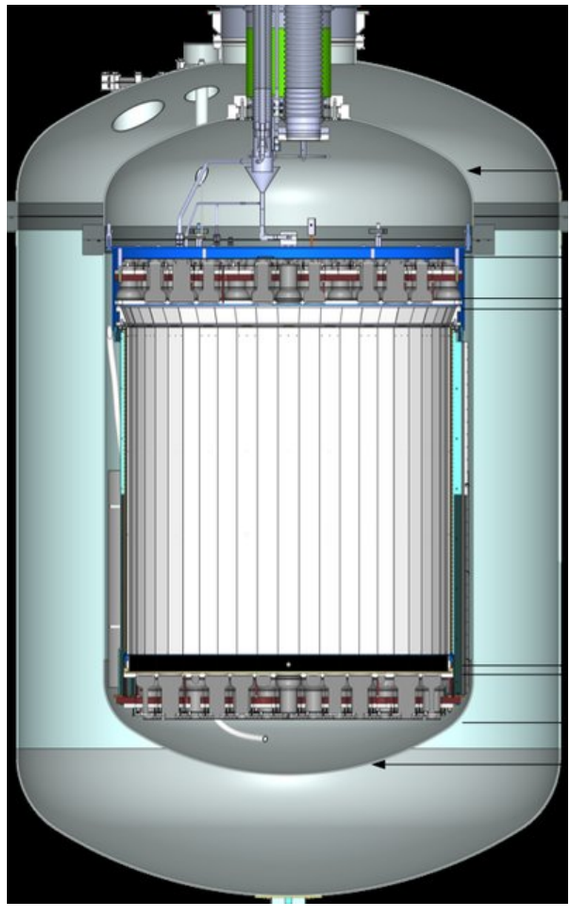
Dark matter: direct searches

Christopher McCabe

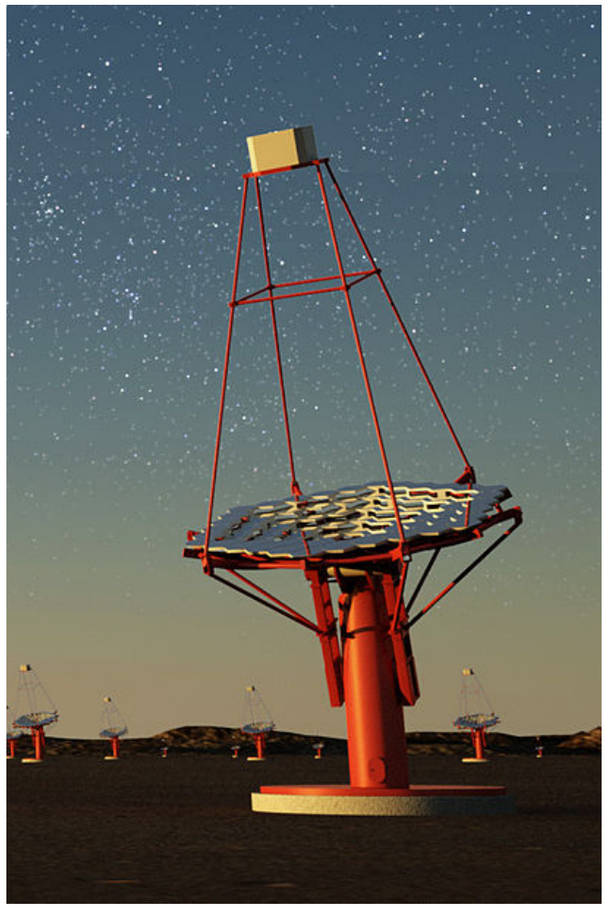
PPAP Community Meeting, University of Birmingham, 13th September 2019

Searching for DM - SM interactions

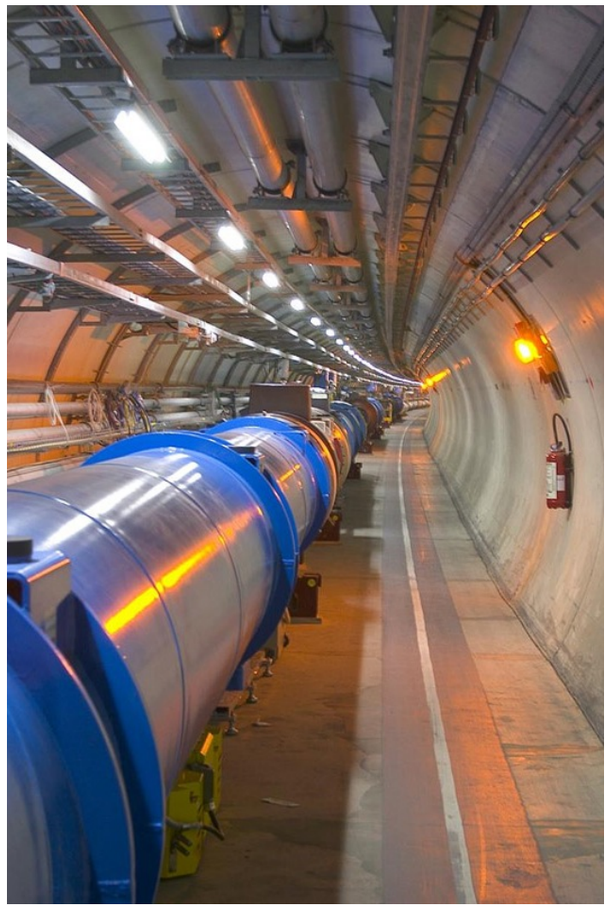
Direct detection



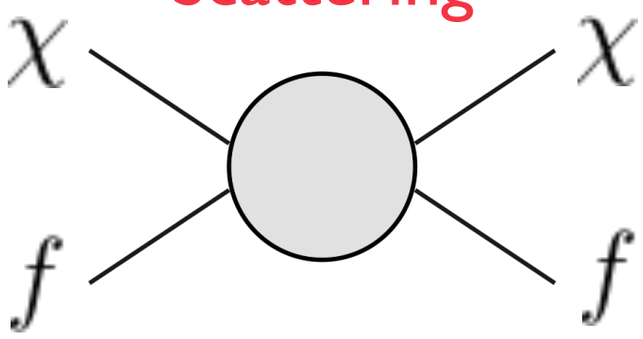
Indirect detection



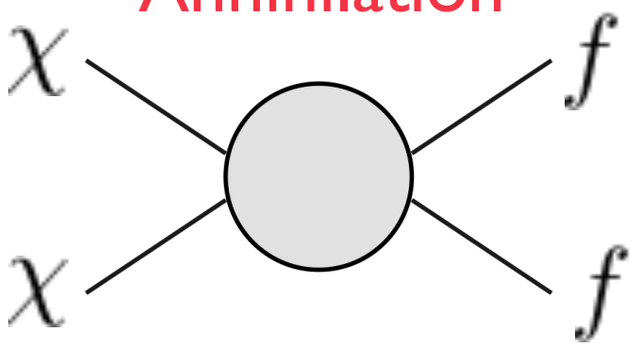
Collider



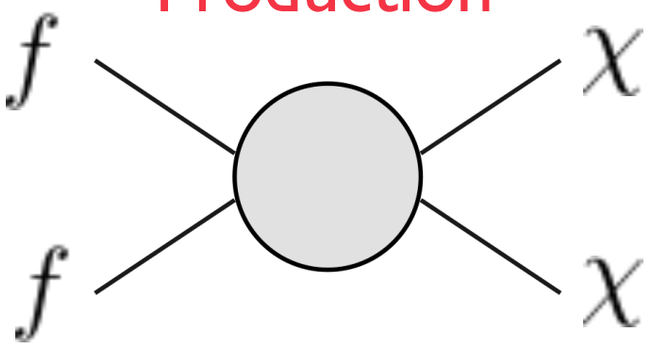
Scattering



Annihilation



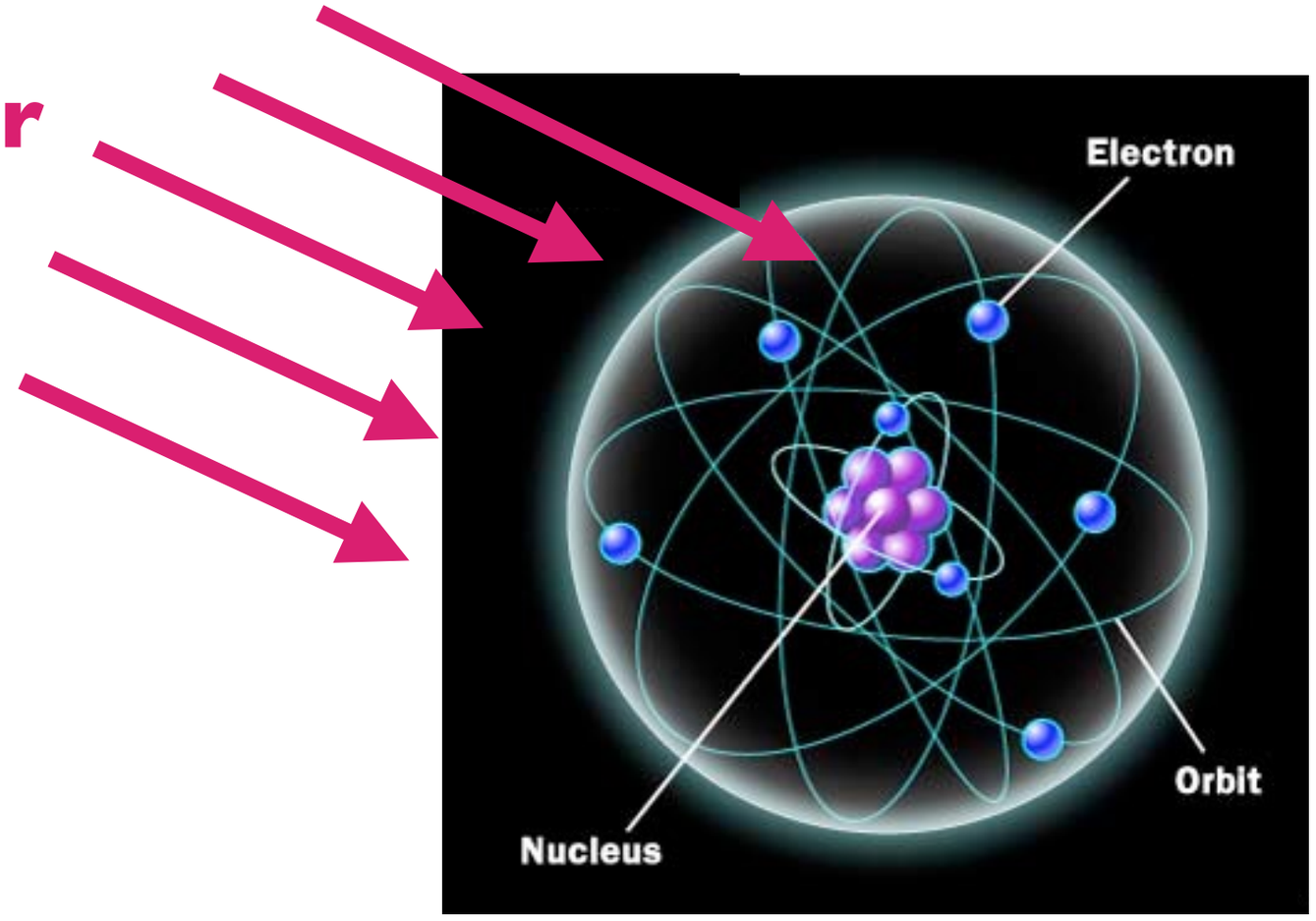
Production



Direct searches

Detect collisions of dark matter with the atom (usually nucleus)

Dark matter flux



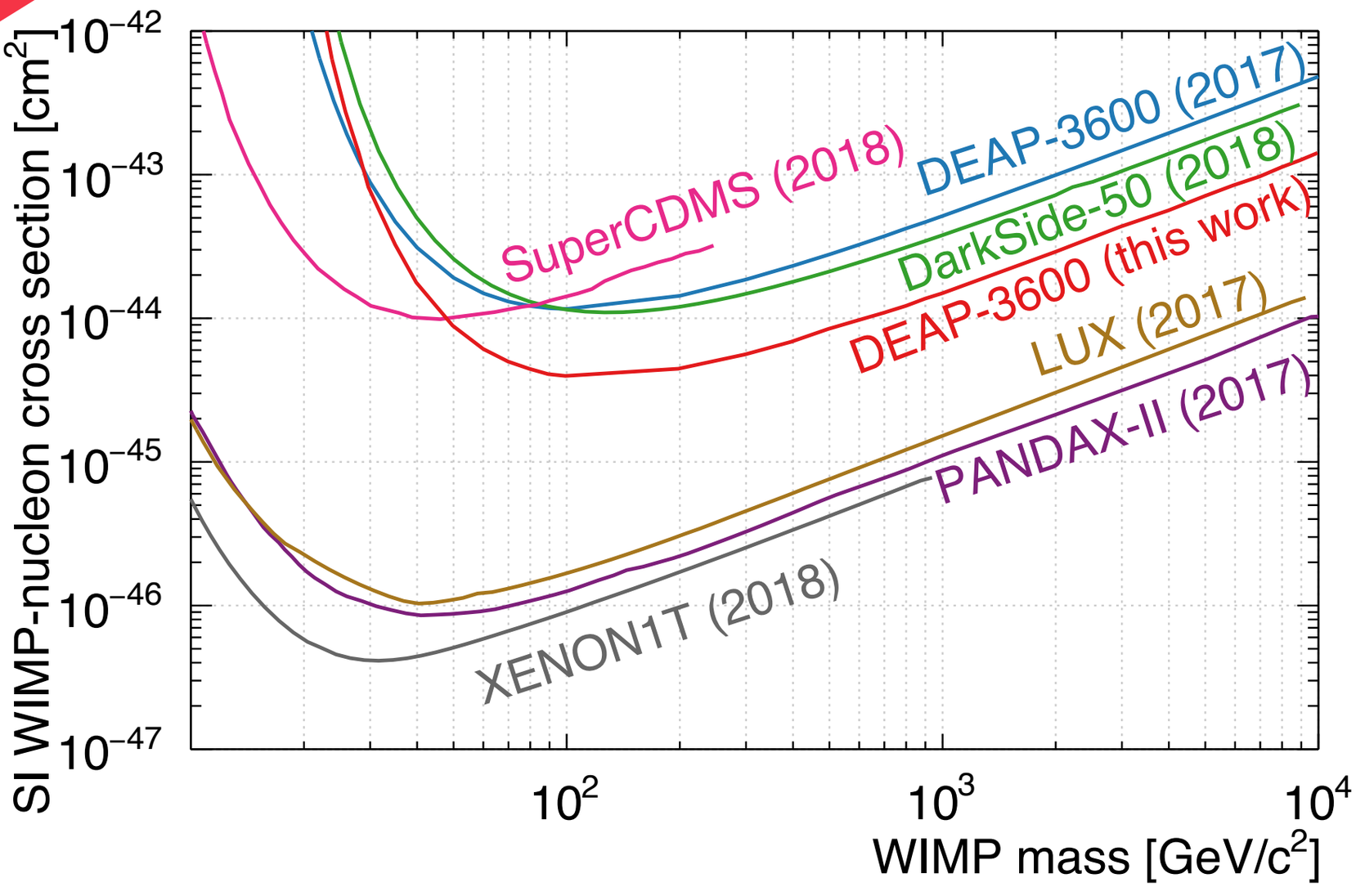
- Searching for **rare** (<1 event/tonne/year) & **low-energy** (~keV) events
- Typically elastic scattering (but also time-dependent, directionality, inelastic, electron-scattering,…)

