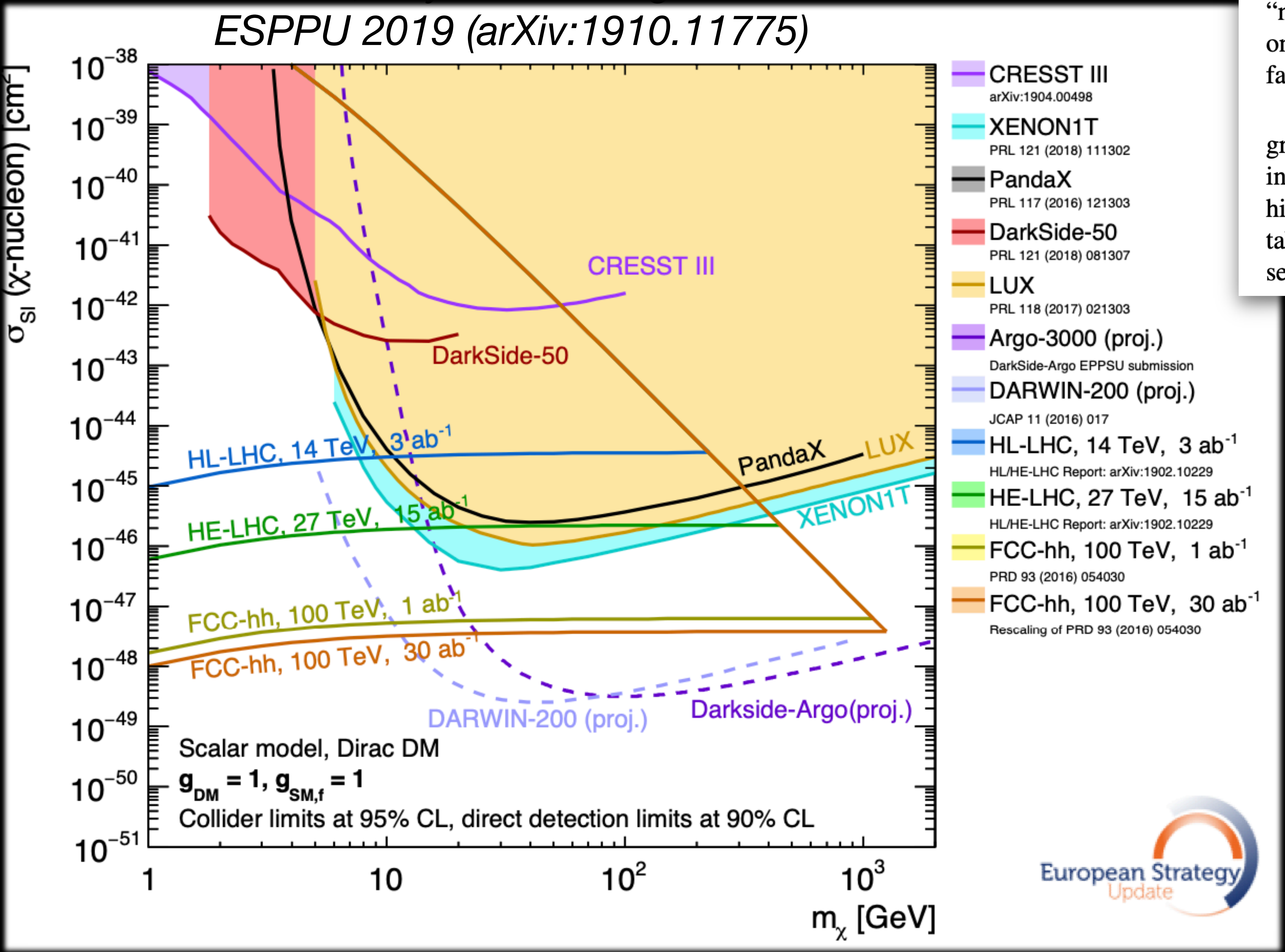
Direct Dark Matter Searches

EFCA-UK European Strategy Initiative
Physics Kick-off Meeting
1st May 2024

Dr Sally Shaw
sally.shaw@ed.ac.uk

Direct Dark Matter Detection in the last ESPP Update

Slide from Jocelyn Monroe, 30th April 2024



Major challenges to future direct detection experiments come from: (a) $\nu - e$ and coherent elastic scattering backgrounds from solar and atmospheric neutrinos, which is known as the "neutrino floor" and shown in the grey hatched region in Fig. 9.1; (b) neutrino flux uncertainties on these backgrounds; and, (c) technology scaling to increase in mass over current searches by factors of 10 or more whilst improving background rejection and lowering radioactivity.

In consideration of the strong synergy between direct dark matter detection and the programme for its production and discovery in high-energy collisions at accelerators as well as in accelerator-based fixed target experiments, discussions at the Open Symposium in Granada highlighted that CERN's support for selected direct dark matter search programmes that can take critical advantage of technology developed at CERN can deliver a decisive boost of their sensitivity.

Direct detection has important complementary with future accelerators:

- Direct detection searches probe above the kinematic reach of future accelerators
- Region of overlap where accelerators can **confirm** direct detection discovery (and vice versa)!

Outline:

- Big Questions
- DM Candidates
- Delve Deep
- Search Wide
- Conclusion

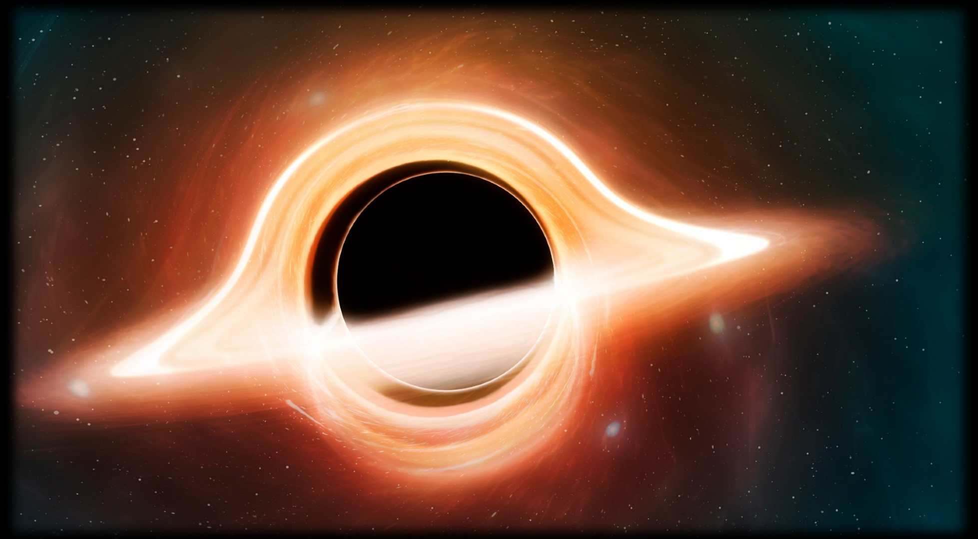
Dark Matter Big Questions

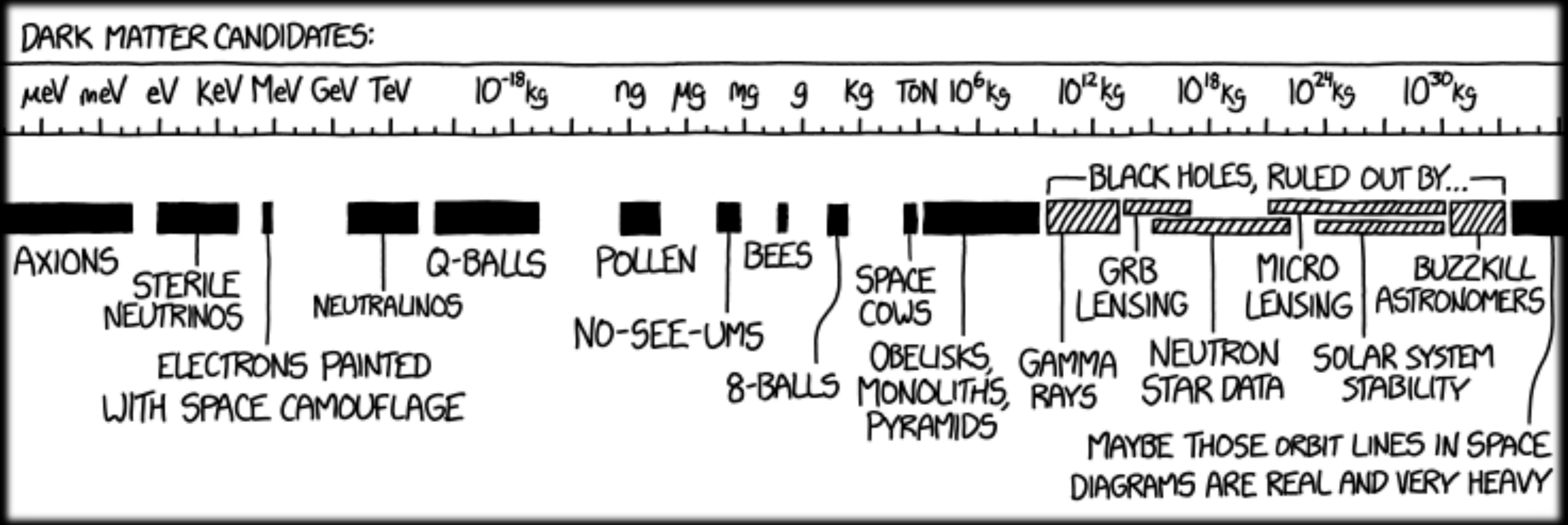
What is the nature of dark matter?

… that's kind of it.

But, in more detail:

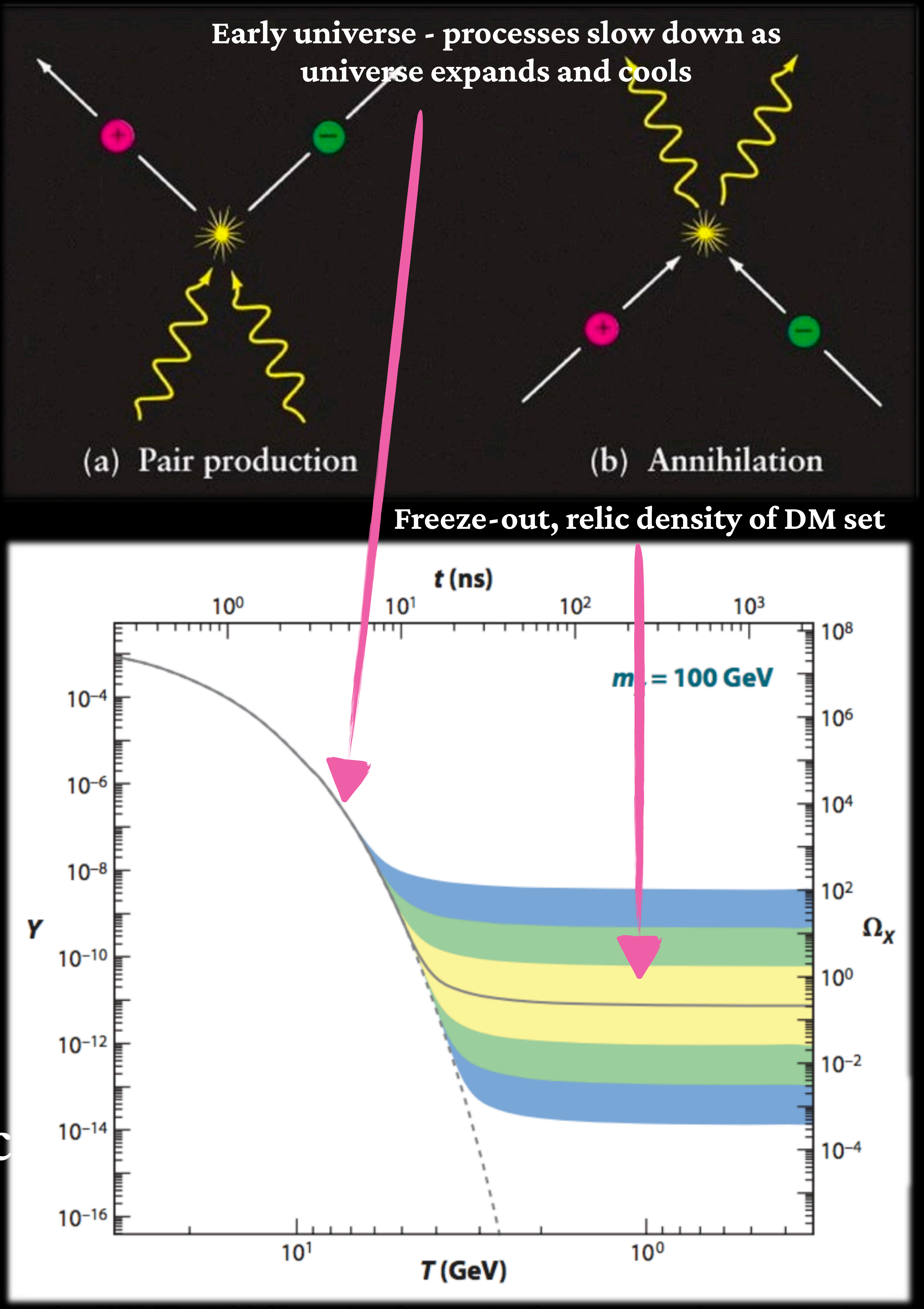
- Is it a particle?
- What are its properties?
- How does it interact?
- Is there one particle or many (a dark sector)?
- How does it explain astrophysical observations?





Particle Dark Matter

- Leading cosmology model is **ΛCDM.**
  - CDM = cold dark matter, has to be **non-baryonic, neutral, stable** (or τ >> age of universe).
- Theoretically well-motivated is the Weakly Interacting Massive Particle (WIMP).
  - ***WIMP miracle:*** measured relic abundance of DM → requires an annihilation cross section consistent with the weak interaction
  - WIMPs expected to couple to the SM through weak force: *WIMP-nucleon scattering*
  - Lightest supersymmetric particle (LSP) from Supersymmetric models is an ideal candidate (e.g. neutralino)



WIMP Dark Matter

An undergrad student I taught:

"Given this paper ["Supersymmetric Dark Matter" by Jungman, Kamionkowski and Griest] is ***older than me,*** *I'm wondering if the current state of the field is one that still favours WIMPs as one of the main focuses of detection efforts."*

WIMP Dark Matter

“Giv ... r” by
*Jungma ... **me,** I'm*
wonderin ... ll favours
WIM ... rts.”

FORBES > INNOVATION > SCIENCE

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group ⓘ

Follow

Feb 22, 2019, 02:00am EST

WIMP Dark Matter

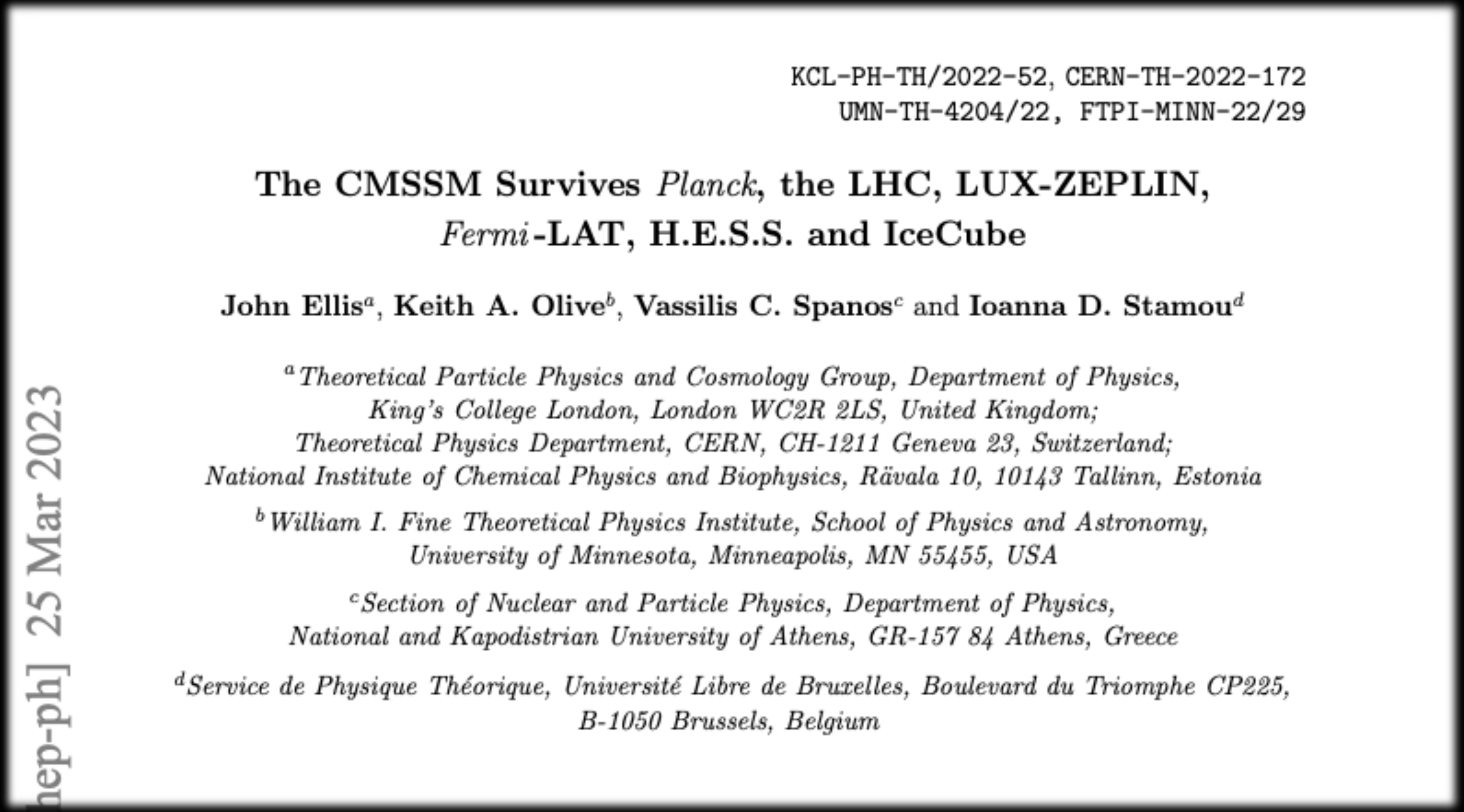
The CMSSM Survives Planck, the LHC, LUX-ZEPLIN, Fermi-LAT, H.E.S.S. and IceCube
Ellis, Olive, Spanos, Stamou
arXiv:2210.16337

2022 paper from Ellis et al reviews the Constrained Supersymmetric extension of the Standard Model (CSSM).

This combines:

- **Planck** measurements of DM density
- **LHC** measurements of Higgs mass & sparticle searches
- **LZ** limit on spin-independent scattering
- **Fermi-LAT** & **HESS** annihilation to photons in dSph and galactic centre
- **IceCube** limits on annihilations to neutrinos in the sun

"Strips" of parameter space show allowed values
"Direct detection can probe essentially all the strips if the sensitivity reaches down to the neutrino 'floor'. **The CMSSM may survive a while yet.**"


KCL-PH-TH/2022-52, CERN-TH-2022-172
UMN-TH-4204/22, FTPI-MINN-22/29

The CMSSM Survives *Planck*, the LHC, LUX-ZEPLIN, *Fermi*-LAT, H.E.S.S. and IceCube

John Ellis[a], Keith A. Olive[b], Vassilis C. Spanos[c] and Ioanna D. Stamou[d]

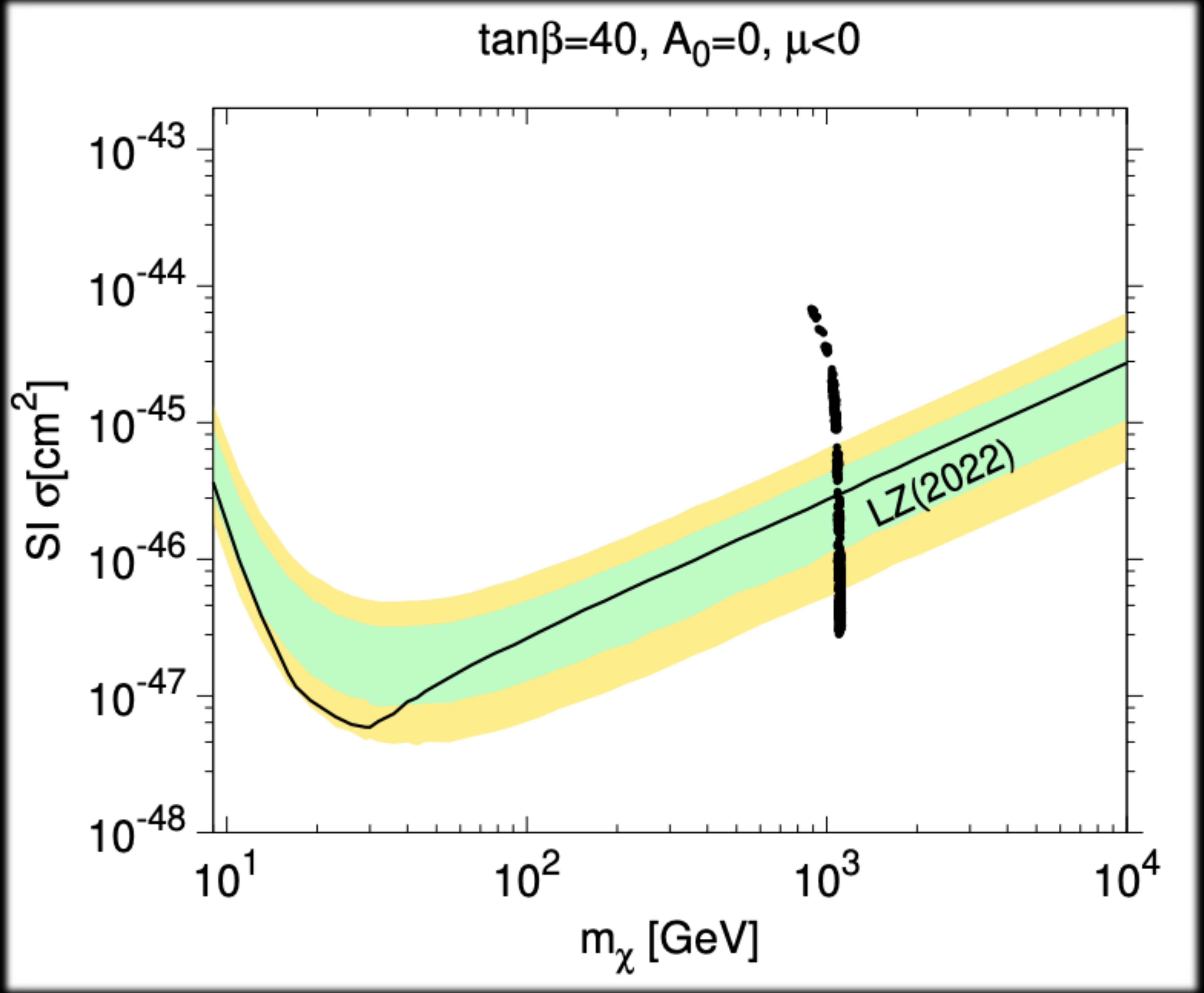
[a] *Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, United Kingdom; Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland; National Institute of Chemical Physics and Biophysics, Rävala 10, 10143 Tallinn, Estonia*

[b] *William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

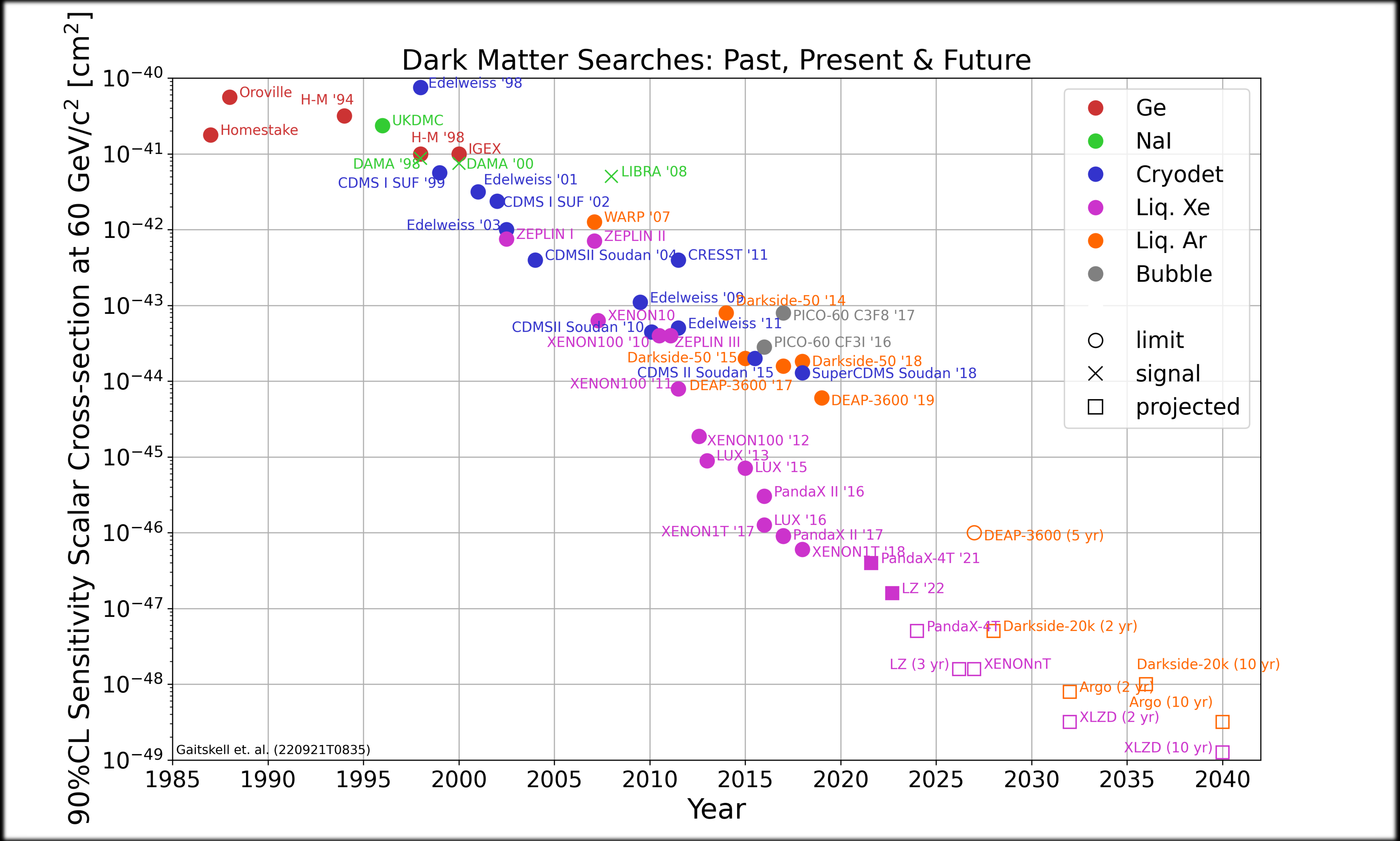
[c] *Section of Nuclear and Particle Physics, Department of Physics, National and Kapodistrian University of Athens, GR-157 84 Athens, Greece*

[d] *Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe CP225, B-1050 Brussels, Belgium*

hep-ph] 25 Mar 2023



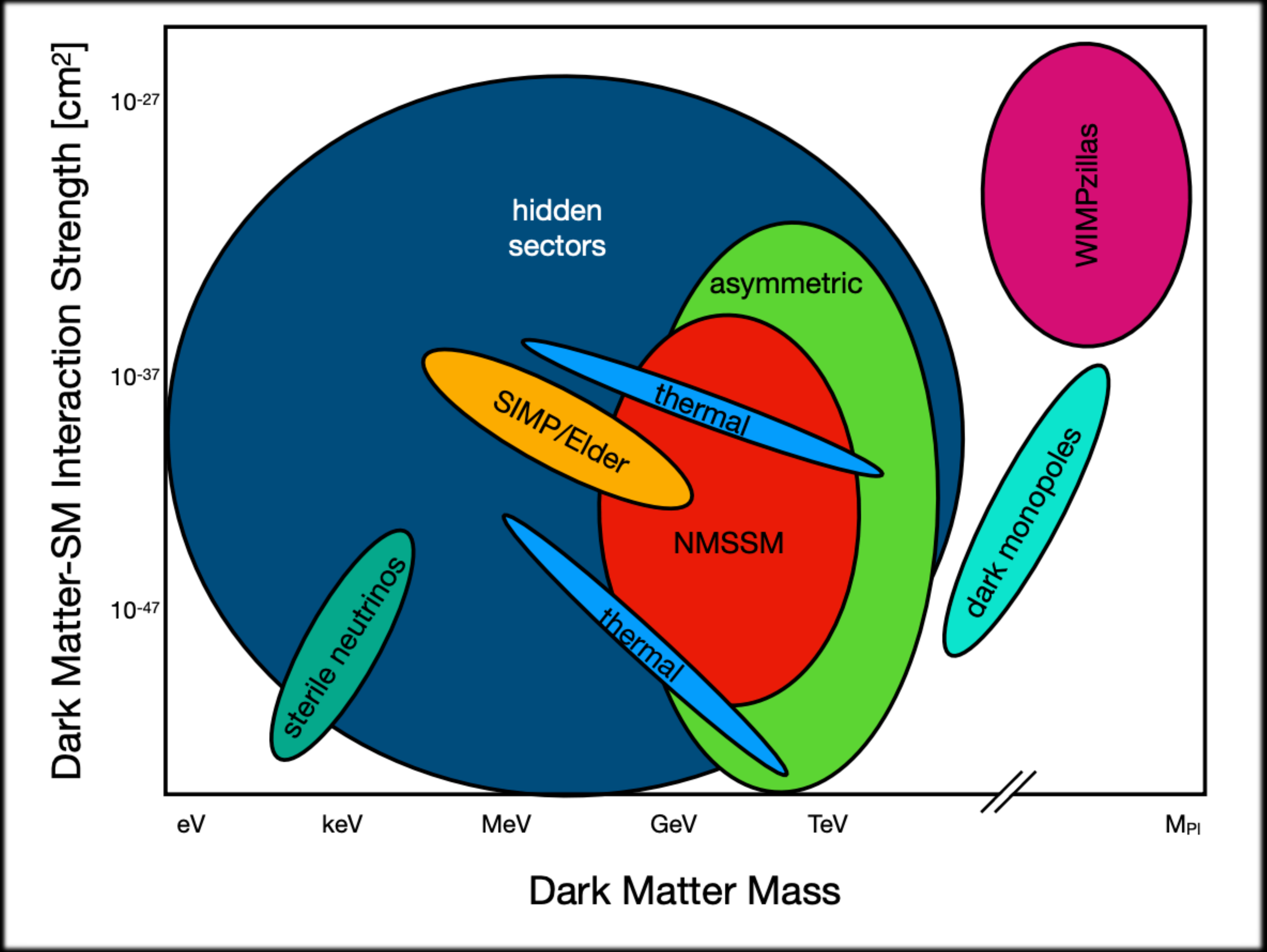
WIMP-Nucleon Cross Section Evolution



Dark Matter Candidates

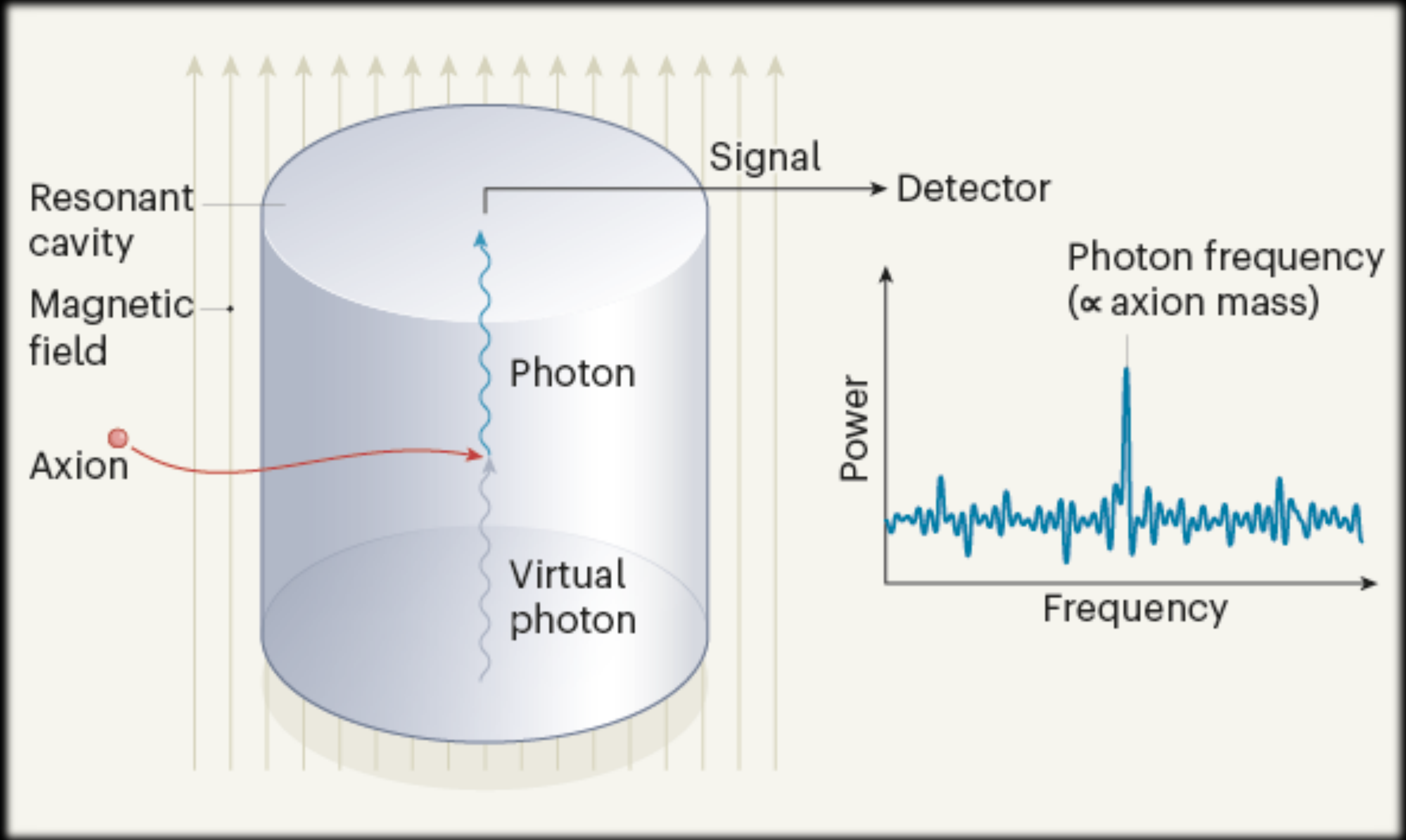
- Many, many candidates beyond “vanilla WIMPs”...
- Experiments to detect DM have an enormous range of masses to cover
- Current experiments are **not sensitive** to many candidates at either ends of the mass range
- Need to “***delve deep and search wide***”

