Simulation-based Studies of the Fiducialization of SNOGLOBE for the NEWS-G Experiment

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WNPPC 2022
February 15, 2022

NEWS-G: New Experiments With Spheres - Gas

Specialize in SPCs (Spherical Proportional Counters) to search for low-mass dark matter (light WIMPs)

Detector: metallic vessel filled with a noble gas mixture; single high voltage sensor held at the center

SNOGLOBE (140 cm SPC) first ran at Laboratoire Souterrain de Modane (LSM) in Summer 2019

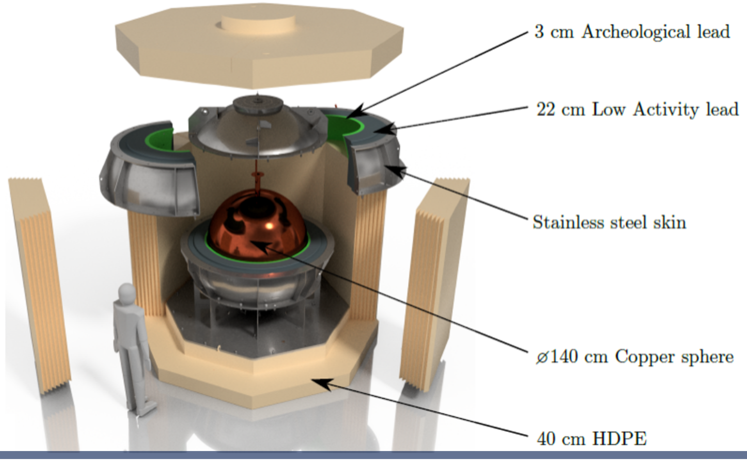
12 days of data with 135 mbar pure CH_4 recorded at LSM

Present: SNOGLOBE is currently installed in SNOLAB, ~2 km underground in Sudbury, Ontario

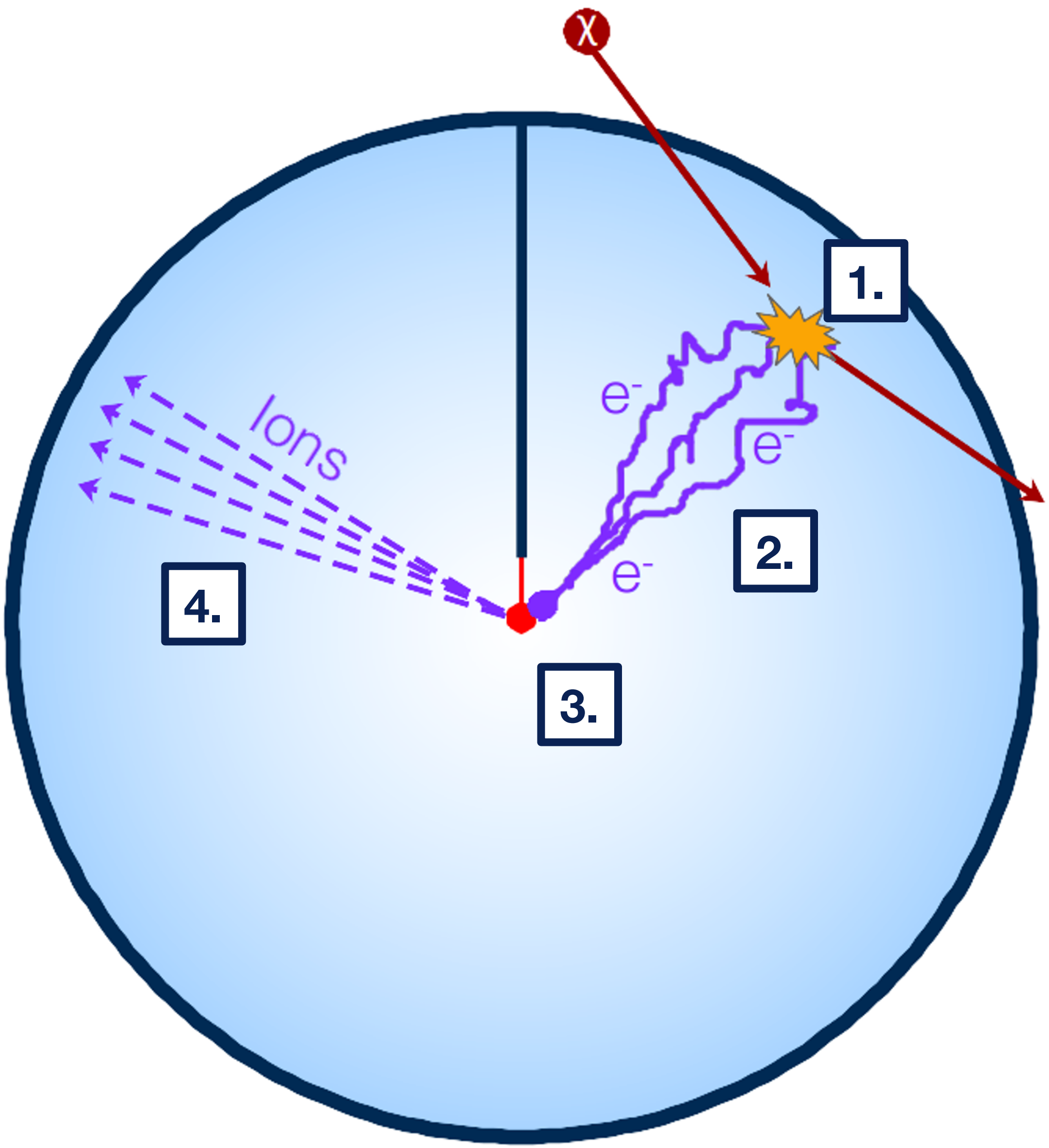
Laboratoire Souterrain de Modane


Currently being installed in SNOLAB

SNOGLOBE @ LSM



SPC Operation Principles



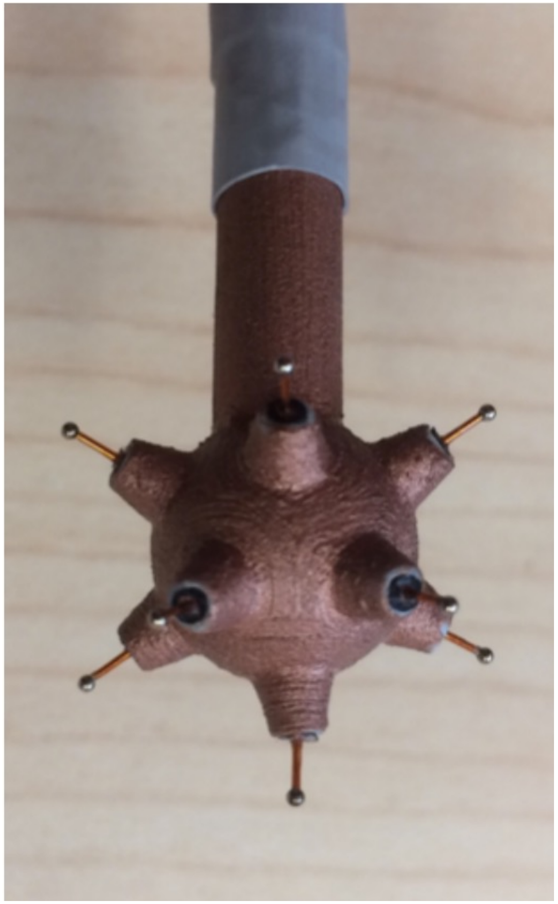
(1) Incident particle(s) scatter off target gas
→ Primary ionization

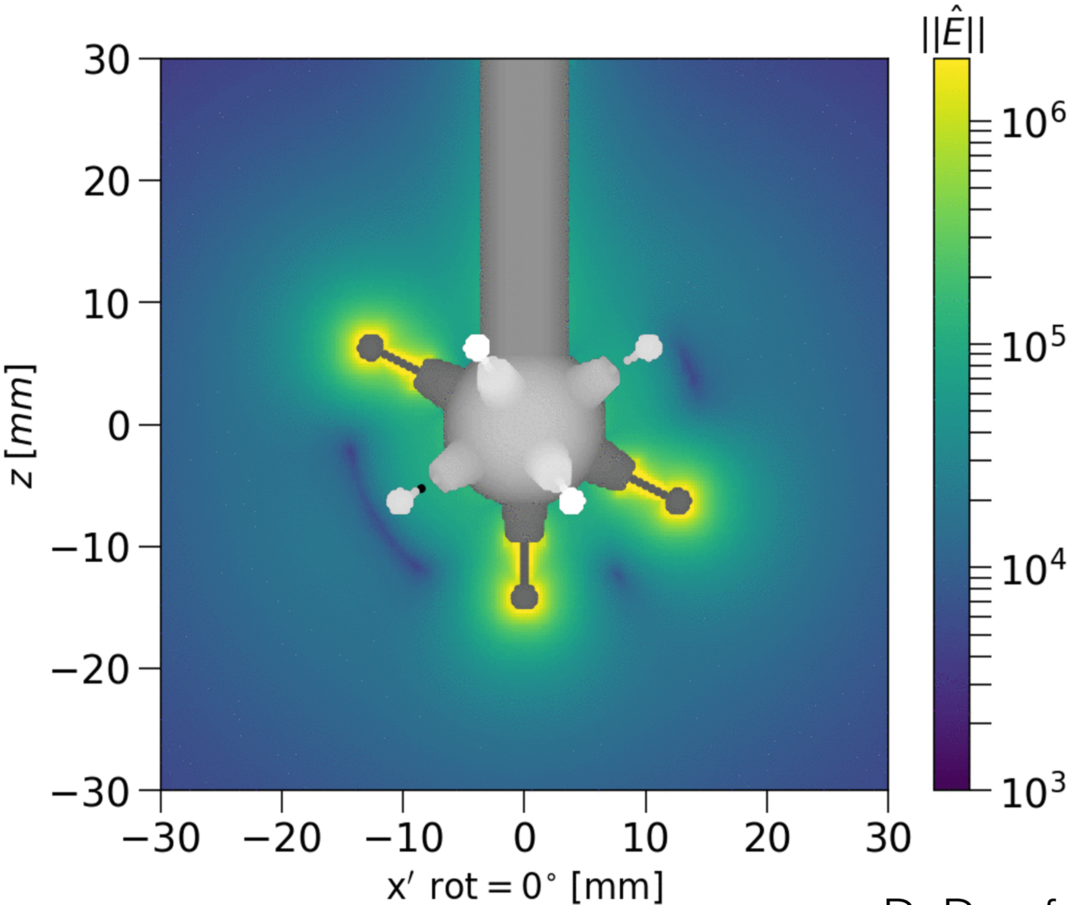
(2) Primary e^- drift towards sensor/anode (~100 μs)

(3) Townsend avalanche
→ Signal amplification from secondary e^--ion pairs

(4) Signal formation
→ Current signal induced by drift of secondary ions

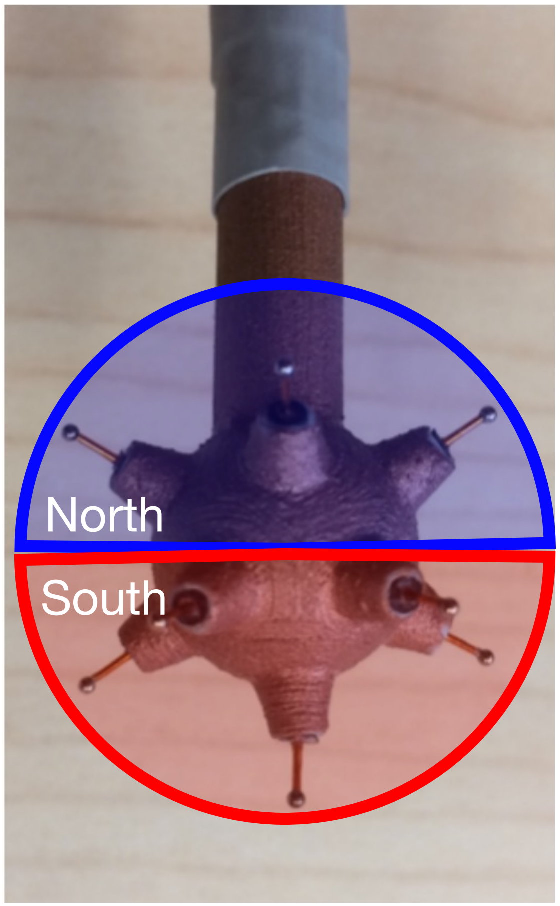
SNOGLOBE uses an "ACHINOS" (sea urchin in Greek) sensor with 11 individual anodes that provides a uniform E-field in larger SPCs

