

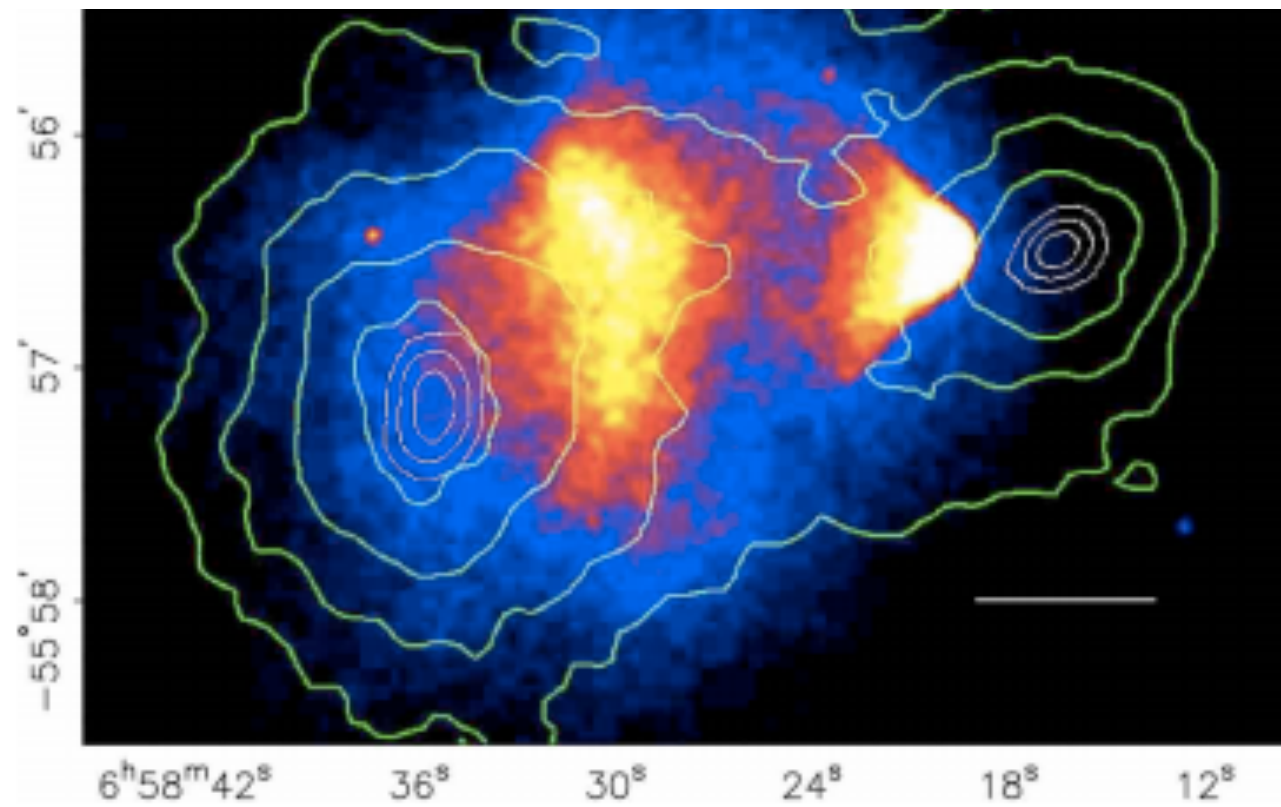
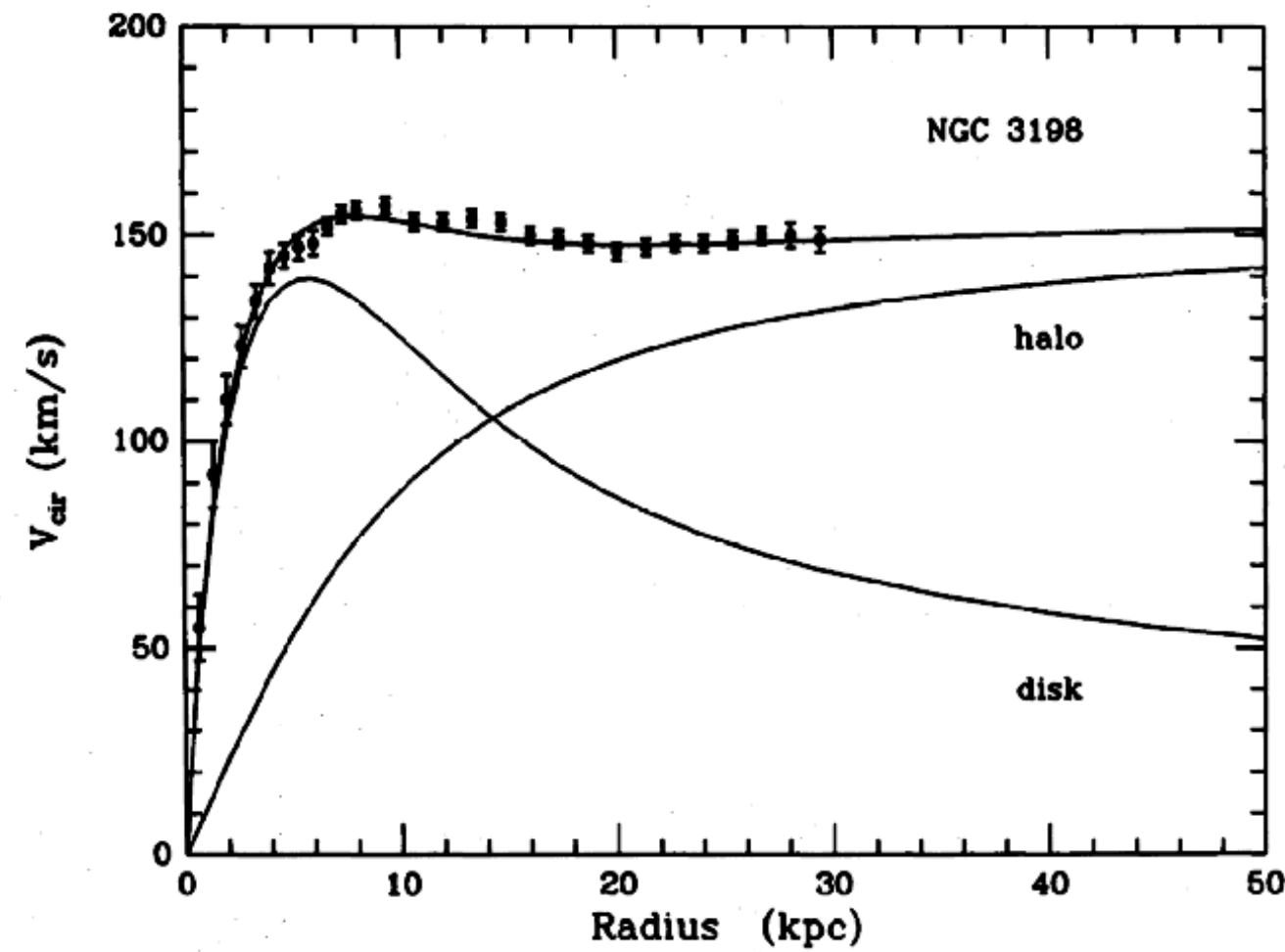
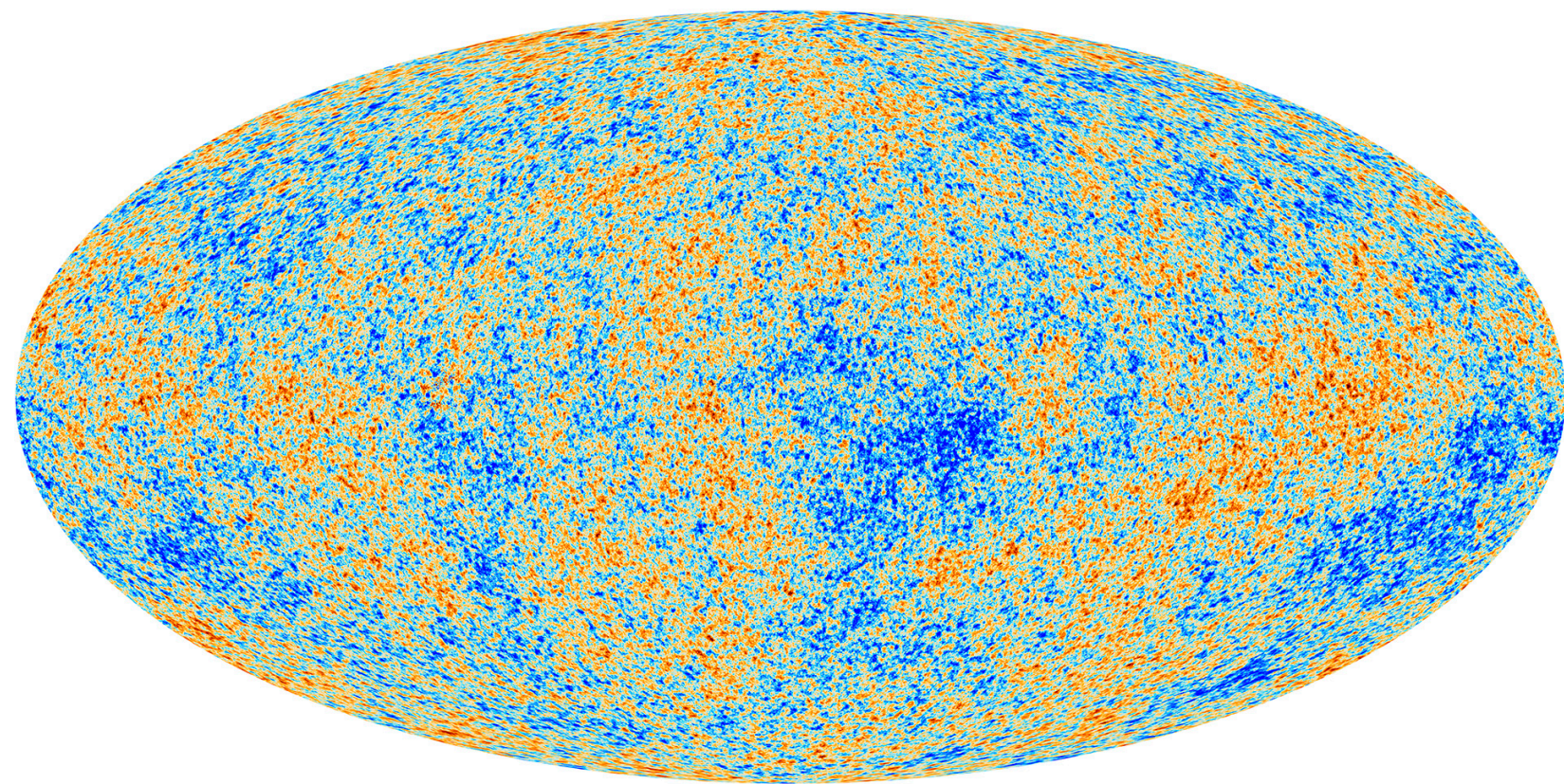
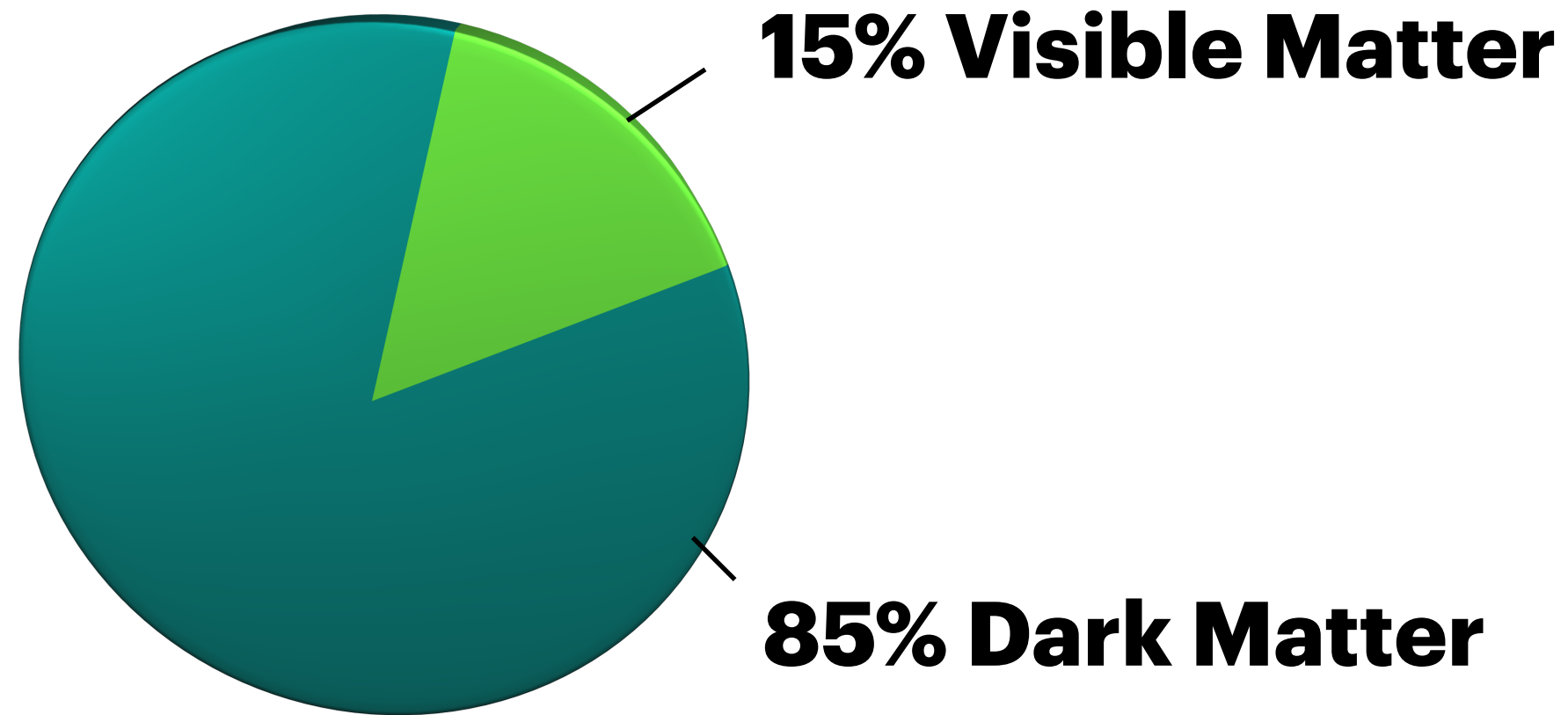
The background features a cosmic scene with a bright star in the upper center, surrounded by a crosshair pattern. The background transitions from a dark blue/purple on the left to a lighter purple on the right, where a dark purple diagonal shape overlaps. The text is white and bold.

**Dark Matter:
Direct Searches
& Other Approaches**

Amy Cottle, UCL

IOP Joint APP, HEPP & NP Annual Conference '24

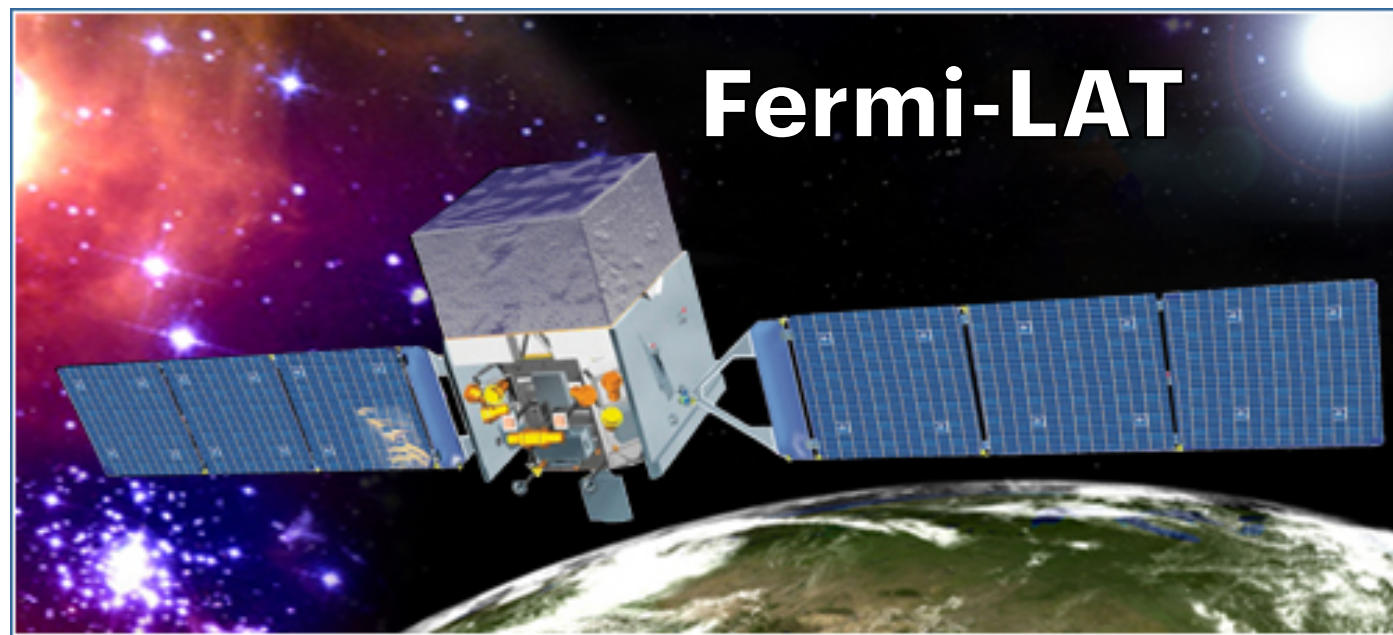
How Do We Know Dark Matter Exists?



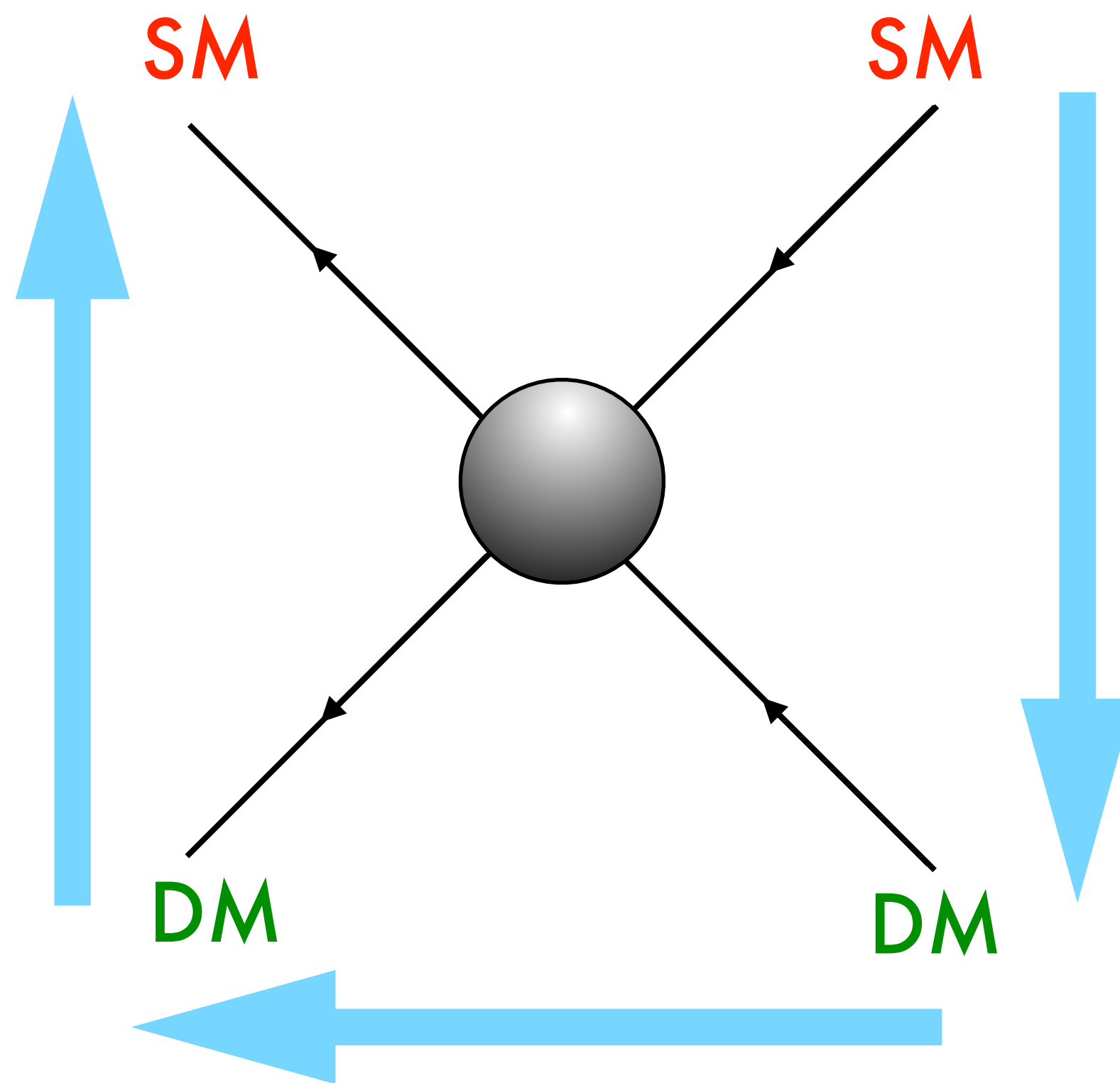
Astrophysical observations: gravitational interactions with ordinary matter

How Might We Find & Study Dark Matter?

