NEWS-G: Search for light Dark Matter with a Spherical Proportional Counter

Konstantinos Nikolopoulos
University of Birmingham

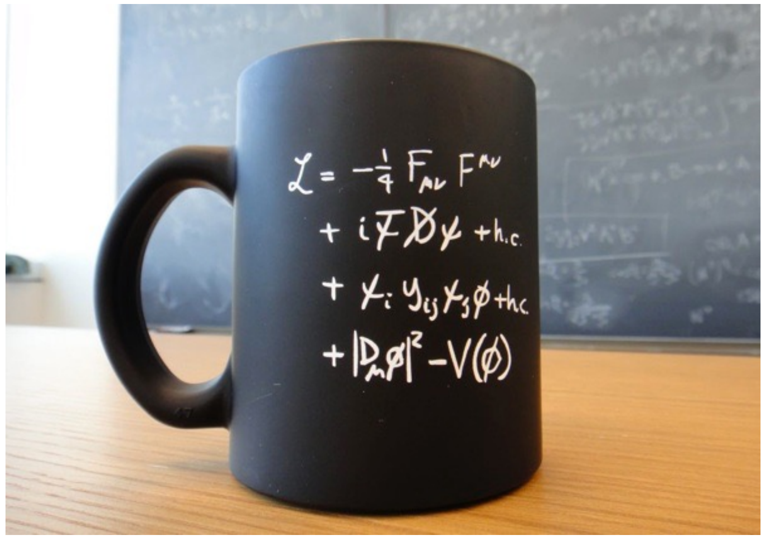

SNOglobe prototype at LSM

Particle Physics Seminar,
November 20, 2019
University of Geneva, Geneva, Switzerland

This project has received funding from European Union's Horizon 2020 research and innovation programme under Marie Skłodowska-Curie agreement DarkSphere-841261

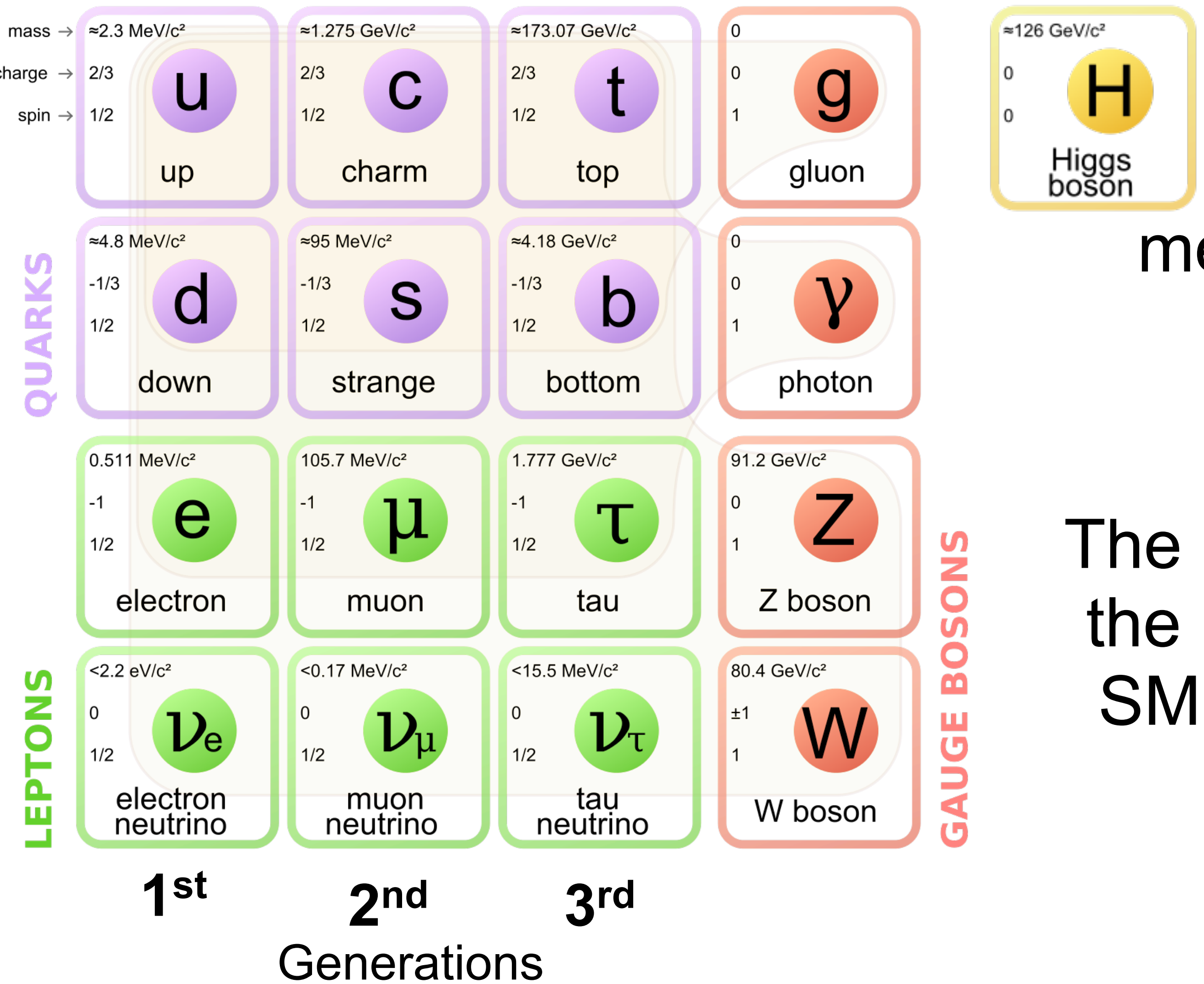
The Standard Model of Particle Physics

The Standard Model describes the **matter particles**
(quarks and leptons, organised in three families)
and their **interactions** (photon for electromagnetism, W/Z bosons for weak interactions, gluon for strong interaction)
and the **Higgs boson**



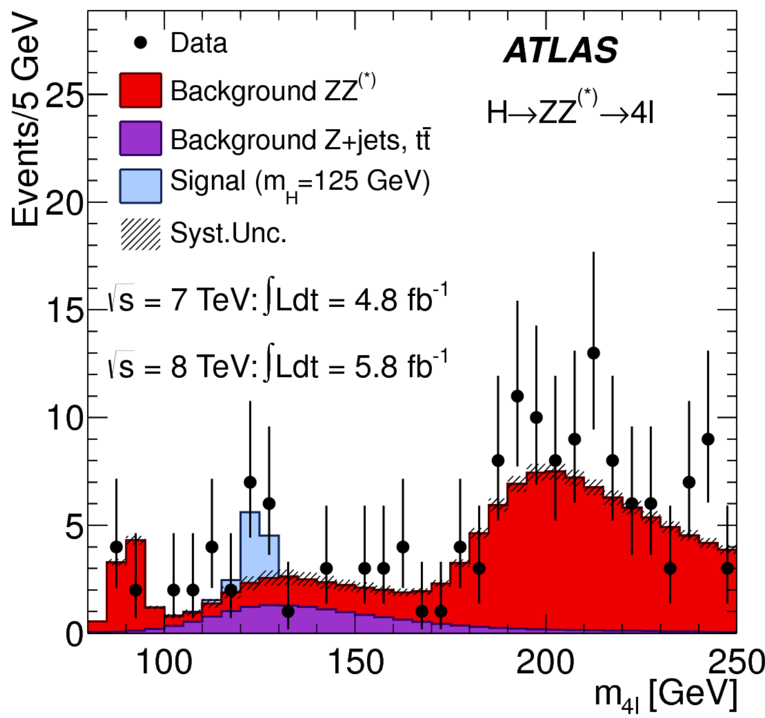
Matter Particles

Force Particles



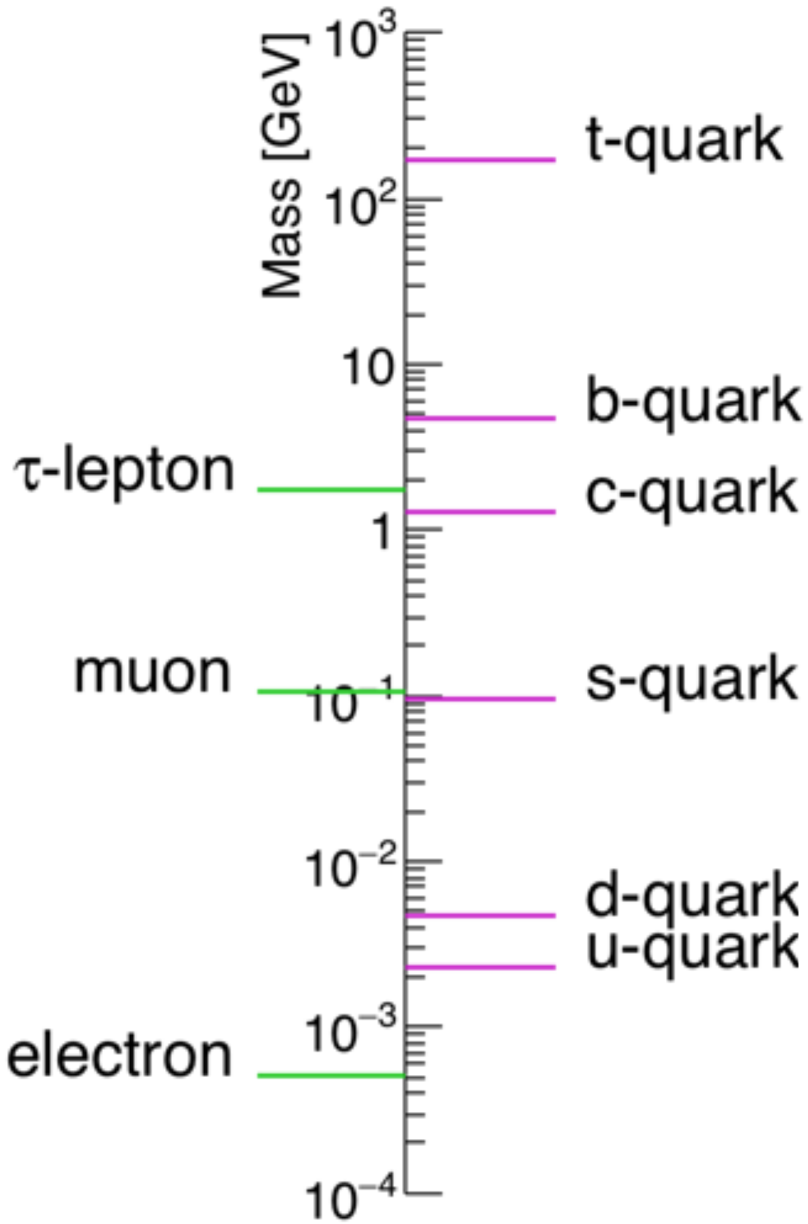
Higgs boson is a new kind of particle
neither **Matter** nor **Force** particle.
Introduced via Brout-Englert-Higgs mechanism for **W±/Z boson** mass generation

The **Higgs boson** was the last particle of the SM to be discovered
→ **July 2012**

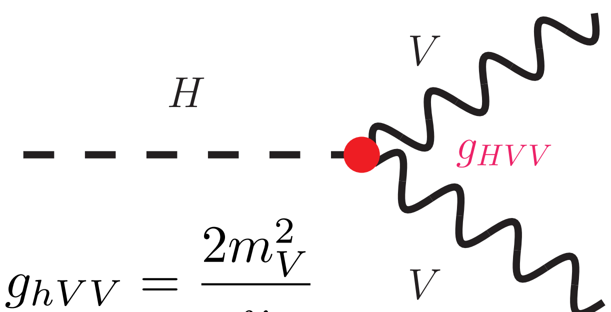


Higgs-fermion interactions: Yukawa couplings

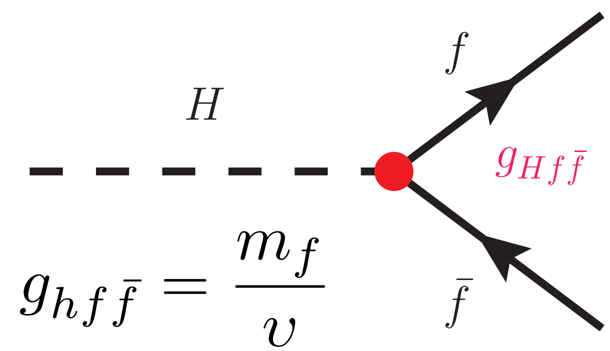
- **Higgs interactions to vector boson:** defined by symmetry breaking
- **Higgs interactions to fermions:** ad-hoc hierarchical Yukawa couplings $\propto m_f$



$$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$$



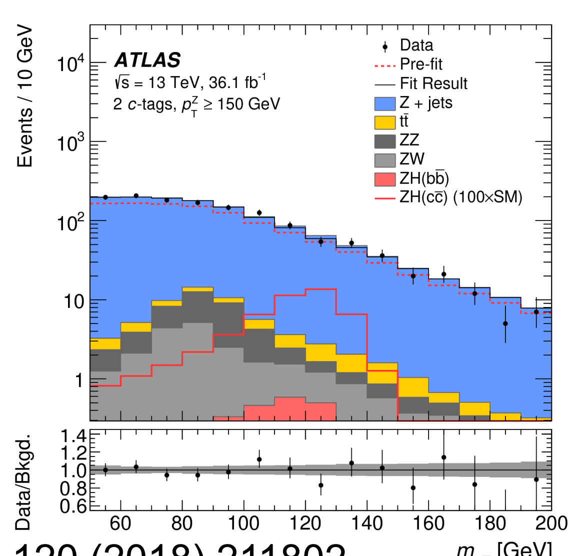
$$g_{hVV} = \frac{2m_V^2}{v}$$



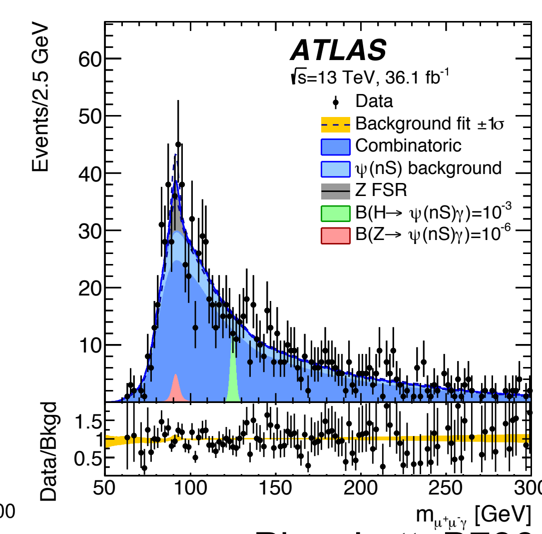
$$g_{hf\bar{f}} = \frac{m_f}{v}$$

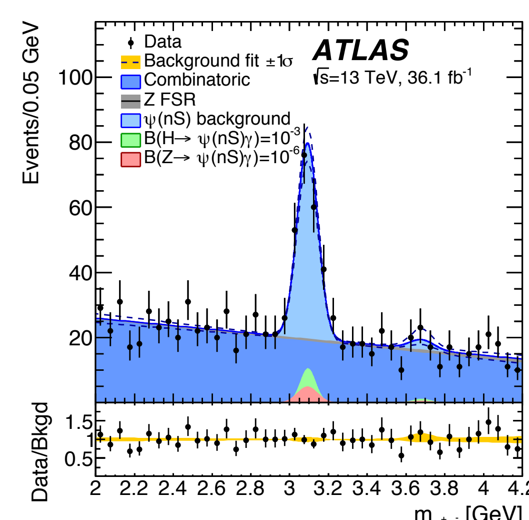
- Yukawa couplings **not** imposed by fundamental principle
- Modified Higgs-fermion couplings in BSM scenarios
- Probing fermion mass generation scale→independent task

Standard Model successful
but matter particle mass hierarchy unexplained!



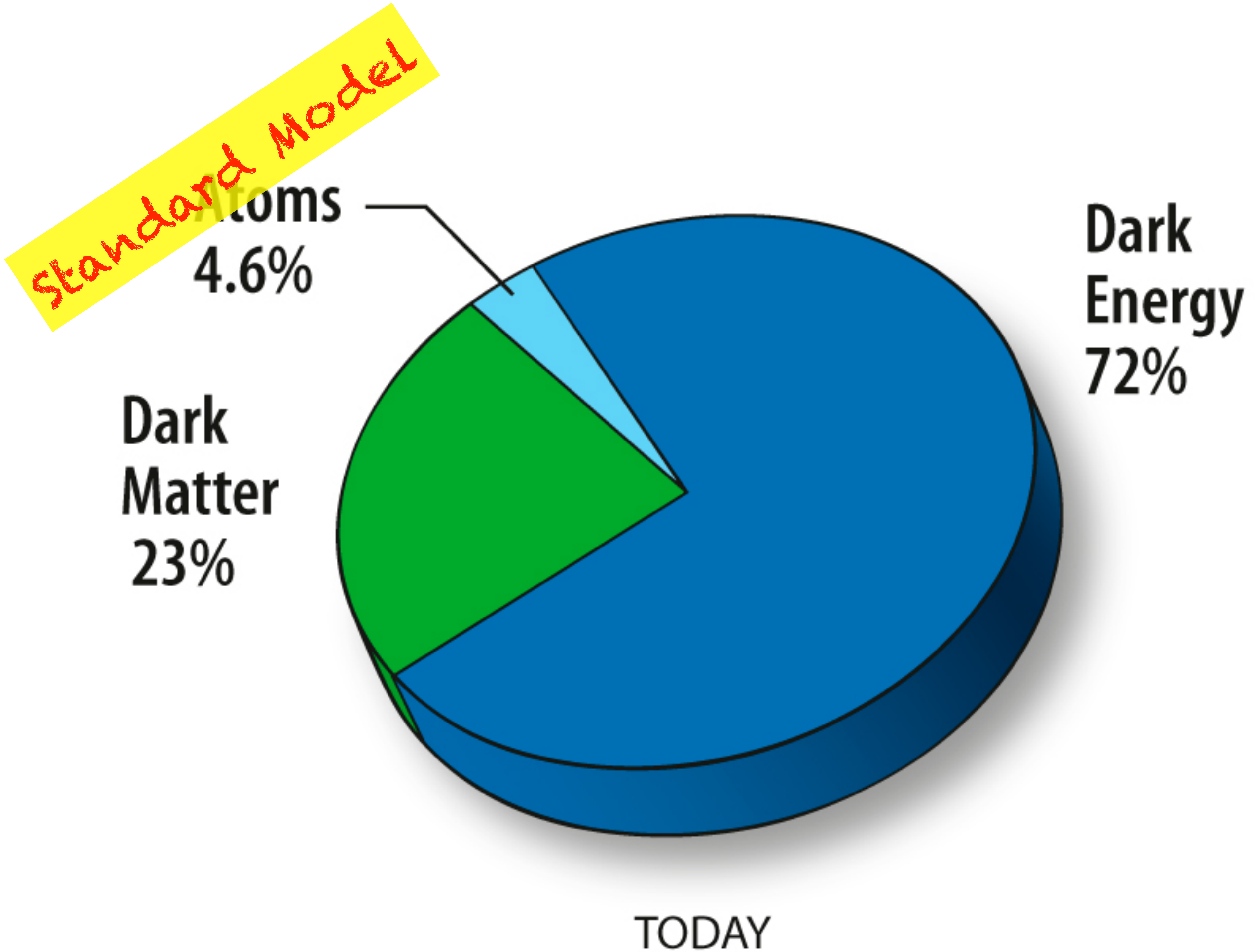
PRL120 (2018) 211802

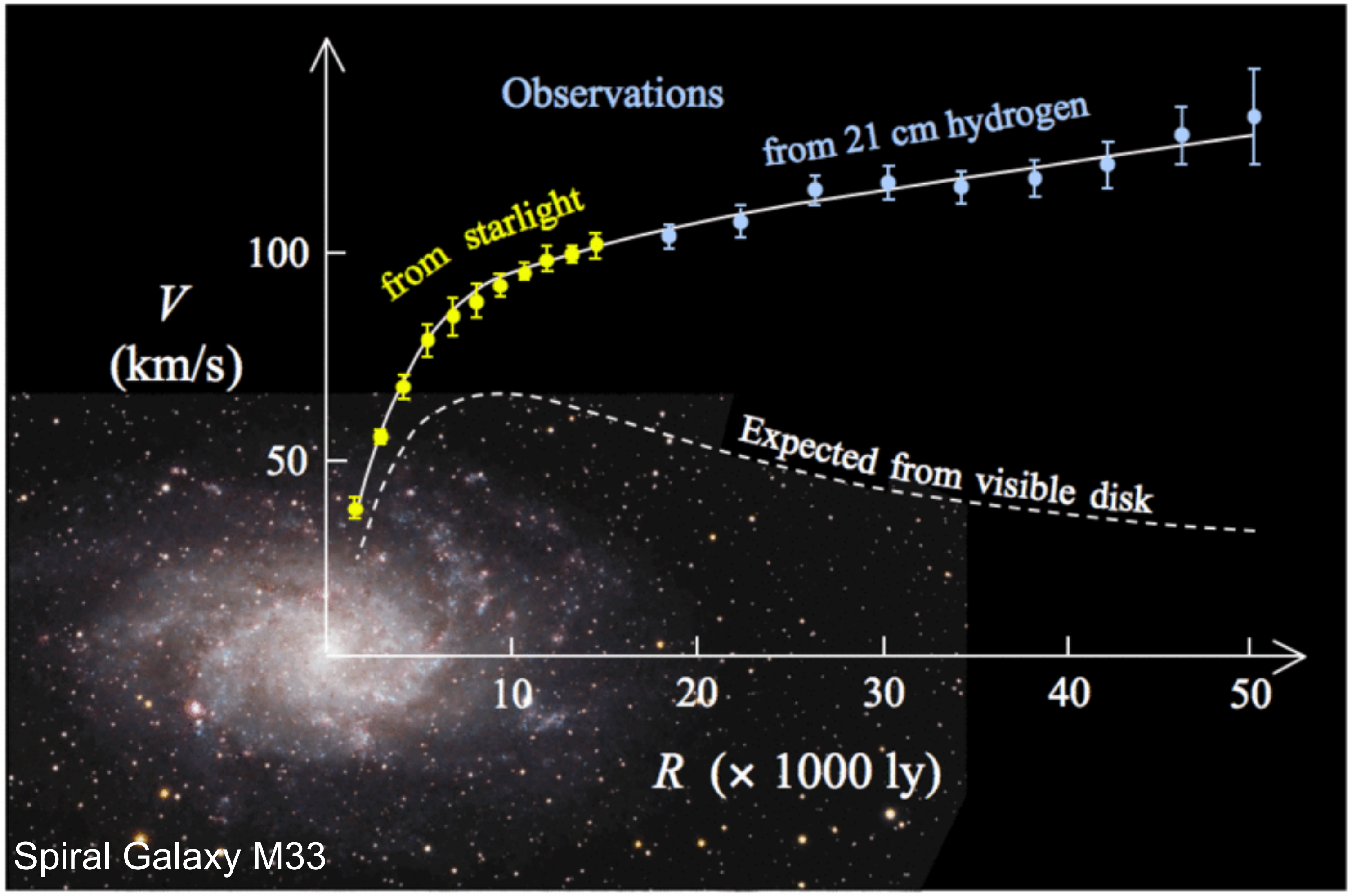


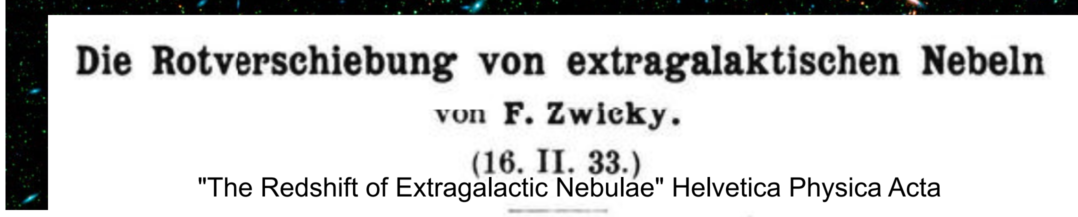


Phys.Lett. B786 (2018) 134

European Research Council
Established by the European Commission


Standard Model
Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY

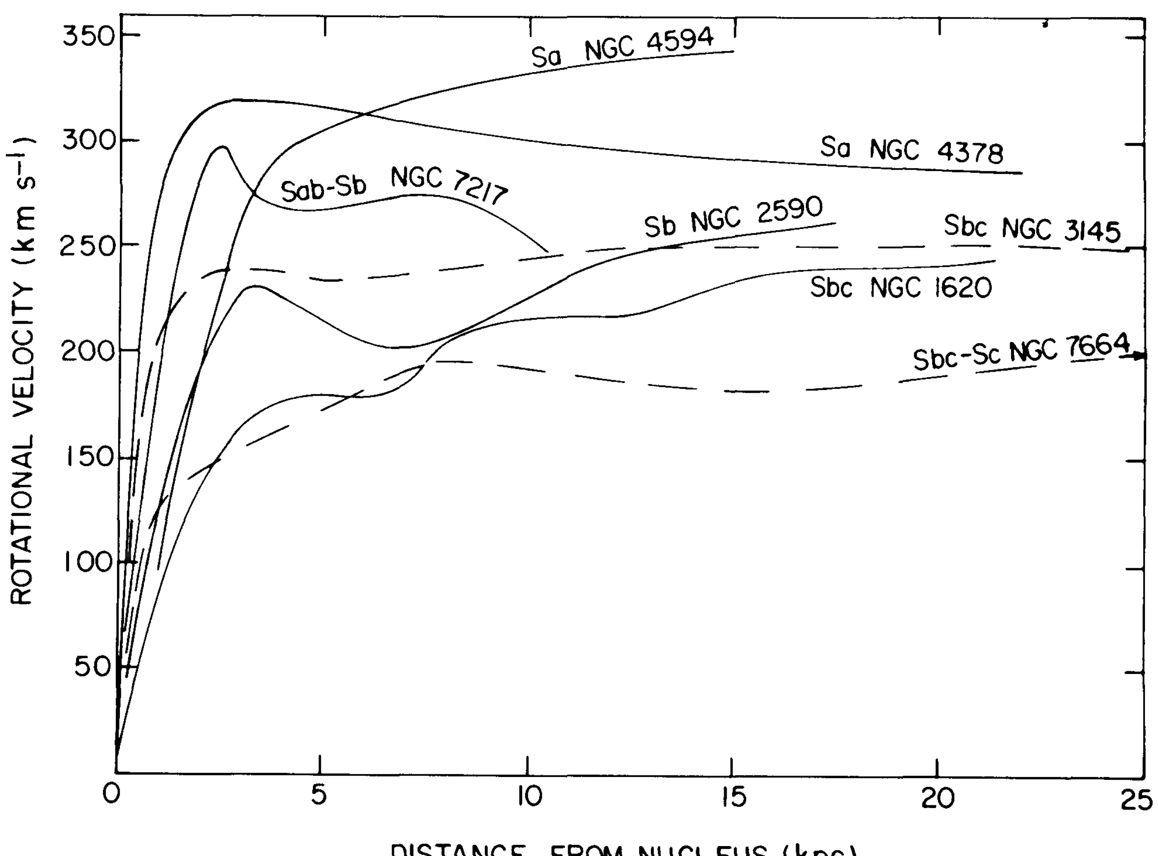



Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

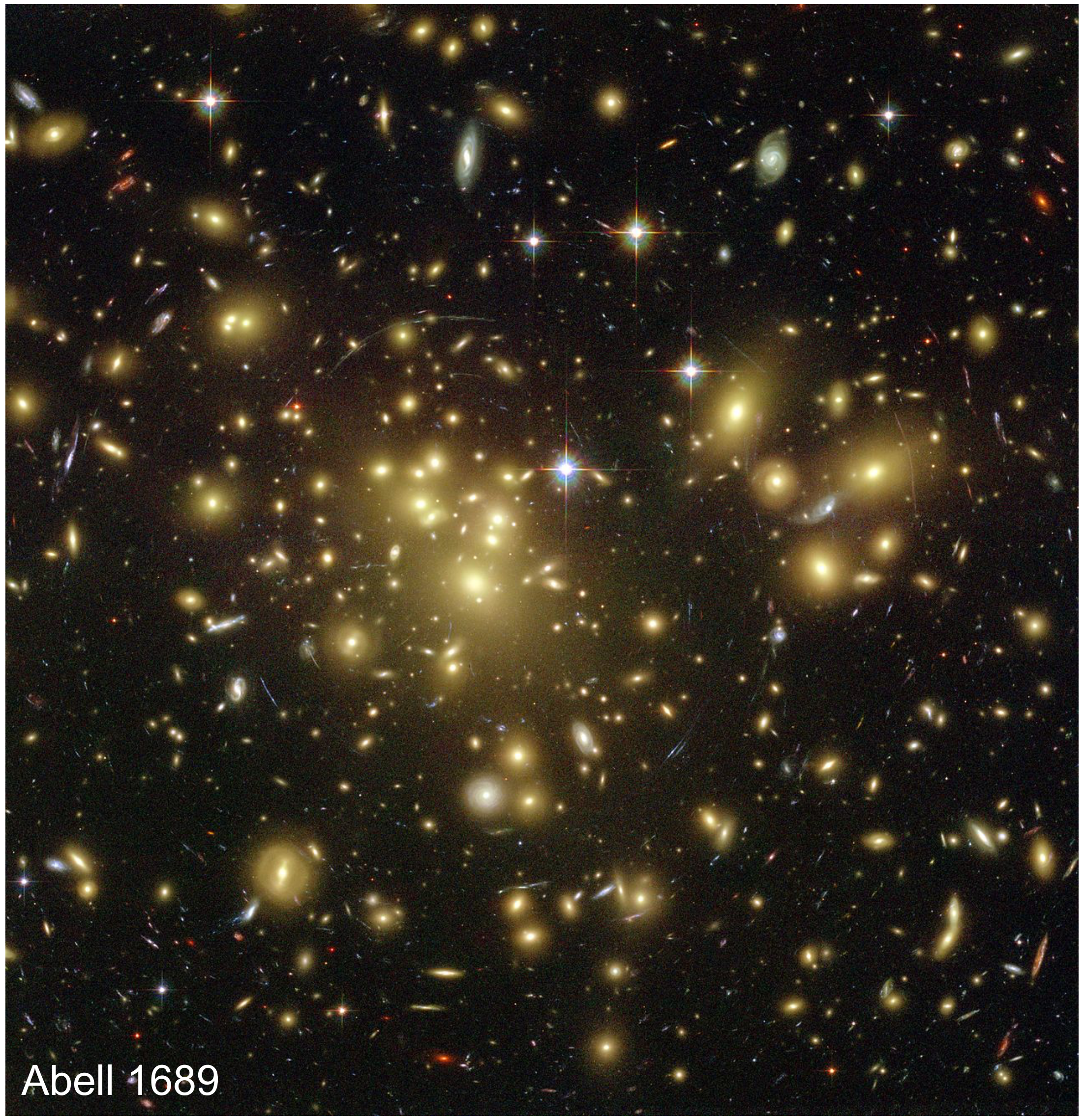
"The Redshift of Extragalactic Nebulae" Helvetica Physica Acta

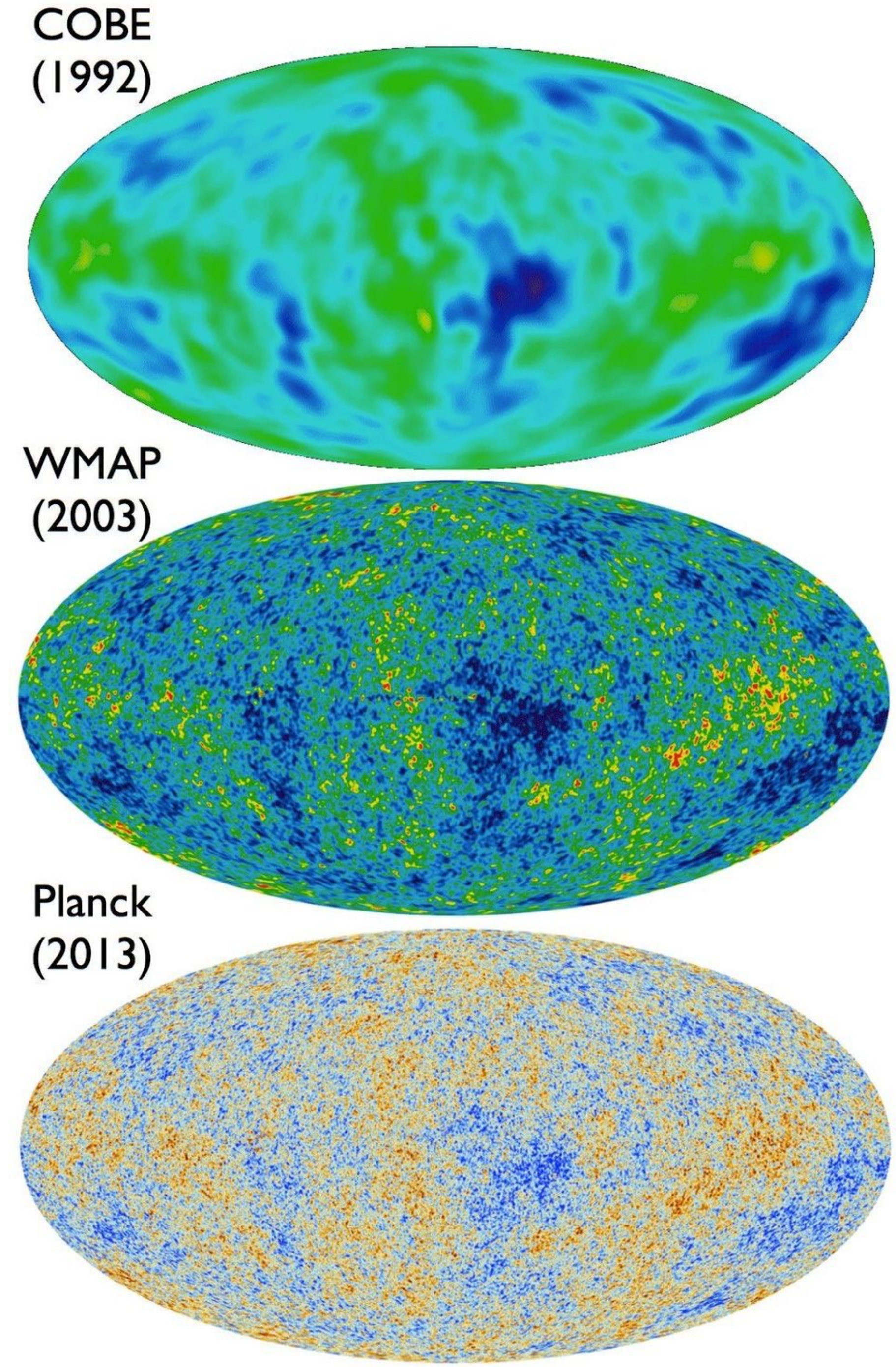



Vera Rubin
1928 - 2016


Fritz Zwicky
1898 - 1974

"In a spiral galaxy, the ratio of dark-to-light matter is about a factor of ten. That's probably a good number for the ratio of our ignorance-to-knowledge. We're out of kindergarten, but only in about third grade." Vera Rubin





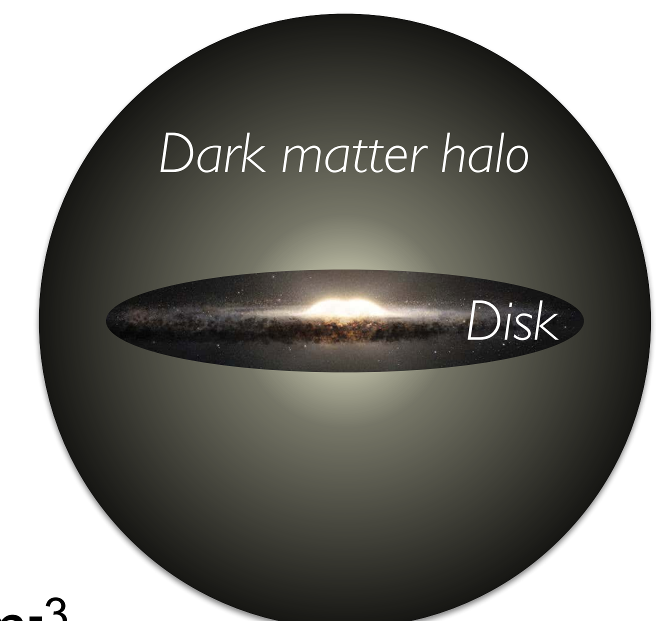
- **Evidence from gravitational interactions over many distance scales**
  - Rotational curves
  - Gravitational lensing
  - Cosmic microwave background
  - Large scale structure formation

- **What we know about Dark Matter**
  - Non-Baryonic
  - Mostly "cold"
  - Electrically neutral (or milli-charged?)
  - "Weakly" interacting
  - $\Omega_{DM}h^2=0.120\pm0.001$
  - Stable or $\tau_{DM} \gg \tau_U$
- **No known particle fits the bill!**

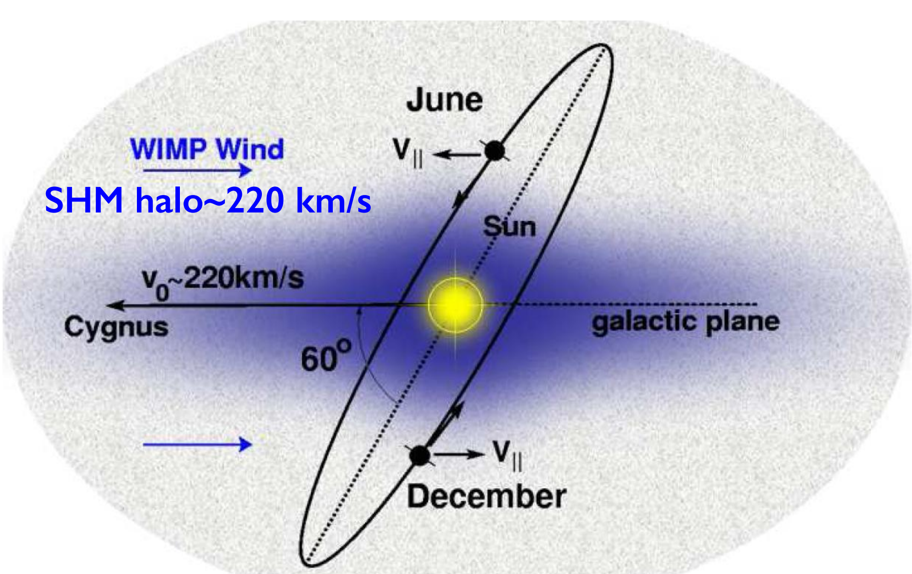
Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 scattering cross-section on nucleons: ?
X^0 production cross-section in hadron colliders: ?
X^0 self-annihilation cross-section: ?

- **Standard Halo Model**
  - Assumptions:
    - Round halo
    - Isotropic
    - Maxwell velocity distribution
    - No substructure



- **Locally…**
  - DM density is ρ~0.3-0.4 GeV cm^{-3}
  - Solar system travelling through "DM Wind"
  - Flux: $10^7/m_\chi$ GeV cm^{-2}s^{-2}
  - Motion of Earth → velocity time dependent
  - Annual modulations in DM flux
- **Gaia sheds new light on DM in our neighbourhood**



Detecting Dark Matter

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

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

- **WIMP "miracle"**
  - Observed relic abundance explained by massive particle (10 GeV - 1 TeV) interacting through weak interaction with baryonic matter

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

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

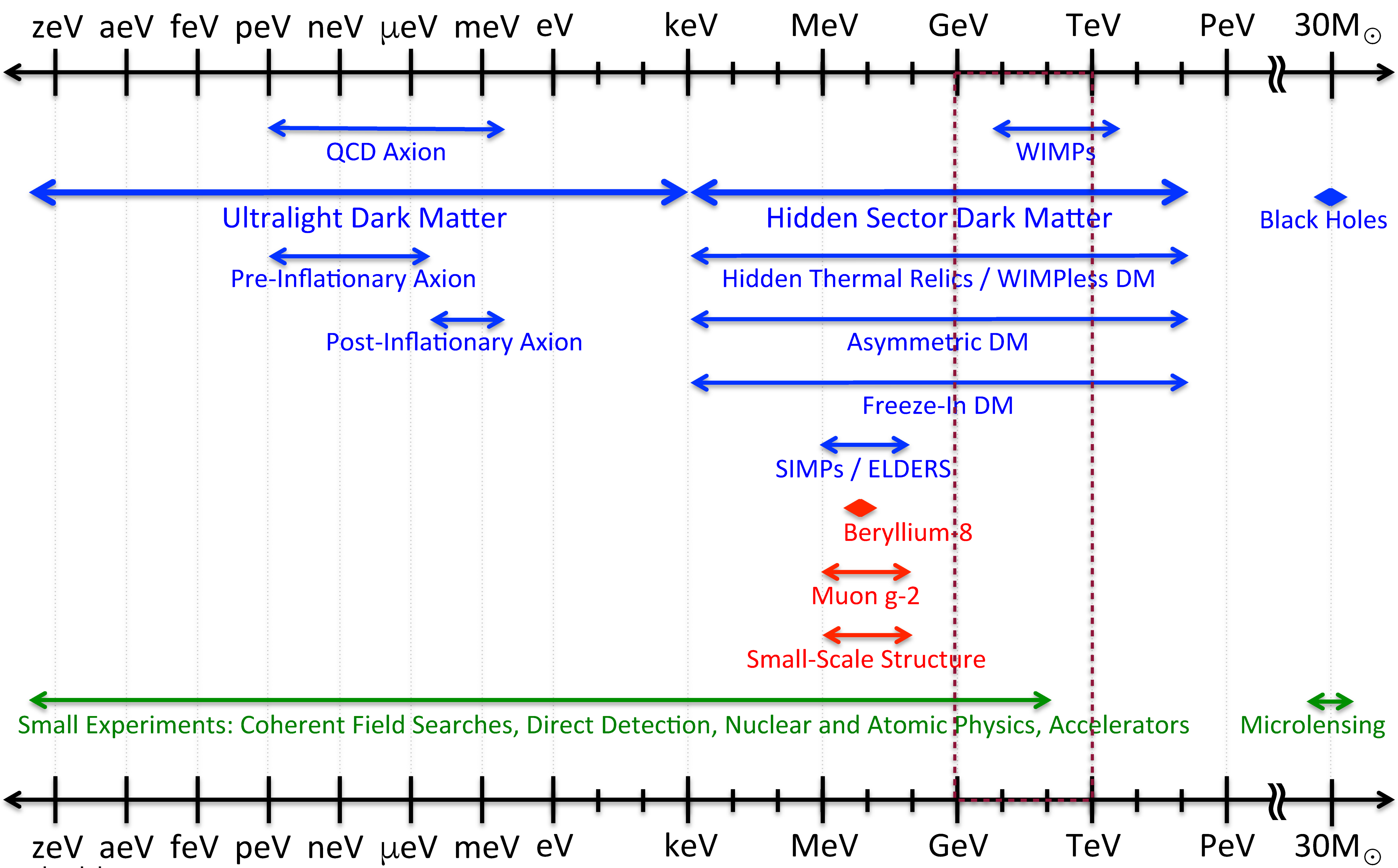
Jonathan L. Feng and Jason Kumar
Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
(Received 4 April 2008; published 1 December 2008)

We propose that dark matter is composed of particles that naturally have the correct thermal relic density, but have neither weak-scale masses nor weak interactions. These models emerge naturally from gauge-mediated supersymmetry breaking, where they elegantly solve the dark-matter problem. The framework accommodates single or multiple component dark matter, dark-matter masses from 10 MeV to 10 TeV, and interaction strengths from gravitational to strong. These candidates enhance many direct and indirect signals relative to weakly interacting massive particles and have qualitatively new implications for dark-matter searches and cosmological implications for colliders.

