Quantum Technologies for Neutrino Mass Consortium

National Physical Laboratory

UNIVERSITY OF CAMBRIDGE

UCL

THE UNIVERSITY OF WARWICK

Prifysgol Abertawe Swansea University

Determination of Neutrino Mass with Quantum Technologies

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

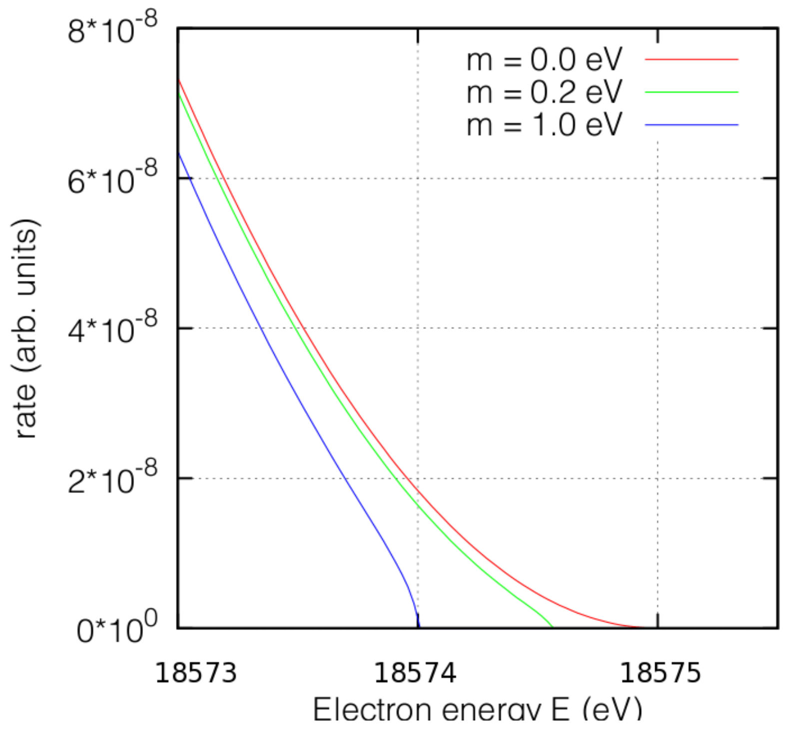
Quantum Leaps to the Dark Side
Cyberspace
9-11 November 2020

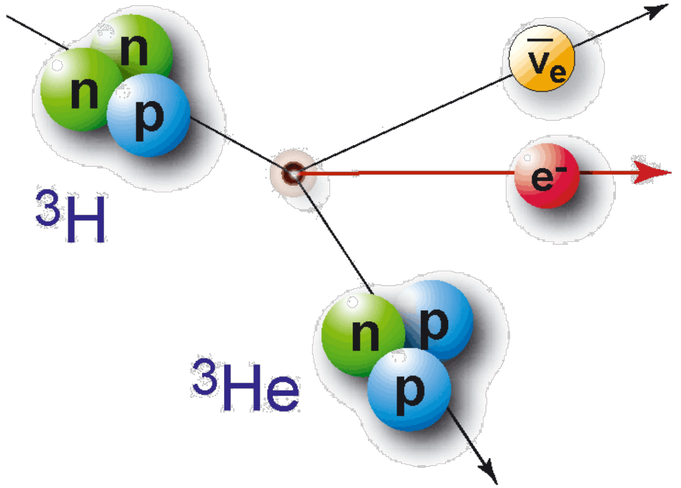
Ruben Saakyan (UCL)

10-Nov-2020

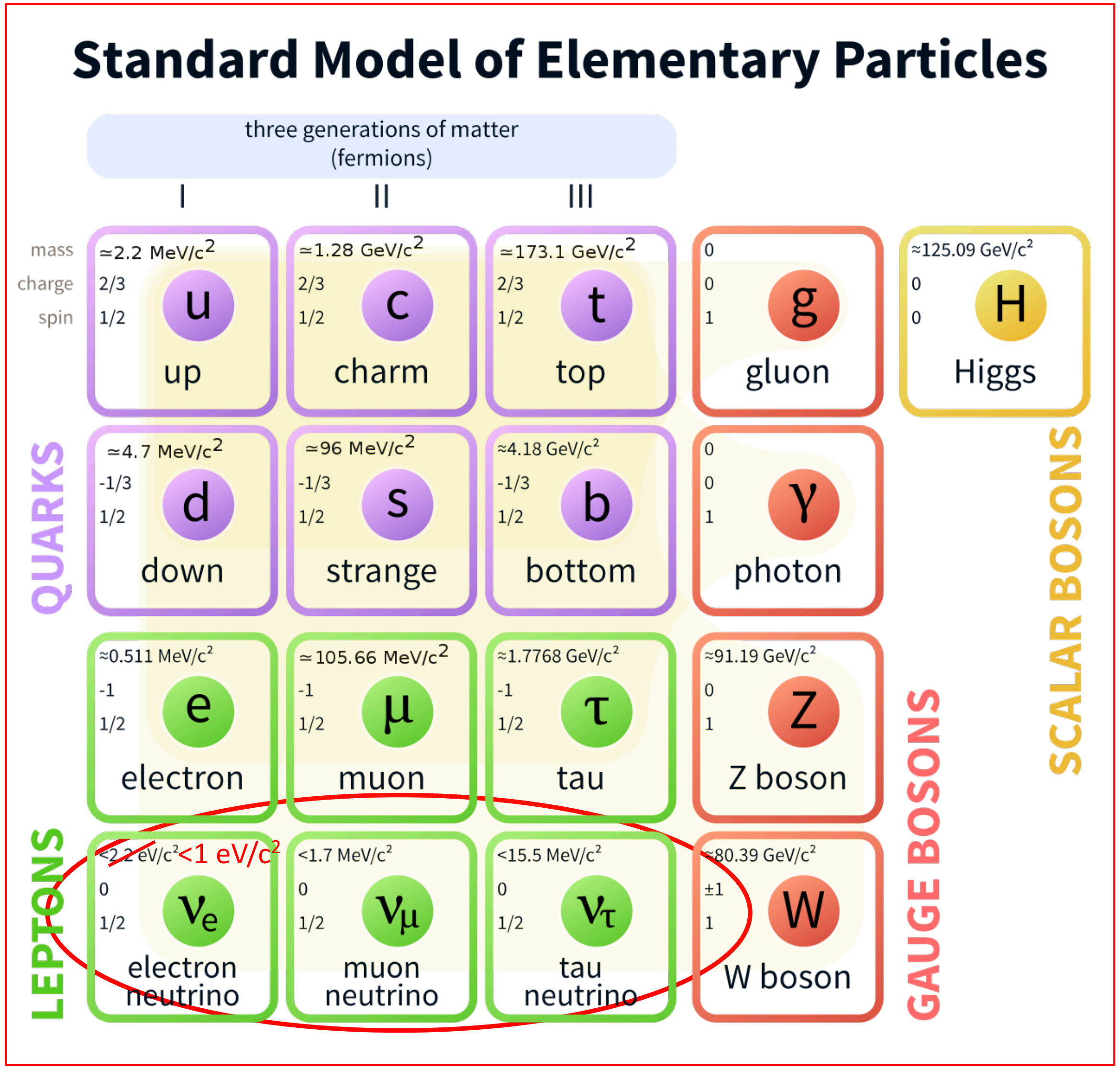
Outline

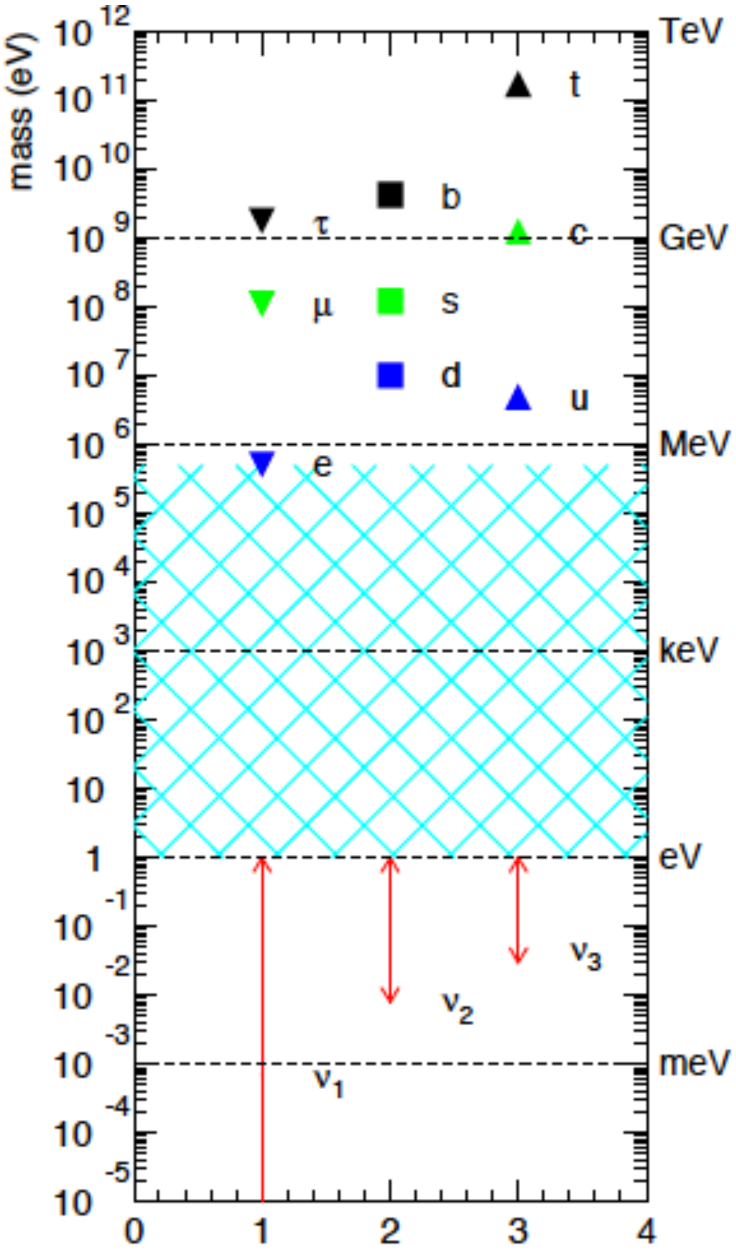
- The question of neutrino mass
- ^{3}H β-decay. State of the art
- ”Never measure anything but frequency…”
- Quantum technologies for ultimate reach
- QTNM proposal
- Future plans



