THE UNIVERSITY *of* EDINBURGH
School of Physics
& Astronomy

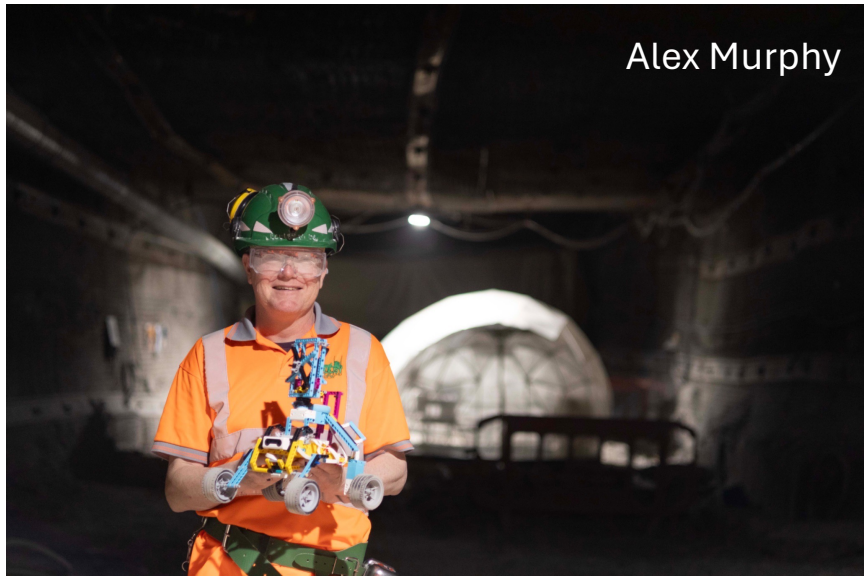
Science and
Technology
Facilities Council

Boulby Underground
Laboratory

Edinburgh-Boulby PhD

Dark matter, new physics & radioassay at the Boulby Mine

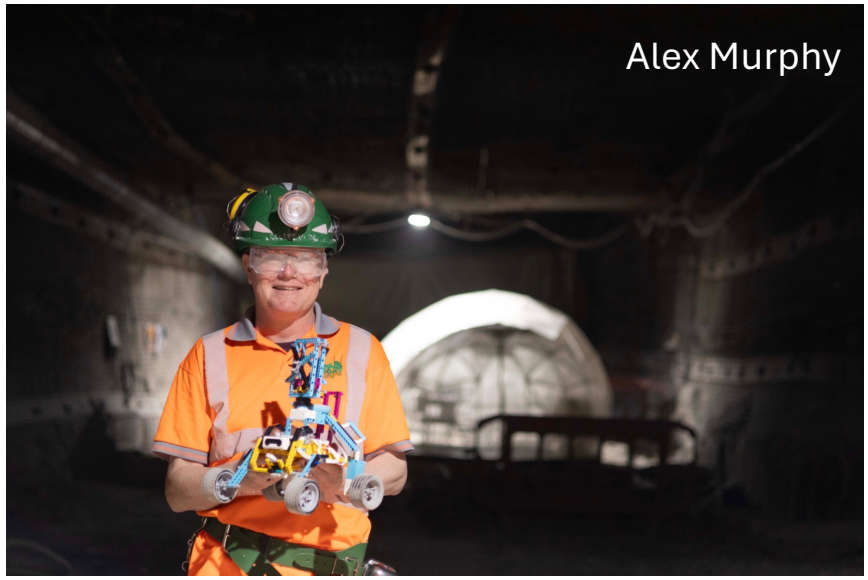
The team



NAIAD, ZEPLIN I, II, III (Boulby)
LUX, LZ, XLZD (SURF)
Deputy Head of School
Director of Public Engagement
Previously many STFC Committees, etc…

Division Leader
Director Boulby Mine
Whole Boulby science programme…

The team



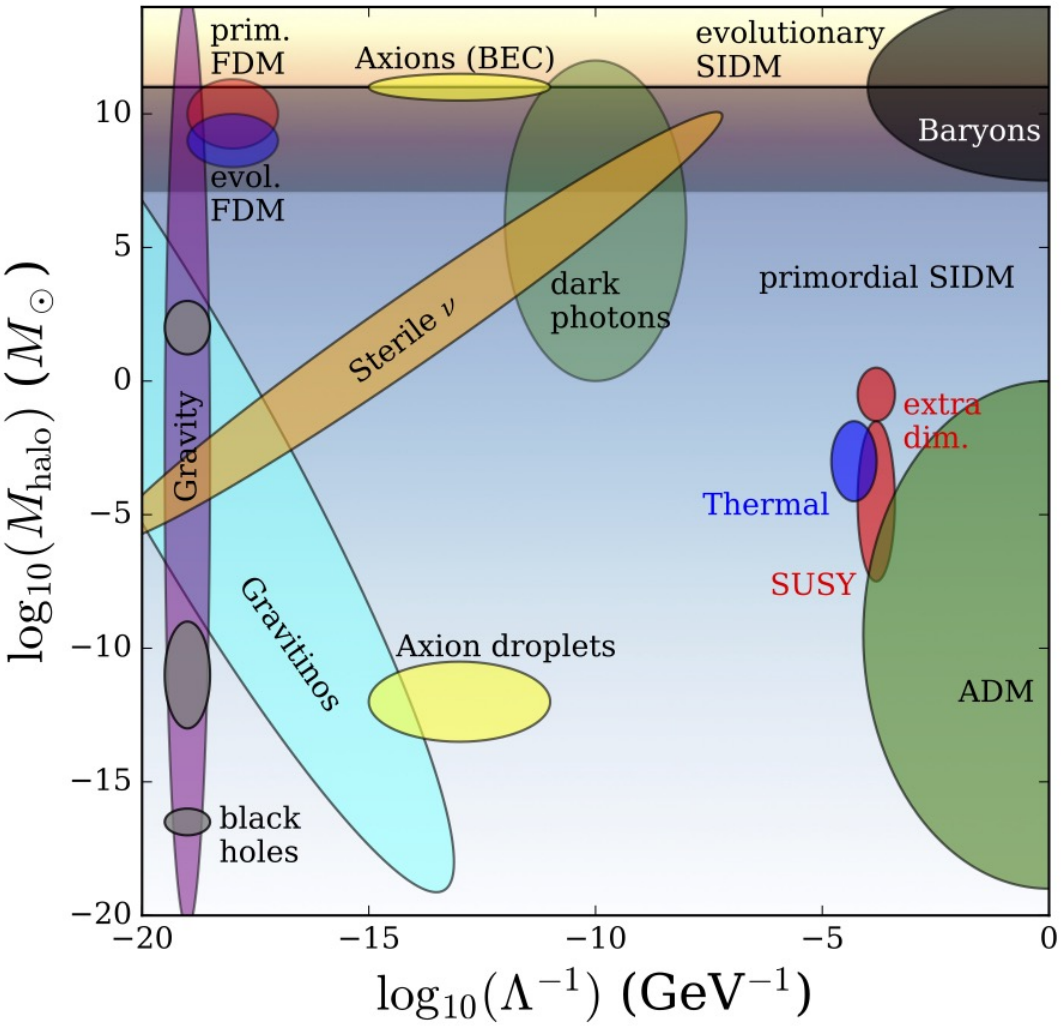
+ STFC Boulby Mine
+ University of Edinburgh Particle Physics
+ Scottish Graduate School in Physics (SUPA)

University of Aberdeen
University of Dundee
The University of Edinburgh
University of Glasgow
Heriot-Watt University
University of St Andrews
University of Strathclyde Glasgow
University of the West of Scotland UWS

Beyond WIMPs!

