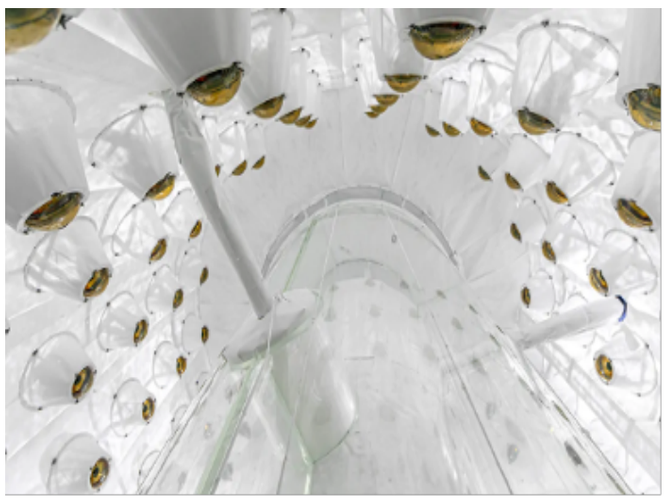
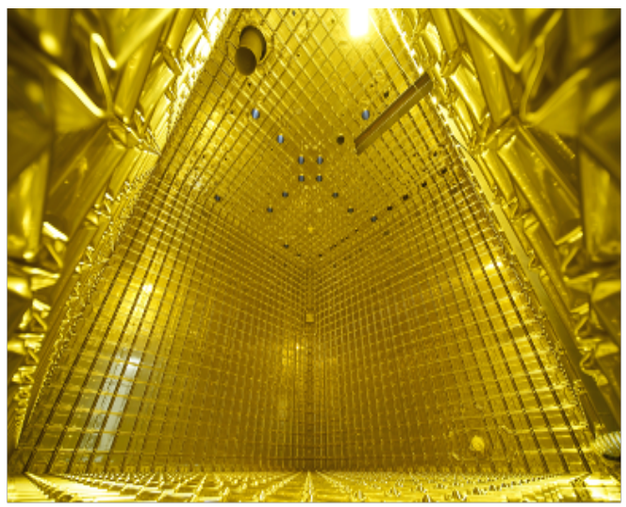
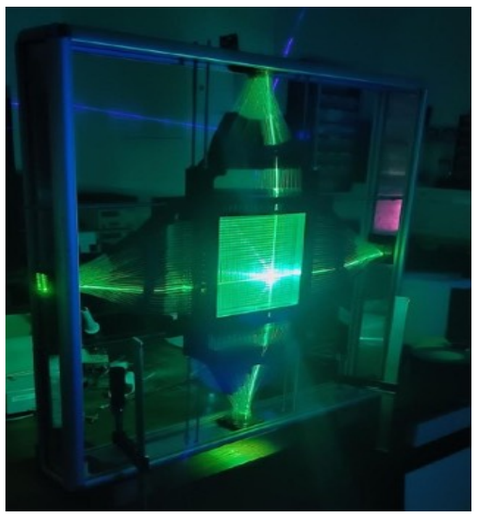
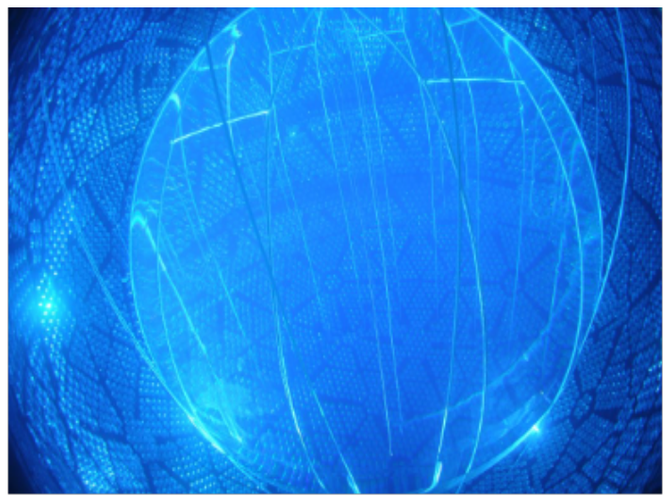





DRD2: Liquid Detectors

R&D for neutrinos, dark matter and opportunities at Boulby

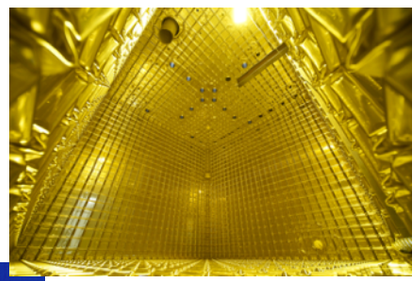
Roxanne Guenette, Jocelyn Monroe, Ruben Saakyan & Paul Scovell

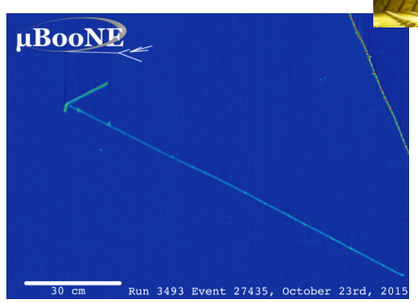
DRD-UK Meeting
11 April 2024

The Science covered

Neutrinos

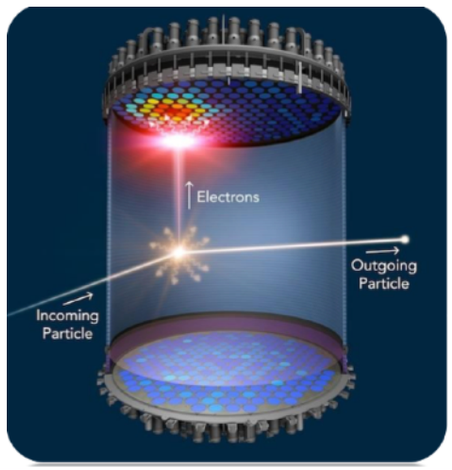
- Oscillation precision measurements (δ_{CP}, mass ordering, θ_{23} octant, sterile νs)
- Neutrino interactions (from CEvNS to DIS)
- Astro neutrinos





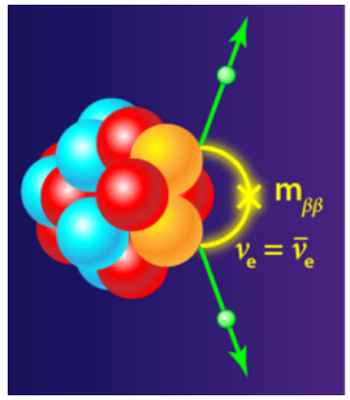
Dark Matter

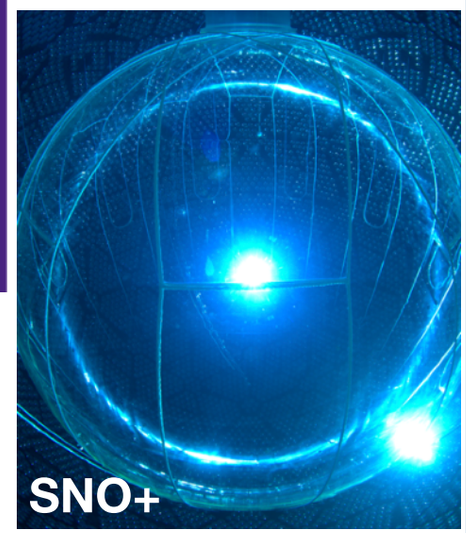
- Direct detection (WIMPs, …)

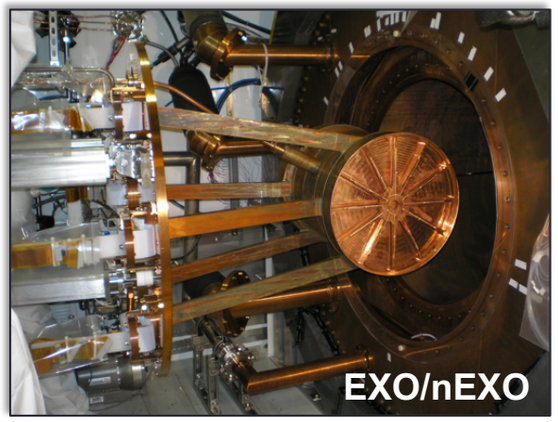


0νββ

- Search for Majorana neutrinos







The Physics Needs (high level overview)

