Multiplexed read out for low threshold detectors in astroparticle physics

Microwave SQUID multiplexing (uMUX) for massive cryogenic bolometers

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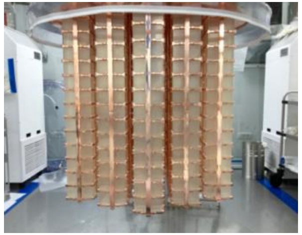
Three Physics Targets — Two Very Different Energy Scales

Neutrinoless Double Beta Decay

RoI ~ MeV

- Q-value of isotope sets the RoI: 130Te at 2.528 MeV Ton-scale experiments running: CUORE (760 kg TeO2)
- Wired readout adequate at this scale -> SOLVED

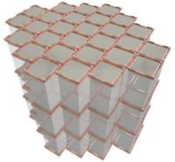


Ton scale: achieved

Coherent Elastic ν-Nucleus Scattering

RoI ~ few keV

- Rate proportional to N^2 — heavy nuclei ideal (Pb, Bi: N=126)
- Solar/SN neutrinos-> O(0.1 - 1 keV) nuclear recoils
- Need O(100 - 1000 kg), hundreds of channels at mK
- Wired readout cannot scale -> bottleneck

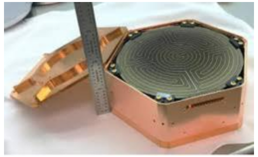


keV scale: readout limited

Sub-GeV Dark Matter

RoI ~ sub-keV to few keV

- Rate proportional to A^2 — coherent nuclear recoil
- 1 GeV/c^2 DM: < 0.8 keV recoil on O
- Same mass scale as CEvNS -> same readout problem



Sub-keV scale: readout limited

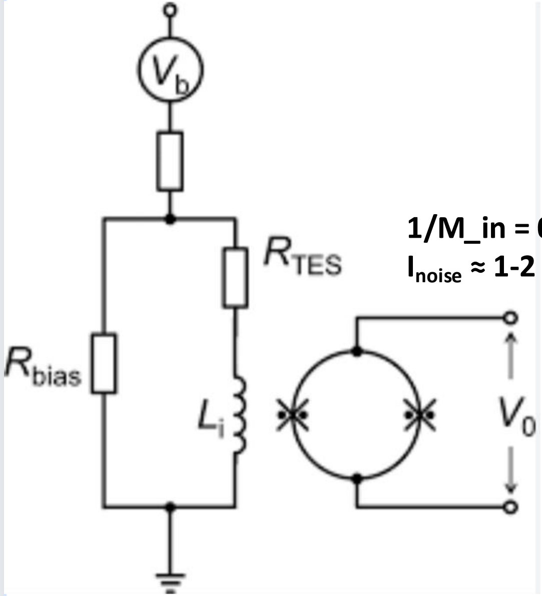
Cryogenic calorimeters at MeV scale: proven, wired readout sufficient. At keV scale: detector physics is ready — readout is the bottleneck.

The Wiring Bottleneck: Conventional SQUID Readout

Problem: wire-limited SQUID readout

- 1 amplifier chain + several wires per channel
- Heat load & wire count limit arrays to ~10s of detectors
- Scaling to 100 - 1000 kg requires hundreds of channels
- Each wire = thermal load
- Wiring harness becomes the dominant engineering challenge

Simplified



1/M_in = 0.4-1 uA/Phi0
I_{noise} ≈ 1-2 pA/sqrt(Hz)

The Wiring Bottleneck: Conventional SQUID Readout

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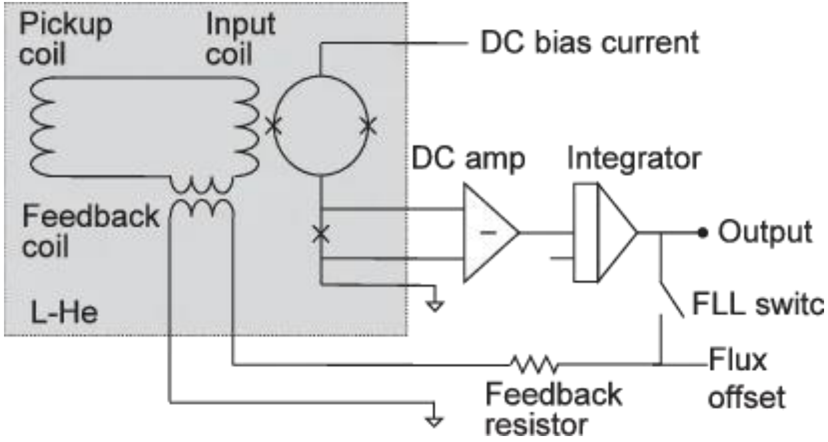
Less simplified (still)



