Project 8

A frequency-based tritium endpoint experiment

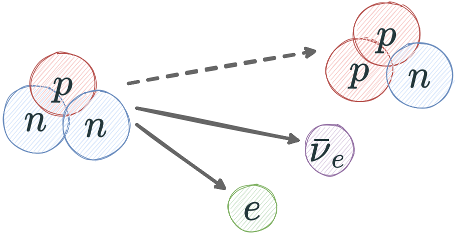
Lake Louise Winter Institute 2022

Wouter Van De Pontseele for the Project 8 Collaboration wvdp@mit.edu

February 23, 2021

Massachusetts Institute of Technology

Project 8: Outline & Introduction



Goal of the Project 8 Experiment

Measure the absolute **neutrino mass** m_β in case of **inverted ordering**, or **limit** m_β to $0.04\,\mathrm{eV}$ in the case of **normal ordering with smaller mass**.

Outline

1. **Neutrino mass** determination
   by measuring cyclotron radiation frequency.
2. Challenges ahead, a **phased approach**.
3. **Quantum**-limited microwave **amplification**.

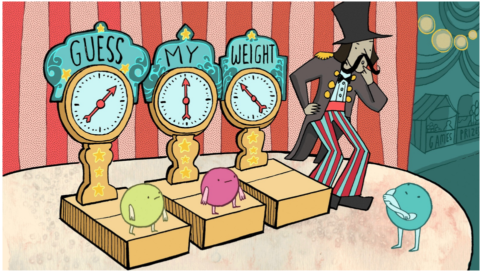
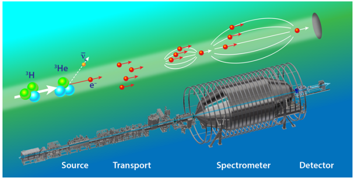


Figure by Symmetry Magazine

NEUTRINO MASS MEASUREMENT: STATUS



Direct methods:

- Rely on the distributions of the neutrino and electron **kinetic energy** in β**-decay processes**.
- Current experimental limit from **KATRIN** is 0.8 eV/c^2. The projected sensitivity is 0.2 eV/c^2

NEUTRINO MASS MEASUREMENT: STATUS

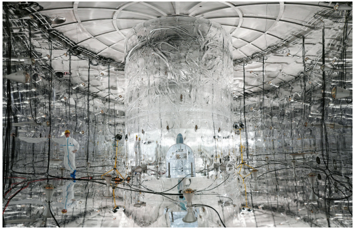


Figure by GERDA

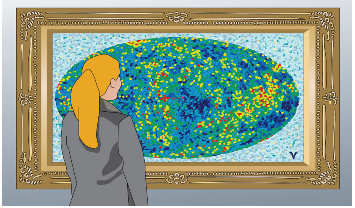


Figure by Symmetry Magazine

Direct methods:

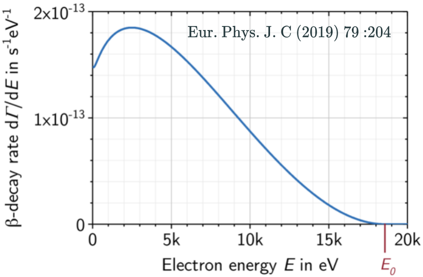
- Rely on the distributions of the neutrino and electron **kinetic energy** in β**-decay processes**.
- Current experimental limit from **KATRIN** is 0.8 $\mathrm{eV/c^2}$. The projected sensitivity is 0.2 $\mathrm{eV/c^2}$

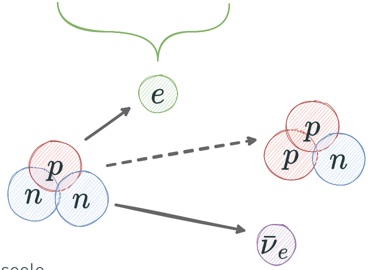
Indirect methods:

- **Neutrino Oscillations** set a lower bound on m_β.
- **Neutrinoless double beta decay**: Currently not yet observed.
- **Cosmology**, through the signatures of growth and evolution of large scale structures in the cosmic microwave background.

→ **Indirect is model dependent.**

NEUTRINO MASS MEASUREMENTS: TRITIUM ENDPOINT METHOD



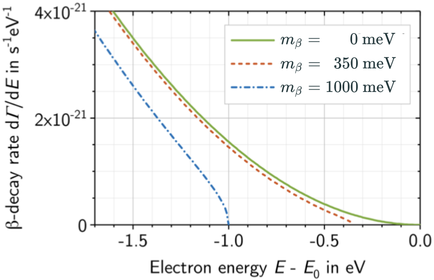


Electron energy distribution from tritium β-decay:

$$\frac{dN}{dE} \sim (E_0 - E)\sqrt{(E_0 - E)^2 - m_\beta^2}$$

$$m_\beta = \sqrt{\sum_{i=1}^{3} \mid U_{ei}^2 \mid m_i^2}$$

zoom in around endpoint E_0



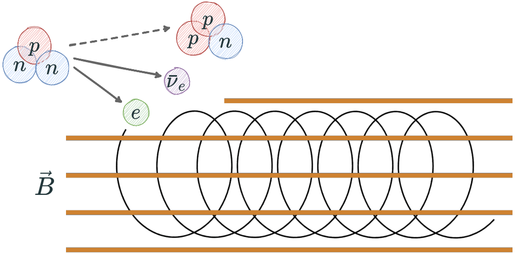
PROJECT 8: A FREQUENCY MEASUREMENT

How to **scale down** the experiment while **increasing** the neutrino mass **sensitivity**?

1. Use a **source inside** the **detector** volume.
2. The use of **cyclotron radiation** emitted by electrons in a magnetic field enables **frequency detection** of microwaves.

The **Project 8 collaboration** employs Cyclotron Radiation Emission Spectroscopy (CRES)

Tritium decays inside a **uniform** $\vec{B}$-field.

