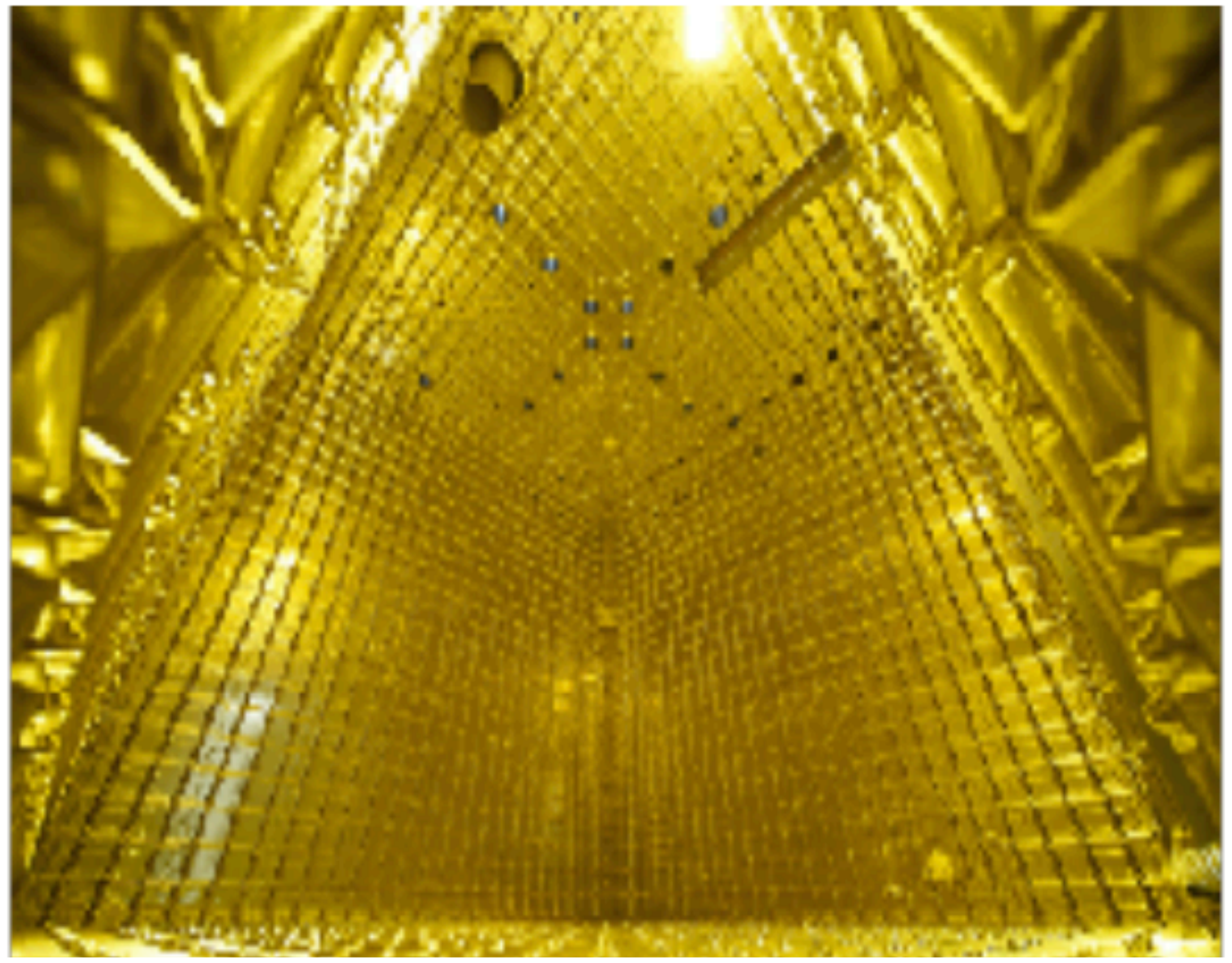
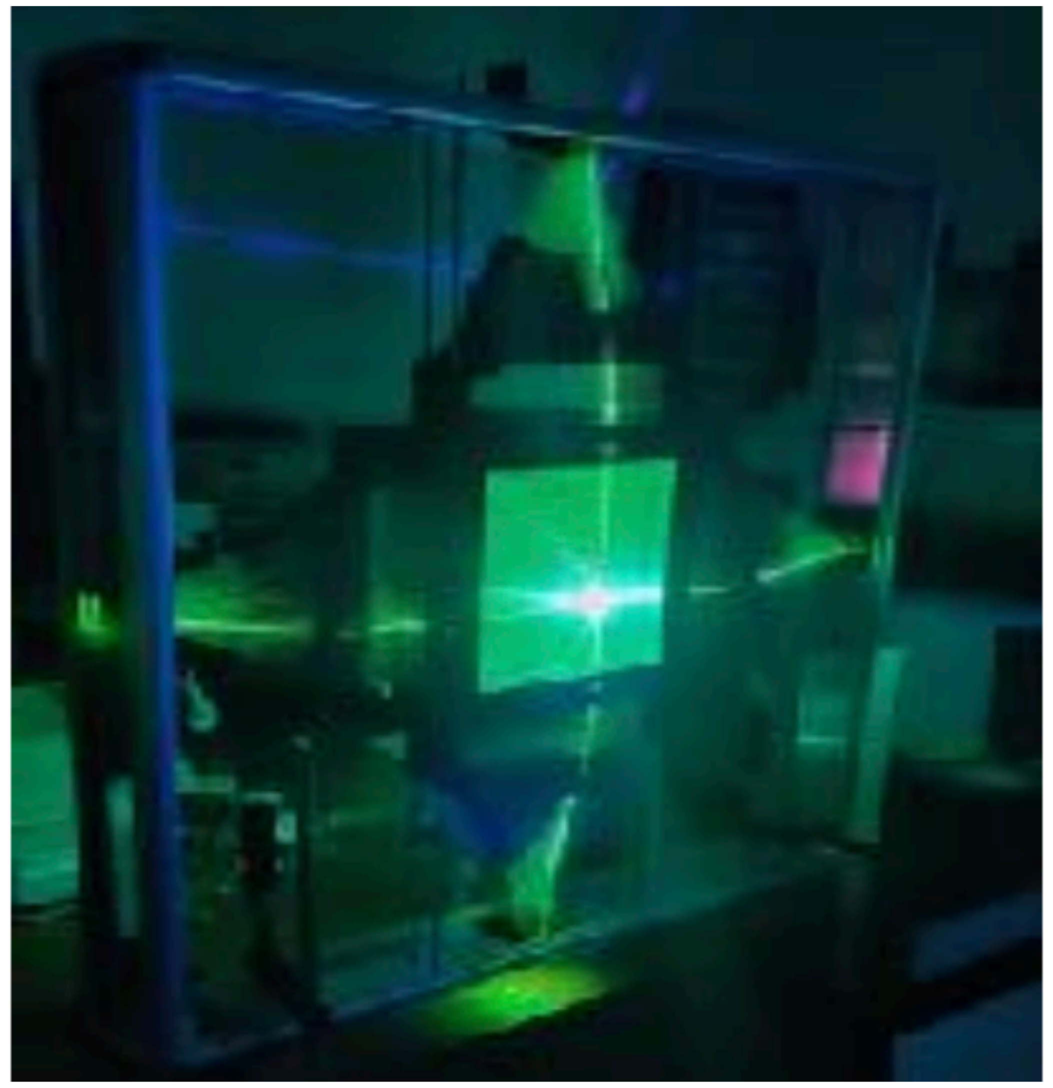
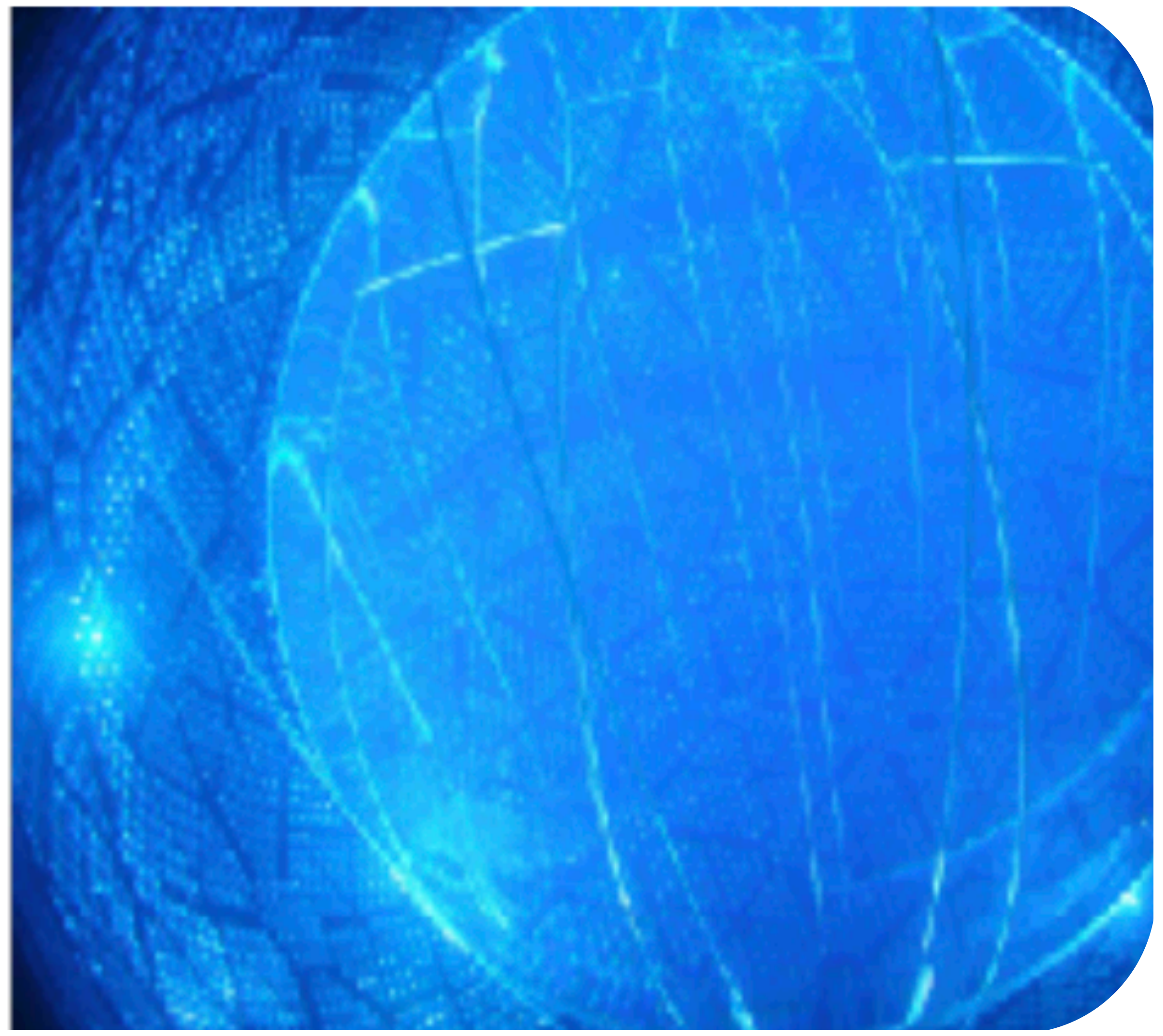
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

KIRCHHOFF-INSTITUT FÜR PHYSIK

Liquid (non-HEP) Detectors - What it needs for Future Research

HighRR Lecture Week, Bergen, 13.06.2024

Belina VON KROSIGK (bkrosigk@kip.uni-heidelberg.de)

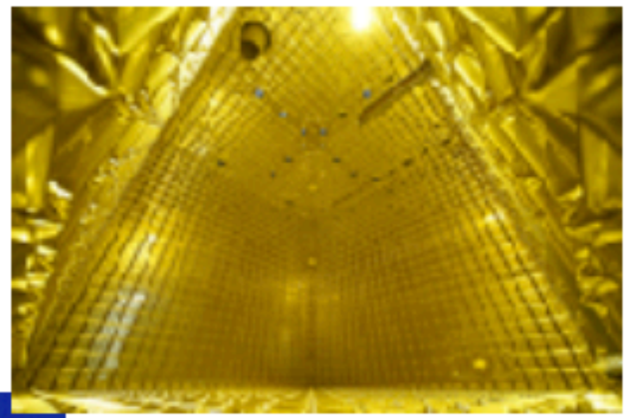
Credit: Roxanne Guenette & Jocelyn Monroe

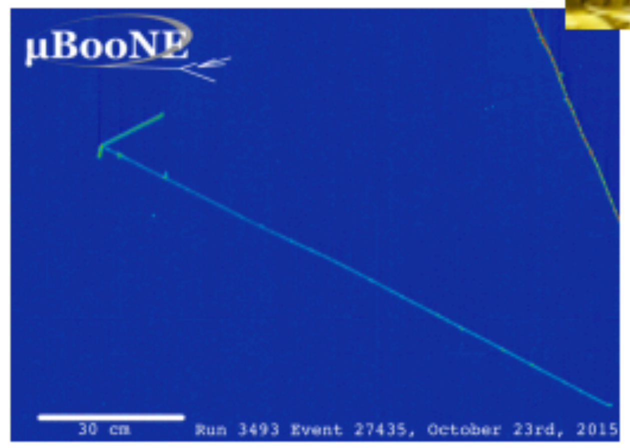
The science of interest: rare event searches

Slide from:
R. Guenette, J. Monroe
DRD2 Collaboration Meeting
5-7 February 2024

Neutrinos

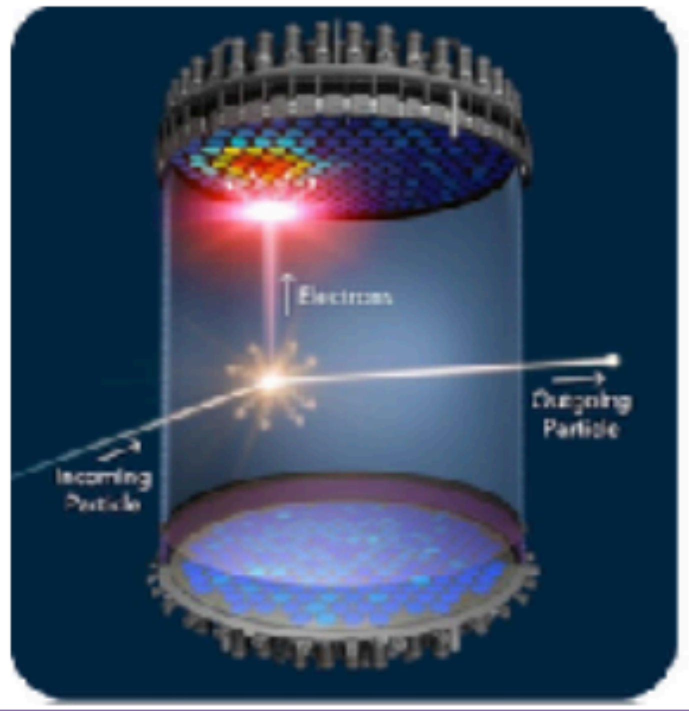
- Oscillation precision measurements (δ_{CP}, mass ordering, θ_{23} octant, sterile νs)
- Neutrino interactions (from CEνNS to DIS)
- Astro neutrinos





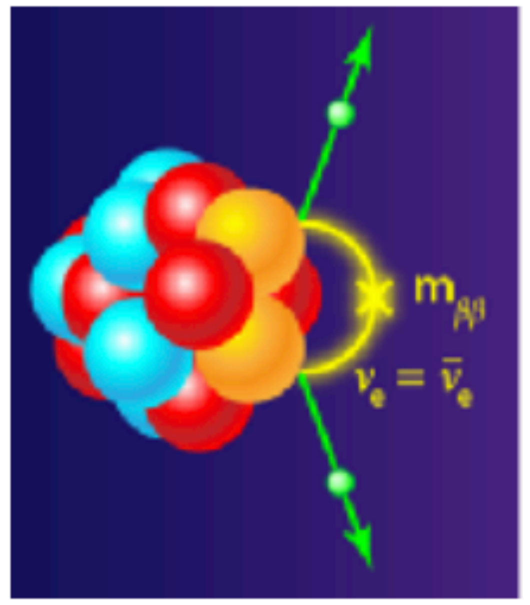
Dark Matter

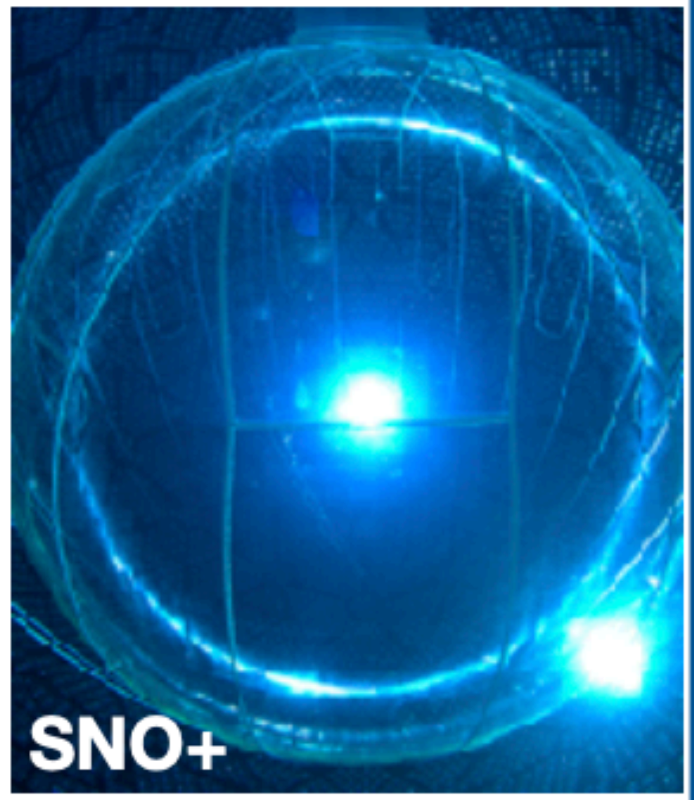
- Direct detection (WIMPs, …)

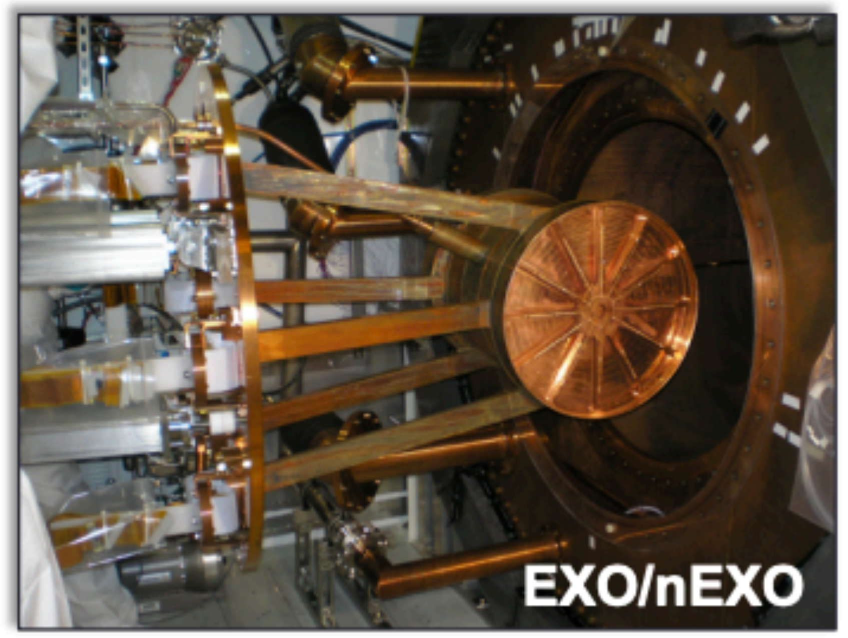


$0\nu\beta\beta$

- Search for Majorana neutrinos







The physics needs (high-level overview)

Slide from:
R. Guenette, J. Monroe
DRD2 Collaboration Meeting
5-7 February 2024

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**

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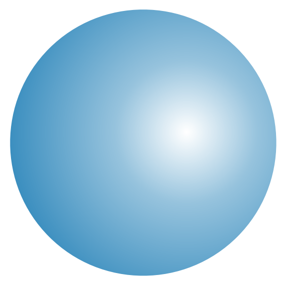
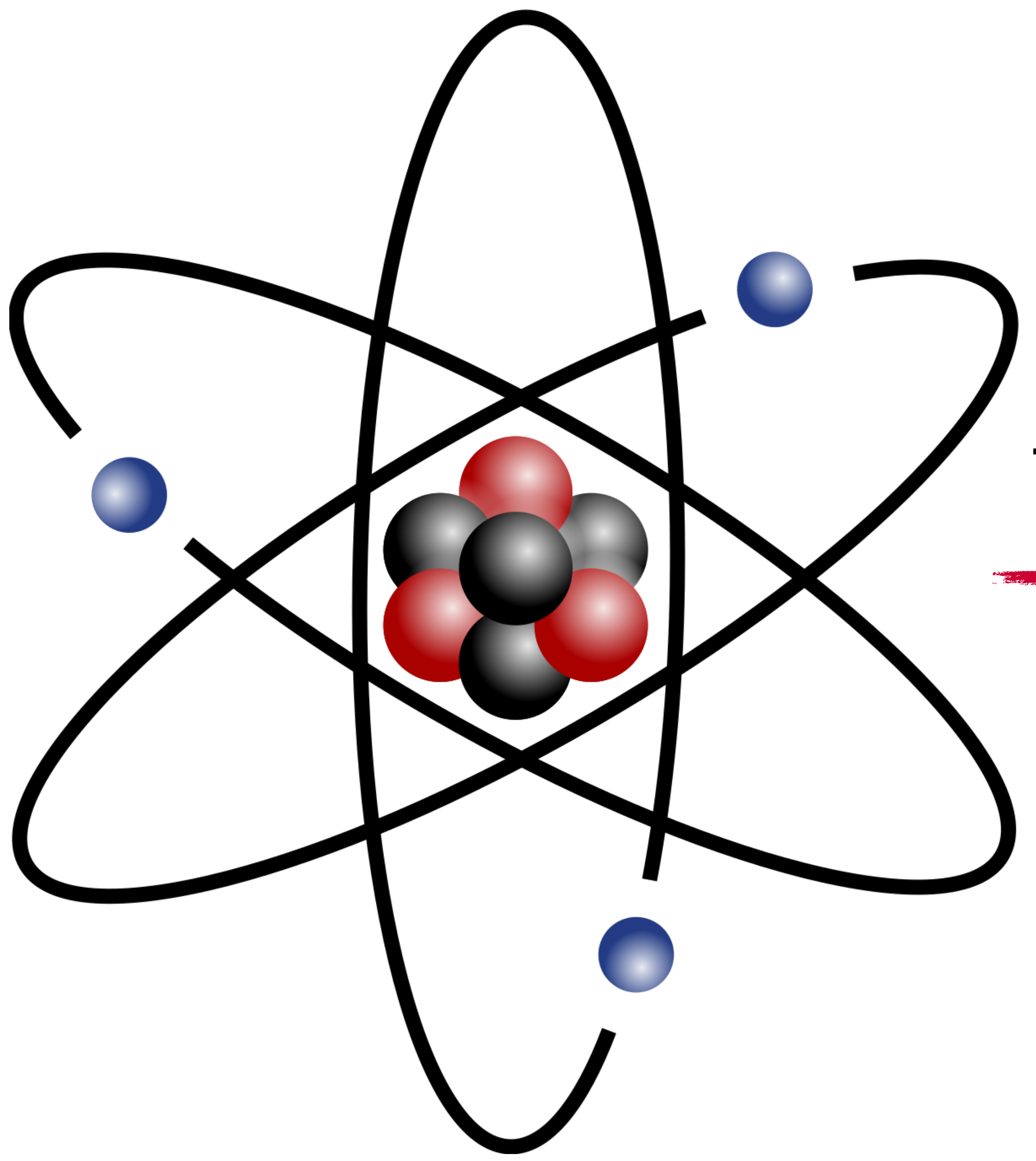
The basic detection principle



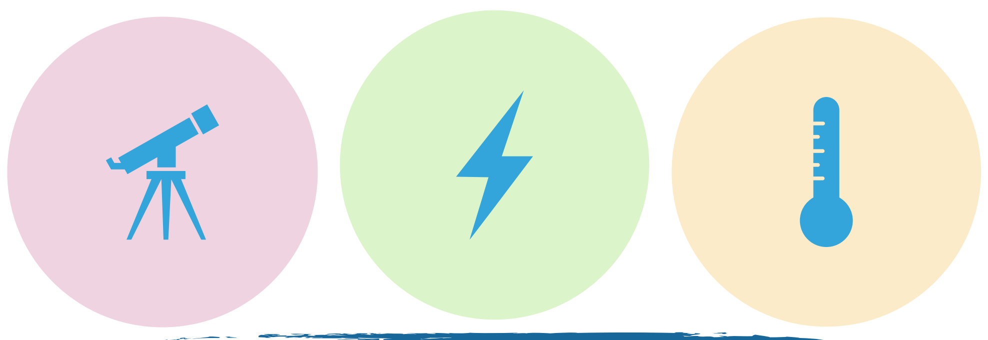
interaction →



final state →

typically the original **scattering partner**

energy deposition →



photons and/or **charges** and/ or **phonons**

Incoming particle (ν or DM)

Atom within the liquid

Final state particle(s)

Secondary (quasi-)particles which will be observed

The basic detection principle

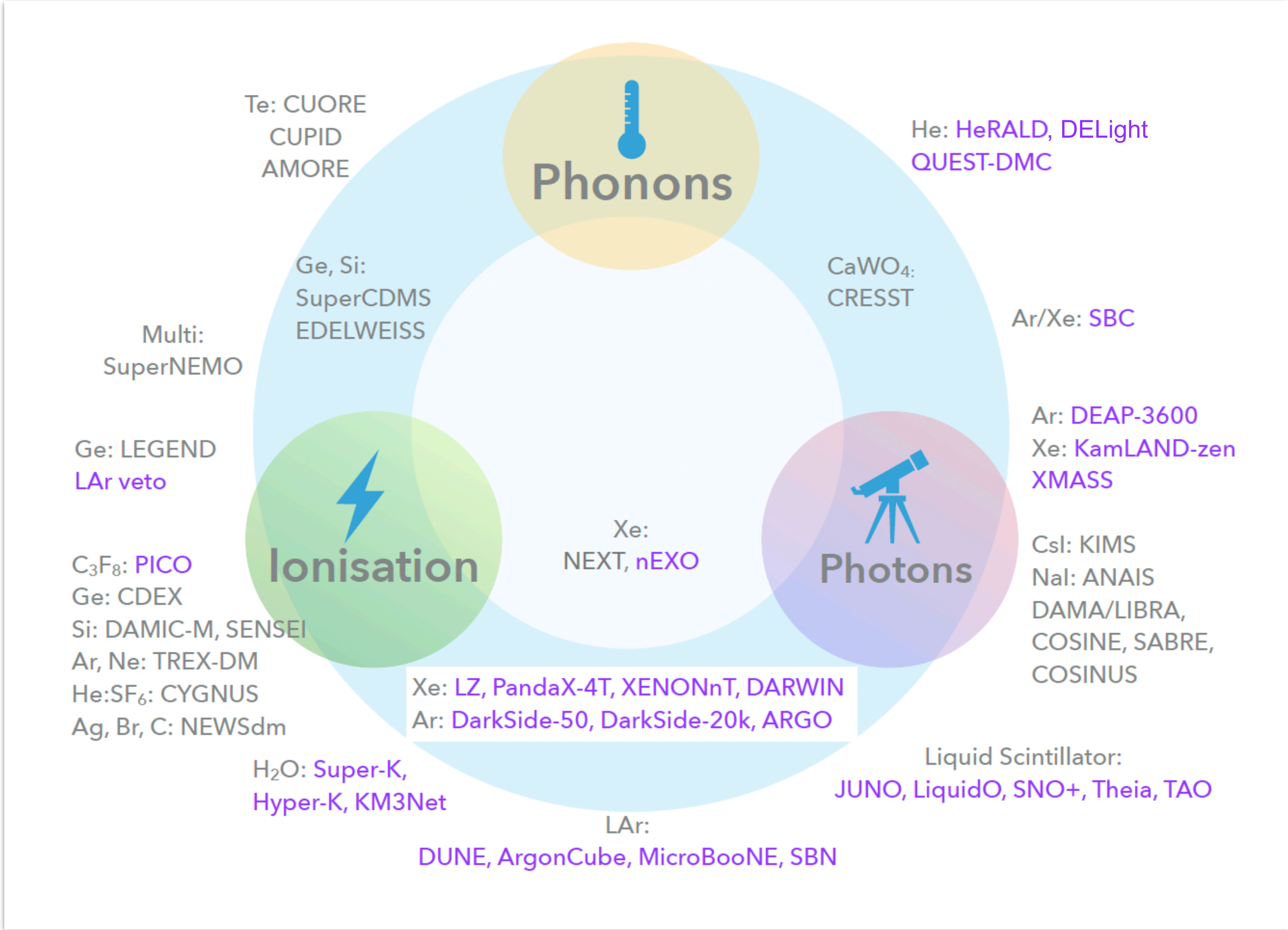
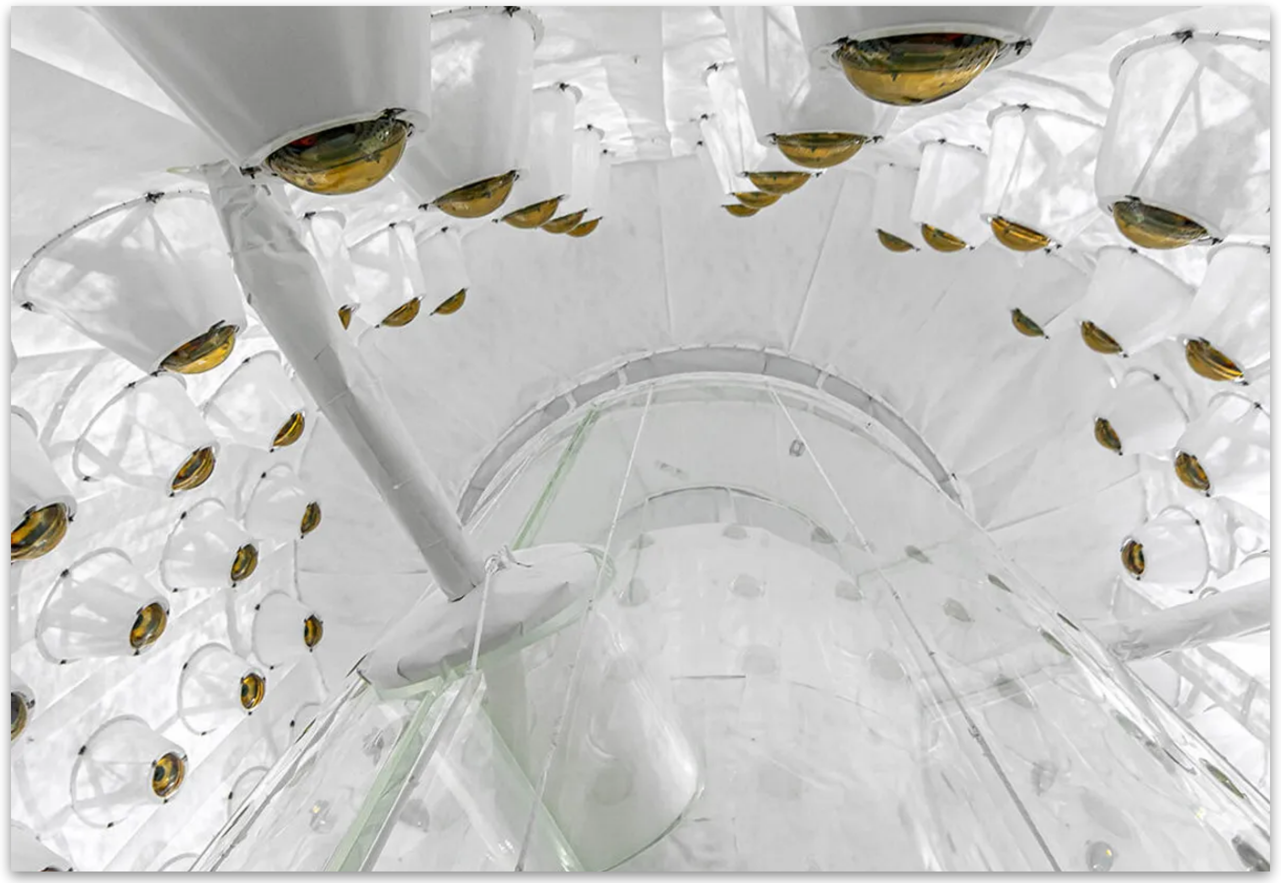
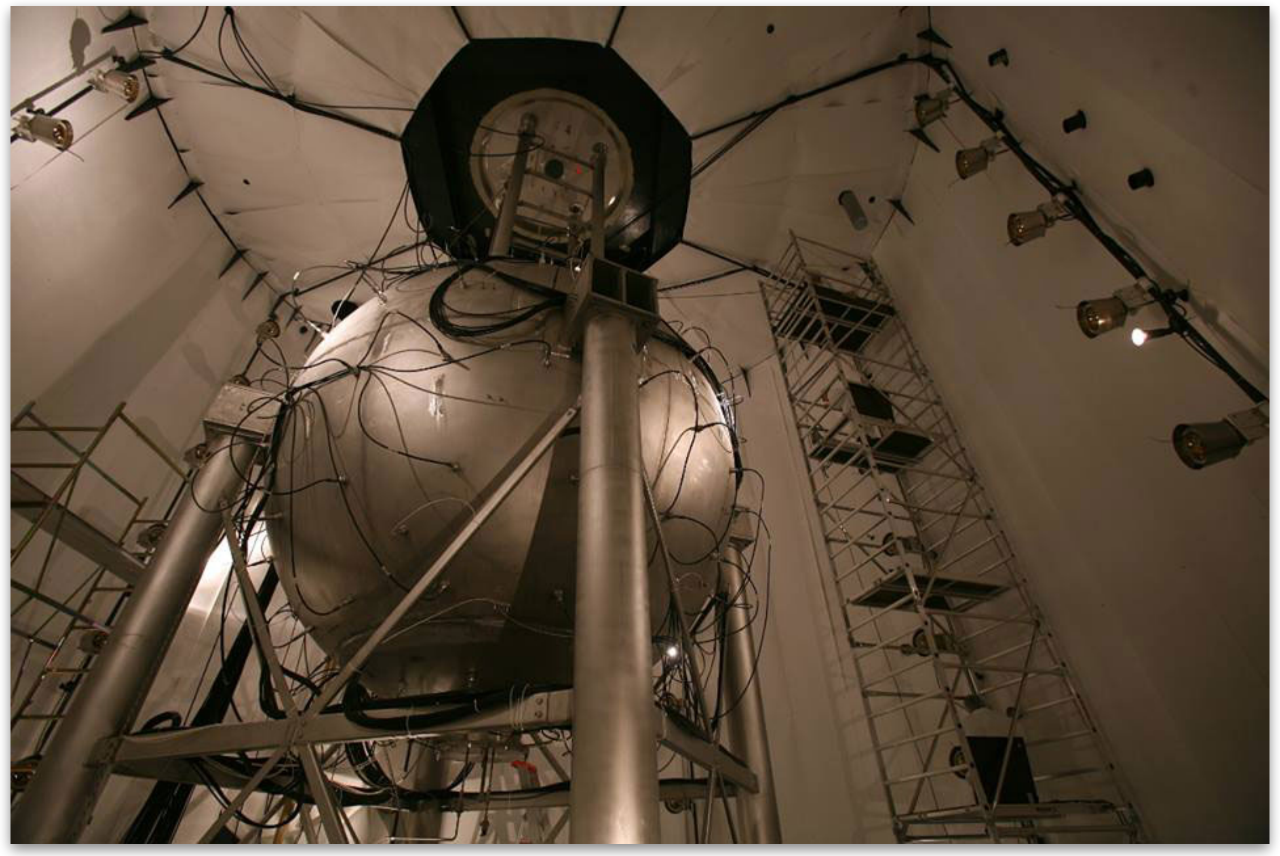