DOI: 10.1103/PhysRevLett.101.231301 PACS numbers: 95.35.+d, 12.60.Jv

Wide field of possibilities!

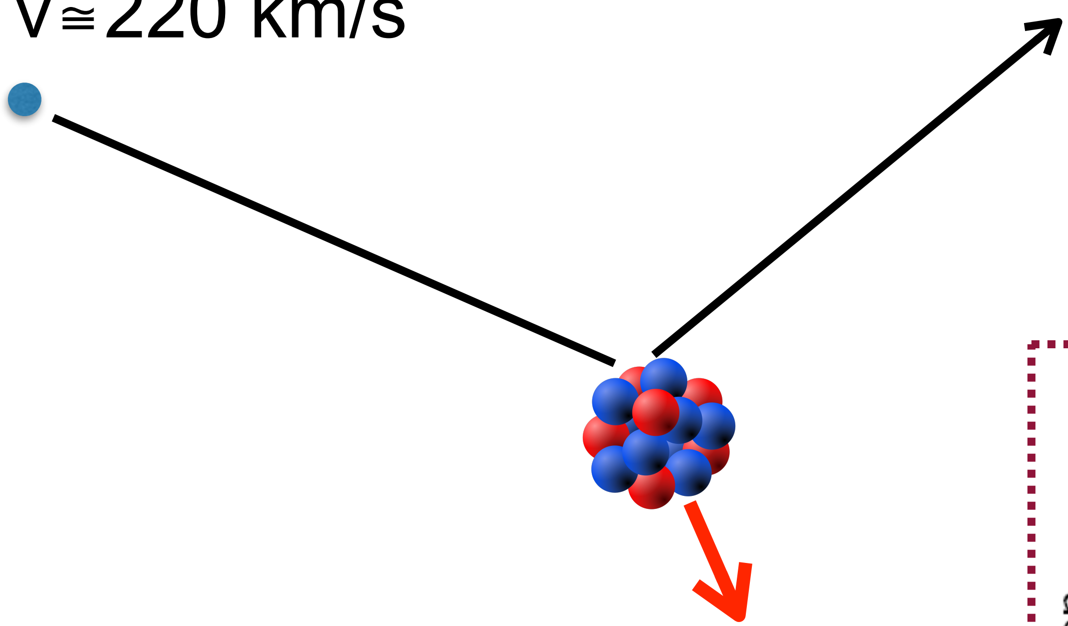
Dark Sector Candidates, Anomalies, and Search Techniques



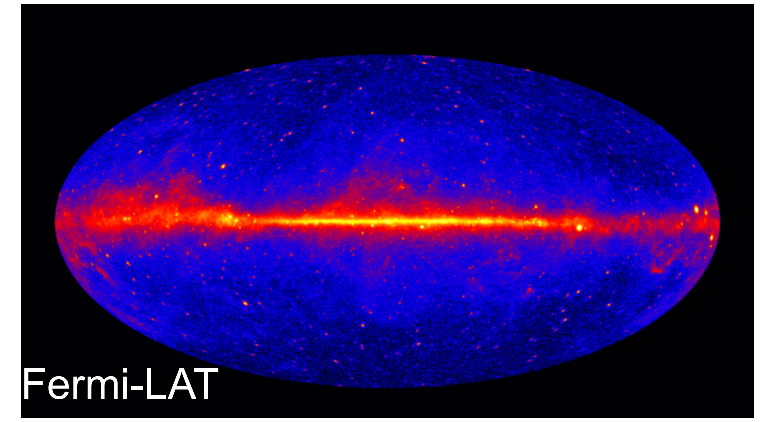
Cosmic visions
1707.04591

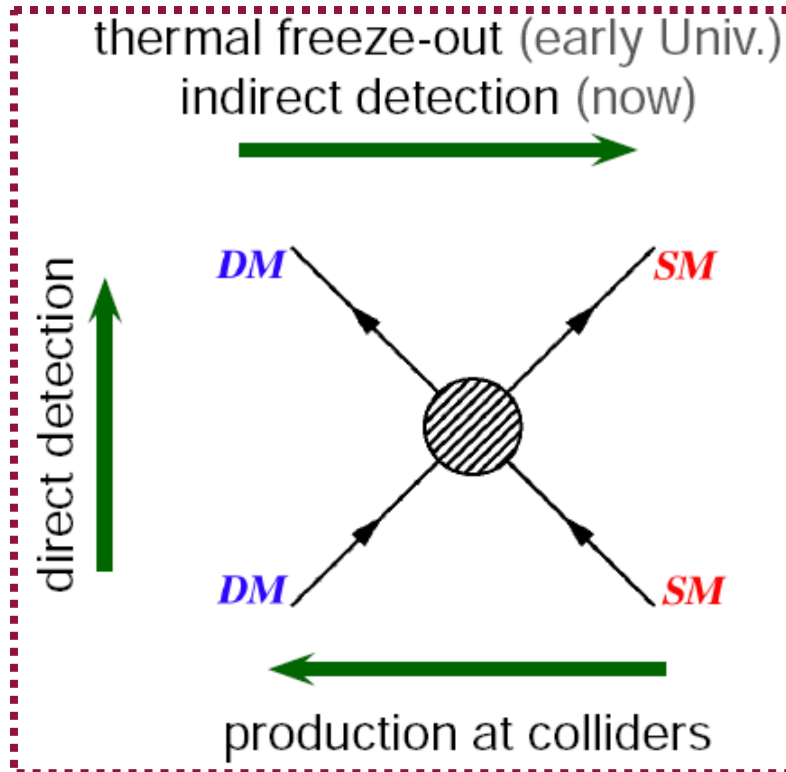
Searching for Dark Matter

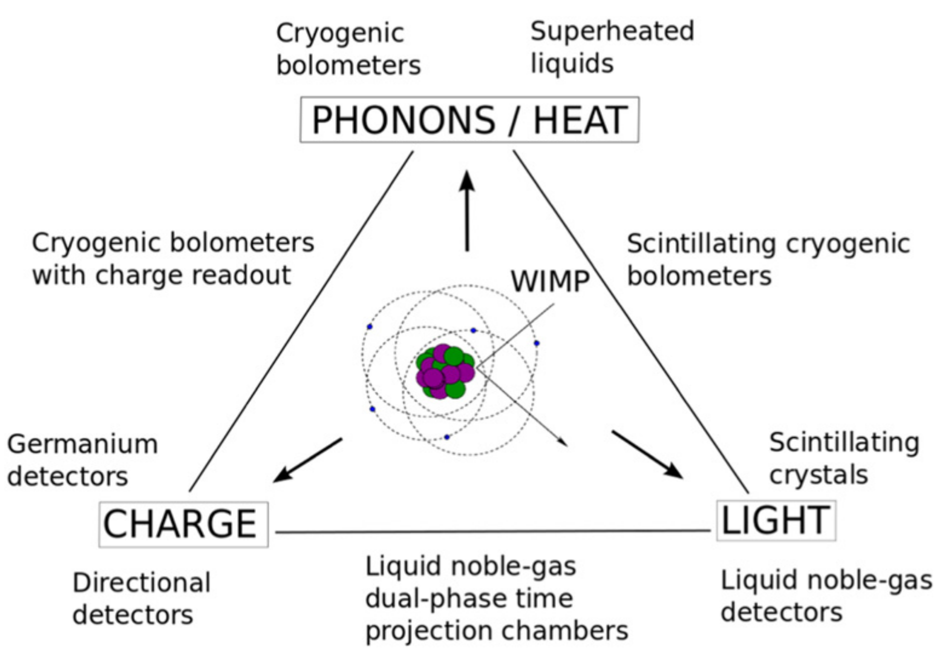
Dark Matter
v≅220 km/s



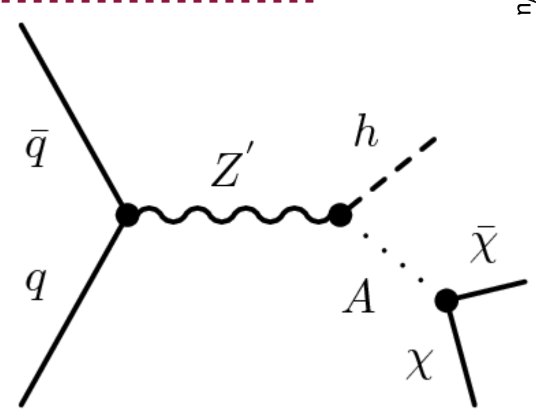
recoil
E~O(10keV)

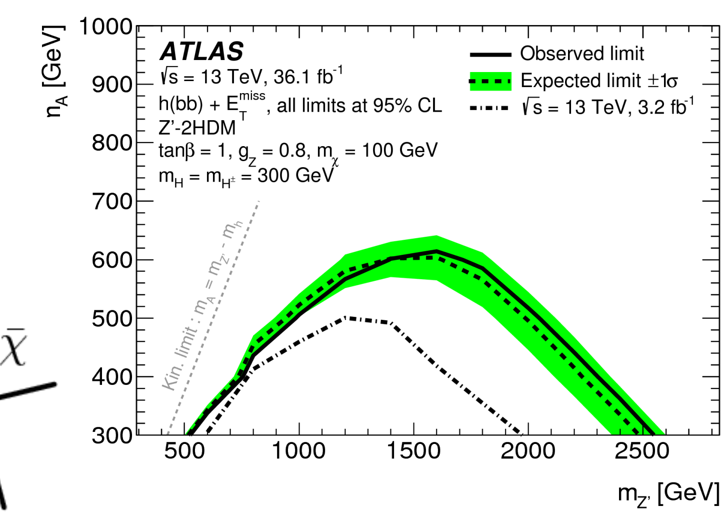






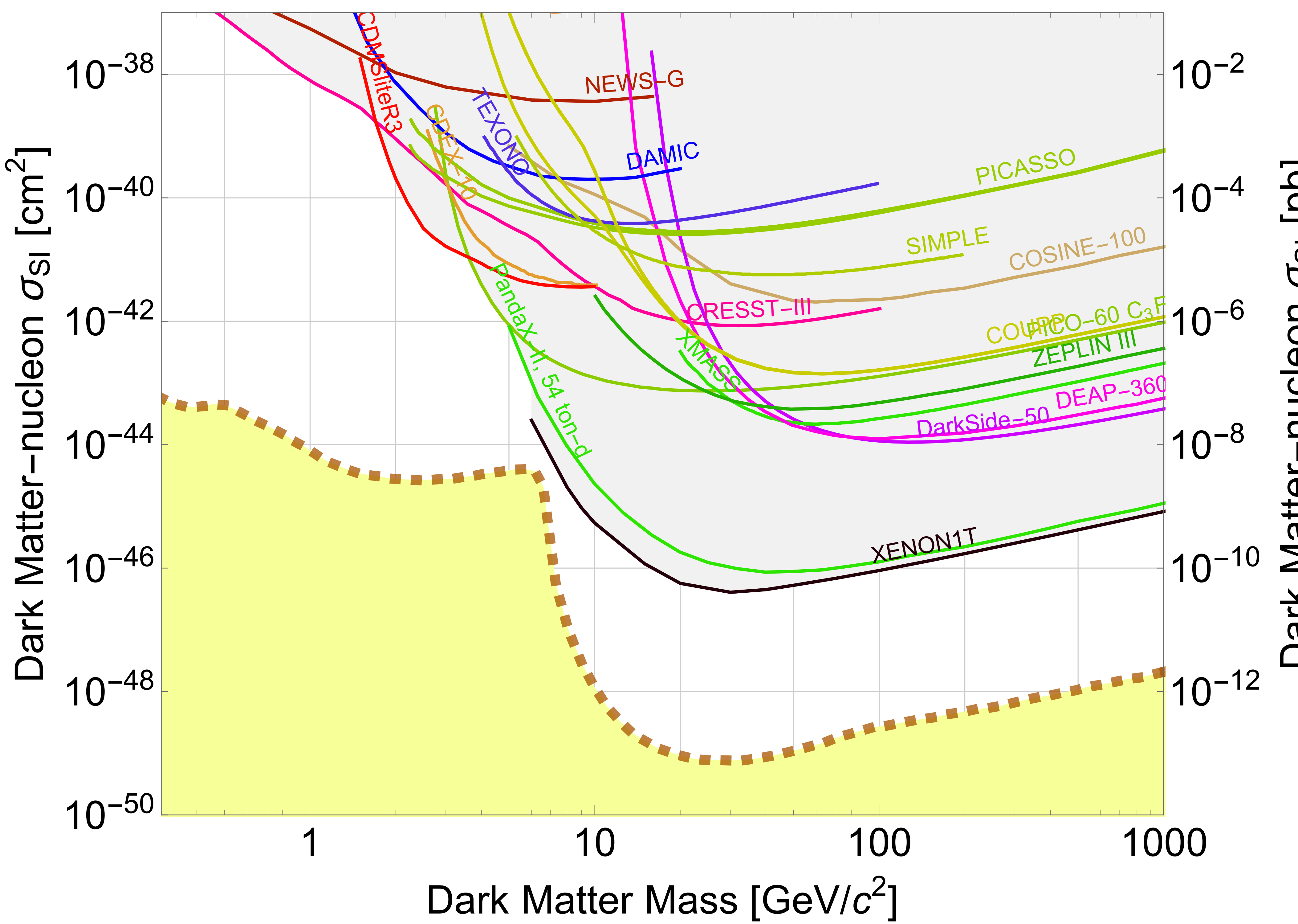
J.Phys. G43 (2016) 013001



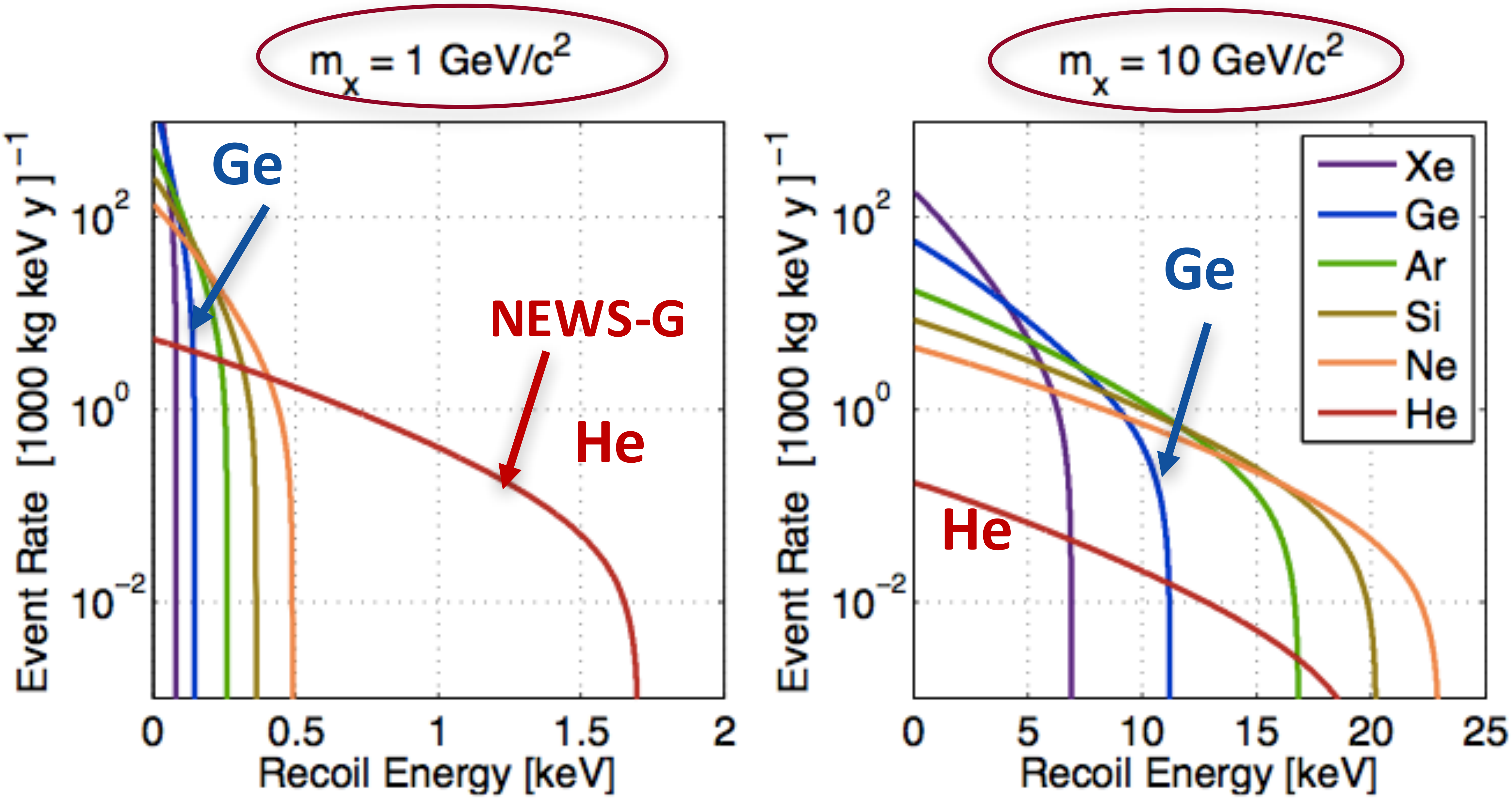


Phys. Rev. Lett. 119 (2017) 181804

Direct Detection: Landscape



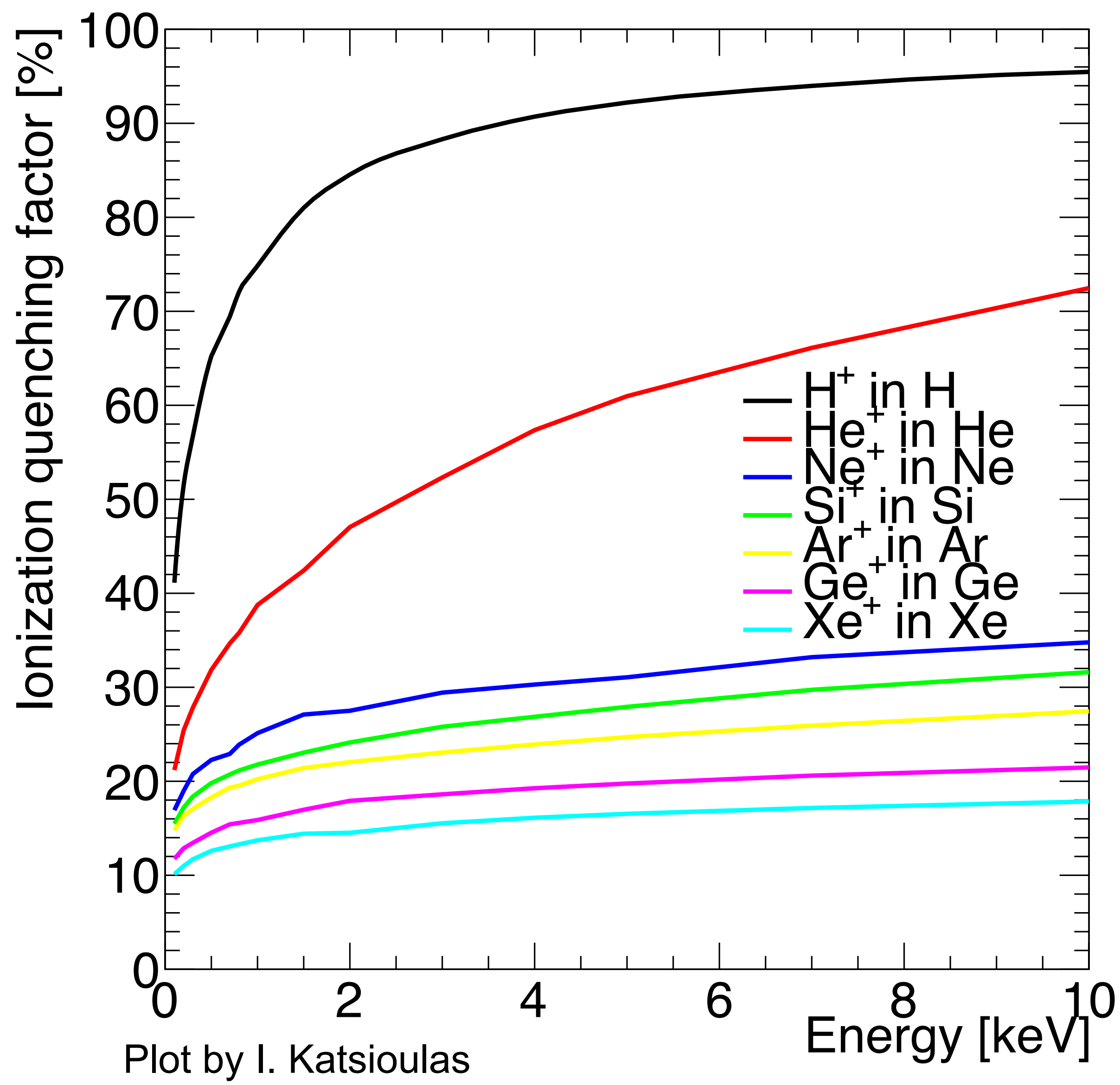
Direct Detection: Target Kinematics



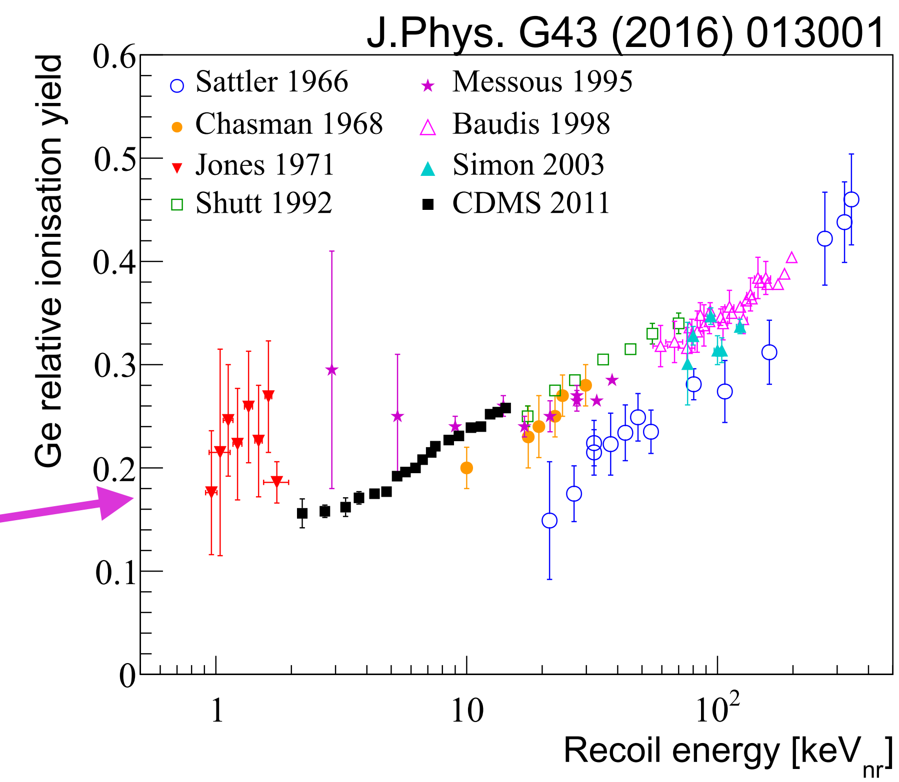
Recoil distributions with various targets

Direct Detection: Quenching Factor

- Quenching factor: fraction of ion kinetic energy dissipated in a medium in the form of ionization electrons and excitation of the atomic and quasi-molecular states.



Plot by I. Katsioulas

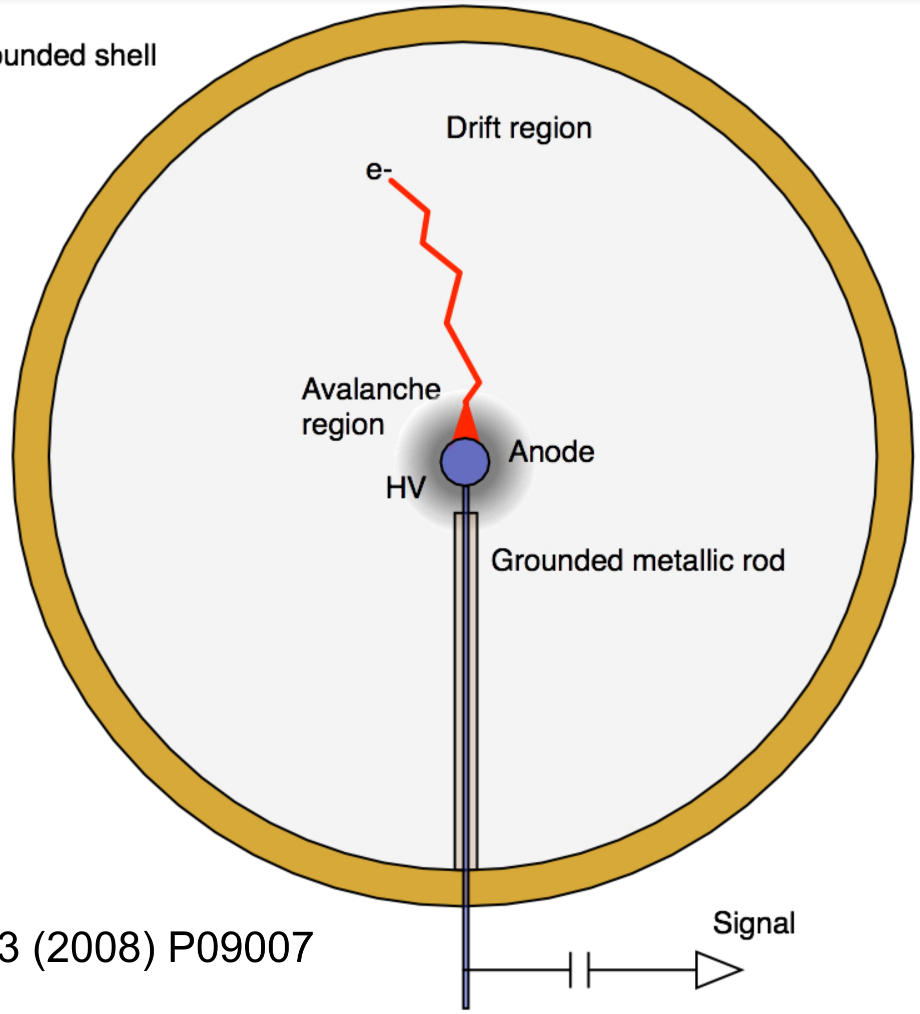


- Direct detection experiment using light gases as target (H, He, Ne)
  - Better projectile-target kinematic match
  - Favourable quenching factor

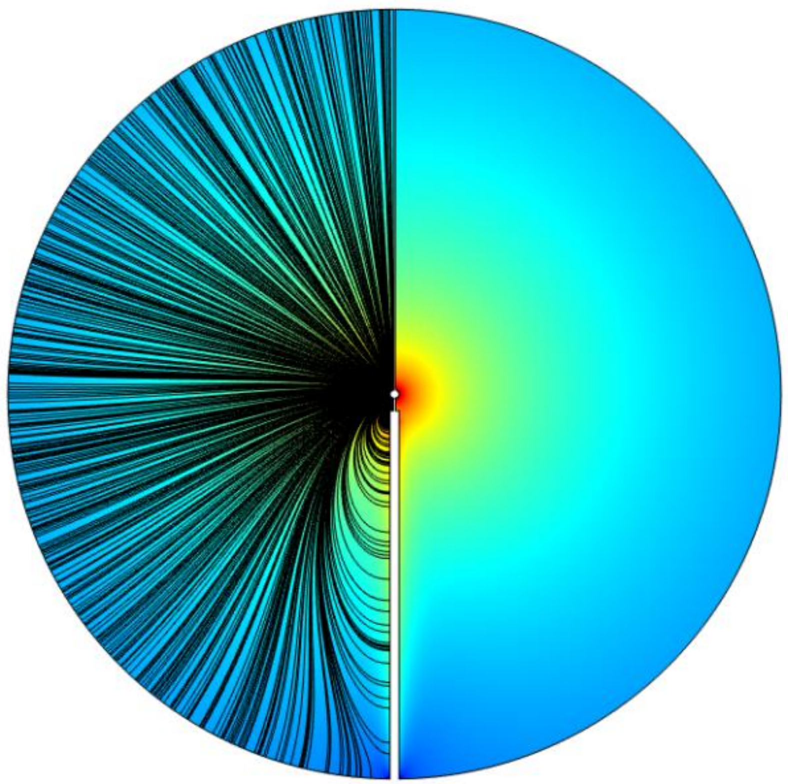
The NEWS-G Collaboration

6th collaboration meeting, LPSC, Grenoble, June 2019

Spherical Proportional Counter



JINST 3 (2008) P09007



$$E = \frac{V_0}{r^2}\frac{r_1 r_2}{r_2 - r_1} \approx \frac{V_0 r_1}{r^2}$$

$$C = \frac{4\pi\epsilon}{r_2 - r_1} r_1 r_2 \approx 4\pi\epsilon r_1$$

$r_1 = \text{anode radius}$

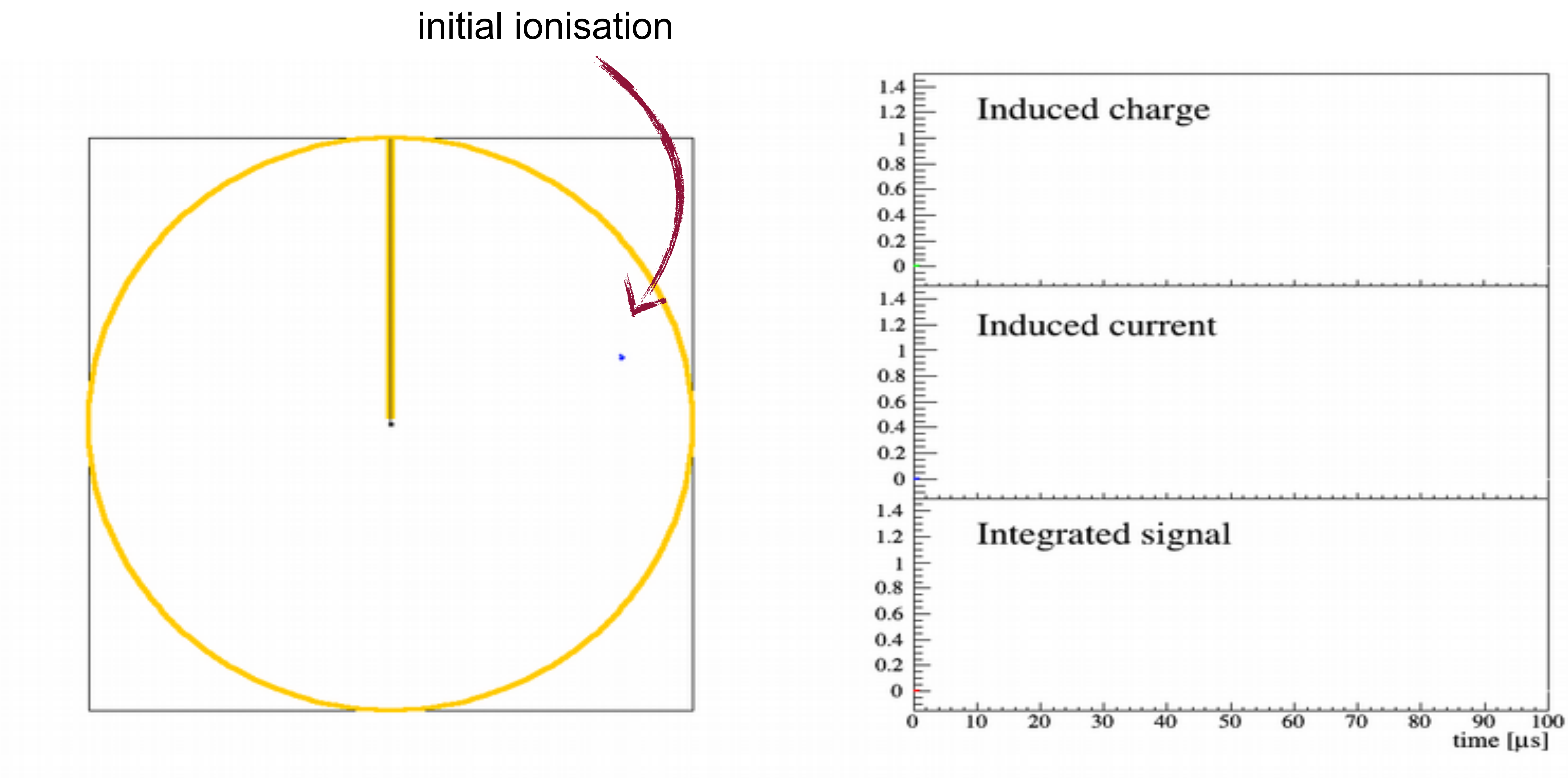
$r_2 = \text{cathode radius}$

Detector volume naturally divided in: "drift" and "amplification" regions.

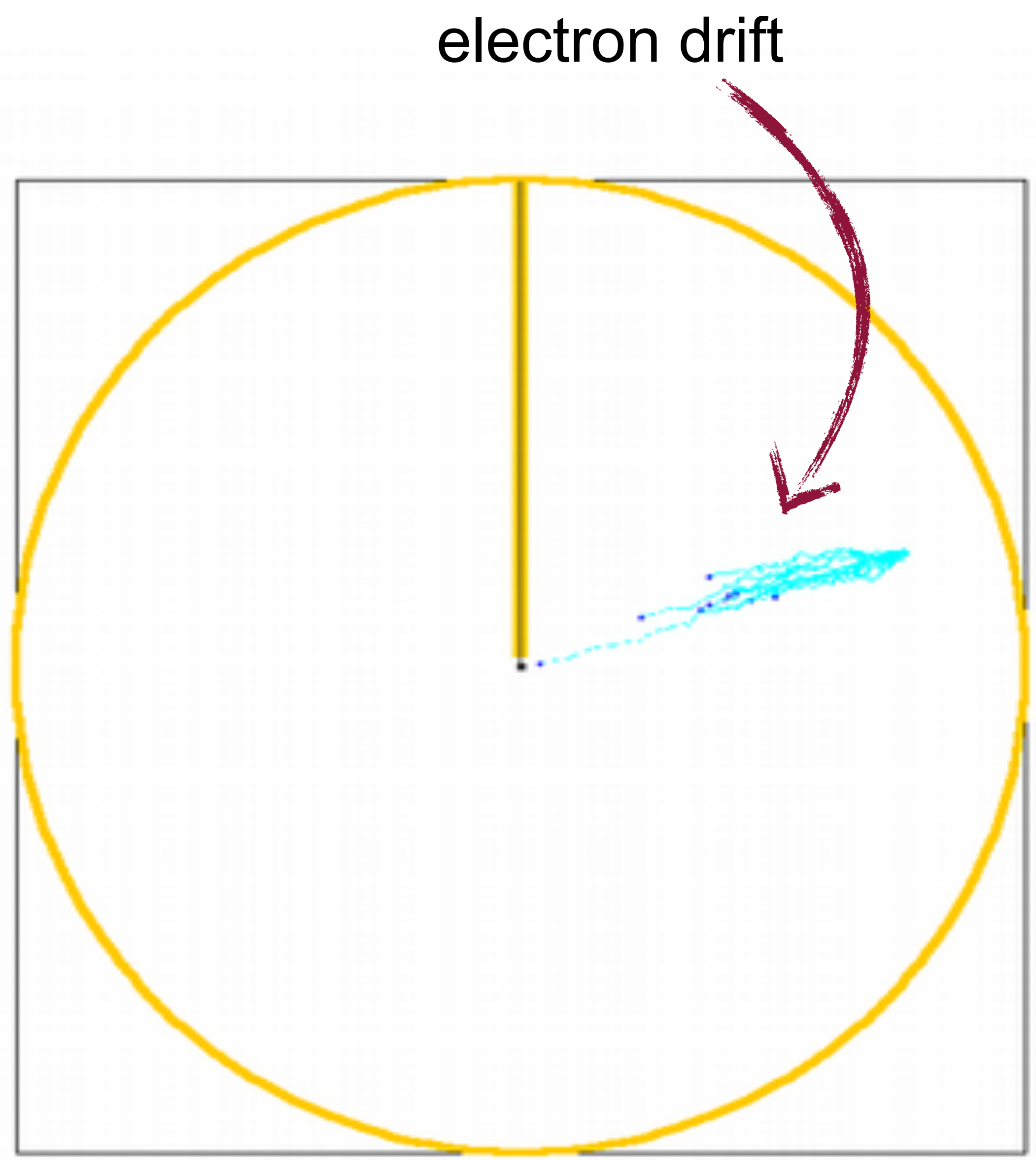
Spherical Proportional Counter: Features

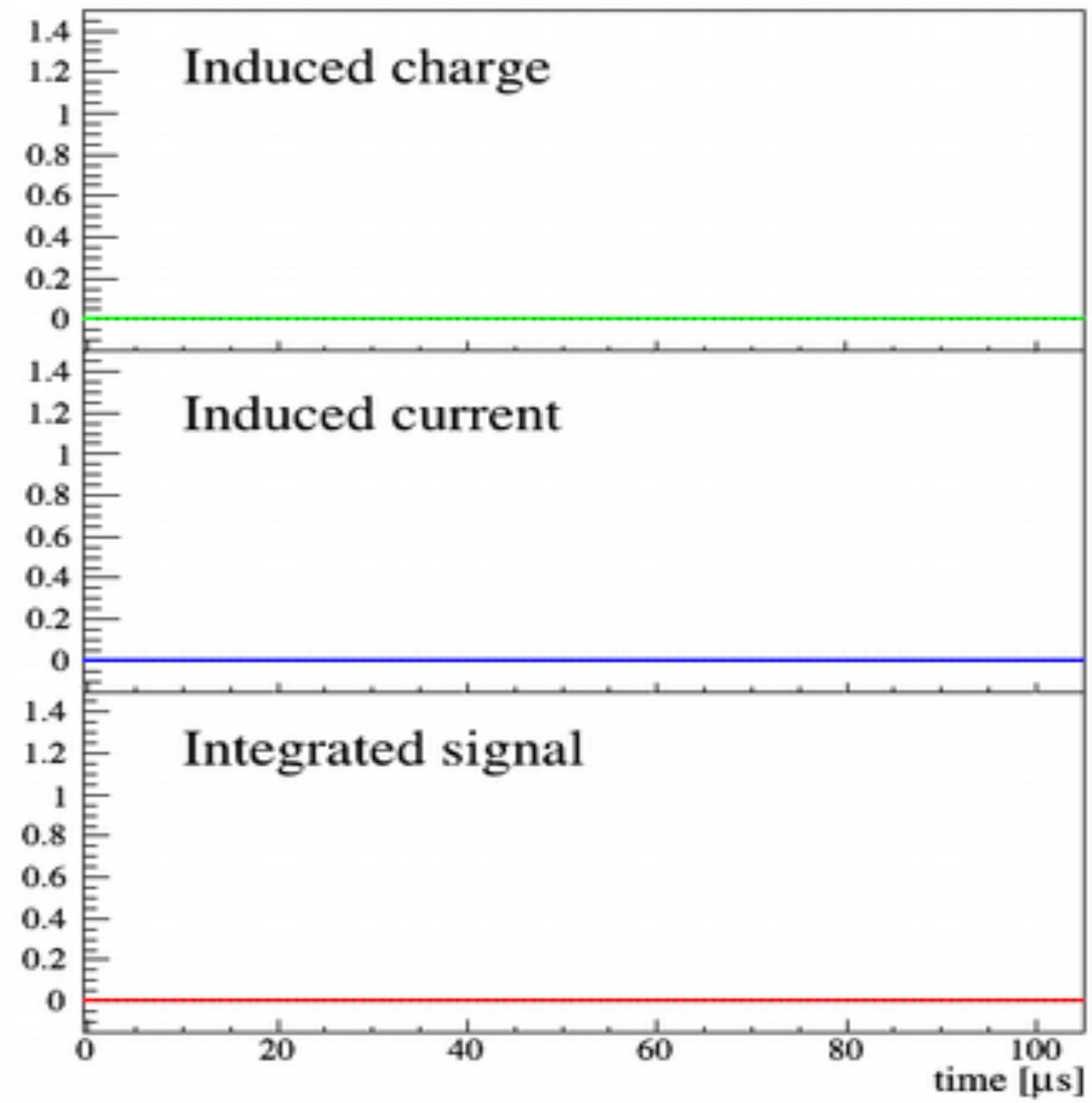
- **Large volume**
  - Small number of read-out channels
- **Low Energy Threshold**
  - Low capacitance
  - High gain
- **Lowest surface to volume ratio**
- **Fiducial volume selection**
  - Through pulse shape analysis
- **Flexible operation**
  - Gas mixture and pressure choice
- Large mass/volume with **one readout channel**
- **Simple sealed mode**

