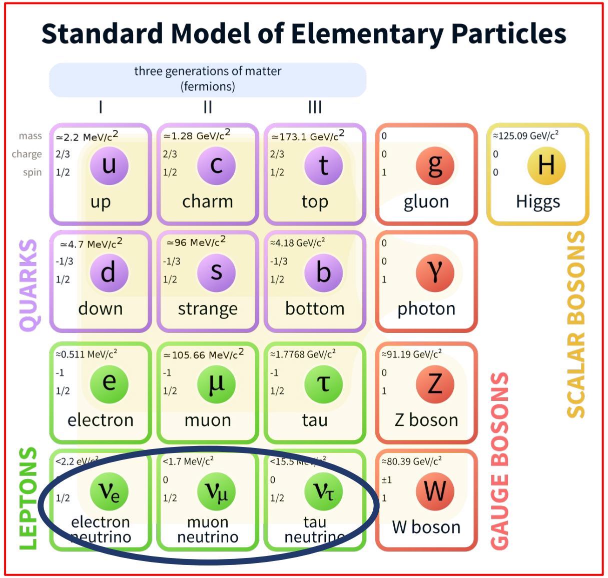
Queen Mary
University of London

QTNM
Quantum Technologies for
Neutrino Mass

Determination of the Absolute Neutrino Mass using Quantum Technologies

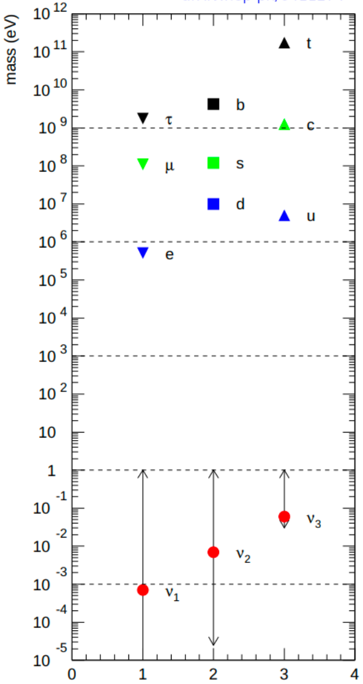
Nicola McConkey

Big questions in Neutrino Physics



- **What is the mass of the neutrino?**
- Neutrino oscillations demonstrate that neutrino mass is non-zero

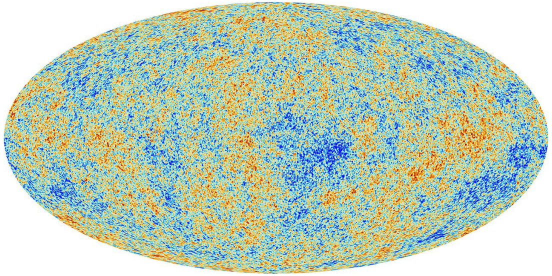
  There must be three distinct neutrino masses
- Absolute mass unknown – but very different from other fermions!
- Different mass generation mechanism?
- Implications for cosmology



arXiv:hep-ph/0411274

How to measure the neutrino mass

Cosmological measurements

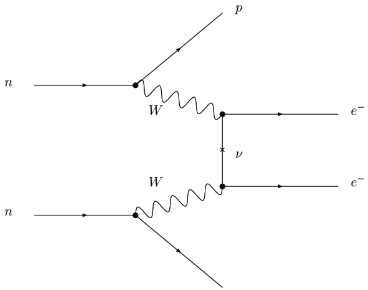


$$\Sigma = \sum_i m_i$$

$$\Sigma < 0.111\ \mathrm{eV}c^{-2}$$

arXiv:2007.08991 [astro-ph.CO] (2021)

Neutrinoless double β-decay

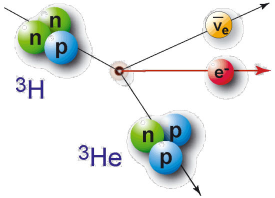


$$m_{\beta\beta} = \sum_i (U_{ei})^2\, m_i$$

$$|m_{\beta\beta}| < 0.036 - 0.156\ \mathrm{eV}c^{-2}$$

arXiv:2203.02139 [hep-ex] (2022)

Direct measurement of β-decay



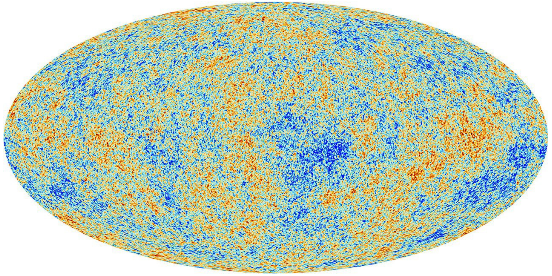
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2\, m_i^2}$$

$$m_\beta < 0.8\ \mathrm{eV}c^{-2}$$

Nat. Phys. **18**, 160-166 (2022)

How to measure the neutrino mass

Cosmological measurements



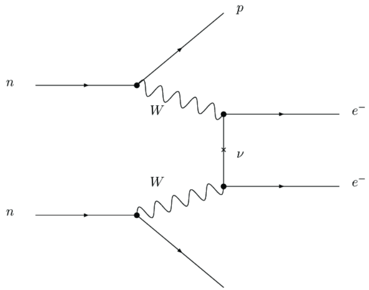
$$\Sigma = \sum_i m_i$$

[Model dependent]

$$\Sigma < 0.111\ \mathrm{eV}c^{-2}$$

arXiv:2007.08991 [astro-ph.CO] (2021)

Neutrinoless double β-decay

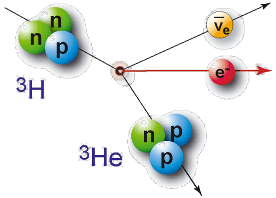


$$m_{\beta\beta} = \sum_i (U_{ei})^2 m_i$$

$$|m_{\beta\beta}| < 0.036 - 0.156\ \mathrm{eV}c^{-2}$$

arXiv:2203.02139 [hep-ex] (2022)

Direct measurement of β-decay



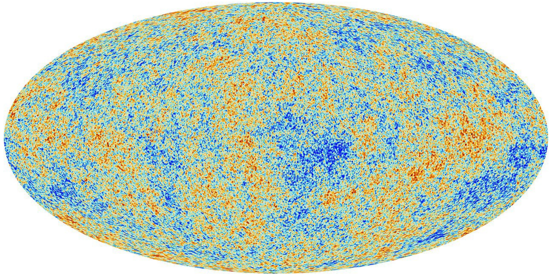
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

$$m_\beta < 0.8\ \mathrm{eV}c^{-2}$$

Nat. Phys. **18**, 160-166 (2022)

How to measure the neutrino mass

Cosmological measurements



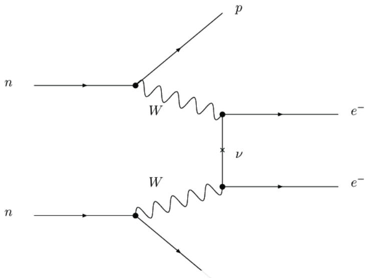
$$\Sigma = \sum_i m_i$$

[Model dependent]

$$\Sigma < 0.111 \text{ eV}c^{-2}$$

arXiv:2007.08991 [astro-ph.CO] (2021)

