Quantum Amplifiers for a Neutrino Mass Measurement

ANIMMA 2021

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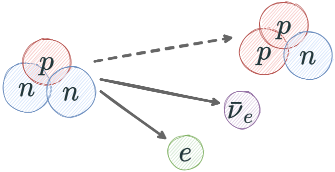
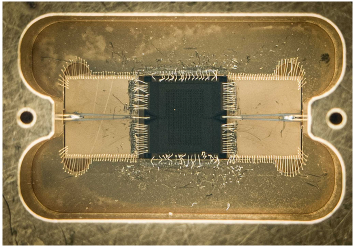
Massachusetts Institute of Technology

Motivation

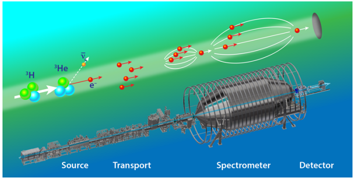
R&D effort to design quantum **amplifiers** tailored to the detection of **microwaves**.
These **low-noise** devices are key to the determination of the **neutrino mass**.





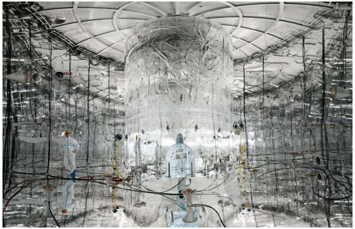
Outline

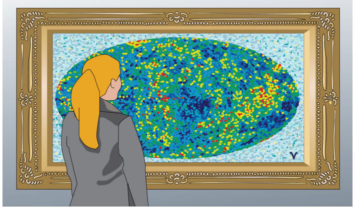
1. **Neutrino mass** determination
   by measuring cyclotron radiation frequency.
2. **Detector design**.
3. **Quantum-limited microwave amplification**.



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





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- Rely on the distributions of the neutrino and electron **kinetic energy** in **β-decay processes**.
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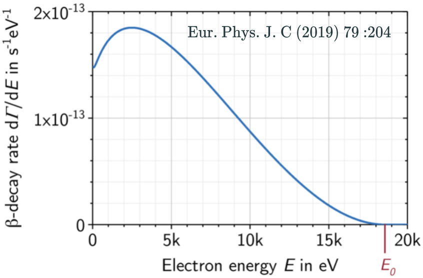
Indirect methods:

- **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.

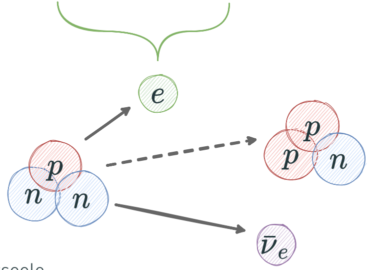
→ **Indirect is model dependent**.



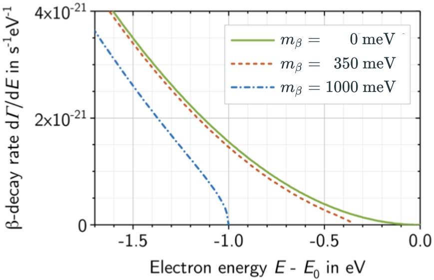
Electron energy distribution from tritium β-decay:

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

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



zoom in around endpoint E_0

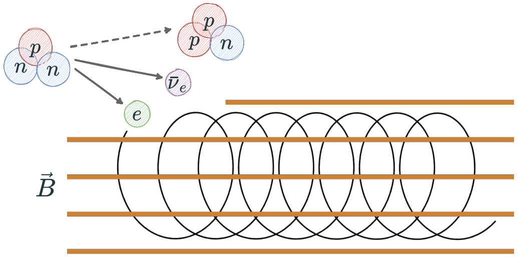


How to **scale down** the experiment while **increasing** the neutrino mass **sensitivity**?

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**)

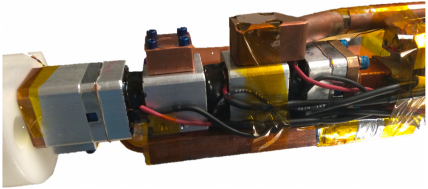
Tritium decays inside a **uniform** $\vec{B}$-field.

