

Cryogenic detectors in HEP

HEPIC

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June 26th, 2025

Why go cryogenic?

Low energy threshold

In comparison to radiation-hard collider detectors (TeV+), weakly interacting massive particle (WIMP) searches (neutrino and dark matter) need significantly lower energy thresholds (keV to GeV).

High density

The sensitivity of neutrino and dark matter (DM) searches is statistics limited. Therefore, the target mass in a detector should be maximal.

Why go cryo?

Conventional target materials that must be cryogenic - Ge, liquid noble gasses.

Lower noise readout - Johnson–Nyquist noise $Q_n = (k_B TC)^{1/2}$

At sub kelvin temperatures, new range of “exotic” materials involving superconductors (SC) and highly sensitive SC readout.

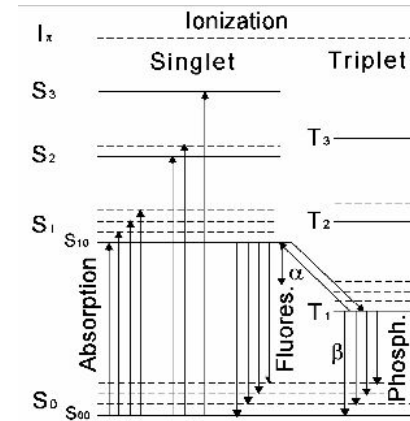
Quantum computing “revolution” in technology - RF amplifiers, SQUIDs, etc.

Conventional HEP detectors

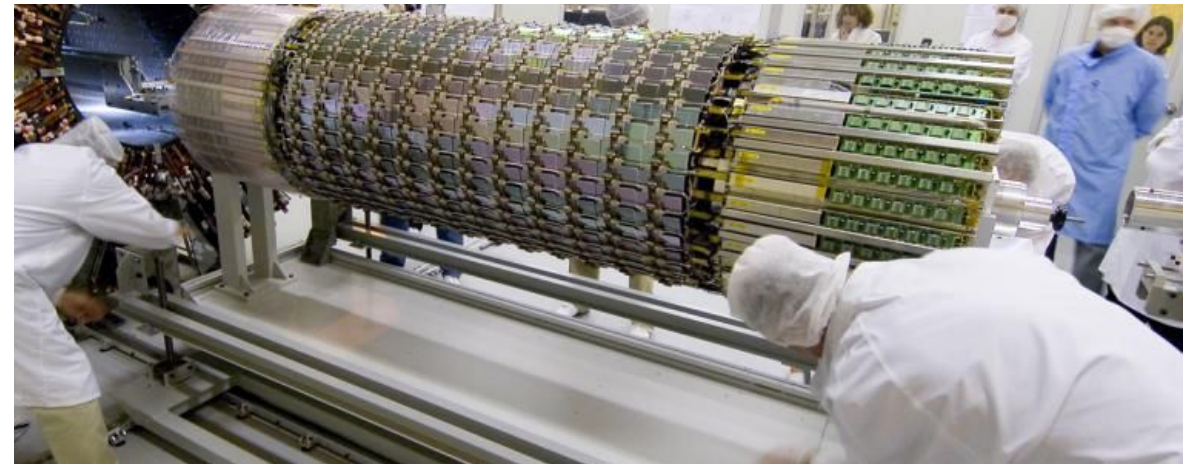
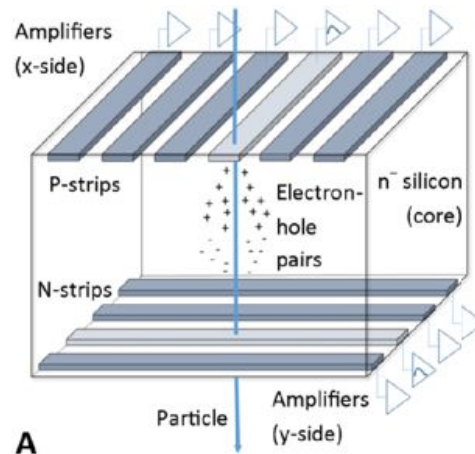
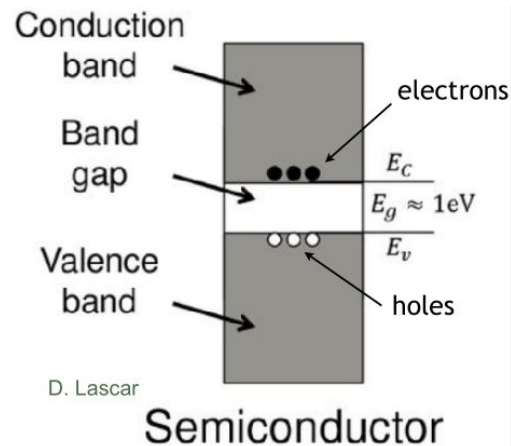
Scintillators: inorganic crystals (NaI, CsI, etc), organic liquids, plastics

Semiconductors (ionization) Si, Ge, CZT.

Noble gasses: (charge + light) Ar, Xe, Kr, Ne, He



Also: Cherenkov, bubble chambers, others



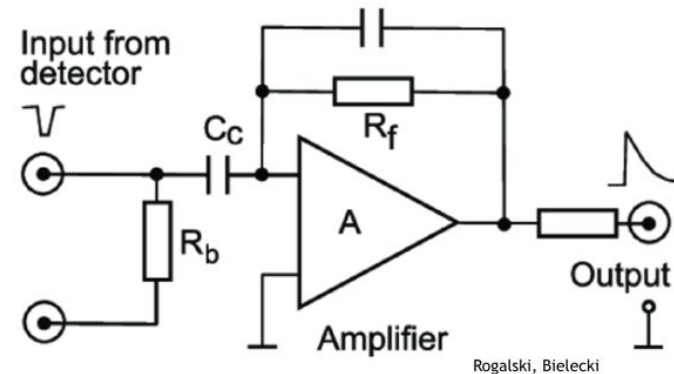
Readout (front end)

Evolution is towards higher channel density and signal processing at the sensor.

Charge readout noise is proportional to:

- C (Optimized Noise $\sim (C)^{1/2}$)
- $(\Delta f)^{1/2}$
- $(T)^{1/2}$
- Feedback & bias $R \sim (T/R)^{1/2}$

The field is now pushing to amplify and digitize in the cryogenic front end. Within power constraints



Nuclear Instruments and Methods in Physics Research A 480 (2002) 713–725



Prospects for charge sensitive amplifiers in scaled CMOS[☆]

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Cryogenic targets

Cryogenic (> 1 K)

- Semiconductors (Ge 77 K)
- Liquid nobles (Xe 165 K, Ar 85 K)

Millikelvin

- Low C crystals (weaker interlayer bonding along the c-axis, low phonon group velocities and low thermal conductance)
- Superconductors

Germanium detectors at 77 K

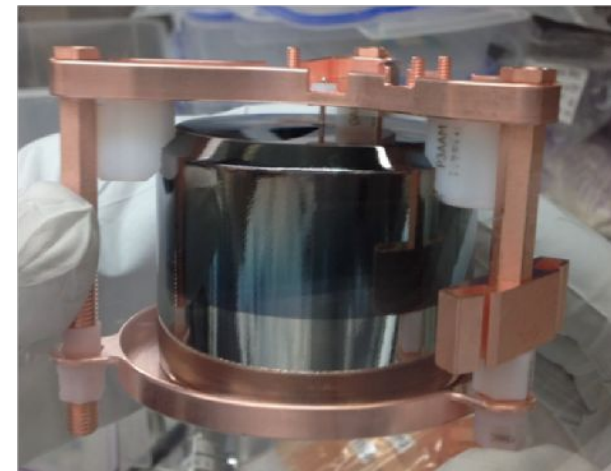
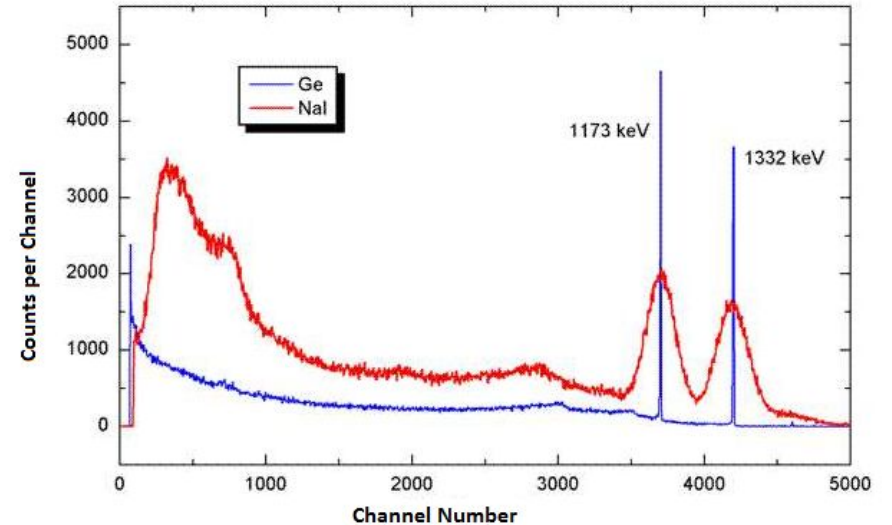
Higher Z than Si (32 vs.14) and density (2.3x).

