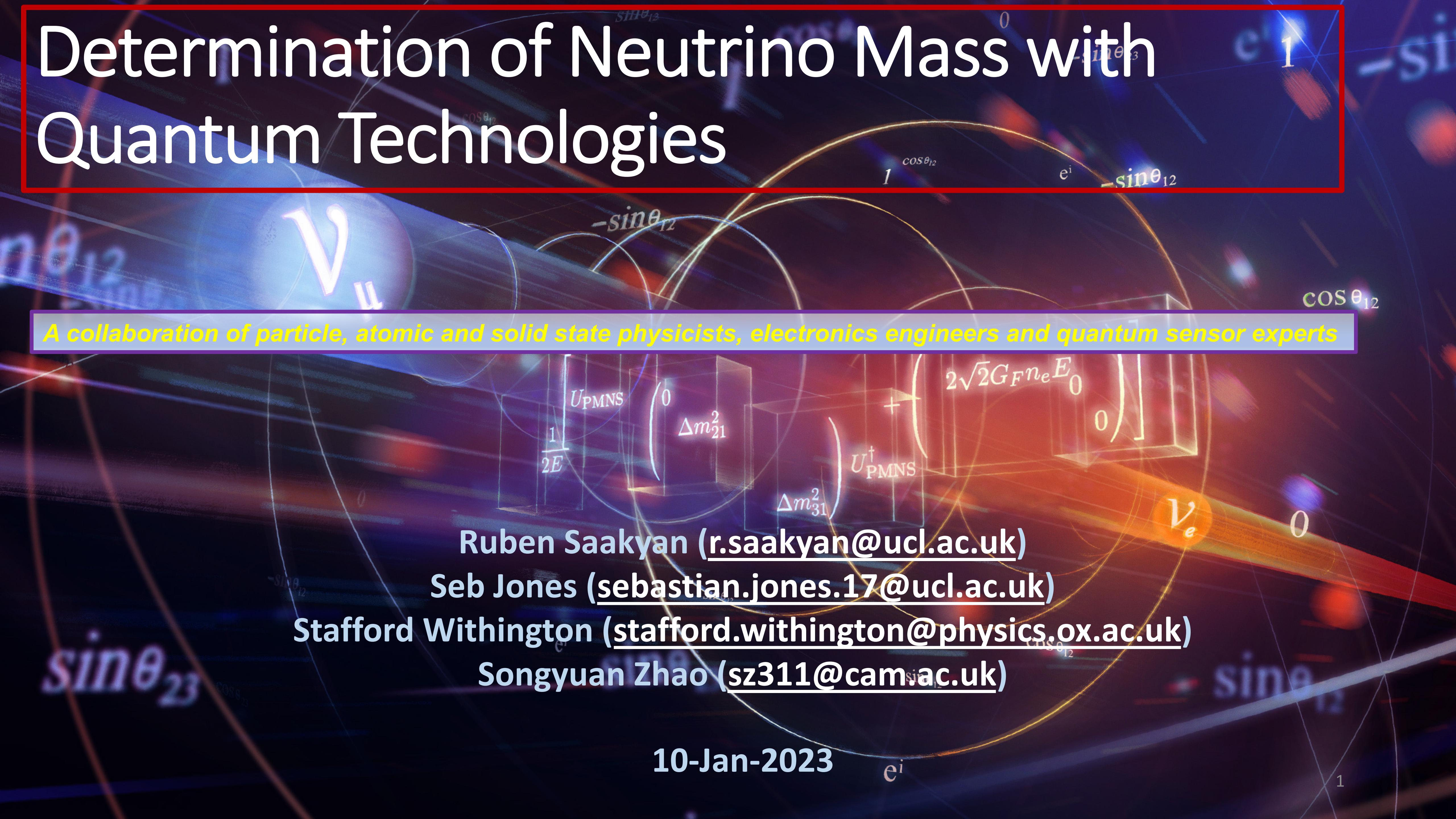

Determination of Neutrino Mass with Quantum Technologies

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

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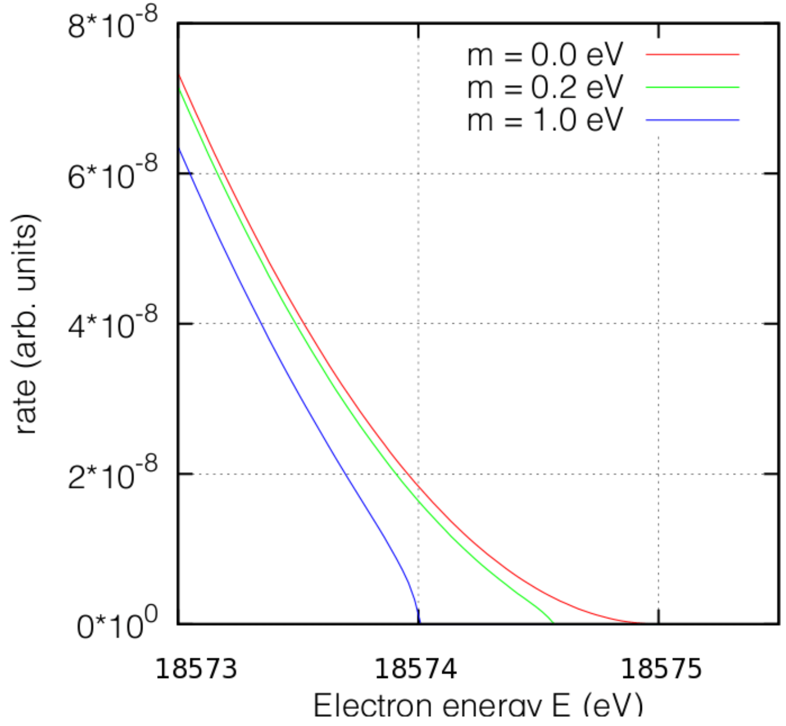
10-Jan-2023

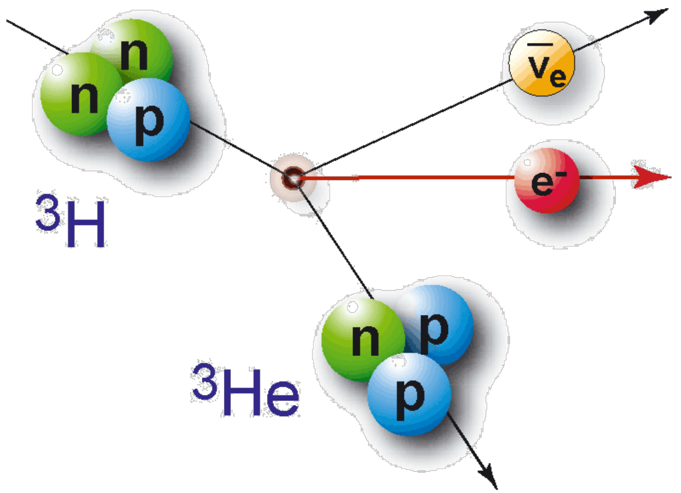
Plan

- QTNM Overview (this lecture): Ruben Saakyan and Seb Jones
  - Neutrino Physics and QTNM
  - Cyclotron Radiation Emission Spectroscopy
- Quantum Electronics (Wed 11-Jan 9:30): Stafford Withington and Songyuan Zhao
  - Quantum Electronics
  - Parametric Amplifiers
- QTNM Tutorial (Wed 11-Jan 11:30): Ruben, Seb, Stafford, Songyan
  - Q&A: Everything you wanted to know… but were afraid to ask
  - Example questions in lectures

