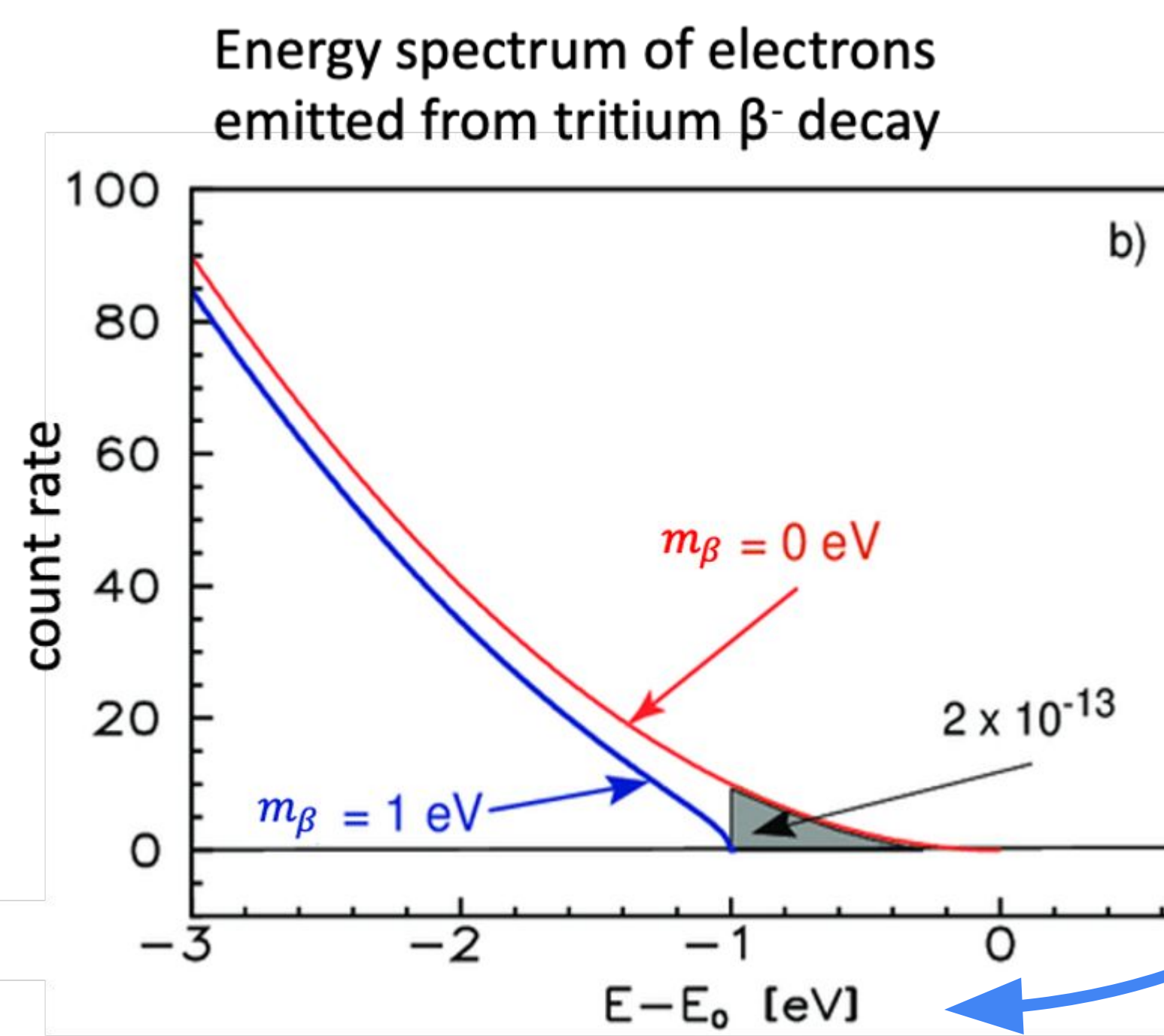
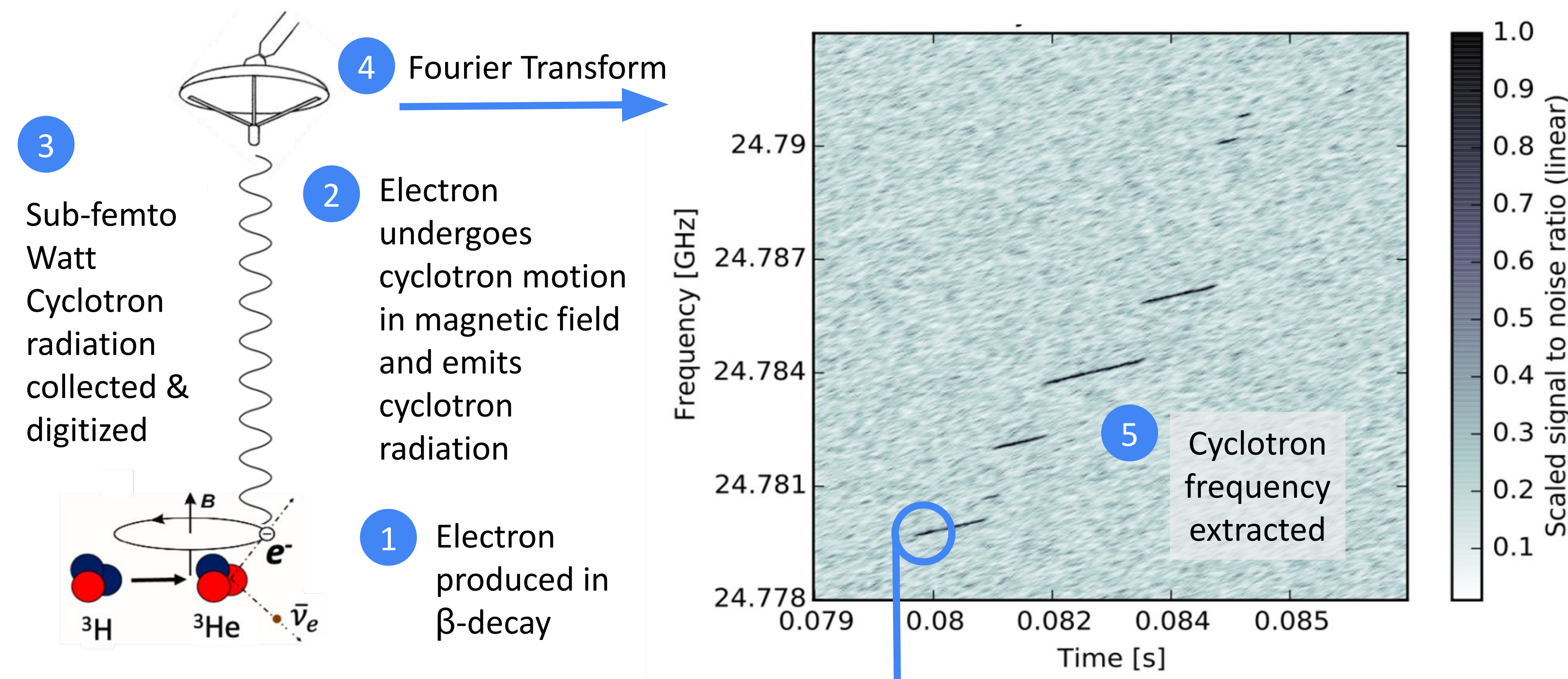
