



New Experimental Searches for Light Dark Matter

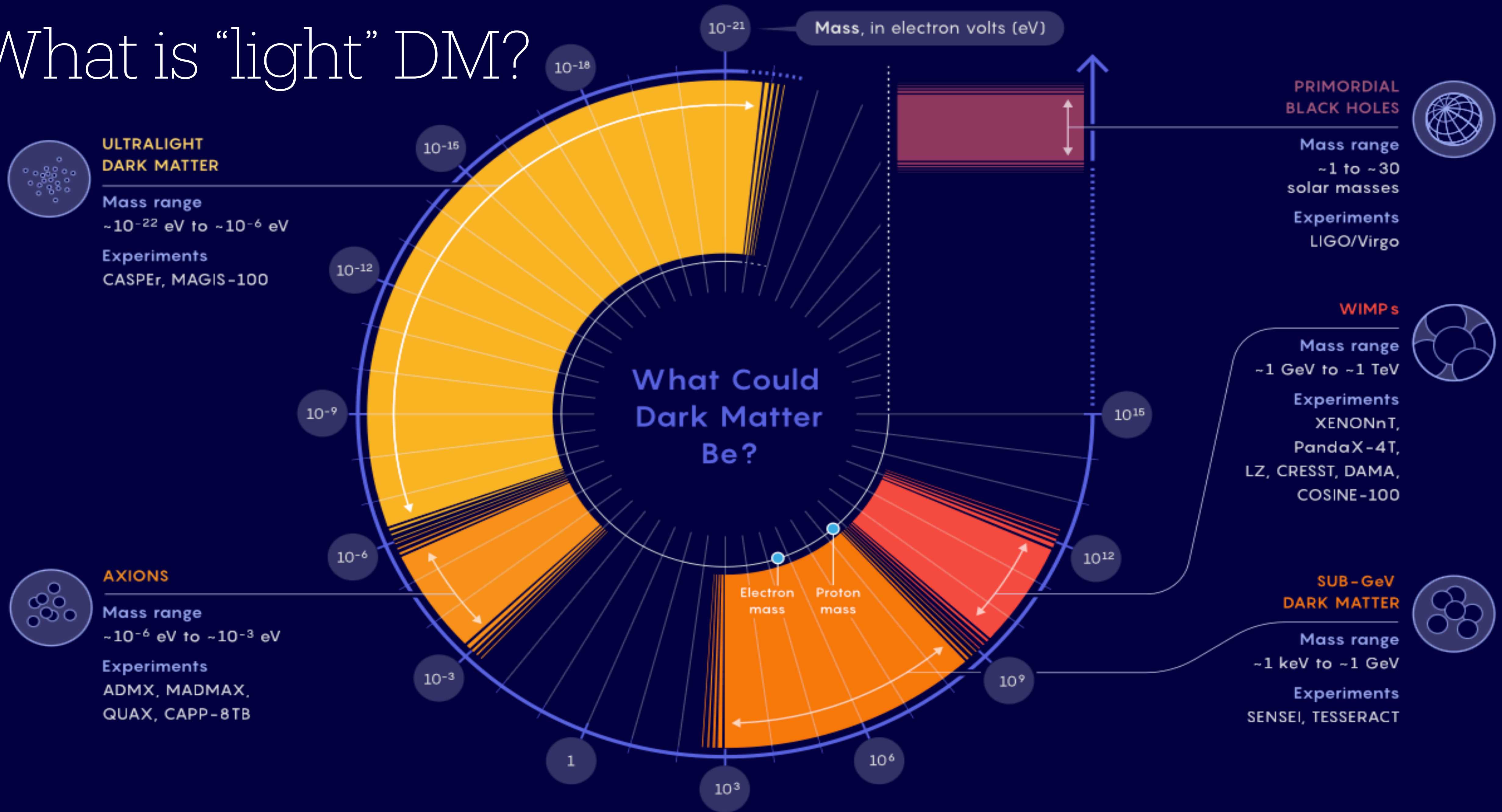
*Artist's
interpretation of
searching for
dark matter
with quantum
technologies*

**“Wandering in the dark”
UK HEP Forum 2025
The Cosener’s House
21st - 22nd October**

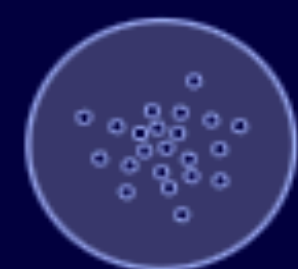
**Ashlea Kemp
UKRI Future Leaders Fellow
STFC Particle Physics Department
Rutherford Appleton Laboratory**



What is “light” DM?



What is “light” DM?



ULTRALIGHT DARK MATTER

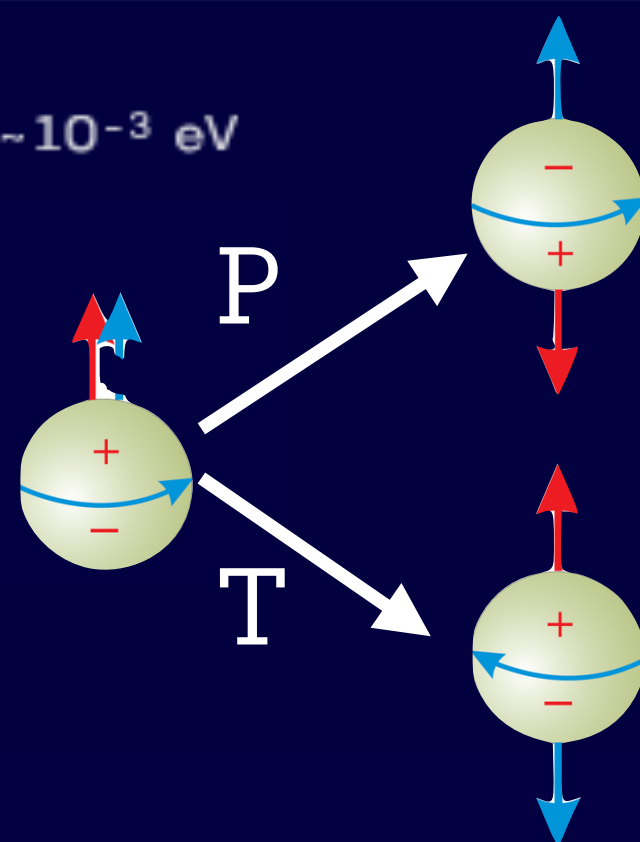
Mass range
 $\sim 10^{-22}$ eV to $\sim 10^{-6}$ eV

Wave-like

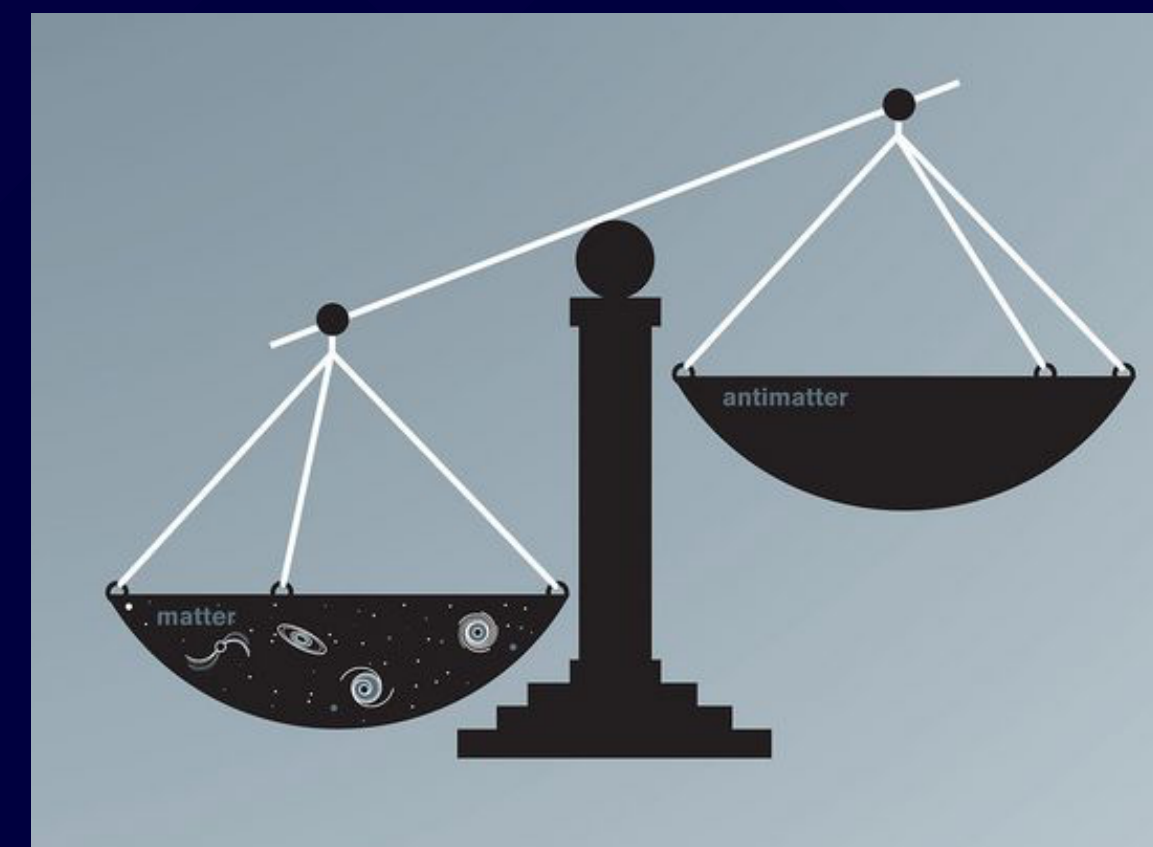


AXIONS

Mass range
 $\sim 10^{-6}$ eV to $\sim 10^{-3}$ eV



What Could
Dark Matter
Be?



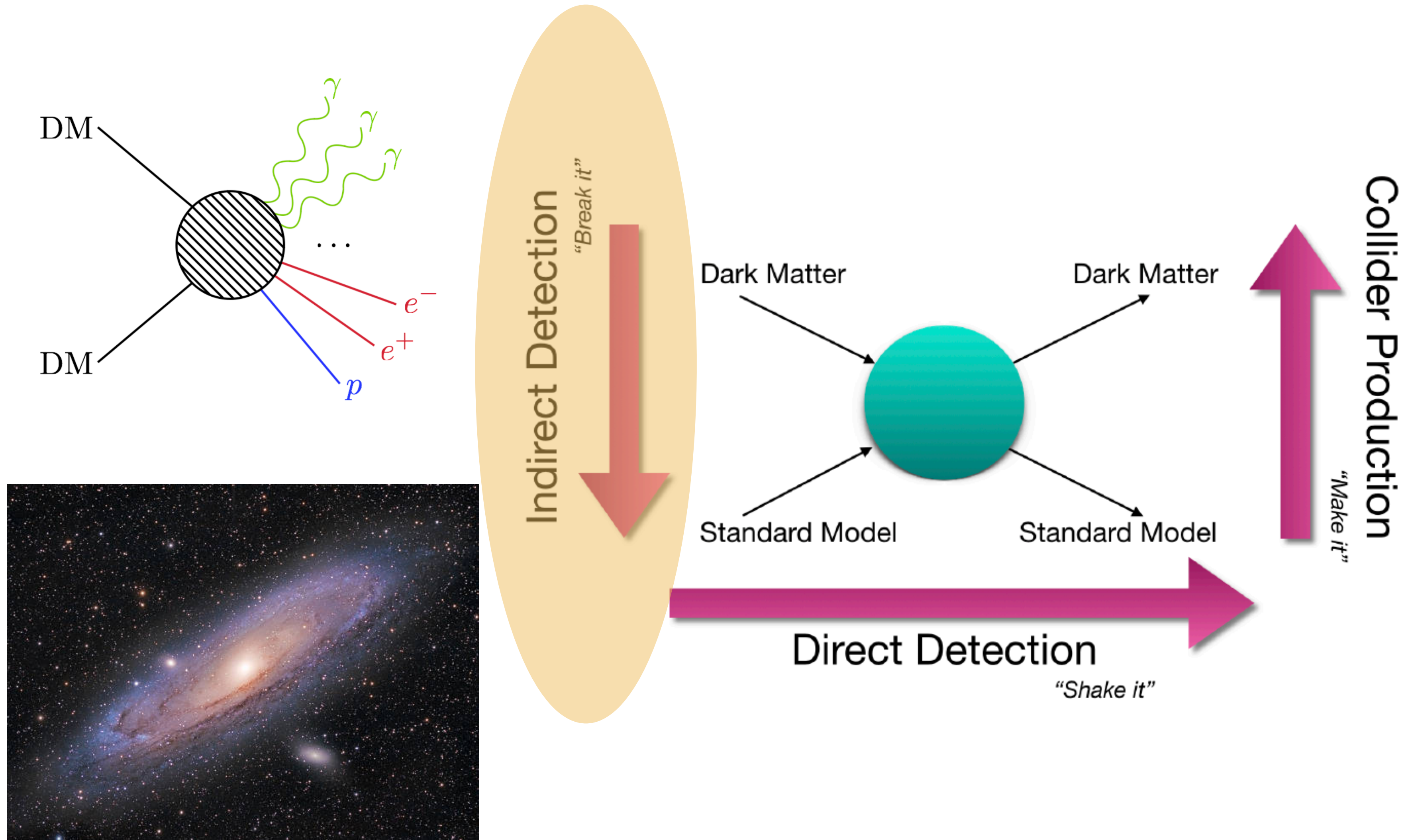
SUB-GeV DARK MATTER

Mass range
 ~ 1 keV to ~ 1 GeV

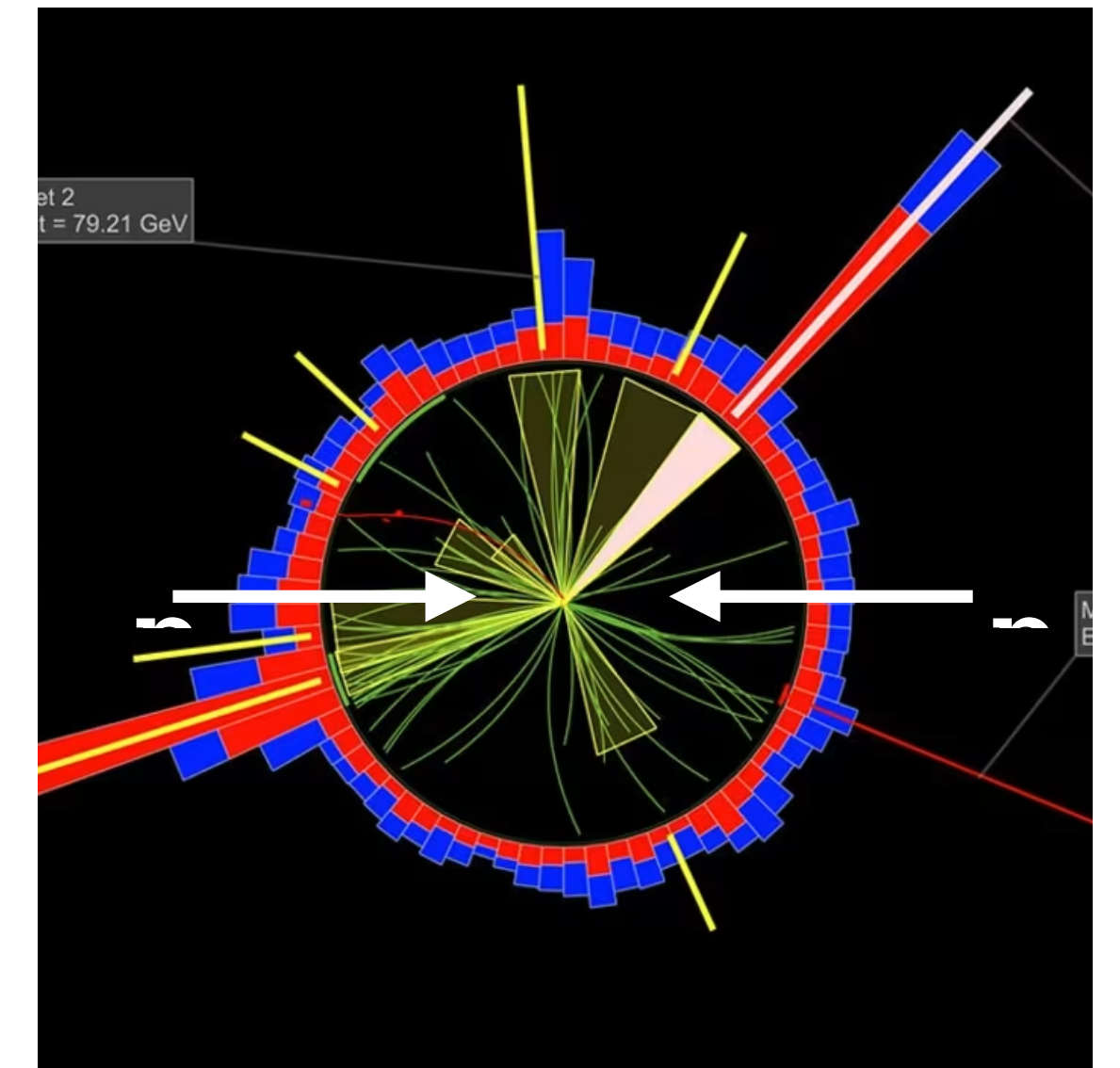
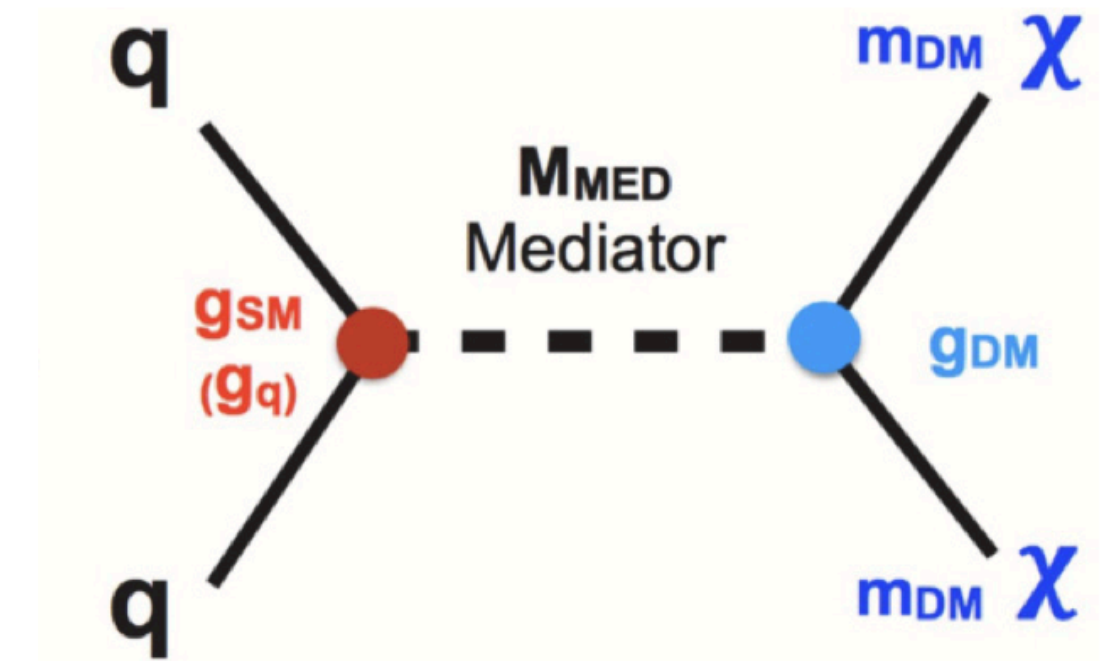
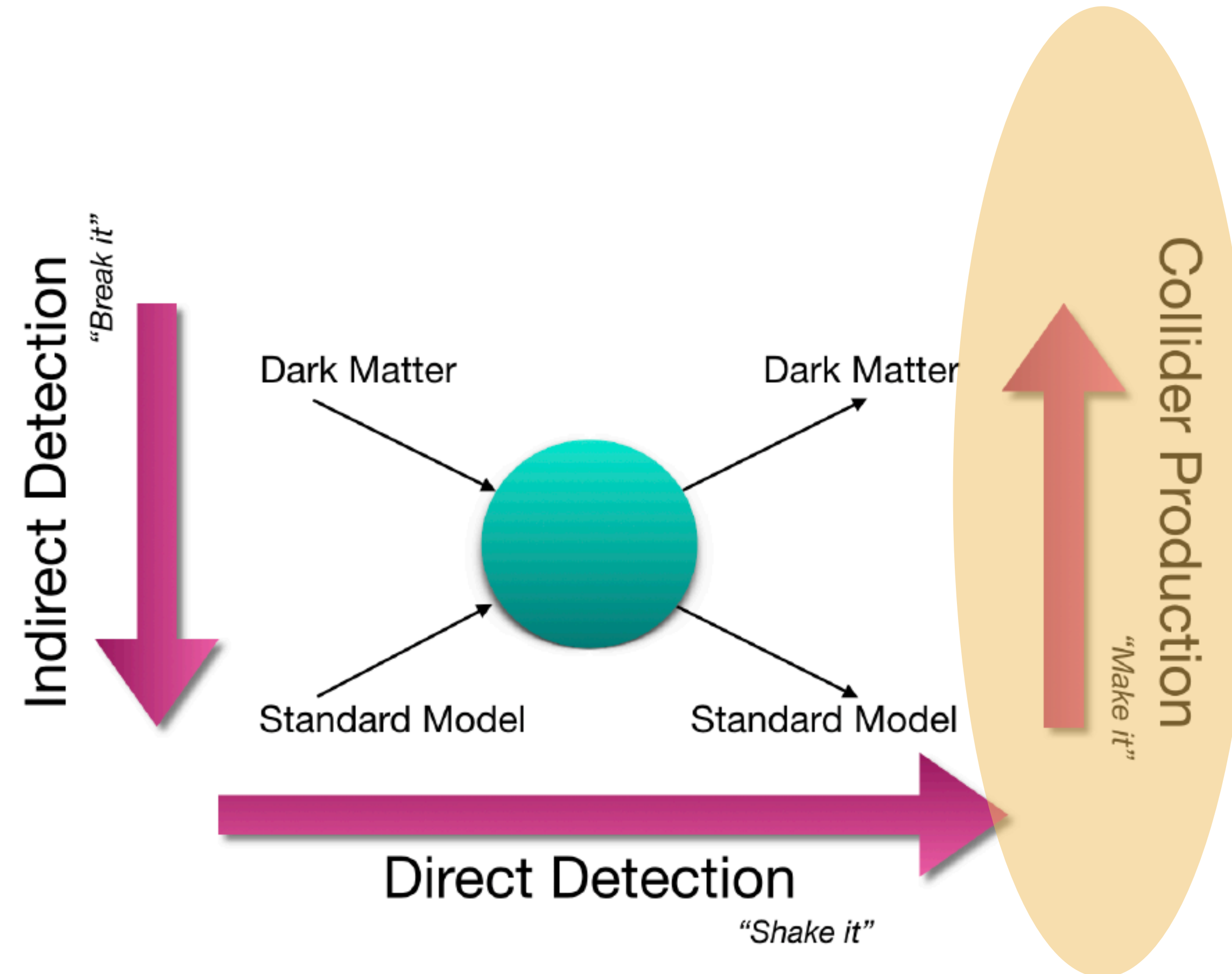


Particle-like

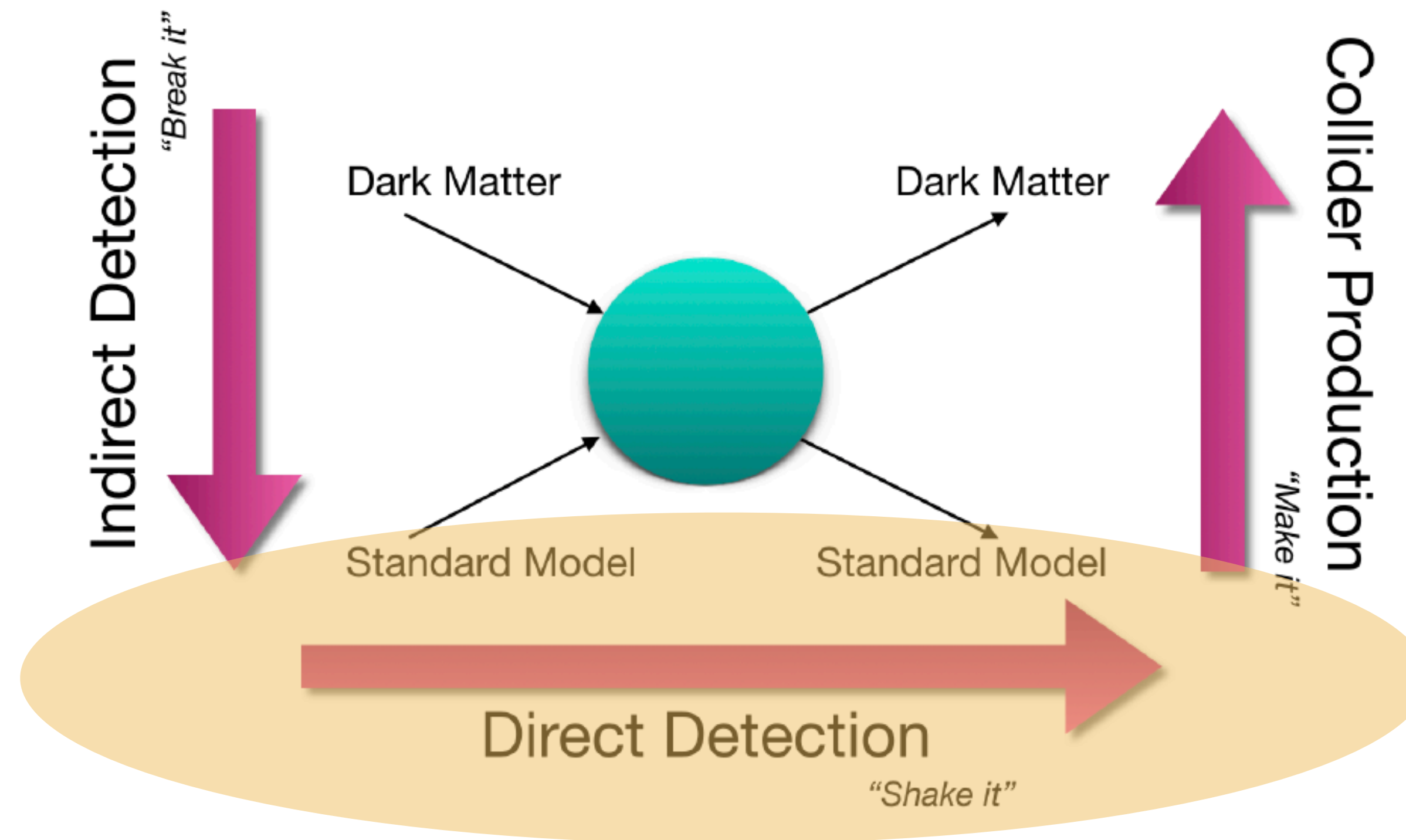
Particle-like DM: An Experimentalist's View



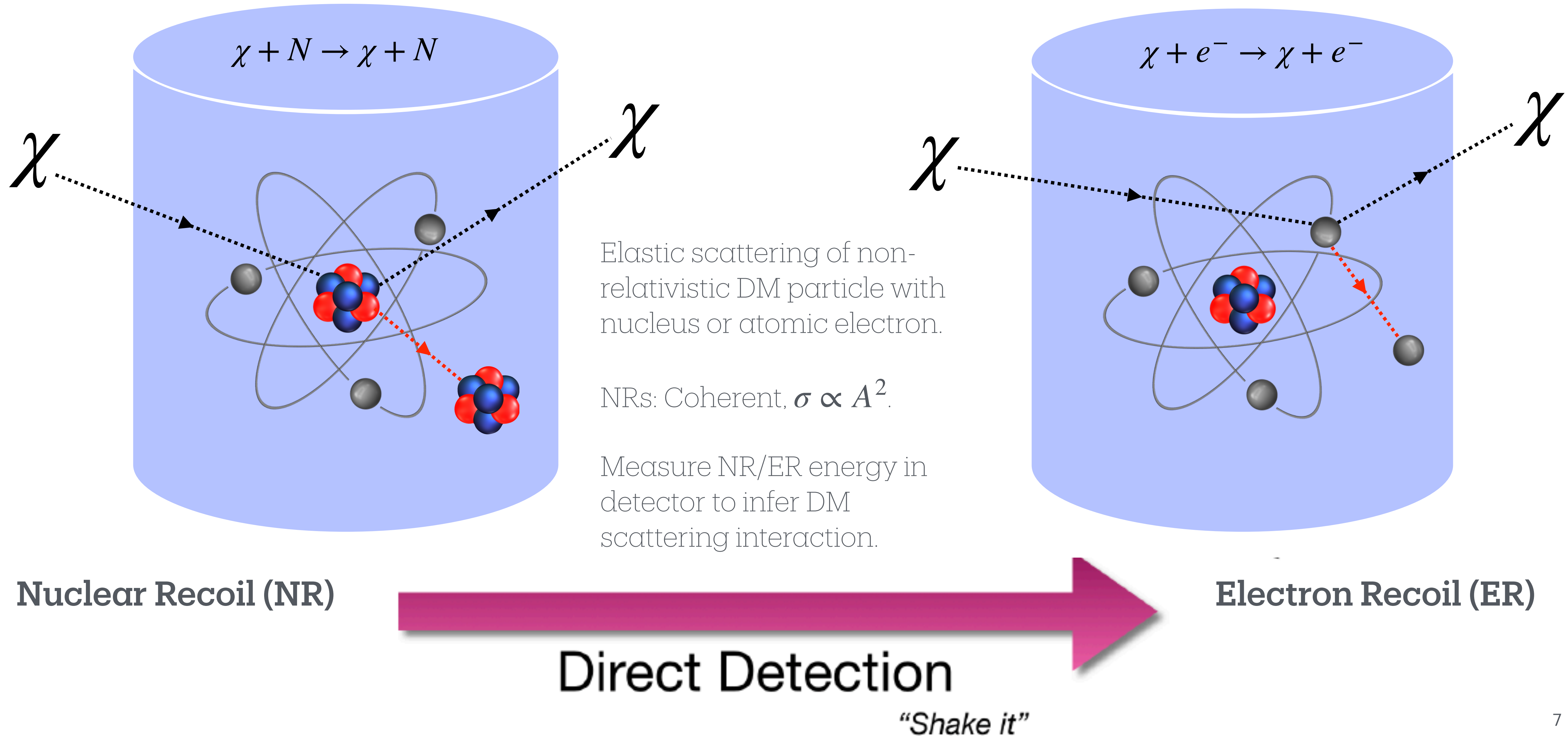
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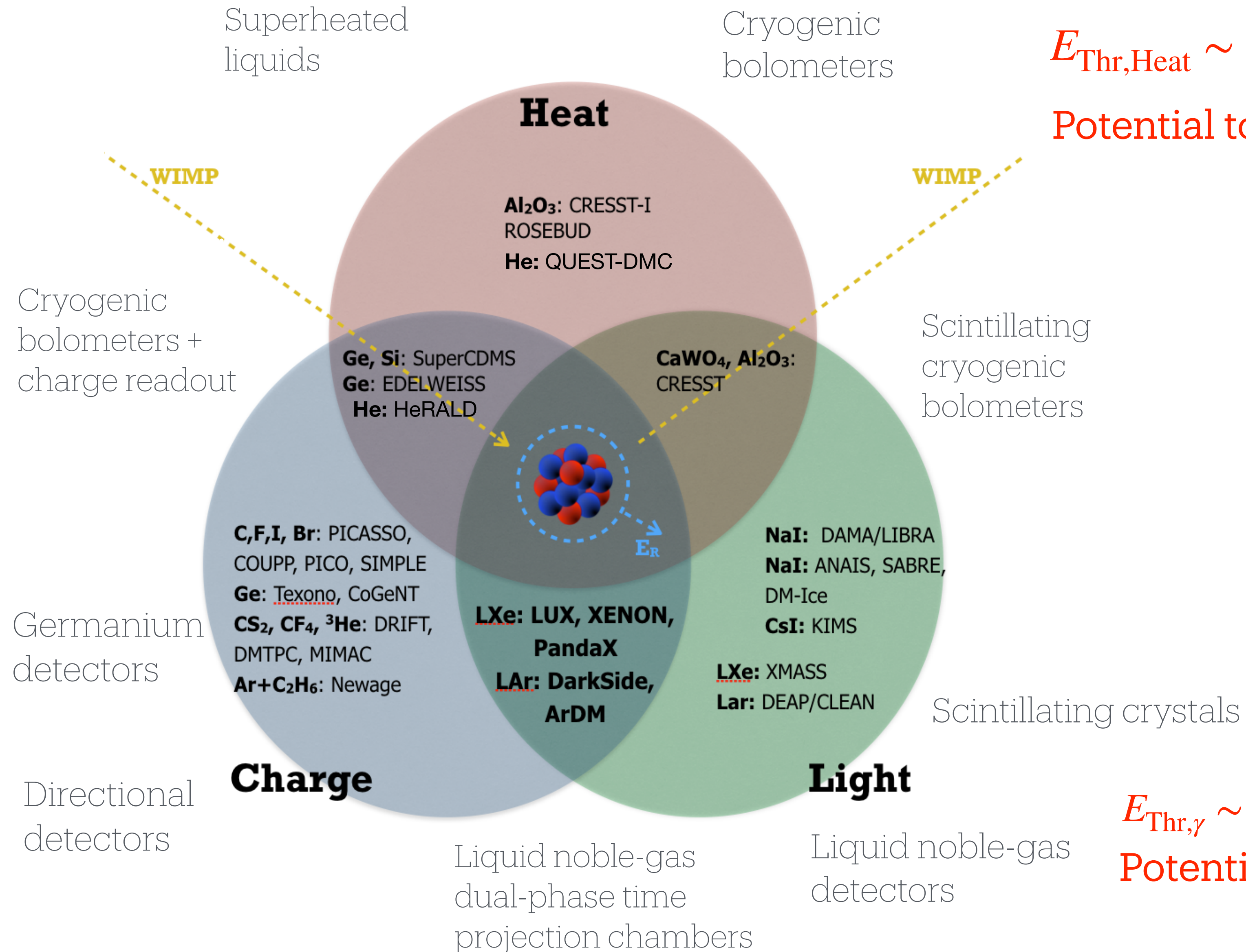
Particle-like DM: An Experimentalist's View



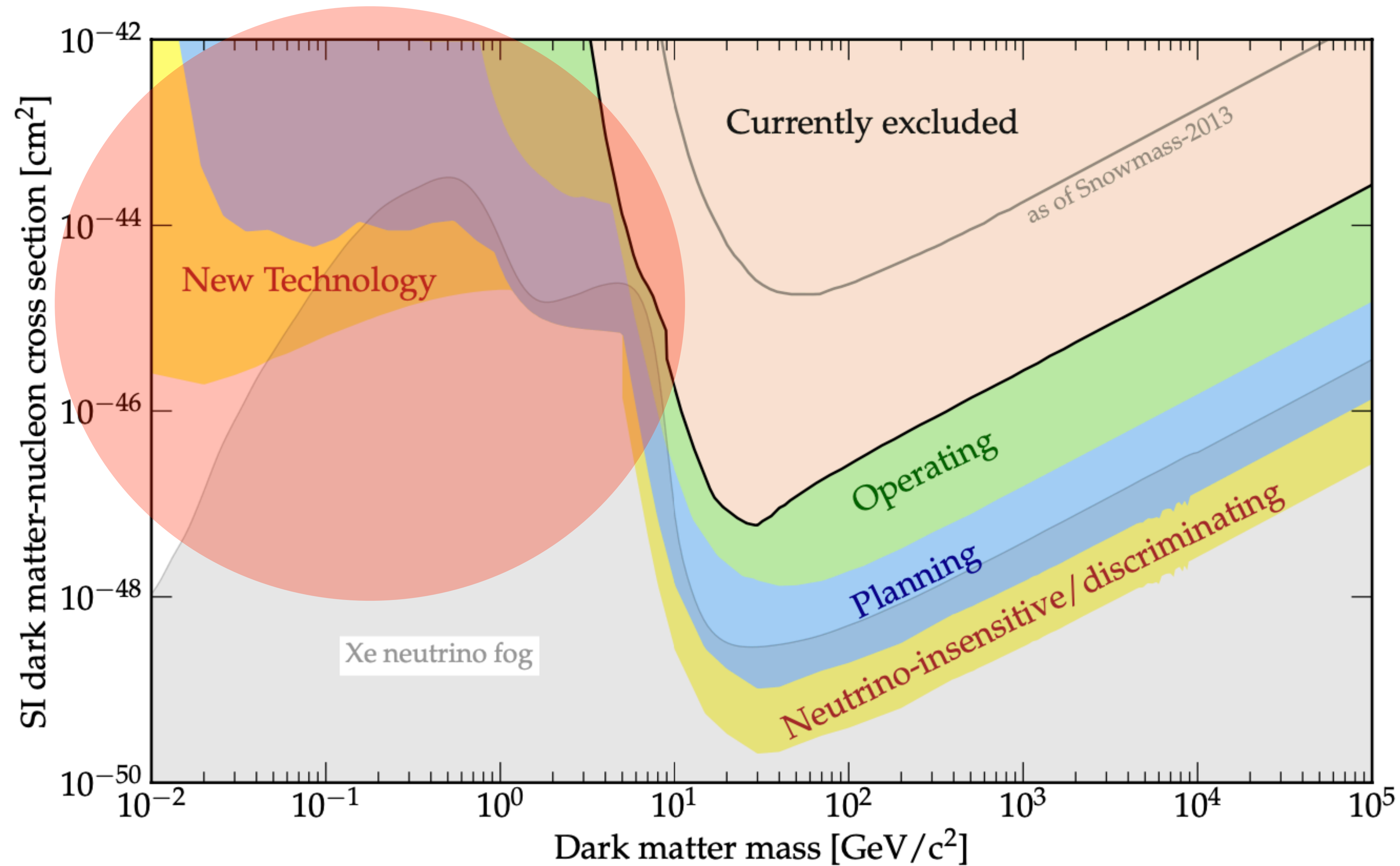
Particle-like DM: Detection Technologies

To reach sensitivity to lower DM masses, experiments need to lower their energy threshold without compromising their background rejection power.

