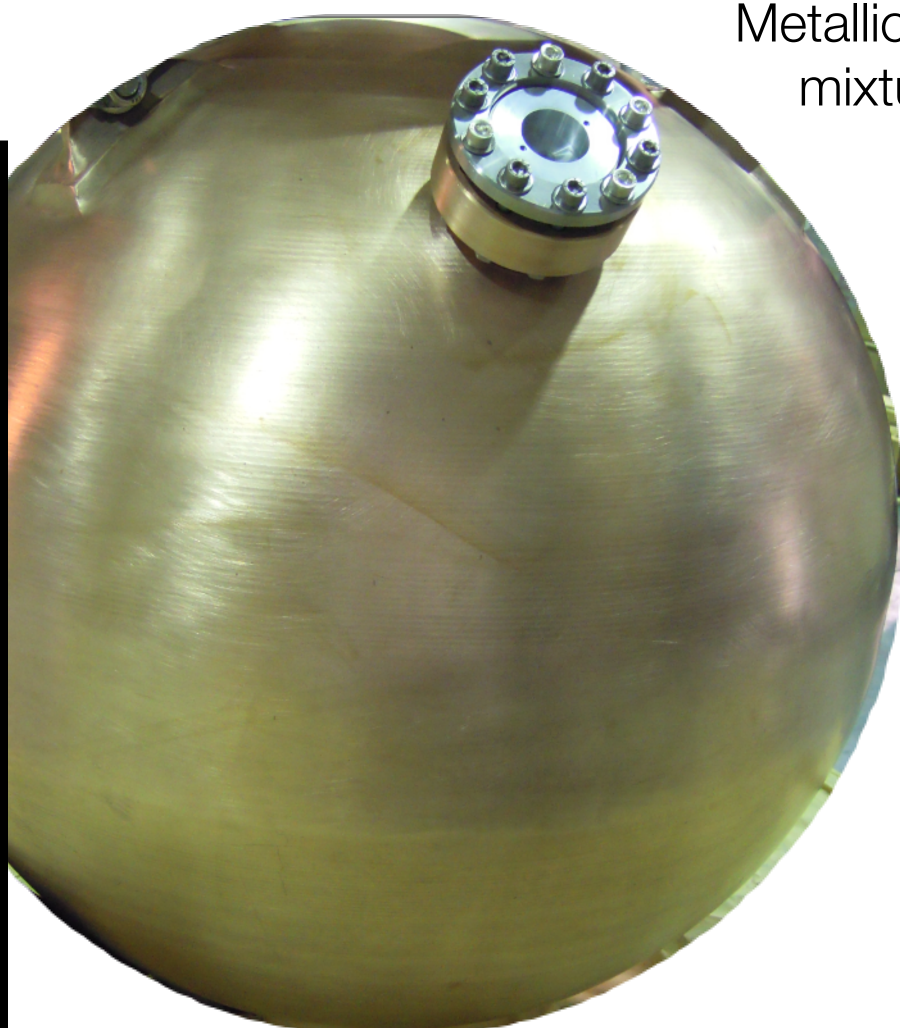
Status of the NEWS-G Dark Matter Experiment

Daniel Durnford

Lake Louise Winter Institute 2019
February 11th

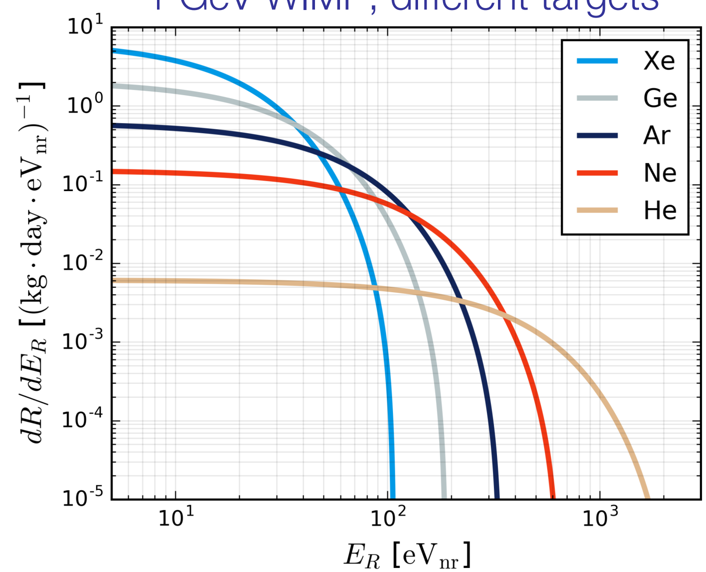
Spherical Proportional Counters (SPCs) to search for low-mass dark matter



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

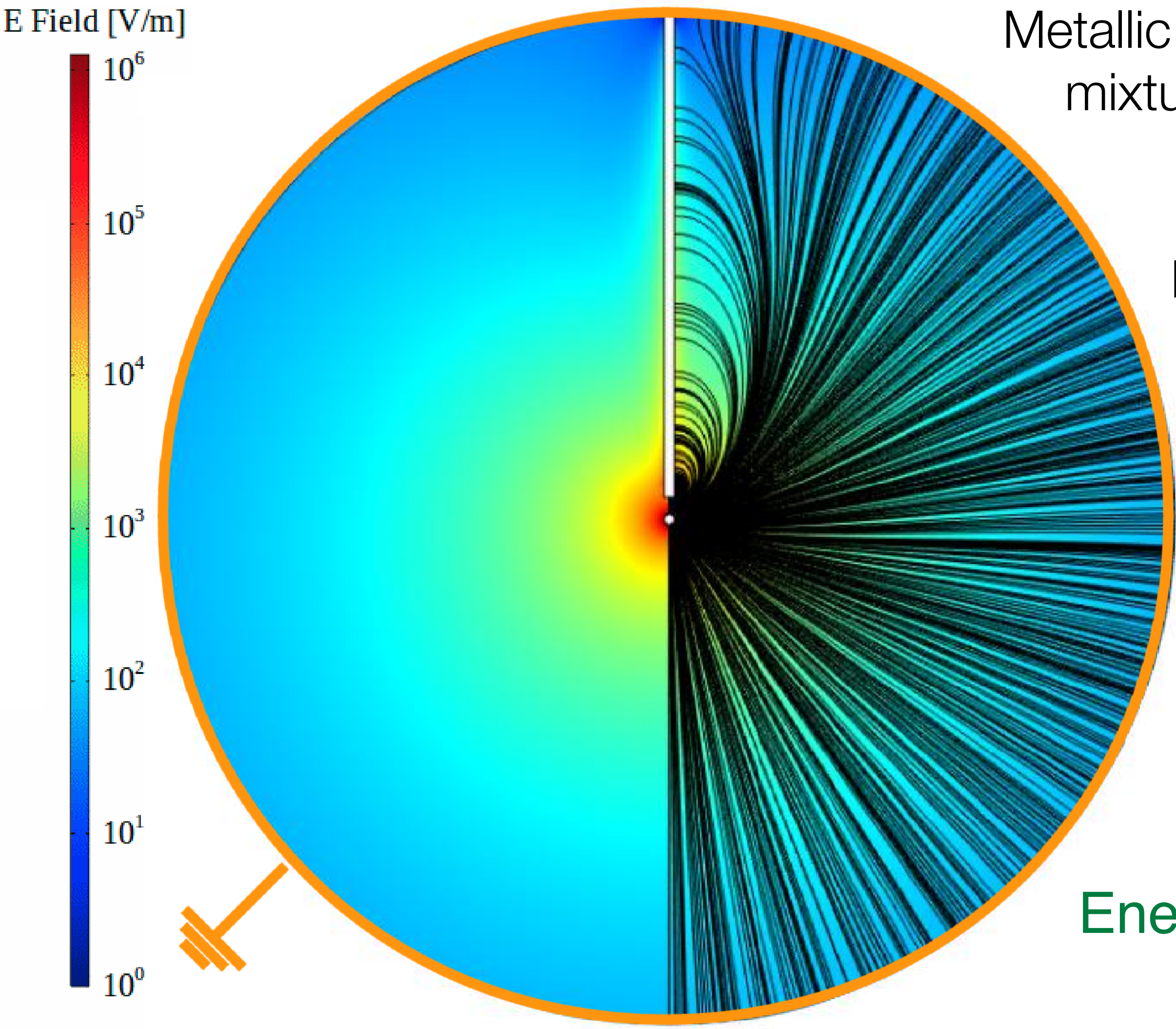
Low-A target atoms increase sensitivity to low-mass WIMPs

1 GeV WIMP, different targets



Spherical Proportional Counters

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

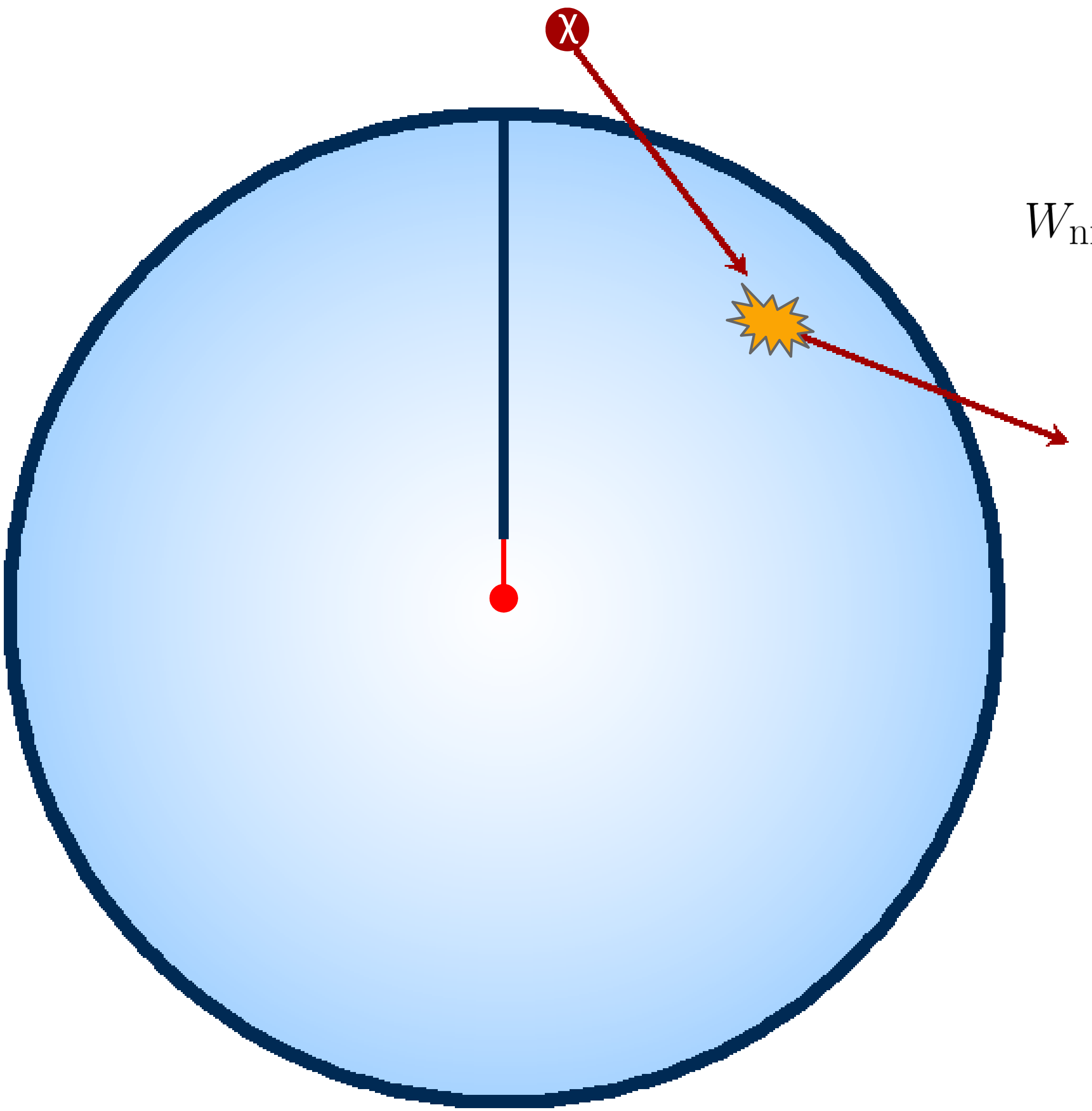
Low-A target atoms increase sensitivity to low-mass WIMPs

Low intrinsic capacitance: ($C \approx 0.3$ pF)

High amplification gain from Townsend avalanche

Energy thresholds of ~10 eV!

Principle of operation



(1) Primary Ionization

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

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

Neon: W_{γ} ~ 36 eV/pair
Q ~ 0.2

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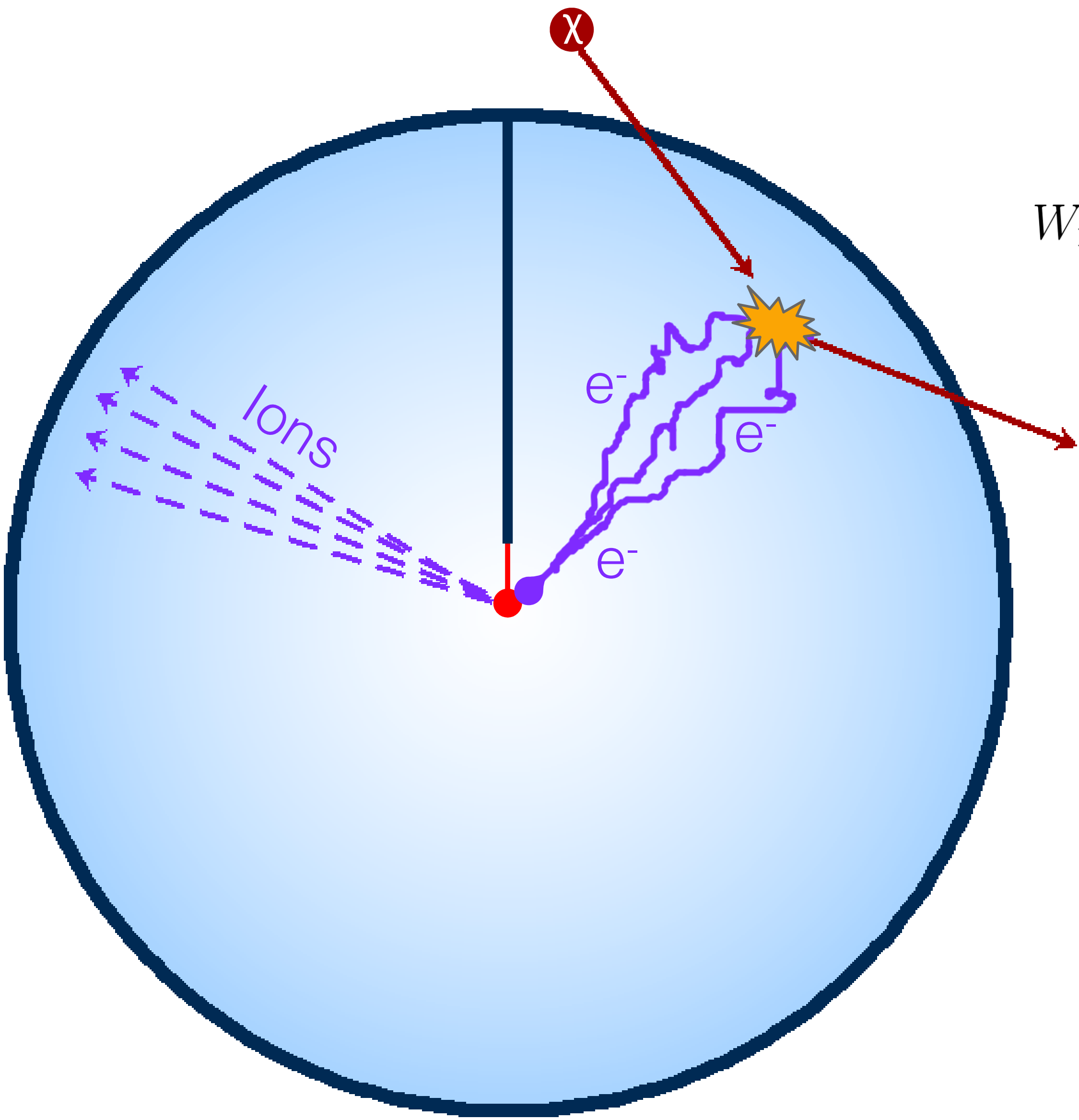

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(2) Drift of charges

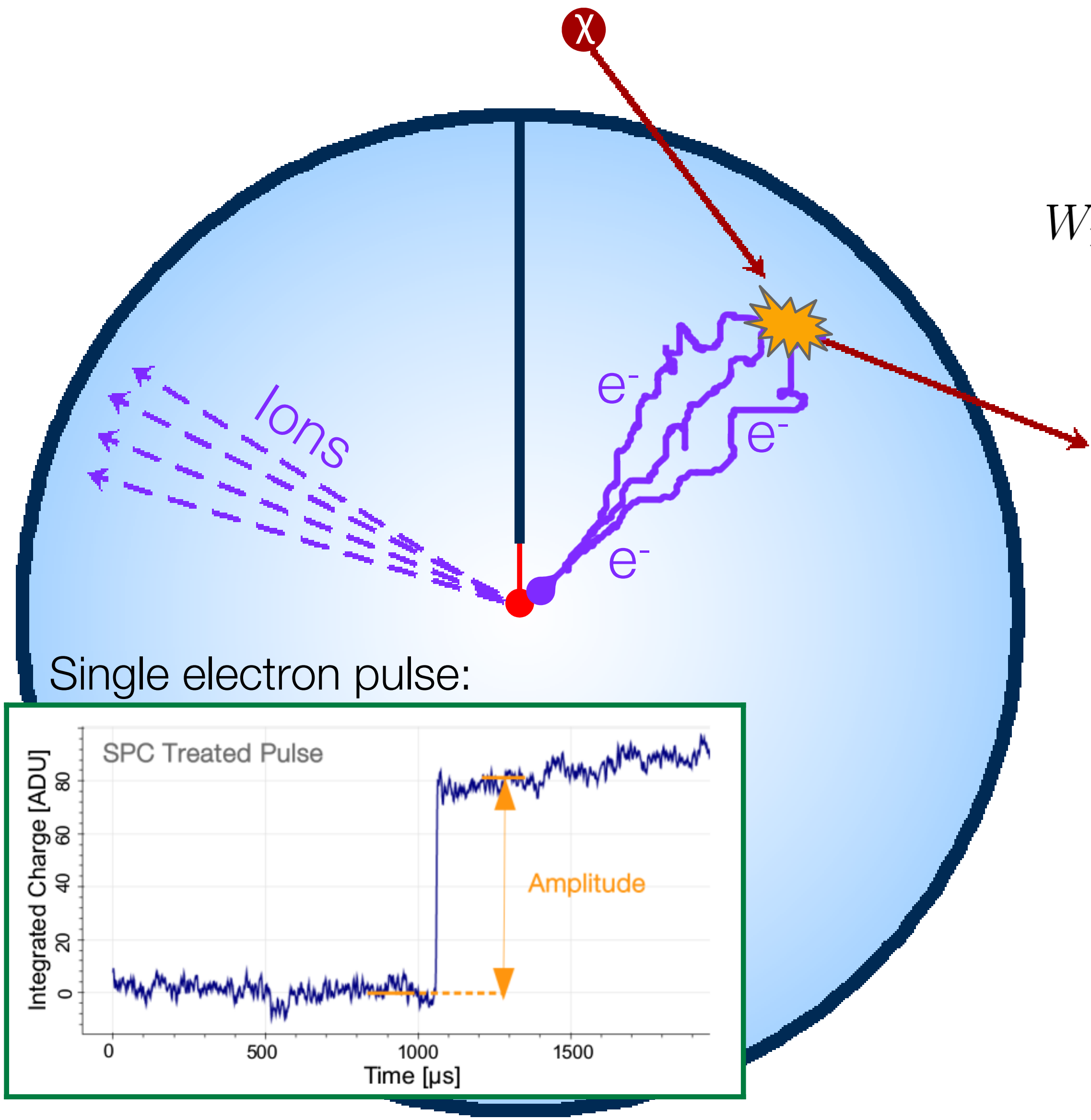
Typical drift time surface -> sensor :
~ 100 μs