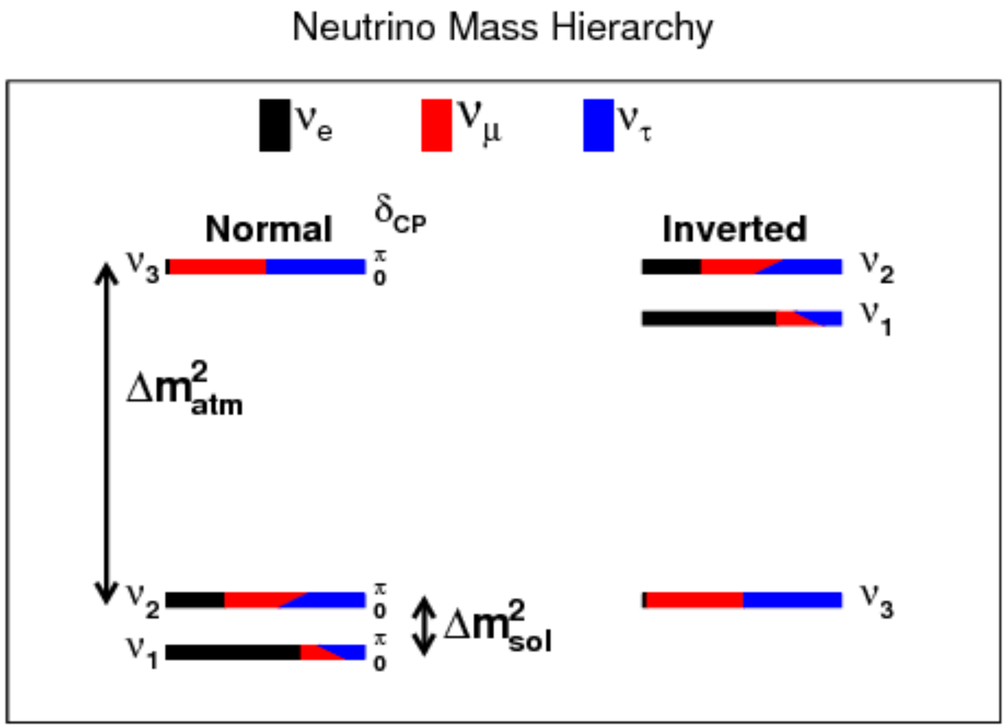


Most abundant particle of matter in the Universe (we still do not know much about)



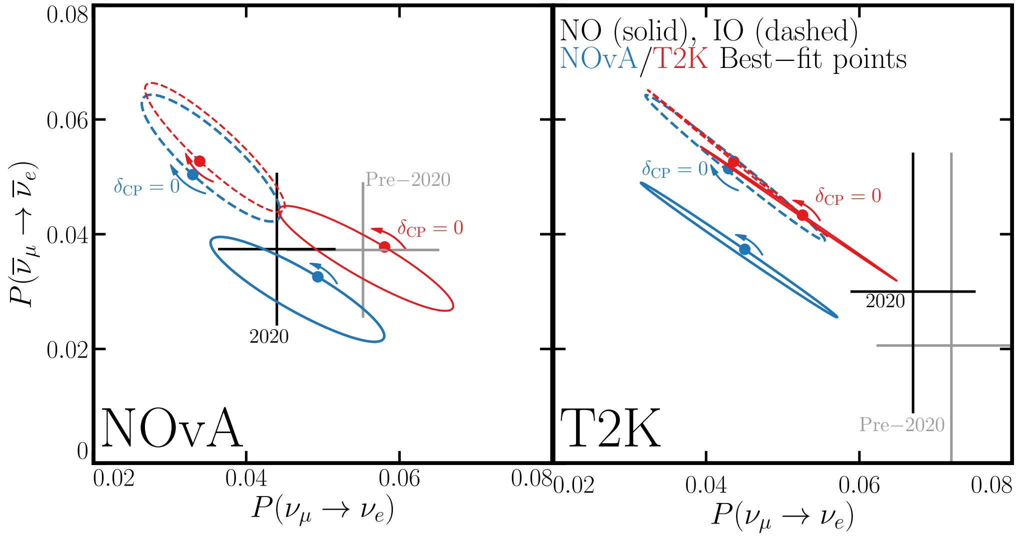


What we know (and don't) from neutrino oscillations



https://globalfit.astroparticles.es/

parameter	best fit ±1σ	2σ range	3σ range
Δm^2_{21}: $[10^{-5}$ eV$^2]$	$7.50^{+0.22}_{-0.20}$	7.11–7.93	6.94–8.14
$\|\Delta m^2_{31}\|$: $[10^{-3}$ eV$^2]$ (NO)	$2.56^{+0.03}_{-0.04}$	2.49–2.62	2.46–2.65
$\|\Delta m^2_{31}\|$: $[10^{-3}$ eV$^2]$ (IO)	2.46±0.03	2.40–2.52	2.37–2.55
$\sin^2\theta_{12}/10^{-1}$	3.18±0.16	2.86–3.52	2.71–3.70
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.66^{+0.16}_{-0.22}$	5.05–5.96	4.41–6.09
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.66^{+0.18}_{-0.23}$	5.14–5.97	4.46–6.09
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.225^{+0.055}_{-0.078}$	2.081–2.349	2.015–2.417
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.250^{+0.056}_{-0.076}$	2.107–2.373	2.039–2.441
δ_{CP}/π (NO)	$1.20^{+0.23}_{-0.14}$	0.93–1.80	0.80–2.00
δ_{CP}/π (IO)	1.54±0.13	1.27–1.79	1.14–1.90



arXiv:2007.08526v1

Still not known:

- Mass ordering
- CP-violation phase
- Is there sterile neutrino(s)
- **Absolute mass**

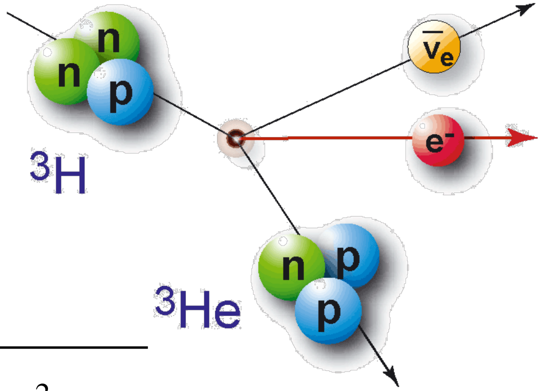
Neutrino mass

- Only solid evidence for Physics beyond Standard Model
- Smallness of mass suggests new mass generation mechanism (not “straight” Higgs)
- Connected to new physics
  - Matter-antimatter asymmetry (CP-violation)
  - Lepton Number Violation
  - Sterile-neutrino

Absolute neutrino mass is a key unanswered question that connects it all.

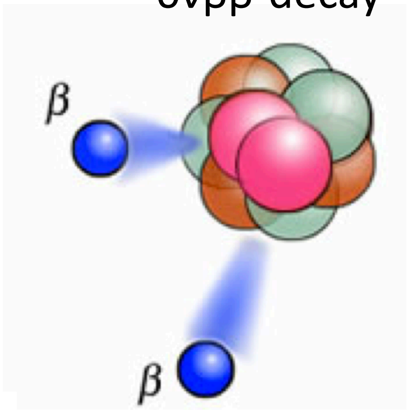
How to access Absolute Neutrino Mass

β-decay



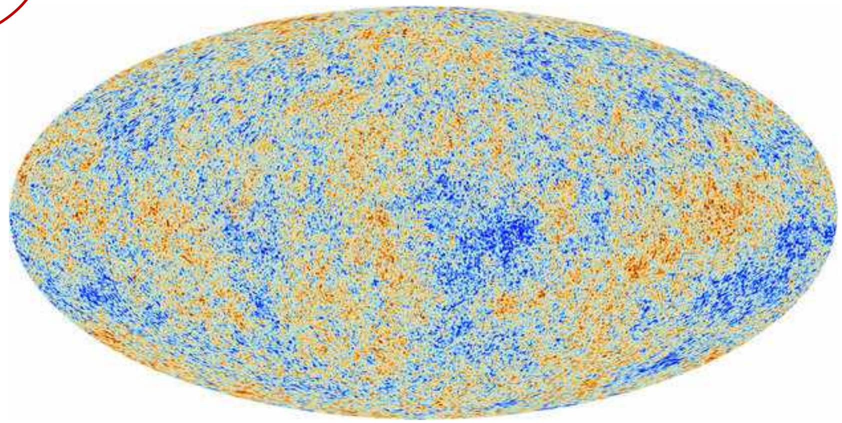
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

0νββ-decay



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

Cosmology



$$\sum_i m_i$$

Model Independent Neutrino Mass Measurement

E. Fermi, Z. Phys. 88 (1934) 161

Old idea!

