Dark matter

LAURA BAUDIS
UNIVERSITY OF ZURICH

SURF LONG TERM VISION WORKSHOP
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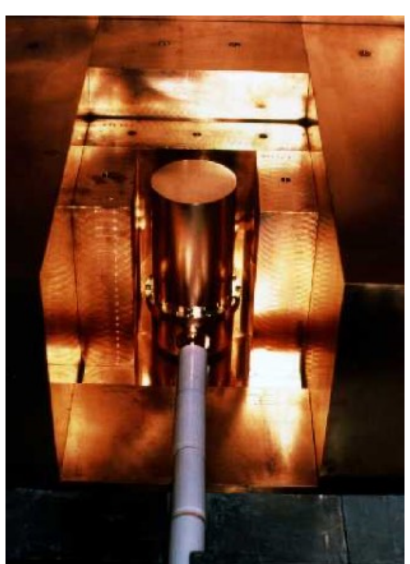
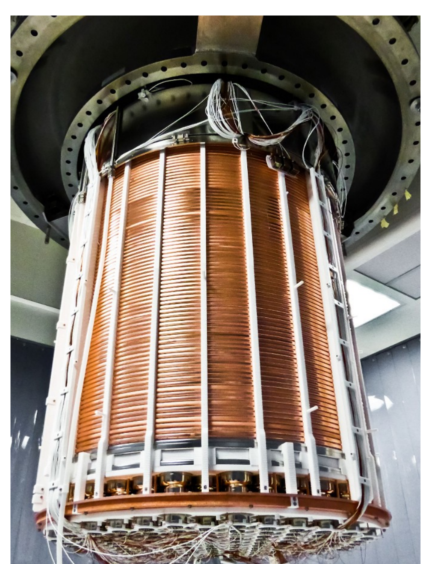
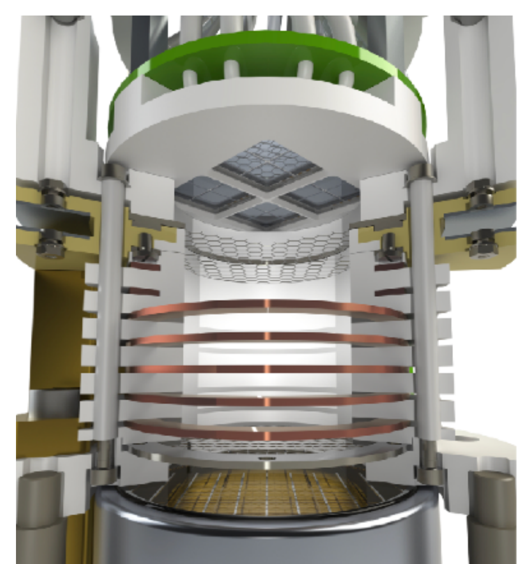
BRIEF INTRODUCTION AND RESEARCH

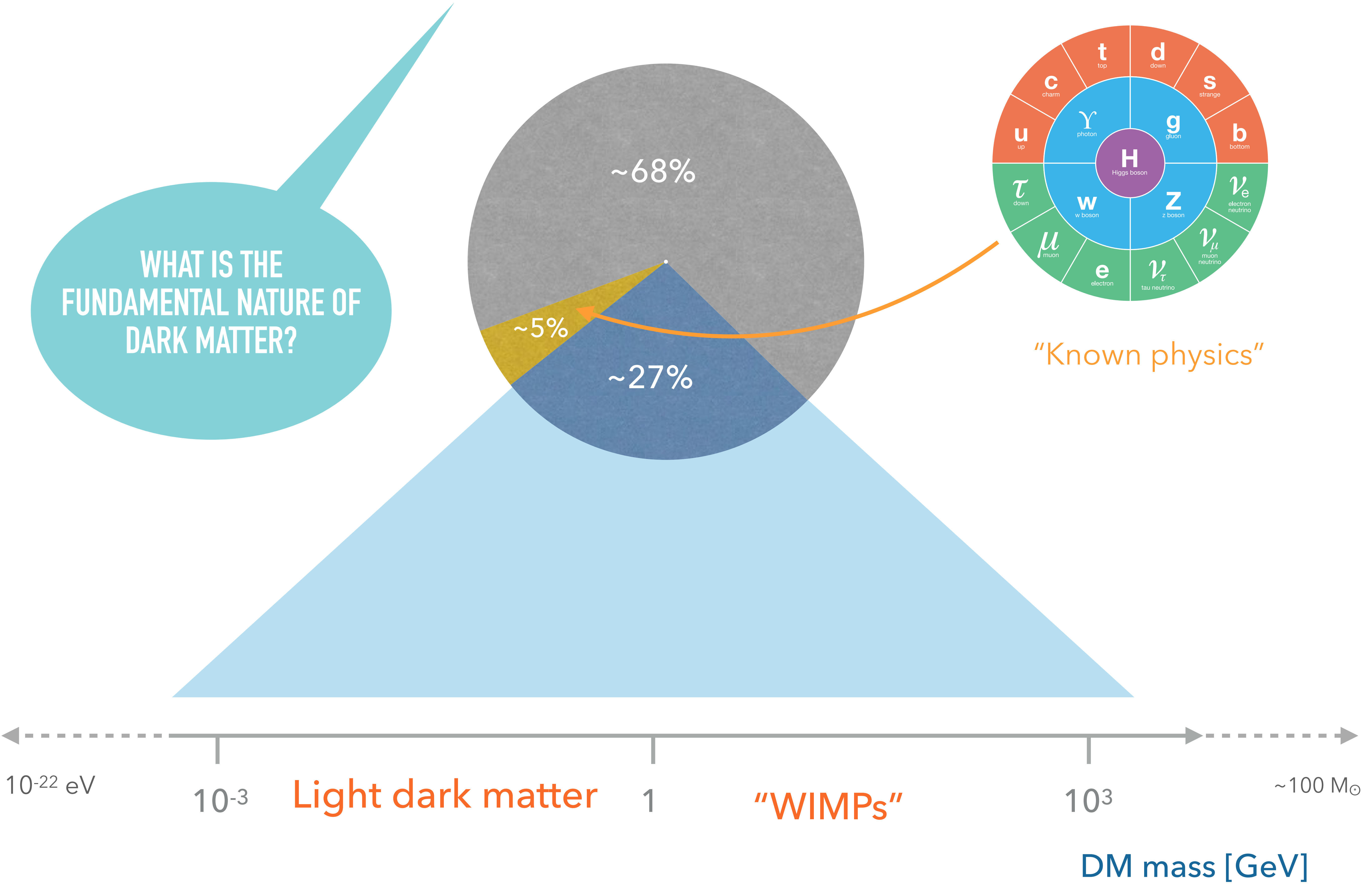
- PhD at the University of Heidelberg (Heidelberg-Moscow and Heidelberg Dark Matter Search Experiments, the GENIUS project)
- Postdoc at Stanford: Cryogenic Dark Matter Search (CDMS)
- Assistant professor UFL Gainesville: CDMS and XENON10 (first phase in the XENON programme)
- Lichtenberg professor for astroparticle physics at RWTH Aachen: XENON10 and XENON100, CDMS
- Professor at UZH (since 2007): XENON100/1T/nT (TPC design, photosensors), GERDA/LEGEND, DARWIN & Xenoscope, Gator (material screening) and detector R&D



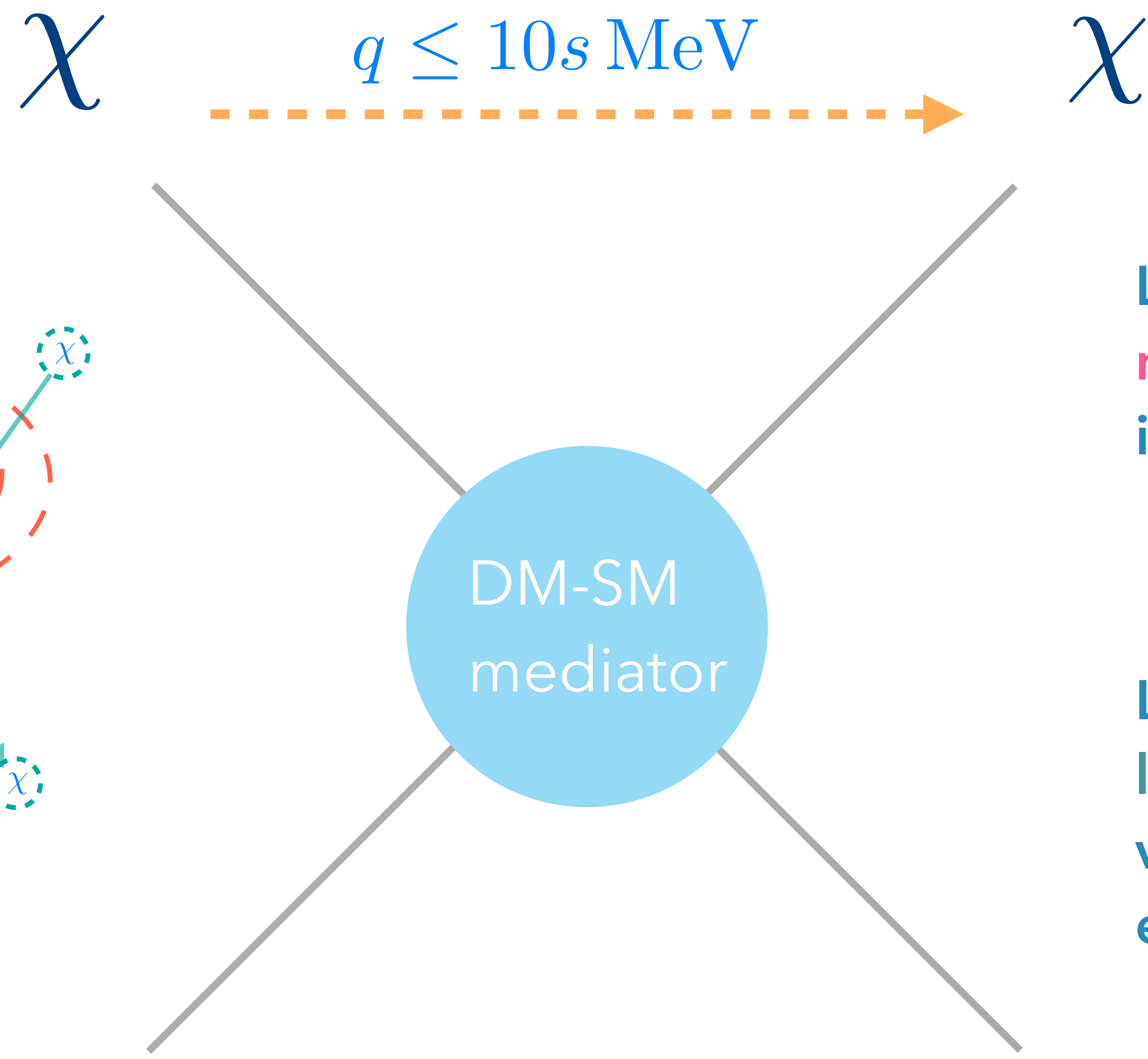


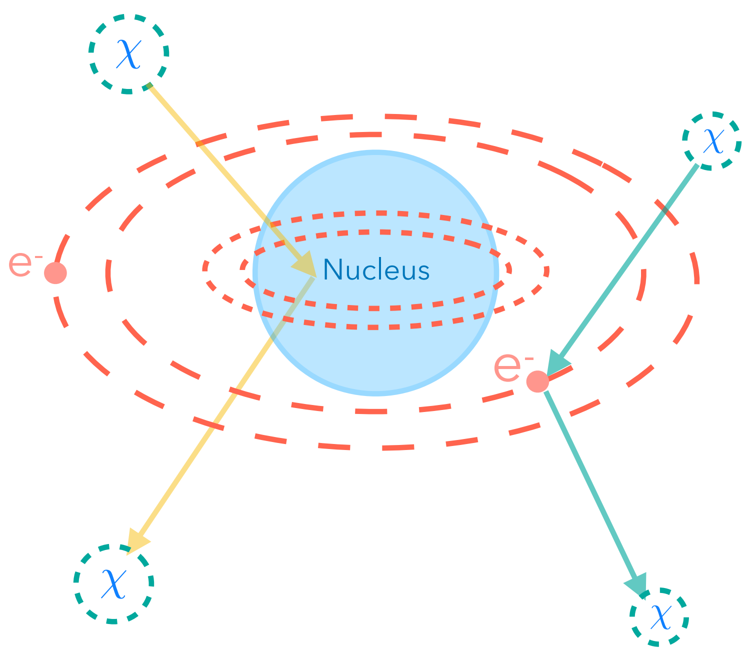




BIG SCIENCE QUESTIONS TO BE ADDRESSED



WHAT ARE THE APPROACHES TO ADDRESSING THESE QUESTIONS?