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

Amplification of signal through Townsend avalanche (tunable with V)

(4) Signal formation

Current induced by the secondary ions drifting away from anode



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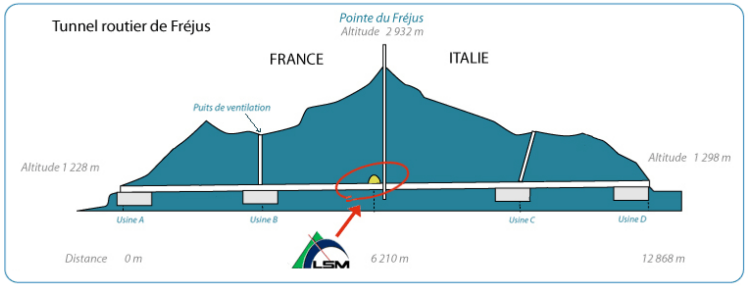
(4) Signal formation

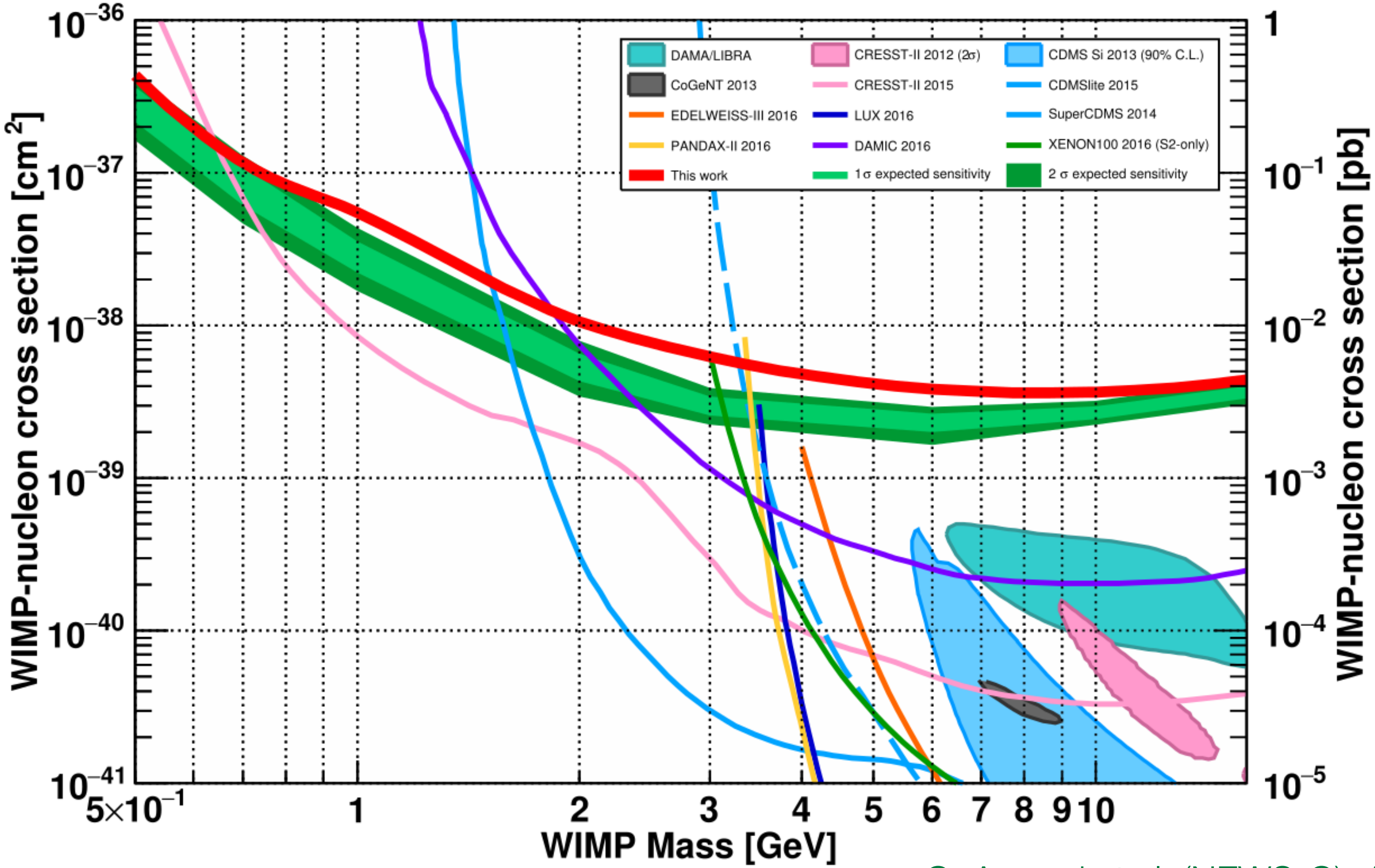
Current induced by the secondary ions drifting away from anode

(5) Signal readout

Induced current integrated by a charge sensitive pre-amplifier 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).

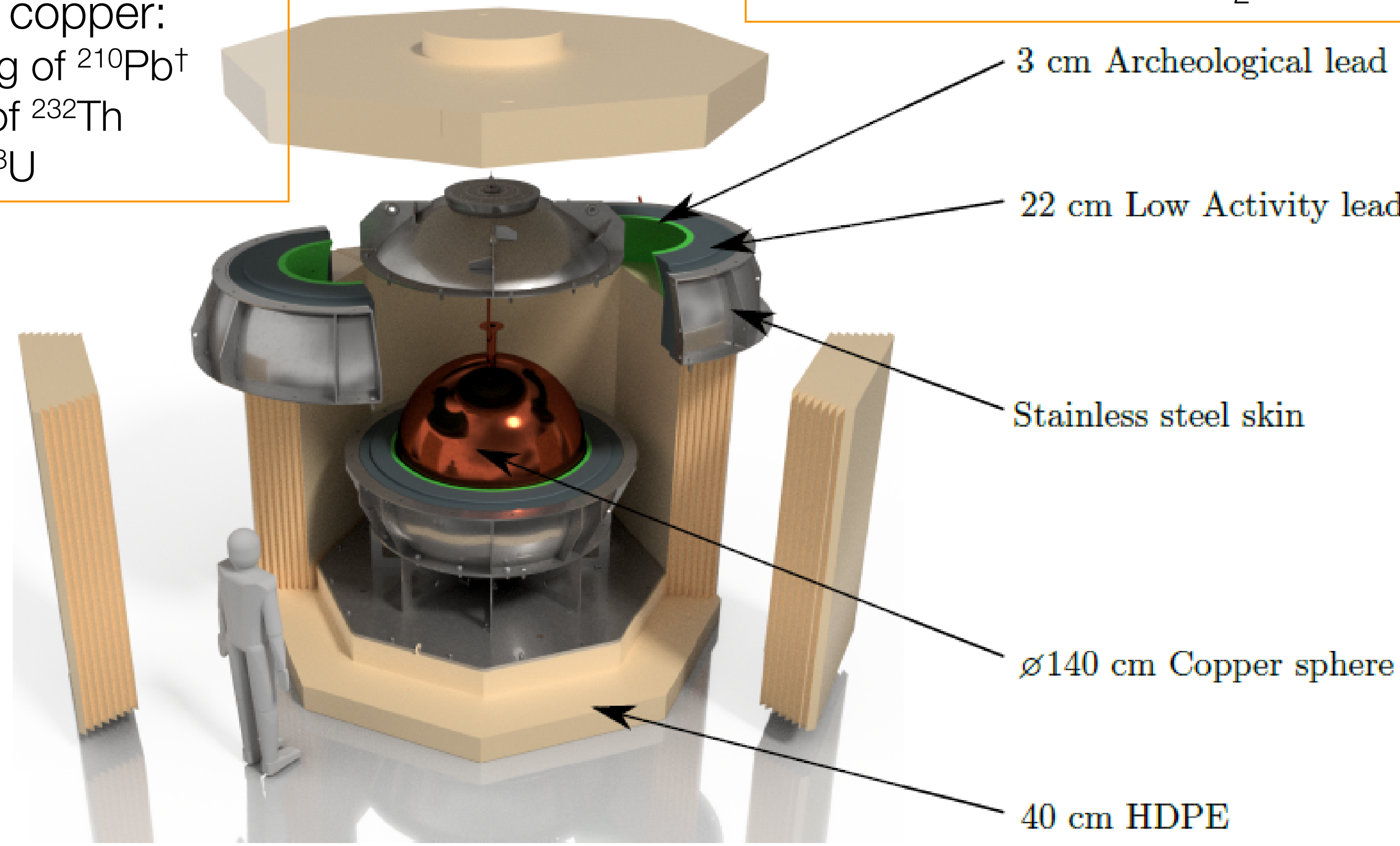
...to be installed in late 2019

Bigger, better SPC to be installed in SNOLAB!

A 140cm SPC made of low activity C10100 copper:

- »36 ± 13 mBq/kg of ^{210}Pb†
- »7 - 25 μBq/kg of ^{232}Th
- »1 - 5 μBq/kg ^{238}U

Compact Lead and PE shield, flushed with N_2



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

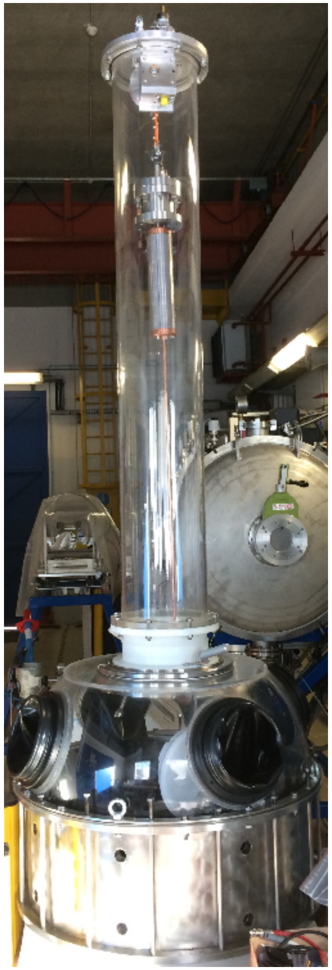
K. Dering

Design and fabrication progress

The two hemispheres of the SPC are complete

Soon: cleaning and electron-beam welding

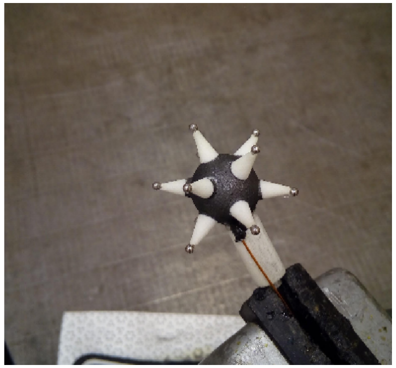
Glove-box to store sensor in radon, O_2 free environment: complete!



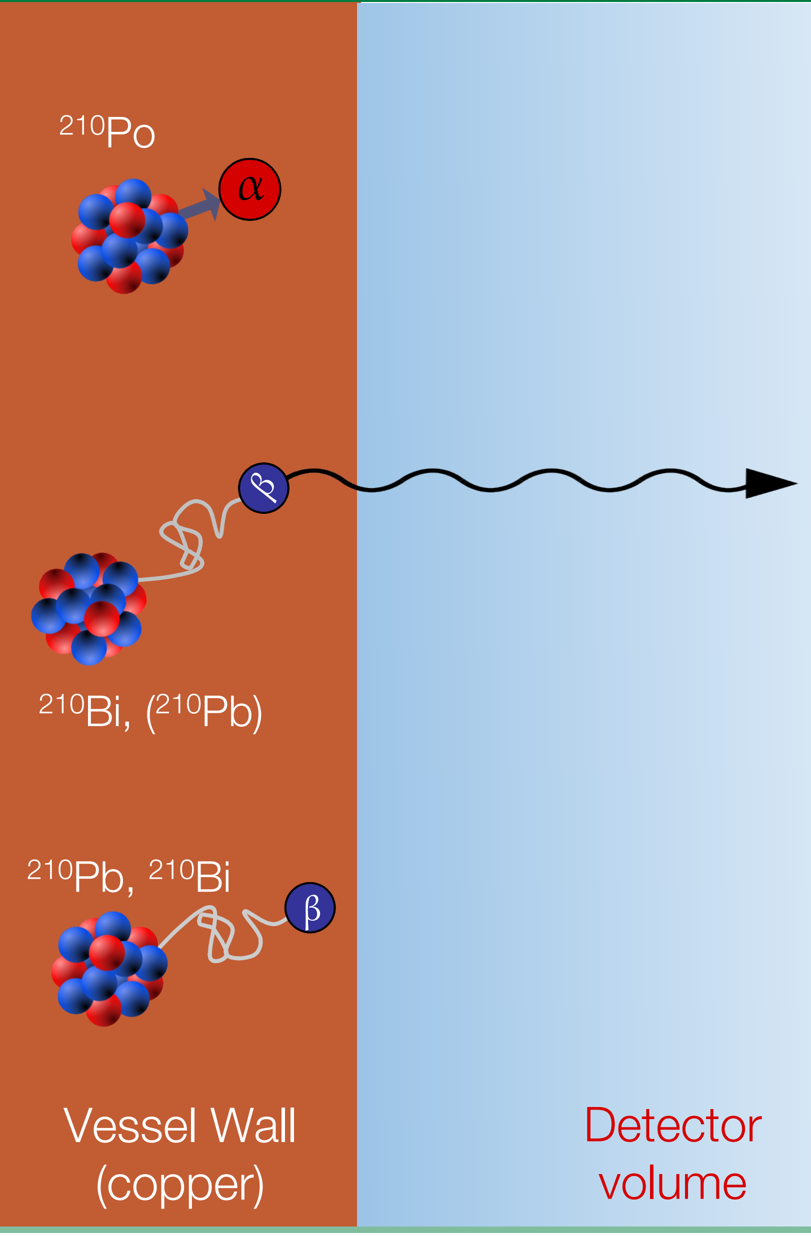
Steel skin of shield, casting of VLA lead nearly complete

Soon: forging archaeological lead, machining PE

Development of multi-electrode sensors ongoing!



Background mitigation



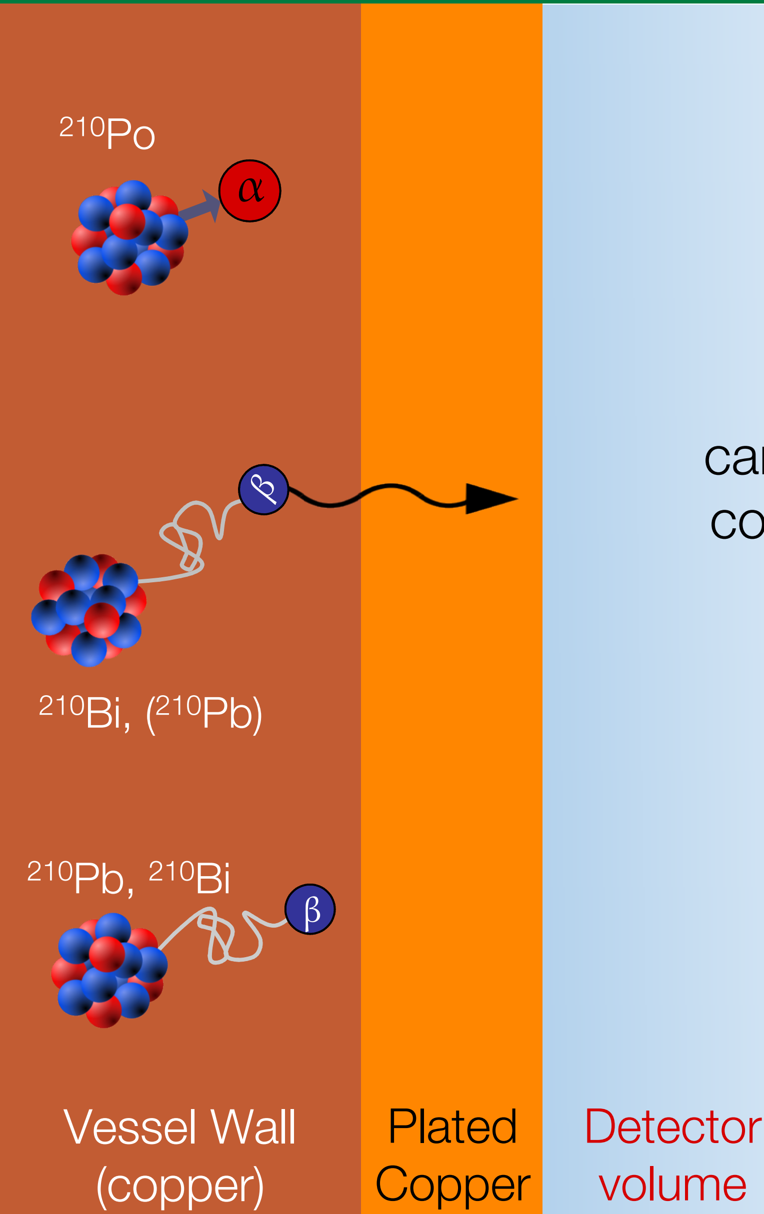
^{210}Pb is a long-lived radio-impurity found in copper

Most radiation is stopped inside the copper but...