FLL limits the bandwidth: 1 channel -> 1 squid

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Solution: Microwave SQUID Multiplexing (uMUX)

- Each TES coupled to an rf-SQUID + high-Q resonator
- All resonators on ONE coaxial feedline
- One HEMT amplifier per array (N_mux = 52-1000)
- 4-8 GHz band: ~ 1300 resonators possible

uMUX: N wiring harnesses -> 1 coax + 1 HEMT => readout stops being the bottleneck

uMUX: Circuit Principle & Flux-Ramp Linearisation

TES -> rf-SQUID

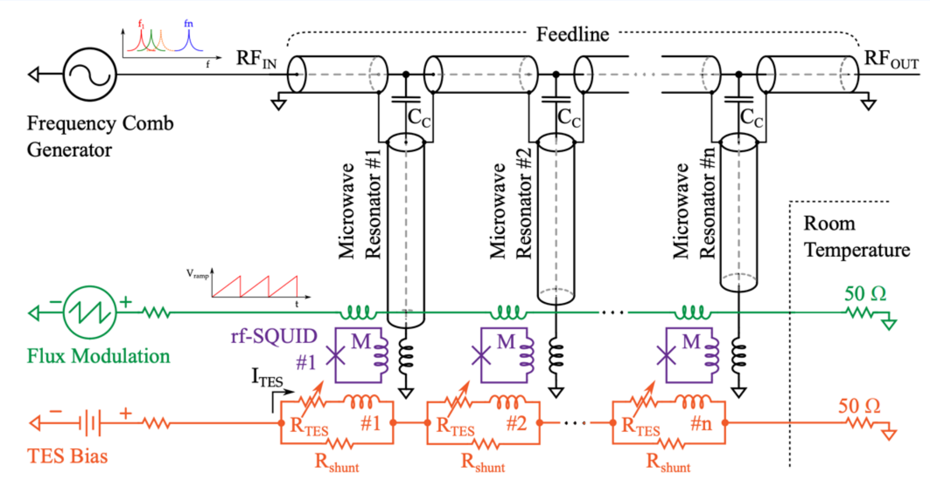
Signal current I_TES produces flux Phi = M_in * I in a dissipationless rf-SQUID. No resistive dissipation at the detector stage.

rf-SQUID -> Resonator

The SQUID acts as a tunable inductance, shifting the resonant frequency of a GHz superconducting resonator.

Flux-Ramp Demodulation

A sawtooth flux ramp drives the SQUID through n_Phi0 = 2 flux quanta per period. The tone phase winds periodically; demodulation extracts the current sample at f_ramp.



HOLMES Collaboration • D.T. Becker (NIST, Boulder) et al.
e-Print: 1910.05217 [physics.ins-det]
DOI: 10.1088/1748-0221/14/10/P10035 (publication)
Published in: JINST 14 (2019) 10, P10035