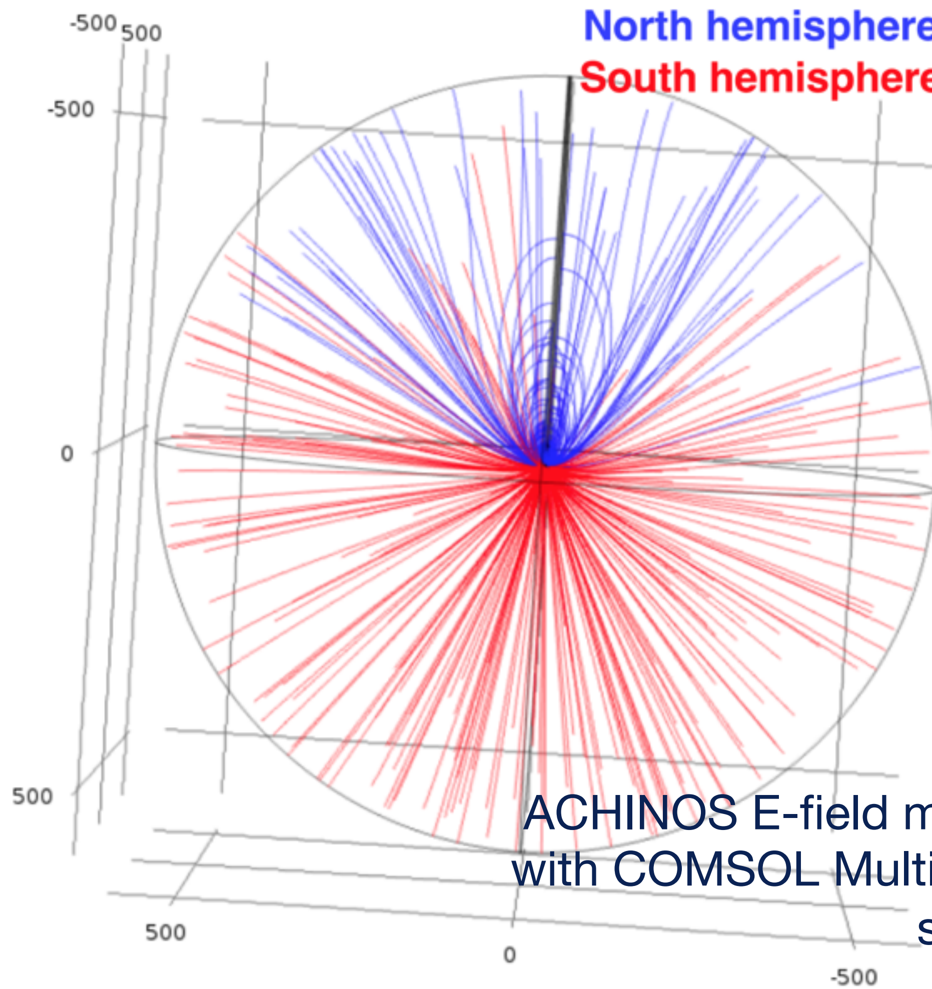




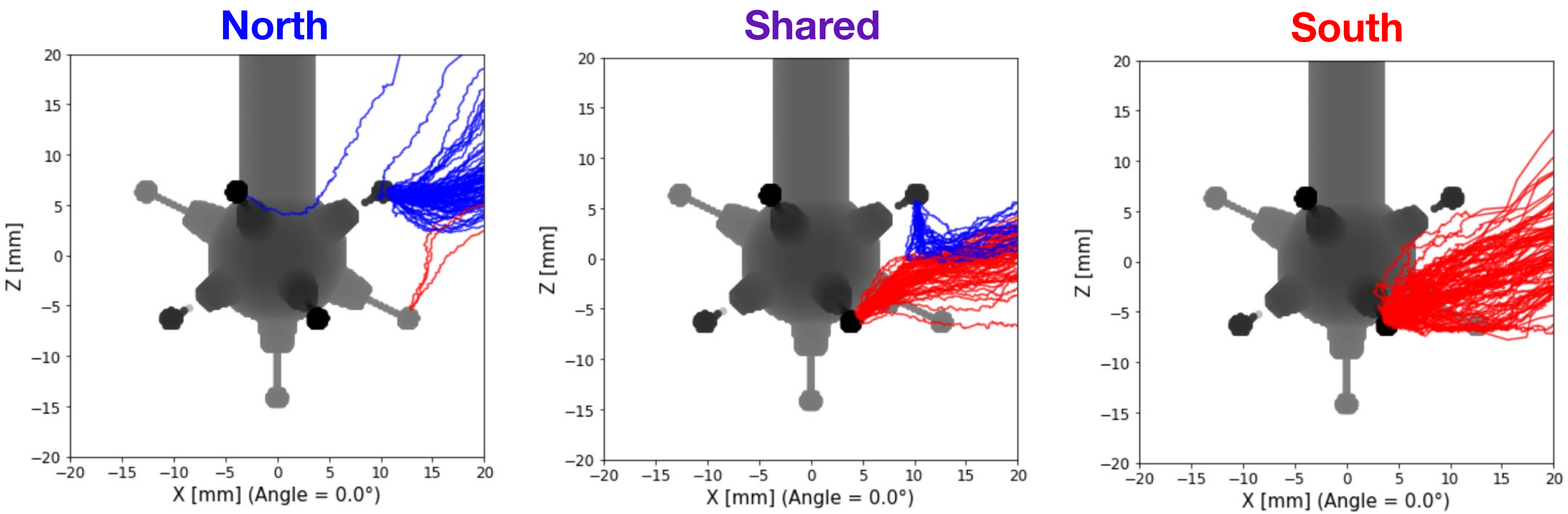
D. Durnford

North and **South** correspond to the hemisphere where each channel's fiducial volume is located (see COMSOL model)





ACHINOS E-field modelled with COMSOL Multiphysics software



Observed events are classified based upon the proportion of primary electrons which arrive at each corresponding channel

If sufficient electrons reach both channels, we observe a “shared” event

Characterizing the fiducial volume for each channel is then critical in determining overall signal acceptance in LSM data

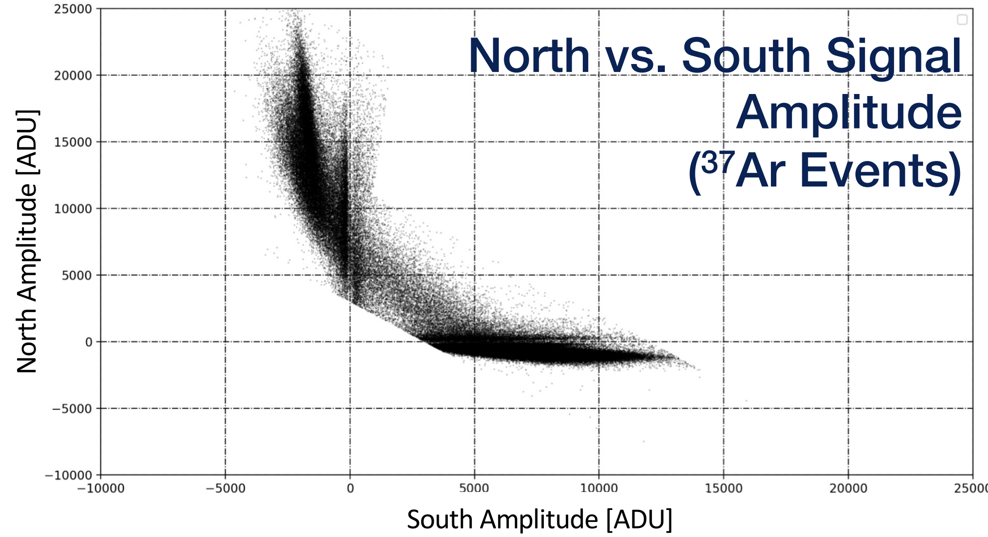
Using LSM data, we characterize the fiducialization of each channel for ^{37}Ar (2.8 keV) events using "**asymmetry**"

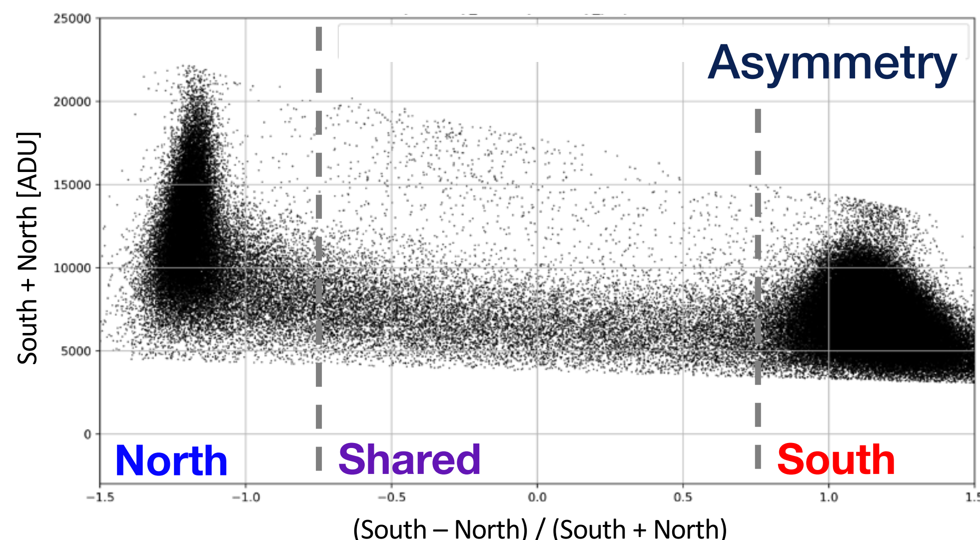
$$Asymmetry = \frac{(South - North)}{(South + North)}$$

This coordinate transform allows for cuts to be placed for defining north/shared/south events (e.g., bottom-right)

Current [-0.75, 0.75] Results

North	Shared	South
22.73%	8.88%	68.38%



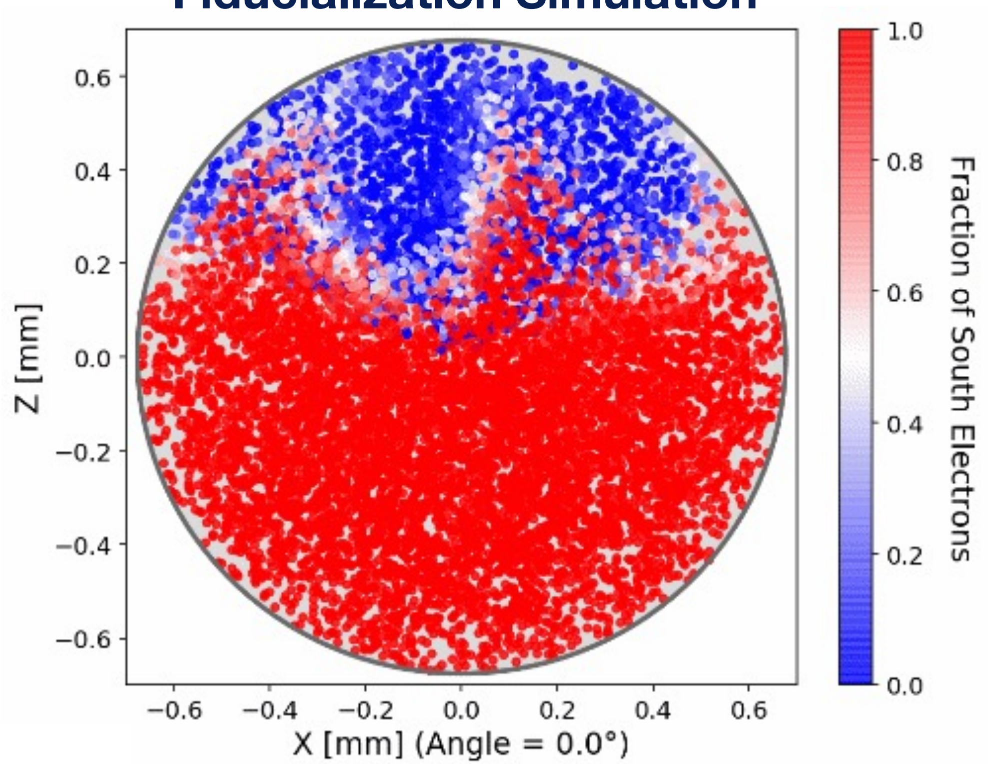


G. Savvidis

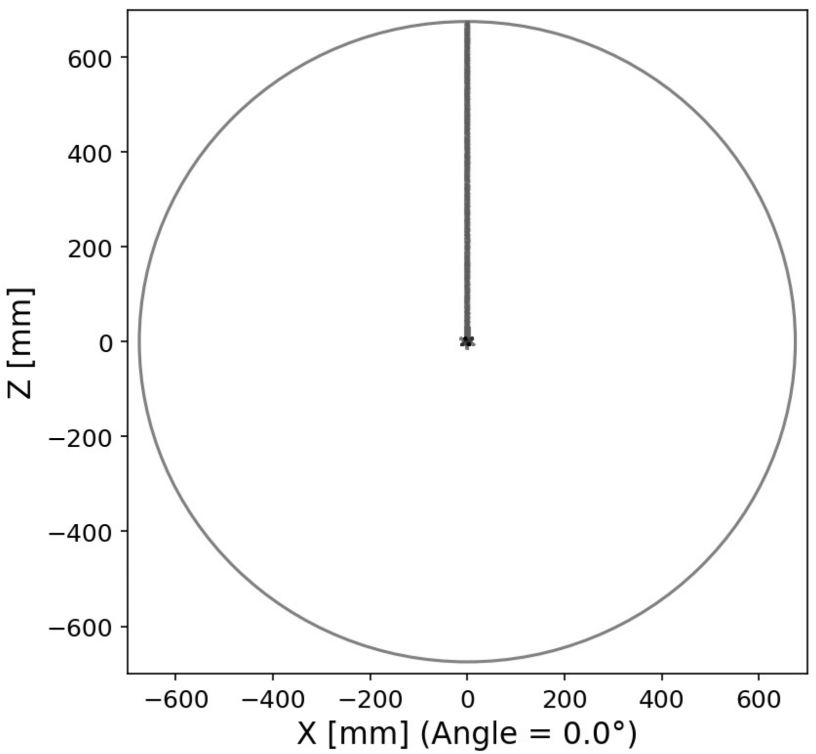
Fiducialization: Drift Simulations

- Electronic drift simulations use COMSOL E-field modelling & drift parameters from Magboltz simulations (based upon drift code developed by Yuqi Deng)
- Given random starting positions, we can track the proportion of electrons which drift to a north/south anode for "events" of N primary electrons (see below)

