Determination of Absolute Neutrino Mass Using Quantum Technologies

QTNM* Consortium

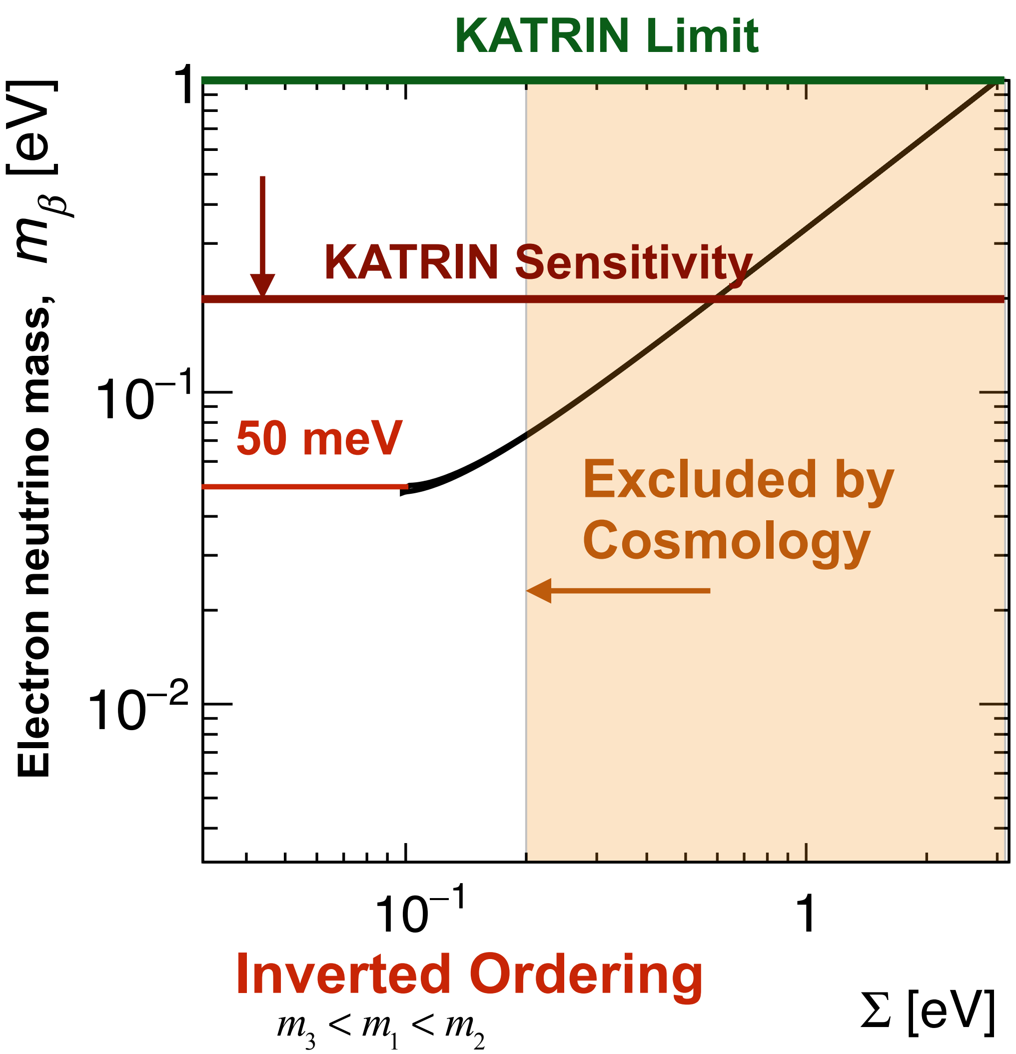
A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

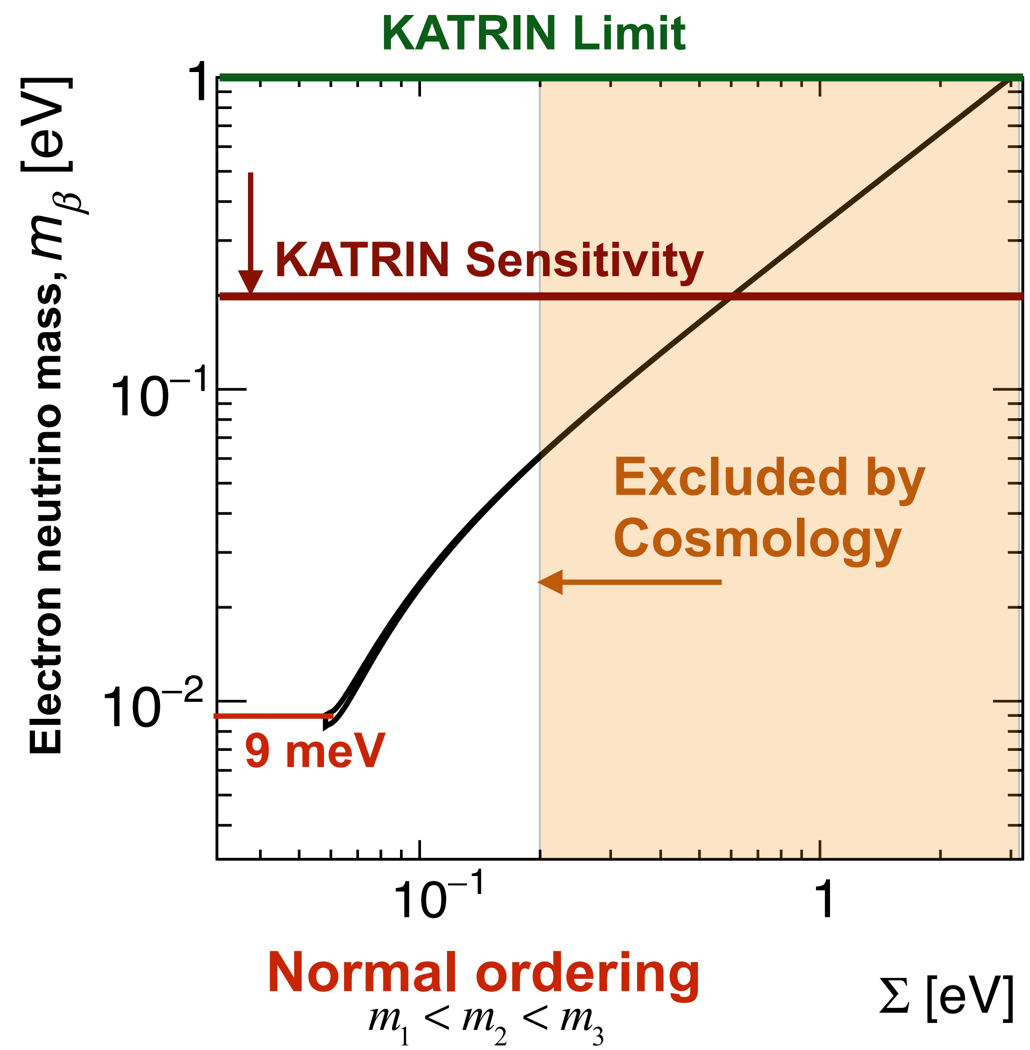
Ruben Saakyan and David Waters

Guest Talk
at
Project-8 Collaboration Meeting

Cyberspace
20-May-2020

*Quantum Technologies for Neutrino Mass





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

- “Kinematic” measurement of β-decay spectrum is the **only model independent method**
- Strong constraints from cosmology but cannot replace **lab measurements**
- Two clear sensitivity goals: **50 meV** for **I.O.** and **9 meV** for **N.O.**
- Potential “Guaranteed” observation **IF** technology demonstrated
  - In absence of “no-go theorem” becomes analogous to Higgs “no-lose” argument that motivated LHC

Absolute Neutrino Mass Workshop @UCL

19 December 2019
UCL
Europe/London timezone

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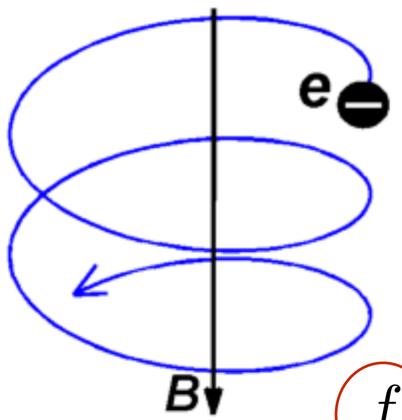
Coffee		UCL	10:00 - 10:30
Welcome & Workshop Aims	Prof. David Waters	UCL	10:30 - 10:45
Neutrino Mass Overview	Prof. Silvia Pascoli	UCL	10:45 - 11:15
Cosmological Neutrino Mass Determinations	Prof. Ofer Lahav	UCL	11:15 - 11:45
Tritium End-Point Experiments and First Results from KATRIN	Prof. Susanne Mertens	UCL	11:45 - 12:30
Lunch		UCL	12:30 - 13:30
Project-8	Prof. Joseph Formaggio	UCL	13:30 - 14:30
Trapping Hydrogen and Deuterium Atoms using Electric and Magnetic Fields	Prof. Stephen Hogan	UCL	14:30 - 15:00
Quantum Technology for Cyclotron Radiation Detection	Prof. Ling Hao et al.	UCL	15:00 - 15:30
Coffee		UCL	15:30 - 16:00
Opportunities at Culham Fusion Lab	Damian Brennan	UCL	16:00 - 16:30
Overview of UK QTFP Proposal	Ruben Saakyan	UCL	16:30 - 17:00
Discussion & Next-Steps			- 17:30



