University of
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Detector R&D requirements for future dark matter experiments

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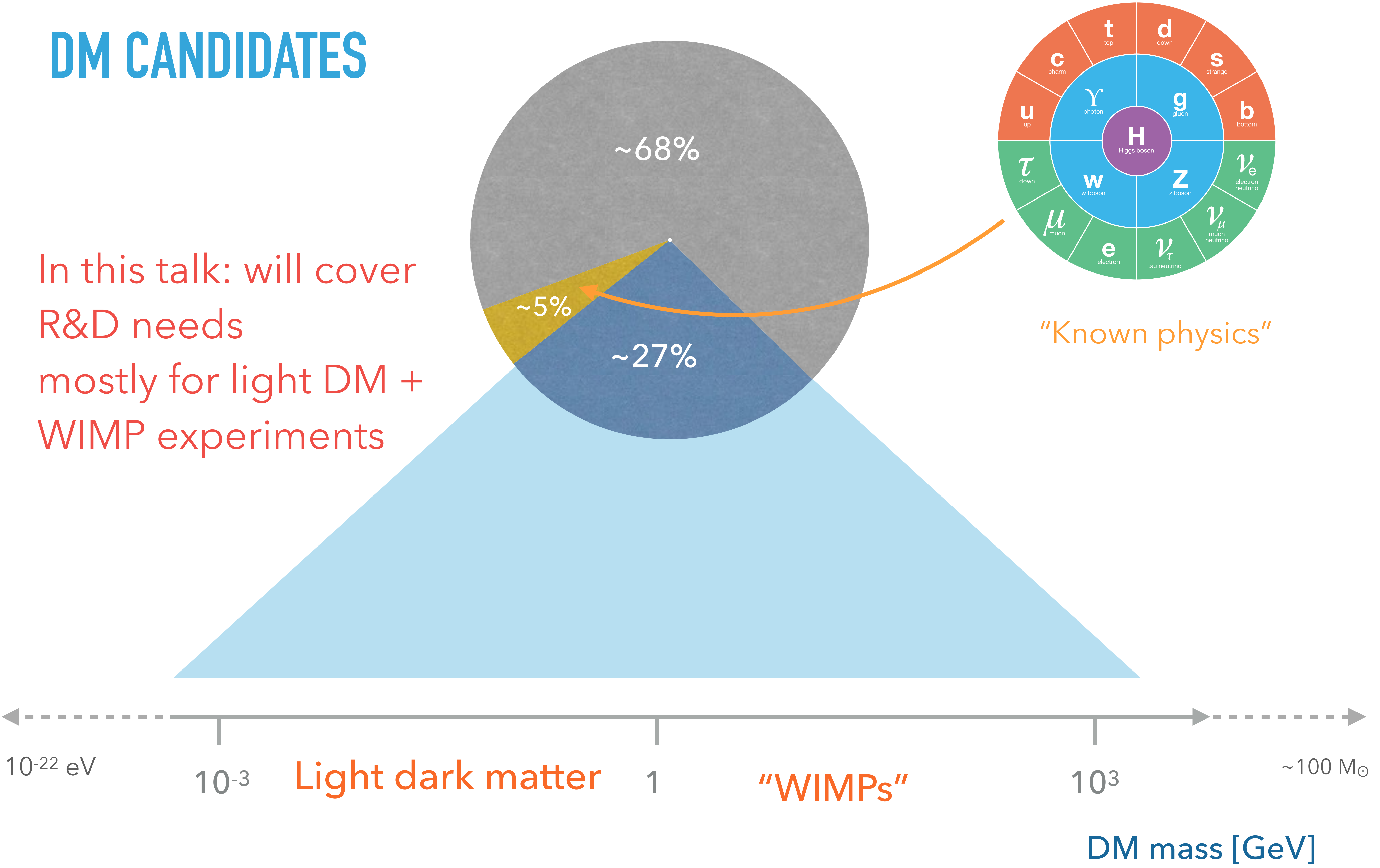
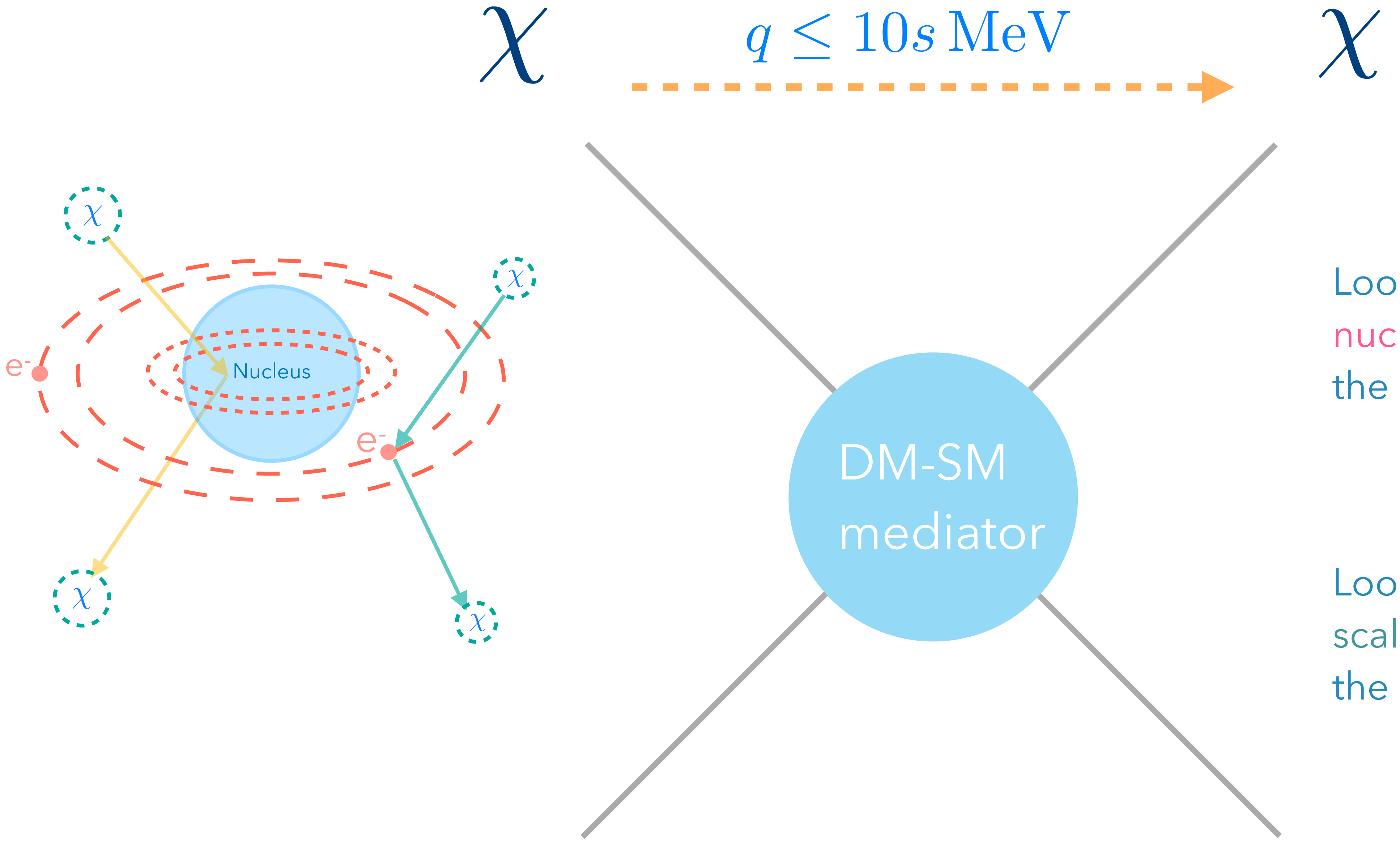
ECFA DETECTOR R&D ROADMAP
INPUT SESSION OF FUTURE FACILITIES II
FEBRUARY 22, 2021

DM CANDIDATES

In this talk: will cover R&D needs mostly for light DM + WIMP experiments



MAIN AIM OF DIRECT DARK MATTER DETECTION EXPERIMENTS



χ $q \leq 10s\,\mathrm{MeV}$ χ

DM-SM mediator

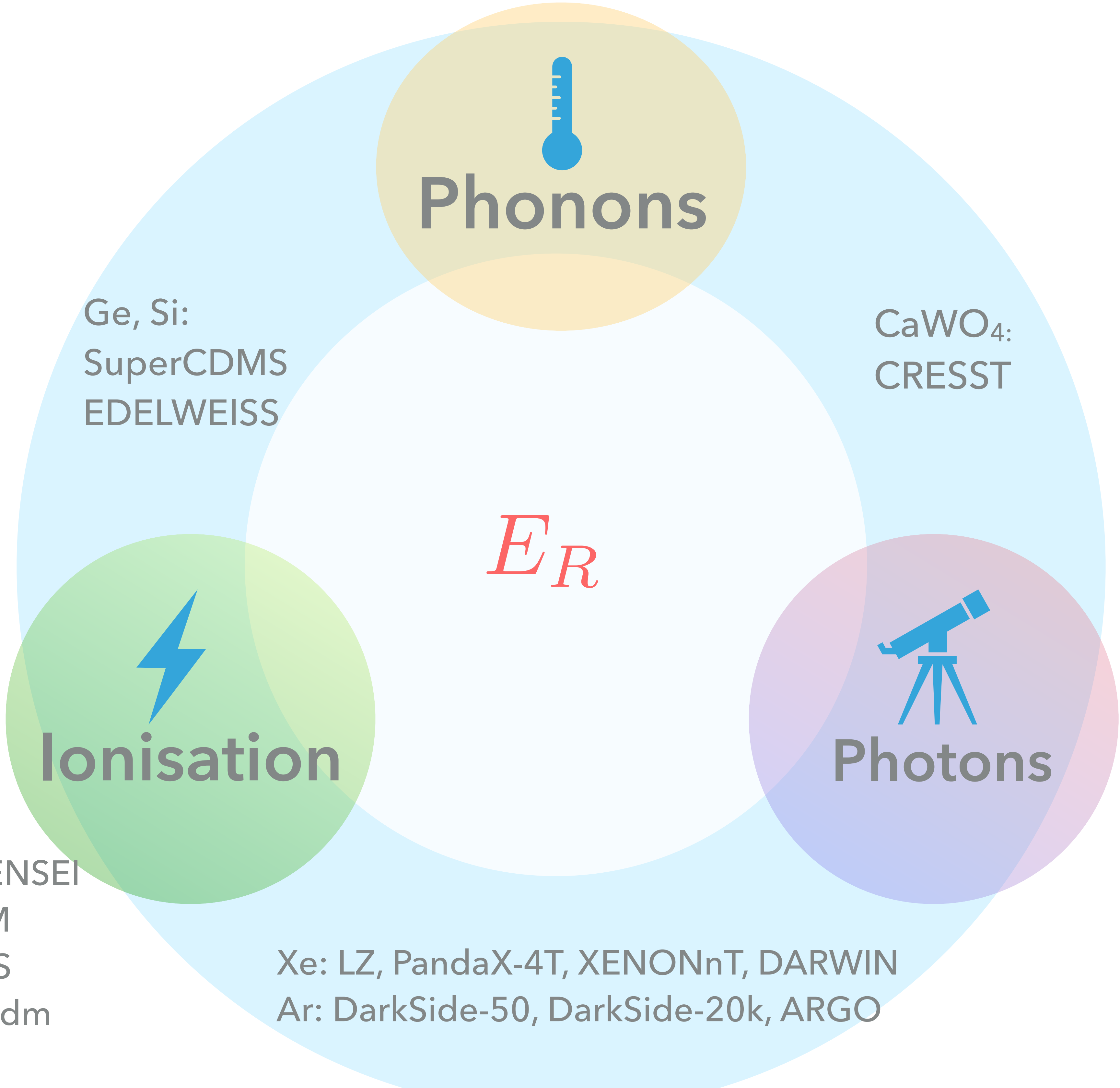
Look for collisions with nuclei or with electrons in the atomic shell

