The CUPID neutrinoless double-beta decay experiment

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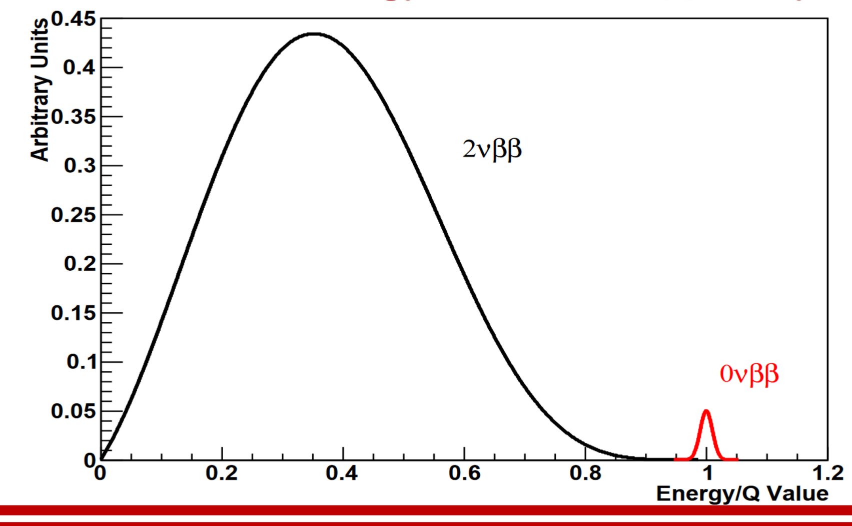
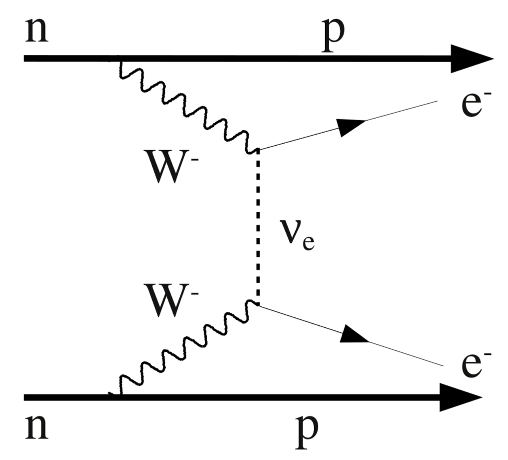
CUPID Experiment

- The CUPID (CUORE Upgrade with Particle Identification) experiment will aim to observe the double beta decay without neutrinos emission (0νββ) by employing a **large and modular low-temperature calorimeter**.
- The 0νββ decay is a second-order rare decay which has been theorised to occur if and only if the neutrinos are **Majorana fermions** (the neutrino and its antiparticle are the same entity).

Summed electron energy spectrum for ββ decay [1]



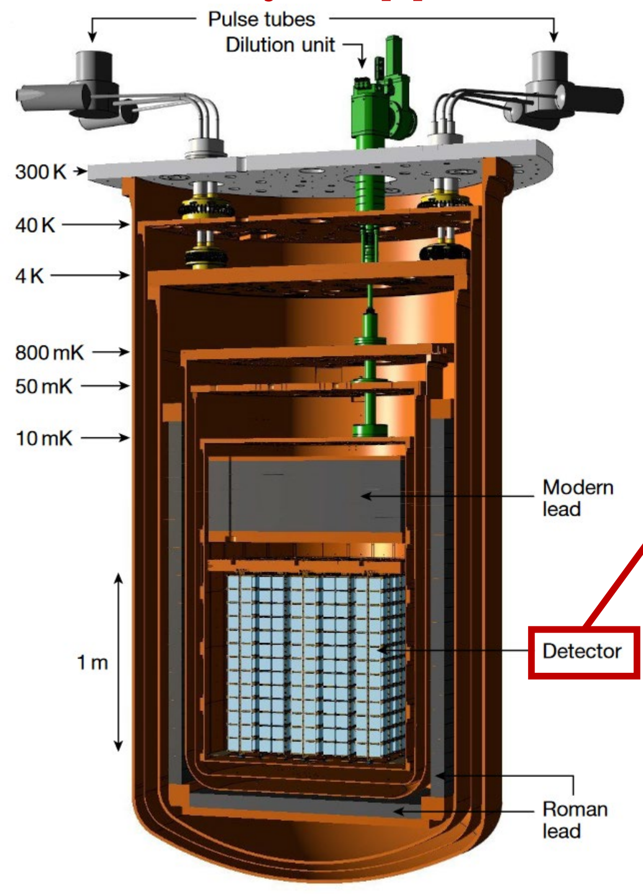
Feynman diagram of a neutrinoless double beta decay [1]

