The QTNM collaboration: a new project for neutrino mass measurement

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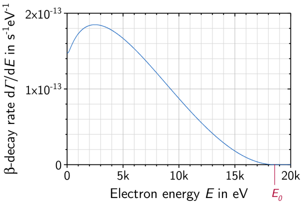
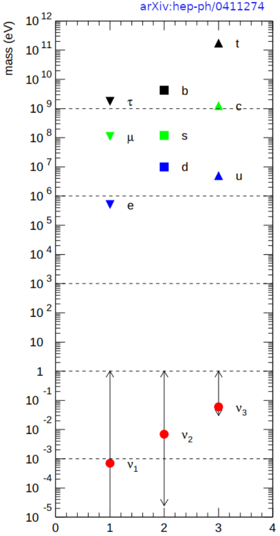
The neutrino

- Existence first postulated by Pauli in 1930 to explain shape of β decay spectrum
- Directly detected by Cowan & Reines in 1956
- Three flavours discovered: ν_e, ν_μ, ν_τ. All appeared to be massless



Neutrino oscillations

- Evidence from atmospheric, solar, reactor and accelerator neutrinos all confirms the existence of neutrino oscillations
- 2015 Nobel Prize awarded to Takaaki Kajita & Arthur B. Macdonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*
- Oscillations arise from mixing between flavour and mass eigenstates of neutrinos
- Neutrino mass scale very different from other fermions



Neutrino oscillations and neutrino mixing

- Mixing between flavour and mass eigenstates given by

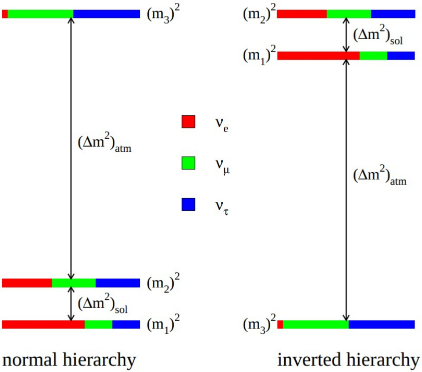
$$|\nu_i\rangle = \sum_i U_{\alpha i} |\nu_\alpha\rangle$$

  where

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

  is a unitary matrix
- Oscillations controlled by the matrix U and the squared differences between the mass eigenstates, $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- These Δm_{ij}^2 control the length/energy scale at which oscillations occur

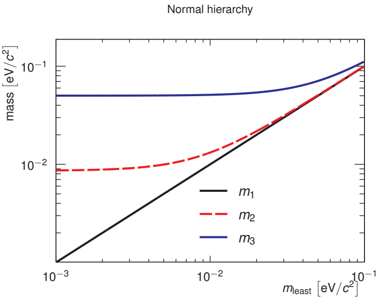
Neutrino mass hierarchy

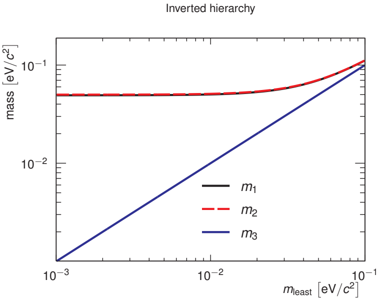


arXiv:1310.4340

- Differences between m_i^2 known from oscillations
- Ordering of mass eigenstates currently unknown
- Lightest mass eigenstate is either m_1 (normal hierarchy) or m_3 (inverted hierarchy)

Possible neutrino masses





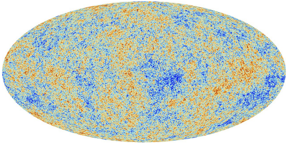
- It is possible the lightest mass eigenstate (either m_1 or m_3) may in fact be massless
- Masses of the other eigenstates are then constrained by the mass splittings

Why measure the neutrino mass?