77 K needed as the 0.67 eV band gap allows leakage current and noise from thermal excitations.

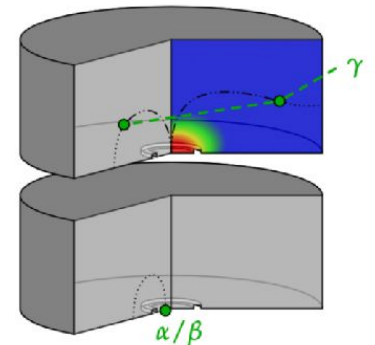
Best energy resolution between keV and MeV of any conventional detector.

A large cylindrical crystal with a small point-contact electrode minimizes C.

LEGEND Neutrinoless double beta $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$
(Ge immersed in a LAr shield)



Multi-site and surface events



Millikelvin calorimeters

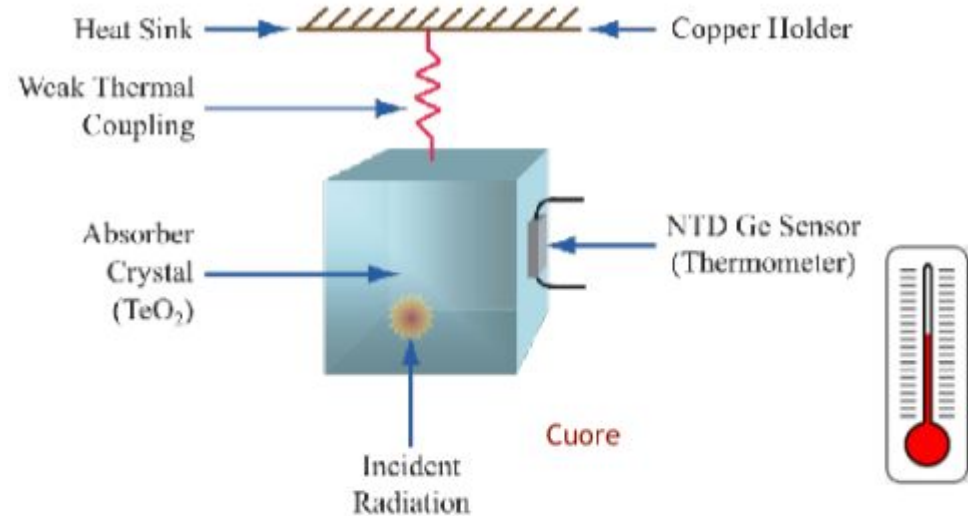
At temperature of 10 mK to 30 mK, energy depositions down to O (100) eV can be detected as a temperature increase, a bolometric detector.

Requires stiff crystals with very low heat capacity

Wide range of detector materials

Can combine with charge - Ge, Si

Can combine with scintillation - CaWO₄



$$\Delta T = \frac{E_{dep}}{C} \quad C_{insulator} \propto T^3$$

CUORE

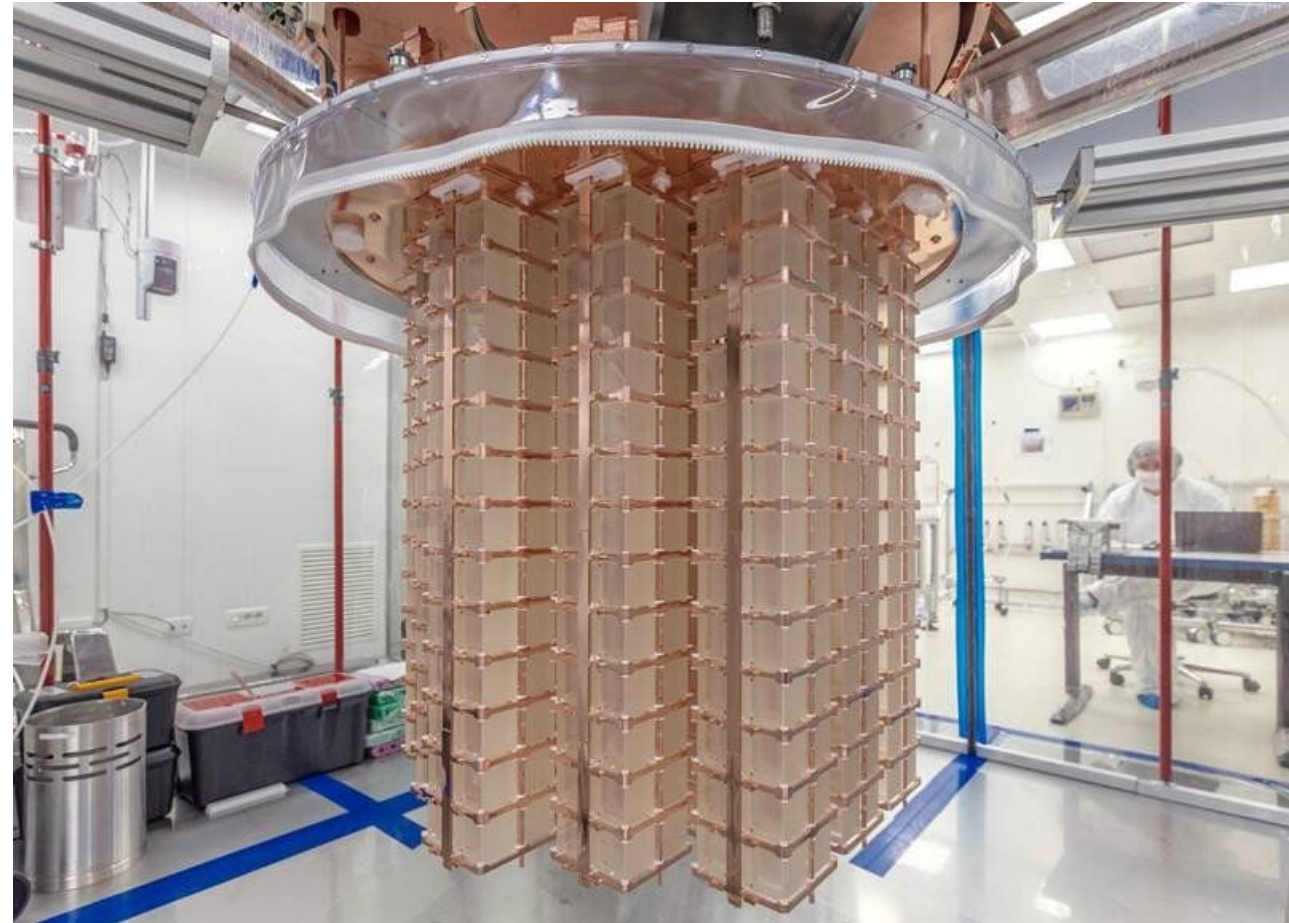
Neutrinoless double beta searches
sensitivity is limited by energy resolution
and isotope mass.

Need ~tonne of suitable double beta
decaying isotopes

In Cuore, cryogenic crystal ^{130}Te in
 TeO_2

Current version: 988 crystals, 741 kg.