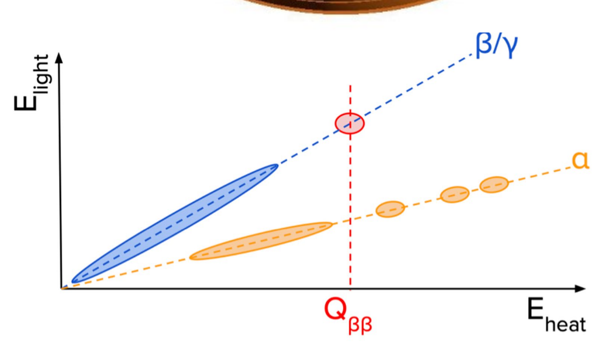


Experimental setup

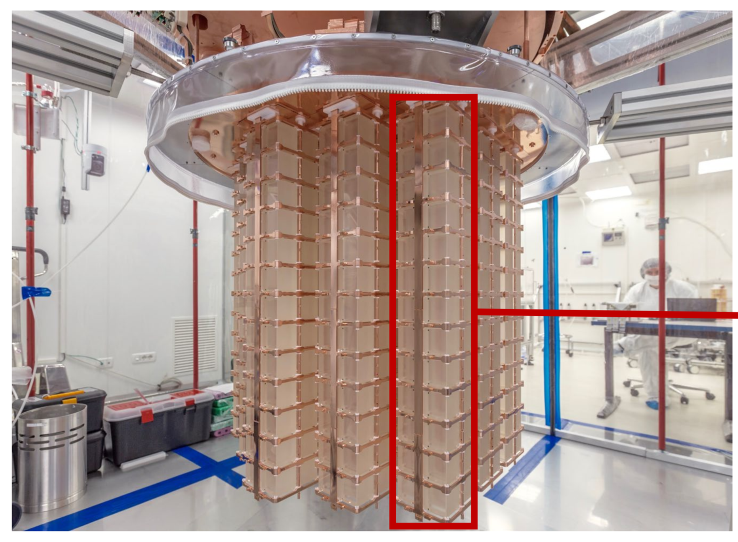
- The calorimeter will be made of **1596 scintillating Li_2MoO_4 (LMO) crystals** grouped in towers and enriched in 100-Mo, isotope with double-beta (2νββ) half-time decay of $T^{1/2} = 7.1 \times 10^{18}$ yr and $Q_{\beta\beta} = 3034$ keV.
- These crystals will be contained in a **cryostat** which has been already developed for the CUORE experiment and that reaches ~ 10 mK.
- The impinging particles release **energy in the crystals in the form of phonons and photons.** A thermal sensor, a Germanium Neutron Trasmutation Doped (Ge-NTD) thermistor, is attached to the LMO to measure the crystal heating due to the phonons thermalisation. The photons escape the crystal and are absorbed by a thin Ge slab, which is heated up and is read out by another Ge-NTD thermistor.
- The difference in emitted light energy from α, β/γ particles enables the **distinction and identification of these particles,** allowing α background suppression.
- **Two light sensors and one heat sensor** for each crystal.

Cryostat [2]