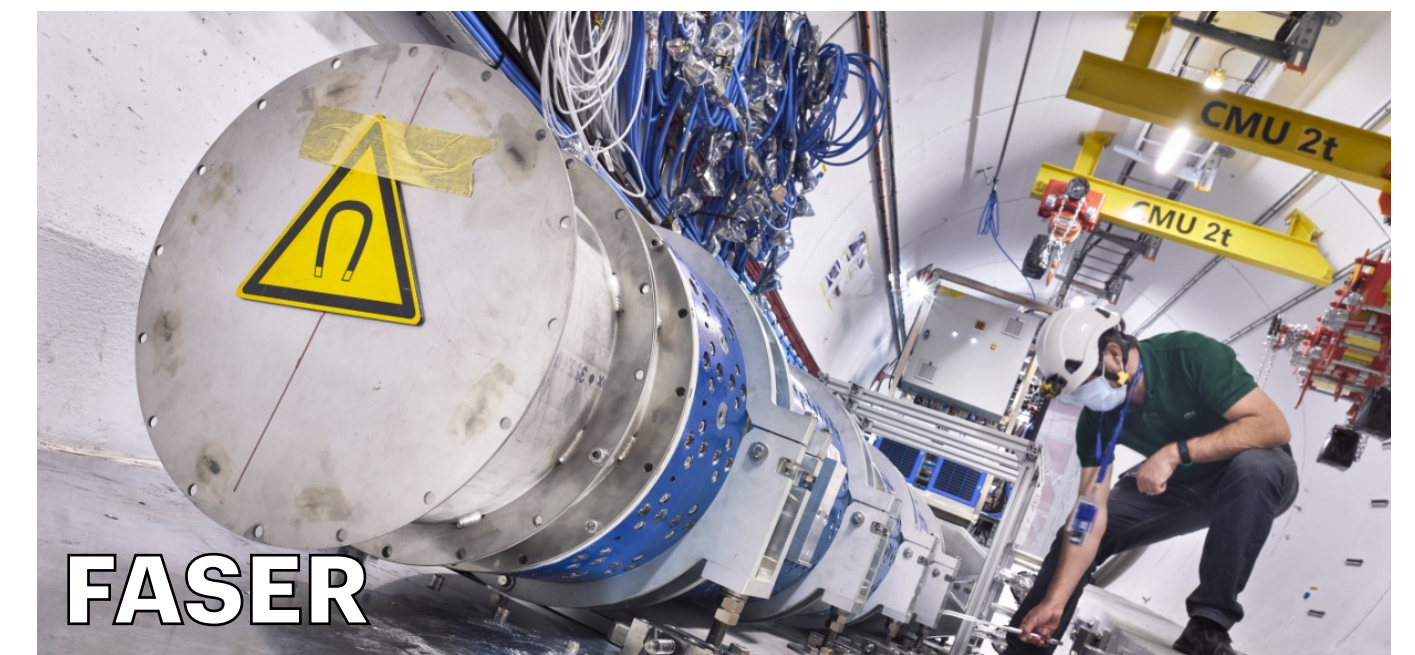
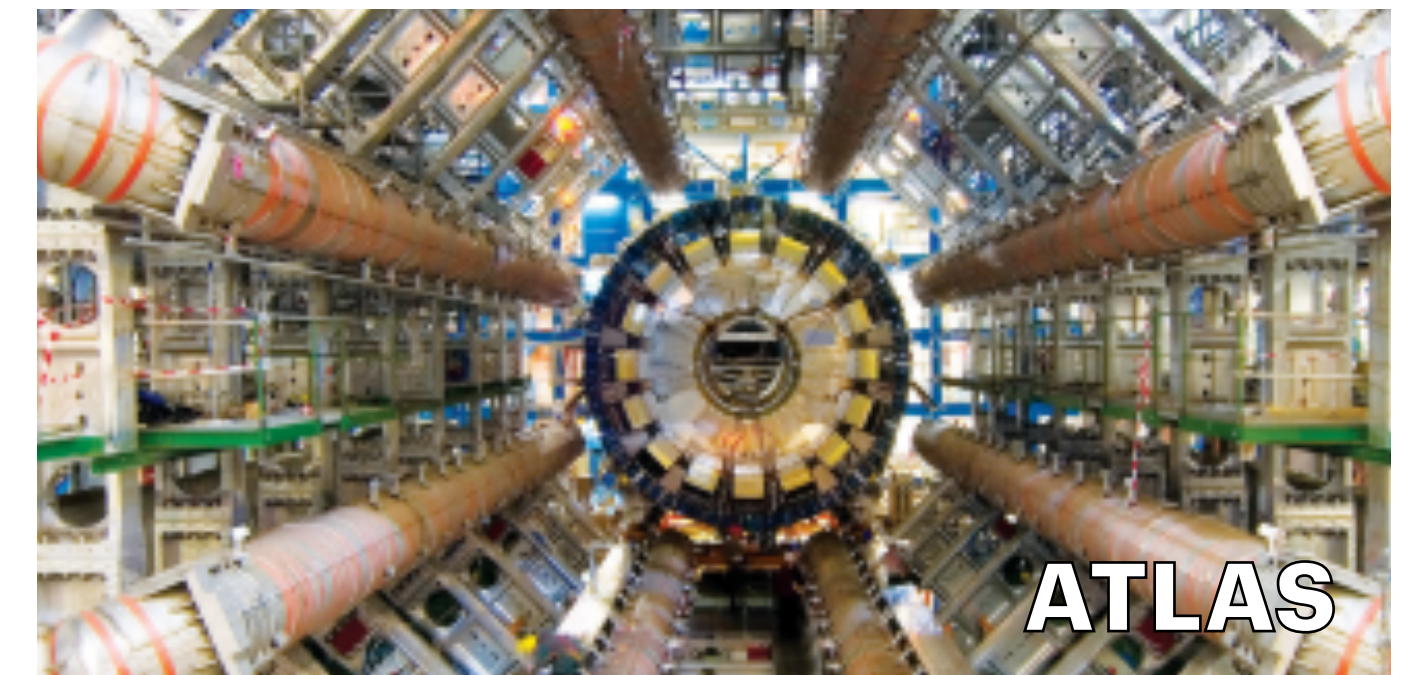
Indirect Detection



Annihilation/conversion/
decay products:
neutrinos, antimatter, γ -rays



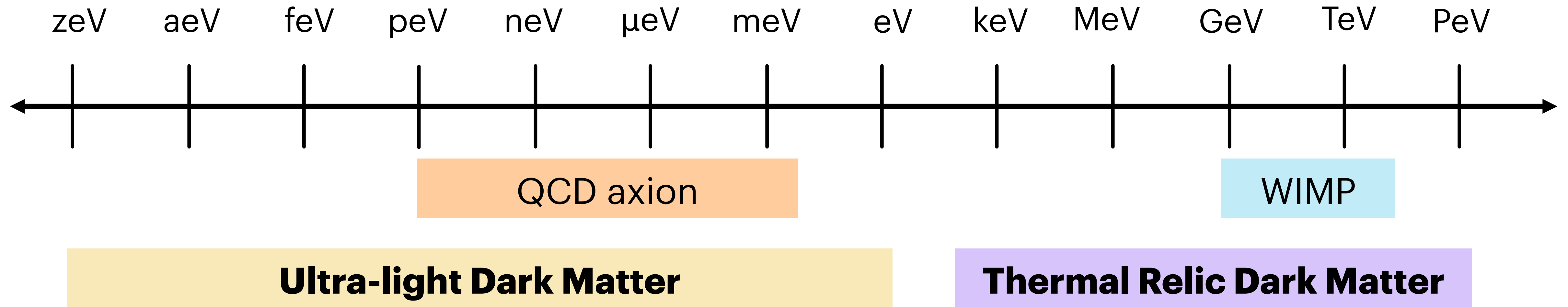
Accelerator Production



Collider, beam dump, fixed target:
Missing momentum searches;
reconstructed long-lived decays

Direct Detection
→ **this talk will focus**
on recent UK efforts

What Could Dark Matter Be?



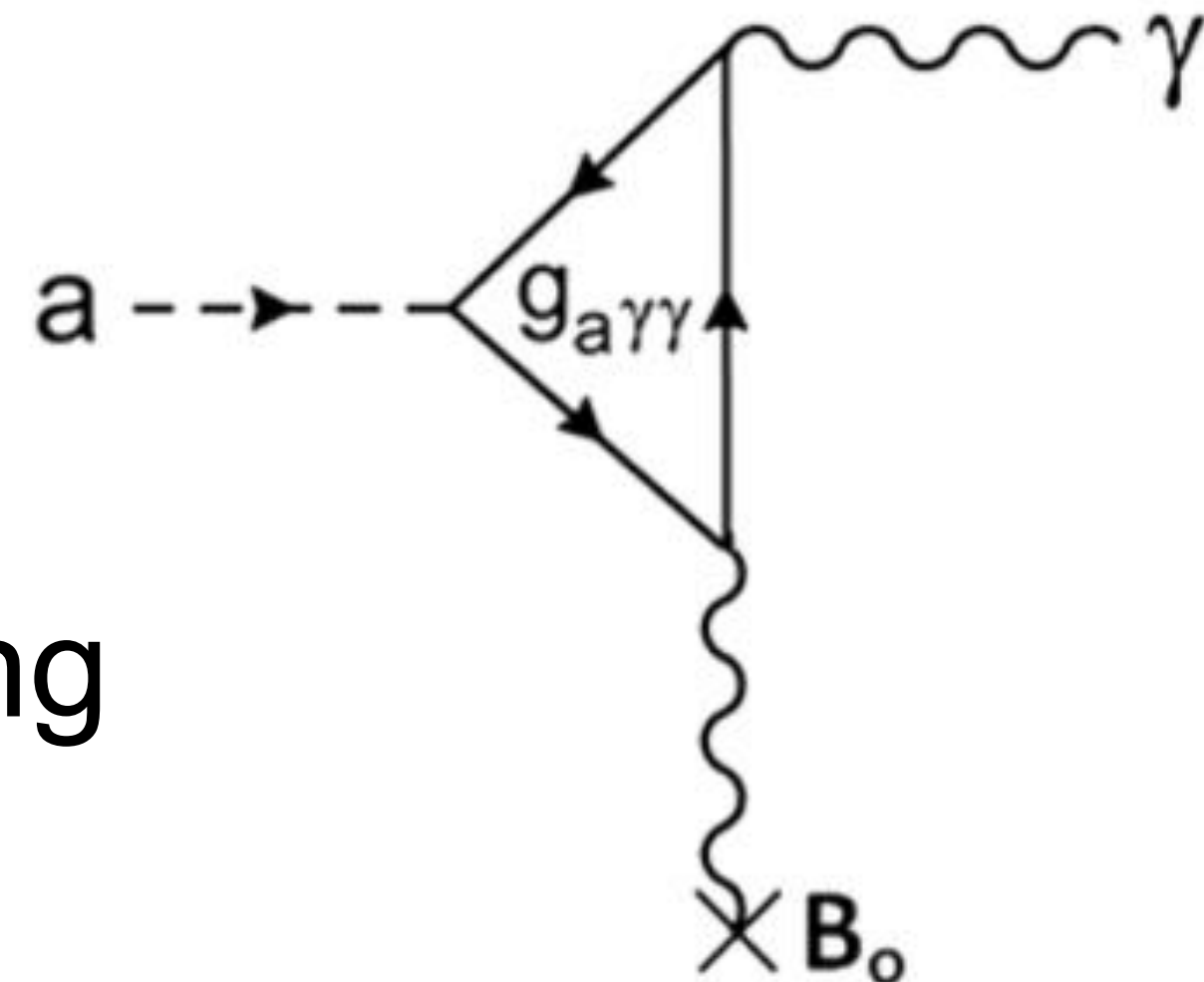
- **Ultra-light dark matter** - wave-like; sub-keV bosonic particles
→ E.g. axions, axion-like particles (ALPs), dark photons
- **Thermal relic dark matter** - particle-like; early universe freeze-out
→ E.g. weakly interacting massive particles (WIMPs); hidden sector DM

Focus on Axions & WIMPs

Axions

Why?

Arise from Peccei-Quinn solution to Strong CP problem



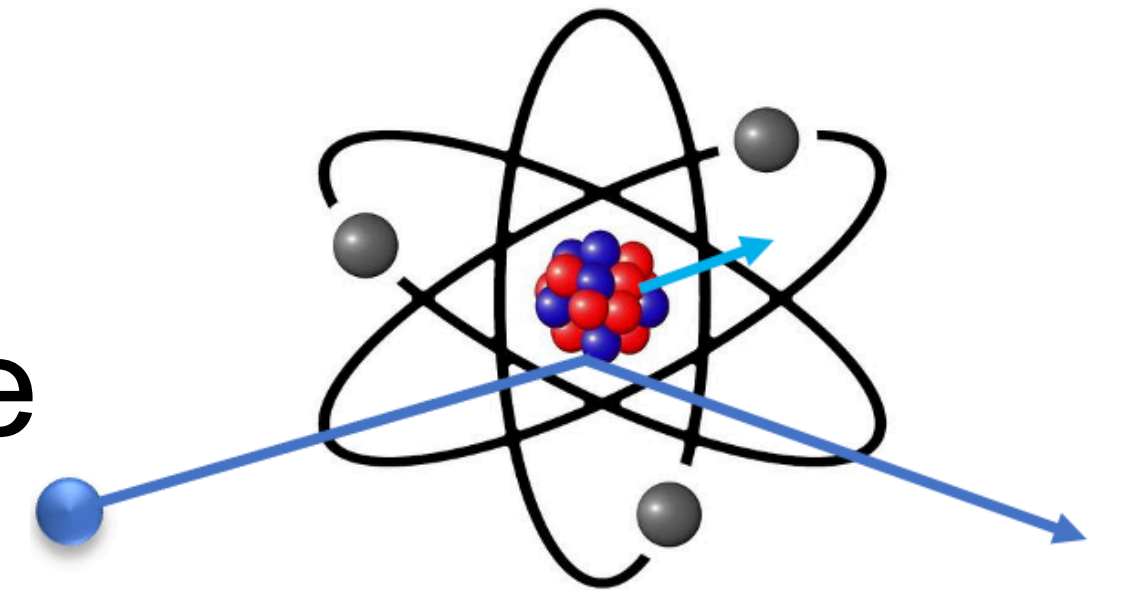
How?

Haloscope: inverse Primakoff effect (conversion to photon in B-field)

WIMPs

Why?

“WIMP miracle”
weak-scale particle
freeze-out →
observed relic abundance



How?

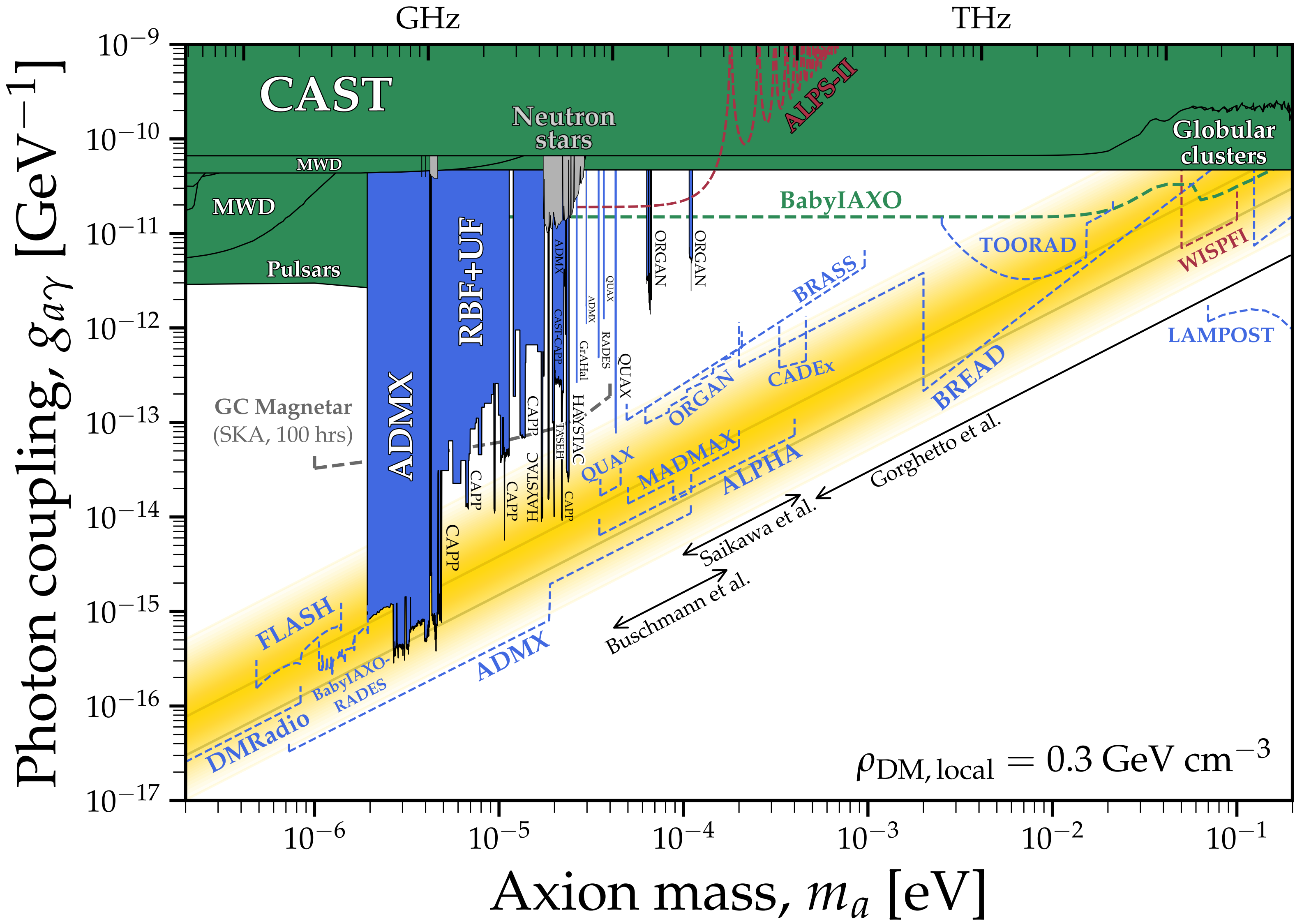
Scattering from nuclei → recoils with heat, ionisation, scintillation

Status of Axion Searches

Many haloscope designs

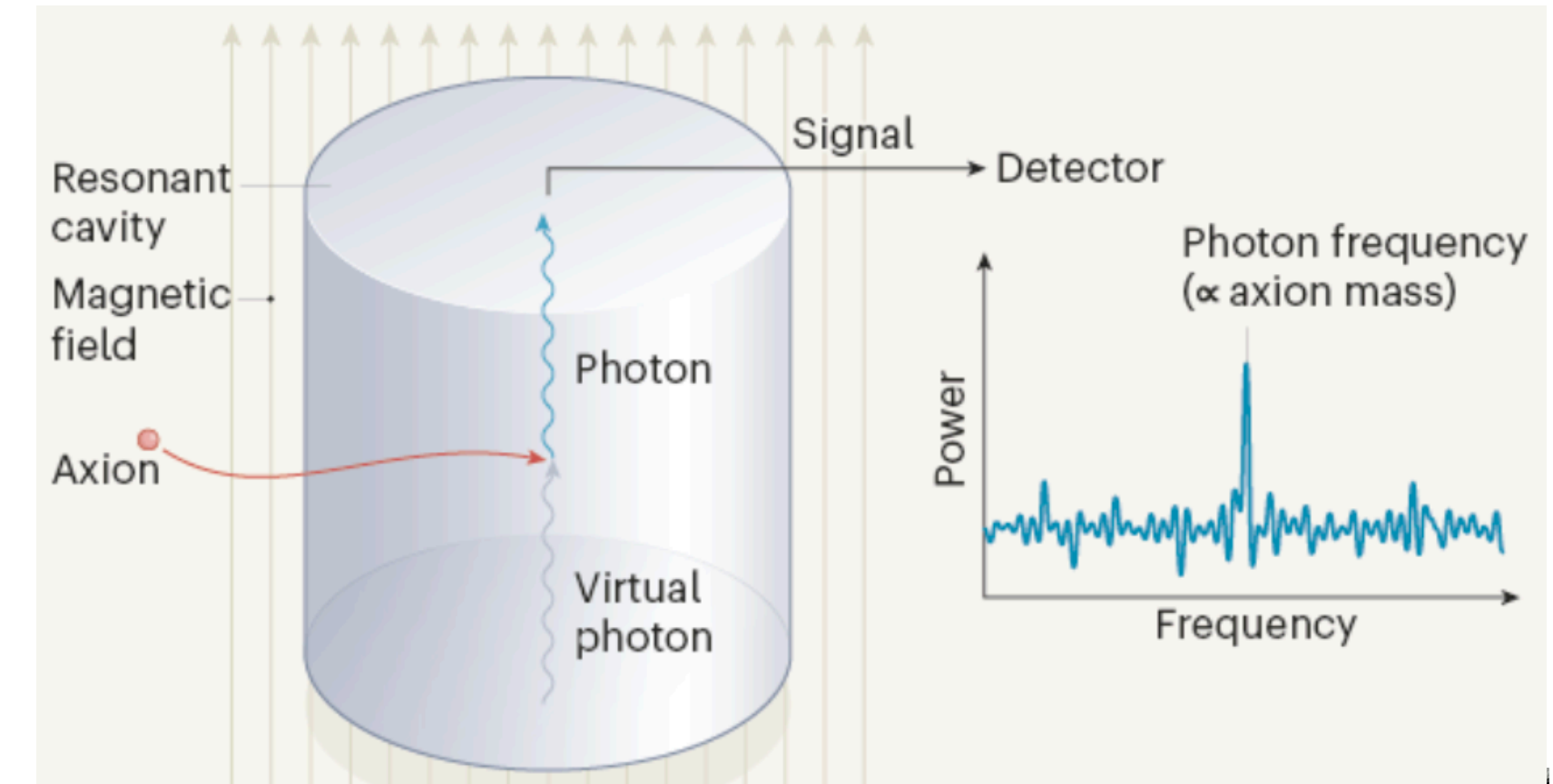
- Microwave cavity (ADMX)
- Dish antenna (BREAD)
- Plasma haloscope (ALPHA)
- Topological insulator (TOORAD)

Several cavity haloscopes online (blue), probing QCD axion models (yellow)