Neutrinoless double β-decay



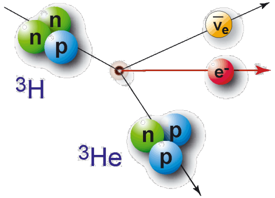
[Requires neutrinos to be Majorana particles]

$$m_{\beta\beta} = \sum_i (U_{ei})^2 m_i$$

$$|m_{\beta\beta}| < 0.036 - 0.156 \text{ eV}c^{-2}$$

arXiv:2203.02139 [hep-ex] (2022)

Direct measurement of β-decay



$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

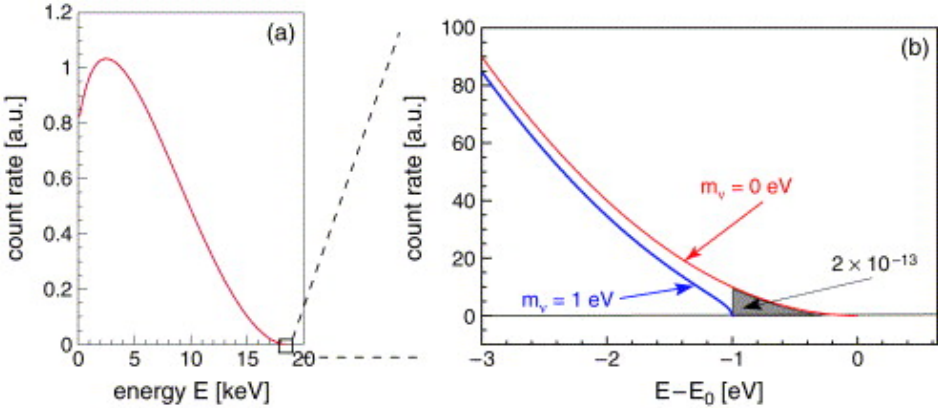
$$m_\beta < 0.8 \text{ eV}c^{-2}$$

Nat. Phys. **18**, 160-166 (2022)

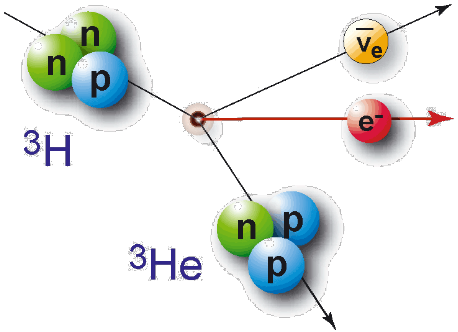
Direct measurement of beta decay

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1} X' + e^{-} + \bar{\nu}_e$$

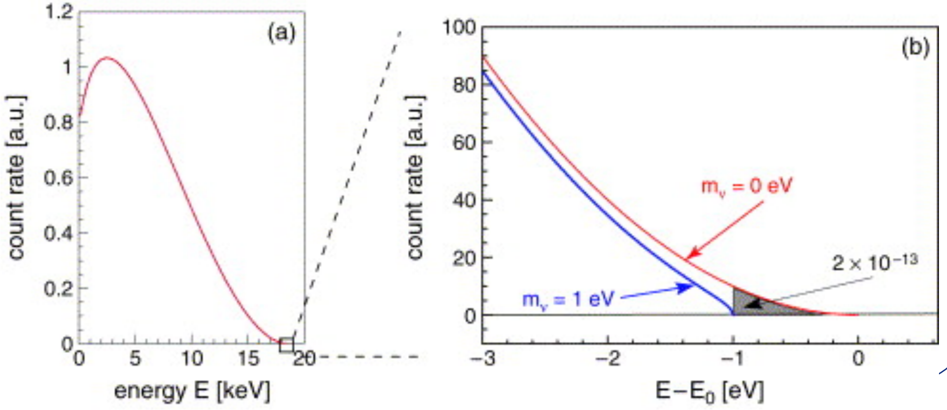
- For β-decay the total energy of the initial state is well known, and the **kinetic energy** of the final state can be **precisely measured**
- Use energy and momentum to constrain neutrino mass
- Measuring the **tail of the electron energy spectrum** with high precision gives the **neutrino rest mass**



Measuring neutrino mass with tritium beta decay



Tritium is a commonly used isotope due to half life and electron energy range



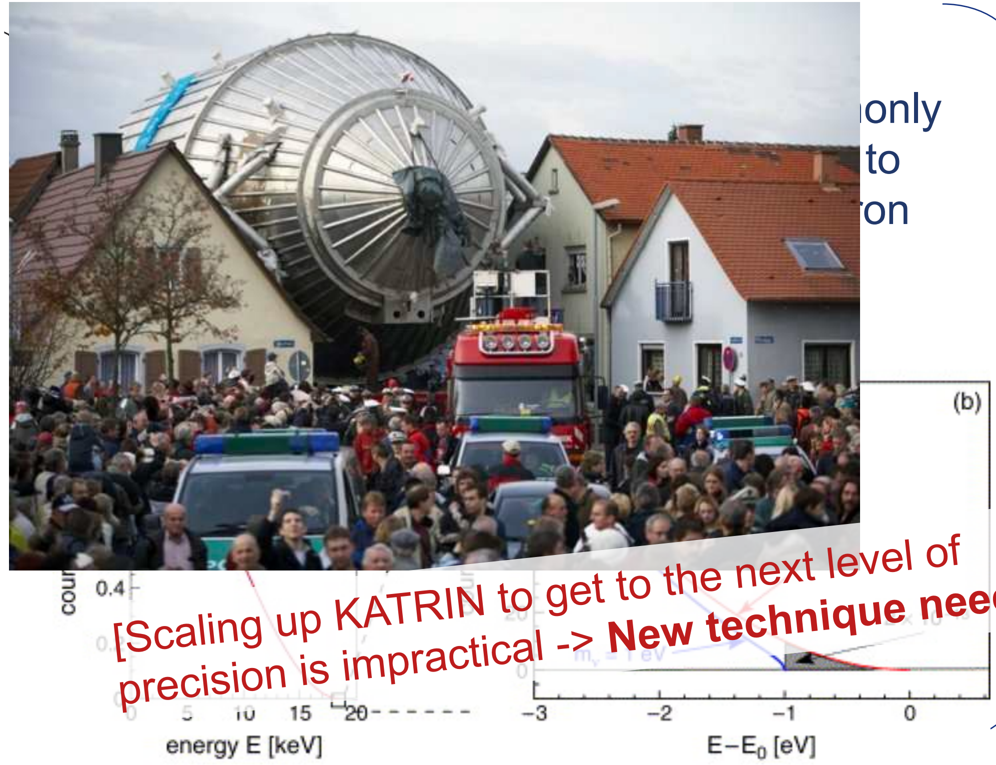
- Precision of electron energy measurement drives the sensitivity to the neutrino mass
- Current state-of-the-art technology has a sensitivity limitation of **0.2eVc^{-2}**
  - Recent results from KATRIN:

$m_\beta < 0.8$ eV c^{-2} at 90%CL

Nat. Phys. 18, 160-166 (2022)

Measuring neutrino mass with tritium beta decay

only
to
on



[Scaling up KATRIN to get to the next level of precision is impractical -> **New technique needed**]