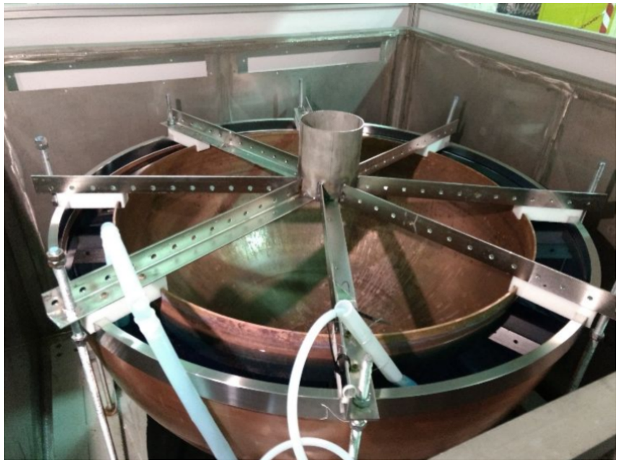
Bremsstrahlung x-rays (~keV) from ^{210}Pb and ^{210}Bi β^- decay in the copper escape, travel through whole volume

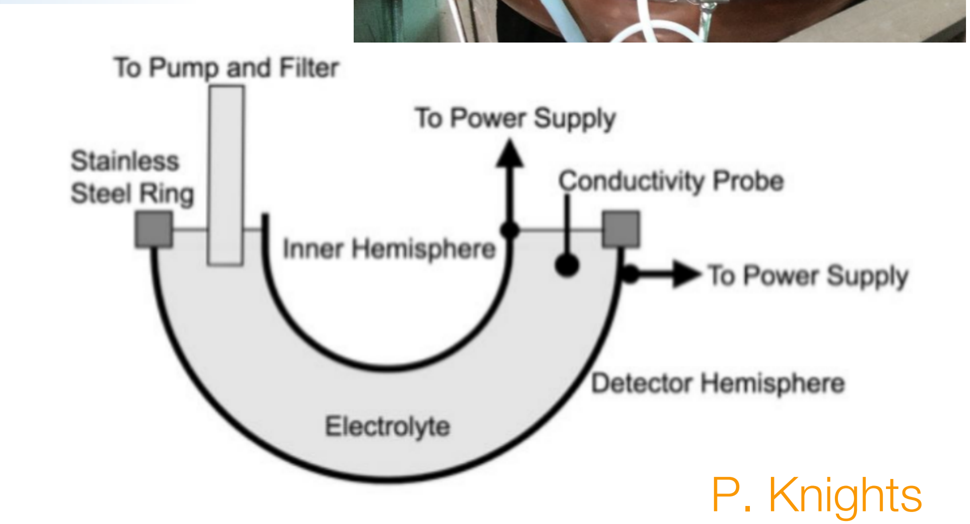
Background mitigation

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

Quenching factor measurements

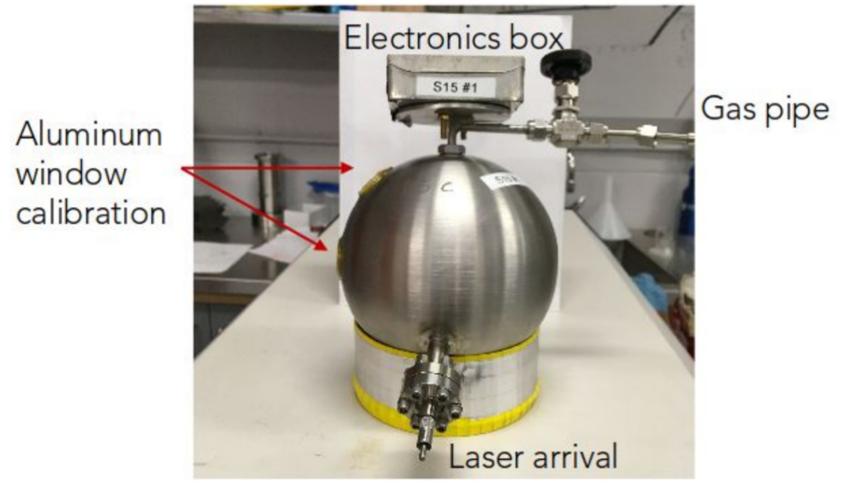
$$W_{\mathrm{nr}} = W_{\gamma}/Q(E)$$

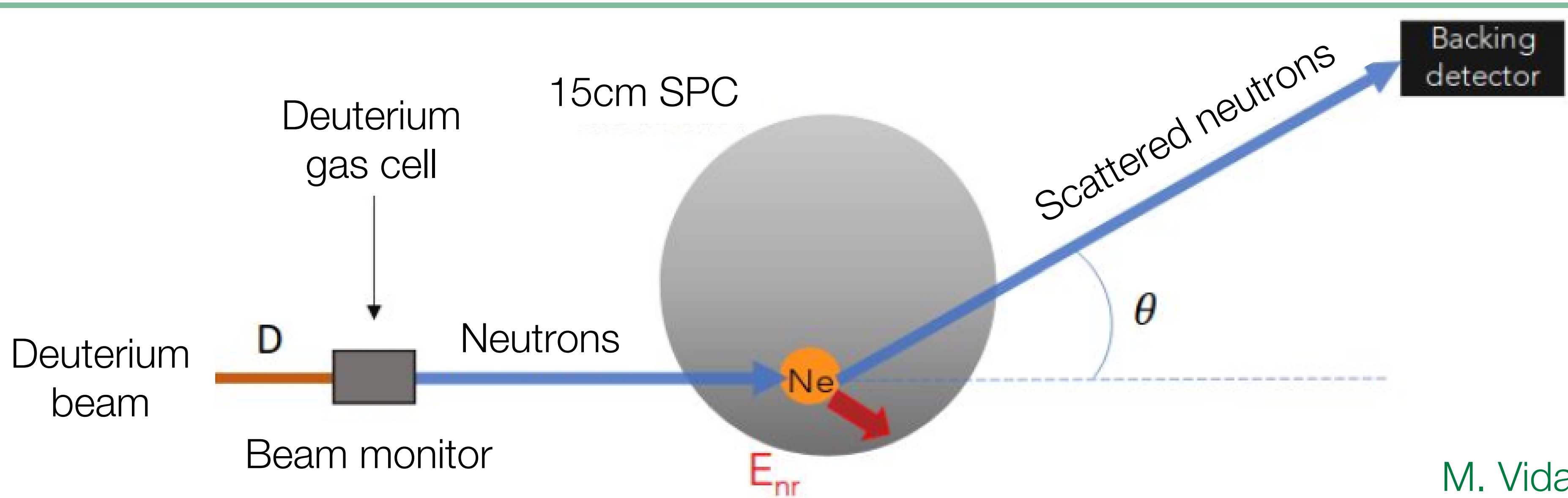
Ongoing measurement campaigns at:

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

Deuterium from a TANDEM accelerator used to produce neutrons: D(D,n)^{3}He

Stainless steel 15 cm Ø sphere





M. Vidal

Quenching factor measurements

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Ongoing measurement campaigns at:

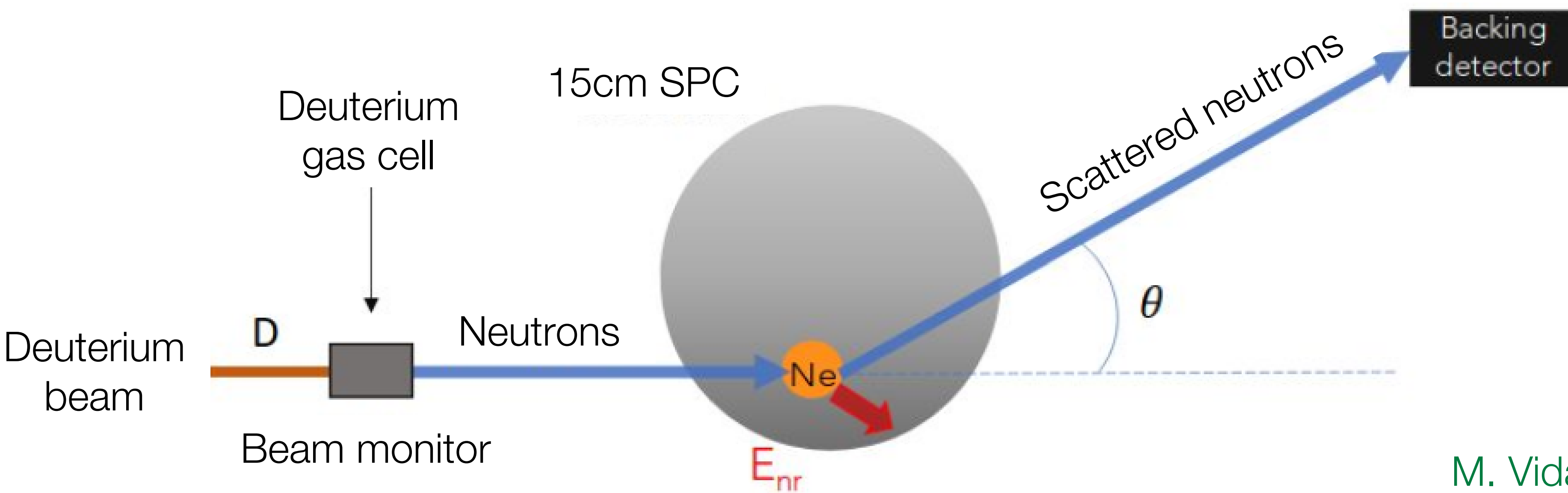
TUNL
Triangle Universities Nuclear Laboratory

Deuterium from a TANDEM accelerator used to produce neutrons: $D(D,n)^3He$

Neon measurement campaign:

Good data at 0.7 keV_{nr}

Working on 0.3 keV_{nr}!



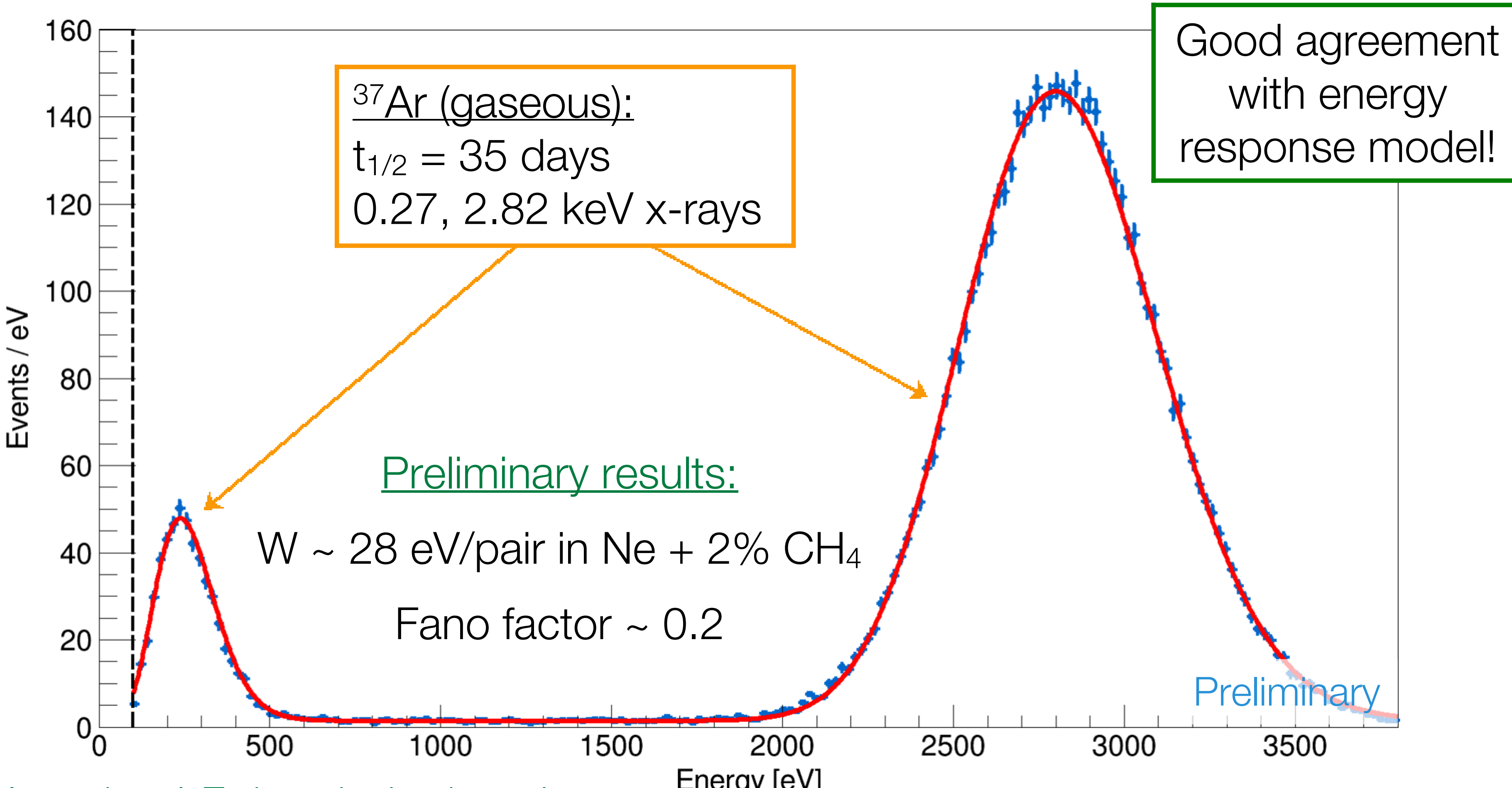
M. Vidal

^{37}Ar calibration

Low energy, detector volume calibration with ^{37}Ar:

D.G. Kelly et al. Journal of Radioanalytical and Nuclear Chemistry 318(1), 279 (2018).

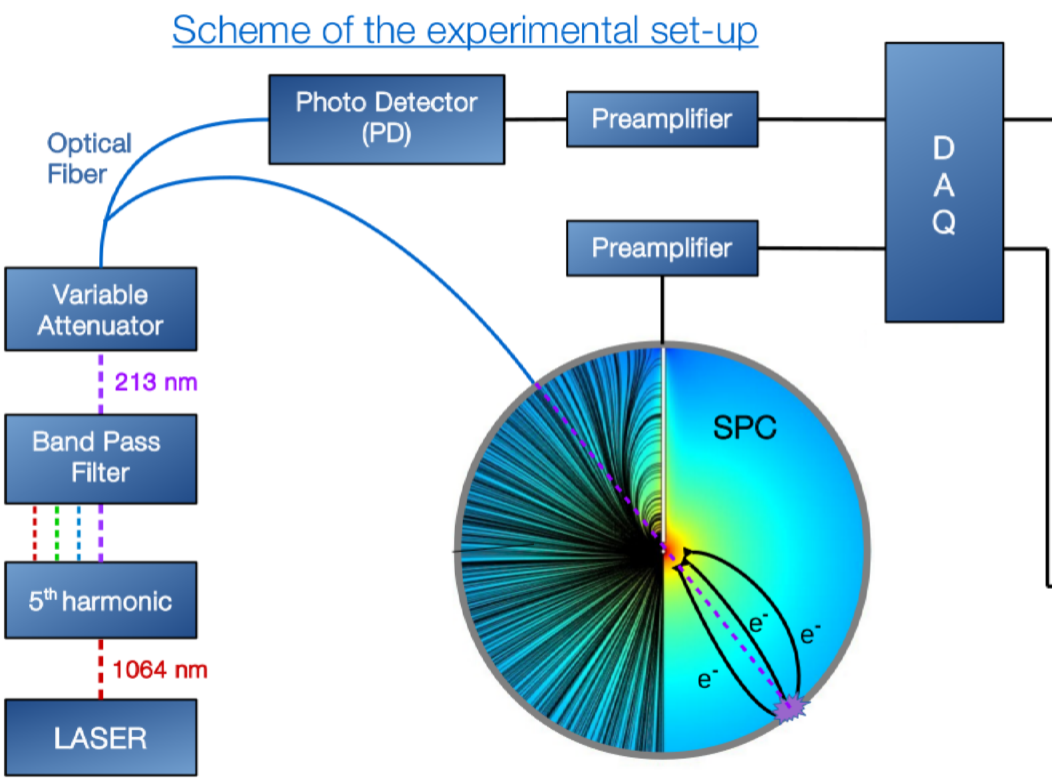
Can also be used to measure the gas properties (W-value, Fano factor)

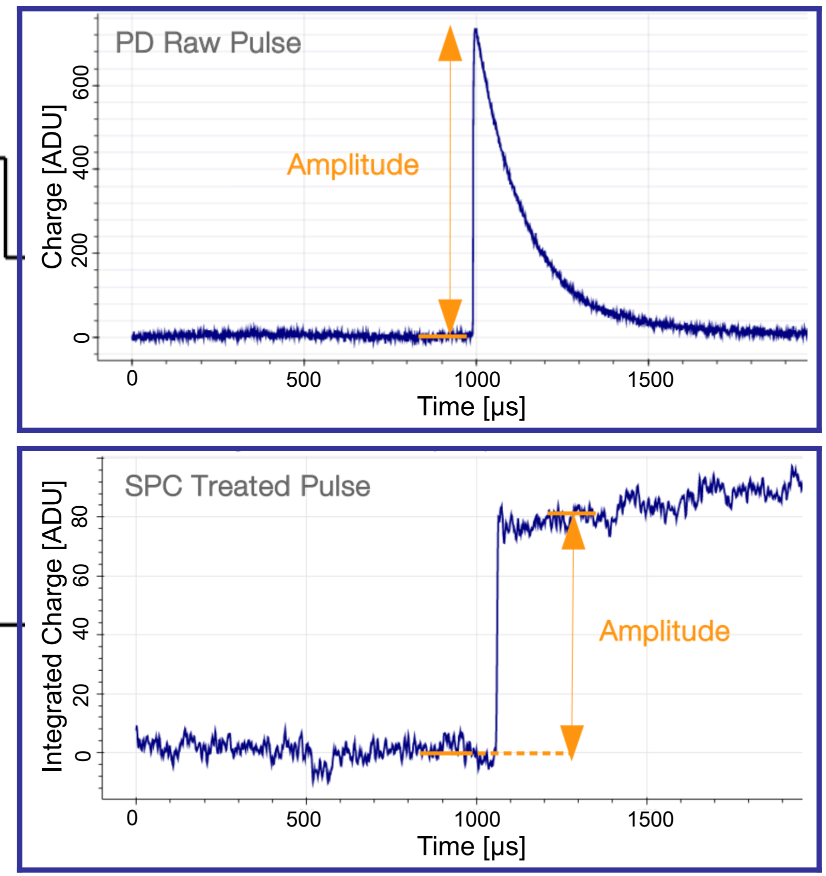


Q. Arnaud et al. To be submitted soon!

UV laser calibration system

- »A 213nm is laser used to extract PEs from the wall of the SPC
- »A photo detector in parallel is used to tag events, monitor laser power
- »Laser intensity can be tuned to extract 1 to 100 photo-electrons