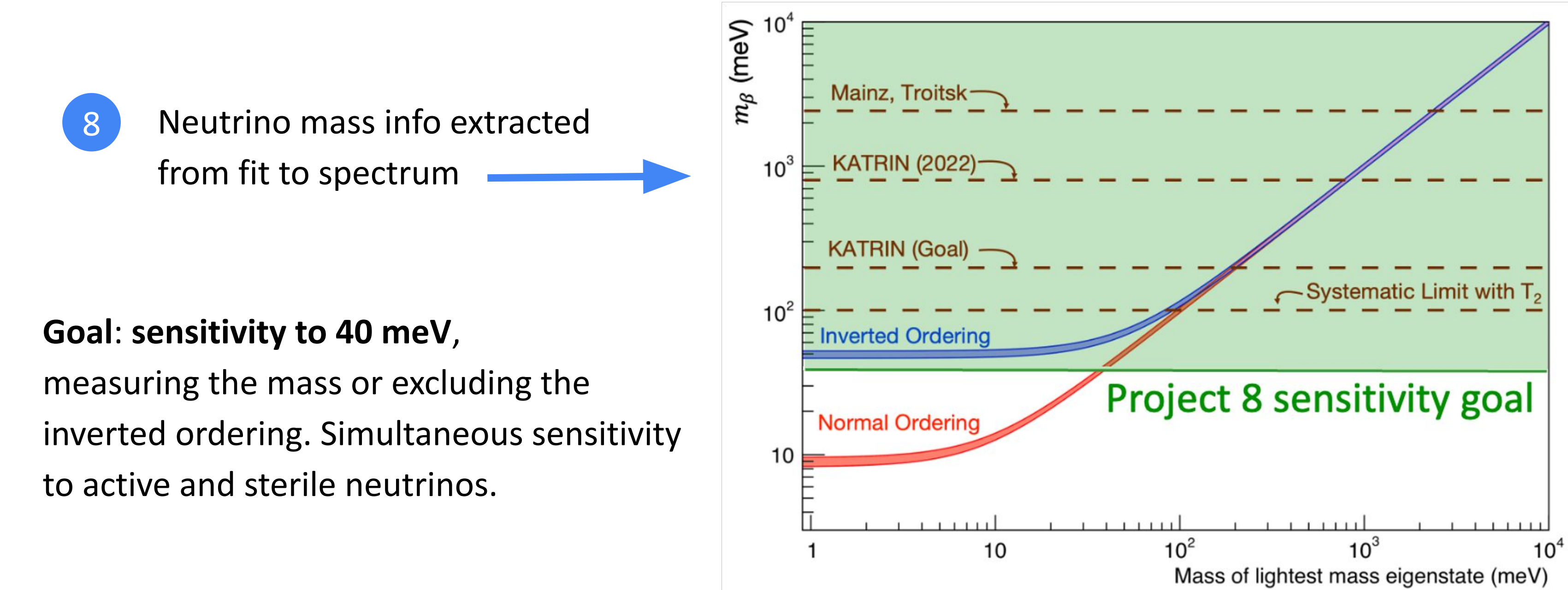


