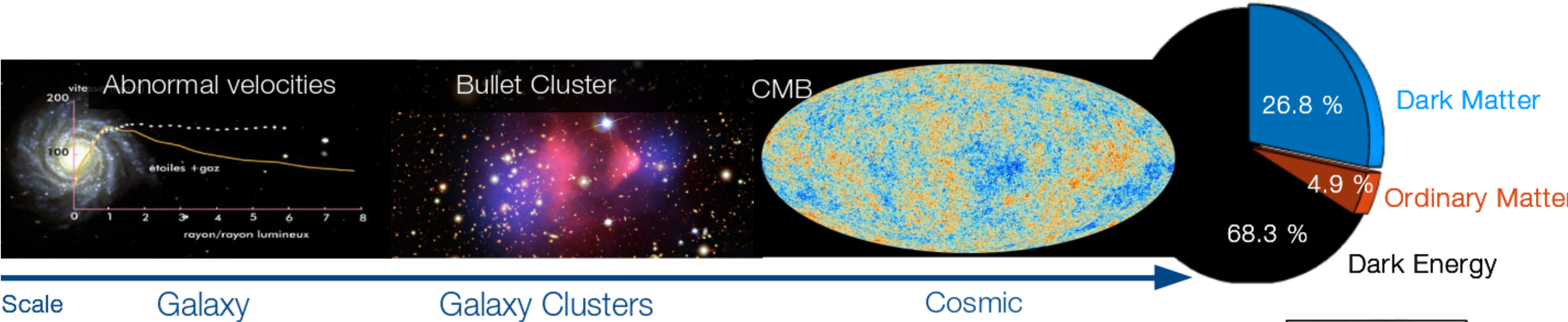
NEWS-G Light Dark Matter Experiment

Daniel Durnford
Supervisor: Prof. Marie-Cécile Piro

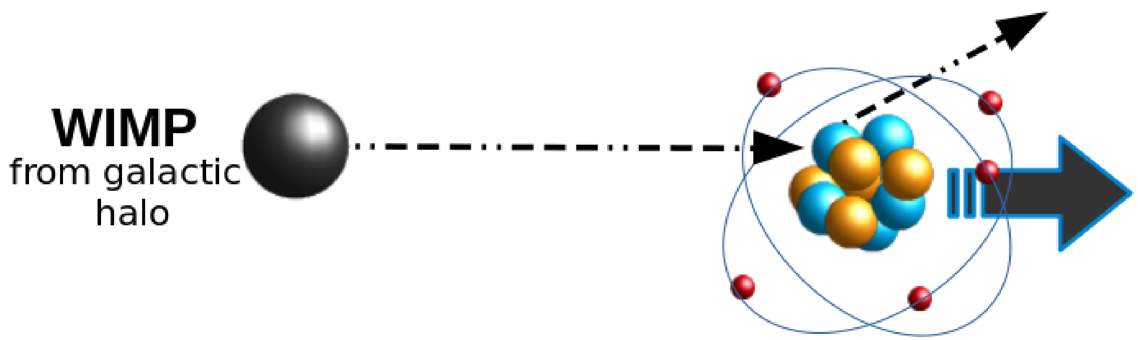
WNPPC 2020
Banff, Alberta,
February 14th

UNIVERSITY OF ALBERTA

CFI FCI

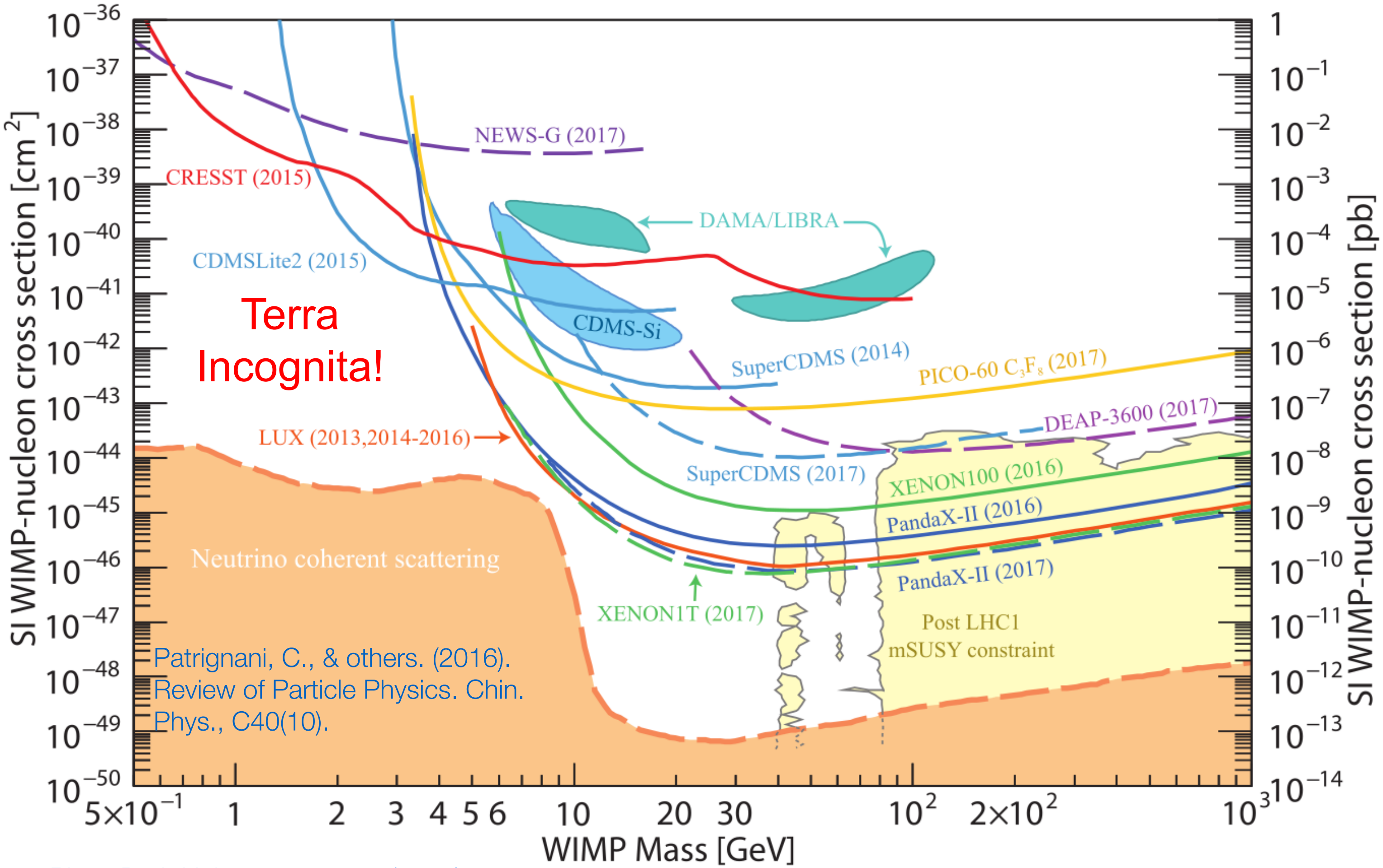


Evidence for the existence of dark matter has accumulated for almost 100 years! Particle dark matter is a leading hypothesis.



Direct detection: searching for elastic scattering of (historically) WIMP dark matter off atomic nuclei

No discovery at 'WIMP miracle' mass regime is motivation for low mass WIMP-like DM such as asymmetric DM, mirror DM, and dark sector models [1-4]

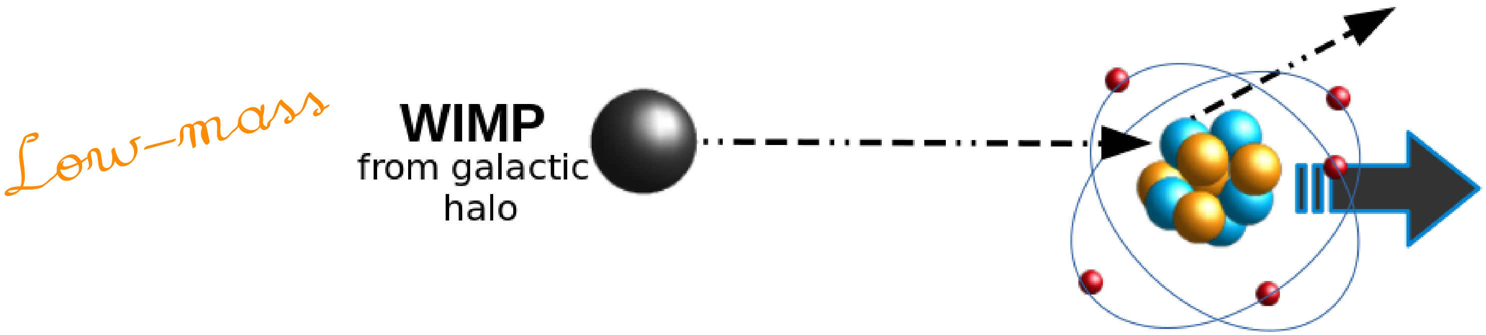


[1] D. Bauer et al, Phys. Dark Univ., 7–8, 16–23 (2015).

[2] R. Essig et al, Dark Sectors and New, Light, Weakly-Coupled Particles (2013).

[3] K. Petraki et al, Int. J. Mod. Phys. A, 28(19), 1330028 (2013).

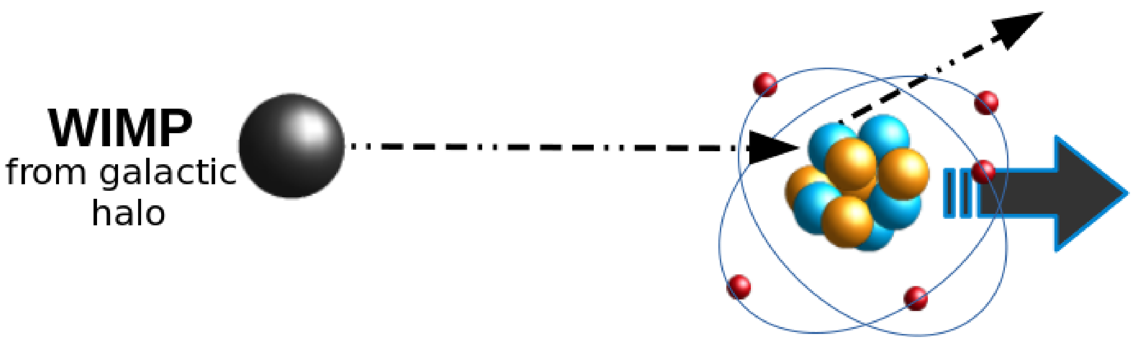
[4] K.M. Zurek, Phys. Rep., 537(3), 91 (2014).



Minuscule energies:

Recoils of $E_R \sim 1$ keV

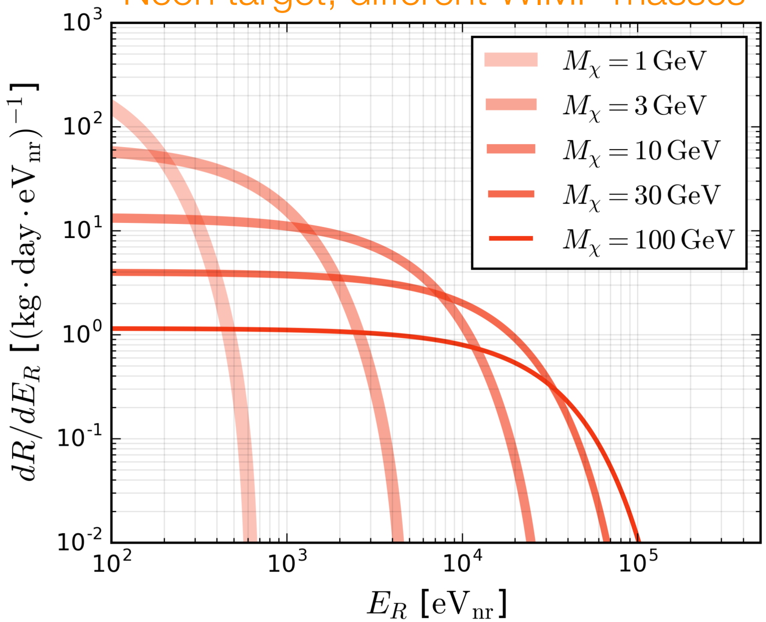
Low-mass



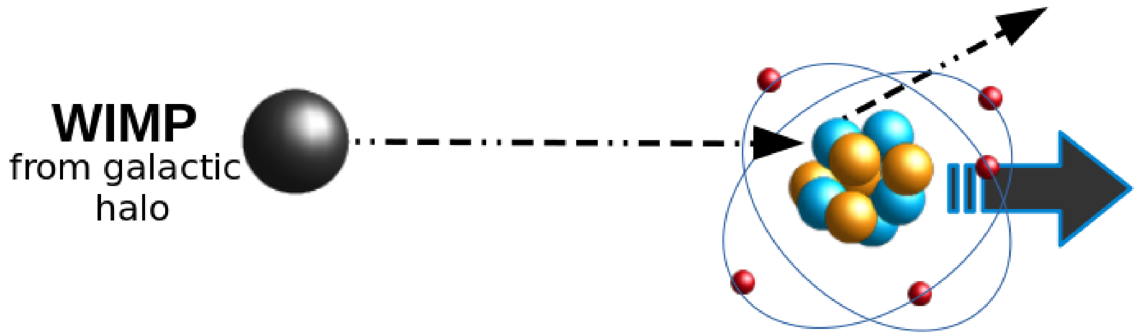
Minuscule energies: → Low energy threshold

Recoils of $E_R \sim 1$ keV

Neon target, different WIMP masses



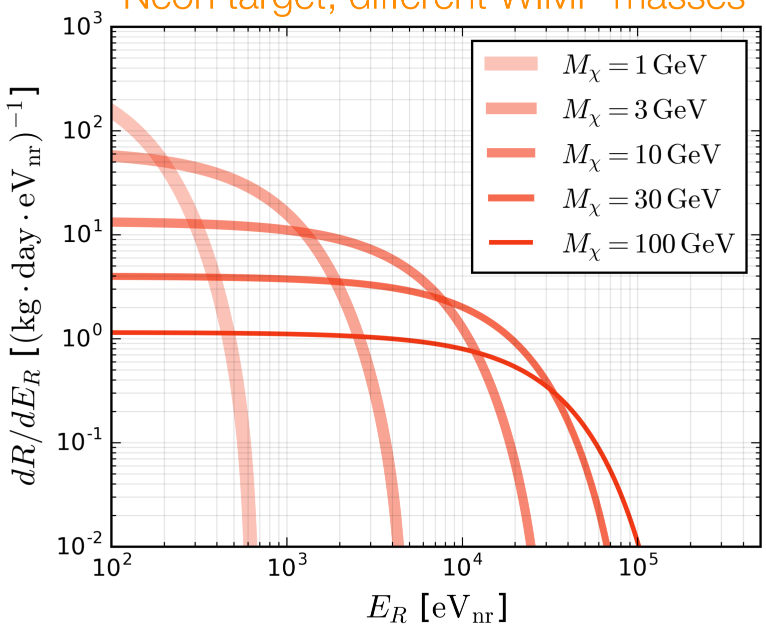
Low-mass



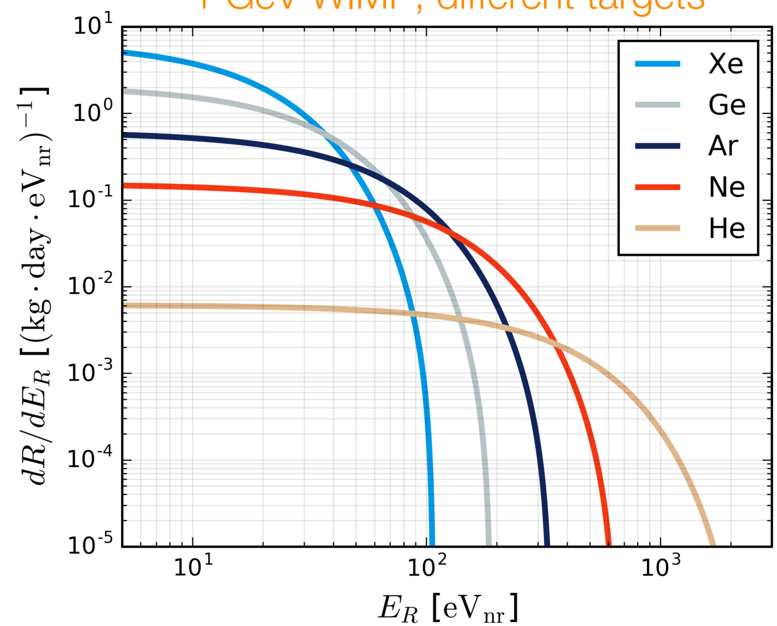
Minuscule energies: → Low energy threshold

