Dark Matter

PPAP Community Meeting
University of Manchester, 21st - 22nd September 2022

Dr Sally Shaw
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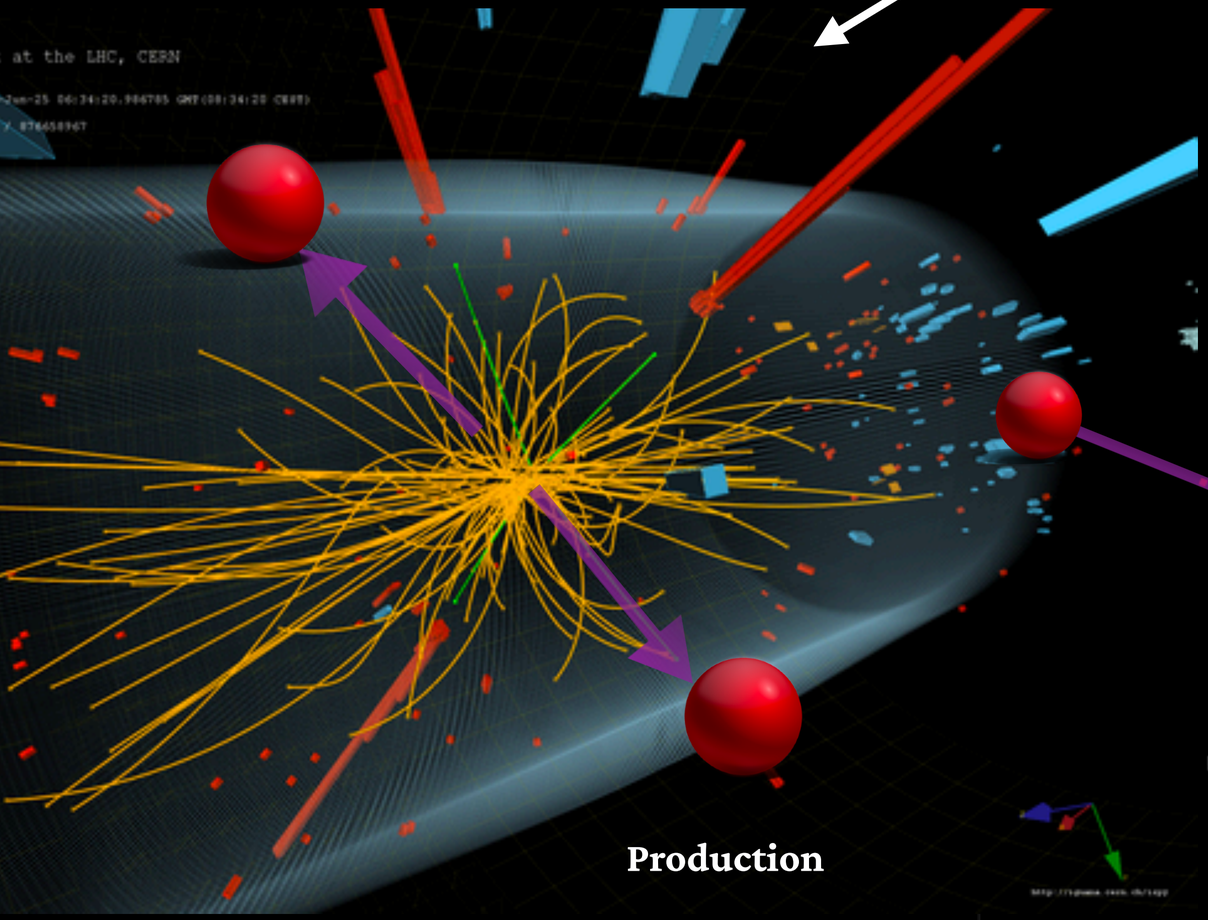
3 ways to detect dark matter particles

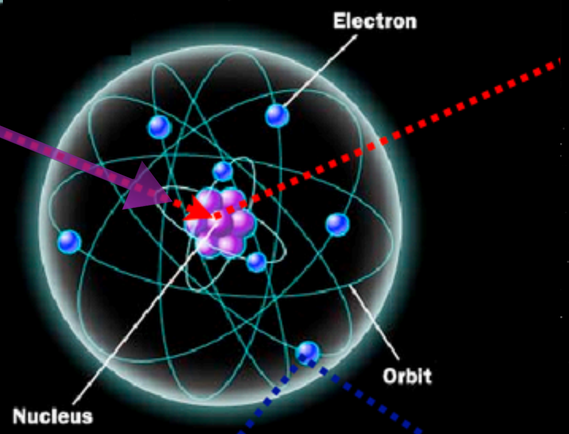
Enabling discovery with a multi-faceted approach

MAKE IT



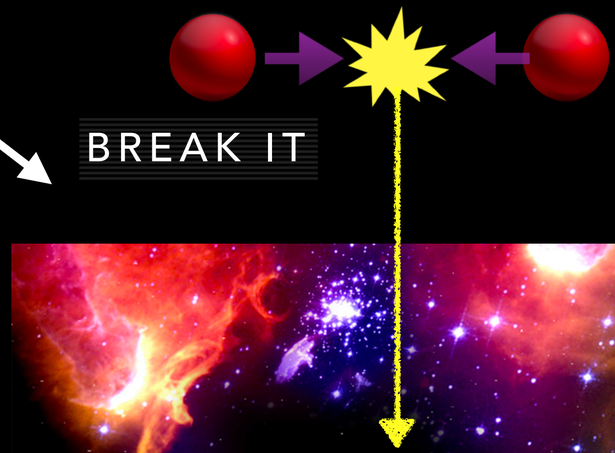
Production

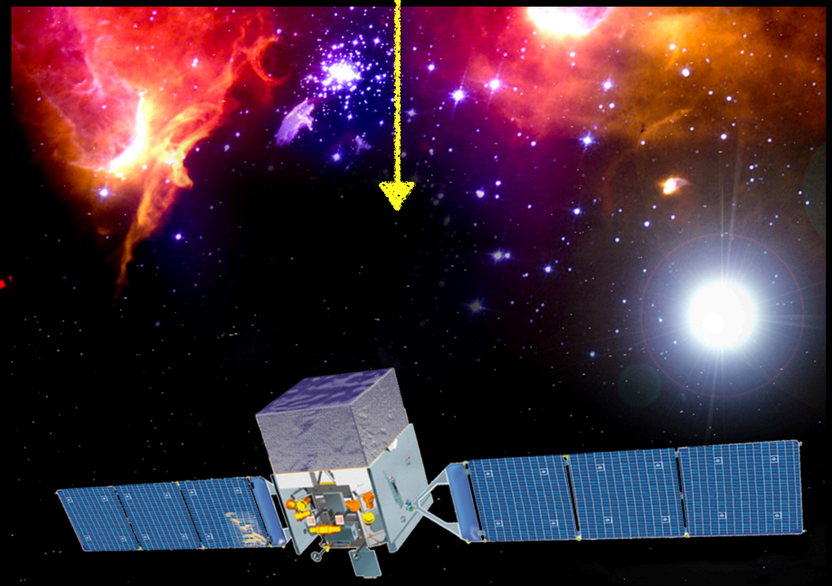
SHAKE IT



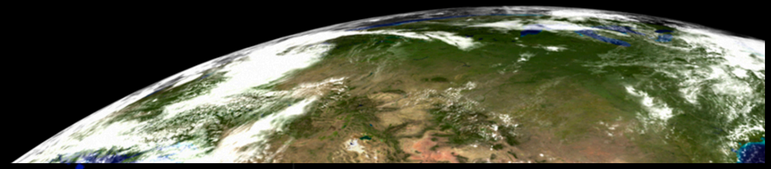
Direct Detection

BREAK IT

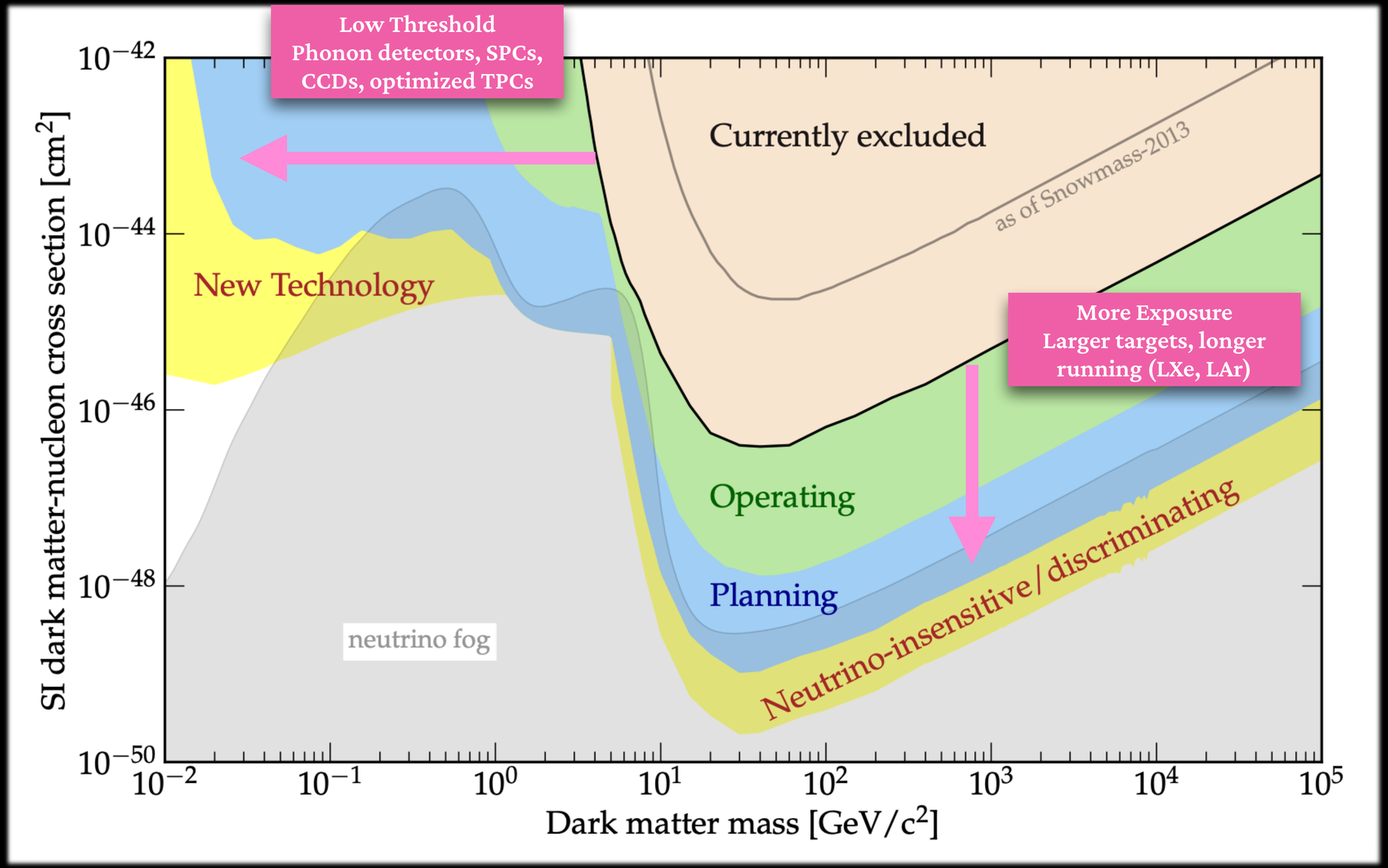




Indirect Detection



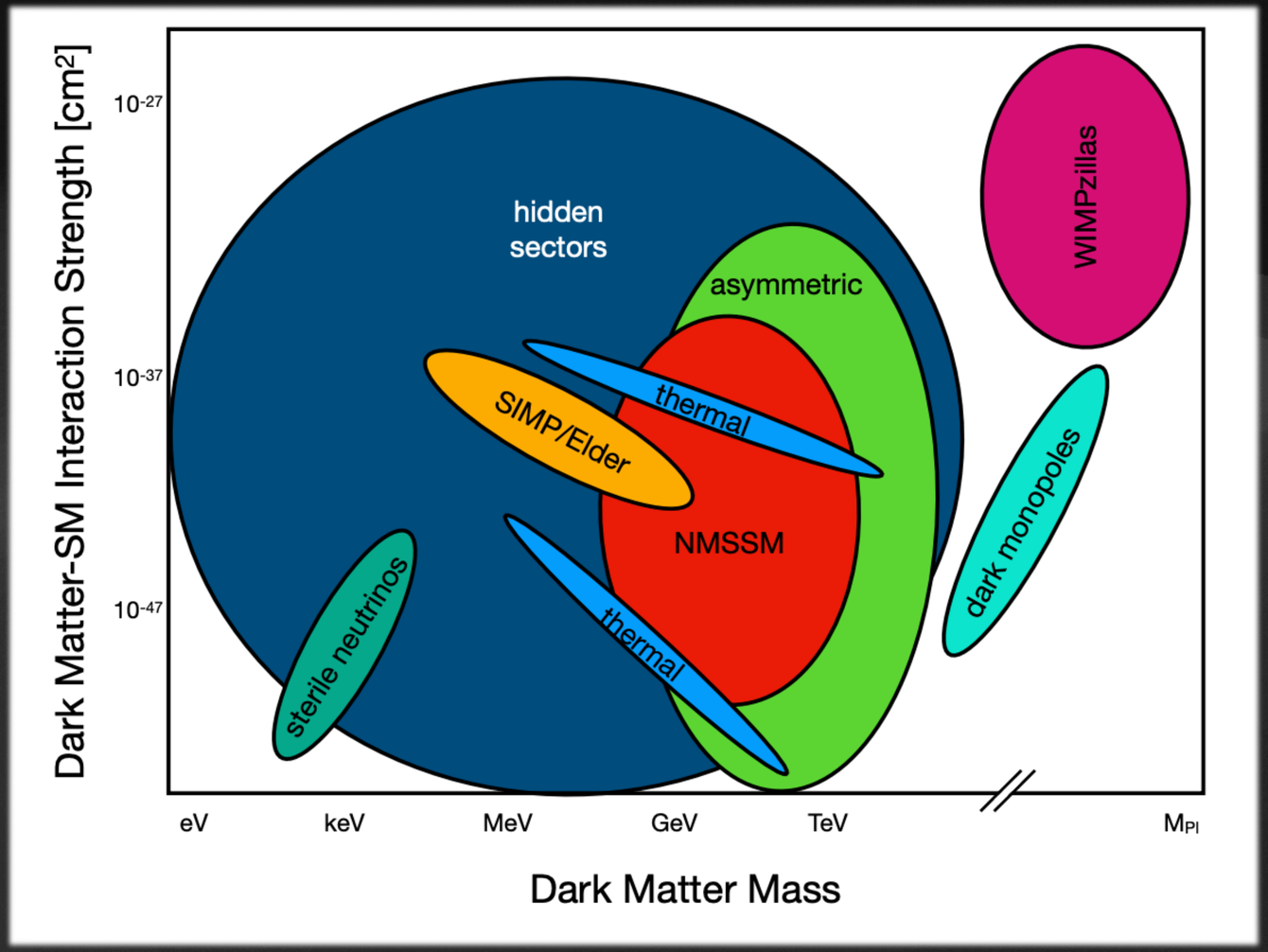
Direct Detection - State of the Field



Dark Matter Phase Space

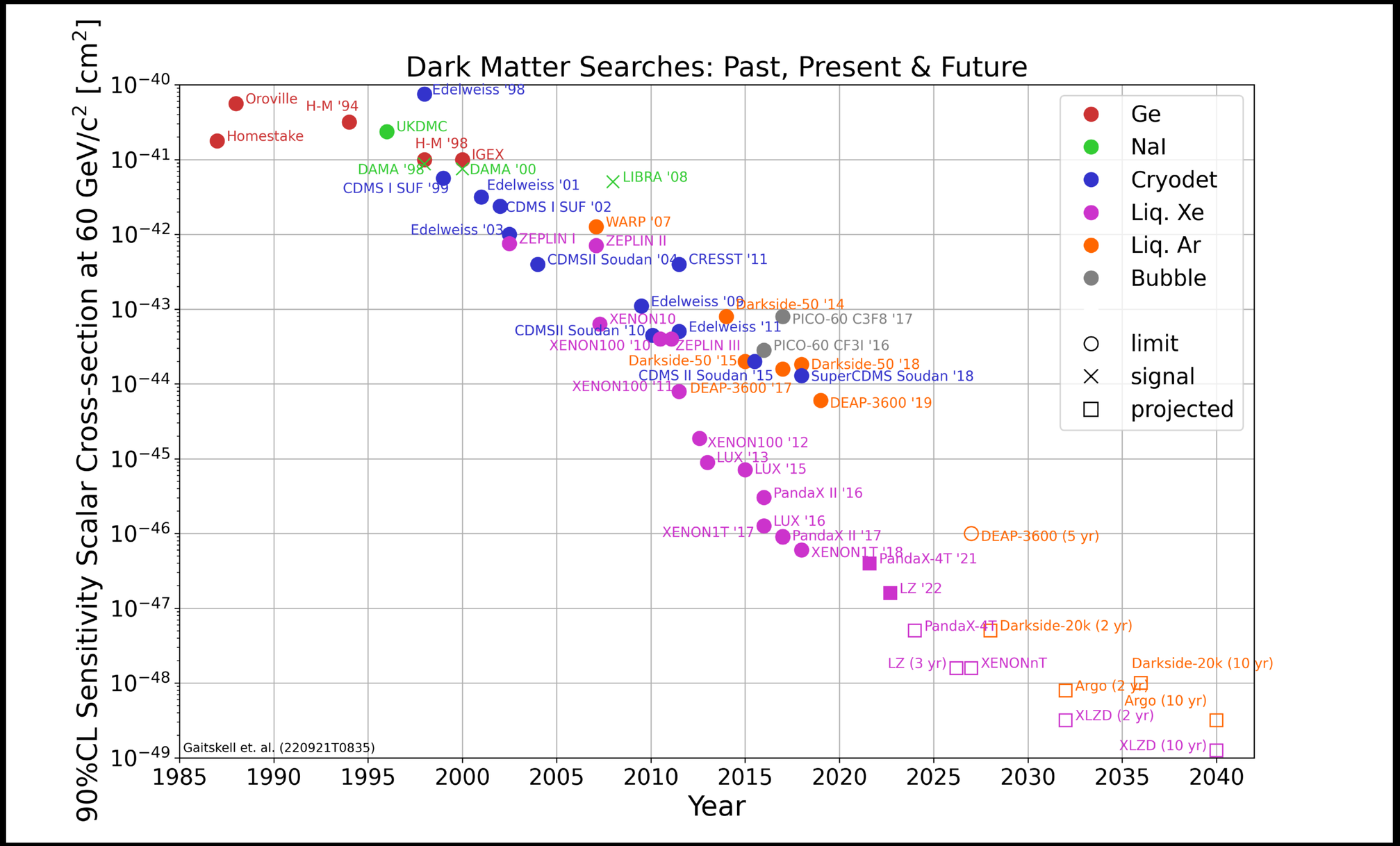
Report of the Topical Group on Particle Dark Matter for Snowmass 2021
arXiv:2209.07426

- Direct detection experiments have an enormous range of masses to cover
- Current experiments are **not sensitive** to many candidates at either ends of the mass range
- Need to "***delve deep and search wide***"
  - continue to **scale up in mass**
  - reduce and understand **low-energy backgrounds**
  - **lower thresholds** (new technology/techniques)