Signal Formation

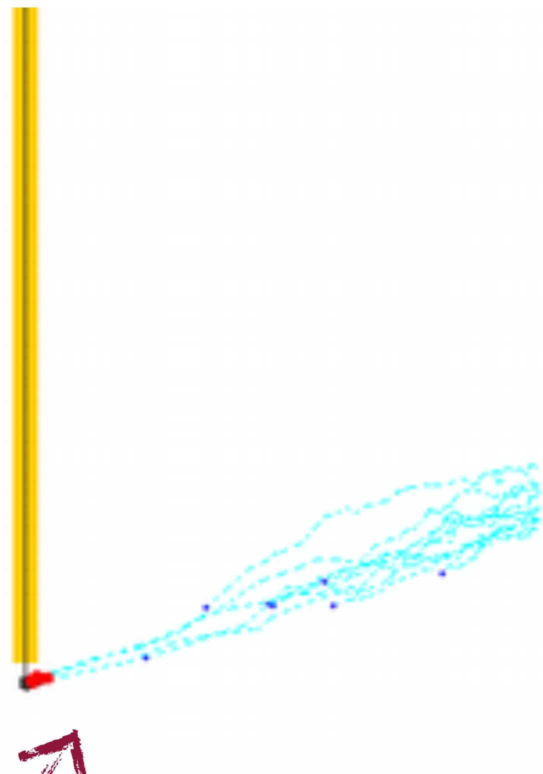


Signal Formation

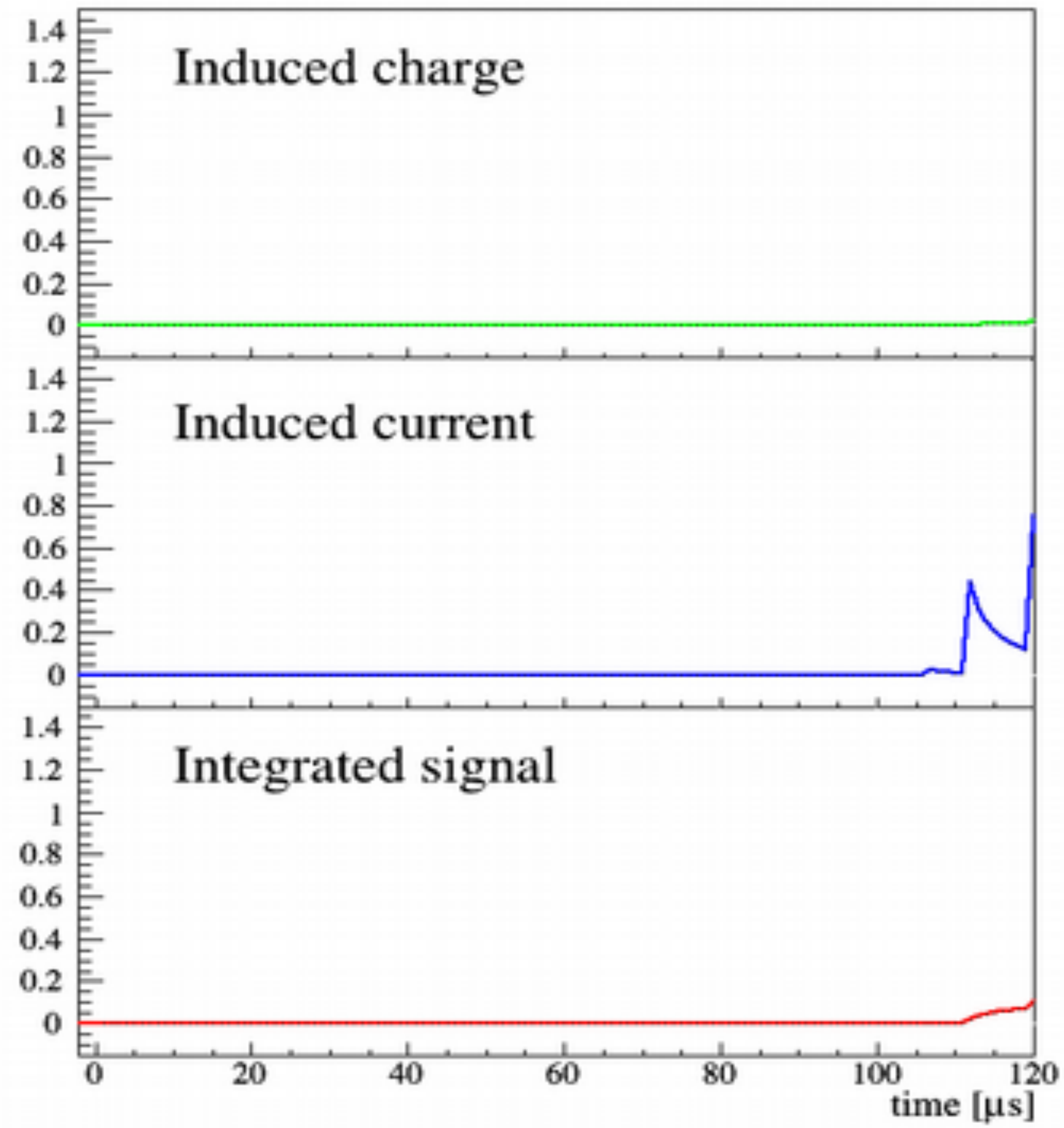




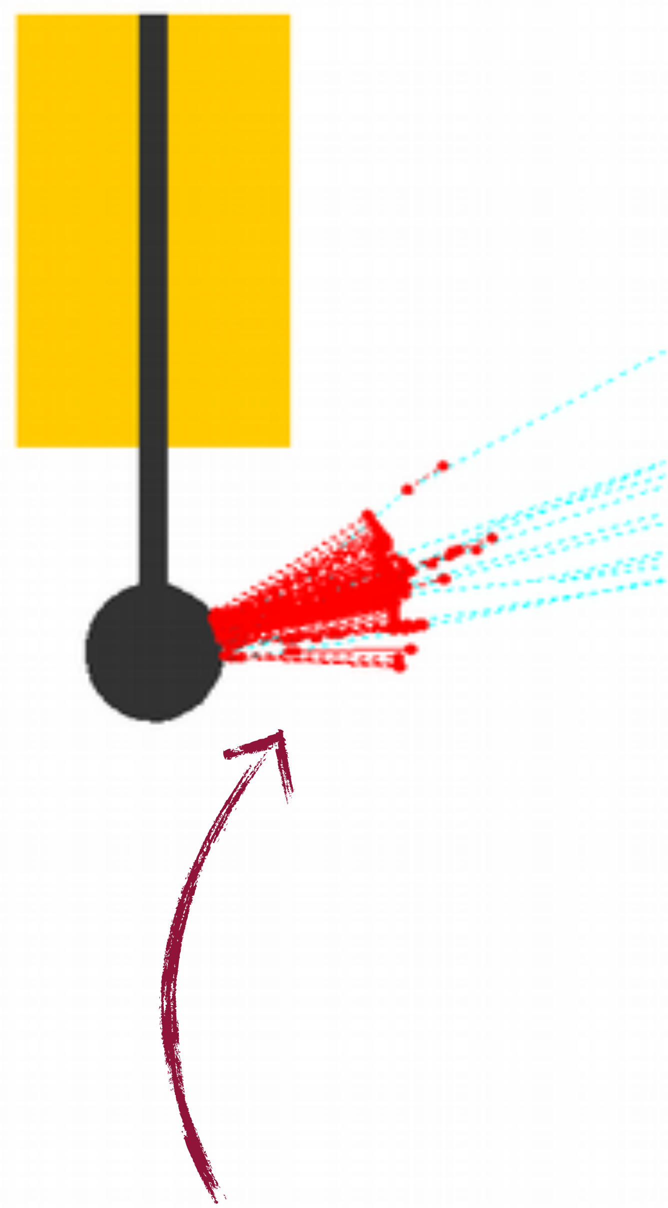
Signal Formation



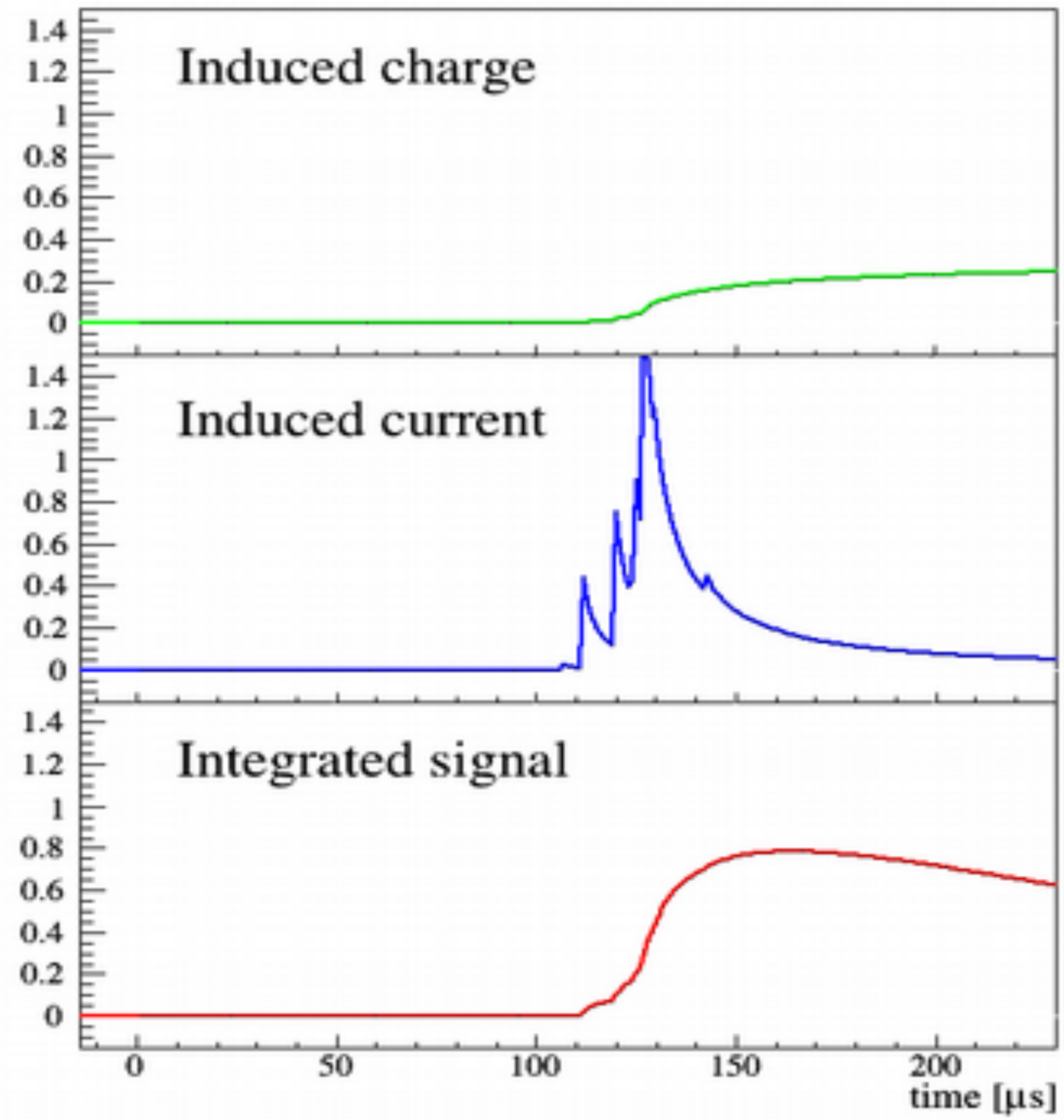
arrival to the anode
and charge multiplication



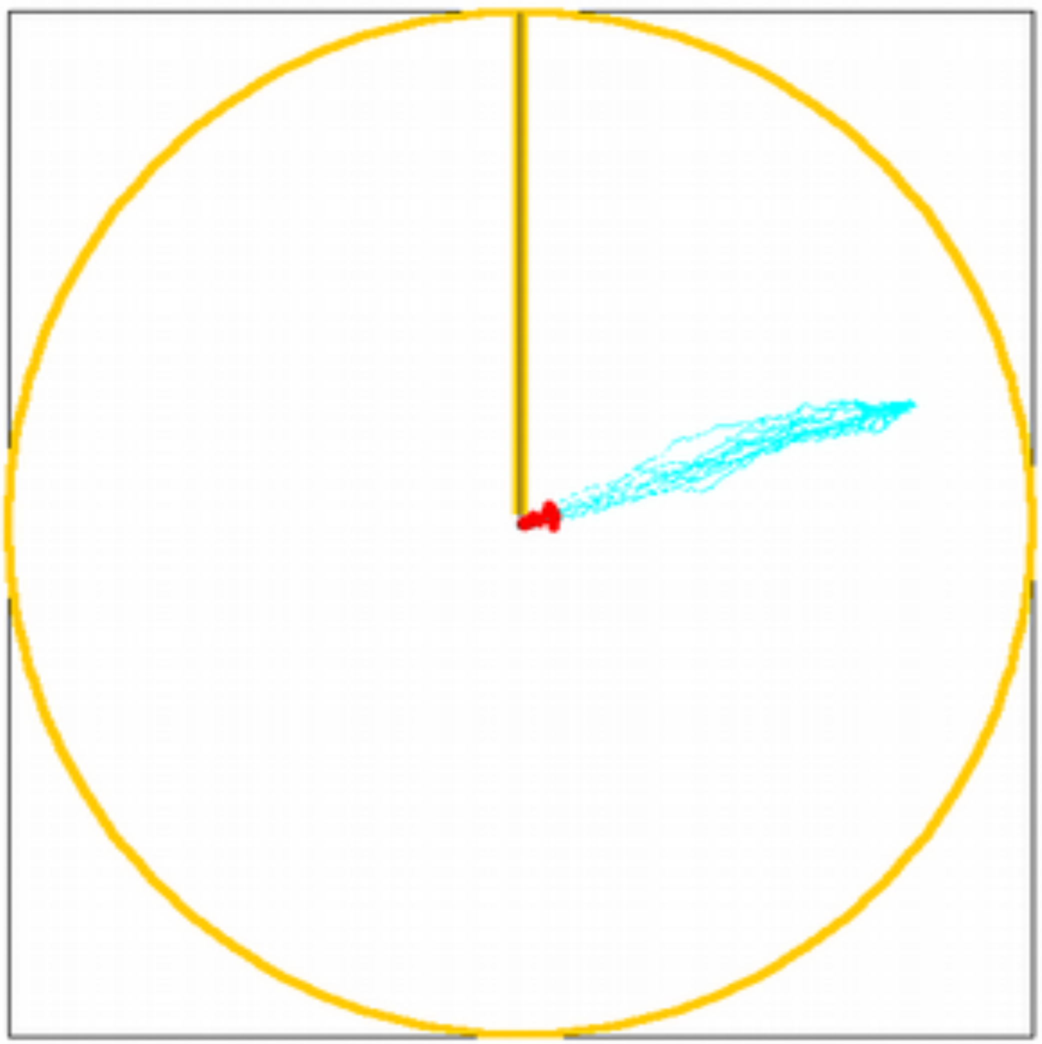
Signal Formation

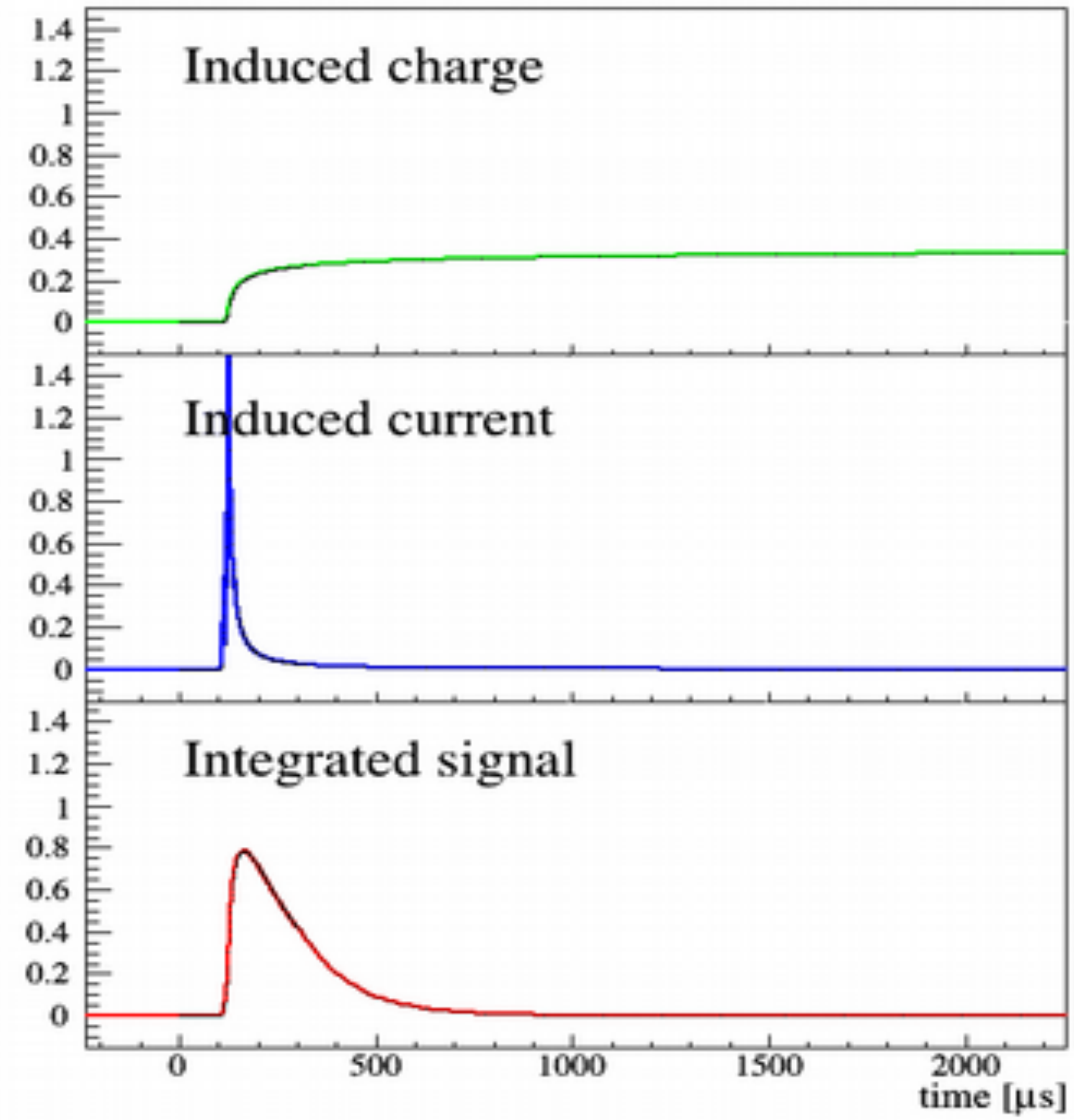


slow drift of ions
towards the cathode

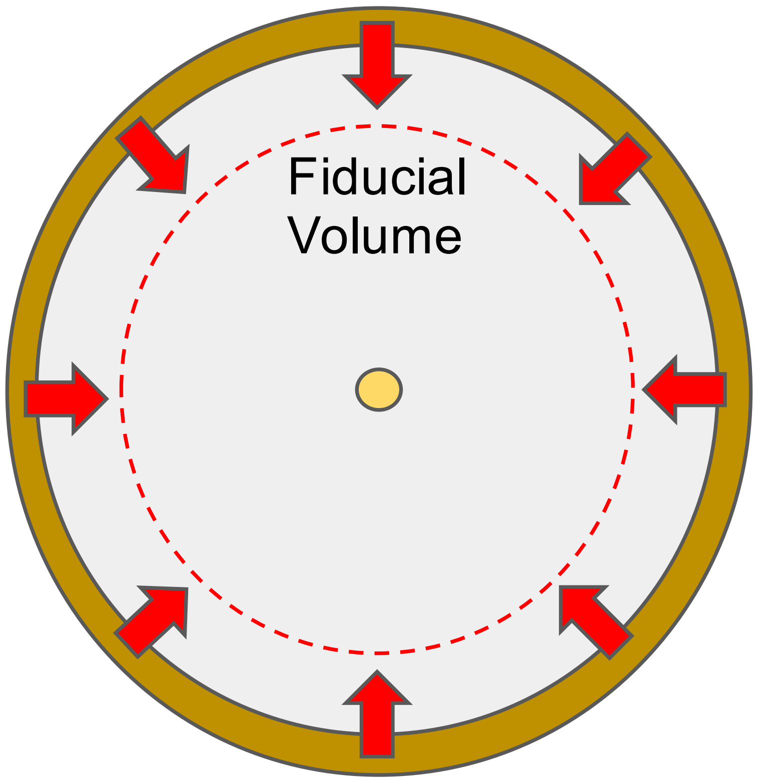


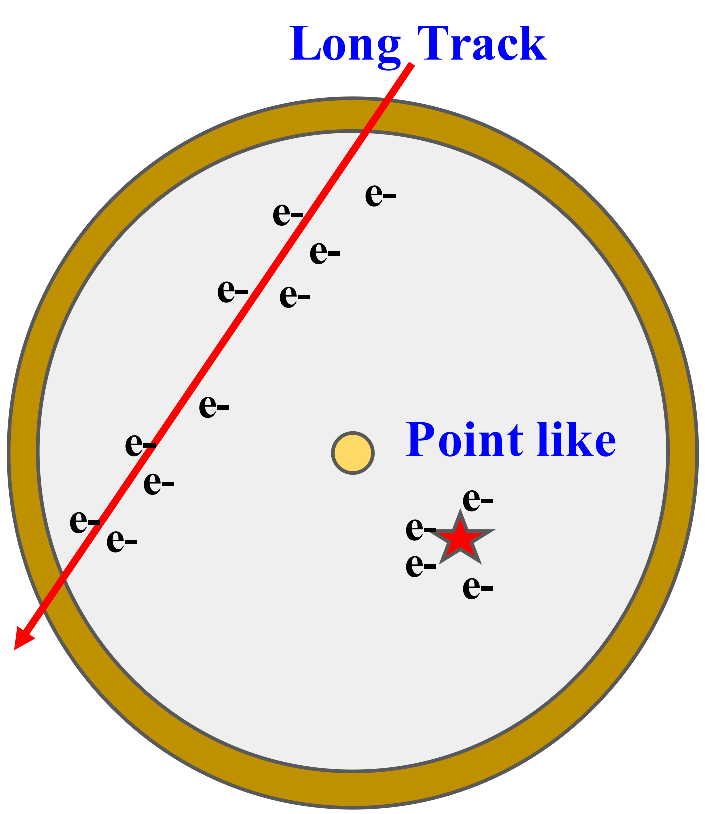
Signal Formation

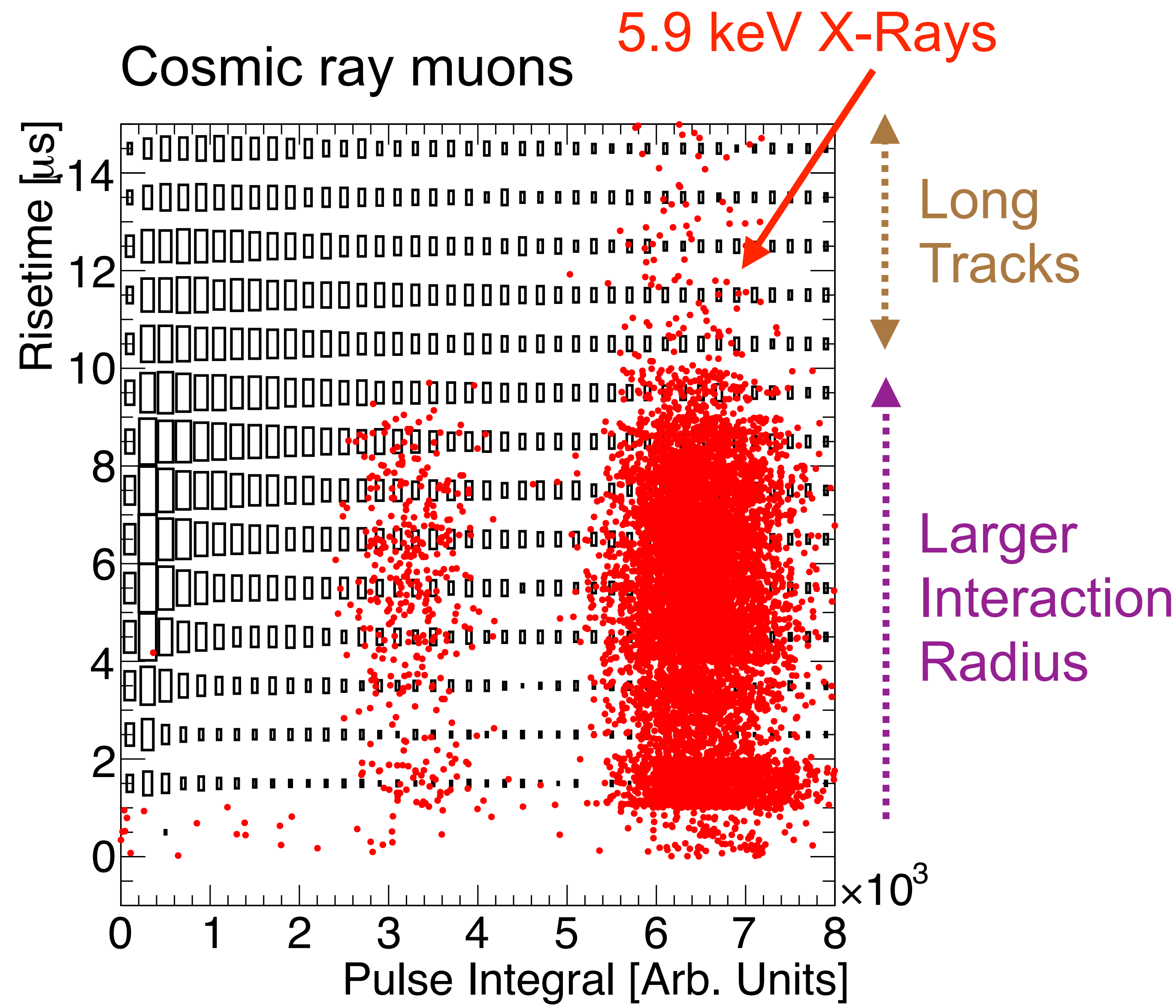




Fiducialisation/Background Discrimination

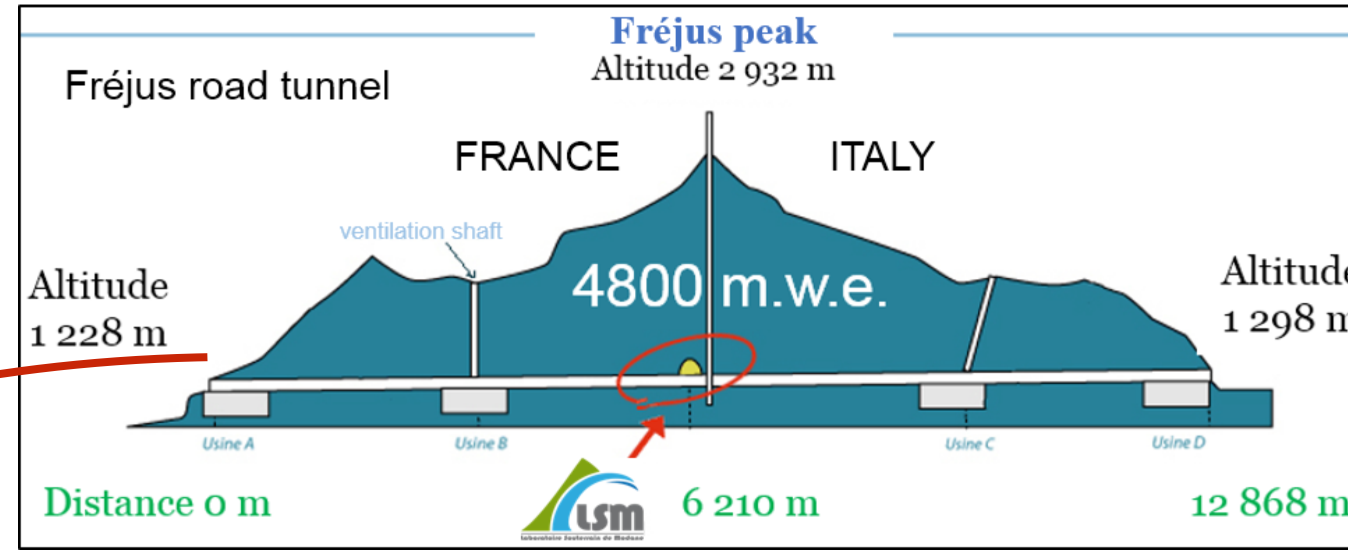


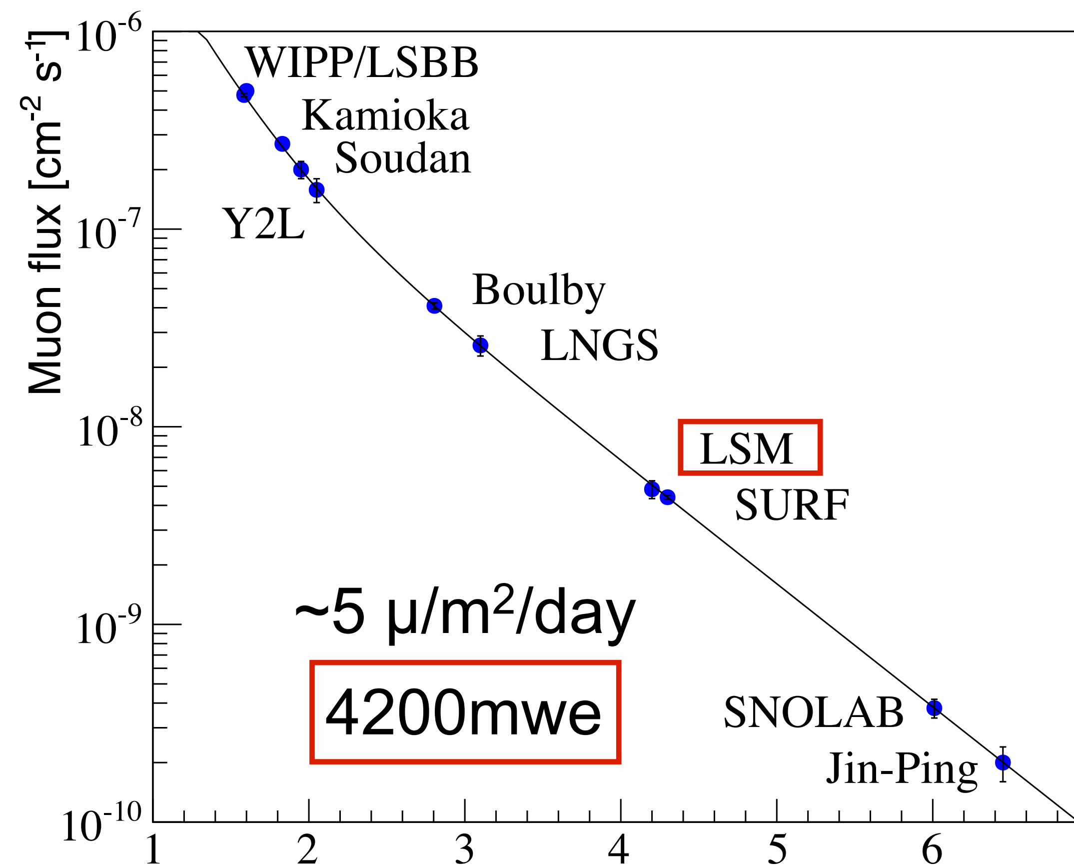




- Primary electron dispersion $\sigma \sim (r/r_{sphere})^3$
  - Detector Fiducialisation
- Background predominantly from vessel construction material
  - Surface events
- Some backgrounds (e.g. cosmic muons) long tracks
  - Rise-time can be used for particle discrimination

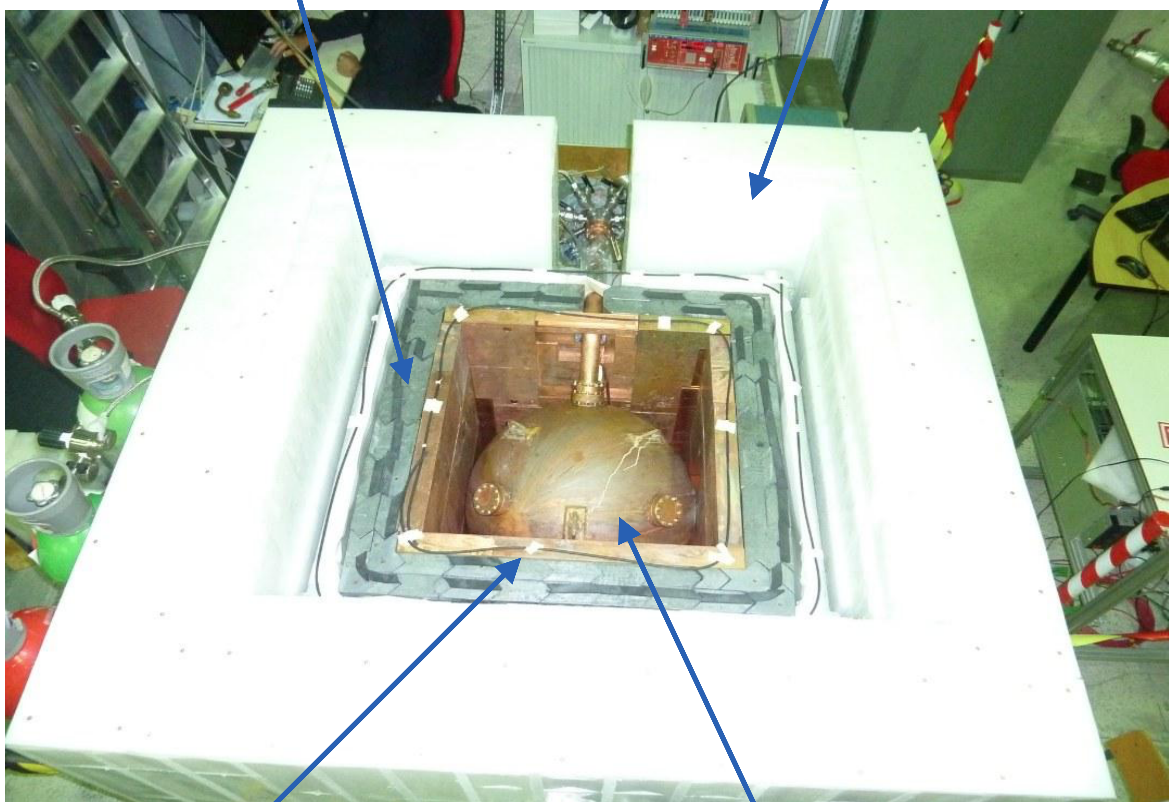
Laboratoire Souterrain de Modane



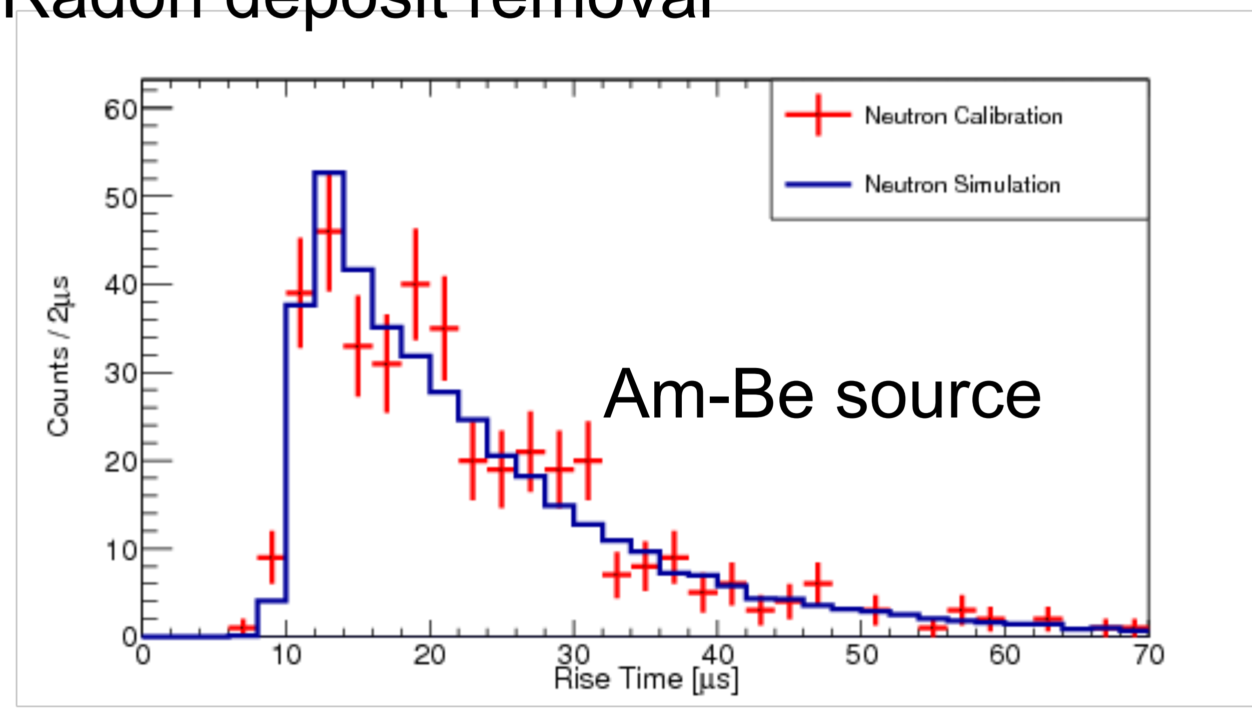


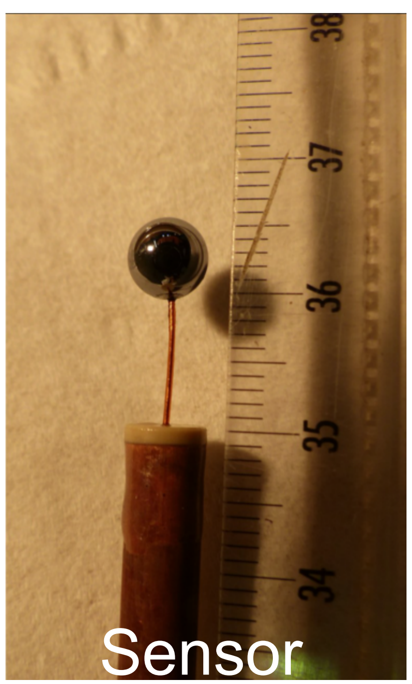
J.Phys. G43 (2016) 013001

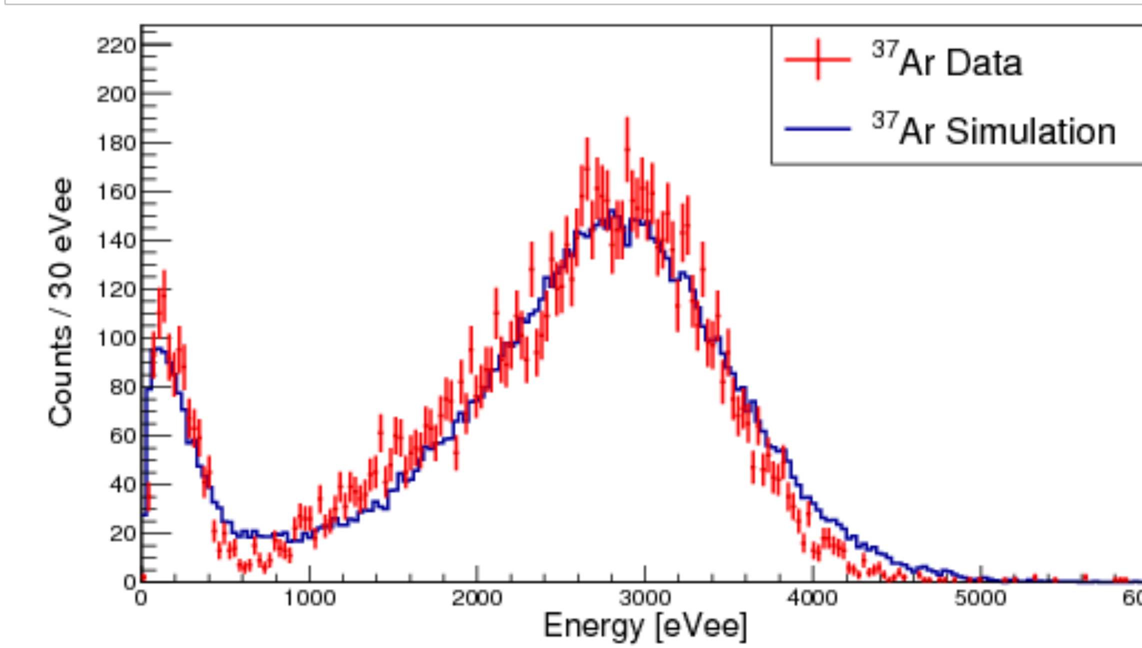
SEDINE: NEWS-G Prototype at LSM



- NOSV Copper vessel (Ø60 cm)
- Equipped with a Ø6.3 mm sensor
- Chemically cleaned several times for Radon deposit removal







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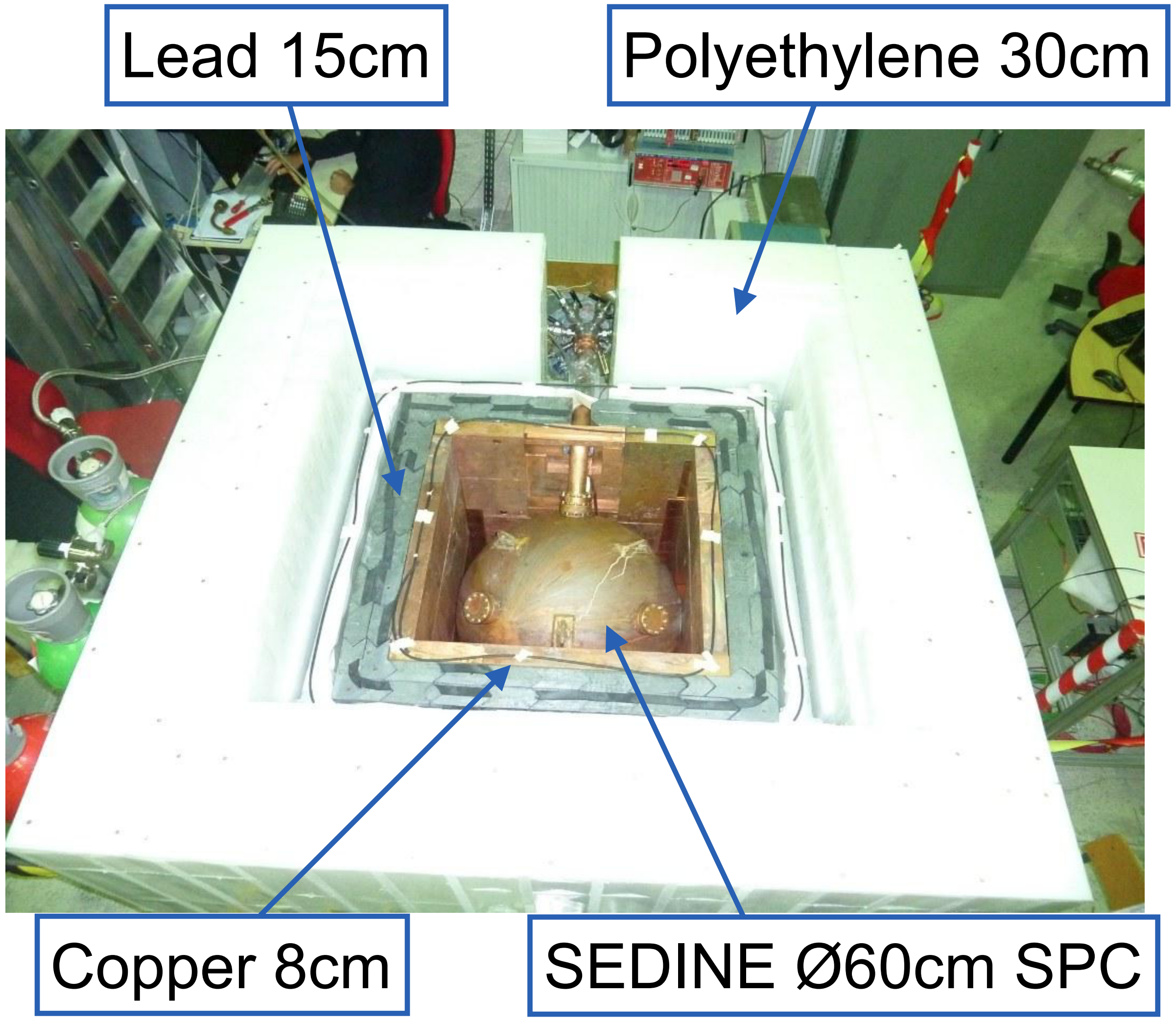