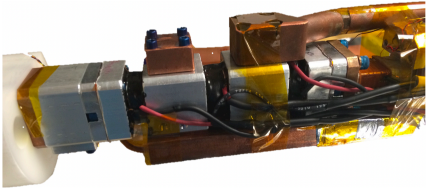


Electron performs **cyclotron motion** with frequency

$$f(B, E_{kin}) = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

PROJECT 8: A PHASED APPROACH

- First detection of **cyclotron radiation from a single electron**. Gaseous ^{83m}Kr used as a source.
  Phys. Rev. Lett. 114, 1162501 (2015)
- Analysis steps
  1. Time series
  2. Frequency spectrum each $\mathcal{O}(0.1\,\mathrm{ms})$.



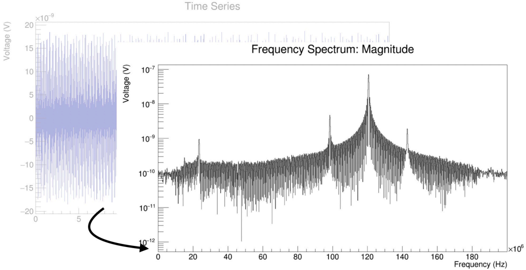
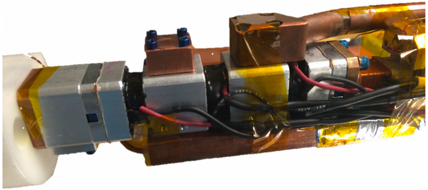
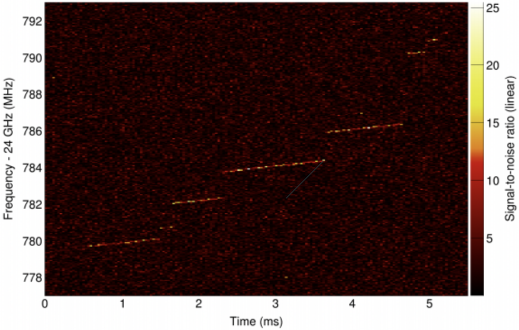


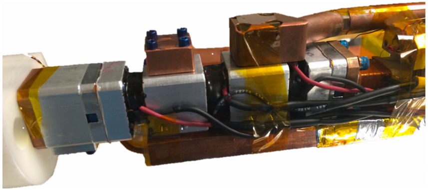
Figure by P. Surukuchi

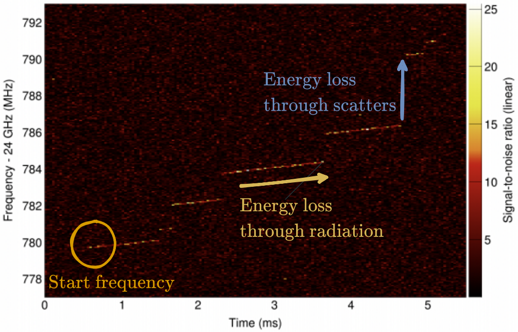
- First detection of **cyclotron radiation from a single electron**. Gaseous ^{83m}Kr used as a source.
  Phys. Rev. Lett. 114, 1162501 (2015)
- Analysis steps
  1. Time series
  2. Frequency spectrum each $\mathcal{O}(0.1\,\mathrm{ms})$.
  3. 2D spectrogram





- First detection of **cyclotron radiation from a single electron**. Gaseous ^{83m}Kr used as a source.
  Phys. Rev. Lett. 114, 1162501 (2015)
- Analysis steps
  1. Time series
  2. Frequency spectrum each $\mathcal{O}(0.1\,\mathrm{ms})$.
  3. 2D spectrogram
  4. Track identification
  5. Start frequency fitting





PROJECT 8: A PHASED APPROACH

PHASE II

- First Project 8 **limit on the neutrino mass** using gaseous tritium and a waveguide antenna.
  Publication in preparation

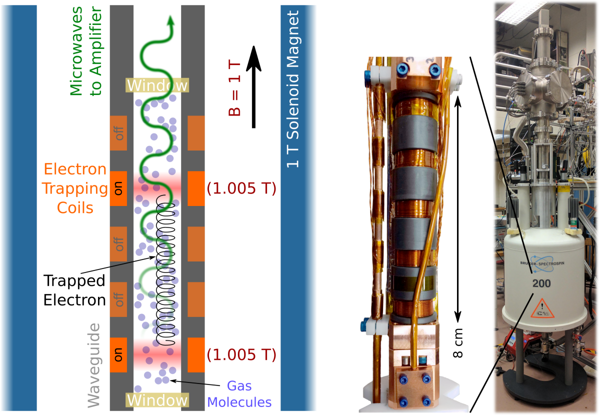


Figure by A. Lindman

PROJECT 8: A PHASED APPROACH

PHASE II

- First Project 8 **limit on the neutrino mass** using gaseous tritium and a waveguide antenna.

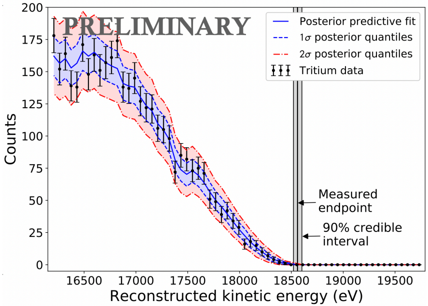
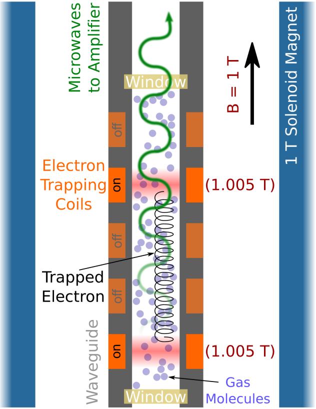


Figure by T. Weiss



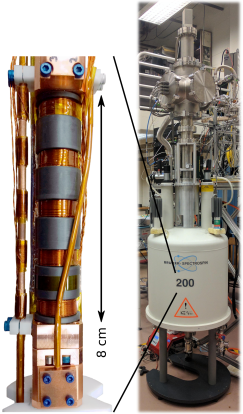
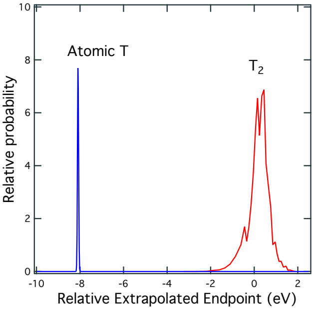
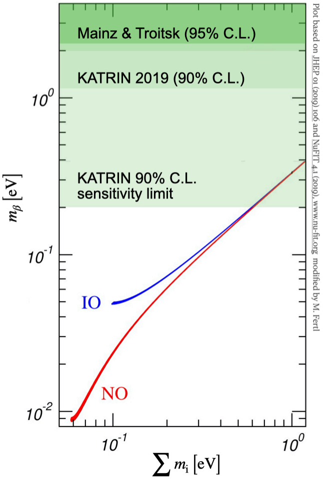


Figure by A. Lindman

ATOMIC TRITIUM DEMONSTRATOR

Atomic tritium is **required** due to uncertainty in **final states** of molecular tritium.





Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

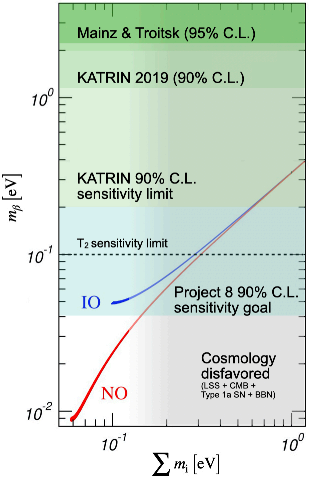
Figure by M. Fertl

ATOMIC TRITIUM DEMONSTRATOR

Atomic tritium is **required** due to uncertainty in **final states** of molecular tritium.

$\Rightarrow$ Create a pure atomic tritium source delivering $\mathcal{O}\left(10^{18}\text{atoms}\,/\text{m}^3\right)$ density.

- A **dissociator** to produce atoms from molecules (thermal cracker).
- **Accomodator** to cool down the atoms to $\approx 8\,\mathrm{K}$
- **Velocity and state** based **selection** of trappable atoms.
- A **magnetic neutral atom trap** (Halbach of Ioffe array)



Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

Figure by M. Fertl

ATOMIC TRITIUM DEMONSTRATOR

Atomic tritium is **required** due to uncertainty in **final states** of molecular tritium.

$\Rightarrow$ Create a pure atomic tritium source delivering $\mathcal{O}\left(10^{18}\text{atoms}/\text{m}^3\right)$ density.

- A **dissociator** to produce atoms from molecules (thermal cracker).
- **Accomodator** to cool down the atoms to $\approx 8\,\mathrm{K}$
- **Velocity and state** based **selection** of trappable atoms.
- A **magnetic neutral atom trap** (Halbach of Ioffe array)

All steps being developed at Project 8 institutions
High-flow hydrogen cracking demonstrated.

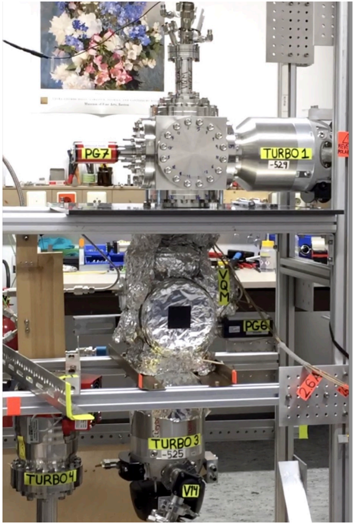


Figure by A. Lindman

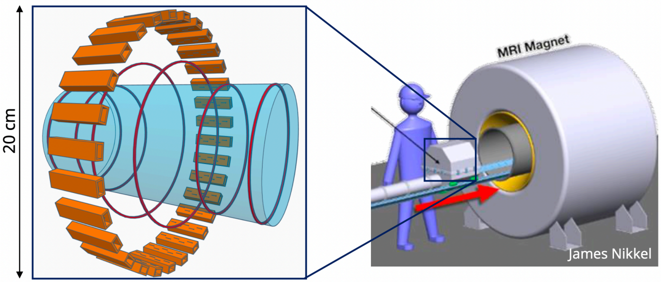
PHASE III: SCALING UP TO LARGE VOLUMES

OPTION 1: CRES IN FREE SPACE

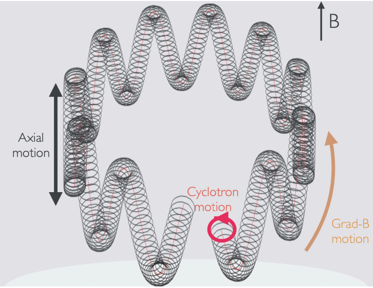
Free space CRES detection with an **antenna array**.

Current R&D focus!

- **Understanding** the different components of the **electron trajectory** and its **radiation**.
- Commercial **≈1 T MRI magnet deployed** at University of Washington.
- Magnetic field and efficiency **calibration** with an **electron gun**.
- Reconstruction techniques using **digital beam forming** and **matched filters**.



James Nikkel



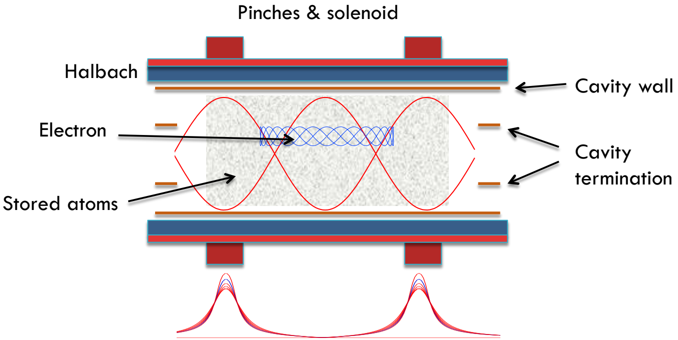
PHASE III: SCALING UP TO LARGE VOLUMES

OPTION 2: MICROWAVE CAVITY

Cavity CRES detection.

Current R&D focus!

- **Higher** radiation energy **collection**.
- Allows for **lower magnetic fields** and **tritium density**.
- **Mode filtering** and open ended cavity prototype design in progress.