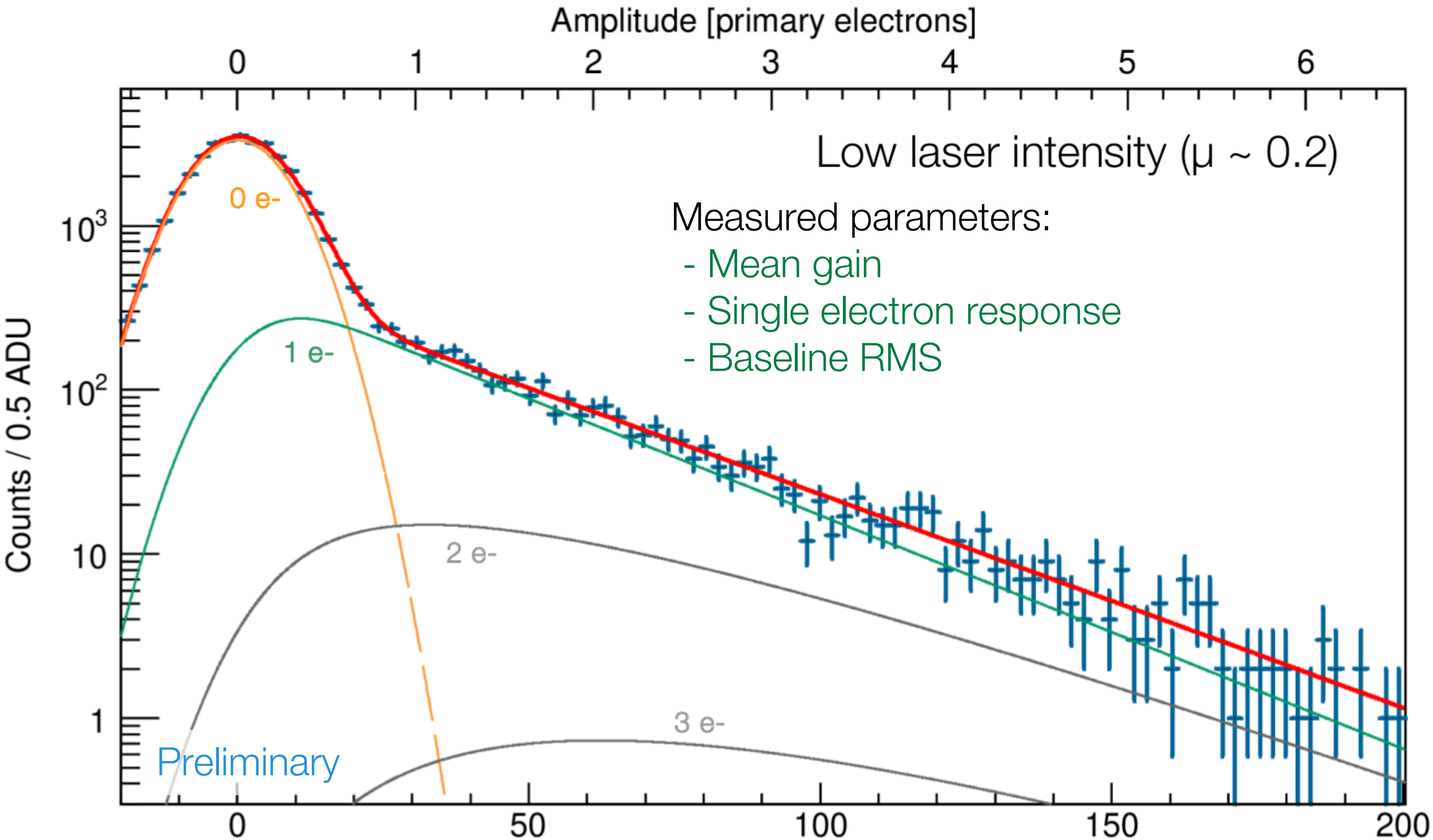




Q. Arnaud et al. To be submitted soon!

UV laser calibration system

Tests detector response model, provides measurement of key parameters



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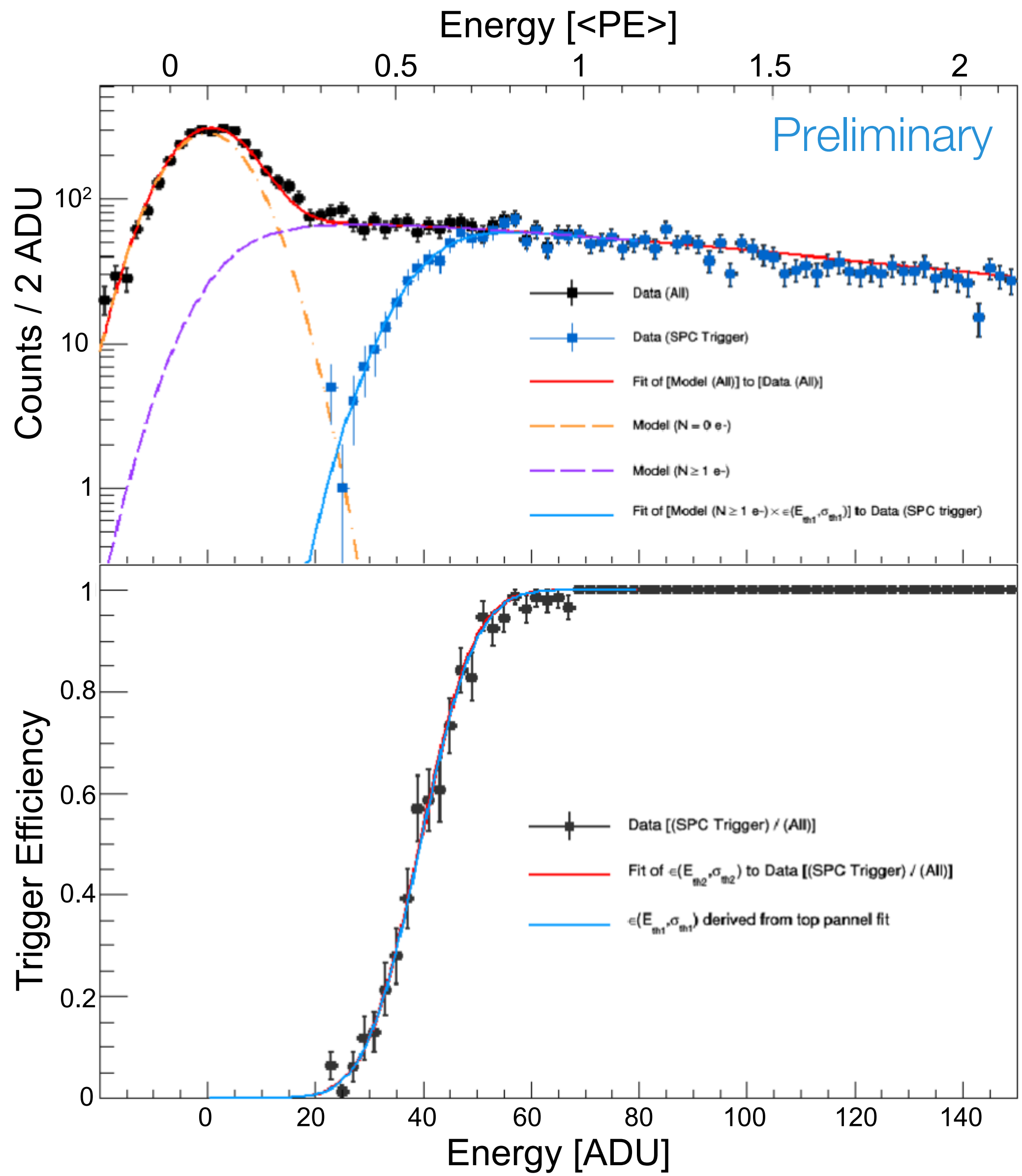
UV laser calibration system

Can be used for measurement of the detector trigger efficiency



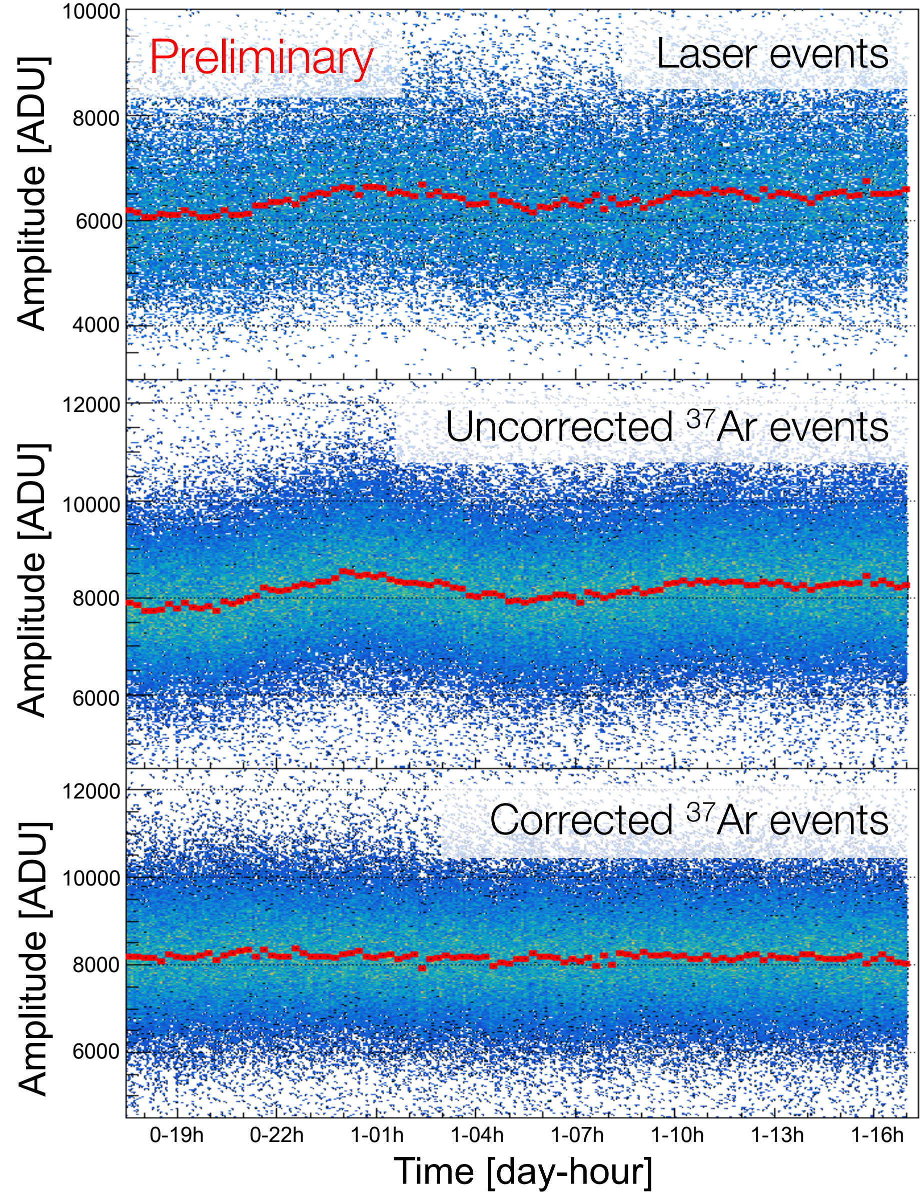
Q. Arnaud et al. To be submitted soon!

UV laser calibration system

Can be used for measurement of the detector trigger efficiency

Real-time monitoring of the detector response, measurements of electron drift times...

Monitoring and correction of gain to ~1% precision



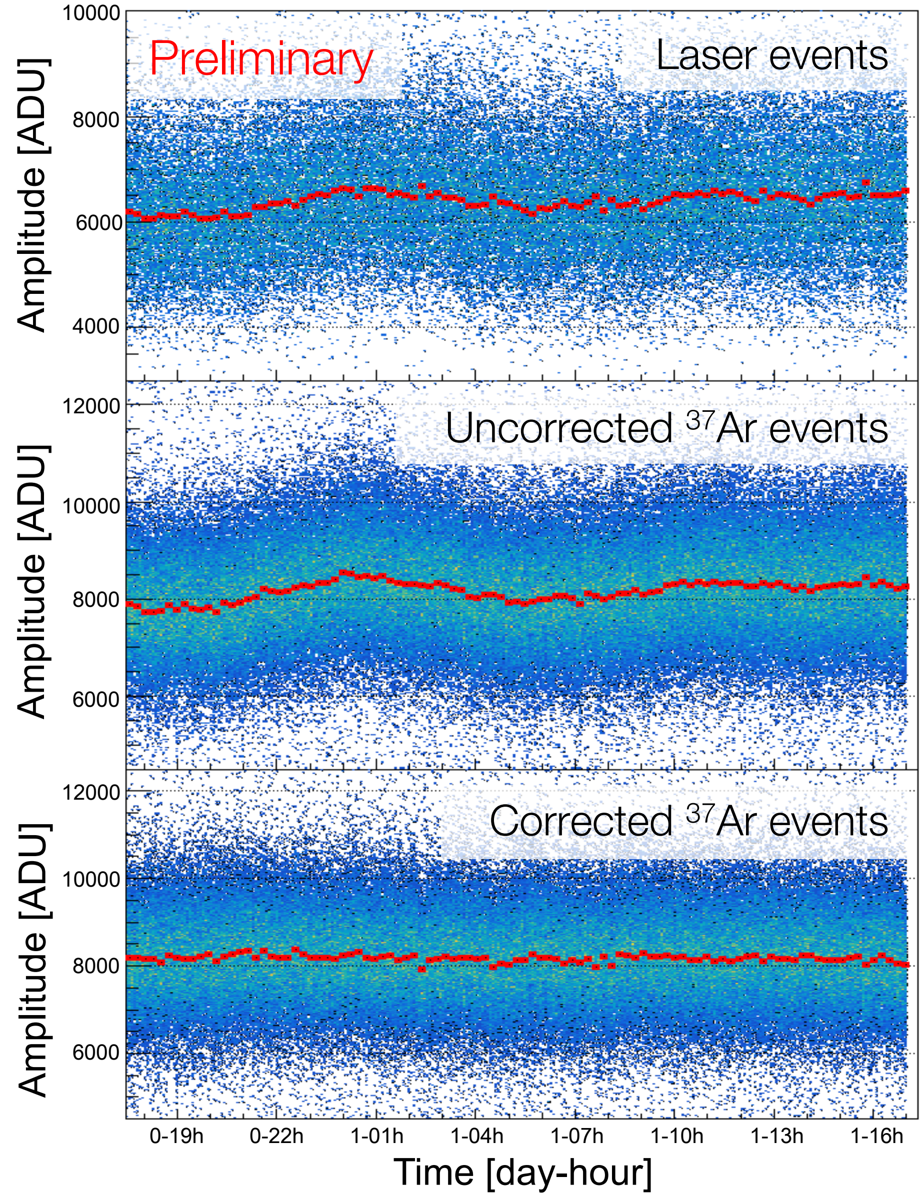
Q. Arnaud et al. To be submitted soon!

UV laser calibration system

Can be used for measurement of the detector trigger efficiency

Real-time monitoring of the detector response, measurements of electron drift times...

Will be operated continuously during WIMP search run



Q. Arnaud et al. To be submitted soon!

Improved understanding of SPCs

Analytical model of detector energy response:

$$\frac{dR}{dE}(E_{ee}) = \int_0^{E_{\max}} \frac{dR}{dE}(E_{nr}) \times \sum_{N=0}^{N_{\max}} \left[P_{\text{COM}}\left(N|\mu, F\right) \times P_{\text{Polya}}^{(N)}\left(E_{ee}|\theta, \langle G \rangle\right)\right] dE_{nr}$$

$$N_{\max} = \left\lfloor \frac{E_{nr}}{I} \right\rfloor \qquad \mu = E_{nr} \times \left(\frac{Q(E_{nr})}{W(E_{nr})}\right)$$

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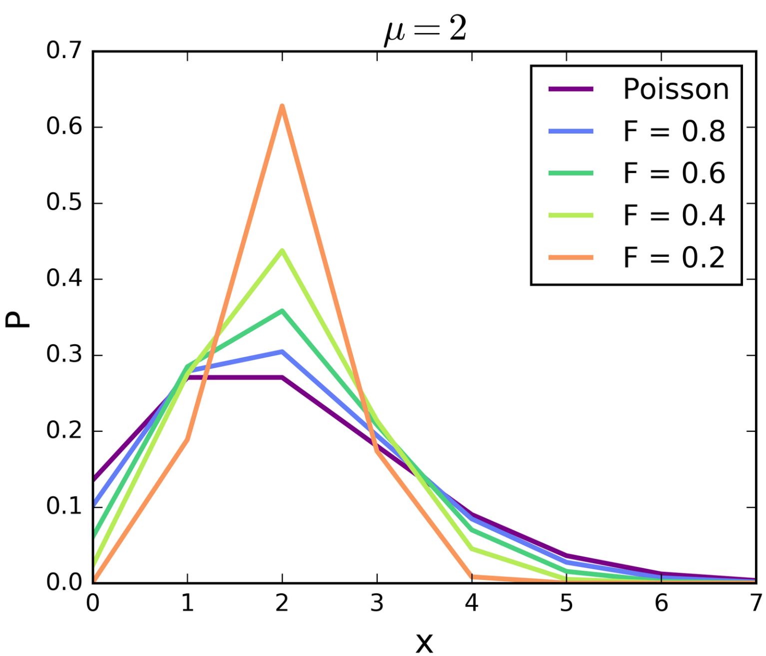
Using the COM-Poisson distribution for primary and Polya for secondary ionization:



D. Durnford et al. Phys. Rev. D98, 103013 (2018)

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

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

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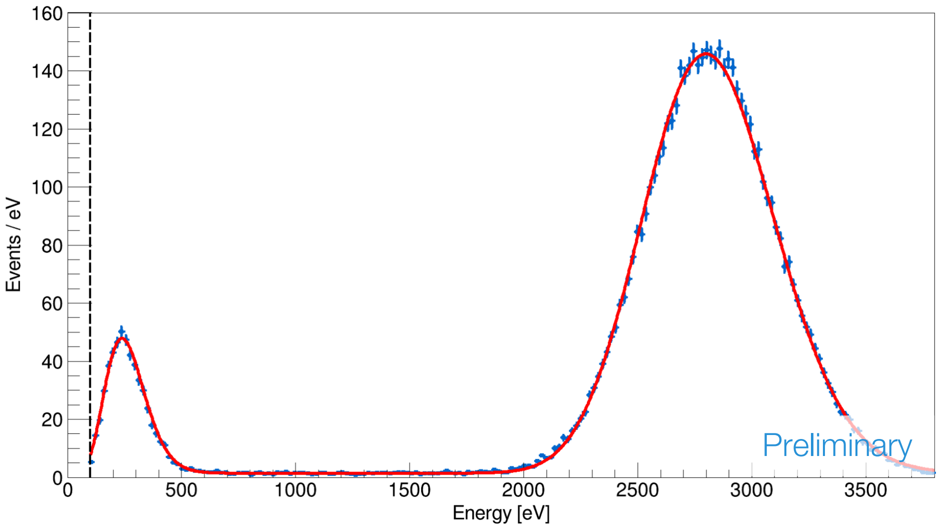
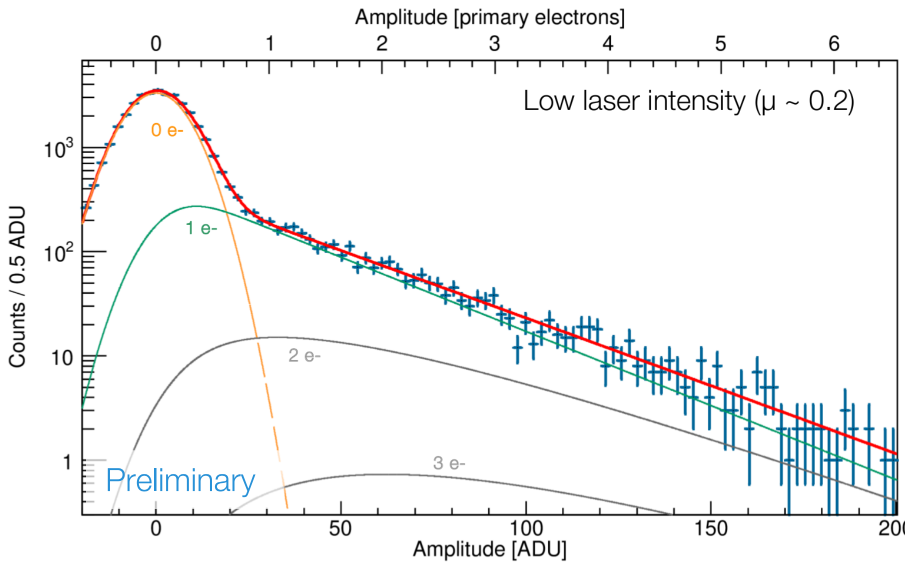
Supported by UV laser and ^{37}Ar data (Q. Arnaud et al. To be submitted soon!)