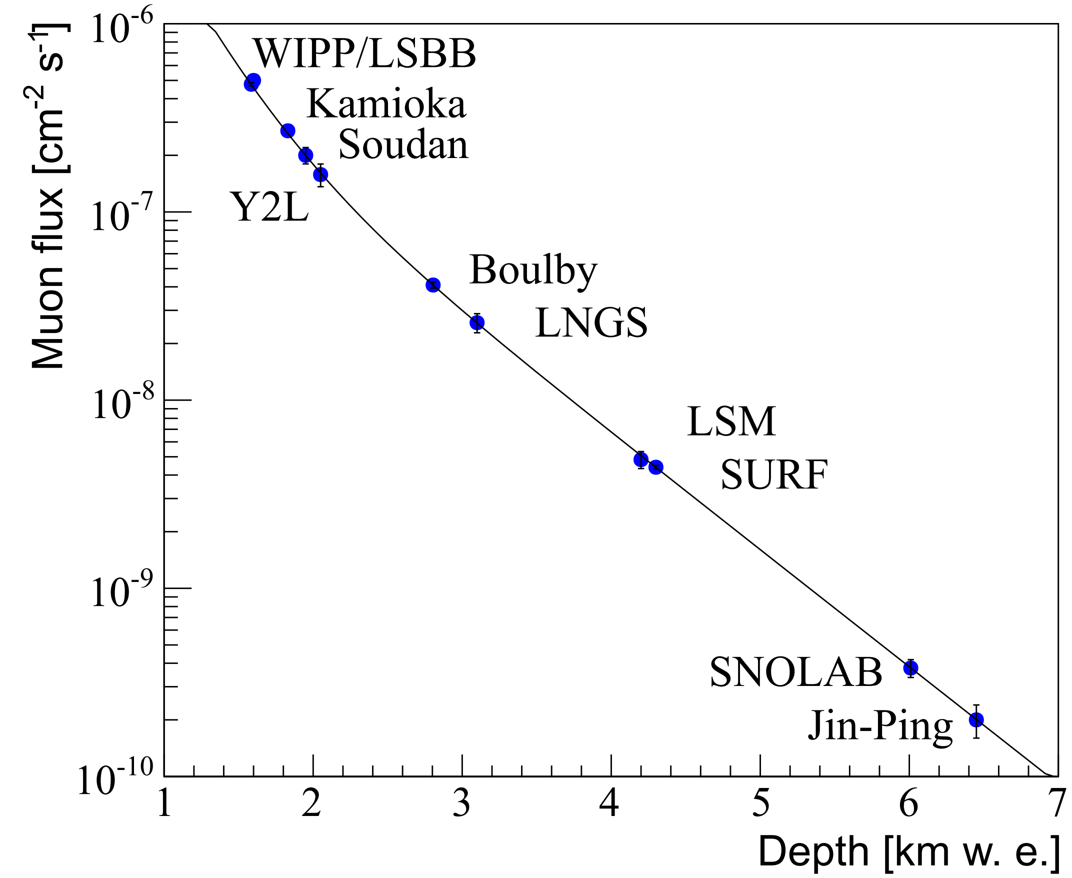


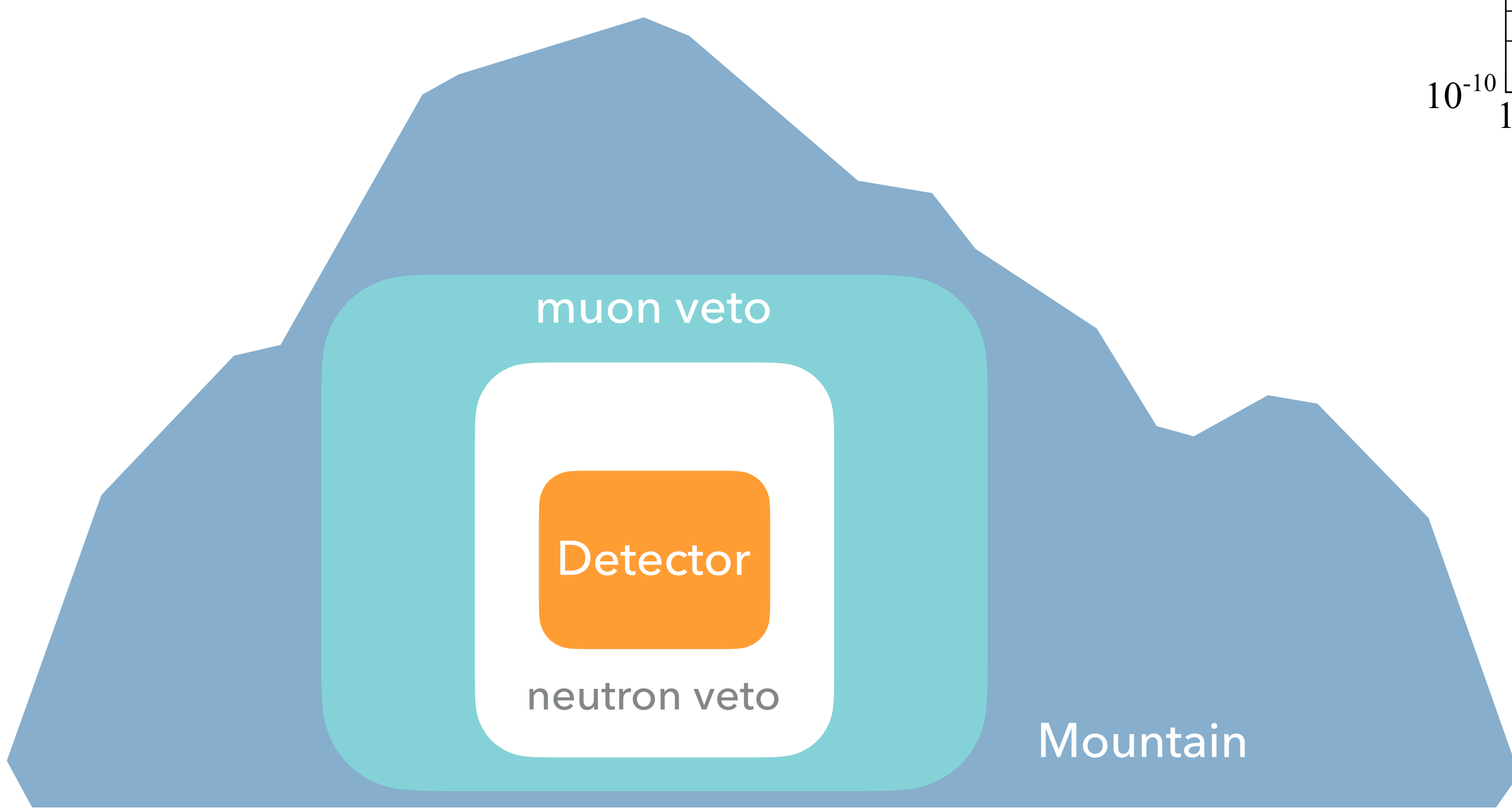
Look for collisions with nuclei or with electrons in the atomic shell

Look for absorption of light scalars or bosons via e.g., the axio-electric effect

BACKGROUNDS OVERVIEW

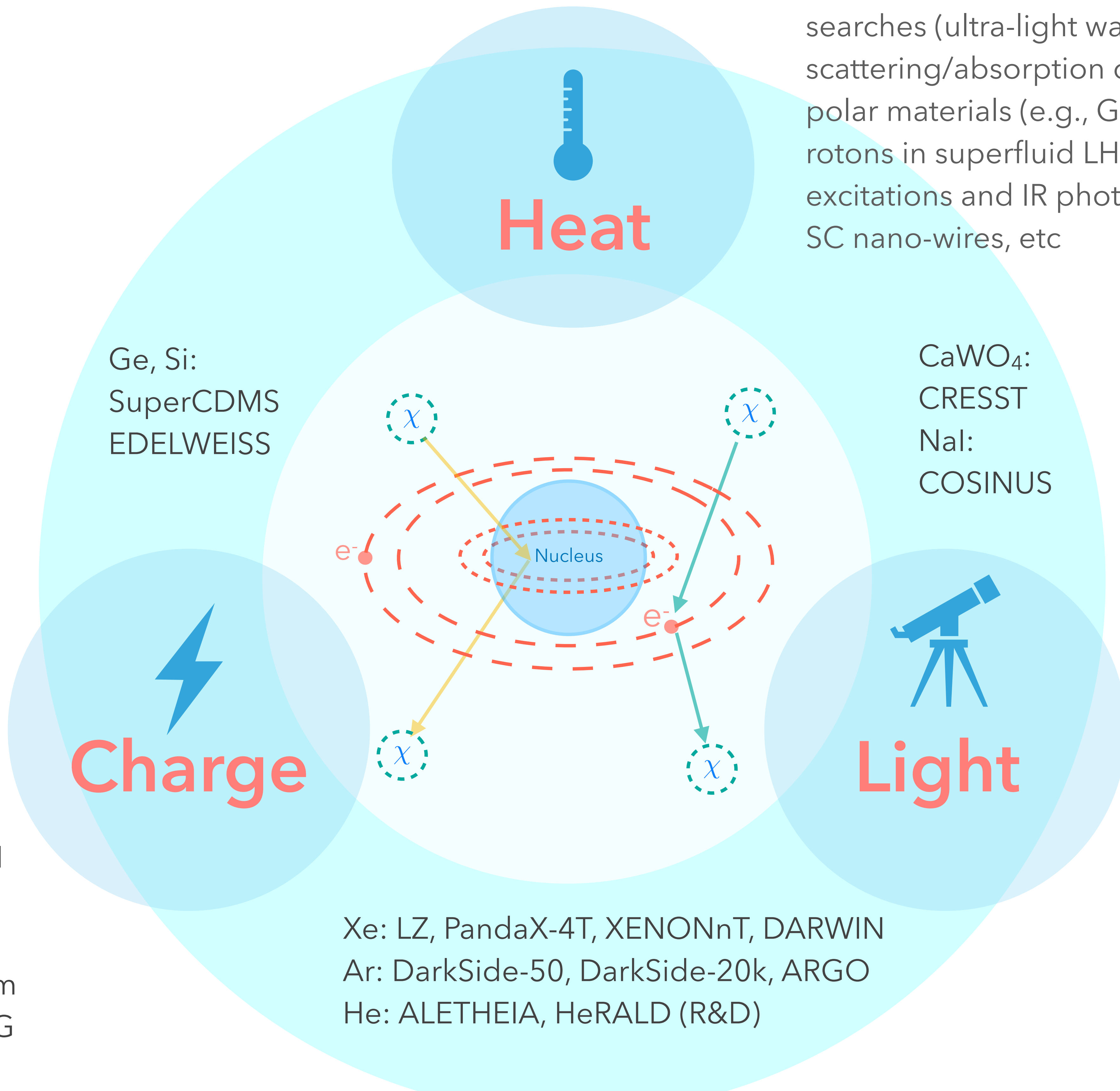
- Muon-induced neutrons
- Cosmogenic activation of materials/targets (^{3}H, ^{32}Si, ^{60}Co, ^{39}Ar, ^{77}Ge, ^{137}Xe)
- Radioactivity of laboratory walls, detector materials (n, γ, α, e^{-})
- Target intrinsic isotopes (^{85}Kr, ^{222}Rn, ^{136}Xe, ^{39}Ar, etc)
- Neutrinos (solar, atmospheric, DSNB)





WHAT ARE THE APPROACHES TO ADDRESSING THESE QUESTIONS?

+ New initiatives: QIS for dark matter searches (ultra-light wavelike dark matter; scattering/absorption of DM particles); polar materials (e.g., GaAs); phonons/rotons in superfluid LHe; molecular excitations and IR photon detection with SC nano-wires, etc



Ge, Si:
SuperCDMS
EDELWEISS

$CaWO_4$:
CRESST
NaI:
COSINUS

C_3F_8: PICO
Ge: CDEX
Si: DAMIC, SENSEI
Ar, Ne: TREX-DM
He:SF_6: CYGNUS
Ag, Br, C: NEWSdm
H, He, Ne: NEWS-G

Xe: LZ, PandaX-4T, XENONnT, DARWIN
Ar: DarkSide-50, DarkSide-20k, ARGO
He: ALETHEIA, HeRALD (R&D)