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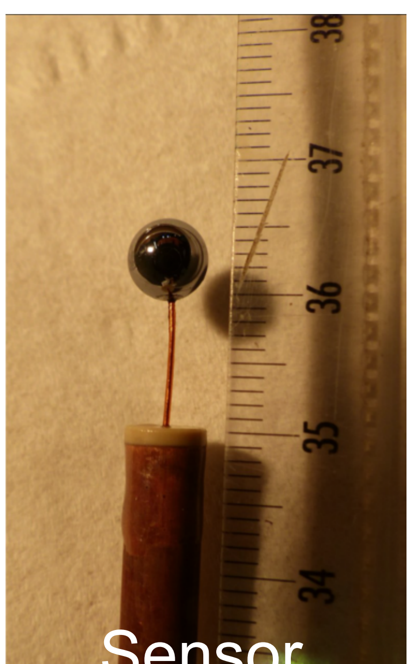
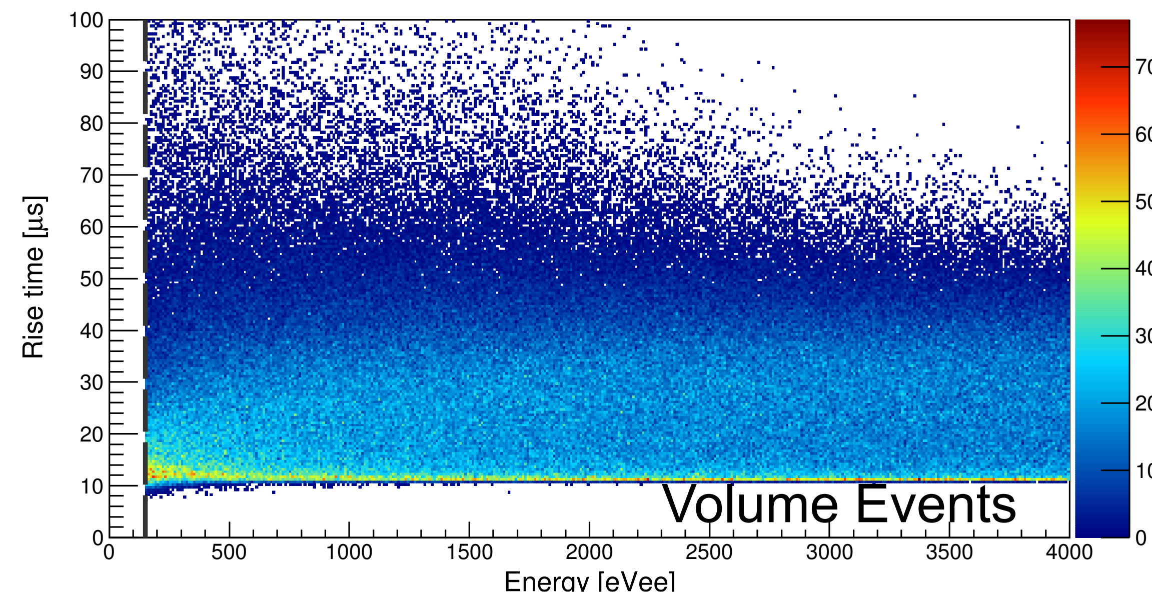
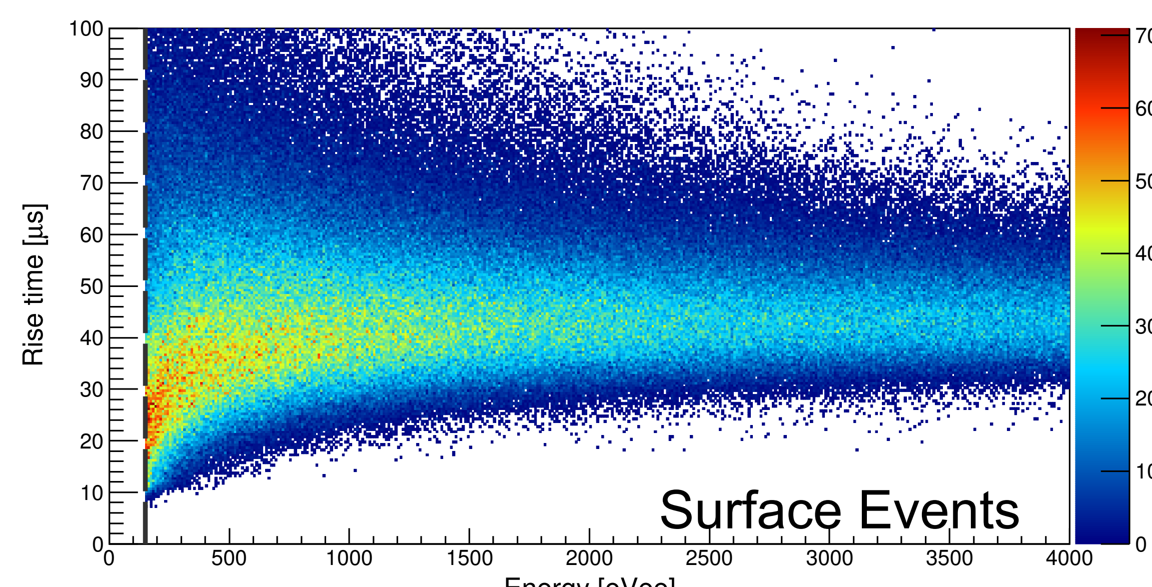
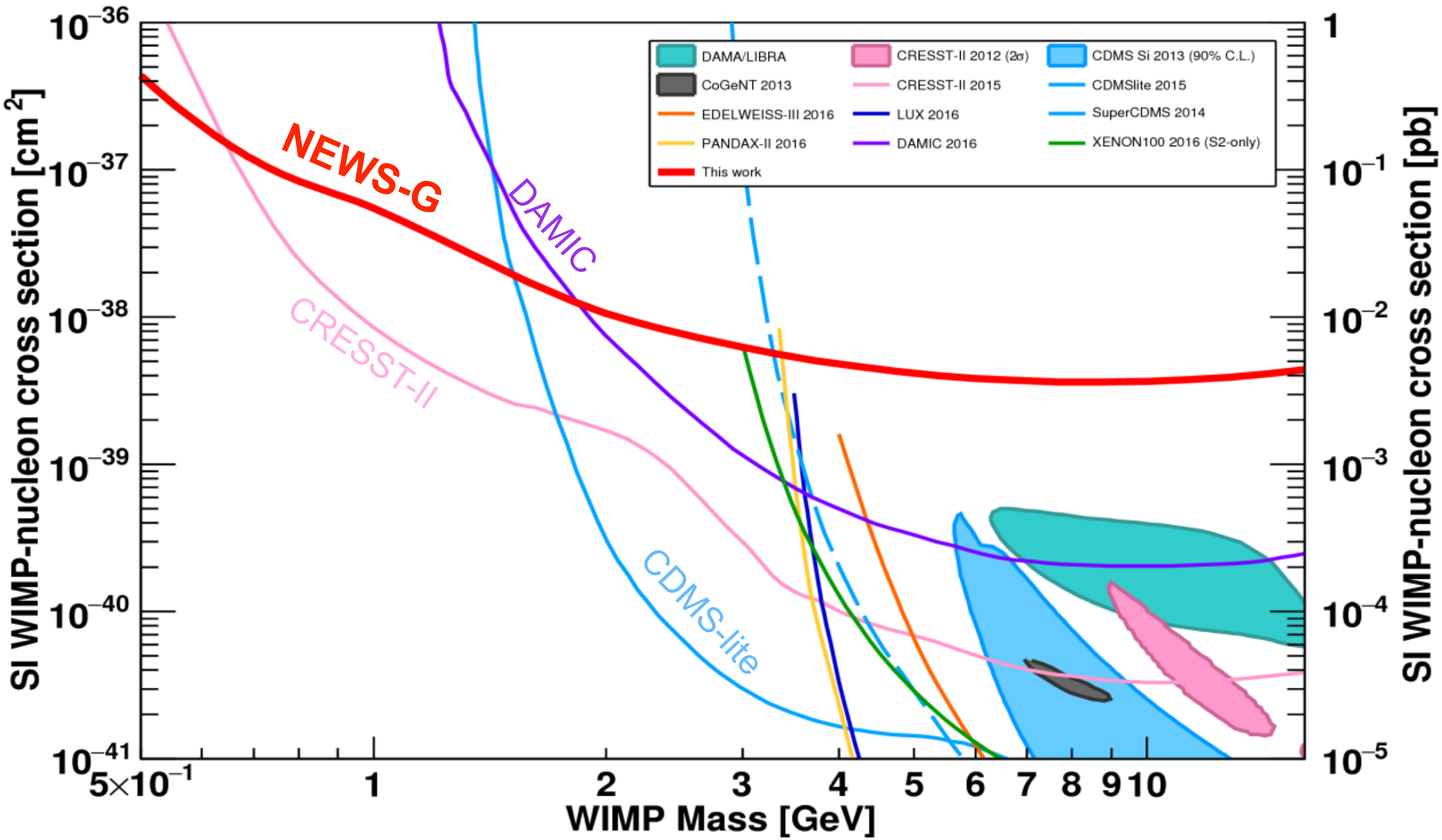






First results of NEWS-G with SEDINE at LSM

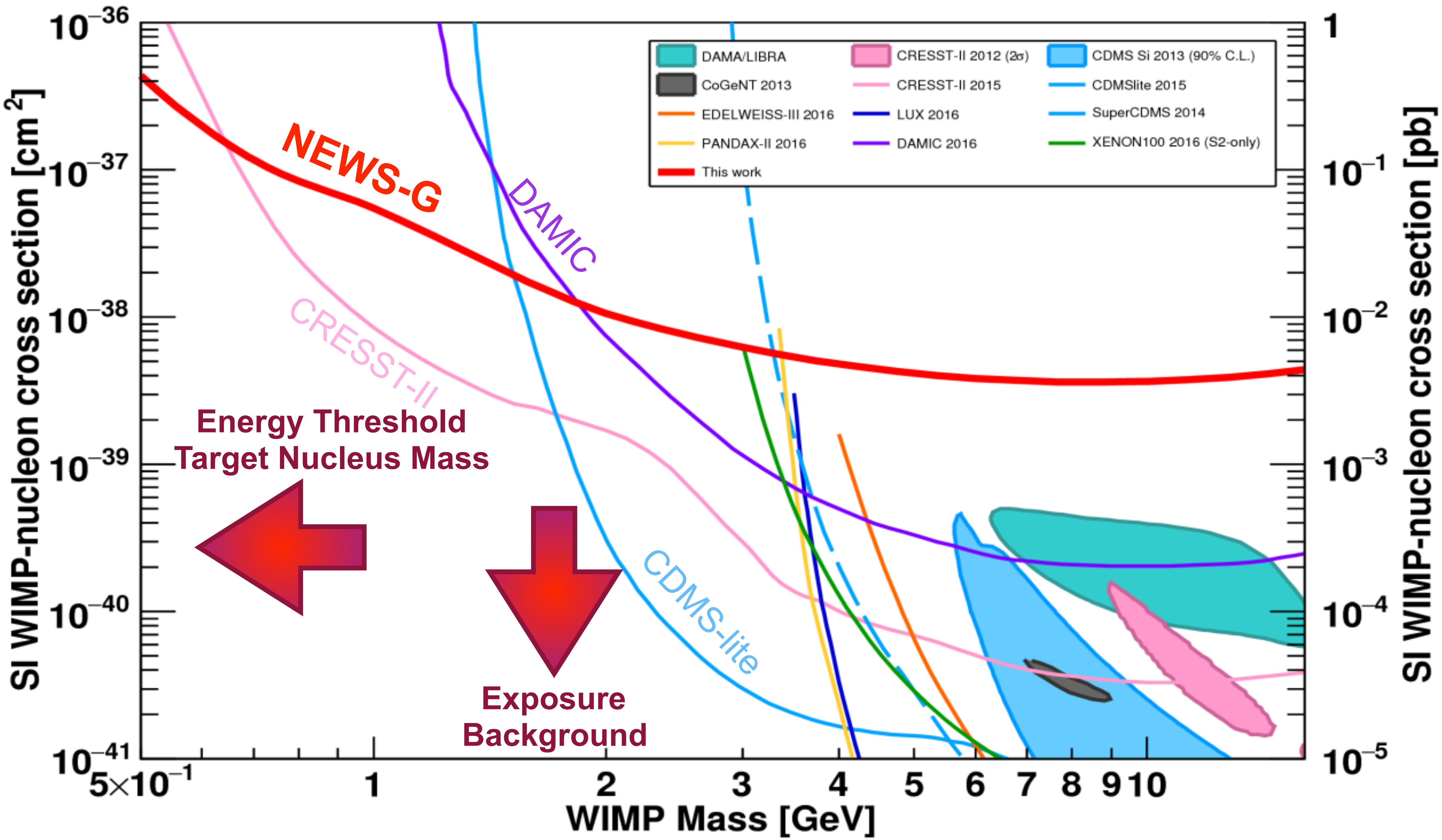
NEWS-G collaboration, Astropart. Phys. 97, 54 (2018)



- **Gas Mixture:** Ne+0.7%CH4 at 3.1 bar
- **Exposure:** 9.6 kg×days (34.1 live-days x 0.28 kg)

First results of NEWS-G with SEDINE at LSM

NEWS-G collaboration, Astropart. Phys. 97, 54 (2018)



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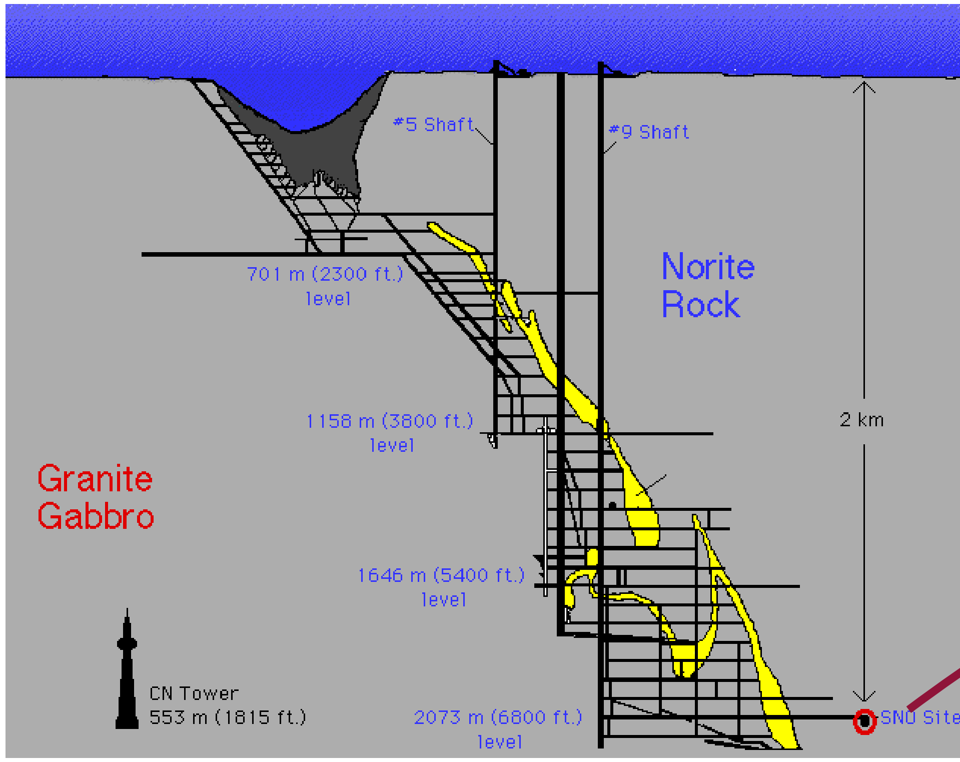
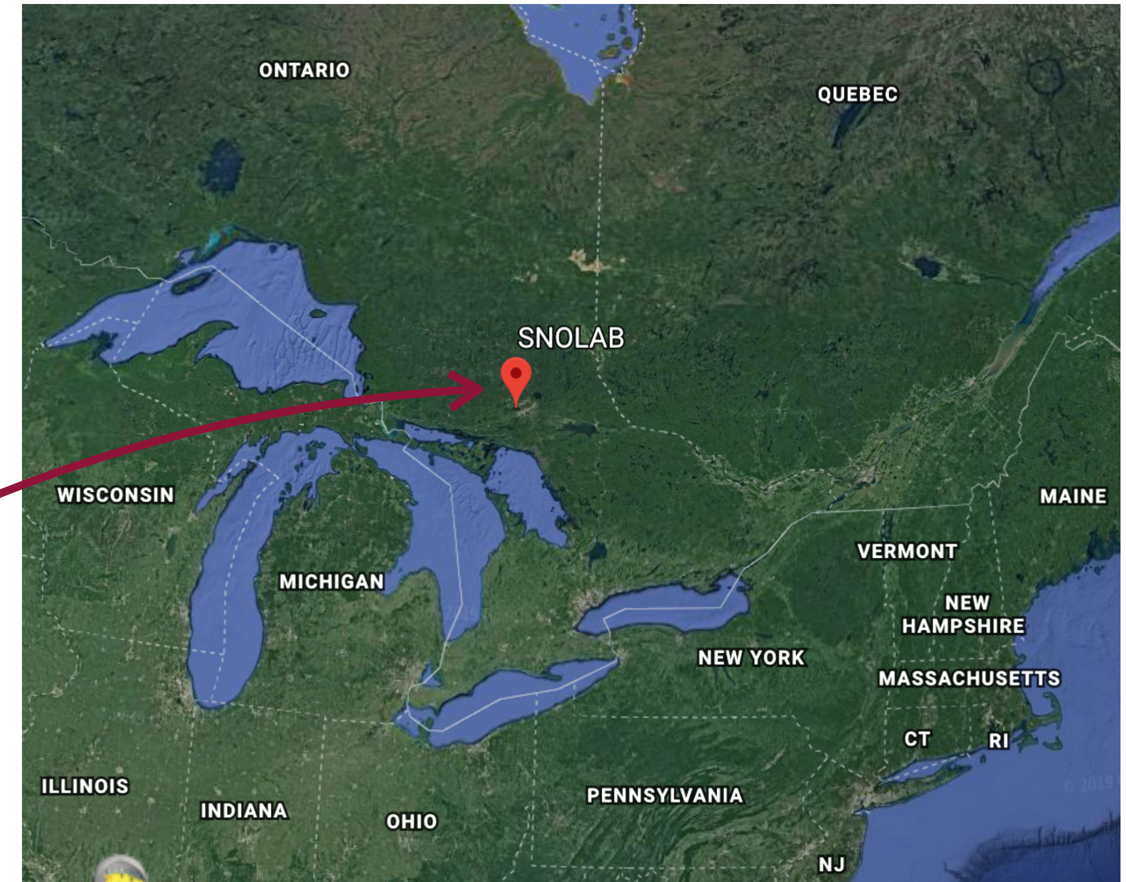
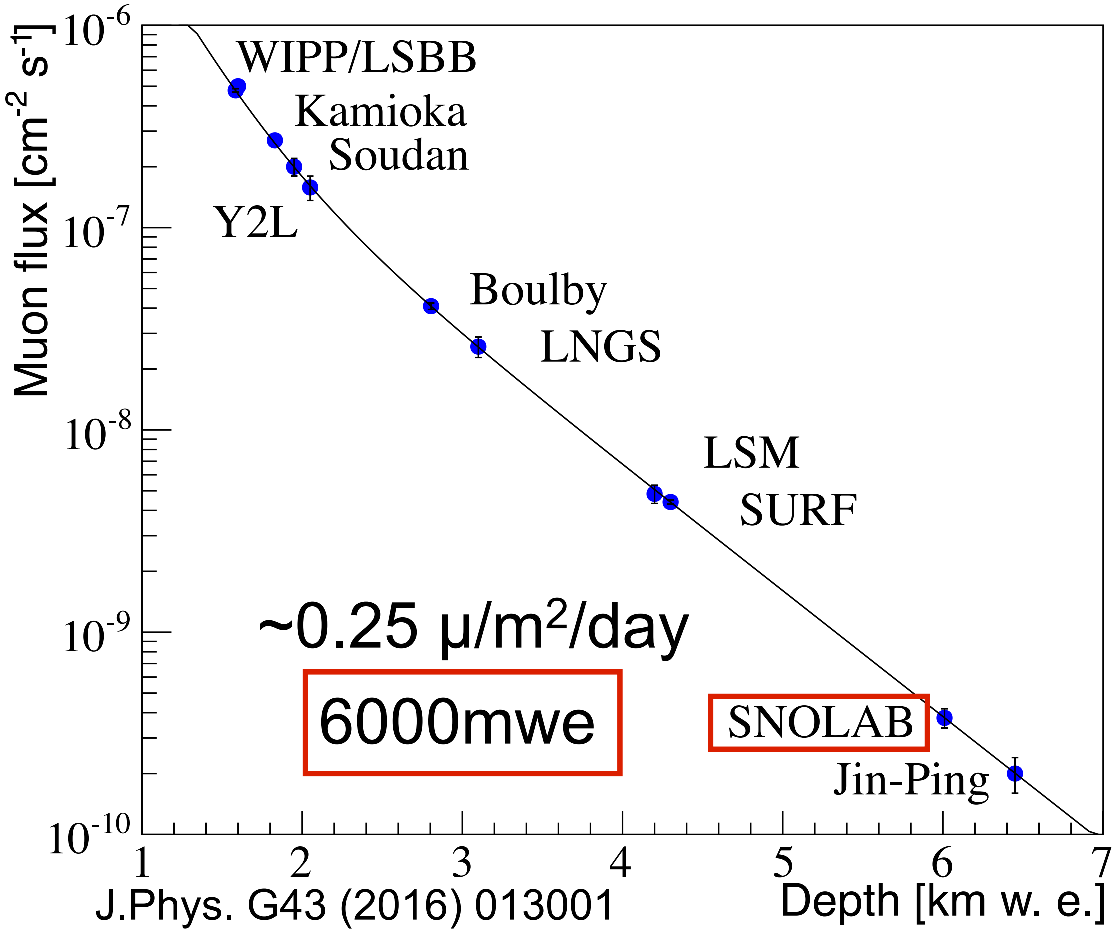
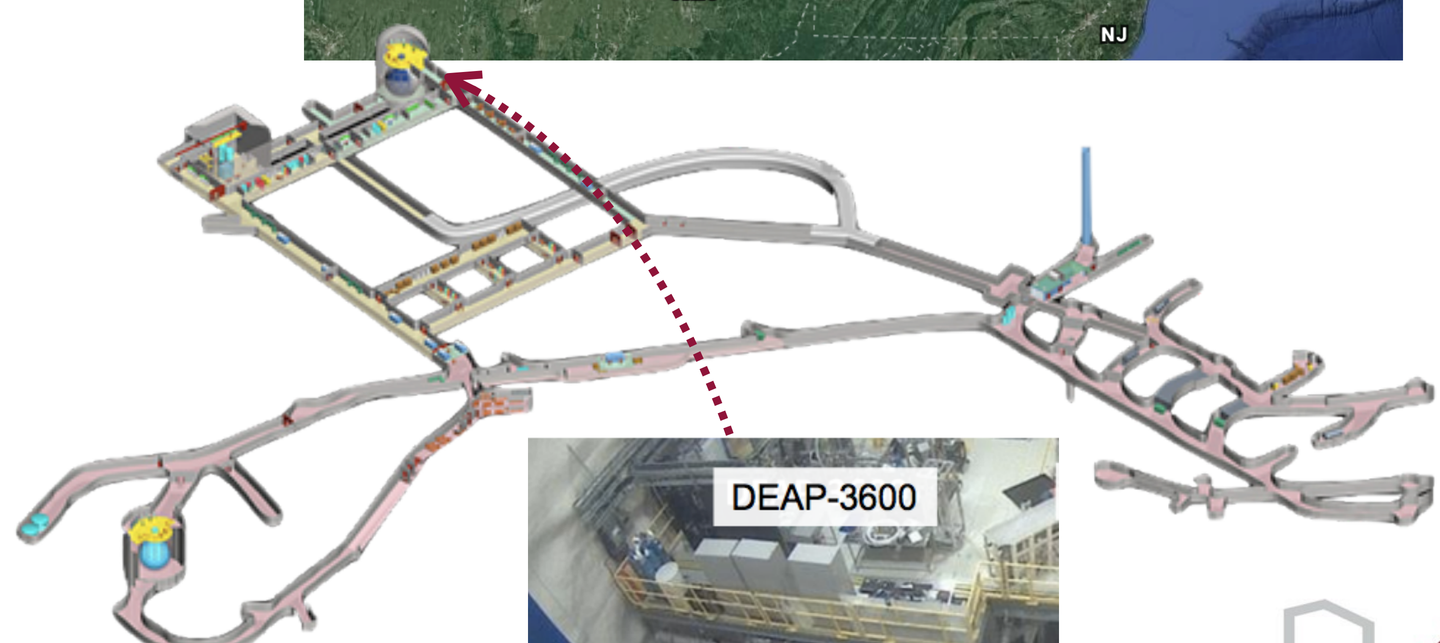
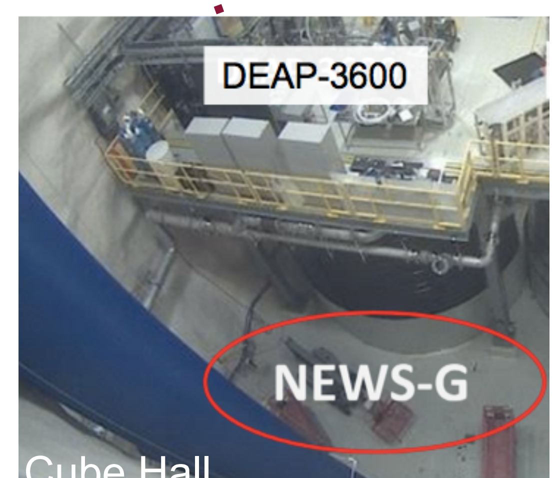
NEWS-G at SNOLAB









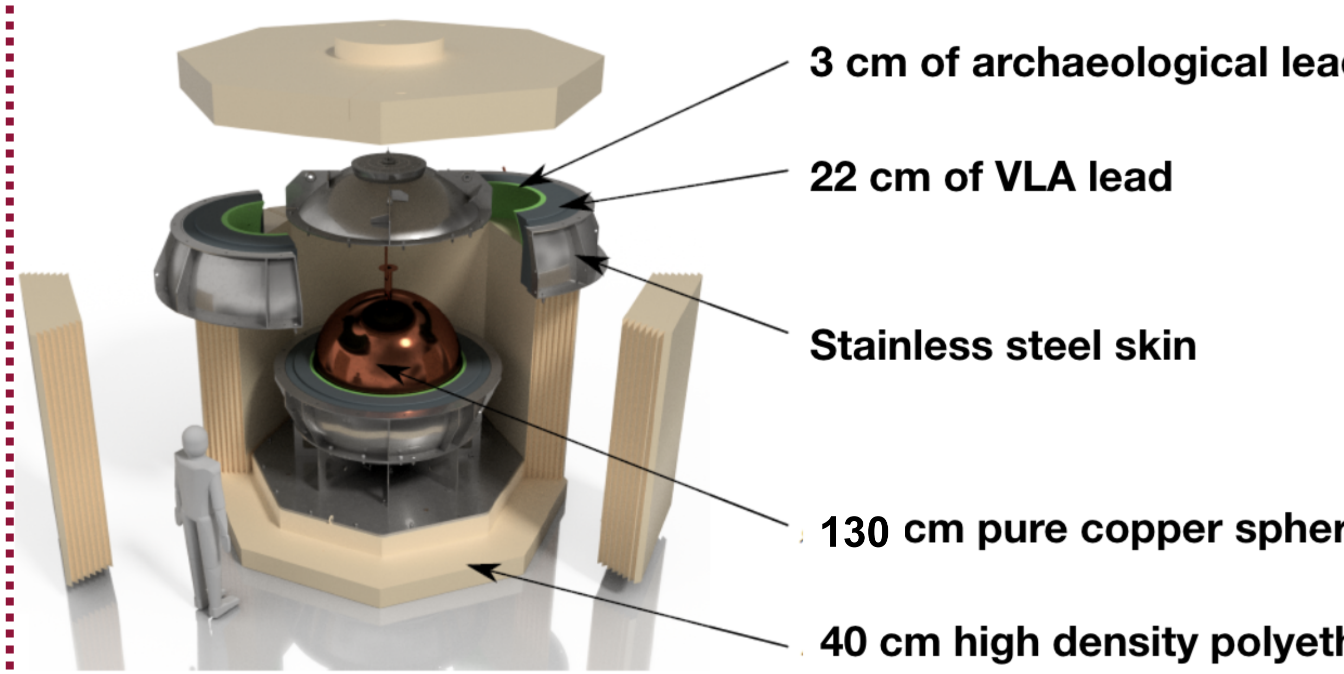


SNOglobe

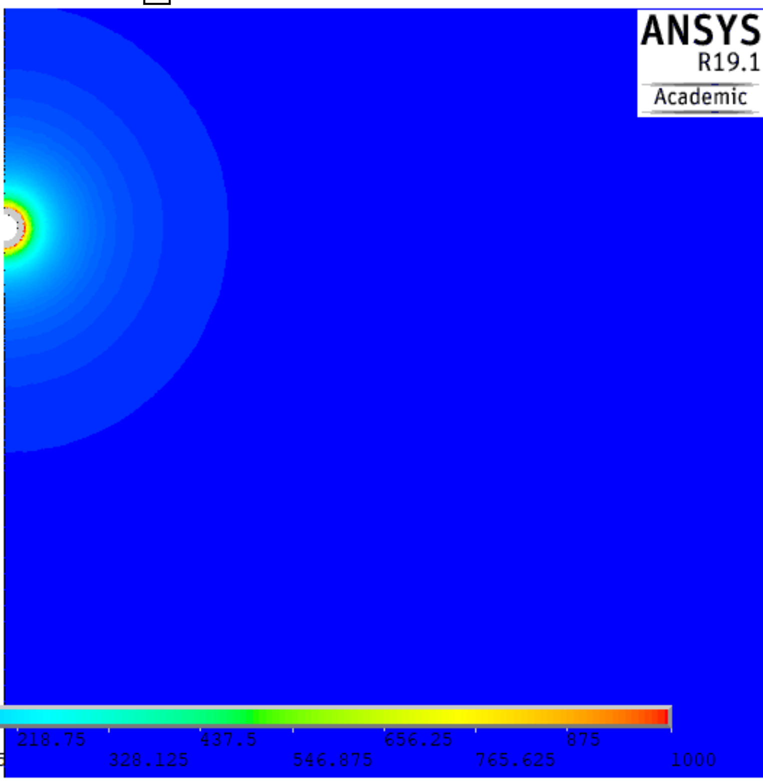
- New detector: SNOglobe
  - Ø130 cm
  - 4N Aurubis Copper (99.99% pure)
  - assembled and commissioned at LSM
  - currently being transferred to SNOLAB
- Detector already operated at LSM (commissioning run)
- Operation in SNOLAB
  - Hydrogen-rich mixtures
  - Improved compact shielding
- Expected to be sensitive to WIMP masses ~100 MeV

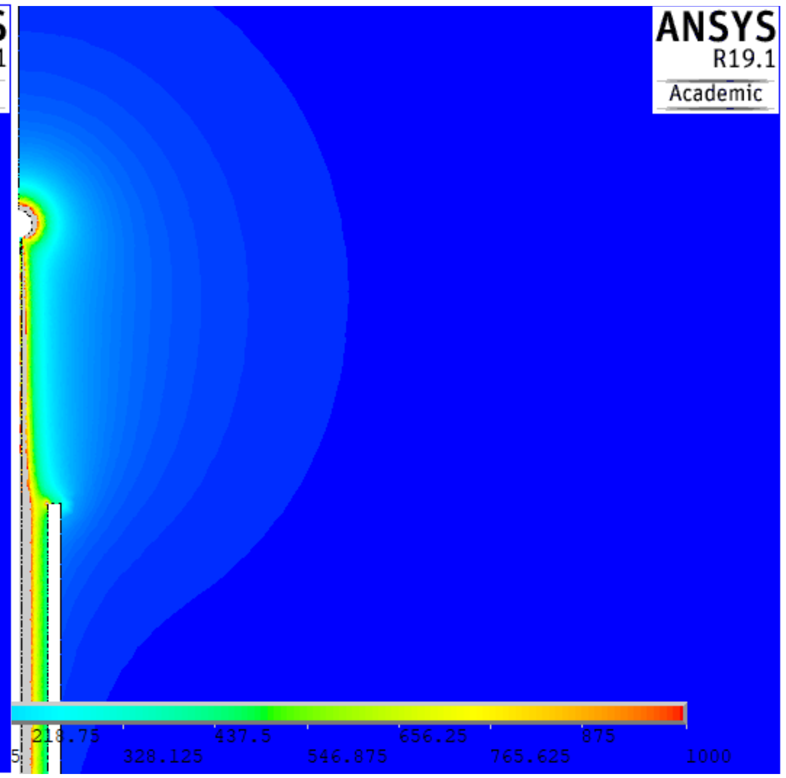
Challenges

- Fiducialisation
  - Detector response uniformity
- Charge collection at large radii and high pressure operation
  - Electric field magnitude
  - Contaminants
- Background
  - Material purity
- Detector simulation/response



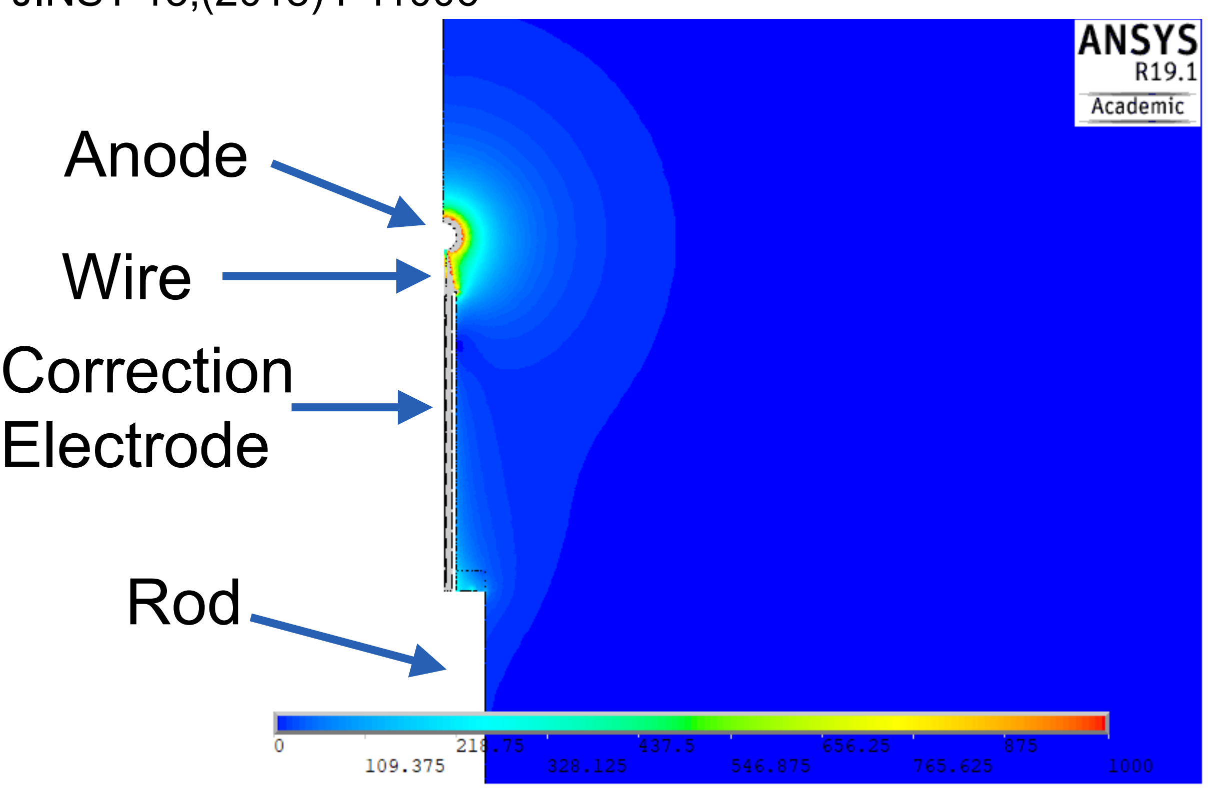
Electric field homogeneity

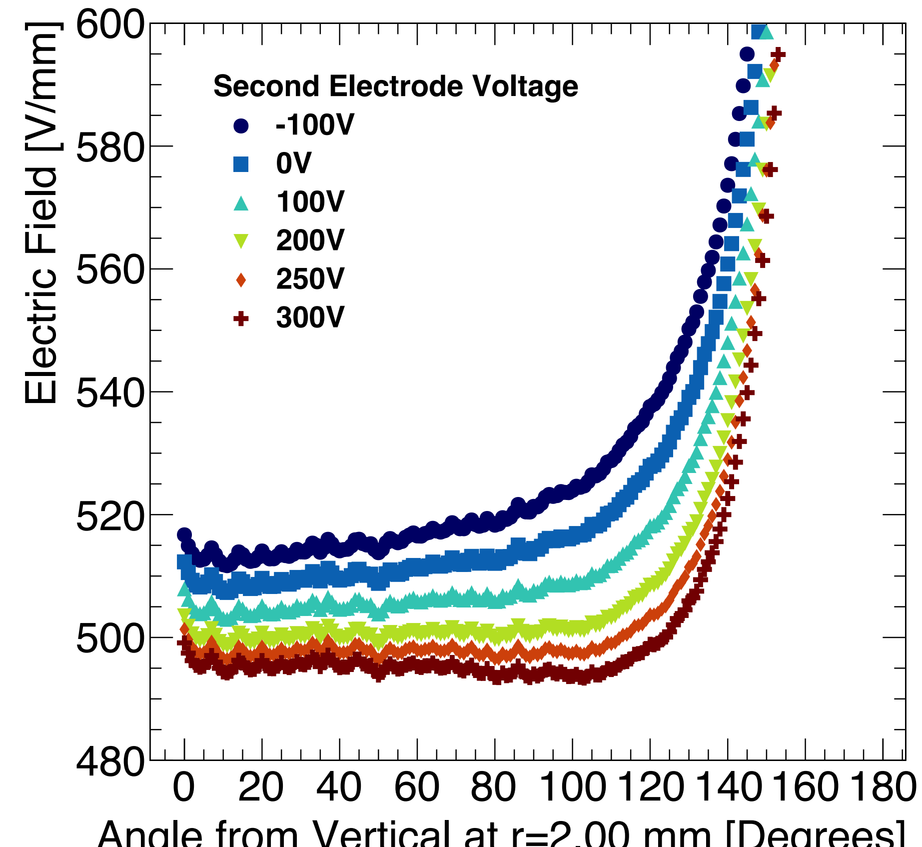




- Ideally, electric field:
  - purely radial
  - strength $1/r^2$
- Reality more complex, as support structure needed for sensor
  - $E=E(r,\theta)$
  - Non-uniform detector response
- Improved field uniformity by adding correction electrode

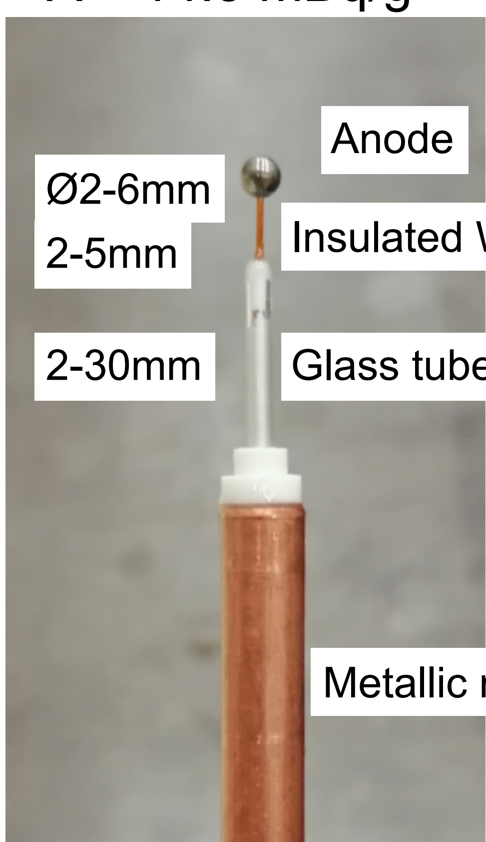
JINST 13,(2018) P11006



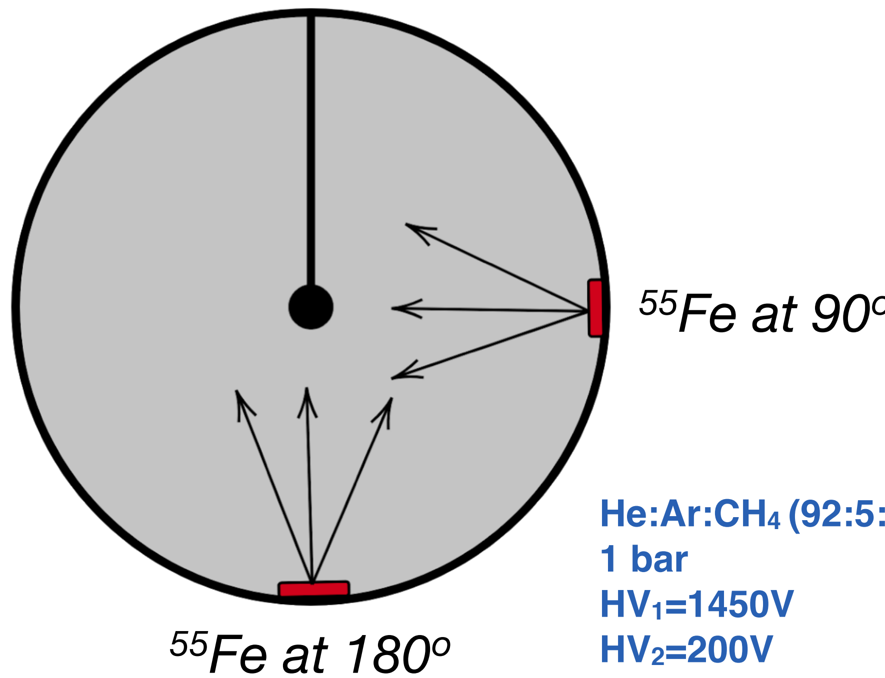


Resistive Glass Electrode

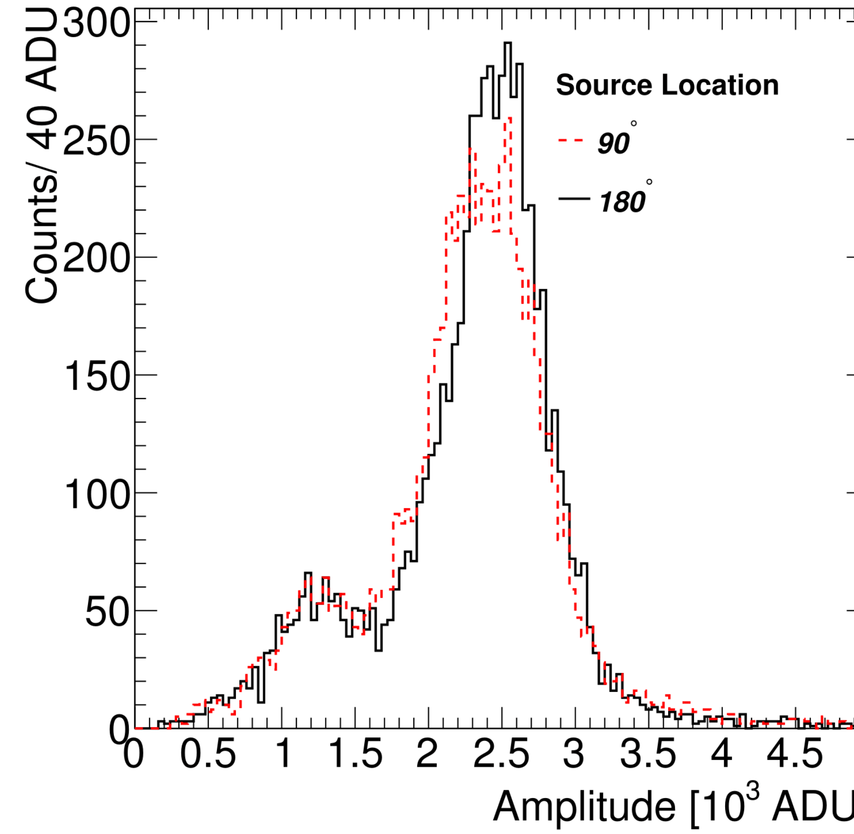
- Spark quenching
- Charge evacuation
- Advantages
  - Simple/Robust
  - Symmetric
  - Low material budget
- Material properties
  - Soda-lime glass
  - $\rho = 5\times10^{10}$ Ωcm
  - d = 2.1-2.25 g/cm^3
  - A = 14.5 mBq/g