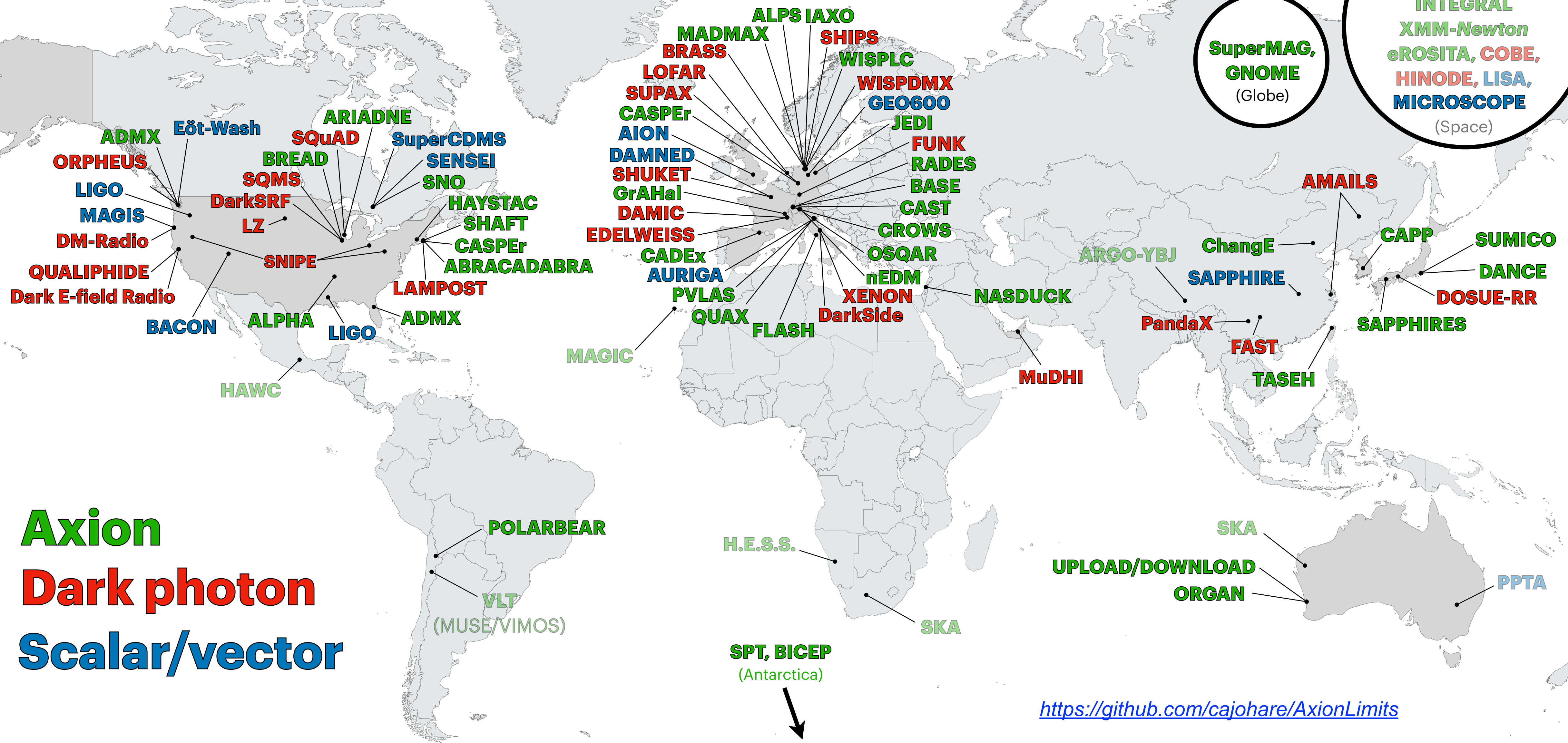


Quantum Sensors for the Hidden Sector (QSHS)

- Collaboration formed 2021; MOU with ADMX
- Part of QTFP programme with aims to develop:
 - Low-noise quantum electronics → scan deeper
 - Resonant feedback circuit → probe masses simultaneously; eliminate tuning rod
- Sheffield test stand → fridge & magnet installed
 - Base temperature of 8.5 mK achieved
 - Oxford TWPA measurements this summer
- Initially, probe axion mass range of 25-40 μeV



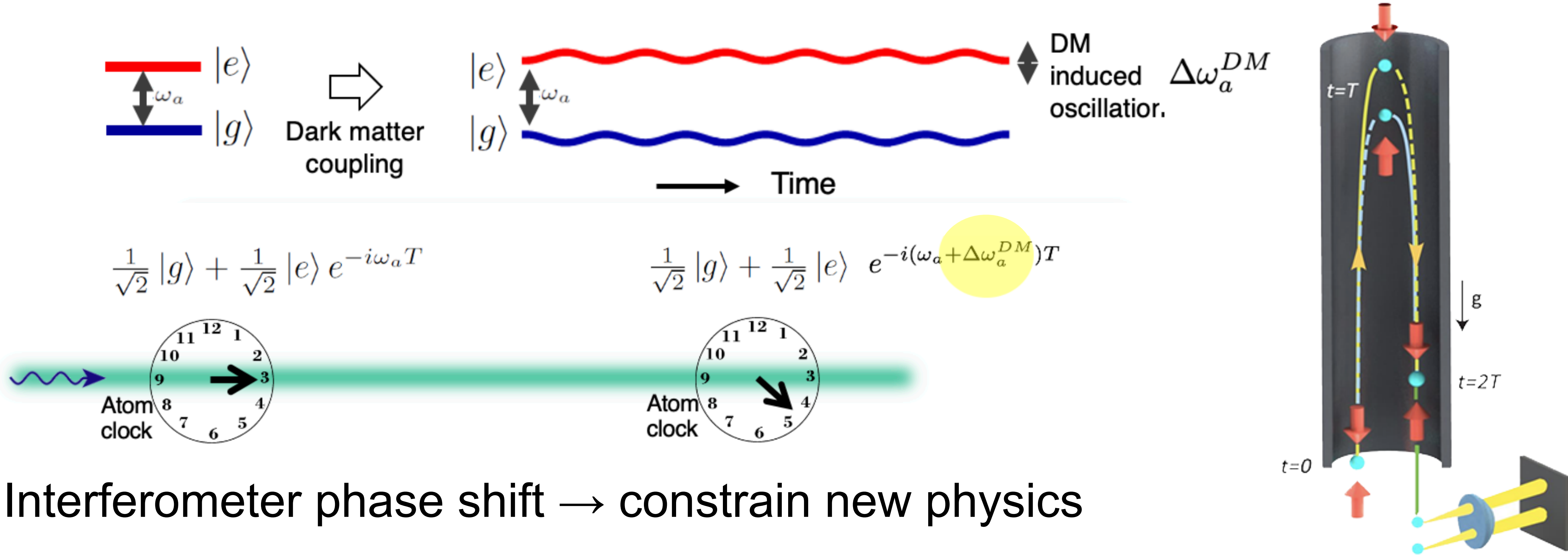
Global Searches for Ultra-light DM



Axion
Dark photon
Scalar/vector

<https://github.com/cajohare/AxionLimits>

Atom Interferometer Observatory & Network (AION)

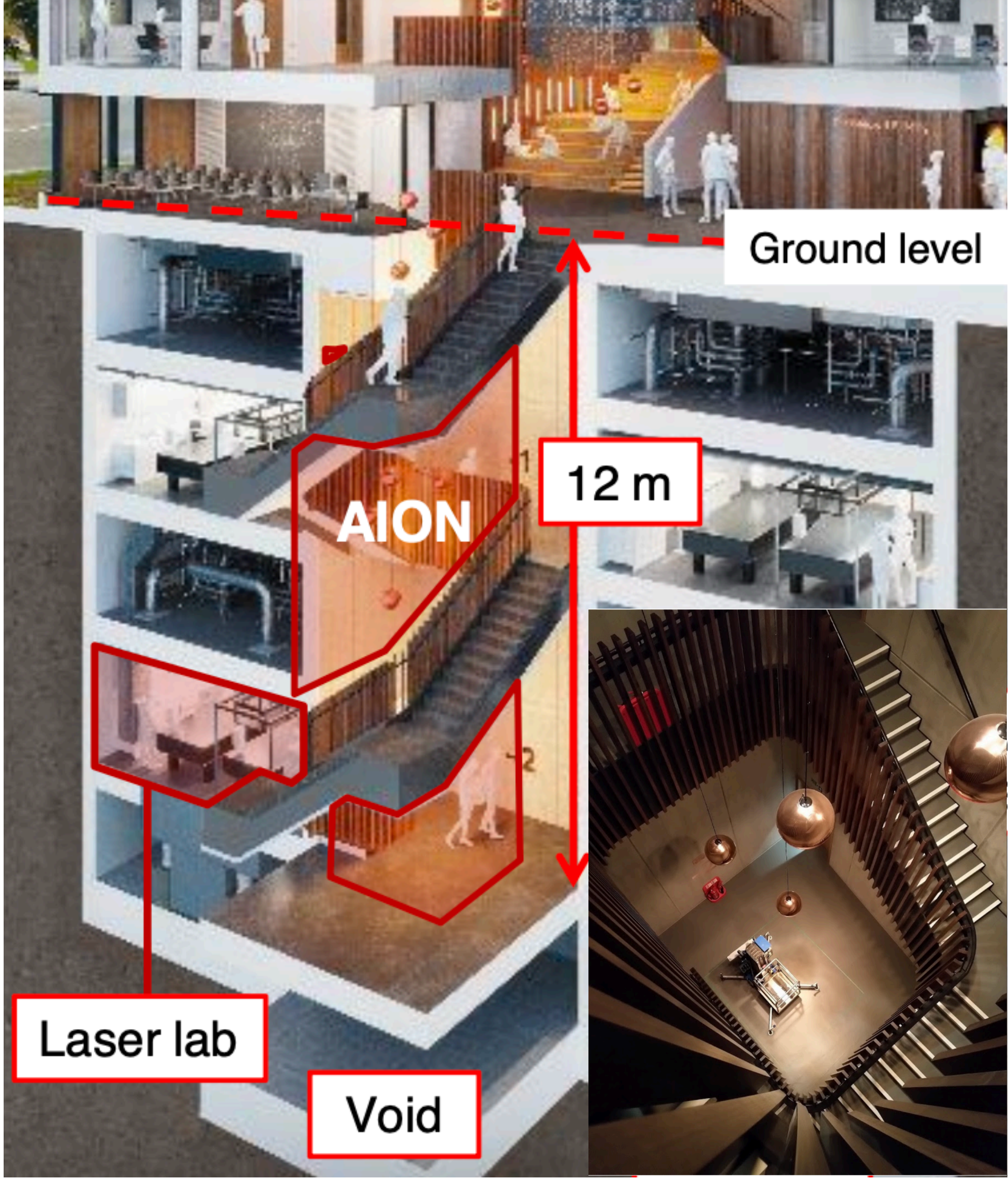
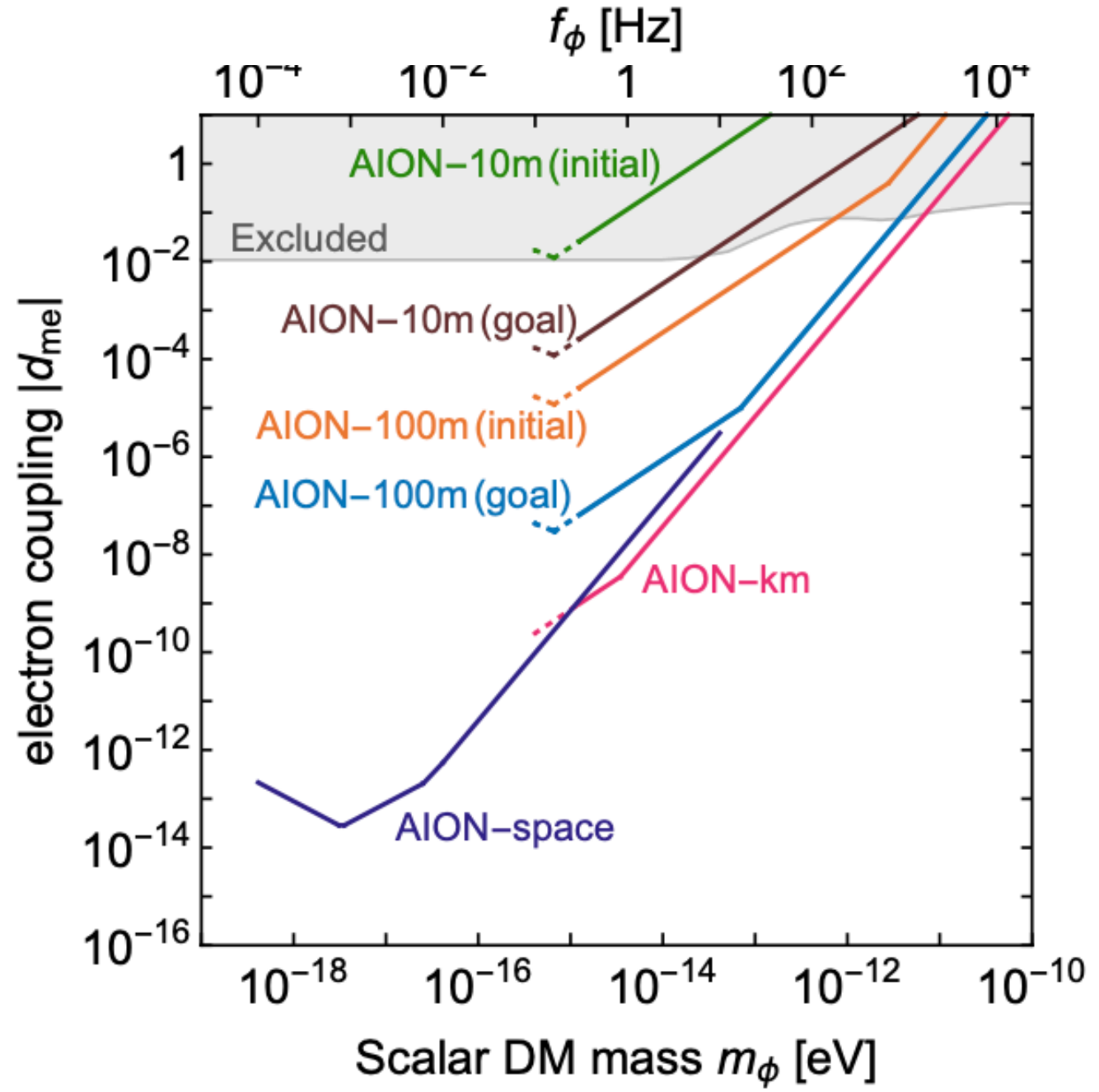


- Interferometer phase shift → constrain new physics
- Coupling to scalar ultra-light dark matter field → changes atomic frequency
- Two interferometers, same laser → lower noise, differential measurement

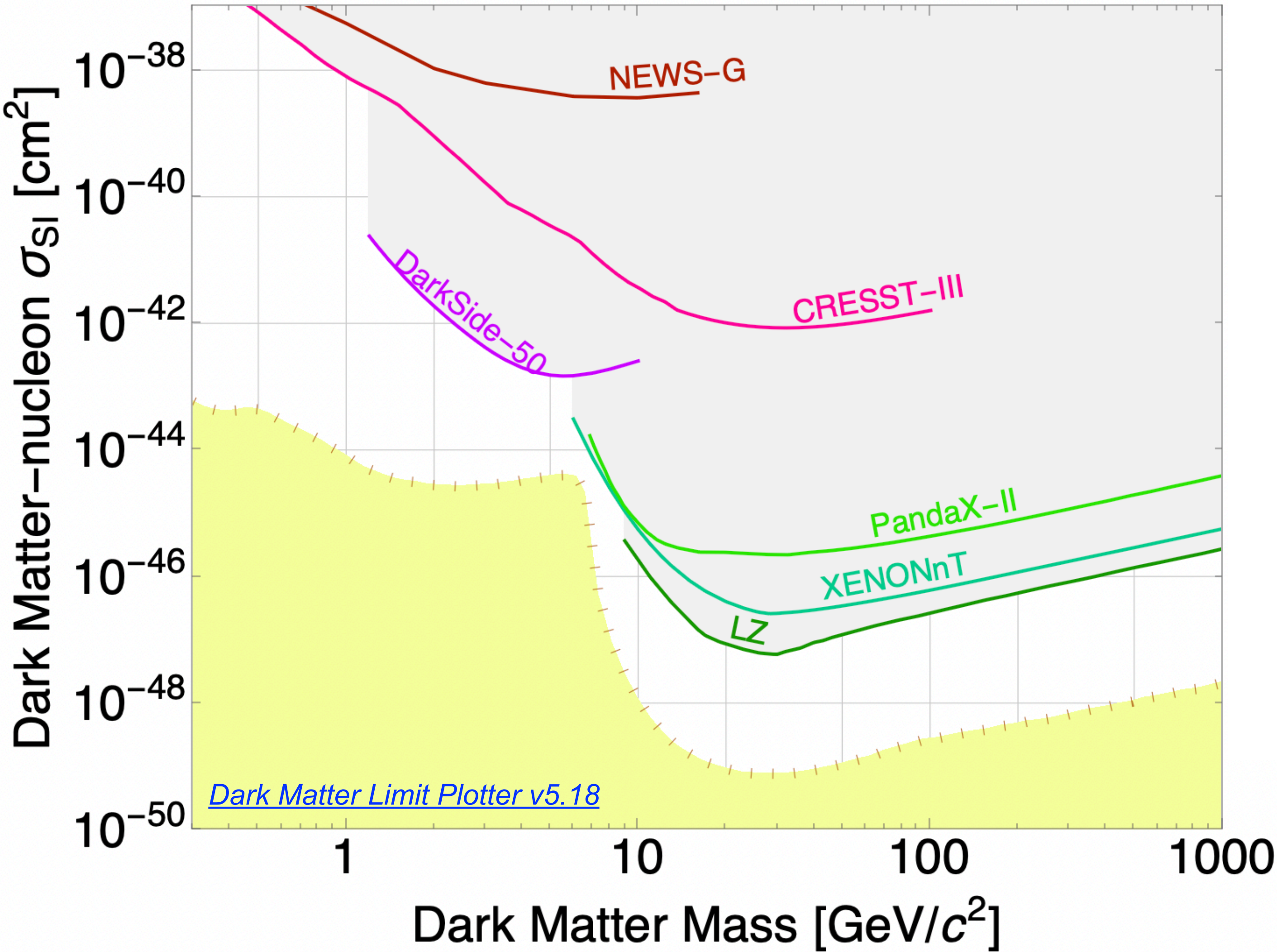
Atom Interferometer Observatory & Network (AION)

- Five ultra-cold Sr labs built by Summer 2023
- Partnership with MAGIS in the US
- **Stage 1 (AION-10)** funded through QTFP
 - Construction expected to start this autumn
- **Stage 2 (AION-100)**
 - Possibility for Boulby to host in mine shaft
- Terrestrial km-scale & space versions planned