Ar: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE

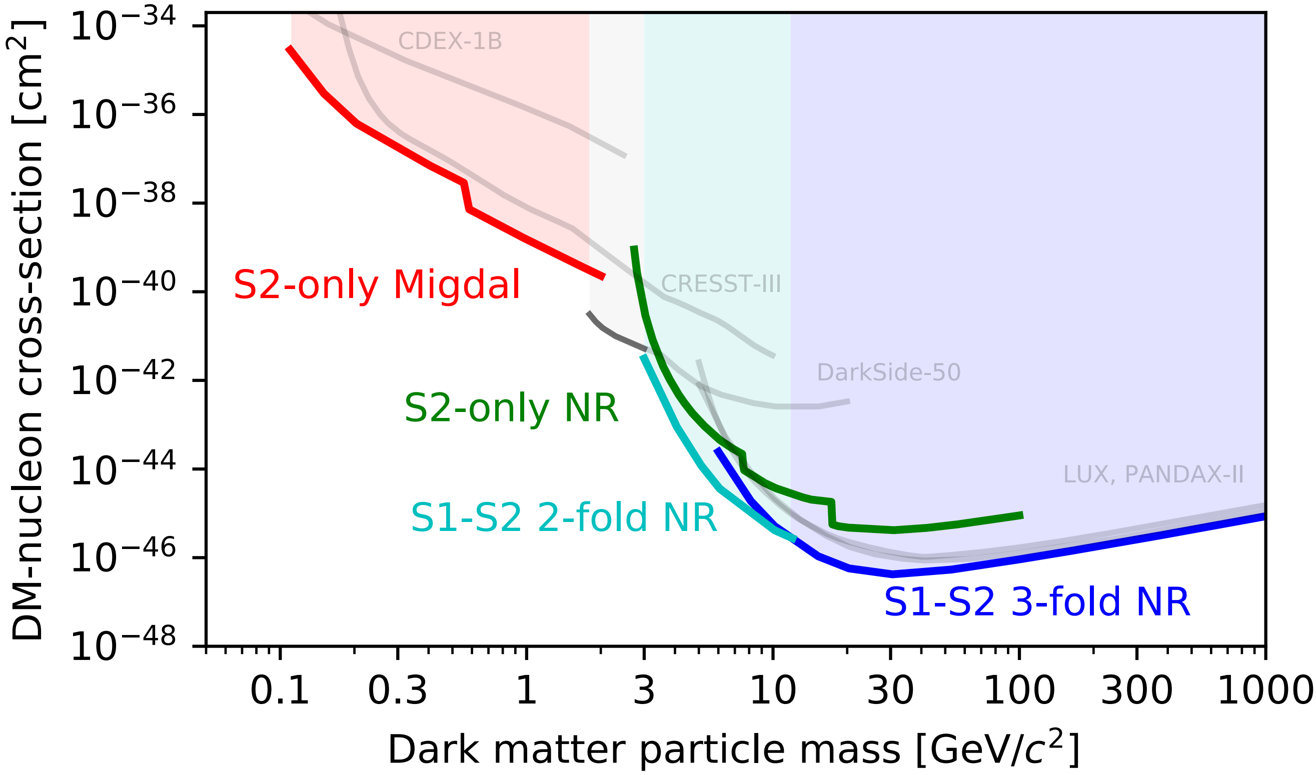
FOCUS: LIQUEFIED NOBLE GASES

- Single and two-phase Ar & Xe detectors, excellent legacy

- Time projection chambers:
  - energy determination, 3D position resolution via light (S1) & charge (S2): fiducialisation
  - S2/S1⇒ ER/NR discrimination
  - Single versus multiple interactions

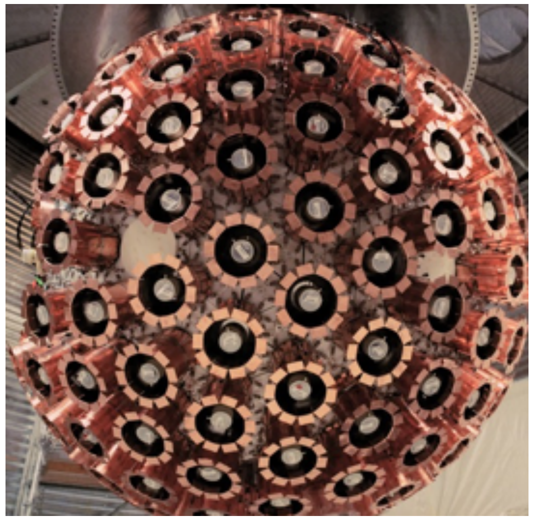
No excess of nuclear recoil events observed so far

$\sigma_{SI} < 4.1 \times 10^{-47} \mathrm{cm}^2$ at $30\,\mathrm{GeV/c}^2$

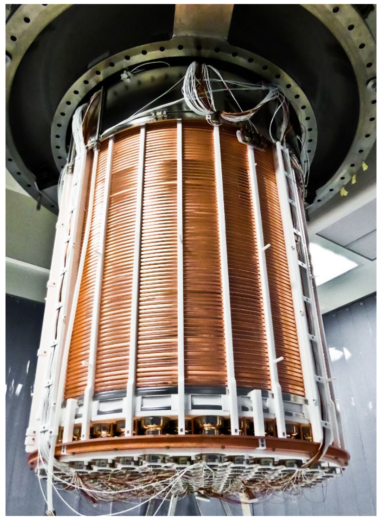


XMASS

DEAP-3600



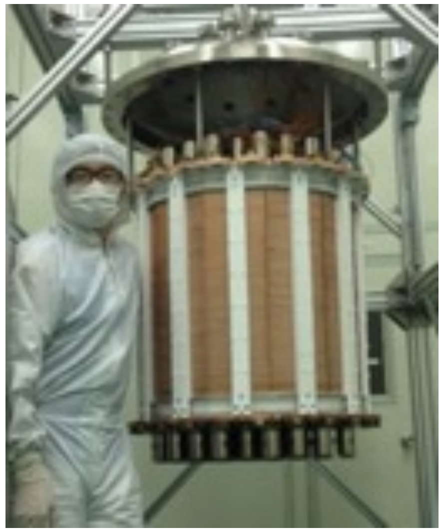
XENON1T



LUX

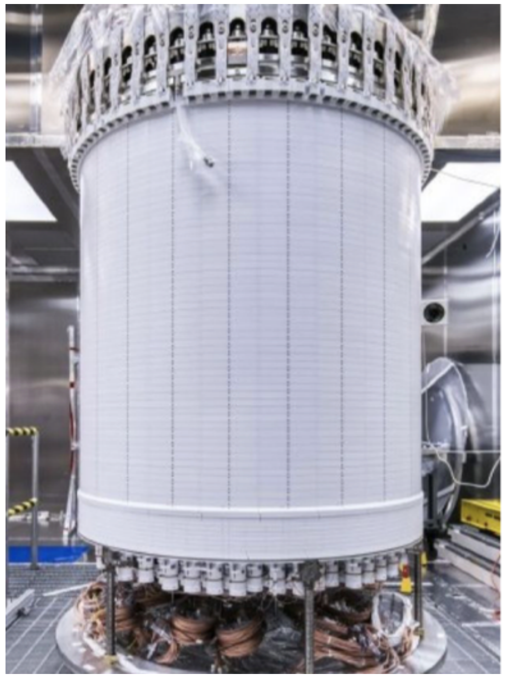
DarkSide-50

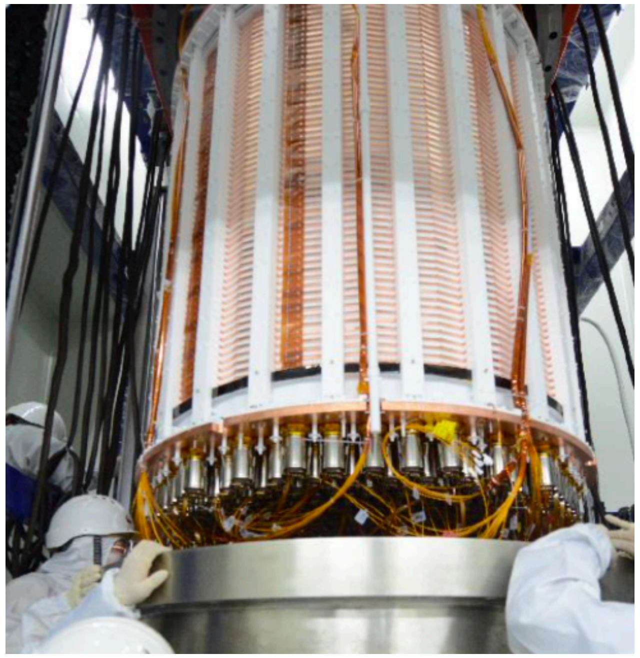
PandaX-II



LUX-ZEPLIN, PANDAX-4T, AND XENON-NT

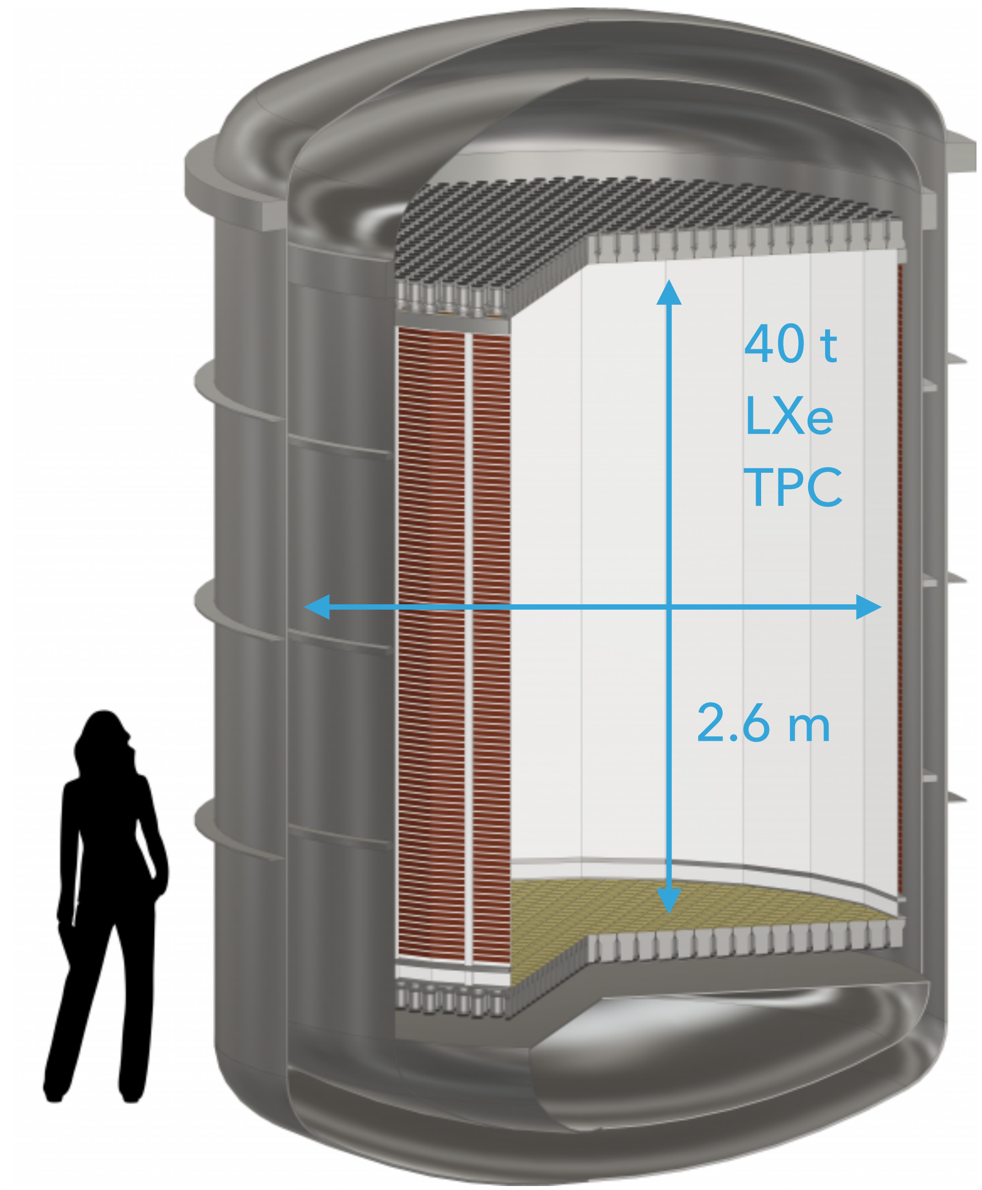
- Scale: 10 t, 6 t and 8.6 t LXe in total
  - TPCs with 2 arrays of 3-inch PMTs
  - Kr and Rn removal techniques
  - Ultra-pure water shields; neutron & muon vetos (LZ, XENON-nT)
  - External and internal calibration sources
- Status: commissioning/data daking at SURF, Jinping and LNGS





DARWIN: BASELINE SCENARIO

- Two-phase TPC: 2.6 m ø, 2.6 m height
- 50 t (40 t) LXe in total (in the TPC)
- Two arrays of photosensors (e.g. 1800 3-inch PMTs)
- PTFE reflectors and copper field shaping rings
- Low-background, double-walled titanium cryostat
- Shield: Gd-doped water, for μ and n



JCAP 1611 (2016) 017

Alternative designs and photosensors under consideration

NEW: DARWIN-LZ Collaboration

- **Future merger of DARWIN/XENON and LZ collaboration to build and operate next-generation liquid xenon detector**
  - new, stronger international collaboration
  - comes after LZ and XENONnT are done
- **Paving the way now**
  - first joint, successful DARWIN & LZ workshop, April 26-27 https://indico.cern.ch/event/1028794/
  - MoU signed July 6, 2021 by 104 research group leaders from 16 countries

Science goals of a large liquid xenon observatory

DIRECT DARK MATTER DETECTION

JCAP 10, 016 (2015)

SOLAR AXIONS

NEUTRINOLESS DOUBLE BETA DECAY ^{136}XE

Eur. Phys. J. C 80, 9 (2020)