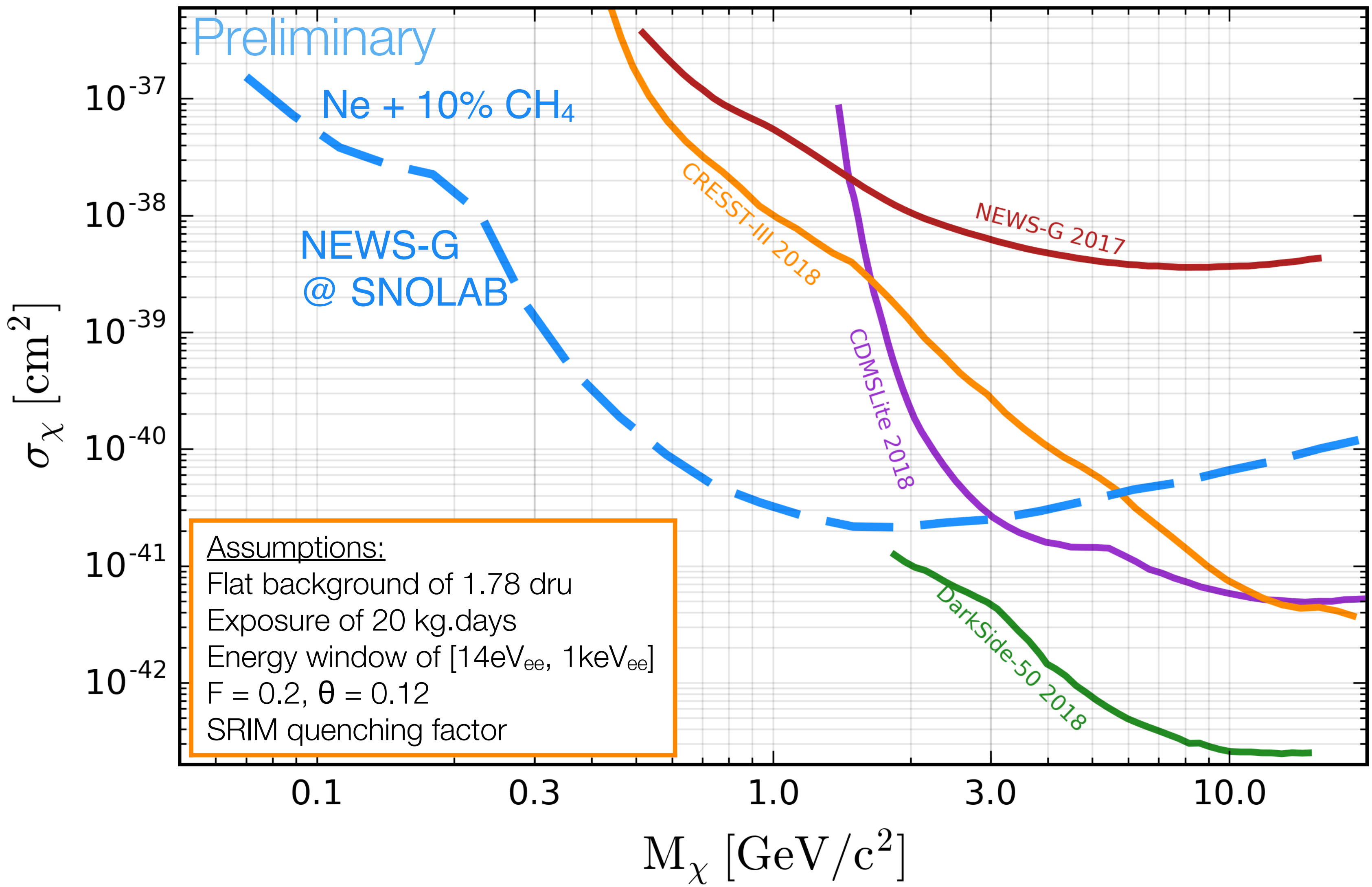




Allows for improved analysis with the optimum interval method

Projected WIMP Sensitivity

Installation in SNOLAB to start late 2019



Thank you!

Queen's University Kingston - G Gerbier, P di Stefano, R Martin, G Giroux, S Crawford, M Vidal, G Savvidis, A Brossard, P Vazquez dS, Q Arnaud, K Dering, J McDonald, M Chapellier, A Ronceray, P Gros, A Rolland, C Neyron
- 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, 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 archaeological lead
- Coordination for lead/PE shielding and copper sphere

Aristotle University of Thessaloníki - 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 Northwest National Laboratory - E Hoppe, R Bunker
- Low activity measurements, copper electro-forming

RMCC (Royal Military College of 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 Knights
- Simulations, analysis, R&D

University of Alberta - MC Piro, D Durnford
- Gas purification, data analysis

Associated labs: TRIUMF - F Retiere

The NEWS-G Collaboration
(September 2018)

Extra Slides

Event simulation

1) Electric field model from finite element software (COMSOL)

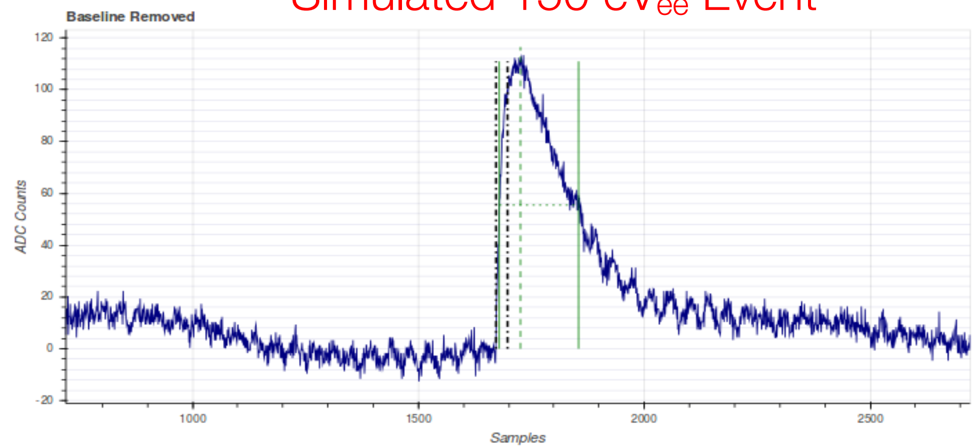
2) Drift of charges simulated with inputs from Magboltz

3) Energy response simulated (see slide 17)

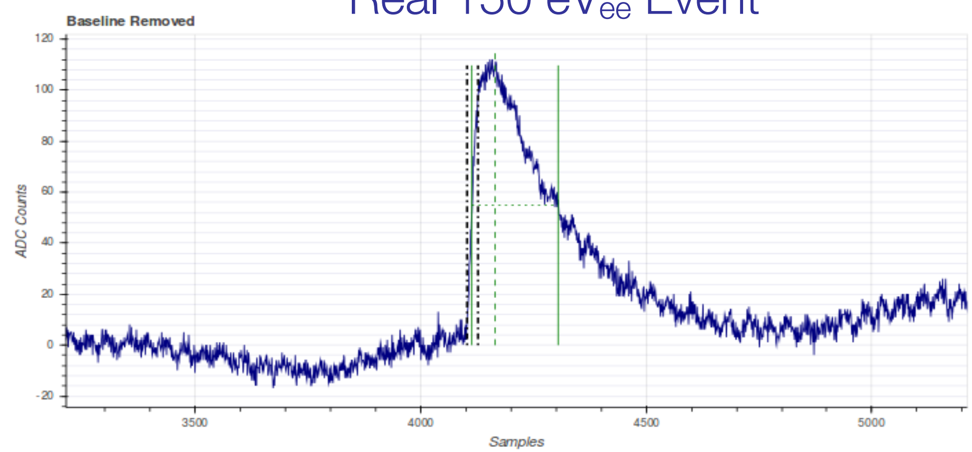
4) Pulses simulated: pre-amp response, ion current, noise

5) Same treatment as real data

Simulated 150 eV_{ee} Event



Real 150 eV_{ee} Event



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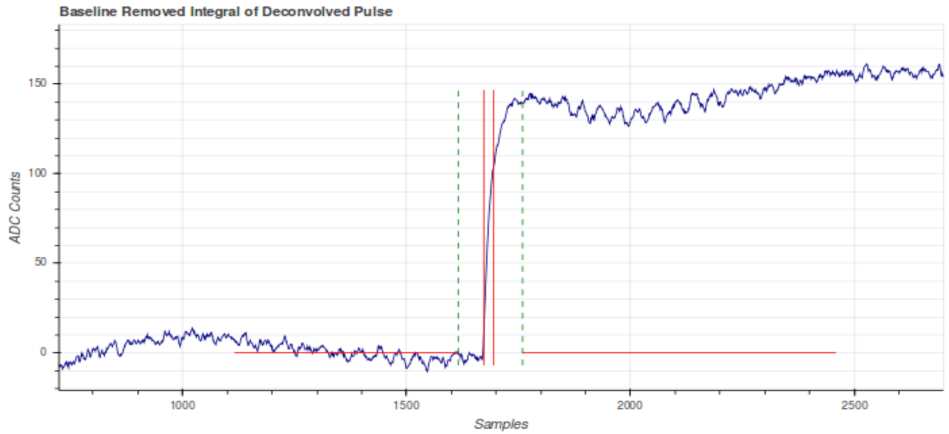

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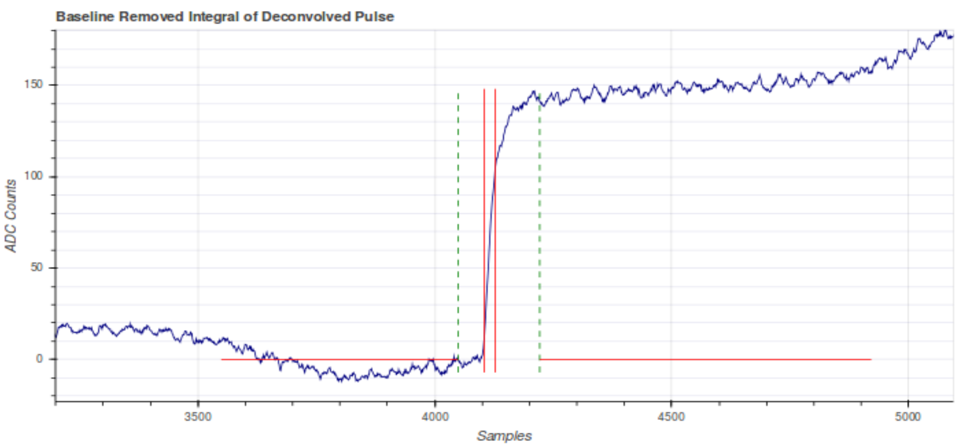

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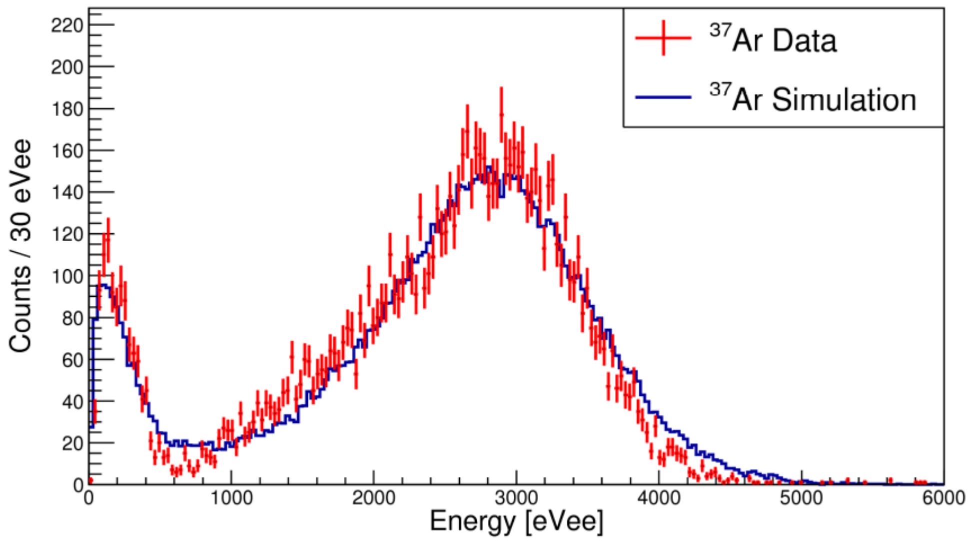
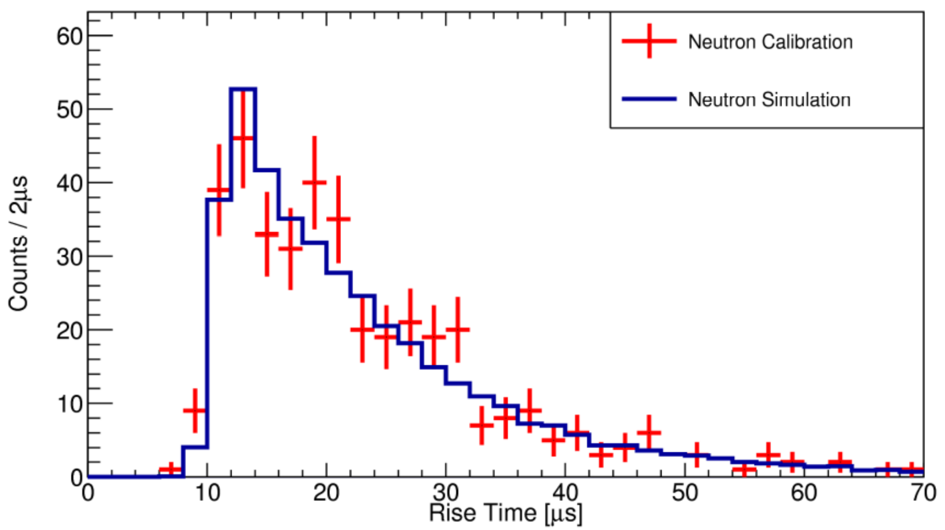
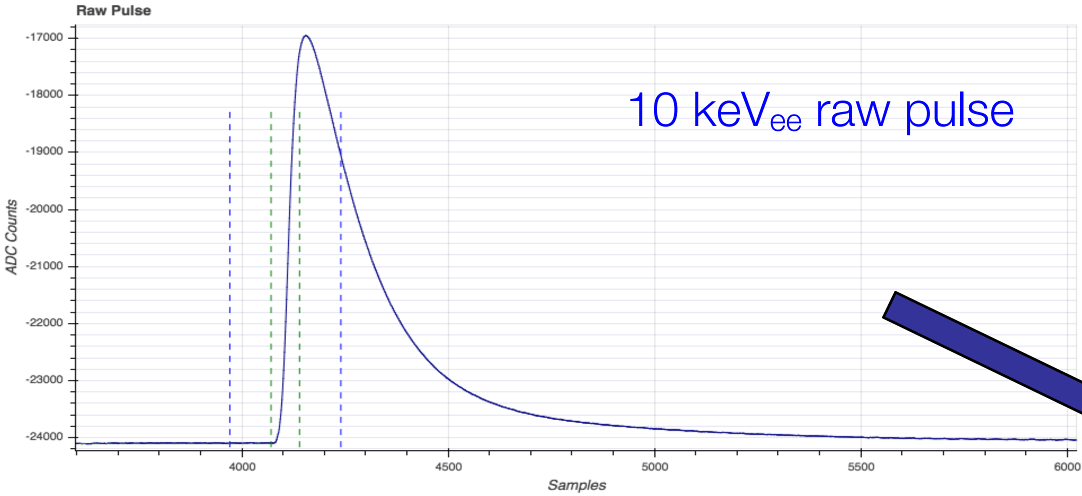
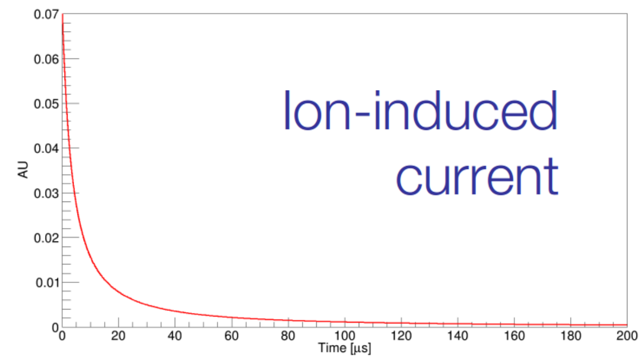


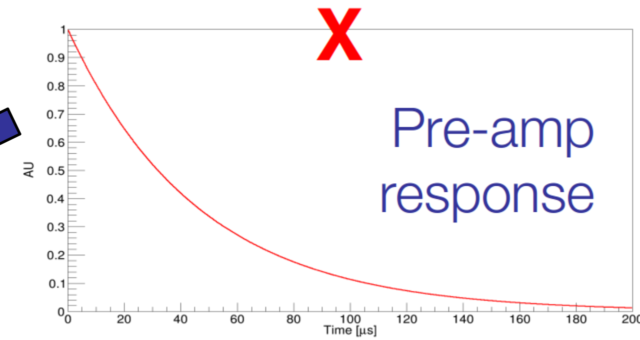


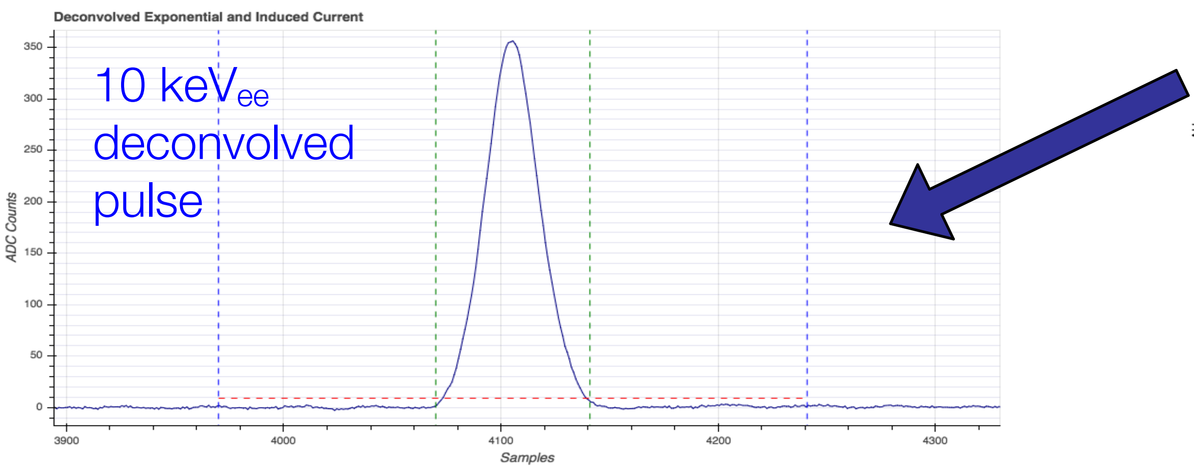
Pulse treatment



Deconvolve for amplifier response and ion-induced current





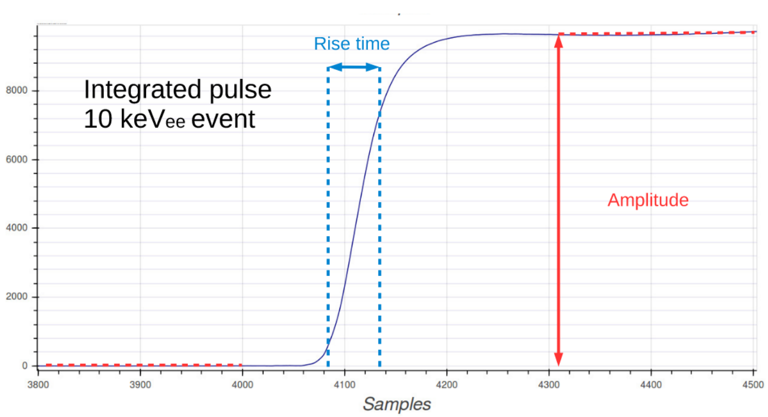


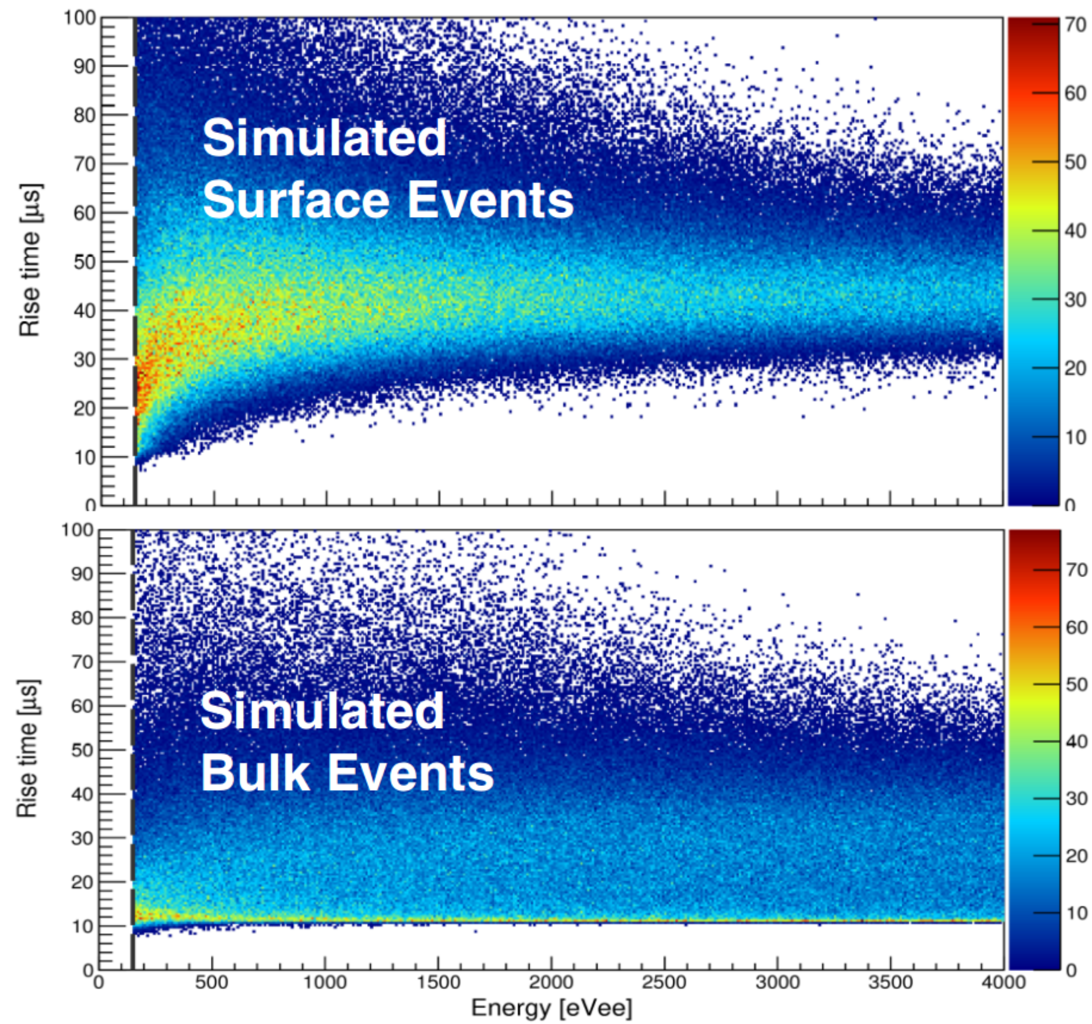
Rise time

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).