State of play

Experiments pushing onwards in two directions

Energy threshold important

Cryogenic detectors & novel techniques

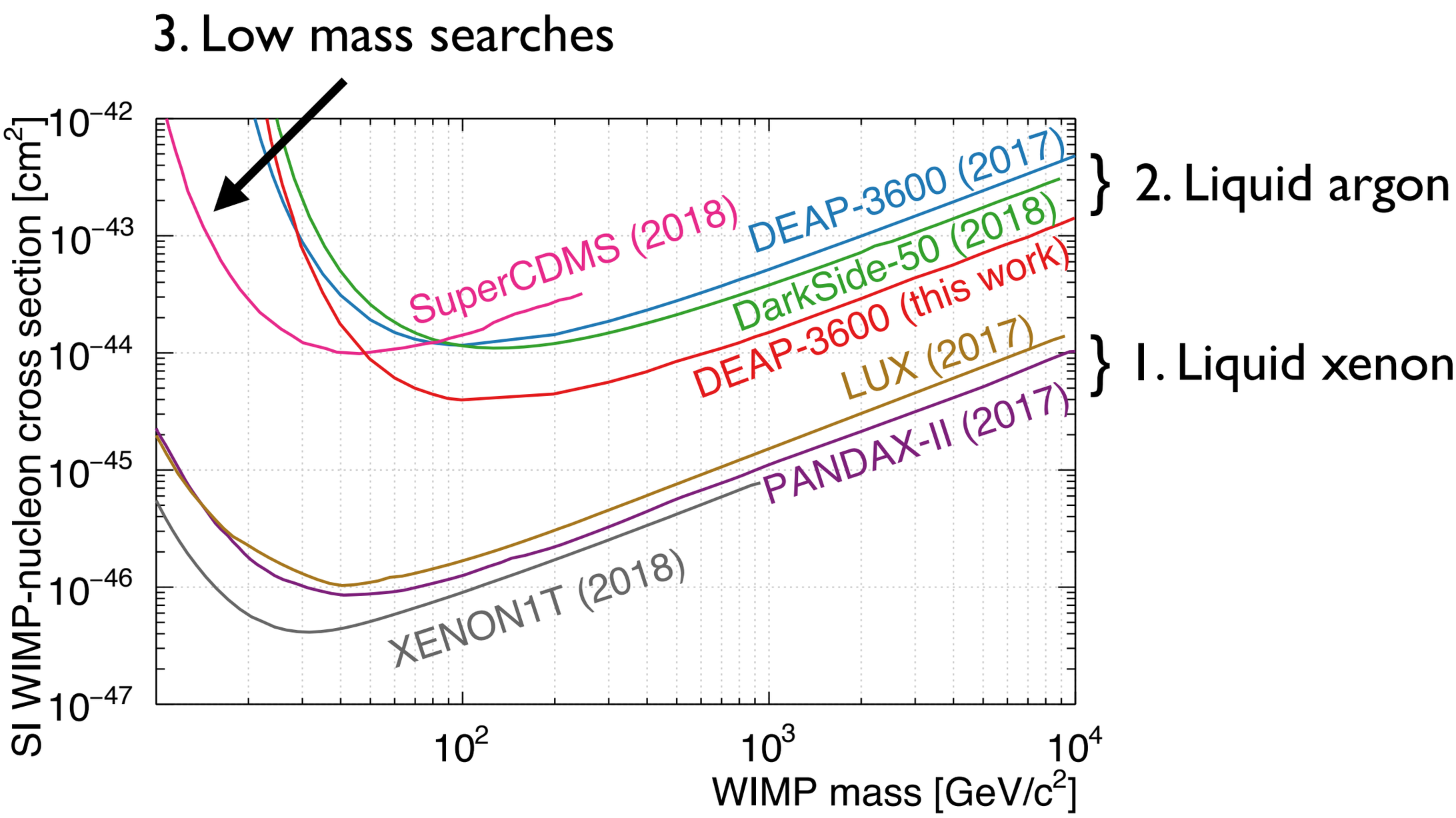


Size (x time) important

Nobel liquids

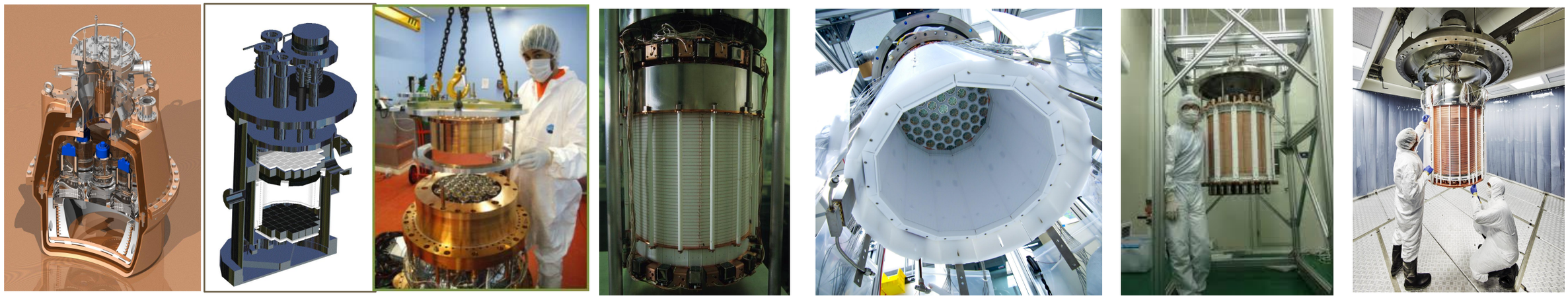
State of play

Experiments pushing onwards in two directions



1. Liquid xenon

Liquid xenon TPCs



UK pioneered the xenon technology with the ZEPLIN programmes…

Liquid xenon TPCs: the future

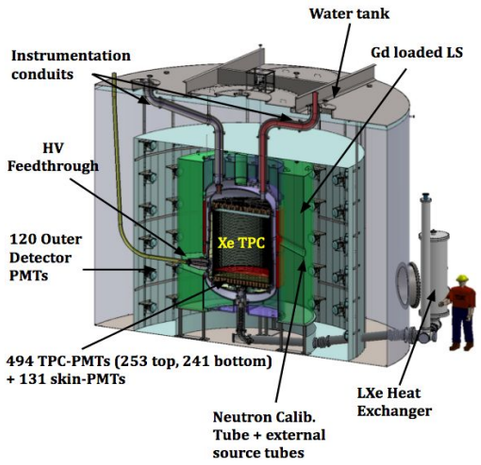
XENON1T

2,000 kg
(1,042 kg)

2017

7.7×10^{-47} cm^2

LZ

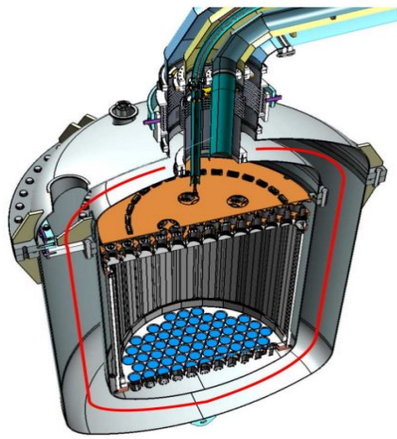


7,000 kg
(5,600 kg)

2020 + 3 live years

1.6×10^{-48} cm^2

XENONnT



5,900 kg
(4,000 kg)

2020 + 5 live years

1.6×10^{-48} cm^2

50,000 kg
(40,000 kg)

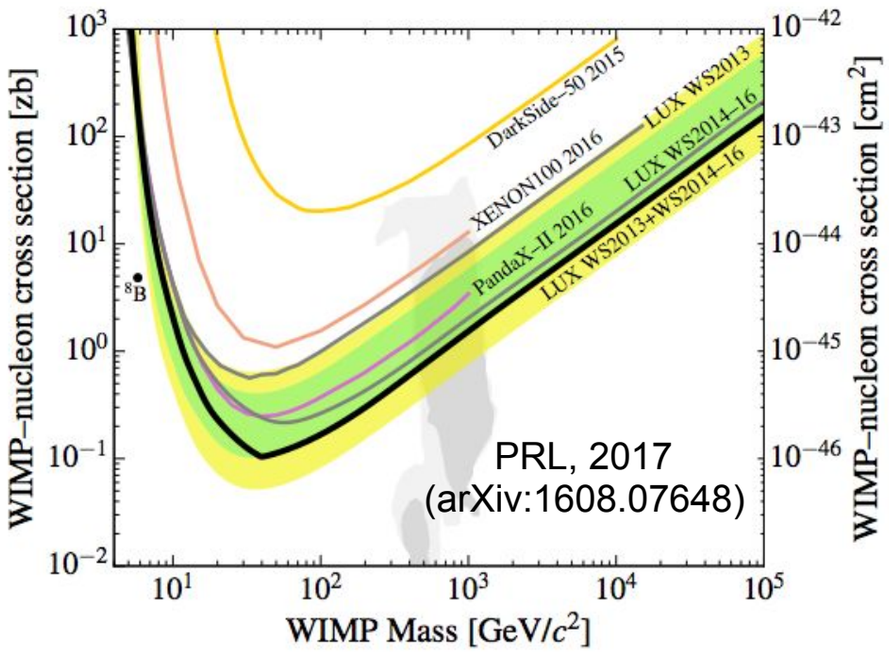
2023 - 2033: ‘Generation 3’

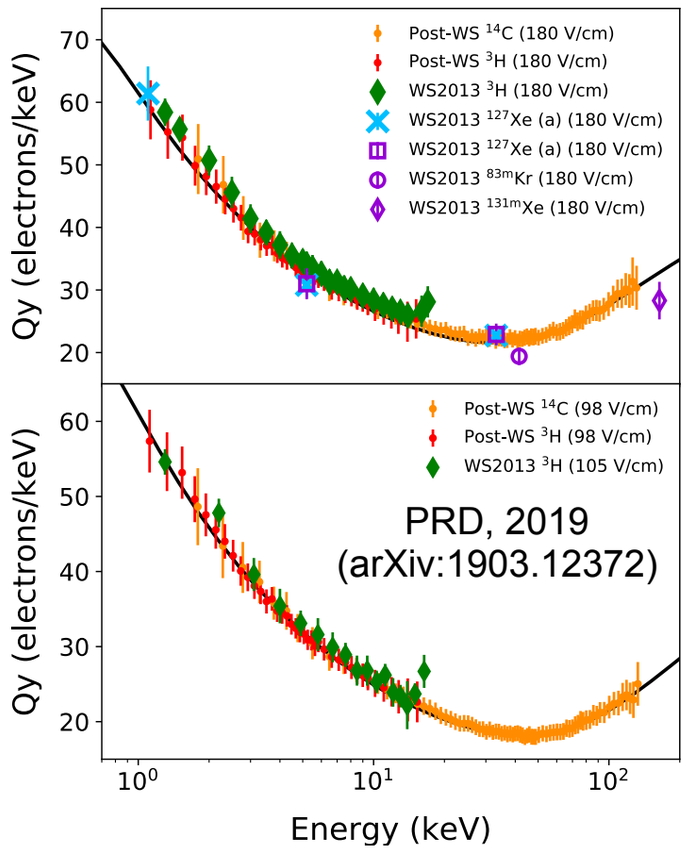
2×10^{-49} cm^2

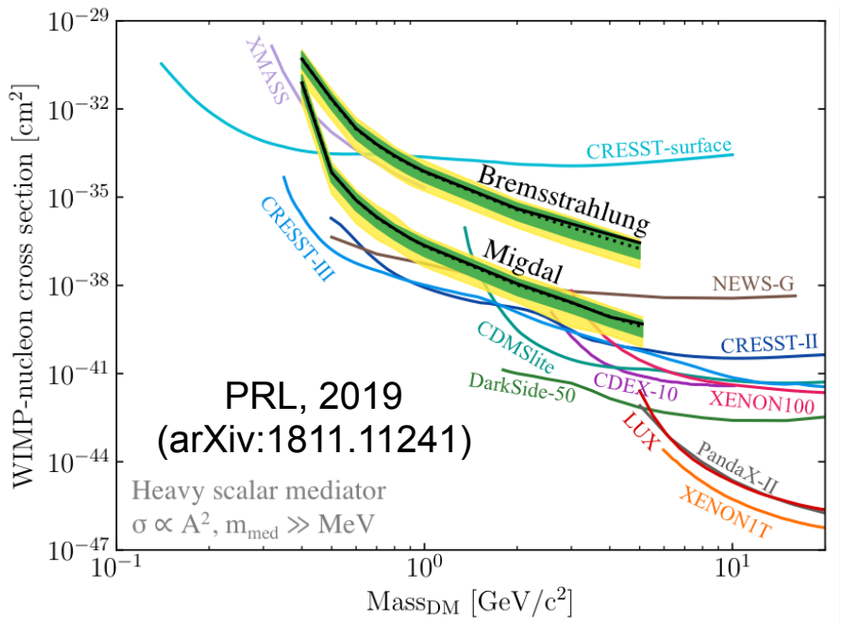
…UK continues its leadership role through LUX and LZ

LUX (SURF, USA)

- UK groups: Bristol, Edinburgh, Imperial, Liverpool, Sheffield, UCL
- Detector now decommissioned (to allow installation of LZ)
- Important Legacies:
  - world-leading limits for Spin-Independent, Spin-Dependent, ALPs
  - unprecedented calibration of light/charge yields (~0.1-100 keV)
  - novel searches extending reach of xenon detectors



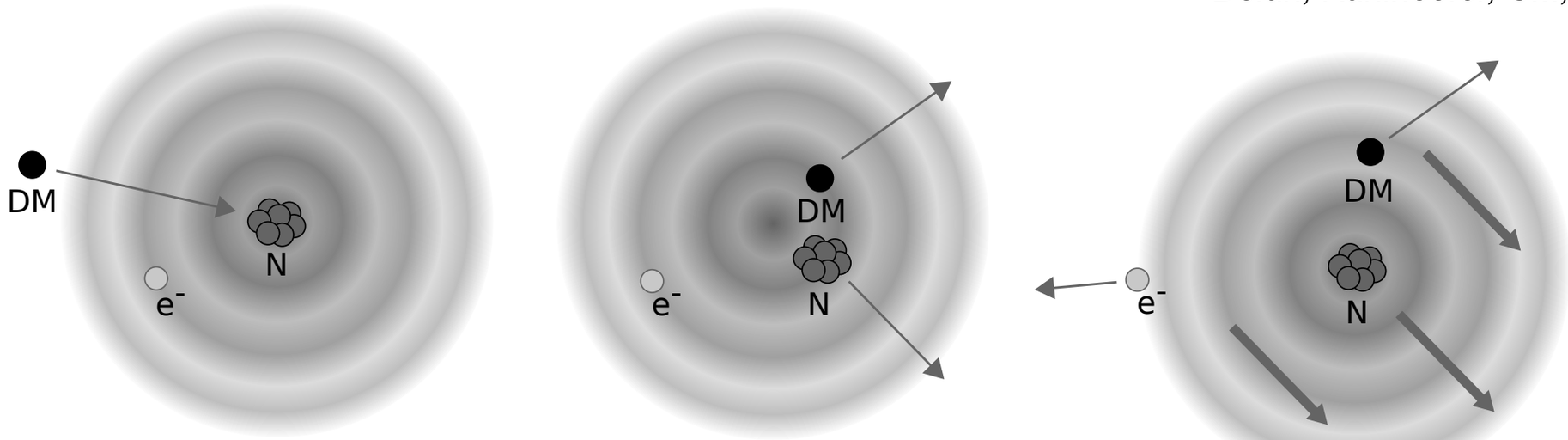




Extending the reach of xenon detectors

Migdal effect:

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906



$$|\Phi_{ec}\rangle \qquad |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle \qquad \mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

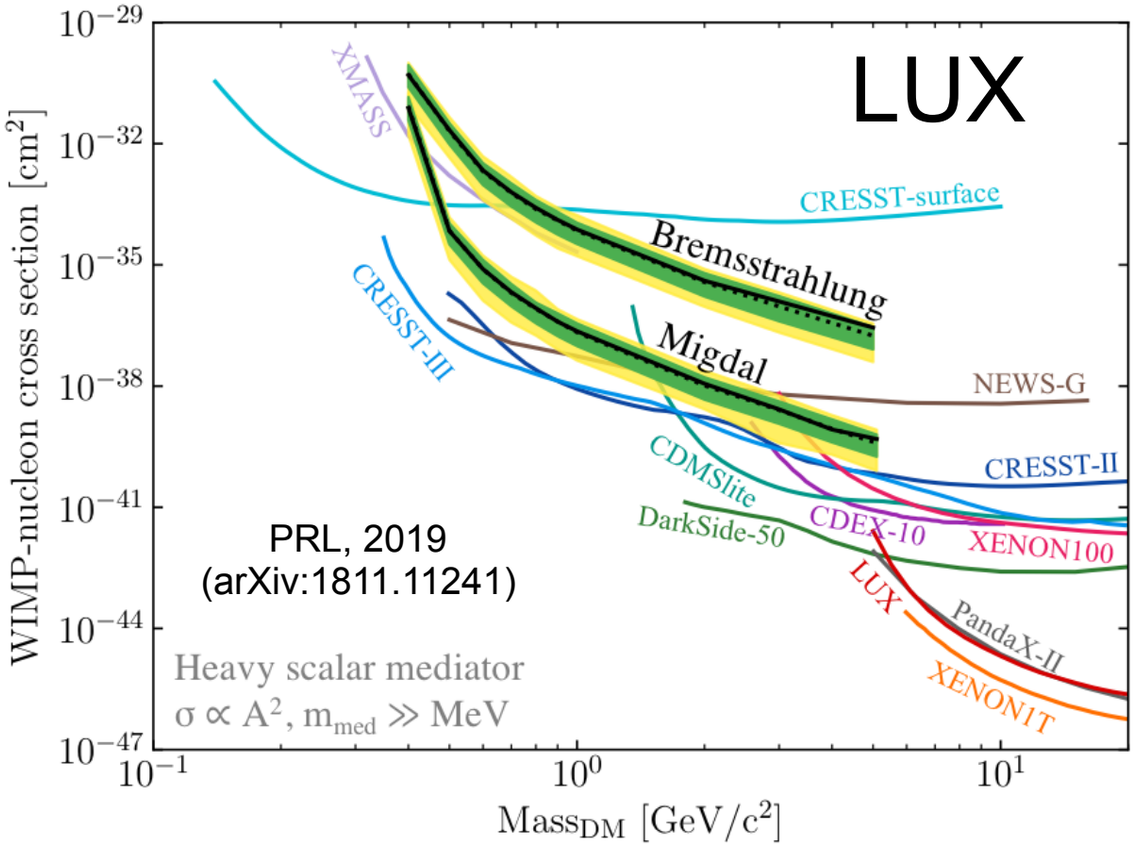
"…it takes some time for the electrons to catch up, which causes ionisation of the atom."