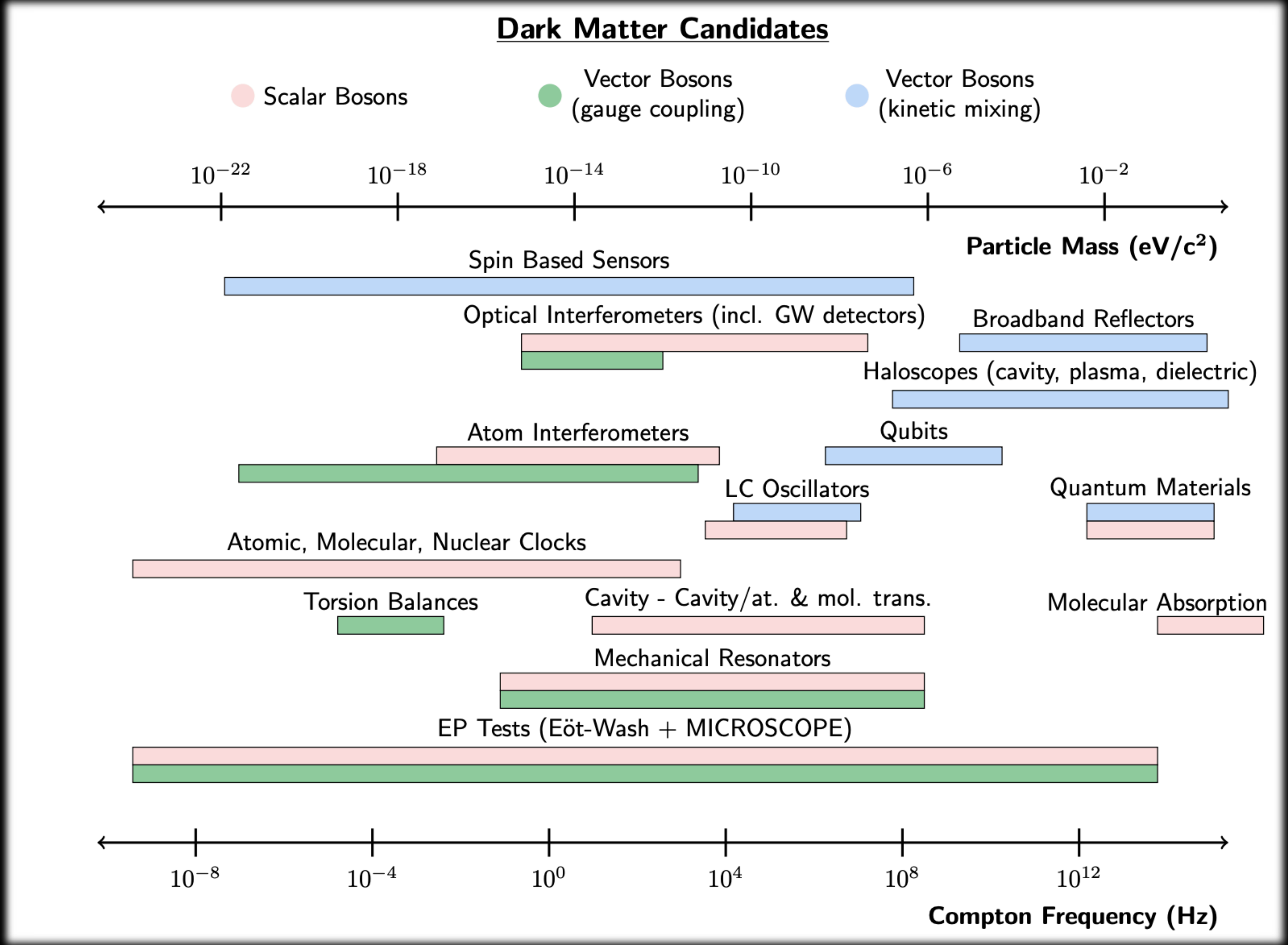
Report of the Topical Group on Particle Dark Matter for Snowmass 2021
arXiv:2209.07426



Axion Dark Matter

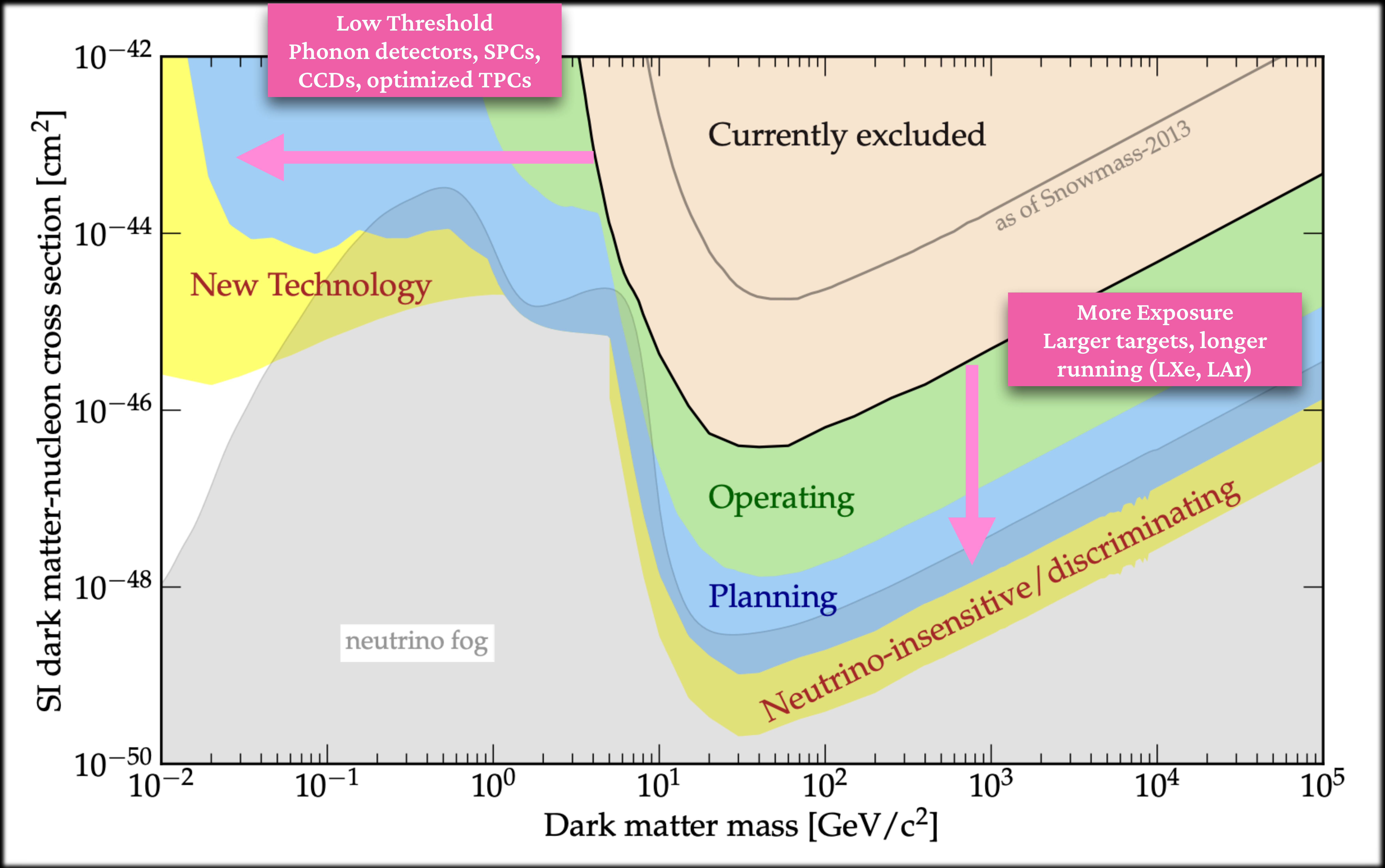
- Wave-like dark matter, mass < eV
- **QCD axion:** proposed to solve the strong CP problem of Quantum Chromodynamics
- **Axion-Like Particle (ALP)** (10^{-20} - 1 eV)
  - share features of the axion (e.g. (pseudo-)scalar, low mass, weak couplings) but don't solve the strong CP problem
- Could be detected via: axio-electric effect, axion→γ conversion in magnetic field, interaction with gluons
- Advances in **quantum sensing** have driven explosion of interest in axions



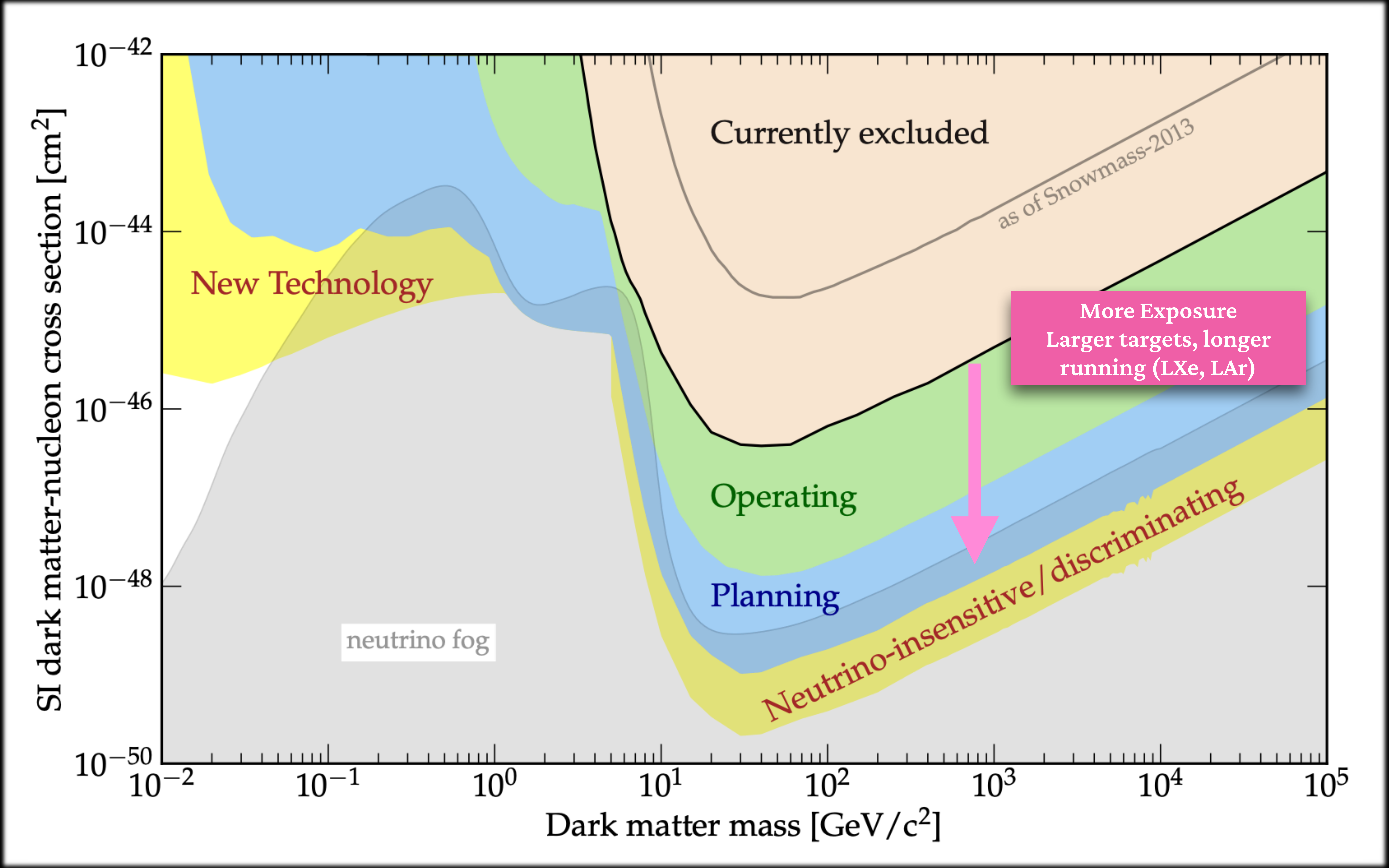


Report of the Topical Group on Wave Dark Matter for Snowmass 2021
arXiv:2209.08125

Delve Deep & Search Wide



Delve Deep



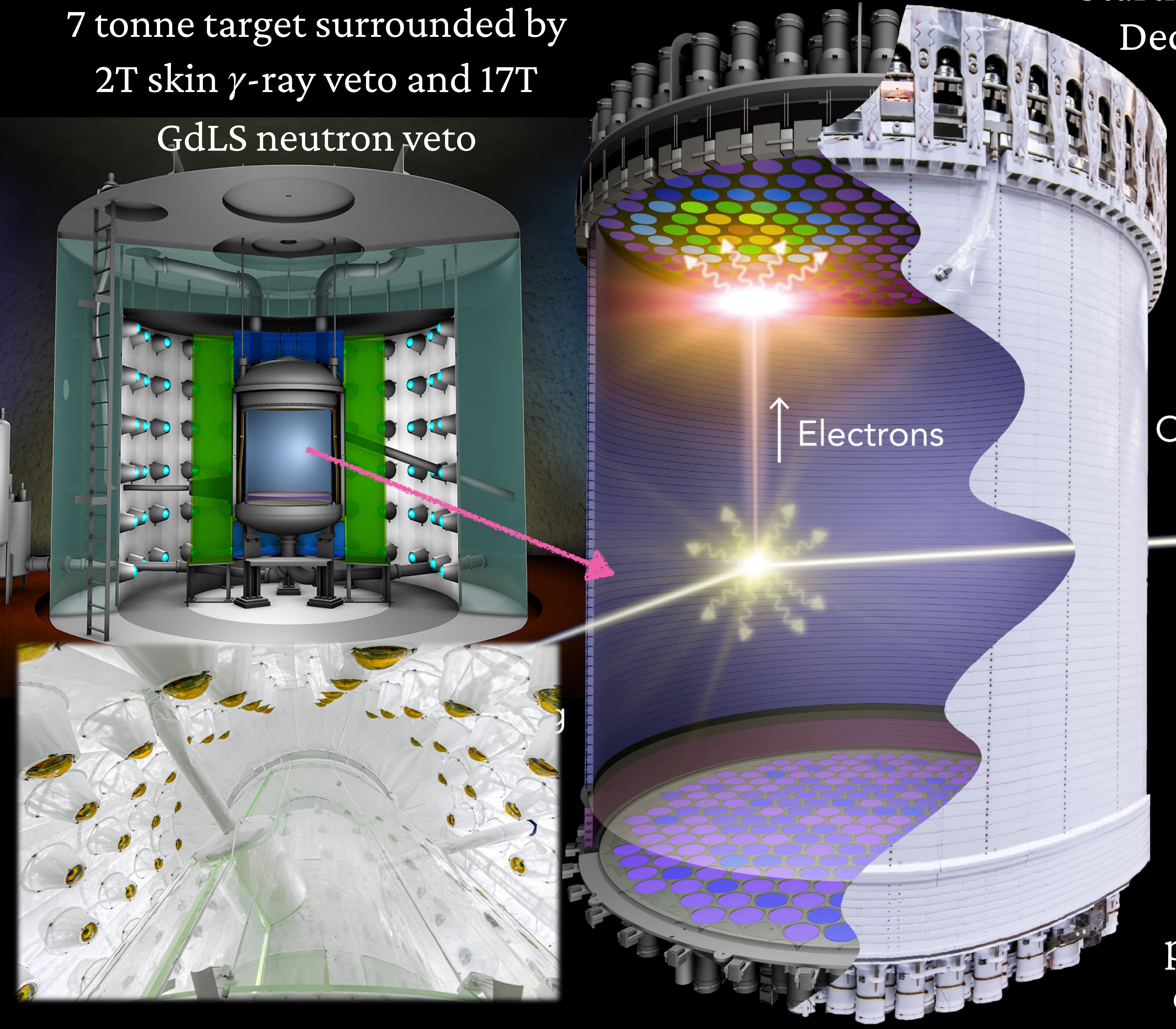
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
SI dark matter-nucleon cross section [cm^2]
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Dark matter mass [GeV/c^2]
Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
neutrino fog
Neutrino-insensitive/discriminating
More Exposure
Larger targets, longer running (LXe, LAr)

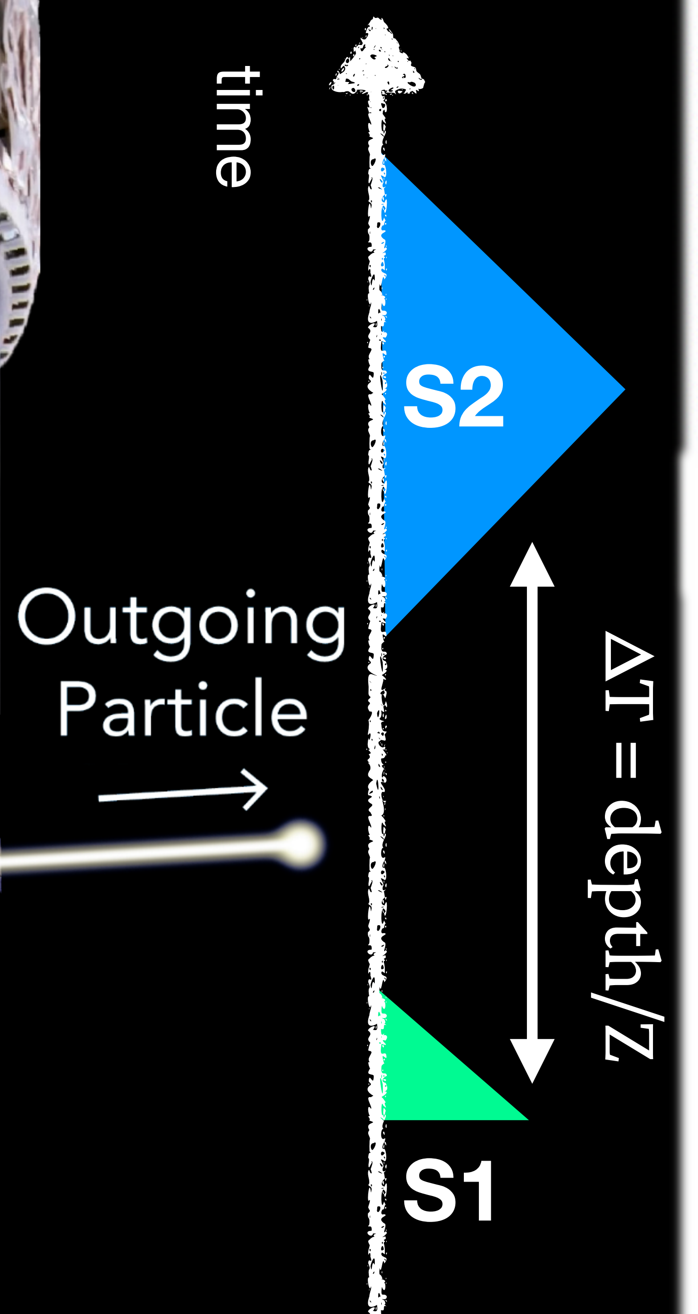
LZ

UK involvement: Bristol, Edinburgh, Imperial, KCL, Liverpool, Oxford, Sheffield, RAL, RHUL, UCL

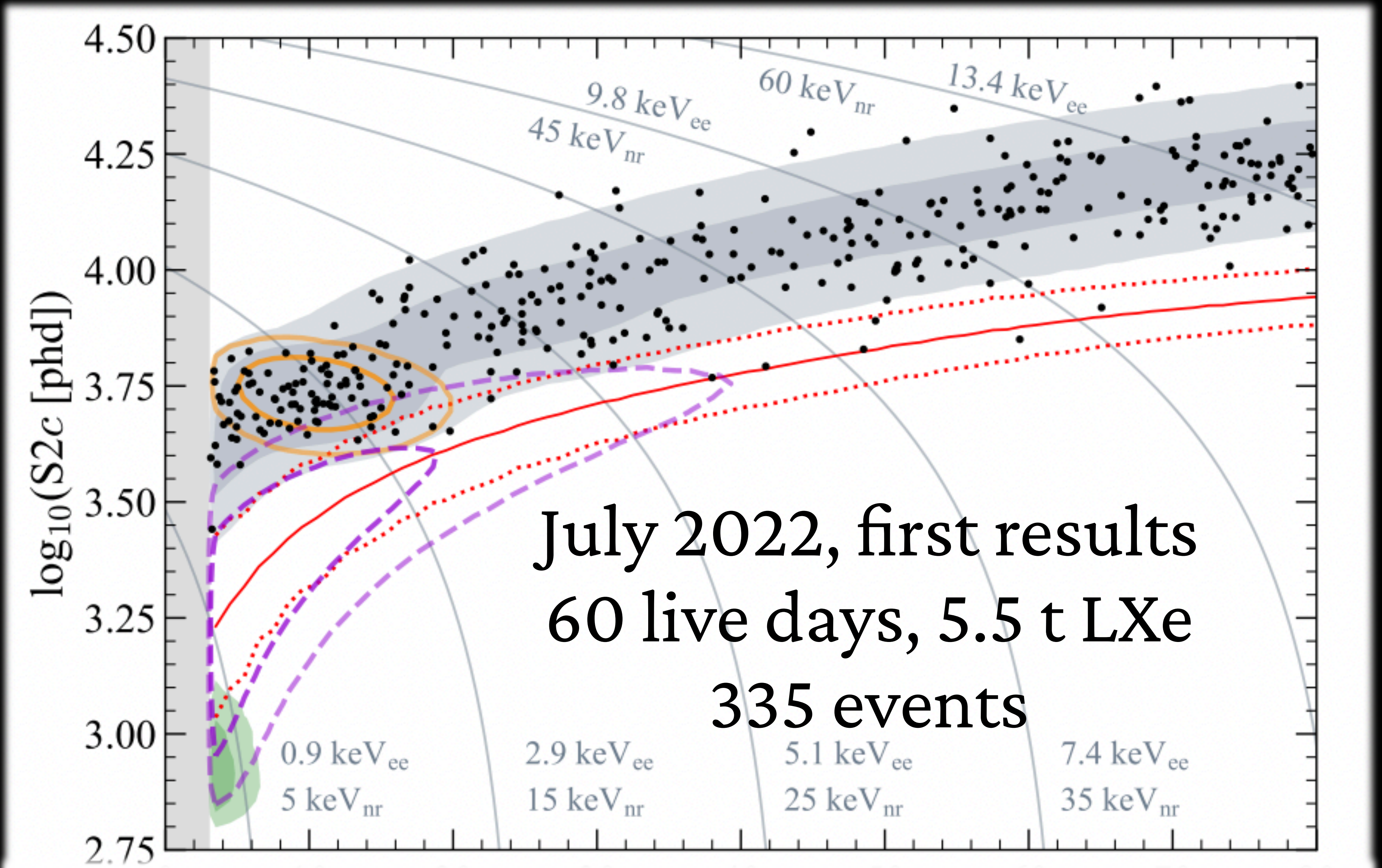
7 tonne target surrounded by 2T skin γ-ray veto and 17T GdLS neutron veto

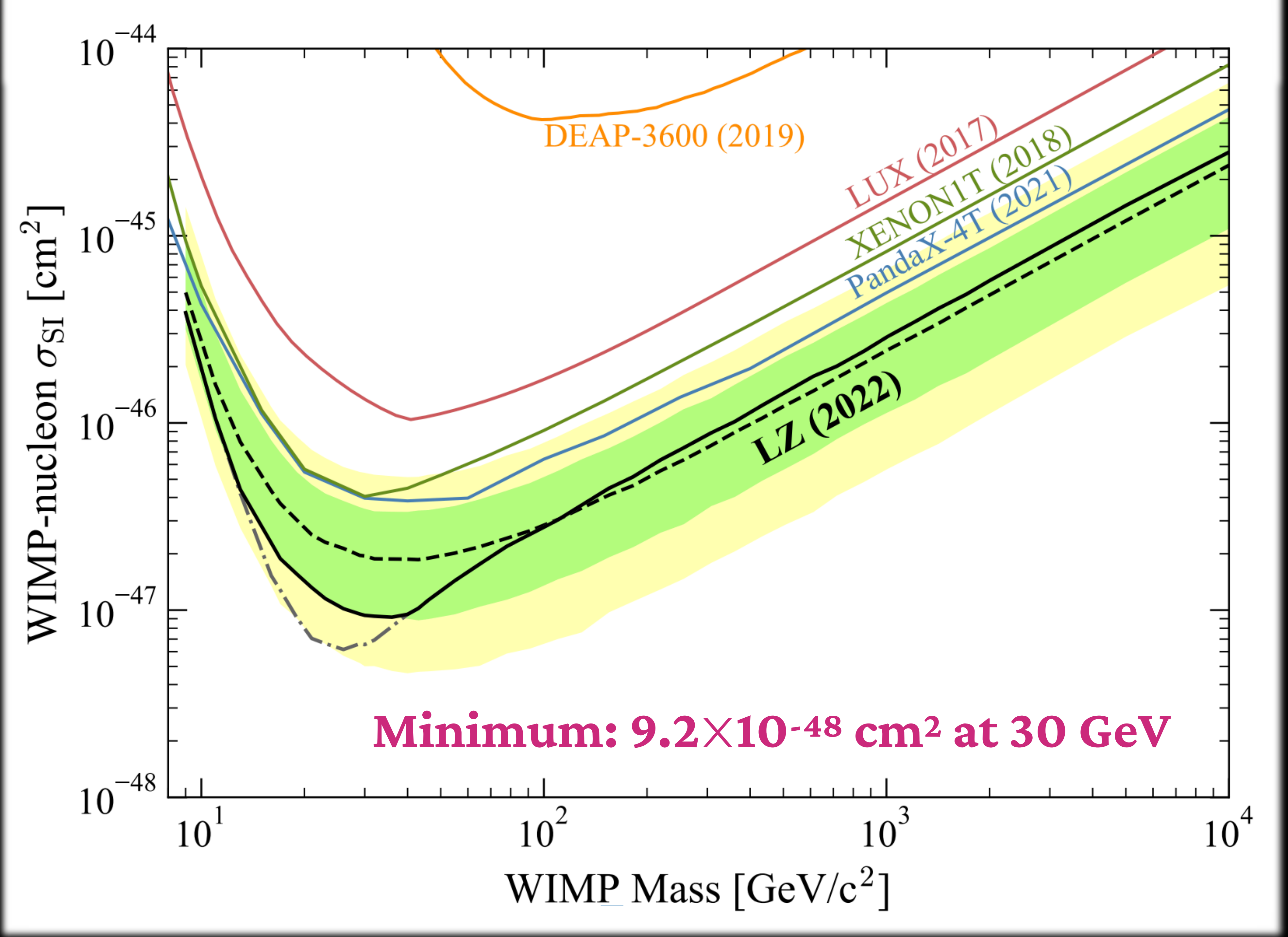
Starting data taking December 2021





Ratio of S2/S2 provides ER/NR discrimination

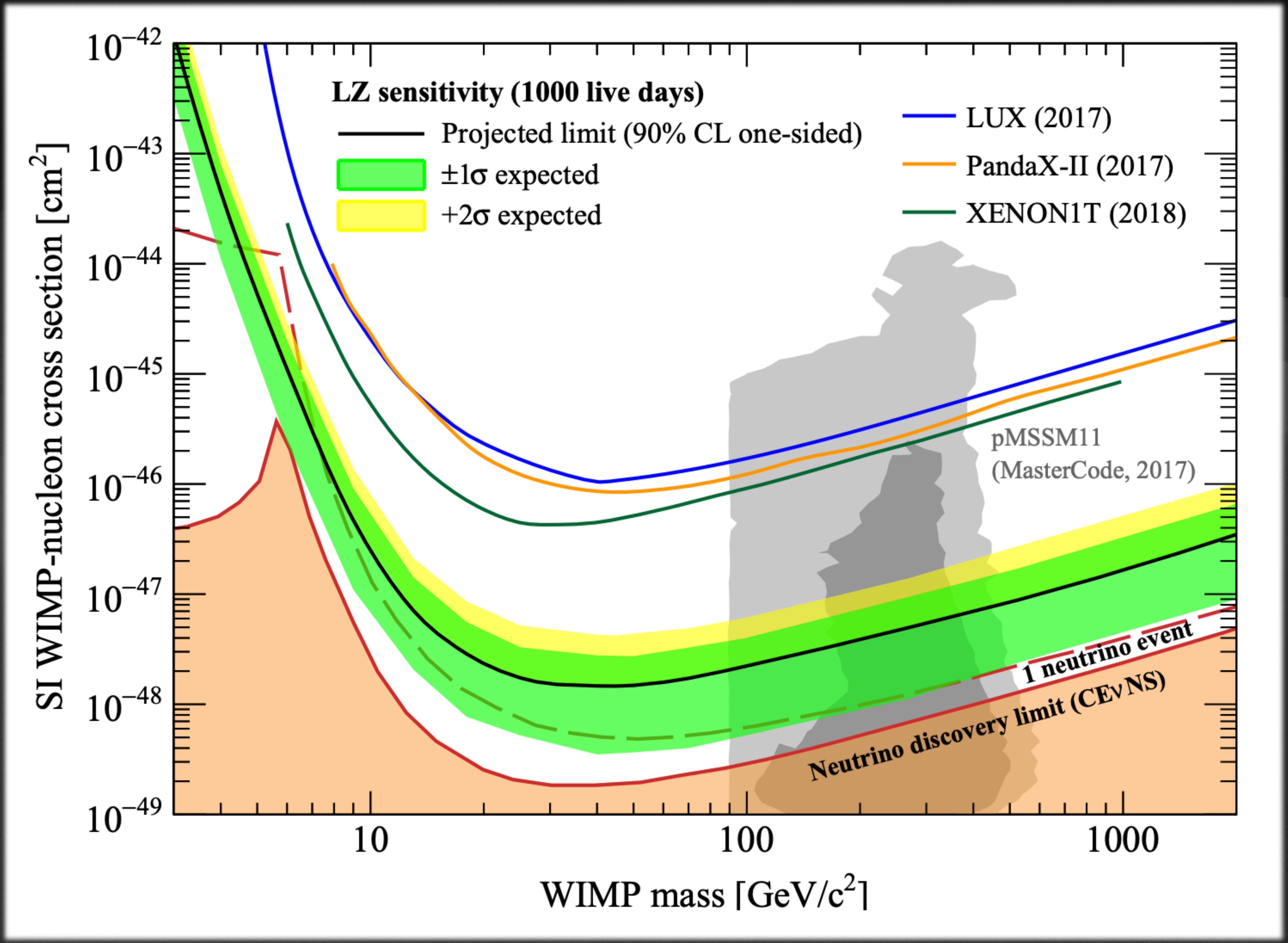




LZ

- Expect new LZ results from longer science run later this year
- Challenges include electron backgrounds and reaching design electric fields
- Full planned exposure: 1000 days
  - Minimum cross section 1.4x10^{-48} cm^2
- Wide range of physics analyses ongoing including:
  - Low mass WIMPs: S2-only searches, Migdal effect
  - Axions, ALPs, hidden photons, mirror DM
  - NR signals: EFT models
  - Multiply Interacting Massive Particles (MIMPs)

Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment
Phys. Rev. D 101, 052002 (2020)



DarkSide-20K

Contact: Jocelyn Monroe, Oxford, jocelyn.monroe@physics.ox.ac.uk

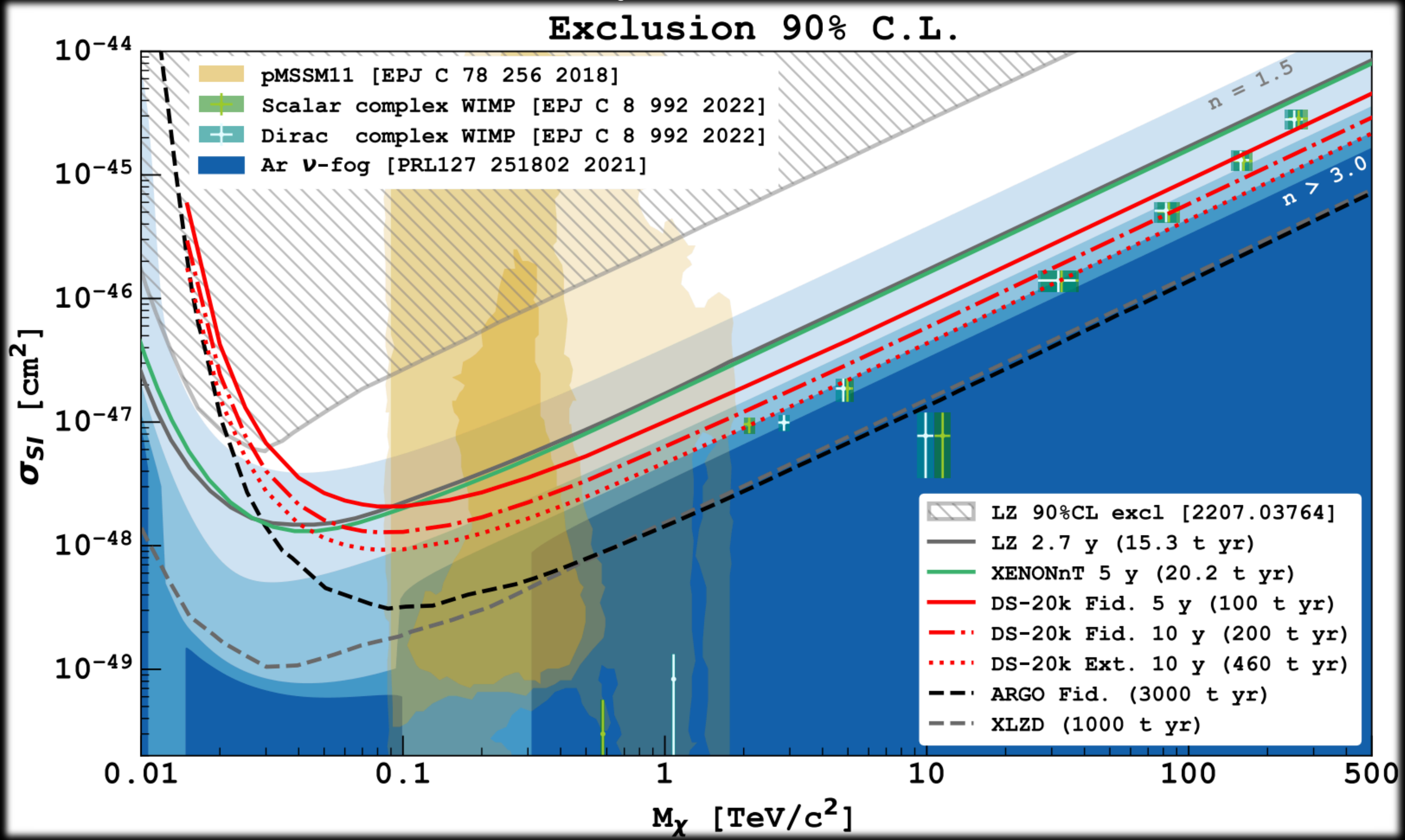
UK involvement: Birmingham, Edinburgh, Lancaster, Liverpool, Manchester, Oxford RHUL, Warwick

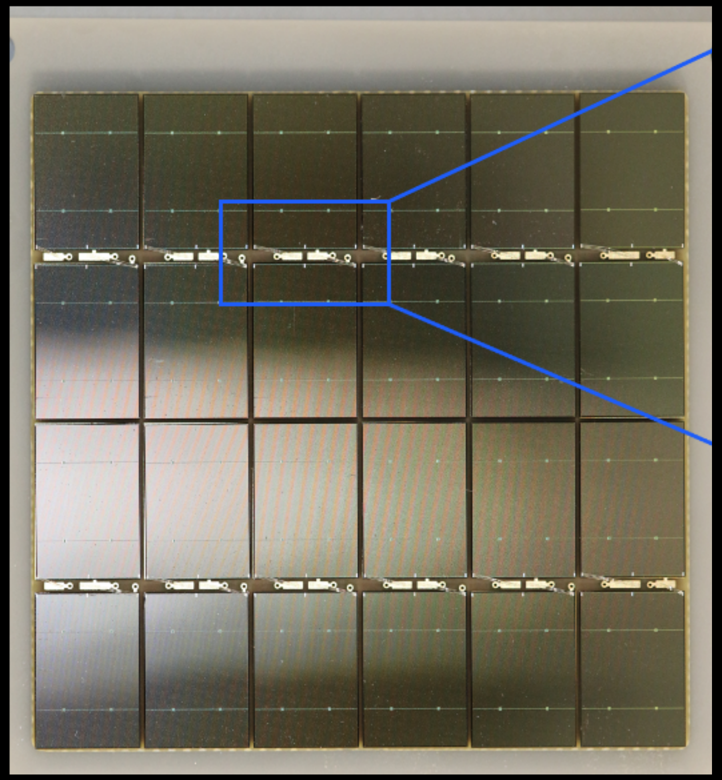
Slide from Jocelyn Monroe, 30th April 2024

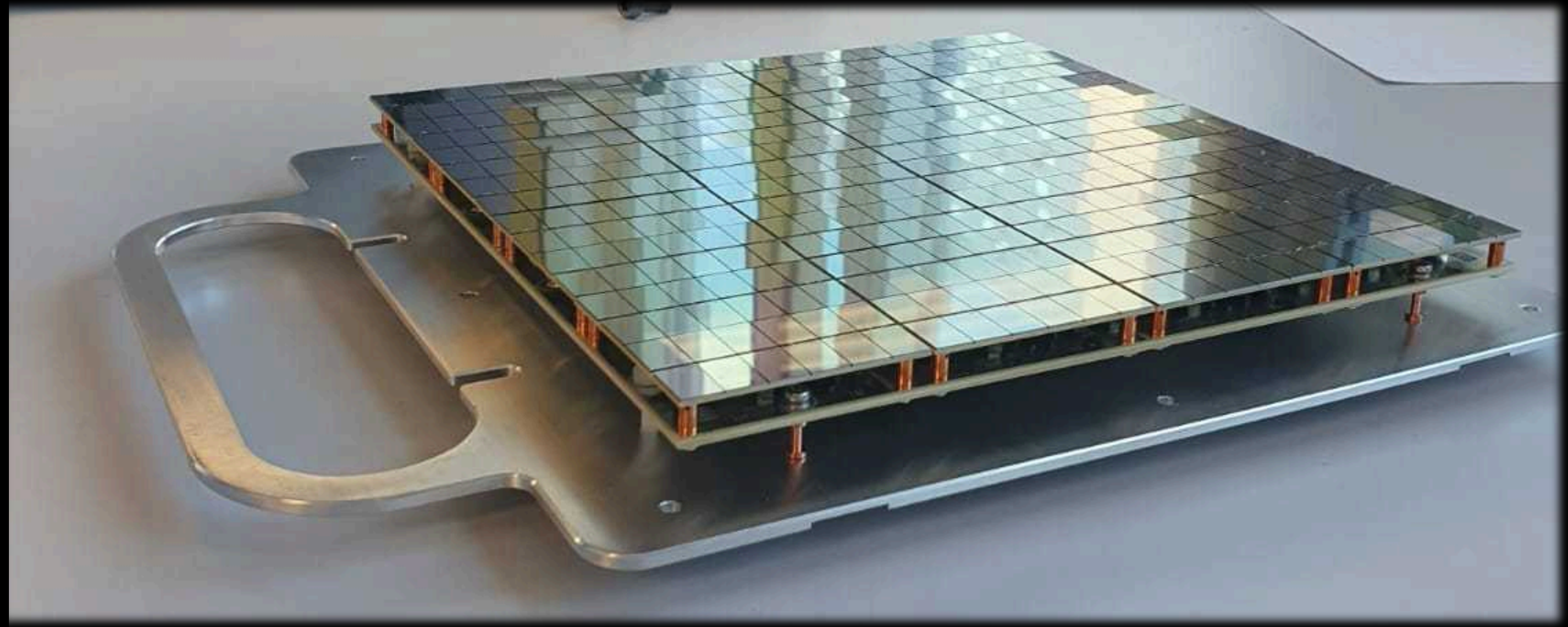
- DarkSide-UK project delivering 7 m^2 of SiPM array detectors, with lower noise, radioactivity and higher photon detection efficiency than PMTs
  - production/qualification of hardware underway at across Birmingham, Edinburgh, Lancaster, Liverpool, Manchester, Oxford, RAL, RHUL, Warwick + radioassay at Boulby
  - Strong synergy with UK involvement in ECFA Liquid Detectors Collaboration ("DRD2") now established at CERN
- DarkSide-20k construction at Gran Sasso Laboratory (LNGS) advanced
  - cryostat and infrastructures in LNGS Hall C complete!
  - Cryogenics system operating in Hall C
  - TPC components in production
  - Installation of UK photodetectors starting 2025, Ar fill 2026.
  - Apr.'24: Positive STFC funding decision on installation phase (2024-6)

UK Ambassador to Italy visits DarkSide-20k, 12/23

DarkSide-20k: A 20 Tonne Two-Phase LAr TPC for Direct Dark Matter Detection at LNGS Eur. Phys. J. Plus (2018) 133:131







XLZD

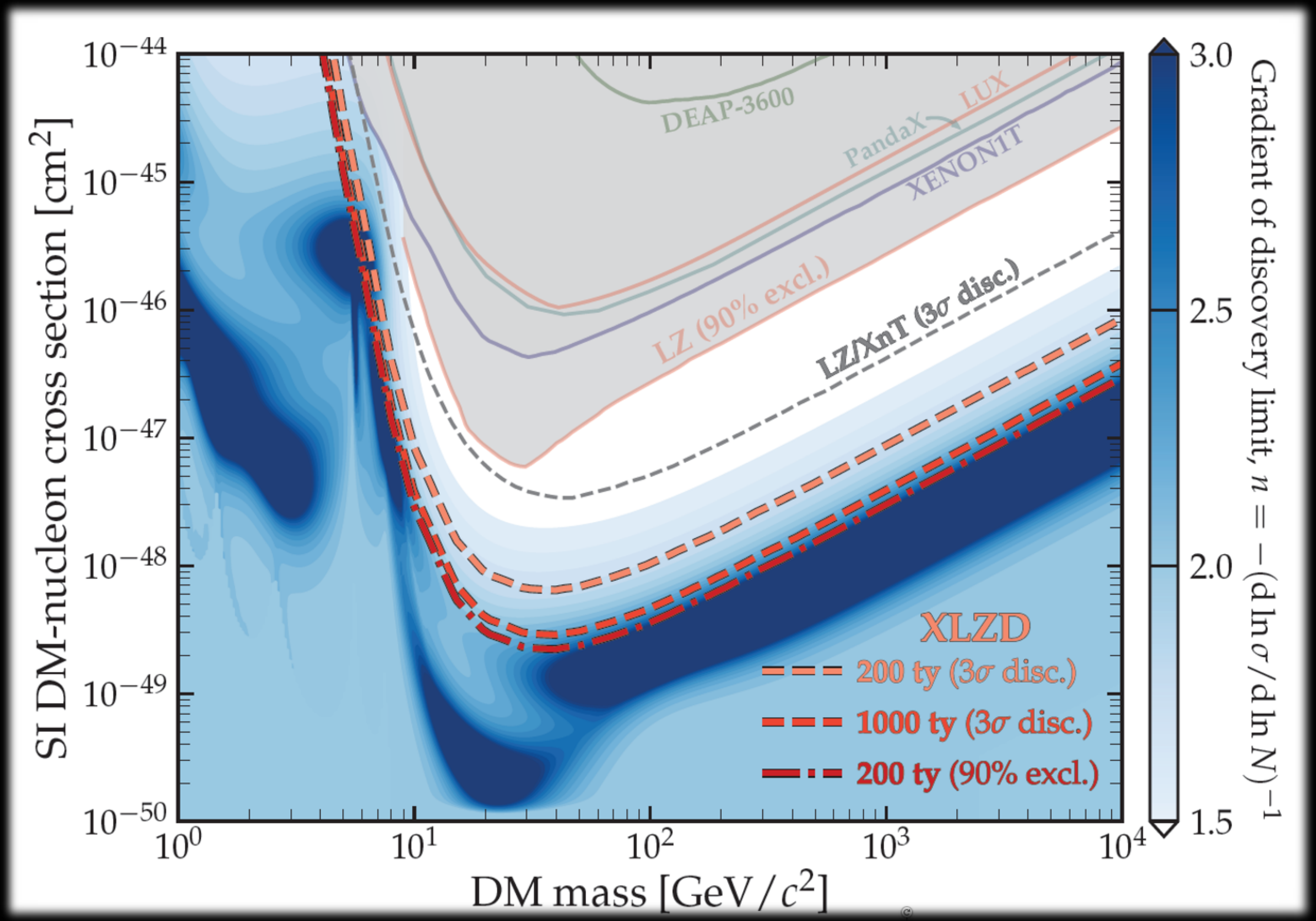
Contact: Henrique Araujo, h.araujo@imperial.ac.uk

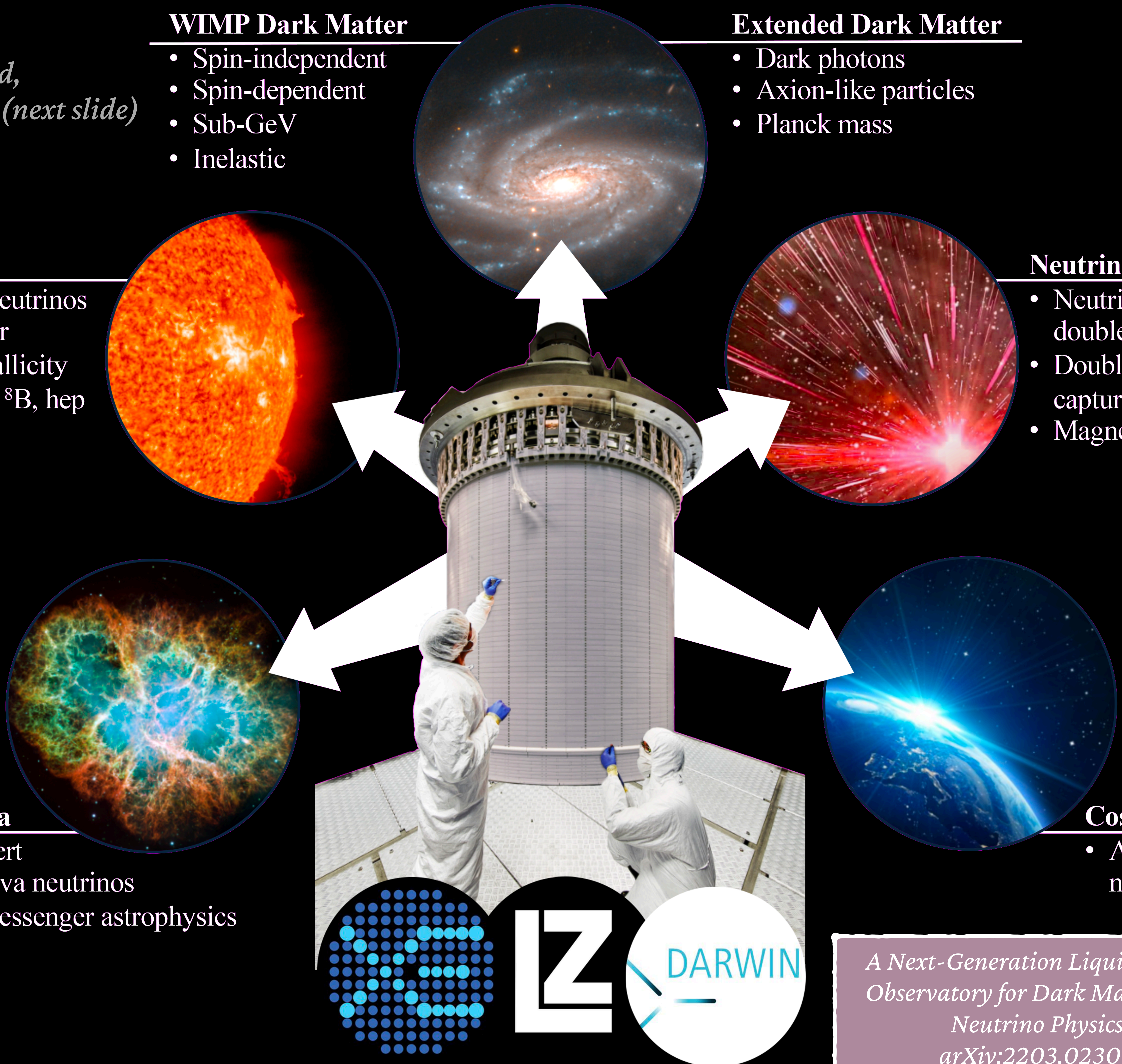
UK involvement: Bristol, Edinburgh, Imperial, KCL, Liverpool, Oxford, Sheffield,, RAL, RHUL, UCL + many more joining for XLZD@Boulby (next slide)

XENON, DARWIN and LZ have joined forces to build a 40T-80T LXe TPC - location TBD.

Science drivers:

- The **ultimate probe of WIMPs** down to the neutrino fog
- A **competitive and economic** search for neutrinoless double-beta decay
- Measurements of multiple astrophysical neutrino signals





WIMP Dark Matter
- Spin-independent
- Spin-dependent
- Sub-GeV
- Inelastic

Extended Dark Matter
- Dark photons
- Axion-like particles
- Planck mass

Sun
- pp neutrinos
- Solar metallicity
- ^{7}Be, ^{8}B, hep

Neutrino Nature
- Neutrinoless double beta decay
- Double electron capture
- Magnetic moment

Supernova
- Early alert
- Supernova neutrinos
- Multi-messenger astrophysics

Cosmic Rays
- Atmospheric neutrinos

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

XLZD

Contact: Henrique Araujo, h.araujo@imperial.ac.uk

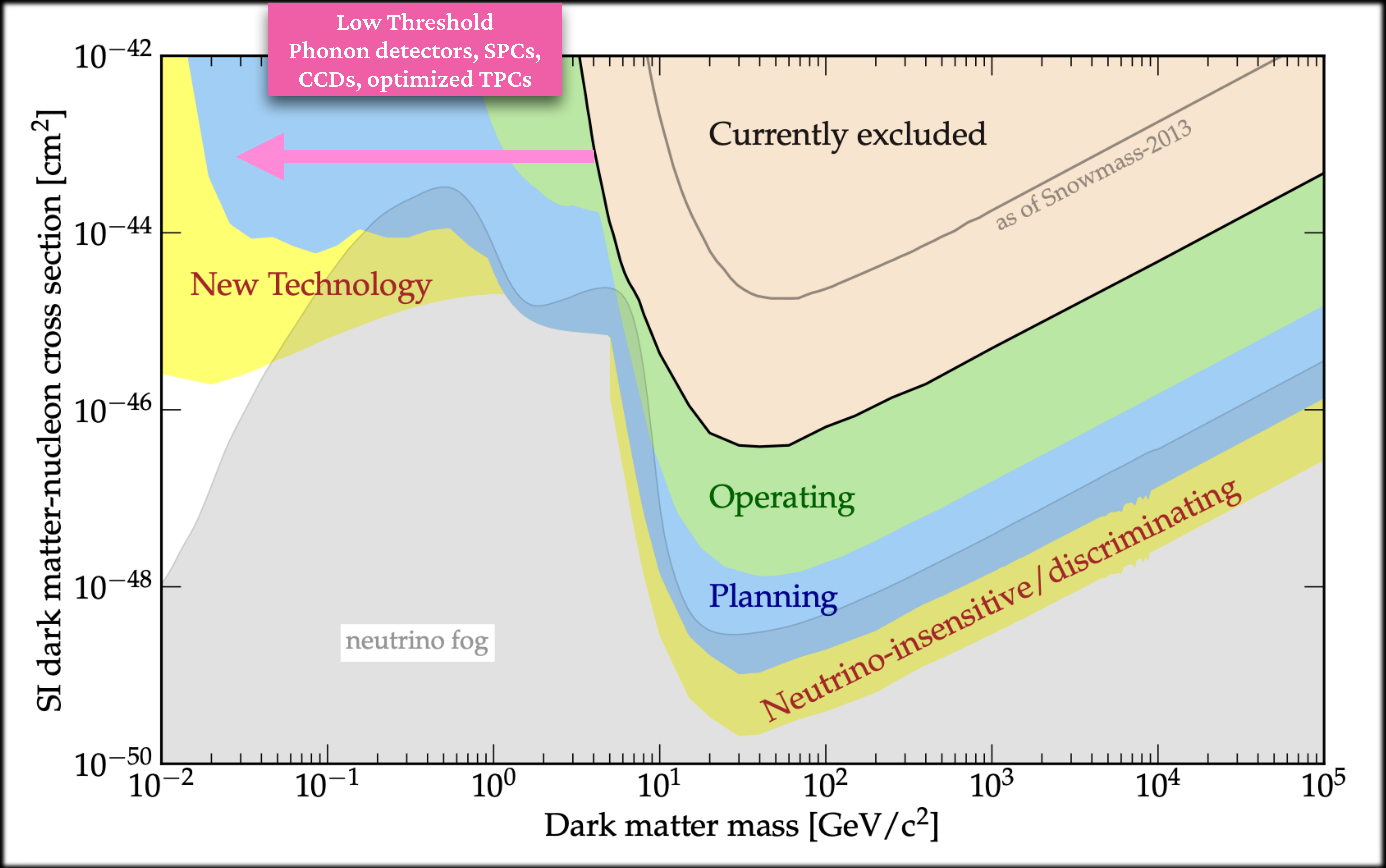
Boulby Underground Laboratory is a strong potential host. SoI Signed by 58 lead researchers from 22 UK institutes.
Preliminary activity proposal submitted for Wave 4 of the **UKRI Infrastructure Fund:**

- Conceptual design report by 2025
- Design of UK scope by 2027
  - Including xenon acquisition, Outer Detector, Cryostat, TPC elements, computing & data centre, clean manufacture & engineering
- Expecting news very soon...

UKRI Science and Technology Facilities Council
Boulby Underground Laboratory

XLZD Meeting at RAL, April 2024

Search Wide



Low Threshold
Phonon detectors, SPCs, CCDs, optimized TPCs
Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
Neutrino-insensitive/discriminating
neutrino fog
SI dark matter-nucleon cross section [cm^2]
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10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Dark matter mass [GeV/c^2]

NEWS-G

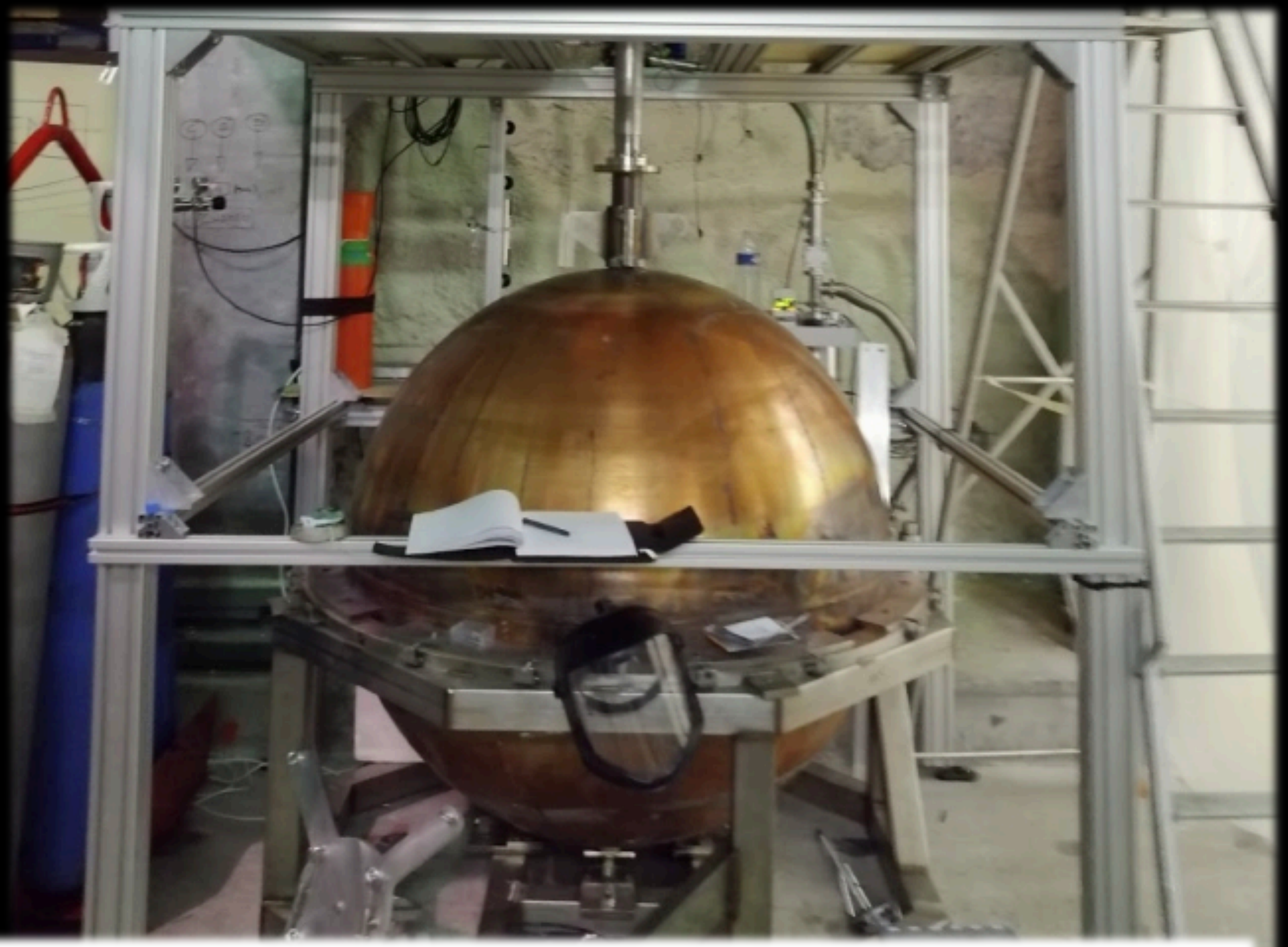
Contact: Patrick Knights, prk@hep.ph.bham.ac.uk