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

Standard Model states

Standard Model states

MAIN DIRECT DETECTION TECHNIQUES/EXPERIMENTS



Phonons

Ge, Si:
SuperCDMS
EDELWEISS

$CaWO_4$:
CRESST

E_R

Ionisation

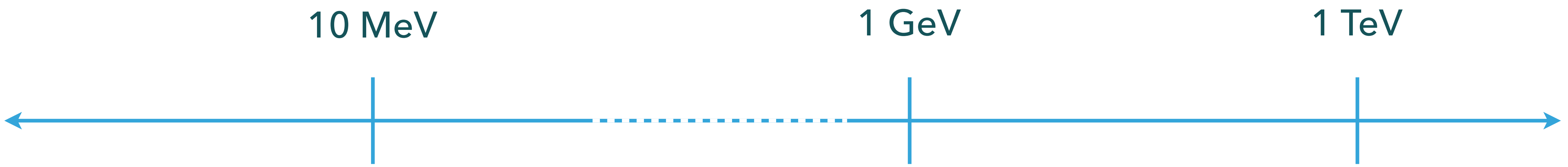
Photons

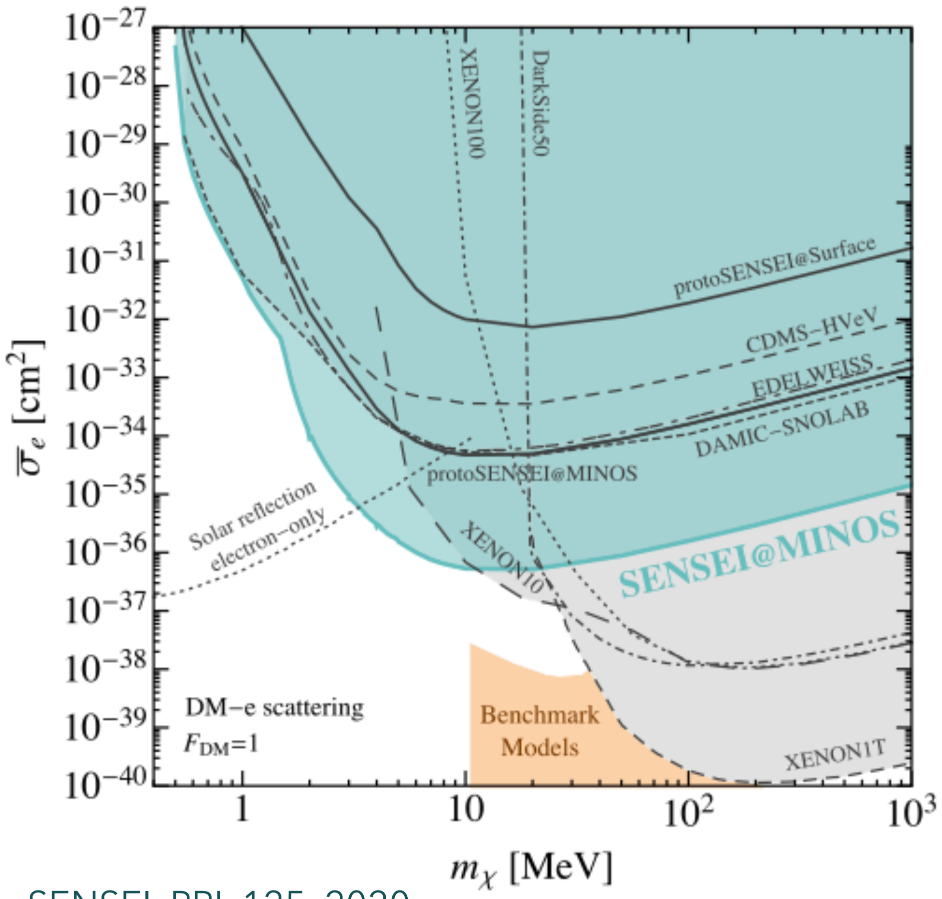
C_3F_8: PICO
Ge: CDEX
Si: DAMIC-M, SENSEI
Ar, Ne: TREX-DM
He:SF_6: CYGNUS
Ag, Br, C: NEWSdm

Xe: LZ, PandaX-4T, XENONnT, DARWIN
Ar: DarkSide-50, DarkSide-20k, ARGO

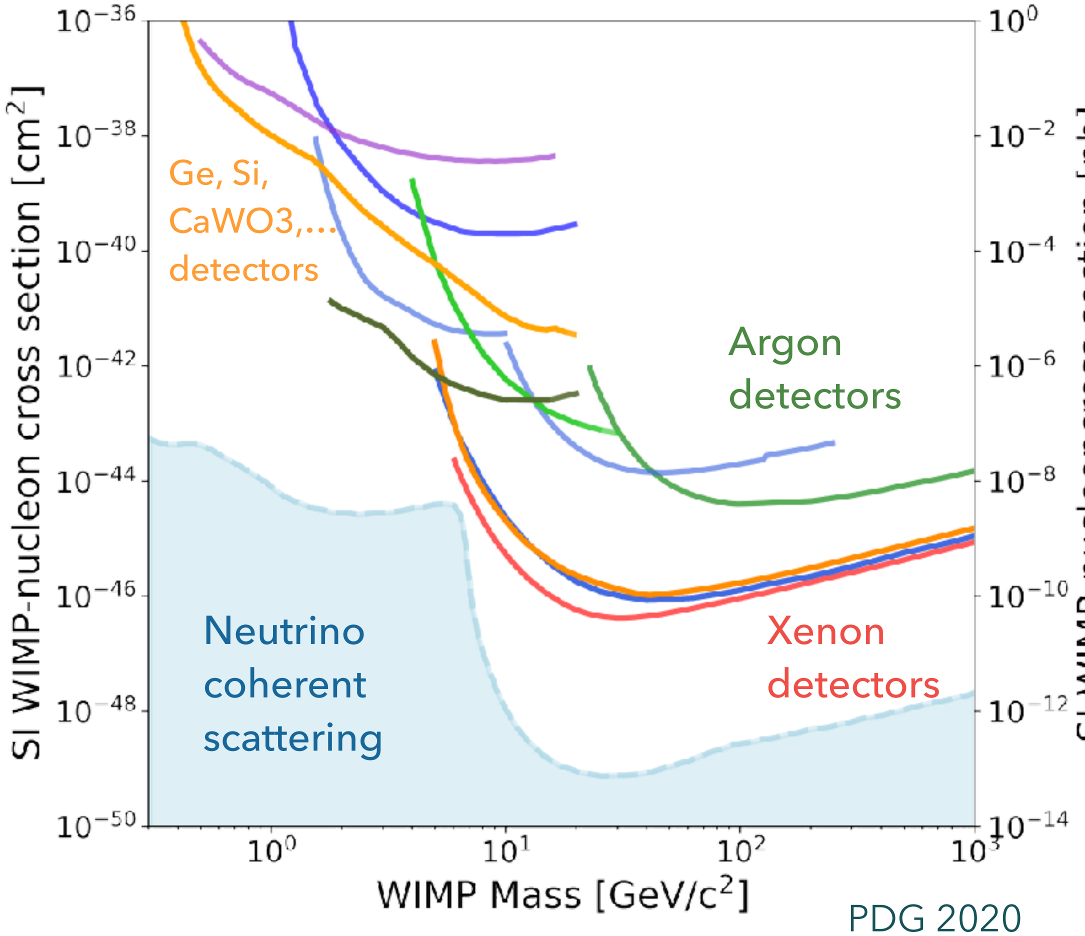
Ar: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE,
COSINUS

THE DIRECT DETECTION LANDSCAPE IN EARLY 2021

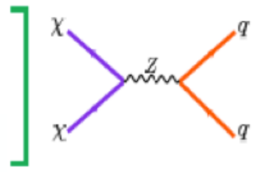


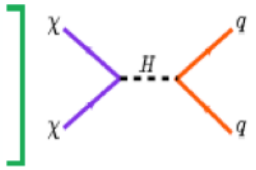


SENSEI, PRL 125, 2020



PDG 2020





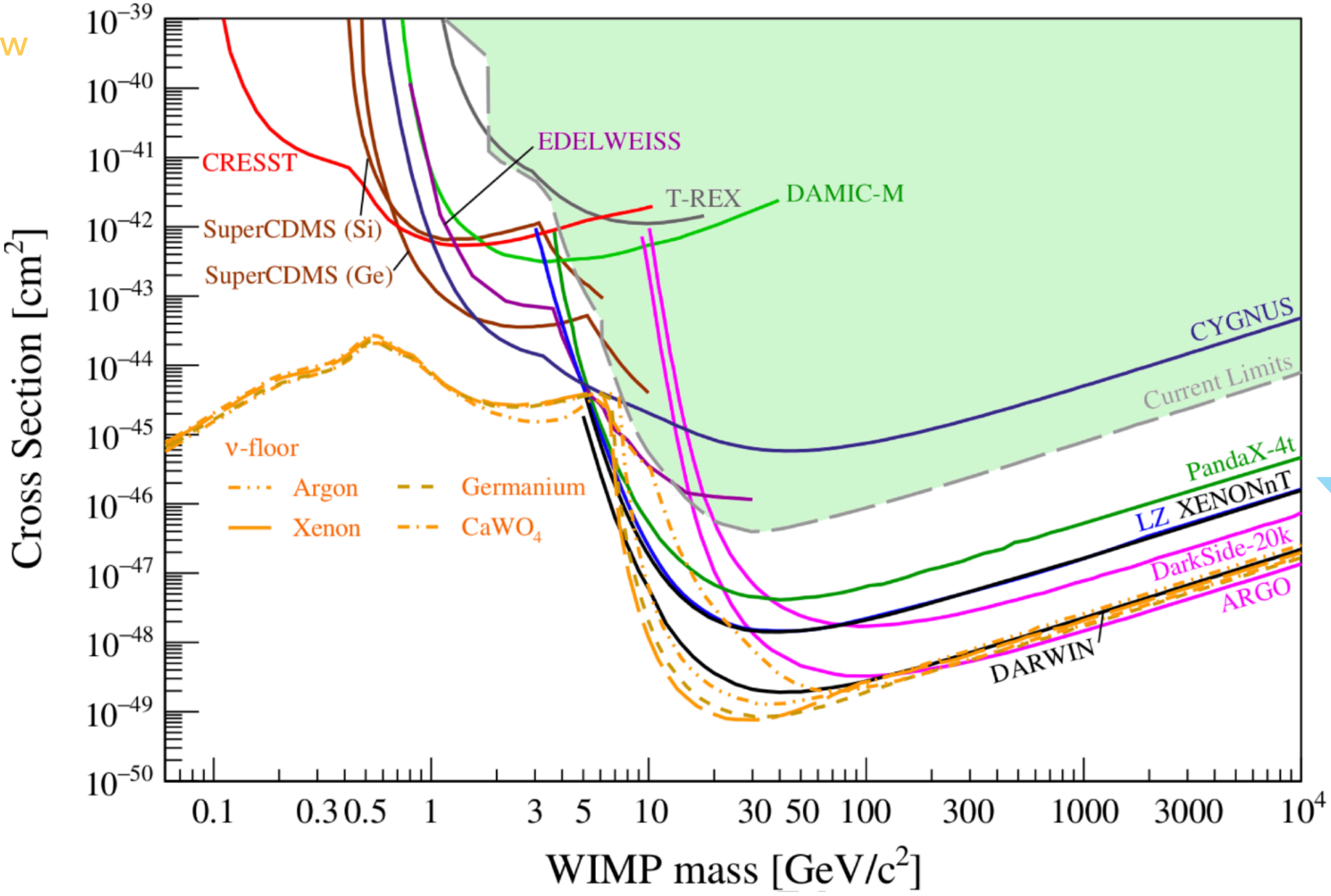
Scattering off electrons

Scattering off nuclei

THE DIRECT DETECTION LANDSCAPE: FUTURE PROJECTIONS

Bolometers

(plus CCDs, new technologies)