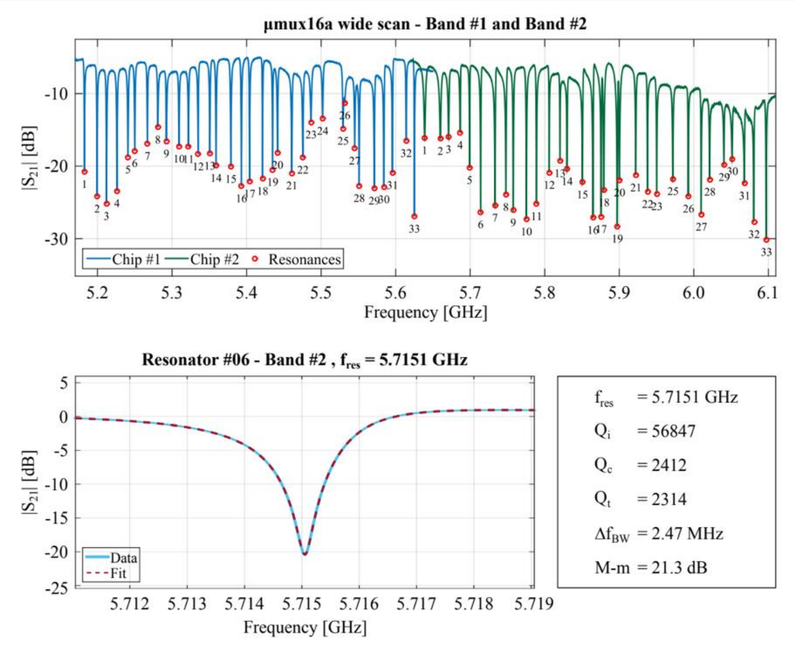
1/M_in ~ 23 uA/Phi0

All N resonators share ONE coaxial feedline + ONE HEMT — from N amplifier chains to 1

Frequency-Division: Lorentzian Resonances on a Shared Feedline

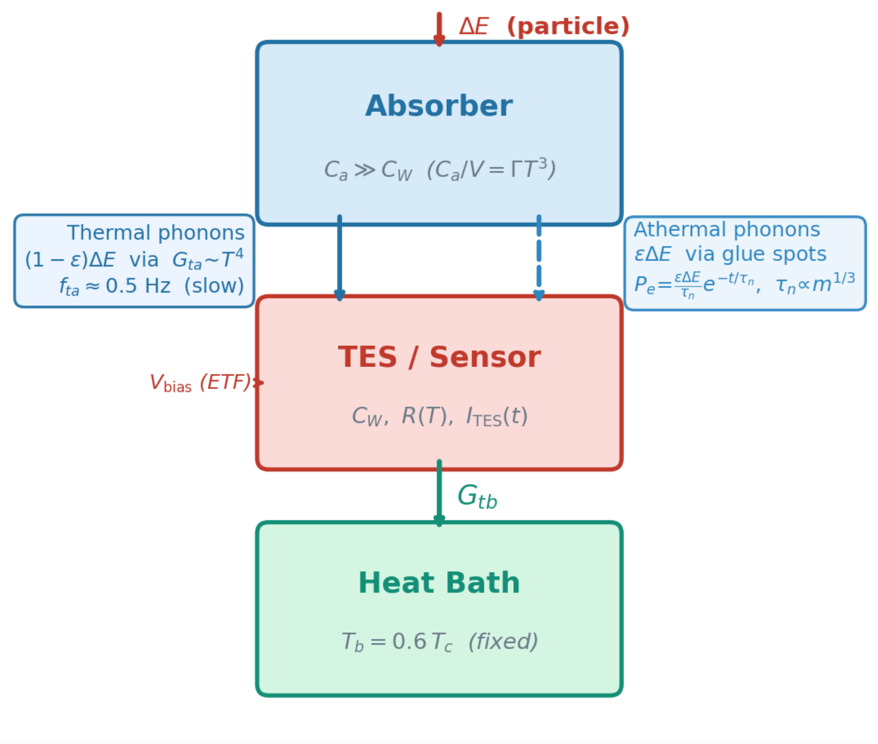
Reading the frequency comb

- Each resonator appears as a Lorentzian dip in |S21| vs frequency
- Resonance position f0 shifts with TES current via rf-SQUID inductance
- bandwidth ~ 100 kHz at 4 GHz
- Channels spaced 3 MHz apart (30x bandwidth) -> negligible crosstalk
- 52-channel tower occupies only ~0.2 GHz of the 4-8 GHz HEMT band
- A 4 GHz band fits ~1300 resonators — ~20 towers on one readout line



