

Where Direct Dark Matter Searches Are Going

PPAP Roadmap Update Discussion

Kimberly Palladino
PPAP
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UNIVERSITY OF OXFORD

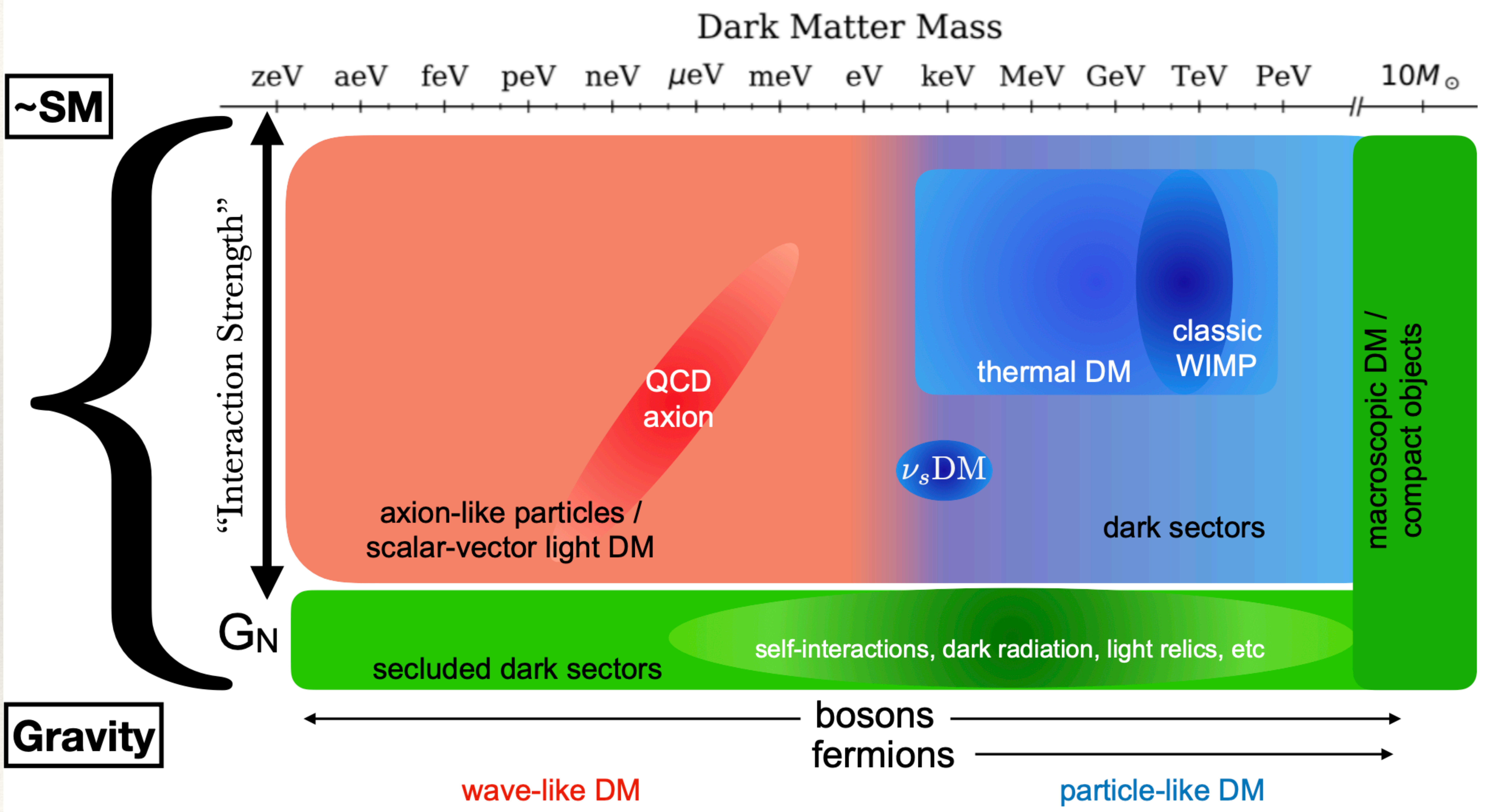
With Many Thanks to A. Cottle's IOP Overview Talk
and the US SNOWMASS process

Today's Outline

- Overview and Context of DM direct detection
- Current Programme & Roadmap
- Future Searches
  - >10 GeV/c^2 Dark Matter
  - 1-10 GeV/c^2 Dark Matter
  - <1 GeV/c^2 Dark Matter
- Conclusions and Questions

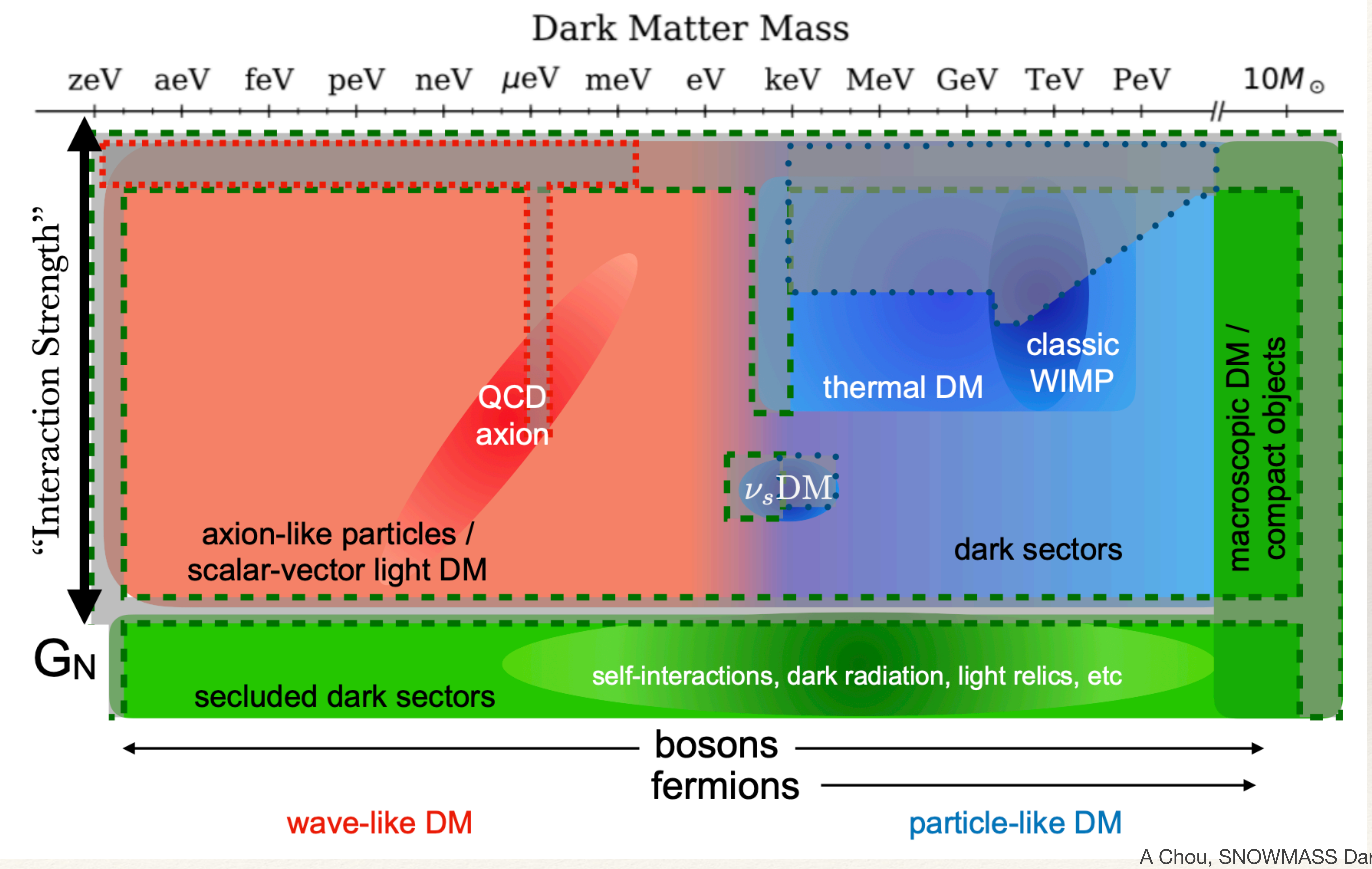
Tom Chitty 2016, New Yorker

A Unified Vision coming from SNOWMASS



A Chou, SNOWMASS Dark Matter Plenary

2021 Status

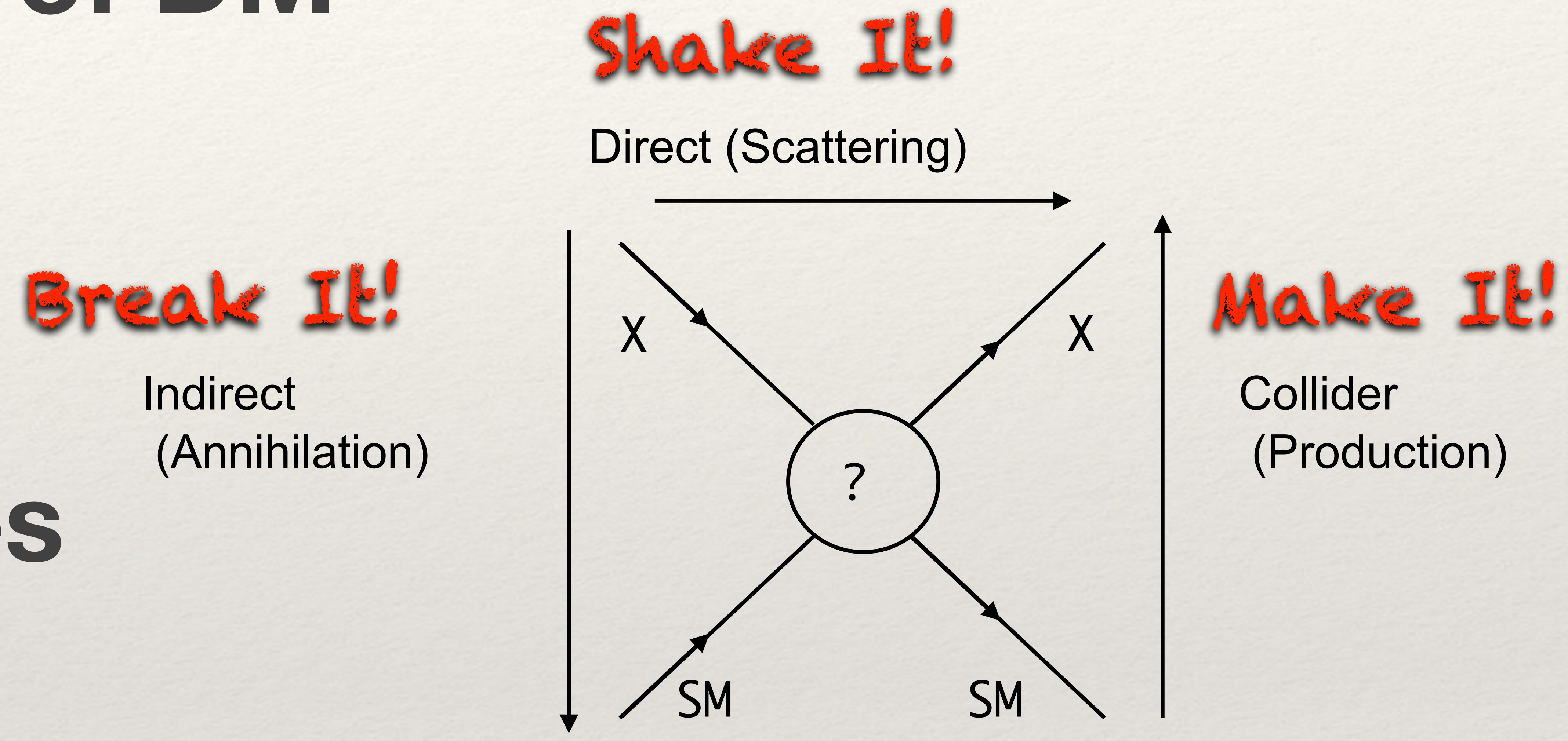


A Chou, SNOWMASS Dark Matter Plenary

Some Context & Caveats: Science

For Dark Matter Science:

- Direct DM searches are tied to:
  - Astrophysical/cosmological evidence of DM
  - Theory candidates for DM
  - Indirect Astrophysical searches
  - Collider Searches
  - Axion and other wavelike DM searches
  - Primordial Black Holes and other astrophysical/macroscopic options



Some Context & Caveats: Experiments

For Dark Matter Experiments

- Direct DM experiments are tied to:
  - UG facilities and neutrino science
  - Int'l collaborations and funding
  - Low background assay facilities, methods, materials and 0vbb community
  - Quantum technologies
  - More nuance than presented here

- Large Experiments are multi-science, rare-event observatories:
  - 0vbb
  - astrophysical neutrinos
  - wavelike DM candidates

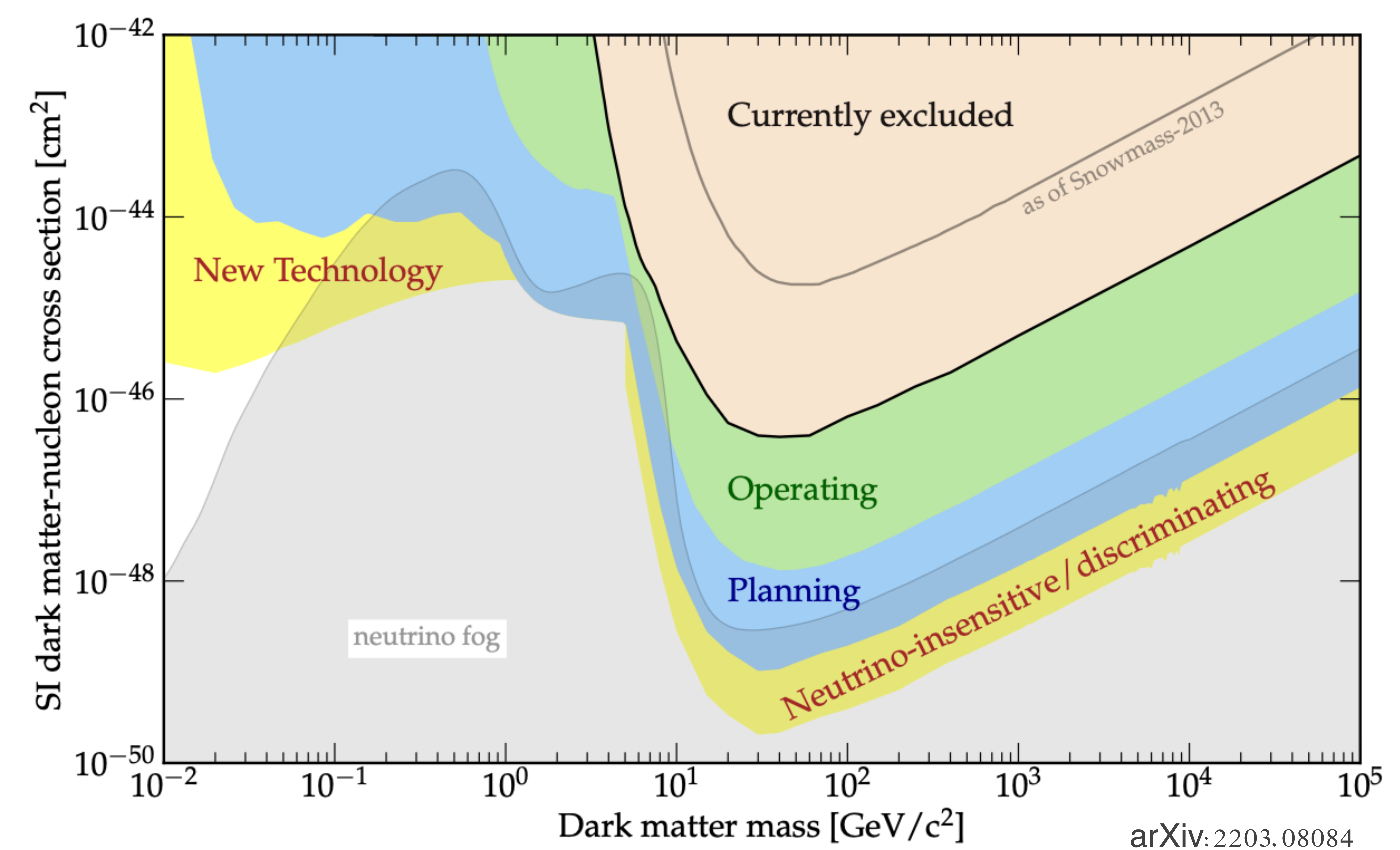
2021 Roadmap Recommendations

Recommendation 7.1: The UK should maintain leadership during R&D, construction and exploitation of Direct DM Detectors over a wide range of DM masses that demonstrate their uniqueness, complementarity, or world-wide competitiveness, and should seek opportunities to grow funding to support projects, including those planned to be constructed within the UK.

Recommendation 7.2: The UK should secure future support outside the current STFC core programme (for example NQTP or other cross-UKRI funding) of dark sector experiments based on successful demonstration of quantum technologies seeded by the QTFP programme. If a growth of funds is not achieved, pursuing the broad PP scientific goals in the dark sector will need to be tensioned with other areas of the core programme.

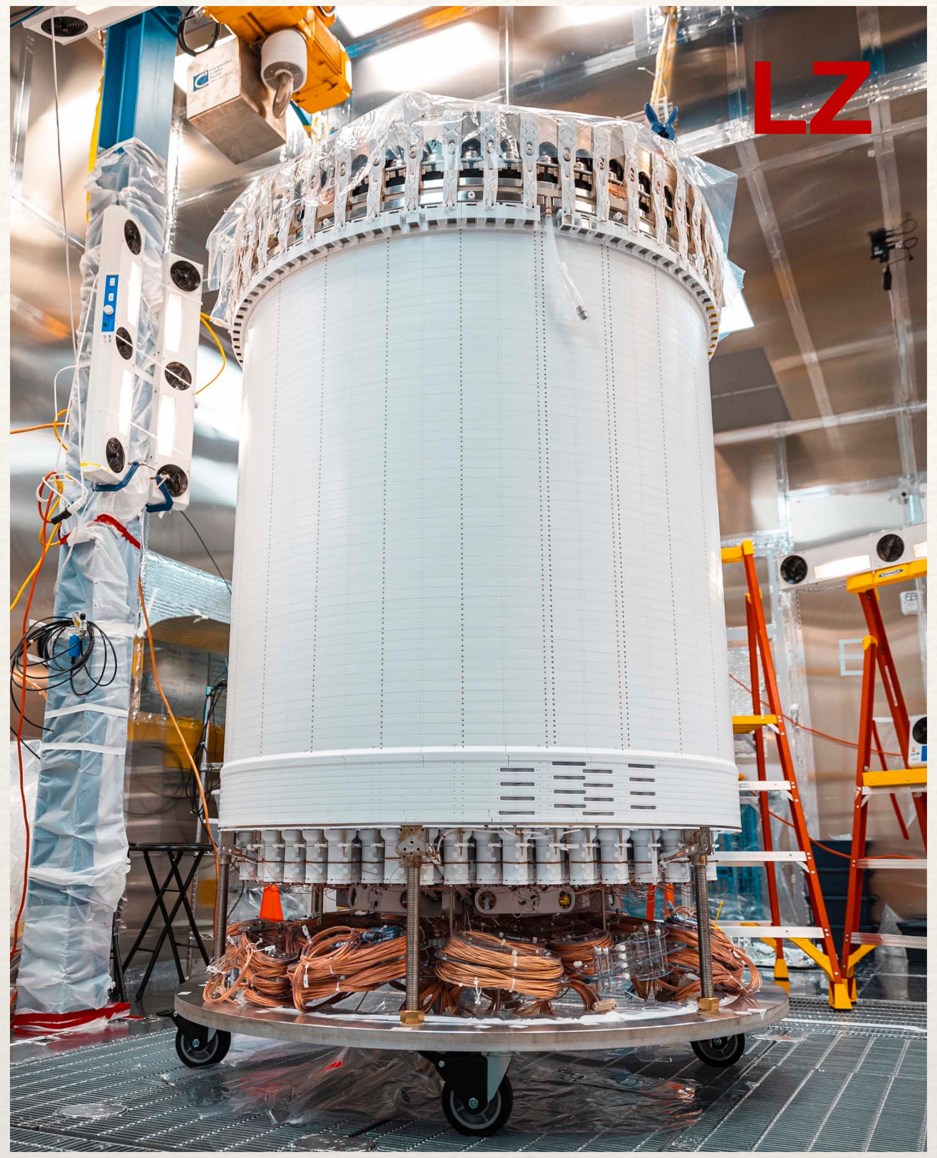
Recommendation 7.3: The UK community of theorists and phenomenologists, collider experimentalists, and direct and indirect detection experimentalists should establish a interdisciplinary programme to explore a synergic approach in DM studies, with greater communication and idea exchange.

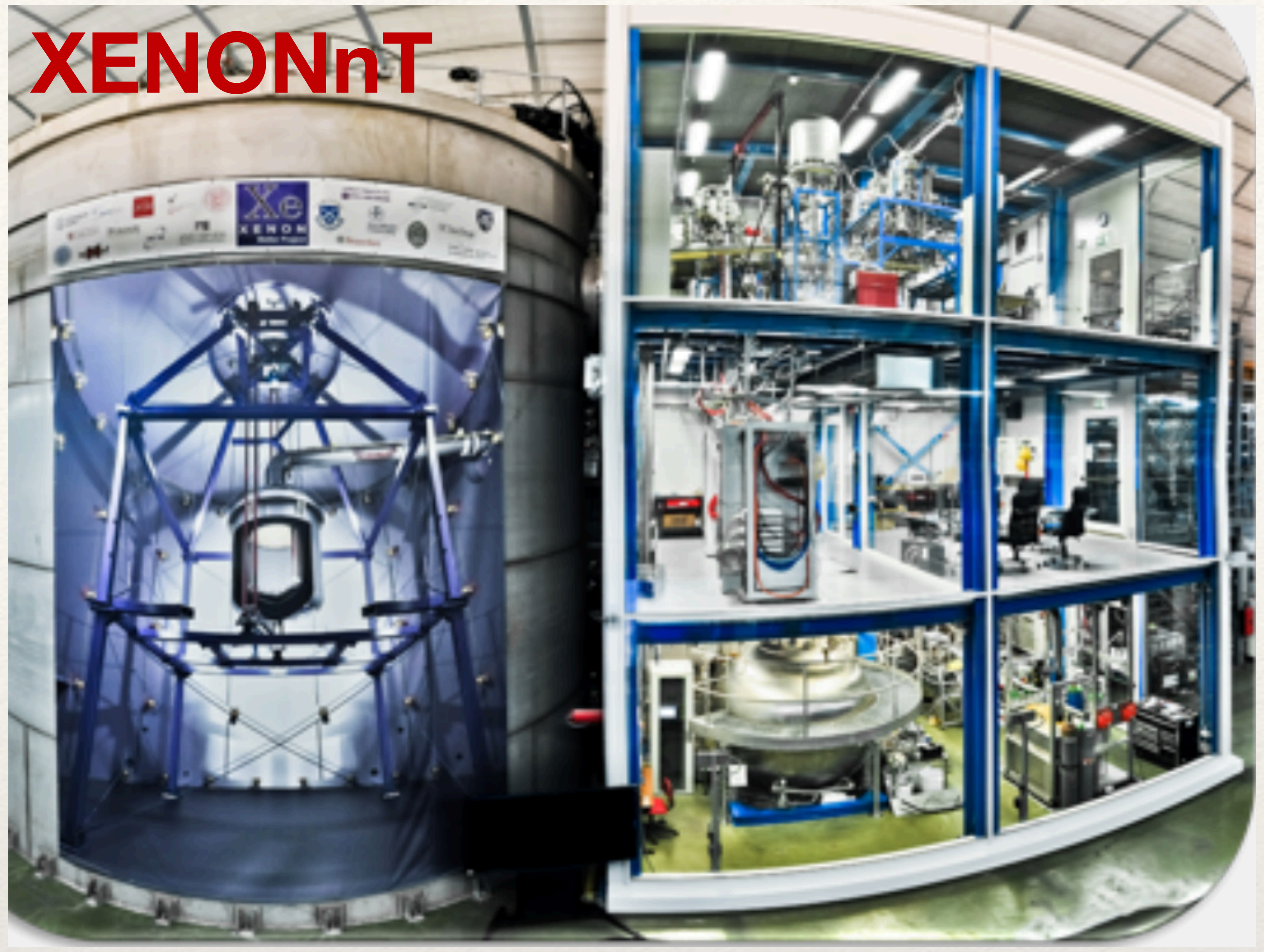
Going to the neutrino fog

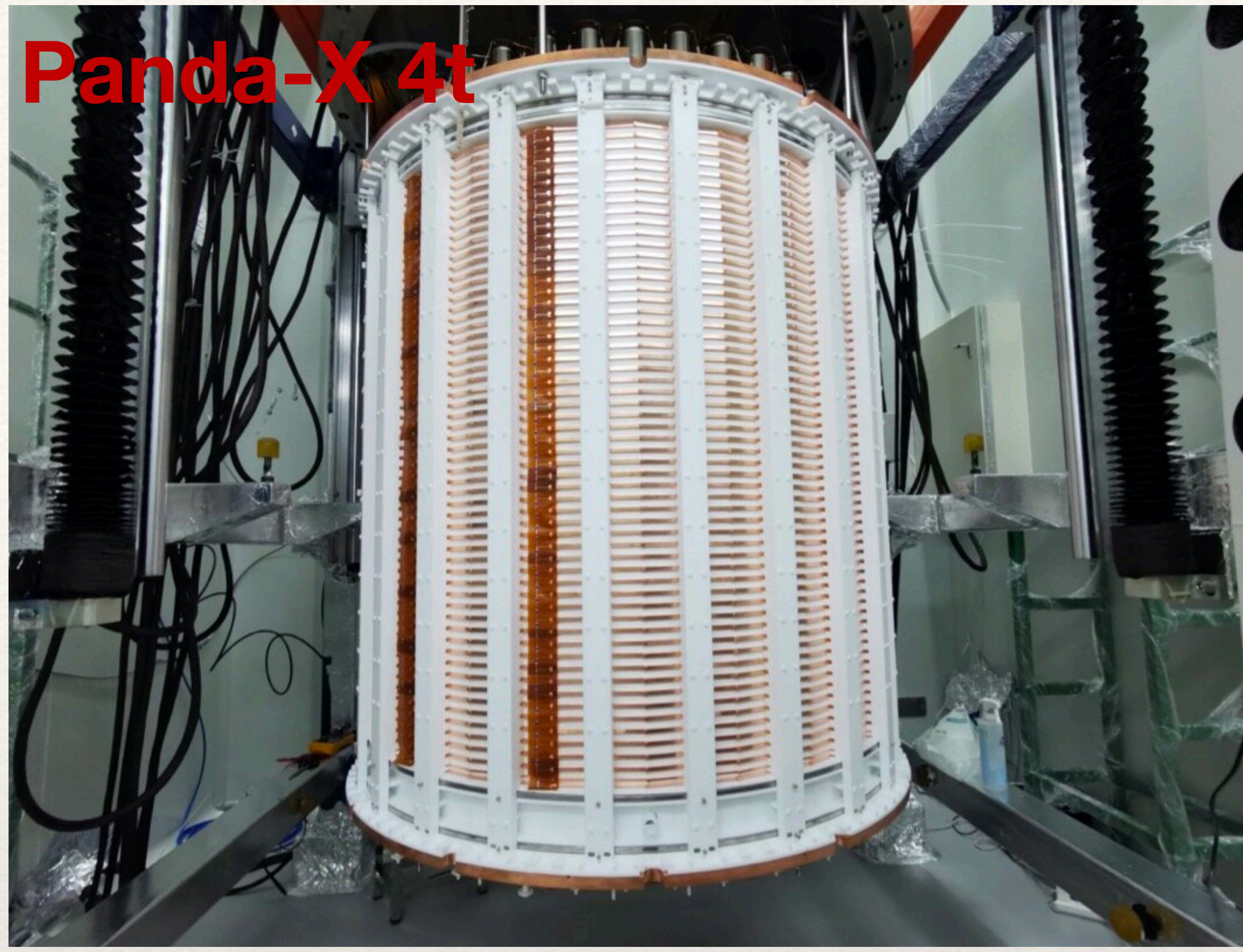


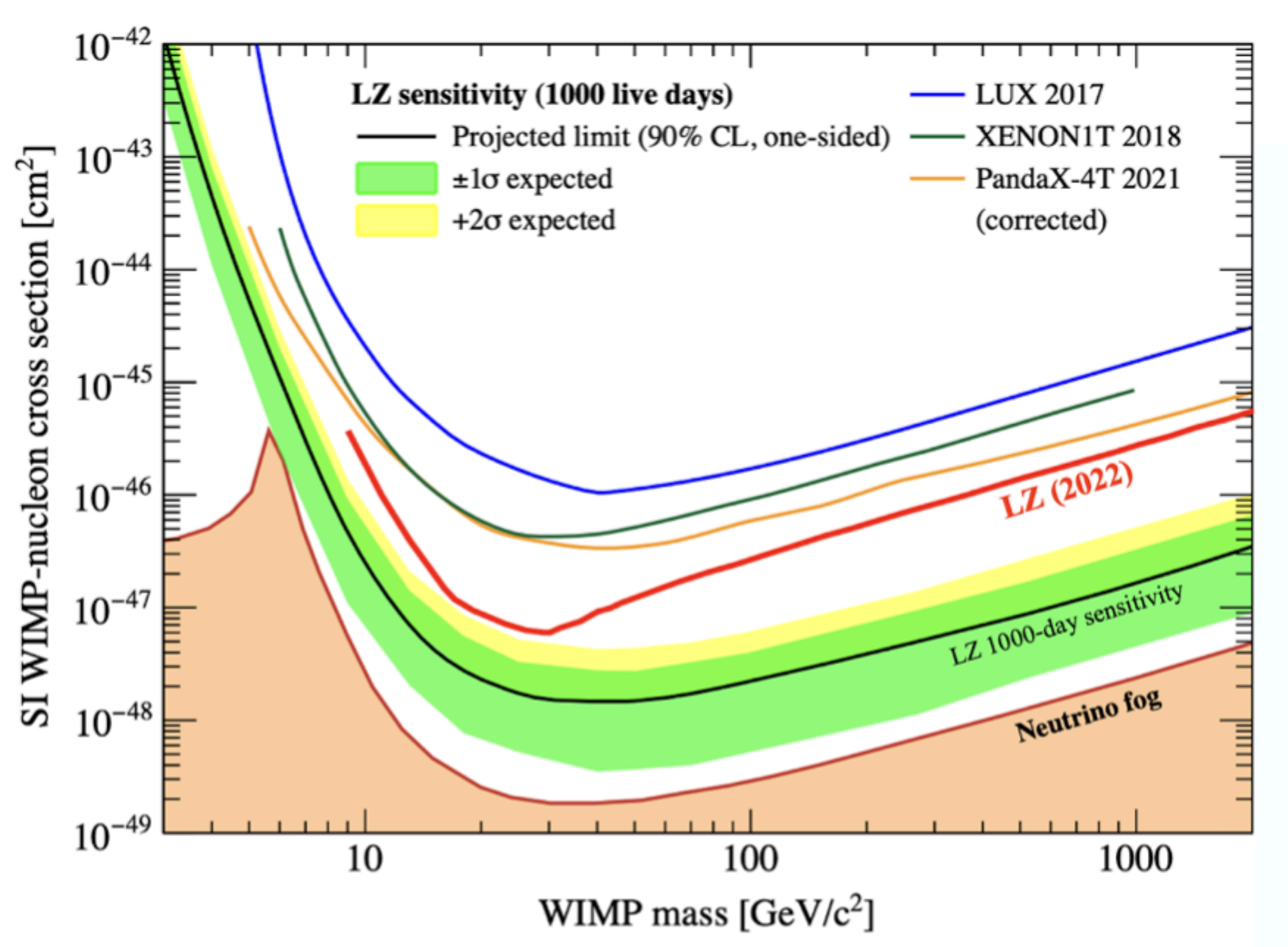
arXiv: 2203.08084

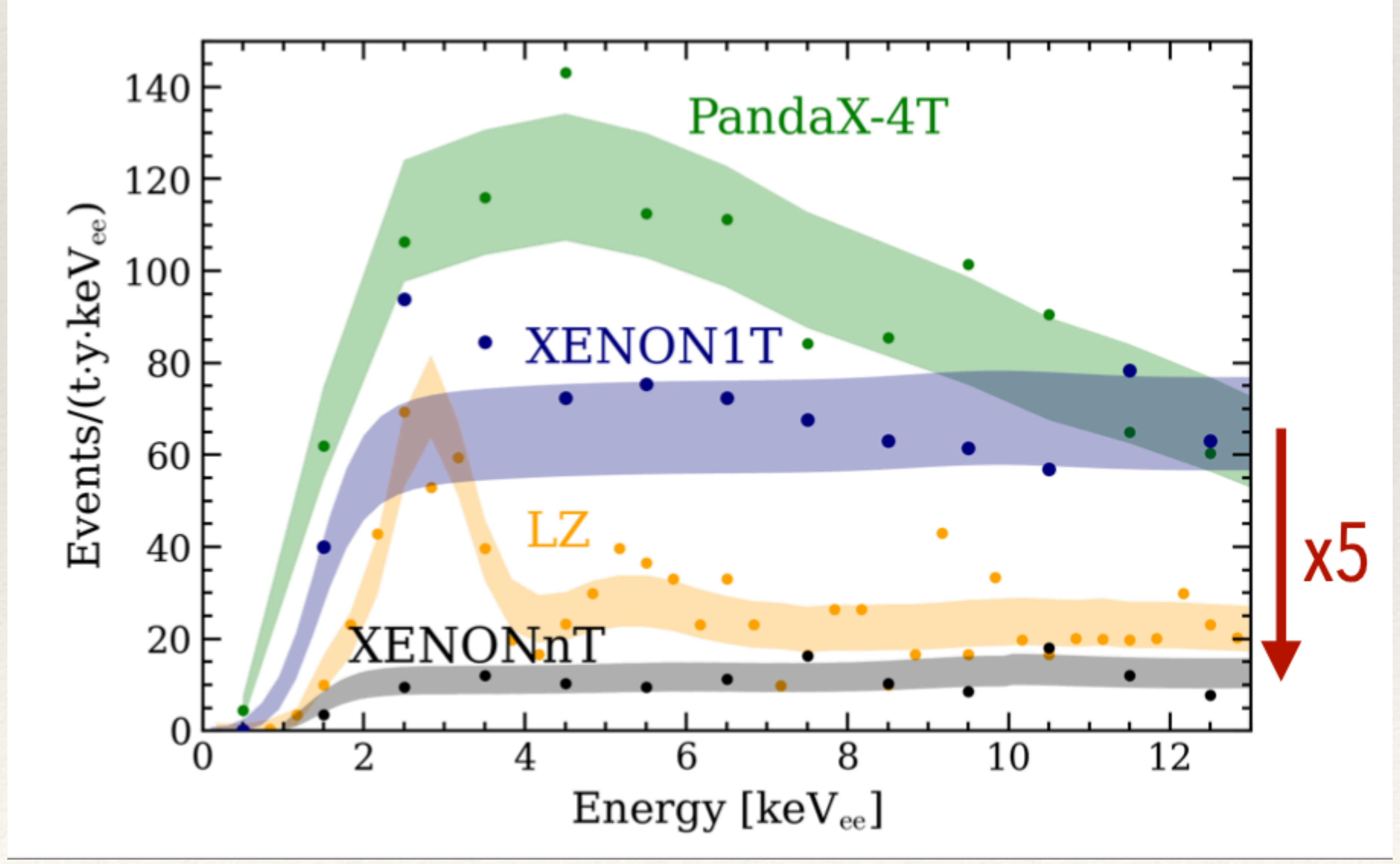
Running Xenon Experiments







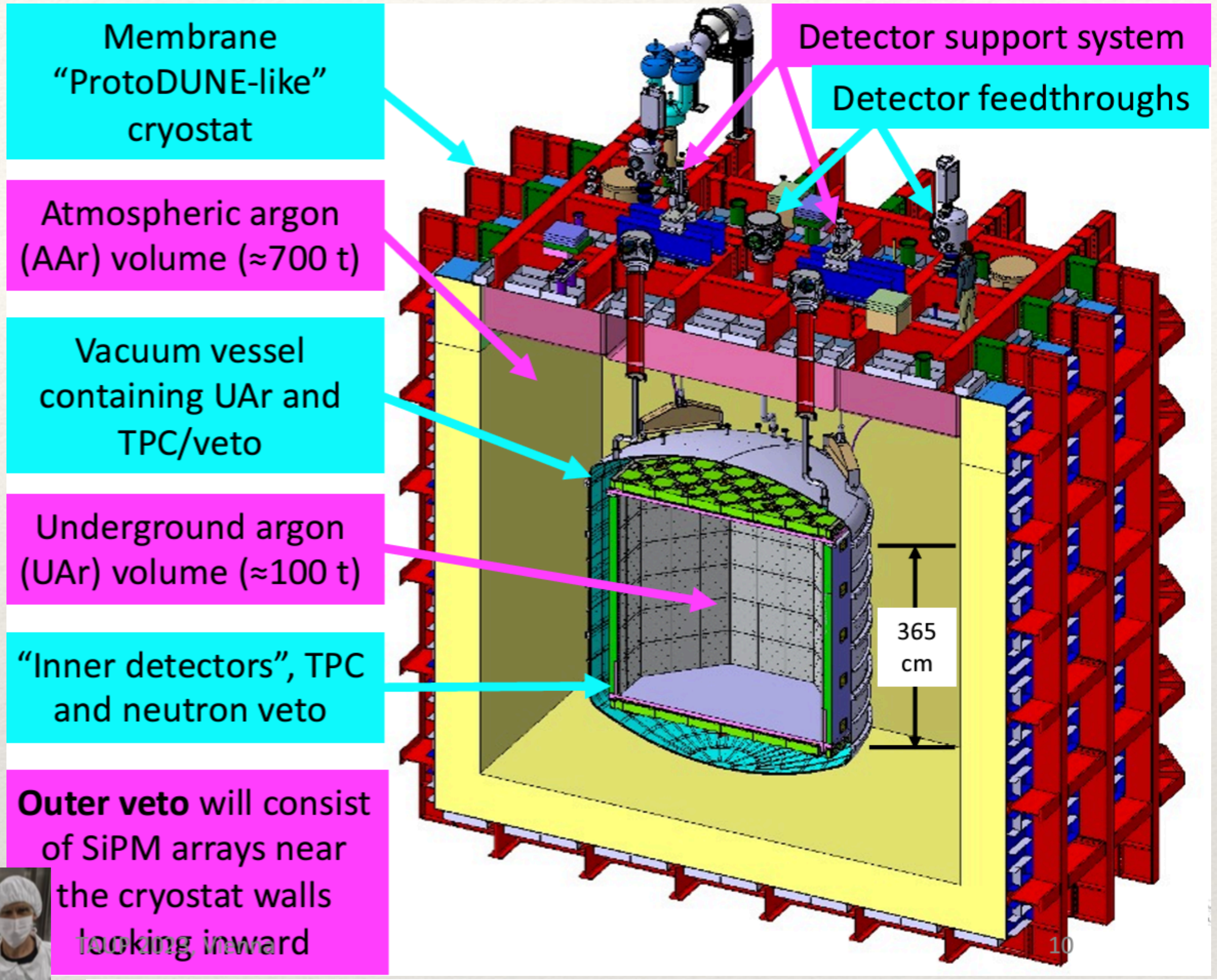


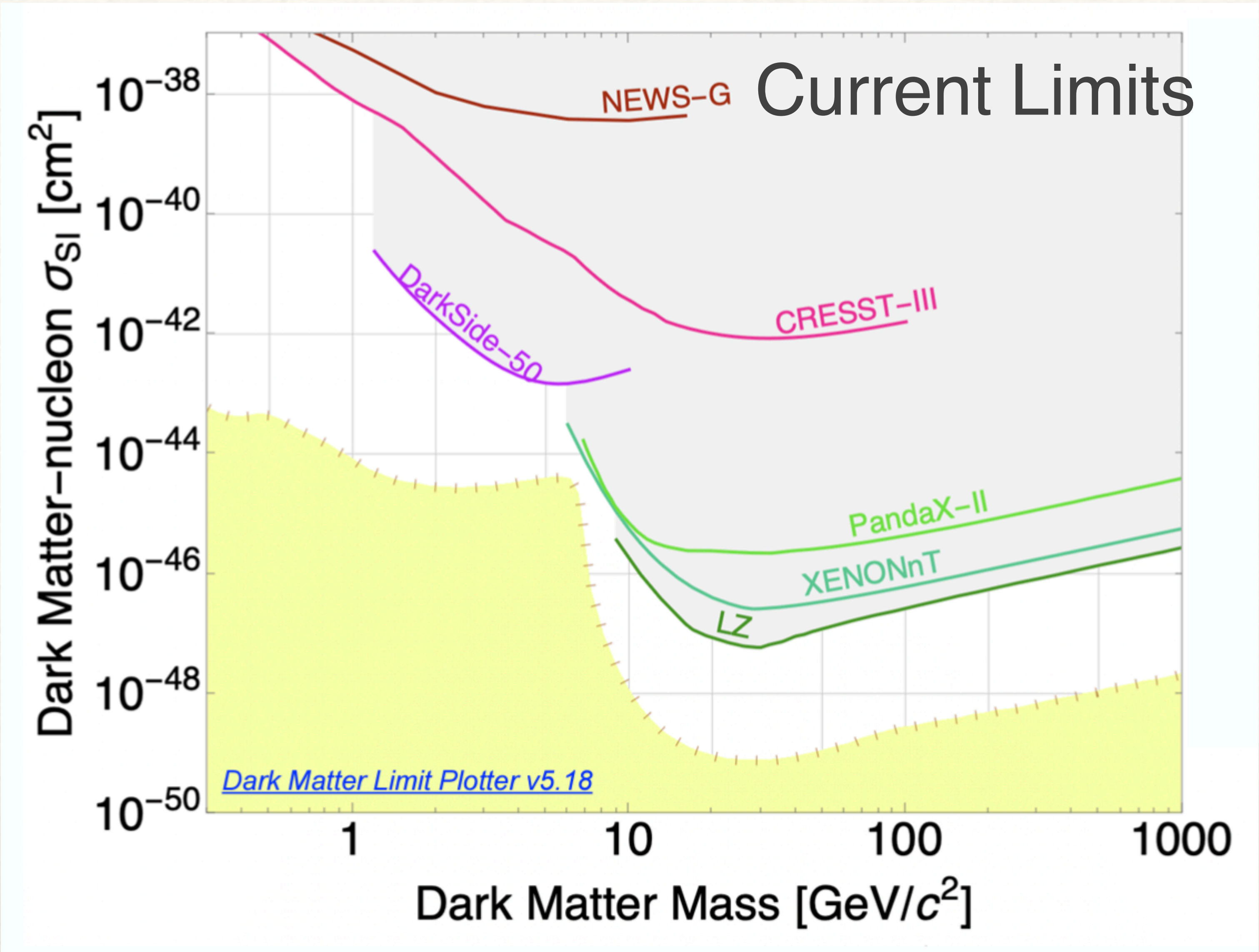


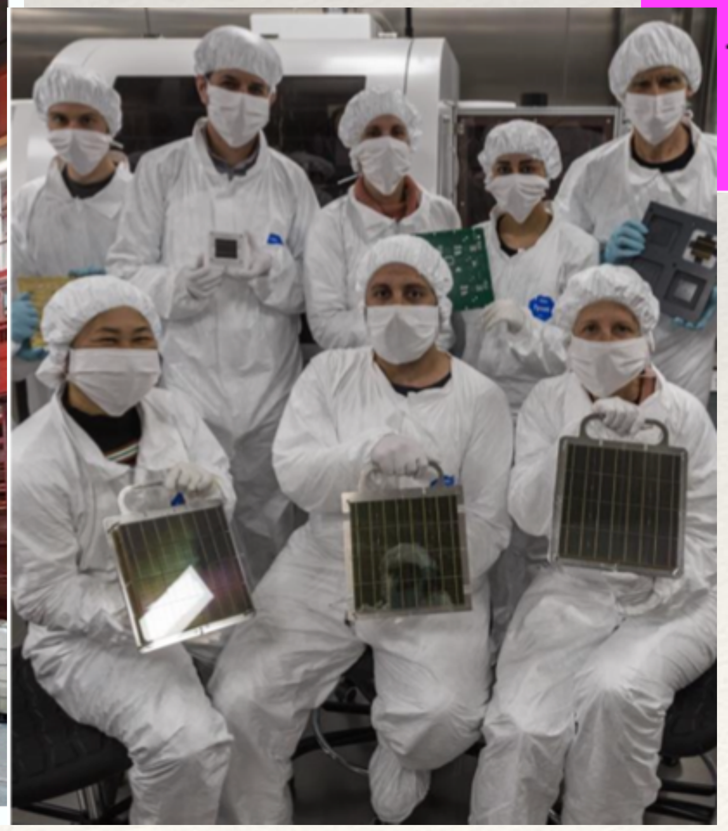
- 3 running experiments that will continue ~5 years
- Continuing their understanding of xenon microphysics
- Science also with electronic recoils, effective field theory models, MIMPs, 0vbb and double electron capture, solar neutrinos, ….

