SOLAIRE

Design and Physics Reach

Claudio Savarese
Royal Society University Research Fellow

MANCHESTER
1824
The University of Manchester

ECFA-UK Meeting on UK studies for the European Strategy Particle Physics Update
Durham - September 24th, 2024

The SOLAIRE Project

32 UK academics and researchers across 11 UK Institutions on the initial proposal

Project Members:
Gianluigi Casse, *University of Liverpool*; Monica D'Onofrio, *University of Liverpool;*
Kirsty Duffy, *University of Oxford;* Patrick Dunne, *Imperial College London;*
Justin Evans, *University of Manchester;* Malcolm Fairbairn, *King's College London;*
Elena Gramellini, *University of Manchester;* Roxanne Guenette, *University of Manchester;*
Ashlea Kemp, *Rutherford Appleton Laboratory;* John Lipp, *Rutherford Appleton Laboratory;*
Nicola McConkey, *Queen Mary University of London;* Jocelyn Monroe, *University of Oxford and Rutherford Appleton Laboratory;* Cheryl Patrick, *University of Edinburgh;*
Kimberley Palladino, *University of Oxford;* Darren Price (PI), *University of Manchester;*
Yorck Ramachers, *University of Warwick;* Claudio Savarese, *University of Manchester;*
Richard Smith, *Daresbury Laboratory;* Stefan Soldner-Rembold, *Imperial College London;*
Andrzej Szelc, *University of Edinburgh;* Alex Tapper, *Imperial College London;*
Morgan Wascko, *University of Oxford and Rutherford Appleton Laboratory;*
Stephen West, *Royal Holloway, University of London;*
Ian Wilmut, *Rutherford Appleton Laboratory;* Joost Vossebeld, *University of Liverpool;*

Researchers:
Jon Taylor, *University of Liverpool;* Andy Blackett-May, *Rutherford Appleton Laboratory;*
Miquel Nebot-Guinot, *University of Edinburgh;* George Korga, *Royal Holloway, University of London;* Martin Spangenberg, *University of Warwick;* Daria Santone, *University of Oxford;*
Gabriela Vitti Stenico, *University of Edinburgh;*

19 International Collaborators so far across 16 Institutions in 7 Countries

Gran Sasso Science Institute, Italy
CIEMAT, Spain
Wroclaw University, Poland
AstroCENT, Poland
University of Milano Bicocca, Italy
University of Bern, Switzerland

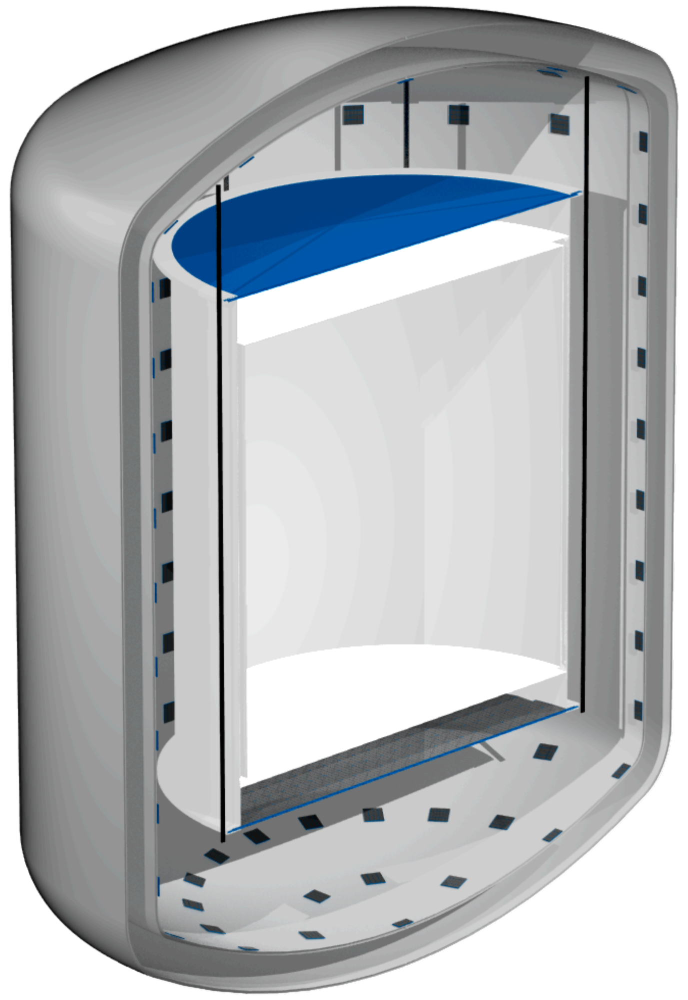
University of Carleton, Canada
SNOLAB, Canada
University of Alberta, Canada
Queen's University, Canada
TRIUMF, Canada

Princeton University, USA
University of California, USA
Williams College, USA
University of Hawaii, USA