Becker et al., JINST 14 P10035 (2019) — Fig. 8

The Thermal Model

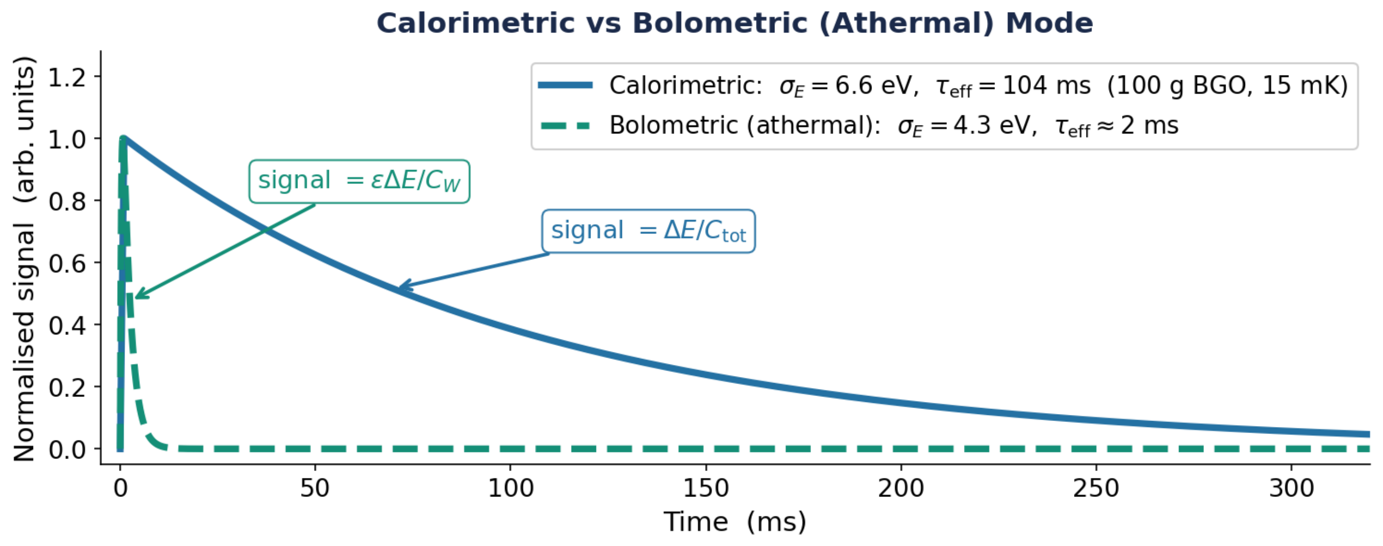


Coupled thermal equations (Pröbst, F., et al. *J Low Temp Phys* **100**, 69–104 (1995) and Pyle, M. e-Print: 1503.01200)

Athermal phonon

- $P_e(t) = (\varepsilon \cdot \Delta E / \tau_n) \cdot \exp(-t/\tau_n)$ — power pulse to TES
- $\tau_n \propto m^{1/3}$ | $\varepsilon =$ phonons thermalized in the TES
- Thermal remainder $(1-\varepsilon)\Delta E$ via $G_{ta} \sim T^4$, $f_{ta} \sim 0.5$ Hz (slow channel)

Two Operating Modes: Bolometric vs Calorimetric



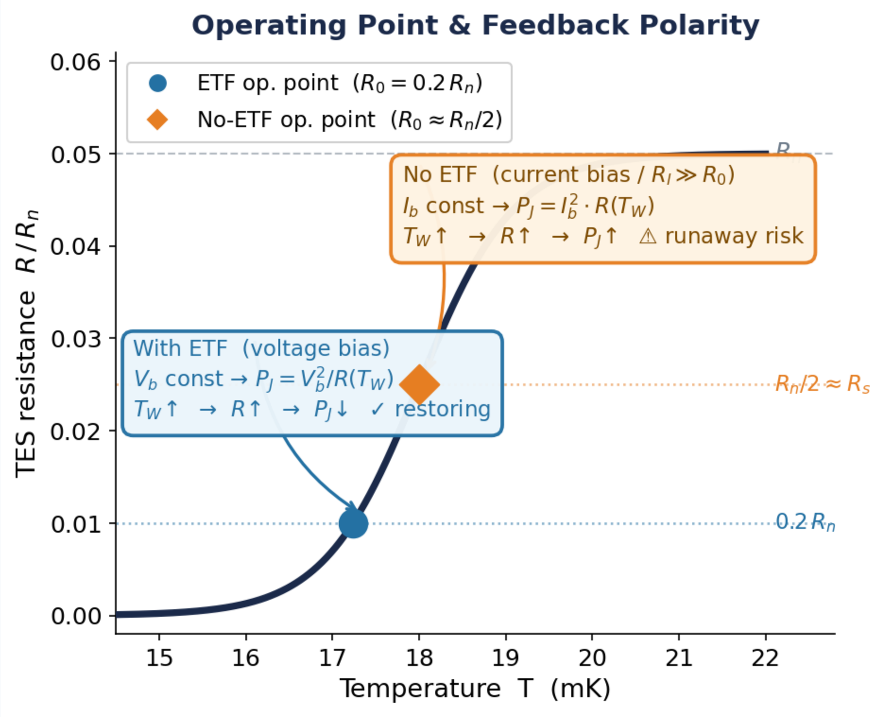
Calorimetric Mode

- Signal = $\Delta E / C_{tot}$ (total deposited energy)
- $\tau_{eff} \approx 104$ ms (slow — both athermal & thermal)
- $\sigma_E \approx 6.6$ eV (100 g BGO, 15 mK)
- ETF optional — P_J provides slow restoring force