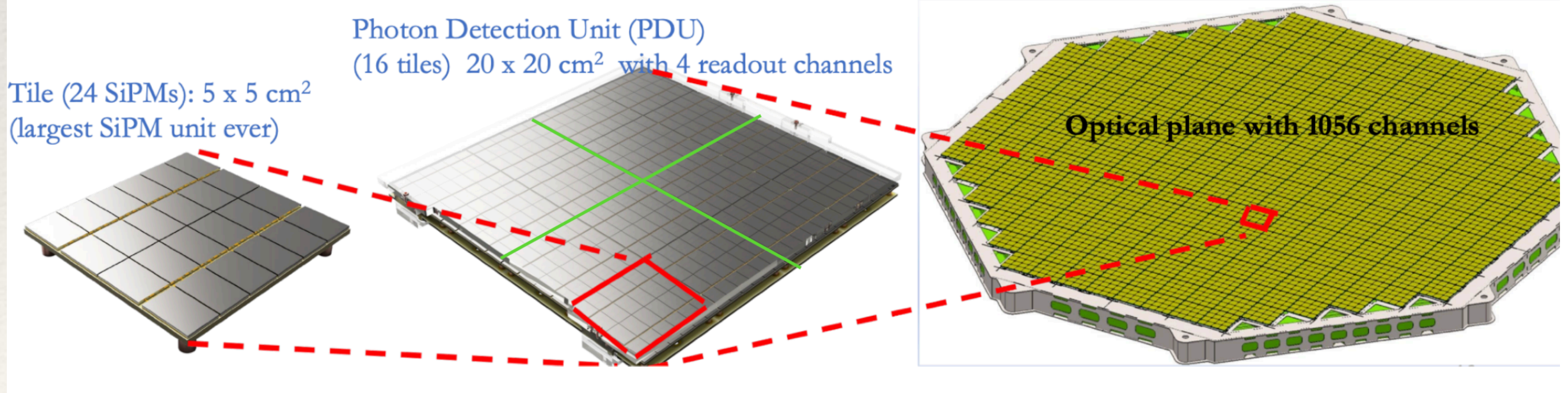
DarkSide–20K

- DarkSide-20k under construction at LNGS, commissioning expected in 2026
  - Technology advances in SiPMs, Gd-loaded acrylic, Ar distillation
  - S2-only leading sensitivity from DarkSide-50 for low masses
- Single phase DEAP-3600 undergoing hardware upgrades

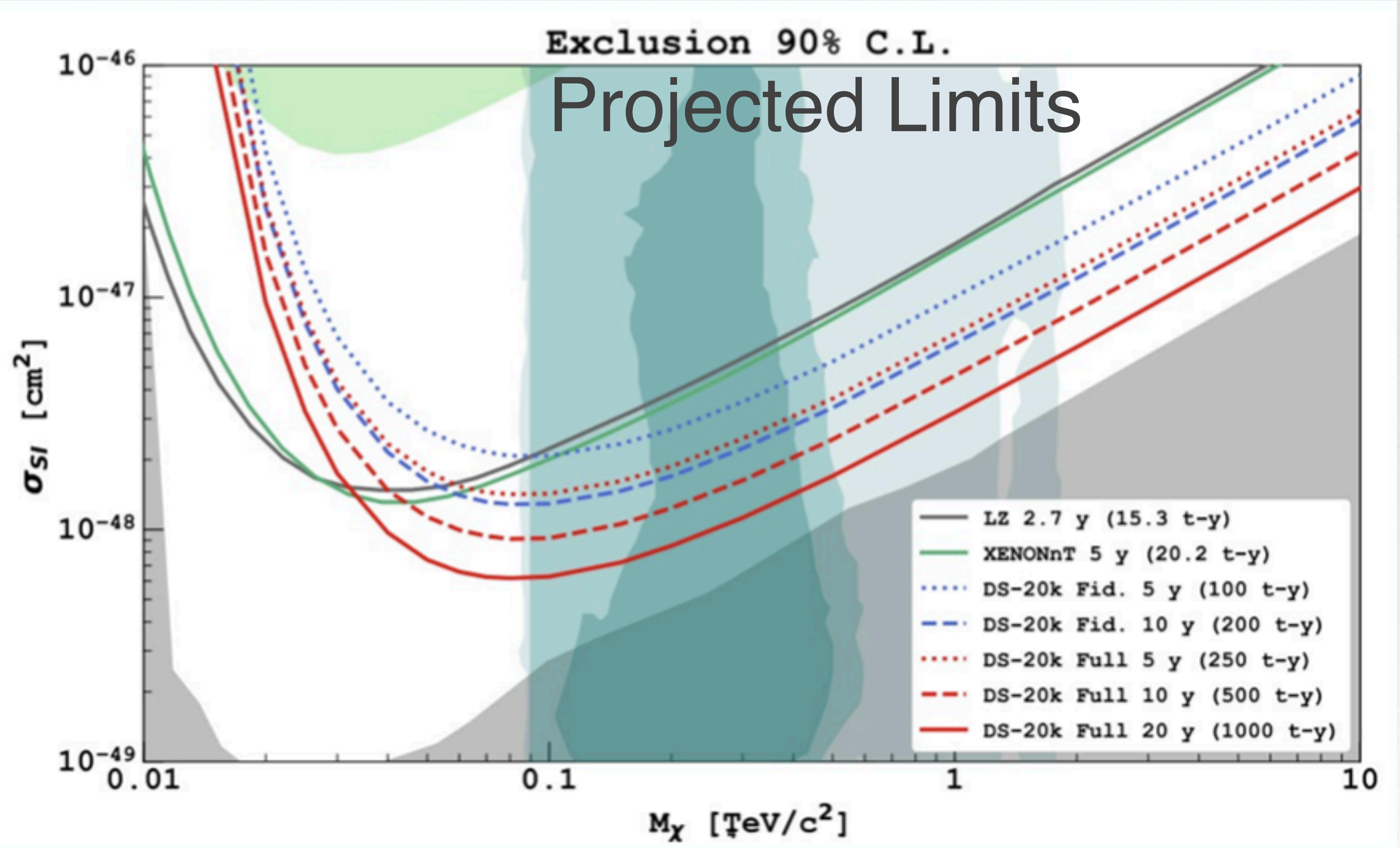




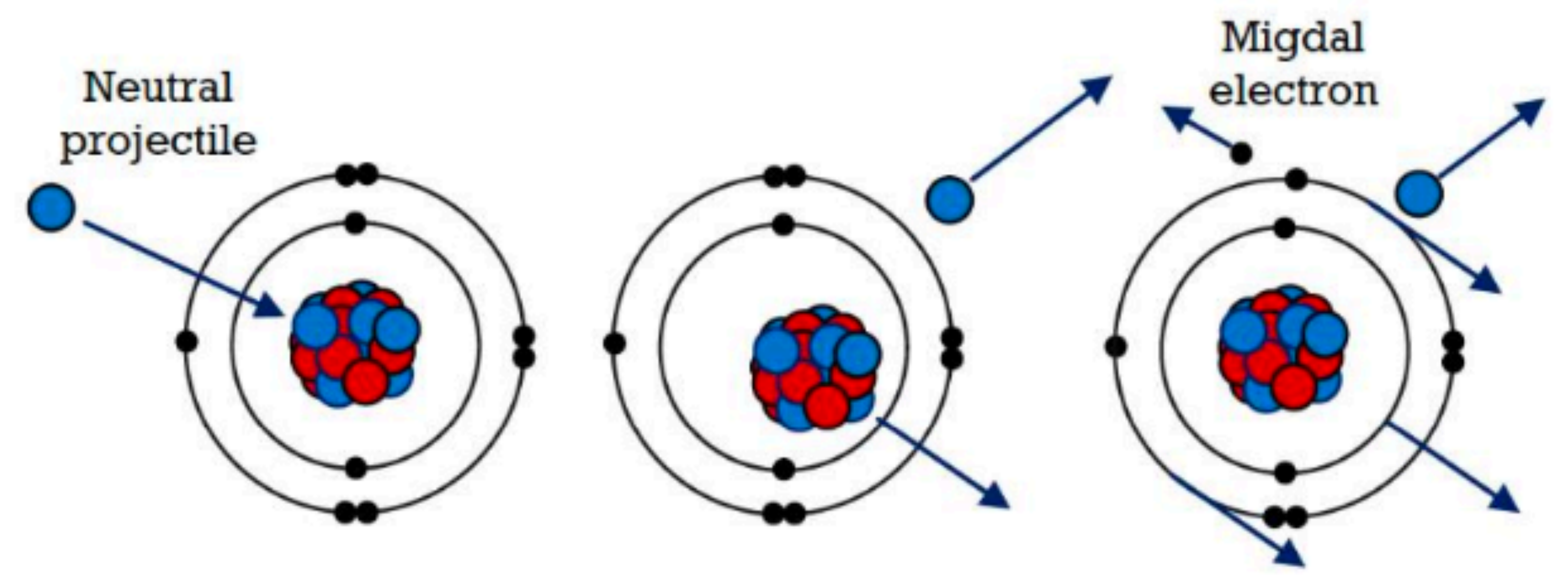




2 optical planes for the TPC
+ 480 channels to instrument the UAr veto

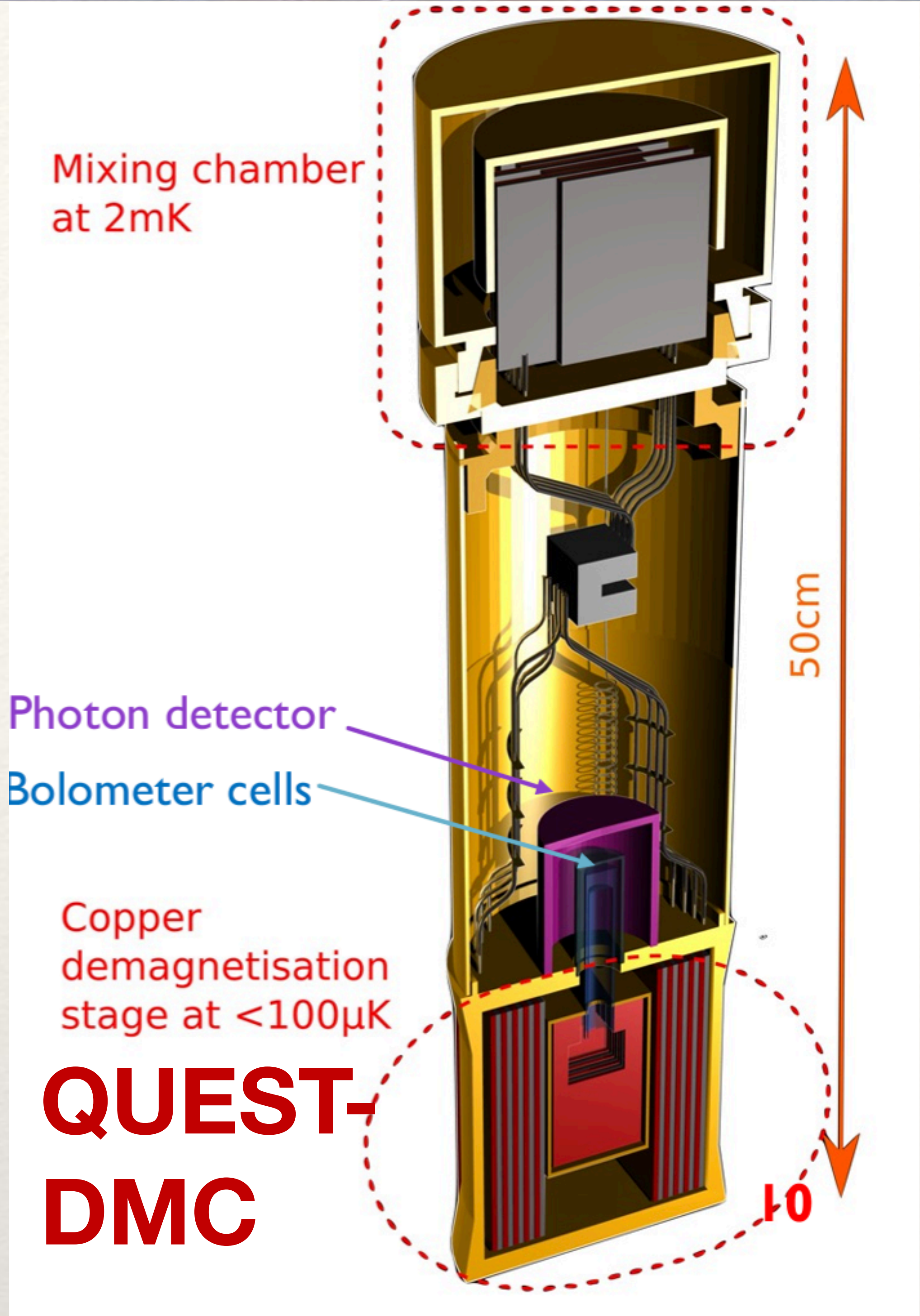


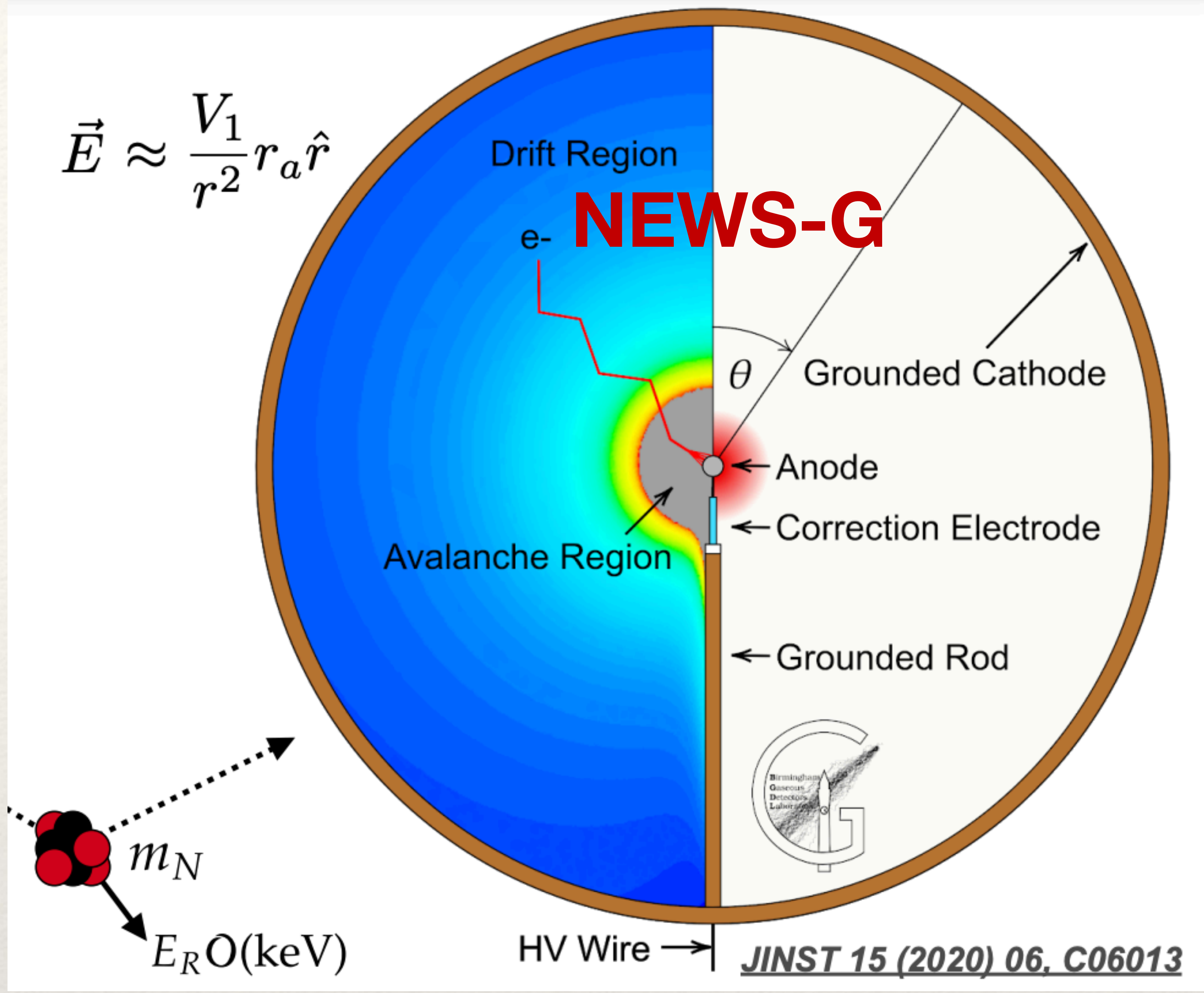
Current UK efforts in Lower Mass Searches

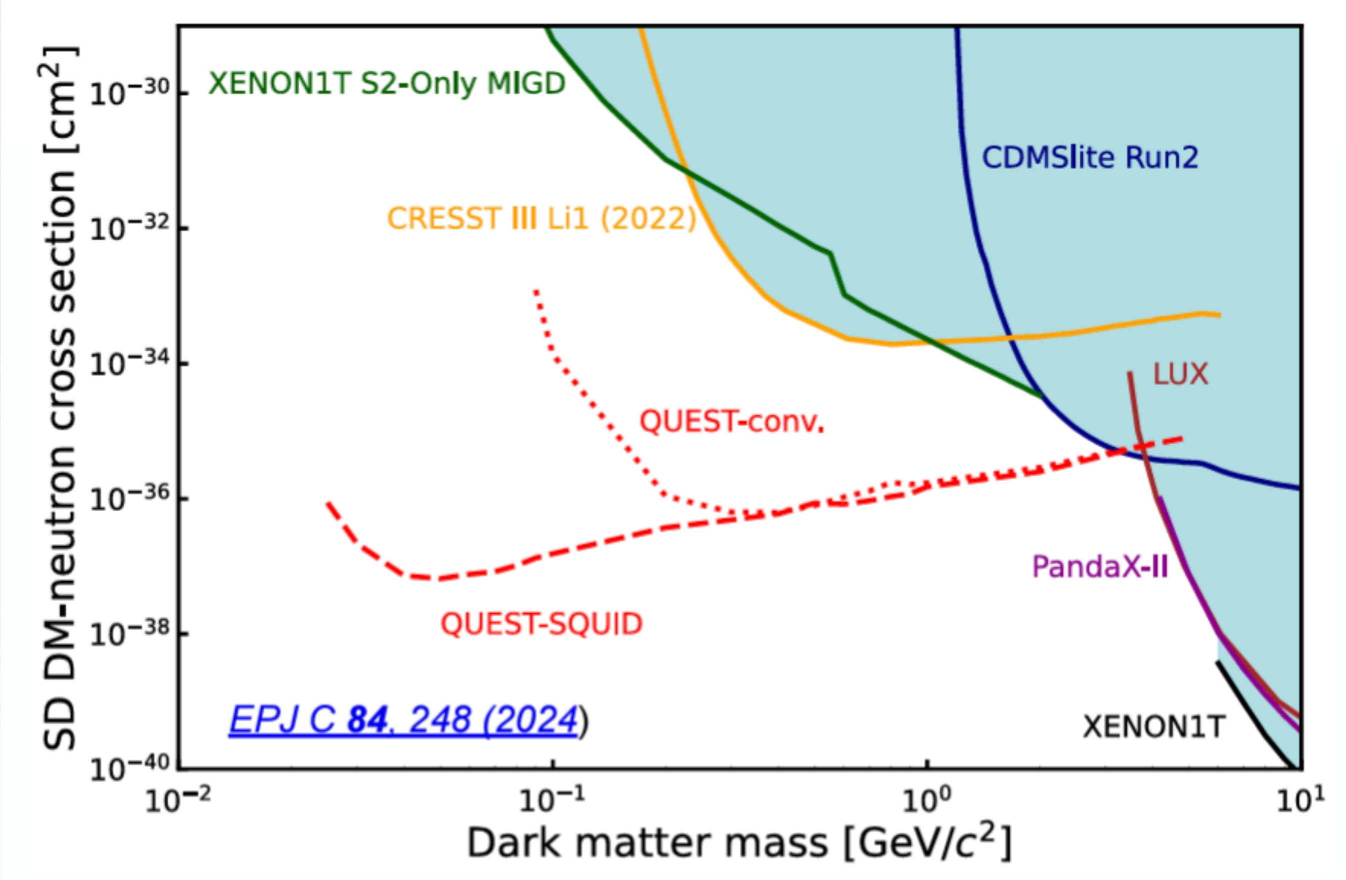


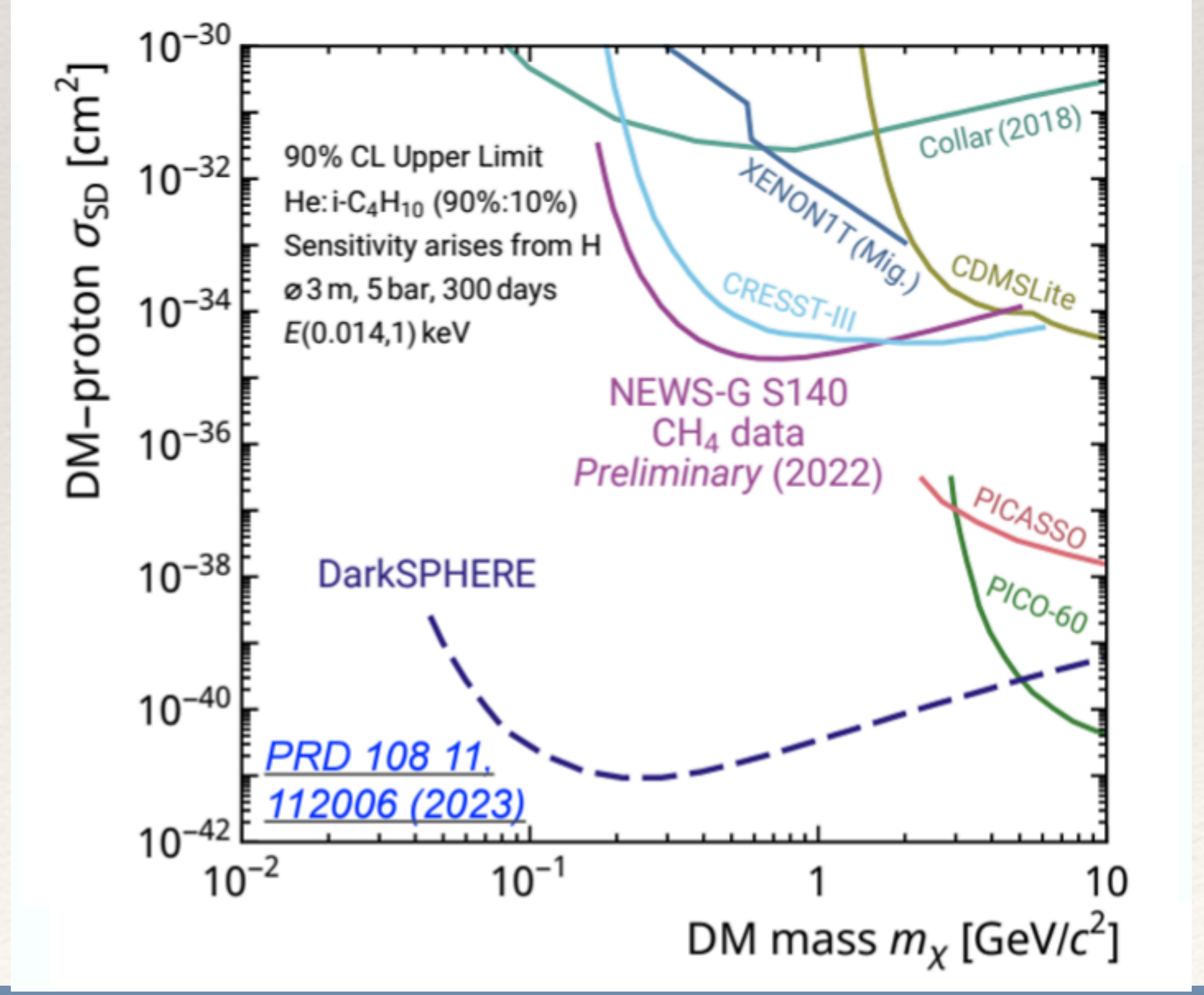
Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.

- **Migdal Collaboration**: Verification of the Migdal effect (ER enhanced signal for an initial NR) for these energies/targets- can extend liquid noble sensitivity to lower masses
  - UK team from Ar and Xe and gas detectors working together
- **QUEST-DMC**: ^{3}He with thresholds < 10 eV
  - a 6 month run of a final configuration will have SD sensitivity <10^{-36} cm^2
- **NEWS-G**: operating at SNOLAB has preliminary results leading in the proton-SD interactions in 0.2-1 GeV/cm^2 mass range









For DM masses > 10 GeV/c^2,
liquid noble detectors are the right technology,
and future experiments can get to the neutrino fog.

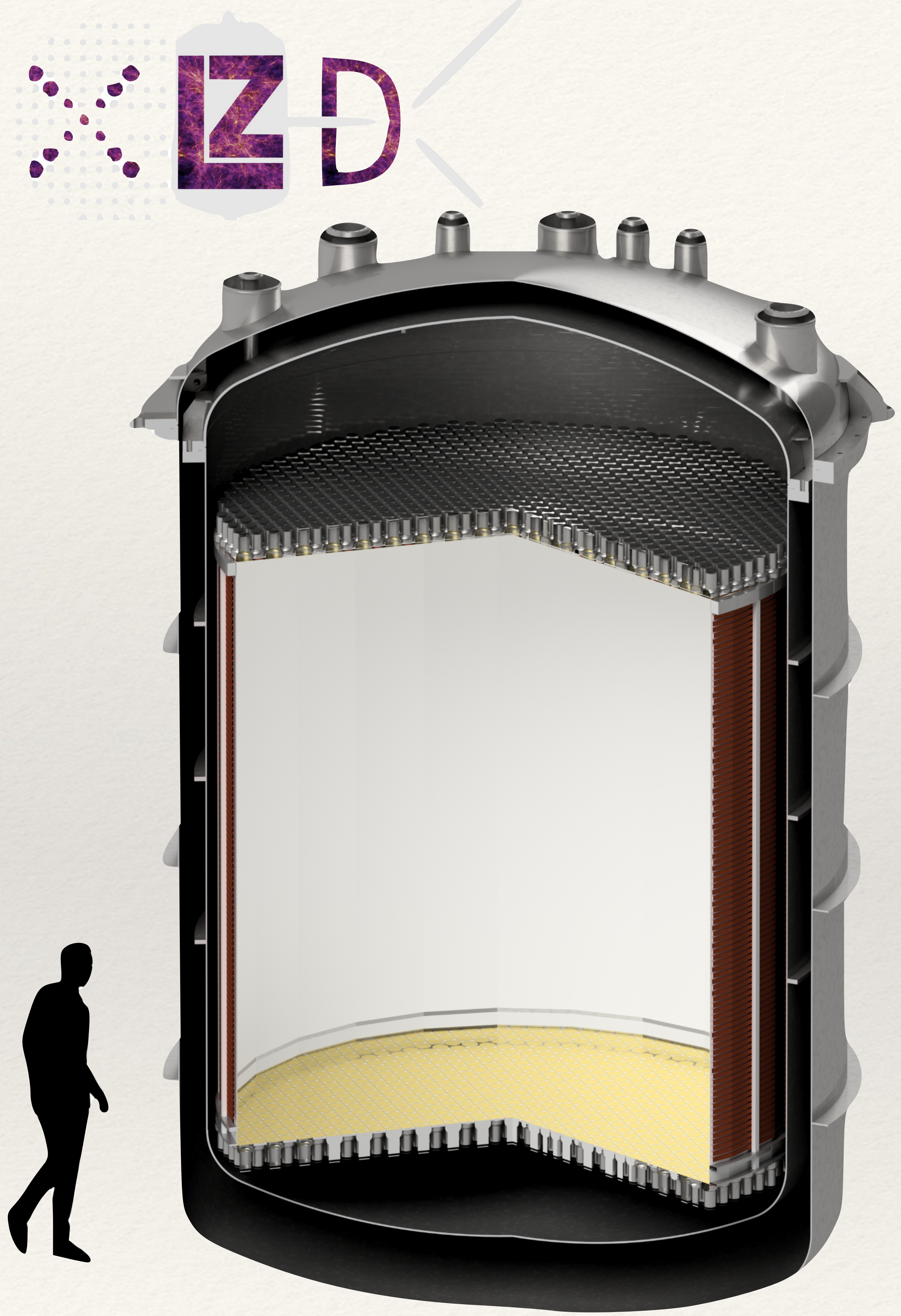
The UK has a chance to host such an experiment.
XLZD is on the faster trajectory due to operating detectors.

The UK will have significant leadership in any experiment, wherever built.

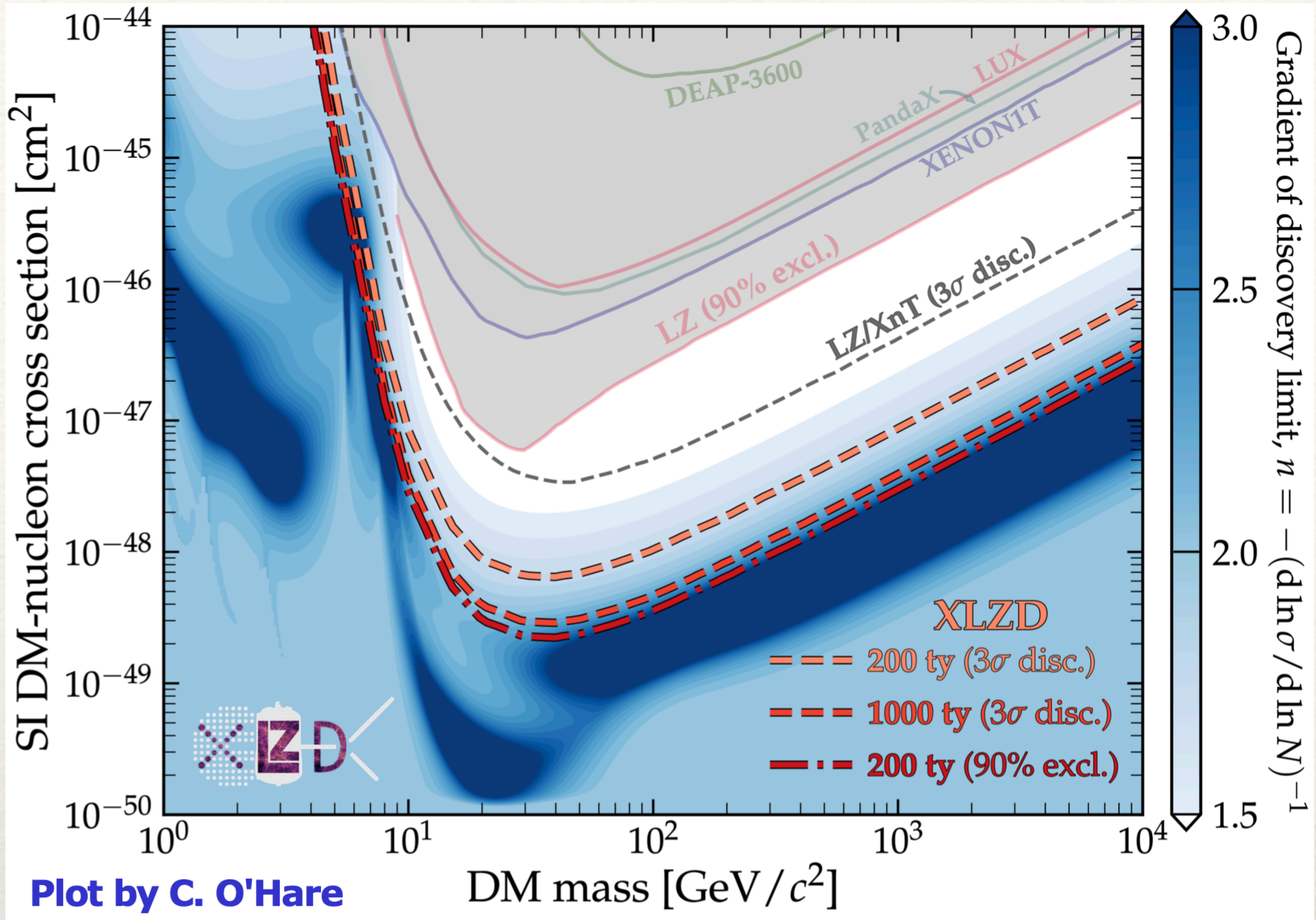
Since the Boulby Expansion and XLZD@Boulby need to seek funding from above STFC, a direct and clear Roadmap Recommendation supporting these programmes is likely necessary to pursue these projects.

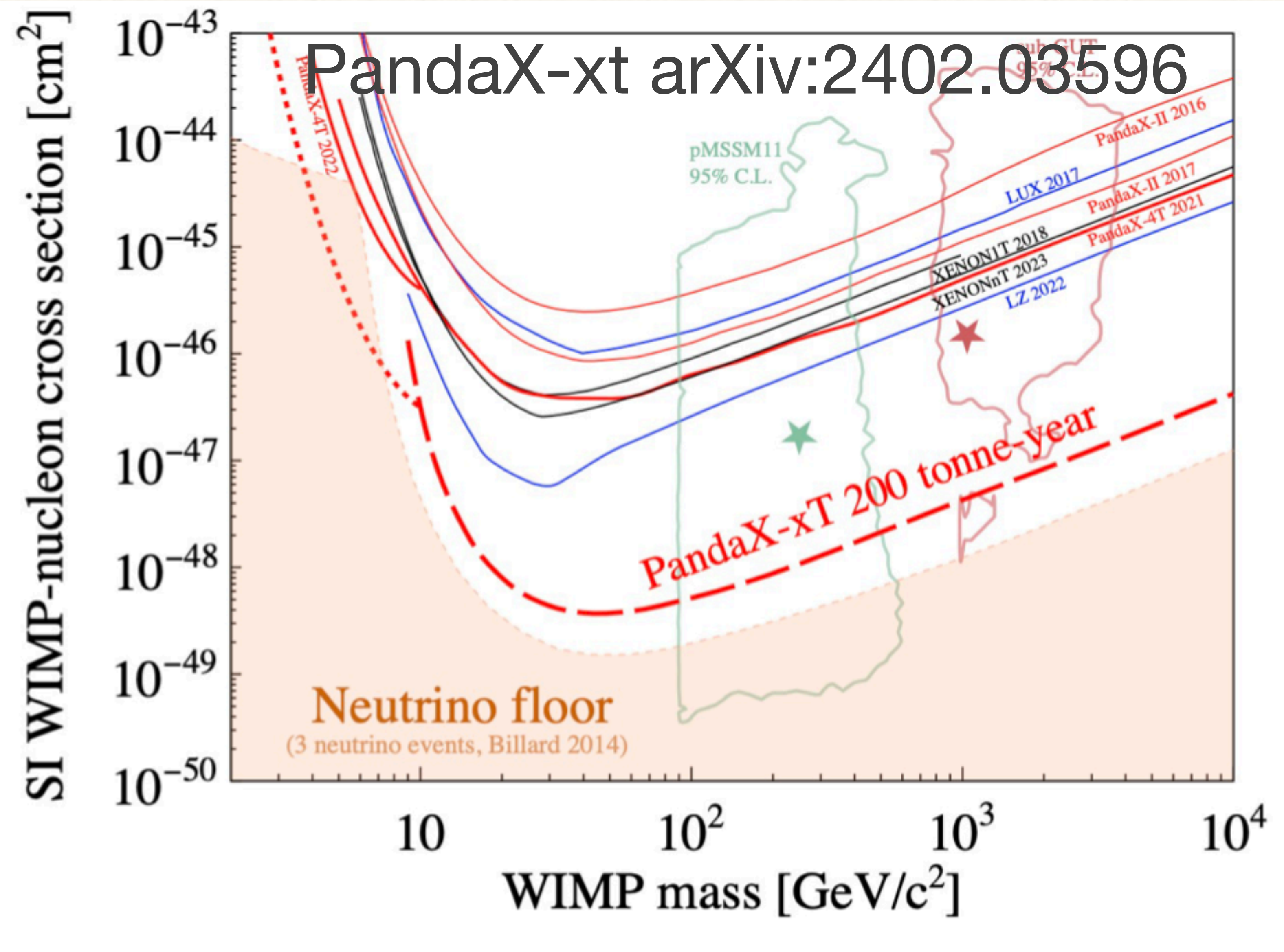
Other efforts should also be supported: should it be more project/R&D explicit, or is current wording sufficient?

Future Xenon Experiments

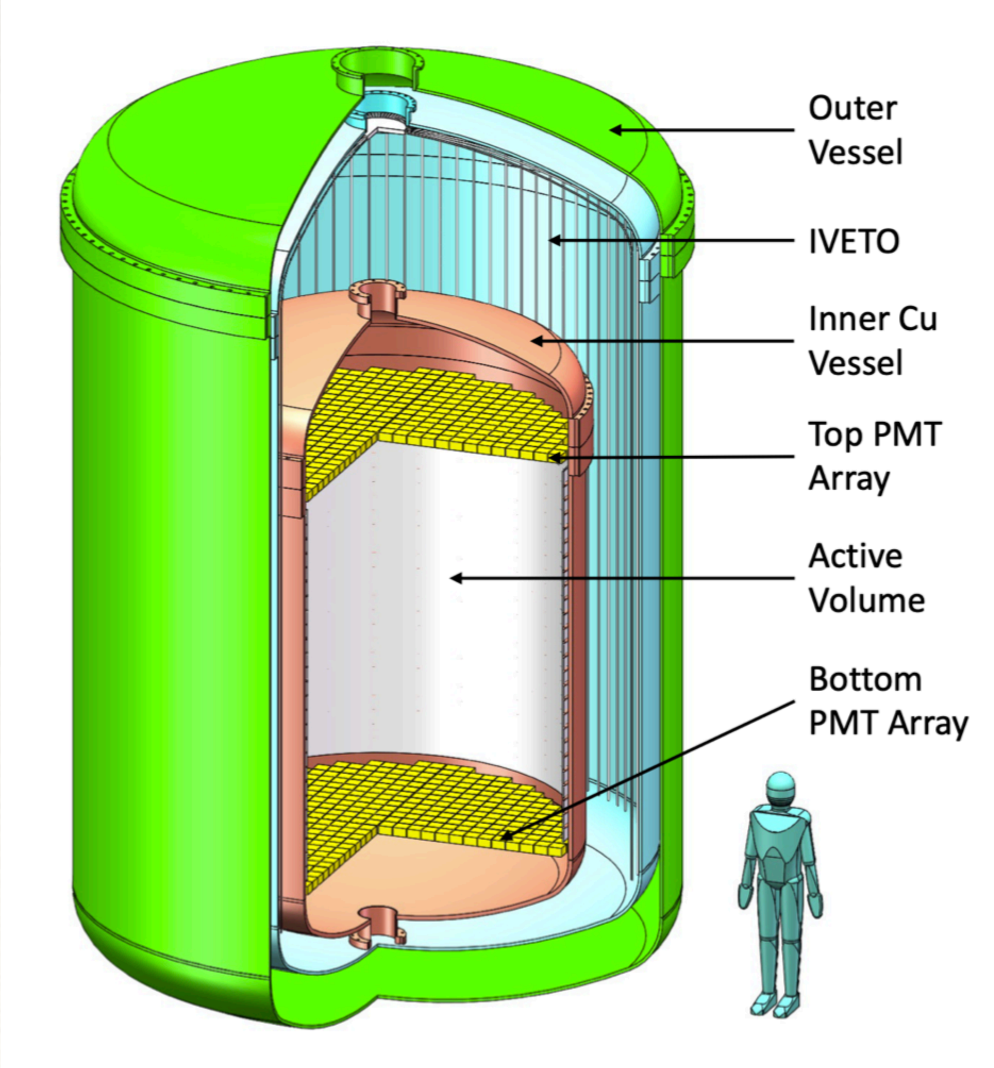


60t fiducial baseline





- XLZD: XENON, LZ (LUX-ZEPLIN), DARWIN
  - 60t fiducial baseline detector, with early science with initial xenon, starting ~2032
- PandaX-xt
  - staged growth of PandaX-4t to 43t fiducial, most infrastructure in place

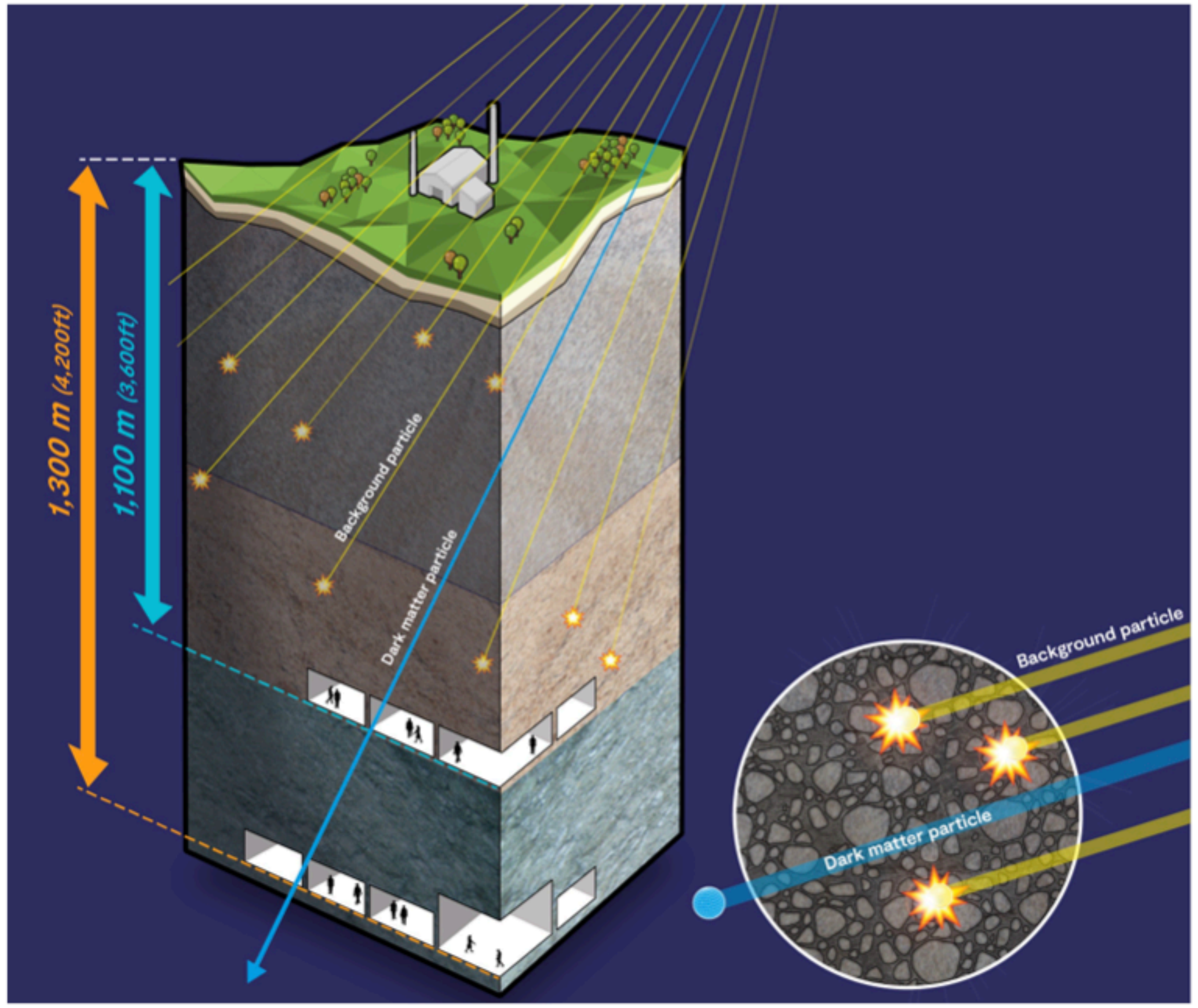


Mark Thomson's April Slide

Boulby Status

We are discussing Boulby "Dark Matter Observatory" with DSIT

- **Stage 0**: £6m for excavation at 1.1km
  - Will commence "at risk" in 2024
- **Stage 1**: ~£50m for a new Boulby Lab at 1.1km
  - Will enable essential pre-construction work for e.g. XLZD
- **Stage 2:** ~£500m for new large experimentation lab at 1.3km plus UK's share of an international project e.g. XLZD



This is ambitious and we are at an early stage, but without ambition…

Science and Technology Facilities Council

XLZD@Boulby Programme

We are proposing to host XLZD in a major new underground laboratory at Boulby.