Figure modified from L. Baudis, ECFA, Plenary Input Session

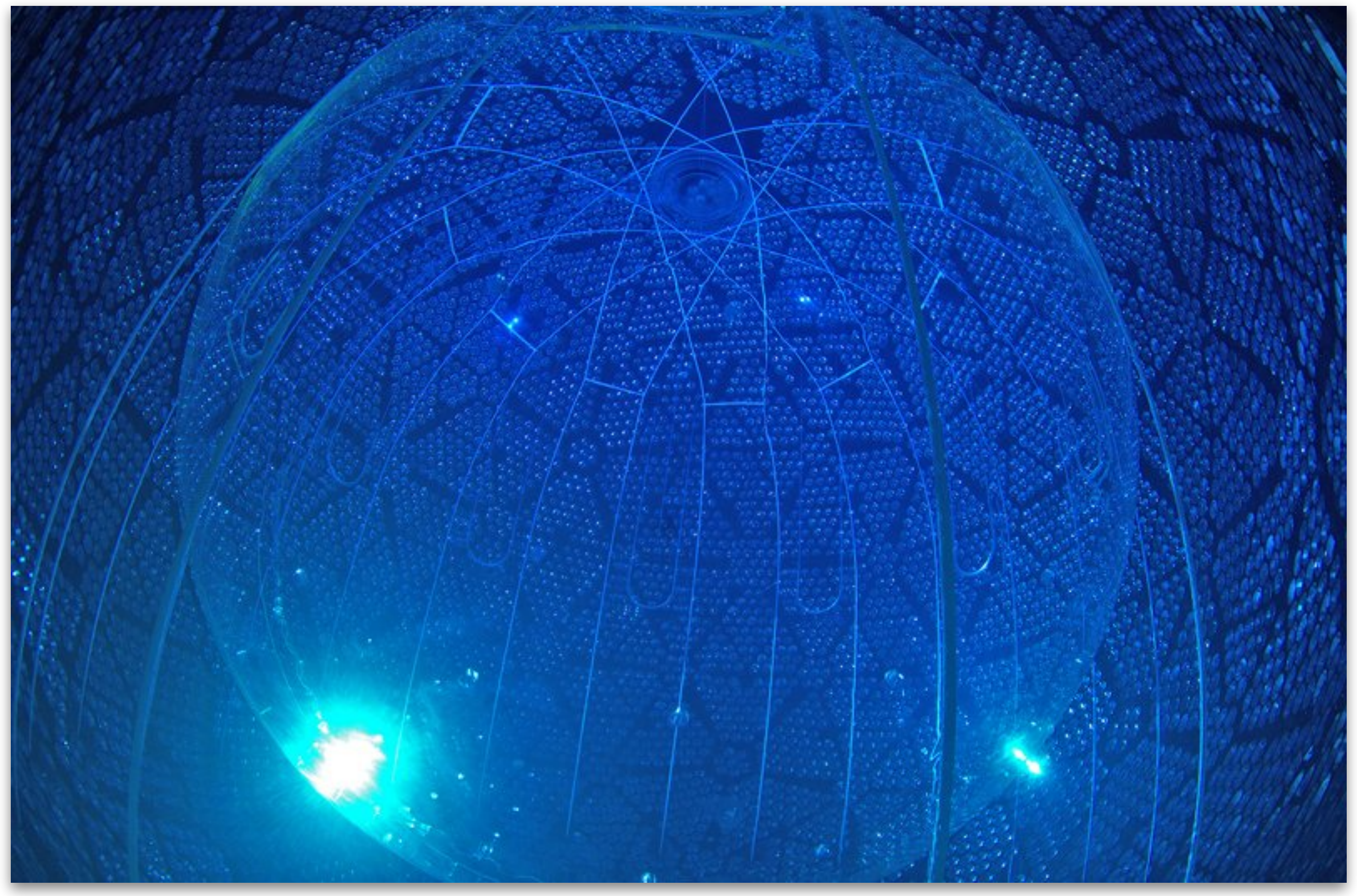
The liquids

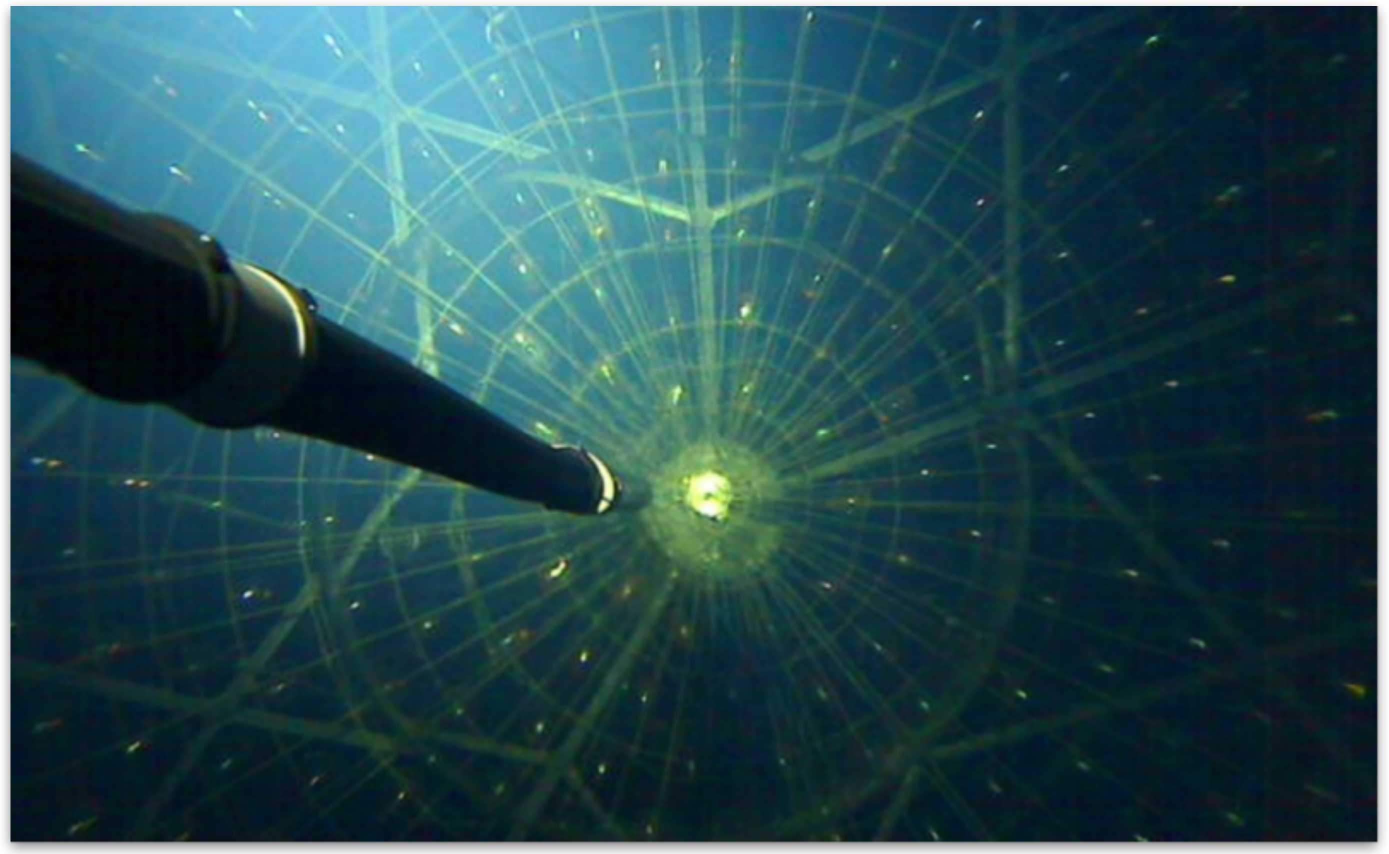
Liquid Noble Gases



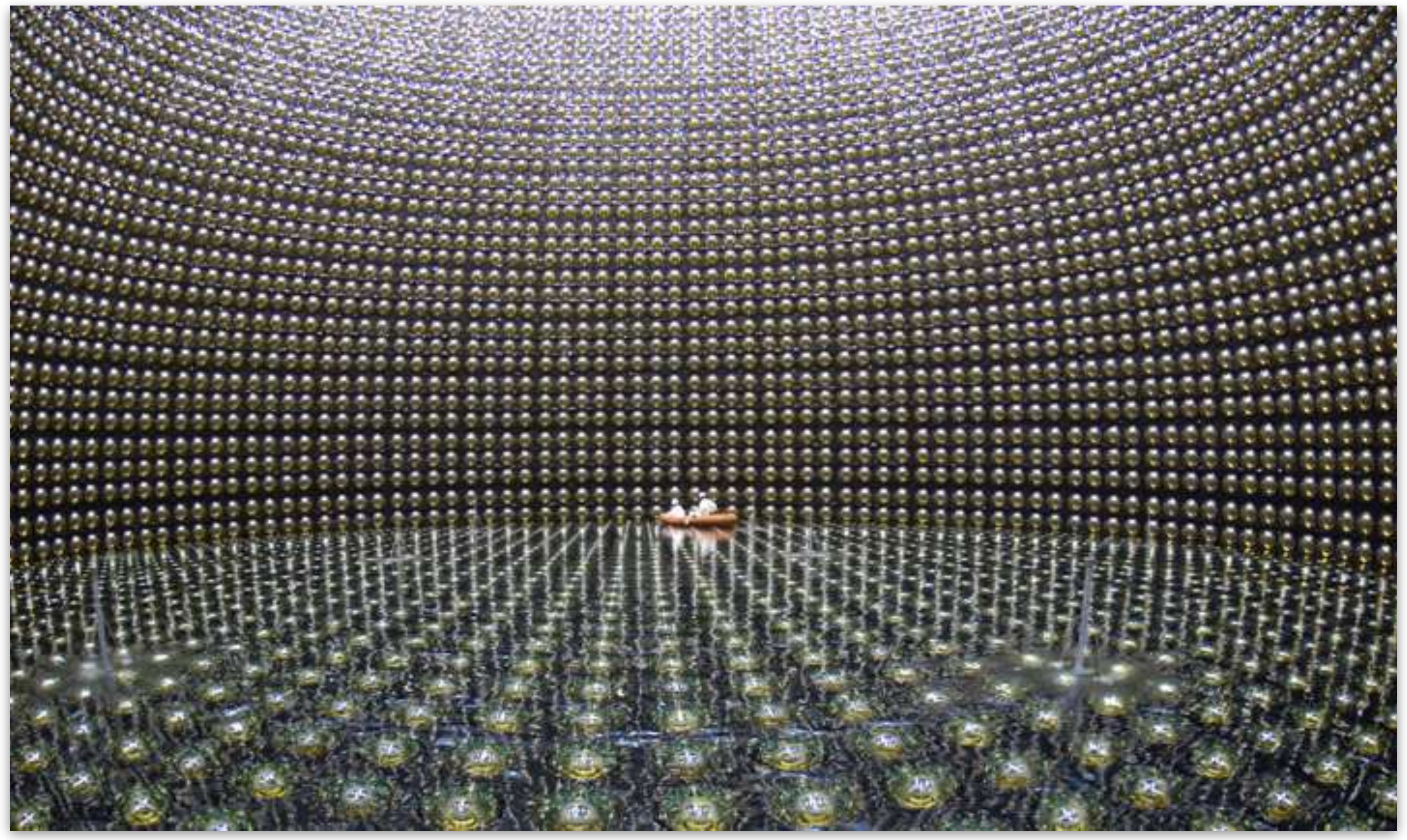


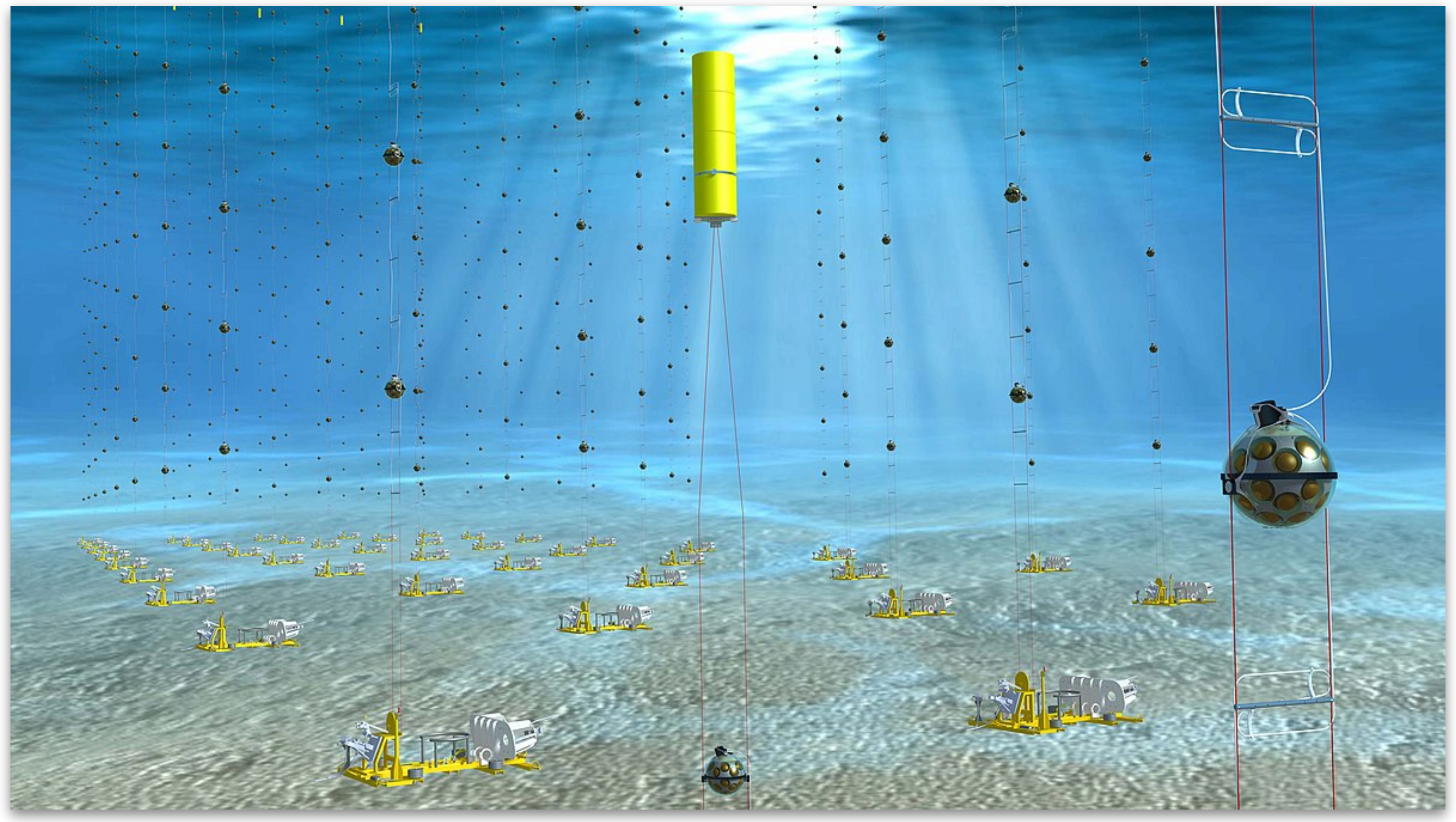
Liquid Scintillator





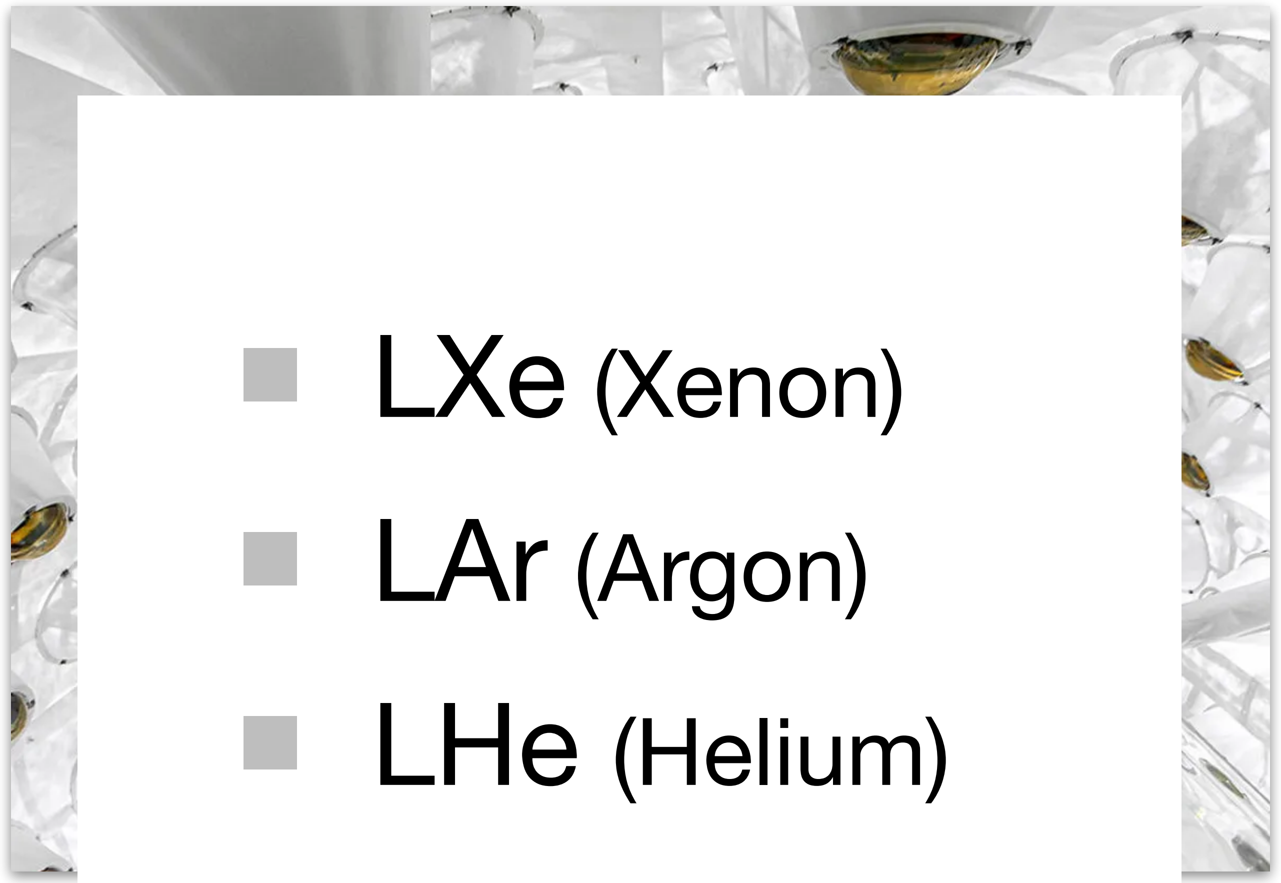
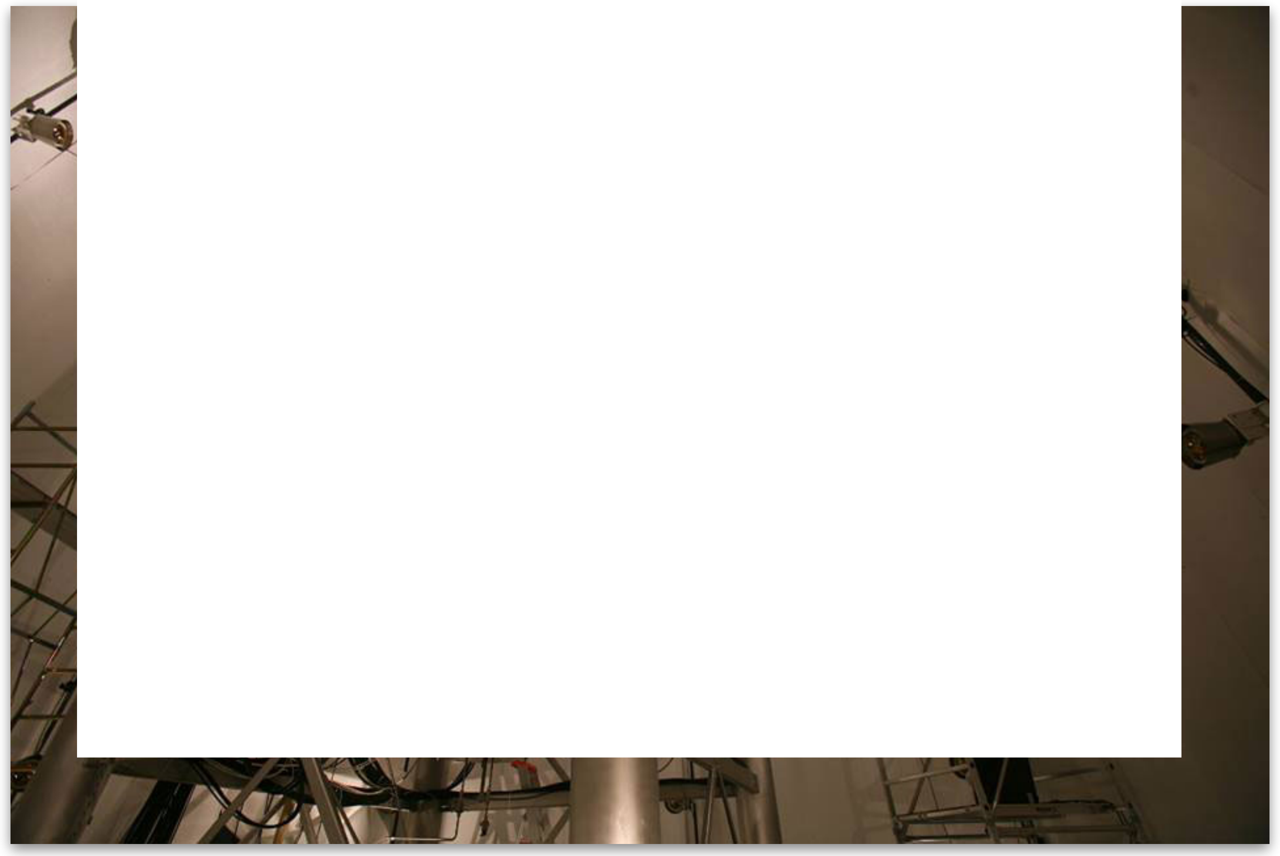
Water





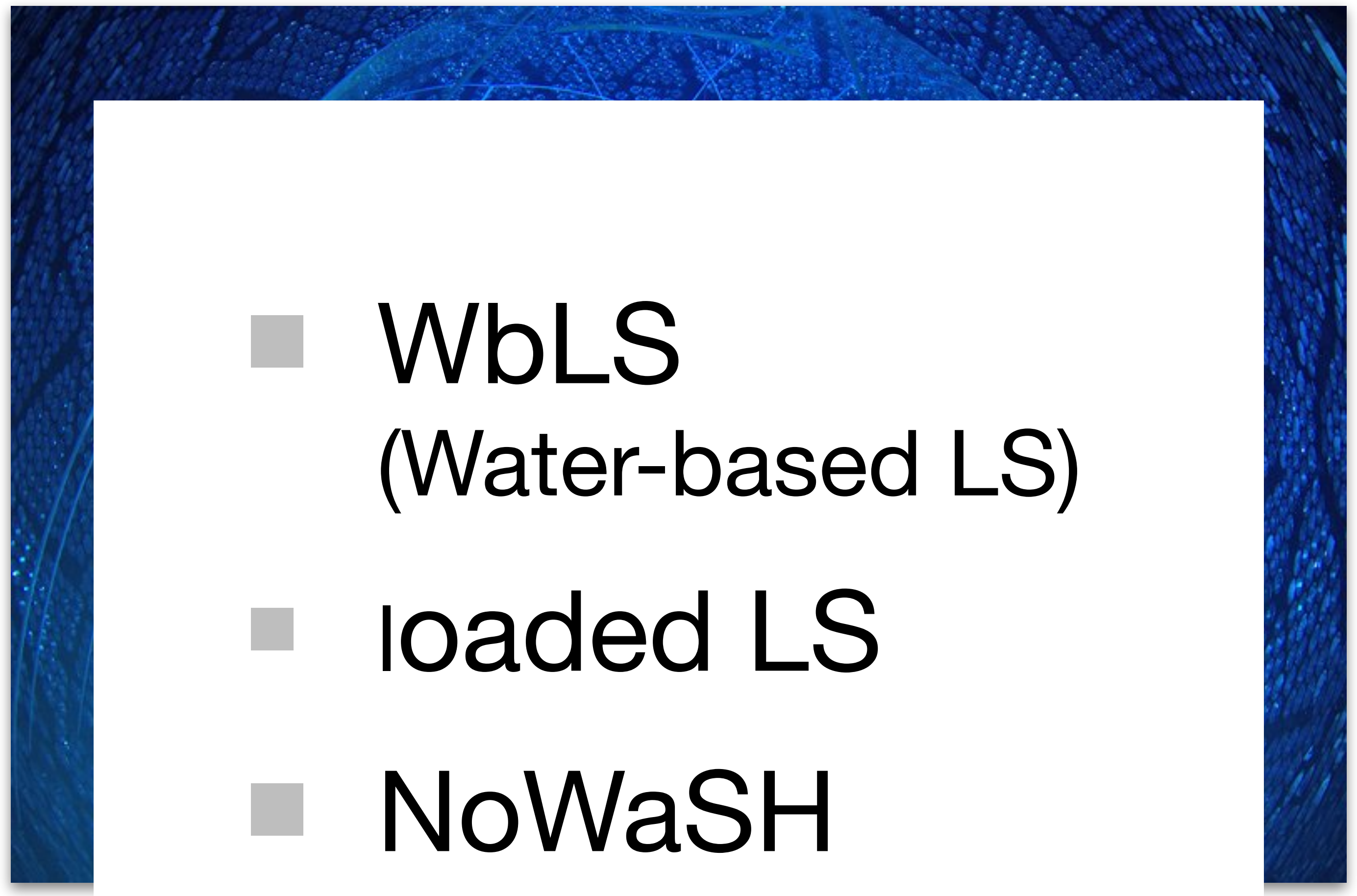
The liquids

Liquid Noble Gases

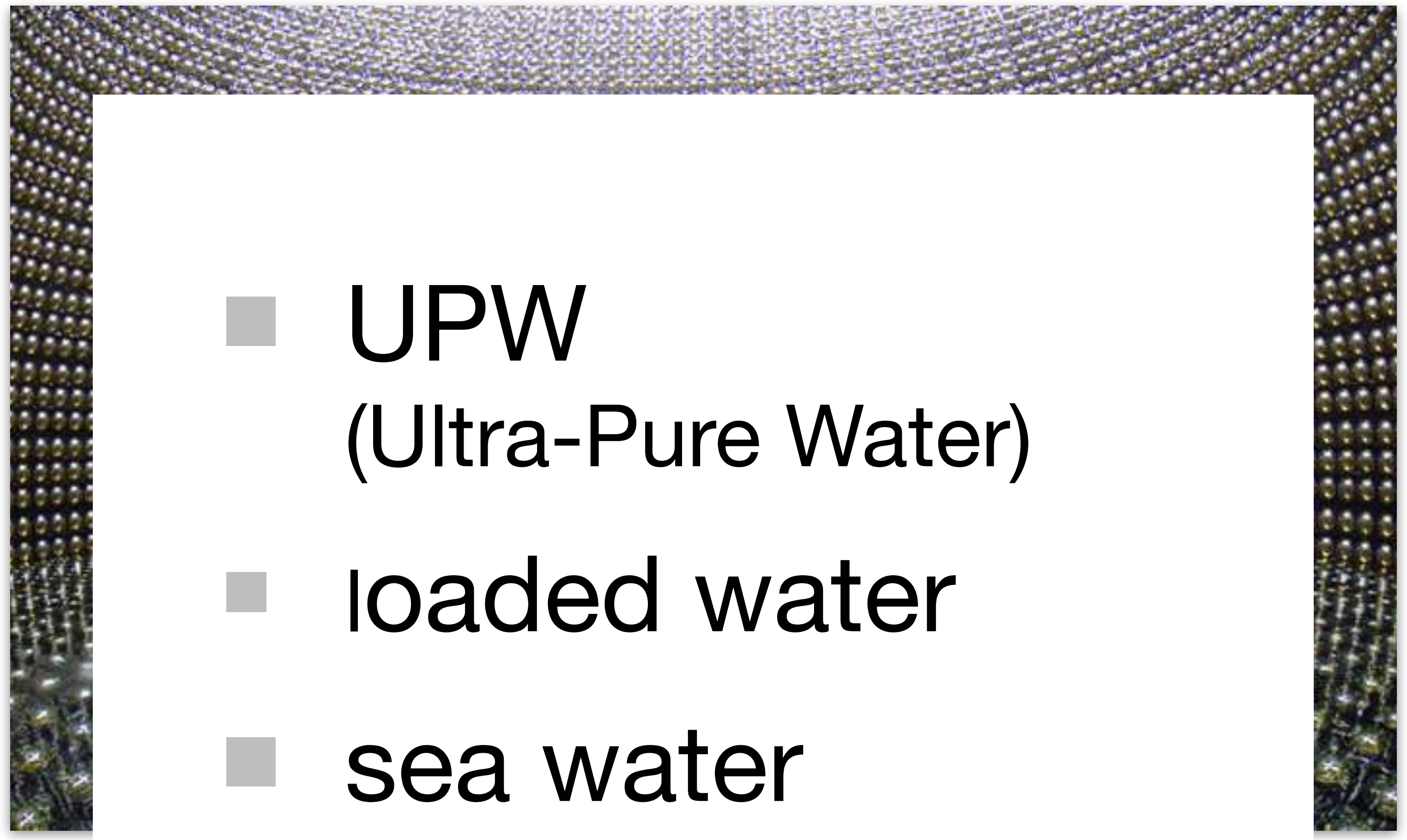
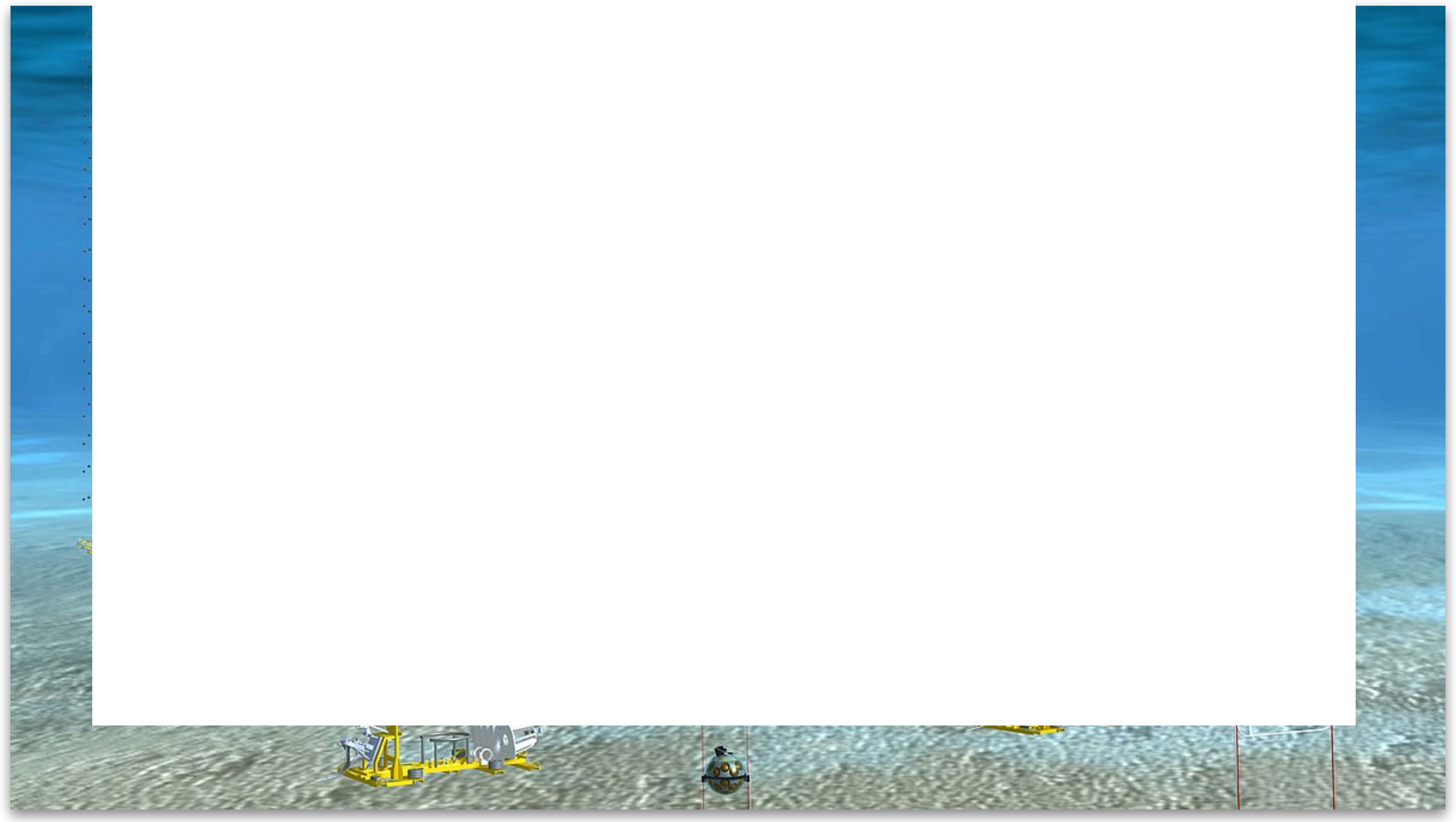
- LXe (Xenon)
- LAr (Argon)
- LHe (Helium)

Liquid Scintillator




- WbLS
  (Water-based LS)
- loaded LS
- NoWaSH
  (New opaque
  Wax Scintillator,
  Heidelberg)

Water

- UPW
  (Ultra-Pure Water)
- loaded water
- sea water

Primary signals and their energy and time scales

Liquid Noble Gases

- **Atomic excitation → dimer formation → dimer decay**
  - after O(ns - µs)
  - O(10^4) photons / MeV
  - VUV - UV
- **Ionization**
  - instantaneous
  - O(10^4) charges / MeV
- **Quasi-particle creation**
  - instantaneous
  - O($10^{5\text{-}6}$) quasi-particles / keV

Liquid Scintillator

- **Atomic excitation / ionization → fluorescence and phosphorescence**
  - after O(ns - µs)
  - O(10^4) photons / MeV
  - UV - visible light

Water

- **Cherenkov light**
  - instantaneous
  - O(10^2) photons / MeV
  - visible light

Primary signals and their energy and time scales

Liquid Noble Gases

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Water

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  - instantaneous
  - $O(10^2)$ photons / MeV
  - visible light

NB: signal collection times can be as slow as ms scale!

Primary signals and their energy and time scales

Liquid Noble Gases

light + charge

or

light + phonon readout

Liquid Scintillator

Water

light readout

NB: signal collection times can be as slow as ms scale!

Primary signals and their energy and time scales

Liquid Noble Gases

light + charge

or

light + phonon readout

Liquid Scintillator

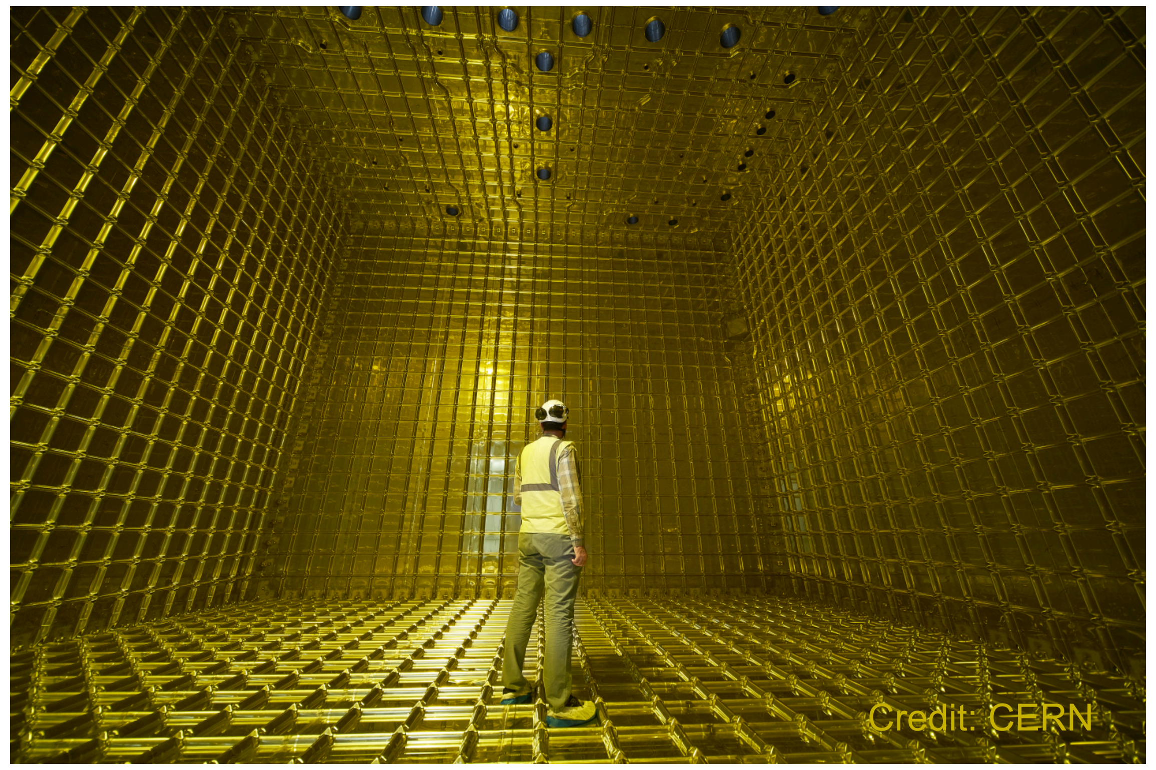
Water

light readout

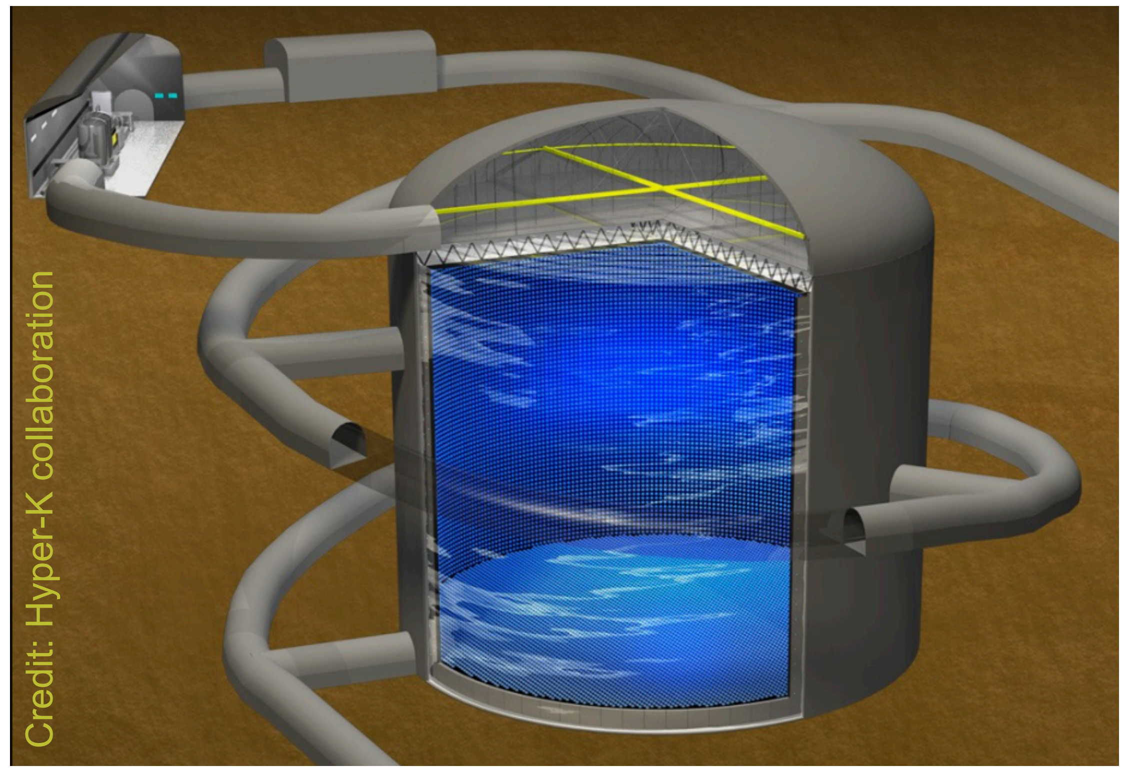
The liquids are used both as main target and for veto detectors.

Categorization of main areas for R&D streamlining

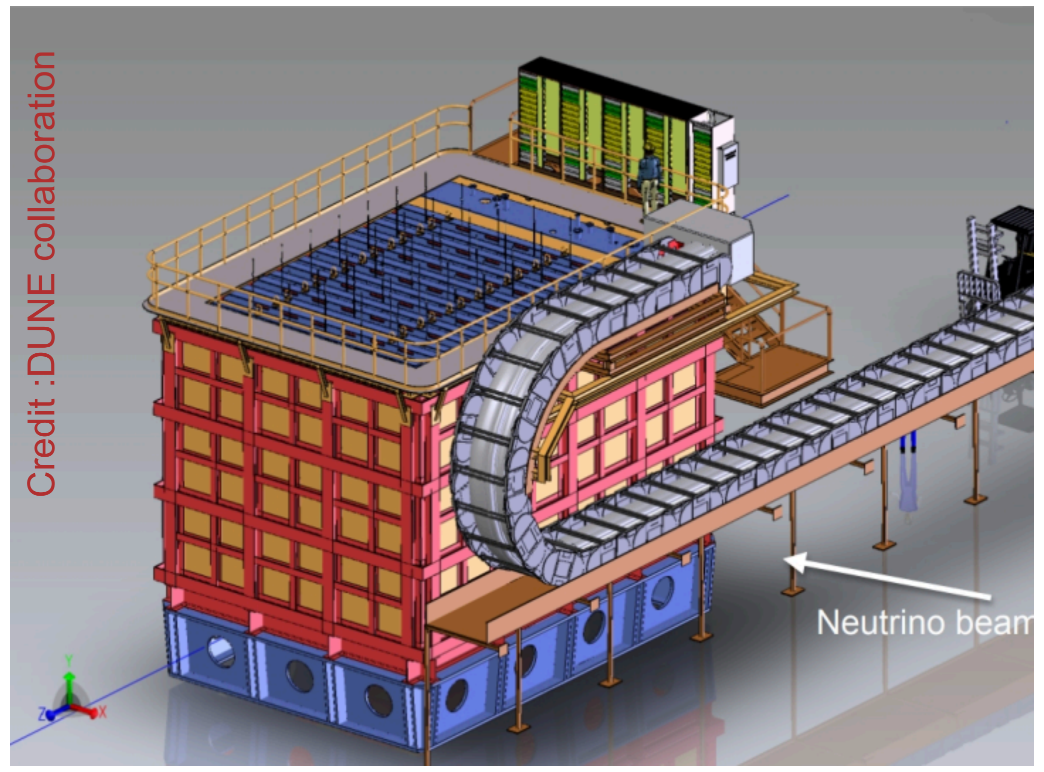
DUNE programme



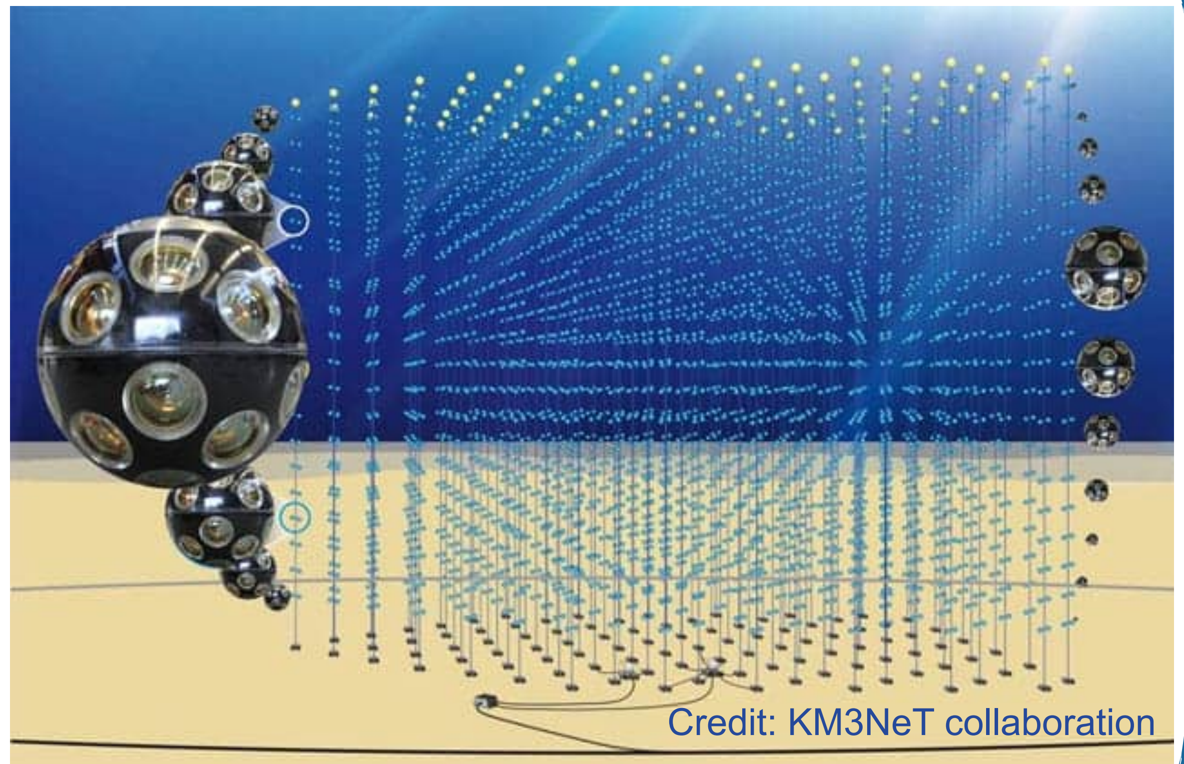
Hyper-K programme



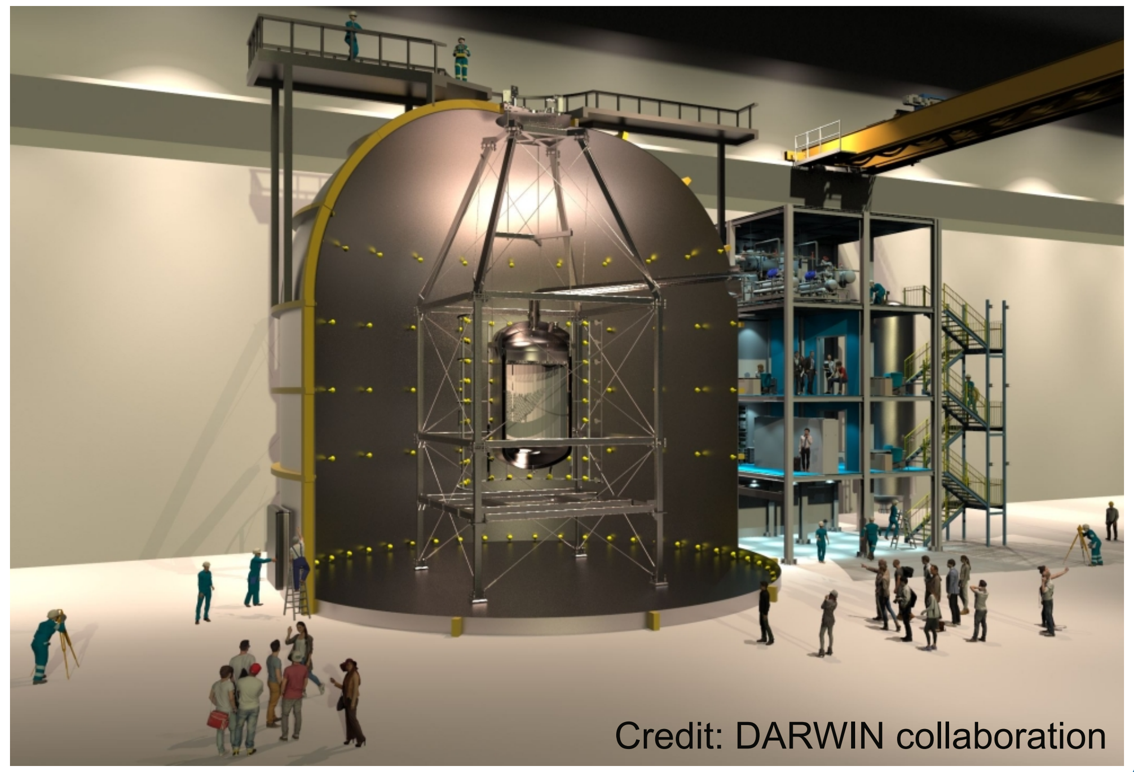
neutrino near detectors



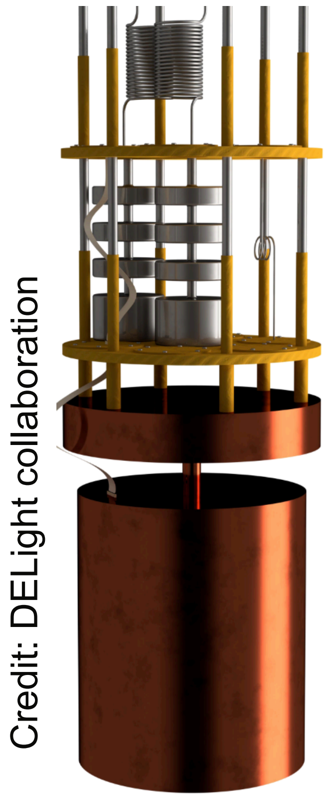
neutrino telescopes



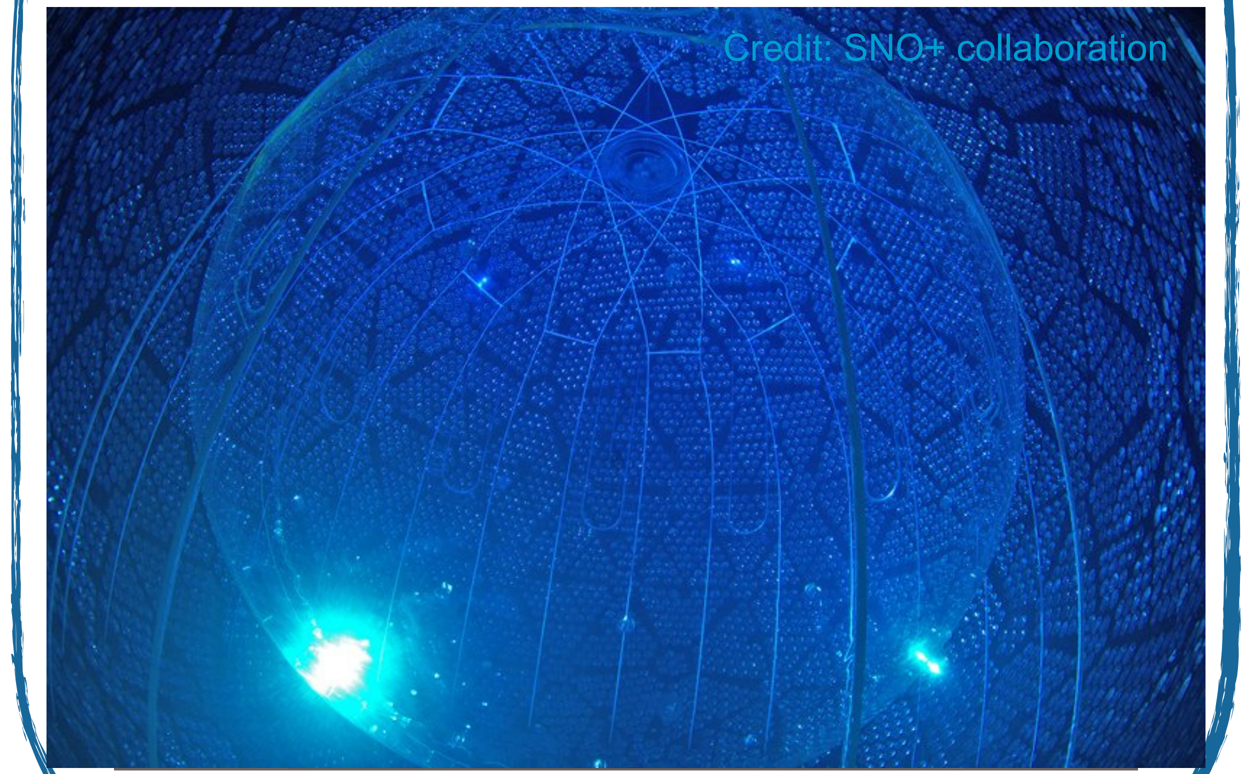
multi-tonne scale
dark matter detectors



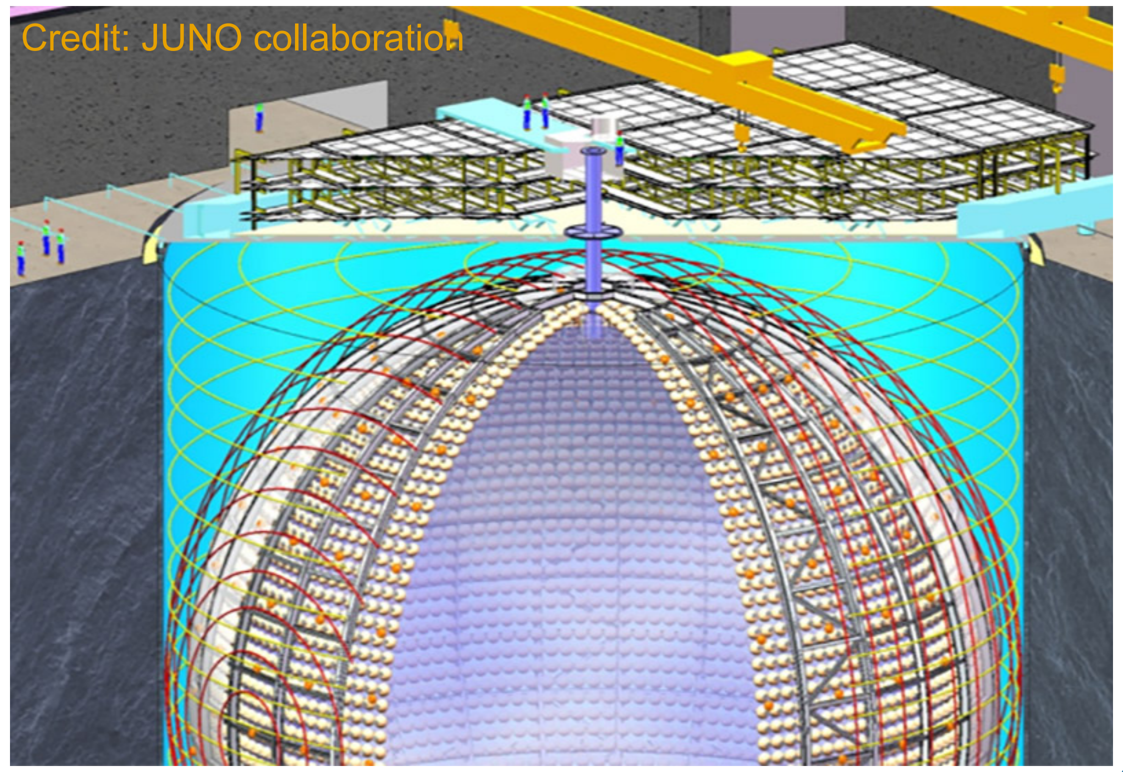
light dark matter
detectors (g- to kg-scale)



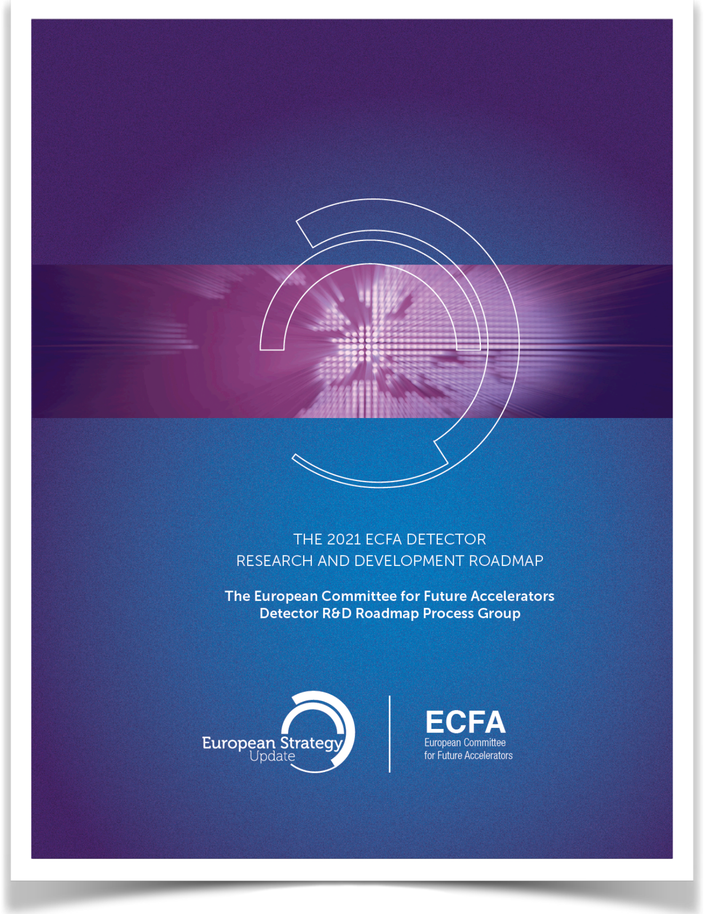
tonne-scale
0νββ experiments

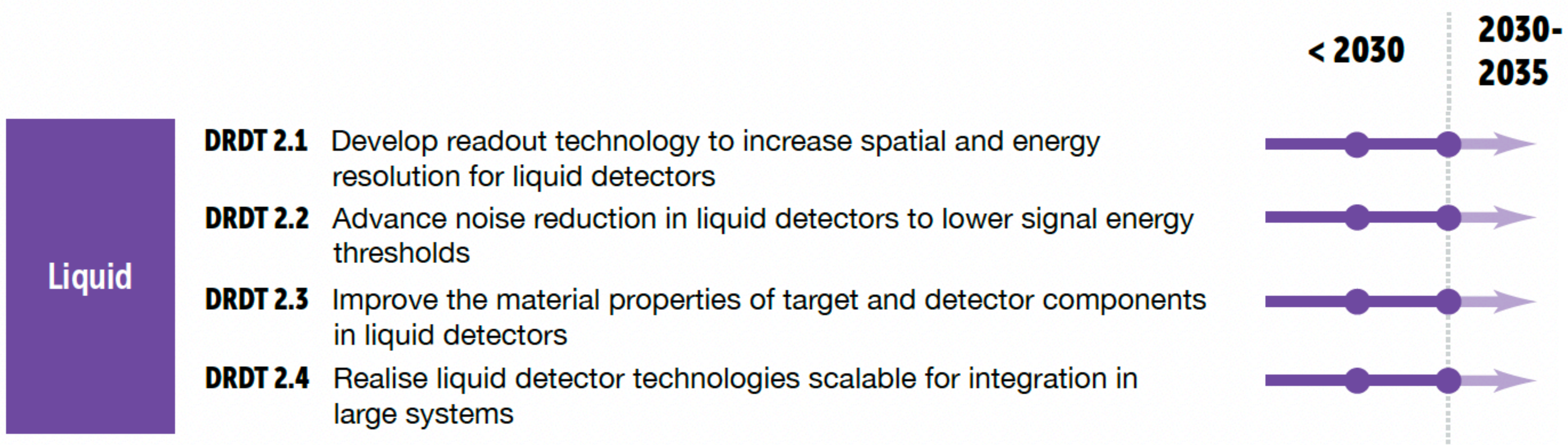


low-energy scintillator
neutrino detectors



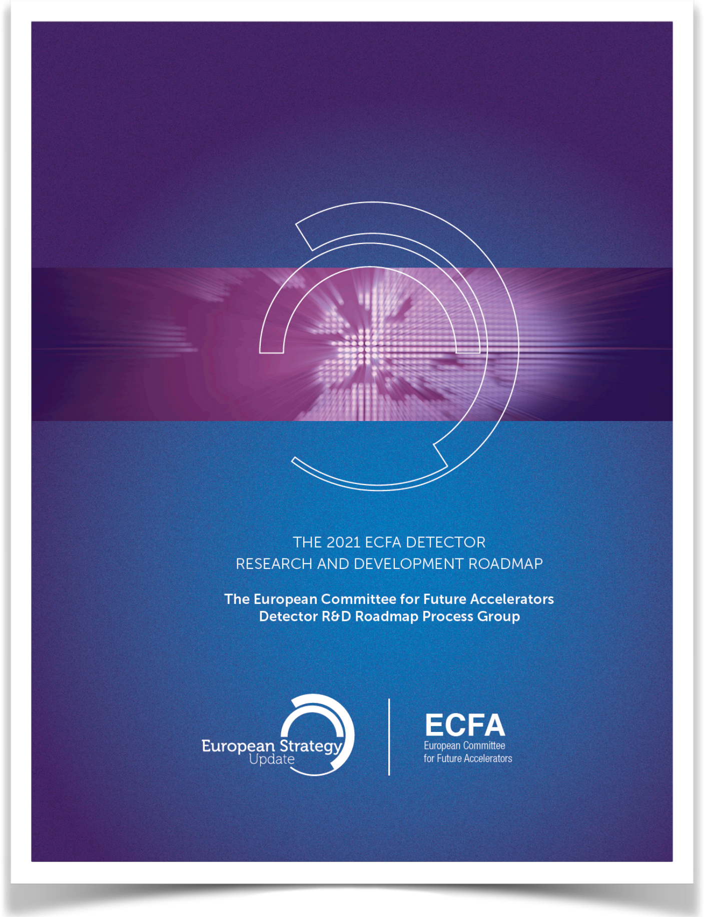
Major detector R&D themes for liquid detectors