Fiducialization Simulation



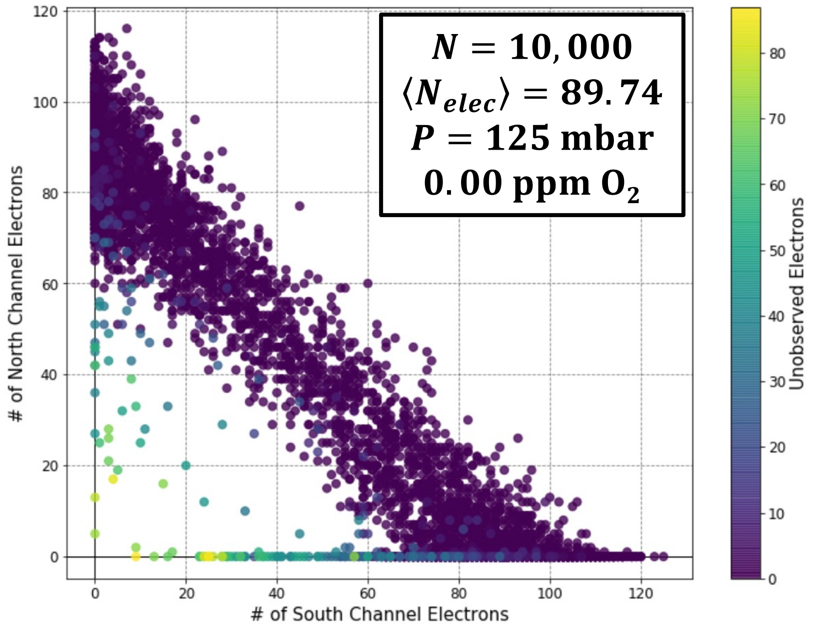
Sample Simulation "Event"



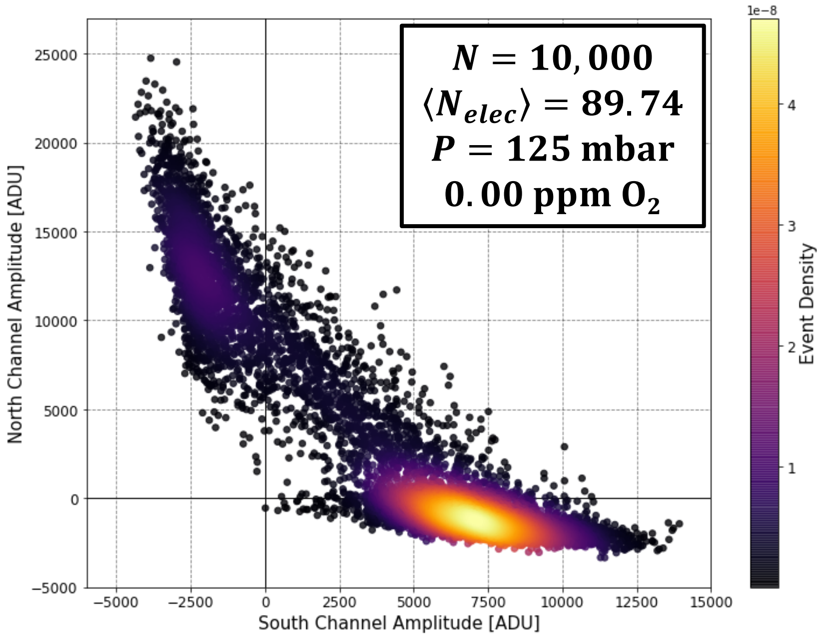
- The results from the ^{37}Ar simulations are electron count distributions (left) illustrating the proportion of electrons in each channel per event

- For the fiducialization analysis to be comparable to LSM data, need to convert numbers of electrons into appropriate signal amplitudes (right)

North Electrons vs. # South Electrons



North Amplitude vs. South Amplitude



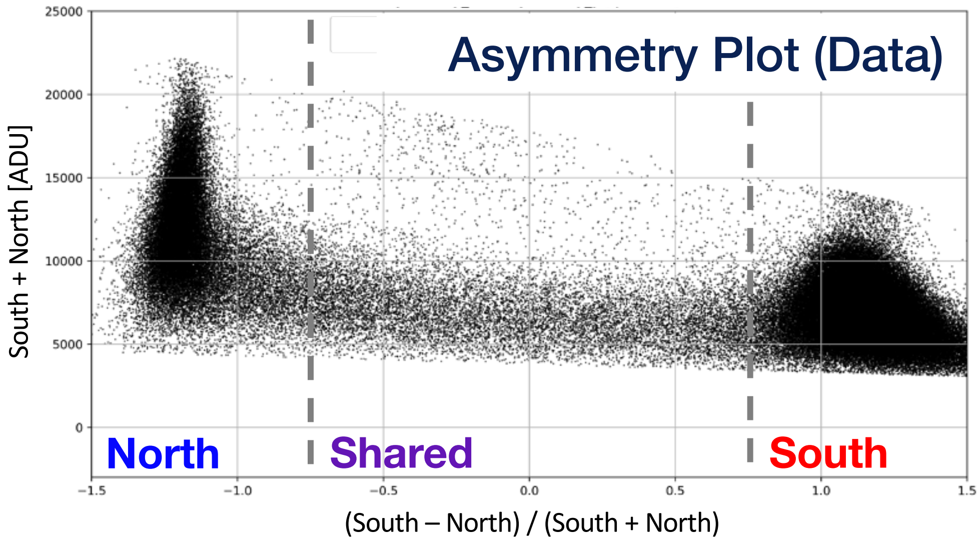
Fiducialization: Analyzing ^{37}Ar Simulation Results

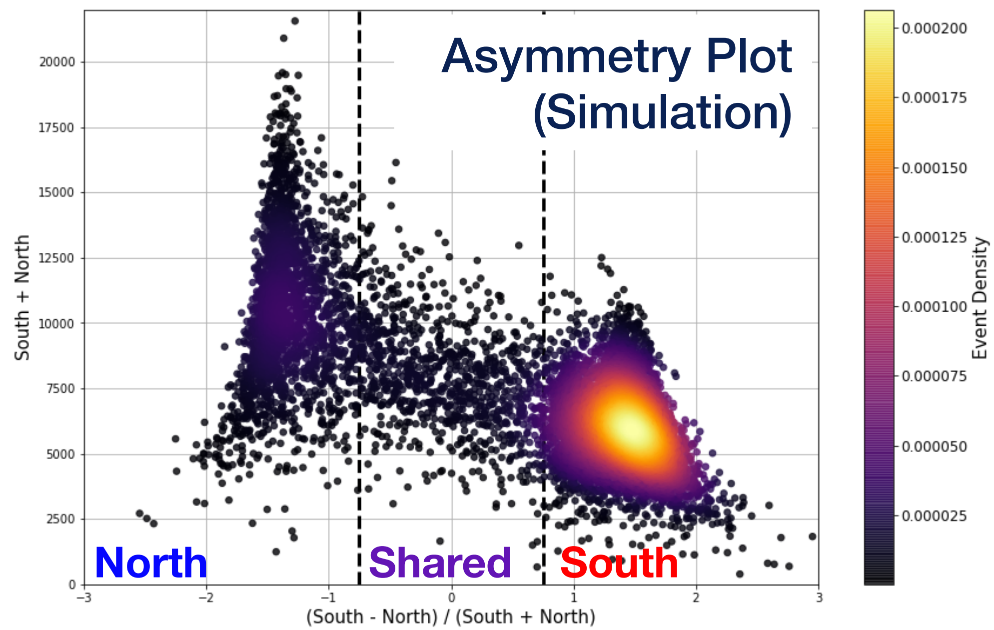
To emulate signal amplitudes, we consider (**from LSM data!**):

- SPC single-electron energy response
- Signal cross-talk between channels
- Baseline noise / resolution

The final distributions can then by modified using the <u>asymmetry</u> transformation (bottom-right)

This analysis process is repeated to evaluate statistical and systematic uncertainties





Fiducialization: ^{37}Ar Simulation Current Results

The following table summarizes the simulation results for ^{37}Ar events. Results are shown for varying systematic gas conditions.

	LSM Analysis	P = 125 mbar O_2 = 0 ppm	P = 145 mbar O_2 = 0 ppm	P = 125 mbar O_2 = 3.95 ppm	P = 145 mbar O_2 = 3.95 ppm
% North	**22.73**	22.395 ± 0.004	22.450 ± 0.005	21.959 ± 0.005	21.891 ± 0.005
% South	**68.38**	69.387 ± 0.005	69.521 ± 0.005	68.934 ± 0.004	68.758 ± 0.006
% Shared	**8.88**	8.220 ± 0.002	8.024 ± 0.003	9.104 ± 0.003	9.346 ± 0.003

Combined Results

% North = 22.2 ± 0.3

% South = 69.1 ± 0.4

% Shared = 8.7 ± 0.7

- Current fiducialization results suggest **consistency** with LSM data analysis
- Validation of fiducialization results supports use of simulations in **studying low-energy regime** (e.g., 2 e^- data)
- Results will be a critical component for LSM analysis paper to be published soon!

Key Takeaways

In summary…

- SPC fiducialization can be characterized via simulation

Current ^{37}Ar SNOGLOBE Fiducialization

	North	Shared	South
Data	22.73%	8.88%	68.38%
Simulation	**~22.2%**	**~8.7%**	**~69.1%**

- Results with LSM ^{37}Ar data suggests consistency between the ratios of north, shared, and south events; support for similar studies at lower energy thresholds (sub keV, 2 electrons)

- Simulation framework can be expanded to further studies such as exploring an SPC directionality channel with an ACHINOS

- Critical for the next phase of the NEWS-G experiment (e.g., specialized CEvNS detectors like NEWS-G3, DarkSphere)

NEWS-G Collaboration

Queen's University Kingston - G Gerbier, G Giroux, R Martin, S Crawford, M Vidal, G Savvidis, A Brossard, F Vazquez de Sola, K Dering, V Millious, 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

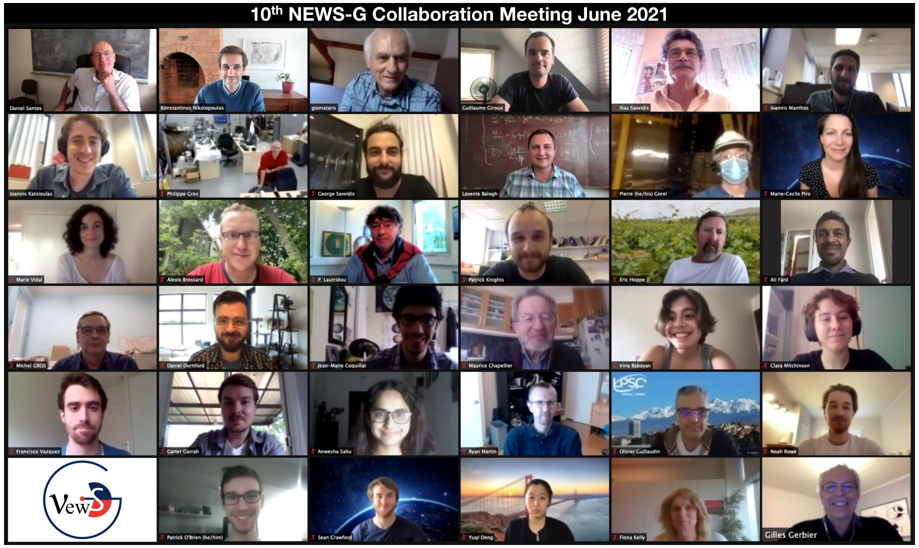
University of Birmingham - K Nikolopoulos, P Knights, I Katsioulas, R Ward
- Simulations, analysis, R&D

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

Associated labs: TRIUMF - F Retiere

Subatech, Nantes – P. Lautridou, F. Vazquez de Sola

The NEWS-G Collaboration (June 2021)

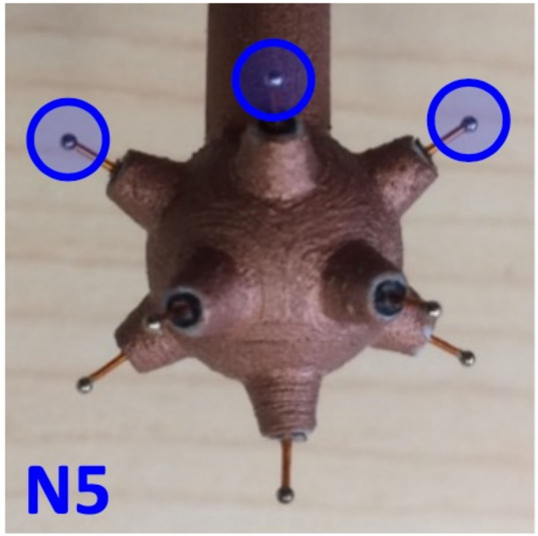


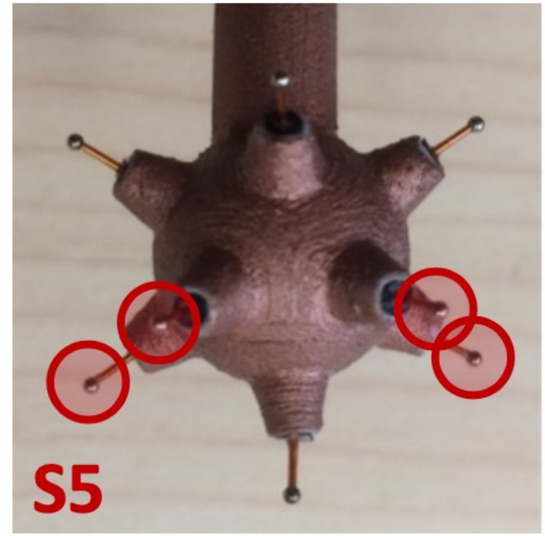
Questions?