$E_{\text{Thr},Q} \sim \mathcal{O}(10 \text{ eV})$
Potential to reach eV



Particle-like DM: Where are we now?



Liquid Noble Detectors

Liquid noble detectors lead constraints for high mass WIMPs, but also have sensitivity to search for low mass DM.

Dual-Phase Time Projection Chambers (TPCs) measure scintillation (S1) and ionisation (S2) signal, which yield low energy thresholds, improved position reconstruction and enhanced background rejection power.

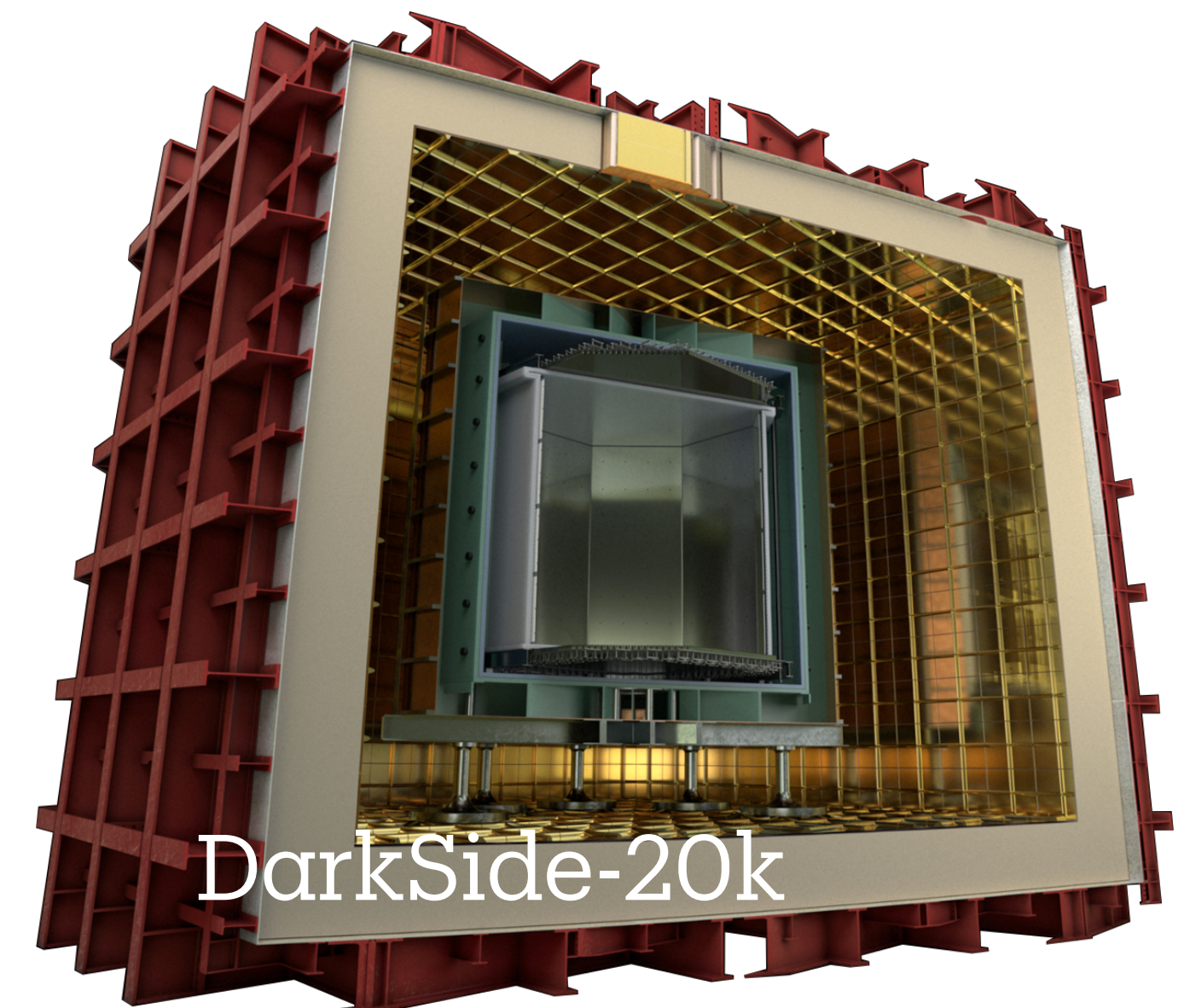
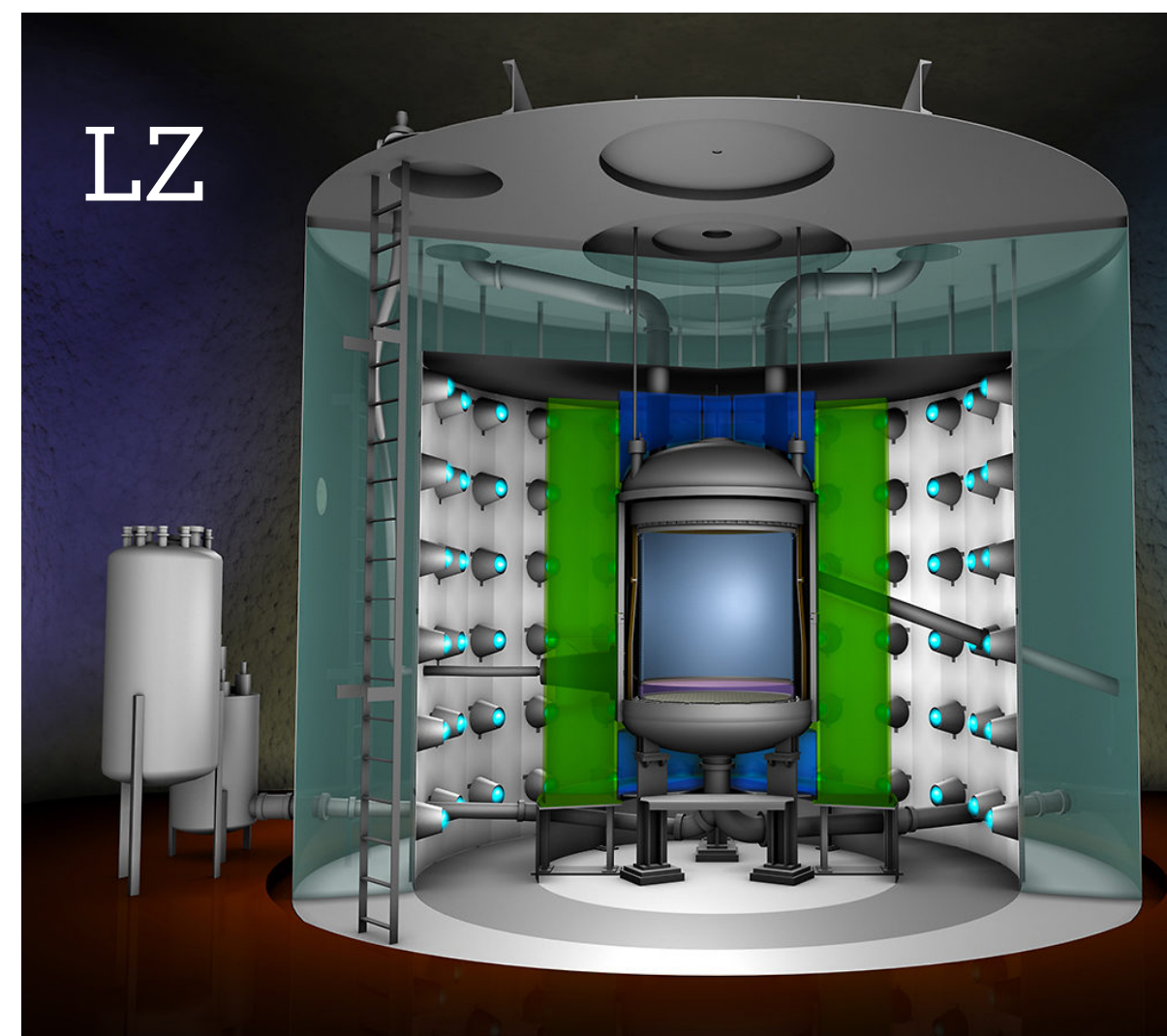
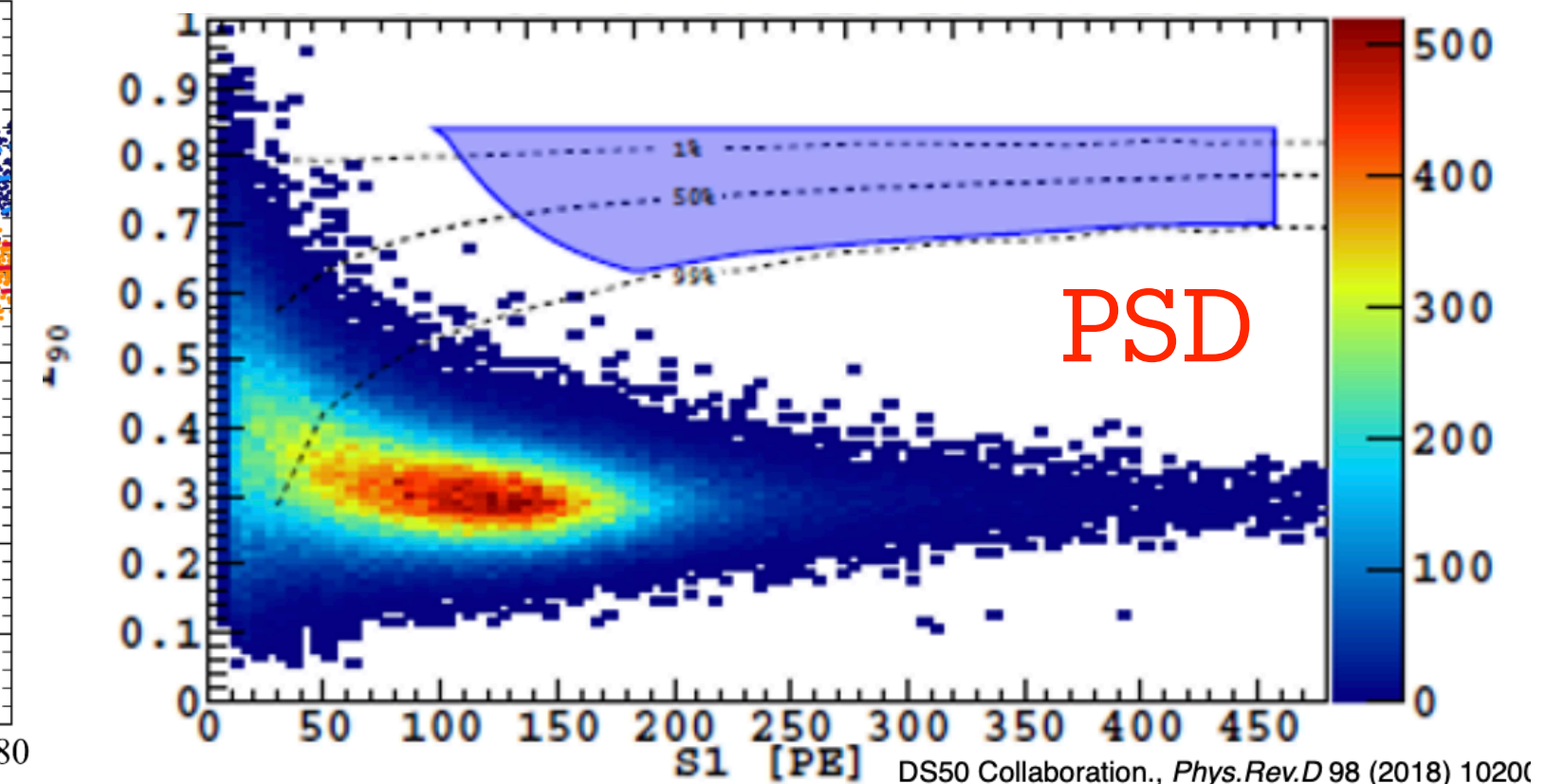
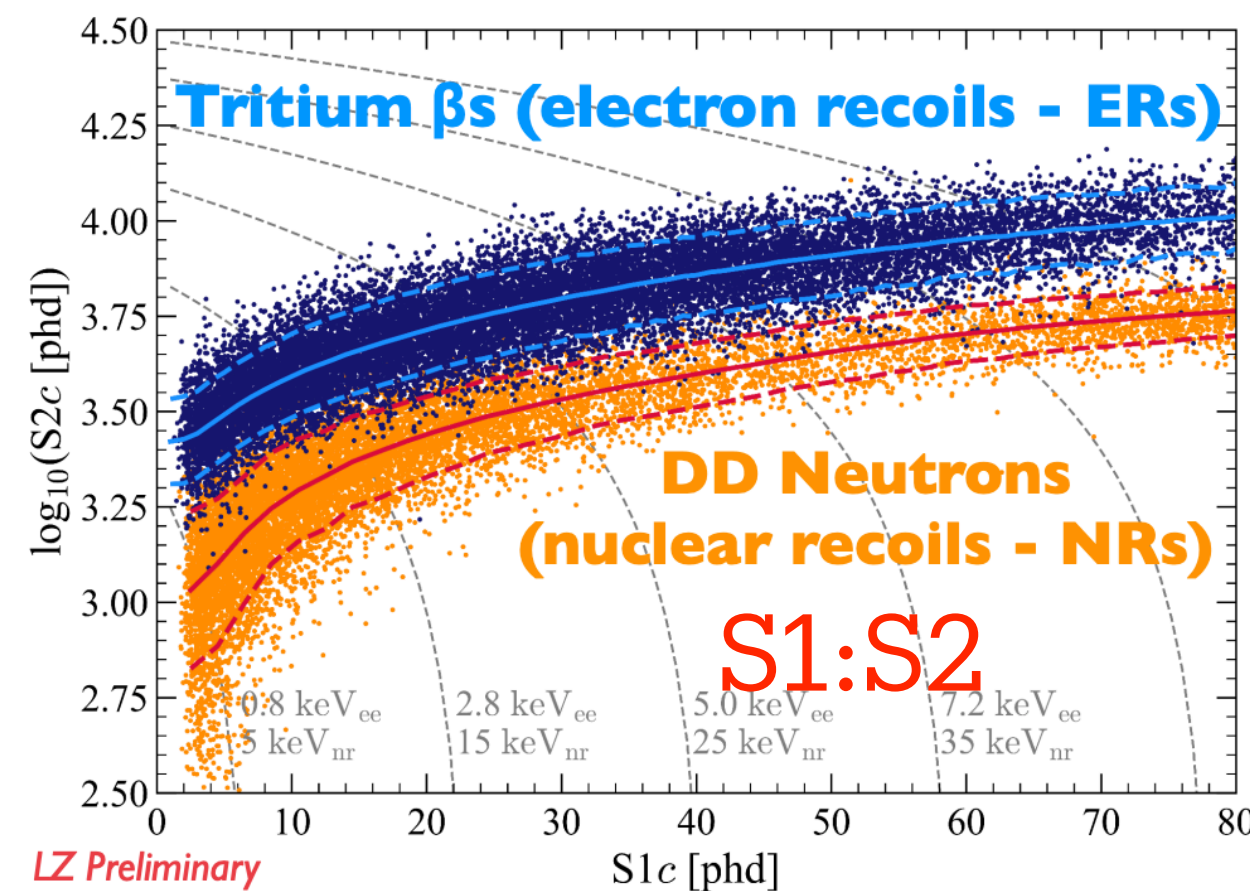
► Xenon: PandaX, XENON-1T, **LZ**

- Lower intrinsic radioactivity; enhanced A^2 boost factor for high-mass spin-independent interactions.

► Argon: DarkSide-50, **DarkSide-20k**

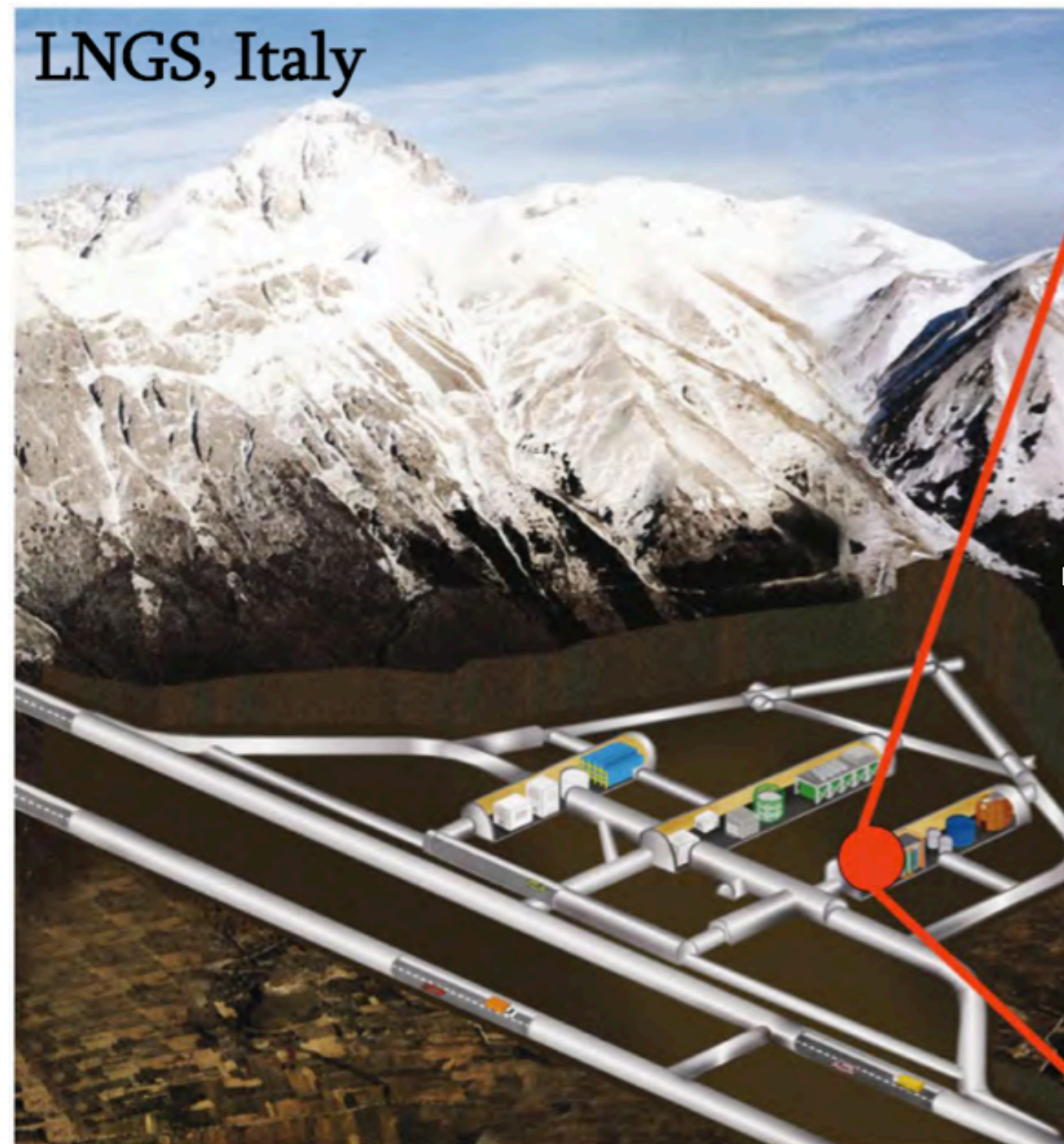
- Strong NR/ER discrimination power from Pulse Shape Discrimination (PSD), better kinematically matched for lighter DM particles.

DarkSide-20k projects unprecedented sensitivity to low mass DM!

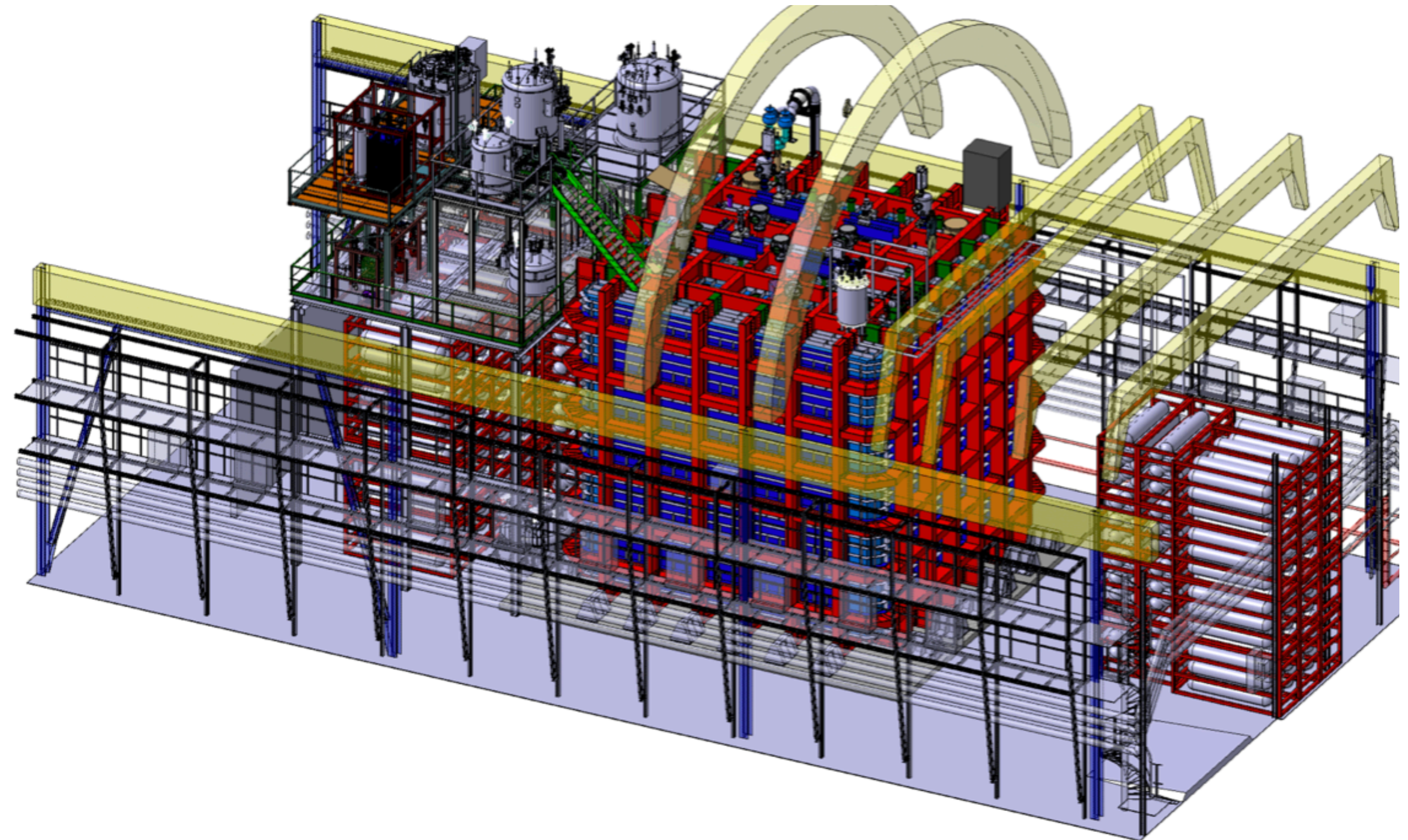


DarkSide-20k Overview

An observatory for dark matter and neutrino physics, under construction at LNGS.



Global Argon Dark Matter Collaboration (GADMC) comprised of 400+ people across 14 countries.

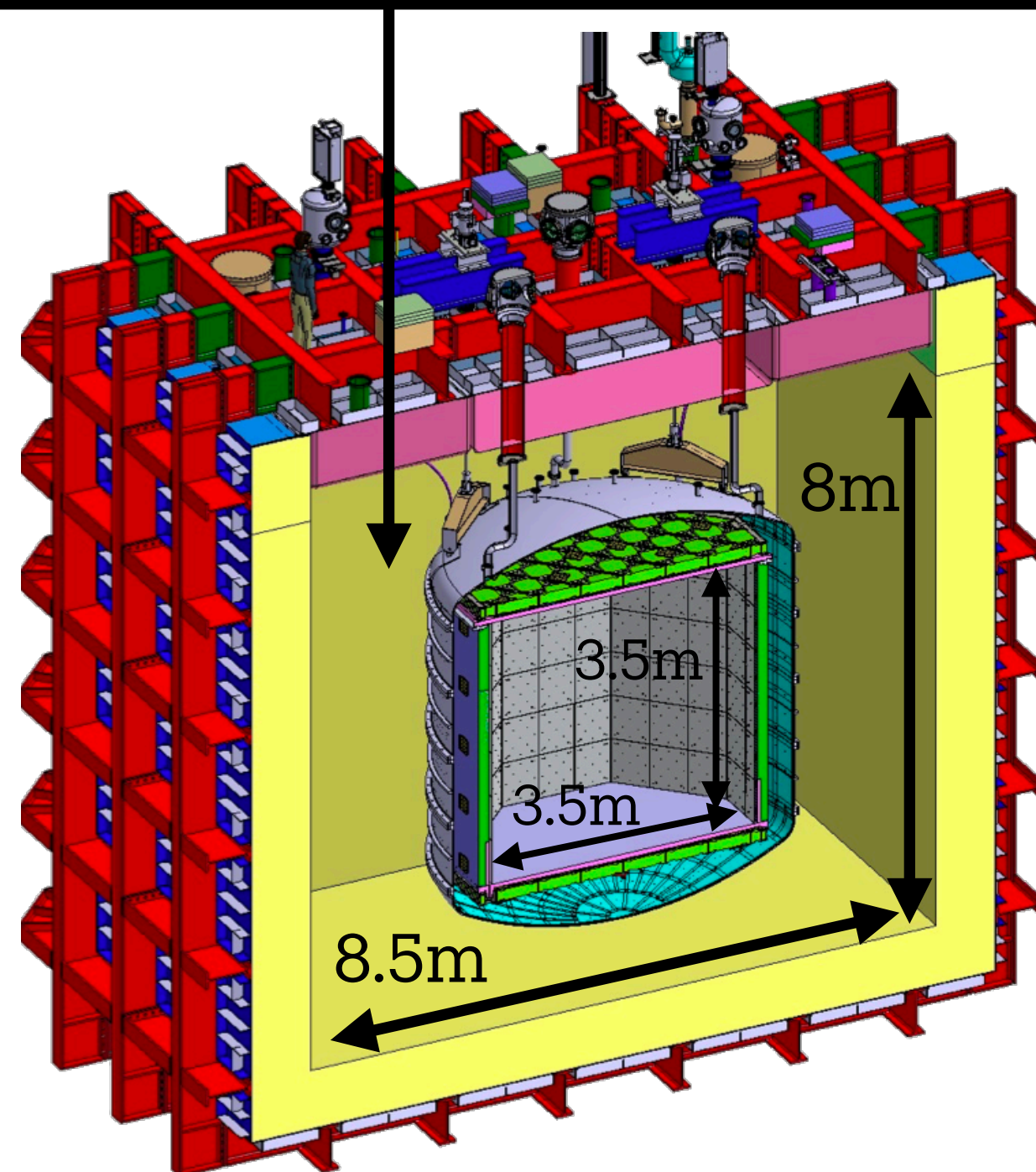


Rich physics programme: broadband search for DM spanning sub-GeV to Planck-scale DM!

DarkSide-20k Detector

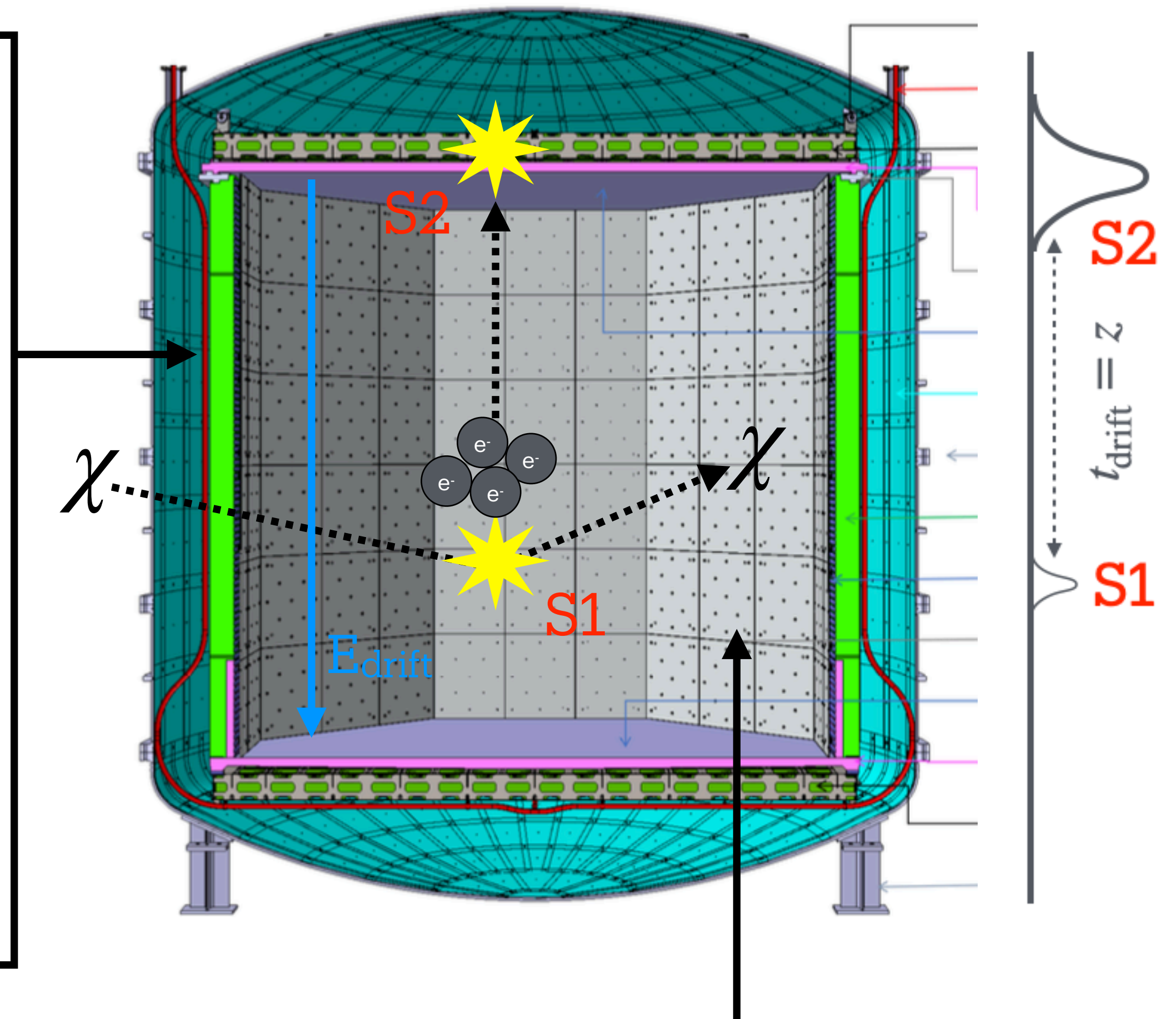
Outer Veto: 650t AAr enclosed in ProtoDUNE(esque) cryostat with sparse SiPM coverage.