Bolometric Athermal Mode

- Signal = $\varepsilon \cdot \Delta E / C_W$ (athermal phonon fraction)
- $\tau_{eff} \approx 10$ ms (faster — ETF speed-up)
- $\sigma_E \approx 4.3$ eV (better — smaller C_W)
- **ETF essential — stabilises R(T) & compresses τ**

Electrothermal Feedback: Stable vs Unstable Operating Point



With ETF (voltage bias, $R\ell \ll R_0$)

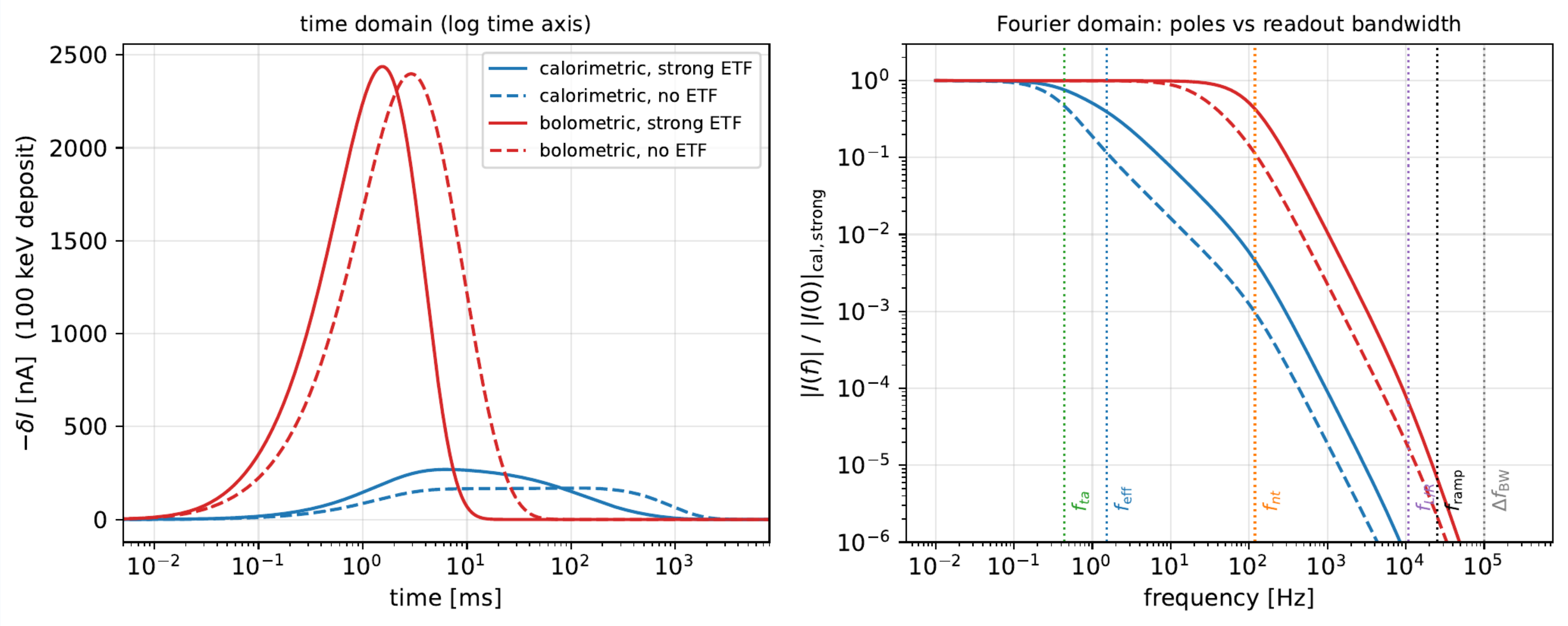
- Operating point: $R_0 \approx 0.2\ R_n$ (low in transition)
- V_b const → $P_J = V^2/R(T_W)$ → T↑ ⇒ R↑ ⇒ P_J↓ ✓ **restoring**
- $\tau_{eff} = \tau_0/(1+\mathcal{L}) \approx \tau_0/4.7$ (fast response)