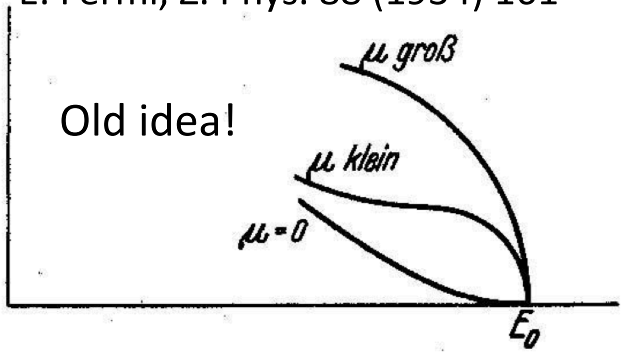


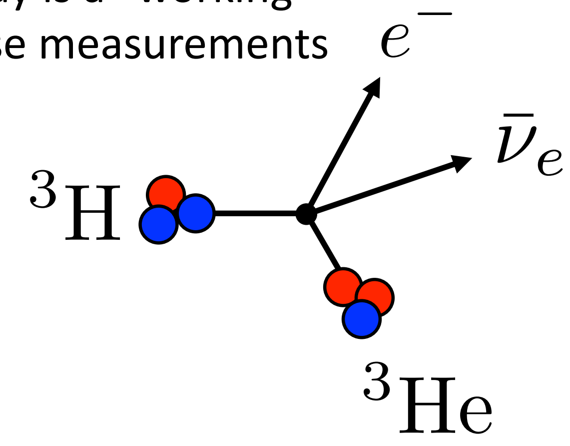
Fig. 1.

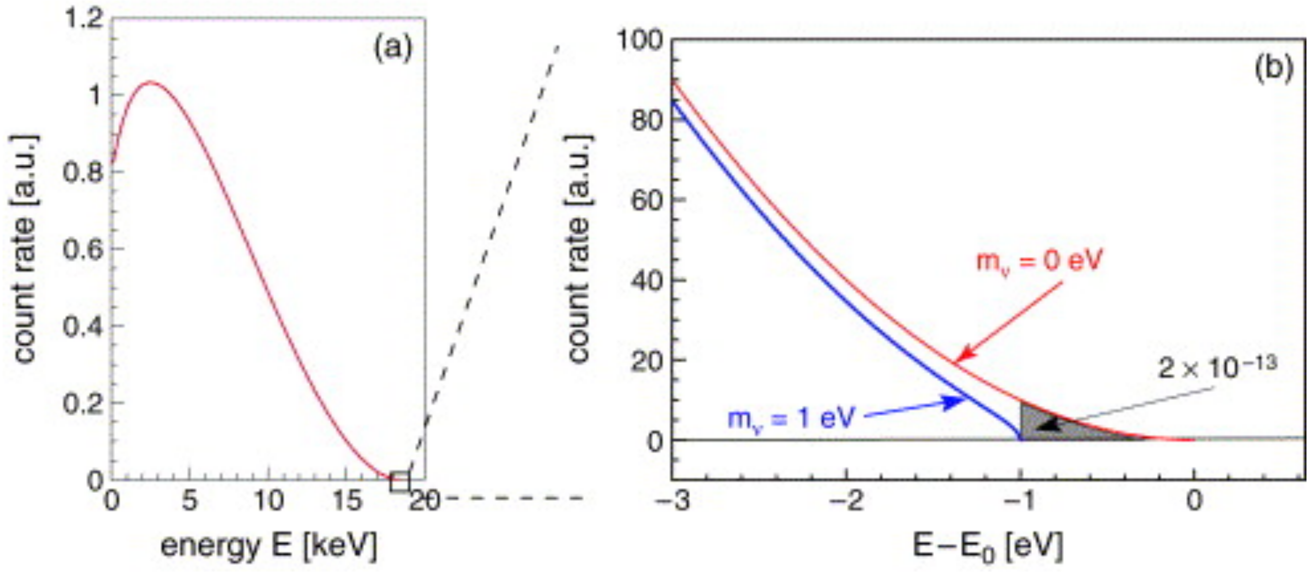
Energy conservation is only assumption!

$$\frac{d\Gamma_i}{dE} = C\, p(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_\nu^2}\,F(E)\,\theta(E_0-E-m_\nu)$$

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

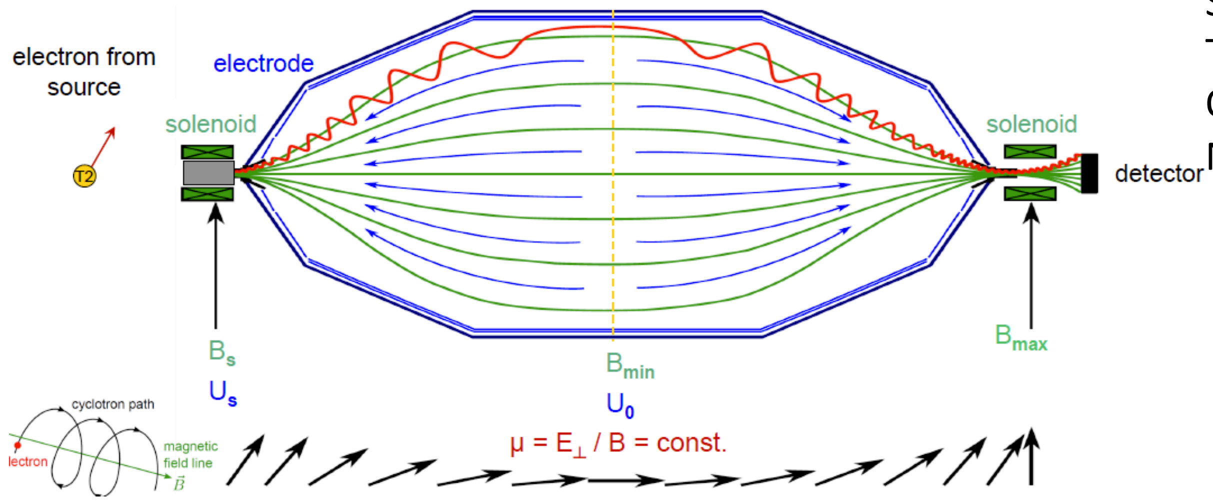
Tritium β-decay is a "working horse" of these measurements



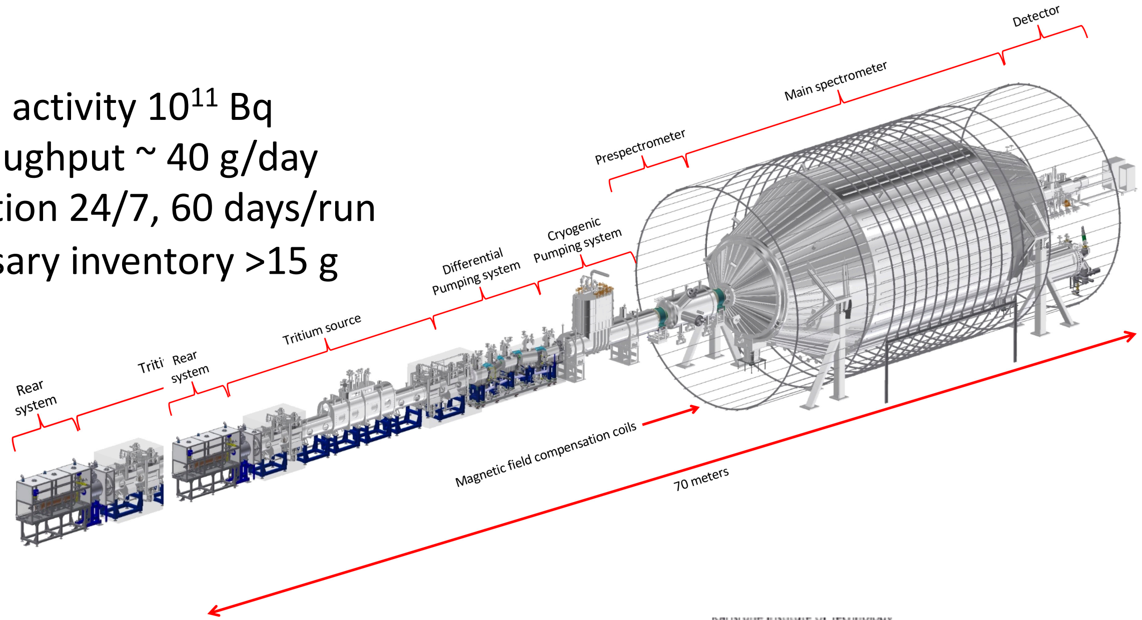


State-of-the-art: KATRIN Experiment

MAC-E Filter



Source activity 10^{11} Bq
T_2 throughput ~ 40 g/day
Operation 24/7, 60 days/run
Necessary inventory >15 g

