European Strategy for Particle Physics

PARALLEL 6 / **DETECTOR TECHNOLOGIES**

Technologies for neutrino and dark matter experiments

Inés Gil-Botella (CIEMAT), Andrea Giuliani (IJCLab)

23-27 JUNE 2025 Lido di Venezia

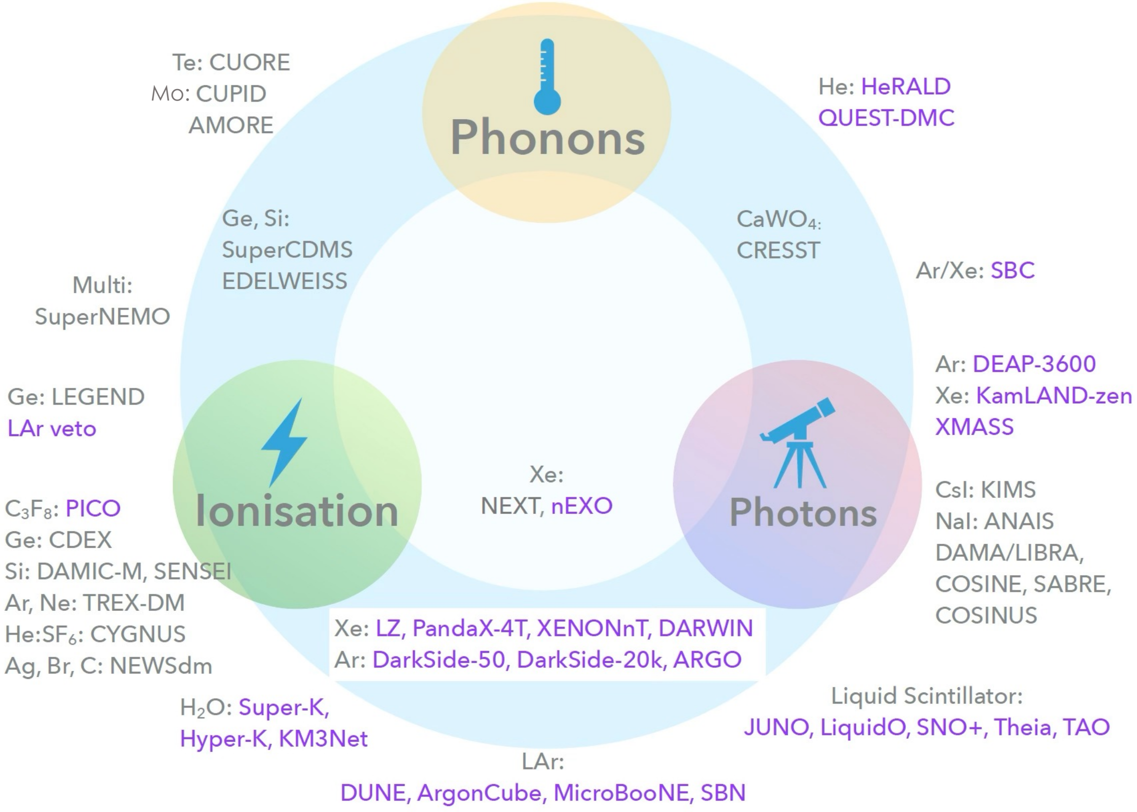
Summary of submissions for neutrino & rare event search detectors (20 + 5)

European Strategy for Particle Physics

PHYSICS TOPIC	#	SHORT TITLE	STATUS	TECHNOLOGIES	DRD
0nbb	197	AMoRE	Running	Macro-bolometers	DRD5(?)
	87	NEXT	Running	High pressure gas TPC	DRD1
	125	SNO+	Running	Photodetectors - liquid scintillators	DRD2
CEvNS	264	CONNIE	Running	CCDs, Skipper CCDs	
	253	COHERENT	Running	CsI, LAr, Ge diodes	
	182	CONUS	Running	Large Ge diode	
Direct neutrino mass	225	Project-8	Future	CRES + microwave receivers	DRD5 (?)
	132	KATRIN	Running	SDD, MMC, ToF (CRES, CCC)	DRD3, DRD5 (?)
	258	ECHo	Running	Micro-bolometers	DRD5(?)
	181	HOLMES +	Running	Micro-bolometers	DRD5(?)
Neutrino oscillations & astro					
Accelerator neutrinos	116	T2K	Running	Photodetectors - Cherenkov	DRD2
	232	SBND	Running	Liquid Argon TPC	DRD2
	119	DUNE	In prep	Gaseous and liquid detectors	DRD1, DRD2
	151	ESSnuSB	Future	WC, super fine-grained scint, emulsion	DRD2
Non-acc neutrinos	263	THEIA	Future	Fast photodetectors - Hybrid WbLS	DRD2, DRD4
	36	JUNO	Ready	Liquid scintillator	DRD2
	53	P-ONE	Future	Fast photodetectors - Cherenkov	DRD2, DRD4
Dark matter and axions	268	DarkSide	Running	Liquid Ar TPC	DRD2
	54	GrAHal	Running	Cryogenic microwave receivers	DRD5
	260	QSDMGW		Quantum microwave detectors	DRD5
	175	XLZD	Future	Liquid Xenon	DRD2
Neu xsec & BSM in colliders	23	FASER	Running	Scint tracking calo, Si track, emulsion	
	63	SND	Running	Si microstrips, emulsion	
	171	NA61/SHINE	Running	Si tracking detector	
	266	3D Pixel Calo	R&D	Metal loaded opaque LS	DRD2