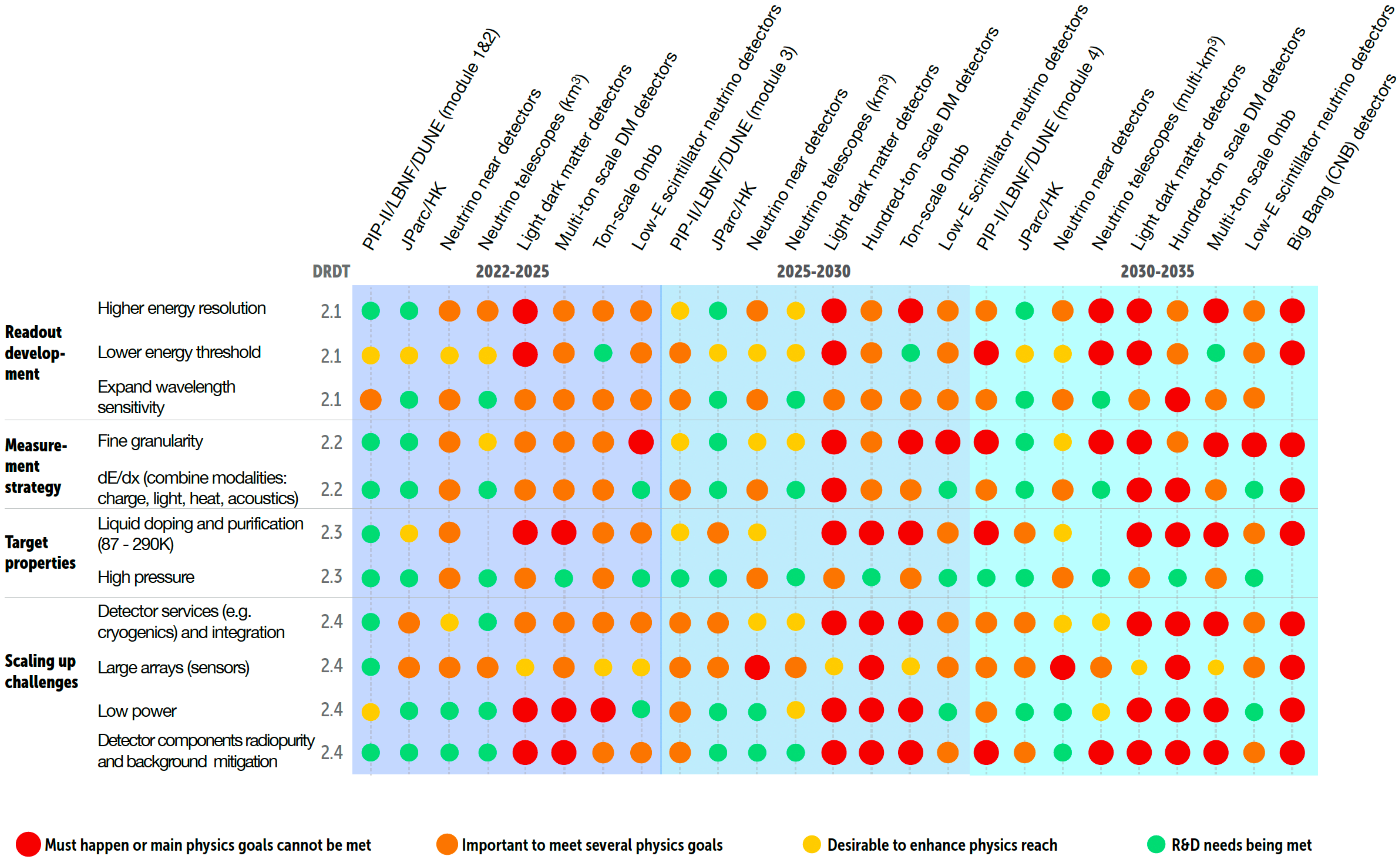




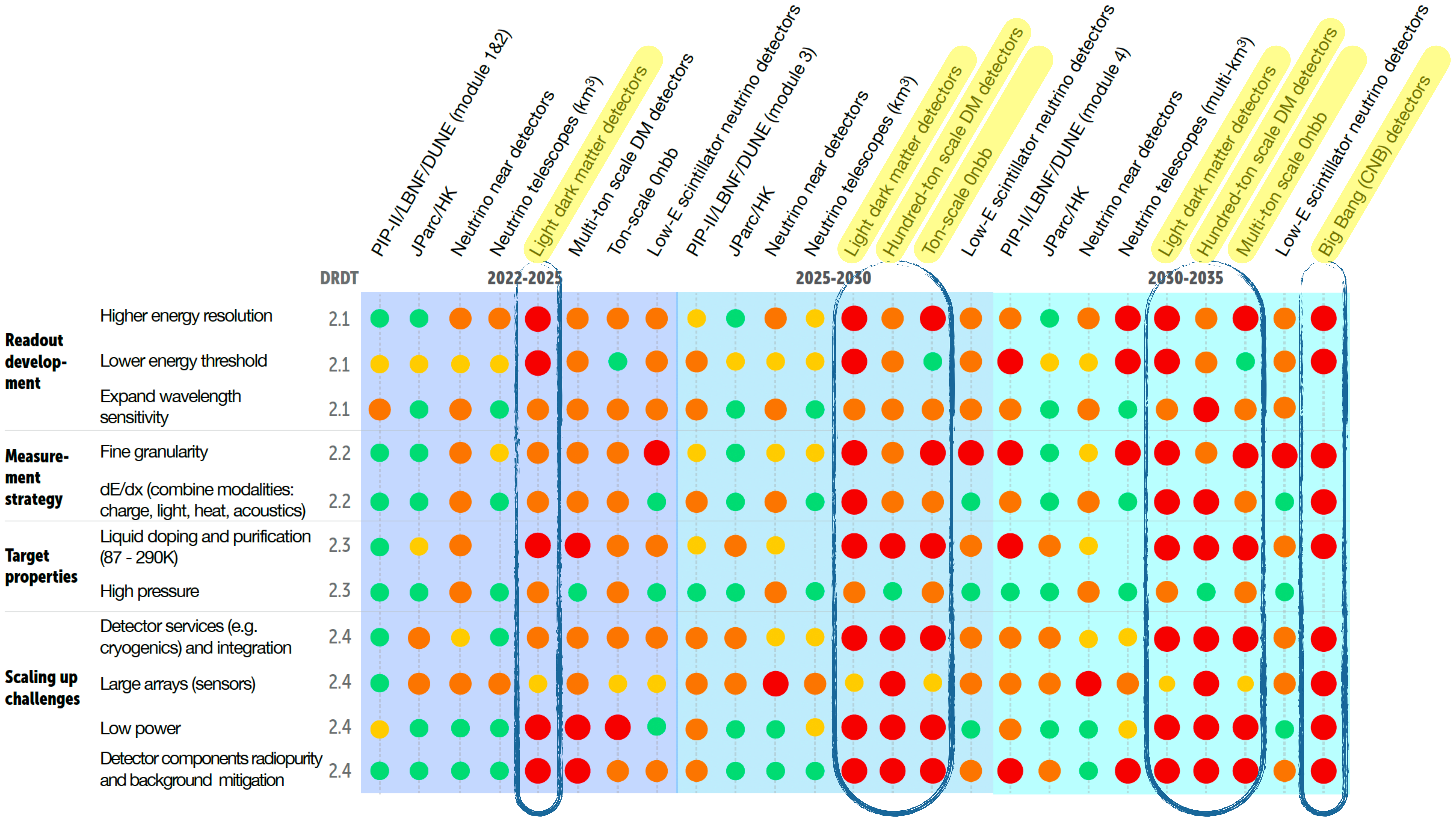
- Readout development
  - Develop readout technology to increase **spatial and energy resolution**
- Measurement strategy
  - Advance **noise** reduction to lower **energy thresholds**
- Target properties
  - Improve the **material properties** of target and detector components
- Scaling up challenges
  - Realize technologies **scalable** for integration in large systems

Major detector R&D themes for liquid detectors





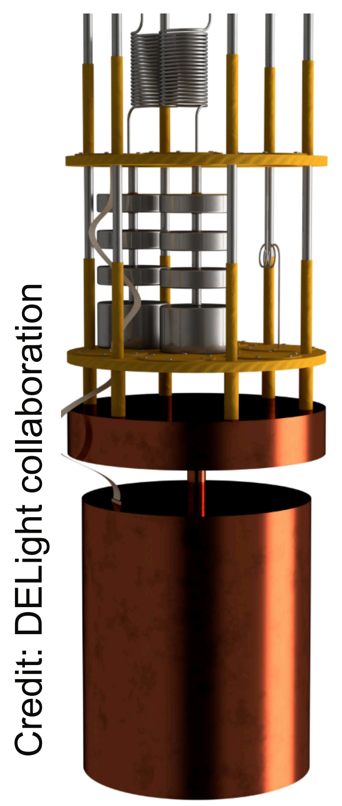
Major detector R&D themes for liquid detectors

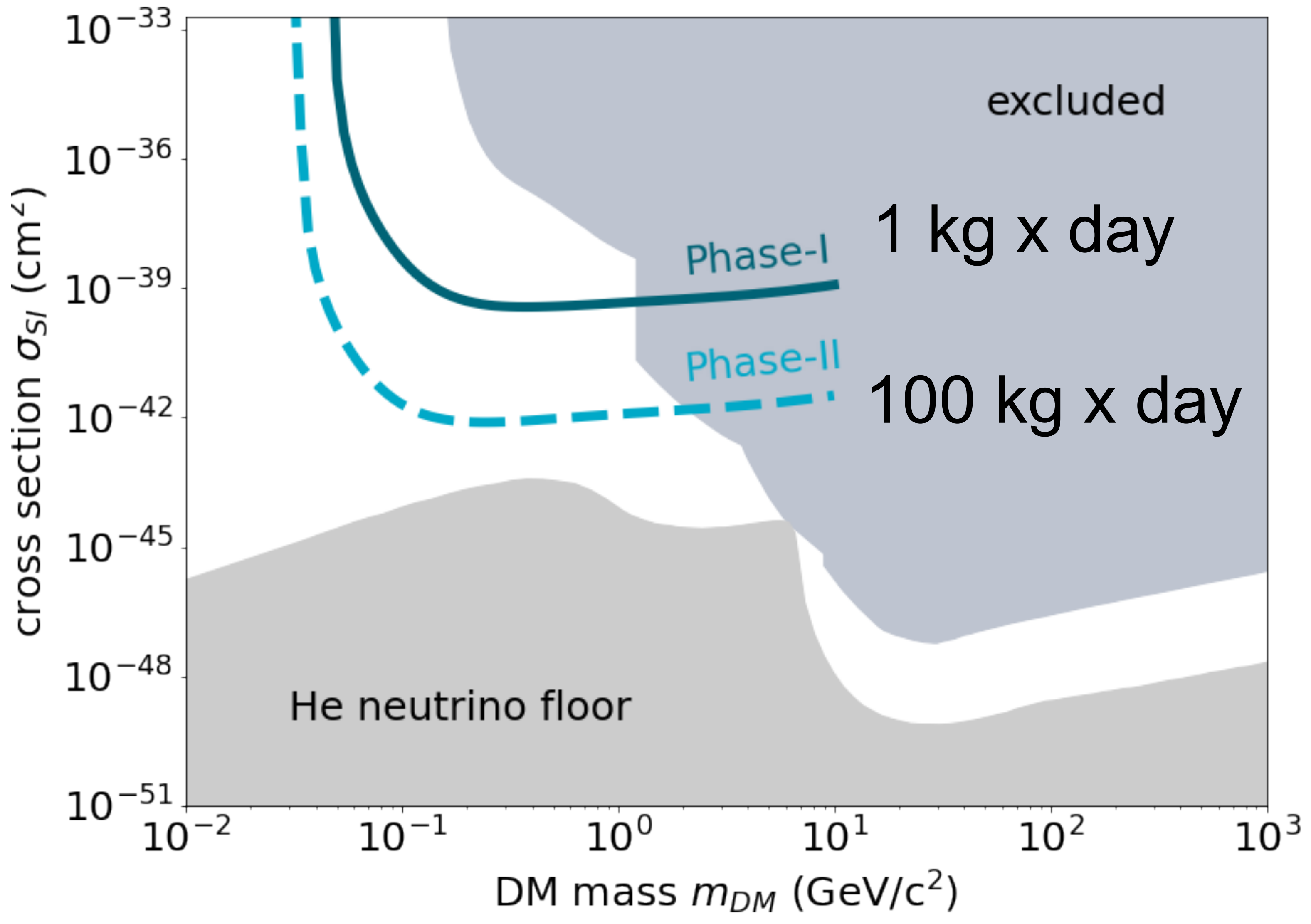


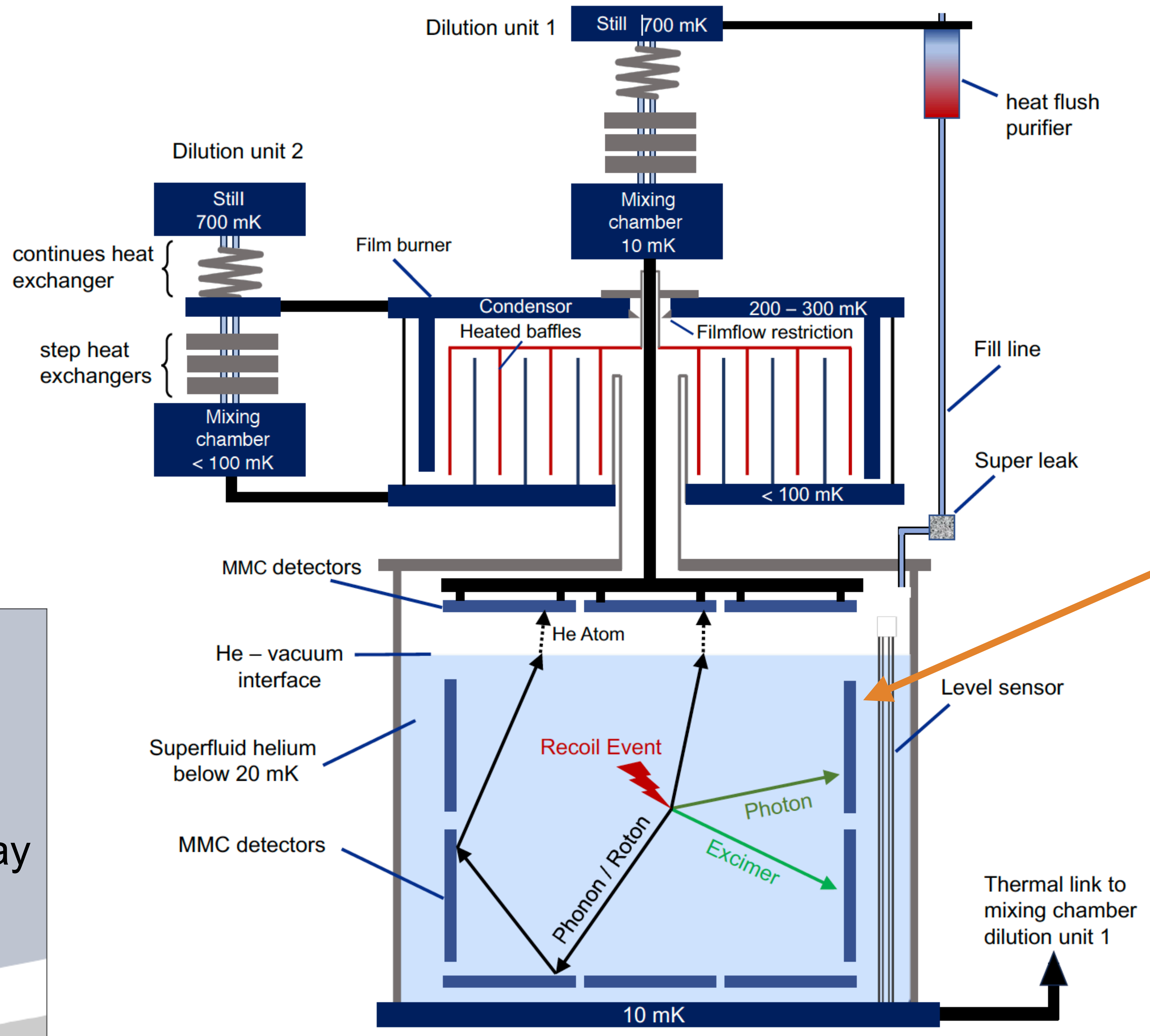
Must happen or main physics goals cannot be met — Important to meet several physics goals — Desirable to enhance physics reach — R&D needs being met

Light dark matter detectors

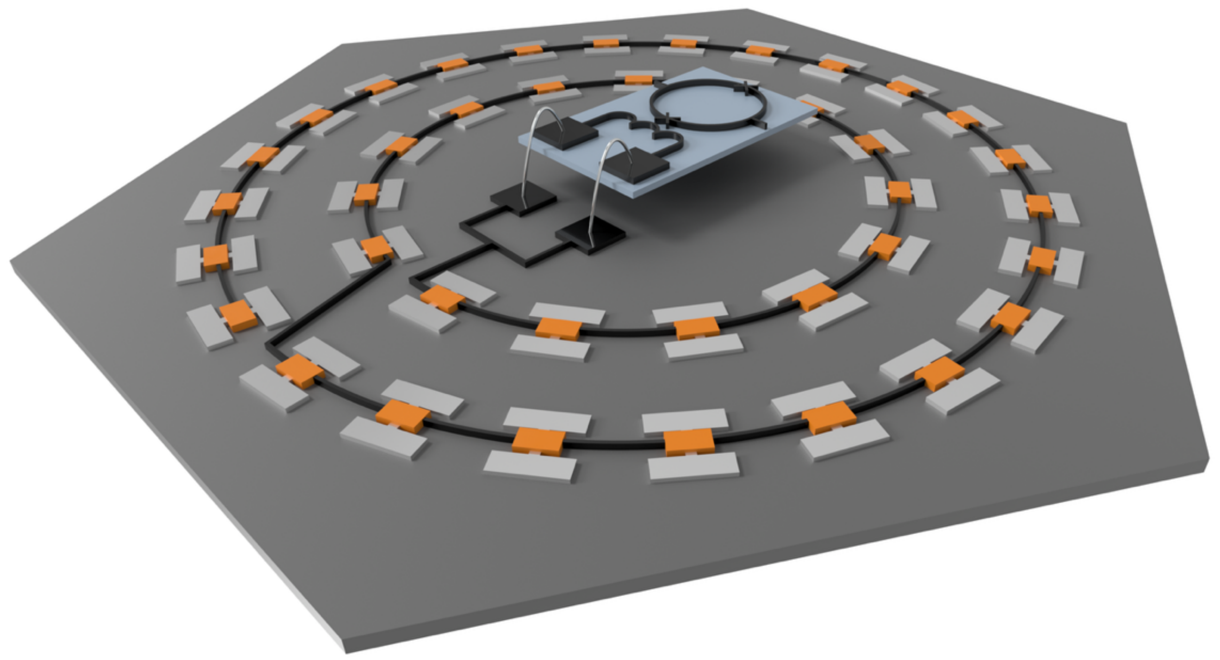
light dark matter detectors (g- to kg-scale)





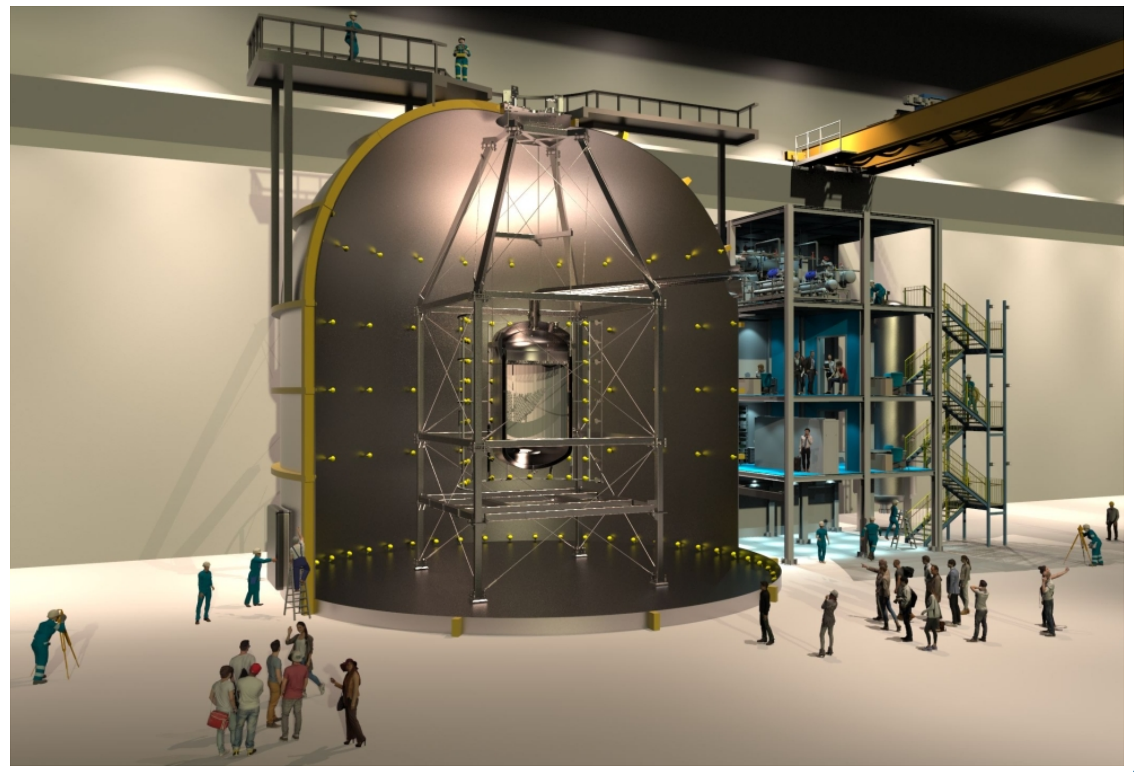


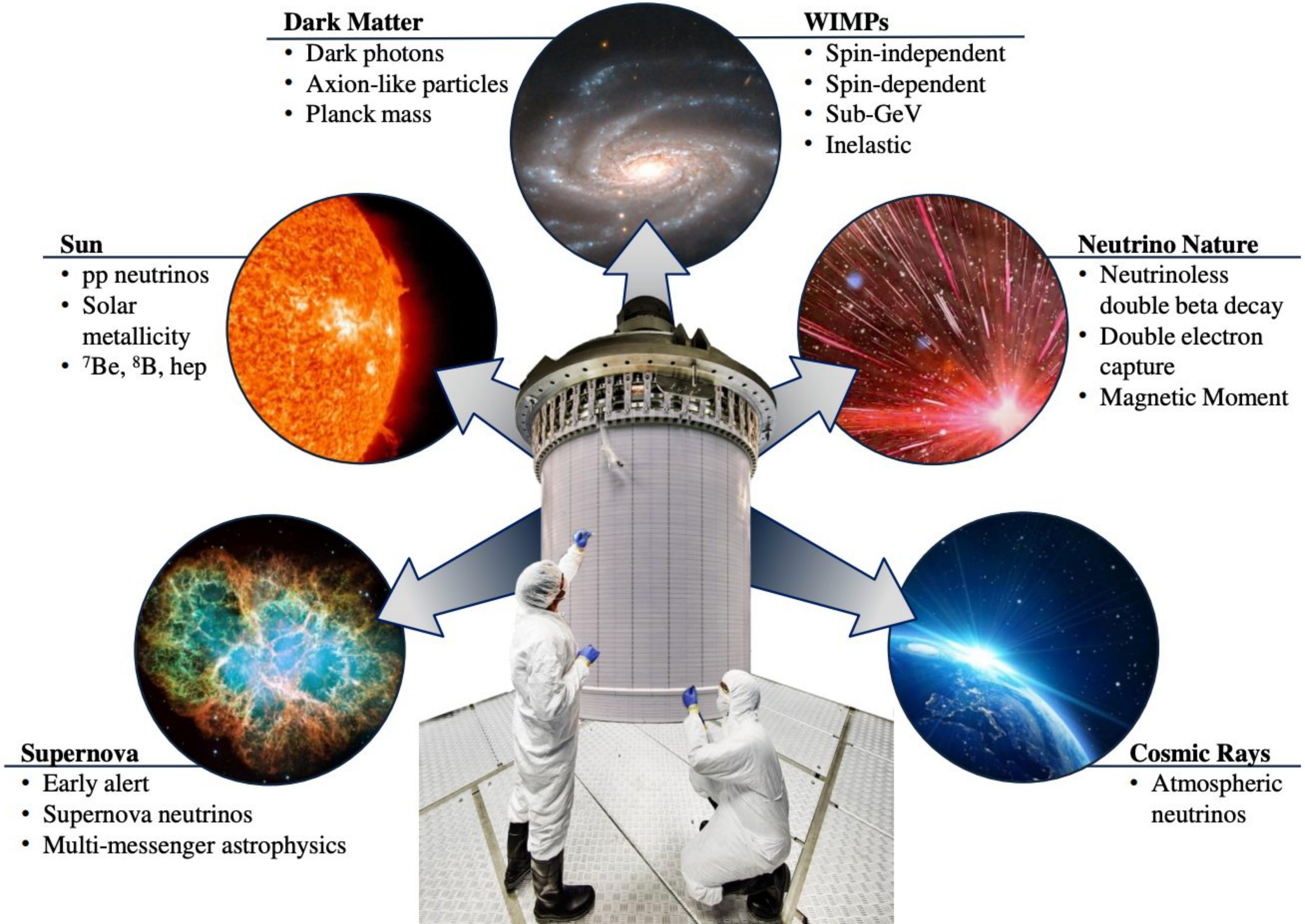
exploration of sub-GeV dark matter mass region with superfluid ^{4}He (LHe)