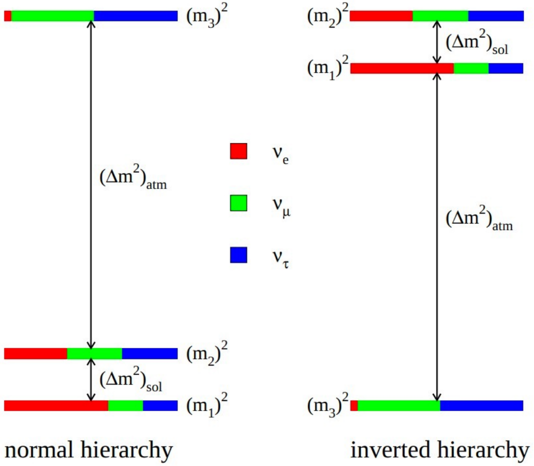
- Precision of electron energy measurement drives the sensitivity to the neutrino mass
- Current state-of-the-art technology has a sensitivity limitation of **0.2eVc^{-2}**
  - Recent results from KATRIN:

$m_\beta < 0.8$ eV c^{-2} at 90%CL

Nat. Phys. 18, 160-166 (2022)

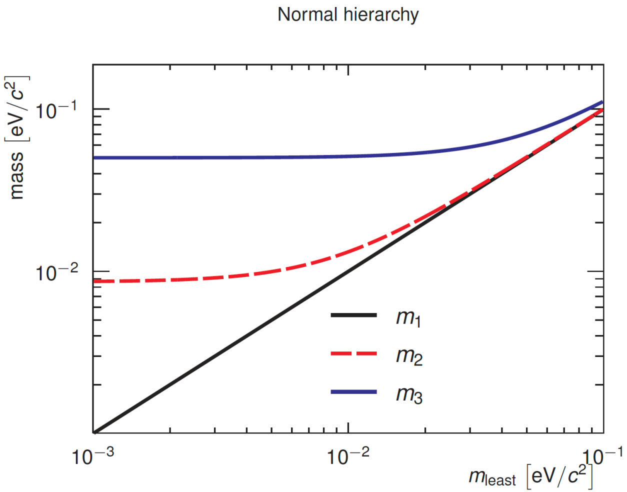
An aside on energy sensitivity motivations

- Neutrino oscillations tell us the mass splittings



arXiv:1310.4340

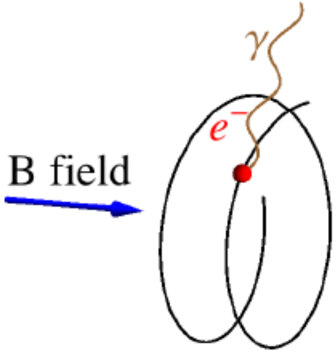
- Mass of lightest neutrino may be zero
- Other neutrino masses are constrained by mass splittings



Motivates reaching a sensitivity to m_β of ~10meV

Cyclotron Radiation Emission Spectroscopy (CRES)

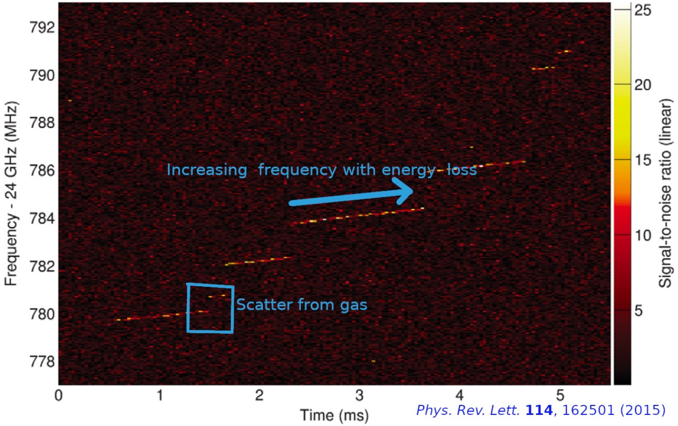
- A new technique for measuring the neutrino mass
- Pioneered by Project-8
- *Measure the frequency of electromagnetic radiation generated due to electron's cyclotron motion in magnetic field*



$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

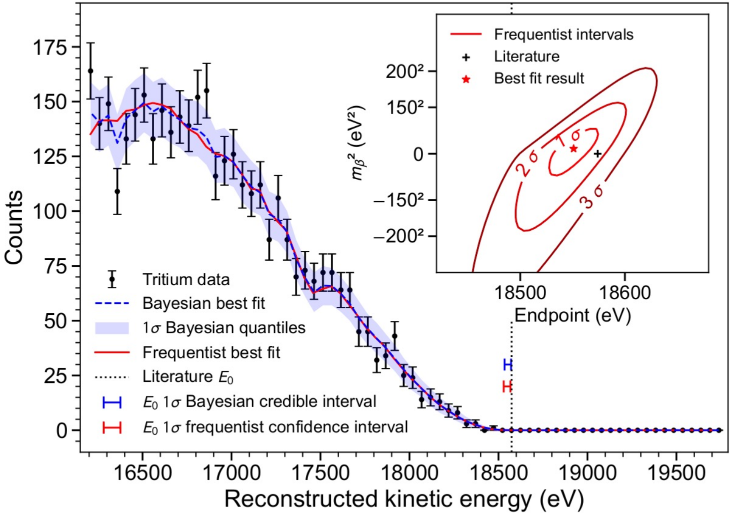
Project-8

- CRES signal from 30 keV 83mKr decay electrons in Phase I



Phys. Rev. Lett. **114**, 162501 (2015)

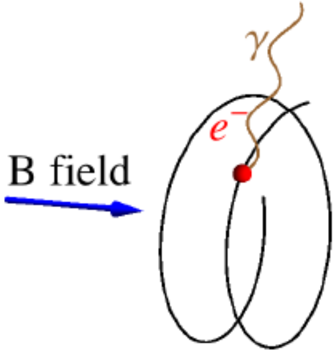
Ashtari Esfahani et al. arXiv:2303.12055 [nucl-ex]



- Phase II with molecular tritium in a ~ 1 T field
- Detected 3742 events over 82 days

Cyclotron Radiation Emission Spectroscopy (CRES)

- A new technique for measurin
  the neutrino mass
- Pioneered by Project-8
- *Measure the frequency of electromagnetic radiation generated due to electron's cyclotron motion in magnetic field*



$$\boxed{f} = \frac{1}{2\pi}\frac{eB}{m_e + \boxed{E_{\text{kin}}}/c^2}$$

QTNM Goal: Measure energy of electron emitted in β-decay of *atomic tritium* using CRES

Quantum Technologies for Neutrino Mass

- UKRI funded as part of Wave 1 of the Quantum Strategy Fund
  - Quantum Technologies for Fundamental Physics consortium
- Bring together experts from particle physics and cold atom physics, atomic and molecular physics and quantum electronics
- First phase of funding to build a demonstrator: CRES Demonstrator Apparatus (CRESDA)