+ other submissions from **astroparticle physics communities** and **countries** with explicit mention to neutrino & rare event search detectors

Detector R&D roadmap for neutrinos & rare event searches



From ECFA Detector R&D Roadmap (oct 2021)

PHYSICS TOPICS:

- Accelerator-based neutrino oscillation experiments
  - CP violation, neutrino mass ordering, precise measurement of oscillation parameters
- Non-accelerator neutrino oscillation experiments (solar, atmospheric, astrophysical neutrinos)
- Neutrinoless double beta decay search: Majorana neutrinos, lepton number violation
- Direct dark matter search experiments
- Direct neutrino mass measurement
- CEvNS

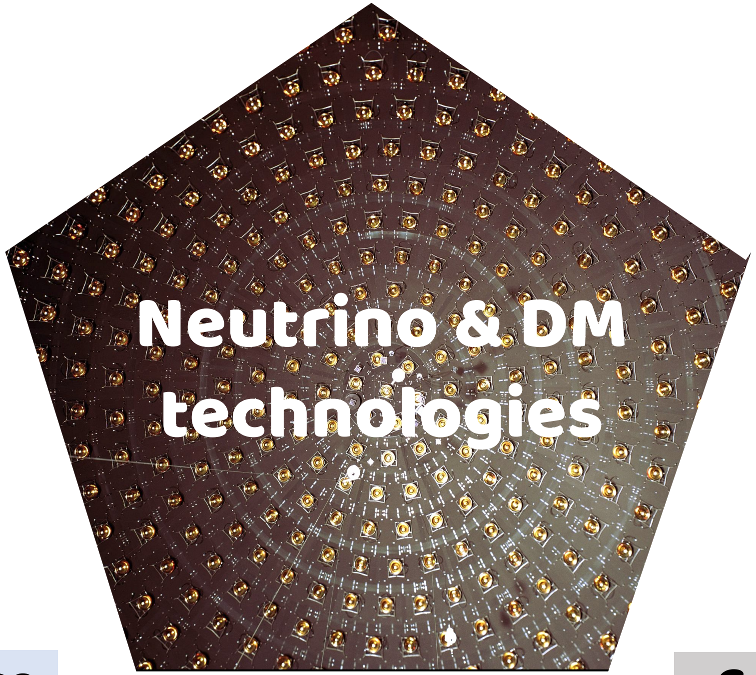
Detection challenges & requirements

- For **neutrino** detection:
  - Very large target volume (~kton)
  - Usually underground locations - low backgrounds
  - Identification of neutrino flavor → different neutrino interactions
  - Precise measurement of the energy and final state particles + neutrino direction
  - Low energy thresholds (~MeV)
- For **dark matter** detection:
  - Signal is very low (signature is low recoil energies ~eV to keV)
  - Signal is very rare (<1 event/(kg y) at low masses and < 1 event/(t y) at high masses
  - Overwhelming background over signal: deep underground location and high radiopurity materials and target
- For **$0\nu\beta\beta$**:
  - Large mass of isotope, very low background, excellent energy resolution
- For **neutrino mass** measurement:
  - Excellent end-point energy resolution, background removal, systematic uncertainties on the source

Key neutrino & DM technologies

Liquid detectors: **WC, LSc, LAr/LXe**
(neutrino oscillations, astro, $0\nu\beta\beta$, DM)

Spectrometers & **RF cavities**
(ν mass, DM)



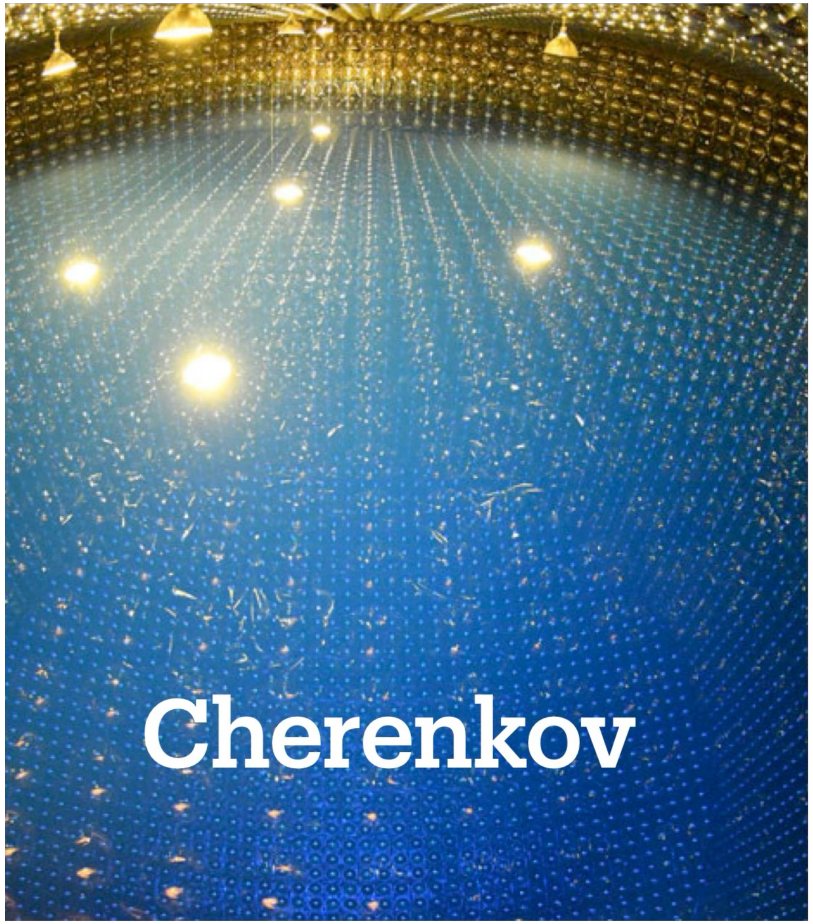
Solid-state detectors
Bolometers, semiconductors, CCDs
($0\nu\beta\beta$, ν mass, CEvNS, DM)