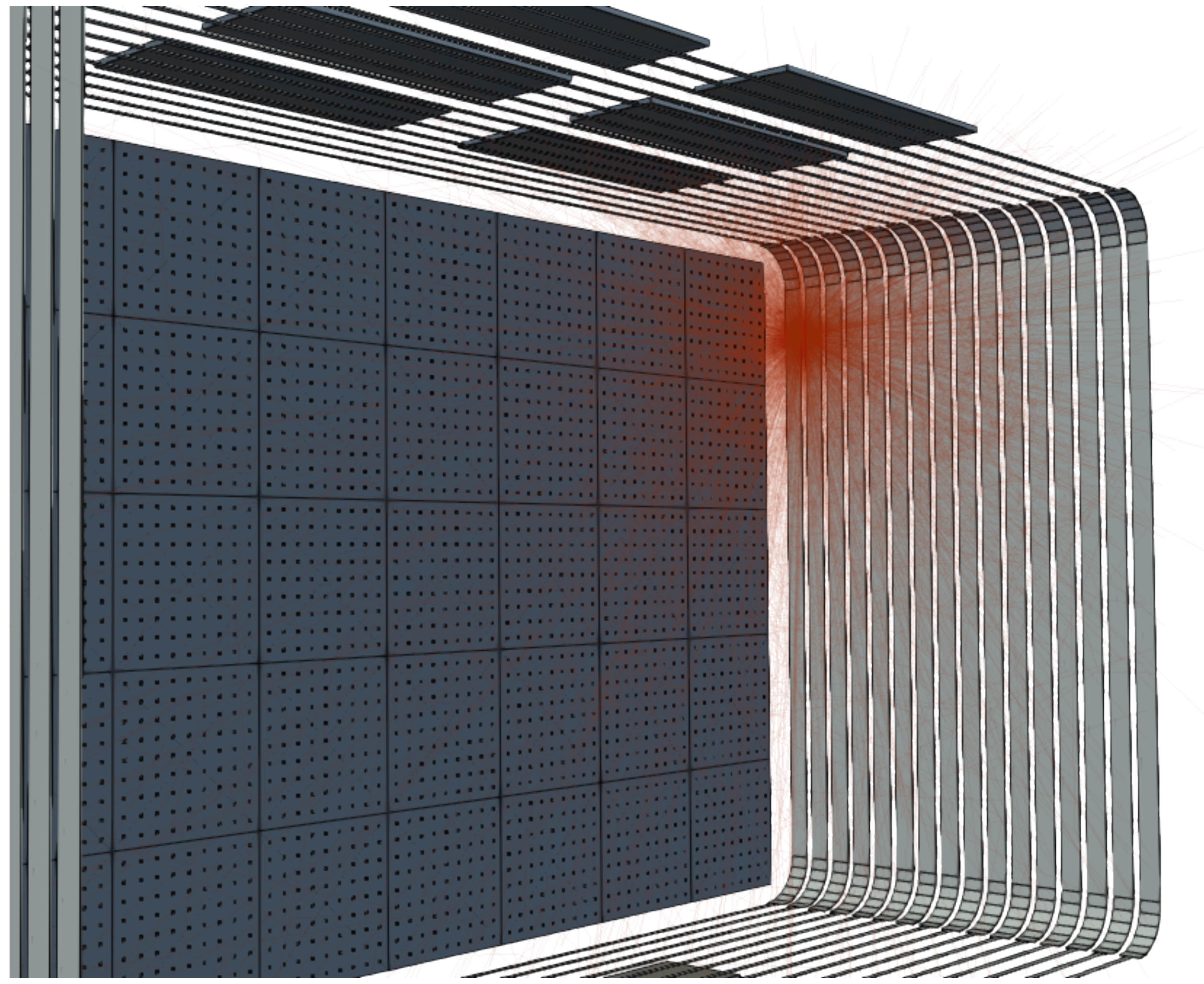
UNICAMP, Brazil

SOLAIRE's origin

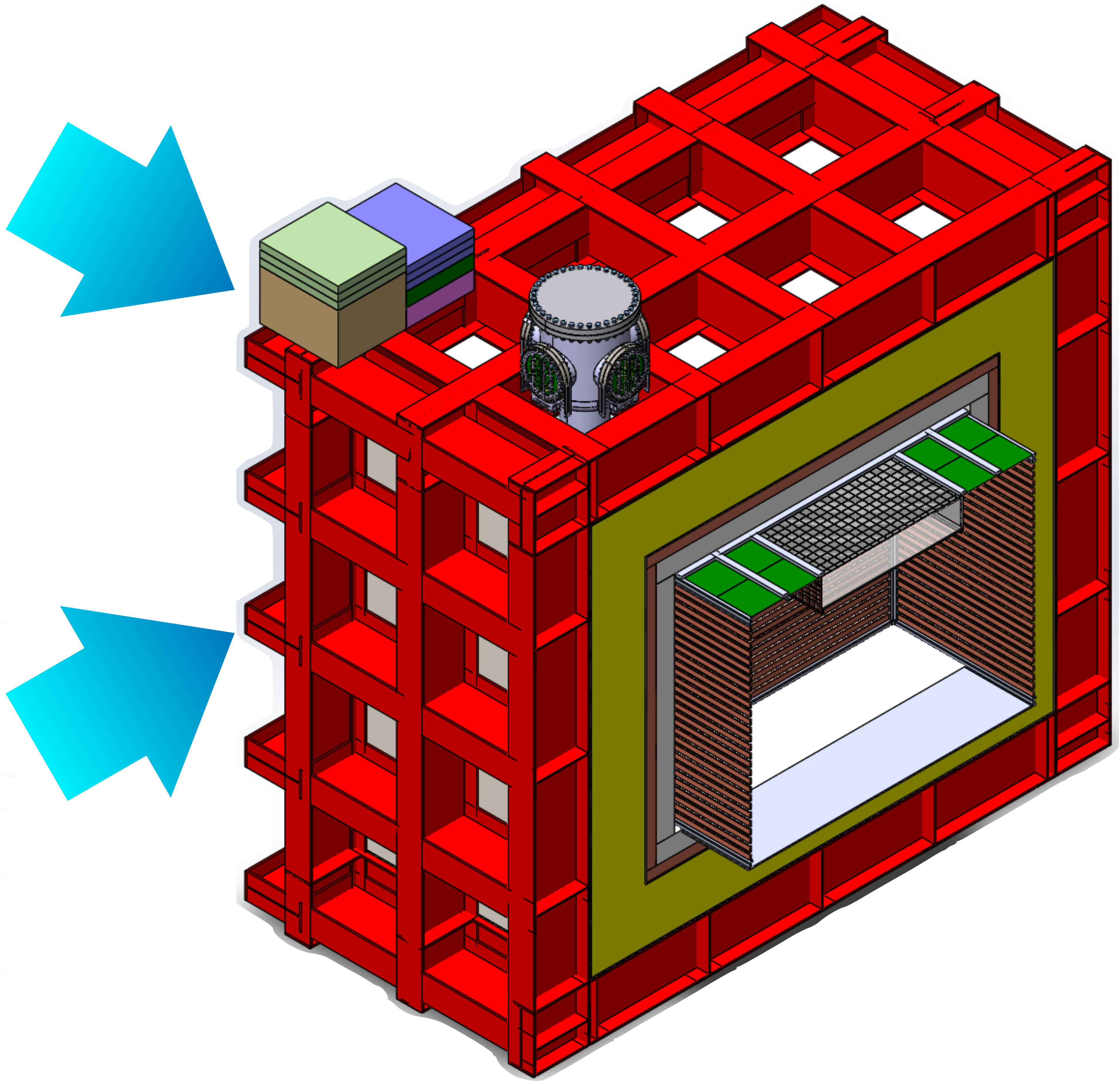
Light Dark Matter Detector



SoLAr Neutrino Detector

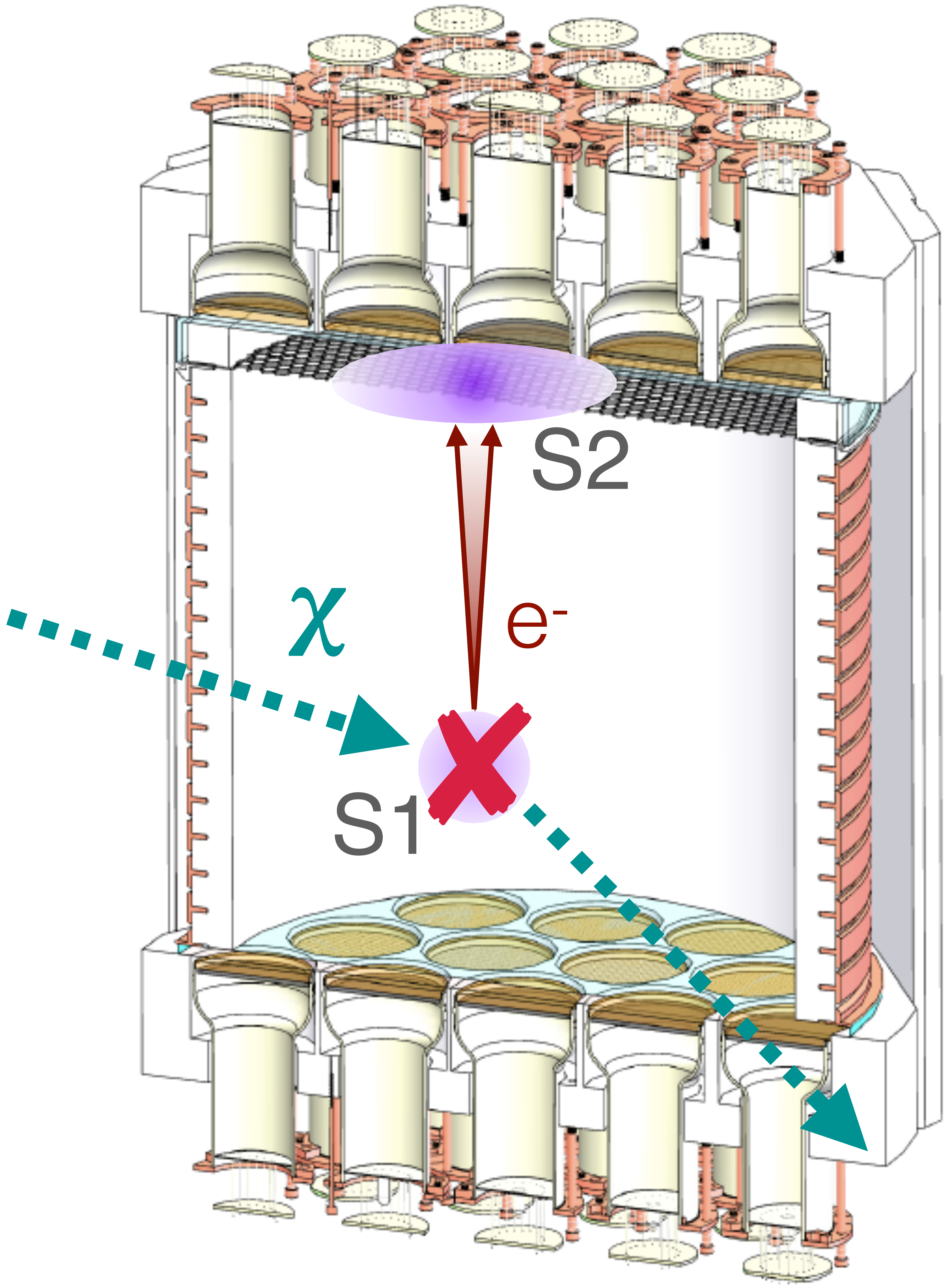


SOLAIRE

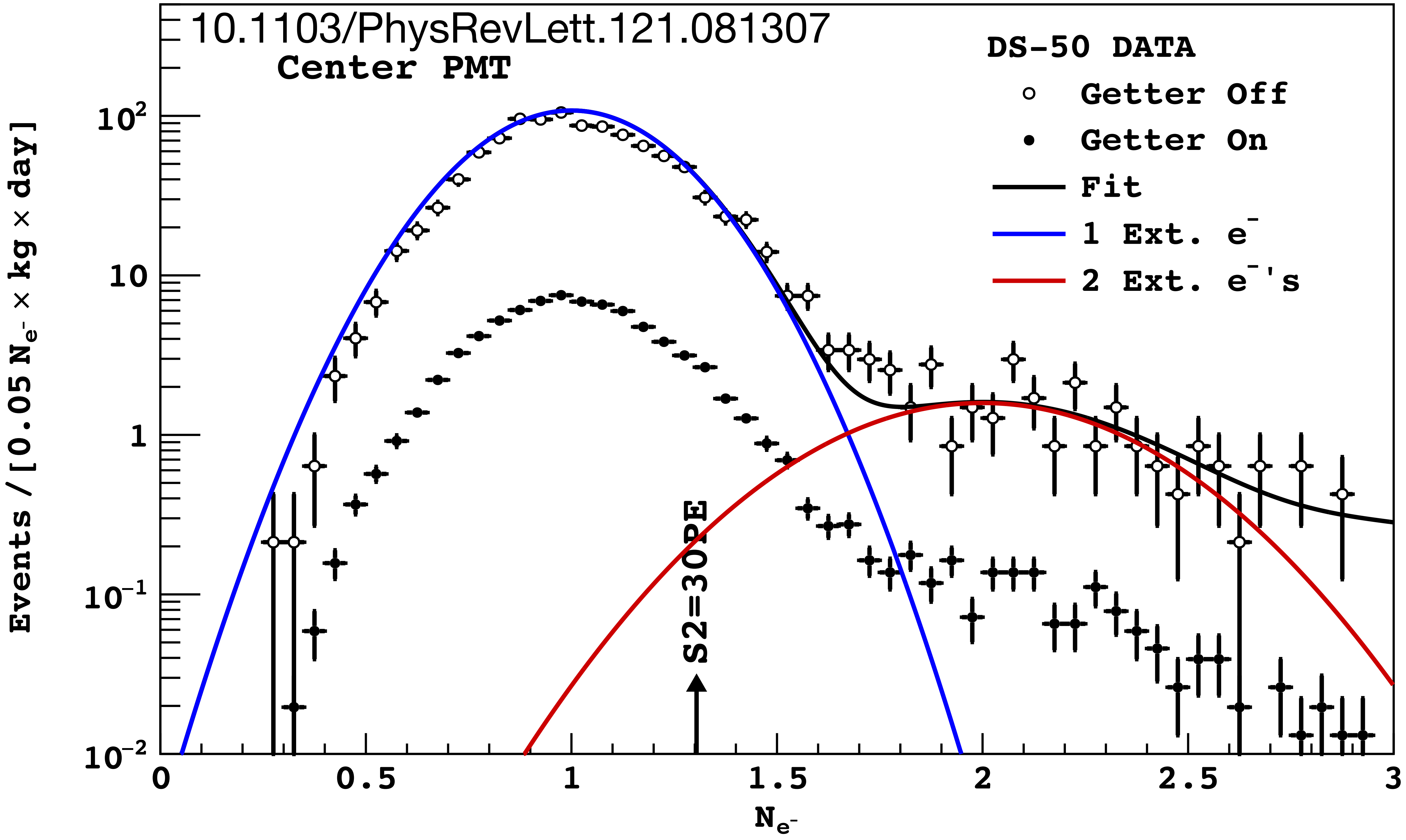


- Both targeting rare events
  - ➡ Compatible radioactivity requirements
- Synergy of techs:
  - DS Readout - Low E
  - SoLAr readout - High E
- In discussion for multiple years with Boulby Underground Lab
- Supported by the GADMC as the next generation LDM detector

S2-only search for LDM

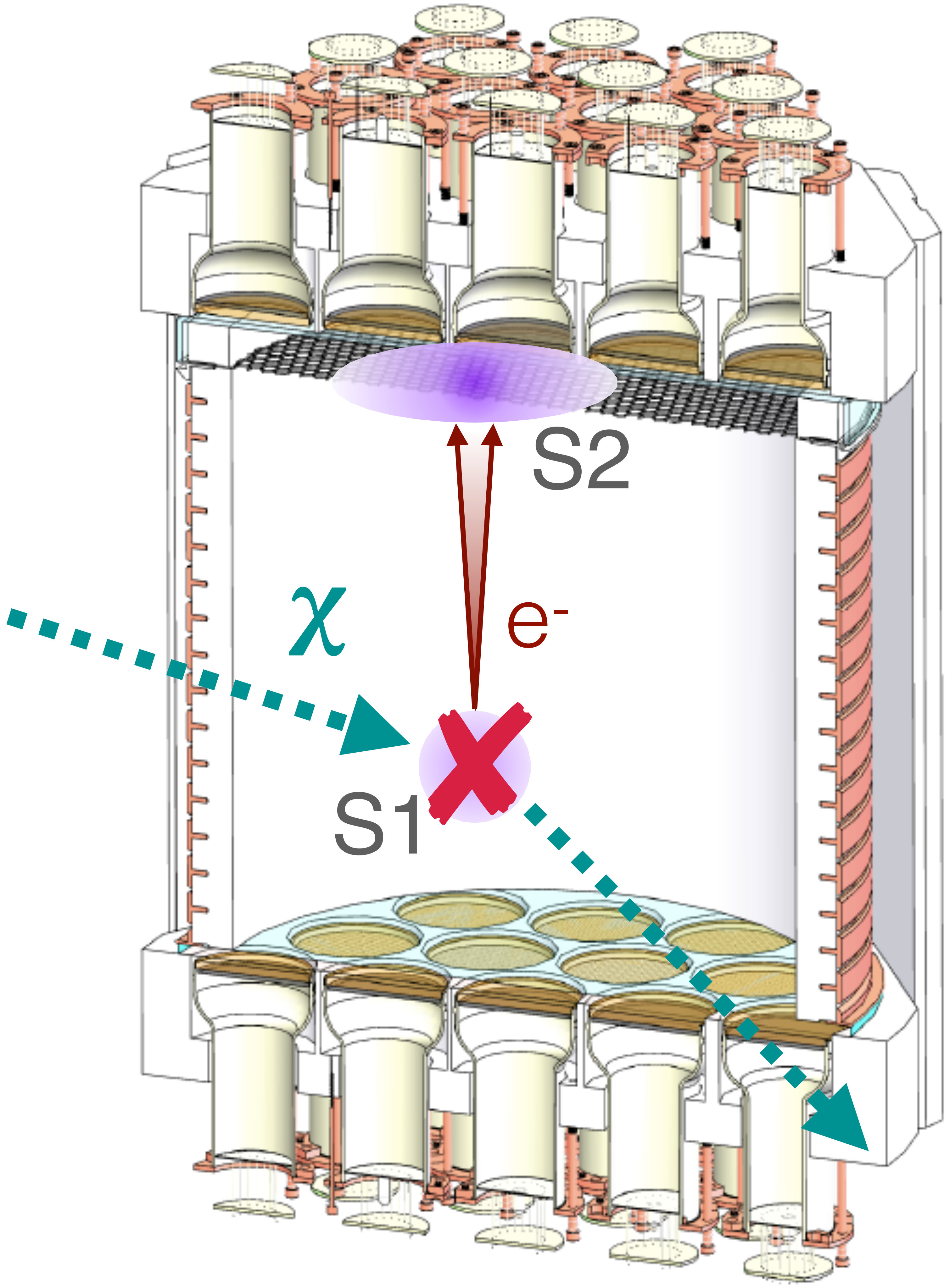


Lower the energy threshold ⇒ Look at the S2 only events



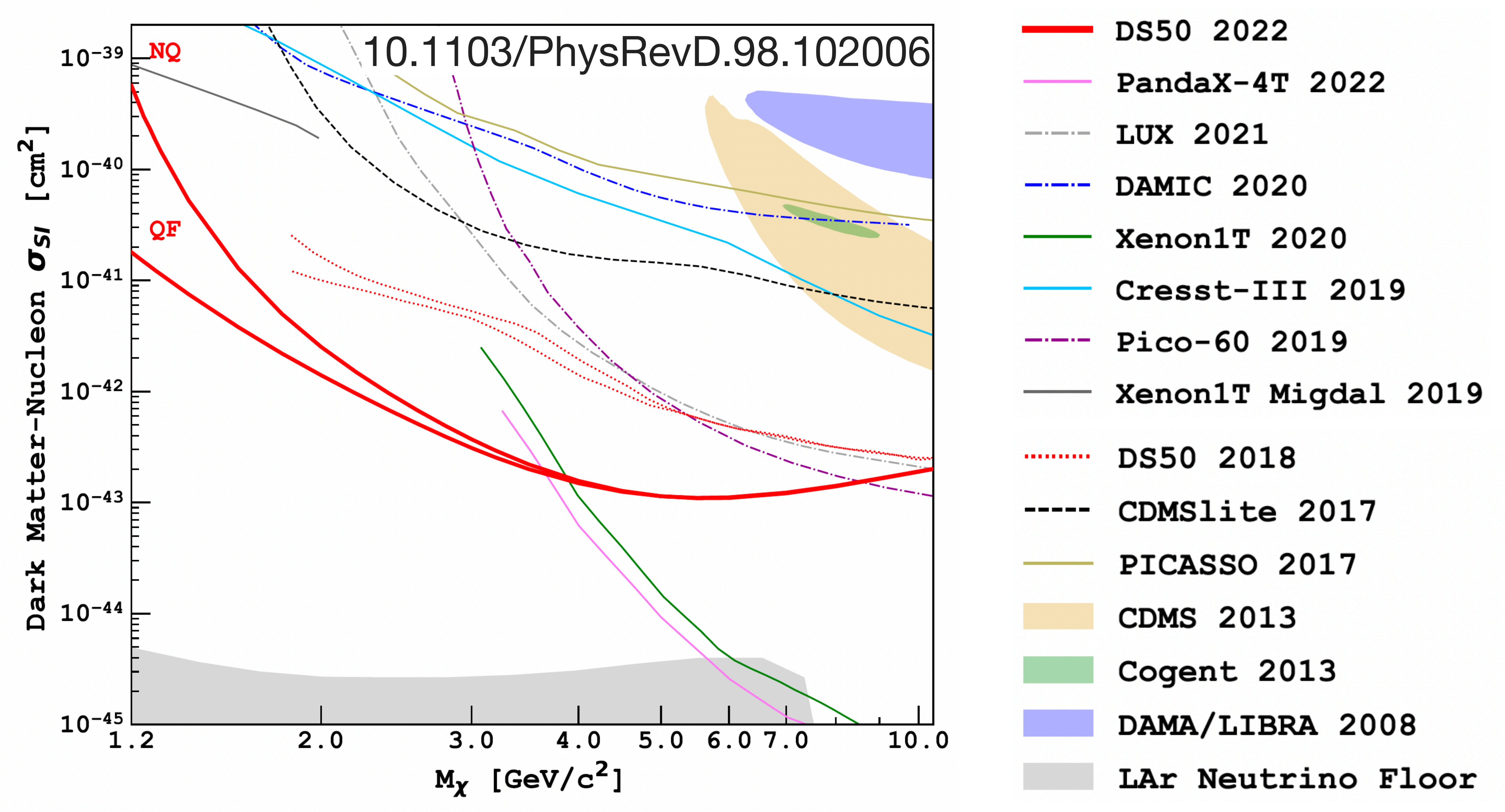
- S2 >> S1 (23ph/e$^-$ in DS50)
- 100% Trigger eff. > ~40PE
- 100% S2 identif. eff. > ~30PE
- Thresholds: <0.1keV$_{ee}$, 0.4keV$_{nr}$