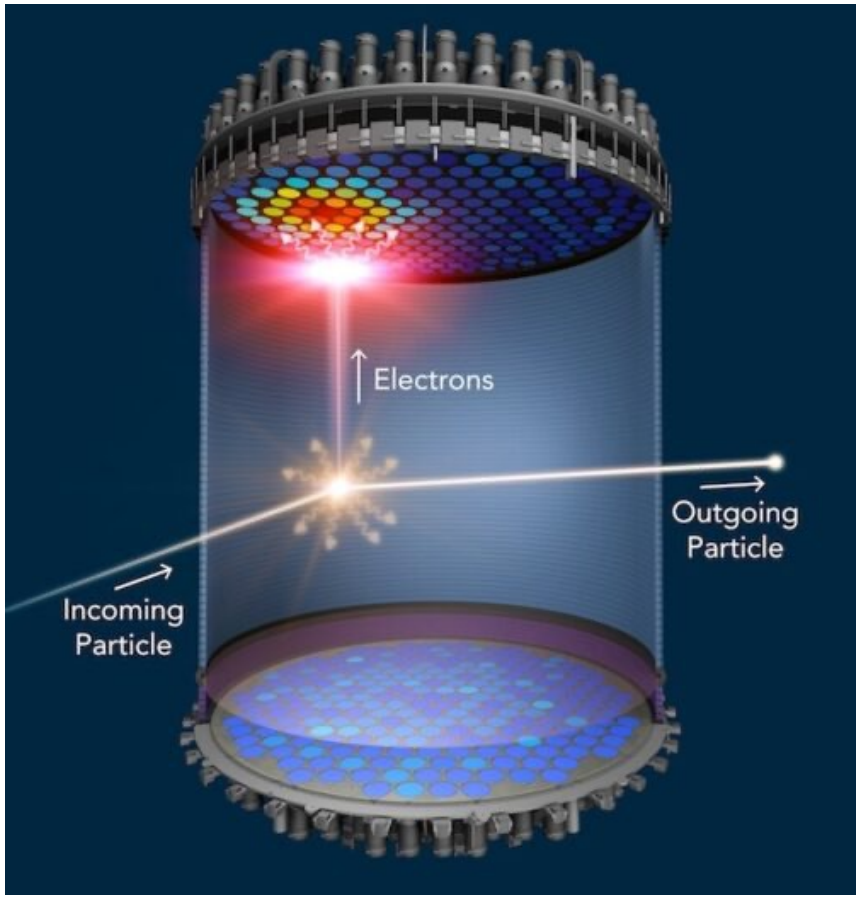
Of the many possibilities…

- Solar axion electric coupling
- Electron couplings to galactic axion-like particles
- Solar neutrino magnetic moment
- Solar neutrino millicharge
- Hidden photons
- Mirror dark matter
- …
- …



e.g. PHYSICAL REVIEW D 108, 072006 (2023)

The (very) basics…



Events generate <u>two</u> signals

- S1
  - A flash of photons from the initial scatter
- S2
  - Electrons liberated from the scatter drift to surface in applied E field
  - Cross from liquid to gaseous Xe
  - Generate second flash of light in the gas

The (very) basics...

Plot S2 vs S1

The (very) basics…

Plot S2 vs S1

- The detector is made of Xe atoms: a nucleus surrounded by electrons (!)
- Incoming particles could scatter from electrons or from nuclei

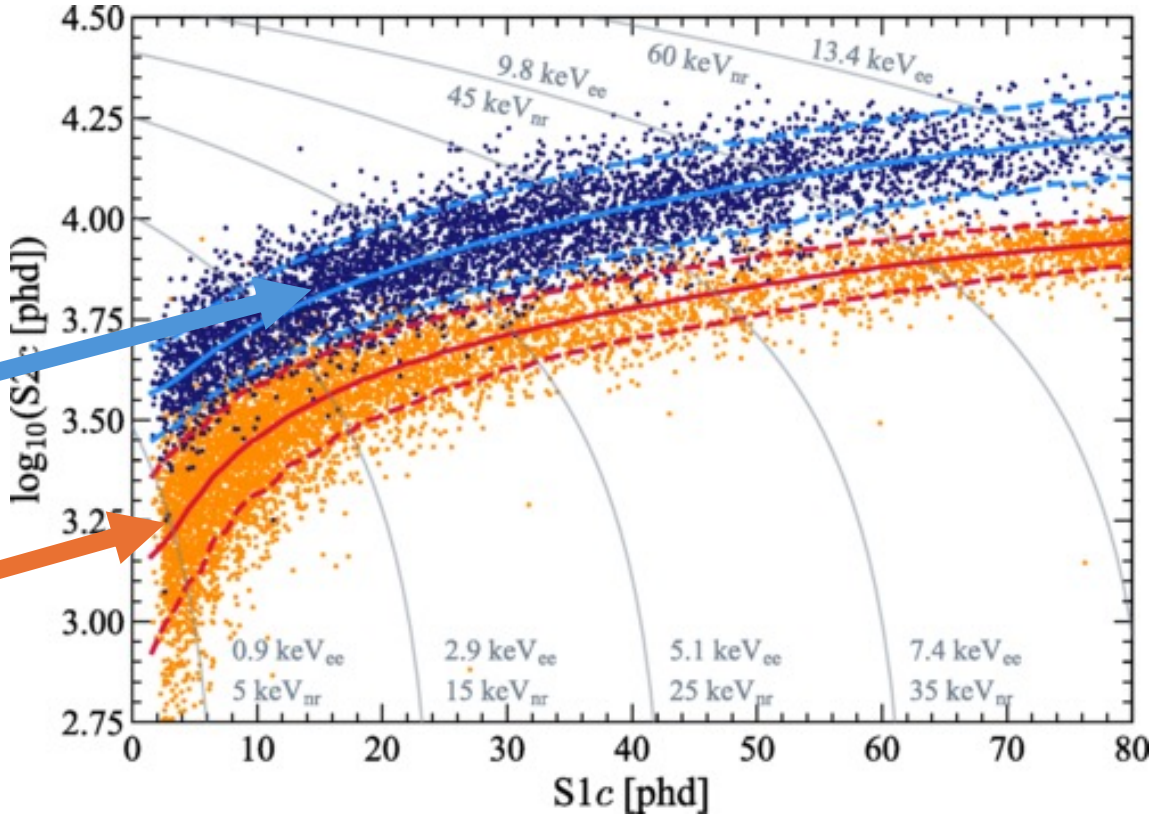
The (very) basics...