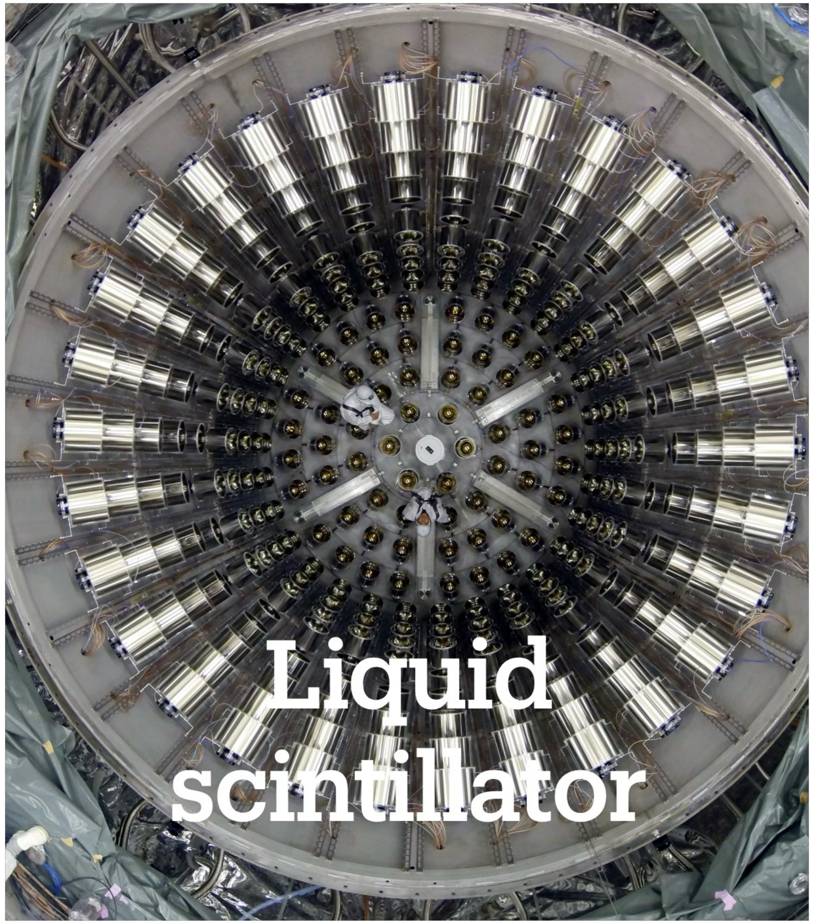
Tracking & **emulsions**
(ν cross-sections)

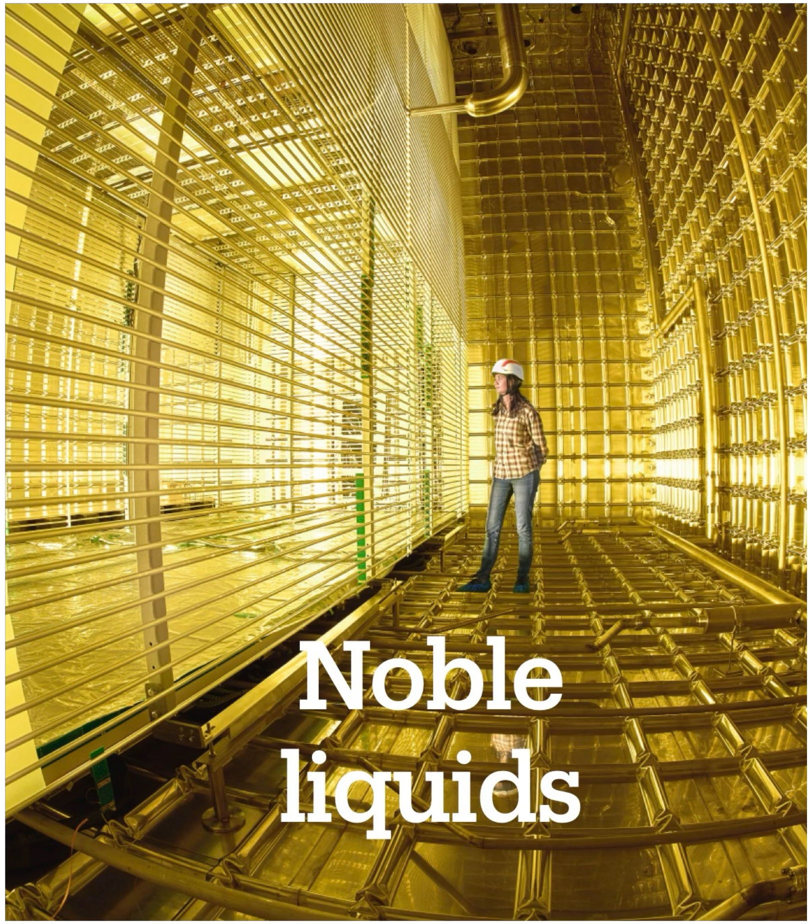
Gas detectors
($0\nu\beta\beta$, ν ND)