Extra slides

2-Electron Results: Event Key

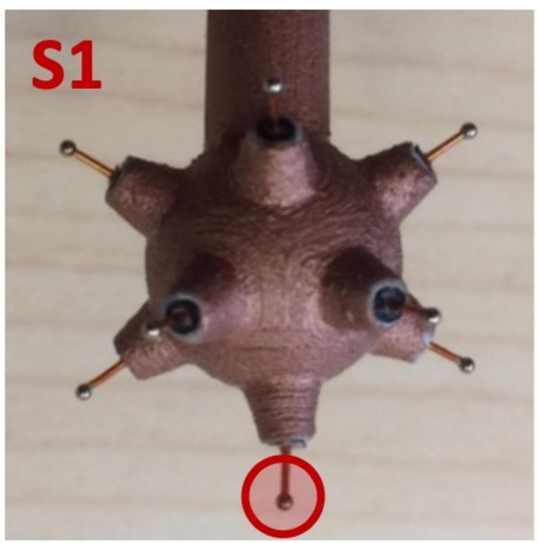
N5
Northern 5 Anodes

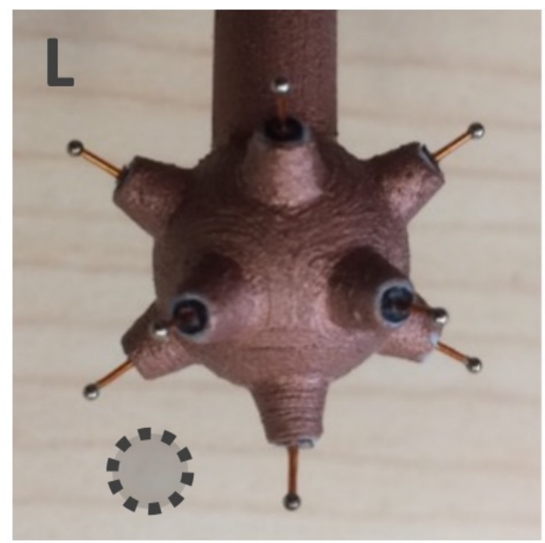




S5
Remaining 5 Southern Anodes

S1
Southern-most Anode





L
Lost Electron

*Due to attachment, stuck at inner surface, or simulation error

2-Electron Results: Current Status

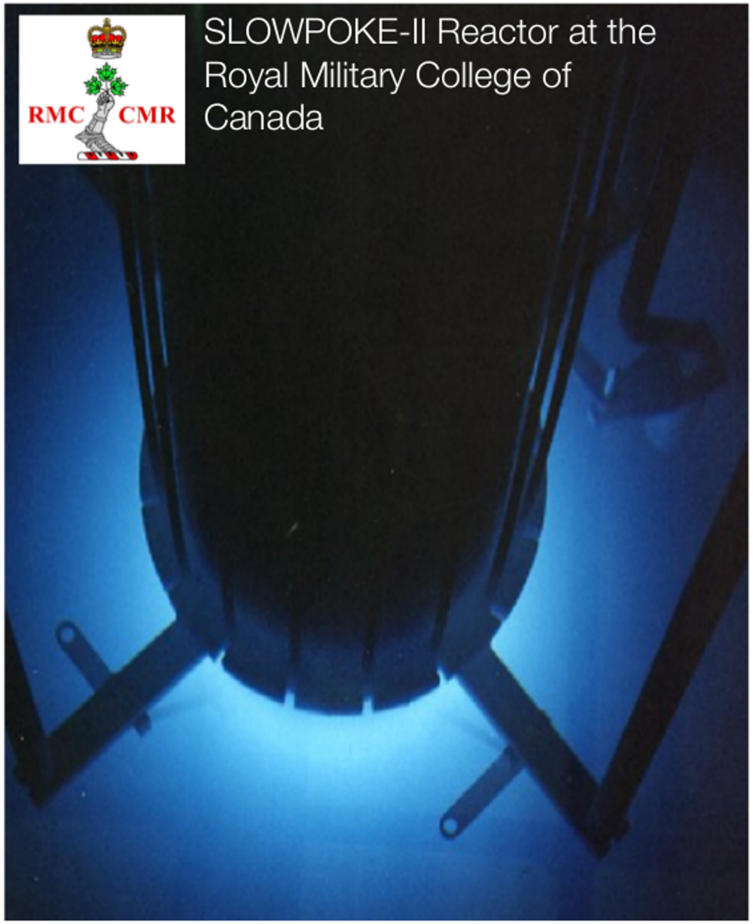
1,000 sample data sets; 1e5 events per sample (from 5e6 events)

e^-_1	e^-_2	P = 125 mbar O_2 = 0 ppm	P = 145 mbar O_2 = 0 ppm	P = 125 mbar O_2 = 3.25 ppm	P = 145 mbar O_2 = 3.25 ppm
N5	L	0.2899 ± 0.0004	0.2899 ± 0.0004	6.8874 ± 0.0006	8.012 ± 0.001
N5	N5	19.992 ± 0.001	20.108 ± 0.001	13.467 ± 0.002	11.8490 ± 0.0009
S5	L	0.6577 ± 0.0004	0.6807 ± 0.0002	16.921 ± 0.003	19.964 ± 0.002
S5	S5	58.232 ± 0.002	58.320 ± 0.003	41.140 ± 0.003	37.132 ± 0.002
S1	L	0.1050 ± 0.0002	0.1140 ± 0.0004	2.7666 ± 0.0008	3.3039 ± 0.0008
S1	S1	9.492 ± 0.002	9.526 ± 0.001	6.876 ± 0.002	6.275 ± 0.002
S1	N5 / S5	3.0801 ± 0.0008	2.9956 ± 0.0007	2.1883 ± 0.0004	1.9074 ± 0.0007
N5	S5	7.657 ± 0.005	7.475 ± 0.002	5.0798 ± 0.0009	4.324 ± 0.002
L	L	0.4904 ± 0.0004	0.4798 ± 0.0003	4.6826 ± 0.0006	7.218 ± 0.001

*To be updated for 3.95 ppm O_2

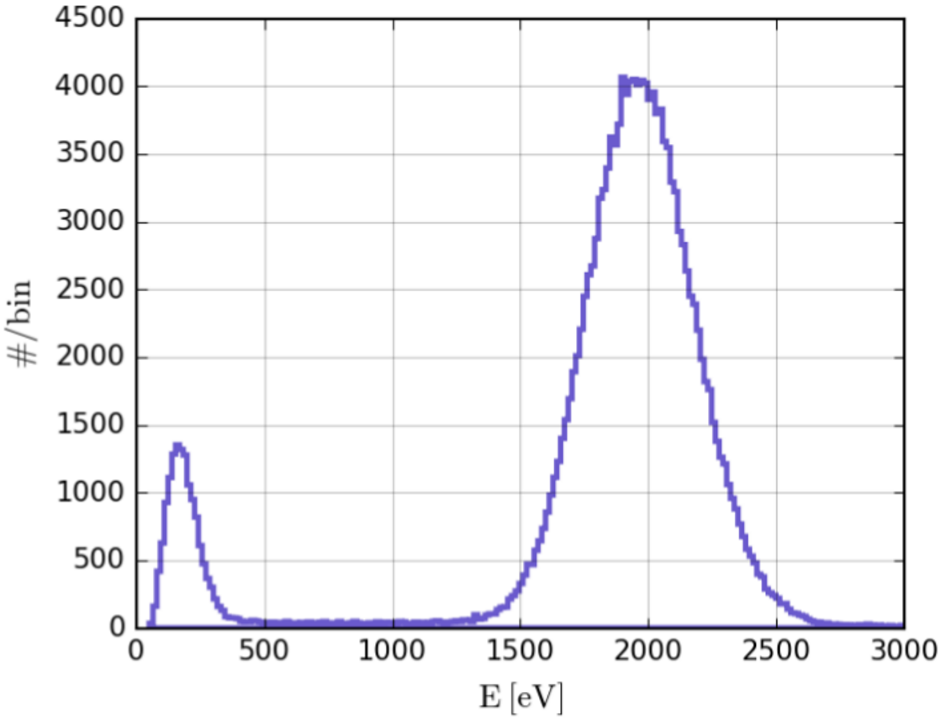
^{37}Ar: radioactive gas that decays via electron capture. But with a 35 day half life, we need a way to produce samples at regularly:

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



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

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



Systematics: Magboltz Parameters

Primary source of error in the simulation results were determined to be gas pressure and the concentration of oxygen (via Magboltz)

Pressure

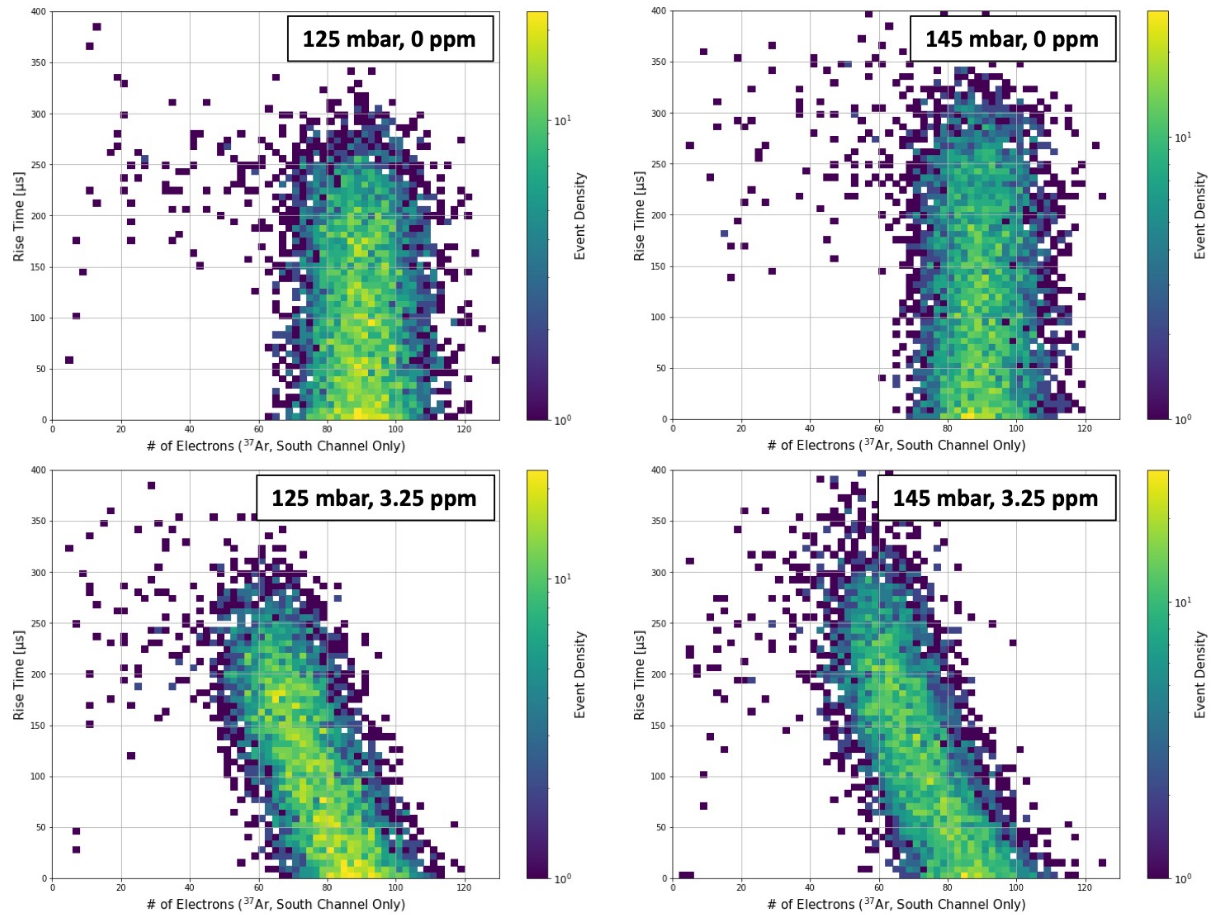
Nominally 135 mbar; ±10 mbar on pressure gauge used at LSM

