NF10: Neutrino Detectors

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NF10 Scope

- The Neutrino Detector Topical Working Group examines a broad range of neutrino detection solutions, focusing on the interplay of physics drivers, new detector ideas, and relevant enabling technologies. Detectors capable of exploring neutrino physics across the full spectrum of possible energies will be considered, from eV to EeV.
  - We do not look in detail at existing detectors or those under construction---if the detector has a TDR already, its physics program and capabilities fall under other Topical Committees.
  - We do not directly include experimental facilities (e.g., underground spaces)

NF10 LsOI

- **NF10 Letters of Intent Summary:**
  - 157 LOIs referencing NF10 (53%)
  - 64 marked as ‘primary’
  - Additional 93 LOIs where NF10 is ‘secondary’

Initially these were categorized by “natural” grouping

NF10 LOI Categories	# of LOIs
New detectors and R&D: Noble element/TPCs	10
New detectors and R&D: WC/scintillator/WbLS	11
New detectors and R&D: Coherent ν detection	7
New detectors: Ultra-high energy detection	4
New detectors: Near detectors	1
New detectors: LHC forward nu detection	1
Dark matter/neutrino detectors	9
New instruments: ASICs	1
New instruments: Optics	1
New instruments: Pixels	3
Simulation packages	4
Analysis tools	5
Calibration and Test Facilities	2
Experimental Facilities	3
Novel detectors	2
TOTAL	**64**

NF10 LsOI

Removing those for existing or already-constructed detectors, and some which were otherwise out-of-scope, showed that these basically fell into four broad categories:

NF10 LOI Categories	# of LOIs
Noble element/TPCs	17
Photon-based ν detectors	18
Low-threshold ν detection	13
Novel Detectors (not included in other categories)	5
TOTAL	**53**

New Detectors and R&D: Noble elements/TPCs

TITLE	Description
Dual-Readout Time Projection Chamber: exploring sub-millimeter pitch for directional dark matter and tau identification in $\nu\tau$ CC interactions	TPC with sub-millimeter pitch for direct dark matter and tau neutrinos.
Improving Large LArTPC Performance Through the Use of Photo-Ionizing Dopants	Photo-ionizing dopants to convert scintillation into directional ionization; signal enhancement, avoid anti-correlations of scint. vs. ionization, linear detector response.
Development of LArTPC Vertical Drift Solutions with PCB Anode Readouts for DUNE	Vertical drift design with PCB anode charge readout. ARAPUCA light detector on the cathode with optical fiber readout and power over fiber.
Low Background kTon-Scale Liquid Argon Time Projection Chambers	Precise timing photon detectors for proton decay (p->Kv) in a LArTPC.
Precision Calibration of Large LArTPC Detectors	Calibration strategies for large LArTPCs.
High-pressure xenon gas time-projection chambers for neutrinoless double-beta decay searches	R&D for HP gas xenon TPC for 0vbb. Replace PMTs with SiPMS (to reduce backgrounds) and explore gas mixtures to reduce diffusion.
Electron multiplication in liquid argon TPC detectors for low energy rare event physics	Charge amplification on LAr. Exploiting the different anodes geometry to quantify gain at different strengths of the electric field
Scintillating and Quenched Gas Mixtures for HPGTPCs	Systematic studies of gas mixture of argon, xenon, nitrogen, etc for HPGTPC for neutrino detection and dark matter searches.
Data Acquisition and Trigger Enhancements for Low-Energy Events in DUNE	Development of intelligent data selection tools and algorithms for enhancing physics program of DUNE. Target low energy (~MeV) single interactions for solar neutrinos, supernovae, astrophysics, and BSM searches.
Applications for Underground Argon	The Global Argon Dark Matter Collaboration (GADMC) is developing facilities for the extraction and purification of underground argon (UAr), which is depleted in 39Ar. Applicable in neutrinos for CEvNS, 0vbb, and DUNE.
The Neutrino Physics program of the Global Argon Dark Matter Collaboration	Neutrino program of the global argon Dark Matter collaboration. Multiple detectors can detect SN, CNO, ^{8}B, v00b decay with Xe doping in LAr
Pixels for charge+light in LArTPCs	Pixels for charge+light in LArTPCs
An R&D Collaboration for Scalable Pixelated Detector Systems	Scalable pixelated detector for neutrino and dark matter with LAr
Q-Pix: Kiloton-scale pixelated liquid noble TPCs	Qpix pixels for large-scale TPCs
Fast Simulations for Noble Liquid Experiments	Optimization of MC simulation for supercomputers to support several noble liquid experiments
NEST, The Noble Element Simulation Technique:	multi-collaboration effort LUX, XENON, nEXO, RED, COHERENT, DUNE, SBN, MicroBooNE, ICARUS, Global Argon; Pool of world data on techniques (light yield, charge yields), interactions, broad physics reach
Wire-Cell Toolkit	Wire-Cell Toolkit software