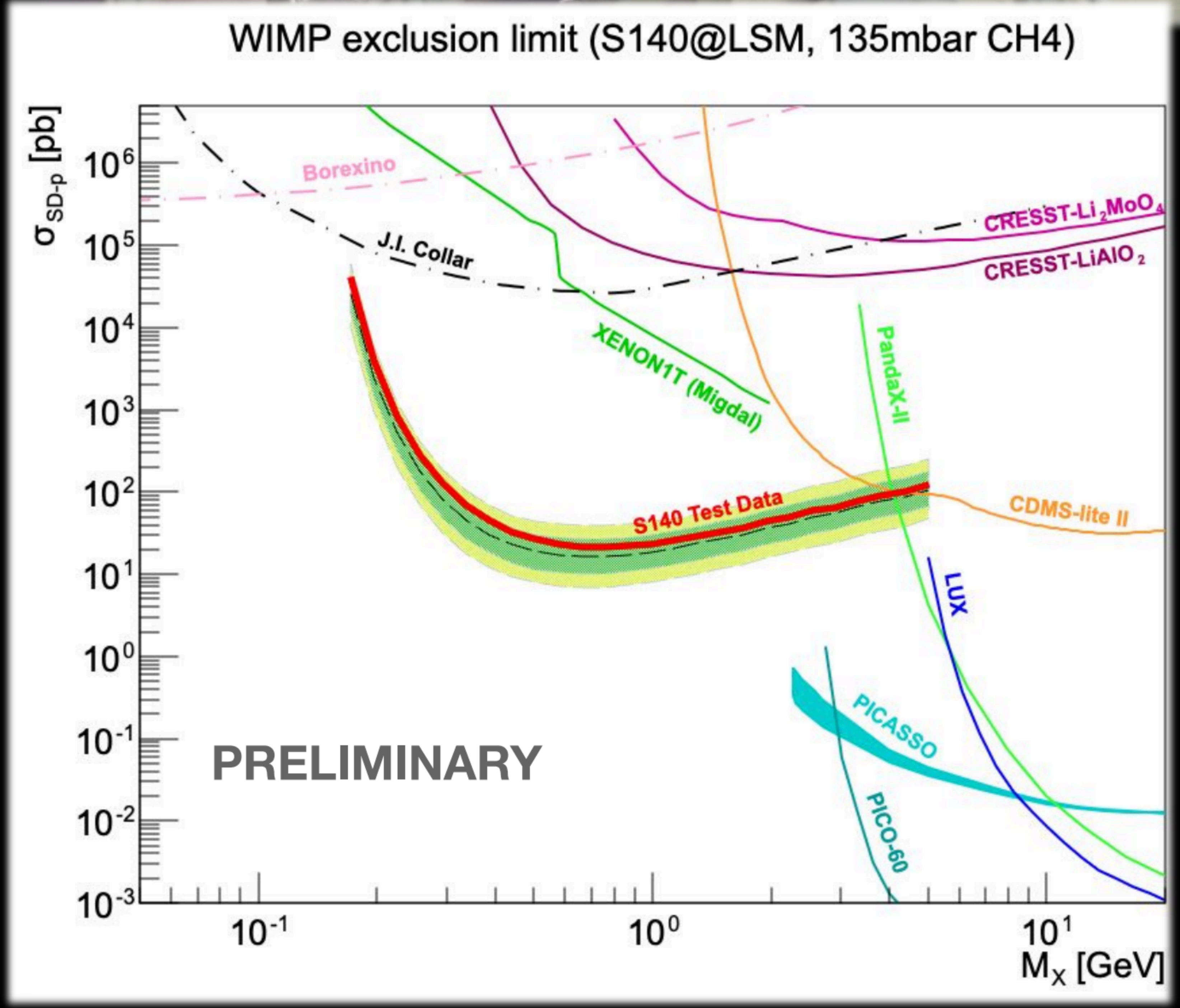
UK involvement: Birmingham

Sub-GeV DM detection with **Spherical Proportional Counters**

- Detects ionisation electrons drifted to an anode
- Easy to swap target gas - check different nuclei
- NEWS-G: preliminary results from test data at LSM (0.12 kg-days, methane target) with 140cm detector shown last year
  - New constraints on spin-dependent **WIMP-proton scattering**
  - Ongoing science run with improvements in noise, gas purity, backgrounds at SNOLAB.
- Next: DarkSphere - 300cm, potentially at Boulby Underground Laboratory

"The search for Light Dark Matter with NEWS-G"
D. Durnford, UCLA DM 2023





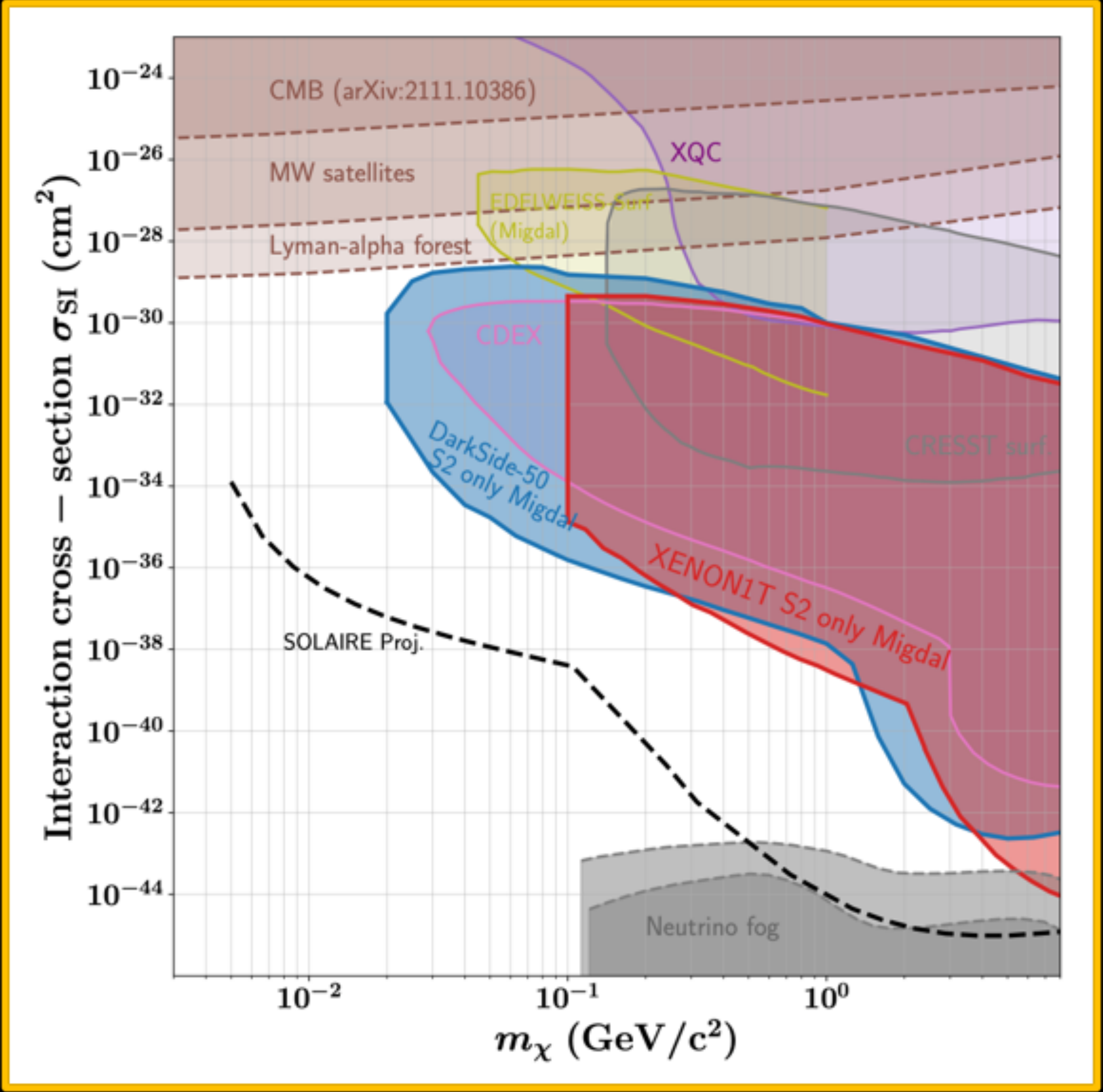
SOLAIRE

Contact: Darren Price, Darren.Price@cern.ch

UK involvement: Edinburgh, Imperial, Liverpool, Manchester, Oxford, QMUL, RAL, Warwick

Dedicated tonne-scale TPC for S2-only searches, proposal to host at **Boulby Underground Laboratory.**

- Leverage existing SiPM photosensor development in the UK
- Develop domestic capabilities in SiPM production, cryogenics and more..
- Enhance UK prospects to contribute to **large experimental facilities**
- Offers an opportunity to target MeV-GeV scale DM-nucleon interactions with sensitivity beyond current capabilities and astrophysics probes



MIGDAL

Contact: Paweł Majewski, pawel.majewski@stfc.ac.uk

UK involvement: Birmingham, Imperial, KCL, Oxford, RAL, RHUL, Sheffield

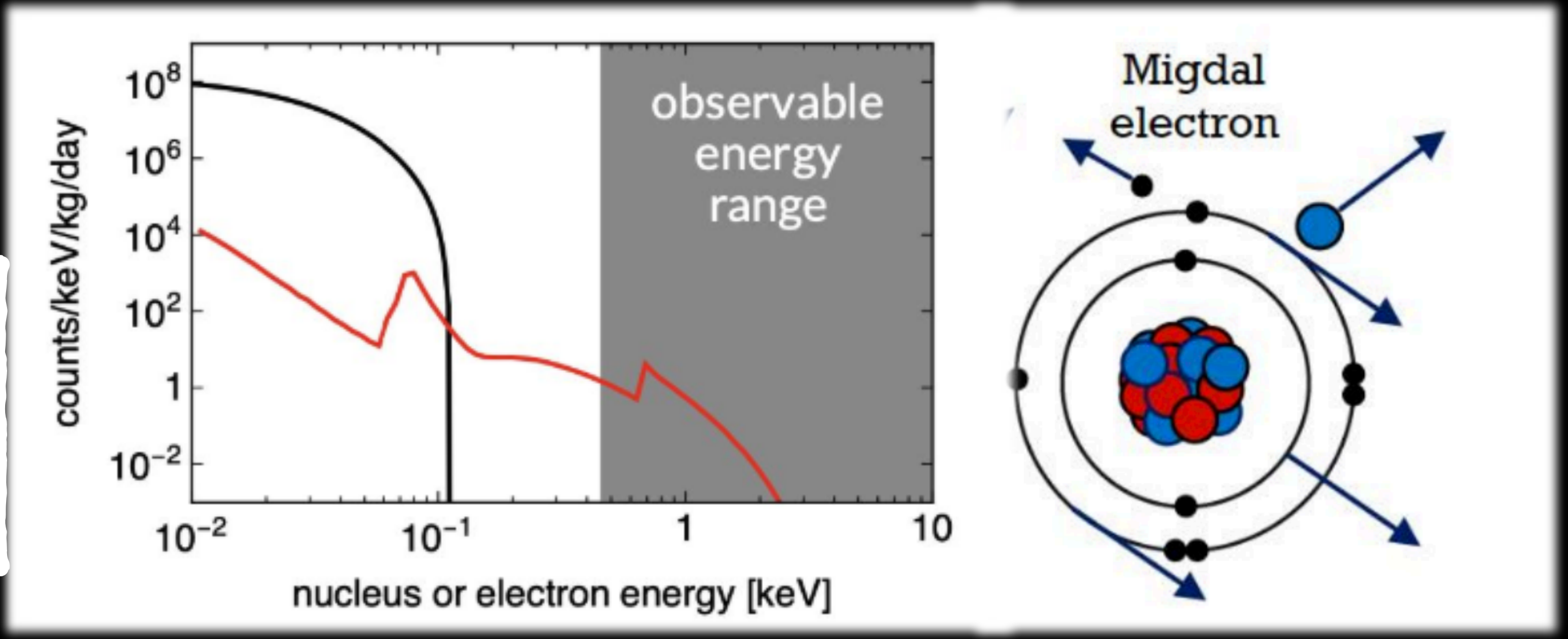
Migdal: theorised effect that produces an ER enhancement on a nuclear recoil signal
→ can make a **sub-threshold** NR visible
→ more sensitivity to **low mass DM**

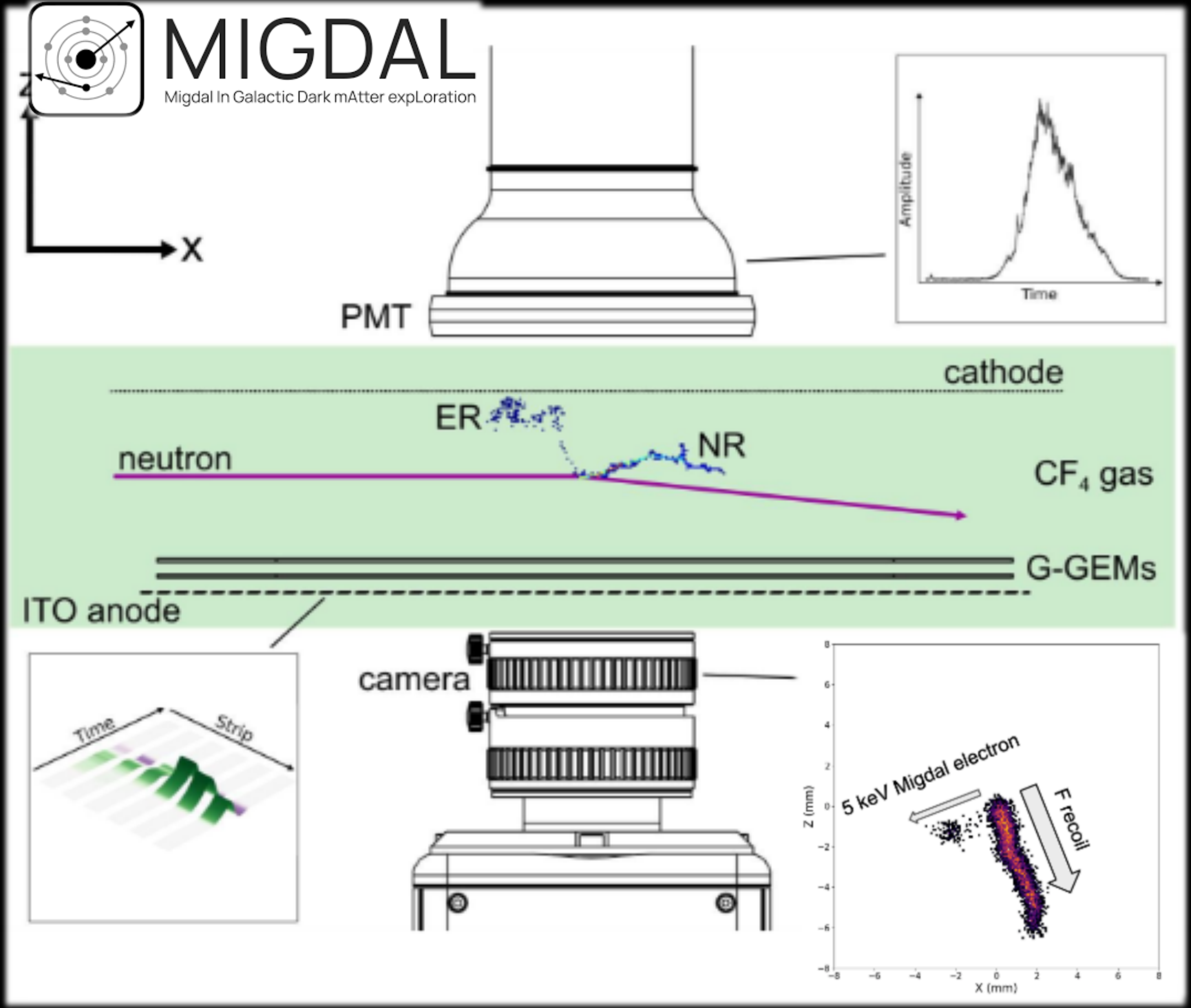
Used for limits for several years but not yet observed after a nuclear scatter!

MIGDAL experiment at RAL:

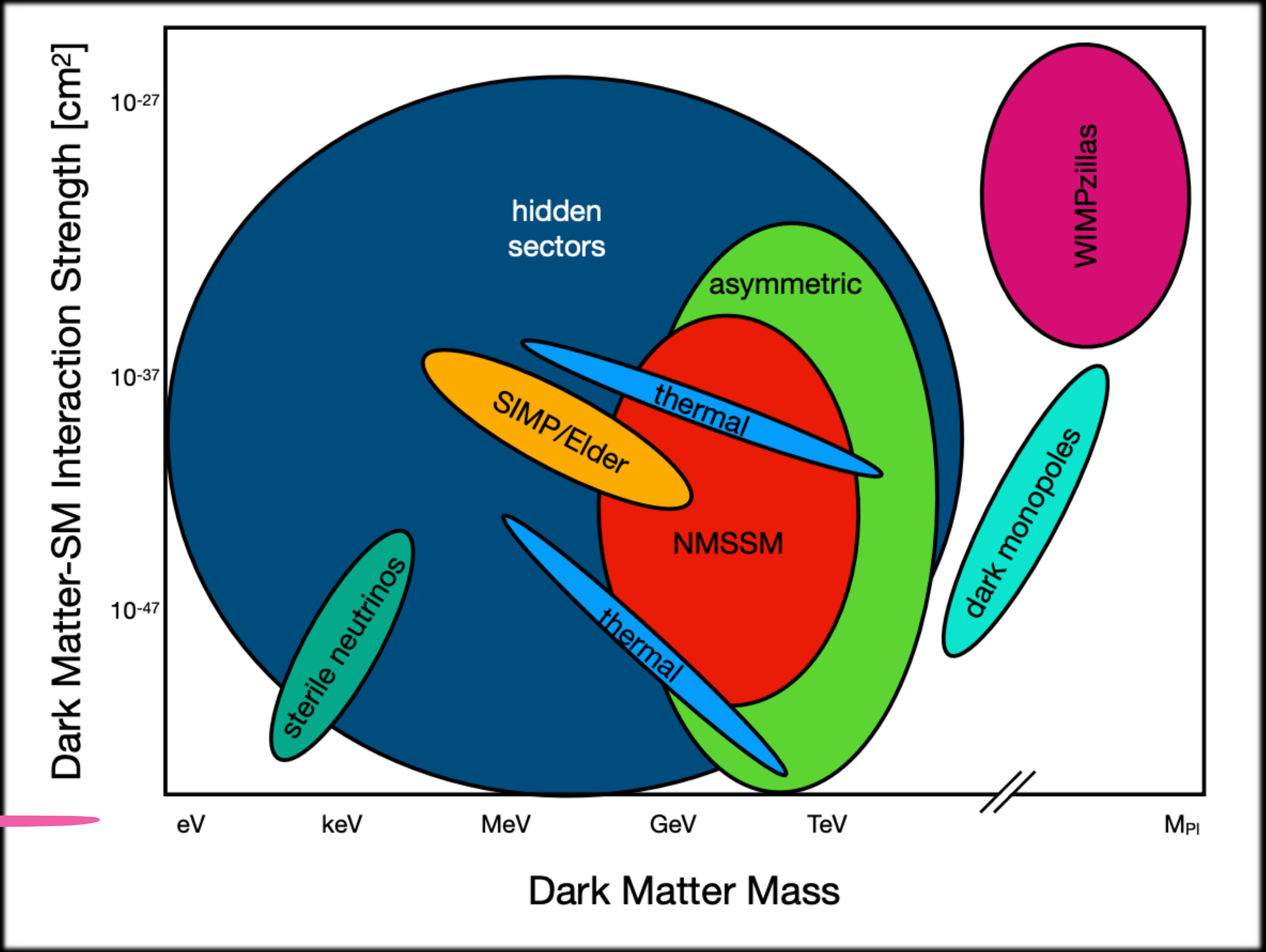
- 50 Torr of CF4 instrumented with GEMs
  - reconstruct tracks of nuclear recoil + electron - goal is to directly observe the effect
- First science run with DD neutrons last summer, second science run earlier this year. Analysis ongoing.

"The Migdal effect for low-mass WIMP search P. Majewski, TPC Symposium 2023"





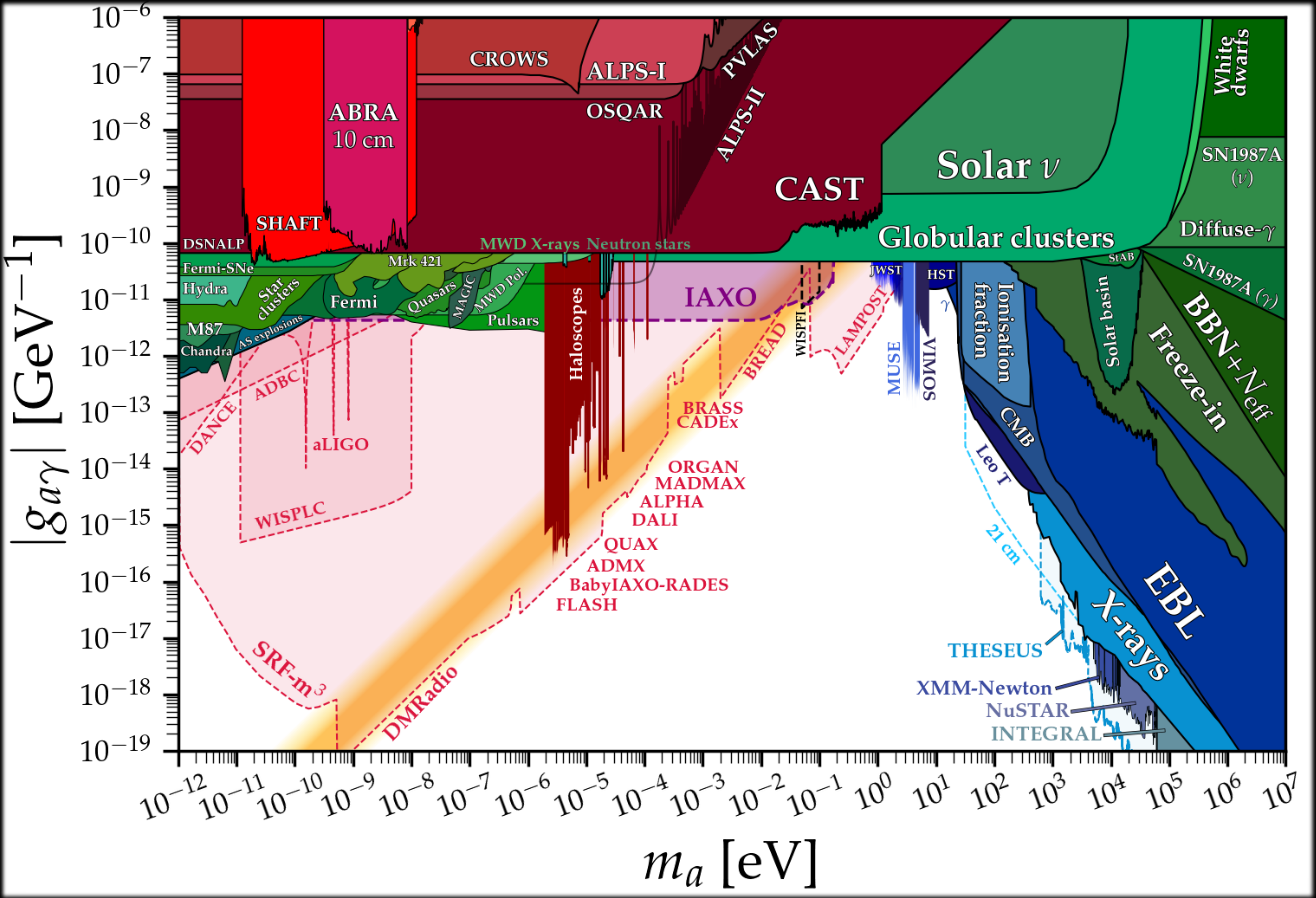
Search Wider?



What about this direction????

Axion-Photon Constraints

Axion Limits, C. O'Hare
Available Online

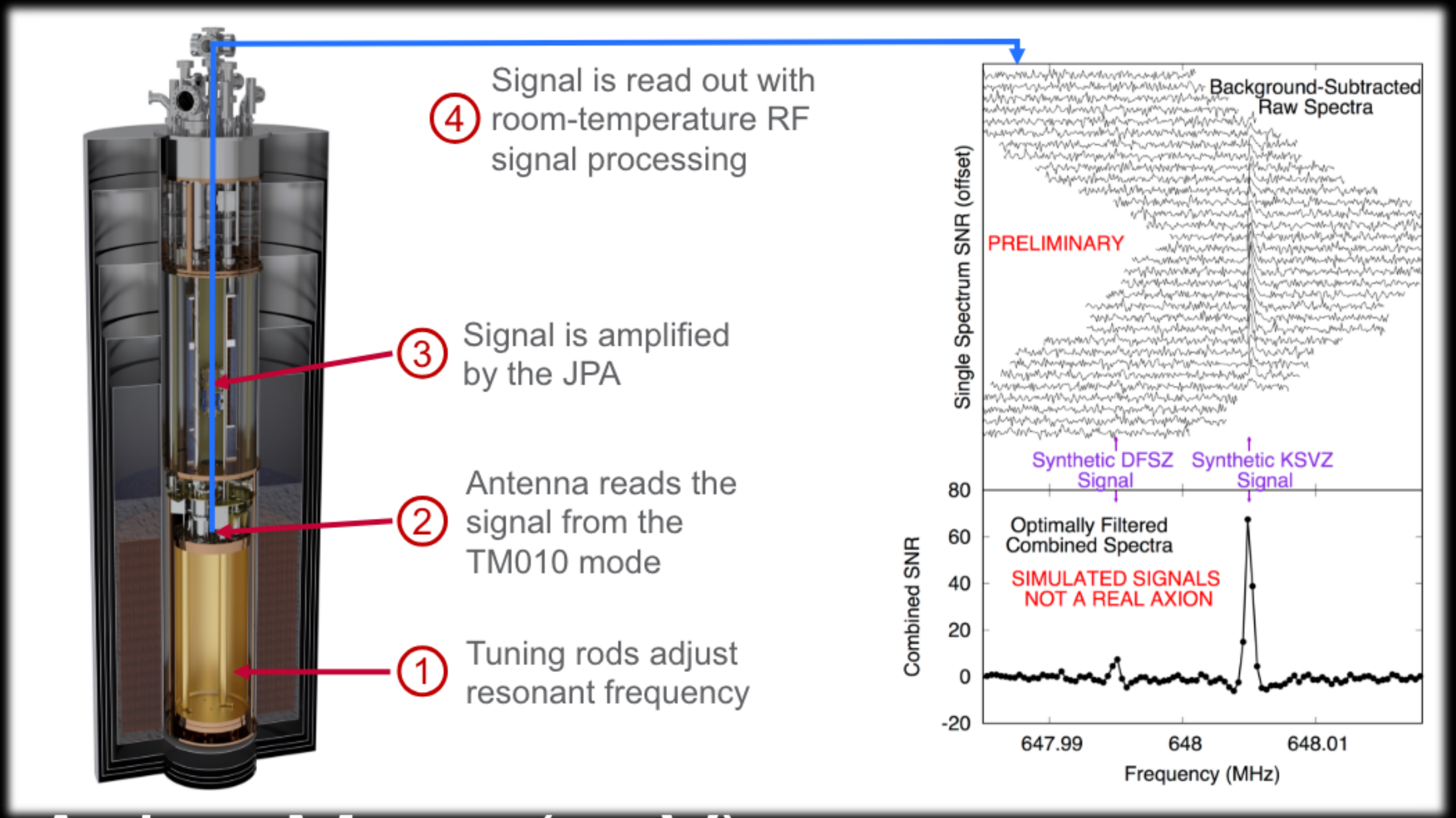


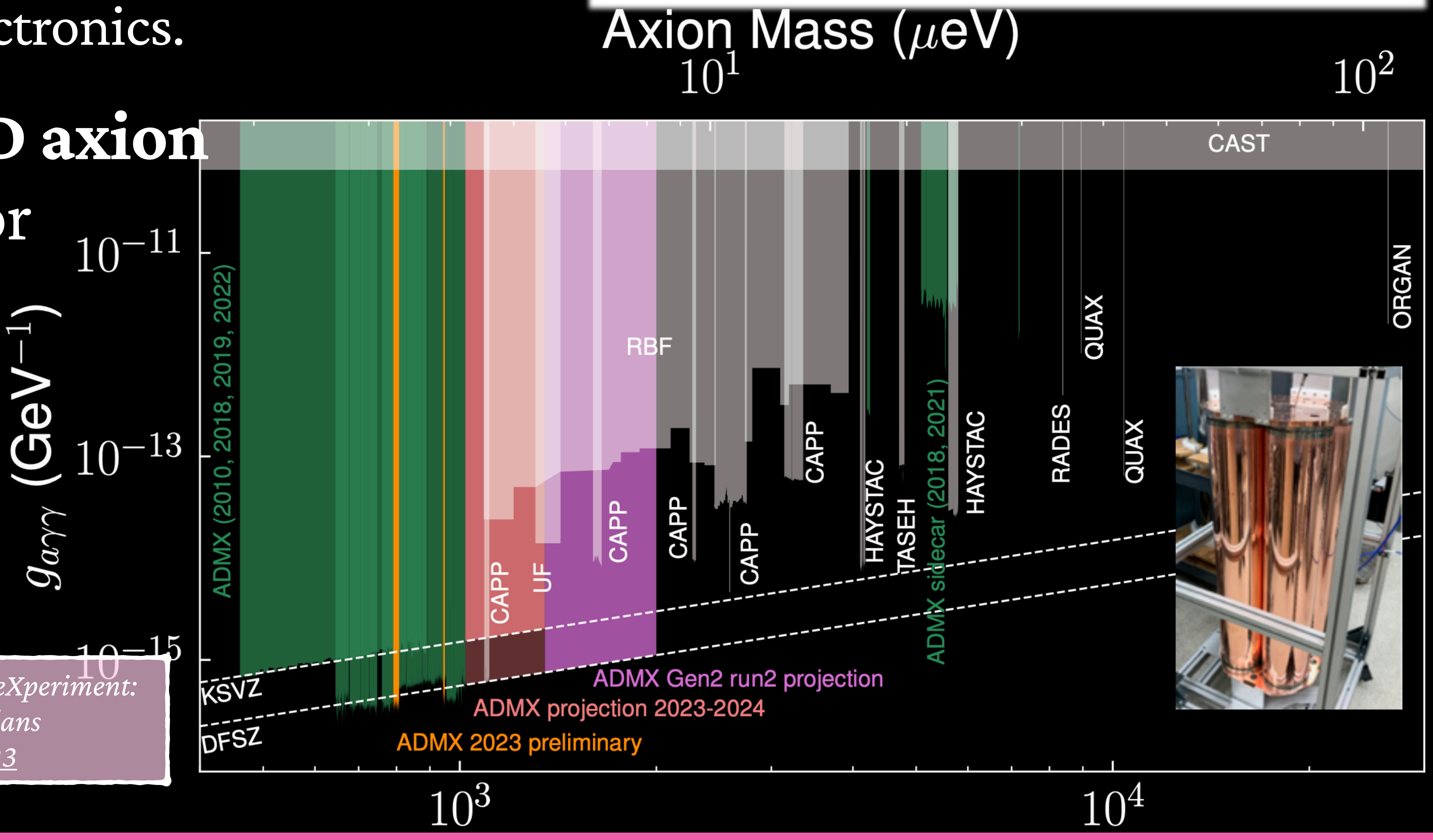
ADMX

Contact: Ed Daw, e.daw@sheffield.ac.uk

UK involvement: Sheffield

- AxioN Dark Matter eXperiment: flagship axion haloscope at CENPA, U Washington
  - Consists of large magnet, a microwave cavity, and ultra-sensitive low-noise quantum electronics.
- **Sensitivity has reached QCD axion scale**, continuing to search for higher masses
  - Technological challenges: need bigger magnet, volume (multiple cavities), less noise





An overview of Axion Dark Matter eXperiment: current status and future plans
D Zhang, UCLA DM 2023

Quantum Tech for Fundamental Physics

UK involvement: Birmingham, Cambridge, Cardiff, Glasgow, Imperial, KCL, Lancaster, Liverpool, Oxford, Sheffield, Strathclyde, RAL, RHUL, Warwick, UCL