Liquid detector technologies

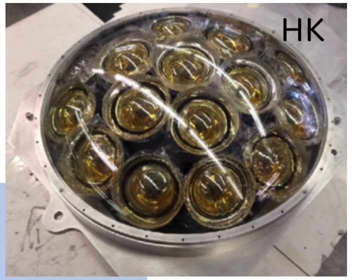
for accelerator-based neutrinos, non-acc neutrinos, $0\nu\beta\beta$, DM experiments

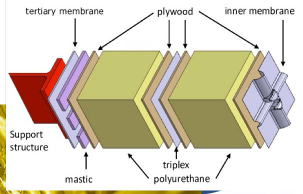


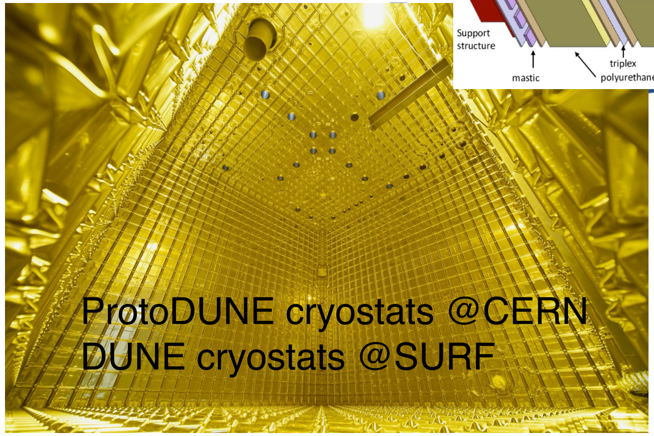




Liquid detectors



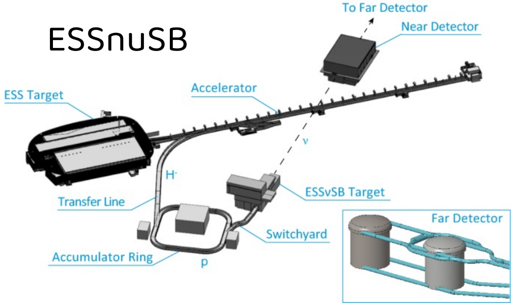


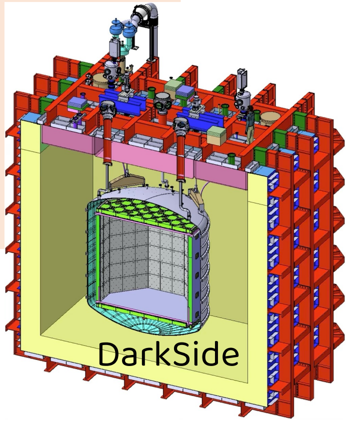


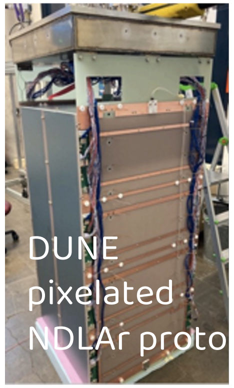
- **State of the art** (running or under construction)

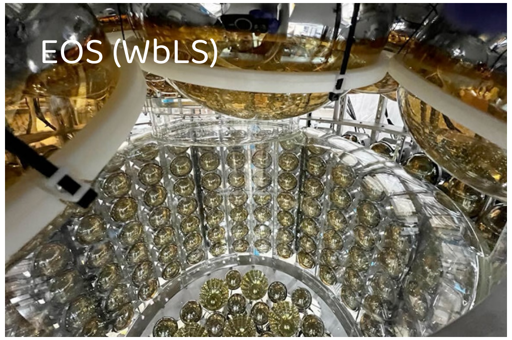
  SK, HK, JUNO, DarkSide, XENON, SBN, DUNE Phase I, KamLAND-Zen, SNO+, ...
  - Intense R&D on photodetection (high QE and time resolution)
  - Gd-loaded WC to enhance neutron tagging
  - Large cryostats: Technological breakthrough from naval industry led by CERN
  - Pixelated readout, cold-electronics developments
- **Challenges/Detector R&D needs**

  (acc νs+astro) DUNE Phase II, ESSnuSB, THEIA, P-ONE, (DM) ARGO, XLZD
  - Very large mass (~kton)
  - Scalability of readout
  - Efficient and fast photodetectors
  - Increase of light yield and backg reduction
  - Metal loaded LS, opaque LS, hybrid WbLS
  - Liquid purification techniques
- **DRDs**:
  - DRD2: Strategic R&D on future liquid detectors identified
    - 86 institutions, 17 countries, 205 members, 4 WPs and 3 WGs
  - DRD4: R&D on non-cryo photosensors

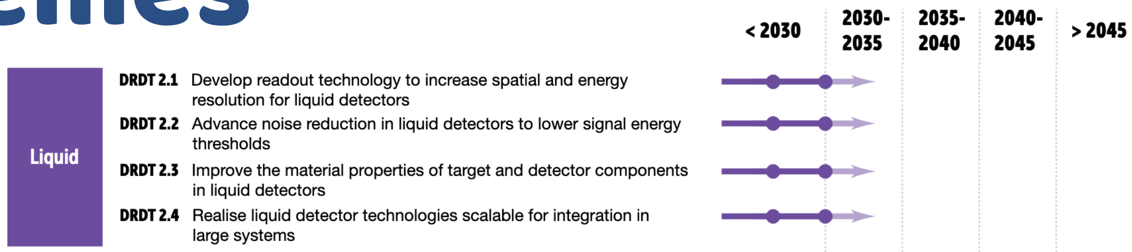








Liquid detector R&D Themes



- **DRDT 2.1 - Develop readout technology to increase spatial and energy resolution for liquid detectors.** Developments should achieve readout of more highly pixellated detectors with greater photon collection capabilities. Advancing liquid detector readout technologies towards greater quantum efficiency while still offering much higher granularity is a further objective.