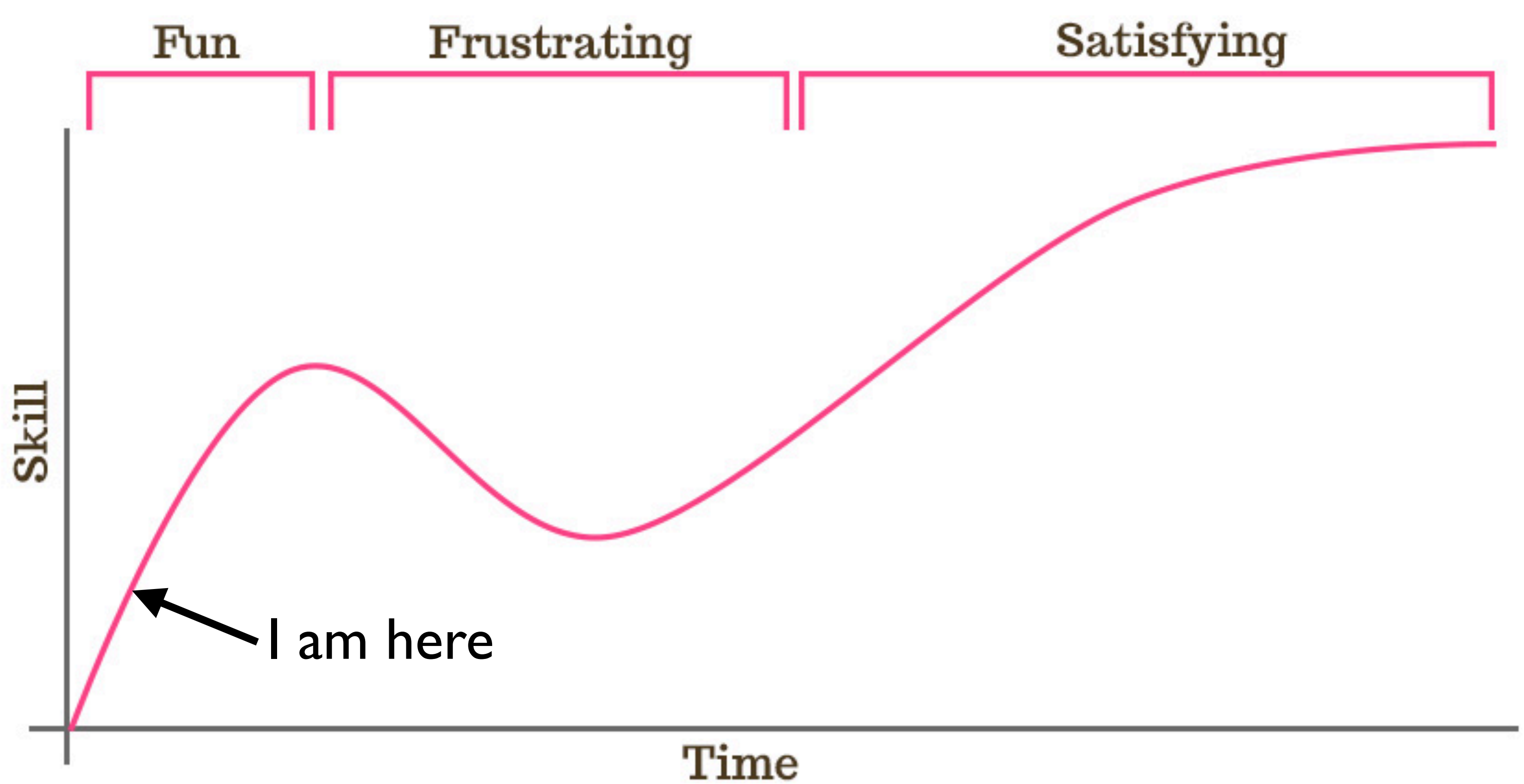
$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\rm kin}/c^2}$$

Overcome technology limitations with:

Cyclotron Radiation Emission Spectroscopy (CRES)

inspired and pioneered by **Project-8**

- Mountain to climb for “traditional” particle physicist to embrace CRES technology



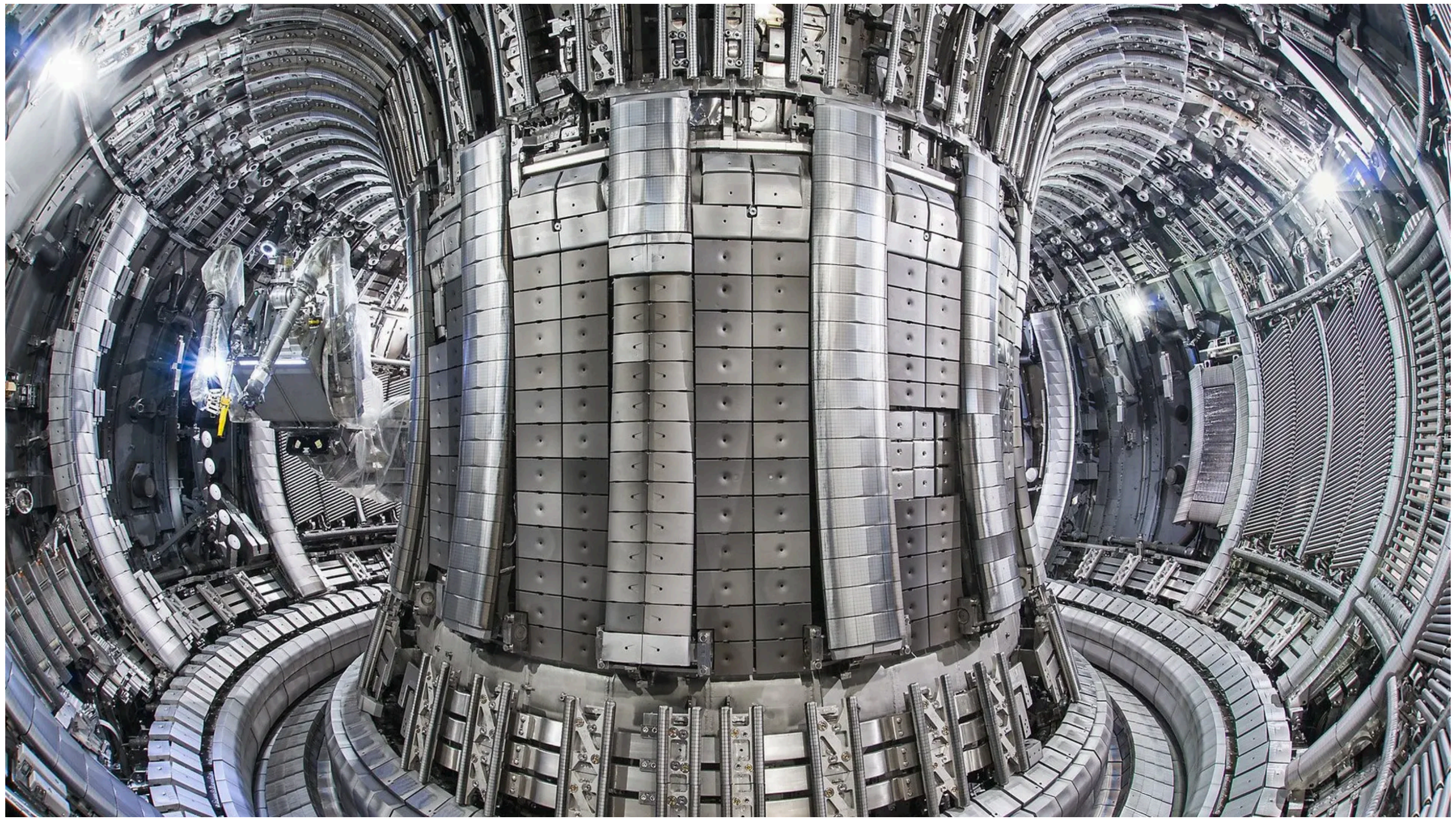
- But significant *relevant* expertise among UK Quantum Tech people