This is example of very large number of
cryogenic detectors

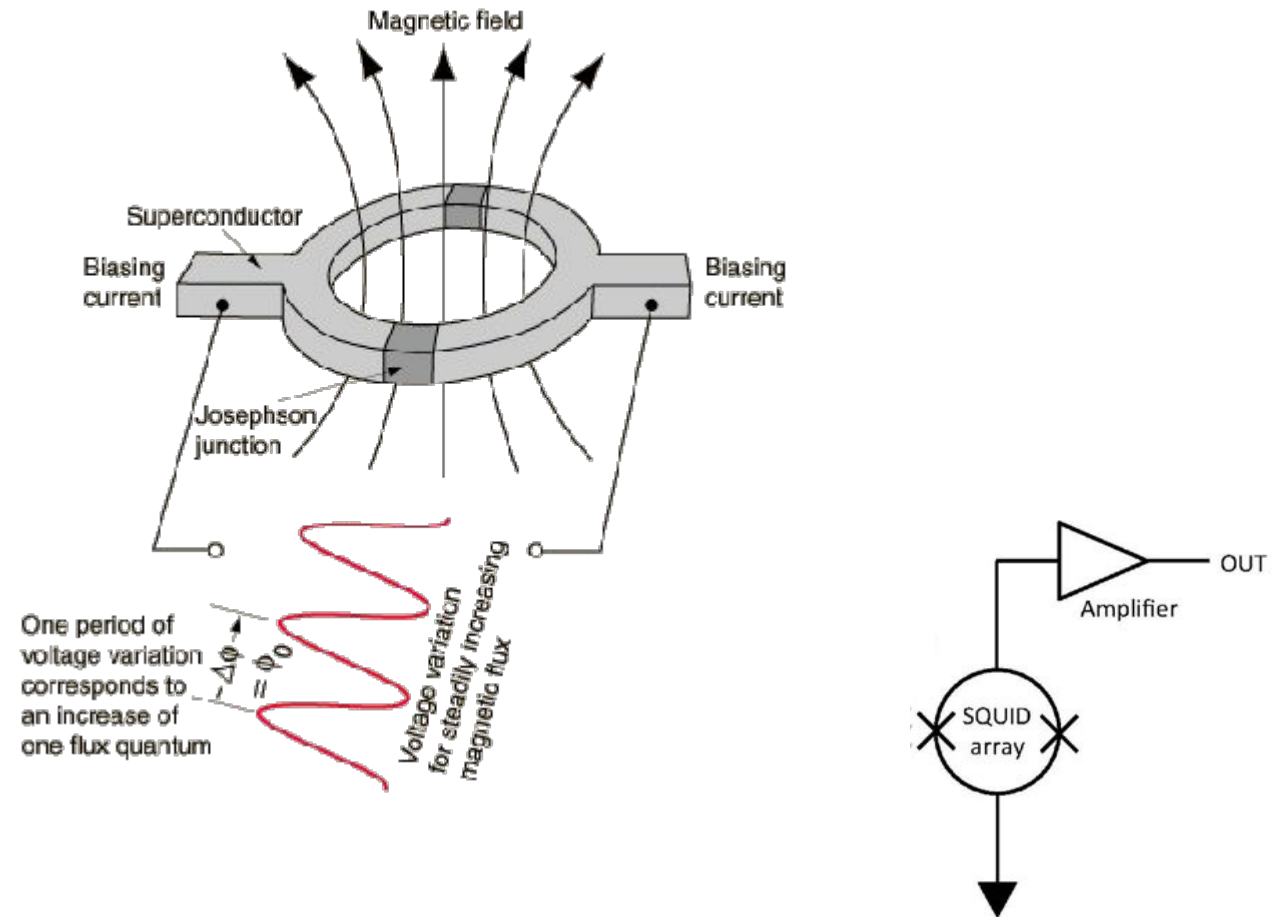


Side note: SQUIDs

Superconducting quantum interference device (SQUID) measure B-Field at scale of magnetic flux quantum:

$$\Phi_0 = h/2e = 2 \times 10^{-15} \text{ Tm}^2$$

Common placed as readout superconducting electronics, such as MRIs



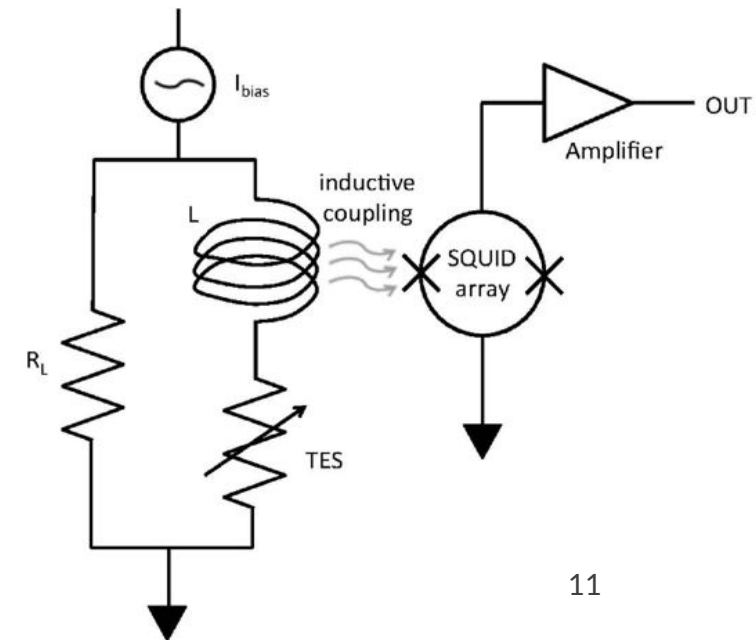
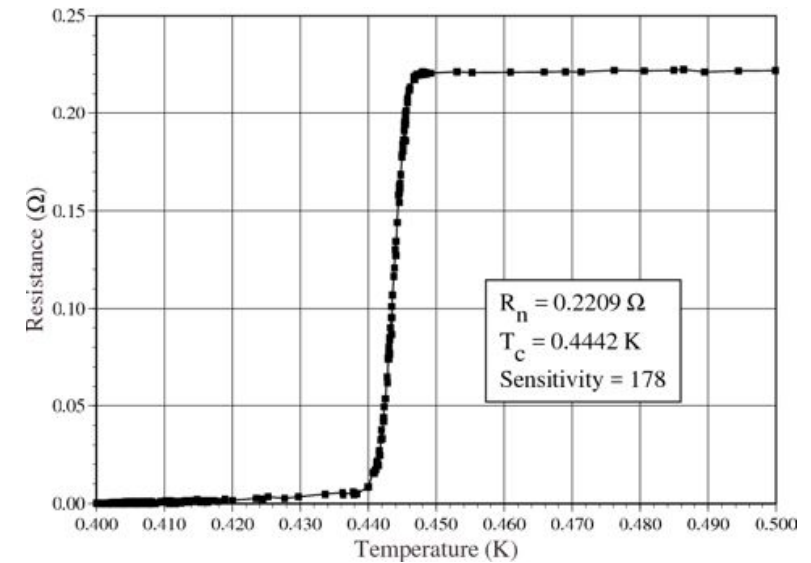
Transition Edge Sensors (TES)

Superconductor in it's SC-normal transition

Constant current: negative electro-thermal feedback
(K. Irwin - Stanford)

Inductively coupled to SQUIDS.

Carriers of signal are quasiparticles (broken Cooper-paired electrons) with \sim meV energy. Huge number of quanta compared to charge or light in more conventional materials.

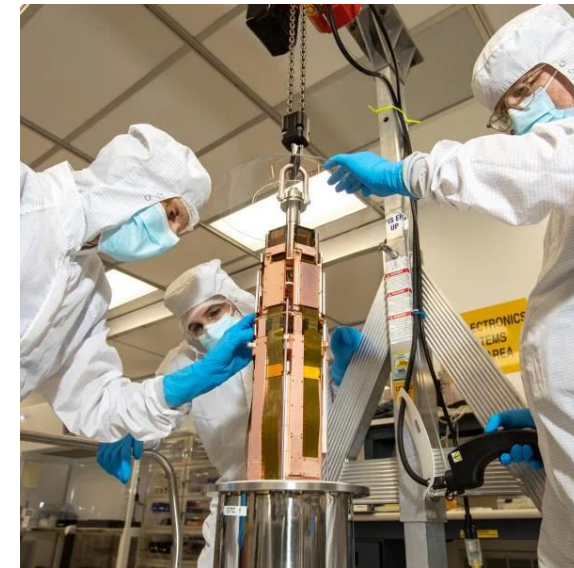
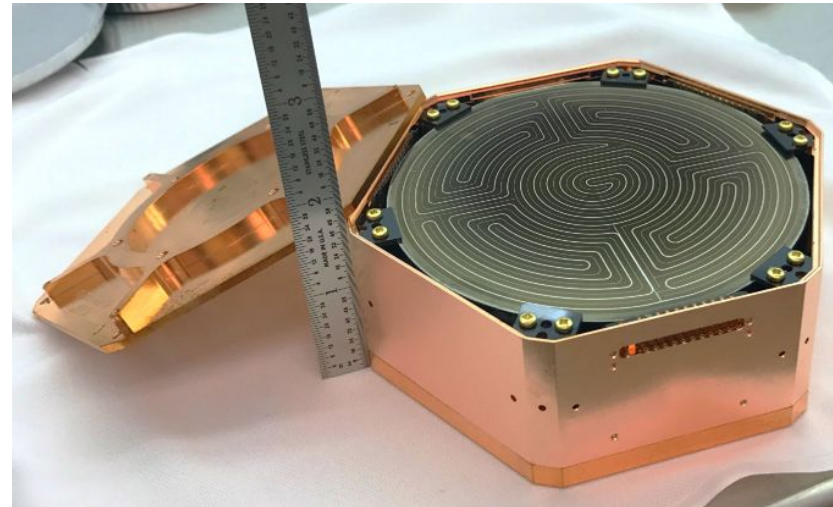
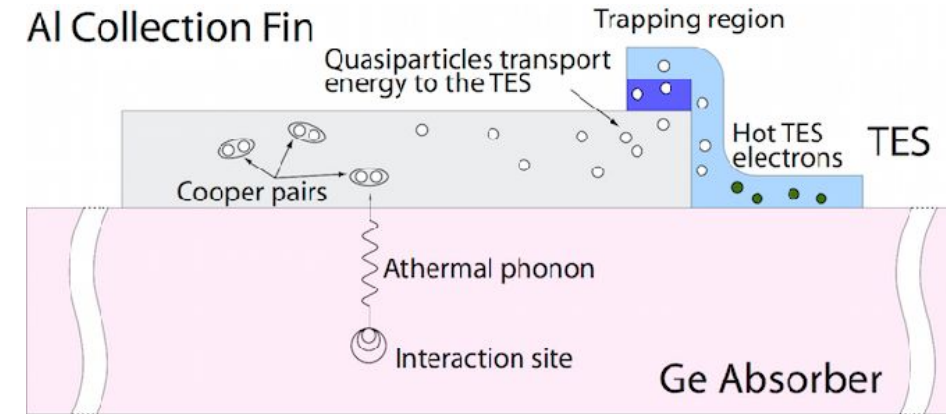


SuperCDMS

Low mass dark matter experiment with combined ionization and phonon measurement for background rejection.