Hundred-ton scale dark matter detectors

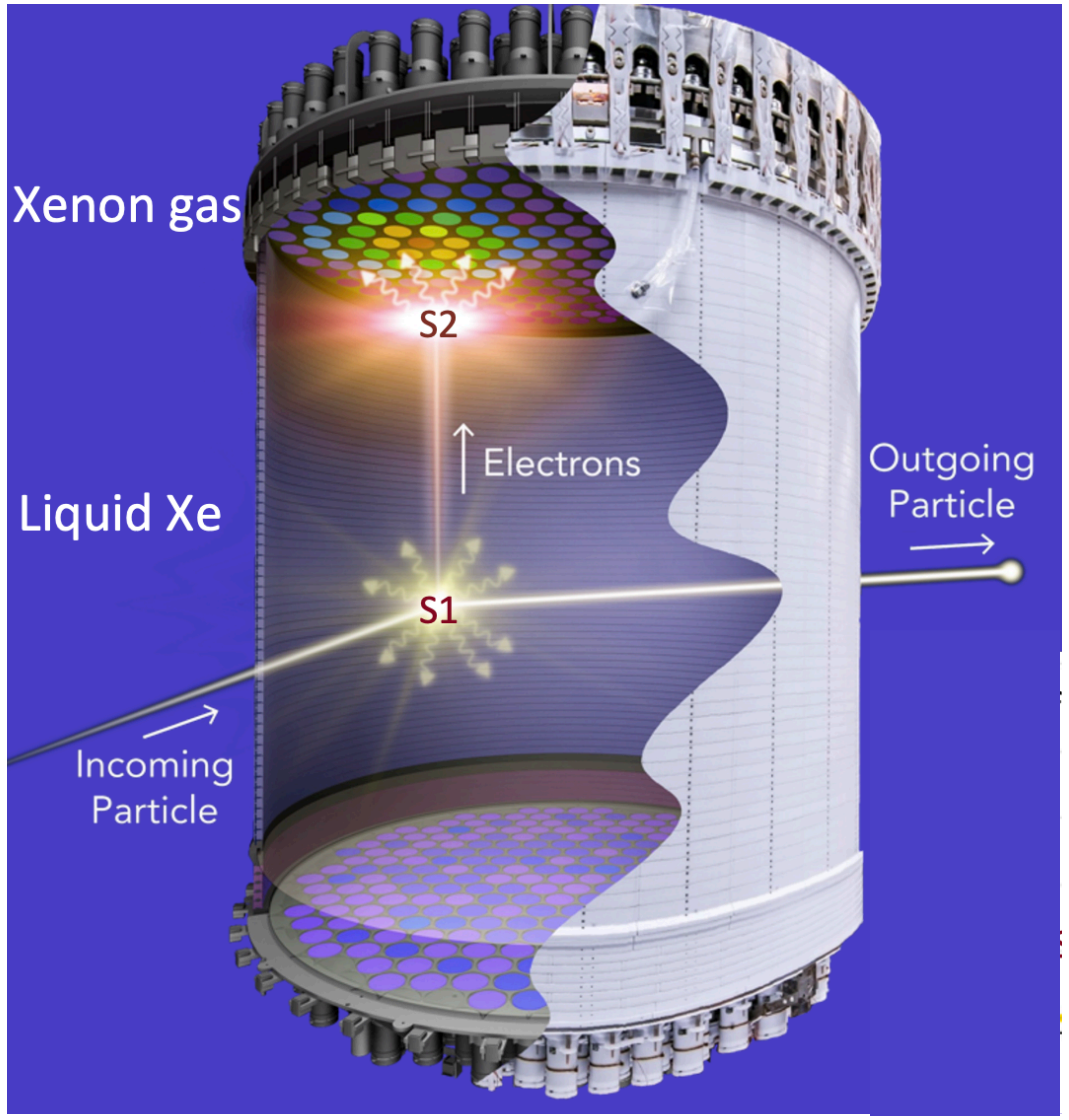
multi-tonne scale
dark matter detectors



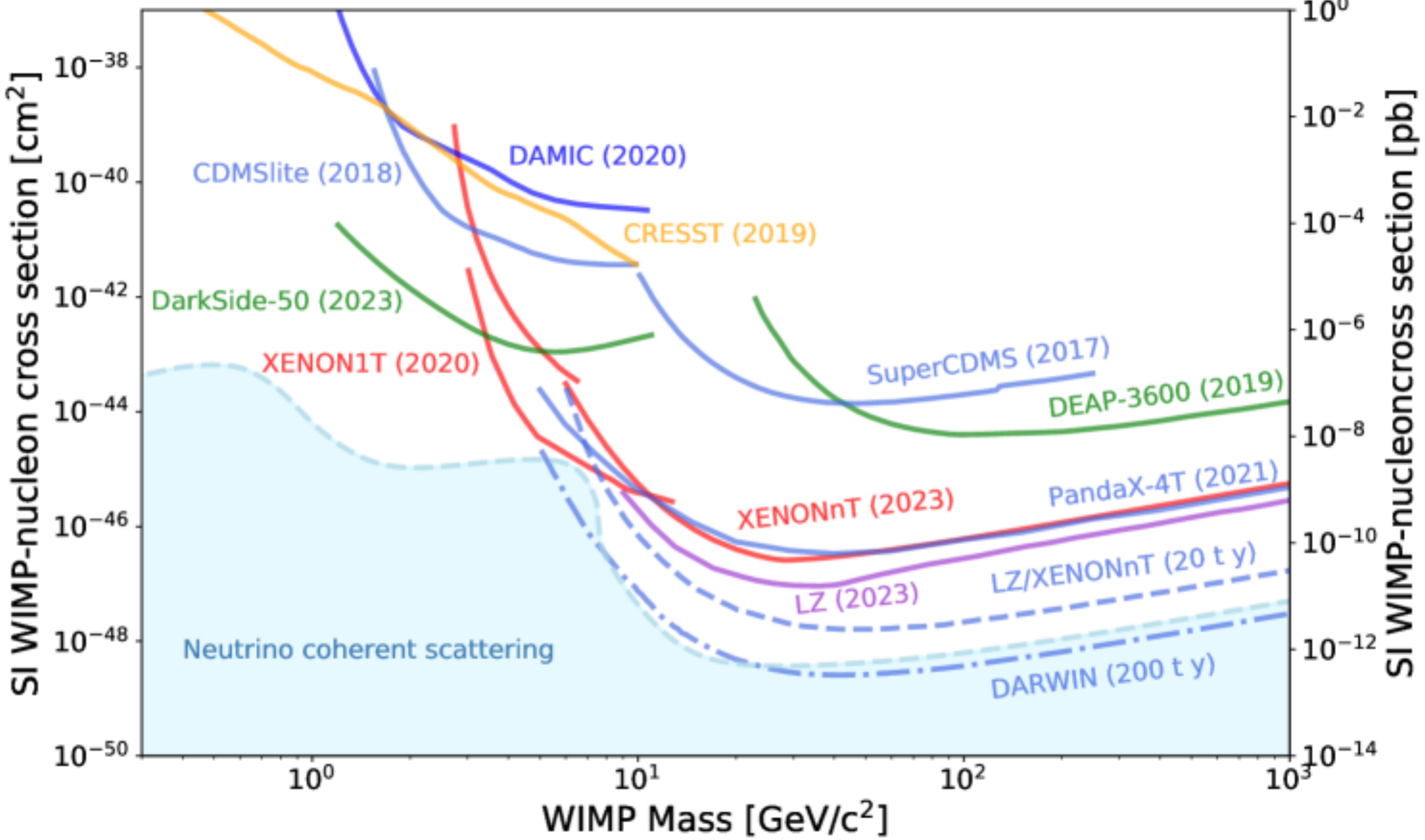


Hundred-ton scale dark matter detectors

Dual-phase xenon and argon TPCs

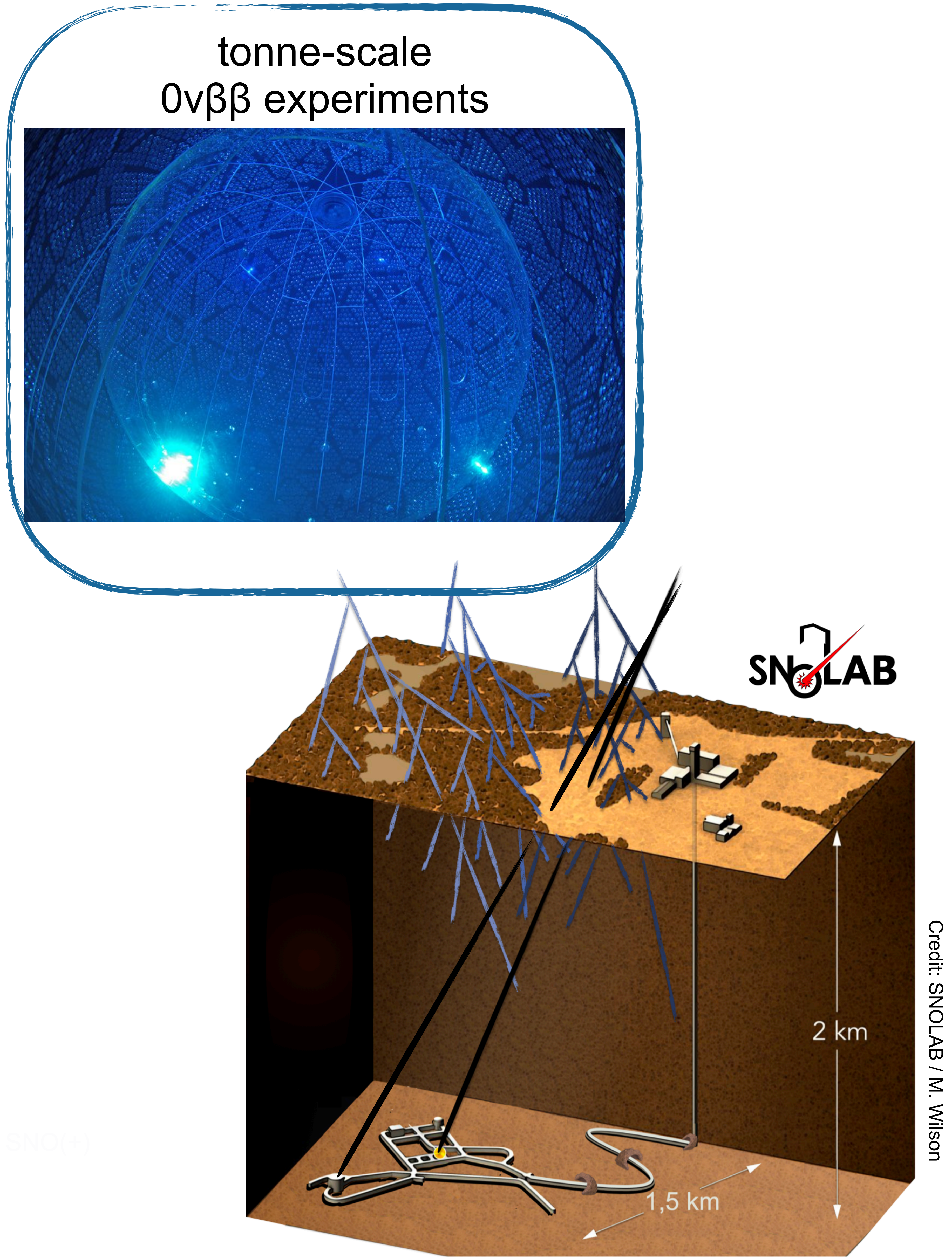


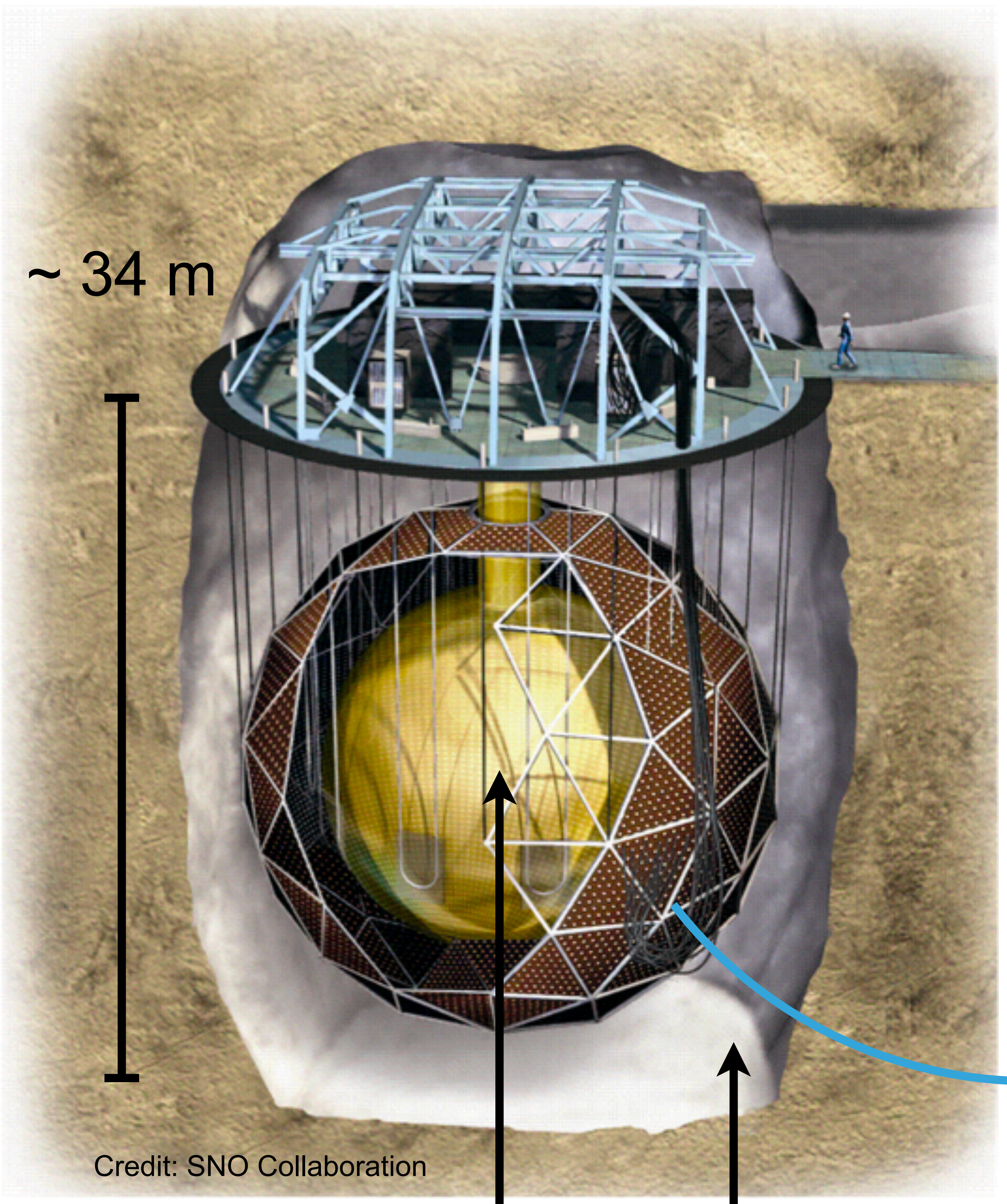
L. Baudis, arXiv:2404.19524



Scintillation light emitted by LAr and LXe: 128 nm and 178 nm, respectively

Ton scale 0νββ detectors

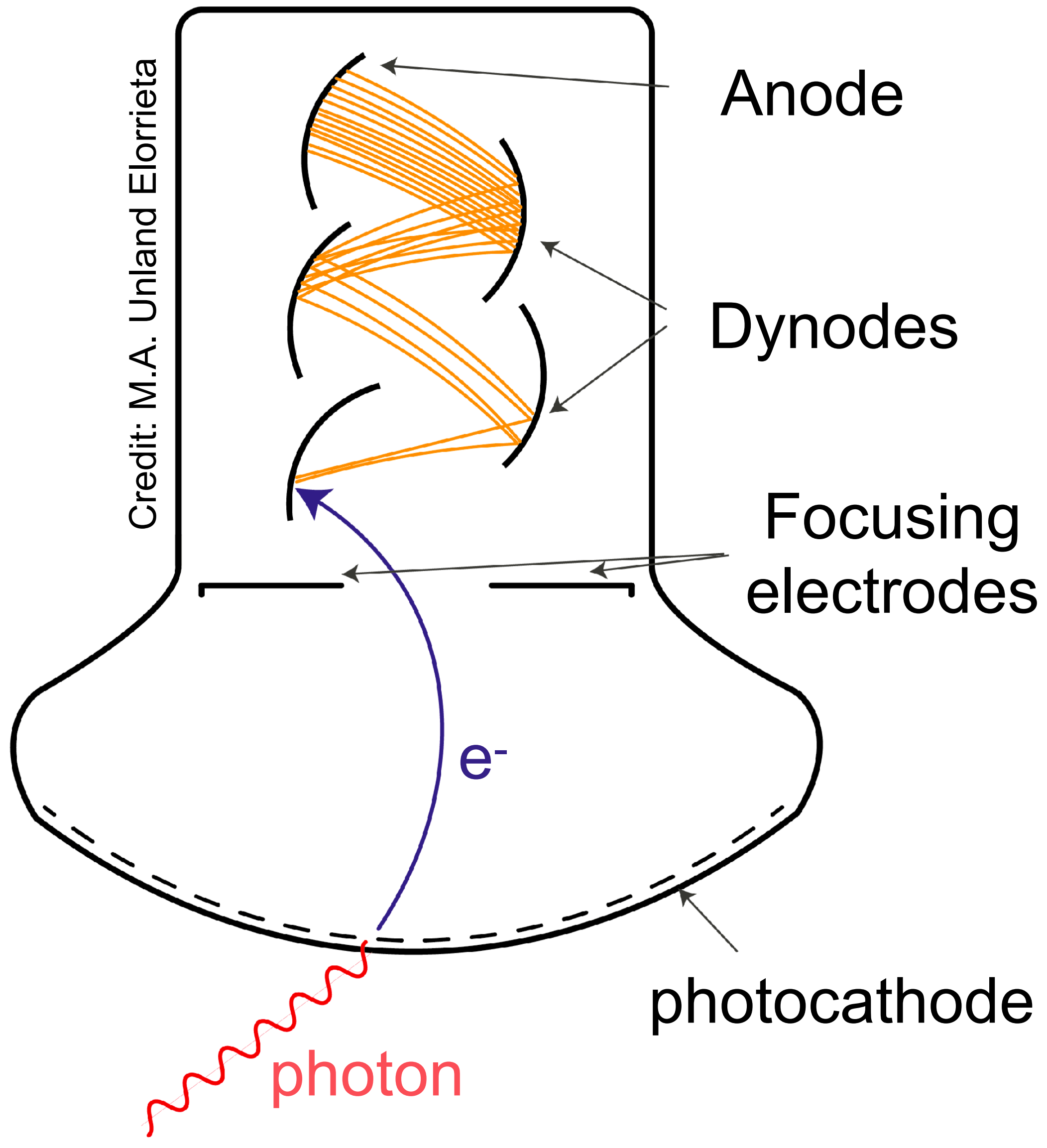




SNO: 1 kt of D_2O

SNO+: 0.78 kt of liquid scintillator

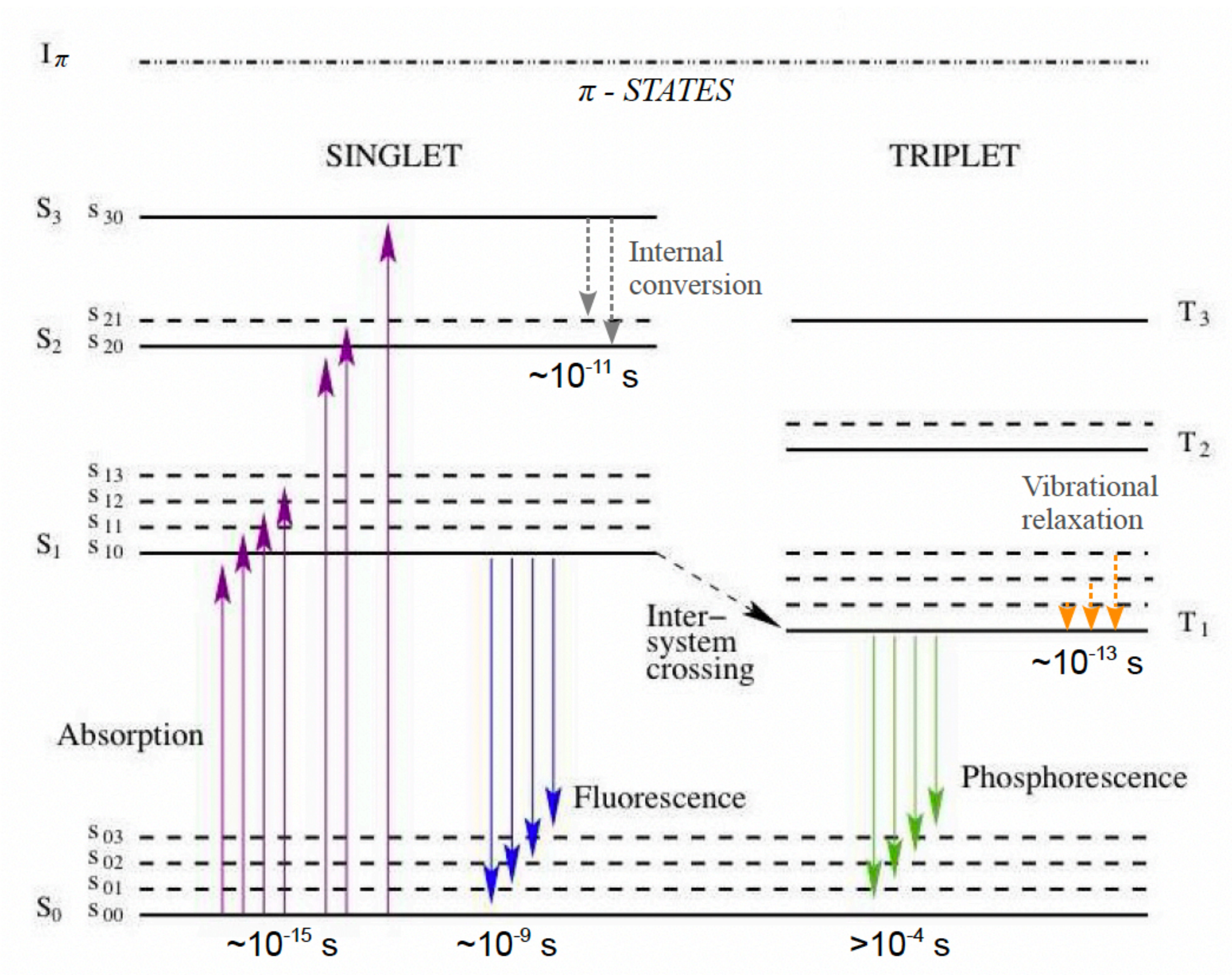
7 kt H_2O

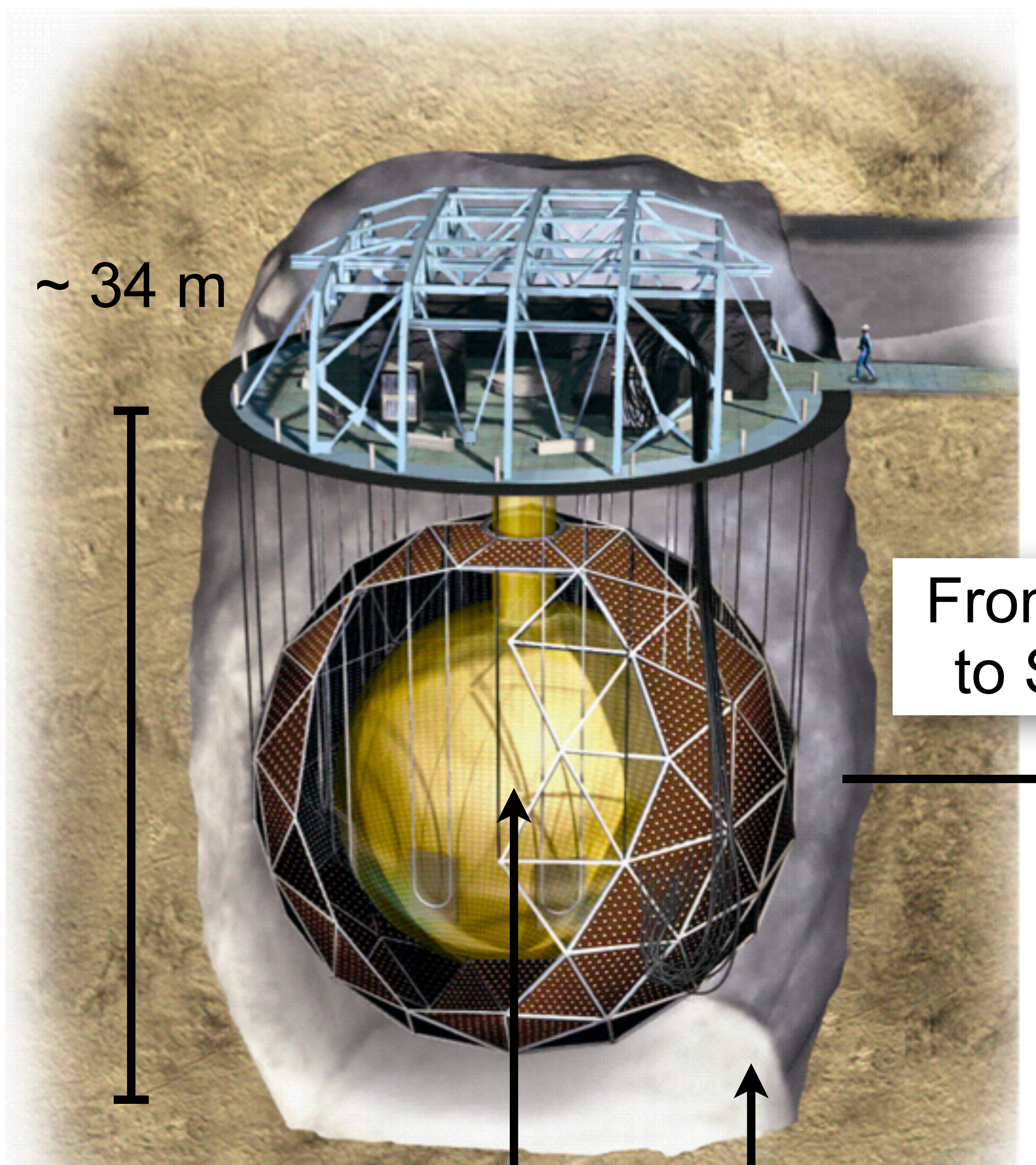


> 9000 PMTs with ø 20cm

Ton scale 0νββ detectors

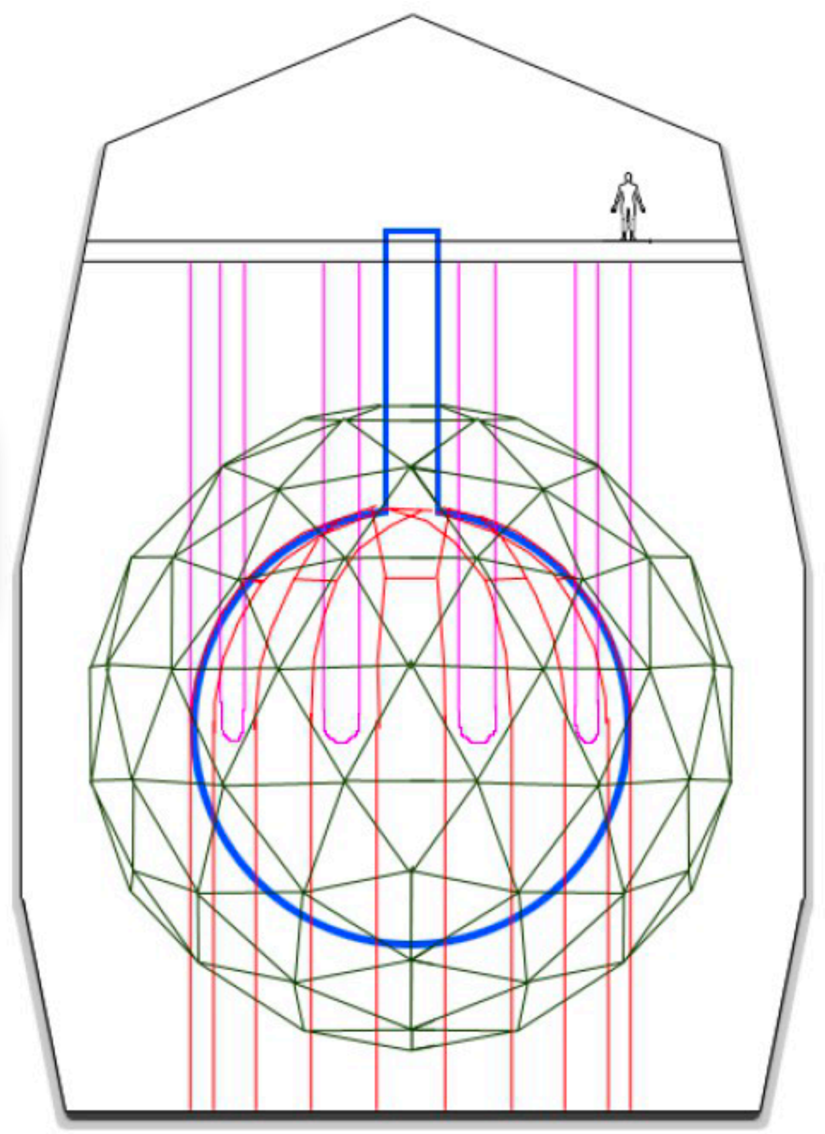
Scintillation light from an organic molecule





Credit: SNO Collaboration

From SNO to SNO+


Credit: SNO+ Collaboration

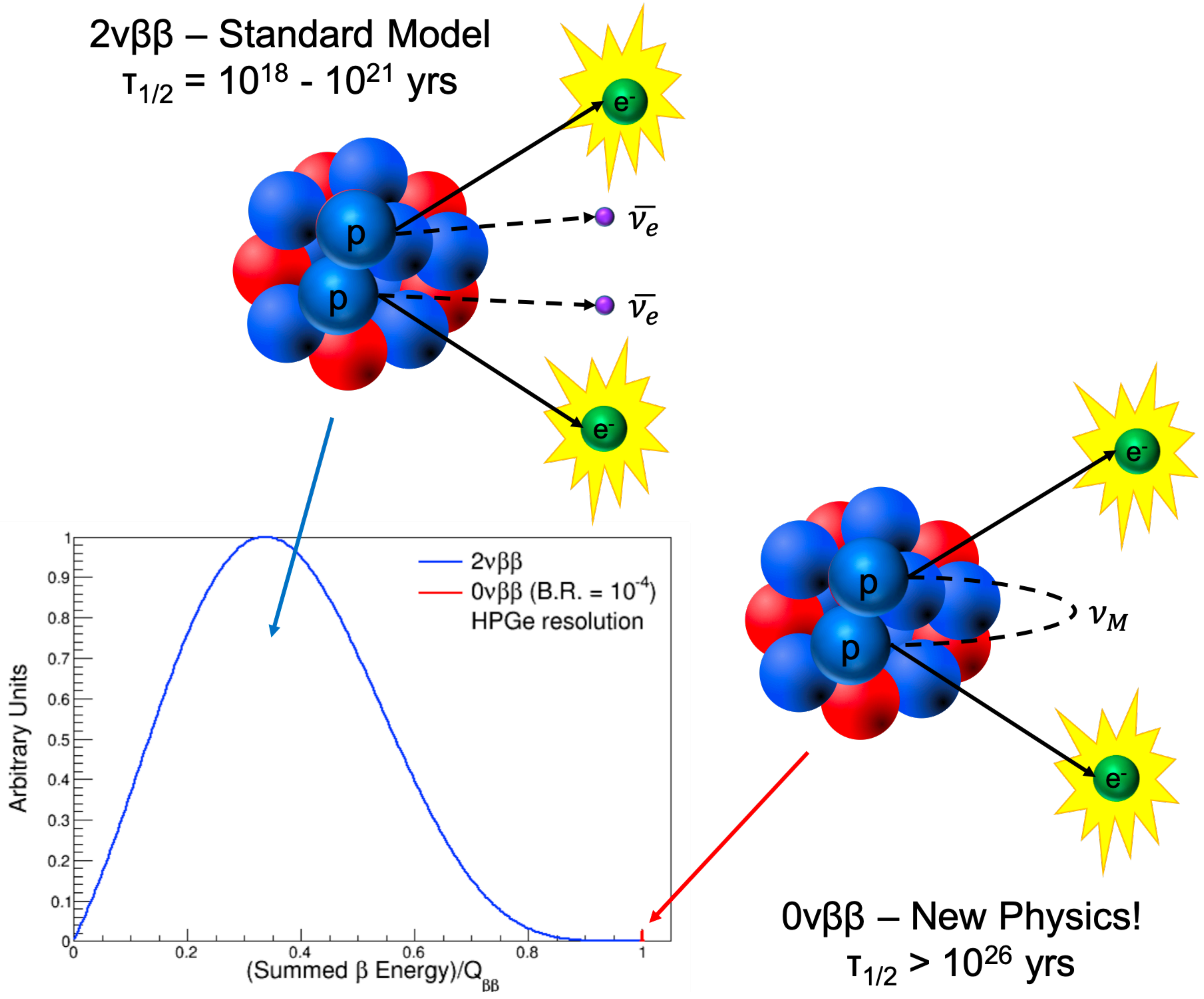
SNO: 1 kt of D_2O

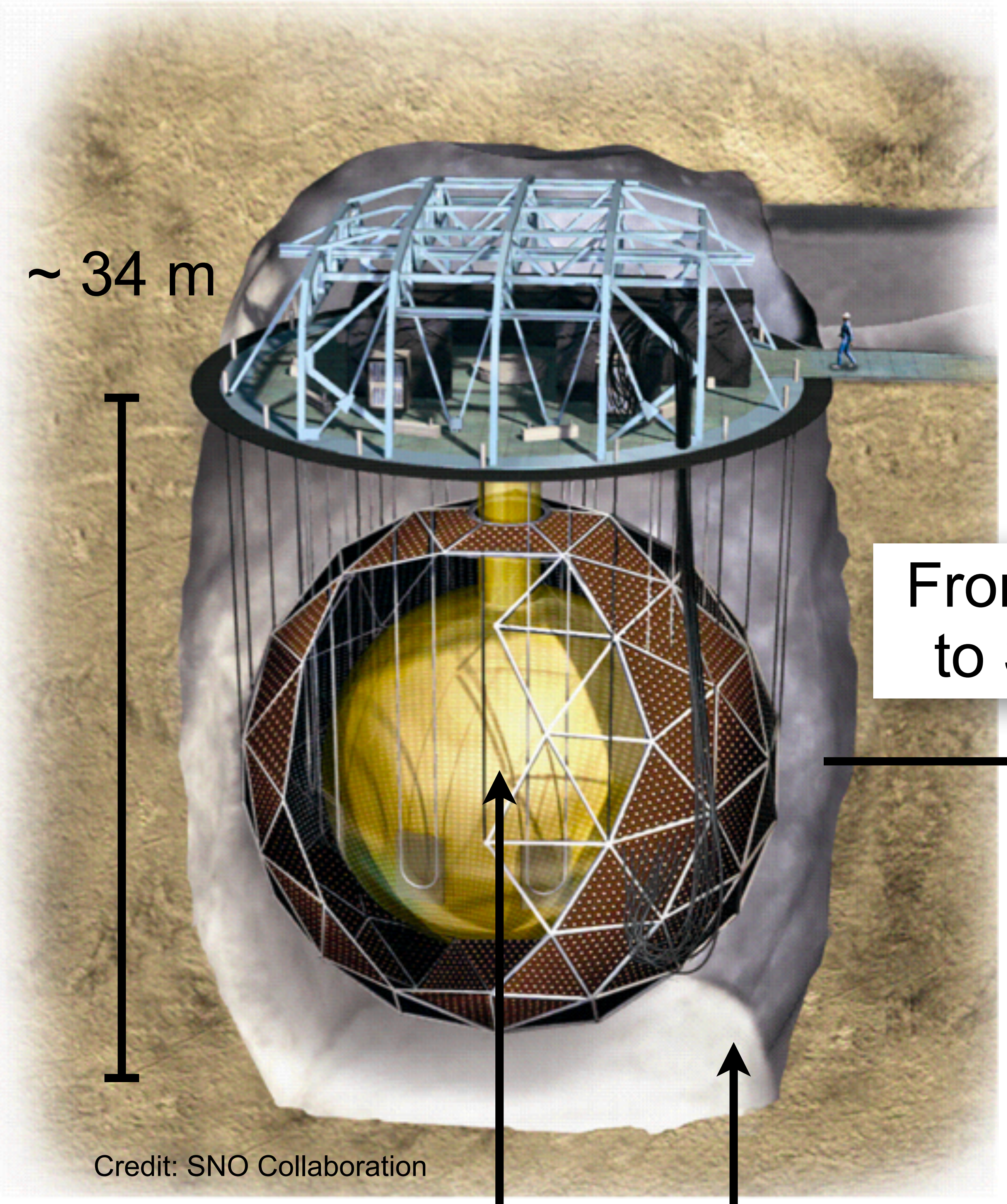
SNO+: 0.78 kt of liquid scintillator

7 kt H_2O

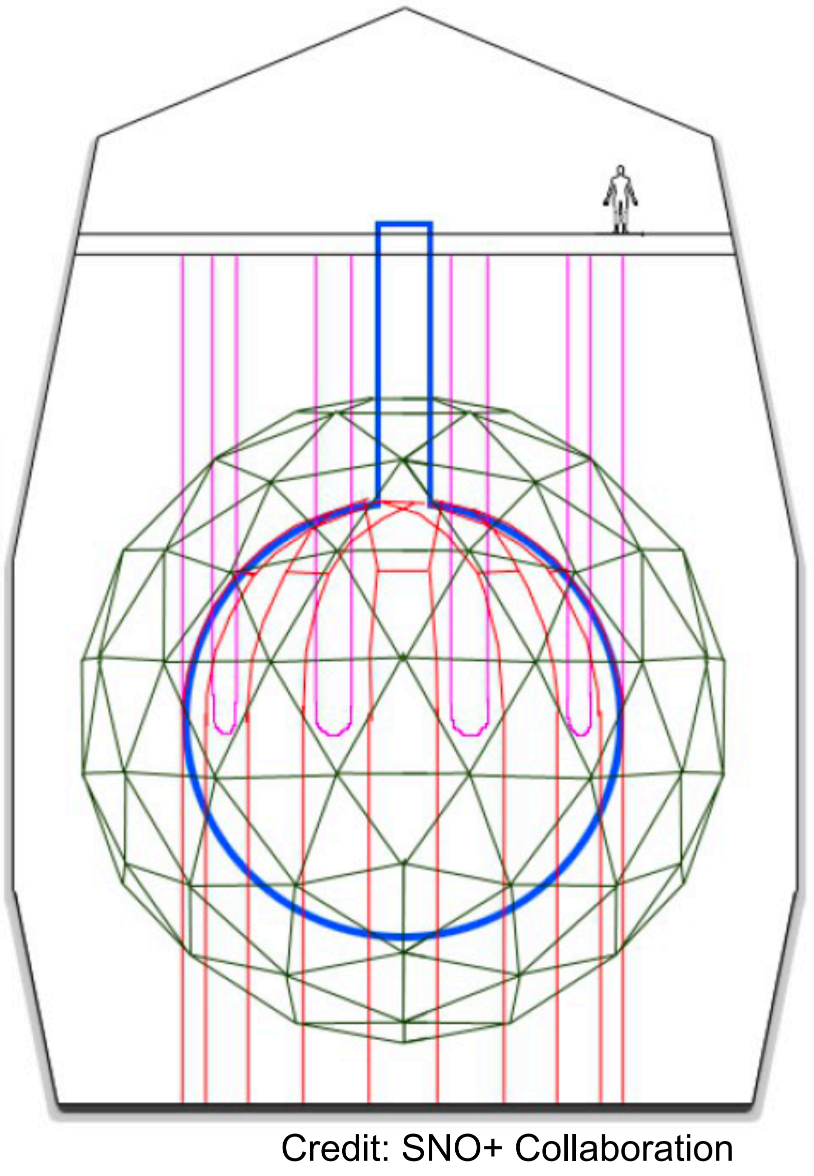
Ton scale 0νββ detectors

Searching for the 0νßß decay of ^{130}Te





From SNO to SNO+



SNO: 1 kt of D_2O

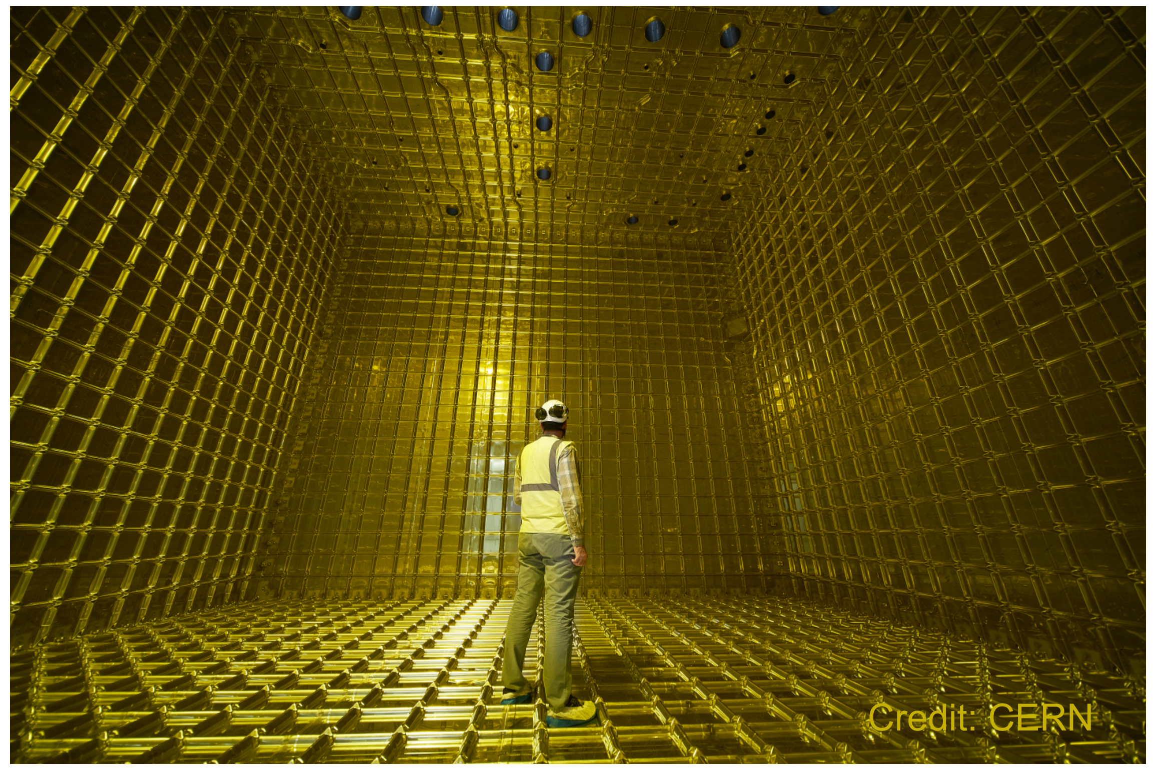
SNO+: 0.78 kt of liquid scintillator

+ ^{130}Te

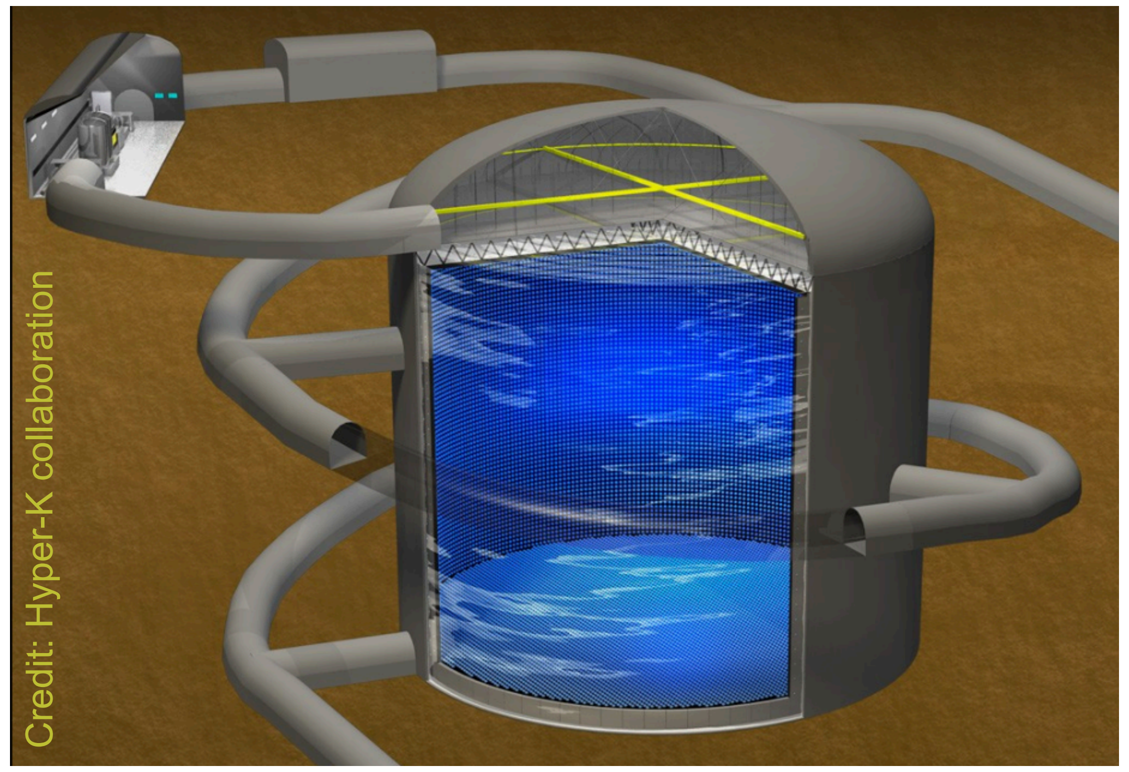
7 kt H_2O

Long baseline accelerator-neutrino programmes

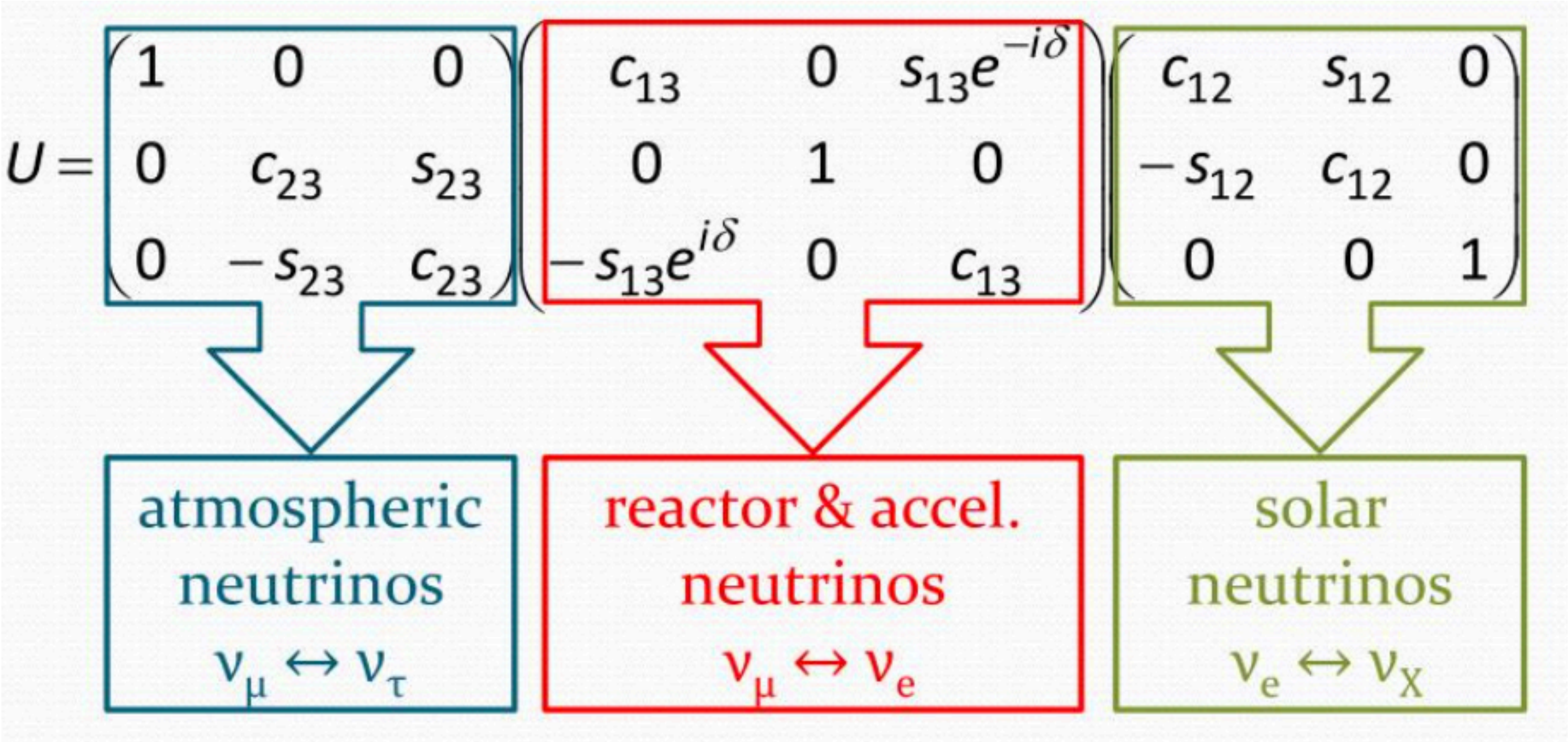
DUNE programme

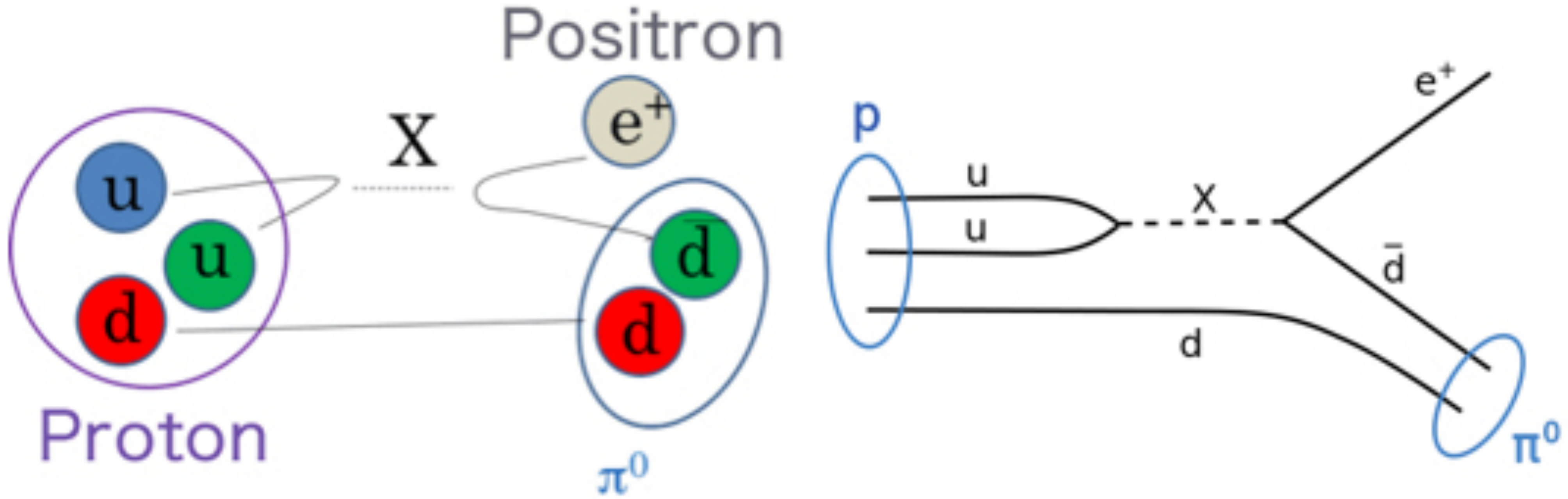


Hyper-K programme



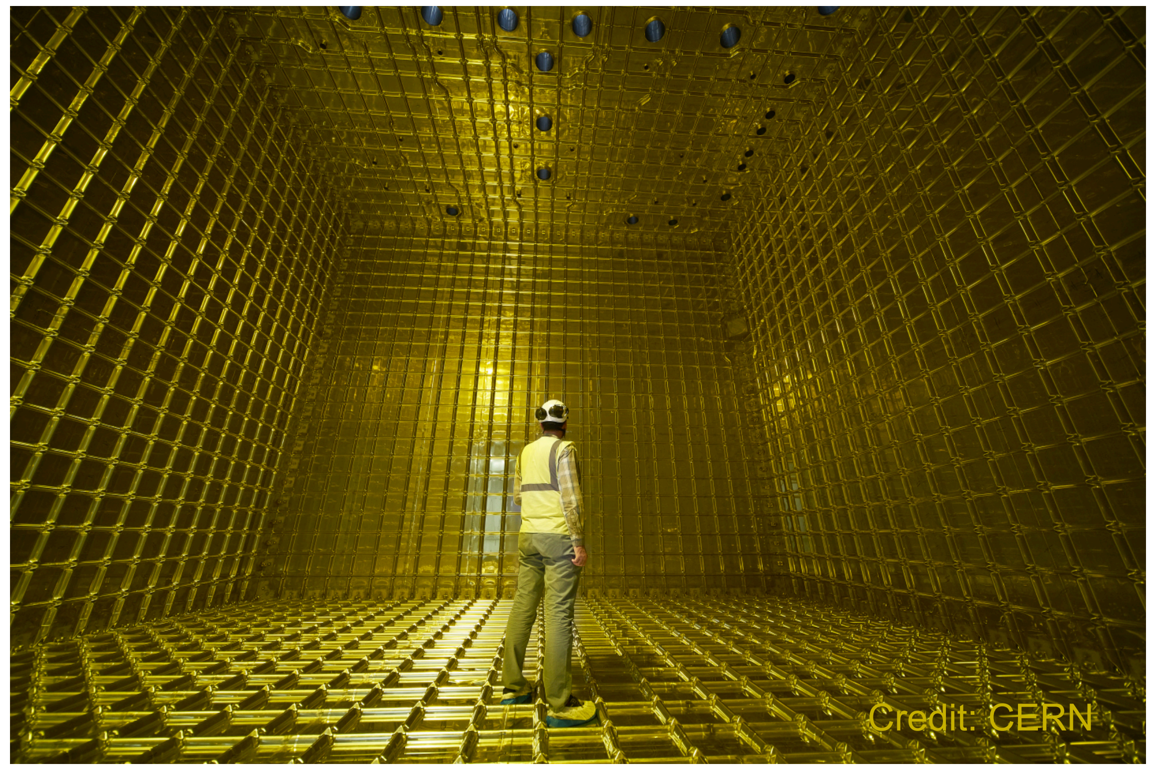
- Science drivers:
  - discovery of CP violation in neutrino oscillations
  - precision measurement of the PMNS matrix parameters
  - study of solar and supernova neutrinos
  - proton decay

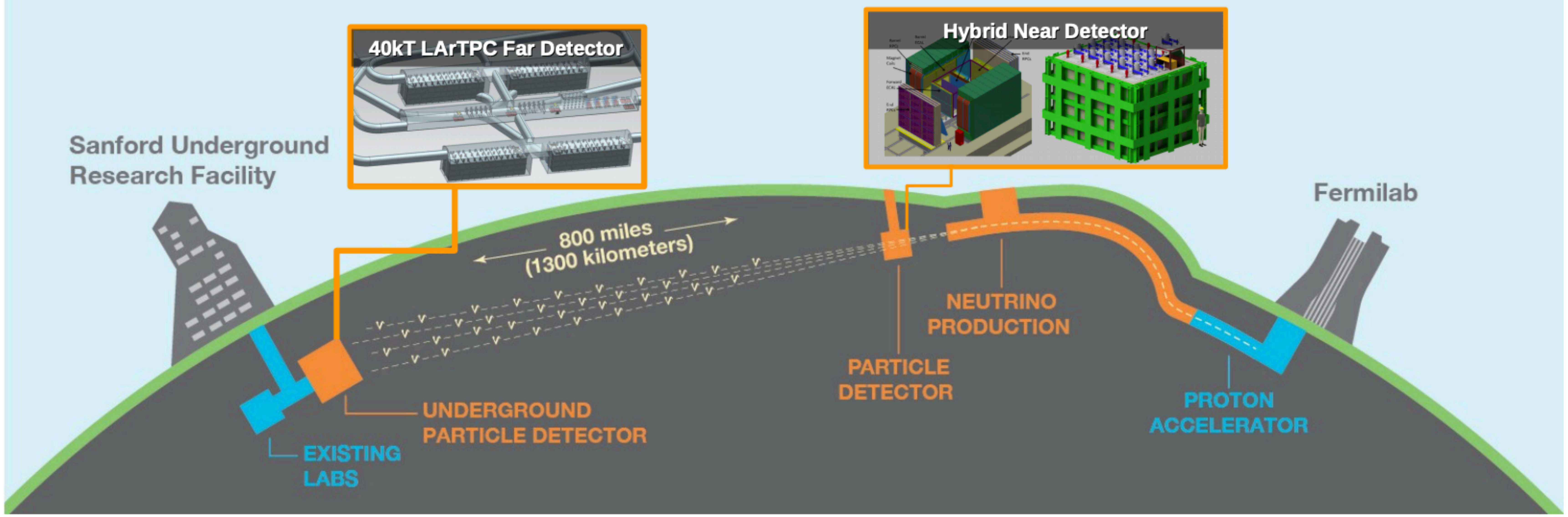




Deep Underground Neutrino Experiment (DUNE)

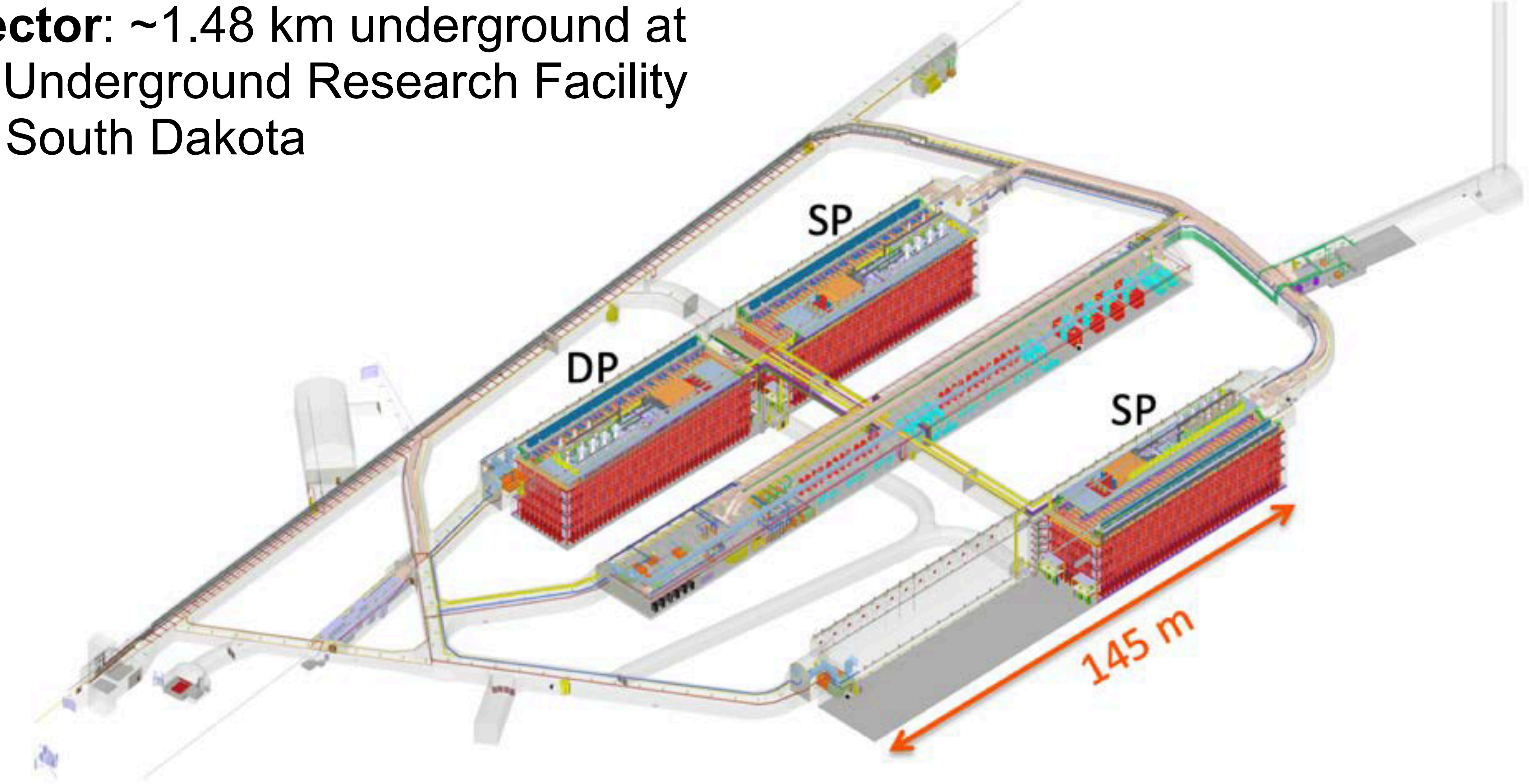
DUNE programme





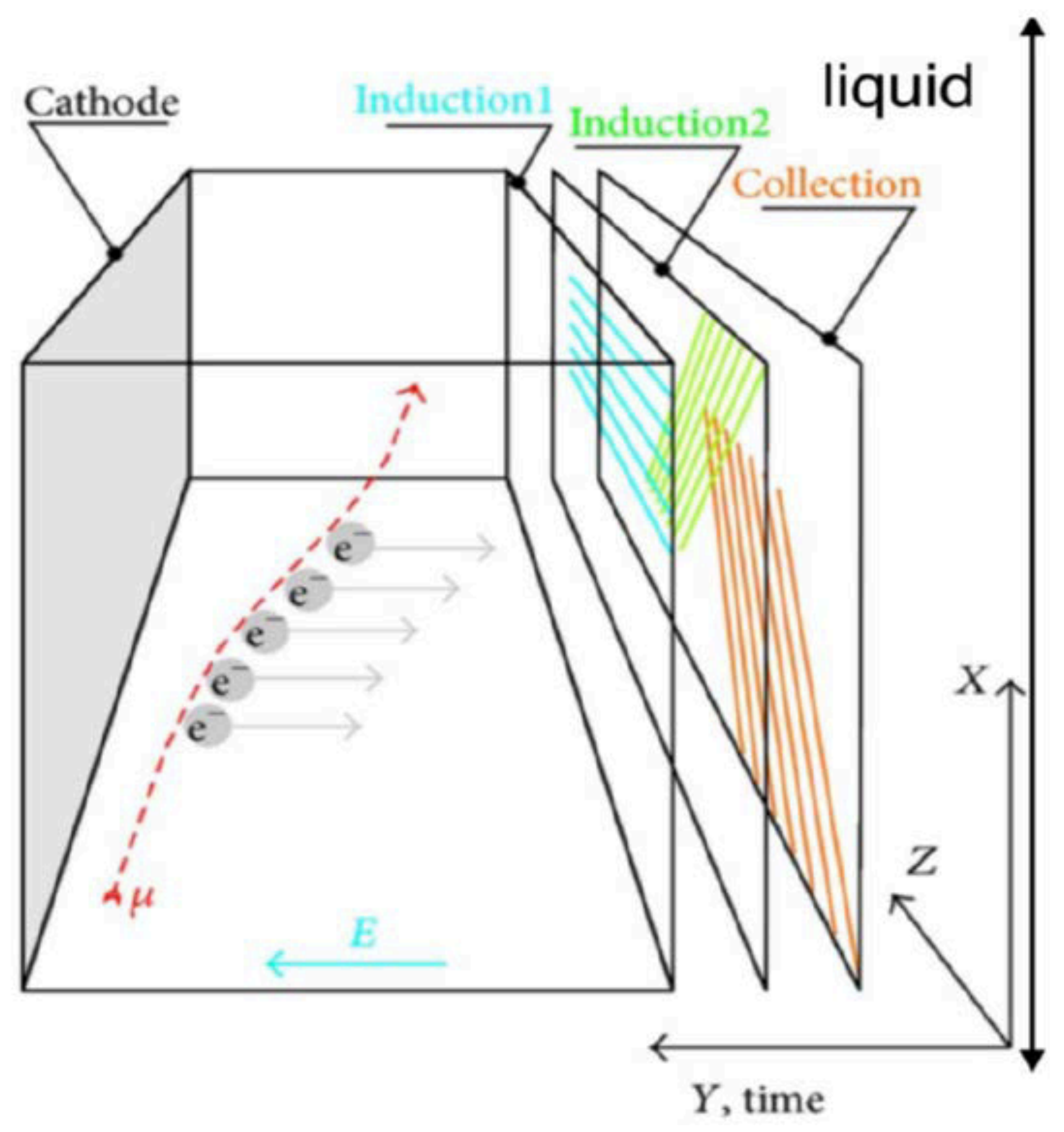
Far detector: ~1.48 km underground at Sanford Underground Research Facility in Lead, South Dakota

- 4 x 10-kt fiducial LAr TPC modules
  - 2 modules horizontal drift
  - 1 vertical drift module
  - 1 “opportunity” module