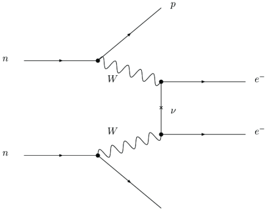
- Evidence for physics beyond the Standard Model
- Very different mass scale suggests different mass generation mechanism (compared to just Higgs)
- Connected to various new physics searches:
  - Lepton number violation
  - Sterile neutrino

Measuring the neutrino mass

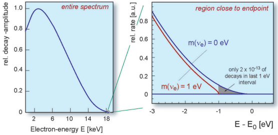
Cosmological measurements



Neutrinoless double β-decay

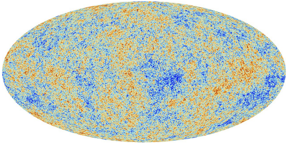


Direct measurement of β-decay



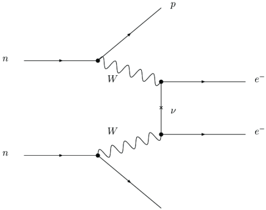
What do we actually measure?

Cosmological measurements



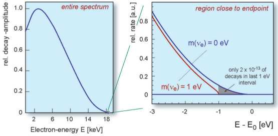
$$\Sigma = \sum_i m_i$$

Neutrinoless double β-decay



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

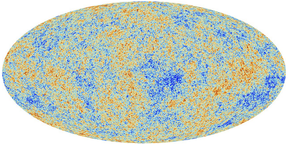
Direct measurement of β-decay



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

Current limits

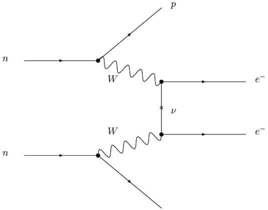
Cosmological measurements



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

arXiv:2007.08991 [astro-ph.CO]

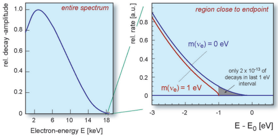
Neutrinoless double β-decay



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

arXiv:2203.02139 [hep-ex] (2022)

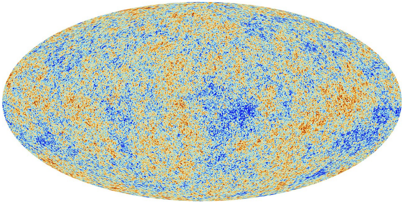
Direct measurement of β-decay



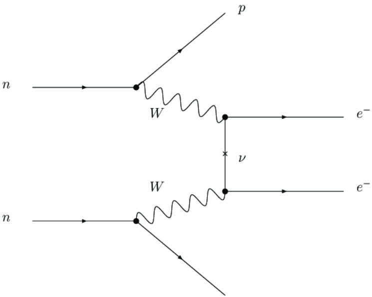
$m_\beta < 0.8\ \mathrm{eV}c^{-2}$

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

The first two have their issues



Relies on cosmological models



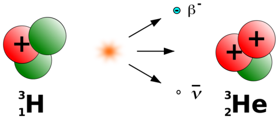
Only works if neutrinos are Majorana particles

- Neither of these are model independent measurements in the same way that direct measurement is

Measurements of β-decay

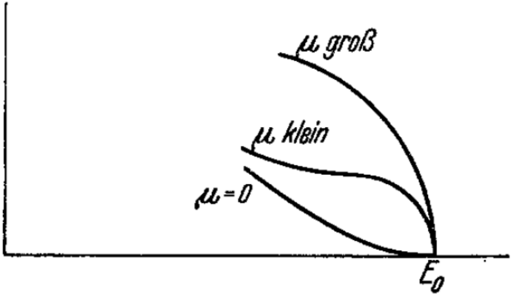
$$^A_Z X \rightarrow ^A_{Z+1} X' + e^- + \bar{\nu}_e$$

- For β-decay the total energy of the initial state is well known and the kinematics of the final state can be precisely measured
- Can use energy and momentum conservation to constrain the neutrino mass
- Processes such as this often referred to as ‘direct measurement’
- Isotope commonly used is tritium