Project 8: measuring neutrino mass by observing tritium β -decay with Cyclotron Radiation Emission Spectroscopy (CRES)

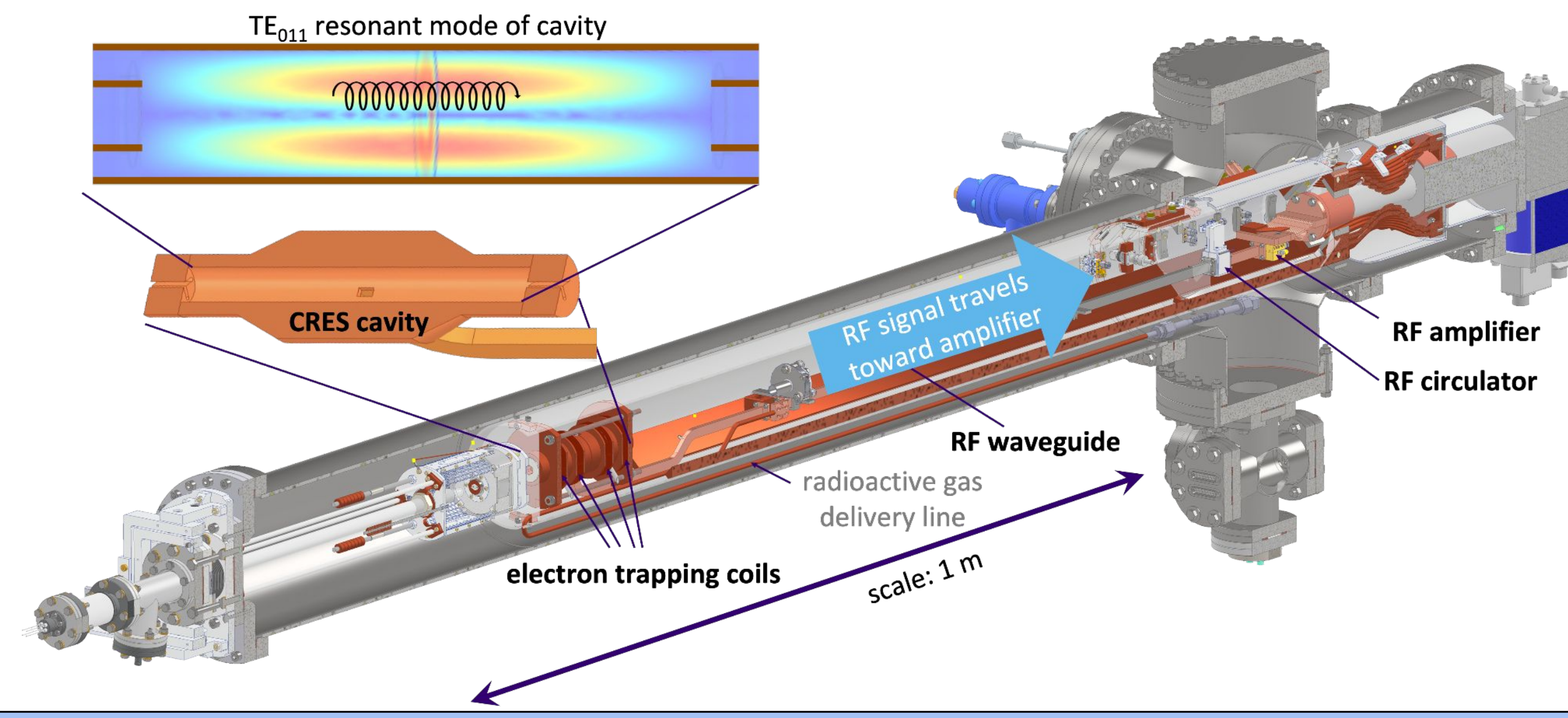


$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

- 6 Kinetic energy of the electron calculated
7 Repeat for a very large number of β -decay electrons to populate endpoint region



CRES Cavity Demonstrator & Towards the Low Frequency Apparatus



Project 8 Follows a Phased approach:

- ✓ Phase I: Detection of CRES from single electrons
- ✓ Phase II: Molecular tritium measurement with $m_\beta < 150$ eV.
- Phase III:
 - a) Resonant cavity approach
 - b) Atomic tritium demonstration
 - c) Lowering the frequency to scale up the volume!
- Phase IV: Combine & Scale to reach target sensitivity of 40 meV