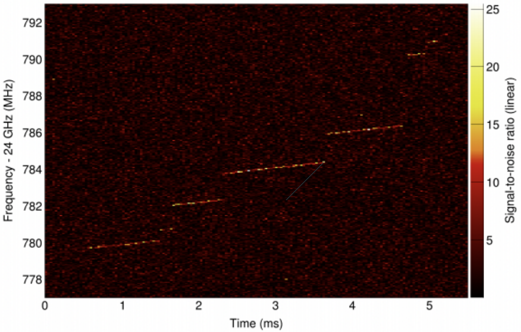


Electron performs **cyclotron motion** with frequency

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

- **Phase I**: First detection of **cyclotron radiation from a single electron**. Gaseous ^{83m}Kr used as a source.
  Phys. Rev. Lett. 114, 1162501 (2015)





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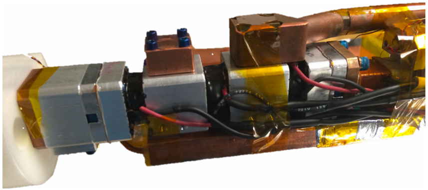

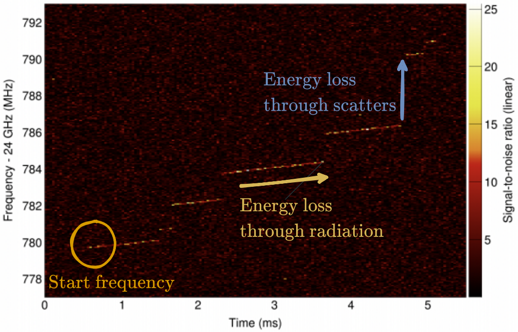

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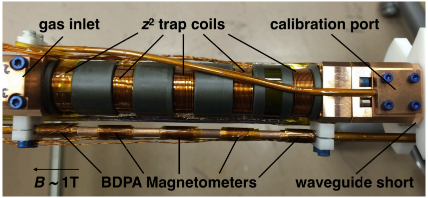

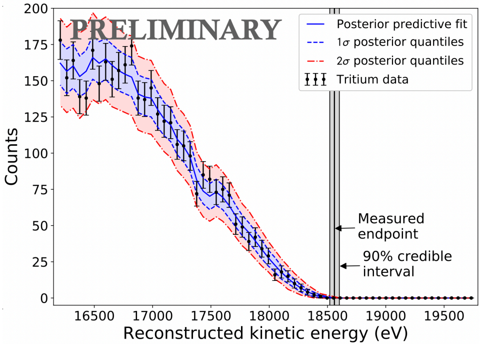

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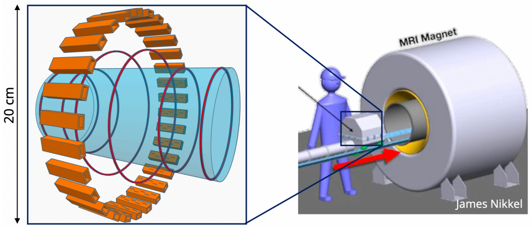
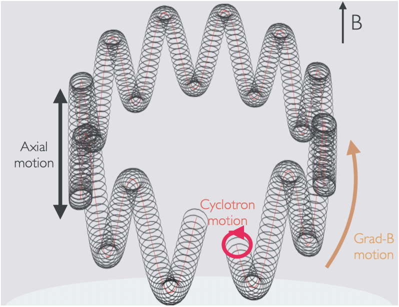
  - **Free space** CRES detection with $\mathcal{O}(100)$ **antenna's**.
  - Exploring atomic tritium as a source.





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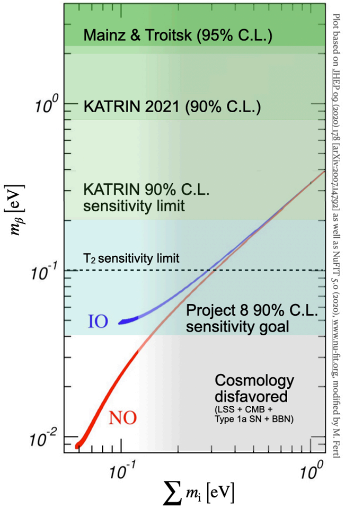
- **Phase IV**: The ultimate neutrino mass experiment probing $m_\beta \approx 40\,\mathrm{meV}$.