Direct measurement

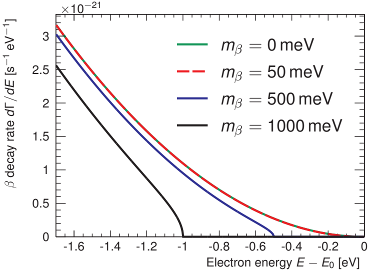
Z. Phys. **88**, 161 (1934)

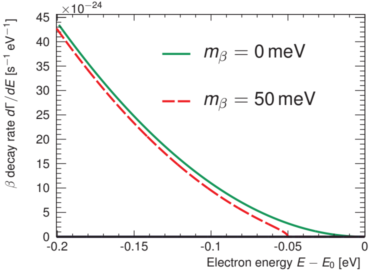


- An old idea – Fermi suggested the shape of the β-ray spectrum could be used to determine the neutrino mass in 1934, as did Perrin separately in 1933

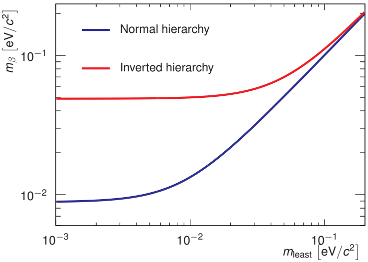
Tritium β-decay spectrum

$$\frac{d\Gamma}{dE} \approx 3r_0\,(E_0 - E)\left[(E_0 - E)^2 - m_\beta^2\right]^{1/2} \Theta\,(E_0 - E - m_\beta)$$



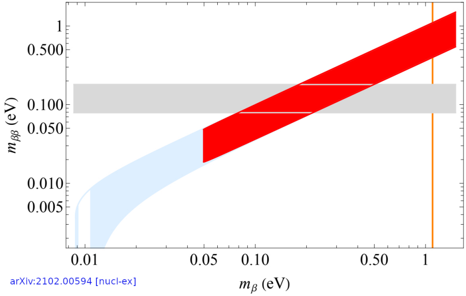


Limits on m_β



- Mass splittings from oscillation experiments provide a lower limit on m_β
  - For normal hierarchy $m_\beta \gtrsim 9\,\text{meV}$
  - For inverted hierarchy $m_\beta \gtrsim 50\,\text{meV}$
- An experiment with a sensitivity below $m_\beta = 50\,\text{meV}$ will determine the mass hierarchy (if still unknown)
- A sensitivity of 9 meV gives us a guaranteed discovery

What can measuring m_β tell us?

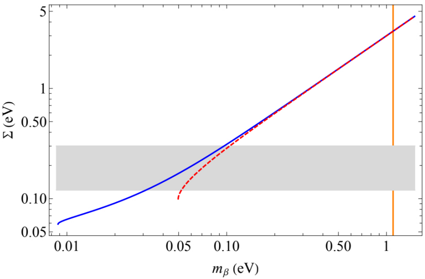


arXiv:2102.00594 [nucl-ex]

- Results can add to those from $0\nu\beta\beta$ experiments – determine Majorana phases
- Red here is IH, blue is NH, width of the band is all possible values of Majorana phases
- Horizontal band is 95% upper bound on $m_{\beta\beta}$ from GERDA

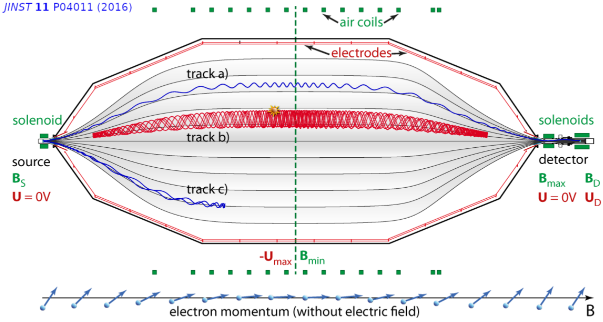
What can measuring m_β tell us?

arXiv:2102.00594 [nucl-ex]



