

Probing New Physics with Cryogenic Detectors

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Standard Model (SM) of Particle Physics



Higgs Boson -- One of the biggest successes of SM

- Predicted in the 1960's
- By 1989, there's a book named "The Higgs Hunter's Guide"
- Discovered in 2012
 - Simultaneously by ATLAS and CMS experiments
- All properties measured to be consistent with the SM predictions -- so far
- Q: Does SM describe everything perfectly well?



https://www.science.org/content/article/long- 3 last-physicists-discover-famed-higgs-boson

Shortcomings of the SM

- Doesn't explain gravity
 - The model seems incomplete at the minimum
- Dark matter and dark energy
- Neutrino properties
 - Non-zero masses
 - Antiparticle of itself?
- A few more...





Standard Model of Elementary Particles

Search for New Physics beyond the SM

As an experimentalist...

- Take known deviations from SM
 Eg: Dark matter, neutrino, etc.
- Chase after them until we understand the source of the deviations





Fermilab

Rare event search experiments

- Finding a needle in a haystack...
- Examples:
- Direct detection of WIMP dark matter
 - <O(1) events/(30 kg years)
 - Signal region <10 keV
- Neutrinoless double beta decay (0vbb)
 - <O(1) events/(500 kg year)
 - Signal region ~ few MeV
- Neutrino coherent scattering (CEvNS)
 - ~O(1) events/(10 kg years)
 - Signal region <1 keV
- **Rare** and **low energy** signal require sensitive detectors in a quiet environment



Numbers benchmarked for Xe-based experiments6taken from Hyun Su Lee's presentation in CARLO 2016 here

Starting with Dark Matter Search as an example...

The Evidence for Dark Matter

Galactic Rotation Curves



https://en.wikipedia.org/wiki/Galaxy_rotation_curve

Gravitational Lensing



smithsonianmag.com



~5 times as much dark matter in the universe as regular matter

DM Search Strategies

Complementarity between different types of experiments







The Dark Matter Wind



- Dark matter apparently blows from Cygnus
- Our speed relative to the dark matter halo is ~220 km/s
- ~100,000 particles/cm²/sec
- About 20 million/hand/sec
- Figure taken from the CYGNUS project



Dark matter direct detection



Dark matter direct detection



- If it's that simple, why haven't we seen it?
 - \circ Small interaction probability \rightarrow Big detectors
 - \circ Small energy deposition when interacting \rightarrow More sensitive detectors

SuperCDMS @ SNOLAB **CUTE SuperCDMS SNOLAB Clean room** 2 km SuperCDMS Experiment **Cryogenics plant** 13

Radon filter plant



Dark Matter Search Playground



Dark Matter Search Playground



Dark Matter Search Playground



The SuperCDMS SNOLAB Experiment



Electron Recoil Backgrounds:

- External and facility: O(0.1 /keV/kg/d)
- Det. setup: O(0.1(Ge)-1(Si) /keV/kg/d)
- Total: O(0.1-1 /keV/kg/d)

Facility designed to be dominated by solar neutrinos in NR background

Facility:

- 6000 m.w.e. overburden
- 15 mK base temperature
- Initial Payload: ~30 kg total
 - 4 stacks of six detectors ("towers")
 - 2 iZIP: 10 Ge / 2 Si
 - 2 HV: 8 Ge / 4 Si

Vibration isolation:

- Seismic: spring loaded platform
- Fridge on active vibration damper
- Cryo coolers: soft couplings
 - Braids, bellows
- Copper cans: hanging on Kevlar ropes ¹⁸

Dark matter direct detection detectors

- Dark matter particle interaction deposits energy
- Detectors measure energy in forms of
 - $\circ \quad \text{Ionization} \rightarrow \text{Charge}$
 - $\circ \quad \text{Scintillation} \to \text{Light}$
 - $\circ \quad \text{Heat} \to \text{Phonons}$
- Stealth signal calls for sensitive detectors