Use Cooper pairs to transport of energy to TES sensor.

Very low noise 4K High Electron Mobility Transistor (HEMT) amplifier front end of charge sensitive amplifier, with ~ 50 e-h noise at ~ 200 pF capacitance.



Noble gasses: workhorse of particle physics

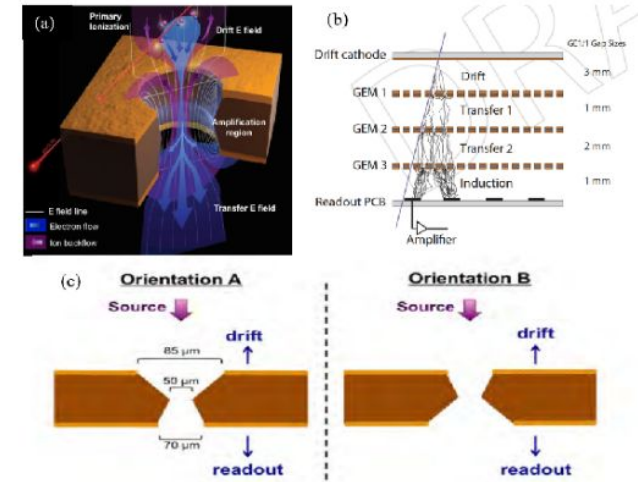
Both ionization and scintillation.

Charge gain is possible with sophisticated electrode structures

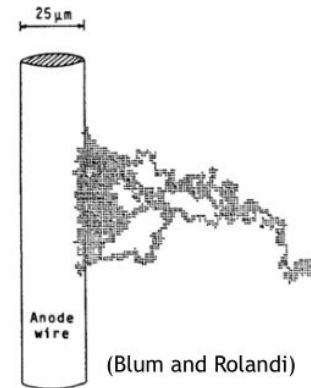
Charged particle tracking and particle ID at colliders. Also x-ray detection. Radiation-hard.

Ar for most applications, Xe for higher stopping power, but limited stopping power in gas.

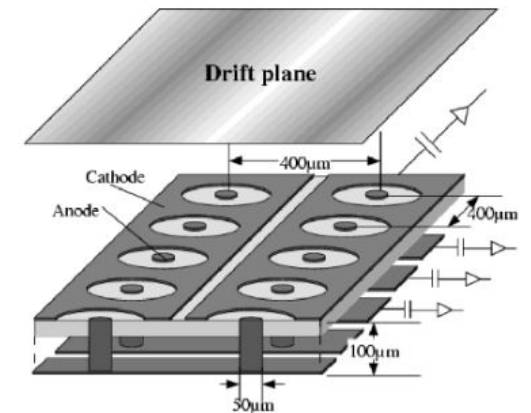
GEMs on kapton circuit board



Electron multiplication for “proportional wire” readout



μ-PIC - on PCB



Liquid Noble Gasses (85 K to 160 K)

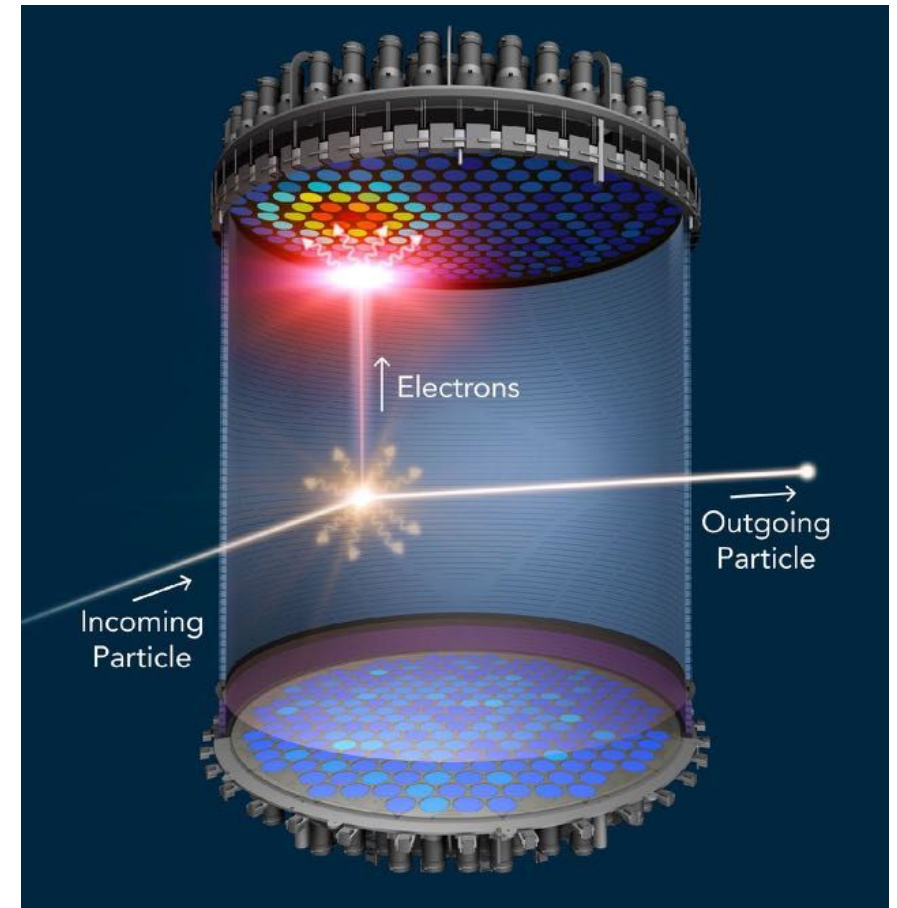
High density

Single phase scintillator, e.g. DEAP, niche application over organic liquid scintillator.

LAr calorimeter, e.g. ATLAS, radiation hard, with ionization readout

Time Projection Chambers (TPC): very powerful even when relatively slow charge readout* (\sim msec/m).

Dual-phase TPCs allow ionization electron amplification. Normally, electroluminescence between wire meshes, also gas electron multipliers(GEMs).



Signal production

Example Xe:

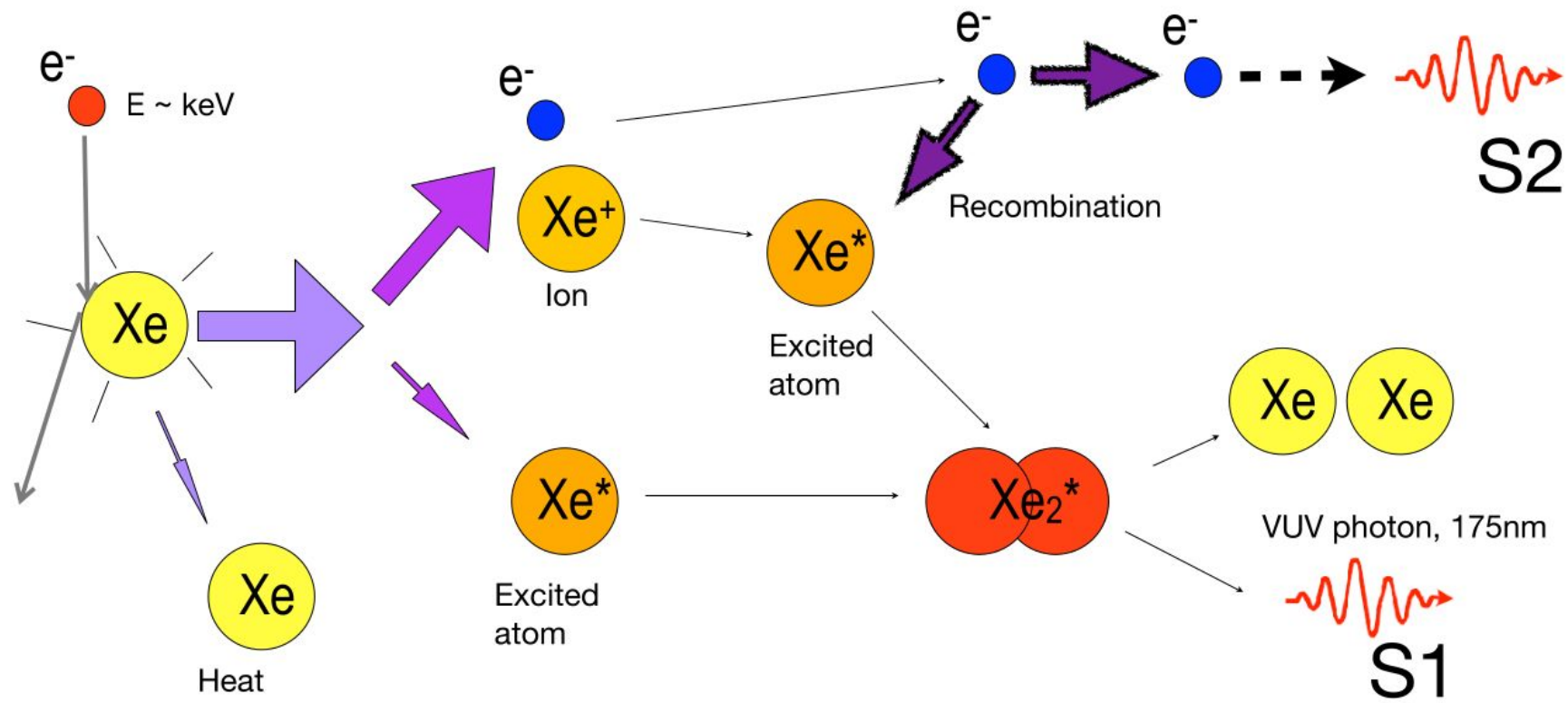


Figure: Gibson/Shutt

Ar is effectively the same, but faster prompt light signal at 128 nm

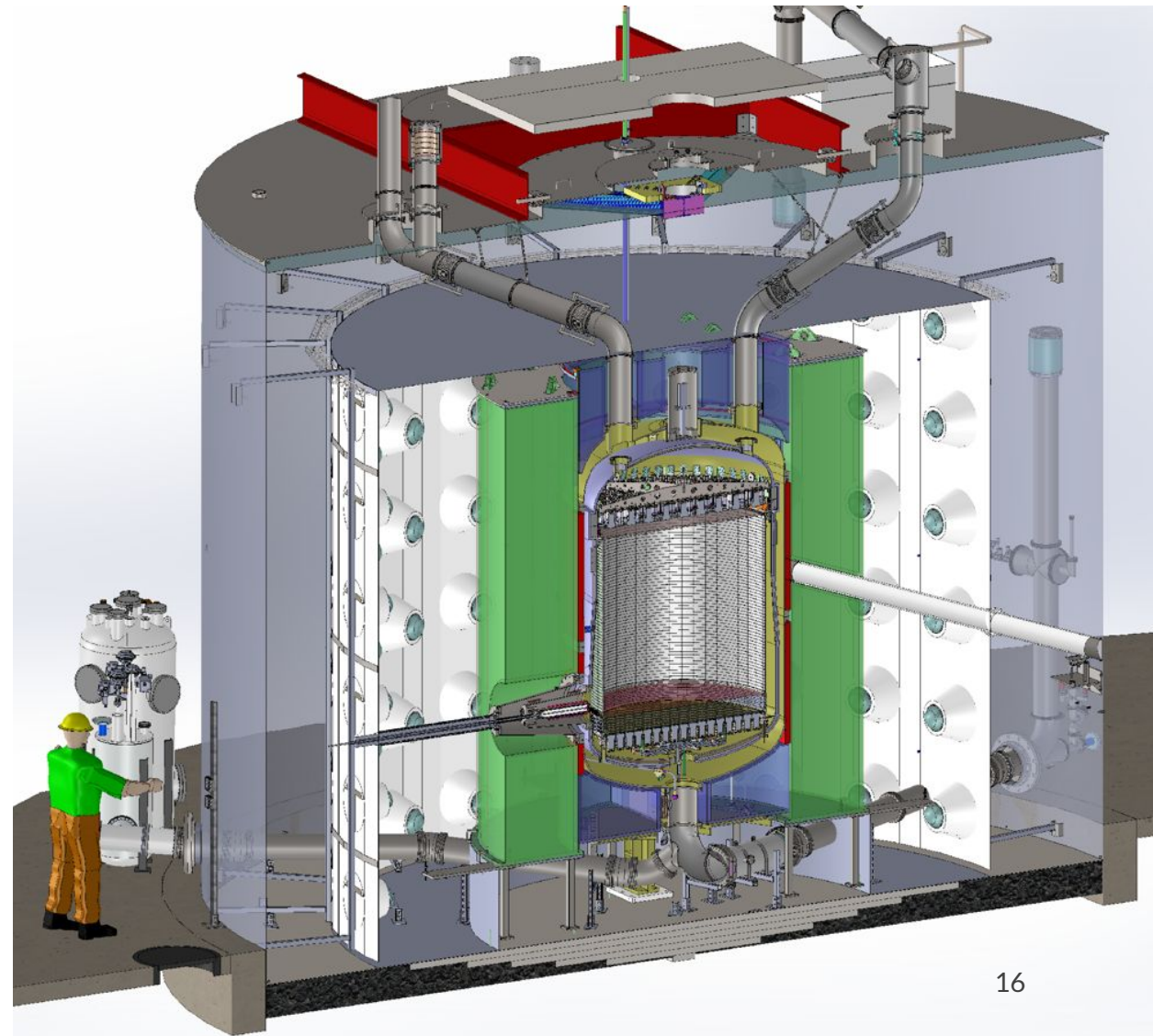
LXe example - LZ

WIMP dark matter search using 7 t LXe dual-phase TPC.

4850 ft underground at SURF, in Black Hills of South Dakota. Extensive LXe purification, handling, and LN based cryogenic system.

500 PMTs* with conventional readout and DAQ. Liquid scintillator outer vito.

Possible 100 t-scale search to follow (XLZD).



LAr example - DUNE (Far Detector)

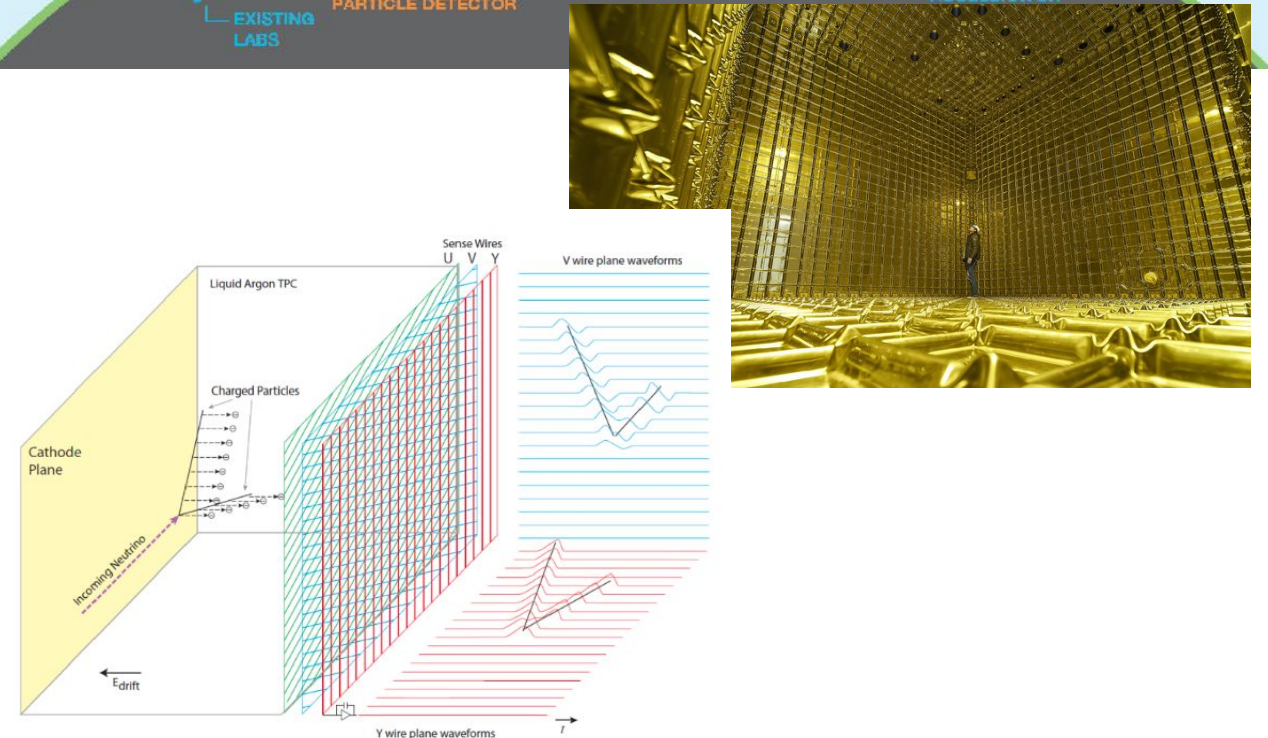
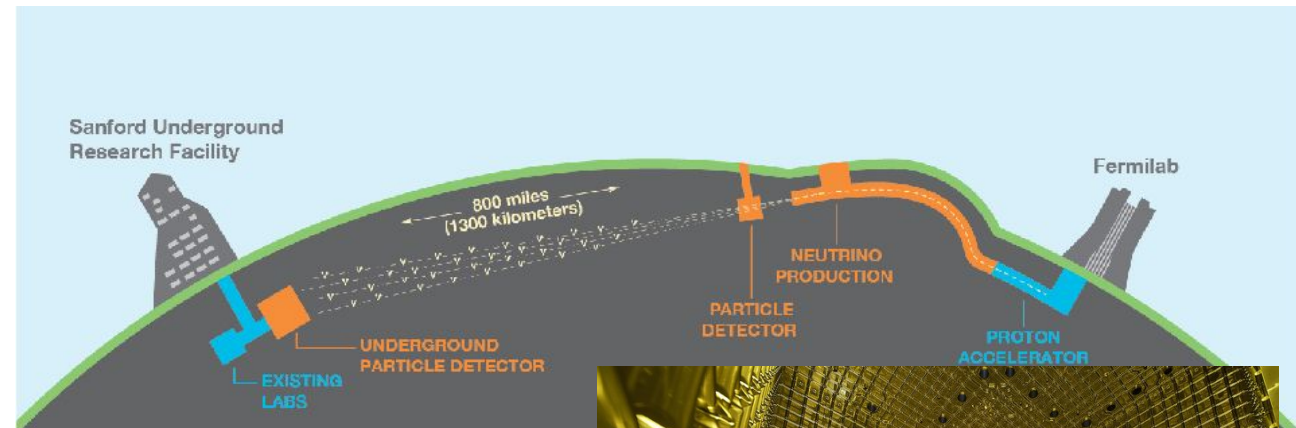
Long-baseline neutrino oscillation experiment

