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Determining Absolute Neutrino Mass using Quantum Technologies

Model Building in Particle Physics: Physics Beyond the SM

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Ref.: https://arxiv.org/abs/2412.06338#

Content

- Absolute neutrino mass measurements and implications for particle physics
- Motivation for Quantum Technologies for Neutrino Mass (QTNM) Project
- Current developments of the QTNM Project
- Summary

Neutrino mass

- Masses of the fundamental particles - Higgs mechanism
- Standard Model: Neutrinos are massless
- Detection of the neutrino oscillations - indirect proof that neutrinos have a mass

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$

Constraints from oscillations

Δm_{ij}^2 $\quad$ U_{PMNS}

Open questions

Normal or Inverted Mass Order ?

δ_{CP} ?

Absolute Neutrino mass: Cosmological measurement

Cosmological probes: effect of the relic neutrinos on the Cosmic Microwave Background and structure formation of the Universe

- Only sensitive to the sum of masses: $\sum m_\nu = m_1 + m_2 + m_3$
- Current limit $\sum m_\nu < 0.113 eV/c^2$ with 90% confidence
  - affected by the choice of astrophysical data
  - depends on the mass ordering
  - weaker confidence if the cosmological model is not ΛCDM

Absolute neutrino mass: Double β-decay

Neutrinoless double β-decay can only occur if ν is a massive Majorana particle.

- If decay occurs, its amplitude would be proportional to the neutrino mass
- Effective Majorana mass: $m_{2\beta} = \sum_{k=1}^{3} U_{ek}^2 m_k$
- Current limit: KamLAND-Zen Collaboration $|m_{2\beta}|$ < 28 - 122 meV/c^2

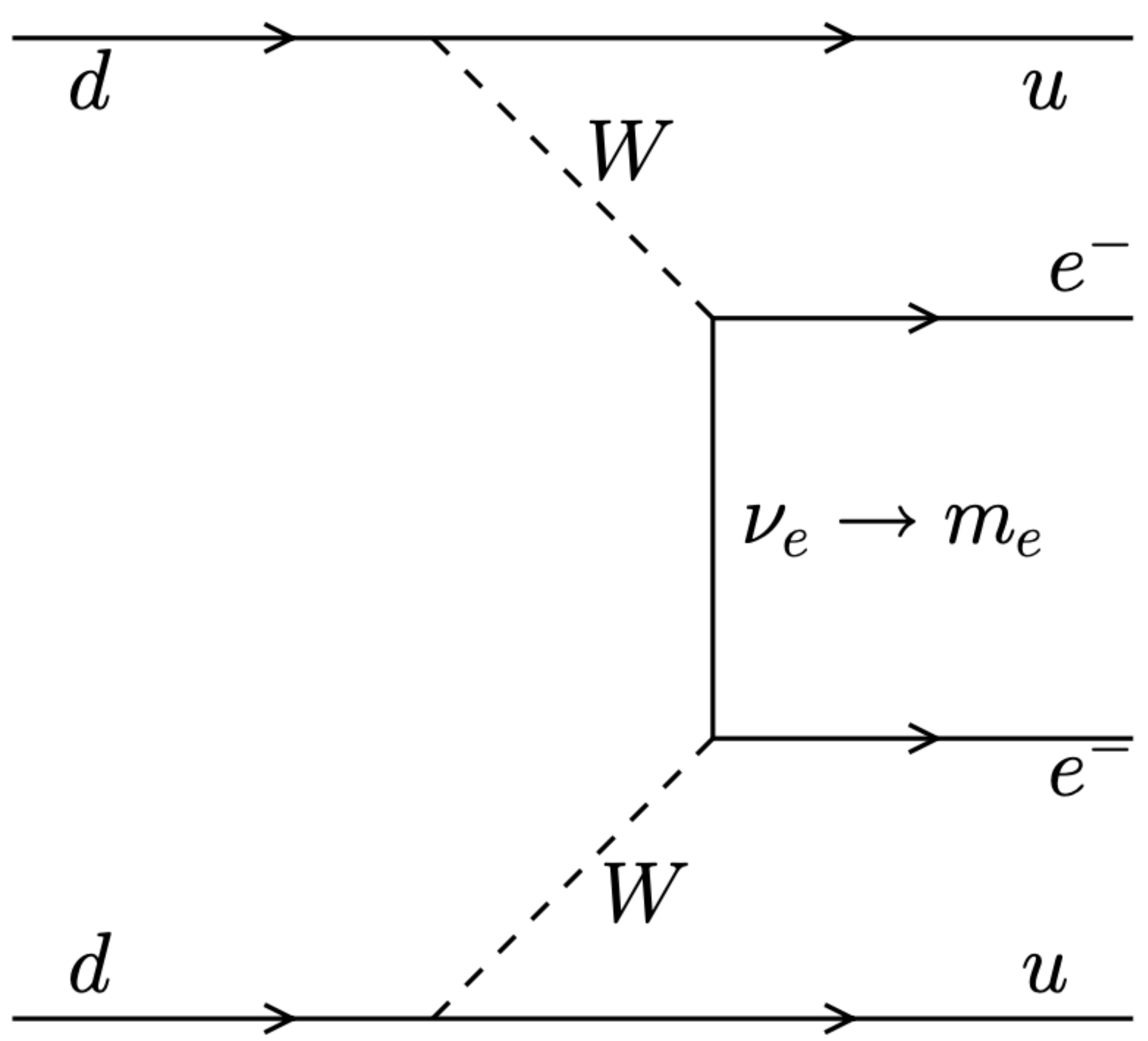


FIG. 14.10. Tree-level quark diagram of a $2\beta^-_{0\nu}$ process.

Source: C. Giunti Fundamentals of neutrino physics and astrophysics

Absolute neutrino mass: β-decay

Observing the **electron spectrum** in nuclear β-decay - the most sensitive method.

$$\mathcal{N}(A, Z) \to \mathcal{N}(A, Z+1) + e^- + \bar{\nu}_e$$

Q - surplus energy of the process: $Q_\beta = M_i - M_f - m_e$

Neutrino energy: $E_\nu = Q_\beta - T$, T - kinetic energy of the electron.