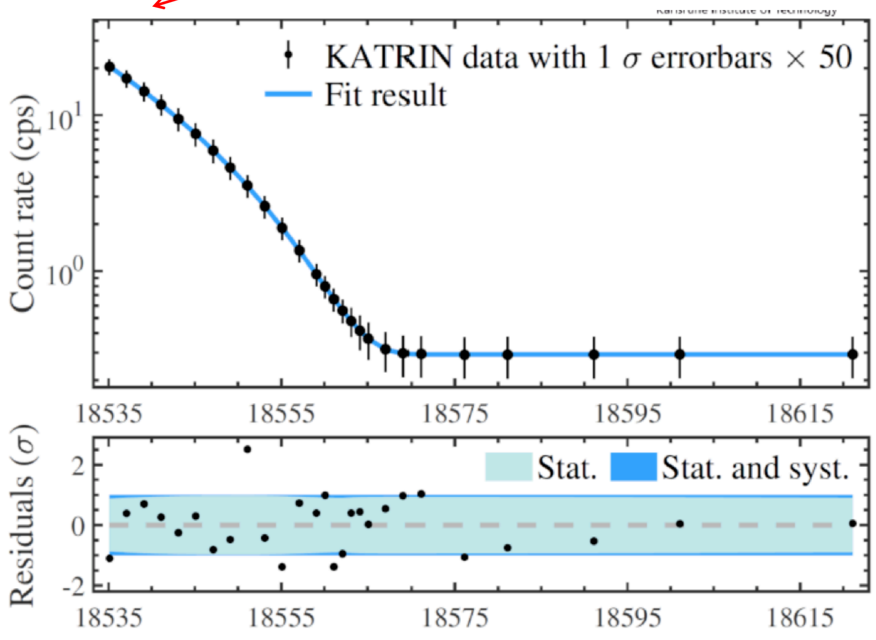


- **KATRIN upper limit on neutrino mass:**

LT $m(\nu) < 1.1$ eV (90% CL)

FC $m(\nu) < 0.8$ eV (90% CL)
< 0.9 eV (95% CL)

>x2 improvement compared to previous result!



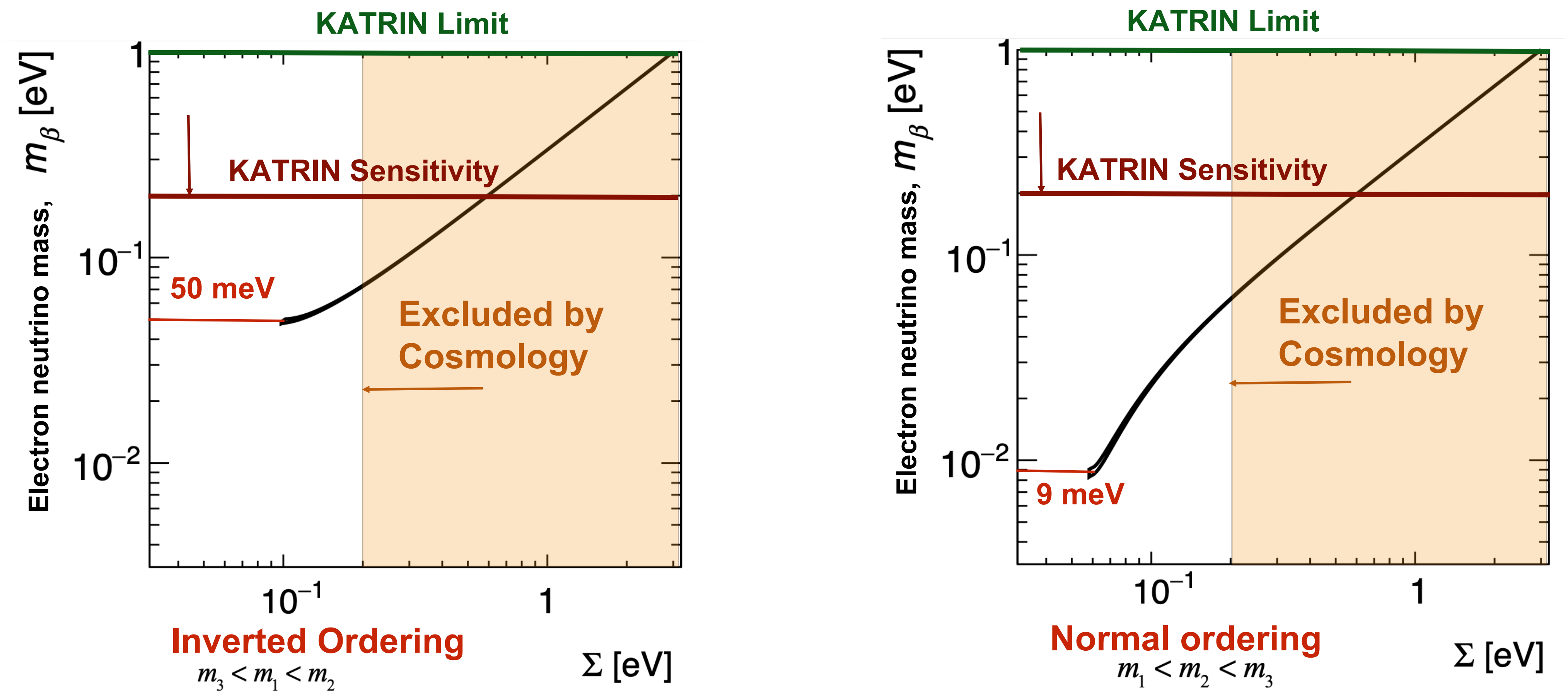
LT: Lokhov-Tkachov
FC: Feldman-Cousins

Ultimate sensitivity ~0.2 eV

$$\frac{\Delta E}{E} \propto \frac{B_{min}}{B_{max}}$$

$$\frac{\Delta E}{E} \leq 0.01\%$$ (~ 5×10^{-5})

Scales with spectrometer size
Already 10m in diameter and 24m in length for **KATRIN**.
MAC-E cannot be scaled up beyond **KATRIN**

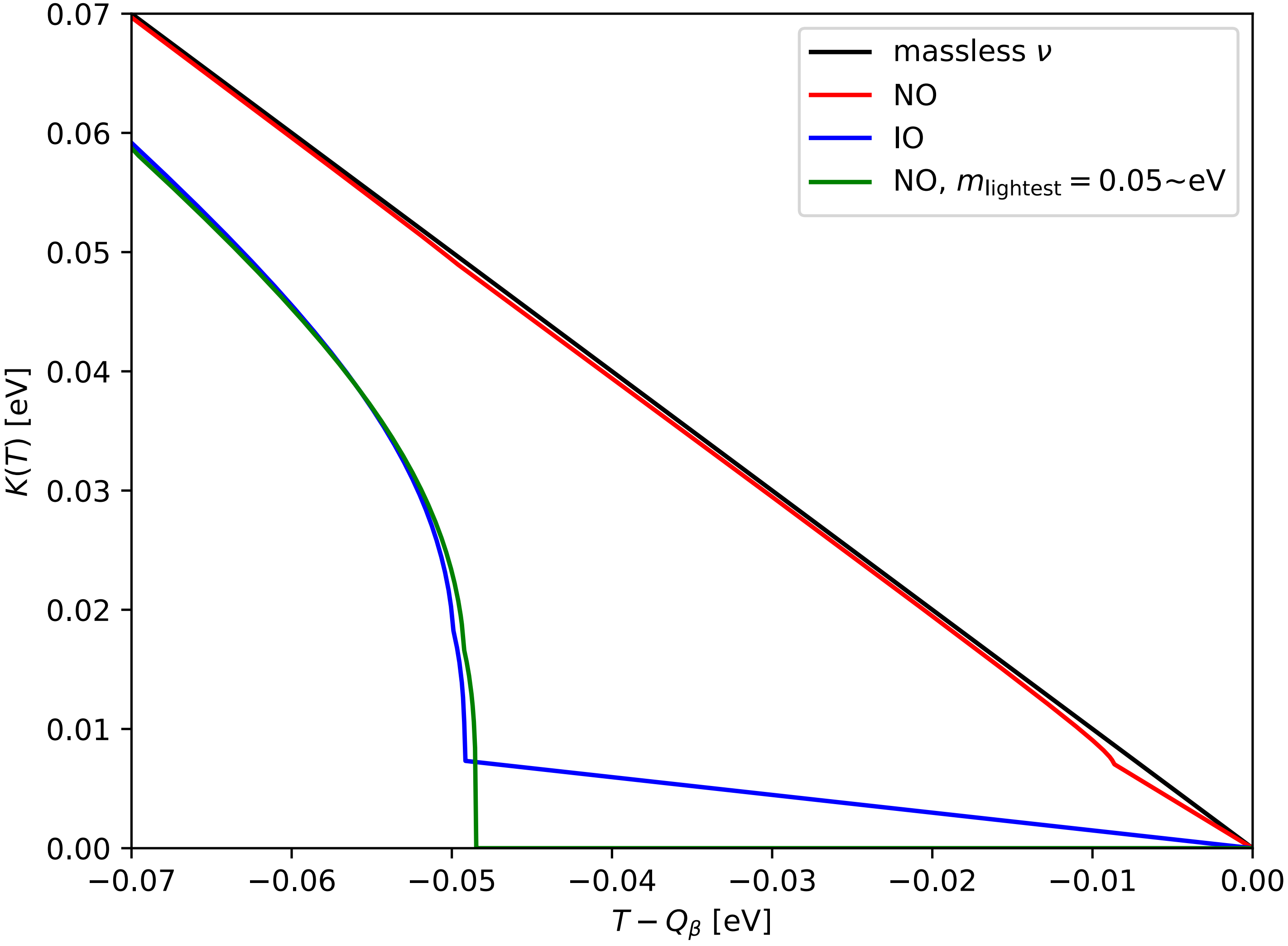


Adapted from M. Agostini et al, Phys. Rev., D96(5):053001, 2017

- 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.**

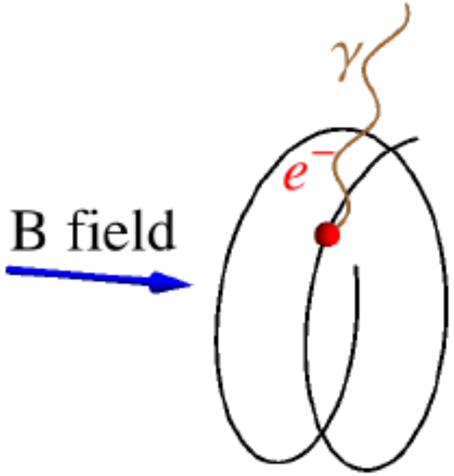
"Guaranteed" observation if technology demonstrated

The Scale of the challenge



How to overcome present technology limitations?