Outline of QTNM Overview

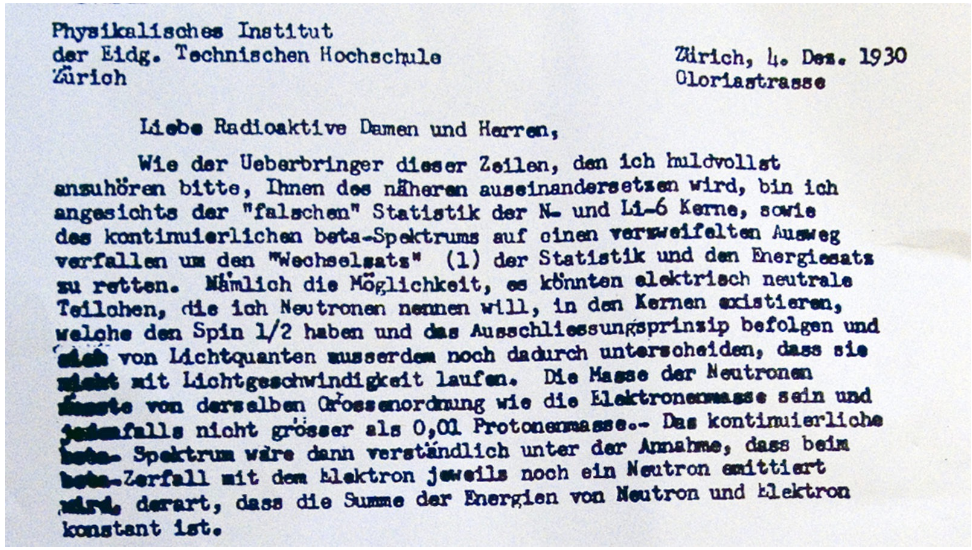
- The question of neutrino mass
- ^{3}H β-decay. State of the art
- ”Never measure anything but frequency…”
- QTNM Project
- Outlook





The Neutrino History

- Existence first postulated by W. Pauli in 1930 to explain the continuous shape of β-spectrum and “save” energy conservation
- Direct detection from a nuclear reactor source by Cowan & Reines in 1956
- Three flavours discovered. “Massless” according to initial Standard Model formulation