Primary objective? Detect and veto cosmogenic muons.



Inner Veto: 35t UAr enclosed in Stainless Steel vessel with HDPE neutron shield surrounding vessel and instrumented with 7 m² of SiPMs.

Primary objective? Detect and veto radiogenic neutrons.



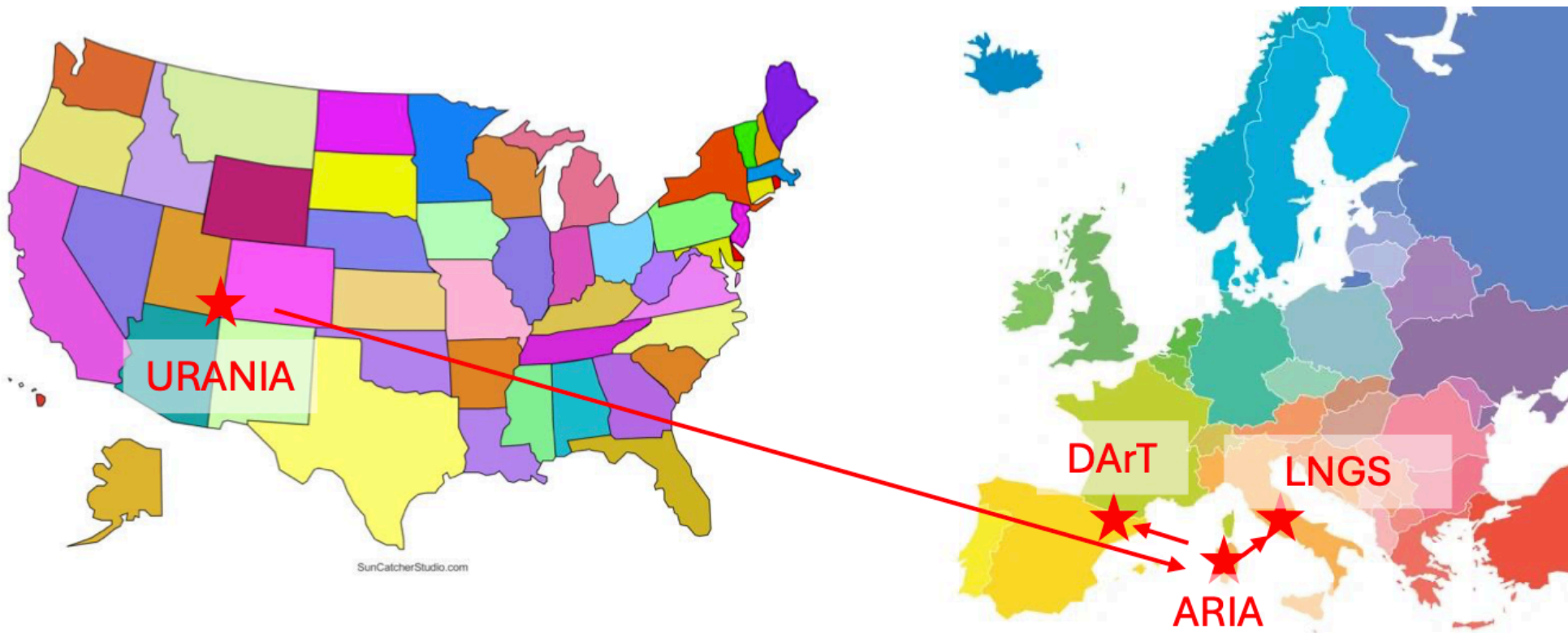
Dual-Phase TPC: 50t UAr enclosed in PMMA barrel with two optical plates of SiPM arrays with 21 m² coverage. Primary objective? Detect candidate DM signals!

DarkSide-20k Key Innovations

1) Use of Underground Argon

Global effort: Extraction in Urania (99.9% pure);
Purification in ARIA (99.999% pure); ^{39}Ar depletion
factor measured in DArT.

Depletion factor ~ 1400 !



A 350-metre-tall tower to purify argon

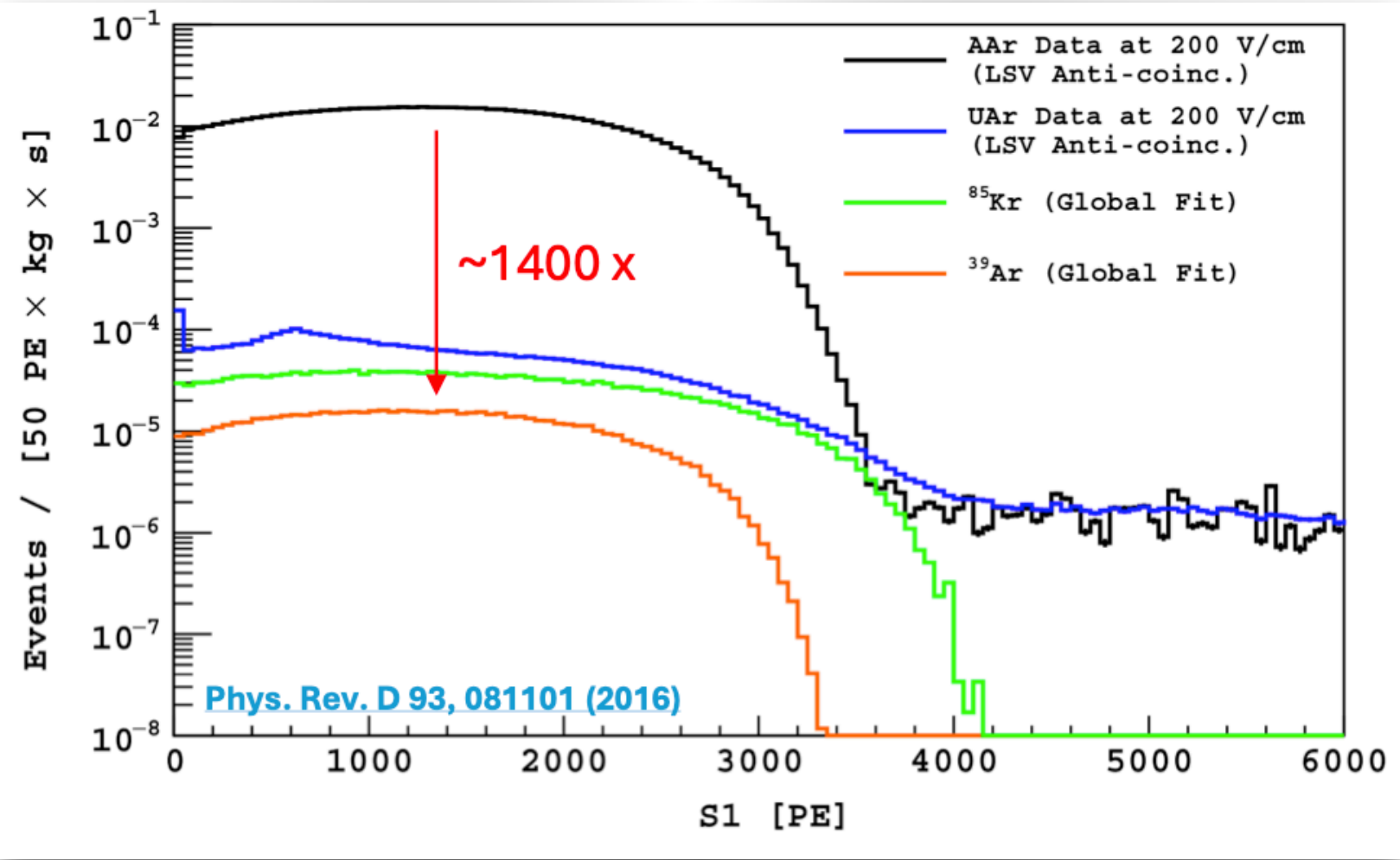
CERN is participating in ARIA, a project to build a 350-metre column to produce extra-pure argon to be used in a dark-matter search experiment

12 DECEMBER, 2017 | By Stefania Pandolfi



On Friday, 24 November, ARIA's top and bottom modules plus one standard module were brought to Building 180 and lined up to precisely test their alignment and interconnections. (Image: Max Brice/CERN)

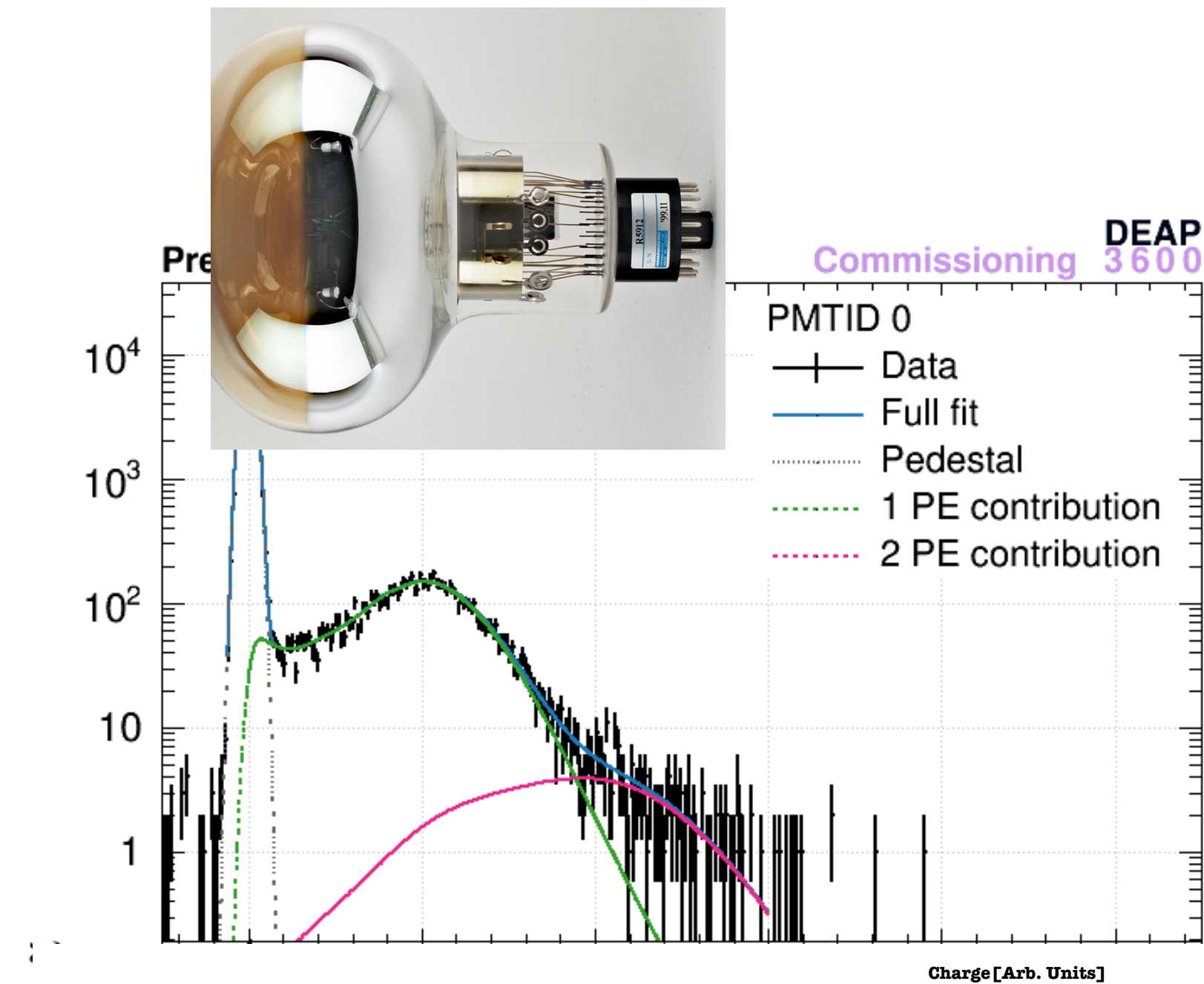
CERN is taking part in a testing-phase project, called ARIA, for the construction of a 350-metre-tall distillation tower that will be used to purify liquid argon (LAr) for scientific and, in a second phase, medical and possibly other uses.



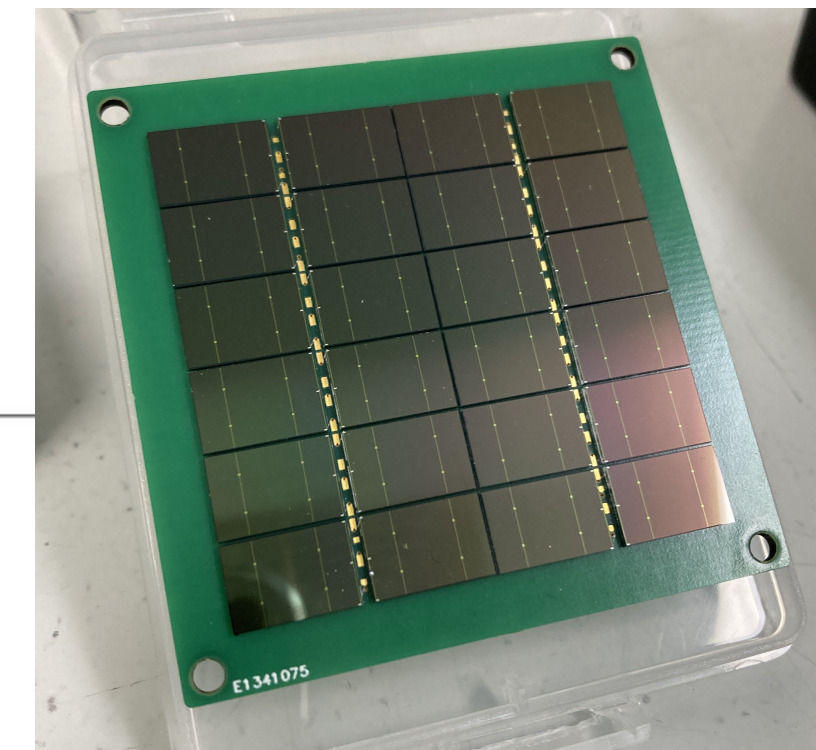
DarkSide-20k Key Innovations

2) First large-scale use of large-area cryogenic silicon photomultiplier (SiPM) arrays instead of photomultiplier tubes (PMTs)

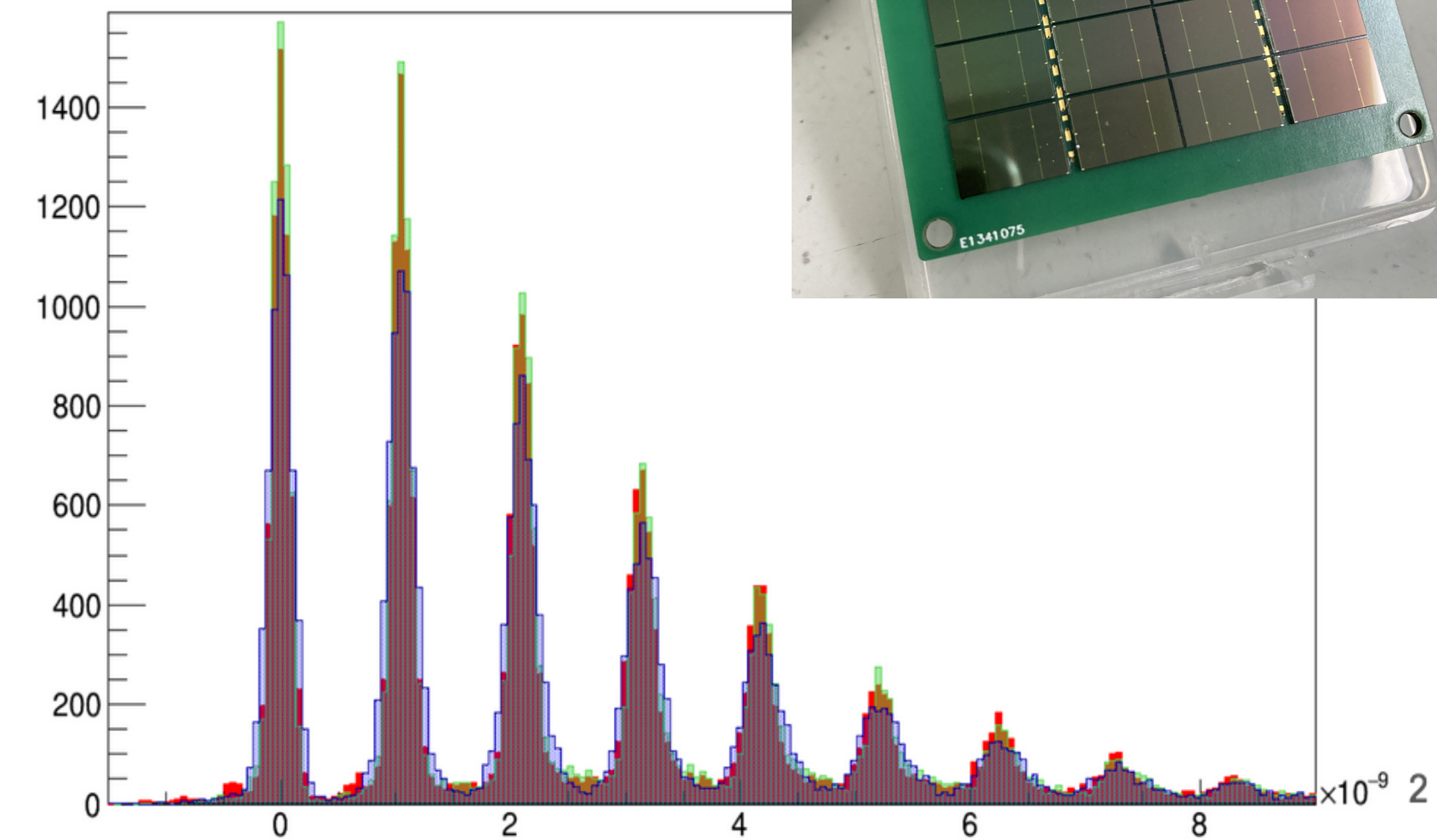
Low noise, high-efficiency photon sensors: tiled arrays of cryogenic silicon sensors developed in collaboration with FBK, achieving >45% photodetection efficiency (PDE) and ~ 1 mHz/mm² dark noise.



UK is delivering 7 m² of these - a key detector system!



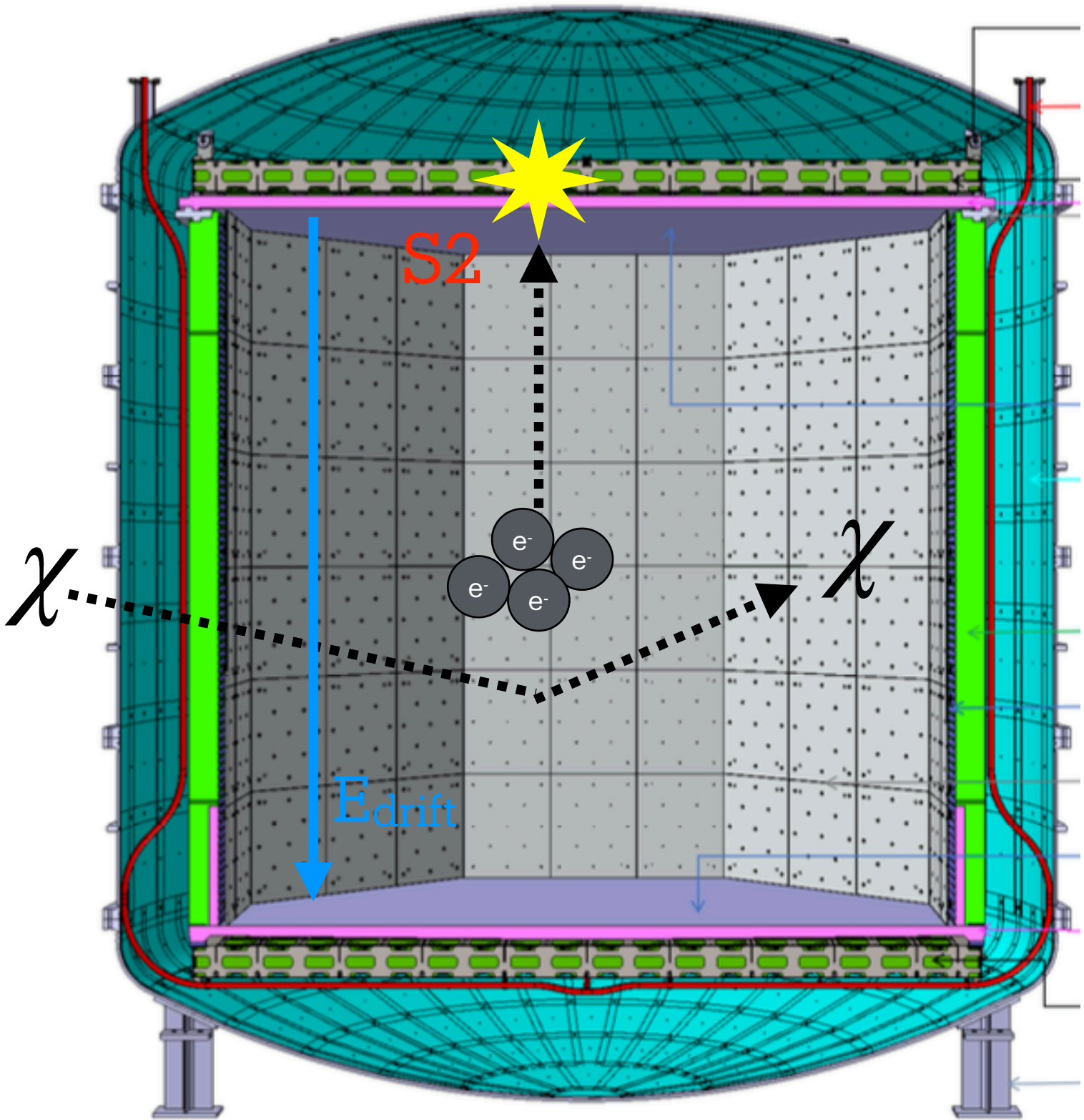
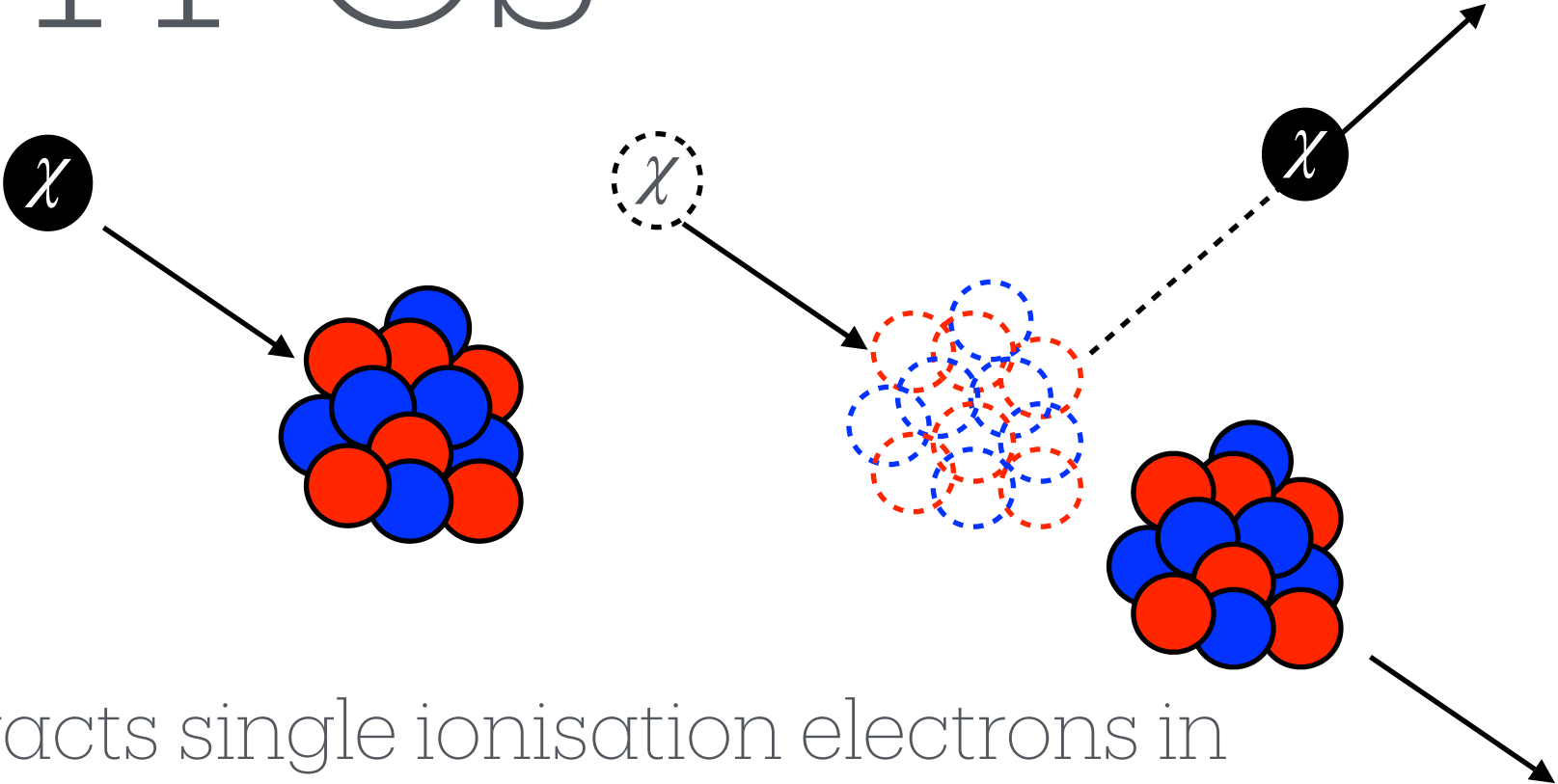
7 m² readout production is complete - funded by STFC Project Funding to install the UK deliverables.



>3x PDE, 10x lower noise, >50x lower radiogenic backgrounds than PMTs.

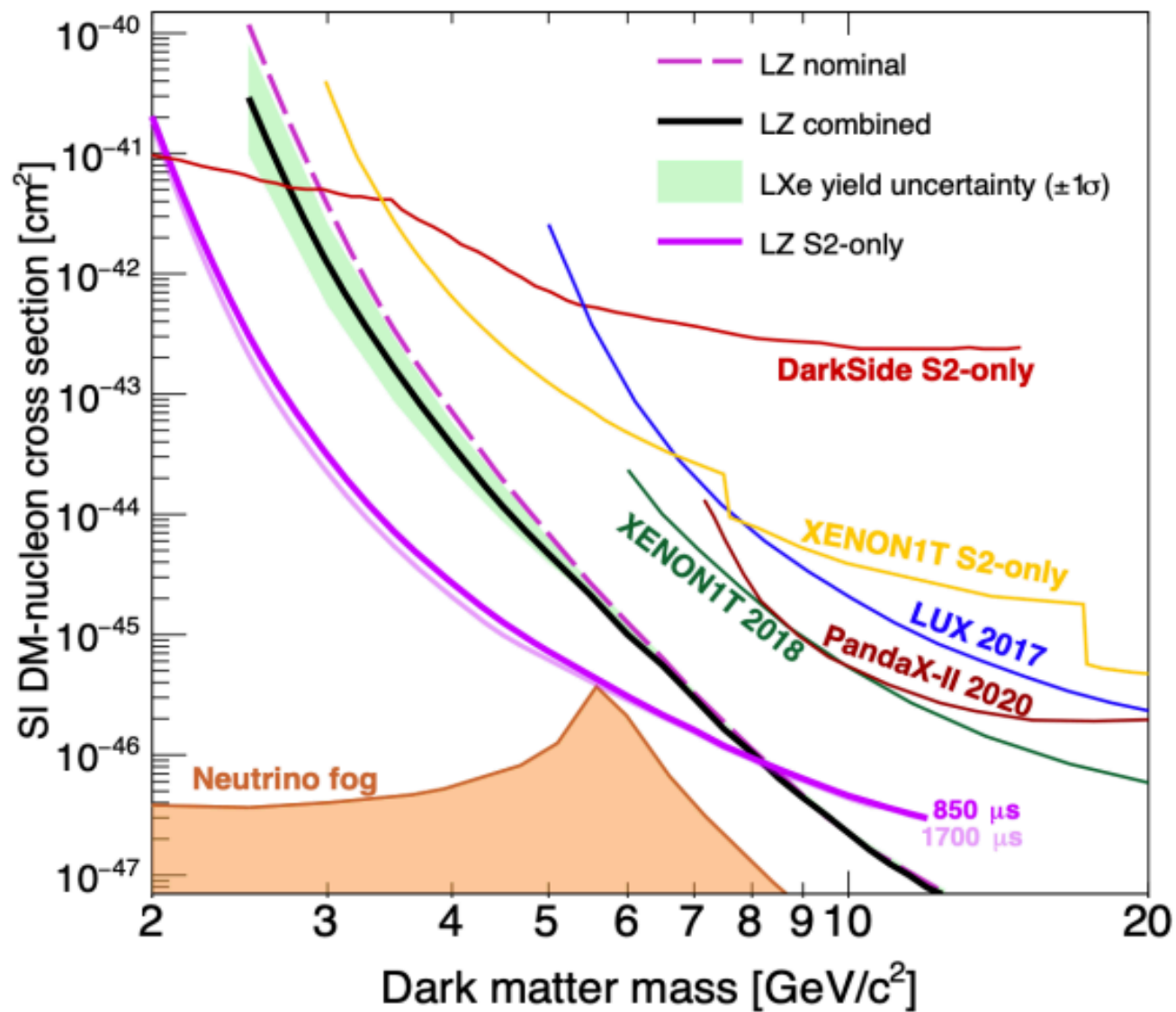
GeV-Scale Dark Matter with TPCs

Dual-phase TPC technology can exploit ionisation signal (S2) only to reach sub-keV recoil energy thresholds for **low-mass WIMP searches** (down to ~1 GeV).

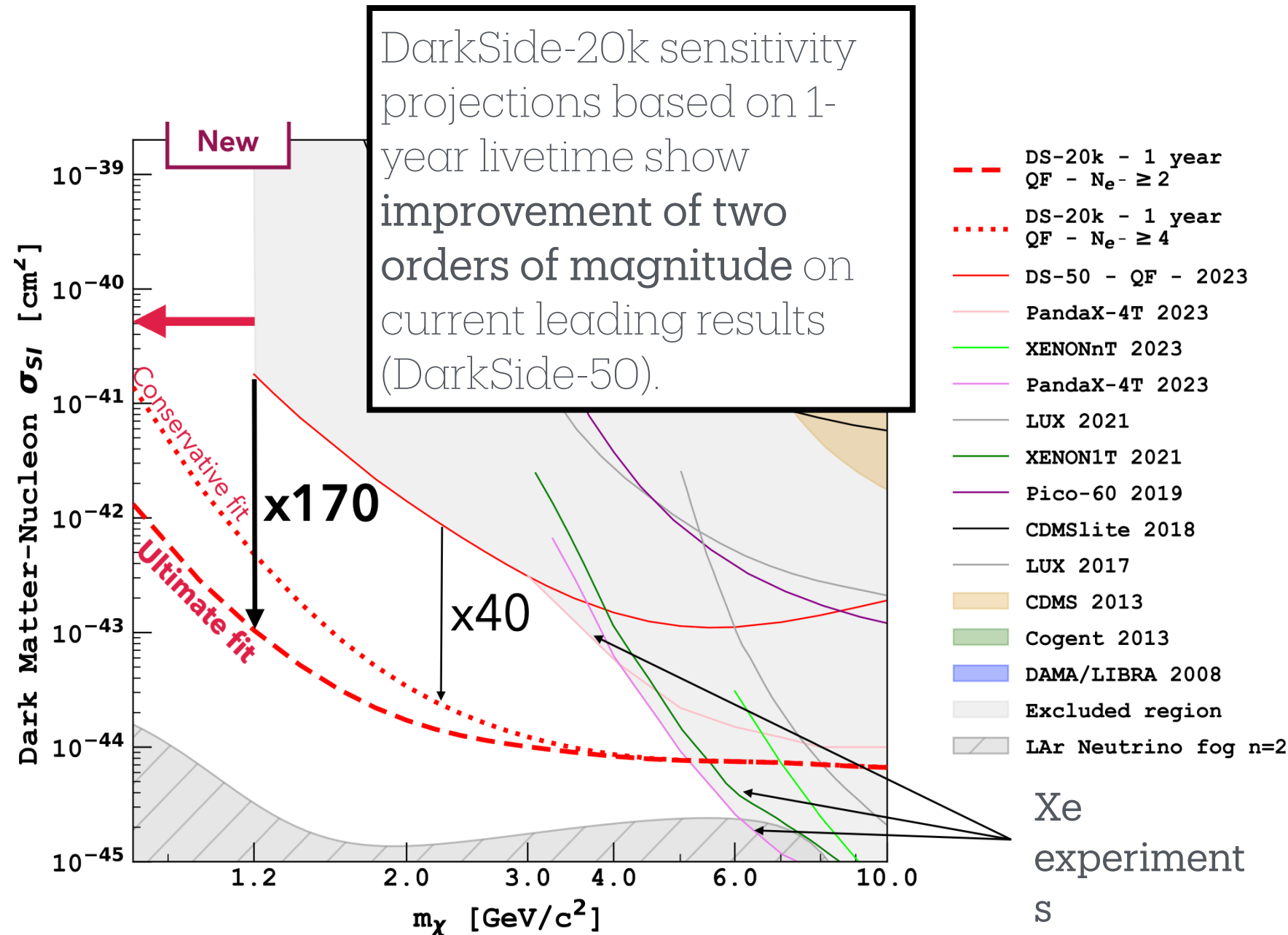


Dual-phase TPC design drifts and extracts single ionisation electrons in gas with near-100% efficiency— signal amplified a further x20 exploiting electroluminescence in the gas phase.