No ETF (current bias, $R\ell \approx R_0$)

- Operating point: $R_0 \approx R_n/2 \approx R_s$ (mid transition)
- I_b const → $P_J = I^2R(T_W)$ → T↑ ⇒ R↑ ⇒ P_J↑ ⚠ **runaway risk**
- Requires careful G_{tb} tuning to avoid thermal runaway

Pulse Formation & Key Time Constants

Pole hierarchy: f_ta (0.1-1 Hz) << f_S/N (2 Hz) << f_eff (1-10 Hz) << f_nt (55-260 Hz) << f_L/R (3.5 kHz) << f_ramp (25 kHz)



100 keV in 100 g BGO at 15 mK. Left: time-domain pulses (-dI plotted). Right: |I(f)| with poles marked vs f_ramp=25 kHz and DfBW=100 kHz.

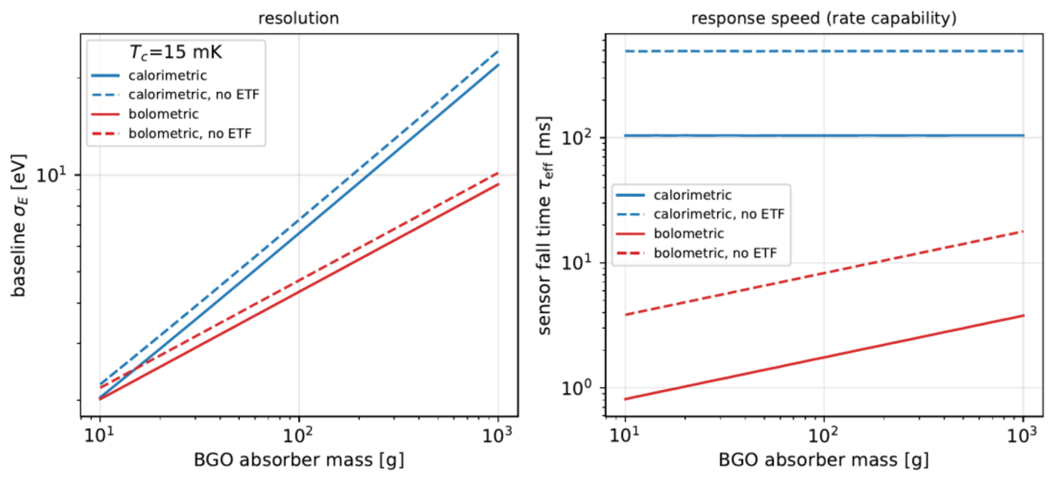
Two Operating Modes on the Same Hardware

CALORIMETRIC — integrates full energy vs C_tot

- G_tb sized for f_S/N ~ 2 Hz << f_nt (integrating limit)
- sigma_E(BGO 100g, 15mK) = 6.6 eV | tau_eff ~ 104 ms
- Best for light crystals < 30 g; thermal component band-limited for heavy ones

BOLOMETRIC (athermal) — measures epsilon*E vs C_W

- G_tb enlarged: f_S/N ~ f_nt | tau_eff ~ 1.8 ms
- sigma_E(BGO 100g, 15mK) = 4.3 eV — overtakes calo above ~30 g
- Strong ETF required for speed + self-stabilization against athermal bursts



Left: resolution vs mass (bolometric overtakes calorimetric above ~30 g). Right: sensor fall time (~100x faster in bolometric mode).