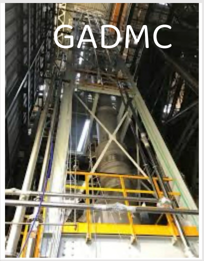
- **DRDT 2.2 - Advance noise reduction in liquid detectors to lower signal energy thresholds**. The expected performance of future liquid detectors requires R&D to achieve lower sensor and electronics noise, as well as developments to measure simultaneously more components of the energy partition: for example light, charge and heat.

- **DRDT 2.3 - Improve the material properties of target and detector components in liquid detectors**. The R&D on material properties for liquid detectors aim to improve the emission properties of the target, for example through doping of Xe in Ar, H in Xe, Gd in H20, and to achieve lower radiogenic backgrounds from the detector components, via target purification, material radioassay, and cryogenic distillation to change isotopic content.

- **DRDT 2.4 - Realise liquid detector technologies scalable for integration in large systems.** Dedicated developments should achieve applications of the previous DRDTs in future detectors ten to a hundred times larger, compared to the current state of the art, and allow coping with increased noise hit rates from detectors with sensor areas reaching 10, 100 and ultimately 1000 m2. This will have to proceed while addressing the step change in complexity, with decade-long construction, in underground or undersea environments, with handling of heat load, value engineering and industrial production.

Liquid detector challenges

European Strategy for Particle Physics



- Very large mass
- Radiopurity & backg mitigation (radioassay, novel materials, Rn fac)
- Target production and purification
- Large-area readouts

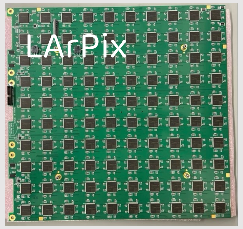
Scalability

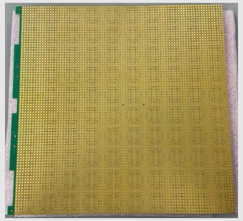
Charge readout

LIQUID DETECTORS

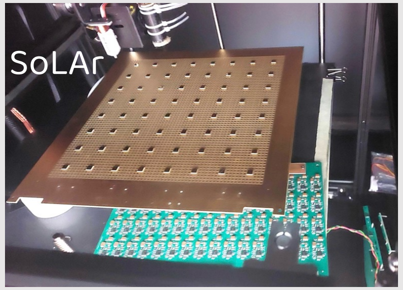
Light readout

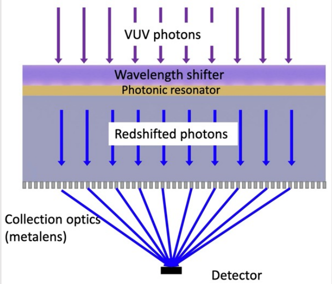
Target properties



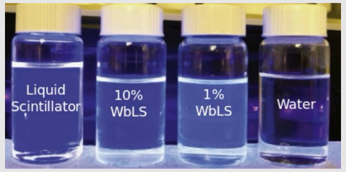


- Amplification of charge in liquid TPCs
- 3D imaging, lower power, lower pixel thresholds
- Multiple modality pixels
- Dual-phase optical TPCs

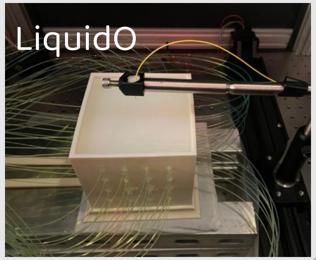




- Increase photodetection efficiency and collection
- WLS, reflectors, metalens
- Digital cryogenic SiPMs
- Power-over-fiber, Signal-over-fiber
- Cryogenic facilities for VUV sensor characterization



- Isotope loading of LS and WC (Te-loading, WbLS)
- Opaque LS
- Loading of noble liquids (Xe doping of LAr)

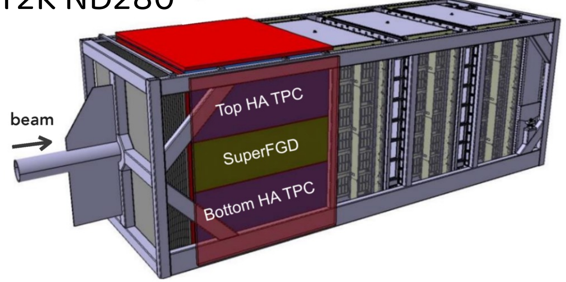


Gas detectors

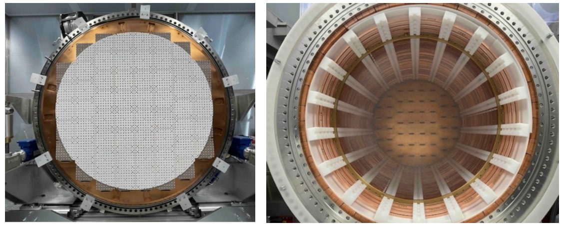
for LBL ND, $0\nu\beta\beta$ experiments

- **State of the art** (running)
  - Gas TPCs (T2K ND280 upgrade, NEXT-100)
- **Challenges/Detector R&D needs**
  - **DUNE ND-GAr**: high pressure magnetized gaseous Ar TPC
    - TPC amplification: MPGDs such as GEMs
    - TPC readout: SAMPA-based electronics
    - Efficient and low-noise readout for primary scintillation light
    - Optimization of gas mixtures
  - **NEXT**: High pressure gaseous Xe TPC
    - Scalability: from 100 kg at 15 bar to ton-scale (NEXT-HD)
    - Ba tagging: NEXT-BOLD R&D towards detecting single Ba2+ ions with high efficiency
- R&D in the context of **DRD1**
  - WP4: Tracking TPCs
    - R&D on IBF reduction, pixel TPC development, optimization of the amplification stage, mechanical structure, low power electronics and FEE cooling, gas mixture