S2



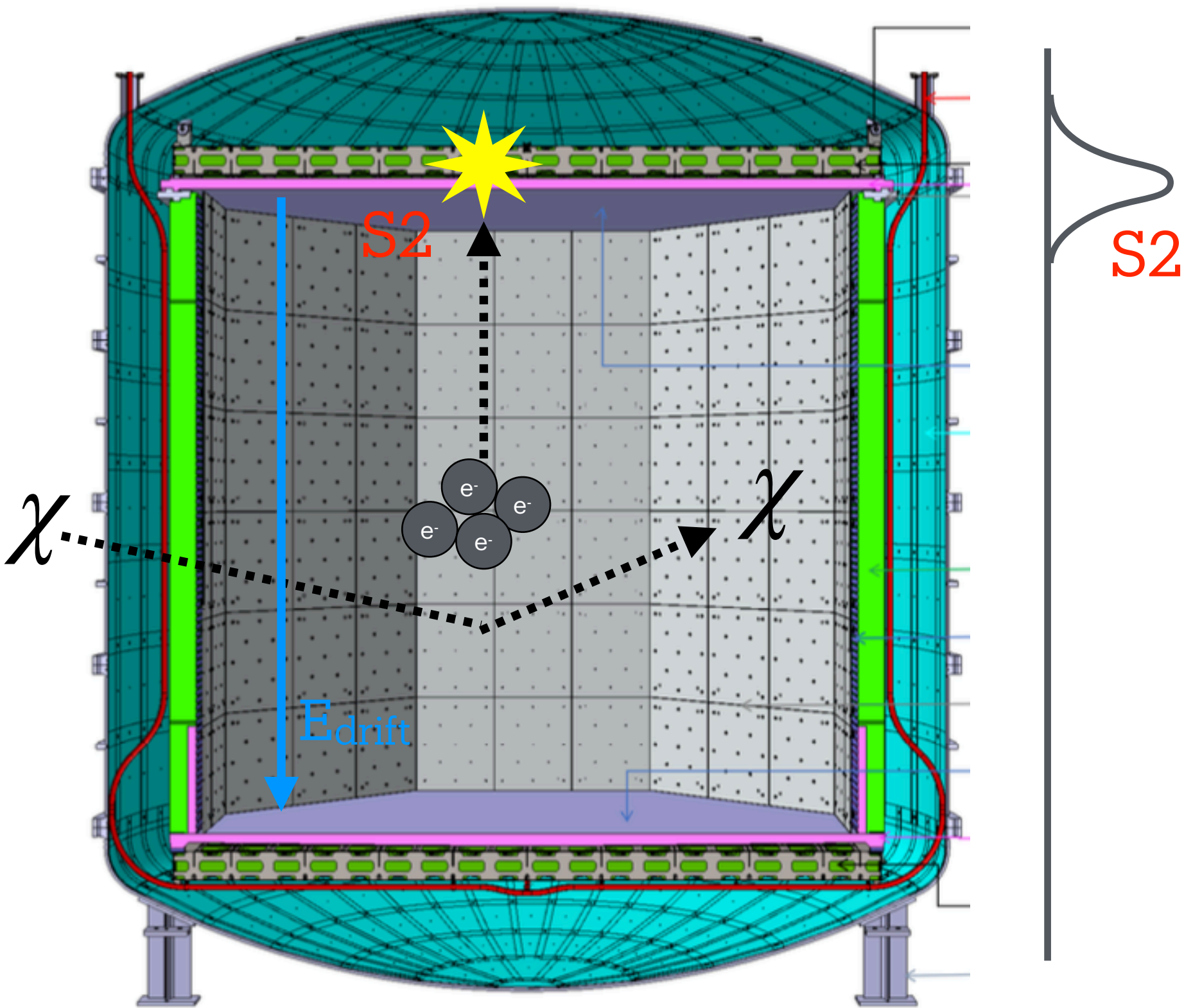
Akerib, D. S., et al. "Enhancing the sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment to low energy signals." *arXiv preprint arXiv:2101.08753* (2021).



Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." *arXiv preprint arXiv:2407.05813* (2024).

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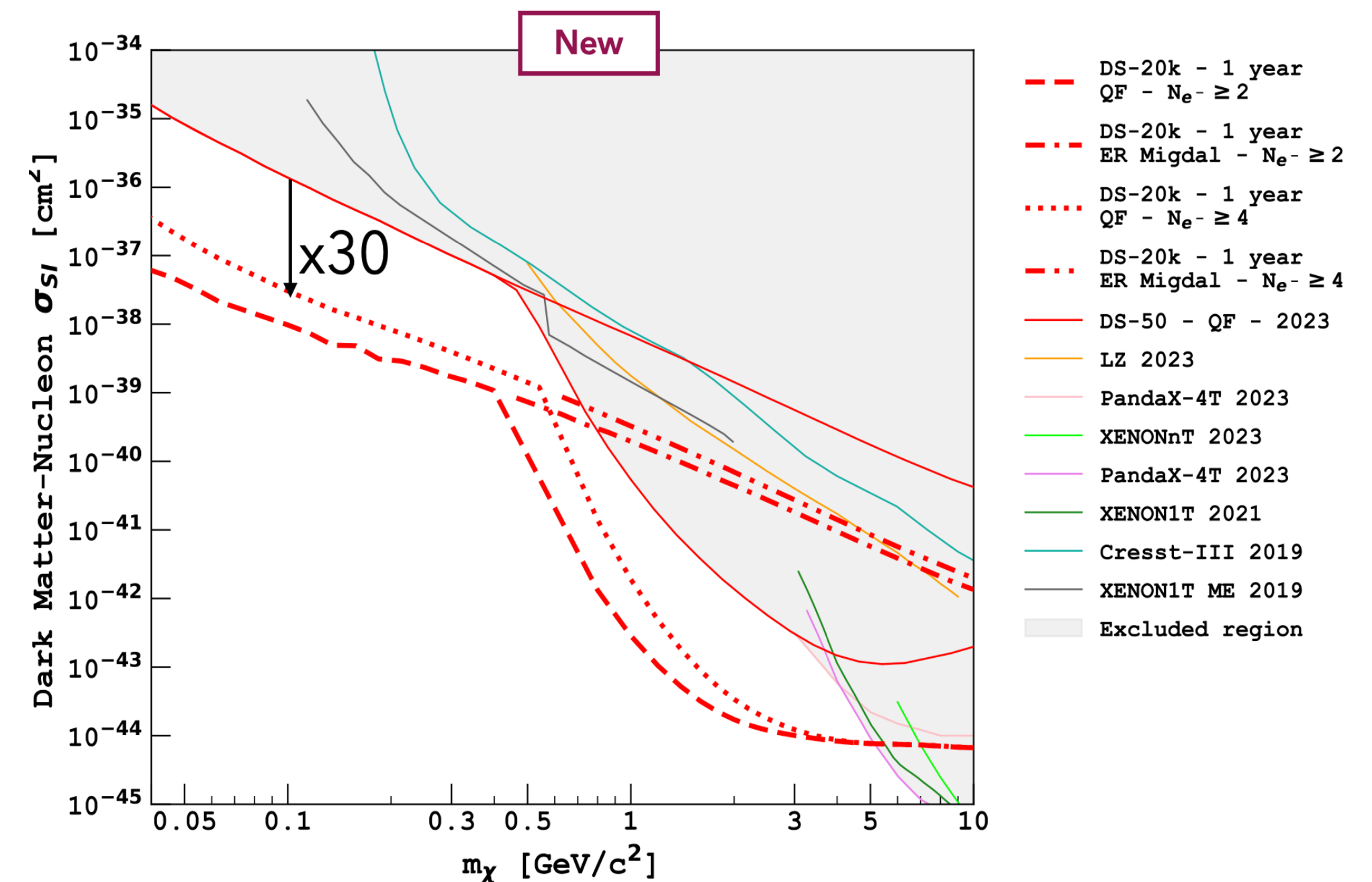
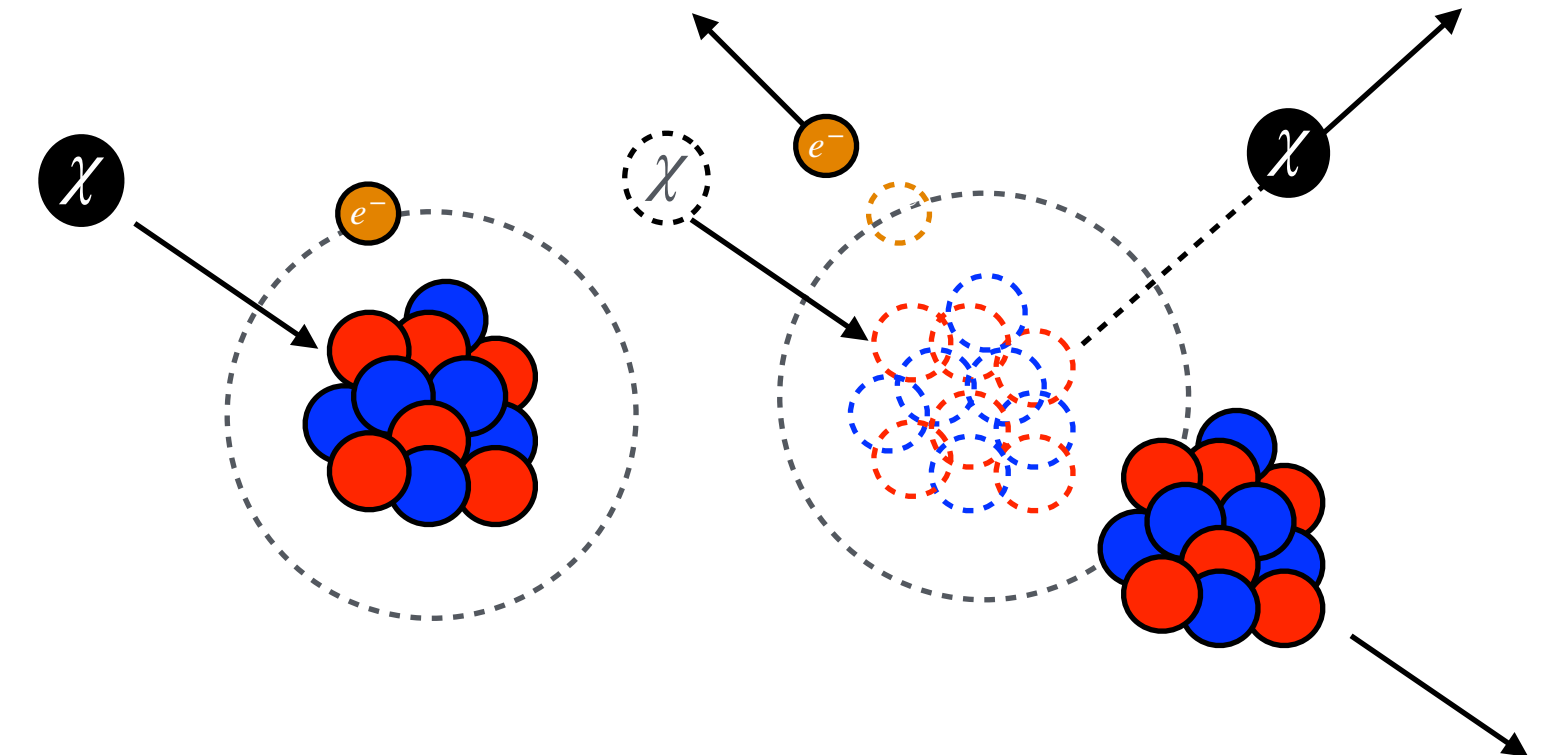


Migdal Effect:

Surrounding electron cloud accelerated after NR, releases de-excitation ionisation.

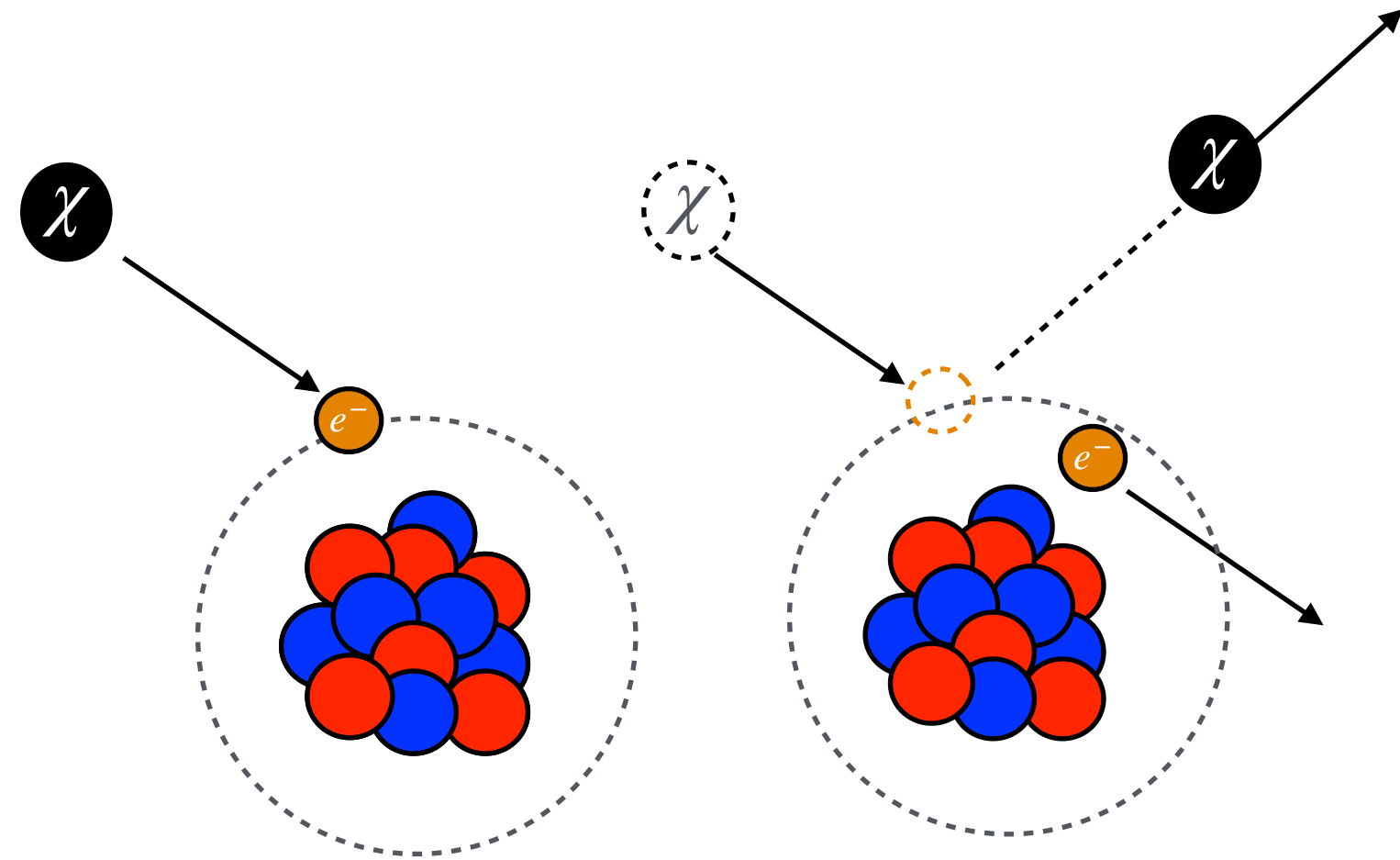
- Additional ionisation signal means even lower energy threshold!

DarkSide-20k projects >1 order of magnitude improvement with respect to current experiments with only a 1-year livetime!



Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." *arXiv preprint arXiv:2407.05813* (2024).

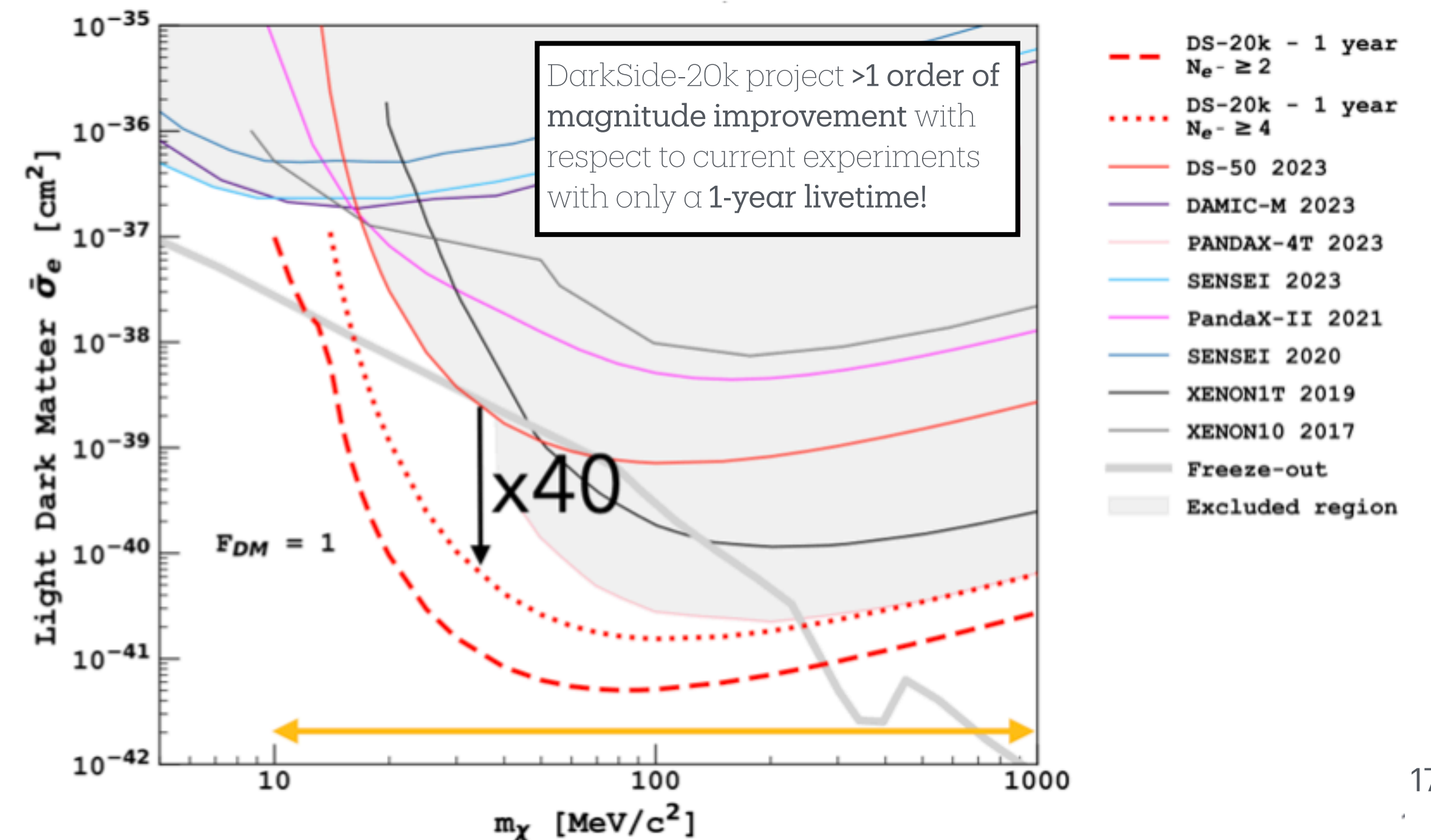
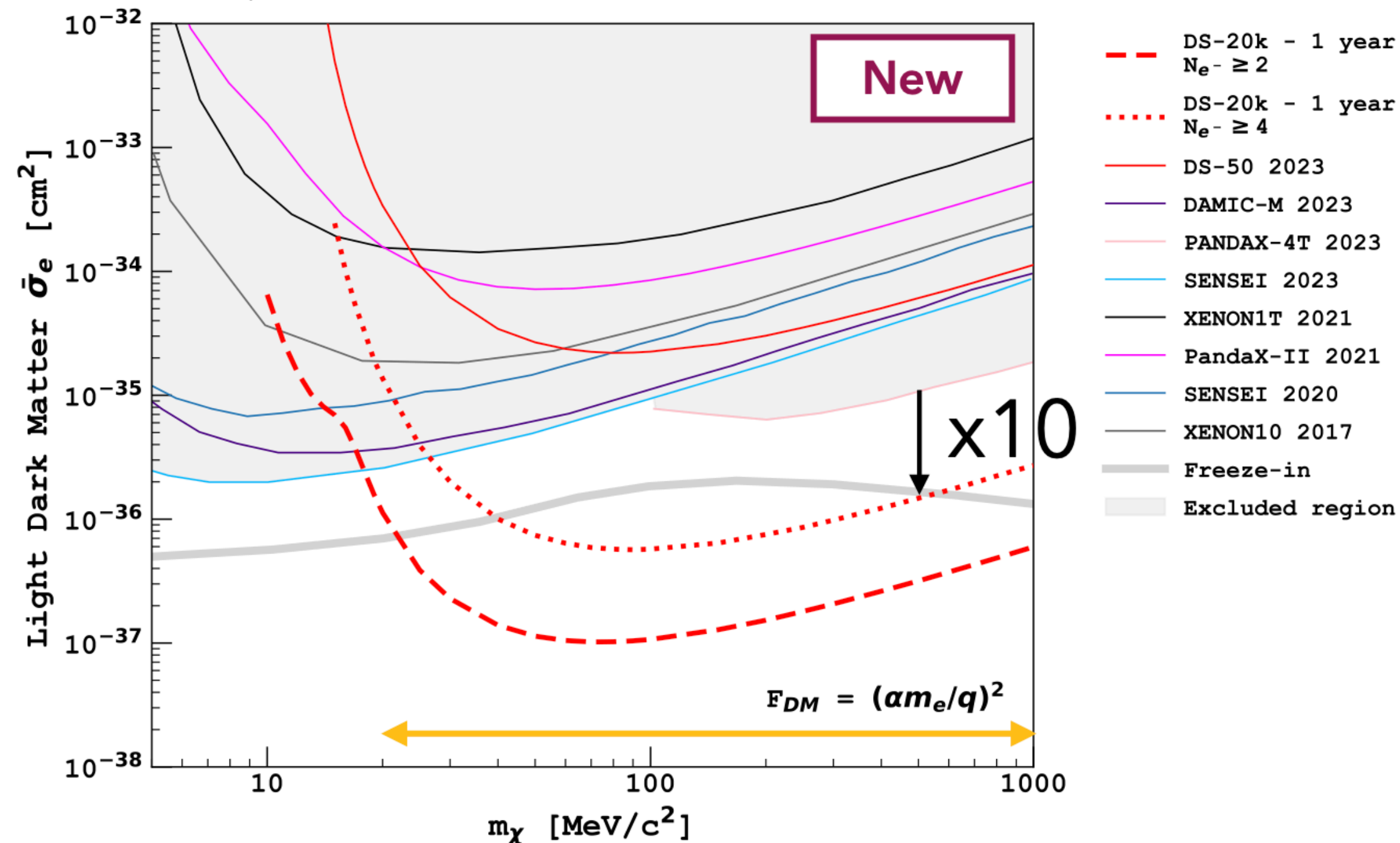
MeV-Scale Dark Matter with TPCs



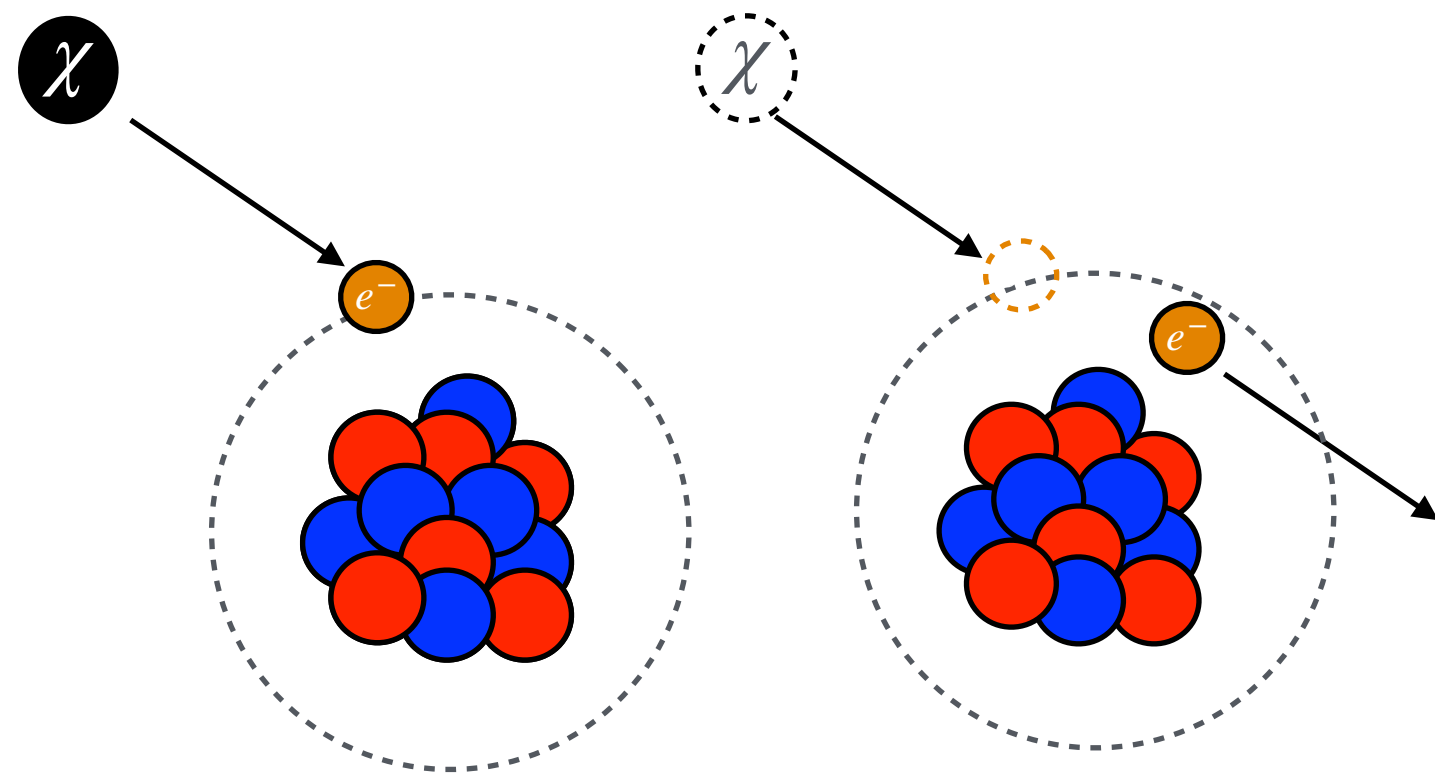
Dual-phase TPCs can also search for ER final states through S2-only search to reach sensitivity to **MeV-scale DM candidates**.

Elastic scattering off atomic electrons: interaction of sub-GeV DM fermion or scalar boson via vector mediator.

Mediator can be light ($m_{\text{med}} \ll m_\chi$) or heavy ($m_{\text{med}} \gg m_\chi$).



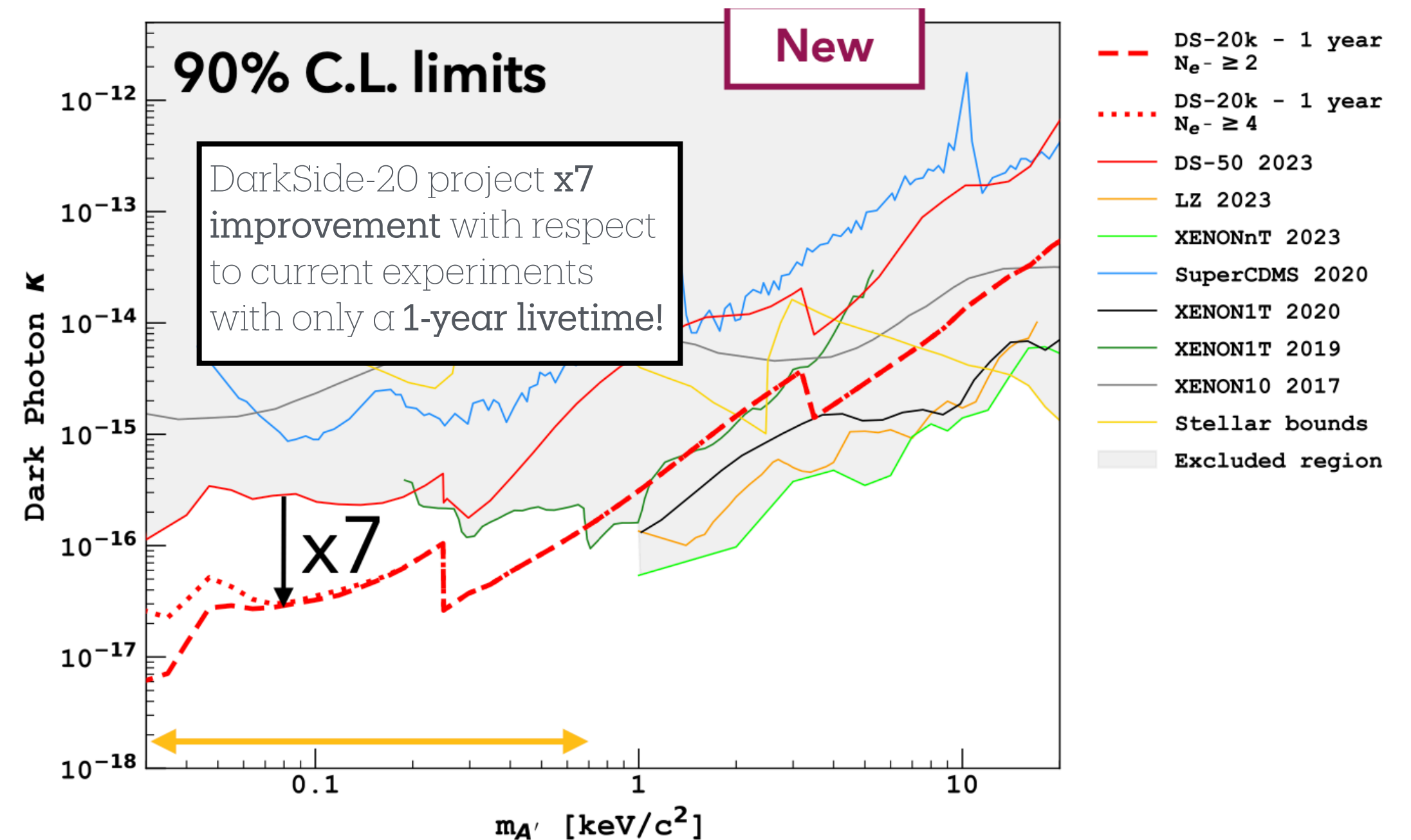
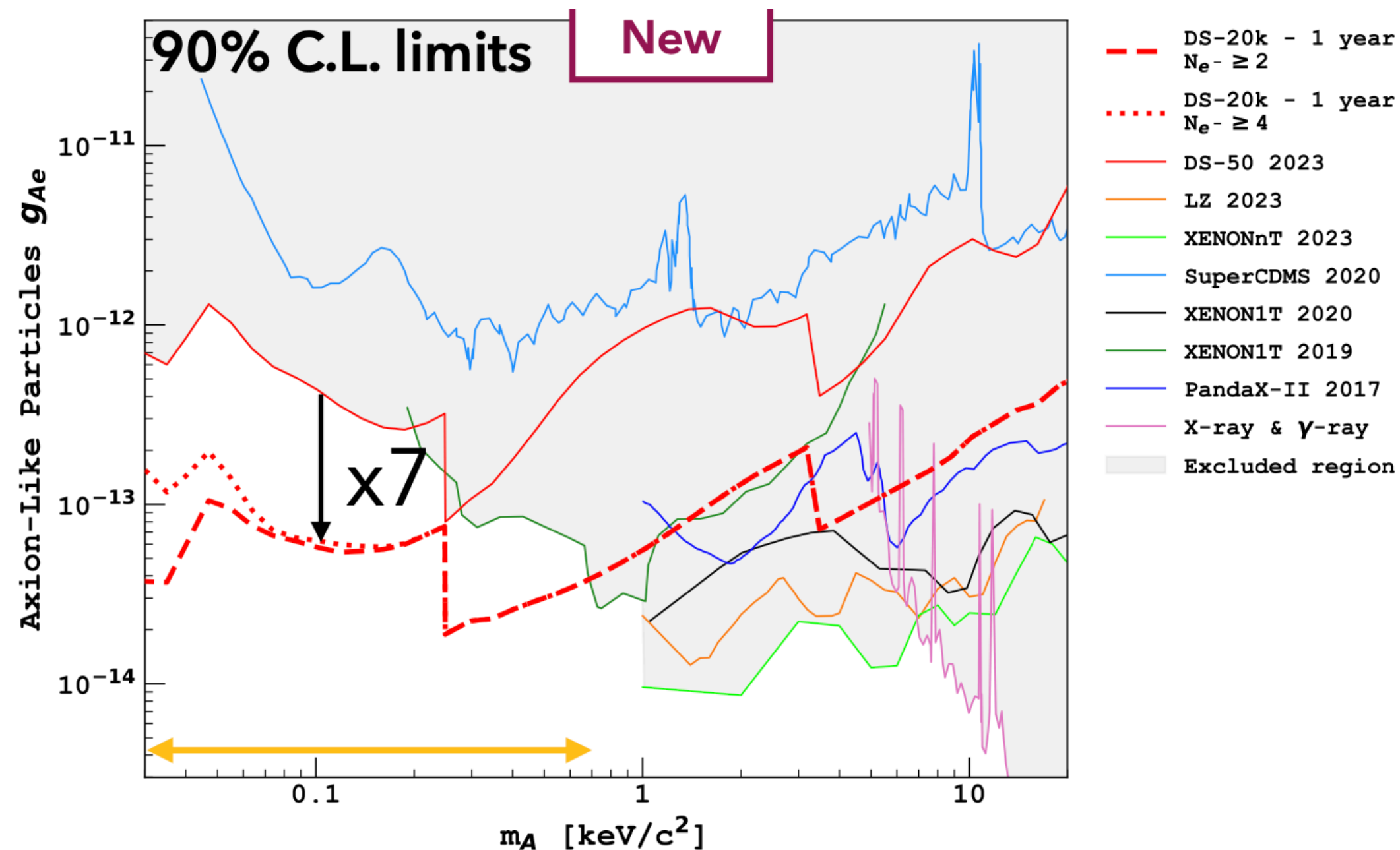
keV-Scale Dark Matter with TPCs



Dual-phase TPCs can also search for ER final states through S2-only search to reach sensitivity to **keV-scale DM candidates**.