SuperCDMS Detector Technology

Discriminating

JZIP Detector:

- Prompt **phonon** and **ionization** signals allow for discrimination between nuclear and electron recoil events detector:
 - Drifting electrons/holes across a potential $(V_{\rm b})$ generates a large number of phonons (Luke phonons).
 - Enables <100 eV low thresholds!
 - Trade-off: No event-by-event NR/ER discrimination



Sensors measure Et, and neh



SuperCDMS Detectors: Posing for the Cameras

- Detectors made of high-purity Ge and Si Crystals
 - Si (0.6 kg each) provides sensitivity to lower dark matter masses
 - Ge (1.4 kg each) provides sensitivity to lower dark matter cross-sections
- Low operation temperature: ~15mK
 - Athermal phonon measurement with TESs
 - Ionization measurement (iZIP) with HEMTs
- Multiple channels per detector to identify event position
- Initial payload will consist of 4 stacks of six detectors ("towers")
 - 2 iZIP: 10 Ge / 2 Si
 - 2 HV: 8 Ge / 4 Si





https://github.com/bloer/bgexplorer-demo

Understanding Background (the haystack) component material Background: extensive material cleaning, tracking and screening • eTraveller: Bookkeeping tool to keep track of material movement Precision accounting for Tower num cosmogenic activations **BGExplorer: Background estimate** sourceclass source based on material assay results and Geant4 based simulations βαckγroµnd **E**Xplorer 25

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SuperCDMS @ SNOLAB Construction Status



SuperCDMS @ SNOLAB Construction Status



Seismic Platform

July 2022 vs Nov. 2024





Cryogenic Underground TEst facility (CUTE)

- Friendly neighbour
- Taking on critical mission of detector testing
 - Exercise and debug detectors
 before SuperCDMS cryostat is in
 place
- Same environment, same electronics
 → similar challenges expected
- First tower test completed earlier this year
- Stay tuned for detailed analysis results!



Detector testing at CUTE

- Operated a HV tower in CUTE
- Gained a tremendous amount of understanding about the detectors and the SNOLAB environment







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Exploring the sensor limit: $HV \rightarrow HVeV$ Detectors





HVeV: Prototype HV detector

- Gram scale
- eV level resolution

Two more facilities for HVeV R&D and operations



Mobile refrigerator, can be deployed in calibration facilities Camping at MP basement now



Cleanroom located ~100 m underground at Fermilab

Single electron-hole pair sensitivity

- "Version 2" of HVeV detectors
- ~3 eV resolution



- Calibrated to hundreds of keV
- Energy resolution < 5% over the full range



091101(R), 2020 031101(R), 2020 2021 032010 ò D. W. Amaral *et al.*, Phys. Re F. Ponce, et al., Phys. Rev. D R. Ren et al., Phys. Rev. D 1 Phys.

Understanding the detector: Nuclear recoil calibration



- Silicon yield (Y) measured down to 100 eV
- Germanium measurement in preparation
- Also exploring even lower energy scale
 - Exploring Lower energy neutrons with ⁵¹V target Ο



Latest Detector Performance

- "Version 3" of HVeV detectors
- Lower transition temperature

eV)

Ē

Size =

(Bin

Counts

Operated at NEXUS and CUTE

- Achieve $\sigma_{h} = 1.097 \text{ eV} \pm 0.003 \text{ eV}$
- Below Silicon bandgap!
- Also with SiO₂ blocking layer
 - Study of leakage ongoing

Energy of Random Triggers



Detector Spectrum

Probing the Neutrinos

- Detector performance approaching neutrino background
- Neutrino interaction through Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
 - First detection in 2017
- Find a neutrino source to study it thoroughly







RICORFICER a reactor neutrino observatory



Grenoble, France Photo credit: Valentina Novati

Institut Laue–Langevin (ILL)



European Synchrotron Radiation Facility (ESRF)