Neutrinos

- **Push Energy thresholds down** to ~1MeV to enhance oscillation physics, supernovae νs study, to enable solar νs …
- **Unambiguous readout**
- **Scalability**

Dark Matter

- **Push Energy thresholds down** to 1 meV/10 eV/1 keV to enable low mass DM/1 GeV DM/ WIMPs.
- **Reduce background rates**
- **Scalability**

0νββ

- **Improve Energy Resolution** to sub-% FWHM
- **Reduce background rates**
- **Scalability**

Future targeted *projects*

Liquid Nobles (Argon/Xenon)

- Dark Matter (Xe): XLZD
  (Few R&D needs from inputs)
- Dark Matter (Ar): Argo/ GADMC
- Neutrinos: DUNE LAr 3rd/4th modules
- 0νββ: nEXO
- Future Kilotonne-scale Xenon detectors:
  https://indico.slac.stanford.edu/event/8015

Liquid Scintillator

- THEIA (WbLS),
- LS 0νββ: SNO+ high Te doping, KL-Z+
- Opaque LS: LiquidO

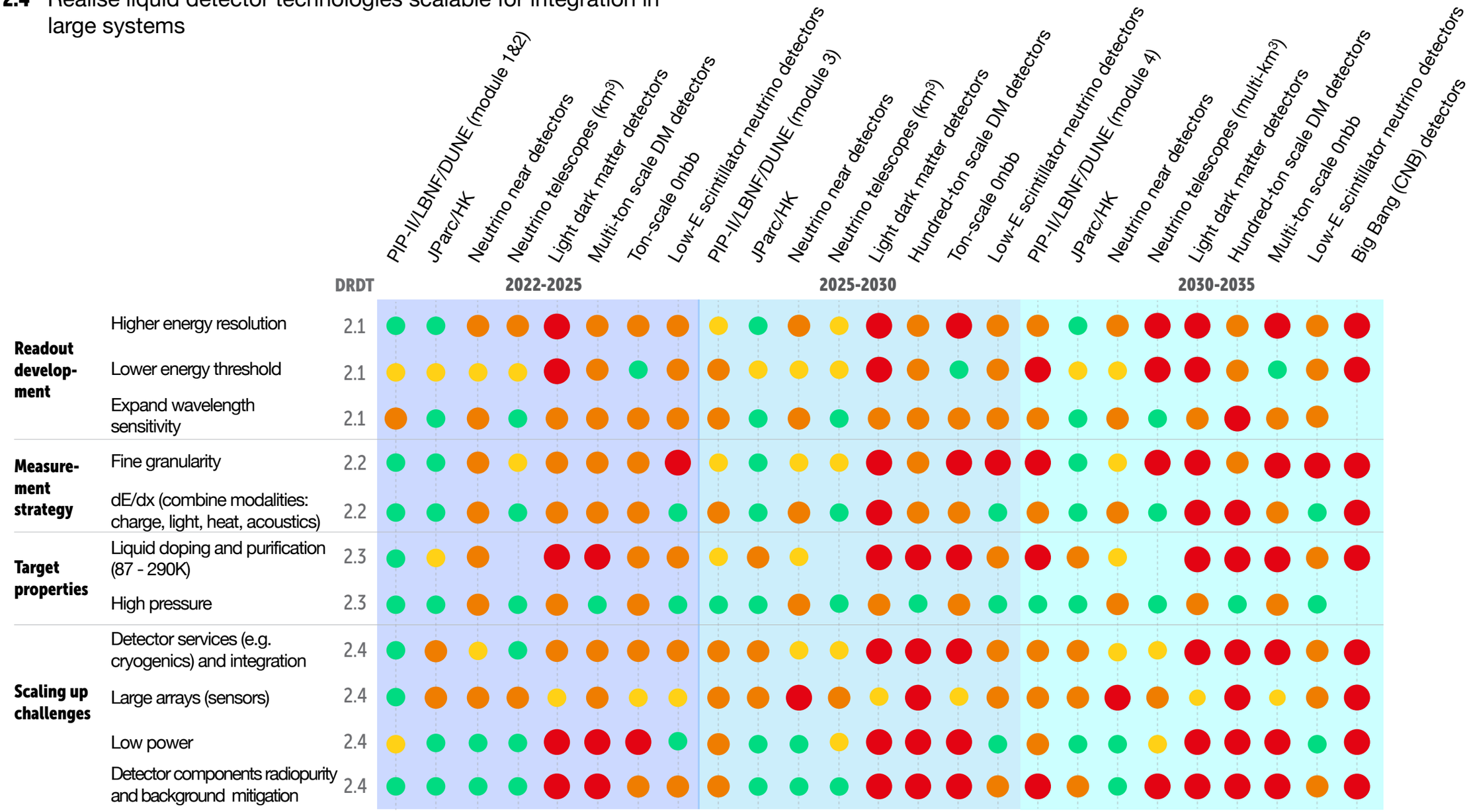
Water Cherenkov

- HyperK
  (Few R&D needs from inputs)
- Future neutrino telescopes

R&D Roadmap for Liquid Detectors (DRD2)

Liquid

- **DRDT 2.1** Develop readout technology to increase spatial and energy resolution for liquid detectors
- **DRDT 2.2** Advance noise reduction in liquid detectors to lower signal energy thresholds
- **DRDT 2.3** Improve the material properties of target and detector components in liquid detectors
- **DRDT 2.4** Realise liquid detector technologies scalable for integration in large systems



Collaboration organisation

- Interim Spokespeople: Roxanne Guenette & Jocelyn Monroe
- Interim Work Package tasks leads:

Charge Readout

Pixels & charge+light
Group leaders
J. Asaadi (US) & E.Gramellini(UK)

Charge-to-light, electroluminescence & amplification
Group leaders
A. Deisting (DE) & K. Mavrokoridis (UK)

Ion detection
Group leaders

No current representation, but topic to consider for future

Light Readout

Increased sensor quantum efficiency
Group leaders
J. Monroe(UK), F. Retiere (CA) & P. Agnes(IT)

Higher efficiency WLS and collection
Group leaders
C. Cuesta (ES), M. Kuzniak (PO) & J. Martin-Albo (ES)

Improved sensors for LS & WC
Group leaders

Entirely covered by DRD4, serves as liaison

Target Properties

Target properties and isotope loading of LS & WC
Group leaders
S. Schopmann (DE), H.Steiger (DE) & M. Wurm(DE)

Target properties and isotope loading of noble elements
Group leaders
C. Franco (FR), A. Szelc(UK) & A. Zani (IT)

Scaling-up Challenges

Radiopurity & background mitigation
Group leaders
J. Dobson (UK) & R. Santorelli (ES)

Detector and target procurement/production & purification
Group leaders
W. Bonivento (IT) & Y. Meh (US)

Large-area readouts
Group leaders
J. Crespo (ES) & G. Fiorillo (IT)

Material properties
Group leaders

No current representation, but topic to consider for future

Task Leaders

Work Packages

WP1

Charge Readout

WP2

Light Readout

WP3

Target Properties

WP4

Scaling-up Challenges

WP1 - Charge Readout

Charge Readout Conveners

Pixels & charge+light Group leaders

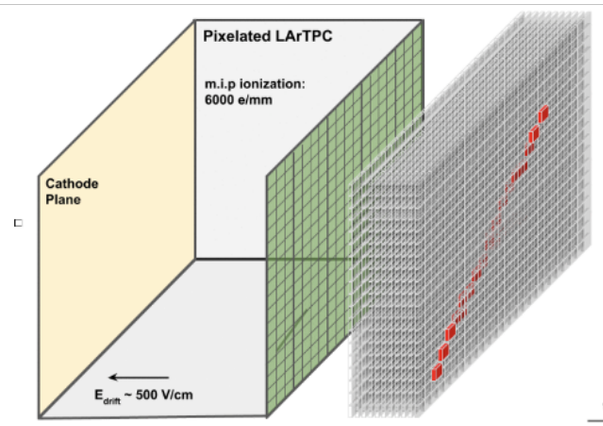
Charge-to-light, electroluminescence & amplification Group leaders