Phys. Rev. Lett. 131, 041002 (*First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment*)

Plot S2 vs S1

- The detector is made of Xe atoms: a nucleus surrounded by electrons (!)
- Incoming particles could scatter from electrons or from nuclei

- Blue data: tritium source (generating **electrons**)
- Orange data are from a DD **neutrons**

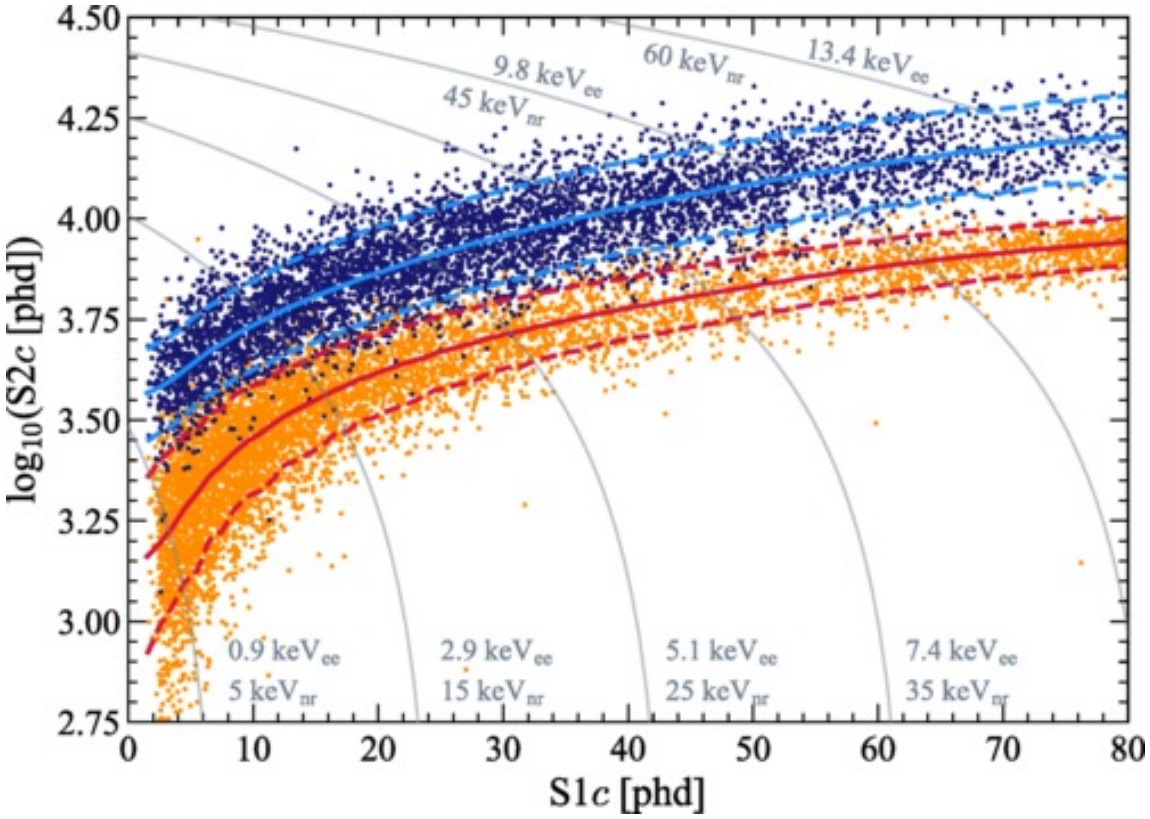


The (very) basics…

Plot S2 vs S1

- Axions, hidden photons, mirror dark matter… are expected to scatter from electrons

Phys. Rev. Lett. 131, 041002 (*First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment*)

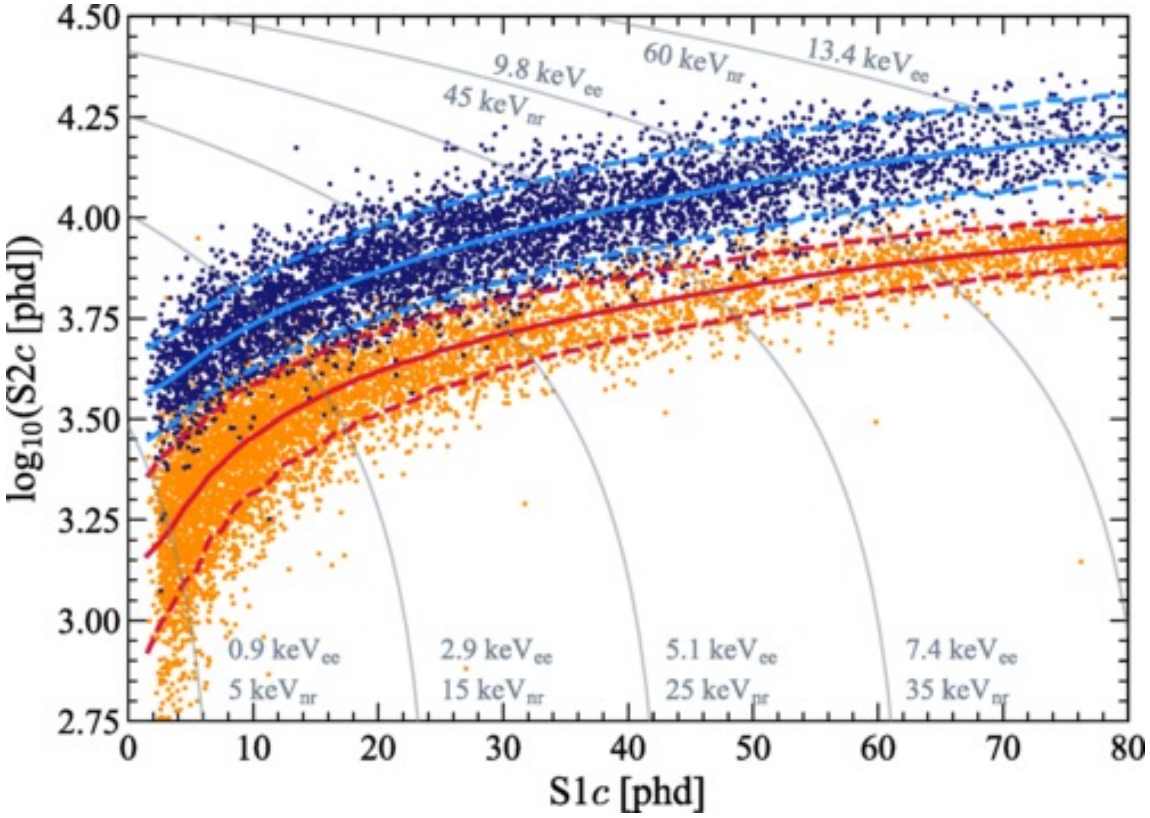


The (very) basics...