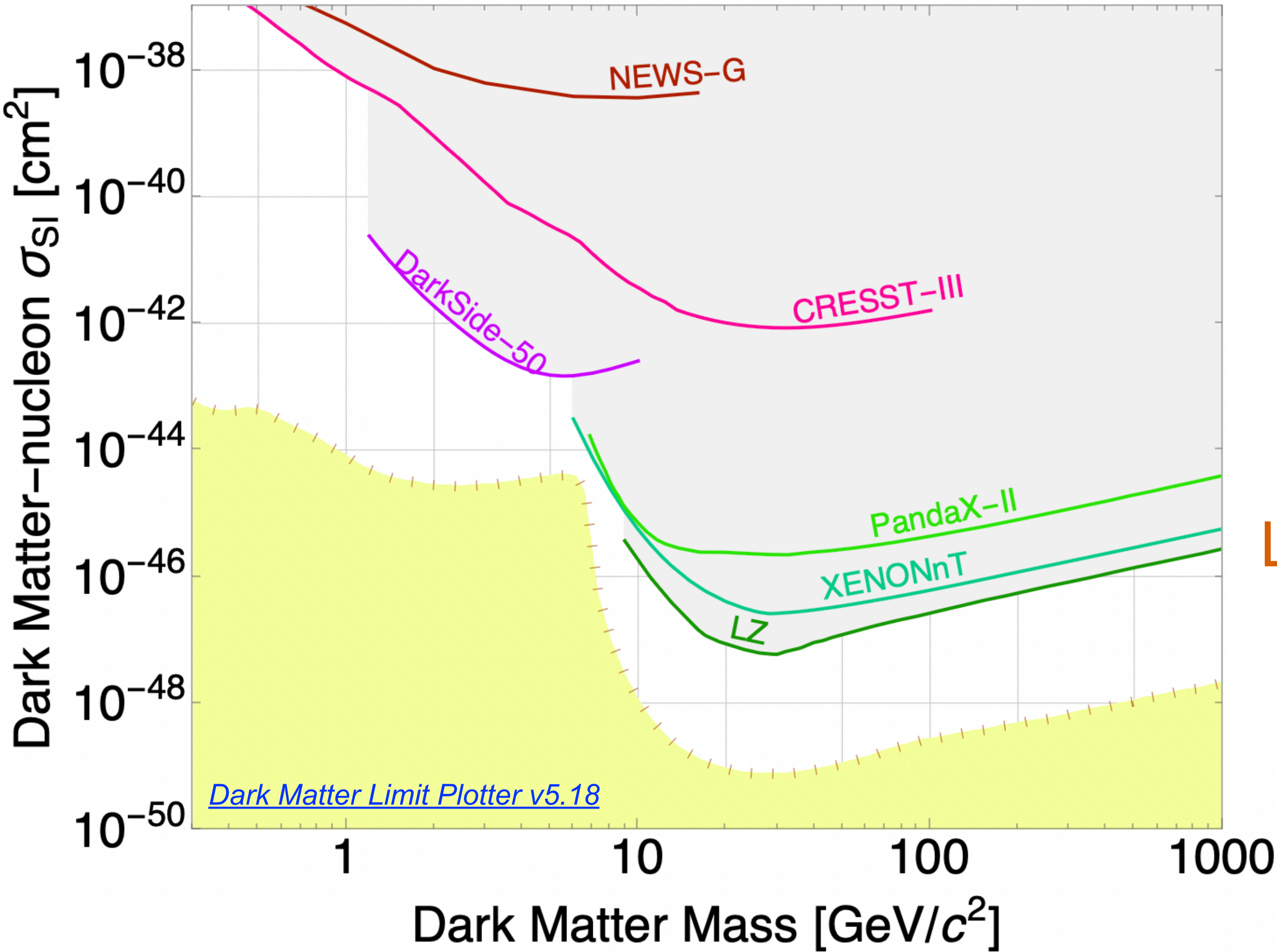
AION-10 @ Oxford's Beecroft



Status of WIMP Searches



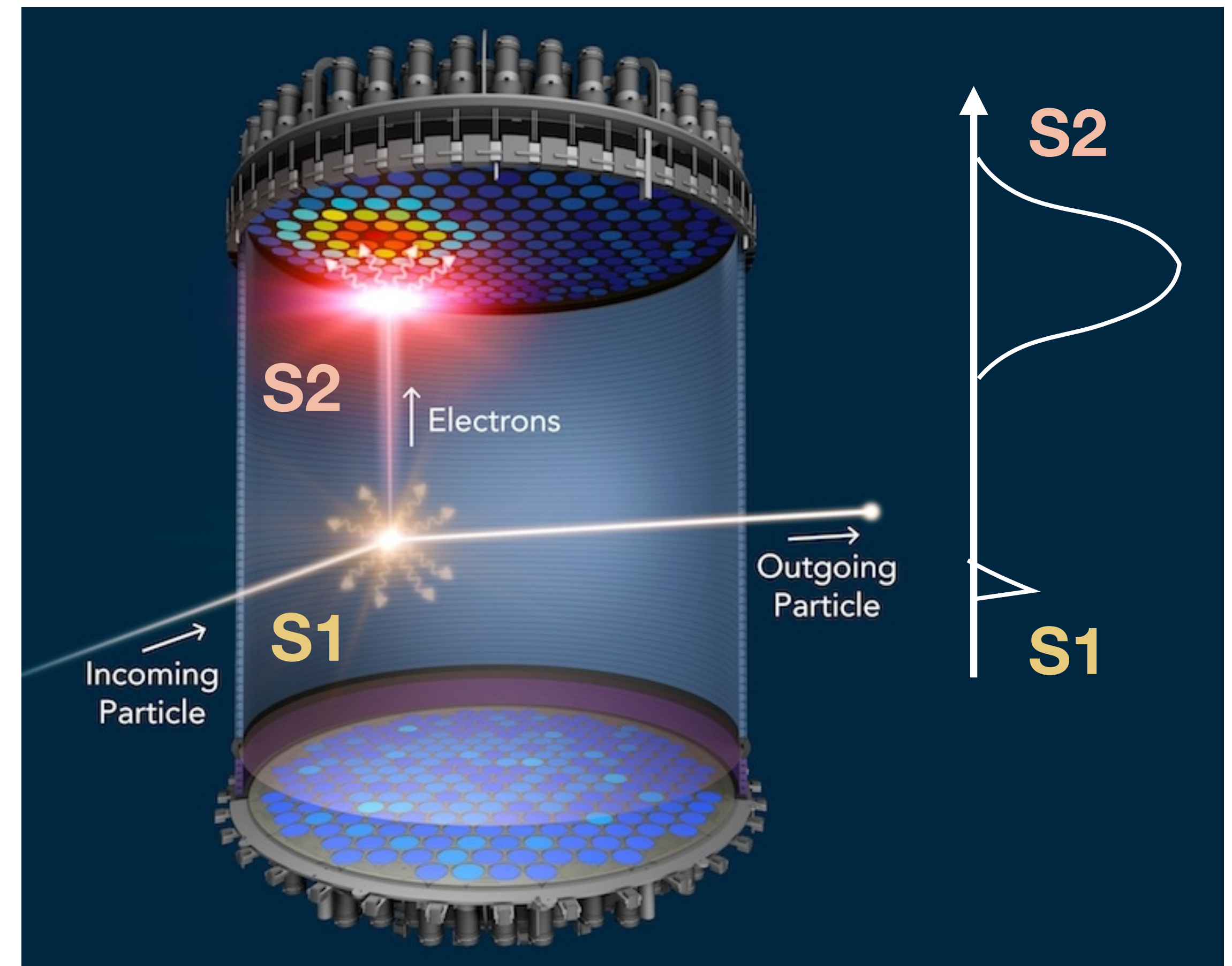
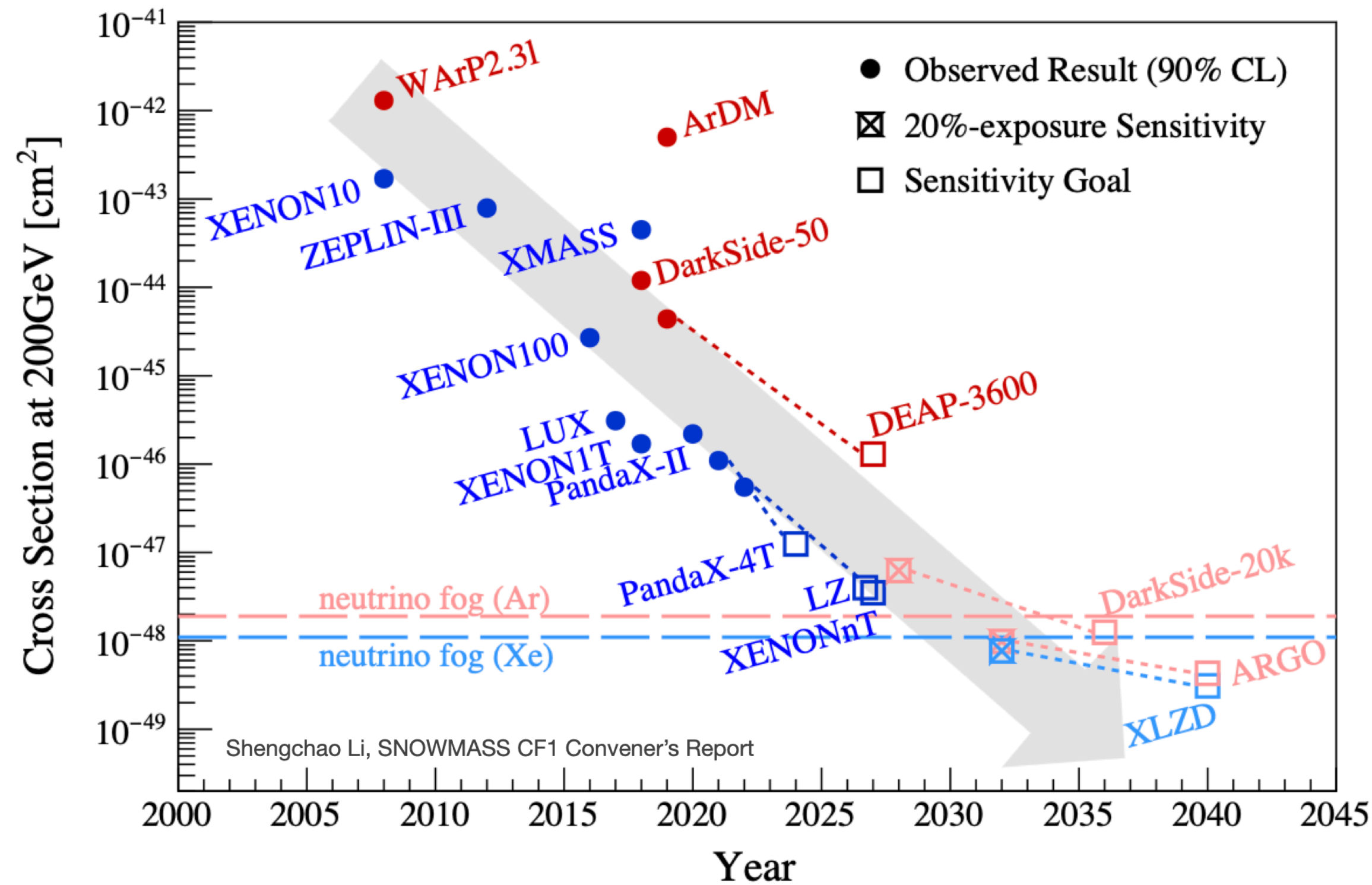
Status of WIMP Searches



Larger Detectors
Lower Backgrounds

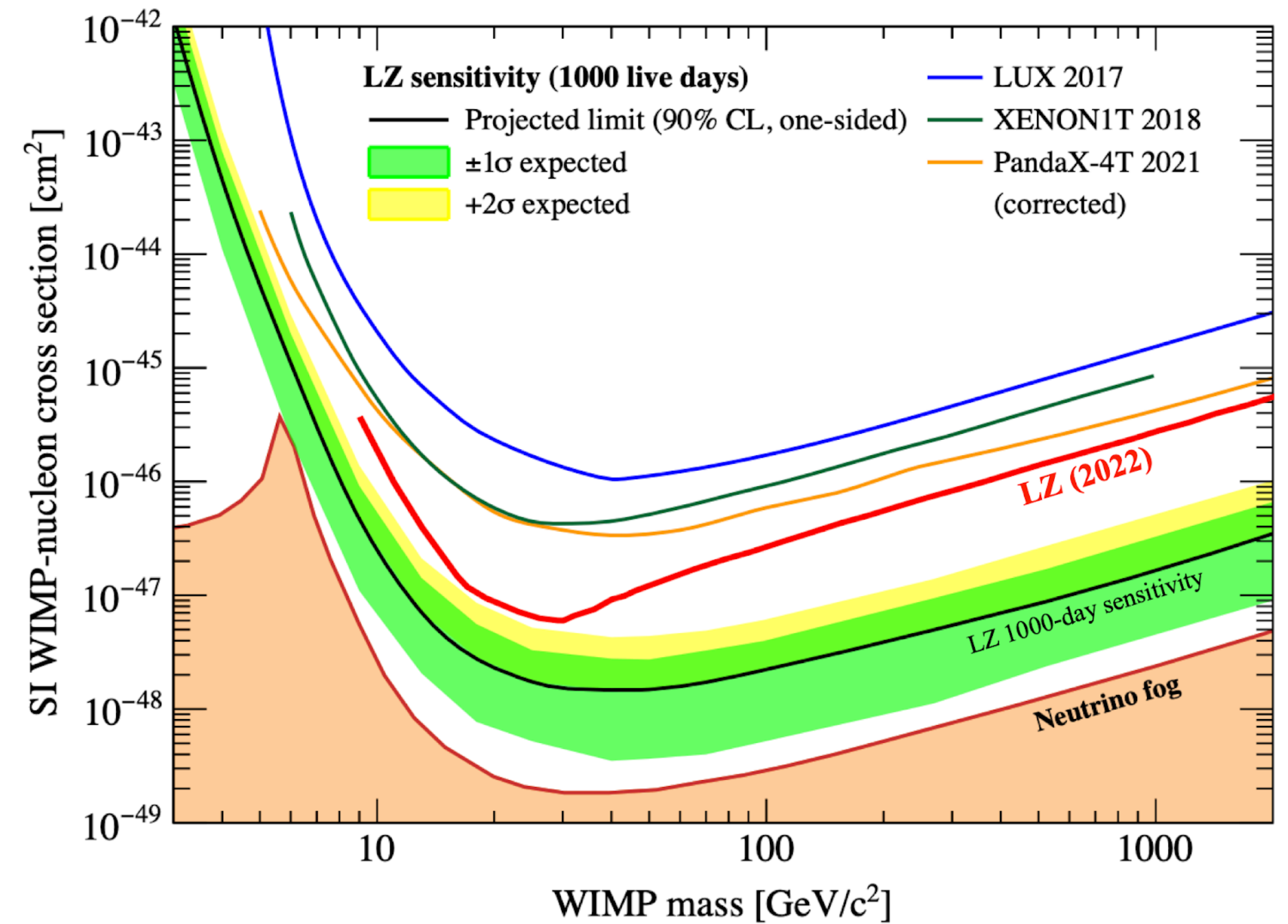
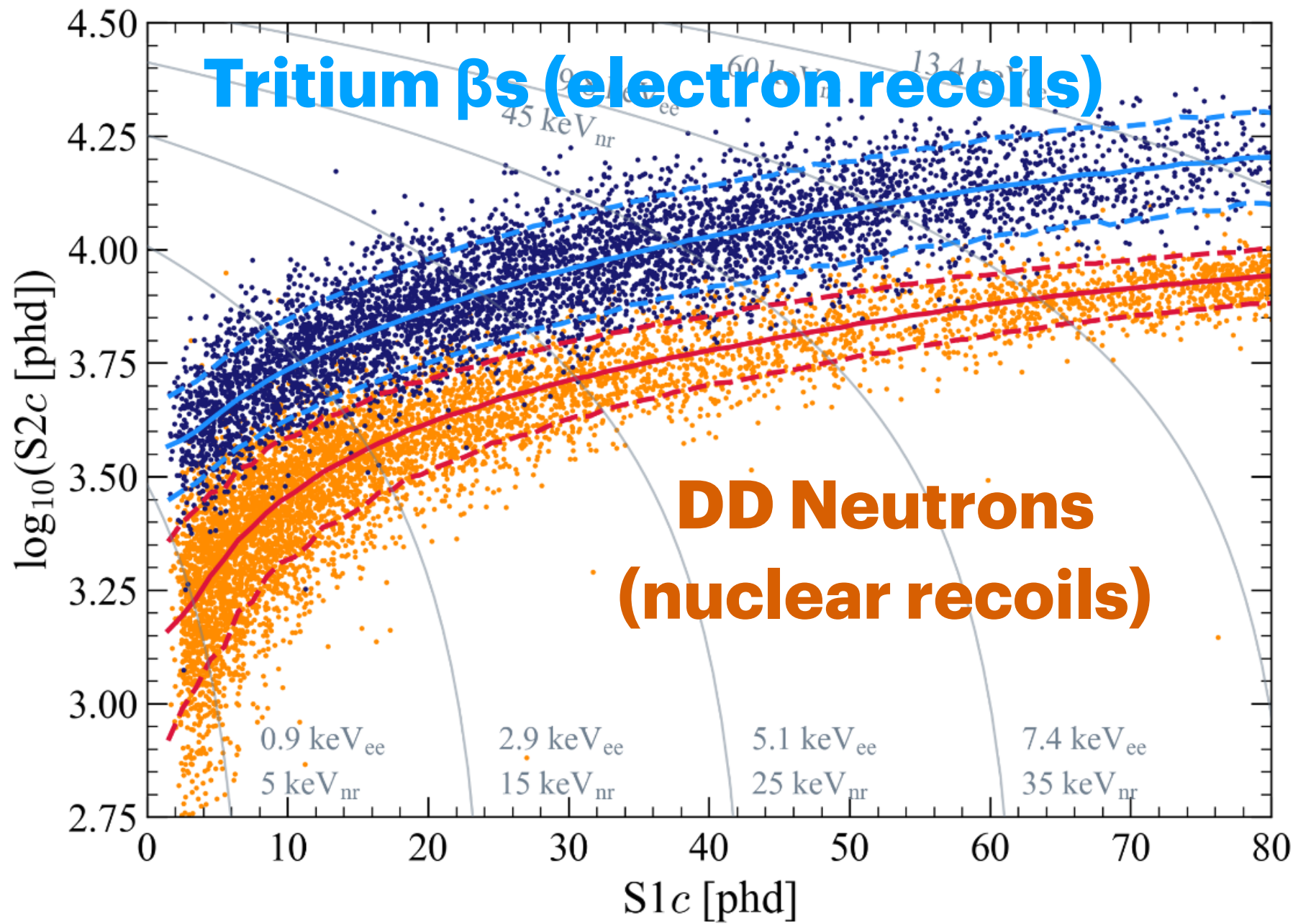


Liquid Noble Detectors



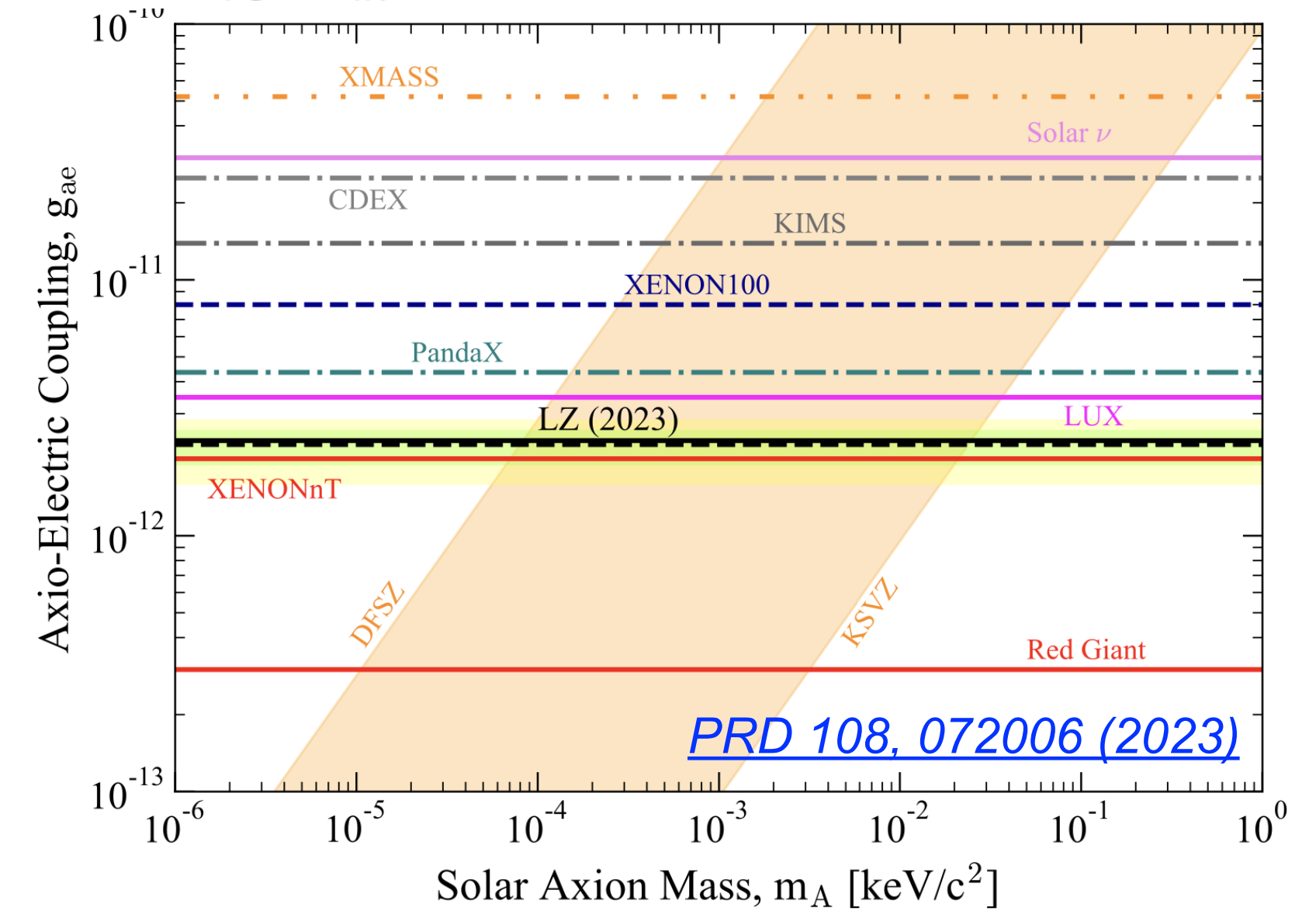
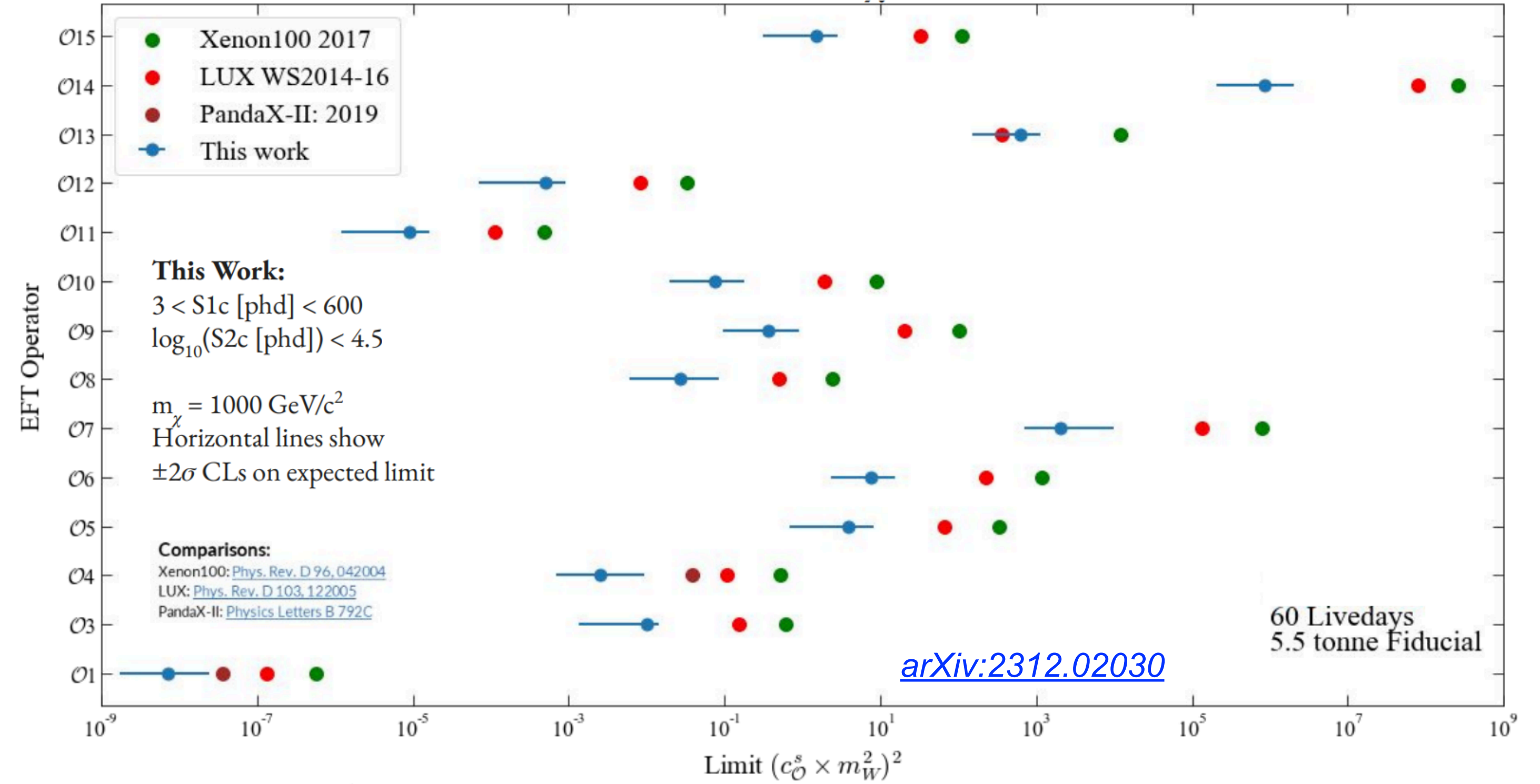
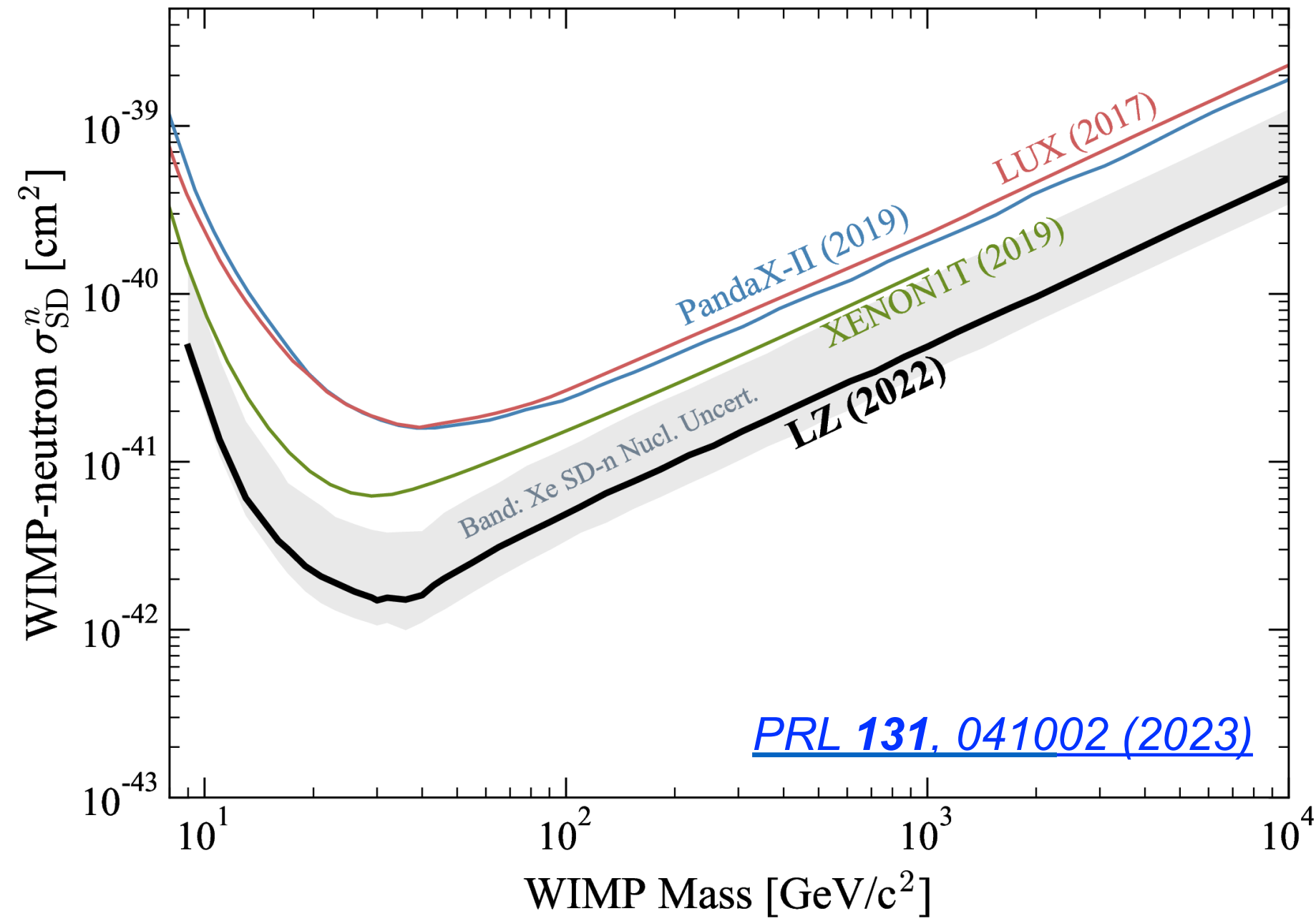
- Xe experiments driving sensitivity to ~ 100 GeV WIMPs last 15 years
- Self-shielding; easily purified; scalable; high scintillation/ionisation yields
- Dual-phase TPC: 3D position reconstruction \rightarrow fiducialisation