DARWIN

GALACTIC ALPS, DARK PHOTONS

LOW-ENERGY SOLAR NEUTRINOS

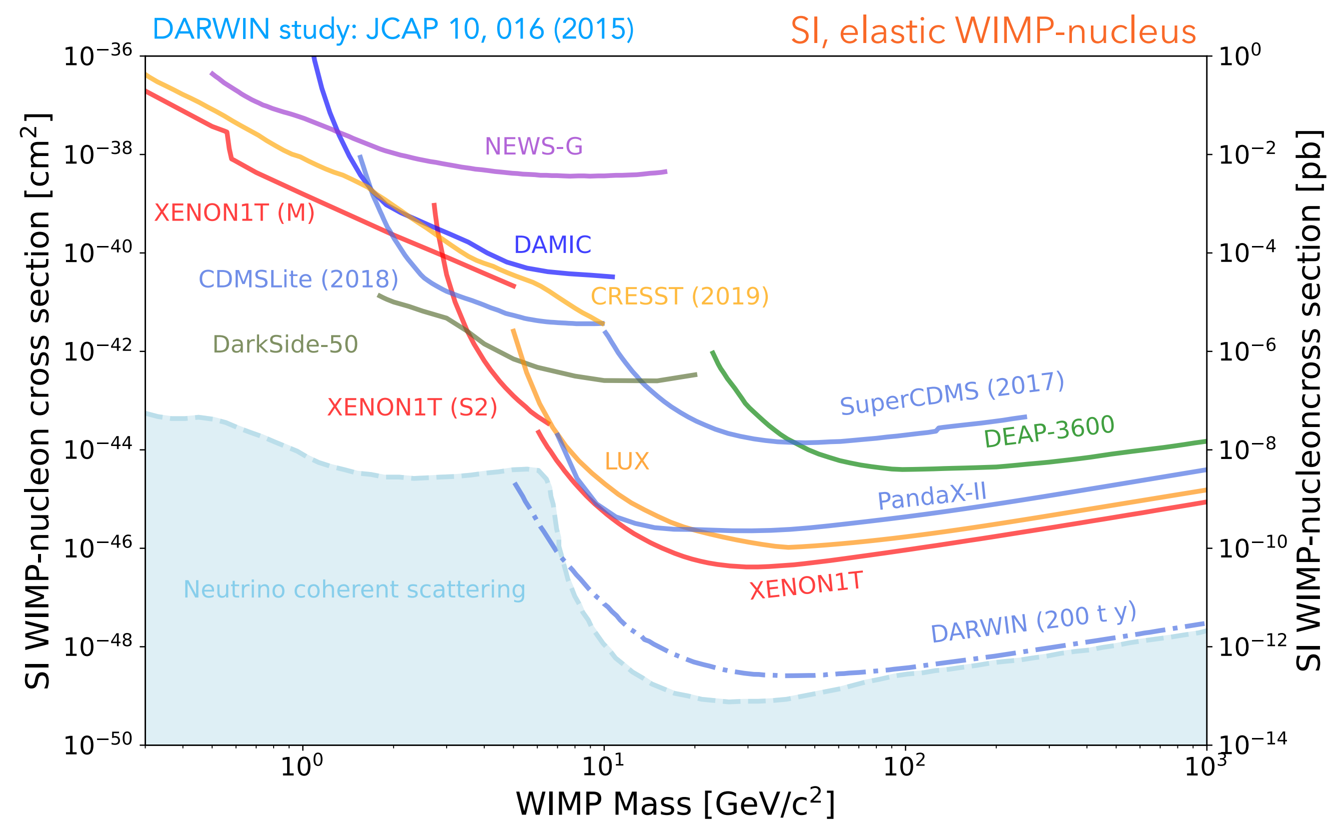
Eur. Phys. J. C 80, 12 (2020)

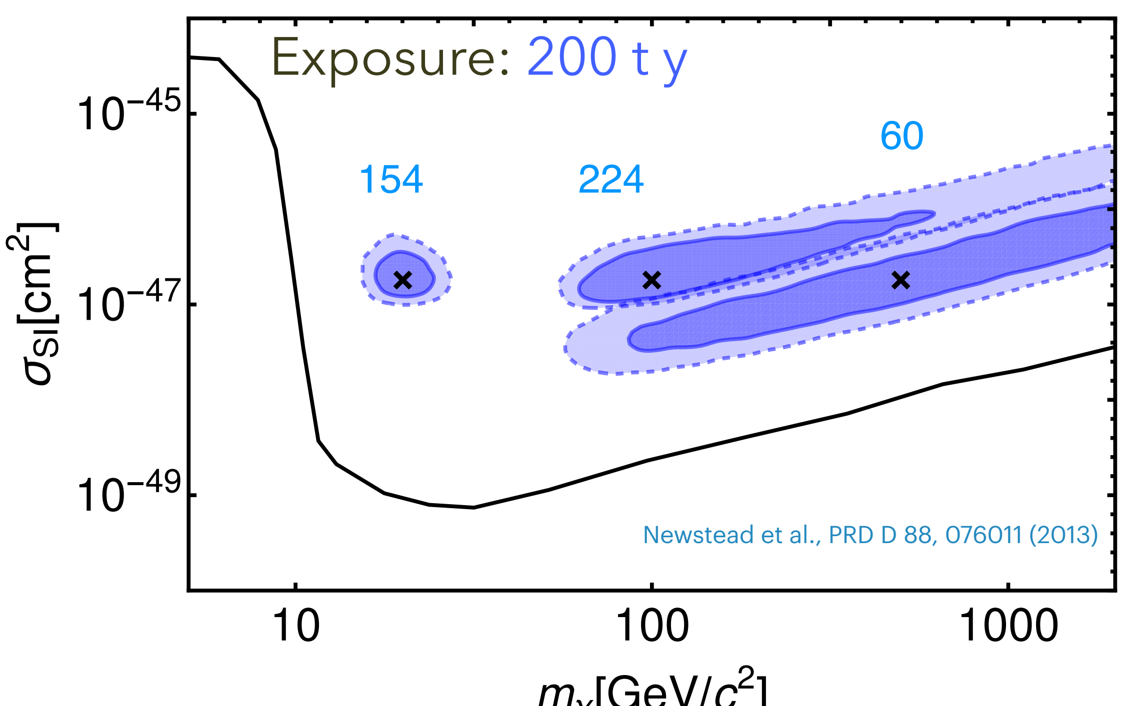
COHERENT NEUTRINO NUCLEUS SCATTERS

SUPERNOVA NEUTRINOS

Example: WIMP dark matter

- Goal: probe dark matter nucleon interactions down to the "neutrino floor"
- Sensitivity to spin-independent and spin-dependent (^{129}Xe, ^{131}Xe) interactions
- Reconstruct DM mass and cross section (for given astrophysical parameters)





1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

Assumptions for DARWIN:

30 t LXe in FV

99.98% ER rejection

(at 30% NR acceptance)

FACILITY DESIGN ASPECTS THAT WOULD BENEFIT THE RESEARCH

- Depth
  - reduce cosmogenic neutron background
  - minimise *in situ* activation/production of radioactive isotopes
- Support facilities: space for material screening and selection
  - HPGe detectors, Rn emanation measurements, neutron activation techniques
- Special underground areas for
  - crystal growth, Cu electroforming; small mechanical workshop
  - cryogenic distillation (^{85}Kr, ^{222}Rn) of noble liquids, underground storage
- Support facilities for cleanliness and detector material treatment
  - "radon-free", class 100 cleanrooms to avoid ^{210}Pb implantation
  - dedicated space for cleaning detector materials (Cu, stainless steel, Ti, PTFE, etc)
- Above ground facilities
  - Offices, cafeteria, lab space, mechanical and electronics workshops, etc

HOW CAN THE FACILITY ASSIST WITH COMMUNITY INVOLVEMENT AND OUTREACH

- Underground lab visits (guided tours) and virtual tours; augmented reality videos
- Various outreach and educational events (open days, researchers' night, science on tap...)
- Participate in existing initiatives, e.g., "dark matter day" (https://www.darkmatterday.com), neutrino day
- Internship programmes for high-school students
- Educational programmes for local teachers
- A local, permanent, interactive exhibition (above ground) to provide insights into the research areas covered by the facility (e.g., videos, interviews, experiments, quizzes, etc)

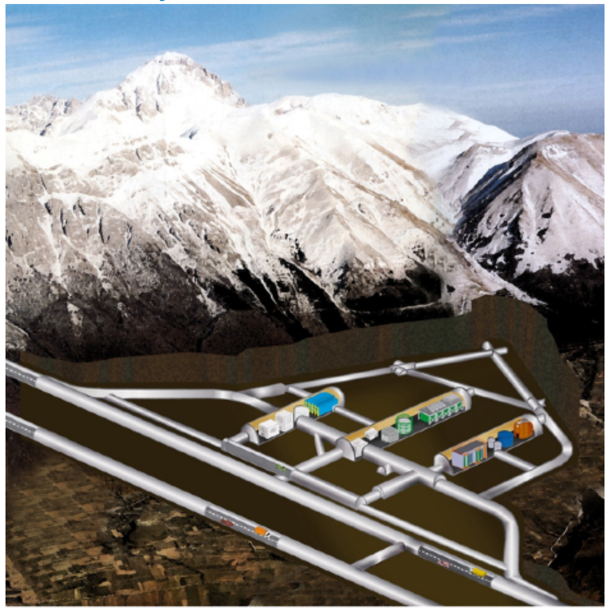
Example: https://www.scienceexploratorium.uzh.ch

ADDITIONAL SLIDES

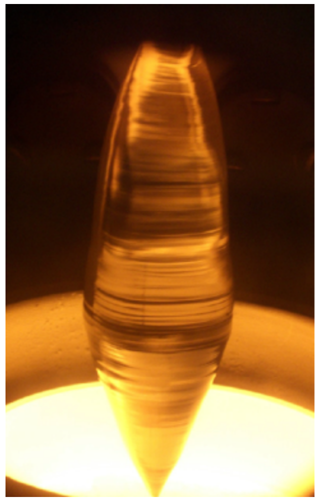
BACKGROUND REDUCTION STRATEGIES

- Deep underground laboratories
  - reduce cosmogenic neutron background
  - reduce *in situ* activation/production of radioactive isotopes
- Material screening and selection
  - HPGe detectors, Rn emanation measurements, neutron activation techniques
- Purification of target materials
  - during production: crystal growth
  - before data taking: cryogenic distillation (^{85}Kr, ^{222}Rn), underground argon (low in ^{39}Ar, ^{42}Ar)
  - during data taking: continuous cryogenic distillation (e.g. for ^{222}Rn)
- Cleanliness and material treatment
  - "radon-free", class 100 cleanrooms to avoid ^{210}Pb implantation
  - dedicated cleaning recipes for various detector materials (Cu, stainless steel, Ti, PTFE, etc)

Example: Gran Sasso Underground Laboratory



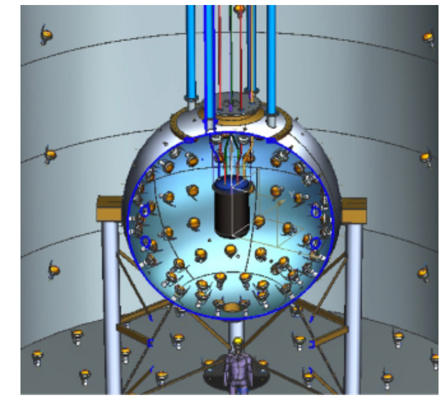
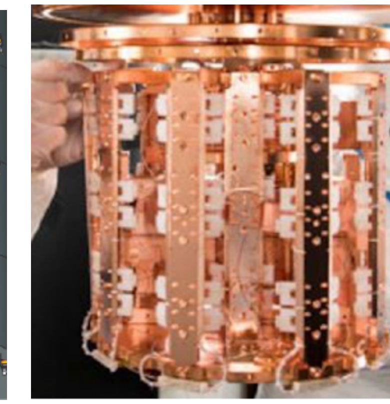
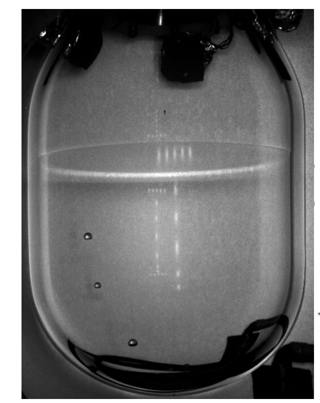
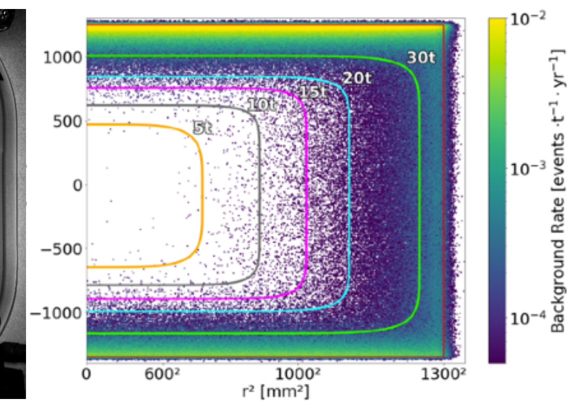
Kr distillation column for XENON1T/nT, EPJ-C 77 (2017) 5