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**.

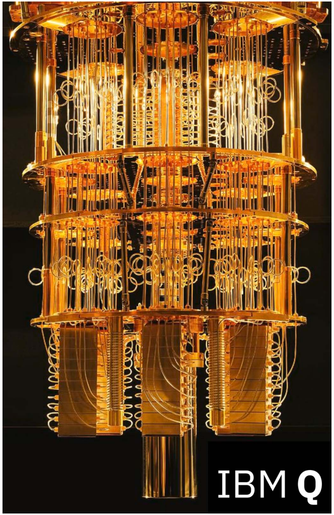
Quantum Amplifiers & Project 8

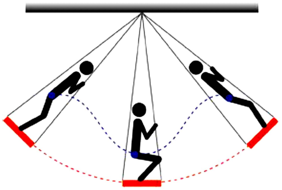
Driven by Quantum Computing

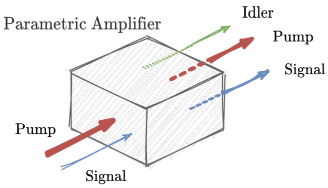
- **Superconducting qubit** signals are weak **microwaves**.
- **First stage amplifier** limits performance.
- Amplifier **bandwidth** enables **multiplexing** of multiple qubits.

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**.







Principle: A non-linearity and a pump wave

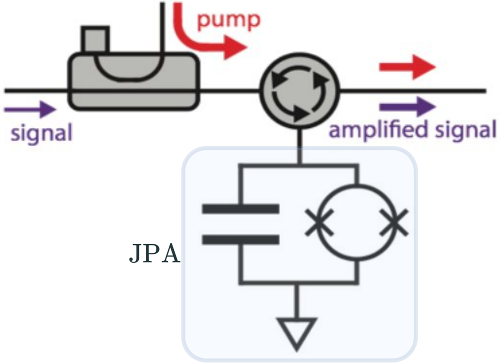
- Swing process: amplification by changing the centre of mass (**pump**) with a certain frequency and phase.
- Amplification of a signal by exchanging pump power into signal and idler. Exploits **Josephson junction as a non-linear circuit element**.
- Parametric amplification requires the pump (ω_p),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