O_2 Concentration

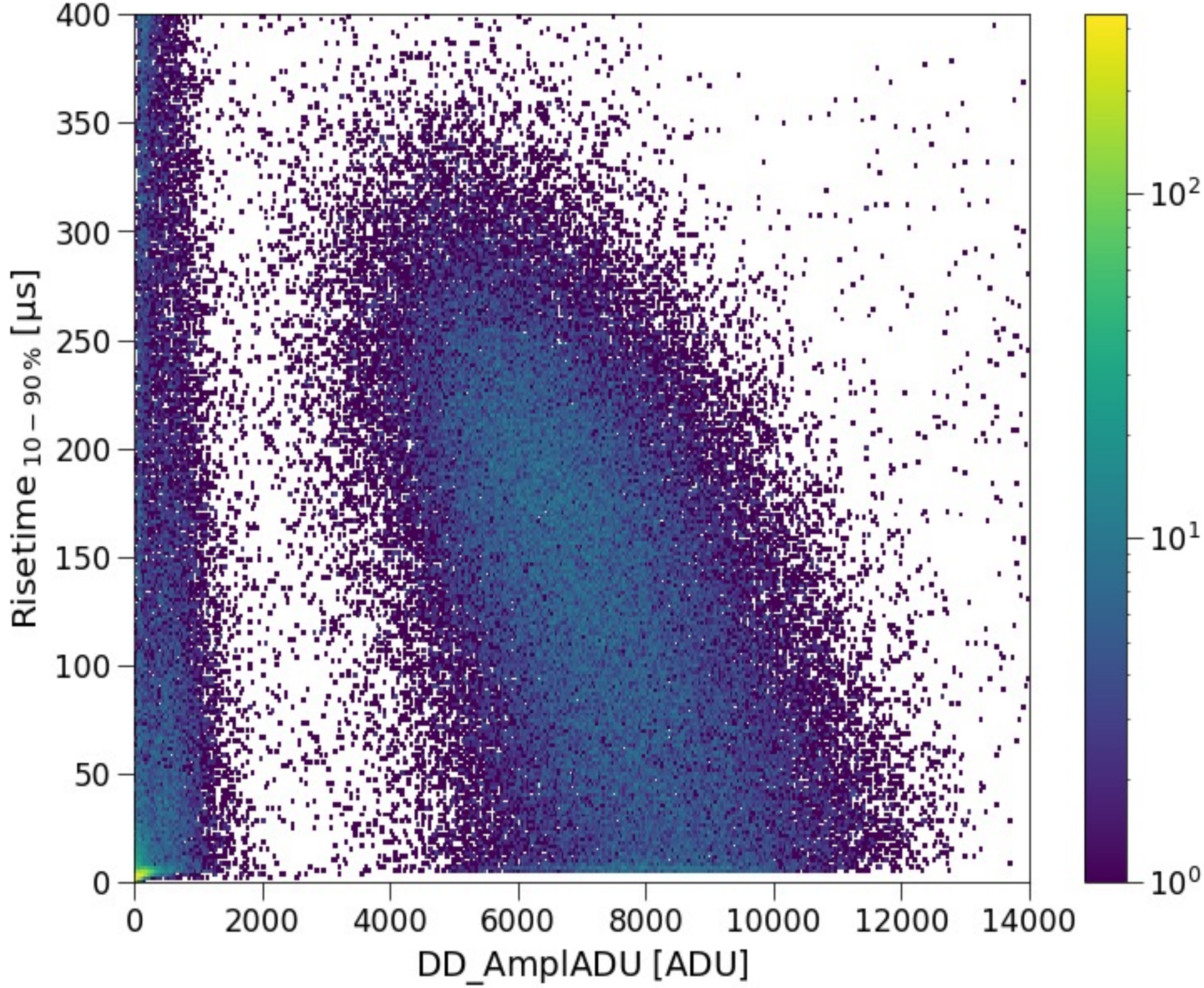
Contaminant gas which results in electron-attachment

No dedicated study of attachment in SPCs yet; uncertain shape

Sample Simulated Rise Time vs. # South Electrons Data



LSM Data: Risetime vs. South Amplitude



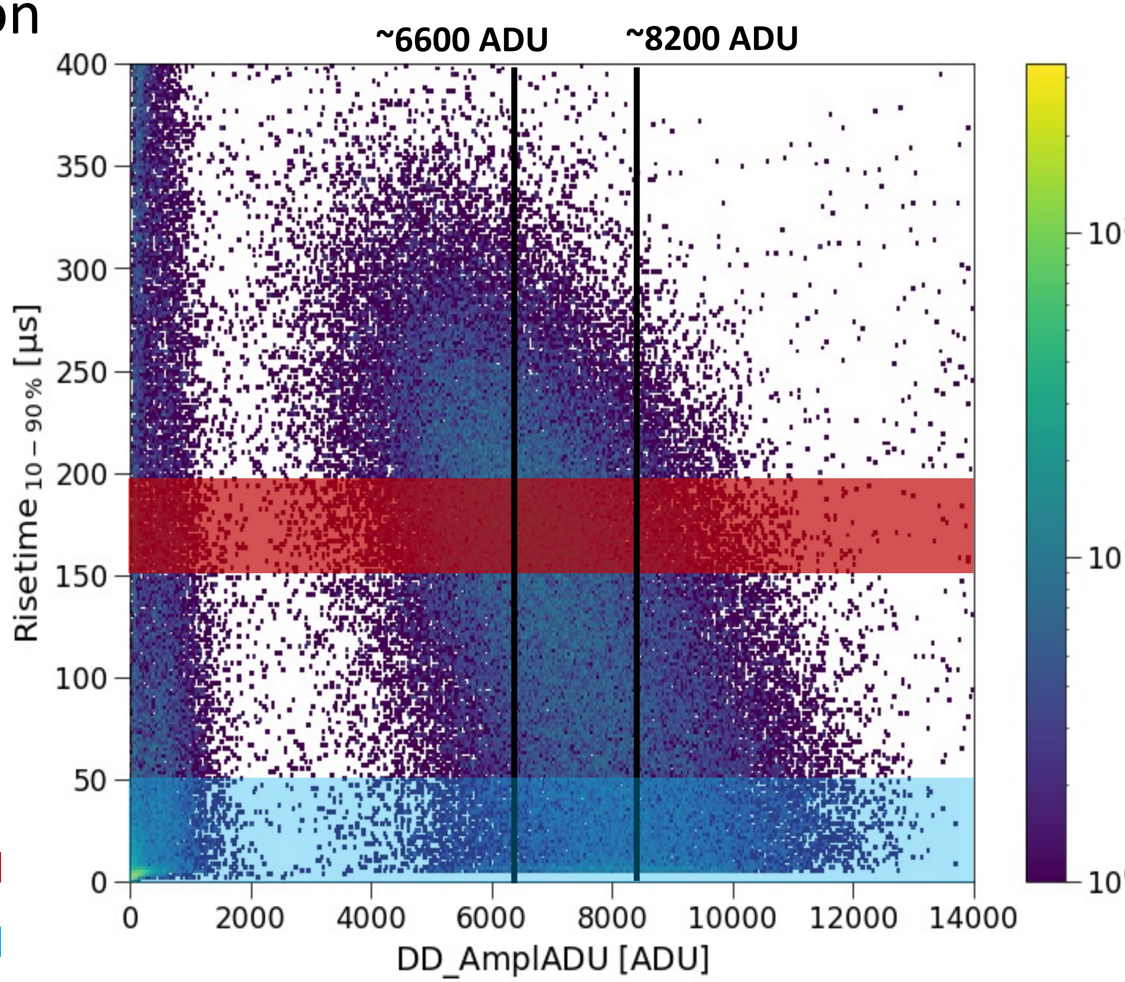
Daniel D.

Attachment Fraction Analysis

The LSM attachment fraction (without uncertainty) is ~0.805, or just over 80%

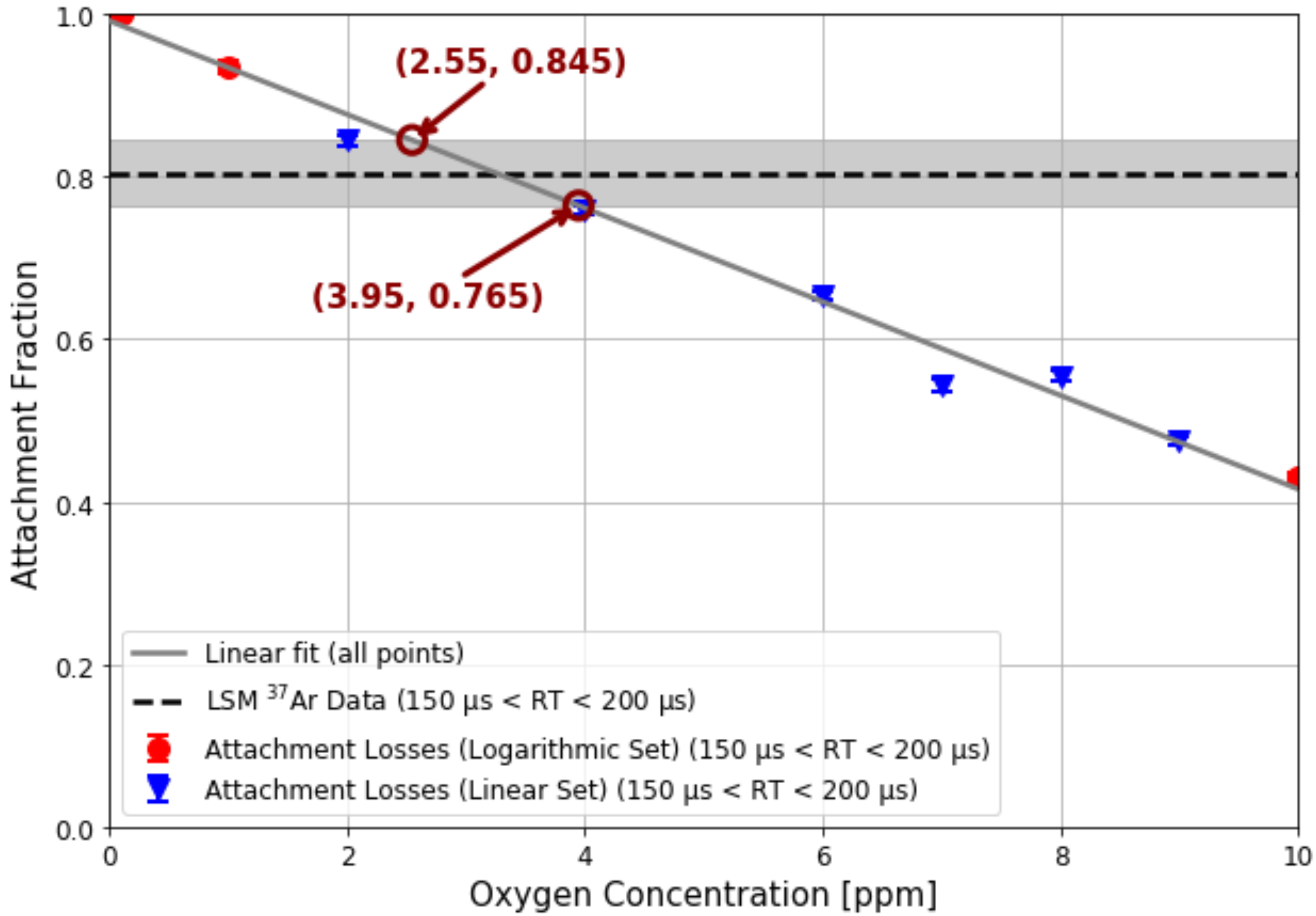
The same analysis is then performed with the simulated data; the 0 ppm simulation is used as the reference value when calculating each AF

$$AF = \frac{Amplitude\ Mean}{0\ ppm\ Amplitude}$$



Systematics: Attachment Due to Oxygen

Via Magboltz, at our lower pressure of 125 mbar we can estimate what amount of O_2 in the simulation results in the same amount of attachment as with the LSM data



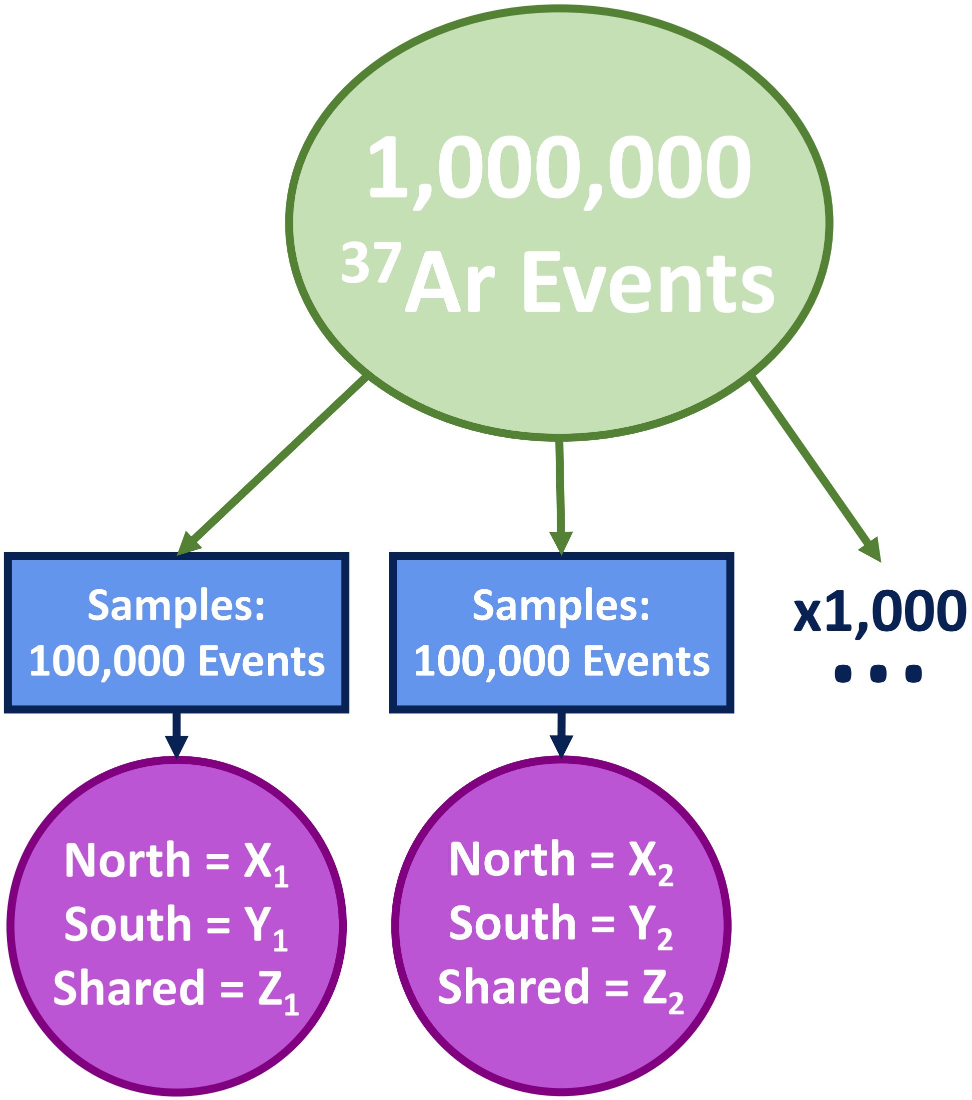
Best Estimate:
~3.25 ppm

Uncertainty range for O_2 is placed at 0 ppm to 3.25 ppm (or 3.95 ppm)

