

# 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)</li>
  - Signal region <10 keV</li>
- Neutrinoless double beta decay (0vbb)
  - <O(1) events/(500 kg year)</li>
  - Signal region ~ few MeV
- Neutrino coherent scattering (CEvNS)
  - ~O(1) events/(10 kg years)
  - Signal region <1 keV</li>
- **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/cm<sup>2</sup>/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 <sup>18</sup>

### 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

Ο

# 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</li>



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 <sup>51</sup>V 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 SiO<sub>2</sub> 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

![](_page_35_Figure_5.jpeg)

![](_page_35_Picture_6.jpeg)

![](_page_35_Picture_7.jpeg)

# RICORFICER a reactor neutrino observatory

![](_page_36_Picture_1.jpeg)

Grenoble, France Photo credit: Valentina Novati

#### Institut Laue–Langevin (ILL)

![](_page_37_Picture_2.jpeg)

European Synchrotron Radiation Facility (ESRF)

![](_page_38_Figure_0.jpeg)

# ILL-H7 reactor site

![](_page_39_Figure_1.jpeg)

- 58 MW nominal thermal power
- ~11 evts/day/kg (goal : 50 eV<sub>nr</sub> 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

![](_page_39_Figure_7.jpeg)

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

# CryoCube detectors

![](_page_40_Figure_2.jpeg)

Particle ID based on Ionization/Heat ratio

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

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

![](_page_40_Picture_7.jpeg)

**Planar :** Fiducial volume = 98.6%

No surface events rejection

![](_page_40_Figure_10.jpeg)

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)

![](_page_41_Figure_3.jpeg)

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

![](_page_41_Picture_5.jpeg)

- 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

![](_page_42_Picture_3.jpeg)

![](_page_42_Picture_4.jpeg)

**Cryostat installation:** Nov 2023 - Feb 2024

![](_page_42_Picture_6.jpeg)

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<sub>ion</sub> > 400 eV<sub>ee</sub>
- Ionization yield:

Q > 0.4

# Baseline resolutions (preliminary):

- Ionization: 40-45 eV<sub>ee</sub>
- Heat: 35-40 eV<sub>ee</sub>

![](_page_43_Figure_10.jpeg)

# Commissioning @ ILL

First in-situ detector performance assessment

#### Reactor ON data

#### Selection of ER events:

- Ionization energy:
   E<sub>ion</sub> > 400 eV<sub>ee</sub>
- Ionization yield:

Q > 0.4

# Baseline resolutions (preliminary):

- Ionization: 45-47 eV
- Heat: 25-27 eV<sub>ee</sub>

![](_page_44_Figure_10.jpeg)

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

![](_page_46_Figure_0.jpeg)

- 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 <sup>47</sup>

#### 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

![](_page_47_Figure_9.jpeg)

![](_page_47_Picture_10.jpeg)

![](_page_47_Picture_11.jpeg)

# 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

![](_page_50_Picture_1.jpeg)

![](_page_50_Picture_2.jpeg)

Pekka Sinervo (PI)

![](_page_50_Picture_4.jpeg)

**Miriam Diamond** (PI)

![](_page_50_Picture_6.jpeg)

Leslie Groer (technician)

![](_page_50_Picture_8.jpeg)

Maddy Zurowski Peter McNamara (post-doc) (post-doc)

![](_page_50_Picture_10.jpeg)

**Gillian Godden** (grad)

![](_page_50_Picture_12.jpeg)

![](_page_50_Picture_13.jpeg)

Ata Sattari

(grad)

Imran Alkhatib (grad)

![](_page_50_Picture_16.jpeg)

Enze Zhang (grad)

![](_page_50_Picture_18.jpeg)

![](_page_50_Picture_19.jpeg)

![](_page_50_Picture_20.jpeg)

**Antoine Rehberg** (grad)

**Matthew Penner** (grad)

![](_page_50_Picture_23.jpeg)

Quark

Qubit

Warren Perry (grad)

### Our team

![](_page_51_Picture_1.jpeg)

Ziqing Hong (PI)

![](_page_51_Picture_3.jpeg)

Tyler Reynolds (post-doc)

![](_page_51_Picture_5.jpeg)

Ariel Zuniga & Vijay Iyer (post-docs)

![](_page_51_Picture_7.jpeg)

Jeter Hall Adjunct (SNOLAB)

![](_page_51_Picture_9.jpeg)

Andrew Kubik Adjunct (SNOLAB)

![](_page_51_Picture_11.jpeg)

Matt Stukel Adjunct (SNOLAB)

![](_page_51_Picture_13.jpeg)

Elspeth Cudmore (grad)

![](_page_51_Picture_15.jpeg)

Mason Buchanan (grad)

![](_page_51_Picture_17.jpeg)

Simon Harms (grad)

![](_page_51_Picture_19.jpeg)

Weigeng Peng (grad)

![](_page_51_Picture_21.jpeg)

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?

![](_page_52_Figure_6.jpeg)

![](_page_52_Figure_7.jpeg)

![](_page_53_Figure_0.jpeg)

![](_page_54_Figure_0.jpeg)

### Iterations of HVeV dark matter experiments

![](_page_55_Picture_1.jpeg)

- Burst events detection and study
- Hypothesis: originated by SiO<sub>2</sub> in the detector holder (PCB)

![](_page_55_Picture_4.jpeg)

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

![](_page_55_Picture_7.jpeg)

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

![](_page_55_Figure_10.jpeg)

### Low mass dark matter search background challenges

![](_page_56_Figure_1.jpeg)

## 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

![](_page_57_Figure_7.jpeg)

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!

![](_page_58_Figure_13.jpeg)

### 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")

![](_page_59_Figure_10.jpeg)

# TES readout of $\text{Li}_2\text{MoO}_4$ 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<sup>-6</sup> counts/keV/kg/yr

![](_page_60_Figure_6.jpeg)

![](_page_60_Figure_7.jpeg)

# 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

![](_page_61_Figure_7.jpeg)

# 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

![](_page_62_Figure_4.jpeg)