Ion detection Group leaders

- Noble Element TPCs with fine-grained readout enable access to detailed neutrino interaction information, from MeV - GeV scales

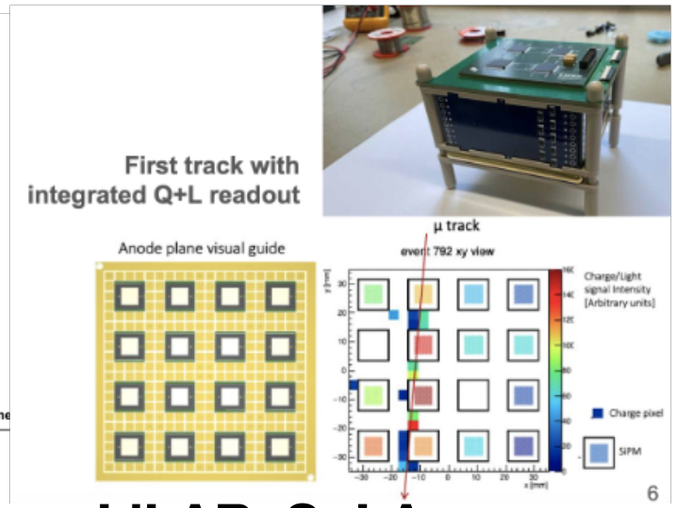
Ultimate goals: **reach 10^7 channels, fC charge, 100 ENC, lower-energy photon detection threshold**

With charge:



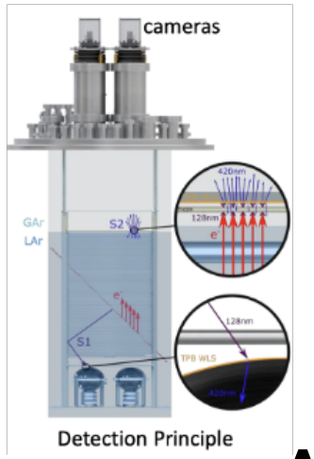
QPix, LArPix, …

With charge + light:

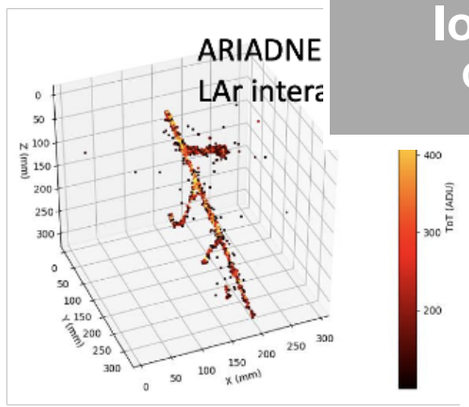


LiLAR, SoLAr, …

With charge-to-light:



ARIADNE

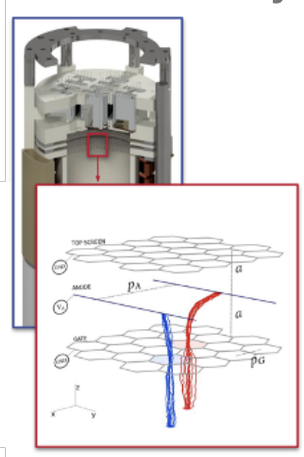


- Novel technologies are needed for charge-to-light conversion to enable future detector sizes and to increase the detector sensitivity.

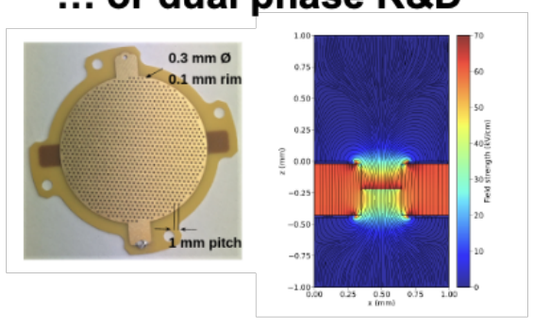
E.g. single phase R&D in Ar and Xe

David Caratelli & Angela Fava
LArCADe: lowering thresholds in LArTPC detectors

F. Kuger *et al* 2022
JINST **17** P03027



… or dual phase R&D



V. Chepel *et al* 2023
JINST 18 P05013

WP2 - Light Readout

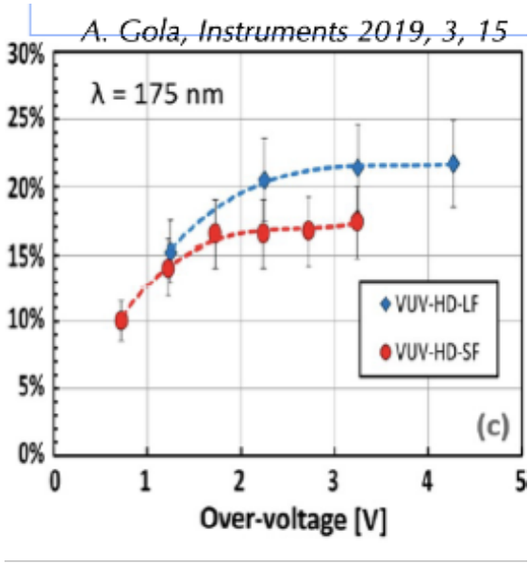
Light Readout Conveners

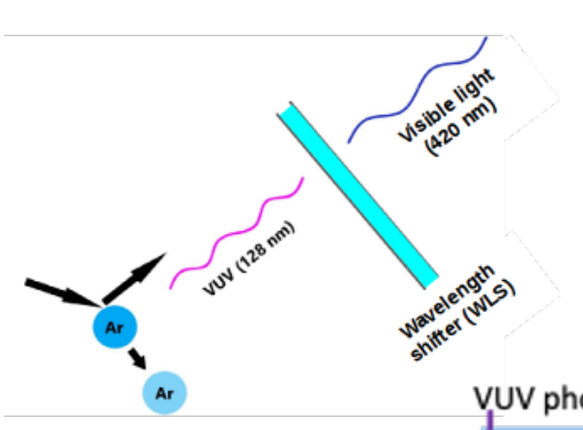
Increased sensor quantum efficiency Group leaders

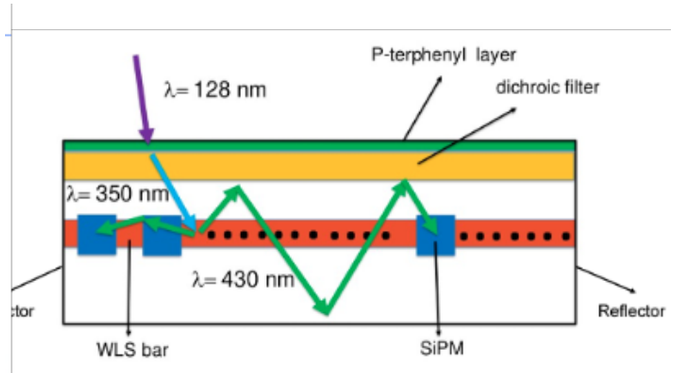
Higher efficiency WLS and collection Group leaders

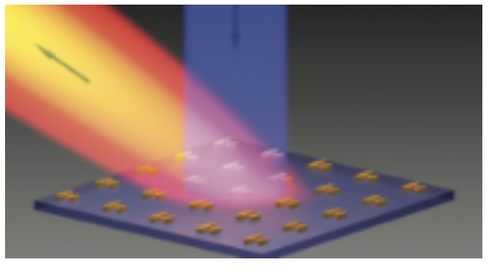
Improved sensors for LS & WC Group leaders