A. Schawlow: "Never measure anything but frequency!"



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

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

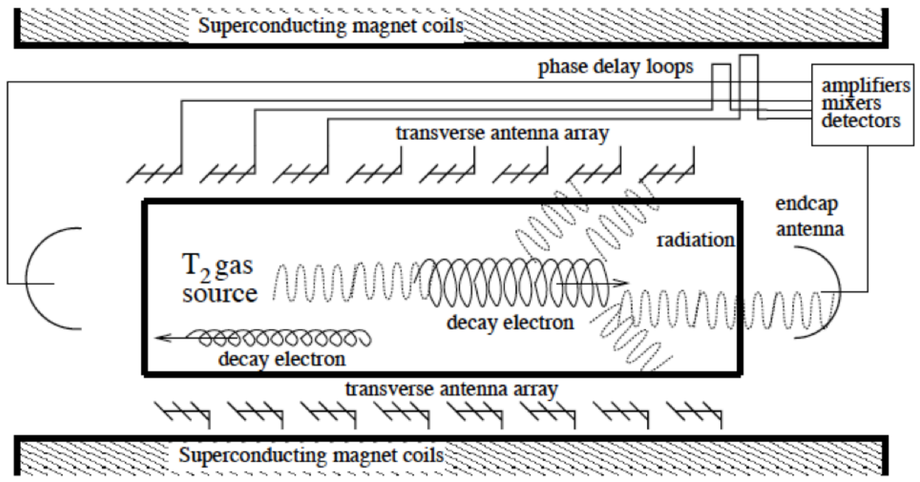
Determine energy of electron emitted in ^{3}H β-decay by measuring the frequency of EM radiation generated due to electron's cyclotron motion in magnetic field

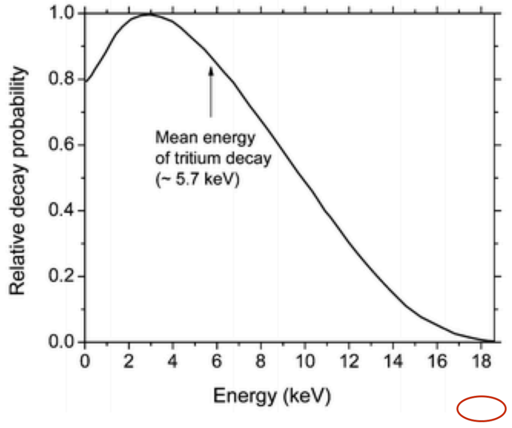
Cyclotron **R**adiation **E**mission **S**pectroscopy (**CRES**)

Concept put forward by **Project-8** Collaboration

- Source **transparent** to microwave radiation
- **No losses** due to e- transport from source to detector
- Leverages exquisite **precision** in **frequency** techniques
- **Differential spectrum** measurement

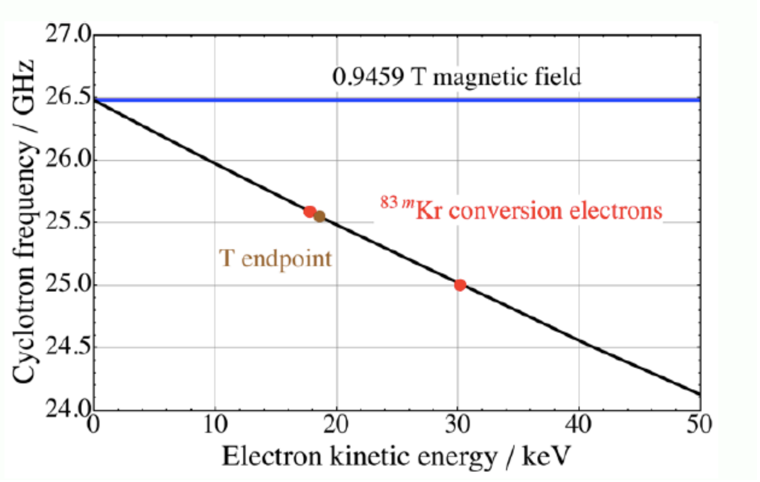
Cyclotron Radiation Emission Spectroscopy (CRES) Concept



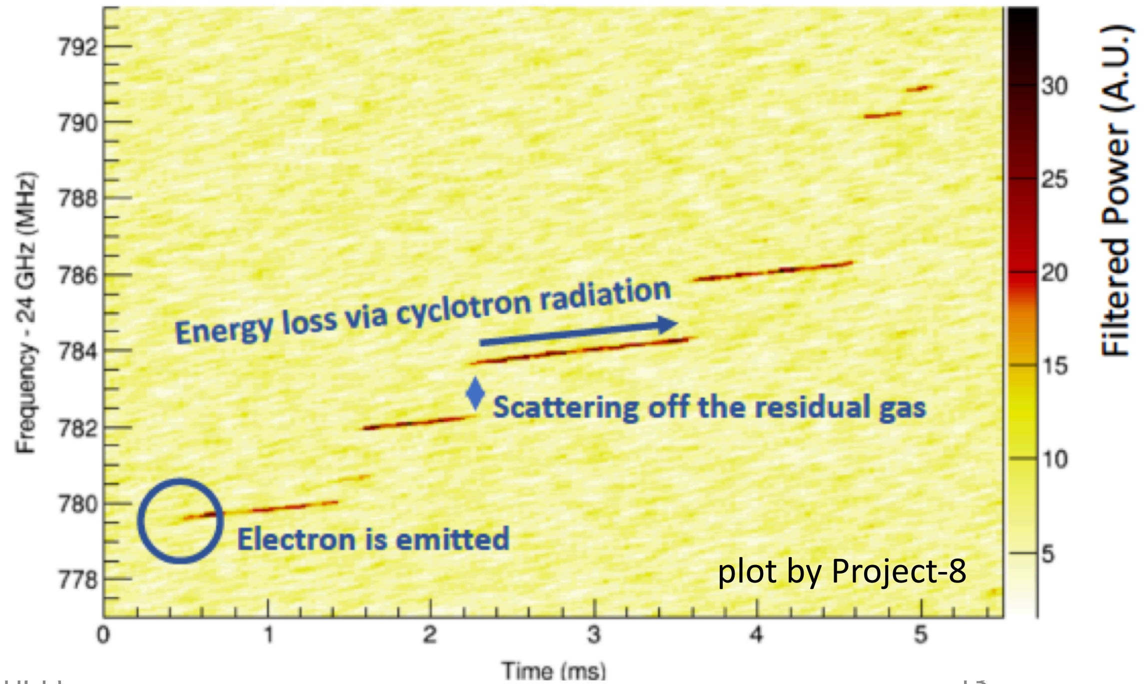


$$^{3}H \rightarrow {}^{3}He + e^{-} + \bar{\nu}_e$$

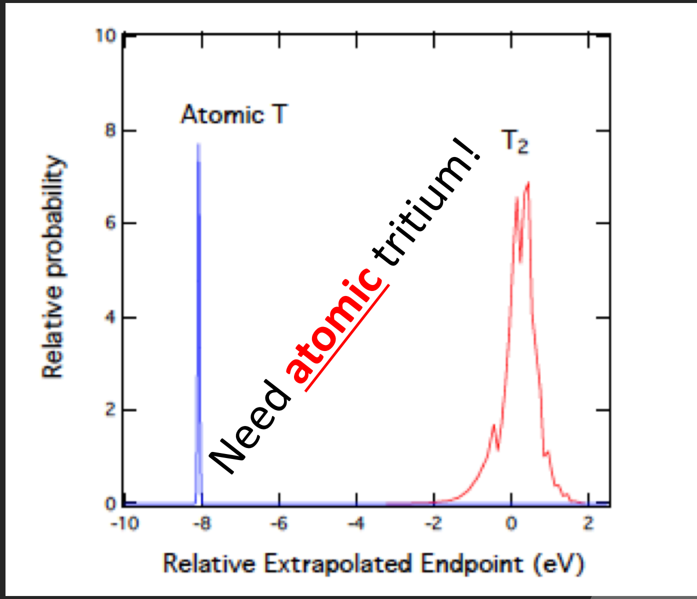
Q_β = 18.6 keV ⇒ ~26 GHz
in 1Tesla B-field