Recoils of E_R ~ 1 keV → Low-A target atom

Neon target, different WIMP masses

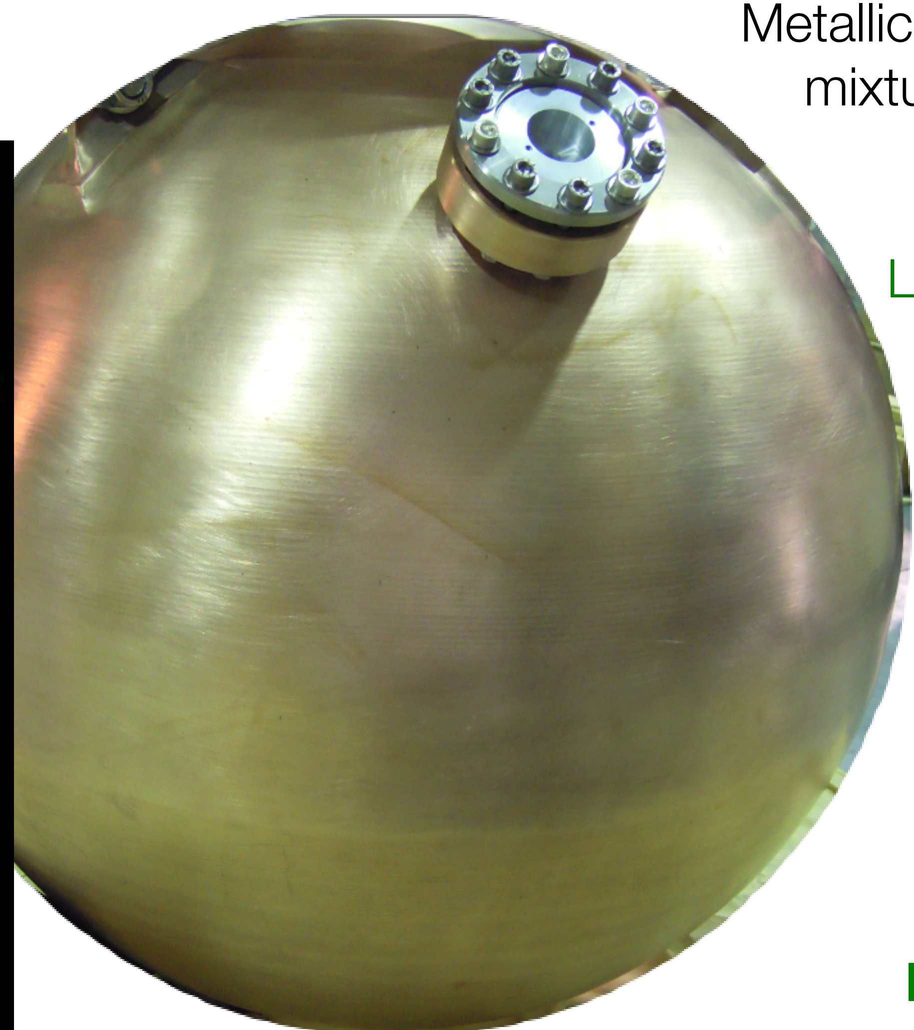


1 GeV WIMP, different targets



The NEWS-G dark matter experiment

Spherical Proportional Counters (SPCs) to search for low-mass dark matter



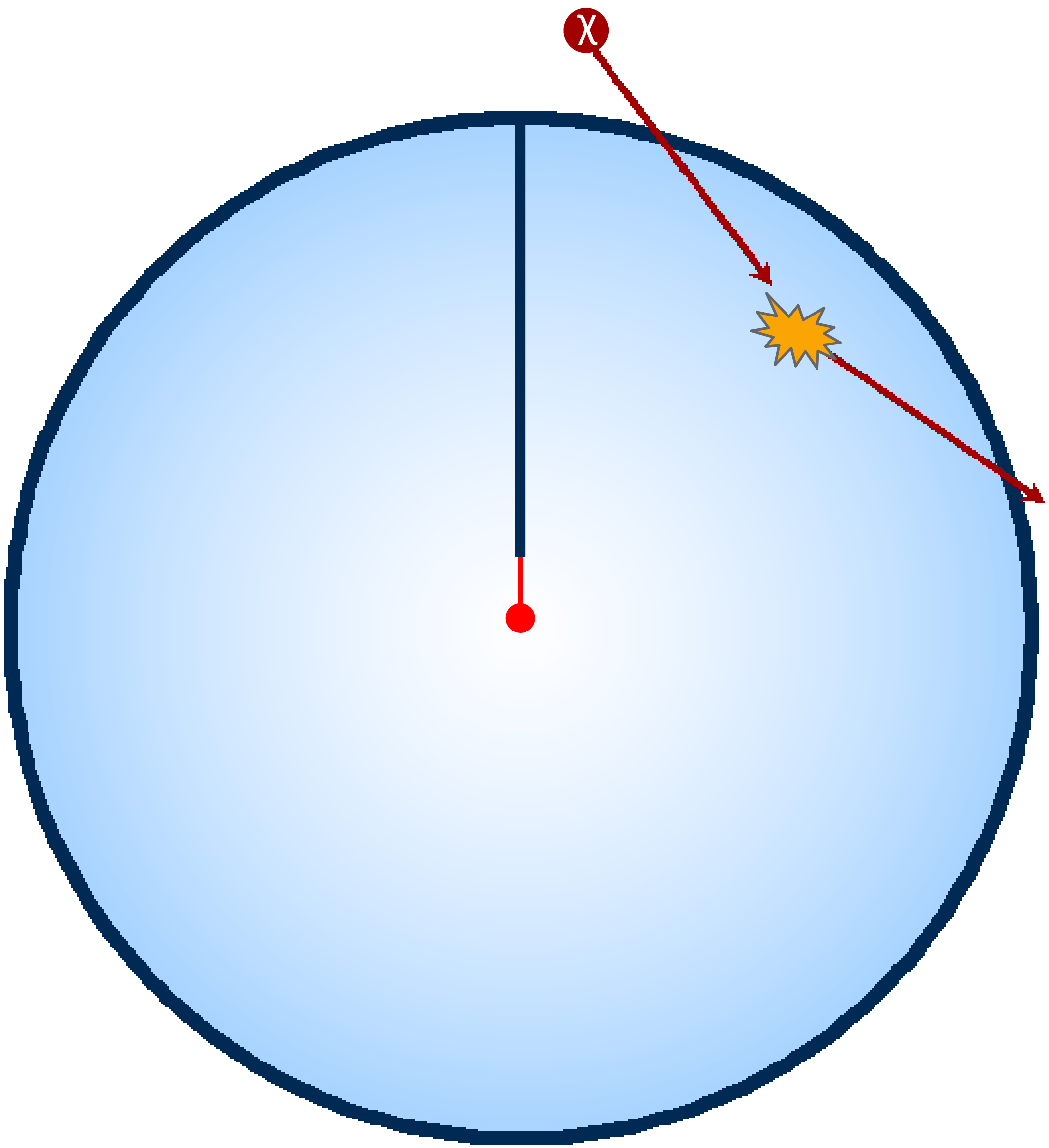
Metallic vessel filled with a noble gas mixture, with a single high voltage anode/sensor

Low-A target atoms increases sensitivity to low-mass WIMPs

Low capacitance (~0.4 pF) decreases electronic baseline noise

Townsend avalanche provides large gain

Energy threshold ~ 10 eV !

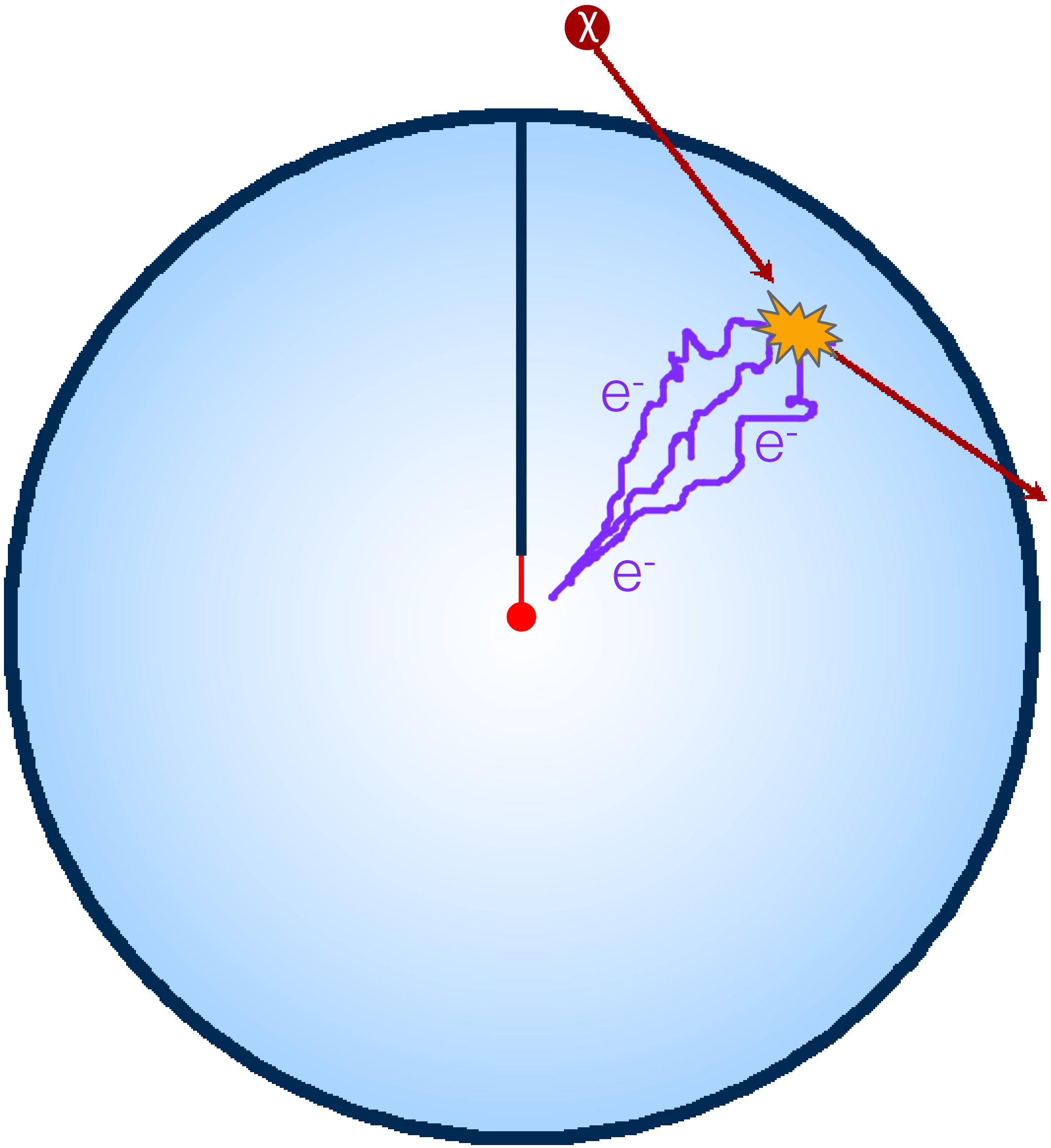


(1) Primary Ionization

$$\langle \# PE \rangle = \frac{E}{W(E)}$$

$$W_{\mathrm{nr}} = W_{\gamma}/Q(E)$$

Neon: W_γ ~ 36 eV/pair
Q ~ 0.2



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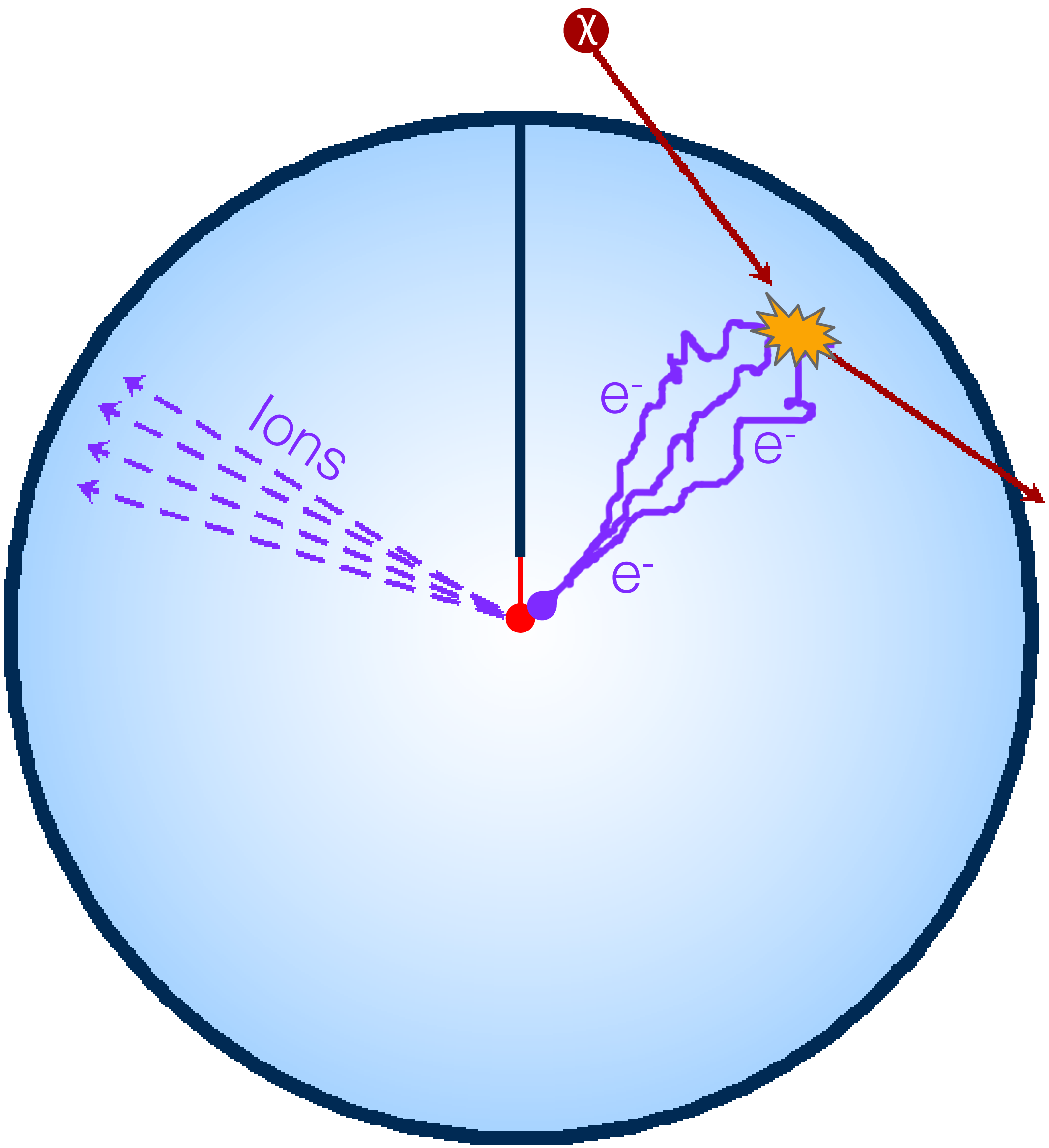
(2) Drift of charges

Radially-dependent diffusion allows for fiducialization (see Yuqi Deng's talk on Saturday!)



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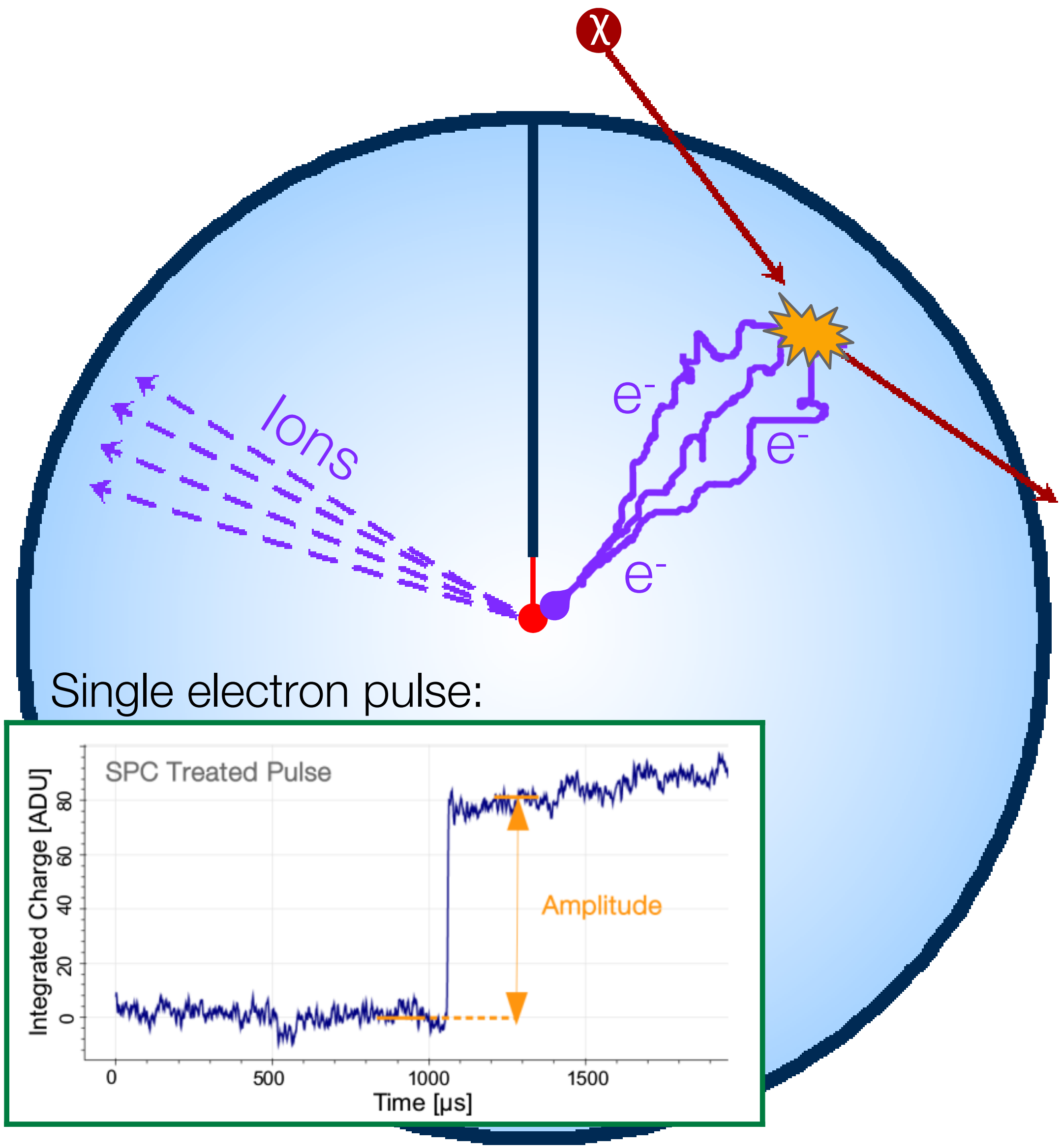
(3) Avalanche of secondary e^-/ion pairs

Amplification of signal through Townsend avalanche (tunable with V)



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Amplification of signal through Townsend avalanche (tunable with V)

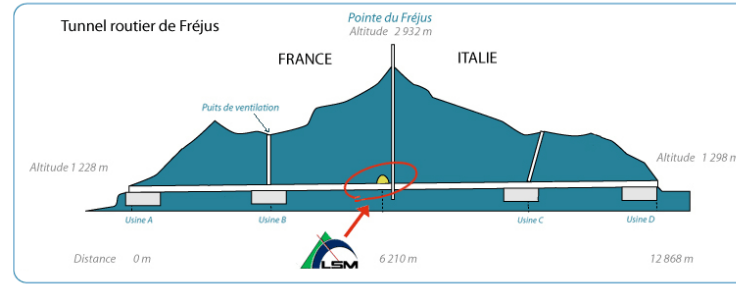
(4) Signal formation

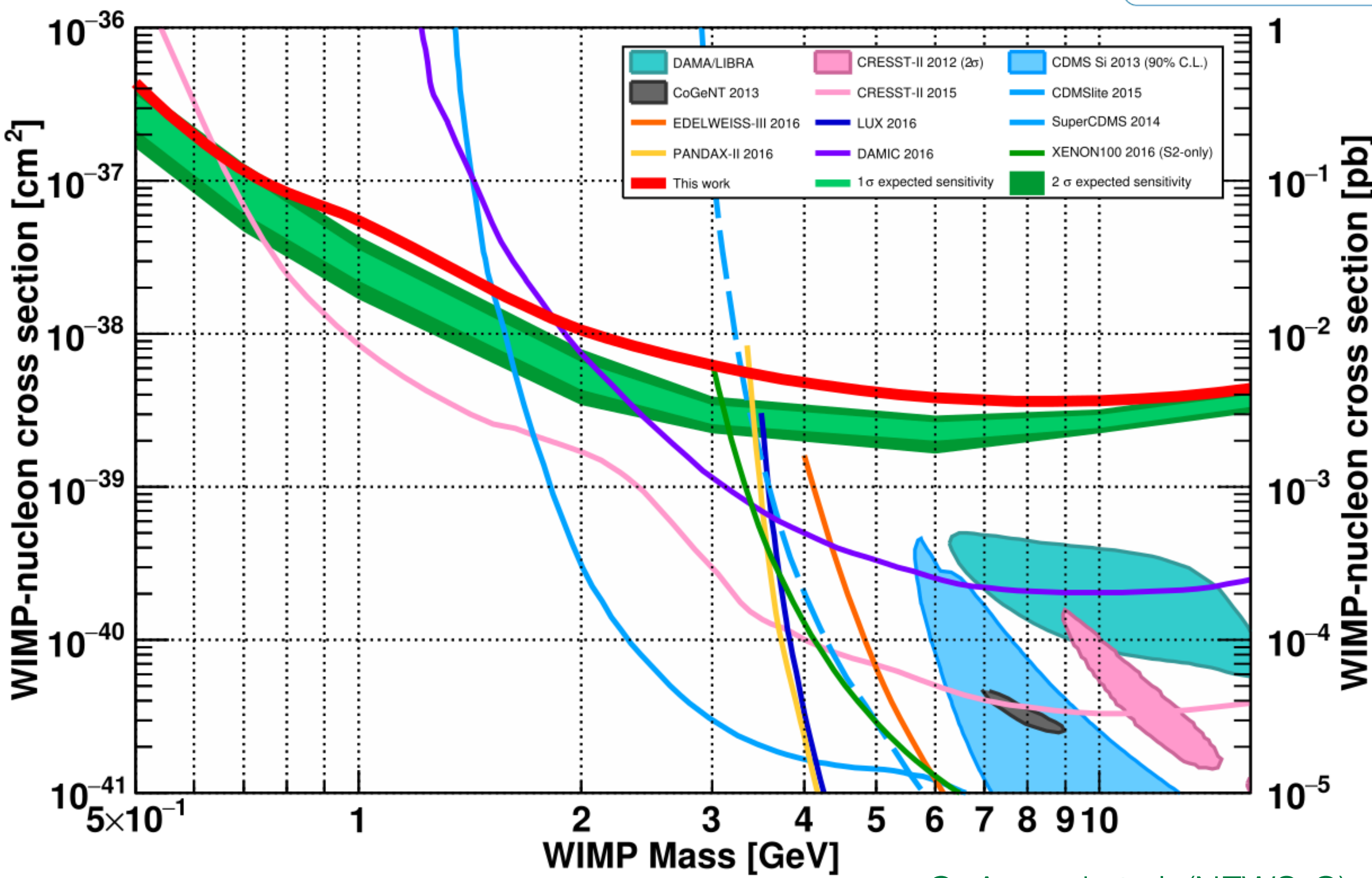
Current induced by the secondary ions drifting away from anode

(5) Signal readout

Current integrated and digitized

Competitive low-mass WIMP limit with a neon target at the Laboratoire Souterrain de Modane



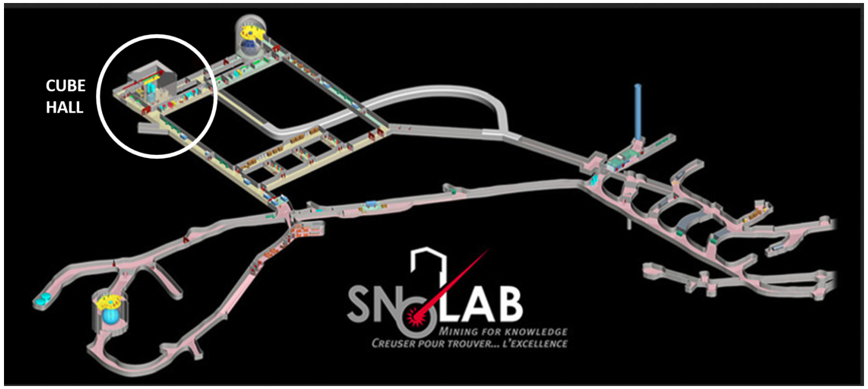


3.1 bars of Ne
+ 0.7% CH_4

42 days of data

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

VewS @ SNOLAB


CUBE
HALL
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

Next generation of NEWS-G

A 140cm ø is SPC currently being installed at SNOLAB!