UK **Expertise** and **Facilities**

pertinent to ν-mass detection based on ^3H CRES

- **Neutrino physics, detector development, MC modelling** (UCL, Warwick):
  - F. Deppisch, R. Nichol, Y. Ramachers, R. Saakyan, D. Waters
- **RF detection of UHE neutrinos and cosmic rays** (UCL)
  - R. Nichol
- **Ultra-cold atom trapping**, Rydberg atoms, Zeeman deceleration (UCL)
  - S. Hogan (world-leading D-atom trapping results)
- **Quantum Electronics** for RF MW signals (Cambridge, NPL, Swansea)
  - S. Withington (Cambridge), L. Hao, J. Gallop (NPL), L.Li (Swansea)
- Quantum 2.0 with “geonium chip” (Sussex)
  - J. Verdu-Galiana
- **H3AT Facility at Culham**

Culham Centre for Fusion Energy

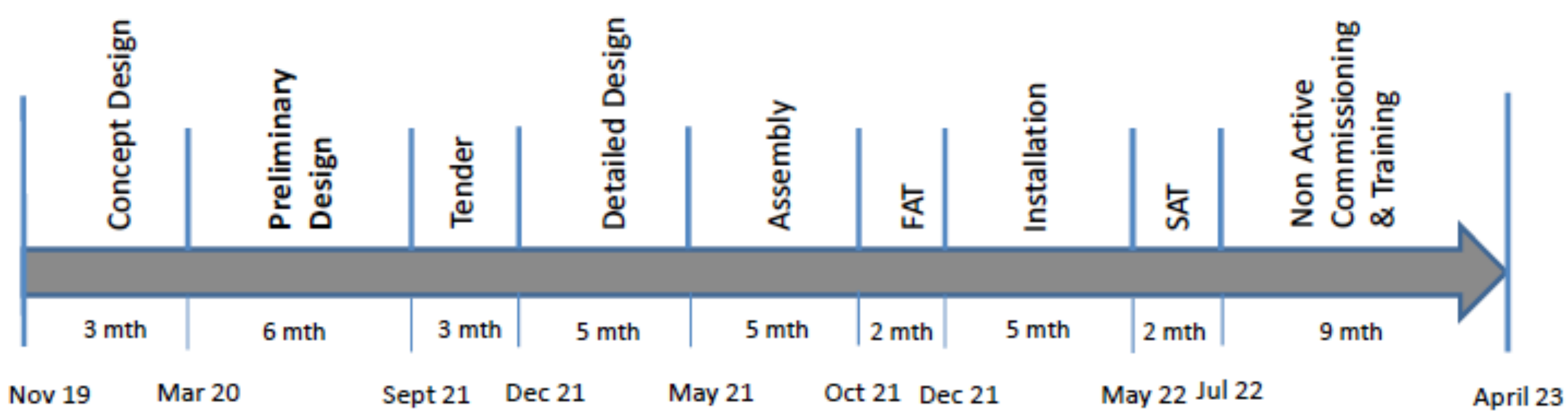


- Early discussions underway
- Strong interest in a fundamental science project at National Lab
- Possible site at H3AT facility

H3AT: Hydrogen-3 Advanced Technology Centre

UK Atomic Energy Authority

- 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.



From UCL Absolute Neutrino Mass workshop, 19-Dec-2019

https://indico.cern.ch/event/849868/

Quantum Sensors for Fundamental Physics

Bottom-up community driven process started in 2018 in UK

Two workshops in Oxford (October'18 and Jan'19) and one in Leicester (May'19)

- Addressing:
  - Nature of dark matter (low mass, axion-like …)
  - Gravitational waves (different frequencies)
  - Variation of fundamental constants
  - Quantum/Classical limits (macroscopic superposition)
  - Neutrino mass
  - ….

UK Institutions map

QSFP Steering Group

Kai Bongs
Themis Bowcock
Ed Daw
John March-Russell
Ruben Saakyan
Ian Shipsey

A £36M call announced on 30 September 2019

Led by STFC but targets both STFC and EPSRC communities

Science & Technology Facilities Council | UK Research and Innovation

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Quantum Technologies for Fundamental Physics

On 30 September STFC and EPSRC will open a research call for the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

The call has total funding of c.£36m and will look to fund up to seven projects of £2m and above each (80% fEC). Requests for over £5m should contact the office before applying. The call will be for research consortia, i.e. joint proposals with a common research programme from groups of researchers in more than one organisation. Successful applications will require interdisciplinary research teams comprising researchers from both the fundamental physics and quantum technology communities.

The call's fundamental physics remit covers quantum science, astronomy, particle physics, particle astrophysics and nuclear physics. Applications to the call will be expected to show how quantum technologies will enhance or enable their research area of interest.

The call will be open to all individuals and organisations eligible for UKRI funding. PSREs are asked to contact the office to check if they are eligible. Grants will commence on 1 May 2020 and end no later than 30 September 2023. Successful projects will be expected to show tangible outcomes and results within the lifespan of the funding. The standard STFC/EPSRC expectation for Research Organisations to contribute to the cost of equipment at around the 50% level will apply.

Applicants will be required to complete an online Intention to Submit form on the STFC website by 31 October 2019 prior to submitting a full application. The closing date for full proposals will be 3 December 2019. Full details on the call, including the application process and assessment criteria, will be published on the STFC website.

25 proposals submitted including "Determination of absolute neutrino mass using quantum technologies" by the QTNM Consortium

Submitted in Dec'19

Quantum Technologies for Neutrino Mass

3 year proposal

UCL

UNIVERSITY OF CAMBRIDGE

NPL National Physical Laboratory

THE UNIVERSITY OF WARWICK

US UNIVERSITY OF SUSSEX

Prifysgol Abertawe Swansea University

To build on ***recent investment in quantum sensors*** *to assess feasibility of an* ***experiment*** *capable of a positive* ***neutrino mass measurement***

The broad aim is to address key challenges of ^3H CRES technology

- **Trapping *O*(10^{20}) T-atoms**
- **Mapping B-field uniformity with <0.1ppm using quantum sensing**
- **Quantum noise limited detection systems in 20-30 GHz range**
- **Atomic trap and cyclotron radiation modelling and validation**

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

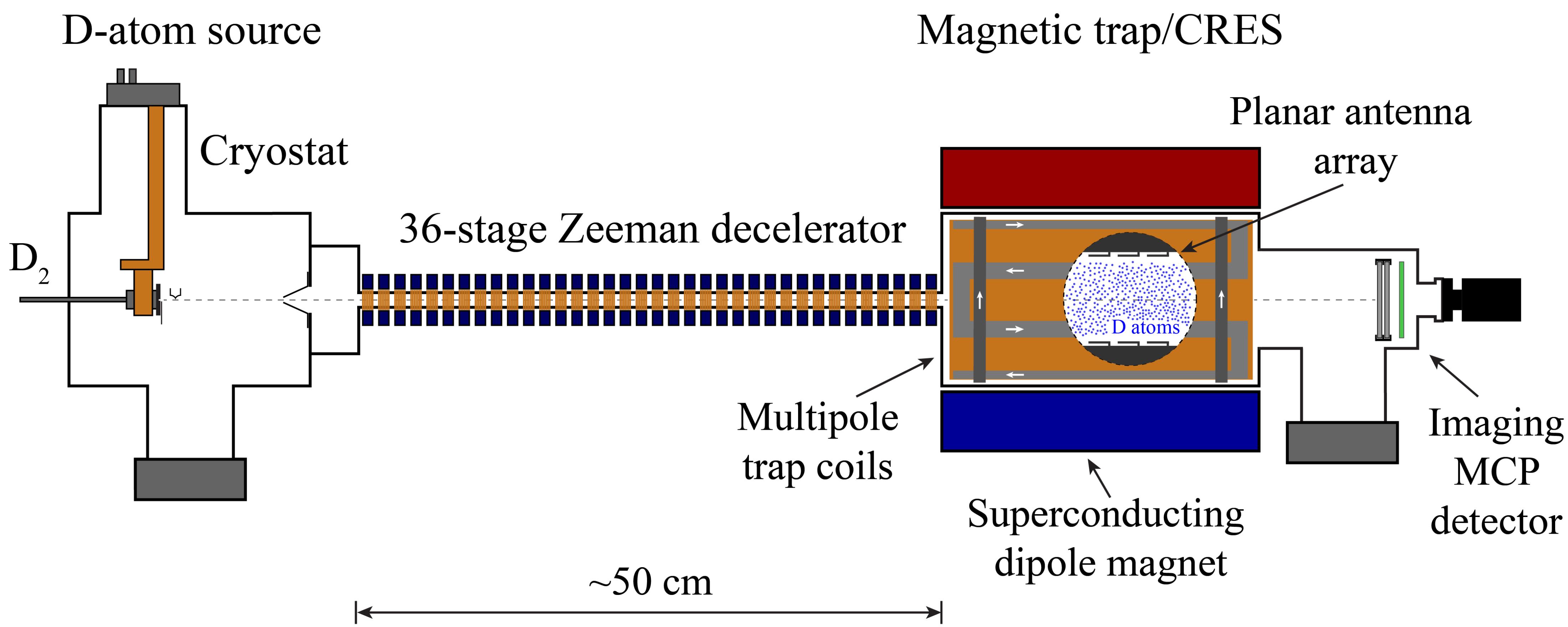
WP3. 3D Magnetic Trap Mapping
In-situ mapping with D atoms as quantum sensors
Rydberg states and Ramsey spectroscopy

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

CRESDA. Atomic Source and Magnetic Trap.