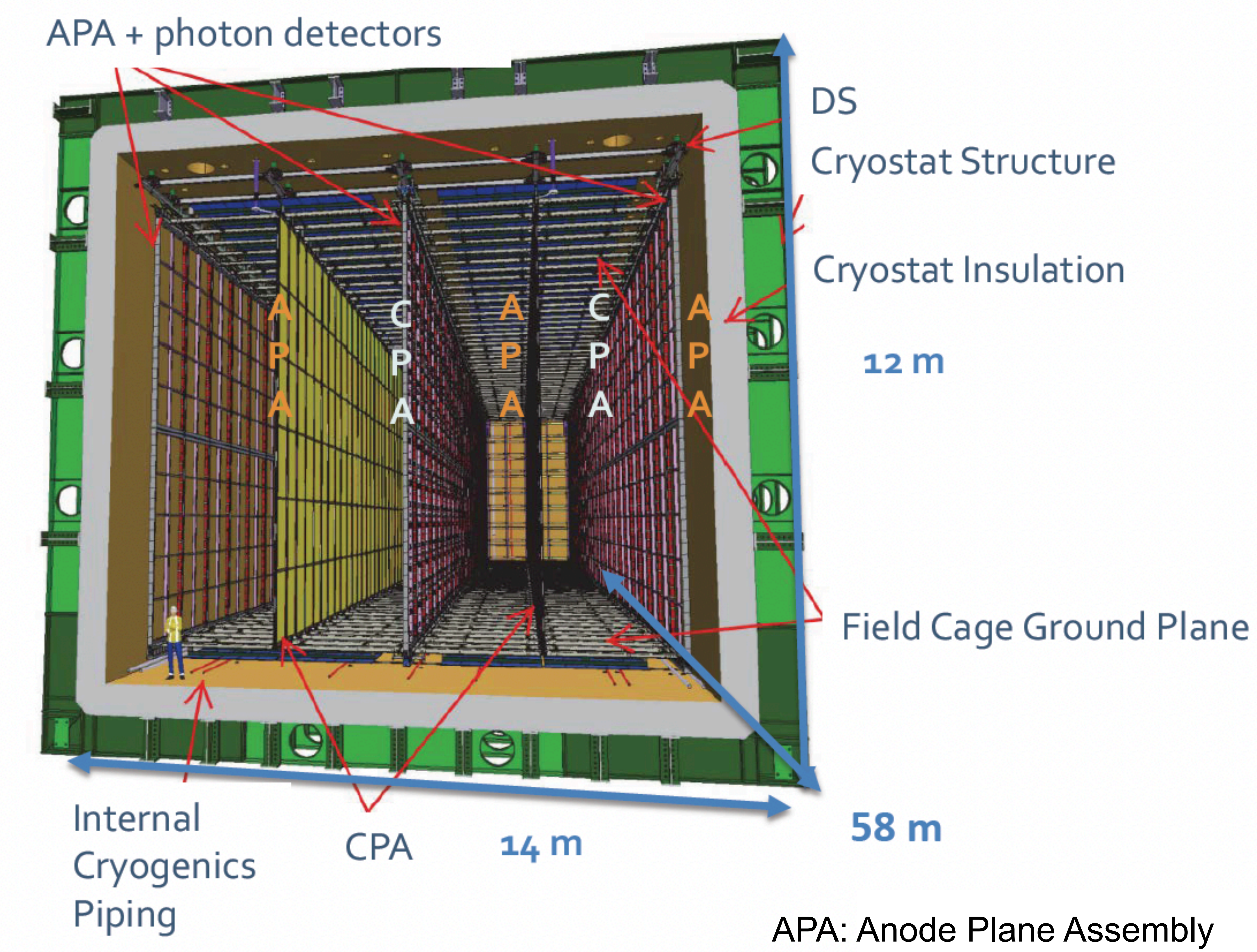


Deep Underground Neutrino Experiment (DUNE)

- **LAr TPC** technology
  - Excellent 3D imaging capabilities – (O(mm) over large volume)
  - Excellent energy measurement capability – fully active calorimeter
  - Particle ID by dE/dx, range, event topology



Far detector 1 (horizontal drift)



APA: Anode Plane Assembly

CPA: Cathode Plane Assembly

Credit: Clara Cuesta

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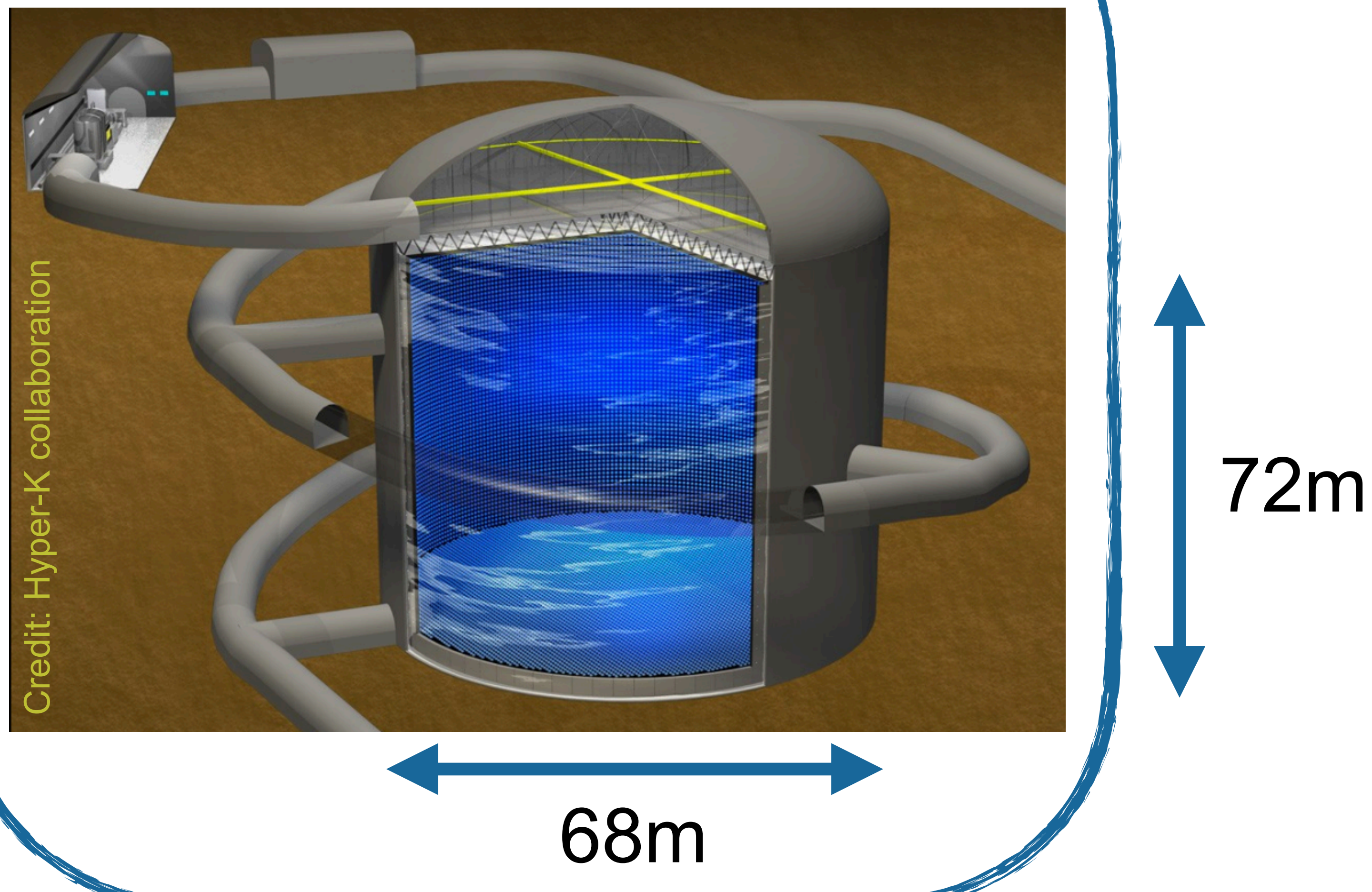
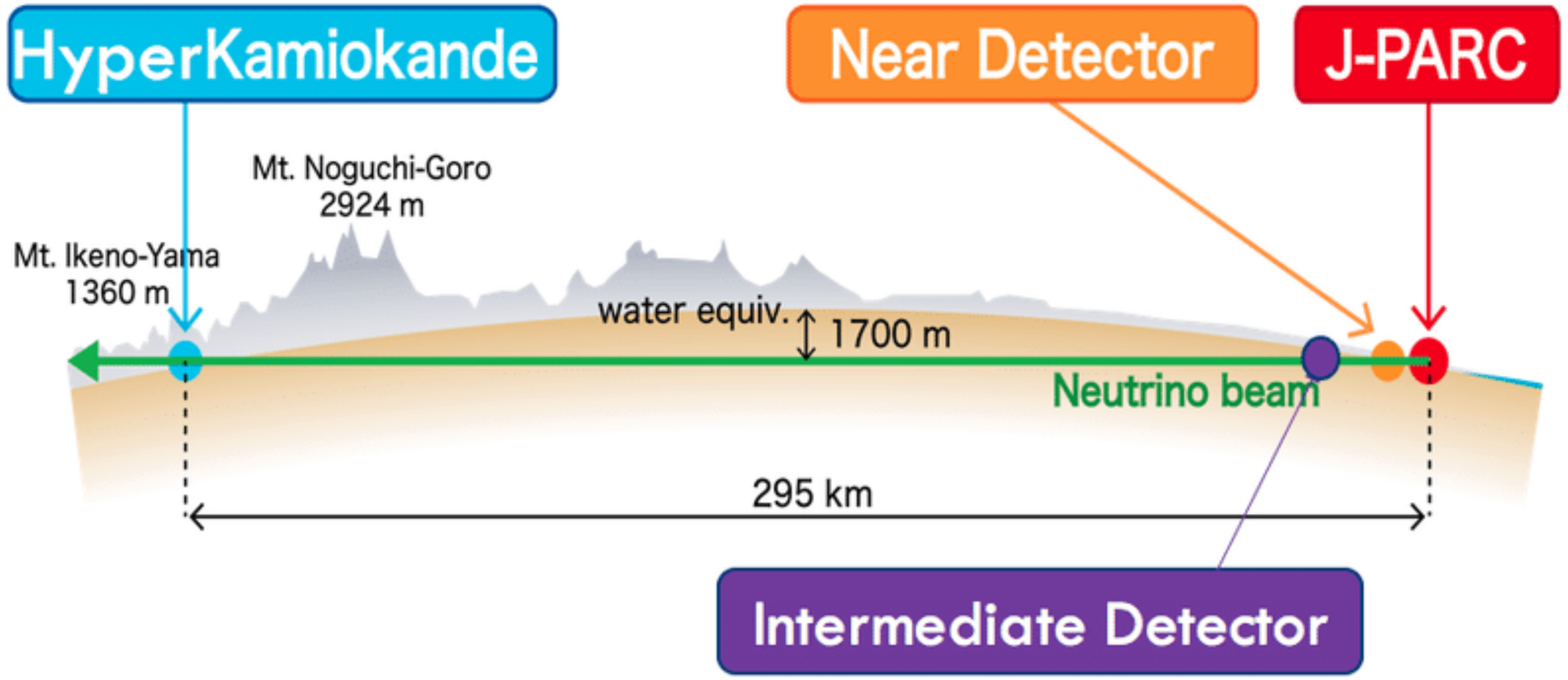
Hyper-Kamiokande

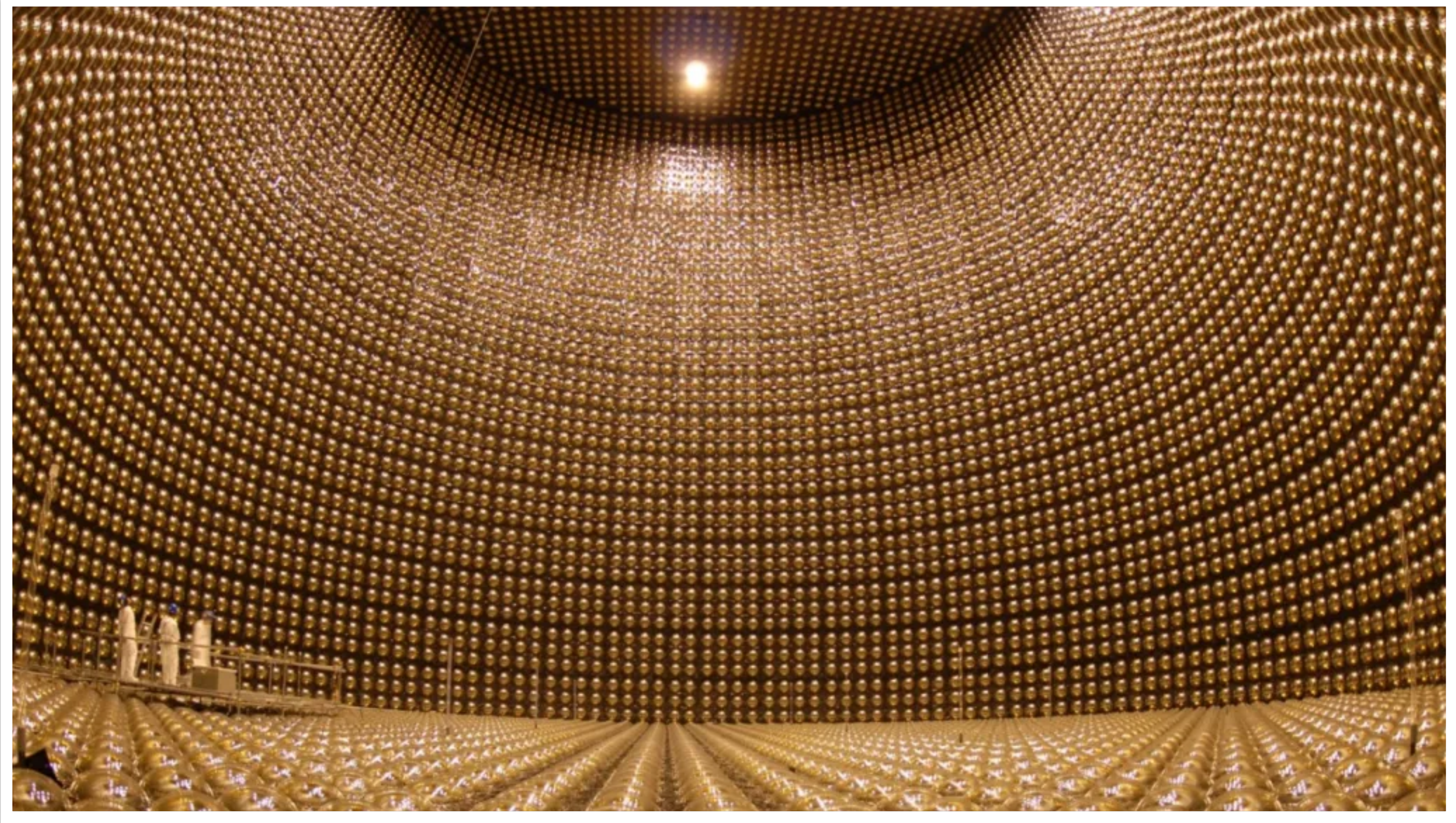
HyperK programme

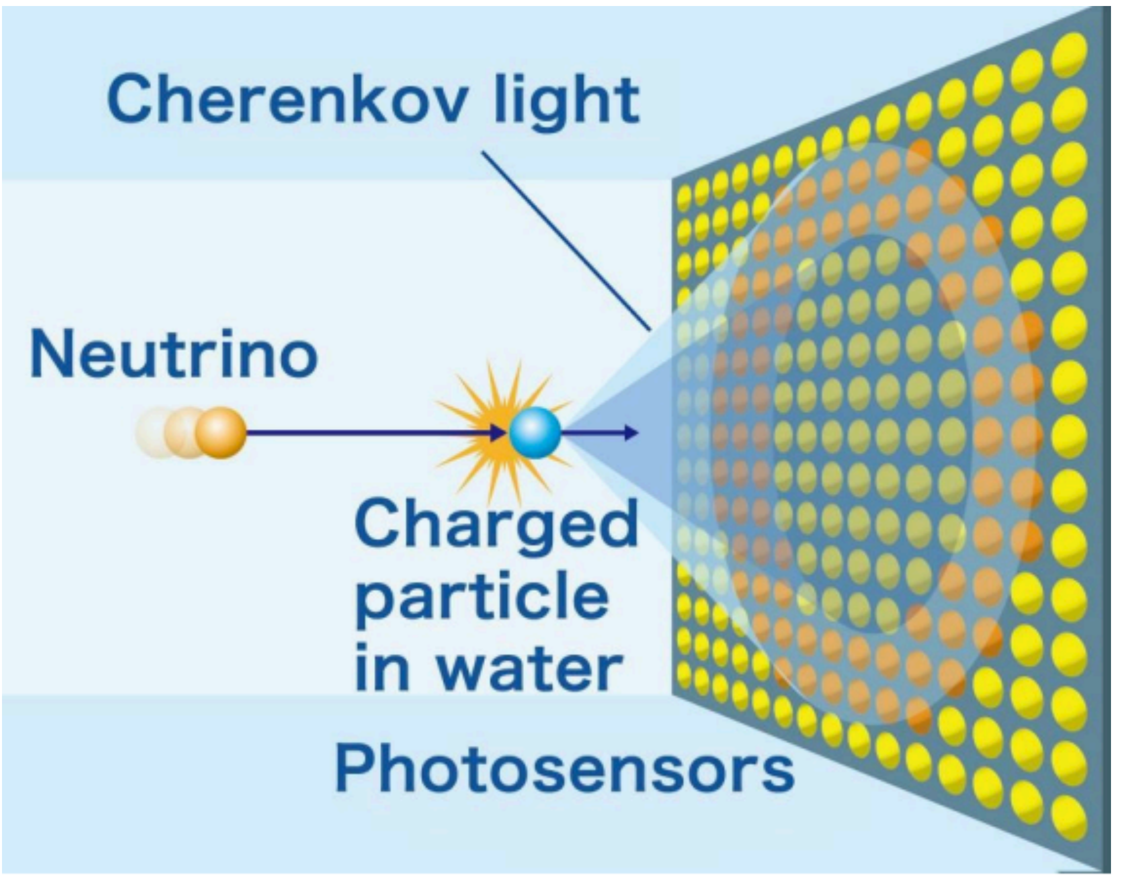




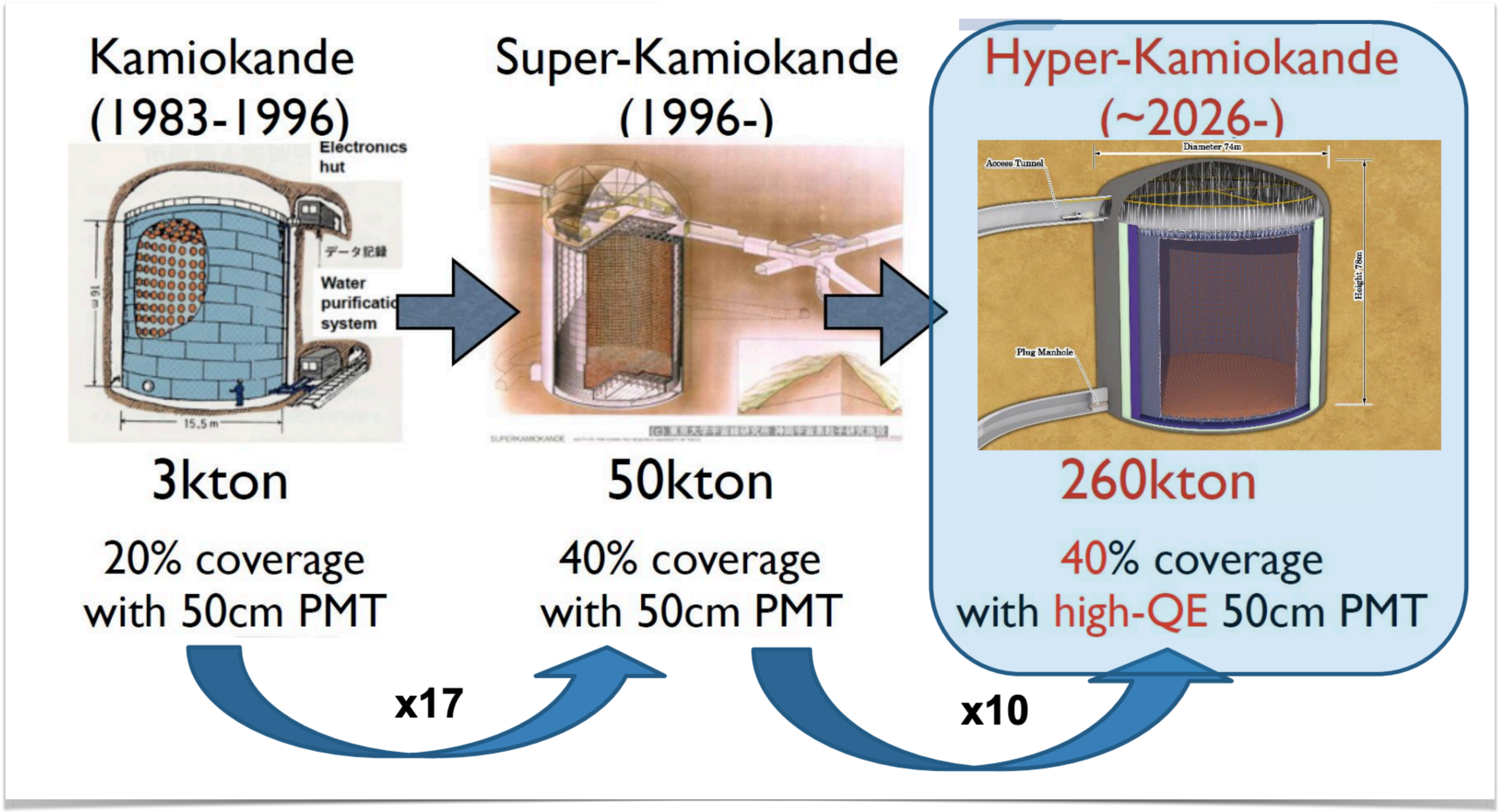
Super-Kamiokande

Credit: Kamioka Observatory, ICRR, University of Tokyo





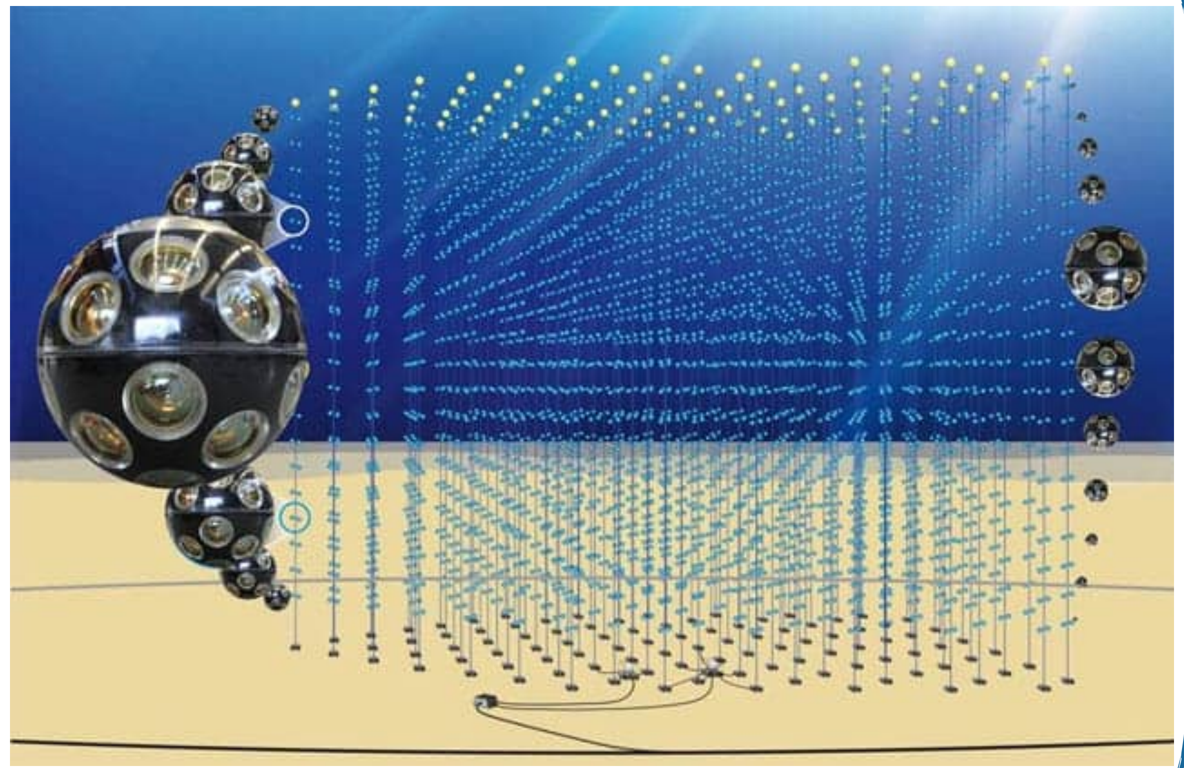
Hyper-Kamiokande

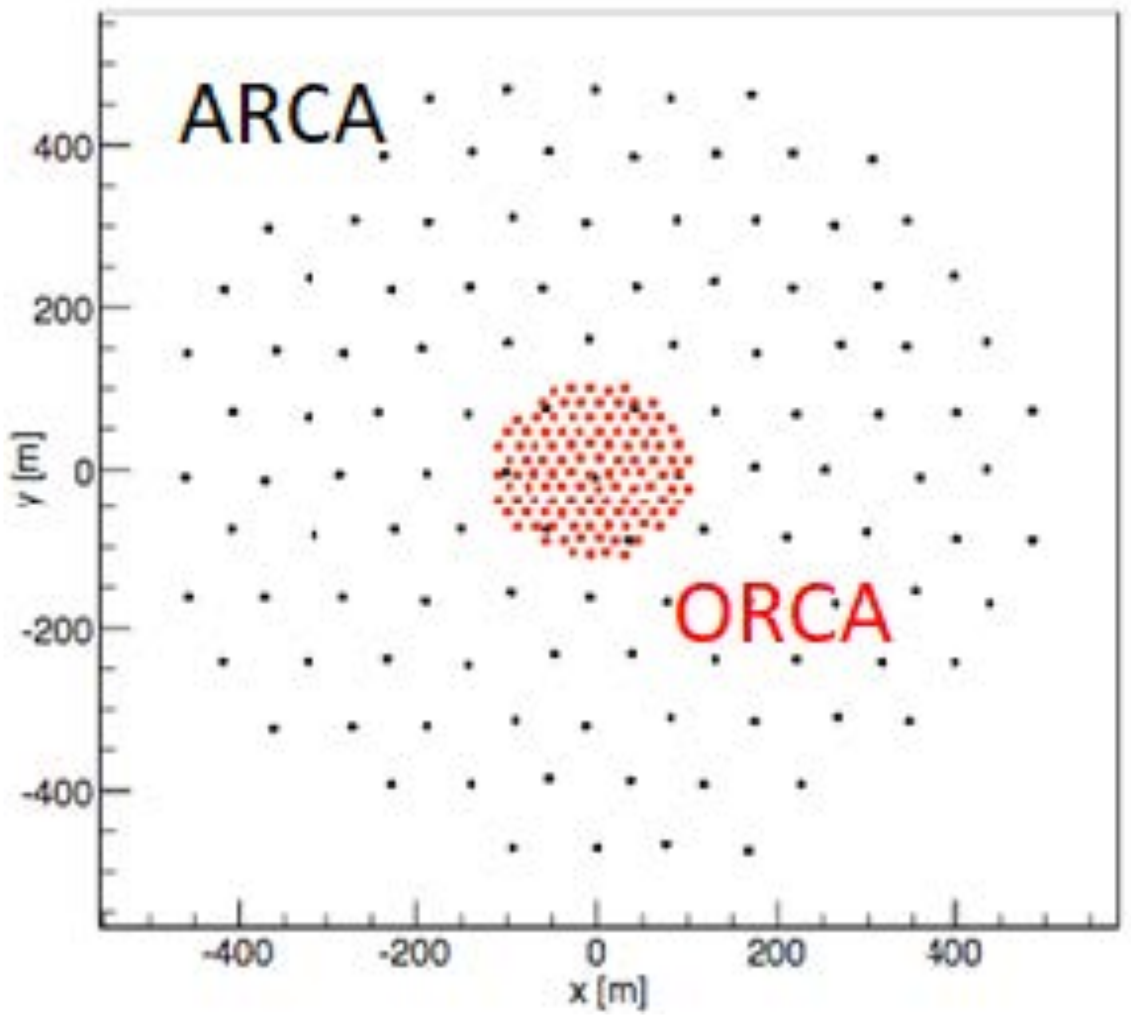


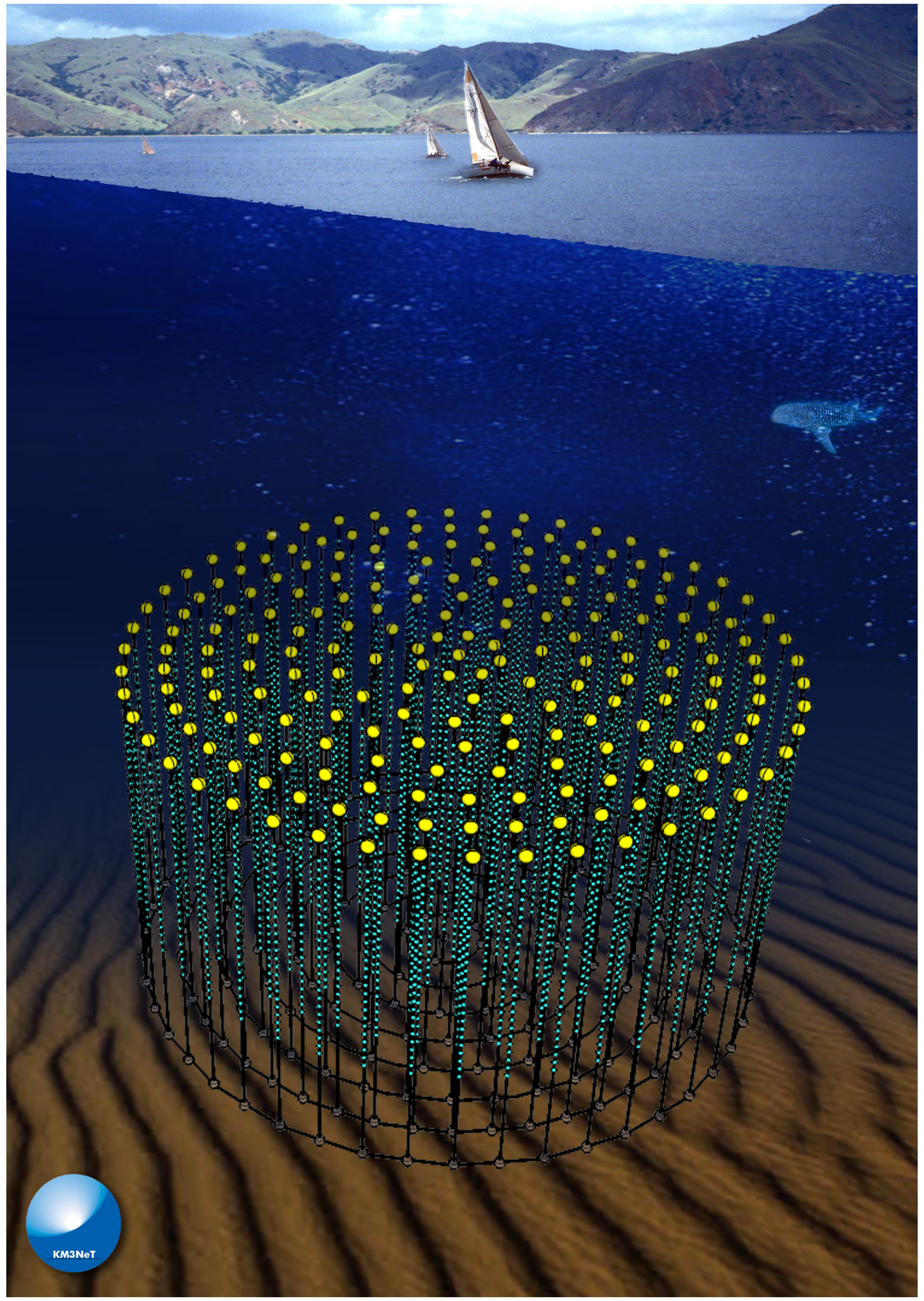
Slide from B. Richards

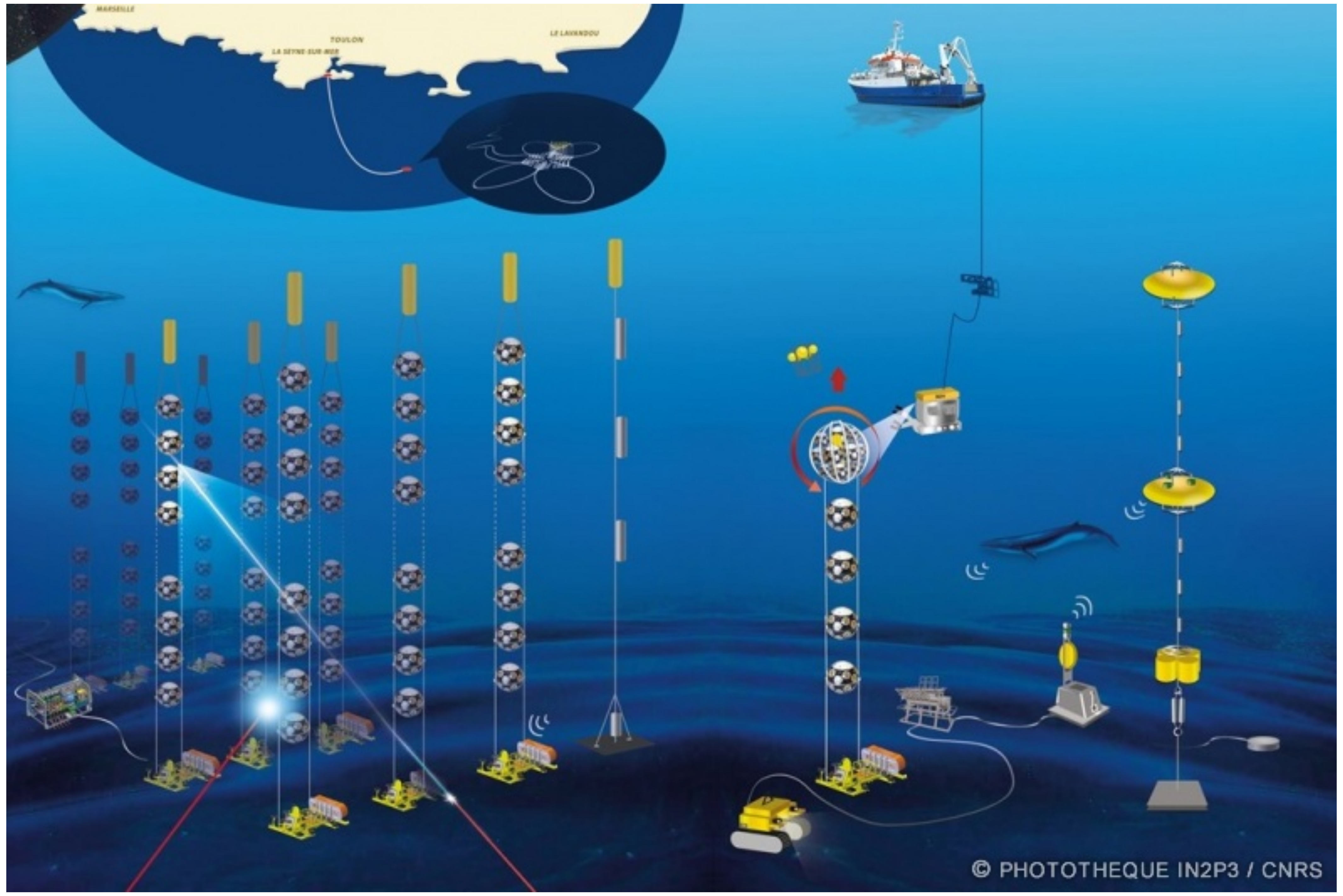
KM3NeT

neutrino telescopes



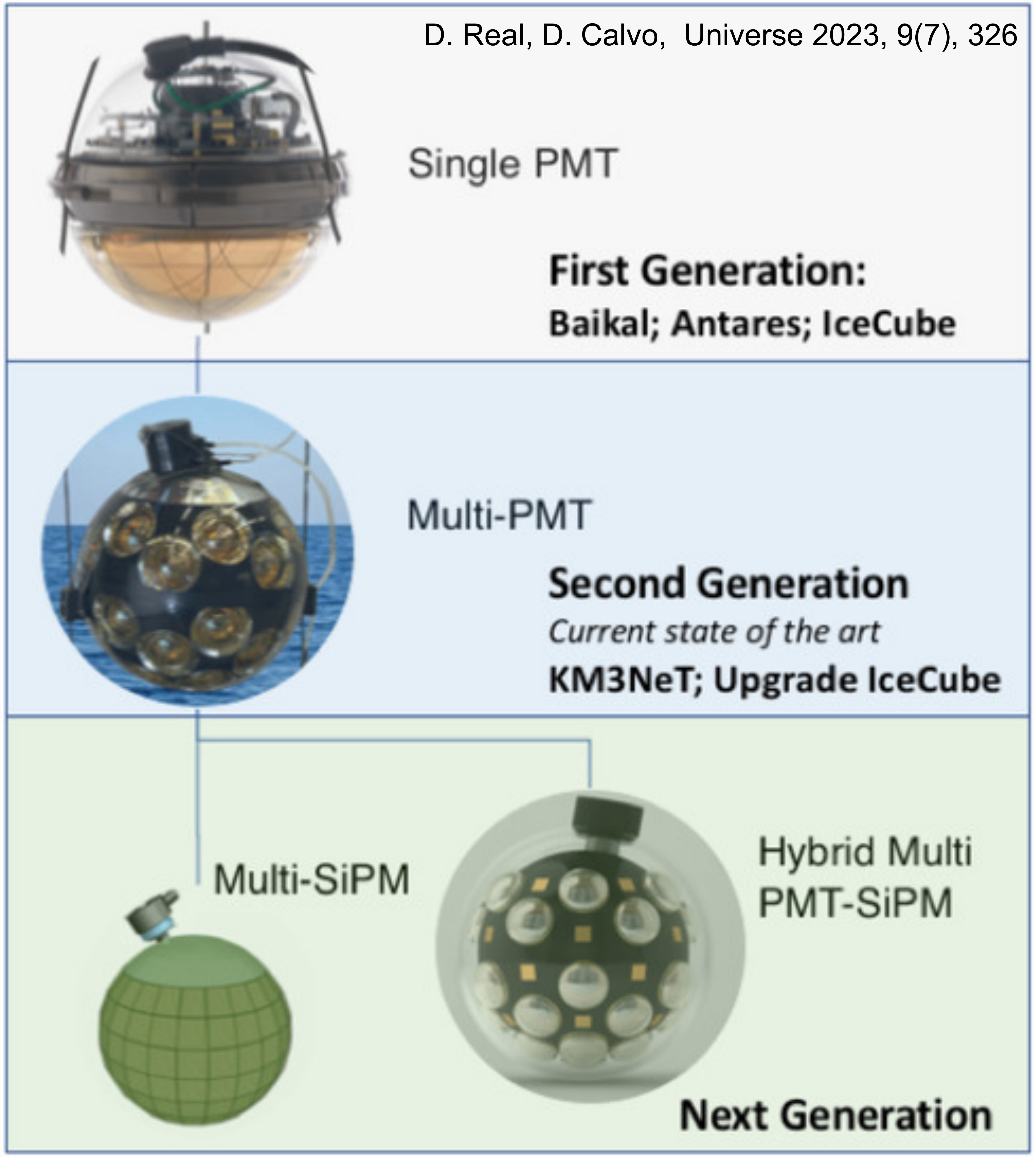






- ARCA at 3.5 km depth in front of Sicily
  - neutrinos from supernovae, GRBs or colliding neutron stars
- ORCA at 2.5 km depth in front of Toulon
  - optimized for energies around 10 GeV (atmospheric neutrinos)

KM3NeT


D. Real, D. Calvo, Universe 2023, 9(7), 326
Single PMT
First Generation:
Baikal; Antares; IceCube
Multi-PMT
Second Generation
Current state of the art
KM3NeT; Upgrade IceCube
Multi-SiPM
Hybrid Multi
PMT-SiPM
Next Generation

Enabling technologies

Enabling technologies (near-term, next 5-10 years)

1. Properties of **noble liquids**

2. **Charge collection** in noble liquids

3. **Purification**, cryogenics, infrastructure, and integration for noble liquids

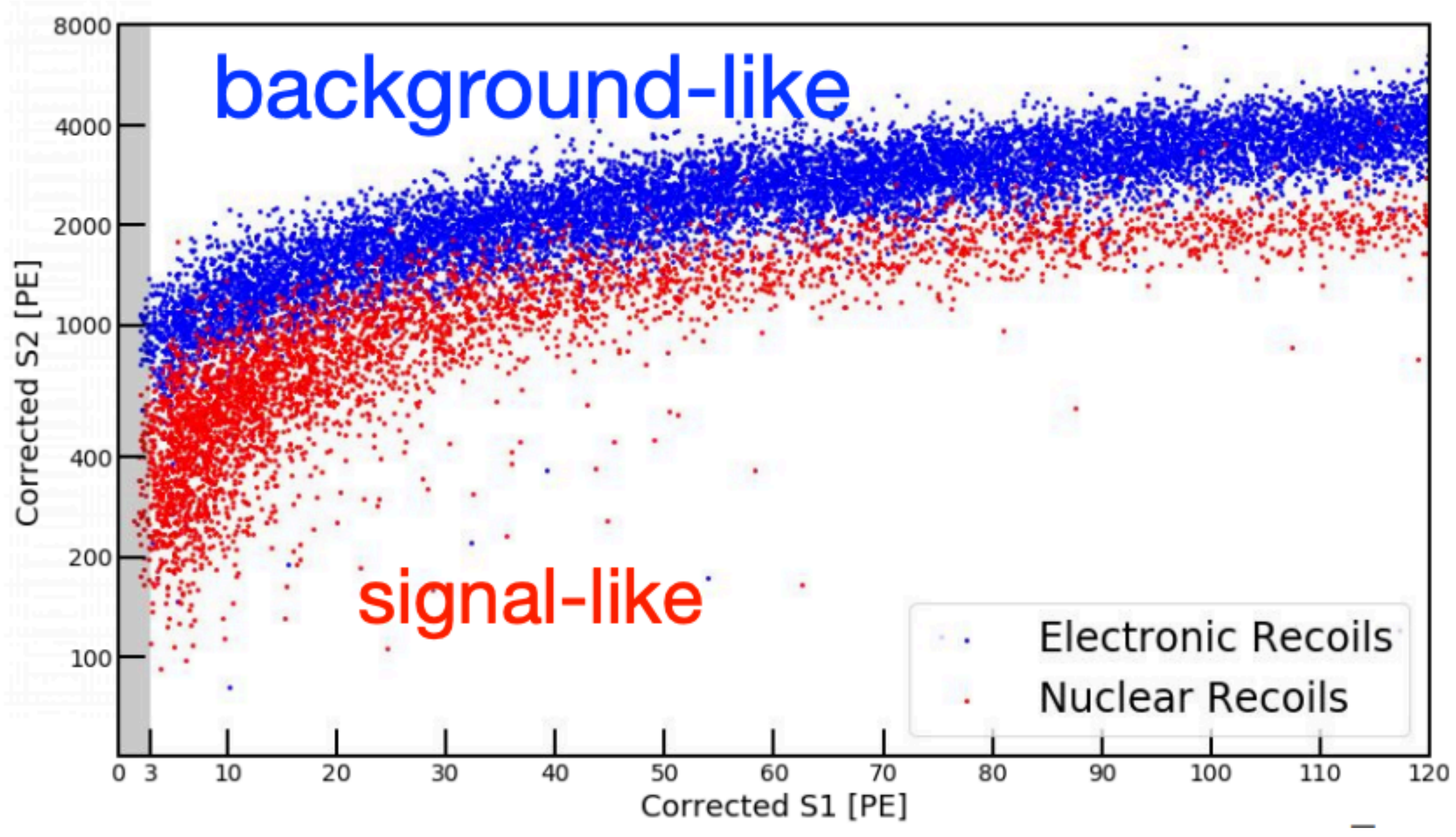
4. **Light collection** in noble liquids and other liquids

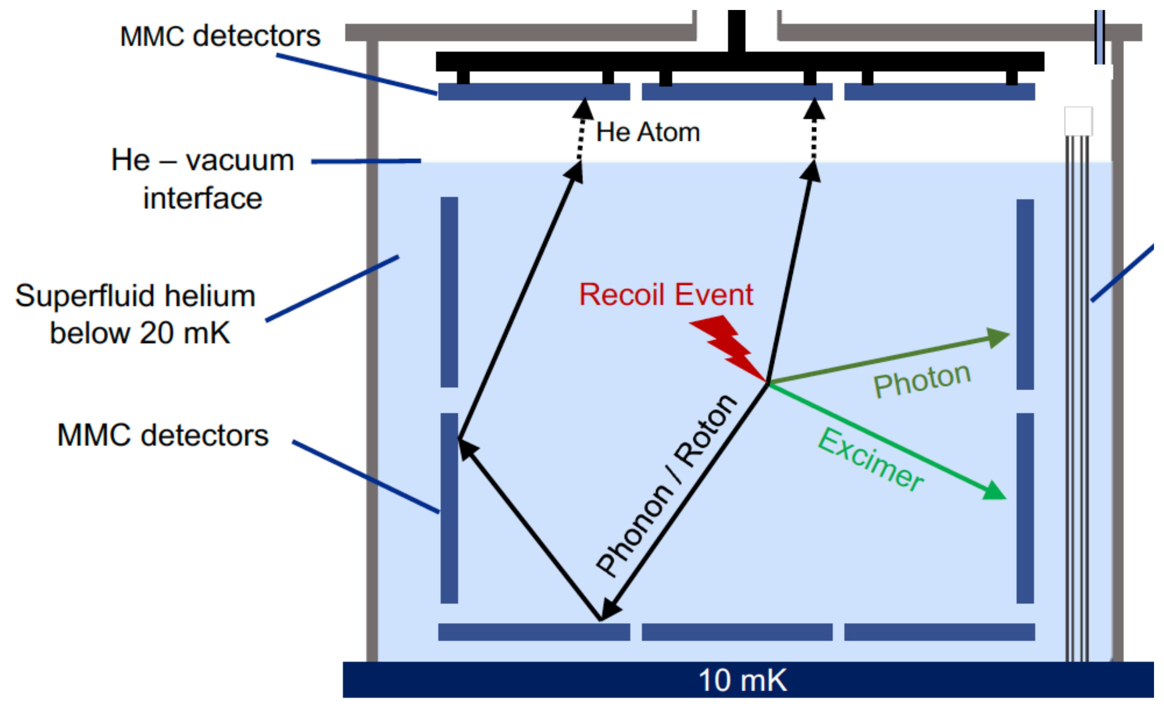
5. Liquid **scintillator** and **water** detectors