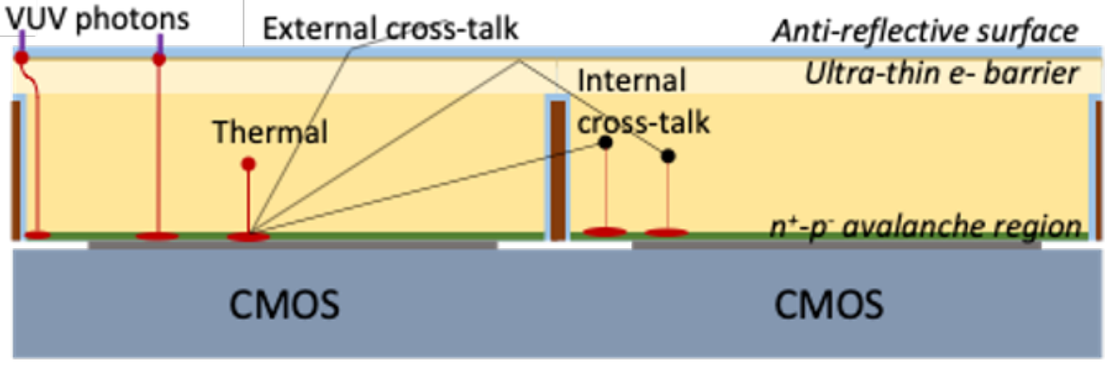
- O(0.1-10) kT experiments are, and are planned, to use liquid noble targets which scintillate in the **VUV wavelength** range (Ar, He, Xe)
  - ➡ Aim: photon readouts reaching O(100 m^2), *cryogenic temperature*
  - ➡ Key challenges: decrease reflectivity, increase collection efficiency, increase quantum efficiency
- Exploration of new materials, i.e. better wavelength shifters, light traps with dichroic filters, coatings optimised for range of angles of incidence, metalenses, and new processes (i.e. BSI-SPAD + passivation)











C. Cuesta, 2nd Liquid Detectors Community Meeting

J. Monroe, 2nd Liquid Detectors Community Meeting

WP3 - Target Properties

Target Properties Conveners

Target properties and isotope loading of LS & WC Group leaders

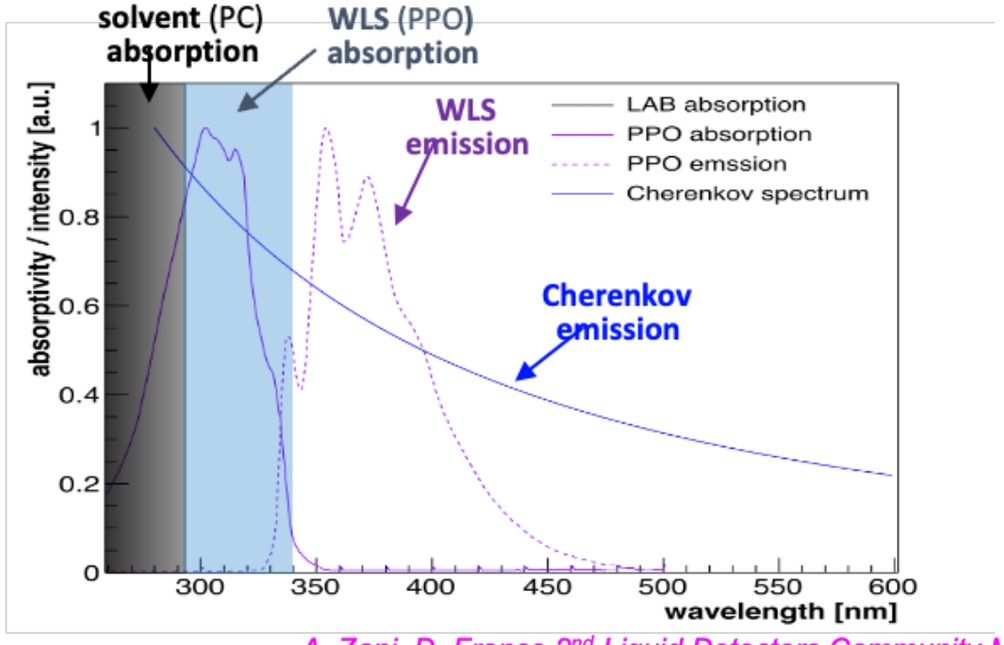
Target properties and isotope loading of noble elements Group leaders

- Aim is to increase photon yield and detection efficiency by doping, *improve* understanding of microphysics, add additional physics/medical capability to large liquid detectors, in two paths….

Cryogenic noble gases (CNG):

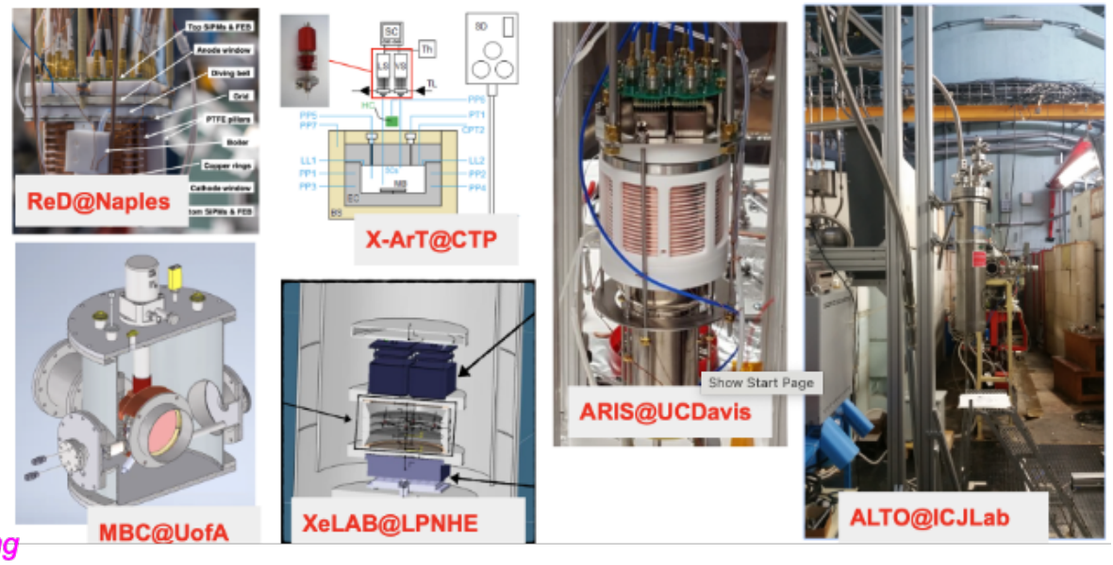
- Liquid Argon
- Liquid Xenon
- Liquid Helium (future?)

➡ Doping of liquid Argon with Xenon or more complex mixtures



Liquid scintillators (LS) (organic/water):

- Solvents: LAB, DIN, PC, Xylene, …
- Diluted Solvents
- Slow Scintillators and Blended
- Solvents Wavelength Shifters
- Water Based Scintillators + Surfactants
- Loading of scintillators with Gd, Te, Xe, Cd, B, Li, In …