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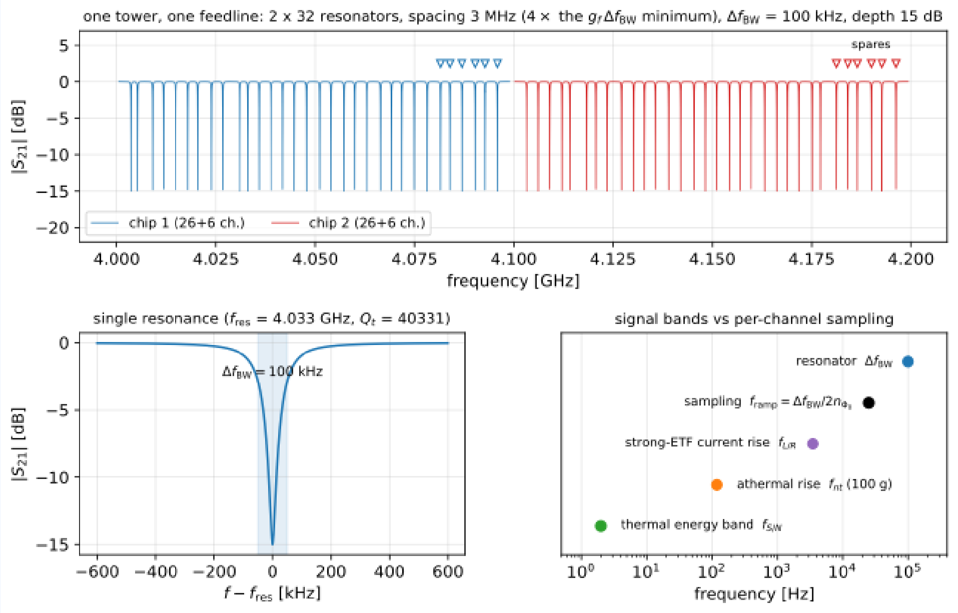
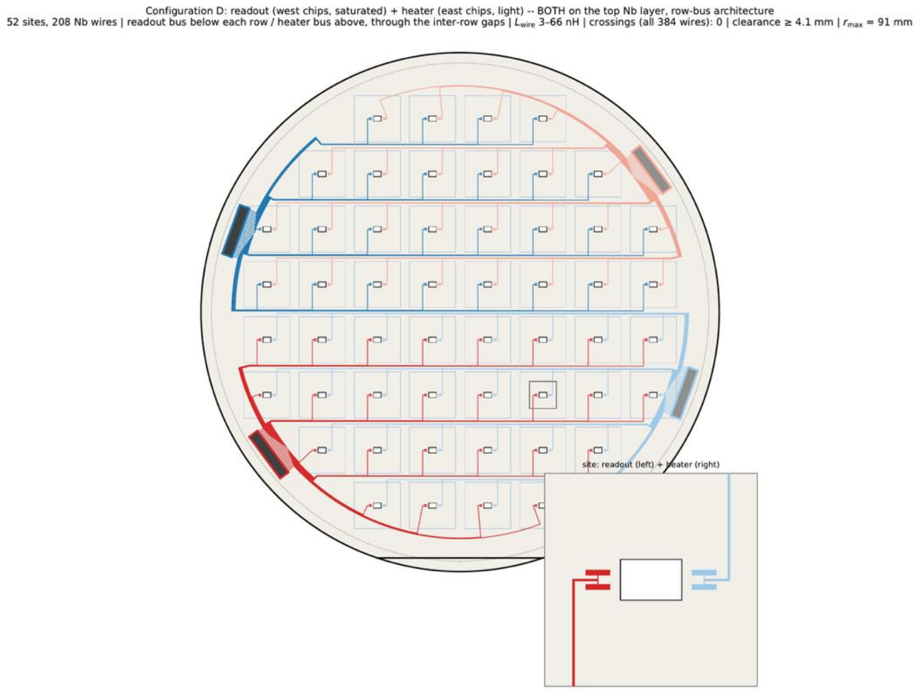
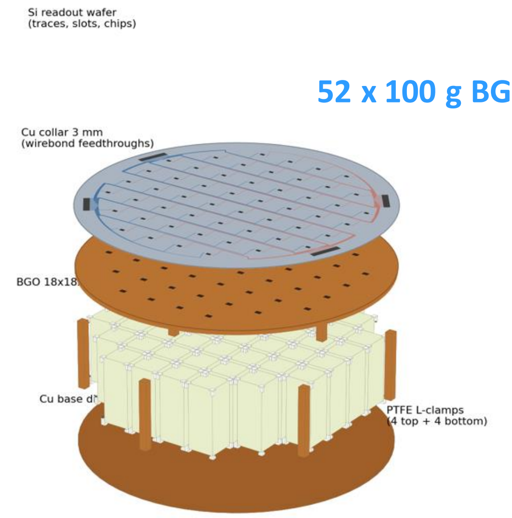


Example Design: 52 BGO Crystals on a 200 mm Si Wafer



Finalized single-layer Nb routing on 200 mm wafer: 52 crystal sites, readout (west) and heater (east) chips.