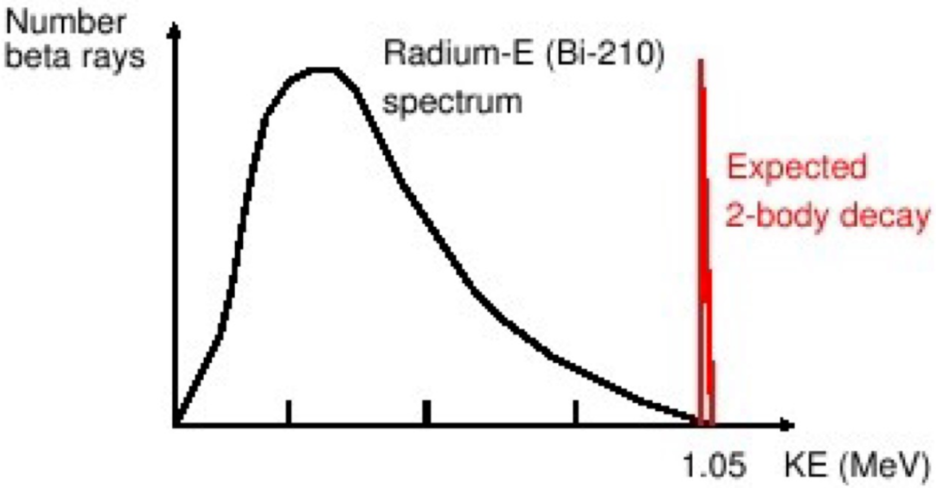


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

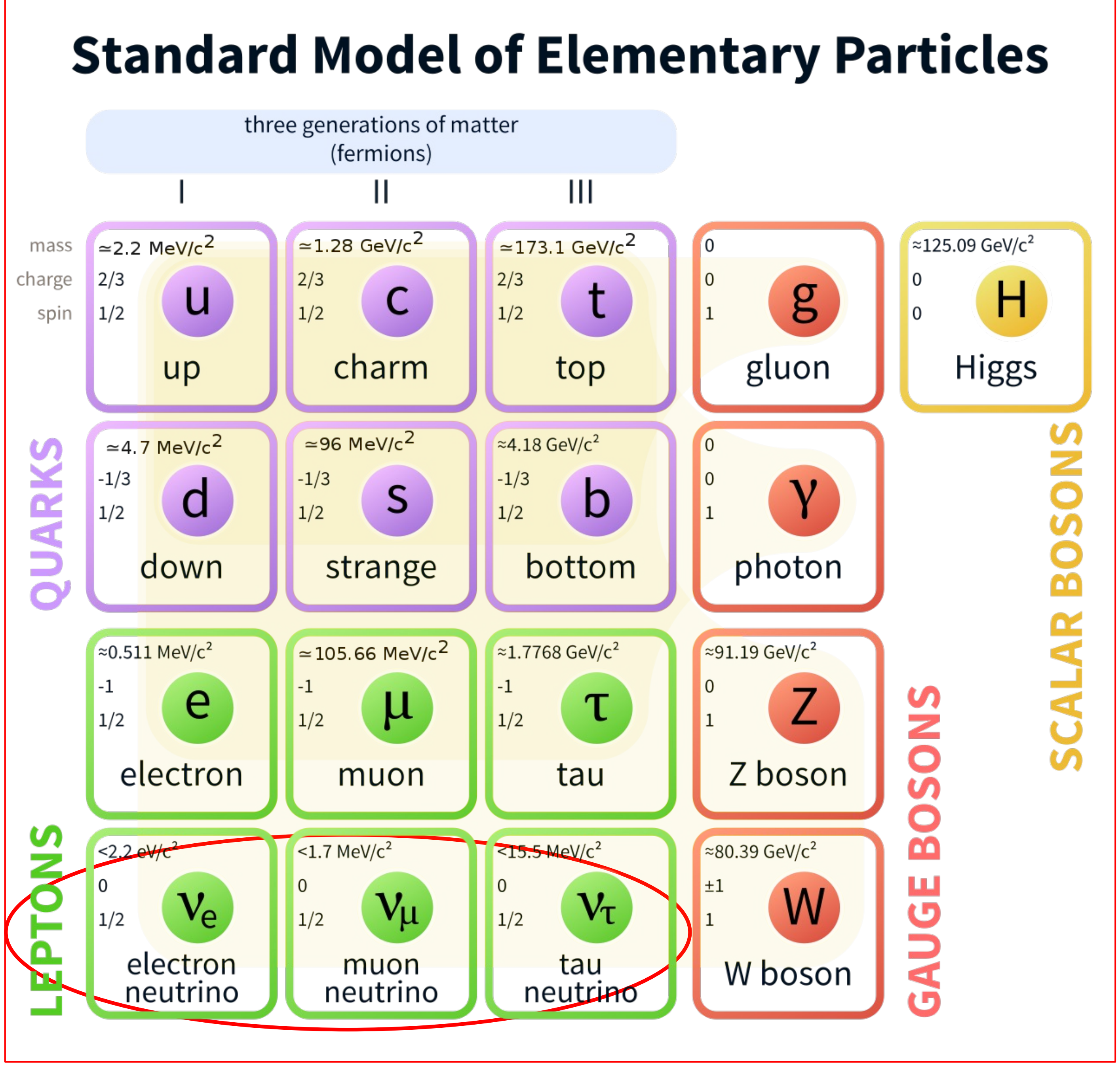
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



“At the present stage of atomic theory we have no arguments for upholding the concept of energy balance in the case of β-ray disintegrations.”

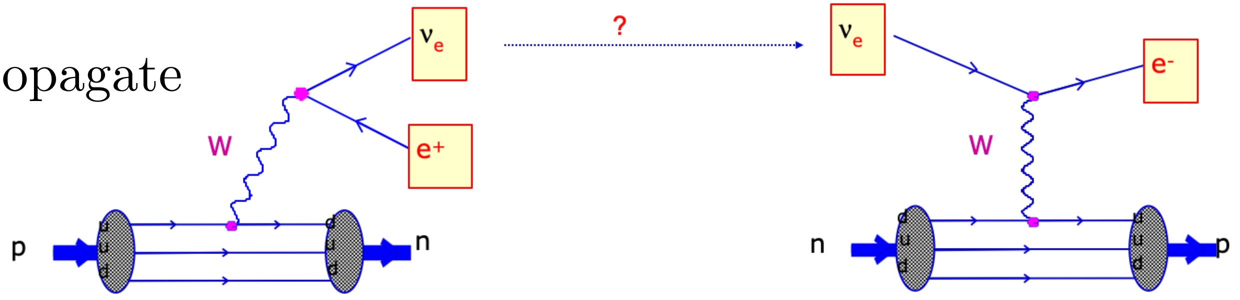
Most abundant particle of matter in the Universe (330 cm^{-3}) that we still do not know much about!