LUX-ZEPLIN



- Based in Davis Cavern @ SURF, South Dakota; operational since 2021
- 7 t active Xe target + 2 t Xe “Skin” & 17 t Gd-loaded liquid scintillator vetoes
- World-leading WIMP search results set with just 6% of planned live time
→ more science data-taking for WIMPs & other new physics analyses

LUX-ZEPLIN



- Spin-dependent & EFT WIMP analyses
- Electron recoil searches e.g. solar axions
- MOU signed with XENON & DARWIN → next-generation experiment, XLZD (Slide 25)

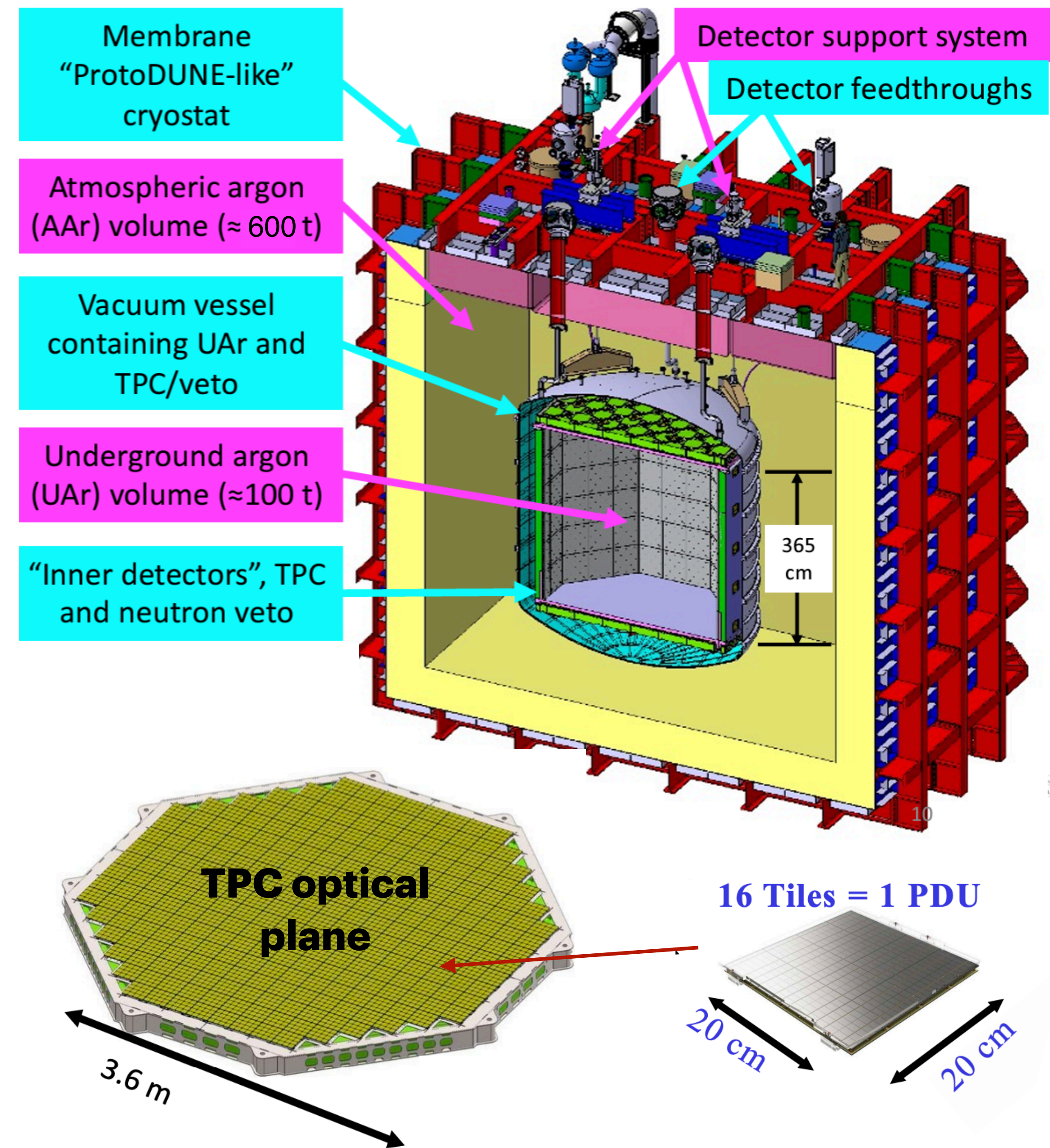
DarkSide-20k

- Global Argon Dark Matter Collaboration (DS-50 + DEAP + MiniClean + ArDM)

Intermediate goal:
DS-20k, 200 ton yr exposure

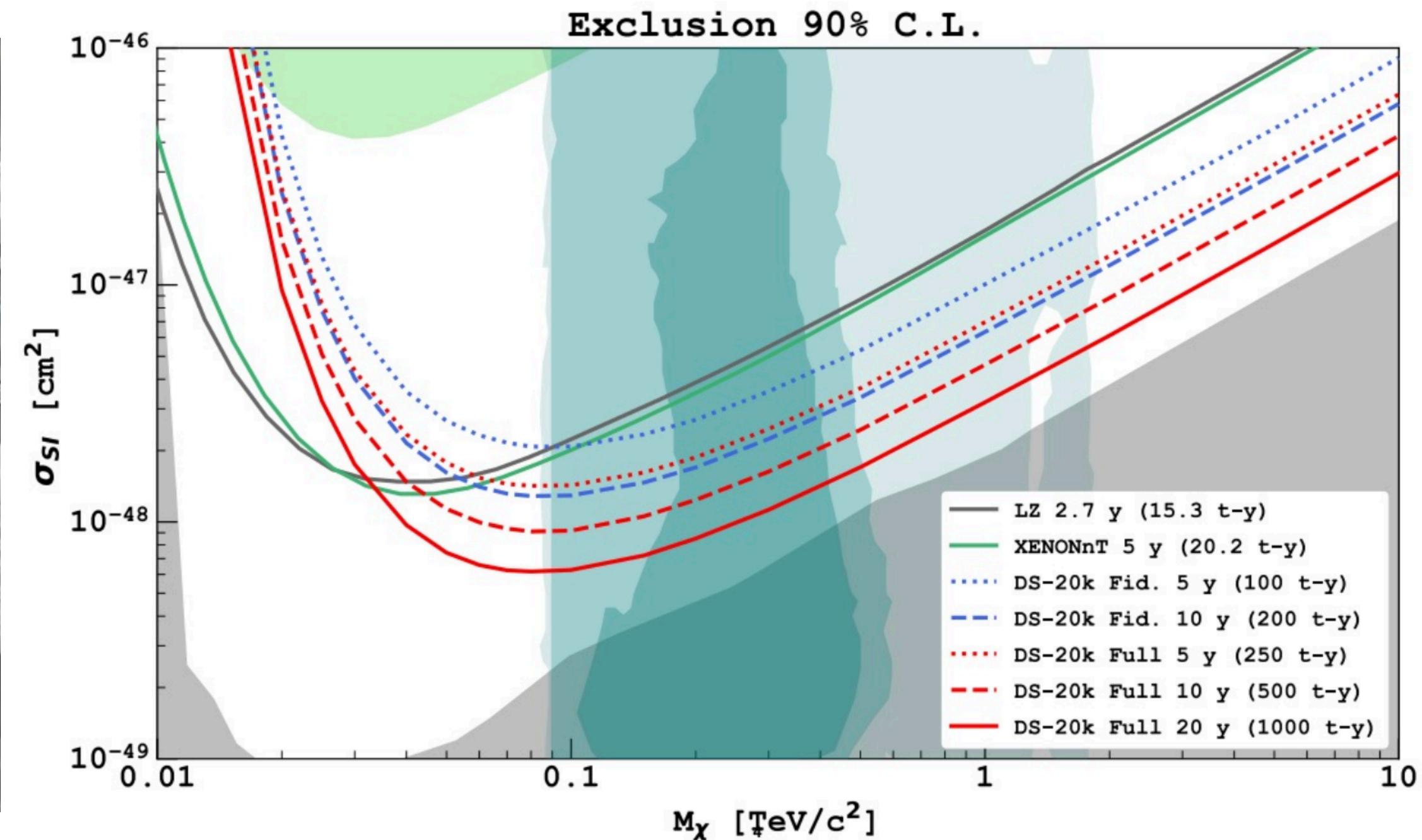
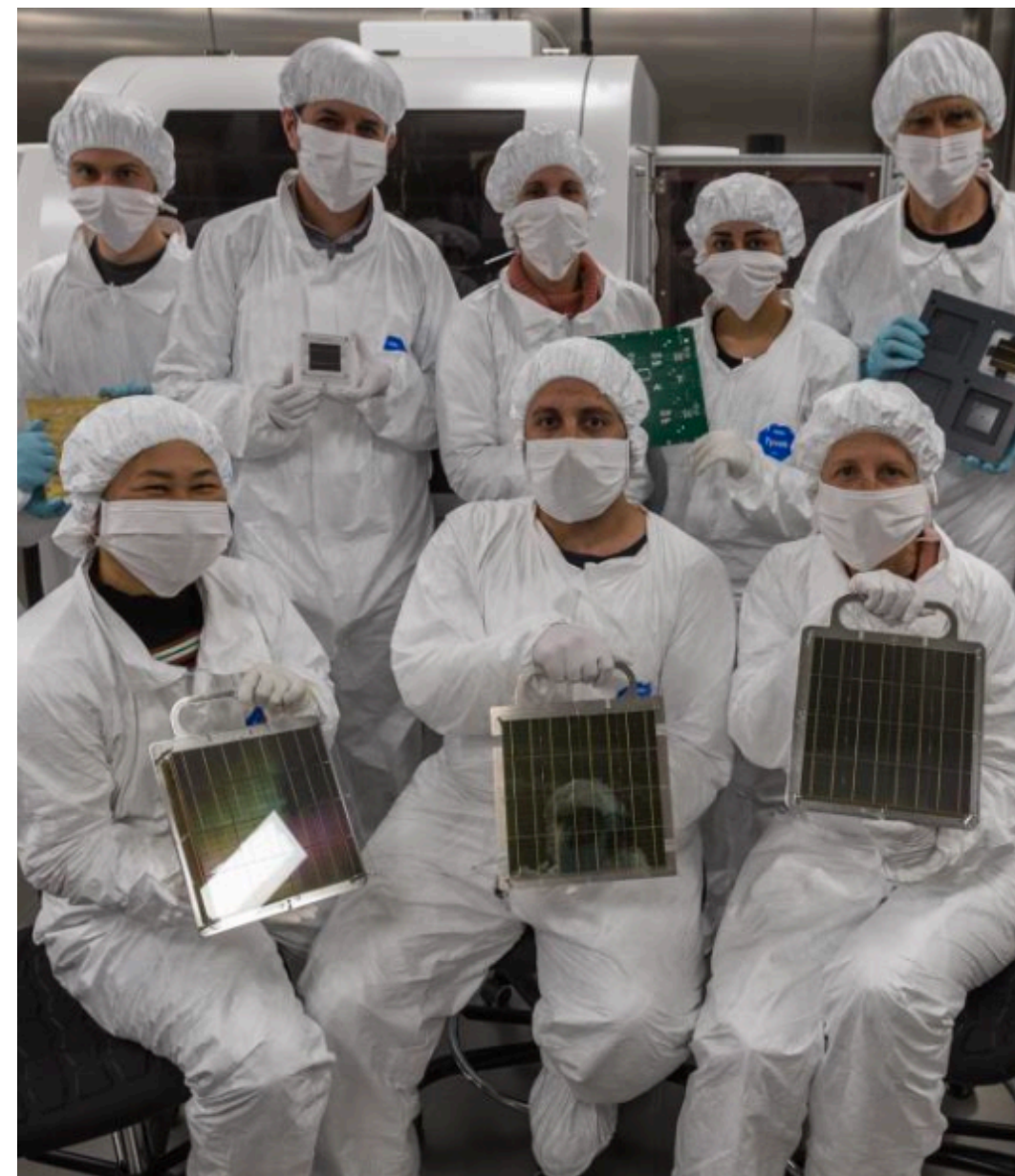
Ultimate goal:
ARGO, 3000 ton yr exposure

- 50 t underground argon (UAr) dual-phase TPC; Gd-loaded PMMA neutron veto
- Distillation column (ARIA) to further remove ^{39}Ar , major β -emitter, from UAr
- Cryogenic photon detection units (PDUs)
→ 26 m² of silicon photomultipliers



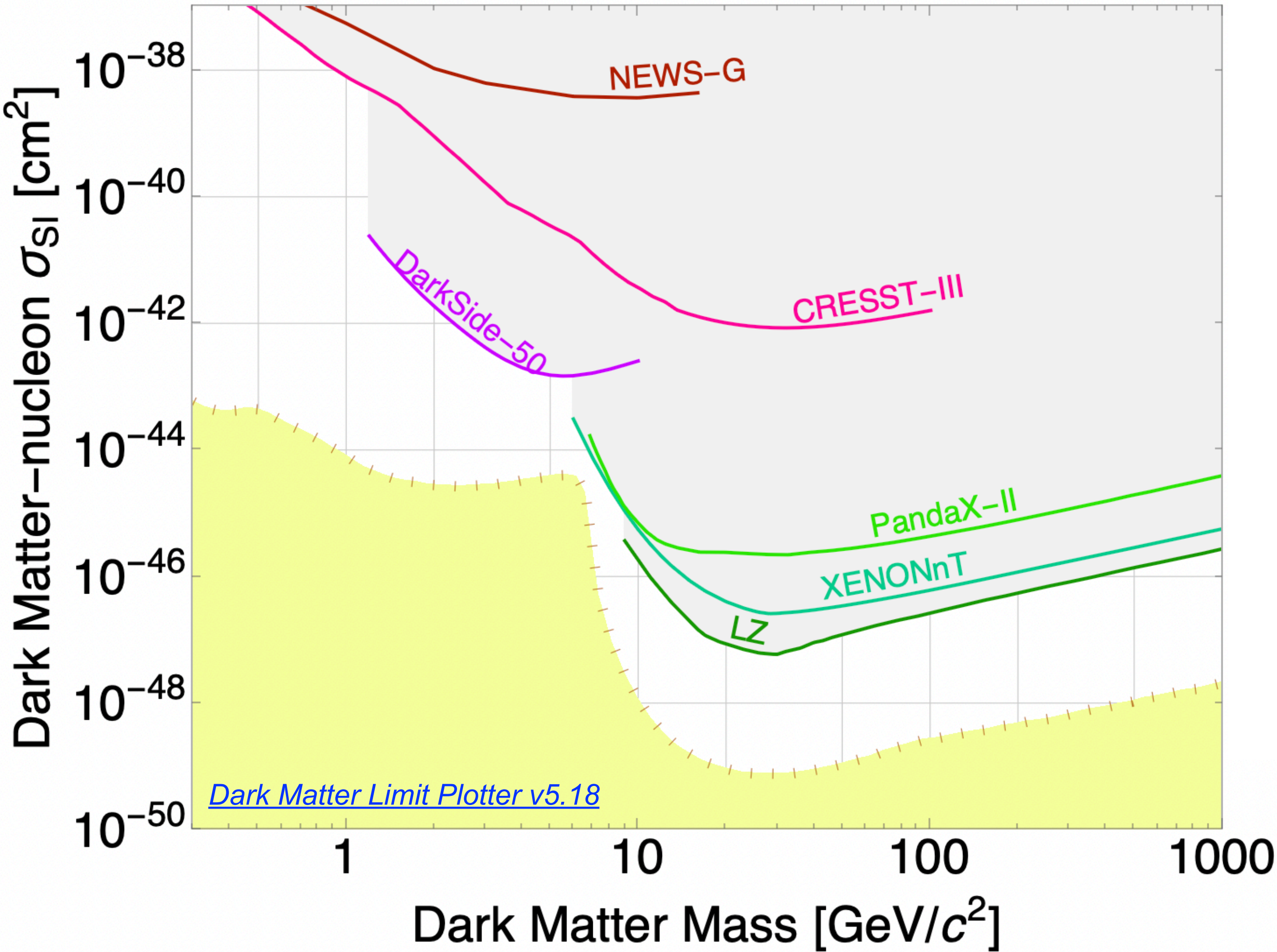
DarkSide-20k

- Clean room at LNGS commissioned 2023
- Full TPC PDU production to start next month
- Cryostat construction to be completed in 2024
- Full commissioning foreseen by end of 2026