See Ian's talk! Some Dark Matter highlights:

AION (contact: Oliver Buchmuller, o.buchmueller@imperial.ac.uk)

- Detection of ultra-light DM using cold strontium atoms through **oscillations in the electron mass and fine-structure constant**
- 10m prototype at Oxford - scale up to 100 and 1000m

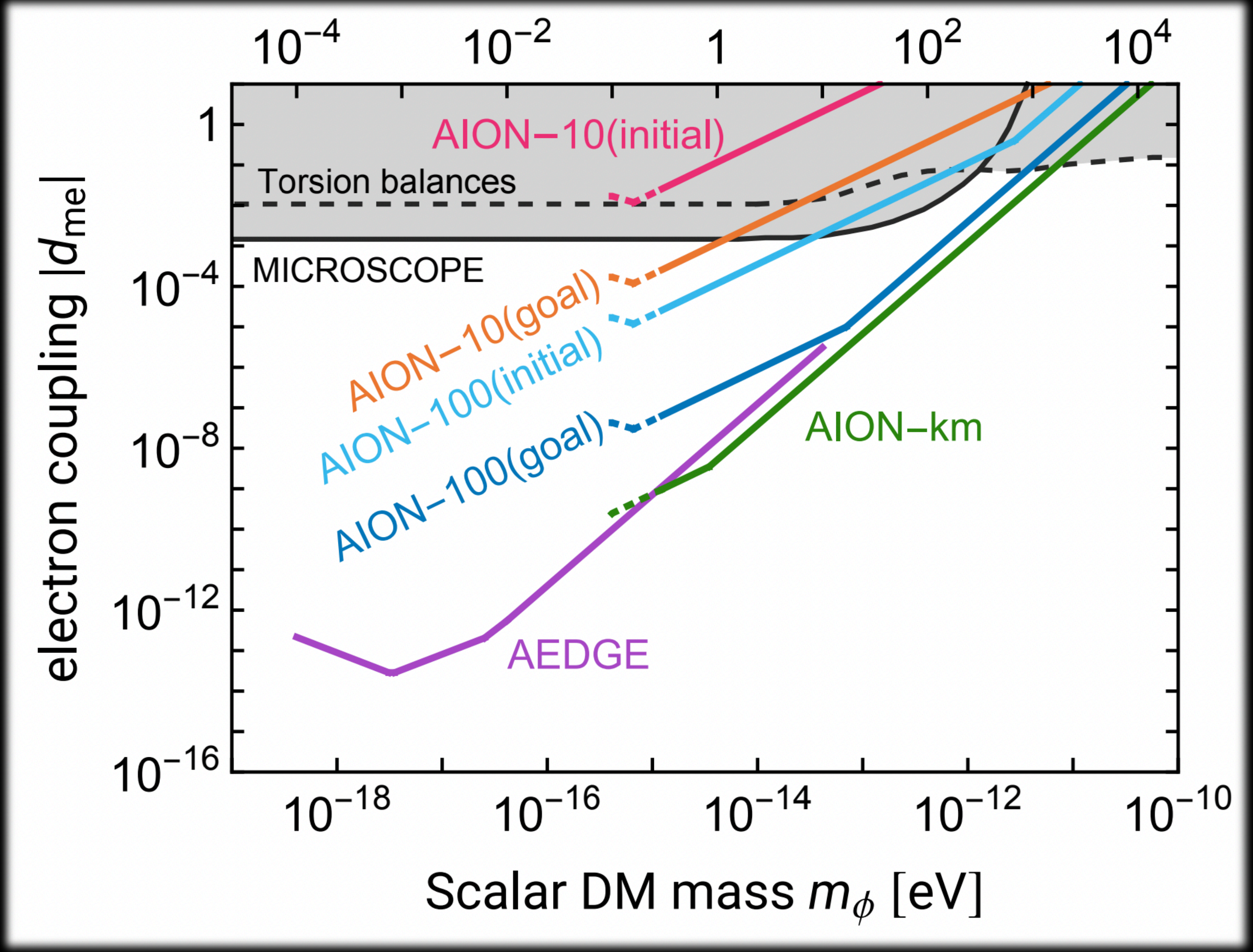
QUEST-DMC (contact: Andrew Casey, A.Casey@rhul.ac.uk)

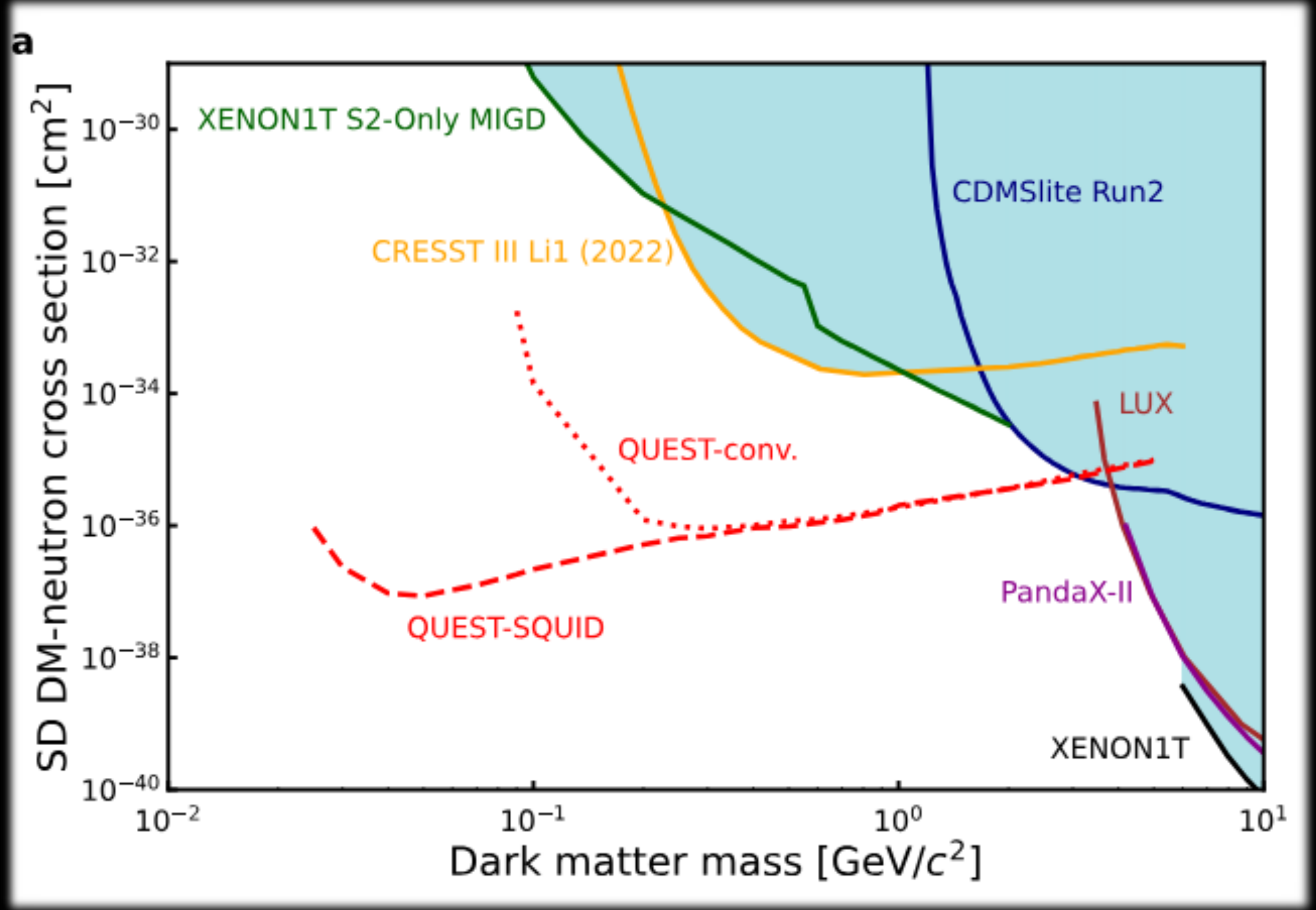
- Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter (sensitive to SD-neutron interaction)
- Ongoing R&D, paper on backgrounds came out earlier this year

QSHS: Quantum Sensors for the Hidden Sector (contact: Ed Daw, e.daw@sheffield.ac.uk)

- Develop novel quantum electronics, collaborate with ADMX, accompanying theoretical work
- Dilution refrigerator and 6T magnet installed at Sheffield
- Planning CDR & full design for UK ADMX experiment
- Future UK hidden-sector search facility at Daresbury

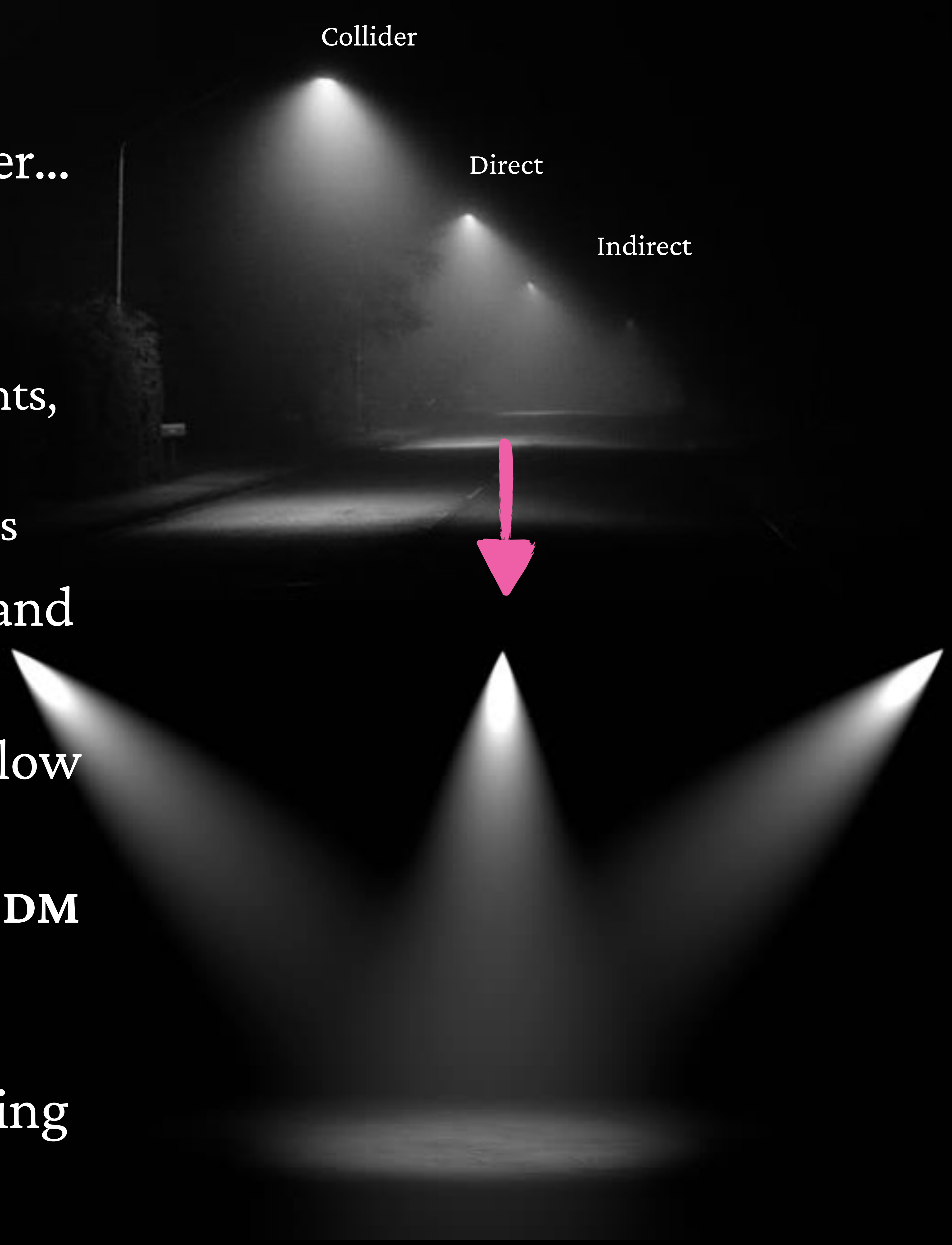
Additionally, **QSNET** tests fundamental constants through clocks, & **QI**: Quantum-enhanced Interferometry for new physics.





Conclusions

- The search for dark matter continues, and grows broader...
- Dual focus on increasing exposure and increasing low mass sensitivity - **delve deep and search wide**
  - UK playing strong role in many large international experiments, potential host for several exciting new ones
  - Lots of exciting UK contributions to be made in next few years
- Quantum sensing driving interest in Axions and ALPs (and vice versa!) - AION, QUEST-DMC, QSHS...
- **Collider constraints are complimentary** to Direct for low mass, but projections are very model dependent
  - Multiple targets in Direct searches can probe a **diverse set of DM models** and **wide range of DM properties**
- Long term goal needs to a consistent **Dark Matter SIGNAL** in multiple experiments/different targets using different techniques- colliders + direct + indirect



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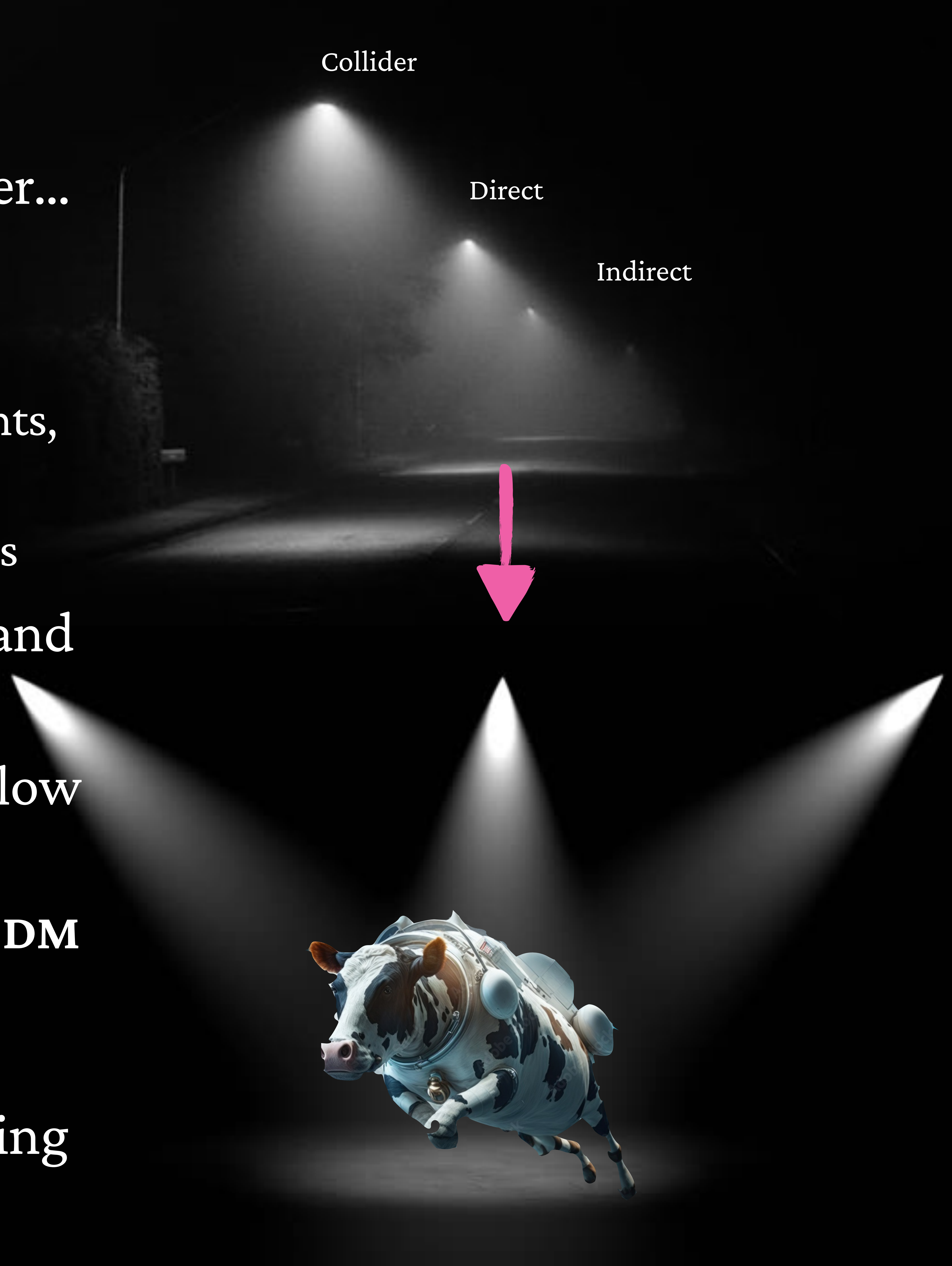
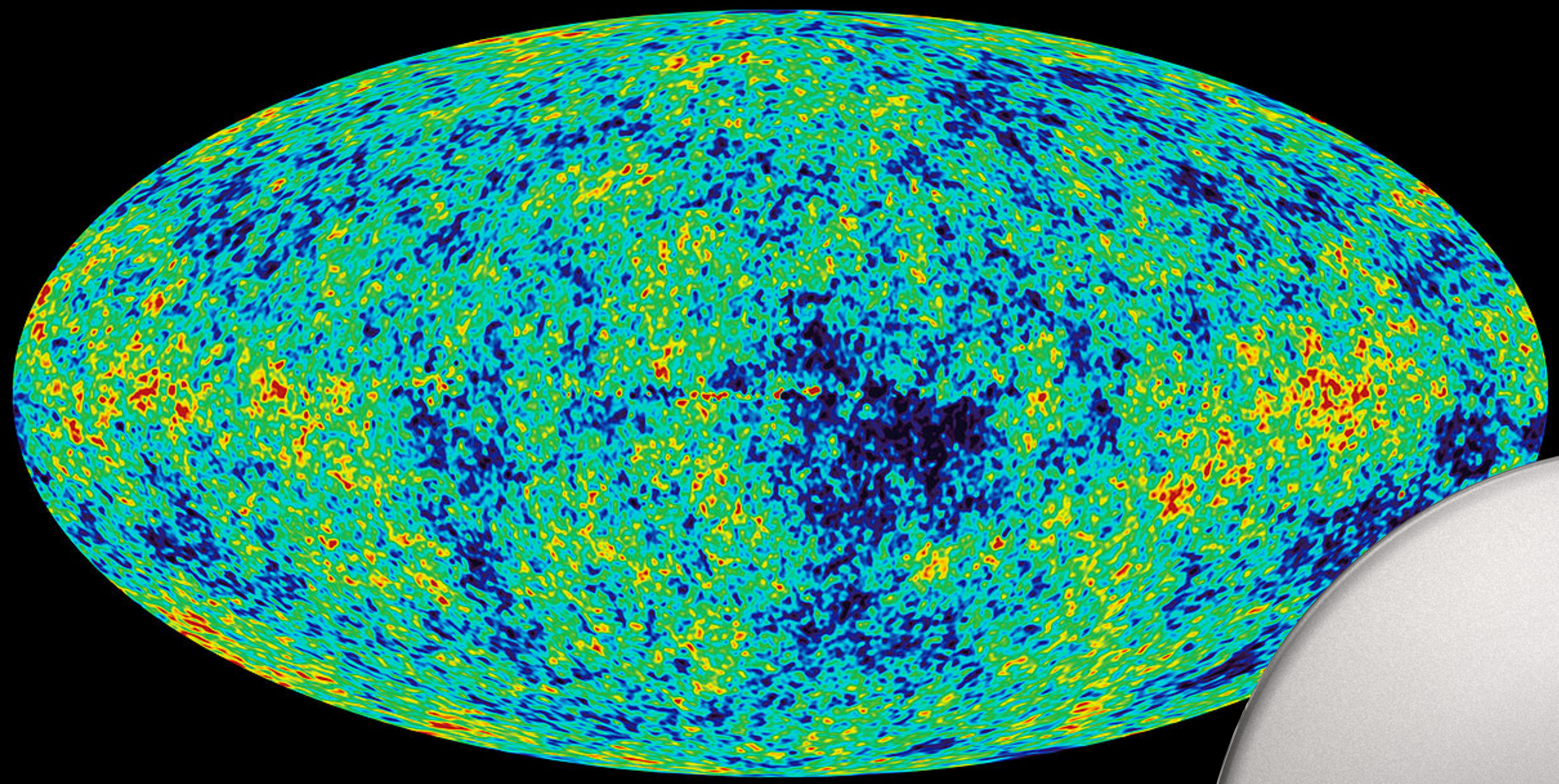
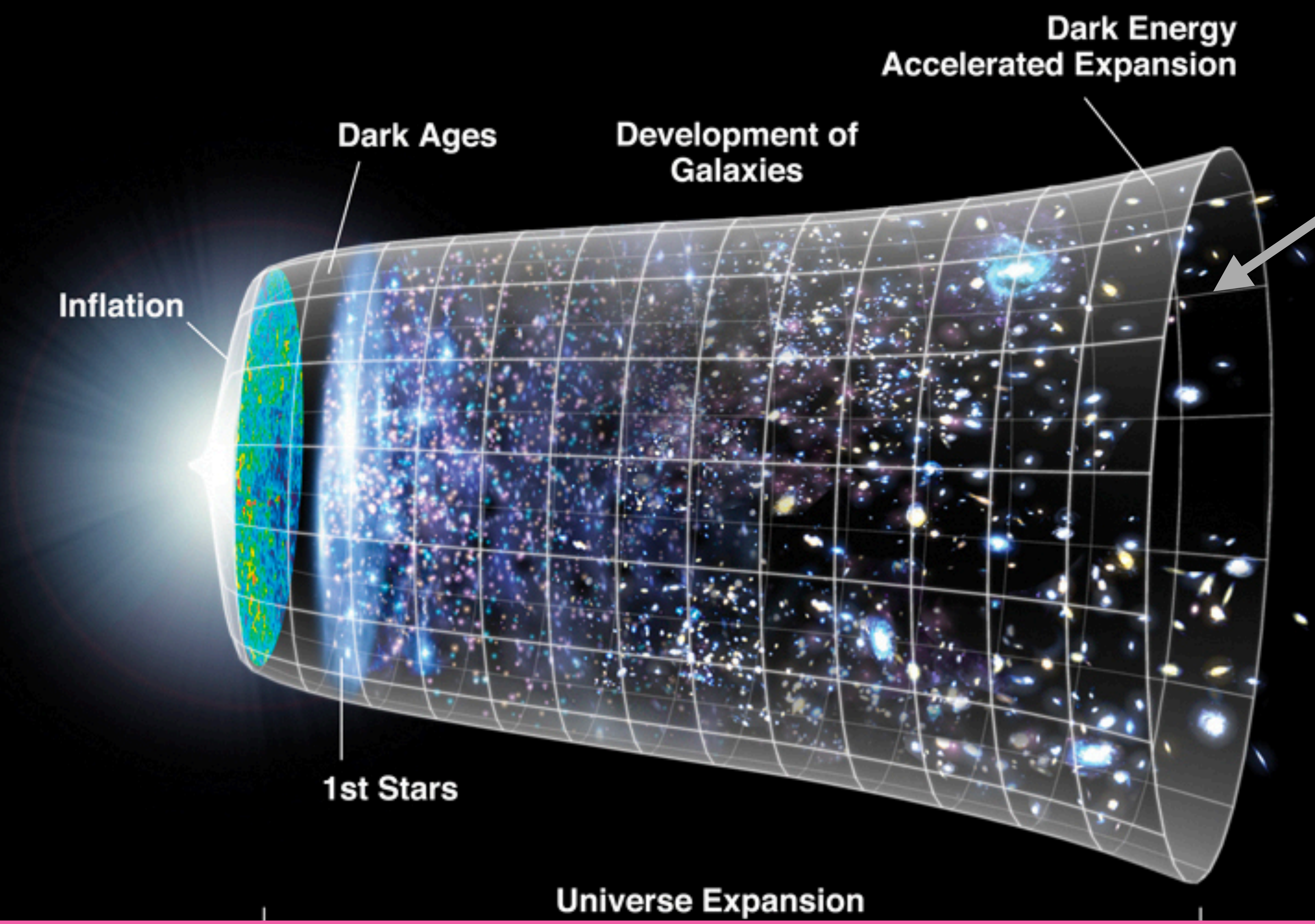
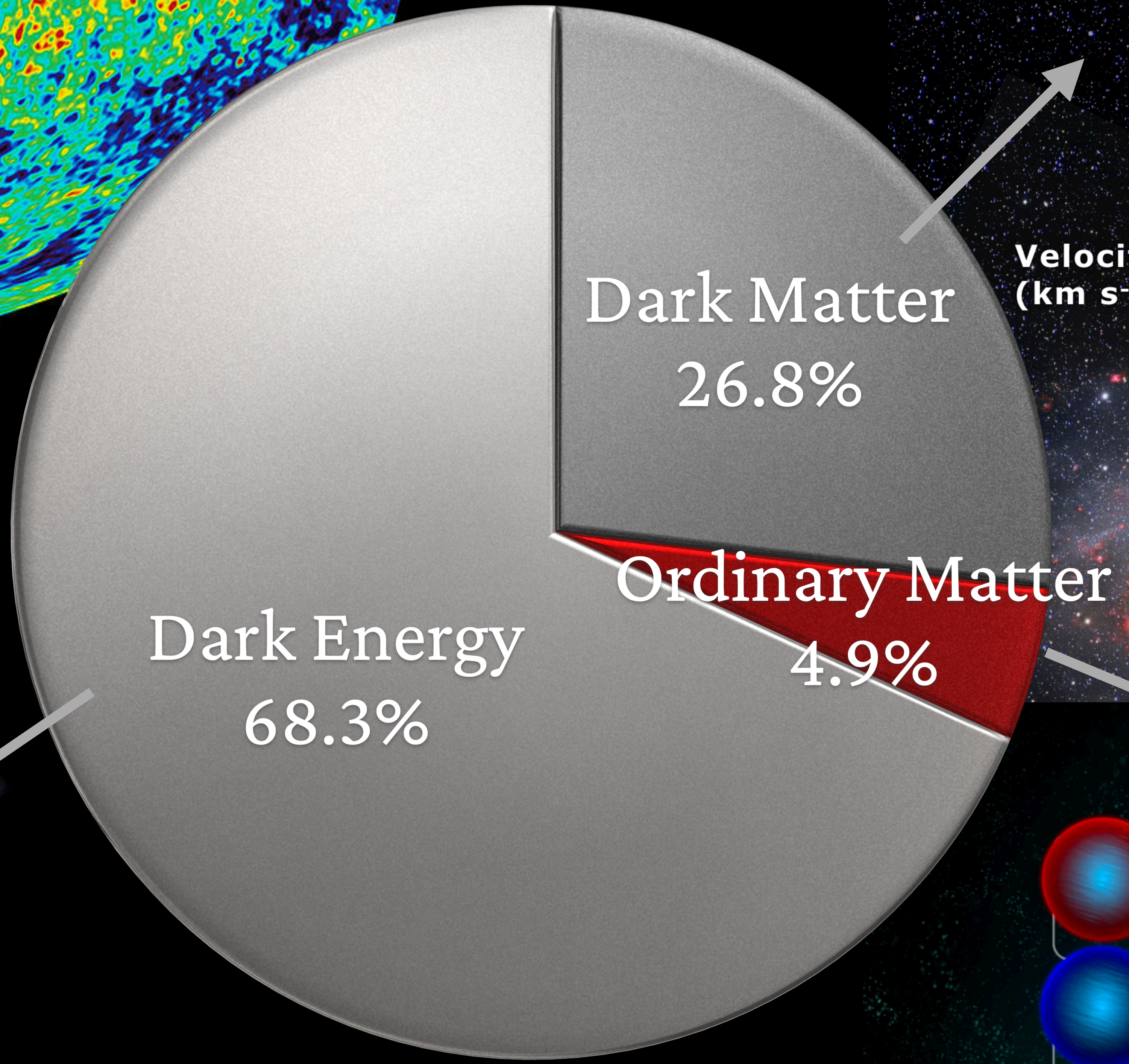
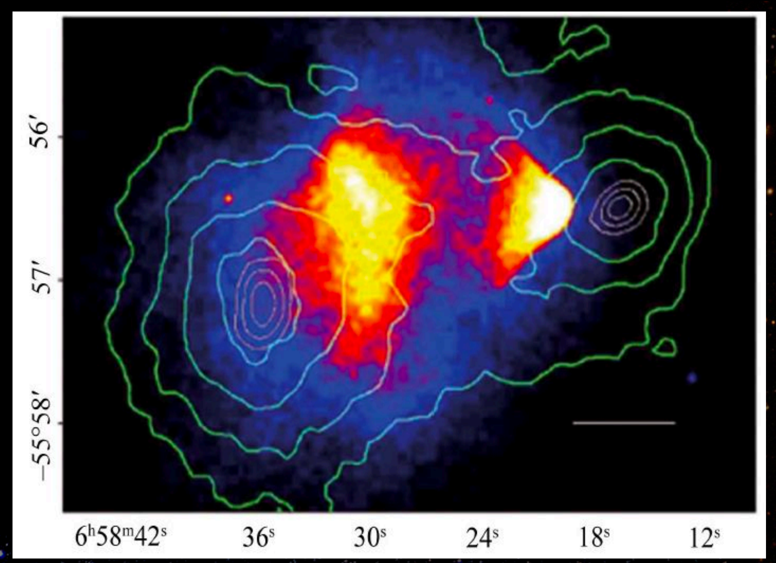