If the electron antineutrino has a mass, the maximal kinetic energy of the electron:

$$T_{max} = Q_\beta - m_{\nu_e}$$

The effect of the m_{ν_e} on the electron spectrum is maximal at its end-point

Source: C. Giunti Fundamentals of neutrino physics and astrophysics

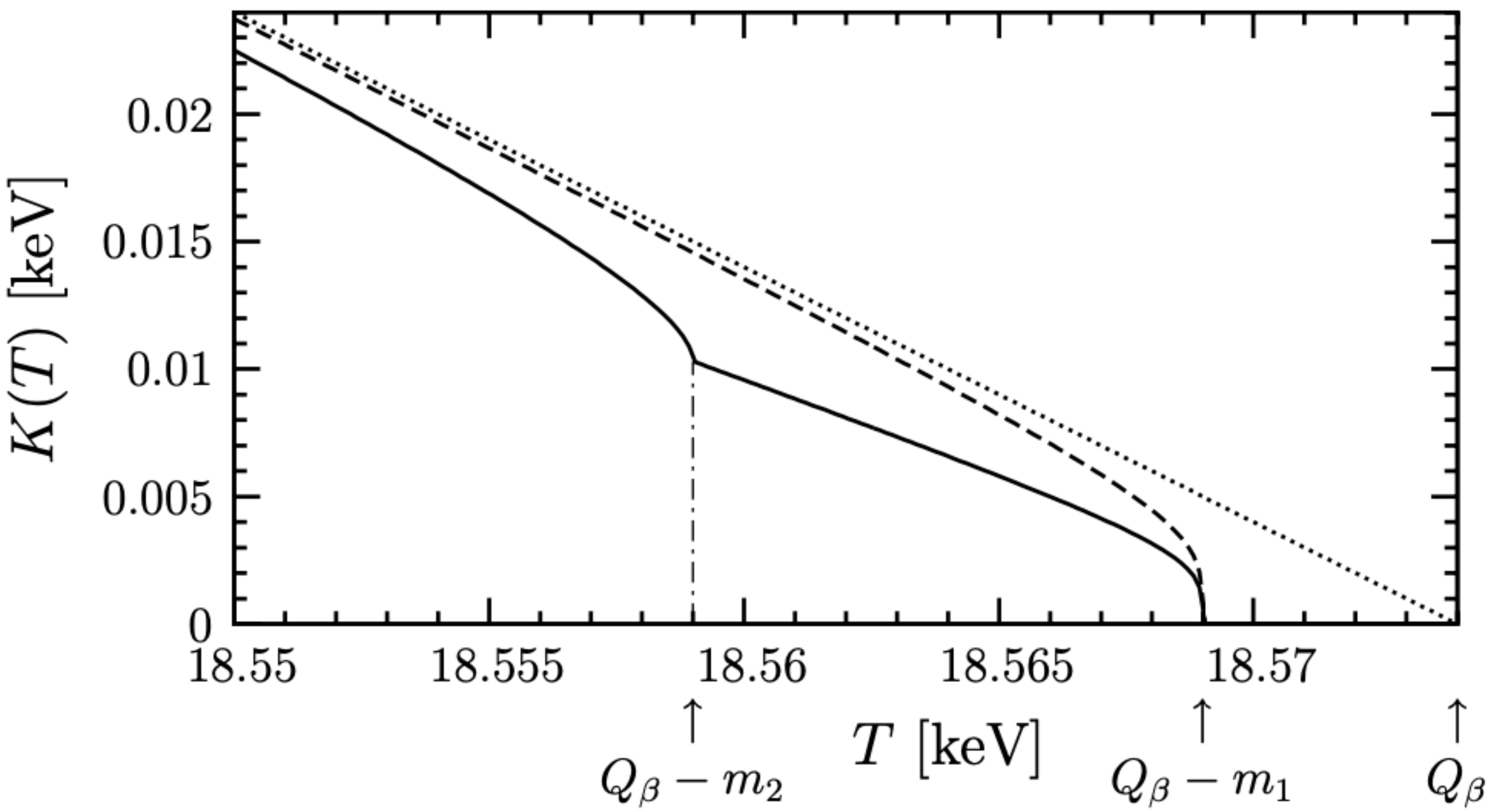
Absolute neutrino mass: β-decay

Tritium β-decay has the smallest Q-value (18.6 keV) → the most stringent limit on m_{ν_e}

Kurie function $K(T) = \left[(Q_\beta - T)\sqrt{(Q_\beta - T)^2 - m_{\nu_e}^2}\right]^{\frac{1}{2}}$

If m_{ν_e} = 0: $K(T) = Q_\beta - T$ - linear function of T

Tritium experiments aim to measure the endpoint of the electron energy spectrum



Source: C. Giunti Fundamentals of neutrino physics and astrophysics

Absolute neutrino mass: β-decay

KATRIN - KArlsruhe TRitium Neutrino experiment, operating since 2018

Technique: measurement of the electron energy spectrum from the T_2 molecules' decay using a high-resolution electrostatic spectrometer

The most sensitive experiment (April 2025): m_{ν_e} < 0.45 eV/c^2 with 90% confidence

. **Limitations:**

Resolution is limited by the size and complexity

Molecules - vibrational and rotational modes →
larger uncertainties

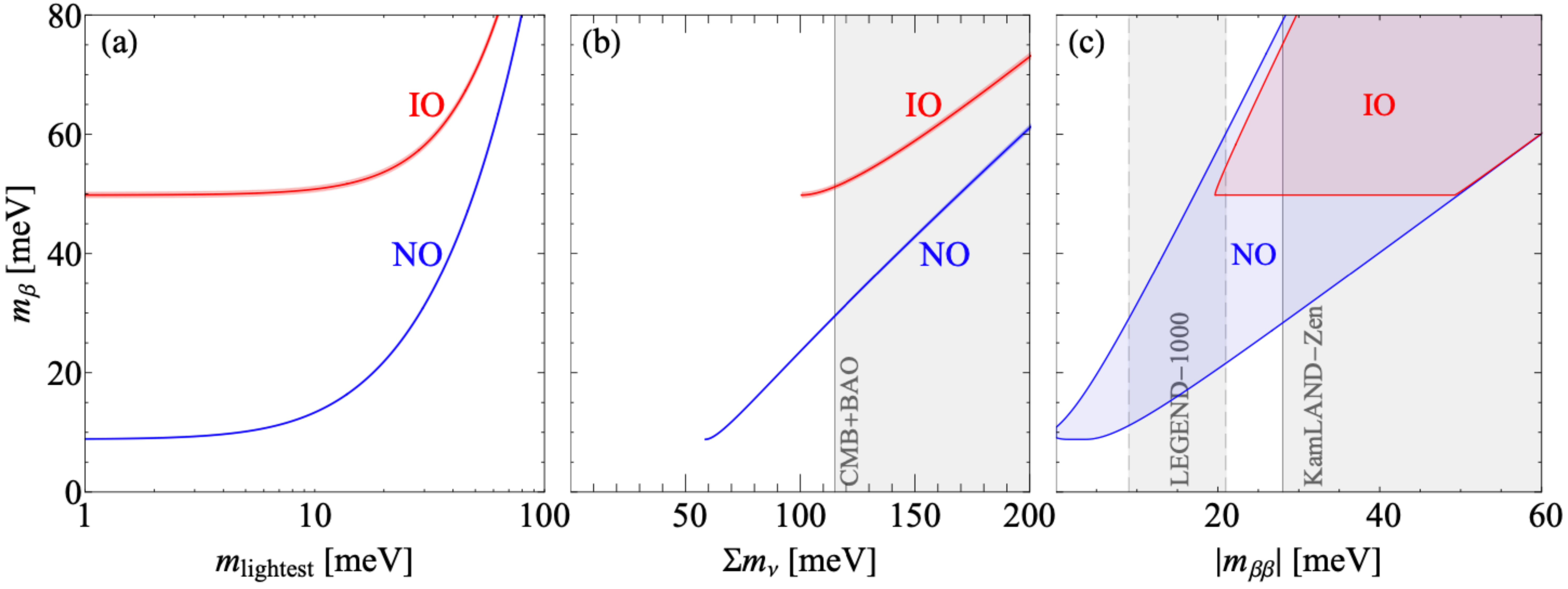
Source: https://fis-landschaft.de/universum/katrin/