Plot S2 vs S1

- Axions, hidden photons, mirror dark matter... are expected to scatter from electrons
- WIMPs are expected to scatter from Xe nuclei

Phys. Rev. Lett. 131, 041002 (*First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment*)



The (very) basics…

Plot S2 vs S1

- Axions, hidden photons, mirror dark matter… are expected to scatter from electrons

- WIMPs are expected to scatter from Xe nuclei

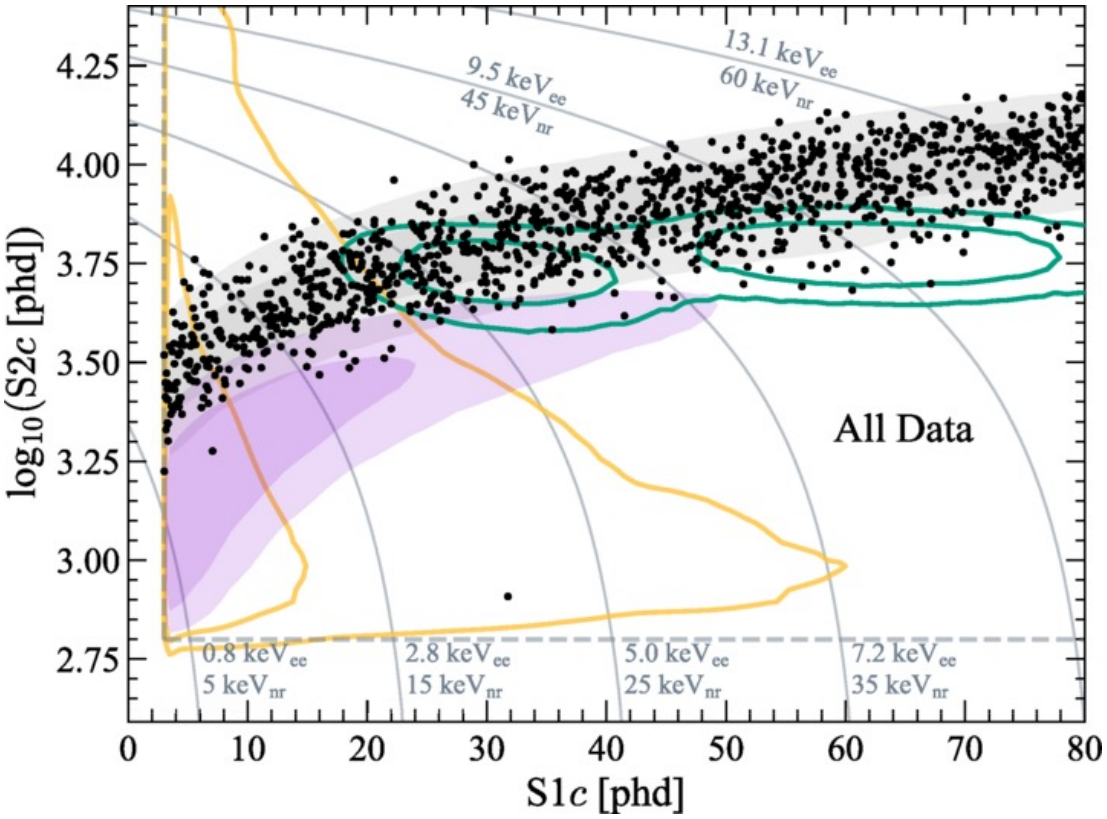
- Take the radioactive calibration sources away… what do we see?

The (very) basics…

Plot S2 vs S1

- Axions, hidden photons, mirror dark matter… are expected to scatter from electrons
- WIMPs are expected to scatter from Xe nuclei
- Take the radioactive calibration sources away… what do we see?

Phys. Rev. Lett. **135**, 011802 (*Dark Matter Search Results from 4.2 Tonne−Years of Exposure of the LUX-ZEPLIN (LZ) Experiment*) - Current worked leading results!



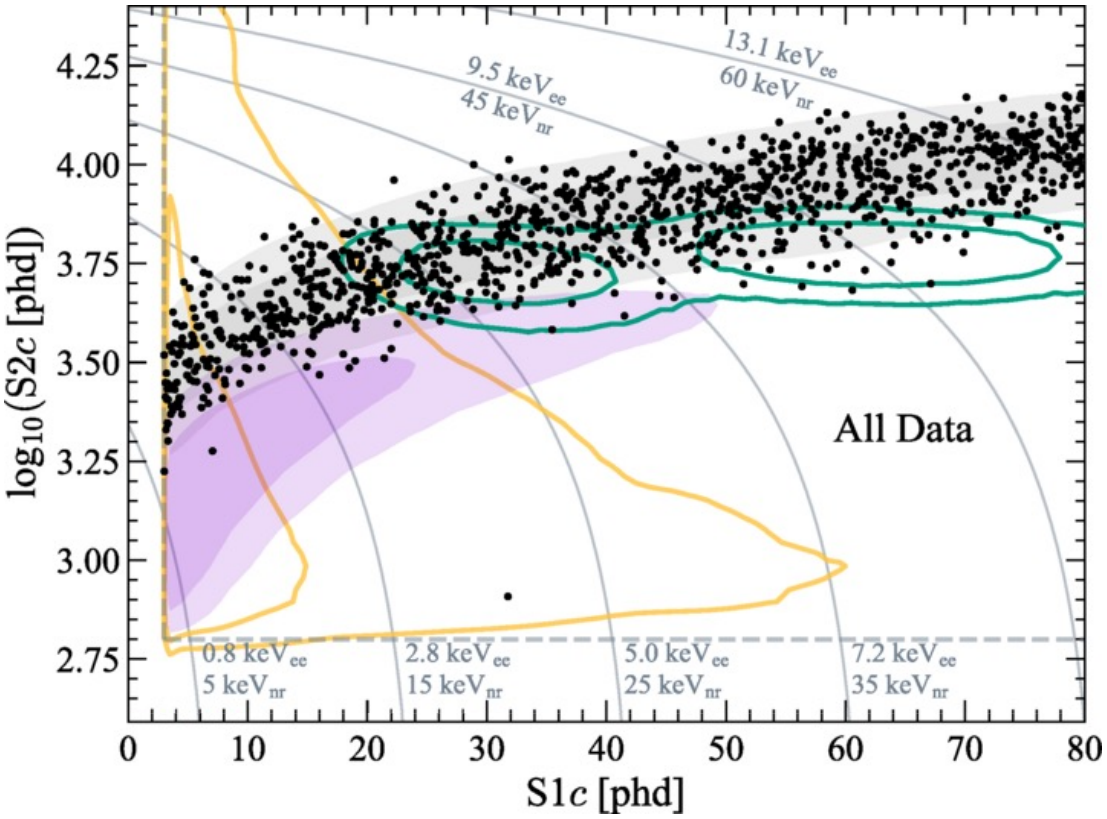
The (very) basics...

Plot S2 vs S1

- We see ‘lots’ of electron recoils

- We see very few nuclear recoils

Phys. Rev. Lett. **135**, 011802 (*Dark Matter Search Results from 4.2 Tonne−Years of Exposure of the LUX-ZEPLIN (LZ) Experiment*) - Current worked leading results!