Noble liquids

Figure: APPEC DM Report, https://indico.cern.ch/event/982757/overview

Scattering off nuclei

MAIN EXPERIMENTAL CHALLENGES TOWARDS THE "NEUTRINO FLOOR"

- To observe a signal which is:
  - very small → low recoil energies: ~eV to keV; perhaps even meV
  - very rare →~<1 event/(kg y) at low masses and < 1 event/(t y) at high masses
  - buried in backgrounds with > 10^6 x higher rates

MAIN TECHNOLOGICAL CHALLENGES: BROAD OVERVIEW

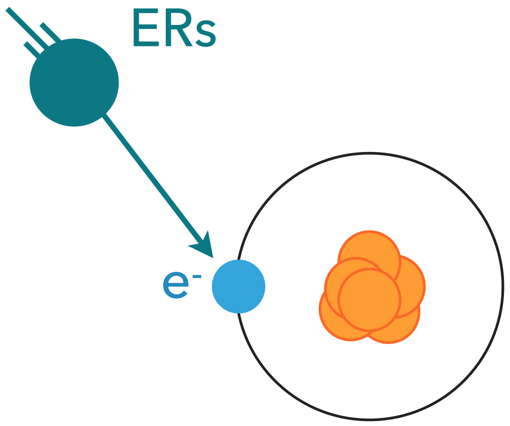
- Bolometers: required exposure is ~ 1 t × year
    - upscaling from ~ kilogram to ~tonne scale
    - crystal purification & growing; background reduction
    - operation of large crystal arrays, dry dilution cryostats at few mK
    - athermal phonon sensors
- Liquefied noble gases: required exposure is ~ 200 t × year
    - upscaling from ~ tonne to 10s of tonnes scale
    - liquid target purification, depletion, distillation & storage; background reduction
    - light and charge readout
    - new modes of detection (heat)

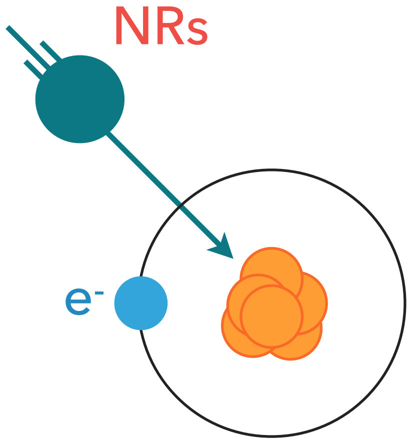
MAIN TECHNOLOGICAL CHALLENGES: BROAD OVERVIEW

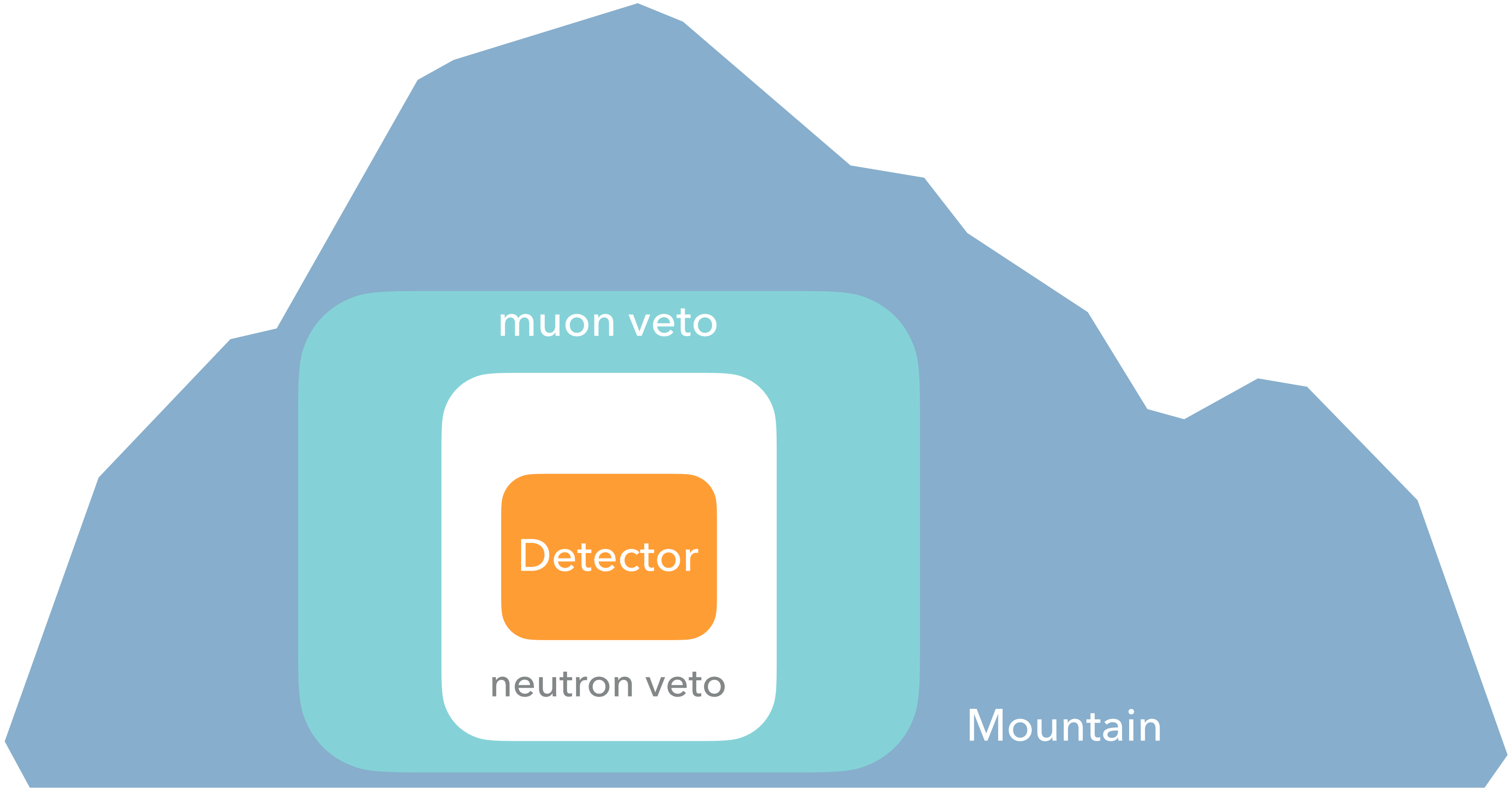
- Ionisation & scintillation detectors
  - development of ultra-pure NaI(Tl) crystals, determination of their quenching factor (relative scintillation efficiency), development of scintillating NaI(Tl) bolometers (e.g., COSINUS)
  - development of sensors and readout schemes for ionisation detectors (e.g., skipper-CCDs)
  - development of scintillating bubble chambers (e.g., SBC at SNOLAB, Ar doped with 10 ppm Xe)
- Directional detectors
  - determine optimal configuration for large target mass detector
  - determine gas mixture, readout
  - demonstrate directionality at low nuclear recoil (~few keV) energies

BACKGROUNDS OVERVIEW

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



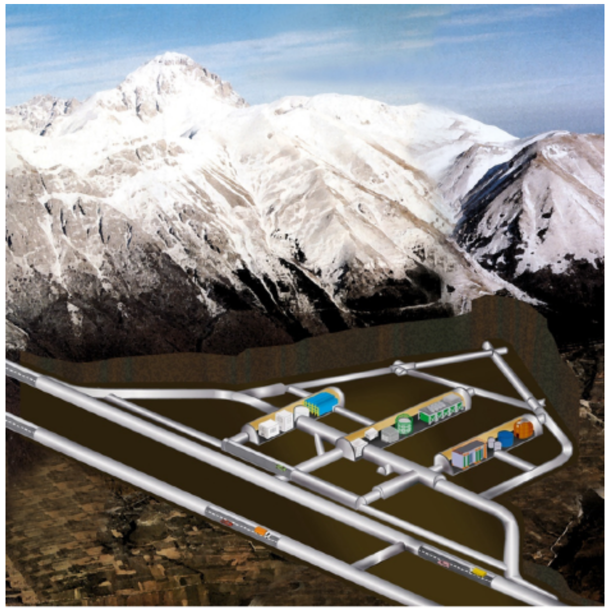




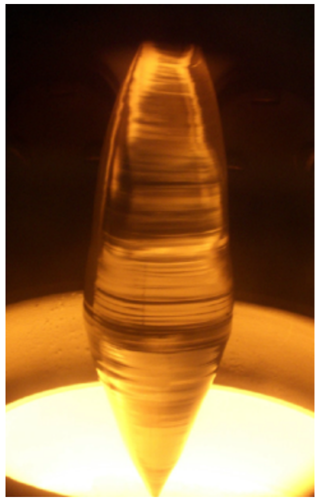
BACKGROUND REDUCTION STRATEGIES

- 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)

Gran Sasso Underground Laboratory



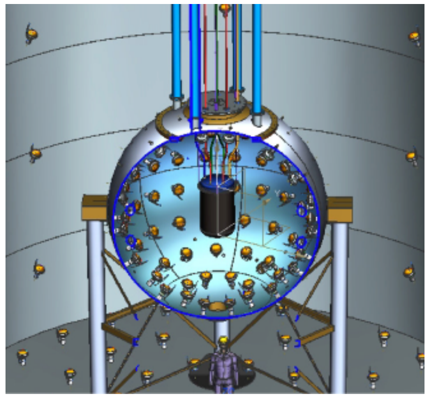
Kr distillation column for XENON1T/nT, EPJ-C 77 (2017) 5