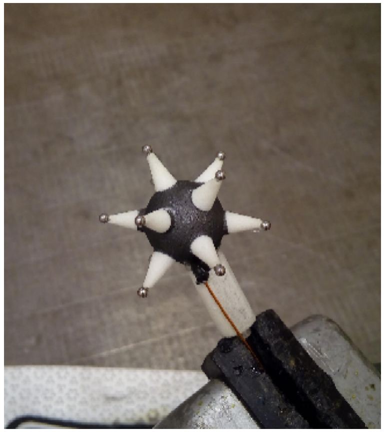
Low activity C10100 copper:

$28.5^{+8.3}_{-7.9}$ mBq/kg ^{210}Pb

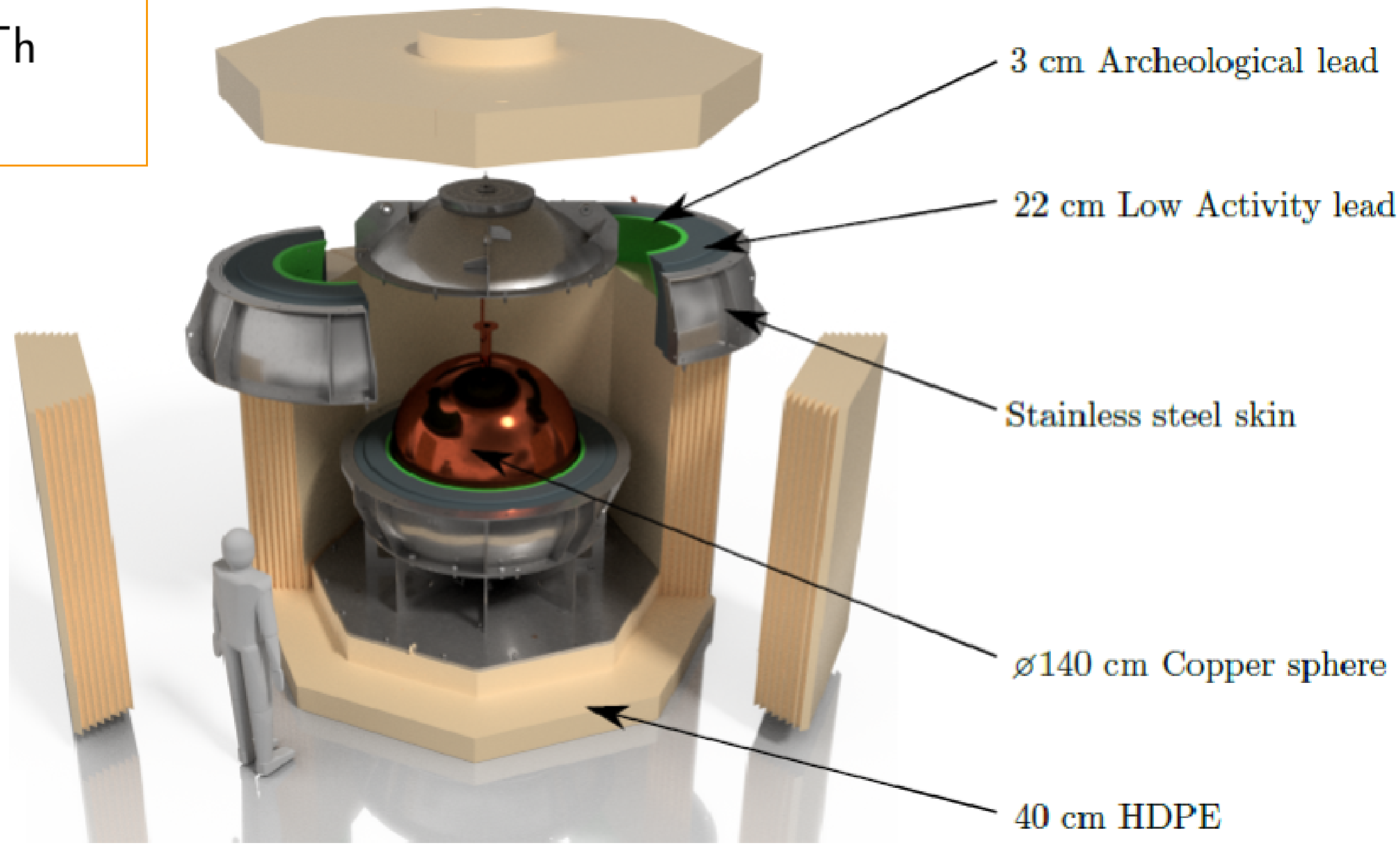
$7 - 25$ μBq/kg ^{232}Th

$1 - 5$ μBq/kg ^{238}U

Compact Lead and PE shield, flushed with N_2



Multi-electrode sensors for improved gain and isotropicity



K. Dering

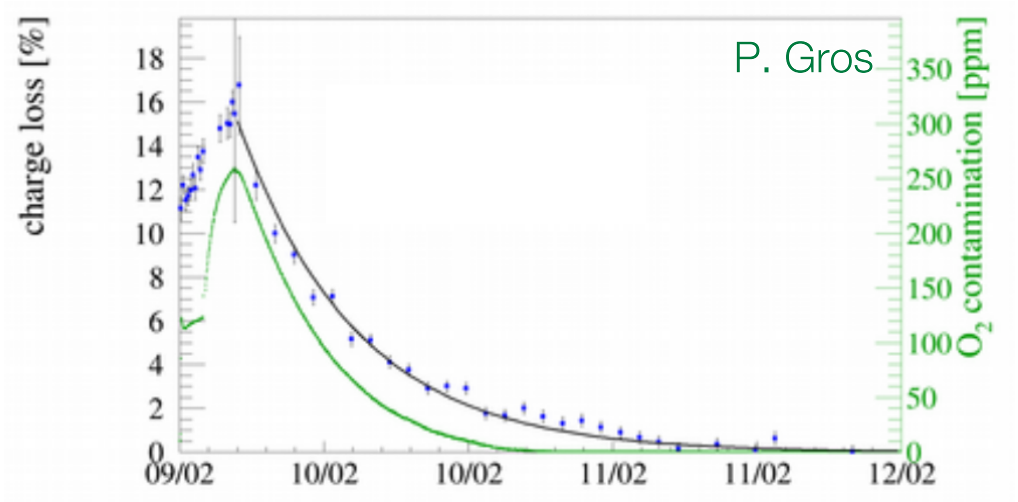
Oxygen and water contamination in the gas can dramatically reduce signal amplification

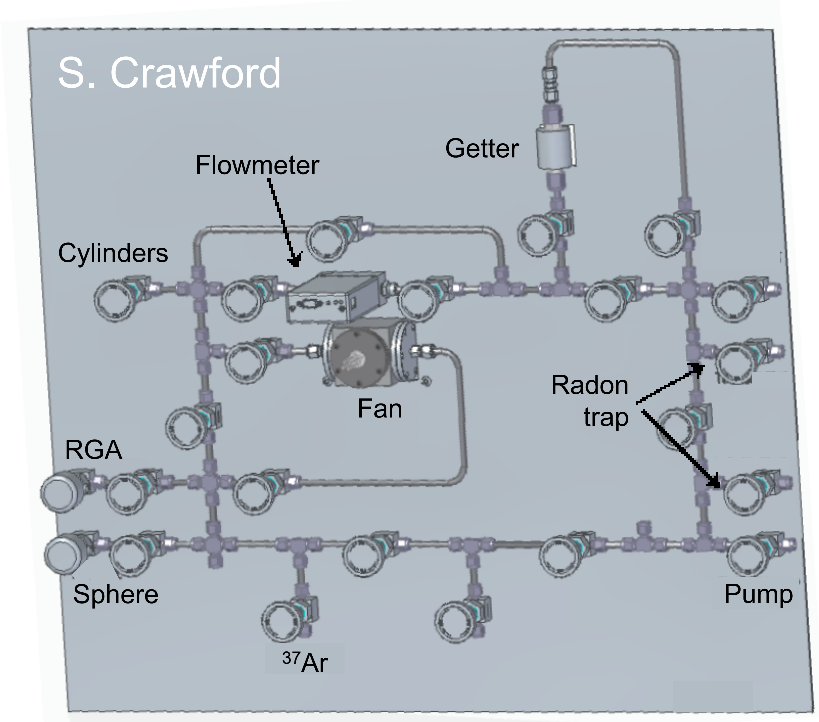
A getter filter and circulation system will be used to remove these contaminants

This will allow for long-term operation of the detector
(> 1 month)

Radon removal and gas composition analysis techniques are also being developed...

See Patrick O'Brien's talk later today!





Next generation of NEWS-G

Commissioning data was taken at the:

LSM
Laboratoire Souterrain de Modane

A water tank was used instead of the PE shield

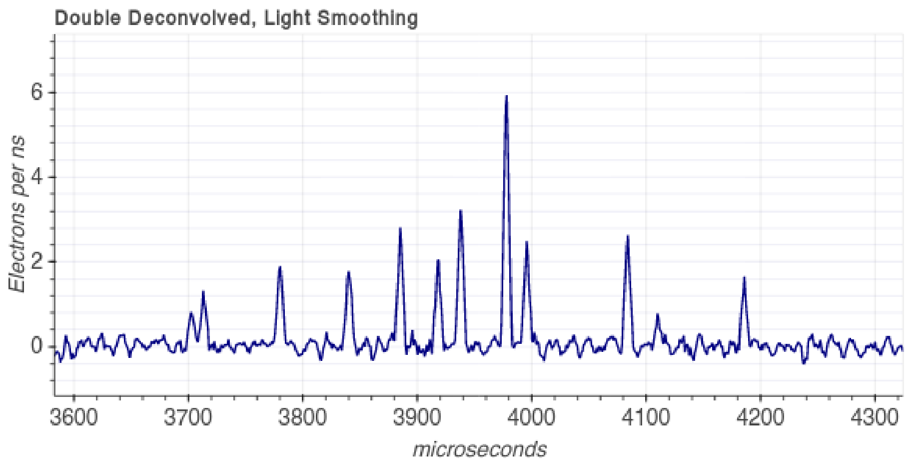
First test of sensor deployment system, electronics

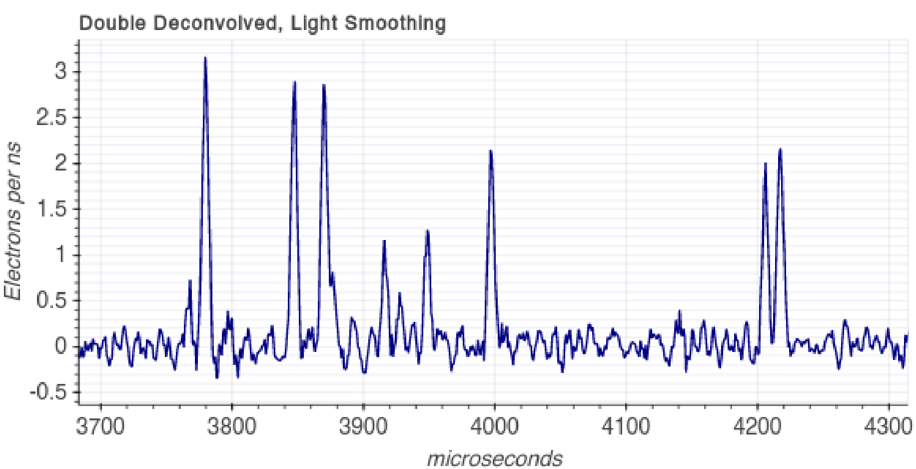
Data taken with Neon and pure CH_4

See Jean-Marie Coquillat's talk Saturday

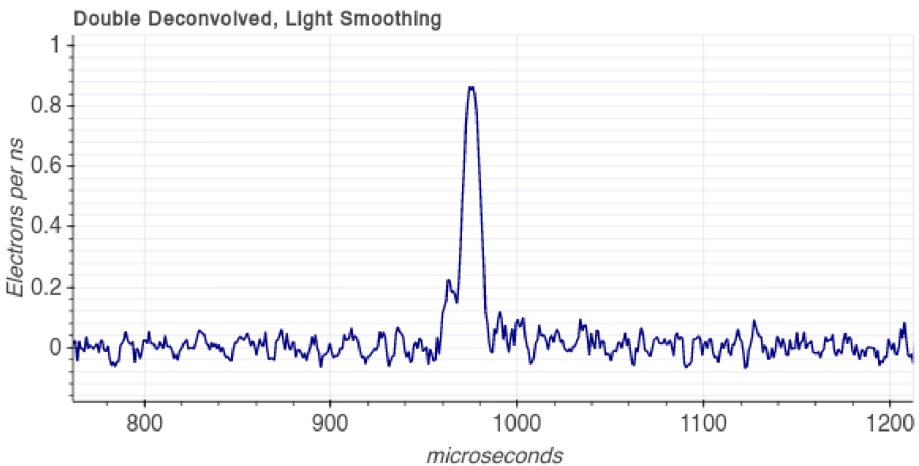
The much larger drift volume allows us to resolve individual electrons in time!

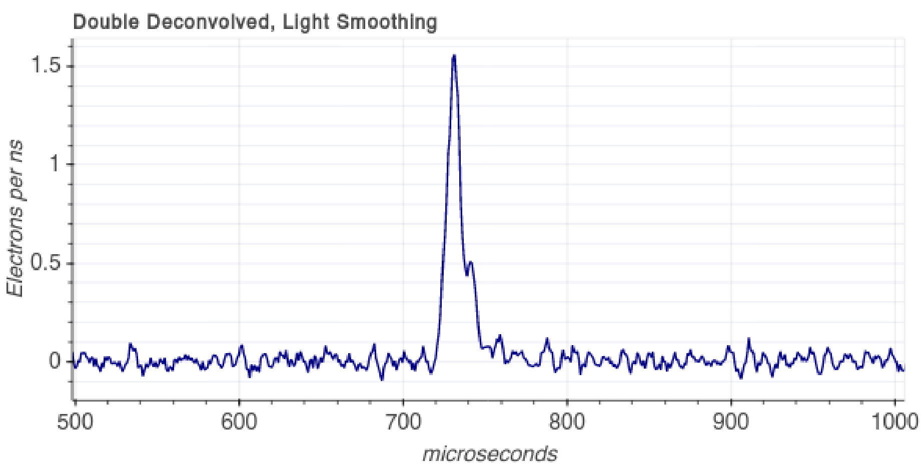
UV Laser events from new 140cm SPC:



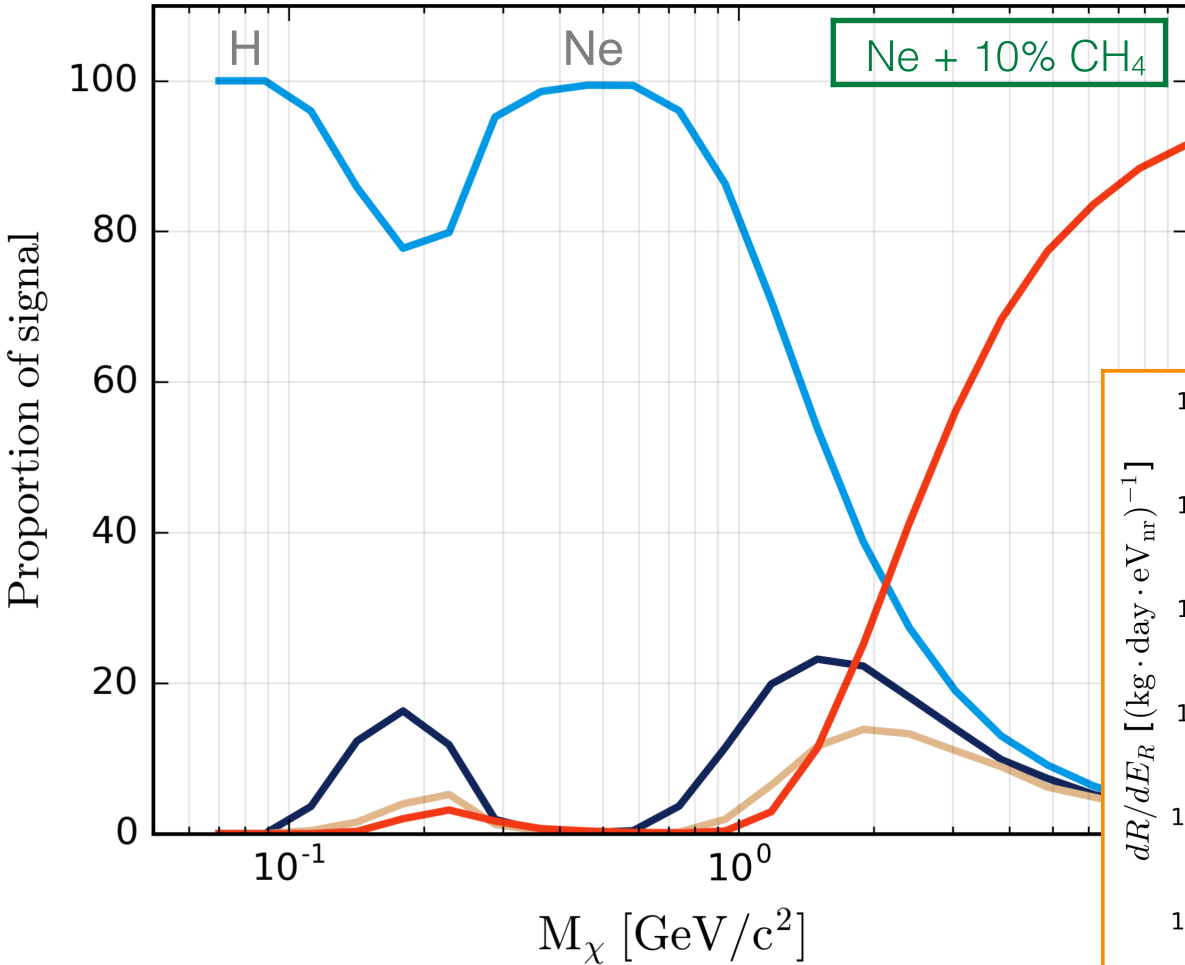


^{37}Ar events from 30cm prototype SPC:

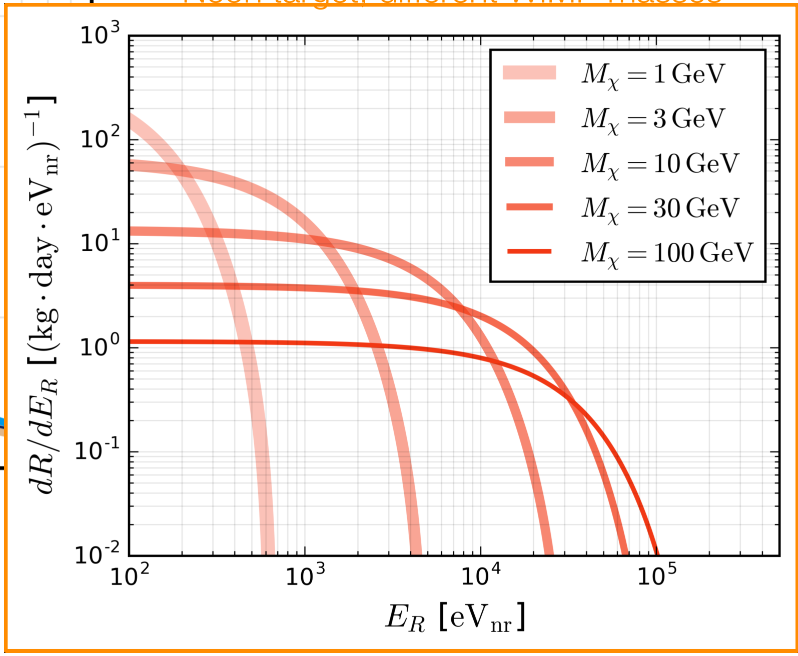




Because the WIMP recoil spectrum is roughly exponential, most sensitivity low DM masses comes from single quanta (1e-) events. Therefore we need to accurately characterize our energy response at this regime.