Nominal infrastructure plan entails a faster Stage 1 facility at 1,100 m (manufacture) and a larger Stage 2 facility at 1,300 m (installation) – STFC is committed to this plan.

Two-stage approach offers a competitive timeline and de-risks XLZD schedule.

We can enable, potentially:

- A larger experiment (up to 80 tonnes of active mass)
- A faster schedule (2032 start of operations)
- Installed in a purpose-designed laboratory

Other underground laboratories are competing to host XLZD; we are making the case that "XLZD will be better in the UK"

XLZD preliminary costs and timeline

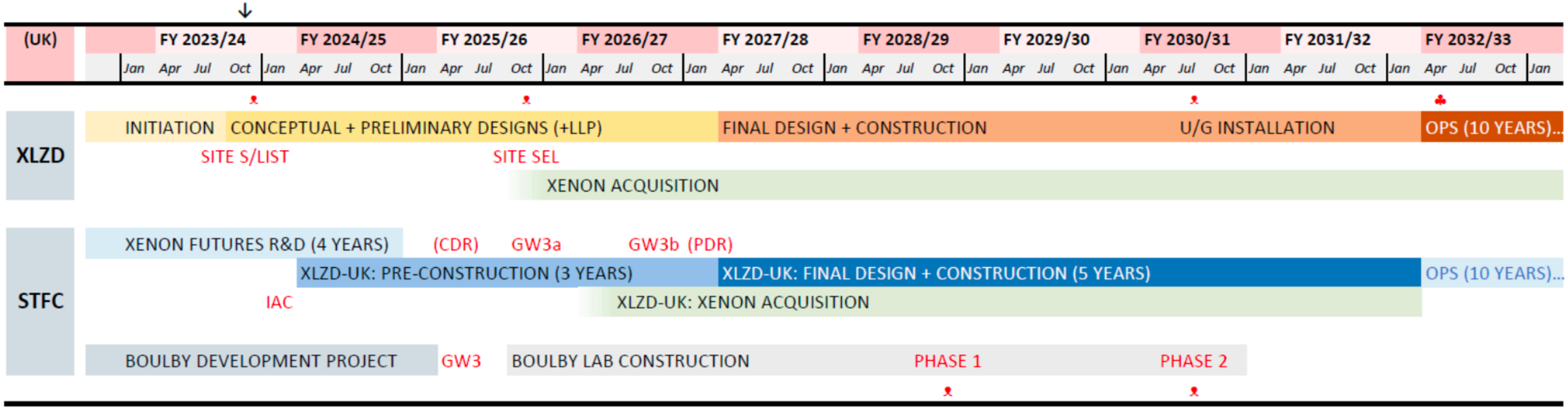
1. A major new underground facility – Boulby Development Project, ongoing

2. One-third of XLZD project cost – UKRI Preliminary Activity will set us off on this road

Combined package of ~500M being discussed with STFC, UKRI and DSIT

XLZD-UK

- **Pre-Construction project** (design): 3.5 years from July 2024; ~£8M
- **Construction project**: 5+ years from 2027; process is coupled to site selection



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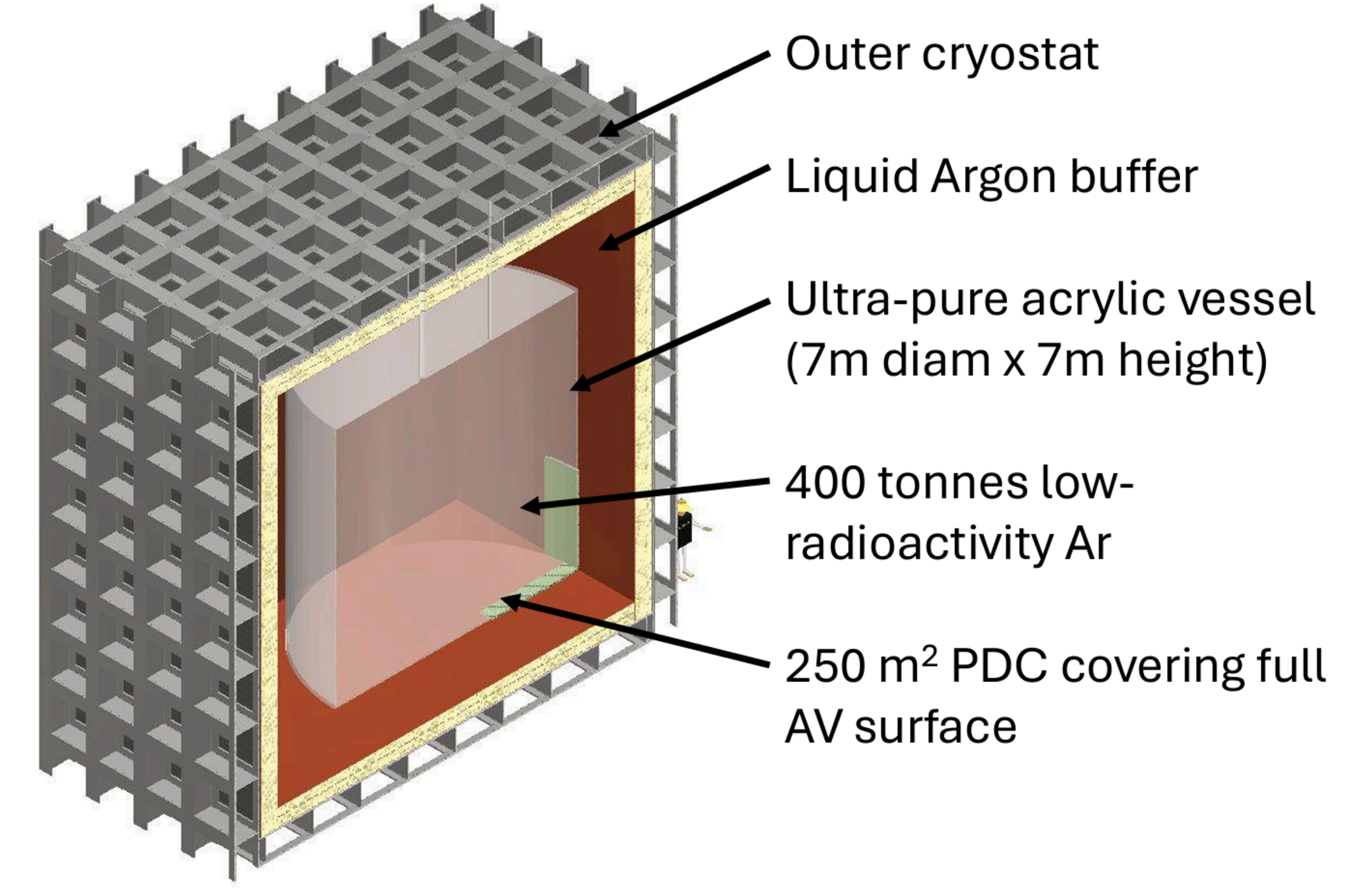
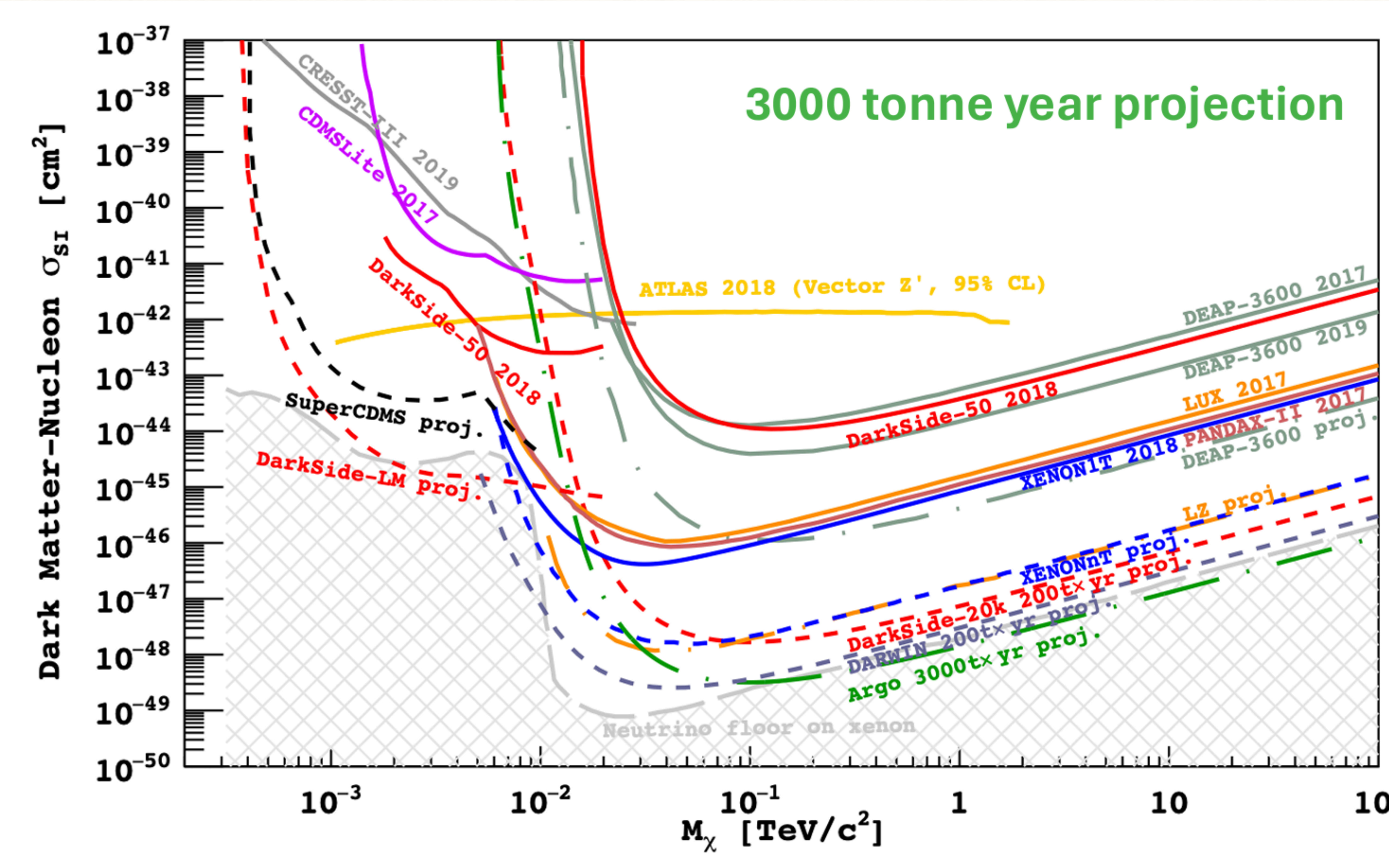
Future Argon Experiment





- Site TBD (but Canadian push to SNOLAB)
- Single phase detector vs Dual phase TPC being studied
- DEAP-3600 location for R&D while DarkSide-20K is operating
- Cold electronics for SiPMs to be Photon to Digital Converters (PDCs)

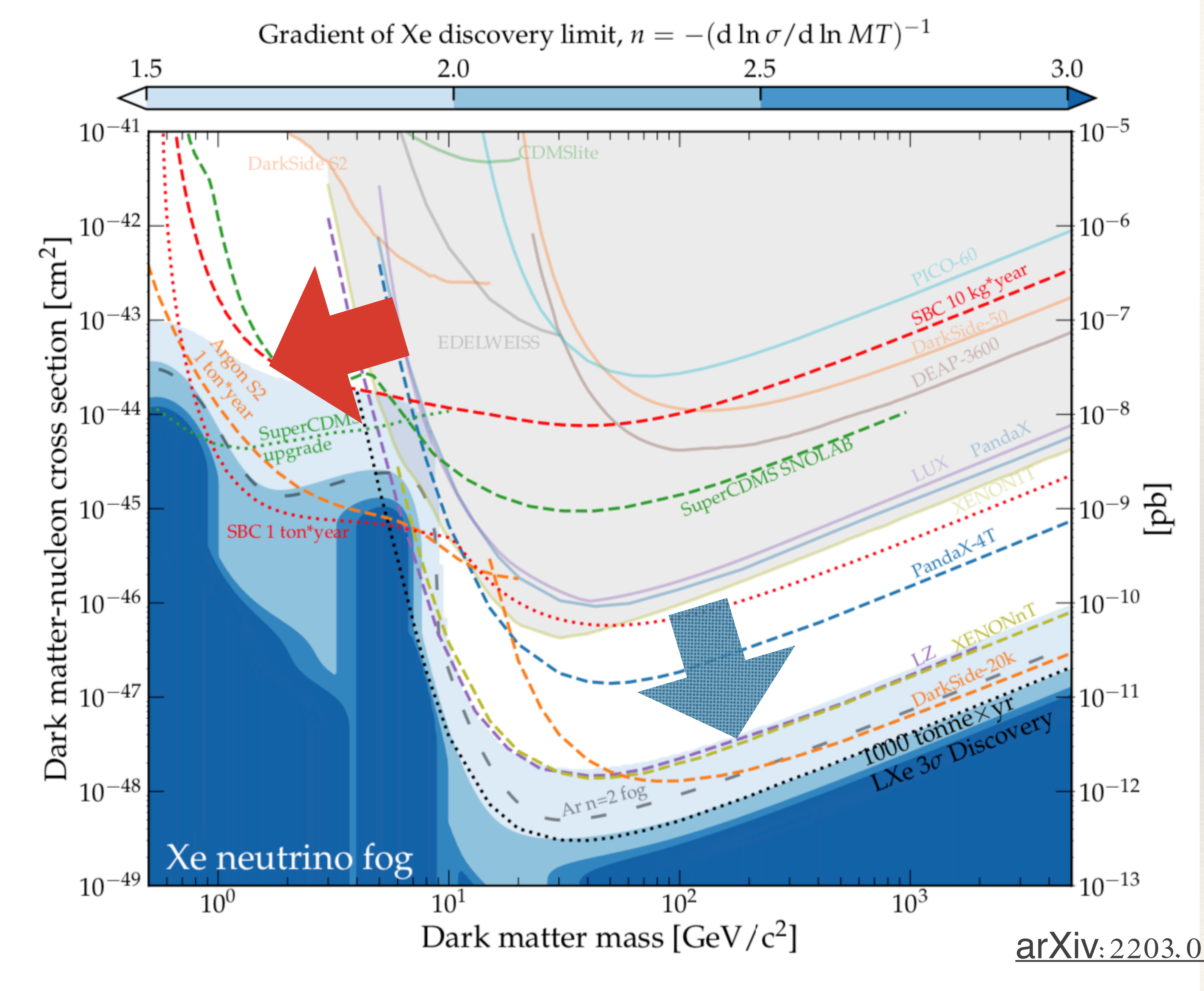
Jillings talk at CAP May 2024

For DM masses 1-10 GeV/c^2,
there is a lot of activity!
Timing may be more important than “best” technology.

Can/will the UK host an experiment in the near future at Boulby?
How do we support potential experiments that could be hosted in the Boulby Phase 1 Expansion space?

Will we participate in any internationally sited collaborations?

Going to Lower Masses



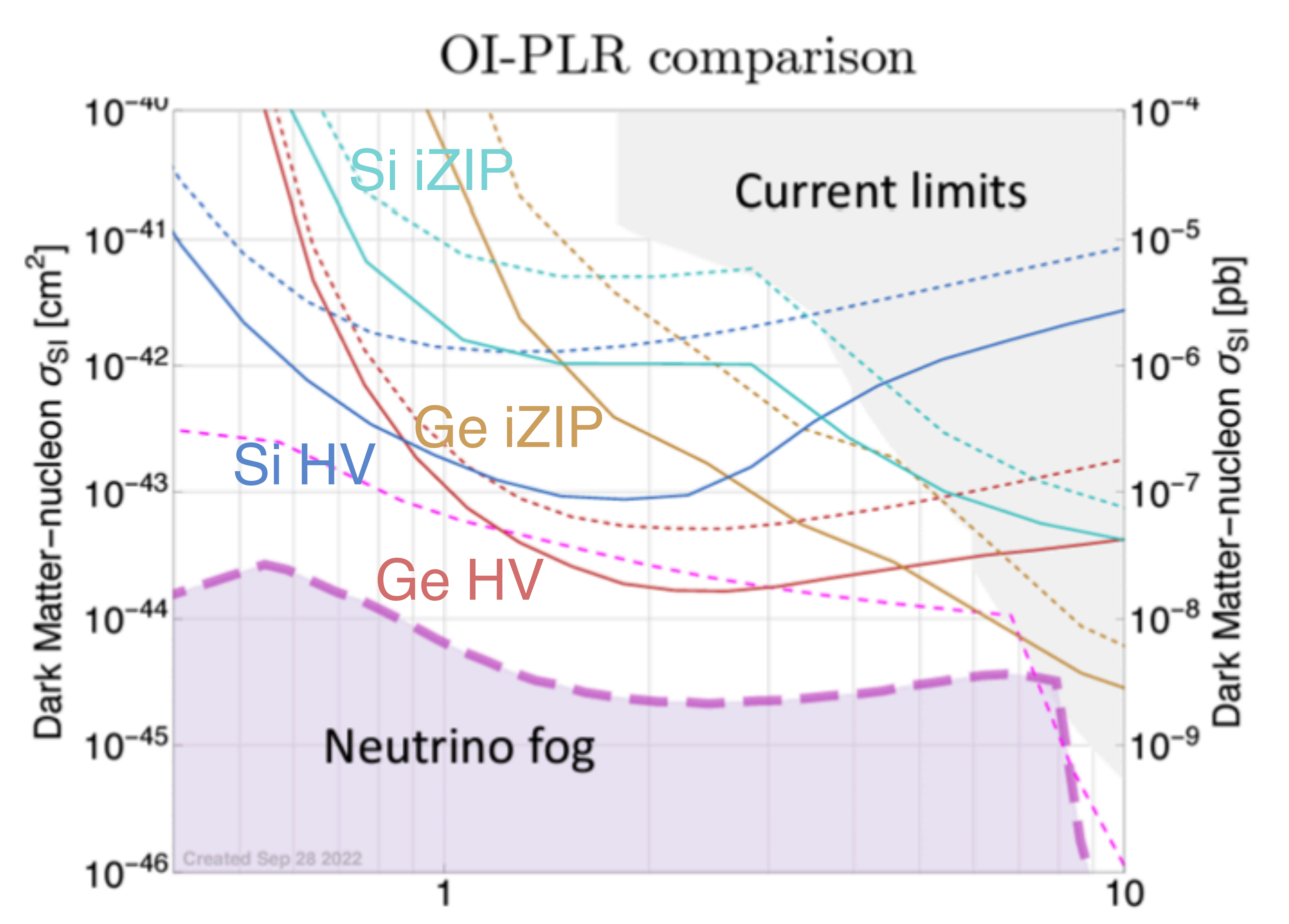
arXiv: 2203.08084

- Lower mass region can be reached by multiple technologies, ones with long histories in the search for dark matter, as well as new.
- Generally smaller target masses (both in total mass, as well as atomic masses), and interest in spin-dependent models too.
- Proposals are in to STFC for Boulby-hosted options, so here I'll talk about international competition or generic techniques.

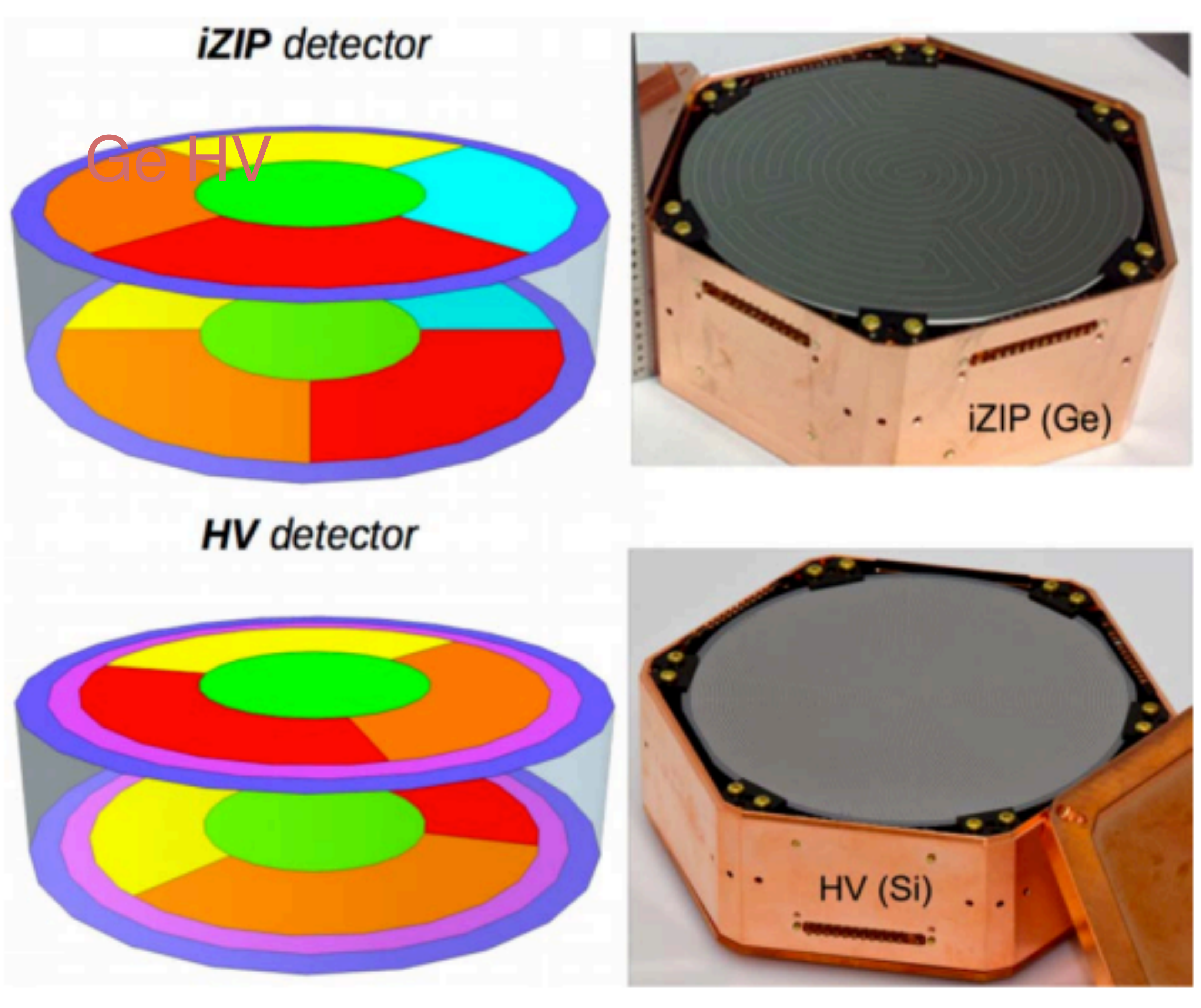
SuperCDMS SNOLAB

- Under construction at SNOLAB, data taking expected end of 2025
- 4 towers: 1 Ge iZIP, 1 Ge & Si iZIP, 2 Ge &Si HV
- Programme, including new detectors and upgrades discussed at arXiv:2203.08463

	Germanium	Silicon
HV	Lowest threshold for low mass DM Larger exposure, no ^{32}Si bkgd	Lowest threshold for low mass DM Sensitive to lowest DM masses
iZIP	Nuclear Recoil Discrimination Understand Ge Backgrounds	Nuclear Recoil Discrimination Understand Si Backgrounds



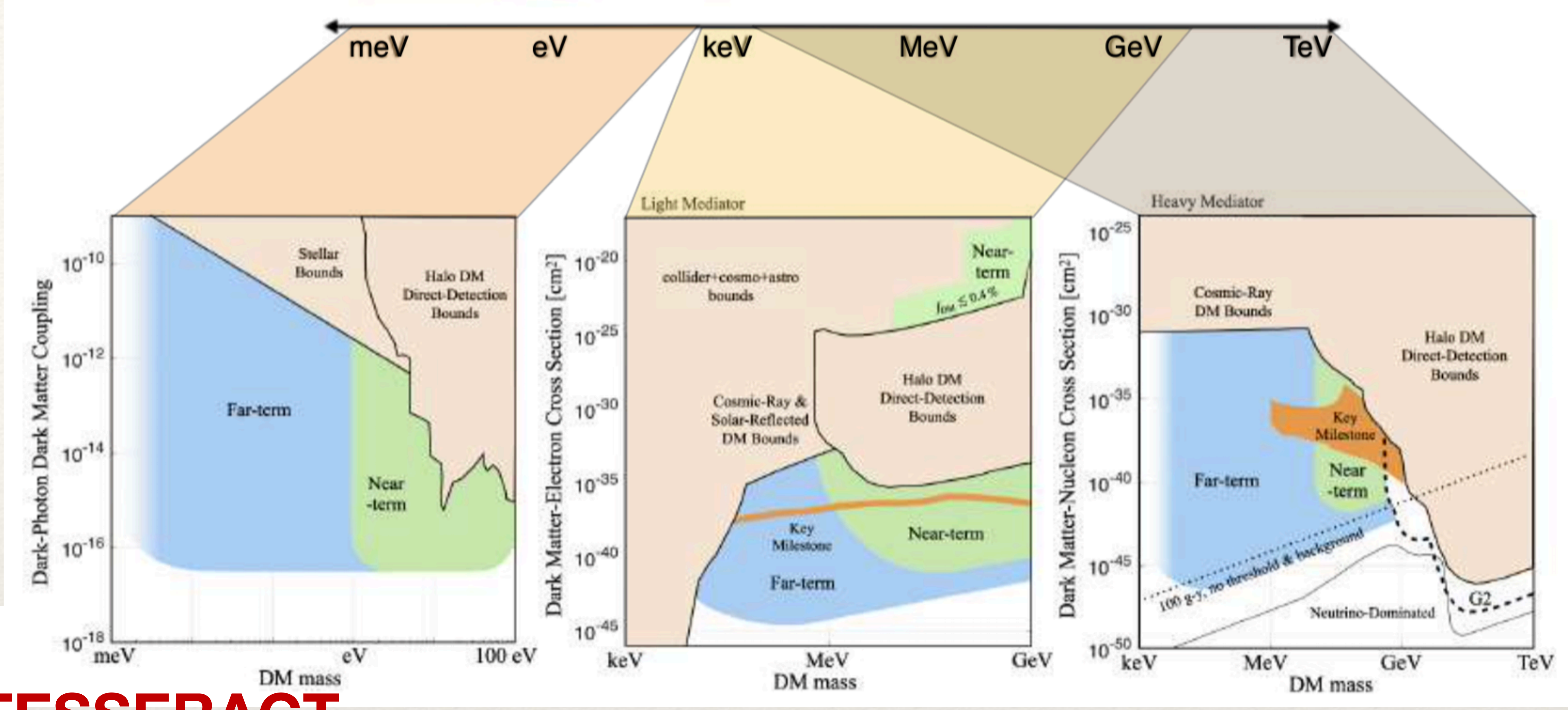
arXiv:2203.08463

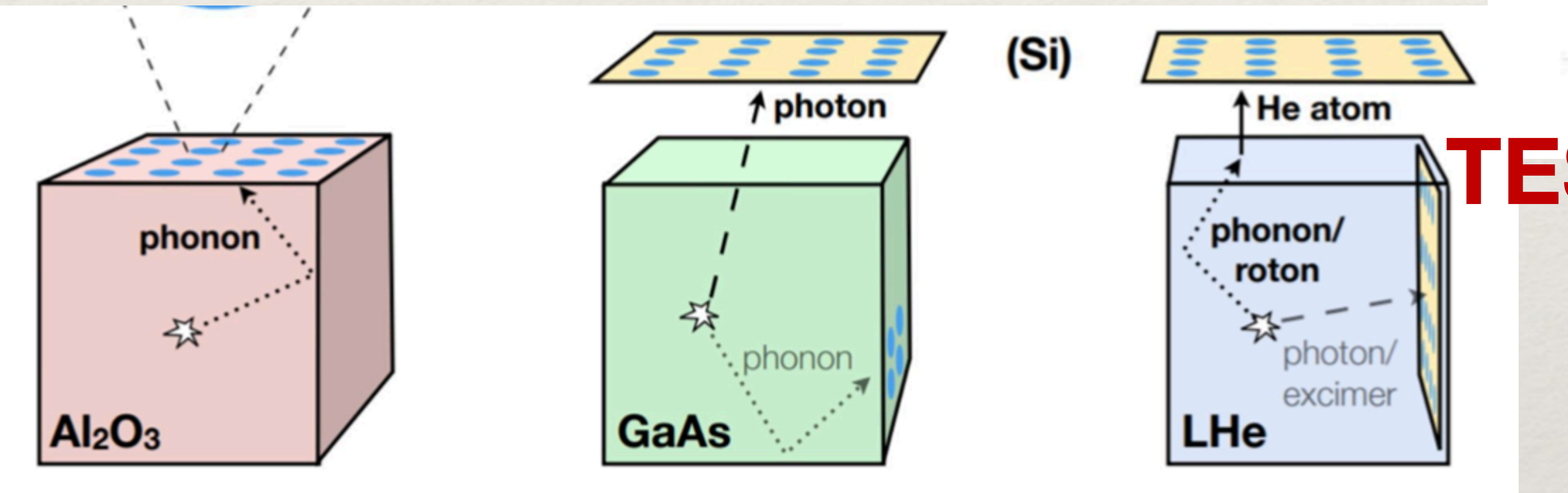


Other Low mass Searches

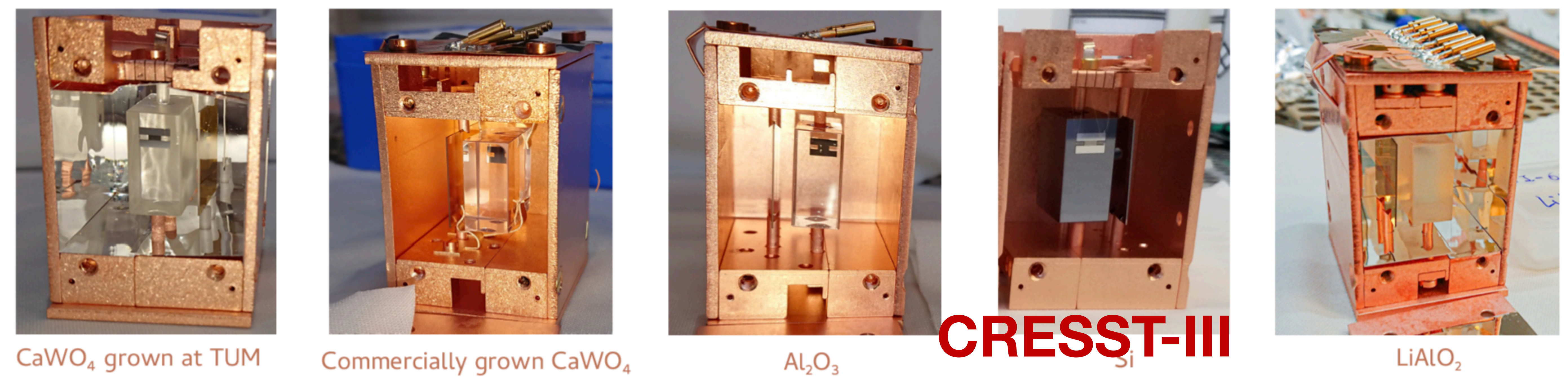
- TESSERACT, with significant investment and hosting from the French will go forward in the next year (US origination)

- Other projects use targets from the past with lower thresholds/more mass
  - Si
  - Ge
  - CaWO4
  - AL2O3
  - Ar
  - CH4
  - He
  - GaAs

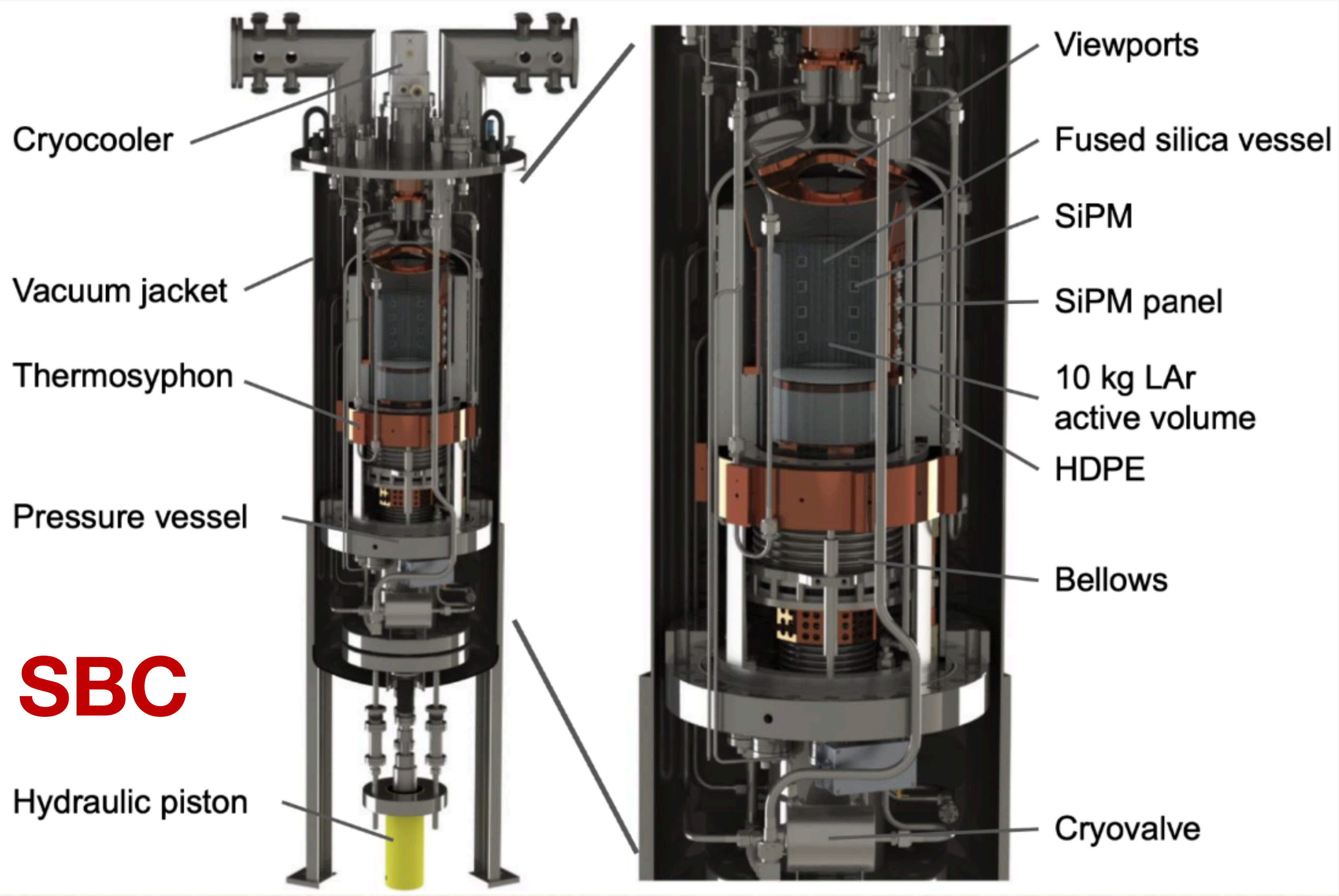




TESSERACT



CRESST-III

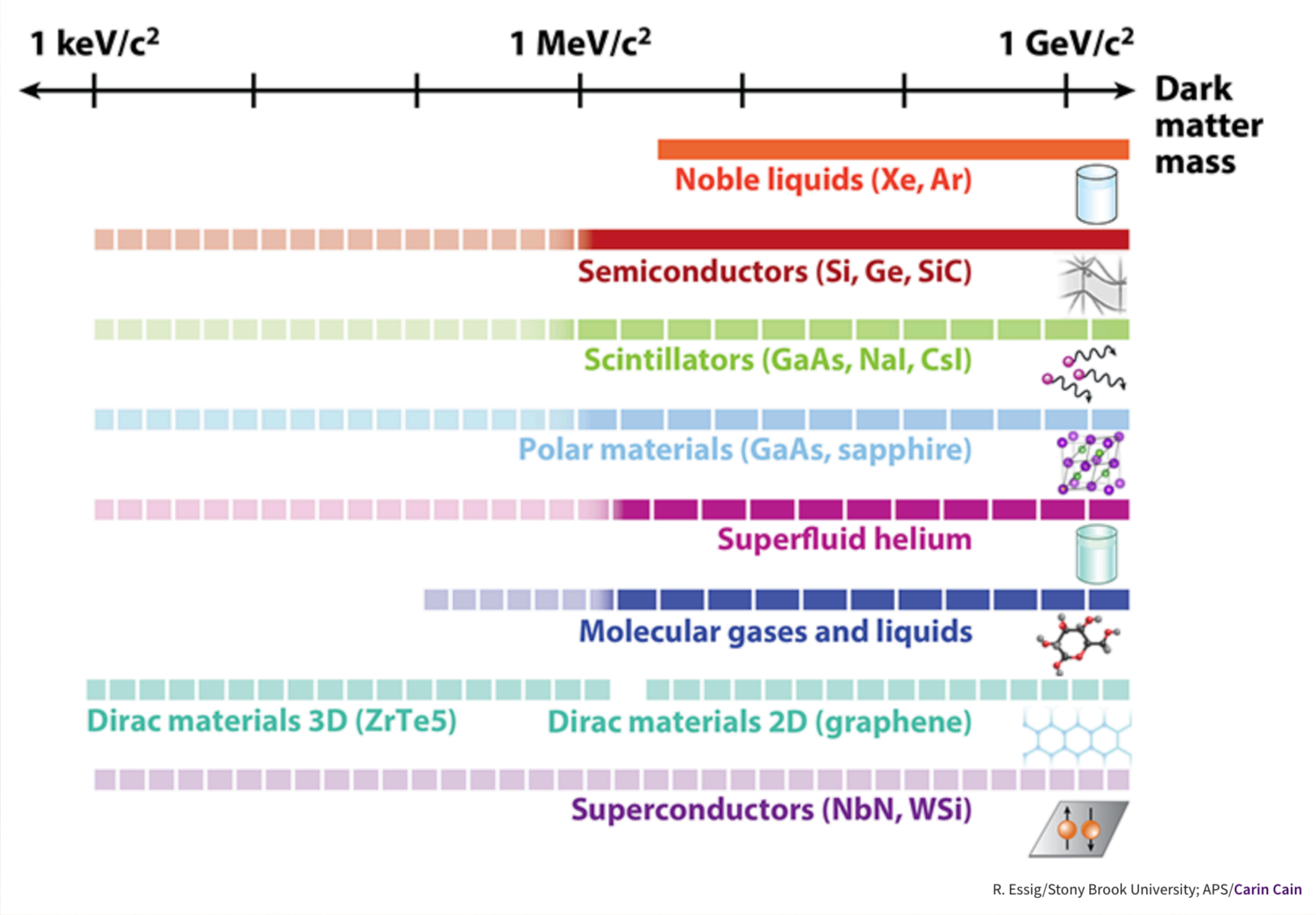


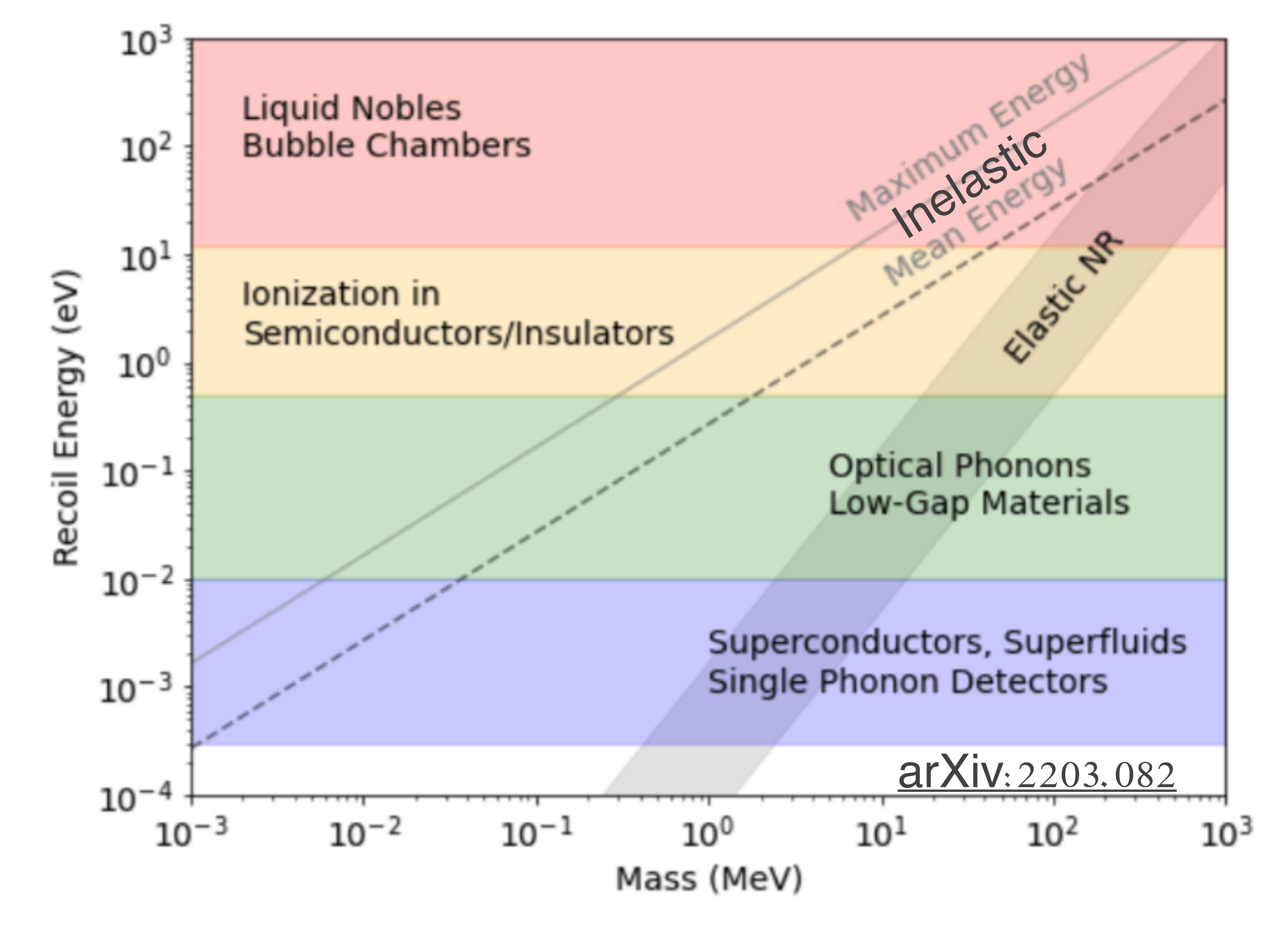
SBC

For DM masses <1 GeV/c^2,
gram scale detectors can produce leading results.
Lots of new ideas, many exploiting quantum technologies.
There are many unknowns.