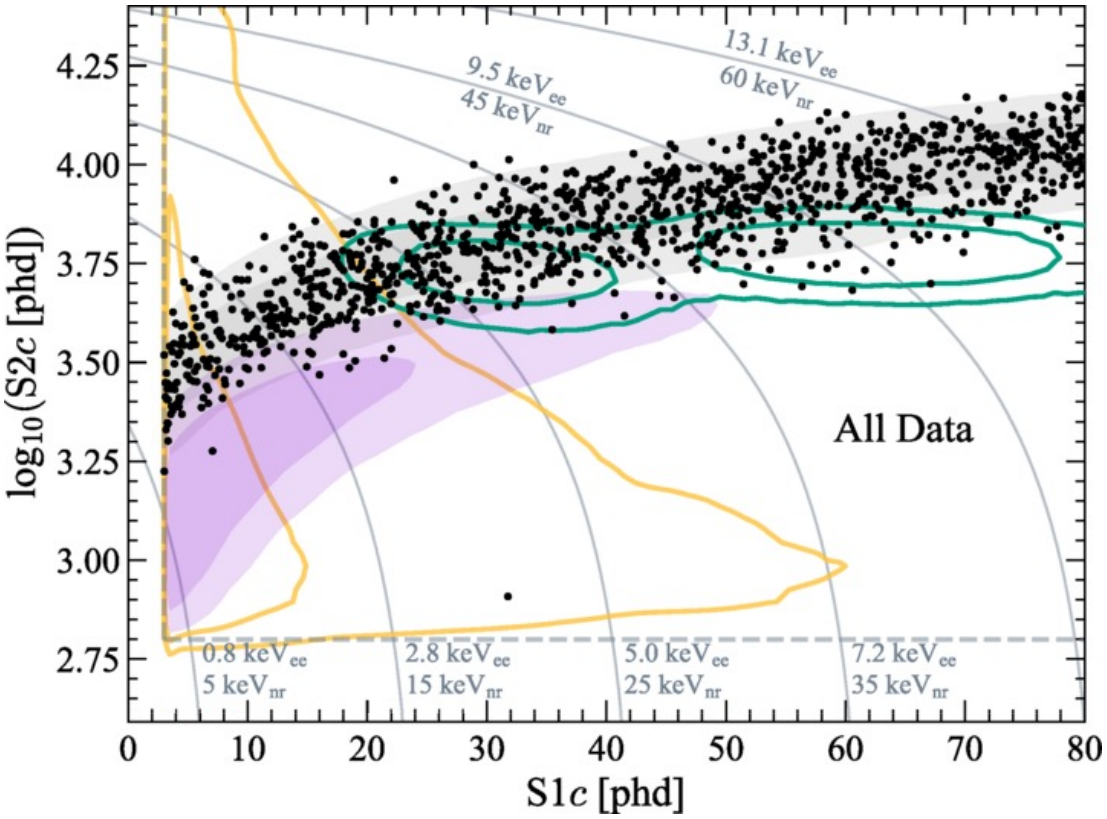
The (very) basics...

Plot S2 vs S1

- We see ‘lots’ of electron recoils
  → we can explain them all
  from expected backgrounds

- We see very few nuclear recoils
  → we can explain them all
  from expected backgrounds

Phys. Rev. Lett. **135**, 011802 (*Dark Matter Search Results from 4.2 Tonne−Years of Exposure of the LUX-ZEPLIN (LZ) Experiment*) - Current worked leading results!



The (very) basics...

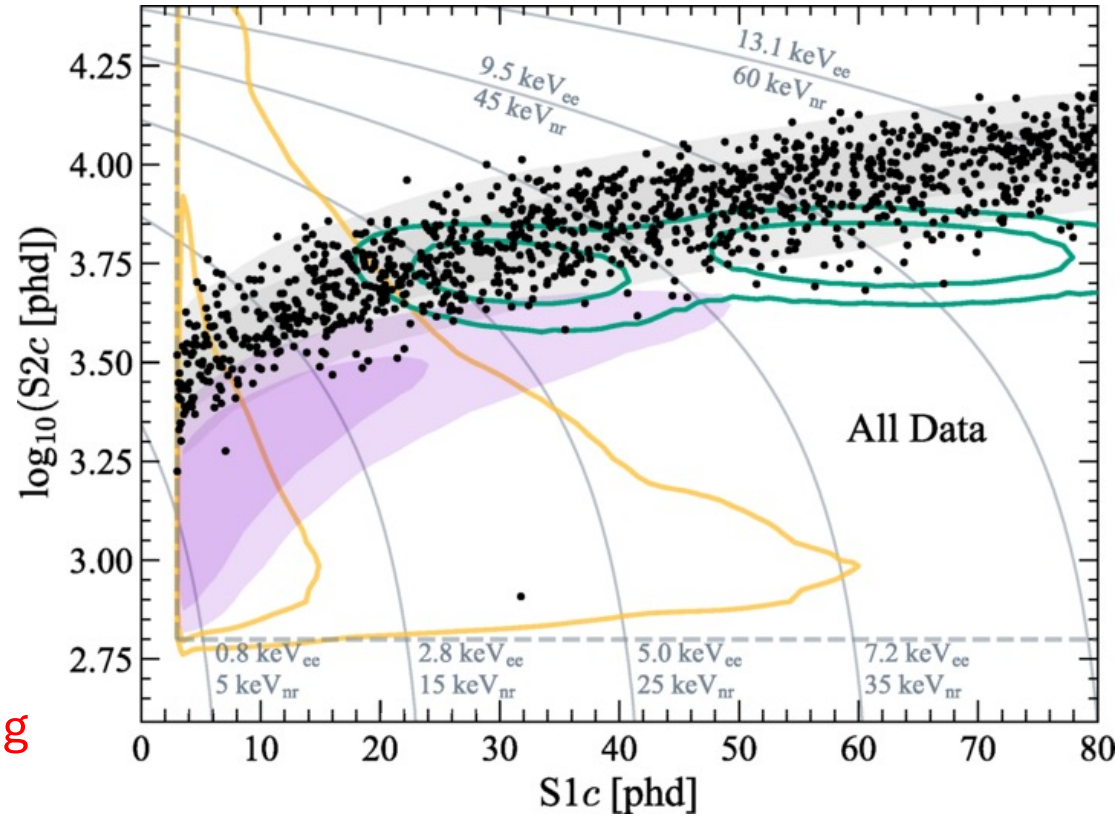
Plot S2 vs S1

- We see ‘lots’ of electron recoils
  → we can explain them all
  from expected backgrounds

- We see very few nuclear recoils
  → we can explain them all
  from expected backgrounds

World-leading results in both cases.
Understanding and **getting rid** of backgrounds is most critical for improving electron recoil searches

Phys. Rev. Lett. **135**, 011802 (*Dark Matter Search Results from 4.2 Tonne−Years of Exposure of the LUX-ZEPLIN (LZ) Experiment*) - Current worked leading results!

