Determination of Absolute Neutrino Mass Using Quantum Technologies

UNIVERSITY OF CAMBRIDGE

A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

presented by

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Stafford Withington — Quantum Sensors and Quantum Electronics

on behalf of the QTNM* Consortium

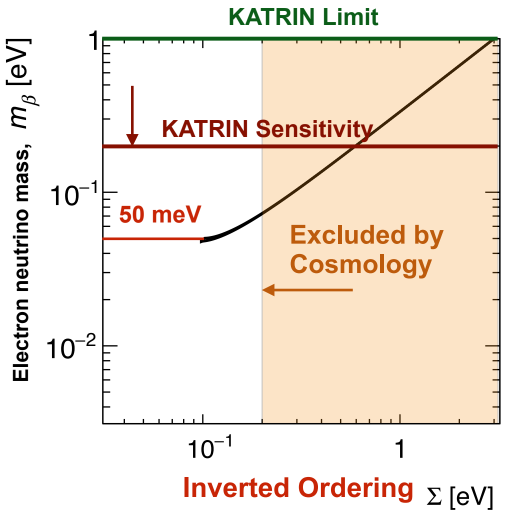
1-Apr-2020

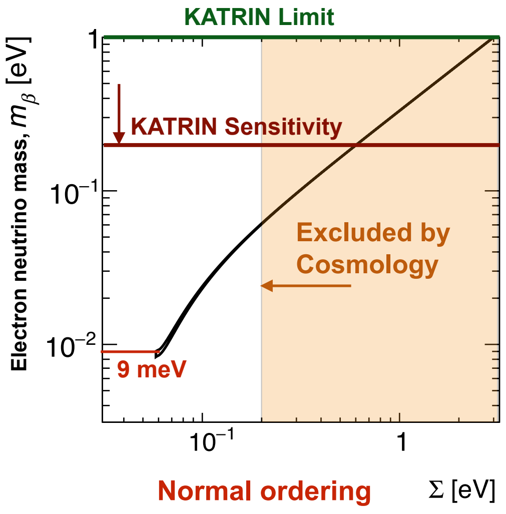
*Quantum Technologies for Neutrino Mass

Thank you for the opportunity to present the proposal on the determination of the absolute neutrino mass with quantum technologies. This proposal was put together by a very diverse community that included experts from neutrino physics, cold atoms and quantum optics and quantum sensors.

Neutrinos:

- **Most abundant particle of matter in the Universe**
- **Absolute mass not known → window to new physics**



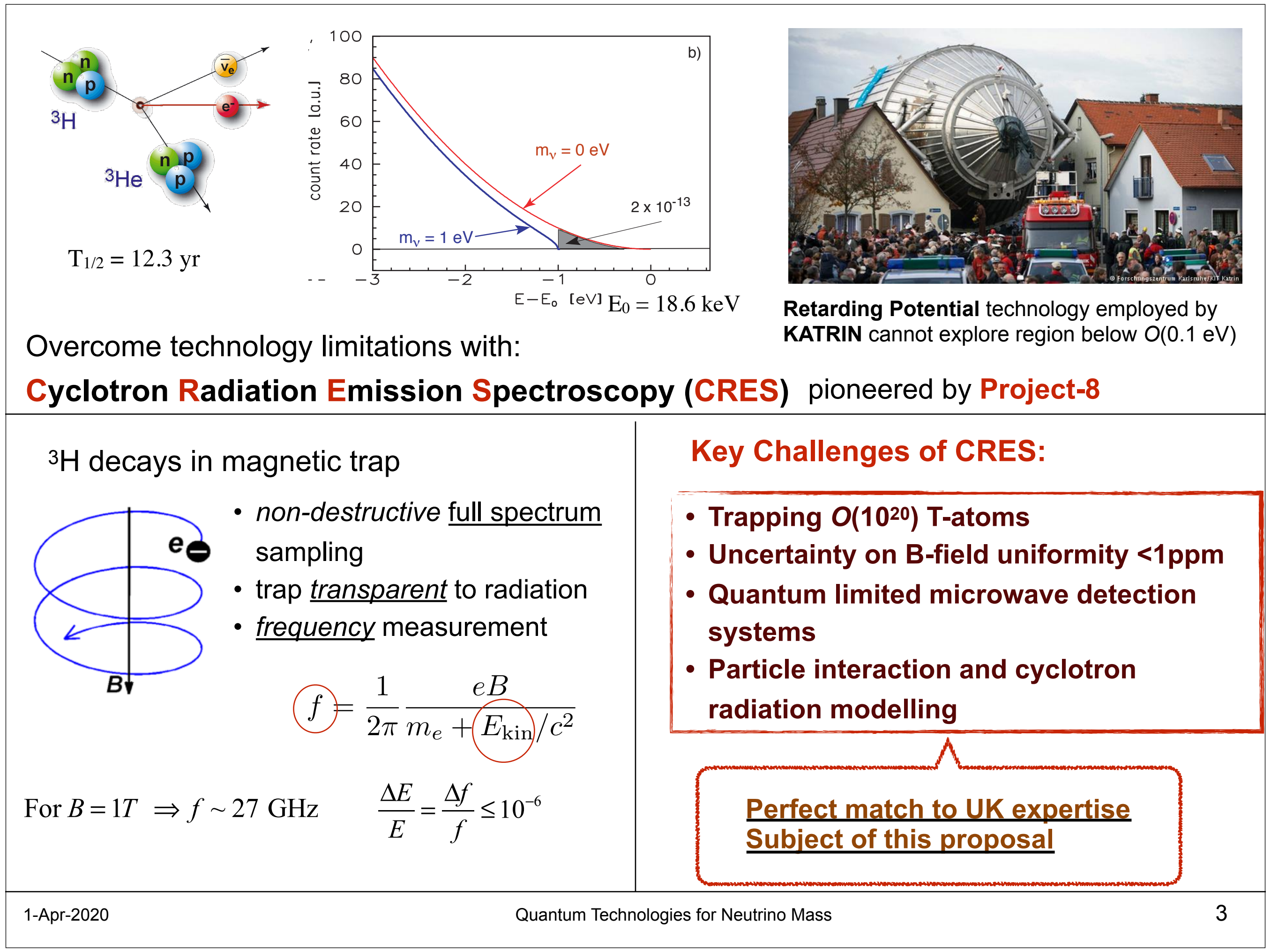


Adapted from M. Agostini et al, Phys. Rev., D96(5):053001, 2017

- Powerful constraints from cosmology but cannot replace **lab measurements**
- “Kinematic” measurement of β-decay spectrum is the **only model independent method**
- Two clear sensitivity goals: **50 meV** for **I.O.** and **9 meV** for **N.O.**

“Guaranteed” observation if technology demonstrated

Determination of the absolute neutrino mass is one of the most pressing questions in modern particle physics.
The plots on the slide show the current best constraints on the neutrino mass for two scenarios: inverted and normal ordering of neutrino masses. Cosmology provides powerful constraints on the sum of neutrino mass eigenstates while the electron neutrino mass is constrained by studying the end point b-decay currently by the KATRIN experiment, which is the only model independent method to measure the neutrino mass.
There are two clear sensitivity goals, 50 meV for inverted ordering and 9 meV for the normal ordering. Even if nature chose in the worst case scenario electron neutrino mass cannot be smaller than 9 meV thereby providing a guaranteed situation if the technology exists. This is a unique situation that has motivated this proposal.