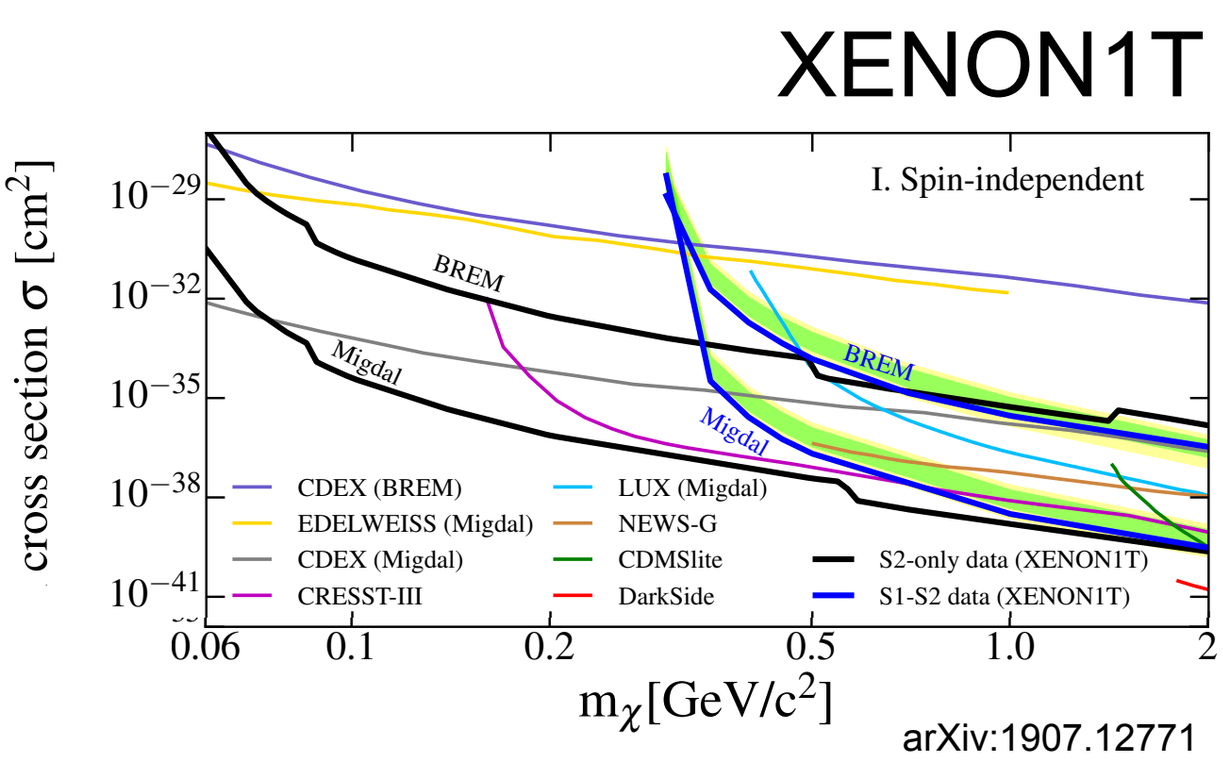
Signal: the ionised electron

[Can also be applied to other targets (Ge, LAr…)]

Extending the reach of xenon detectors

Migdal effect:





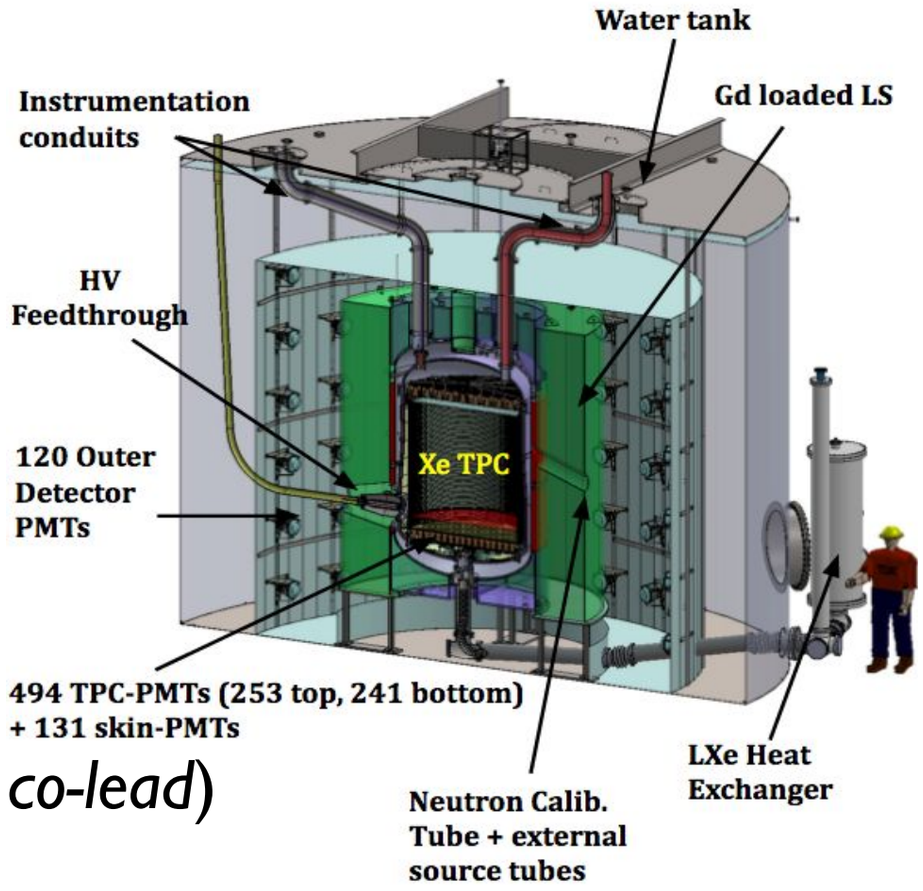
Signal: the ionised electron

Outcome: xenon competing with dedicated low-mass detectors

See also single scintillation photon search, arXiv:1907.06272, (co-lead Imperial)

LZ (SURF, USA)

STFC funded construction project
Commissioning early 2020
Science goal: 1000 live days & 5.6 tonne fiducial mass



UK involvement (approx 50/250 members)

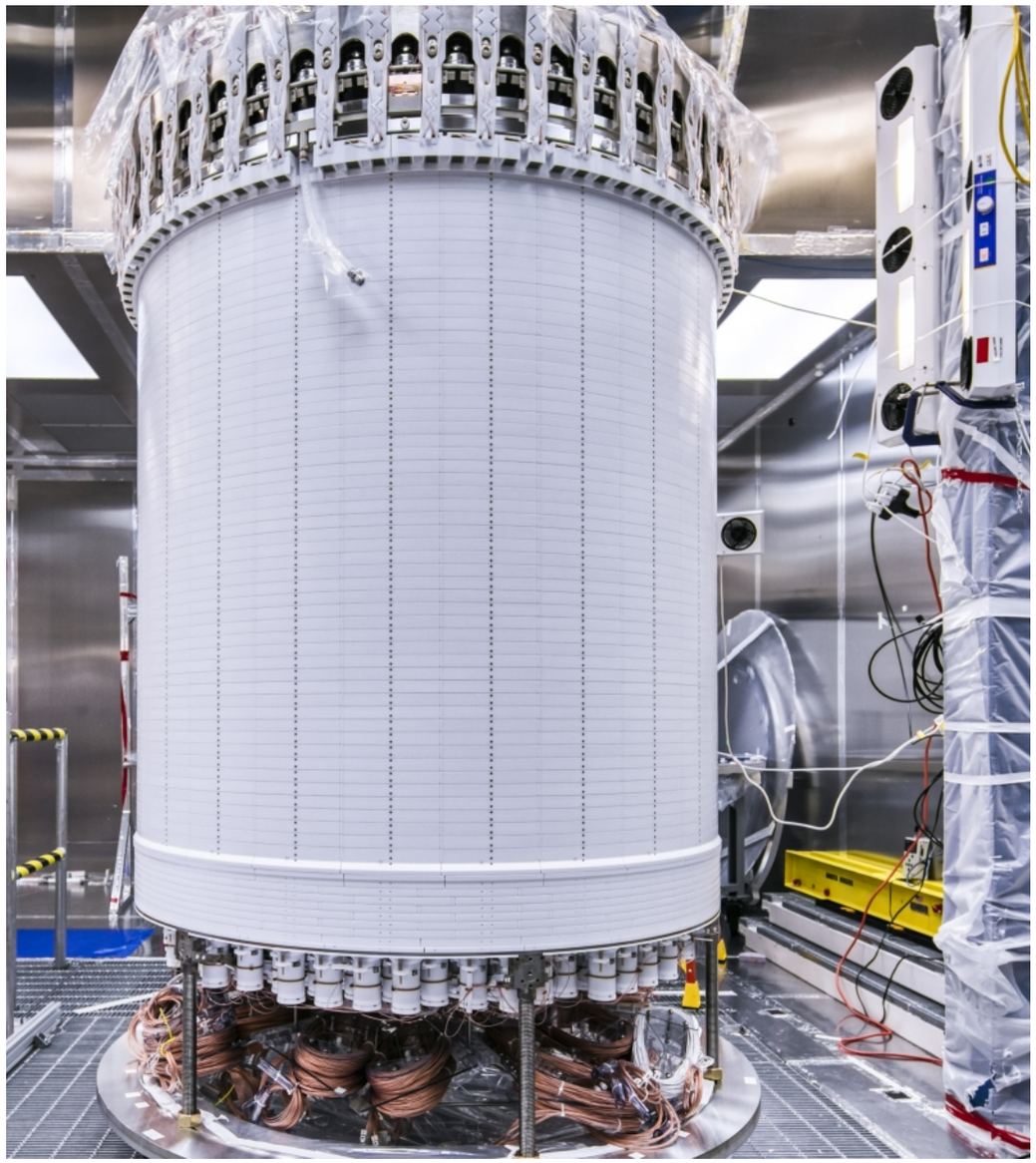
- *Bristol*: software development
- *Edinburgh*: skin veto, cleanliness
- *Imperial*: PMTs, data centre, detector system (*project co-lead*)
- *Liverpool*: outer detector calibration systems
- *Oxford*: internal sensors
- *RAL*: cryostat (*project co-lead*), calibration source delivery
- *Royal Holloway*: optical simulations
- *Sheffield*: background simulations
- *UCL*: backgrounds and assays (*project co-lead), (Physics coordinator*)

UK co-lead on 3/11 WPS; 2/7 Exec. board; 6/30 technical board

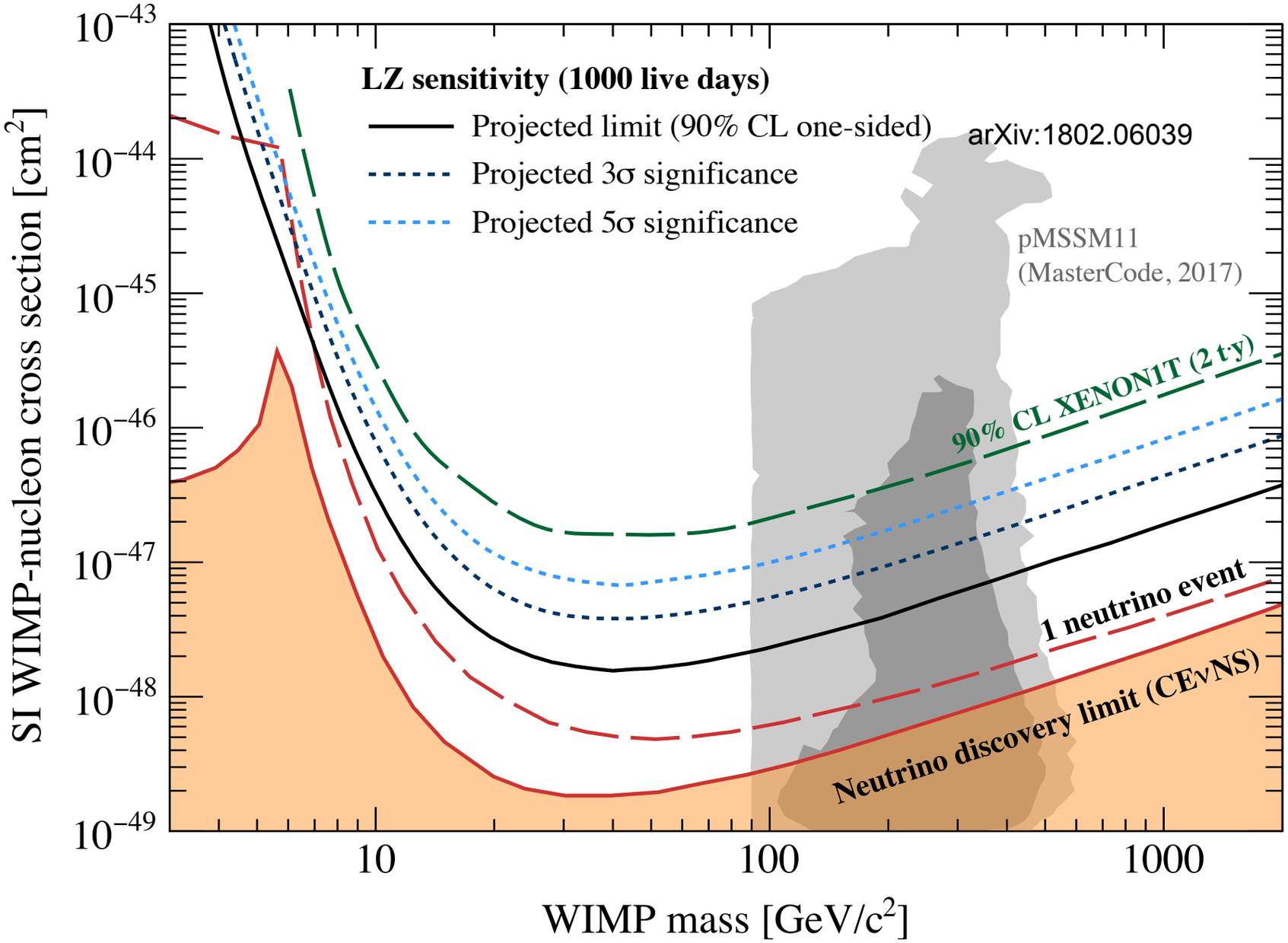
LZ Time Projection Chamber assembly completed

Collaboration puts together the 'heart' of LUX-ZEPLIN dark matter detector

August 2, 2019 Erin Broberg



LZ (SURF, USA)