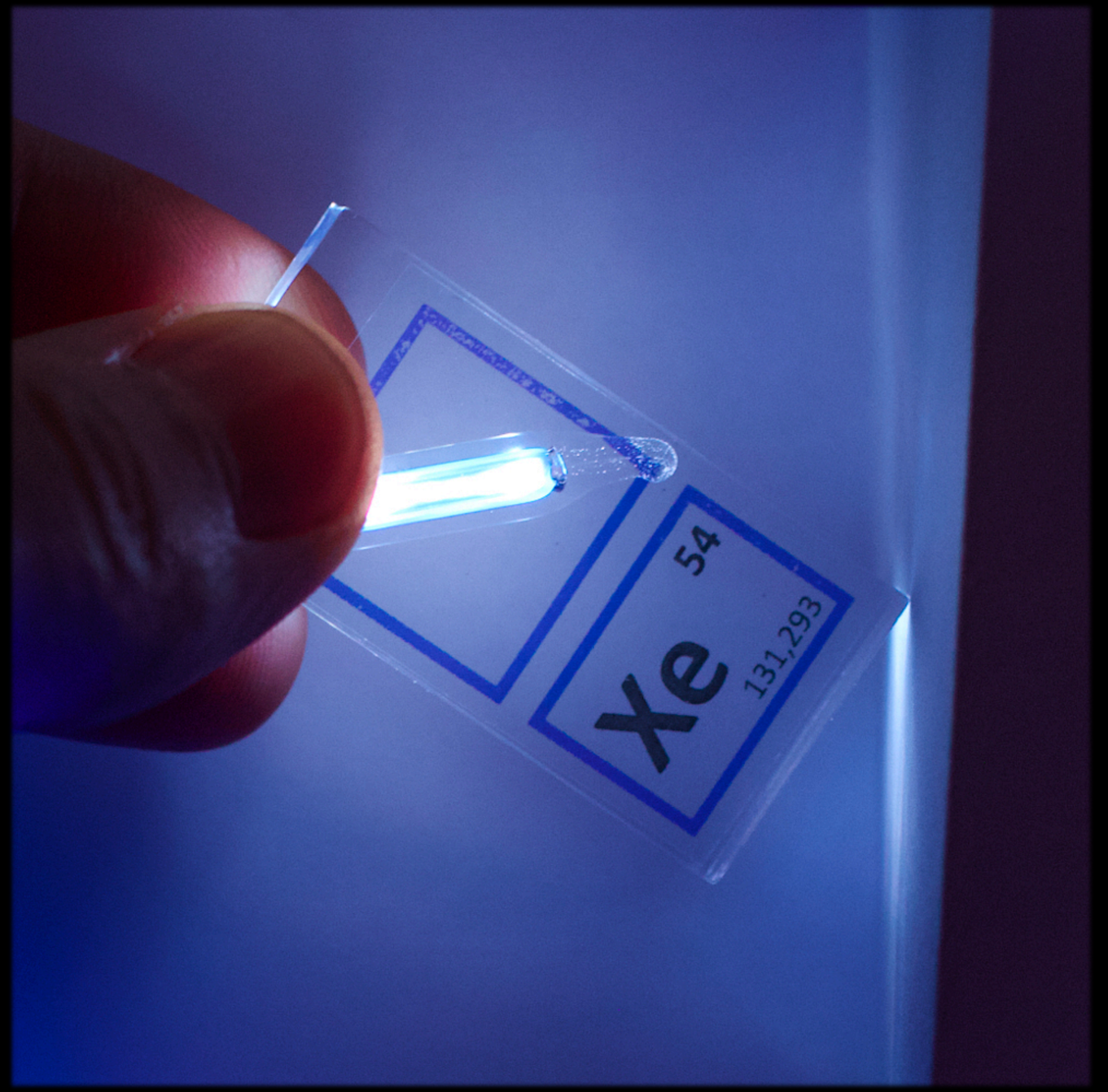


Particle Dark Matter Candidates

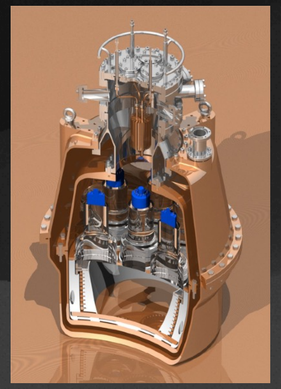
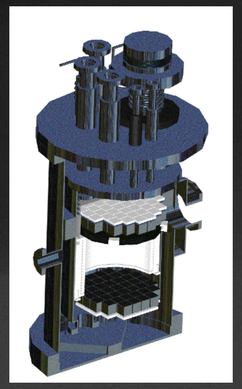
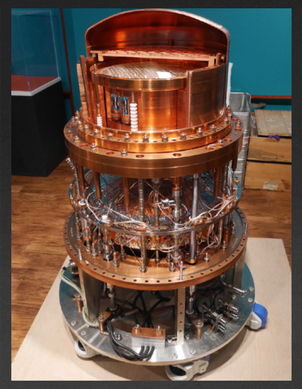
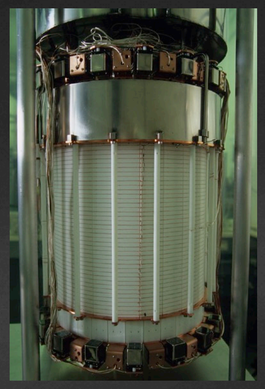
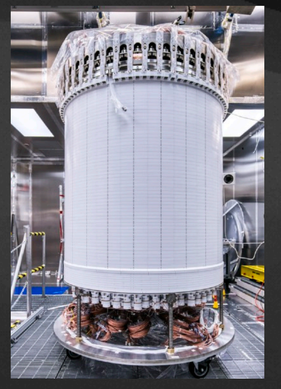
Status of Direct Detection



Liquid Xenon

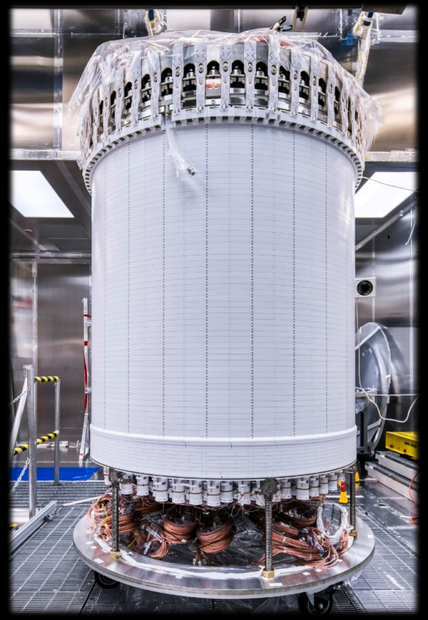


History of Direct Detection with Liquid Xenon

ZEPLIN-II	XENON10	ZEPLIN-III	XENON100	LUX	PANDAX-II	XENON1T	LZ
							
31 kg (7.2 kg)	15 kg (5 kg)	12 kg (7 kg)	62kg (34 kg)	250 kg (100 kg)	580 kg (362 kg)	2,000 kg (1,042 kg)	7,000 kg (5,500 kg)
6.6×10^{-43} cm^2	8.8×10^{-44} cm^2	8.1×10^{-44} cm^2	3.4×10^{-44} cm^2	2.2×10^{-46} cm^2	2.5×10^{-46} cm^2	4.1×10^{-47} cm^2	5.9×10^{-48} cm^2
2007	2007	2008	2010	2016	2016	2019	2022

Future of Direct Detection with Liquid Xenon

LZ



7,000 kg
(5,500 kg)

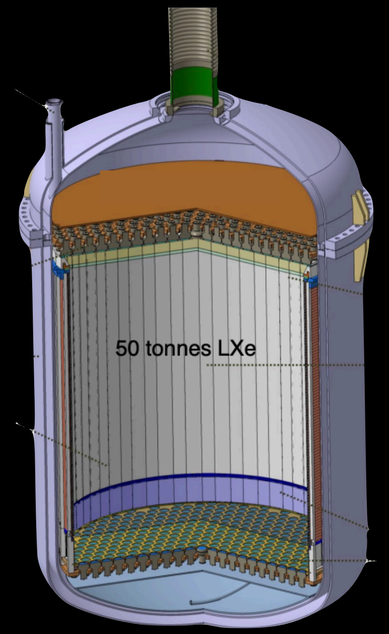
Projected for 15 t-y:
1.4×10^{-48} cm^2

XENONnT

5,900 kg
(4,400 kg)

Projected for 20 t-y:
1.4×10^{-48} cm^2

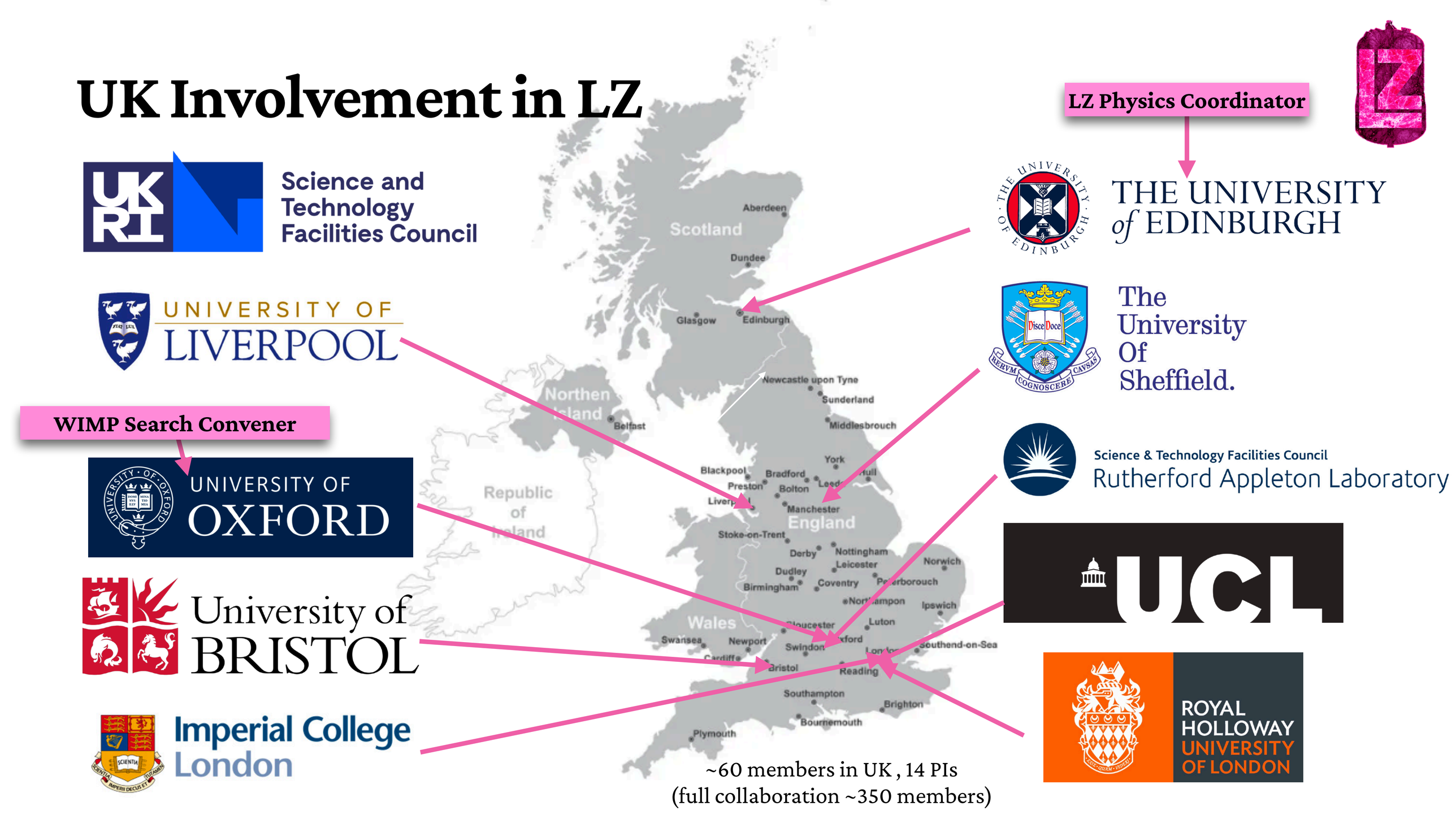
“G3” / XLZD Consortium



40,000 - 100,000 kg

Projected for 1000 t-y:
1.4×10^{-49} cm^2

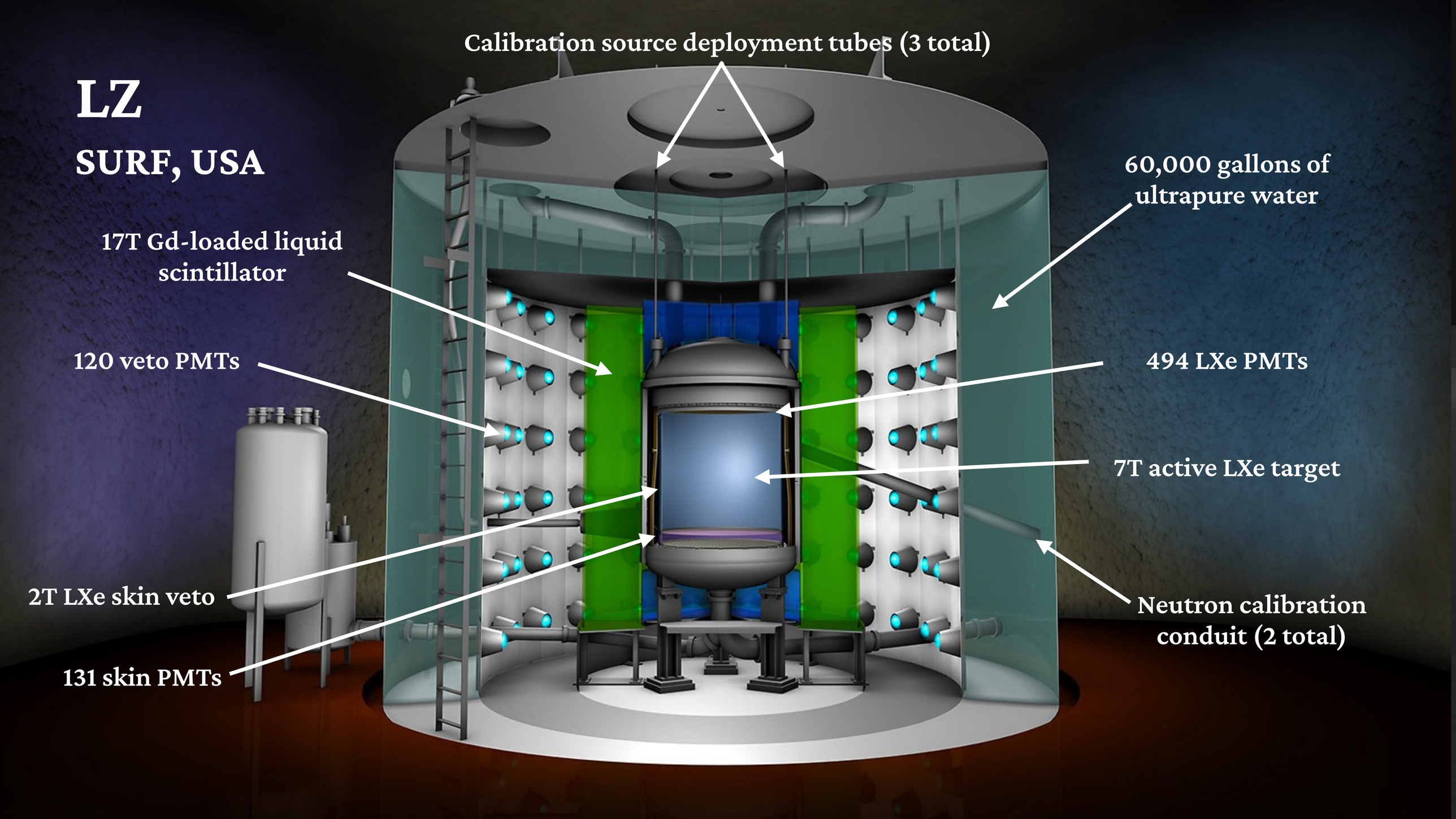
UK Involvement in LZ



~60 members in UK , 14 PIs
(full collaboration ~350 members)

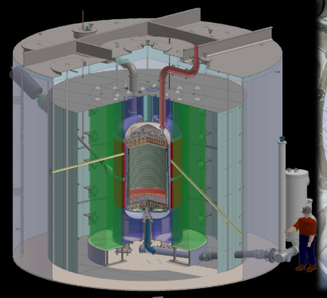
LZ

SURF, USA

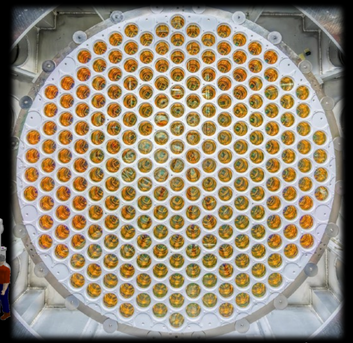

Calibration source deployment tubes (3 total)
60,000 gallons of ultrapure water
17T Gd-loaded liquid scintillator
120 veto PMTs
494 LXe PMTs
7T active LXe target
2T LXe skin veto
Neutron calibration conduit (2 total)
131 skin PMTs

LZ Timeline

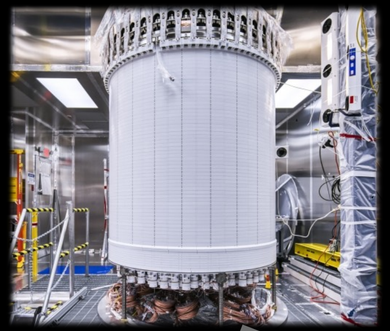
CD3 & TDR
March 2017



PMT arrays arrive
Dec 2018

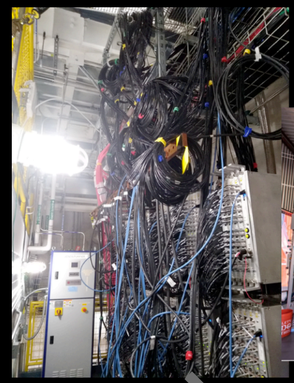


TPC Complete
Aug 2019



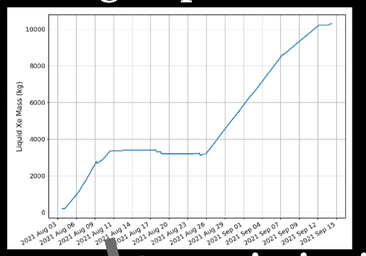
Cryostat & TPC move
underground
Oct 2019