$T_{1/2} = 12.3$ yr

$E_0 = 18.6$ keV

Retarding Potential technology employed by **KATRIN** cannot explore region below *O*(0.1 eV)

Overcome technology limitations with:

Cyclotron Radiation Emission Spectroscopy (CRES) pioneered by **Project-8**

^{3}H decays in magnetic trap

- *non-destructive* full spectrum sampling
- trap *transparent* to radiation
- *frequency* measurement

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

For $B = 1T \Rightarrow f \sim 27$ GHz $\quad \frac{\Delta E}{E} = \frac{\Delta f}{f} \leq 10^{-6}$

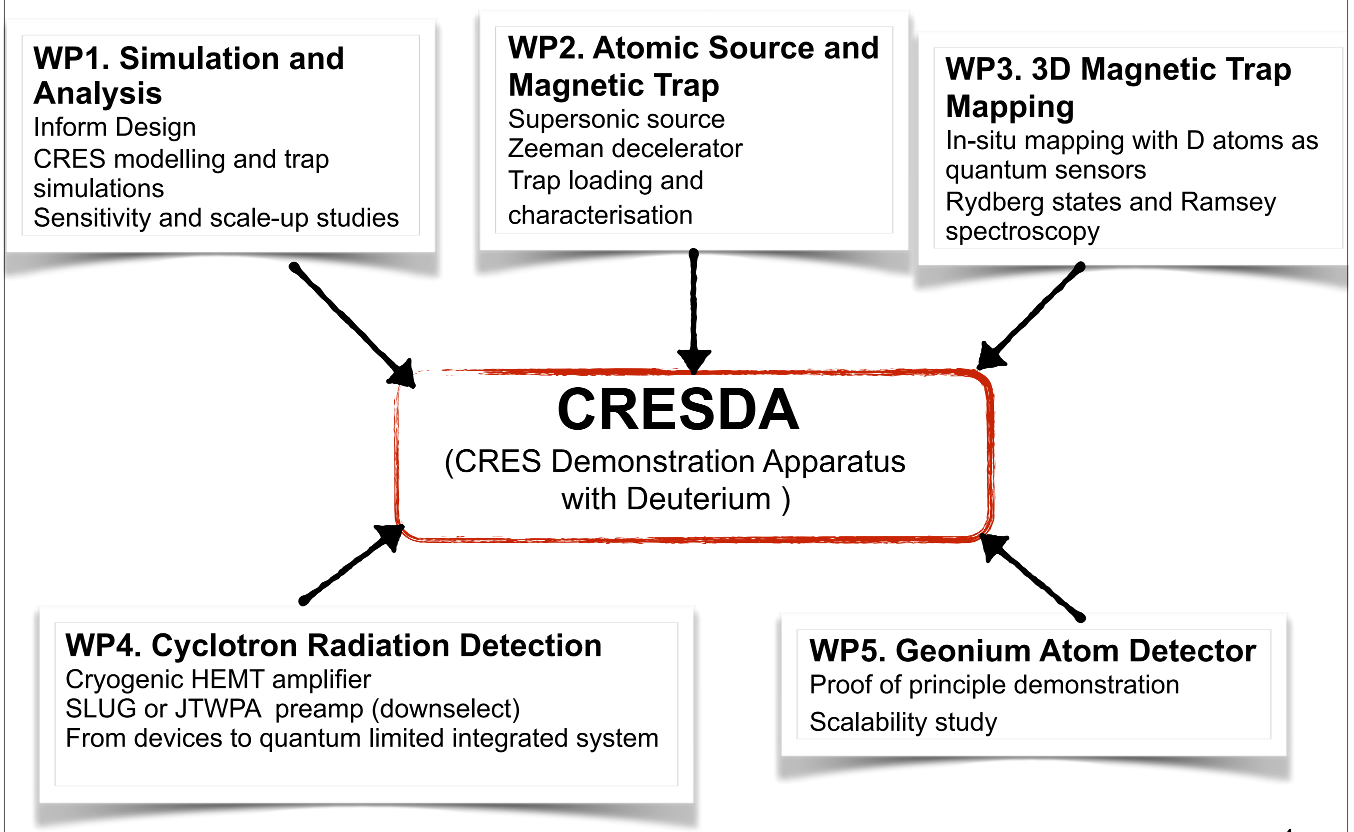
Key Challenges of CRES:

- **Trapping *O*(10^{20}) T-atoms**
- **Uncertainty on B-field uniformity <1ppm**
- **Quantum limited microwave detection systems**
- **Particle interaction and cyclotron radiation modelling**

Perfect match to UK expertise
Subject of this proposal

Studying the end-point of tritium beta-decay to measure the neutrino mass has a long history. The current state of the art is represented by the KATRIN experiment employing an electrostatic retarding potential technology. This technology cannot explore the region below 0.1 eV. An alternative approach is a Cyclotron Radiation Emission Spectroscopy (CRES) technique pioneered by the Project-8 experiment. Here tritium is magnetically trapped and the energy measurement is replaced with a frequency measurement of the cyclotron radiation emitted by electrons in a magnetic field. This approach has a number of key advantages that may allow the ultimate 9 meV resolution to be reached. However, a number of formidable challenges must be overcome. One needs to move from molecules to atoms and trap 10^20 of them. The magnetic field must be known with a ppm precision. Quantum limited microwave detection systems must be developed and accurate modelling of processes in the trap must be carried out. All this provides a perfect match to existing UK expertise and is the subject of this proposal.