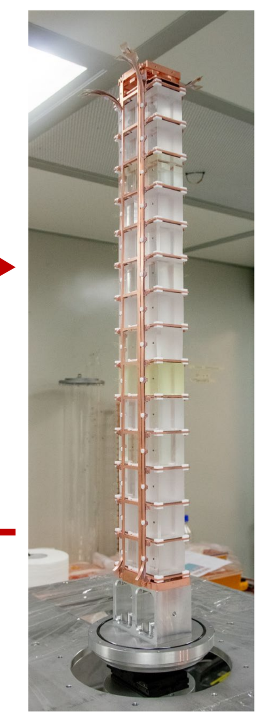




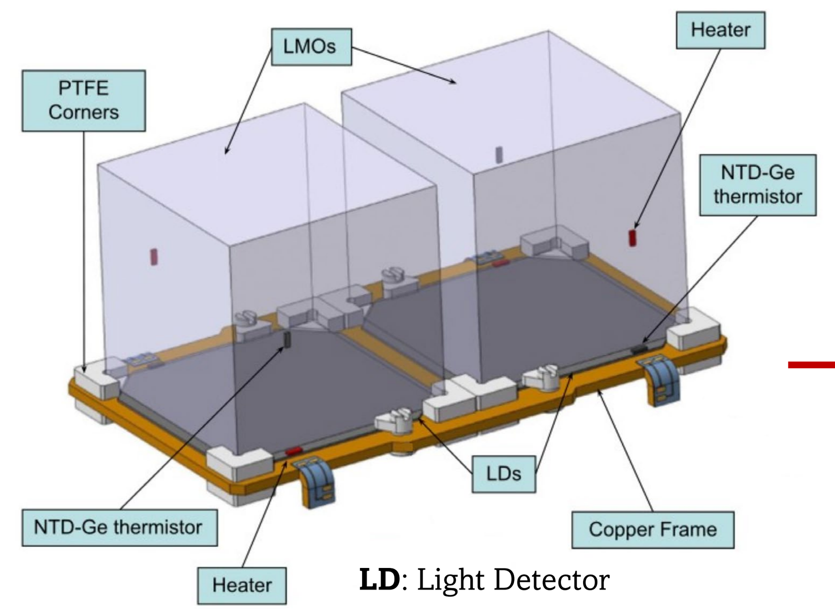
CUORE detector towers



Prototype of a single CUPID detector tower



Focus on two crystals [3]



LD: Light Detector

The light and heat sensors' signals are sent to the amplifying electronics.

Pile-up rejection and background level

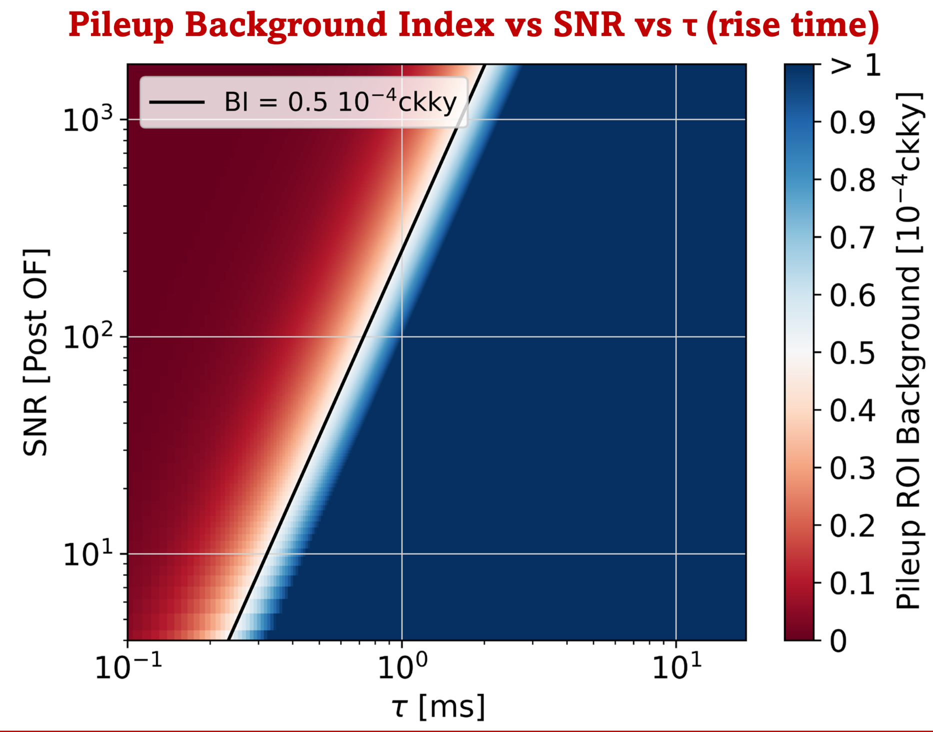
- Since the light signals are faster (~ 0.5 ms rise time) than heat signals (~ 5 ms rise time), the simultaneous readout of heat and light will contribute to the **abatement of the 2νββ pile-up** in the region of interest.
- The employment of the **Neganov-Luke effect** for the light channel will result in twofold improvement: enhanced pile-up rejection due to an increase in signal-to-noise ratio (SNR) and a reduction in electronics jitter (better time resolution). The application of an electric field across the slab results in an additional increase in temperature, above that generated by the photon flux, caused by the acceleration of the photon-induced electron-hole pairs.
- The CUPID experiment will aim at reaching a $\sim 10^{-4}$ counts/(keV · kg · yr) **background level**, about two orders of magnitude lower compared to the CUORE experiment.
- CUPID will have an expected **half-life discovery sensitivity** of $T^{1/2} > 1 \times 10^{27}$ yr, corresponding to an **effective neutrino mass** of $m_{\beta\beta} < 12 - 20$ meV, covering the whole inverting hierarchy and more.