Axion-like particles can be absorbed by atomic electrons via the axio-electric effect (analogous to the photoelectric effect). Similar process for hidden photons.

Entire rest mass converted to energy and absorbed by atom: results in mono-energetic peak centred at m_χ (smeared by detector resolution).



Cryogenic Detectors for Sub-GeV DM

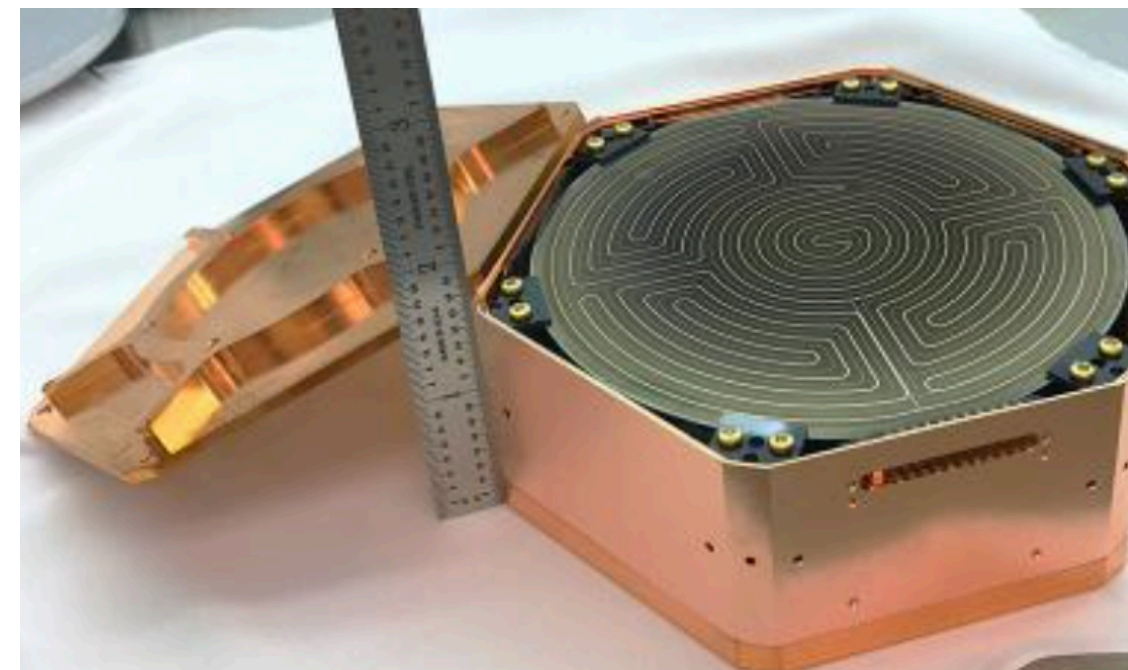
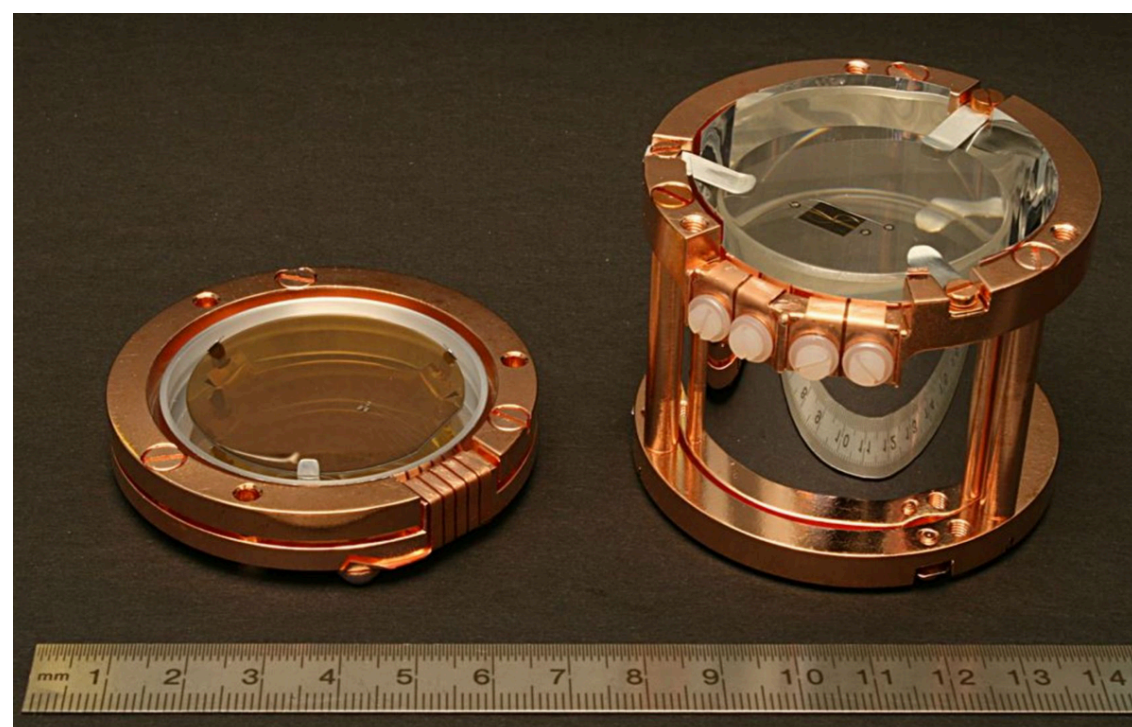
Low-mass cryogenic experiments have potential to reach meV recoil energy thresholds through measuring the heat partition: opportunity to probe even smaller DM masses!

- ▶ Limited by readout technology and higher background levels, though background can be suppressed by also measuring light/charge partition.

Scintillating Crystals

Al_2O_3 , CaWO_4 (CRESST)

Recoil energy from heat, particle ID from heat/scintillation ratio.



Semiconductors

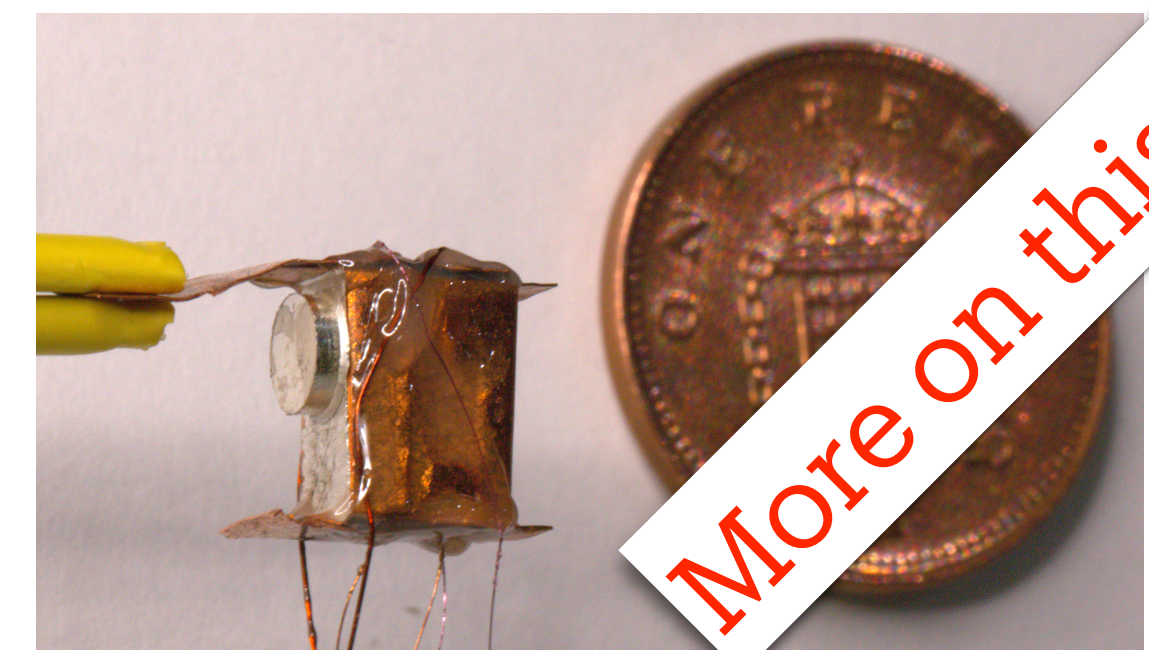
Ge, Si detectors (EDELWEISS, SuperCDMS)

Recoil energy from heat, particle ID from heat/ionisation ratio.

Superfluid Helium Bolometers

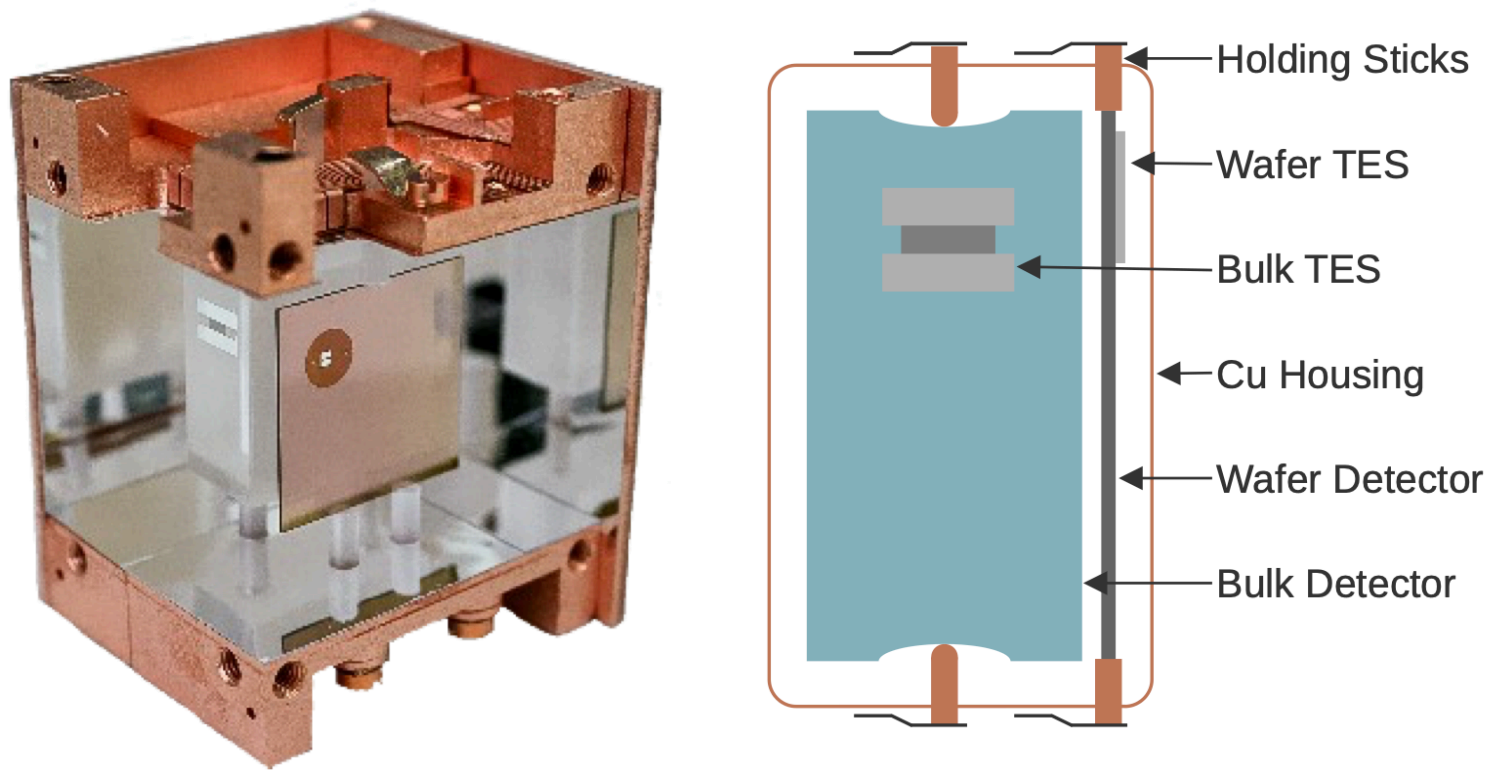
He-4 (HeRALD) or He-3 (QUEST-DMC).

Recoil energy from quasiparticles (heat), particle ID from quasiparticle/scintillation ratio.



Cryogenic Detectors: CRESST

CRESST detectors mounted in dilution refrigerator at LNGS & operated at ~10 mK.

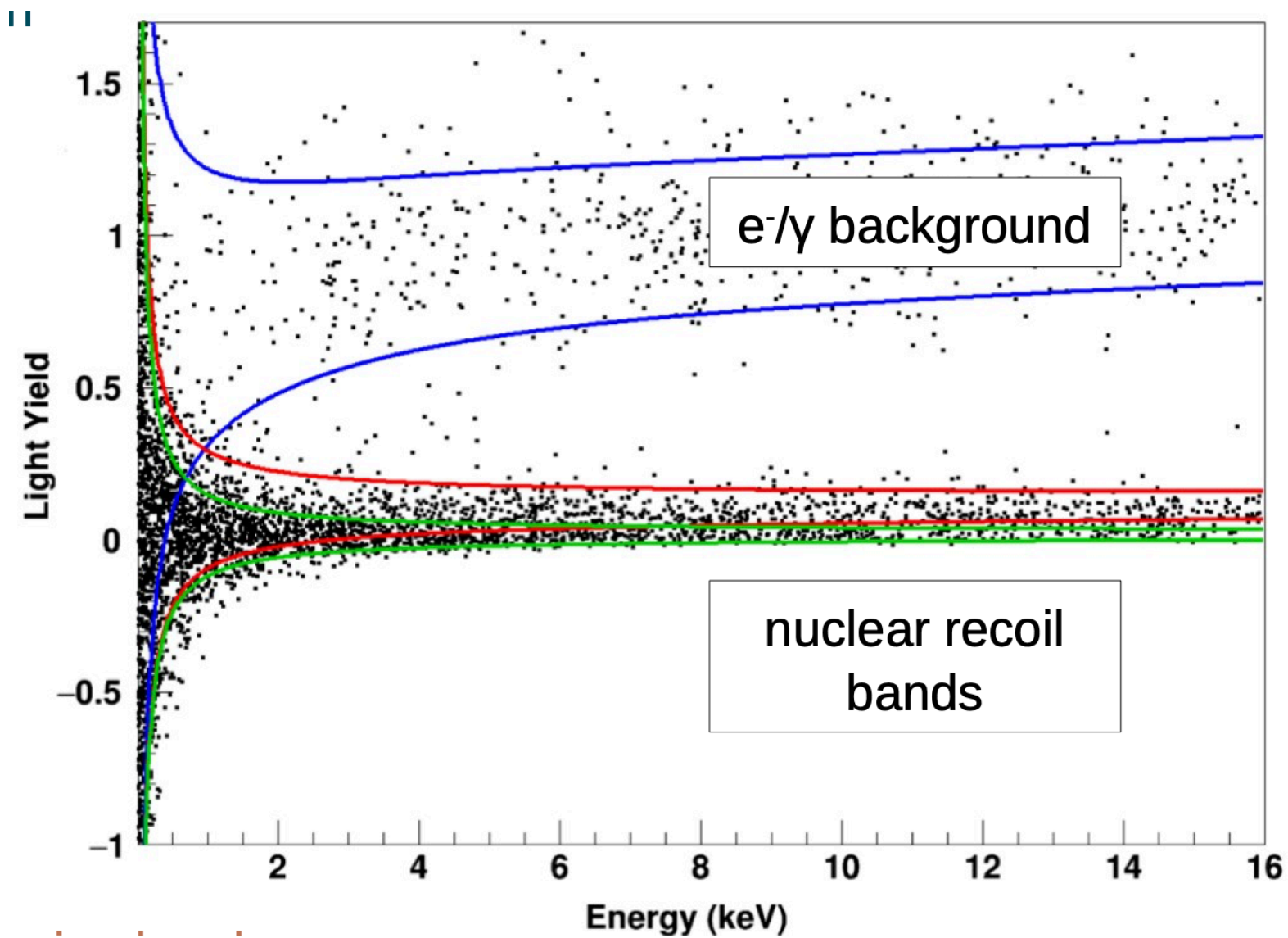


Main absorber: CaWO_4 crystal.

Thin wafer detector: silicon-on-sapphire serves as light detector for scintillation absorbers.

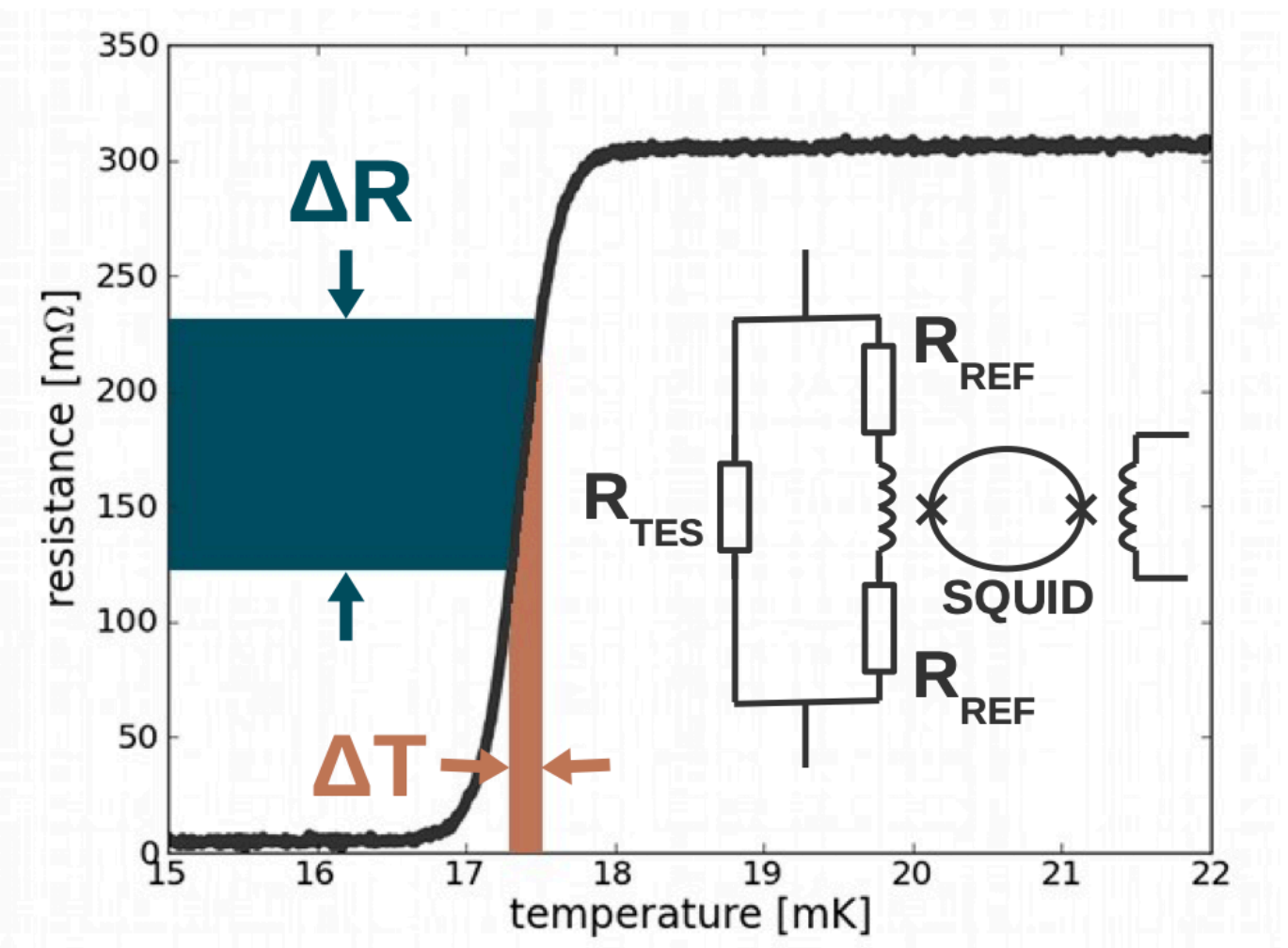
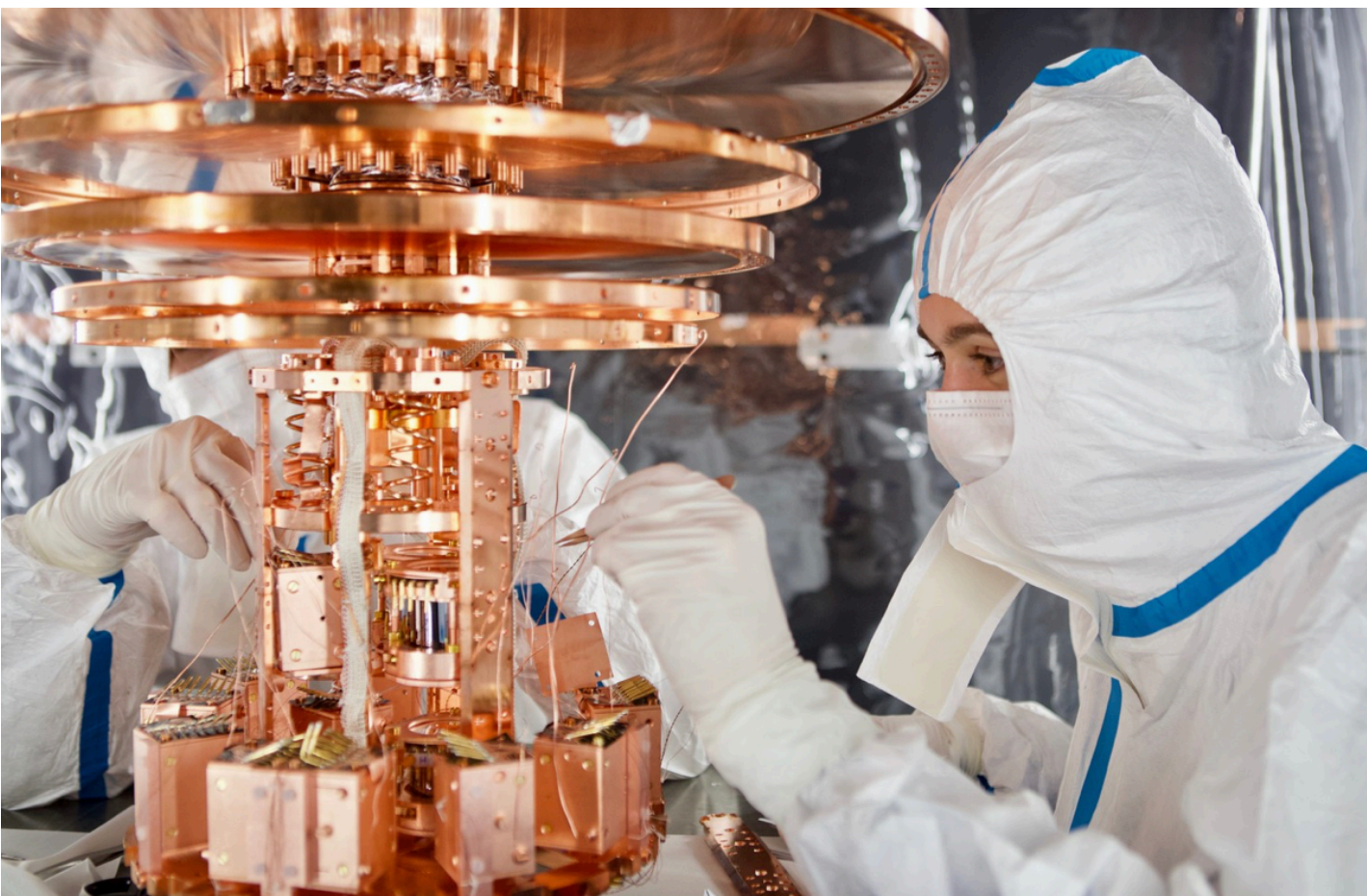
Sensors: transition edge sensors (TES) evaporated onto crystals.

- ▶ Temporary increase in temperature from energy deposition results in large increase in resistance and measurable, proportional drop in electrical current.



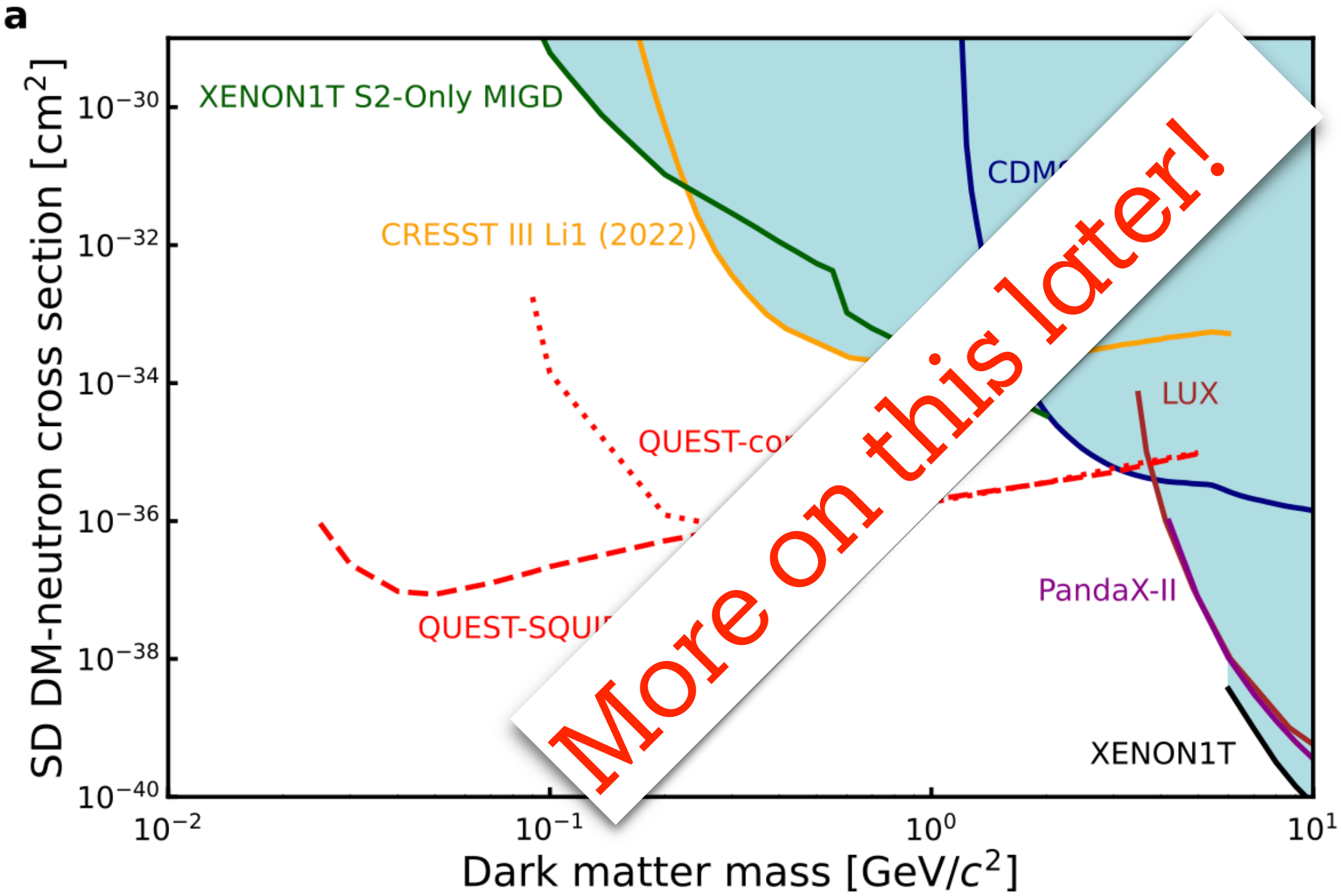
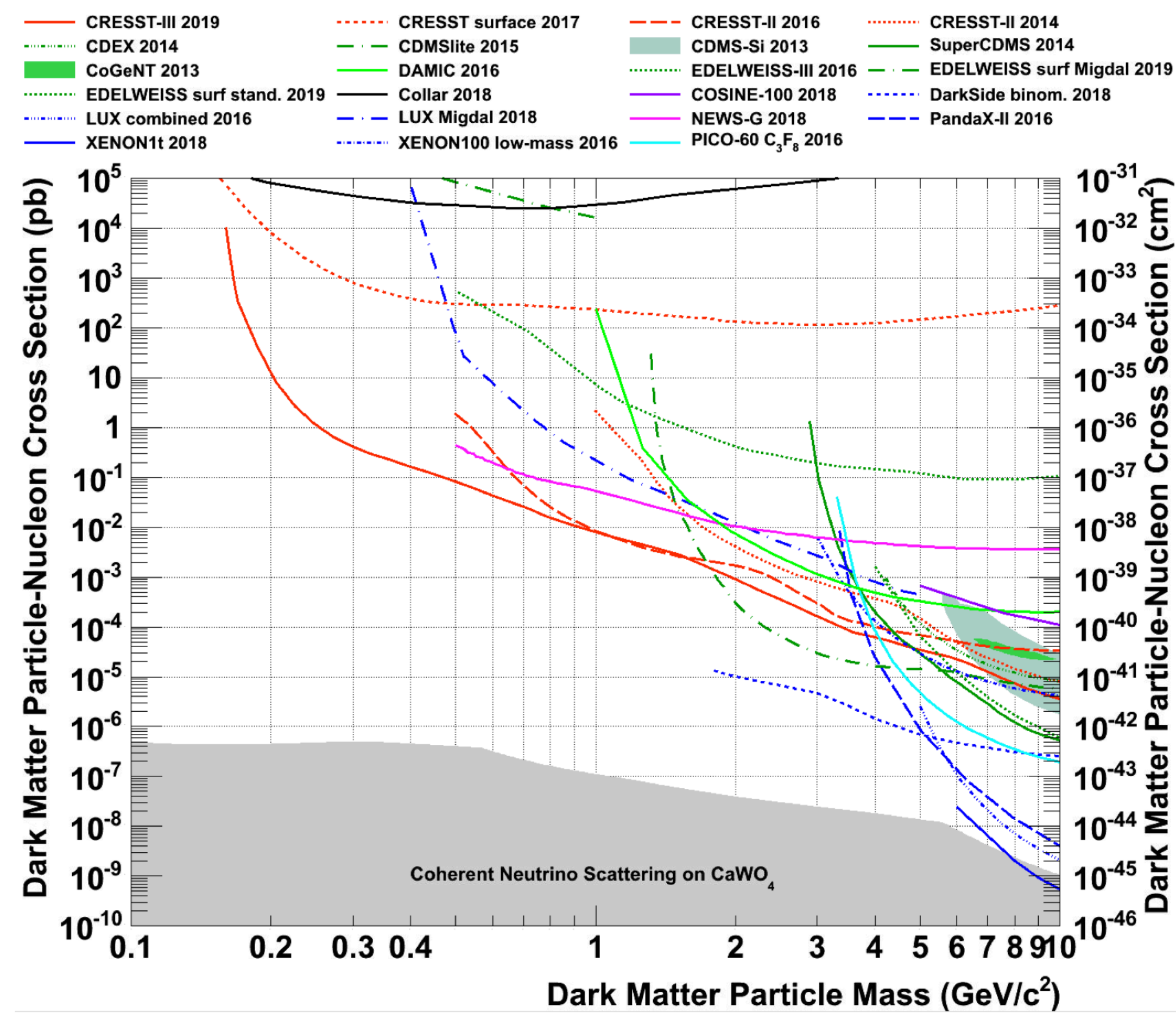
Light yield (detected light energy / energy in main absorber) is higher for ERs compared to NRs.

Position and width of ER/NR bands obtained from neutron calibration data: used for ER background suppression.



Sub-GeV DM with Cryogenic Detectors

Spin-independent ($\leftarrow$) and spin-dependent ($\rightarrow$) interactions can be probed using different targets.



QUEST-DMC collaboration, et al. "QUEST-DMC superfluid ³He detector for sub-GeV dark matter." *The European Physical Journal C* 84.3 (2024): 248.

Abdelhameed, Ahmed H., et al. "First results from the CRESST-III low-mass dark matter program." *Physical Review D* 100.10 (2019): 102002.

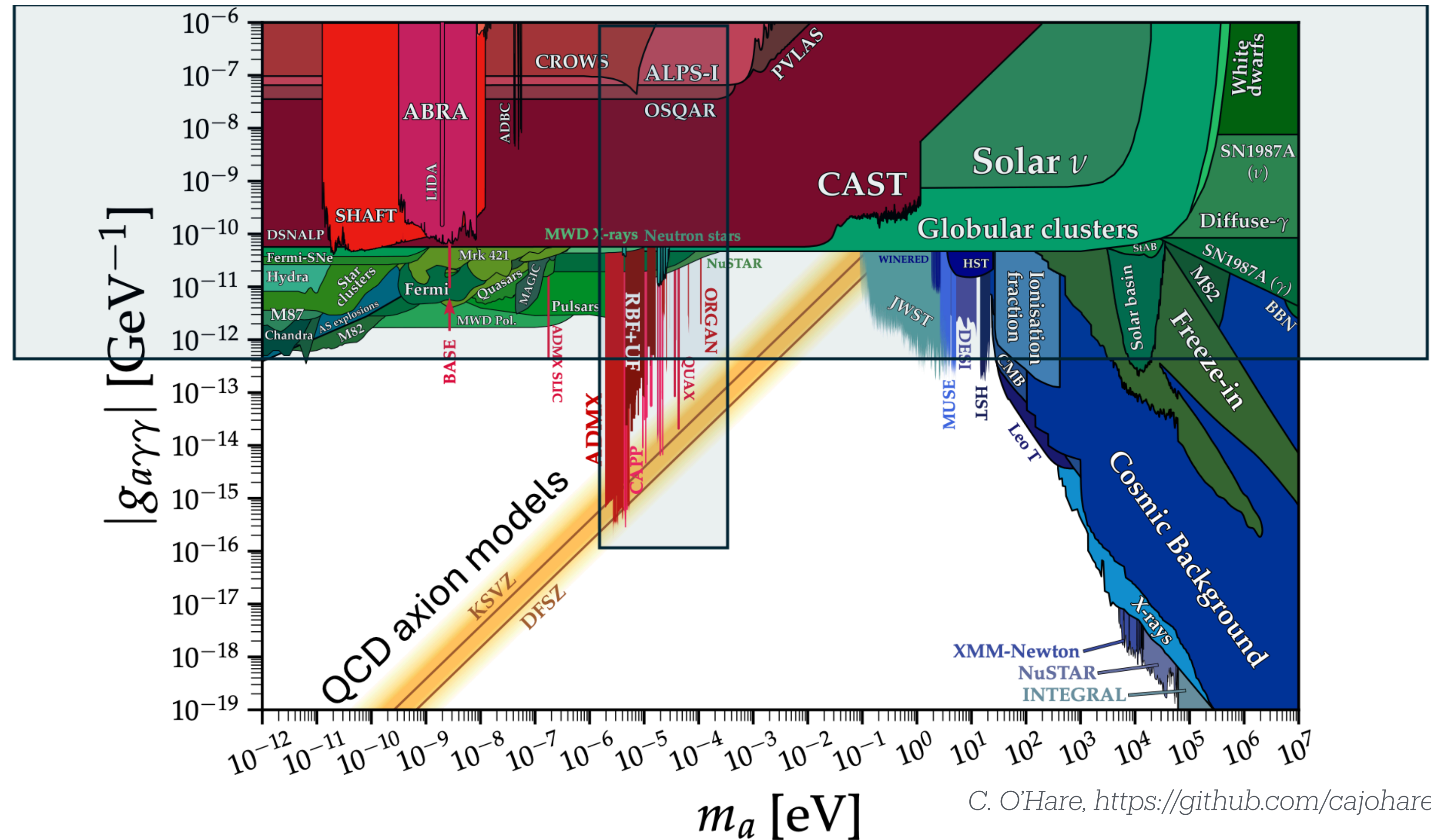
Wave-like DM: An Experimentalist's View

Axions

Axion searches fall into two categories – “wide and shallow” are NOT looking for QCD axions, they look for a wider class of “axion like particles”. “Narrow and deep” look for QCD axions.