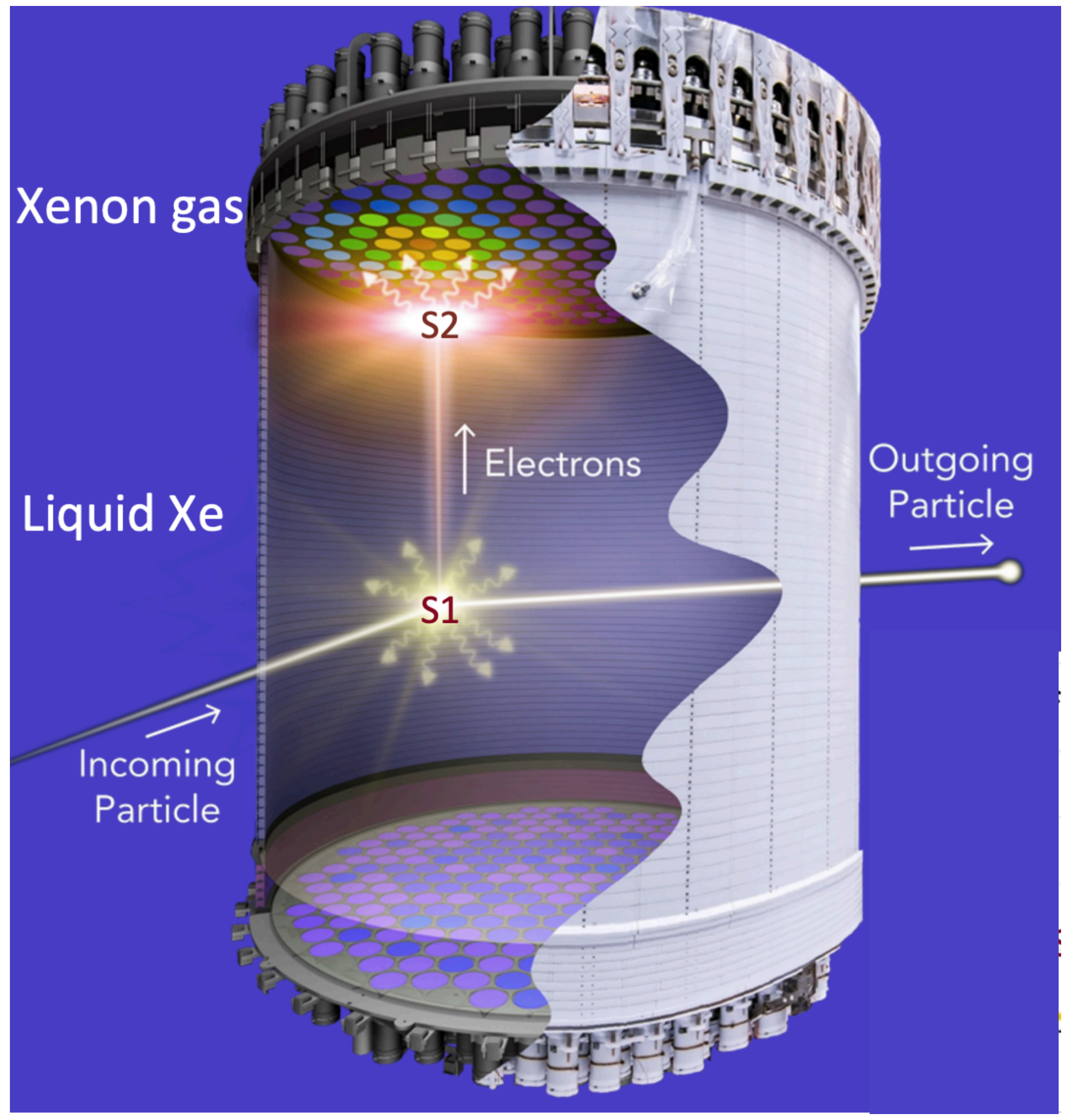
1 Properties of noble liquids

- intrinsic key properties
  - multiple signal channels (light and potentially charge or quasiparticles)
  - high scintillation yield
  - high, interaction-type-dependent charge or quasiparticle yield
  - long electron lifetime

PSD in xenon (LXe TPC)







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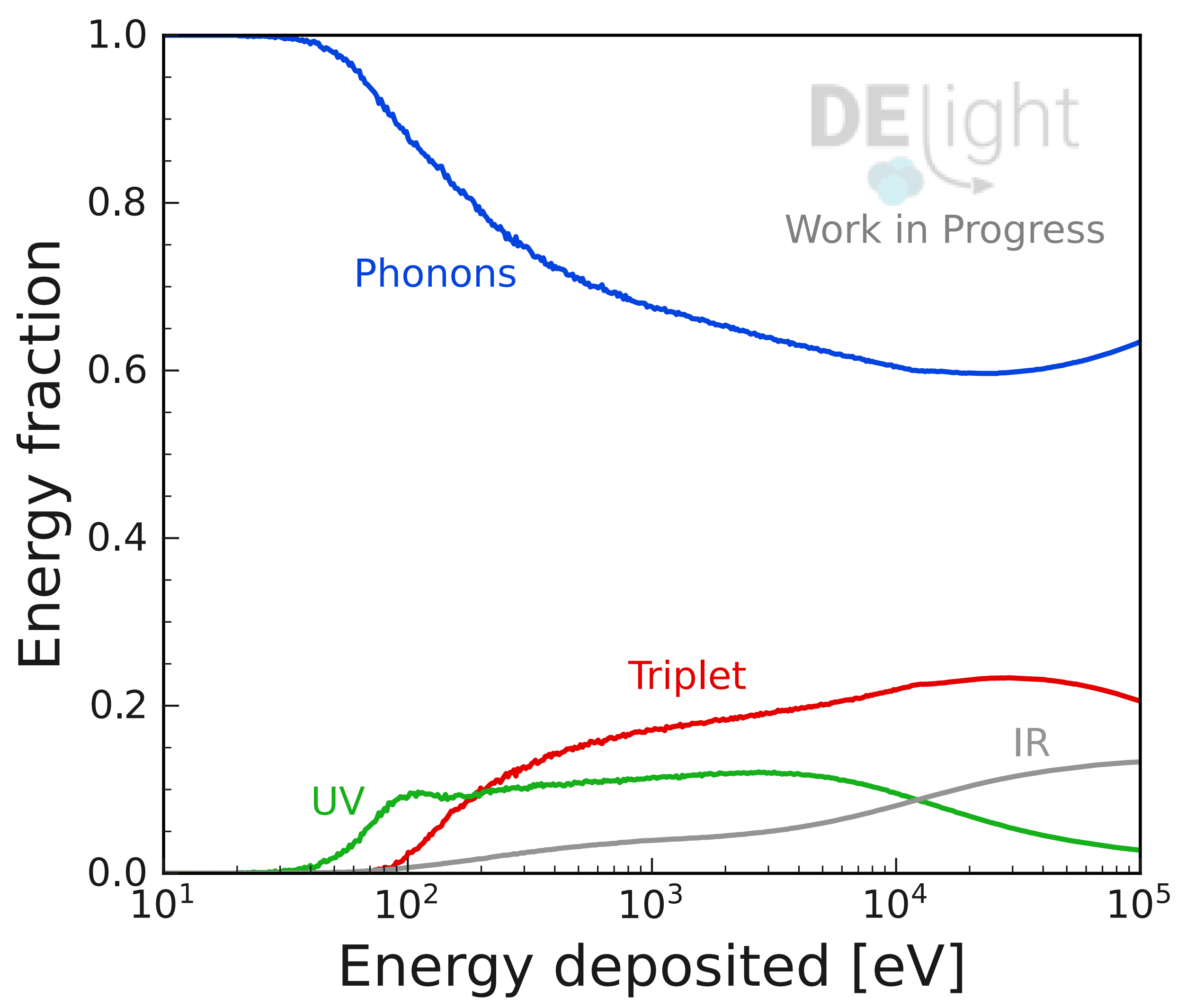
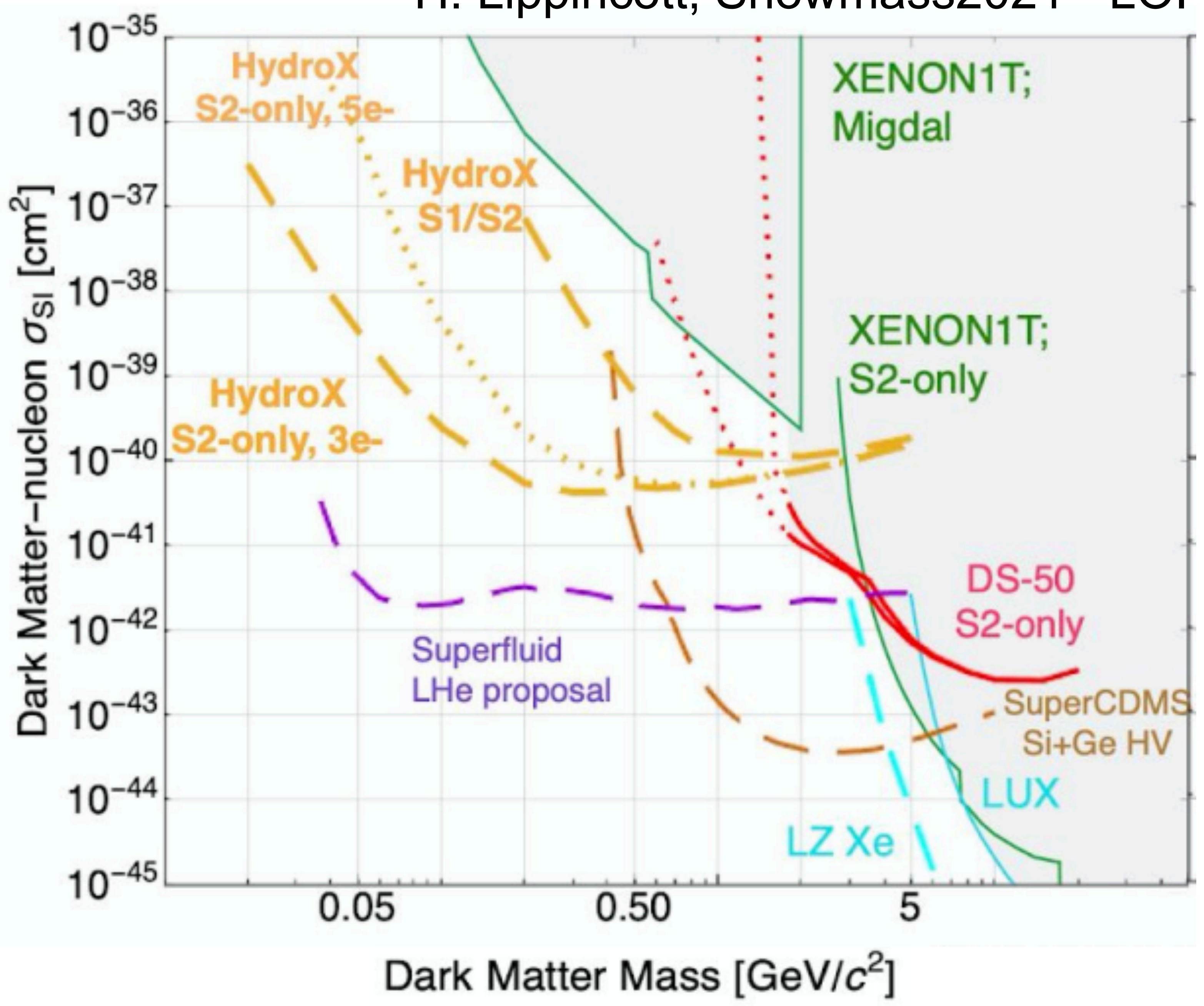
1 Properties of noble liquids - R&D

- Microphysics of liquids
  - Better understanding of energy partitioning to improve energy resolution and threshold
  - Doping techniques
    - **Xe in Ar**: to shift light from VUV to UV for higher quantum efficiency (avoid WLS coatings)
    - **H_2 in Xe**: low-mass target to increase sensitivity at low DM masses (e.g. HydroX as upgrade to multi-ton scale Xe detectors)

Signal partitioning in LHe (nuclear recoil)



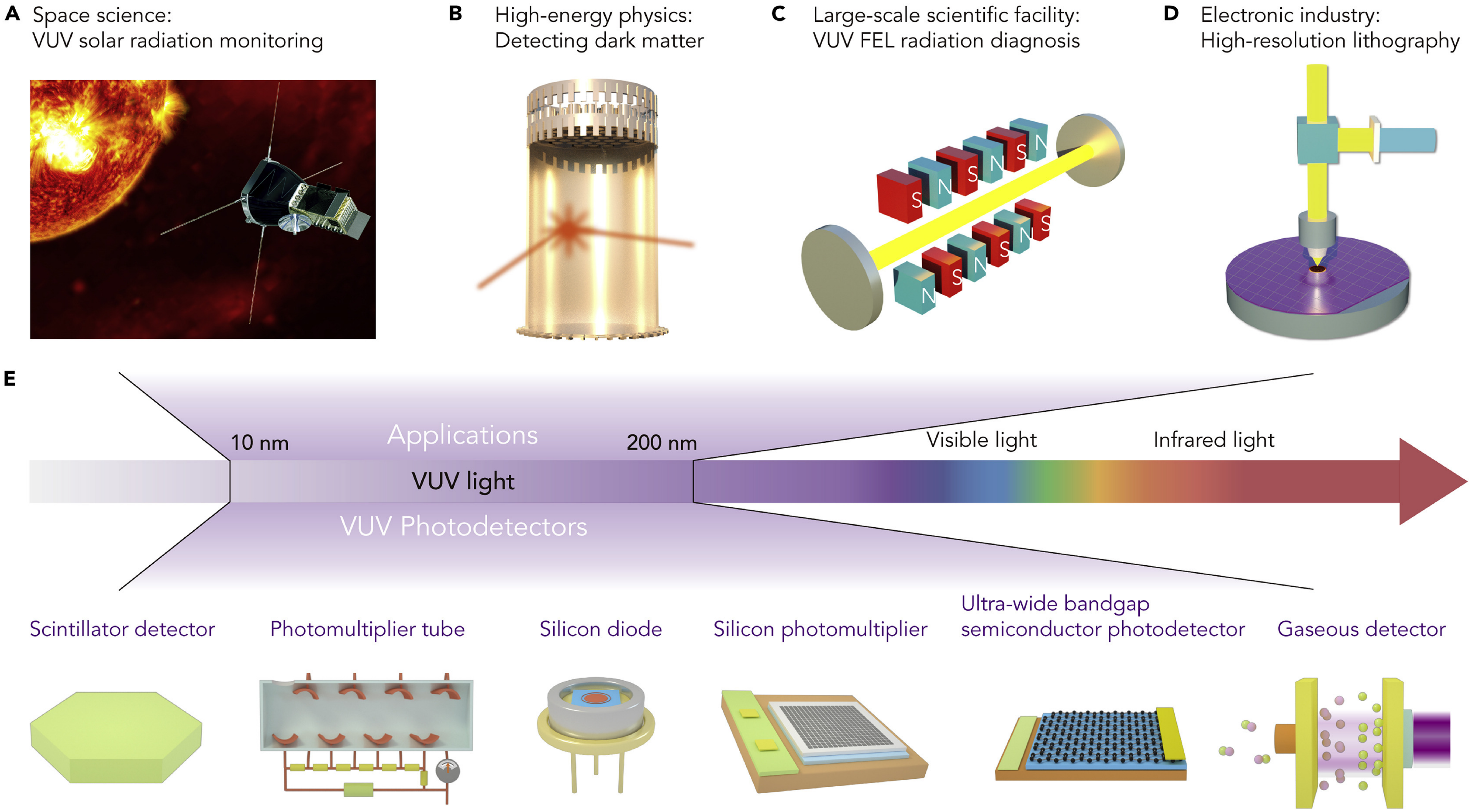
H. Lippincott, Snowmass2021 - LOI



1 Properties of noble liquids - R&D

- Light emission / detection
  - developing photon detectors with VUV-sensitivity
  - exploiting sub-dominant emissions (e.g. near-IR light component in LAr)

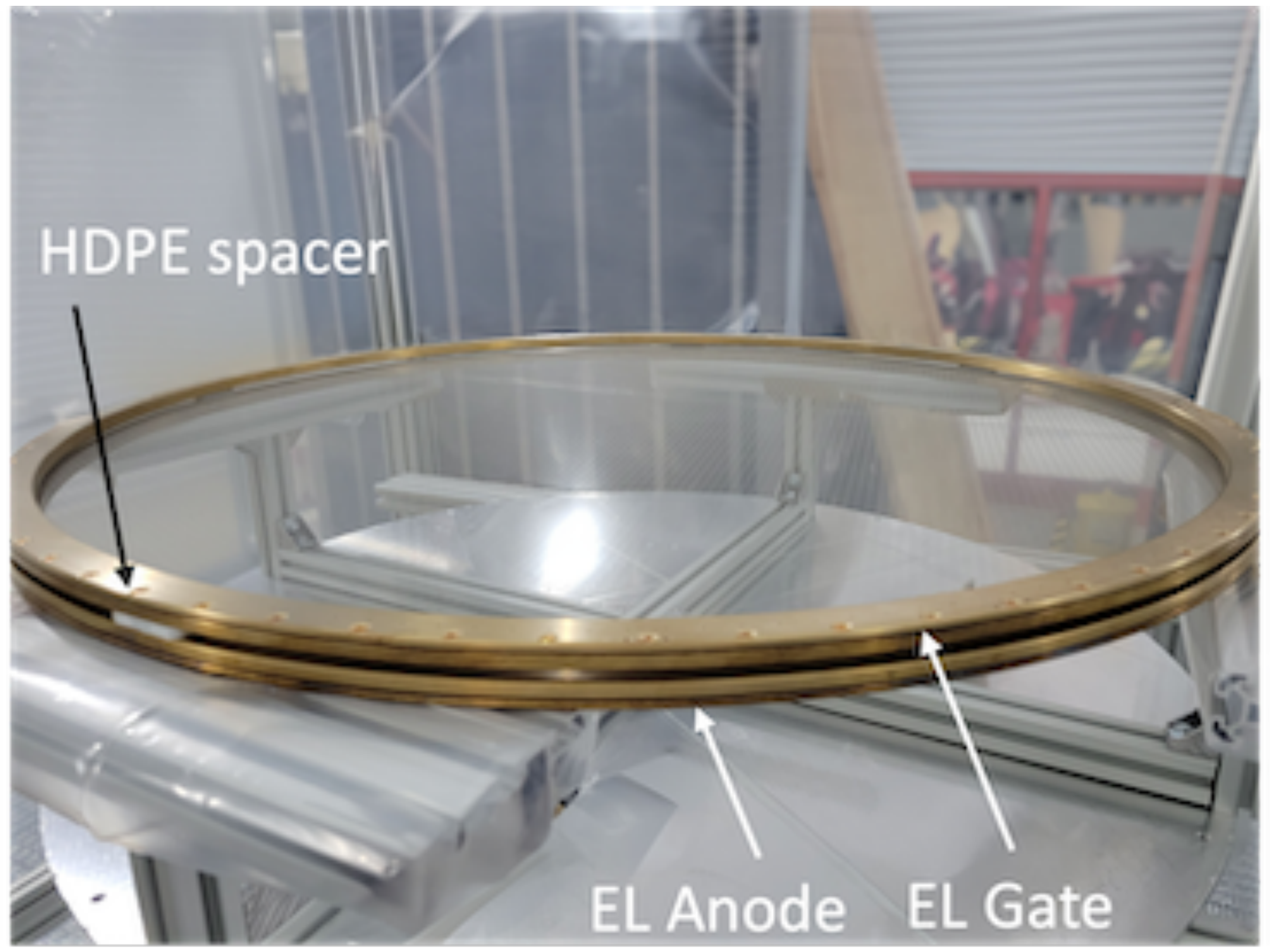
W. Zheng, Volume 23, Issue 6, 26 June 2020, 101145

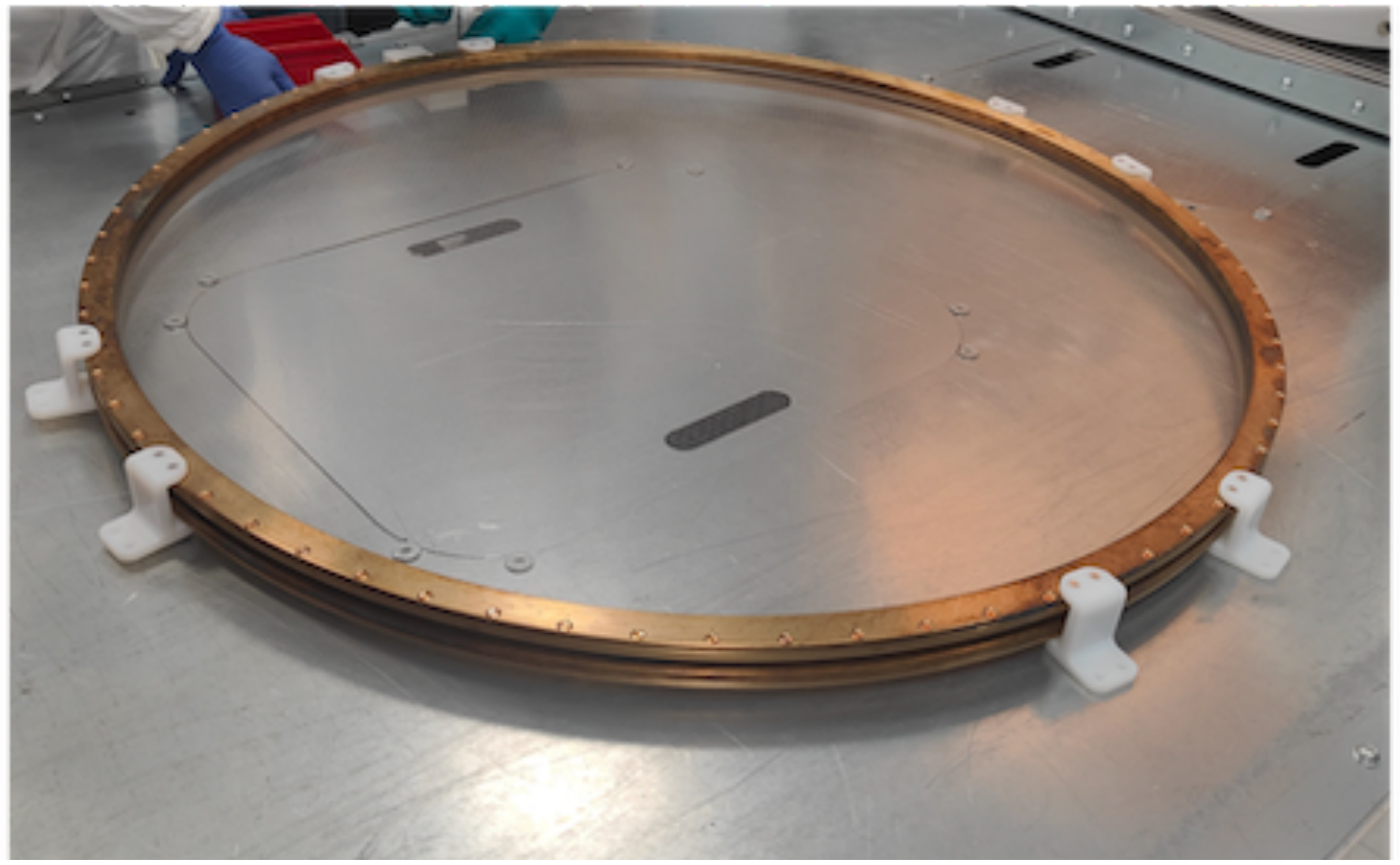
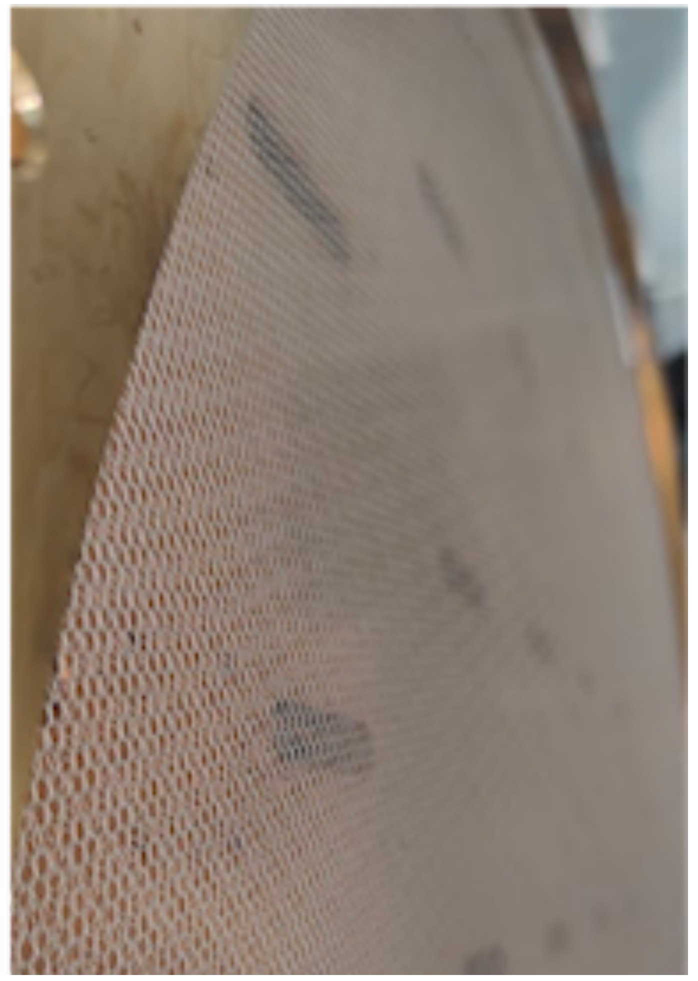


1 Properties of noble liquids - R&D

- Higher voltages to drift electrons over up to 10 m scale
  - HV feed-throughs must deliver 50 kV or more to the cathode
  - Dielectric properties of liquid must be better understood
  - Detailed models of light emission from HV breakdown required
  - Electrodes with large (>2.5 m) diameters: wire, mesh/ woven, micro-pattern

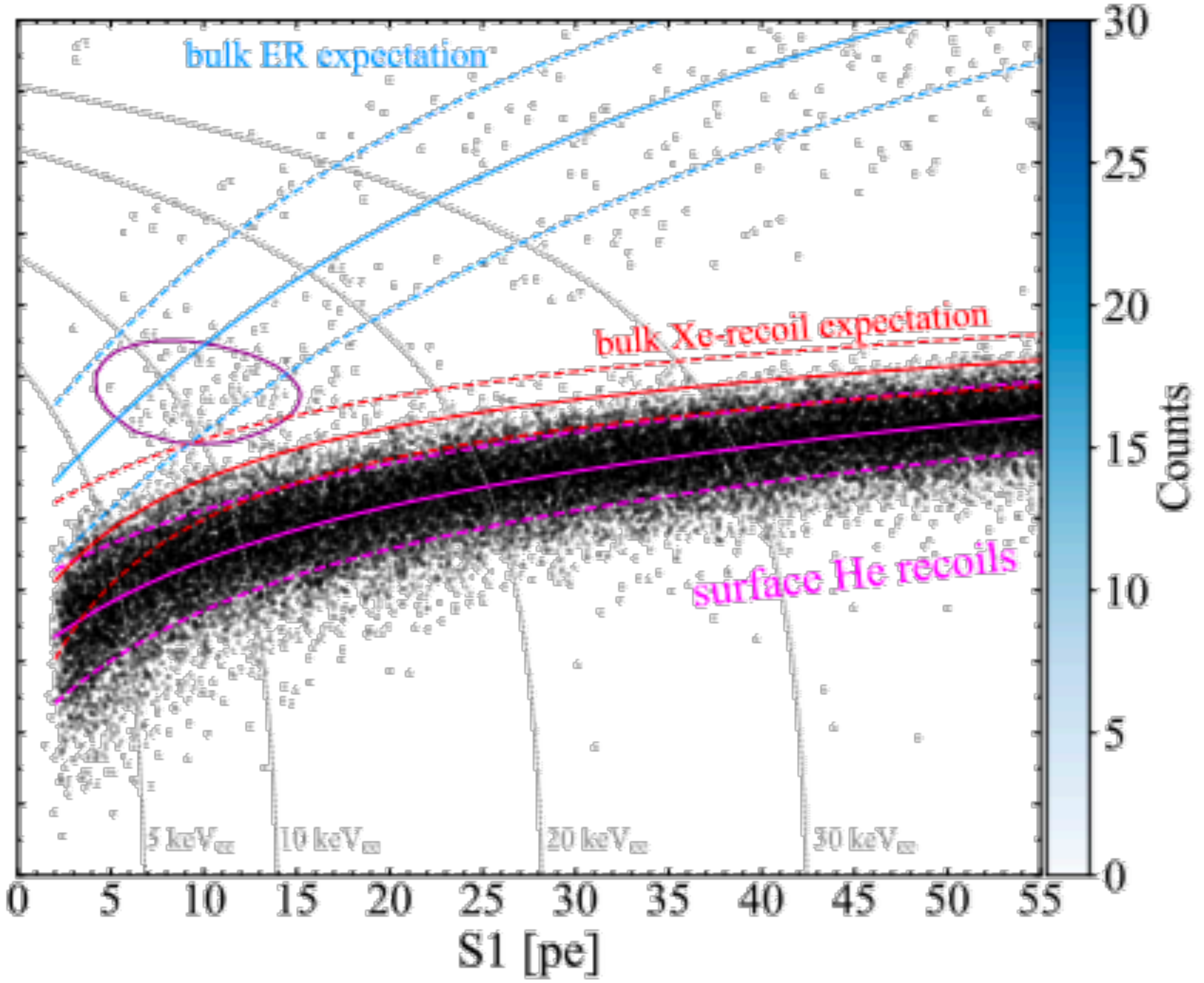
NEXT-100, arXiv:2311.03528v2

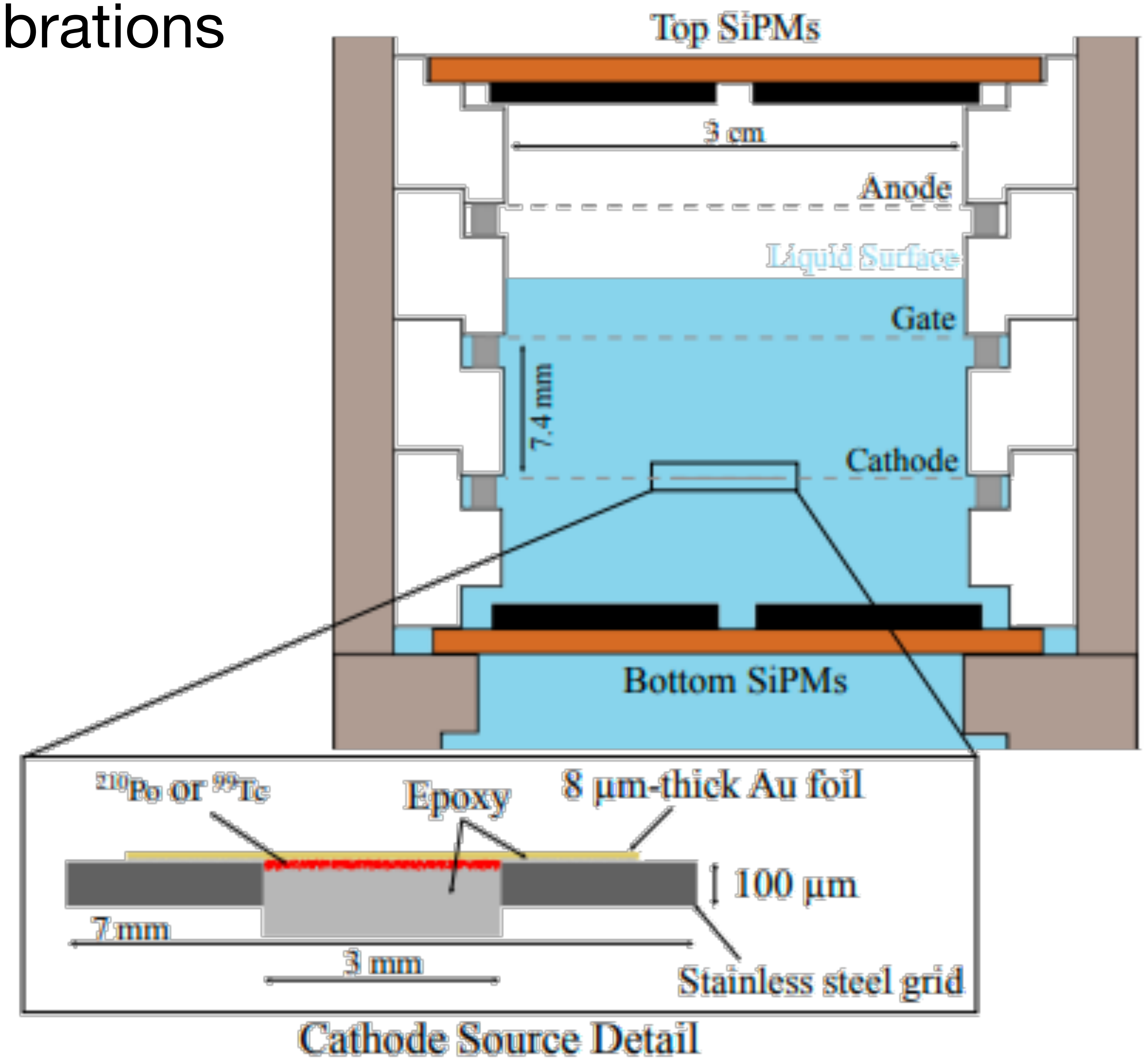



1 Properties of noble liquids - R&D

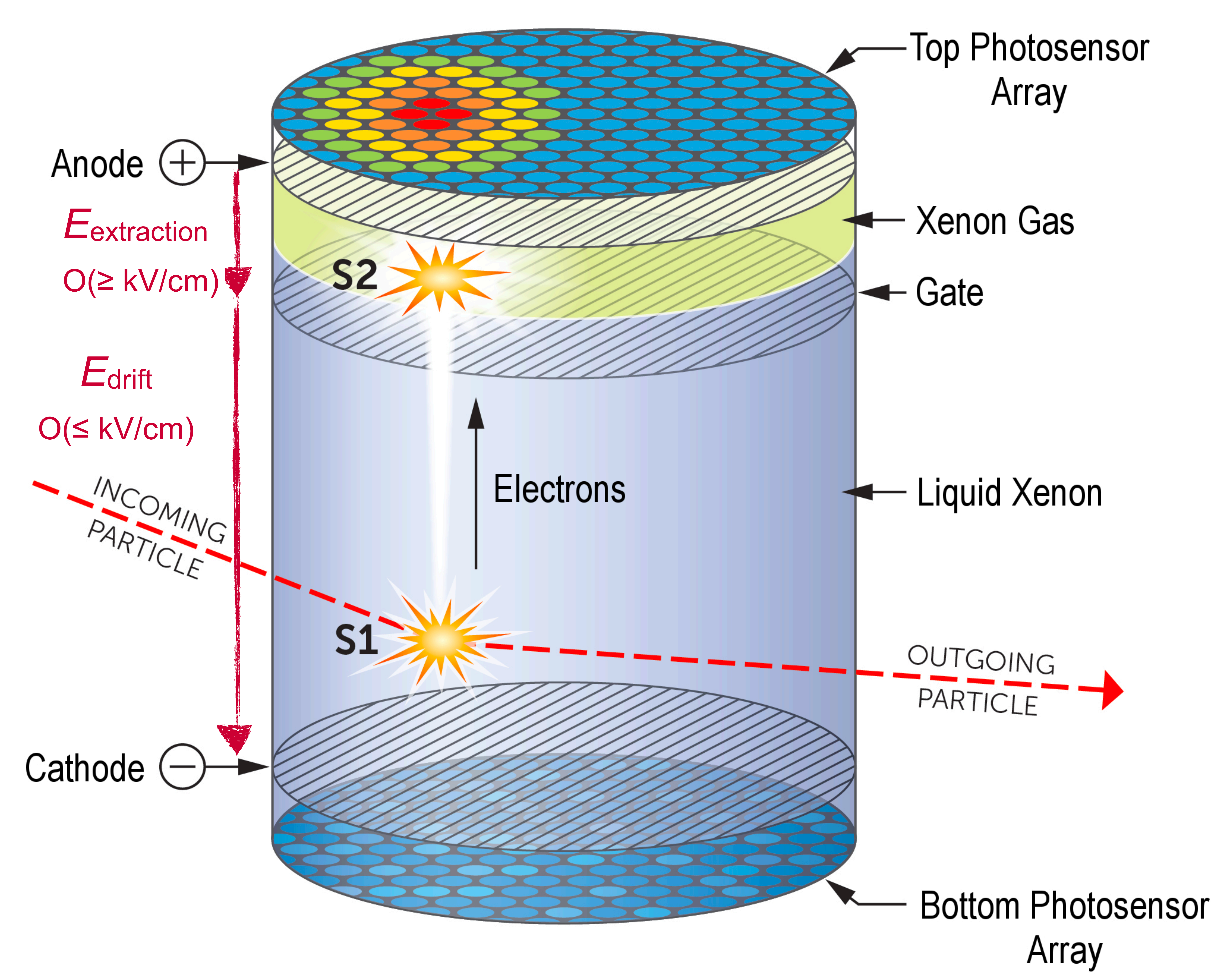
- Calibration
  - New methods needed to ensure calibration capabilities throughout large volumes
  - New methods needed for low energy nuclear recoil calibrations





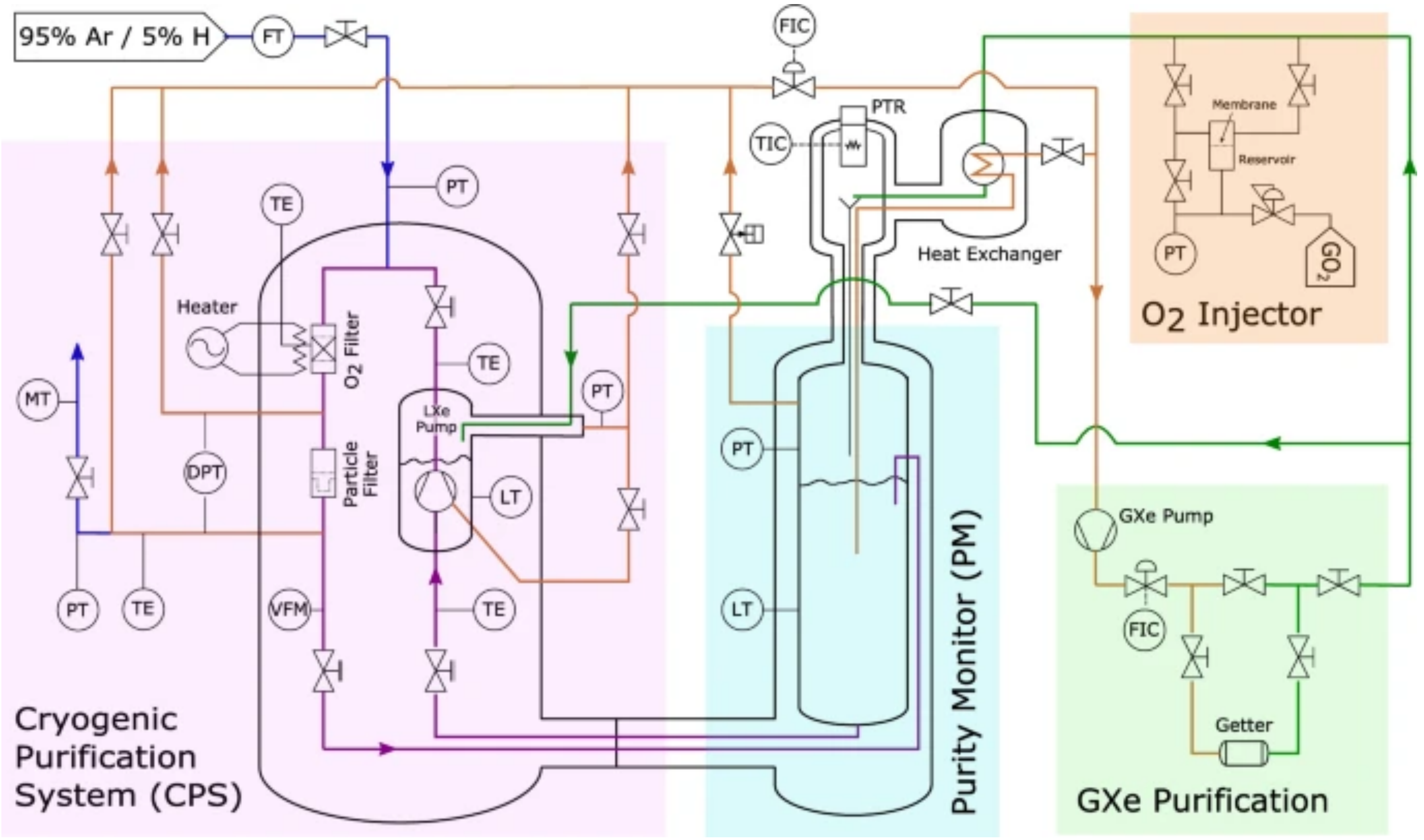
2 Charge collection in noble liquids

- Charges from ionization with density of
  - 26,000 e-/cm for 4.0 MeV/cm in LXe
  - 9,000 e-/cm for 2.1 MeV/cm in LAr
- Overall acquired charge
  - **≥ 50,000 e- for LXe**
  - **~ 20,000 e- for LAr**
- O(1 mm/μs) drift velocity for 1 kV/cm E-field
- Charge diffusion during drift informs design granularity of the collecting anode



2 Charge collection in noble liquids - R&D

- Liquid impurities
  - LXe and LAr must be purified (H_2O, electronegative impurities) for high light and charge yield
  - Mean e^- lifetimes for LXe / LAr around 1-10 ms in a ~ 9 t total mass for impurity concentration around 10 ppt
    - Modern technologies allow notably lower impurity concentrations

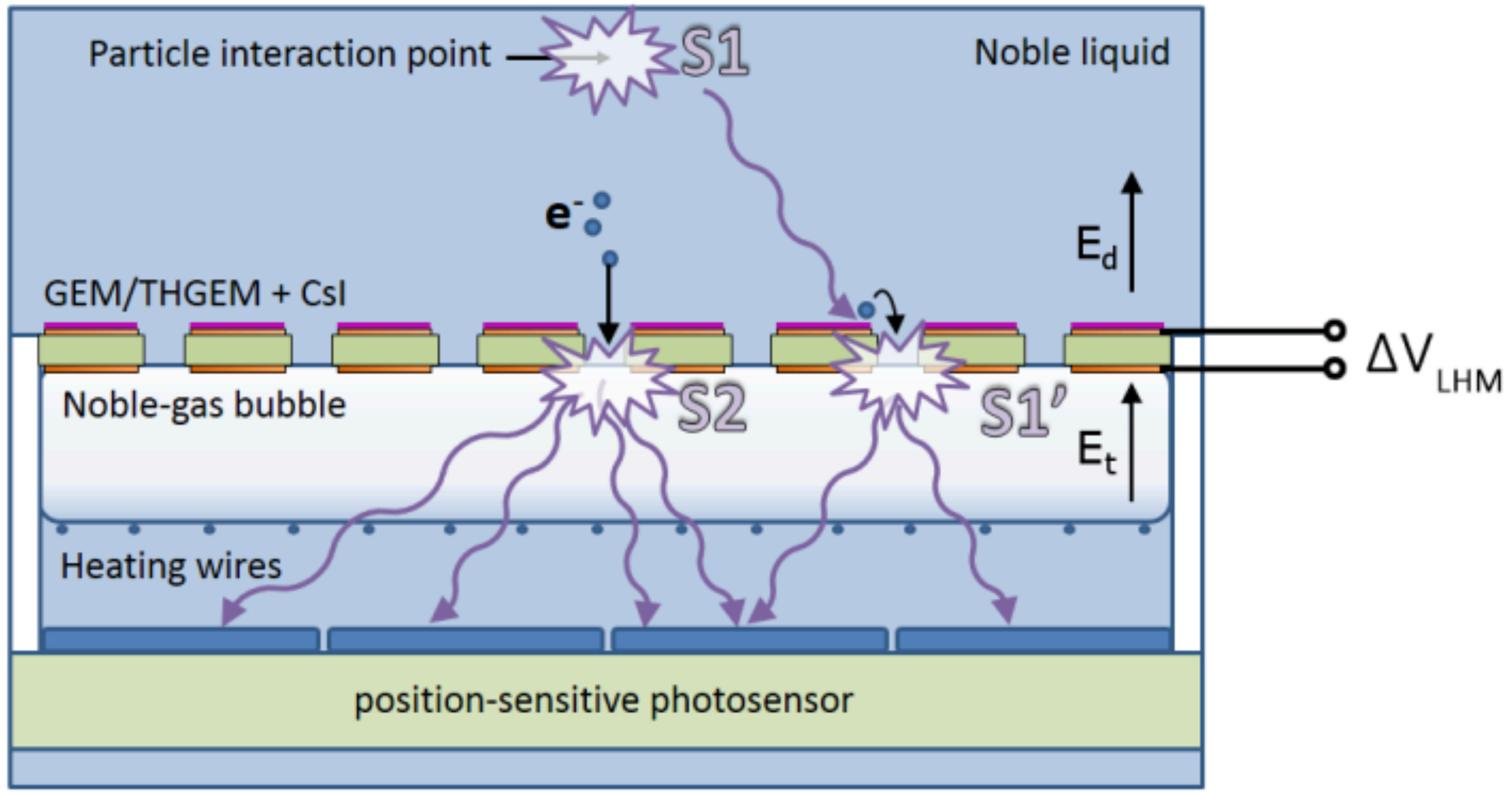


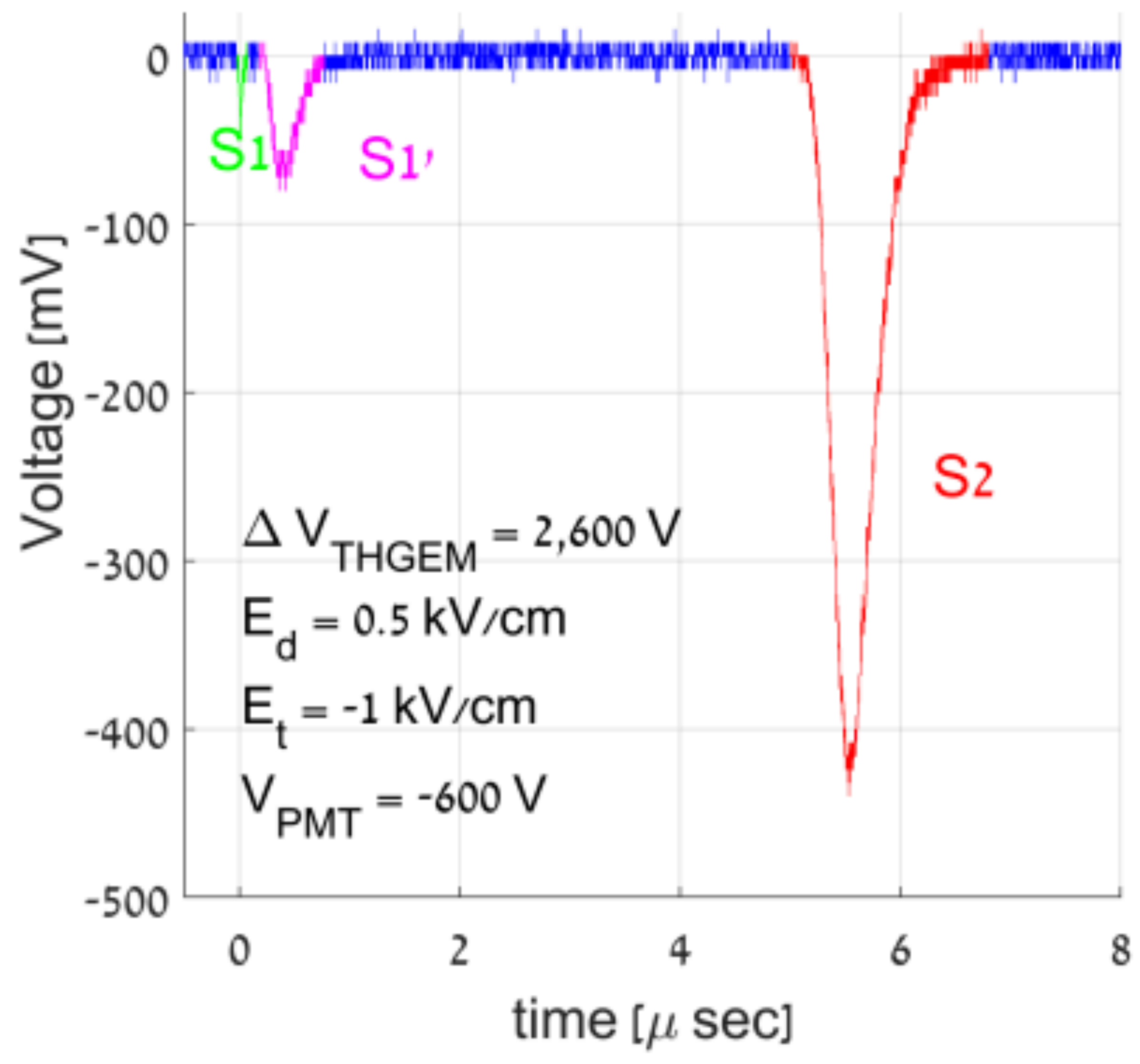
Xeclipse apparatus at Columbia University, E. Aprile et al.