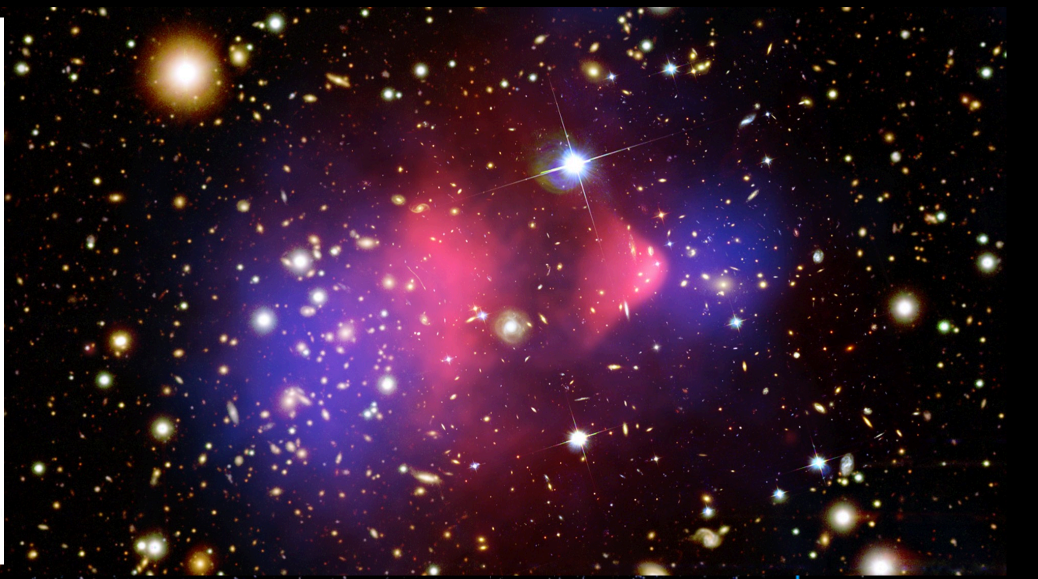
Back Up / Extra Slides

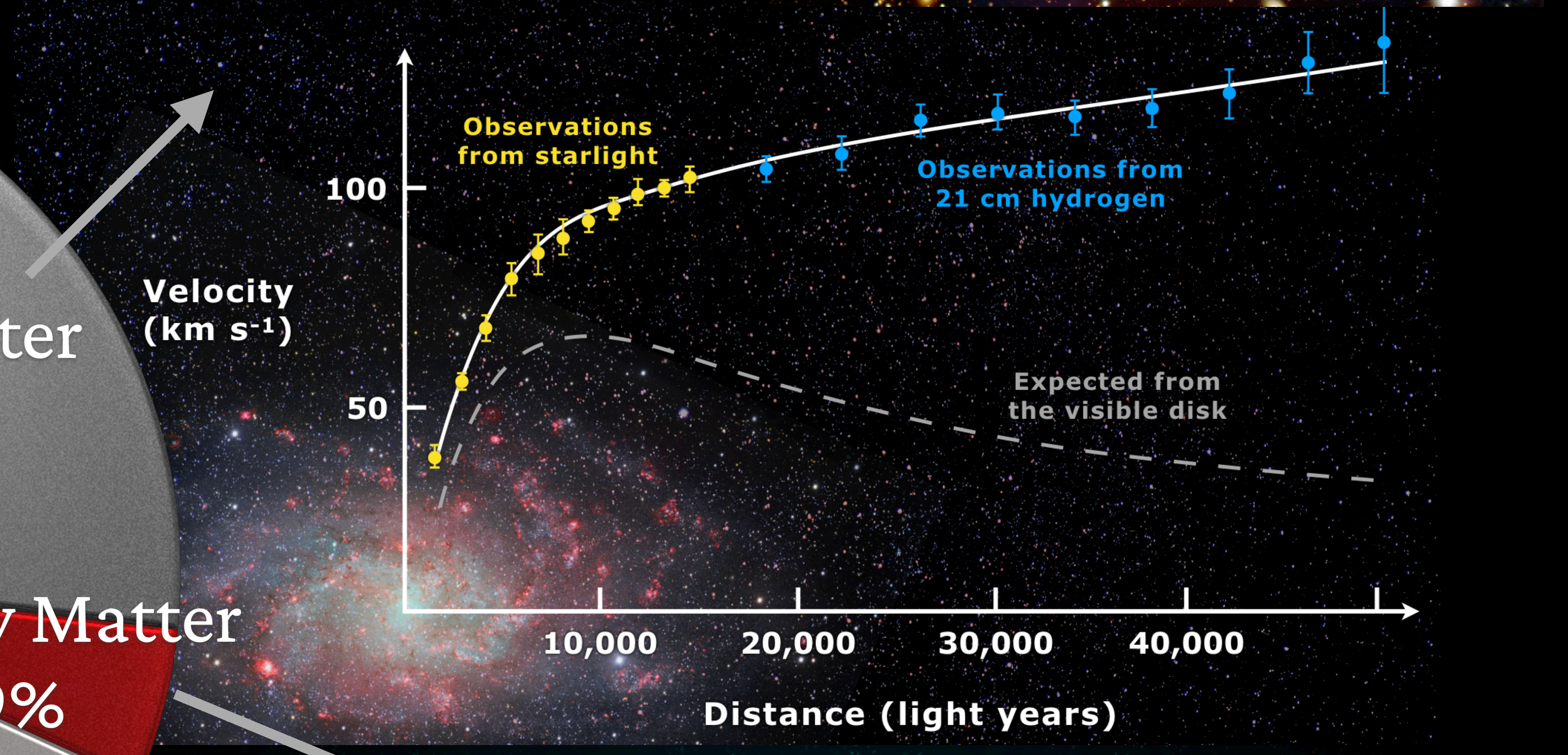


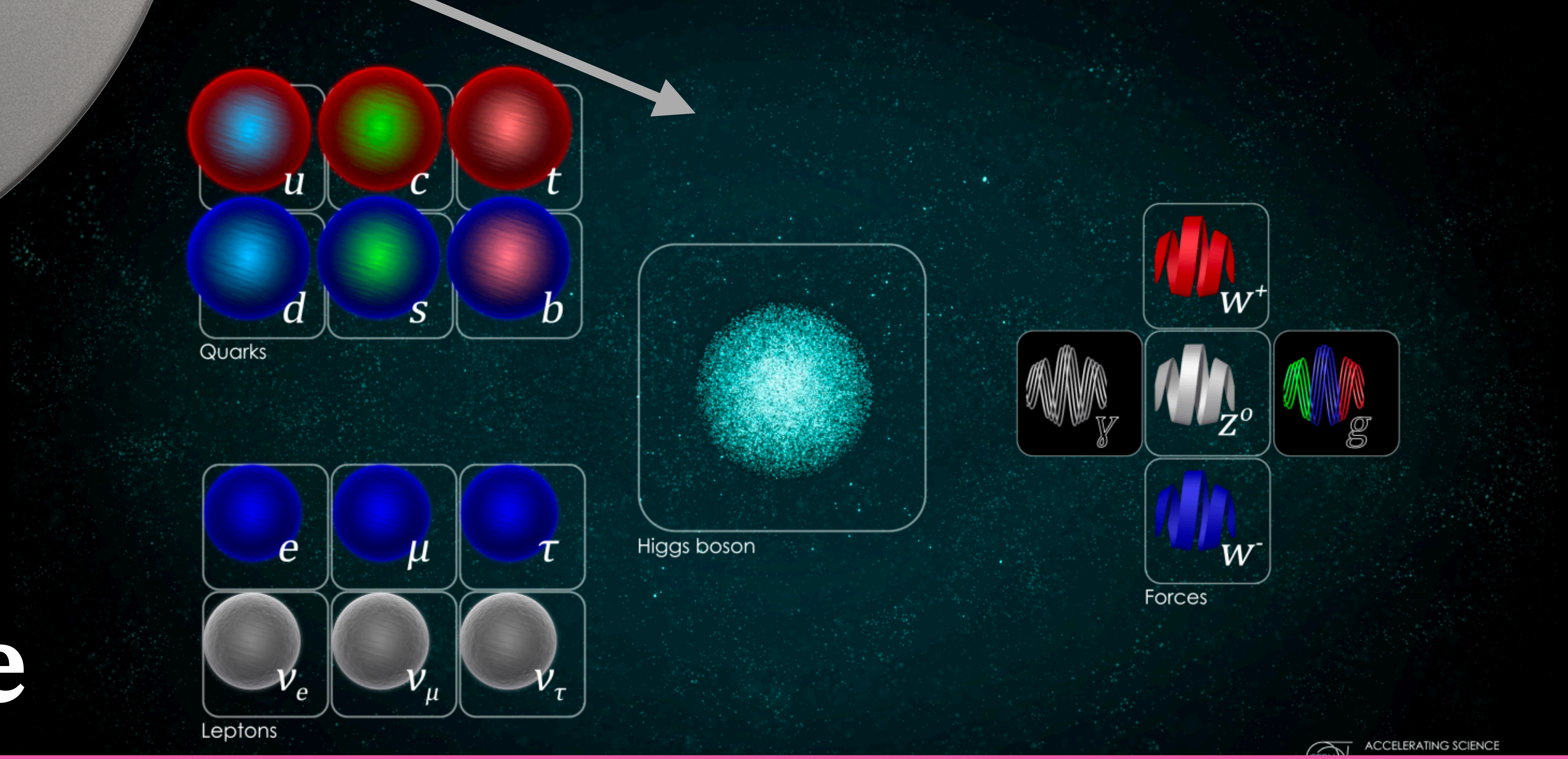












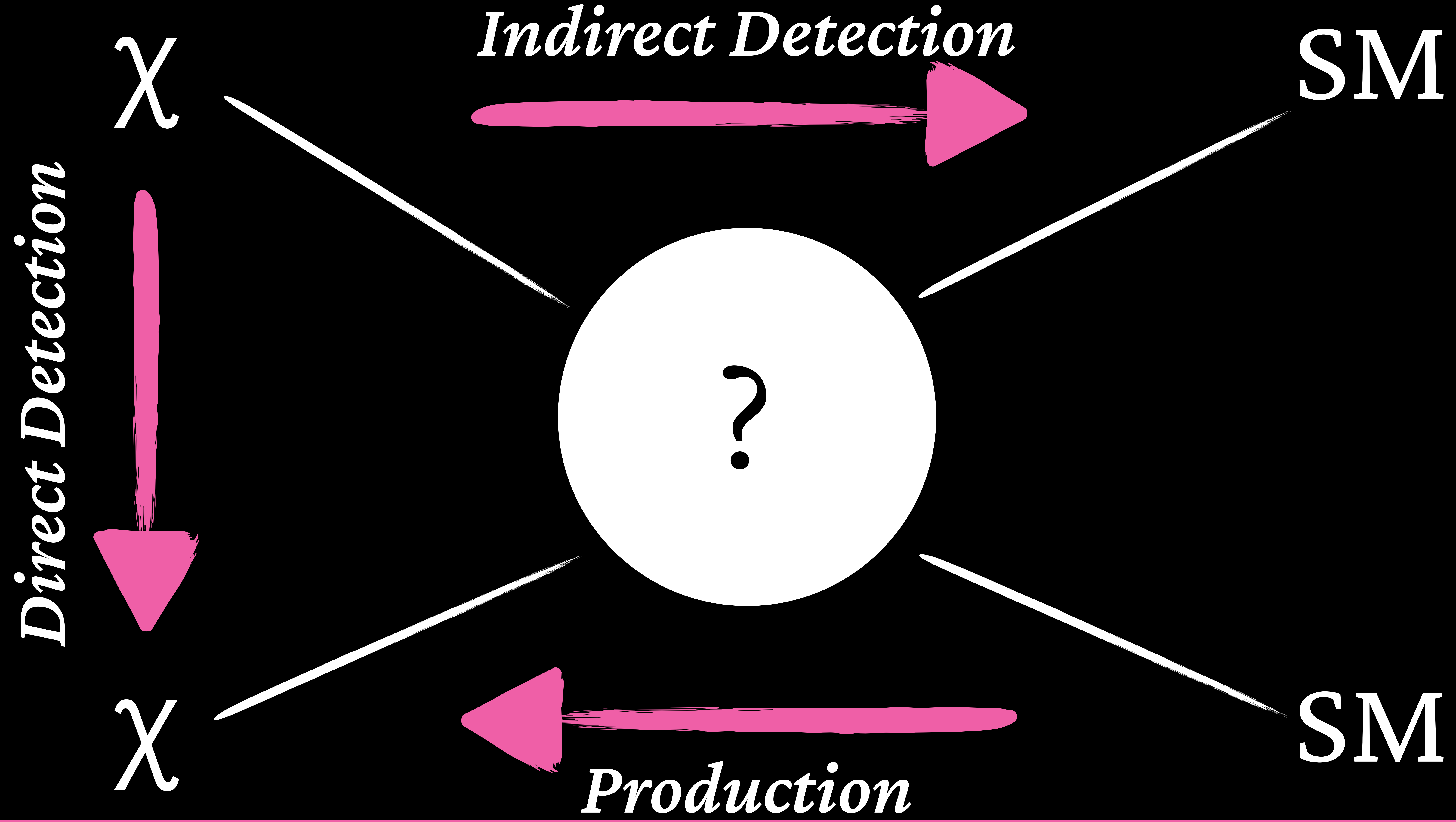
The Universe

3 ways to detect dark matter particles

Enabling discovery with a multi-faceted approach

3 ways to detect dark matter particles

Enabling discovery with a multi-faceted approach

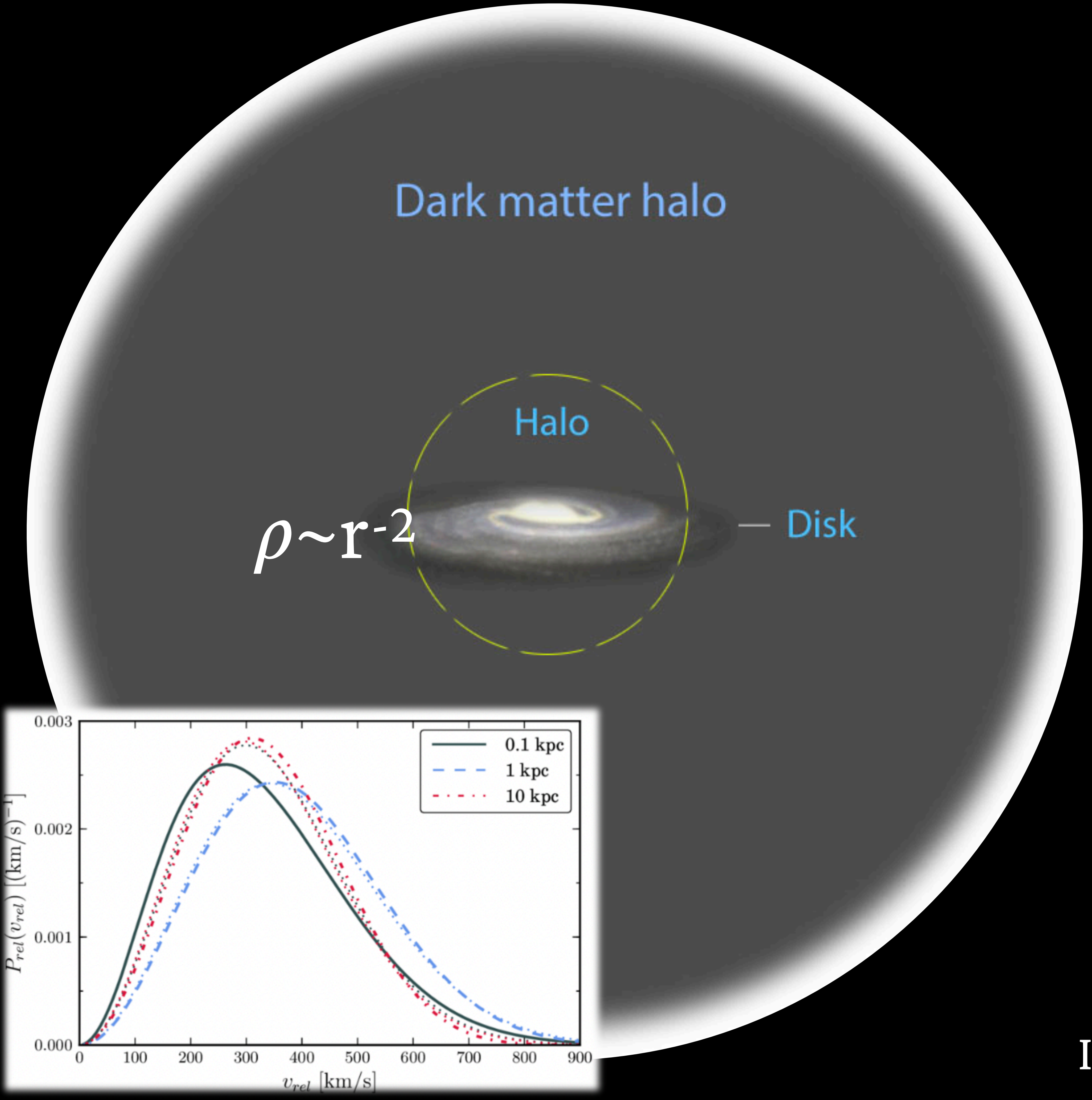


Direct Detection

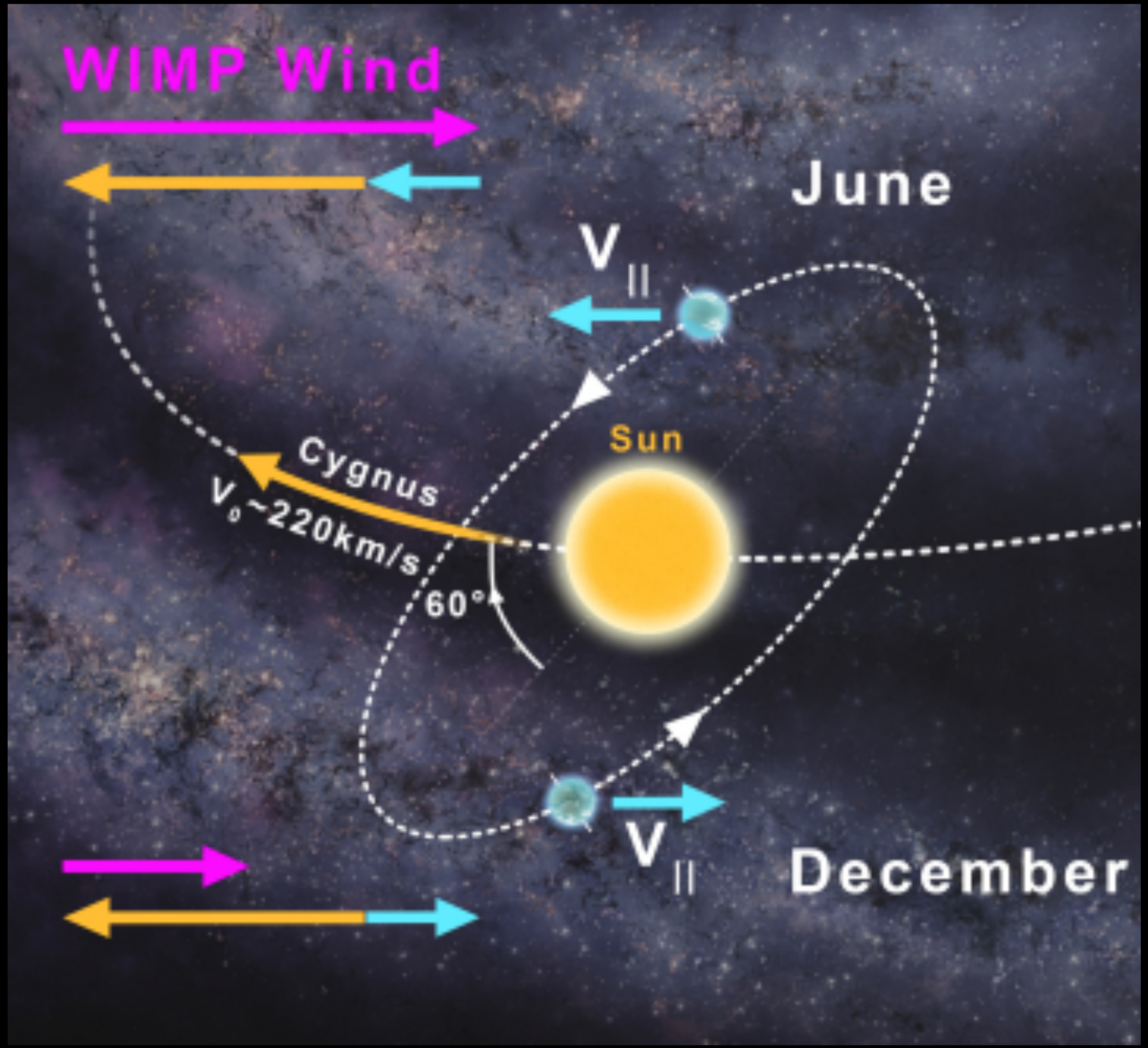
Dark matter exists in a halo extending far beyond the visible boundaries of the galaxy

detector exposure | particle/ nuclear physics | astrophysics

$$\frac{dN}{dE_R} = \epsilon \frac{\rho}{2 m_\chi \mu_{\chi N}} \sigma_0 F^2(E_R) \int_{v_{min}} \frac{f(\bar{v})}{v} d^3 v$$



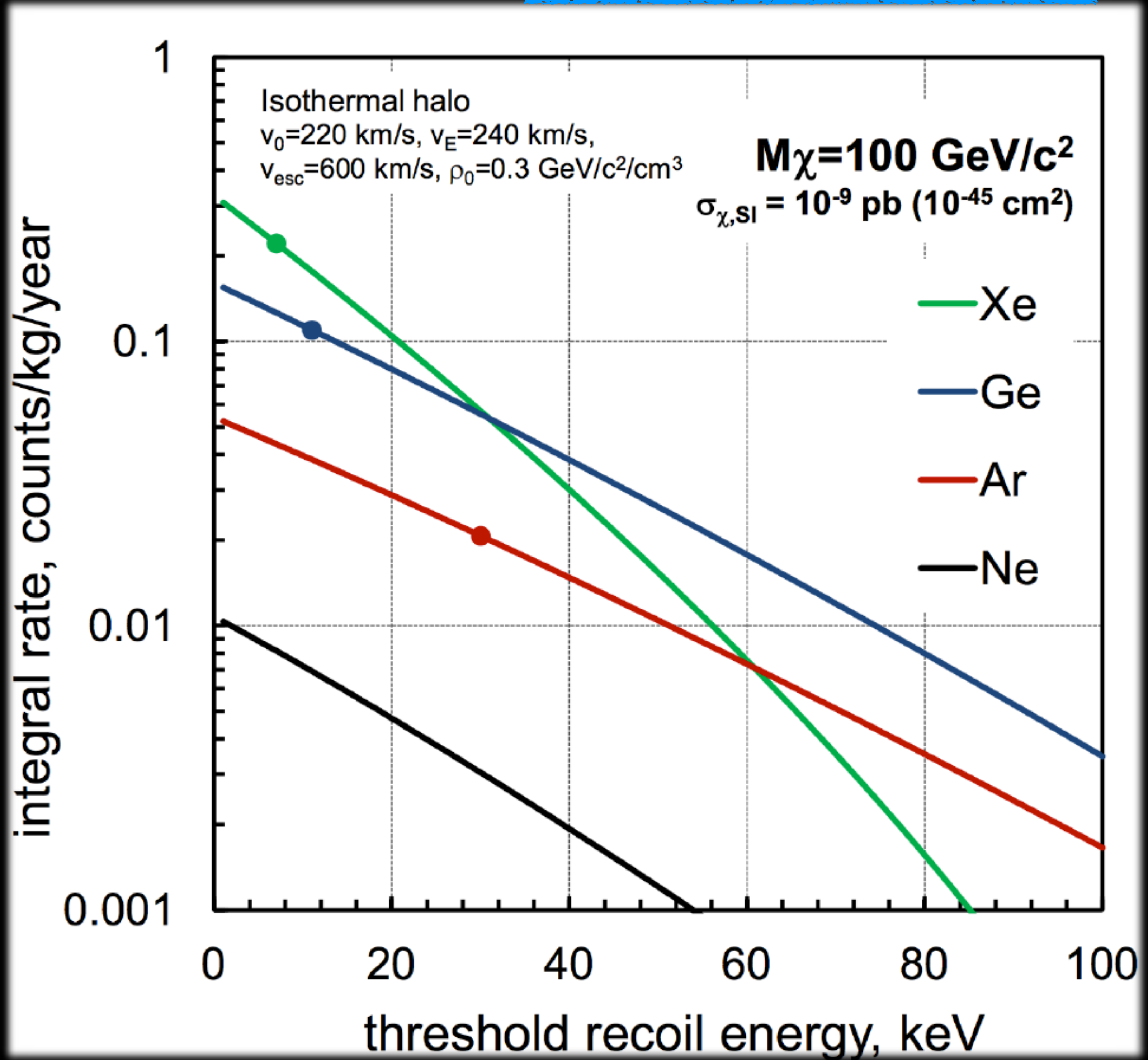
Dark matter follows a **velocity distribution** within the halo (in the Galactic frame) with a maximum velocity of v_{esc}



In Earth's frame, see an **annual modulation.** DM has a higher relative v in June than Dec

→ more likely to be above detector threshold

→ peak rate in June, minimum in Dec

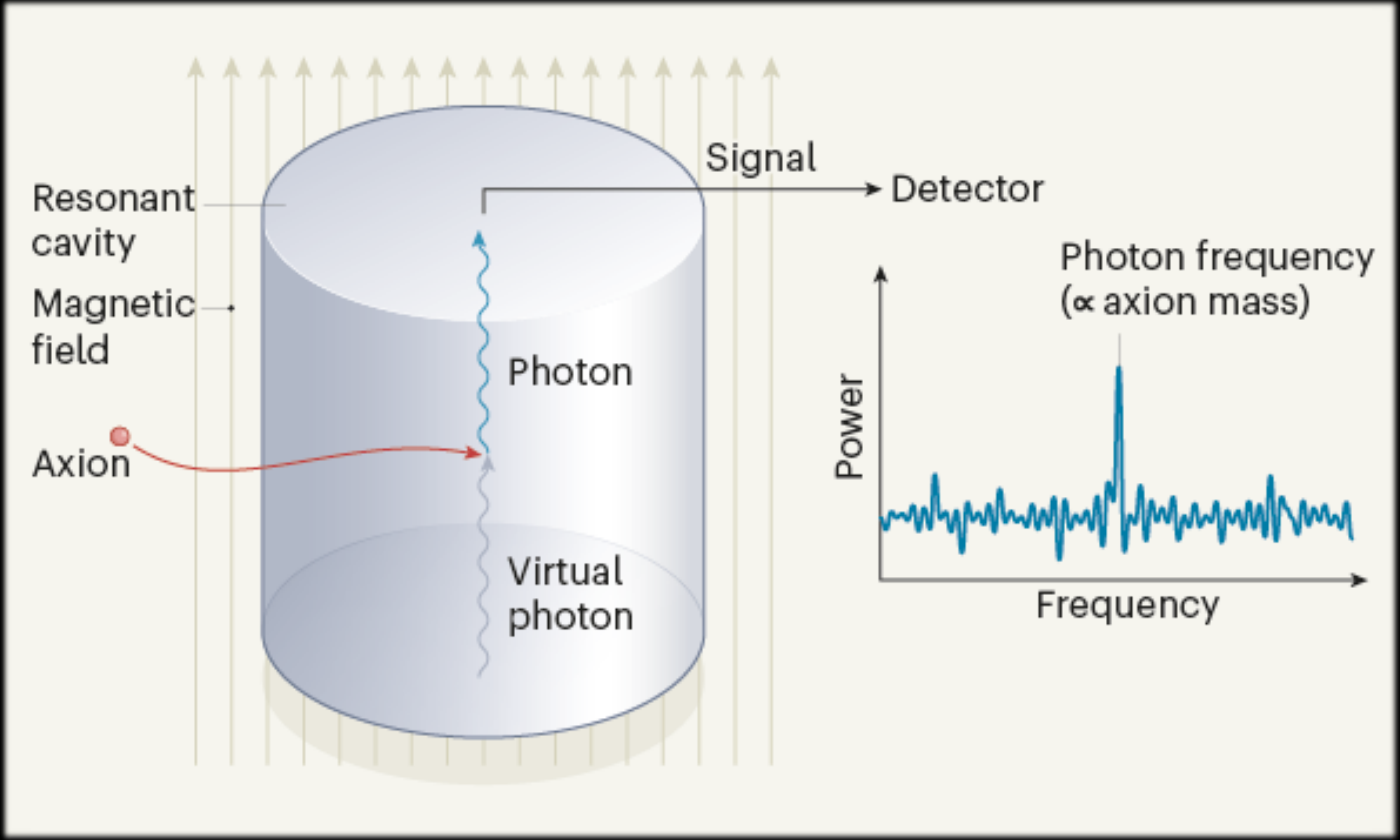


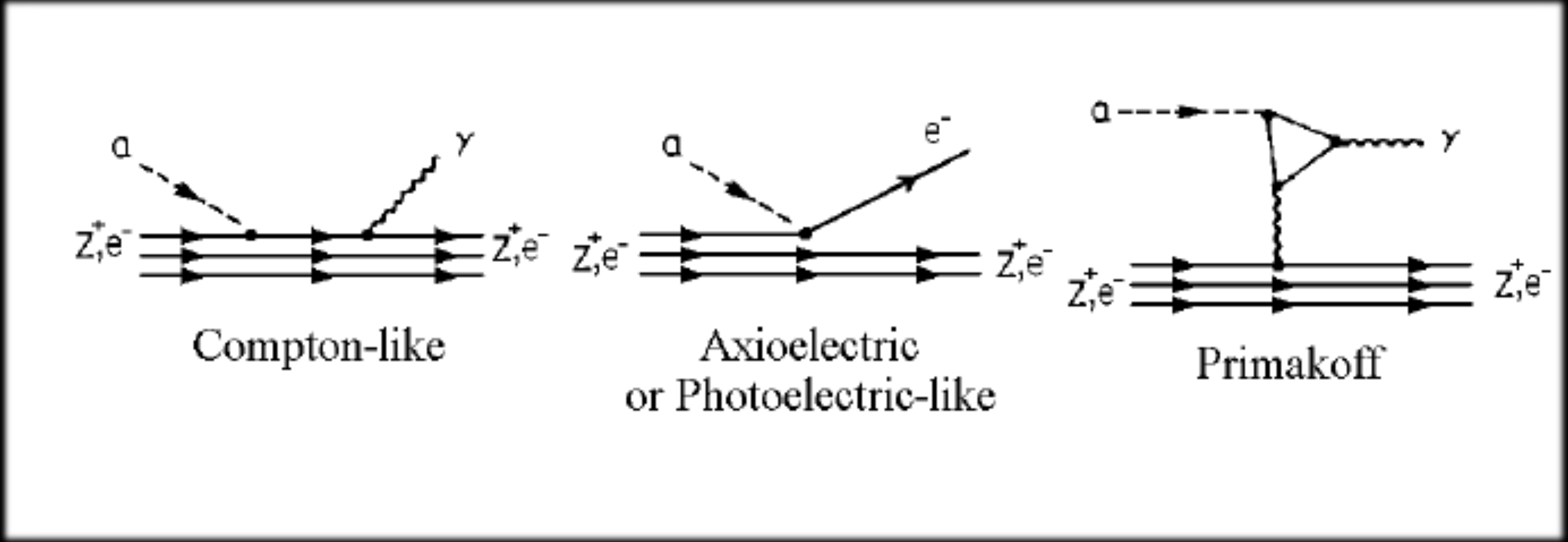
DM v translated to recoil energy in DM-scattering, get an **exponentially falling rate**