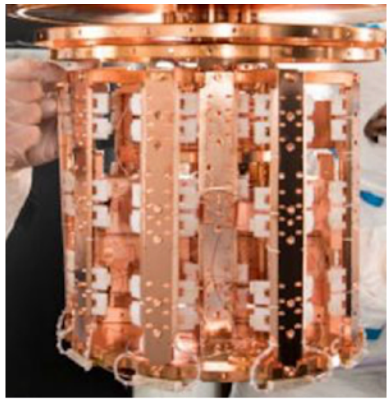


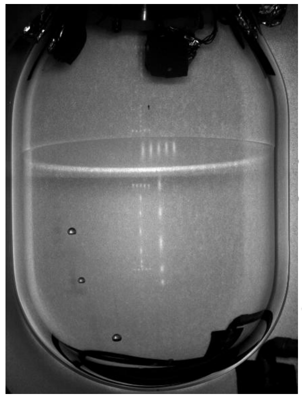
Crystal growth for CRESST

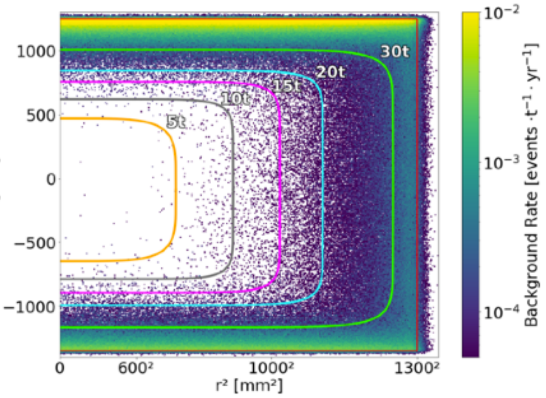
BACKGROUND REJECTION STRATEGIES

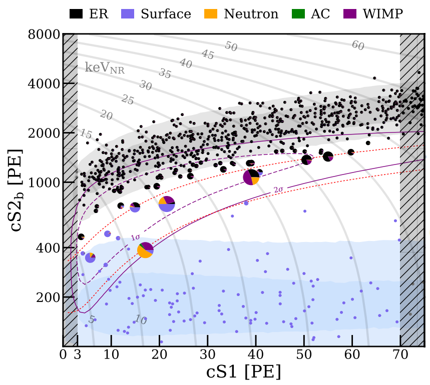
- Active muon and neutron shields
  - tag muon-induced neutrons
  - tag radiogenic neutrons (emitted by materials in (α,n)- and fission reactions)
- Detector design
  - granularity (e.g., tag events in multiple crystals)
  - position reconstruction ⇒ fiducialisation & single versus multiple interactions
  - 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)

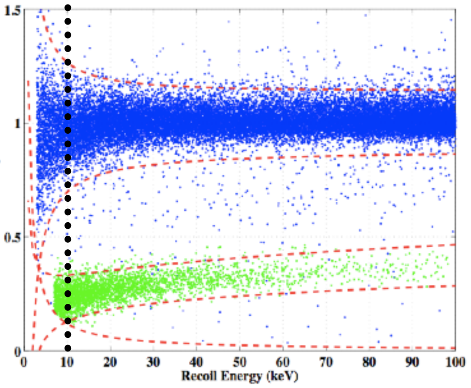


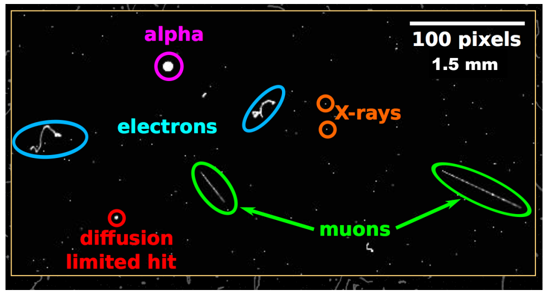








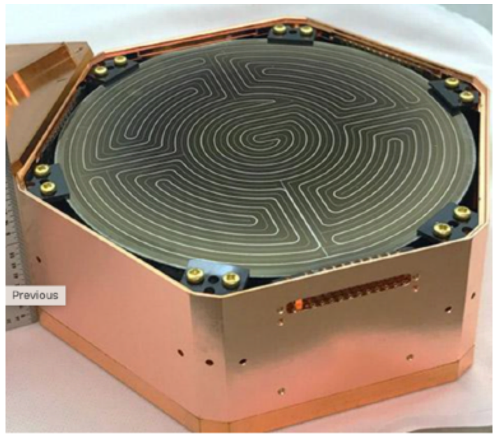




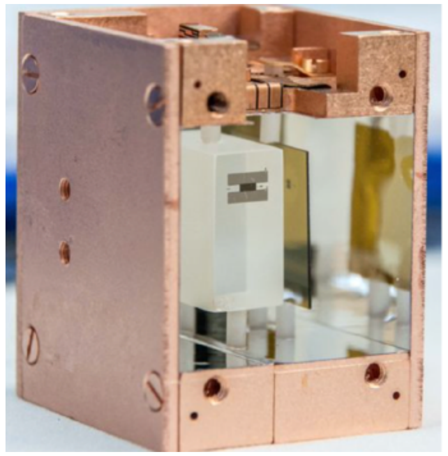
TECHNOLOGICAL CHALLENGES AND R&D: BOLOMETERS

- 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)



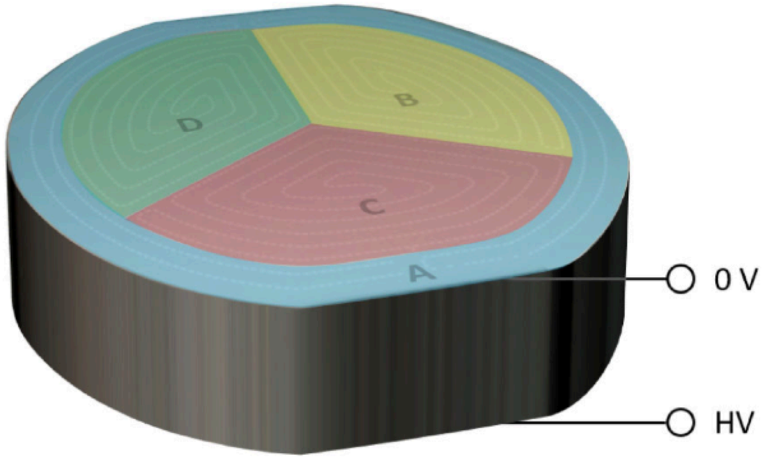
Edelweiss detectors (charge & phonons)



CRESST detector (light & phonons)

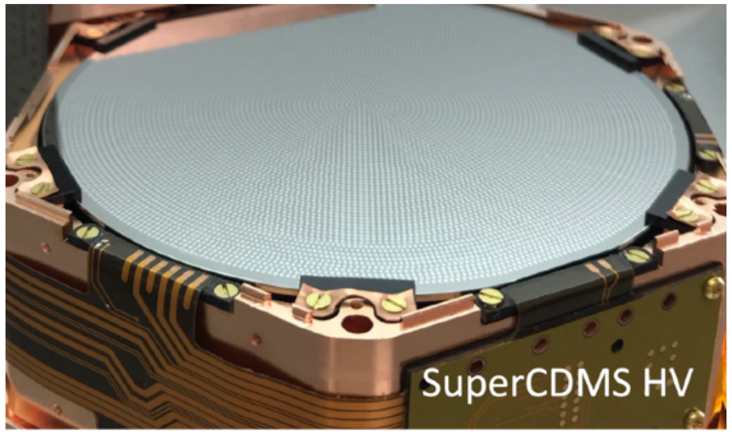
TECHNOLOGICAL CHALLENGES AND R&D: BOLOMETERS

- 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

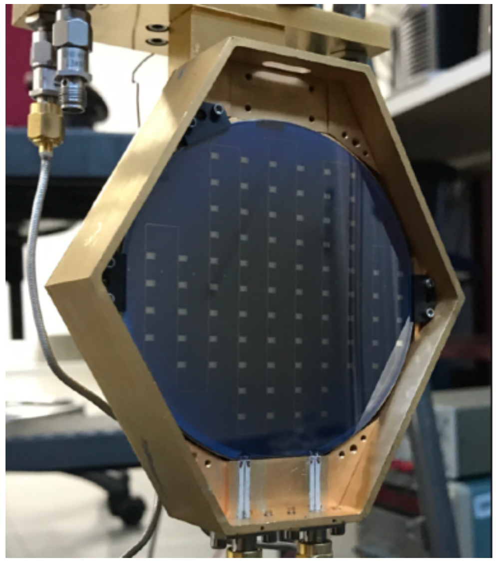


CDMSlite: phonon amplification via NTL-effect; V ~ -70 V => E_{th} ~ 65 eV

CDMS collaboration: PRD 97, 2018



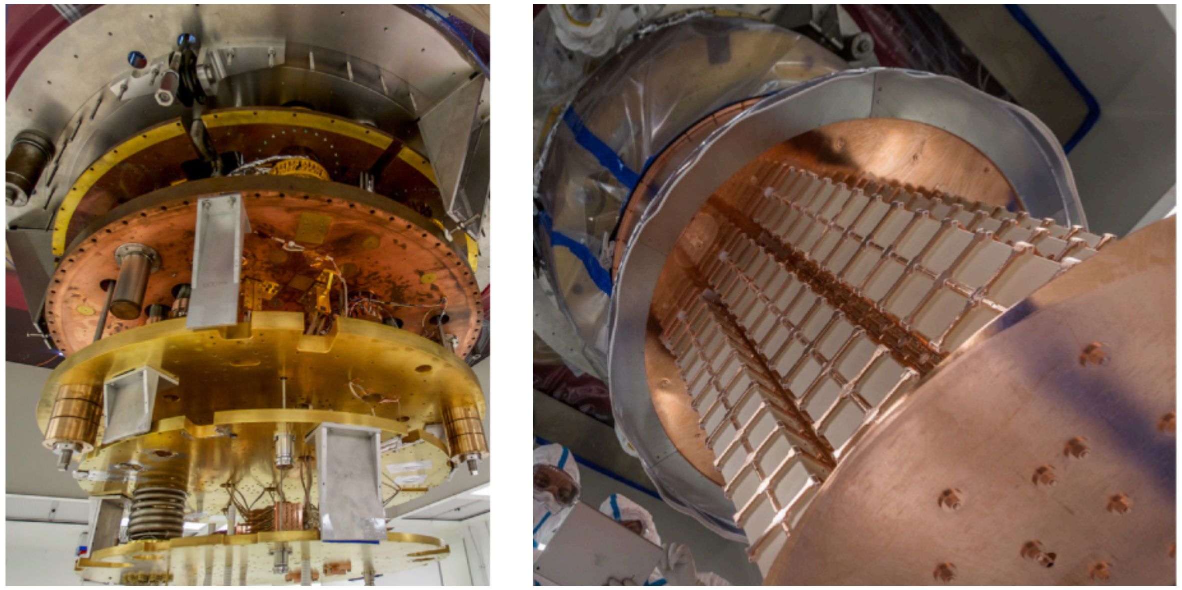
SuperCDMS HV detectors



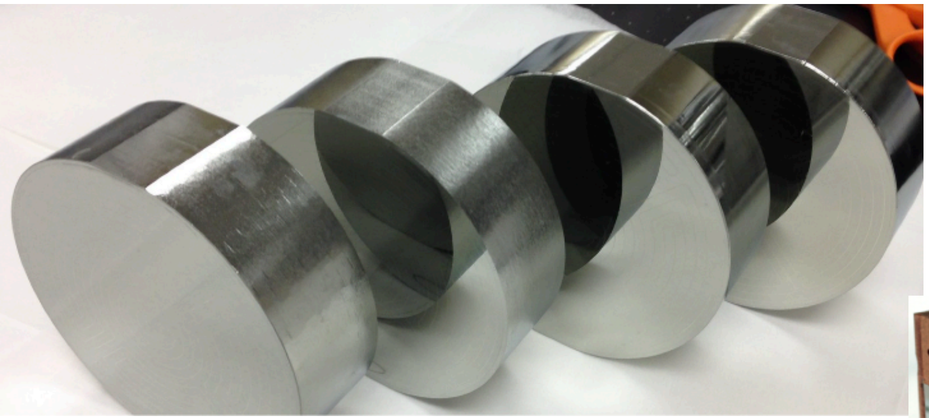
Ge/Si substrate with KID readout; S. Golwala et al.