Absolute neutrino mass: implications for particle physics

- Neutrino mass ordering → test neutrino mass and fermion flavour models
- Cosmological $\sum m_\nu$ and laboratory m_β → confirmation of ΛCDM model
- Lower limits for $|m_{\beta\beta}|$
- From oscillations: $m_\beta \gtrsim$ (8.82 ± 0.11) meV/c^2. If after reaching this sensitivity still nothing

↓

New approach towards neutrino masses



Motivation for the Quantum Technologies for Neutrino Masses

- Oscillation experiments provide no information about the absolute mass values
- **Current sensitivity**: 0.2 eV/c^2 (KATRIN experiment)
- **Promising approach:** detection of the cyclotron radiation
- Recent developments in quantum technologies can be beneficial for different areas of the experiment

Goal of the experiment

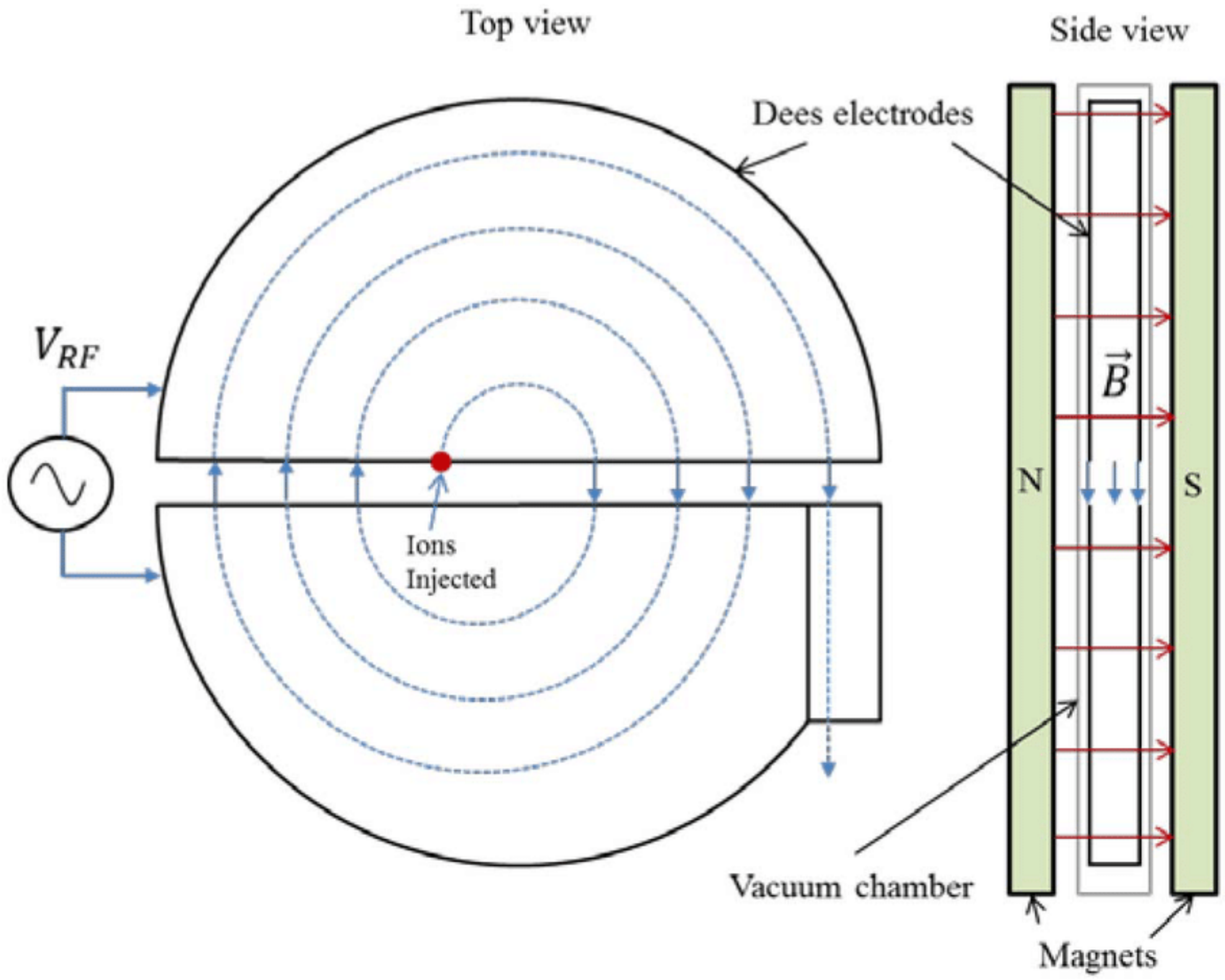
Development of the new experimental apparatus to measure the absolute neutrino mass with a sensitivity ~ 10 meV/c^2

Source: https://www.katrin.kit.edu/128.php

Cyclotrons

- Particle Accelerator (1930s)[1]
- Constant magnetic field, alternating voltage source[2]
- $\overrightarrow{F_L} = e[\overrightarrow{E} + (\vec{v} \times \overrightarrow{B})]$
- Works well for non-relativistic regime
- Constant cyclotron frequency[3]:

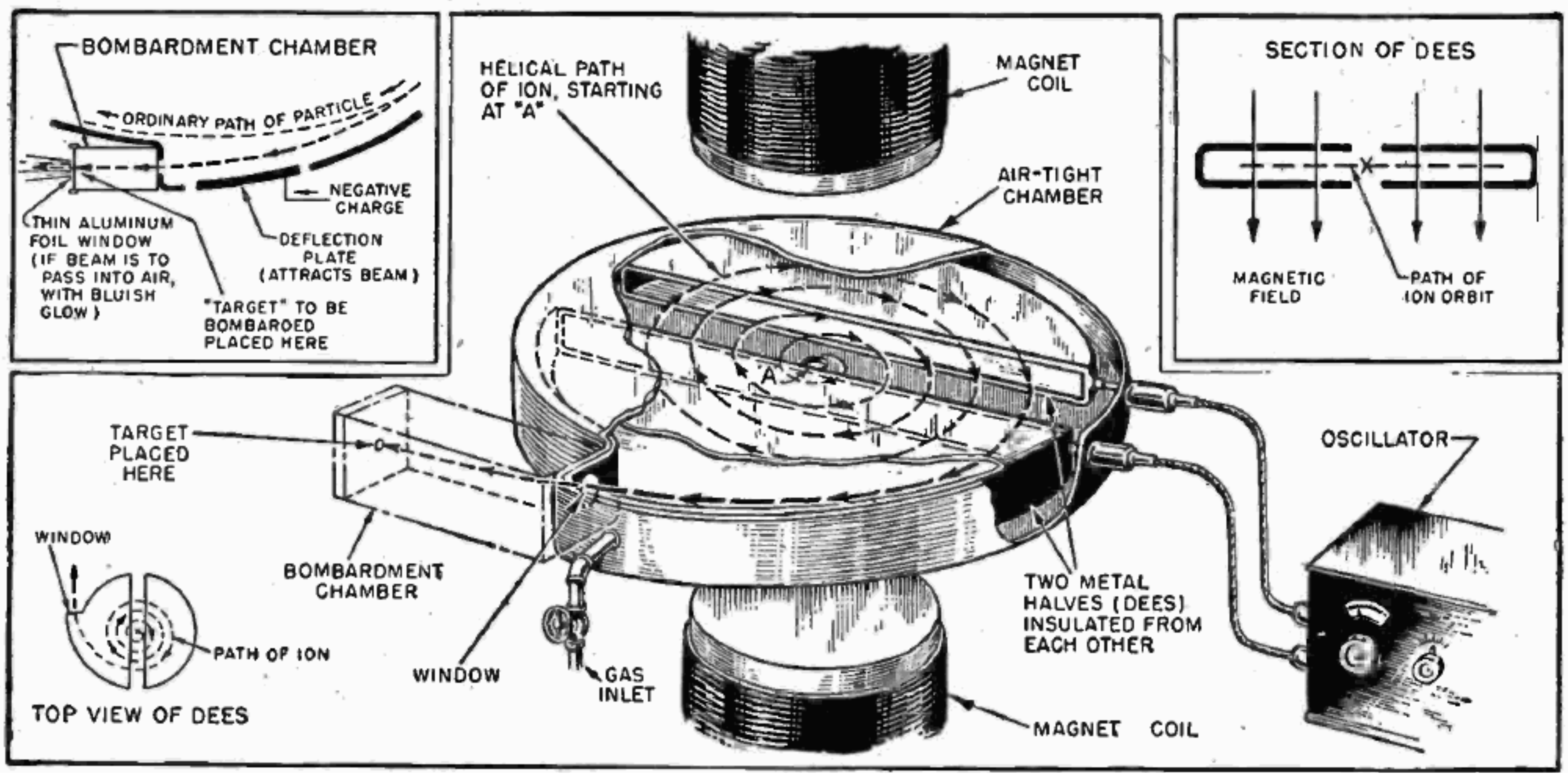
$$\nu_{cyc} = \frac{eB}{2\pi m}$$



Source: https://www.researchgate.net/figure/Schematic-view-of-the-classical-cyclotron-principle_fig21_283861027

[1]: https://www.britannica.com/technology/cyclotron
[2]: https://www.simply.science/images/content/physics/Electromagnetism/machines_devices/Concept_map/Cyclotron.html
[3]: https://en.wikipedia.org/wiki/Cyclotron

Cyclotrons



Source: https://en.wikipedia.org/wiki/Cyclotron

CRES Experimental Setup[4]

Cyclotron **R**adiation **E**mission **S**pectroscopy

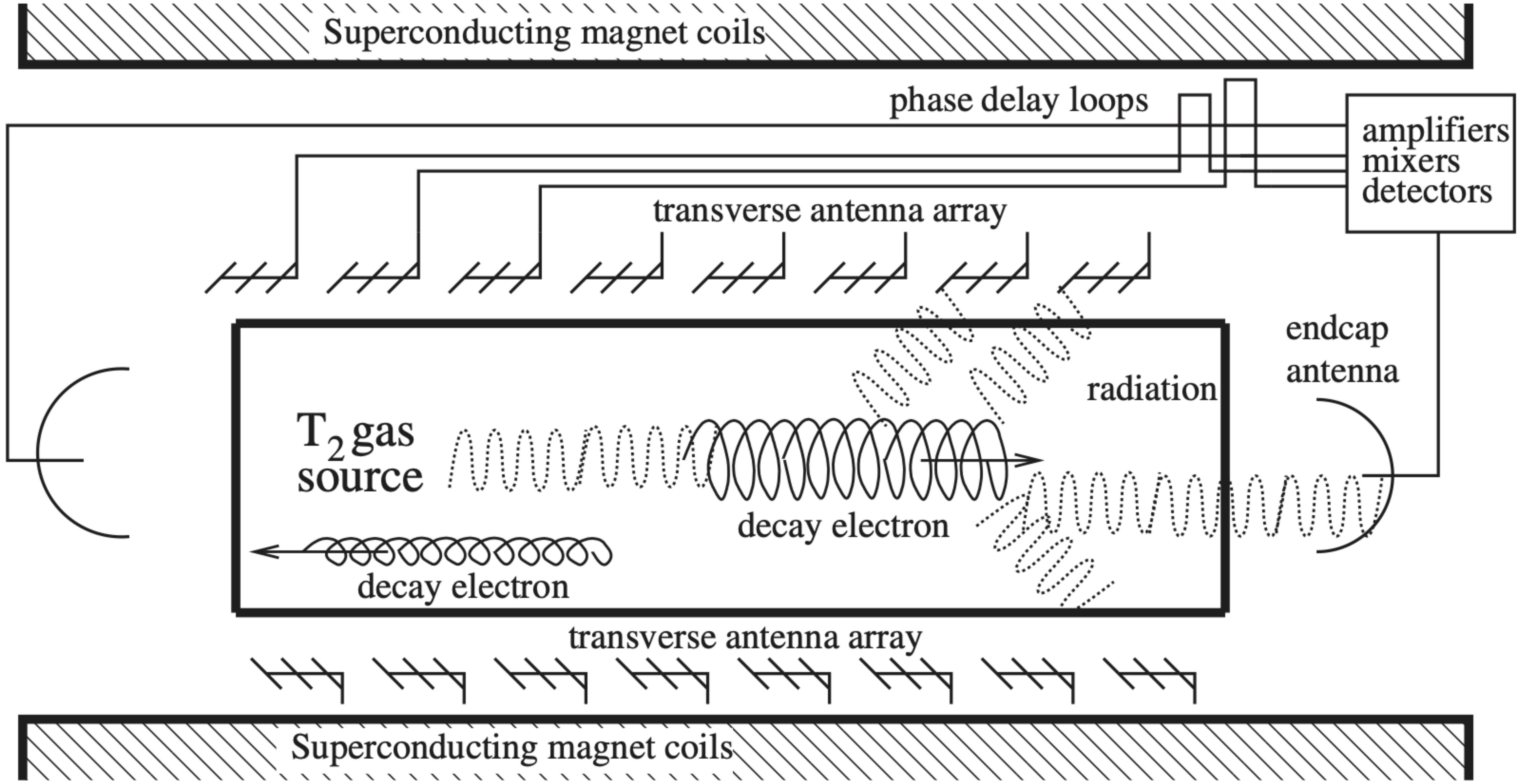
- Detect cyclotron radiation from mildly relativistic electrons (diluted T_2 decay)
- Cyclotron radiation frequency depends on energy:

$$\nu_{CR} = \frac{eB}{2\pi(m_e + E_e/c^2)} \sim \text{GHz}$$

- Maximum electron kinetic energy:

$$E_0 = 18.6\,\text{keV}$$

- Detect signal using antennas



Source: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.80.051301

[4]: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.80.051301

CRES Technique

Cyclotron **R**adiation **E**mission **S**pectroscopy

- ➡ Implementation over a wide range of energies (including the endpoint $18.6\,\mathrm{keV}$)
- ➡ Enclose the measurement region in the spectrometer using a waveguide
- ➡ Choose the antenna configuration (end-caps or transverse arrays)
- ➡ Optimise all components and maximise radiation collection efficiency
- ➡ Usage of microwave frequency metrology
- ➡ Precise determination of cyclotron radiation frequency