UCL

UNIVERSITY OF OXFORD

UNIVERSITY OF CAMBRIDGE

Prifysgol Abertawe
Swansea University

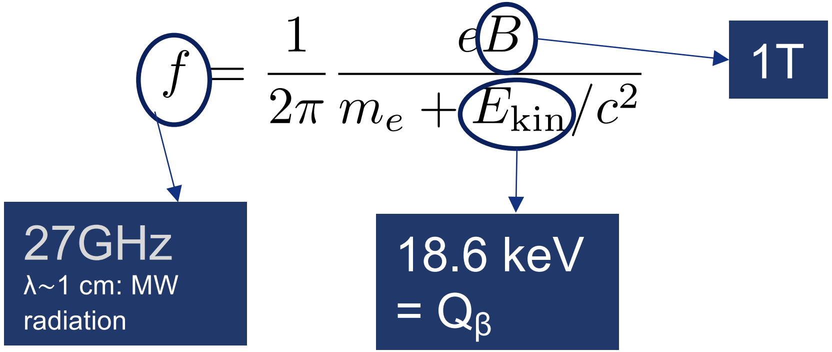
WARWICK
THE UNIVERSITY OF WARWICK

Queen Mary
University of London

NPL
National Physical Laboratory

Quantum Technologies for Neutrino Mass

- CRESDA will use Quantum-limited amplifiers to measure microwave e$^-$ signal
- Magnetic field mapping with <1μT absolute precision and ~ 1mm spatial resolution
- CRESDA0 will operate with H/D atoms and an electron source
- Working with Culham Centre for Fusion Energy (CCFE) – UK T facility
  - Compatibility of design with future T operation / suitable operation space



$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$

1T

27GHz
λ~1 cm: MW radiation

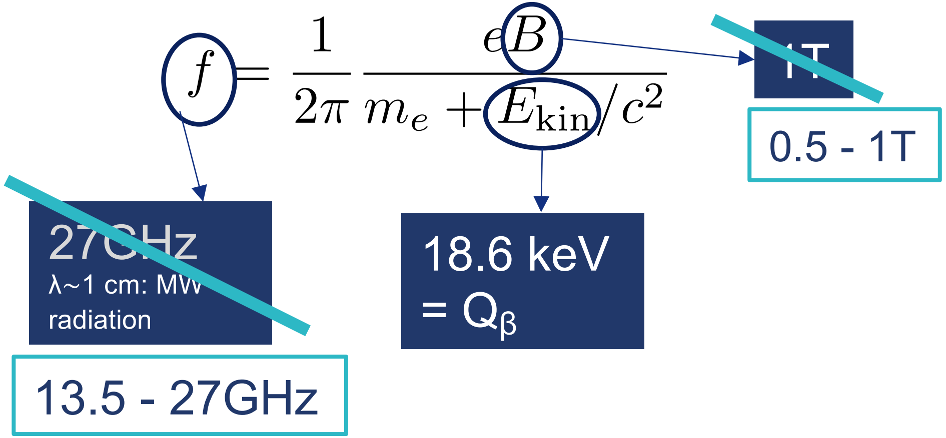
18.6 keV = Q_β

CCFE
CULHAM CENTRE FOR FUSION ENERGY

Queen Mary
University of London

Quantum Technologies for Neutrino Mass

- CRESDA will use Quantum-limited amplifiers to measure microwave e$^-$ signal
- Magnetic field mapping with <1μT absolute precision and ~ 1mm spatial resolution
- CRESDA0 will operate with H/D atoms and an electron source
- Working with Culham Centre for Fusion Energy (CCFE) – UK T facility
  - Compatibility of design with future T operation / suitable operation space



$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$

~~1T~~

0.5 - 1T

~~27GHz~~

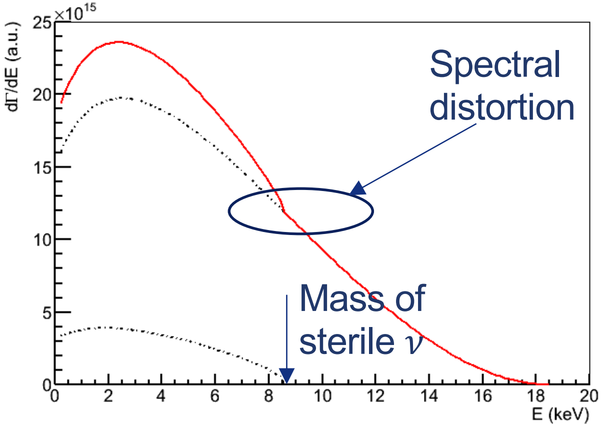
~~λ~1 cm: MW radiation~~

13.5 - 27GHz

18.6 keV = Q_β

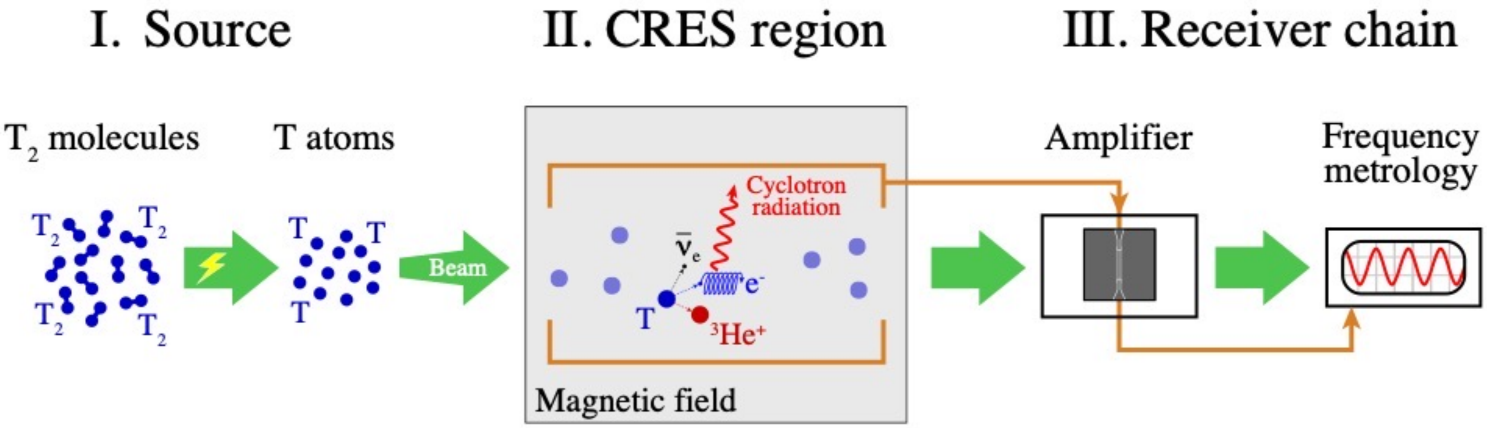
CRES: Advantages and Challenges

- Precision frequency measurement
  - precision neutrino mass measurement!
- CRES gives a **differential spectrum**
  - Opens up the potential for a model-independent kinematic **"Sterile" neutrino search**



- ~20GHz Microwave radiation – challenging to collect
- Radiated power is very small (sub-fW)
  - Millimeter wave ultra low noise amplifiers
- Require atomic tritium to decrease the rotational and vibrational excitation states of molecular tritium
  - Production and preservation of atomic T is a key challenge
- Need an intense source of T
  - Spectrum endpoint (last 1eV) contains 2.9 x 10^{-13} of the events