Pinches & solenoid

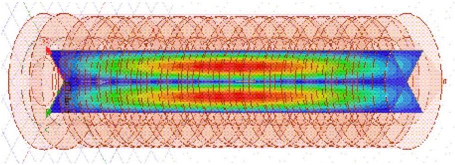
Halbach

Cavity wall

Electron

Cavity termination

Stored atoms



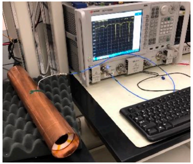
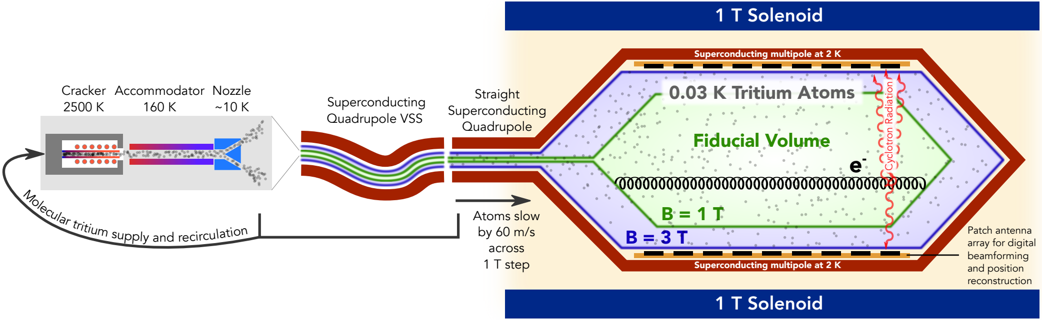


Figure by H. Robertson & A. Ziegler

Phase IV, putting it all together!

Neutrino mass experiment **covering the inverted ordering**, probing $m_\beta \approx 40\,\mathrm{meV}$.

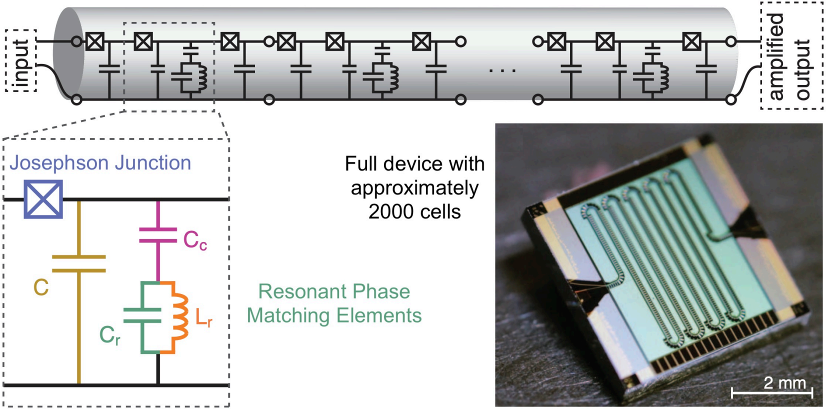


- The **signal power of cyclotron radiation** per electron in a fixed magnetic field is constant. $P \sim B^2, \quad P \approx 1\,\mathrm{fW}$ for $B \approx 1\,\mathrm{T}$

SNR ratio needs to be maximised by **minimising the noise**.

QUANTUM AMPLIFIERS & PROJECT 8

JOSEPHSON TRAVELING-WAVE PARAMETRIC AMPLIFIER (JTWPA) [MACKLIN ET AL., 2015]



Full device with approximately 2000 cells

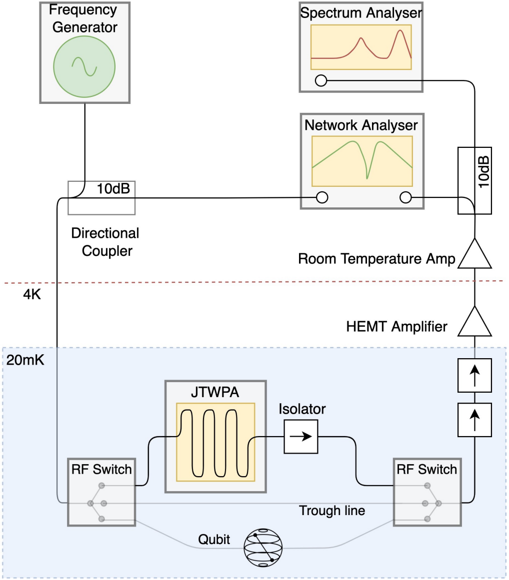
Resonant Phase Matching Elements

Chain of phase matched cells with Josephson Junctions, bandwidth $\mathcal{O}(\mathrm{GHz})$.

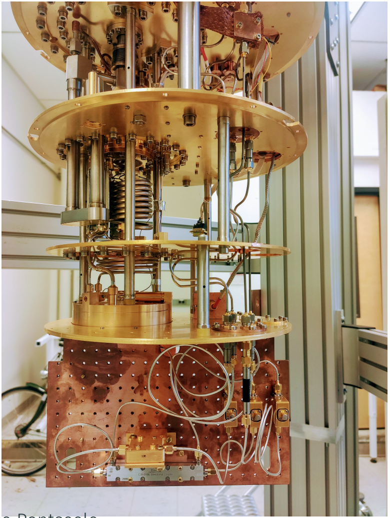
MEASUREMENT SETUP FOR JTWPAS AT MIT

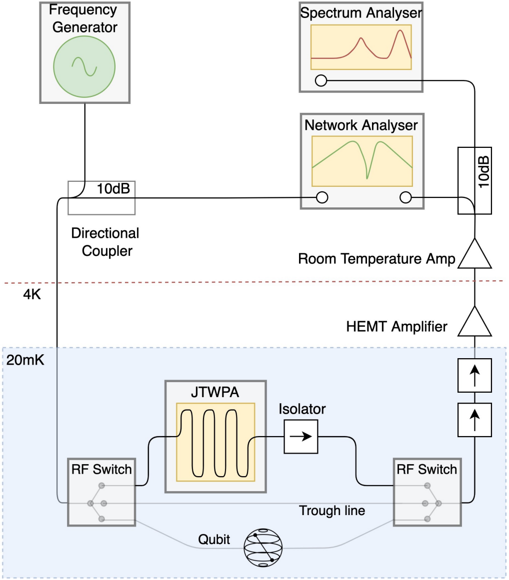
- **Dilution refrigerator** setup using network analyser and spectrum analysers for readout.
- **through line** for **insertion loss** measurements.
- Open Transmission line **qubit** for **power calibration** and noise measurements.
- Proto-type **JTWPAs** in the 4 GHz to 7 GHz and $\mathcal{O}(23\,\text{GHz})$ range, fabricated by Lincoln Laboratories.