Electronics installation
Autumn 2020



Kr operation
Jan - Aug 2021

Xe fill
Aug-Sept 2021



Commissioning
Autumn 2021

2017 2018 2019 2020 2021 2022

Science running!
Dec 2021

Cryostat arrives
May 2018

OD tanks go
underground
Oct-Nov 2018

FFR assembly
Dec 2018

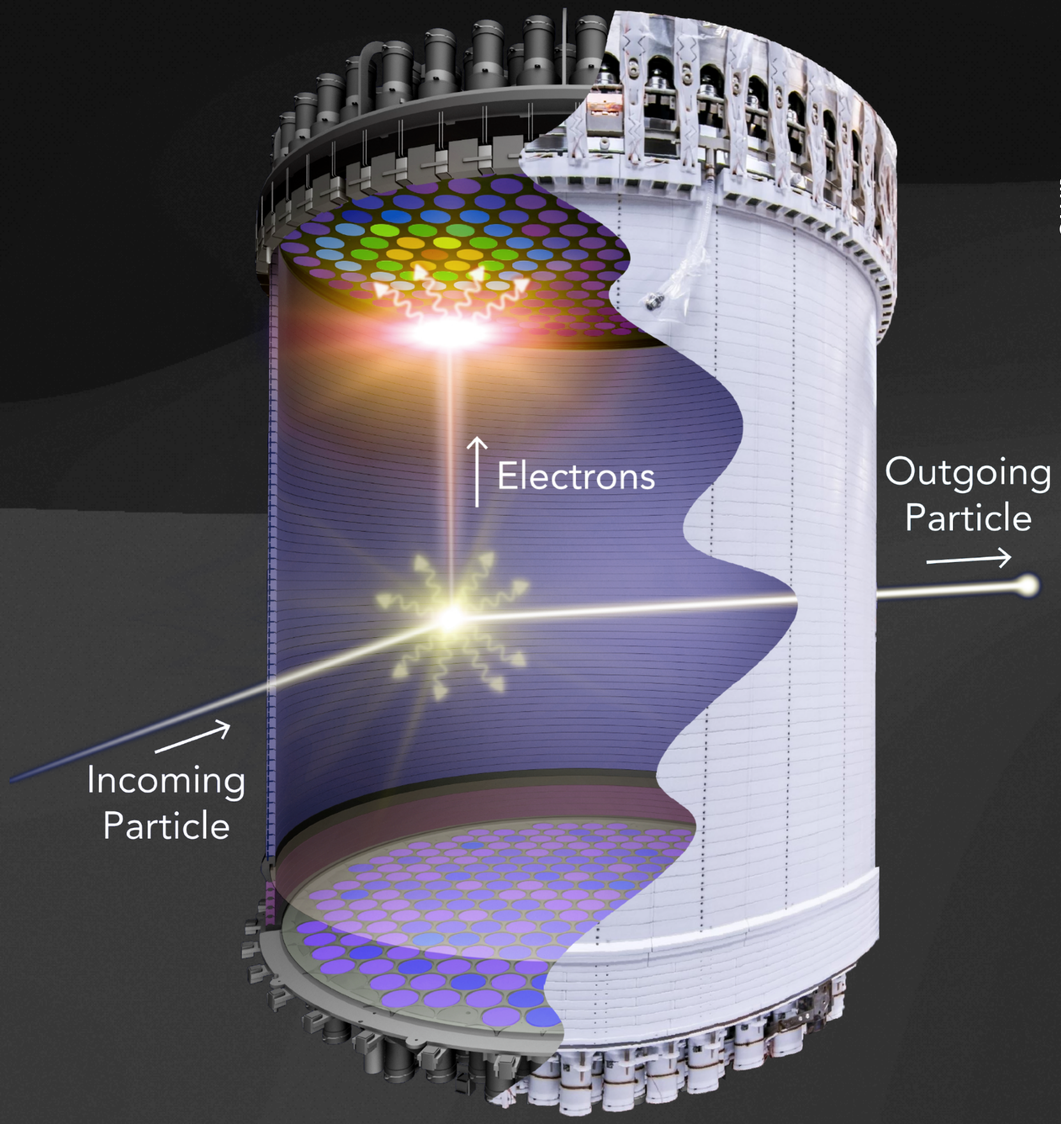
Grid manufacture
Spring 2018

HV install & sealed
March 2020

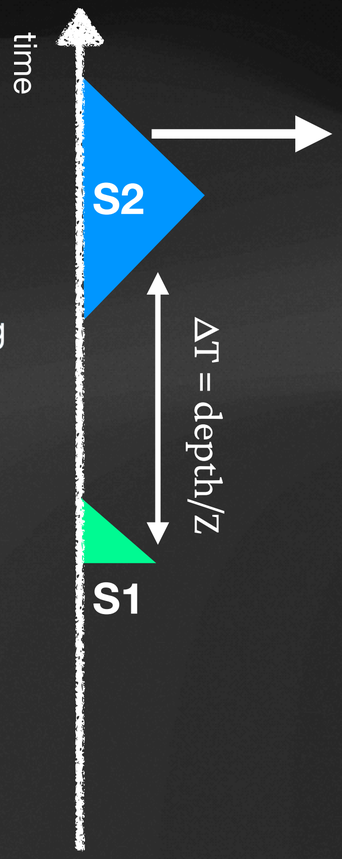
OD construction
Winter 2020

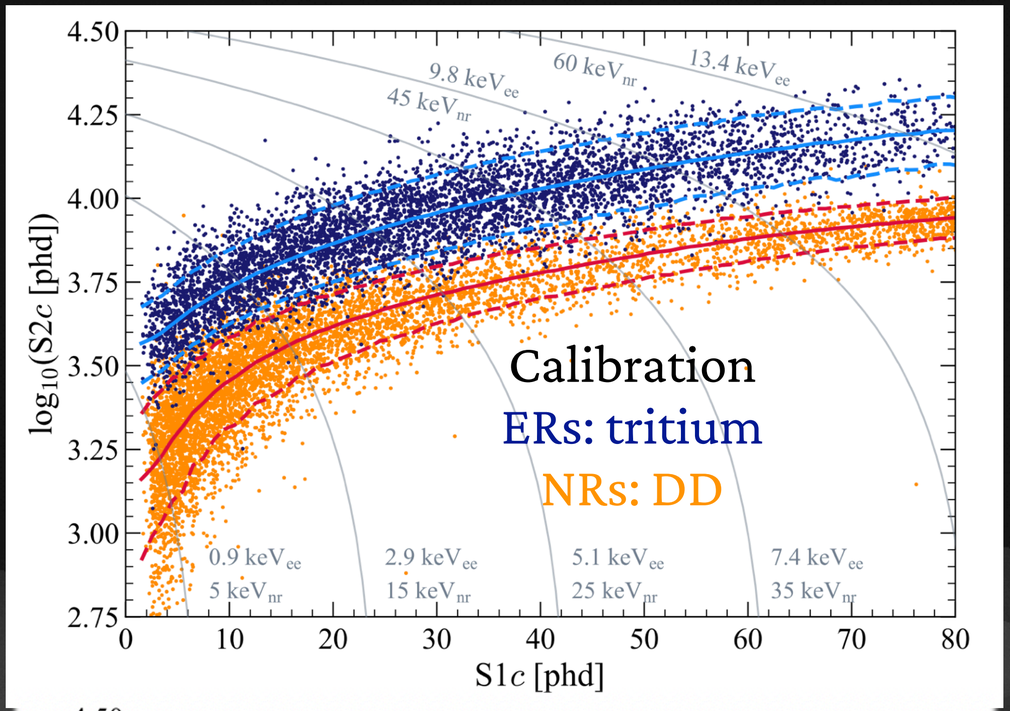
LZ First Science Run

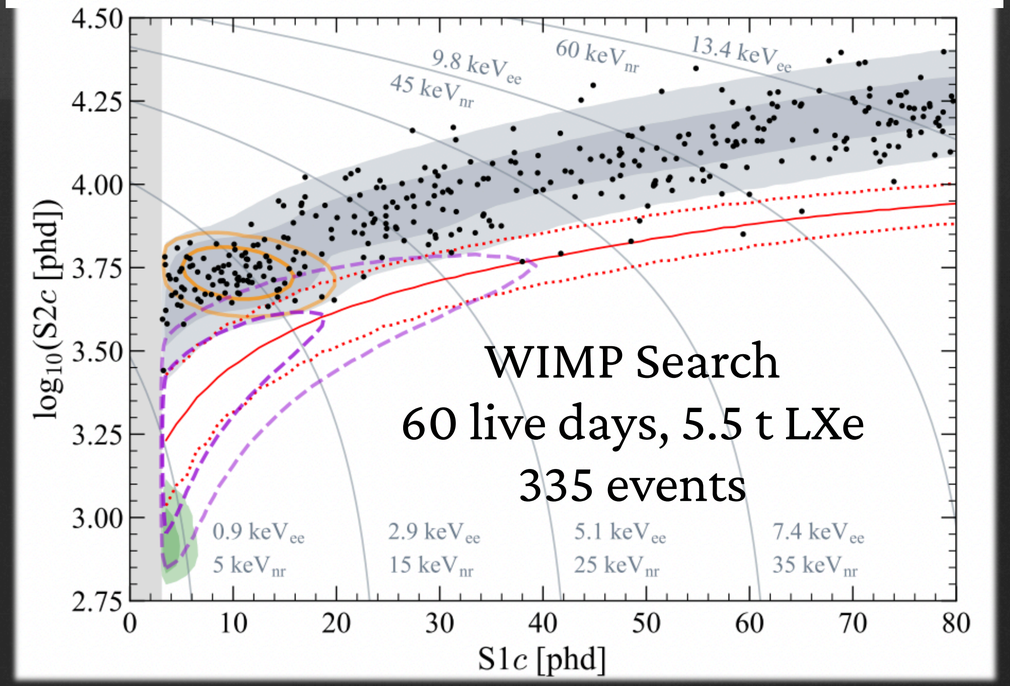
First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment arXiv:2207.03764



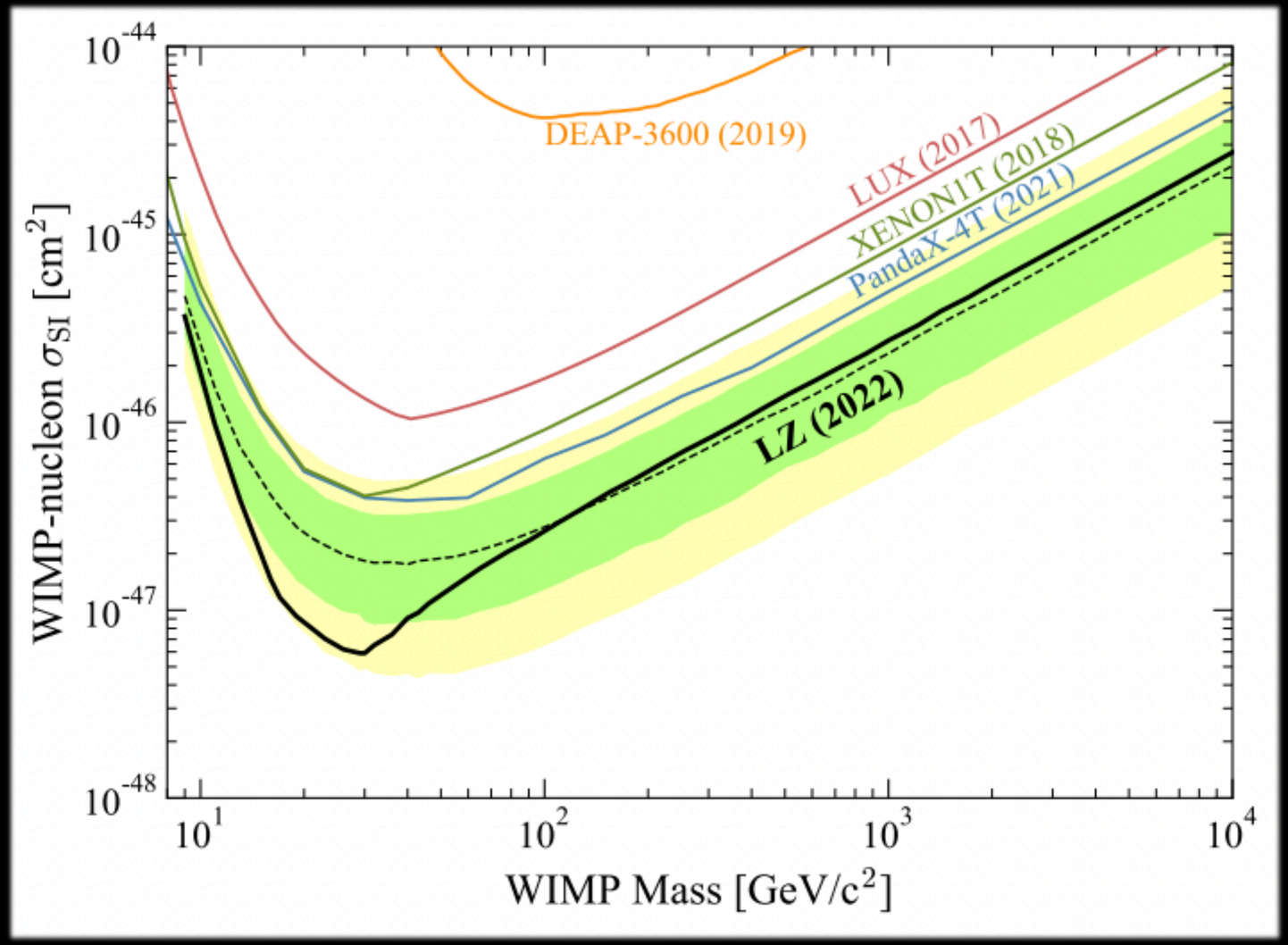
Ratio of S2/S2 provides ER/NR discrimination





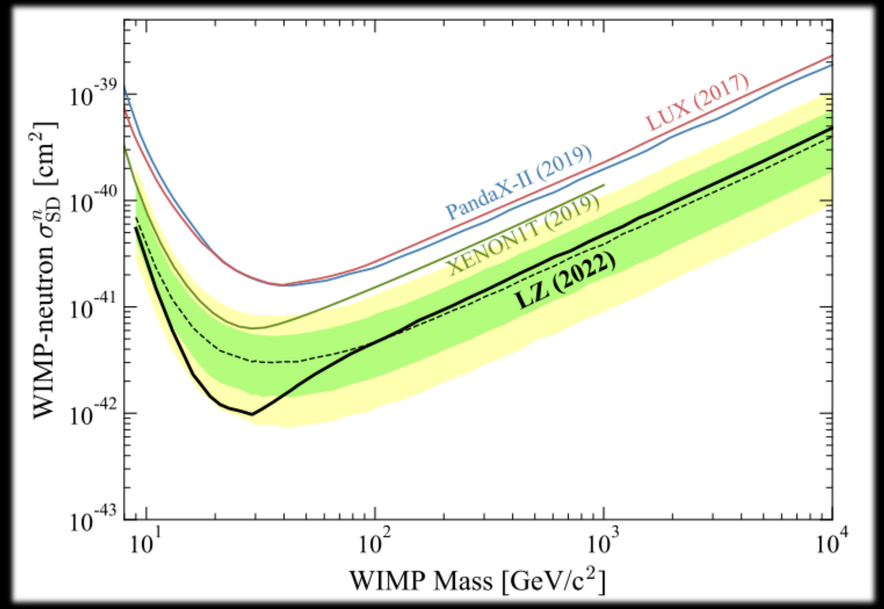


LZ First Results - July 2022

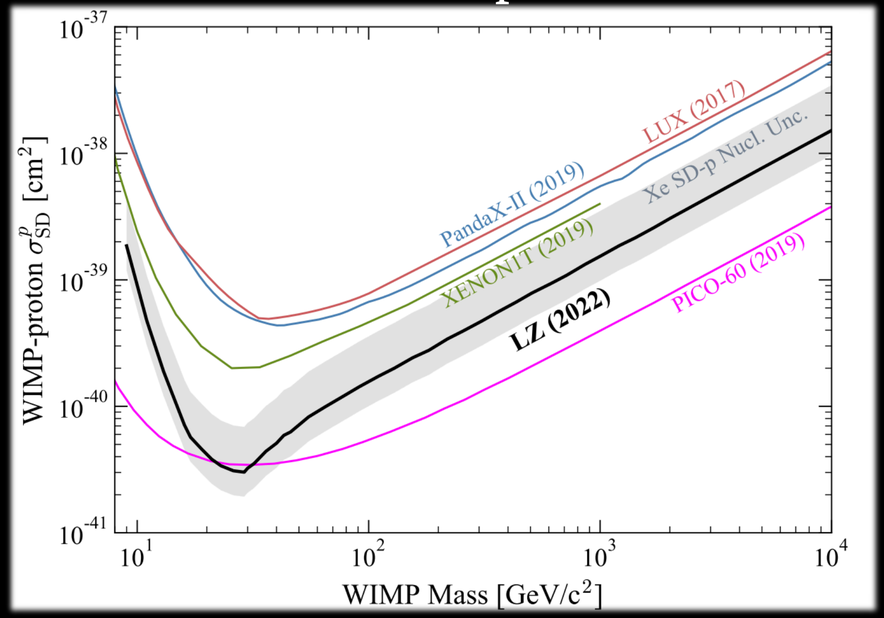


Minimum: 5.9×10^{-48} at 30 GeV

SD: WIMP-neutron



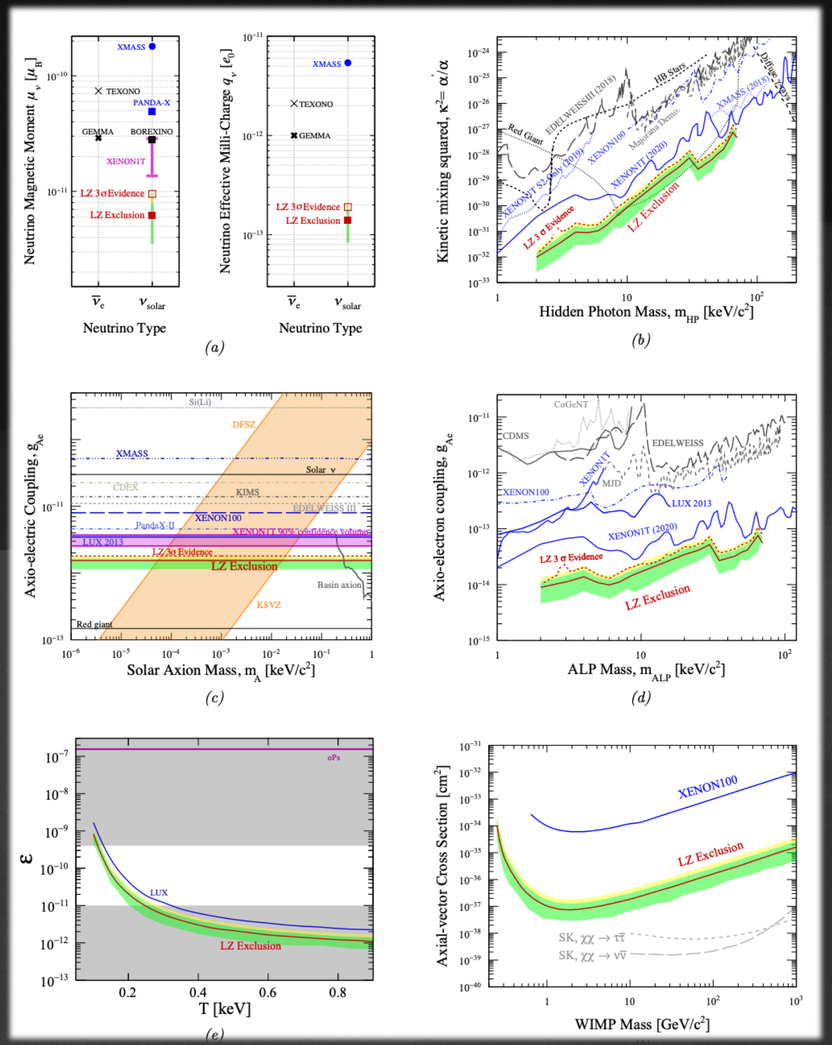
SD: WIMP-proton



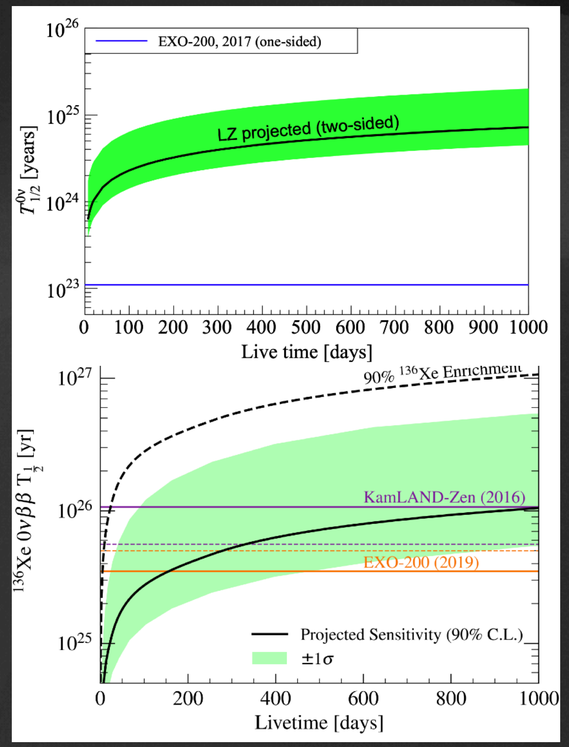
LZ Physics Reach

Wide range of physics analyses ongoing on Science Run 1 data & preparing for more data:

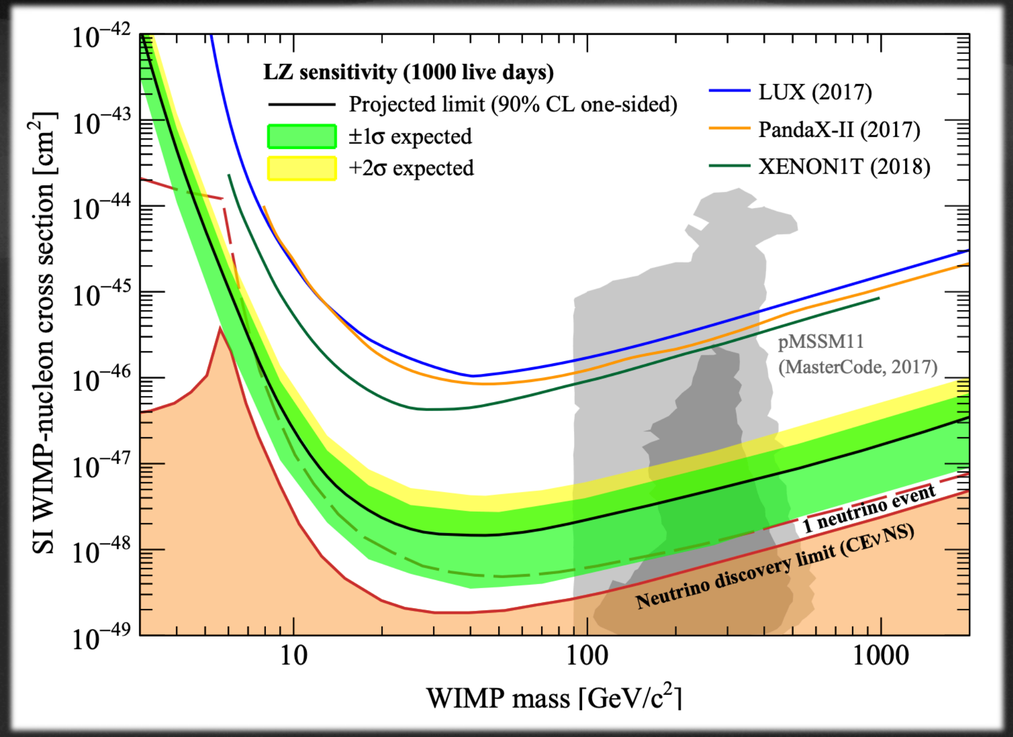
- Low mass WIMPs: S2-only searches, Migdal effect
- Low energy ER signals: axions, ALPs, hidden photons
- NR signals: EFT models
- High energy ER signals: neutrino studies ($0\nu\beta\beta$, double electron capture/DEC)



Projected sensitivities of the LUX-ZEPLIN (LZ) experiment to new physics via low-energy electron recoils
arXiv:2102.11740



Xe136: arXiv:2104.13374
Xe134: arXiv:1912.04248

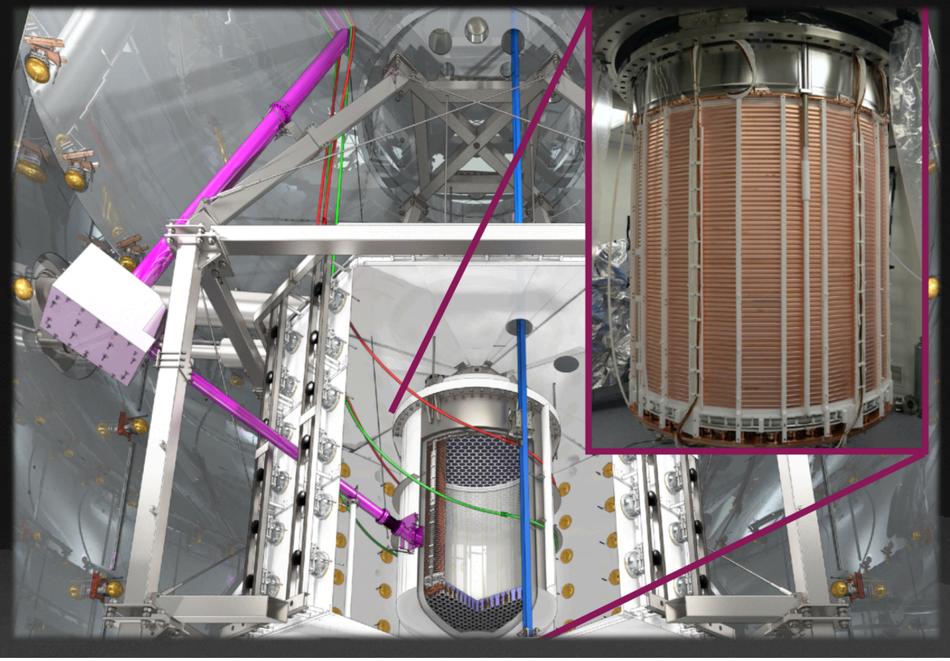


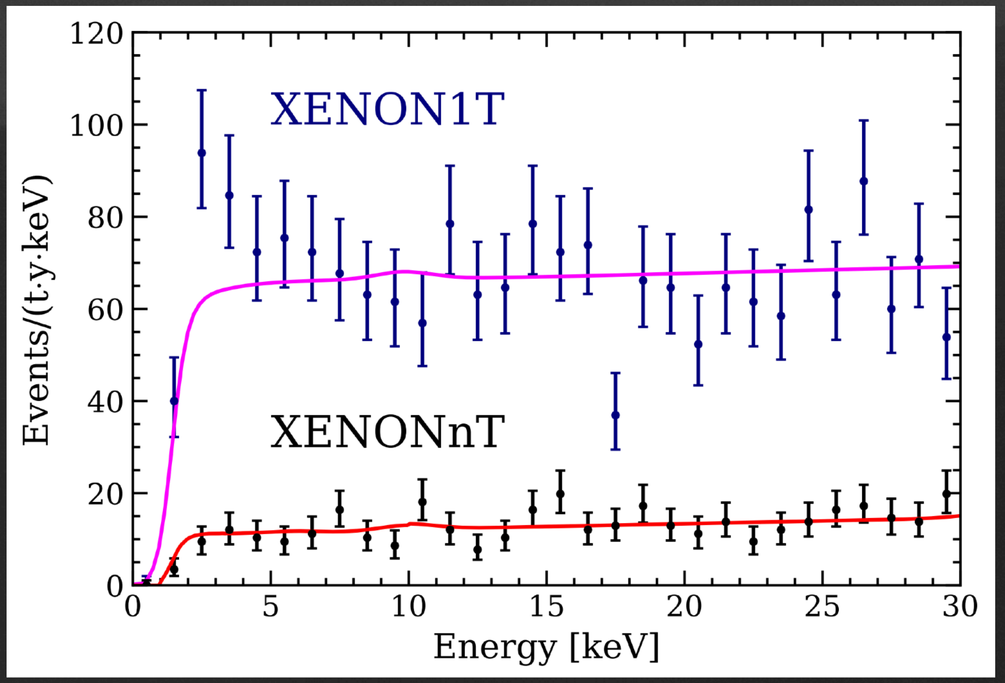
Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment
arXiv:1802.06039

XENONnT

LNGS, Italy

- ~6 t LXe target, enclosed in water Cherenkov veto (future plans for Gd-doping of water)
  - Inline radon distillation → < 1 μBq/kg
- First science run: 97.1 livedays collected
  - Issues with fields - ran with drift field 23 V/cm (XENONnT sensitivity paper: 200 V/cm, LZ: 190 V/cm)
- Background in the (1, 30) keV search region lowest ever achieved in a dark matter detector, ~5 times lower than in XENON1T
- No NR limit yet
- **ER excess in XENON1T definitively ruled out**
- Limits published for solar axions, ALPs, ν magnetic moment, dark photons





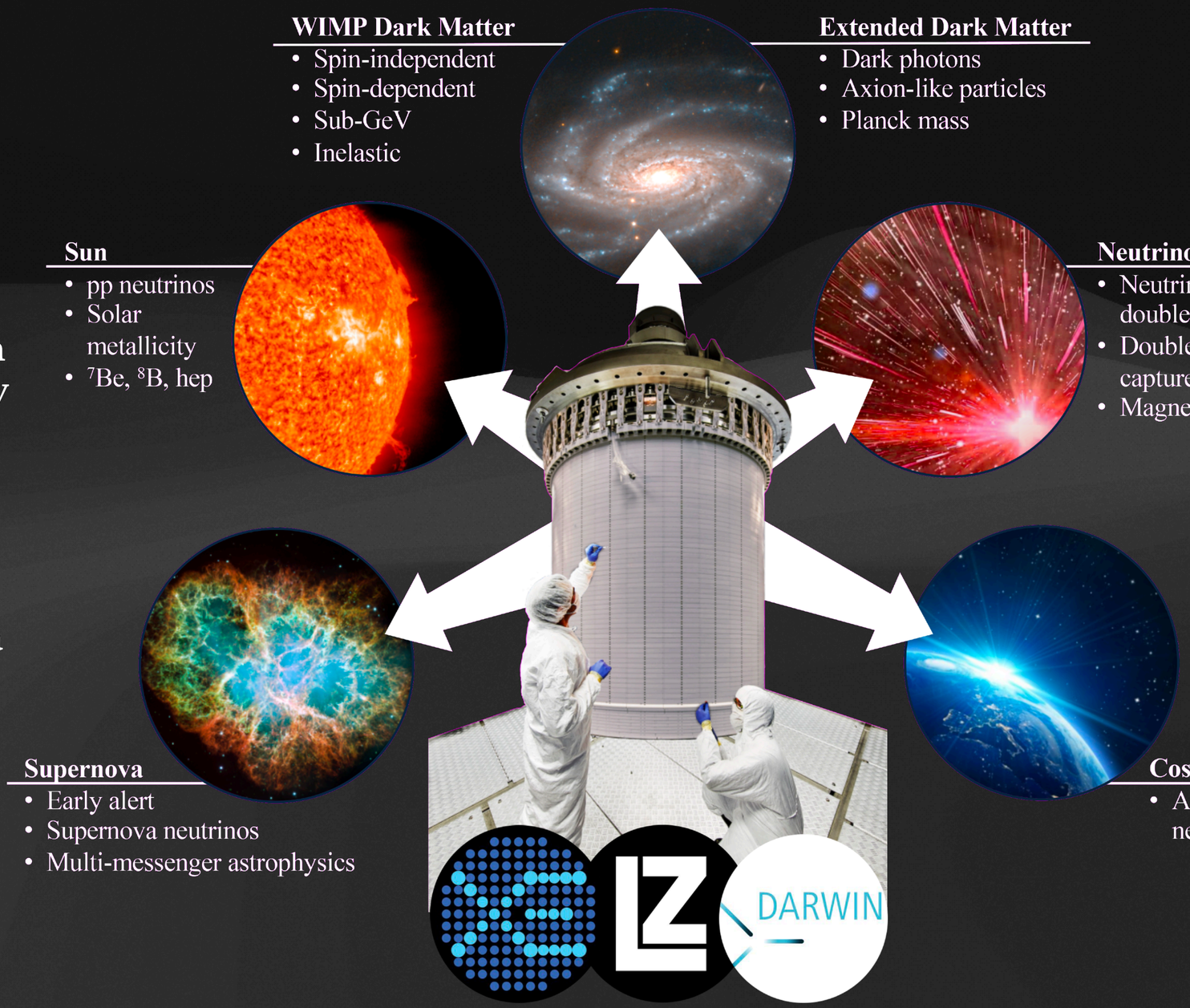
Search for New Physics in Electronic Recoil Data from XENONnT
arXiv:2207.11330

XLZD

XENON, DARWIN and LZ have joined forces to form the **XLZD** consortium.

Science drivers:

- The ultimate probe of WIMPs down to the neutrino fog, with potentially **transformative implications** for particle physics and our view of the Universe
- A **competitive and economic** search for neutrinoless double-beta decay, which is so **fundamental** to nuclear physics and the origin of matter
- Measurements of multiple astrophysical neutrinos signals at lowest energies, with **key insights** into the physics of neutrinos



XLZD Consortium

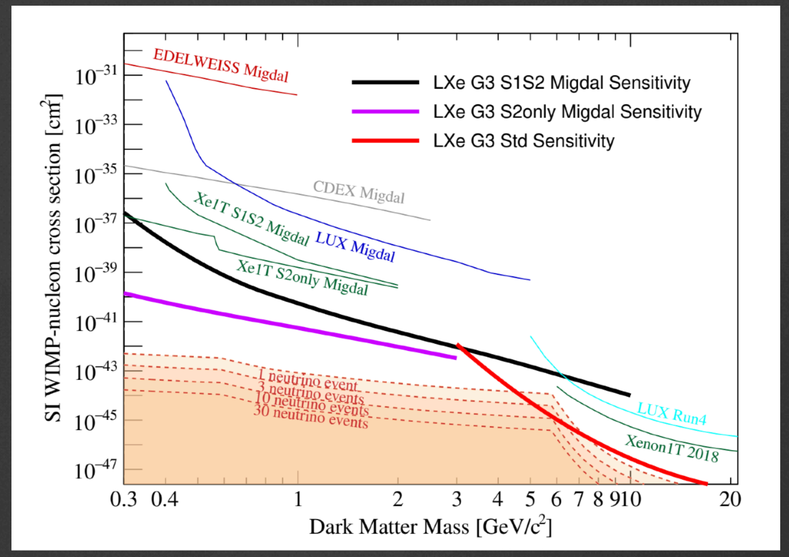
First meeting at KIT (Karlsruhe) June 2022

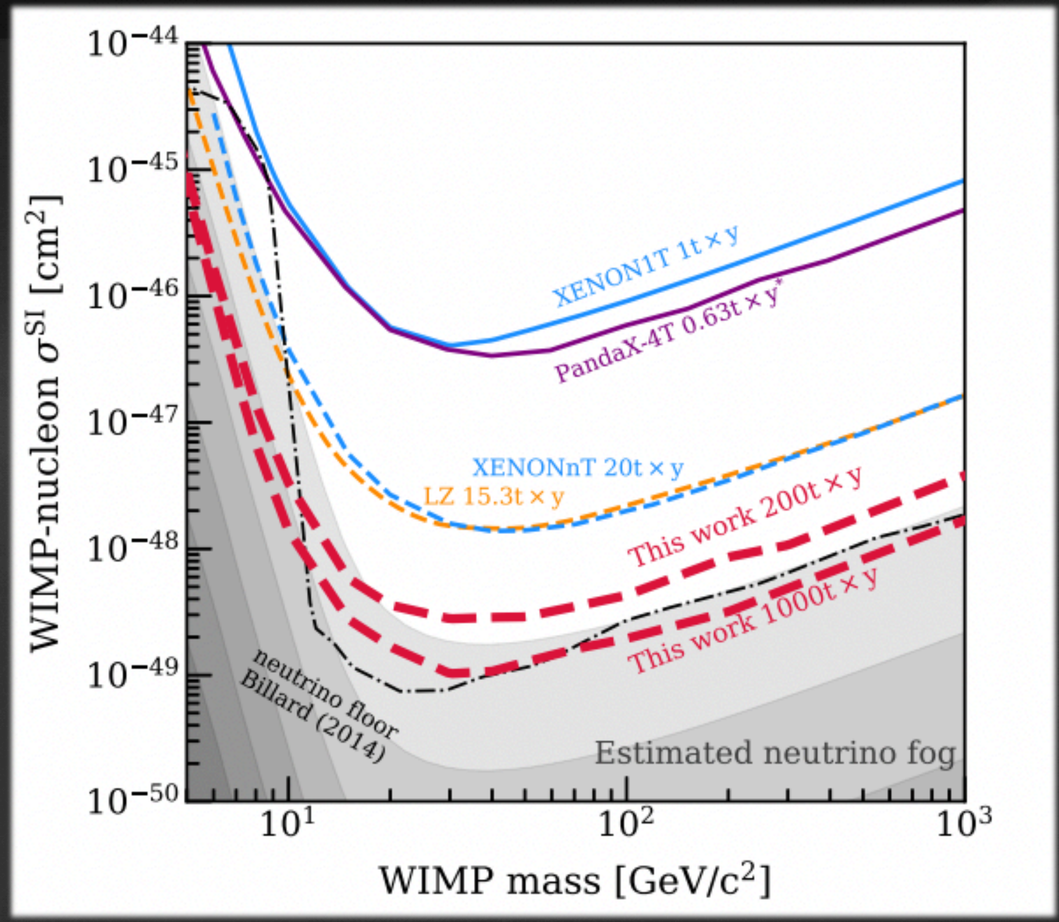
XLZD Sensitivity Projections

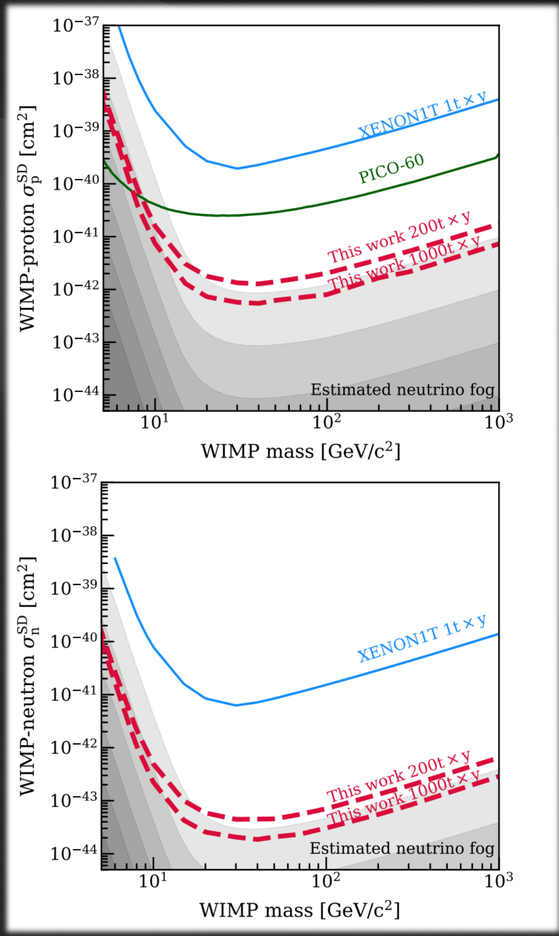
A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics
arXiv:2203.02309

Projected sensitivities showing final planned exposure for LZ and XENONnT and 200 t×y + 1000 t×y for the next generation experiment.