Quantum Technologies for Neutrino Mass Proposal



WP1. Simulation and Analysis
Inform Design
CRES modelling and trap simulations
Sensitivity and scale-up studies

WP2. Atomic Source and Magnetic Trap
Supersonic source
Zeeman decelerator
Trap loading and characterisation

WP3. 3D Magnetic Trap Mapping
In-situ mapping with D atoms as quantum sensors
Rydberg states and Ramsey spectroscopy

CRESDA
(CRES Demonstration Apparatus with Deuterium)

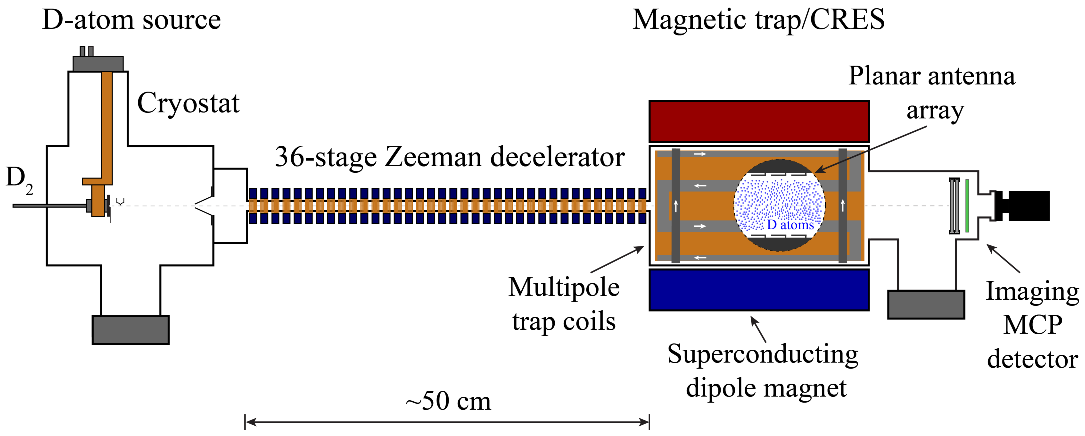
WP4. Cyclotron Radiation Detection
Cryogenic HEMT amplifier
SLUG or JTWPA preamp (downselect)
From devices to quantum limited integrated system

WP5. Geonium Atom Detector
Proof of principle demonstration
Scalability study

The proposal is subdivided into five interconnected work packages with the aim to build, commission and run CRES Demonstration Apparatus (CRESDA for short) that would operate with Deuterium atoms but will be Tritium ready. The goal is to experimentally demonstrate the performance and scalability of the technique to the ultimate sensitivity of 9 meV.

Work packages 2 and 3 address the challenges of trapping, controlling and monitoring of an unprecedented number of D/T atoms. WP4 and WP5 will deliver systems capable of quantum limited measurement of the microwave radiation. WP1 connects them all, informs the design and assesses the technique scalability.

CRESDA. Atomic Source and Magnetic Trap.

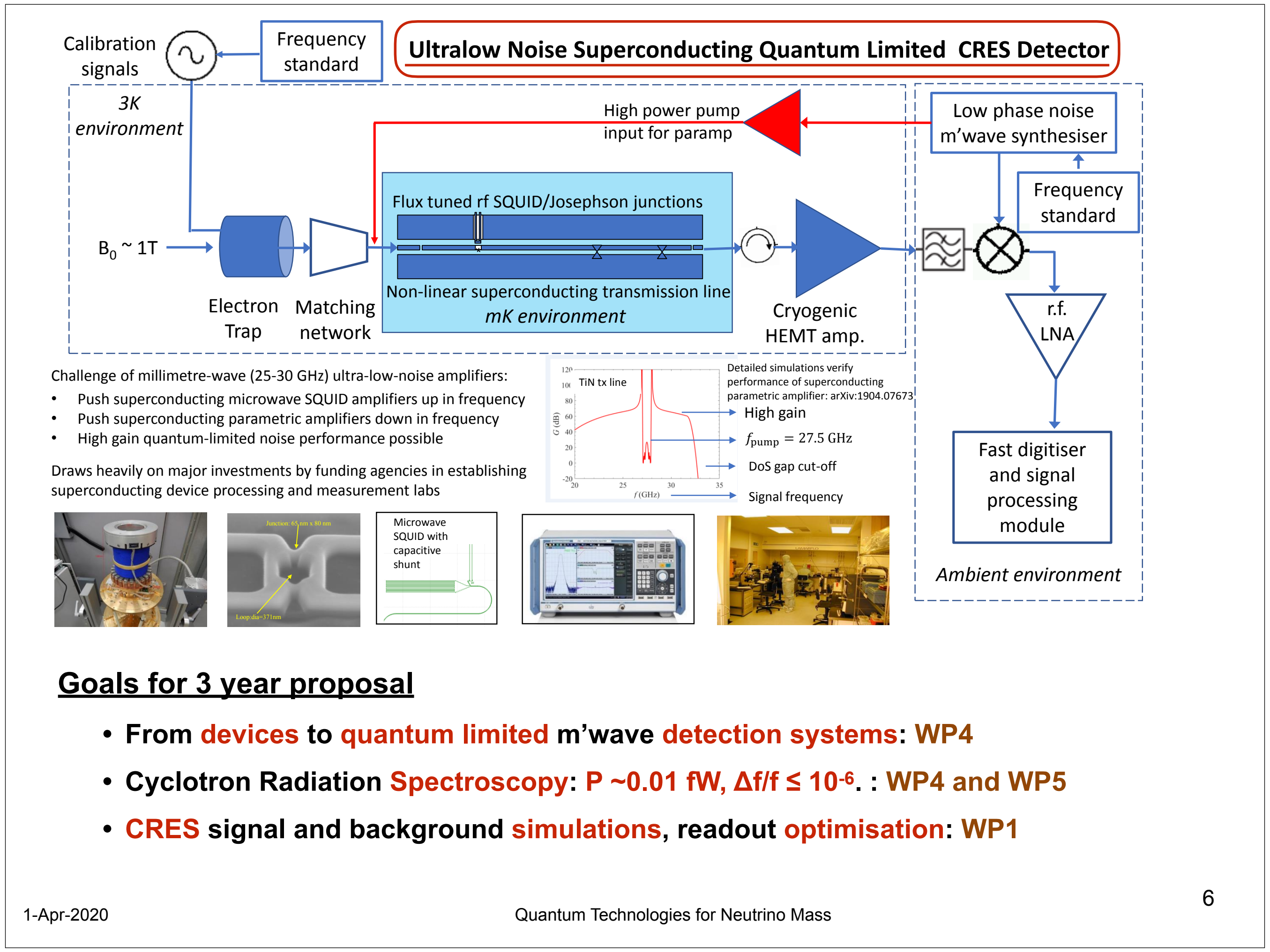


Goals for 3 year proposal

- **Trapping 10^{14} D-atoms in 1L tap at T = 1K, $\rho \sim 10^{14}$ cm^{-3} : WP2**
- **Mapping B-field uniformity in a trap with ≤ 1ppm precision: WP3**
- **Atomic beam line, trap and scaling up simulations: WP1**

Pathway to 10^{20} T-atoms

CRESDA will be built and commissioned at UCL and will consist of a Deuterium atom source on the left, a 36 stage Zeeman decelerator to cool D-atoms to below 1K and a magnetic trap with an antenna array that will couple the cyclotron radiation signal with a microwave detection system shown in the next slide.
The concrete goals of the 3 year proposal are to demonstrate feasibility of trapping unprecedented number of Deuterium atoms (up to 10^14) in a 1L trap, map the B-field uniformity in the trap with a sub-ppm precision, model D and T-atoms behaviour in the trap and ultimately to demonstrate the scalability to the necessary number of tritium atoms.