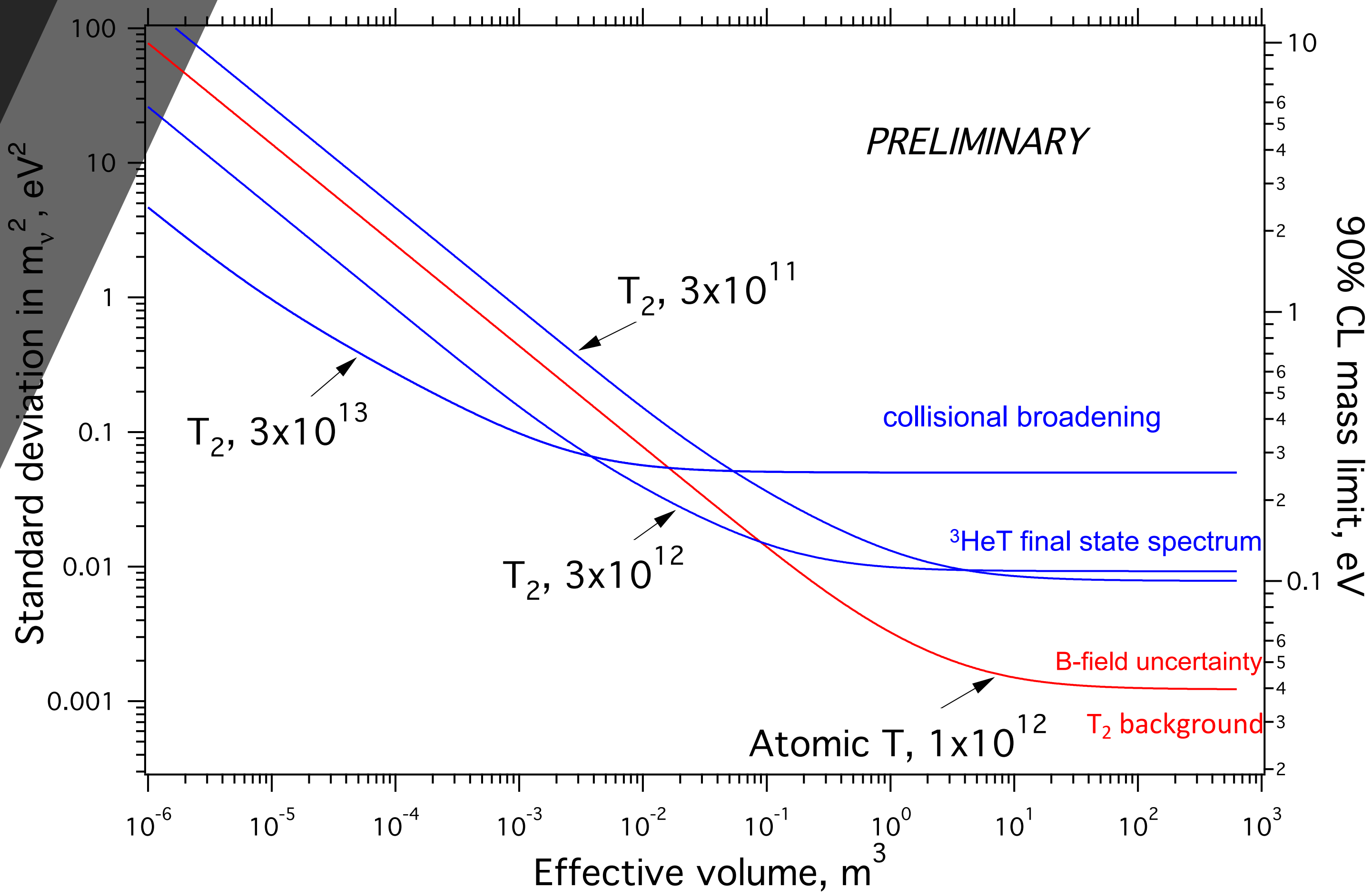
Proof of principle by Project-8 using ^{83m}Kr conversion electrons



CRES Challenges



Courtesy of Project-8



CRES Challenges

Three main obstacles on the the way to "guaranteed" observation, O(10 meV)

- Trapping O(10^{20}) T-atoms in a magnetic trap
- Mapping B-field with ≤0.1 ppm precision using quantum sensing
- Quantum devices for microwave (25-30GHz) spectrometry, sub-sub-fW, $\Delta f/f < 10^{-6}$

Determination of Absolute Neutrino Mass Using Quantum Technologies

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

Quantum Technologies for Neutrino Mass Consortium

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

3-yr proposal goal:

Technology demonstration for neutrino mass determination from ^{3}H $\boldsymbol{\beta}$-decay

- Trapping ~10^{20} D/T atoms
- B-field mapping with $\lesssim$0.1ppm precision
- Quantum limited micro-wave electronics

Ultimate goal:

Neutrino mass measurement at a Tritium facility (e.g. *Culham Centre for Fusion Energy*)

*Building on **recent investment in quantum sensors** to assess feasibility of an **experiment** capable of a **guaranteed neutrino mass measurement***

CRESDA

CRES Demonstration Apparatus

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

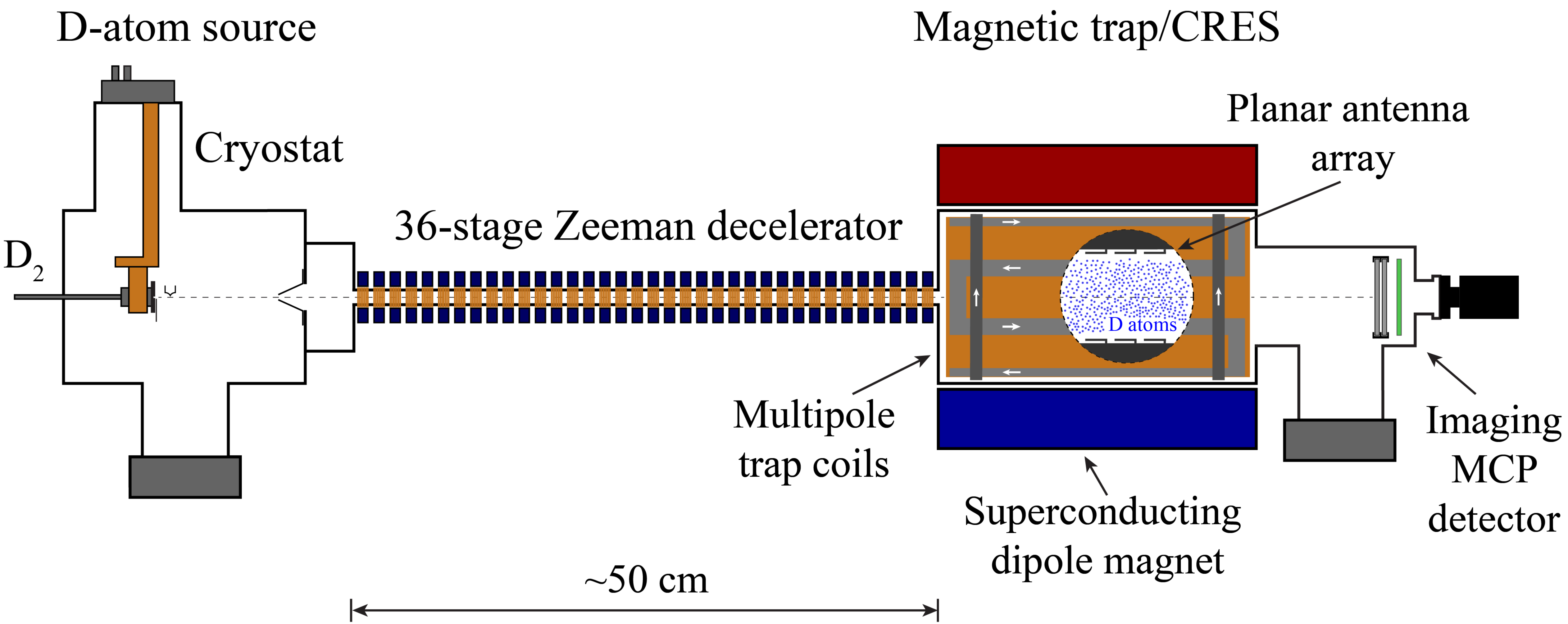
Rydberg states and Ramsey spectroscopy

WP4. Cyclotron Radiation Detection

Cryogenic HEMT amplifier

SLUG or JTWPA preamp (downselect)