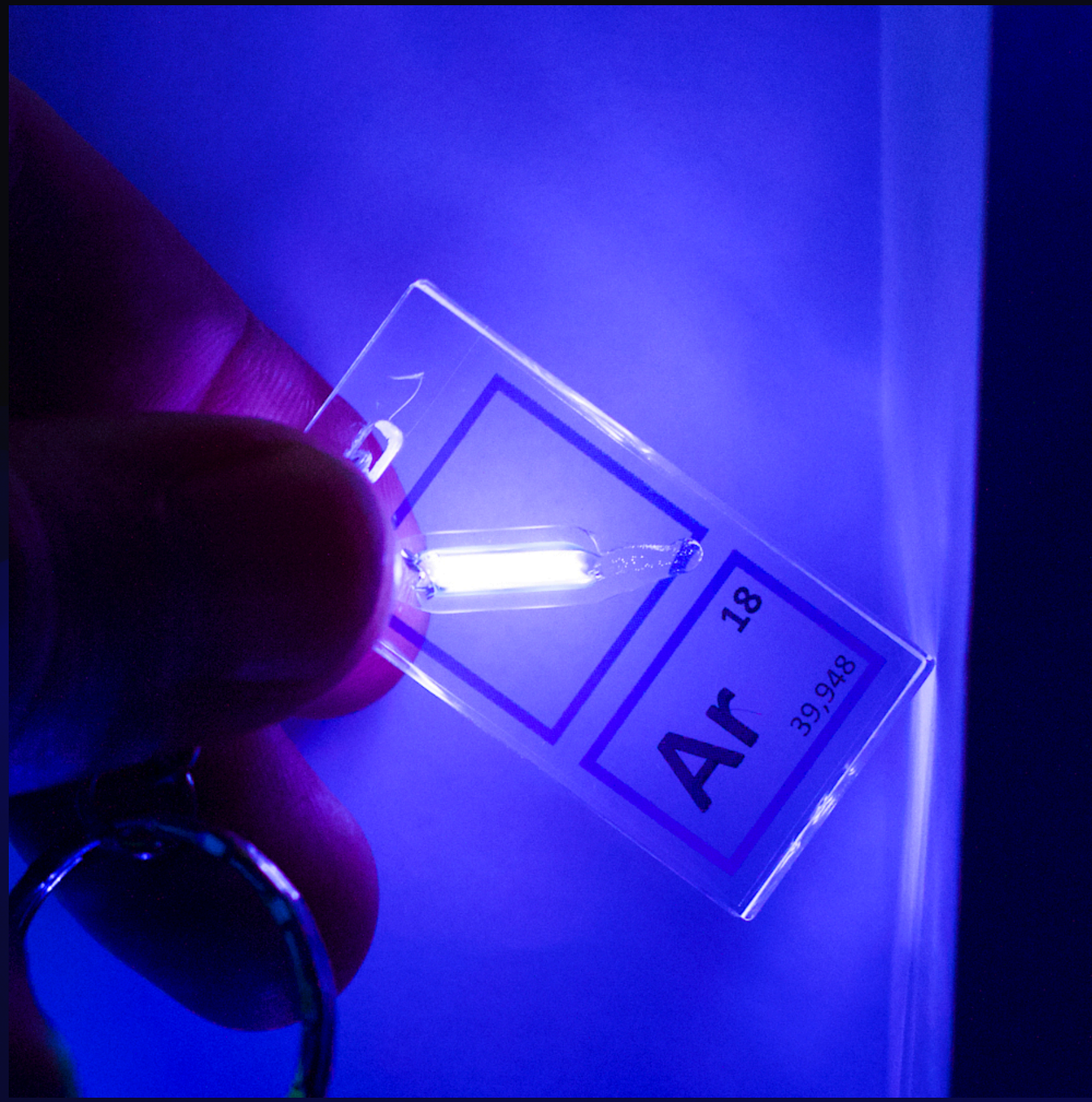
Low mass sensitivity using Migdal







Liquid Argon



DEAP-3600

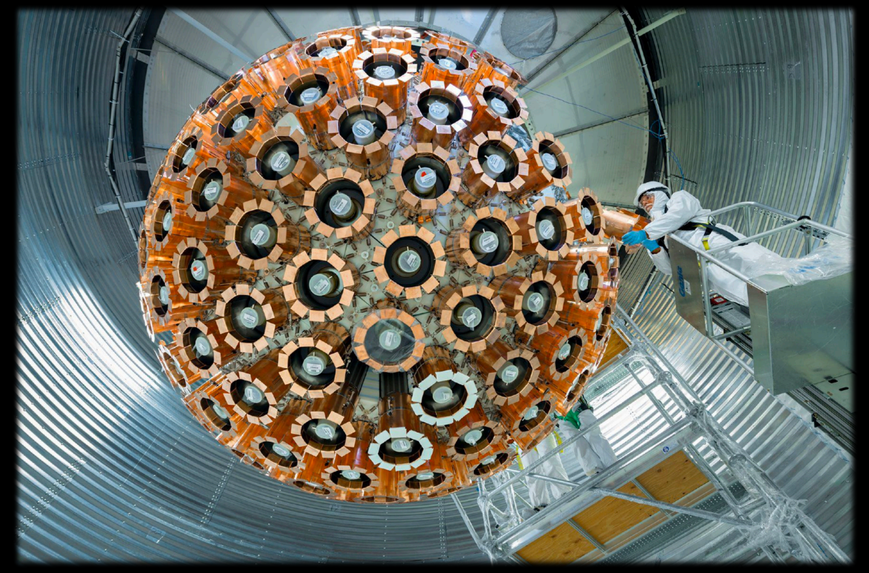
SNOLAB, Canada

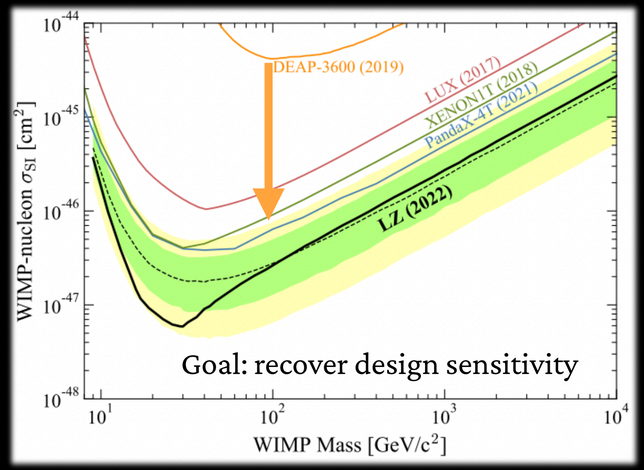
- DEAP-3600 WIMP search sensitivity impacted by “neck” background
  - Surface α-decays + condensation + poor light collection → topology mimicking NR events
- New constraints on Planck-scale mass dark matter from multiple scatters published last year
- Upgrade to be finished this year, Ar fill scheduled for winter 2022, data taking scheduled to resume in Spring 2022

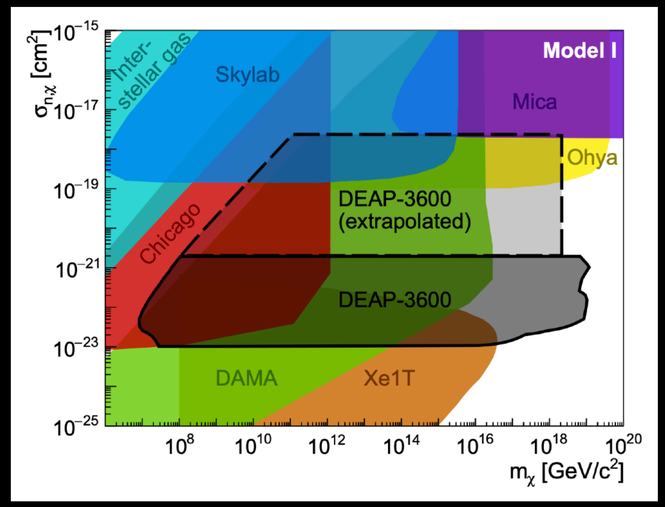
Science & Technology Facilities Council
Rutherford Appleton Laboratory

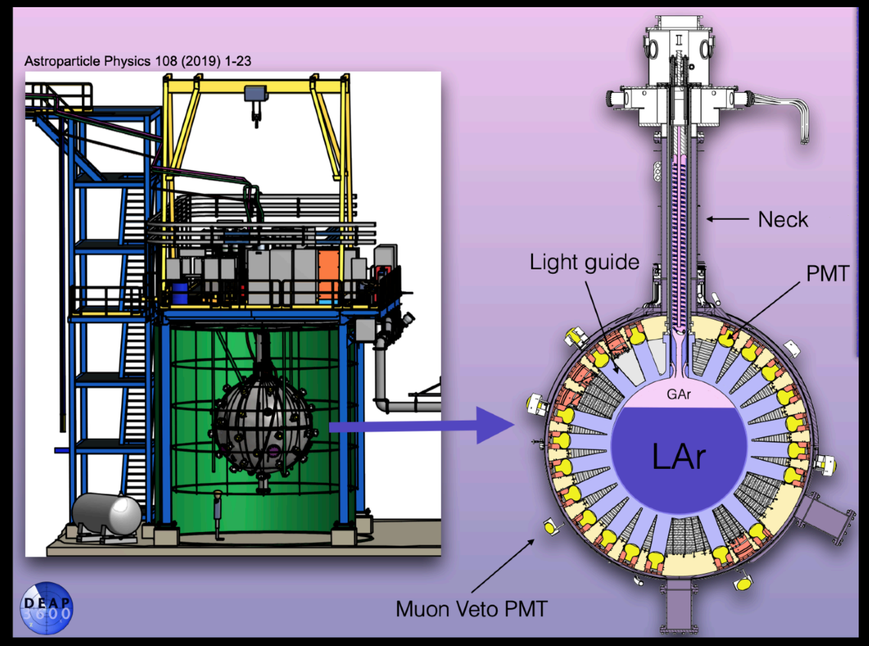
ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF SUSSEX









“Overview and recent results from the DEAP-3600 experiment”
A. Erlandson, Vienna, IDM 2022
“Constraints on dark matter-nucleon effective couplings with DEAP-3600 and prospects for the next campaign”
Vicente Pesudo, Vienna, IDM 2022

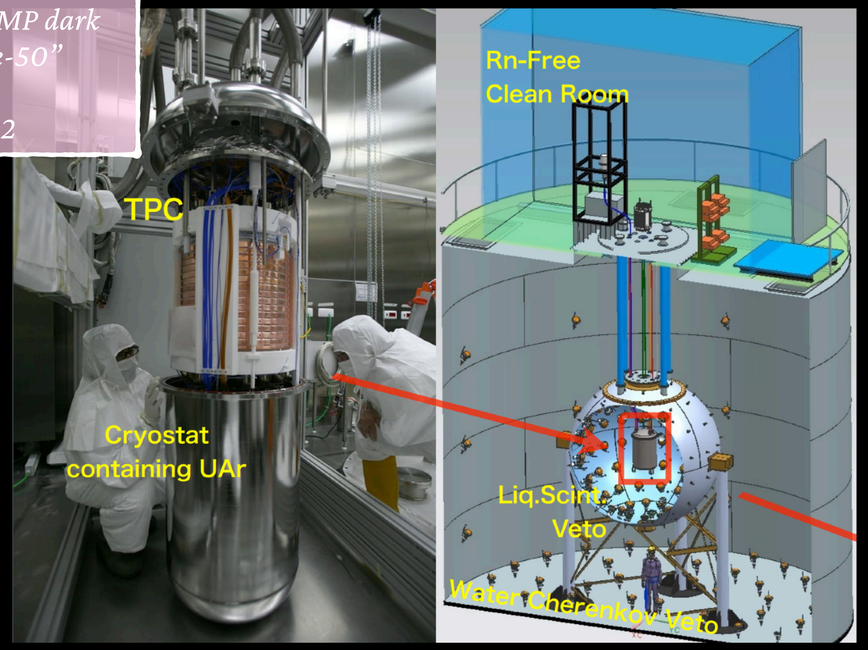
ROYAL HOLLOWAY UNIVERSITY OF LONDON

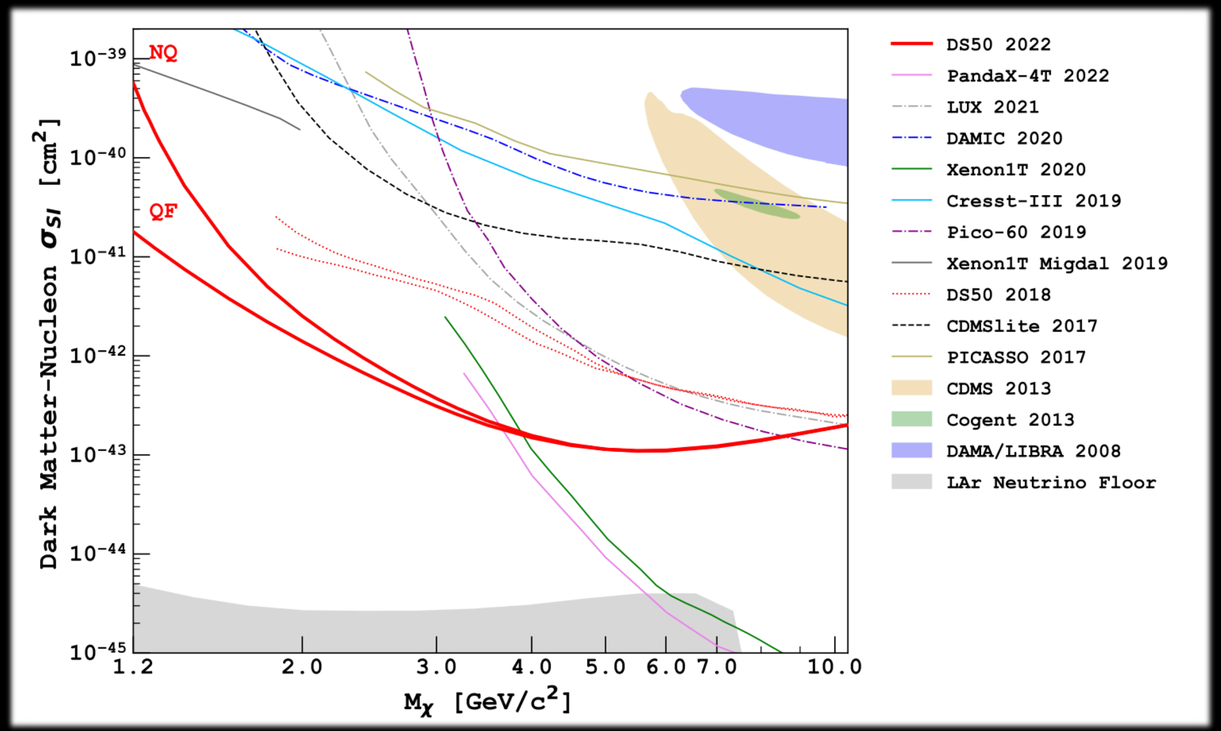
"Search for low mass WIMP dark matter with DarkSide-50"
Masato Kimura
Vienna, IDM 2022

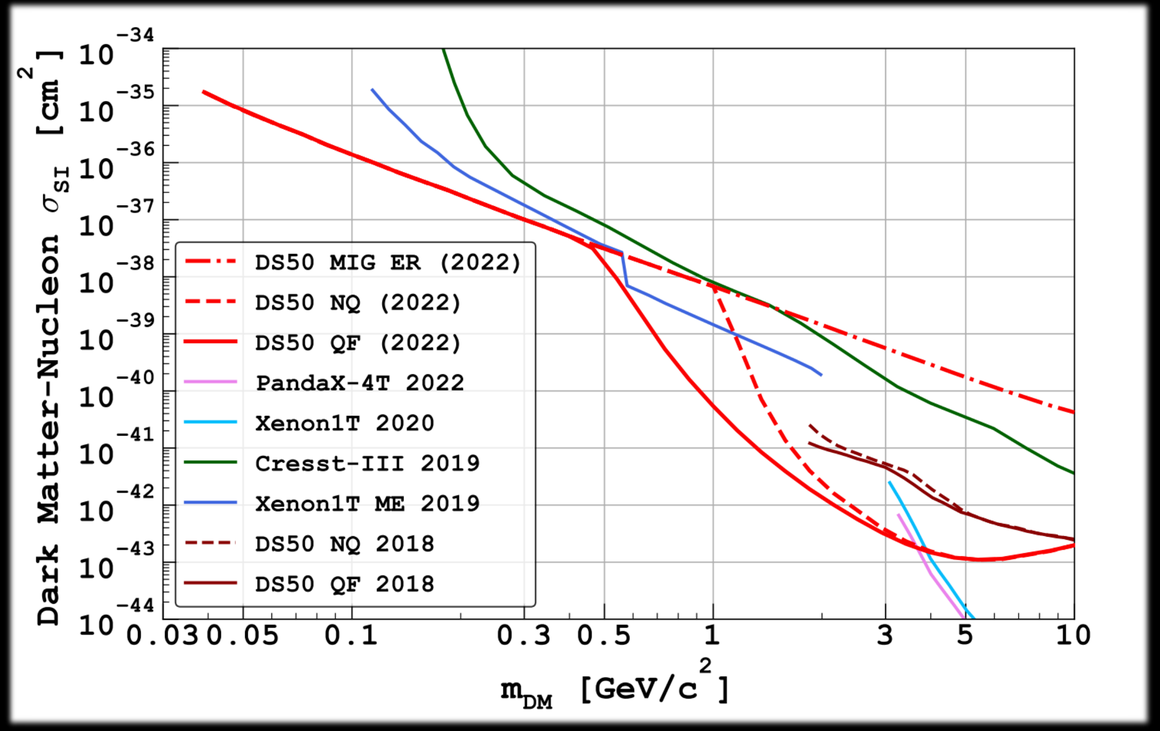
Darkside-50

LNGS, Italy

- Dual phase liquid Argon TPC: 46.4 kg of Underground Argon (UAr)
- Recent updates to low mass WIMP search
  - Extended exposure, improved data selection, better calibration, better background modeling
- Additional new sub-GeV limit using Migdal Effect