Challenge of millimetre-wave (25-30 GHz) ultra-low-noise amplifiers:

- Push superconducting microwave SQUID amplifiers up in frequency
- Push superconducting parametric amplifiers down in frequency
- High gain quantum-limited noise performance possible

Draws heavily on major investments by funding agencies in establishing superconducting device processing and measurement labs

Detailed simulations verify performance of superconducting parametric amplifier: arXiv:1904.07673

Goals for 3 year proposal

- **From devices to quantum limited m'wave detection systems: WP4**
- **Cyclotron Radiation Spectroscopy: P ~0.01 fW, Δf/f ≤ 10^{-6}. : WP4 and WP5**
- **CRES signal and background simulations, readout optimisation: WP1**

In order to reach the challenging resolution and ultra-low noise requirements for millimetre-wave detection in the range of 25-30GHz a 3 stage quantum limited CRES detector will be developed as part of WP4 consisting of either SQUID or Josephson junction based preamplifier, a cryogenic amplifier and a room temperature readout electronics. To push the energy resolution even further a technique based on a single electron captured in a planar Penning trap, known as geonium atom will be explored. The readout and signal processing will be optimised using methods developed in WP1.

Updates and Outlook

- Visit to **Culham Centre for Fusion Energy**
  - Strong interest in a major **fundamental science project at National Lab**
  - Possible site at **new H3AT facility**
- Absolute Neutrino Mass workshop on 19-Dec-2019 at UCL https://indico.cern.ch/event/849868/
  - Endorsement of proposal and strategy by KATRIN and Project-8
  - Discussions of **joint strategy** with Project-8
  - **Culham**: Willingness to engage through direct support/consulting and H3AT site planning
- Next step: **moving CRESDA to Culham**
  - Commissioning with Tritium at potential ultimate site
  - *O*(1eV) neutrino mass sensitivity
- Establishing **international collaboration** for ultimate experiment
- TDR and Full Proposal
- Possibility to host **final experiment on UK soil**

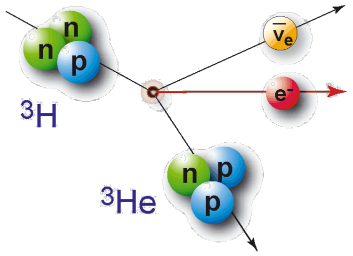
Finally I would like to conclude but giving a couple of updates and an outlook in to the future. We have developed closed connections with the Culham Centre for Fusion Energy, a major site licensed for handling tritium, who expressed a strong interest in hosting a major basic science project in their recently approved new H3AT facility. In December last year we held a workshop at UCL where our proposal received a strong endorsement from Project-8 and KATRIN.

If the 3 year project proposed here is successful the next step we envisage is to move CRESDA to Culham and commissioning run the apparatus at the potential site of the final experiment. This will also allow us to probe a neutrino mass with a competitive sensitivity and important to pave the way to a full proposal by large international collaboration for an groundbreaking experiment that could be hosted on the UK soil.

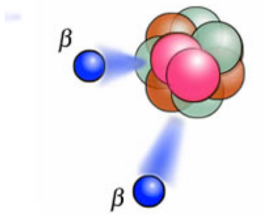
BACKUP

Absolute Neutrino Mass Parameters

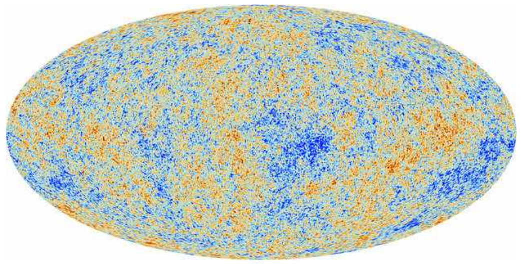
$$m_{\nu_e} = \sqrt{U_{e1}^2 m_1^2 + U_{e2}^2 m_2^2 + U_{e3}^2 m_3^2}$$



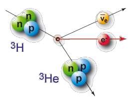
$$\langle m_{\beta\beta}(\nu_e) \rangle = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}$$