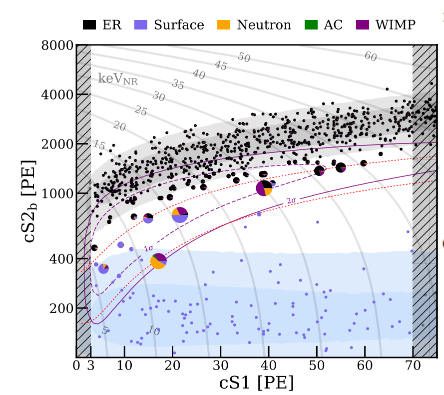


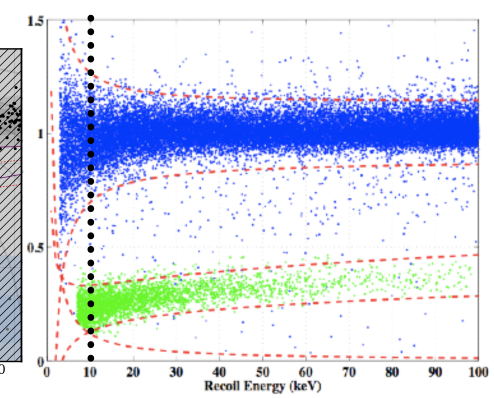
Crystal growth for CRESST

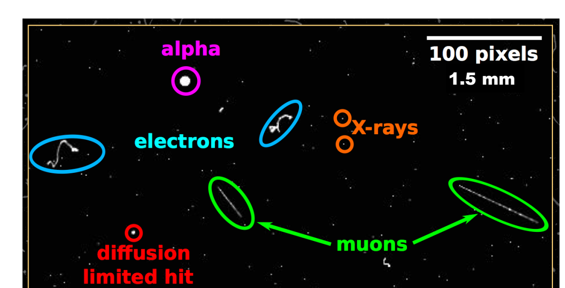
BACKGROUND REJECTION STRATEGIES

- Active muon and neutron shields
  - tag muon-induced neutrons
  - tag radiogenic neutrons (emitted by materials in (α,n)- and fission reactions)
- Detector design
  - granularity (e.g., tag events in multiple crystals)
  - position reconstruction ⇒ fiducialisation & single versus multiple interactions
  - surface versus bulk events discrimination
- Background identification and rejection
  - ratio of phonon, scintillation, ionisation signals: depends on $\frac{dE}{dx}$
  - pulse shape discrimination
  - tracks (e.g., in CCDs or gaseous detectors)



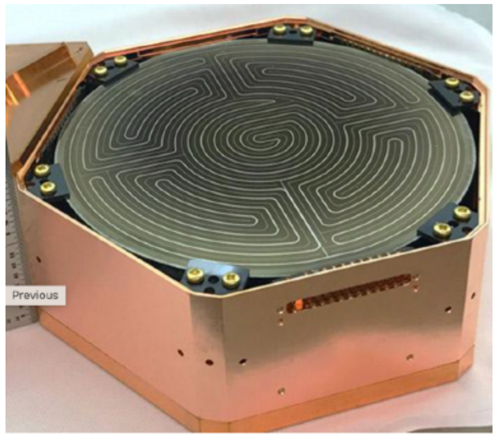




TECHNOLOGICAL CHALLENGES AND R&D: BOLOMETERS

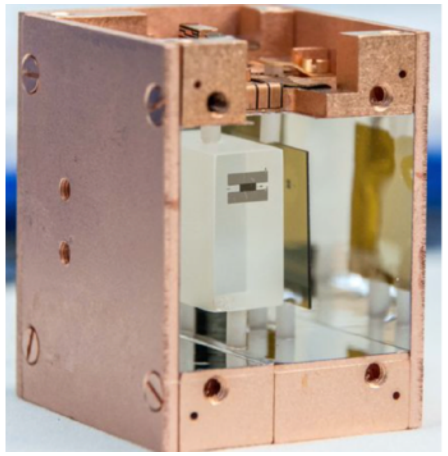
- Detector performance and configuration
  - phonon sensors (e.g., develop TES based on athermal phonon sensors, NTDs, KIDs)
  - adapt existing sensors for lower energies→ see e.g., CDMSlite
  - investigate new insulating or semiconductor target materials
- Target mass
  - operate large arrays of detectors
  - maximise mass per detector (reduce number of readout channels); reduce mass for lower energy threshold & higher resolution
  - investigate dry dilution refrigerators (control mechanical vibrations)
- Background control
  - powder purification for crystal growth (e.g., $CaWO_3$ crystals)
  - underground crystal growth and detector development (avoid cosmogenic activation, e.g., ^{32}Si in Si-based detectors)
  - reduce surface backgrounds (etching, reduce exposure to ^{222}Rn, etc)

SuperCDMS detector (charge & phonons)



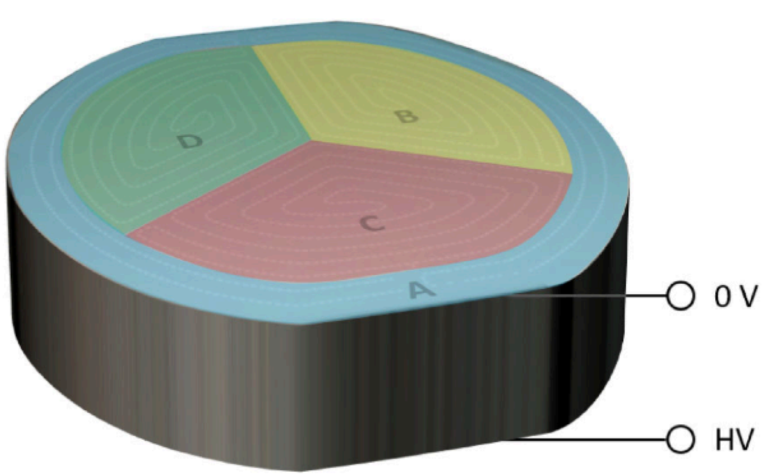
Edelweiss detectors (charge & phonons)

CRESST detector (light & phonons)



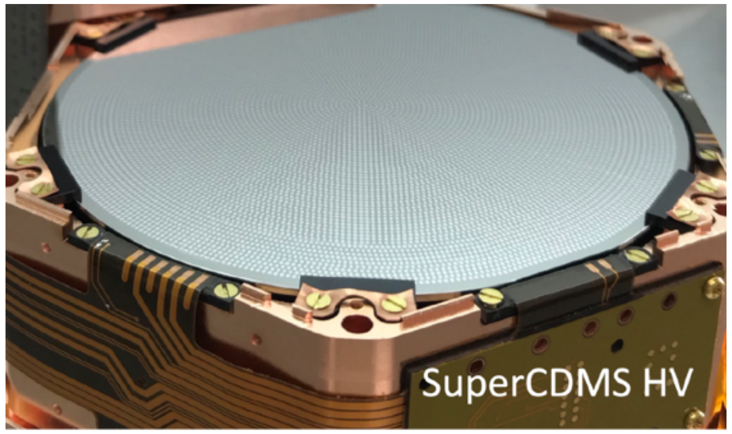
TECHNOLOGICAL CHALLENGES AND R&D: BOLOMETERS

- Detector performance and configuration
  - phonon sensors (e.g., develop TES based on athermal phonon sensors, NTDs, KIDs - fundamentally athermal sensors, non-dissipative devices)
  - lower energies→ see e.g., CDMSlite to SuperCDMS: increase surface area coverage of the phonon sensor; operate at higher applied potentials; fabricate TES with lower operational T, reduce noise to achieve E_{th} < 10 eV
  - new insulating or semiconductor target materials: enhance sensitivity to LDM

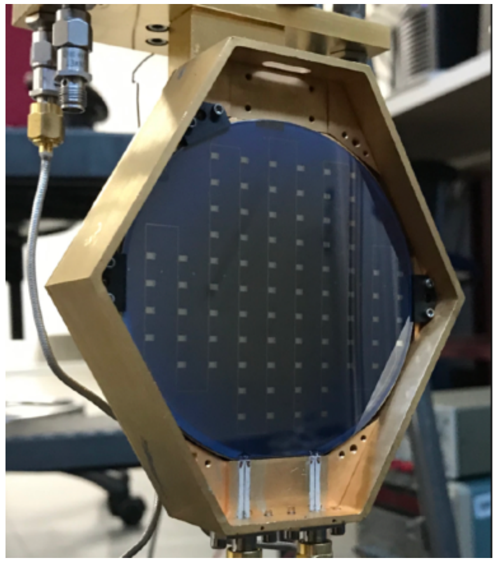


CDMSlite: phonon amplification via NTL-effect; V ~ -70 V => E_{th} ~ 65 eV

CDMS collaboration: PRD 97, 2018



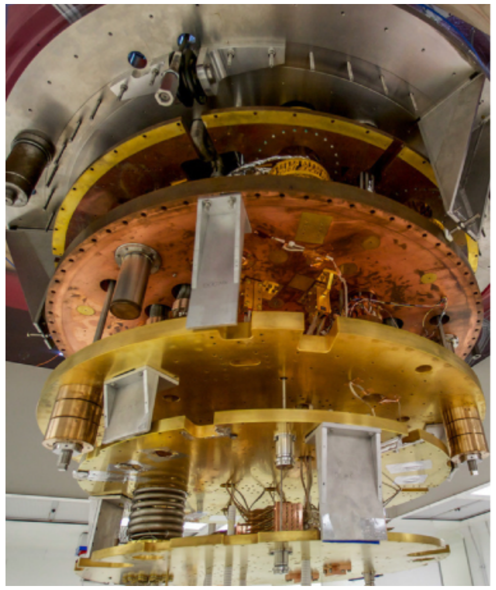
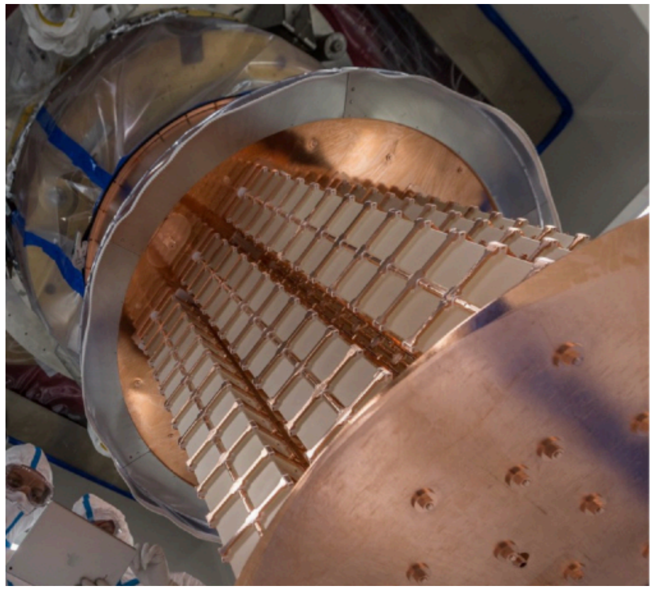
SuperCDMS HV detectors



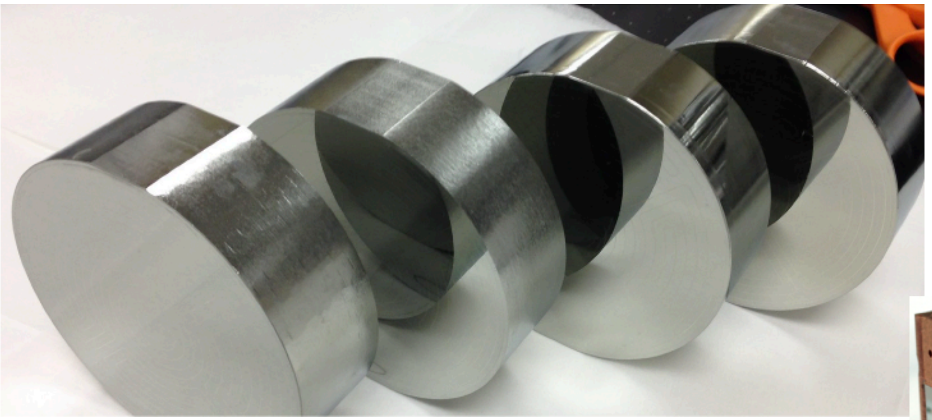
Ge/Si substrate with KID readout; S. Golwala et al.