Will the UK engage/lead/develop more of these options following the Boulby call? Will this be limited to QTFP?

Below a GeV: technologies

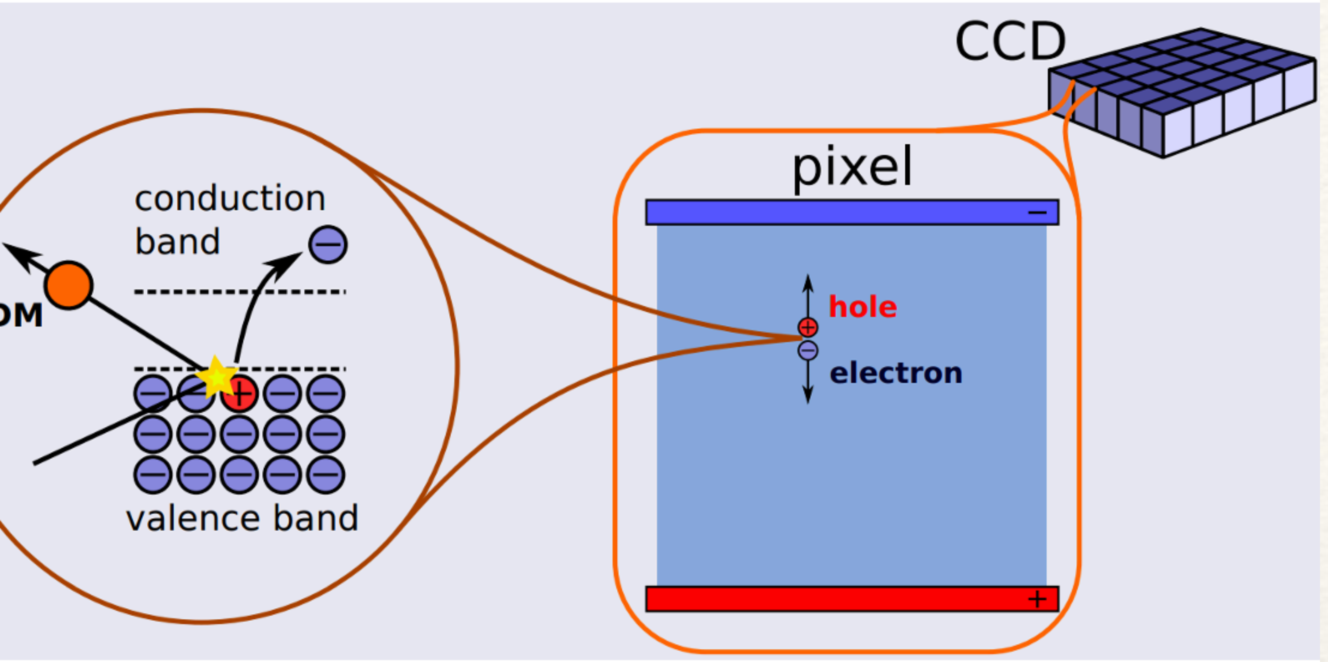


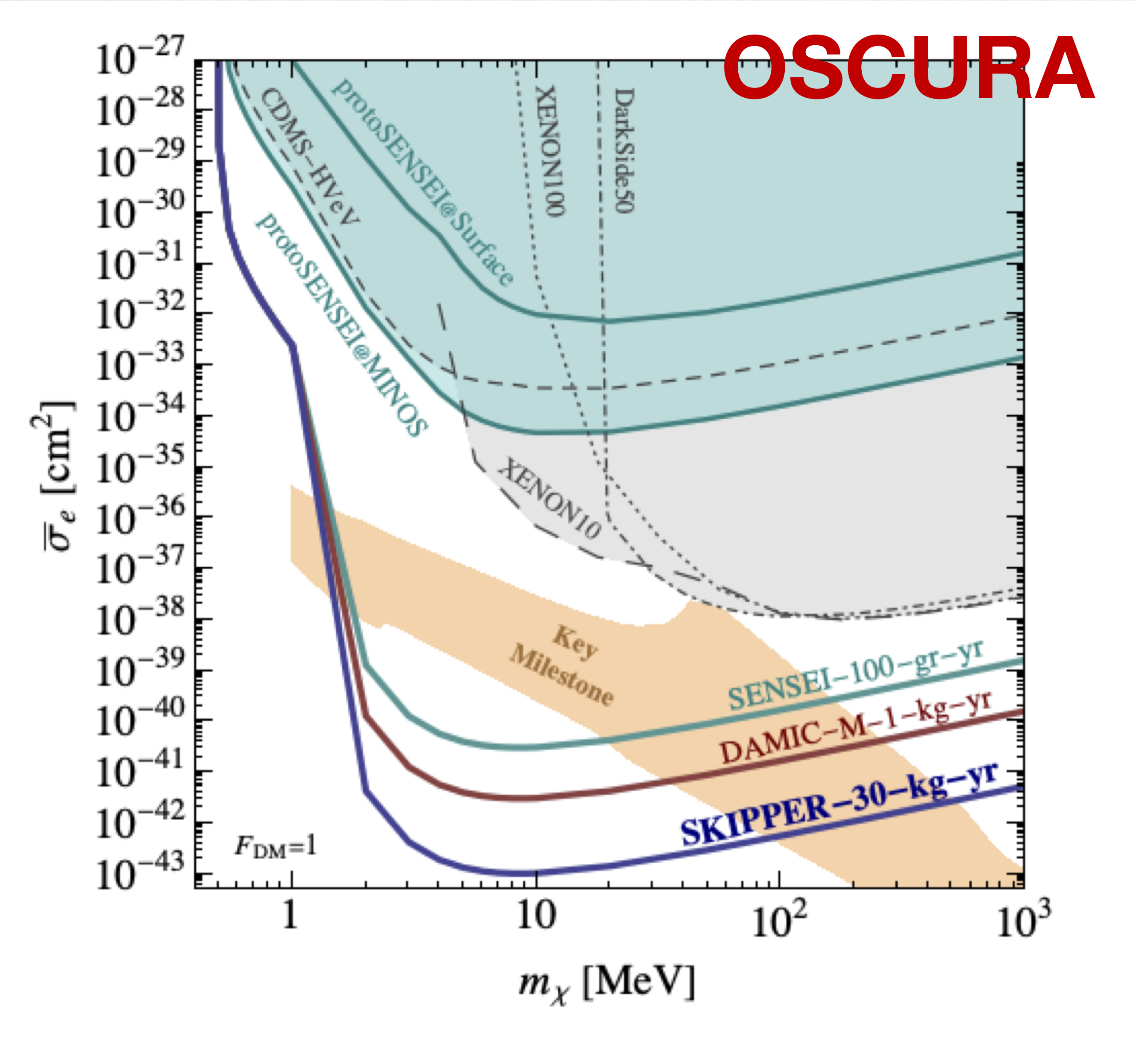


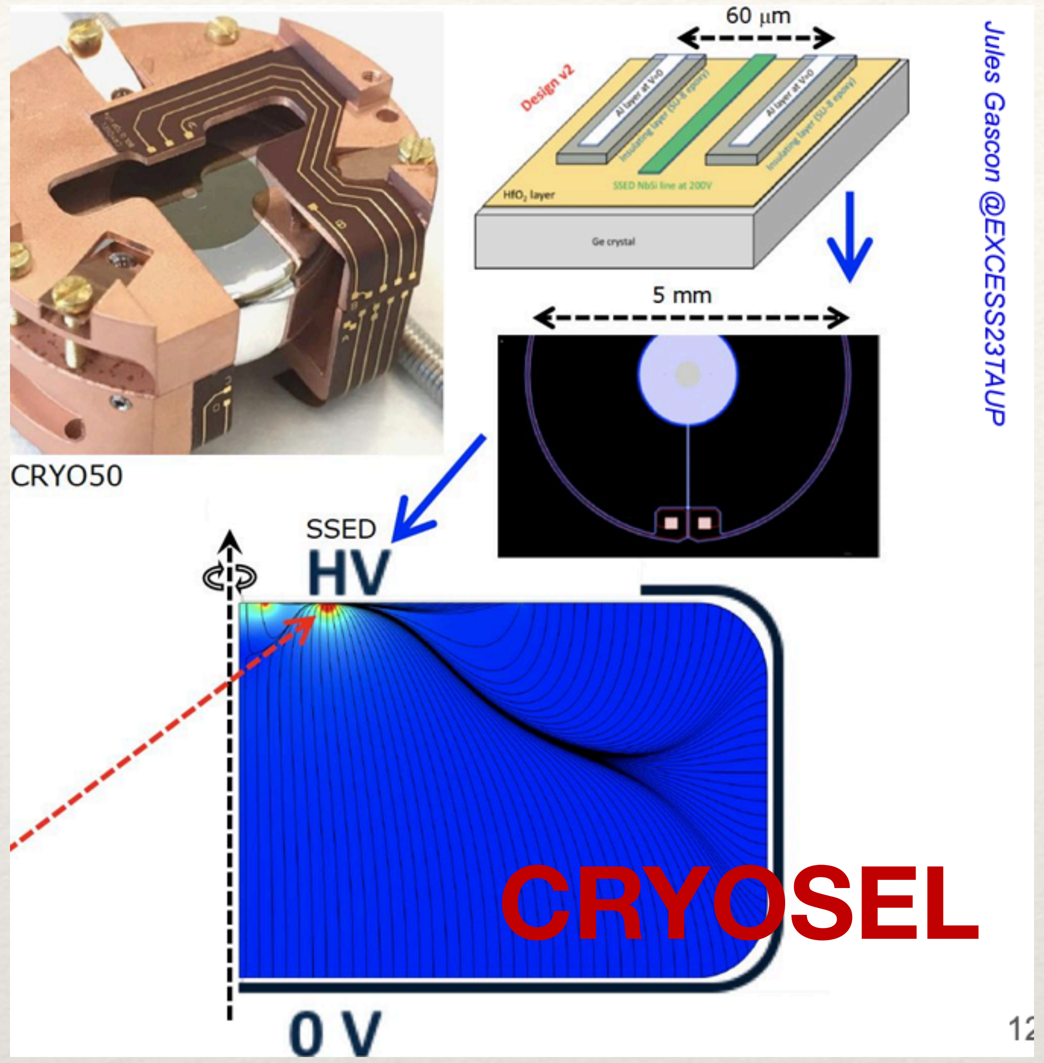
DM–electron scattering and absorption now of interest

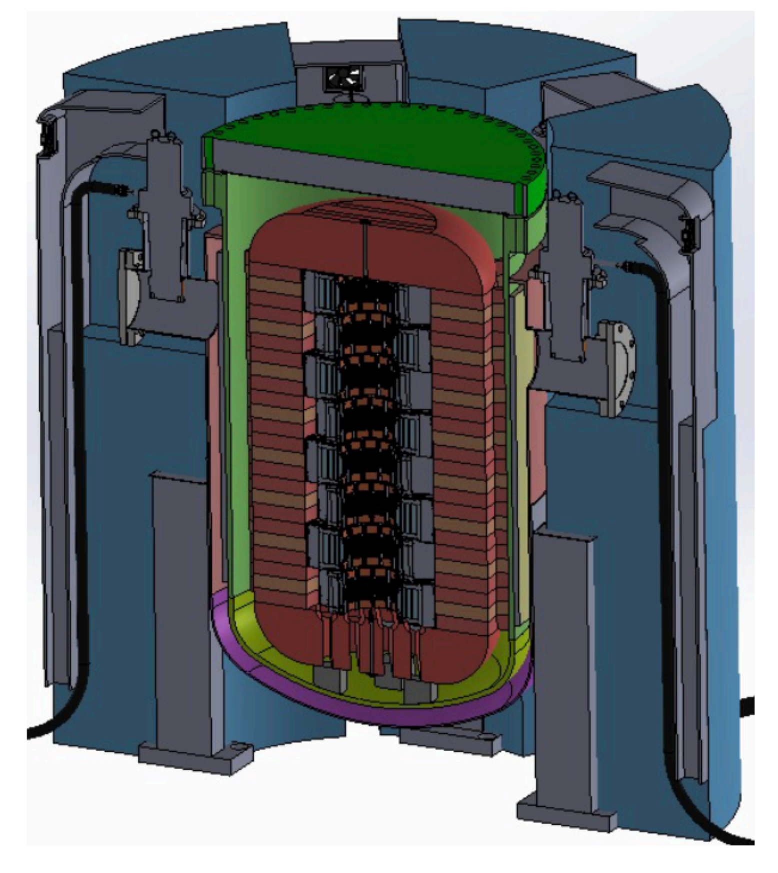
So many new detectors…

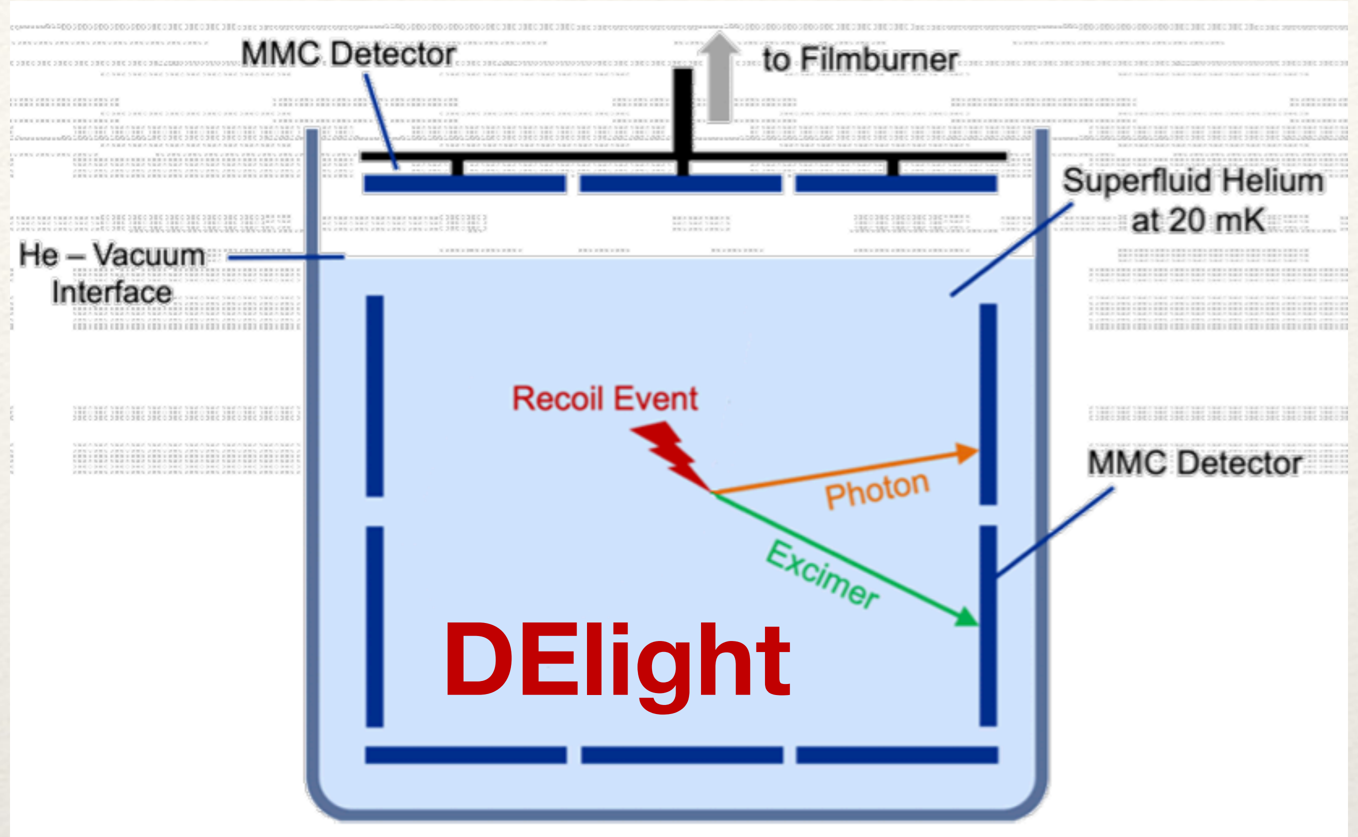
so many ~~hot~~ cold technologies: SNSPDs, TESs, KIDs, MMCs, superfluid He, superconducting QUBITs …

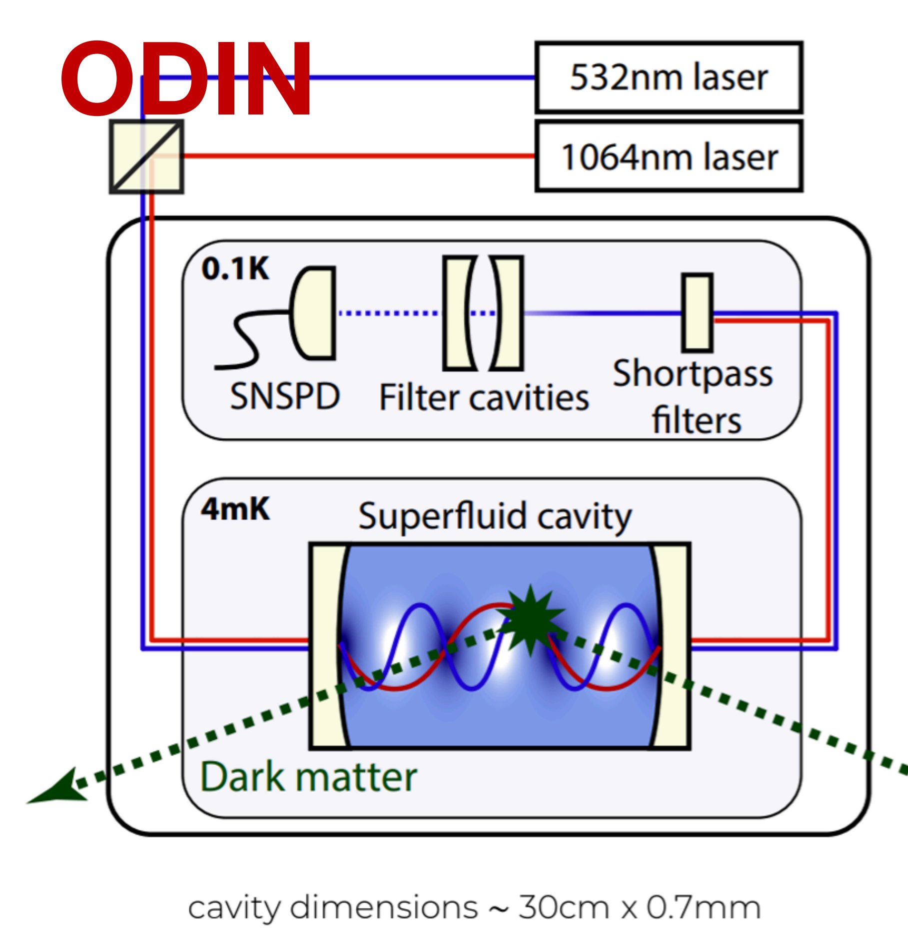


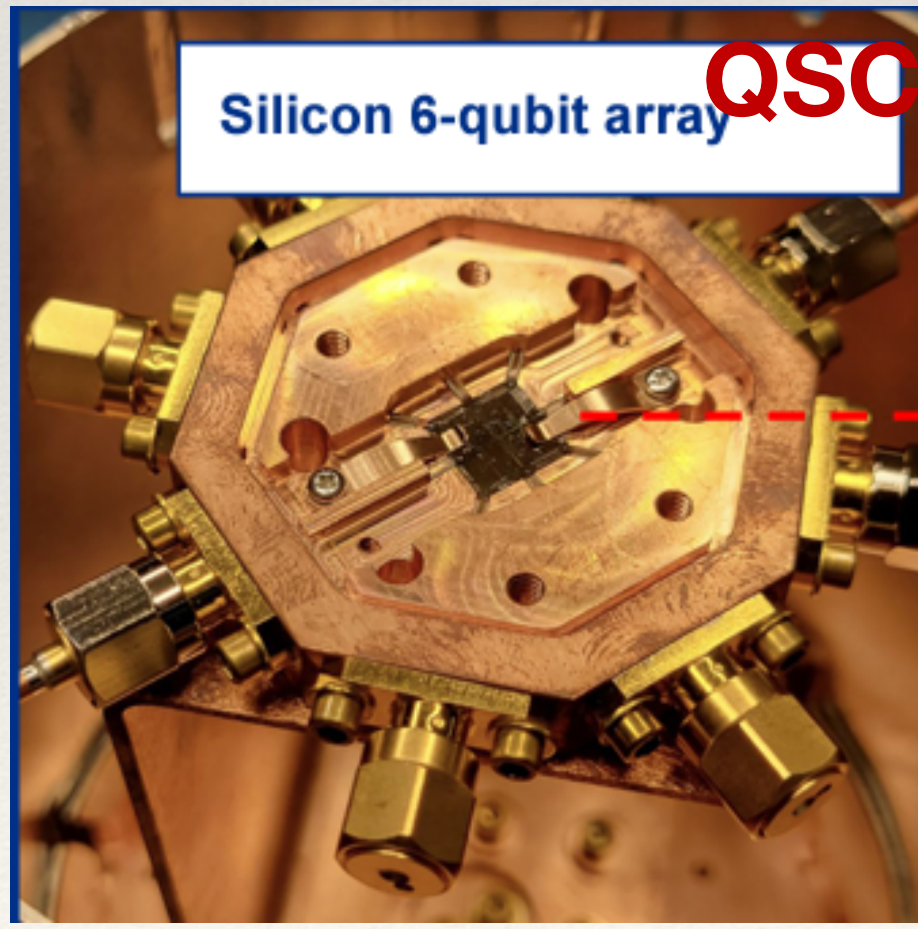




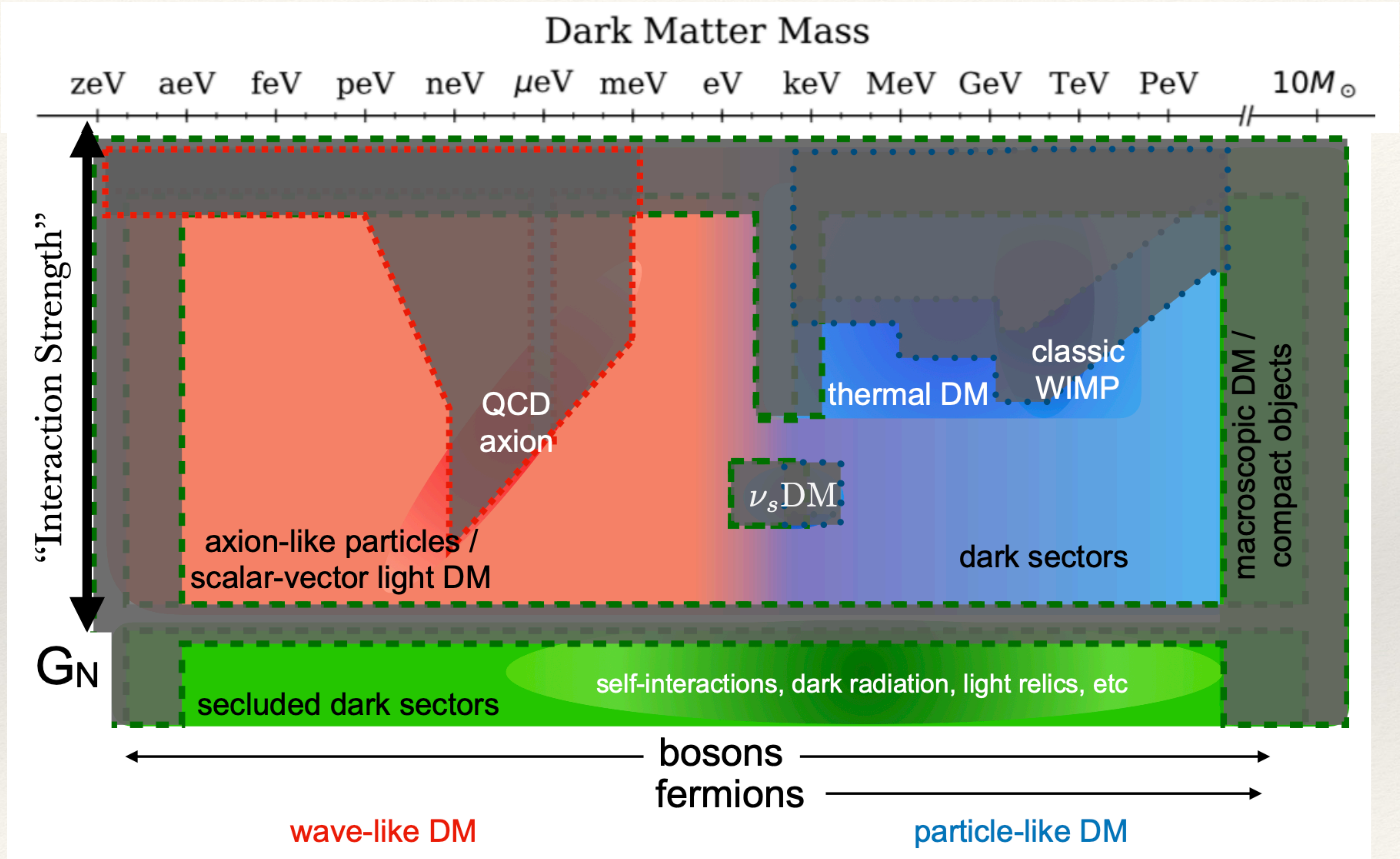








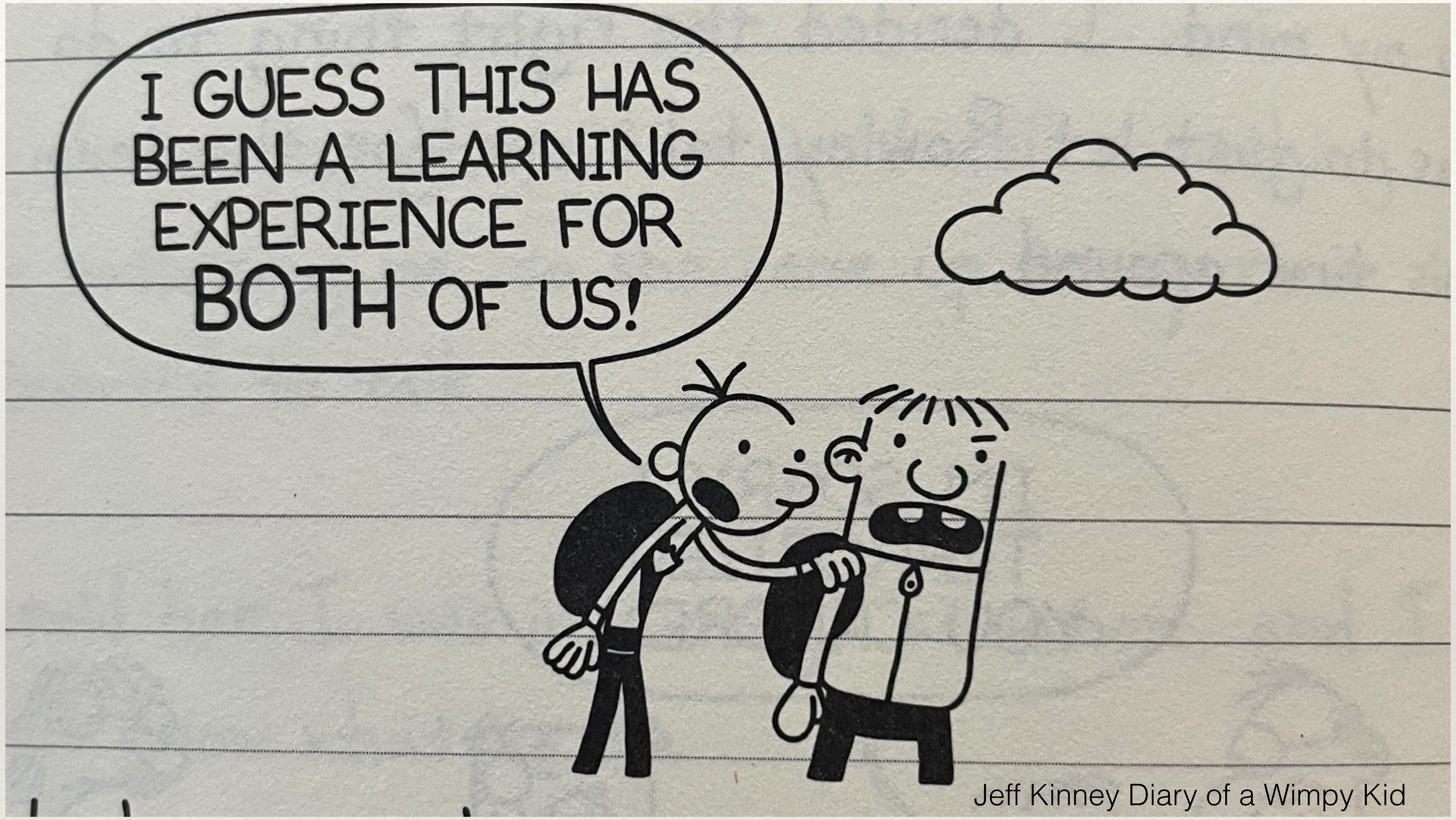
If we Search Deep and Wide, in 20 years



A Chou, SNOWMASS Dark Matter Plenary

I hope there is a dark sector with **many** interesting new particles, which solve current mysteries and open new ones.

Backup Slides



Jeff Kinney Diary of a Wimpy Kid

US DOE Response to P5 (Procario Update at DPF)

G3 Dark Matter

- From P5 Recommendation 2, Priority 4 out of 5 :
  - An **ultimate Generation 3 (G3) dark matter** direct detection experiment reaching the neutrino fog, in coordination with international partners and **preferably sited in the US**.
- DOE response and actions:
  - At the present time, based on the Snowmass Community Summer Study, there have been two proposals for G3 Dark Matter detectors : XLZD and ARGO
  - P5 recommended a **domestic site for the experiment in the higher funding scenario** and an international site in the lower funding scenario.
  - Start with site independent R&D as we understand the funding that will be available.
    - Engage with partners who are interested in hosting.
  - DOE will entertain proposals by U.S. groups for pre-project R&D.

Recommendation 3

- Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.
  - Implement a **new small-project portfolio at DOE**, Advancing Science and Technology through Agile Experiments (ASTAE), across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

- DOE response and actions:
  - DOE will initiate fabrication of 1-3 DMNI projects
    - 5 projects remain under consideration
  - The key word for new projects is AGILE.
- P5's call for agile implies that we should complete these experiments quickly, and shift course when it comes time to start new ones.
  - 2 years for R&D, 2-3 for fabrication, 2-3 to operate, and then decommission.
    - This is still 6-8 years.
  - Start a new projects fabrication every year.

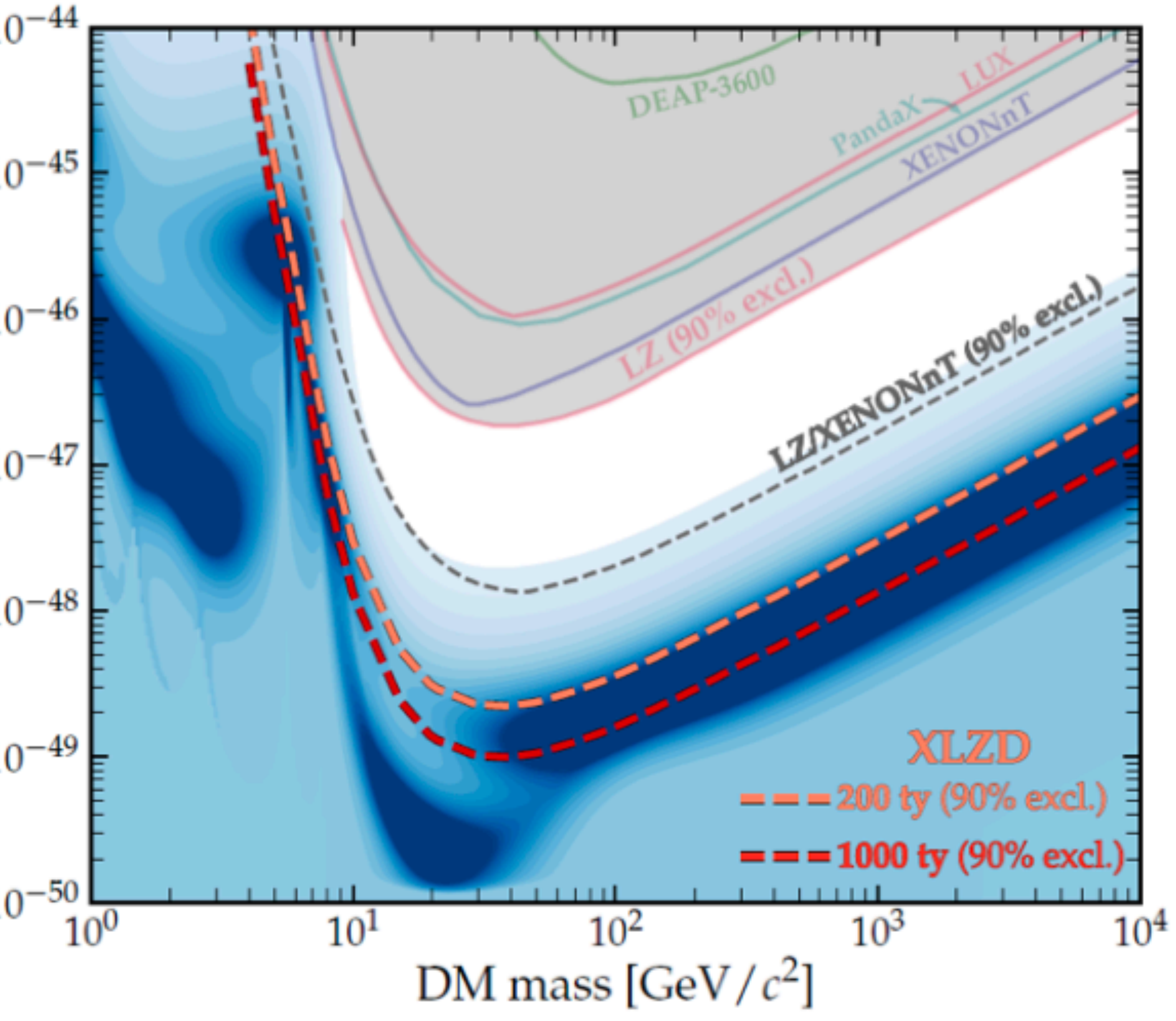
Strategic Review of PP Recommendations

72. STFC should also encourage the development of an exciting programme of non-collider physics at CERN and elsewhere to give continuity in physics exploitation.
73. The UK should have an R&D portfolio that contains elements that are generic, i.e. not specialised to a specific project proposal while aligning with the European technology roadmaps. It should also include targeted involvement in feasibility studies for new projects at modest cost. The UK should invest in research projects in sustainable energy usage, e.g. in accelerator R&D. The portfolio should have both low- and high-risk elements.
74. STFC should encourage government bodies to develop a coherent plan to attract a major international research infrastructure to the UK, preferably in particle physics.

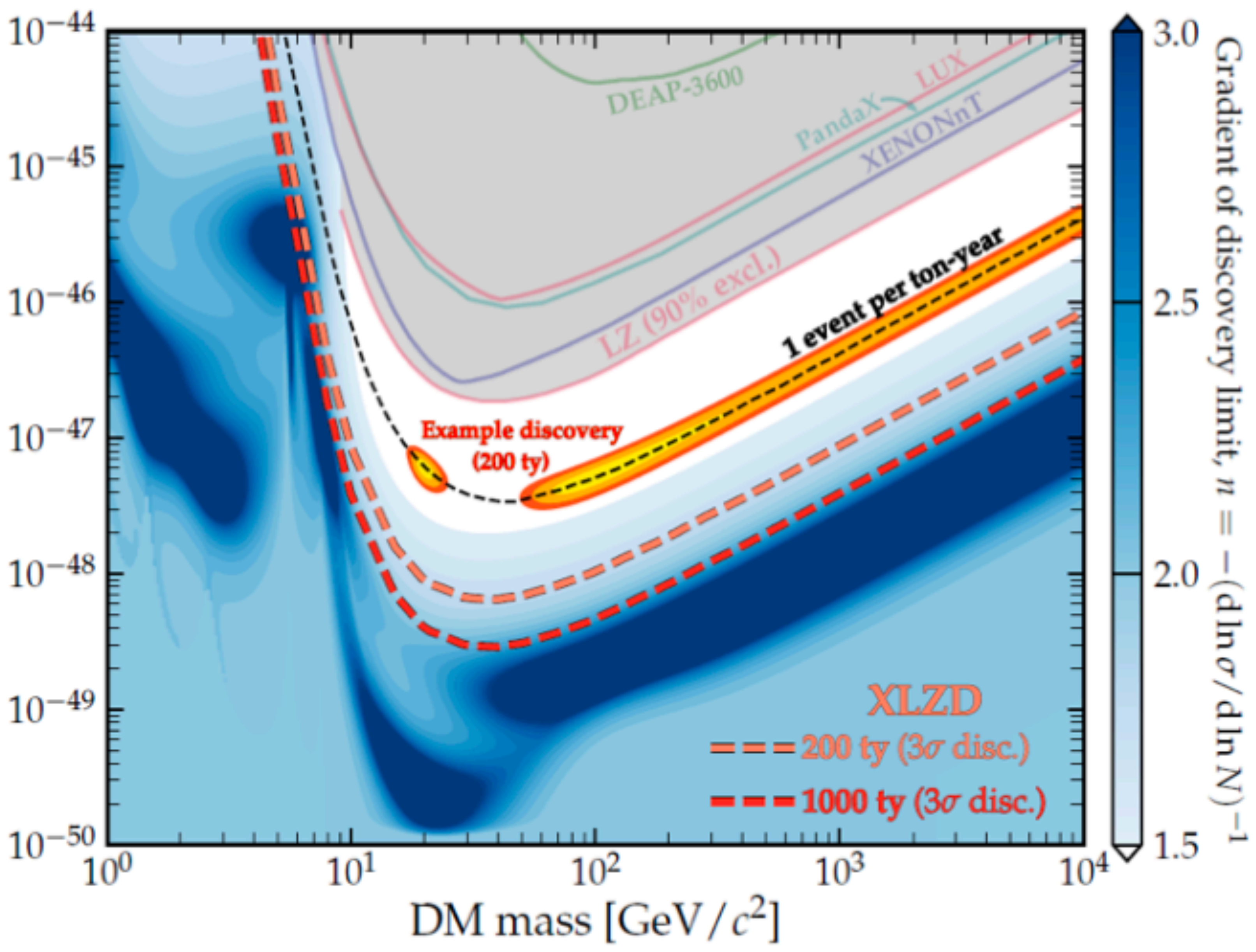
88. The current funding 'silo' for Particle Astrophysics should end and those projects defined as being predominantly particle-physics related should be evaluated and funded within the particle-physics structures.

XLZD Projected Reach

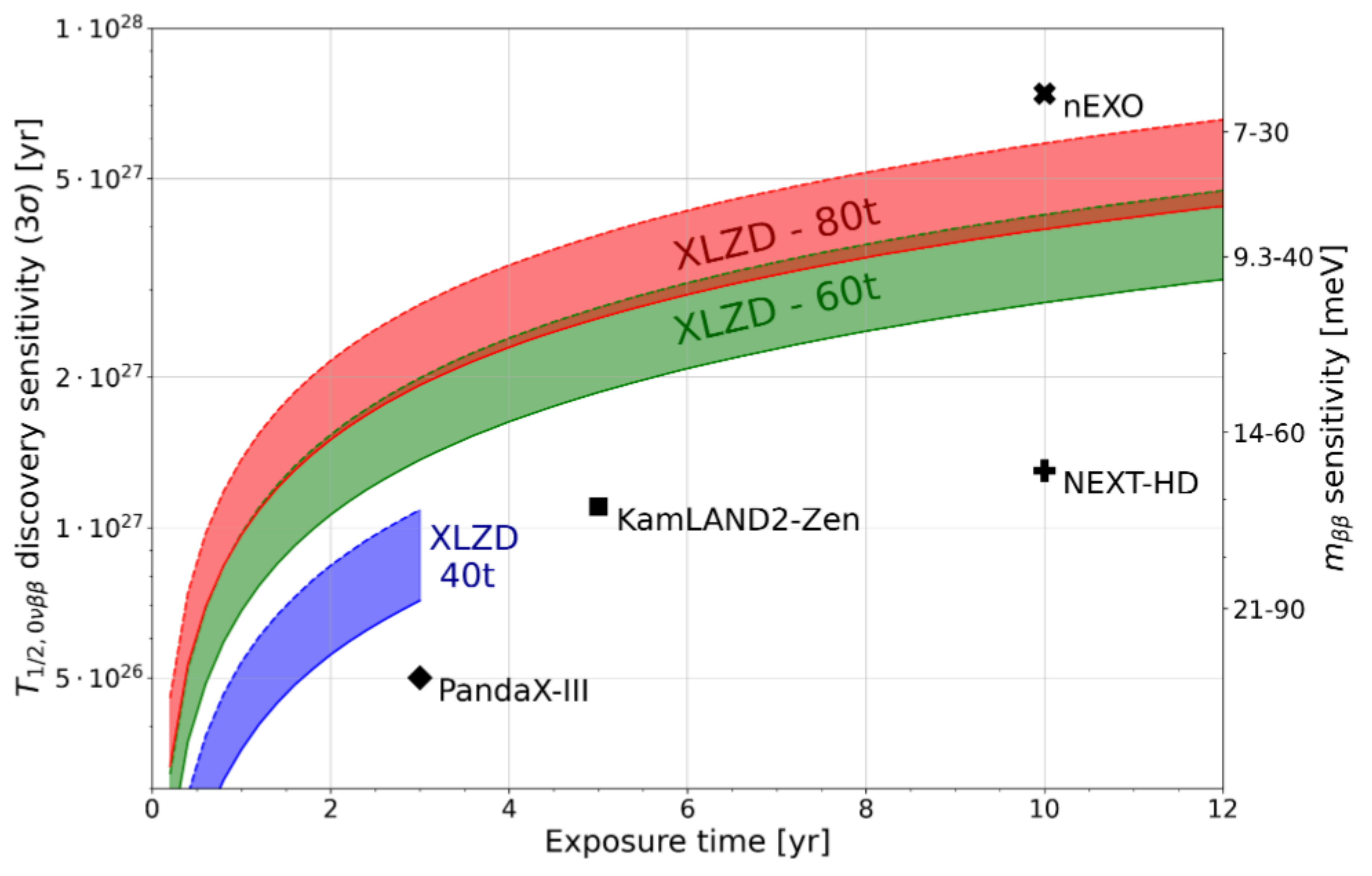
SI-nucleon sensitivity



SI-nucleon discovery



0vbb discovery



XLZD: Why now?