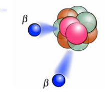


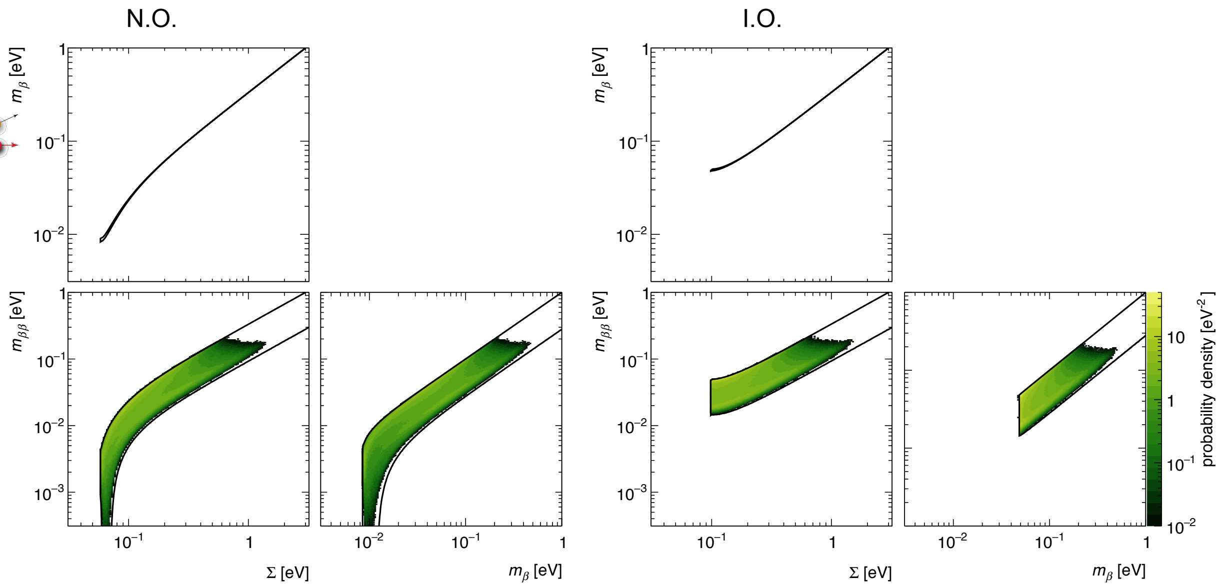
$$\Sigma = m_1 + m_2 + m_3$$



Neutrino masses and their correlations

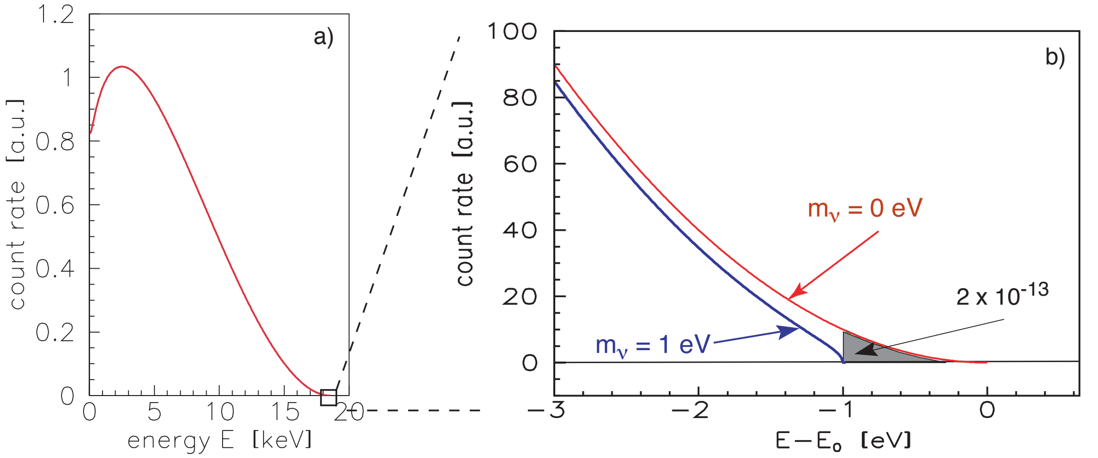






M. Agostini et al, Phys. Rev., D96(5):053001, 2017

- No uncertainties on m_β
- No cancellations with m_β



$$\frac{dN}{dE_e} = 3rt\left(E_0 - E\right)\left[\left(E_0 - E\right)^2 - m_\nu^2\right]^{1/2}$$

r - rate in $\Delta E = 1eV$ with $m_\nu = 0$

b - background rate

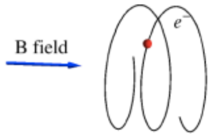
$$N_{tot} = \underbrace{rt\left(\Delta E\right)^3\left[1 - \frac{3}{2}\frac{m_\nu^2}{\left(\Delta E\right)^2}\right]}_{\text{signal}} + \underbrace{bt\Delta E}_{\text{background}}$$

$$\sigma_{m_\nu^2} = \frac{2}{3rt\Delta E}\sqrt{N_{tot}} = \frac{2}{3rt}\sqrt{rt\Delta E + \frac{bt}{\Delta E}}$$

$$\Delta E_{opt} = \sqrt{\frac{b}{r}}$$

How to overcome present technology limitations

A. Schawlow: “Never measure anything but frequency!”

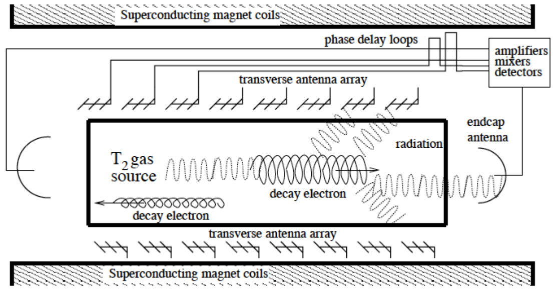


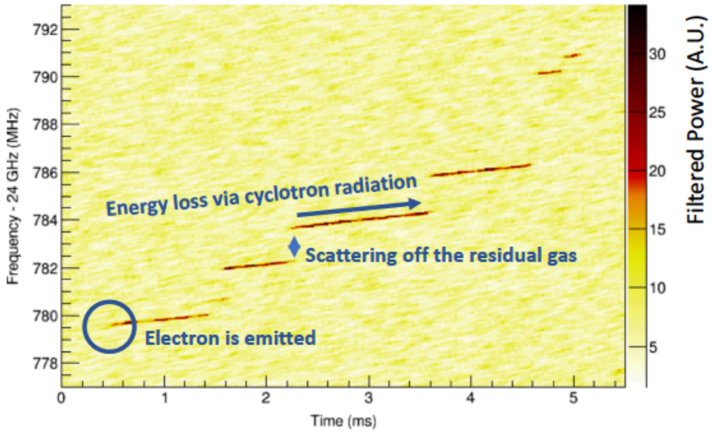
$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

$$f \cdot \frac{\Delta E}{E} \sim \Delta f; \quad \frac{\Delta f}{f} \sim 10^{-6}$$

Cyclotron Radiation Emission Spectroscopy (CRES)