Gas handling improvements

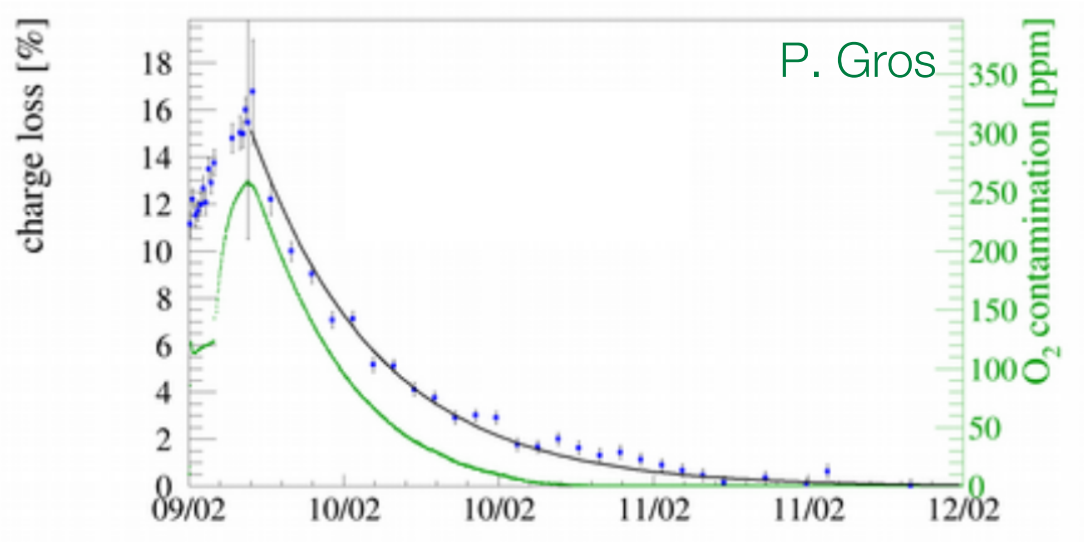
»Oxygen and water in the gas can dramatically reduce signal amplification

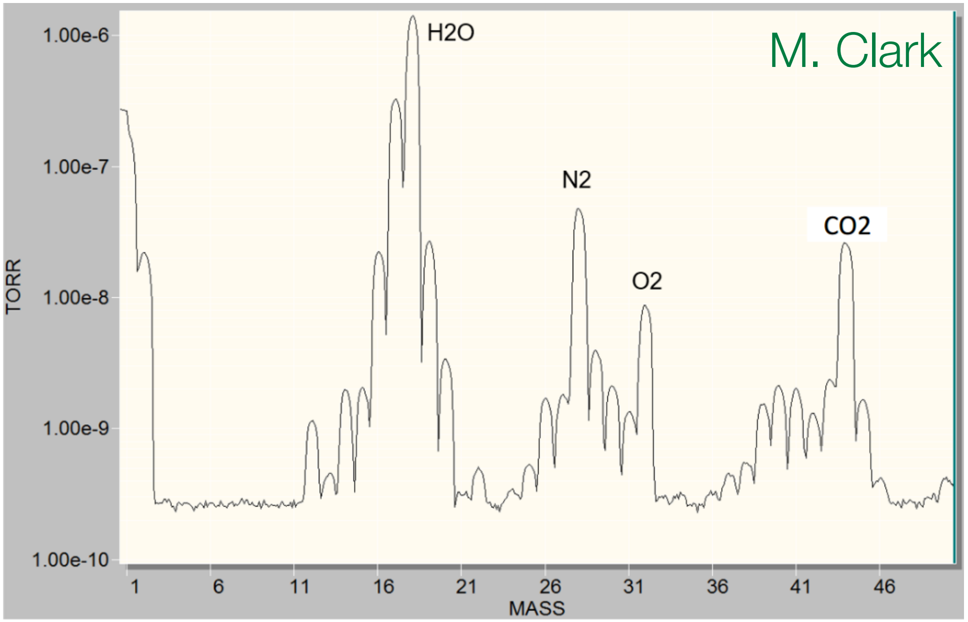
»A “getter” filter will be used to remove these contaminants

»A residual gas analyzer will be used to measure gas contaminants in-situ

»A radon trap will be used (radon mostly emitted by the getter)

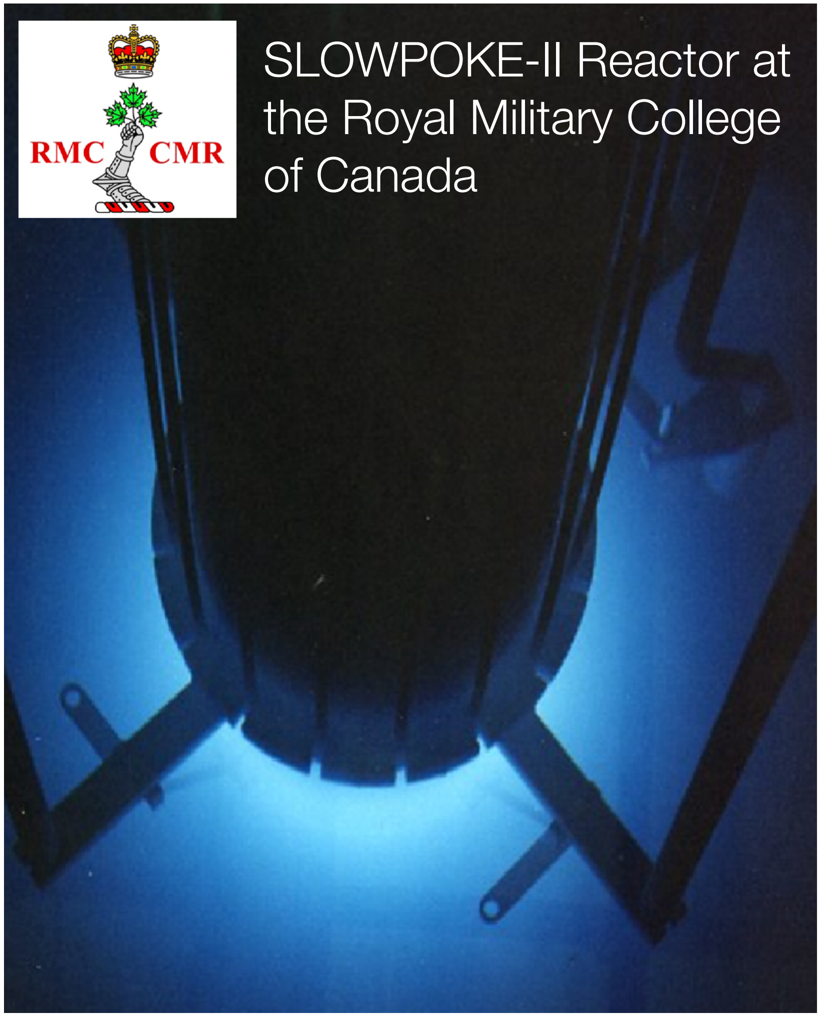
»Testing of activated carbon traps is ongoing





Production of ^{37}Ar

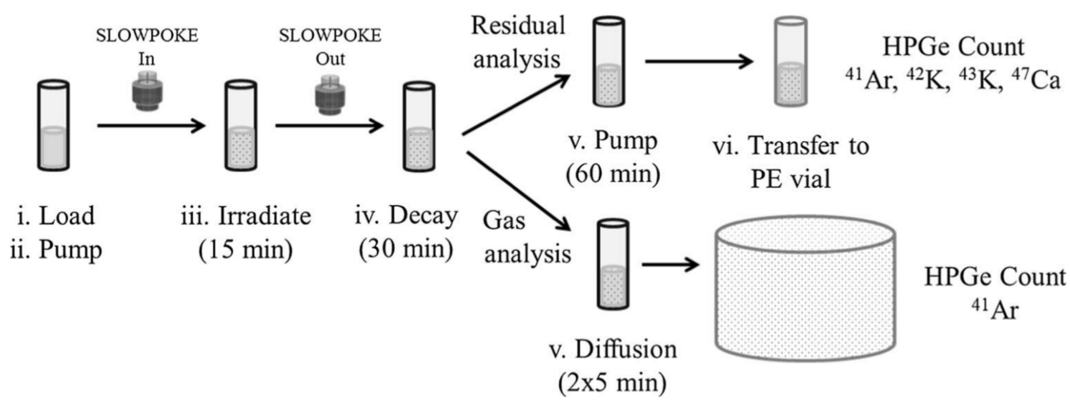
Collaborators at the RMCC produce samples with a fission reactor:



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

Source produced in an oxygen-free environment

Counting of gaseous and solid by-products allows for indirect measurement of ^{37}Ar production



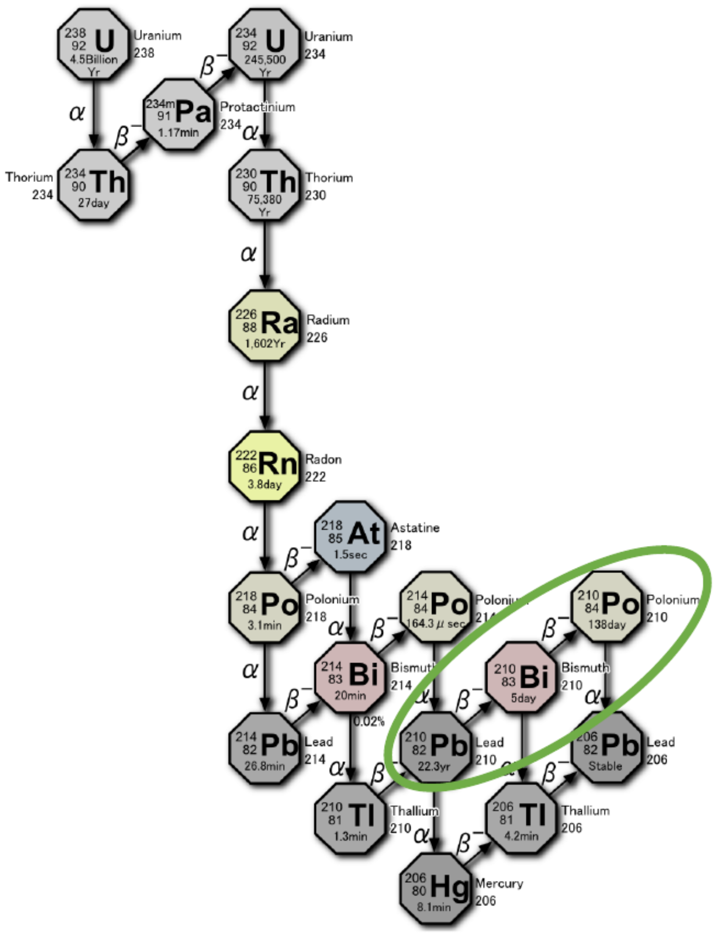
D.G. Kelly et al. Journal of Radioanalytical and Nuclear Chemistry 318(1), 279 (2018).

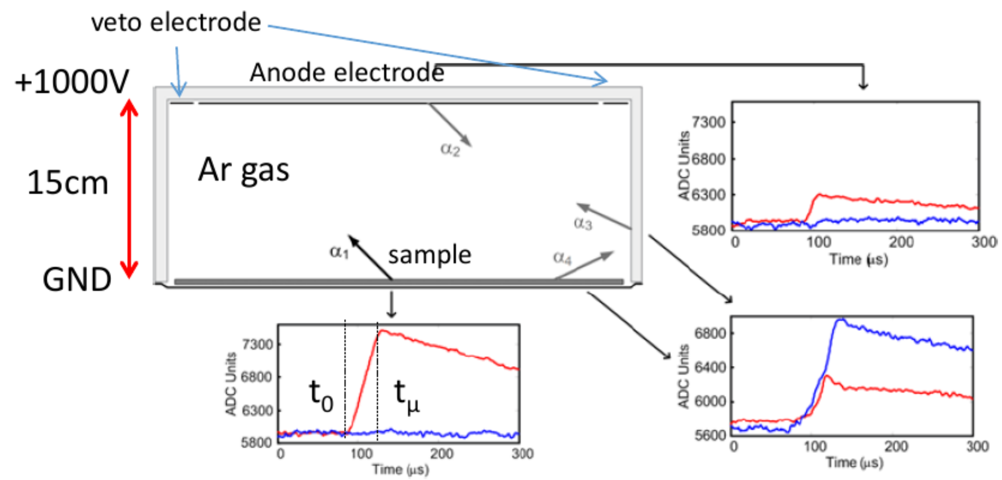
Measurement of ^{210}Pb

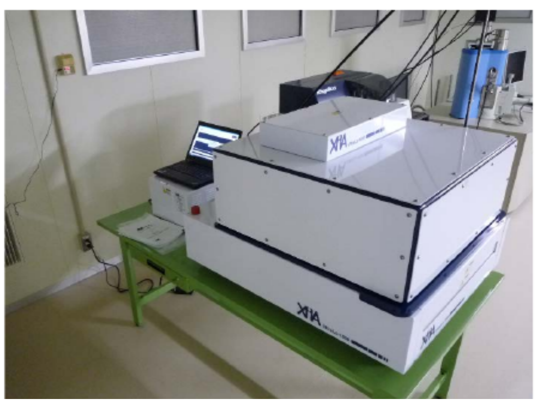
Can't entirely eliminate background, so it must be measured

The XMASS collaboration from measures ^{210}Po alpha's with an XIA detector

The ^{210}Po activity can be used to calculate the concentration of ^{210}Pb







K Kobayashi (LRT 2017)

signal

veto signal

By measuring rise time (t_μ-t_0), surface event can be distinguished from event in Ar gas or ceiling.

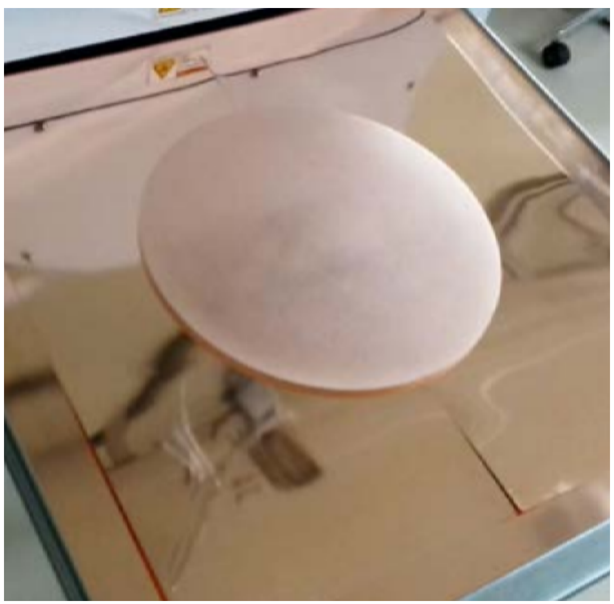
Measurement of ^{210}Pb

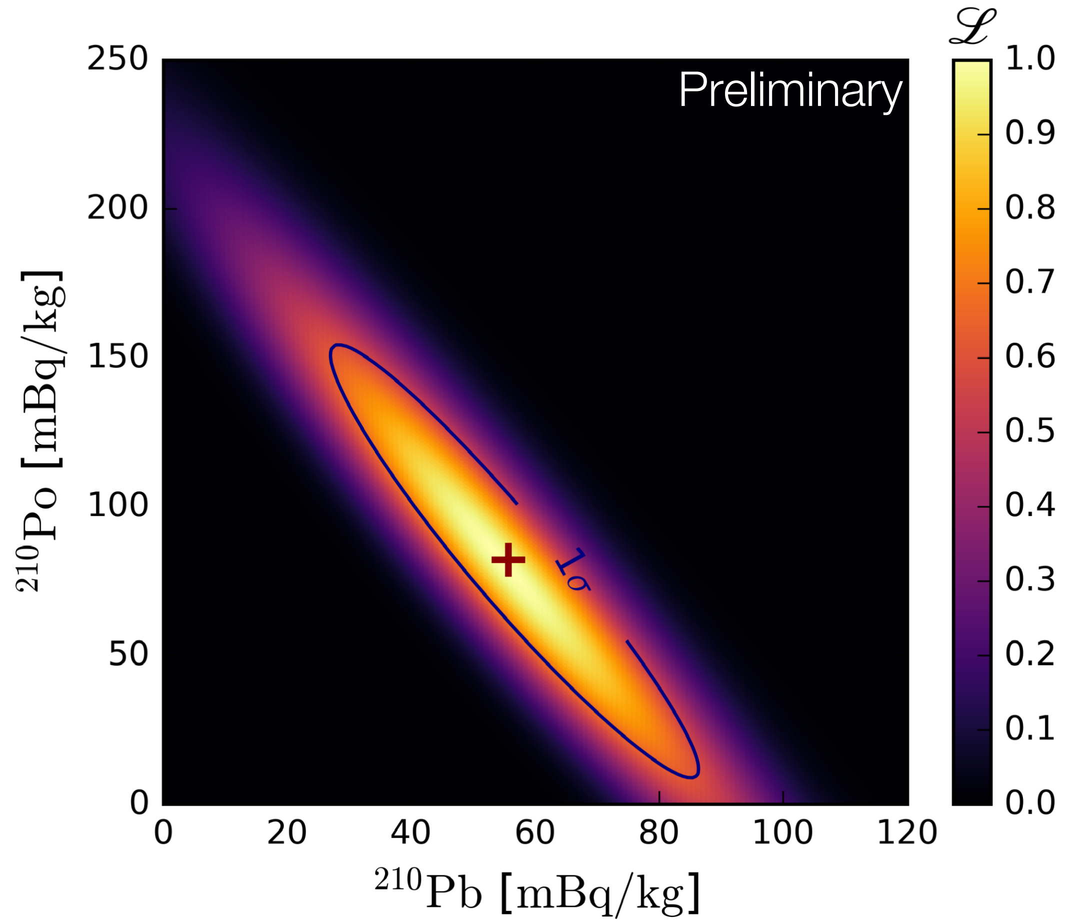
They have already published on this technique:

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

NEWS-G is collaborating with them to measure a sample of our copper:

Measurement campaign ongoing!