Cryogenic testing of antenna and cavity designs using generated waveforms starting.



MEASUREMENT SETUP FOR JTWPAS AT MIT





CONCLUSIONS

Project 8: A Frequency-based Neutrino Mass Measurement

- Measure **electron kinetic energy** from tritium decays to obtain the neutrino mass.
- In practice: A high-precision **cryogenic microwave frequency experiment**.
- **Phase I&II** completed
  ^{83m}Kr calibration and **molecular tritium endpoint** measurement **using CRES**.

Phase III: Paving the path towards phase IV

- Demonstration of **Scalibility**: Explore CRES in a large source volume with **free-space antenna or cavity**-based detection.
  Measure the **tritium endpoint** with a m_β **sensitivity** of $\mathcal{O}(5\,\mathrm{eV})$.
- **Atomic Tritium** Demonstrator
  A pure atomic tritium source at the optimum Phase IV density of $\mathcal{O}\left(10^{18}\text{atoms }/\text{m}^3\right)$.

Case Western Reserve University
B. Monreal, Y-H. Sun, R. Mohiuddin
Harvard-Smithsonian Center for Astrophysics
S. Doeleman, J. Weintroub
Indiana University
W. Pettus
Johannes Gutenberg Universitat, Mainz
S. Böser, M. Fertl, A. Lindman, C. Matthé,
R. Reimann, F. Thomas, L. Thorne
Karlsruhe Institute of Technology
T. Thümmler
Lawrence Livermore National Laboratory
K. Kazkaz
Massachusetts Institute of Technology
J. Formaggio (spokesperson; PI), P. Harrington,
M. Li, J. Pena, J. Stachurska, W. Van de Pontseele
Pacific Northwest National Laboratory
J.K. Gaison, N. Oblath,
J. Tedeschi, B. VanDevender
Pennsylvania State University, State College
C. Carmona-Benitez, L. de Viveiros, R. Mueller, A. Ziegler
University of Washington
A. Ashtari Esfahani, C. Claessens, P. Doe, S. Enomoto,
E. Novitski, H. Robertson, G. Rybka
Yale University
K. M. Heeger, J. Nikkel, L. Saldaña, P. Slocum,
P. Surukuchi, A. Telles, J. Wilhelmi, T. Weiss

Thank you!

wvdp@mit.edu

Additionally I want to acknowledge the research groups lead by Kevin O'Brien and Will Oliver at MIT. This work is supported by the US DOE Office of Nuclear Physics, the US NSF, and investments at all institutions.

REFERENCES

C. Macklin, K. O'Brien, D. Hover, M. E. Schwartz, V. Bolkhovsky, X. Zhang, W. D. Oliver, and I. Siddiqi. A near–quantum-limited josephson traveling-wave parametric amplifier. *Science*, 2015. doi:10.1126/science.aaa8525.

L. Fasolo, A. Greco, and E. Enrico. Superconducting josephson-based metamaterials for quantum-limited parametric amplification: A review. In Jagannathan Thirumalai and Sergey Ivanovich Pokutnyi, editors, *Advances in Condensed-Matter and Materials Physics*, chapter 5. IntechOpen, Rijeka, 2020. doi:10.5772/intechopen.89305.

T. Elo, T. S. Abhilash, M. R. Perelshtein, I. Lilja, E. V. Korostylev, and P. J. Hakonen. Broadband lumped-element josephson parametric amplifier with single-step lithography. *Applied Physics Letters*, 114(15):152601, 2019. doi:10.1063/1.5086091.

PROJECT 8: THE CHALLENGES OF SCALING UP

- An accurate neutrino mass measurement relies on **high statistics** in the tail of the tritium endpoint.
- Scattering time and atomic tritium source/trap restrictions **constrain the density**.

→ **Phase IV** will need a **high triggering efficiency** in combination with a **large volume**.

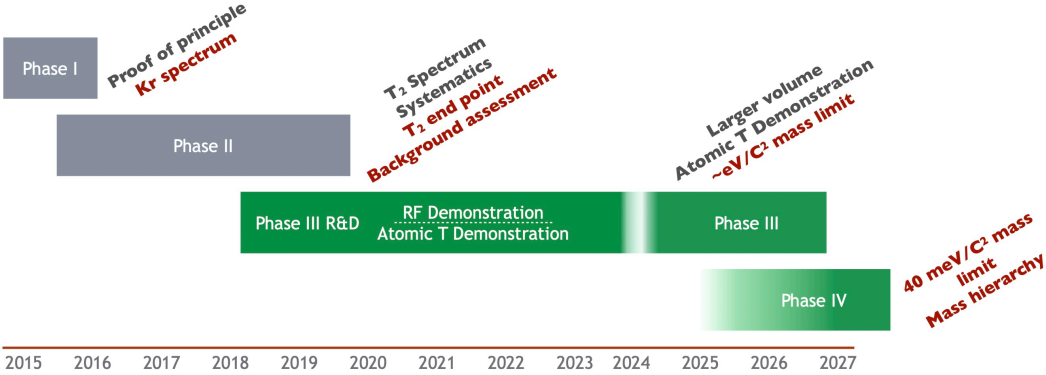
- The **power of cyclotron radiation** per electron is

  $$P \sim B^2, \quad P \approx 1\,\mathrm{fW} \text{ for } B \approx 1\,\mathrm{T}$$

  In a constant field, the **signal power is constant**
- The proposed **free space multi-antenna readout** will have a **lower coverage and lower received power per channel.**

→ The **signal to noise power ratio** needs to be maximised by **minimising the noise power**.