New Detectors and R&D: “Photon-based” Detectors

TITLE	Description
Cherenkov/scintillation separation via spectral photon sorting with dichroicons for next-generation neutrino detectors	Dichroicon technology used to identify pure Cerenkov photons outside a scintillation spectrum
Alternative Design for Large Scale Liquid Scintillator Detectors: Stratified LIquid Plane Scintillator (SLIPS)	SLIPS --- floating liquid scintillator on glycol to save PMT costs, reduce external backgrounds, broad program including neutrinoless double beta decay
ANNIE Detector R&D	Upgrade of ANNIE detector with WbLS and add more LAPPDs for new neutron measurements.
Neutrino Physics and Nuclear Security Motivations for the Continued Development of Organic Scintillators with Pulse Shape Discrimination Capability and 6 Li-doping	Development of PS plastic scintillators doped with ^{6}Li for nuclear security motivations
An Application of Pulse Shape Sensitive Plastic Scintillator - Segmented AntiNeutrino Directional Detector (SANDD)	Development of PS plastic scintillators doped with ^{6}Li or ^{10}B to discriminate neutrons and gamma-ray
A kiloton-scale water-based liquid scintillator detection concept for the Advanced Instrumentation Testbed in Northern England	kton-scale anti-ν_e detection for the purpose of nuclear non-proliferation. Monitoring of nuclear power plant 25km away in a underground facility.
A Method to Load Tellurium in Liquid Scintillator to Study Neutrinoless Double Beta Decay	SNO+ collab. A method to dilute Te(OH)6 and butanediol with DDA in organic LS for ν00β decay
THEIA : Water-based Liquid Scintillator	Technology to separate Cher- and Scintilight. Detection of geo-nus, anti-ν_e, solar neutrinos, beam neutrinos.
A 50 Ton Scale Water Cherenkov Test Platform in a Charged Particle Test Beam	Studies of performance and response of different detectors, Gd loading and WbLS, and calibration.
Antineutrino detection at THEIA	Large scale novel detector with the characteristic to discriminate cerenkov from scintillation light. Photon detector PMT or LAPPDs and Dichroicons. Detections of geo-neutrinos and anti-ν_e neutrinos.
Encapsulation of Photosensors in kton--Mton Scale Neutrino Detectors	Encapsulation of photosensors in kton–Mton neutrino detectors to prevent backgrounds, provides chemically inert gaseous environment, enabling deployment of calibration devices. Work planned for AIT–NEO
Analog Photon Processor ASIC	Analog Photon Processor: ASIC for photon sensors (low photon rate) focusing on Nphotons, timing. Motivation: cost, dynamic range, higher precision, analysis time.
Spectral Photon Sorting With The Dichroicon	Dichroicon: Discrimination of scint/Cher light, PID, dichroic Winston cones+PMTs, SiPM or LAPPD; functionality demonstrated with prototypes, broad application, liq. scint + water-based liq. scintillator
Chroma Photon Ray Tracer for Large-Scale Detectors	Fast Optical MC simulation with massive parallel calculation inside GPU
The RAT(-PAC) simulation and analysis code base	Open source GEANT4 toolkit that offer to simulation capability and analysis tools for high precision event modeling, evaluation and characterization from small setups to large scale detectors.
LiquidO: a Novel Approach to Detecting Neutrinos	Neutrino detector with opaque scintillator and optical fibers allowing imaging of the events down to MeV
3D-projection Scintillator Tracker (3DST) in SAND, a DUNE Near Detector Subsystem	3DST/SAND --- pixelated liquid scintillator, neutron detection capability
CHESS	Test facility for fast photodetectors and LS properties, for future large detectors such as THEIA.