From devices to quantum limited integrated system



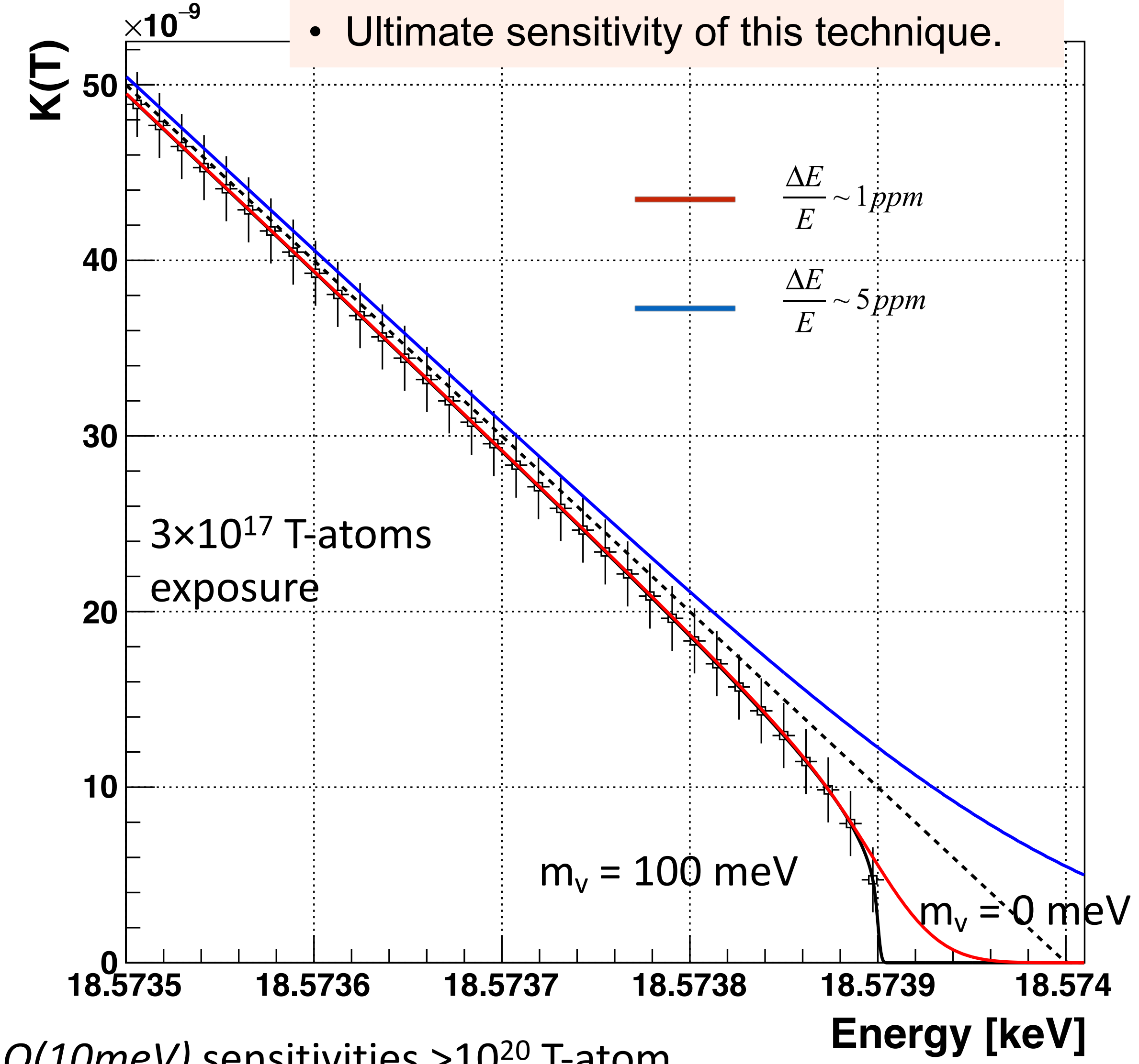
- *Demonstration with D-atoms*
- *But make it T-ready!*

CRESDA

WP1. Simulations and Analysis.

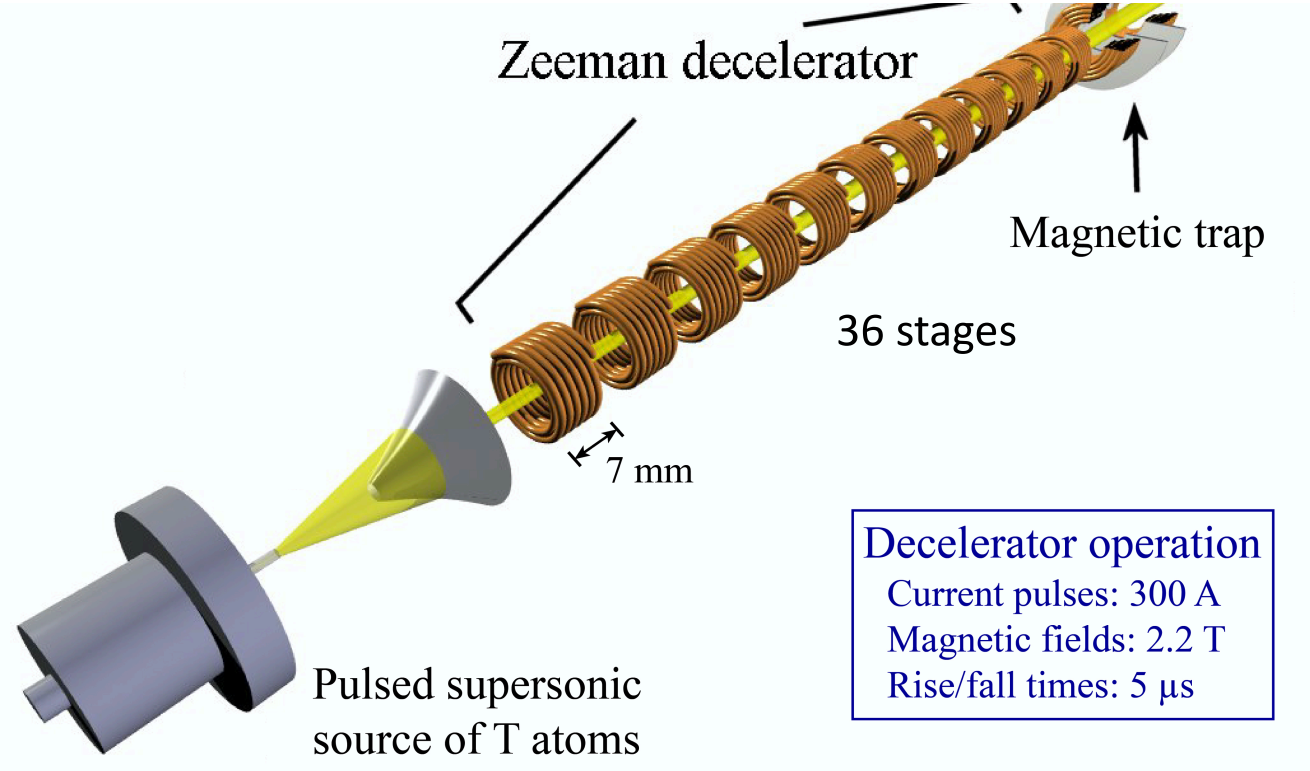
- Nuclear/atomic effects.
- Spectrum fitting for m_{ν}.
- Effect of massive and/or sterile neutrinos on electron energy distribution.
- 3D particle trajectory simulations
- Atoms and electrons in trap, collision, ionisation, plasma effects
- RF emission, propagation and detection
- Noise and background

- Sensitivity of CRESDA@"Culham"
- Ultimate sensitivity of this technique.



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

WP2. Atomic Beam Source and Magnetic Trap



- 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 50 m/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. 3-D Magnetic Field Mapping

- 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 $\Longrightarrow$ possible contribution to “proton radius puzzle”

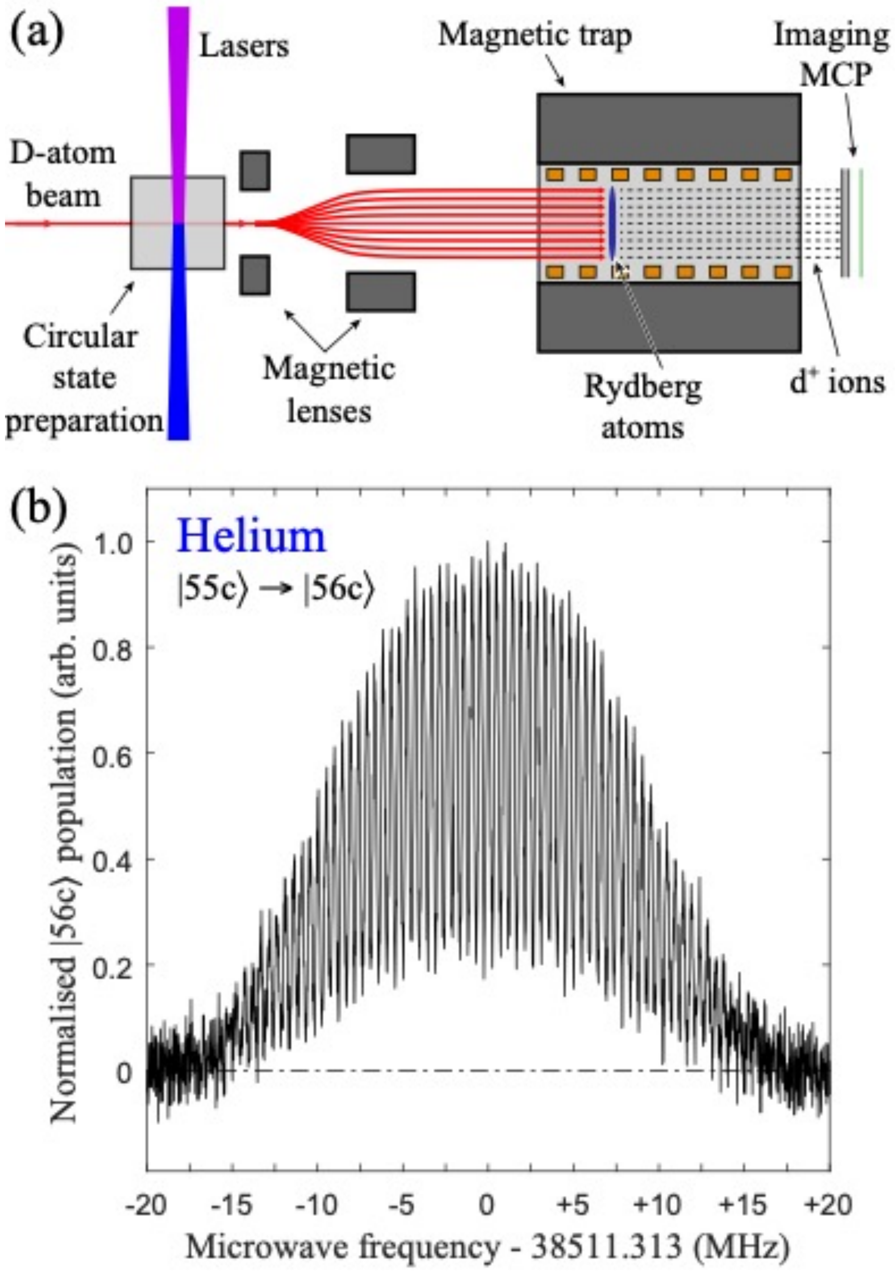
$$f = \frac{1}{2\pi} \frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