Project-8



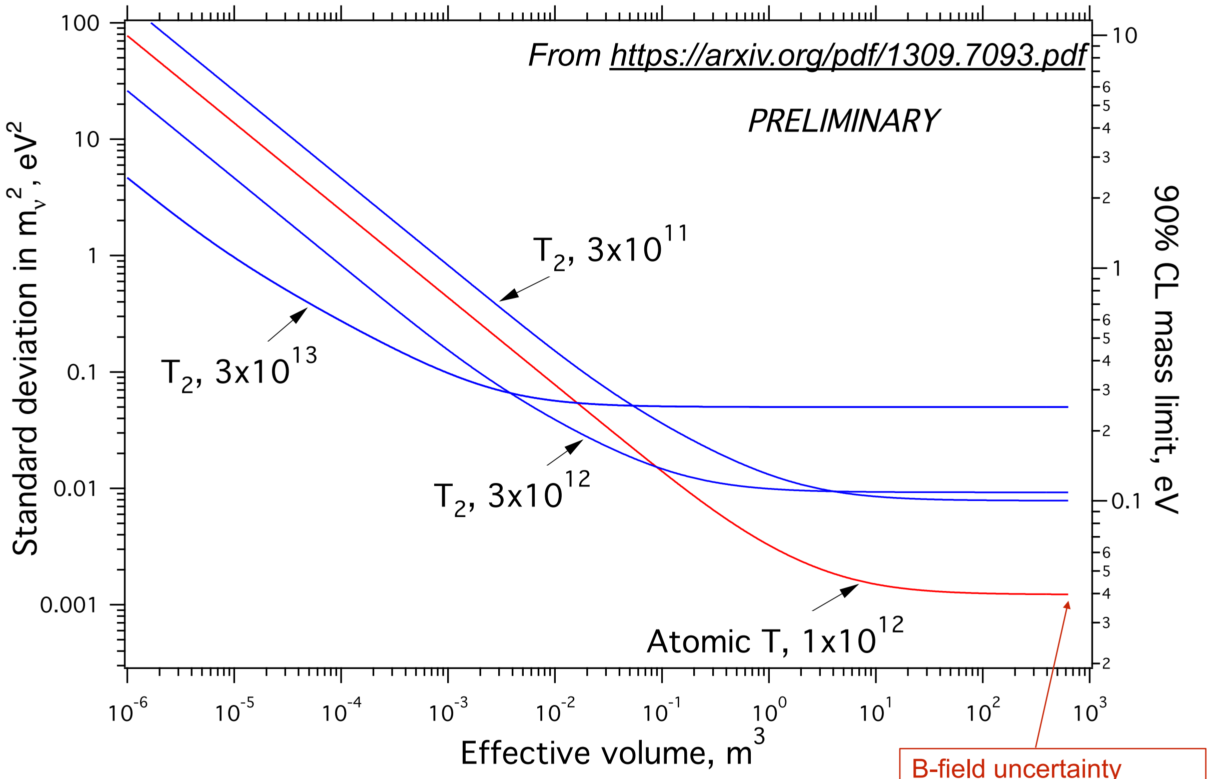


Energy loss via cyclotron radiation

Scattering off the residual gas

Electron is emitted

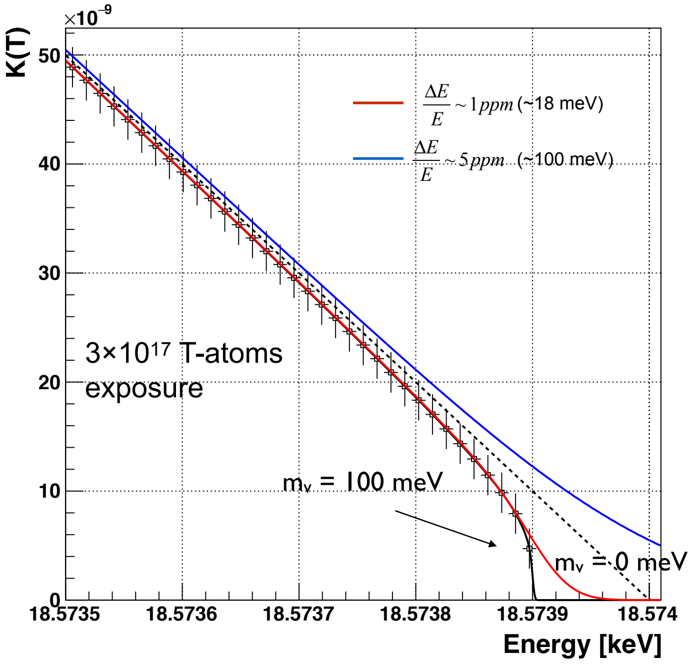
Project-8 Sensitivity



From https://arxiv.org/pdf/1309.7093.pdf

B-field uncertainty
T_2 background

WP1. Simulation and Analysis

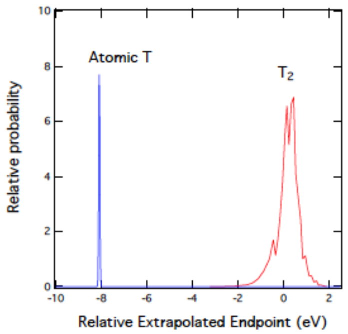


For *O(10meV)* sensitivities >10^{20} T-atoms exposures required

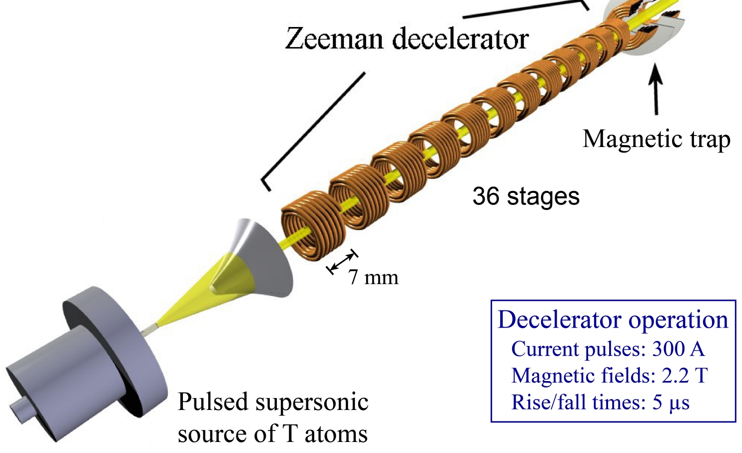
Tasks

- 3D atomic beam simulations. Input to WP2 to interpret TOF measurements from Zeeman decelerators
- Cyclotron emission and detection modelling. Input to WP4 and 5.
- Atomic Trap simulations. Modelling large ensemble of T-atoms with long residence time. Electron-gas interactions. Link to WP2.
- CRES Analysis and Sensitivity. Spectrogram analysis with ML techniques to extract maximum information (inc. e.g. spatial distribution of decays). Scale-up modelling and ultimate sensitivity.