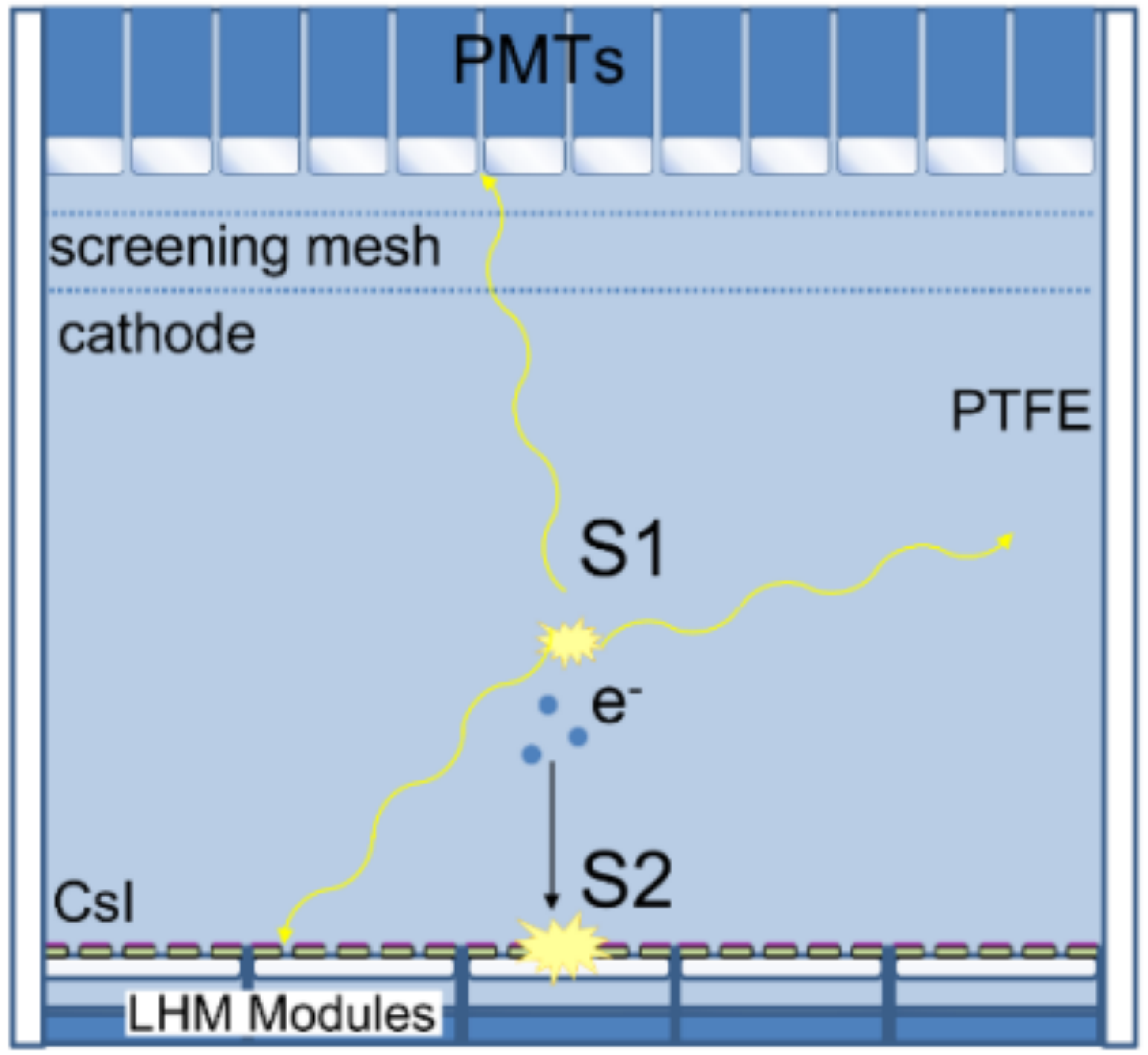
2 Charge collection in noble liquids - R&D

A. Breskin, 2022 JINST 17 P08002

- Charge amplification
  - several orders of magnitude amplification in gas phase via electroluminescence
  - amplification in liquid requires R&D
    - doping LAr with small percentages of LXe suggests amplification by factor ≥ 100 in LAr
    - exploitation of localized electroluminescence suggests potential amplification in LXe





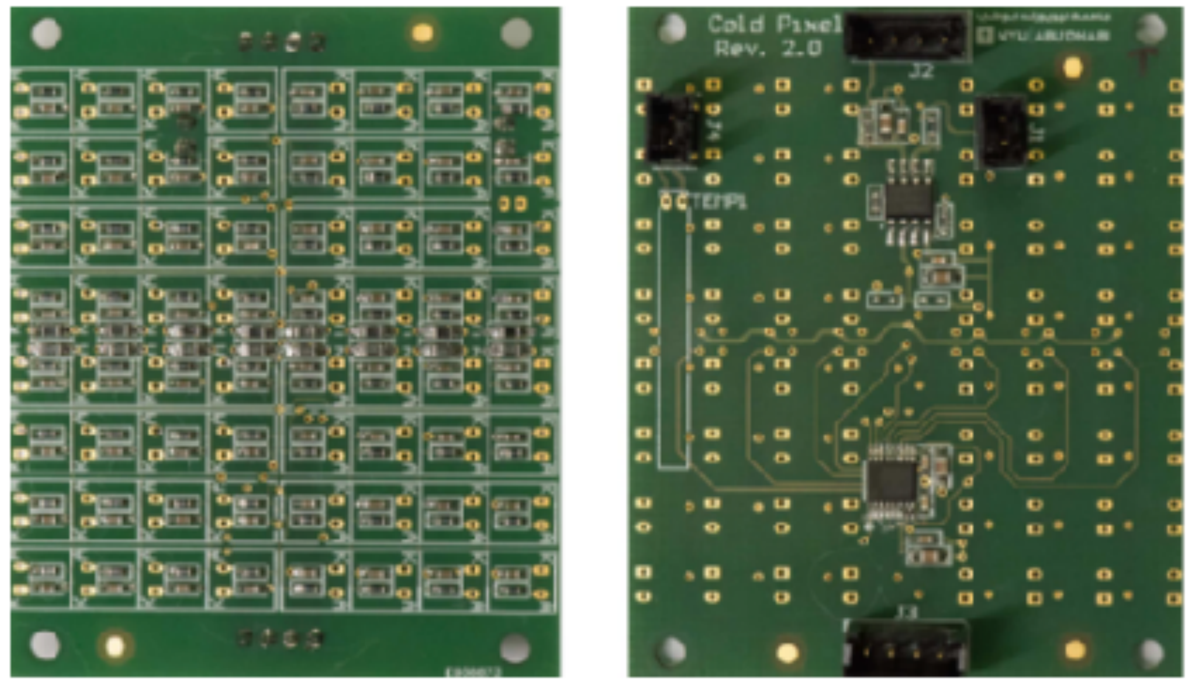


2 Charge collection in noble liquids - R&D

Images from L. Baudis and J. Asaadi

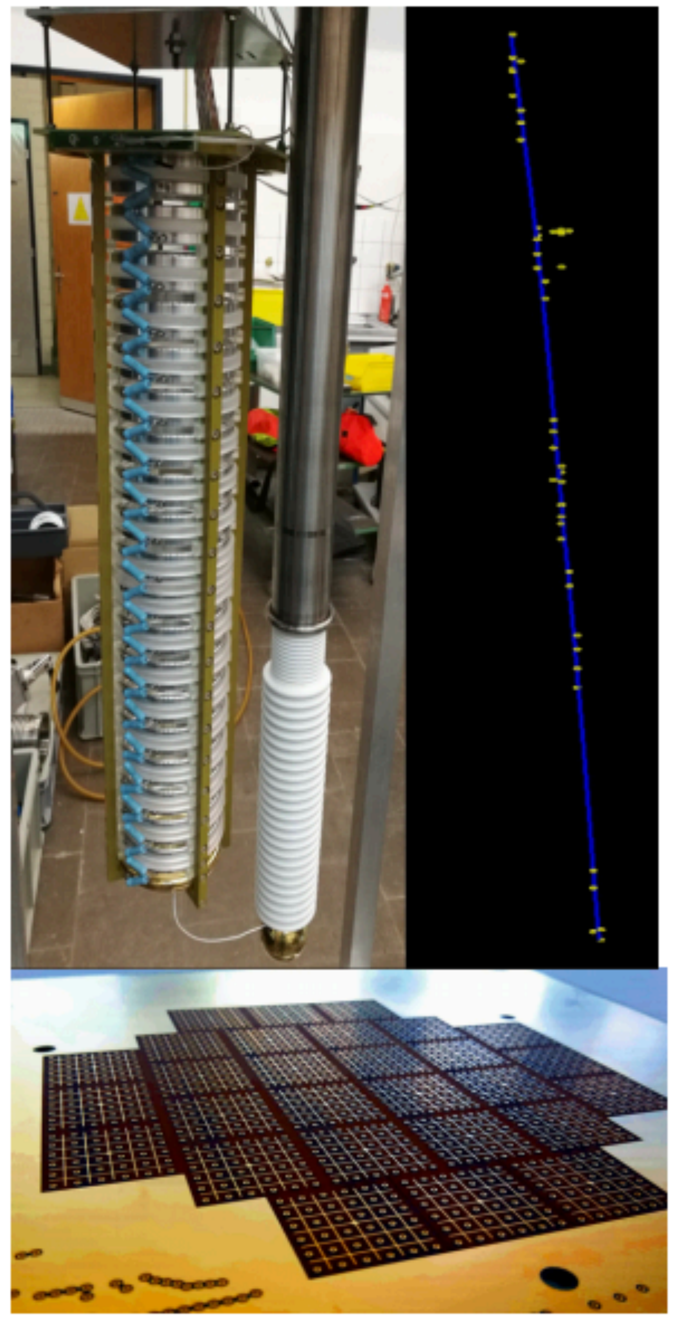
Charge readout structures

- High lumi applications (e.g. LBN near-detectors): Pixel electrodes on PCBs instead of “standard” wire planes for X-Y measurement, to eliminate risk of reconstruction ambiguities
- Amplification stability
- Cryogenic low-noise, low-radioactivity, low-heat dissipation readout
- Integrated, simultaneous readout of light and charge



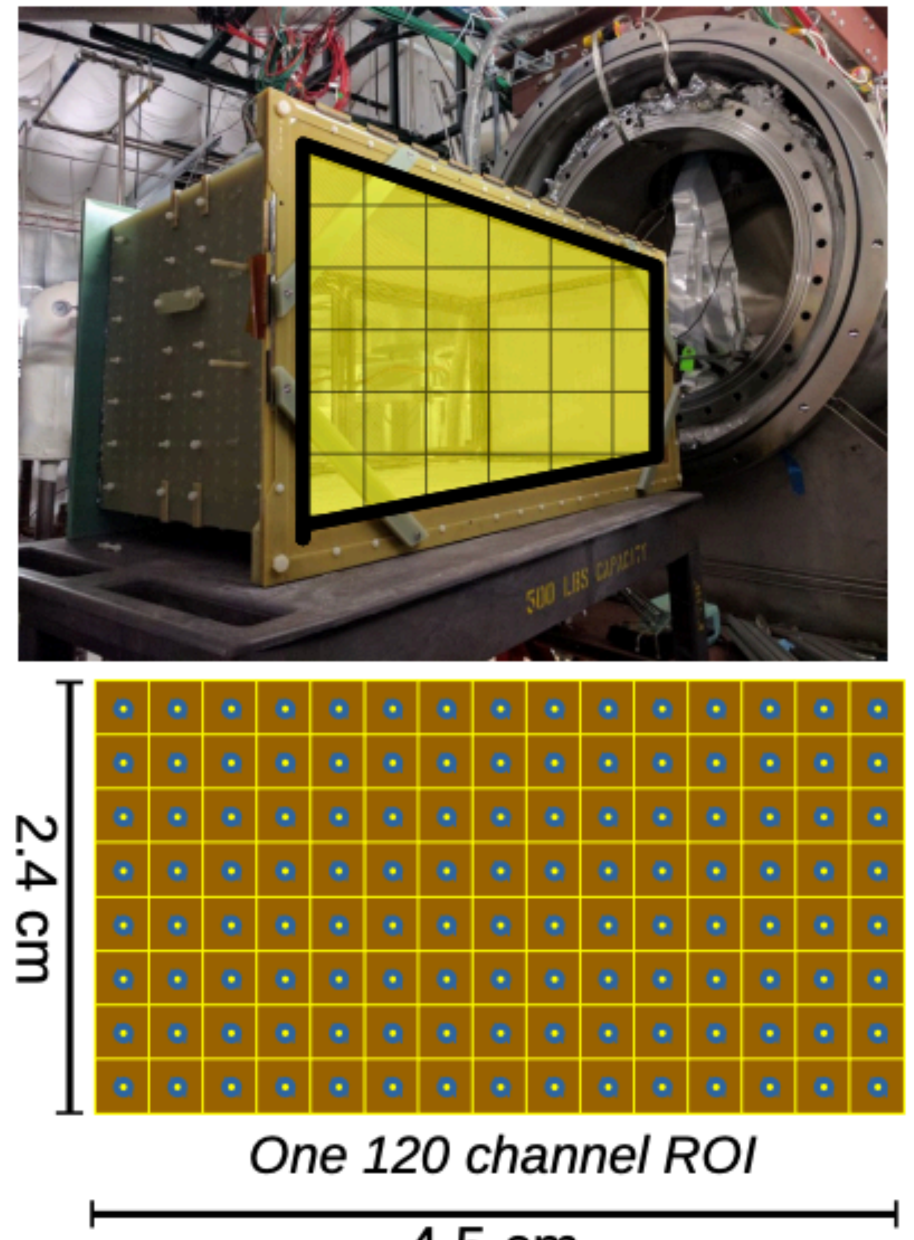
Cryogenic preamp for SiPMs, NIM 936, 2019

Demonstrated Summer 2016



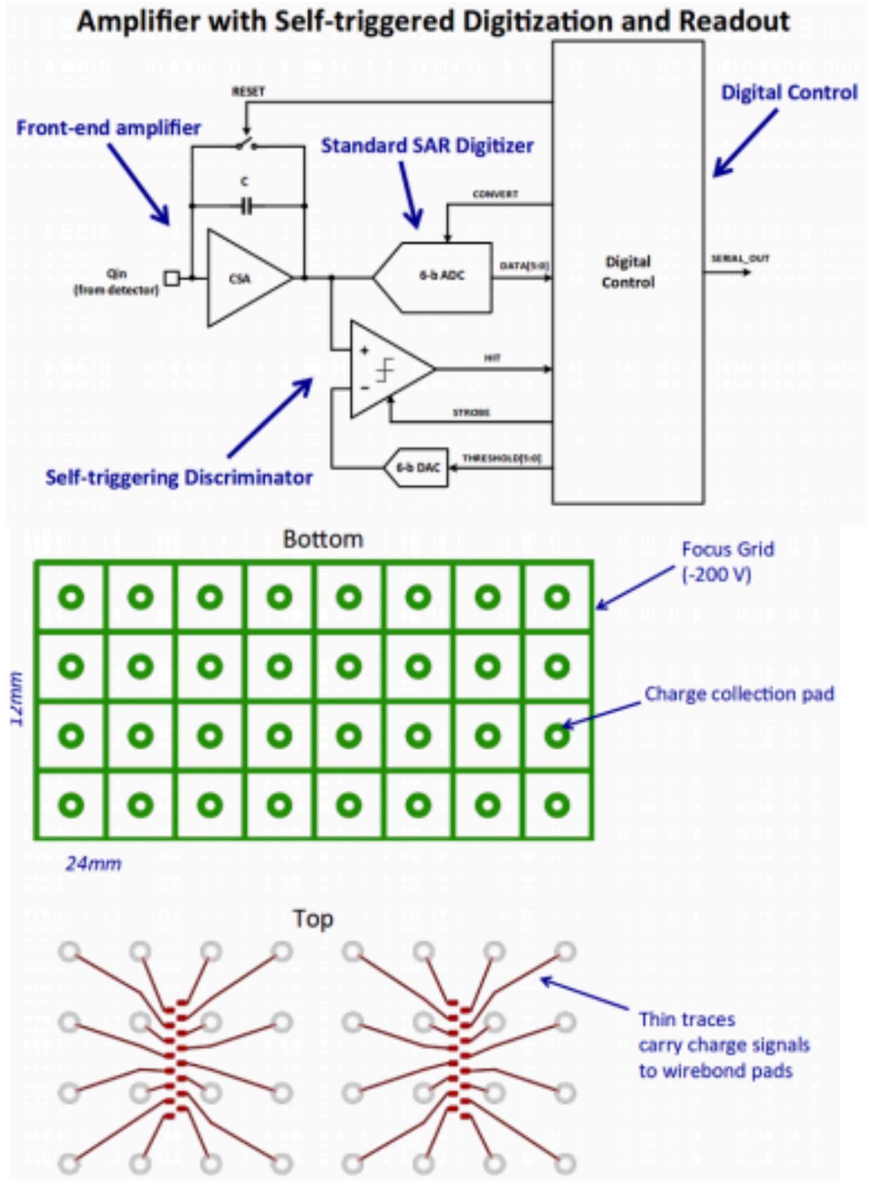
Multiplexed Pixel LArTPC Demonstrator
(1008 pixels readout with 32 channels)

Taking data Nov-Dec 2017



Highly-multiplexed Pixel LArTPC in a Testbeam
(28,800 pixels readout with 480 channels)

Benchtop chip tests December 2017

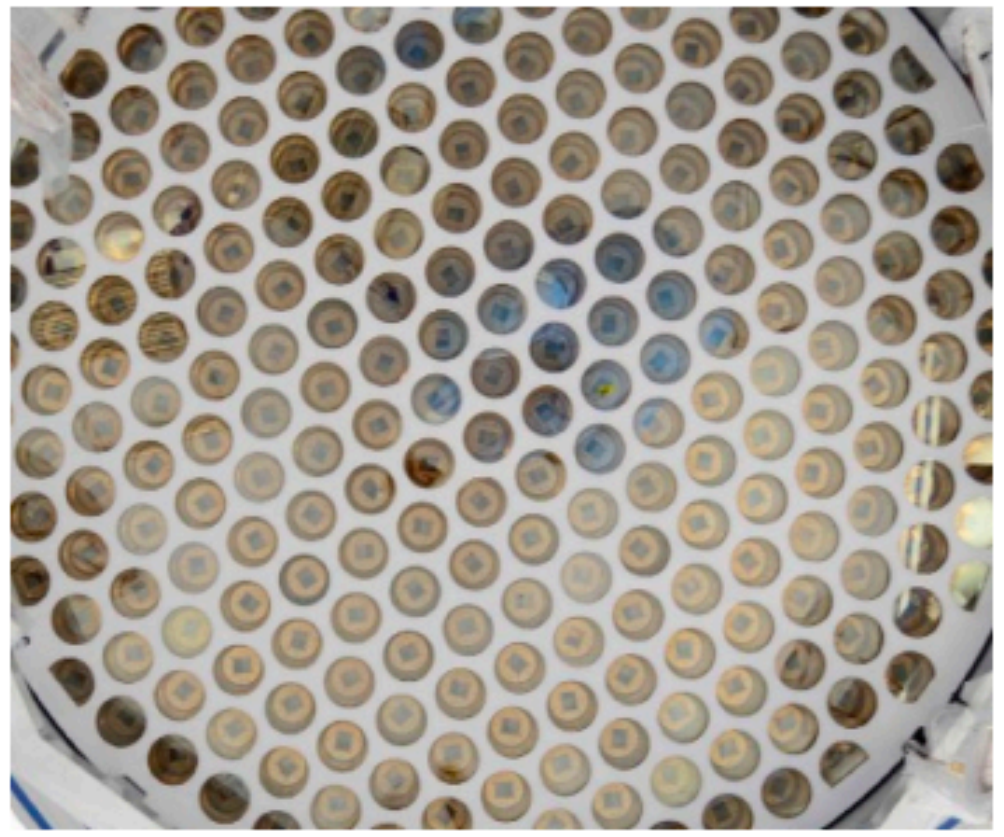


Truely 3d front end ASIC for LArTPC digital LArTPC Pixel Readout (LArPIX)

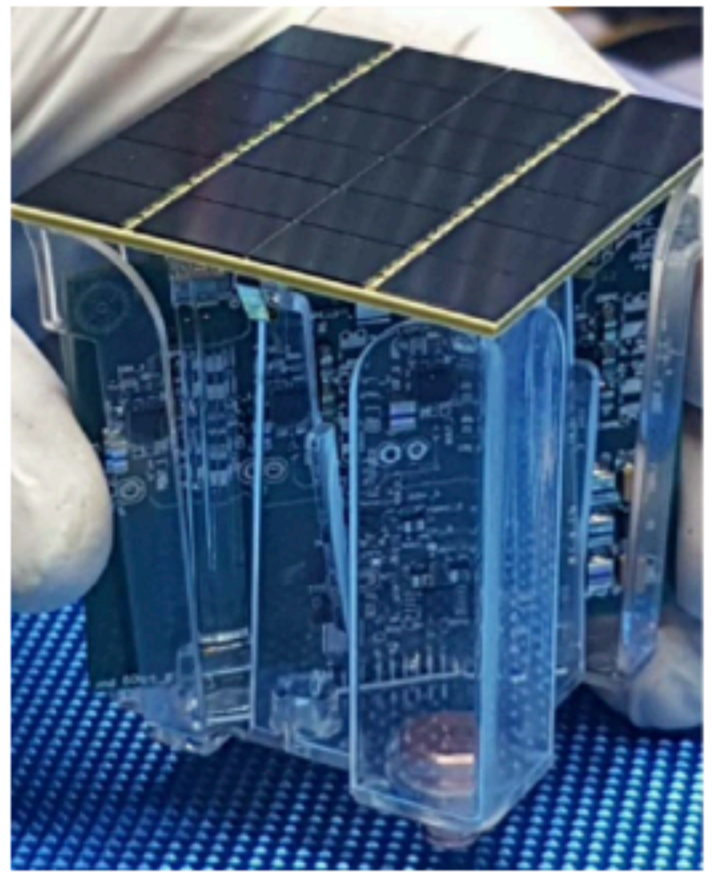
2 Charge collection in noble liquids - R&D

- Light and charge
  - **Photomultipliers**: established technology, low DCR (~0.02 Hz/mm^2), high QE (mean around 34%, up to > 40% at 175 nm)
    - *issues*: lower radioactivity required, after-pulsing due to vacuum leaks and light emission
  - **SiPM arrays**: lower radioactivity / area, lower voltage
    - *issues*: dark count rate (too high by ~ factor 50 at least)
    - ⇒ low-field SiPMs (reduce band-to-band tunneling), digital SiPMs

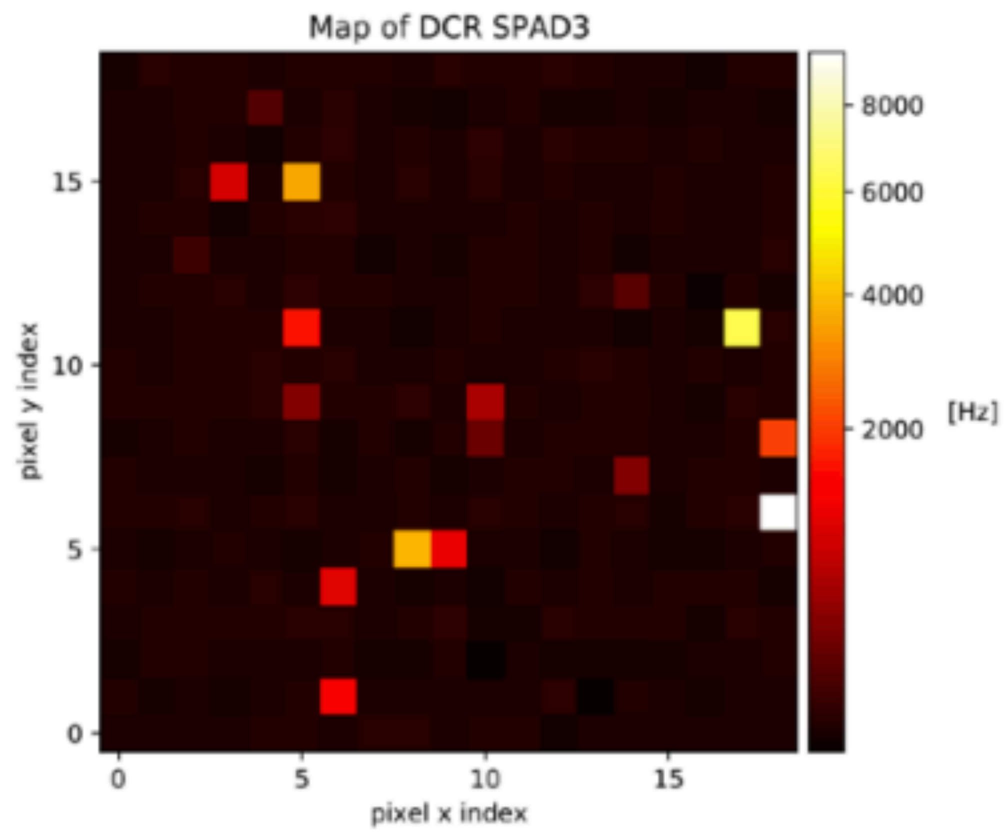
PMT array for XENONnT



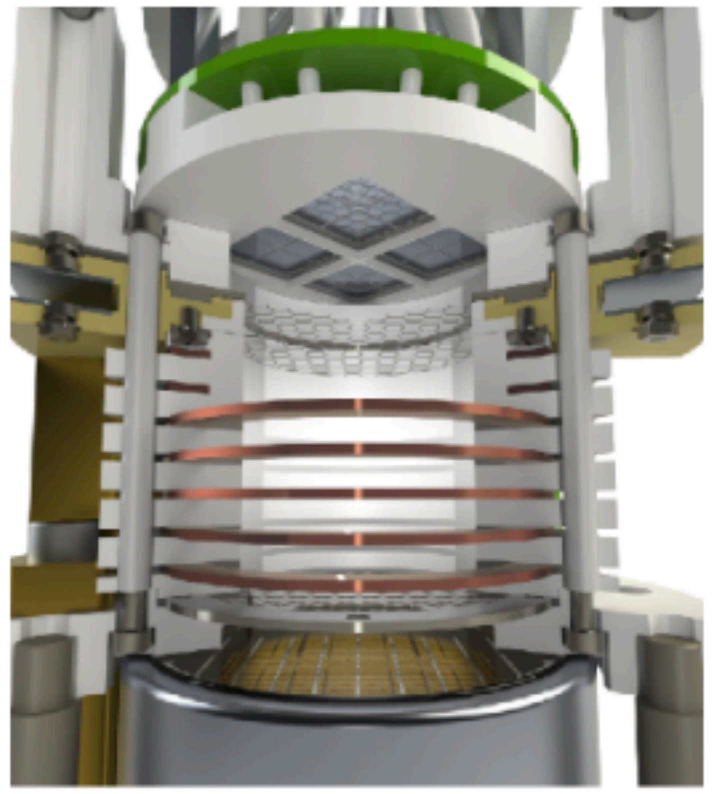
SiPM arrays for Darkside-20k



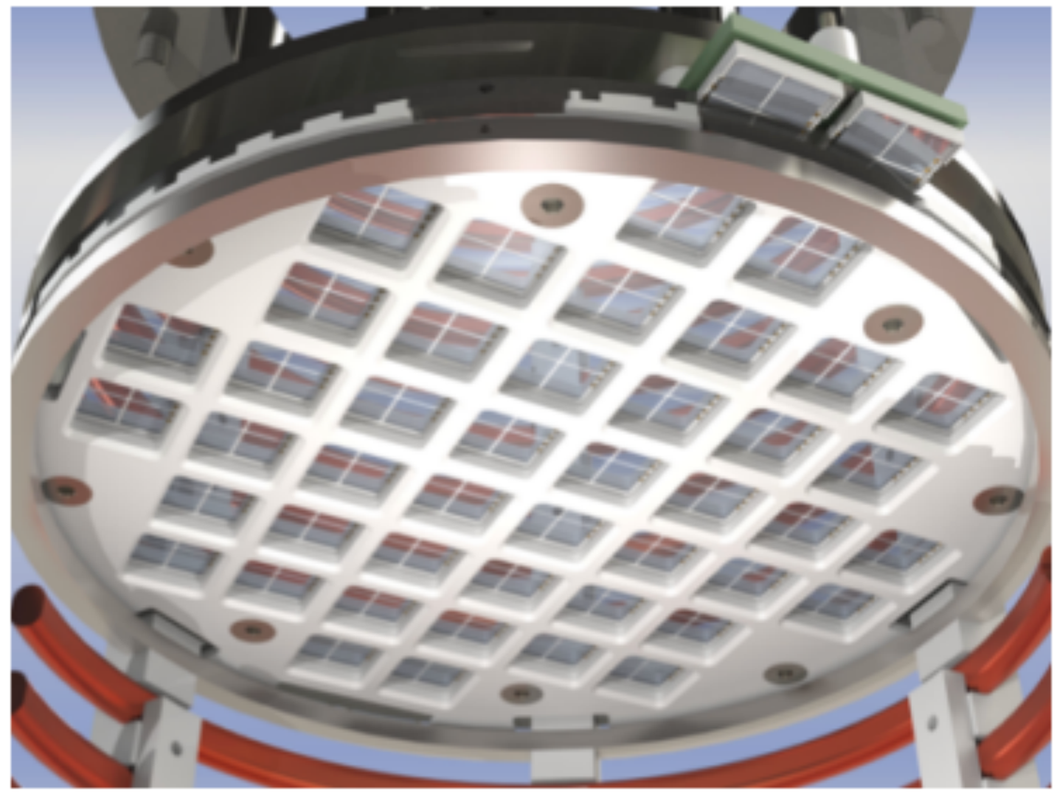
Digital SiPM



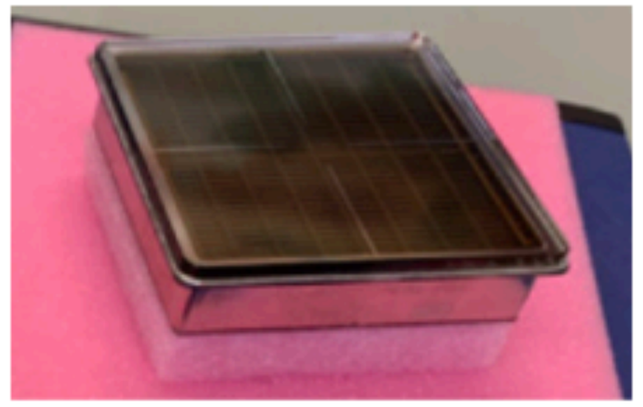
Two-phase TPC with SiPM array



EPJ-C 80, 2020



SiPM array, DARWIN demo



2''x 2'' flat panel PMT (R12699) R&D for DARWIN

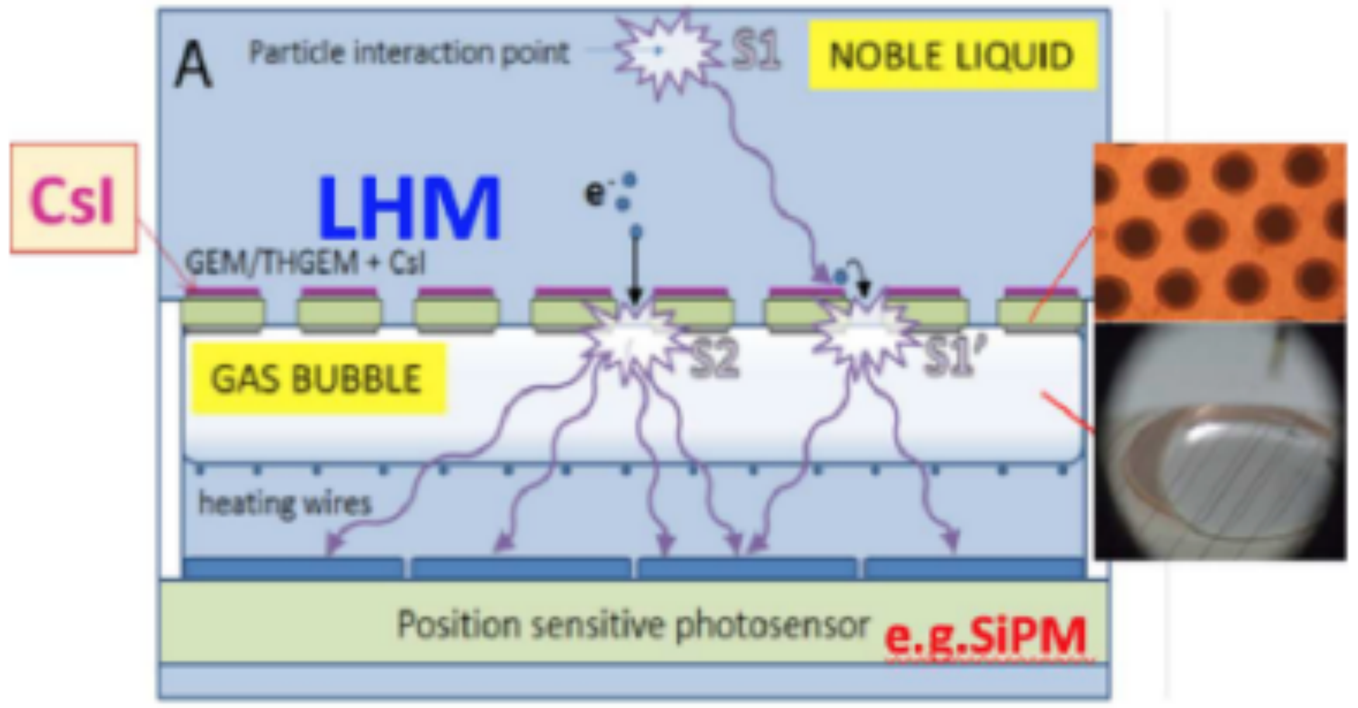
3'' (R1311 low-rad PMT by XMASS), JINST 15, 2020

Images from L. Baudis

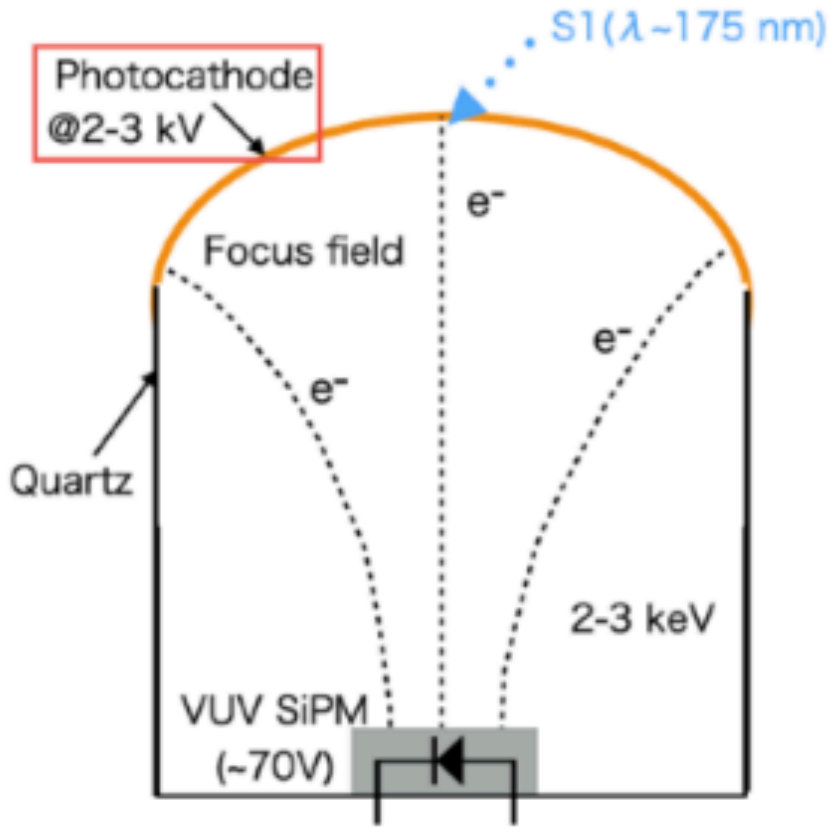
2 Charge collection in noble liquids - R&D

Images from L. Baudis

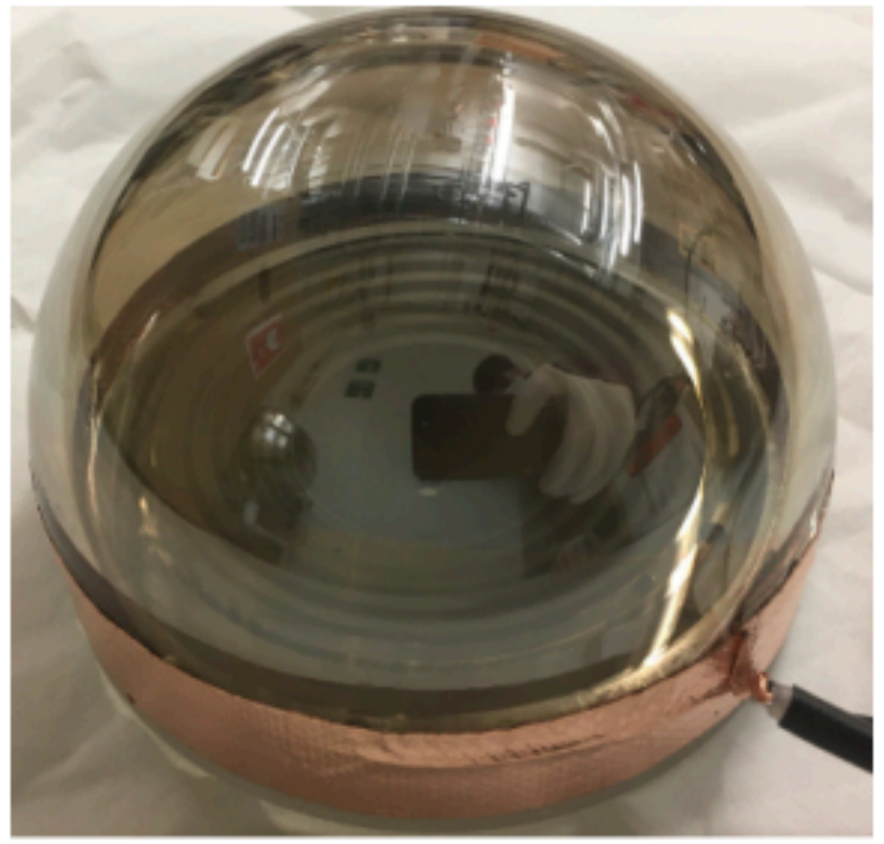
- Light and charge
  - **Hybrid sensors**: e.g., ABALONE, VSiPM, SIGHT
    - SiPM + Quartz + photocathode: reduced radioactivity compared to PMTs
    - lower DCR compared to SiPM arrays (photosensitive area difference)
  - **Bubble-assisted Liquid Hole Multipliers**: local vapor bubble underneath GEM-like perforated electrode in LXe

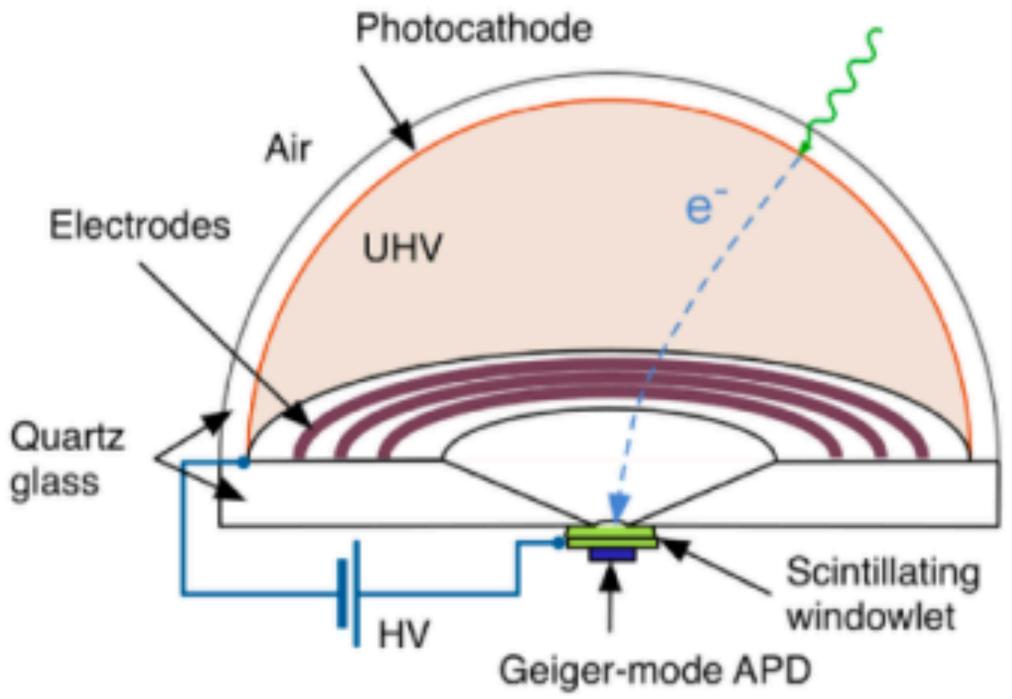


Liquid hole multipliers
JINST 13, 2018



Hybrid photosensor: Hamamatsu XE5859





Hybrid photosensor: ABALONE; left (DARWIN R&D with SiPM); right: NIM 954, 2020

2 Charge collection in noble liquids - R&D

- Cryogenic front-end electronics
  - Number of readout channels ~ number of sensors and/or meters-long TPC wires
  - Challenges for cryogenic front-end electronics include heat dissipation
  - Cryogenic optical transmission of signals (e.g. in DUNE and DarkSide-20k) requires transmission driver and receiver development
  - Pixel electronics require independent front-end channels for each pixel, likely operating in cold (even immersed in the cryogenic liquid) with a potentially destructive dissipation heat
  - The handling of high bandwidths, the improvement of the S/N ratio, and the reduction of cost/channel will be crucial for large-scale pixel readout

3 Purification, cryogenics, infrastructure for noble liquids

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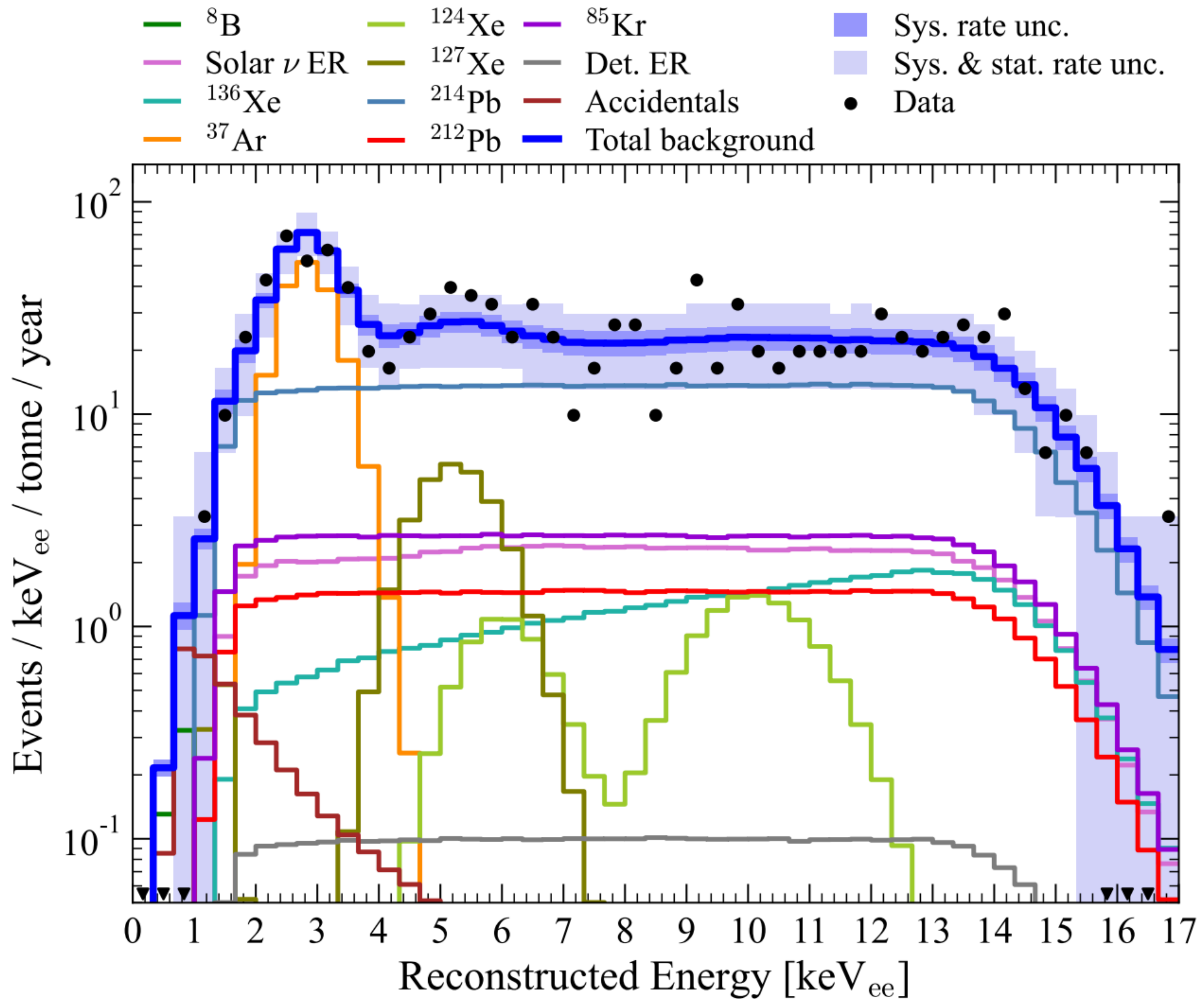
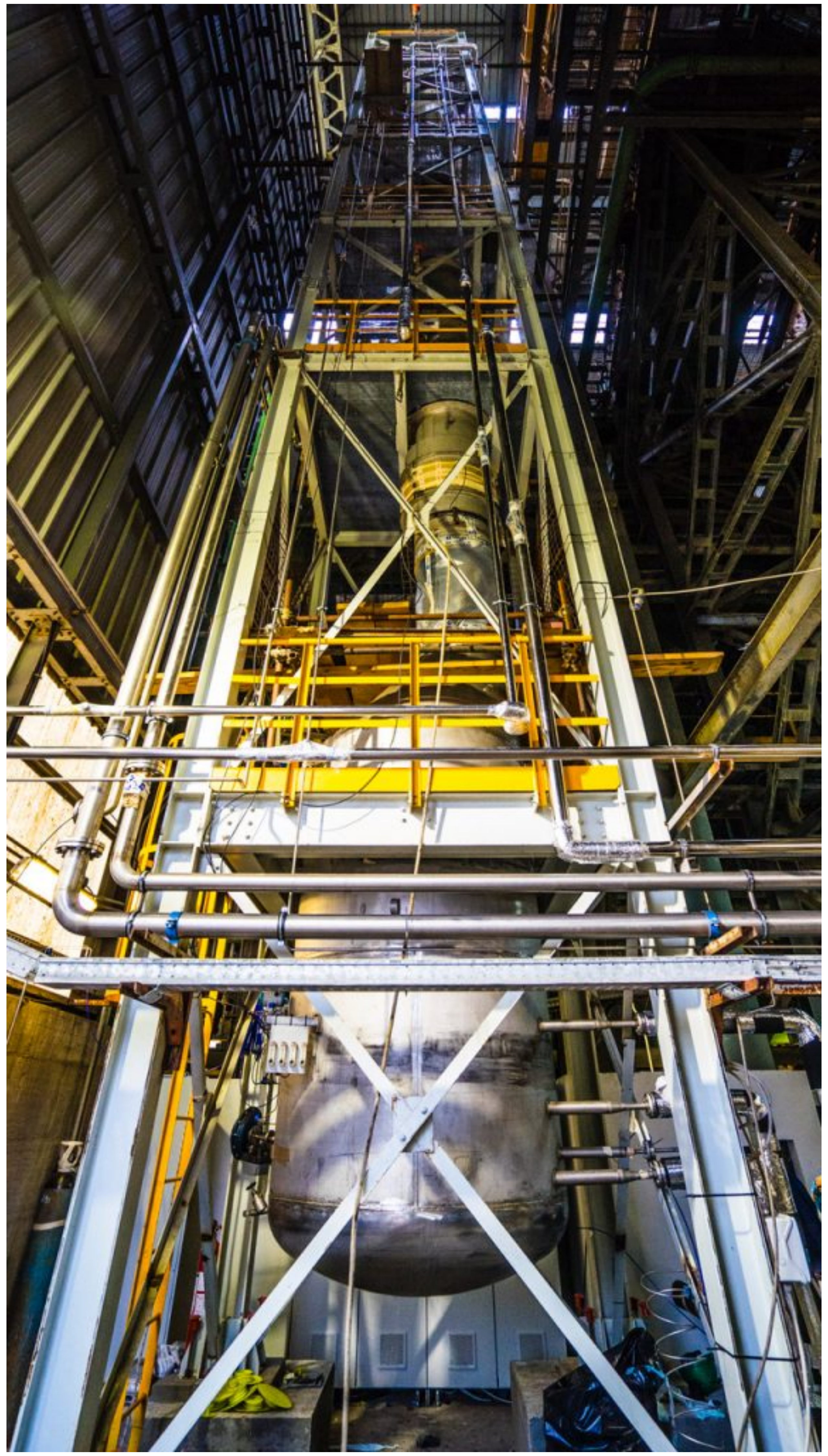
- Target radiopurity
  - Primarily of concern for the low-background experiments
  - Near absence of impurities like ^{39}Ar, ^{222}Rn, ^{85}Kr is crucial
  - LAr: large-scale cryogenic ^{40}Ar distillation efforts currently under development (ARIA project)
  - LXe: focus on ^{222}Rn: continuous cryogenic distillation needed