A. Zani, D. Franco 2nd Liquid Detectors Community Meeting

WP4 - Scaling-up challenges

Scaling-up Challenges
Conveners

Radiopurity & background mitigation
Group leaders

Detector and target procurement/production & purification
Group leaders

Large-area readouts
Group leaders

Material properties
Group leaders

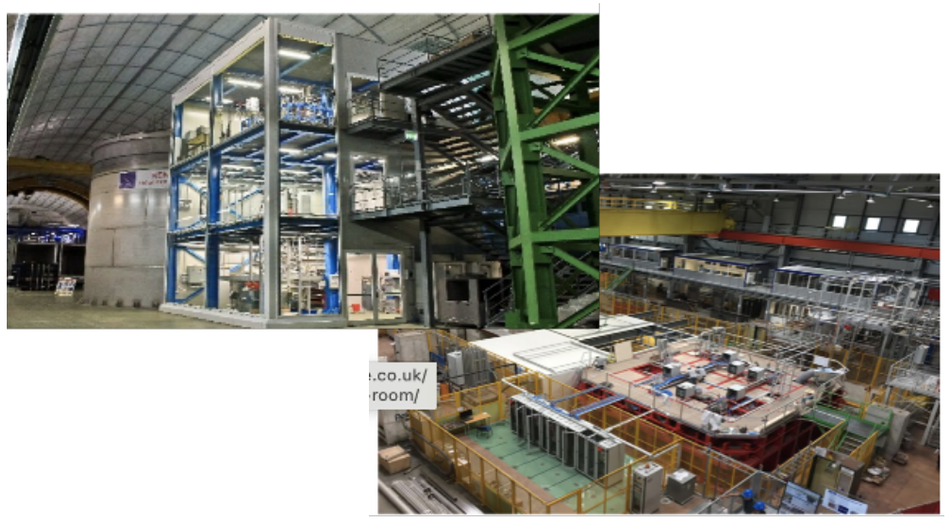
- Background reduction requirements get commensurately harder: reaching *1 event/kg/**millennium***
  - ➡ Key challenges: radiopurity of *all* detector materials, including target liquids!
- Developments in production/purification thus far owned by experiments
  - ✓ UAr production led by GADMC development of major infrastructures (URANIA, ARIA), use cases for DarkSide-20k / LEGEND-1000 / COHERENT / ARGO
  - ✓ Xe purification in each of current experiments + developments towards XLZD/DARWIN
- LSc challenges in scale-up synthesis of laboratory-prepared fluorescence materials
- Gd-doping now widespread in use, R&D needs on increasing concentration, purity, optics
- Large scale assembly and test facilities needed, including underground

Vision: develop DRD2 Collaboration coordinated requests to 'access-giving' infrastructures

<u>CERN Neutrino Platform</u>
- Large scale cold box, cryogenics
- Charged particle beam

<u>Gran Sasso ++</u>
- Underground facility
- Cryogenic infrastructure

<u>Local labs for specific tests</u>
- Readout
- Assembly



W. Bonivento, J. Dobson, G. Fiorillo, 2nd Liquid Detectors Community Meeting

Infrastructure	Location	Work Package . Task	Current/Future
MMP Common Test Platform	SNS	1.1	Current
MMP Common Test Platform	CERN (potentially Neutrino Platform)	1.1	Future
ARIADNE	Liverpool	1.2	Current
NUXE	UCSD	1.2	Future
PANCAKE	Freiburg	1.2	Current
PIONEER	TRIUMF	2.1	Current
BUTTON	Boulby	2.1	Current
QE, noise vs. (λ, T)	CIEMAT, Liverpool, Napoli	2.1	Future
CLEAR	TRIUMF	2.1	Future
SOLAIRE	Boulby	2.1	Future
Materials characterisation	Nikhef	2.2	Future
WLS/light collection	Astrocent	2.2	Future
1TBNL, 30TBNL	BNL	3.1	Current
1TBNL, 30TBNL	BNL	3.1	Current
Xenoscope	Zurich	3.2	Current
WbLS Testbeds	various	4.2	Current
100 tonne-scale WbLS facility	TBD	4.2	Future
URANIA	Colorado	4.2	Current
ARIA	Sardinia	4.2	Current
Neutrino Platform	CERN	4.3	Current
WCTE	CERN	4.3	Current

DRD2 Collaboration

- DRD2 held its first Collaboration Meeting in February (https://indico.cern.ch/event/1367848
- Currently ~160 members from 71 institutions
- Large breath of R&D efforts were presented
- Use/sharing of infrastructure is desired and was discussed
- Recently elected the new Collaboration Board Chair (Walter Bonivento)
- In process to vote the by-laws to proceed to spokespeople elections
- You are welcome to join at any time! Email Roxanne, Jocelyn or Walter

roxanne.guenette@manchester.ac.uk
jocelyn.monroe@physics.ox.ac.uk
walter.bonivento@cern.ch

DRD2: UK input

Charge readout

- Manchester
- Liverpool

Light readout

- Edinburgh
- Manchester
- Liverpool
- Open Uni.
- RAL/STFC
- RAL PPD
- Royal Holloway
- Royce Institute
- Sussex
- York

Target Properties

- Edinburgh
- Liverpool
- King's
- Oxford

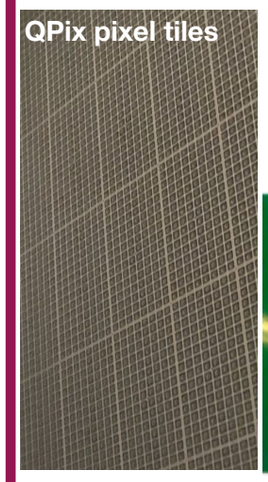
Scale-up challenges

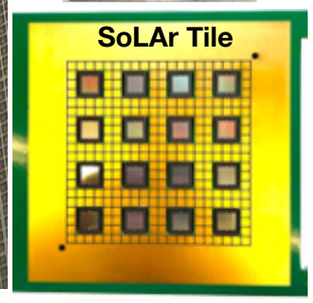
- Boulby (STFC)
- Edinburgh
- King's
- RAL PPD
- Sheffield
- UCL

DRD2: UK input

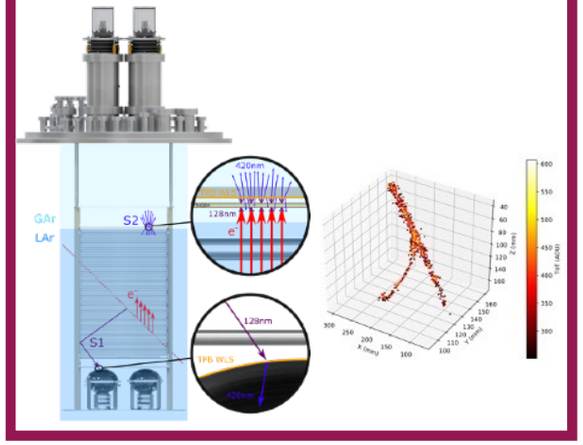
Charge readout

- Pixel development (QPix, SoLAr)



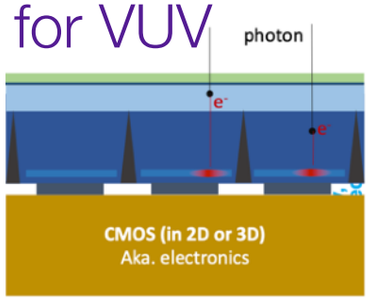


- Amplified optical readout (ARIADNE)

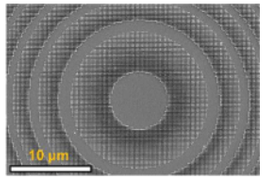


Light readout

- Development of back-end illuminated sensors for VUV

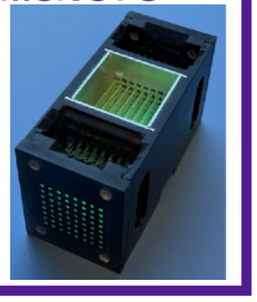


- Metalenses for light collection



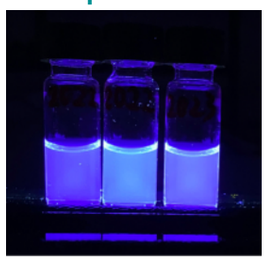
- Wavelength shifters

- New fibers for opaque scintillators

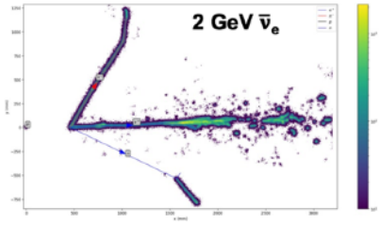


Target Properties

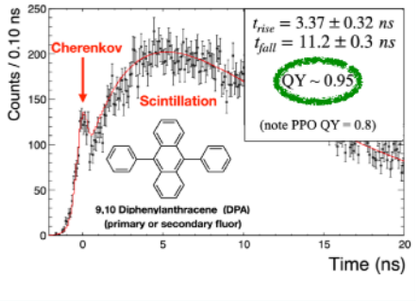
- Quantum dots Liquid Scintillators



- Opaque Liquid Scintillator (LiquidO)