Why LAr

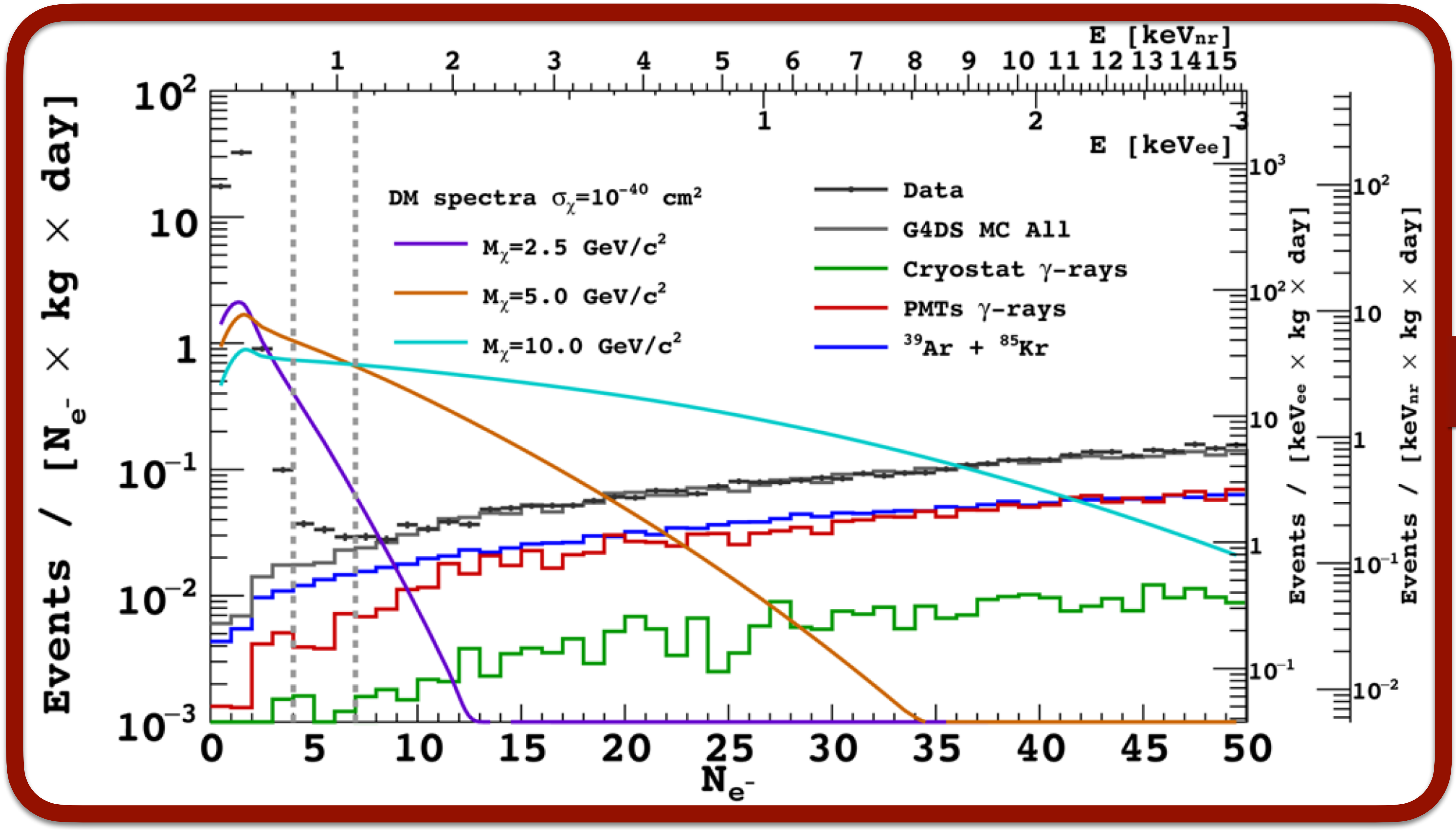


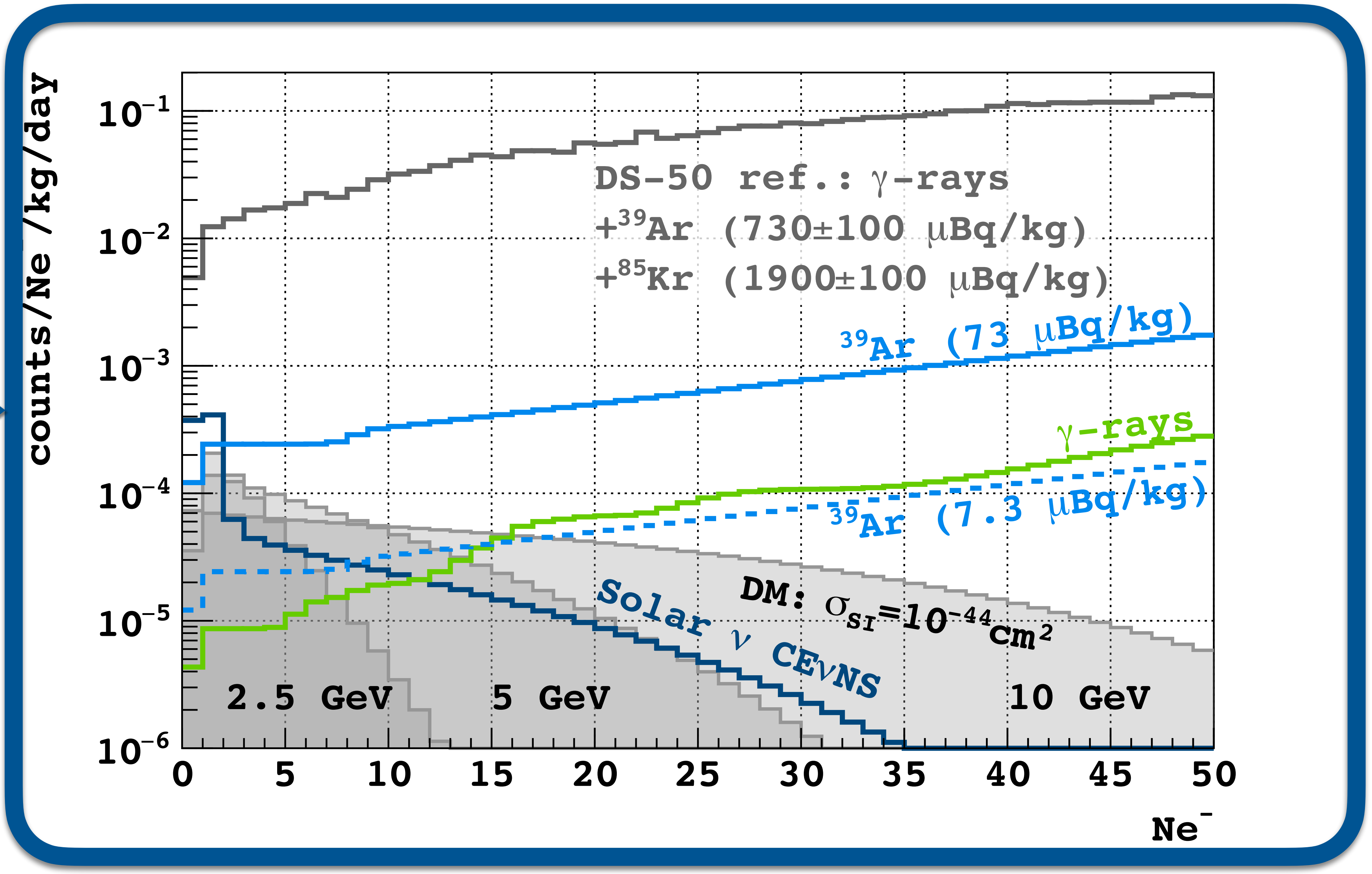
Kinematics: momentum transfer is maximal when $M_{DM} \sim M_{Target}$

Inefficient p-transfer



LDM Drives





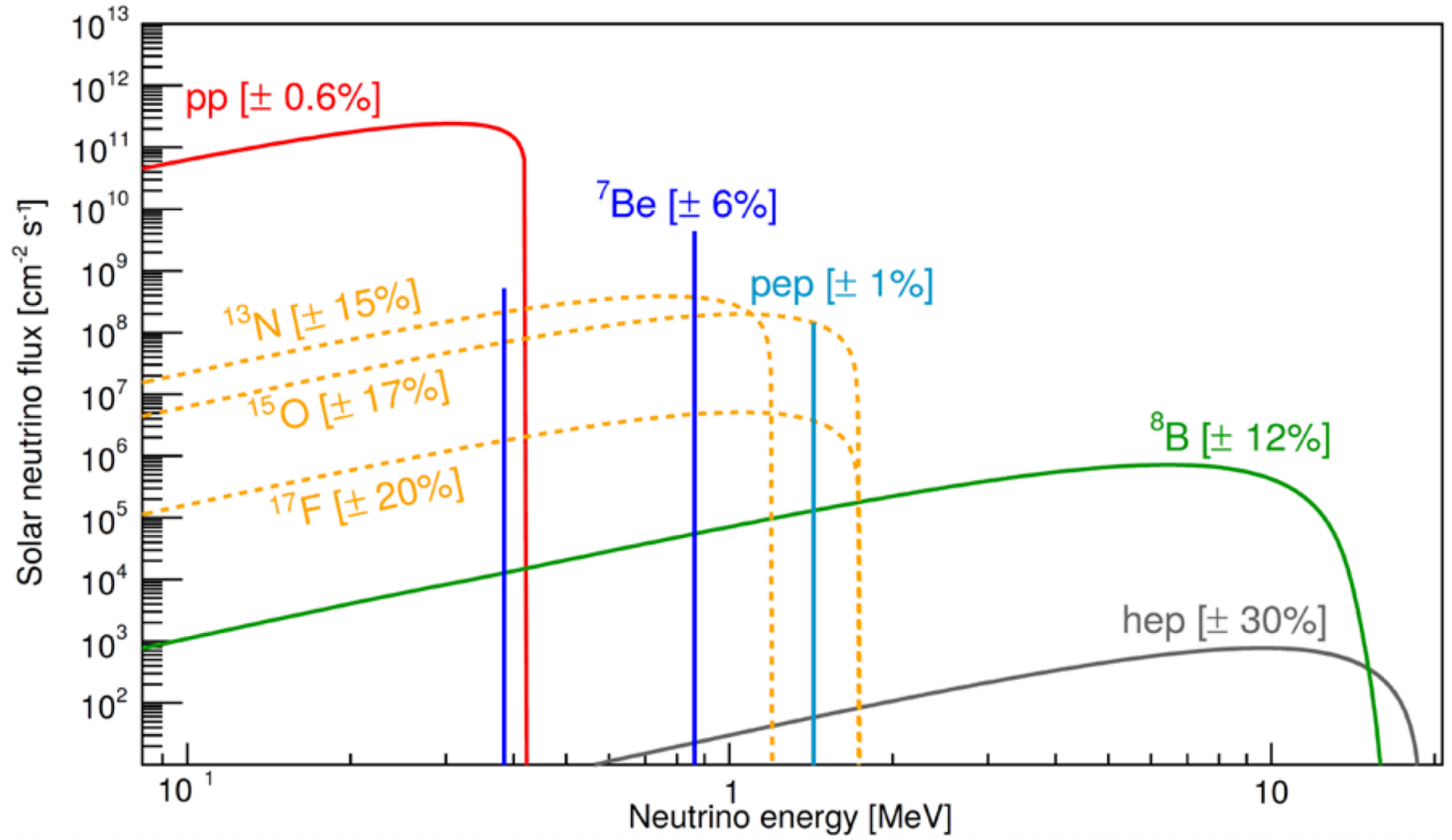
10.1103/PhysRevLett.121.081307
10.1103/PhysRevLett.121.111303

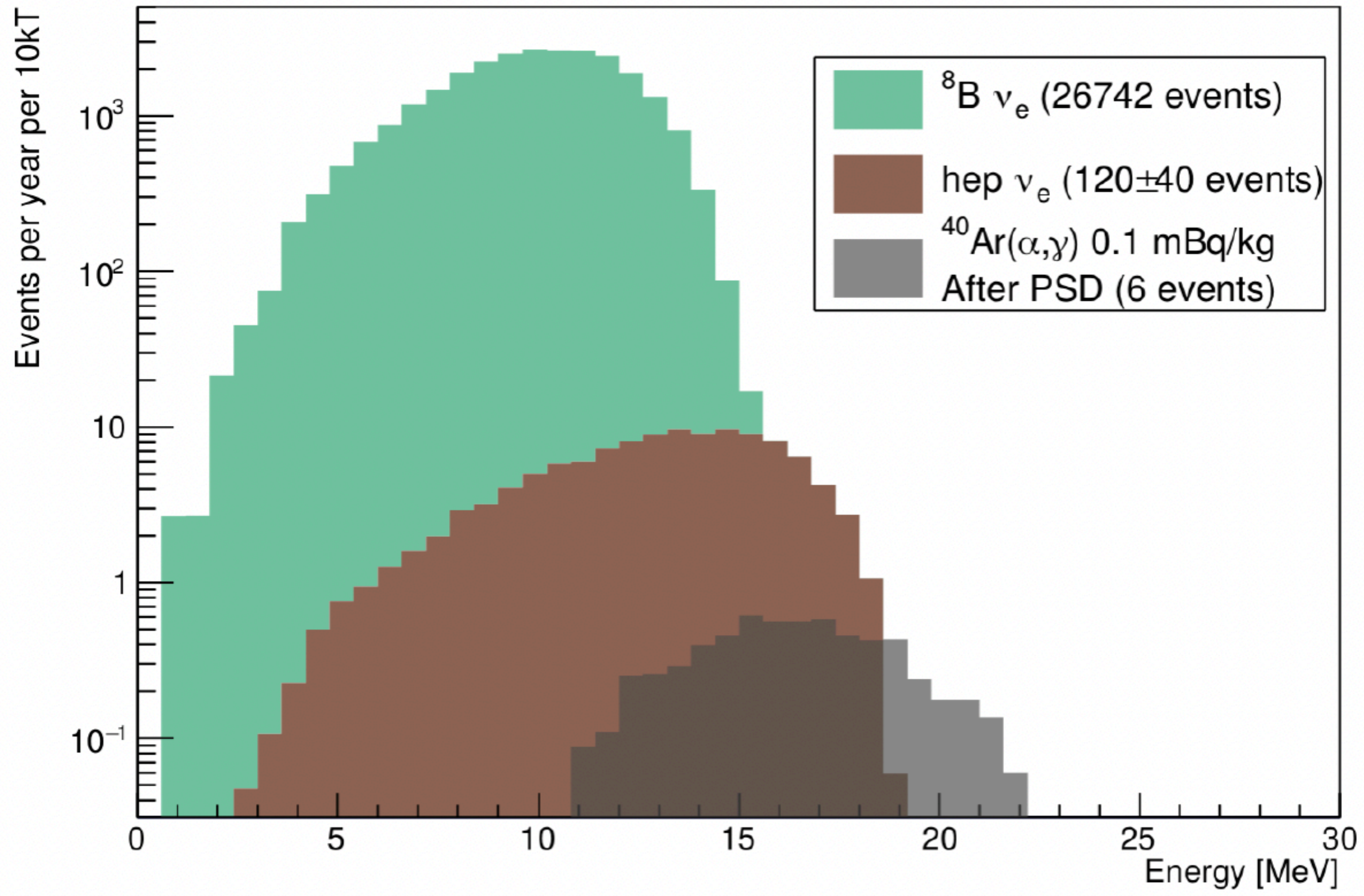
10.1103/PhysRevD.107.112006

LDM backgrounds

- Beta spectra in DS50: ^{39}Ar + ^{85}Kr
- Compton scatters from gammas in TPC + photosensors + cryostat
- Low N_e events: Spurious Electrons

SoLAr Readout Drives





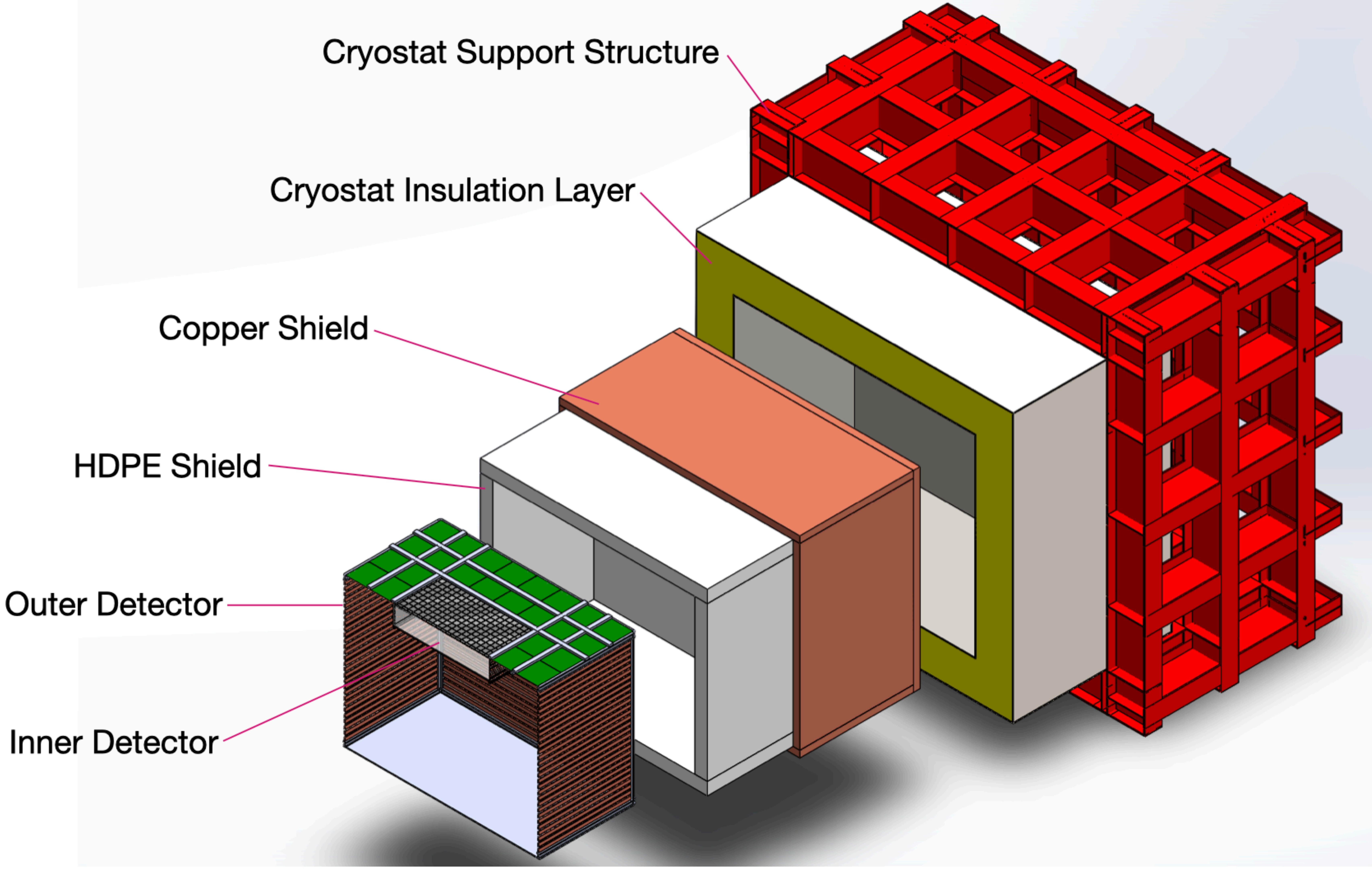
- **Aim:** demonstrate technology for a future kton-scale detector to observe neutrinos from the *hep* branch: $^3\mathrm{He} + p \rightarrow e^+ + \nu_e$ and precise measurement ^{8}B flux