ILL-H7 reactor site



- 58 MW nominal thermal power
- ~11 evts/day/kg (goal : 50 eV_{nr} threshold)
- ~15 m.w.e of overburden
- 3 to 4 cycles per year : **ON/OFF modulation** to subtract uncorrelated backgrounds

Slide from Nicolas MARTINI, Magnificent CEVNS, 2024 Fast and thermal neutron flux characterized : RICOCHET COII. EPJC 83 (2023), 20



Reactogenic neutrons negligible (~10%) Targeted neutron background levels achievable to reach **S/B=1** Slide from Nicolas MARTINI, Magnificent CEvNS, 2024

CryoCube detectors



Particle ID based on Ionization/Heat ratio

$$Q = E_{ion}/E_{recoil}$$

- Electronic recoils : Q = 1
- Nuclear recoils : Q ~ 0.3 (Lindhard)



Planar : Fiducial volume = 98.6%

No surface events rejection



FID : Fiducial volume = 62%

Surface events rejection

Final detector design will be based on on-site data-driven CEvNS sensitivity

CryoCube specifications . MiniCryoCube:

3 Ge bolometers with their cold electronics (1 K)



CryoCube (Spring 2025): 3 MiniCryoCubes per level, 2 levels → Array of 18 x 38 g @ ~10 mK



- Heat resolution: 20 eV (RMS)
- Ionization resolution:
 20 eVee (RMS)
- Timing resolution:
 ~100 us @ 100 eV
- Detector payload:
 680 g
- Two detector technologies: planar and FID electrodes

→ Achieve Particle ID down to O(10) eV with a rejection > 10^3

Paper on Ionization performances of the MiniCryoCube: RICOCHET Coll. EPJC **84** (2024), 186

Slide from Nicolas MARTINI, Magnificent CEvNS, 2024

Commissioning @ ILL

Outer shielding (Mar 2023): Lead for gammas: 20 cm Polyethylene for neutrons: 35 cm Soft iron for magnetic field: ~1 ton





Cryostat installation: Nov 2023 - Feb 2024



RUN012 (Feb 2024): Cryogenic validation run → Minimum temperature without payload: 8.6 mK

Commissioning @ ILL

First in-situ detector performance assessment

Reactor OFF data

Selection of ER events:

- Ionization energy:
 E_{ion} > 400 eV_{ee}
- Ionization yield:

Q > 0.4

Baseline resolutions (preliminary):

- Ionization: 40-45 eV_{ee}
- Heat: 35-40 eV_{ee}



Commissioning @ ILL

First in-situ detector performance assessment

Reactor ON data

Selection of ER events:

- Ionization energy:
 E_{ion} > 400 eV_{ee}
- Ionization yield:

Q > 0.4

Baseline resolutions (preliminary):

- Ionization: 45-47 eV
- Heat: 25-27 eV_{ee}



Similar ON/OFF performances

Prospects

2024:

- Finalization of outer and cryogenic muon veto installation
- Commissioning of readout electronics and synchronization
- First data-driven CEvNS sensitivity estimation from commissioning phase

Spring 2025:

- Completion of the full CryoCube payload and dedicated electronics
- Beginning of the RICOCHET CryoCube neutrino science phase

2025-2026:

• Cumulate 7 ON/OFF reactor cycles to achieve nominal exposure



- Large detector array
- Lower threshold
- Faster detector response
- More variety of detector target materials

Potential solution:

- TES-based detector
 - Remember the 1 eV prototype?
- "Remote readout"
- Microwave multiplexing readout ⁴⁷

NIM A 1057 (2023) 168765

Modular TES detector

- Thermally couple a TES thermometer onto an arbitrary target
- Target can be almost any solid: semiconductor, metal, superconductor, etc
 - **12 eV** resolution achieved on 1 gram silicon
 - **0.85 keV** resolution on 21 gram Li_2MoO_4
 - Excellent detector also for neutrinoless double beta decay!
 - Ask me later if you're interested
- Further improvements to come







Conclusions

- Searching for Physics beyond the Standard Model remains an intriguing field
- Cryogenic phonon detectors play a critical role
- **SuperCDMS** well suited for low mass DM searches
 - Low threshold enables low mass NR searches
 - HVeV detectors achieve 1 eV phonon resolution and 0.01 charge resolution
- **Ricochet** commissioning at ILL started
 - First batch of detector works well, more to come
 - Expect 7 reactor cycles in 2025-2026
 - Next generation detector in the development
- Stay tuned!