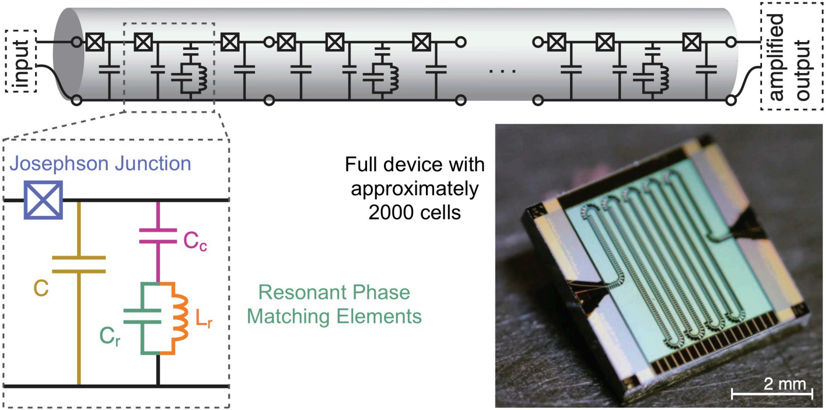
$$2\omega_p = \omega_s + \omega_i$$

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

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

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

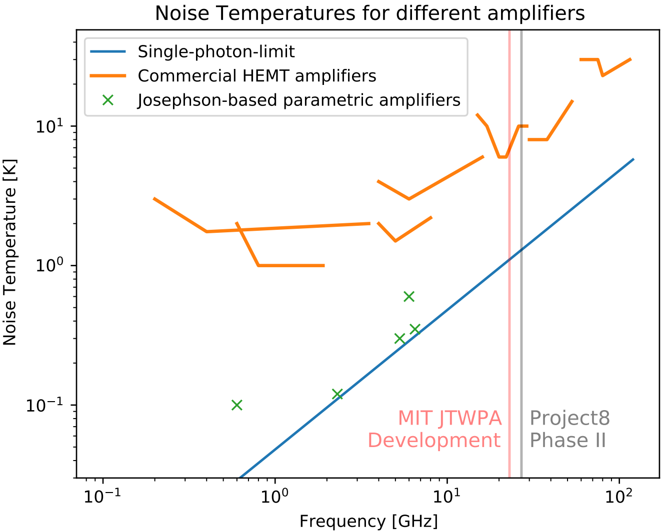


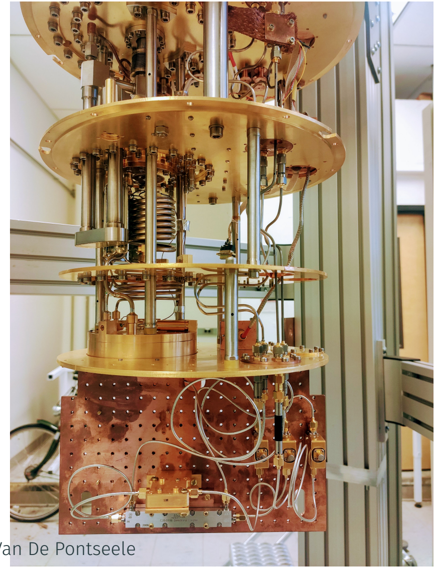


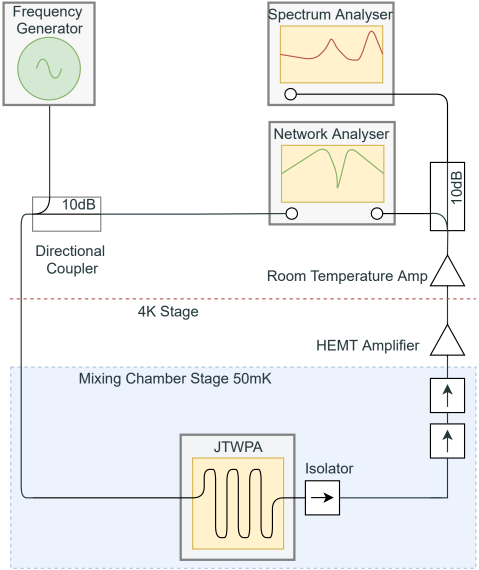
Chain of cells improves phase matching, enhancing the amplifier bandwidth to $\mathcal{O}(\mathrm{GHz})$.

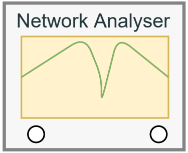
Quantum amplifiers have a **noise temperature an order of magnitude below** the current best off-shelf cryogenic amplifiers.

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

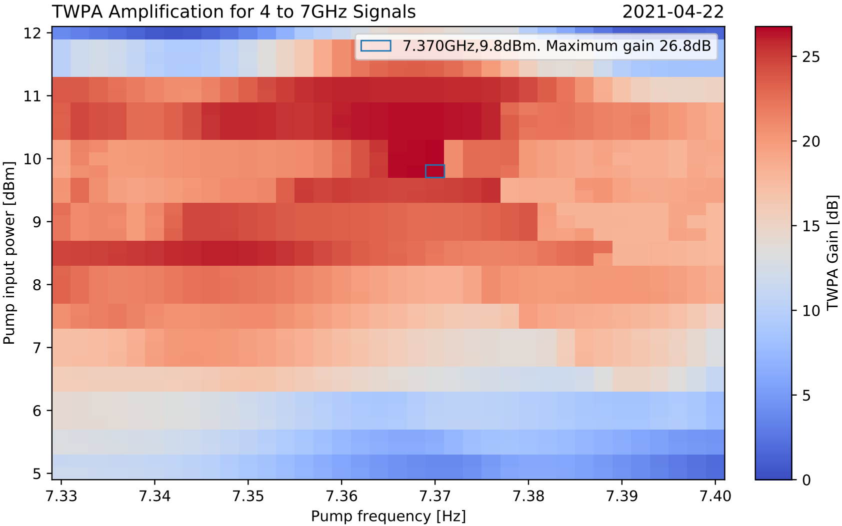


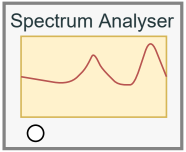



Frequency Generator
Spectrum Analyser
Network Analyser
10dB
10dB
Directional Coupler
Room Temperature Amp
4K Stage
HEMT Amplifier
Mixing Chamber Stage 50mK
JTWPA
Isolator