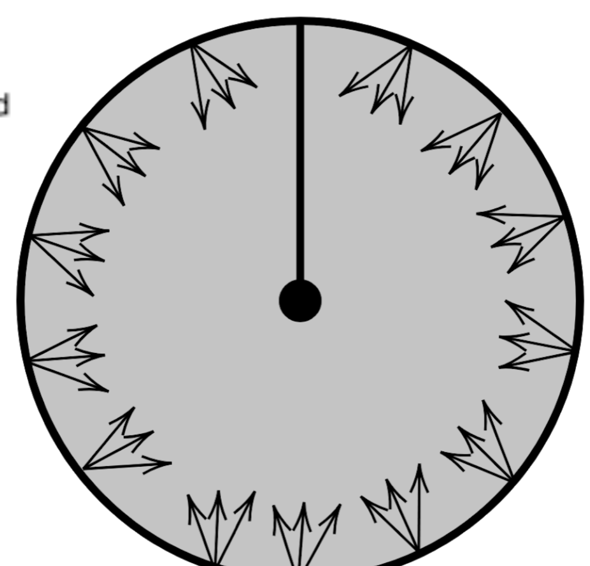
Irradiation with 5.9 keV X-rays



He:Ar:CH_4 (92:5:3)
1 bar
HV_1=1450V
HV_2=200V
2 mm Ø anode

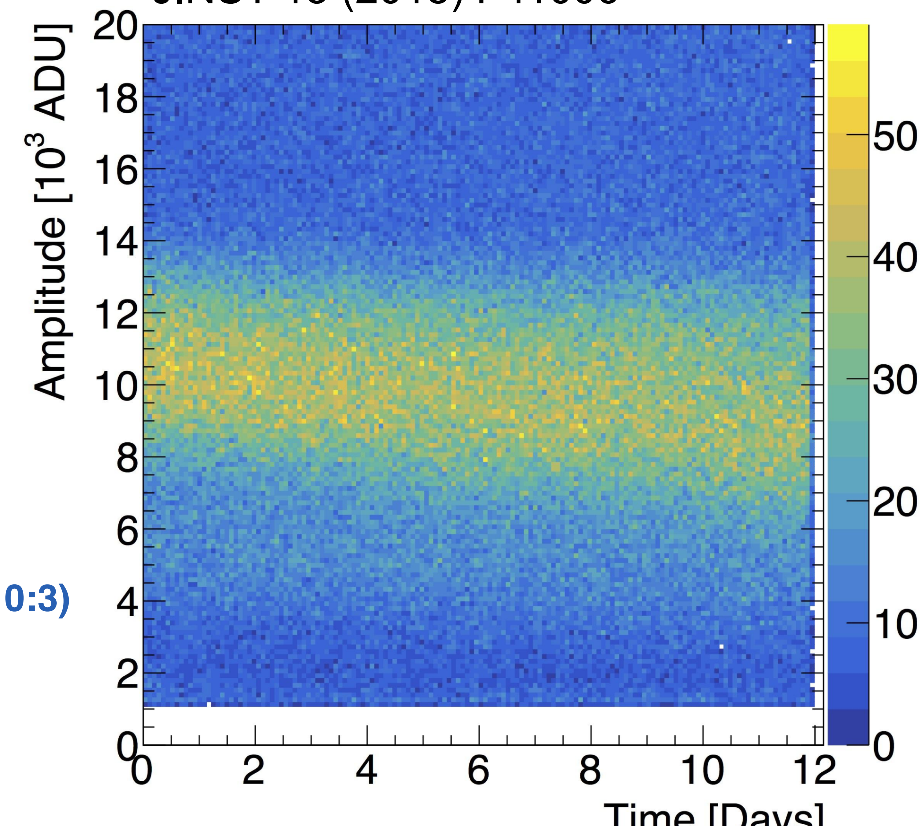


6.4 keV iron fluorescence induced by environmental radiation



He:Ar:CH_4 (87:10:3)
2 bar
HV_1 = 2350V
HV_2 = 0V
2 mm anode

JINST 13 (2018) P11006



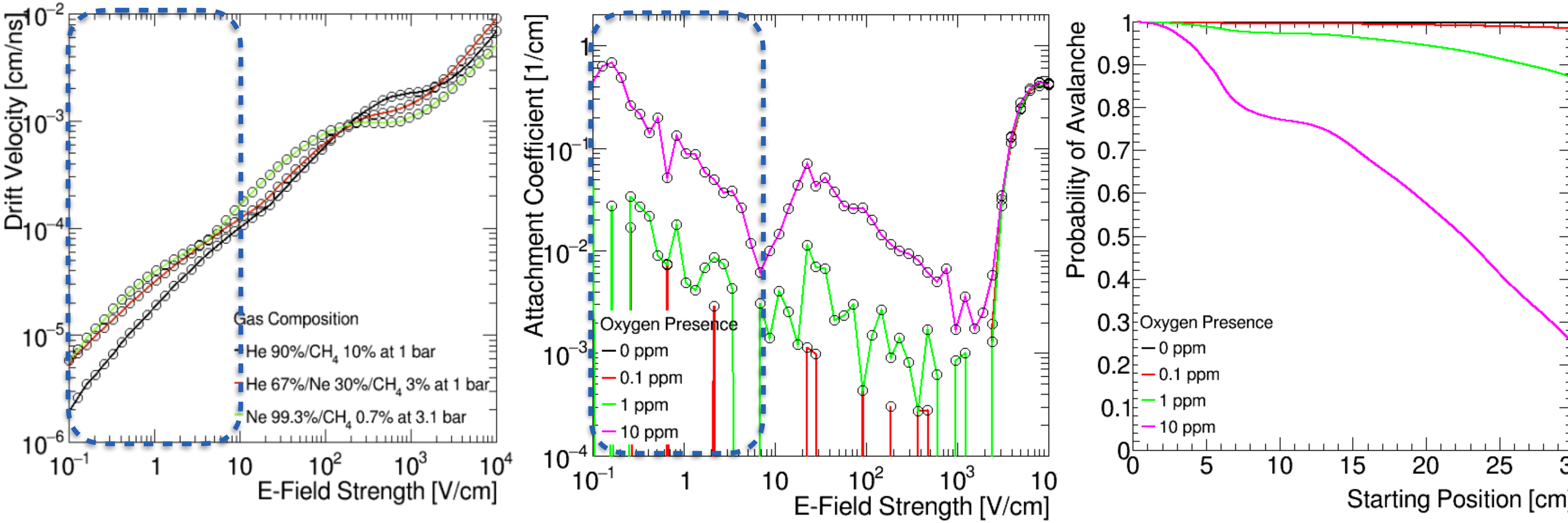
Charge collection in low electric field

- Gain and drift velocity both depend on E/P
- At large radii
  - Low drift velocity
  - Susceptibility to attachment
- Crucial aspects
  - Electric field magnitude
    - Depends on anode voltage and radius
  - Gas quality

$$\ln(G) = \int_{E(r_1)}^{E(r_2)} \alpha\left(E/P\right)\frac{dr}{dE}dE$$

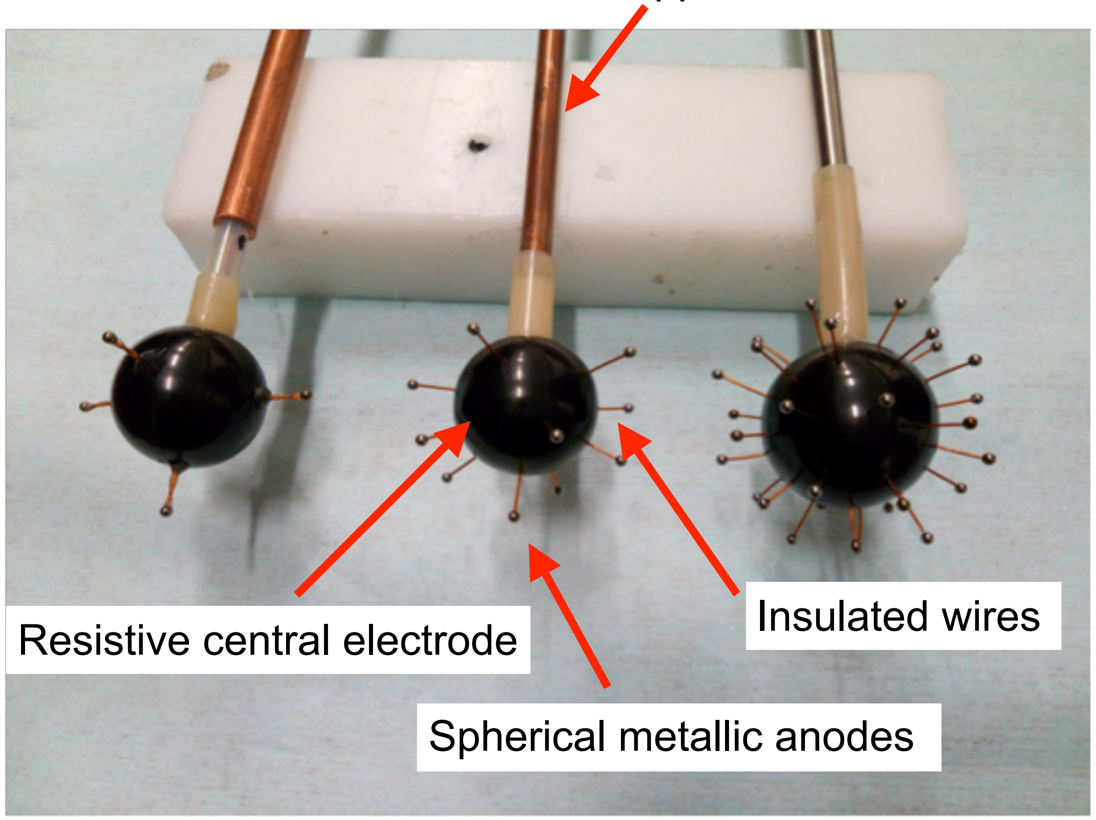
$$v_{drift} = \mu\frac{E}{P}$$

$$E(r) \approx \frac{V_0}{r^2}r_1$$



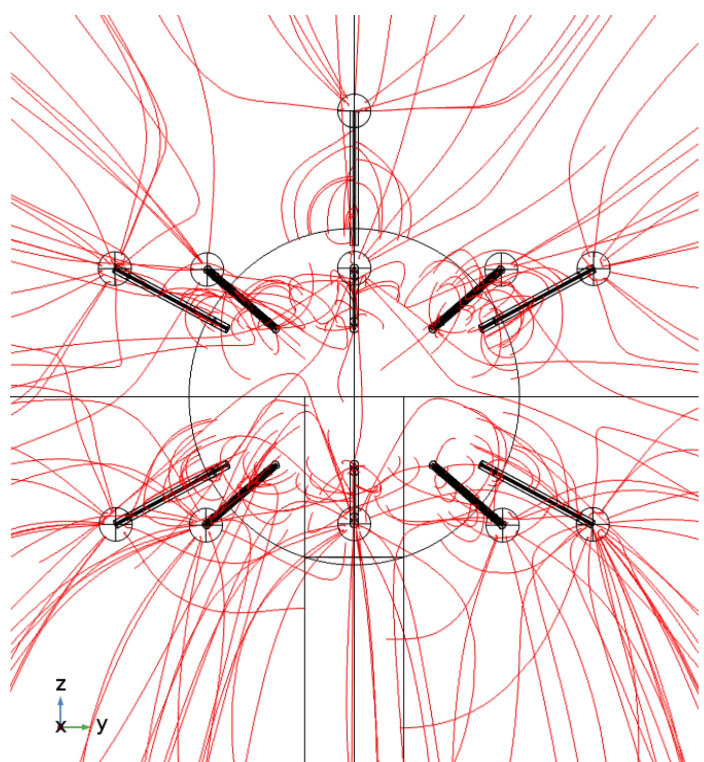
Magboltz study on gas properties and sensitivity to contaminants

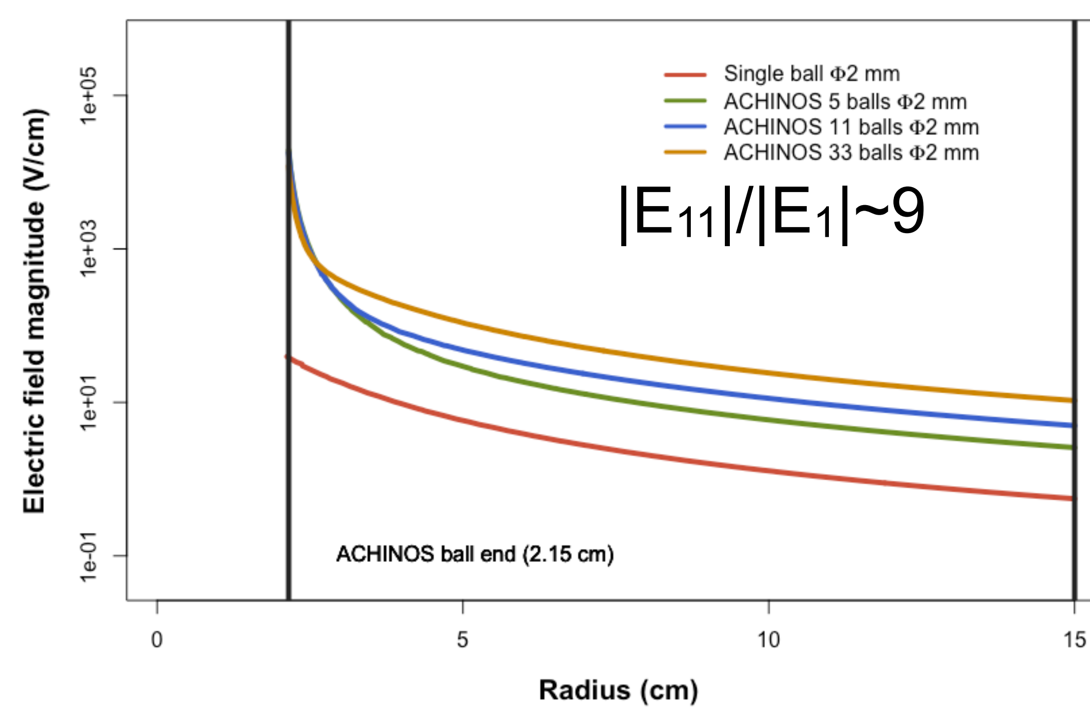
Multi-anode sensors: Achinos



- Achinos: Multiple anode balls placed at equal radii
  - Same gain but increased field at large radii
  - Decoupling Gain and Drift
    - Amplification tuned by anode radius
    - Volume E-field tuned by structure size and number of anodes
  - Anodes can be read out individually
    - TPC-like capabilities
- Prototypes: 5, 11, 33 metal balls ∅2mm successfully operated
- 3D printed Achinos sensors built and operated

JINST 12 (2017) P12031





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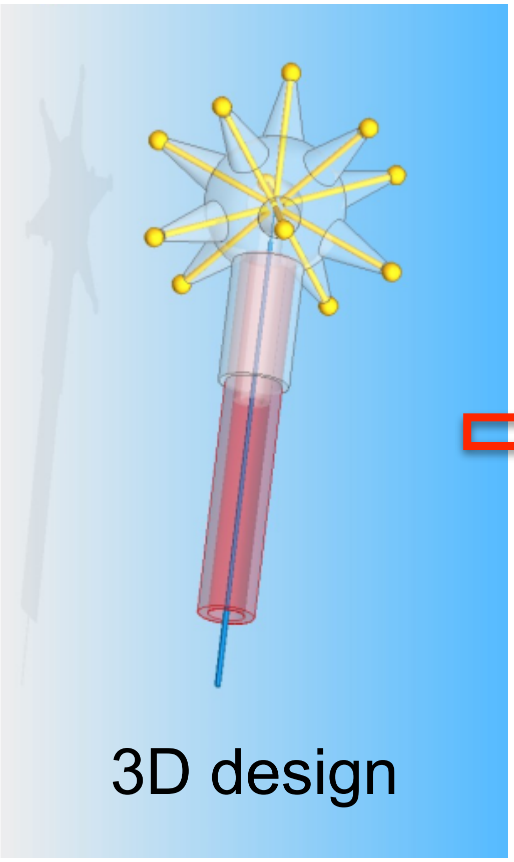
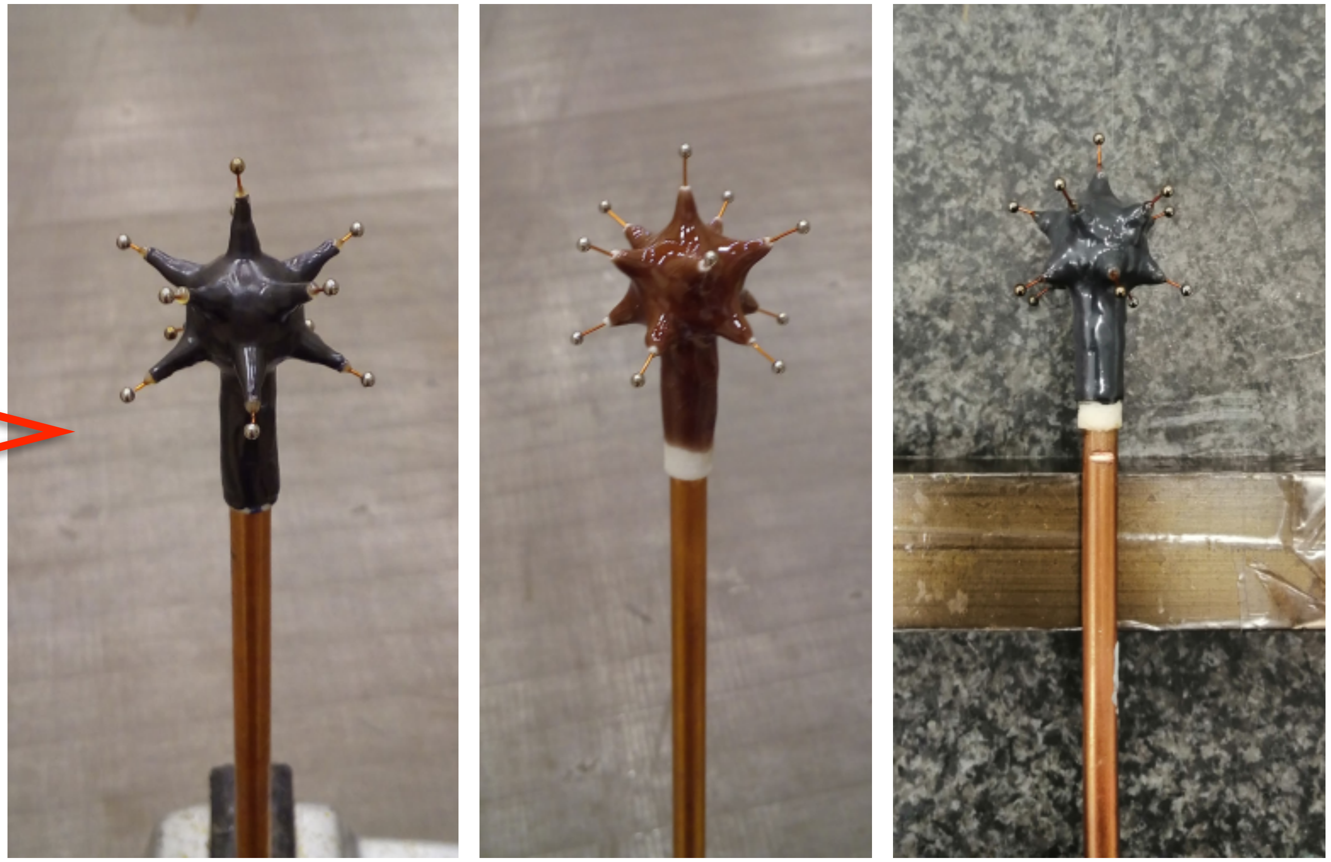
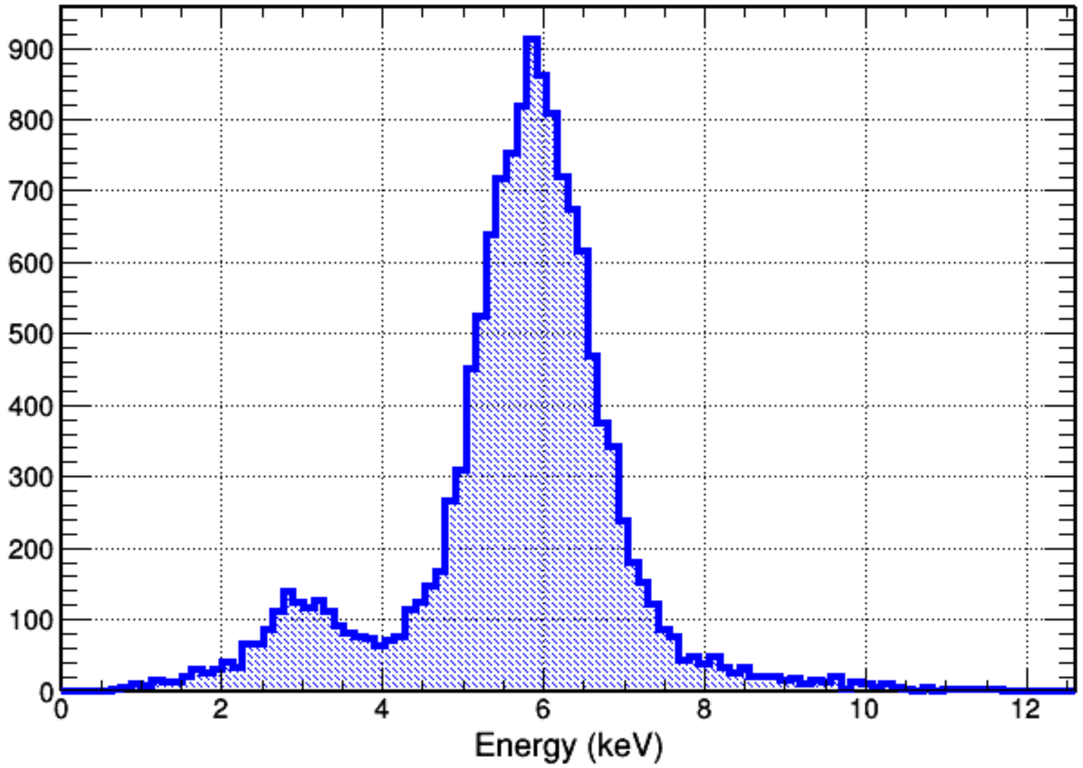
Achinos second generation modules





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

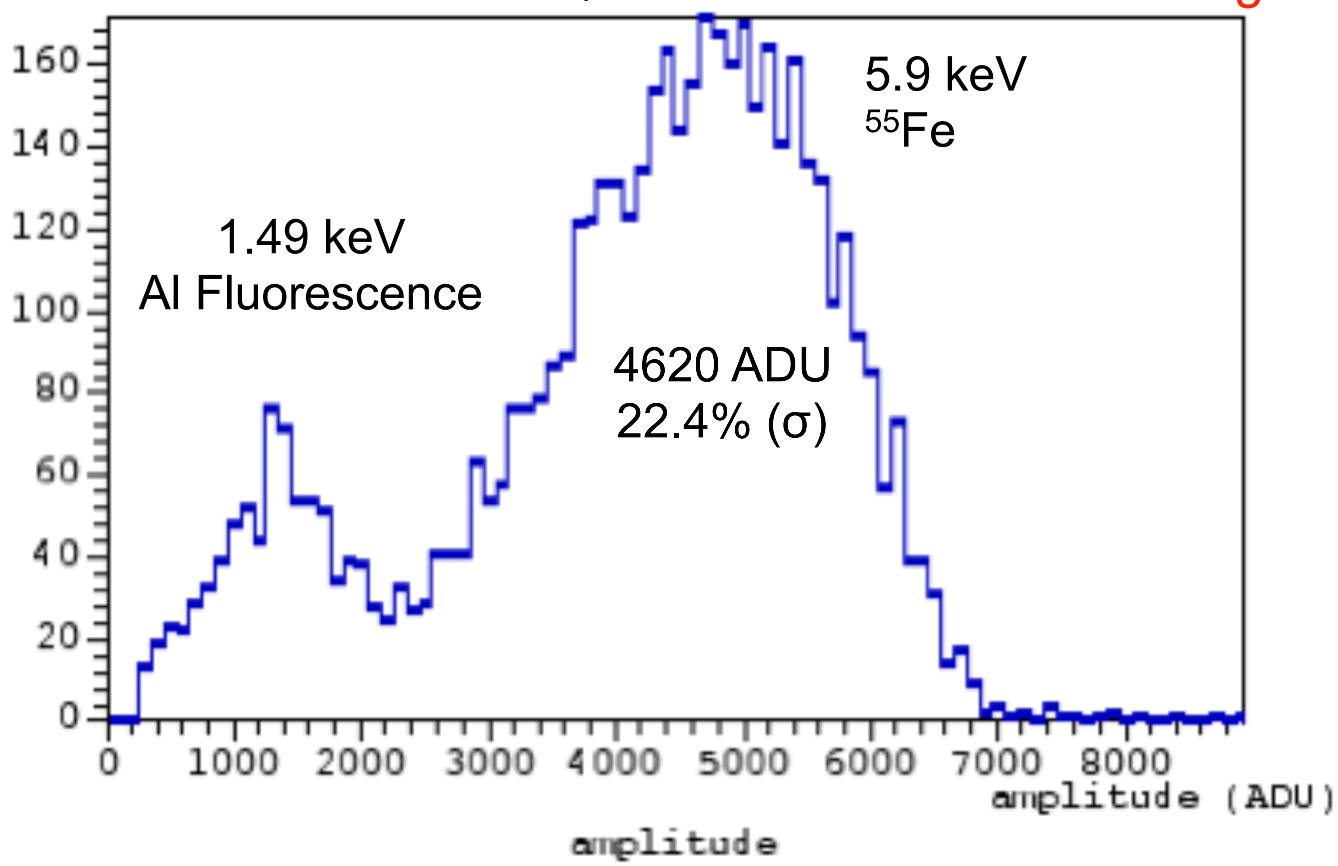


He:Ar:CH4 (56:37:7)
455 mbar
HV1 = 1100 V, HV2 = -100 V
2 mm Ø anodes

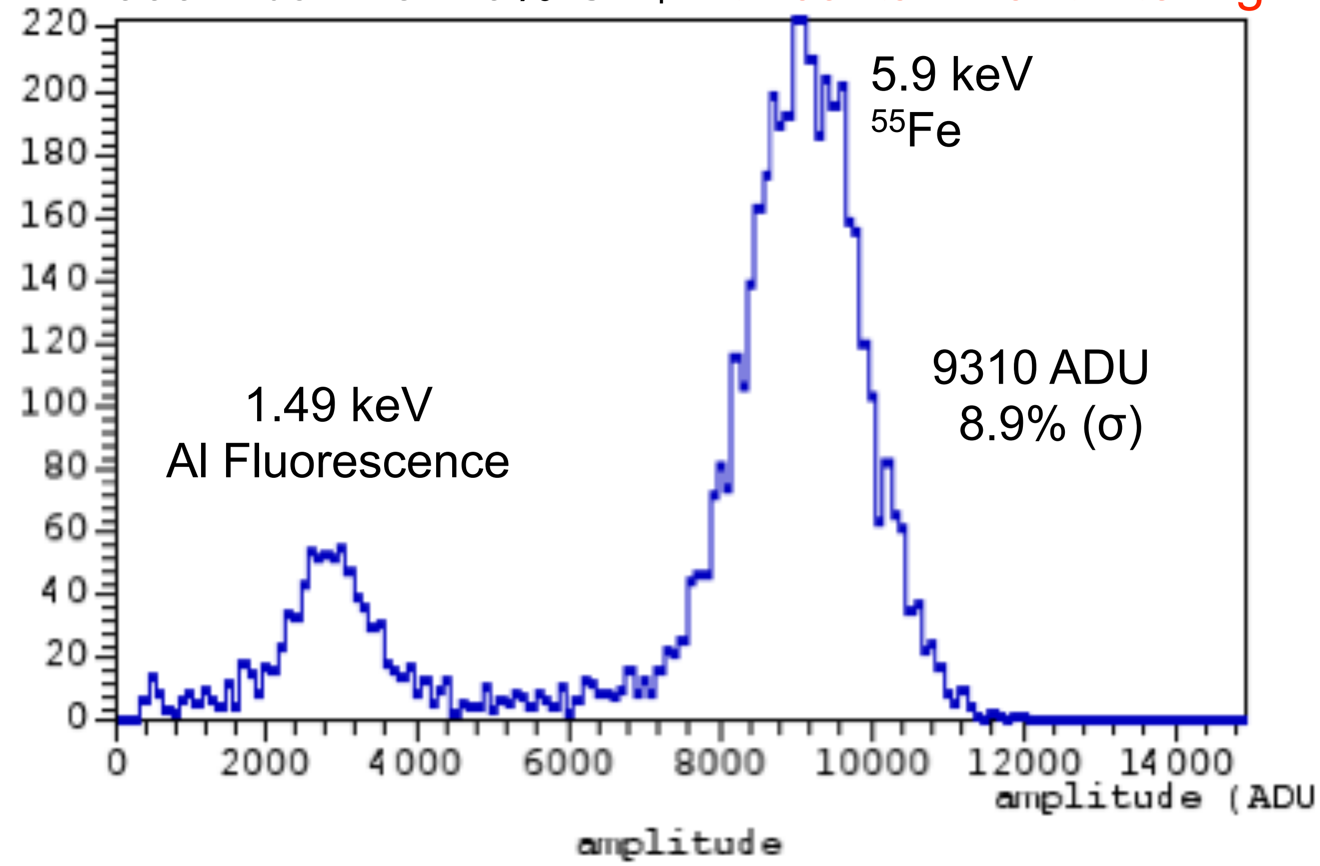
- Good energy resolution
- High pressure operation (~2 bar)
- Resistive layer materials tested:
  - Araldite/Graphite, Araldite/Cu
  - Polymer resistive paste
  - DLC (Diamond Like Carbon)

Gas Purification

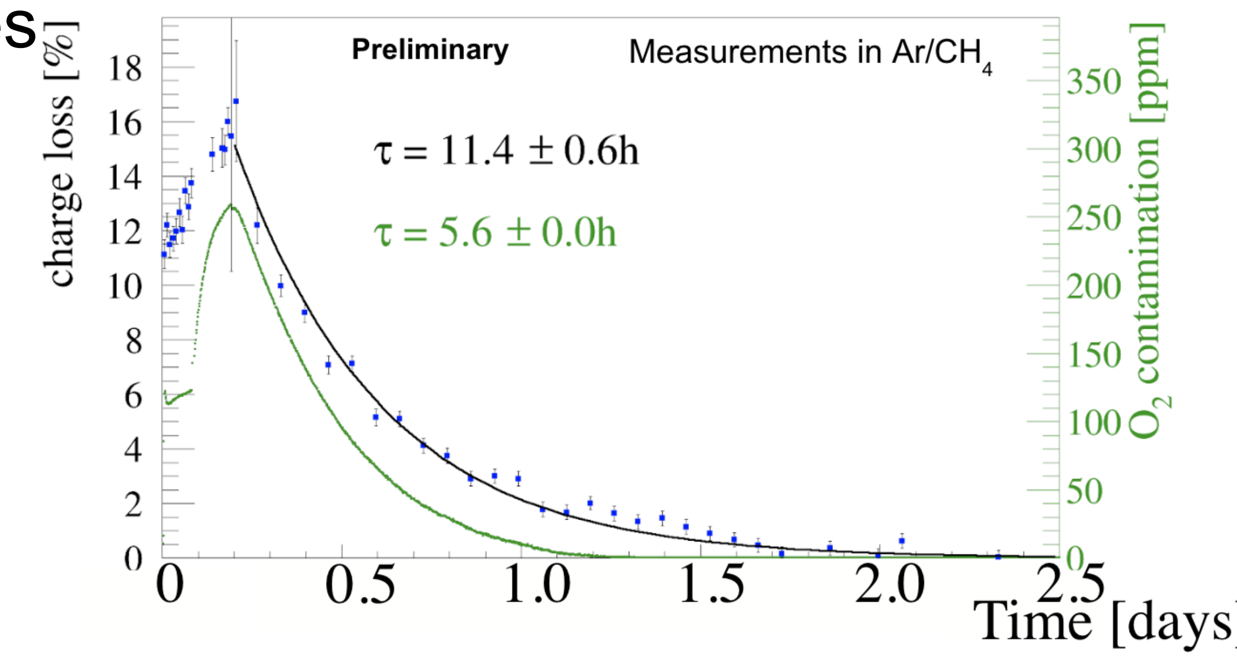
600 mbar He+10% CH_4 without contaminant filtering



600 mbar He+10% CH_4 with contaminant filtering



- Contaminants: O_2, H_2O, electronegative gases
- Filtering with: Getter, Oxysorb
- Filtering in a gas re-circulation system
  - SAES MicroTorr Purifier (MC700 902-F)
  - Incorporated with Residual Gas Analyser
- Improved filtering efficiency in large sphere



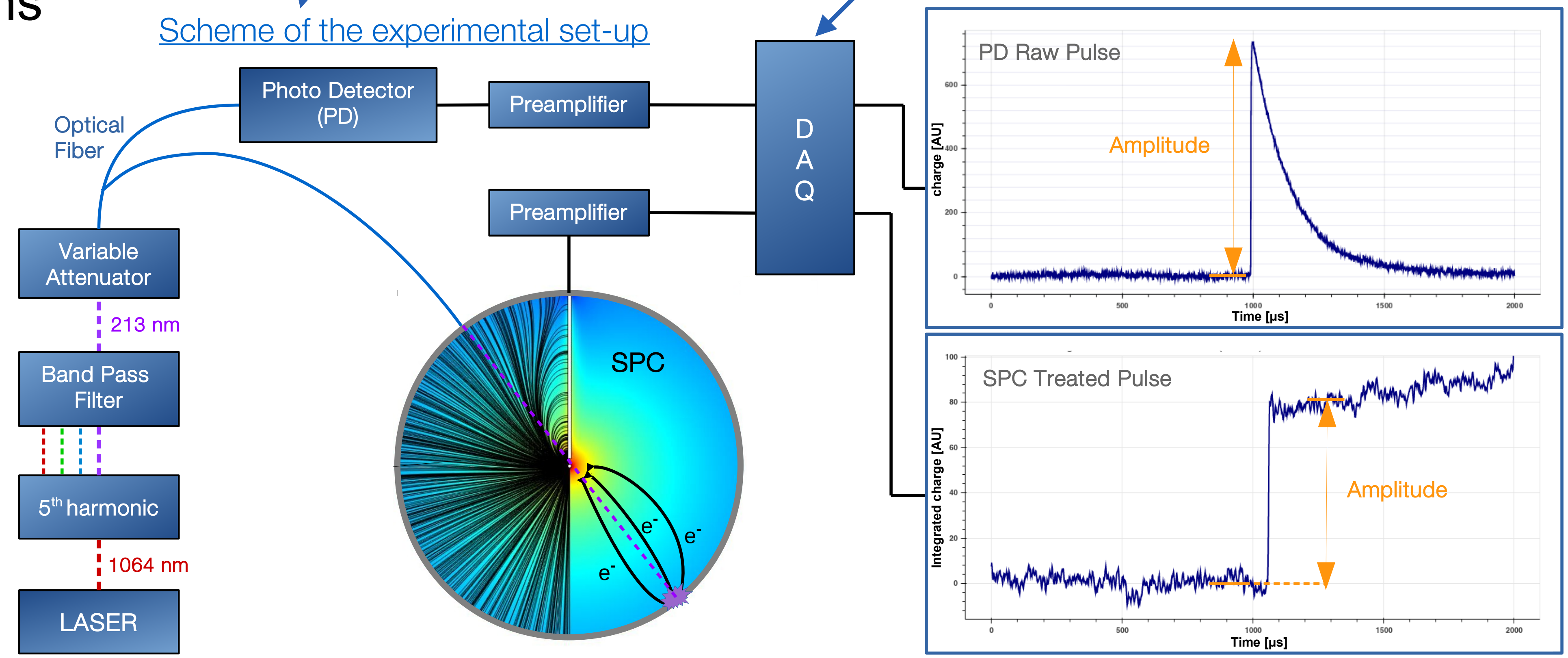
Laser Calibrations

Phys. Rev. D 99, 102003 (2019)

Parallel photo-detector to tag laser events

Tunable transmission to control the mean number of electrons

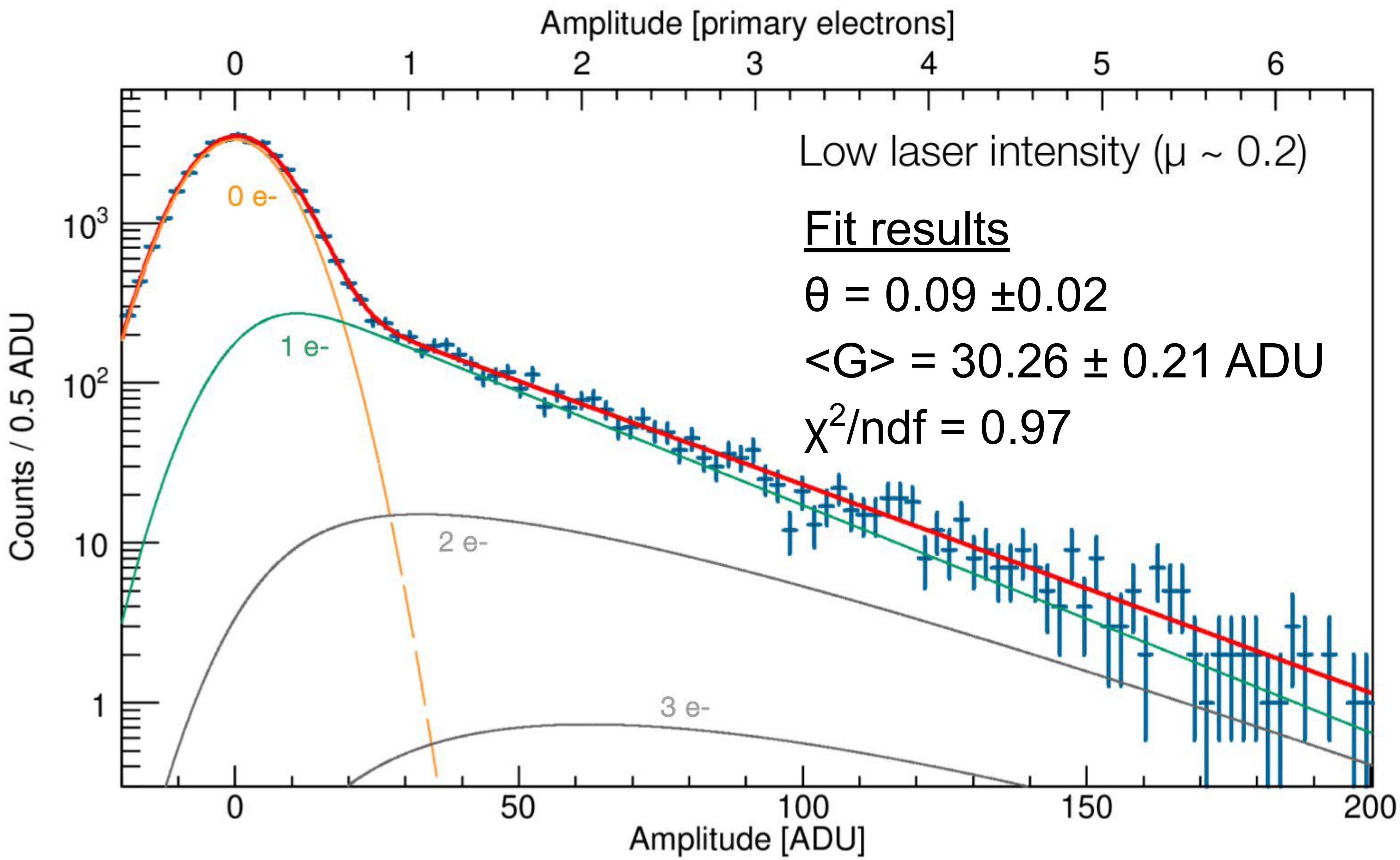
Common DAQ for timing analysis between two channel



A powerful UV laser capable of extracting 100s of electrons

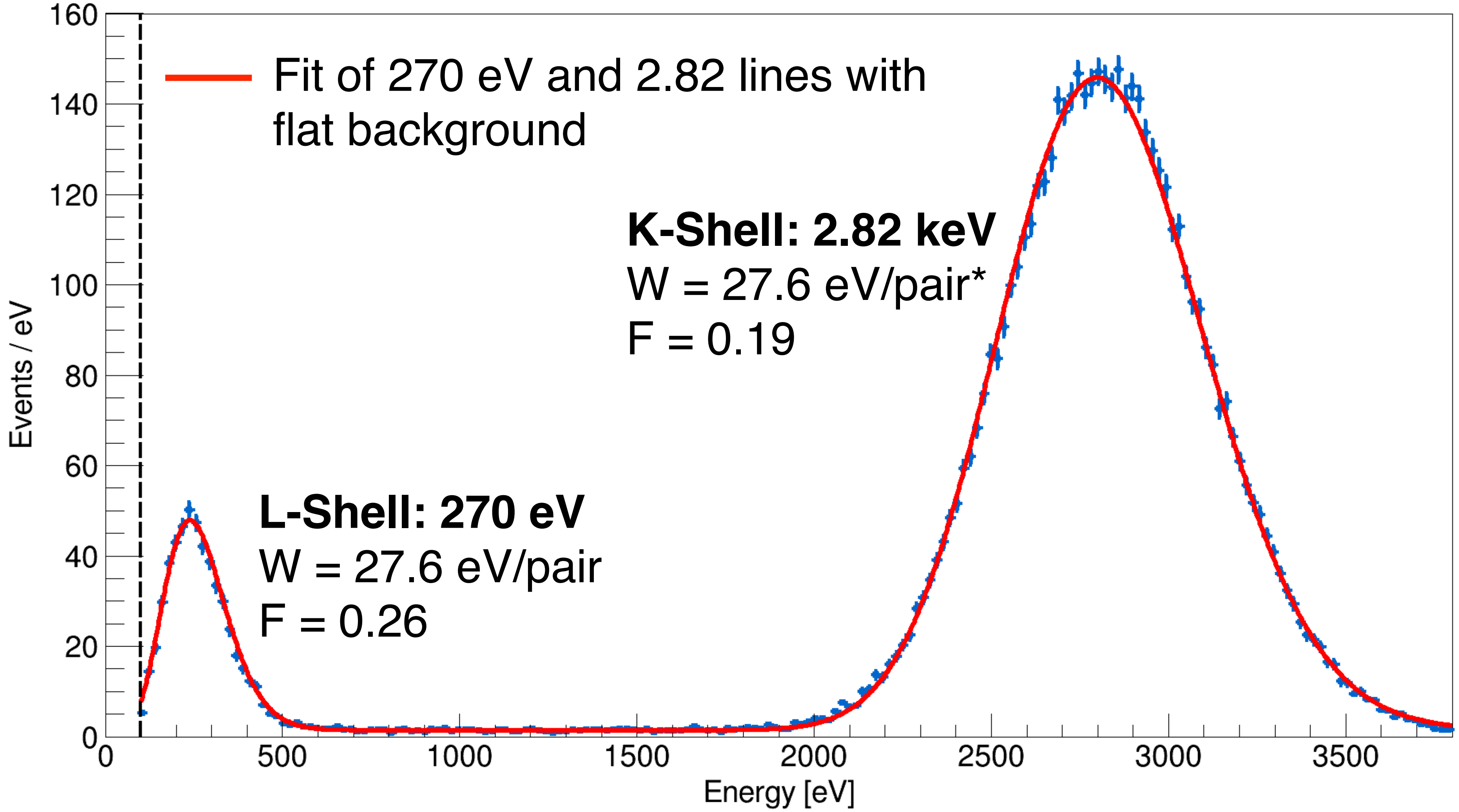
- 213 nm laser used to extract primary electrons from detector wall
- Photo-detector in parallel tags events and monitors laser power
- Laser intensity can be tuned to extract 1 to 100 photo-electrons