Neon target, different WIMP masses

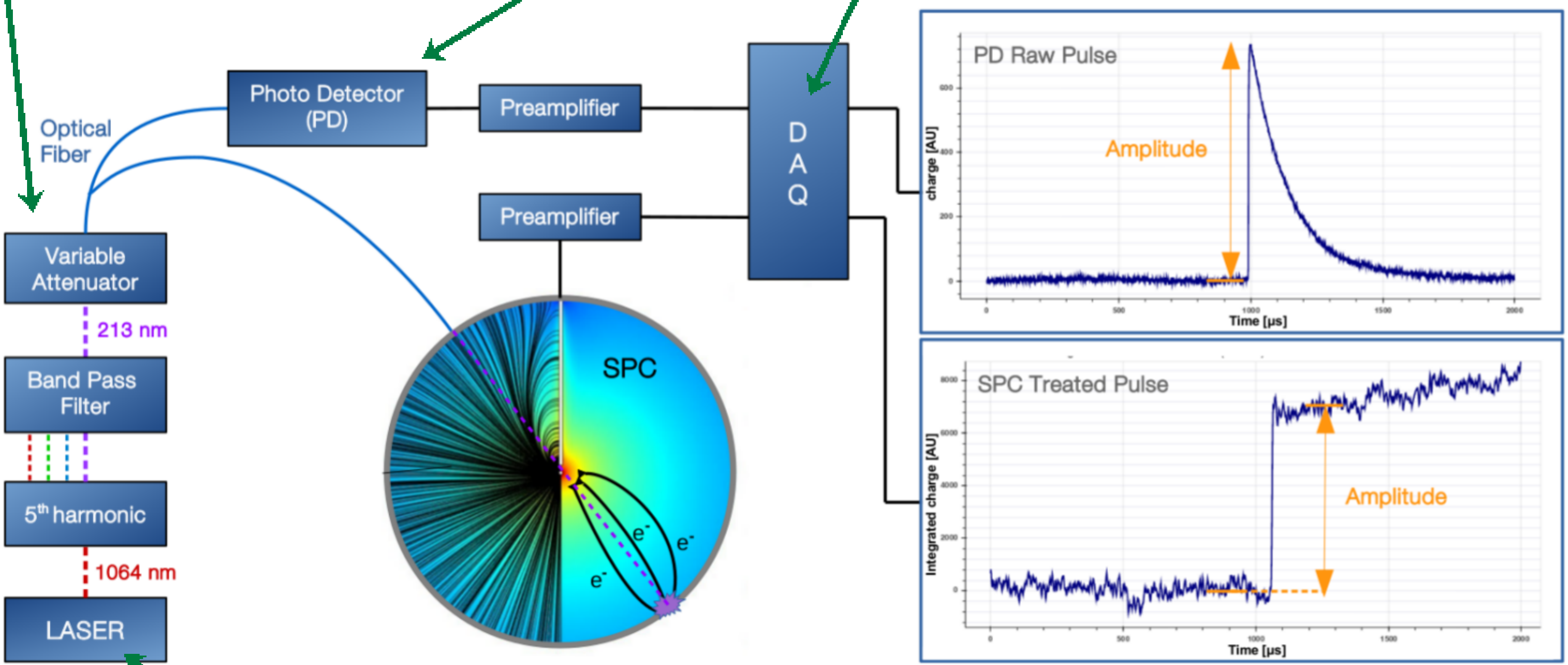


Q. Arnaud et al. (NEWS-G Collaboration), Phys. Rev. D 99, 102003 (2019)

Tunable transmission to control the mean number of electrons

Parallel photo-detector to tag laser events

Common DAQ for timing analysis between two channels

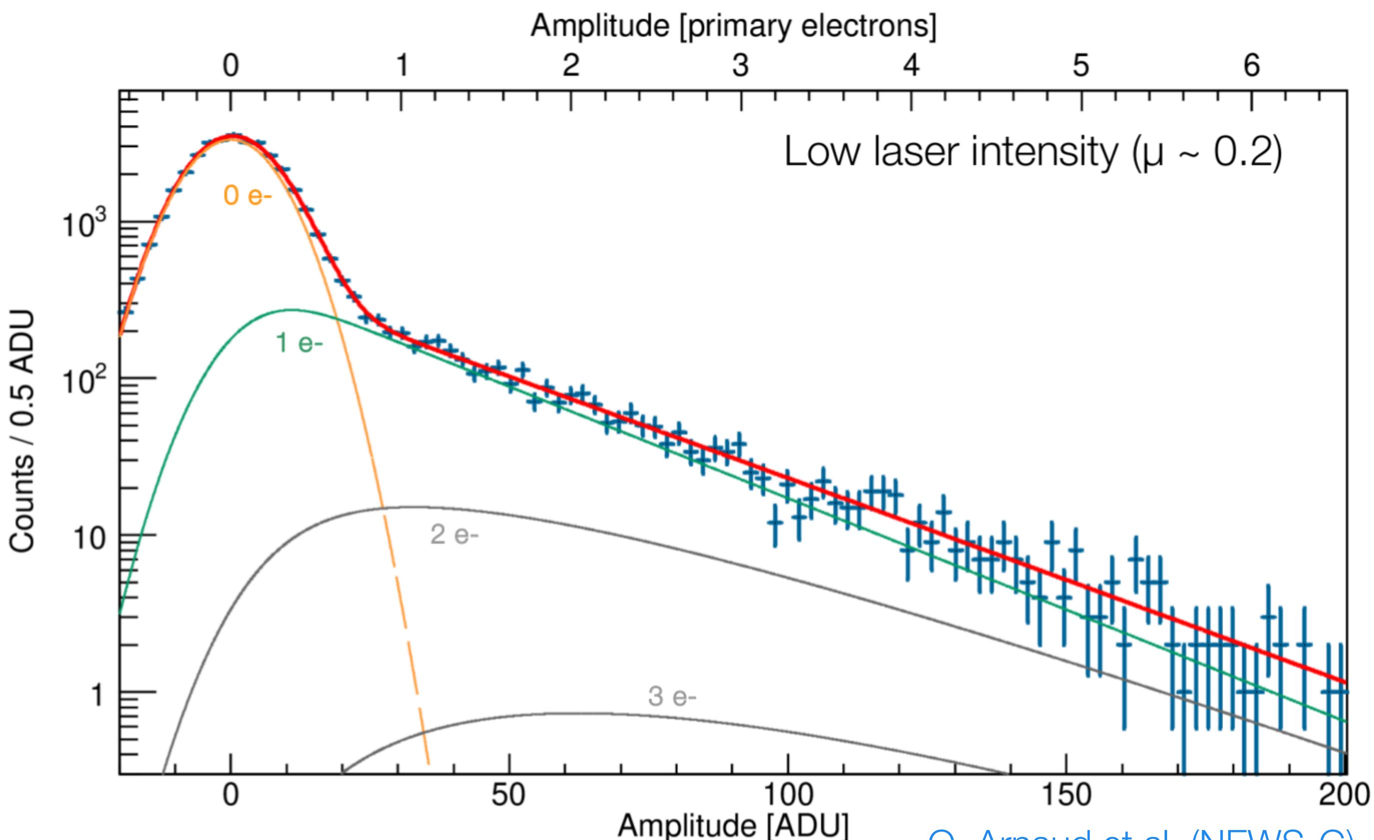


A powerful UV laser capable of extracting 100s of electrons

The excellent fit validates the avalanche response model [5]:

$$\mathcal{F}\left(E'\right) = P_{\text{Poisson}}\left(0|\mu\right) + \sum_{n=1}^{\infty} P_{\text{Polya}}^{(n)}\left(E'|\theta\left\langle G\right\rangle\right) \times P_{\text{Poisson}}\left(n|\mu\right)$$

(This is then convolved with a Gaussian to incorporate baseline noise)



Data Parameters:

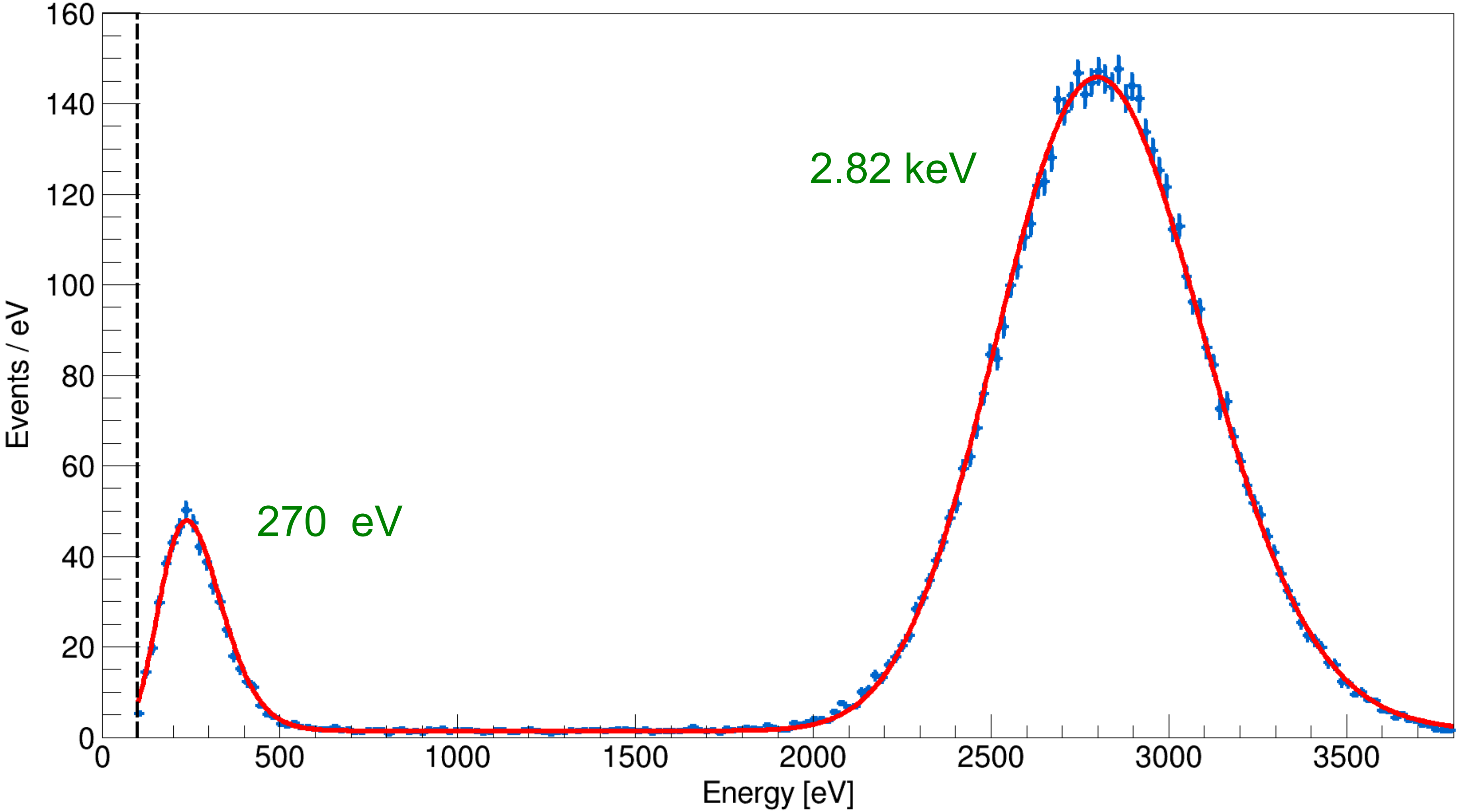
Ne + 2% CH4
P = 1.5 bar
HV = 1200 V

Fit results:

θ = 0.09 ±0.02
<G> = 30.26 ± 0.21 ADU
χ^2/ndf = 0.97

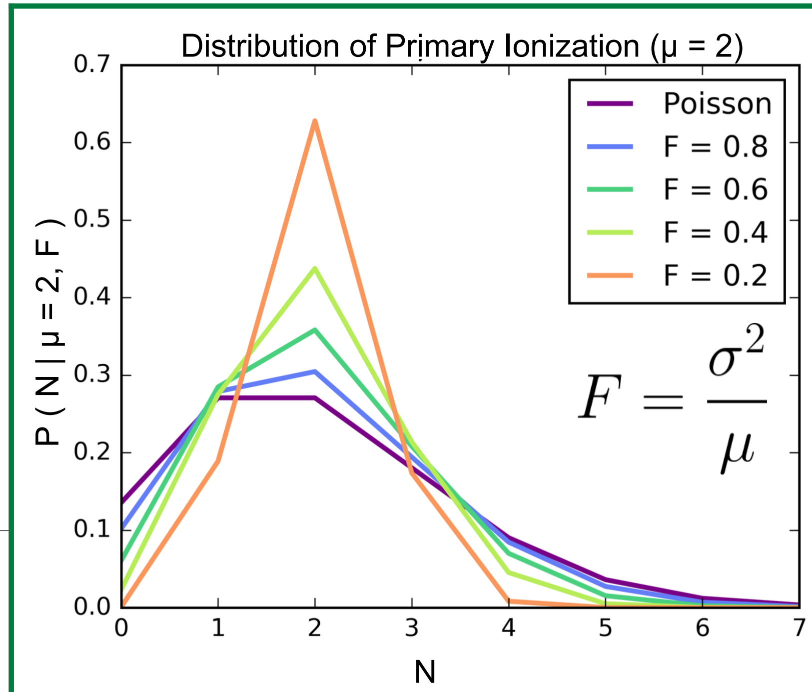
Q. Arnaud et al. (NEWS-G), Phys. Rev. D 99, 102003 (2019)

^{37}Ar is a gaseous calibration source:
- Two low-energy calibration points
- Allows us to calibrate the detector response to volume events

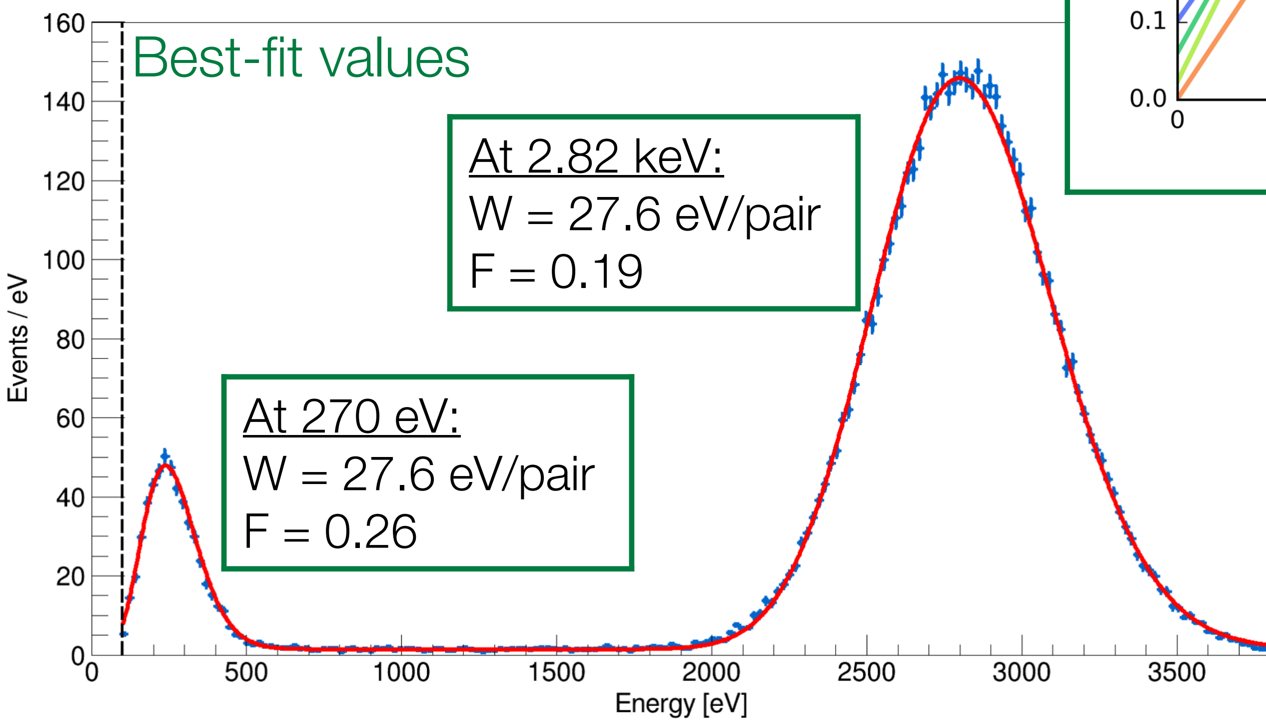


A test of our model for primary ionization -
D. Durnford et al, Phys. Rev. D 98, 103013 (2018)

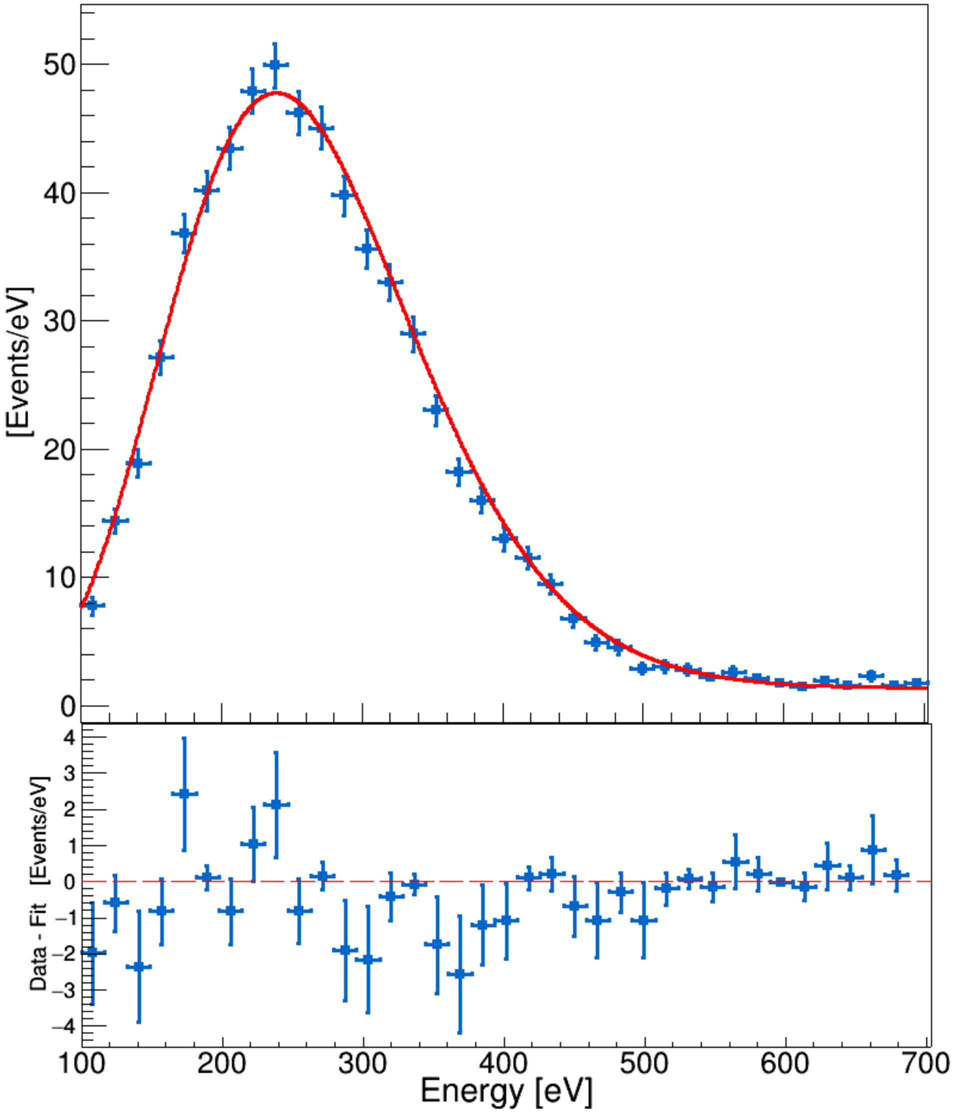
$$f\left(E'\right) = \sum_{N=1}^{N_{\rm max}} P_{\rm CMP}\left(N|\mu, F\right) \times P_{\rm Polya}^{(\rm N)}\left(E'|\left\langle G\right\rangle, \theta\right)$$