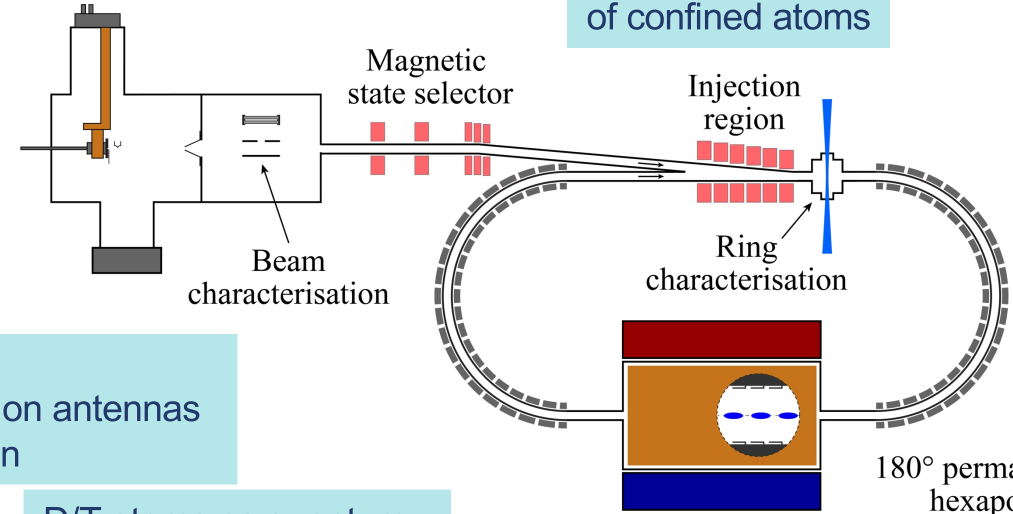
CRESDA Outline



CRES Demonstrator Apparatus

H/D/T atomic source
H/T atoms cooling
and confinement

Extensive characterisation of confined atoms



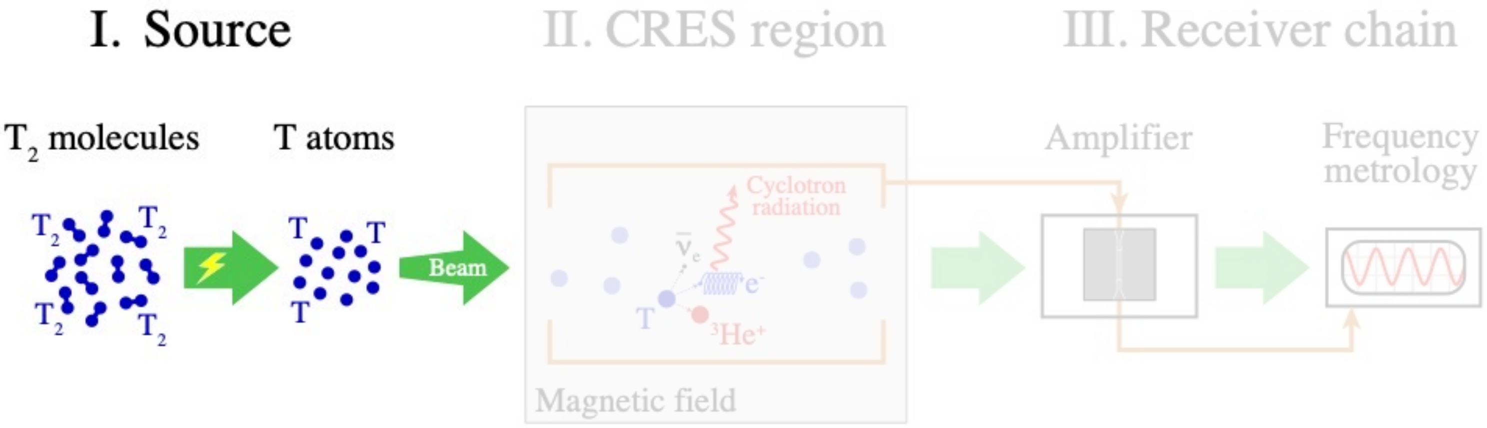
CRES region

- Magnetic trap
- Microwave collection antennas
- Signal amplification

Storage ring

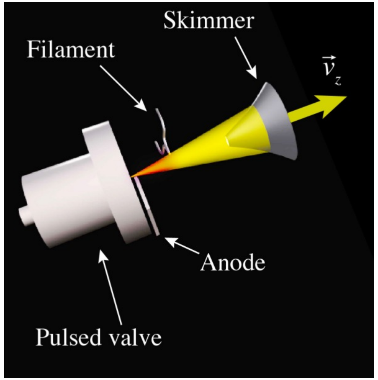
D/T atoms as quantum sensors for 3D B-field uniformity mapping

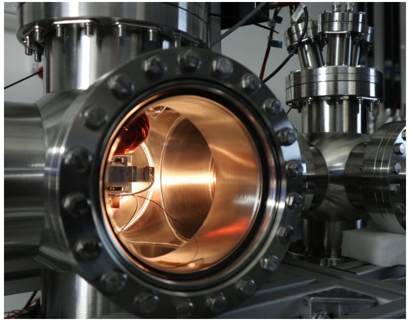
CRESDA Outline

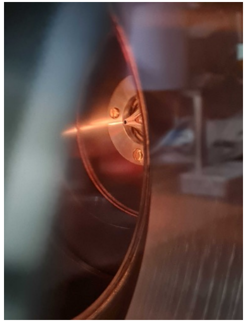


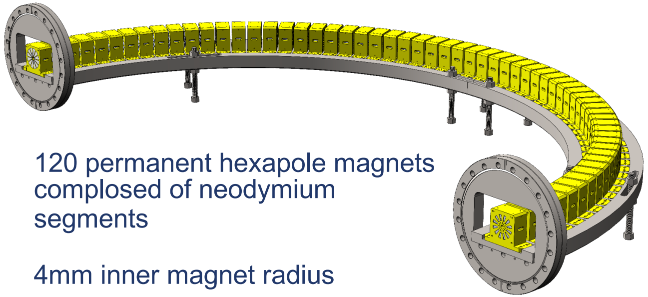
Atomic source and storage ring

- **Create an atomic T (and H) source** from T_2 (H_2)
- Molecular dissociation using DC discharge seeded with e^- from tungsten filament
- Cryogenic pulsed supersonic source
  - beam with narrow velocity distribution
  - cooled to reduce mean longitudinal velocity
- Characterisation using Resonance Enhanced Multi Photon Ionisation REMPI