- Te loading and slow fluor



Scale-up challenges

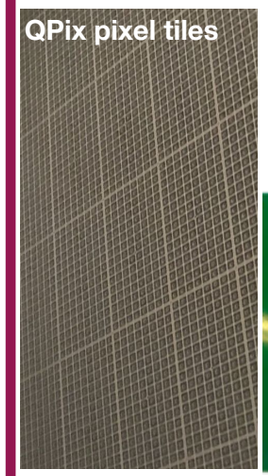
- New radioassay techniques

- Novel low-bkg material

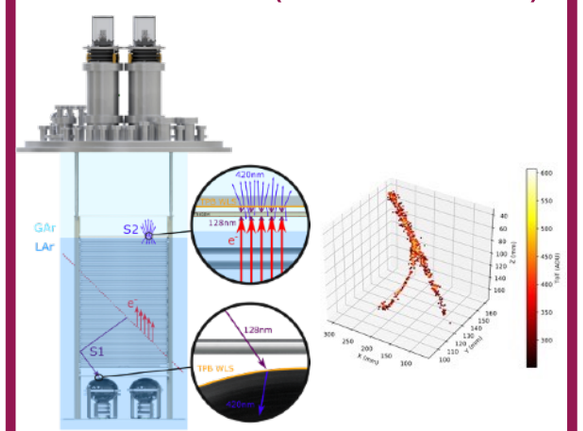
DRD2: UK input -> A coherent picture?

Charge readout

- Pixel development (QPix, SoLAr)

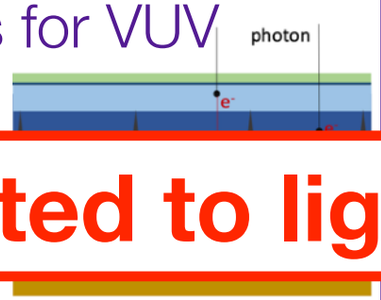


- Amplified optical readout (ARIADNE)



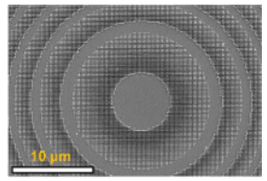
Light readout

- Development of back-end illuminated sensors for VUV

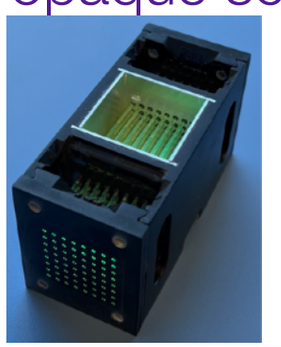


All related to light!

- Metalenses for light collection



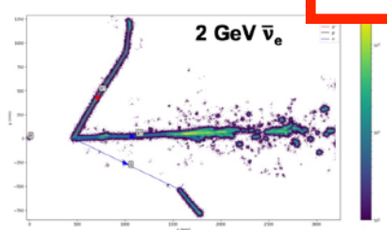
- Wavelength shifters
- New fibers for opaque scintillators



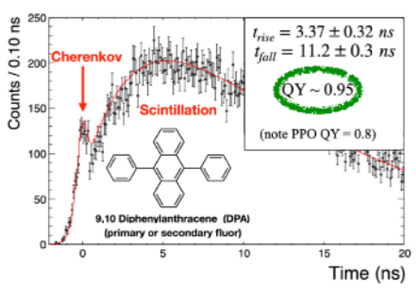
Target Properties

- Quantum dots Liquid Scintillators

- Opaque Liquid Scintillator (Li



- Te loading and slow fluor



Scale-up challenges

- New radioassay techniques

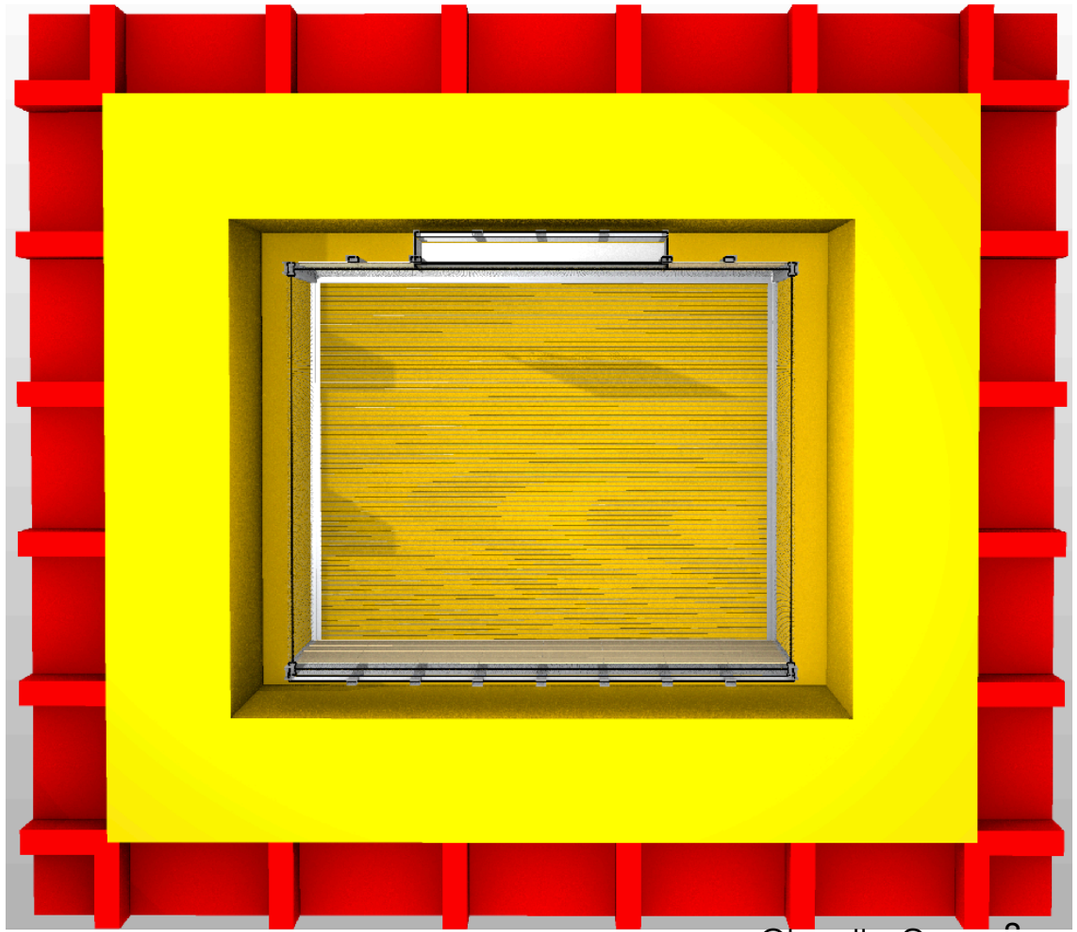
- Novel low-bkg material

underpinned by low background

Opportunities at Boulby: SOLAIRE

- Under the UKRI invite-only research grant call “to deliver a dark matter science project at the Boulby Underground Laboratory”

- SOLAIRE proposal is a low-mass dark matter experiment that enables studies for neutrino physics and infrastructure for R&D demonstration