TECHNOLOGICAL CHALLENGES AND R&D: BOLOMETERS

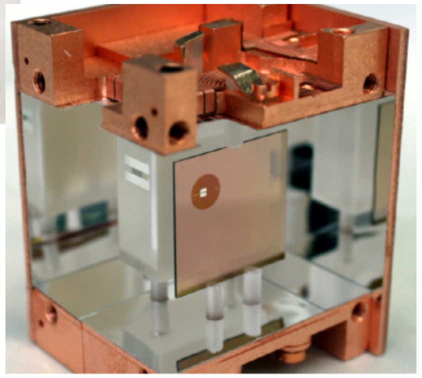
- Target mass
  - operate large arrays of detectors (example: the CUORE 0νββ-experiment at LNGS)
  - maximise mass per detector (reduce number of readout channels): e.g., 1.4 kg Ge and 0.6 kg Si detectors SuperCDMS SNOLAB
  - reduce mass for lower energy threshold and higher resolution: e.g., 24 g CaWO3 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



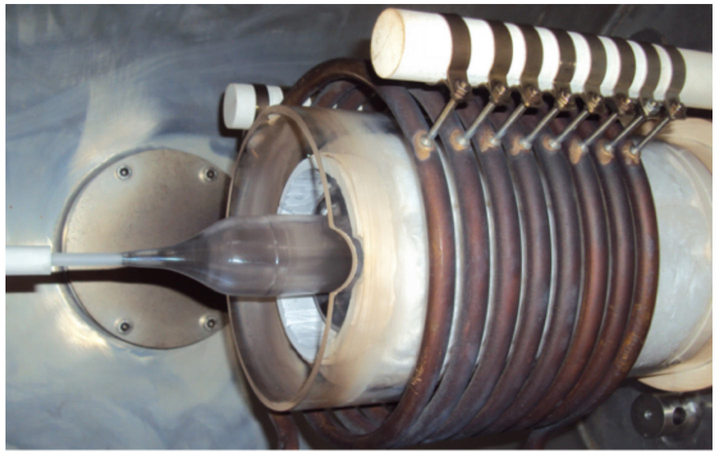
Ge crystals for SuperCDMS (SNOLAB iZIP detectors)



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

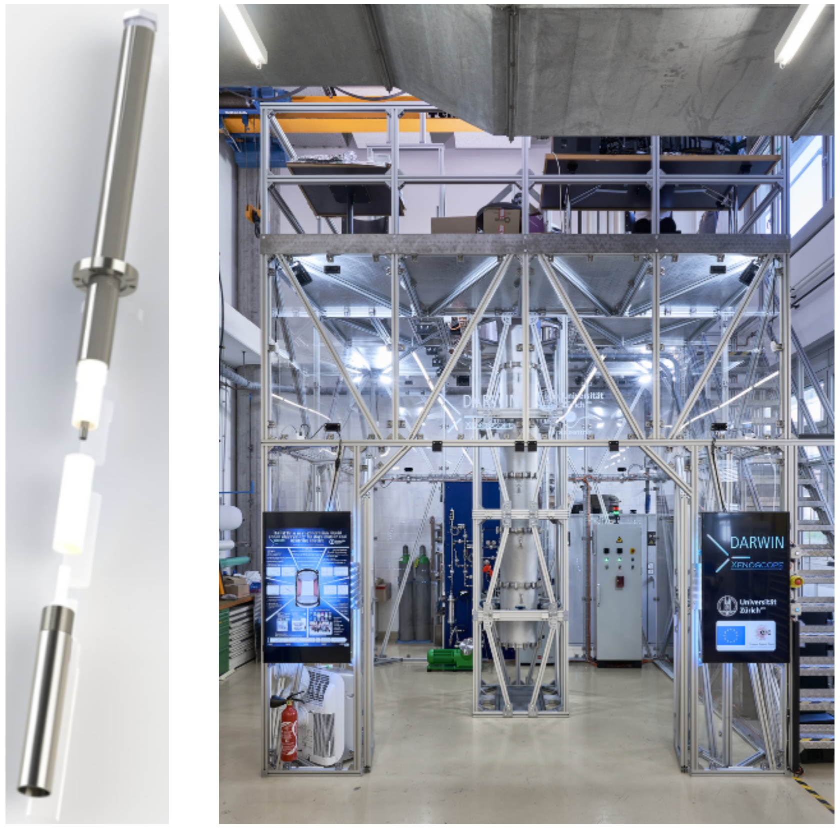
MAJORANA Demonstrator: electroforming Cu underground

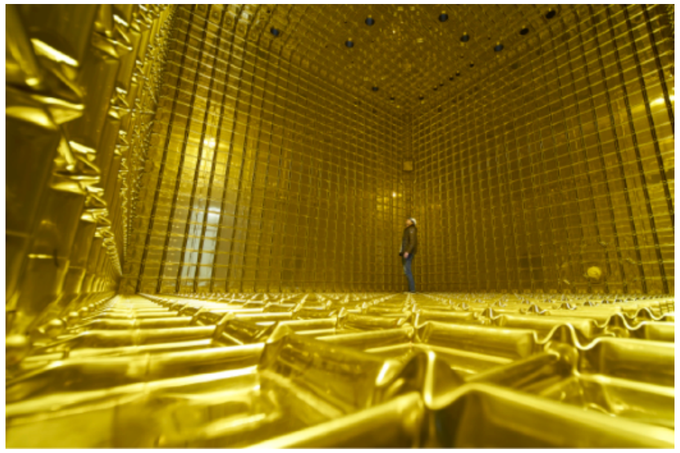
TECHNOLOGICAL CHALLENGES AND R&D: NOBLE LIQUIDS

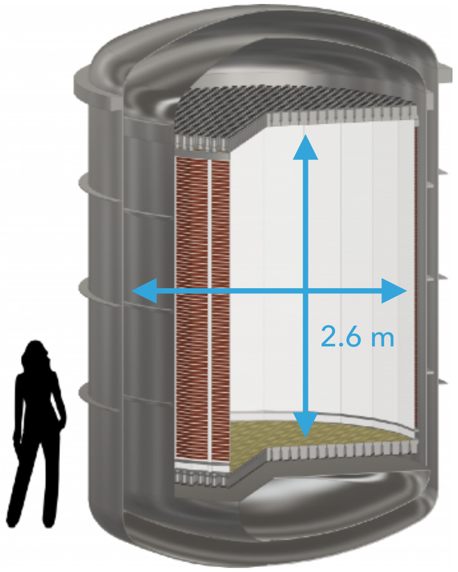
- Detector performance and configuration
  - single phase versus two-phase TPCs
  - light (PMTs, SiPM arrays, hybrid detectors) and charge sensors & readouts
  - decrease energy threshold (increase LCE)
- Target mass
  - xenon procurement is challenging, limited market availability
  - argon depleted 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



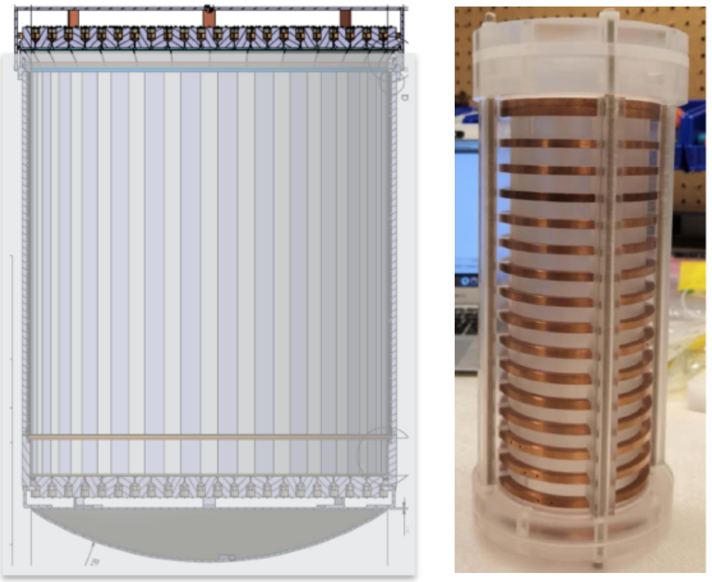
DARWIN Ti cryostat (a la LZ)

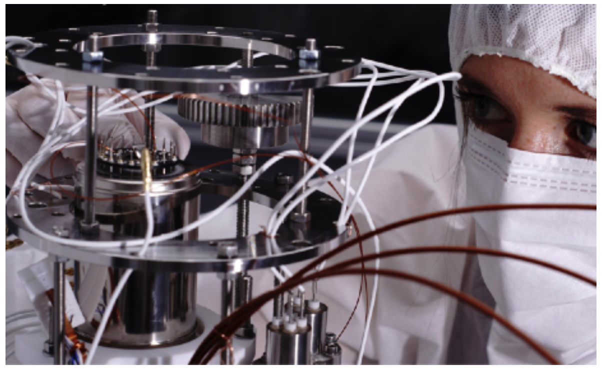

2.6 m diameter Xe TPC demonstrator for DARWIN

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)





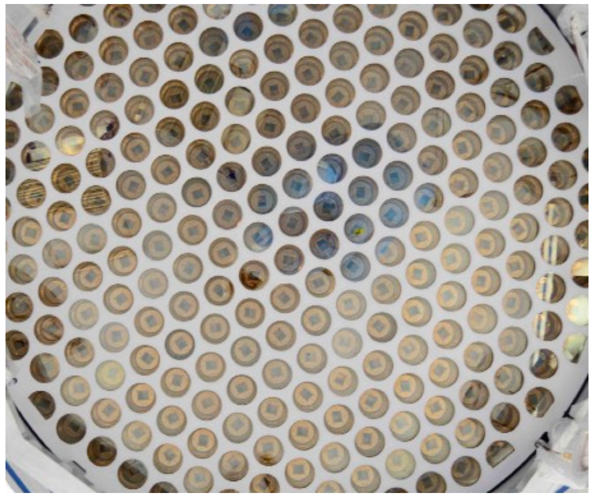
Hermetic TPC R&D for DARWIN

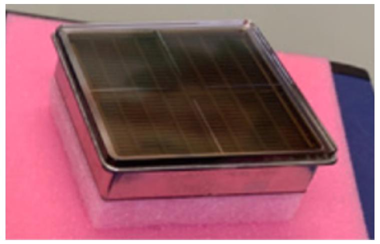
SBC: argon doped with xenon, arXiv: 2101.08785