Low-Noise Cryogenic CRES Readout & Quantum Amp Developments

Intended frequencies for large scale demonstrators at 560MHz and ≈ 150 MHz,

Power reduced to $\mathcal{O}(0.1)$ attoWatt for sub-millisecond signals

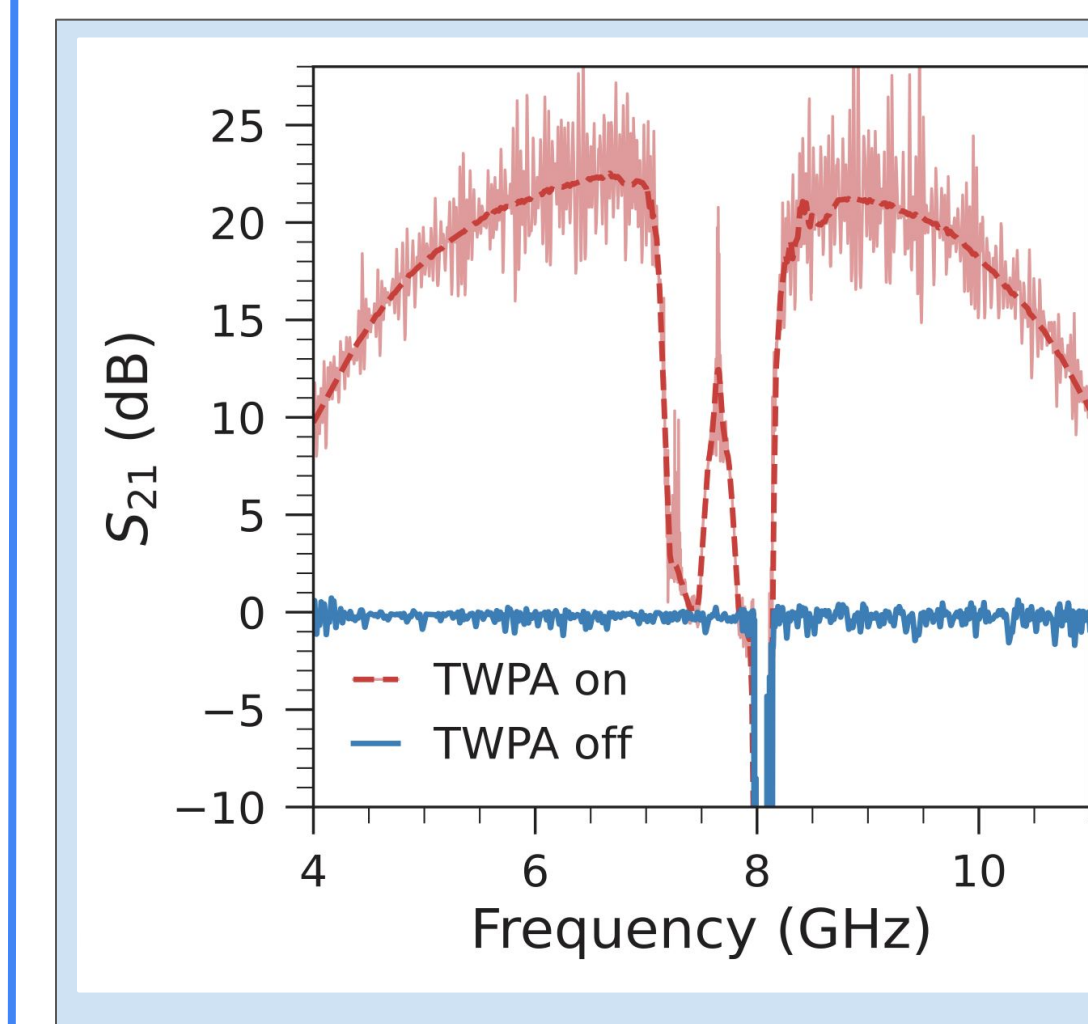
Sub-eV energy electron energy reconstruction requires part-per million frequency measurement.

Total noise budget (T_{sys}) at 560MHz is approximately 300mK.

1. Thermal decoupling from 4K cavity by overcoupling
2. Superconducting transfer to dilution refrigerator
3. Reflections cooled by matched load at ≈ 20 mK
4. Near-quantum limited microwave amplifier

Josephson junction-based amplifiers using Floquet mode enhanced resonant phase-matching, designed for superconducting qubits. Achieving system quantum efficiency (η_{sys}) >65%.