120 permanent hexapole magnets complosed of neodymium segments

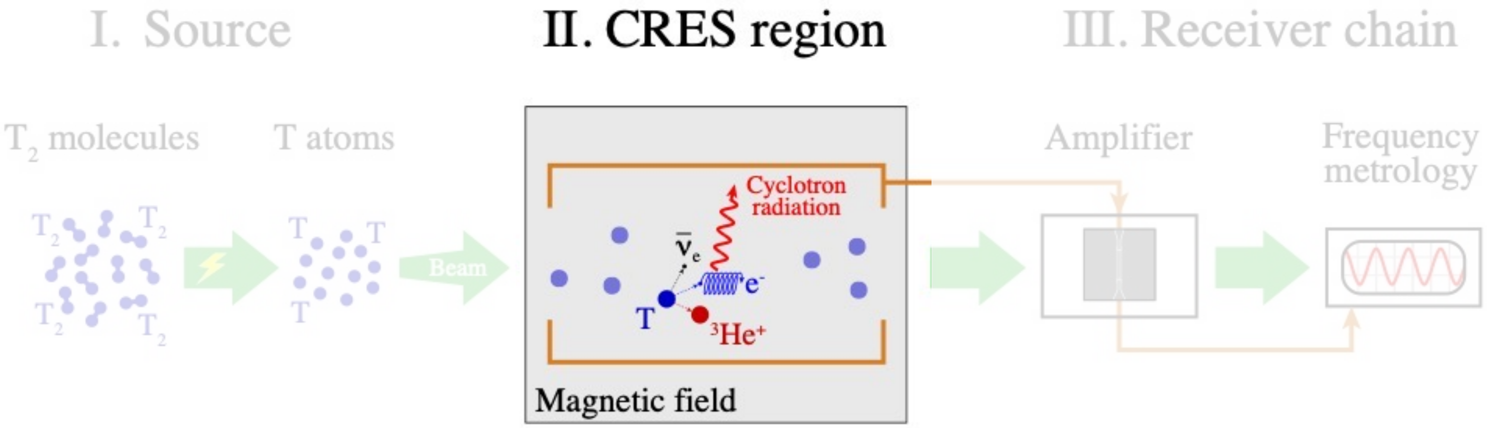
4mm inner magnet radius

1.2m overall diameter

- Racetrack storage ring to confine hydrogen / tritium atoms

  Atoms orbit the ring and pass through CRES measurement regions

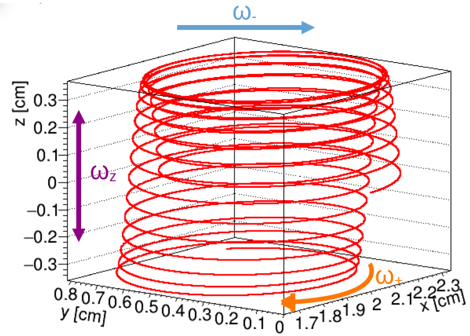
CRESDA Outline

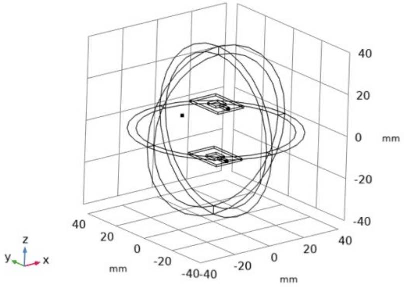


The CRES Region:
Electron trapping and Signal collection

- **Challenge:** collecting microwave radiation of sub-fW power
- Must be fast, high efficiency, good signal to noise
- Complex trade off between field of view and gain
- Three options under development for QTNM
  - Antennas
  - Waveguides
  - Resonant cavities

arXiv:2401.03247v1





- **Challenge:** Daughter electrons from T decay are near relativistic in speed

  Need to measure for >20us in order to collect enough power

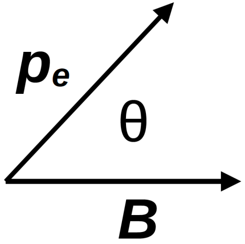
- Electrons can be trapped in a magnetic bottle trap while sufficient power is collected

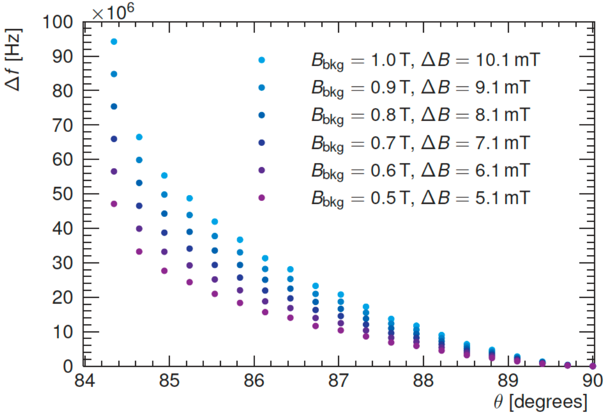
  0.1mT local minimum “no-work” trap

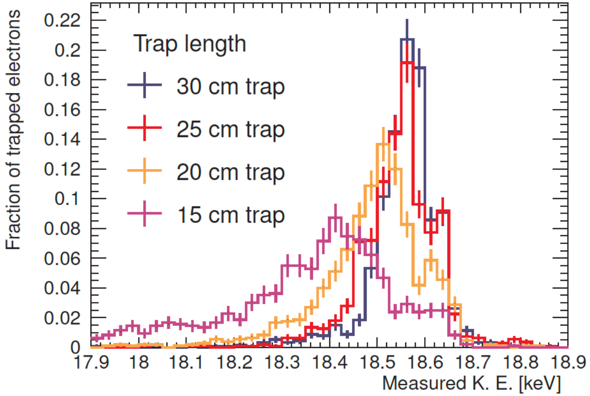
Trap simulation

- Electrons with different pitch angles experience different B fields
- Leads to endpoint electrons radiating at different frequencies

- Simulations to study the effect of trap design on energy resolution
- Longer trap -> electron spends more time in the homogeneous B-field region
  - Easier to reconstruct e^- energy







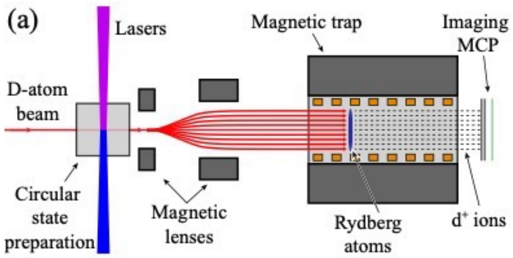
The CRES Region – Field uniformity measurements

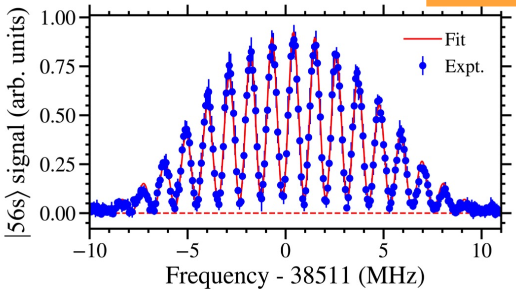
- B field directly affects sensitivity to neutrino mass

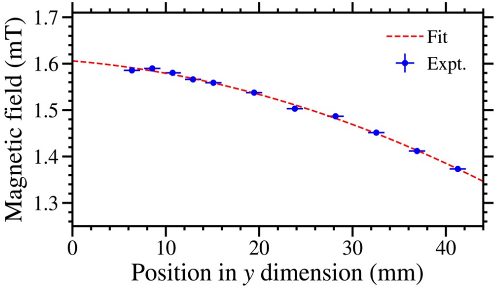
$$\boxed{f} = \frac{1}{2\pi}\frac{e\boxed{B}}{m_e + \boxed{E_{\text{kin}}}/c^2}$$

- Require a uniform and well understood B field
  - Aim for <1ppm resolution in measurement
- Current results:
  - *Absolute precision ±2 μT, relative ±900nT*
  - *Spatial resolution ±0.87mm Electrometry abs precision ~ 85 μV/cm*

- Rydberg atom magnetometry and electrometry
  - Atoms in circular Rydberg states as quantum sensors
- Ramsey spectrum of transition between circular Rydberg states