- **Requirements:**
  - Low cryostat radioactivity to suppress $^{40}\mathrm{Ar}(n, \gamma)$ and $^{40}\mathrm{Ar}(\alpha, \gamma)$ reactions
  - Technology - Dual pixel charge and light readout

    ➡ Energy resolution: 7% @ 5MeV

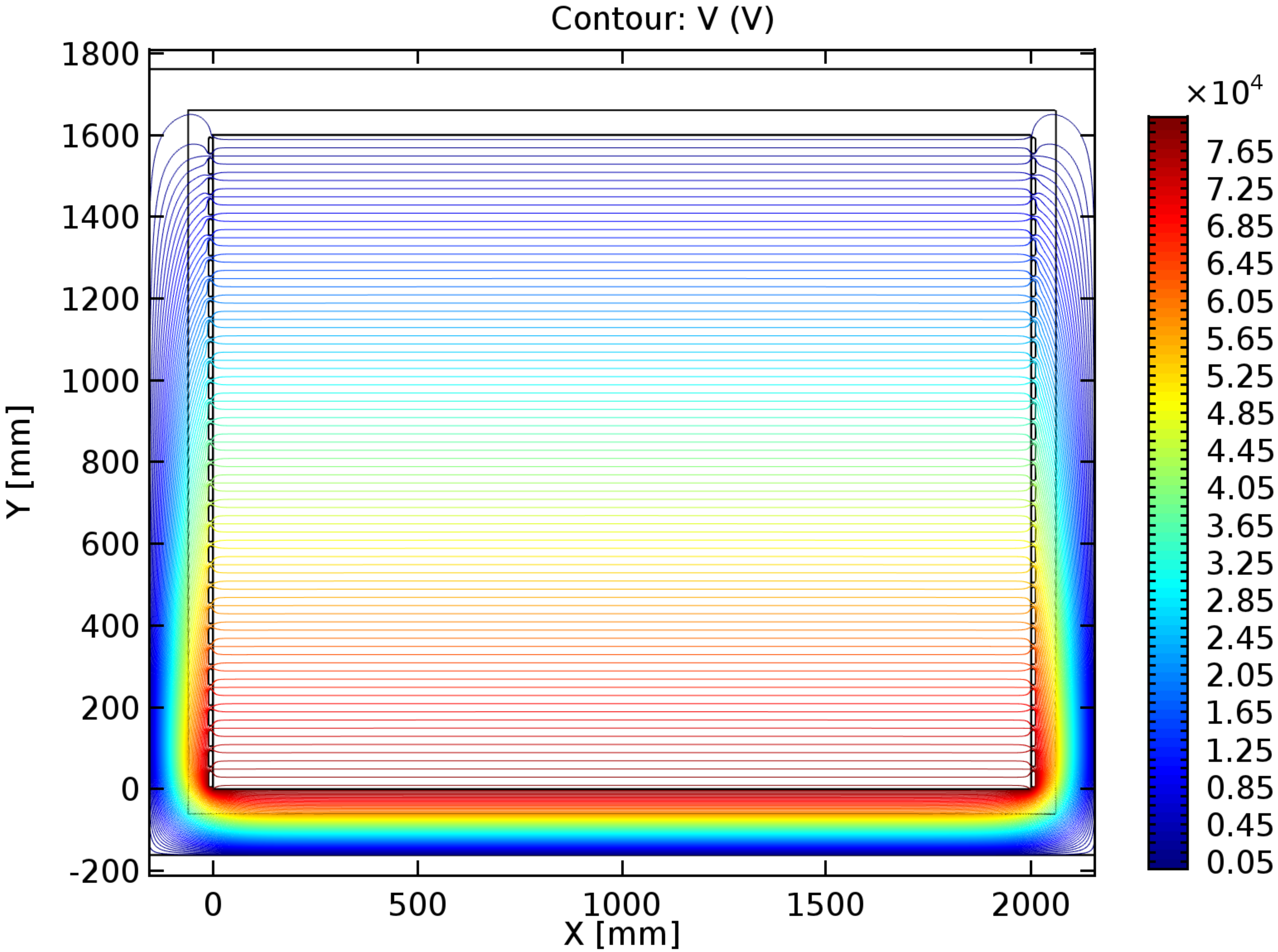
    ➡ 3D position reconstruction with mm-like resolution

Cryostat and passive shielding



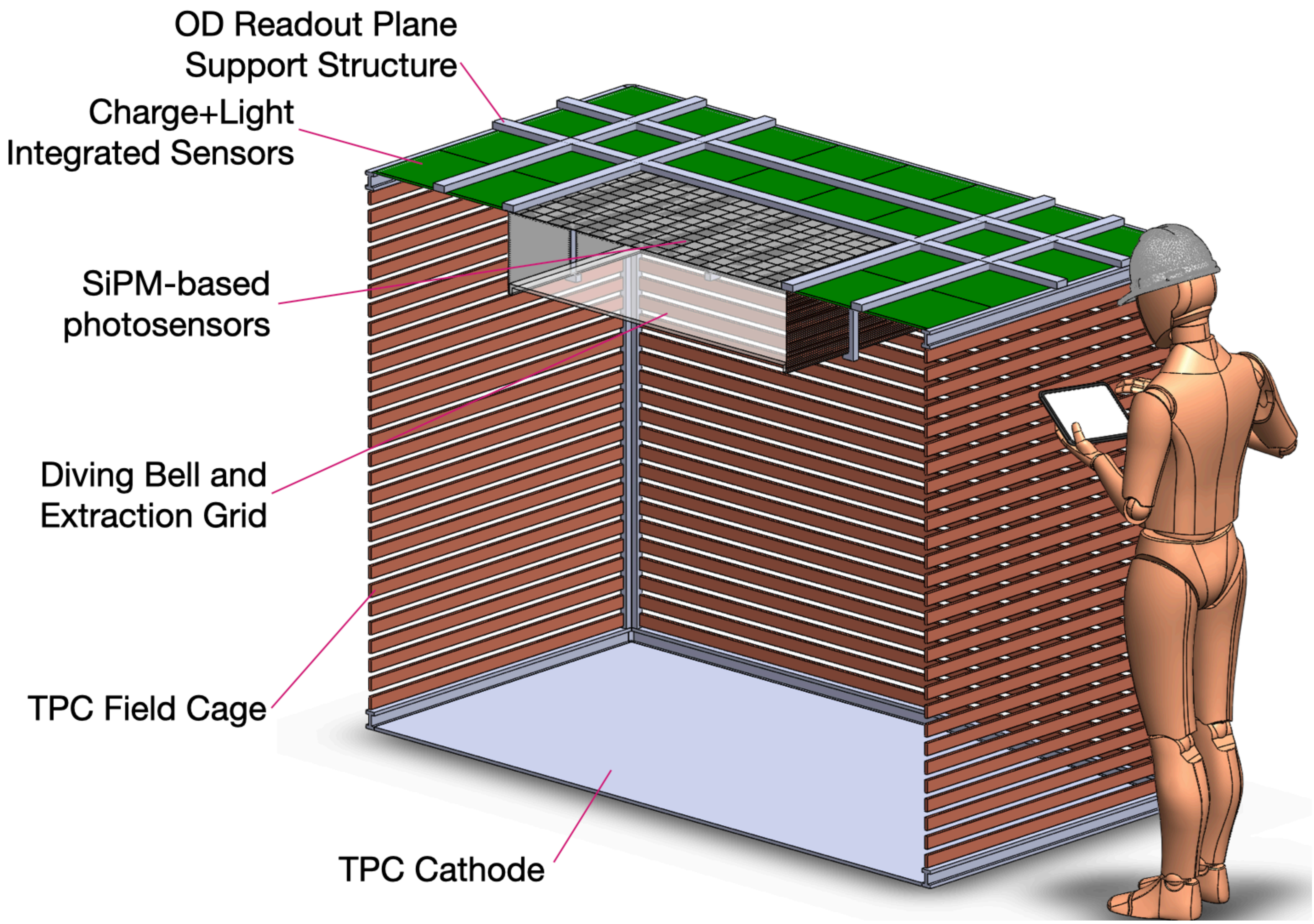
- Proto-Dune Style Membrane Cryostat by Neutrino Platform
- Outer dimensions (with support beams): ~ 4.2 x 4.2 x 3.7 m^3
- Inner dimensions: ~ 2.5 x 2.5 x 2.0 m^3
- Passive shielding:
  - ~7 cm of OF 99.995% copper
  - ~13 cm of high-purity HDPE

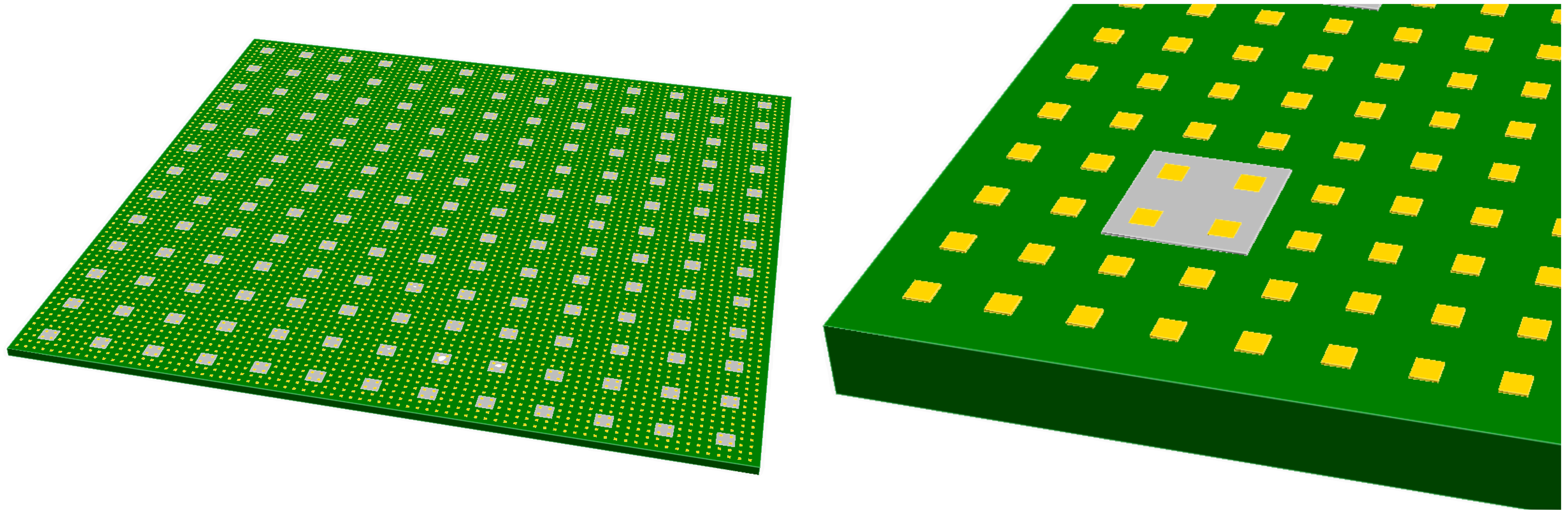
TPC



- Single Phase TPC
- Dimensions: 2 x 2 x 1.6 m^3
  - ➡ 9 tonnes of LAr (atmospheric)
- Nominal drift field: 500V/cm
  - ➡ Same as SBND, good for LDM search
- ProtoDune/SBND Structure:
  - Field cage: copper or stainless steel
  - Cathode: stainless steel
  - Anode: integrated sensors

Outer Detector





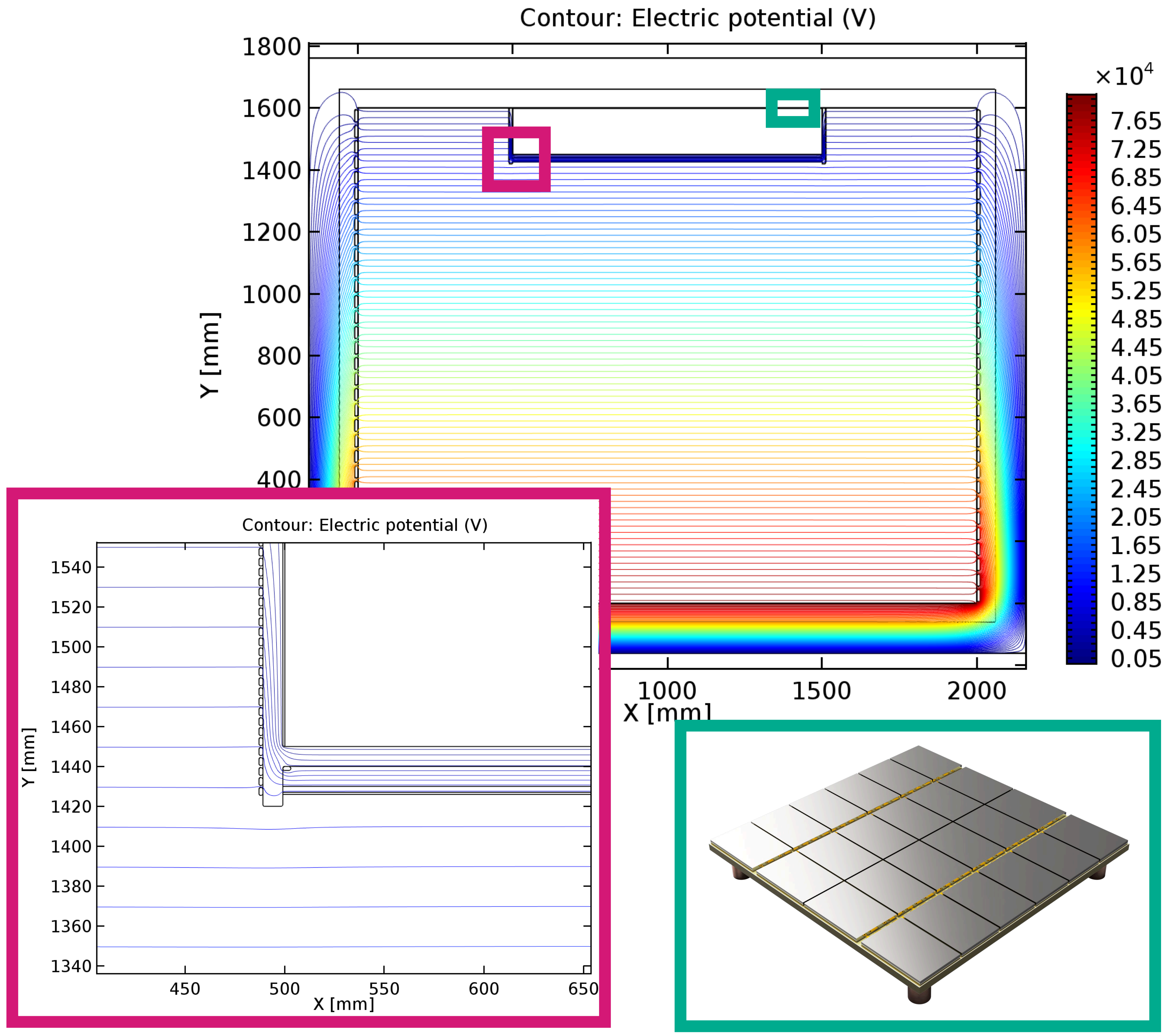
- Reflector+WLS on cathode and field cage
- Readout: charge+light integrated sensors
- 48 boards of 25 x 25 cm^2 instrumenting 3m^2