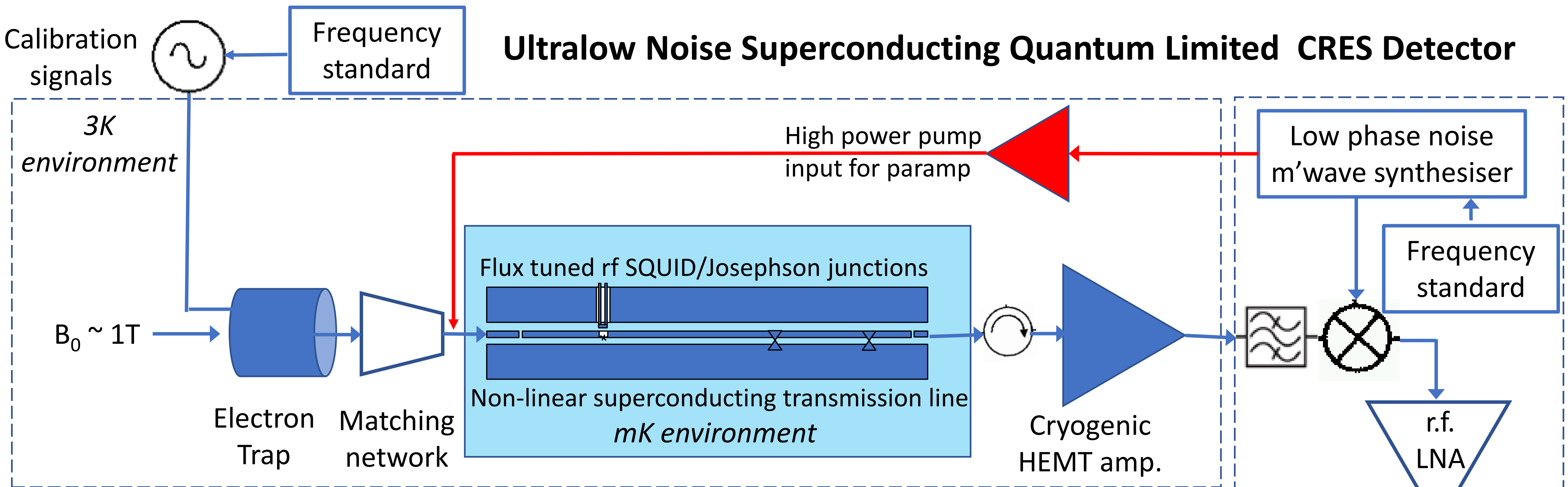
Goals for 3 year proposal

- Trapping D-atoms in 1L tap at T < 1K with ρ~10^{12}-10^{14} cm^{-3} : WP2
- Trapped atom density and temperature characterisation by laser and microwave spectroscopy : WP2
- Mapping B-field uniformity using quantum sensing in a trap with ≤ 1ppm precision: WP3
- Atomic beam line, trap and scaling up simulations: WP1

Pathway to 10^{20} T-atoms

CRES Detectors. Goals for 3 year proposal

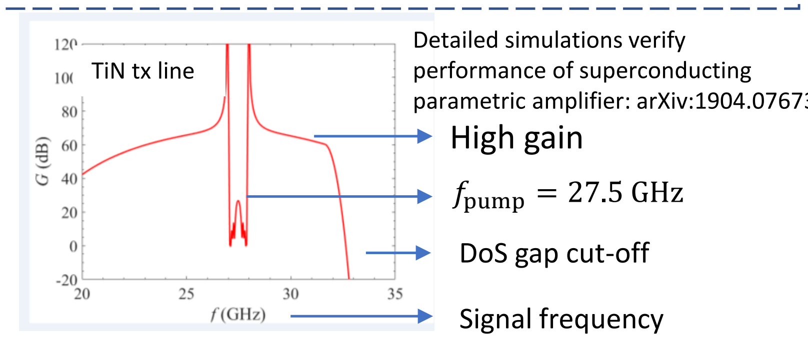
- **From devices to quantum noise limited m'wave detection systems: WP4**
- **High S/N Cyclotron Radiation Spectroscopy: P ≤ 0.01 fW, Δf/f < 10^{-6}. : WP4 and WP5**
- **CRES signal and background simulations, readout optimisation: WP1**

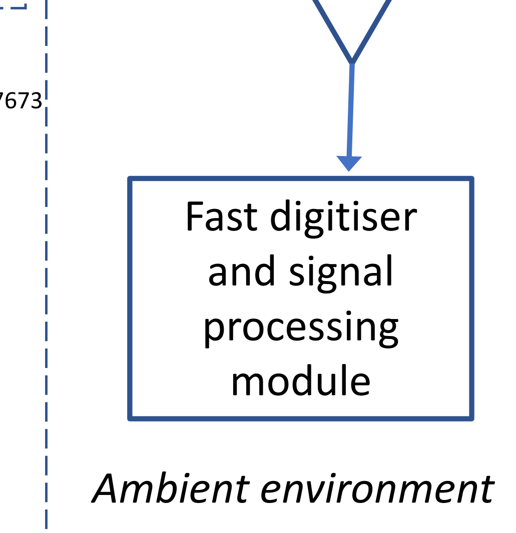


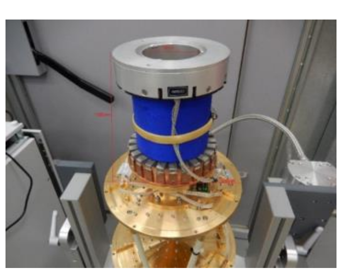
Challenge of millimetre-wave (25-30 GHz) ultra-low-noise amplifiers:

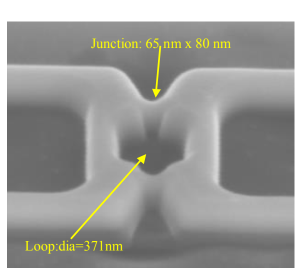
- Push superconducting microwave SQUID amplifiers up in frequency
- Push superconducting parametric amplifiers down in frequency
- High gain quantum-limited noise performance possible

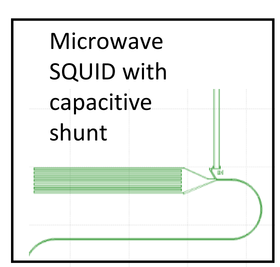
Draws heavily on major investments by funding agencies in establishing superconducting device processing and measurement labs

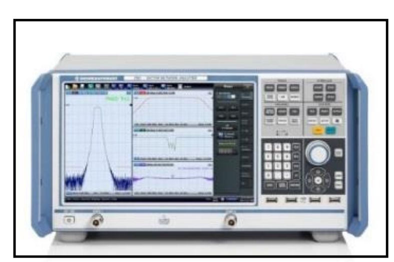












Proposal Status

Special thanks to Project-8 and KATRIN for their support letters!