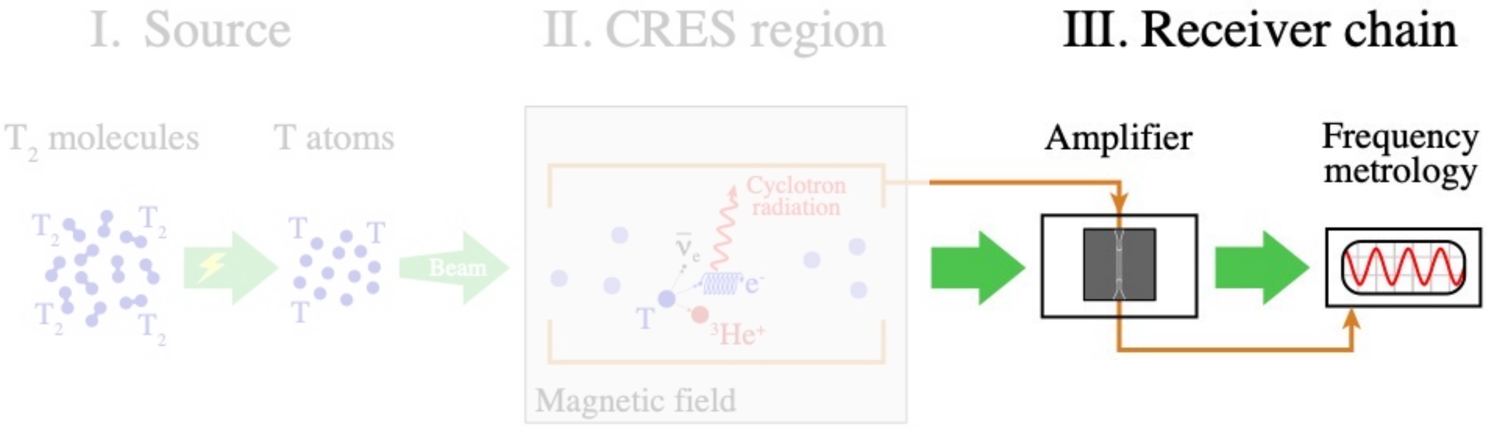






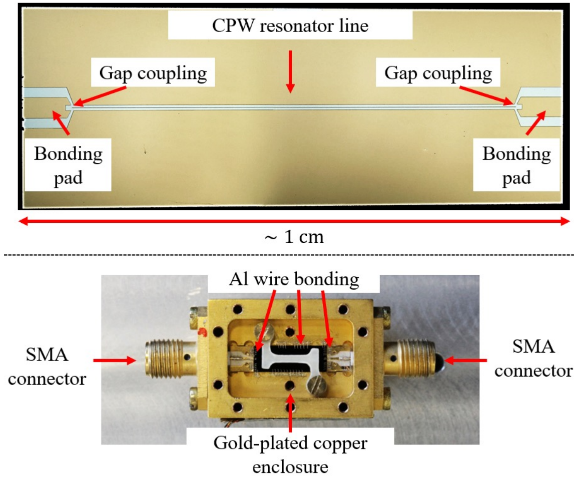
Zou and Hogan, *Phys. Rev. A* **107**, 062820 (2023)

CRESDA Outline

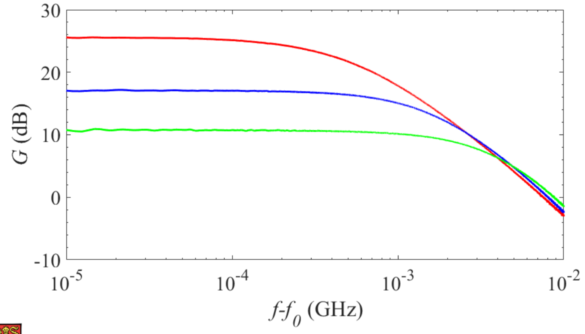


Quantum-limited amplifiers for MW radiation

- **Resonant / Travelling Wave Kinetic Inductance Parametric Amplifiers**
  - Two port resonators operating as amplifiers
- Superconducting thin-film NbN paramps designed, fabricated
- Good gain results achieved in CRES frequency range
  - Showing potential for operating at 4K as well as 100mK
  - Affordable multichannel readout



- Single-port scheme under development and testing with promising results so far!



Gain profile at 18 GHz
at different operating points

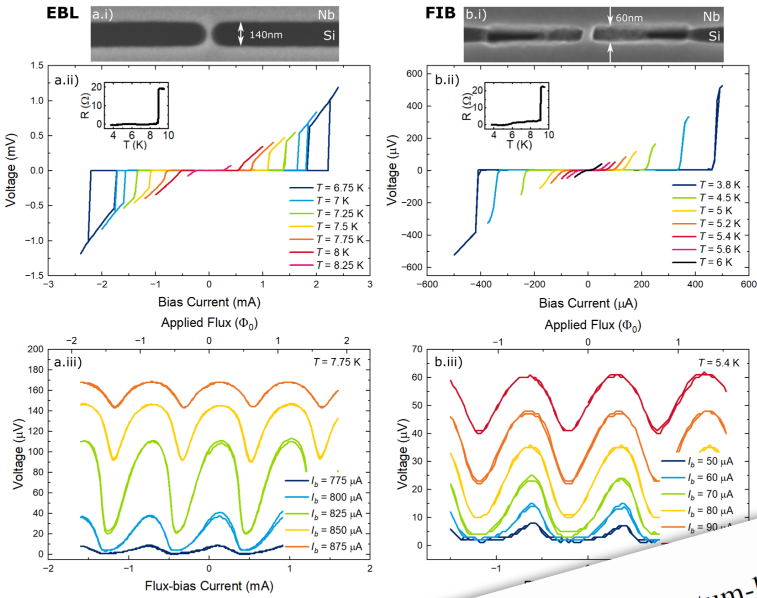
https://arxiv.org/abs/2306.00685

UNIVERSITY OF OXFORD

UNIVERSITY OF CAMBRIDGE

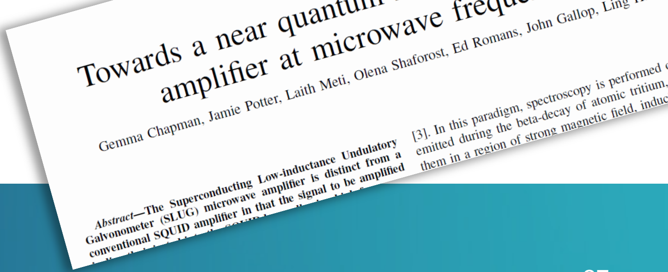
Quantum-limited amplifiers for MW radiation

- Based on **Superconducting Low Inductance Undulatory Galvanometers (SLUG) and** utilising nanobridge weak link **Josephson junctions**
- High frequency MW amplifiers operating at 28GHz
- Recent paper comparing nanobridges fabricated by different techniques
  - Both show promising results!
    - Gain ~15dB at 20GHz
  - EBL ideal for higher operating frequencies
  - FIB operate more readily at lower temperatures



NPL

National Physical Laboratory



Towards a near quantum-limited planar SLUG amplifier at microwave frequencies

Gemma Chapman, Jamie Potter, Laith Meti, Olena Shaforost, Ed Romans, John Gallop, Ling Hao