GRAND ALIGNMENT…

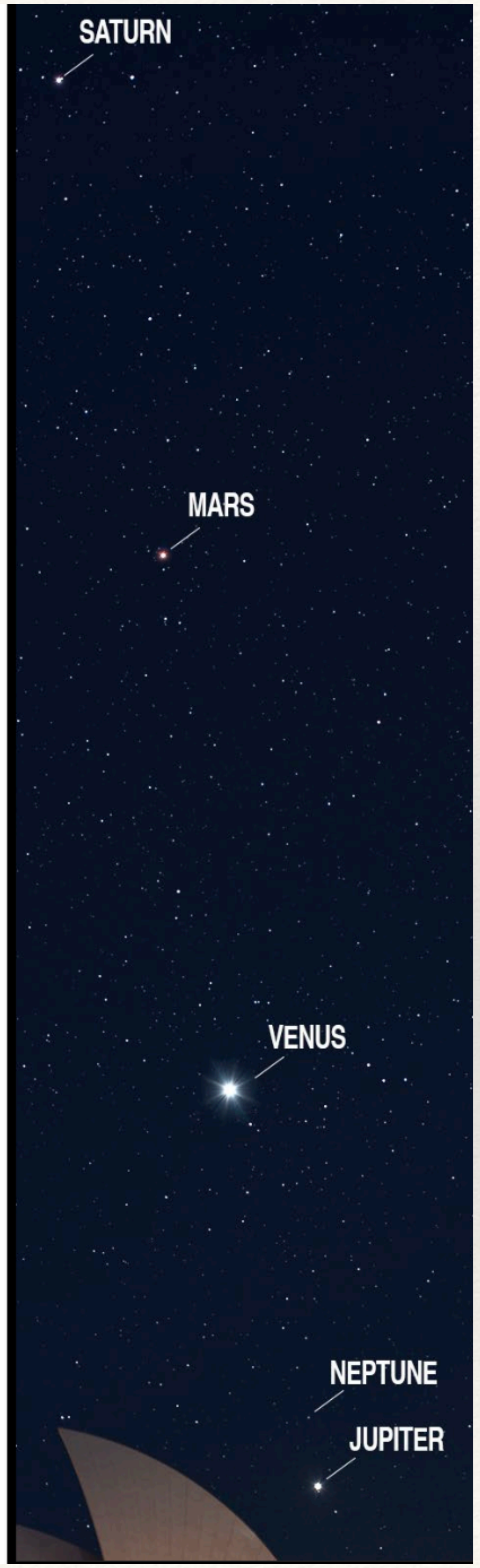
With XLZD
- UK at the barycentre of global collaboration and could bridge US & EU funding timelines
- UK has long tradition in dark matter searches and pioneered LXe-TPCs for this science

With STFC and UKRI
- UK has not hosted a major experiment for decades – appetite to do so now; perfect alignment with STFC Strategic Delivery Plan 2022–25

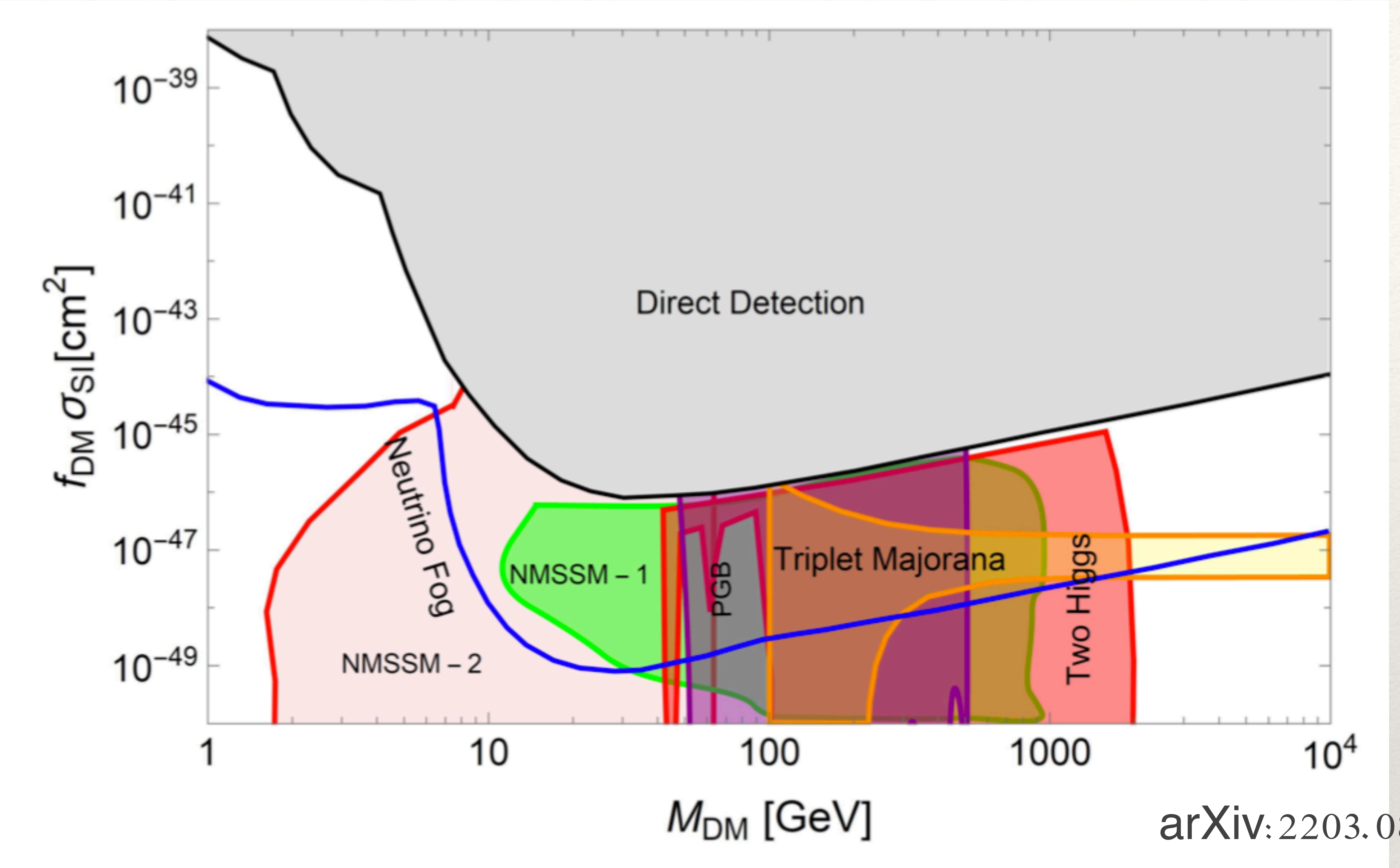
With HM Government
- Investment in “big science” infrastructure and international science – post Brexit
  - “Science Superpower” agenda
- Investment in the North-East of England and skills development
  - “Levelling-up” agenda
- Industrial strategy
  - “Build Back Better” strategy, Small Modular (nuclear) Reactors, ...
- Environmental impact of Big Science
  - “Net-Zero” agenda

There is an opportunity here that is perhaps unique!

But there is also a general election…

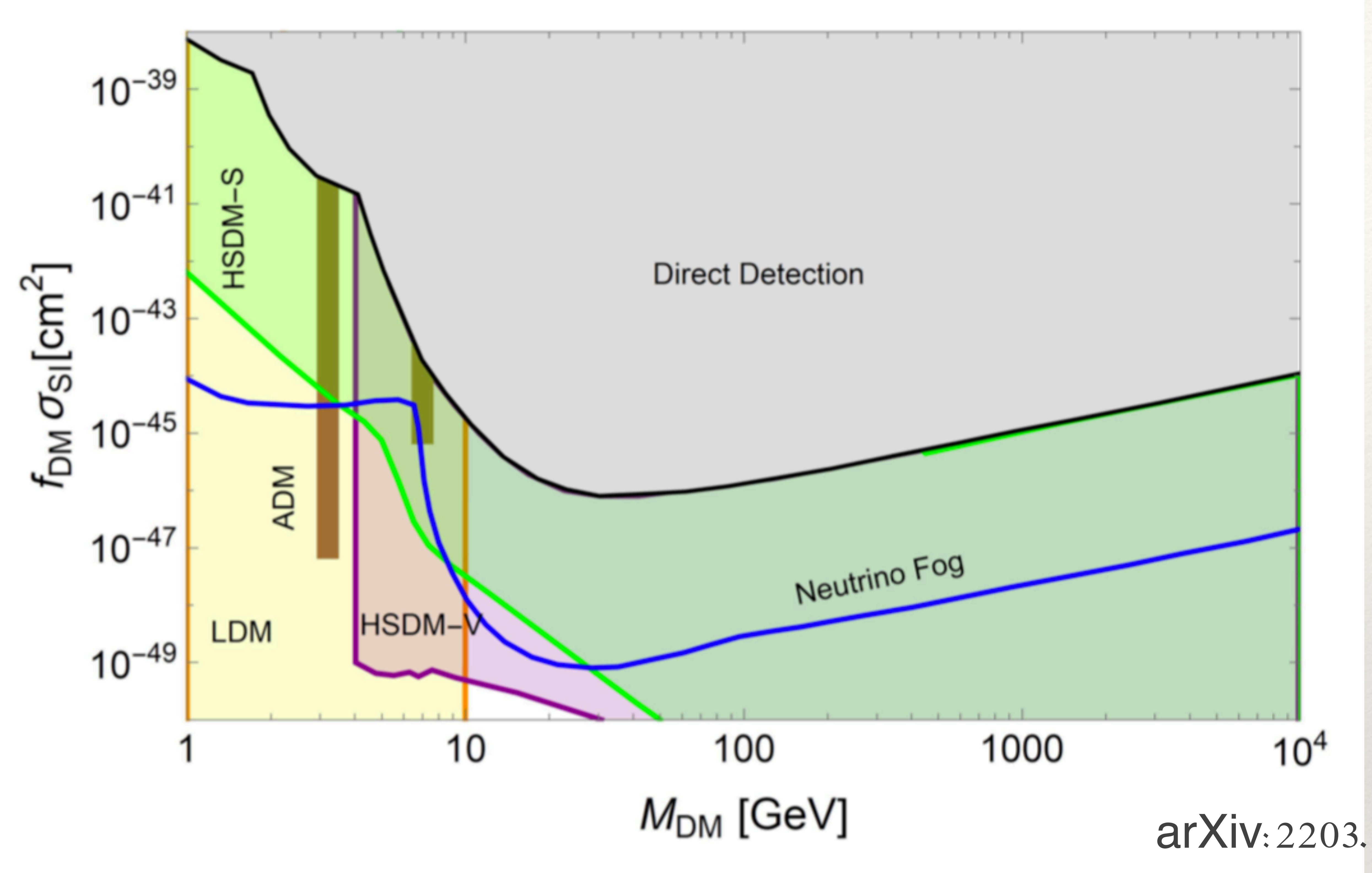


A Modern WIMP view



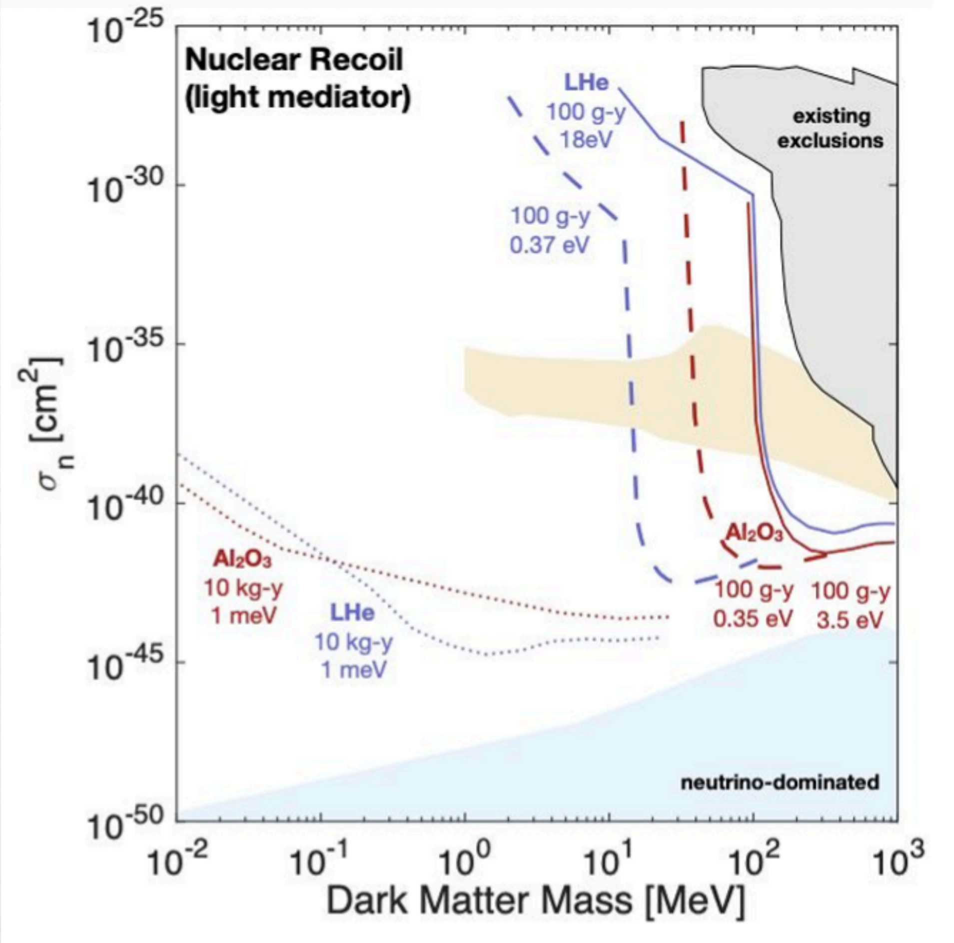
arXiv: 2203.08084

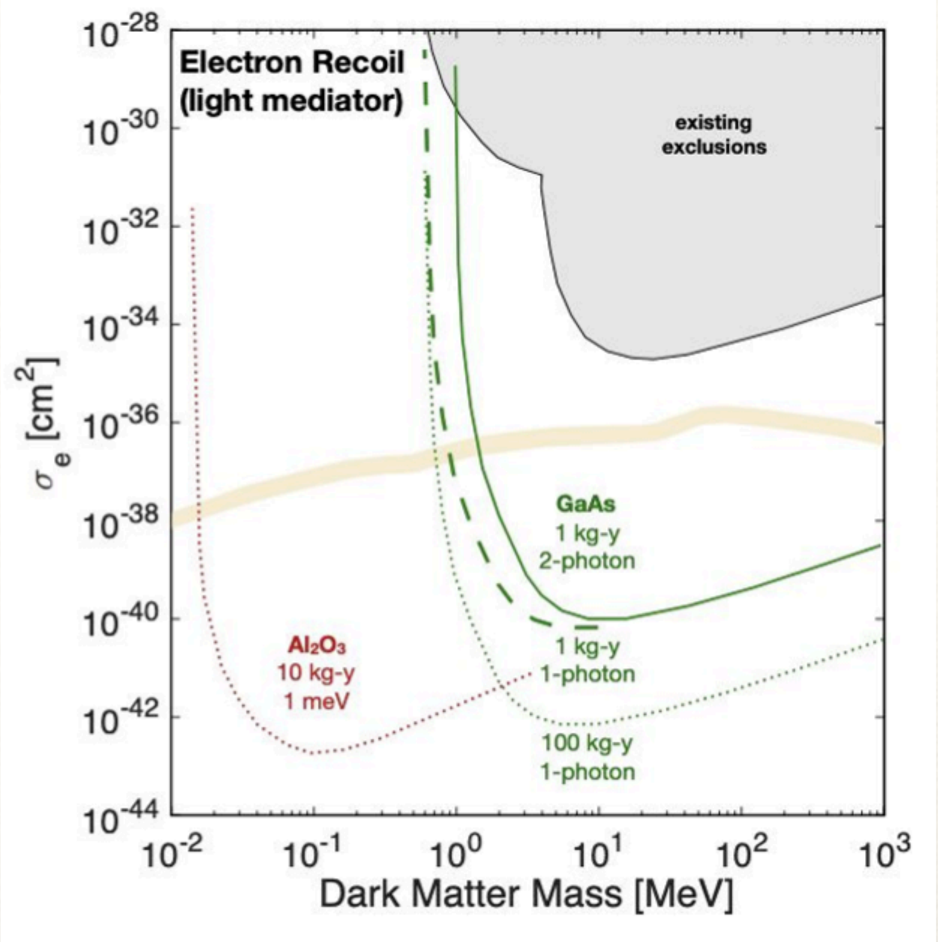
High Mass Particle DM Beyond the WIMP



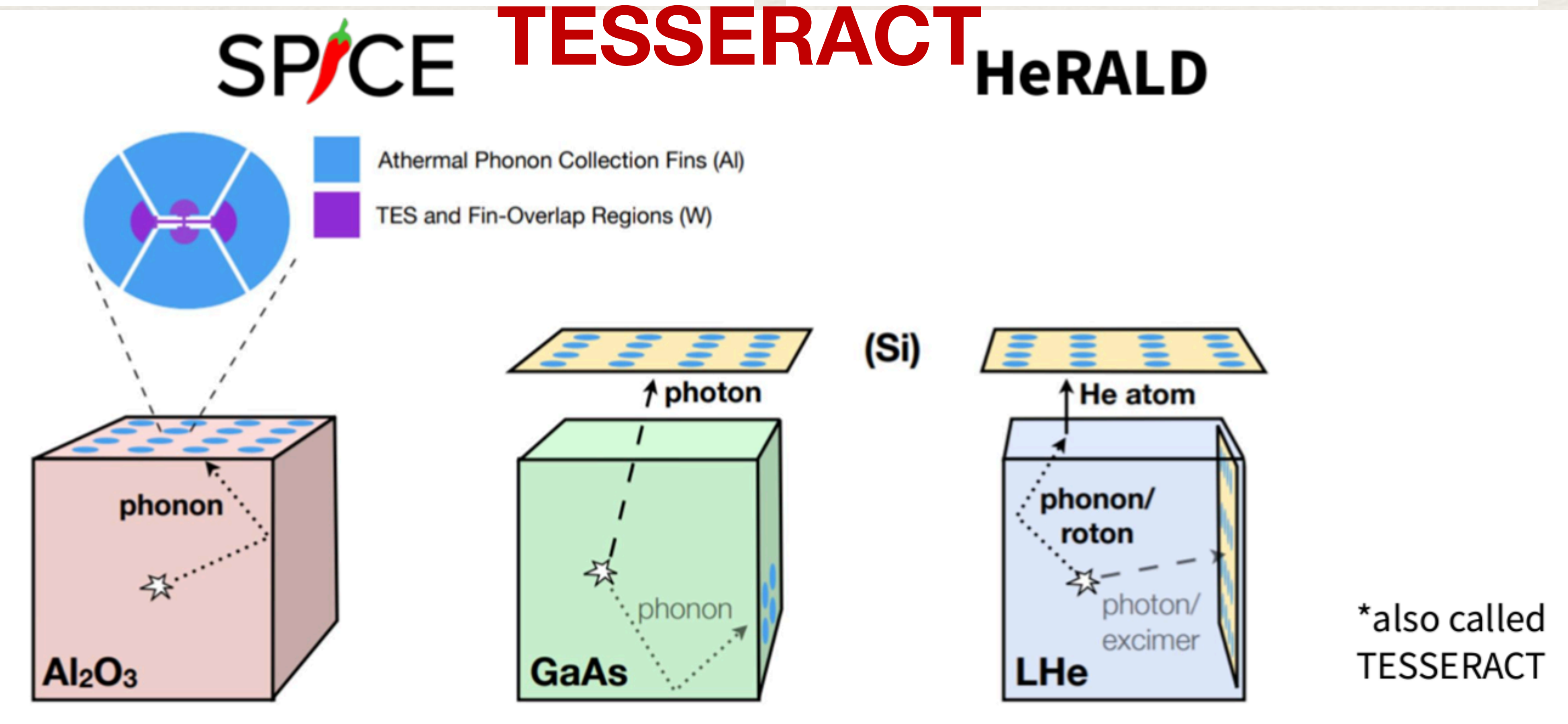
arXiv: 2203.08084

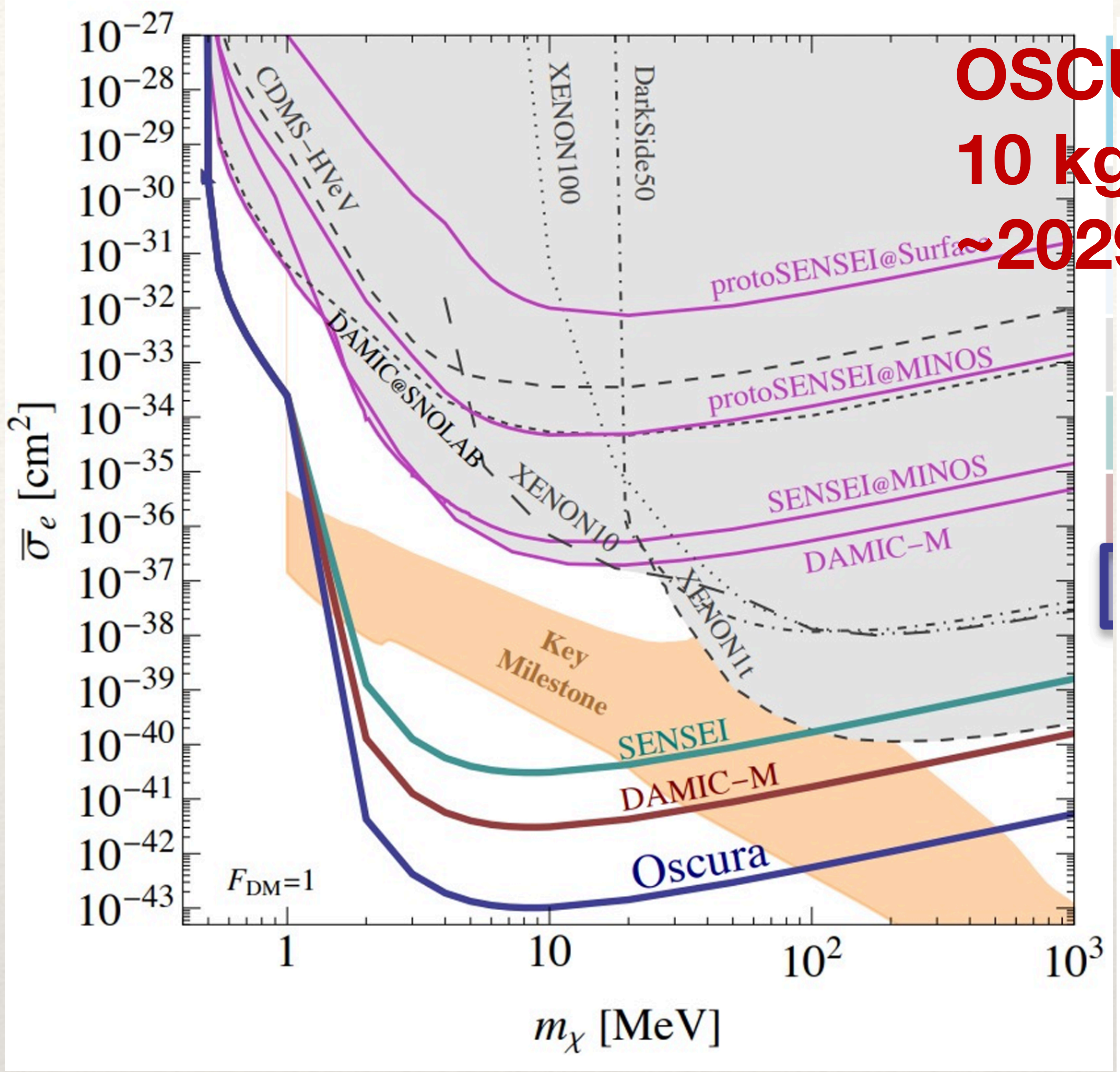
Funded in the US BRN



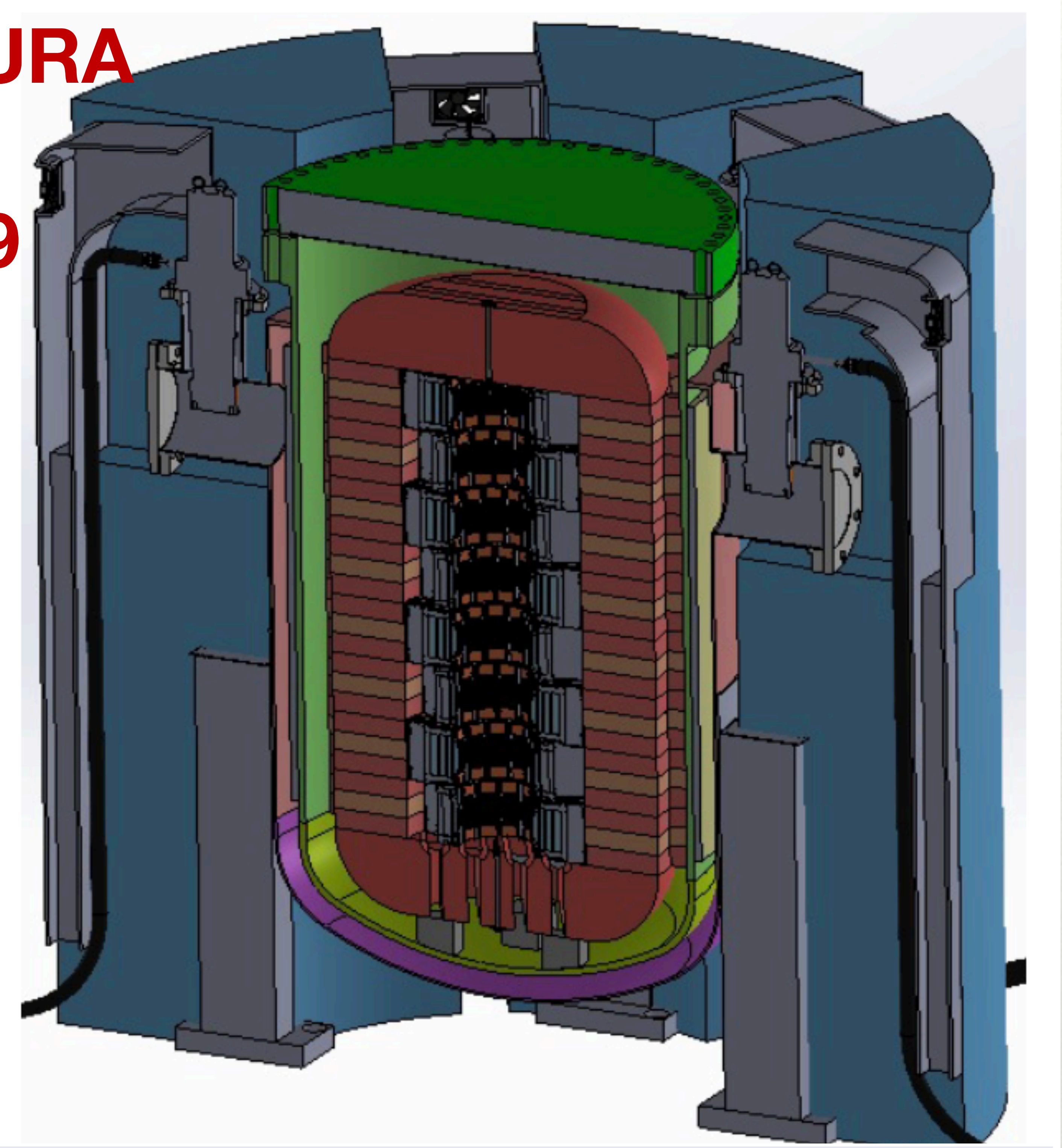


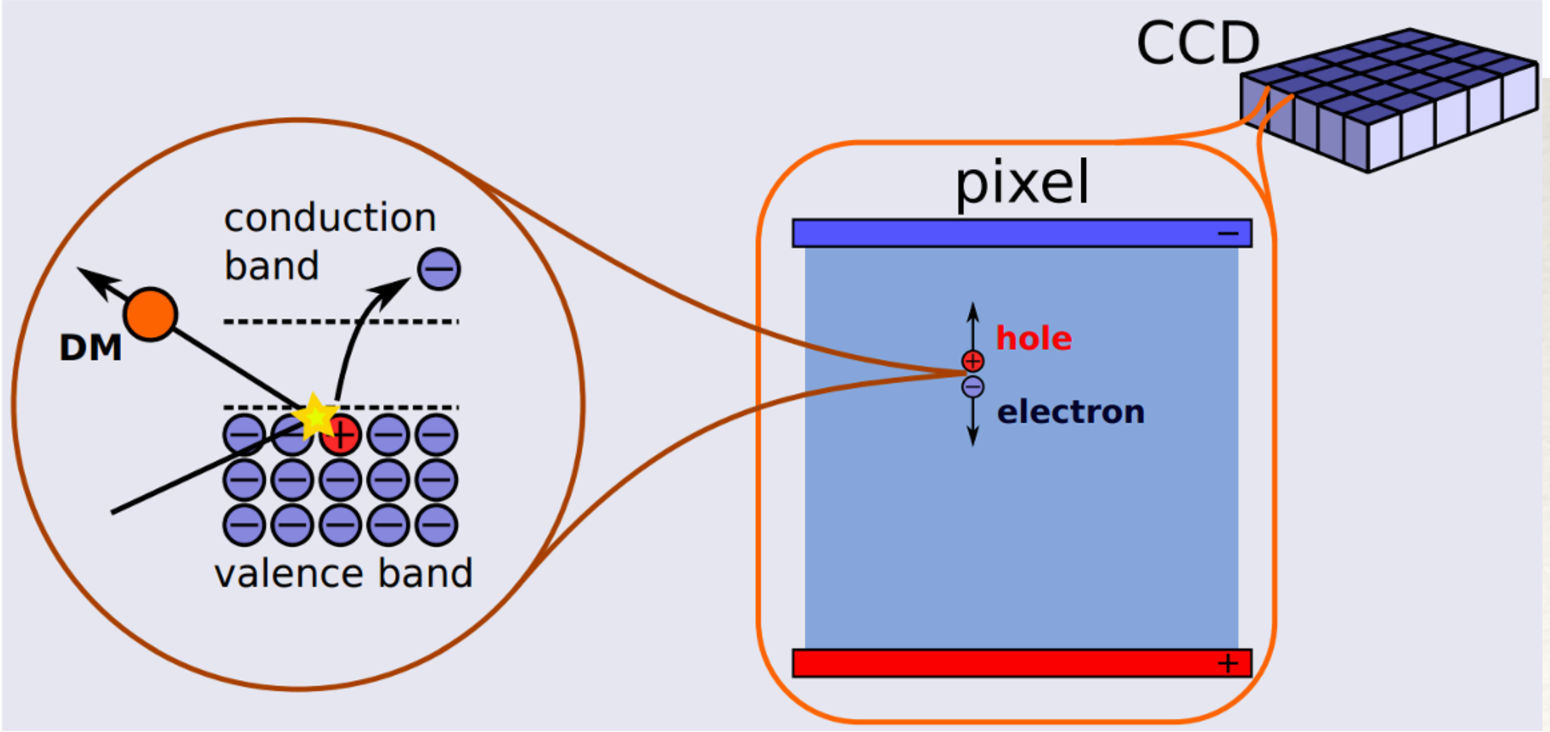
TESSERACT





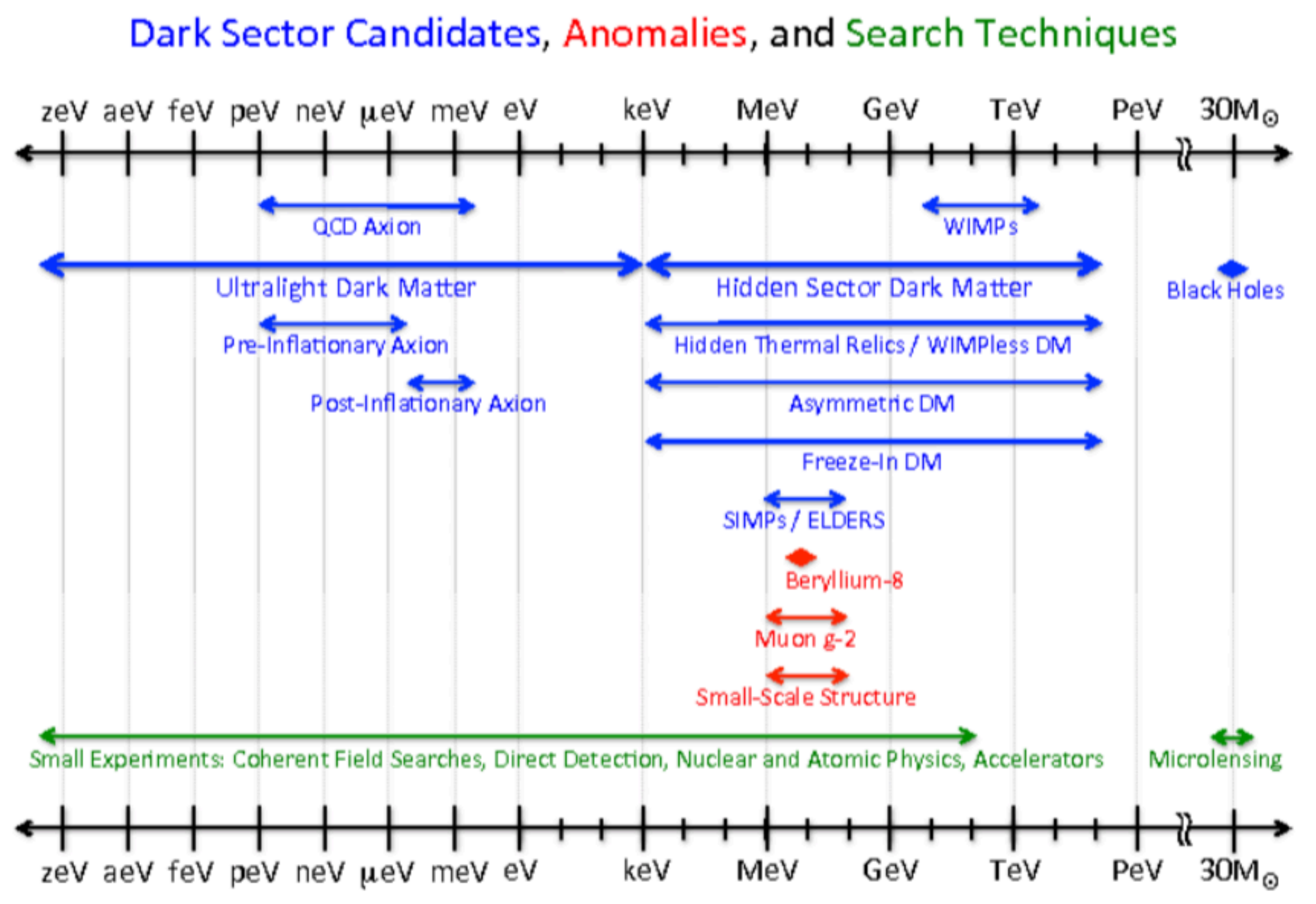
OSCURA
10 kg
~2029





- Athermal phonons, scintillating crystals, superfluid helium, skipper CCDs
- Updates from TAUP 2023

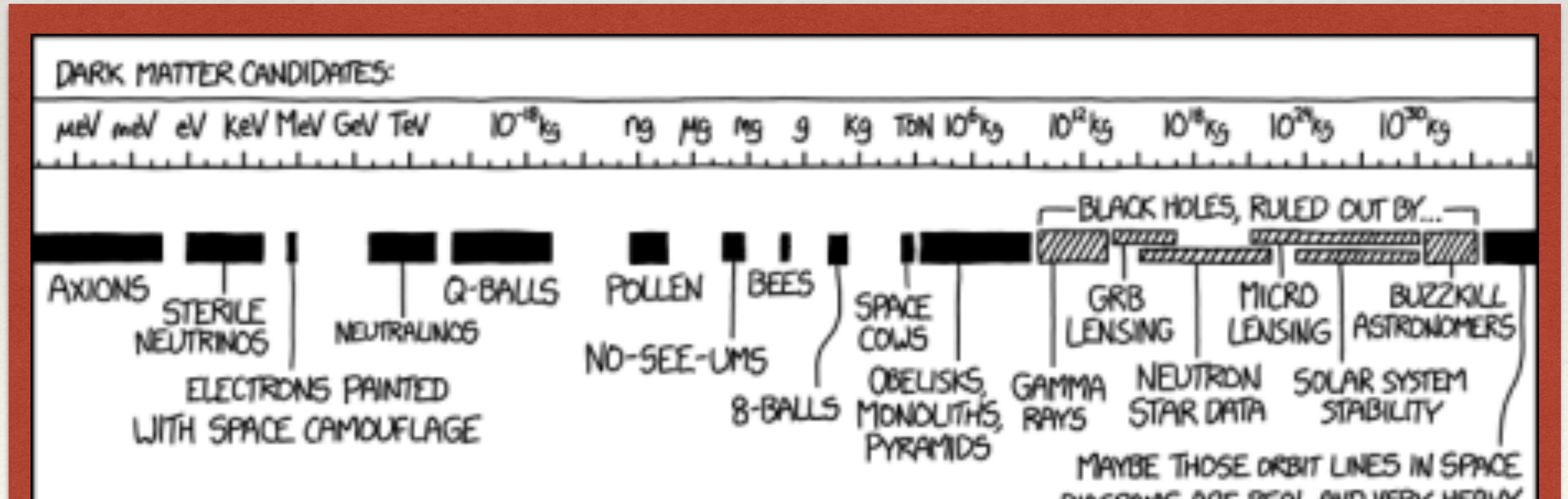
Models



[US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report]

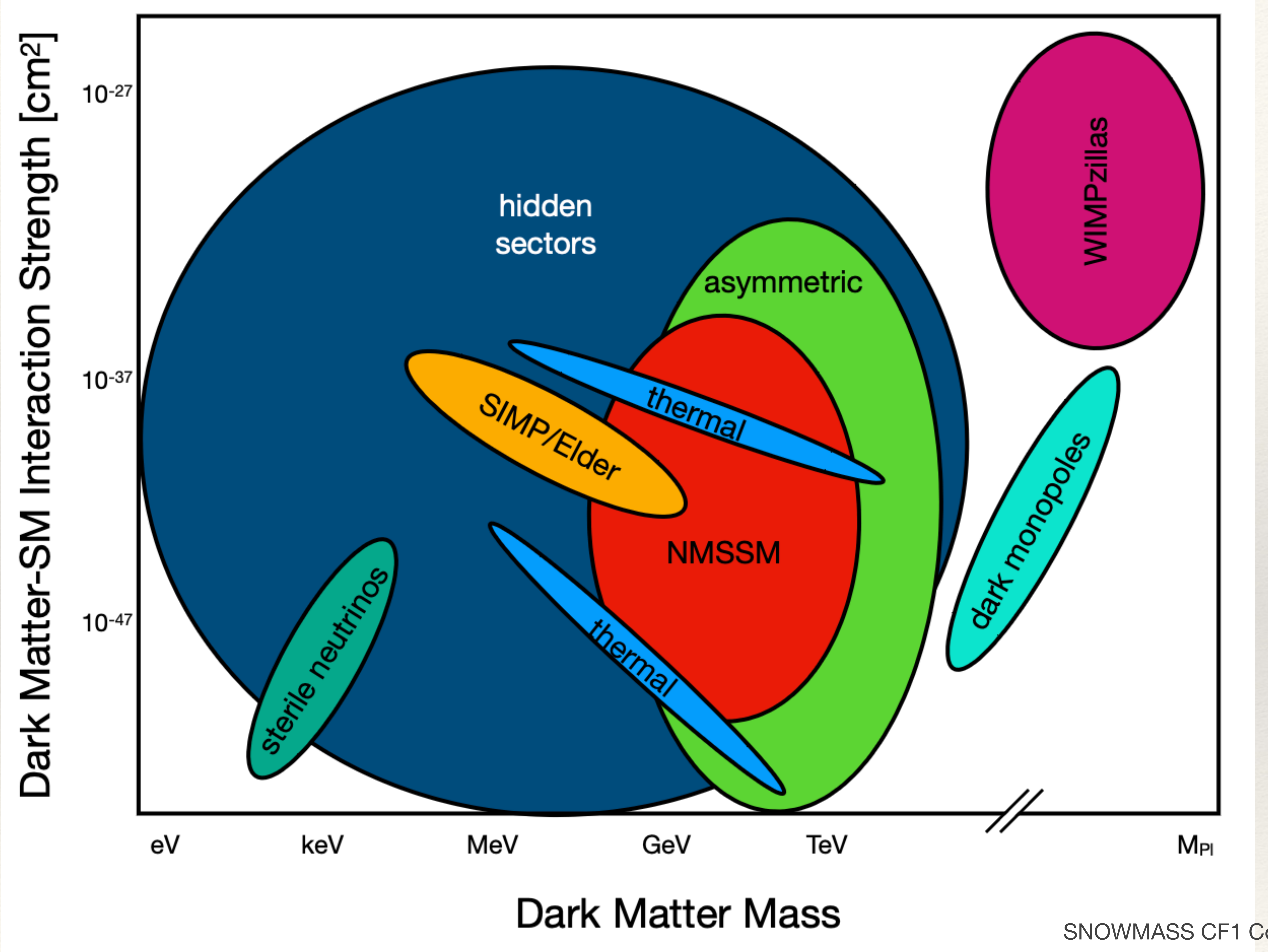
- Canonical Dark matter is:
  - non-relativistic
  - electrically neutral
  - limited self-interactions
  - density of DM ~0.3-0.45 GeV/cm^3

  - Some theories push these boundaries
  - Can dark matter candidates fit with other theories or open problems?