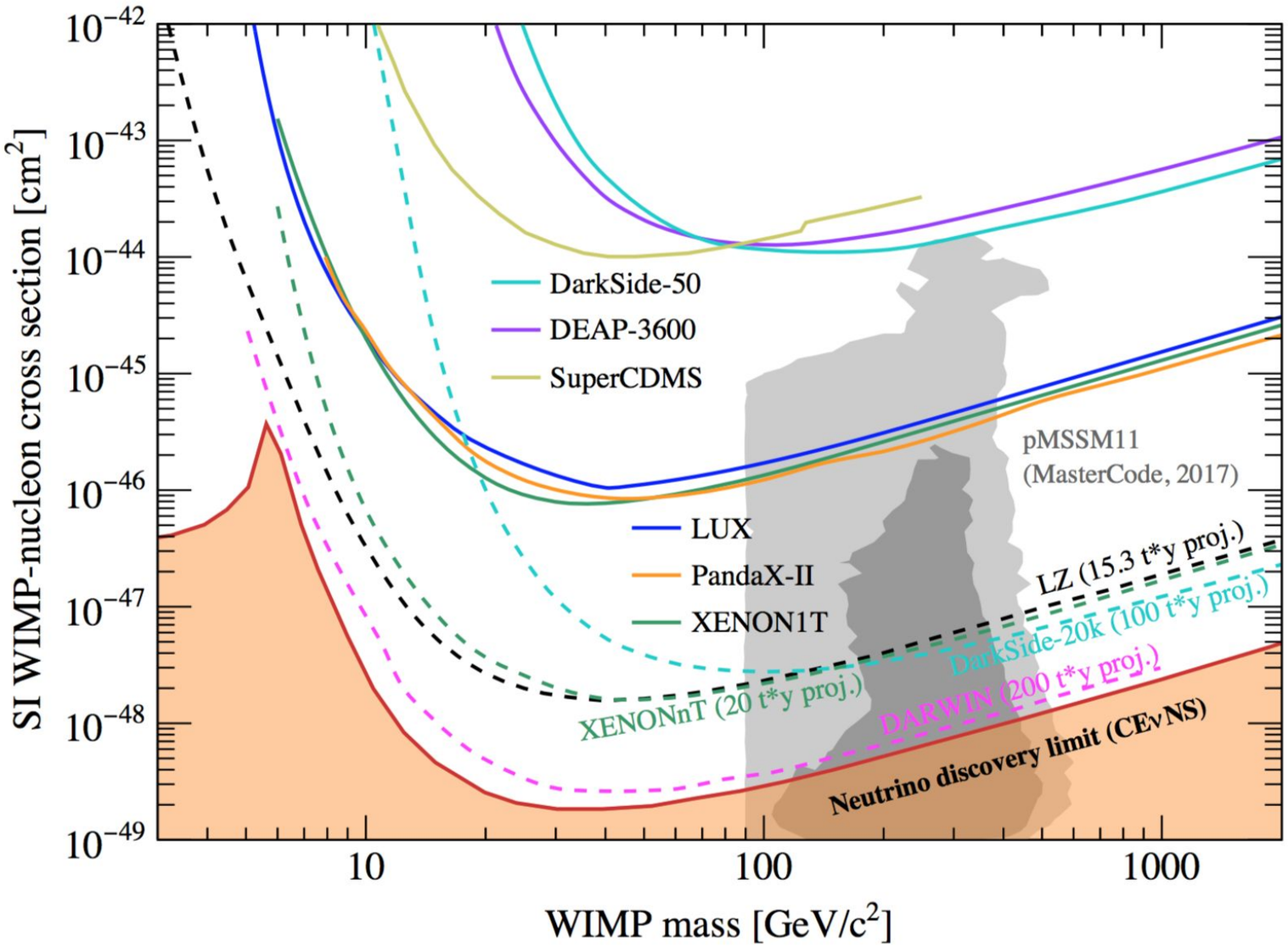


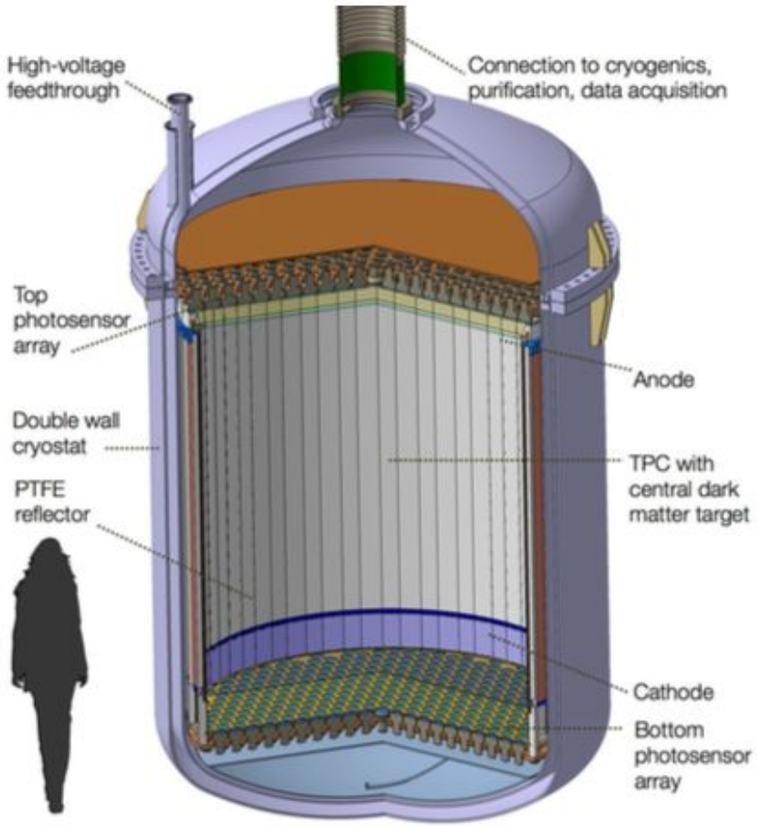
LZ improves on XENON1T by x40

(Competitor: XENONnT similar sensitivity on similar timescale)

Xe Generation-3 (G3)

High statistics measurement **or** explore to the neutrino floor





G3 R&D → Technical design → Construction → Exploitation

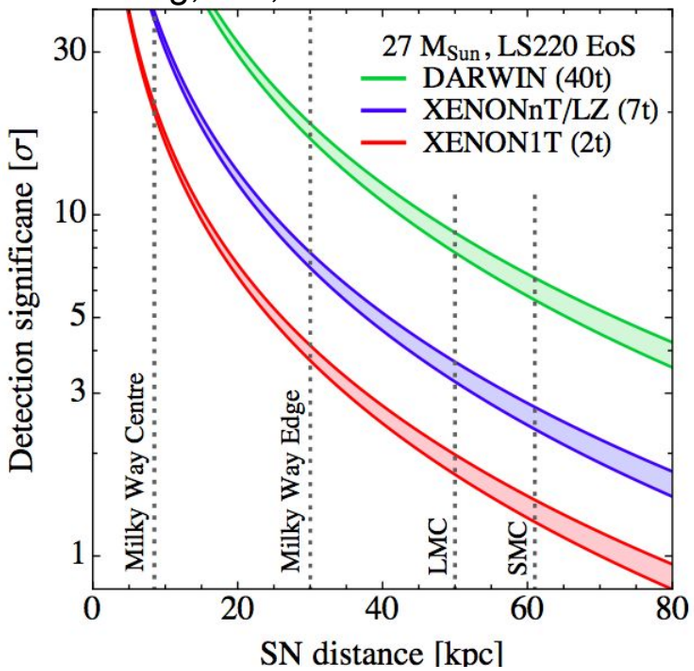
2019-23 → 2023-25 → 2025-29 → 2029+

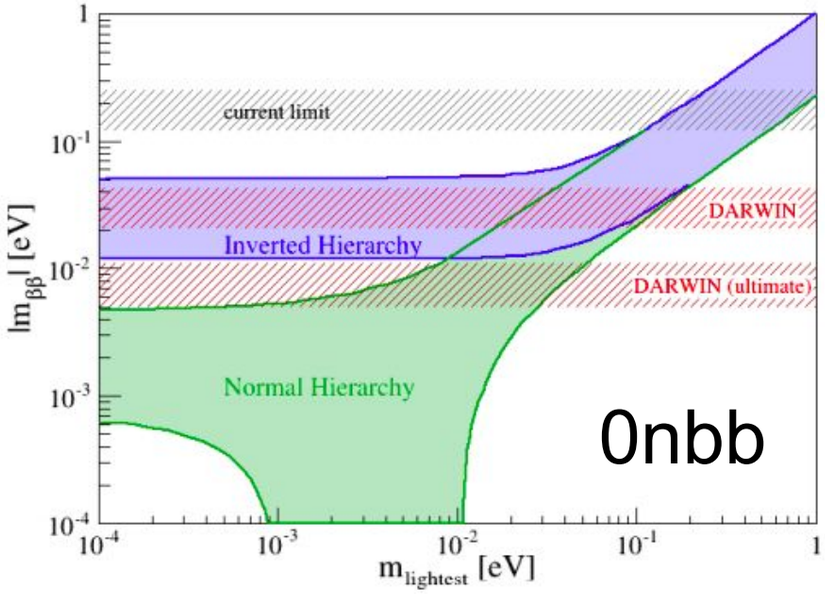
Xe Generation-3 (G3)

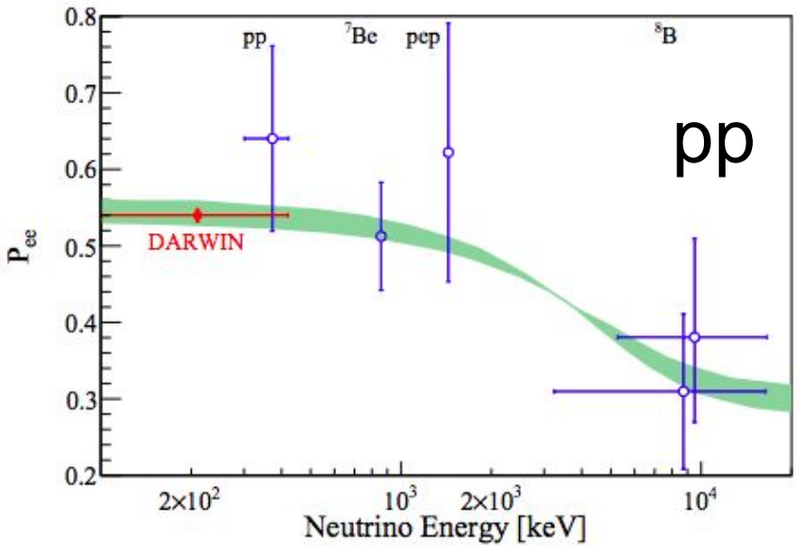
Size + low backgrounds + NR + ER = science beyond WIMPs

Solar neutrinos (pp & B8), supernova neutrinos,
neutrinoless double beta decay, axions… see eg arXiv:1606.07001

Lang, CM,… PRD 2016







UK R&D mapped to UK expertise:
engineering issues from scaling up; background mitigation; SiPMS;
calibrate Migdal effect; target doping Xe with H, Ne (low masses);

2. Liquid argon

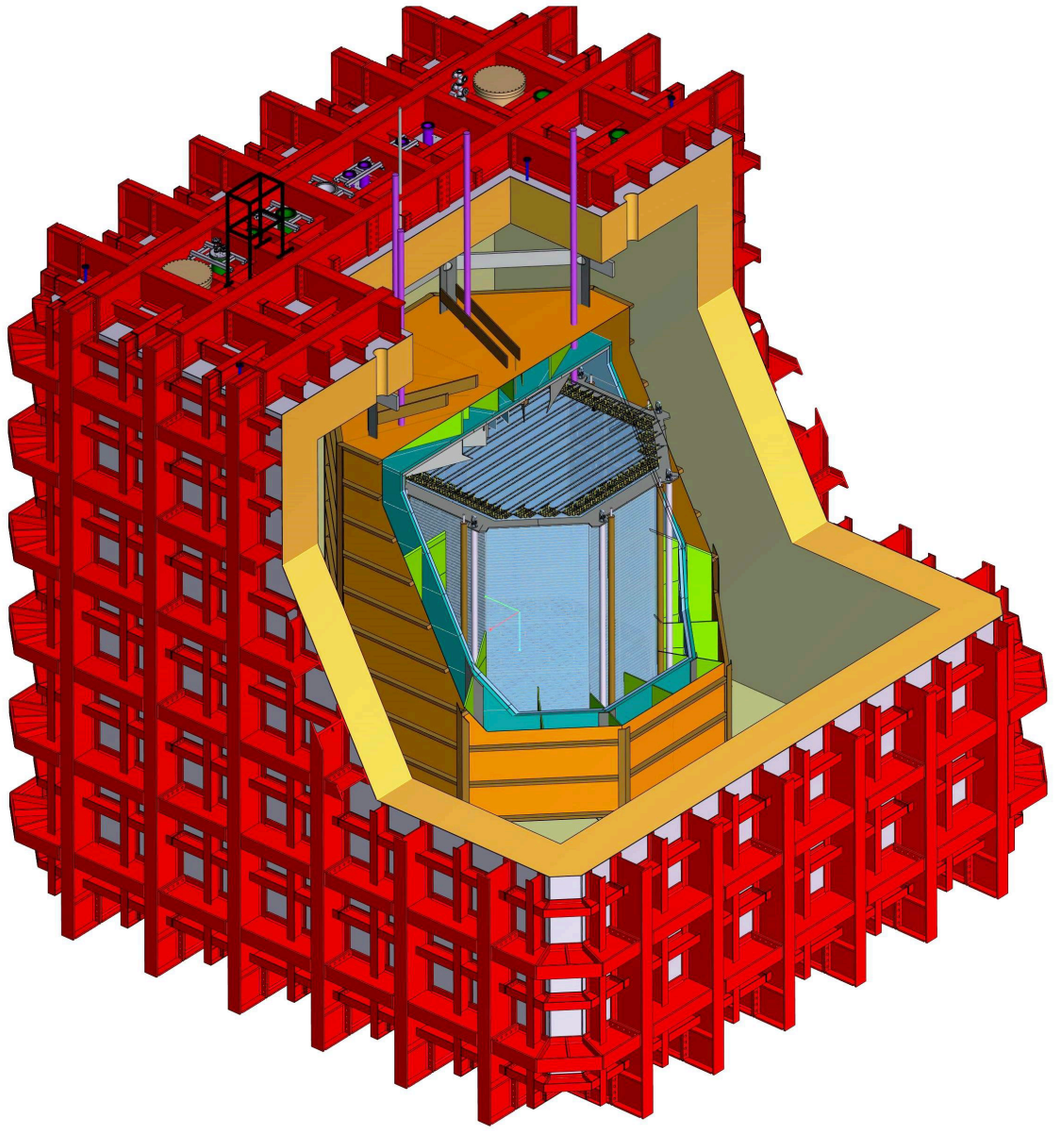
Liquid Argon TPCs

DEAP-3600
(running)

DarkSide-50
(running)

miniCLEAN

ArDM



DarkSide-20k
2022~

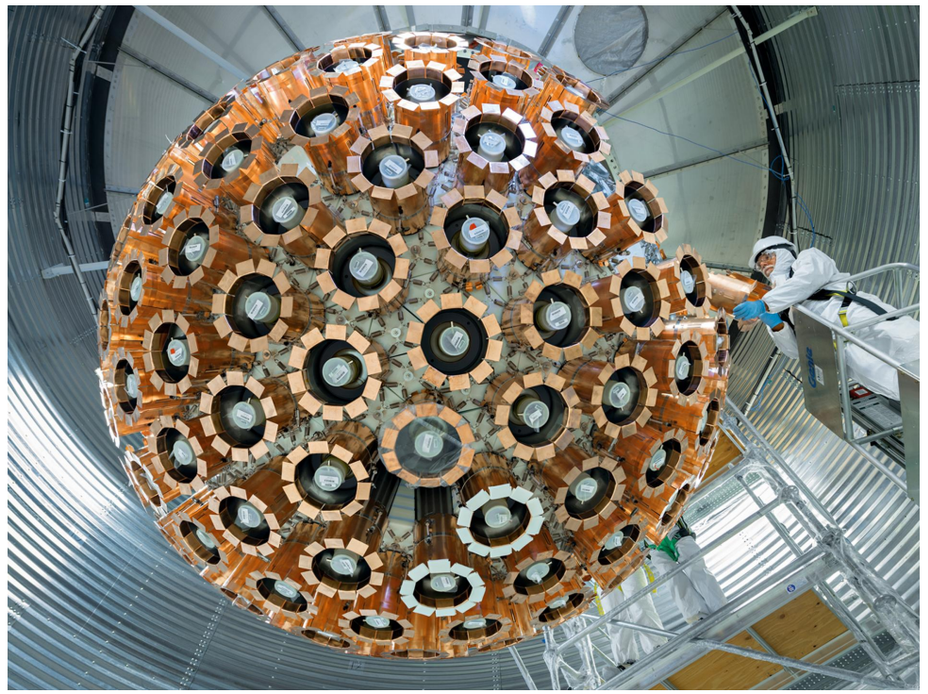
~300 tonnes

ARGO
2029~

DEAP-3600 (SNO-lab, Canada)