Flagship DoE experiment for years to come

Far Detector LAr TPC, 17 kt* modules, each 60 x 12 x 14 m³, 3.4 neutrinos/hr

Wire or strip charge readout.

Sparse SiPM + light trap/ wavelength shifter (WLS) light readout



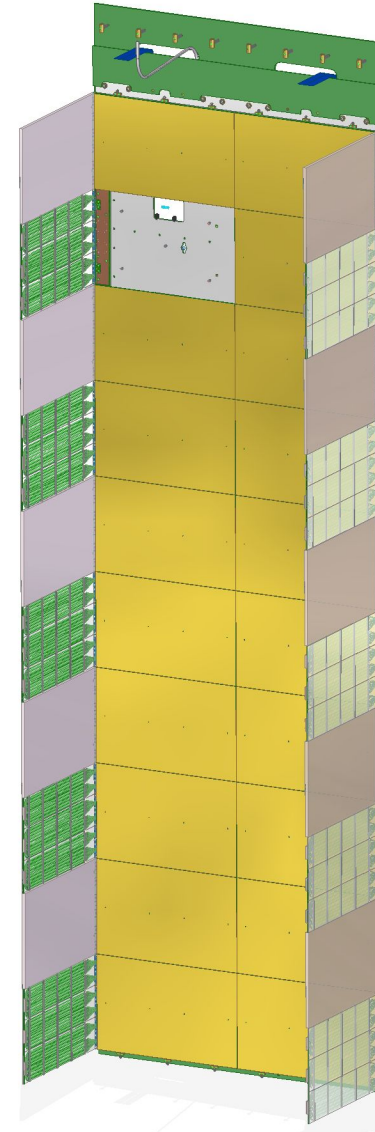
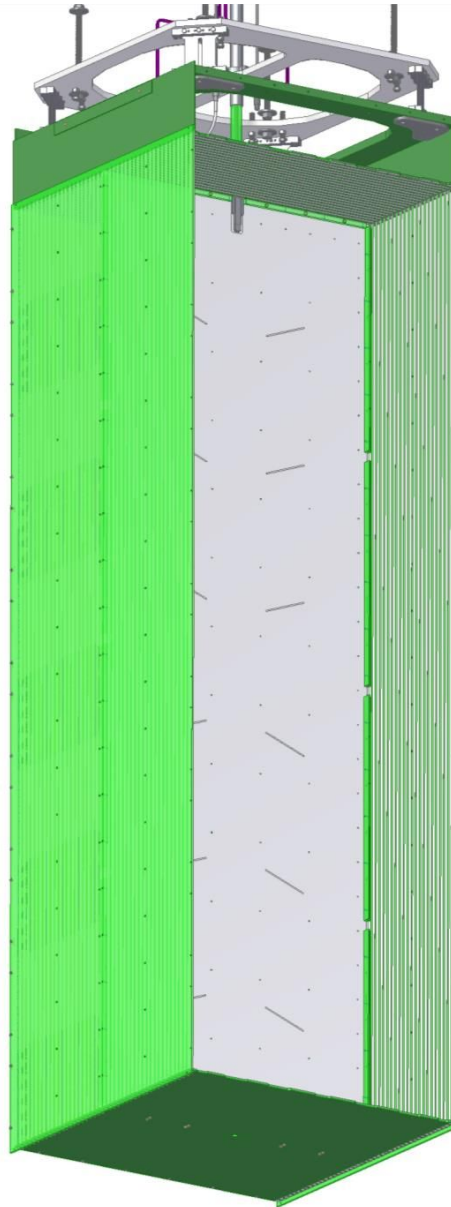
LAr example - DUNE Near Detector

Near site is a high multiplicity environment: 150 t detector sees **20 neutrinos/10 μ s**

Detector segmented into 35 modules

Optically isolated modules with dielectric light readout.

Pixelated anode (flat response as function of angle)



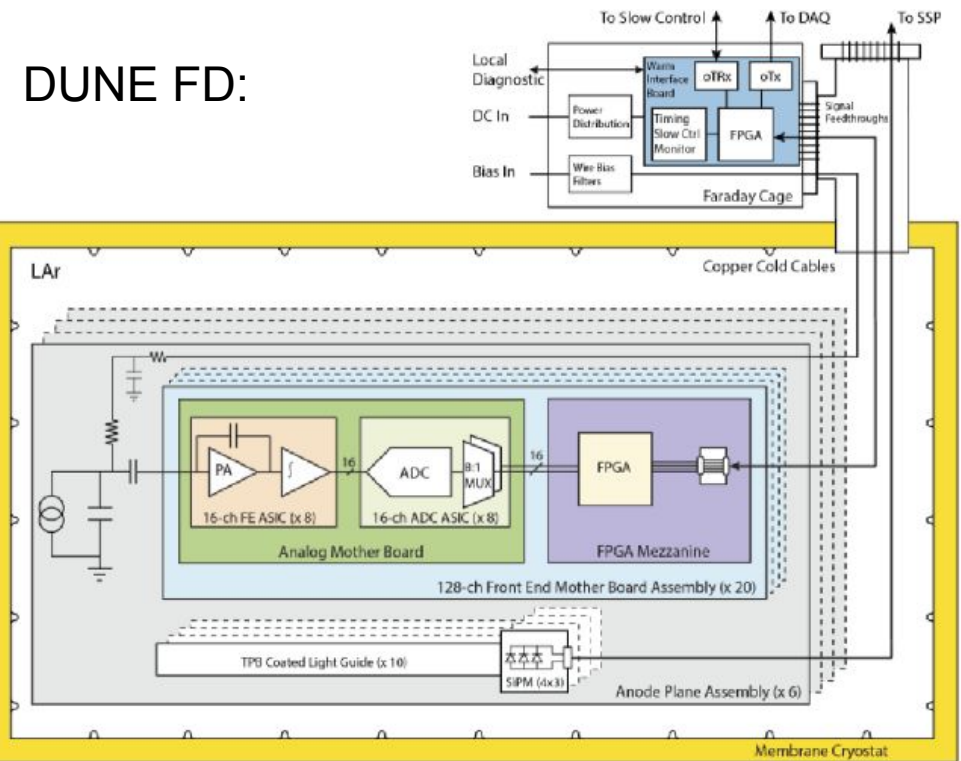
Charge readout in TPCs

Challenges: many channels, large size of detector, strong power limitations in LAr

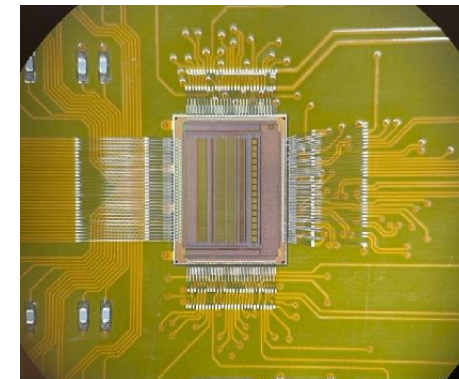
Various prototype detectors used warm electronics; suffered noise and power due to cabling. Eventual development of ASIC CMOS readout,

Challenge is combining cryogenics, multi-channels, low noise, lower power, digitization + triggering.