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

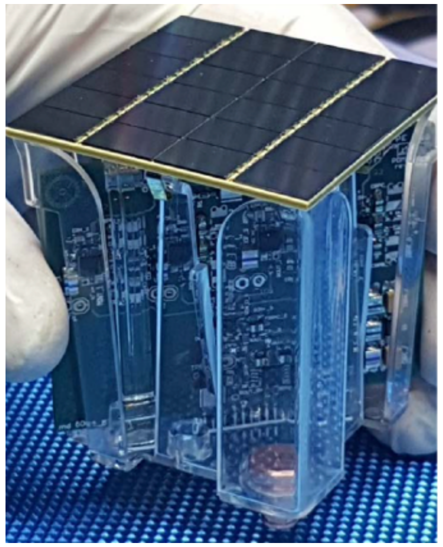




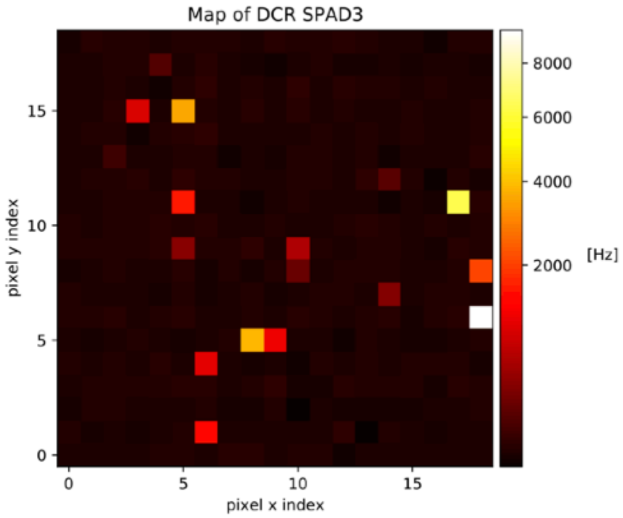
2''x 2'' flat panel PMT (R12699) R&D for DARWIN

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

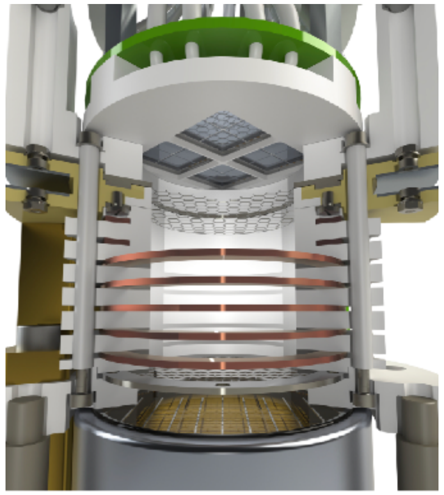
SiPM arrays for Darkside-20k



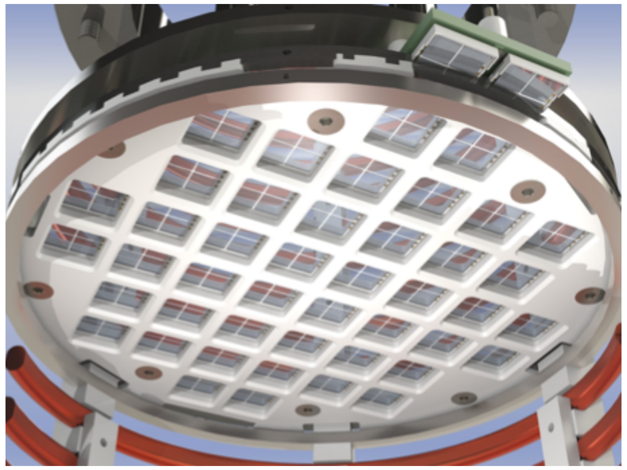
Digital SiPM



Two-phase TPC with SiPM array



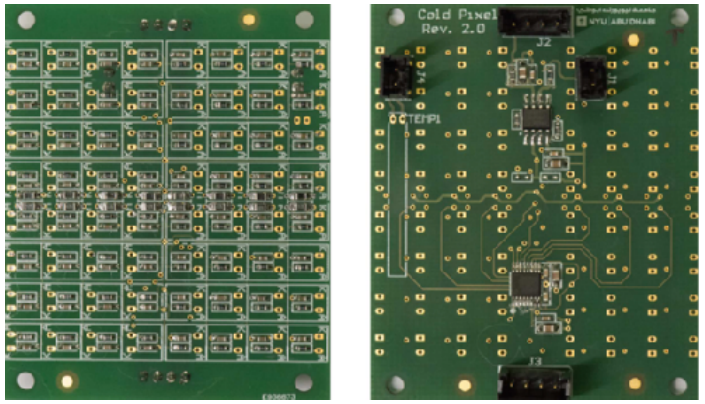
EPJ-C 80, 2020



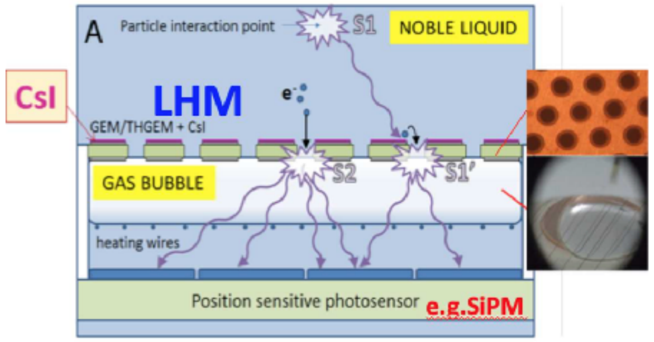
SiPM array, DARWIN demo

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

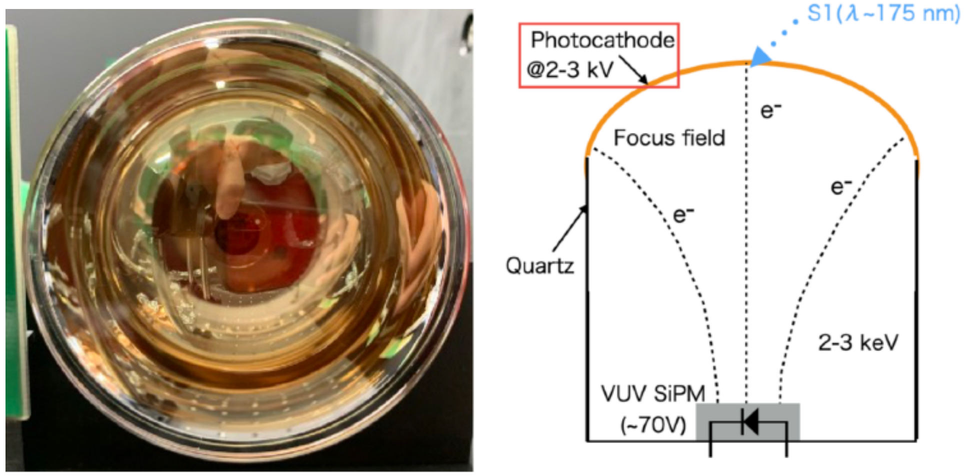
- **Hybrid sensors:** e.g., ABALONE, VSiPM, SIGHT
  - SiPM + Quartz + photocathode: reduced radioactivity compared to PMTs
  - lower DCR compared to SiPM arrays (photosensitive area difference)
- Cryogenic low-noise, low-radioactivity, low heat dissipation readout
- **Bubble-assisted Liquid Hole Multipliers**: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



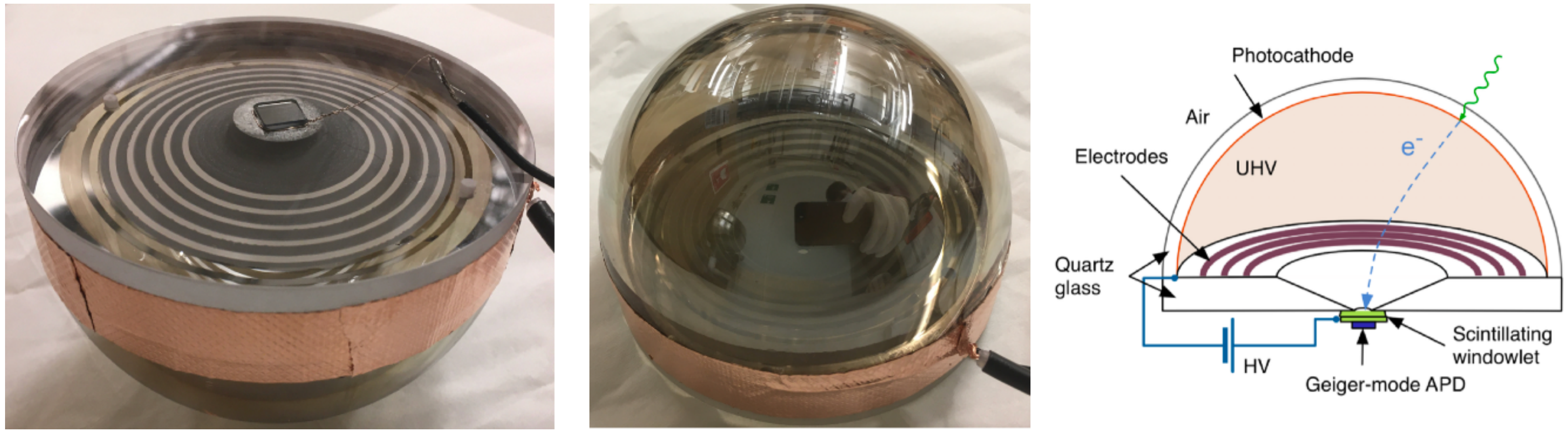
Cryogenic preamp for SiPMs, NIM 936, 2019