New Detectors and R&D: Low-threshold ν detection

TITLE	Description
COHERENT LOI 5: Instrumentation Development	CEvNS with different technology: LAr detectors, High-purity Ge detectors, CsI(Na)
Towards Directional Nuclear Recoil Detectors: Tracking of Nuclear Recoils in Gas Argon TPCs	Gaseous argon TPCs to track nuclear recoils down to 10-100 um. Provides directionality - key feature. GEM-based GAr TPC.
Magnetic Microcalorimeters for CEvNS Detection	MMC for CEvNS, for sterile, non-standard interactions, neutrino magnetic moment,
Neutrino Physics with Noble Liquid Bubble Chambers	Liquid Xenon bubble chamber, sub-keV threshold for CEvNS detection, threshold goal: 100eV; prototype demonstrated 0.5keV threshold; 10kg detector under construction
Far-Future COHERENT physics program at the SNS	COHERENT far future: precision physics at lowE, low threshold to explore magnetic moment and light mediator searches, Ge detectors, cryogenic scintillators; large monolithic detectors.
Noble Liquids for the Detection of CEvNS from Artificial Neutrino Sources	Liquid noble detection of CEvNS with 100kg scale DM detectors at the SNS or reactors, physics: new physics with CEvNS + characterization of detectors for solar neutrino and DM detection beyond the neutrino floor
Reactor Neutrino Detection Experiment using Skipper CCDs.	Construction of a short-baseline neutrino program based on Skipper Charge Coupled Devices (Skipper-CCDs) at a nuclear reactor facility. Very low energy threshold ~eV.
CYGNUS: A nuclear recoil observatory with directional sensitivity	Direct WIMP detection using MPGDs – Solar ν
Cryogenic Carbon Detectors for Dark Matter Searches	Low thresholds dark matter searches with diamond or sic crystal - CEvNS
A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility	Direct WIMP detection – Solar ν / CEvNS
Phonon-Mediated KID-Based Detectors for Low-Mass Dark Matter Detection and Coherent Elastic Neutrino-Nucleus Scattering	KIDs (kinetic inductance detectors) for low-mass DM and neutrino coherent scattering.
BULLKID: Low-threshold Kinetic Inductance Detectors for neutrino and dark matter searches	DM and CEvNS. Detector based on the phonon-mediated KIDs.
Nuclear Recoil Calibration Techniques for Dark Matter and Neutrino Experiments	Overview and discussion on nuclear recoil calibration techniques

Novel Detectors (Not Already Included Elsewhere)

TITLE	Description
Neutrino Detector Spacecraft	Idea to run neutrino detector in space, detector operated unshielded in space, delayed timing pulse coincidence technique to reduce backgrounds, science goals: solar neutrinos with high rate in close solar orbit, DM searches without solar neutrino background in high orbits.
Neutrino / Dark Particle Detectors for the HL-LHC Forward Beam	FASER---emulsion or possible LArTPC detector for LHC neutrinos
An Andean Deep-Valley Detector for High-Energy Tau Neutrinos	TAMBO, a Deep-Valley air shower detector, possibly in Peru, for high-energy tau neutrino detection (1-100 PeV). Motivation is that it is complementary to ICECUBE etc that struggle with taus
Paleo Detectors	Direct WIMP detection in natural minerals
A next-generation cosmic-ray detector to study the physics and properties of the highest-energy particles in Nature	40,000km^2 cosmic ray detector