CRYO ASIC - full system on chip for nEXO:

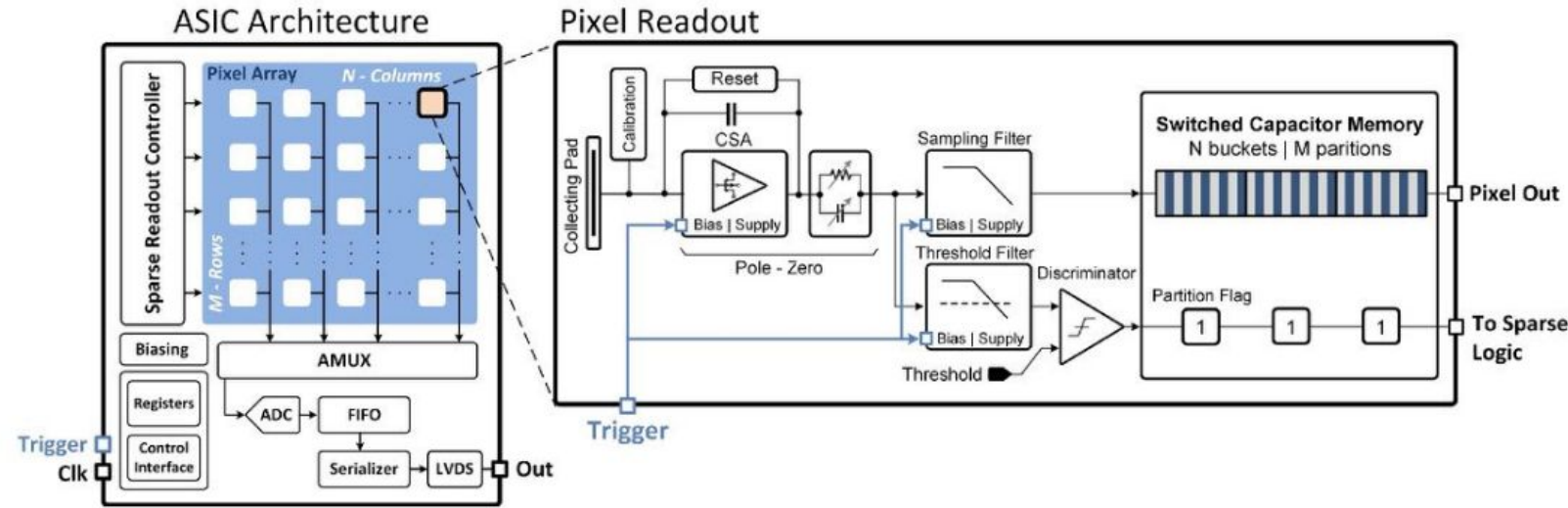
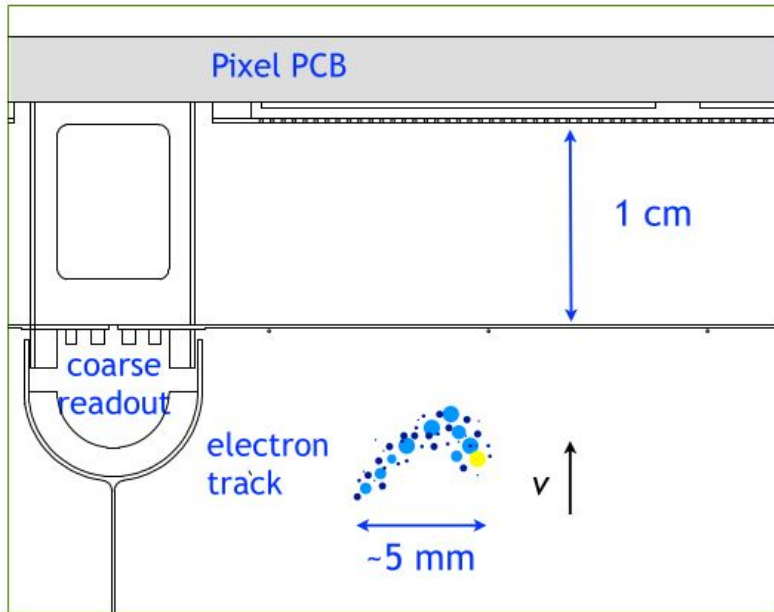


nEXO ASIC:



Grid Activated Multi-Scale pixel readout (GAMPix)

Anode region



Coarse (cm-pitch) induction grids, followed by fine grained pixels. Coarse grids measure integral charge, with $\sigma_e \sim 15 e^-$. Pixel chips powers-up with coarse grid signal. Power reduced by 10^3 to 10^4 (low pixel occupancy)

Preliminary analysis: $\sim 1 \mu s$ pixel turn on, with $\sim 30 e^-$ noise

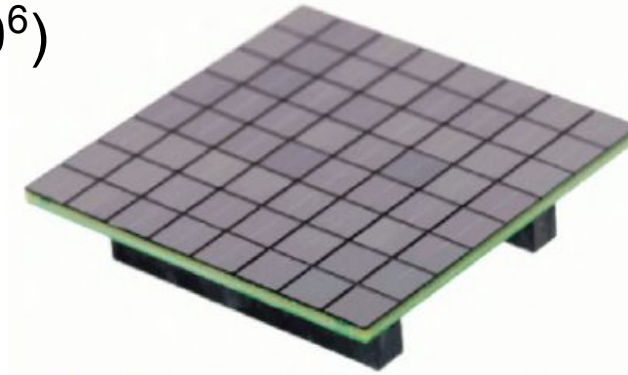
Light readout in TPCs

Both PMTs and SiPMs have very significant gain (10^6) easing demands on electronics.

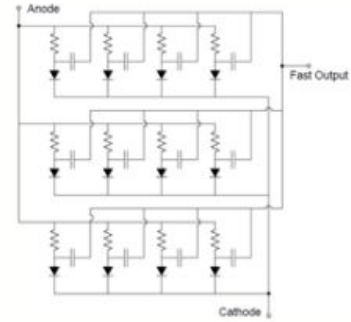
SiPMs - massive array of single-photon avalanche photodiodes. Summed linear response.

SiPMs are increasingly replacing PMTs as detector of choice. But, much higher dark current. Wide variety of readout efforts, signal is less complex than charge readout.

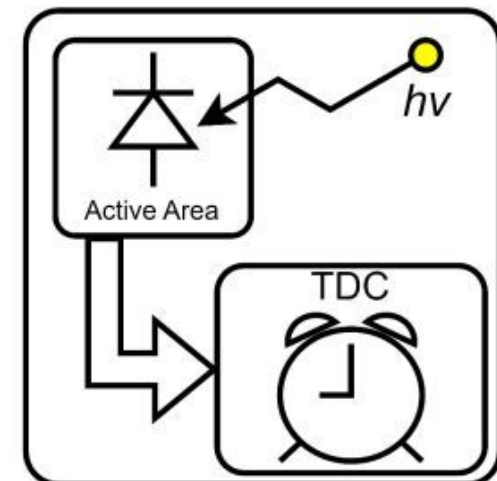
SiPM performance continuing to increase: Hamamatsu, FKB reporting 30% QE at 128 nm, But, need for significant ASIC readout development, or transition to Digital SiPM



sensL ArrayJ-60035-64P-PCB
64 pcs of 6x6mm²



Arrayed in series or parallel



Cryogenic cooling

Liquid nitrogen 77K, conventional refrigerant via Joule-Thomson pressure throttling based systems.
Two phase heat transport - thermosyphons

Pulse tube refrigerators (glorified Joule-Thomson),
breakthrough: 4K replaces LHe refrigerant.

Below 4K, pumped ^4He to 1.2K; pumped ^3He to $\sim 0.3\text{K}$; Adiabatic Demagnetization Refrigerator (ADR) to $\sim 0.1\text{K}$ or lower.

Dilution ($^4\text{He} + ^3\text{He}$) refrigerators to 5 mK,
Transformed by quantum computing.



Cryogenic Cabling Issues

Channel count, feedthroughs.