Liquid hole multipliers JINST 13, 2018



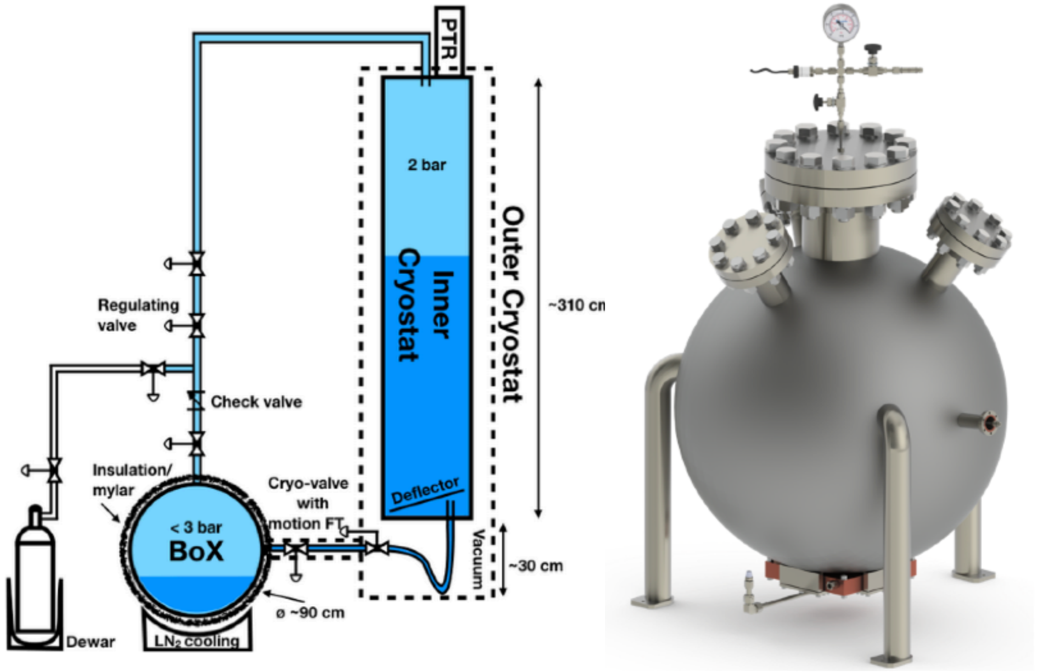
Hybrid photosensor: Hamamatsu XE5859



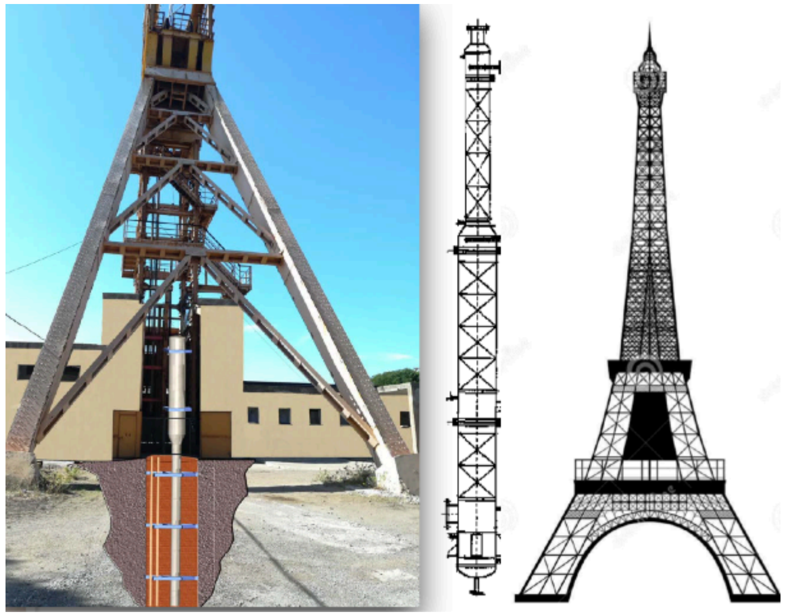
Hybrid photosensor: ABALONE; left (DARWIN R&D with SiPM); right: NIM 954, 2020

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)



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



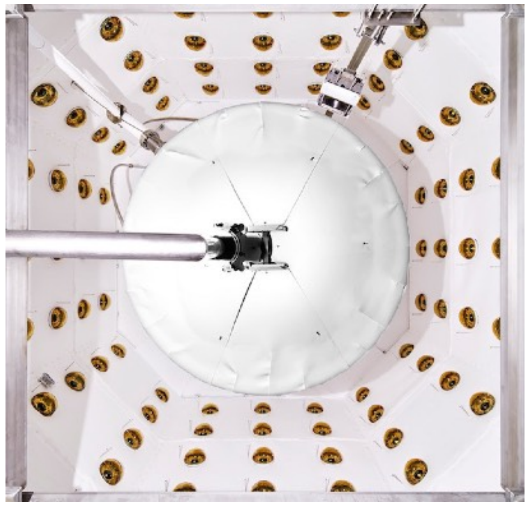
ARIA underground purification system for argon (DarkSide-20k)

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

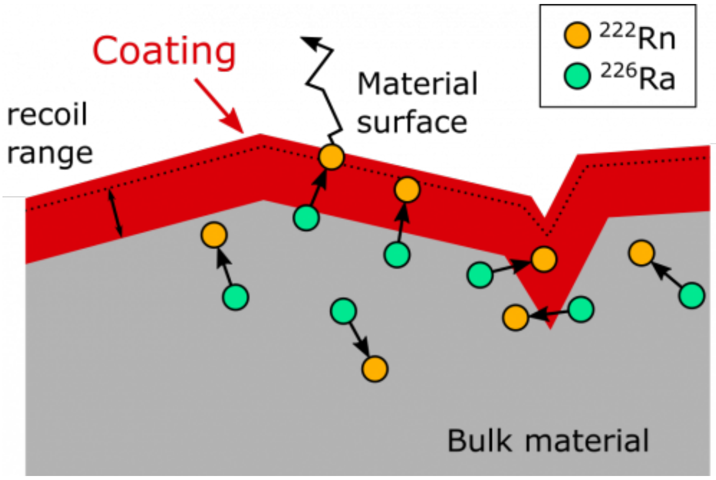
R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: BACKGROUND CONTROL

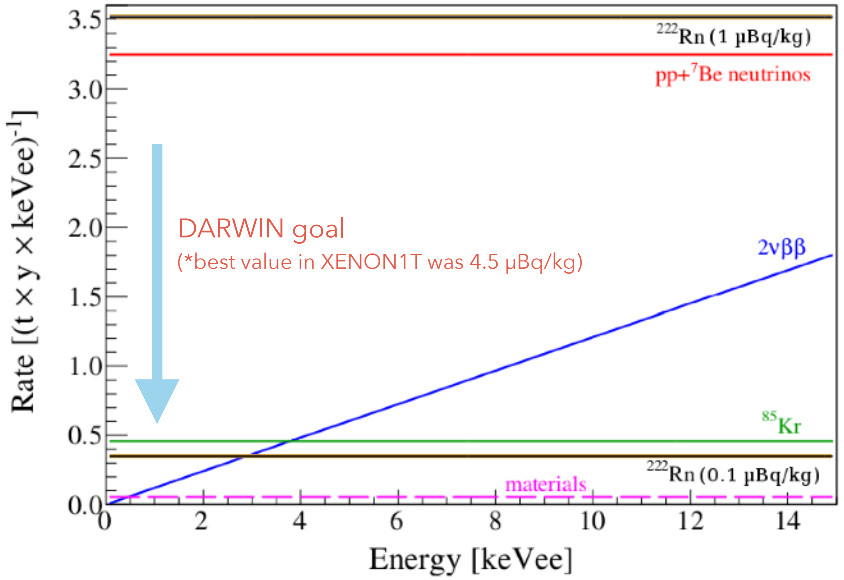
- ^{222}Rn distillation column (goal is 0.1 μBq/kg, background below ER from pp solar neutrinos; DEAP-3600 reached 0.15 μBq/kg in LAr)
- "Radon-free" circulation pumps; coating techniques to avoid radon emanation (electrochemical, sputtering, epoxy based)
- ^{85}Kr distillation (^{nat}Kr goal is 0.1 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

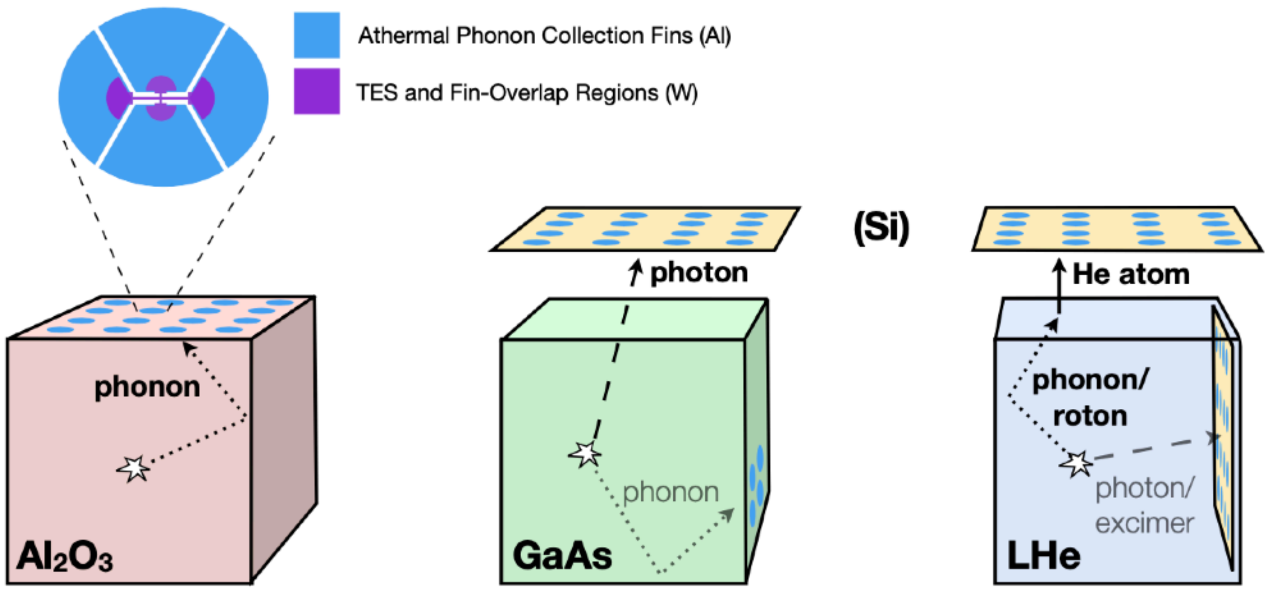




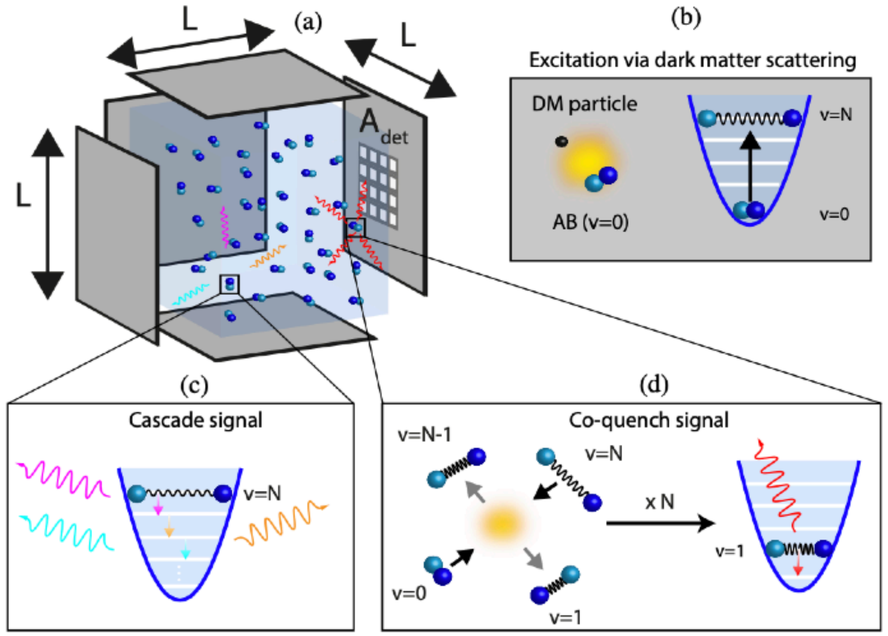
DARWIN goal
(*best value in XENON1T was 4.5 μBq/kg)

NOT COVERED IN THIS TALK

- Detector calibration techniques , ex-situ and in-situ (e.g., calibration at very low ER & NR energies)
- Noise sources (e^- emission from photoionisation on impurities, delayed emission of trapped e^-, IR backgrounds) and detector physics backgrounds (e.g., E-field effects)
- 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