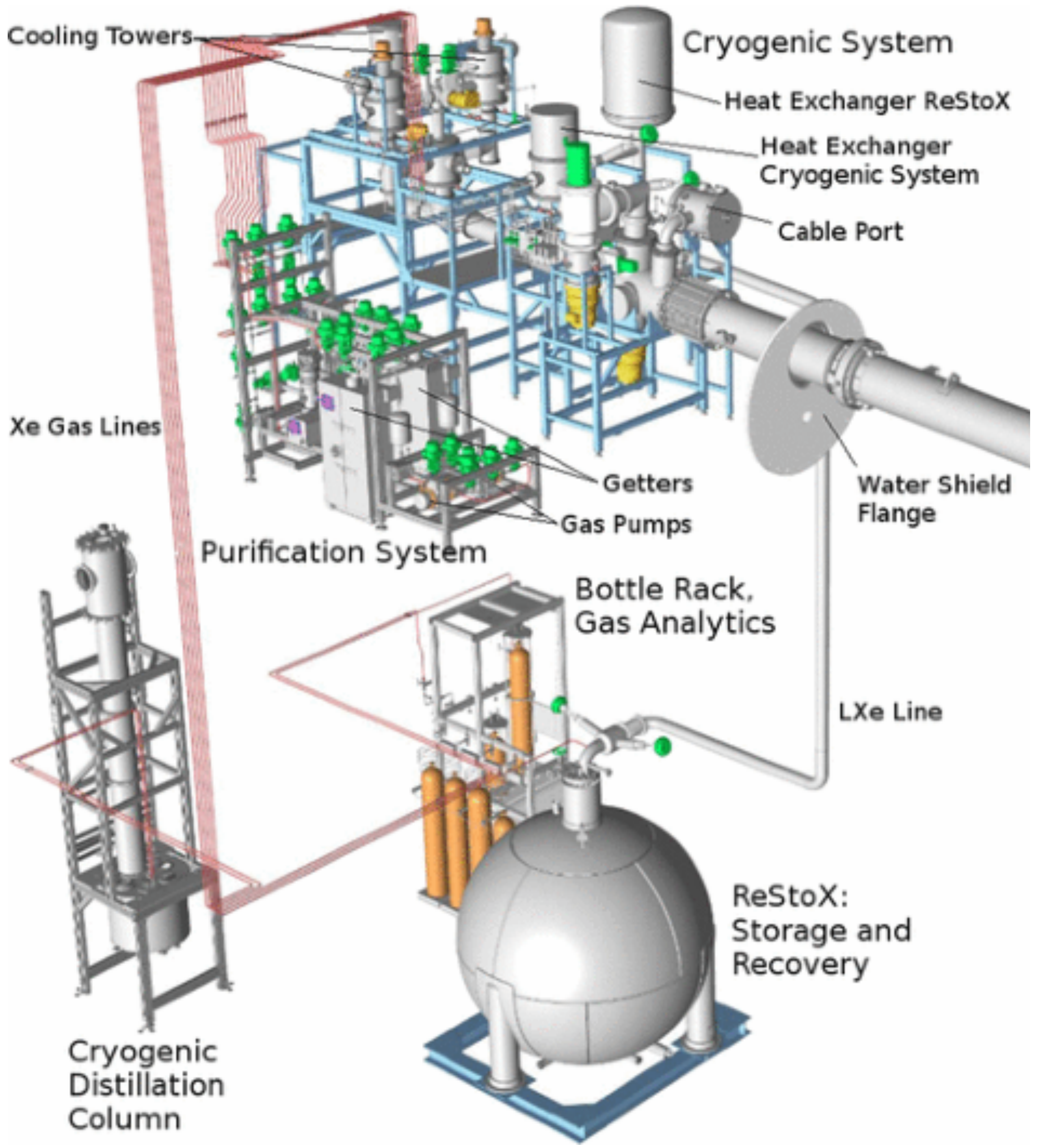


Distillation column, ARIA project



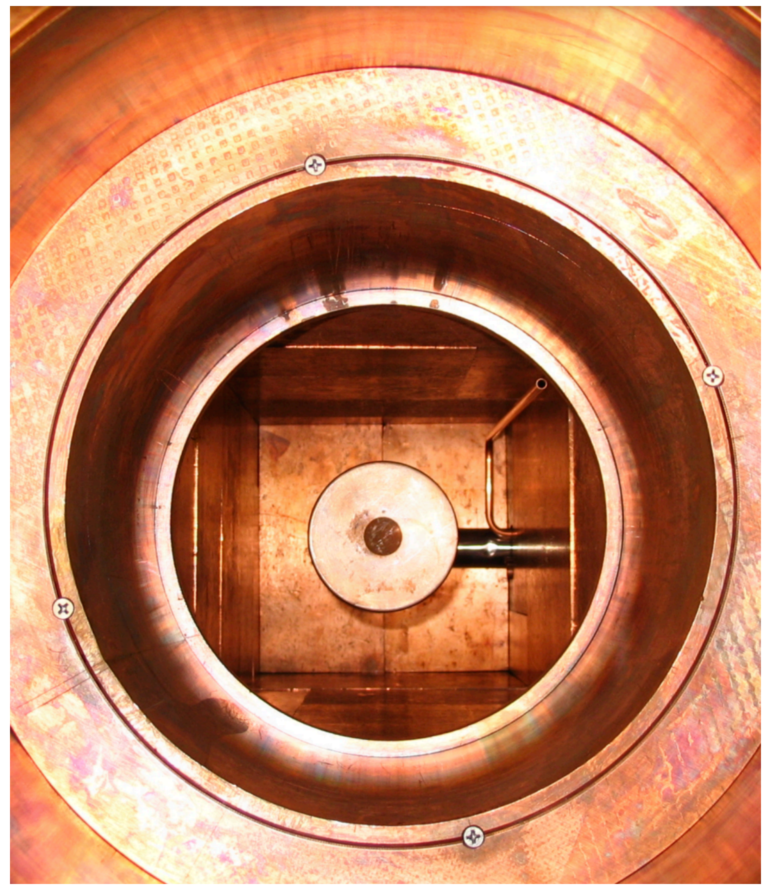
3 Purification, cryogenics, infrastructure for noble liquids

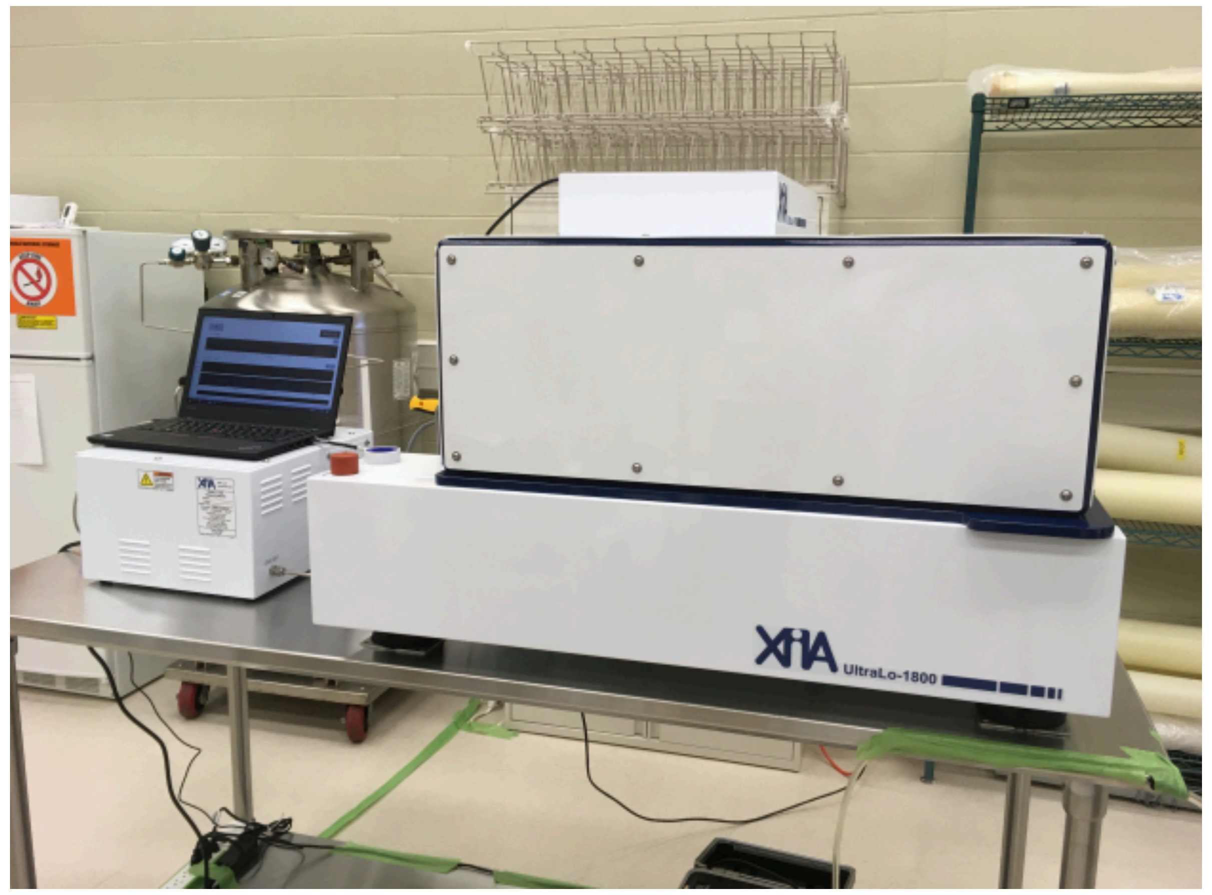
- Cryogenics
  - increasingly complex cryogenic systems
  - need to facilitate circulation of LAr/LXe to maintain cleanliness
  - thermodynamic solutions necessitates ultra-clean compressors and heat exchangers
  - technologies needs similar to those of particle accelerators, and detector cooling solutions in HEP experiments
    - for different reasons, both communities need clean, non-polluting components in their respective cryogenic and cooling systems
  - multi-ton storage components with rapid noble liquid recovery systems in case of emergency

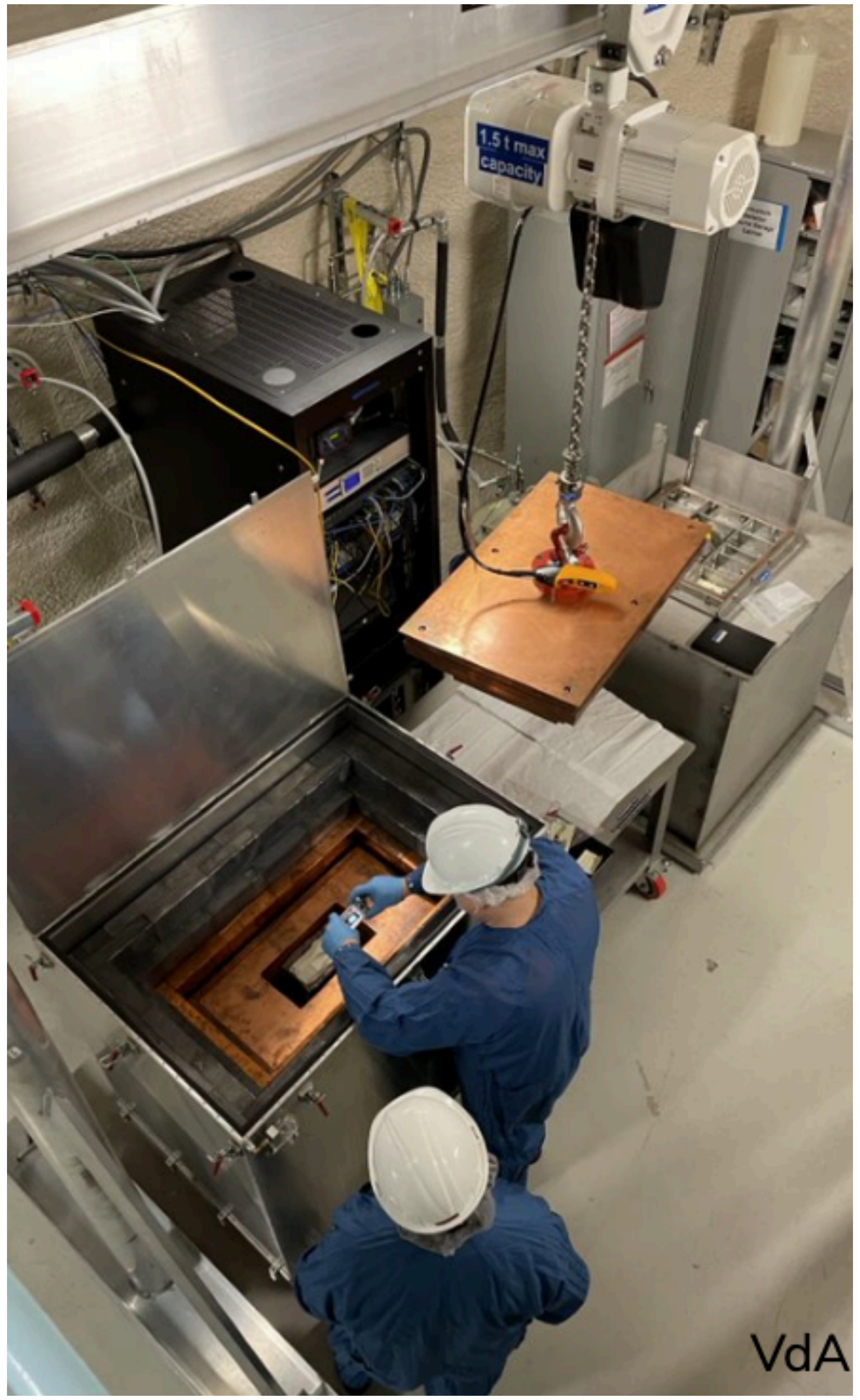


3 Purification, cryogenics, infrastructure for noble liquids

- Radioassay
  - extensive screening campaigns in UG labs
  - highly specialized radon emanation measurements
  - R&D for mitigation of emanation backgrounds by investigating material selection procedures and options for surface treatment in systematic way
  - ultra-sensitive trace analysis capabilities need to developed for a much larger scale

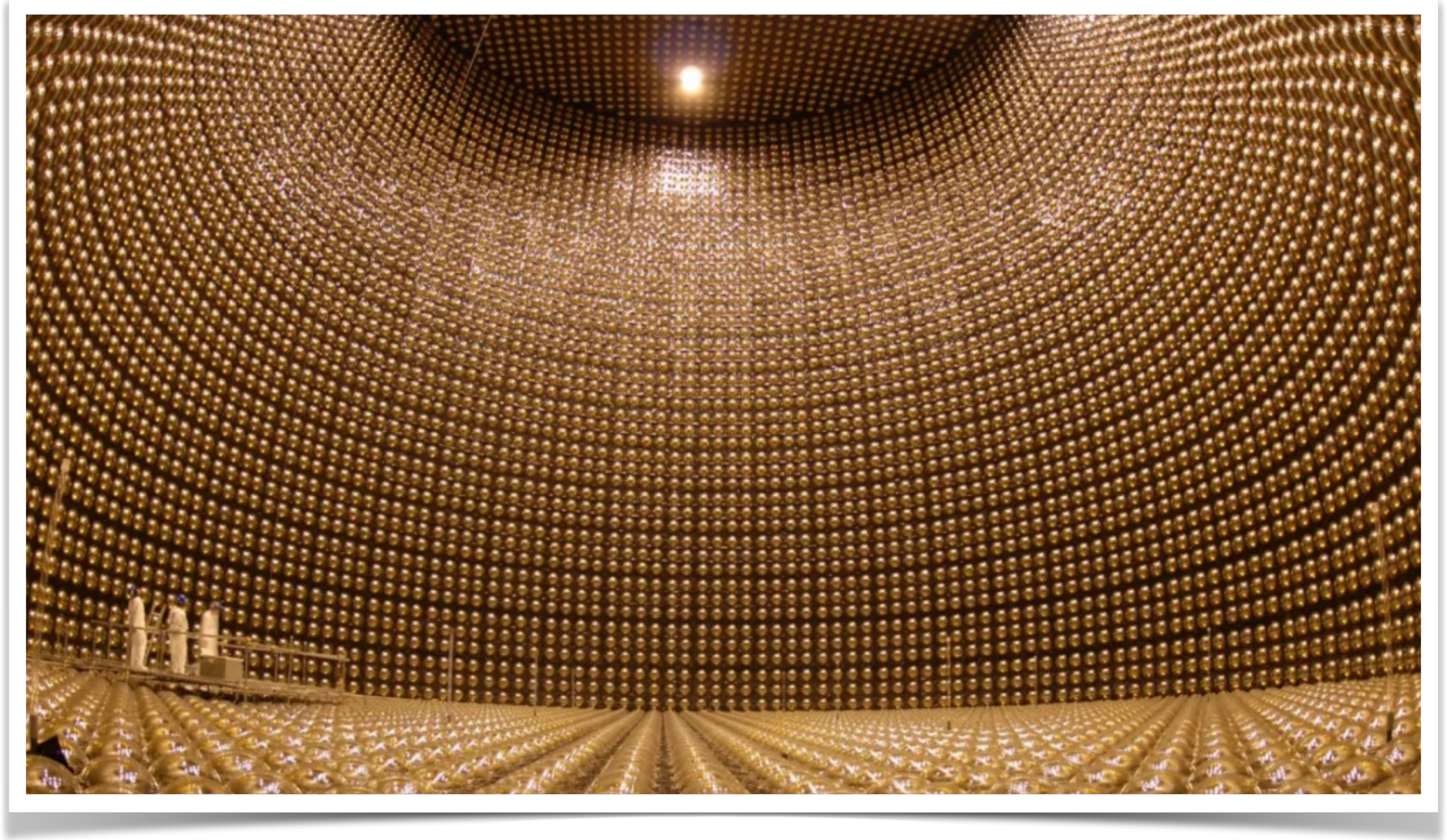


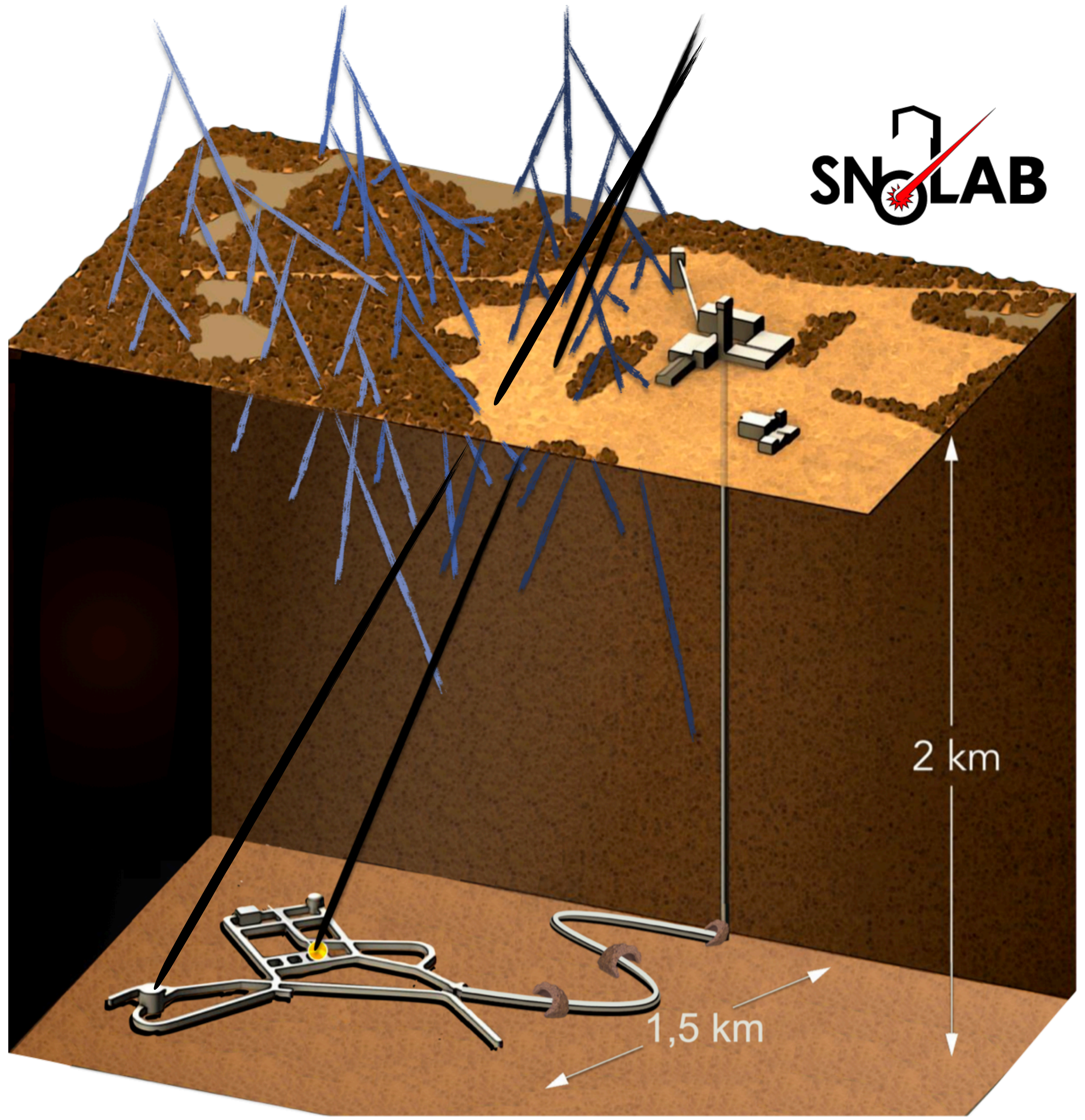




4 Light collection in noble liquids and other liquids

- Main challenges:
  - photosensor coverage over huge surfaces
  - extreme environments (e.g. underground, undersea, and / or at cryogenic temperatures)
  - single photon sensitivity
  - long term operation and stability (≥ 10 years between detector accesses)
  - numbers of readout channels as well as data volume
  - very different time scales (both ~ns and ~ms at same time)
  - radiopurity of light collection, sensing, front-end electronics and signal transmission technologies





Credit: SNOLAB / M. Wilson

4 Light collection in noble liquids and other liquids

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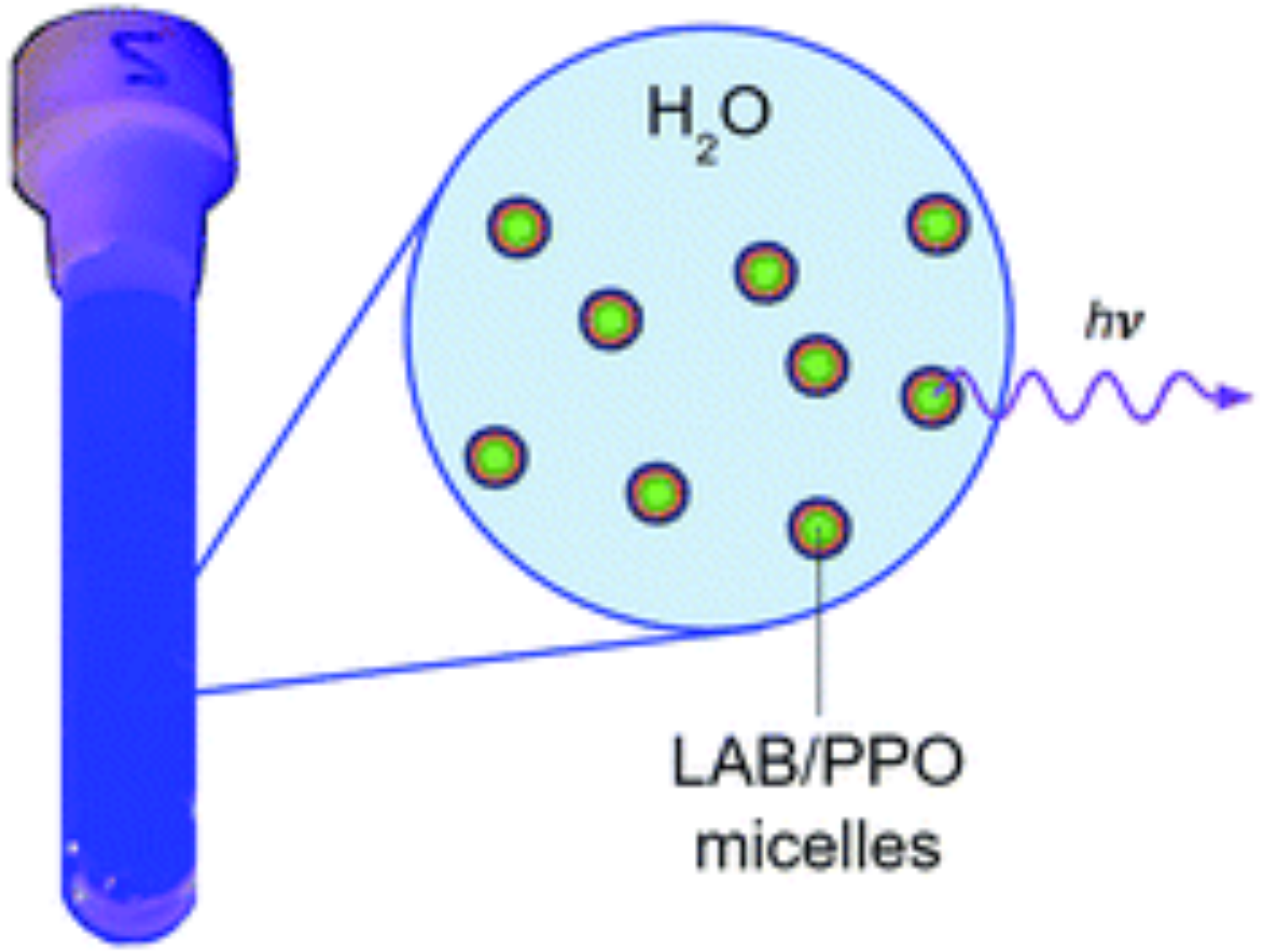
- Huge photosensitive areas
  - reducing dark current rate (DCR)
  - reducing channel count through summing SiPM signals in arrays
  - increasing S/N through front-end electronics design (mitigate large output capacitance of arrays)
  - improving timing resolution

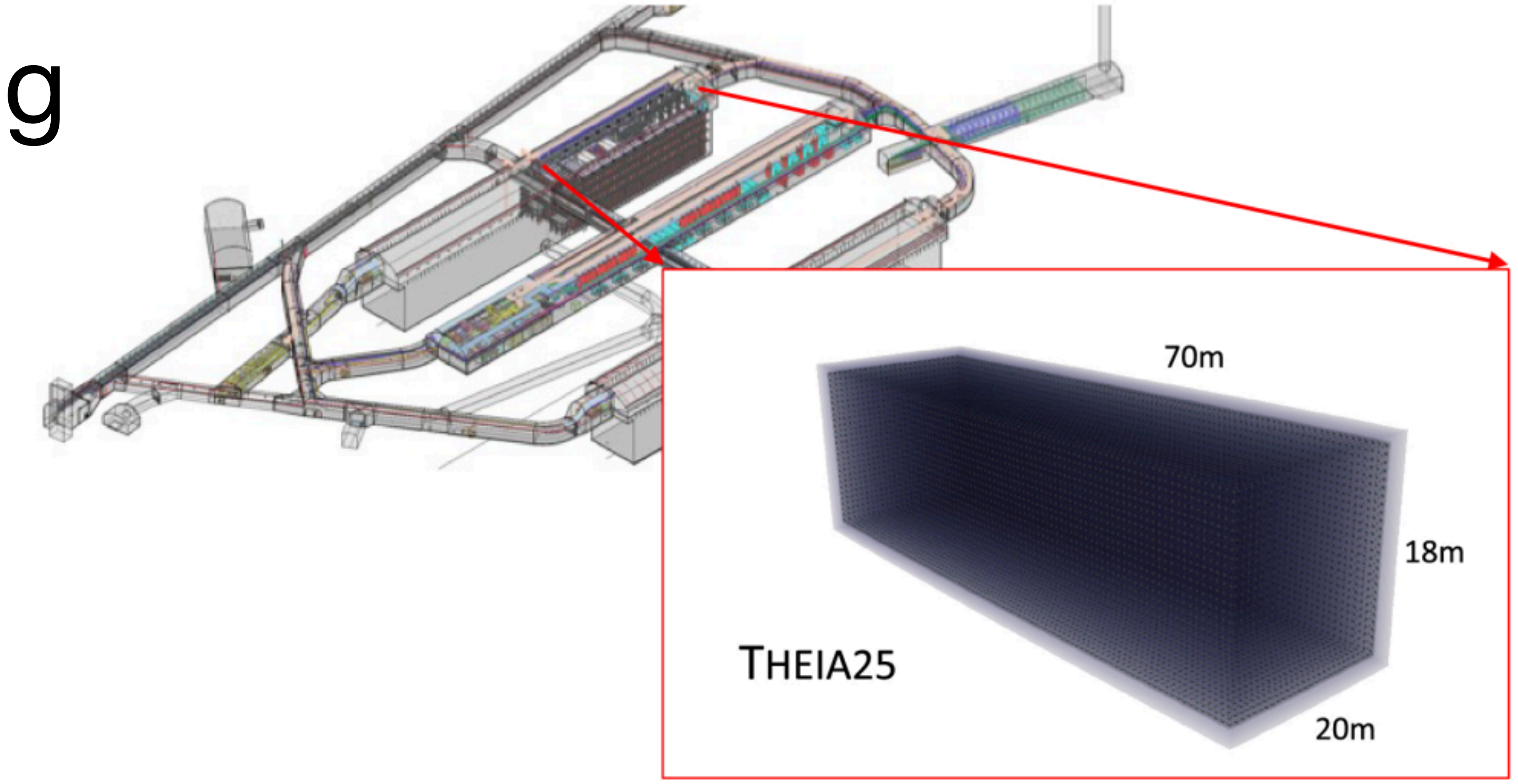
Experiment	Type	Photon detector	Area (m^2)
nEXO	LXe	SiPMs (FBK [Ch2-18], Hamamatsu [Ch2-19]), digital 3D-SiPM	5
DARWIN	LXe	PMTs, SiPMs or Hybrids (SIGHT, ABALONE)	8
TAO	LSci	FBK SiPMs	10
DarkSide-20k	LAr	SiPMs (FBK NUV-HD triple-dopant)	30
ARGO	LAr	SiPM is baseline option	200
DUNE	LAr	Light guide or trap + SiPM	10-1000

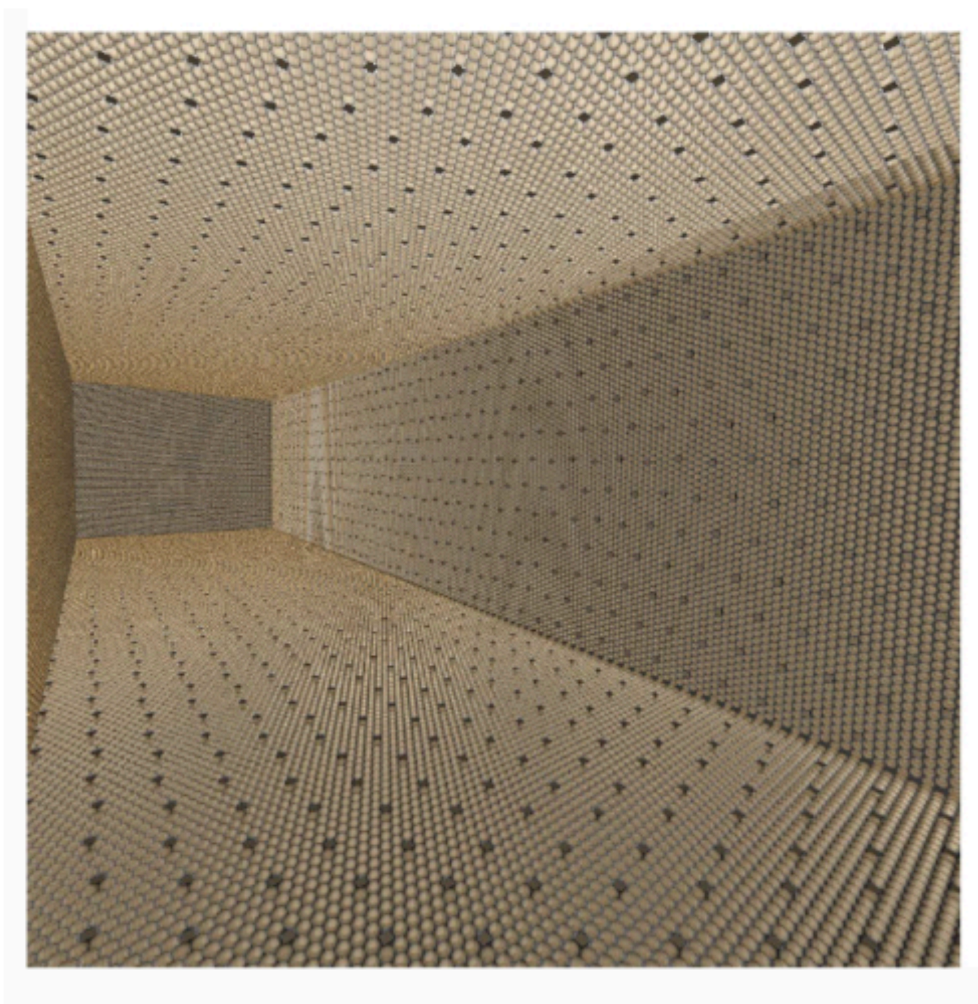
5 Liquid scintillator and water detectors

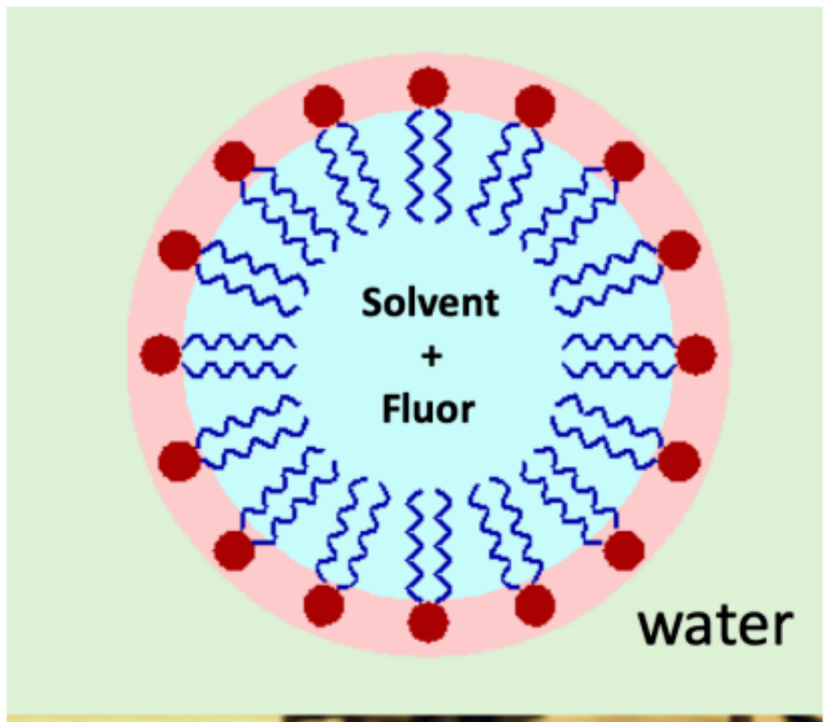
Credit: THEIA collaboration

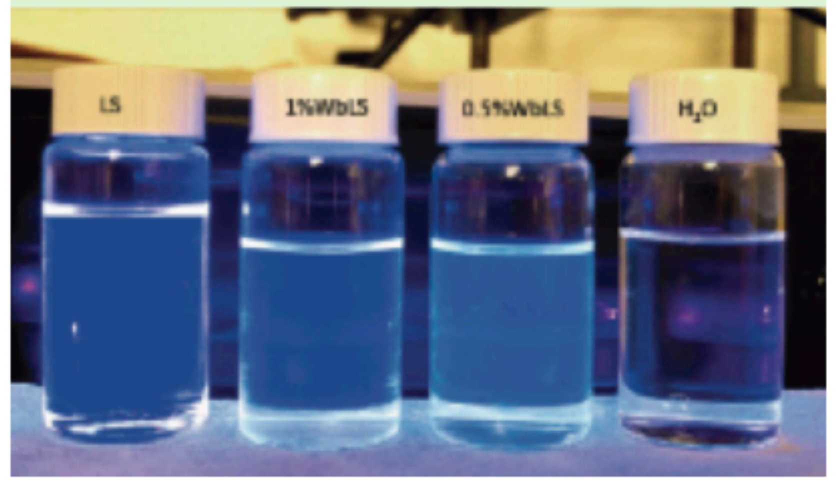
- Radiopurity, radiopurity, radiopurity…
- Liquid composition
- Low temperatures
- Opacity
- Hybrid detectors for event reconstruction
- Liquid doping











5 Liquid scintillator and water detectors

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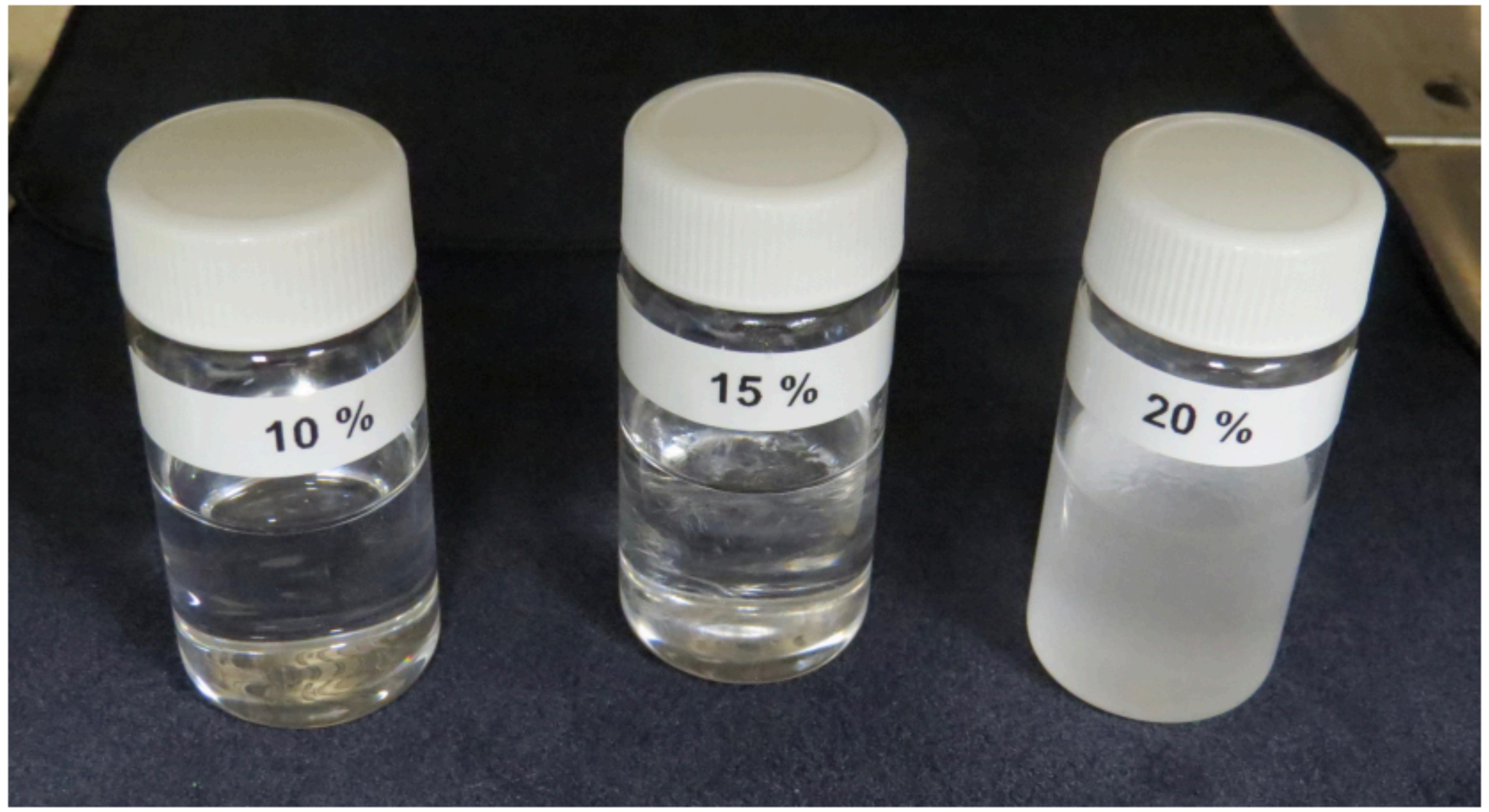
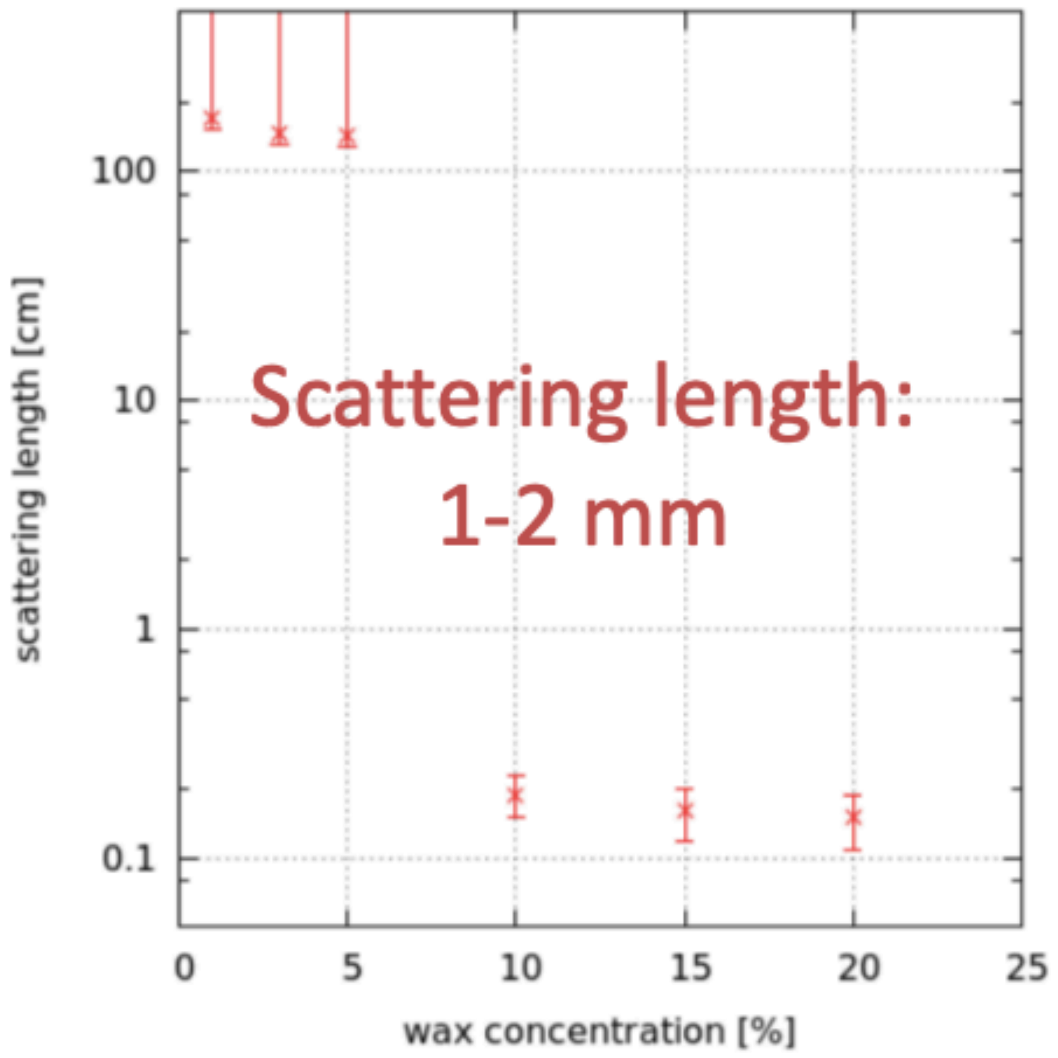
Opaque scintillators

- Light collection at origin using fibers + fast readout
- Highly improved vertex resolution by light confinement
- Wax based scintillator (NoWaSH)
- High metal loading possible (up to 10%), suspensions
- Potential applications: reactor, geo, 0νββ, solar,…





Slide from
C. Buck

Required R&D readiness (high-level, non-exhaustive overview)

Earliest feasible start date, such that R&D is not the limiting factor.