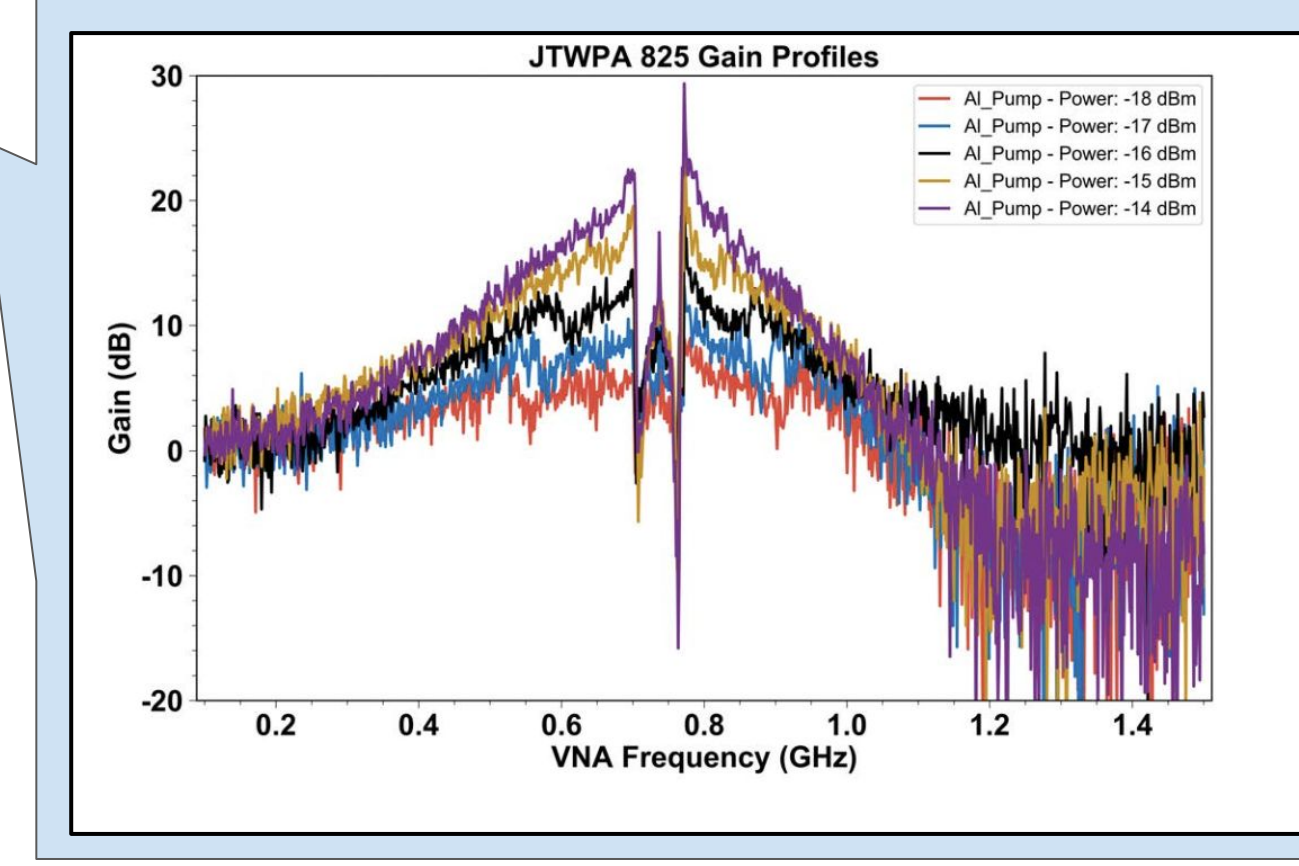
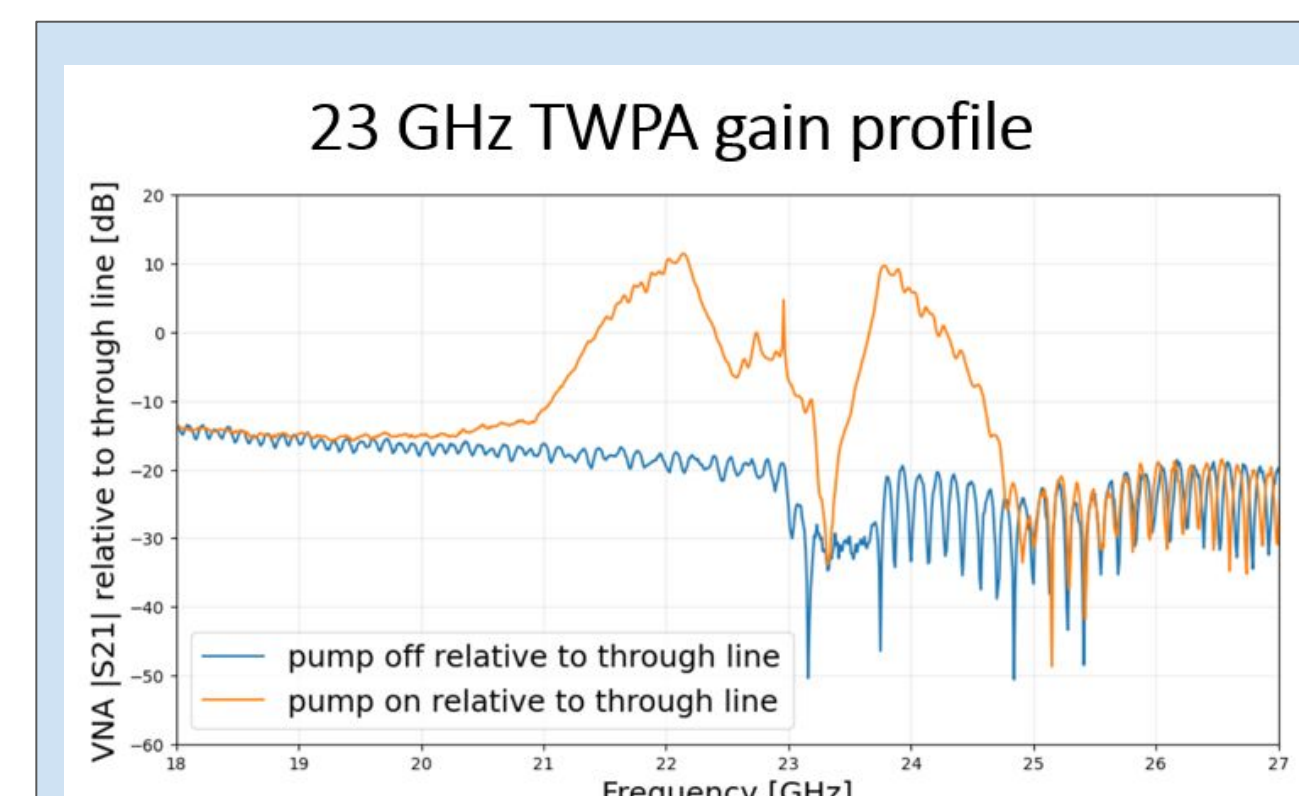