QCD axions are motivated to solve strong CP problem but are a leading DM candidate.

Acts as a cold DM candidate in some mass ranges, but exhibits wave-like properties due to its low mass.



“Deep” searches achieve high sensitivity using resonance, but take a long time as resonator must be tuned.

Wave-like DM: An Experimentalist's View

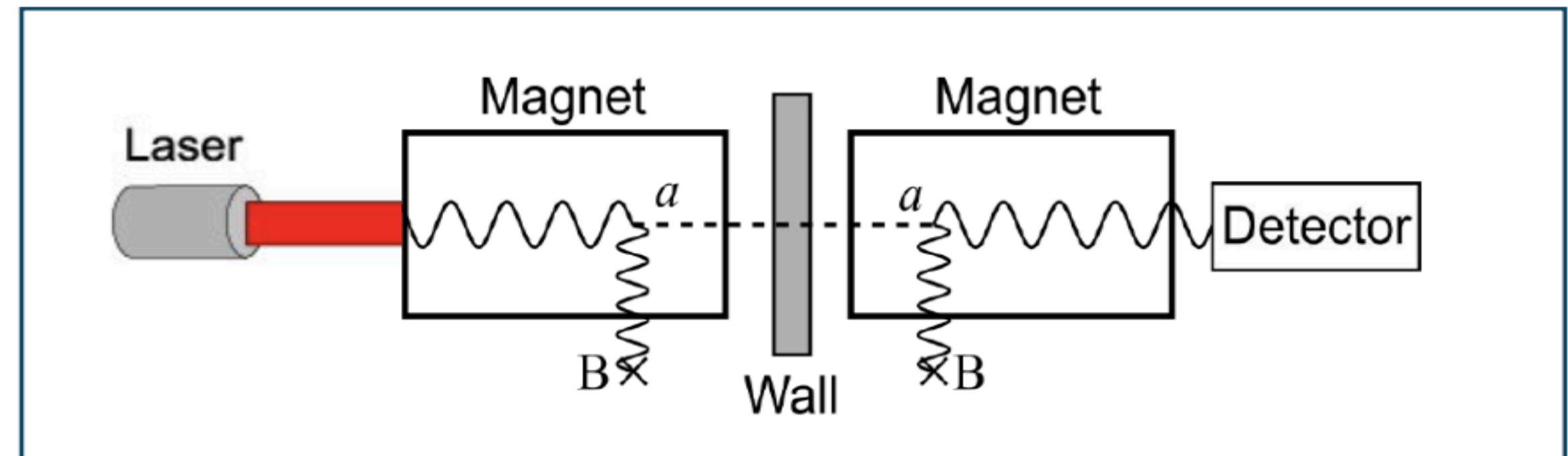
Axions

Detection principle of QCD axions: detect weak conversion of axions into photons in the presence of a strong $\vec{B}$ field.

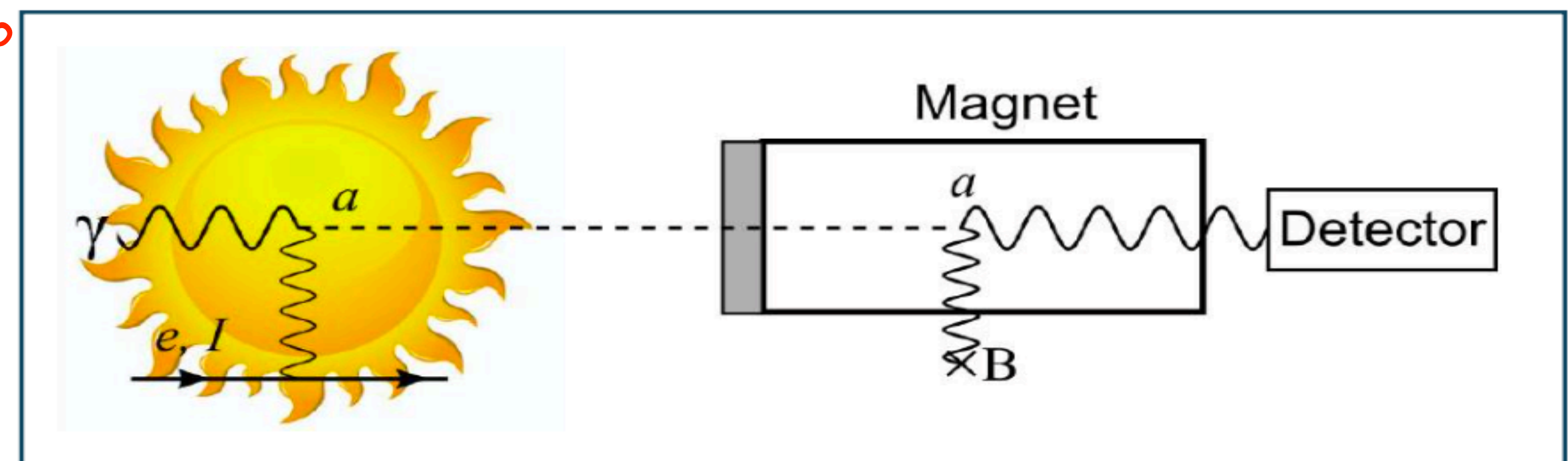
Detectors:

- ▶ Haloscopes (relic axions).
- ▶ Light-shining-through-walls (lab axions).
- ▶ Helioscopes (solar axions).

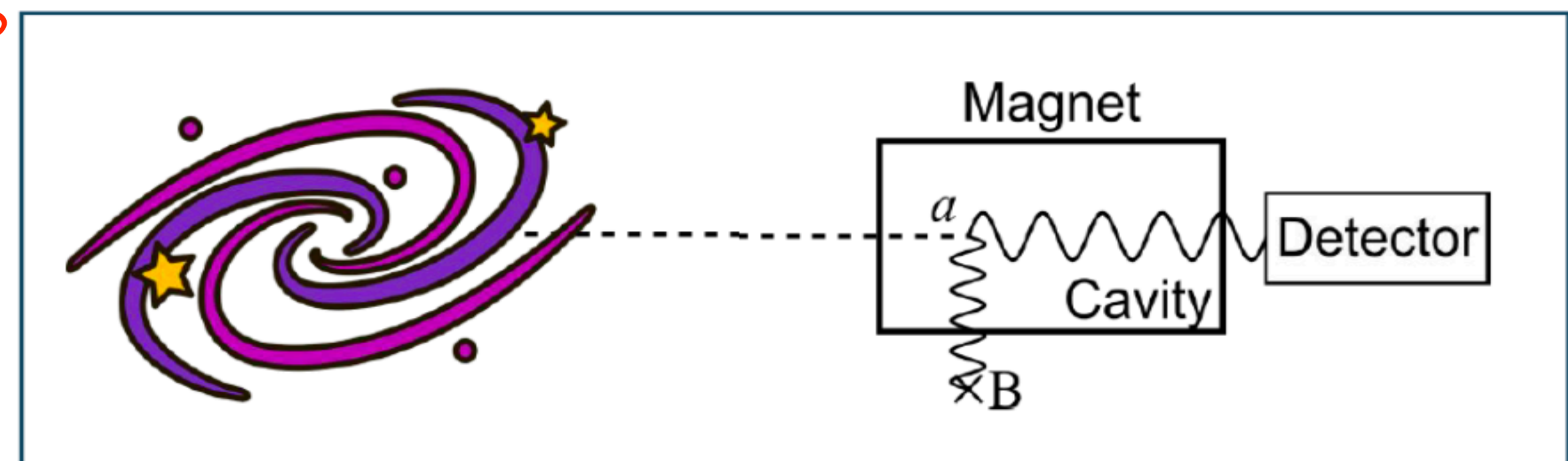
LSW



Helioscopes



Haloscopes



Wave-like DM: An Experimentalist's View

Ultralight DM

Broader category of very light dark matter candidates, which includes axion(-like particles) but also other particles.

Can be much lighter than QCD axions that solve the strong CP problem, with masses as low as 10^{-22} eV.

Exhibits wave-like properties on a galactic scale - a scalar field permeating the Universe.

Detection principle: detect changes to fundamental constants or phase shifts.

Detectors:

- ▶ Interferometry
- ▶ Atomic clocks
- ▶ + more?

Strong overlap with
quantum sensor
development...

- ▶ **Quantum Technologies for Fundamental Physics (QTFP) programme.**

Quantum Technology for Fundamental Physics

About QTFP:

- £40M programme to **transform our approach** to understanding the universe and its evolution

QI: Quantum-Enhanced Interferometry for new physics
PI: Hartmut Grote

QSNET: A network of clocks for measuring the stability of fundamental constants
PI: Giovanni Barontini

QTNM: Determination of absolute neutrino mass using quantum technologies
PI: Ruben Saaykan

QSHS: Quantum sensors for the hidden sector
PI: Ed Daw

AION: A UK atom interferometer observatory and network
PI: Oliver Buchmuller

QSimFP: Quantum simulators for fundamental physics
PI: Silke Weinfurtnner

QUEST-DMC: Quantum enhanced superfluid technologies for dark matter and cosmology
PI: Andrew Casey

7 projects funded in late 2020 to demonstrate how QT could solve some of the greatest mysteries in fundamental physics, **including the search for DM.**

17 further small grants funded in **2022**: <https://uknqt.ukri.org/our-programme/qtfp/>

Particle-like Sub-GeV DM: QUEST-DMC

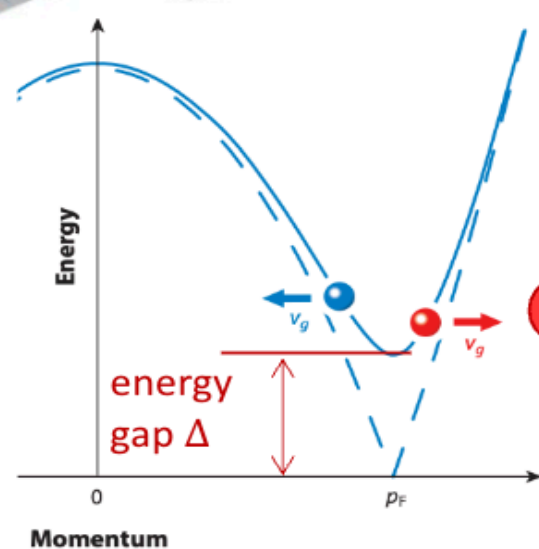
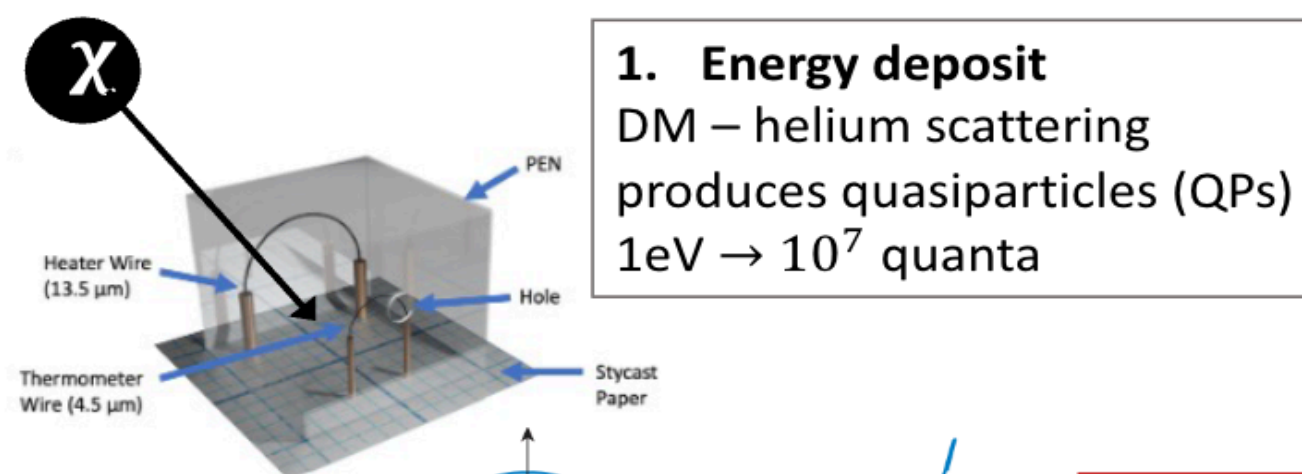
Two physics goals linked experimentally through combining quantum sensors with ^3He at ultra-low temperatures:

- How did the early universe evolve?
- What is the nature of Dark Matter?

Superfluid ^3He provides quantum analogue of cosmological first-order phase transition predicted ~ 10 ps after Big Bang in BSM models

Search for sub-GeV dark matter with spin-dependent interactions (motivated by asymmetric models) enabled through:

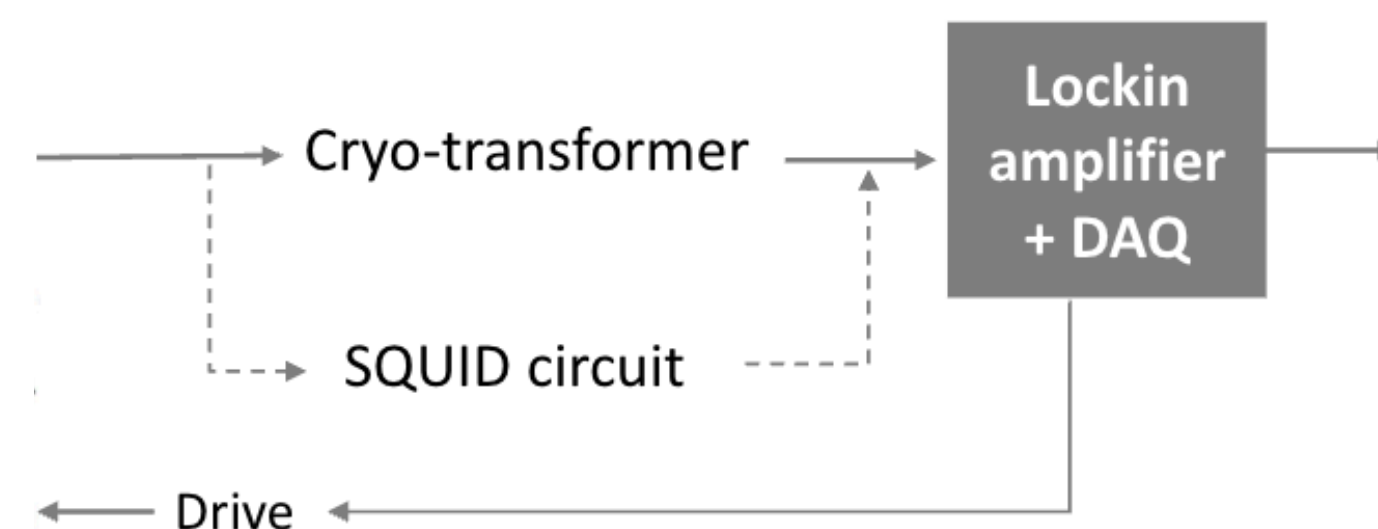
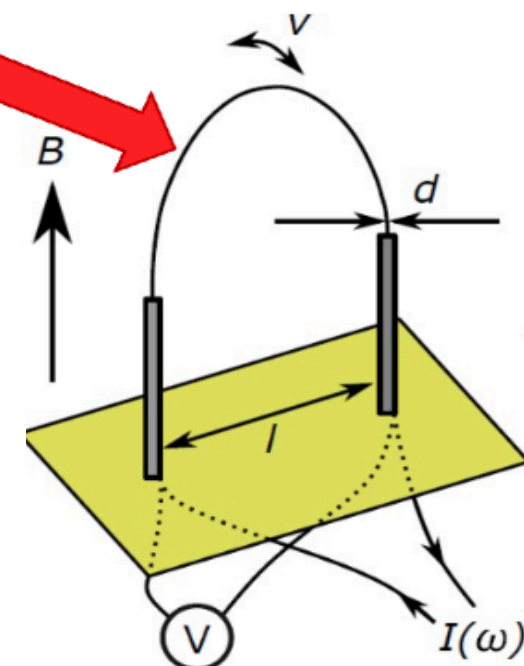
- (Quantum) superfluid ^3He
- Quantum technologies:
 - Nanomechanical resonators (NEMS)
 - Superconducting Quantum Interference Device (SQUID) readout



2. Ballistic propagation
QP collisions with nanowire exert damping force

3. Bolometry

- nanowire driven by AC current in vertical B field
- measure increase in resonance width from damping



London Low-Temperature Laboratory (RHUL)



Lancaster Low Temperature Physics, Isolab



Particle-like Sub-GeV DM: QUEST-DMC

Helium is second most abundant element in our Universe.

Two isotopes: ^4He (2p,2n) and ^3He (2p,1n).

- ▶ ^4He (99.9999% abundant) vs ^3He (0.0001%).
- ▶ Different physical properties related to difference in net spin.

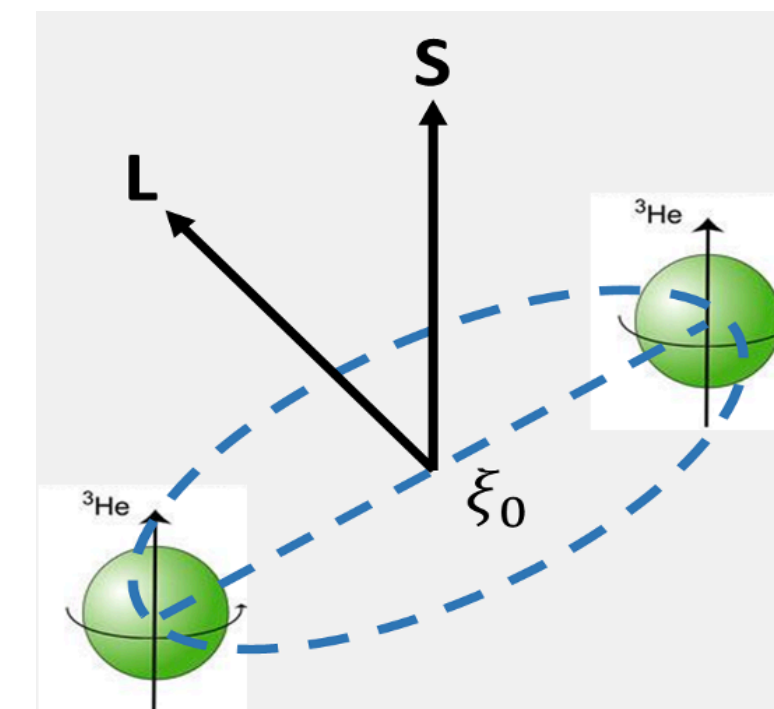
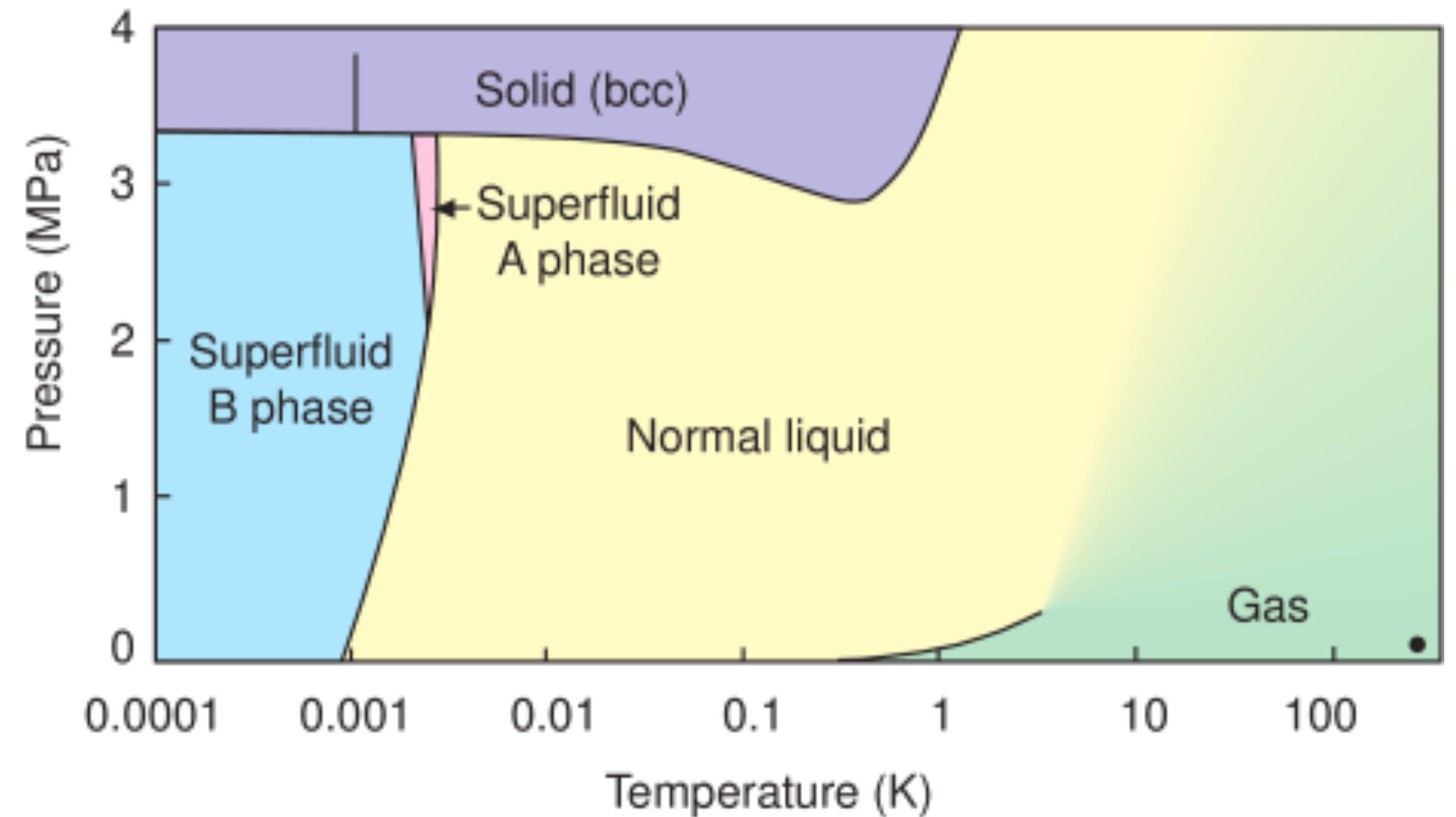
^3He nucleus has 2 protons and just 1 neutron,

- ▶ Spin-1/2: Fermi-Dirac Condensate.

Superfluid ^3He formed by condensation of Cooper pairs of ^3He atoms. Quasiparticles (heat) produced by Cooper pair breaking.

- ▶ Energy required to break up a Cooper pair $\sim 10^{-7}$ eV!

Phase diagram of ^3He



With ^3He , we can probe spin-dependent dark matter interactions!

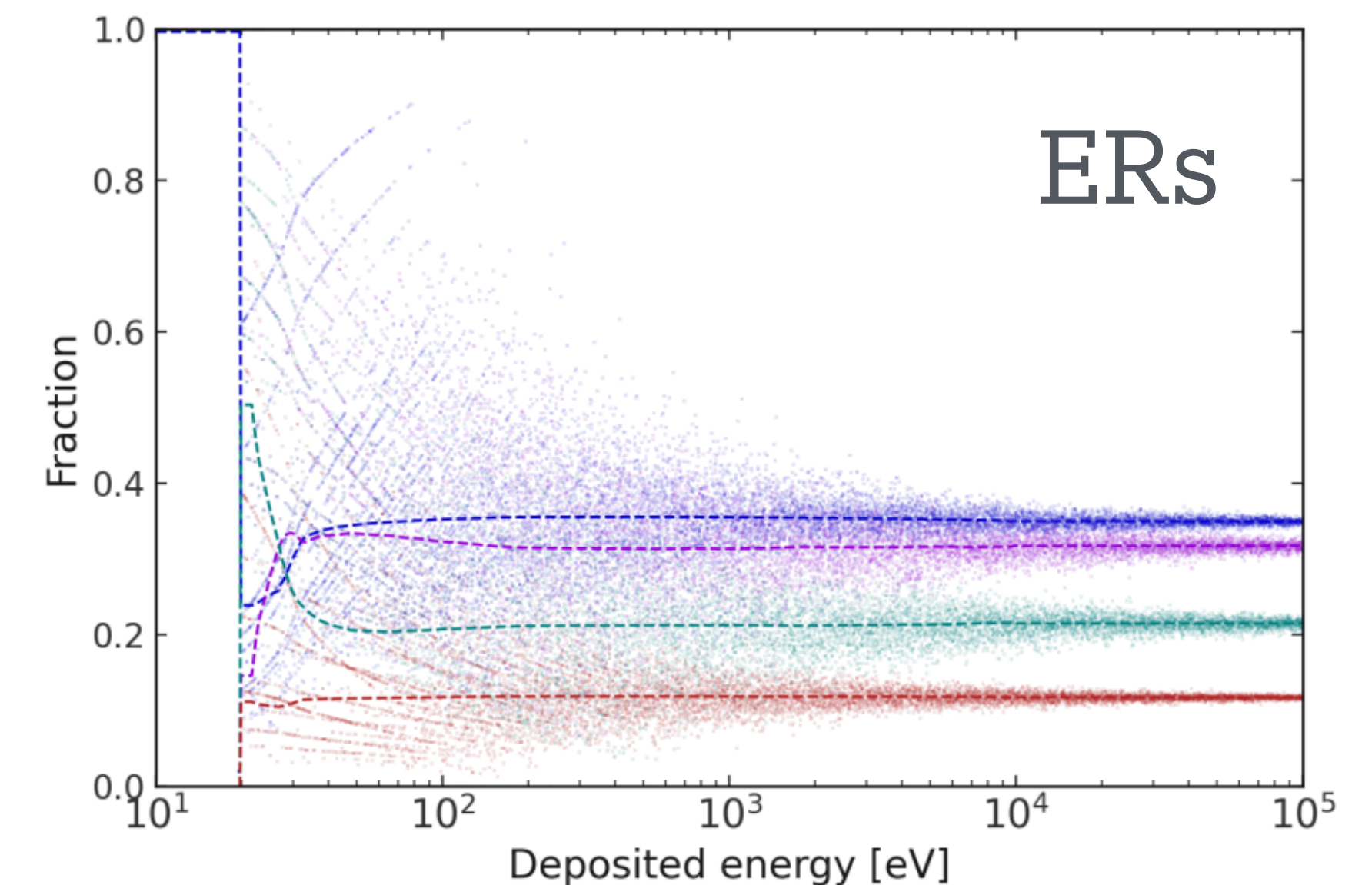
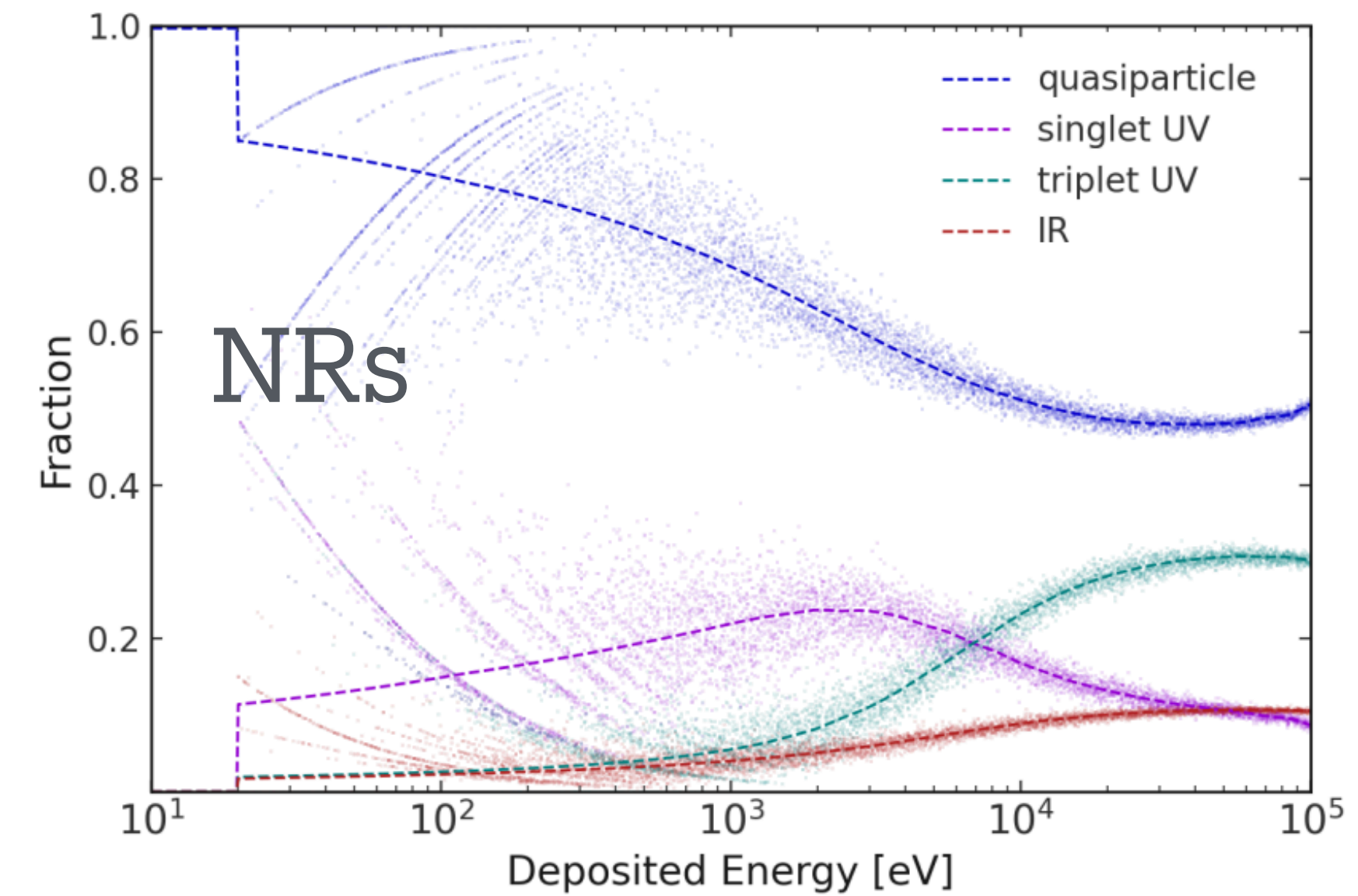
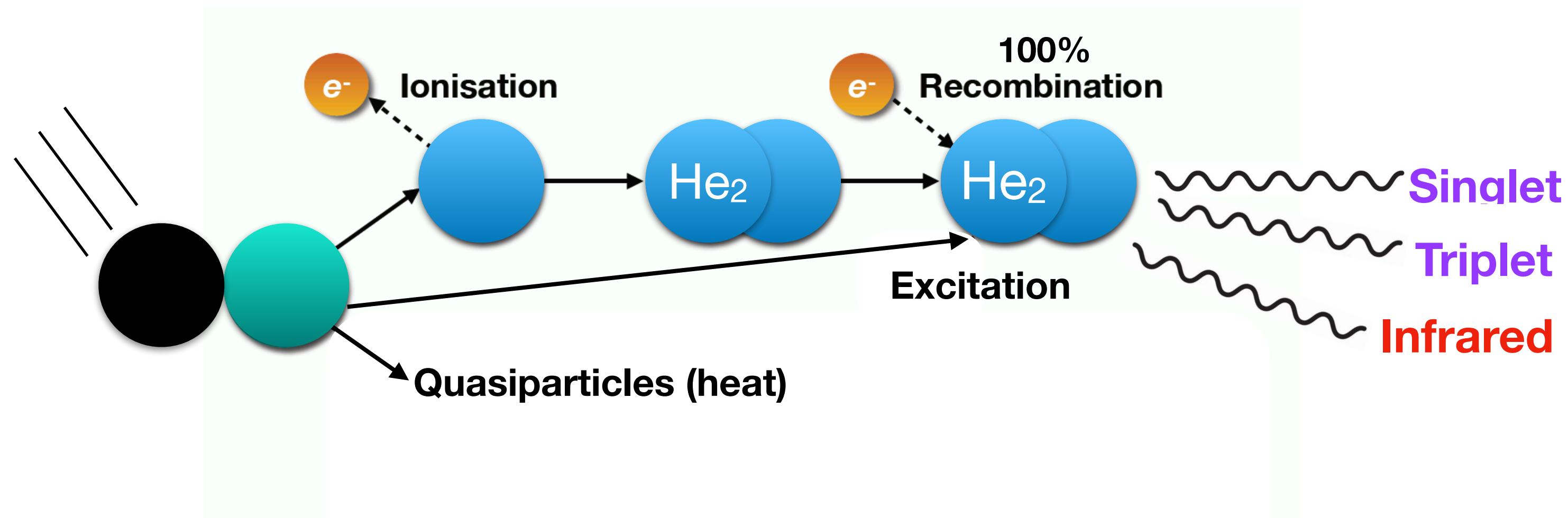
Particle-like Sub-GeV DM: QUEST-DMC

Scattering event between WIMP and ^3He nucleus [NR] or atomic electron [ER] results in heat from QPs, and scintillation light from de-excitation.