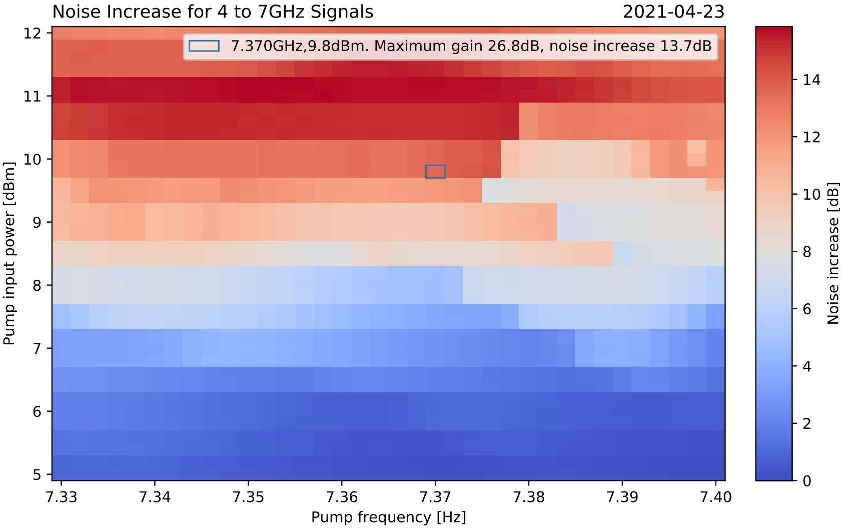


Transmission network analyser measurement, **compared to a JTWPA without pump.**



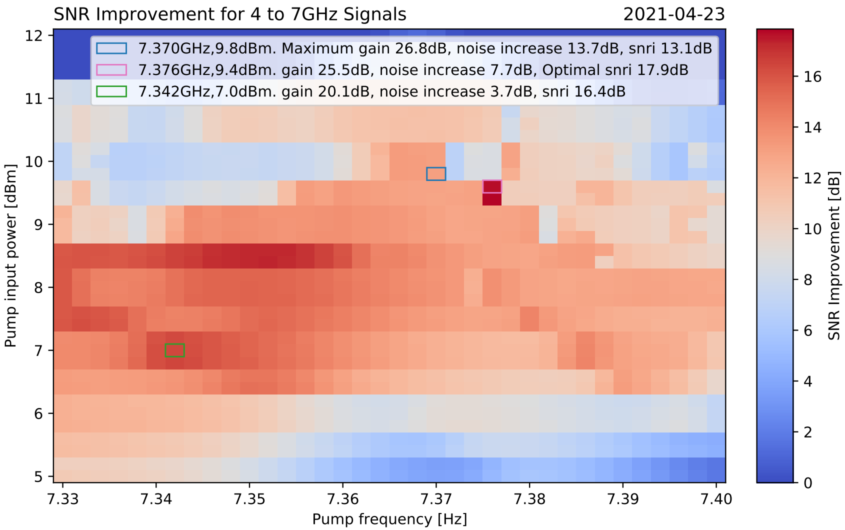


Spectrum analyser measurement of the **noise floor, compared to a JTWPA without pump.**



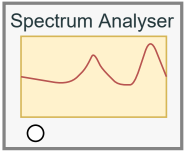
Quantitative indicator to **optimise pump settings**:

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

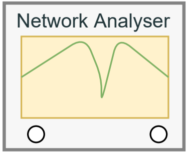


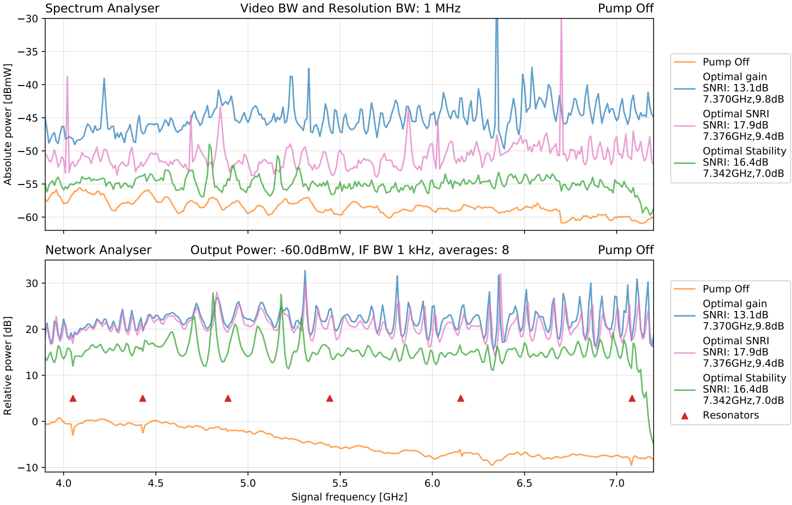
JTWPA OPTIMAL PUMP SETTINGS COMPARED

Noise Increase:



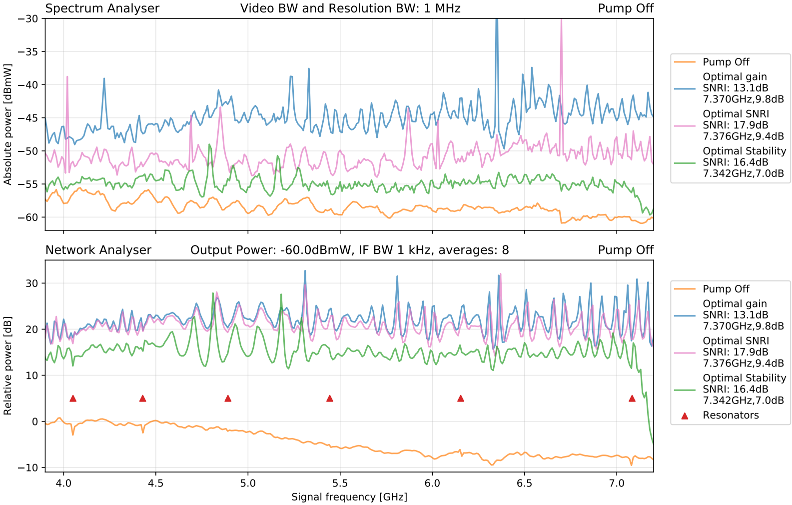
Gain:





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

Gain above 20 dB with a Signal-to-Noise Ratio Improvement (SNRI) above 15 dB in the 3 GHz **bandwidth**.



Conclusions

Project 8: The Ultimate Neutrino Mass Measurement

- Measure **electrons kinetic energy** from tritium decays to obtain the neutrino mass.
- In practice: A high-precision **cryogenic microwave frequency experiment**.

Josephson-based Parametric Amplifiers

- Fast developing field driven by qubit readout.
- Enable **quantum-limited noise temperatures for microwave signals**.

Current Steps and Challenges

- **Adapt amplifier and packaging designs** to access a wider range of frequencies.
- **Characterise** performance in **magnetic fields** and with **antenna readout**.

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Indiana University
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T. Thümmler (PI)
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Thank you!

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PROJECT 8

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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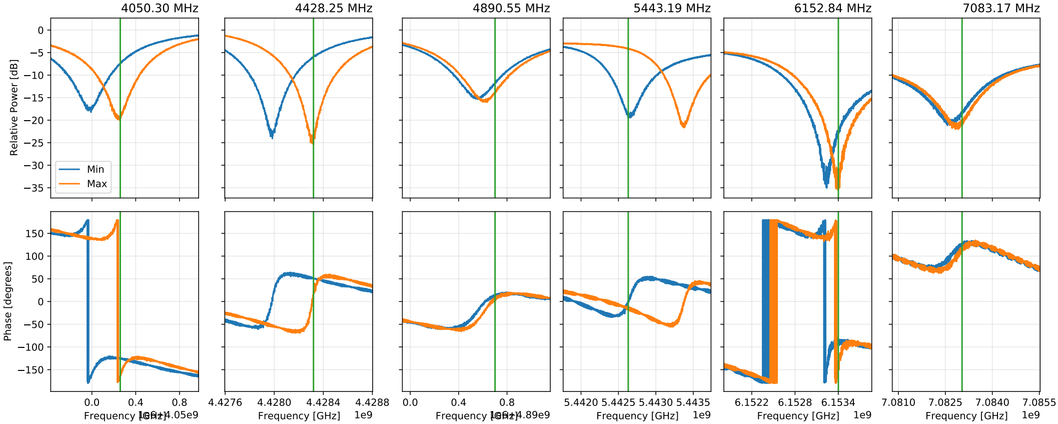
Characterisation of Resonator Multiplexing Device