Goals and Challenges

Cyclotron **R**adiation **E**mission **S**pectroscopy

- High phase-space density atomic T sources
- Long observational time t_{obs}
- Precise determination of cyclotron radiation frequency and kinetic energies of electrons
- Precise characterisation of the magnetic field:
  - $\sigma_B \simeq \pm 200\,\mathrm{nT}$ & $\sigma_{\nu_{CR}} \simeq \pm 5\,\mathrm{kHz}$ for energy resolution of $\pm 100\,\mathrm{meV}$
  - Limitation of sensors operation at $4\,K$ temperature
- Minimise uncontrolled electric fields from instrumentation imperfections

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The QTNM Project

- Build on the work done by **Project 8** collaboration & recent quantum technologies
- Measure neutrino mass down to $\sim 10\,\mathrm{meV}$
- Sensitivity on $m_\beta^{90\%} = \sqrt{1.28\sigma_{m_\beta^2}}$:

$$\boxed{m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2\, m_i^2}$$

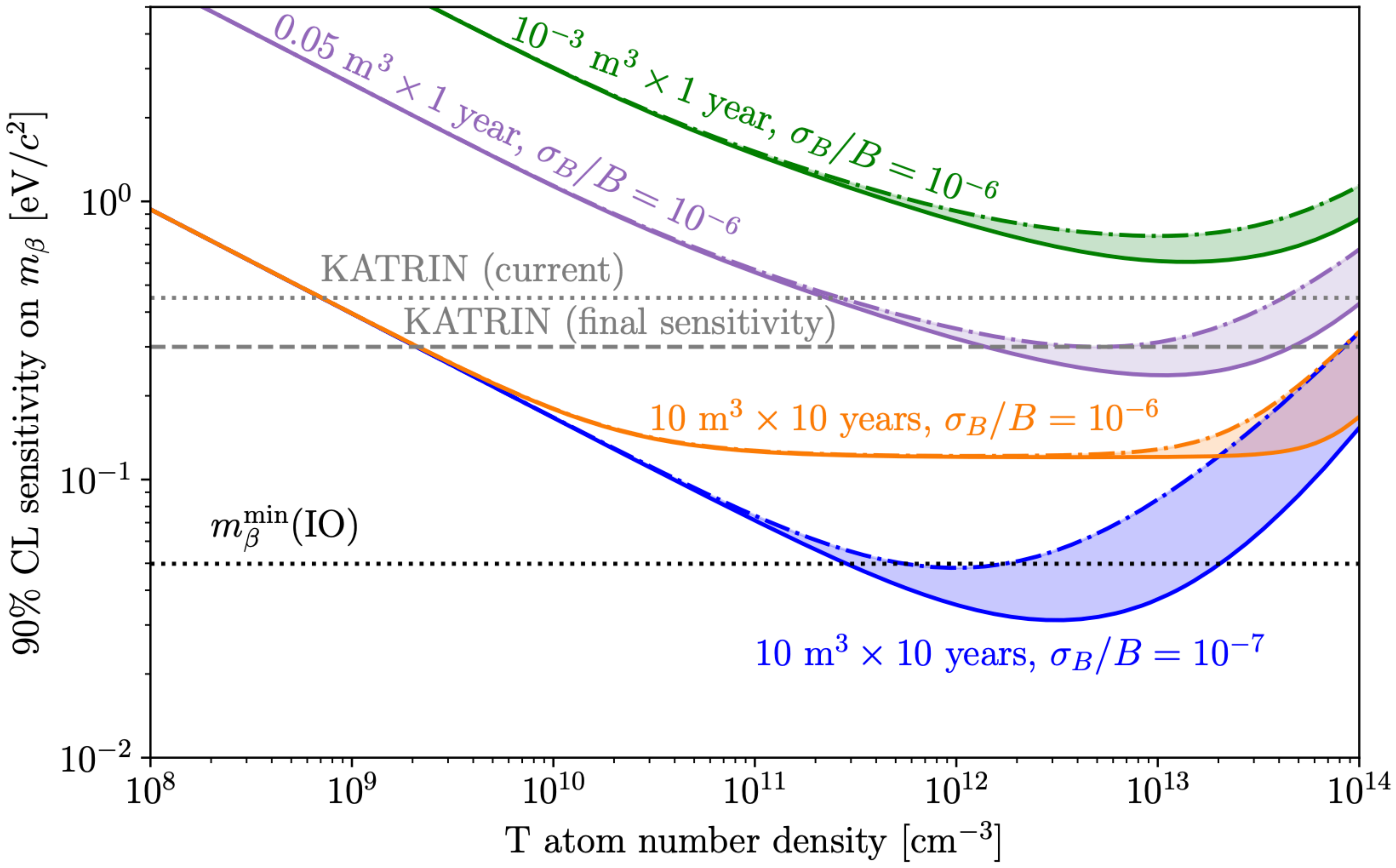
  - Precision of magnetic field characterisation
  - Precision of the cyclotron frequency determination:
    - t_{obs} [5,6] $\rightarrow$ upper limit on the frequency precision
    - t_{obs}^{-1} $\rightarrow$ lower limit on the frequency precision

$\Big\}$ Resolution window

[5]: H. Cramér. Mathematical Methods of Statistics. Princeton, NJ: Princeton Univ. Press, 1946.
[6]: C. Rao. "Information and the Accuracy Attainable in the Estimation of Statistical Parameters". In: Breakthroughs in Statistics: Foundations and Basic Theory. Ed. by Samuel Kotz and Norman L. Johnson. New York, NY: Springer New York, 1992, pp. 235–247.