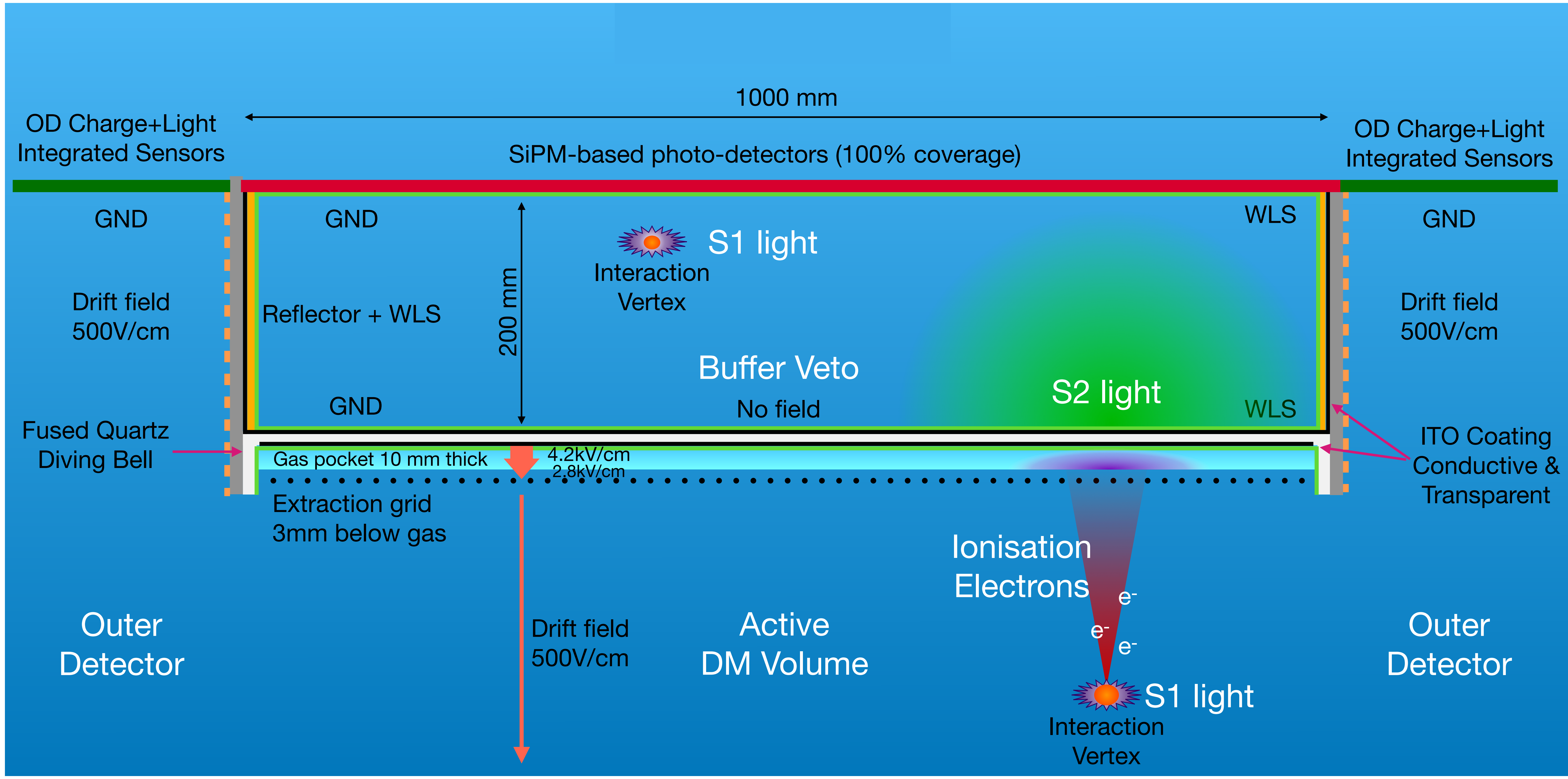
- Board:
  - 78 x 78 = 6084 1mm^2 charge pixels
  - 13 x 13 = 169 6mm^2 Hamamatsu VUV SiPMs
  - 96 Q-Pix/LArPix chips to readout the charge
  - 3 LightPix chips to readout the light

- 10% anode optical coverage

➡ 3% photon detection efficiency

Inner Detector

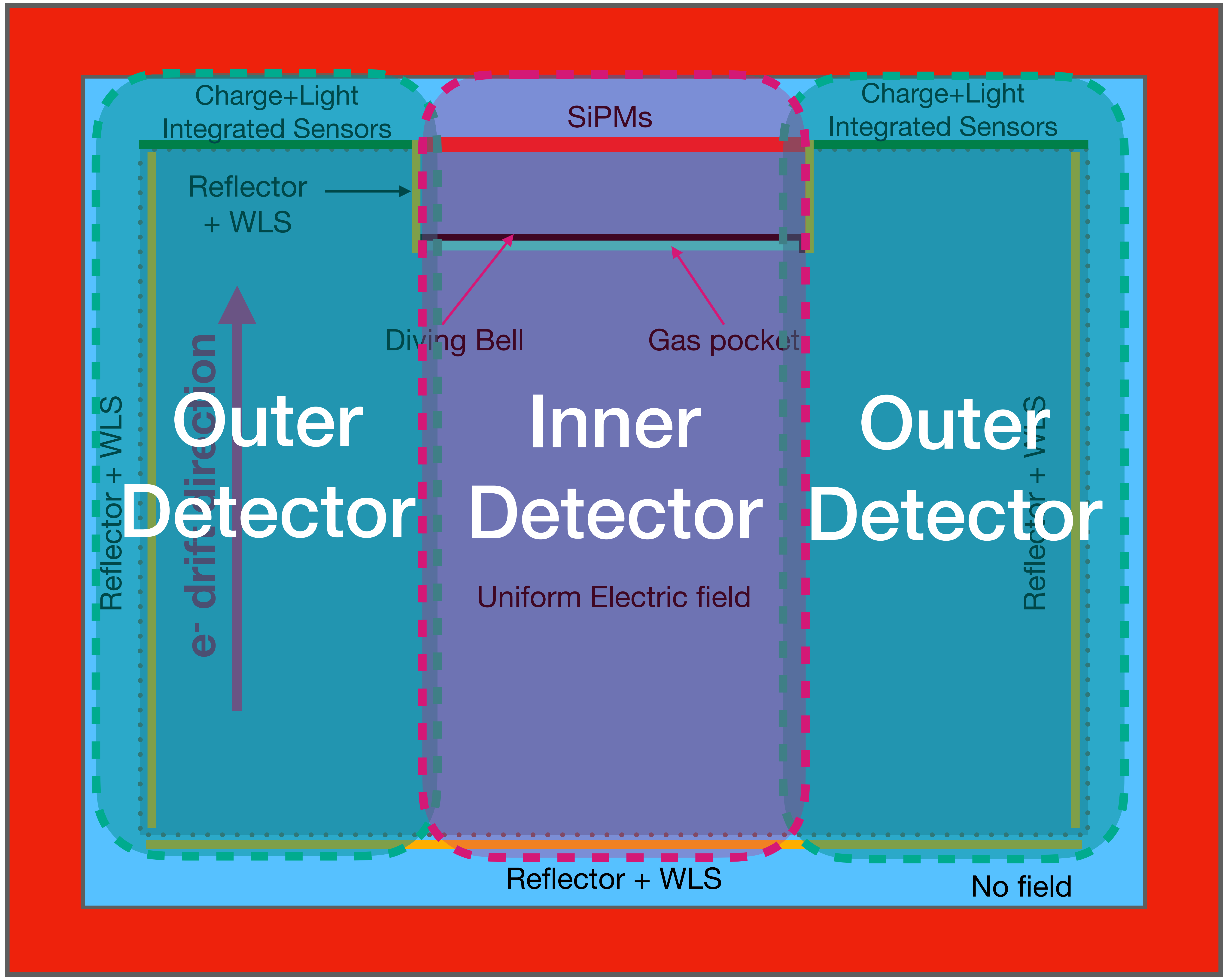




- ID is deployed as a module in the TPC. Fill with Underground Argon (>1400 less ^{39}Ar than AAr).
- The volume above the diving bell contains LAr, but ***E*** null field. Active veto against SiPMs' radioactivity.
- 1m^2 of DarkSide-like SiPMs organized in 400 25cm^2 tiles+readout channels. New, cleaner, thinner FEBs.

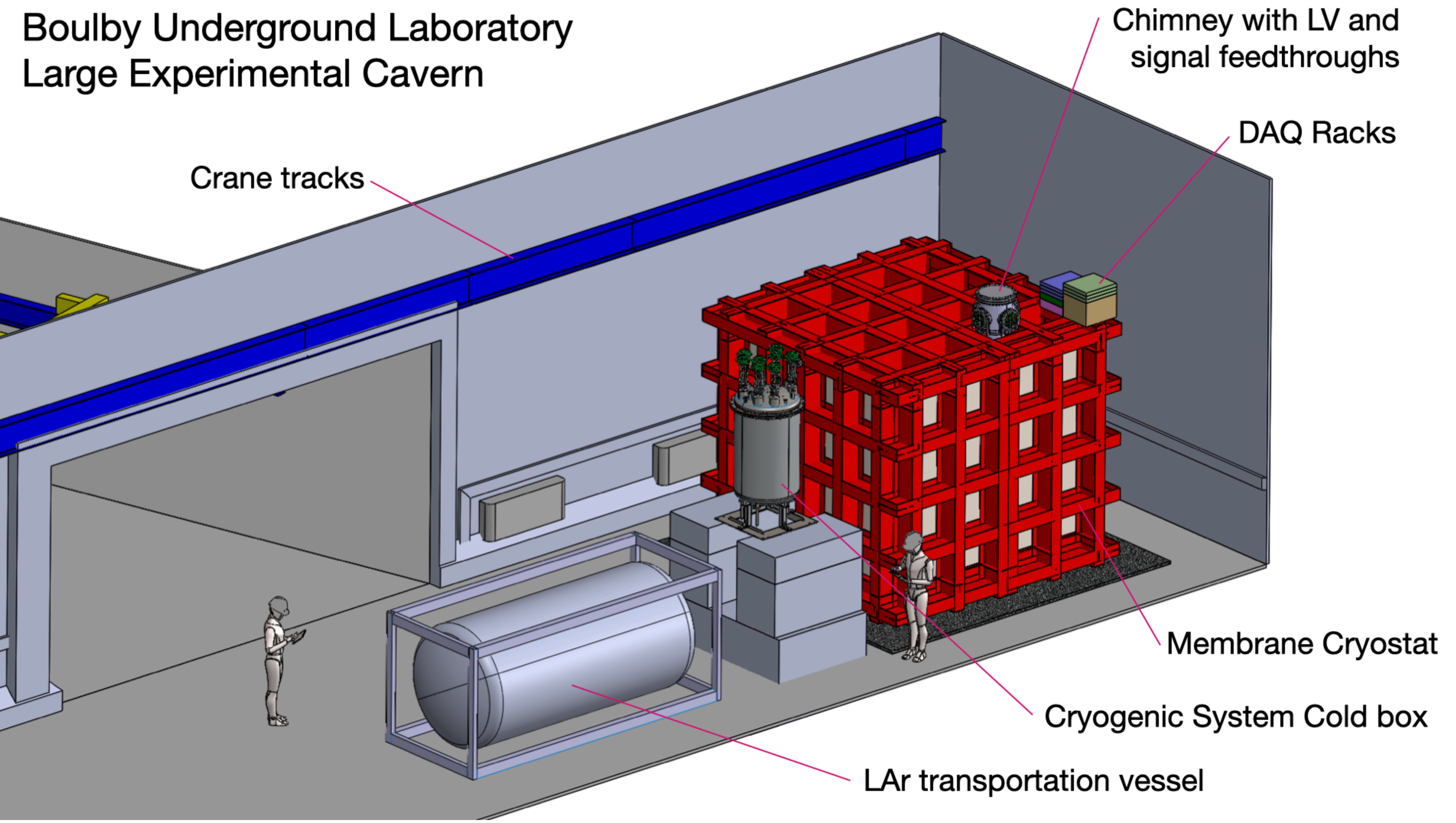
A Staged Approach

SOLAIRE sketch NOT to scale



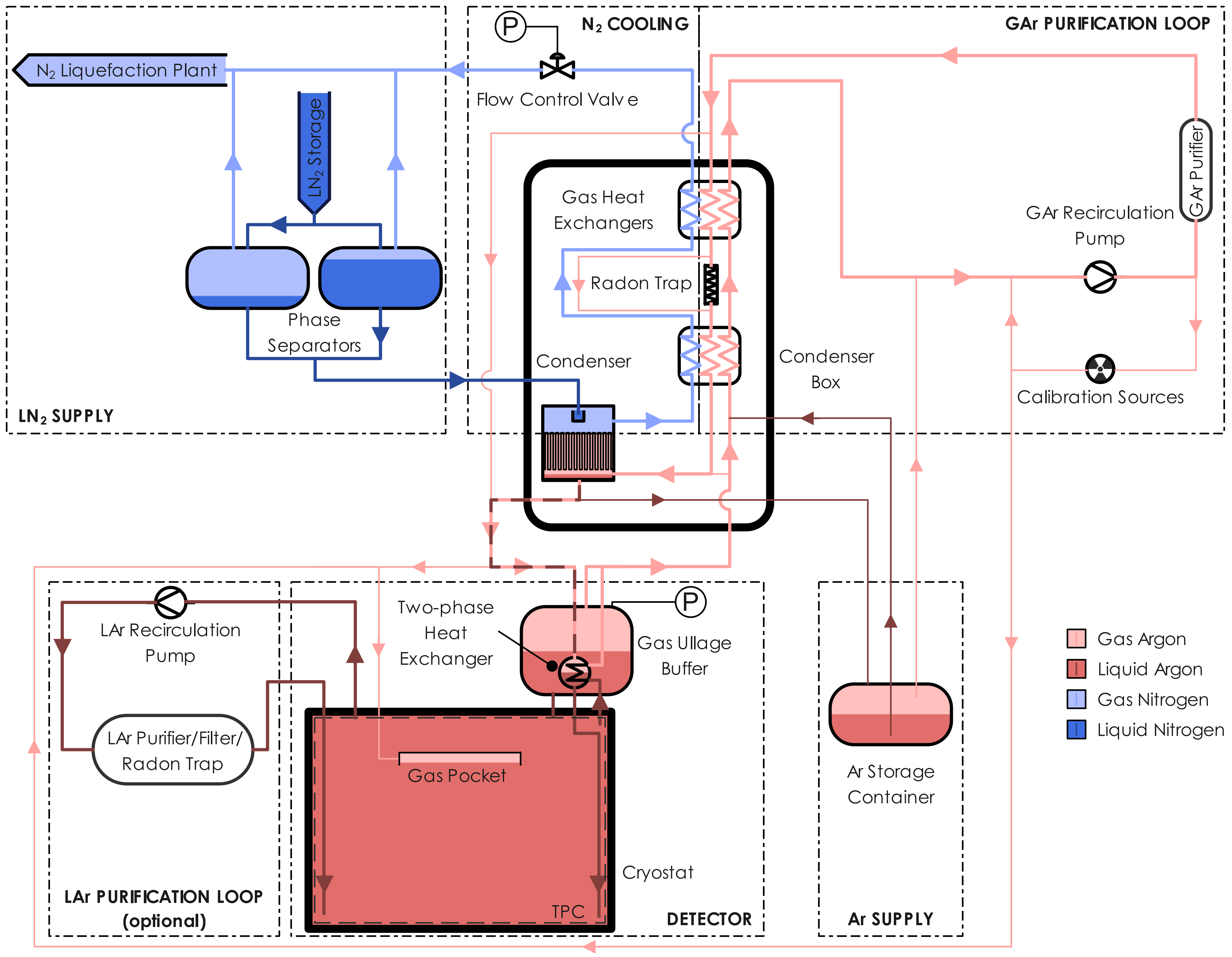
- **Phase 1- Atmospheric Argon fill**
  - Only OD is commissioned and demonstrates SoLAr dual-readout capabilities (6 months, Q4 2027 - Q2 2028)
  - The central section in the anode readout might be instrumented with additional boards, depending on international funding.
- **Phase 2 - Underground Argon fill**
  - ID is commissioned, OD acts as γ veto
  - At least 12 months of DM science runs Q1 2029 - Q1 2030

Cryogenics & fielding @ Boulby



- Multiple Gar and LAr extraction points to clean the target from impurities.

  ➡ Suppression of Spurious Electrons.