Bonus Slides

Our team





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Miriam Diamond (PI)



Leslie Groer (technician)



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Simon Harms (grad)



Weigeng Peng (grad)



Stefan, Tom, Birgit (post-doc neighbours)

Neutrinoless double-beta decay ($0v2\beta$)

- Double-beta decay with the emission of two neutrinos
- $2\vee 2\beta: (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu_e}$

• 0v2β is a hypothetical nuclear process

$$\mathsf{Ov2}\beta:(A,Z)\to(A,Z+2)+2e^{-1}$$

 Fundamental question: Is neutrino its own anti-particle?









Iterations of HVeV dark matter experiments



- Burst events detection and study
- Hypothesis: originated by SiO₂ in the detector holder (PCB)



- Coincidence measurement
- Confirmed external origin of this
 background and its reduction with •
 coincidence detections



- Removed PCB from detector holder
- Elimination of quantized background above 1eh peak



Low mass dark matter search background challenges



Silicon Compton Steps

- Using Compton steps:
- Irradiate with O(100) keV gamma rays.
 - Scattering with atomic electrons.
- Scattering probability proportional to number of electrons that can be excited
 - Binding energies creates step-like structures
- Can be used for calibration down to 100 eV



Similar structure confirmed by CCD data from DAMIC-M (PhysRevD 106, 092001, 2022) 58

Silicon Compton Steps **Ongoing efforts**

- Cs-137 calibration data with Si HVeV detector at NEXUS
- Expected features:
 - 662 keV Cs gamma line Ο
 - 447 keV Compton edge Ο
 - 8.04 keV Copper x-ray Ο
 - **Detector housing!**
 - Si 1.84 keV Compton step Ο
 - Si 99/150 eV Compton steps Ο
- Cross-calibration with optical photon calibration at high voltage
 - Single e-h peaks visible up to a few keV Ο
- Results expected this year!



SuperCDMS Detectors & Dark Matter Mass Scales

- Dark Matter Mass Ranges
 - "Traditional" Nuclear Recoil:
 - Low Threshold NR:
 - HV Detector:
 - Migdal & Bremsstrahlung:
 - Electron recoil:
 - Absorption (Dark Photons, ALPs): HV, no discrimination,

Full discrimination,≥Limited discrimination,≥HV, no discrimination,~no discrimination,~HV, no discrimination,~HV, no discrimination,~

≥ 5 GeV
≥ 1 GeV
~0.3 - 10 GeV
~0.01 - 10 GeV
~0.5 MeV - 10 GeV
~1 eV - 500 keV ("peak search")



TES readout of Li_2MoO_4 for

- LMO-TES readout
 - RMD crystal in NEXUS measurement setup
 - 21 g 2 cm cube
 - 0.5 ms rise-time
 - A full size CUPID detector with this response would result in a remaining pile-up background of 5 x 10⁻⁶ counts/keV/kg/yr





TES readout of Li_2MoO_4 for

LMO-TES readout

- Good baseline resolution in 1st test
- Sufficient dynamic range
- Energy dependent broadening to be understood
- · Sensitivity to surface events near Au film
 - Possibility of surface background suppression to be investigated



Detecting Low Mass DM

- Low mass WIMP models predicts low recoil energies
- Direct detection experiments often limited by energy resolution and threshold
- Electron recoil models also require ideally single charge sensitivity