Single-phase liquid argon detector
3.6 tonnes (1 tonne fiducial)
Pulse shape discrimination for particle ID

World's most sensitive argon-experiment



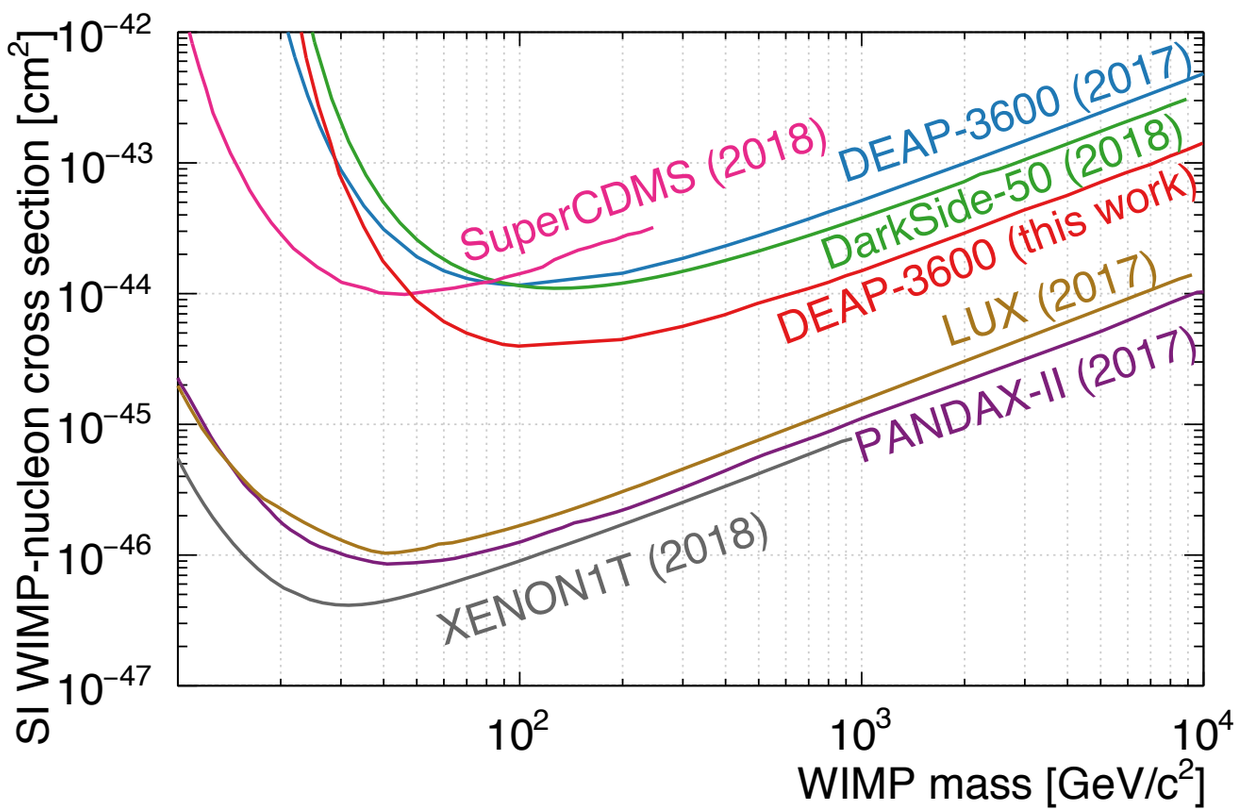
DEAP-3600 (SNO-lab, Canada)

Successes:

- Demonstrated extremely low (lowest) ^{222}Rn backgrounds (0.2 mBq/kg)
- Pulse shape discrimination can be used to control ER backgrounds to neutrino floor

Limit yet to reach design sensitivity:

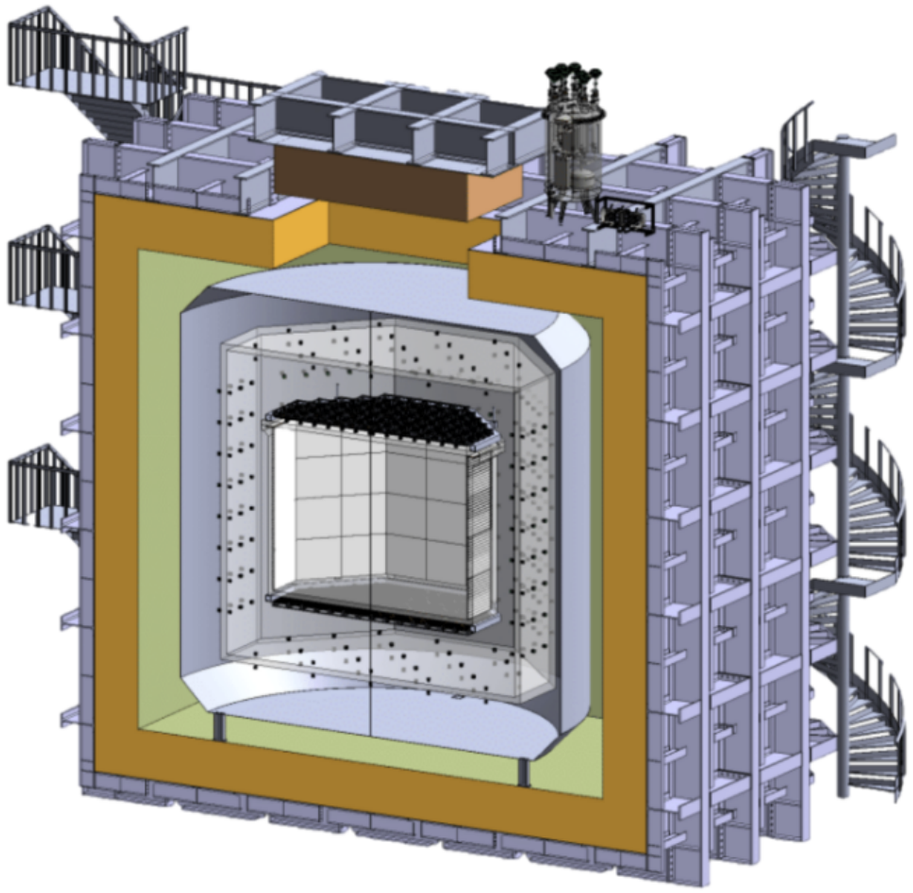
- Some background contamination from the detector neck
- Detector being re-configured to remove these events and likelihood analysis will be employed to reach design sensitivity (end-2020)

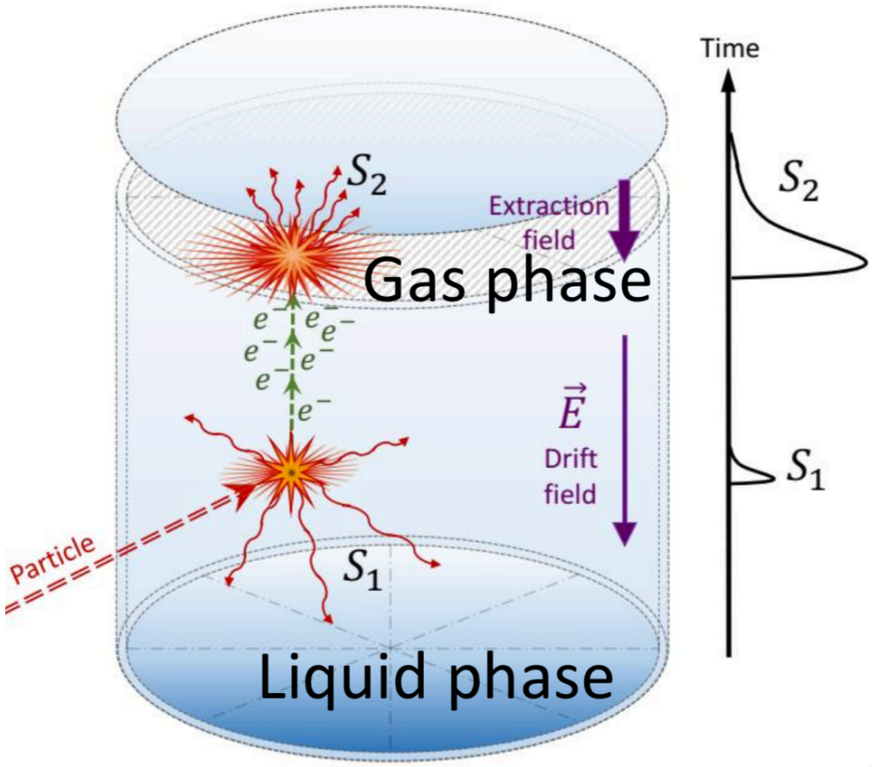


Darkside-20k (Gran Sasso, Italy)

- 50 tonne liquid underground Ar
- 700 tonne liquid atmospheric Ar outer detector

- Global collaboration: >350 physicists
- 11 countries, >55 institutes





Unlike DEAP-3600, will be ***dual-phase*** with pulse shape discrimination

Darkside-20k (Gran Sasso, Italy)

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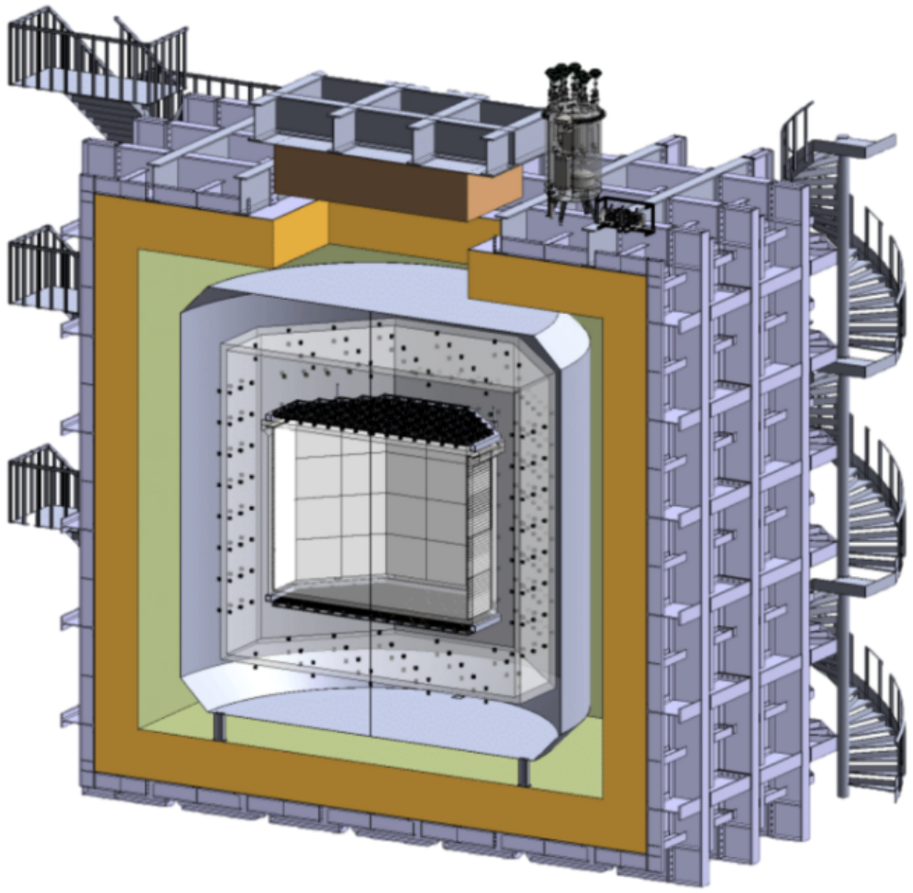
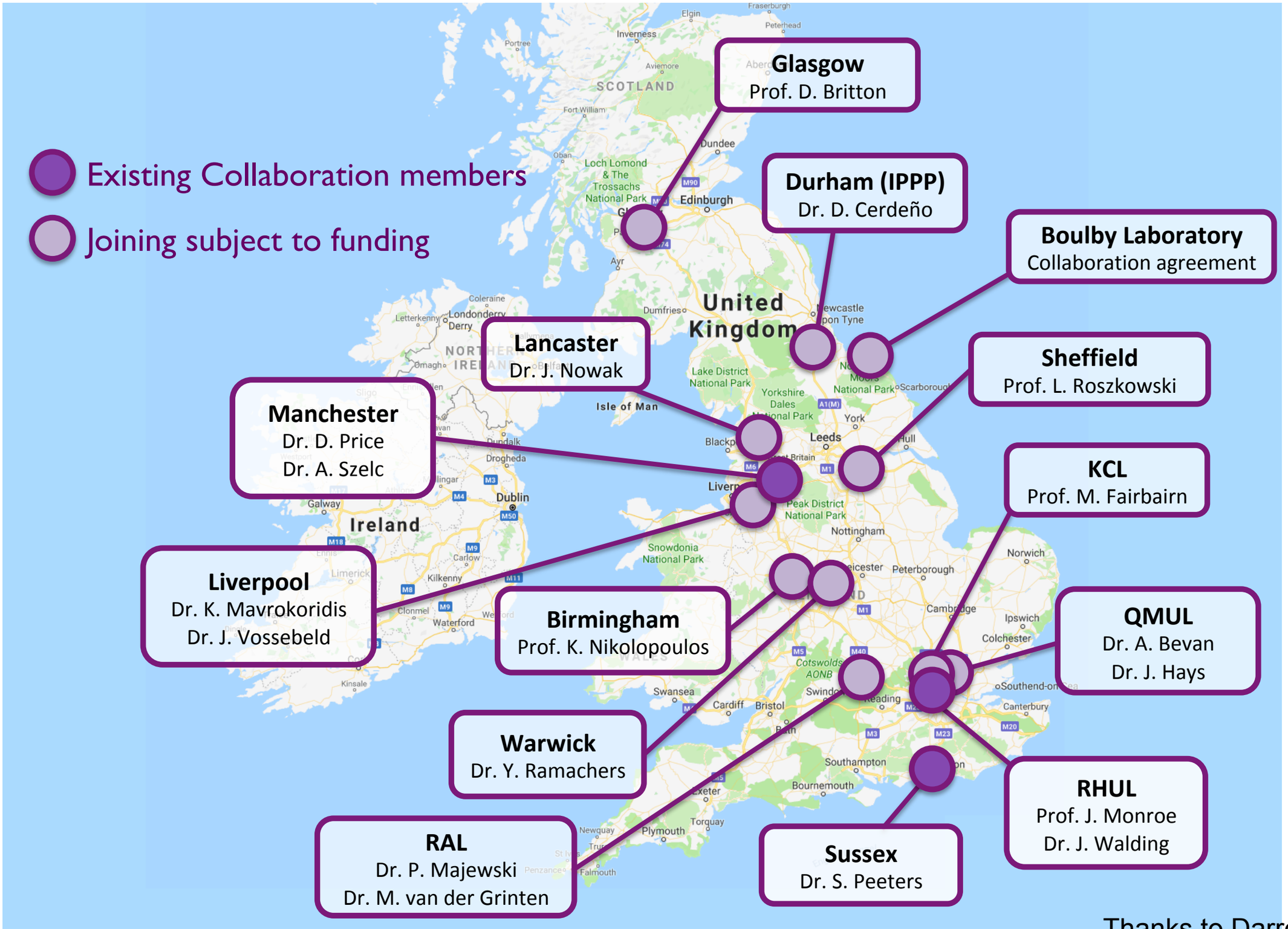


Two key innovations:

1. first large-scale use of large-area cryogenic silicon photon detection modules (PDMs) instead of PMTs.
    1. >3x photon detection efficiency,
    2. 10x lower background, and
    3. 10x lower noise noise