→ threshold very important

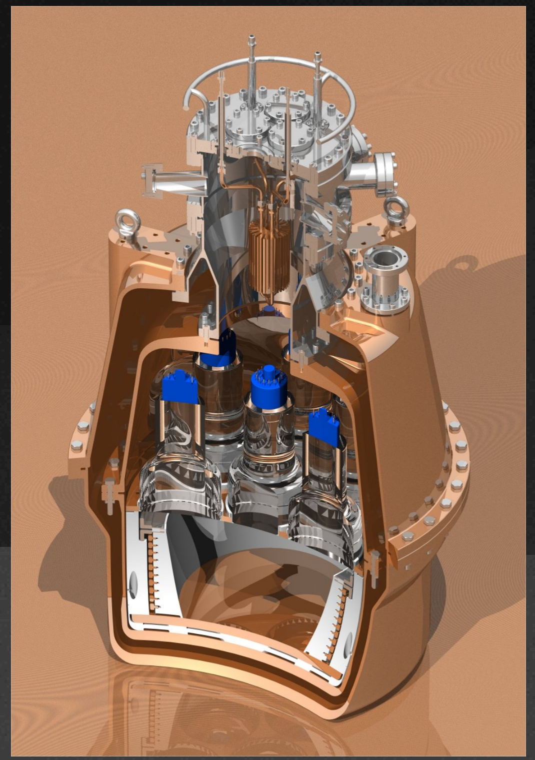
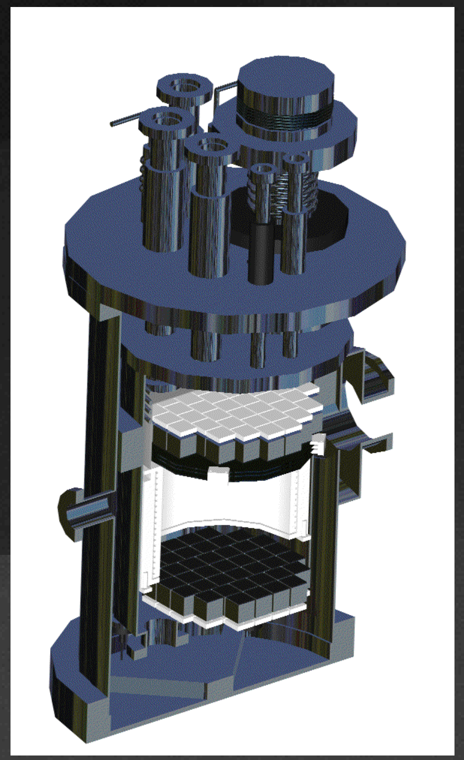
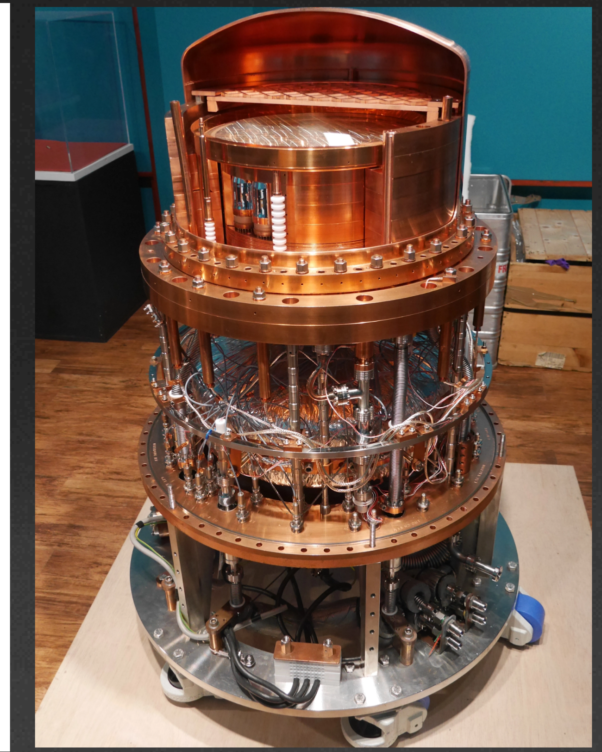
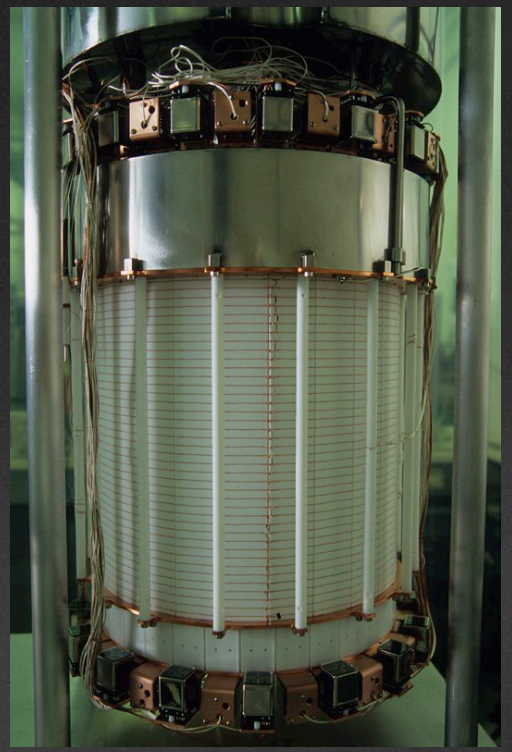
Axion Dark Matter

- Very broadly, two classes of experiment:
  - Haloscope
    - Axion converts to photon in magnetic field
    - Scan over resonant frequencies - enhanced signal at right photon frequency (∝ axion mass)
  - Direct detection through interaction with electron
    - Manifests as electron recoil signal - feasible search in direct DM experiments

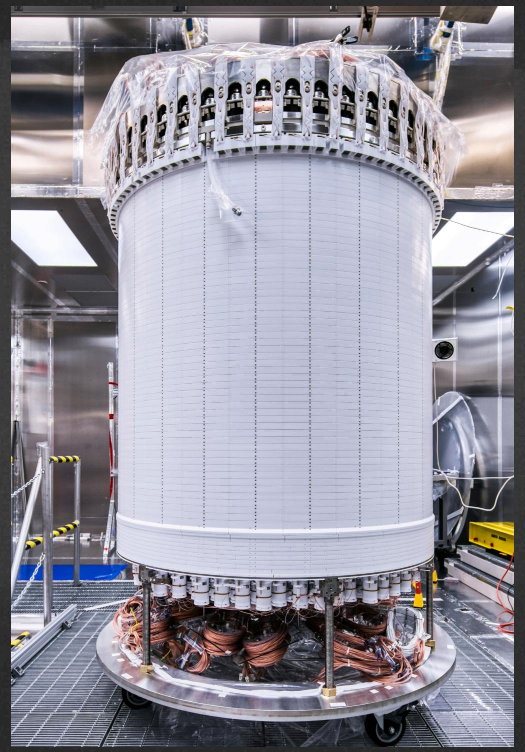




History of Direct Detection with Liquid Xenon

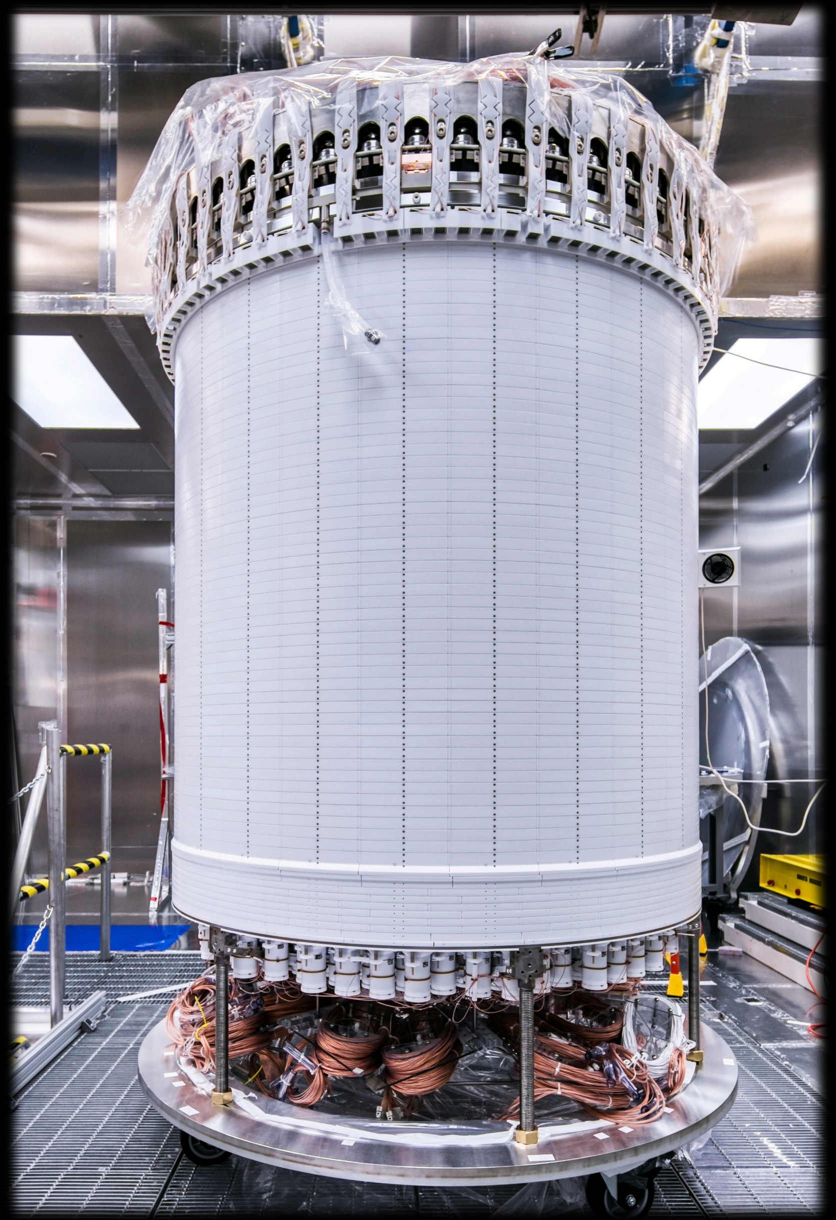



ZEPLIN-II	XENON10	ZEPLIN-III	XENON100	LUX	PANDAX-II	XENON1T	LZ	XENONnT
31 kg (7.2 kg)	15 kg (5 kg)	12 kg (7 kg)	62kg (34 kg)	250 kg (100 kg)	580 kg (362 kg)	2,000 kg (1,042 kg)	7,000 kg (5,500 kg)	6,000 kg (?,??? kg)
6.6×10^{-43} cm^2	8.8×10^{-44} cm^2	8.1×10^{-44} cm^2	3.4×10^{-44} cm^2	2.2×10^{-46} cm^2	2.5×10^{-46} cm^2	4.1×10^{-47} cm^2	9.2×10^{-48} cm^2	2.6×10^{-47} cm^2
2007	2007	2008	2010	2016	2016	2019	2022	

Future of Direct Detection with Liquid Xenon

LZ



7,000 kg
(5,500 kg)

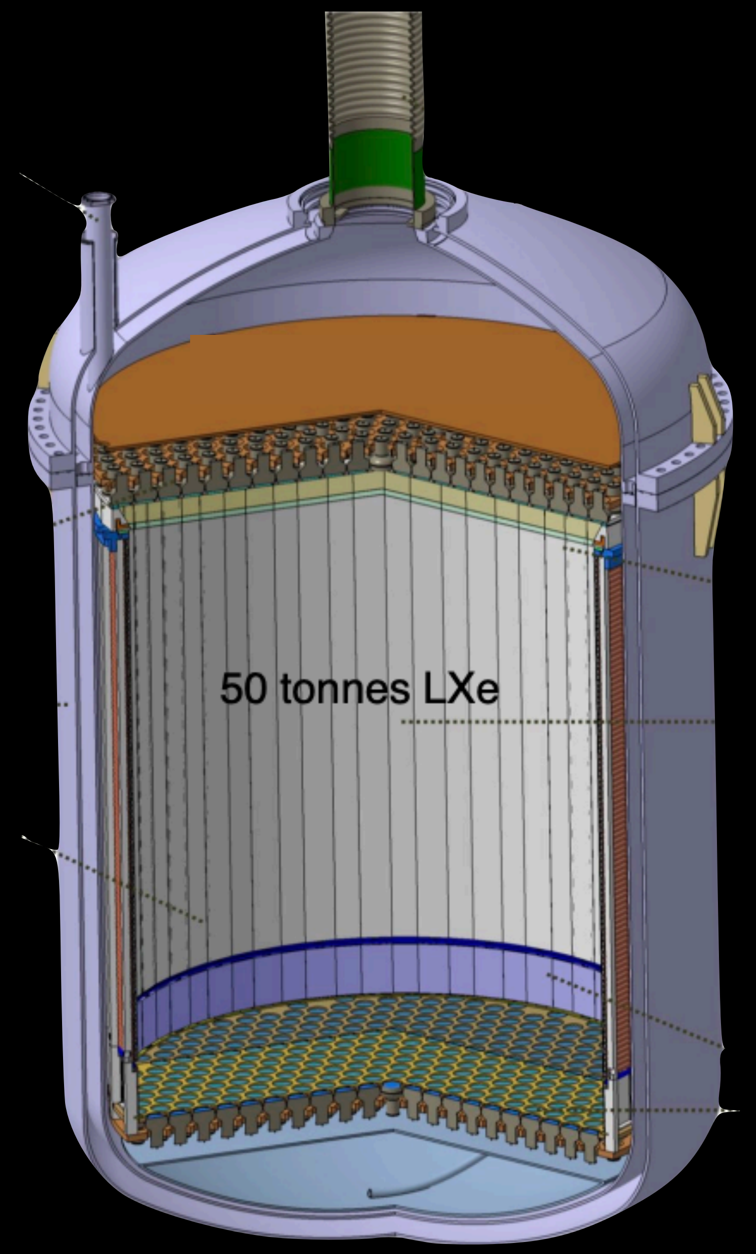
Projected for 15 t-y:
1.4×10^{-48} cm^2

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

LZ

UK Involvement

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

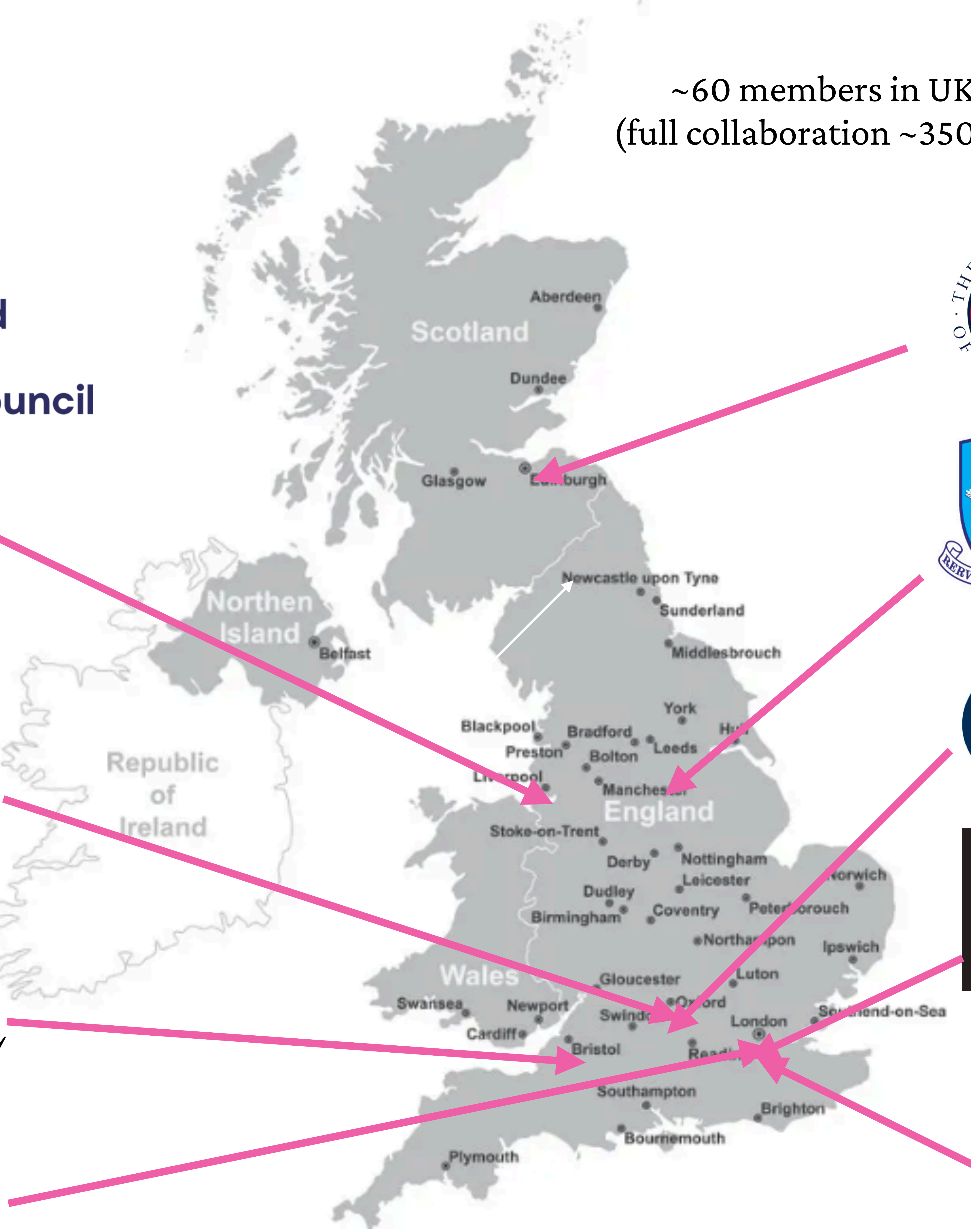
Science and Technology Facilities Council

UNIVERSITY OF LIVERPOOL

UNIVERSITY OF OXFORD

University of BRISTOL

Imperial College London



THE UNIVERSITY of EDINBURGH

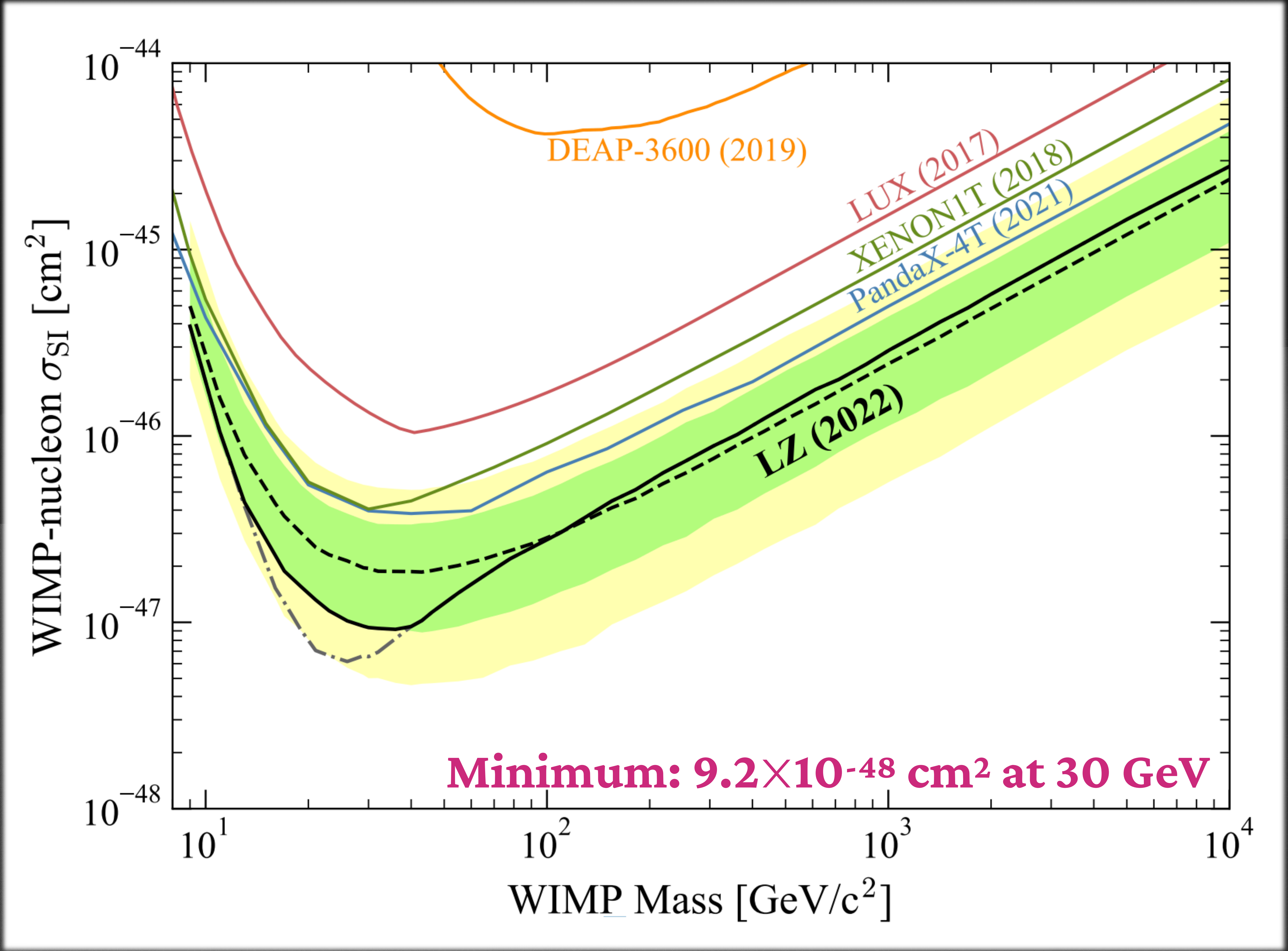
The University Of Sheffield.

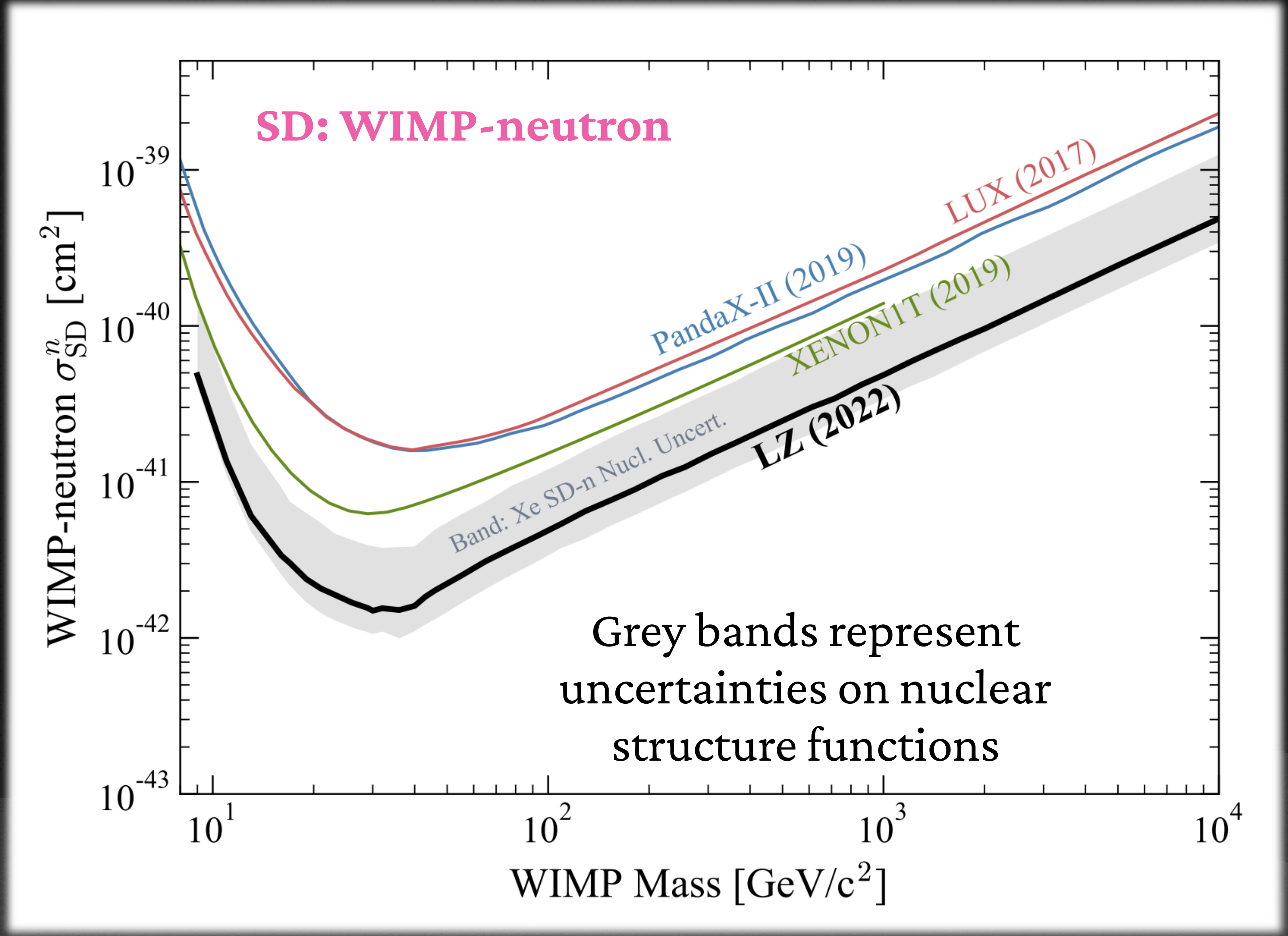
Science & Technology Facilities Council
Rutherford Appleton Laboratory