Randall Munroe, 2018, XKCD

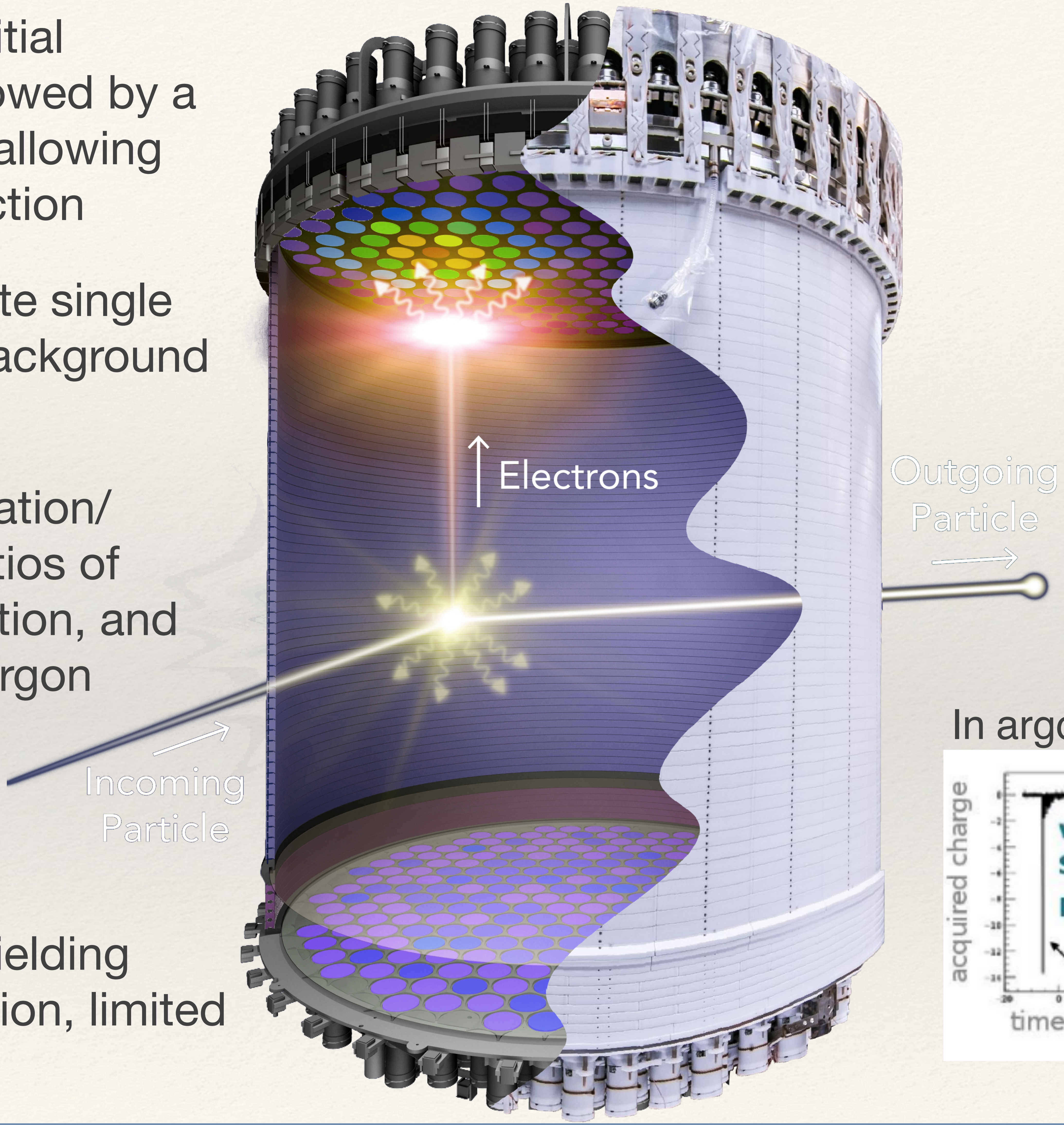
An updated cartoon for particle dark matter

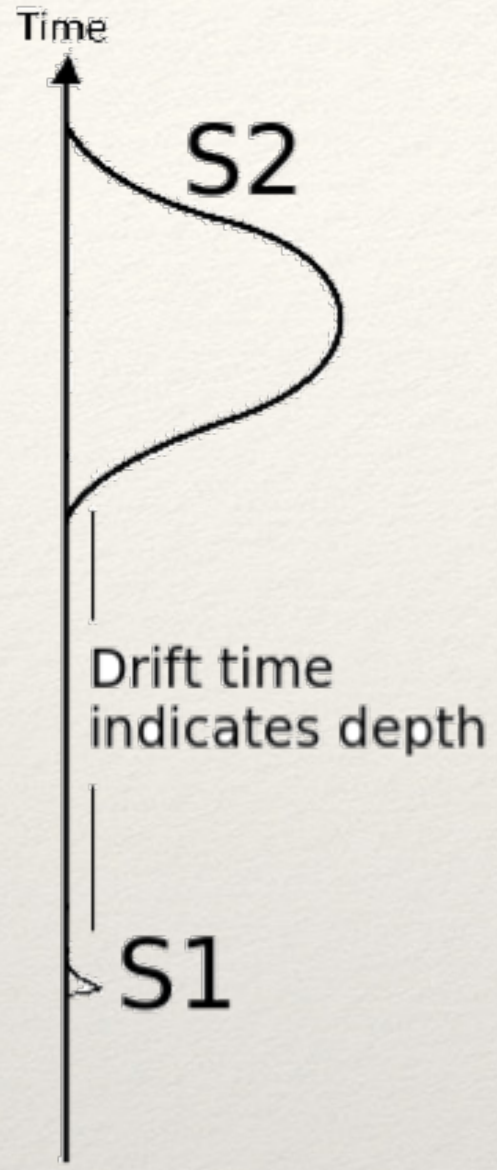


SNOWMASS CF1 Convener's Report

Liquid Noble Time Projection Chambers

- Interactions give an initial scintillation signal followed by a signal from ionization allowing for position reconstruction
- Good ability to separate single scatter signals from background multiple scatters
- Background discrimination/ particle ID given by ratios of scintillation and ionization, and scintillation timing in argon
- Other benefits: self shielding against external radiation, limited radioactivity in targets

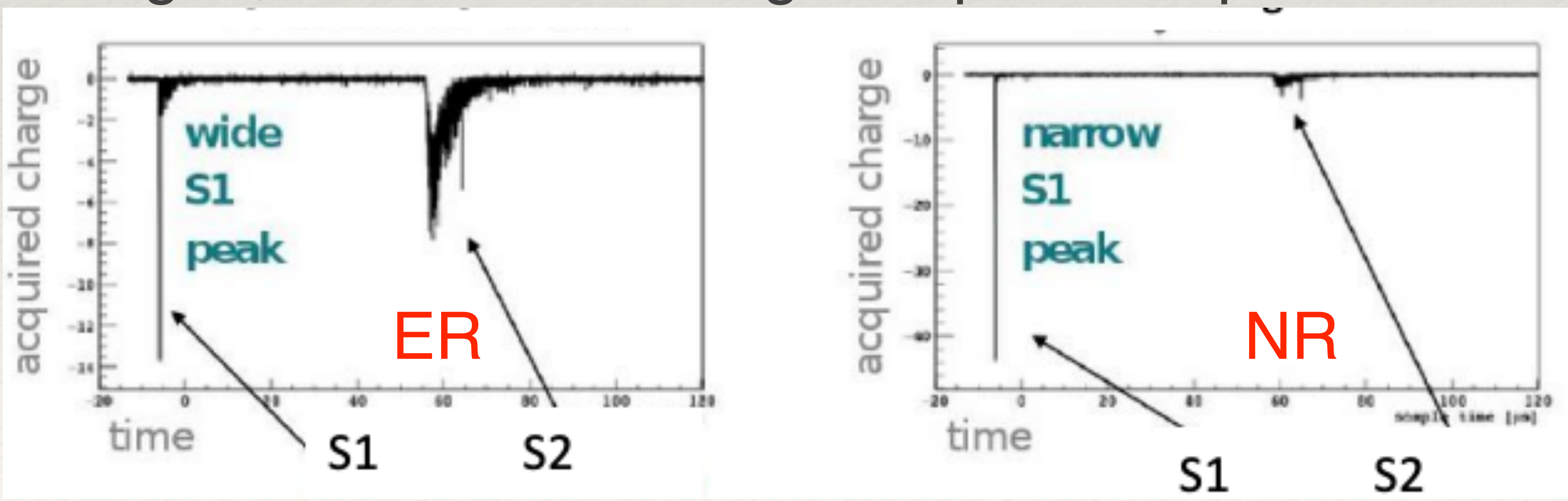




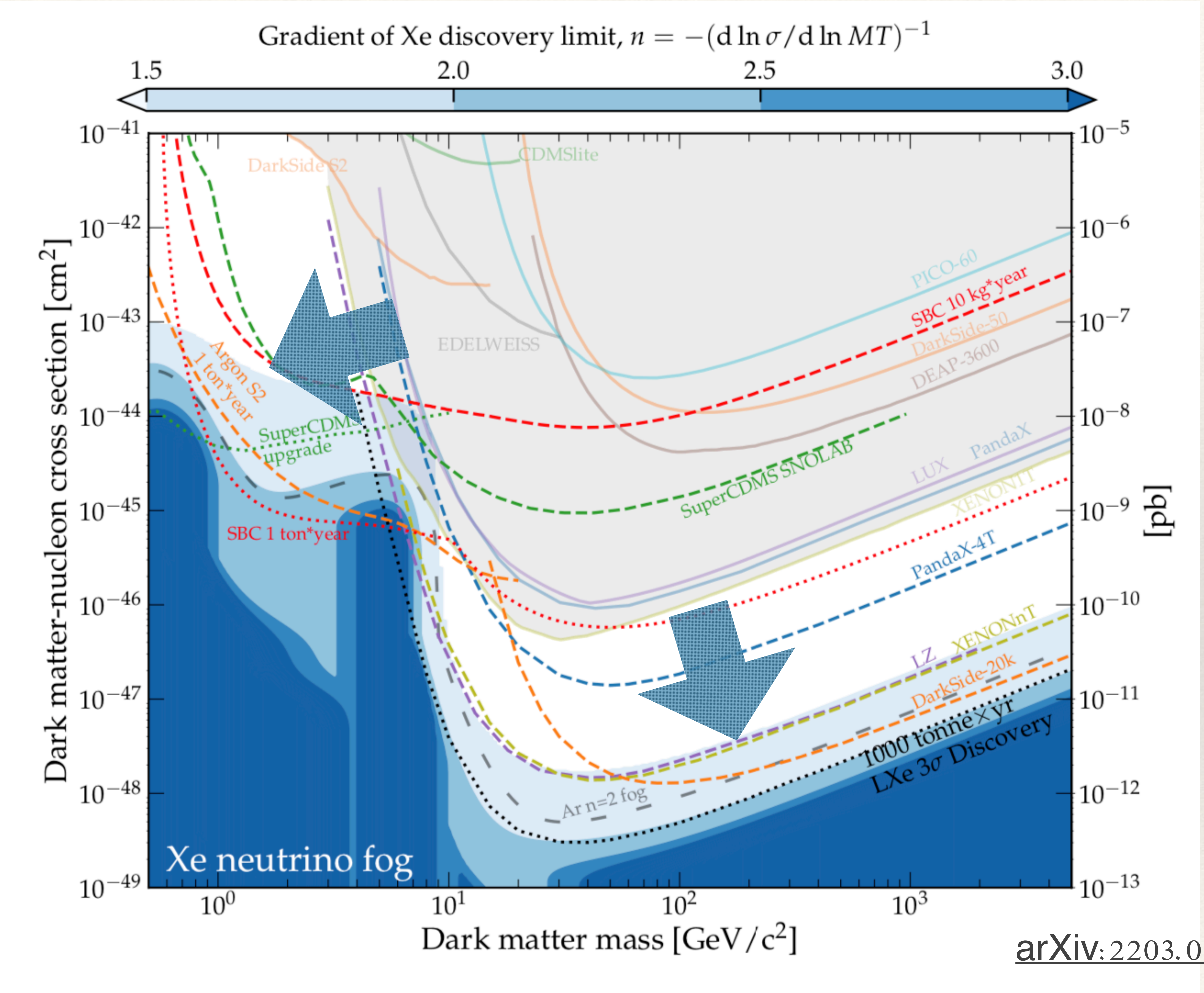
Large detectors with sensitivity over many orders of magnitude of DM mass.

Physics beyond WIMP searches also.

In argon, scintillation timing also provides particle ID

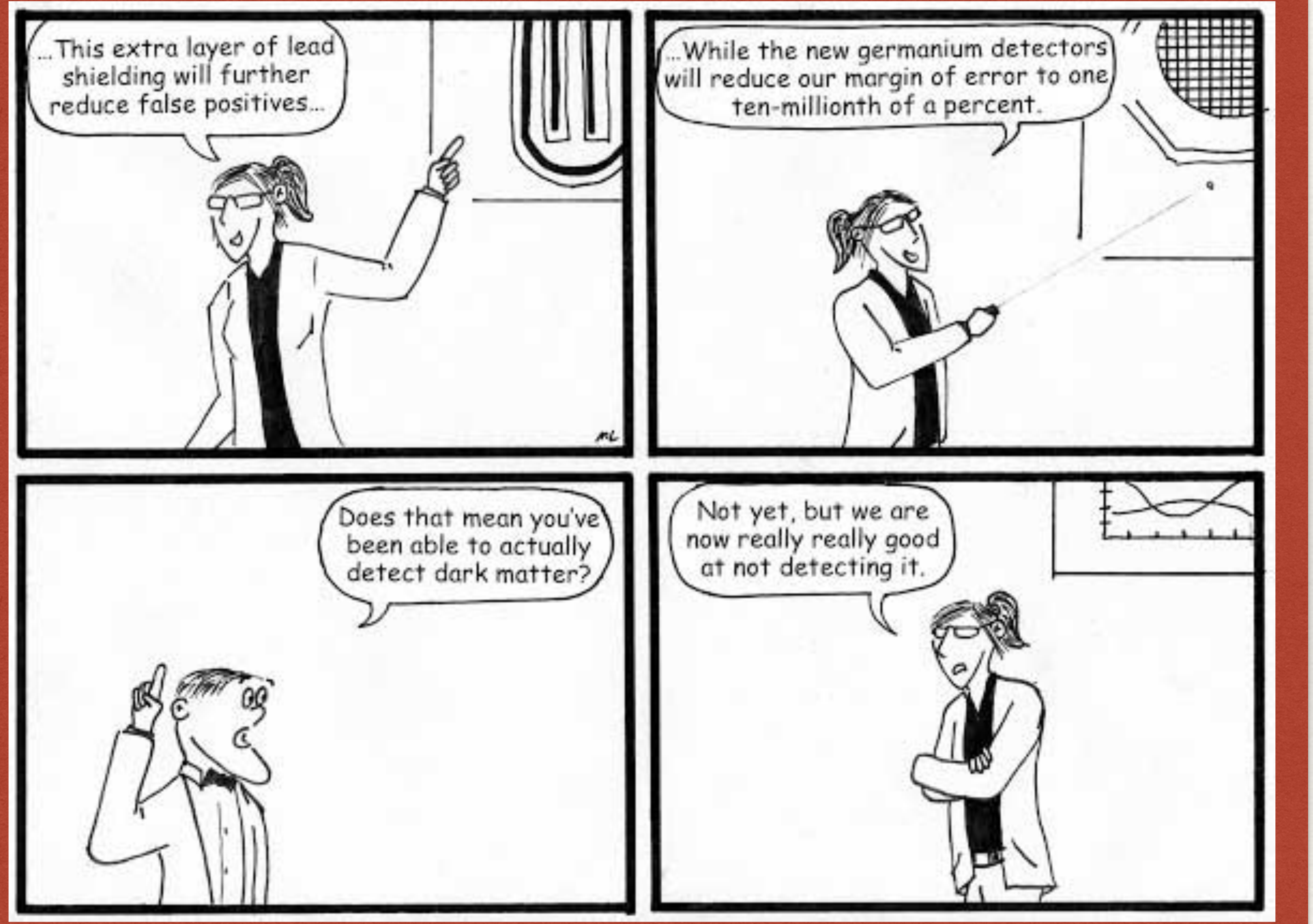


Spin Independent Direct DM status



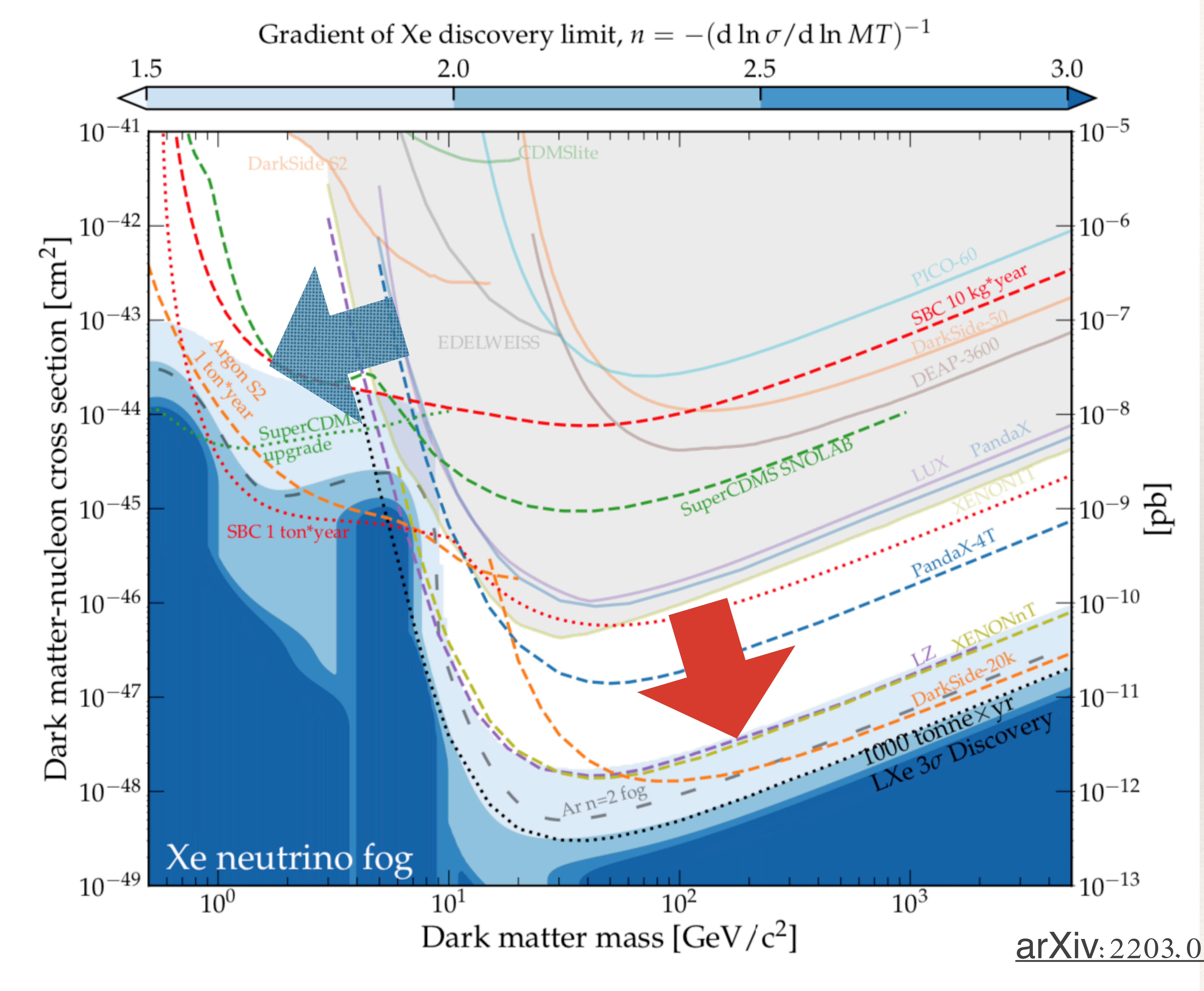
arXiv: 2203.08084

Focus on spin-independent DM-nuclear scattering



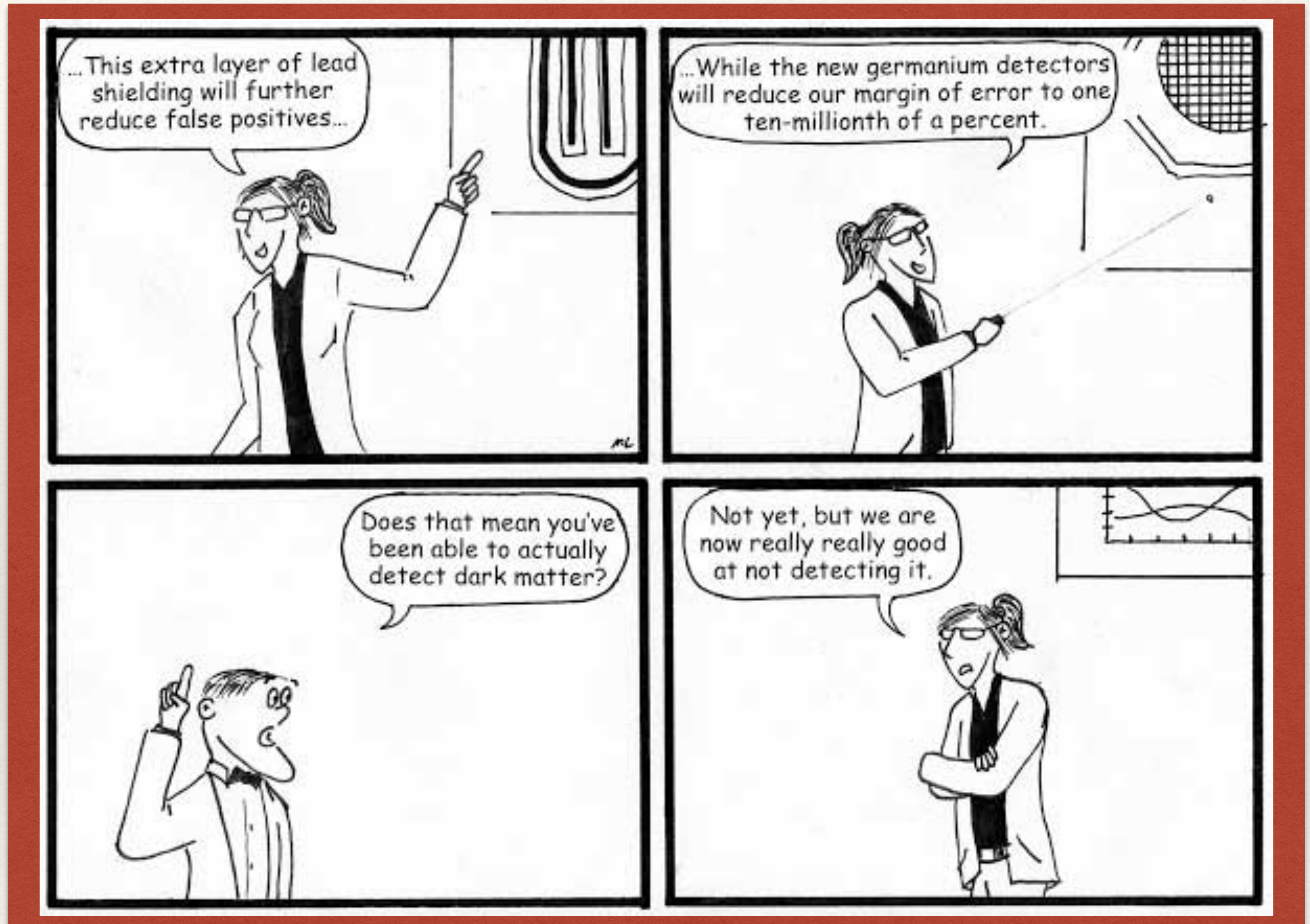
Michael Lucibella 2014, APS.org

Spin Independent Direct DM status



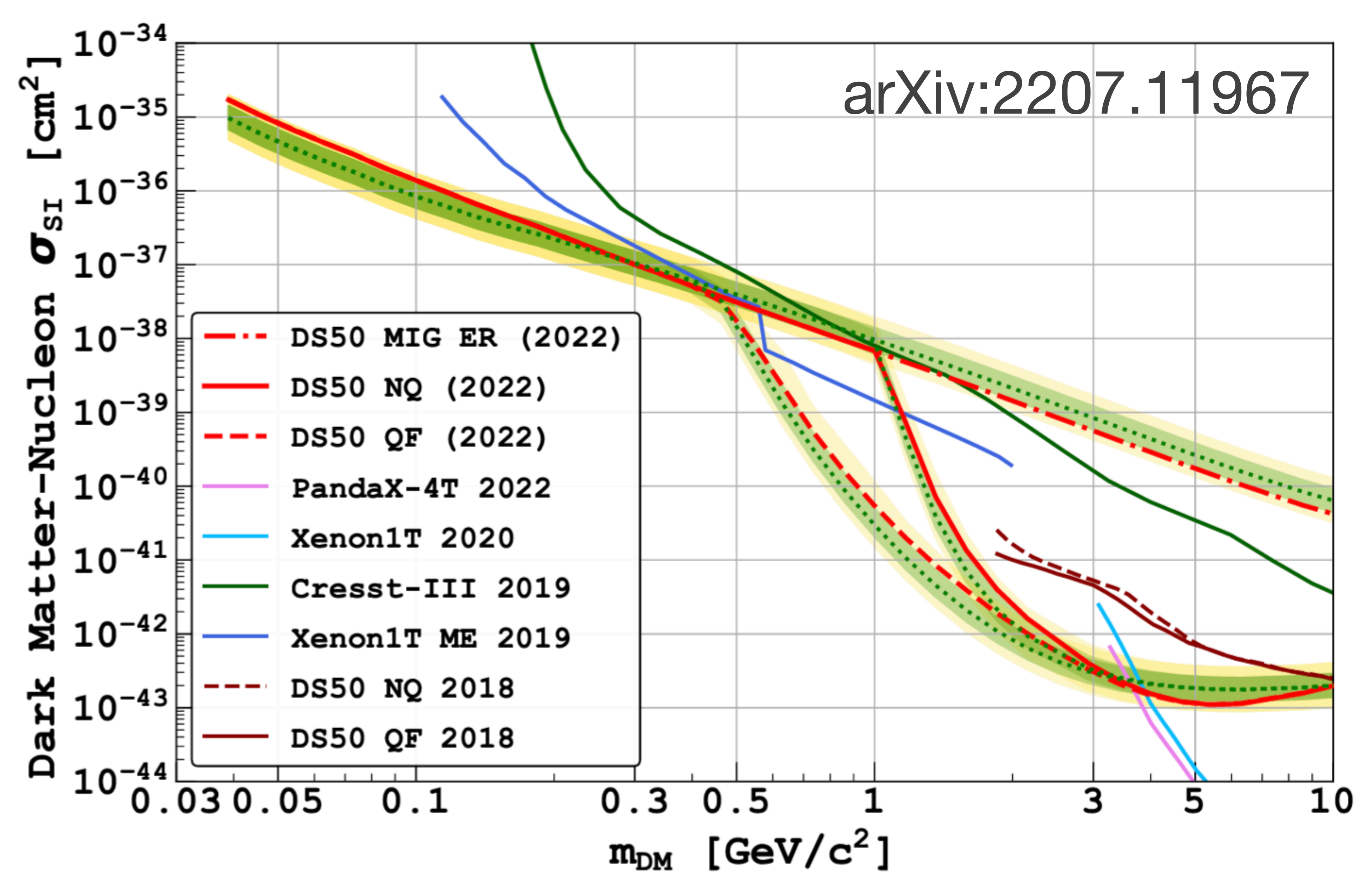
arXiv: 2203.08084

Focus on spin-independent DM-nuclear scattering

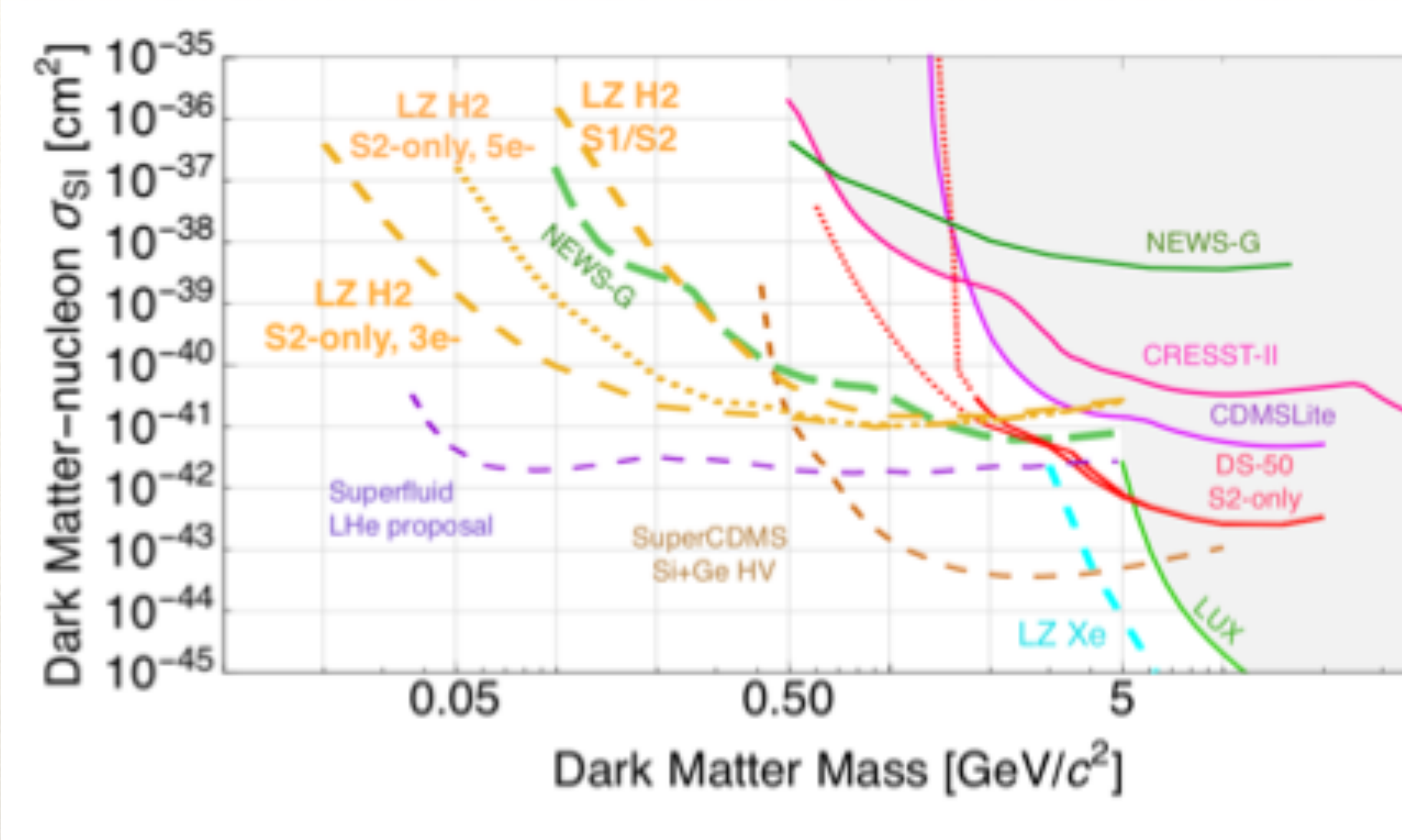


Michael Lucibella 2014, APS.org

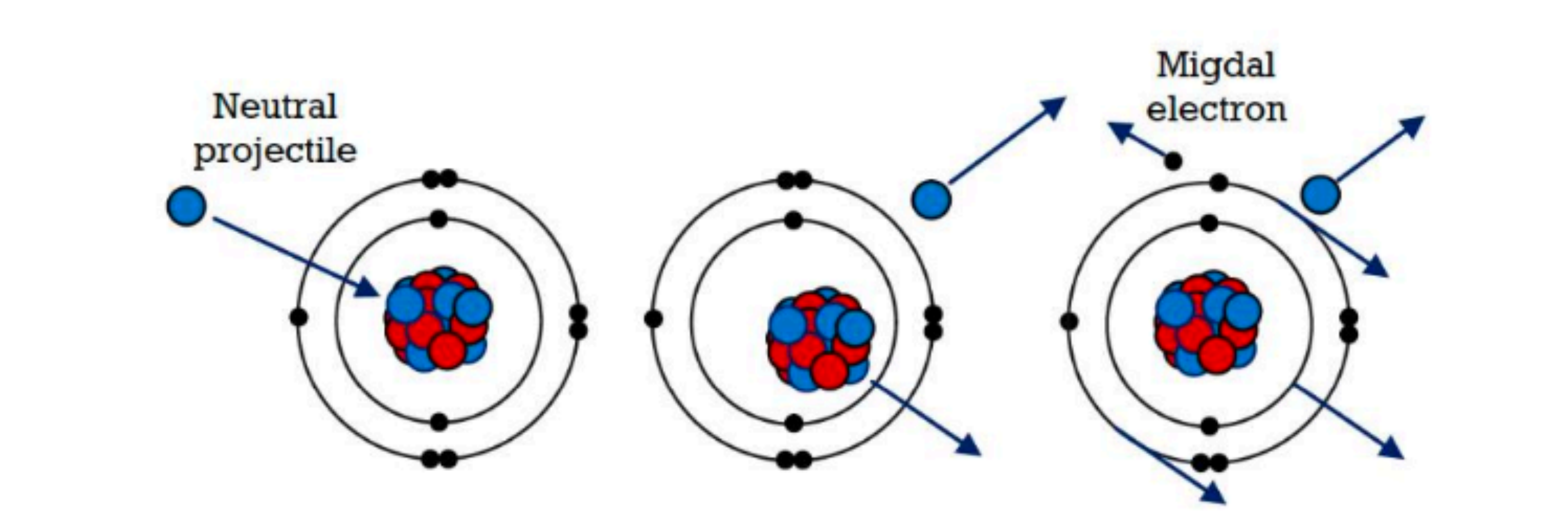
Once more, from the nobles...



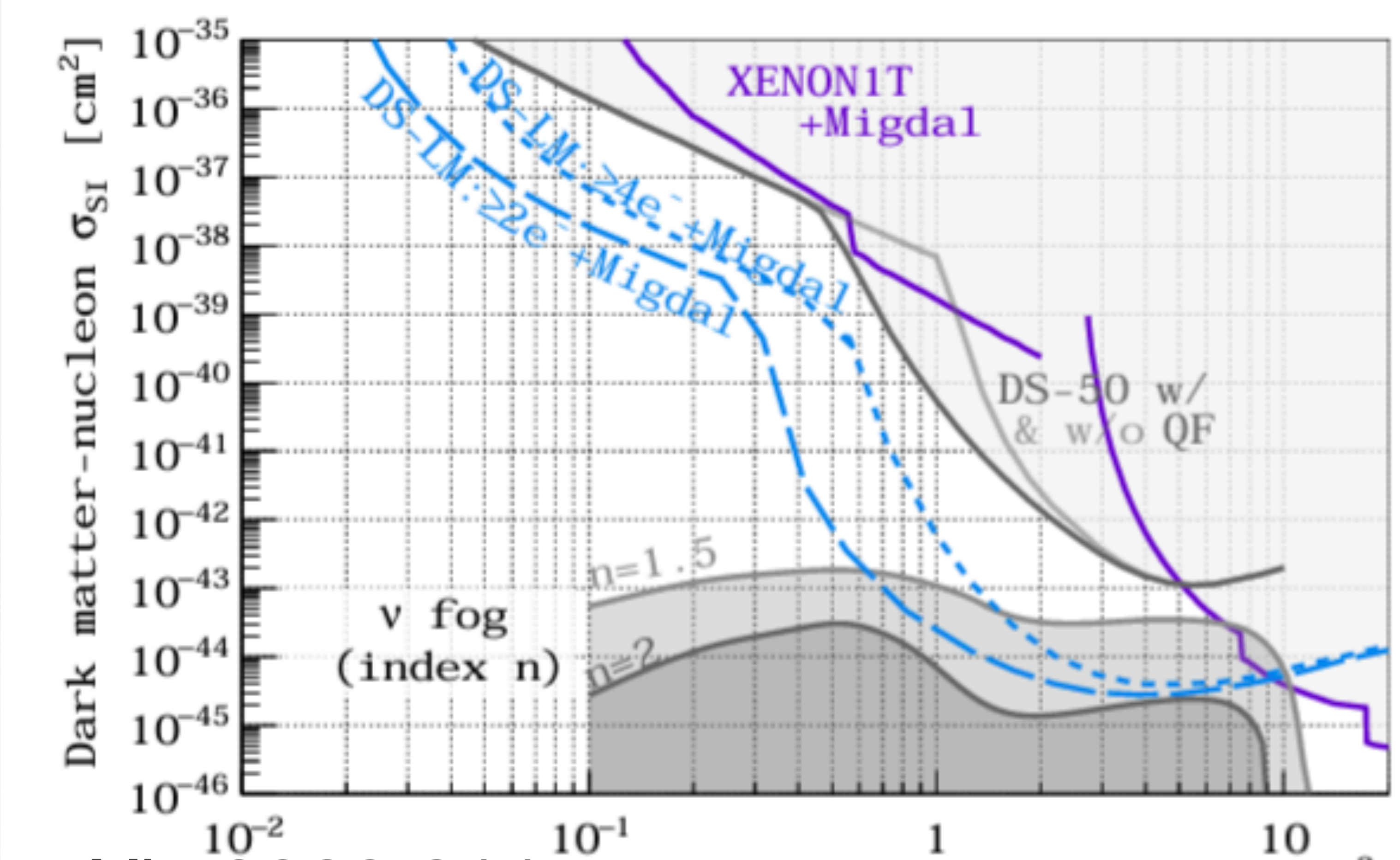
- Future: S2-only searches from current detectors (with Migdal?)
- HydroX
  - Proposed doping of LXe detector with H
- DarkSide-LowMass
  - Proposed 1T detector to get to neutrino fog in 1t-yr exposure



- Leading limits are from DarkSide-50 with a low threshold enabled by ionization only signals (no background discrimination)
- These signals may be enhanced by the Migdal effect, but **this needs to be confirmed**!
- Microphysics uncertainties too

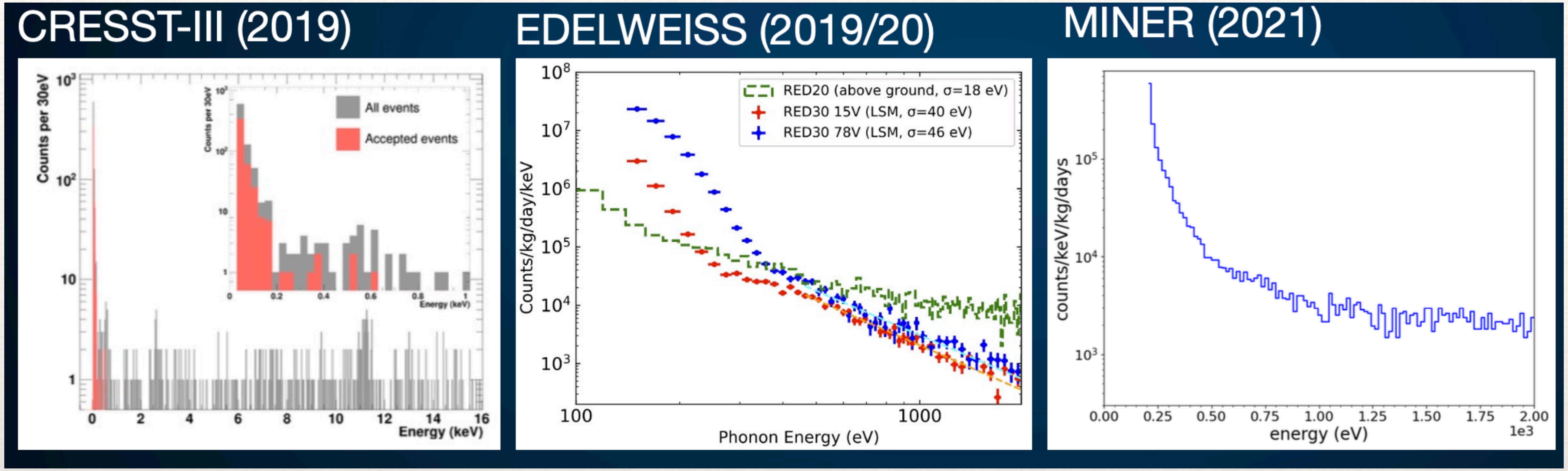


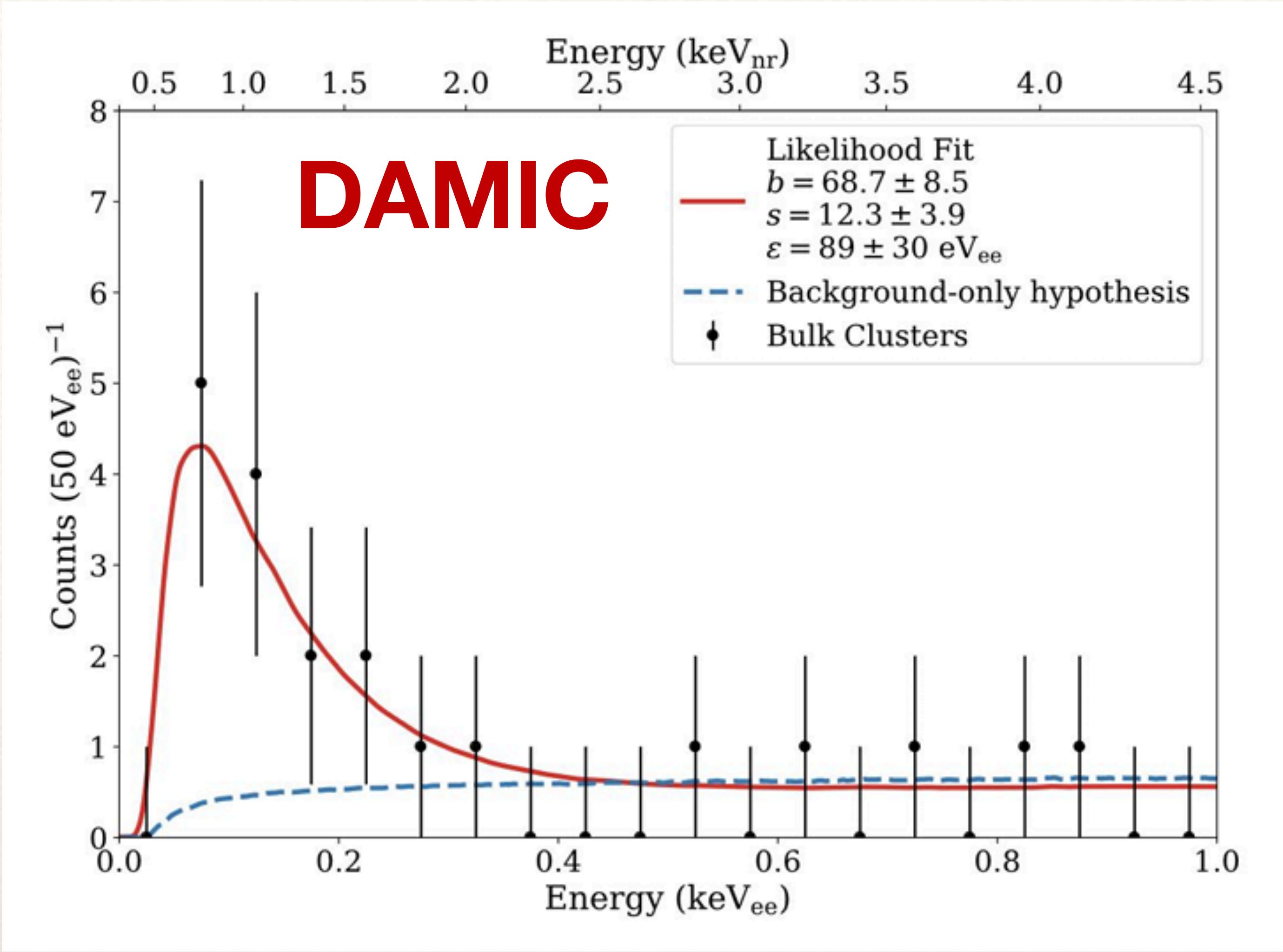
Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.



arXiv:2209.01177

Low energy EXCESS





Reindl, UCLA Dark Matter 2023, Baxter, TAUP 2023

- Excesses in **cryo-detectors** (non-ionizing, decaying, …) have possibly one common origin! Hot suspect: interface and bulk stress. Currently focused research topic, transferable impact expected (qubits, …).
- Excesses in **CCDs** (single electron production) can be explained by dark current and detector effects, but further reduction is required or future experiments (e.g. OSCURA).
- The **DAMIC excess** remains a riddle.