3. Atmospheric LAr outer detector to veto the limiting background: neutrons

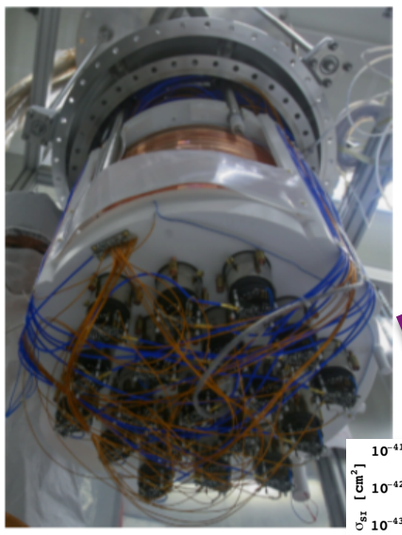
Darkside-20k: UK institutes



Thanks to Darren Price

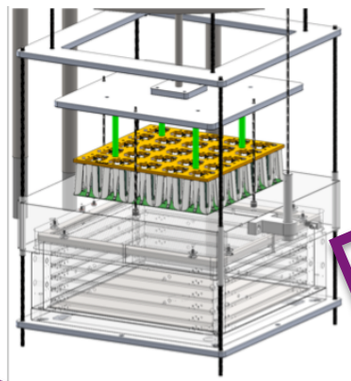
The Path to DarkSide-20k

DarkSide-50

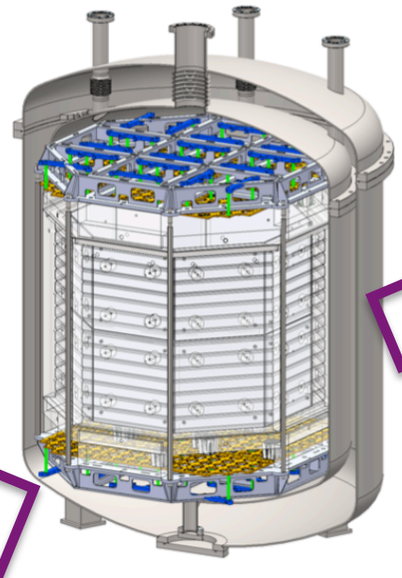


50 kg

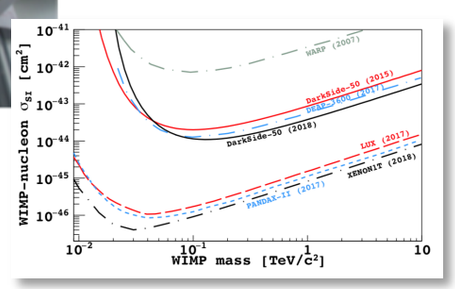
DS proto-proto 2019



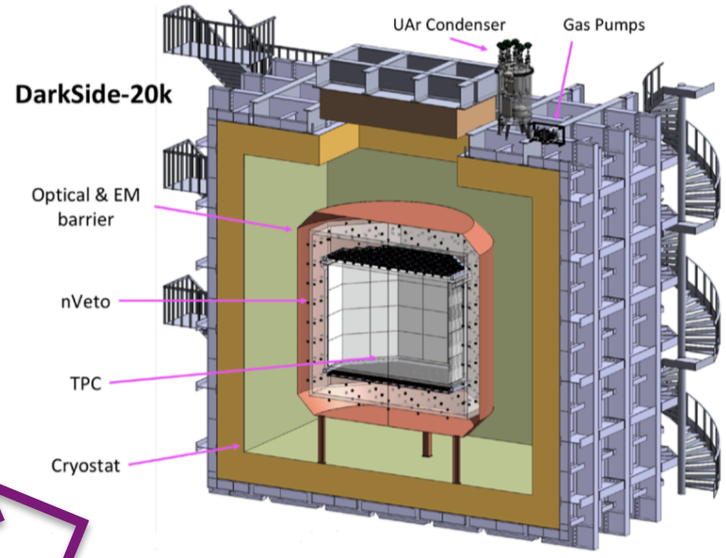
DS proto-1T 2020



1 tonne



DarkSide-20k 2022—2027

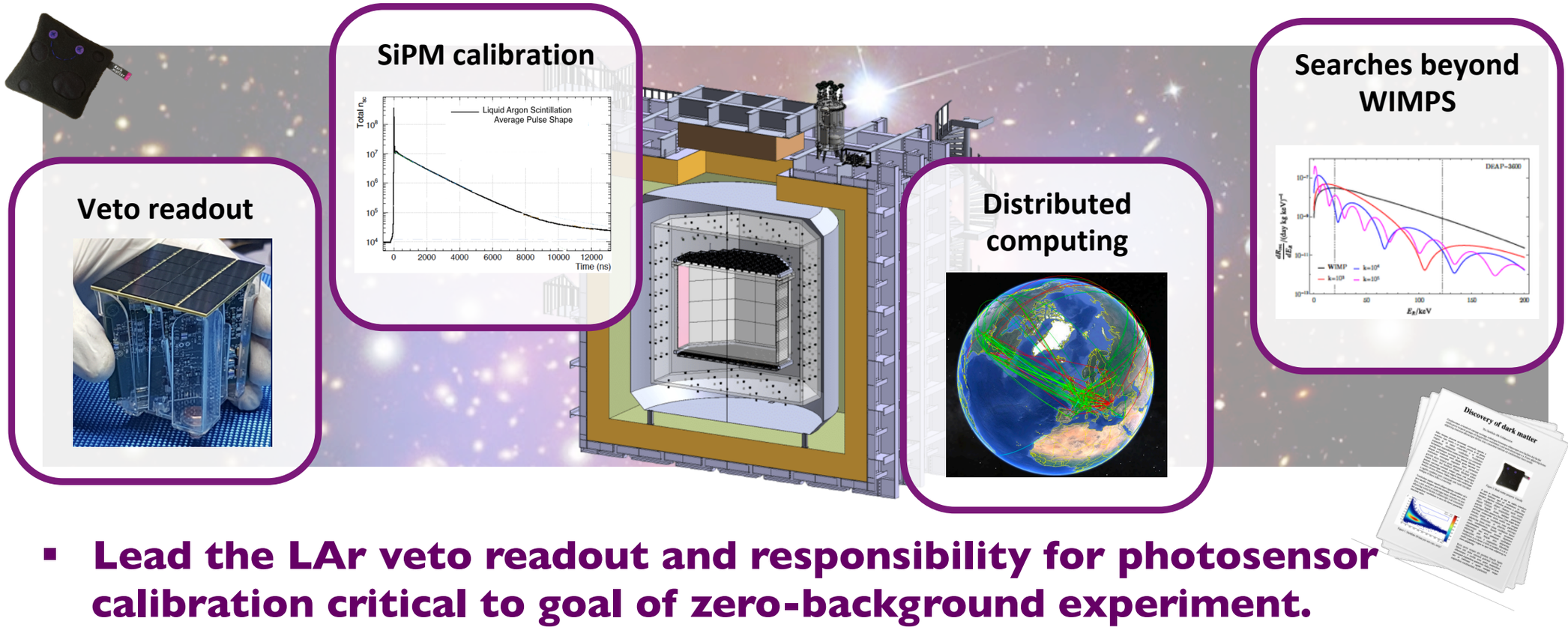


50 tonnes
(40 T fiducial)

Aggressive timescale to match liquid xenon

Thanks to Darren Price

DarkSide-20k: UK contributions



- **Lead the LAr veto readout and responsibility for photosensor calibration critical to goal of zero-background experiment.**
  Propose to deliver 3000 large area SiPMs, starting from foundry wafer through sensor calibration.
  Benefit from development/retention of expertise in low-noise high detection efficiency sensor technology

- **Distributed computing challenges at the level of LHC.**
  Leverage existing UK expertise and leadership

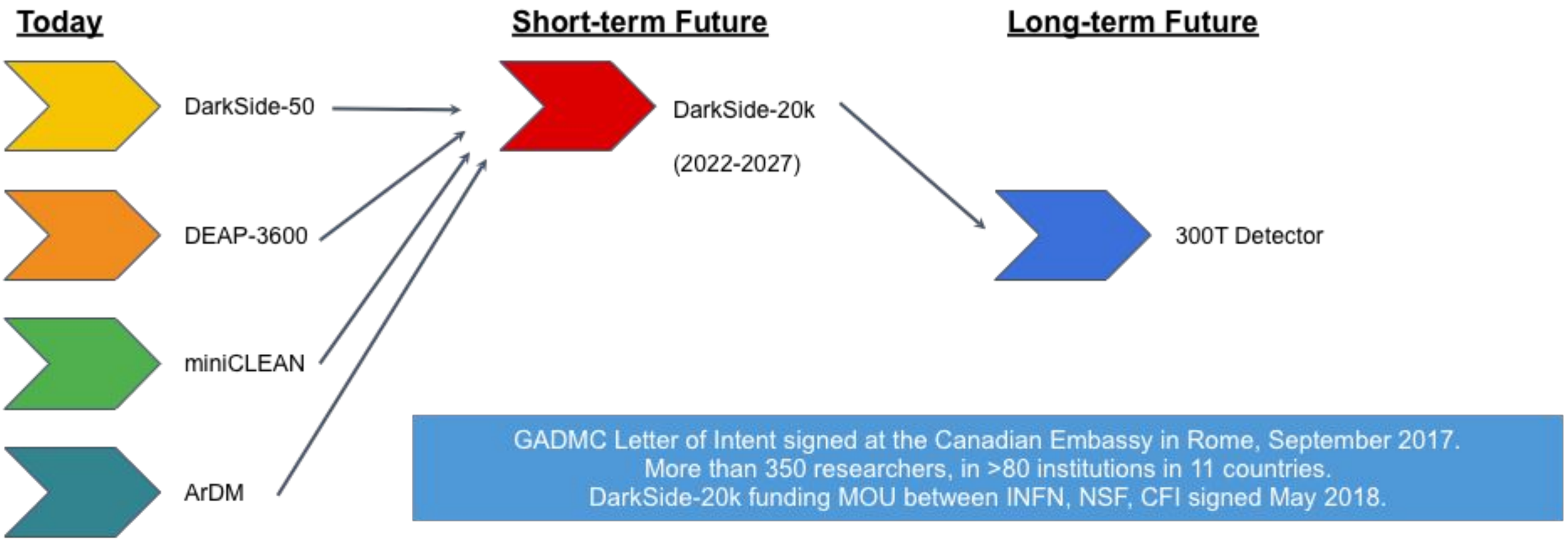
- **Expand DM (and neutrino) physics programme of experiment.**
  Synergies with DUNE and existing DM programme

- **Positions UK for strong future exploitation programme.**

Thanks to Darren Price

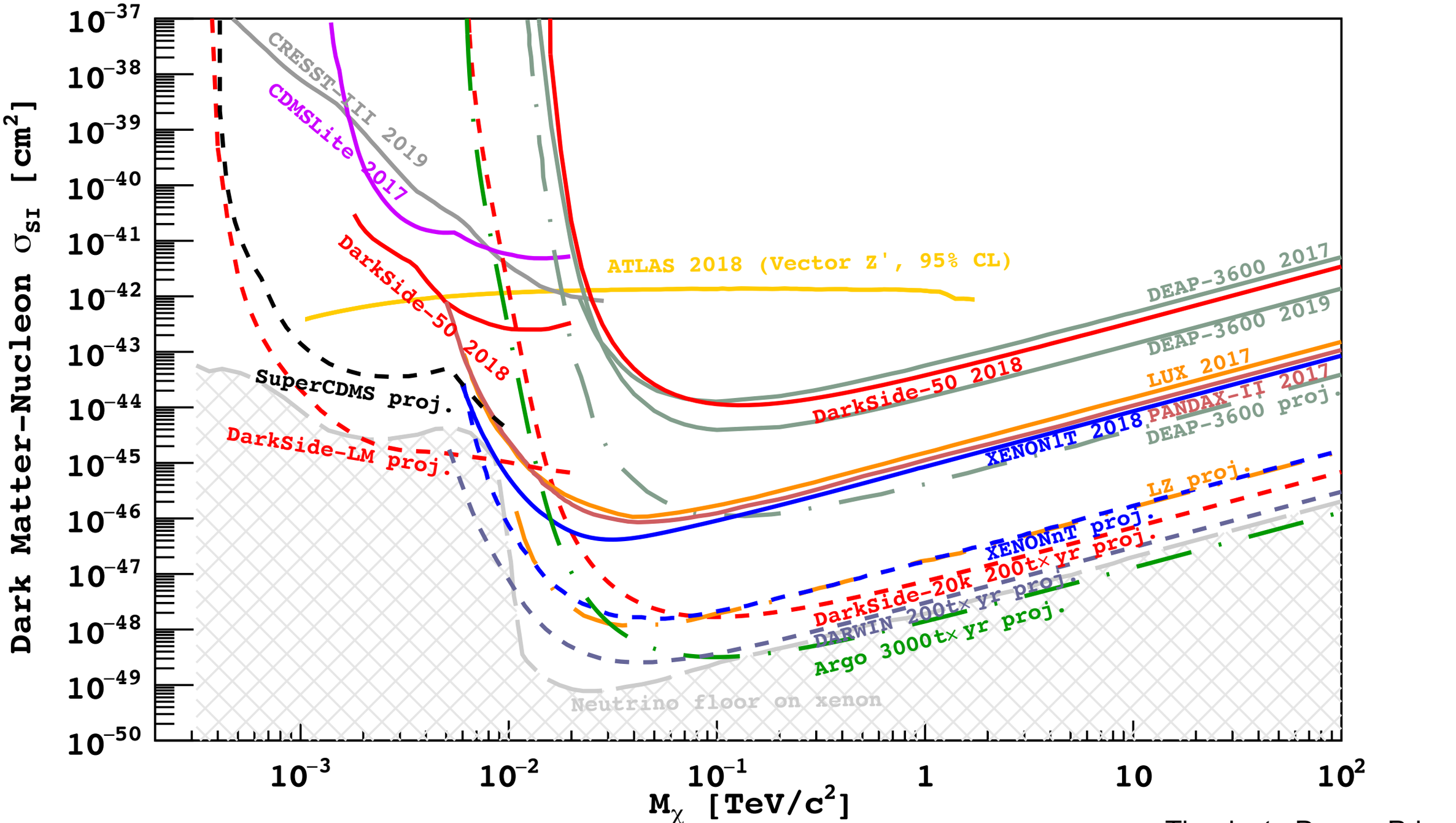
Beyond DarkSide-20k

Argon



Argon reach

High statistics measurement **or** explore to the neutrino floor

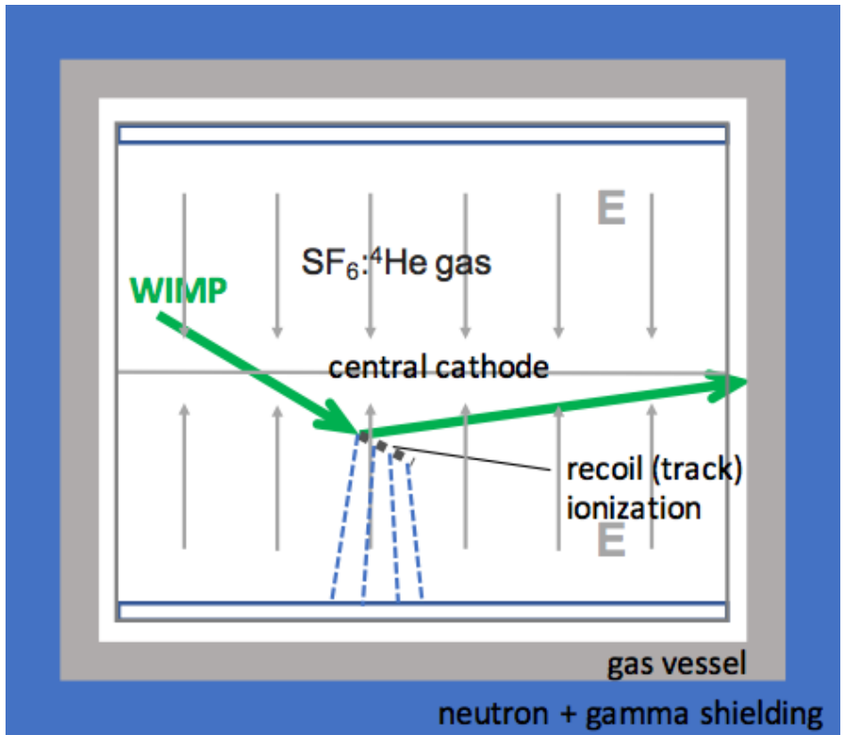


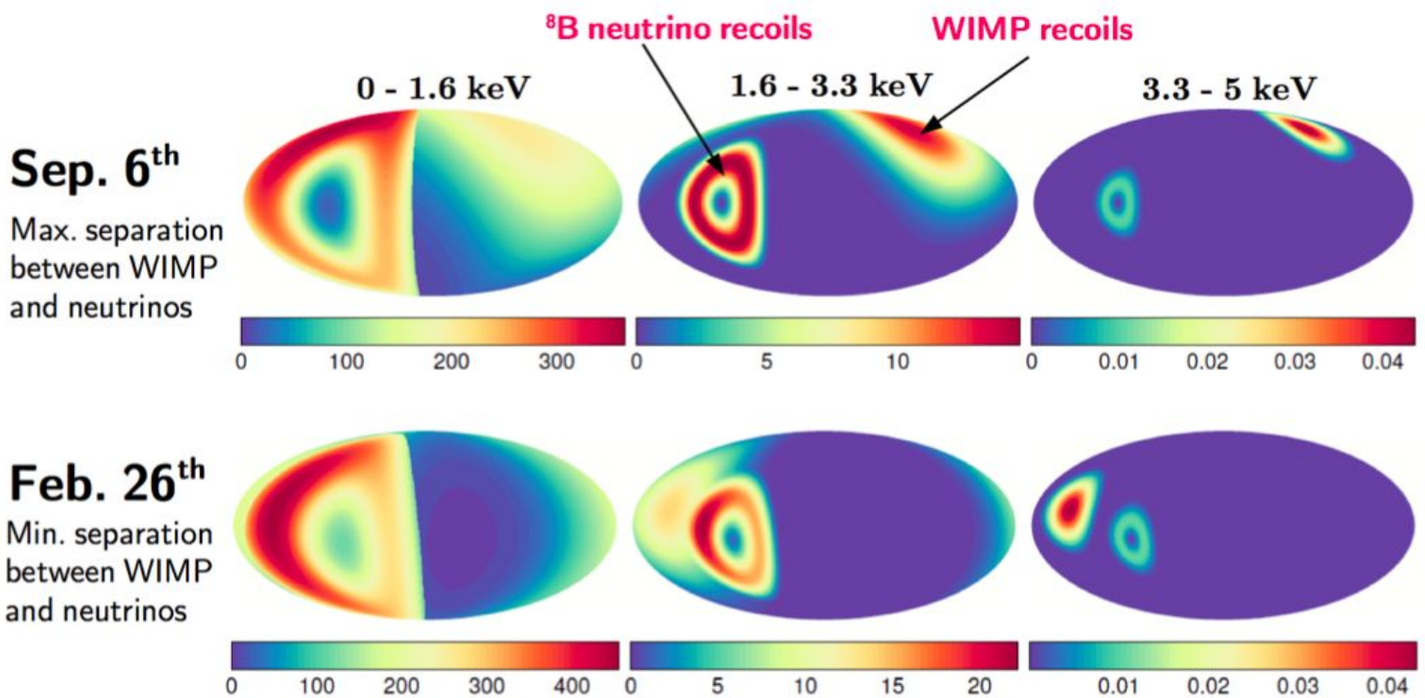
Thanks to Darren Price

Beyond the neutrino floor?