TECHNOLOGICAL CHALLENGES AND R&D: BOLOMETERS

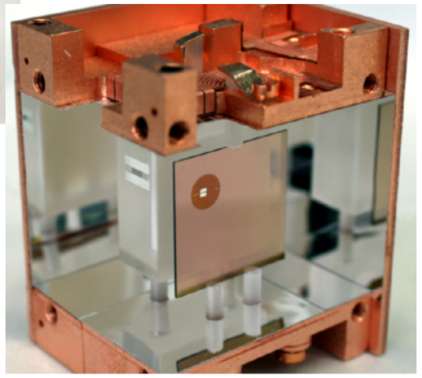
- Target mass
  - operate large arrays of detectors (example: the CUORE 0νββ-experiment at LNGS)
  - maximise mass per detector (reduce number of readout channels): e.g., 1.4 kg Ge and 0.6 kg Si detectors SuperCDMS SNOLAB
  - reduce mass for lower energy threshold and higher resolution: e.g., 24 g CaWO3 detector for CRESST, with E_{th} ~100 eV
  - investigate vibration-isolated, dry dilution refrigerators with base temperatures down to few mK (e.g., NEXUS @ Fermilab)

CUORE collaboration: dilution refrigerator and detector arrays



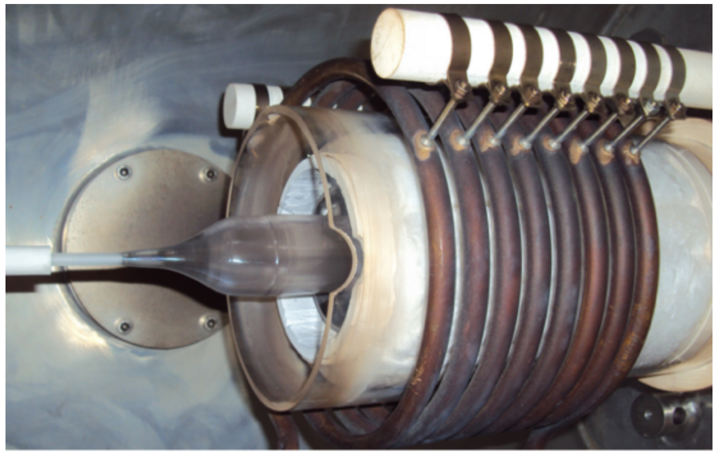
Ge crystals for SuperCDMS (SNOLAB iZIP detectors)



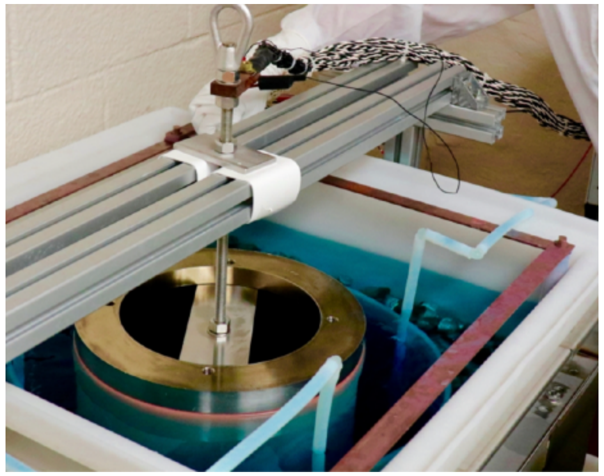
CRESST-III detector module

TECHNOLOGICAL CHALLENGES AND R&D: BOLOMETERS

- Background control
  - powder purification & crystal growth (chemical purification techniques, trace impurity analysis, segregation of impurities during crystal growth)
    - examples → crystal growth for CRESST at TUM; Ge zone refining, crystal growth and characterisation at USD, pire.gedamarc.org
  - underground crystal growth and detector development (avoid cosmogenic activation)
    - example → electroformed Cu at SURF (4850 feet level) for Majorana Demonstrator
  - reduce surface and/or Compton backgrounds: active veto cryogenic detectors



CRESST: crystal growth in Czochralski furnace



MAJORANA Demonstrator: electroforming Cu underground

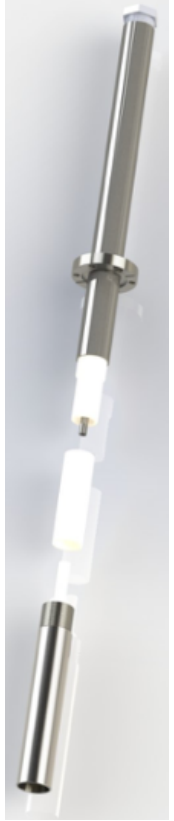
TECHNOLOGICAL CHALLENGES AND R&D: NOBLE LIQUIDS

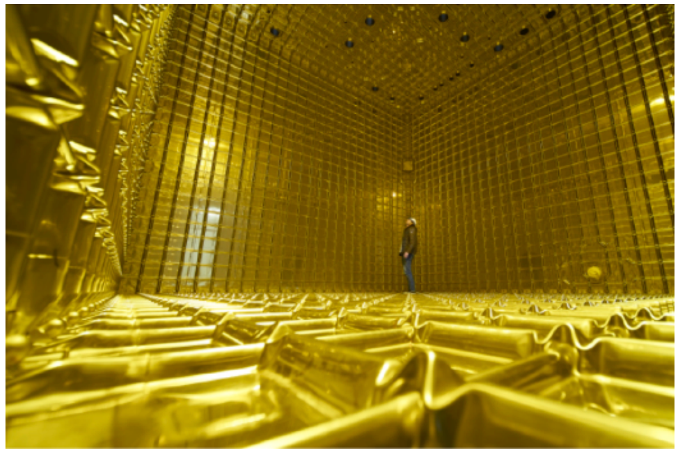
- Detector performance and configuration
  - single phase versus two-phase TPCs
  - light (PMTs, SiPM arrays, hybrid detectors) and charge sensors & readouts
  - decrease energy threshold (increase LCE)
- Target mass
  - xenon procurement is challenging, limited market availability
  - argon depleted in ^{39}Ar must be extracted from underground wells
  - both xenon and argon must be purified (H_2O, electronegative impurities) for high light and charge yield
  - gas/liquid storage and recuperation techniques
- Background control
  - distillation columns for krypton and radon
  - surface treatments to decrease radon emanation into the liquids
  - material screening and selection, radon emanation measurements

R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: TPC DESIGN AND DETECTOR

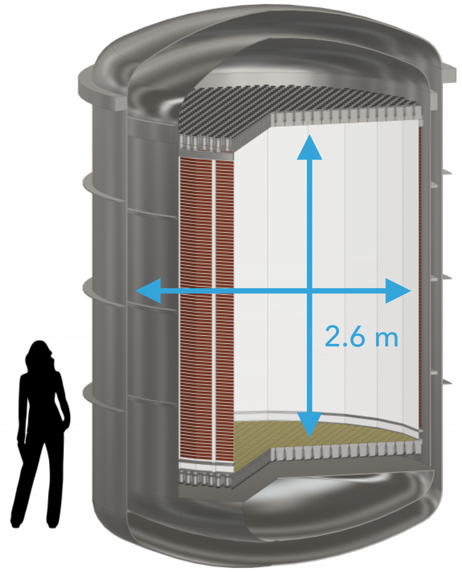
- Demonstrate e^--drift over large (>2.5 m) distances
    - high-voltage feed-throughs: must deliver 50 kV or more to the cathode (vacuum seal → cryofitting)
    - electrodes with large (>2.5 m) diameters: wire, mesh/woven, micro-pattern
- reflective (and WLS in the case of Ar) coatings to optimise light collection efficiency
- cryostat design: stability; reduce the amount of material and hence gamma and neutron emitters close to the TPC

2.6 m tall Xe TPC demonstrator for DARWIN





Cryostat a la DUNE for Darkside-20K



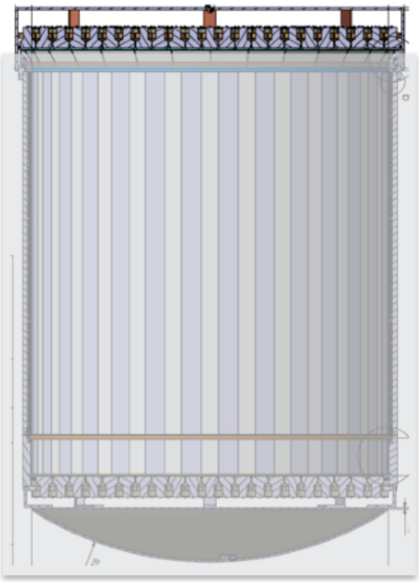
DARWIN Ti cryostat (a la LZ)

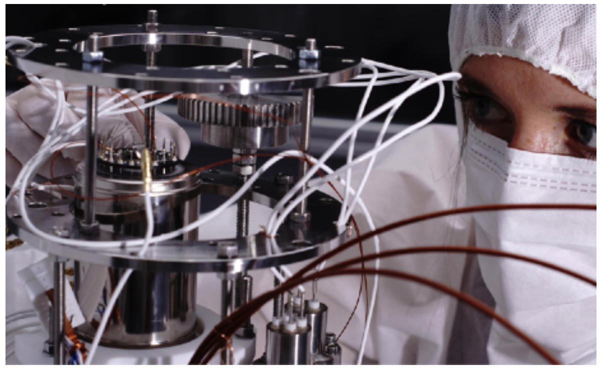
2.6 m diameter Xe TPC demonstrator for DARWIN

R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: TPC DESIGN AND DETECTOR

- New detector designs
  - single-phase TPCs
    - both light (S1) and charge (via proportional scintillation, S2) in liquid phase
    - simplify TPC design, alleviate the need for liquid level stabilisation at liquid/gas interface, mitigate the delayed, single e^- background
  - sealed/hermetic TPC
    - to prevent radon diffusion into the inner TPC volume (^{222}Rn goal in next-generation detectors is 0.1 μBq/kg), increase purification efficiency (larger e-lifetime)
    - acrylic with thin PTFE layer as TPC wall, fused silica window, graphene coated fused silica as cathode, platinum coated mesh on fused silica as anode
  - 4-π coverage with light sensors
  - Bubble chambers: SBC LAr doped with Xe: detect S1 and heat, instead of S2

R&D on sealed TPC for DARWIN; JINST 16 P01018 (2021)





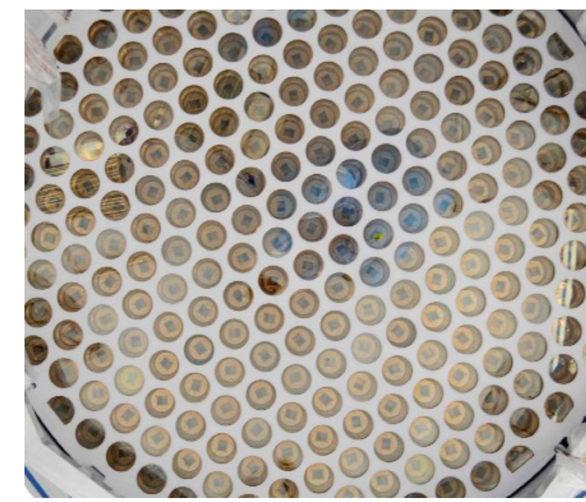
Hermetic TPC R&D for DARWIN

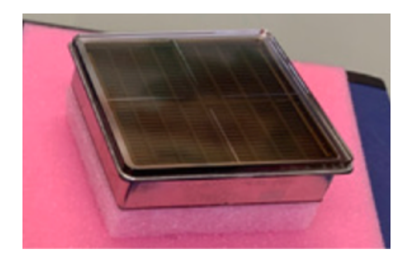
SBC: argon doped with xenon, arXiv: 2101.08785

R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: 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, long-term stability in cryogenic liquids (AP rates due to vacuum leaks) and light emission
- **SiPM arrays:** lower radioactivity/area, lower voltage; main issue → dark count rate (too high by ~ factor 50 at least)
    - low-field SiPMs (reduce band-to-band tunneling) , digital SiPMs

PMT array for XENONnT

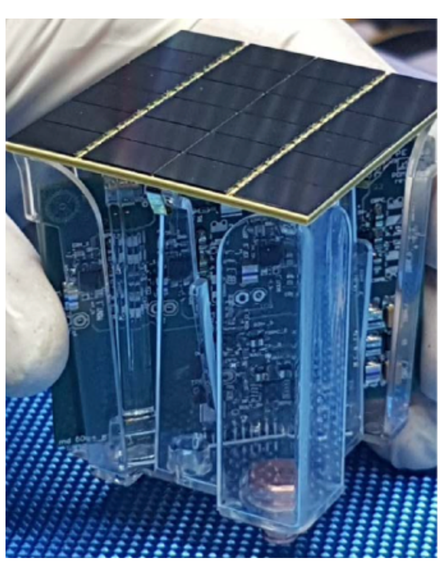




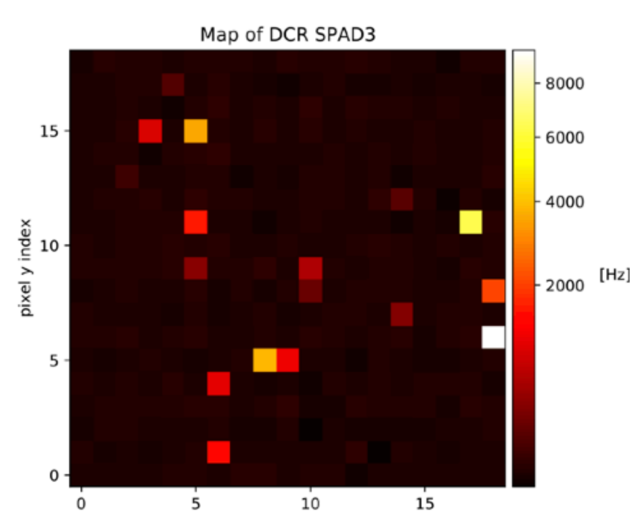
2''x 2'' flat panel PMT (R12699) R&D for DARWIN