19.7 eV threshold for ERs [ionisation energy in He].

10^7 QP produced per eV deposition in ^3He .

Fraction of energy deposited in heat vs light is different for NRs and ERs, and is a function of energy.



Particle-like Sub-GeV DM: QUEST-DMC

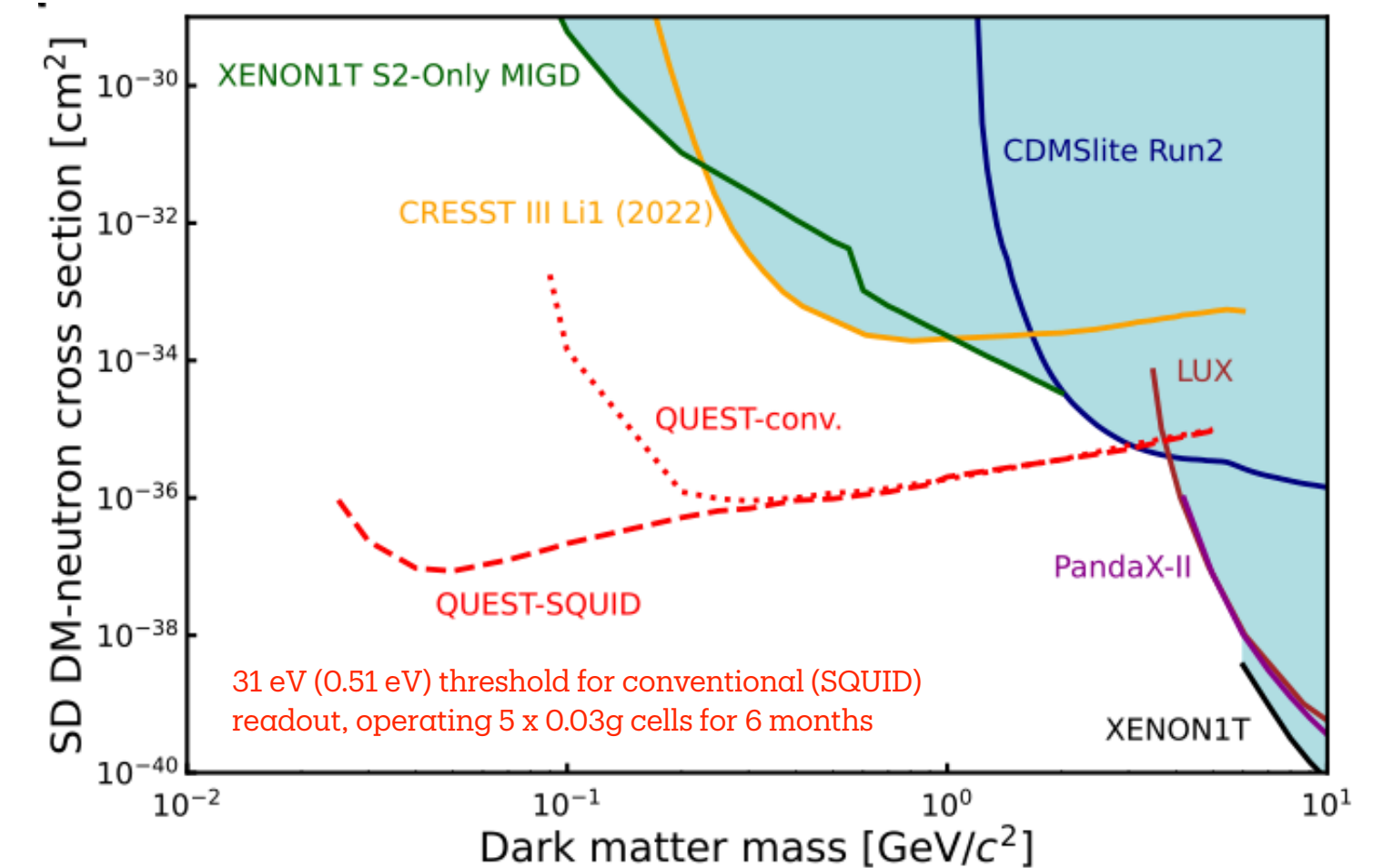
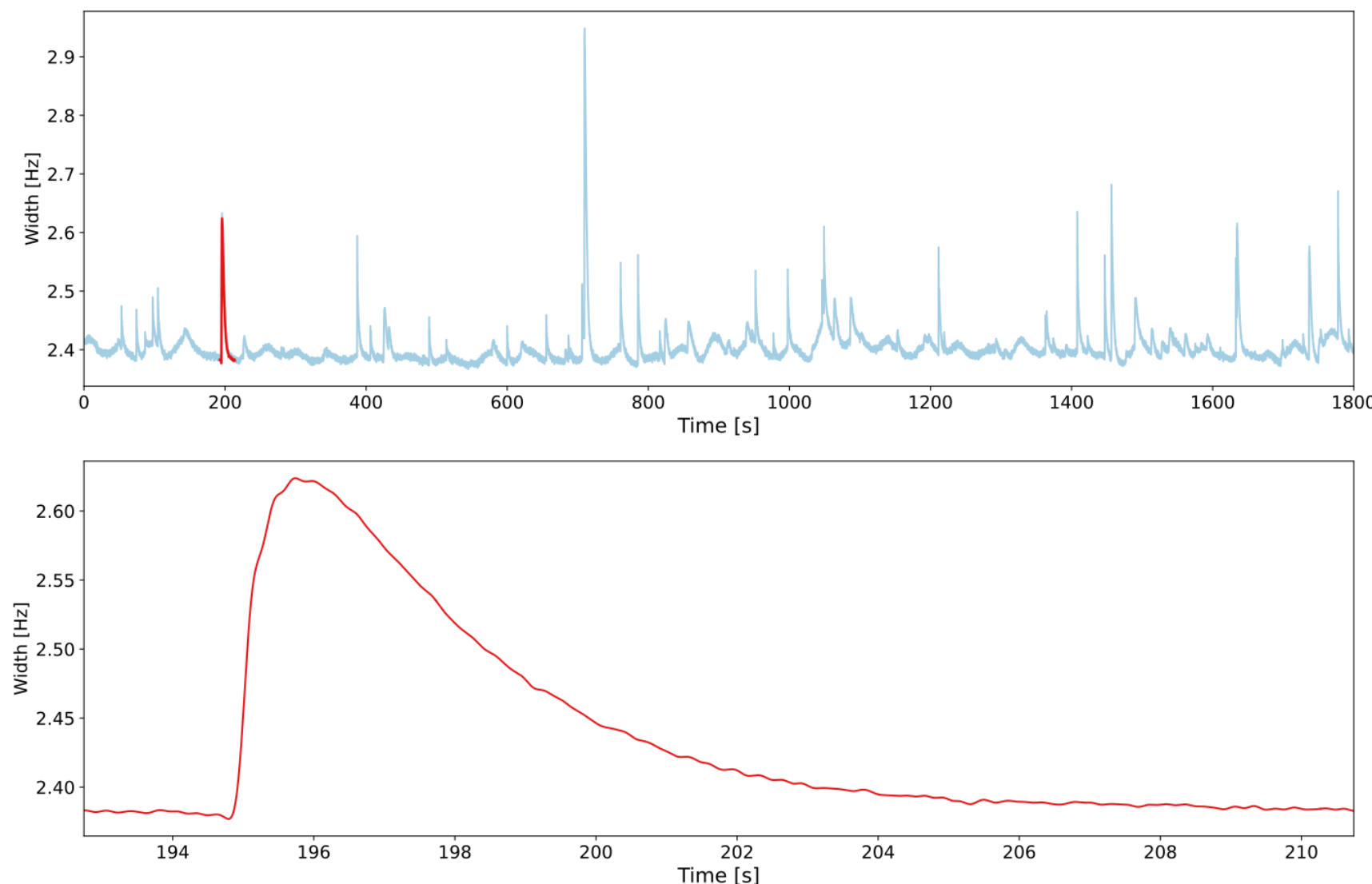
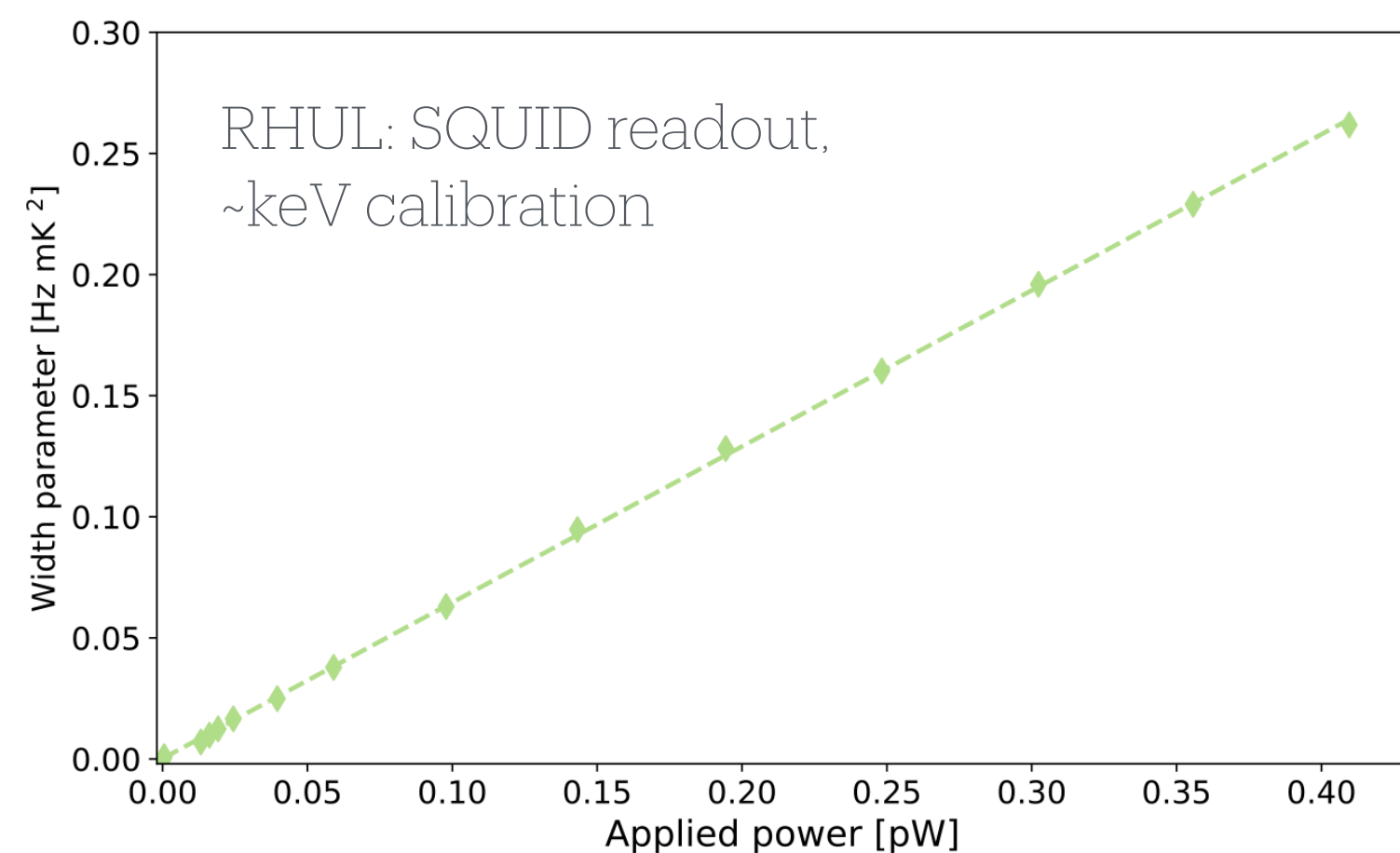
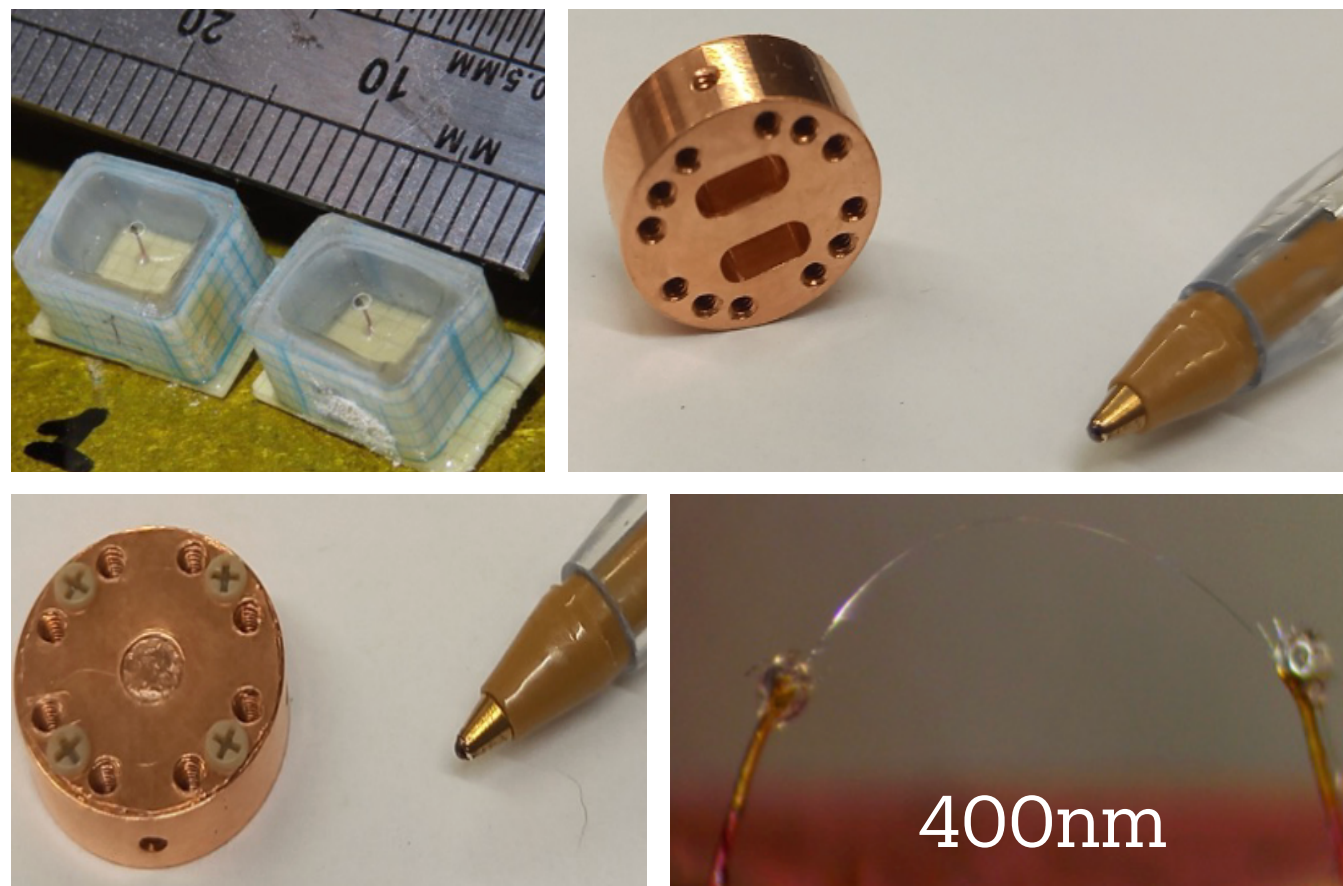
Underpinning of multiple technologies critical for achieving goal of world-leading sensitivity to sub-GeV dark matter candidates.

Operated up to 4 bolometers at $<300\ \mu\text{K}$ with smallest nanowires ever made

Demonstrated calibration down to femtowatt scales ($\sim\text{few keV}$)!

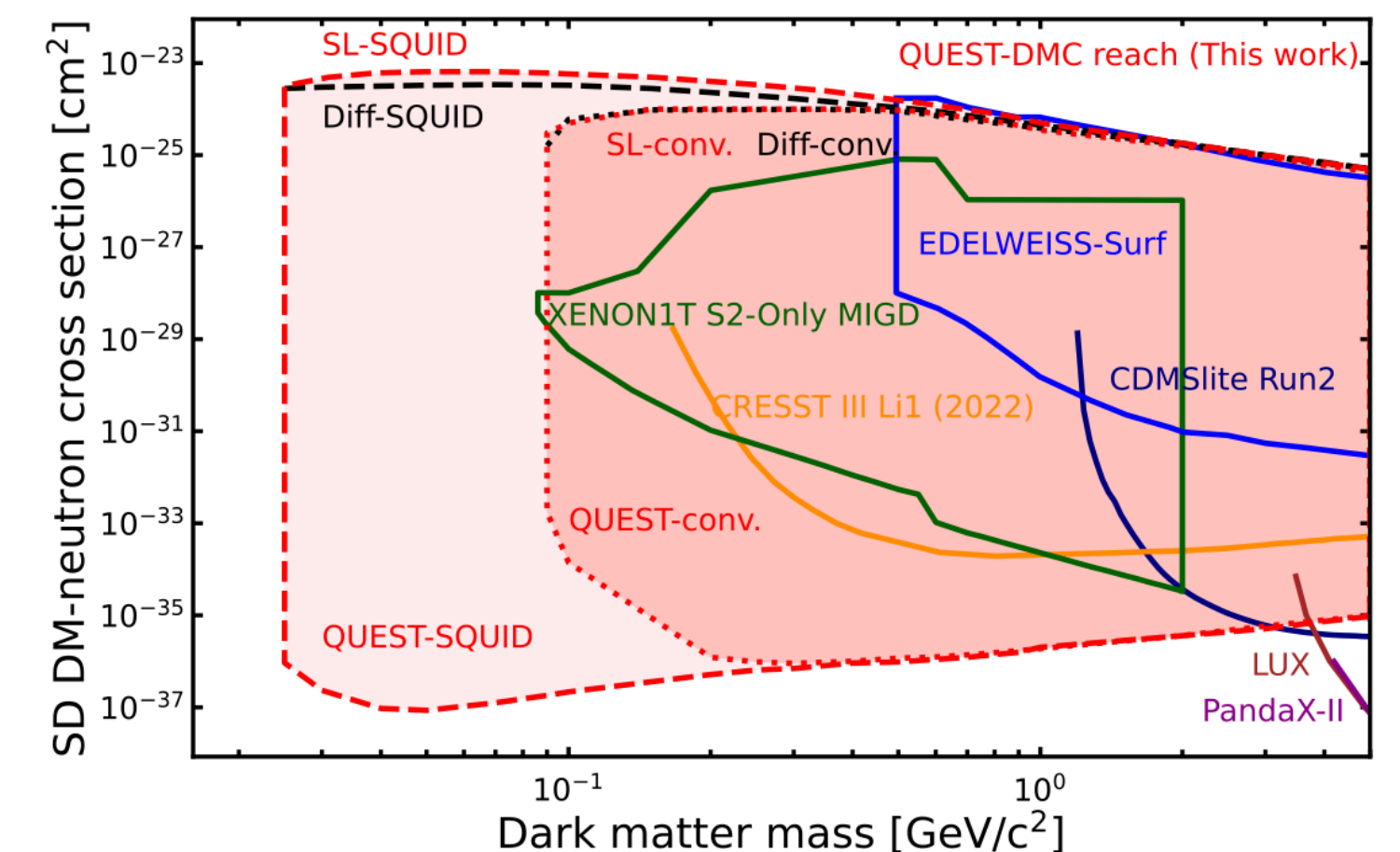
Developed SQUID readout of nanowires

- Leason, E., et al. "Development of superfluid helium-3 bolometry using nanowire resonators with SQUID readout for the QUEST-DMC experiment." *arXiv:2508.10602* (2025).



Eur. Phys. J. C (2024) 84:248

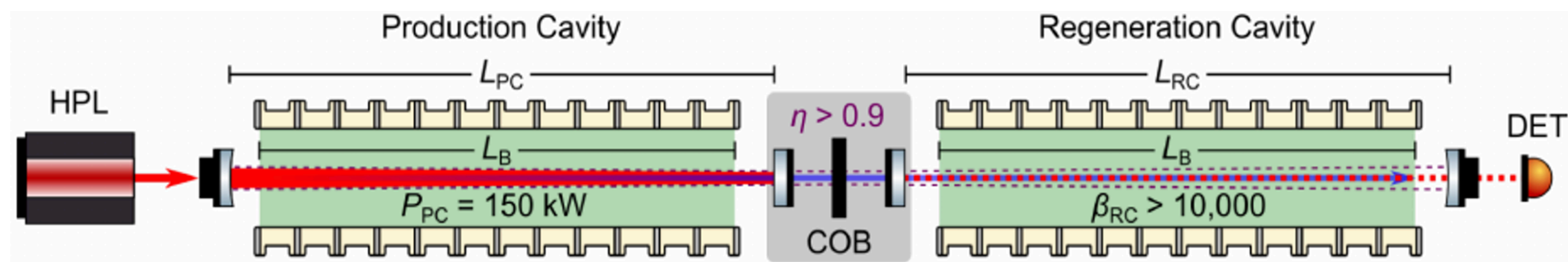
Published several papers on DM sensitivity to different operators and mapping from EFT to NREFT, and on the sensitivity ceiling.



Journal of Cosmology and Astroparticle Physics 202504 (2025): 017.

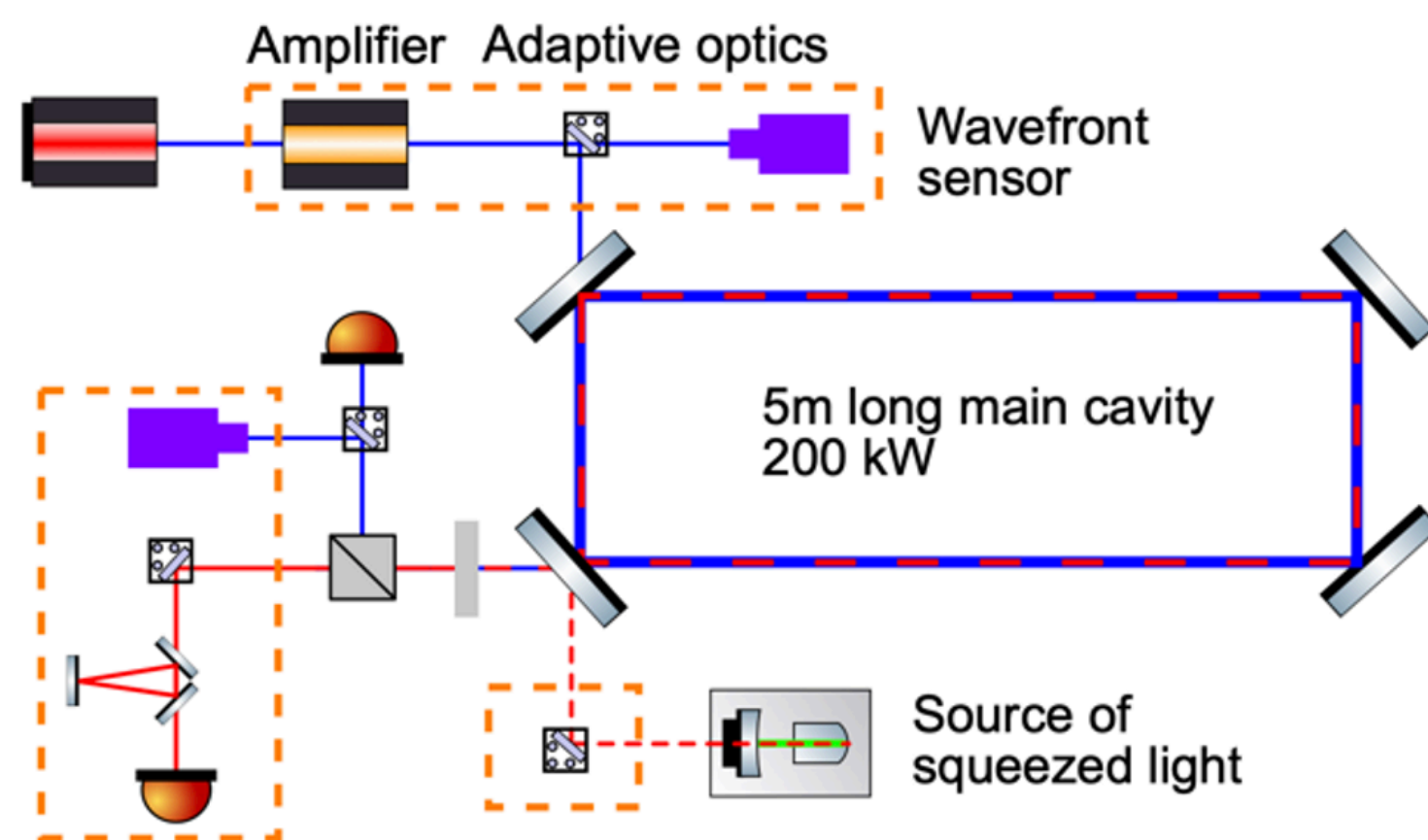


Wave-like Axion Dark Matter: ALPS II/LIDA



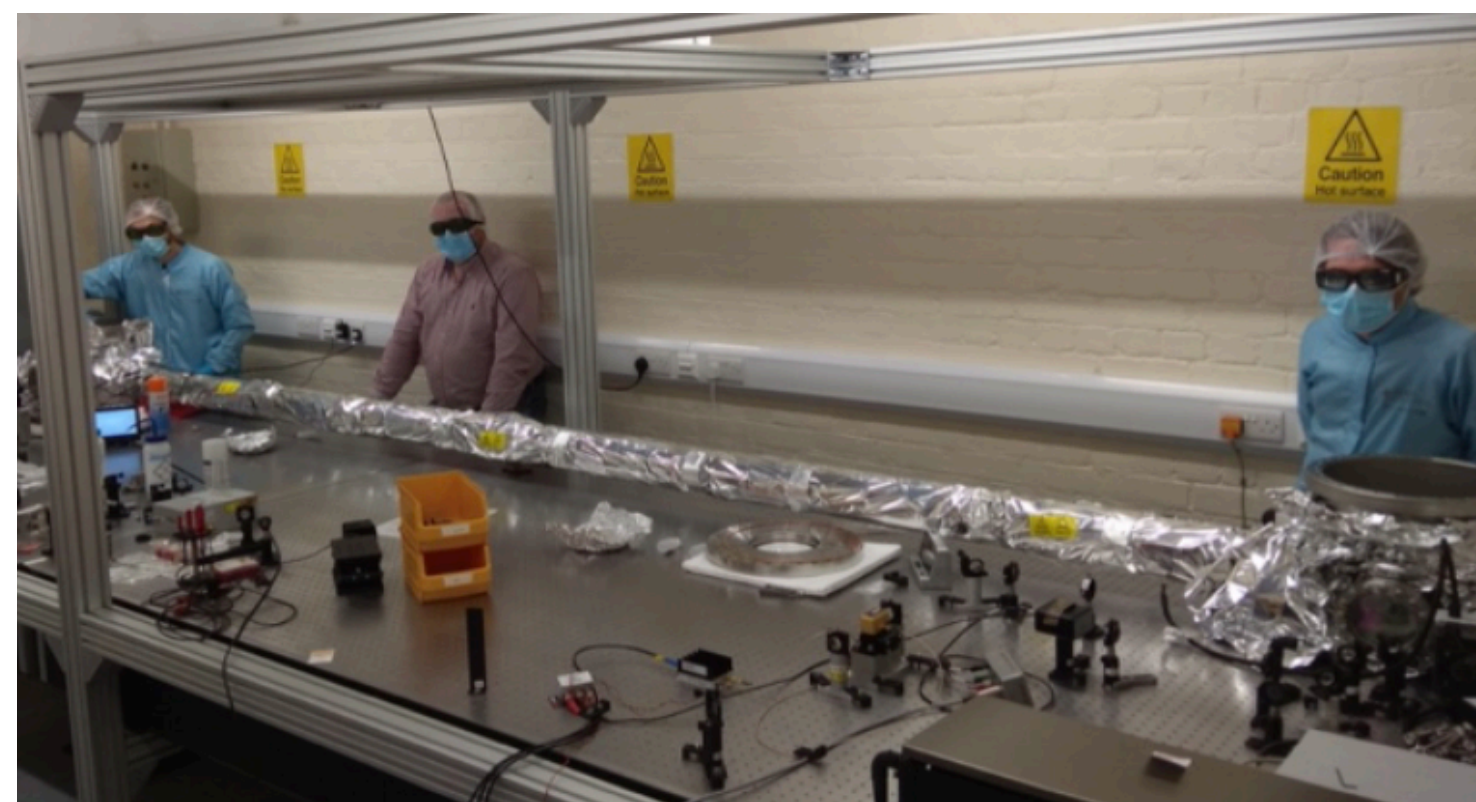
ALPS II at DESY:

- Light-Shining-through-a-Wall experiment to search for axion-like particles.
- Tungsten-based TES microchips and SQUID readout installed on dilution refrigerator funded by QTFP & DESY (successfully installed at 20 mK)



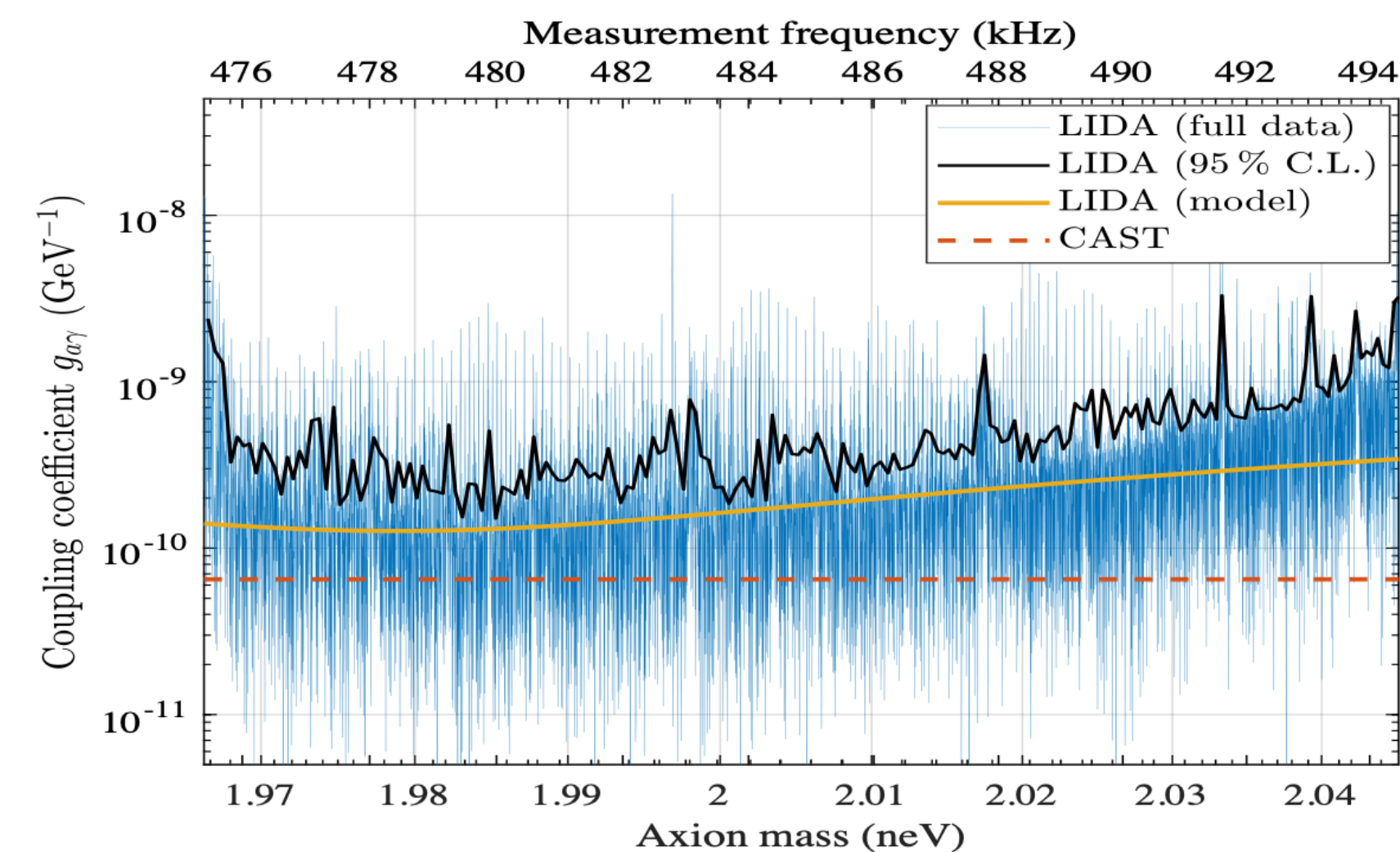
Using squeezed state of light to mitigate readout shot noise

World record of laser intensity in precision interferometry (>100 kW).



LIDA: Searching for axion dark matter in our galaxy via coupling of axions to photons.