Directional Detection

Directional detectors designed to probe beyond the neutrino floor

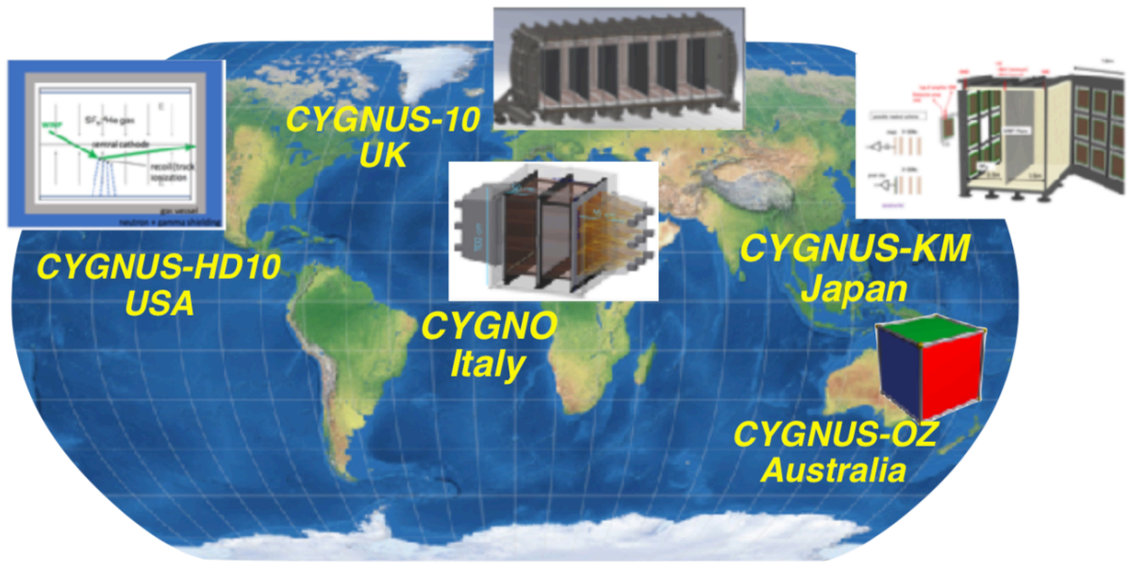




CAJ O'Hare et. al. Phys. Rev. D 92, 063518 (2015)

DRIFT (Sheffield): Directionality pioneer hosted at Boulby

CYGNUS Vision



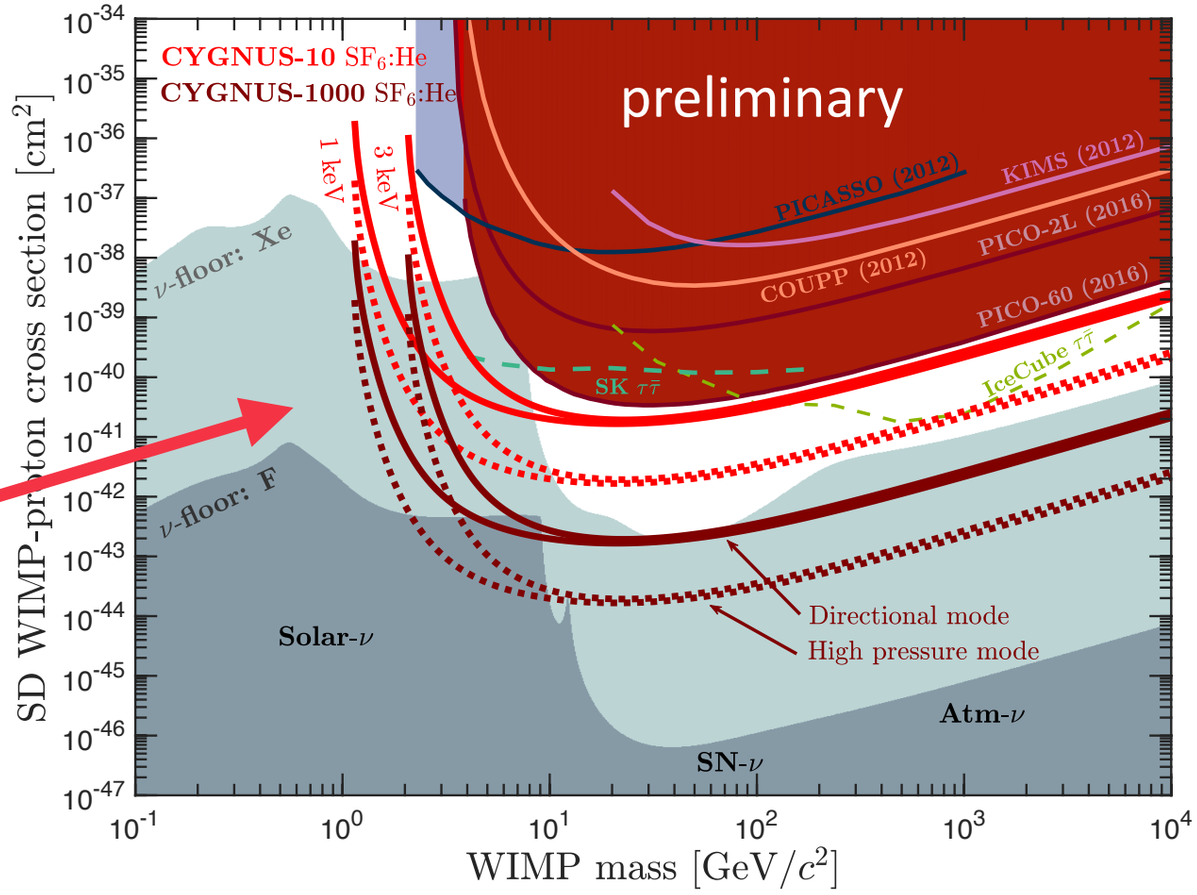
A multi-site Galactic Nuclear Recoil Observatory

Steering group:

- Neil Spooner (Sheffield, UK)
- Sven Vahsen (Hawaii, USA)
- Kentaro Miuchi (Kobe, Japan)
- Elisabetta Baracchini (GSSI/INFN, It
- Greg Lane (ANU, Australia)

thanks to Ciaran O'Hare

Going beyond the neutrino floor

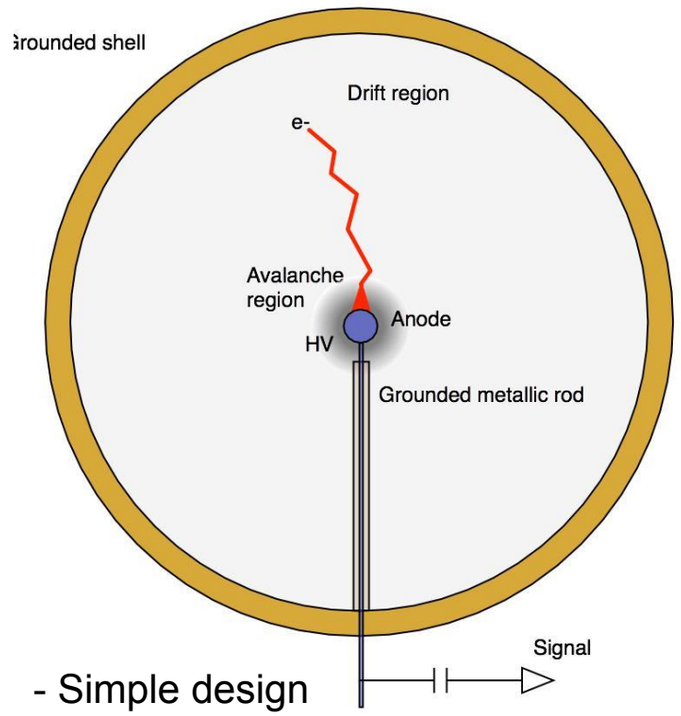


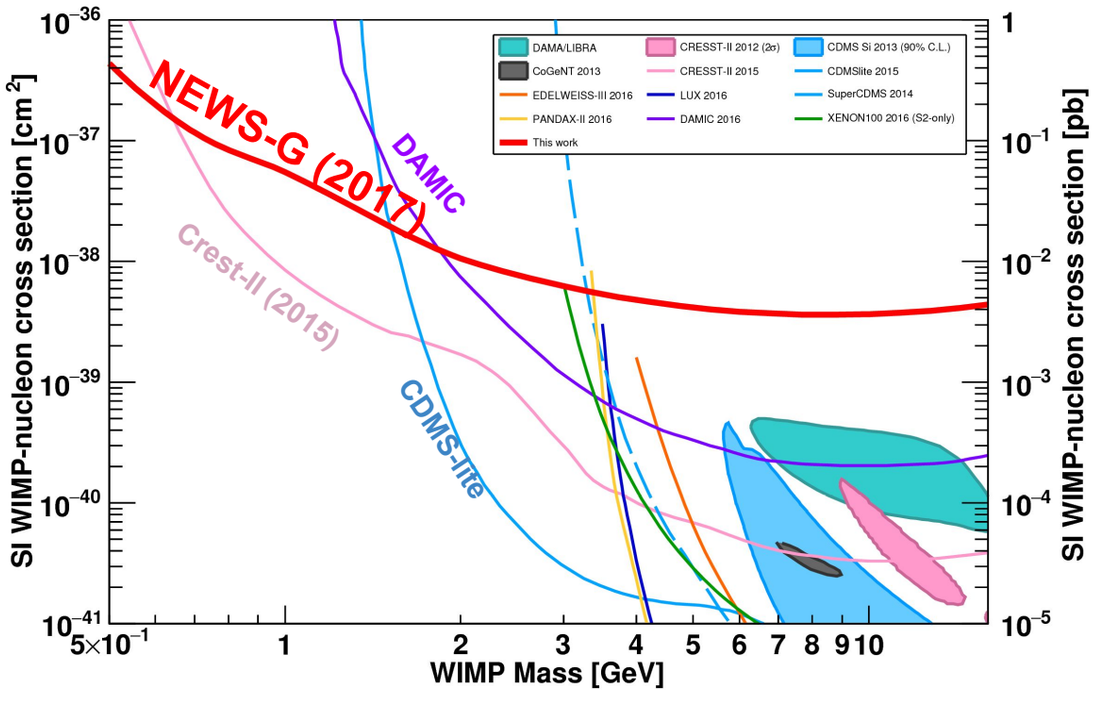
3. Dedicated low-mass searches

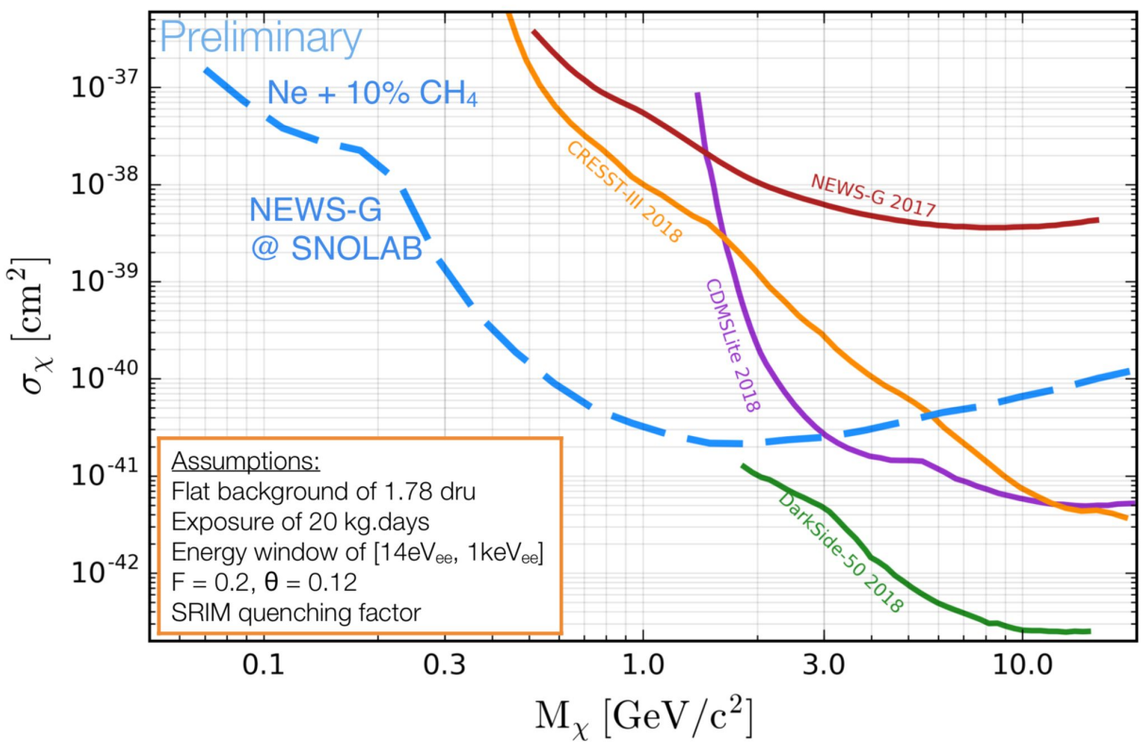
NEWS-G

Spherical proportional counter targeting low mass dark matter

- University of Birmingham
- PI: K Nikolopoulos
- Contributing to detector physics simulations, data analysis and R&D