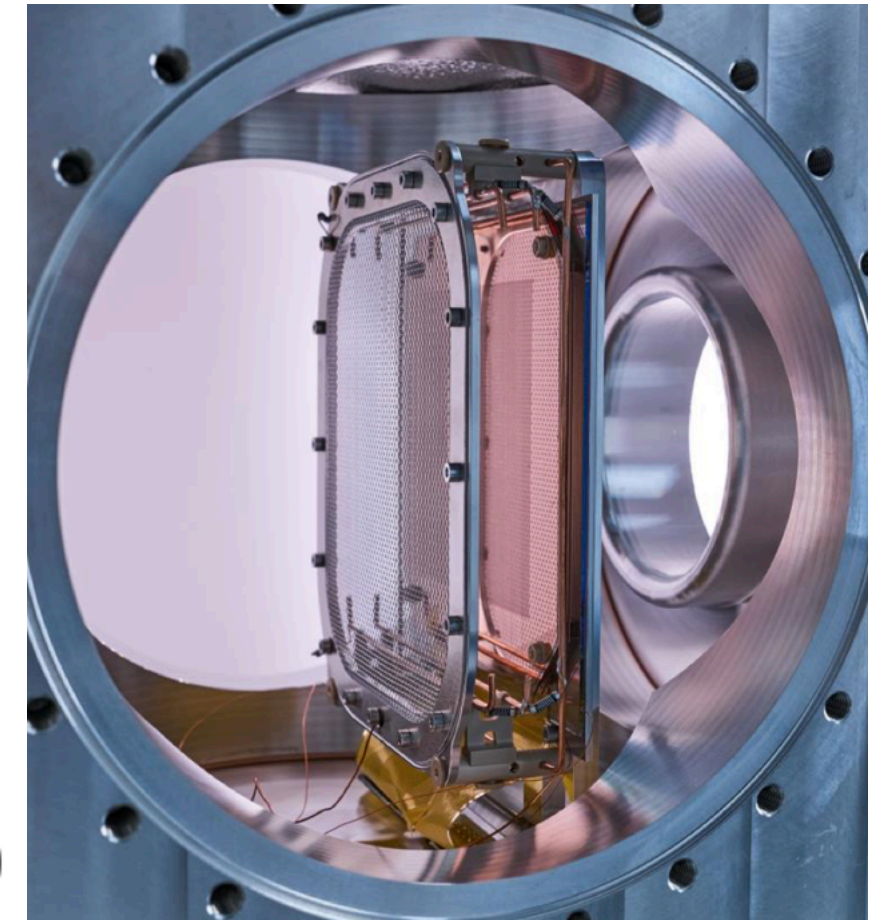
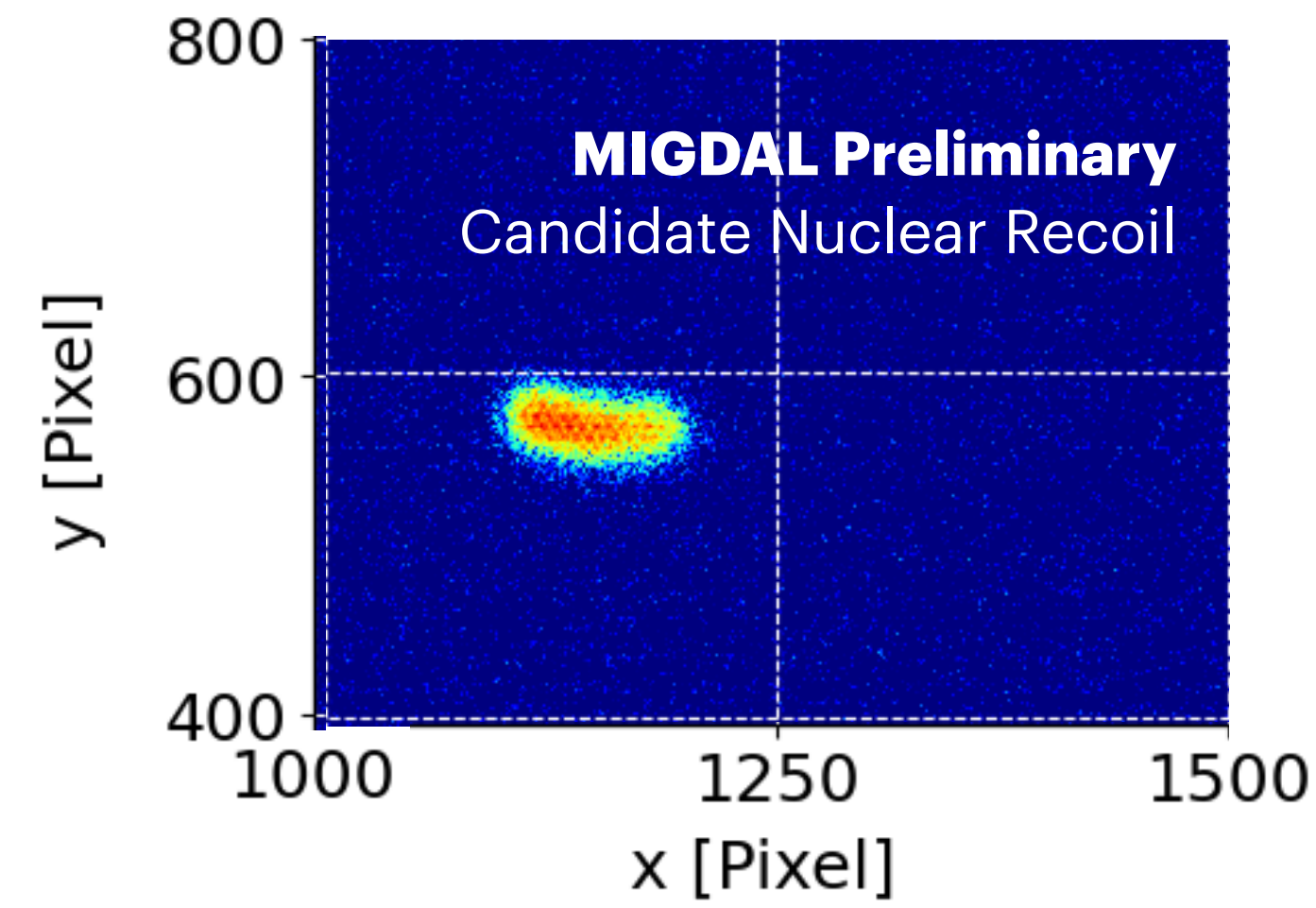
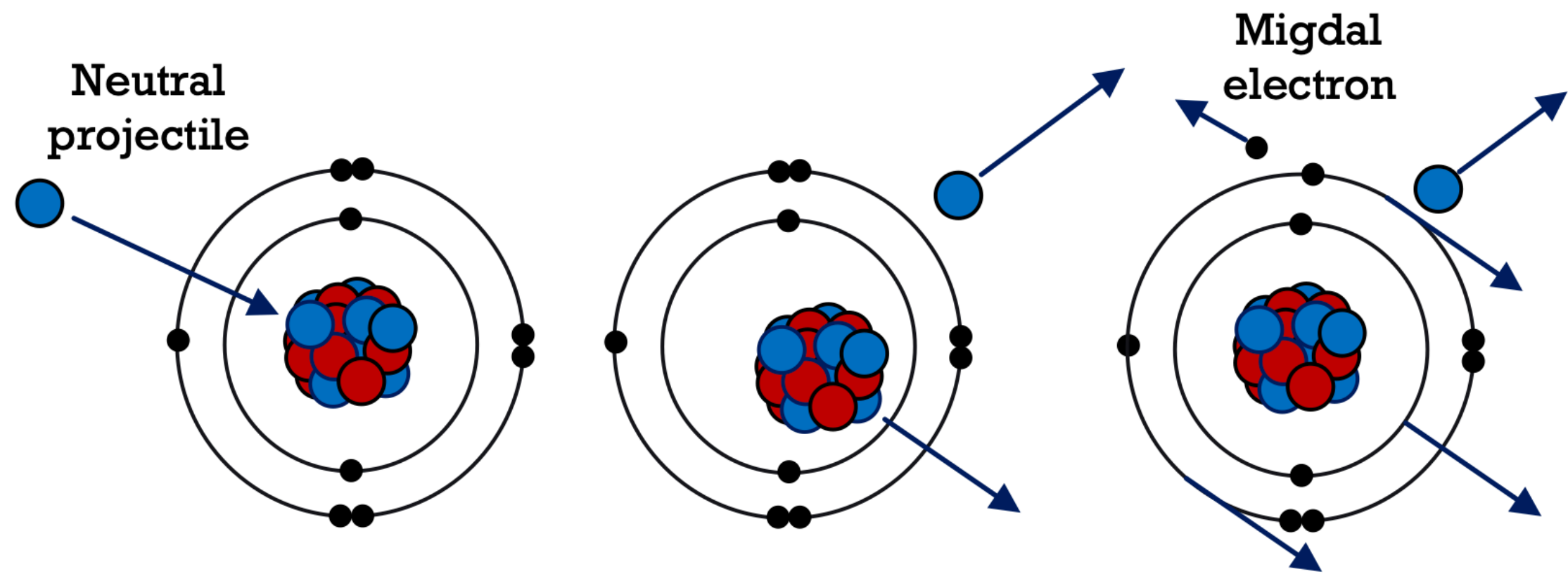


Status of WIMP Searches

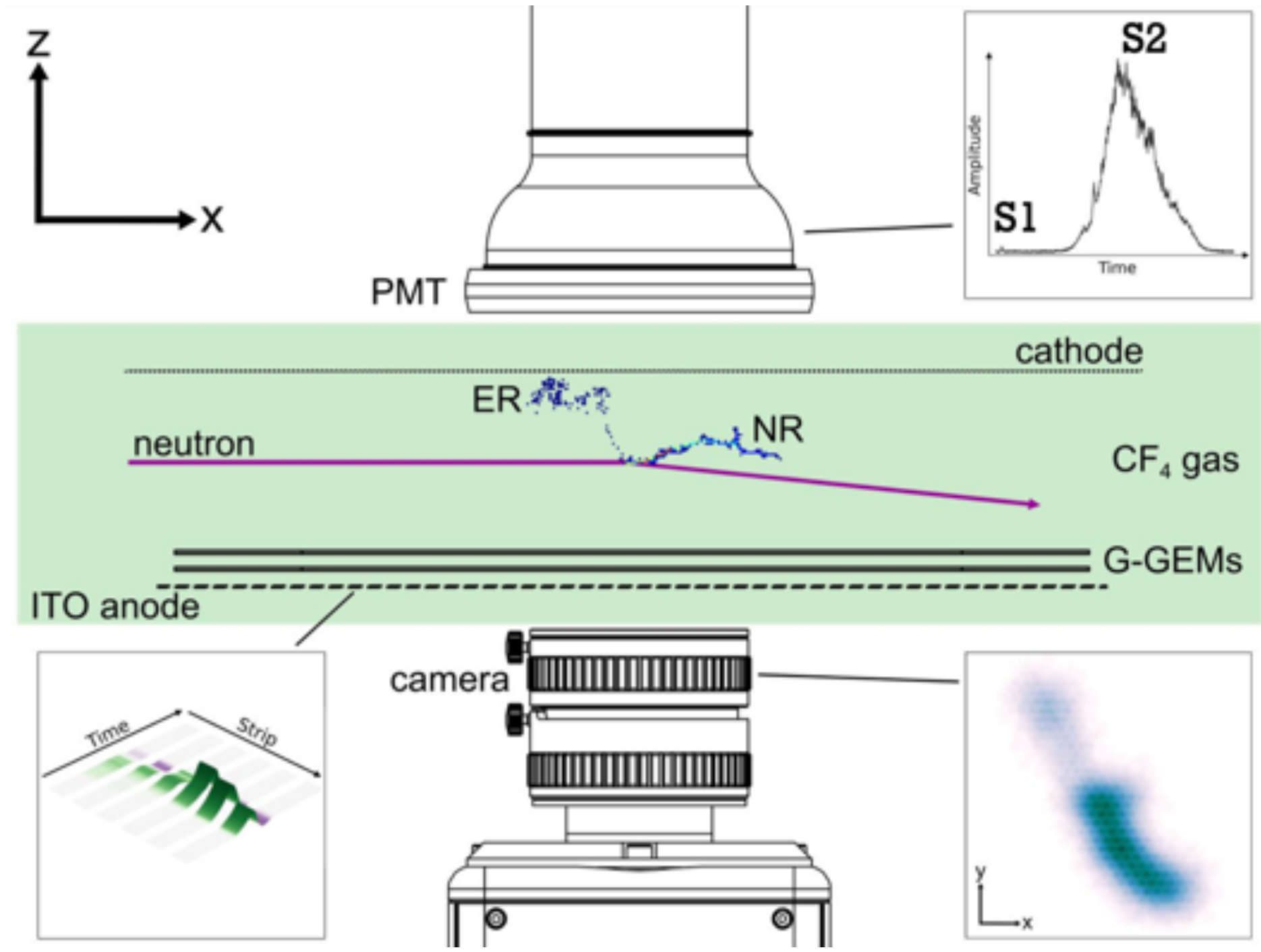
Lower
Thresholds



Migdal Effect & MIGDAL

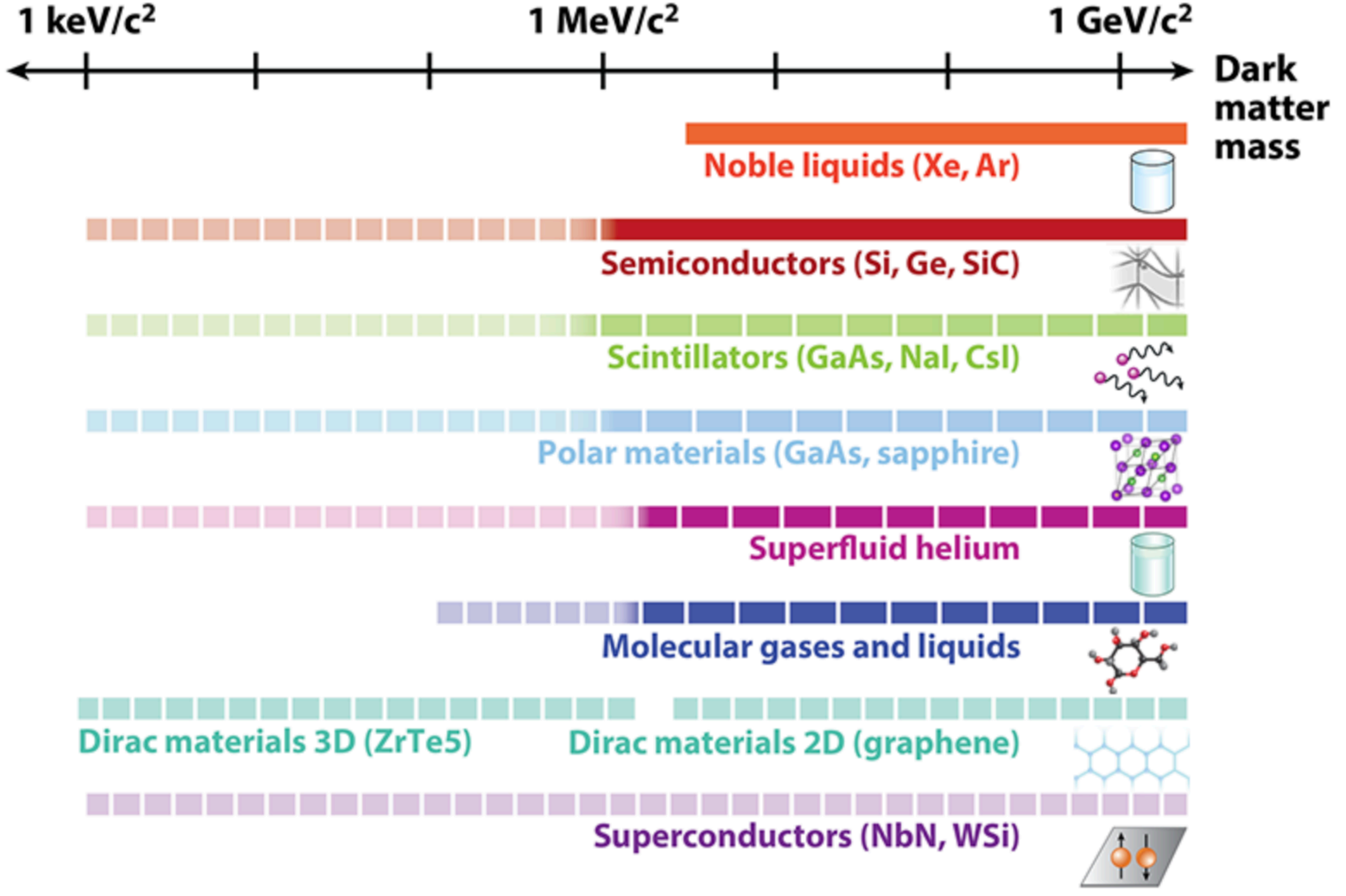
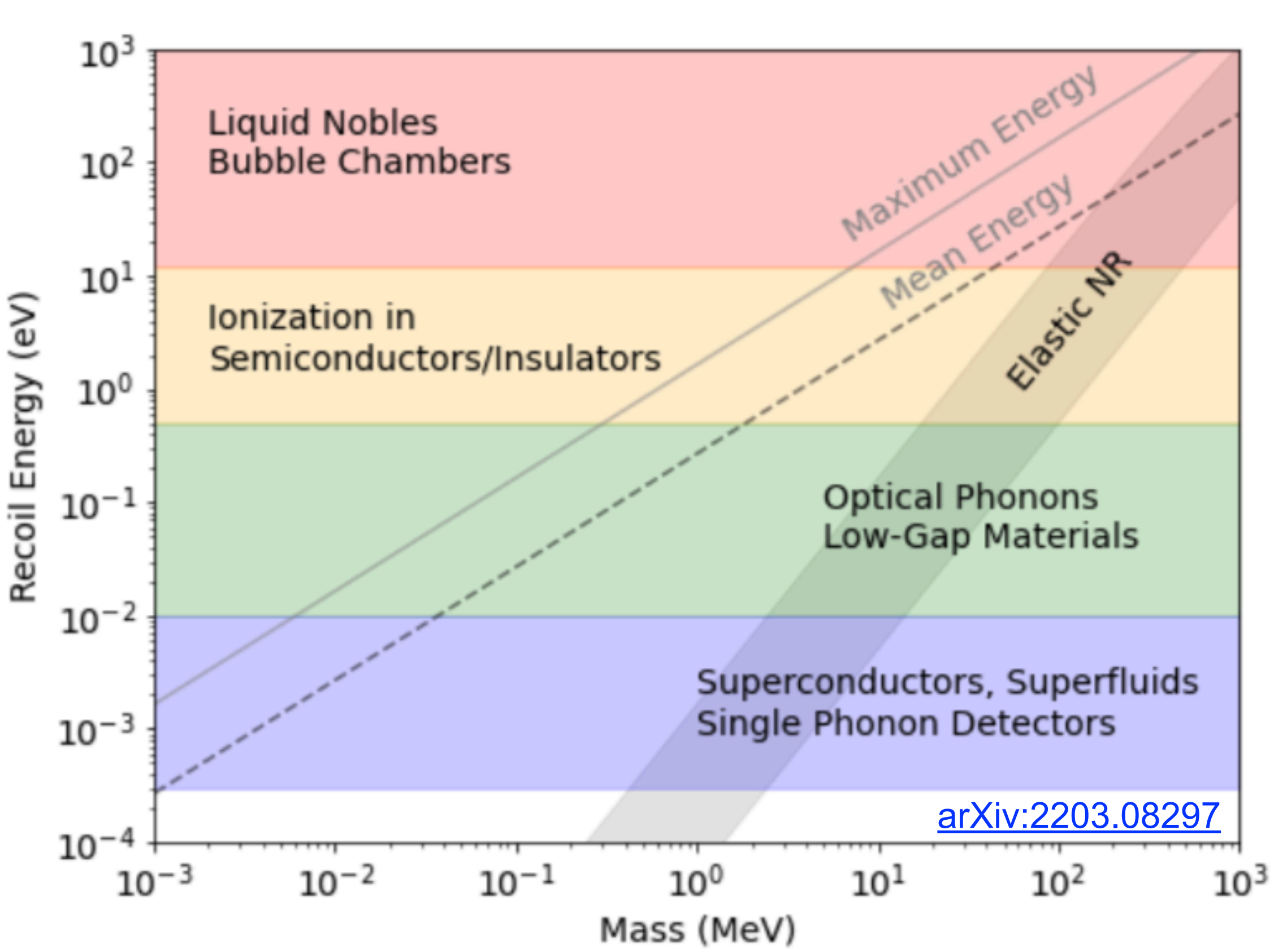


- Atomic electron emission with nuclear scatter
 - visible recoils above detection threshold
 - extend low-mass DM reach of liquid nobles
- MIGDAL aims for first observation of this effect
 - low pressure gas optical TPC with CF_4
 - 3D image electron + nuclear recoil topology
- Science runs with DD generator at ISIS/RAL



[Astropart. Phys. 151 102853 \(2023\)](#)