Polarisation axis of linearly polarised light rotated with a period corresponding to axion frequency; measure rotation with the detector,



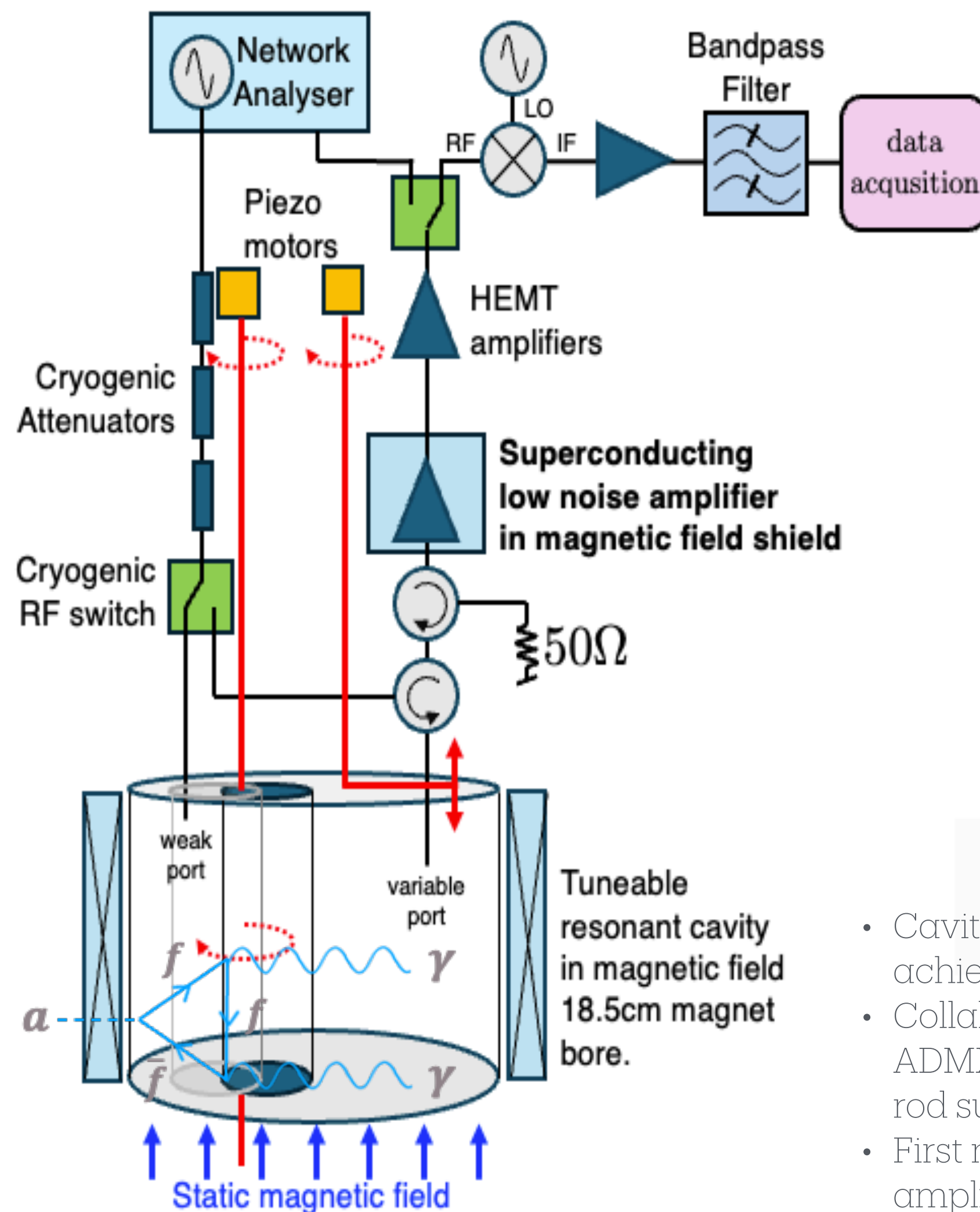
First results: Competitive constraints at axion mass of 2 neV: *Phys. Rev. Lett.* 132, 191002 (2024)
New J. Phys. 26 055002 (2024)



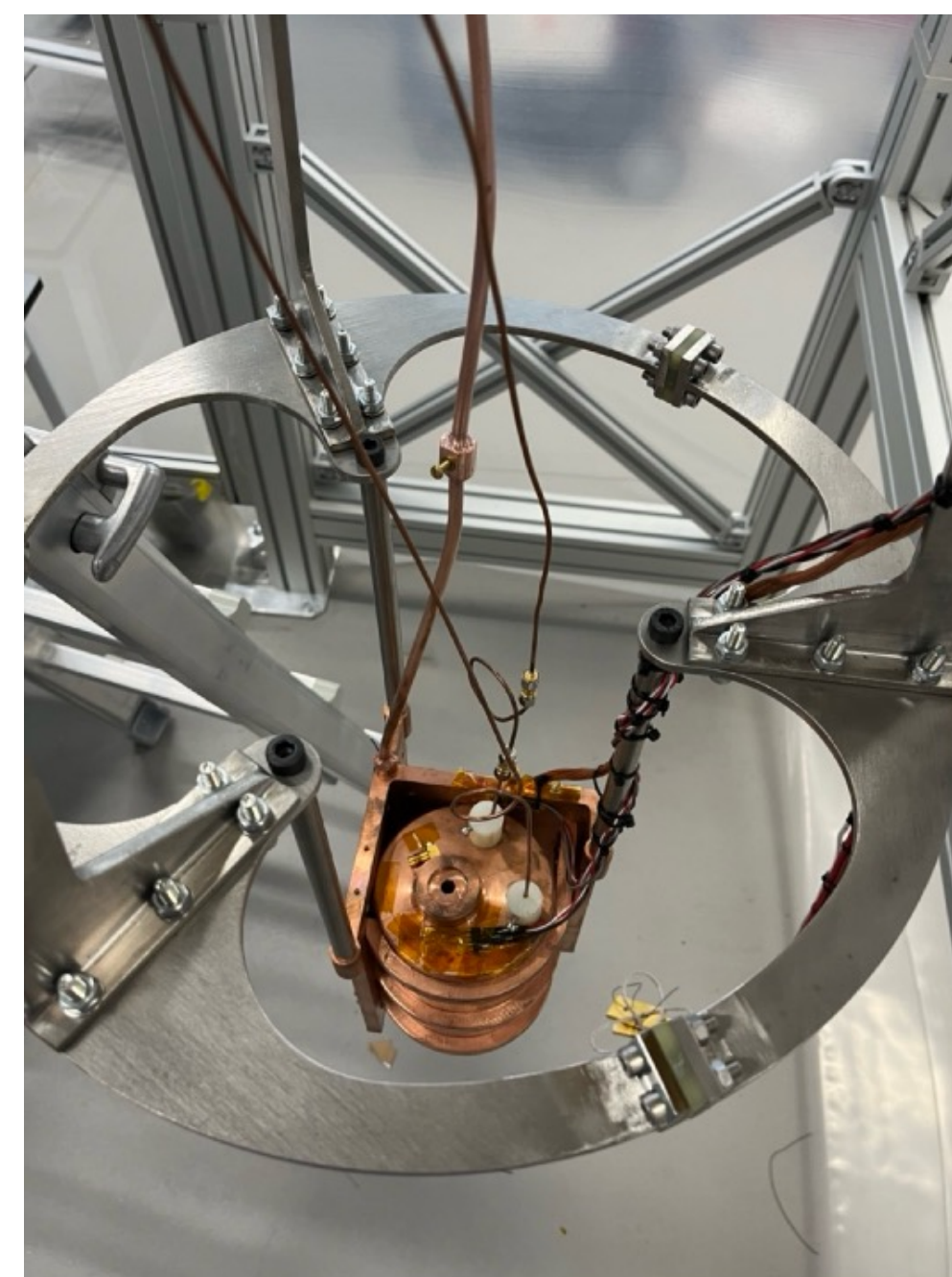
Wave-like Axion DM: QSHS

Quantum Sensors for the Hidden Sector (QSHS):

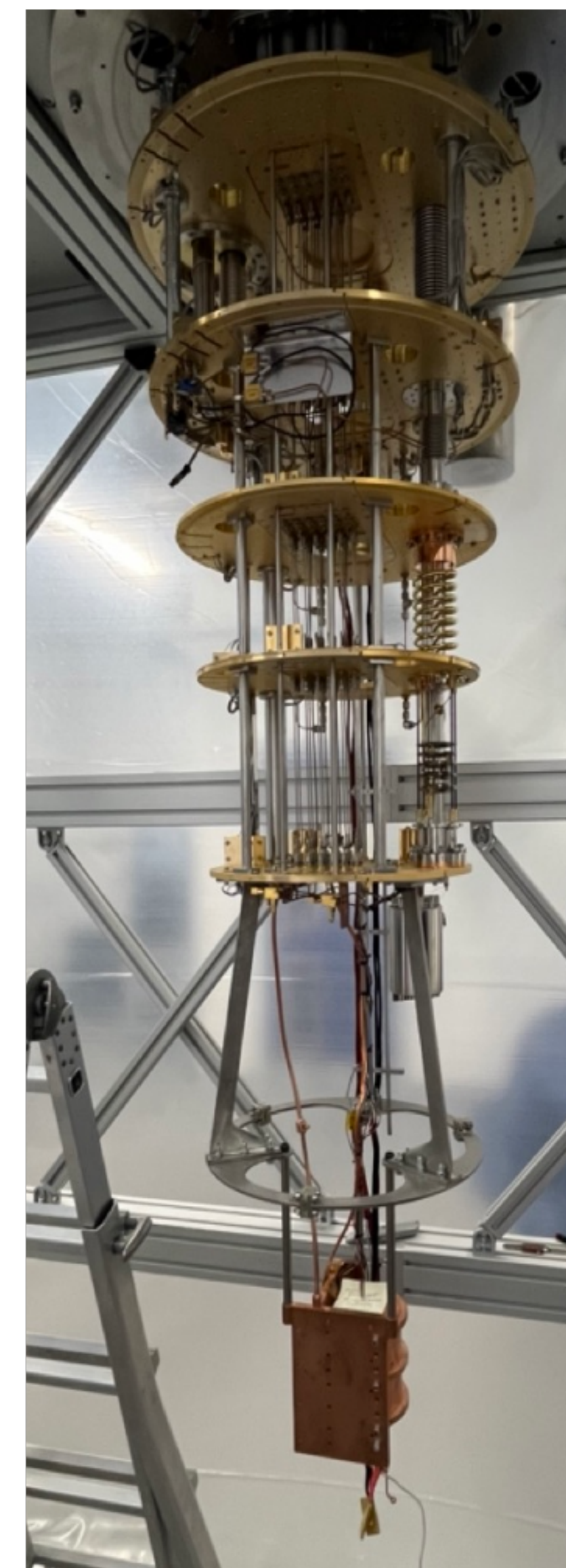
- Develop and test quantum and high-sensitivity electronics for axion dark matter and other hidden sector particle searches
- Drive operating temperature of cavity searches down to ~ 10 mK: enable single photon detection operation.
- Perform first search for galactic halo axion dark matter at $\sim \mu\text{eV}$ mass scale



Cavity installation and resonator characterisation in dilution fridge at Lancaster:
New Journal of Physics 27.10 (2025): 105002.

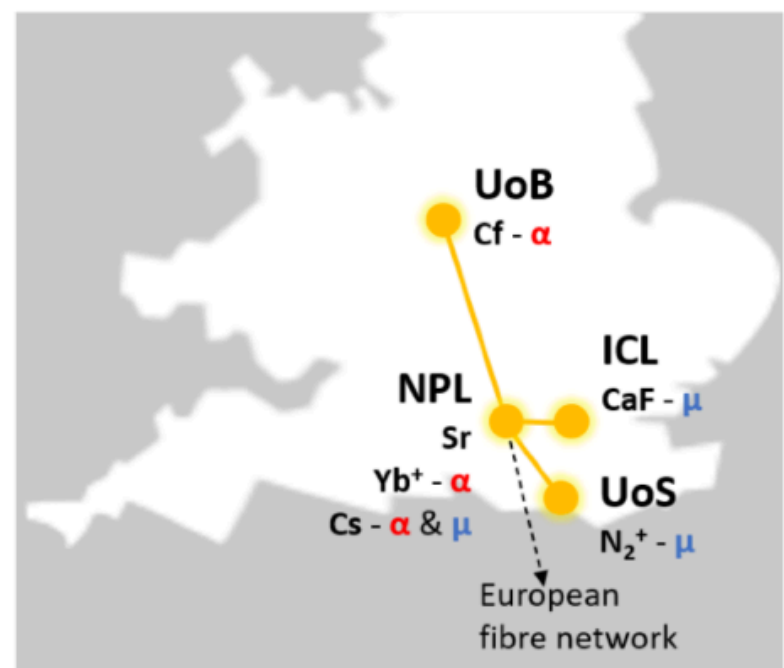


- Cavity tuning at 85mK cavity temperature achieved & magnet operates at 8T
- Collaboration with ADMX fruitful: QSHS made ADMX cavities and ADMX adopted QSHS's tuning rod support scheme.
- First noise temperature measurements on HFET amplifiers performed in-situ.
- **First axion search using QSHS will happen in 2025!**

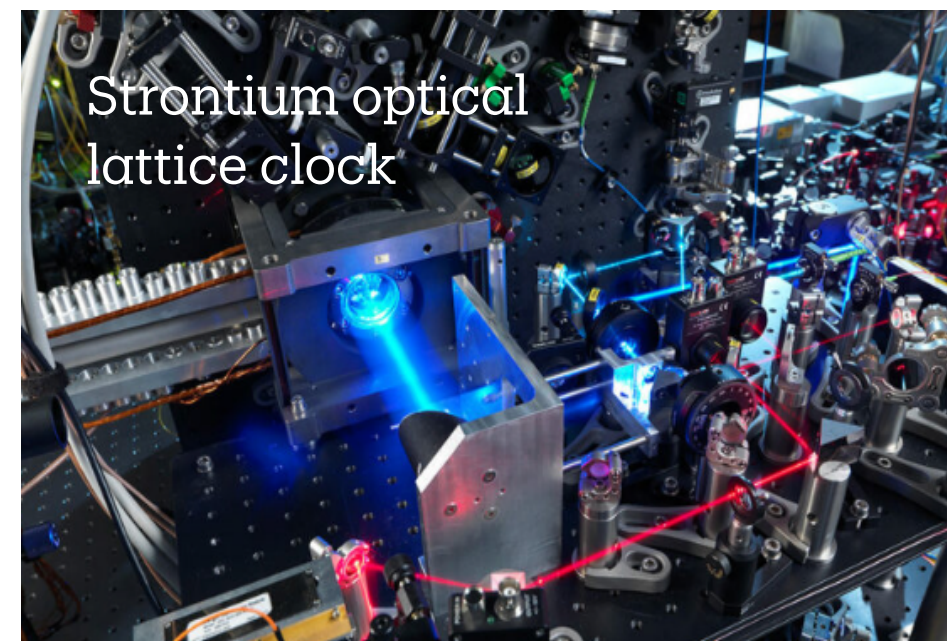


Wave-like ULDM: QSNET

QSNET: Development of network of clocks chosen for their different sensitivities of variations of fine structure constantly (α) and electron-to-proton mass (μ)

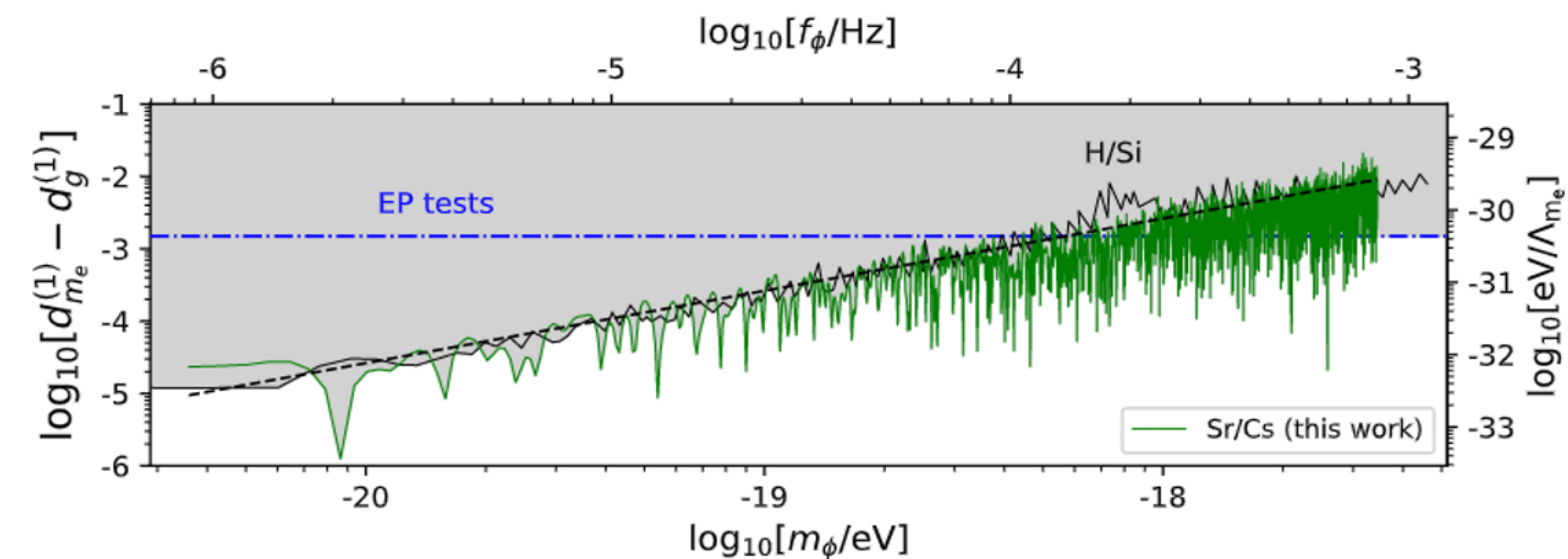
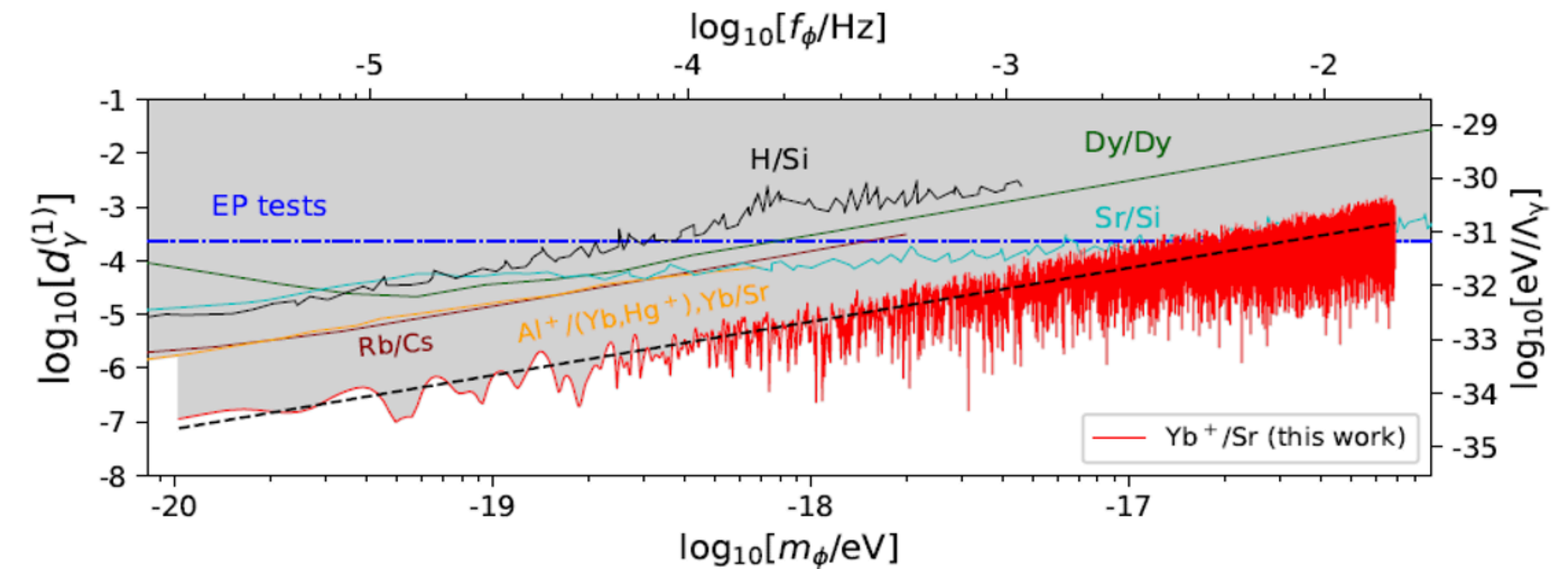


Clock	$K\alpha$	$K\mu$
Yb ⁺ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N ₂ ⁺ (2.31 μm)	0	0.5
Cf ¹⁵⁺ (618 nm)	47	0
Cf ¹⁷⁺ (485 nm)	-43.5	0



Search for ultralight DM:

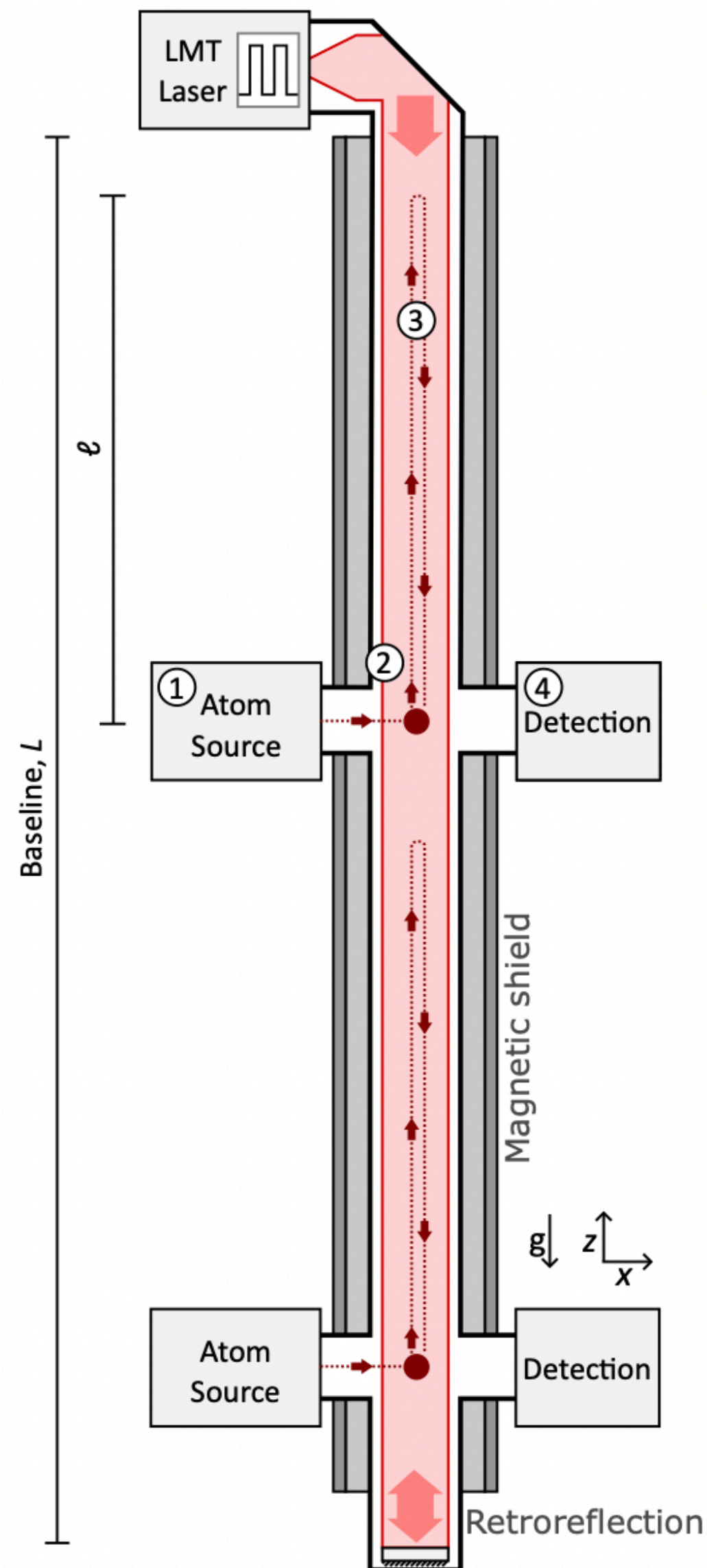
- Hypothetical ultralight DM scalar field couples to EM field,
- Dynamic DM field causes a corresponding change/oscillation in the fine-structure constant α .
- α determines the strength of the EM interaction: changes in α alter atomic energy levels.
- **Comparison between two clocks can be used to obtain a limit on the time variation of fundamental constant α and set constraints on ultralight dark matter.**



NPL: World-leading constraints on ultralight dark matter (*New J. Phys.* 25 9, 093012 (2023))
 & most accurate clock in Europe

- Lots more exciting developments!

AION Wave-like ULDM: AION



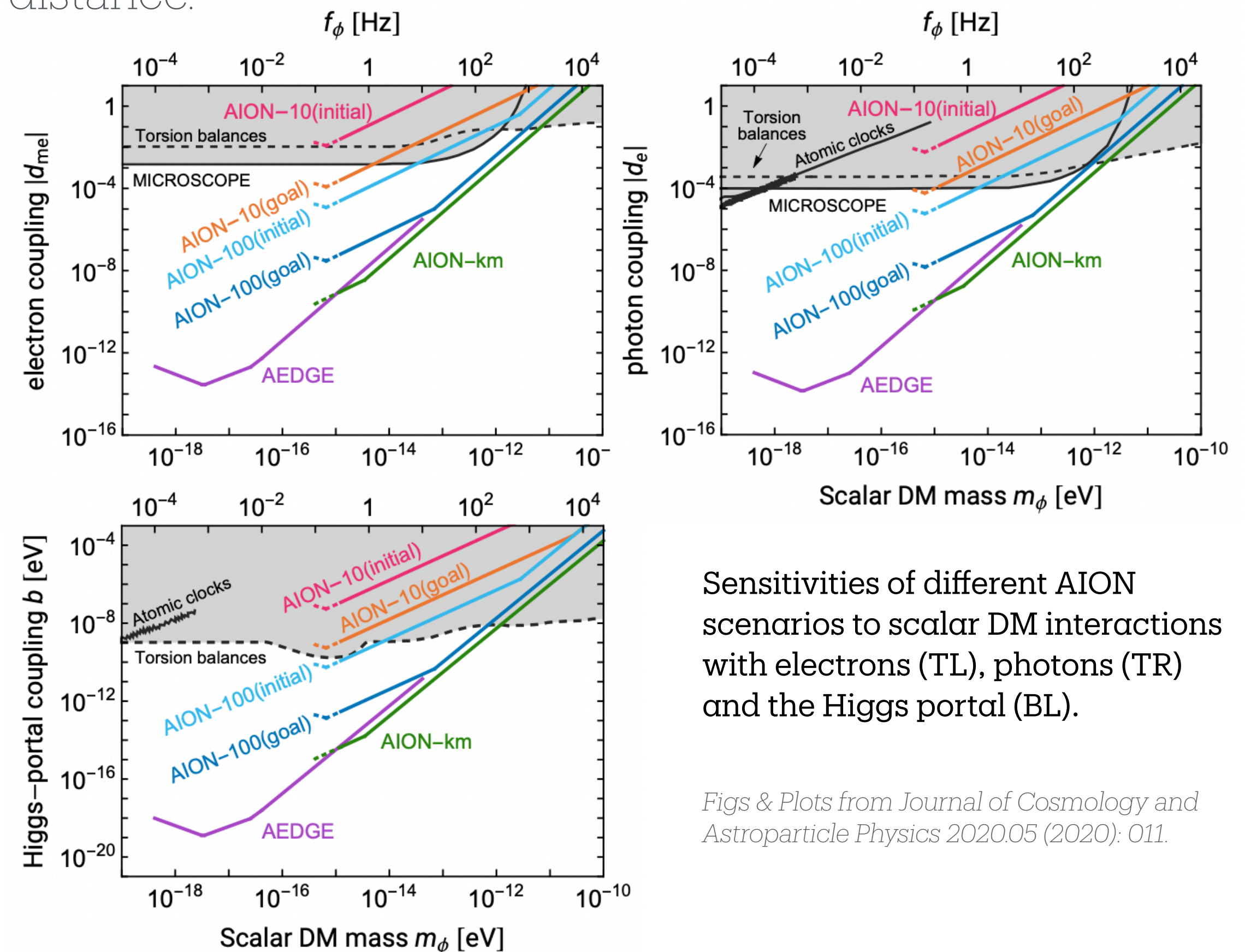
Atom Interferometry:

- Cooled strontium atoms launched upwards and freefall ~ 1 s in two separate interferometers.
- Laser fired at falling atom causes it to split into two quantum states.
- Second laser reunites atoms, third laser measures atoms.
- If something delayed one of the atoms, will measure interference pattern (no signal alignment).

Differential measurement suppresses common noise sources and systematics.

Ultralight dark matter (ULDM) is detected via its differential effects on the atomic transition frequencies.

Network of separated interferometers increases ULDM sensitivity by measuring the phase shift over a larger effective distance.



Sensitivities of different AION scenarios to scalar DM interactions with electrons (TL), photons (TR) and the Higgs portal (BL).

Figs & Plots from Journal of Cosmology and Astroparticle Physics 2020.05 (2020): 011.

Summary & Outlook

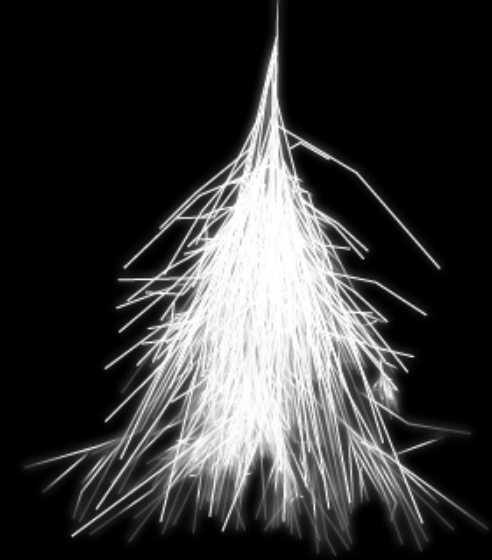
Huge increase in interest in light dark matter in recent(ish) years.

Vast range of experiments/
experimental techniques
developed to search a broad mass
range (10^{22} eV - 1 GeV)

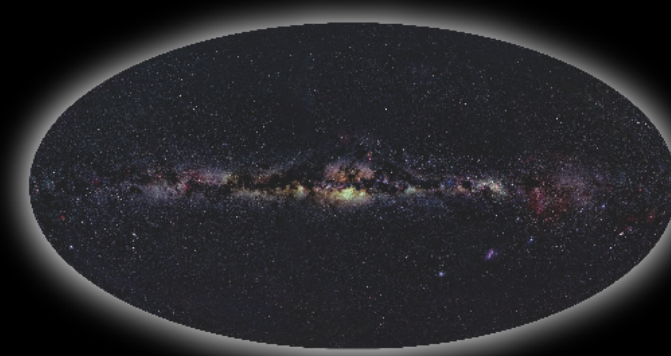
- Strong overlap with quantum sensor development.

Every time we've enhanced our technological capabilities, we've opened a new observational window: dark matter next?!

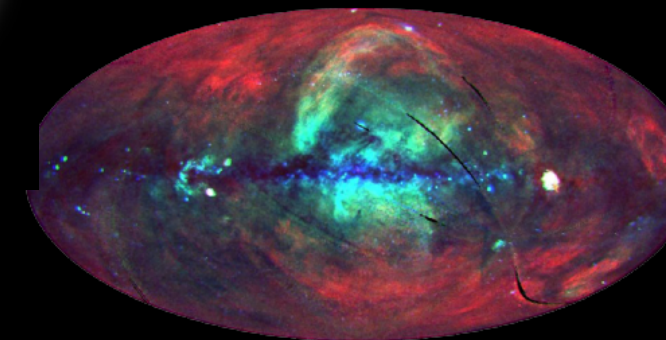
cosmic-rays



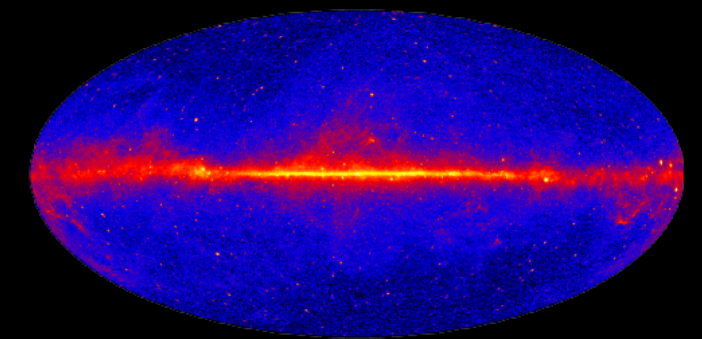
infrared/optical



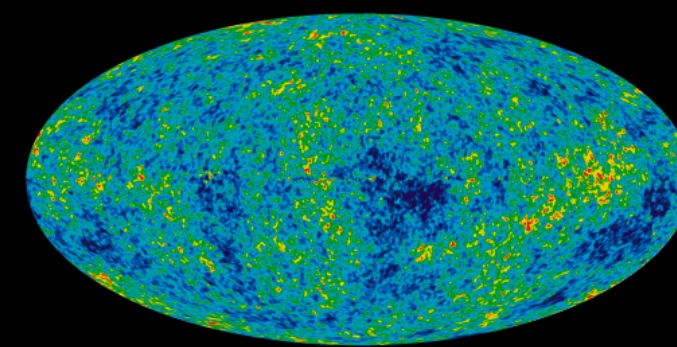
X-rays



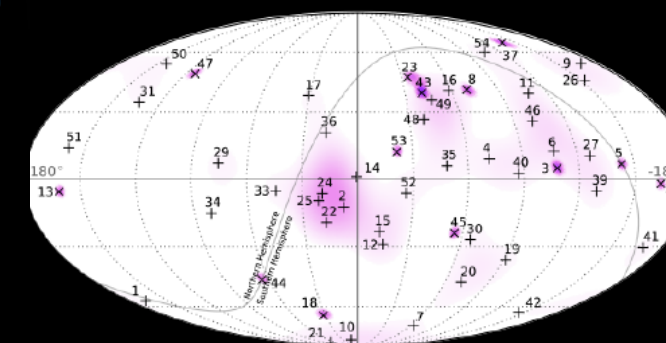
gamma-rays



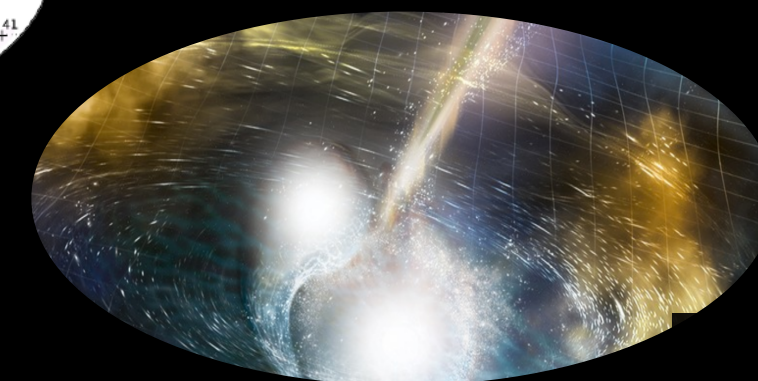
radio/microwave



neutrinos



gravitational waves



dark matter?

dark energy?

quantum gravity?