WP2. Atomic Beam Source and Magnetic Trapping



Need atomic T due to uncertainties in final states of molecular T_2

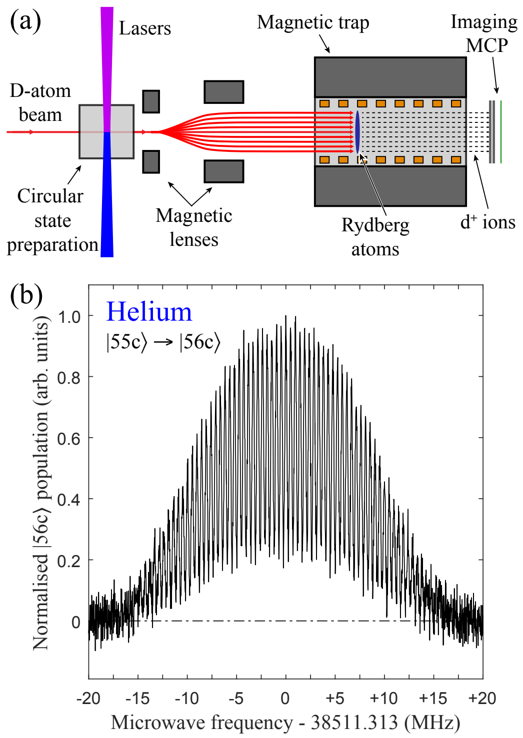


Decelerator operation
Current pulses: 300 A
Magnetic fields: 2.2 T
Rise/fall times: 5 μs

Tasks

- D-atom Source. Cryo-cooled supersonic source based on electric discharge of D_2. Output: D-atoms with 650±50 m/s, 10^{14}-10^{15} cm^{-3}.
- Zeeman Decelerator. Successfully demonstrated for D-atoms and suitable for high densities. Output D-atoms with 50m/s, T~0.1K.
- Magnetic Trap. 1L multipole superconducting magnetic trap. Optimisation of loading technologies. Density characterised by laser and MW spectroscopy. Identify traces of D_2 by comparing REMPI spectra of D_2 and D.

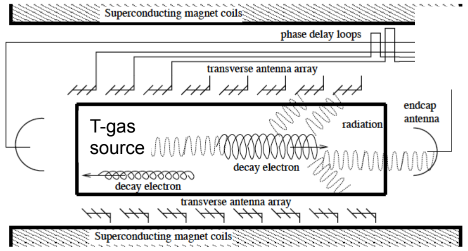
WP3. 3D B-field Mapping by Quantum Sensing.



$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2} \Rightarrow \frac{\Delta f}{f} \sim 10^{-6} \Rightarrow \frac{\Delta B}{B} \sim 10^{-6}$$

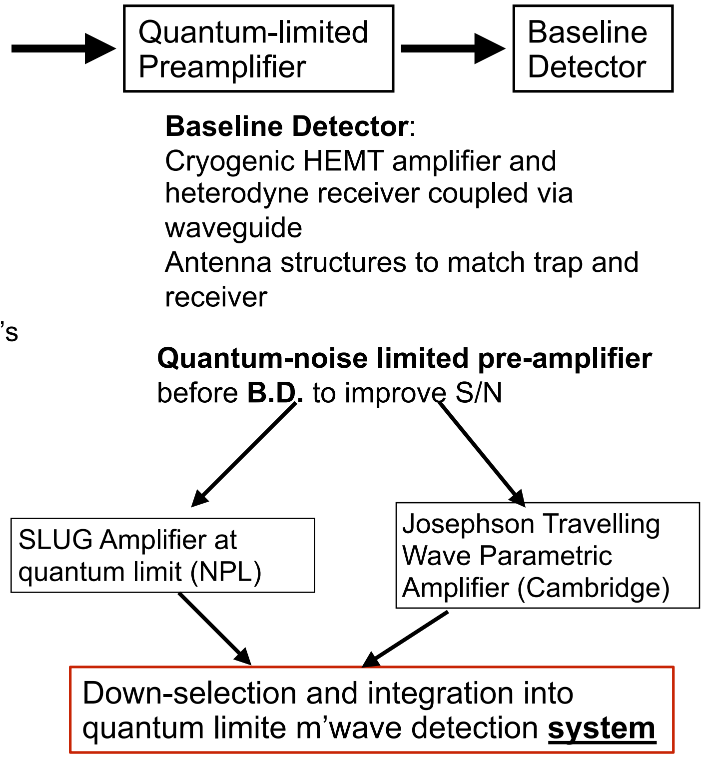
- High-res MW spectroscopic measurement of transitions between circular Rydberg states by Ramsey spectroscopy.
- State selective ionisation and ion imaging
- Measuring B-field with precision 0.1ppm possible.
- Spatial resolution at a level of 0.1mm
- Scheme can be used for precise determination of Rydberg constant ⟹ possible contribution to “proton radius puzzle”

WP4. Cyclotron Radiation Detection



- CRES signal: 27GHz, sub-fw, only 100's of MW photons in receiver
- Resolution Δf/f~10^{-6} or better!
- Requires amplifiers at quantum noise limit (0.6K)

- Installation on CRESDA
- Performance characterisation with monochromatic e-sources:
  - photoionisation of confined D-atoms (eV scale)
  - radioactive sources ^{83m}Kr (keV scale).



Quantum-limited Preamplifier

Baseline Detector

Baseline Detector:
Cryogenic HEMT amplifier and heterodyne receiver coupled via waveguide
Antenna structures to match trap and receiver

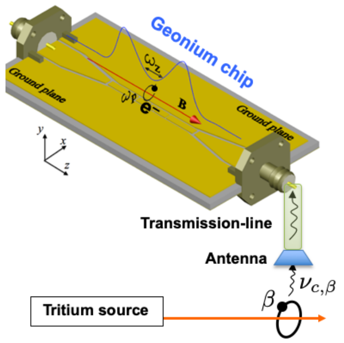
Quantum-noise limited pre-amplifier before **B.D.** to improve S/N

SLUG Amplifier at quantum limit (NPL)

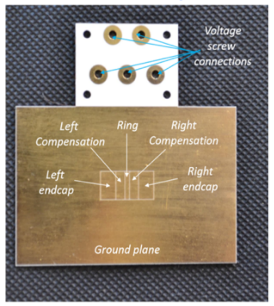
Josephson Travelling Wave Parametric Amplifier (Cambridge)

Down-selection and integration into quantum limite m'wave detection **<u>system</u>**

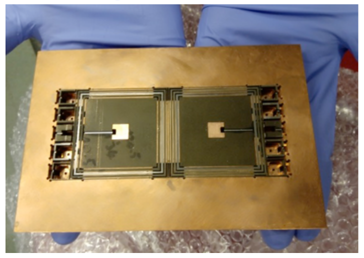
WP5. Geonium Atom CRES Detector.