Electronics jitter

$$\sigma_t = \frac{C}{V_{amp}} \sqrt{\frac{\overline{e^2_{amp}}}{f_{BW}}}$$

- $\overline{e^2_{amp}}$: input referred amplifier noise
- f_{BW}: amplifier bandwith frequency
- V_{amp}: signal voltage amplitude
- C: constant

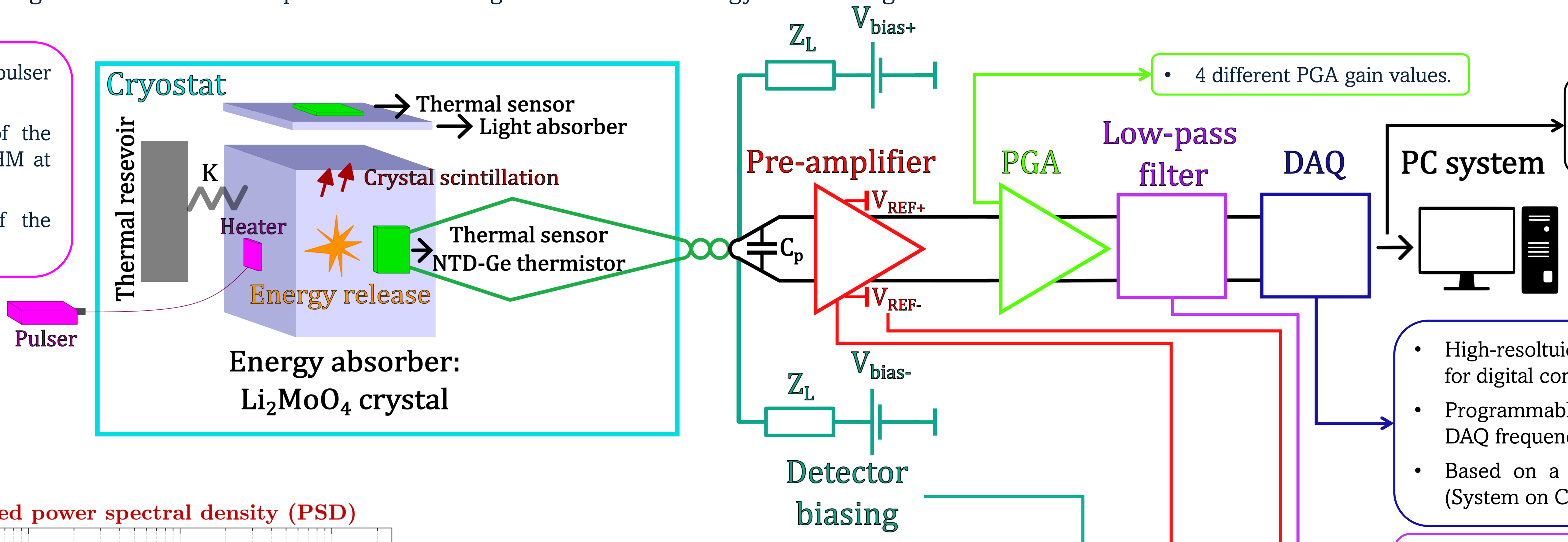
Pileup Background Index vs SNR vs τ (rise time)



Signal detection and acquisition

- A dedicated **biasing circuit** makes a current flow through the thermistor.
- When there is an energy release in the absorber, the thermistor transforms the heat signal into an electrical (voltage) signal, which is then fed into **the acquisition system**.
- The acquisition system is made of a differential voltage pre-amplifier, a Programmable Gain Amplifier (PGA), a low-pass filter and a Digital Acquisition system (DAQ). The DAQ data is sent to a PC system via a standard Ethernet connection. The lines are optically coupled, allowing the control room to be located anywhere.
- A **very stable (~ ppm/°C) pulser circuit** generates an electrical signal onto a stable resistor glued to the crystal, the so-called heater. These pulses emulate the release of energy by particles in every crystals, enabling the detection and compensation of the long-term drift in the energy conversion gain of the detector.

- High precision pulser generator.
- Energy resolution of the order of 20 eV FWHM at 1 MeV.
- Thermal stability of the order of ppm/°C.



- 4 different PGA gain values.

- DAQ readout through an optically coupled standard Ethernet interface.

- High-resolutuion 24-bit ADC for digital conversion.
- Programmable (up to 24 kHz) DAQ frequency acquisition.
- Based on a FPGA with SoC (System on Chip).