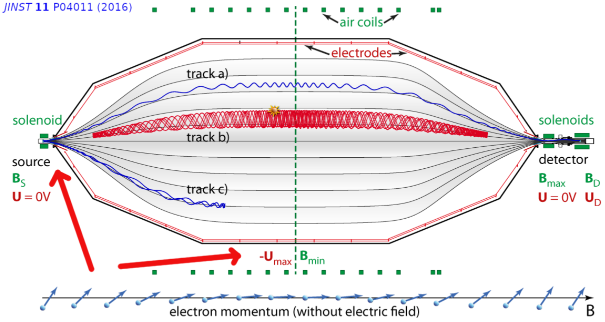
- Similarly, results can be used to augment existing limits from cosmology
- Red here is IH, blue is NH
- Horizontal band: 95% CL upper bound on Σ from cosmology

MAC-E filter – Current state of the art



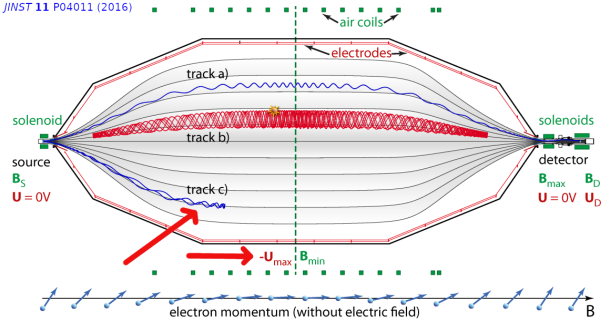
- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic

MAC-E filter – Current state of the art



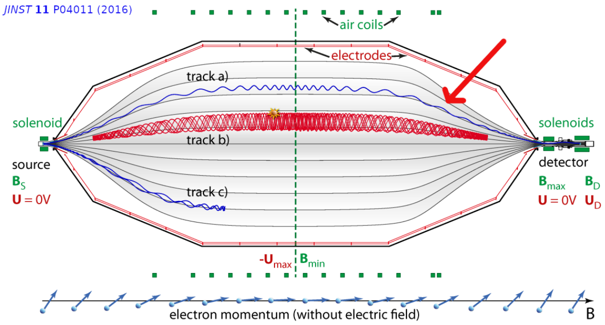
- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic
- Electrons emitted in source region with high magnetic field, B_S, and travel adiabatically along field lines to analysing region with much lower field, B_{min}

MAC-E filter – Current state of the art



- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic
- Retarding potential at central analysing plane prevents electrons without sufficient energy from passing

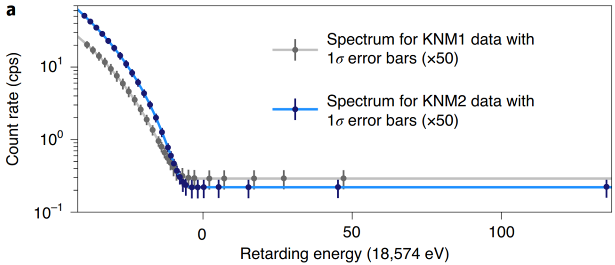
MAC-E filter – Current state of the art



- **M**agnetic **A**diabatic **C**ollimation – **E**lectrostatic
- Those electrons with sufficient energy to pass the potential barrier are re-accelerated and detected