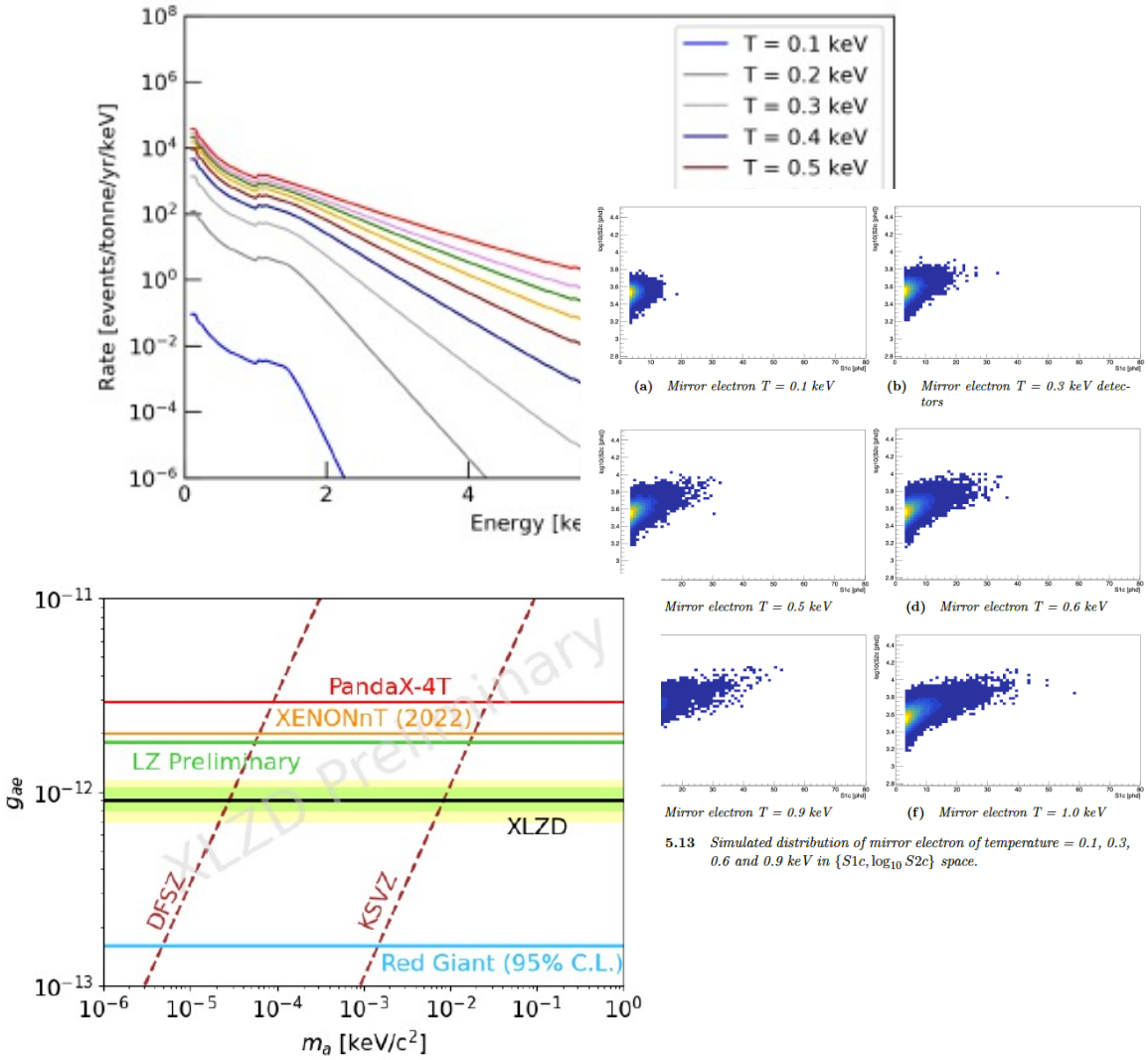


The (very) basics…

Things to do…

- What event rates (spectra) do we expect for the various physics models?
  (given the design of XLZD)

- Consider more of the many possibilities yet to be explored…



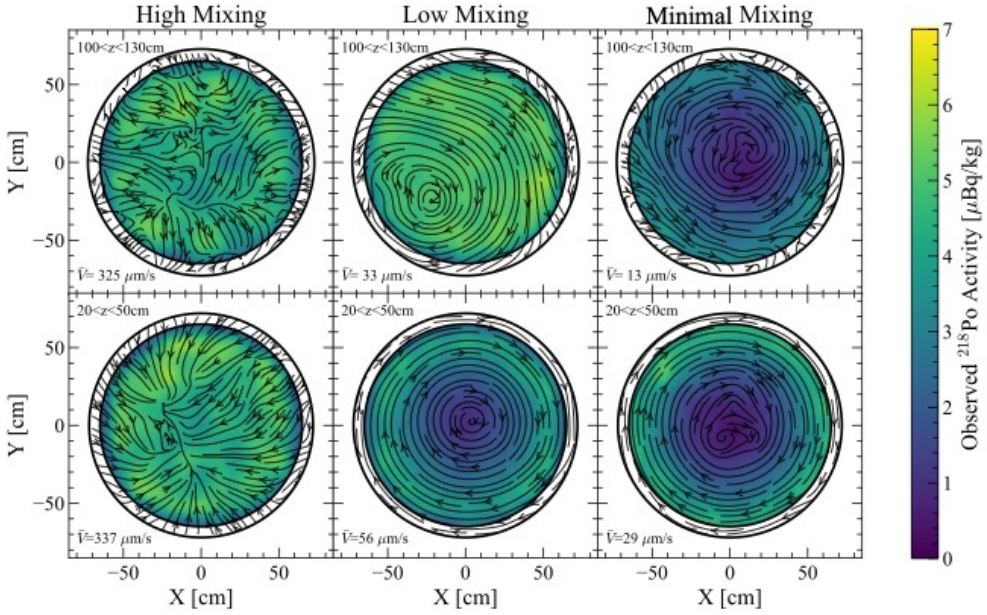
The (very) basics...

Things to do...

- What backgrounds do we expect from known sources?
  (given the design and location of XLZD)

- What can we do to reduce or mitigate these?

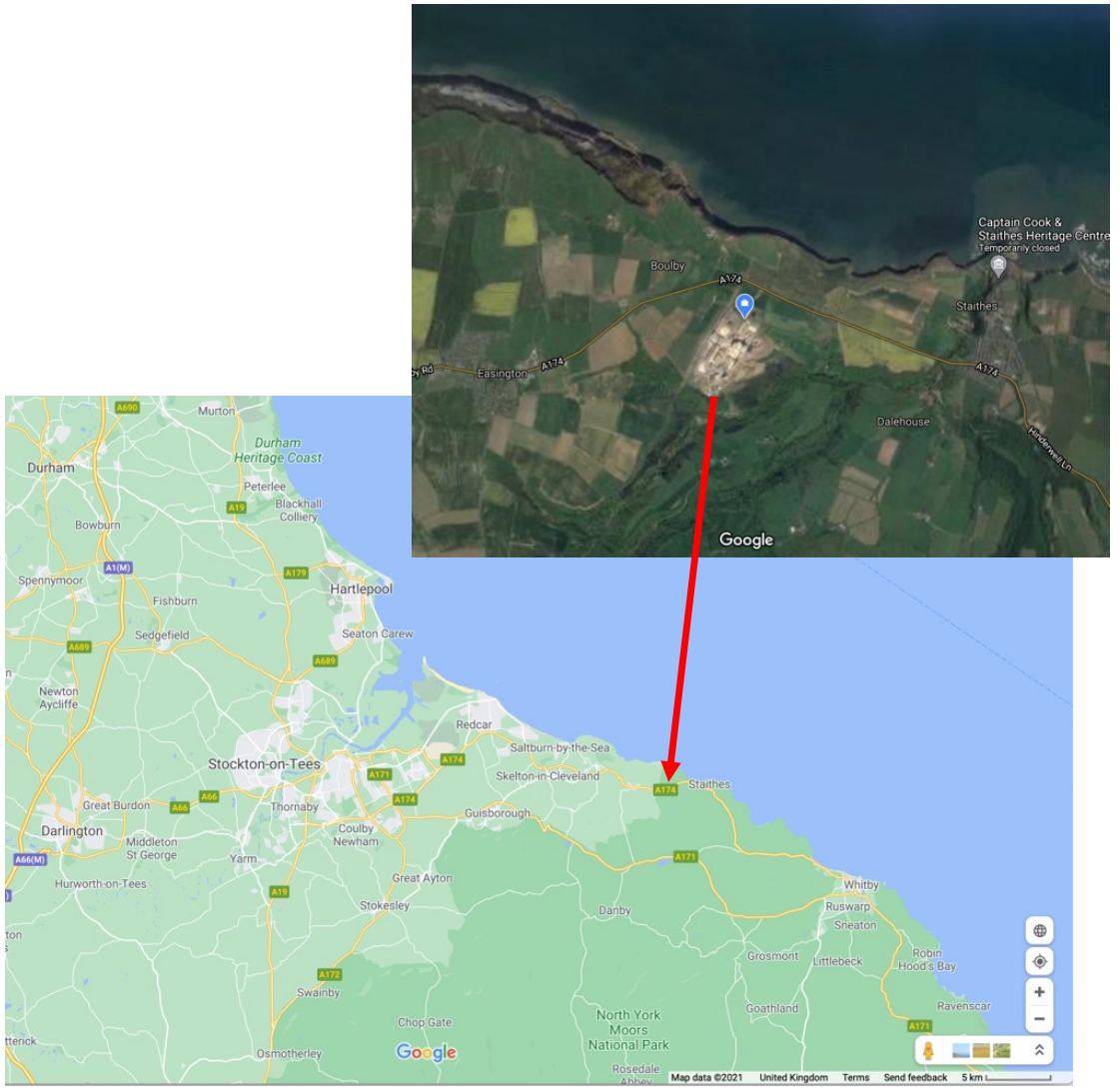
Component	Source	Expected Events	Fit Result
1	β decays + Det. ER	215 ± 36	222 ± 16
2	ν ER	27.1 ± 1.6	27.2 ± 1.6
3	^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
4	^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
5	^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
6	^{8}B CEνNS	0.14 ± 0.01	0.14 ± 0.01
7	Accidentals	1.2 ± 0.3	1.2 ± 0.3
	Subtotal	273 ± 36	280 ± 16
8	^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
9	Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
Signal	30 GeV/c^2 WIMP	-	$0.0^{+0.6}$
	Total	-	333 ± 17