Sensitivity of a CRES experiment

- Bands represent the range of sensitivities expected by the frequency precision limits
- Instrumented volume of $10\,m^3$ can surpass the final limit projected for KATRIN
- NO case toward $\sim 10\,\mathrm{meV}$ lower bound:
  - Increase instrumented volume
  - Increase B accuracy

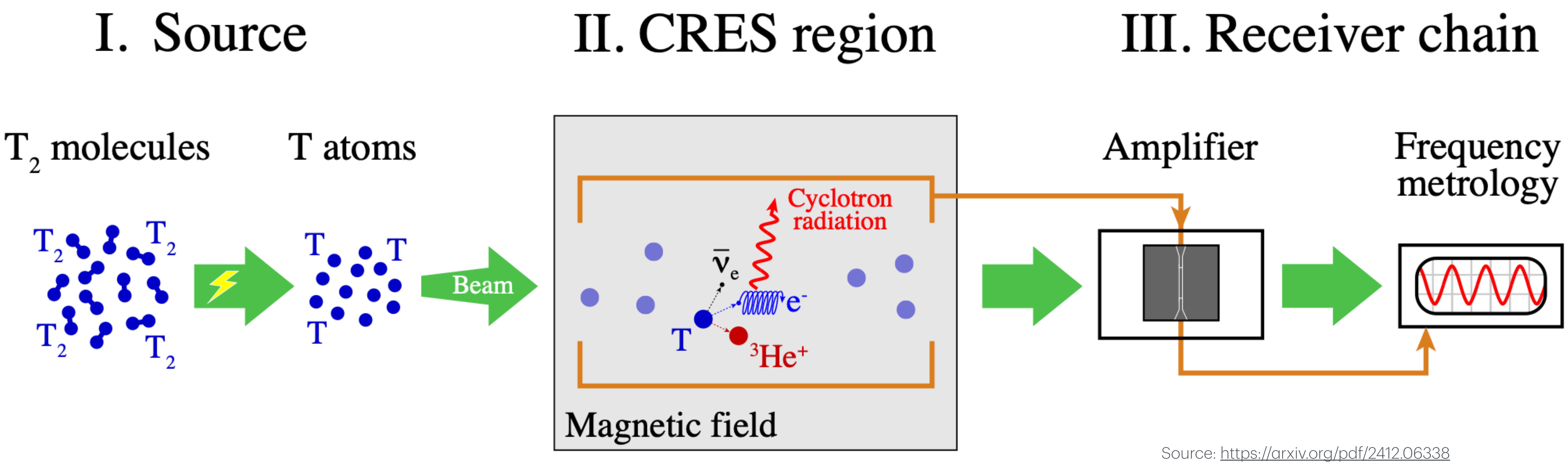


Source: https://arxiv.org/pdf/2412.06338

Goals of QTNM

- Development of high phase-space density sources of T atoms
- Construction of CRES spectrometer with total instrumented volume $\sim 10\,m^3$
- Exploit atomic quantum sensors for high-precision & minimally-invasive B mapping
- Development of a multichannel antenna to collect cyclotron radiation
    - High efficiency & low background noise
- Development of scalable multichannel quantum-noise-limited cryogenic microwave receivers
    - Precise microwave frequency metrology

Workflow of QTNM apparatus



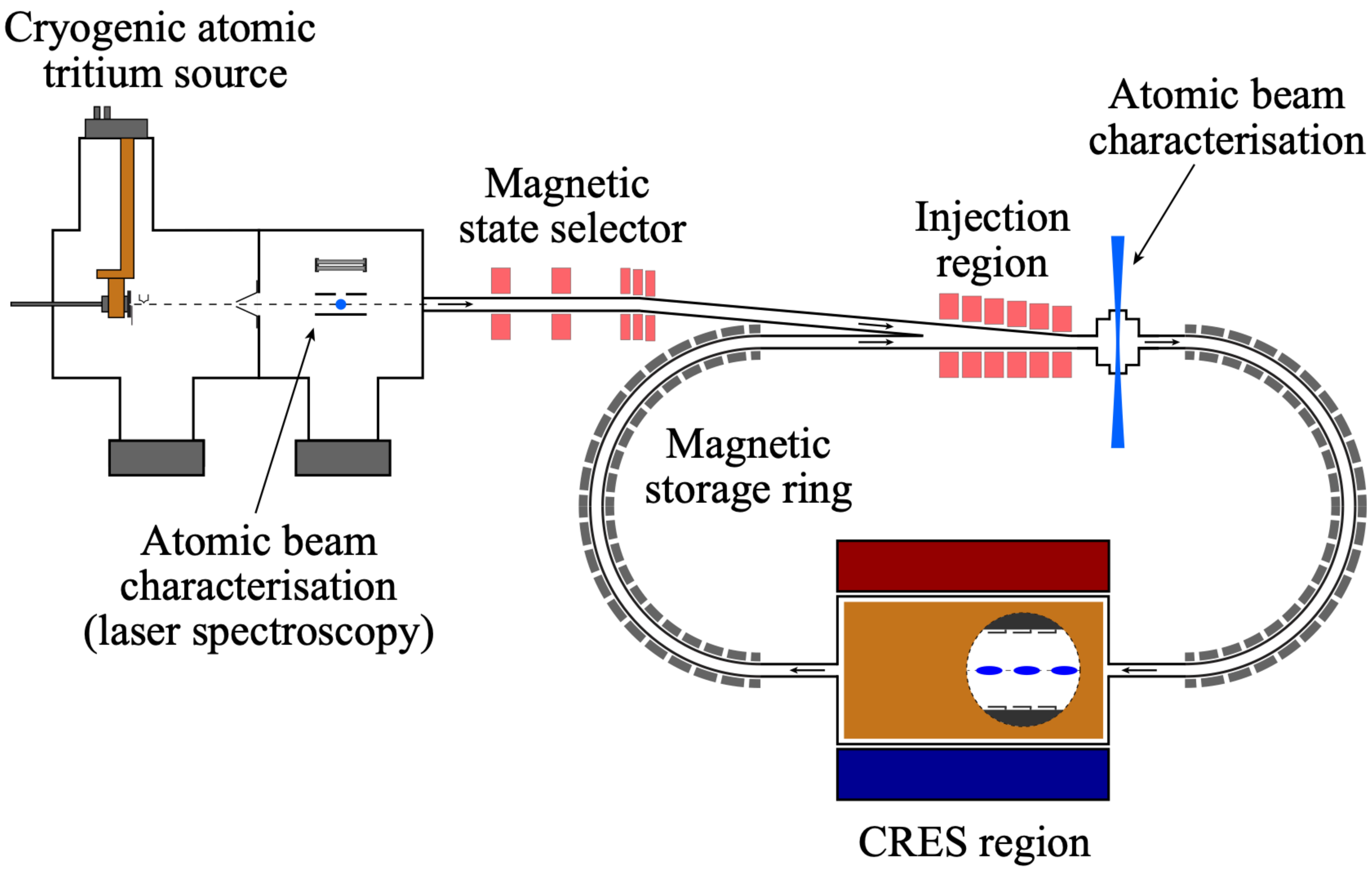
Source: https://arxiv.org/pdf/2412.06338

- I : High-density source of T atoms produced by dissociation of T_2 molecules
- II : CRES region ($4\ K$) where cyclotron radiation from electrons in a uniform magnetic field is collected
  - Atoms in high Rydberg states used as quantum sensors
- III : Receiver chain where the cyclotron radiation will be amplified and measured
  - Purpose-developed quantum-noise-limited amplifiers

Current developments

Prototype QTNM storage ring

- Increase the separation between the curved sections $\longrightarrow$ install more CRES modules
- Total instrumented volume $\sim 10\,m^3$ achievable with 640 modules



Source: https://arxiv.org/pdf/2412.06338

Atomic magnetometry and electrometry

- High precision of the neutrino mass measurement -

  thorough understanding of the magnetic and electric fields in the CRES region.