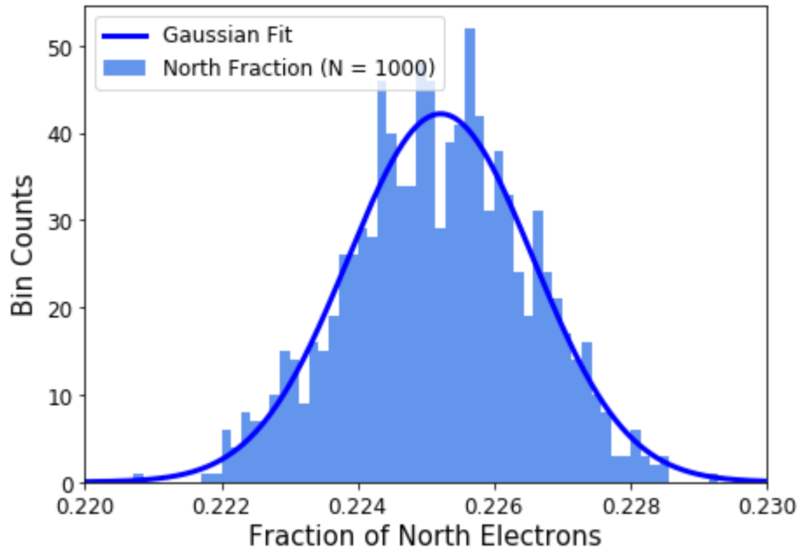
To characterize statistical uncertainties, I generate ^{37}Ar event data sets of size N = 1e6 for the 4 following cases:

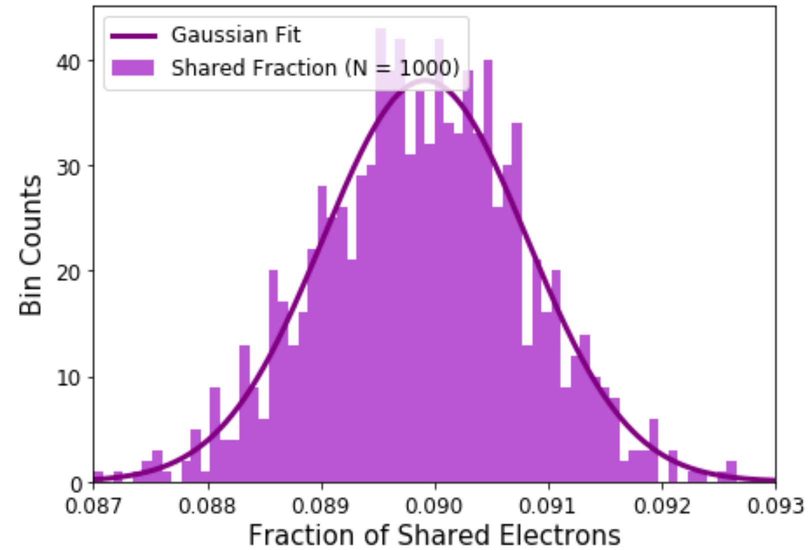
1. P = 125 mbar, O_2 = 0 ppm
2. P = 145 mbar, O_2 = 0 ppm
3. P = 125 mbar, O_2 = 3.95 ppm
4. P = 145 mbar, O_2 = 3.95 ppm

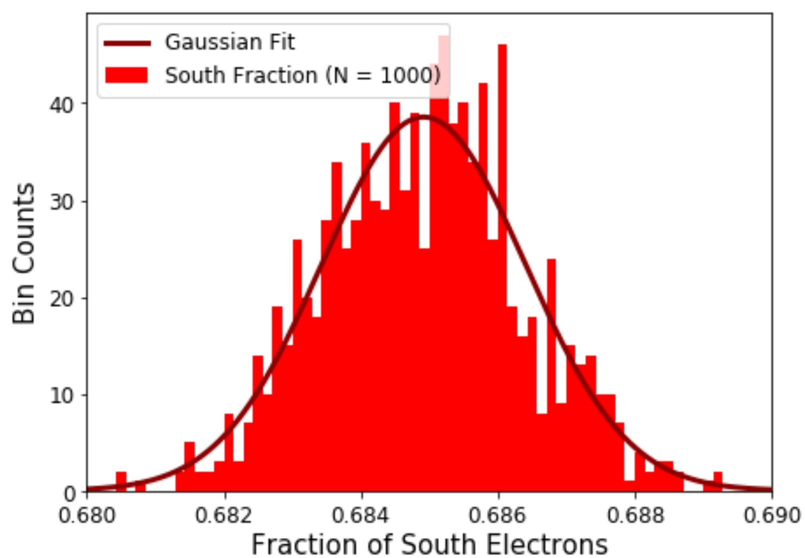
Evaluated north, south, and shared events + statistical uncertainties through sampling with replacement (“bootstrapping”)



^{37}Ar Simulations: Statistical Analysis II





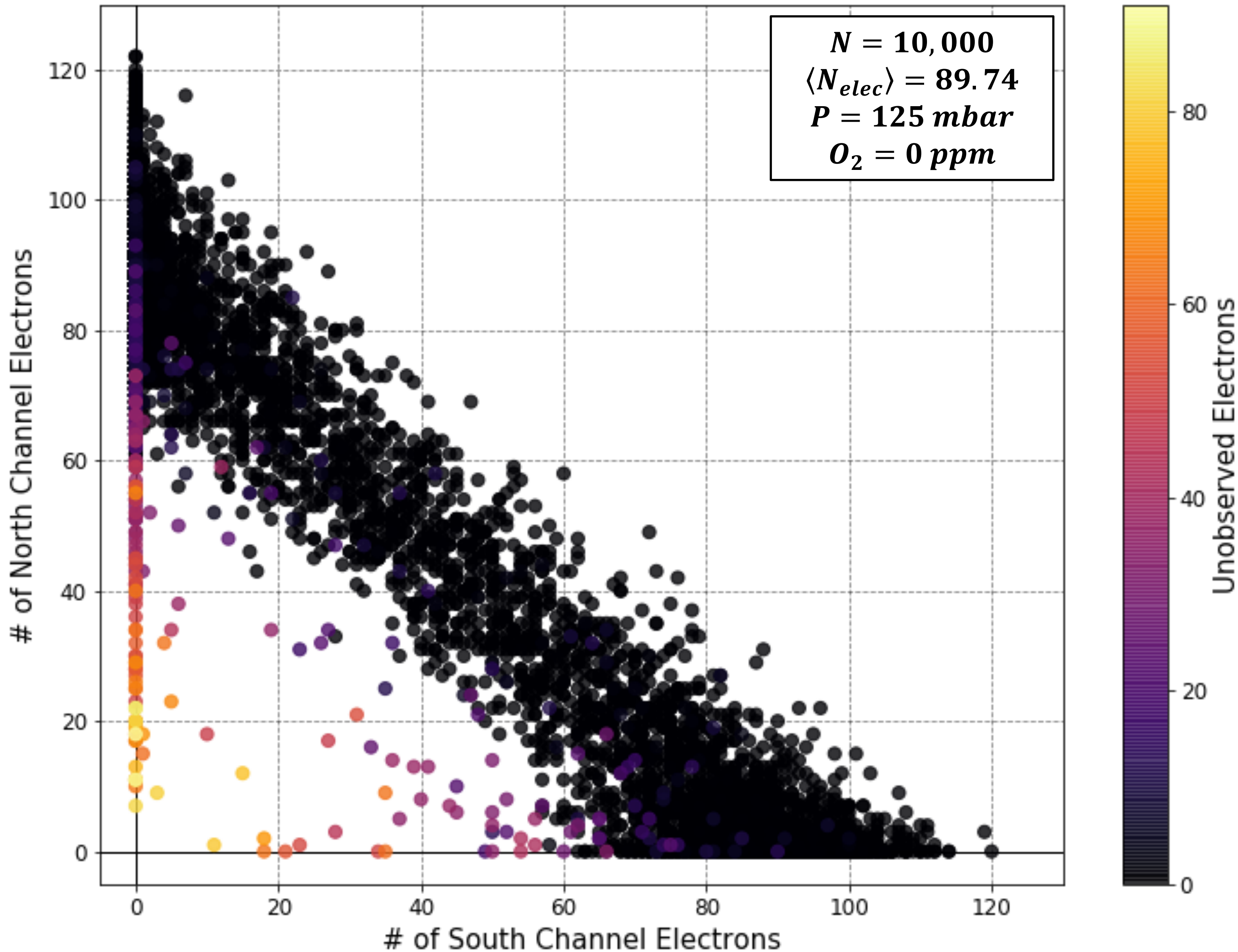


Example analysis results from random sampling; uncertainties taken from Gaussian fit