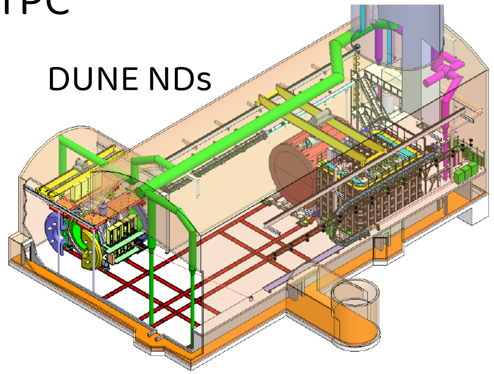
T2K ND280



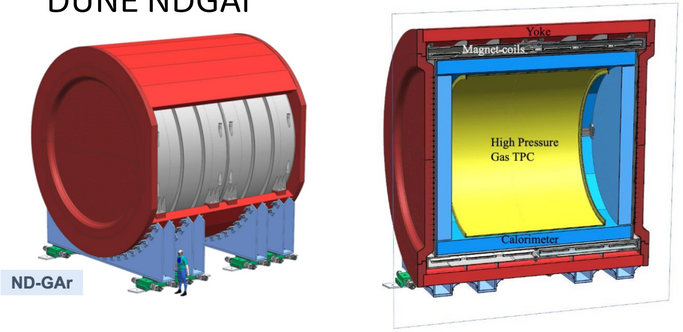
NEXT-100

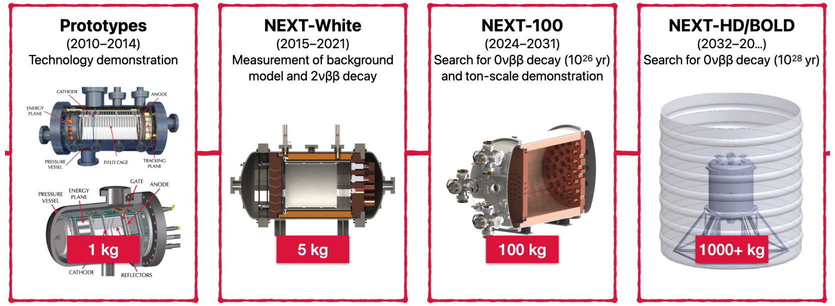


DUNE NDs



DUNE NDGAr





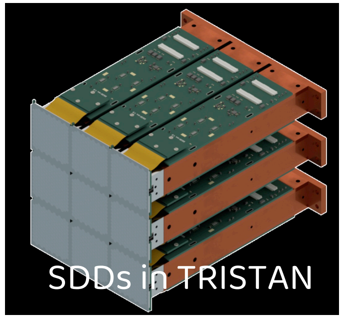
Solid-state detectors: state of the art

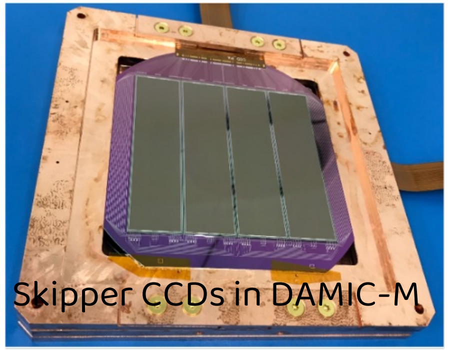
for $0\nu\beta\beta$, ν mass, CEvNS, DM experiments

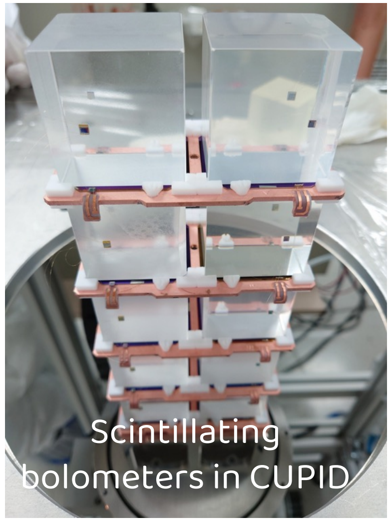
Solid-state detectors

- **Ionization**
  - ~1 eV mediating excitations
  - Room temperature or mild cryogenics
- **Phonons Quasi-particles**
  - < 1 meV mediating excitations
  - Extreme cryogenics (~10 mK)

Technologies	Projects (color code for physics topics)
HP Ge diodes	LEGEND, CONUS100, COHERENT (Ge-Mini)
Si drift detectors	KATRIN (TRISTAN)
Skipper CCDs	CONNIE, DAMIC-M
Crystal-based macro-bolometers	CUORE/CUPID, AMoRE, CRESST, TESSERACT, NUCLEUS, RICOCHET
MMC	ECHo, KATRIN++ (also → AMoRE)
TES	HOLMES (also → CRESST, TESSERACT, NUCLEUS, RICOCHET)


SDDs in TRISTAN


Skipper CCDs in DAMIC-M


Scintillating bolometers in CUPID

Extensive overlap among technologies and physics topics in a multifaceted scenario potentially fosters **cross-disciplinary contributions and transversal collaboration**