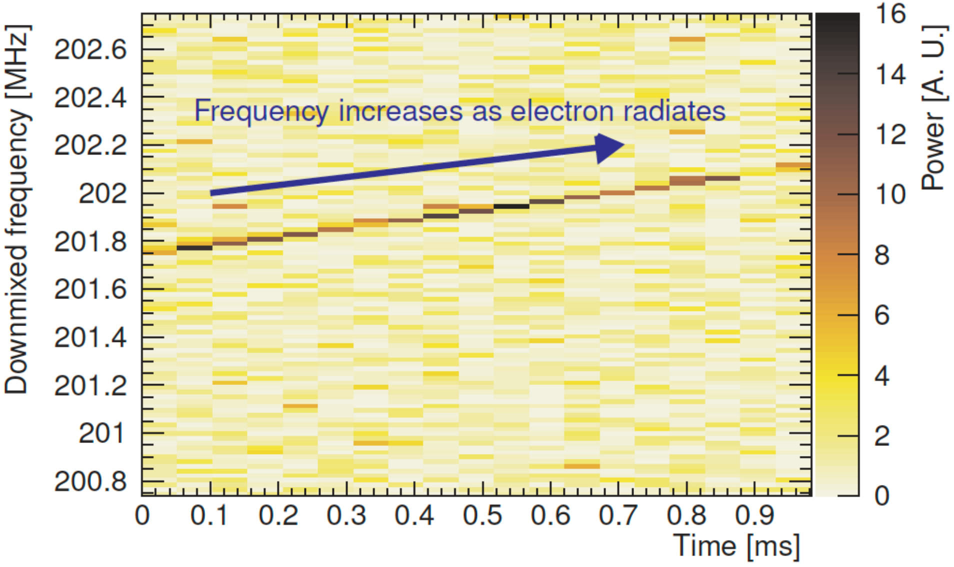
Abstract—The Superconducting Low-inductance Undulatory Galvonometer (SLUG) microwave amplifier is distinct from a conventional SQUID amplifier in that the signal to be amplified

[3]. In this paradigm, spectroscopy is performed
emitted during the beta-decay of atomic tritium,
them in a region of strong magnetic field, induc

Queen Mary University of London

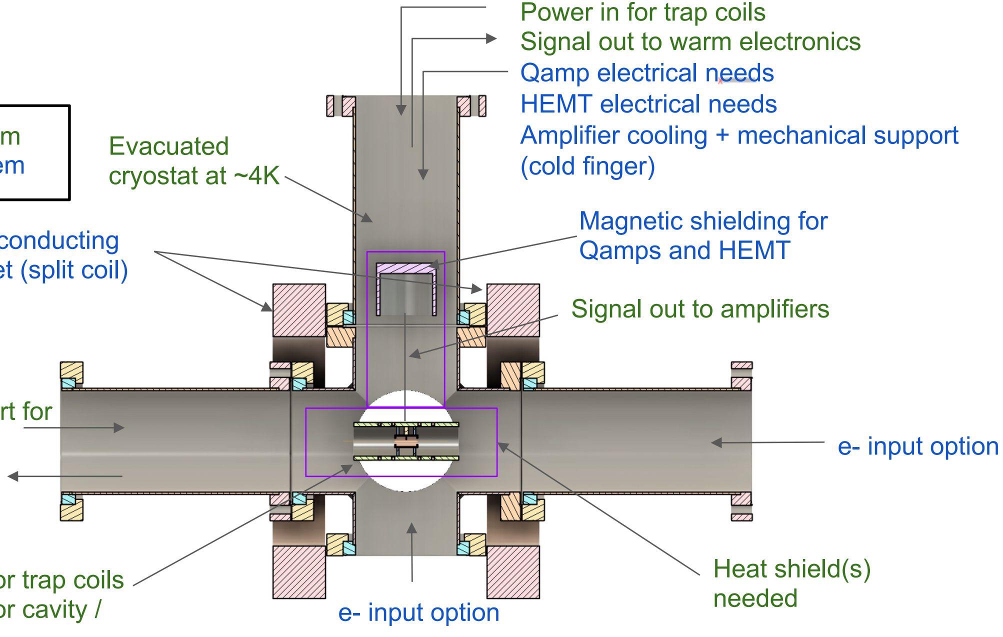
Signal: Spectrograms

- QAmp + Second amplification stage with HEMT
- Downmixing and signal readout happens post-amplification
- CRES Signals
  - Signal “chirps” as electron radiates energy
  - Scatters on gas molecules give discrete jumps in frequency
- Studying trigger options for this distinctive structure



CRES systems integration

- **CRESDA0**
- Staged approach to integrate and test components
    - Design with forward compatibility in mind
- 4K central region with MW source + electron source(s), traps + antennas
- Link to HEMT and Qamps (100mK)
- Connect CRES region to source and ring



First integrated system
Upgrade to first system

Power in for trap coils
Signal out to warm electronics
Qamp electrical needs
HEMT electrical needs
Amplifier cooling + mechanical support (cold finger)

Evacuated cryostat at ~4K

Superconducting magnet (split coil)

Magnetic shielding for Qamps and HEMT

Signal out to amplifiers

Cold finger (Mechanical support for main structure)
Vacuum pump

e- input option

Mechanical support for trap coils
Mechanical support for cavity / signal collection

e- input option

Heat shield(s) needed

Future outlook for QTNM

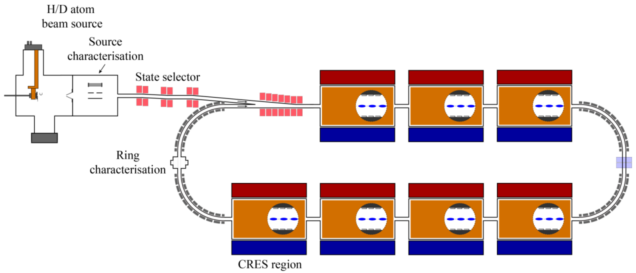
QTNM
Quantum Technologies for Neutrino Mass

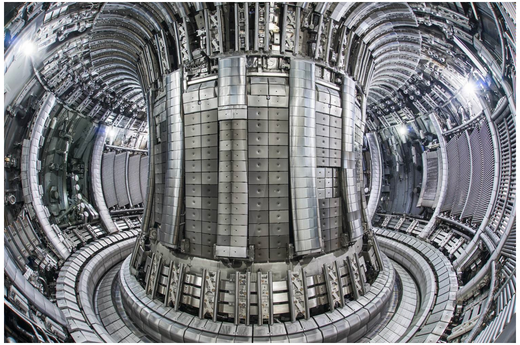
- **Demonstration of technology with H/D**
  - This phase of the project
- Moving CRESDA to a tritium facility
  - Tritium phase demonstration
  - O(eV) sensitivity

- **“Ultimate” international project**
- Consolidating technological breakthroughs from KATRIN, Project 8 and QTNM
- Build and operate a detector with phased sensitivity

  100 meV ⇨ 50 meV ⇨ 10 meV

  (plus sterile neutrino programme)





CCFE
CULHAM CENTRE FOR FUSION ENERGY

Summary

- **Quantum technology** can be used to enable **fundamental measurements in neutrino physics**
  - Development of technology to measure high-frequency (GHz) low amplitude signals
- The goal for Quantum Technologies for Neutrino Mass is to build an experiment to measure the **beta decay of atomic tritium**, and hence the **absolute neutrino mass**(es)
- QTNM are building CRESDA to demonstrate the combination of these technologies
  - CRESDA0 will operate with H/D atoms and an electron source
  - Moving CRESDA to a tritium facility will enable first T measurements
  - Scale up to "next generation" larger volume apparatus to give groundbreaking sensitivity to ν_{mass}
- Excellent progress in all areas of system development, CRESDA0 integration and assembly starts this year!
- Stay tuned for the **QTNM White Paper** detailing the experiment and outlining physics goals

Thank you

Queen Mary
University of London