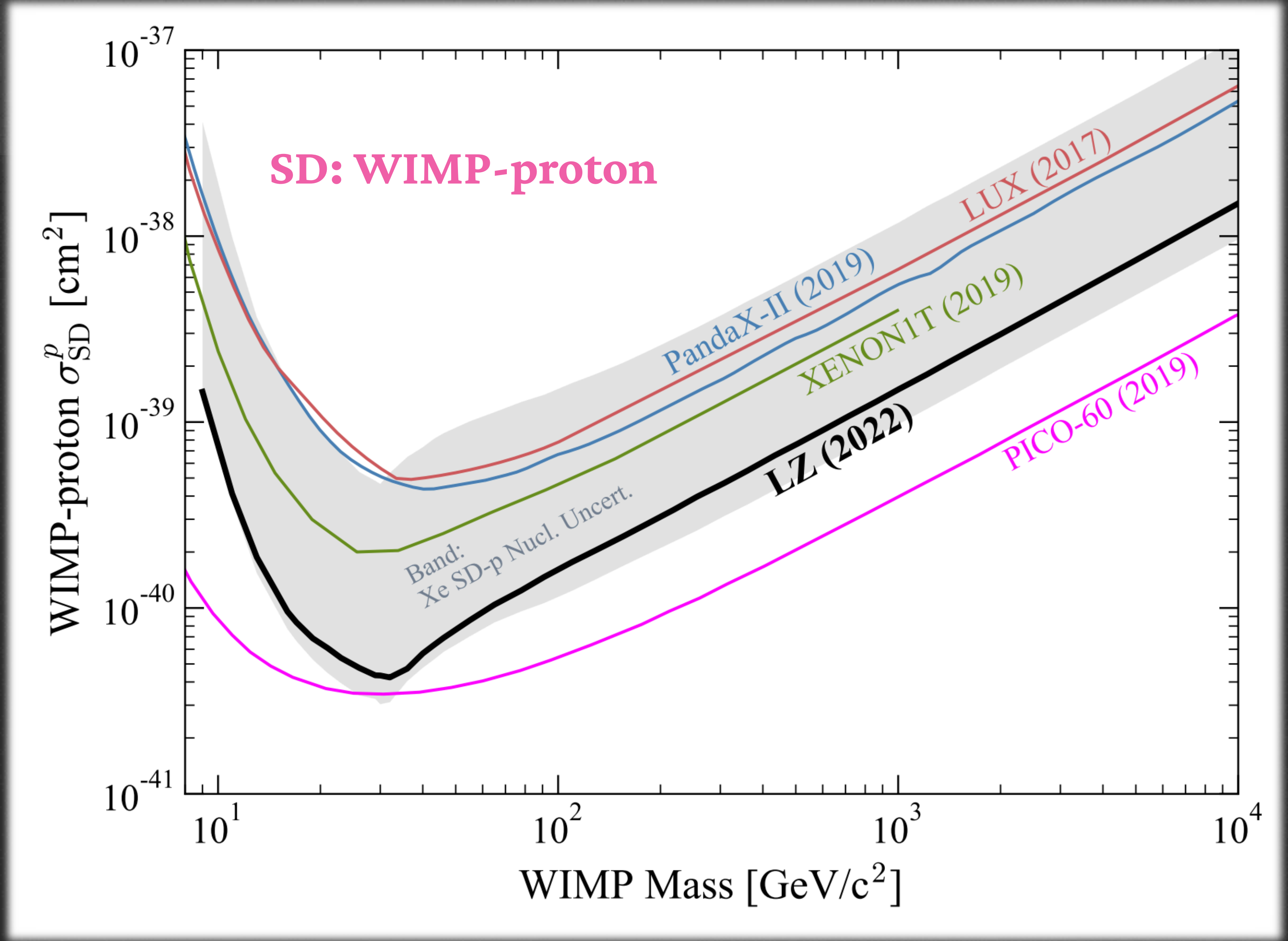
UCL

ROYAL HOLLOWAY UNIVERSITY OF LONDON

LZ First Results





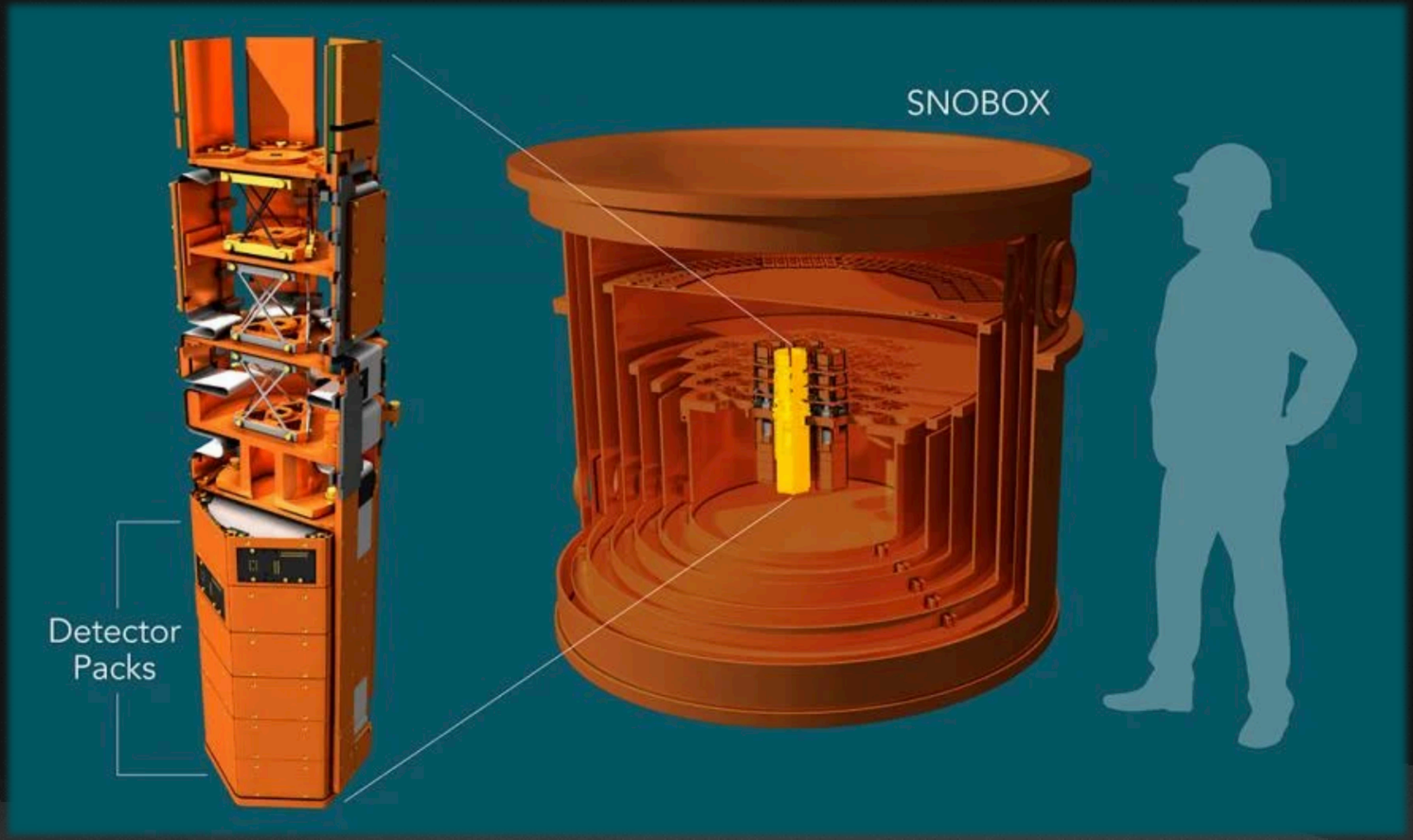


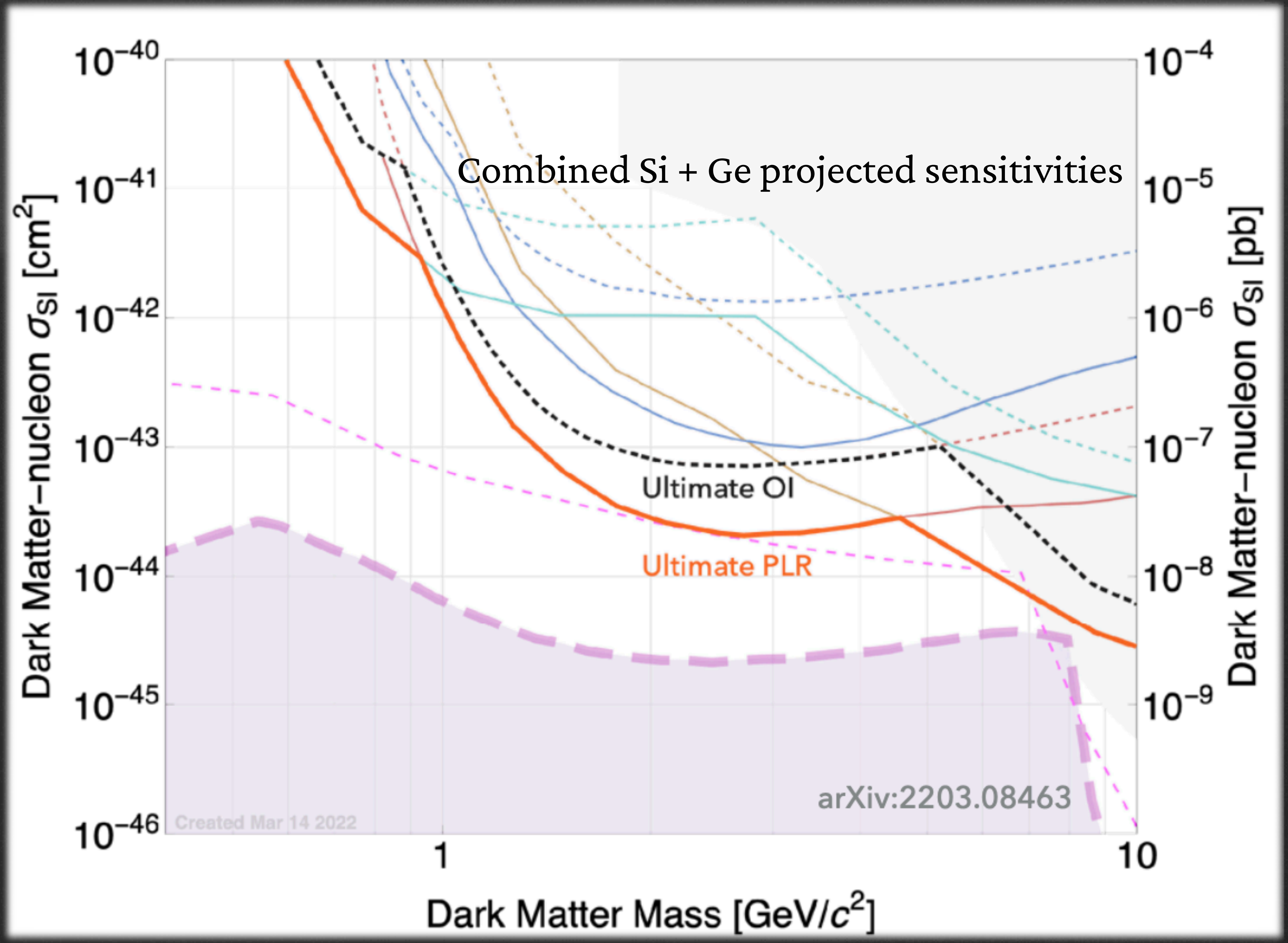
SuperCDMS

UK involvement: Durham

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





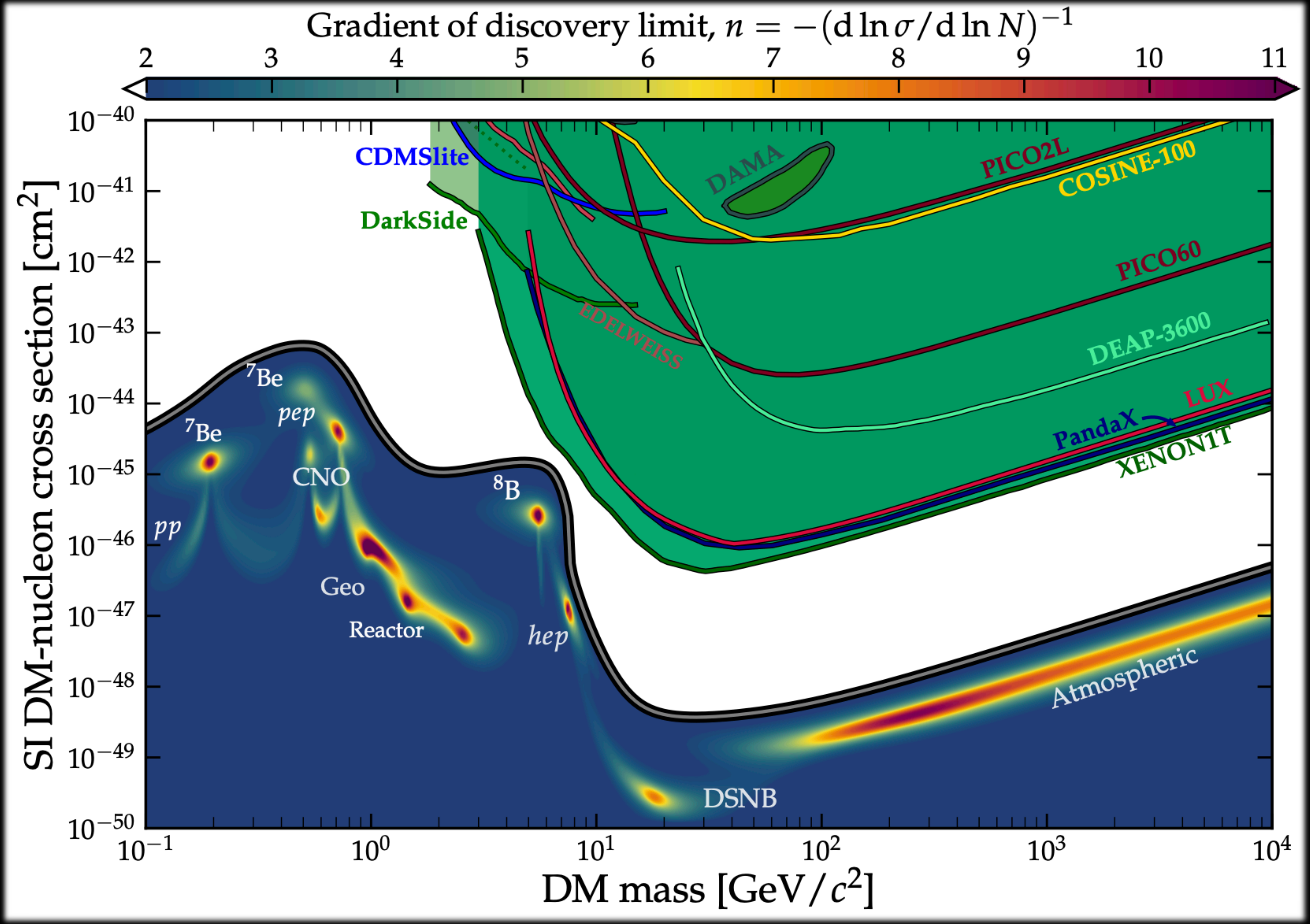
"Overview of the SuperCDMS experiment"
Matthew Wilson
Vienna, IDM 2022

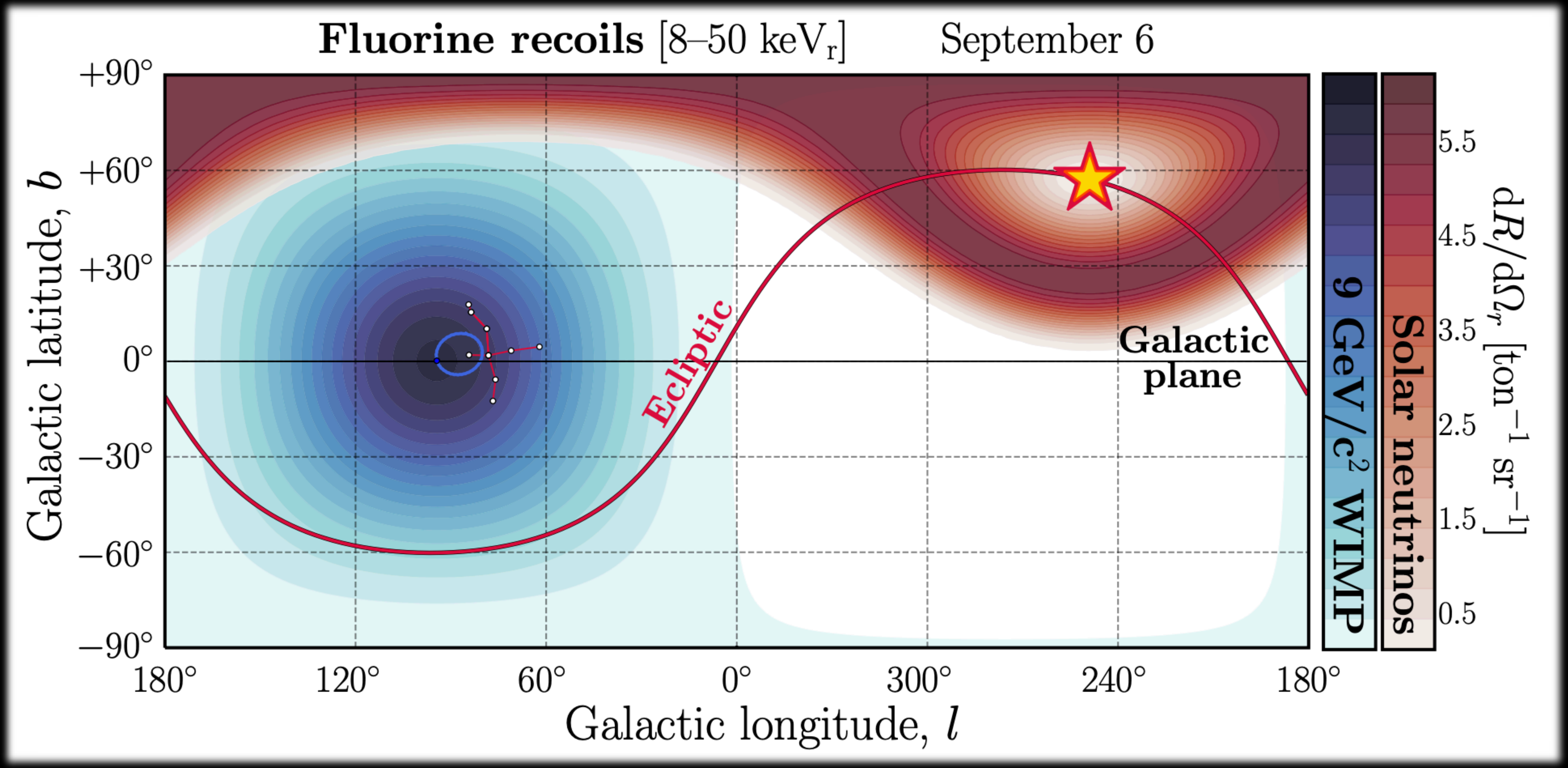
Directional Detection

Overcoming the neutrino floor

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

**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*



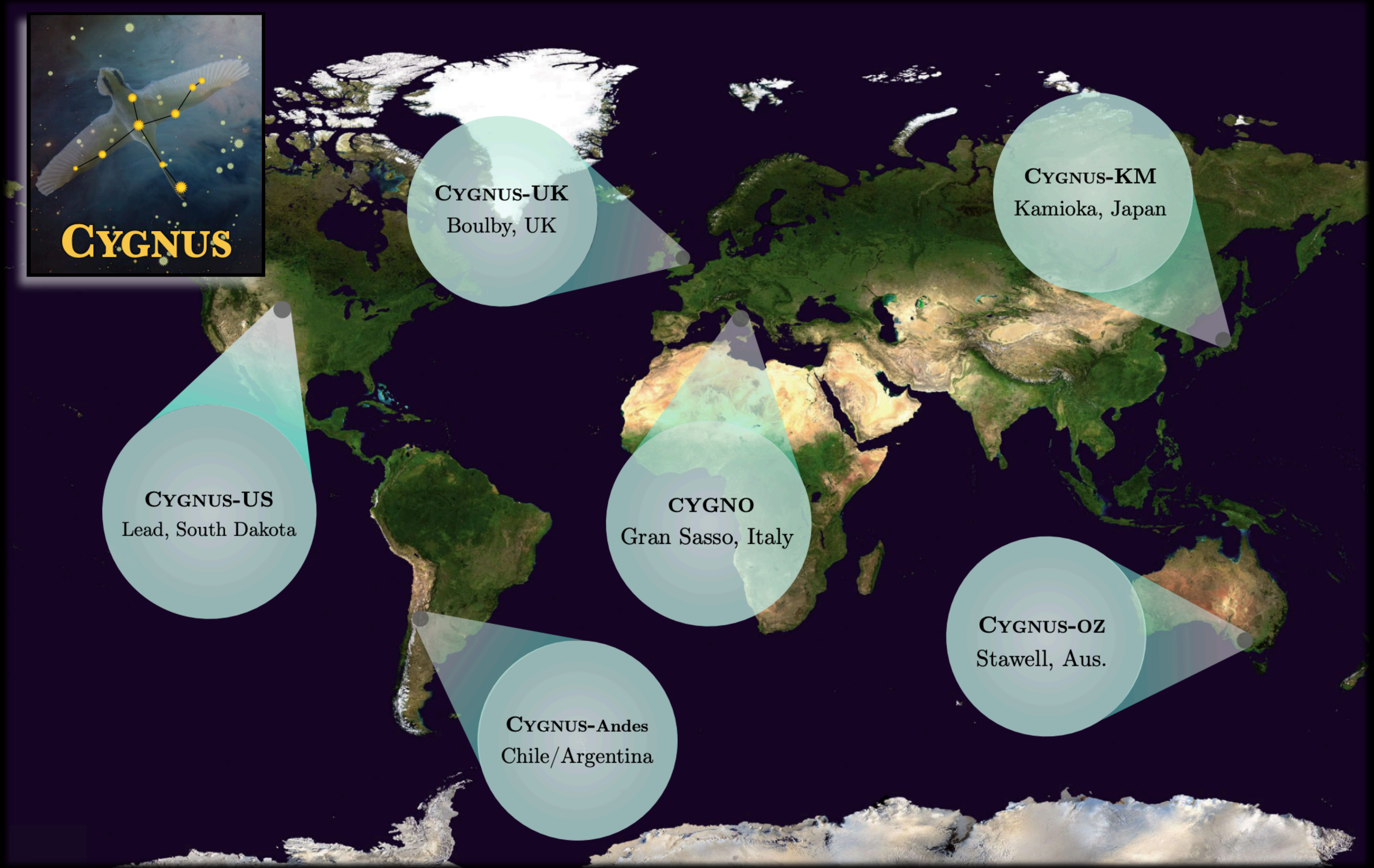


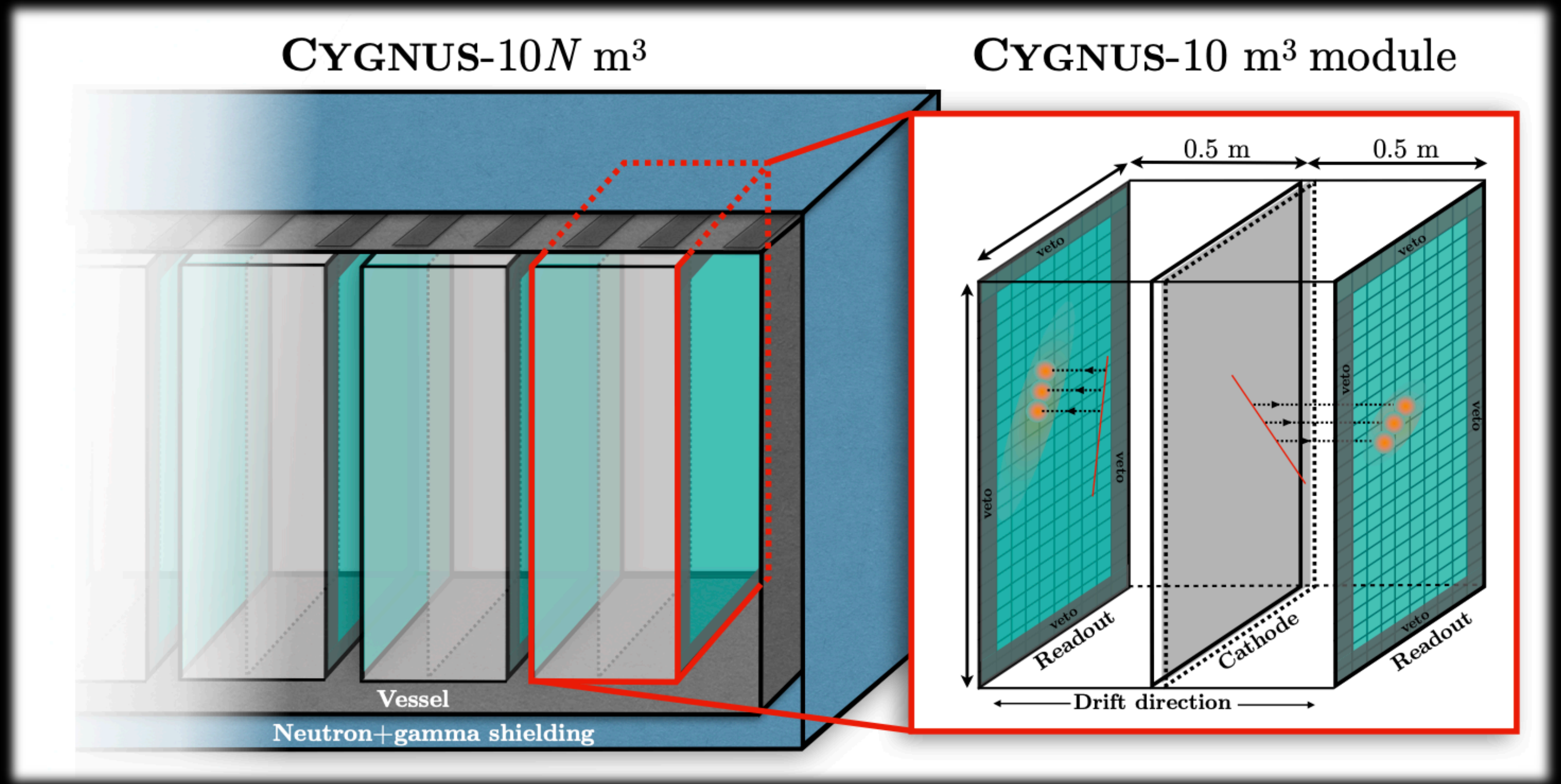
Directionality allows clear discrimination of neutrinos (position tracks the sun) from DM (always from Cygnus)

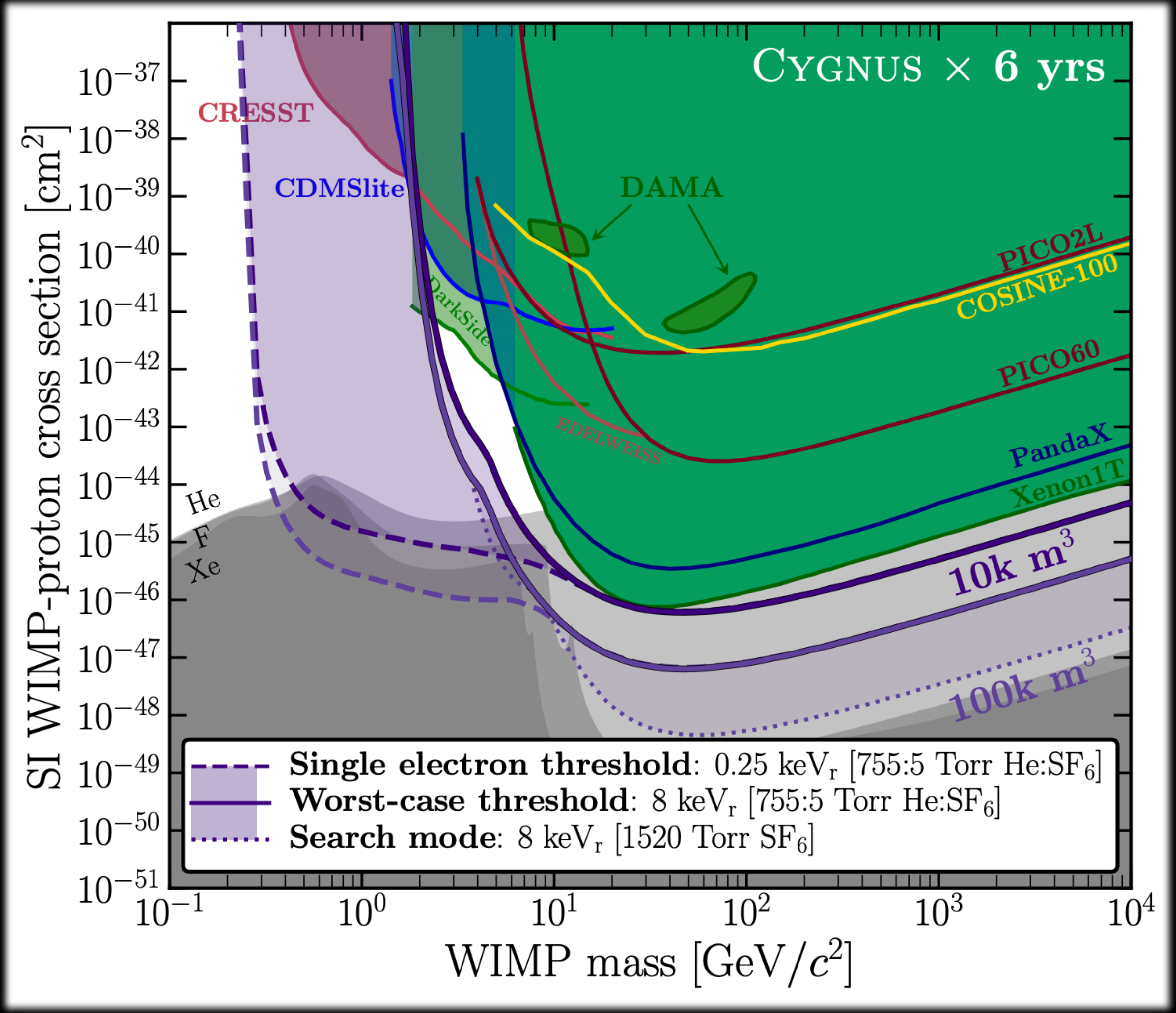
CYGNUS

UK involvement: Sheffield

- Long term CYGNUS Vision: Multi-site Galactic Recoil Observatory with directional sensitivity to WIMPs and neutrinos using low-density gas TPCs
- Targeting low-mass WIMP region (~10 keV) with directionality
- Prototyping in various stages across the world







Low Mass DM

- Light (< 1 GeV) DM invokes technological challenges for detection
- Interaction is mix of DM-nucleus, scattering DM-e scattering and both depending on 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)

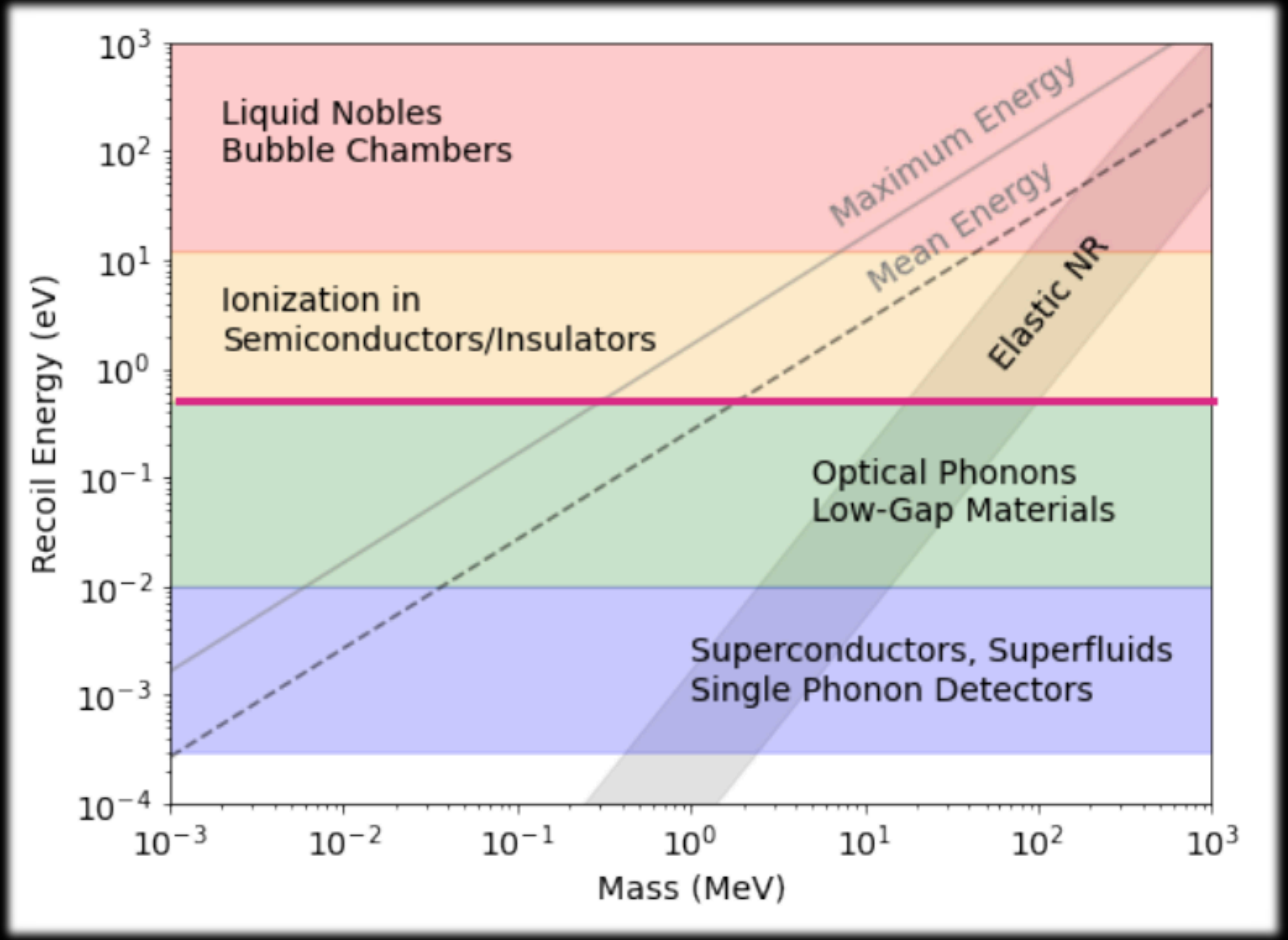
Larger experiments that can employ special techniques/ considering upgrades:

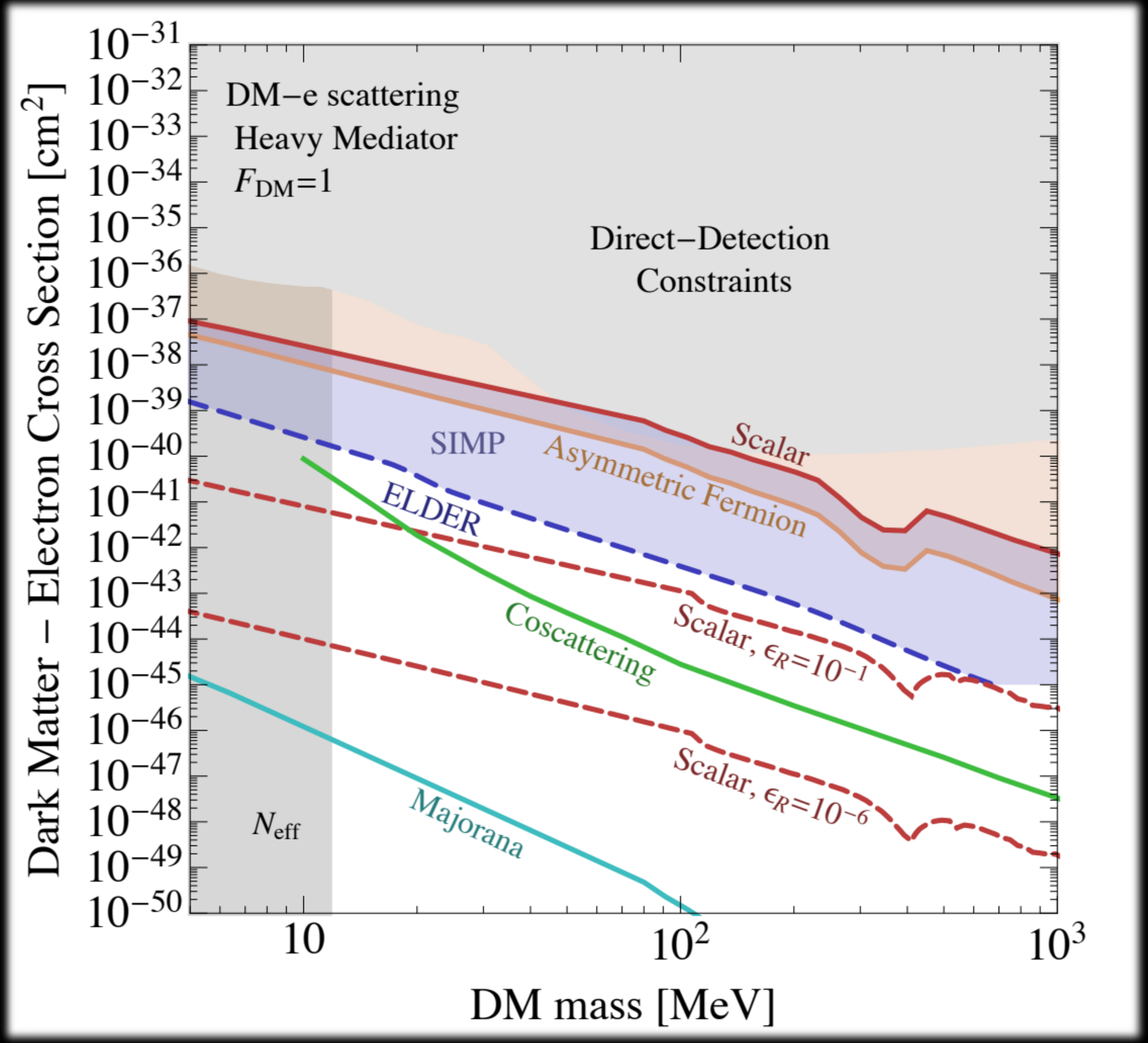
- LZ
- XENONnT
- Darkside-20K

"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





Axion-Photon Constraints

Axion Limits, C. O'Hare
Available Online