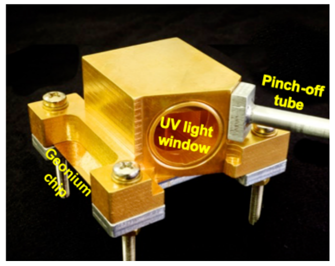
Geonium chip



Magnetic field source



Cryogenic vacuum chamber



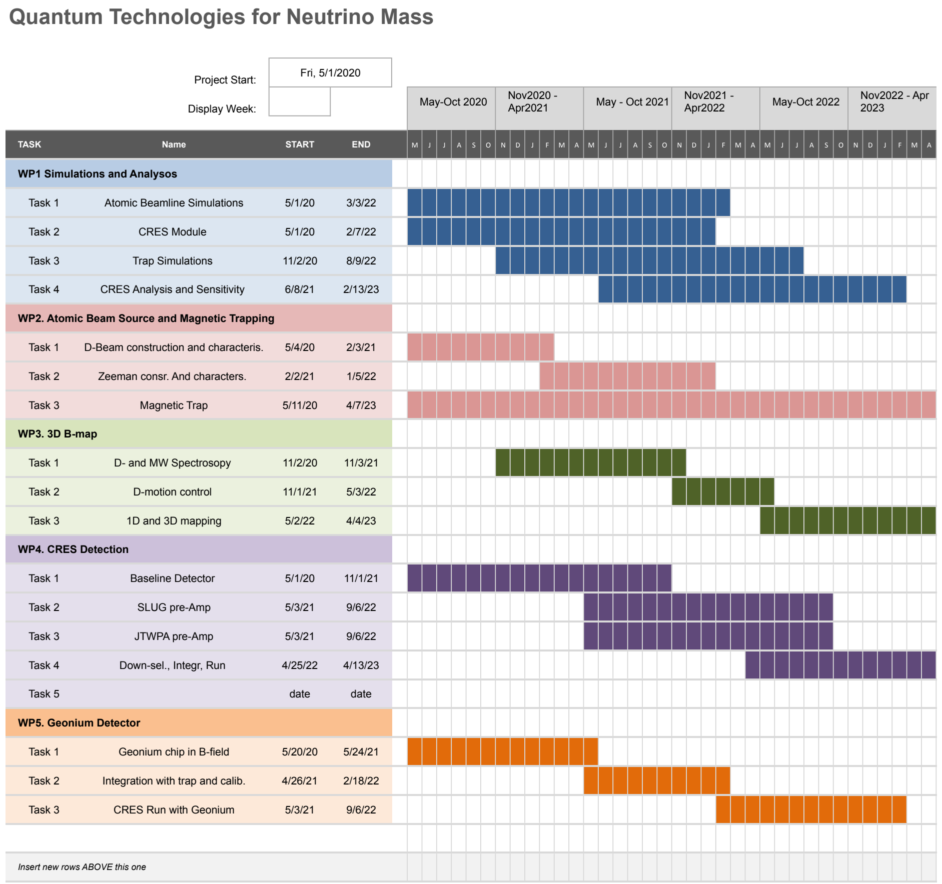
- Single electron captured in a planar Penning trap (“geonium atom” on a chip).
- A quantum resonator with a Q-value of 10^9. Possibility to reach sub-meV resolution
- Tuning to a specific frequency with very narrow bandwidth (e.g 25Hz for 25GHz of CRES in 1T field) — “one detector per energy bin”
- Fabrication of “geonium chip”
- Installation on CRESDA
- Characterisation with monochromatic e-source

QTNM Proposal Full Economic Costs

Item	WP1	WP2+3	WP4	WP5
Manpower, k£	760	1,065	1,850	590
Equipment and consumables, k£	26.5	802	520	85
TOTAL, k£	**786.5**	**1,867**	**2,370**	**675**
Travel, k£	**75**			
Grand Total, k£	**5,700**			

RC Contribution: 4,500 k£

QTNM Proposal Timeline



Quantum Technologies for Neutrino Mass

Project Start: Fri, 5/1/2020

Display Week:

TASK	Name	START	END
WP1 Simulations and Analysos			
Task 1	Atomic Beamline Simulations	5/1/20	3/3/22
Task 2	CRES Module	5/1/20	2/7/22
Task 3	Trap Simulations	11/2/20	8/9/22
Task 4	CRES Analysis and Sensitivity	6/8/21	2/13/23
WP2. Atomic Beam Source and Magnetic Trapping			
Task 1	D-Beam construction and characteris.	5/4/20	2/3/21
Task 2	Zeeman consr. And characters.	2/2/21	1/5/22
Task 3	Magnetic Trap	5/11/20	4/7/23
WP3. 3D B-map			
Task 1	D- and MW Spectrosopy	11/2/20	11/3/21
Task 2	D-motion control	11/1/21	5/3/22
Task 3	1D and 3D mapping	5/2/22	4/4/23
WP4. CRES Detection			
Task 1	Baseline Detector	5/1/20	11/1/21
Task 2	SLUG pre-Amp	5/3/21	9/6/22
Task 3	JTWPA pre-Amp	5/3/21	9/6/22
Task 4	Down-sel., Integr, Run	4/25/22	4/13/23
Task 5		date	date
WP5. Geonium Detector			
Task 1	Geonium chip in B-field	5/20/20	5/24/21
Task 2	Integration with trap and calib.	4/26/21	2/18/22
Task 3	CRES Run with Geonium	5/3/21	9/6/22

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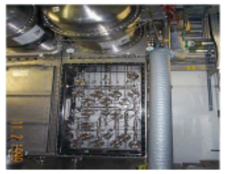
H3AT

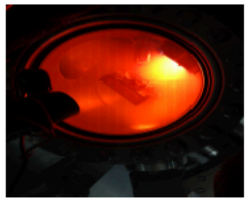
Building

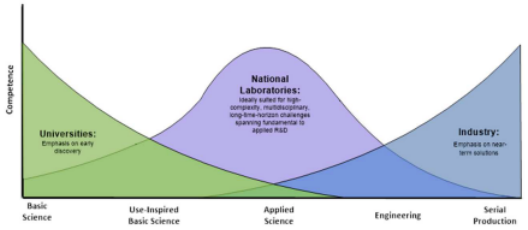
Experiments

Tritium Systems



Control and Safety systems





H3AT

- A £40M state of the art facility
- Up to 100g T2 inventory. No increase in site discharge authorisation.
- ITER like tritium fuel cycle able to operate in closed loop. Uranium bed storage and delivery, Impurity Separation, Cryogenic Distillation, Water Detritiation Systems.
- Fuel cycle feeds flexible test cells/gloveboxes for experiments/component qualification.
- Also contains tritium wet chemistry, solid waste detritiation and C-14 laboratory
- Inactive test space, office and training facilities.
- Interim H3AT in the Culham MRF. Target: H3AT facility open 2022.

Timeline