Solid-state detectors: challenges

- **Extreme radiopurity**
  - Surface events, gamma rays, cosmogenic isotopes, internal crystal contamination
- **Active background rejection**
  - Particle discrimination (electron vs nuclear recoils – alpha vs beta/gamma)
    - Hybrid detection in two channels: ionization + light; ionization + heat
    - Pulse shape discrimination (alpha vs beta/gamma, surface vs bulk)
- **Low threshold**
  - Sub-keV to few-eV required for CEvNS and light DM
- **Energy resolution**
  - Around 0.1 % at the MeV scale ($0\nu\beta\beta$) and at the keV scale (ν mass)
- **Scalability**
  - From few detectors to tens (DM), thousands ($0\nu\beta\beta$) or ten-of-thousands (ν mass) elements
- **Multiplexed cryogenic readout**
  - Needed for bolometric and calorimetric arrays based on TES and MMC (ν mass)
- **Integration with challenging experimental environments**
  - Near-reactor shielding (CEvNS), ultra-high vacuum (KATRIN), deep undergr labs (DM, $0\nu\beta\beta$), dilution refrigerators (CEvNS, DM, $0\nu\beta\beta$)

Solid-state detectors: R&D directions

European Strategy for Particle Physics

New sensor development

- TES, MMCs, KIDs – overlap with quantum sensors (all physics topics)

Enhancement of detector platforms (CEνNS, DM)

- NUCLEUS: eV-threshold bolometers
- RICOCHET: Ge bolometers with hybrid readout (heat + charge)
- DAMIC-M: ultra-low noise Skipper CCDs (single electron detection)
- TESSERACT: multiple low-temperature technologies in the same environment

Advanced detector materials

- Crystals for bolometers containing $0\nu\beta\beta$ isotopes (Mo, Zr, Nd), low-background Si/Ge, CCDs (DM, CEνNS)
- Enhance scintillation in specific crystals for hybrid detections (heat + light) (CUPID)

Upgrade paths with solid-state arrays

- TRISTAN: pixelated Si SDD arrays for KATRIN's sterile neutrino program

Large-scale isotopical enrichment ($0\nu\beta\beta$)

- Extend centrifuge method (Zr, Nd)
- New technologies (Laser separation, scale up Ion Cyclotron Resonance technique)

Low-vibration dilution refrigerators

- Large volumes (several m^3) at mK temperature with vibration isolation ($0\nu\beta\beta$, DM, CEνNS)
  → Technological synergy with superconductive Qubit developments

Spectrometers, RF cavities, spin-based detectors: state of the art

for ν mass, DM, dark sector, (GW) experiments

- **Spectrometers**: KATRIN - European flagship effort to determine the absolute neutrino mass using a molecular tritium source and a MAC-E filter for an integral spectrum
- **Spin-based detection:** magnetic signals induced by exotic fields on spin systems - CASPEr, GNOME
- **Radiofrequency (RF) cavities** in a magnetic field and **RF receivers** to detect **extremely weak EM signals** usually via a low-noise cryogenic quantum amplifier

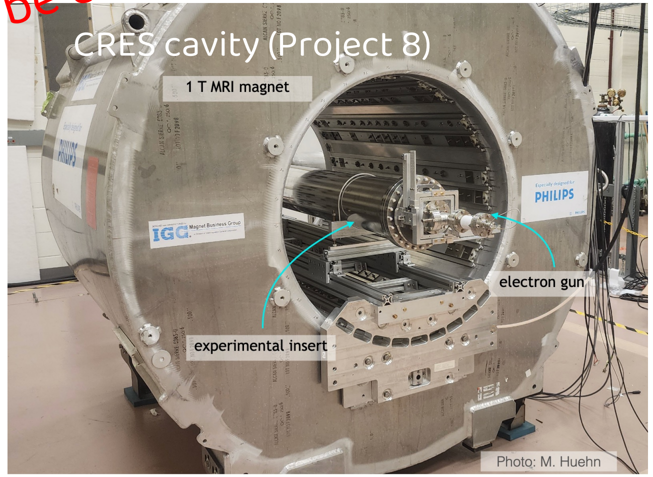
→ Beyond KATRIN for neutrino mass and for Axions-ALPs, DM, and primordial Gravitational Waves (kHz-GHz)

Physics objective	Detection Principle	Signal Type	Key Role of RF
Neutrino mass (Project 8, KATRIN++)	Cyclotron Radiation Emission Spectroscopy (CRES)	RF from beta decay electrons	Frequency → electron energy
Axions, Dark Photons (GrAHal, RADES, SRF)	Axion → photon in B-field (Primakoff effect) Hidden photon–photon mixing in a resonator	Resonant photon signal Weak EM mode in cavity	Power spectrum → axion mass Resonance & noise suppression
Primordial GWs (MAGO, GravNet, RADES)	EM excitation via spacetime perturbations	Sideband or excess power	Sensitive phase/amplitude readout

Spectrometers, RF, spin-based: challenges & R&D directions

- **Cavities**
  - High-Q superconducting/hybrid cavity development under magnetic fields
  - Develop low-noise, high-Q superconducting materials for GHz-range operation
  - Reliable, low-loss tuning systems
- **Sensors/electronics**
  - Integration of Josephson Parametric Amplifiers and future single-photon sensors
  - CASPEr: Enhance spin polarization efficiency and quantum amplification techniques
  - GNOME: Optimize sensor synchronization and background discrimination algorithms
  - Advanced cryogenic and mechanical damping solutions
- **CRES and tritium source**
  - Scalable CRES-compatible magnet systems and precision frequency analysis
  - Atomic tritium source (for Project8 and KATRIN++)
    - Cryogenic systems for trapping and cooling atomic tritium (few mK)
    - Beamline and trap engineering for atomic tritium handling and injection