TIME LINE



Phase I

Proof of principle
Kr spectrum

Phase II

T_2 Spectrum
Systematics
T_2 end point
Background assessment

Phase III R&D

RF Demonstration
Atomic T Demonstration

Phase III

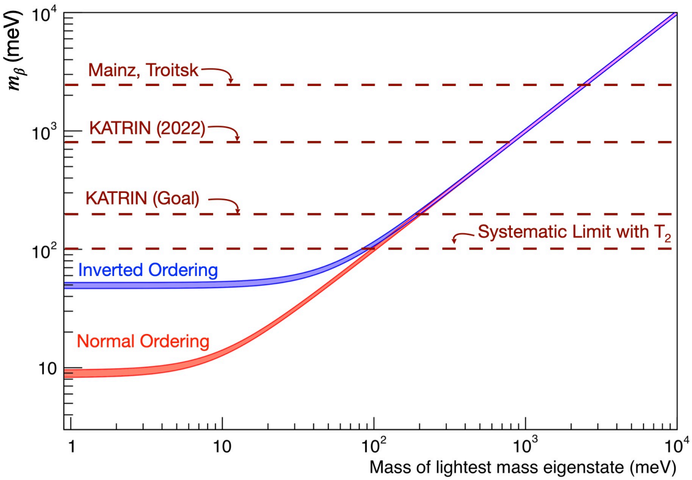
Larger volume
Atomic T Demonstration
~eV/C^2 mass limit

Phase IV

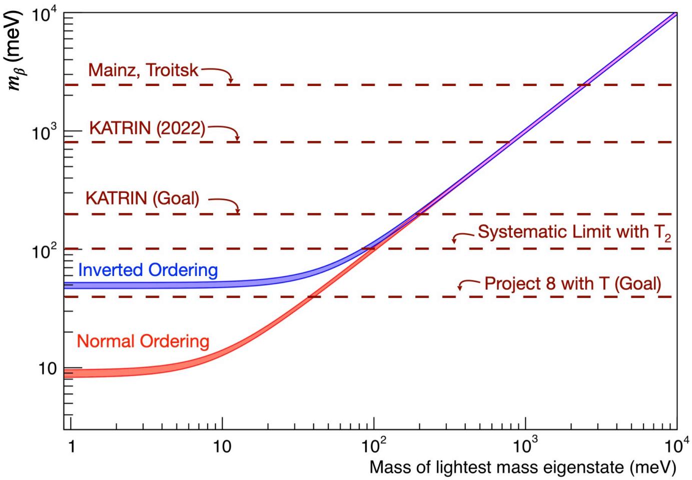
40 meV/C^2 mass limit
Mass hierarchy

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

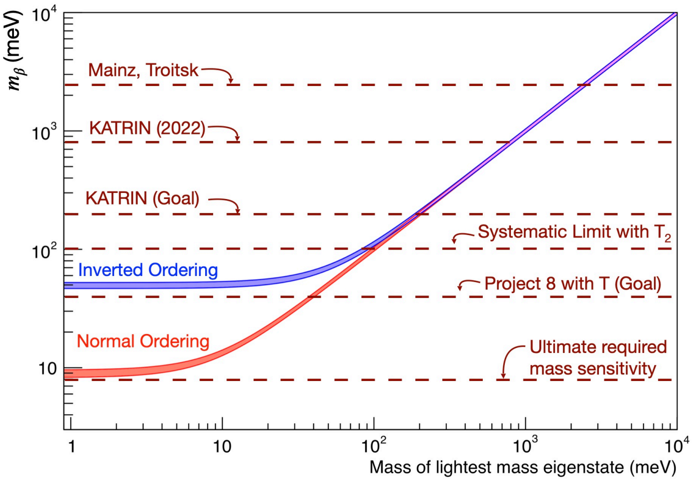
THE ULTIMATE PROJECT 8 MASS SENSITIVITY



The Ultimate Project 8 mass sensitivity

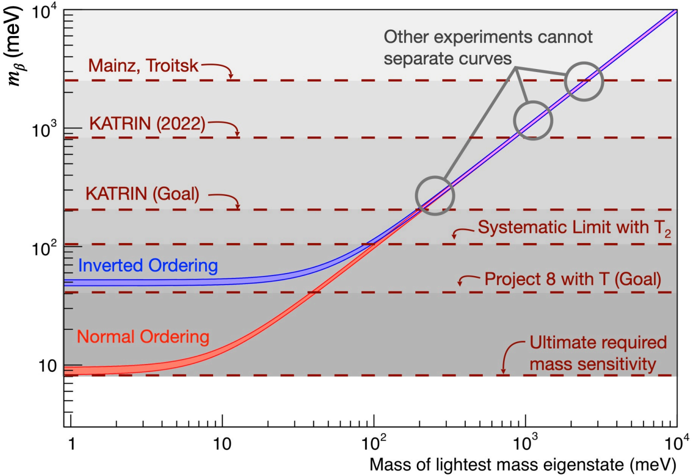


THE ULTIMATE PROJECT 8 MASS SENSITIVITY



Wouter Van De Pontseele

THE ULTIMATE PROJECT 8 MASS SENSITIVITY



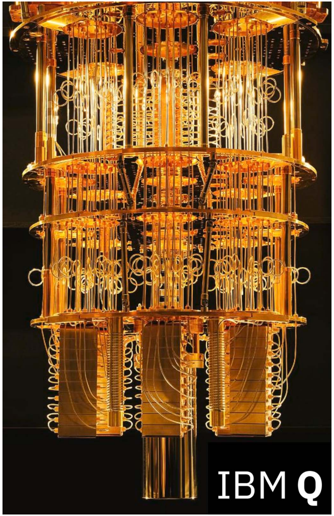
QUANTUM AMPLIFIERS: INTRODUCTION

Driven by Quantum Computing

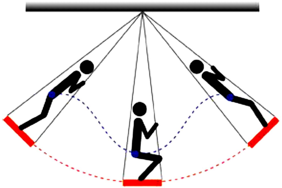
- **Superconducting qubit** signals are weak **microwaves**.
- **First stage amplifier** limits performance.
- Amplifier **bandwidth** enables **multiplexing** of multiple qubits.