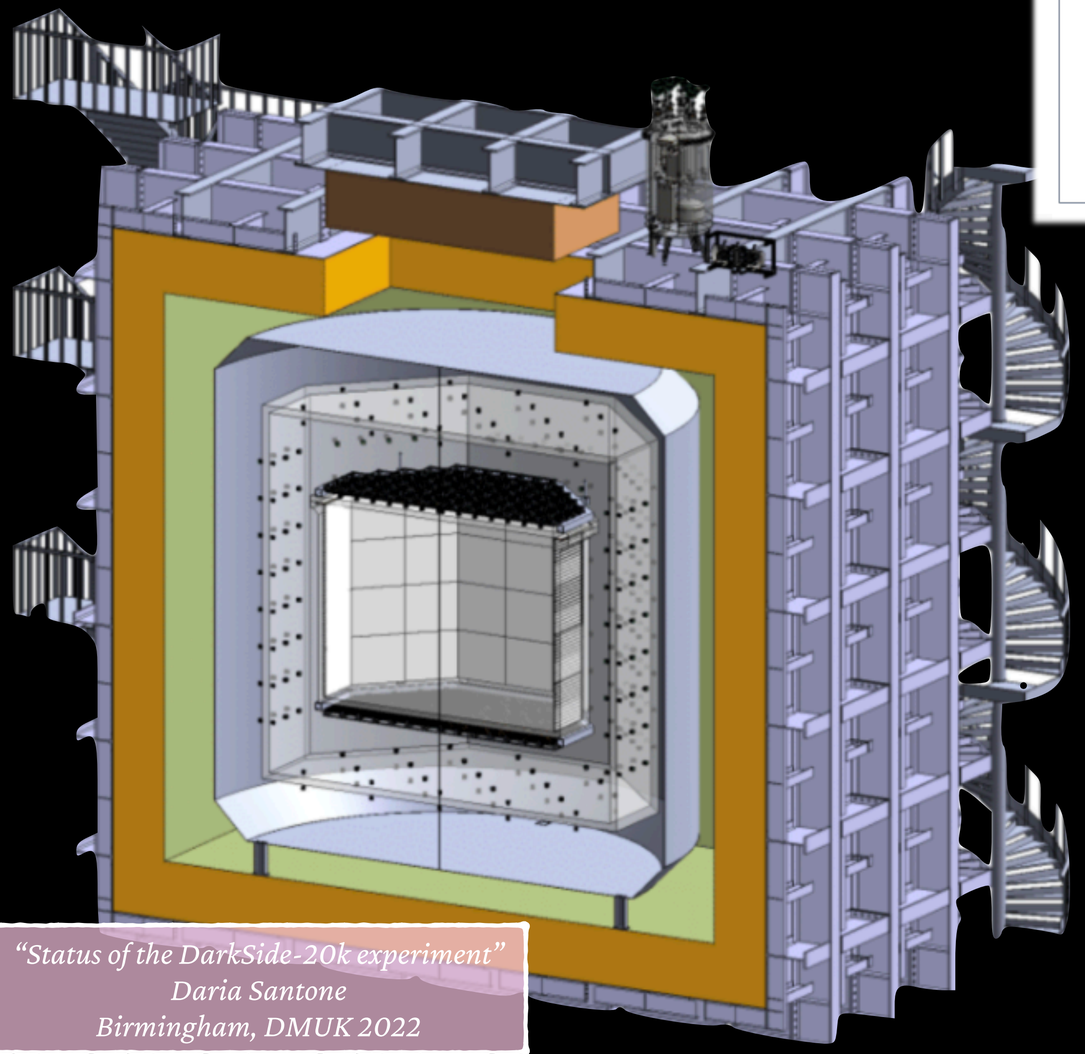


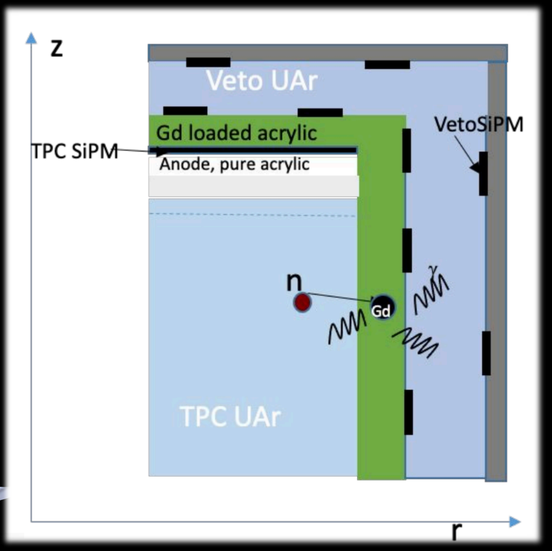


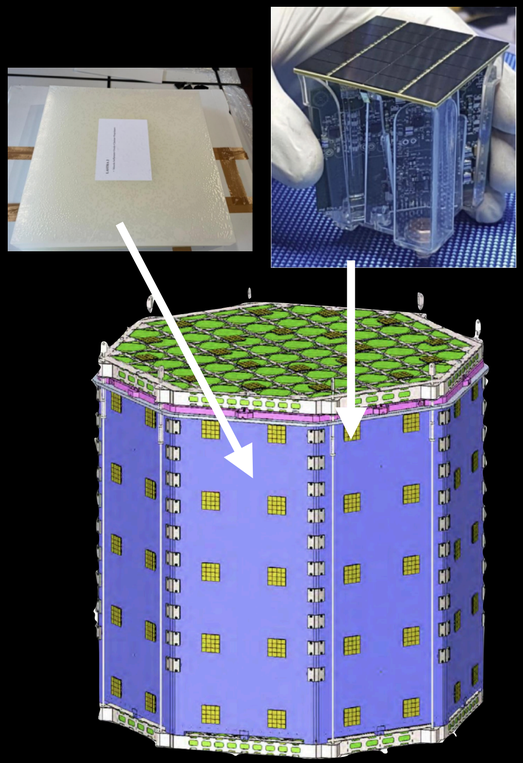
Darkside-20K

DS-50 + DEAP + MiniClean + ArDM

- Dual phase liquid Argon TPC: 50 tons of Underground Argon (UAr)
- Gadolinium loaded acrylic (Gd-PMMA) surrounding TPC wall for neutron capture
- Single phase, 35 ton UAr Veto detector
- ProtoDUNE-like cryostat hosting 650 tons of Atmospheric Argon (AAr)
- TPC & veto equipped with 28 m^2 of Silicon Photomultiplier (SiPMs) readout
- Aim to reach LZ full sensitivity in 5 years





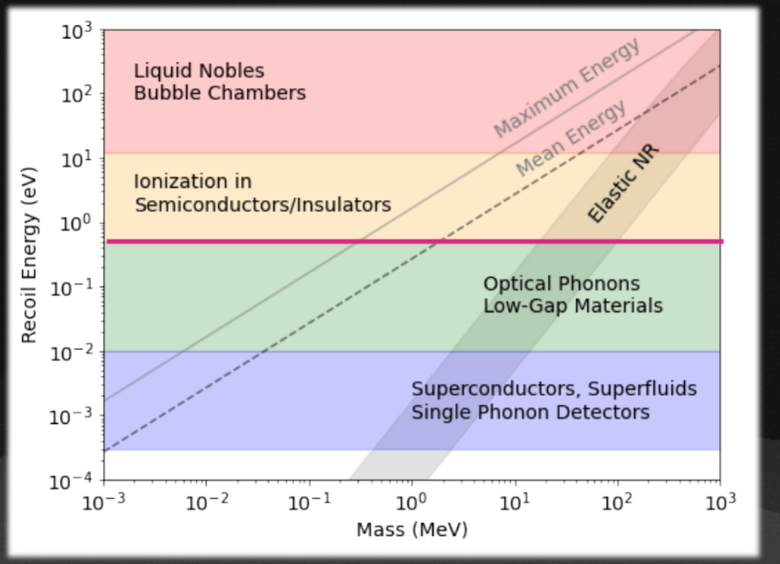


"Status of the DarkSide-20k experiment"
Daria Santone
Birmingham, DMUK 2022

Dedicated Low Mass Searches

Light Dark Matter

- LXe leads at ~1 GeV+ but low mass sensitivity fundamentally limited by ionisation energy of Xe (13 eV) → For MeV DM maximum kinetic energy is ~ 1 eV
- Mix of DM-nucleus, scattering DM-e scattering and both depending on the model
- Need **different technology** - lots of small scale experiments currently probing the low mass regime & proposals for upgrades for larger experiments e.g. H-doping in LZ (HydroX)



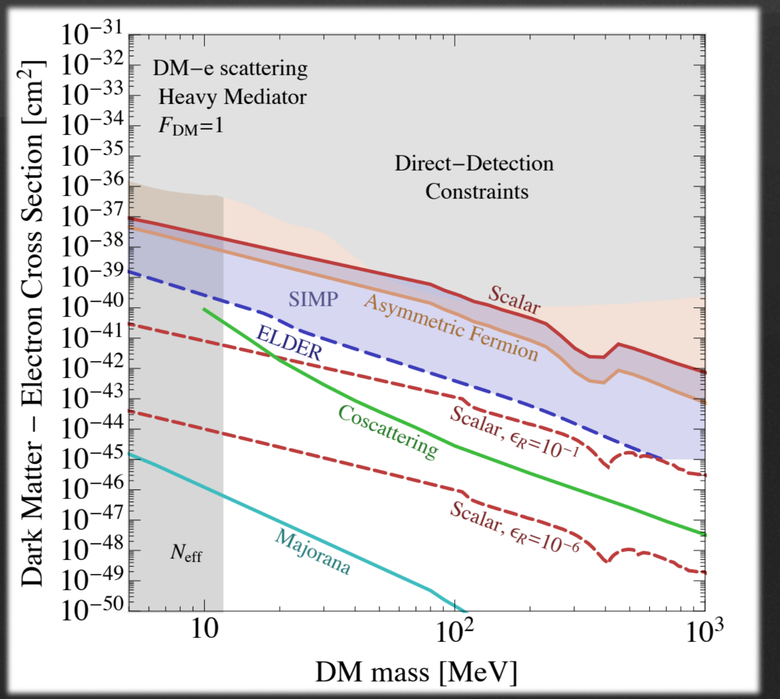
Experiments specifically designed for low mass:

- SuperCDMS (Si, Ge)
- DarkSide-LowMass (LAr)
- SENSEI (Skipper-CCD)
- DAMIC-M (Skipper CCD)
- CRESST-III ($CaWO_4$,$LiAlO_2$, Al_2O_3, Si)
- NEWS-G (Ne/methane SPC)

Larger experiments that can employ special techniques/ considering upgrades:

- LZ
- XENONnT
- Darkside-20K

"The landscape of low-threshold dark matter direct detection in the next decade" Snowmass2021 Cosmic Frontier arXiv:2203.08297



This is by no means an exhaustive list of light DM candidates....

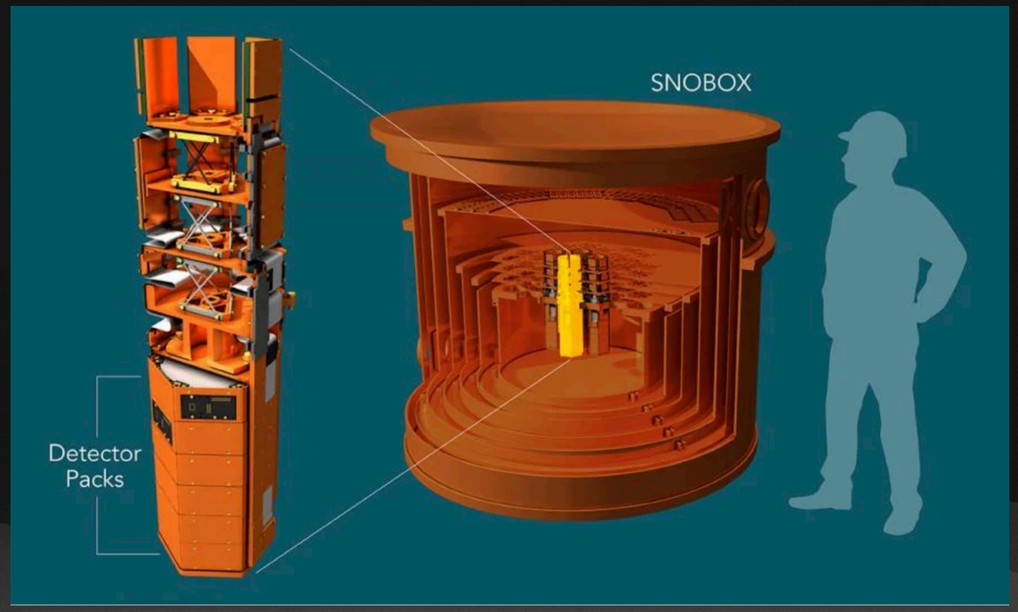
Candidate	Light WIMPs	Solar Axion	ALPs	Sterile ν	Hidden Photons
Mass	sub-GeV	μeV - meV	10^{-11} - 10^{3} eV	keV	1 keV - 10 GeV
Detection Methods	ionisation-only searches, phonons, Migdal effect, doping of LXe with light elements	Axio-electric effect (ER spectrum), conversion to γ in microwave cavities	Axio-electric effect (mono energetic ER), conversion to γ in microwave cavities	Decay to ν through active/ sterile mixing	Dark photo-electric effect, decay products

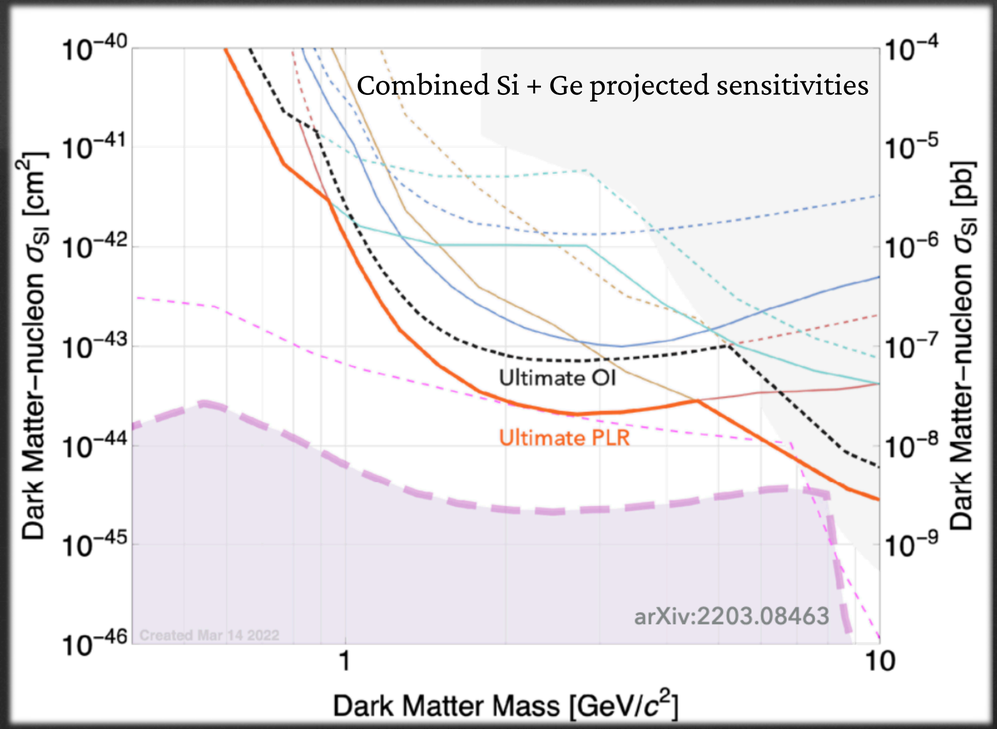
SuperCDMS

SNOLAB, Canada

- Target materials: Si (0.6 kg), Ge (1.4 kg)
  - ~1000 sensors per crystal
- Two types of detector: Interleaved Z-sensitive Ionization and Phonon (iZIP) & High Voltage (HV)
  - iZip → ER/NR discrimination
  - HV → low threshold
- Timeline: testing and characterization is ongoing
  - Commissioning: 2023
  - First underground testing & early science: 2024
  - First science run with initial payload: early 2024
  - First results: 2025

"Overview of the SuperCDMS experiment"
Matthew Wilson
Vienna, IDM 2022





Darkside-LowMass

Under Consideration

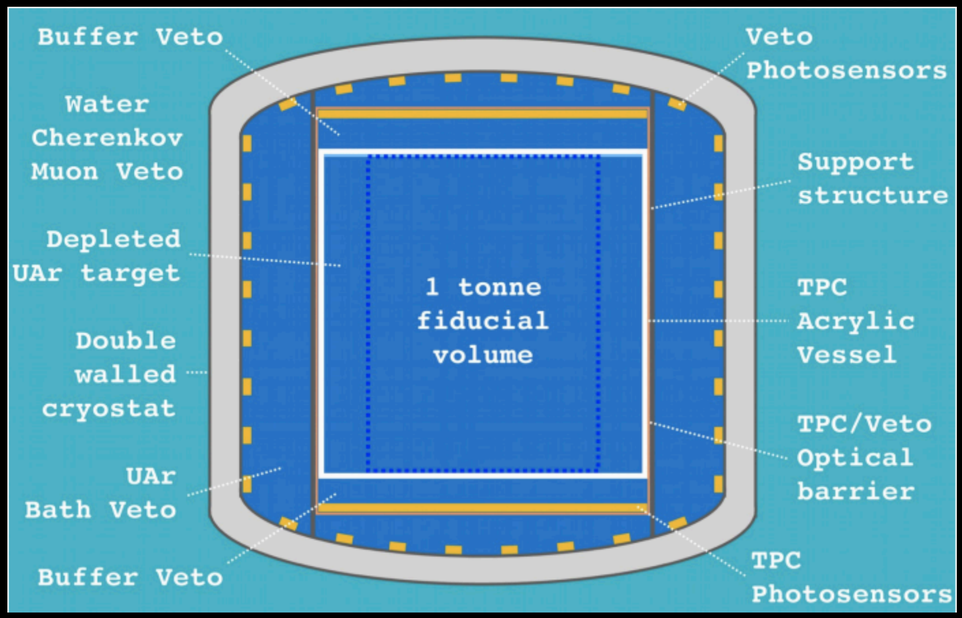
Dedicated tonne-scale TPC for S2-only searches.
Proposed location: **Boulby, UK**

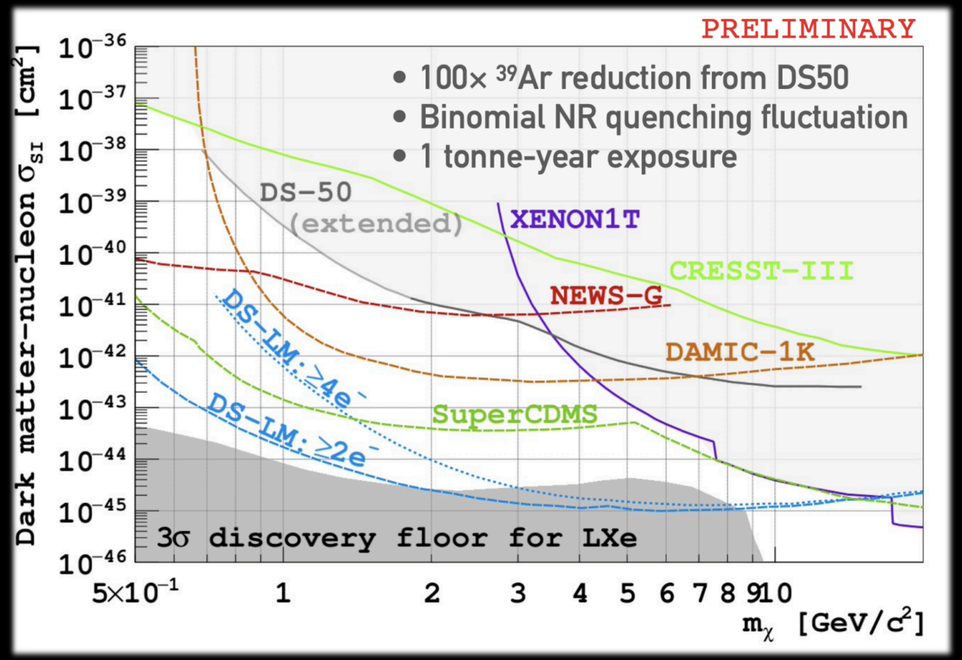
Needs:

- Reduction of Ar radioactivity to reach 1 μBq/kg (with UAr and Aria distillation column)
- SiPM radioactivity reduction to 1 mBq/PDM (x20 reduction on current generation)
- An Outer Detector to veto single neutron scatters (WATCHMAN?)