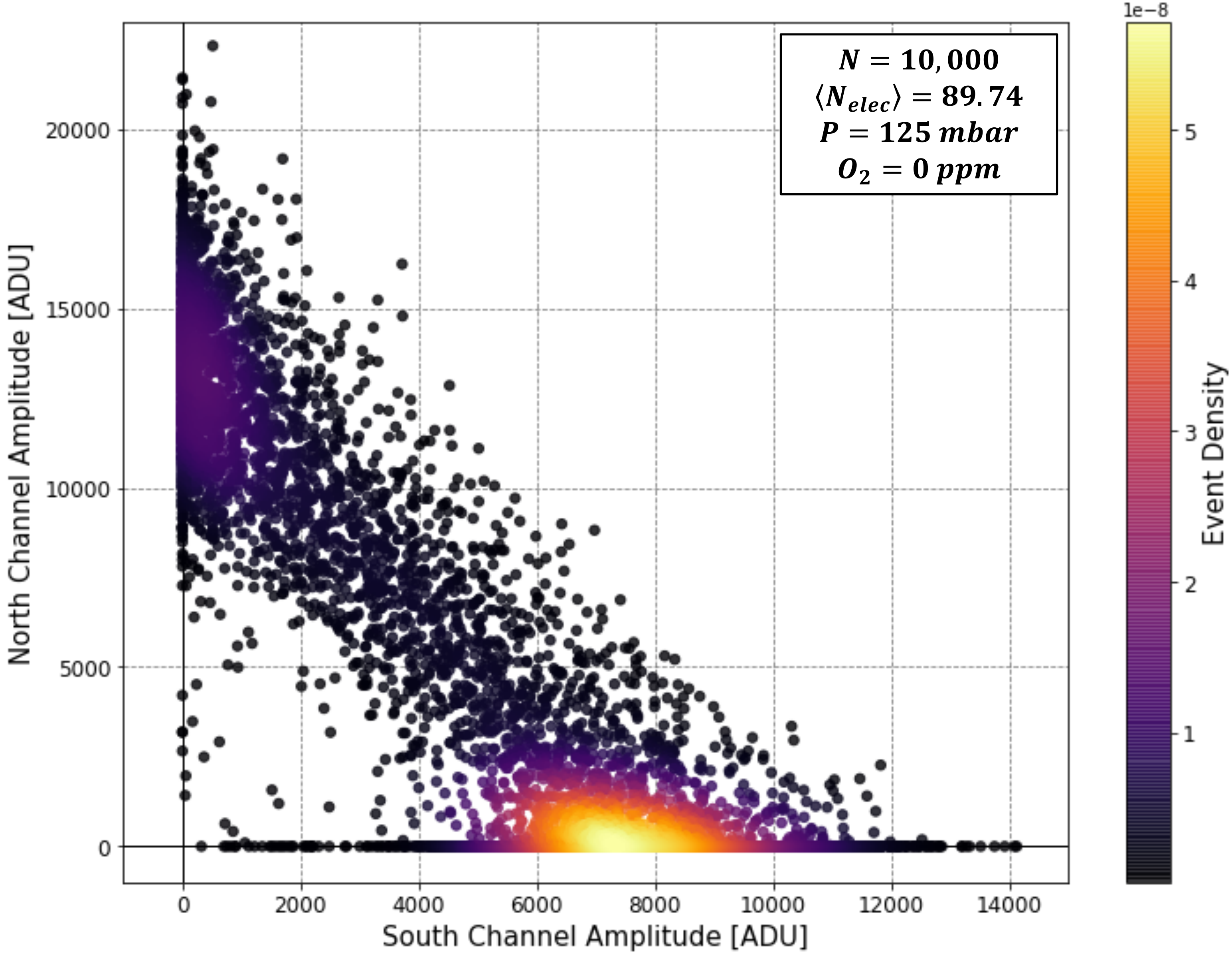
P = 125 mbar, O_2 = 0 ppm

North = 0.2252 ± 0.0014
South = 0.6849 ± 0.0015
Shared = 0.0899 ± 0.0009

Creating Signal Amplitudes: Starting Point



Step 1. Pull Signal Amplitude per PE from Polya



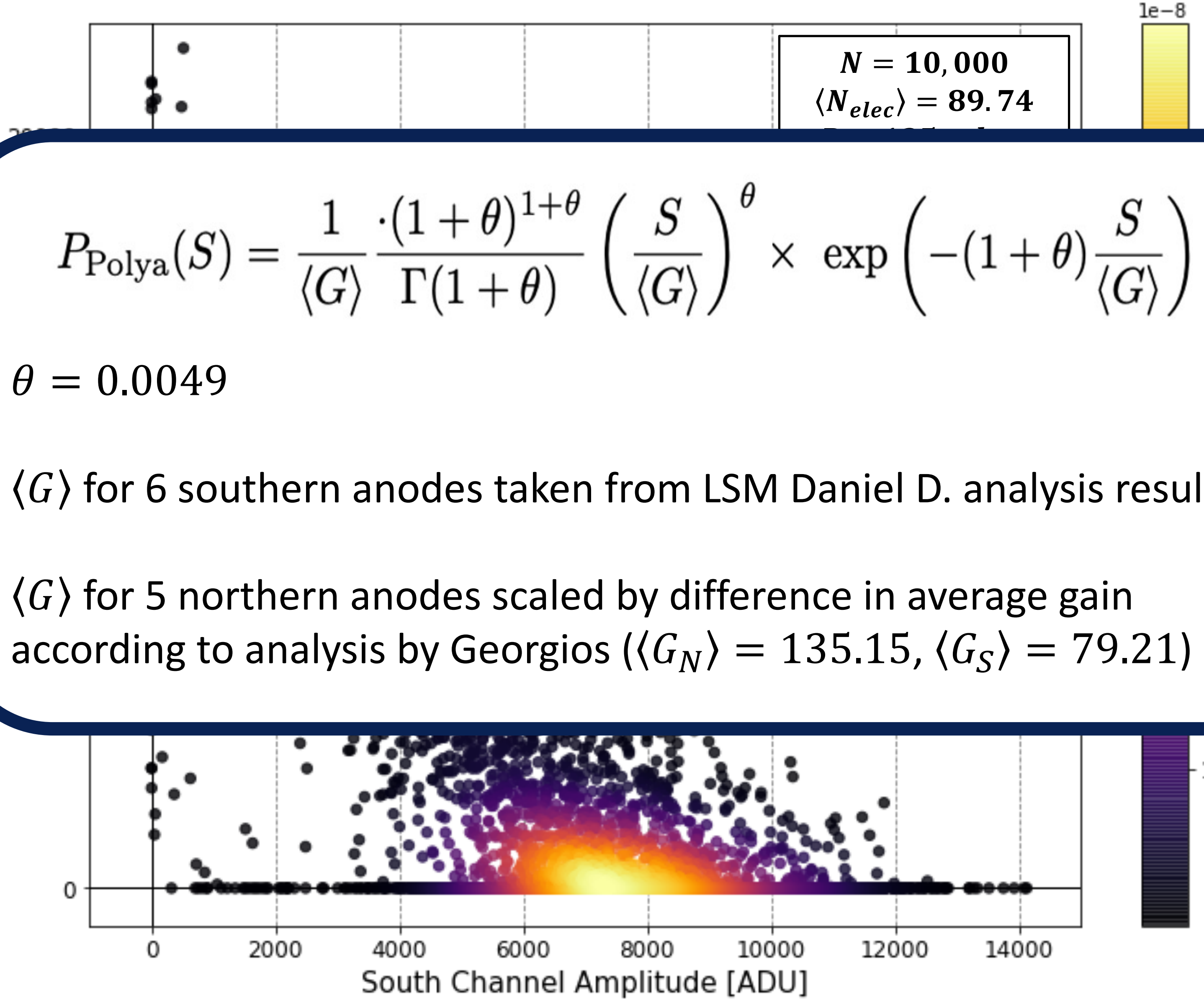
Step 1. Pull Signal Amplitude per PE from Polya

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

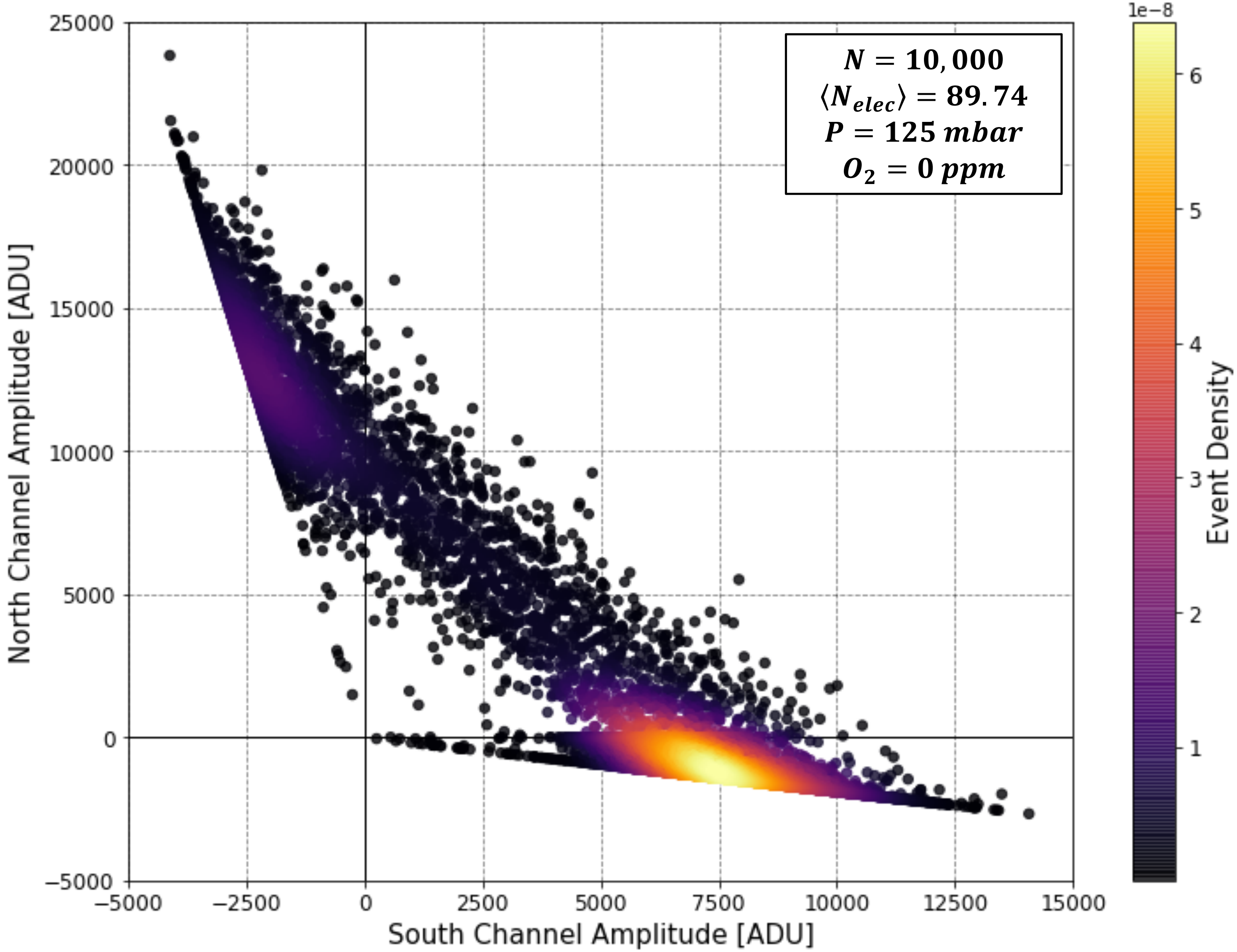
$\theta = 0.0049$

$\langle G \rangle$ for 6 southern anodes taken from LSM Daniel D. analysis results

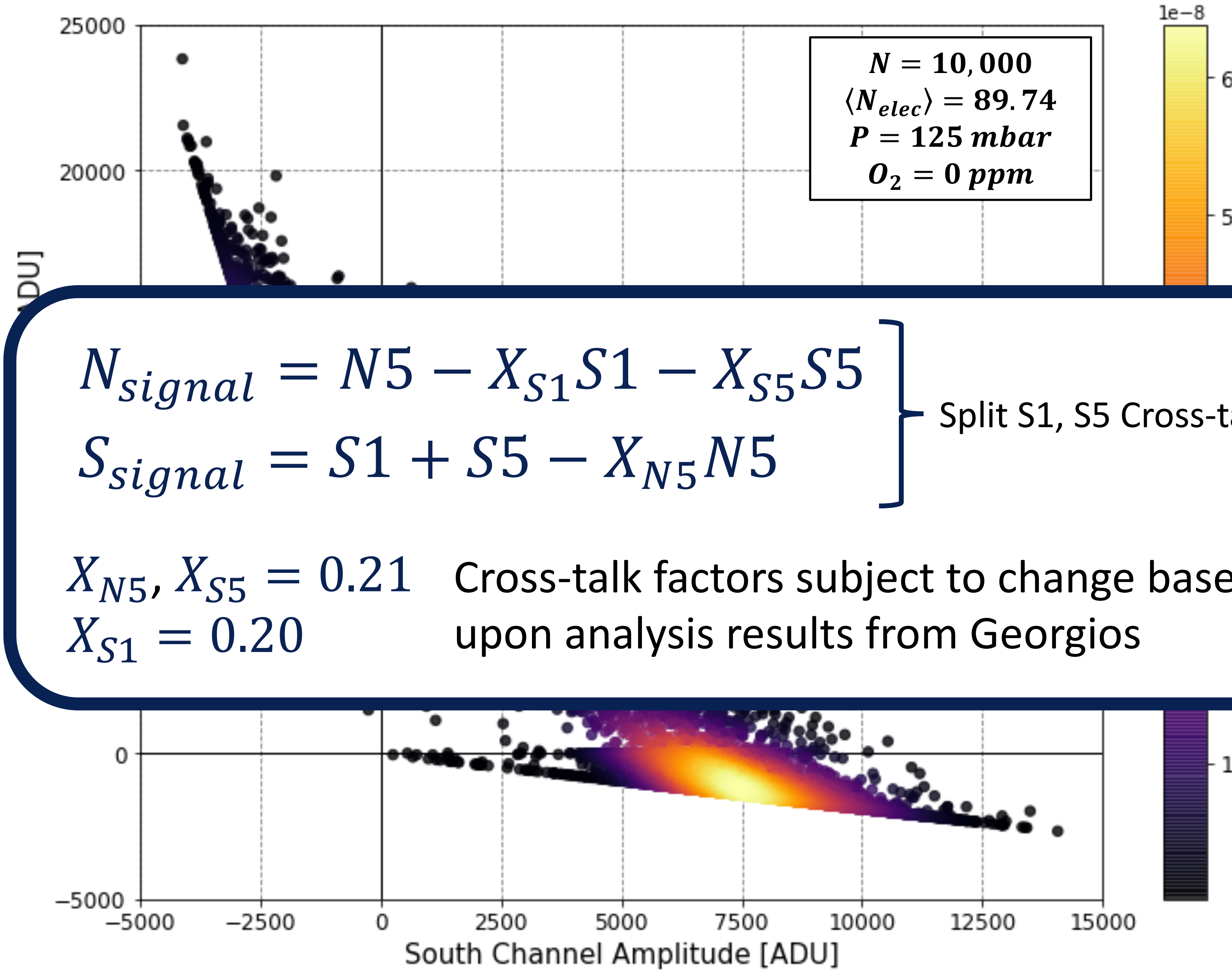
$\langle G \rangle$ for 5 northern anodes scaled by difference in average gain according to analysis by Georgios ($\langle G_N \rangle = 135.15$, $\langle G_S \rangle = 79.21$)