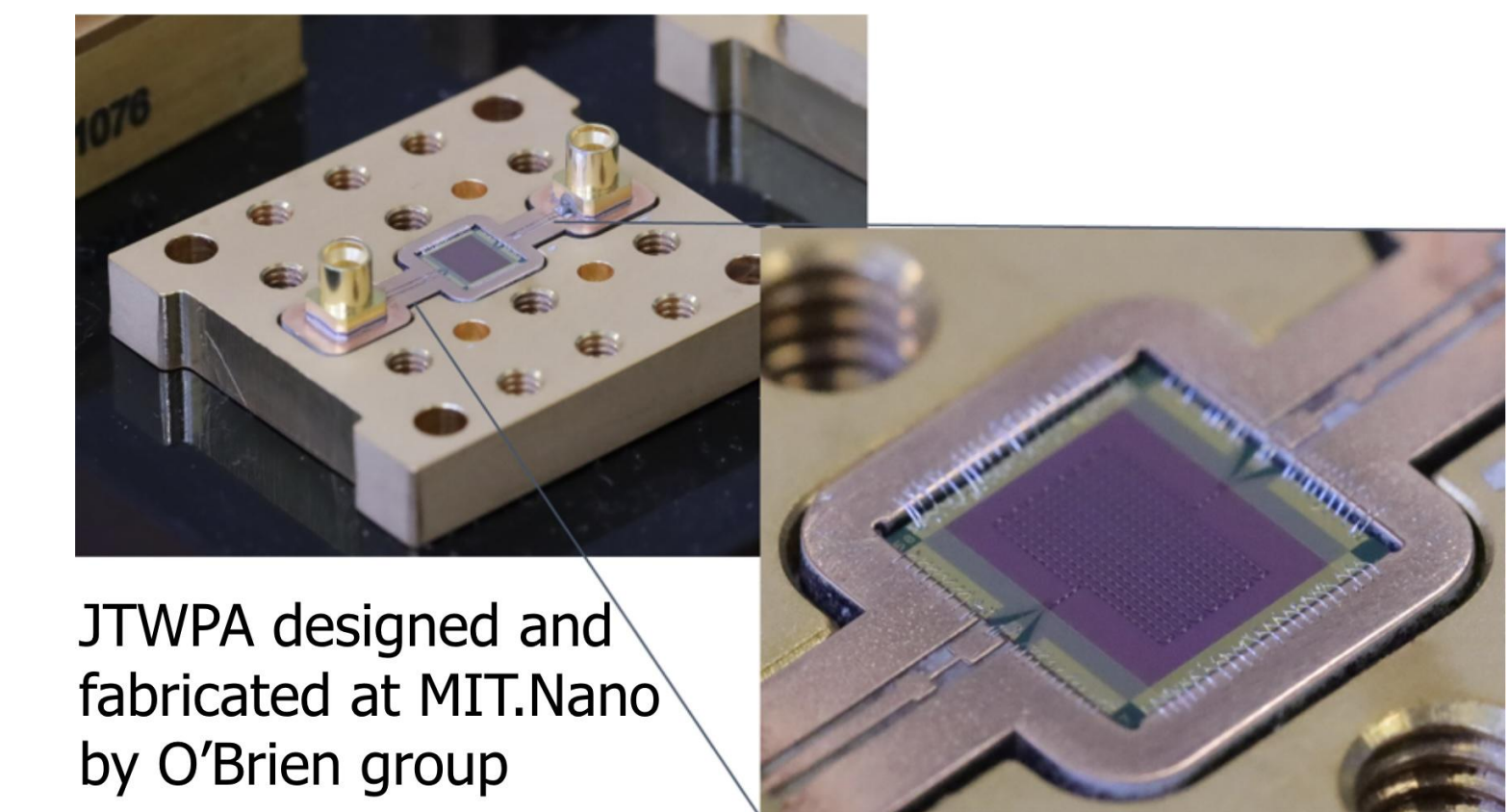
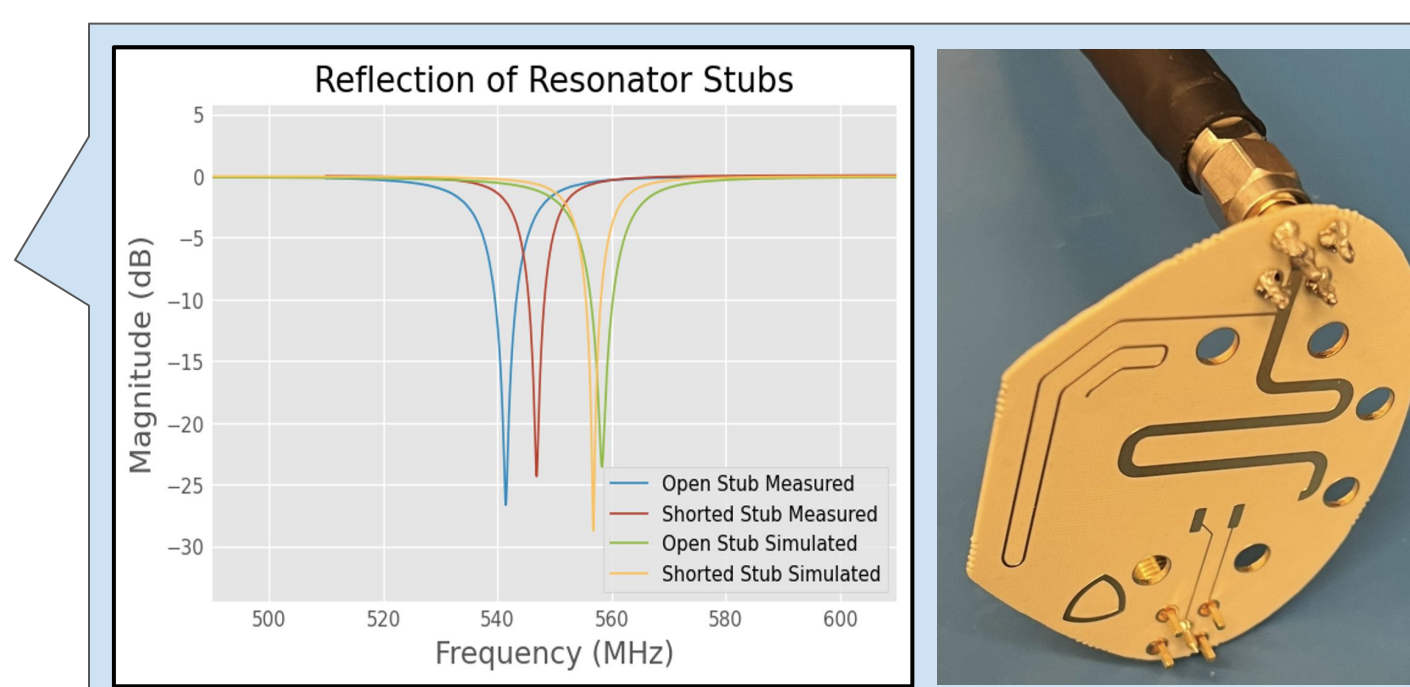
$$\eta_{sys, on(off)} = \frac{\hbar\omega}{k_B T_{sys, on(off)}}$$