Multiple experiments see rising signals near t

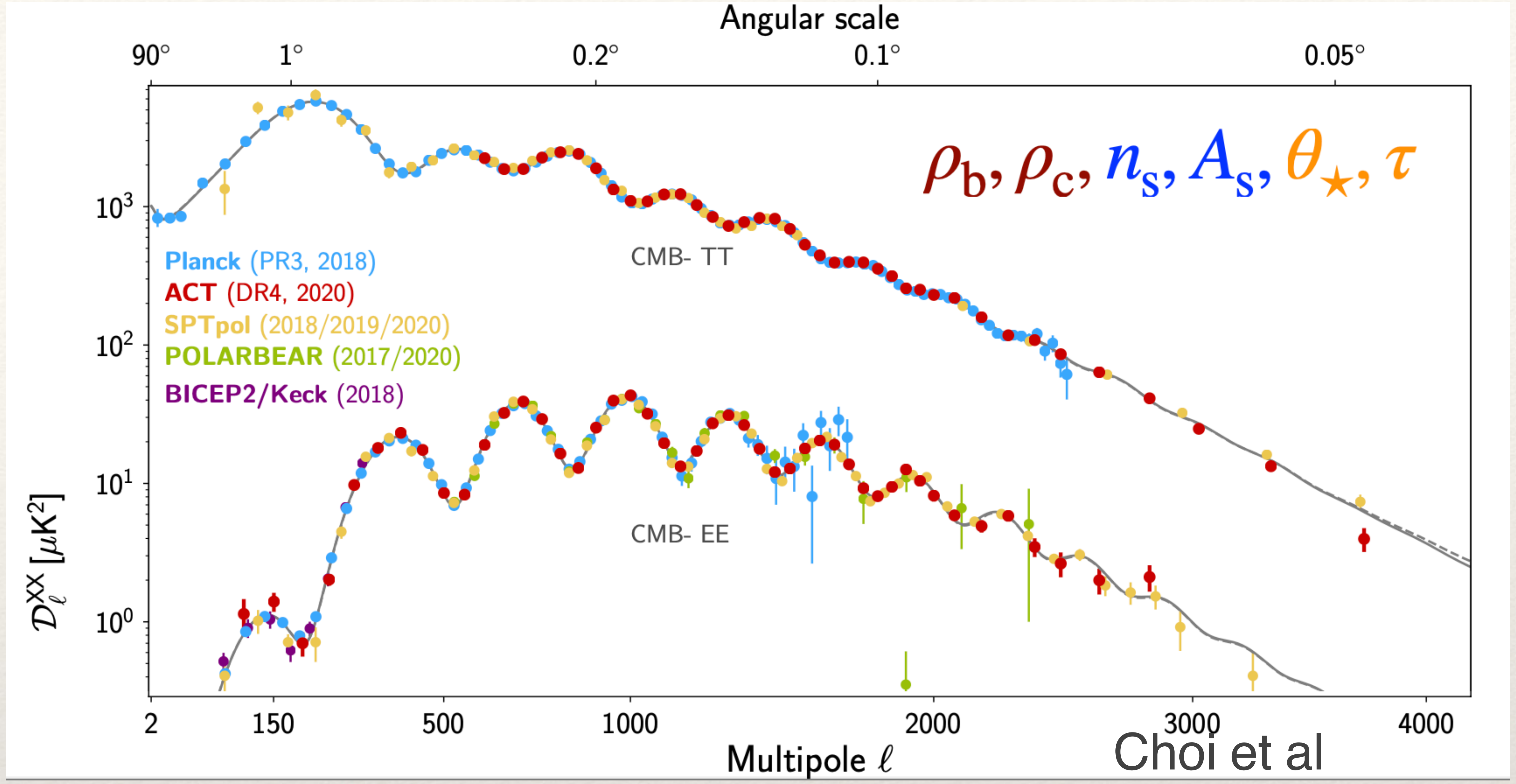
EXCESS initiative: SciPost Phys. Proc. 9, 001 (2022)

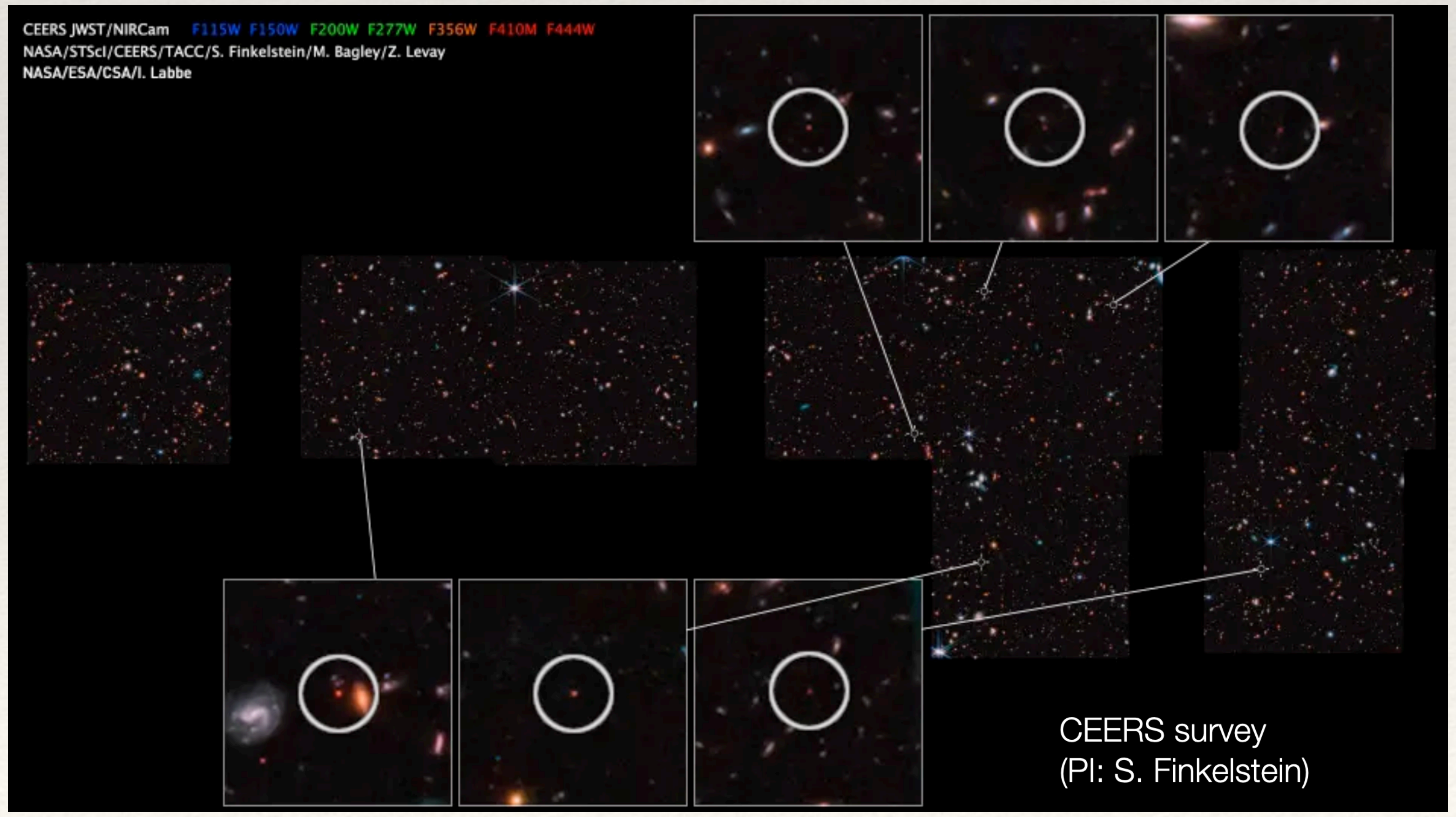
- Not Dark Matter
- Not the same backgrounds
- Can it be mitigated?

Astronomy and Cosmology

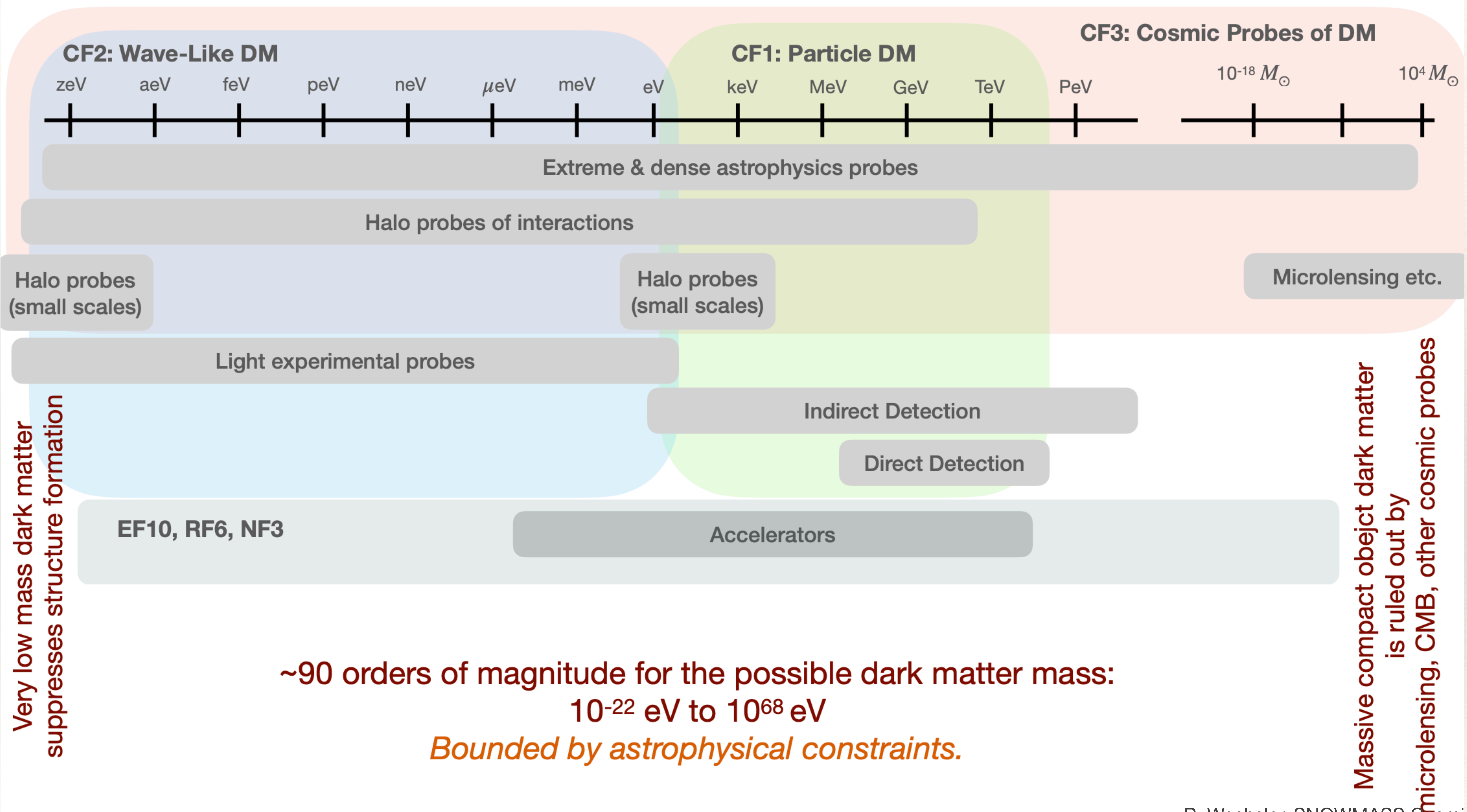
- Our cosmological models work really well

- But…
  - many big young galaxies seen by the James Webb Space telescope
  - different measured values for the Hubble constant
  - Black Holes are surprising us too, could they be dark matter?





Complementarity



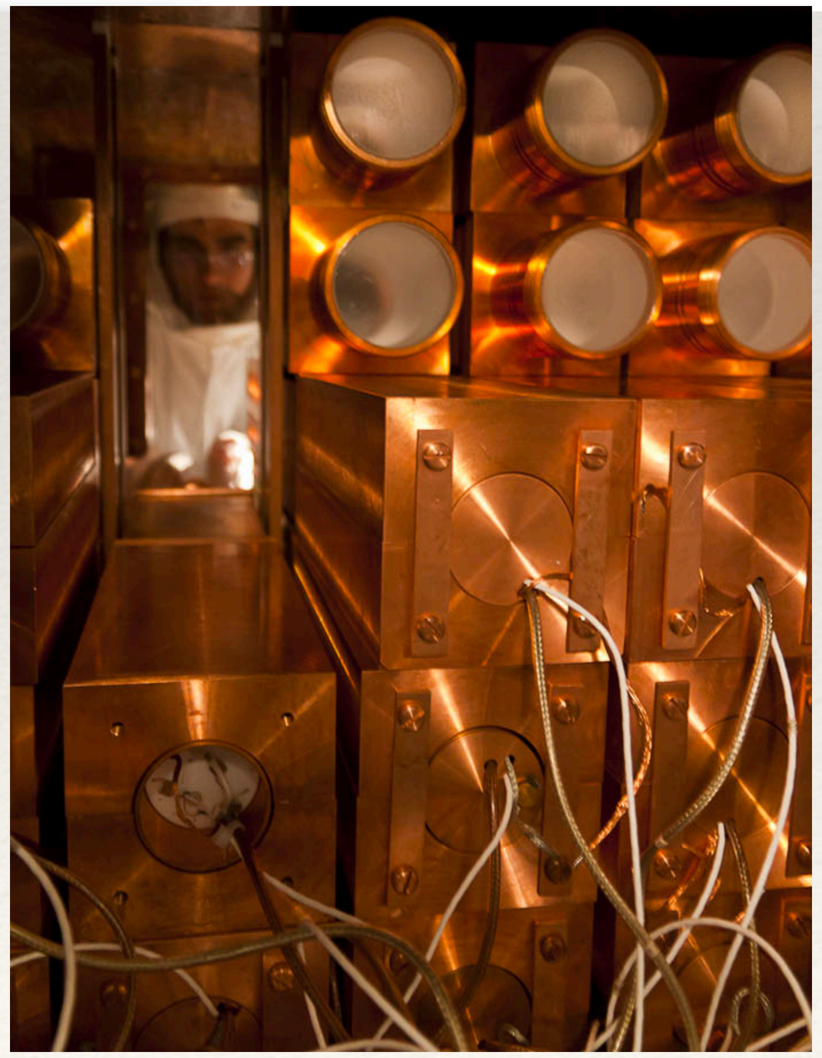
R. Wechsler, SNOWMASS Cosmic Probe Plenary

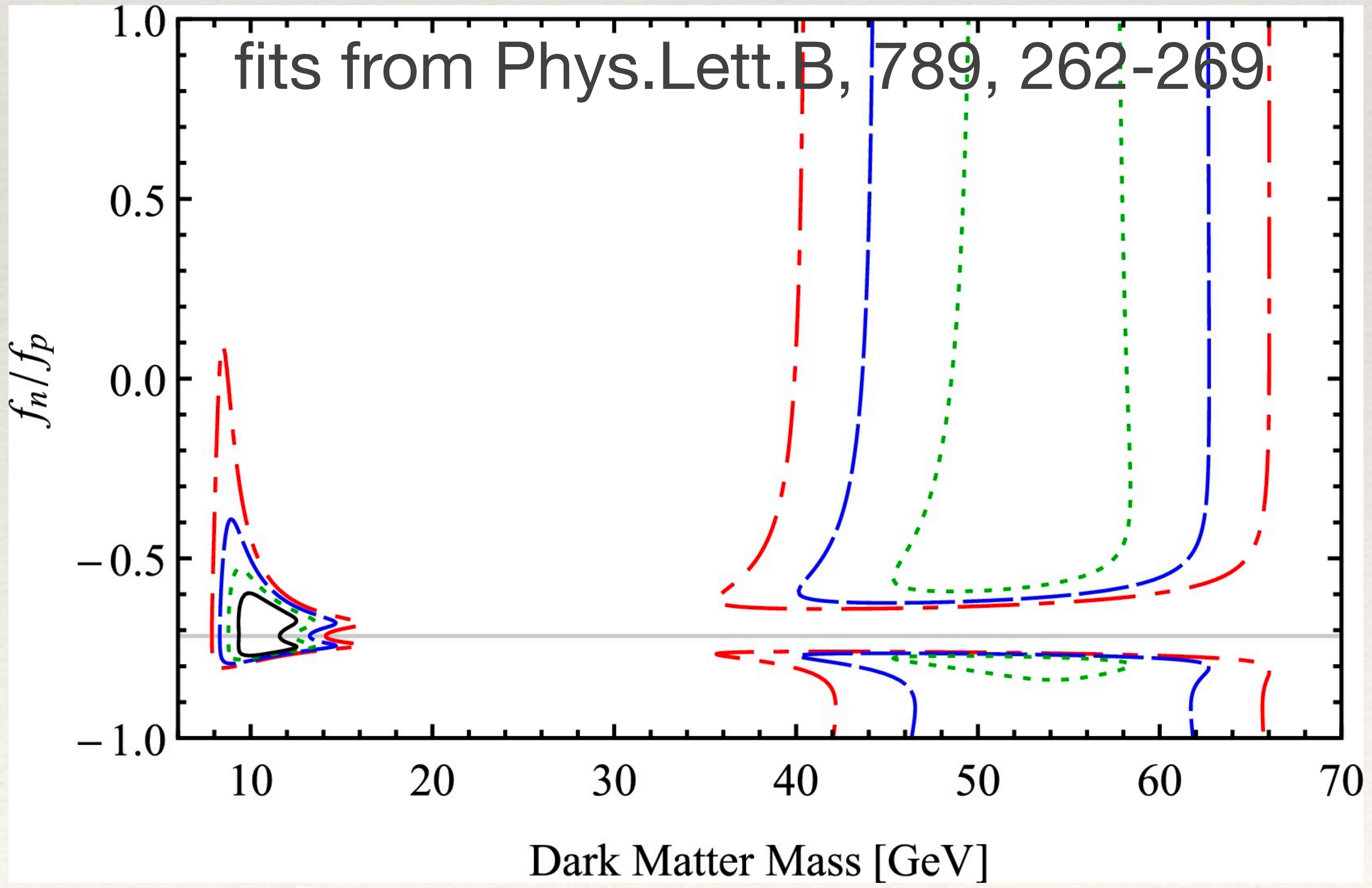
We will have definitive refutation (or confirmation) of the DAMA/LIBRA signal in NaI soon.

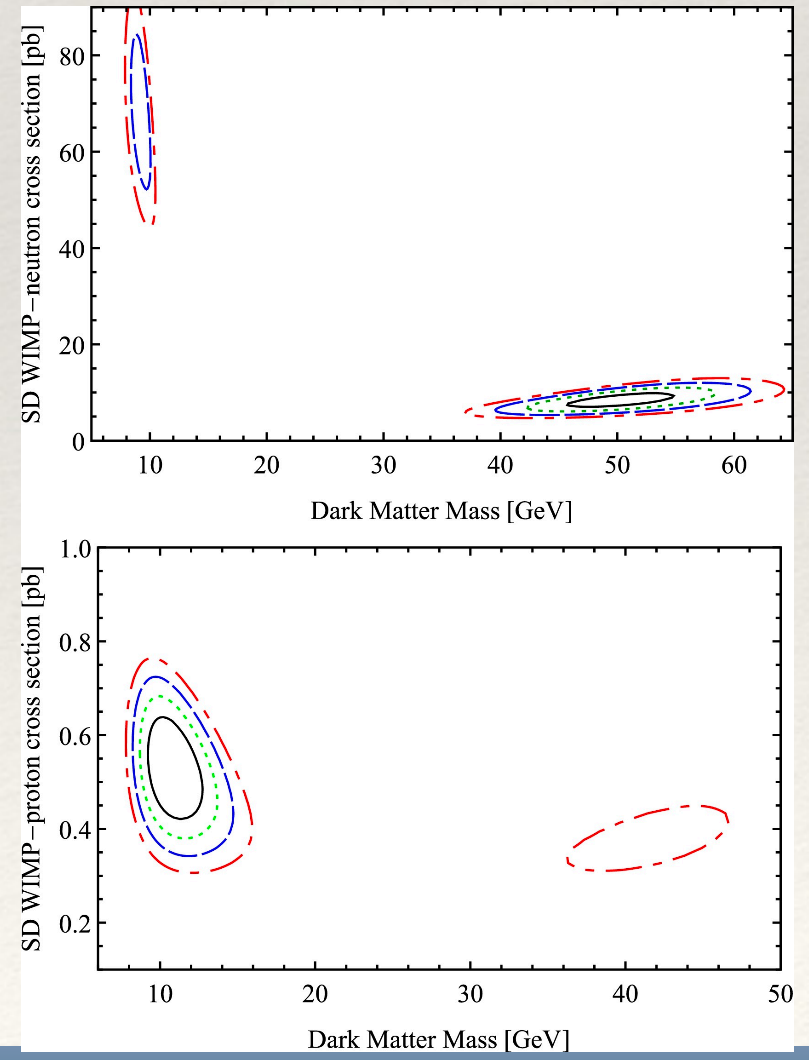
NaI crystals: DAMA/LIBRA signal

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)

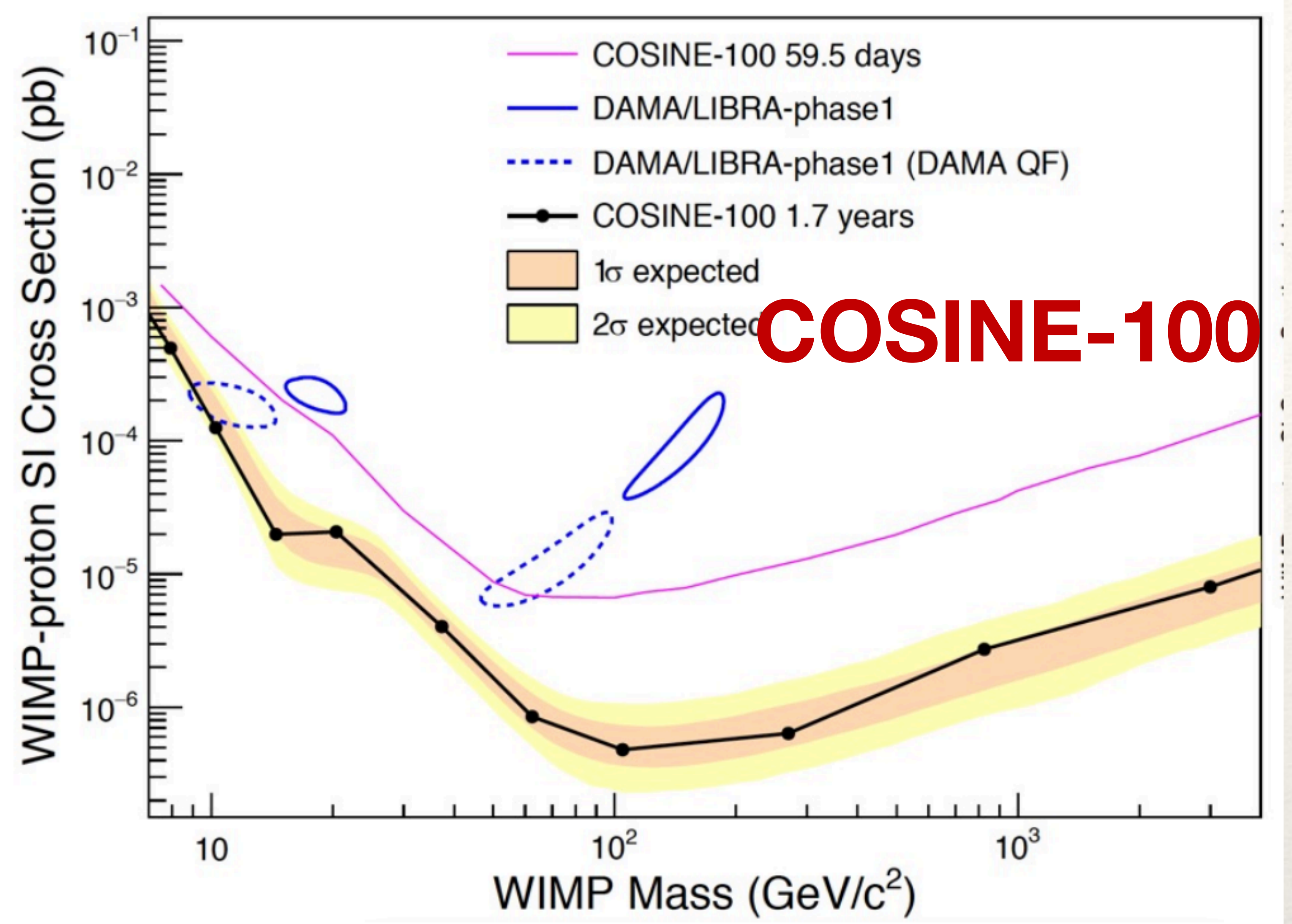
- Annual Modulation seen at $>13\sigma$
- Not SI isospin-conserving
- Isospin-violating SI at ~10 GeV/c²,
  - or SD at 10 or 45 GeV/c²
- Also studied with updated quenching

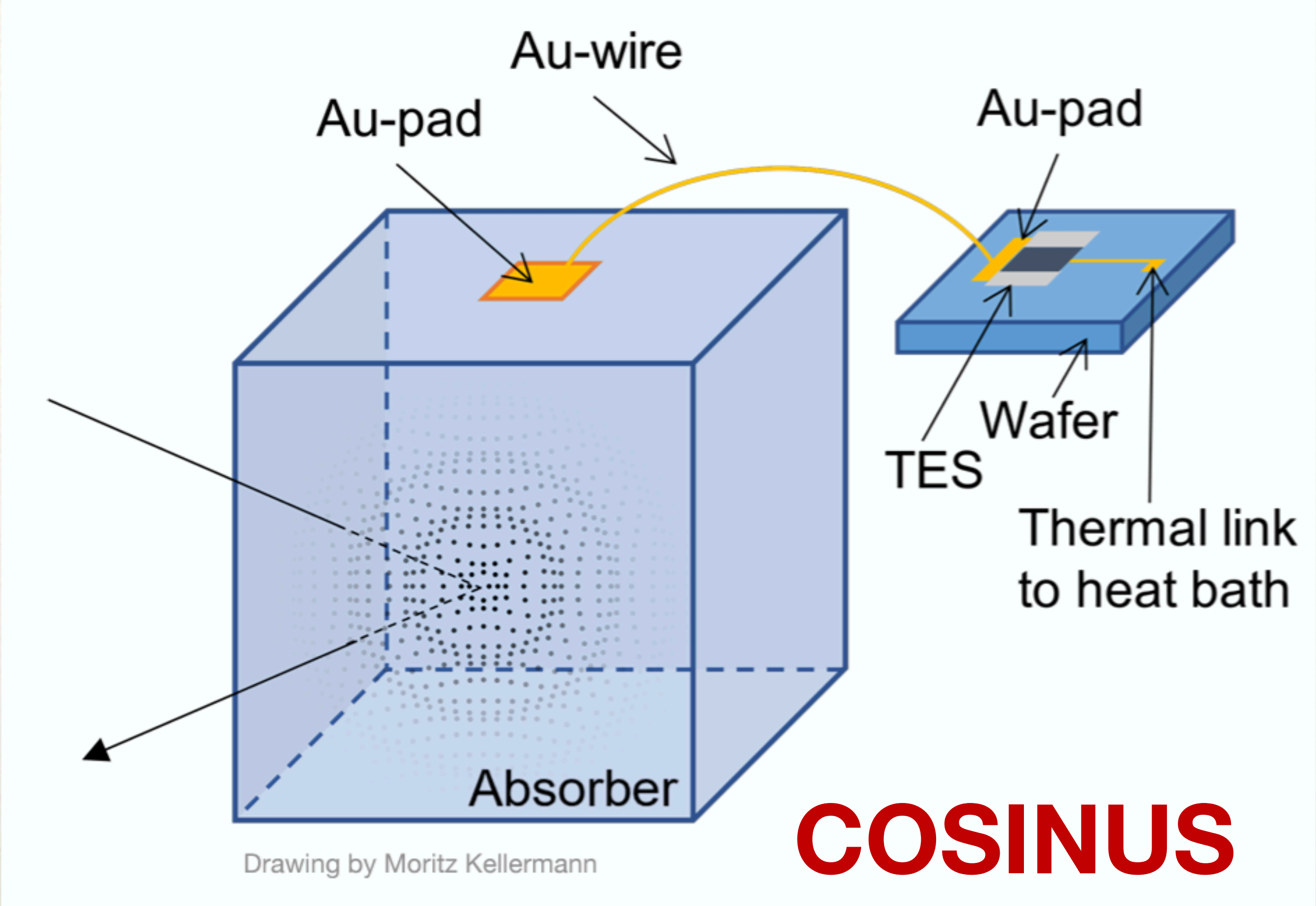






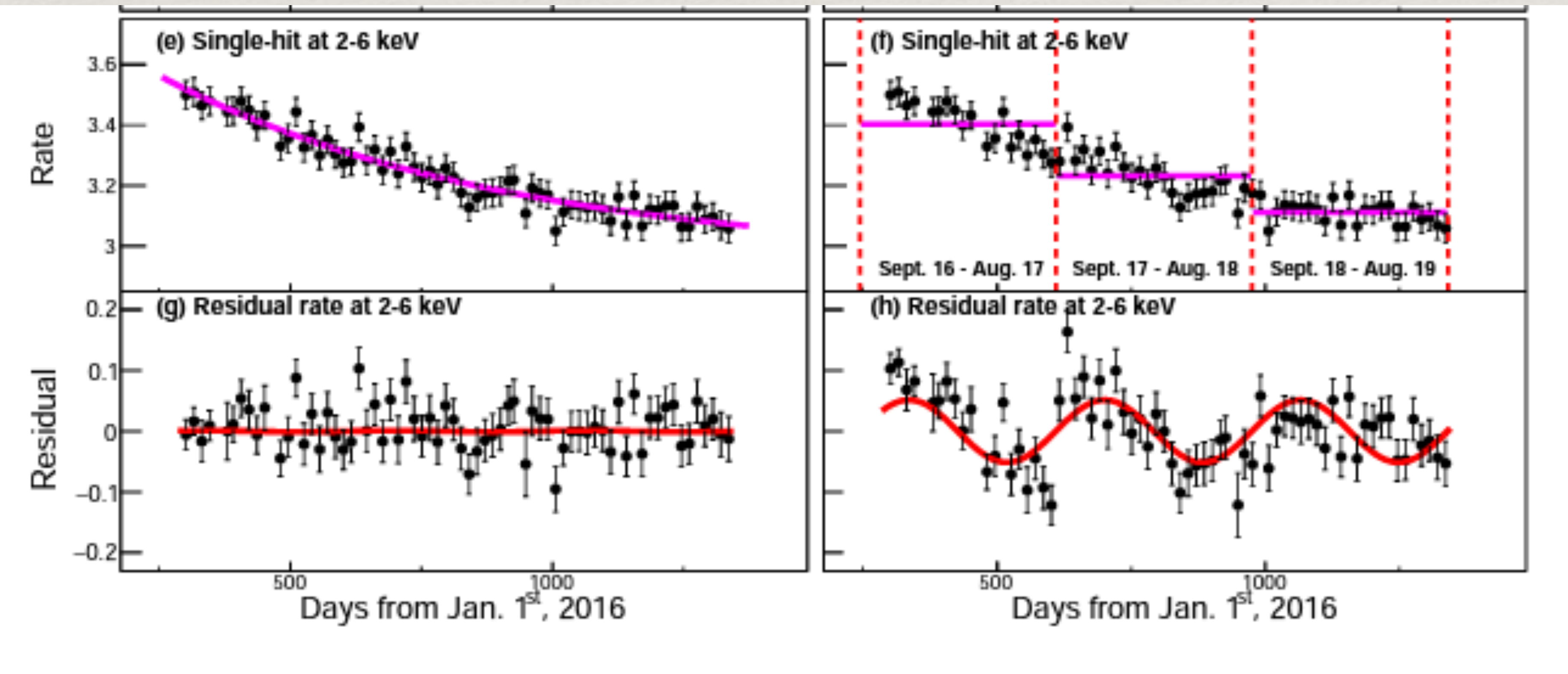
NaI tests: ongoing and future

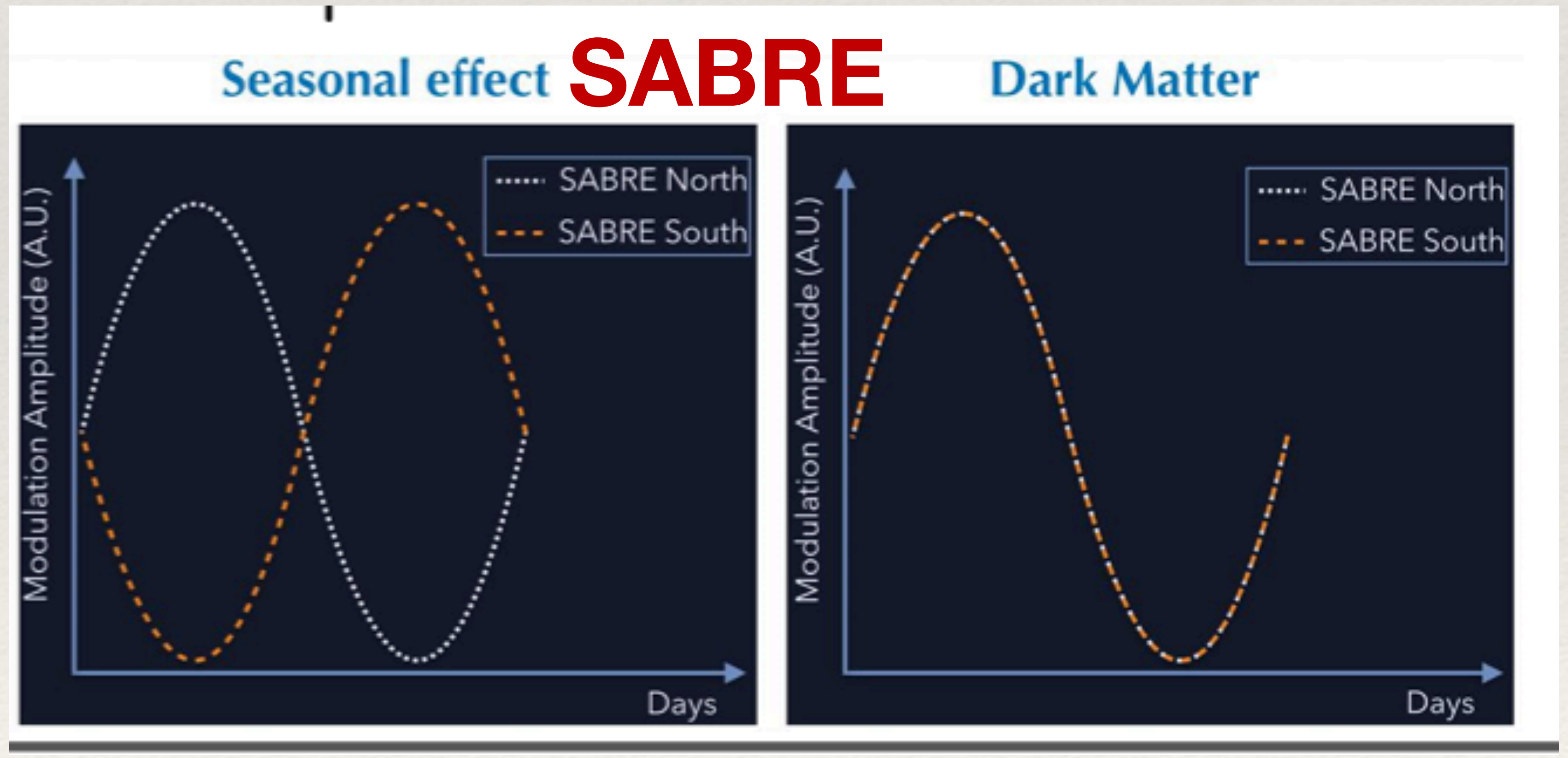


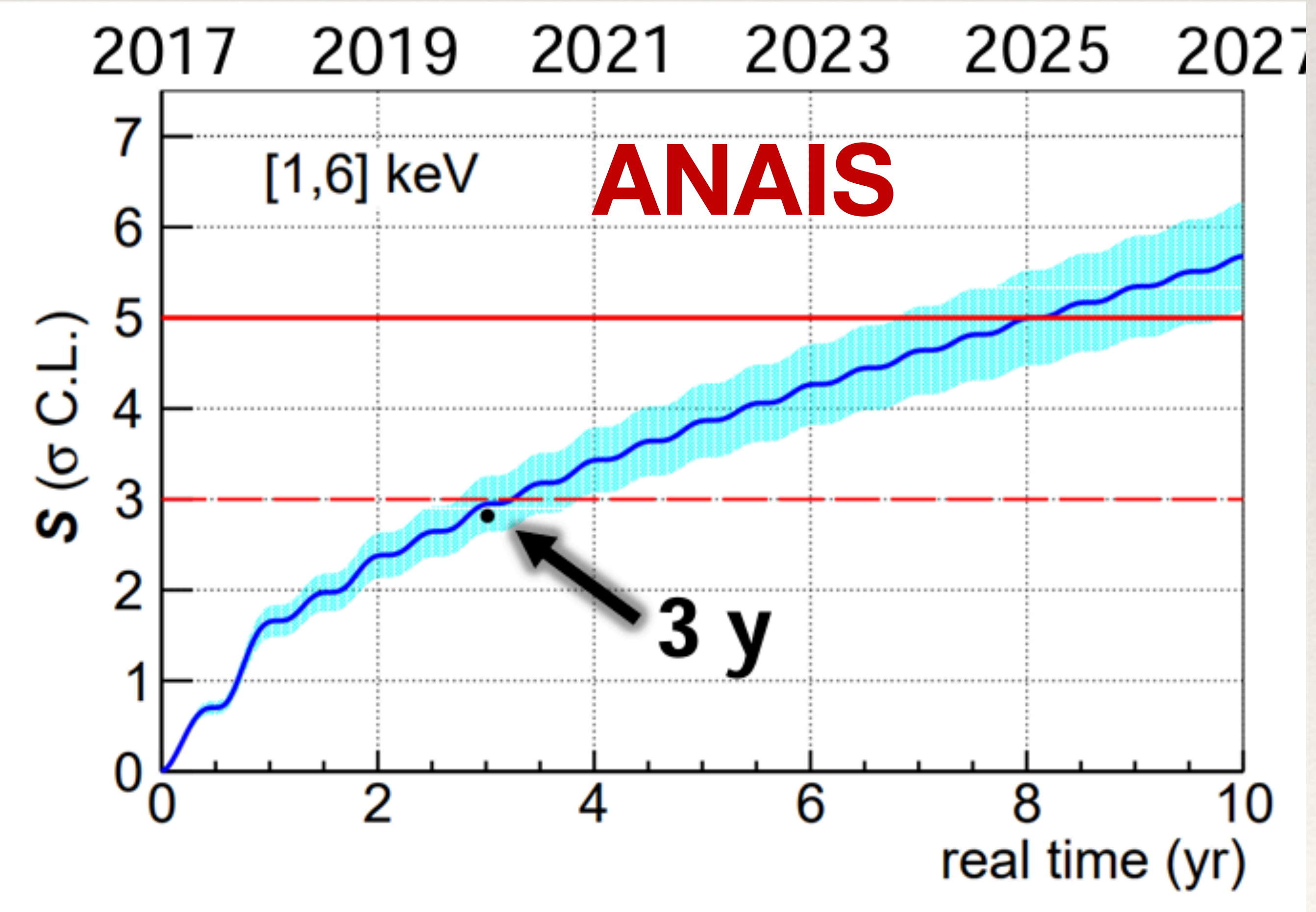


- Multiple NaI detectors - we'd like to know the cause of the modulation, not just rule out DM.
- ANAIS-112, running, could be on track for 5 σ rejection of DAMA by 2025.
- COSINE saw that how calibrations are handled can induce a modulation of residuals, Moved lab in 2023.
- COSINUS cryogenic search with discrimination, starting this year.
- SABRE: low bkgd crystals, with Northern and Southern sites, also starting this year.