- Precision:
  - Magnetic field ~1 μT
  - Electric field ~ 100 μV/cm

How to achieve such precision and keep the measurement minimally invasive?

↓

Tritium atoms as quantum sensors

Atomic magnetometry and electrometry

- **Circular Rydberg States** - highly-excited electronic states. Electron has the largest possible m_l and l quantum numbers for any **n**.

- **Advantages**:

  + Energy level shifts due to magnetic and electric fields (Zeeman and Stark effects) can be precisely **analytically calculated**.

  + The same energy level shifts can be **accurately measured** by Ramsey spectroscopy.

  + Very sensitive to the magnetic and electric fields.

    Pair of states that differ in **n ± 1** - precise sensors.

    Tiny field variation - detectable changes in energy.

Atomic magnetometry and electrometry

Ramsey Spectroscopy Technique

1. Preparation of the state superposition

   - Short microwave pulse with frequency matching the ΔE of the states ⟶ quantum superposition

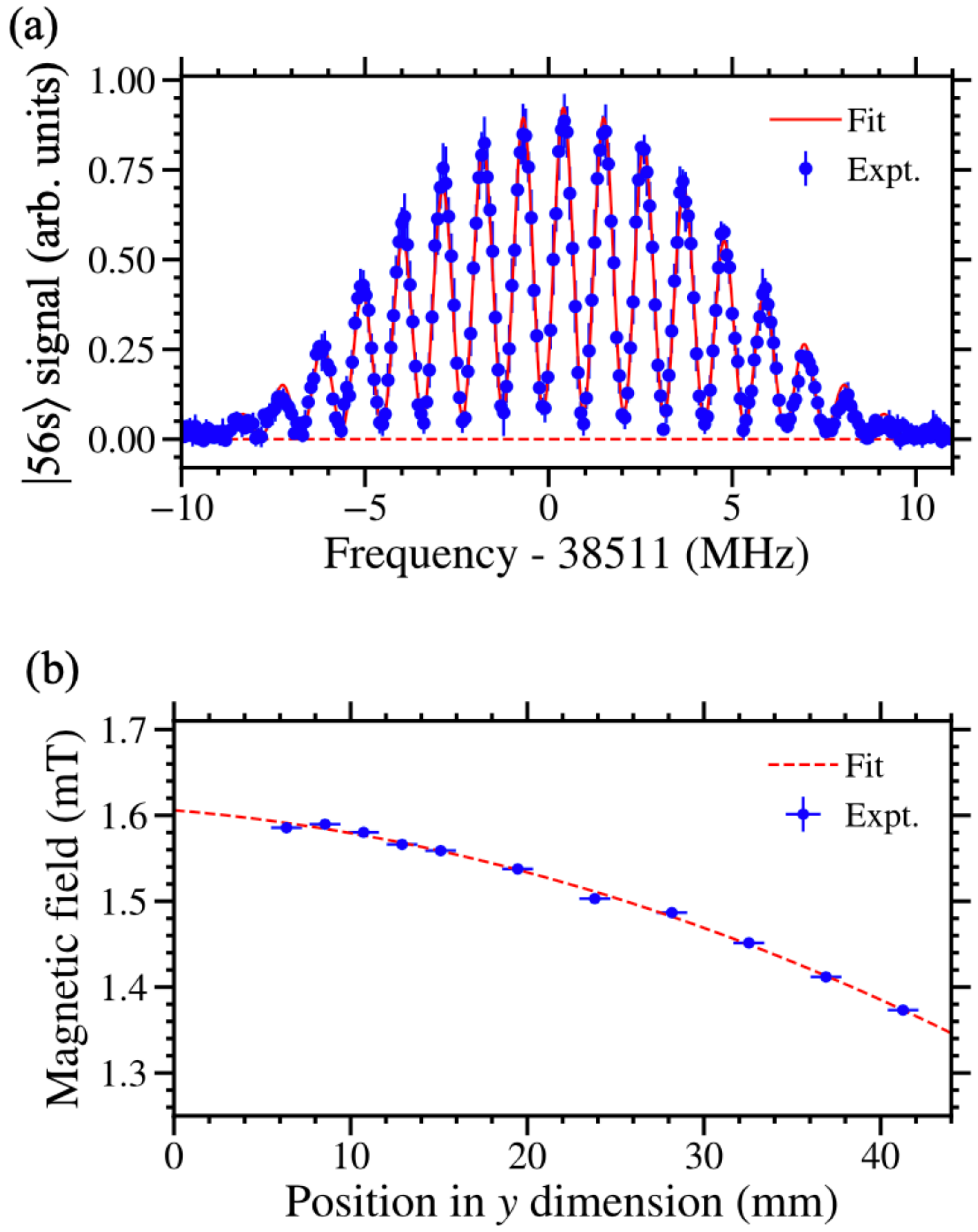
2. Superposition state freely evolves over time

   - The relative phase difference encodes the effects of the fields.

3. Projection of the resulting superposition on the two basis Rydberg states

   - Second microwave pulse ⟶ projection of the superposition ⟶ interference fringes

Field's strengths can be deduced from the interference



QTNM electron spectrometer

- Requirements:

  A. Detect electrons in the energy range of interest

  B. Measure the frequency of the cyclotron radiation

  C. Provide information on the trajectories of the electrons

- Experimental challenges:

  ? Cyclotron radiation receivers

  ? Electrons confinement

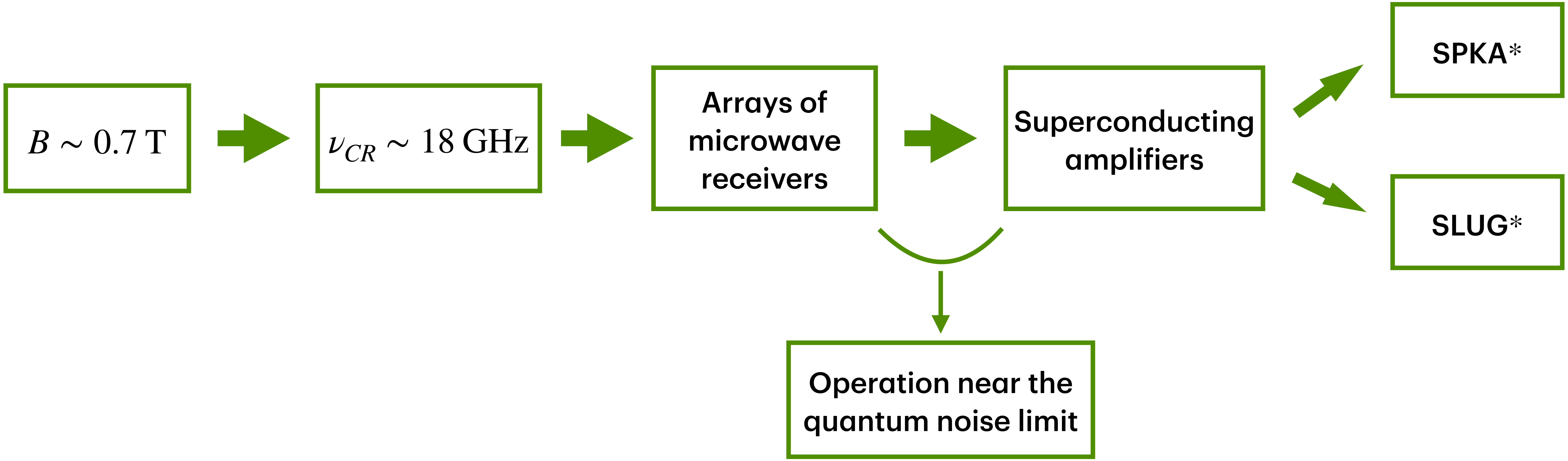
  ? Event-based trigger system

  ! High Signal-to-Noise ratio

  ↓

  Superconducting amplifiers

Superconducting Microwave Amplifiers

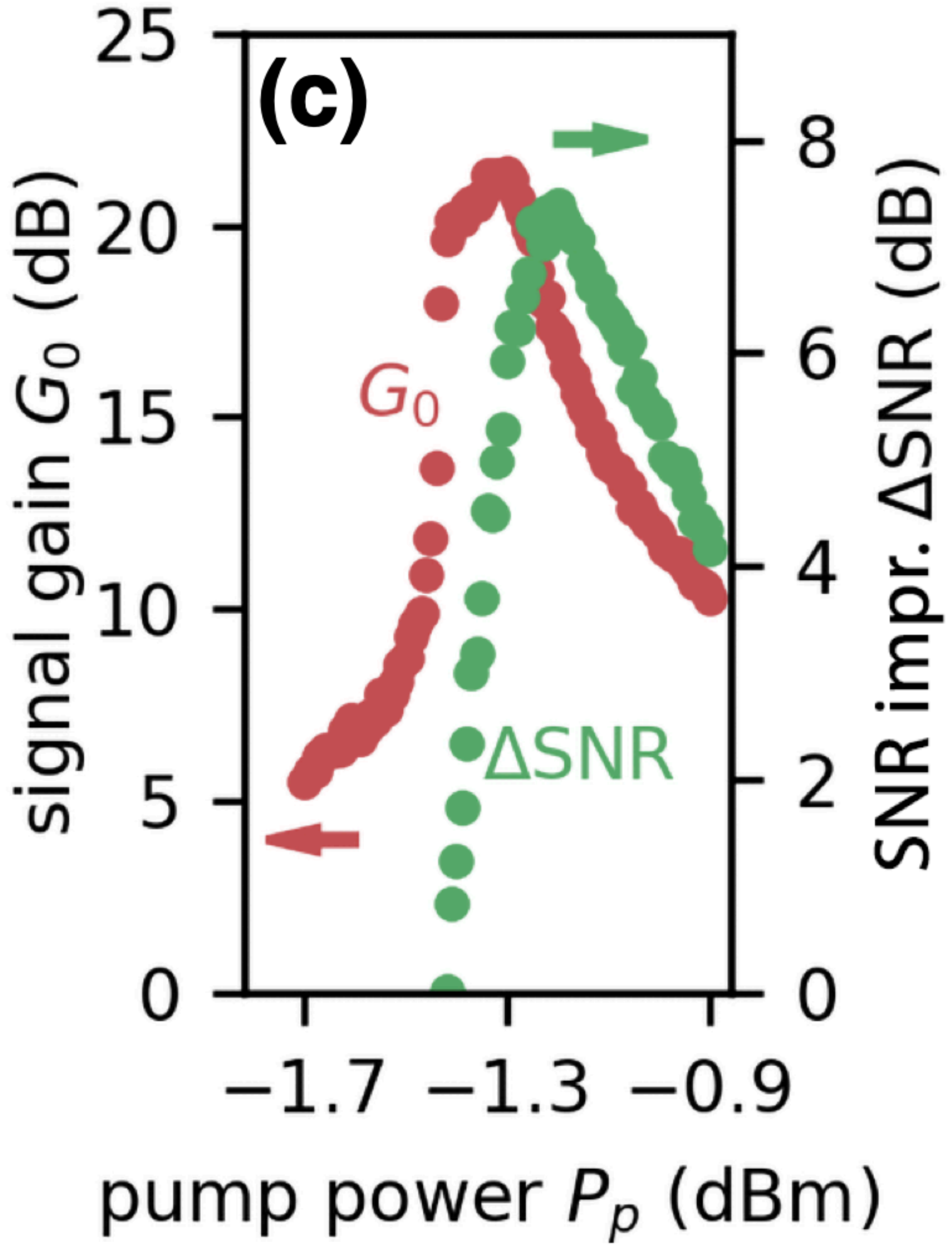


***S**uperconducting **P**arametric **K**inetic-Inductance **A**mplifiers
***S**uperconducting **L**ow-Inductance **U**ndulatory **G**alvanometer (SLUG)

Superconducting Microwave Amplifiers

Superconducting Parametric Kinetic-Inductance Amplifiers[7] (SPKA)

- High gain $\sim (10 - 30)\,\mathrm{dB}$
- Minimal added noise
- Maximal Signal-to-noise ratio (SNR)
- Operation at temperatures $\sim 4\,K$
- Easy to manufacture, simple and robust operation
- $\Delta\mathrm{SNR} = \mathrm{SNR}_{\mathrm{ON}} - \mathrm{SNR}_{\mathrm{OFF}}$



Source: https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.21.014052

[7]: https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.21.014052

Summary

- Neutrino oscillations remain the strongest support for physics BSM
- Neutrino absolute mass is crucial to understanding the origin of matter and evolution of the early Universe
- Promising, model-independent approach through precise measurement of the β-decay spectrum of atomic tritium
- **QTNM** project aims to tackle the absolute neutrino mass using quantum technologies and **AMO*** experimental methods
- **QTNM** proposal surpasses the capabilities of the **KATRIN** experiment
- High phase-space density atomic tritium source, electron spectrometer to measure electron energies near the $18.6\,\mathrm{keV}$ endpoint with precision below $0.1\ \mathrm{eV}$
- Collaboration with international projects like **Project 8**, **KATRIN** and **PTOLEMY**
- The scientific milestone includes sensitivities $\sim 0.05\ \mathrm{eV}$ for IO, and $0.01\ \mathrm{eV}$ for NO neutrino masses
- Potential to explore BSM physics and test advanced quantum technologies with applications beyond fundamental physics

*Atomic, Molecular and Optical Physics