- Argon transport vessels provide on-site storage capability
- UKRI STFC RAL + Daresbury responsible for safety scope

Backgrounds & Suppression Strategies

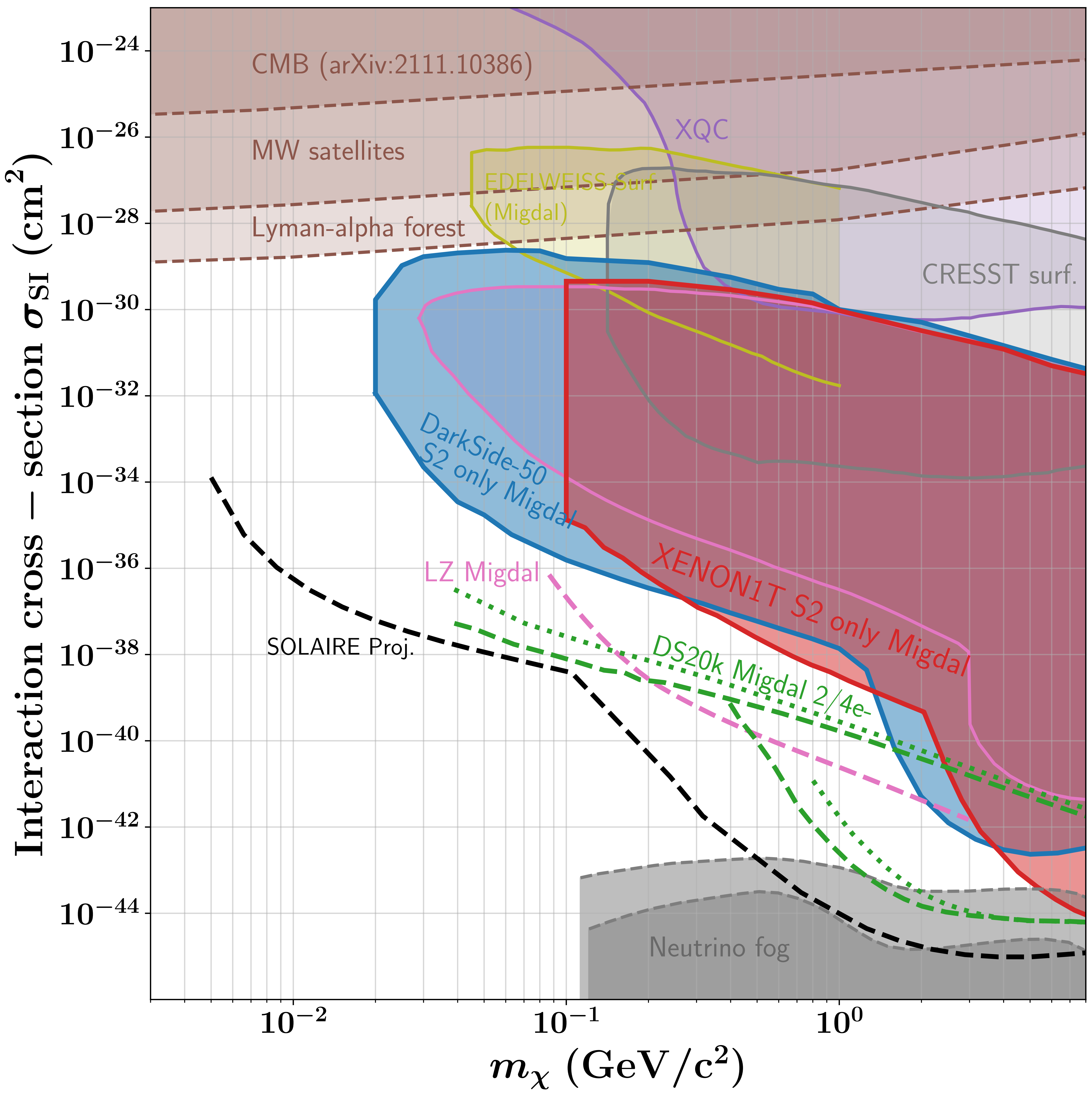
- **Betas:**
  - ^{39}Ar ➡ 7.3(73) uBq/kg in UAr ← optimistic(conservative) scenario
  - ^{85}Kr, ^{3}H or other contaminants ➡ Completely suppressed by ARIA chemical purification plant
- **Gammas:**
  - From TPC materials and SiPMs

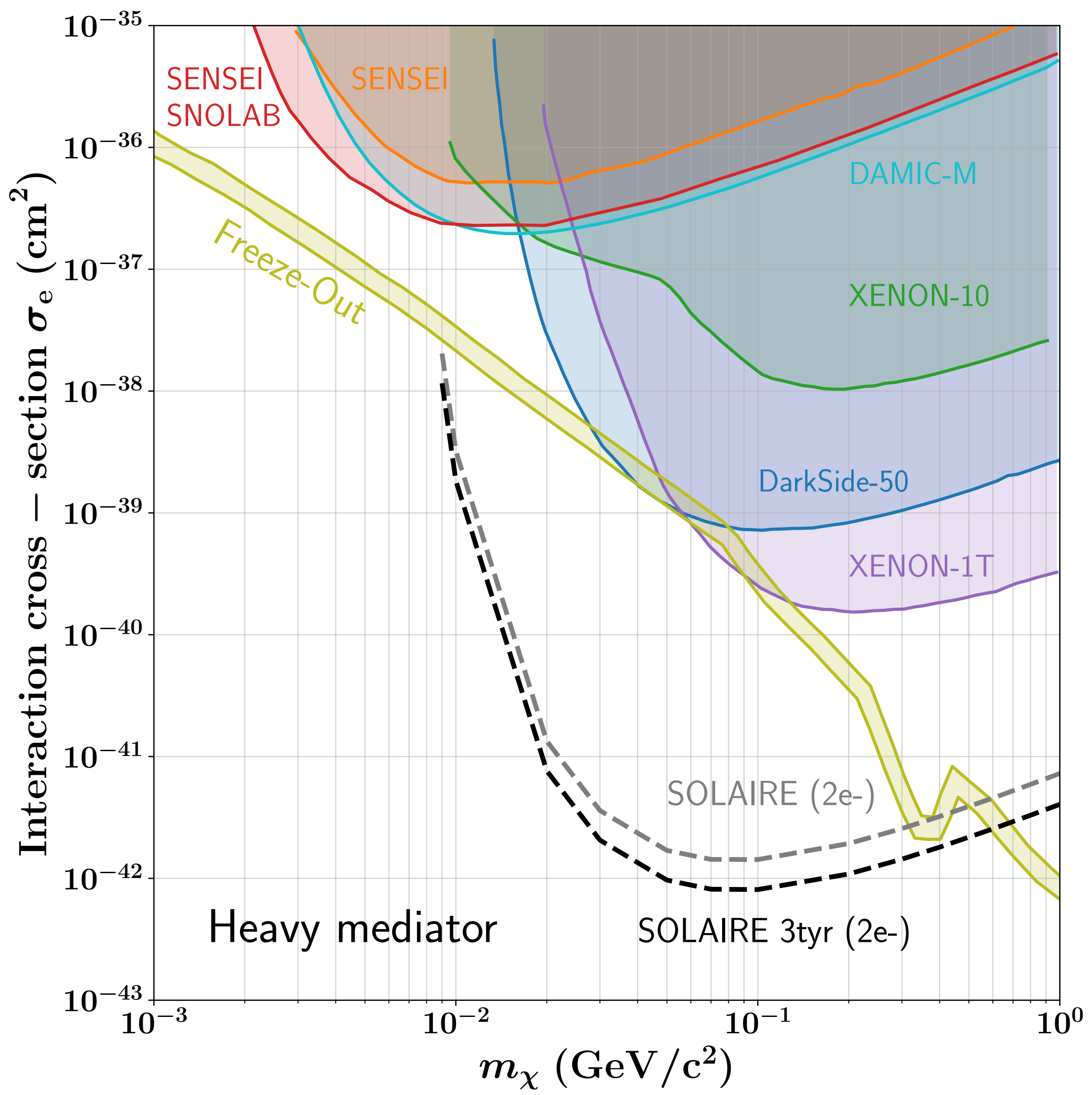
    ➡ No lateral walls, R&D on SiPMs, active gamma veto to reduce Compton continuum
  - From cryostat and cavern:

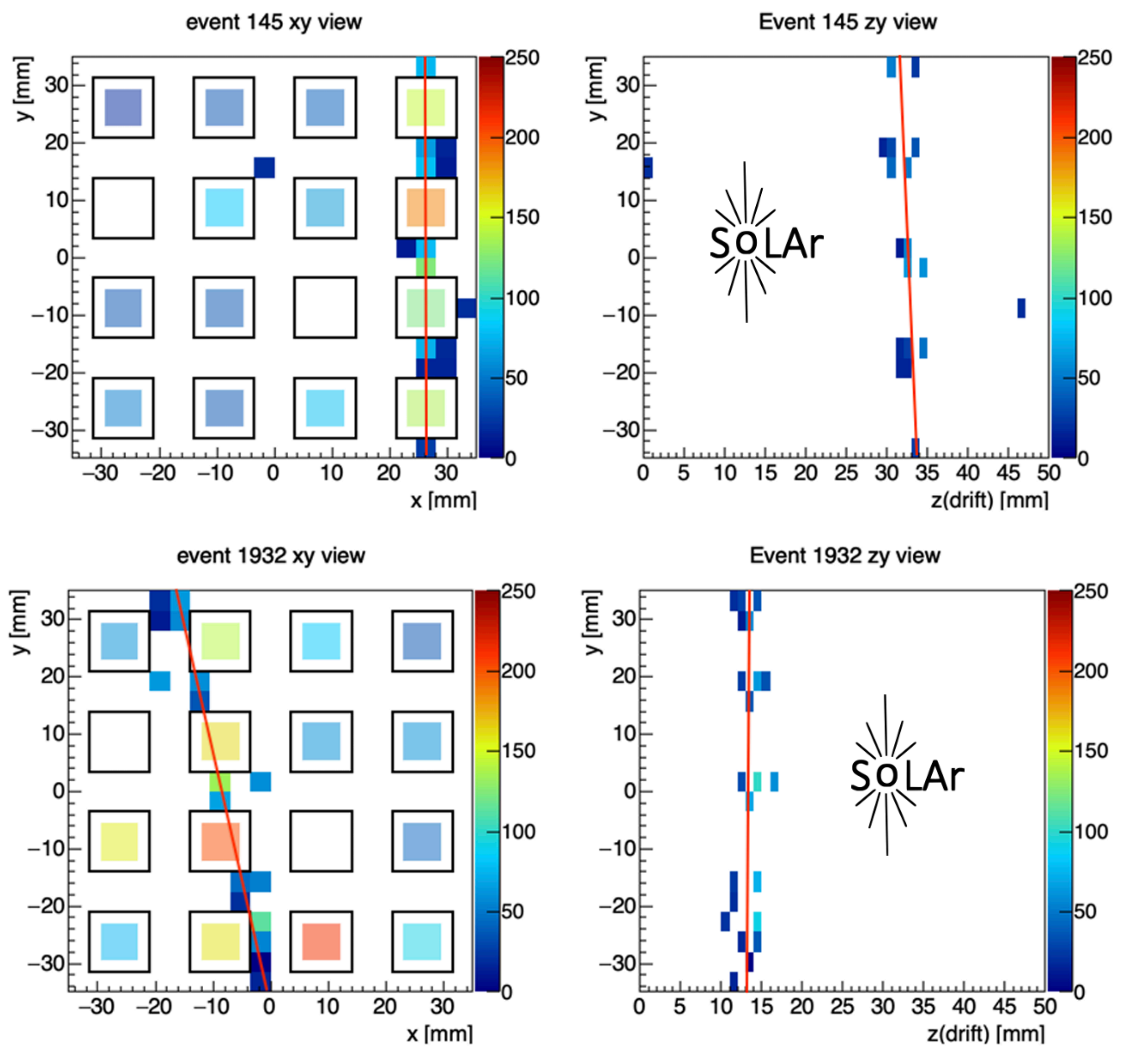
    ➡ passive shielding of copper and HDPE
- **Neutrons** - Important for neutrino physics goals ➡ suppressed by HDPE inner lining shield
- **Spurious Electrons:**
  - Lower than DS-50 levels

    ➡ avoidance of TPB, purification system with extraction of argon in gas and liquid phases

Physics Reach







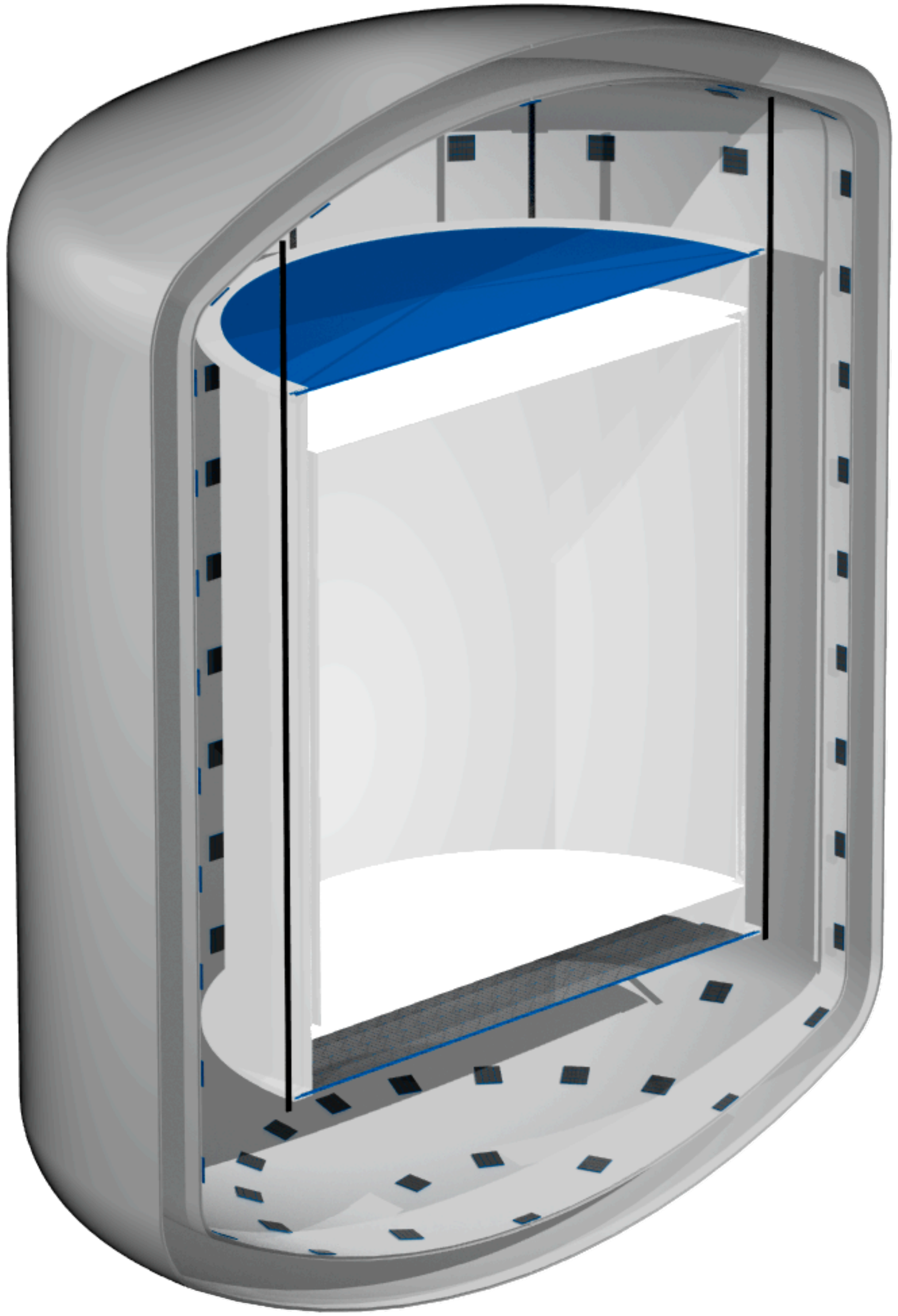
- Leading SI WIMP-nucleon cross-section sensitivity
    - Substantial sensitivity <0.1GeV/c² using Migdal
- Electron scattering DM:
    - x100 improvement over existing light and heavy mediator limits
- Demonstration of technology for Neutrino Physics

Conclusions

- SOLAIRE offers an opportunity to the UK to host an international DM experiment with **world-leading discovery potential** and **multiple science outputs** by the end of the decade.
- Beyond the 1 yr DM run, this facility can be **upgraded** (new detectors, dopants, etc.) to **extend its reach** and **physics sensitivity** beyond currently planned period (2030 onward).
- It capitalizes on investments in **LAr** (for neutrinos and DM), **silicon photosensor production**, and **testing capability**, promoting international leadership in a unique new experimental facility.
- Development, installation and operation of SOLAIRE supports **expertise and capability building** for a future liquid noble detector at scale at Boulby.
- Provides a unique **international facility** for deployment of new technologies for underground rare event searches from the DRD initiative.