SciAdv 7 46 '21

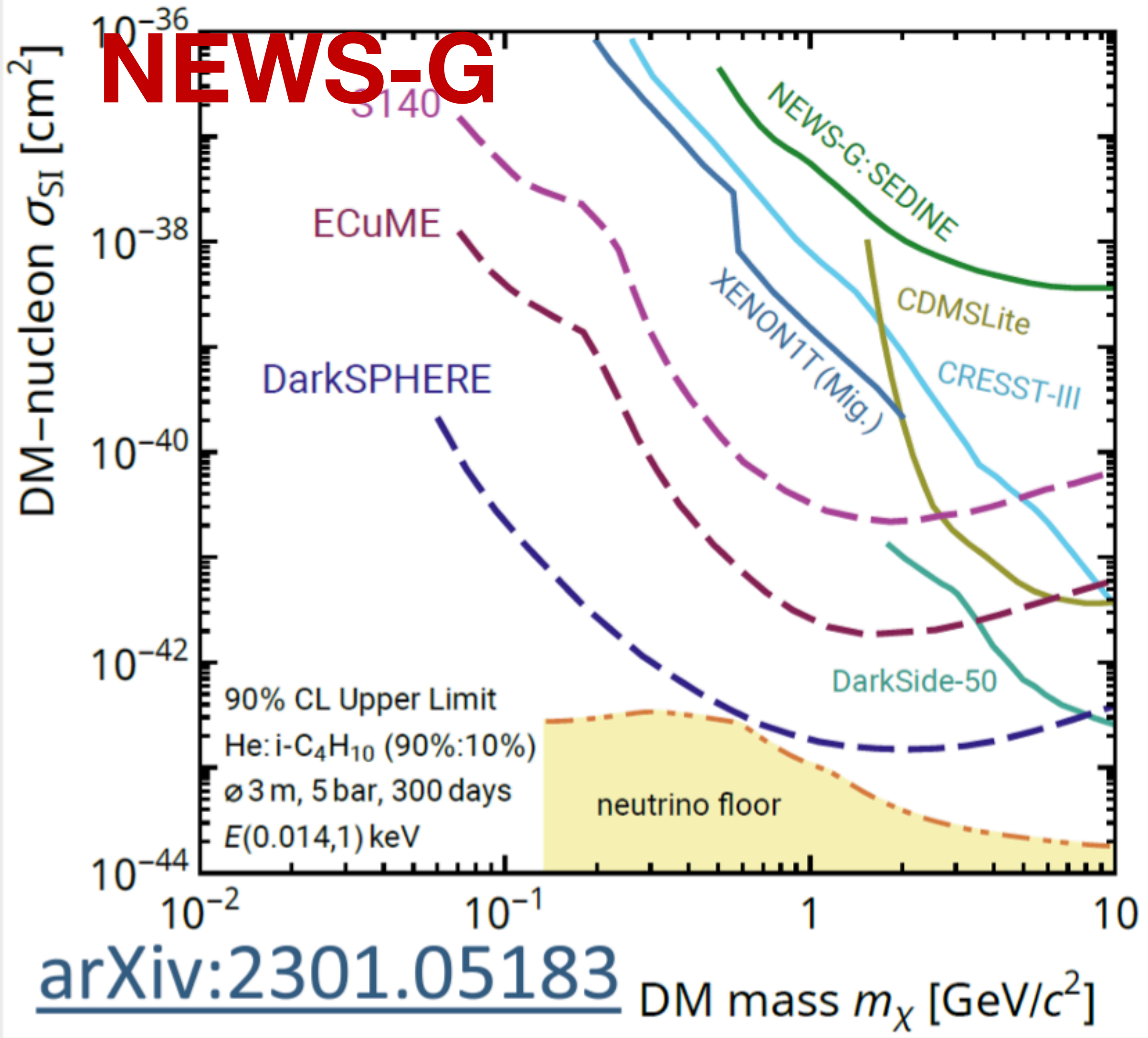




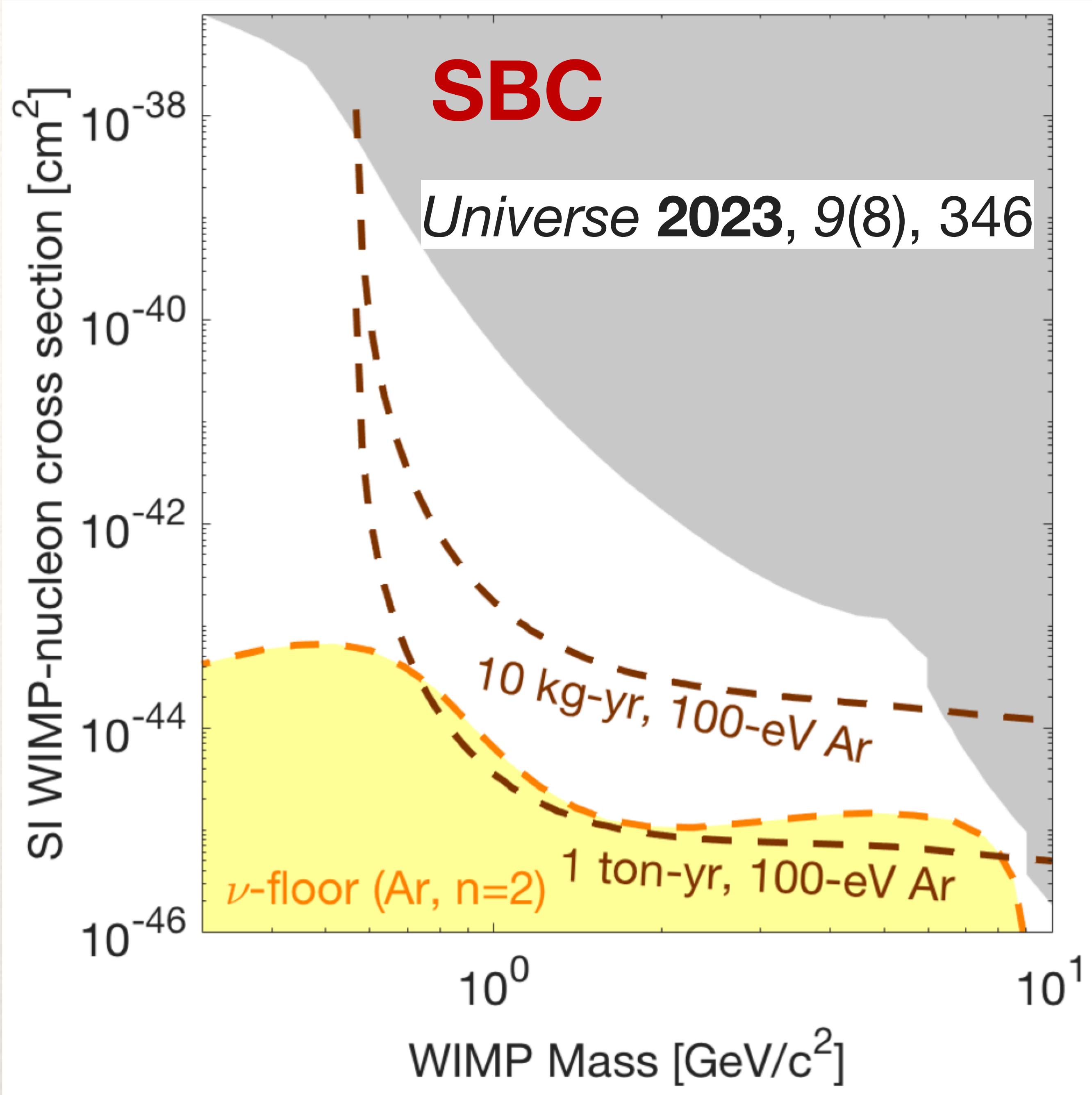


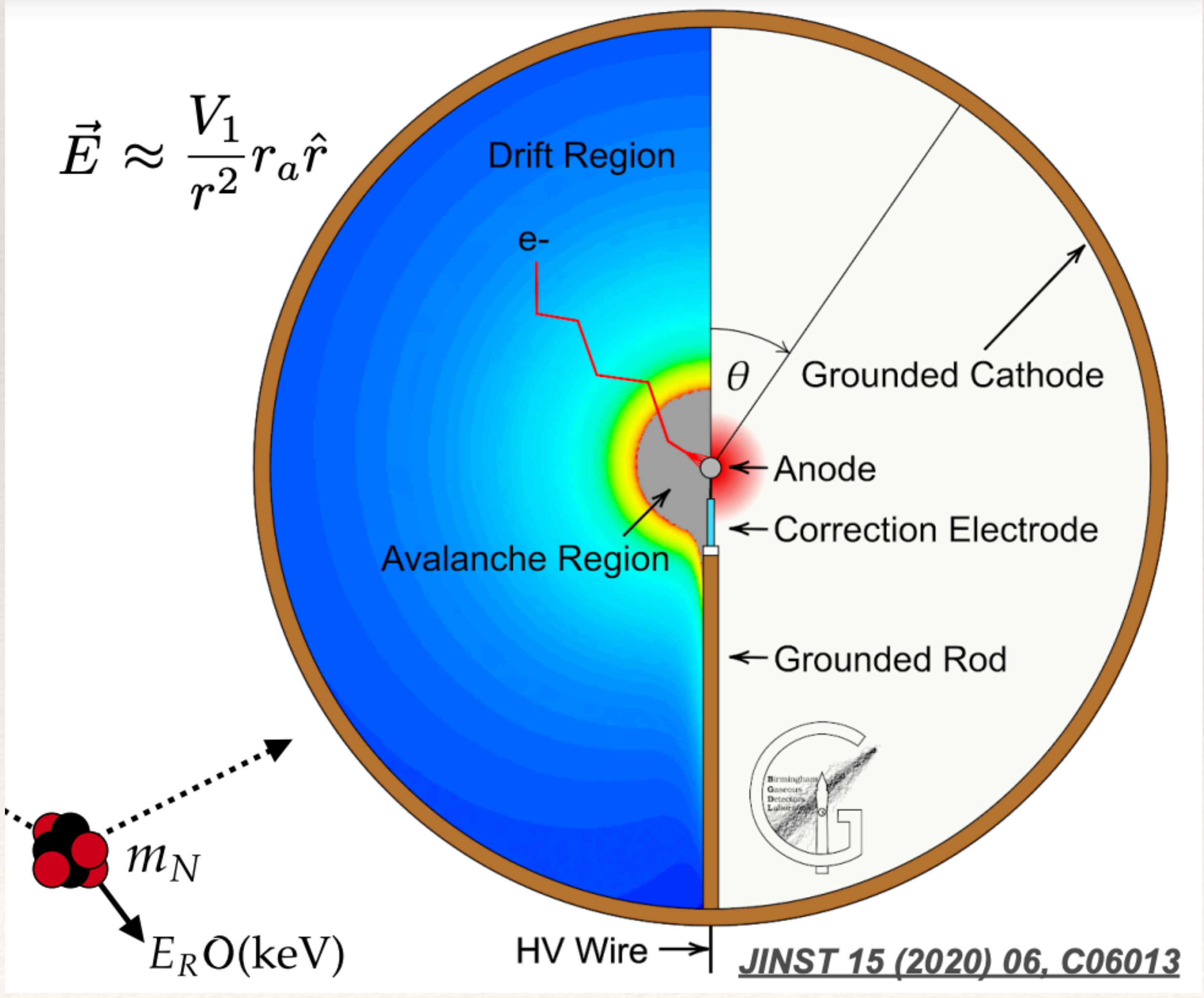
Is it just an analysis artifact? arXiv:2208.05158

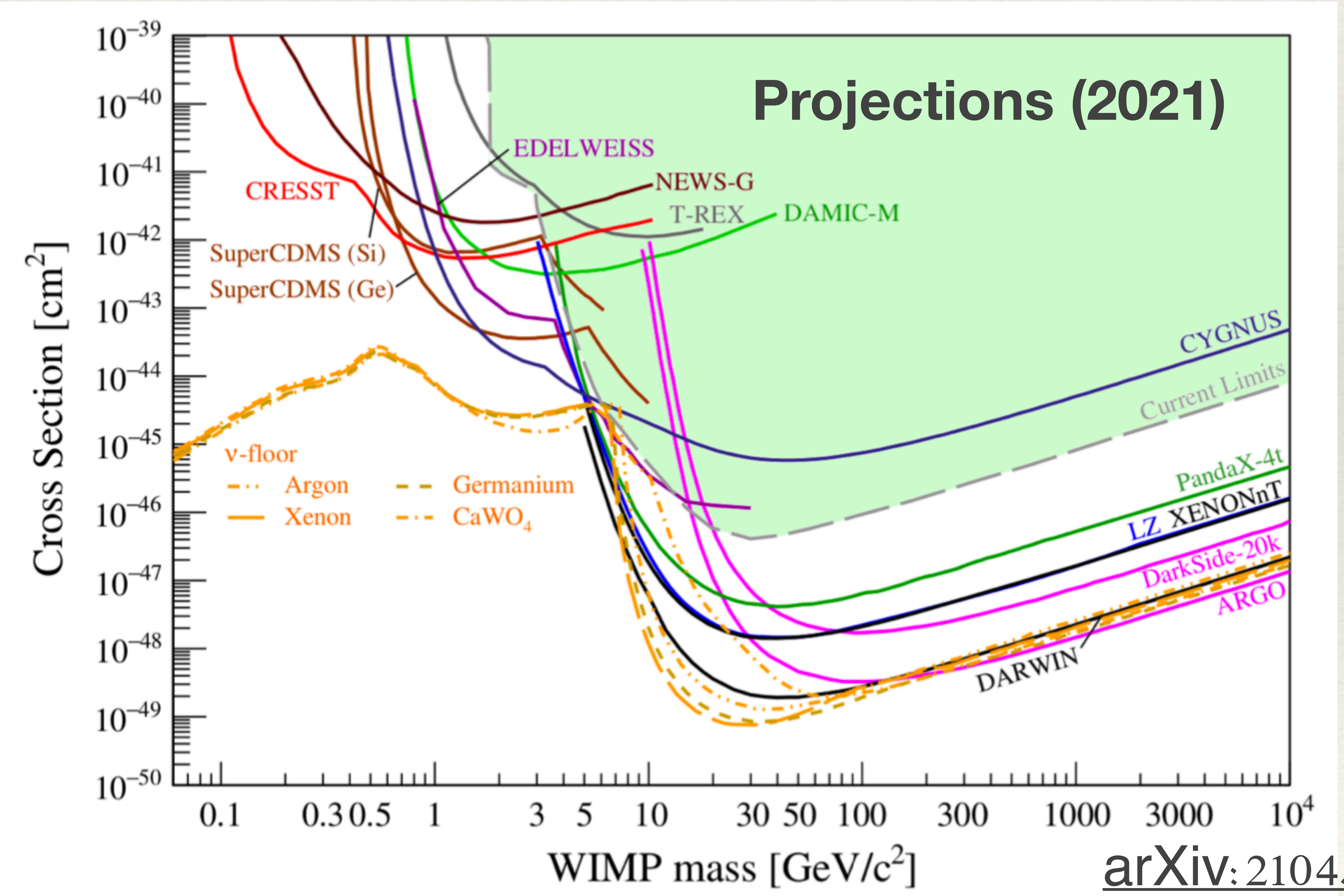
Technologies new and old

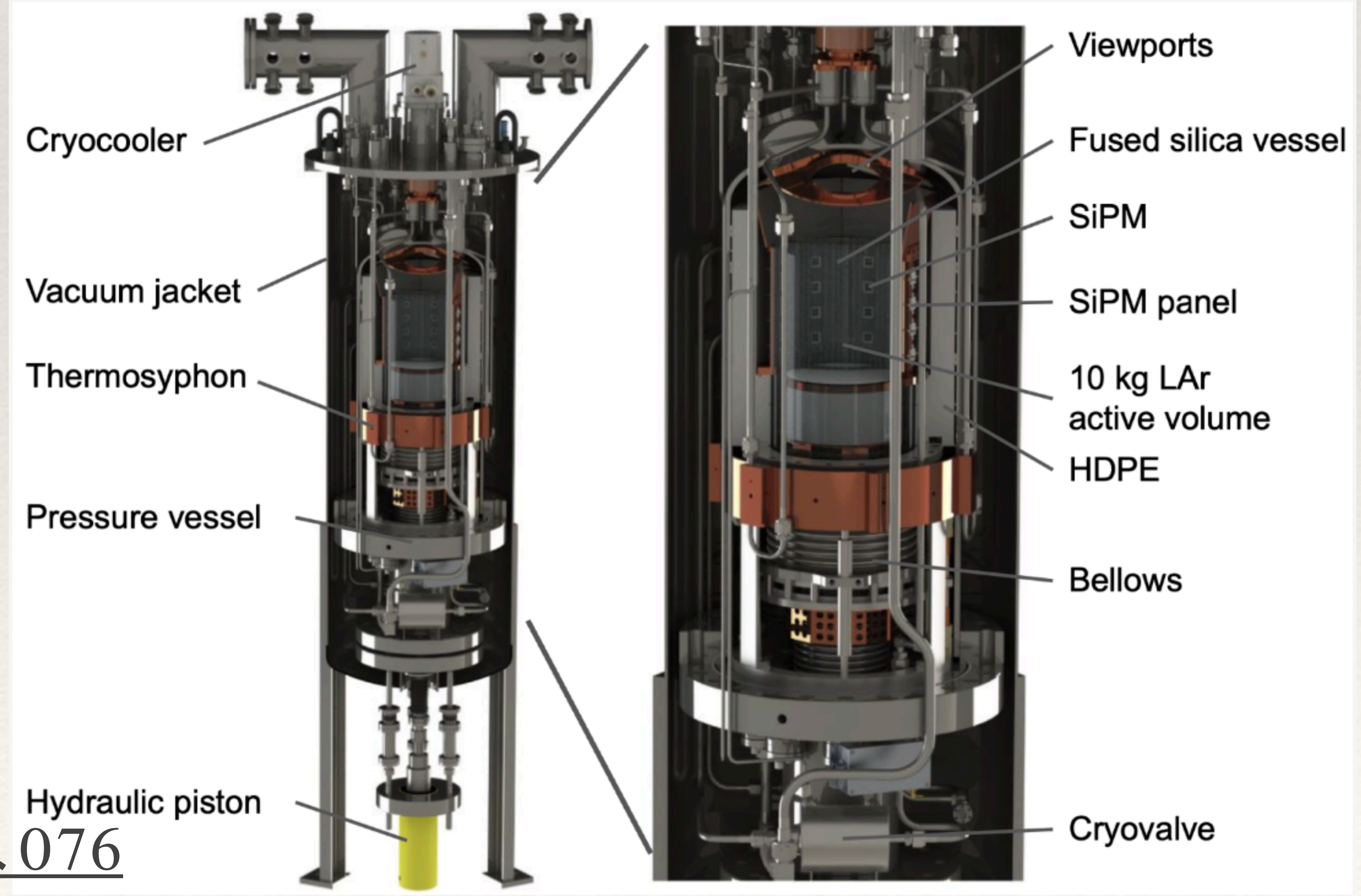


- Signals from nuclear recoils
- Semiconductor targets: Si, Ge
- Scintillating bolometers CaWO4
- Spherical Proportional Counter
- Scintillating Bubble Chamber (LAr)

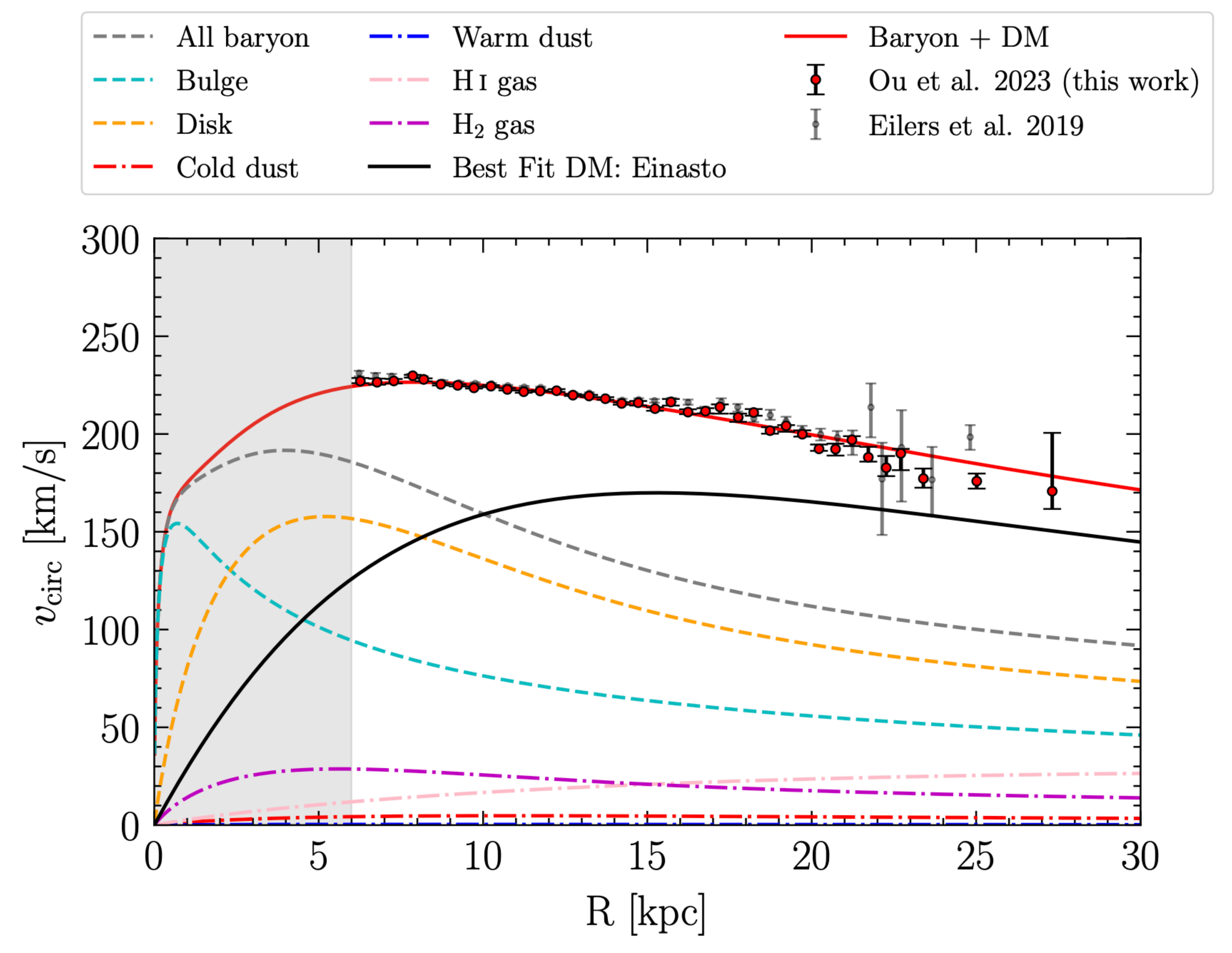






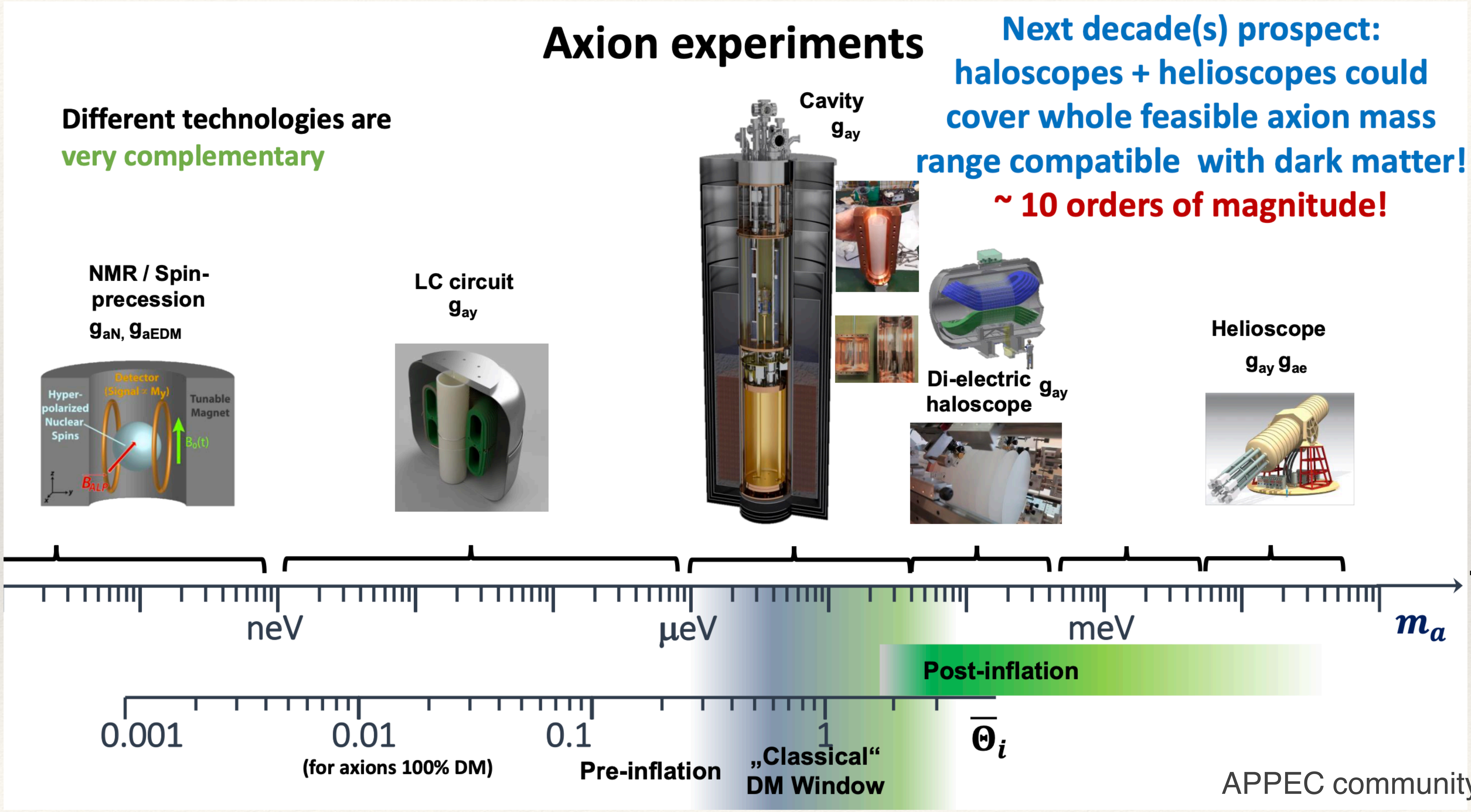


Milky Way Galactic Rotation Curve



- Updated with Gaia, 2MASS and WISE
- Galaxy model: best fit cored Einasto
- arXiv:2303.12838

Axions and Bosonic Dark Matter



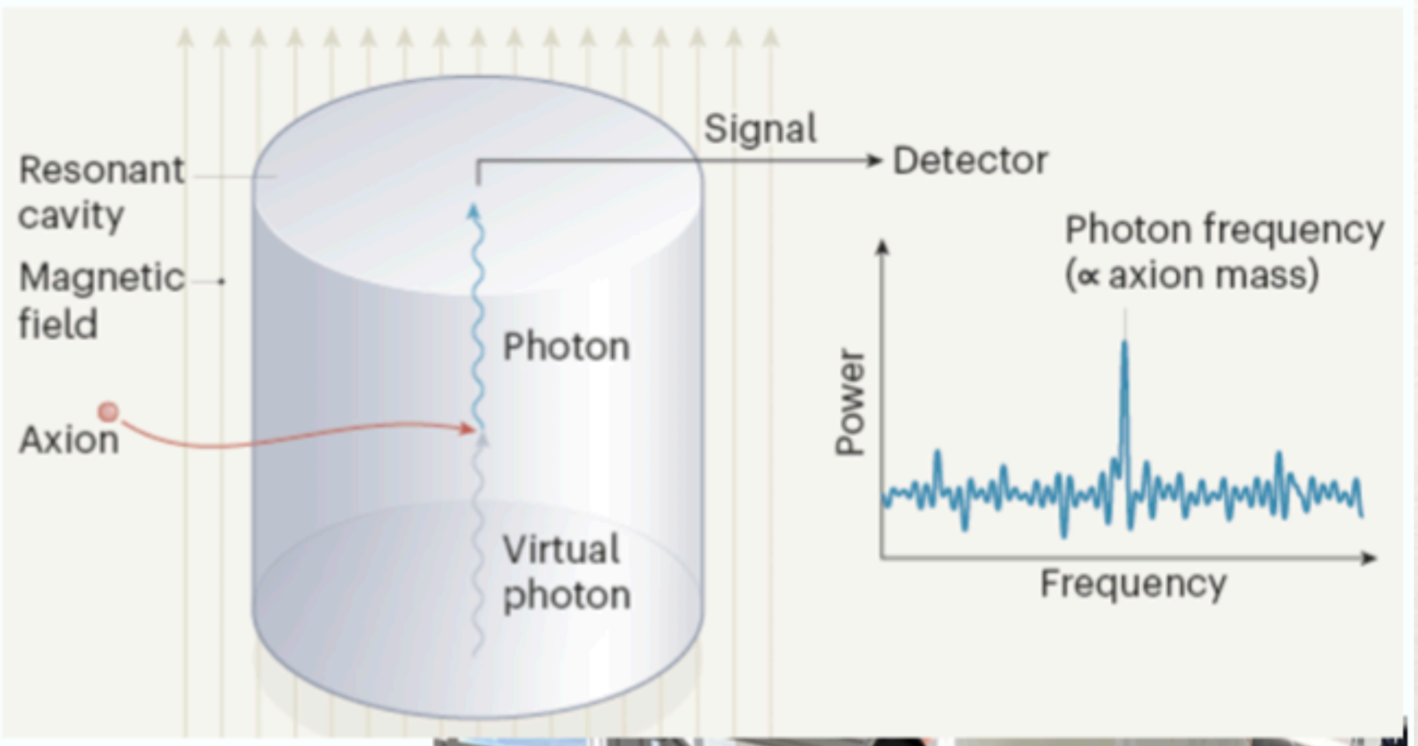
APPEC community discussion slides

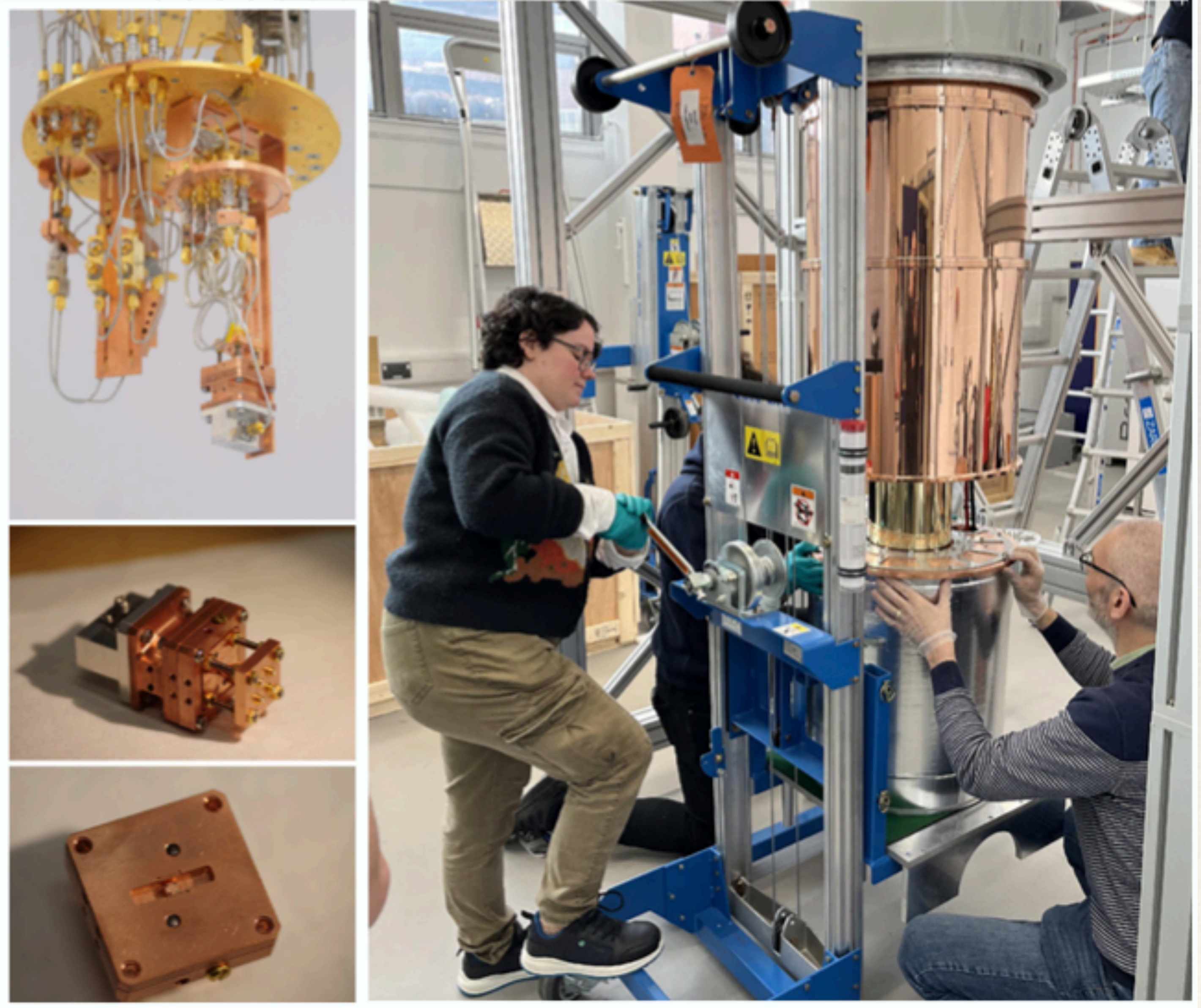
Many ways
to get axions
in theories

Many ways to
look
for axions
in
experiments

UK efforts in Wavelike DM*

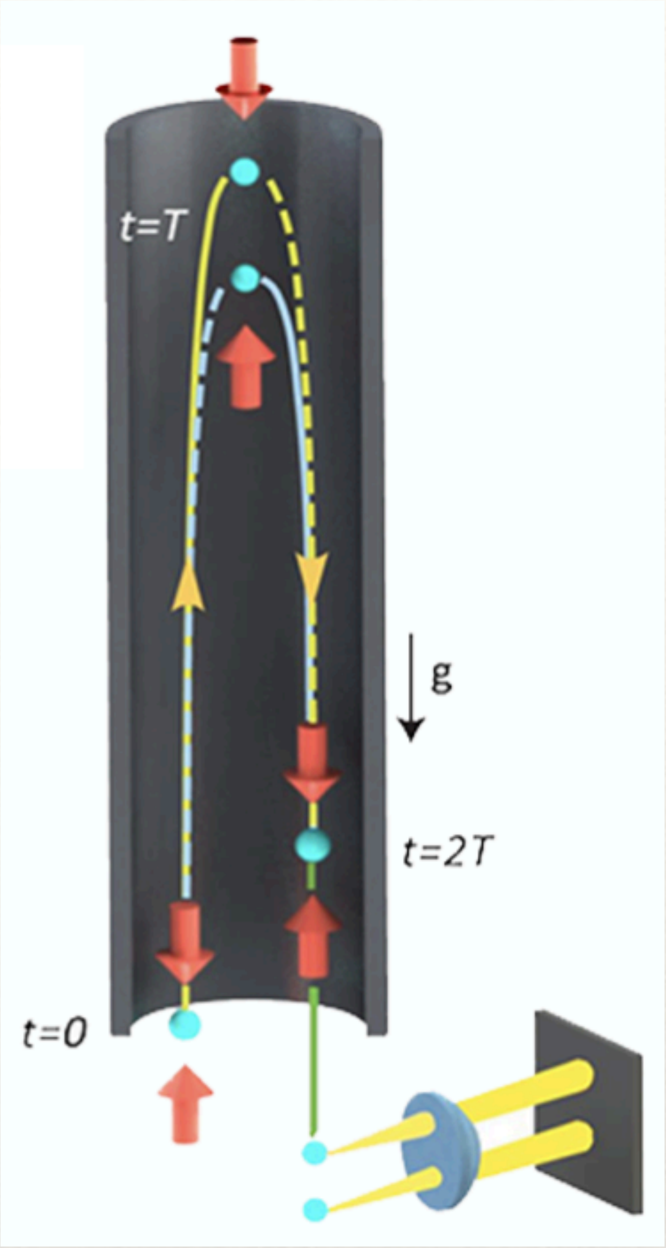
Quantum Sensors for the Hidden Sector

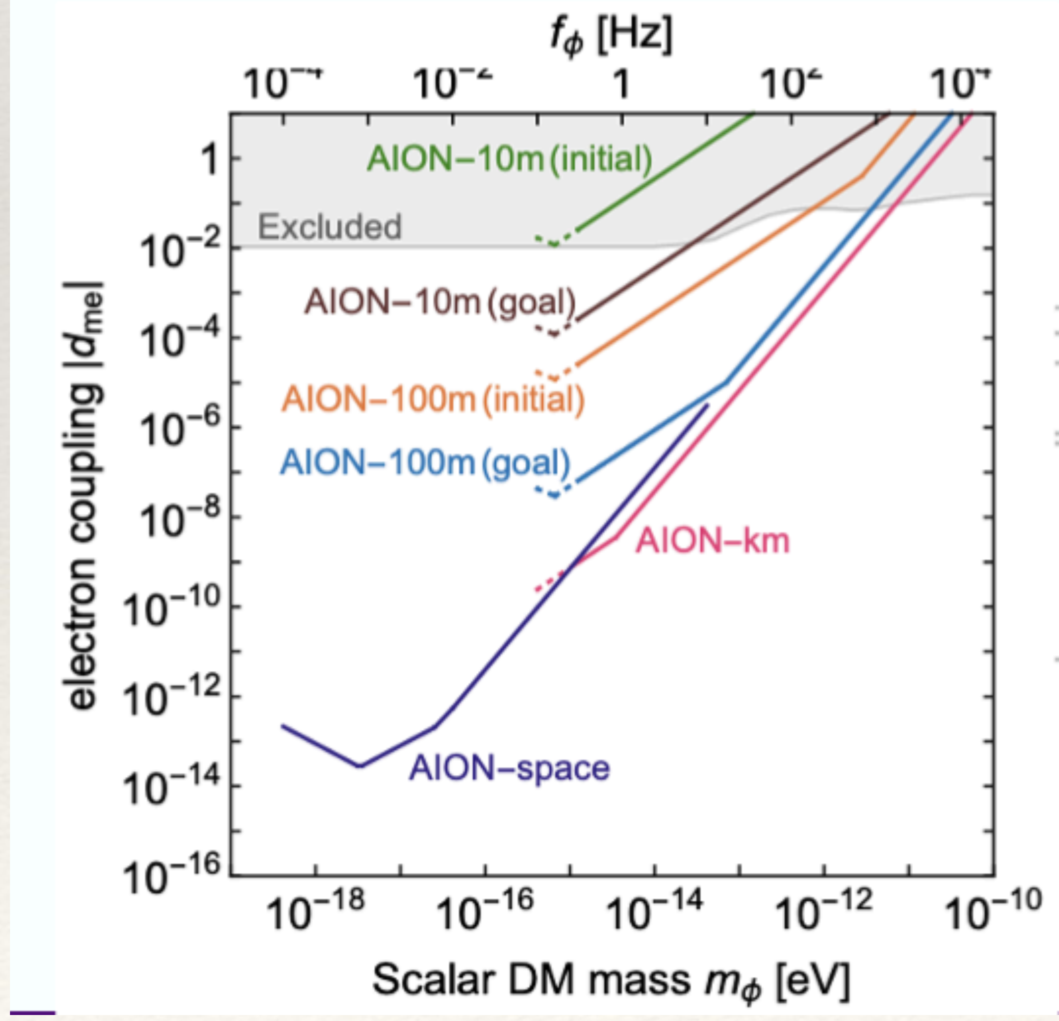




*more tomorrow

- QTFP Funded
- **QSHS** is working on quantum enhanced scanning of the QCD axion parameter space, MOU with ADMX
- **AION** has access to scalar dark matter, and gravitational waves in its larger incarnations, MOU with MAGIS
- Many other projects are also exploring the dark sector, including the newer 2022 grantees!

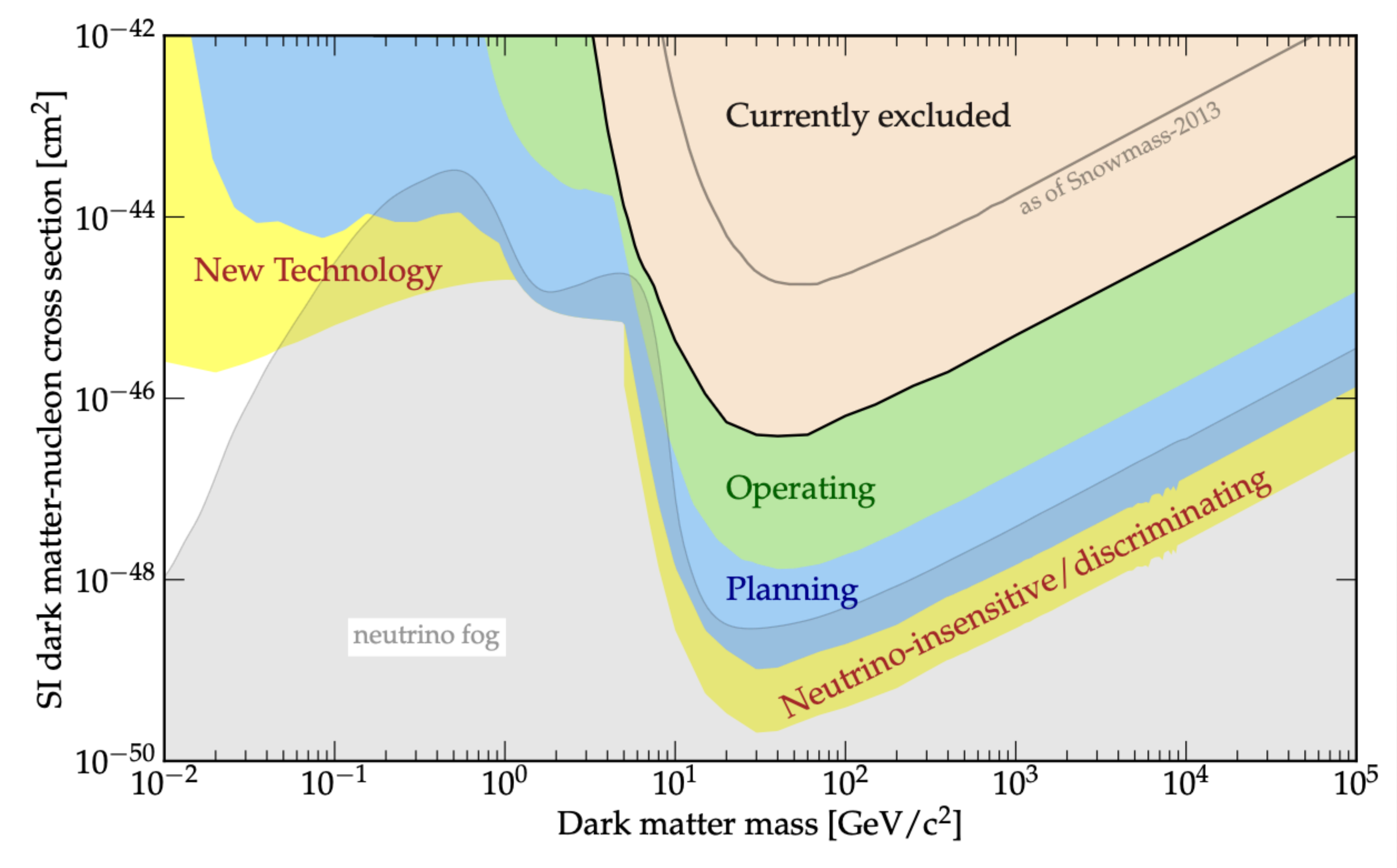


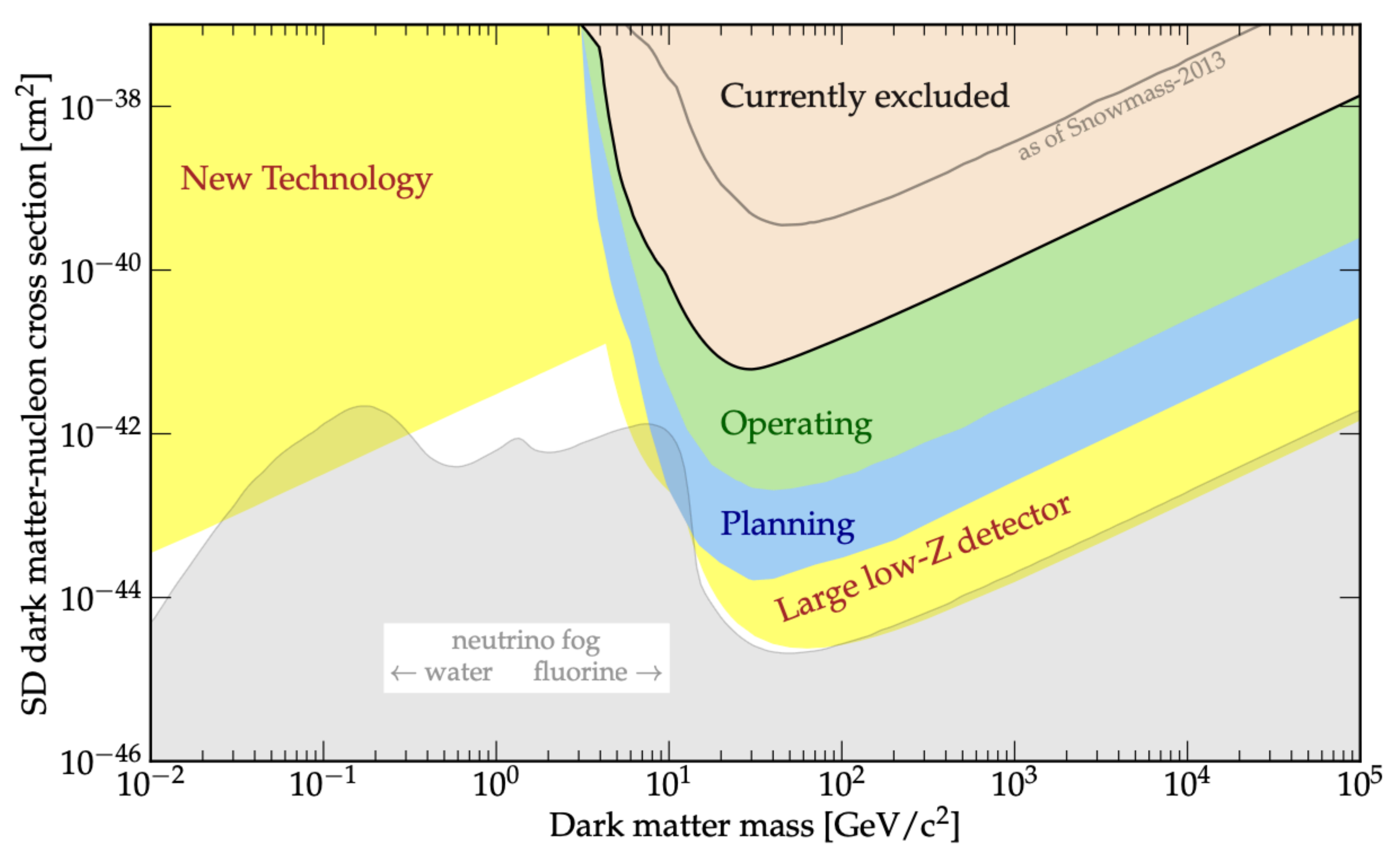


A quantum jump sensor for dark matter detection
Institution: Imperial College London
Principal investigator: J. Devlin

- **Development of levitated quantum optomechanical sensors for dark matter detection**
  Institution: UCL
  Principal investigator: P. Barker

Direct Detection Sensitivities





arXiv: 2203.080