Modelling Single Electron Response



- N photo-electrons are extracted from the surface of the sphere: Poisson
- Each photo-electron creates S avalanche electrons
- Sum the contributions of all N photo-electrons: N^{th} convolution of Polya
- The overall response is convolved with a Gaussian to model baseline noise

Measurements of gas properties

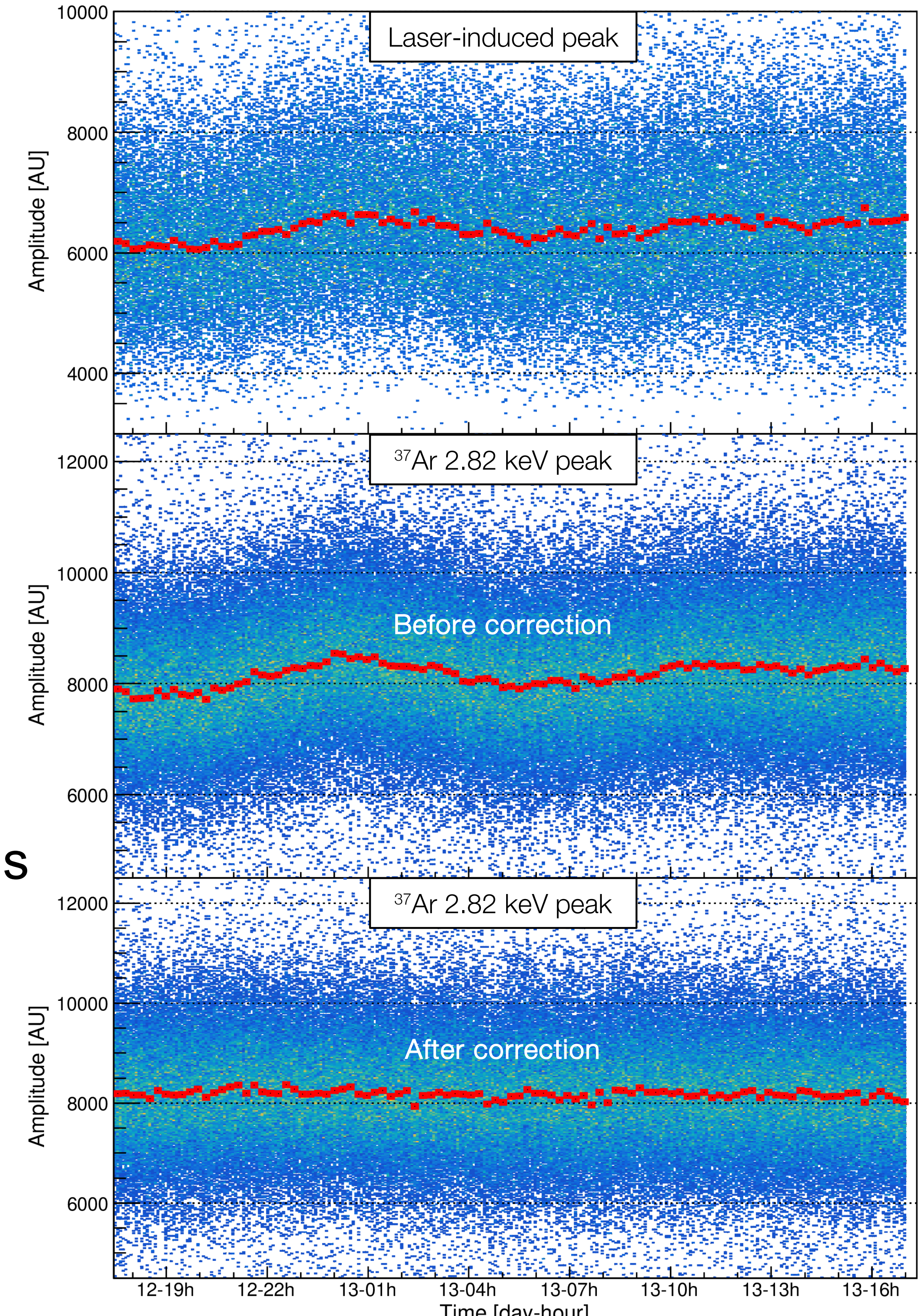


- ^{37}Ar produced by irradiating Ca power with a high flux of fast neutrons
- Together with laser calibrations, can find W (mean Ionization energy) with 1% precision for target gas, and set upper limits on F (Fano factor)
- Detector response modelled:
  - Primary ionisation (COM-Poisson) Phys. Rev. D 98, 103013 (2018)
  - Avalanche (Polya)

*The W-value at 2.82 keV was calculated directly from <G> and fixed for this fit

Detector Monitoring

- Physics runs are days-weeks long, response fluctuations induced by:
  - temperature/pressure changes
  - O_2 contamination
  - sensor damage
  - …
- ^{37}Ar calibrations
  - crucial information
  - can only be used at the end of a run
- Laser system
  - detector response monitoring in physics runs



Simulation: Geant4 and Garfield

Inspired by: NIM A935 (2019) 121

Detector is initialised and initial particle is generated

↓

Geant4 tracks particles and interactions

↓

Electrons with energy <2 keV are passed to Garfield++

↓

Heed calculates further ionisation and δ-electrons produced

↓

Using the gas transport parameters, ionisation electrons are transported up to the avalanche region

↓

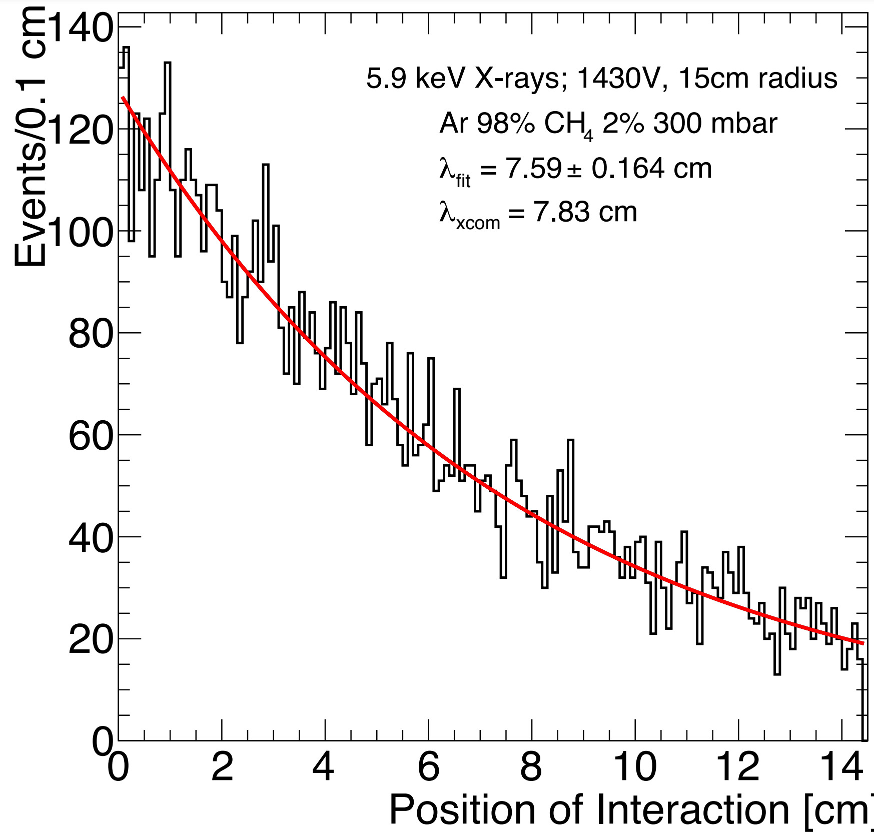
Electron avalanche is simulated

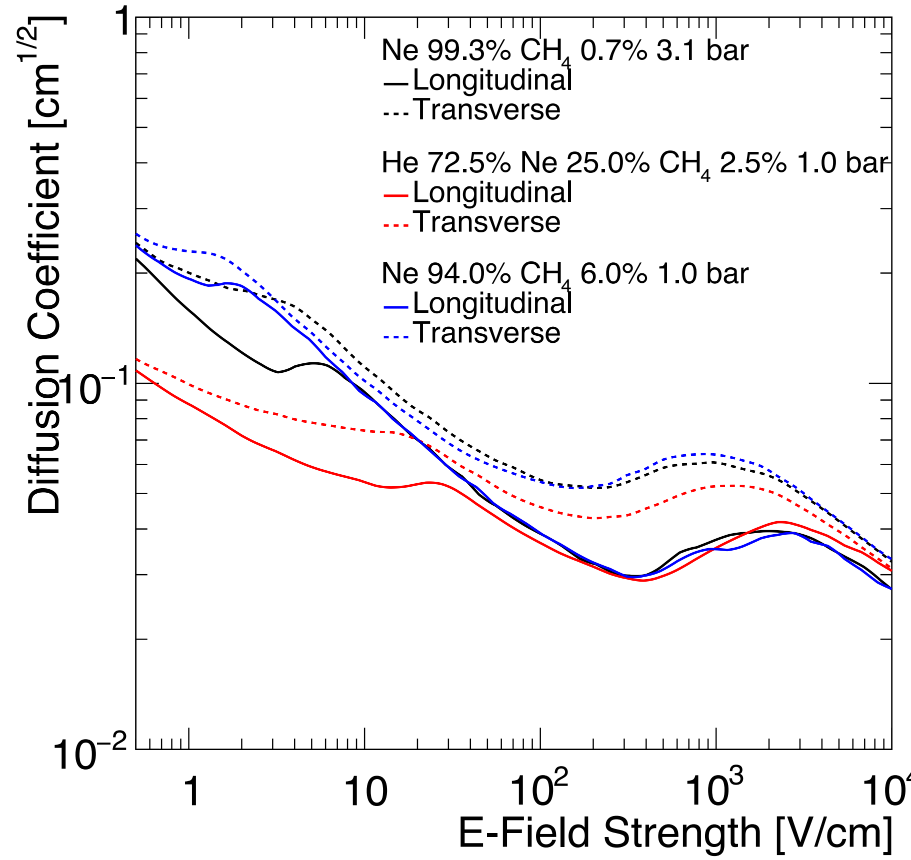
↓

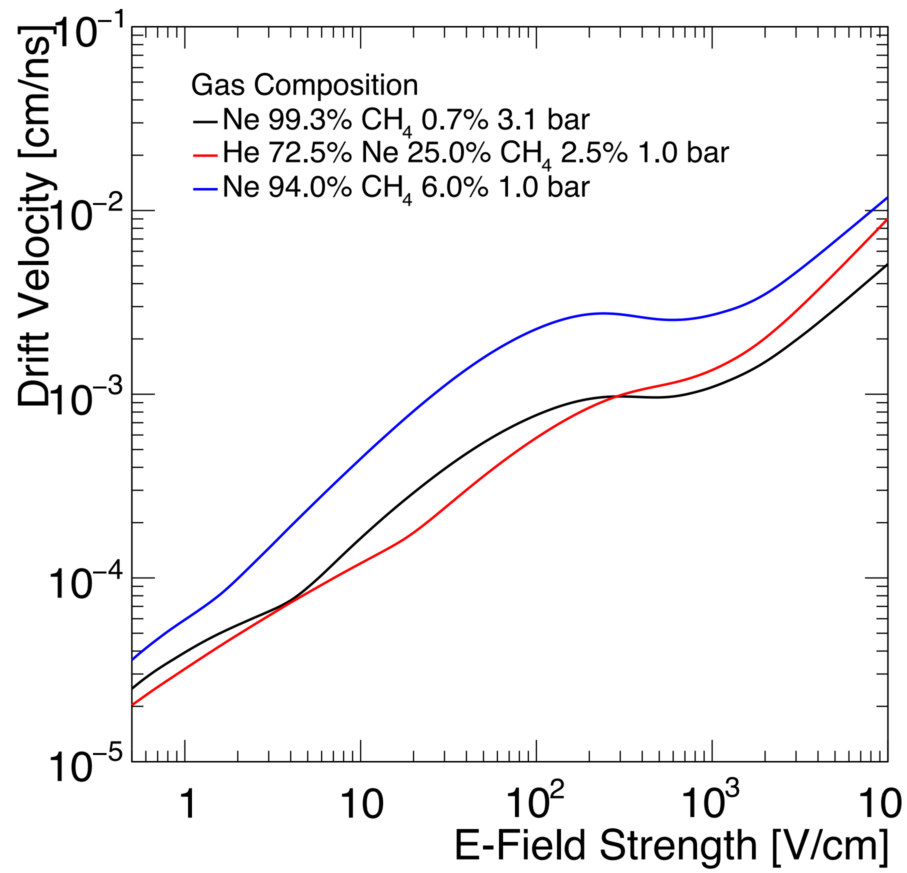
Ions and electrons produced in avalanche drift in electric field, and induced electric current is calculated

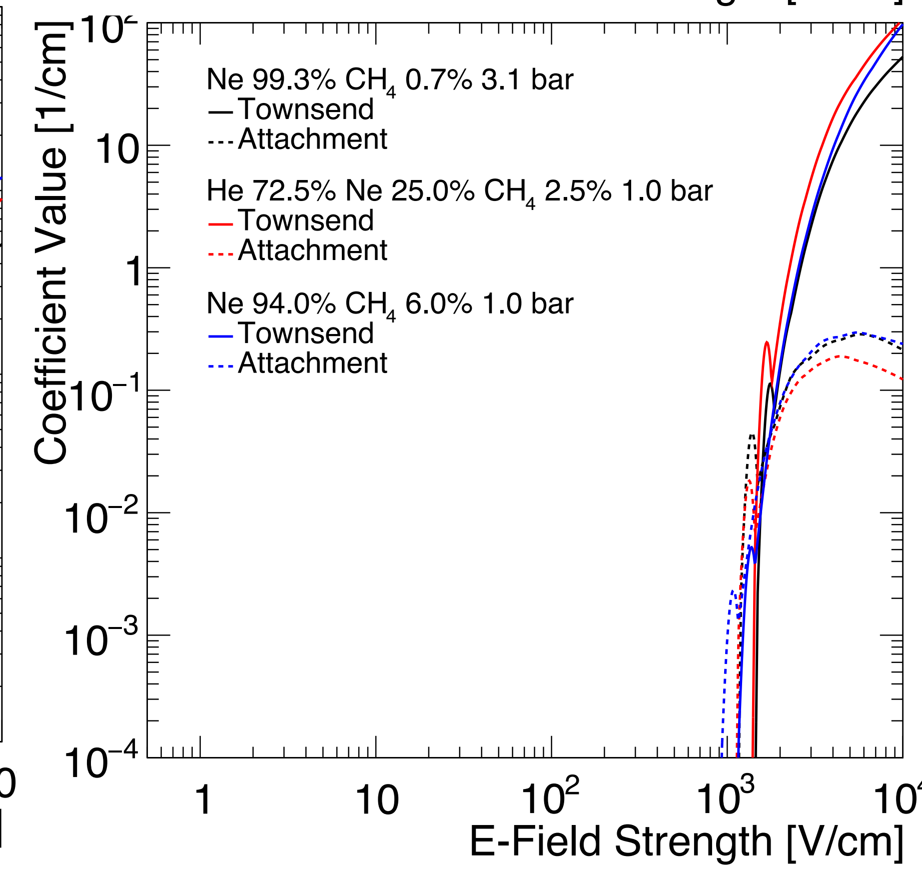
↓

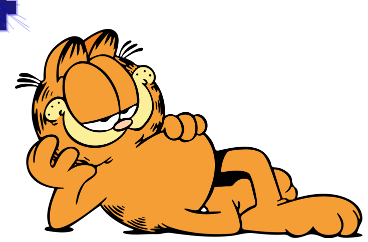
Signal is processed through electronics module to form pulse





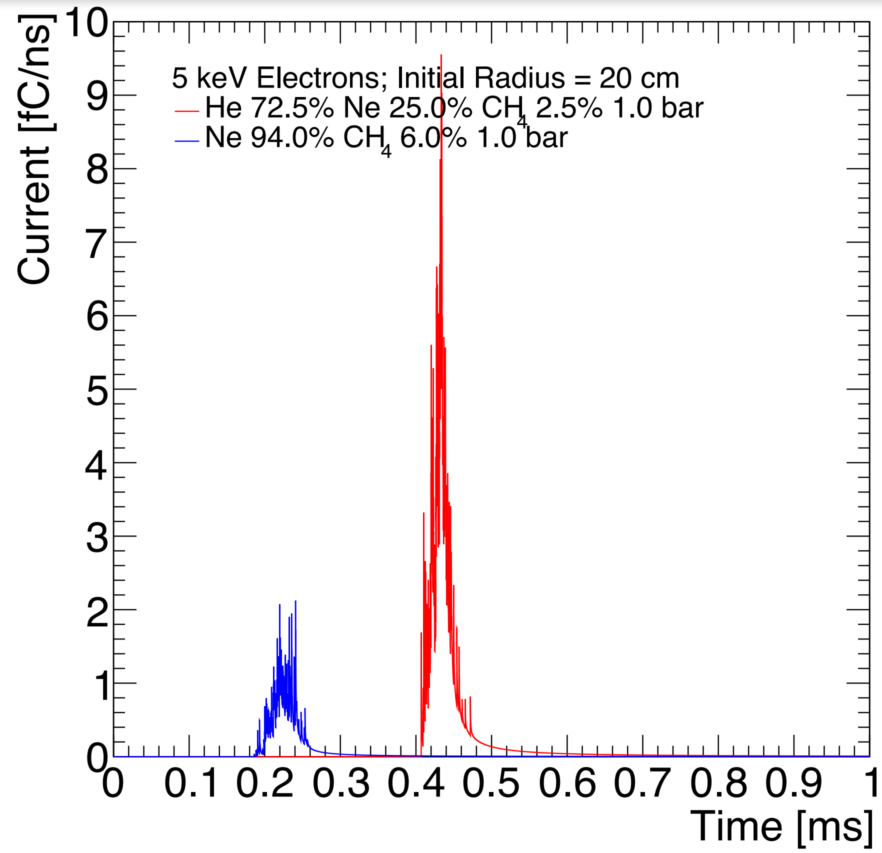


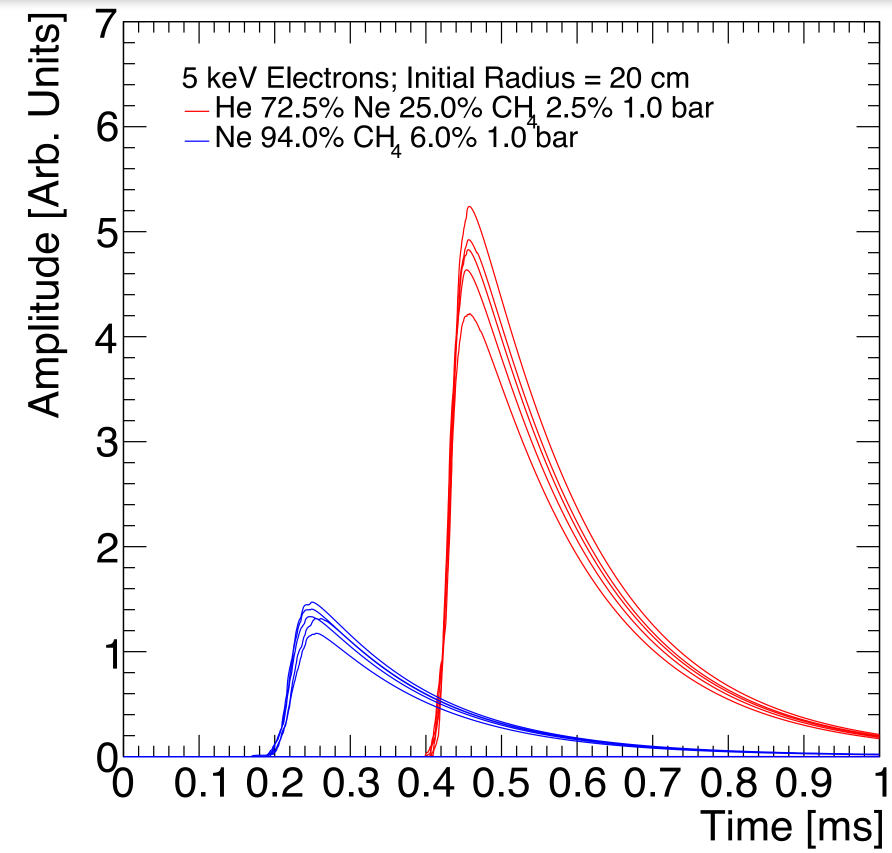


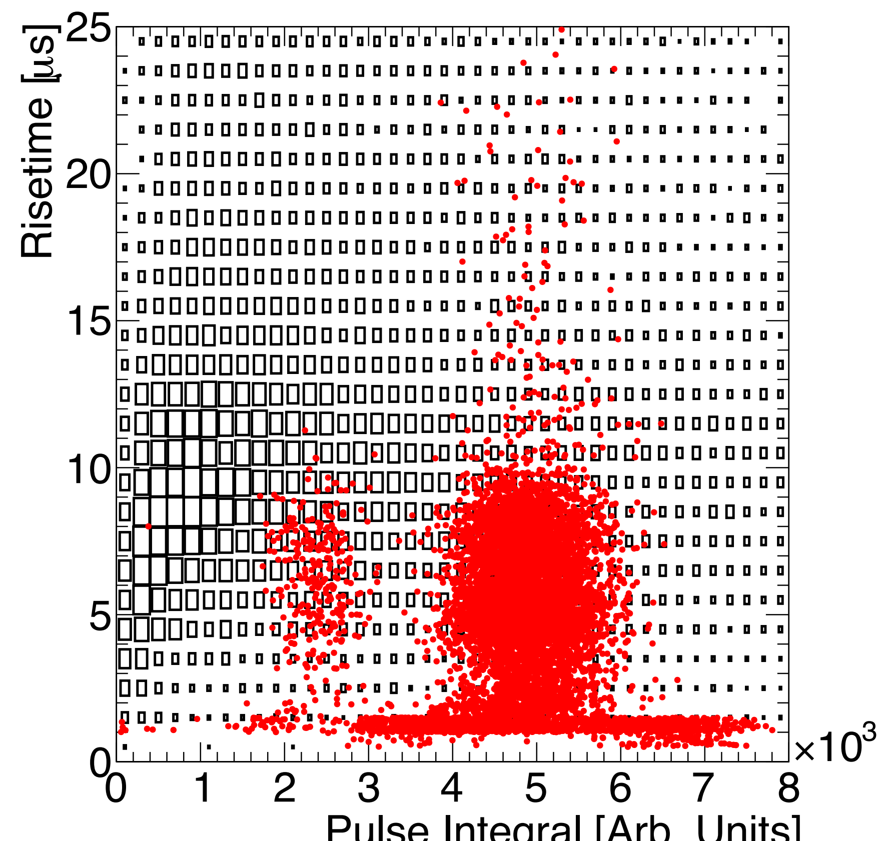


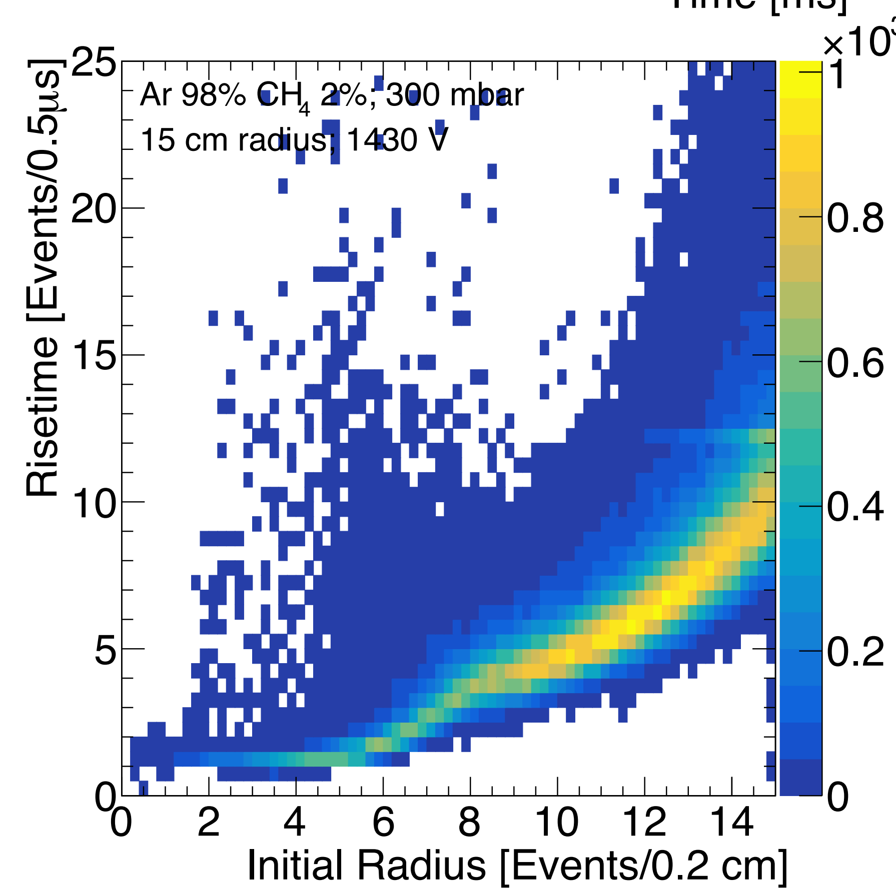
IEEE-NSS 2019 R. Ward N-32-02

Simulation: Geant4 and Garfield





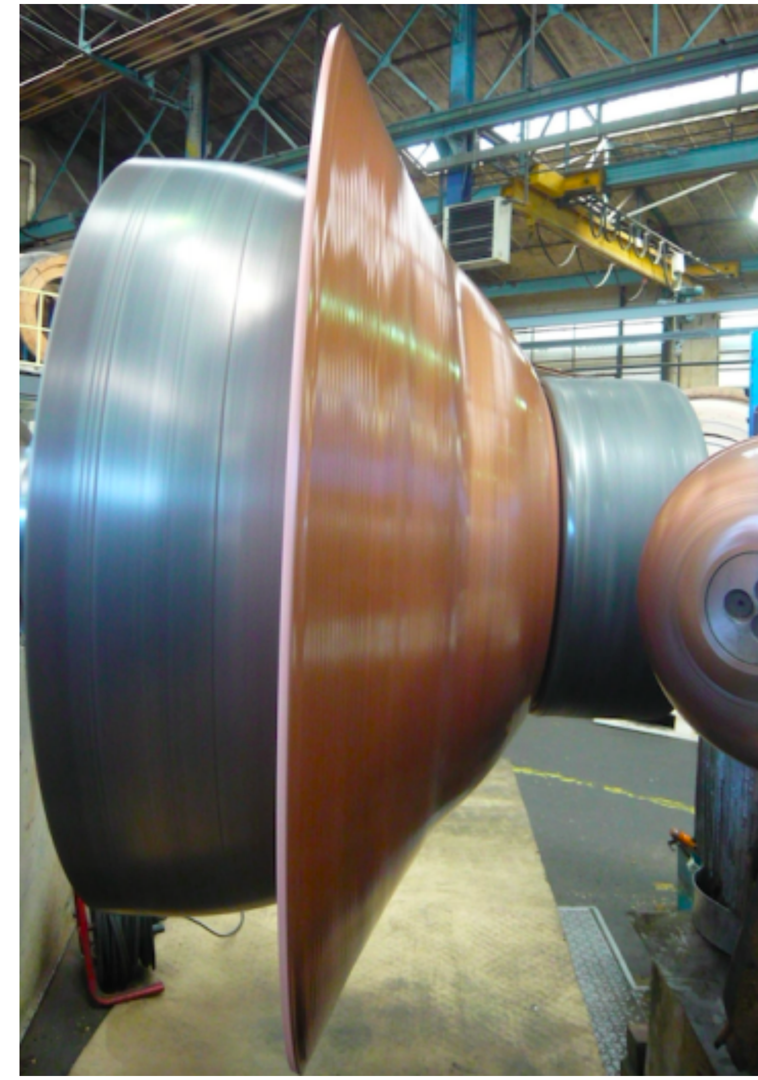


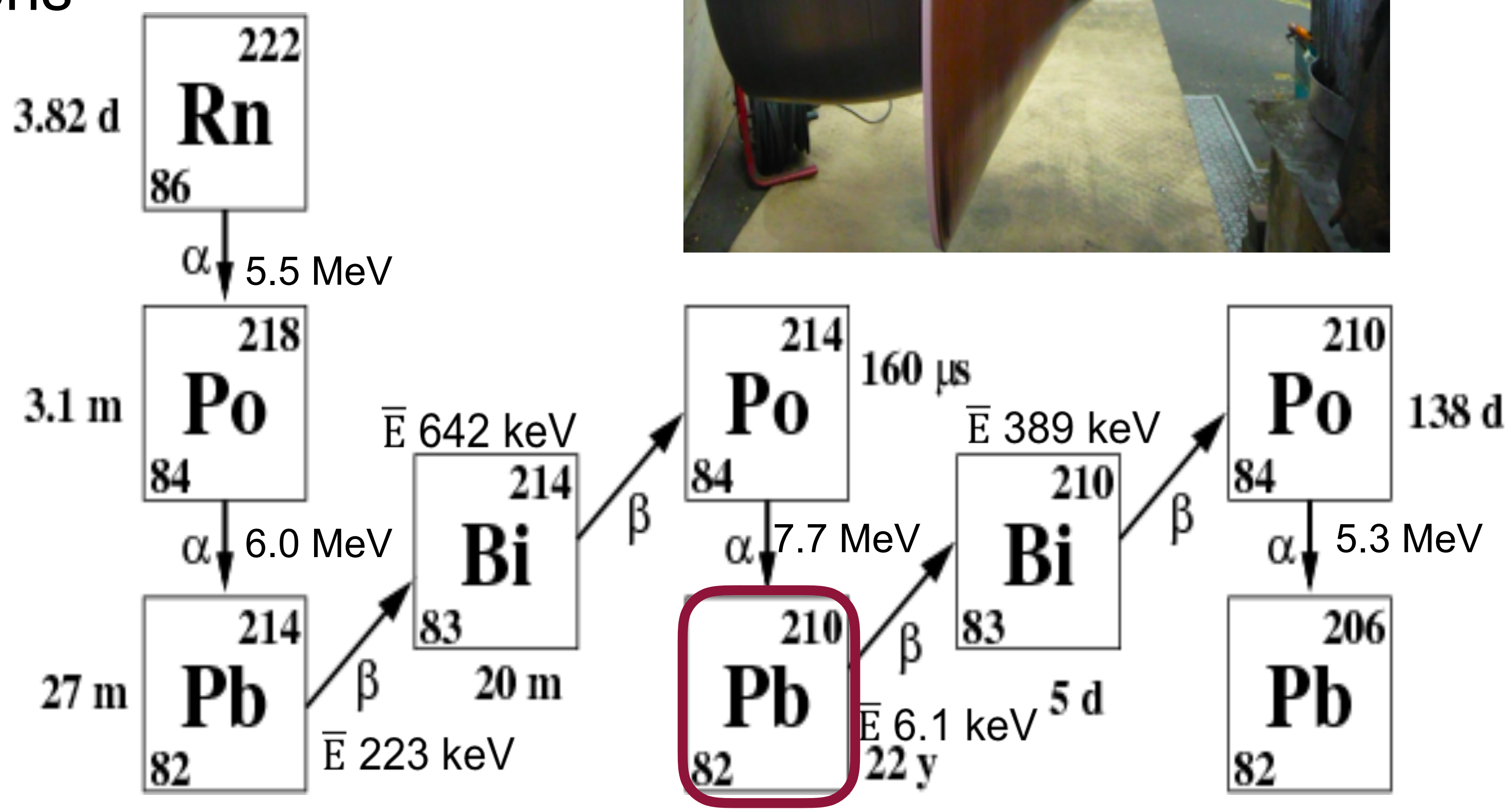


IEEE-NSS 2019 R. Ward N-32-02

Copper for SNOglobe

- Copper common material for rare event experiments
  - Strong enough to build gas vessels
  - No long-lived isotopes
    - Longest is ^{67}Cu $t_{1/2}$=62h
  - Low cost/Commercially available at high purity
- 4N Aurubis copper (99.99% pure)
  - Spun into two hemispheres
  - Hemispheres electron-beam welded together
- Backgrounds in Copper
  - ^{63}Cu(n,α)^{60}Co from fast neutrons
  - Minimise exposure to surface
- Contaminants
  - U/Th decay chain traces
  - Deposited by ^{222}Rn

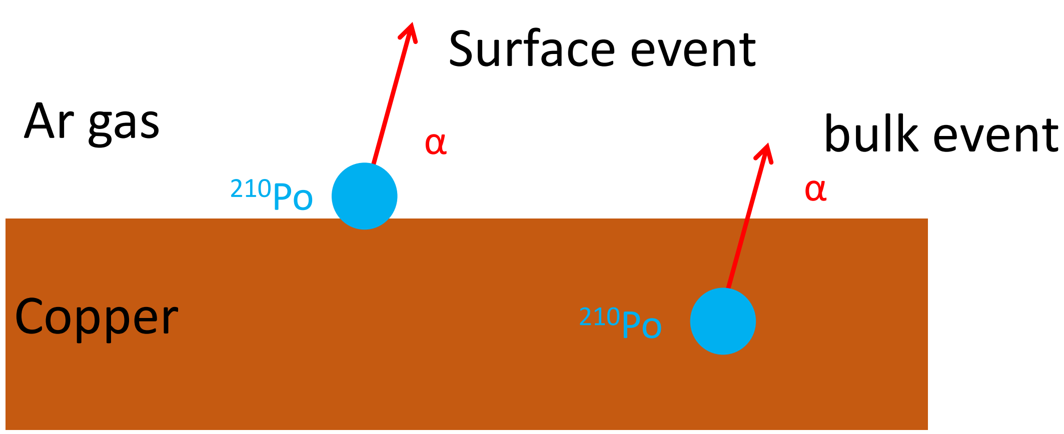




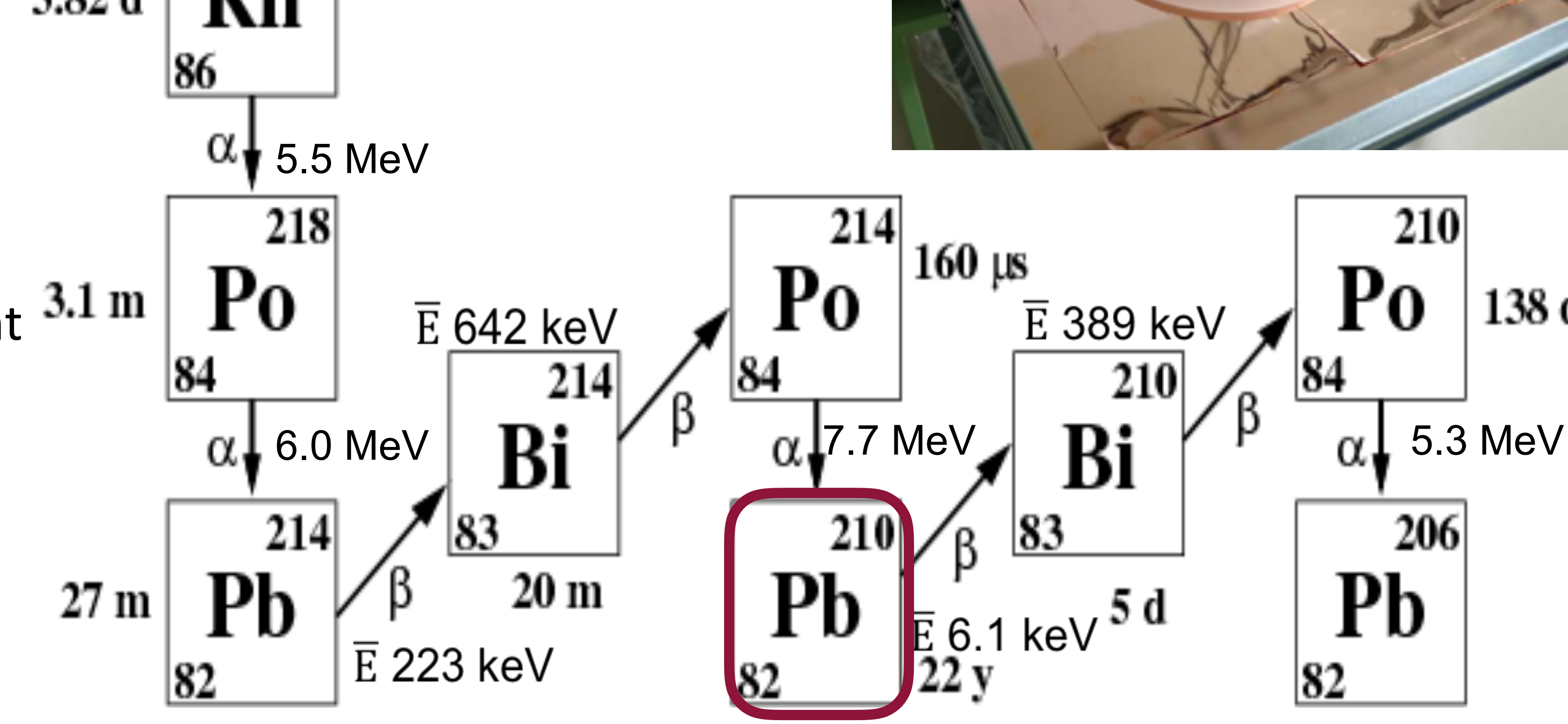
^{210}Pb in SNOglobe Copper

- Typically, ^{238}U/^{232}Th measured directly by mass spectroscopy
  - Measured: ~10 µBq/kg (ICP-MS)
- Recent development: XIA UltraLo
  - measure ^{210}Po decay α-particles → infer ^{210}Pb activity
  - Confirmed ^{210}Pb contamination by ^{222}Rn in production
  - ^{210}Pb out of equilibrium: 29 ± 10 (stat)$^{+9}_{-3}$ mBq/kg
    - dominant background