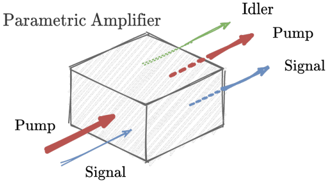
Similarities with Project 8

- **Cyclotron emission** is in the **microwave** region.
- **Trigger efficiency** ultimately depends on the noise **performance** of the **first stage amplifier**.
- Interest in **multiplexing** of **antenna channels**.
- **Bandwidth** requirements driven by **calibration sources**.



PARAMETRIC AMPLIFICATION [FASOLO ET AL., 2020]





Principle: A non-linearity and a pump wave

- Swing process: amplification by changing the centre of mass (**pump**) with a certain frequency and phase.
- Amplification of a signal by exchanging pump power into signal and idler. Exploits **Josephson junction as a non-linear circuit element**.
- Parametric amplification requires the pump (ω_p), signal (ω_s),and idler (ω_i) frequencies to satisfy **energy conservation**,

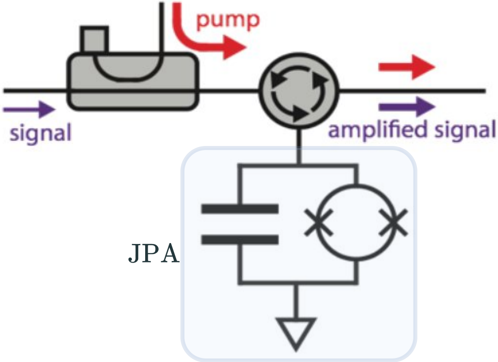
$$2\omega_p = \omega_s + \omega_i$$

and **momentum conservation** (phase matching),

$$\Delta k = 2k_p - k_s - k_i = 0$$

JOSEPHSON PARAMETRIC AMPLIFIERS [ELO ET AL., 2019]

- **Single cell with Josephson Junction**, small footprint.
- **Circular device**, input and output over the same line.
- **Small** amplification **bandwidth** of **$\mathcal{O}(100\,\mathrm{MHz})$**.
- Demonstrated with central frequency from $0.6\,\mathrm{GHz}$ to $7\,\mathrm{GHz}$.
- Loops are **sensitive to magnetic fields.**

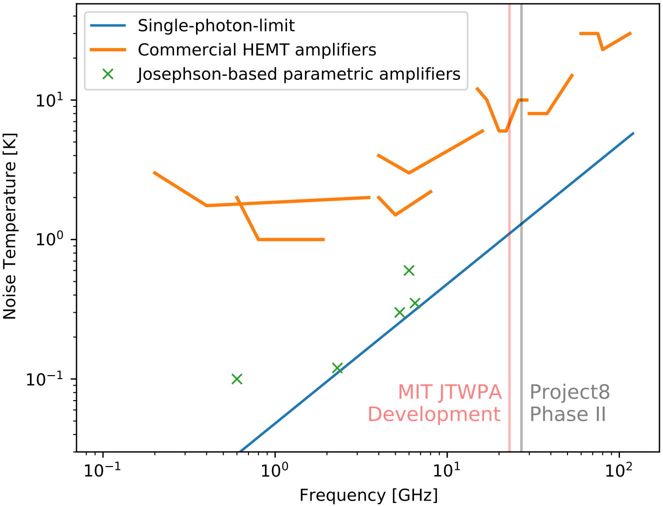


WHY QUANTUM AMPLIFIERS: THE NOISE TEMPERATURE

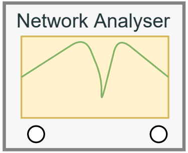
Quantum amplifiers have a **noise temperature an order of magnitude below** the current best off-shelf cryogenic amplifiers.

Current R&D to **demonstrate JTWPA's in the frequency range and magnetic fields proposed by Project 8.**

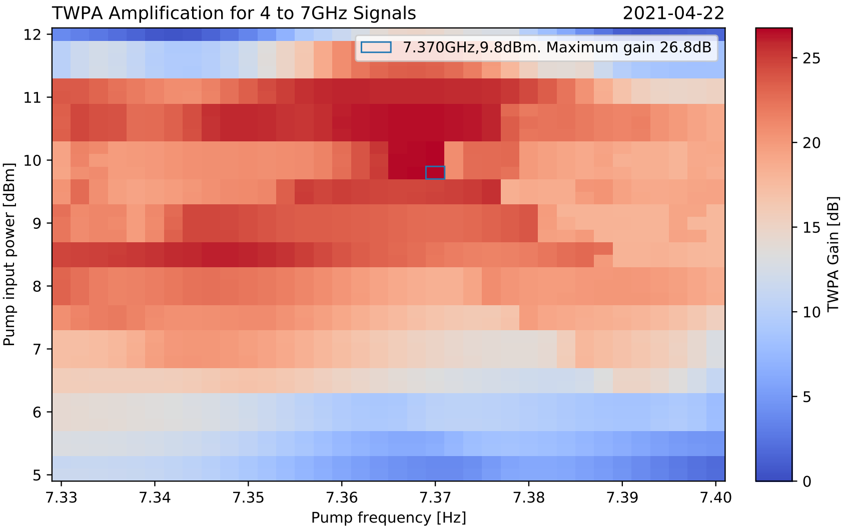
Noise Temperatures for different amplifiers



TWPA CHARACTERISATION: GAIN AS A FUNCTION OF PUMP POWER/FREQUENCY

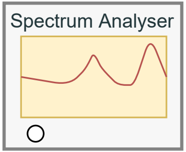


Transmission network analyser measurement, **compared to a JTWPA without pump**.