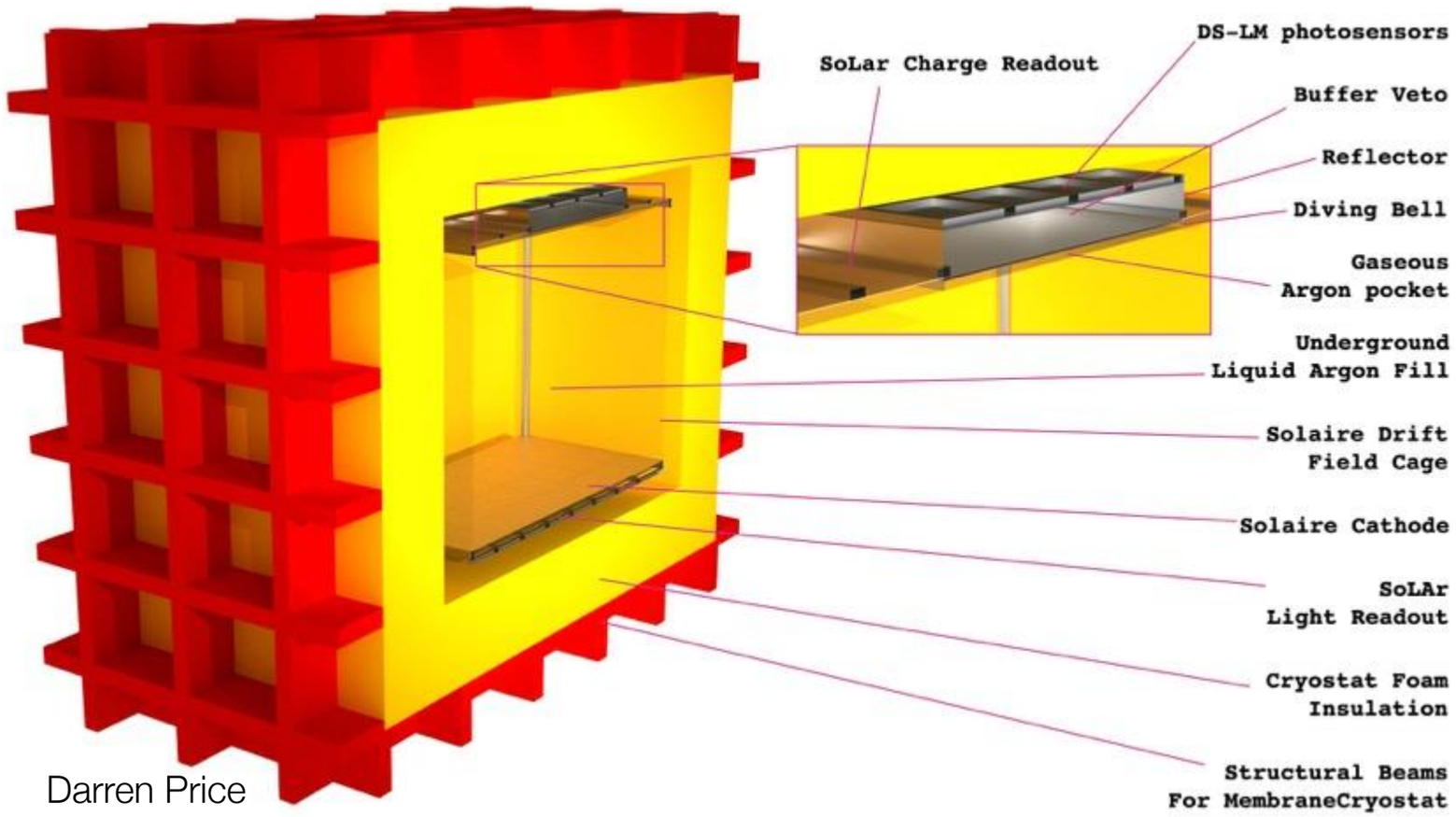


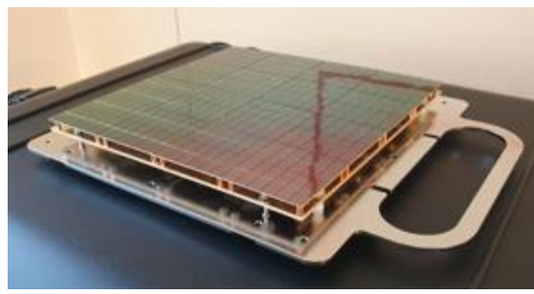
SOLAIRE concept

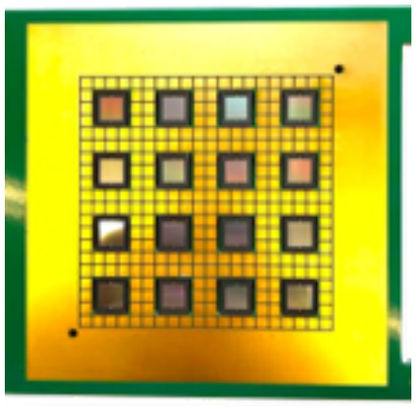
- Central 1 ton dual-phase LAr region surrounded by a 12 ton single-phase LAr TPC (Phase 1: AAr, Phase 2: UAr, Phase 3: adding dopants?)

- Initial studies suggest excellent prospects for competitive sensitivity in dark matter

- Early opportunity for people interested in future sensor technologies to test instrumentation in large low-background volumes undergrounds







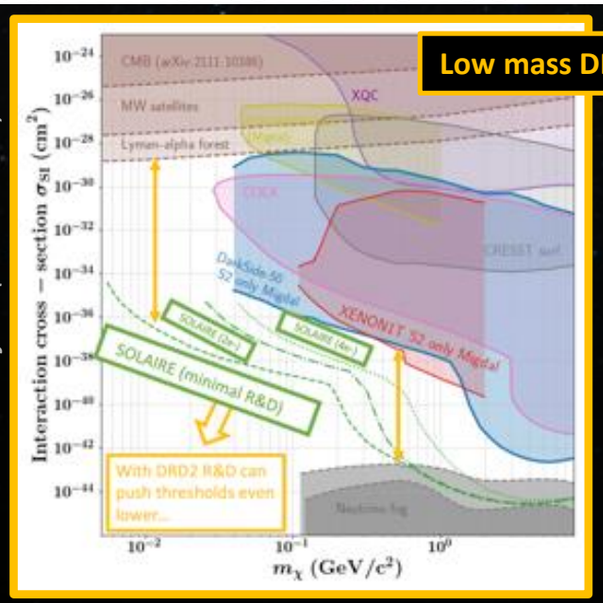
Darren Price

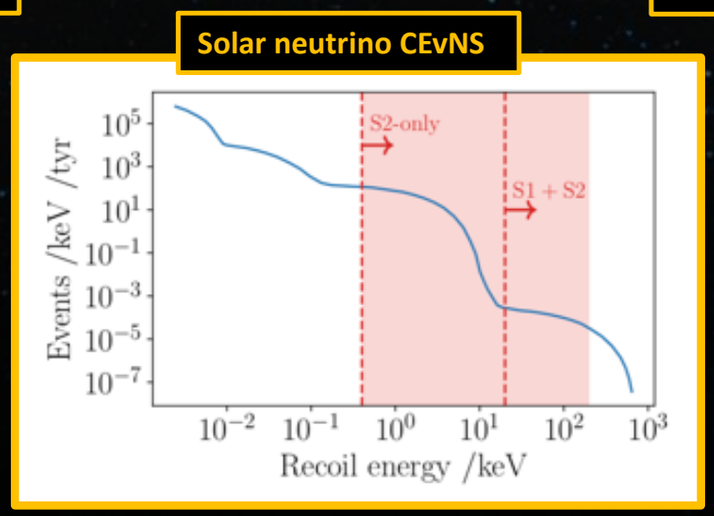
SOLAIRE Community

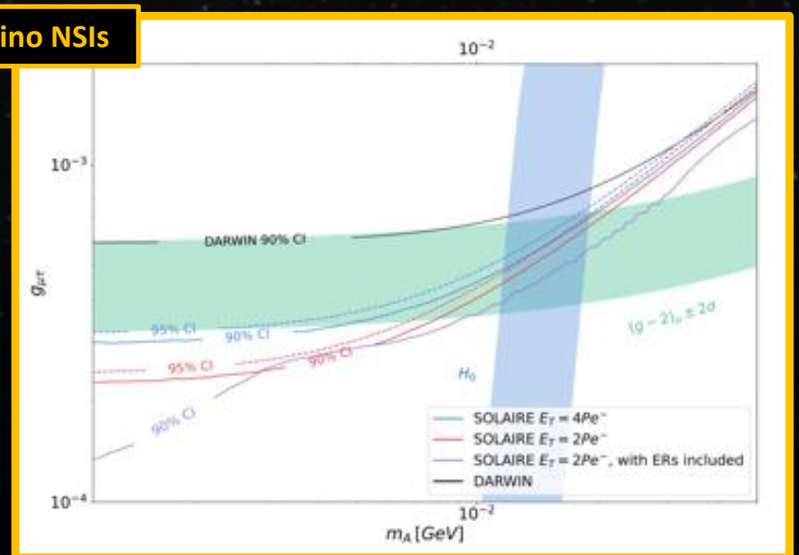
- Dark matter, neutrino and instrumentation communities