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

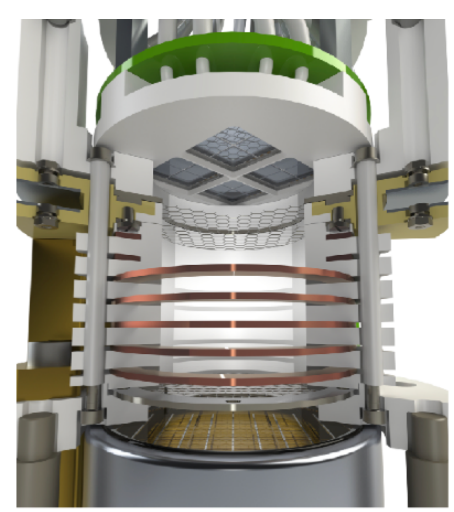
SiPM arrays for Darkside-20k



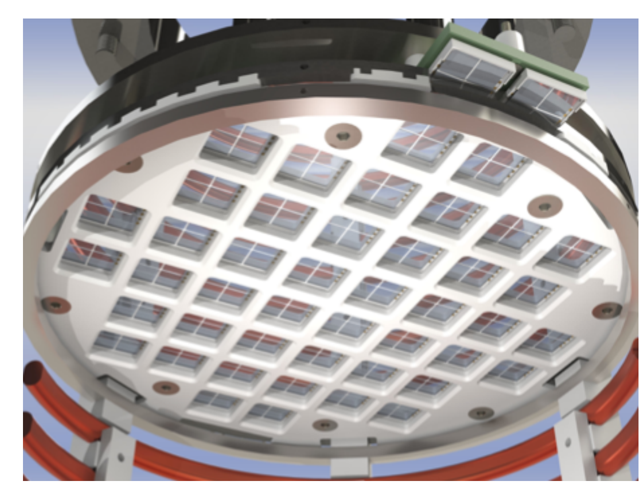
Digital SiPM



Two-phase TPC with SiPM array



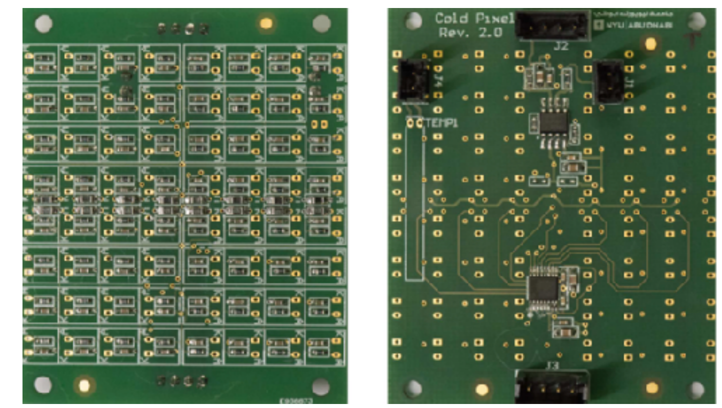
EPJ-C 80, 2020



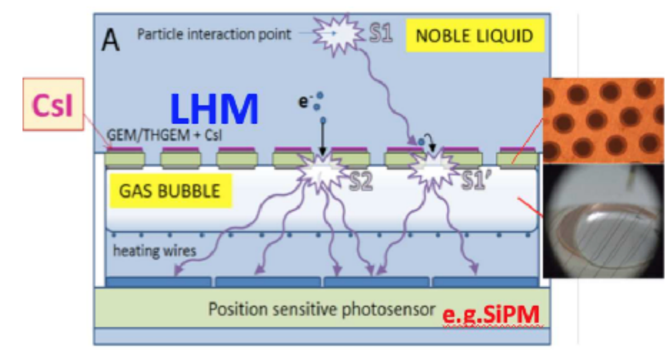
SiPM array, DARWIN demo

R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: LIGHT AND CHARGE

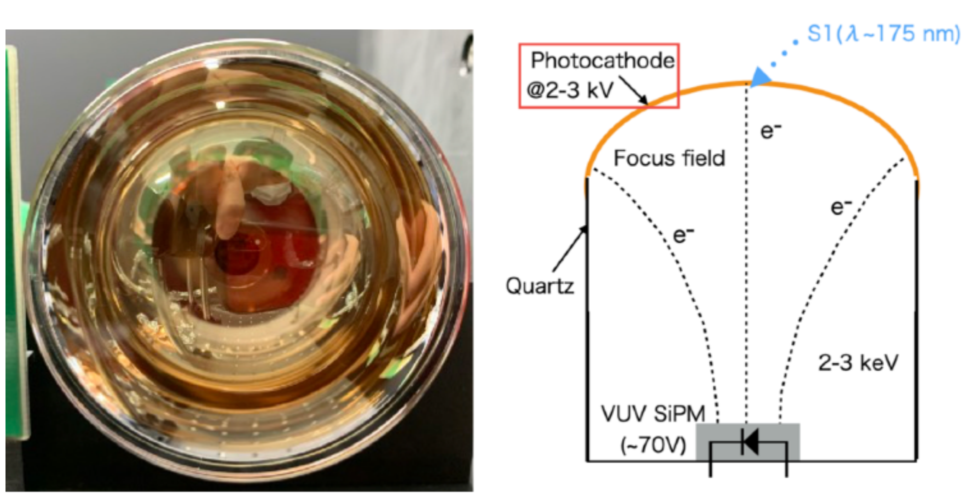
- **Hybrid sensors:** e.g., ABALONE, VSiPM, SIGHT
  - SiPM + Quartz + photocathode: reduced radioactivity compared to PMTs
  - lower DCR compared to SiPM arrays (photosensitive area difference)
- Cryogenic low-noise, low-radioactivity, low heat dissipation readout
- **Bubble-assisted Liquid Hole Multipliers**: local vapour bubble underneath GEM-like perforated electrode in LXe



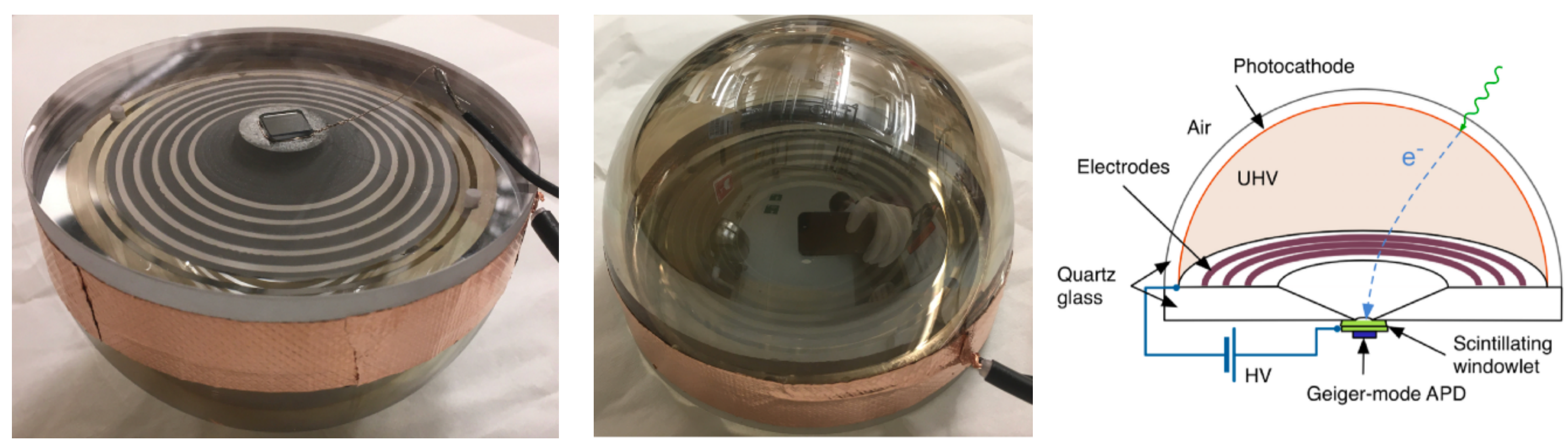
Cryogenic preamp for SiPMs, NIM 936, 2019



Liquid hole multipliers JINST 13, 2018



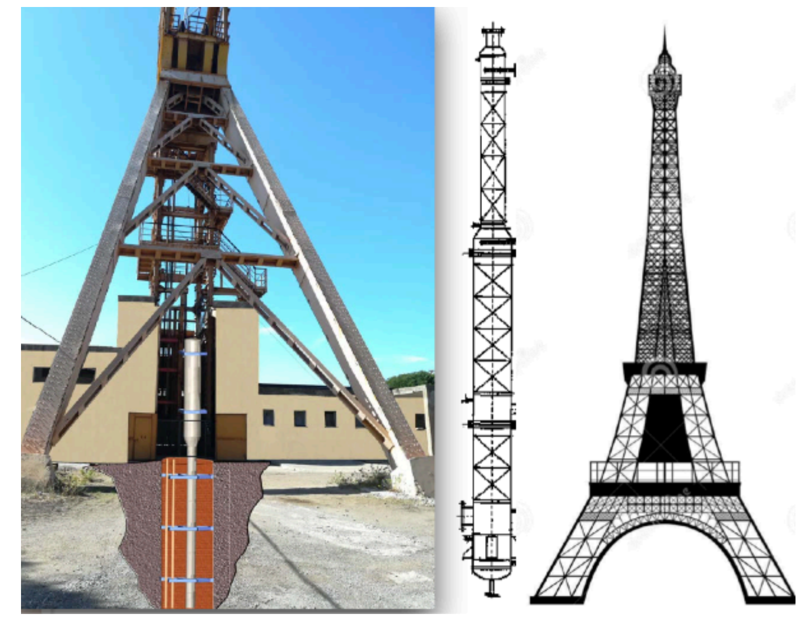
Hybrid photosensor: Hamamatsu XE5859



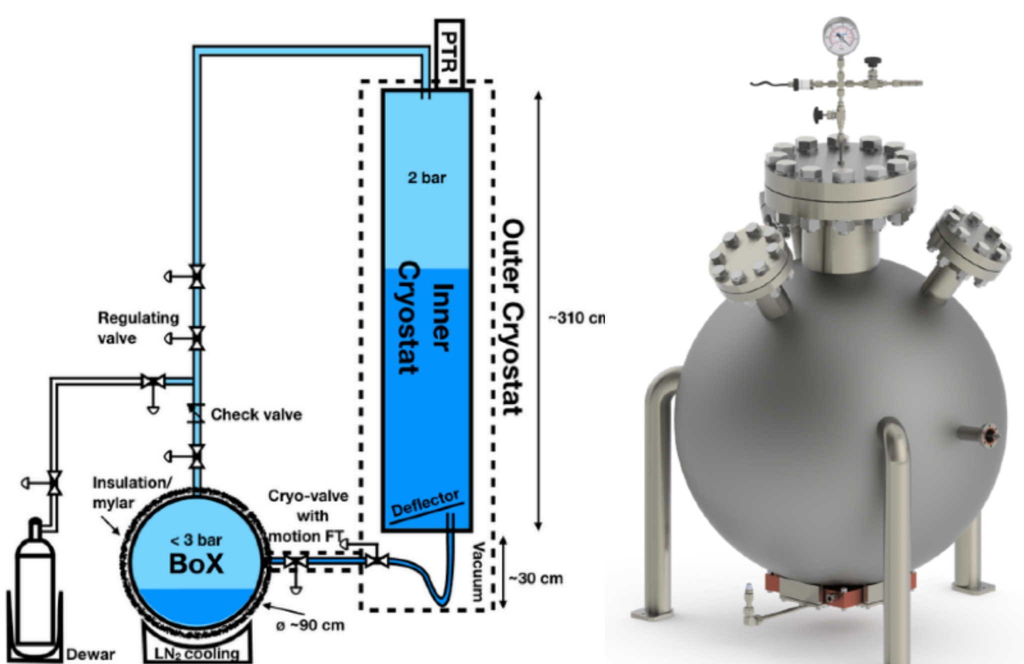
Hybrid photosensor: ABALONE; left (DARWIN R&D with SiPM); right: NIM 954, 2020

R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: TARGET

- Low-radioactivity argon: extraction (Urania plant, 330 kg/d), purification (ARIA facility, 10 kg/d)
- Fast purification in liquid phase for large e-lifetime; radon-free filters
- Gravity-assisted recuperation and storage
- Doping techniques (e.g., Xe in Ar, H_2 in Xe)
- Xe in argon: to shift light from 128 nm to 175 nm, see SBC (avoid WLS coatings)
- H_2 in xenon: low-mass target (increase sensitivity at low DM masses < 100 MeV; e.g. HydroX as upgrade to multi-ton scale xenon detectors)



ARIA underground purification system for argon (DarkSide-20k)



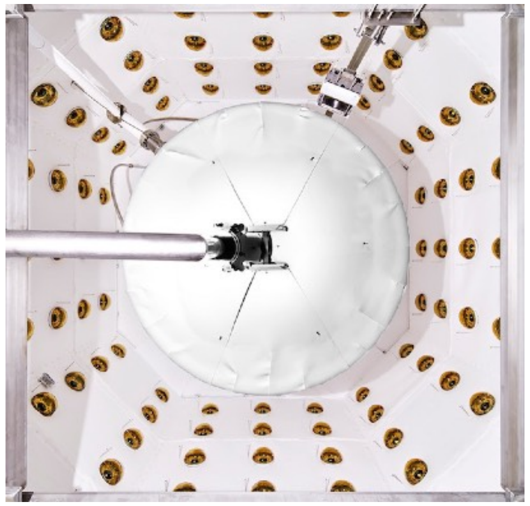
Gravity assisted Xe recuperation and storage system (Ball of Xenon, BoX) for Xenoscope (DARWIN R&D)