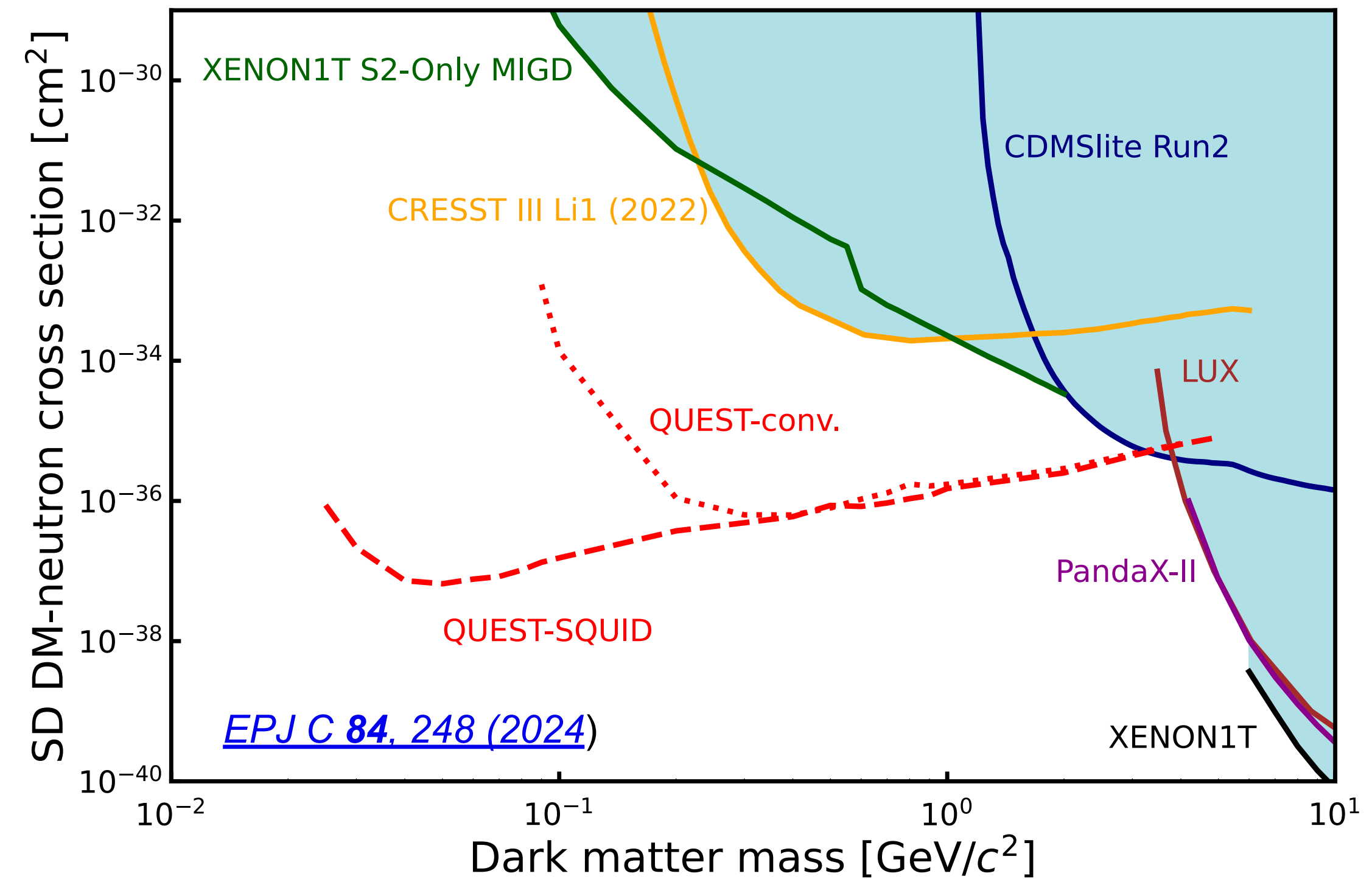
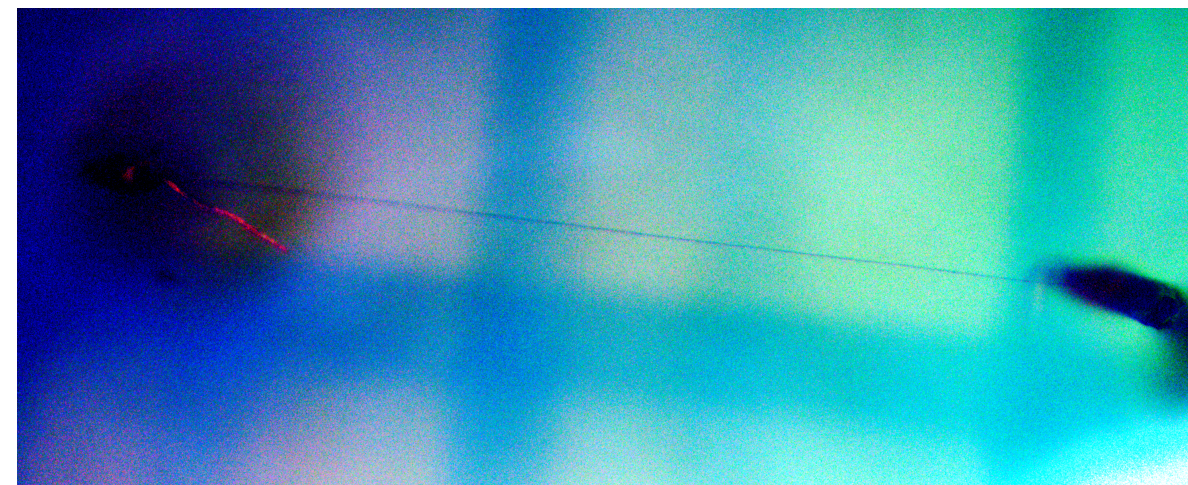
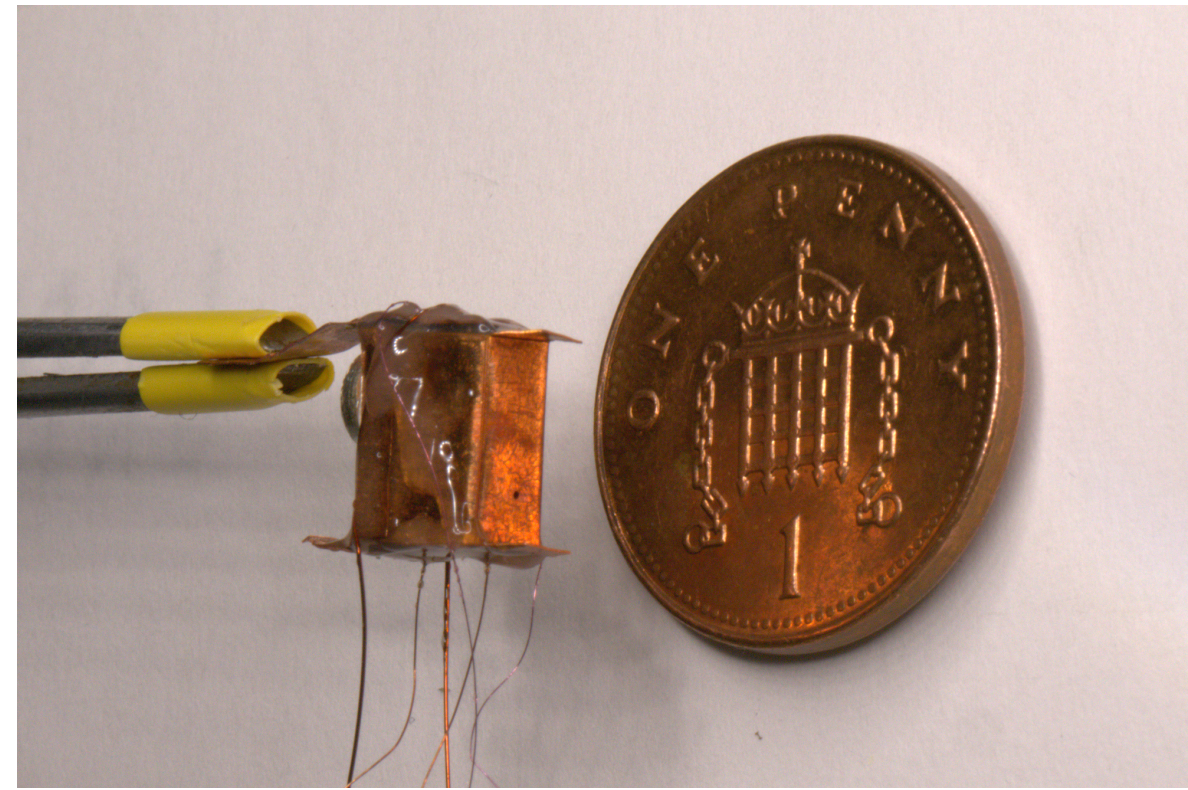
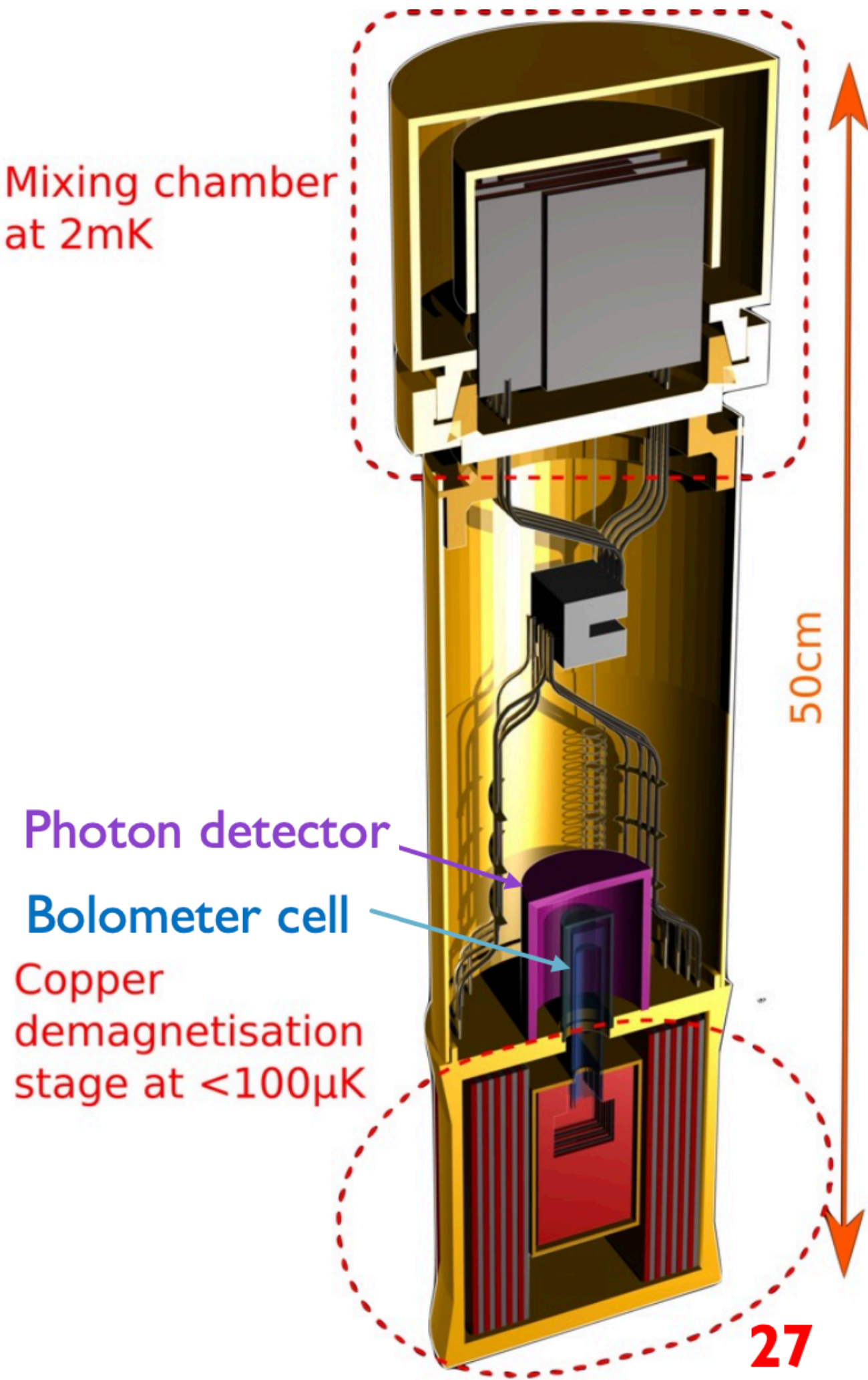
Pushing Further Towards Sub-GeV Masses



R. Essig/Stony Brook University; APS/Carin Cain

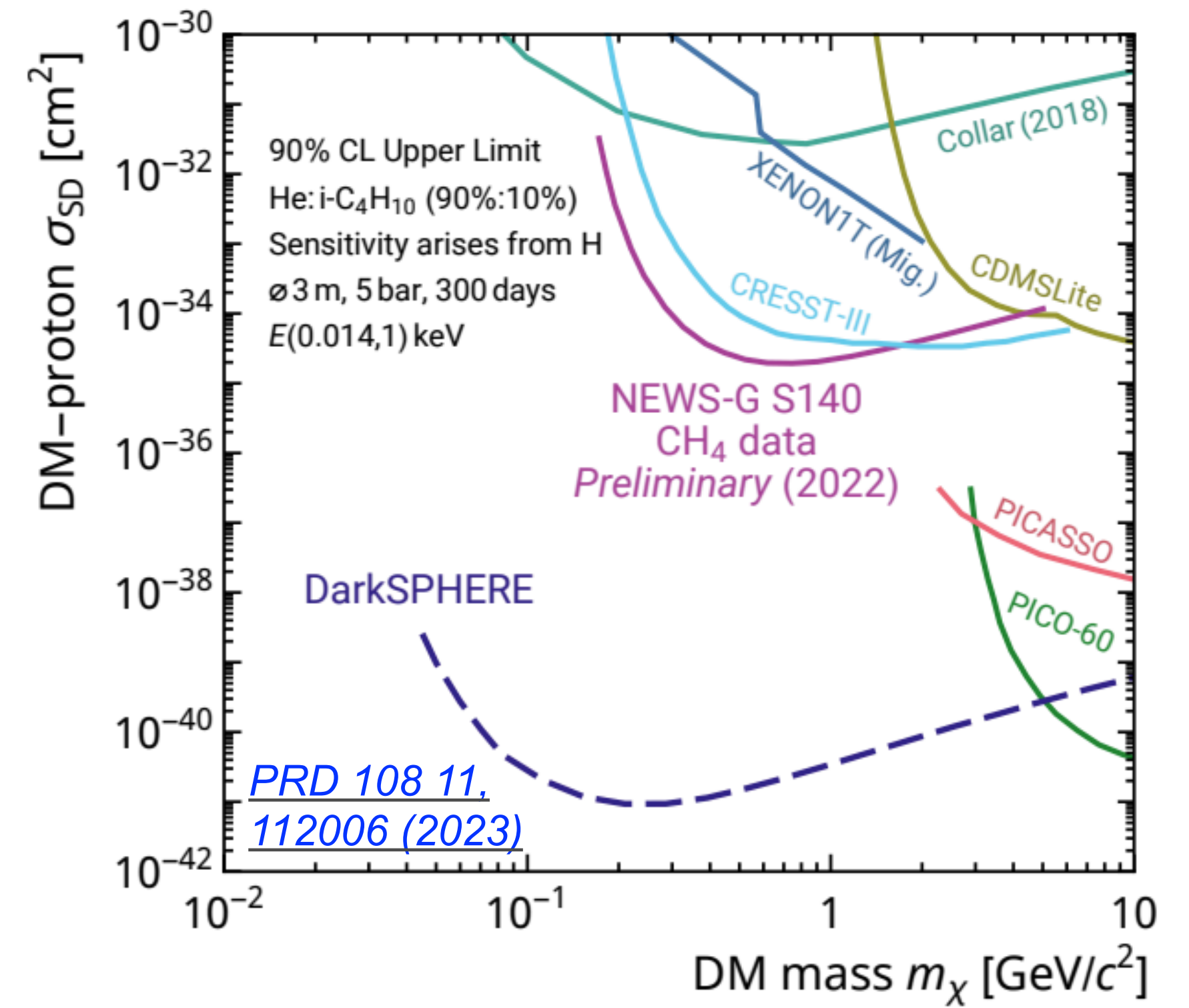
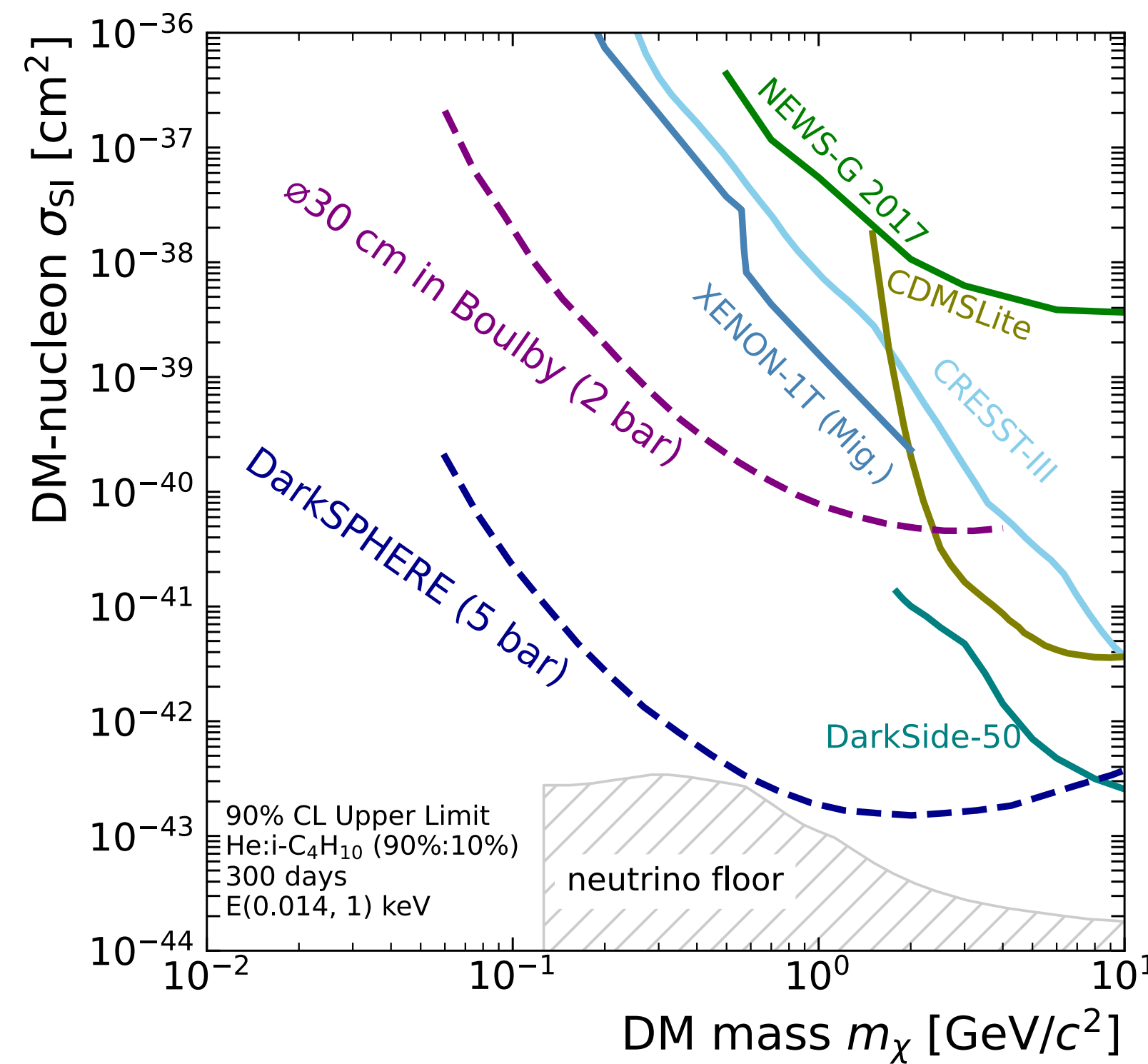
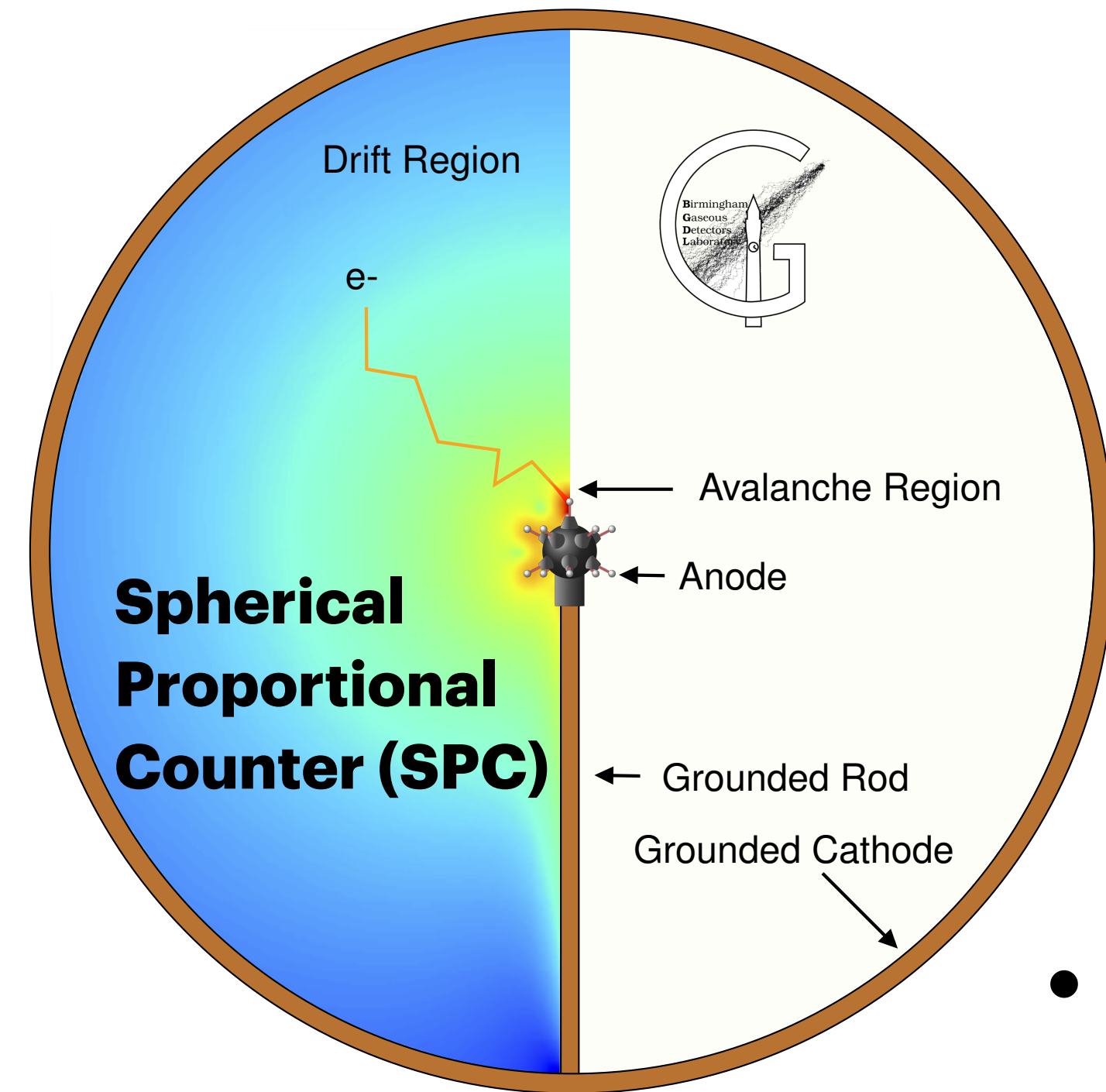
- Inelastic scatters \rightarrow DM-bound electron scattering; collective excitations
- Quanta production \rightarrow threshold limit: $\sim 10 \text{ eV}$ Xe ionisation; $< \text{meV}$ superfluids