First phase: Ultrapure UAr (1 μBq/kg) and SiPMs (1 mBq/PDM) building on STFC-funded UK R&D
Potential second phase: doped LAr (Xe, allene, He) for reach and extra sensitivity

"DarkSide-20k experiment and its veto" - Marek Walczak , Queen's University, Canada, TeVPA

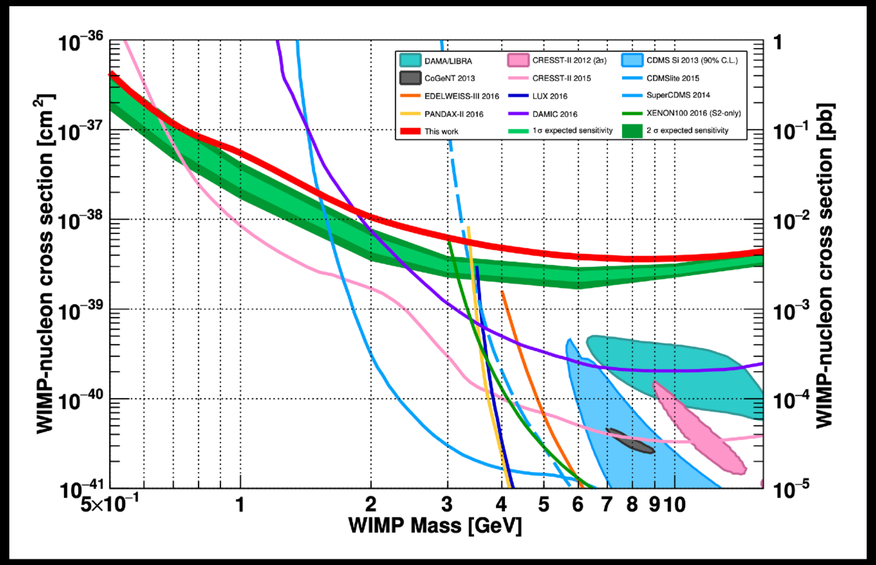




NEWS-G

SNOLAB, Canada

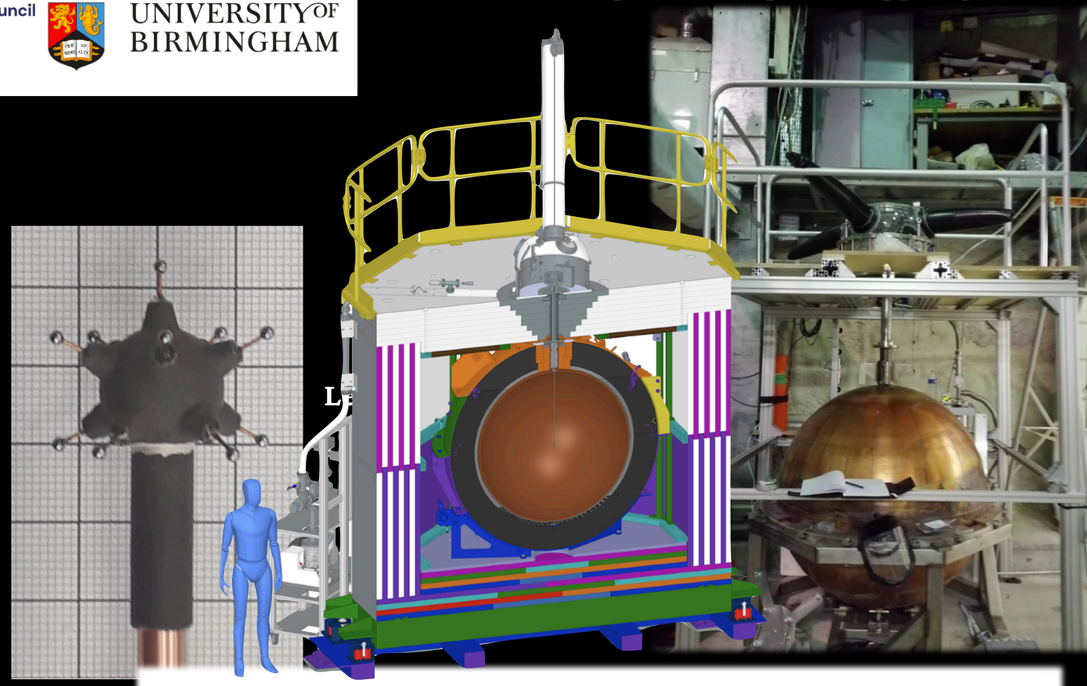
- Sub-GeV DM detection with Spherical Proportional Counters
- SEDINE - 60cm prototype, Ne+CH_4 target results published in 2018
- 135cm detector being commissioned at SNOLAB
- New measurements of quenching factor of neon nuclei in neon gas using TUNL neutron beam

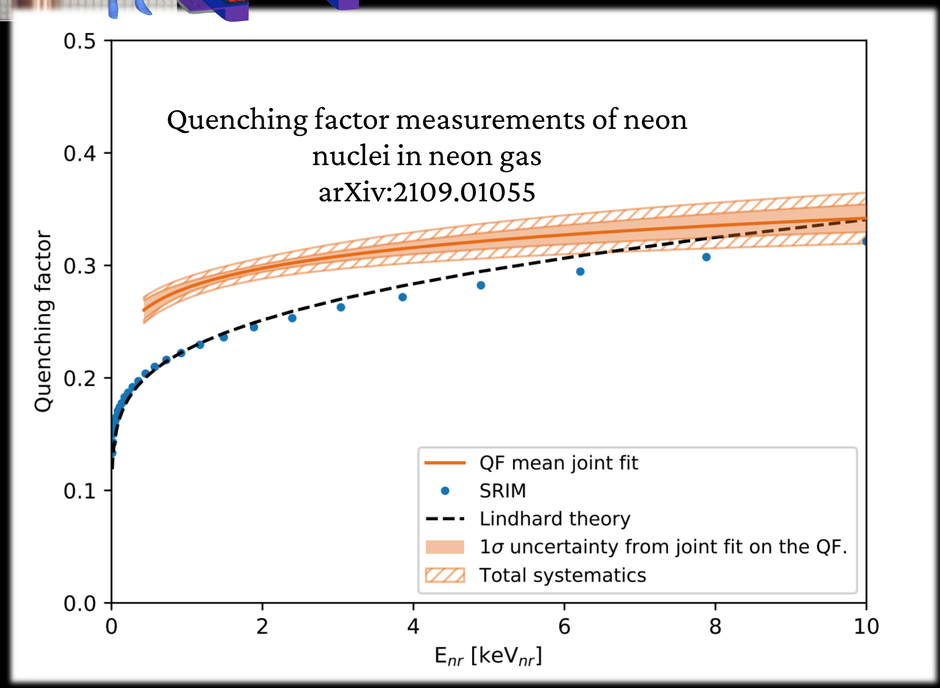


"The NEWS-G detector at SNOLAB"
arXiv:2205.15433

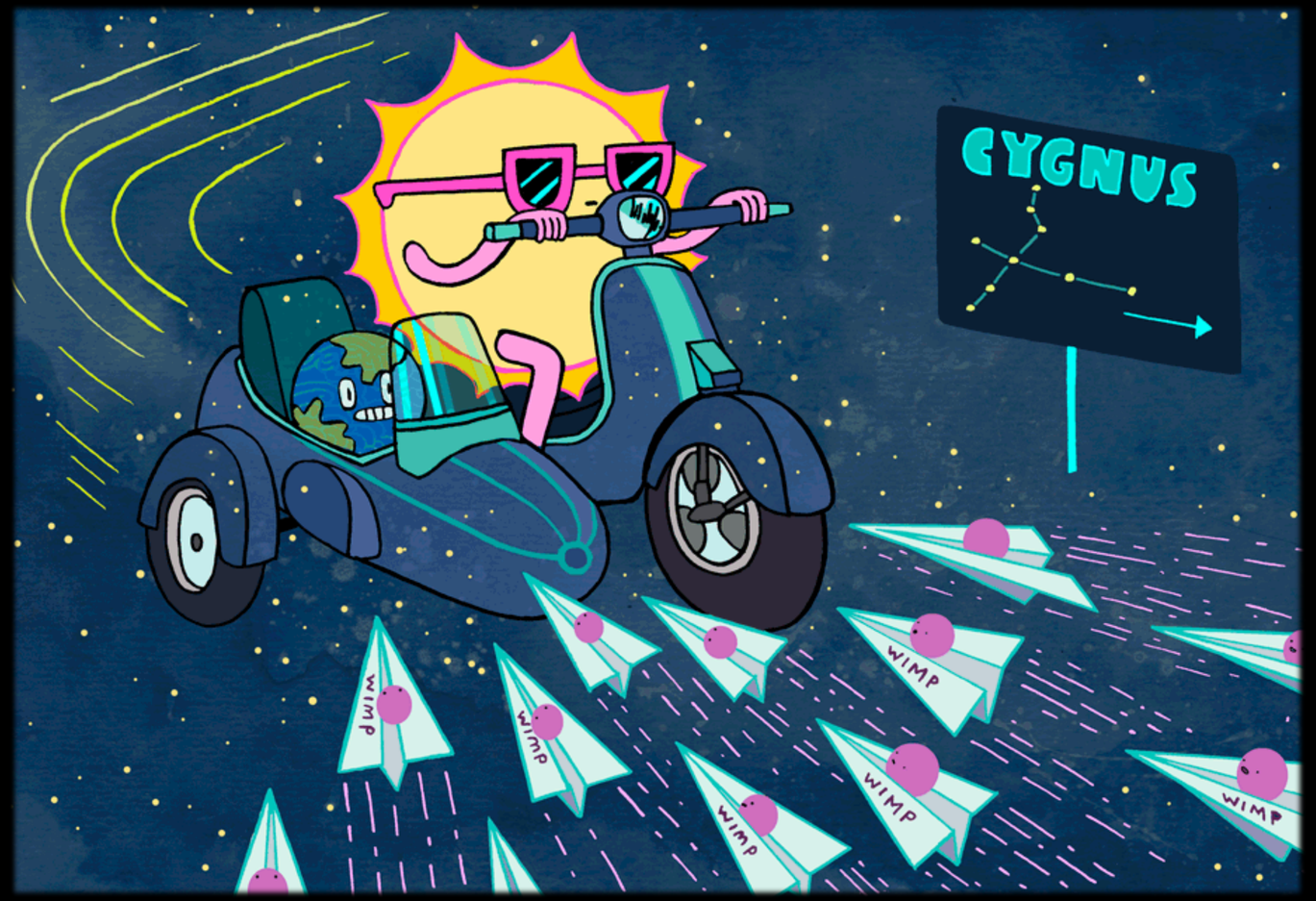
"Status and Future Prospects of the NEWS-G Experiment"
P Knights, Vienna, IDM 2022

Ultrapure electroplated copper sphere





Directional Detection

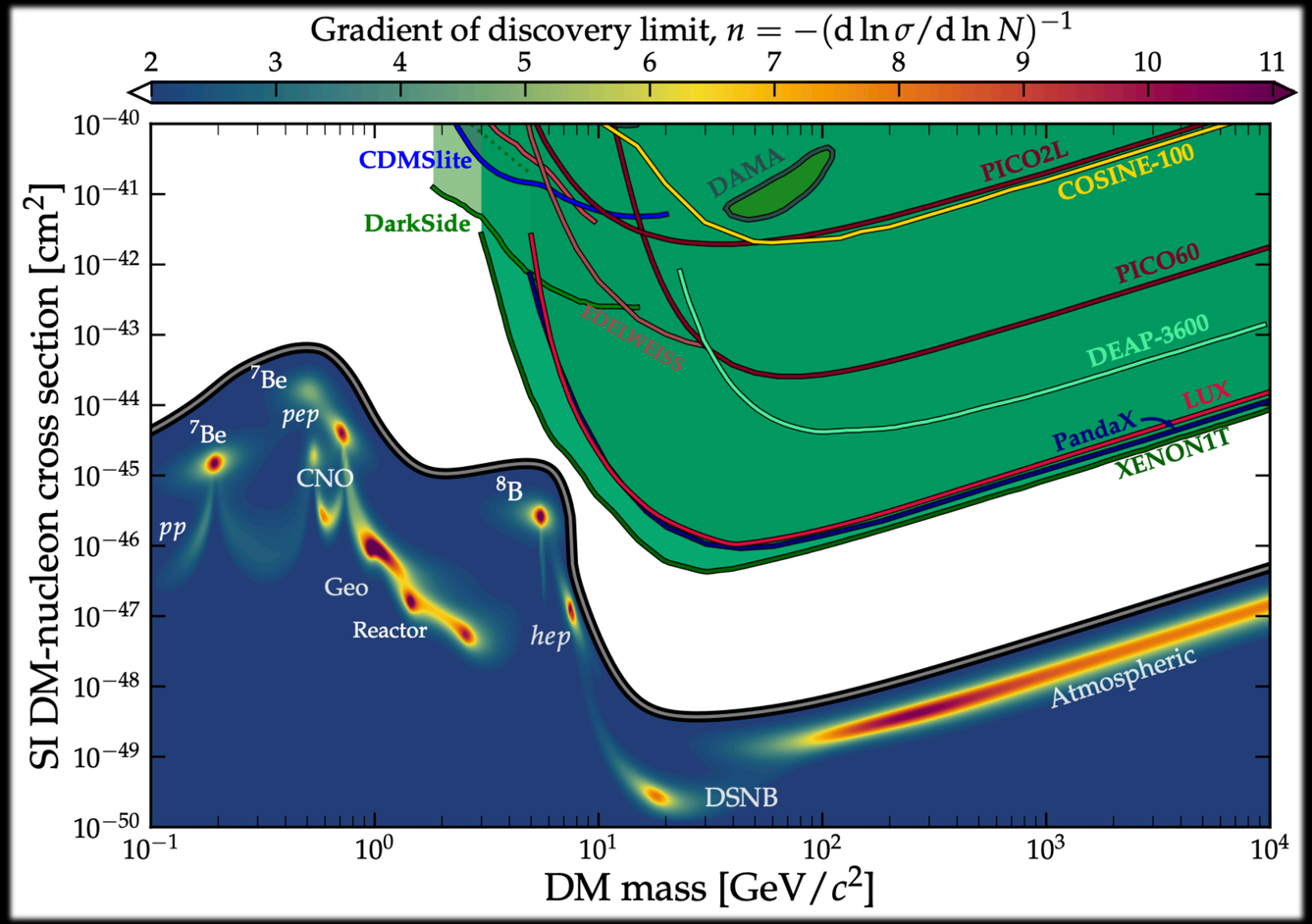


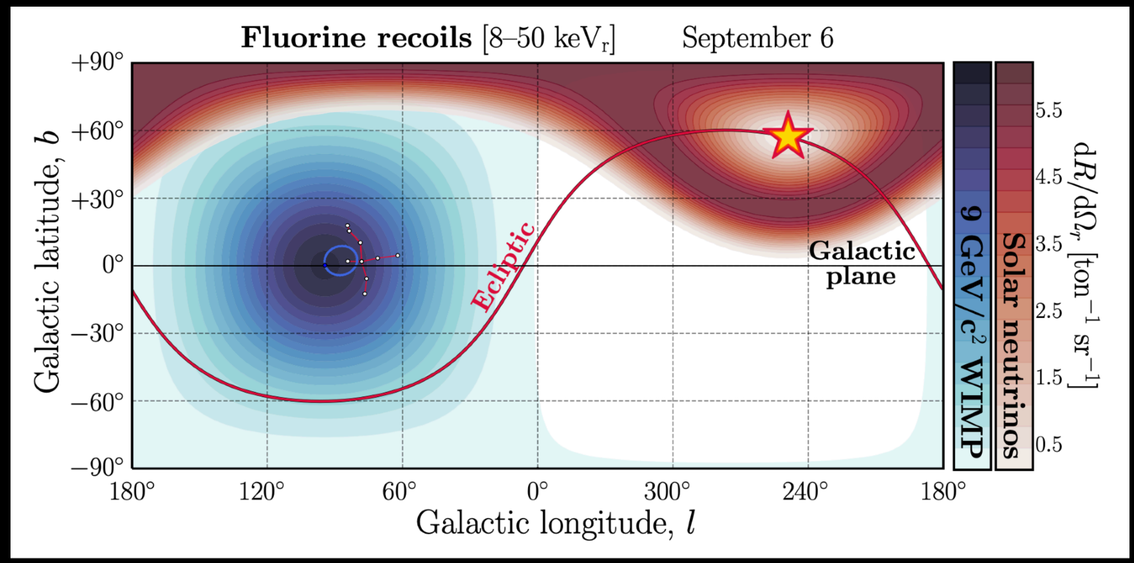
Directional Detection

Overcoming the Neutrino Floor/Fog*

*The neutrino fog is defined to be the regime for which n > 2, with the neutrino "floor" being the largest cross section for each mass where this transition occurs

Direct DM experiments will soon be limited by detecting CEνNS from astrophysics neutrinos





Directionality allows clear discrimination of neutrinos (position tracks the sun) from DM (always from Cygnus)