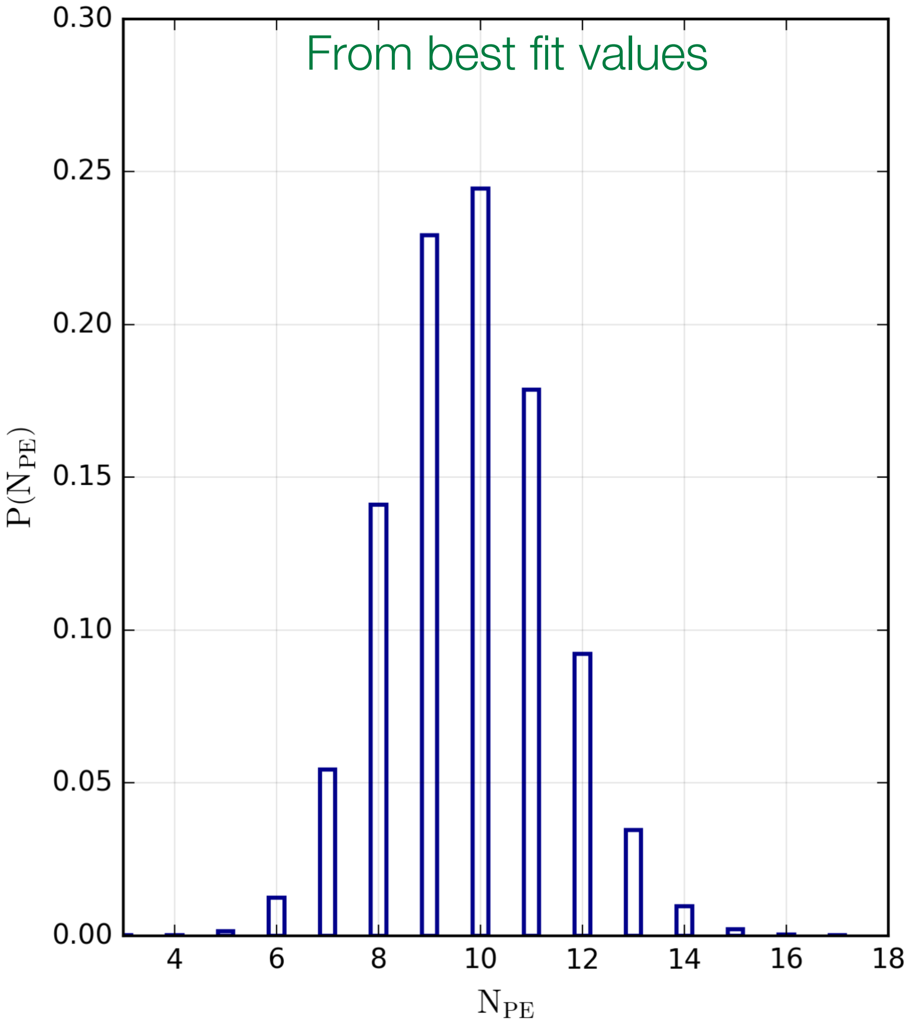


Also allowed for measurements of the W-value, Fano factor of this gas mixture at different energies:



In particular, the fit of the L-shell gives empirical support for COM-Poisson





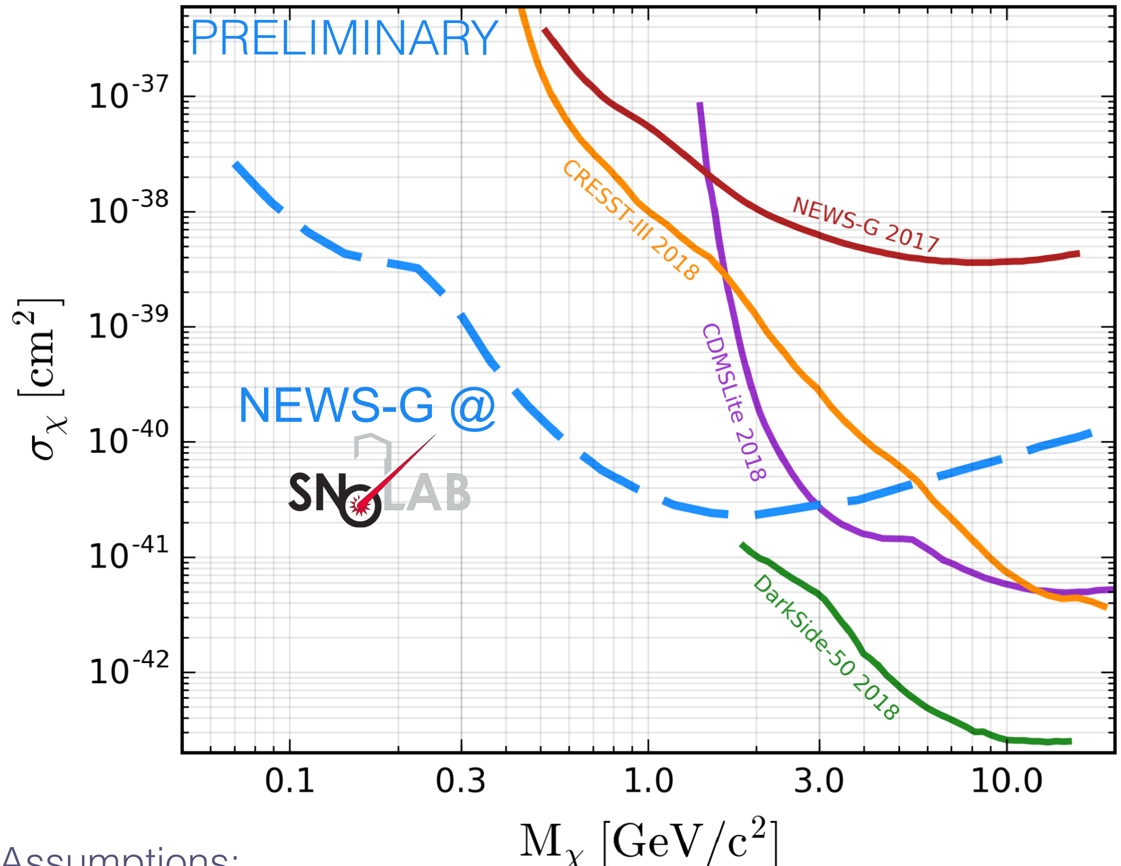
$\lambda = 1.03\text{x}10^4$
$\nu = 3.99$

→

$\mu = 9.79$
$F = 0.261$

NEWS-G is expected to be sensitive to WIMP masses ~100 MeV using H-rich gas and an energy threshold < 50 eV_{nr}

Installation is in progress, with first data expected in summer 2020!




Currently being installed in SNOLAB

Assumptions:

Ne + 10% CH_4, Exposure: 20 kg days, F = 0.2, θ = 0.12,
SRIM quenching factor, Background: 1.78 dru, ROI: 14 eV_{ee} - 1 keV_{ee}
Optimum Interval Method

Thank you!

Queen's University Kingston - G Gerbier, G Giroux, P di Stefano, R Martin, S Crawford, M Vidal, G Savvidis, A Brossard, F Vazquez de Sola, K Dering, G Nunzi, J McDonald, M Van Ness, M Chapellier, P Gros, JM Coquillat, JF Caron, L Balogh
- Copper vessel and gas set-up specifications, calibration, project management
- Gas characterization, laser calibration on smaller scale prototypes
- Simulations/Data analysis

IRFU (Institut de Recherches sur les Lois fondamentales de l'Univers)/**CEA Saclay - I Giomataris**, M Gros, JP Mols
- Sensor/rod (low activity, optimization with 2 electrodes)
- Electronics (low noise preamps, digitization, stream mode)
- DAQ/soft

Aristotle University of Thessaloníki - I Savvidis, A Leisos, S Tzamarias
- Simulations, neutron calibration
- Studies on sensor

LPSC/LSM Laboratoire de Physique Subatomique et Cosmologie, Laboratoire Souterrain de Modane) **Grenoble** - D Santos, M Zampaolo, A DastgheibiFard JF Muraz, O Guillaudin
- Quenching factor measurements at low energy with ion beams
- Low activity archaeological lead
- Coordination for lead/PE shielding and copper sphere

Pacific Northwest National Laboratory - E Hoppe, R Bunker
- Low activity measurements, copper electro-forming

RMCC Kingston - D Kelly, E Corcoran, L Kwon
- ^{37}Ar source production, sample analysis

SNOLAB Sudbury - P Gorel, S Langrock
- Calibration system/slow control

University of Birmingham - K Nikolopoulos, P Knights, I Katsioulas, R Ward
- Simulations, analysis, R&D

University of Alberta - MC Piro, D Durnford, Y Deng, P O'Brien
- Gas purification, data analysis

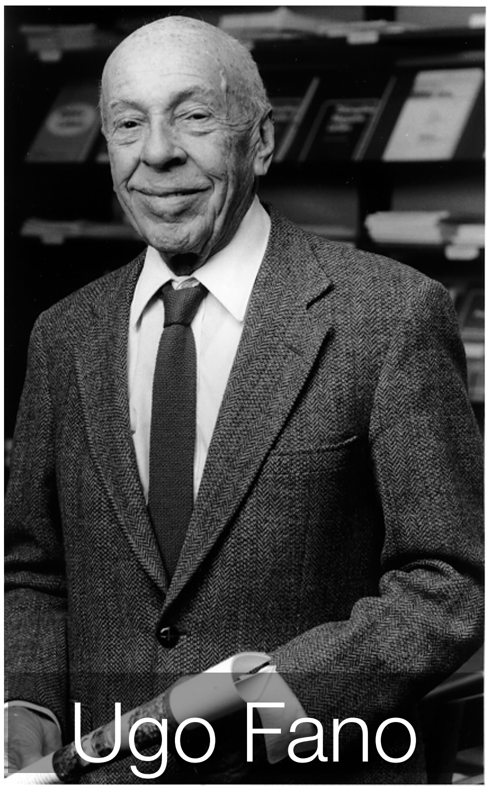
Associated labs: TRIUMF - F Retiere

The NEWS-G Collaboration
(November 2019)

Extra Slides

The statistics of primary ionization

$$F = \frac{\sigma^2}{\mu}$$



Measurements of F in different substances have been made:

$$F \lesssim 0.2$$

A. Hashiba et al., NIM A 227(2), 305–310 (1984).

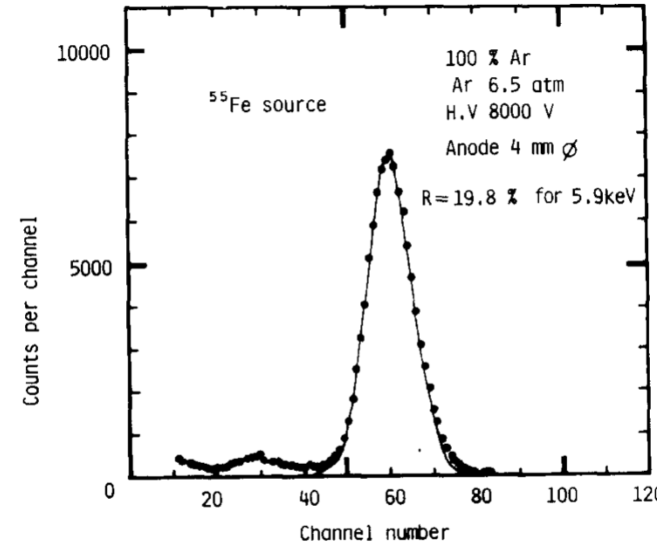


Fig 3 A typical pulse height spectrum of proportional scintillation produced by X-rays from a ^{55}Fe source in argon

Medium	F
Si	0.155 ± 0.002 (3 keV e^-)
	0.134 ± 0.003 (F-Kα)
Ar	0.23 ± 0.05 (^{55}Fe)
	0.20 ± 0.02 (5.3 MeV α)
Ar+0.8% CH4	0.19 (5.68 MeV α)
Xe (gas)	0.170 ± 0.007 (soft x-rays)
Xe (liquid)	0.033 ± 0.045
Ge	0.121 ± 0.001 (Al-Kα)

Calculations based on electron scattering cross sections confirm that at high energy F approaches an asymptotic limit

At low energies, F is expected to tend to 1

B. Grosswendt, J. Phys. B 17(7), 1391–1404 (1984).

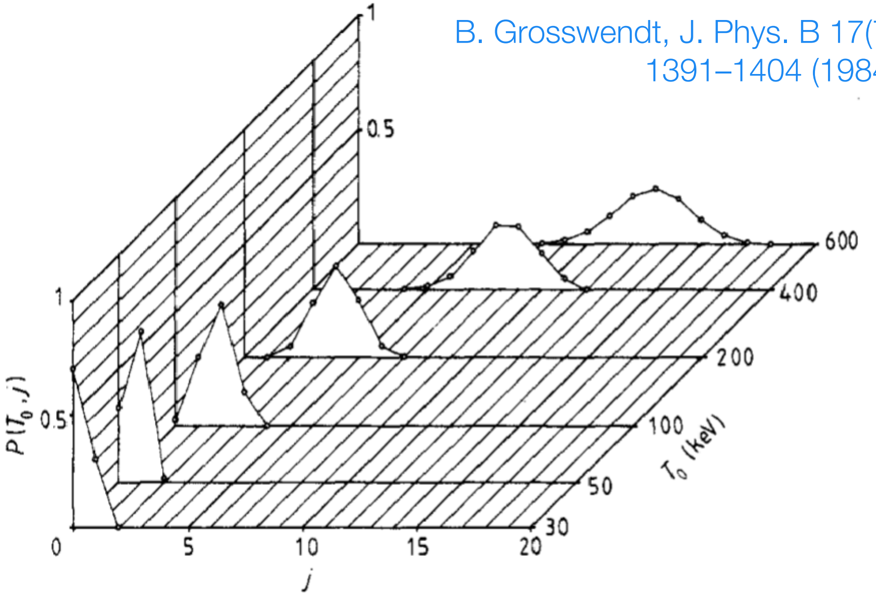


Figure 4. Three-dimensional plot of the probability $P(T_0, j)$ that exact-j ionisations are produced upon the complete slowing down of electrons of initial energy T_0 in He.

B. Grosswendt and E. Waibel, Radiation Protection Dosimetry 13(1–4), 95–102 (1985).

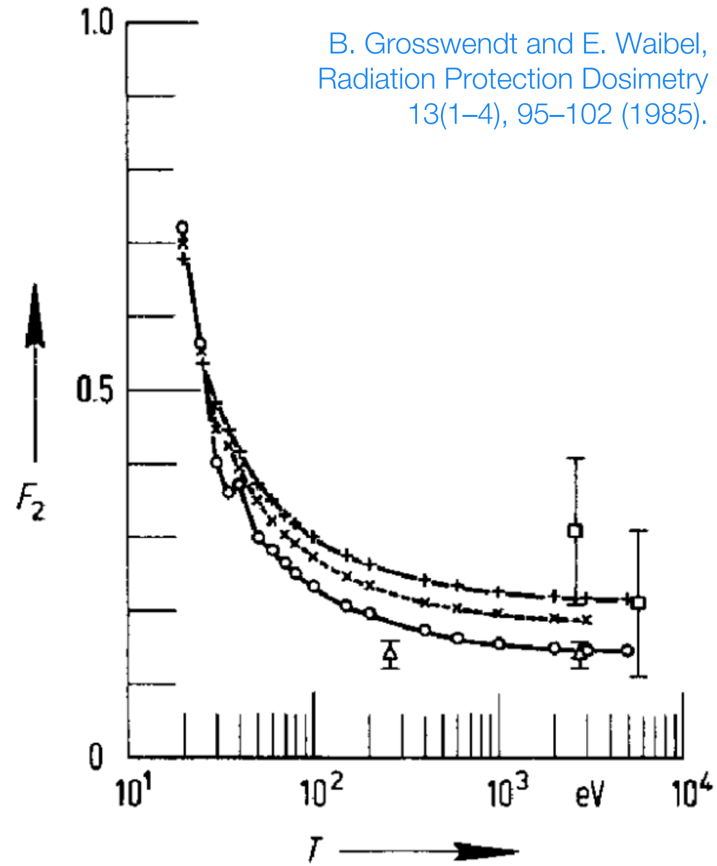
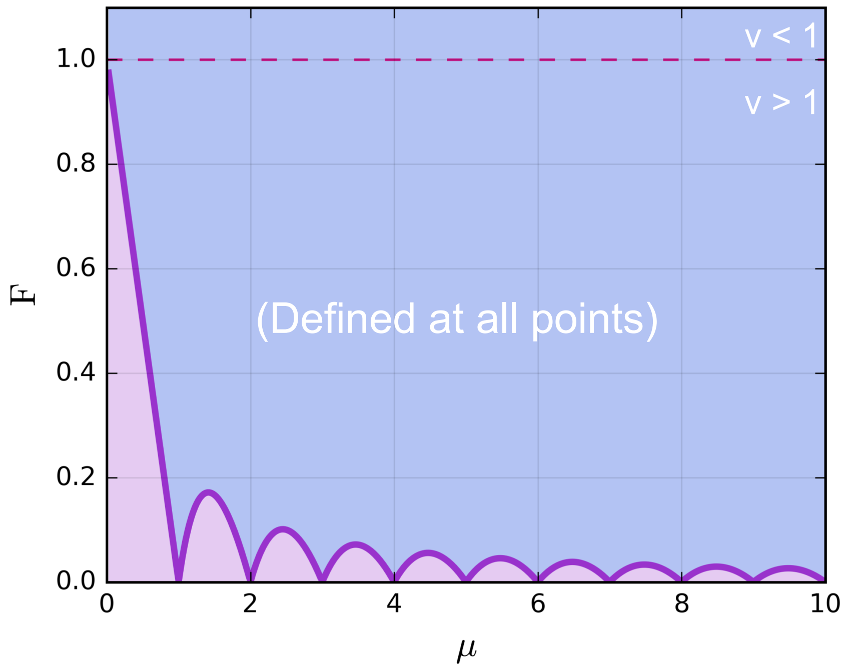


Figure 5. Dependence of Fano factor F_2 for electrons completely stopped in methane (+——+), argon[(12)] (○——○) and a gas mixture of 50% methane and 50% argon (×---×) on the electron energy T compared with experimental results for a gas mixture of 90% argon and 10% methane of Hurst *et al*[(13)] for 2.6 keV and 5.9 keV X rays (□) and of Neumann[(14)] for 0.26 keV and 2.82 keV electrons (△).