QUEST-DMC



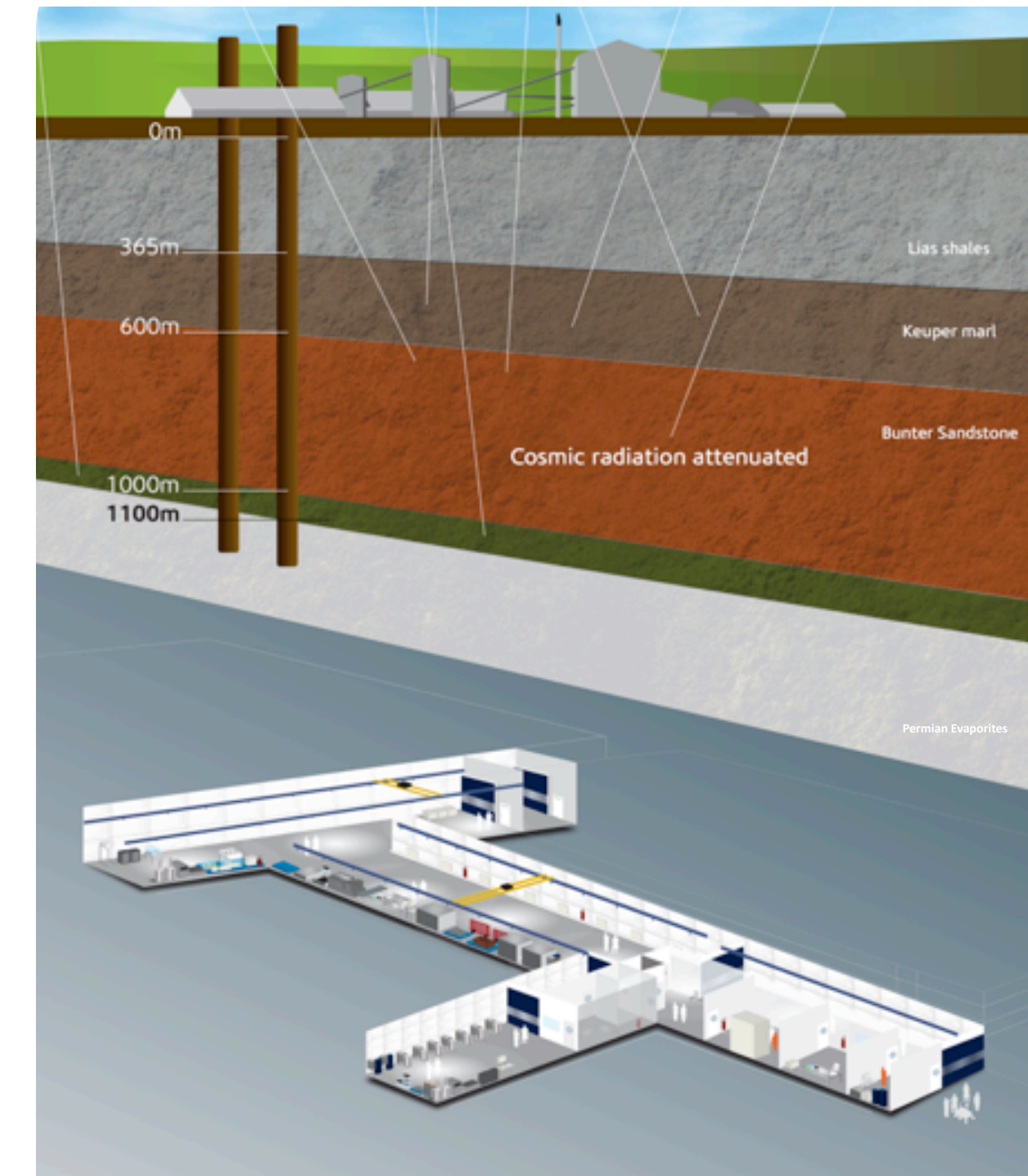
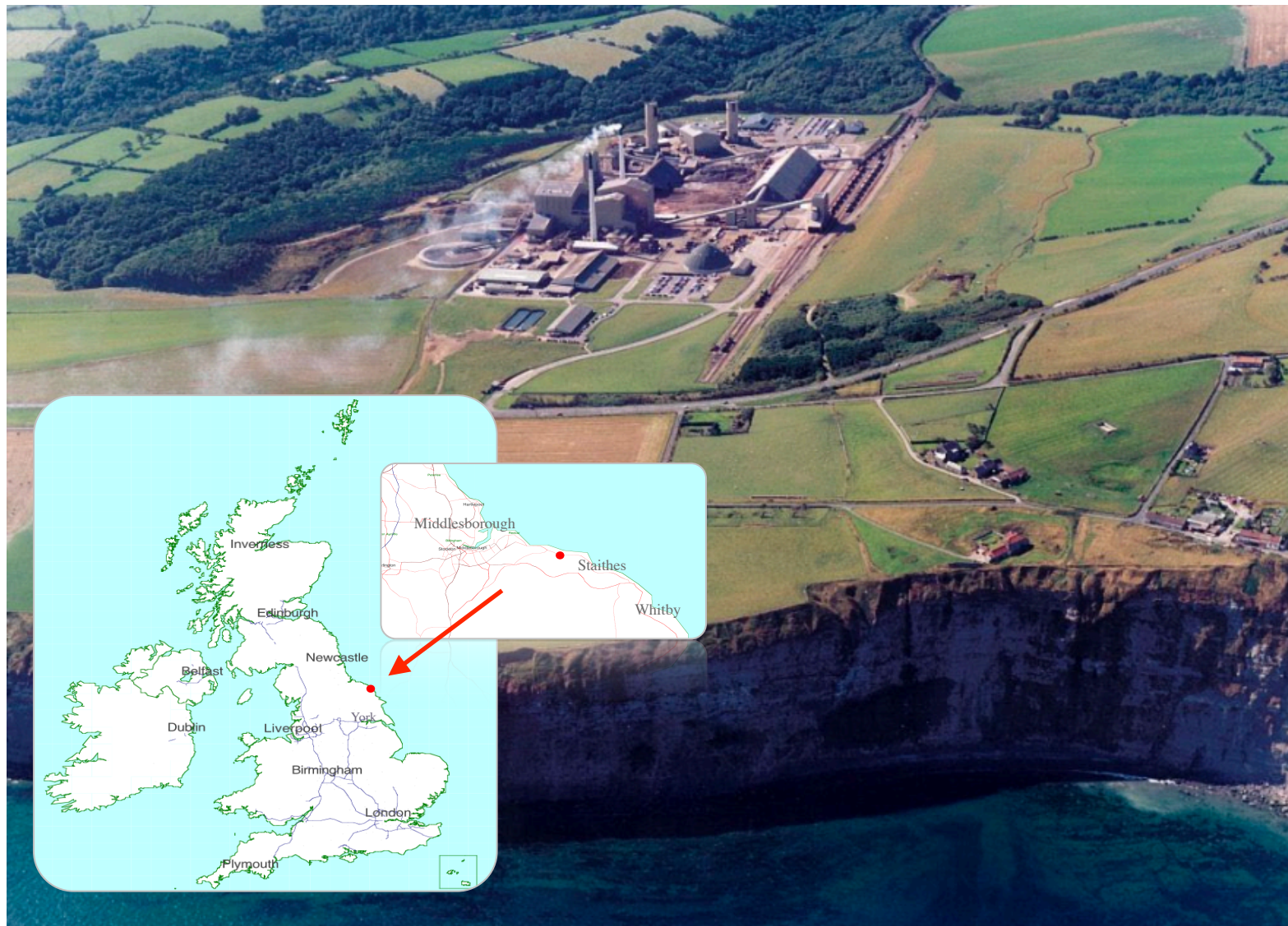
- QTFP funded; quantum-amplified superfluid ^3He detector
- Detect quasiparticles (heat) & light at $<10\text{ eV}$ threshold
- New bolometer construction & installation ongoing; proof-of-concept SQUID readout of nanowires performed
- 6 month data-taking run \rightarrow SD sensitivity $<10^{-36}\text{ cm}^2$

NEWS-G



- SPCs with different gas mixtures for light DM searches
- $\varnothing 140$ cm ultrapure Cu “S140” finished first physics run @SNOLAB in 2023
→ preliminary: world-leading limits on proton SD interactions in 0.2-1 GeV range
- DarkSPHERE: proposed $\varnothing 3$ m fully electroformed Cu detector; invited to submit proposal for Boulby Future Underground Dark Matter Science call

Boulby Underground Laboratory



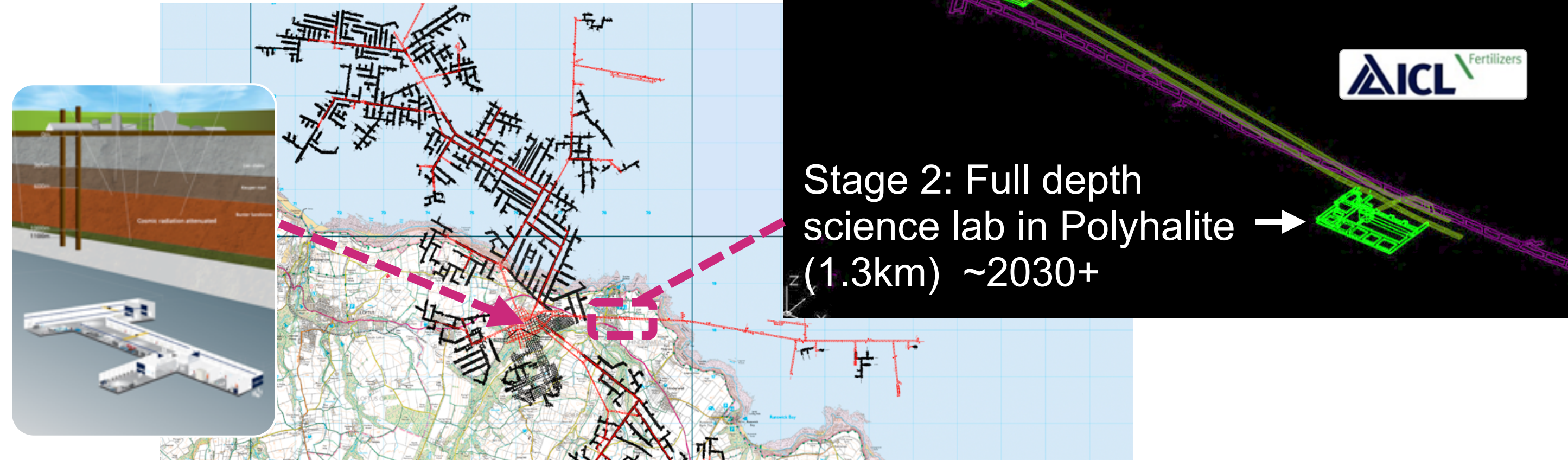
- UK's deep underground science facility, operated by STFC in partnership with mine operators, ICL-UK → one of five such facilities in Europe; <15 worldwide
- Multidisciplinary (e.g. astrobiology), not just low-background particle physics
- Long history of dark matter including ZEPLIN, DRIFT, NEWS-G R&D
- Boulby UnderGround Screening (BUGS) - world-class material assaying

Future Development @ Boulby

Funding opportunity

Future underground dark matter science experiments

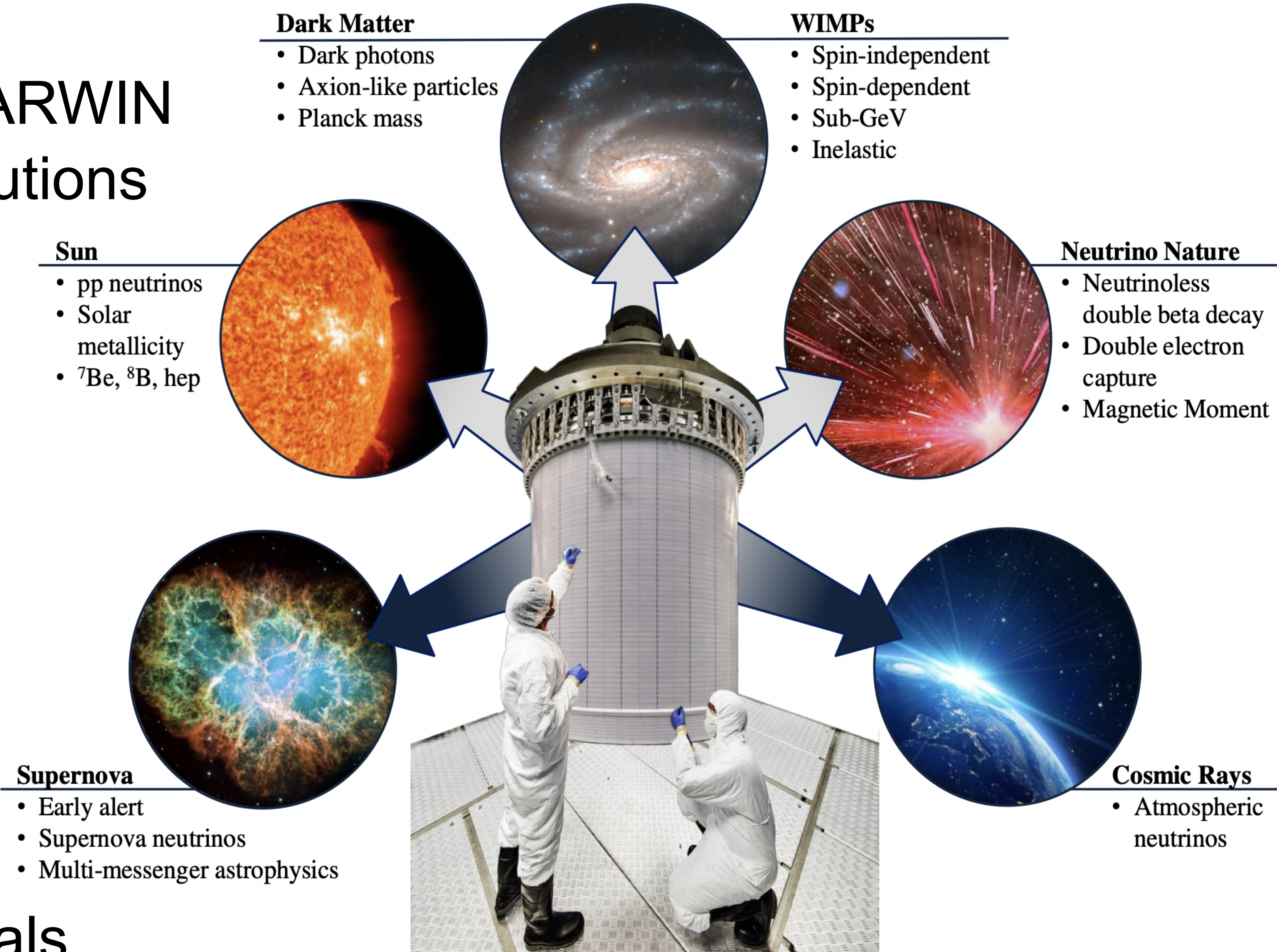
Opportunity status:	Open
Funders:	Science and Technology Facilities Council (STFC)
Funding type:	Grant
Total fund:	£10,000,000



- Boulby Development Project - next level planning and preparing for a *“...greatly expanded underground science facility in the North East, with potential to host a major international science infrastructure, such as a next generation dark matter experiment.”* [STFC strategic delivery plan (2022-2025)]
- Site design & development: Stage 1 excavations due to start in **2024**
- Short term: maximally exploit current facilities → funding call now open!
- Medium-to-long term: major expansion of facilities to enable the UK to host next-generation, world-leading science projects coming **2030+**

XLZD

- XENON + LUX-ZEPLIN + DARWIN
→ 350+ members, 60+ institutions
- 60-80t (active) LXe target
- Rare-event observatory
 - Ultimate probe of WIMPs down to the neutrino fog
 - Competitive detector for $(^{136}\text{Xe}) 0\nu\beta\beta$ decay
 - Sensitive to multiple astrophysical neutrino signals



Planning for XLZD @ Boulby

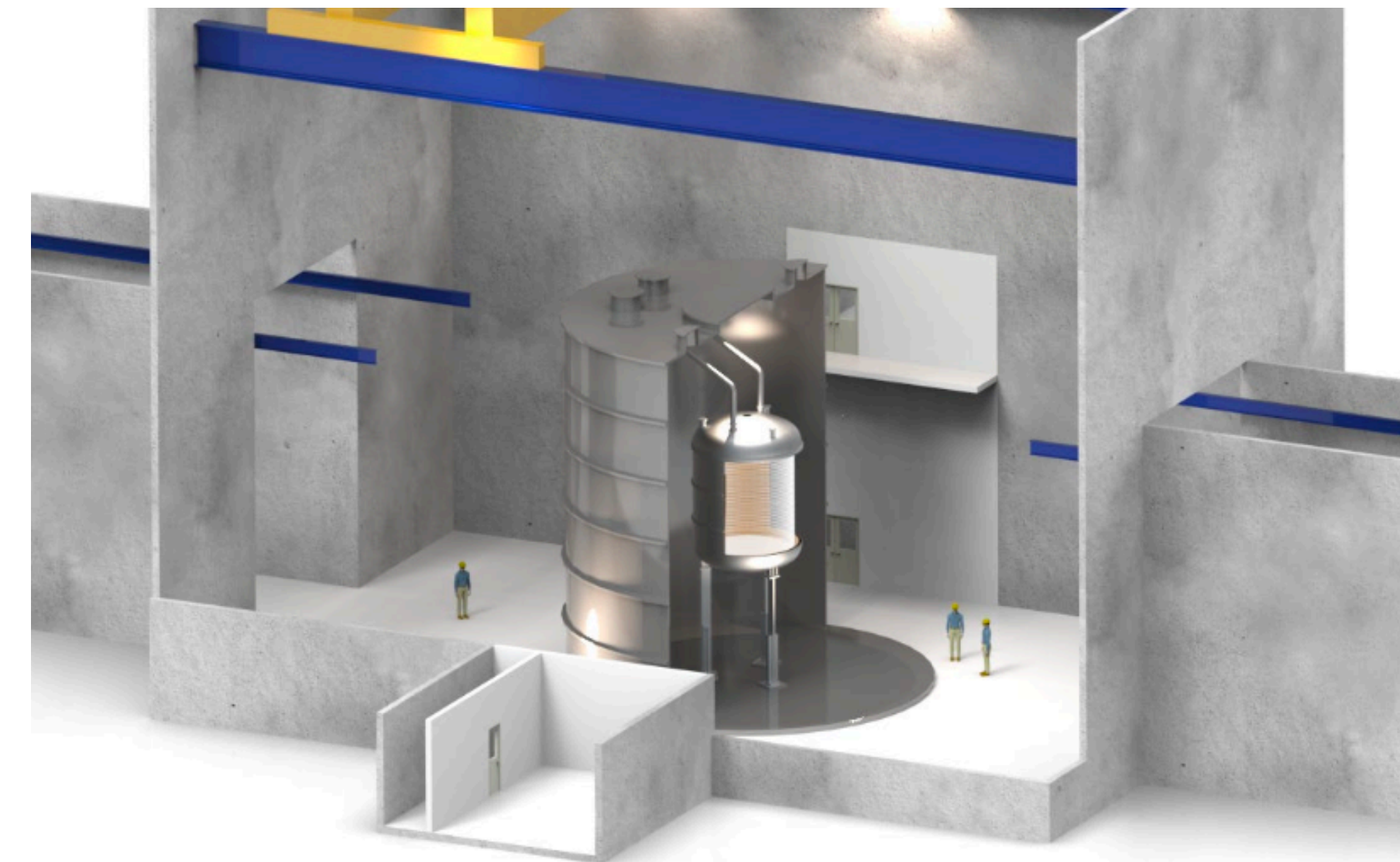
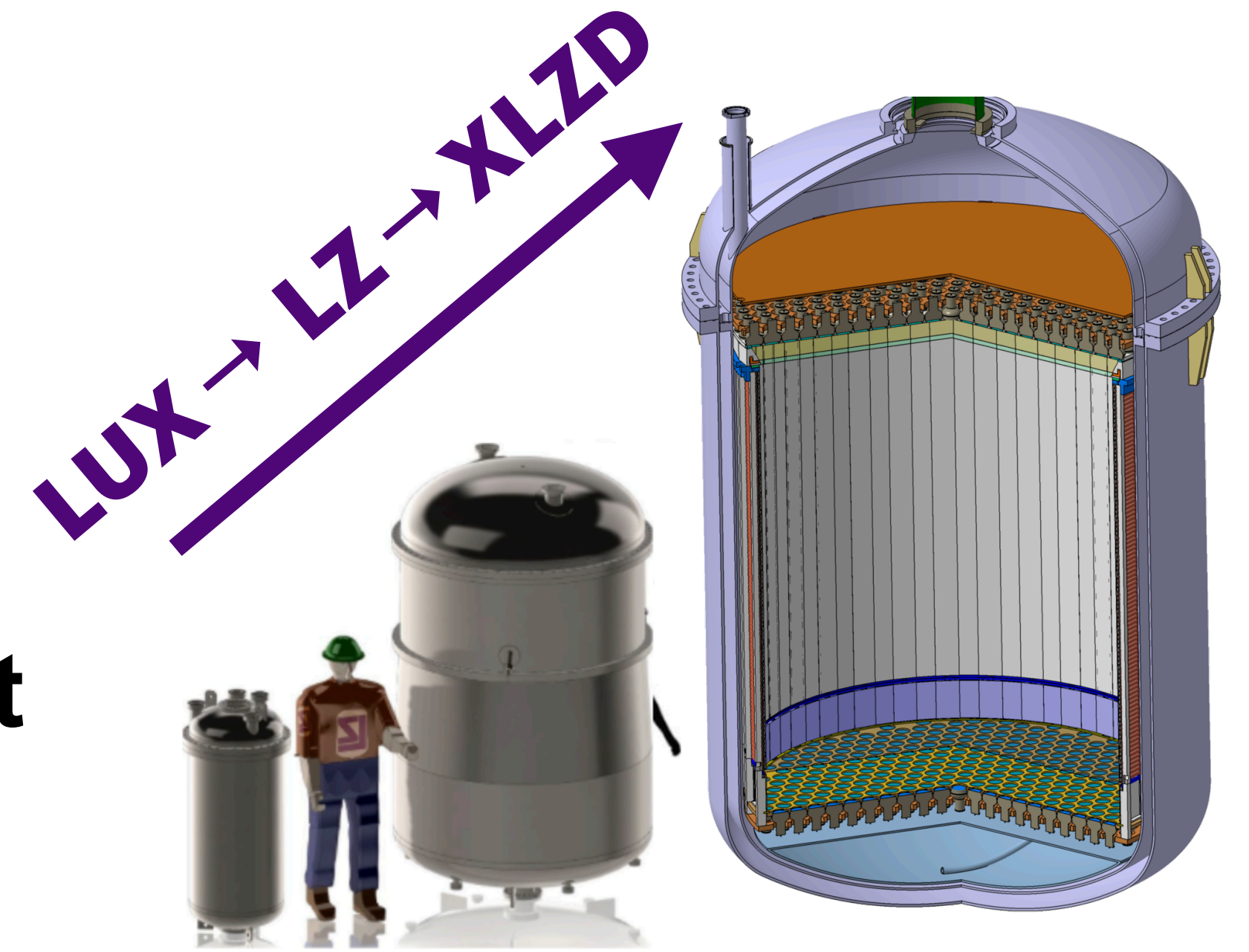
Two project stages:

- Pre-construction - 3-4 years from 2024
→ **UKRI Infrastructure Fund: outcome imminent**
- Construction - 5+ years from 2027
→ coupled to site selection ~2025

Development closely coordinated with XLZD-UK

→ two-stage facility for competitive schedule

- Stage 1 - Clean Manufacture Facility (~2028)
- Stage 2 - new lab @ 1300m depth (~2030)



Pre-conceptual design

Conclusions

- More diverse approaches to look for candidates across a wide range of masses, not just WIMPs and axions - **“search wide, delve deep”**
- Quantum boom: **four of seven QTFP projects** towards dark matter
- **Dark matter in the UK is growing**; potential to host on home soil
 - Open call for intermediate-scale experiment to start 2025 @ Boulby
 - XLZD @ Boulby: exciting & **unique opportunity for the UK to host** a major project, back in the home of the first xenon experiment!
- Lots more to hear at this conference
 - Wednesday Session D parallels; QTFP & early career prize plenaries



XLZD WIMP Reach