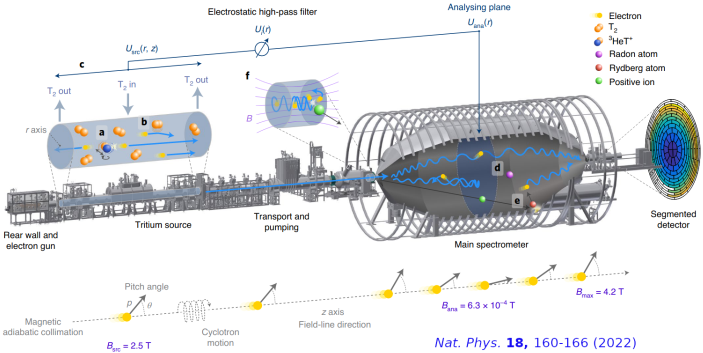
MAC-E filter – Current state of the art

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



- Repeat this for different retarding potentials in order to generate spectrum

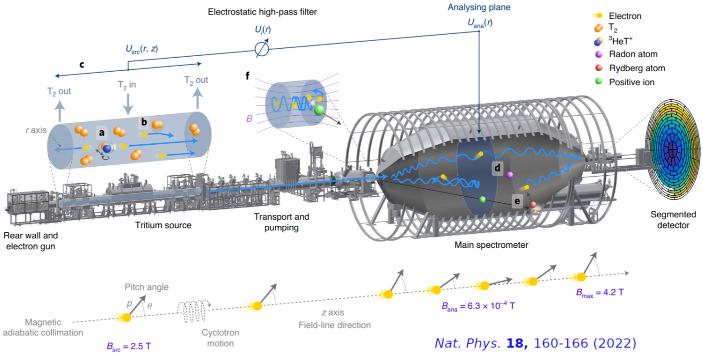
KATRIN experiment



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

- Current best limits on m_β are produced by the KATRIN experiment, shown here
- 70 m long beamline
- Spectrometer is 9.8 m in diameter and 23.3 m in length held at pressure of 10^{-11} mbar

KATRIN experiment



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

- Most recent combined results give upper limit of $m_\beta < 0.8$ eVc^{-2}
- This is expected to be extended down to 0.2 eVc^{-2} with the addition of further data

Limitations of MAC-E filters

- To increase statistical power, can increase source size
- However, source thickness is limited by $\sigma n_s \leq 1$ where σ is electron inelastic cross-section and n_s is the number density
- For a MAC-E filter:

$$\frac{\Delta E}{E} = \frac{B_{\text{ana}}}{B_{\text{src}}} = \left(\frac{R_{\text{src}}}{R_{\text{ana}}}\right)^2$$

- Therefore, increasing R_{src} requires a corresponding increase in the spectrometer size

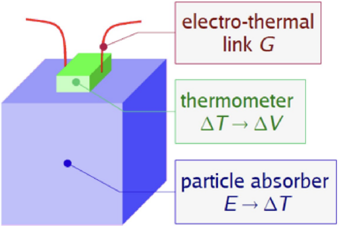
Limitations of MAC-E filters

- Impractical to scale KATRIN up – spectrometer is already $\sim 10\,\mathrm{m}$ in diameter

- We require a different technique for $m_\beta < 0.2\ \mathrm{eV}c^{-2}$

Are calorimetric techniques the solution?

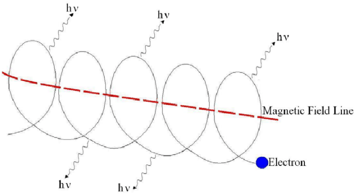
- Can embed isotopes in microcalorimeter – these decay via electron capture
- Calorimeter measures the atomic de-excitation energy (minus the neutrino's energy)
- ^{163}Ho used by ECHo and HOLMES collabs.



- In order to get required energy resolution for a high enough activity may require thousands or 100s of thousands of microcalorimeters operated at mK level

CRES overview

- **C**oherent **R**adiation **E**mission **S**pectroscopy
- Concept pioneered by Project 8 collaboration - *Phys. Rev. D* **80**, 051301(R)



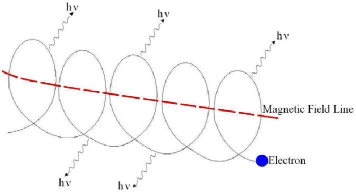
$$f = \frac{1}{2\pi} \frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

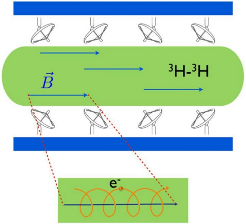
- Determine energy of β-decay electron by measuring the frequency of the emitted EM radiation due to motion in magnetic field