Dark Matter science

Credit: Ellen Sandford (Manchester)

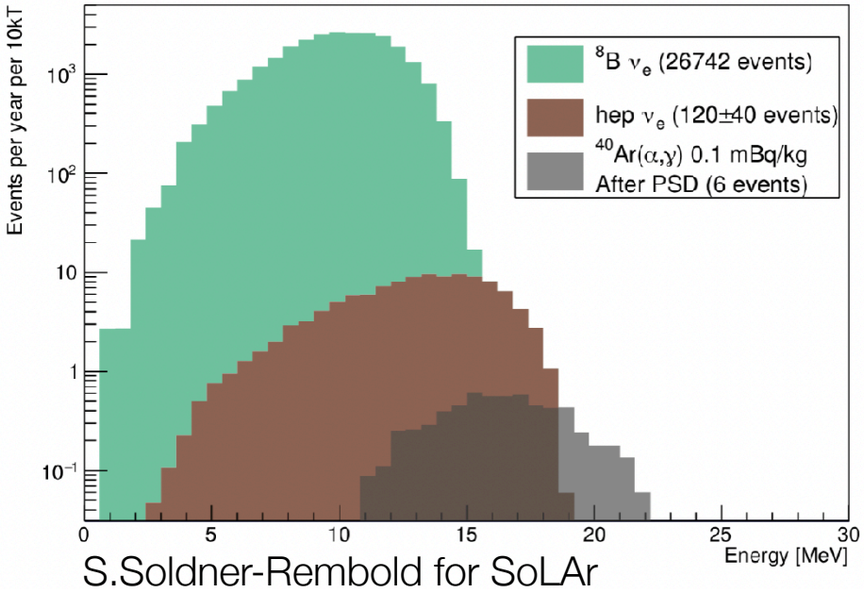




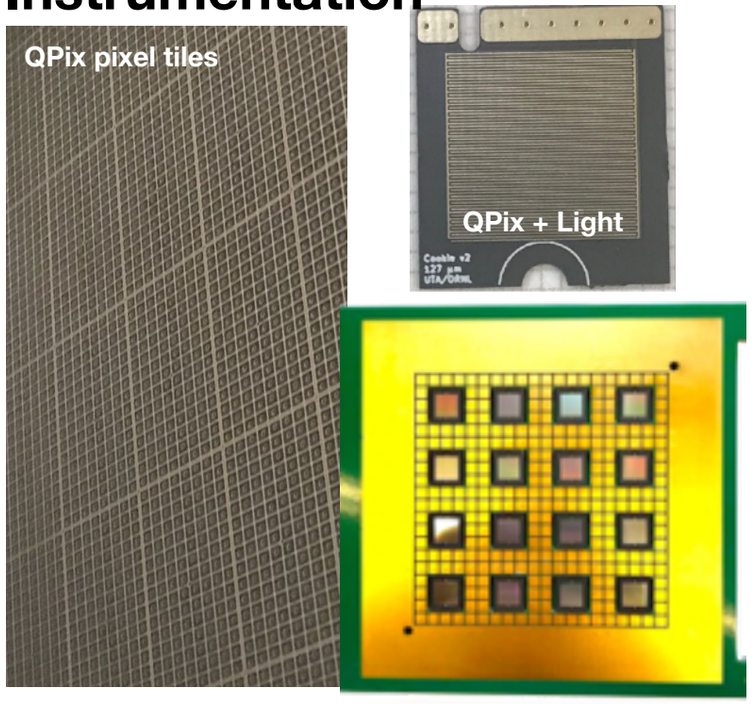


Credit: Hayden Casey (Manchester)

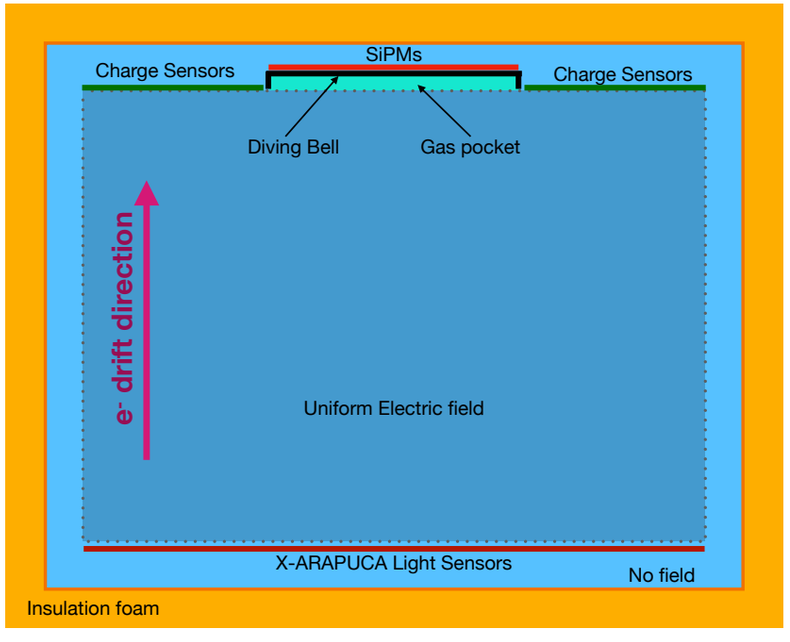
Solar Neutrino



Instrumentation



SOLAIRE sketch NOT to scale



SOLAIRE status

- UKRI has invited SOLAIRE to submit a full proposal

- Organisation:
  - WBS0: Management and Boulby Laboratory liaison
  - WBS1: Detector infrastructure & installation
  - WBS2: Inner detector
  - WBS3: Outer detector
  - WBS4: Physics and software

- Each work package will have a UK-lead and a non-UK lead

- WP meetings expected soon (open to all interested participants!)

- If you want to get involved contact Darren Price (Darren.Price@manchester.ac.uk)

Summary

- DRD2 collaboration spans a wide range of R&D activities and a lot of interests for collaborative efforts

- In the UK, the theme of *Light Detection* seems to allow for some coherence without excluding efforts

- SOLAIRE offers a unique and strategic opportunity to connect to Boulby and for instrumentation test bed and should attract DRD2 experts (join in!)

- We need to think about the Early Stage R&D Grant call to decide what proposal(s) to put forward under DRD2-UK

Backup

SOLAIRE timeline

Phased construction and operation plan

PHASE 0
Construction begins

Phase 1: 2025—27
Atmospheric argon fill
Outer detector commissioning, dedicated neutrino studies

Phase 2: 2027—2030
Installation of diving bell
Purified underground argon fill
Inner detector commissioning, dark matter search

[Phase 3]: 2030+
Post-bid opportunities
Extension of DM search with dopants, facility use for instrumentation testing…

Phased construction and commissioning/science plan

1: Atmospheric argon fill: commissioning cryostat, field cage etc.; opportunity for instrumentation testing in large Ar volumes and complementary science outputs + proof-of-principle studies

2: Ultra-radiopure underground argon fill: installation and commissioning of diving bell and exploitation of dark matter search program

(3: Beyond funding call, potential opportunities for expansion of science programme, unique national infrastructure for instrumentation development and testing)