Advancing noble element/TPC technologies

- Drivers for new technologies and detectors
  - Enhancing low-energy capabilities
    - Astrophysics (solar, supernova νs)
    - dark matter
    - $0\nu\beta\beta$
  - Exploitation and enhancing rich particle ID and tracking information
    - Pixelization
    - Charge+light readout
  - Reducing data volumes
  - Improvements in precision via calibration and analysis

Advancing noble element/TPC technologies

- There are many examples of R&D directions aimed at enhancing the performance and physics reach of future noble element/TPC detectors:
  - Liquid and High-pressure gas TPCs
  - New charge readout technologies
    - Pixelated charge readouts, multiple approaches being explored
    - Multi-modal pixels (detect both charge and light)
    - Electron multiplication in TPCs to extend low-energy reach
    - Dual-readout TPCs (micron-scale tracking of positive ions)
    - Orientation – vertical drift with PCB readout
  - Techniques for scintillation light detection
    - Arapucas
  - Doping of noble liquids/gases
    - Xenon doping in argon to wavelength shift
    - Photo-ionizing dopants to enhance charge readout signals for low-energy physics
    - Underground argon
  - DAQ and new approaches to triggering
  - Better physics through analysis
    - Improving calibration techniques
    - Development of cutting-edge simulation, reconstruction, and analysis techniques
    - Use of HPC and advanced algorithms to analyze huge datasets

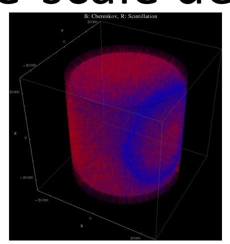
“Photon-based” ν Detectors

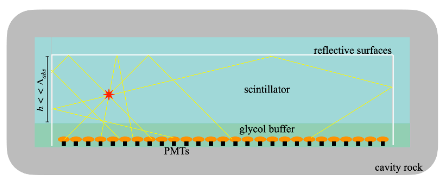
- Drivers for new technologies and detectors
  - Very broad physics programs
    - Long-baseline oscillations
    - Low-energy solar neutrinos
    - Supernova burst diffuse supernova background neutrinos
    - Reactor and source antineutrinos and neutrinos
    - $0\nu\beta\beta$
  - Exploitation of Cherenkov and scintillation light in “hybrid detectors”
    - Low energy background reduction (e.g. solar ν pointing)
    - High-energy background reduction (e.g., detached vertices for π^0 production and decay)
  - Very large-scale detectors for high-mass requirements
    - Nucleon decay
    - Astrophysical and Atmospheric νs
  - Cost reduction
    - Scaling up for $0\nu\beta\beta$ to normal hierarchy

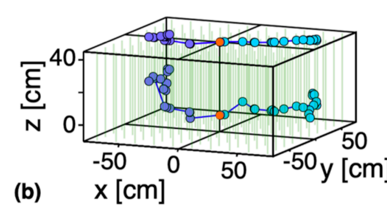
“Photon-based” ν Detectors

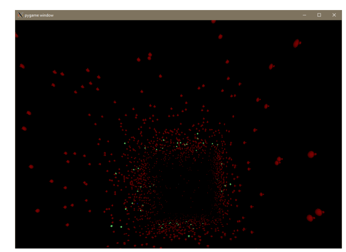
Very broad range of physics targeted: from ~10 keV to ~10 GeV