Boulby Mine

- Boulby Mine is located in the north-east of England
- About 25 minutes north-west of Whitby
- Commercial Polyhalite and Salt mine

Credit: Qualter Hall



Credit: Google Maps

Boulby Mine

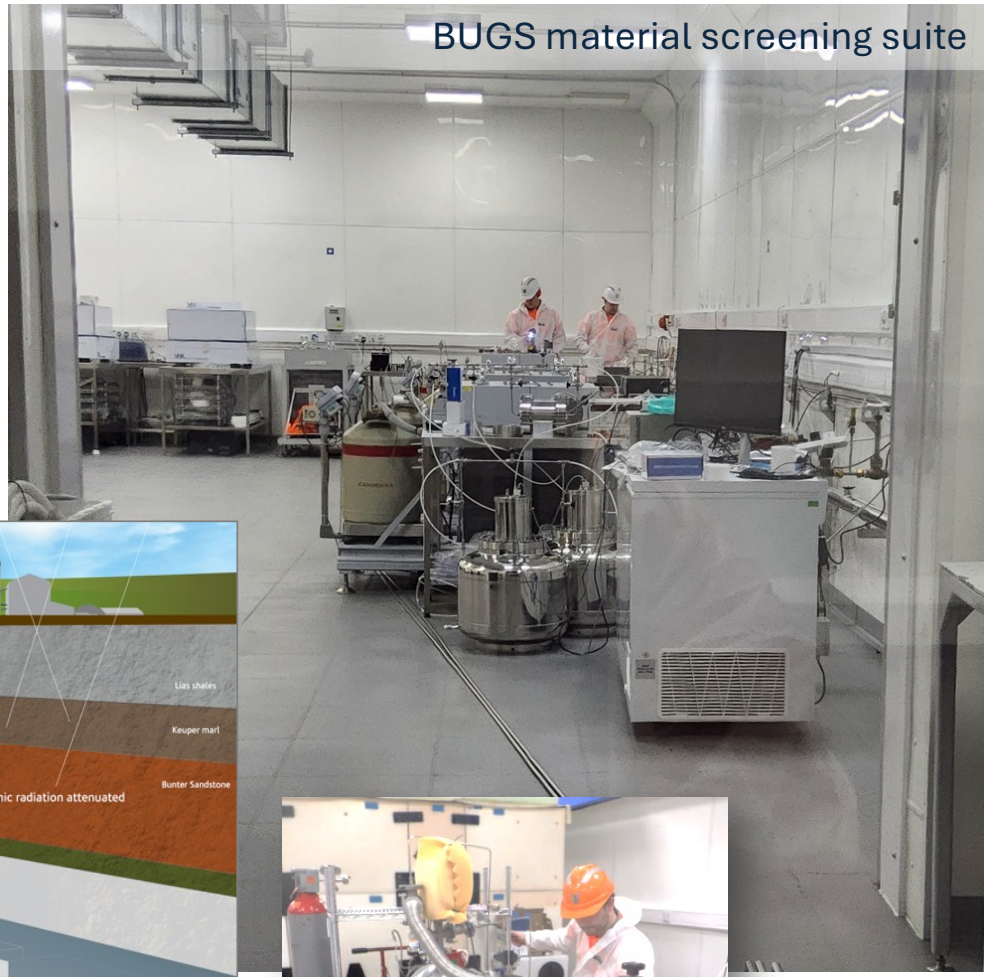
- B
  th
- A
  w
- C
  S

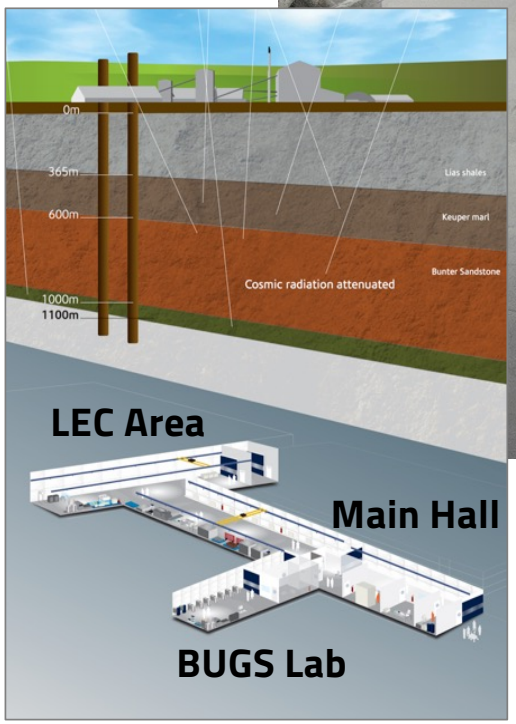
Credit: Qualter Hall

Credit: Google Maps

Current Boulby Facility

- Boulby currently hosts NEWS-G/Dark-Sphere R&D, XLZD pre-construction cleanliness/radiopurity
- The BUGS lab provides ultra-low background material screening for experiments worldwide, like LZ, XLZD, Darkside, LEGEND