52 x 100 g BGO = 5.20 kg(east)



Wiring

On-wafer Nb traces: 3-66 nH -> total L_in+L_wire < 1.1 uH -> tau_L/R ~ 46 us -> resolution impact < 10^-4

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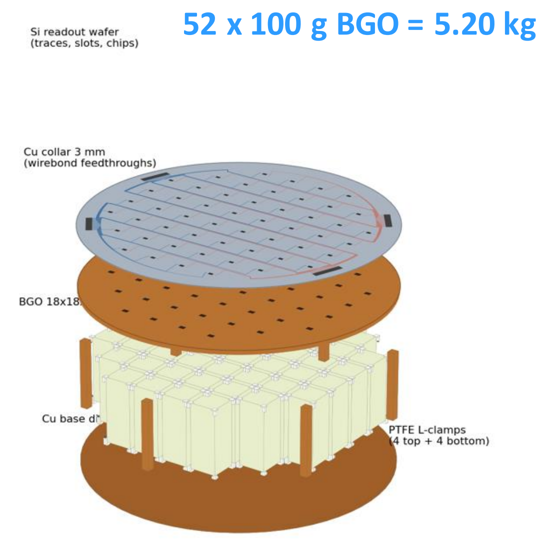
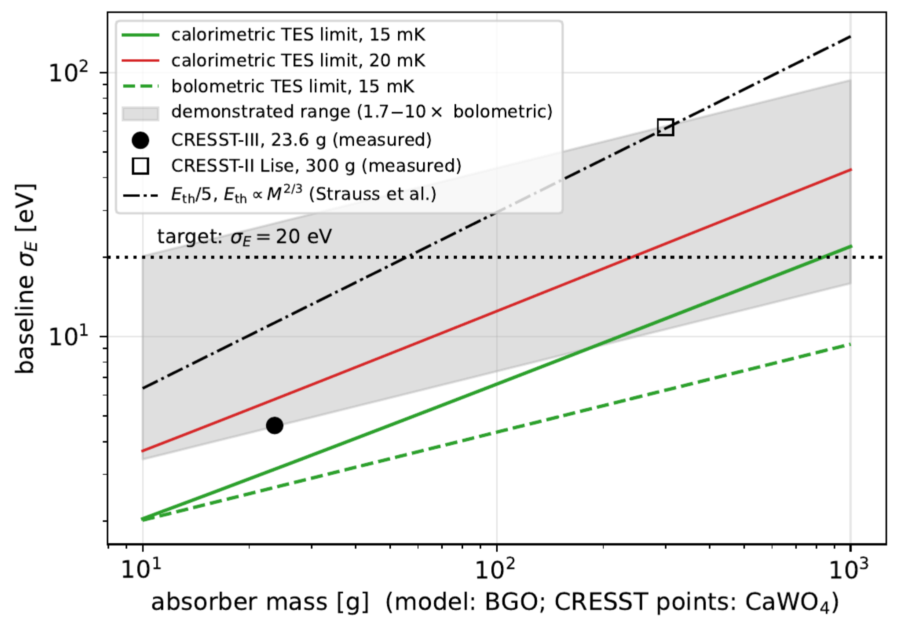


52 x 100 g BGO = 5.20 kg



TES-limited resolution vs mass (BGO example). Grey band: x1.7-10 above bolometric limit (CRESST anchors). Key result is material-independent: sigma ~ sqrt(C_tot).

The Key Design Change: SQUID Input-Coil Sensitivity

Current uMUX devices

1/M_in ~ 23 uA/Phi0

(bare rf-SQUID, M_in ~ 90 pH)

sqrt(S_I_ro) ~ 20-40 pA/rtHz

2-4x above detector noise -> limiting

Required for massive calorimeters

1/M_in = 0.4-1 uA/Phi0

(multi-turn transformer, M_in ~ 2-21 nH)

sqrt(S_I_ro) ~ 0.4-2 pA/rtHz

Conclusions

uMUX is the enabler for future many channels/large scale cryogenic calorimeters

- The bandwidth can serve all TES operations:

- Ton scale 1 keV threshold detectors
- Many-kg scale sub-keV sensitive detectors
- Bolometric for massive units
- Calorimetric for light units
- ETF for better stability & shorter signals

- Routing does not introduce a limiting L
- Need to tune the squid sensitivity