- Monolithic or segmented
- Future ν detectors enabled by:
  - New photon sensors (HQE and fast PMTs, SiPMs, LAPPDs)
  - New photon collectors (Arapucas, dichroicons, lenses)
  - New materials (slow/fast fluors, “milky” scintillators, water-based liquid scintillators)
  - New “loading” approaches (Gd, Te, Xe, Li…)
  - Advances in computing and simulation (GPU ray-tracers, machine learning, etc.)
- Many large-scale prototypes
  - ANNIE, NuDOT, EOS, BNL 30 T
- Many large-scale detector ideas
  - Theia
  - LiquidO
  - SLIPS
  - Artemis









“Photon-based” white paper draft will serve as basis for relevant NF10 report section

Other relevant white papers will be submitted (e.g. Theia white paper)

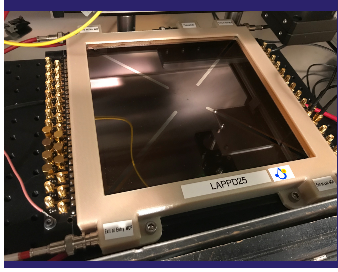
Particular interest in hybrid “Cherenkov/scintillation” detectors…

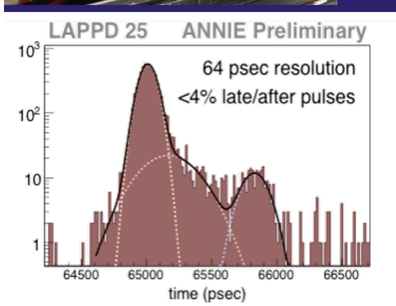
Hybrid Scintillation/Cherenkov Detectors

Multiple independent handles achieve:

Many new technologies for discriminating "chertons" from "scintons"

LAPPDs

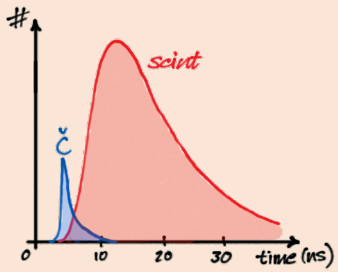




Timing

"instantaneous chertons" vs. delayed "scintons"

→ ns resolution or better

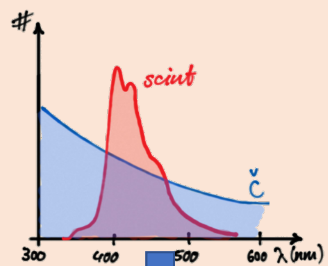


M. Wurm

Spectrum

UV/blue scintillation vs. blue/green Cherenkov

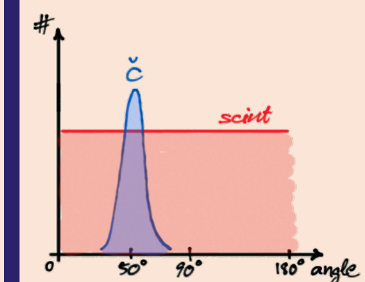
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle

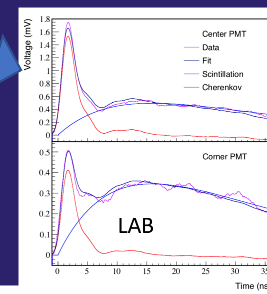
→ sufficient granularity

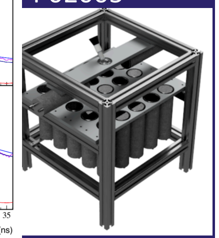


- **90% purity for Chertons**
- **Little loss of scintons**

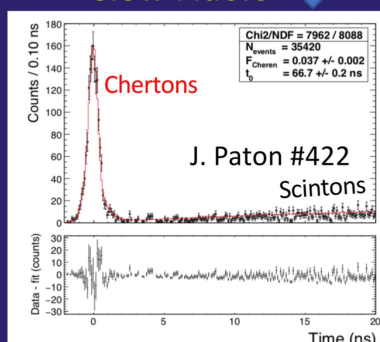
FlatDot measurements

Gruszko et al, JINST 14 (2019) 02, P02005



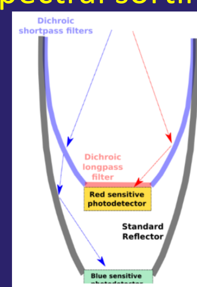


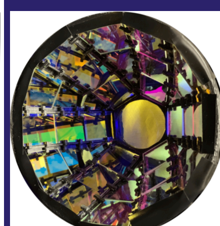
Slow Fluors

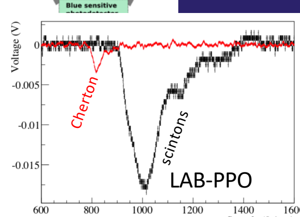


Biller, Leming, Paton NIMA 972 (2020) 164106

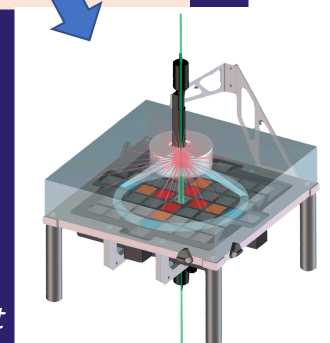
Spectral sorting--Dichroicons







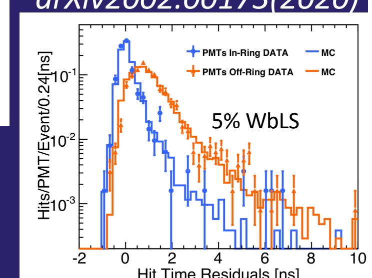
Kaptanoglu et al, PRD 101 (2020) 7, 072002



Caravaca et al, EPJC (2017) 77:811

CHESS Measurements

Caravaca et al, arXiv2002.00173(2020)



“Photon-based” ν Detectors White Paper

Contents

Low-Threshold Neutrino Detectors

✓ **Common challenges of low-energy neutrino detectors**
- Improving **resolution** and threshold
- Understanding and rejecting **backgrounds**
- Increasing target mass and detector **scalability**
- Establish low-energy **calibration**

1. **The eV frontier of neutrino detectors**
   - Cryogenic particle detectors for CEvNS
   - CCD-based detectors for CEvNS
   - Detectors for neutrino mass
   - Future detectors for relic neutrinos
   - New detector concepts
2. **Optimized "conventional" detectors**
   - HPGe detectors
   - Scintillation detectors
   - Bubble chambers
   - Gaseous detectors
   - Liquid noble gas detectors
3. **Dark Matter detectors for solar neutrinos**
   - Multi-ton liquid noble detectors
   - Large-scale cryogenic detectors

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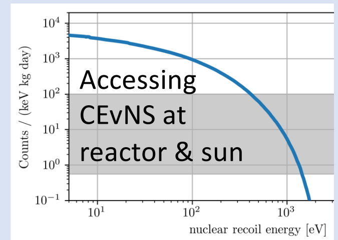
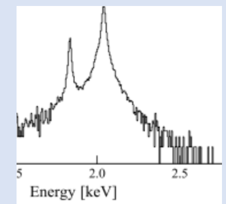
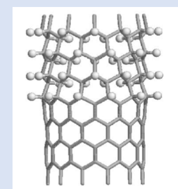
Physics drives detectors towards the eV scale…



Precise measurements of endpoints



Future detectors will go to meV’s



Applications

Neutrinos for Society !

Low-Threshold Neutrino Detectors

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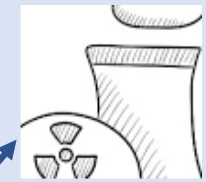
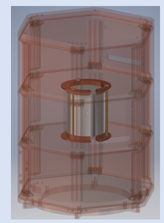
Challenging backgrounds

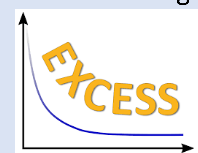
moving detectors above ground





Advanced Passive and active shielding required!

