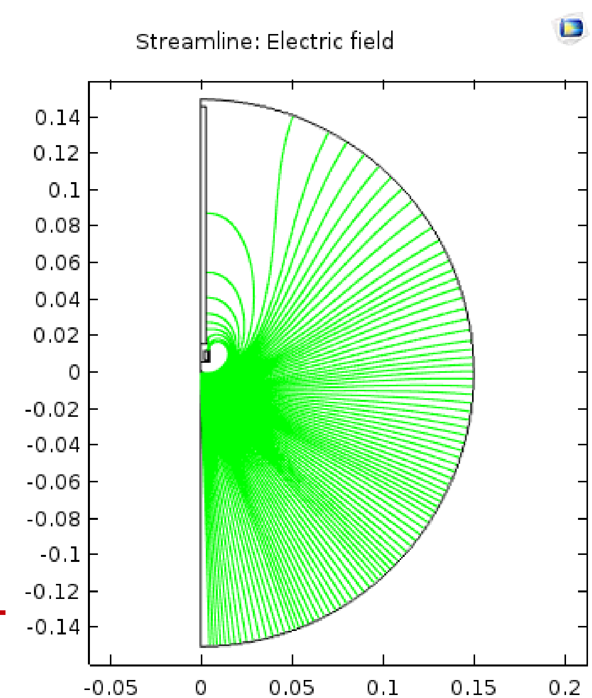
Electric filed lines reaching the lower half of the sensor



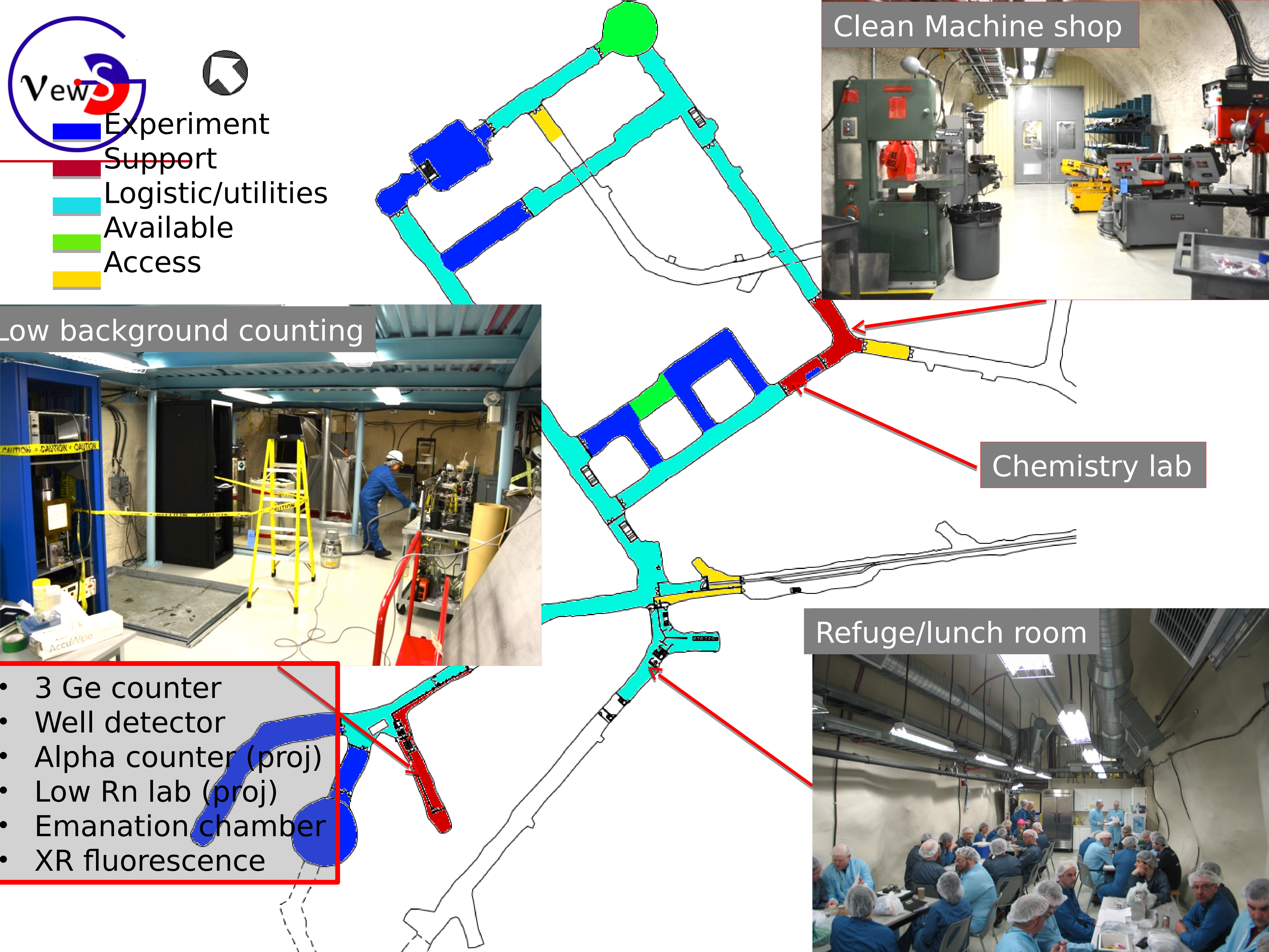
HV2 = +50 V



HV2 = 0 V



HV2 = -50 V


Experiment
Support
Logistic/utilities
Available
Access
Clean Machine shop
Low background counting
Chemistry lab
Refuge/lunch room
• 3 Ge counter
• Well detector
• Alpha counter (proj)
• Low Rn lab (proj)
• Emanation chamber
• XR fluorescence