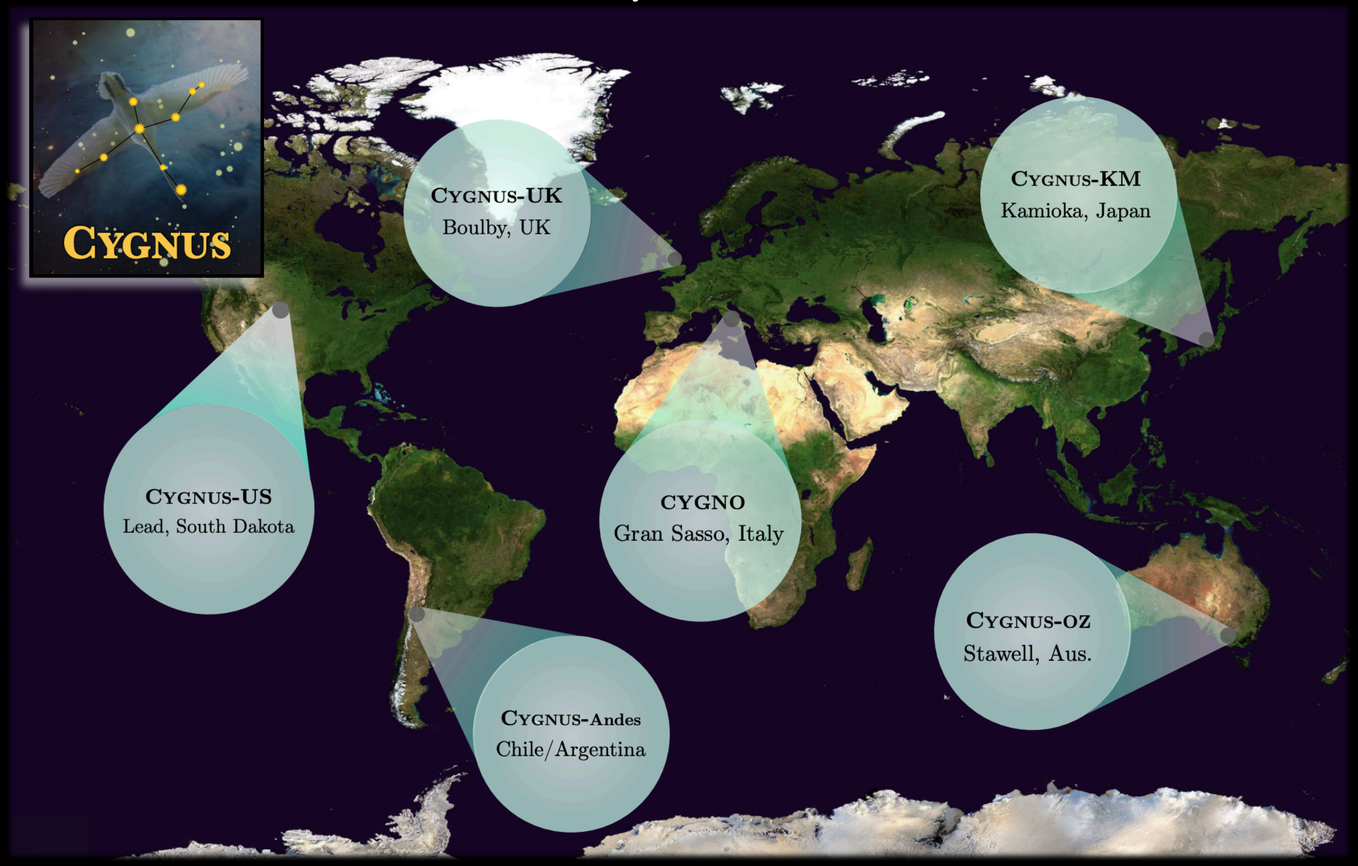
CYGNUS

A Galactic Nuclear Recoil Observatory using low-density gas TPCs

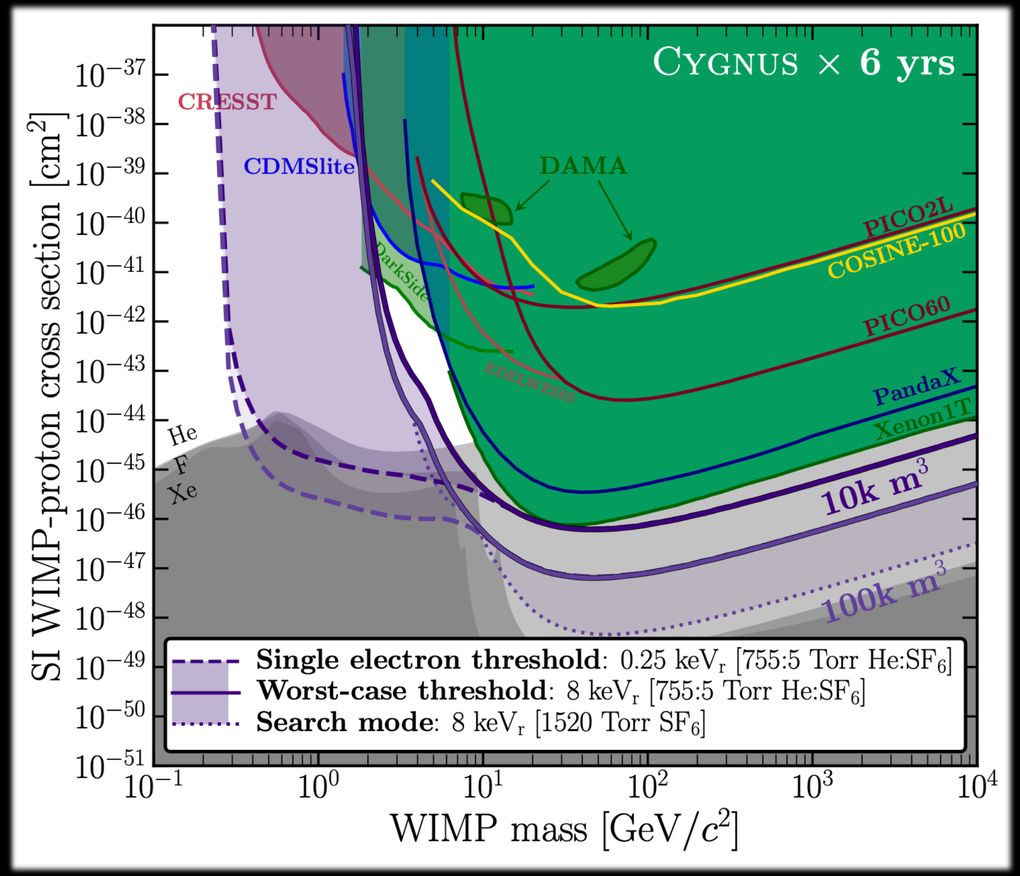
The University Of Sheffield.

Science and Technology Facilities Council

Long term CYGNUS Vision: Multi-site Galactic Recoil Observatory with directional sensitivity to WIMPs and neutrinos

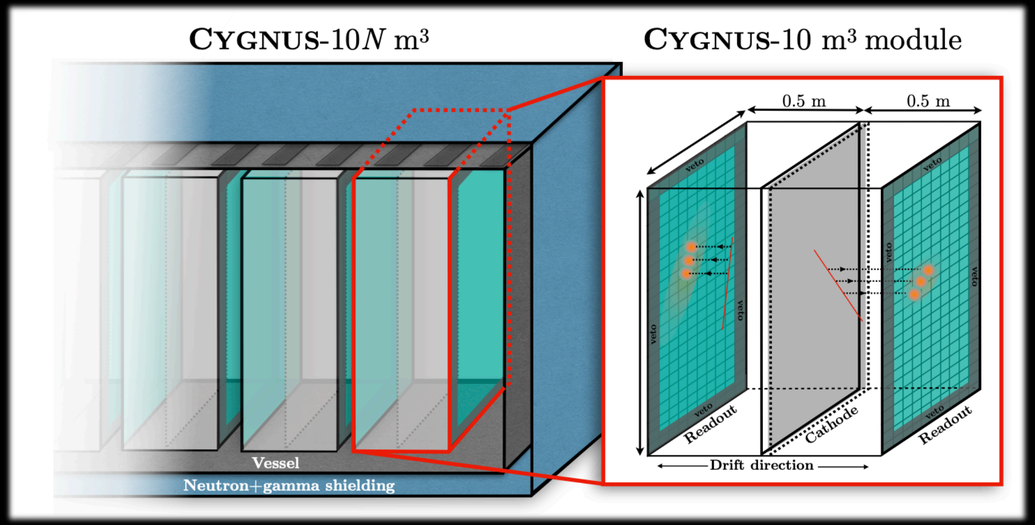


Targeting low-mass WIMP region (~10 keV) with directionality and recoil discrimination



CYGNUS
Directional R&D

"CYGNUS: Directional Neutrino and Dark Matter Detection"
Sven Vahsen, Seattle, SNOWMASS 2022

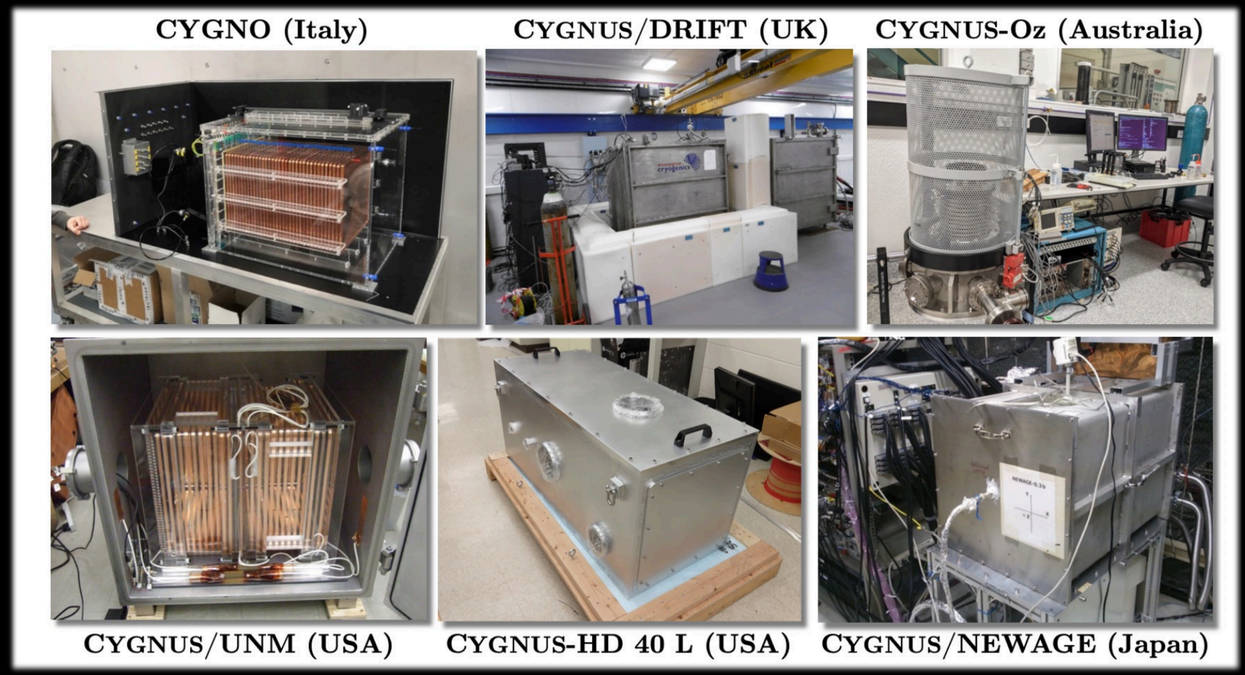


- **DRIFT**: Directionality pioneer based at Boulby
- **CYGNUS**: International collaboration of directionality experiments
  - 1-10 m3 unit cells, ~ 100-1000 cells
  - Negative ion SF_6+He target demonstrated
    - Fluorine: SD WIMP sensitivity
    - Helium: SI, low mass sensitivity
  - Recent R&D at Sheffield:
    - Multi-Mesh ThGEM (MMTHGEM) - optimisation of mesh transparency
    - Radon removal from SF6 with molecular sieves

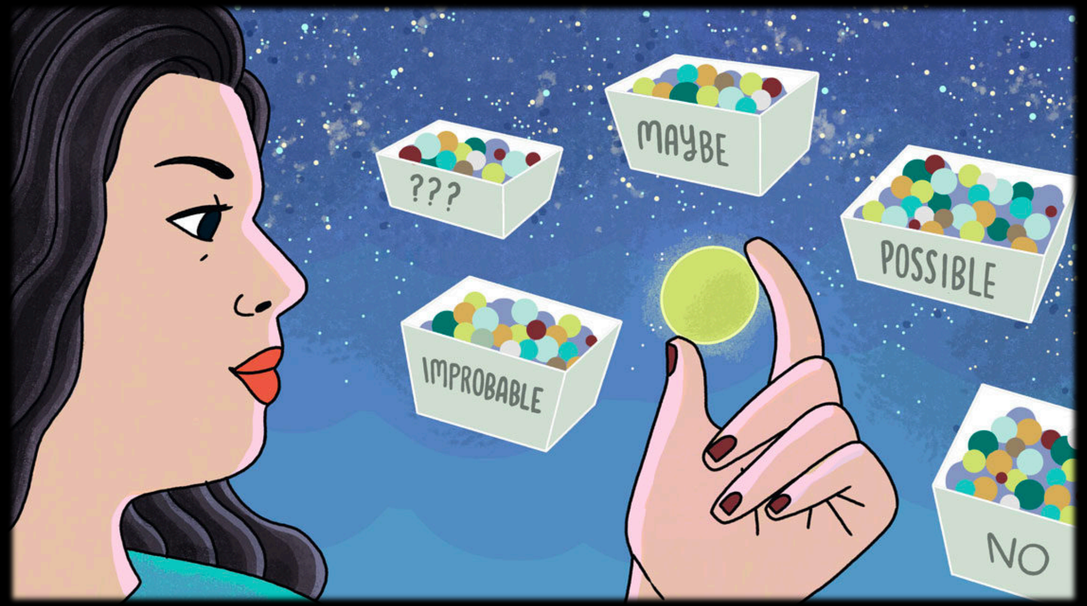
Possibility to measure directionality of CEνNS

→sensitive to new physics via recoil-angle distribution

Prototypes & Experiments



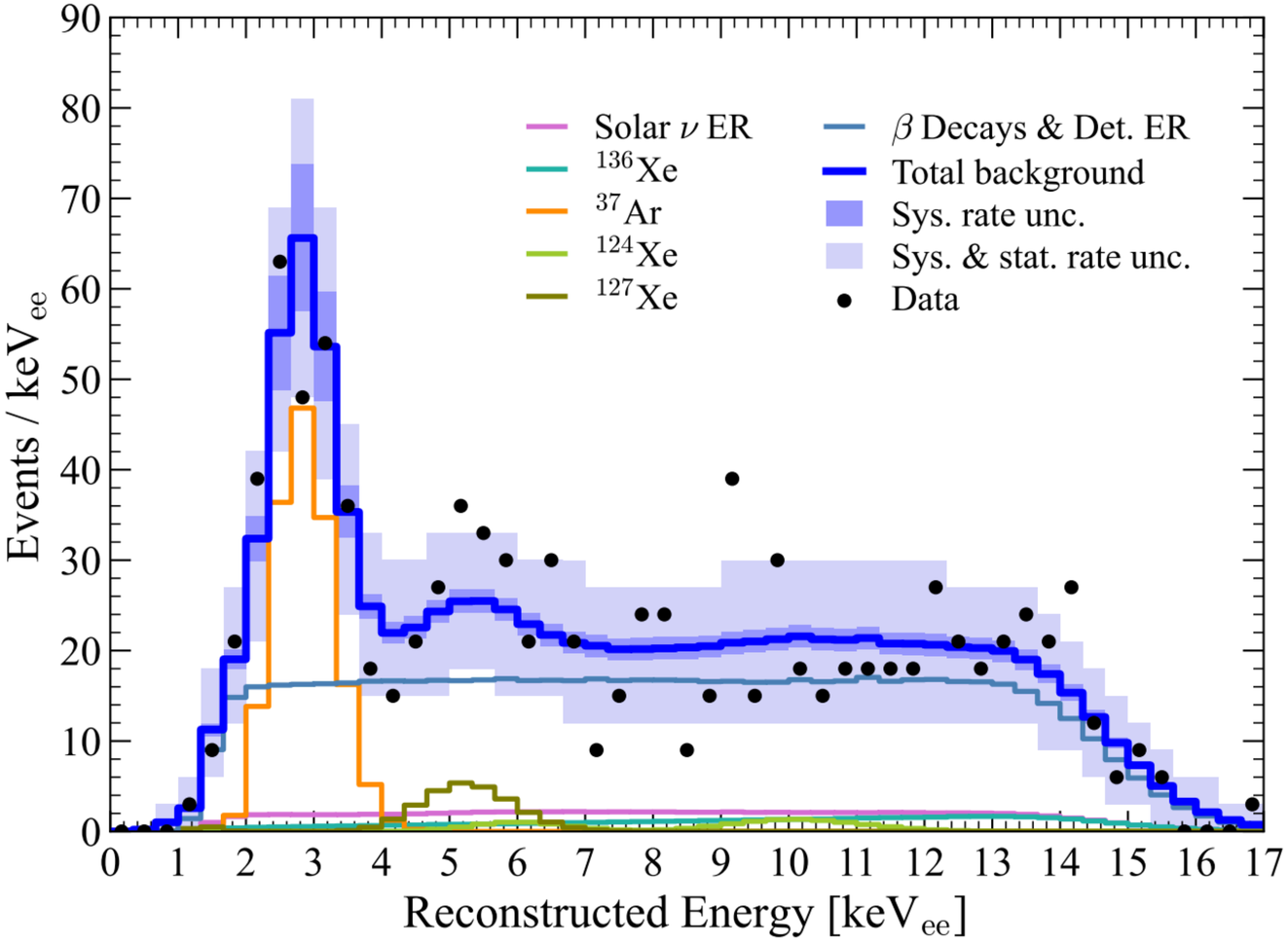
Summary

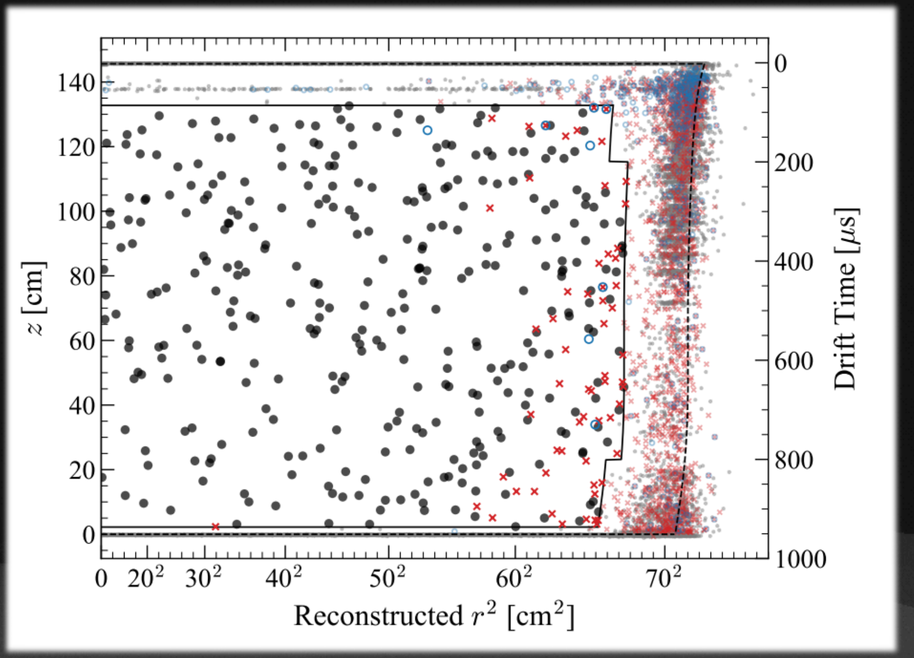


- The search for dark matter continues, and grows broader…
  - We need a dual focus on increasing **exposure** and increasing **low mass sensitivity**
- UK playing strong role in world-leading LZ experiment
  - LZ has **UK-based Physics Coordinator** (Edinburgh) & **WIMP Search Convener** (Oxford)
- Next-gen / "G3" LXe: **XLZD consortium** formed, first meeting June 2022
  - Steering Committee - ⅔ LZ members are UK -based
  - XLZD (50-1000t of LXe) will be a **Rare Event Observatory**: probe WIMPs down to neutrino fog, $0\nu\beta\beta$, other neutrino physics → upcoming paradigm shift in particle physics
- Multiple dedicated efforts to search for **low mass DM** where constraints are weak
  - UK involvement in Super-CDMS, DarkSide-LowMass, NEWS-G, CRESST-III
- **Boulby Underground Laboratory** continues to stand out as a world-leading low-background & cleanliness centre - in-situ screening, cleanliness, fabrication & operation
  - Feasibility study for Boulby as a host facility for future major international rare event search experiments is ongoing

Back Up

LZ First Science Run





Source	Expected Events	Fit Result
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Darkside-20K

Sensitivity Projection