Thank you!

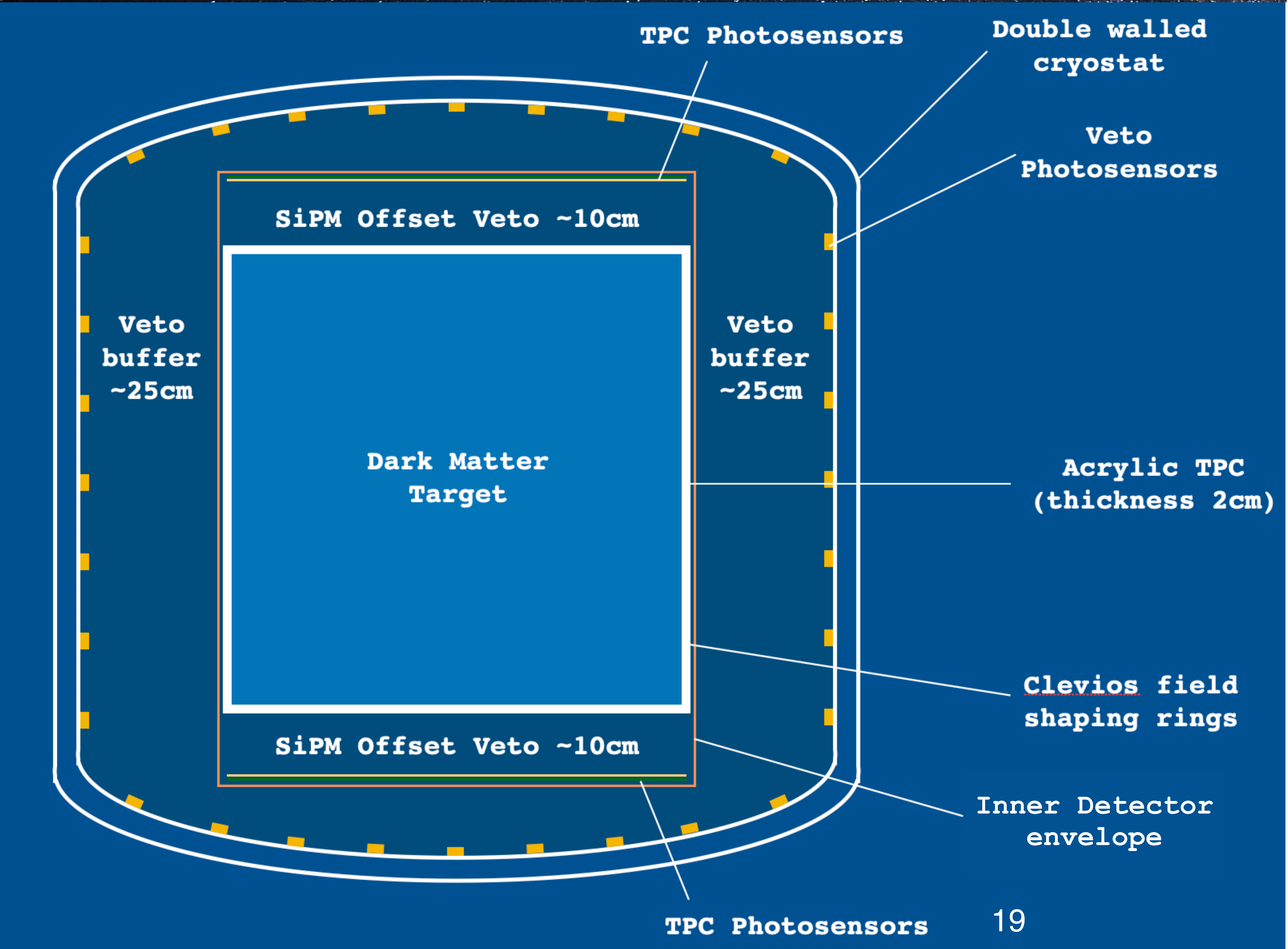
LDM Design Drives



Reduce radioactivity and improve target purity

- **Betas:** use UAr passed in Aria distillation column
    - Aria will completely separate out any ^{85}Kr, ^{3}H or any other chemical contaminant - Throughput O(100kg/d)
    - Aria can deplete the UAr of ^{39}Ar by x10 - Throughput O(10kg/d)
- **Gammas:** SiPM photosensors + active veto around the DM target
    - Limited R&D on substrates and materials will lower “DS-20k style” photosensors to the necessary level.
    - The LAr surrounding the target must be instrumented as a veto
- **Spurious Electrons:** improved purification system
    - Already funded R&D to study the SEs generation mechanism and allow the design of targeted mitigation.

LDM Design Drives

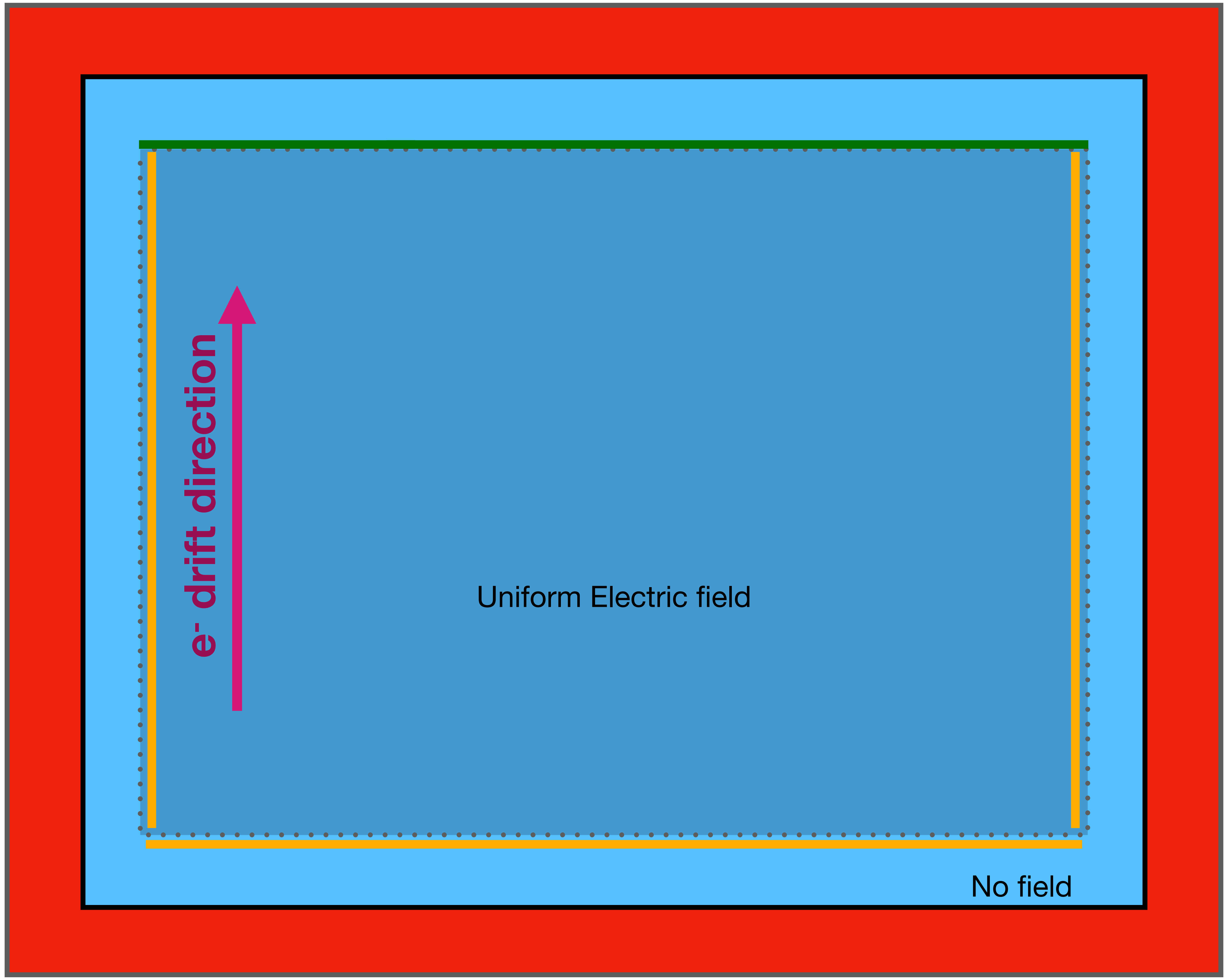


Gamma Active Veto

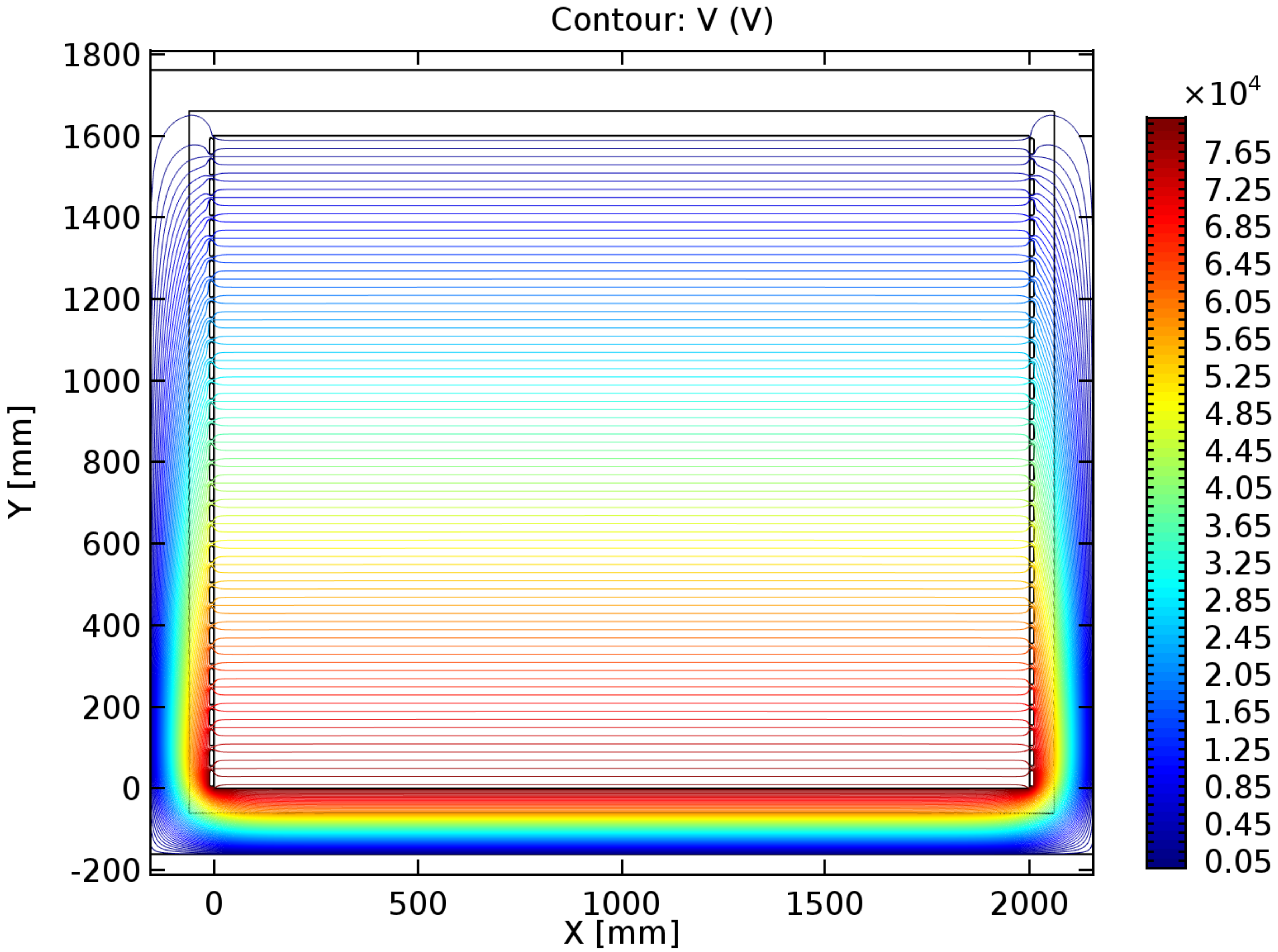
- The TPC is designed with minimal amounts of material to lower radioactivity and to avoid dead volumes
- External LAr volumes are active to detect gamma scattering in and out of the TPC and veto such coincidences.
- Energy threshold: 100 keV

Conceptual design

SOLAIRE sketch NOT to scale

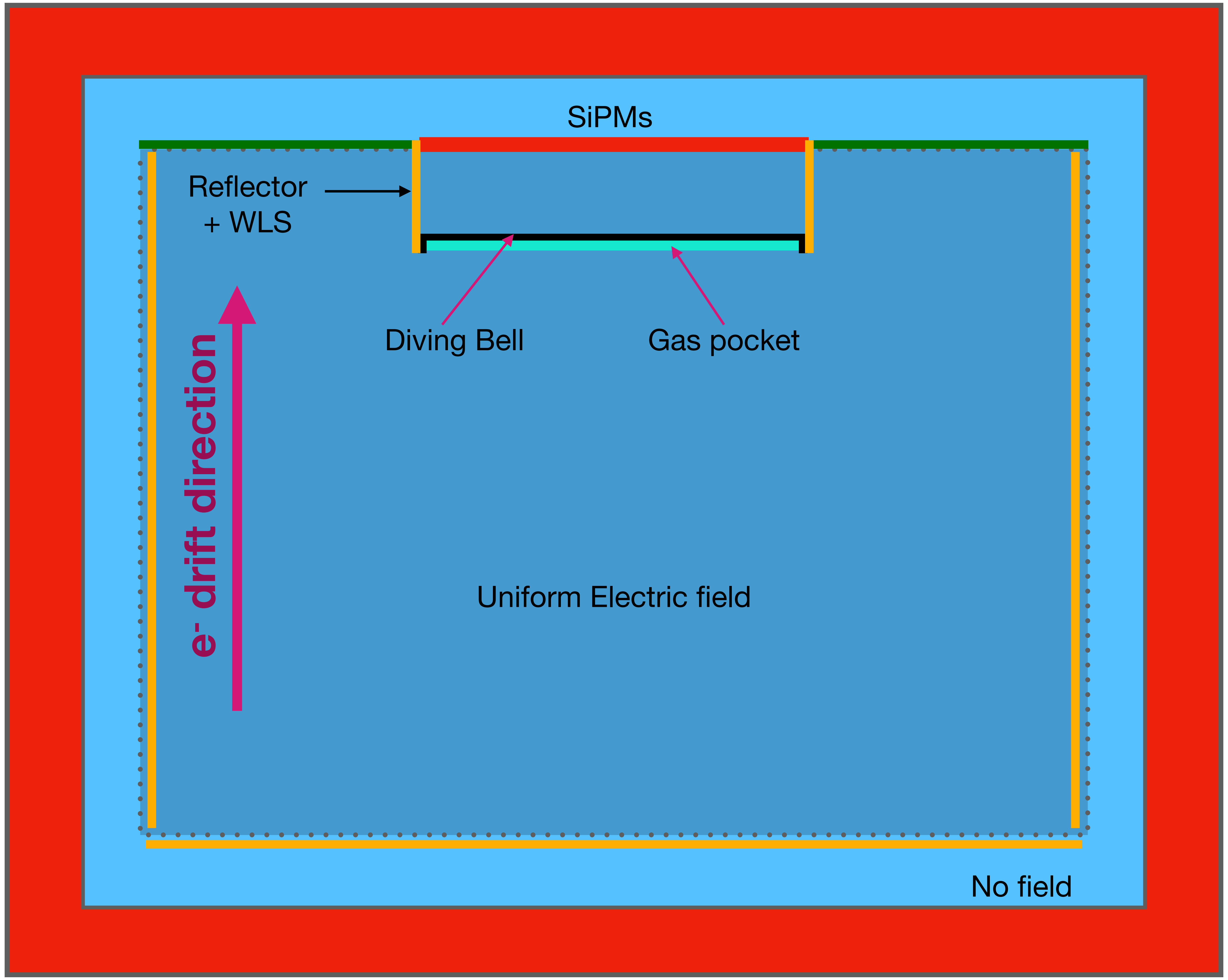


- Have a **single drift electric field** for the DM detector (ID) and SoLAr (OD)