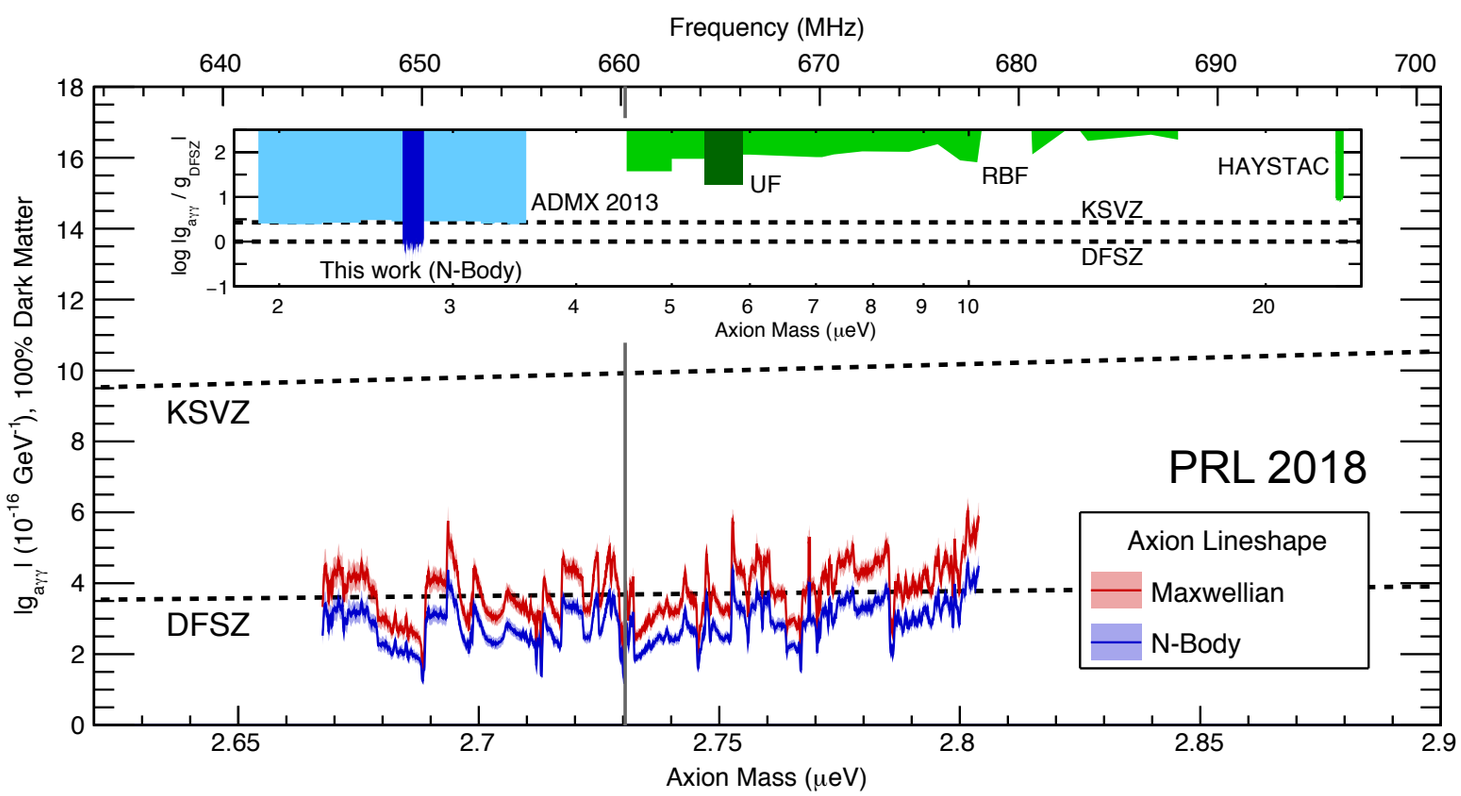
4. Ultra-light dark matter searches

ADMX (Washington, USA)

- Axions well-motivated as solve QCD strong CP problem
- Ultra-light (micro-eV), pseudoscalars

ADMX: search using a tuned electromagnetic resonator in a magnetic field

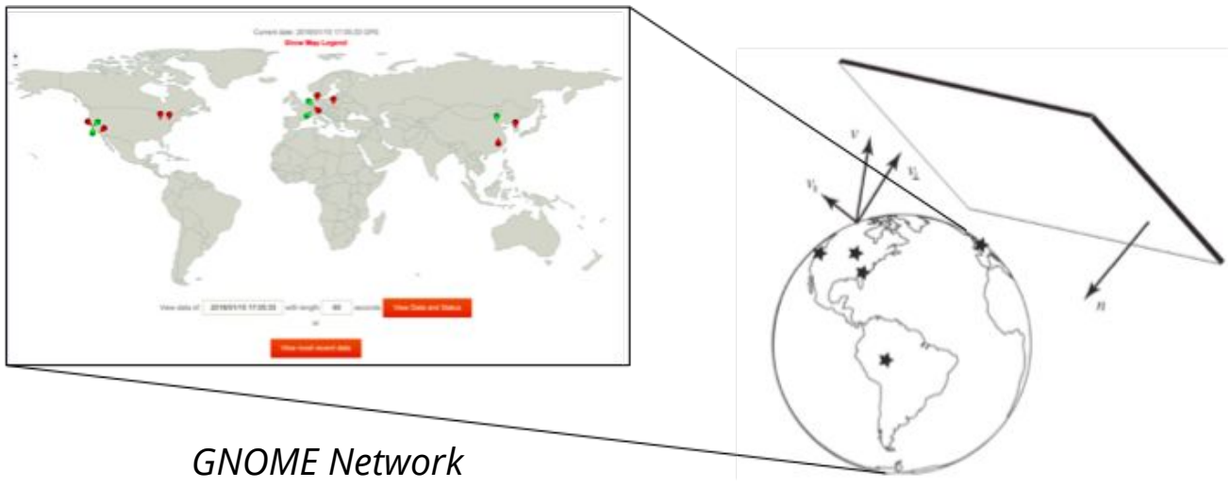
UK involvement (***Lancaster, Sheffield***): developing active cavity resonators to enhance mass range coverage



Now probing the preferred parameter space

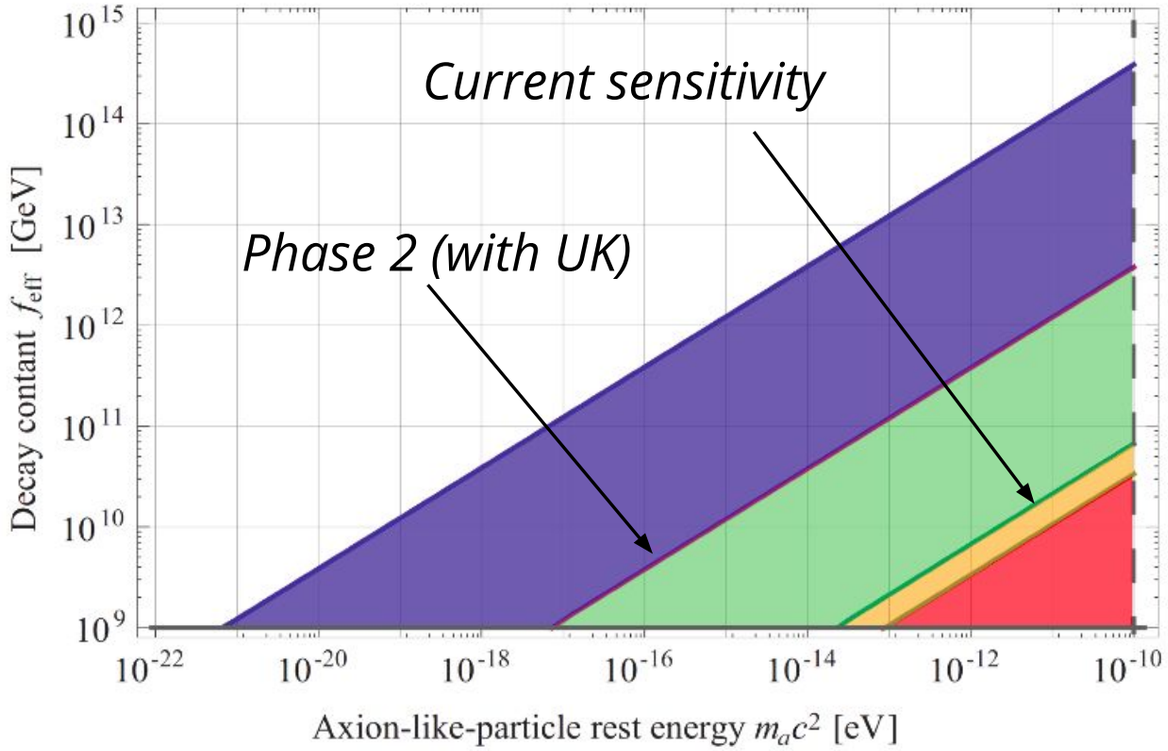
GNOME network

- Optically Pumped Magnetometers (OPM): sensitive to the crossing of domain walls
- Need coincident measurements between two or more instruments to reject false positives
- UK OPM (Birmingham) already operational



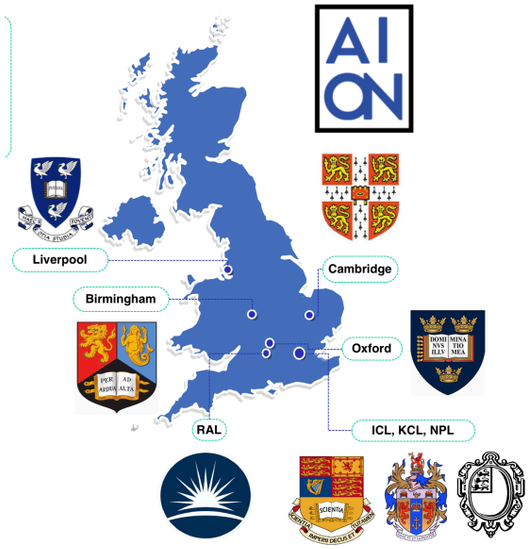
GNOME Network (USA+EU+China)

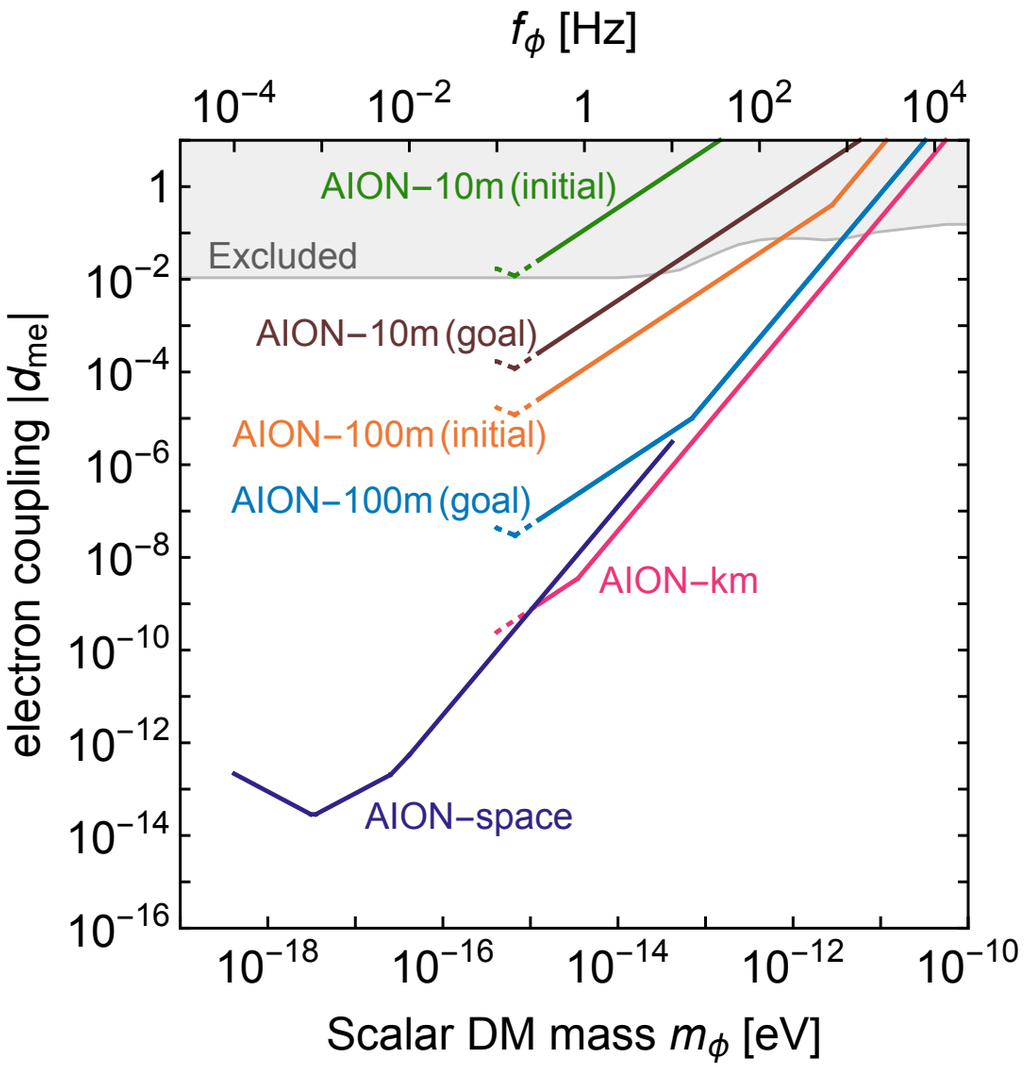
Axion domain wall detection

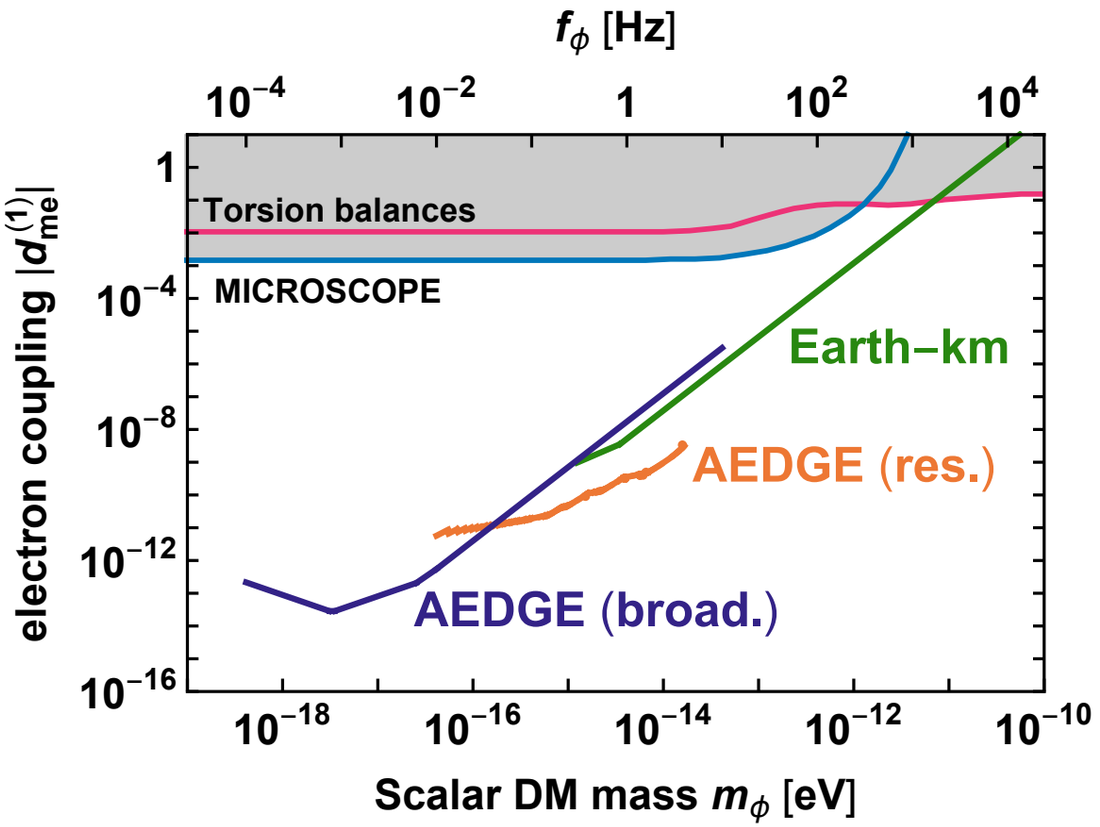


Atom interferometers: AION/AEDGE

- Ultra-light scalar dark matter can induce variations of the electron mass and fine-structure constant







Take home message

- Future bright for dark matter in the UK
  - world leading activities at forefront of the field
  - aligned with international programmes

> *APPEC encourages the continuation of a diverse and vibrant programme (including experiments as well as detector R&D) searching for WIMPs and non-WIMP Dark Matter. With its global partners, APPEC aims to converge around 2019 on a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.*

- Nobel liquids can probe from MeV scale (Migdal + electron scattering) to multi-TeV scale (nuclear recoils) and neutrino physics (solar, supernova, ++)

My view

- No brainer to support liquid Xenon at G3 (UK contributions internationally recognised, proven tech across multiple experiments, sensitive to spin-dependent and spin-independent signals)

- Development for DarkSide-20k should also be a priority: need multiple targets to characterise any dark matter signal + some unique physics opportunities (eg CNO neutrino flux measurement)

- We don't know what dark matter is: support smaller scale experiments to ensure we cover all theory space