This R&D could be covered in DRD5

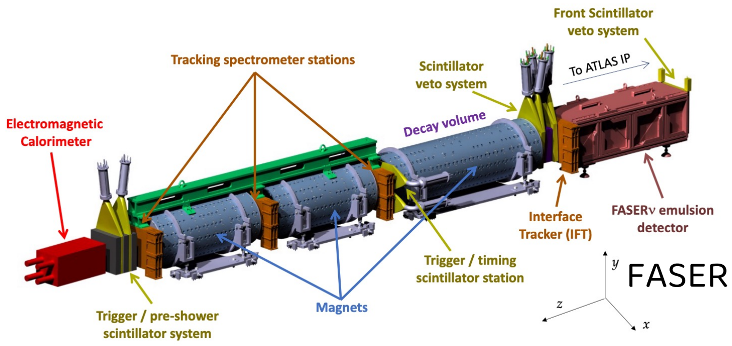


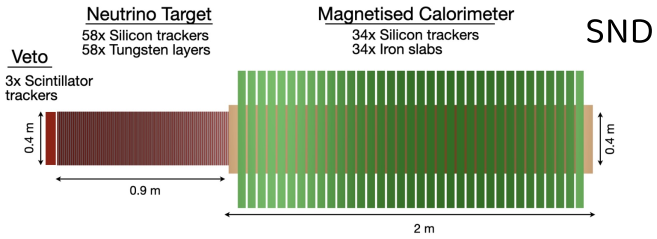
Tracking/emulsion detectors

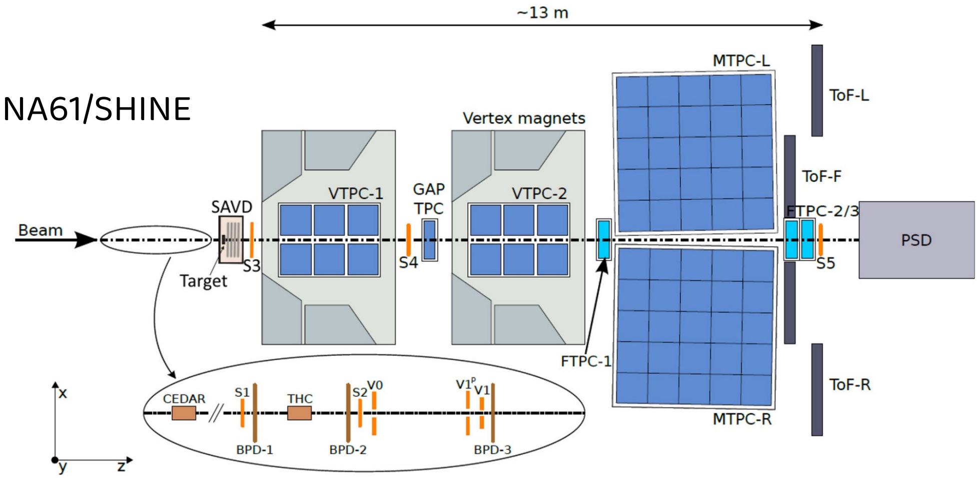
European Strategy for Particle Physics

for ν interaction measurements at colliders

- **State of the art** (running)
  - **FASER, SND** : TeV neutrinos from LHC
  - **NA61/SHINE**: Hadron production measurements at CERN SPS for neutrino flux predictions
- **Challenges/Detector R&D needs**
  - FASERν: upgrade detector for HL-LHC (or FPF)
    - high-granularity scintillator-based tracking calorimeters, high-precision silicon tracking layers & advanced emulsion-based detectors
  - SND: upgrade detector for HL-LHC
    - silicon-strips + magnetized calorimeter
    - crucial in the design for SHiP
  - NA61/SHINE: detector upgrade for Run4
    - New silicon tracking detector (+ new low-E beamline)
- Related **DRDs**
  - DRD1







CERN Neutrino Platform: unique infrastructure!

- It has been instrumental in enabling European participation in LBL neutrino experiments worldwide
- Crucial to advancing new technologies and planned R&D for neutrino detection and rare event searches
- Cryogenics system successfully developed and operated for years
- Hosting two 770-ton LAr TPCs in addition to large-size cold boxes and medium-size TPCs
- Test-beams available
- Strong technical team of experts
- Acting as a reference center for coordinated R&D activities and large-scale prototyping

Conclusions

European Strategy for Particle Physics

- **R&D on neutrino detectors and rare event search** experiments is crucial to enable fundamental research in particle physics beyond colliders
  - Technology developments need strong support from the particle physics community
  - DRDs are important to coordinate strategic R&D and share knowledge and facilities beyond individual experiments
- Important **technological challenges** ahead (promising R&D ongoing) related to:
  - Scalability
  - Increase spatial and energy resolution
  - Background control and mitigation
  - Innovative quantum sensors
- **Connections with industry** established (photodetectors, cryostats…)
- **Specialized research infrastructures** are needed for R&D on neutrinos & DM detectors
  - CERN Neutrino Platform is a unique R&D facility that has enabled the European participation in leading long-baseline neutrino projects in US and Japan
  - It is crucial to continue (and expand) the CERN Neutrino Platform to develop the R&D program needed for the future experiments
- Aim at exploiting **synergies in detector instrumentation with APPEC**
  - Complementarity with other infrastructures and underground laboratories

Thanks!

Inés Gil-Botella (CIEMAT), Andrea Giuliani (IJCLab)