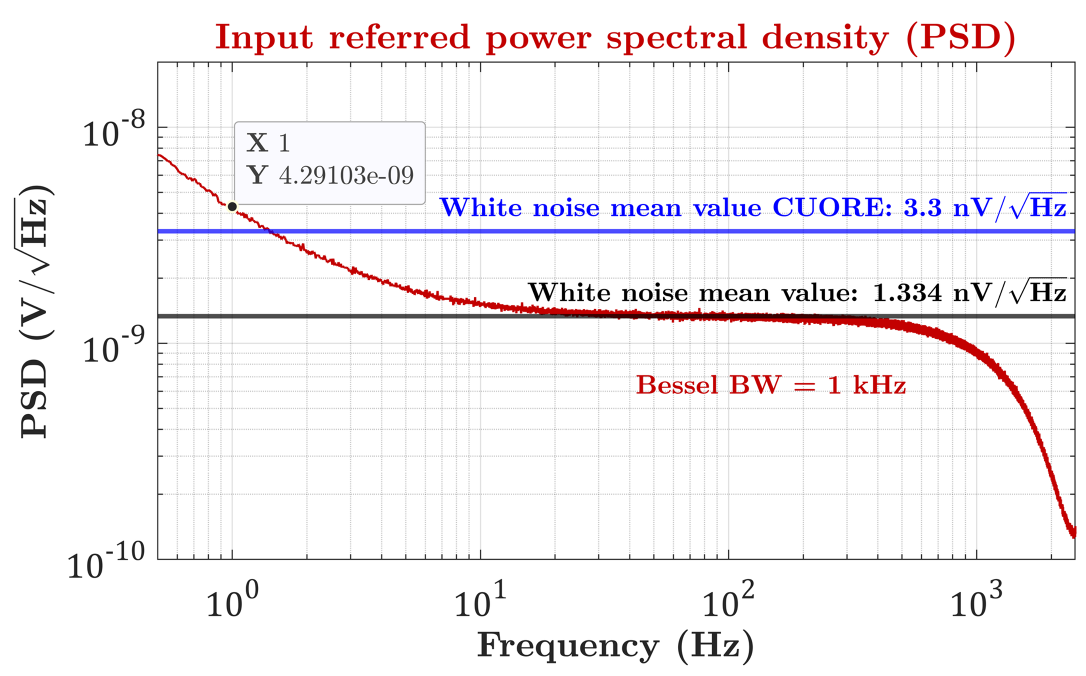
- 6-pole programmable (24 Hz to 2.5 kHz) Bessel antialiasing filter.

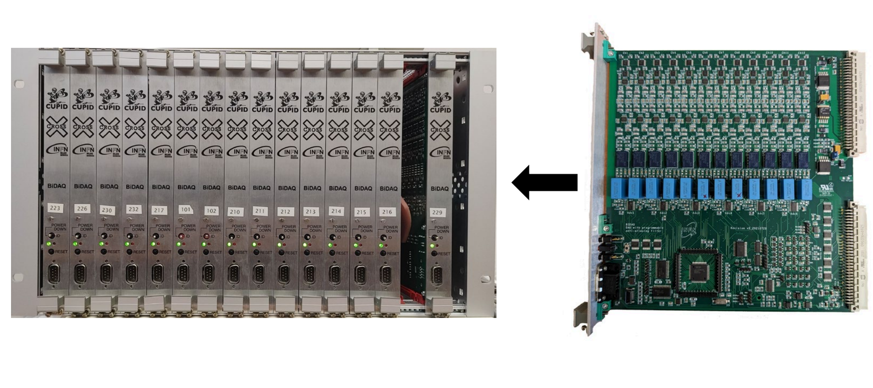
- 0 to ±55 V programmable V_{bias}.
- $Z_L = 30$ GΩ or $Z_L = 5$ GΩ.

- Differential voltage amplifier with a selected pair of Junction Field-Effect Transistors (JFETs) at the inputs.
- Ultra-low noise: $\sim 1.3 - 1.4\ nV/\sqrt{Hz}$ white noise referred input power spectral density.
- Fixed JFET voltages and currents for high gain stability.

- A custom board supplies a super precise and stable $\pm 5\ V_{REF}$ voltage.

Input referred power spectral density (PSD)





References:
[1] L. K. Kogler, 'A measurement of the 2 neutrino double beta decay rate of Te-130 in the CUORICINO experiment', LBNL--5226E, 1052174, Nov. 2011. doi: 10.2172/1052174.
[2] D. Q. Adams et al., 'Search for Majorana neutrinos exploiting millikelvin cryogenics with CUORE', Nature, vol. 604, no. 7904, pp. 53–58, Apr. 2022, doi: 10.1038/s41586-022-04497-4.
[3] K. Alfonso et al., 'Optimization of the first CUPID detector module', Eur. Phys. J. C, vol. 82, no. 9, p. 810, Sep. 2022, doi: 10.1140/epjc/s10052-022-10720-3.