"The challenge"



Workshop series, Next: Feb15-17

https://indico.scc.kit.edu/event/excess2022

Low-Threshold Neutrino Detectors

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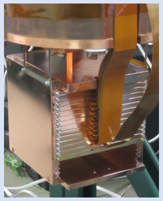
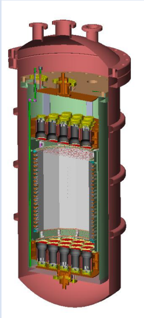
Exploiting full physics potential requires scalability of next–gen detectors

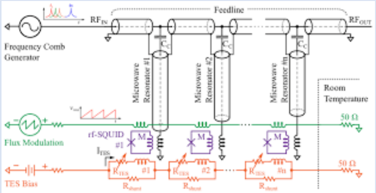


Use "mass products"

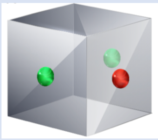
Optimizing commercial detectors

Using Multi-ton DM detectors





Use technologies ready for multiplexing



Passive neutrino detectors !?

Low-Threshold Neutrino Detectors

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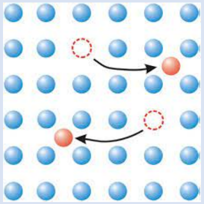
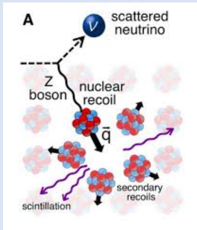
3. **Dark Matter detectors for solar neutrinos**
   - Multi-ton liquid noble detectors
   - Large-scale cryogenic detectors

Understanding the low-energy detector response

Low-energy nuclear recoils



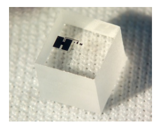
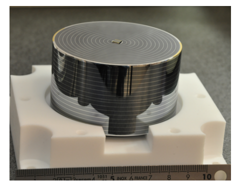
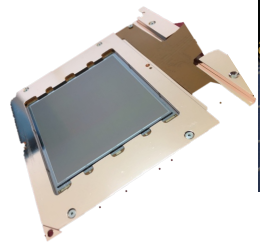
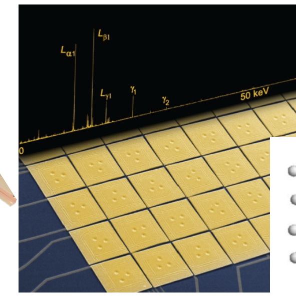
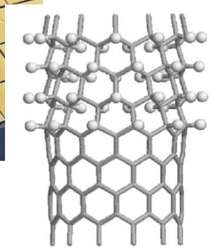


Secondary processes: **Quenching**

Low-Threshold Neutrino Detectors

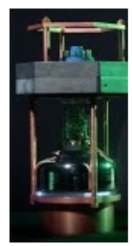
✓ **Common challenges of low-energy neutrino detectors**

- Improving **resolution** and threshold
- Understanding and rejecting **backgrounds**
- Increasing target mass and detector **scalability**
- Establish low-energy **calibration**

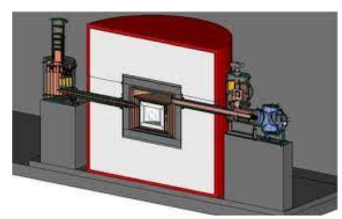
1. The eV frontier of neutrino detectors

- Cryogenic particle detectors for CEvNS
- CCD-based detectors for CEvNS
- Detectors for neutrino mass
- Future detectors for relic neutrinos
- New detector concepts




2. Optimized "conventional" detectors

- HPGe detectors
- Scintillation detectors
- Bubble chambers
- Gaseous detectors
- Liquid noble gas detectors

3. Dark Matter detectors for solar neutrinos

- Multi-ton liquid noble detectors
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NF10 Report Outline

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