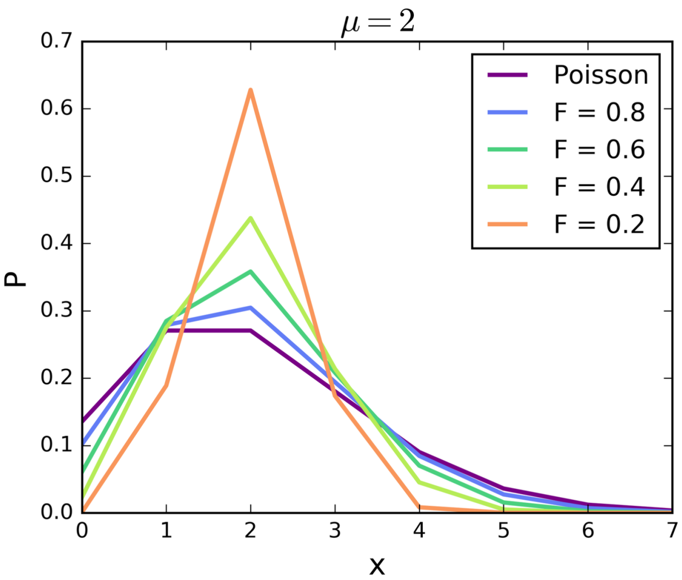
Accounting for the Fano factor

Properly modelling primary ionization statistics is still an open question

We plan to use the COM-Poisson distribution to do this:
D. Durnford et al. Phys. Rev. D98, 103013 (2018)

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

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



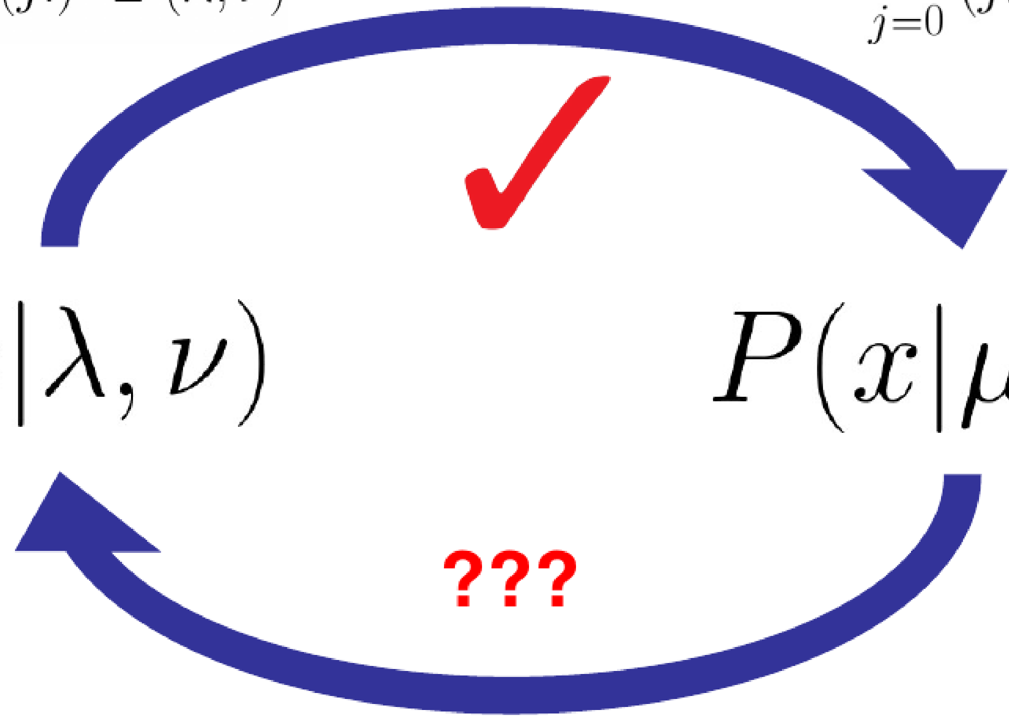
»A flexible, 2 parameter discrete distribution
»Can be used for model F > 1 or F < 1
»Extensive published work on fitting data
»The distribution parameters do not correspond to physical quantities, but look-up tables have been created to allow for practical use of this distribution

Accounting for the Fano factor

The problem...

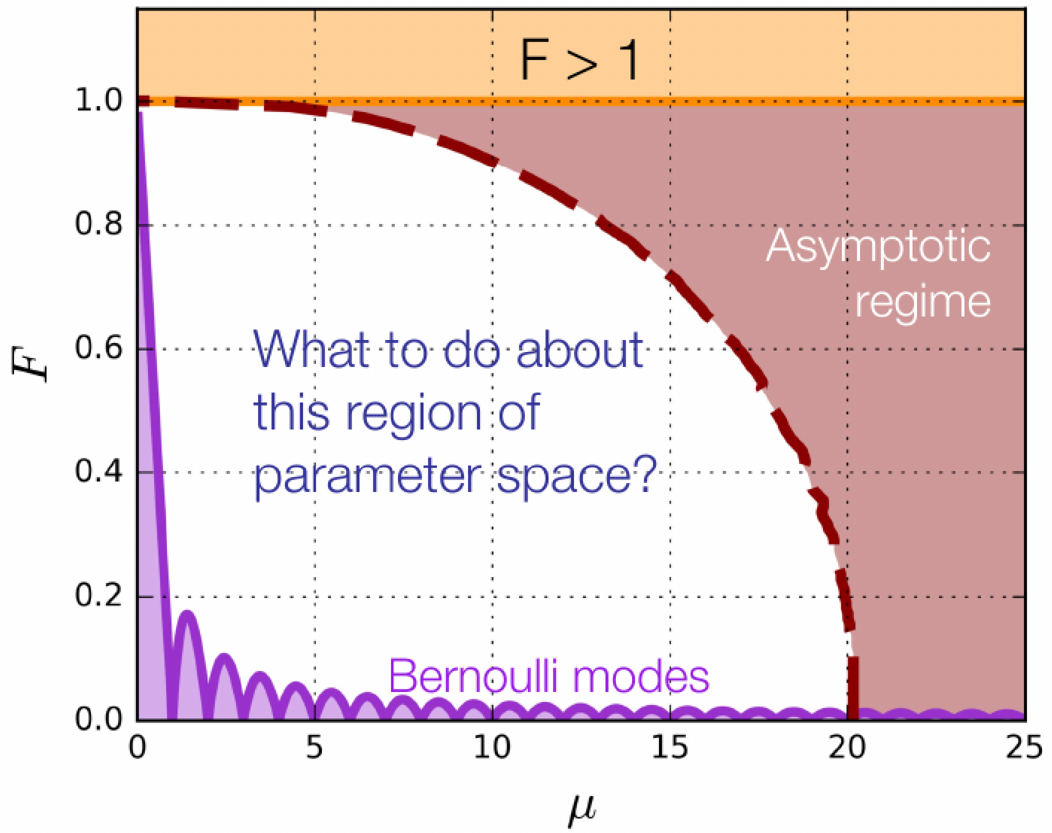
$$\mu\left(\lambda,\nu\right)=\sum_{j=0}^{\infty}\frac{j\lambda^{j}}{\left(j!\right)^{\nu}Z\left(\lambda,\nu\right)} \qquad \sigma^{2}\left(\lambda,\nu\right)=\sum_{j=0}^{\infty}\frac{j^{2}\lambda^{j}}{\left(j!\right)^{\nu}Z\left(\lambda,\nu\right)}-\mu\left(\lambda,\nu\right)^{2}$$

$$P(x|\lambda,\nu) \qquad P(x|\mu,F)$$



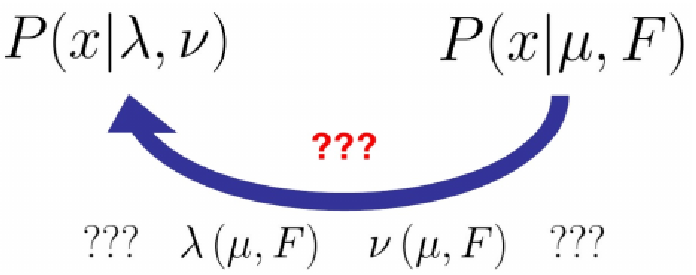
$$??? \quad \lambda\left(\mu,F\right) \quad \nu\left(\mu,F\right) \quad ???$$

Accounting for the Fano factor



At high μ/F, there are asymptotic expressions we can use!

Solves this problem:

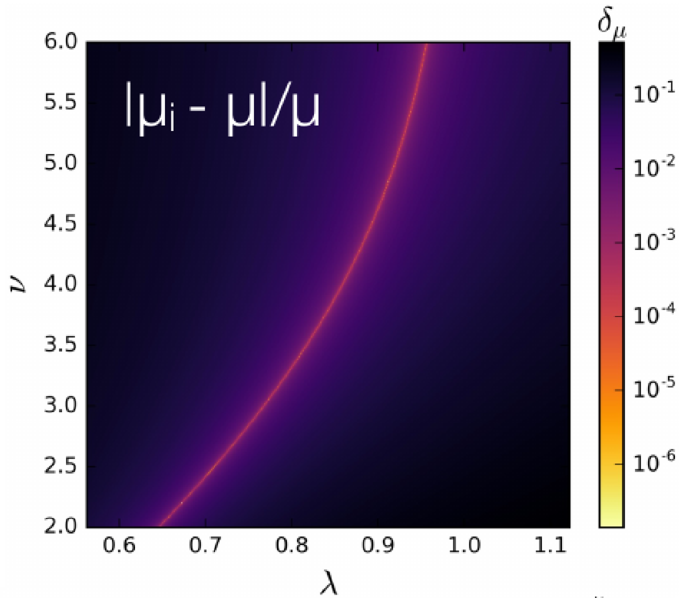


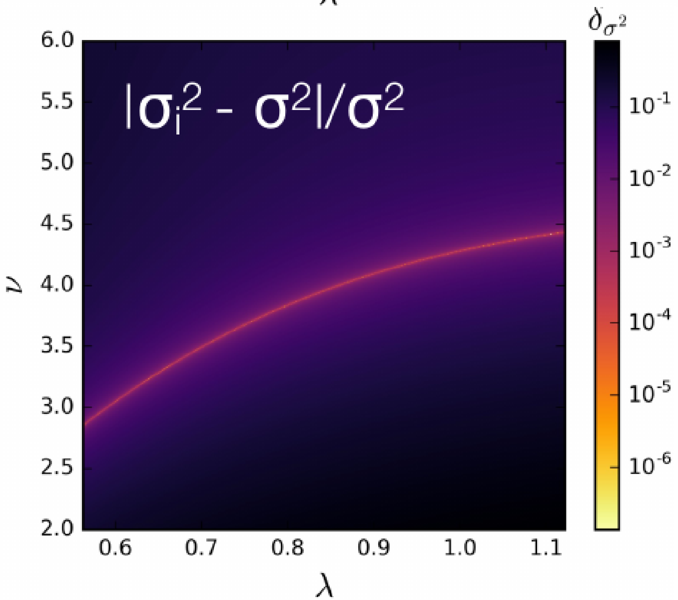
$$\lambda(\mu, F) \approx (\nu\mu F)^{\nu}$$

$$\nu(\mu, F) \approx \frac{2\mu + 1 + \sqrt{4\mu^2 + 4\mu + 1 - 8\mu F}}{4\mu F}$$

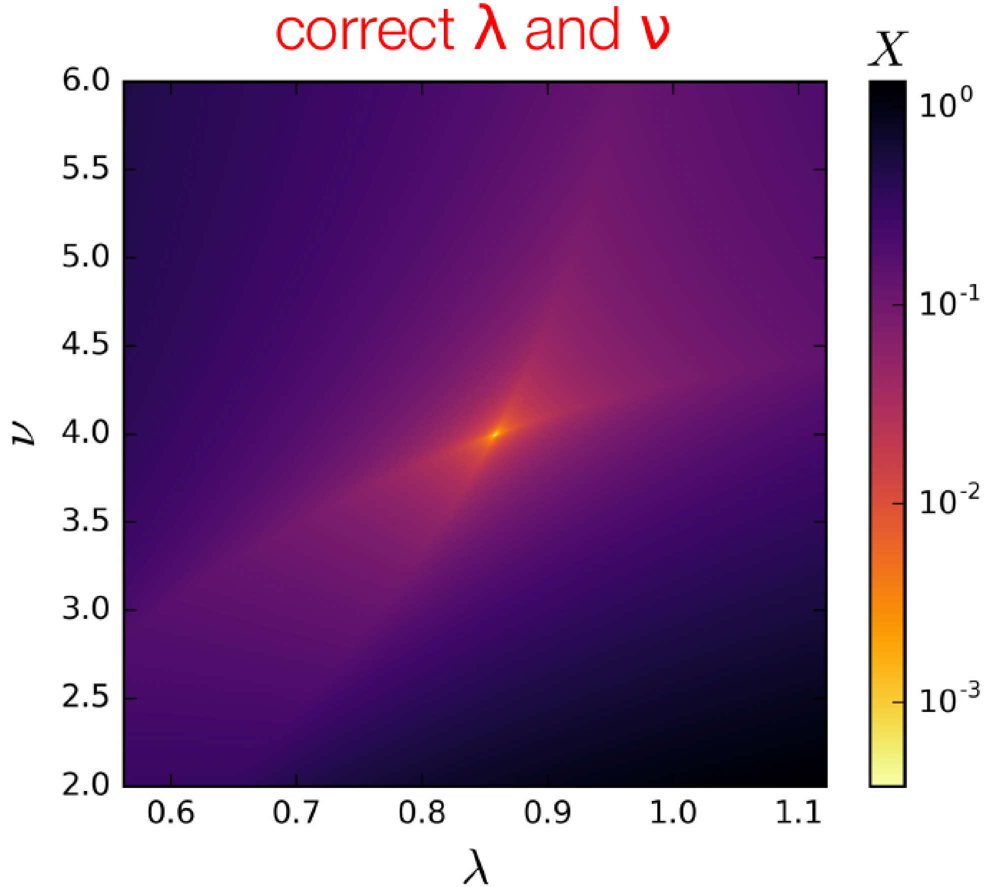
Accurate to ≤ 0.01%

Accounting for the Fano factor





Minimize X to find the correct λ and ν

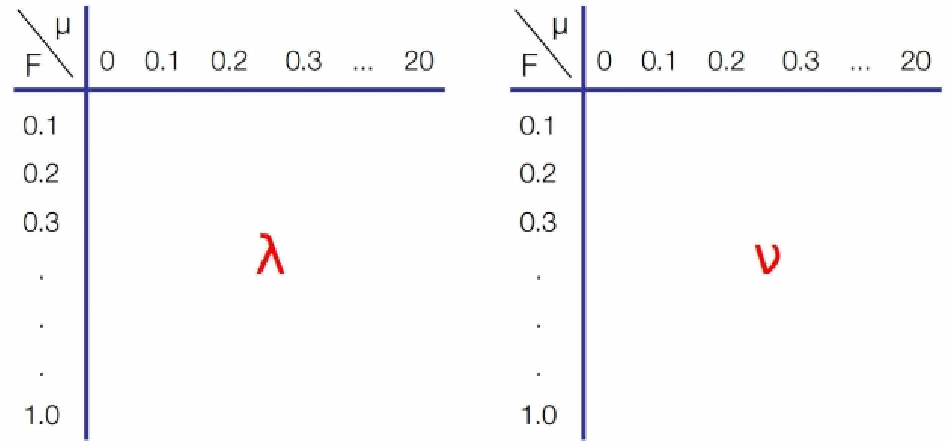


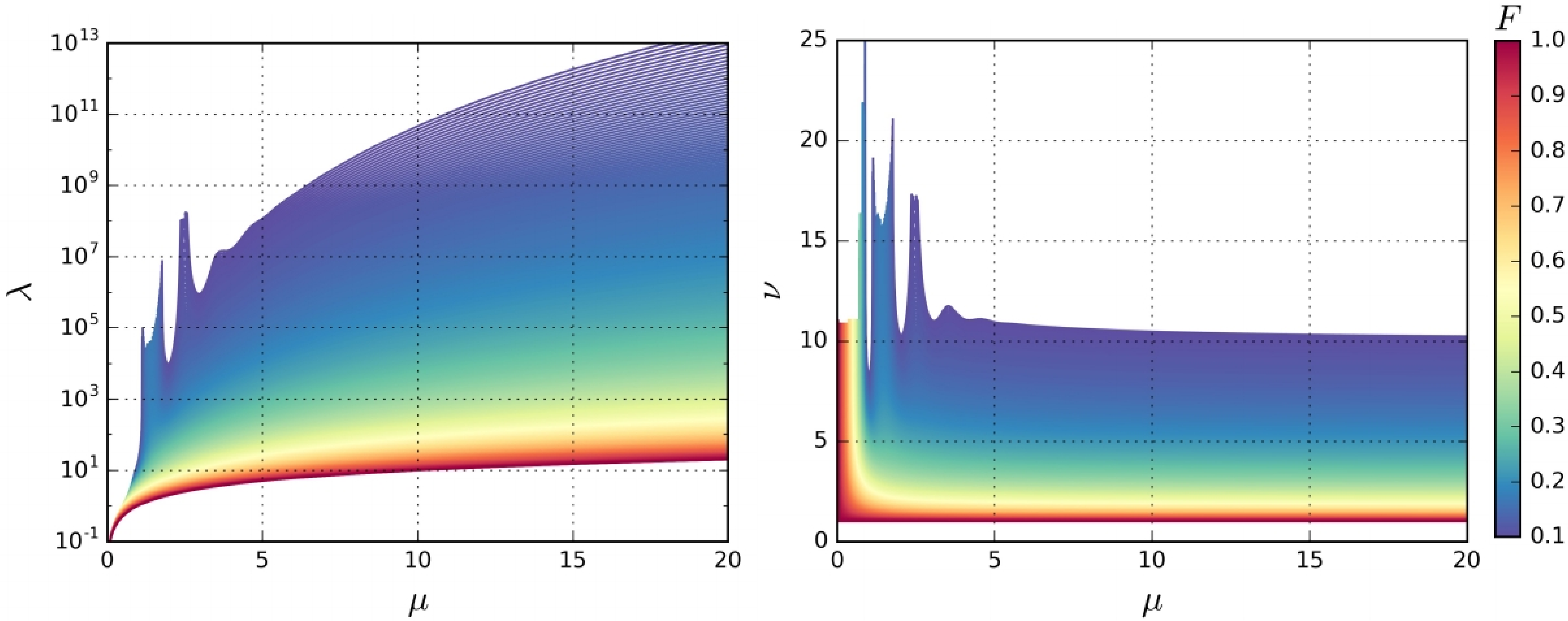
$$X = \left(\left| w_1 \frac{\mu - \mu_i}{\mu} \right| + \left| w_2 \frac{\sigma^2 - \sigma_i^2}{\sigma^2} \right| \right)^p$$