CRES overview

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

- $E_{\mathrm{kin}} = Q_\beta = 18.6\,\mathrm{keV}$, $B = 1\,\mathrm{T}$
- $f = 27\,\mathrm{GHz}$, $\lambda \sim 1\,\mathrm{cm}$, MW radiation





CRES advantages

- No losses while transporting e^- from the source to the detector (c.f. MAC-E filters)
- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$
- The source (tritium gas) is transparent to MW radiation
- Differential spectrum measurements

CRES challenges

- Radiated powers are very small

$$\text{Total radiated power (fW)} \approx 2.026 \times 10^{-2}\ f_B^2(\text{GHz})\ \beta^2$$

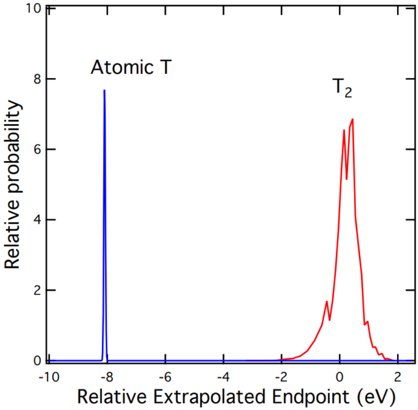
- For an 18.6 keV electron ($\beta \approx 0.26$) this is about 1 fW

CRES challenges

- Radiated powers are very small
- Atomic tritium source required

- Molecular tritium has rotational and vibrational excitations that broaden the endpoint peak
- Key challenge for any future experiment

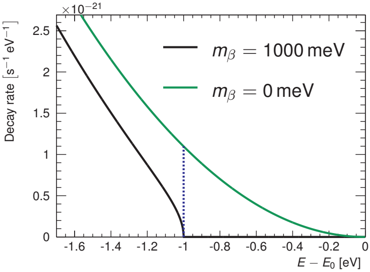
arXiv:2102.00594 [nucl-ex]



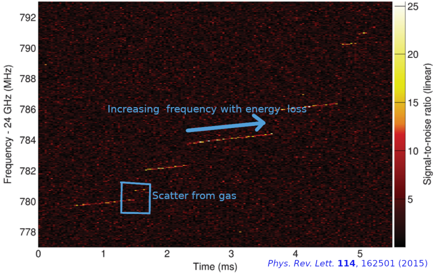
CRES challenges

- Radiated powers are very small
- Atomic tritium source required
- Need to trap and observe $\sim 10^{20}$ tritium atoms

- Last eV of the spectrum contains 2.9×10^{-13} of the events
- Necessitates an intense source

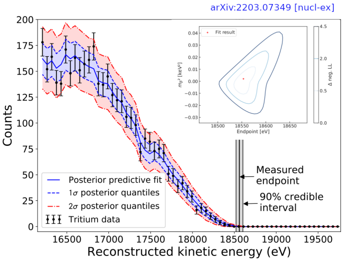


Project 8



- Above: CRES signal from 30 keV ^{83m}Kr decay electrons
- Project 8 Phase I

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



QTNM collaboration

Quantum Technologies for Neutrino Mass Collaboration

- **Proposal goal: build a demonstrator apparatus for determining neutrino mass via CRES from tritium β-decay – CRESDA**
- This entails:
  - Show proof of atomic trapping $\sim 10^{20}$ deuterium atoms
  - Mapping magnetic field with $\lesssim$ 0.1 ppm precision
  - Using quantum limited electronics
  - Experiment should be 'tritium ready' – to be built at UCL
- Unique advantages from quantum electronics knowledge and large trap/beamline which should allow scalability for increased m_β sensitivity