Step 2. Introduce Cross-Talk



Step 2. Introduce Cross-Talk



$$N_{signal} = N5 - X_{S1}S1 - X_{S5}S5$$

$$S_{signal} = S1 + S5 - X_{N5}N5$$

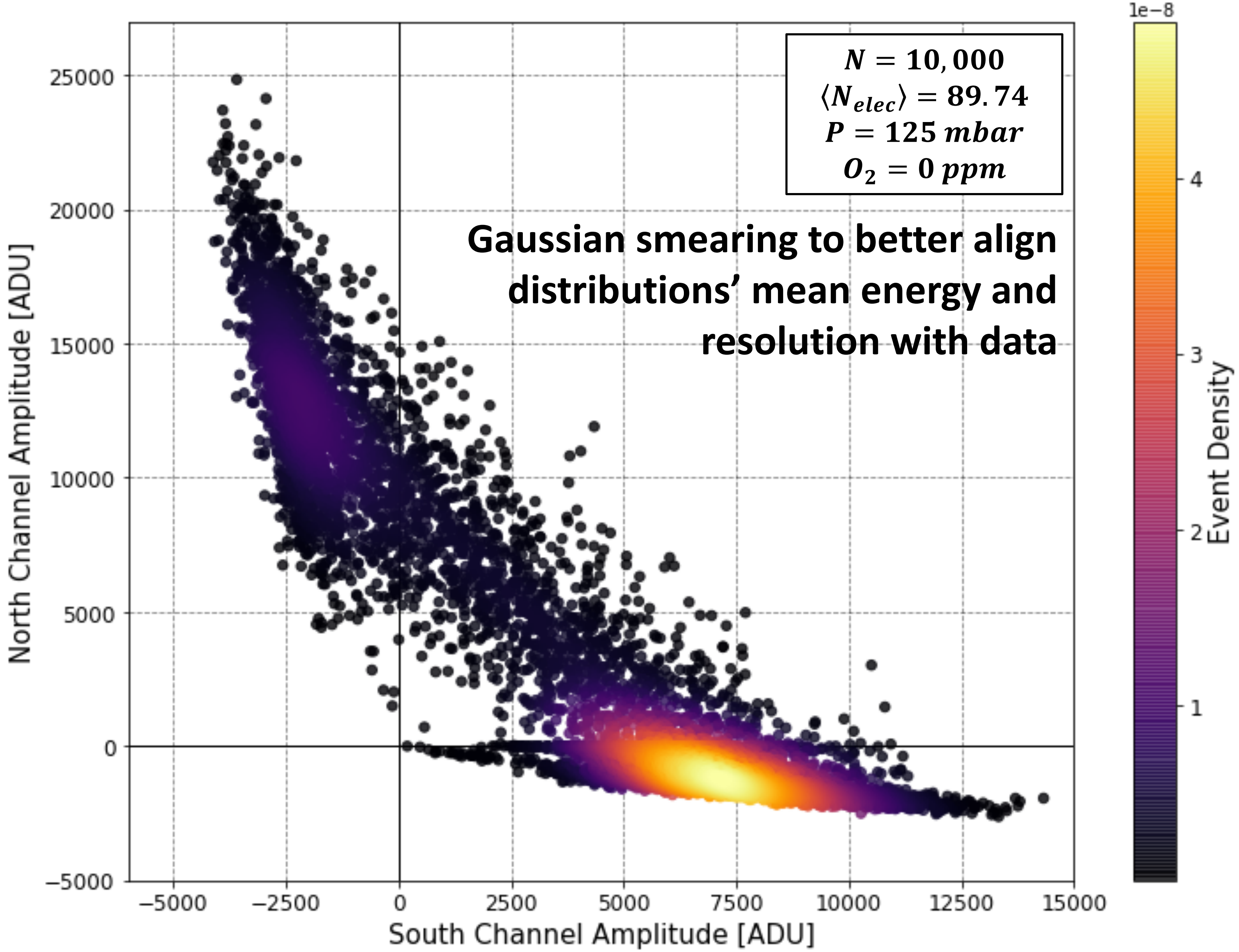
Split S1, S5 Cross-talk

$X_{N5}, X_{S5} = 0.21$

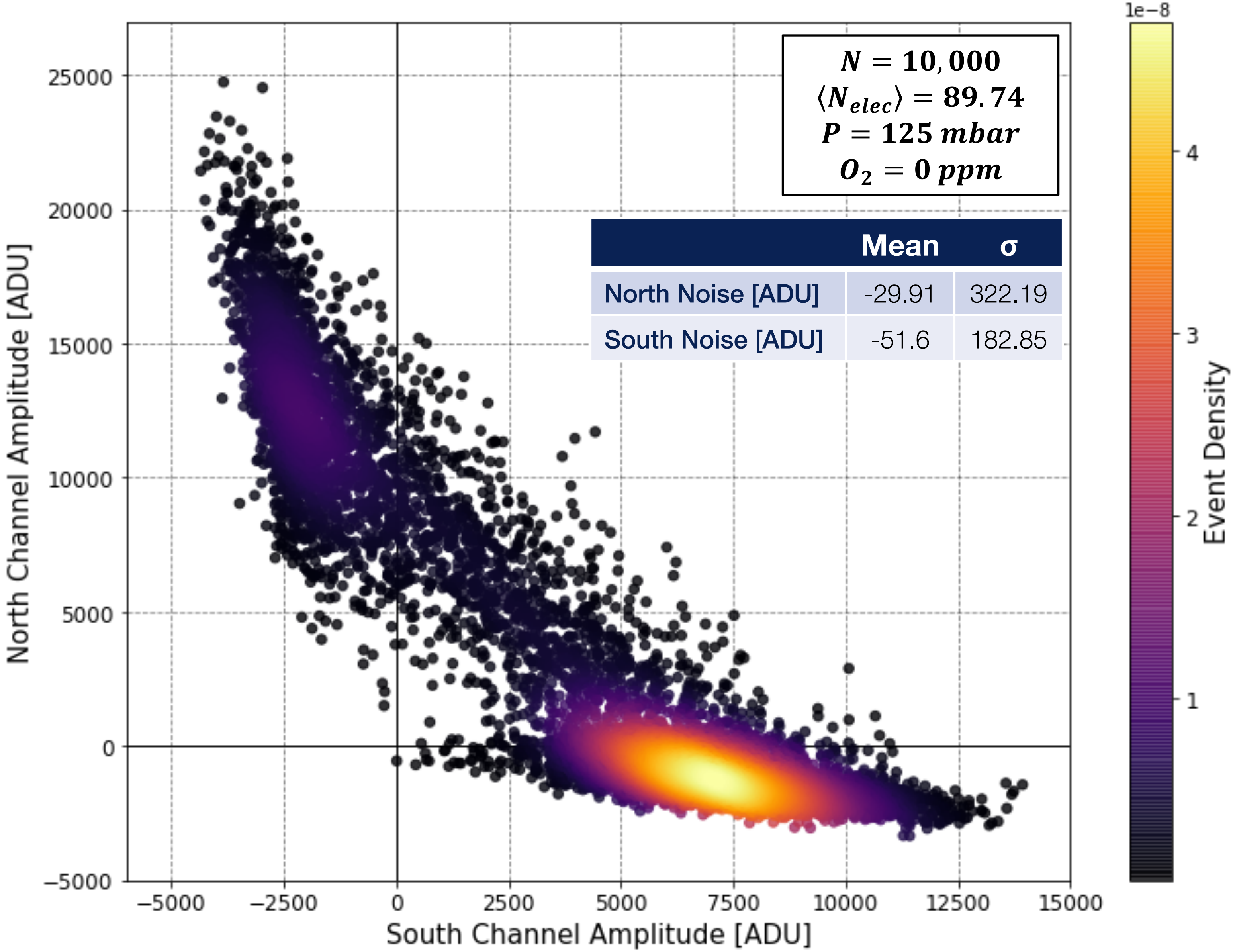
$X_{S1} = 0.20$

Cross-talk factors subject to change based upon analysis results from Georgios

Step 3. Perform Amplitude/Resolution Scaling



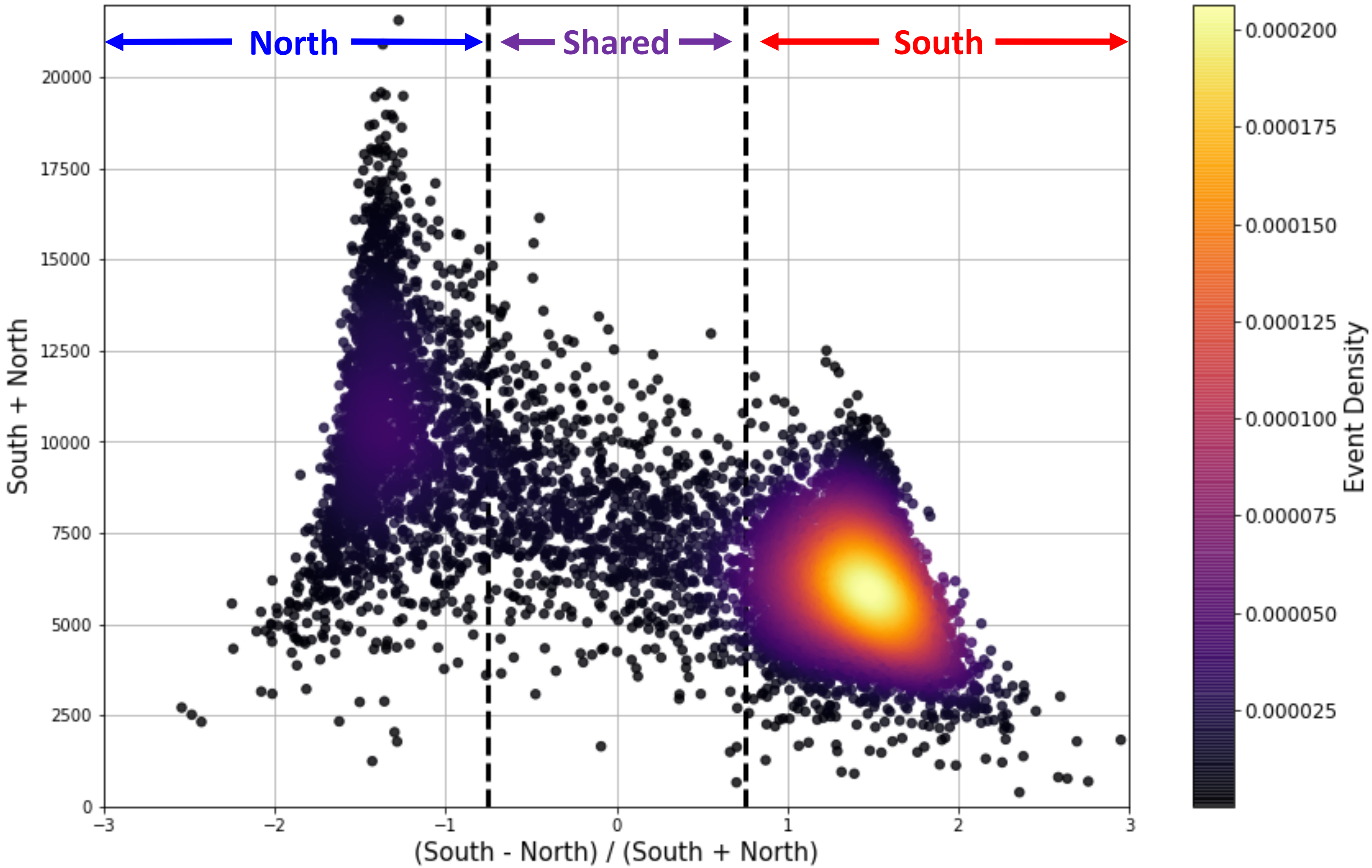
Step 4. Smear With Gaussian Baseline Noise



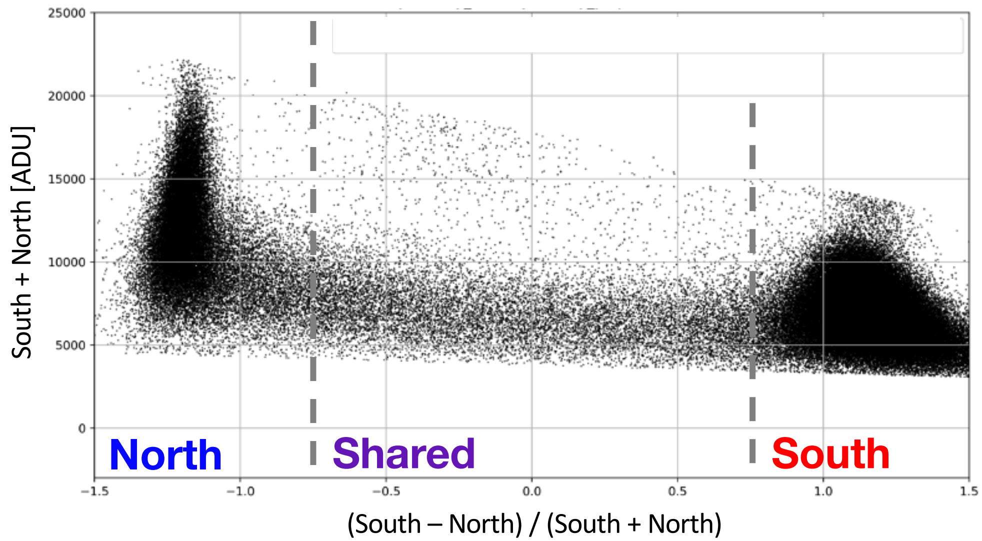
$N = 10,000$
$\langle N_{elec} \rangle = 89.74$
$P = 125\ mbar$
$O_2 = 0\ ppm$

	Mean	σ
North Noise [ADU]	-29.91	322.19
South Noise [ADU]	-51.6	182.85

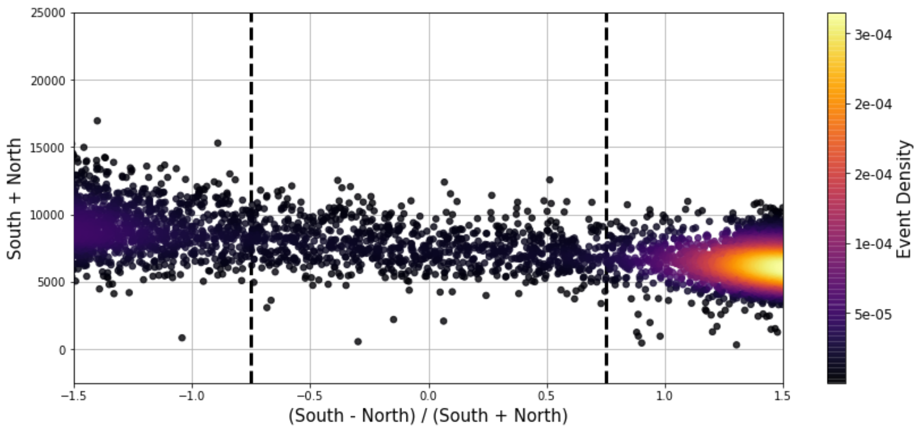
Step 5. Asymmetry Plot Coordinate Transform



Example Asymmetry Data from LSM



Asymmetry (P = 125 mbar, 0.00 ppm O_2)



Asymmetry (P = 145 mbar, 3.95 ppm O_2)