The COnway Maxwell - Poisson (COM-Poisson) distribution:

$$P(x|\lambda,\nu) = \frac{\lambda^x}{(x!)^\nu Z(\lambda,\nu)}$$

$$Z(\lambda,\nu) = \sum_{j=0}^{\infty} \frac{\lambda^j}{(j!)^\nu} \quad \lambda \in \{\mathbb{R} > 0\}, \quad \nu \in \{\mathbb{R} \geq 0\}$$



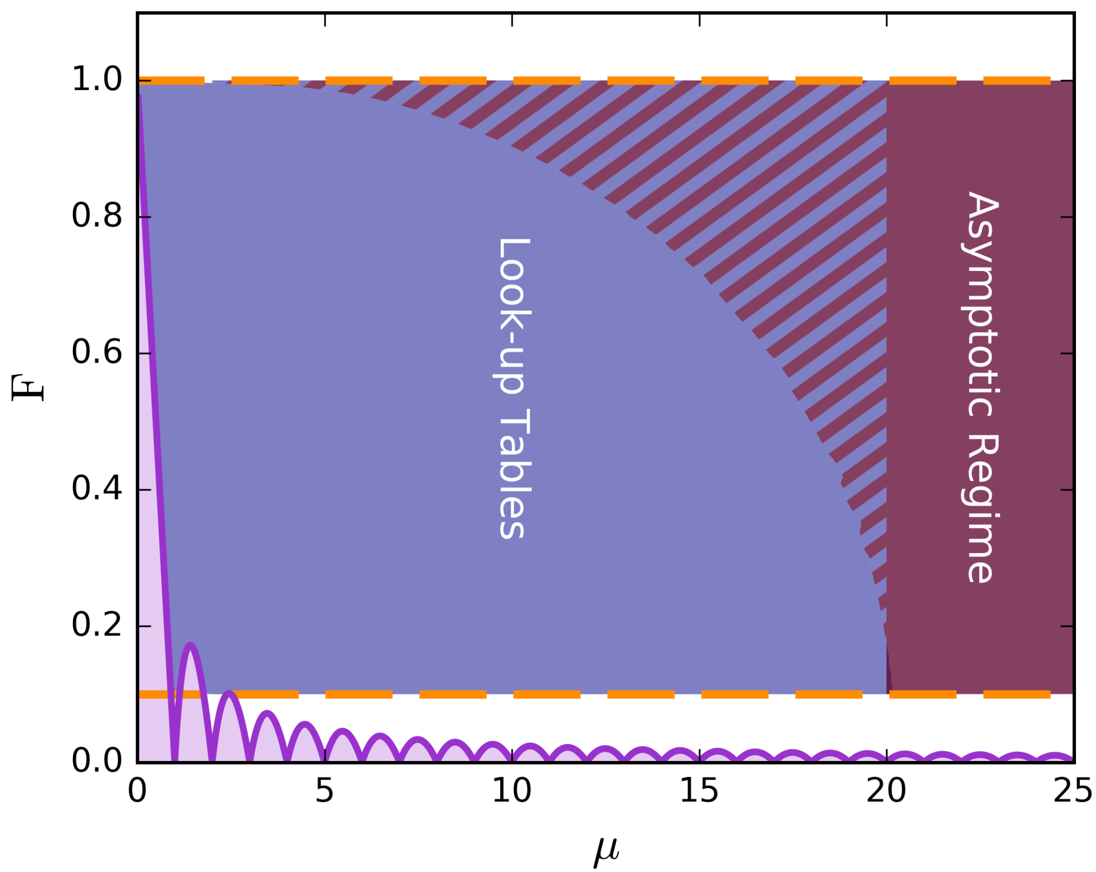
It is defined at every point in μ/F space (including over-dispersion)

Mean and variance given by:

$$\mu(\lambda,\nu) = \sum_{j=0}^{\infty} \frac{j\lambda^j}{(j!)^\nu Z(\lambda,\nu)} \quad \sigma^2(\lambda,\nu) = \sum_{j=0}^{\infty} \frac{j^2\lambda^j}{(j!)^\nu Z(\lambda,\nu)} - \mu(\lambda,\nu)^2$$

Higher moments calculated with:

$$E\left(X^{n+1}\right) = \lambda \frac{\partial}{\partial\lambda} E(X^n) + E(X)E(X^n), \quad \text{for } n \geq 1$$



D. Durnford, Q. Arnaud, and G. Gerbier
Phys. Rev. D 98, 103013 (2018)

At high μ/F, there are asymptotic expressions that can be used to solve for the distribution parameters [36]

Accurate to ≤ 0.01% in μ and F

At low μ/F, a 2D optimization algorithm is used to find the correct values of λ and ν

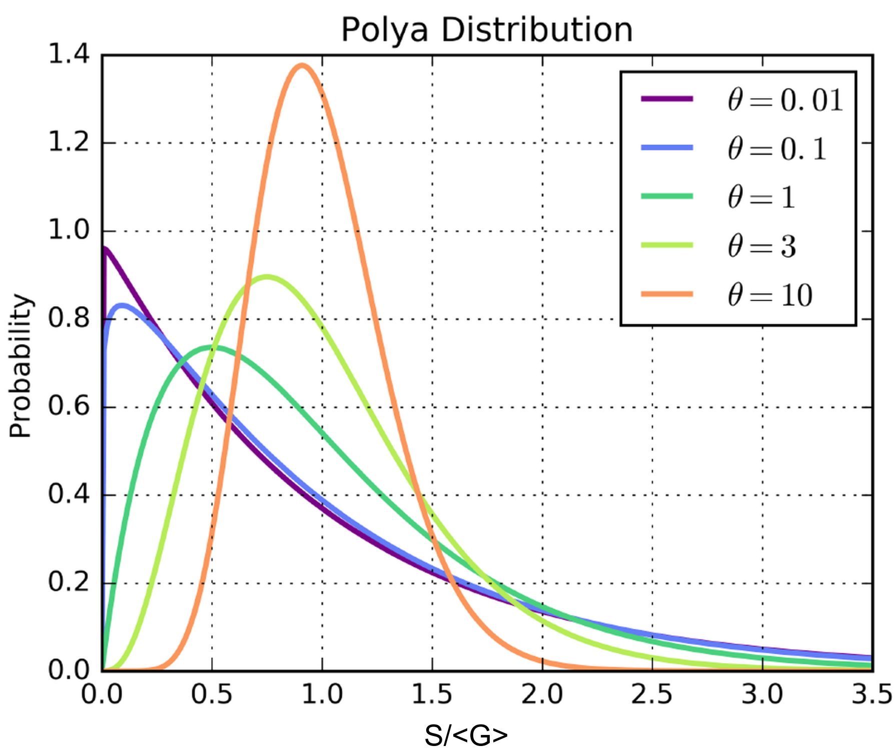
Results are stored in look-up tables for quick interpolation, accurate to ≤ 0.1%

Tables and code to use them available at: https://news-g.org/com-poisson-code/

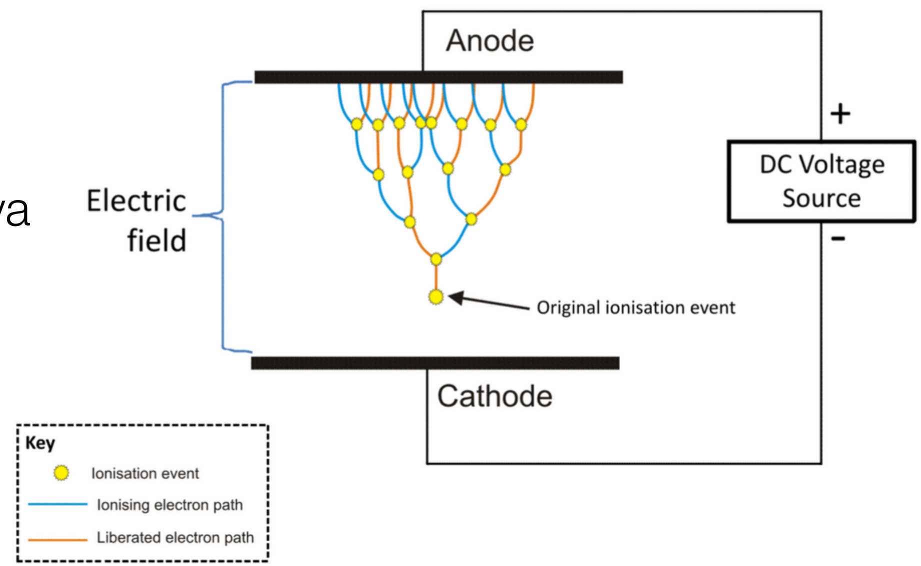
Charge avalanche statistics

The distribution of the number of avalanche pairs *"S"* is approximately exponential

It is known to be well-described by the Polya distribution, with shape parameter θ:

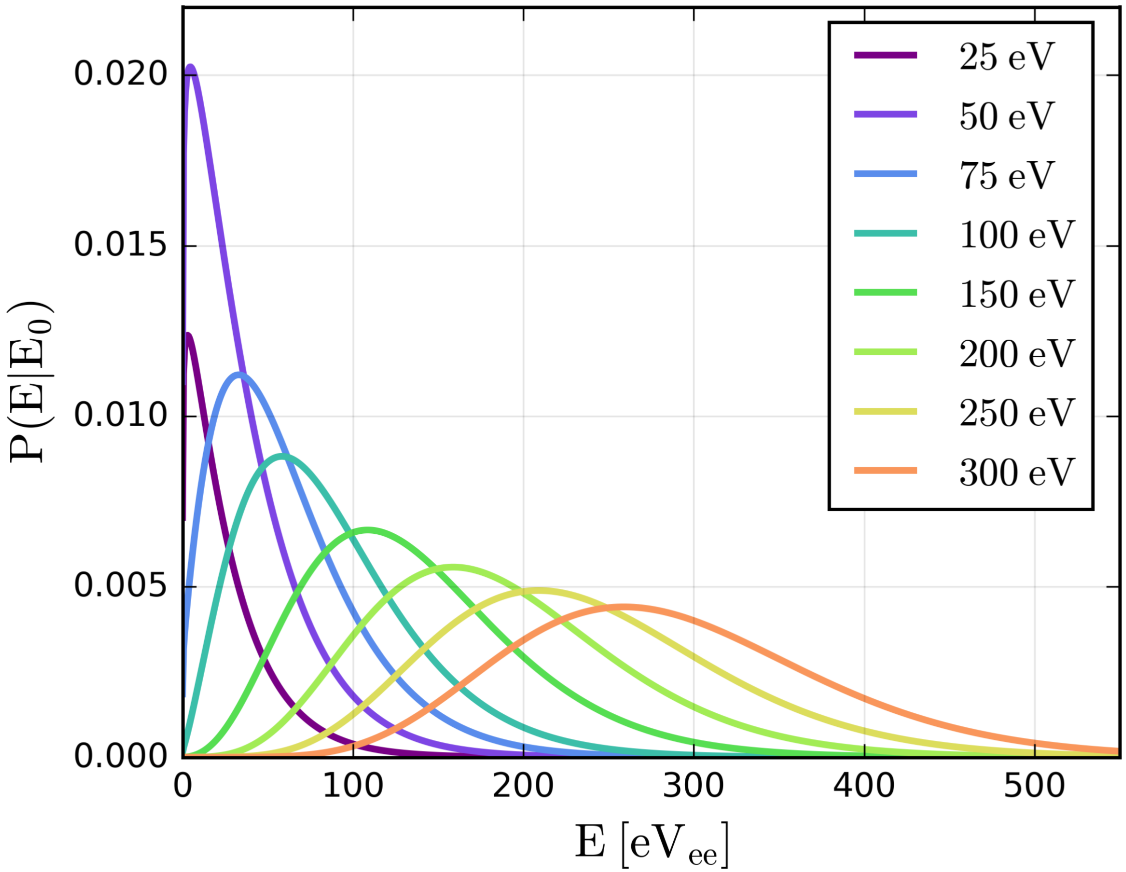


Visualisation of a Townsend Avalanche



$$P_{\text{Polya}}\left(S|\left\langle G\right\rangle,\theta\right) = \frac{1}{\left\langle G\right\rangle}\left(\frac{(1+\theta)^{1+\theta}}{\Gamma(1+\theta)}\right) \times \left(\frac{S}{\left\langle G\right\rangle}\right)^{\theta} \exp\left(-(1+\theta)\frac{S}{\left\langle G\right\rangle}\right)$$

SPC detector response model



Analytical formula for overall detector response

This example:

F = 0.2, θ = 0.1

(Loss of signal at low energy because non-zero probability of having 0 primary electrons)

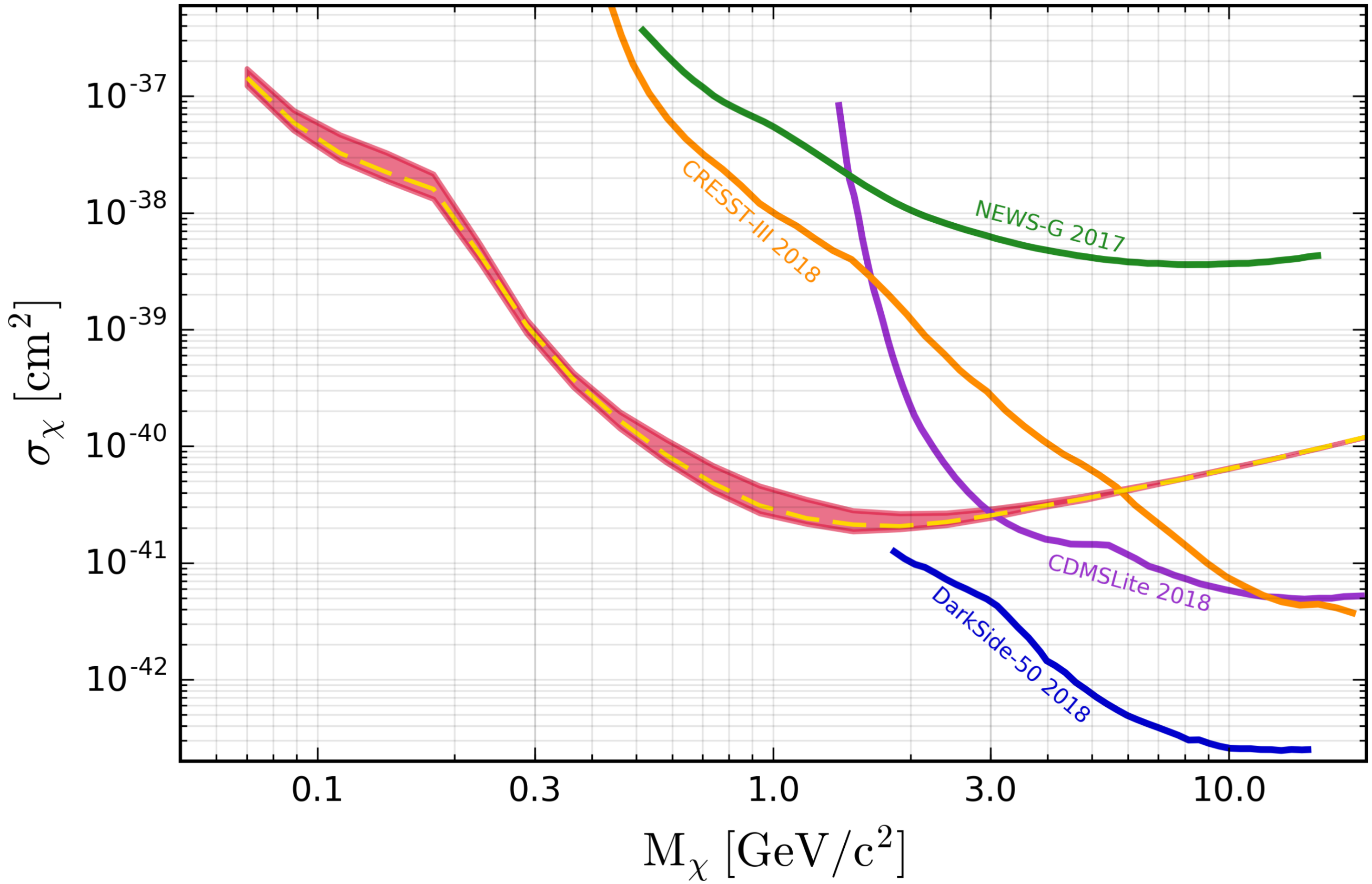
$$\mathcal{F}\left(E|E_0\right) = \sum_{n=1}^{n_{\max}} P_{\mathrm{COM}}\left(n|\lambda\left(\mu, F\right), \nu\left(\mu, F\right)\right) \times P_{\mathrm{Polya}}^{(n)}\left(E|\theta, \langle G\rangle\right)$$

$$\mu = \frac{E_0}{W(E_0)} \qquad n_{\max} = \left\lfloor \frac{E_0}{I} \right\rfloor$$

The impact of energy resolution

For NEWS-G at SNOLAB, our energy response (F/θ) can shift limits on WIMP SI scattering by ~ a factor of 2

The impact is limited because of the broad avalanche response



Range of F/θ:
1/0 → 0.16/0.15

Best fit of [7]:
F=0.19, θ=0.12

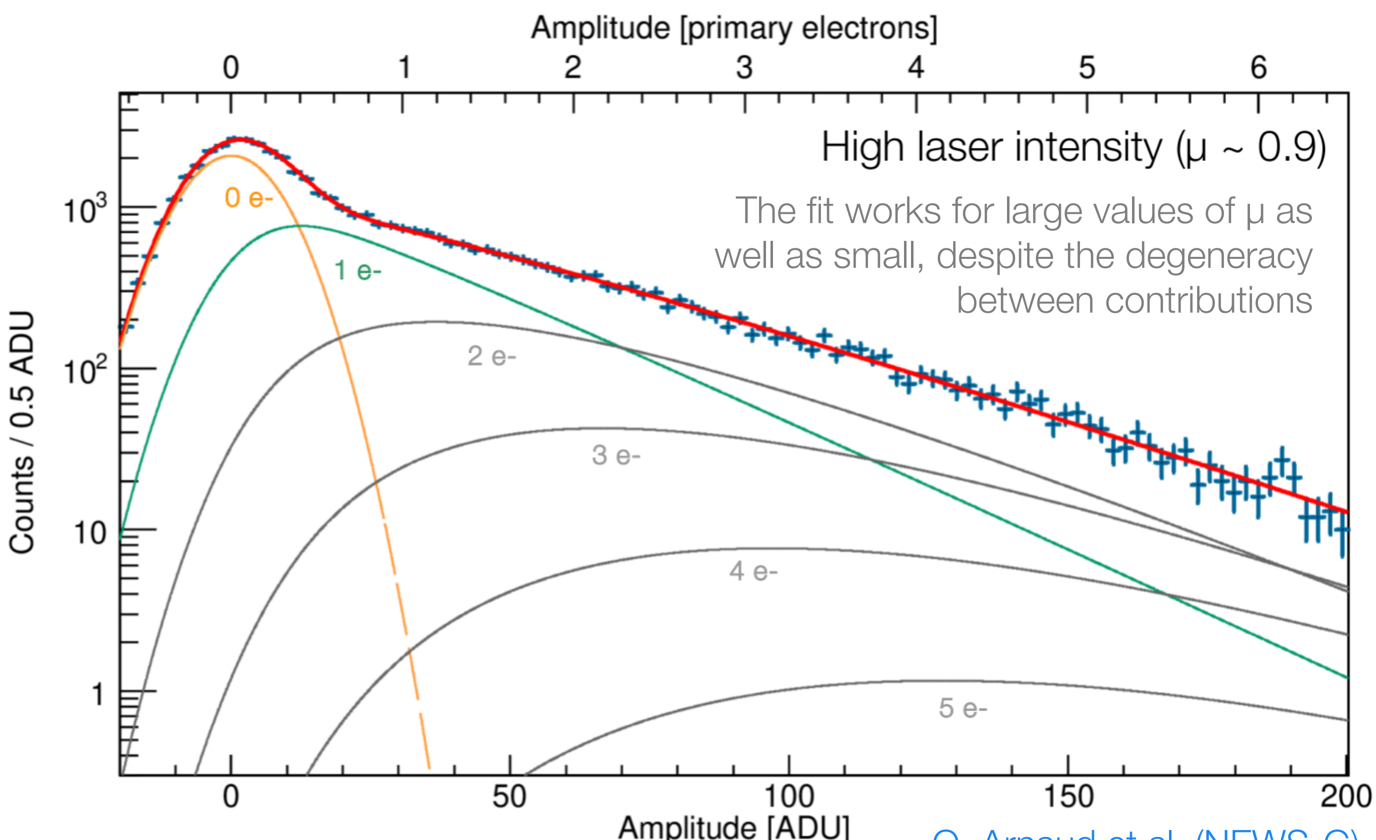
Assumptions:
Ne + 10% CH_4,
Exposure: 20 kg days
SRIM quenching factor
Background: 1.78 dru
ROI: 14 eV_{ee} - 1 keV_{ee}
Median OI Method

Single electron response characterization

The excellent fit validates the avalanche response model [5]:

$$\mathcal{F}\left(E'\right) = P_{\text{Poisson}}\left(0|\mu\right) + \sum_{n=1}^{\infty} P^{(n)}_{\text{Polya}}\left(E'|\theta\left\langle G\right\rangle\right) \times P_{\text{Poisson}}\left(n|\mu\right)$$

(This is then convolved with a Gaussian to incorporate baseline noise)



Q. Arnaud et al. (NEWS-G), Phys. Rev. D 99, 102003 (2019)

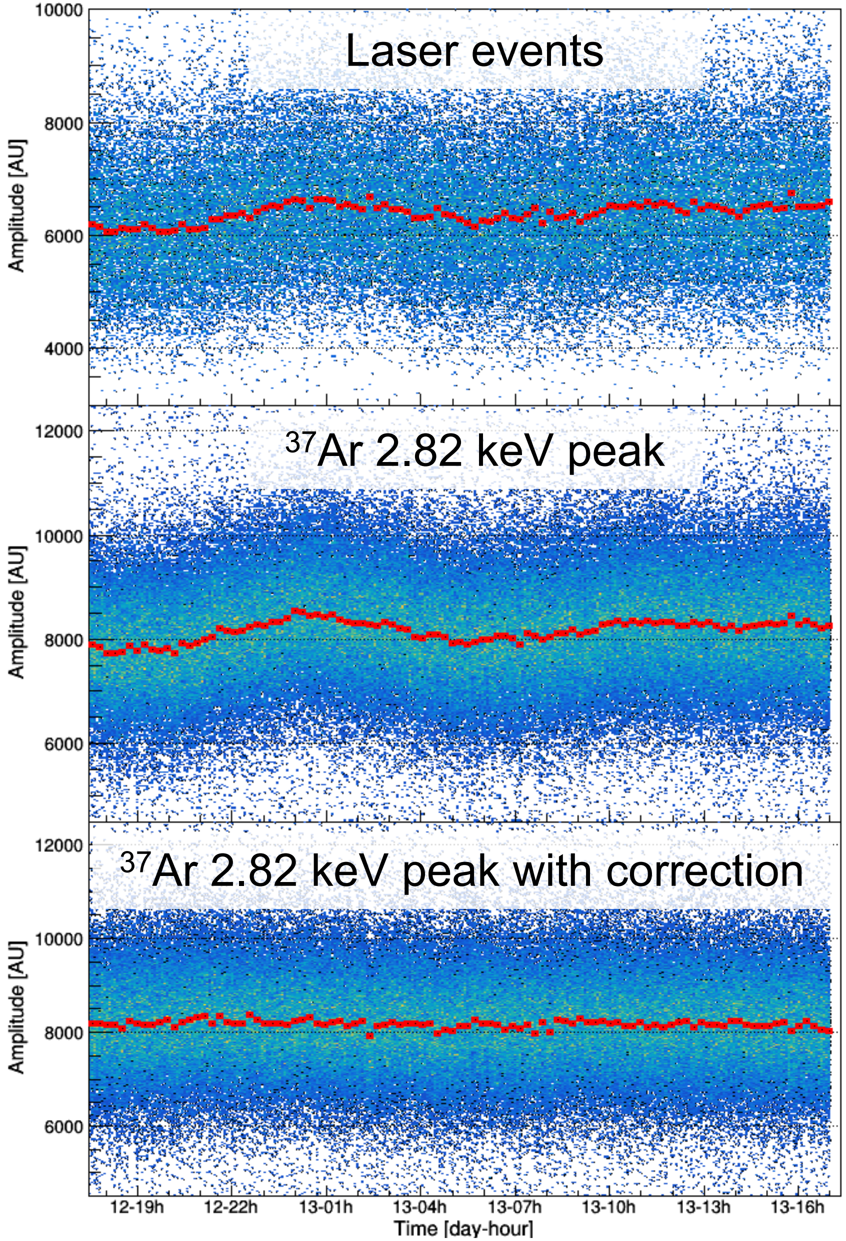
Data Parameters:

Ne + 2% CH4
P = 1.5 bar
HV = 1200 V

Fit results:

θ = 0.09 ±0.02
<G> = 30.26 ± 0.21 ADU
χ^2/ndf = 0.97

Detector monitoring



The UV laser can be used to monitor the detector response during physics runs

Long-term fluctuations in gain can be caused by temperature changes, O_2 contamination, sensor damage...