QTNM collaboration

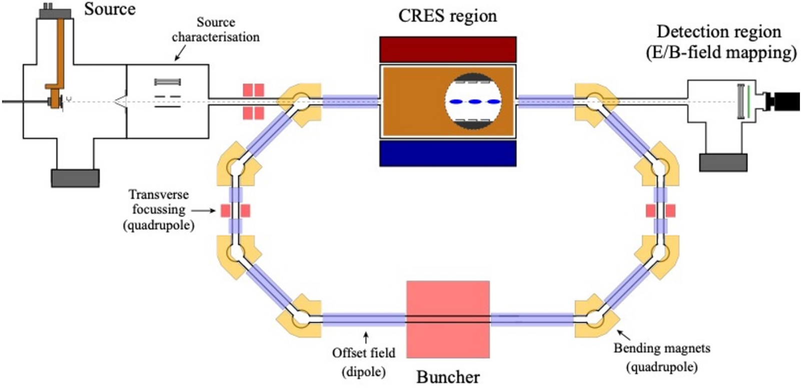
NPL National Physical Laboratory · UCL · University of Cambridge · Warwick, The University of Warwick · Swansea University Prifysgol Abertawe

Quantum **T**echnologies for **N**eutrino **M**ass Collaboration

CCFE Culham Centre for Fusion Energy

- **Ultimate goal**
- Move CRESDA to Culham for demonstrations with tritium (2025)
- Eventual international consolidation with Project 8, etc. to build an experiment with $\sim$ 10 meV sensitivity (2029)

CRESDA outline



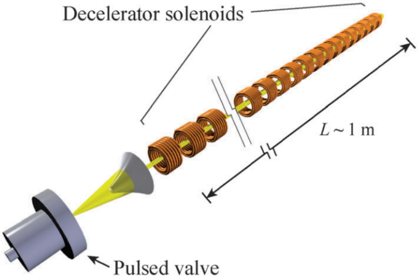
- Consists of source, atomic trapping beam line and instrumented CRES region

Atomic source and trapping

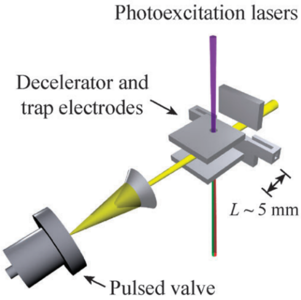
- Atomic source produces deuterium atoms at a speed of $\sim 650\,\mathrm{m\,s^{-1}}$
- Atoms can be cooled with Zeeman deceleration or Rydberg-Stark deceleration

Zeeman decelerator

Phys. Chem. Chem. Phys. **13**, 18705 (2011)

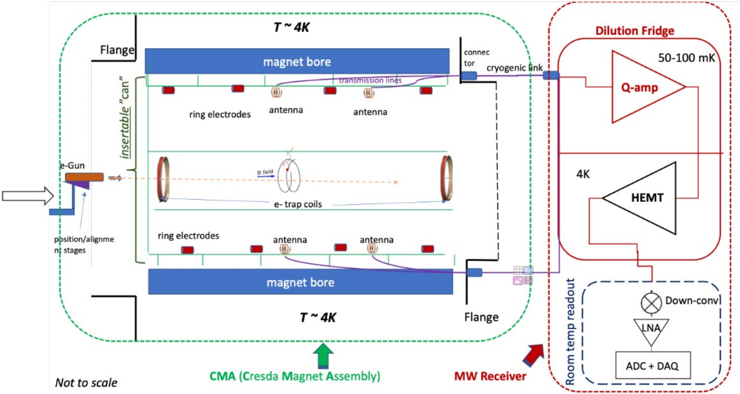


Rydberg-Stark decelerator



CRES Magnet Assembly (CMA)

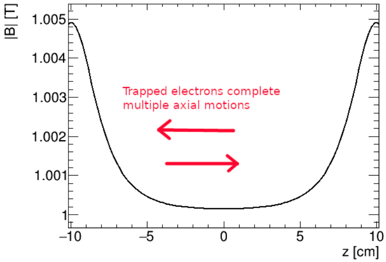
Source of (10-20 keV electrons to simulate Tritium β-decay