XIA UltraLo-1800
https://www.xia.com/ultralo-theory.html

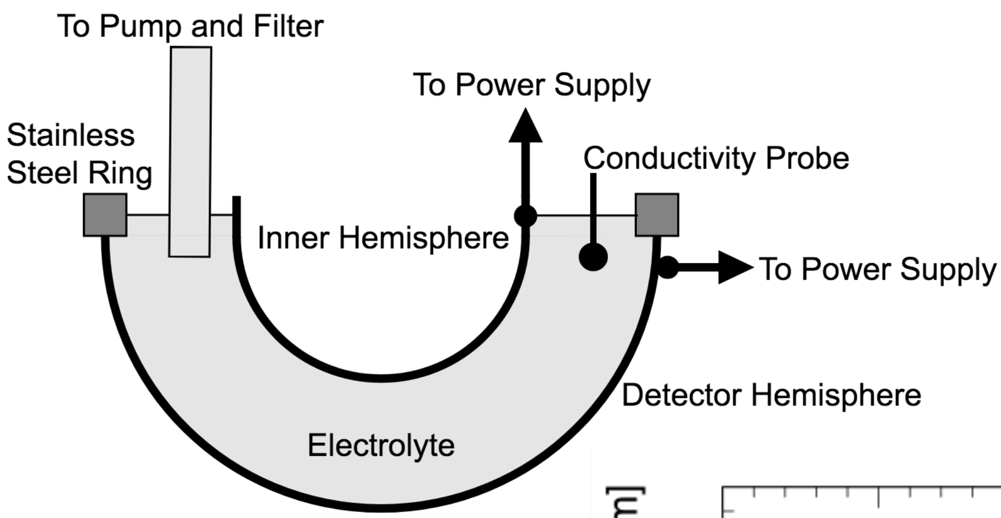


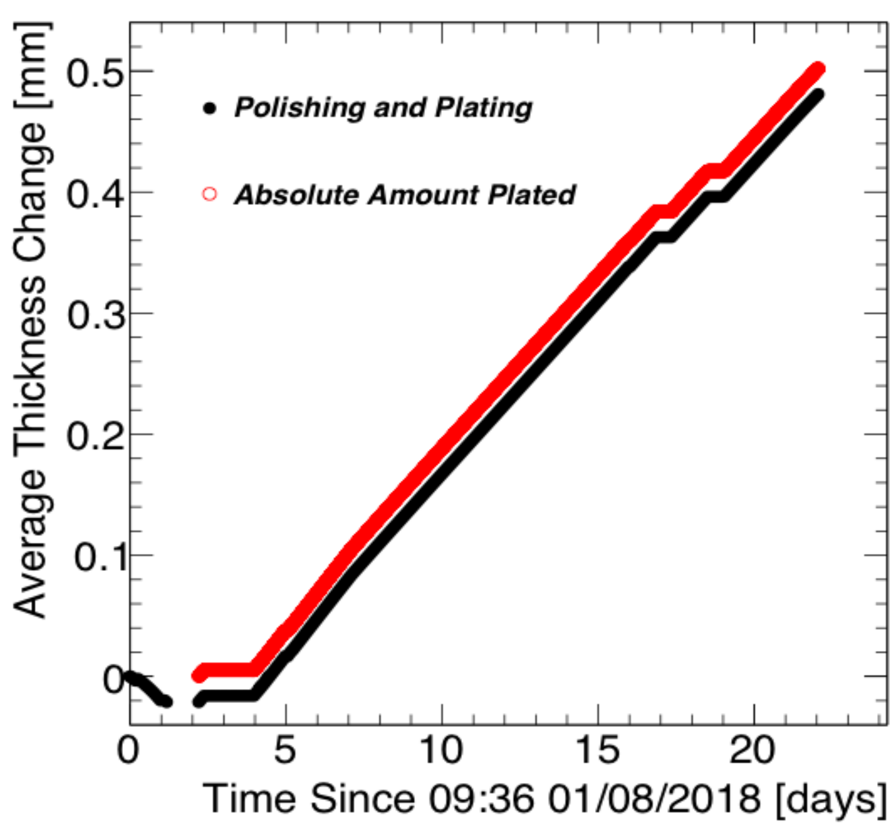
Kobayashi LRT2017

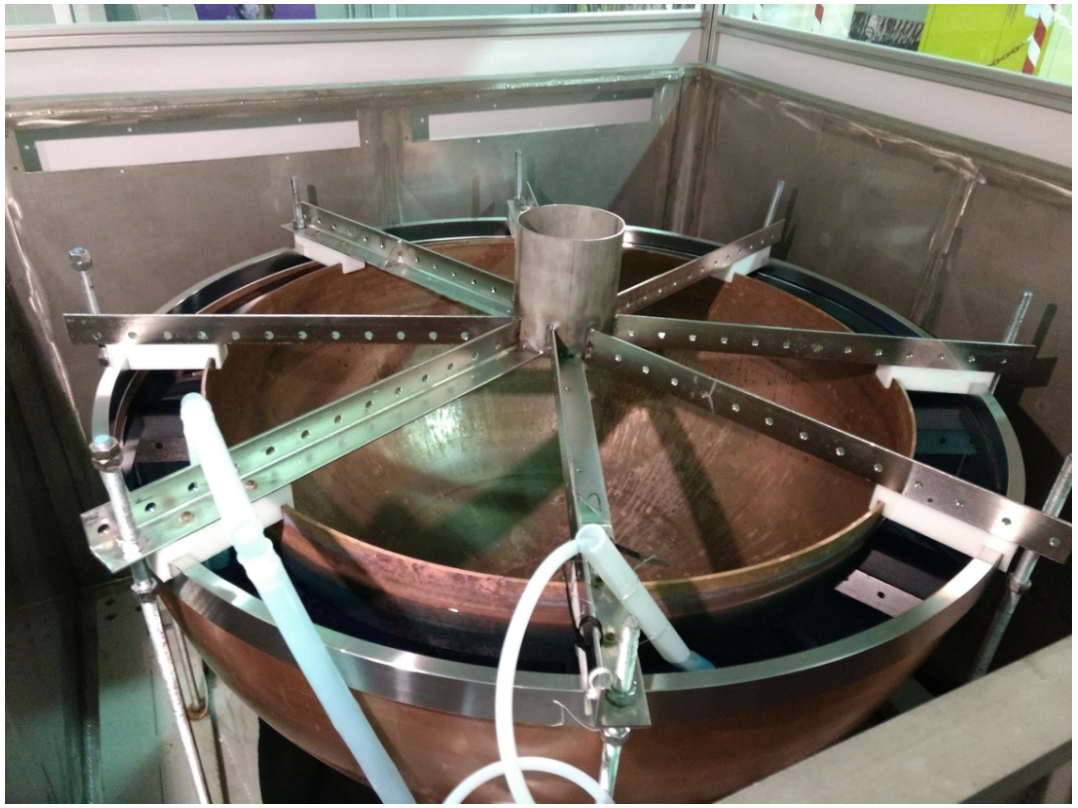


Copper Electroplating

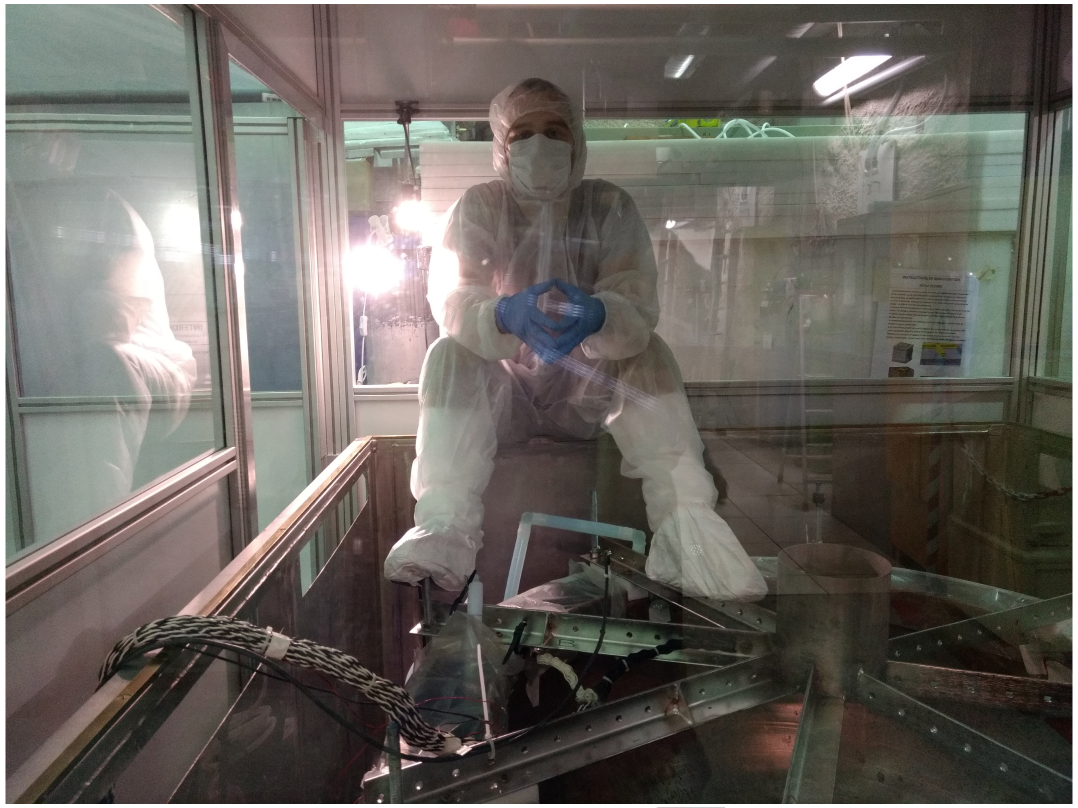
- PNNL expertise in Cu electroforming
- Detector inner surface electroplated
  - Plating continued for ~15days
  - ~500μm pure copper plated
  - Good surface quality achieved







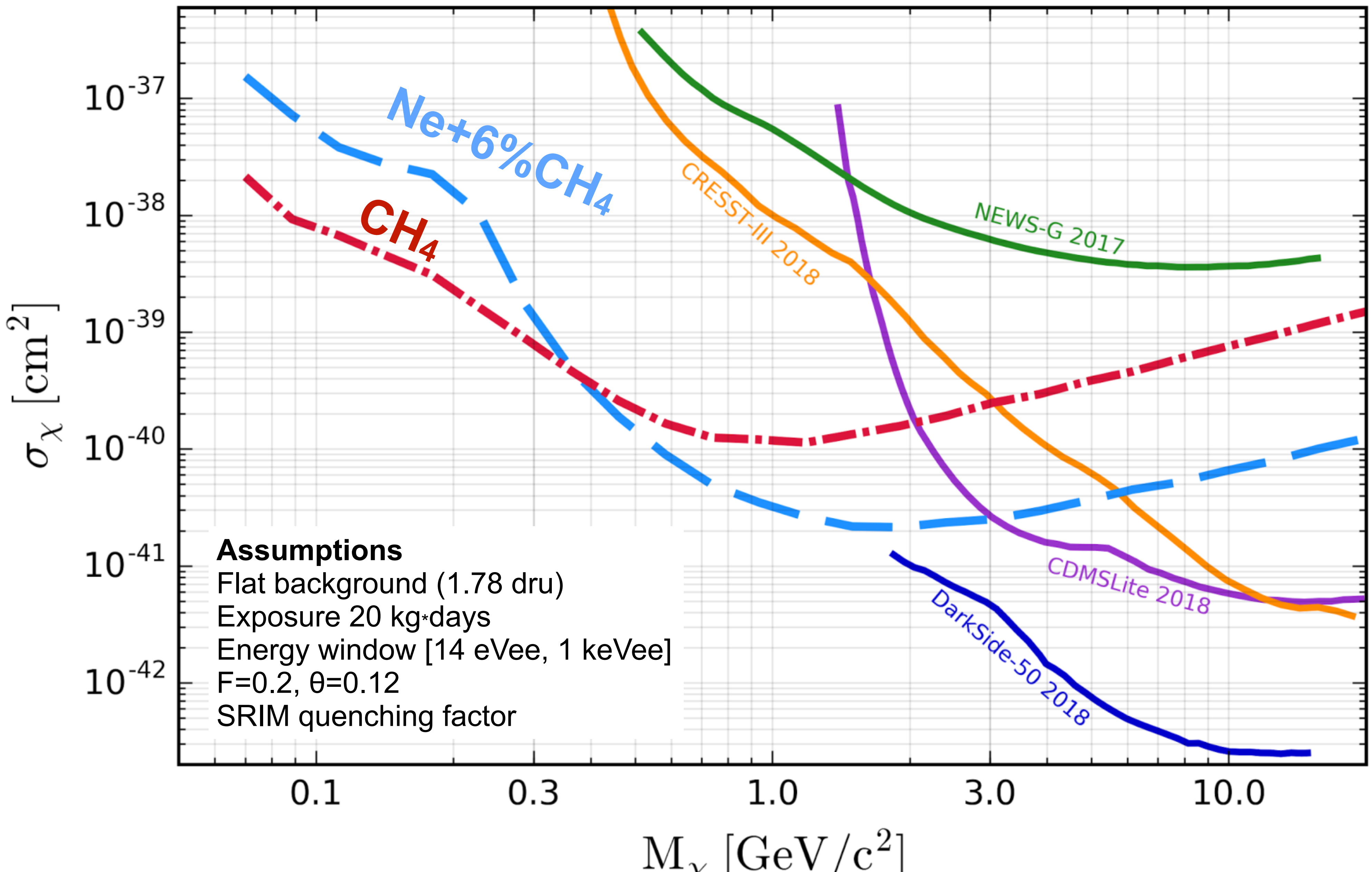
Electroplating setup at LSM

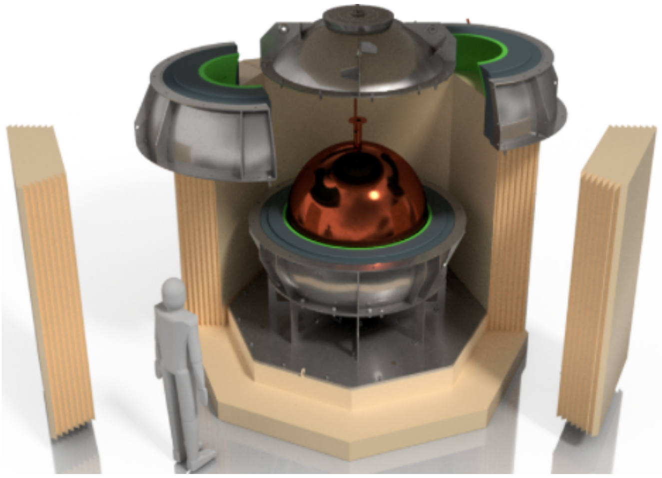


Copper Electroplating

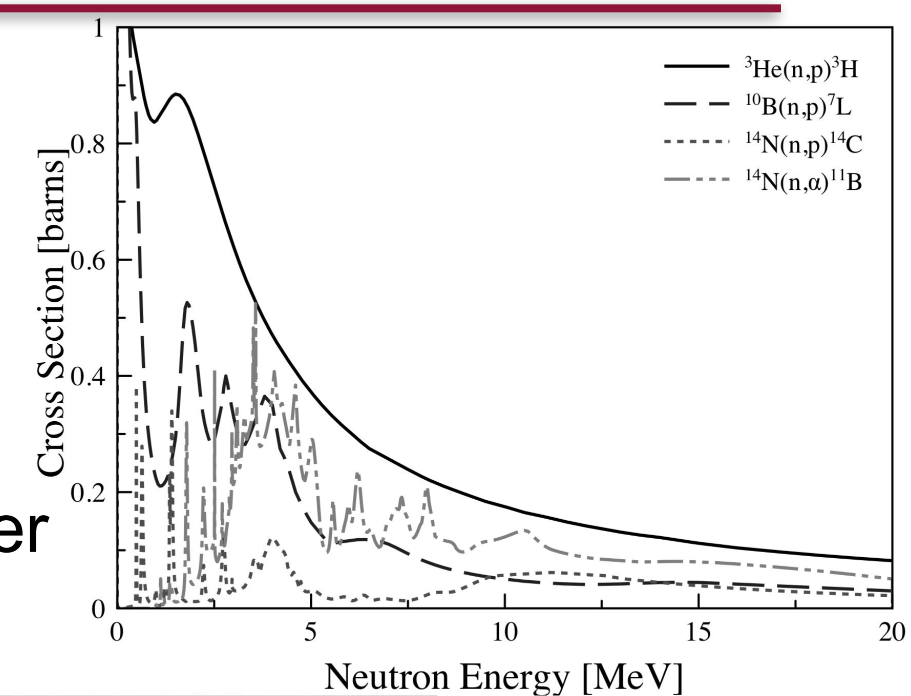
- Suppress backgrounds from:
  - Bremsstrahlung X-rays from ^{210}Pb
  - ^{210}Bi β-decays in copper
  - Geant4: background reduction from 4.58 to 1.96 dru for <1 keV
- Copper deposition rate ~36 μm/day
  - Promising: fully underground electroformed detector
  - Electroformed copper <3mBq/kg

SNOglobe: Physics Potential

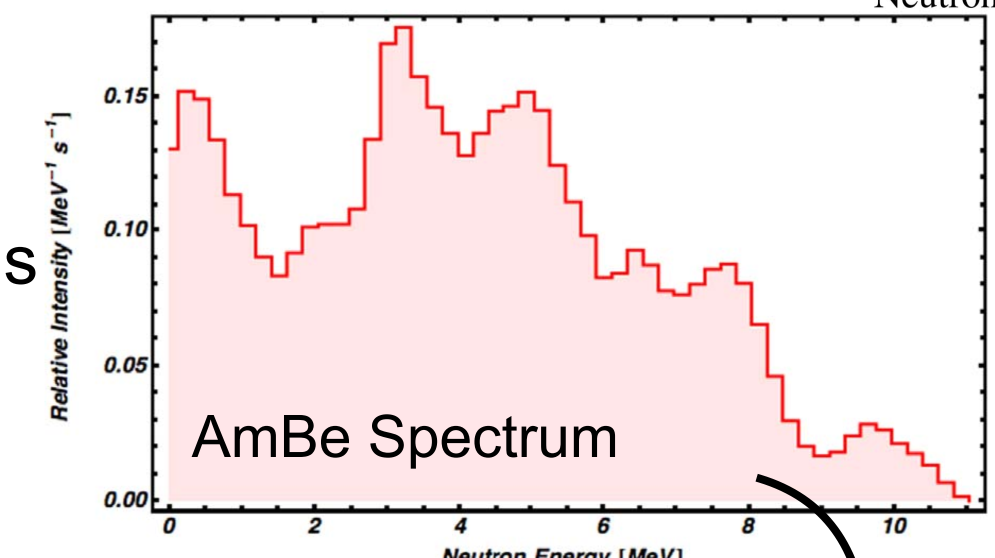




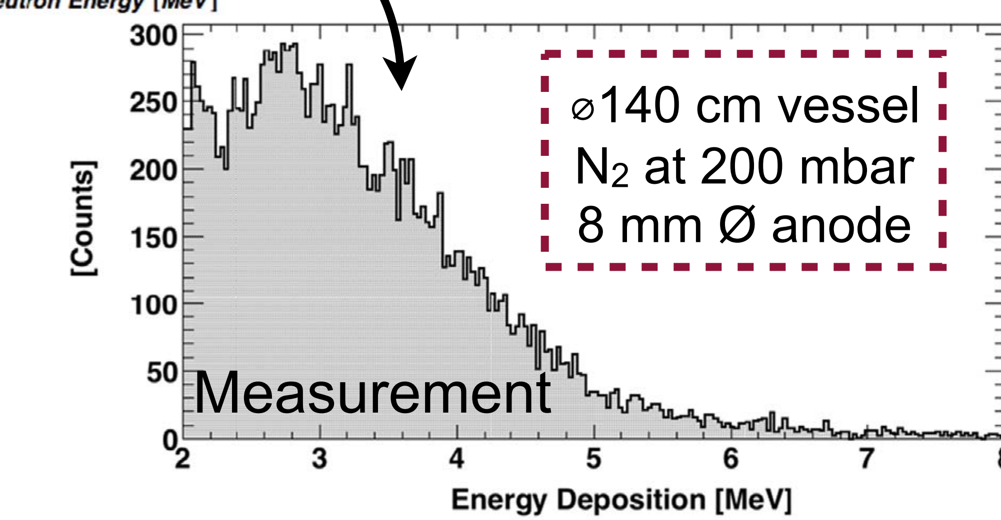
Neutron spectroscopy



- **Neutrons: important background in DM searches**
  - Identical signature to signal events
- Few measurements at underground laboratories
  - ^{3}He-based detectors extremely expensive
- Neutron spectroscopy with Spherical Proportional Counter
  - Using Nitrogen as gas
  - $^{14}N+n \rightarrow {}^{14}C+p$ **+** 625 keV
  - $^{14}N+n \rightarrow {}^{11}B+\alpha$ **-** 159 keV
- Initially demonstrated:
  - ^{252}Cf, ^{241}Am^{9}Be, ambient fast neutrons
  - Thermal neutrons
  - Operation at 0.2-0.5 bar
  - HV reached 6 kV



NIM A847 (2017) 10

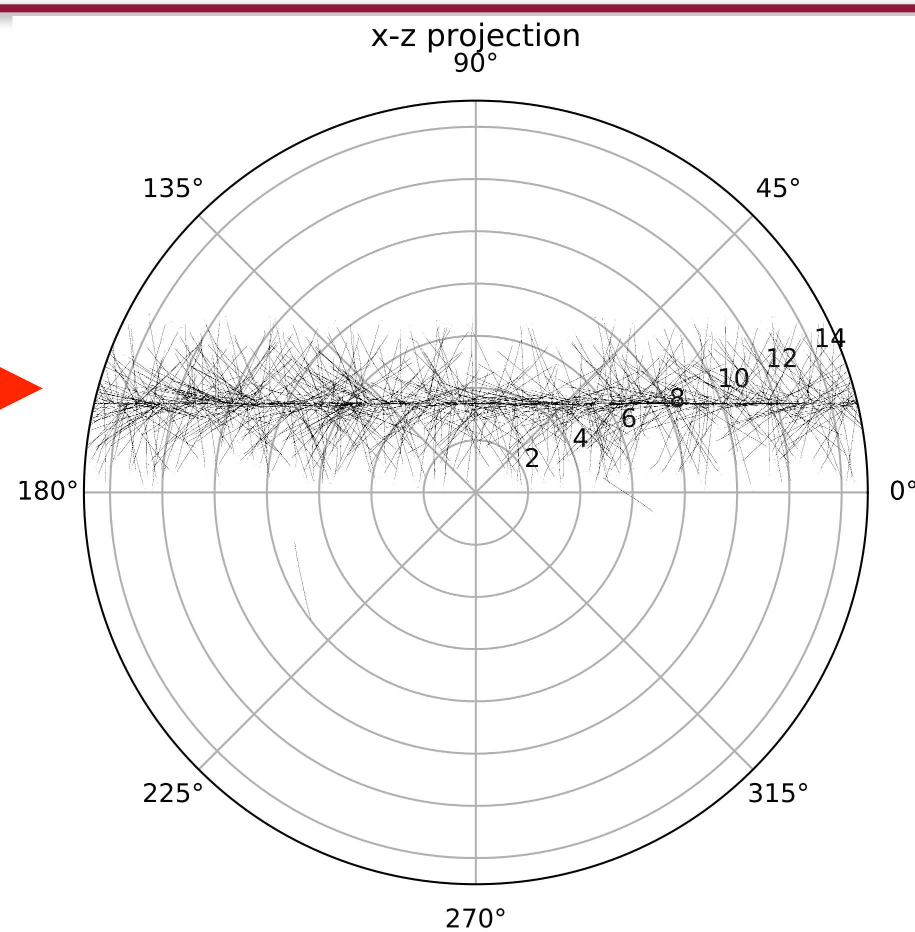


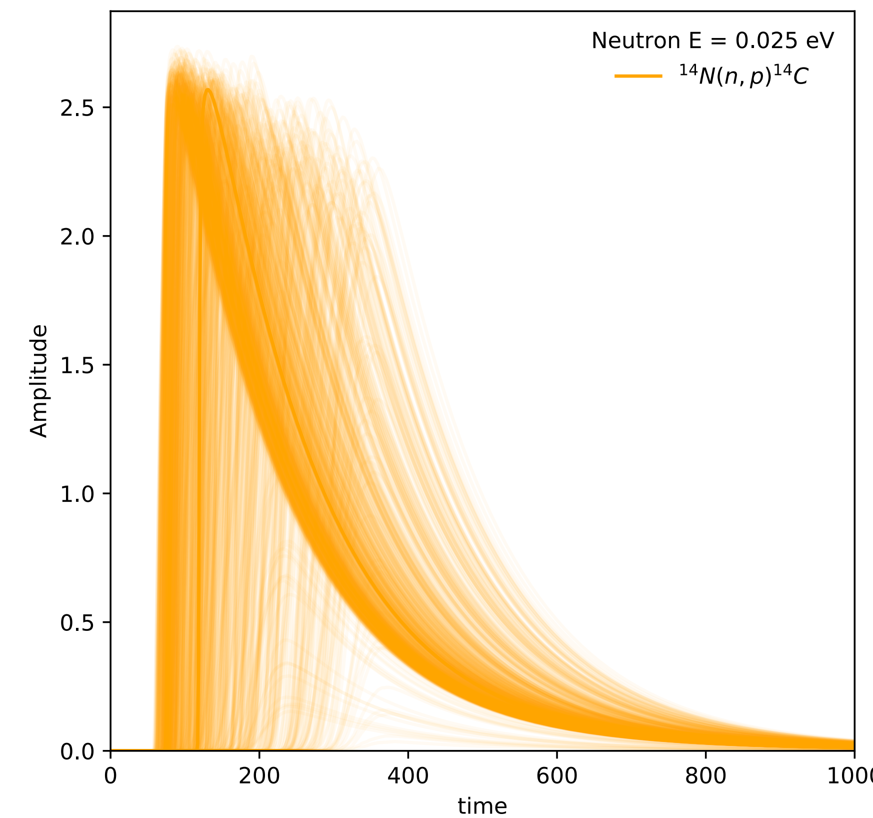
- **Limiting Factors:**
  - Wall effect
  - Sparking/Stability
  - Low pressure operation
  - Impurities
  - Charge collection efficiency

Progress in all fronts!

Simulation of neutron transport

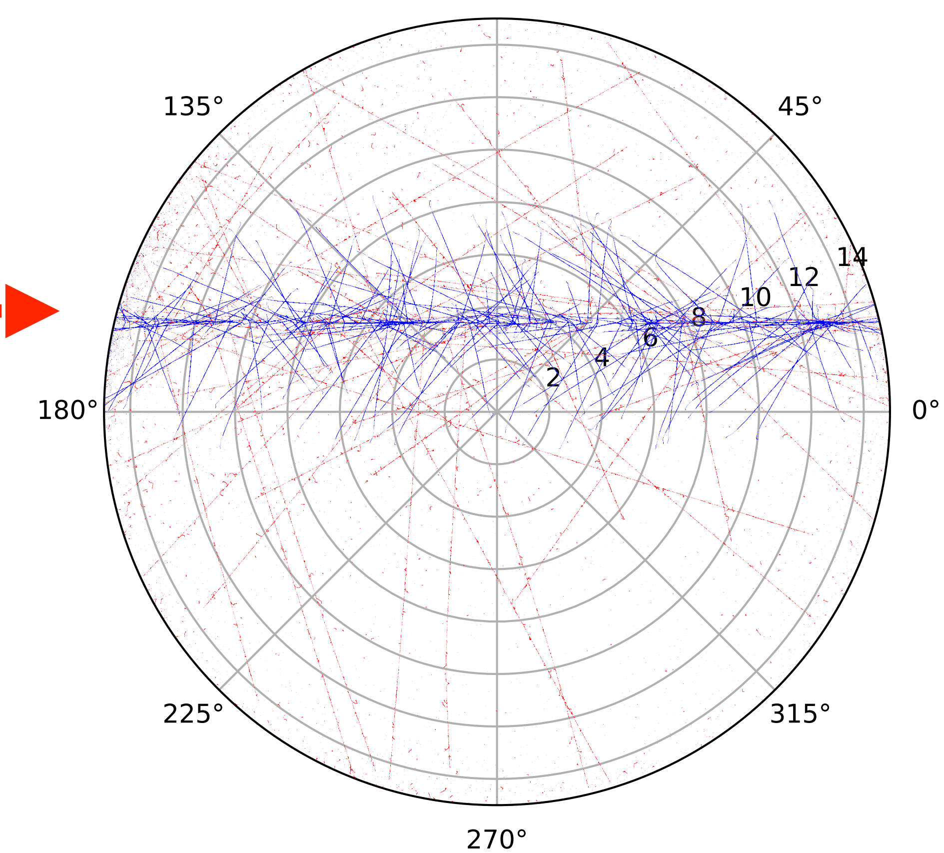
Neutron Beam
0.025 eV

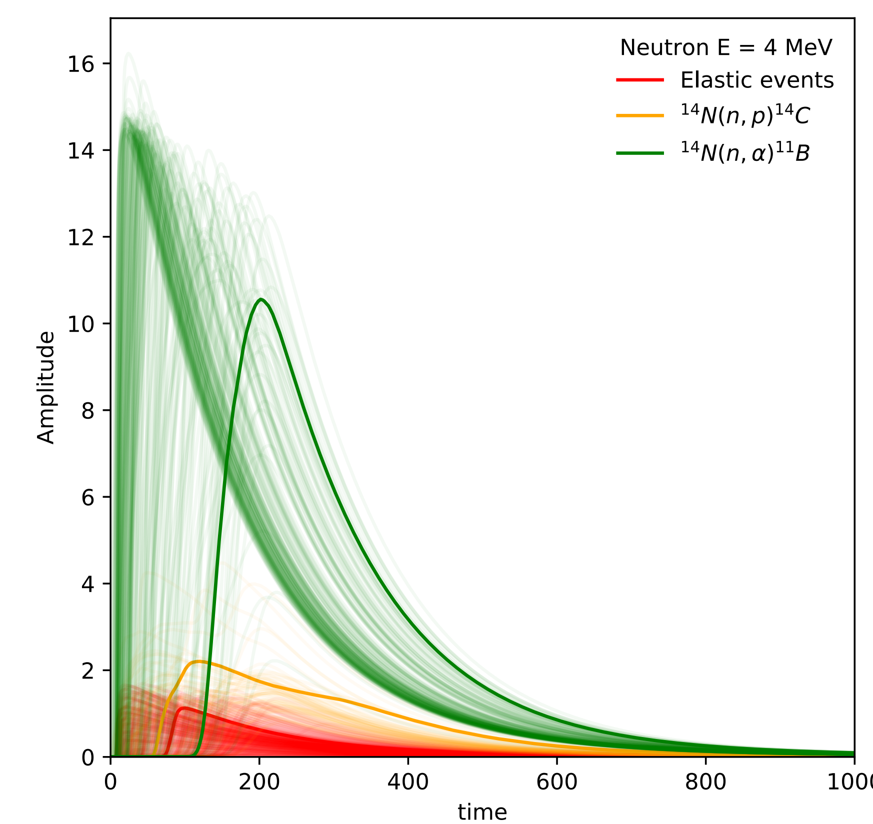




Parameters
Ø30cm vessel
N_2 at 300mbar
Ø2mm anode

Neutron Beam
4 MeV





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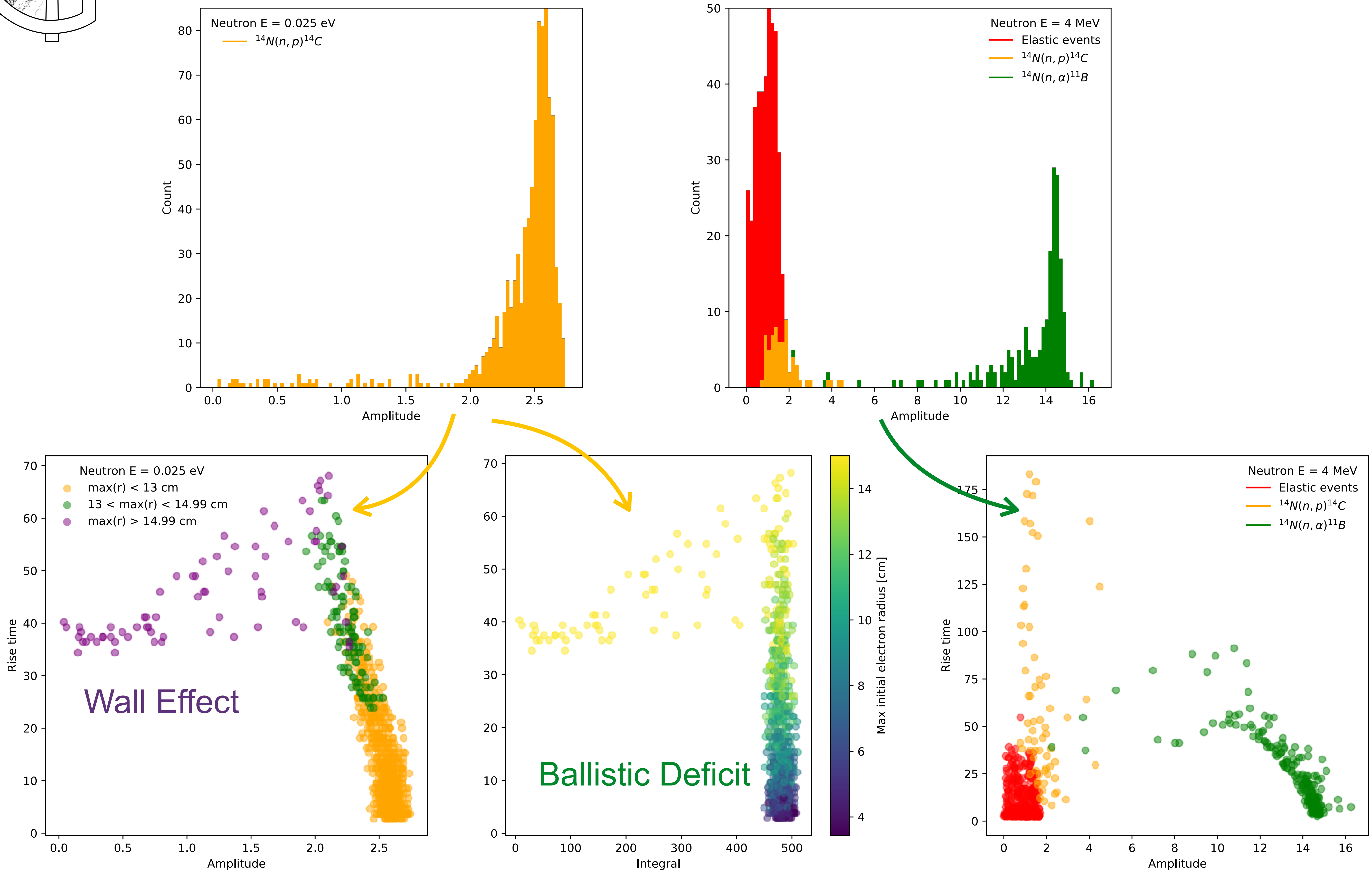
Simulation of neutron transport



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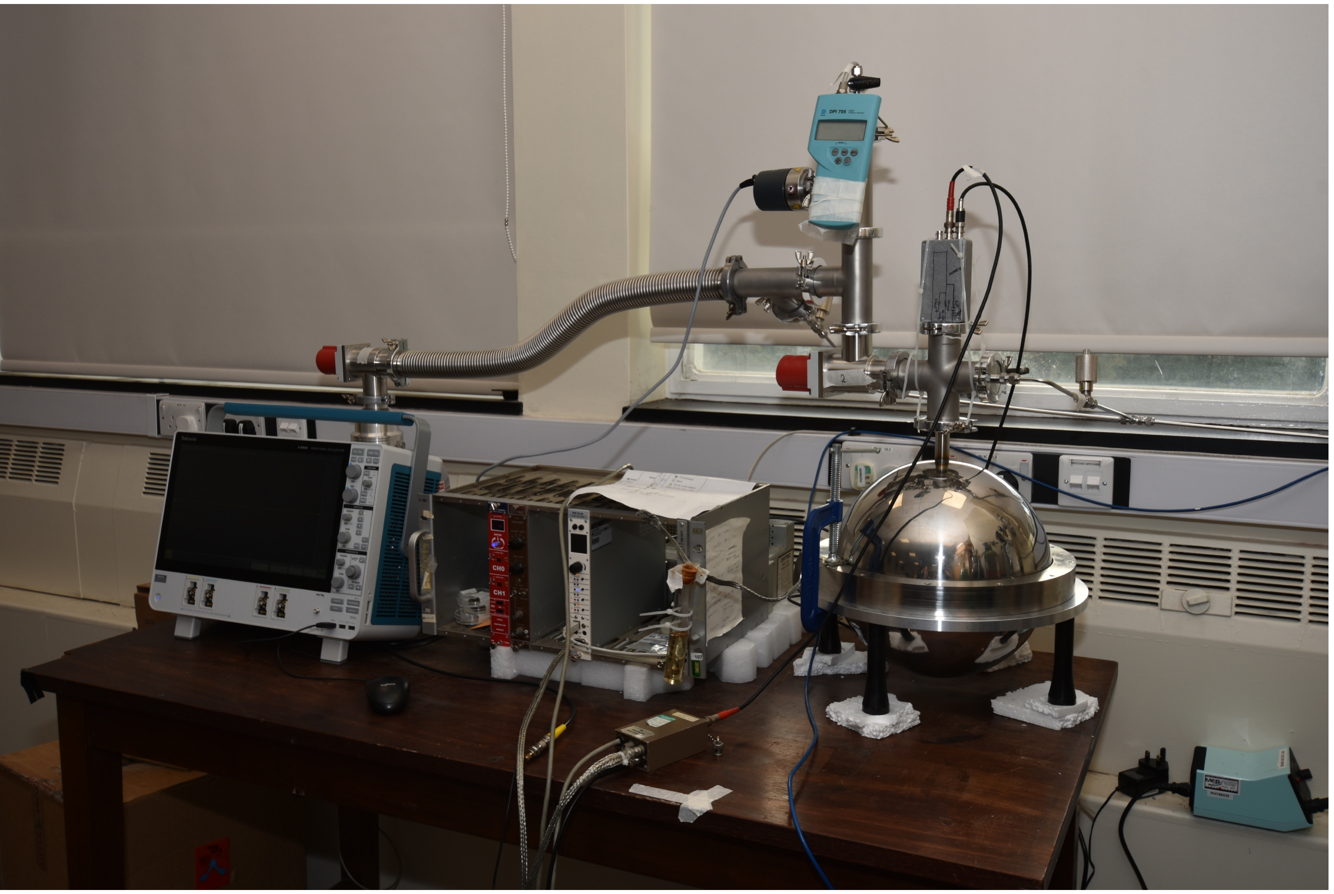
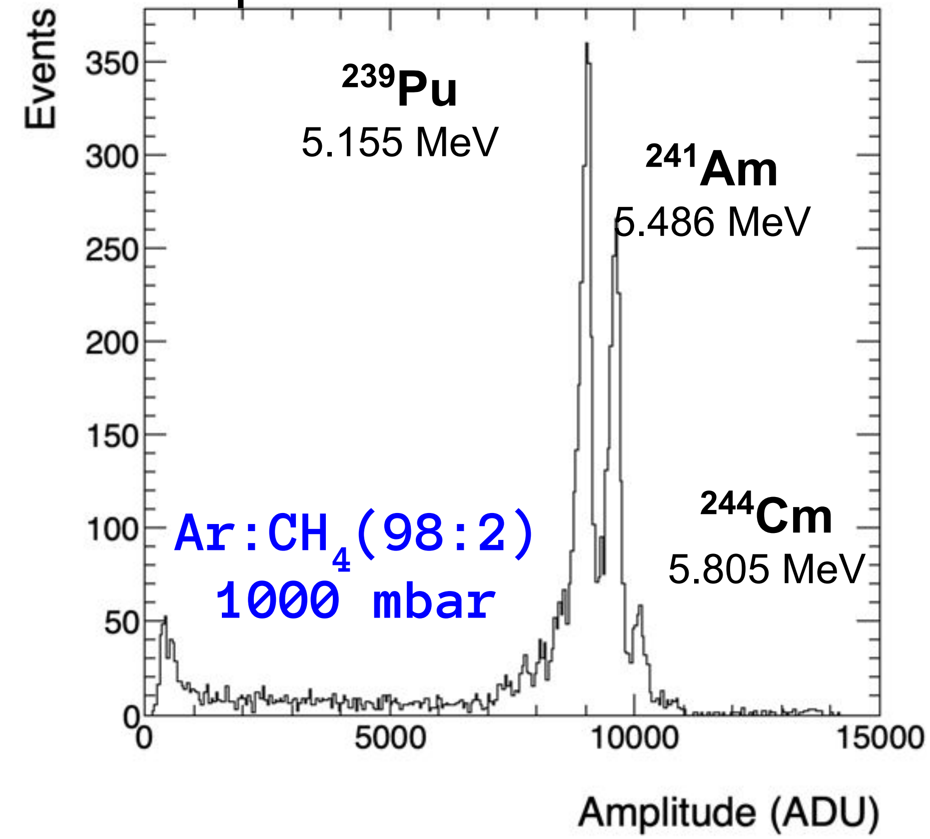
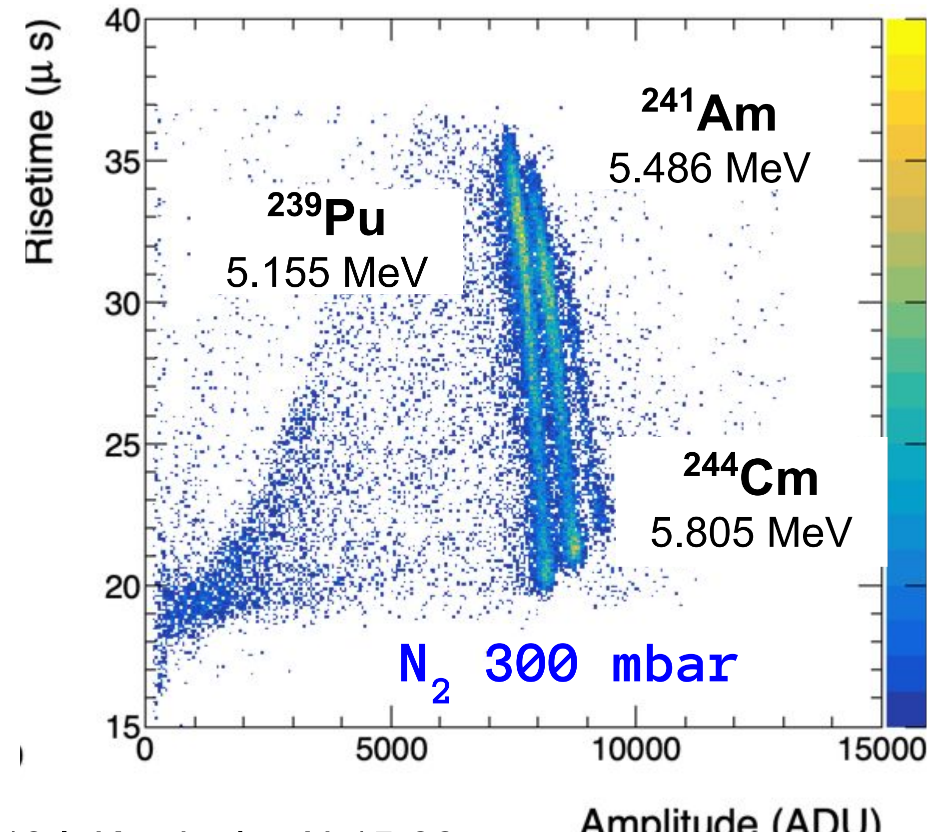
R&D at Birmingham



Triple-α source calibration





Detector Configuration
Ø30cm vessel
Ø3mm anode
SAES MicroTorr Purifier

- Aim to operate at 1-2 bar
  - Minimising wall effect
  - Larger target mass
- Calibraition with mono-energetic neutrons
- Validation of simulations with measurements

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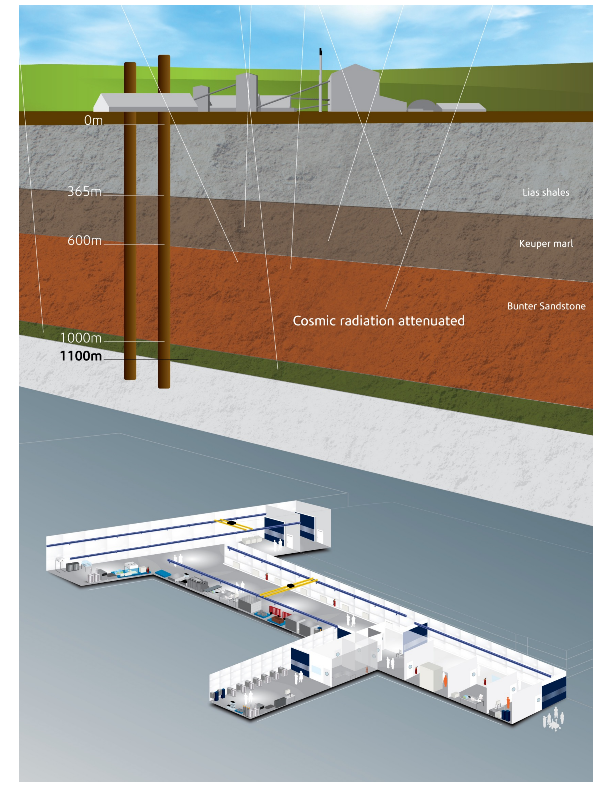
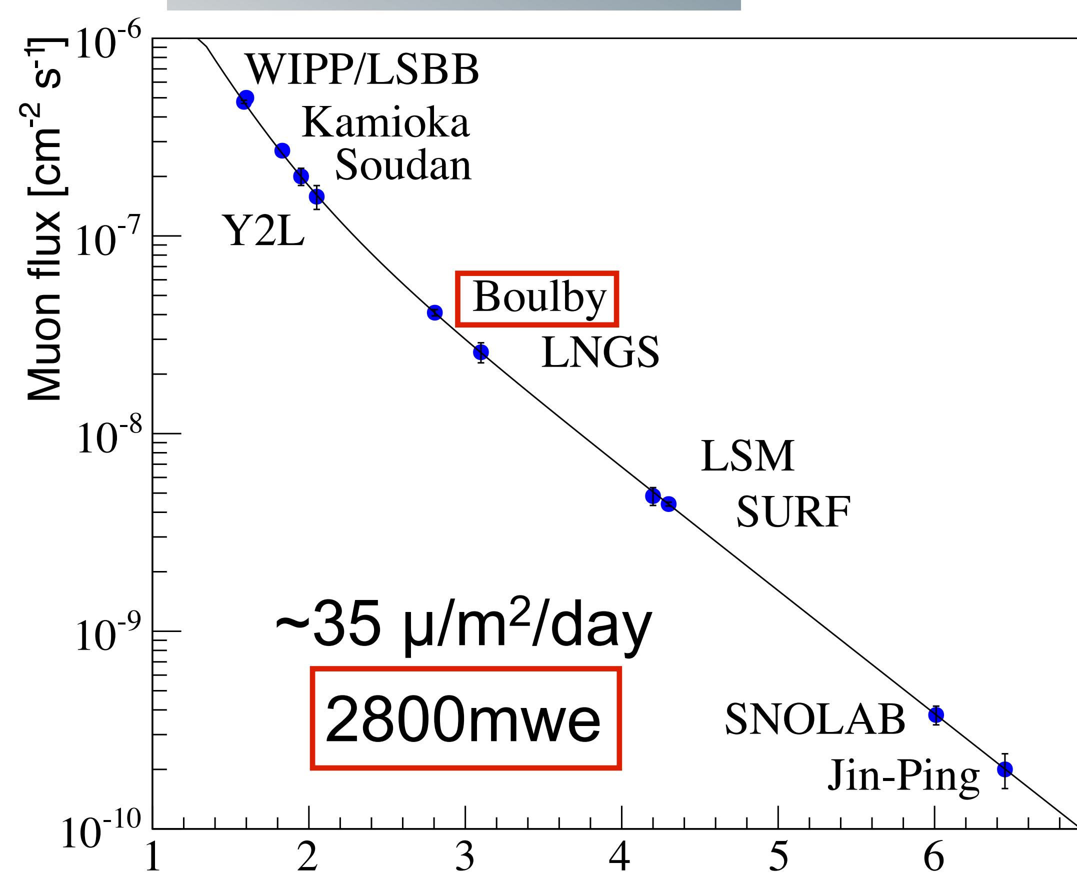
R&D at Boulby





J.Phys. G43 (2016) 013001

R&D at Boulby

- Installing a Ø30cm spherical proportional counter at Boulby
  - scheduled for first week of December 2019
- Aim to measure neutron flux
  - thermal/fast neutrons
  - n/γ discrimination
- This will allow comparison with earlier measurements
  - including energy information
  - methodology applicable to all other underground laboratories
- Also perform instrumentation R&D at controlled environment

Summary

- NEWS-G searches for DM candidates with mass 0.1 – 10 GeV
  - First competitive results with gaseous detector
- SNOglobe sensitivity to light DM
  - Lighter targets
  - Improved shielding/materials/procedure
  - Lower energy threshold
- Sensor Development
  - Improved electric field uniformity
  - ACHINOS: electric field in large detectors
- Improved gas quality: Getter, Recirculation, RGA
- Improved calibration/monitoring: ^{37}Ar, Laser
- Neutron spectroscopy applications!
- Many physics opportunities!

