FREQUENCY MULTIPLEXING OF CRYOGENIC SENSORS
FOR THE RICOCHET EXPERIMENT

CPAD Workshop

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Open questions in particle physics ...

• What can we learn from coherent $\nu$ scattering at a reactor?
• How do particle interactions in superconducting crystals look like?

... And more practical ones ...

• How to lower the recoil threshold?
• Can we scale up the readout of segmented cryogenic detectors?

... Can quantum technologies help?
CE$\nu$NS was proposed 50 years ago!
Flavour-independent and sensitive to new physics.

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\[
\frac{d\sigma}{dE_{\text{recoil}}} = \frac{G_F^2 M}{4\pi} [Z(1 - 4\sin^2 \theta_W) - N]^2 \left(1 - \frac{M_N E_r}{2E^2_\nu}\right) F_W^2(q^2)
\]

Target trade-off between \( \sigma \propto N^2 E^2_\nu \) and \( E^\text{max}_r \approx \frac{2E^2_\nu}{M_N} \)

[Freedman, 1974]
COHERENT ELASTIC $\nu$-NUCLEUS SCATTERING

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Flavour-independent and sensitive to new physics.

$$\frac{d\sigma}{dE_{\text{recoil}}} = \frac{G_F^2 M}{4\pi} \left[ Z(1 - 4\sin^2 \theta_W) - N \right]^2 \left( 1 - \frac{M_N E_r}{2E^2_{\nu}} \right) F^2_w(q^2)$$

Target trade-off between $\sigma \propto N^2 E^2_{\nu}$ and $E^\text{max}_r \approx \frac{2E^2_{\nu}}{M_N}$

First observed by COHERENT at the Spallation Neutron Source, Pion decay at rest source kg-scale sodium-doped CsI scintillator in 2017.

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CEνNS has been discovered... Why would we look for it at a reactor?

Reactor neutrino energies are an order of magnitude below pion-decay-at-rest neutrinos → **Recoil energies** are two orders of magnitude lower!

- Form factor less important, almost purely coherent.

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### Diagram Description

- **Event rate vs. Recoil Energy**
- **v-flux**: $10^{12} \text{ cm}^{-2} \text{s}^{-1}$
- **Ge Target**
- **Standard Model**
- **Reactor neutrino nuclear recoil endpoint**: $\sim 1 \text{ keV}$

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- **higher sensitivity to new physics**
  - Neutrino magnetic moment
  - BSM Light Mediators
  - Sterile neutrino oscillations

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- Reactors offer **challenging background** conditions with muons, gamma’s and neutrons.
Ricochet aims to build a low-energy reactor neutrino observatory at the ILL reactor in France.

- A double cryogenic detector payload: Cryocube (Germanium crystals) and Q-Array (Superconducting crystals).
- Modular kg-scale detector
- Complementary technologies with Discrimination between electronic (ER) and nuclear recoil (NR)
- Active R&D with the first phase starting to take $\nu$ data mid 2024.

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THE RICOCHET EXPERIMENT: CRYOCUBE + Q-ARRAY

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The detectors and readout chain envisaged can be broken up into four parts that are designed, fabricated and tested individually. Each of these has applications beyond CE$\nu$NS and is pursued by many quantum computing and fundamental physics projects.
CRYOGENIC FREQUENCY MULTIPLEXING

**Diagram:**
- Ti + Au Crystal
- TES
- RF Multiplexer
- TWPA
- Frequency symbol (ν)
Why?

- **Mass/size per detector limited** to the $O(\text{cm})$ scale to keep heat capacity small and have *ballistic phonon and QP propagation* [Hochberg et al., 2016].
- CE$\nu$NS, $0\nu\beta\beta$ and WIMP *rates scale with detector mass*.
- Next generation experiments will aim at $O(100)$ *channels*.
- **Minimise heat load** and cold-stage complexity.
MULTIPLEXING TES ARRAYS

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• Frequency domain multiplexing
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- **Time domain multiplexing**
  Noise scales with $\sqrt{\#\text{channels}}$.
- **Frequency domain multiplexing**
  Limited by single SQUID bandwidth of $\mathcal{O}(\text{MHz})$.
- **Code domain multiplexing**
  TES-SQUID wiring complexity scales as $(\#\text{channels})^2$. 
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  → Microwave-SQUID multiplexing ($\mu$MUX)
MICROWAVE MULTIPLEXING: THE CONCEPT

FROM HOLMES (2019)
Resonator devices fabricated using tri-layer Al process at Lincoln Laboratories.
Resonator monitoring and phase demodulation from Holmes (2019)

\[ |S_{21}| \text{ [dB]} \]

\[ \delta f \]

\[ \phi(S_{21}) \text{ [rad]} \]

\[ \delta \phi \]

\[ f_0 \]

\[ f \]

\[ \phi_1 = 9.83 \]

\[ \phi_2 = 3.21 \]

\[ \phi_3 = 1.36 \]

\[ \phi_4 = 0.67 \]

\[ \phi_5 = 0.36 \]

\[ \phi_6 = 0.20 \]

\[ \text{ramp} \]

\[ \text{free oscillations} \]

\[ \text{transient} \]

\[ \text{Time [ms]} \]

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MICROWAVE MULTIPLEXING: MEASUREMENT SETUP

- Frequency Generator
- Spectrum Analyser
- Network Analyser
- HEMT Amplifier
- Room Temperature Amp
- Directional Coupler
- RF Switch
- Resonators
- Isolator
- RF Switch
- 4K
- 10dB
- 20mK
- Through line
Resonant frequency depends on the current through the inductance.