NOT COVERED IN THIS TALK

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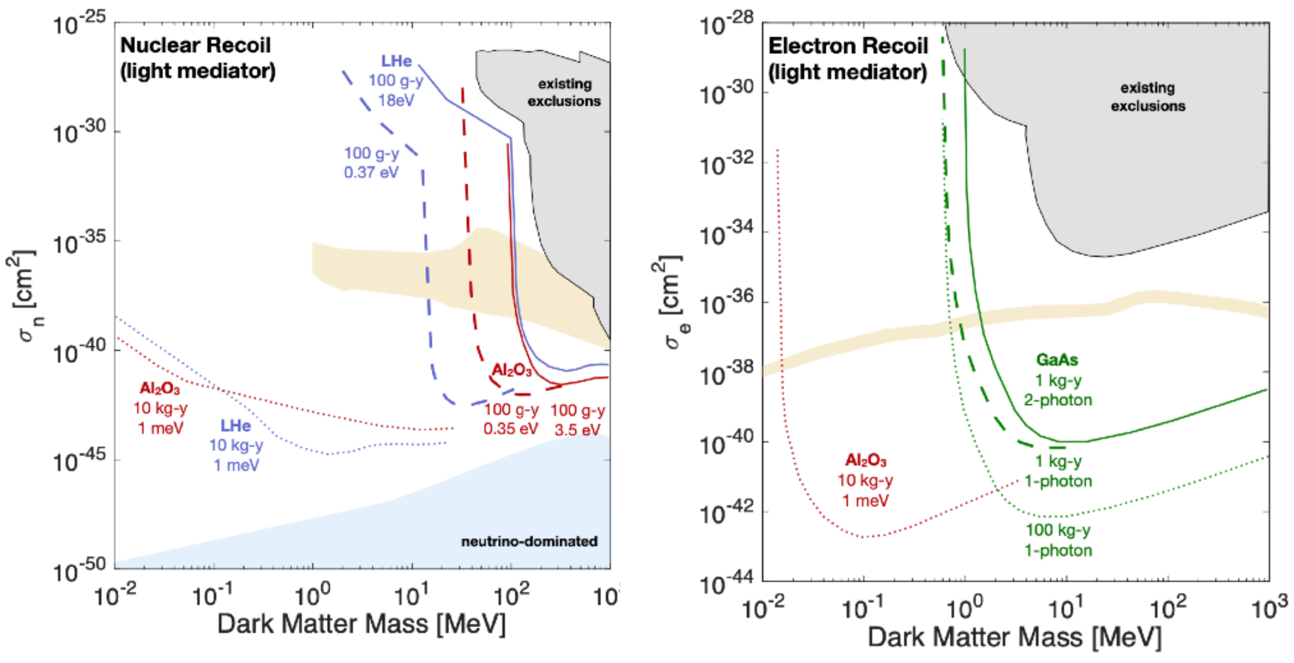
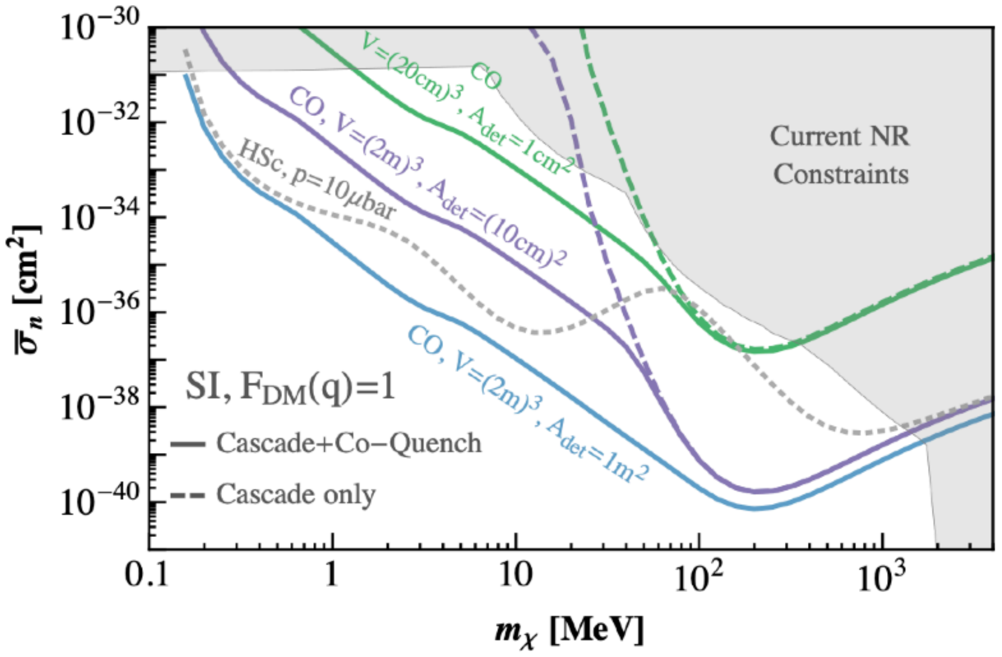


Snowmass21 LoI: The TESSERACT DM project



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

SUMMARY AND OUTLOOK

- Next-generation dark matter detectors must reach the required sensitivities (overall sizes, detector configurations & background levels) to probe the available parameter space for particle dark matter above the neutrino floor
- Typically, background levels below the neutrino floor and mass scales of 10s kg-100s kg (region <1 GeV) and 10s-100s of tons (region > 1 GeV) required
- Simple extrapolations of existing technologies to larger scales are not sufficient
- Strong R&D programmes to enhance detector performance, optimise detector configurations and reduce background levels
- Many new R&D efforts towards measuring energies down to meV, and extend the sensitivities to lower DM masses (MeV-scale and below)
- Technological innovations also benefit other fields

LITERATURE & MATERIAL

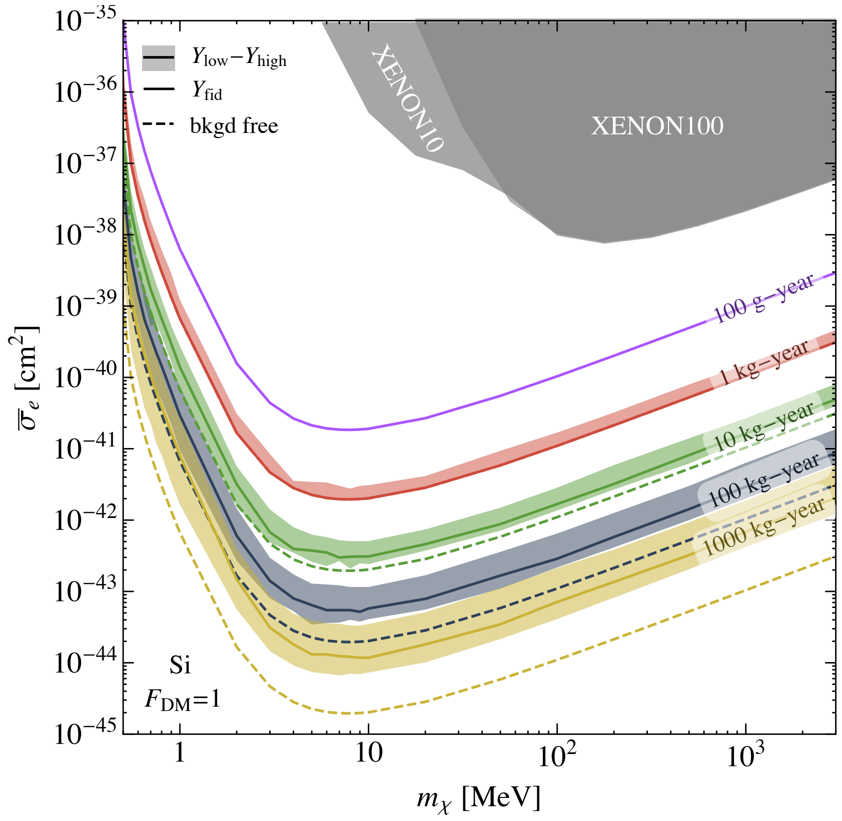
- Various experimental collaborations
- Snowmass Cosmic Frontier talks and LoIs (https://snowmass21.org)
- APPEC dark matter preliminary report (https://indico.cern.ch/event/982757/overview)
- APPEC DM community workshop (in particular talks by Federica Petricca, Giuliana Fiorillo)

THE END

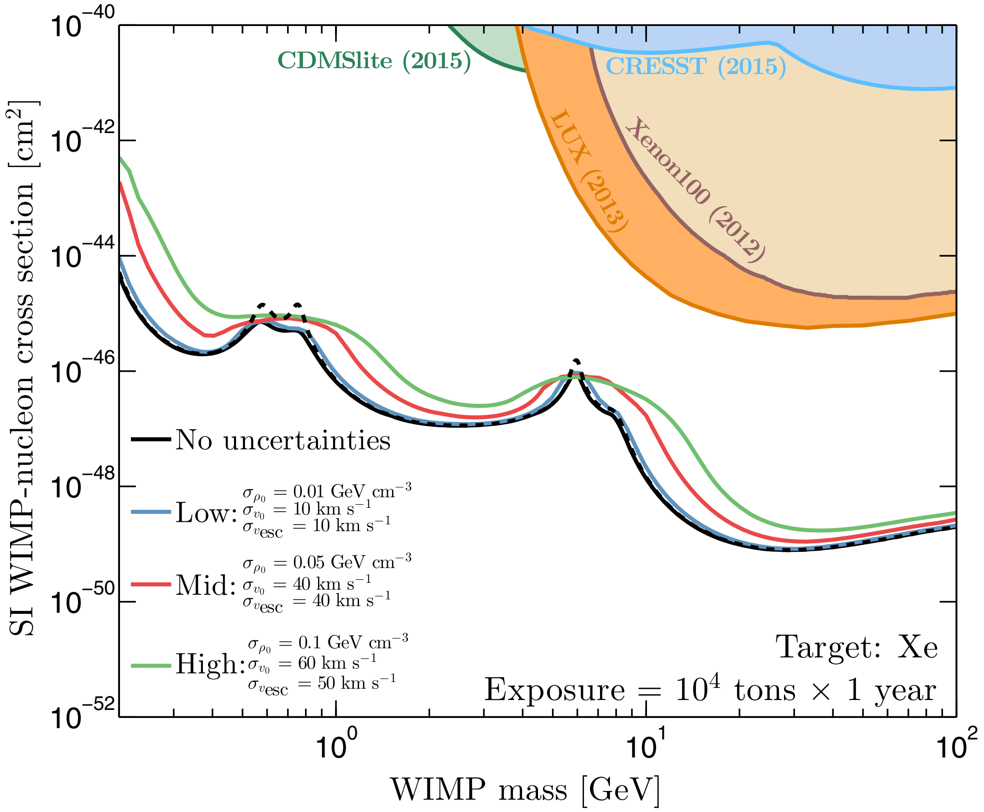
NEUTRINO BACKGROUNDS

- Low mass region: limit at ~ 0.1- 10 kg year (target dependent)
- High mass region: limit at ~ 10 ktonne year
- But: annual modulation, directionality, momentum dependance, inelastic DM-nucleus scatters, etc

Discovery limits (2-σ) for various ionisation efficiencies Y, solar ν background only



DM-electron scatters (R. Essig,at al, PRD97, 2018)



DM-nucleus scatters (C.A.J. O'Hare, PRD94, 2016)