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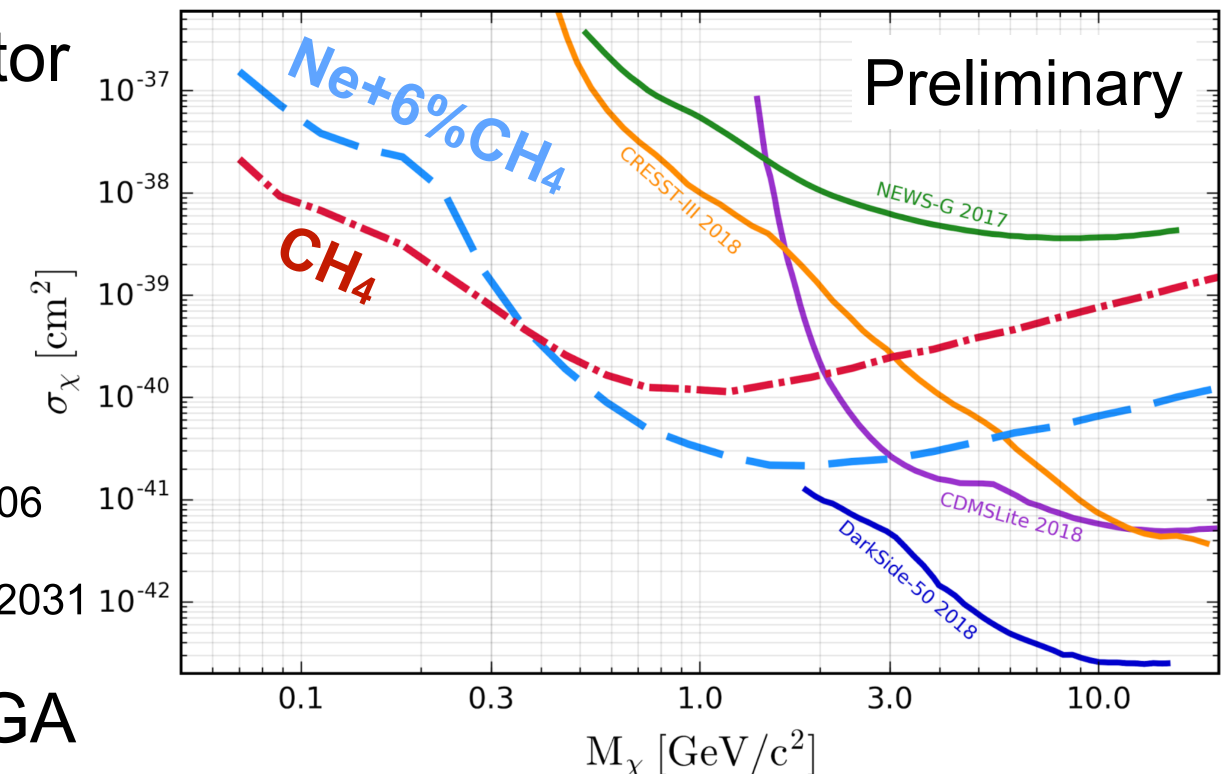
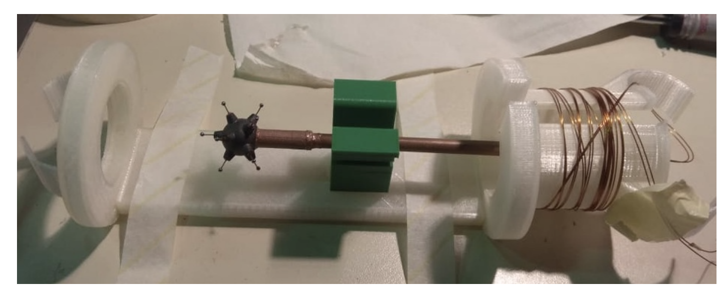
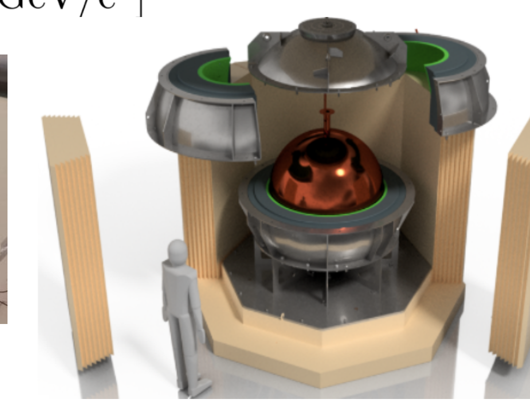
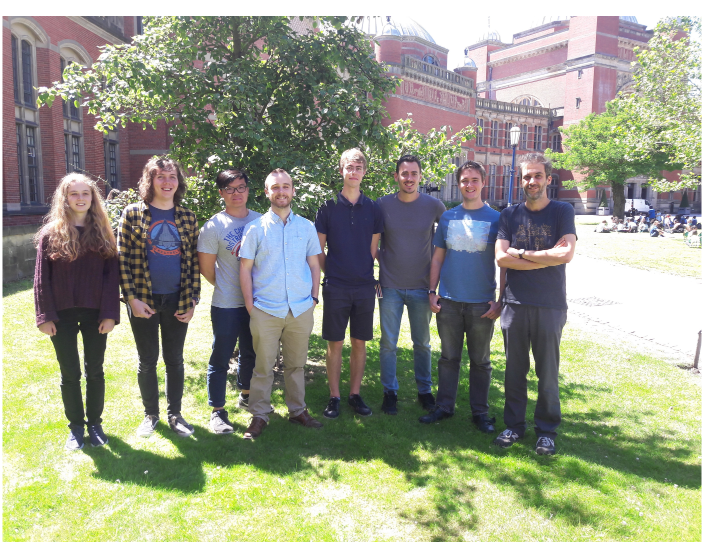


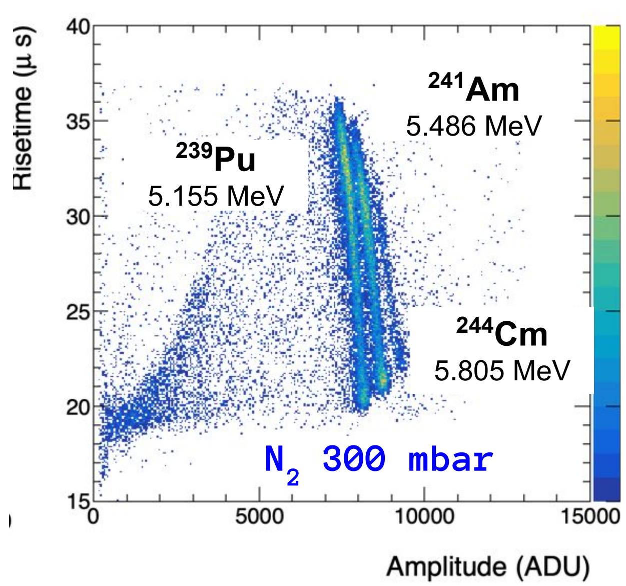
JINST 13 (2018) P11006

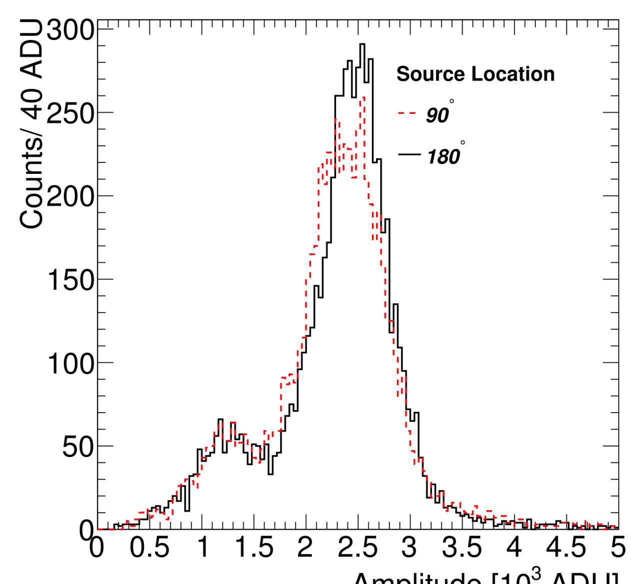
JINST 12 (2017) P12031





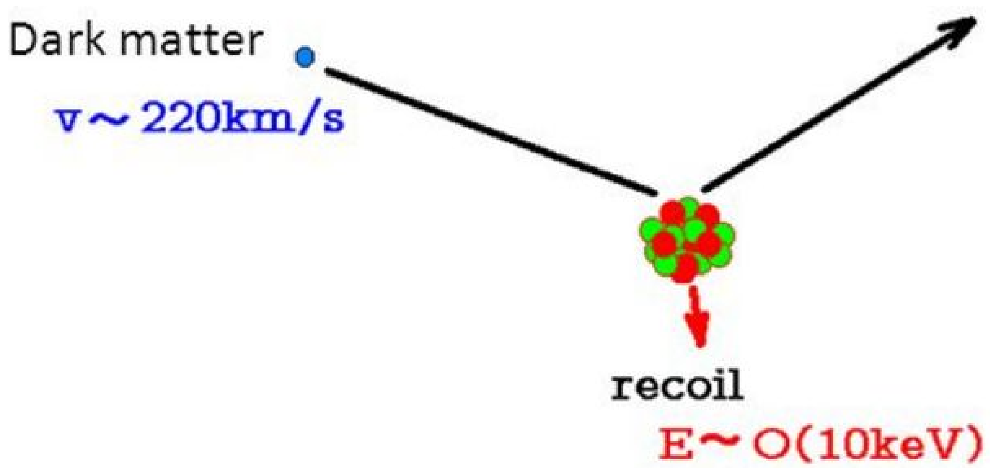






Additional Slides

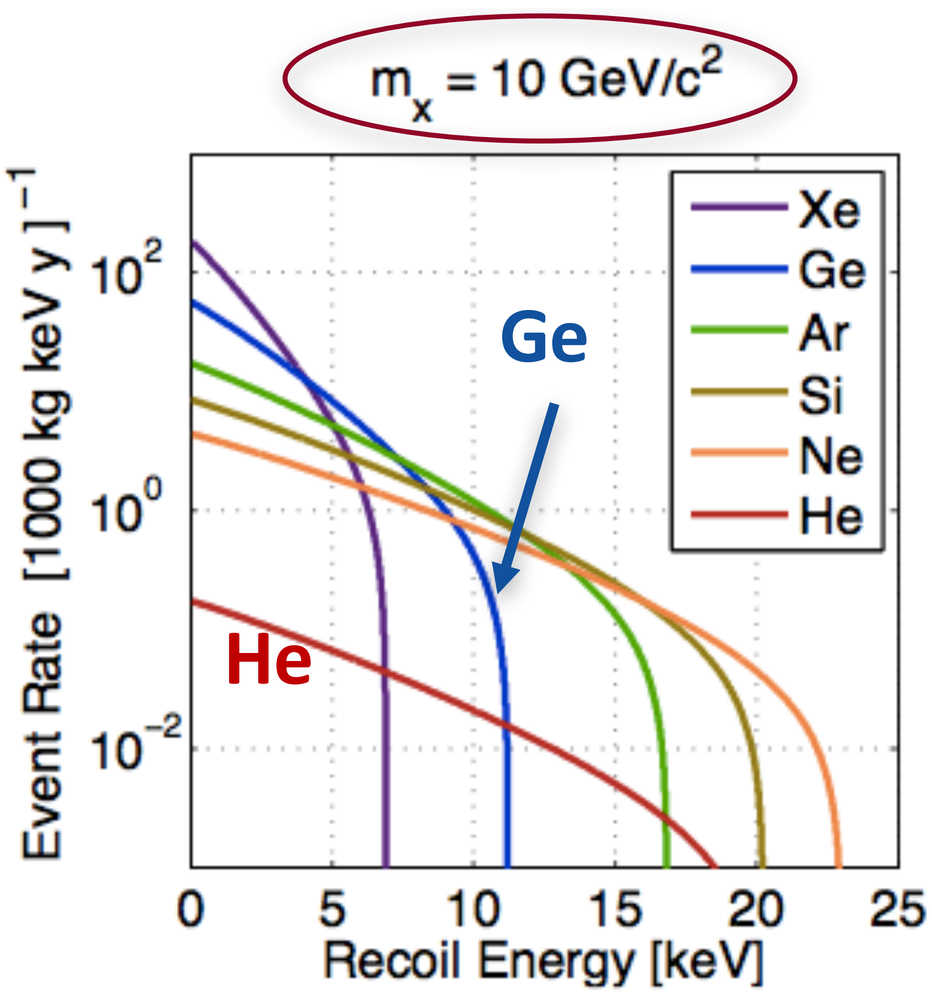
Searching for light DM: Recoil Energy

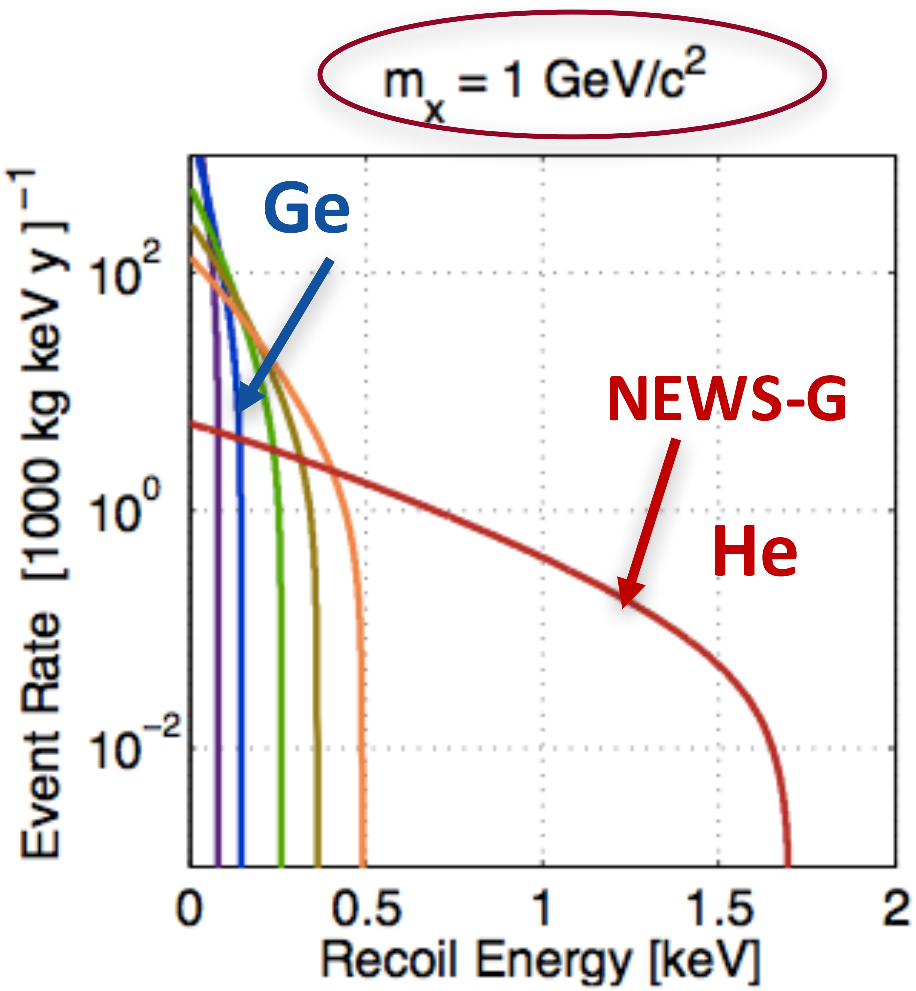


Recoil energy during DM scattering, E_R:

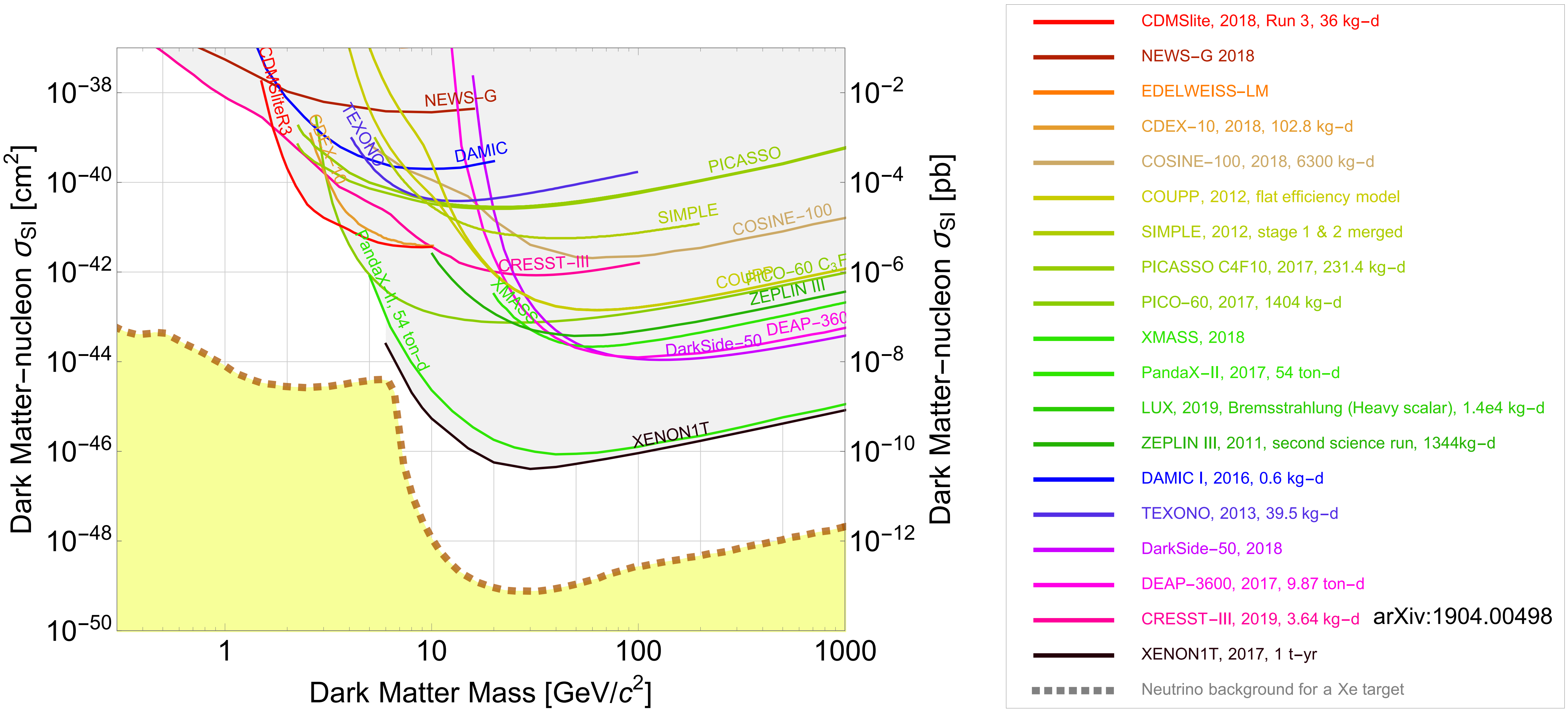
$$E_R = \frac{1}{2} m_\chi u^2 \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} \frac{1 + \cos\theta}{2}$$

max E_R: head-on-collision and $m_\chi = m_N$



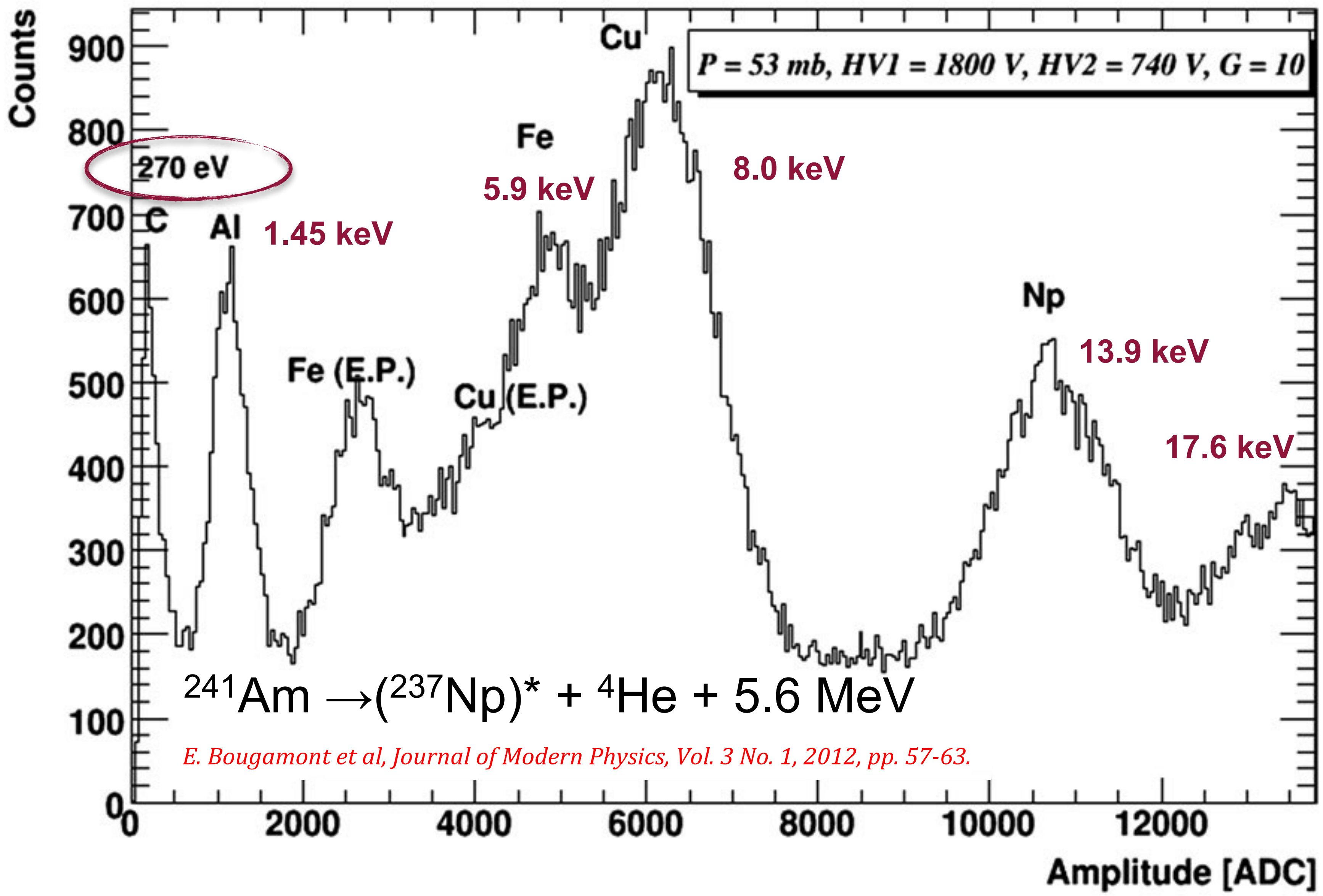


State of the art in Direct DM searches

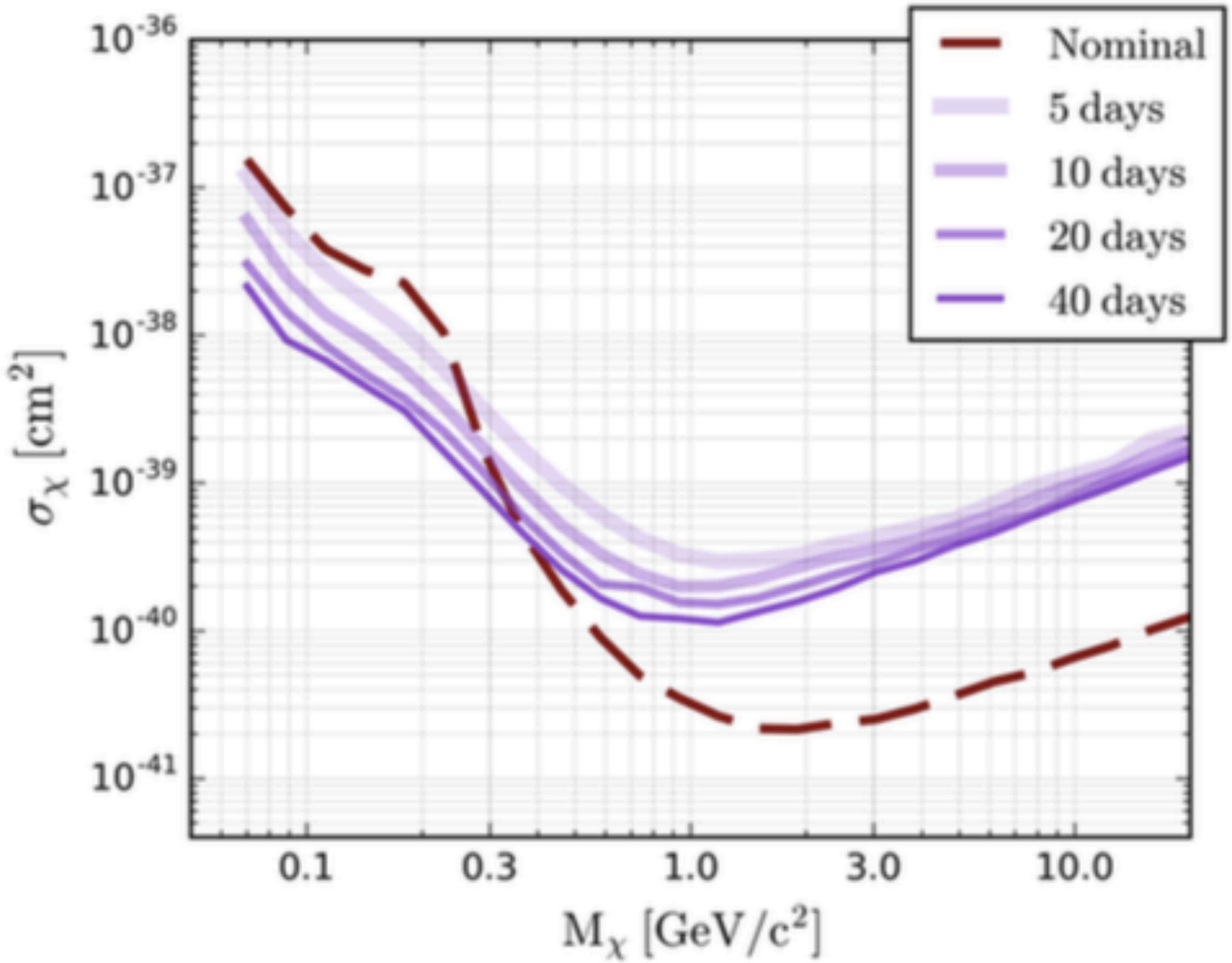


arXiv:1904.00498

Low Energy Capabilities



- Spherical Proportional Counter 130cm diameter
  - Ar + 2% CH_4
- Single Electron detection
- Energy threshold < 50 eV
  - Tested with single electrons extracted from Copper with UV lamp

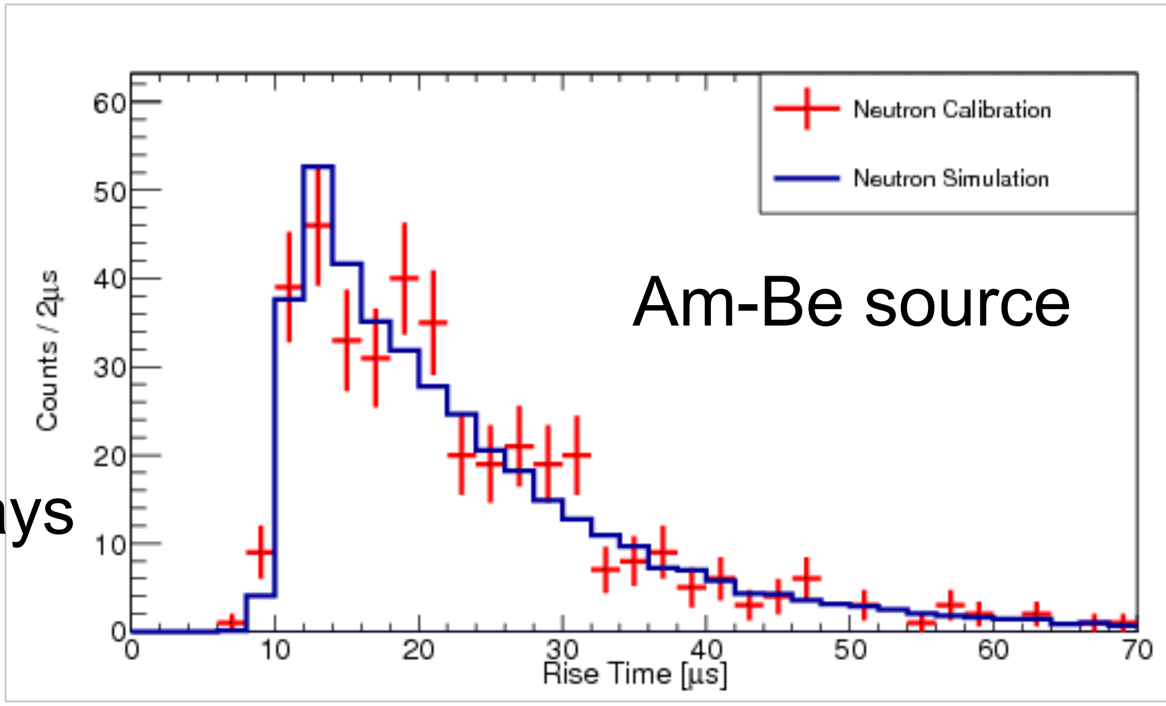


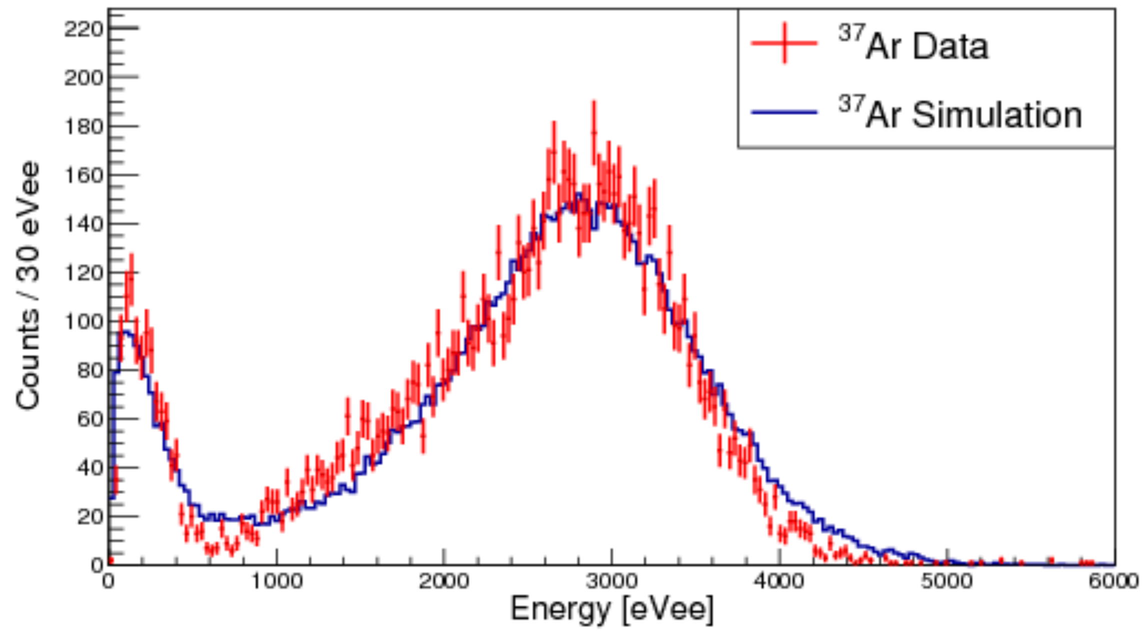
2bar Ne+10% CH4
Flat background,
1.67±0.5
F = 0.2, θ=0.12
SRIM Q
W = 28 eV
14 eV_{ee} -1 keV_{ee}
500 trials

200mbar CH4
Flat background,
3.4±0.5
F = 0.2, θ=0.12
SRIM Q
W = 28 eV
14 eV_{ee} -1 keV_{ee}
500 trials

SEDINE: Data taking conditions

- **Target:** Neon + 0.7% CH_4 at 3.1 bar (282 gr)
- **Run time:** Continuous data taking for 42.7 days
  - **Exposure:** 34.1 live-days x 0.282 kg =9.6 kg.days
- Anode high voltage 2520 V, no sparks
  - Absolute Gain ~3000.
  - Loss of gain 4% throughout the period
- Sealed mode, no recirculation.
- **Read-out:** Canberra charge sensitive preamplifier (τ_{RC}=50 μs)
- **Calibration:** ^{37}Ar gaseous source,8 keV Cu fluorescence line, AmBe neutron source





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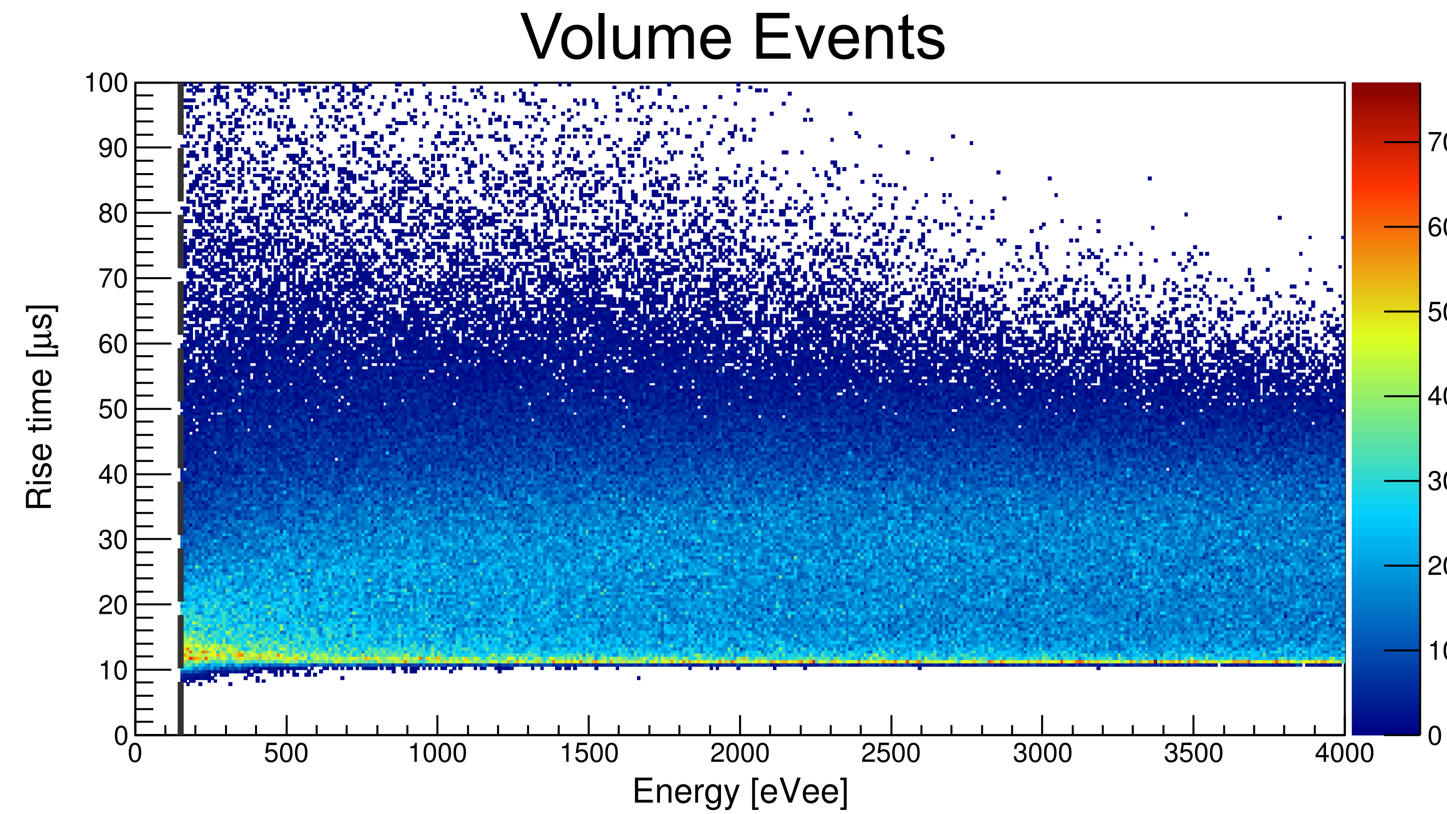
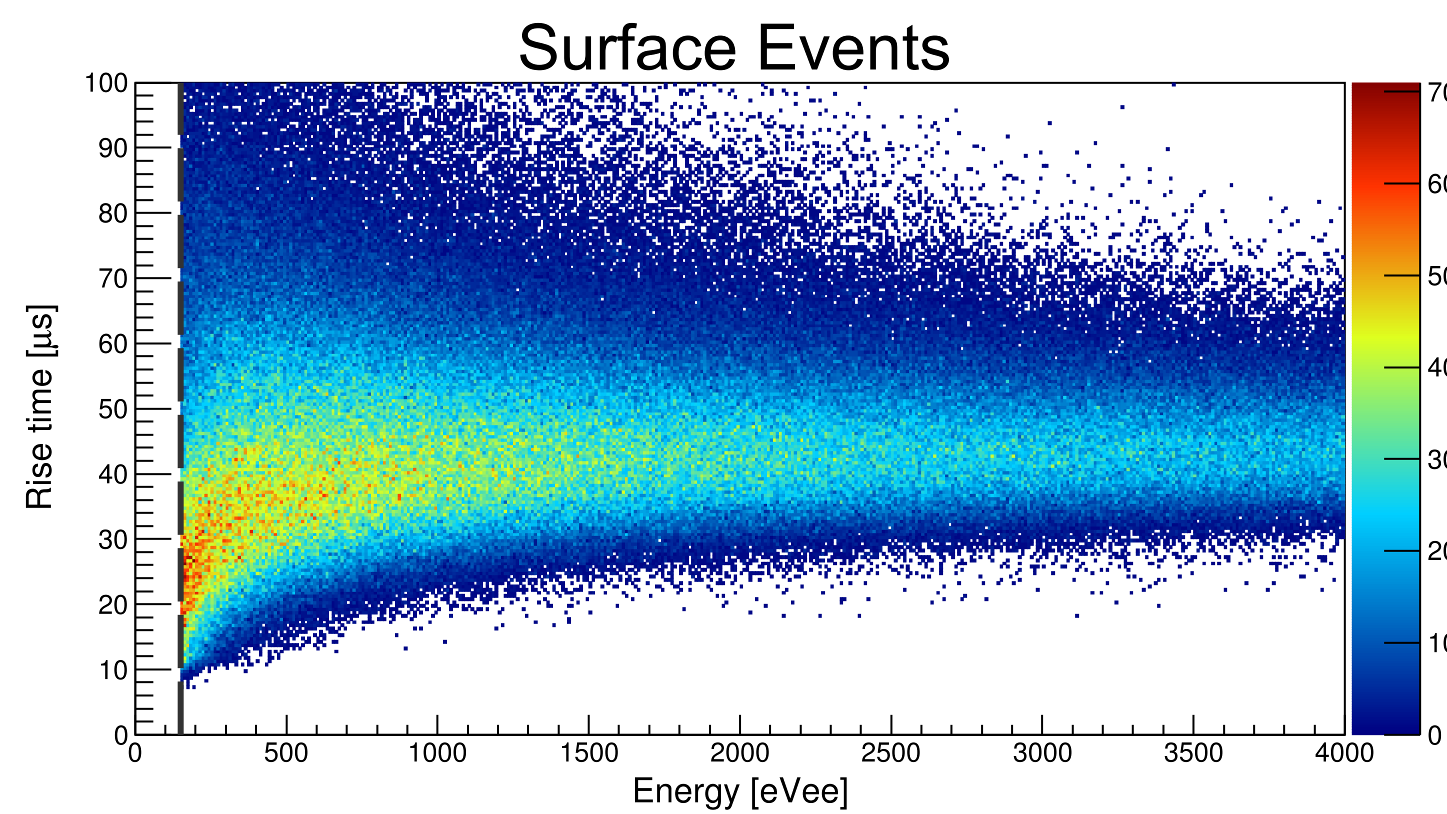
SEDINE: Background simulation

- Anticipated main backgrounds:
  - Volume: Compton electrons
    - ^{208}Tl and ^{40}K in the rock
    - ^{238}U, ^{232}Th, and ^{60}Co copper shell/shielding
  - Surface: Radon decay products
  - Chemical Cleaning (nitric acid)
    - >200eV: 180 mHz → ~2mHz
    - <200eV: 400 mHz → ~20mHz
- Pulse simulations include:
  - Electric field (FEM)
  - Diffusion (Magboltz)
  - Avalanche process
  - Signal induction
  - Preamplifier response





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SEDINE: Event Selection

- Analysis threshold: 150 eVee (~720 eVnr)
- 100% trigger efficiency (threshold @ ~35 eVee)
- Optimised Signal Region determined with Boosted Decision Tree (8 candidate masses)
- 1620 events selected in preliminary ROI
  - Failed BDT
  - Pass 0.5 GeV BDT: 15 events
  - Pass 16 GeV BDT: 123 events
  - Pass BDT for other masses