- **Periodicity** enables determination of flux quantum \( \Phi_0 \).
Resonant frequency depends on the current through the inductance.

- **Periodicity** enables determination of flux quantum \( \Phi_0 \).
- **Sensitivity** of \( \approx 4\mu\Phi_0/\sqrt{\text{Hz}} \) measured, Translates to \( \approx 30\text{pA}/\sqrt{\text{Hz}} \) TES current noise.
Comparison of design and measured parameters

- $|S_{21}|$ fit to extract resonant frequency, internal and external quality factor.
- Fit of resonant frequency as a function of SQUID flux and probe tone power to obtain inductances.

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MULTI-RESONATOR READOUT WITH TONE TRACKING

[Yu et al., 2023]

Fully automated readout using SLAC Microresonator RF (SMuRF) Electronics.

- Complexity moved to warm electronics.
- FPGA-based resonator tone-tracking.
- DAQ with TES-pulse demodulation.
- Capable of up to $\mathcal{O}(1000)$ channels.

Test setup at MIT with 18 resonator device.
Injected signal-like pulse train reconstructed with MIT multiplexer and SMuRF electronics!
CONCLUSION & OUTLOOK
CONCLUSION & OUTLOOK

The Ricochet Experiment

- CEνNS **cross-section** using cryogenic detectors.
- Expected to take reactor **data in 2024** in France.

Superconducting Crystal and TES Measurements

- **Pulses** in prototype superconducting Al crystal.
- Energy **calibration using sources** in progress.

Q-Array RF multiplexed Readout

- Optimised **18-resonator devices fabricated**.
- R&D into **high dynamic range quantum amps**.
Thank you!

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Joseph Formaggio & Ricochet,
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William Oliver, Steve Weber,
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Cyndia Yu, Shawn Henderson, Zeeshan Ahmed

The transferred momentum of a \( \nu \) ping pong ball of a nucleus bowling ball is \( \approx 2E_\nu \). The interaction will only be coherent if the transferred momentum is small compared to the radius of the nucleus:

\[
2E_\nu < \frac{1}{r_N} \approx \frac{3\sqrt{A}}{200 \text{ MeV}}
\]

For higher \( E_\nu \), form factors need to be taken into account.
The recoil energy of the nucleus can be calculated exactly like Compton scattering:

\[ E_r = \frac{E_{\nu}^2(1 - \cos \theta)}{M_N + E_{\nu}(1 - \cos \theta)} \]

\[
\frac{d\sigma}{dE_{\text{recoil}}} = \frac{G_F^2 M}{4\pi} [Z(1 - 4 \sin^2 \theta_W) - N]^2 \left(1 - \frac{M E_r}{2 E_{\nu}^2}\right) F_W^2(q^2)
\]
The recoil energy of the nucleus can be calculated exactly like Compton scattering

\[ E_r = \frac{E^2}{M_N} \left( 1 - \cos \theta \right) + E_{\nu} \left( 1 - \cos \theta \right) \]

Trade-off between \( \sigma \propto N^2E_{\nu}^2 \) and \( E_{r_{\text{max}}} \approx \frac{2E_{\nu}^2}{M_N} \)

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The COHERENT Experiment at the Spallation Neutron Source, Oak Ridge National Laboratory

**Pion decay at rest** source with a 14.6-kg sodium-doped CsI scintillator in 2017.

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Map out $N^2$ dependence and test the SM with a variety of technologies and targets!

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# Current Status of CE$\nu$NS Reactor Experiments

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<tr>
<th>Experiment</th>
<th>Technology</th>
<th>Location</th>
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</thead>
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<tr>
<td>$\nu$Gen</td>
<td>HPGe, ionisation</td>
<td>KNPP, Russia</td>
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<td>Si/Ge, MKIDs</td>
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<tr>
<td>CONNIE</td>
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<td>CONUS</td>
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<td>News-G</td>
<td>Spherical proportional counter</td>
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<td>Neon</td>
<td>NaI(Tl) crystal</td>
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<td>SBC</td>
<td>Scintillating bubble chamber</td>
<td>Mexico</td>
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THE RICOCHET EXPERIMENT @ ILL REACTOR IN FRANCE

Reactor Core
8.8m distance to core
12.8 evts/day/kg (above 50eV threshold)

Cryostat & Shielding

Local Crane (1t)

Technical Cabin (pumps etc.)

Control Cabin

Shielding Rails

Calibration Source

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Basic thermalised microcalorimeter principle

- Energy $E$ gets deposited into the absorber and thermalises.
- Strong thermal link $G_{\text{sensor-absorber}}$ connects to the sensor.
- Absorber-sensor system heats up with $\Delta T = E/C_{\text{tot}}$.
- Weak thermal link with bath sets the decay time of the pulse.

Small absorber+sensor heat capacity leads to large thermalised signals at millikelvin temperatures!