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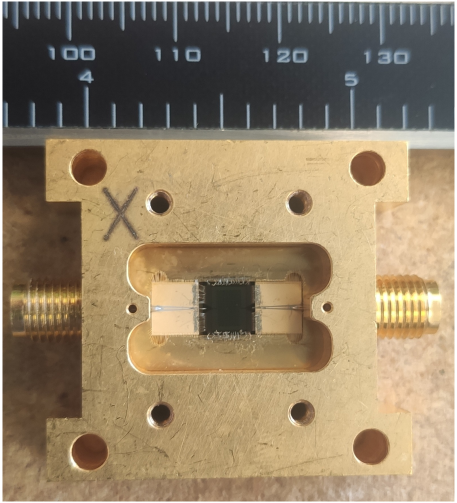
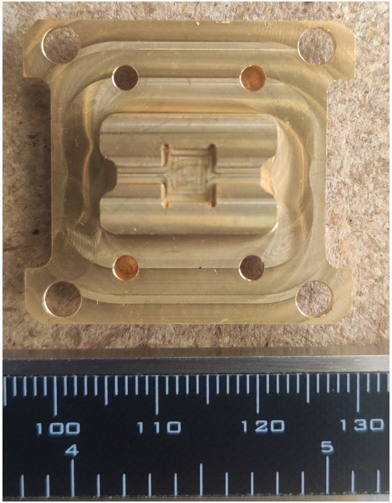
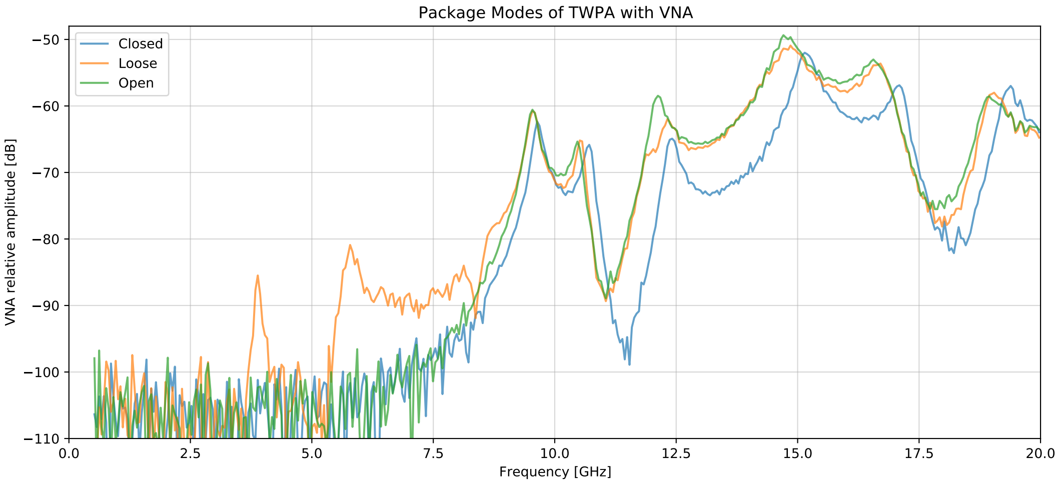
TWPA Package modes: Package design