LXe purification system (5 L/min LXe, faster cleaning; 2500 slpm) for XENONnT

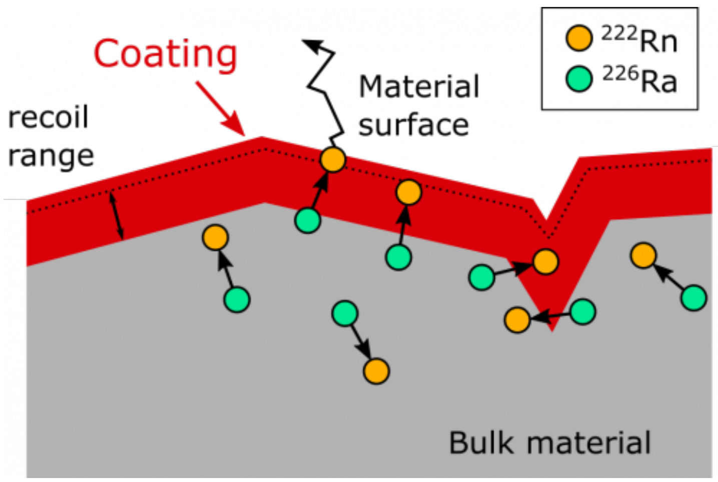
R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: BACKGROUND CONTROL

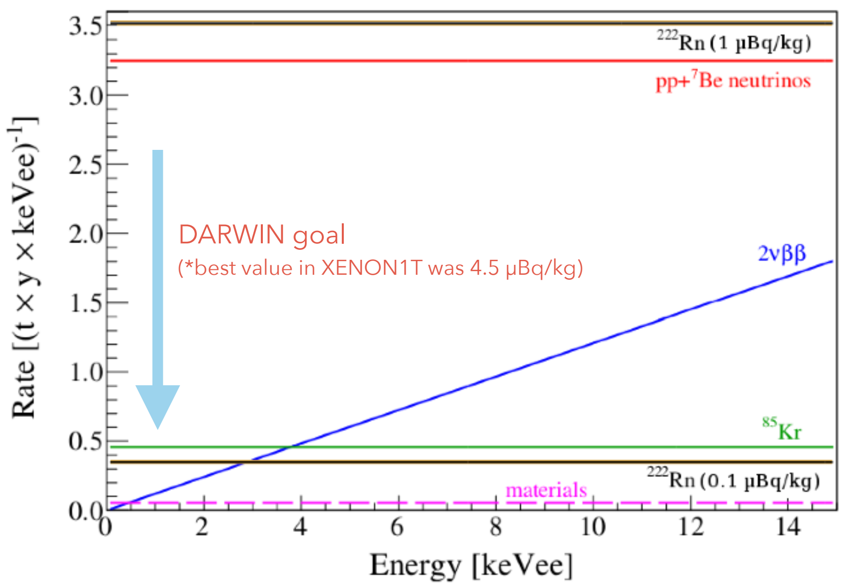
- ^{222}Rn distillation column (goal is 0.1 μBq/kg, background below ER from pp solar neutrinos; DEAP-3600 reached 0.15 μBq/kg in LAr)
- "Radon-free" circulation pumps; coating techniques to avoid radon emanation (electrochemical, sputtering, epoxy based)
- ^{85}Kr distillation (^{nat}Kr goal is 0.1 ppt, achieved < 0.026 ppt)
- Radiopure materials
- Active neutron vetos (e.g., Gd doped water)

Rn distillation column for XENONnT (reduce ^{222}Rn - hence also ^{214}Bi - from pipes, cables, cryogenic system)



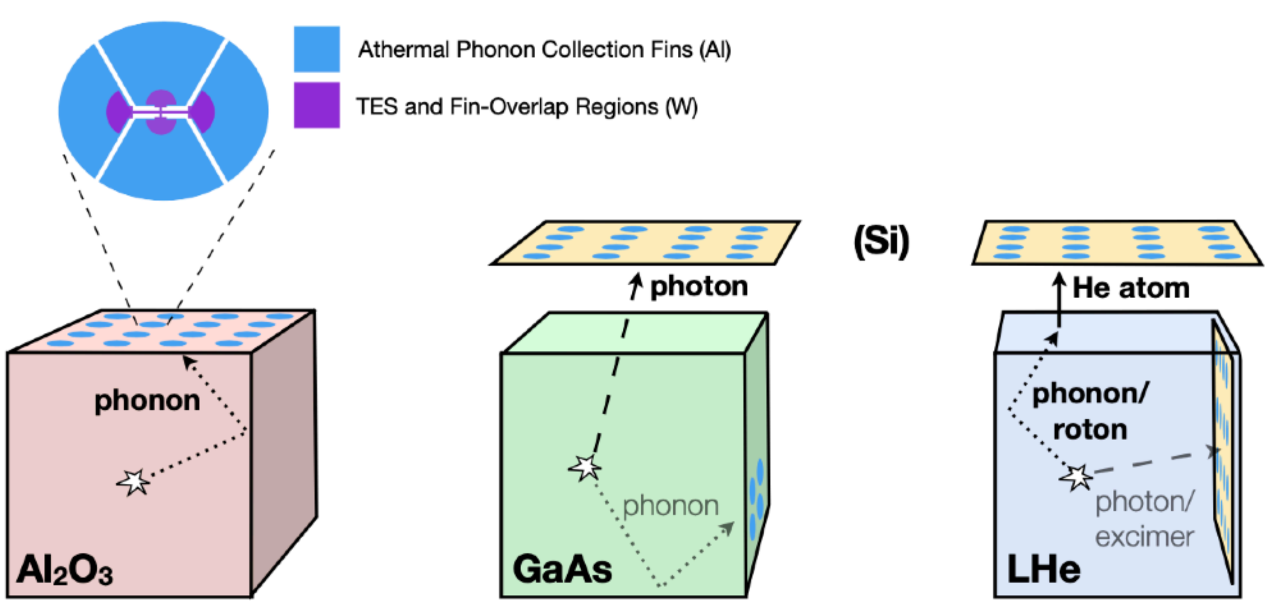
n-veto (Gd doped (0.5% $Gd_2(SO_4)_3$) water) in XENONnT



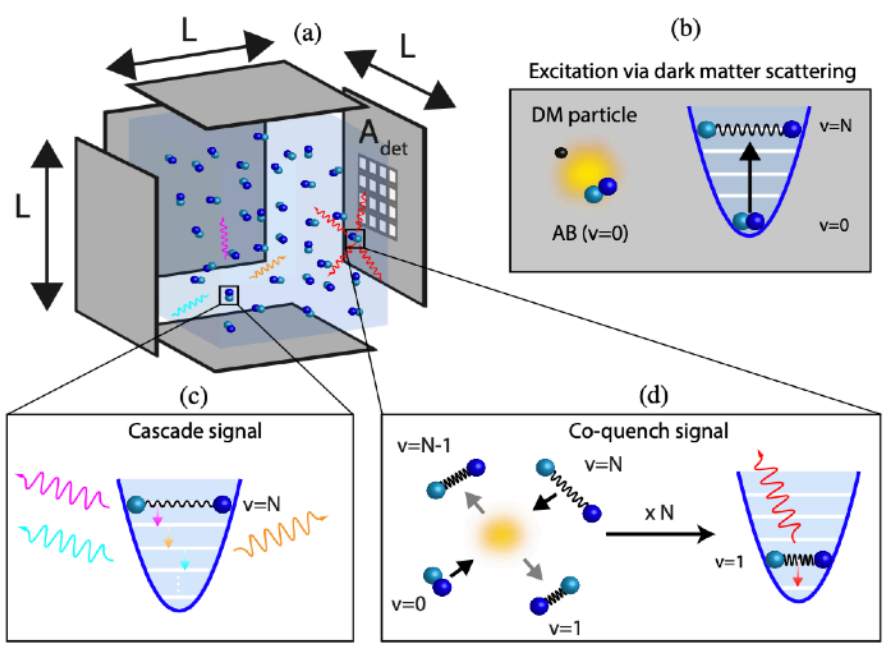


OTHER TECHNIQUES

- QIS for dark matter searches (ultra-light wavelike dark matter; scattering/absorption of DM particles)
- Polar materials (e.g., GaAs); phonons/rotons in superfluid liquid helium; molecular excitations and IR photon detection with SC nano-wires, etc
- Detectors for axion and ALP dark matter



Matt Pyle, Dan McKinsey, et al., Snowmass CF1 meeting, Oct 2020 (GaAs + Sapphire -> SPICE; liquid helium -> HERALD)



K. Berggren, R. Essig et al., Snowmass CF1 LoI: low P, low T molecular gas target (e.g, CO), ro-vibrational molecule excitation

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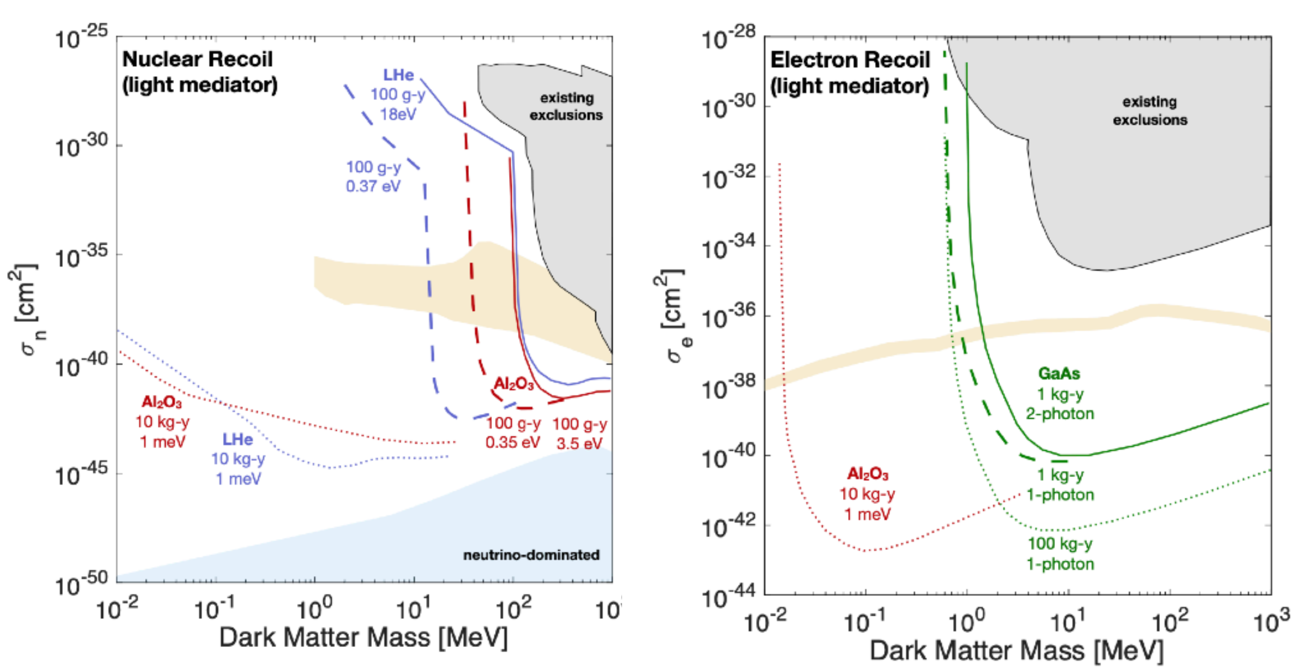
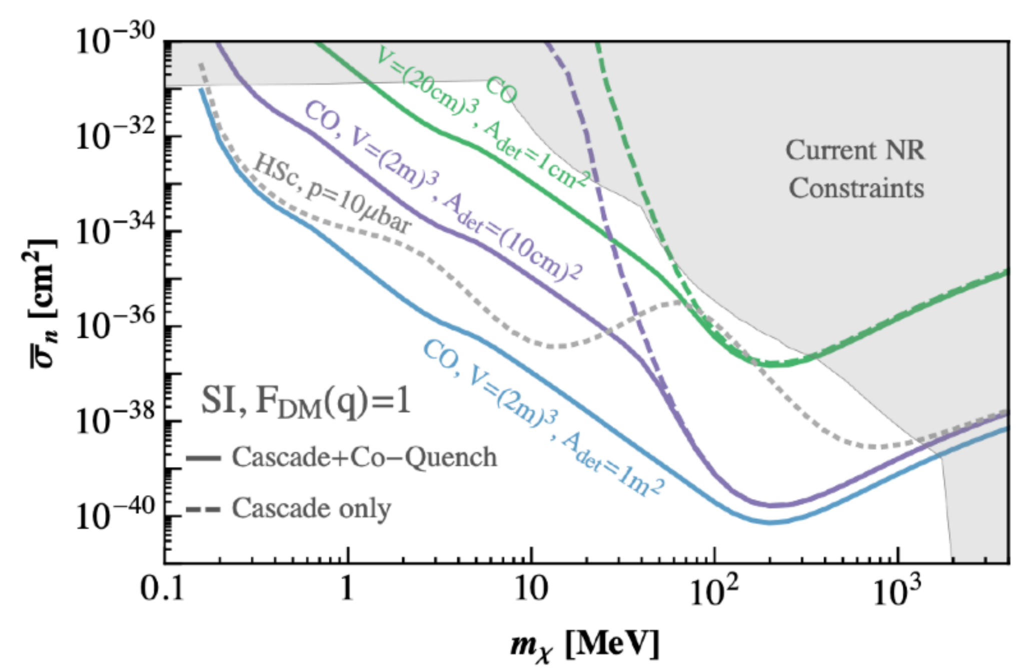


Snowmass21 LoI: The TESSERACT DM project



K. Berggren, R. Essig low P, low T molecular gas target (e.g, CO)