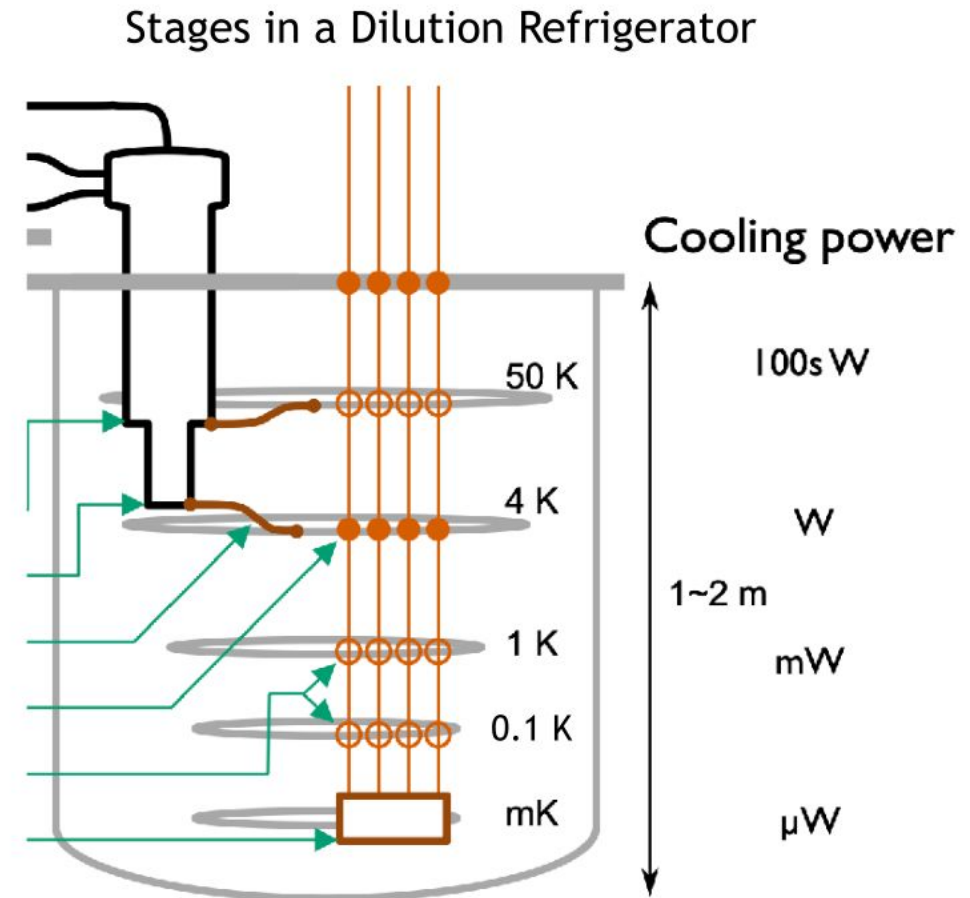
Power-resistance - Weidemann-Franz:

$$P \cdot R = \frac{k}{\sigma} \Delta T = 25 \text{ nW } \Omega \frac{T \Delta T}{\text{K}^2}$$

Heat sinks - needed especially $< 1 \text{ K}$ to protect sensors from power.

Below 4K - SC cables have near-zero heat load, but relatively high capacitive noise.

Motivation for digital signal transmission and/or photonics.

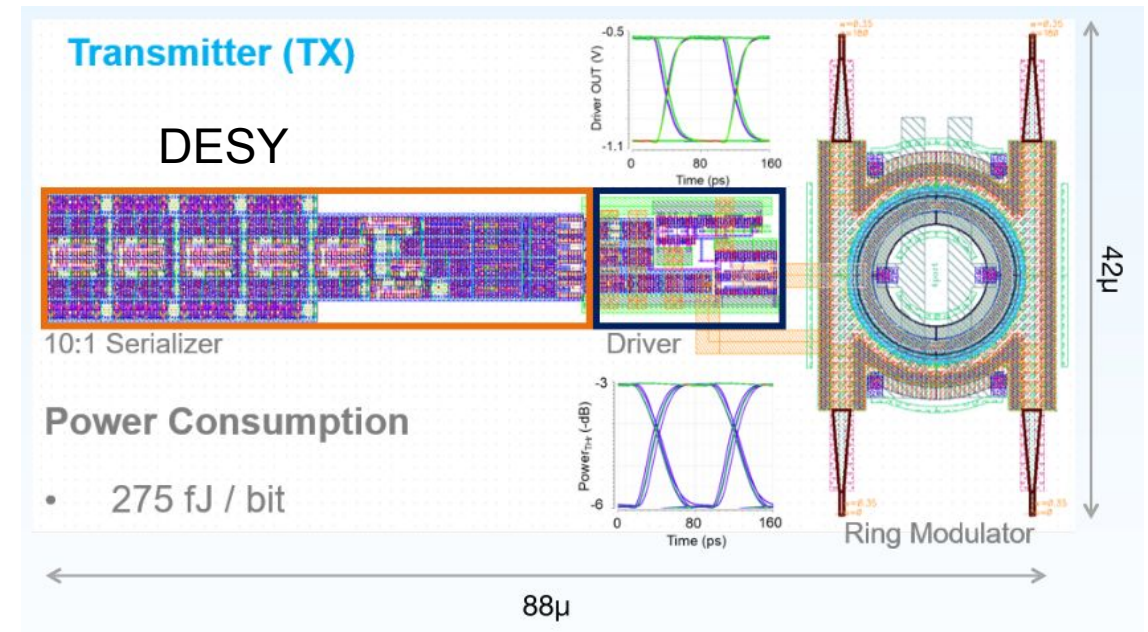


Photonics

Cryogenic fiber-coupled diodes have been demonstrated, but are power hungry.

External lasers with data transmission via modulation of a ring resonator in CMOS, such as Sherbrooke's silicon photonics DAQ, or FNAL's SParkDream, are promising.

Quantum computing industry is also developing such systems



A manufacturable platform for photonic quantum computing

<https://doi.org/10.1038/s41586-025-08820-7>

PsiQuantum team*

Received: 30 July 2024

Other cryogenic instrumentation

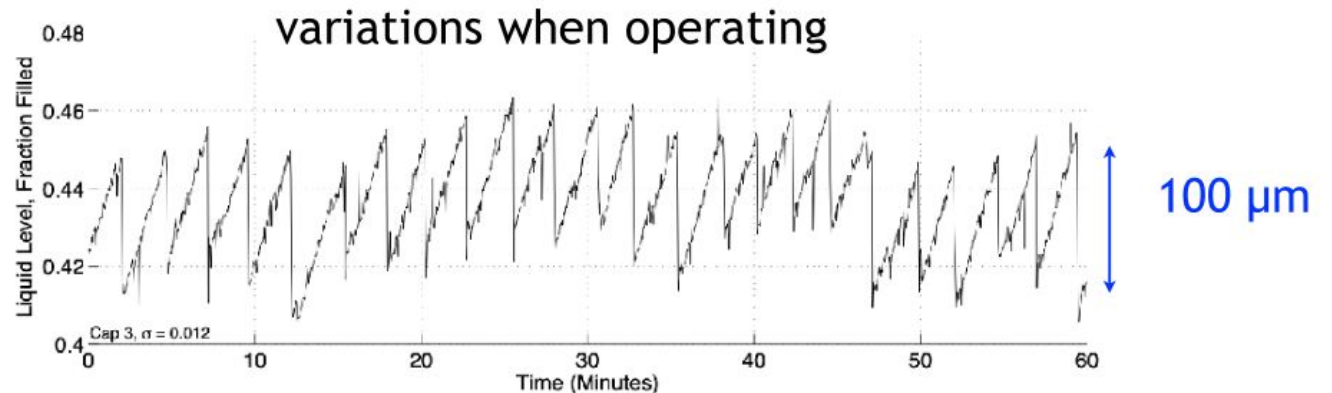
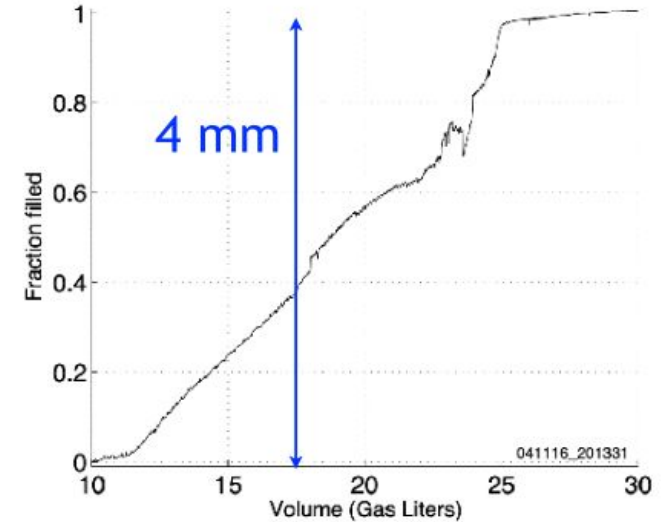
Experiments require significant slow-control/monitoring of conditions: voltages, current, pressures/temperature, liquid levels, motion, etc.

Cryogenic readout would have the same positive benefit here with reduced noise and thermal leakage.

Example: liquid level measured precisely in ~40 g LXe TPC.

Not measurable in LZ with remote readout. Need cryogenic circuitry!

Detector Filling



Energy resolution improved when correlated with liquid height

Summary

Rich set of detectors provided by cooling materials

Liquid nobles

Much of technology fairly mature, high-channel density applications coming to fore
Cryogenic front end ASIC readout now established, but not yet widespread or mature -
cost barriers.

SiPMs readout only starting.

SubK

Technology now driven by developments in quantum computing.

Focus to date is multiplexing + low temperature electronics to reduce wiring between
mK and 4K.

CMOS readout and processing and photonics at 4K is growth area.