- Submitted in Dec'19
- International and *interdisciplinary* panel
- Written response to reviewers comments in Feb'19
- Successfully went through several sift stages to final interview held on 1-Apr-2020 (11 out of 25 proposals)
- Original expectation of decision in mid-Apr with earliest start in May (!). But delayed amid current crisis

Summary

- Absolute Neutrino Mass measurement with CRES is a unique and exciting opportunity
  - One of most important measurements in particle physics can be done with *O*(≥ $100M investment)
- Need critical mass community to convince the world it must be done. Employ "no-lose" LHC Higgs argument?
- Huge technological challenge. Phased approach and exploring ***different*** techniques is the way forward to be ambitious and responsible at the same time.
- QTNM proposal submitted exploiting UK expertise in atomic traps, quantum electronics and neutrino physics. Awaiting outcome announcement.
- Promising engagement with Culham Centre For Fusion Energy
  - **H3AT** Facility, 100g Tritium inventory.
  - Strong interest in a major **fundamental science project at National Lab**

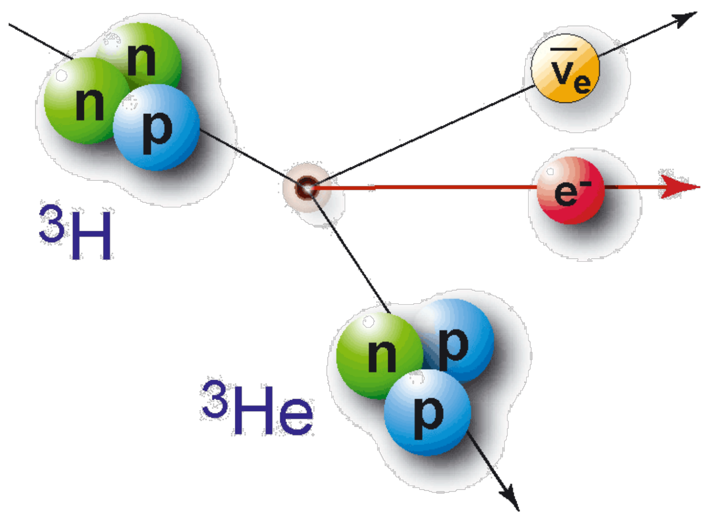
Outlook

- Expect and hope for close collaboration with Project-8. We have a LOT to learn!
- If **CRESDA** successful, moving it to **Culham**
  - Commissioning with Tritium
  - *O*(1eV) neutrino mass sensitivity
- Joining forces to establish **international collaboration** for “ultimate” experiment
- Possible location of “ultimate” experiment in **Culham** could unlock resources on a different scale: UK Infrastructure and Strategic Priorities Fund

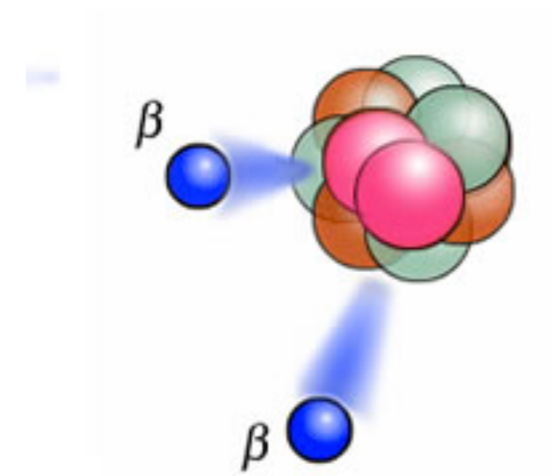
BACKUP

Absolute Neutrino Mass Parameters

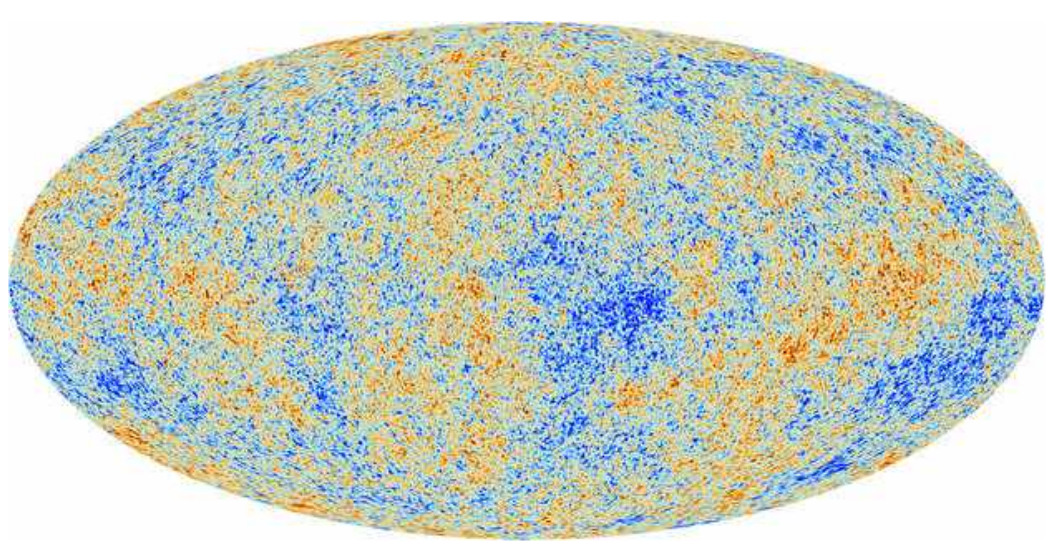
$$m_{\nu_e} = \sqrt{U_{e1}^2 m_1^2 + U_{e2}^2 m_2^2 + U_{e3}^2 m_3^2}$$



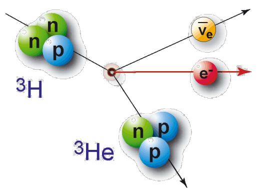
$$\langle m_{\beta\beta}(\nu_e) \rangle = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}$$

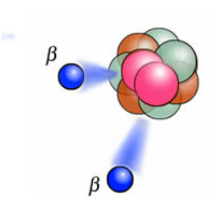


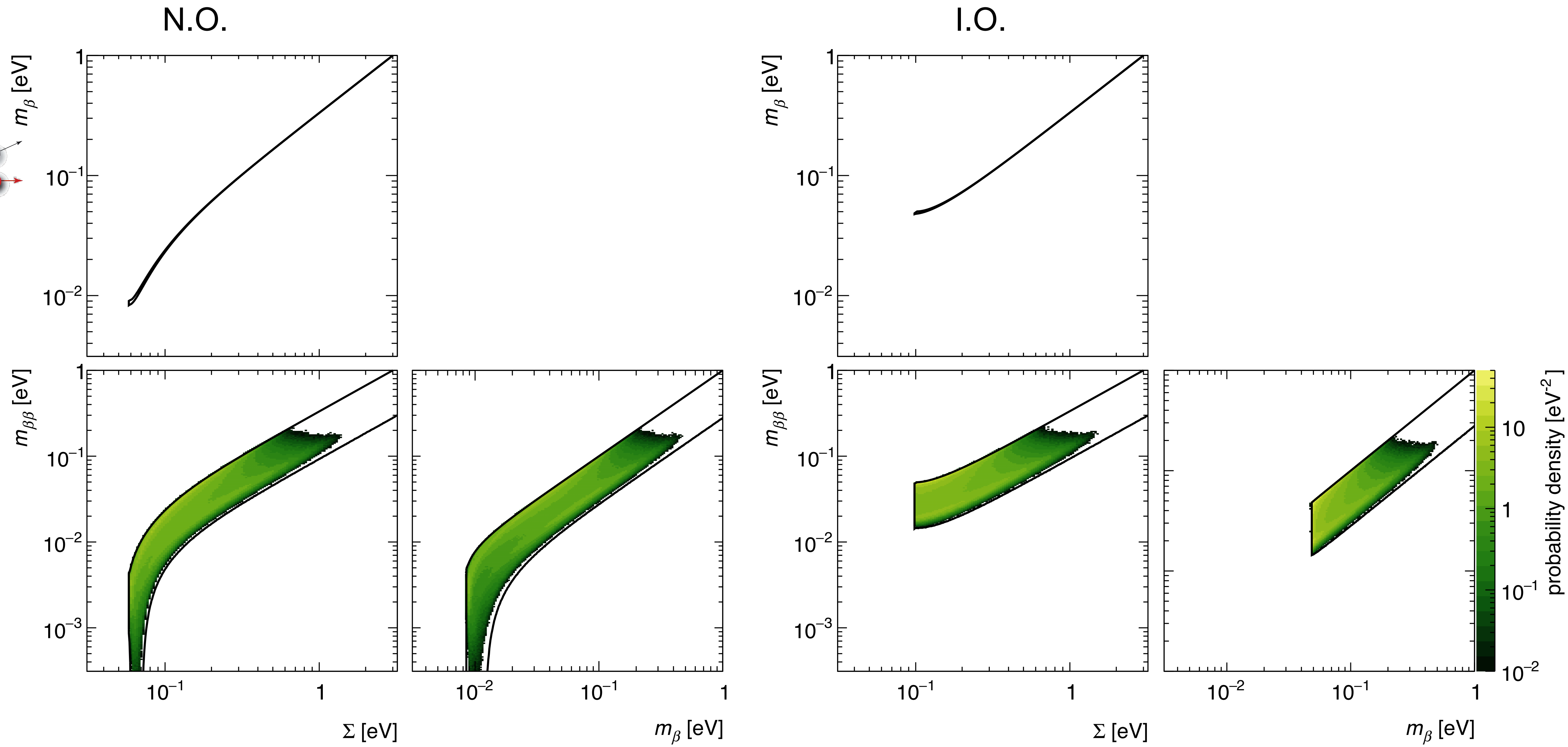
$$\Sigma = m_1 + m_2 + m_3$$



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

Quantum Sensors for Fundamental Physics

Collaborations formed as a result of workshops held
Highly interdisciplinary community:
Exploiting breakthroughs in quantum technologies to address particle physics questions

The Workpackages (WP)

The Workpackages (WP) are:

WP1
Using Quantum Technology to Search for Low-mass Particles in the Hidden Sector
Participants/Collaborators ›
Join this group ›

WP2
MaQS (pronounced "Max") Macroscopic quantum superpositions for physics beyond the standard model
WP2 workshop slides ›
Participants/Collaborators ›
Join this group ›

WP3
AION A UK Atom Interferometer Observatory and Network
Join this group ›

WP4
Absolute neutrino mass
Participants/Collaborators ›
Join this group ›

WP5
Quantum Simulators of Fundamental Physics
Participants/Collaborators ›
Join this group ›

WP6
QSNET Networked Quantum Sensors for Fundamental Physics
Join this group ›

WP7
Searches for a Fifth Force and Dark Matter using Precision Atomic Spectroscopy
Join this group ›

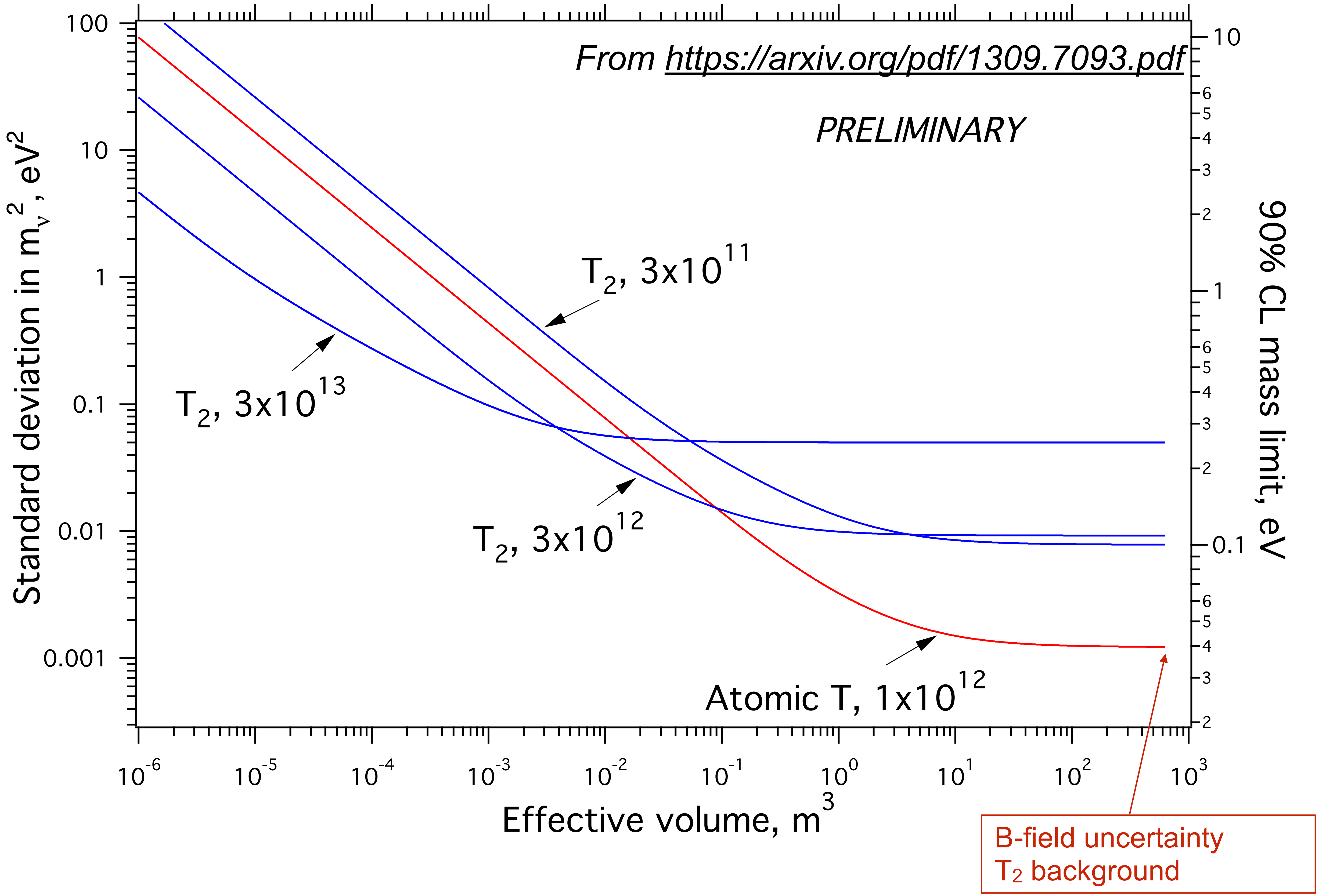
WP8
Fundamental physics from precision studies of exotic atoms
Participants/Collaborators ›
Join this group ›

WP9
LIST – Lorentz Invariance Space Test
Participants/Collaborators ›
Join this group ›

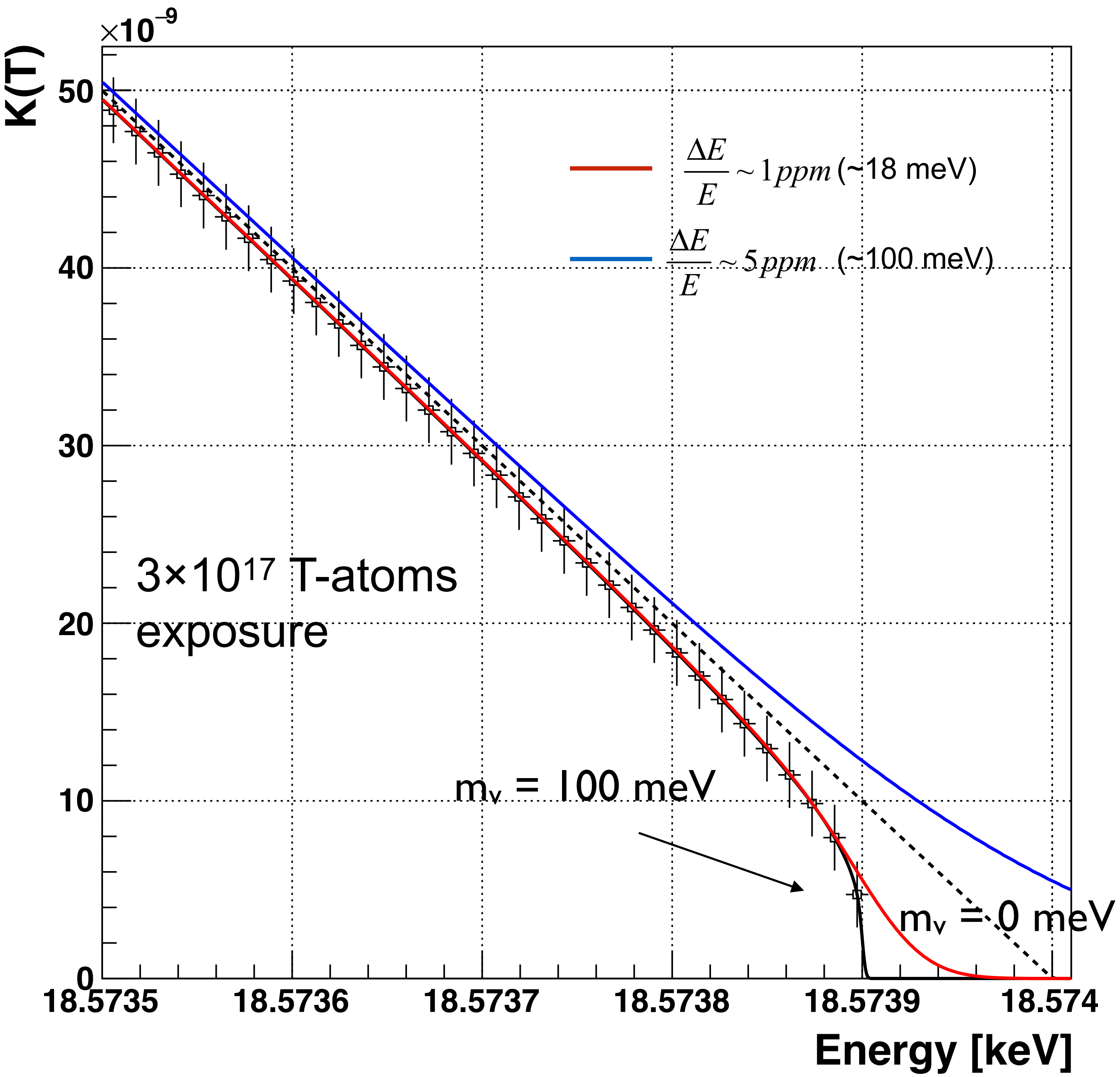
WP10
Quantum sensors for fundamental physics: Collective quantum excitations as quantum sensors
Participants/Collaborators ›
Join this group ›