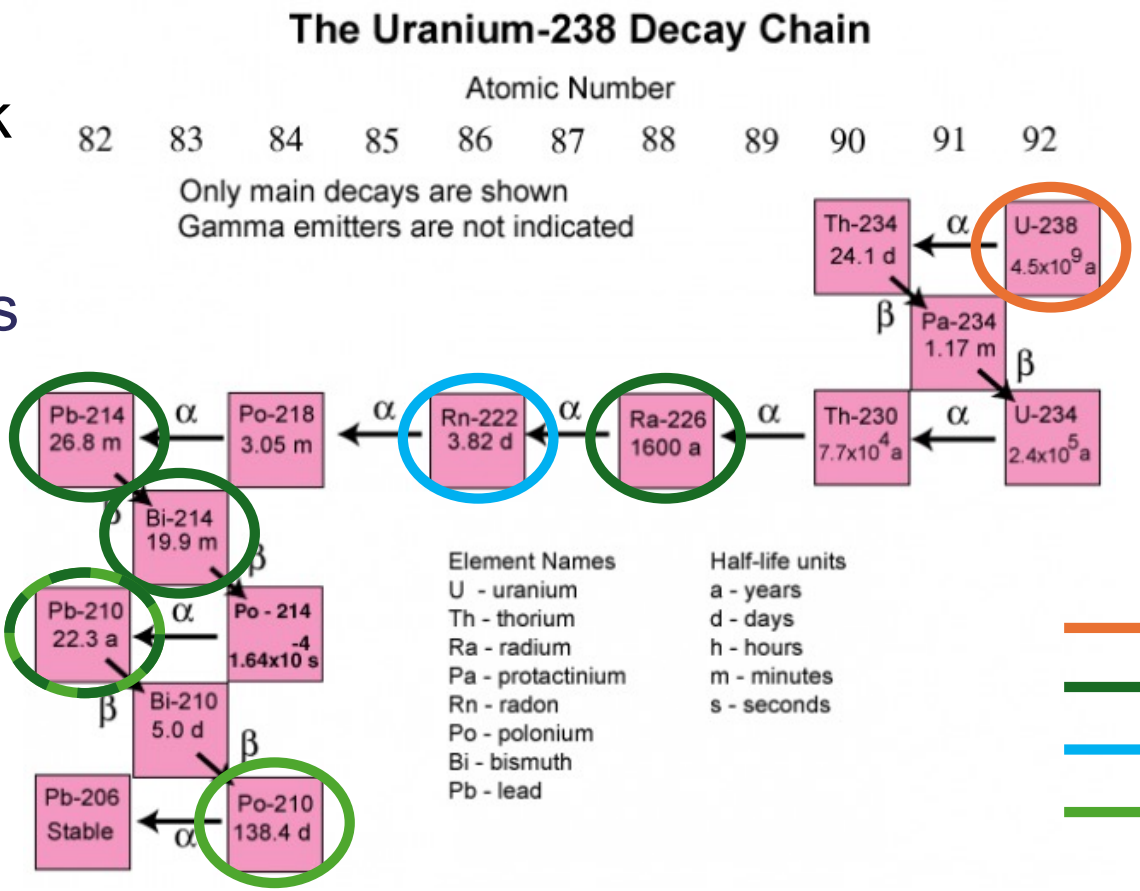

BUGS material screening suite




NEWS-G: Spherical TPC R&D

Boulby Focus: Why is Radiopurity Important?

- Radiopurity is a key factor in design of state-of-the-art dark matter detectors
- The result is only as good as the radiopurity of the system

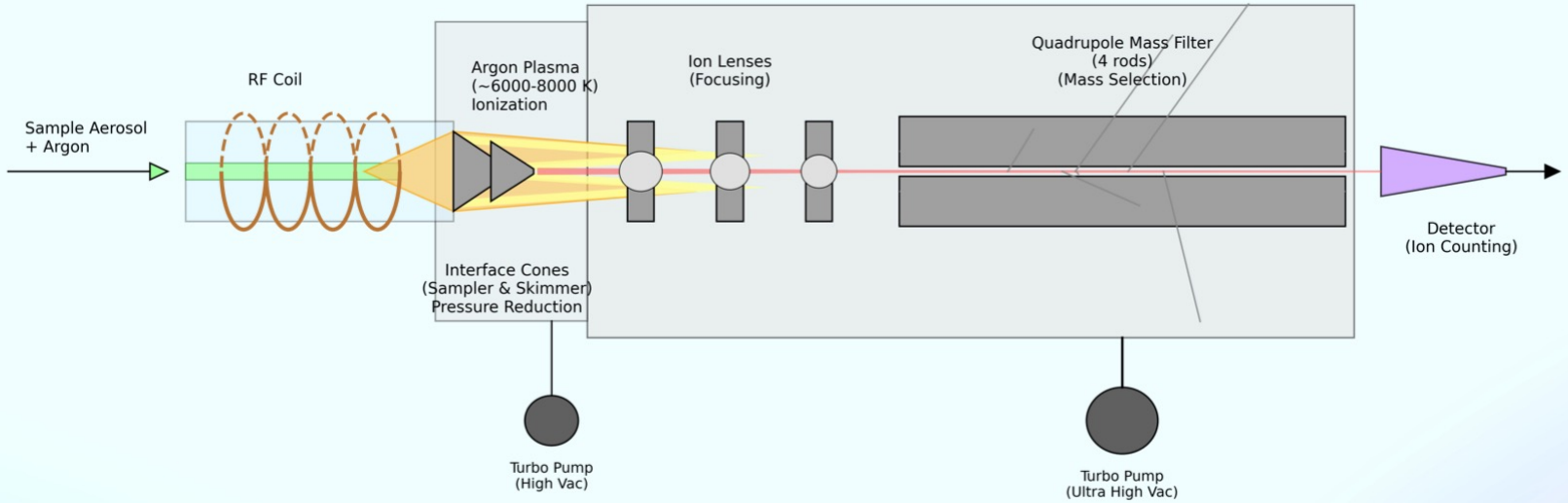


Many radioisotopes in decay chain

- Alphas -> neutrons (α,n)
- Neutrons -> "WIMPs"
- Radon -> no fiducial
- Gammas -> $$$

ICP-MS
HPGe
RnEM
Surface Alpha

The ICP-MS Technique at Boulby



- Measures elemental concentration (atom counting)
- Ultra-trace sensitivity (ppt-ppq for U/Th)
- Small sample mass required (mg-g)
- Rapid measurement time (~minutes)

- Crucial: Ultraclean sample prep @ Boulby cleanroom
- Destructive analysis technique
- Challenge: Cleanliness aspect

ICP-MS Sample Preparation at Boulby

- **Dedicated Low-Background Lab Space:** On-surface ISO 6 cleanroom -> Minimize ambient background.
- **High-Purity Reagents & Water:**
  - PURELAB® flex 3 delivers Ultra-Purity Water (18.2 MΩ·cm)
  - UltraPure Acid grade coupled with the Milestone subCLEAN sub-boiling distillation system
- **Methodology:**
  - Isotope Dilution (IDMS) with non-natural tracers (^{229}Th, ^{233}U) -> provides the most accurate results for U/Th quantification
  - Matrix separation using the prepFAST MC system, a fully automated, low-pressure chromatography unit.
- **Labware Management:**
  - PTFE, PFA and Pyrex labwares
  - Acid leaching with the traceCLEAN acid steam cleaning system
  - Screening/selection of low-background labware materials

Instrumentation

Clean Chemistry

Ultra-Trace Triangle

Sample Preparation

Conclusion

- This PhD blends cutting edge data analysis with cutting edge material characterisation
- Working with existing data (LZ)
- Helping to develop the cutting edge (XLZD)

- There is still compelling parameter space that could yield a positive result from LZ – you could be responsible!