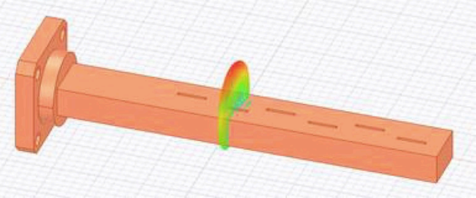


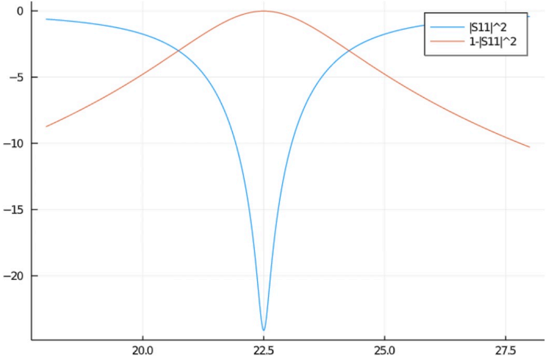


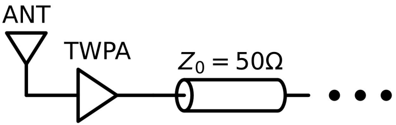
TWPA Package modes: VNA measurement

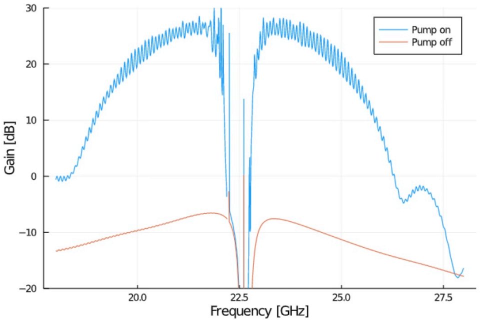


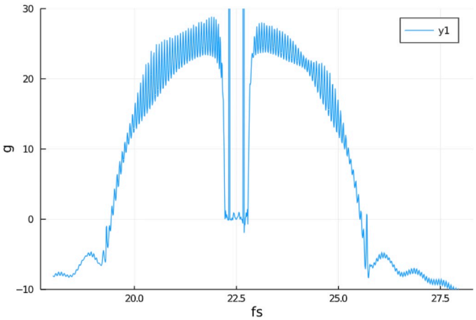
High-Frequency Antenna





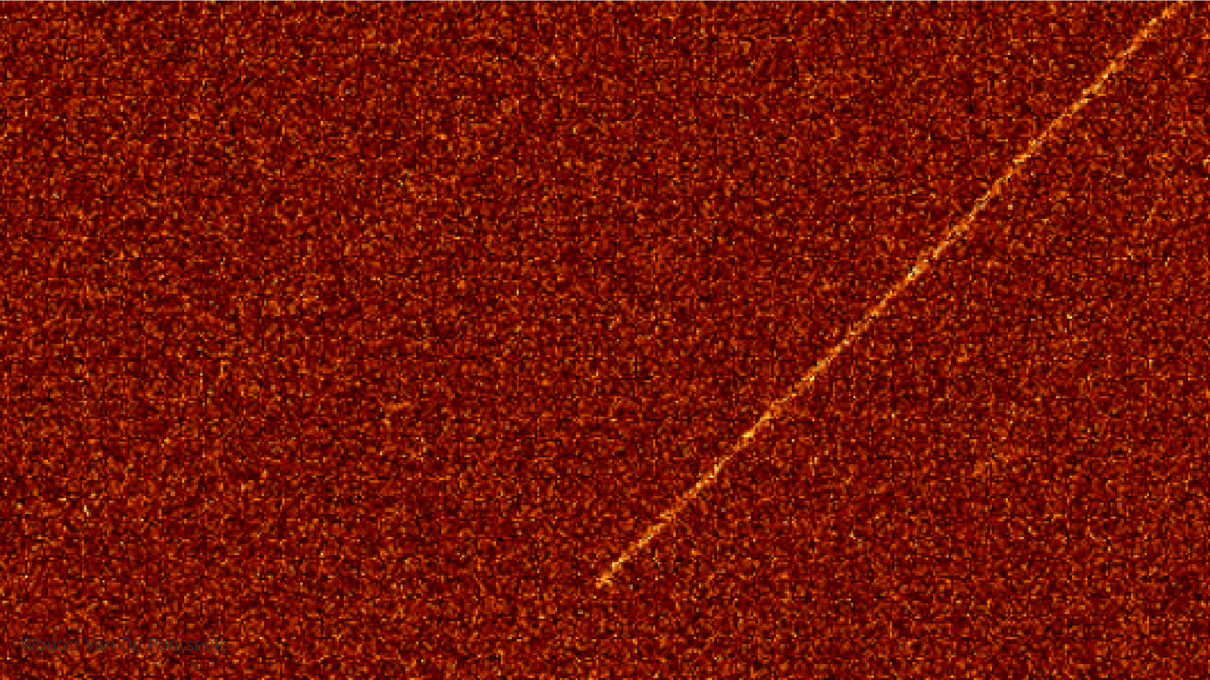






Only TWPA

TWPA+Antenna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