WP11
QI: Quantum-enhanced Interferometry for New Physics

Project-8 Sensitivity



WP1. Simulation and Analysis

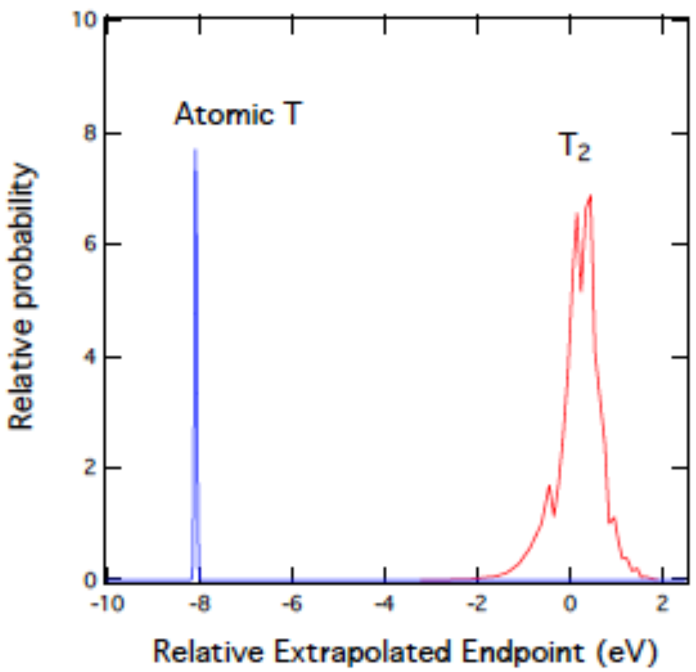


For *O(10meV)* sensitivities $>10^{20}$ T-atoms exposures required

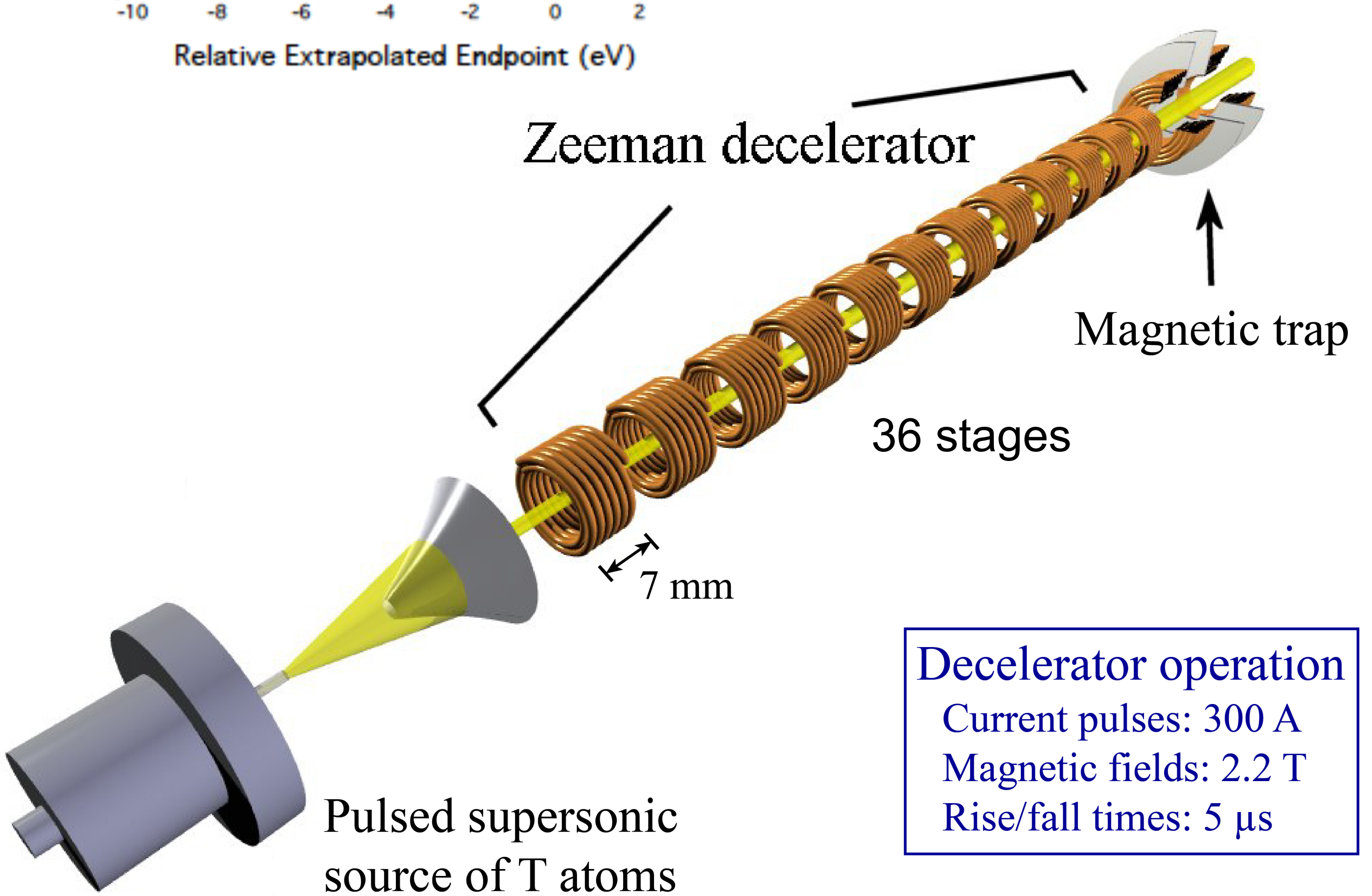
Tasks

- 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



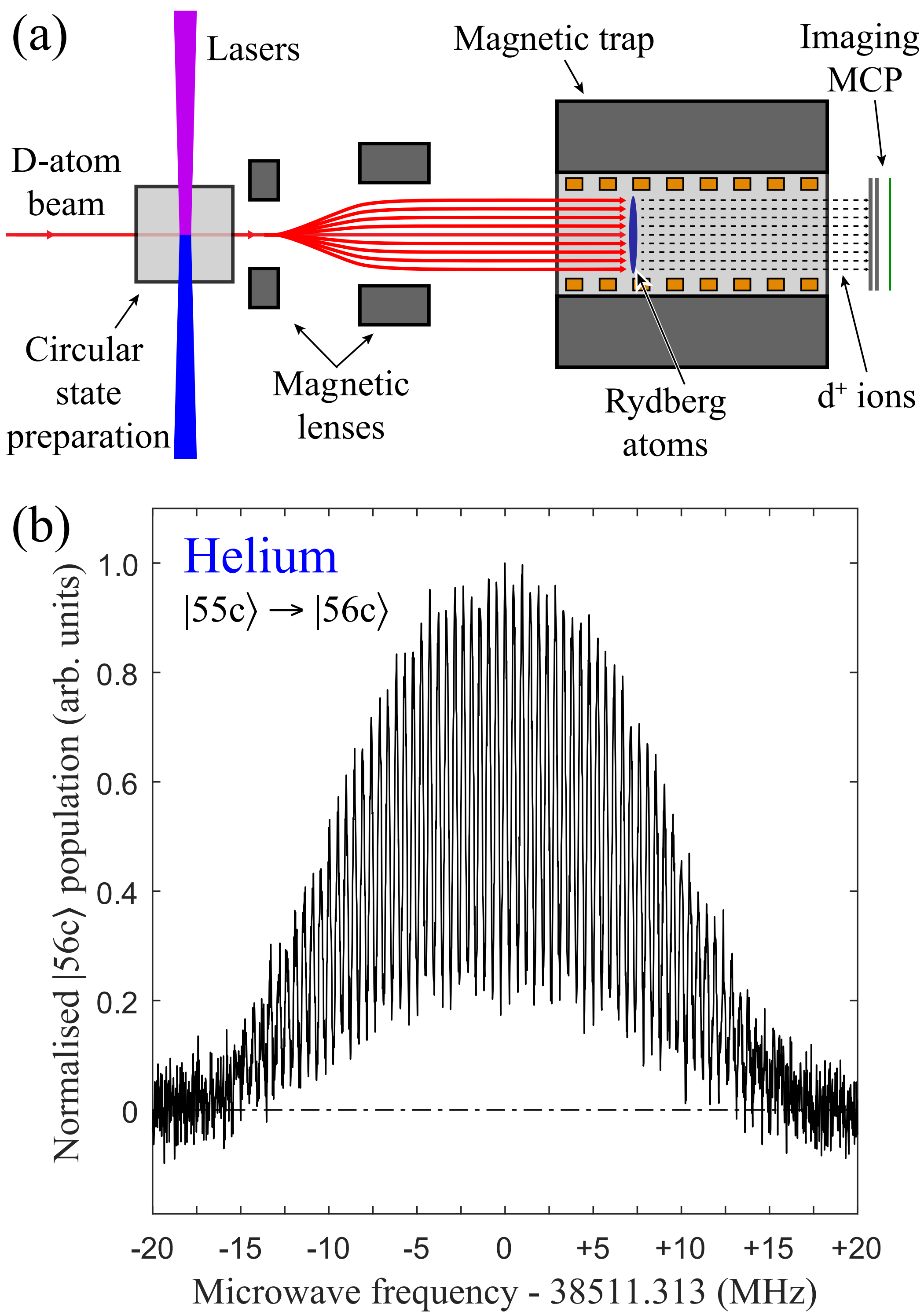
Need atomic T due to uncertainties in final states of molecular T_2



<u>Tasks</u>

- <u>D-atom Source</u>. 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}.
- <u>Zeeman Decelerator</u>. Successfully demonstrated for D-atoms and suitable for high densities. Output D-atoms with 50m/s, T~0.1K.
- <u>Magnetic Trap</u>. 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.