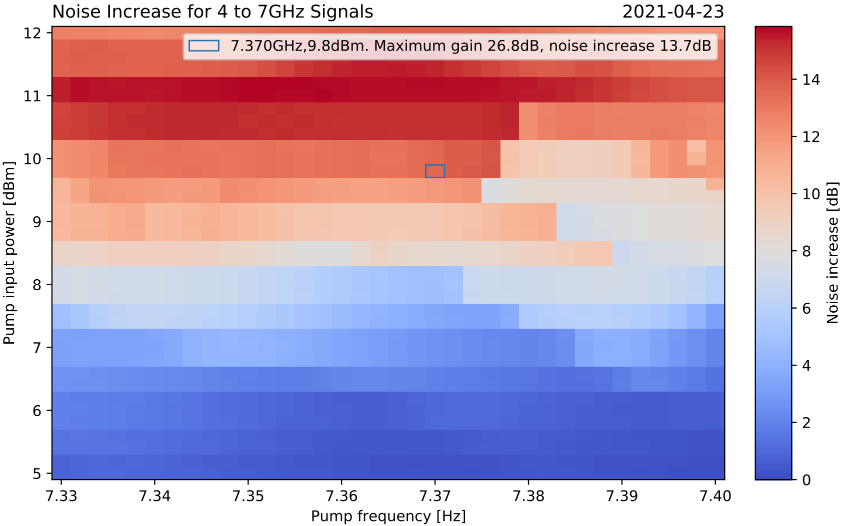


Wouter Van De Pontseele

TWPA Characterisation: Noise as a function of Pump power/frequency



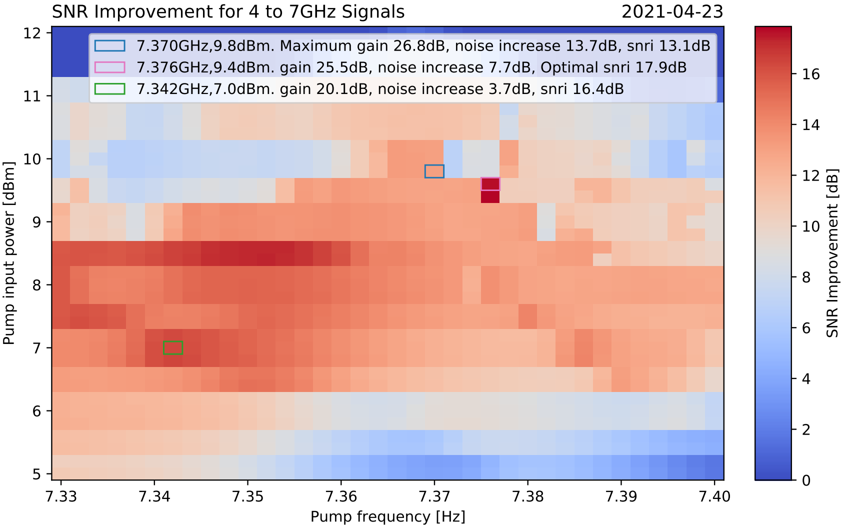
Spectrum analyser measurement of the **noise floor, compared to a JTWPA without pump.**



TWPA CHARACTERISATION: SIGNAL TO NOISE RATIO IMPROVEMENT

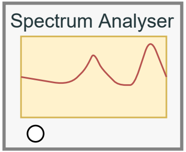
Quantitative indicator to **optimise pump settings**:

$$\mathit{SNRI}[\mathrm{dB}] = \mathit{Gain}(\mathit{TWPA})[\mathrm{dB}] - \text{noise increase}[\mathrm{dB}]$$

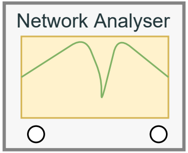


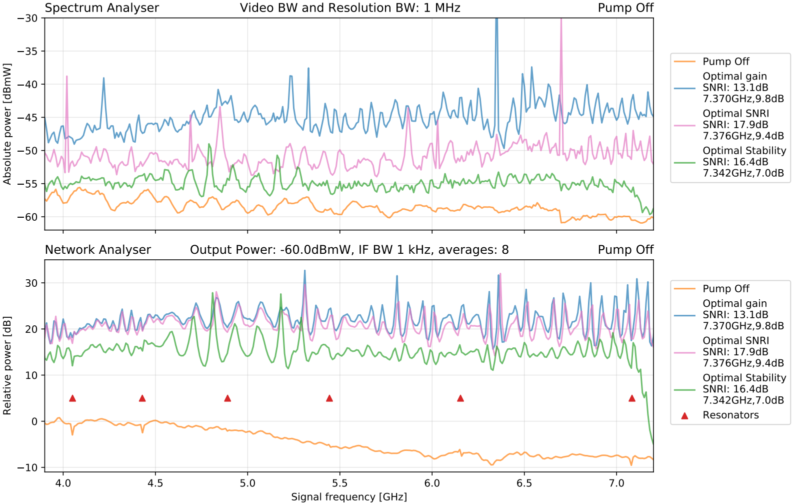
JTWPA OPTIMAL PUMP SETTINGS COMPARED

Noise Increase:



Gain:



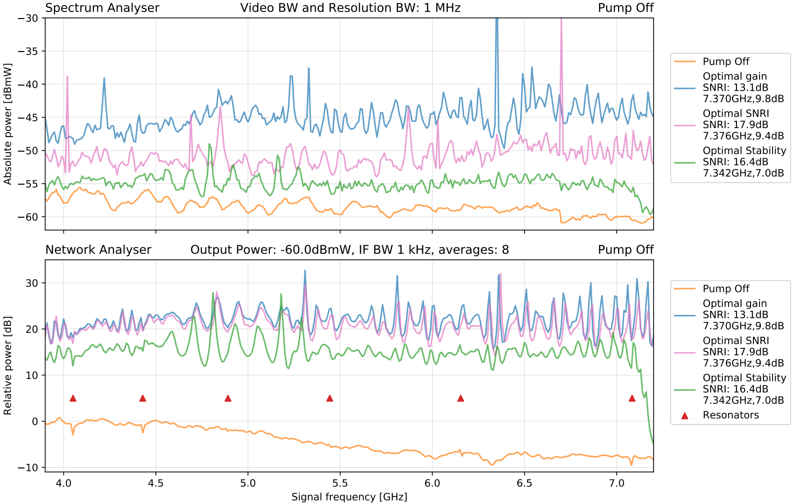


Wouter Van De Pontseele

JTWPA OPTIMAL PUMP SETTINGS COMPARED

In practice, optimal **operating point** chosen to limit the **spurious peaks**.

Gain above $20\,\mathrm{dB}$ with a Signal-to-Noise Ratio Improvement (SNRI) above $15\,\mathrm{dB}$ in the $3\,\mathrm{GHz}$ **bandwidth**.



Wouter Van De Pontseele

TWPA Antenna Integration