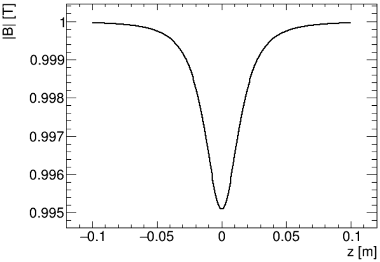


CRES region trapping

$$\Delta f \sim \frac{1}{t_{\text{obs}}}$$

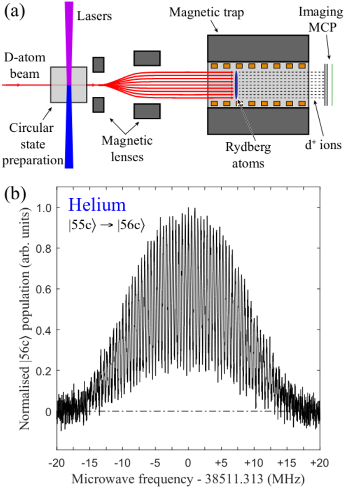
- Therefore must be able to observe electrons for 10s or 100s of μs
- Require trapping field of order 1 mT against 1 T background
- Several designs currently being explored





Magnetic field mapping

- Measuring electron energy with resolution of 10^{-6} requires that *B*-field be known to similar level
- Circular Rydberg states can used to measure the magnetic field
- Deuterium or tritium atoms can be used as quantum sensors for *B*-field mapping down to precision of 0.1 ppm
- Potential spatial resolution of 0.1 mm



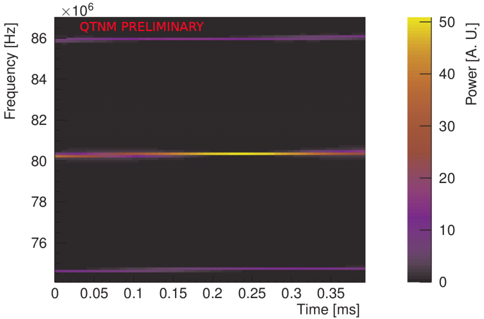
Mol. Phys. **117**, 3108 (2019)

Quantum-limited microwave amplifiers

- To detect small CRES signal, require quantum-limited amplifiers
- Various options currently being explored:
  - Resonant Kinetic Inductance Parametric Amplifiers
  - Travelling Wave Kinetic Inductance Parametric Amplifiers
  - **S**uperconducting **L**ow-Inductance **U**ndulatory **G**alvanometer (SLUG)

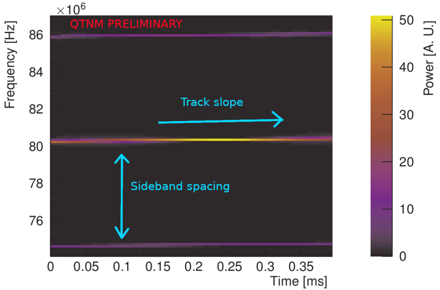
Simulation

- Work ongoing to optimise trap and antenna designs
- Can simulate an (idealised) decay electron signal in a variety of traps using custom software
- Right shows our simulated 'chirping' electron signal (without noise) after down-mixing and sampling



Reconstruction and analysis

- CRES signal contains a lot of information about electron dynamics
- 'Sideband spacing' contains information about e^- angle w.r.t. B-field
- Key parameter to determine different B-field experienced by each e^- and therefore reconstruct energy



- Looking at matched filters, ML techniques to identify signals and reconstruct correctly

Summary

- The neutrino mass scale remains unknown but the answer has the potential to provide key constraints in several areas
- Current measurement techniques (MAC-E filters) are at their limits and cannot take us to an experiment with guaranteed discovery potential
- CRES is a recent technique that allows the measurement of electron energy at unprecedented precision
- The QTNM collaboration is building on unique quantum techniques to demonstrate the viability of a CRES experiment
- Provides the exciting possibility of having the ultimate neutrino mass experiment in the UK