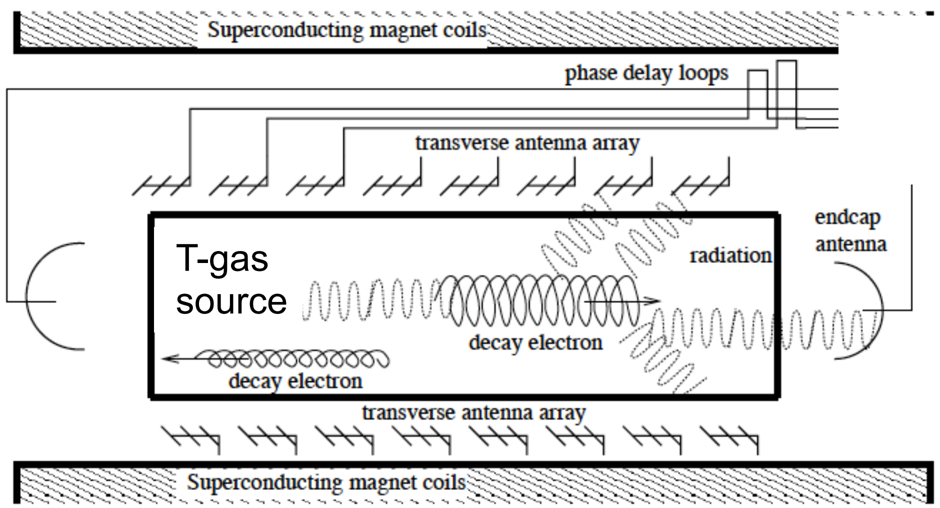
WP3. 3D B-field Mapping by Quantum Sensing.



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

- 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



→ Quantum-limited Preamplifier → Baseline Detector

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

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

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

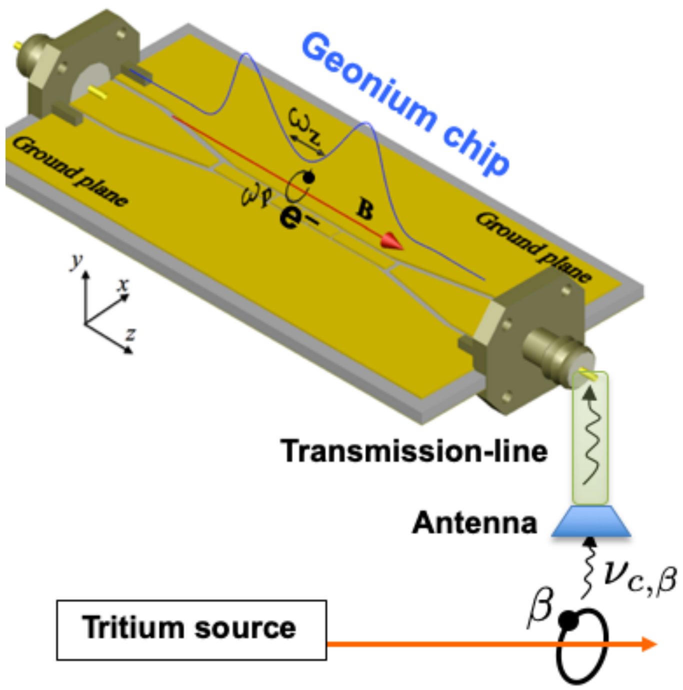
SLUG Amplifier at quantum limit (NPL)

Josephson Travelling Wave Parametric Amplifier (Cambridge)

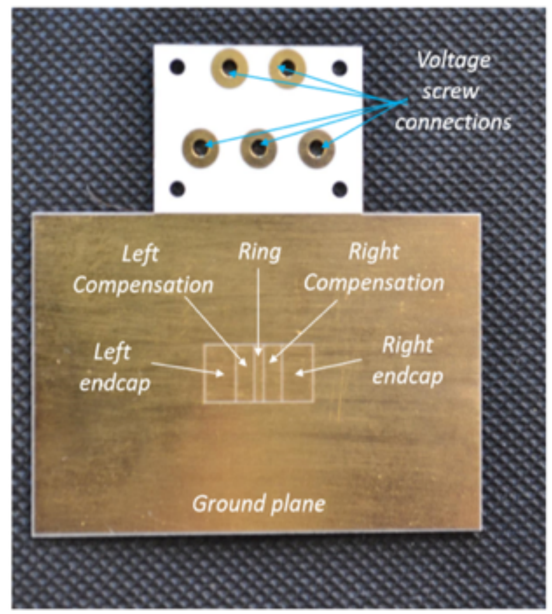
Down-selection and integration into quantum limite m'wave detection **system**

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

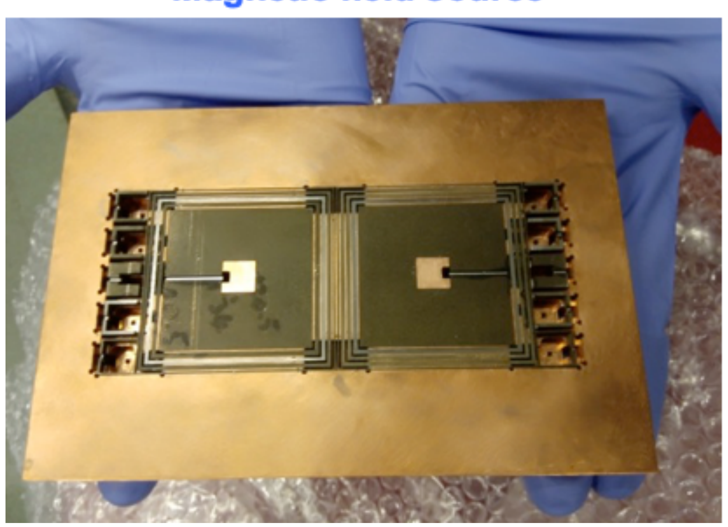
WP5. Geonium Atom CRES Detector.



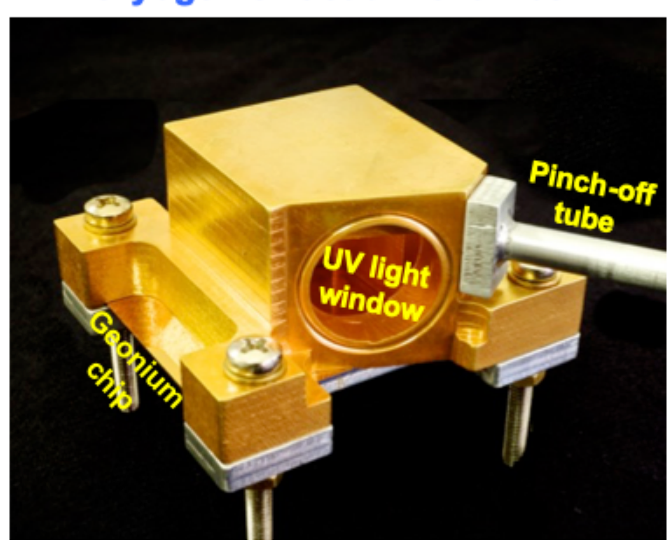
Geonium chip



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

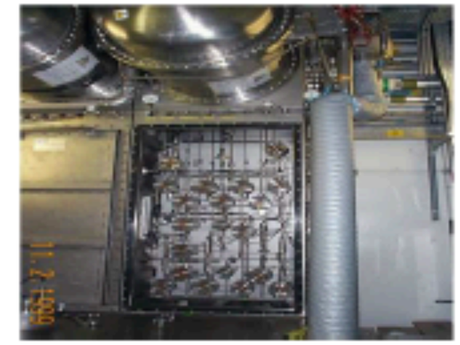
H3AT

UK Atomic Energy Authority

Building

Experiments

Tritium Systems



Control and Safety systems