While well demonstrated at 4-10GHz, we redesigned devices, packages and PCB to enable operation at frequencies matched to Project 8 demonstrators.

Results of prototypes with gain at 24GHz & 560MHz

560MHz 2D resonator R&D for noise, signal injection, and reconstruction algorithm tests.

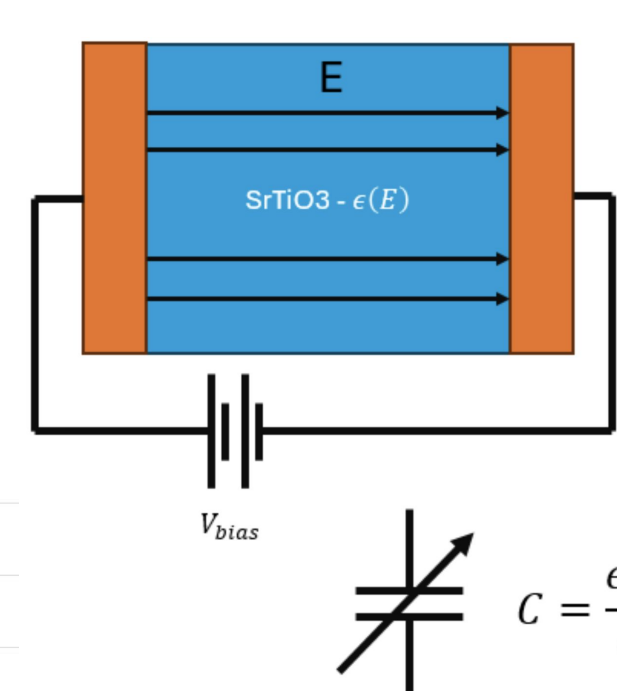
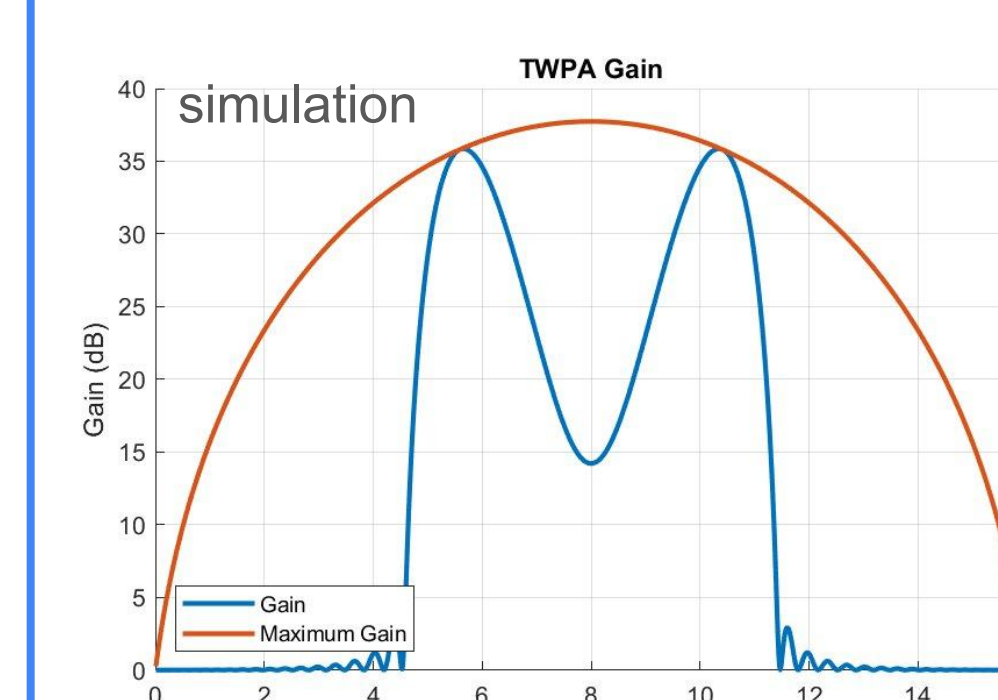


Next steps

At Mines, we intend to demonstrate quantum-limited readout of a 4K 2D-cavity losslessly connected to a cold bath at ≈ 20 mK and various amplifier technologies:

TWPAs with Dolan-style JJs from MIT (a) and JPAs from NIST using a modified, low-loss Trilayer JJ (b).

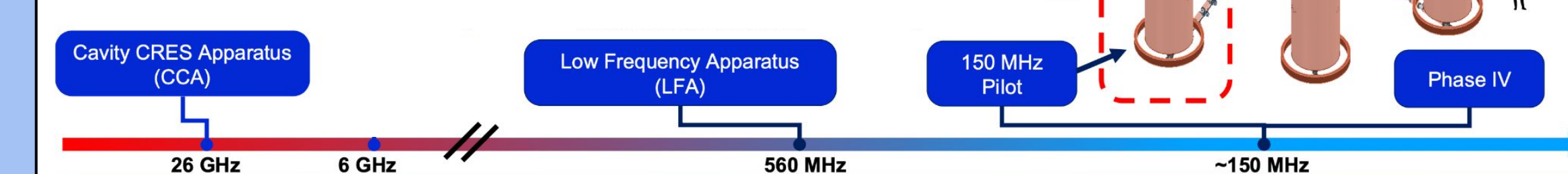
+ Non-linear dielectric TWPA using SrTiO₃ fabricated at Mines (c).



Potential for increased dynamic range & magnetic insensitivity.

Conclusions

Project 8's Phased approach towards large scale cavity CRES requires radiative cooling, lossless transfer lines and quantum amplification at sub-GHz frequencies.



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