$$\Downarrow$$

$$\frac{\Delta f}{f} \sim 10^{-6}$$

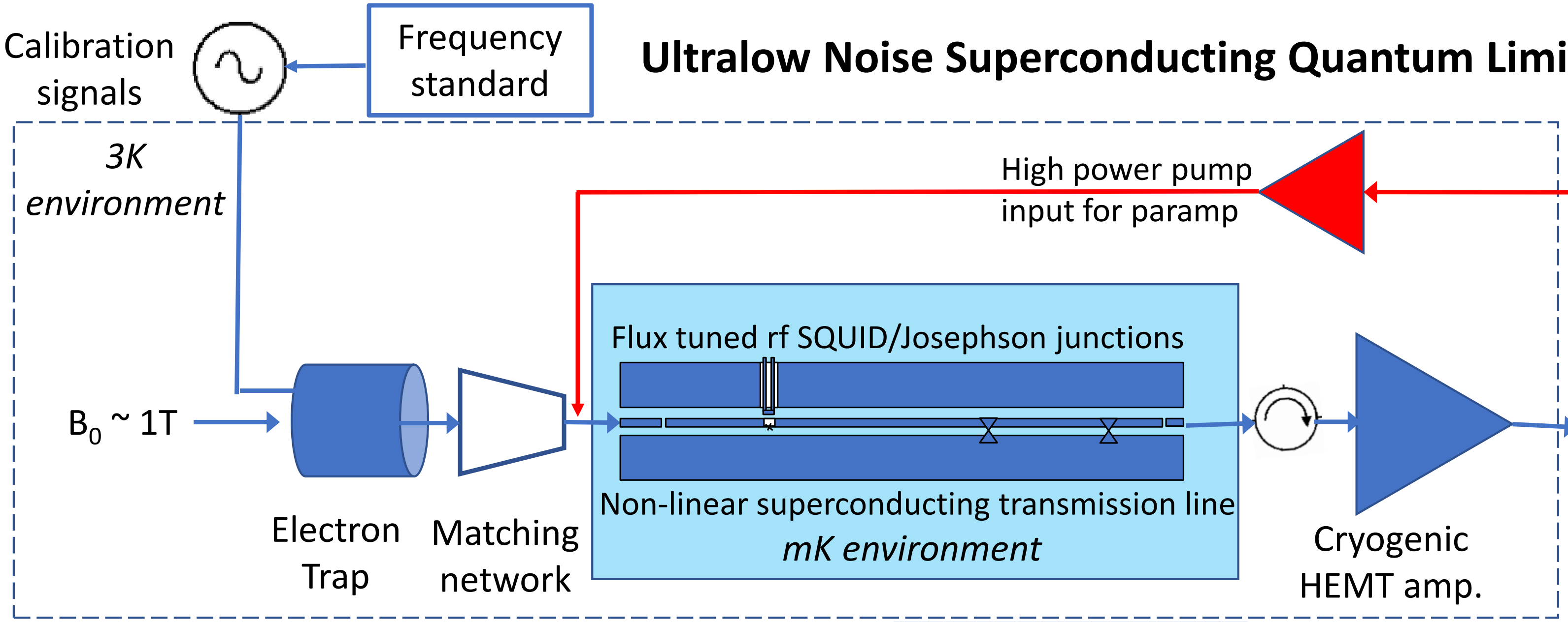
$$\Downarrow$$

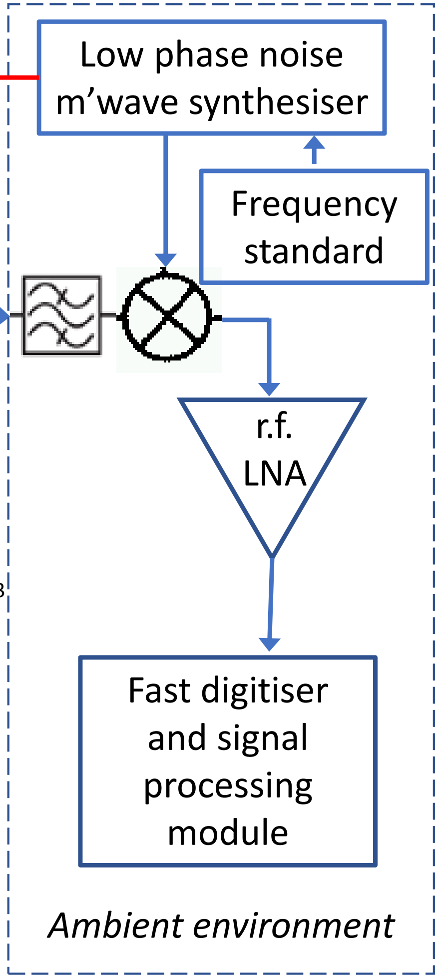
$$\frac{\Delta B}{B} \sim 10^{-6}$$



WP4. Cyclotron Radiation Detection.

Ultralow Noise Superconducting Quantum Limited CRES Detector

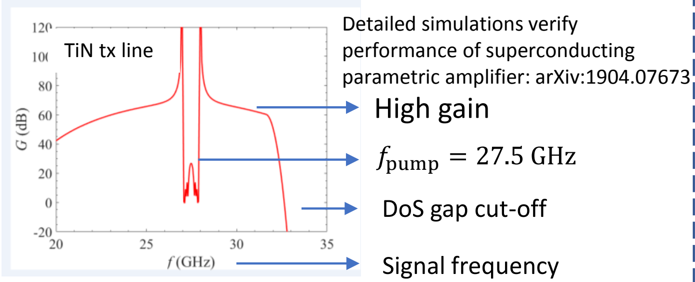


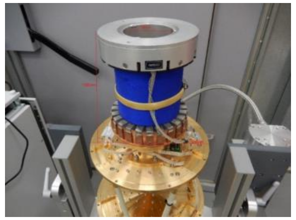


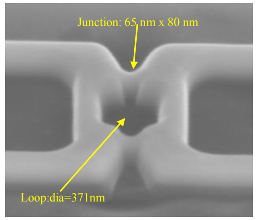
Challenge of millimetre-wave (25-30 GHz) ultra-low-noise amplifiers:

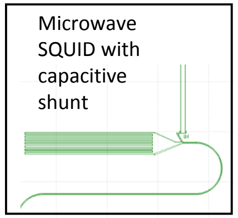
- Push superconducting microwave SQUID amplifiers up in frequency
- Push superconducting parametric amplifiers down in frequency
- High gain quantum-limited noise performance possible

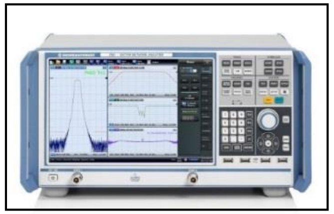
Draws heavily on major investments by funding agencies in establishing superconducting device processing and measurement labs



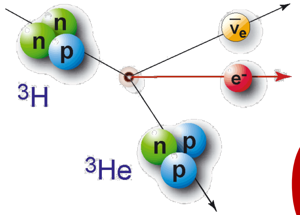




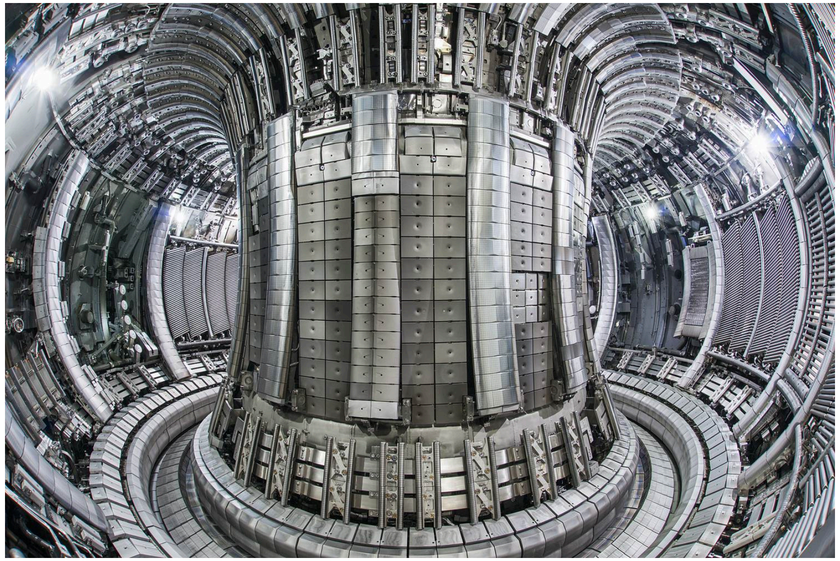




From **devices** to **quantum** noise limited microwave **detection systems**



QTNM



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Future Outlook

- The goal of this 3yr proposal is to build and operate CRESDA at UCL and to demonstrate technology with Deuterium but *which is Tritium ready*.
- Next step is to move **CRESDA** to a Tritium centre (strong engagement with **Culham**!) and operate it with Tritium.
- The above will have its own physics programme ($\langle m_\nu \rangle$ ~1 eV, *sterile neutrino*) and act as technology demonstration for *ultimate international project.*
- Ultimate international project that consolidates technological breakthroughs elsewhere (e.g. Project-8) to build and operate a detector achieving a phased sensitivity of 50 meV and 10 meV and probing sterile neutrino.
- Hosting the ultimate neutrino mass experiment in the UK at Culham would be a unique opportunity and major advantage.