Conceptual design

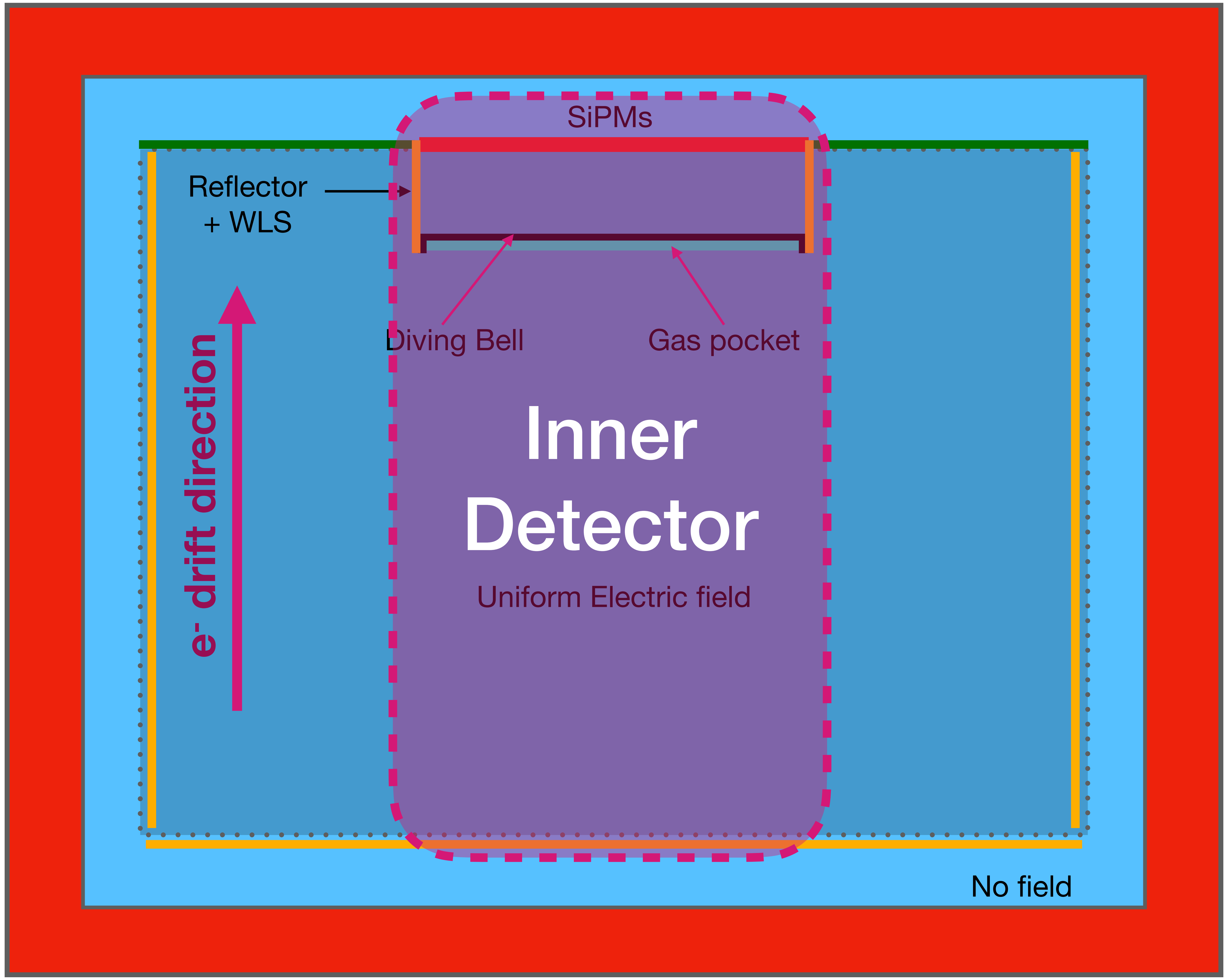
SOLAIRE sketch NOT to scale



- Have a **single drift electric field** for the DM detector (ID) and SoLAr (OD)
- Top the central part of the anode with a diving bell to form a thin gas pocket
- Instrument the area above the diving bell with DarkSide-like SiPM-based photosensors.

Conceptual design

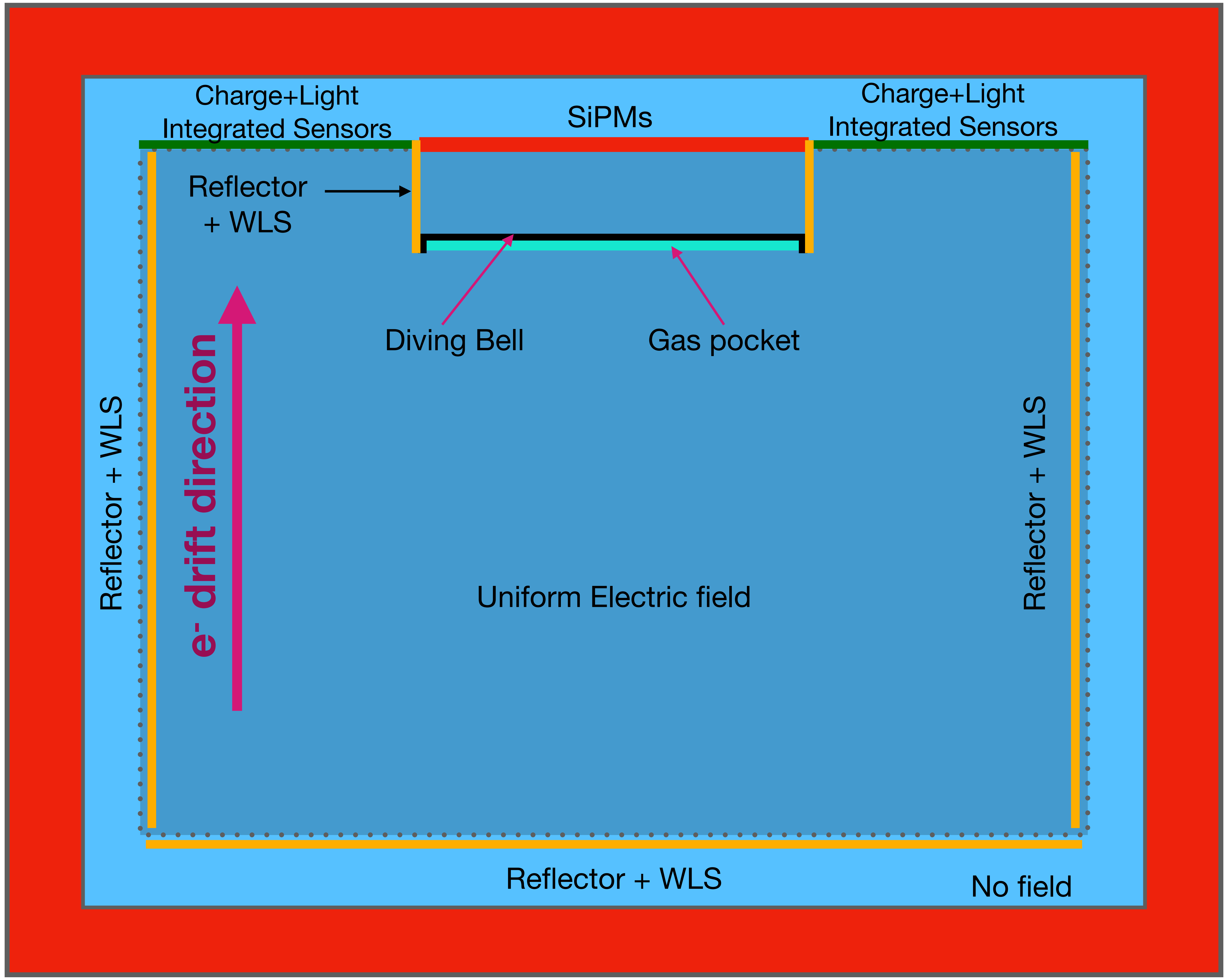
SOLAIRE sketch NOT to scale



- Have a **single drift electric field** for the DM detector (ID) and SoLAr (OD)
- Top the central part of the anode with a diving bell to form a thin gas pocket
- Instrument the area above the diving bell with DarkSide-like SiPM-based photosensors.

Conceptual design

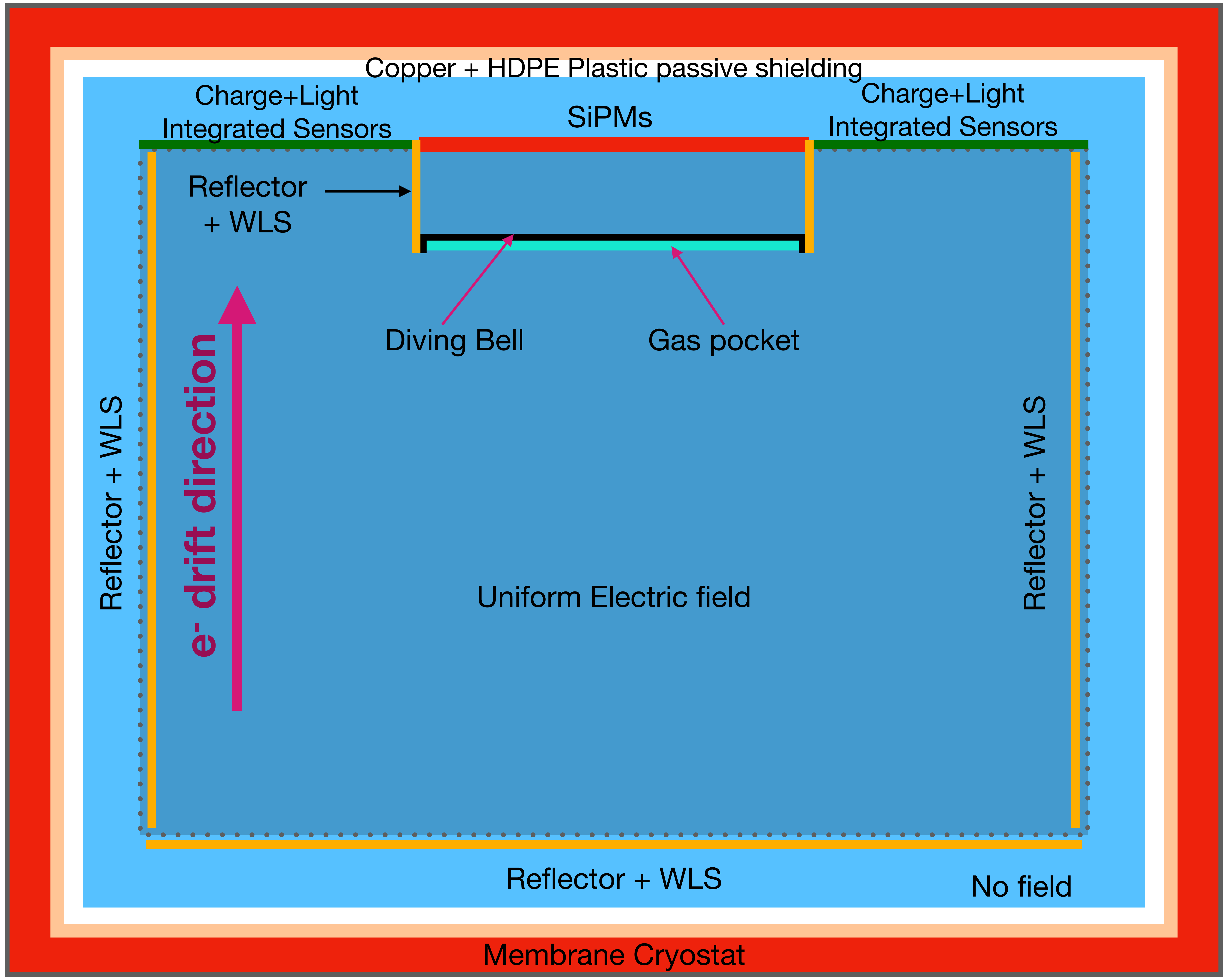
SOLAIRE sketch NOT to scale



- Have a **single drift electric field** for the DM detector and SoLAr
- Top the central part of the anode with a diving bell to form a thin gas pocket
- Instrument the area above the diving bell with DarkSide-like SiPM-based photosensors.
- Instrument the rest of the anode with SoLAr charge&VUV integrated sensors
- Mount WLS+reflectors on all other surfaces to enhance energy threshold and resolution

Conceptual design

SOLAIRE sketch NOT to scale



- Have a **single drift electric field** for the DM detector and SoLAr
- Top the central part of the anode with a diving bell to form a thin gas pocket
- Instrument the area above the diving bell with DarkSide-like SiPM-based photosensors.
- Instrument the rest of the anode with SoLAr charge&VUV integrated sensors
- Mount WLS+reflectors on all other surfaces to enhance energy threshold and resolution
- Passive shielding to suppress radiogenic events from cryostat and cavern.

High Level Milestones

Milestone Number	WBS Task Number	Milestone Short Description	Target Date (Quarter, Year)
M1	1.1.3.4	Cryostat and Cryogenics Design Review	Q3, 2025
M2	1.2.2.4	Boulby infrastructure requirements Review	Q3, 2025
M3	4.1.0.2	DAQ and Trigger Review	Q4, 2025
M4	2.2.8	Outer Detector readout production readiness review	Q1, 2026
M5	1.1.3.3	Start of Cryostat installation	Q1, 2026
M6	1.2.3.1	Outer Detector installation plan Review	Q1, 2026
M7	1.4.4.2	Argon transport underground Review	Q2, 2026
M8	1.1.3.5.4	Argon cryogenics surface commissioning start	Q3, 2026
M9	4.1.6	Start of DAQ and trigger commissioning	Q3, 2026
M10	1.1.3.5.5	Start of Argon cryogenics underground commissioning	Q4, 2026
M11	1.2.3.2	Start of Outer detector installation	Q1, 2027
M12	3.2.3.19	Inner Detector readout production readiness review	Q1, 2027
M13	3.2.3.20	Inner Detector Tile Production Start	Q2, 2027
M14	1.1.4.7	Atmospheric liquid argon delivery to underground	Q3, 2027
M15	4.4.6.1.2	Start of Outer detector commissioning	Q4, 2027
M16	4.4.6.1.4	Start of AAr run (Phase 1)	Q4, 2027
M17	1.2.4.1	Inner Detector installation plan Review	Q4, 2027
M18	1.2.4.2	Start of Inner detector installation	Q3, 2028
M19	1.1.4.14	Underground liquid argon delivery to underground	Q3, 2028
M20	4.4.6.2.2	Start of Inner detector commissioning	Q4, 2028
M21	4.4.6.2.4	UAr science run (Phase 2) start	Q1, 2029
M22	4.4.5	First DM search result	Q1, 2030