Laser monitoring data could even be used to correct for long-term fluctuations

Q. Arnaud et al. (NEWS-G), Phys. Rev. D 99, 102003 (2019)

Trigger efficiency

The laser can be used to directly measure the efficiency of our triggering algorithm

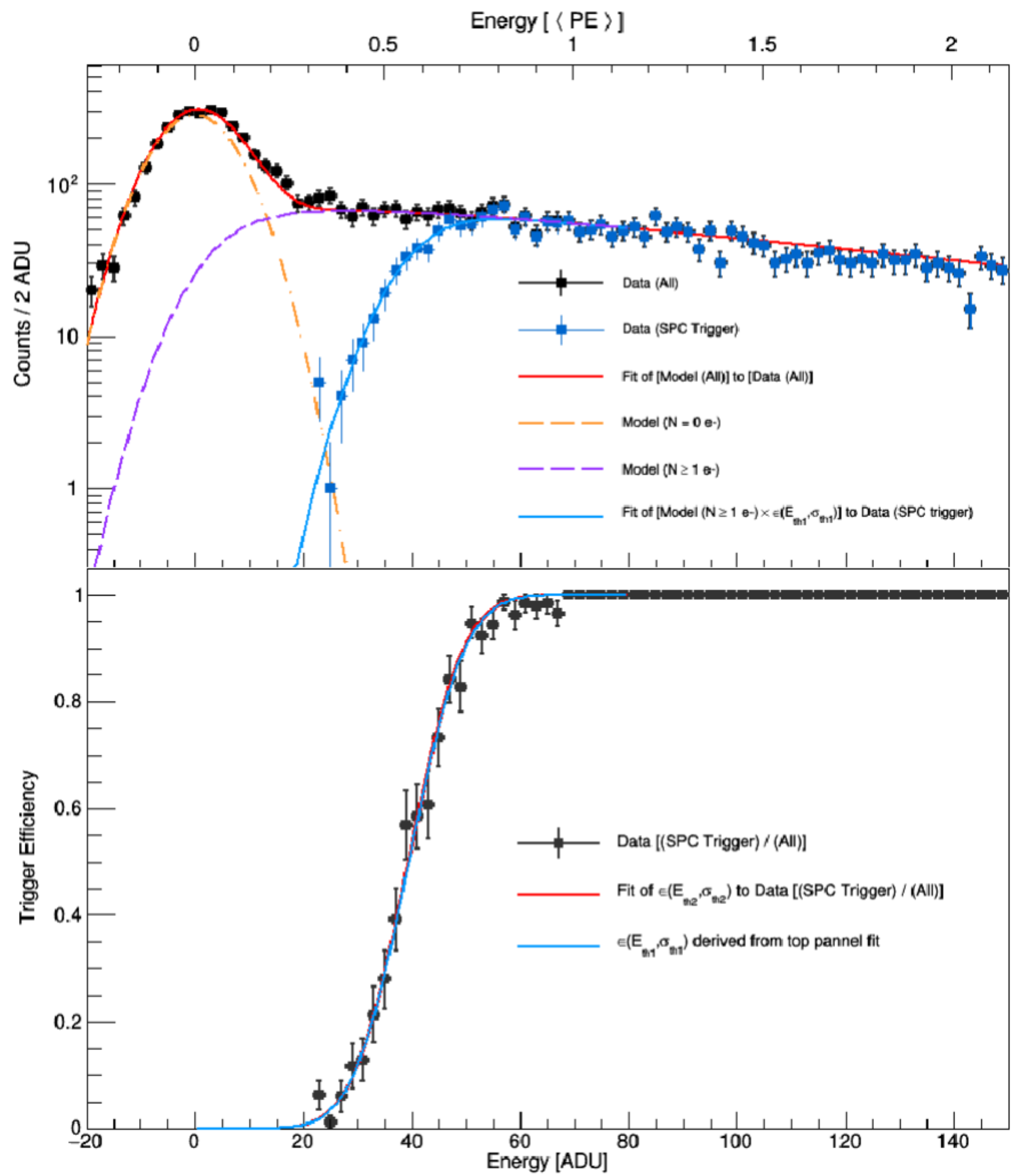
Method 1:

SPC-triggered spectrum divided by photo-detector triggered spectrum (this does not account for null laser events)

Method 2:

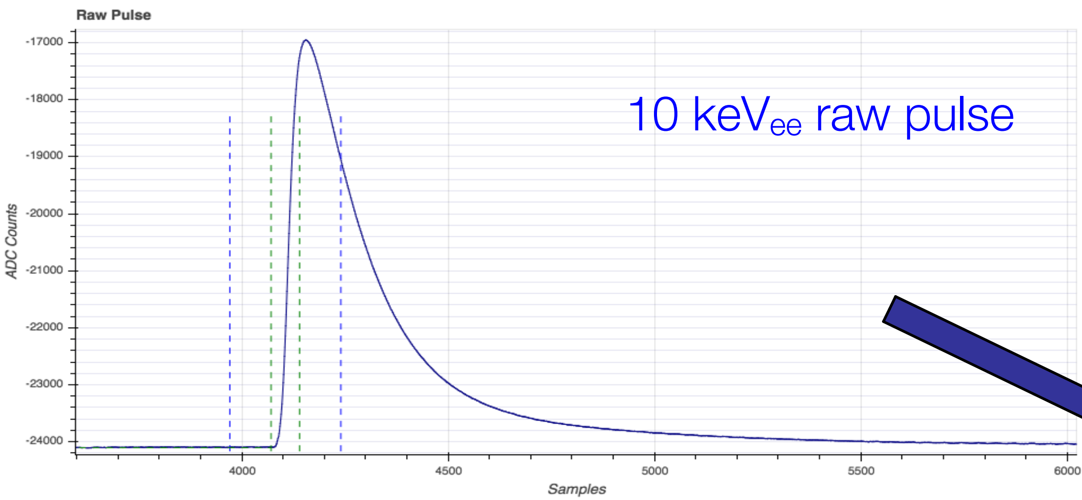
Fit total spectrum (0 PE + > 0 PE events), then fit > 0 PE spectrum multiplied by error function with <G>, θ, and σ fixed.

> Demonstration of ~10 eV energy threshold:
> 16 eV in this example

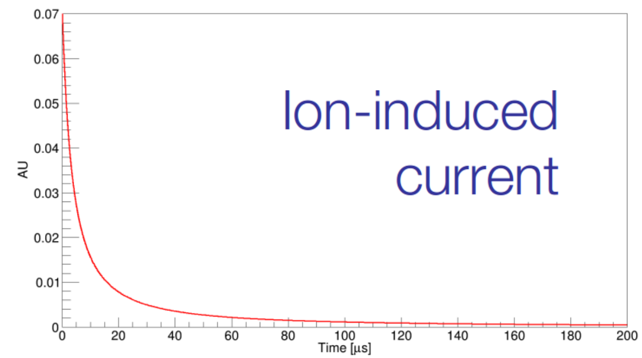


Q. Arnaud et al. (NEWS-G), Phys. Rev. D 99, 102003 (2019)

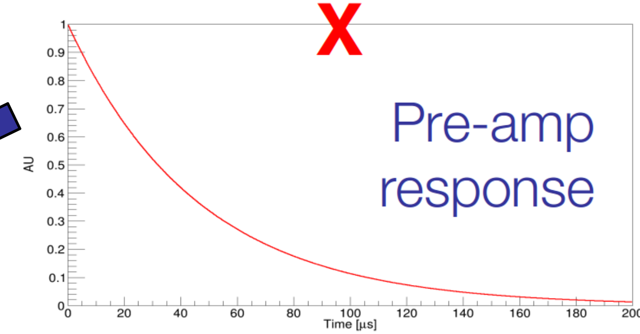
NEWS-G: Pulse treatment

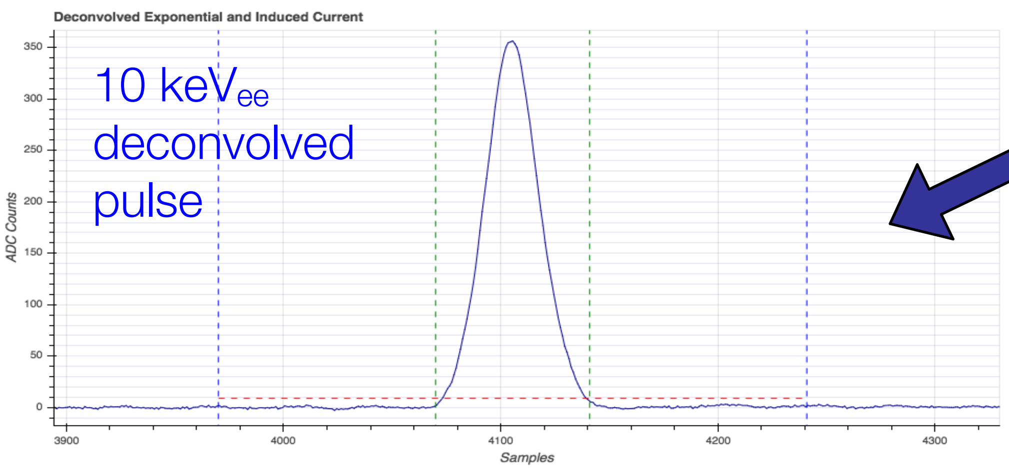


Deconvolve for amplifier response and ion-induced current



X



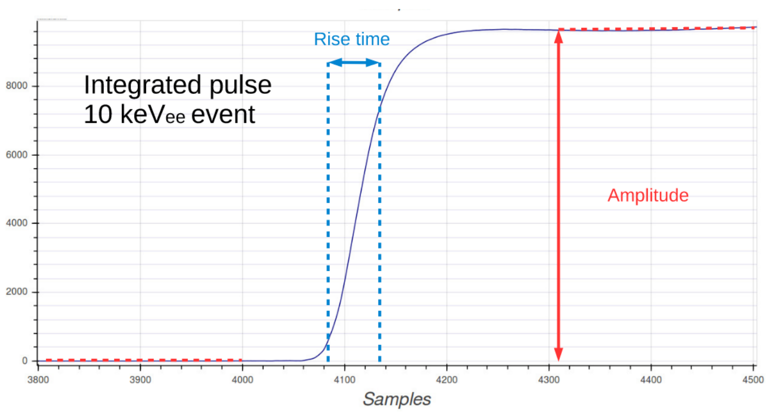


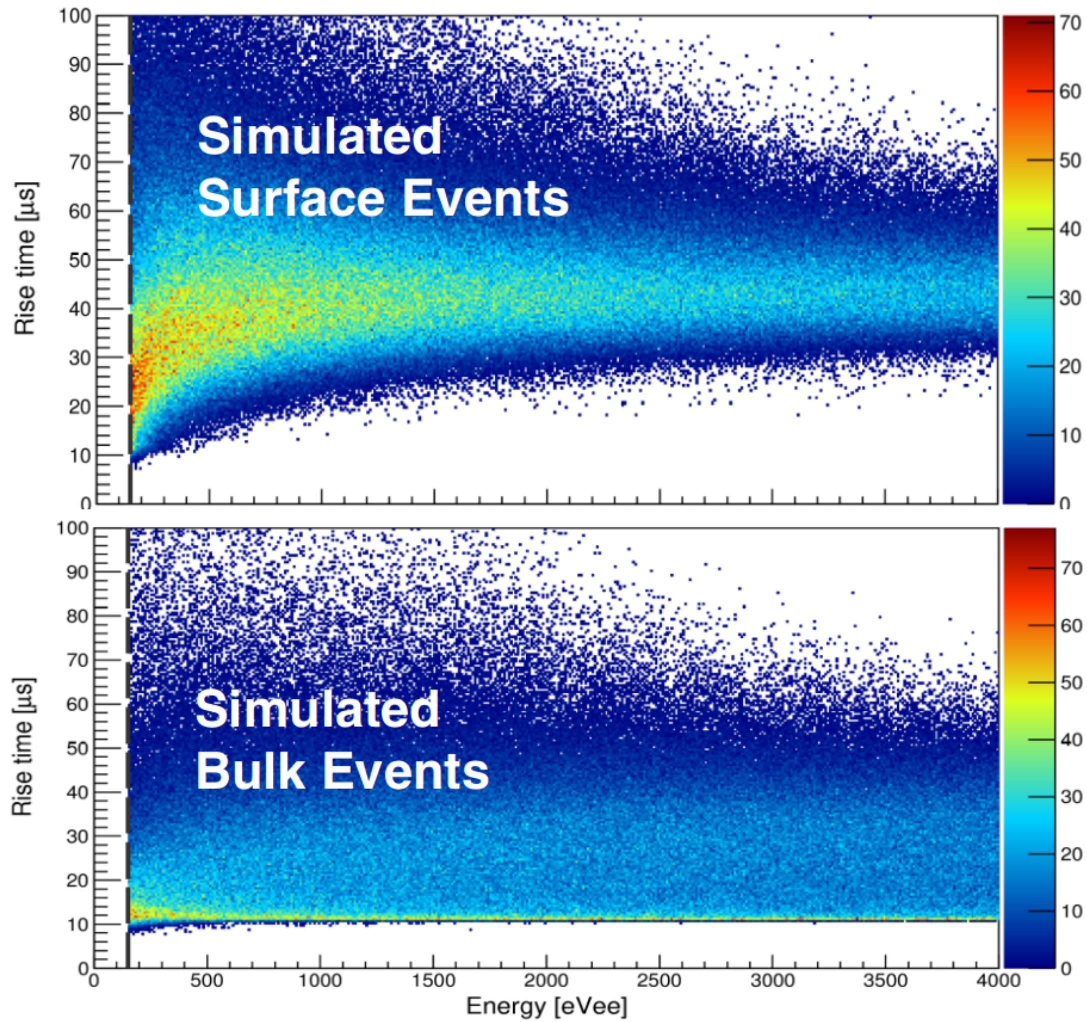
NEWS-G: PSD

Gaussian dispersion in arrival time due to diffusion of charges:

$$\sigma(r) = \left(\frac{r}{r_{sphere}}\right)^3 \times 20\mu s$$

Rise time used for surface event discrimination

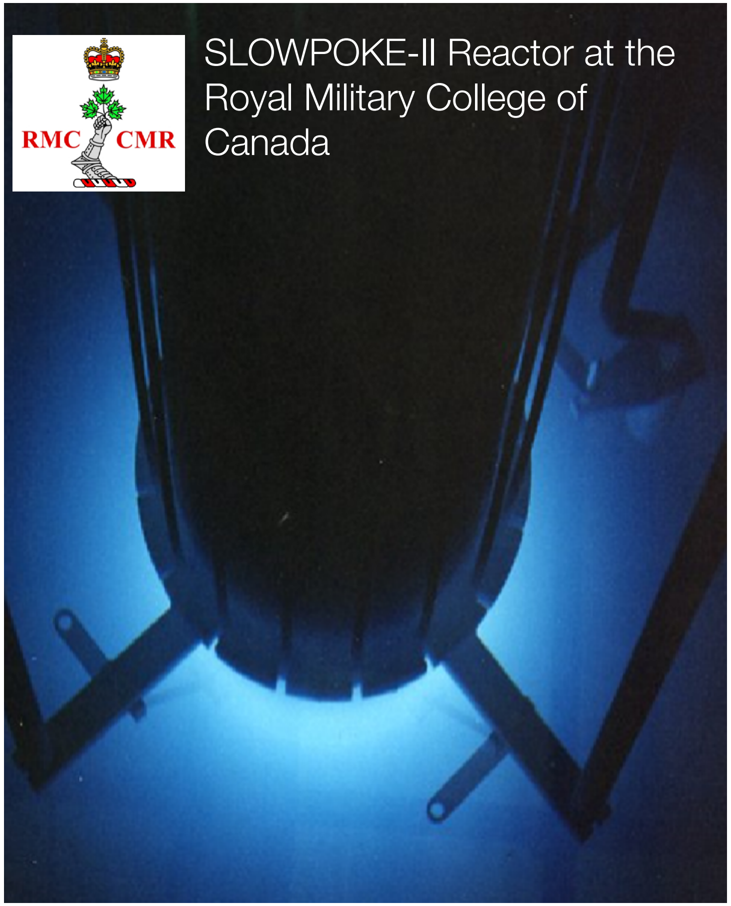




Q. Arnaud et al. (NEWS-G), Astropart. Phys. 97, 54 (2018).

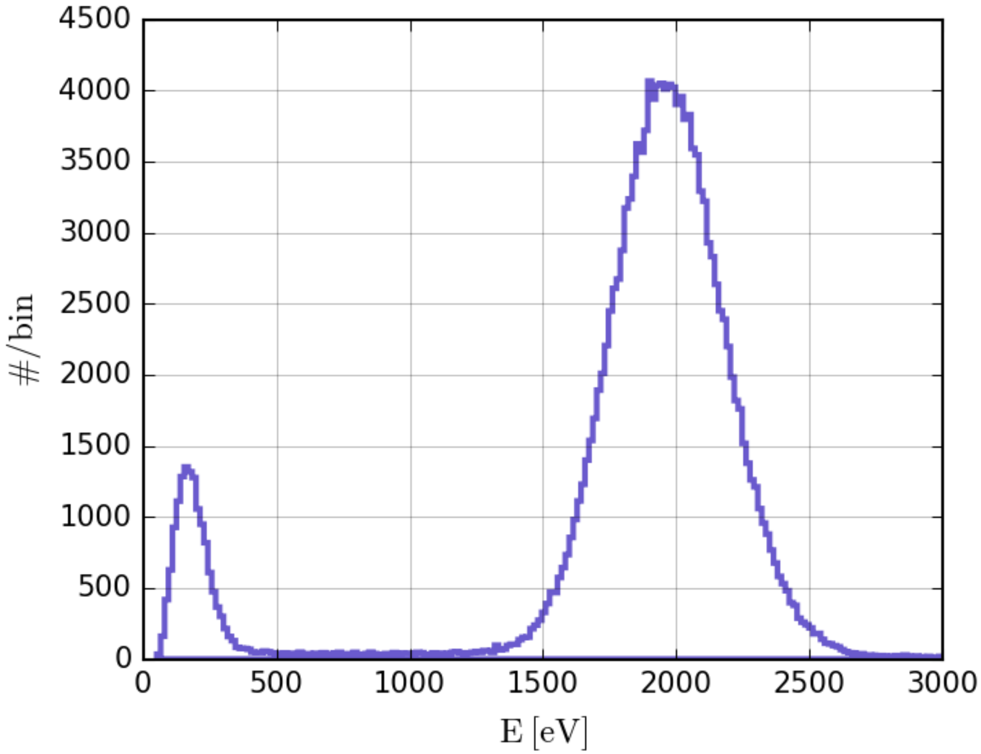
^{37}Ar: radioactive gas, decays via electron capture