Accounting for the Fano factor

The minimization algorithm is relatively slow

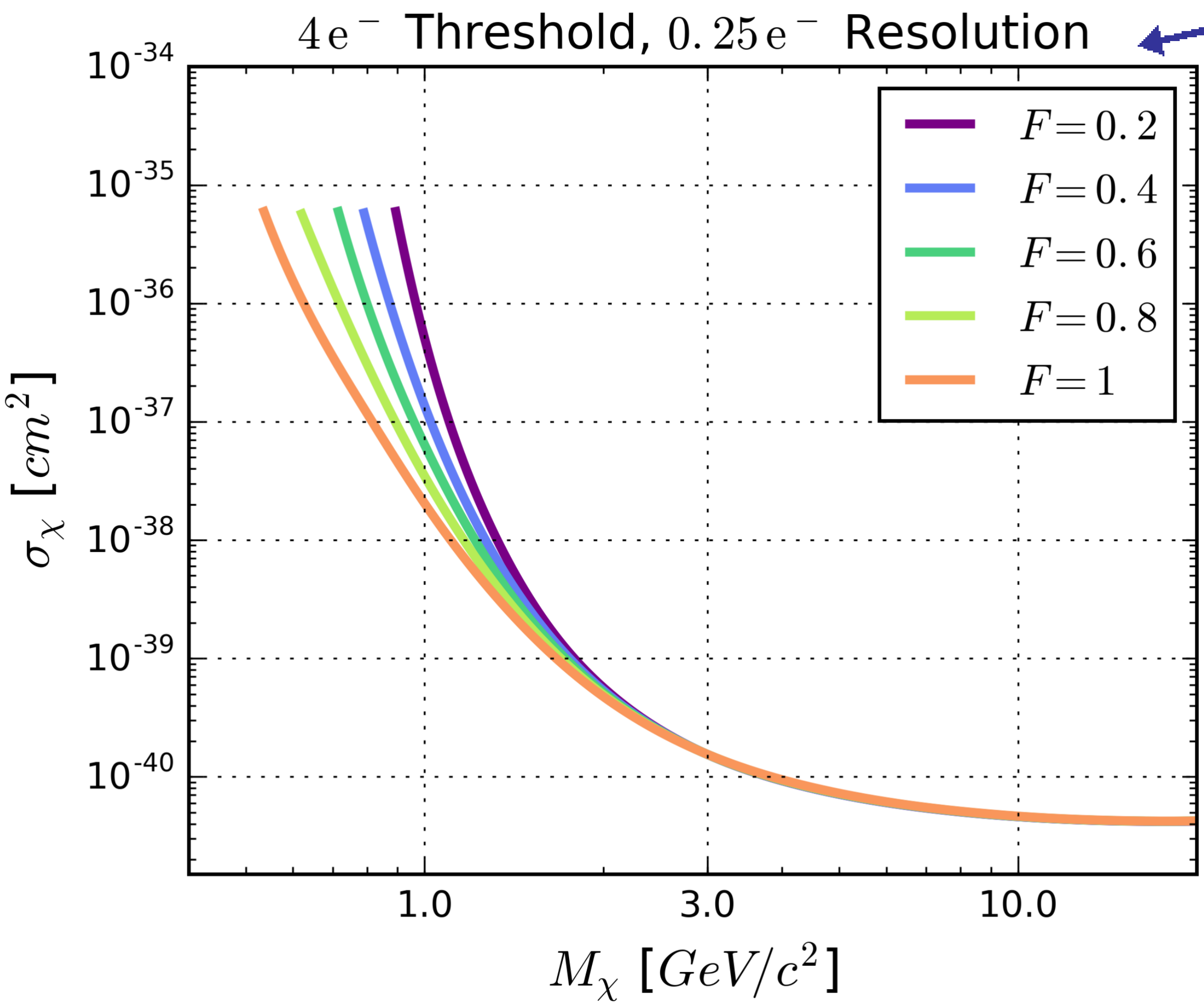
We have run it for a large range of values of μ/F and stored the results in look-up tables





Accounting for the Fano factor

We can use this tool to assess the impact on low-mass DM experiments



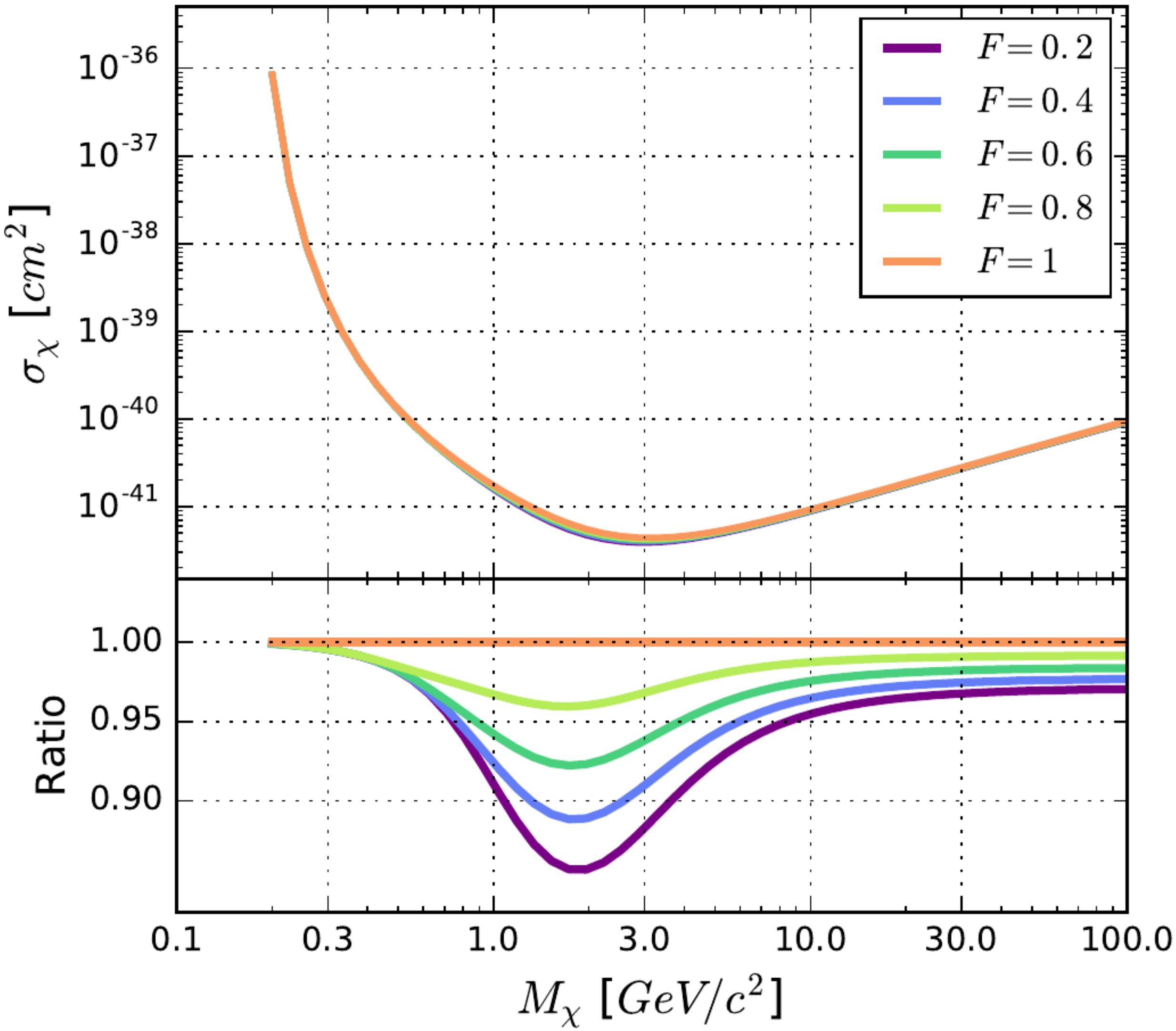
(i.e. CCD detectors like DAMIC)

F can have a big impact!

Neon experiment modelled with COM-Poisson + Gaussian resolution

Accounting for the Fano factor

We can use this tool to assess the impact on low-mass DM experiments



...but probably won't for NEWS-G

Neon experiment modelled with COM-Poisson + Polya, $1e^-$ to 1 keV_{nr} energy window

Why not the binomial distribution?

$$P(k|n,p) = \binom{n}{k} p^k (1-p)^{n-k}$$

$$p \in [0,1] \qquad n \in \mathbb{N}_0$$

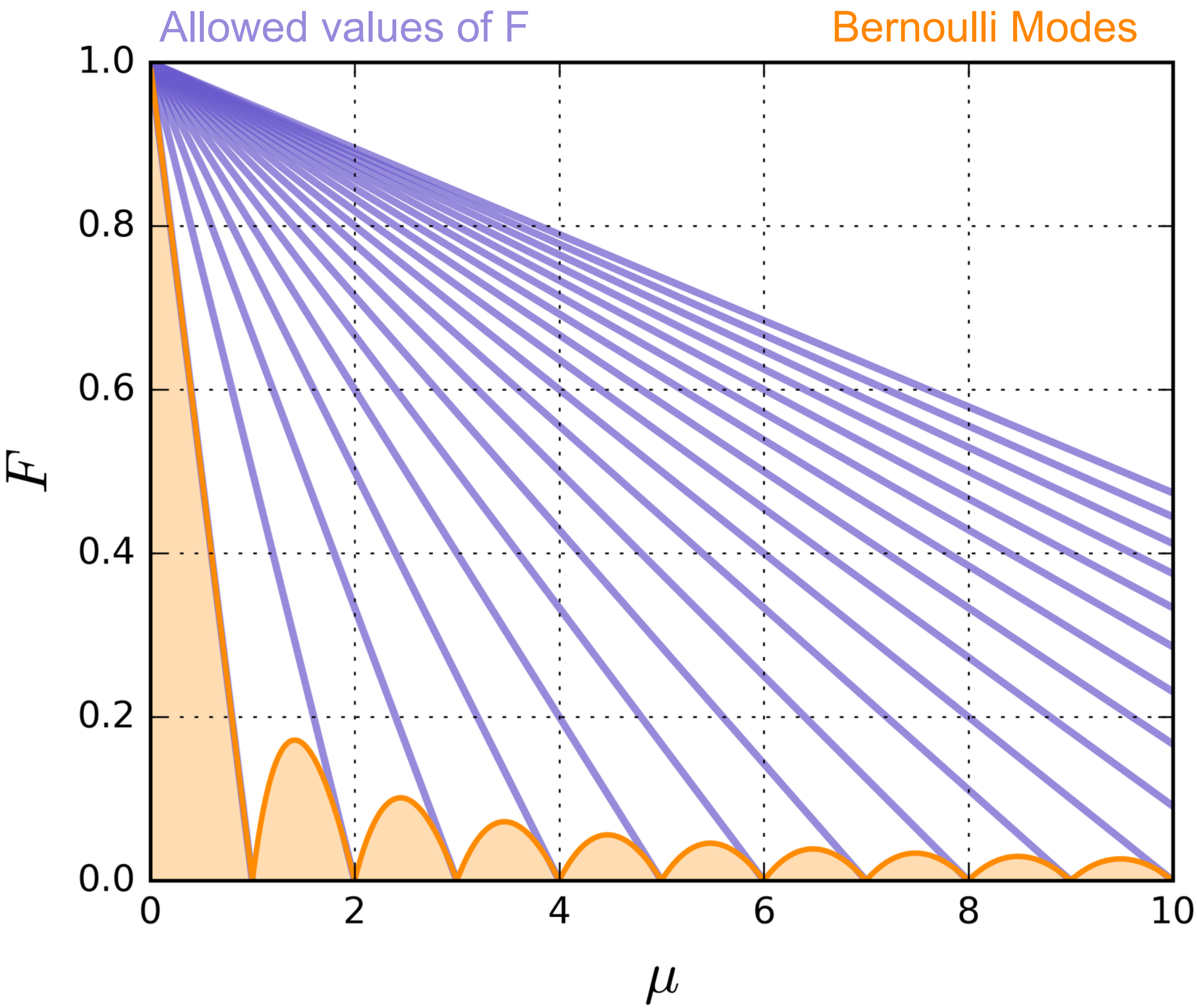
$$\mu = np \quad \sigma^2 = np(1-p)$$

$$\implies F = 1 - p$$

$$\therefore F = 1 - \frac{\mu}{n}$$

Some values of F are possible with the binomial distribution...

Why not the binomial distribution?

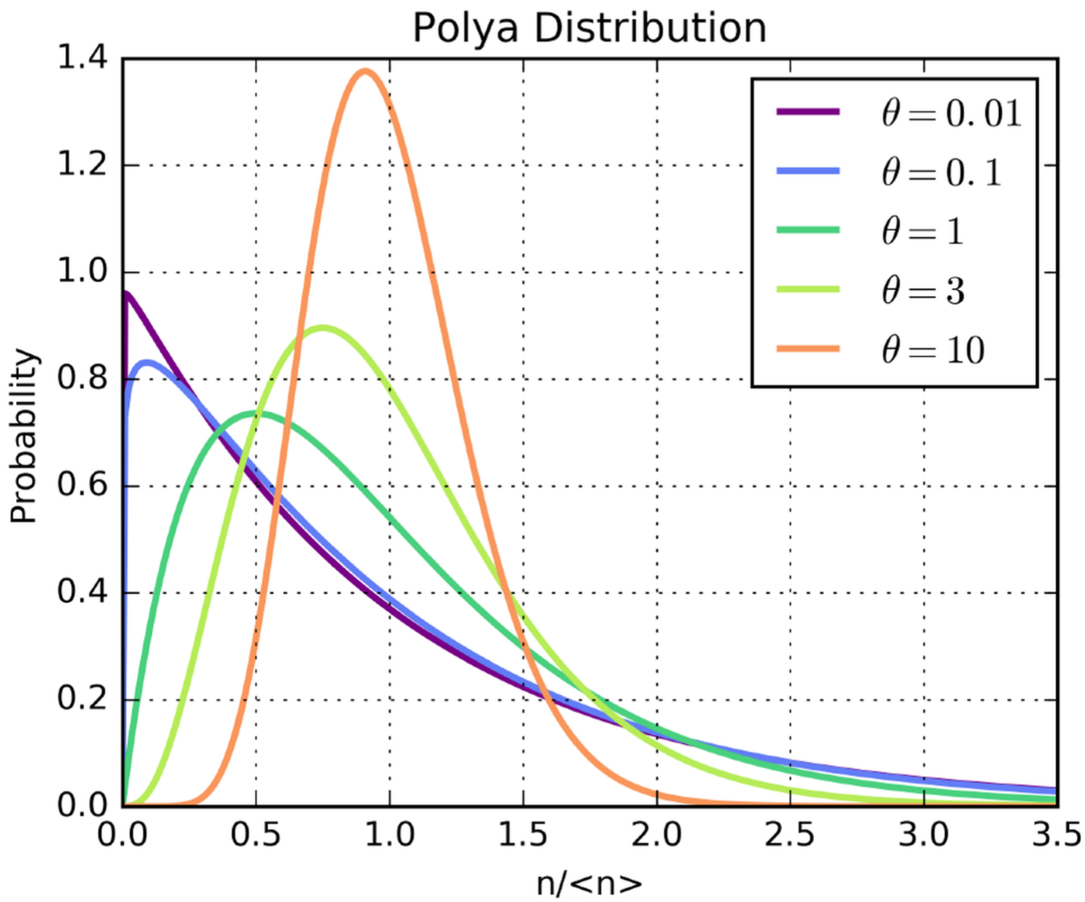


...But not any value of F!

n is an integer so only certain values are possible

In the single electron regime, very few values are allowed

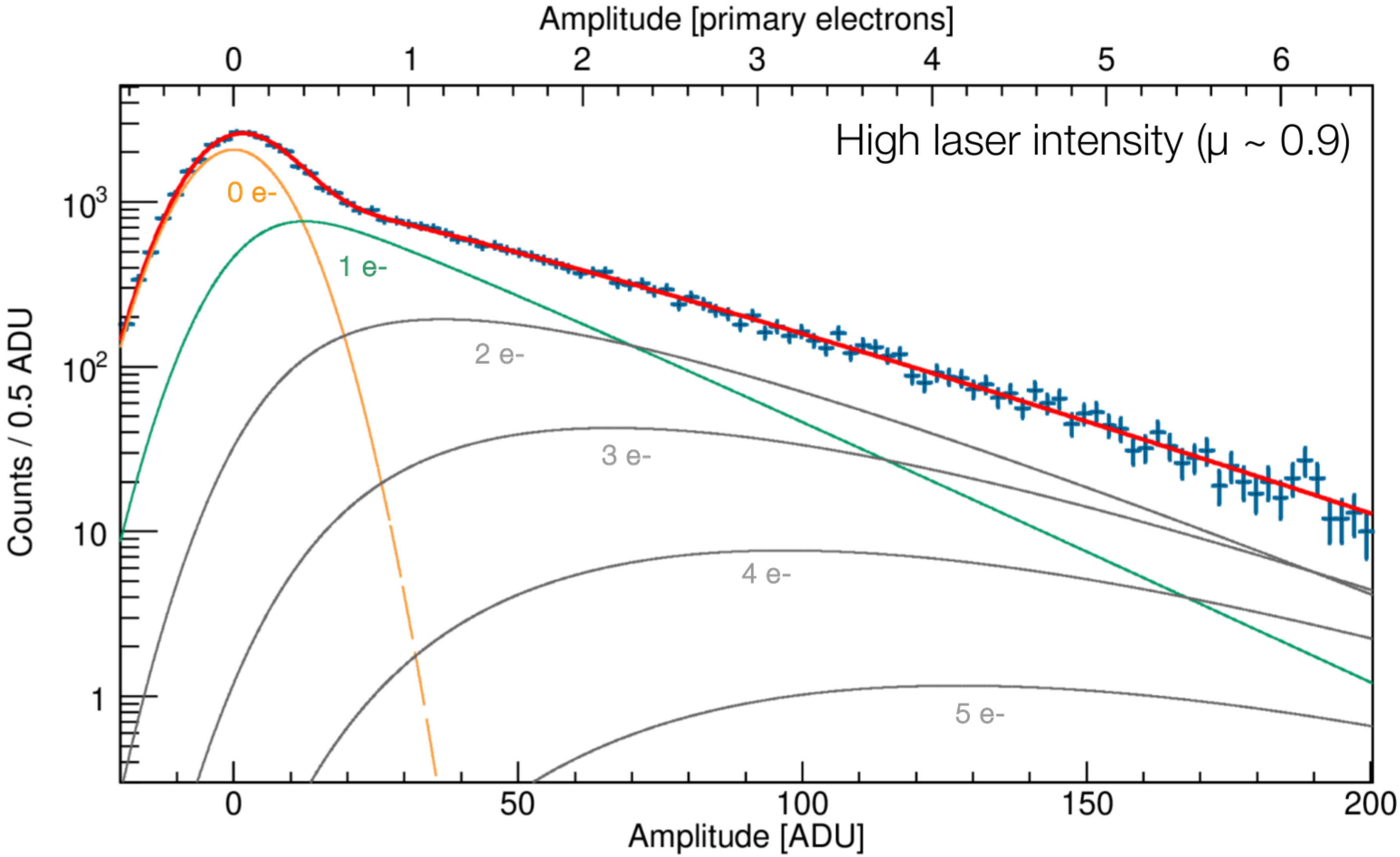
The Polya distribution



$$P\left(\frac{n}{\langle n\rangle}|\theta\right) = \frac{(1+\theta)^{(1+\theta)}}{\Gamma(1+\theta)}\left(\frac{n}{\langle n\rangle}\right)^{\theta} e^{-(1+\theta)\frac{n}{\langle n\rangle}}$$

UV laser studies

Laser data can even be fit at high intensities (many primary electrons)



UV laser studies

»Reconstructed proportional to laser intensity as expected
»Fits of all parameters performed individually and jointly for different laser intensities