37 day half life, so we need a way to produce samples at regularly - generated in a small fission reactor, then injected into an SPC:



$^{40}Ca(n,\alpha)^{37}Ar$

Decay produces 2.82 keV and 270 eV x-rays, generated uniformly throughout the detector:



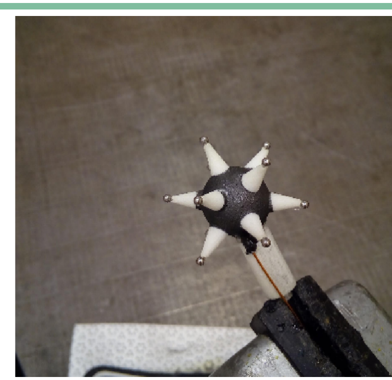
Design of new detector

The two hemispheres of SPC formed by "spinning", electron-beam welded together

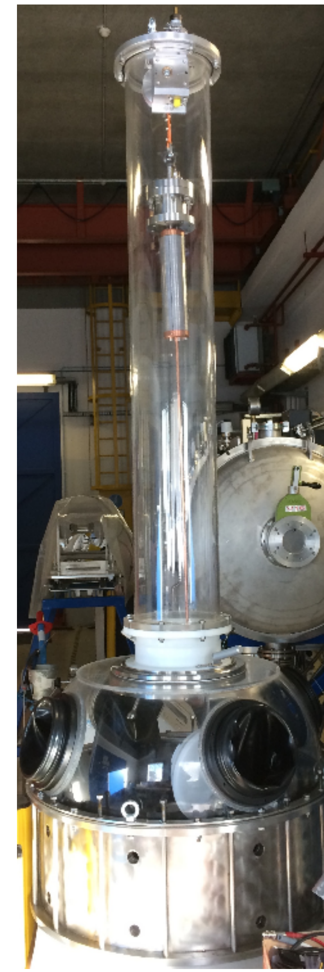
Steel skin for shield

VA and archaeological lead

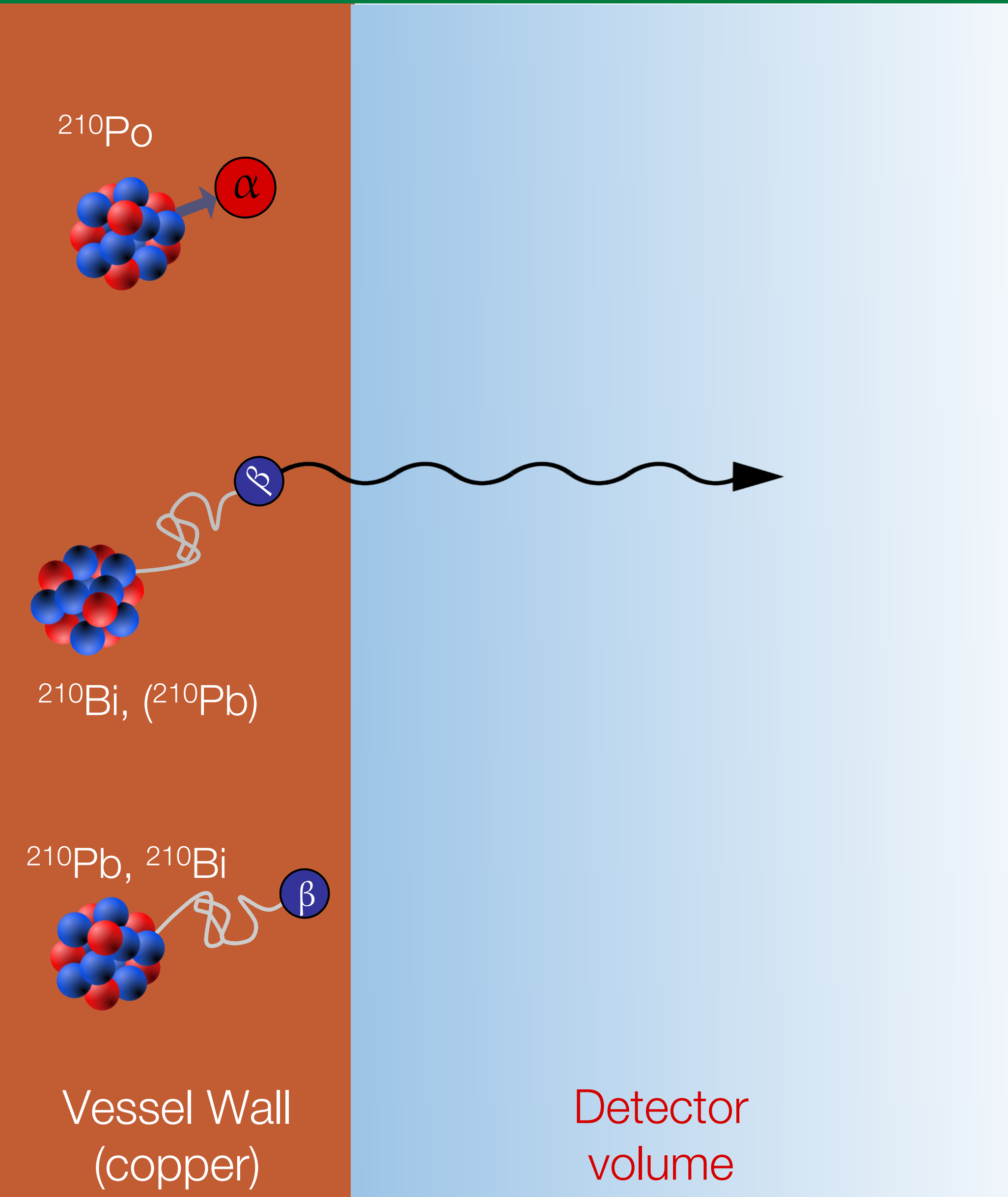
Development of multi-electrode sensors!



Glove-box to store sensor in radon, O_2 free environment



Background mitigation

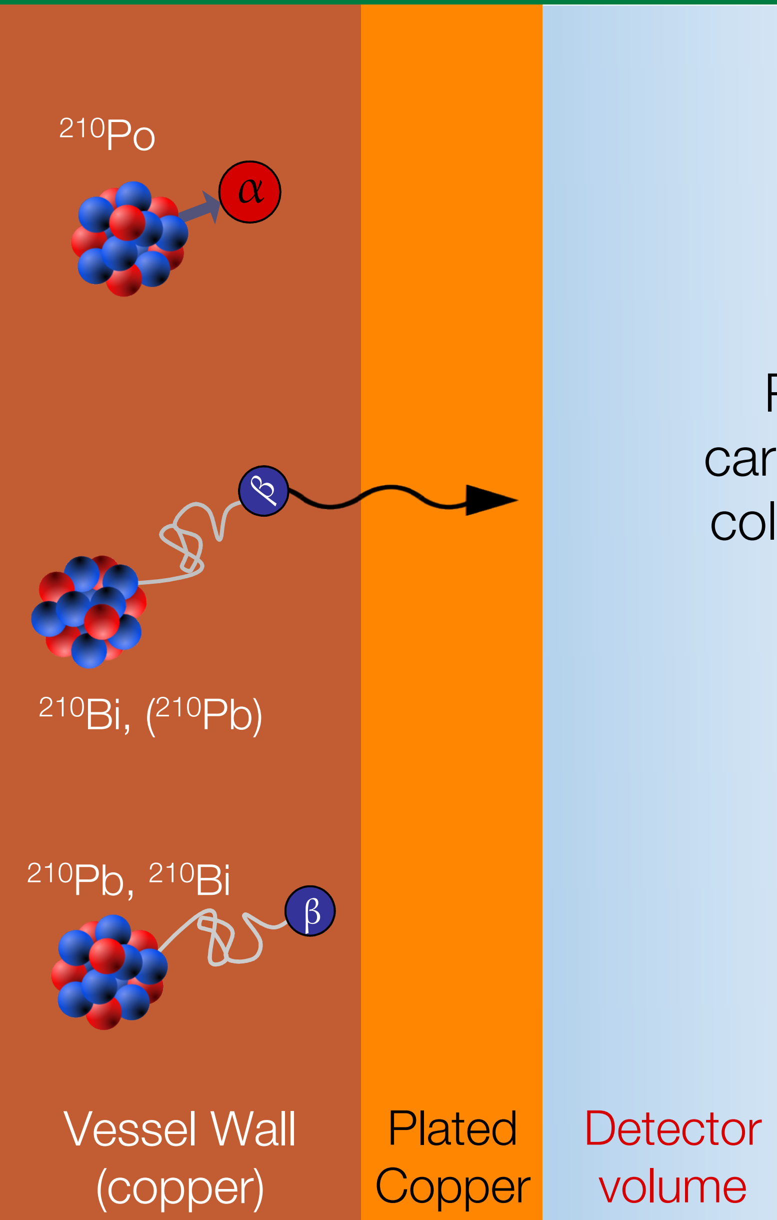


^{210}Pb is a long-lived radio-impurity found in copper

Most radiation is stopped inside the copper but...

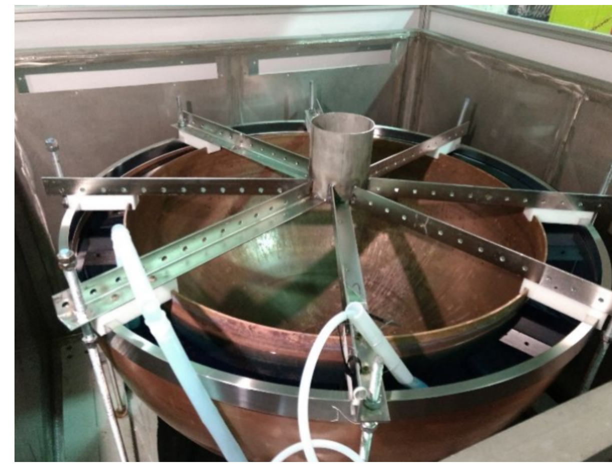
Bremsstrahlung x-rays (~keV) from ^{210}Pb and ^{210}Bi **β^-** decay in the copper escape, travel through whole volume

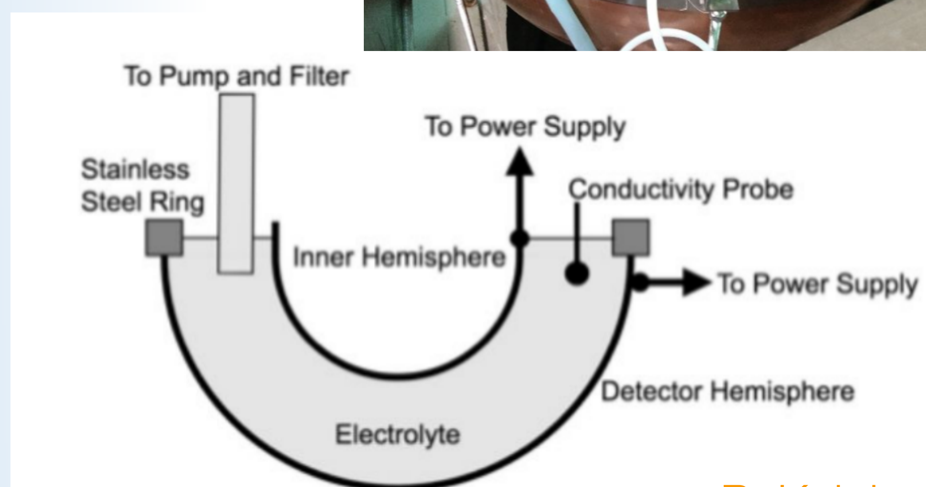
Background mitigation



Plating ~0.5mm of pure copper will reduce this background by ~70% below 1 keV and the total rate by ~98%

Plating successfully carried out at the LSM in collaboration with PNNL





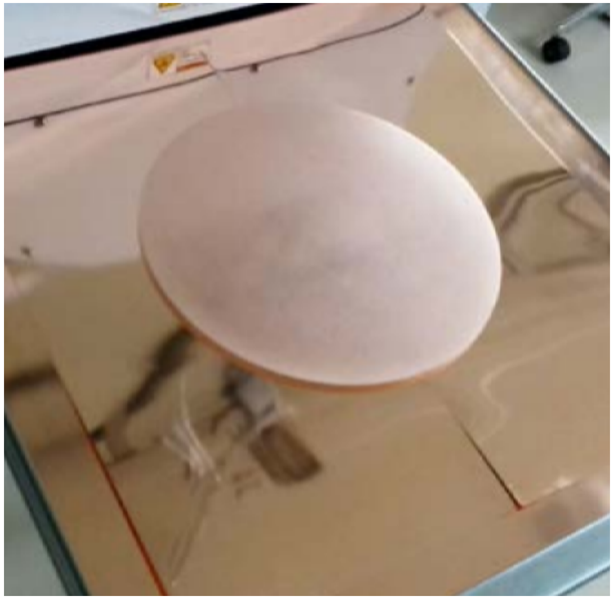
P. Knights

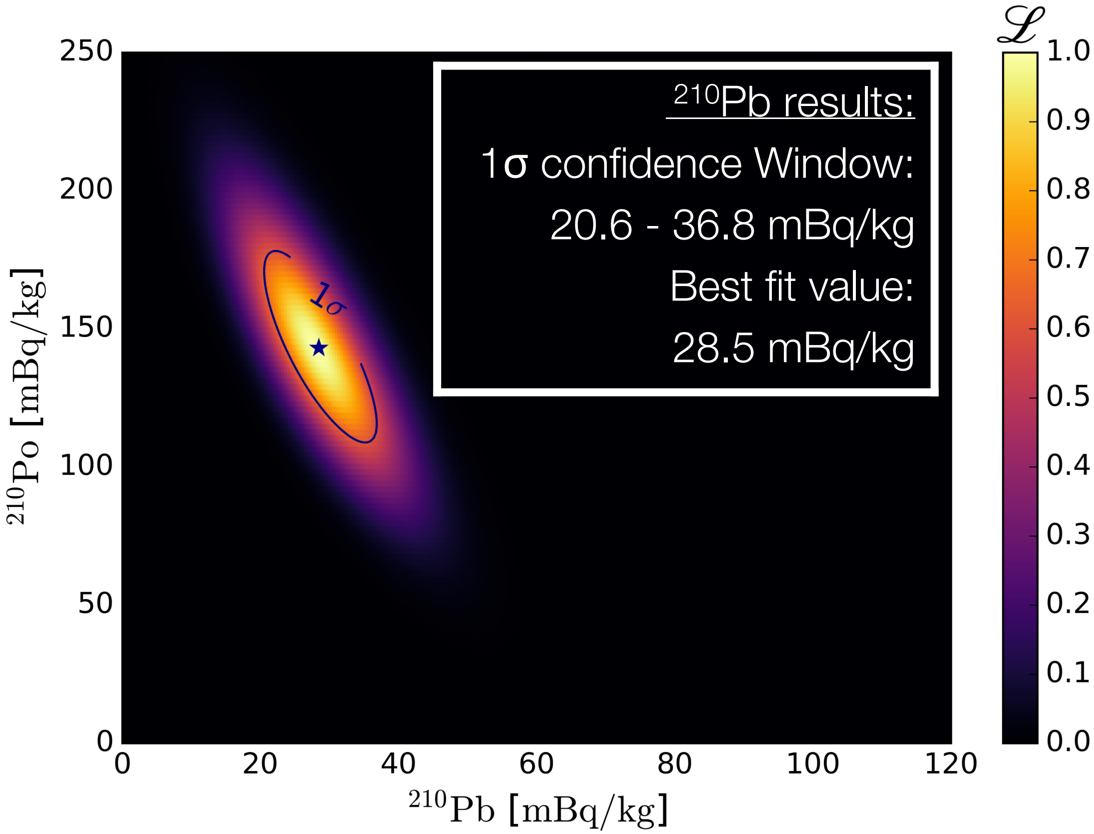
Measurement of ^{210}Pb

Measurement of Po-210 α's over time to extract Pb-210 activity

K. Abe et al. Nucl. Instrum. Methods Phys. Res., Sect. A 884, 157 (2018).

Measurement campaign done by XMASS





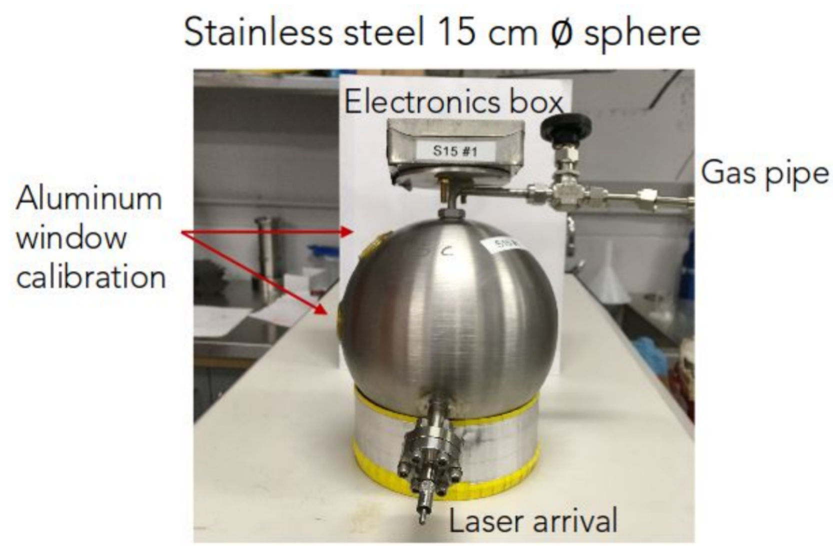
Quenching factor measurements

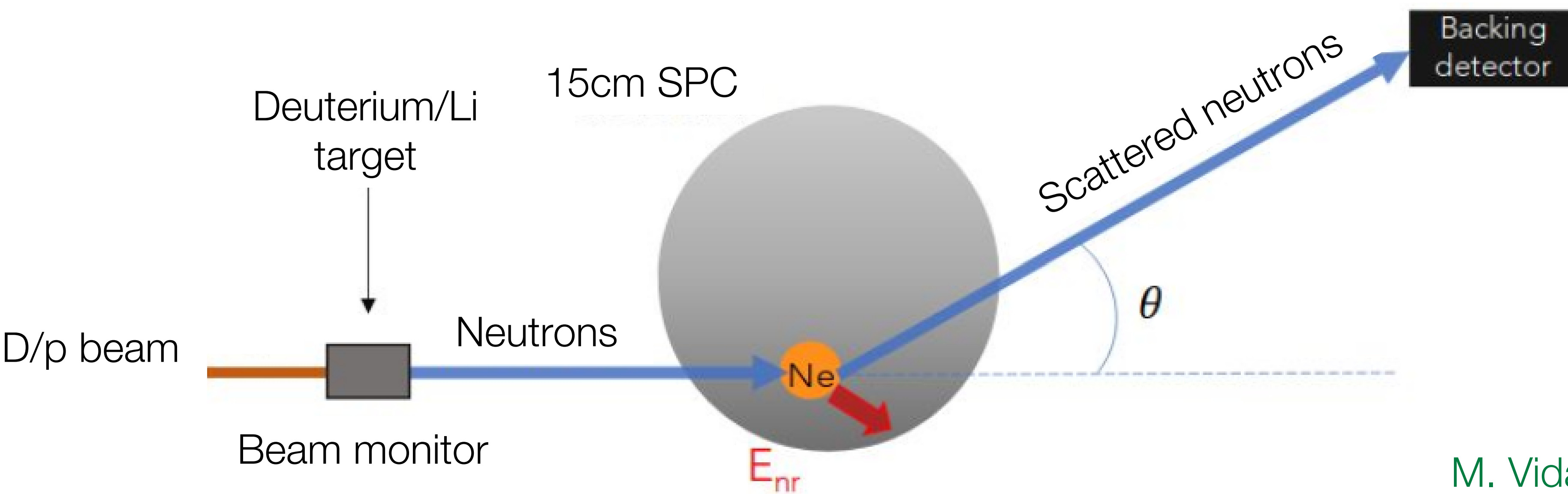
$$W_{\mathrm{nr}} = W_\gamma / Q(E)$$

Measurement campaigns at:

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

Beam from a TANDEM accelerator used to produce neutrons: D(D,n)^{3}He, p(^{7}Li,n)^{7}Be





M. Vidal