Mass assumed to be zero in SM (for good reasons which was now experimentally shown not to be true (neutrino oscillations)



Neutrino Oscillations

- Neutrinos interact as flavour eigenstates but propagate as mass eigenstates



- Mixing between neutrino mass and flavour eigenstates is governed by a unitary matrix

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

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

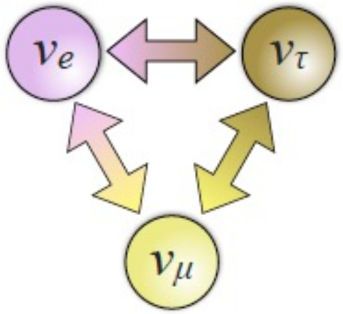
- The end observable effect is neutrino oscillations between flavours

simplified two-neutrino case

$$\boxed{P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)}$$

with

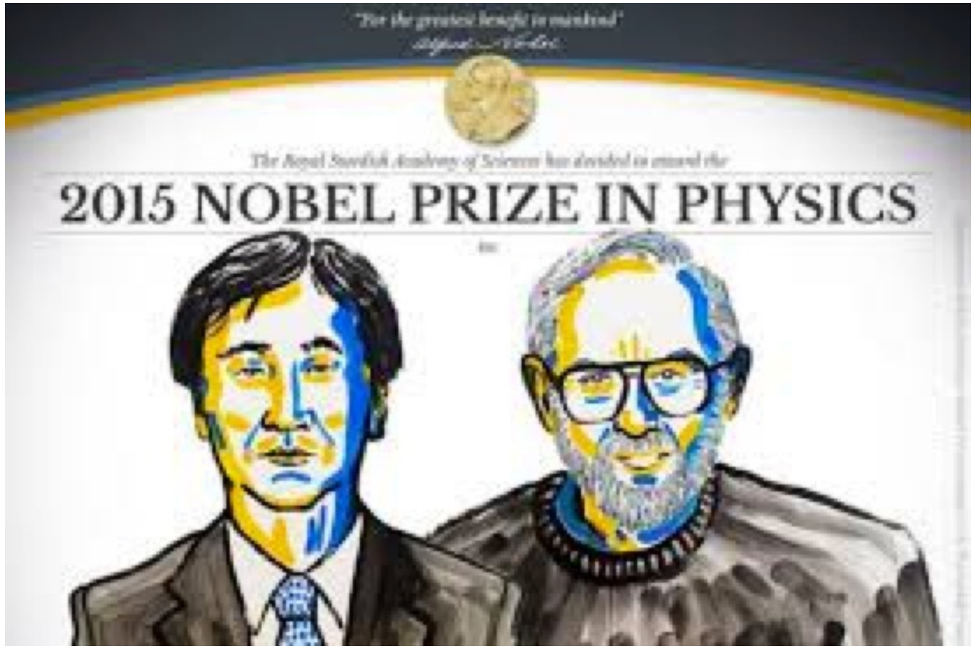
$$\boxed{\Delta m^2_{21} = m^2_2 - m^2_1}$$



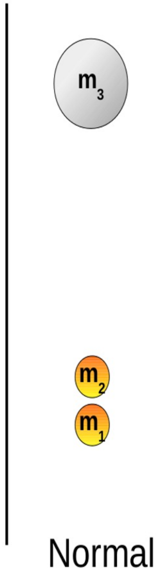
Neutrino Oscillations → **Non-zero neutrino mass**

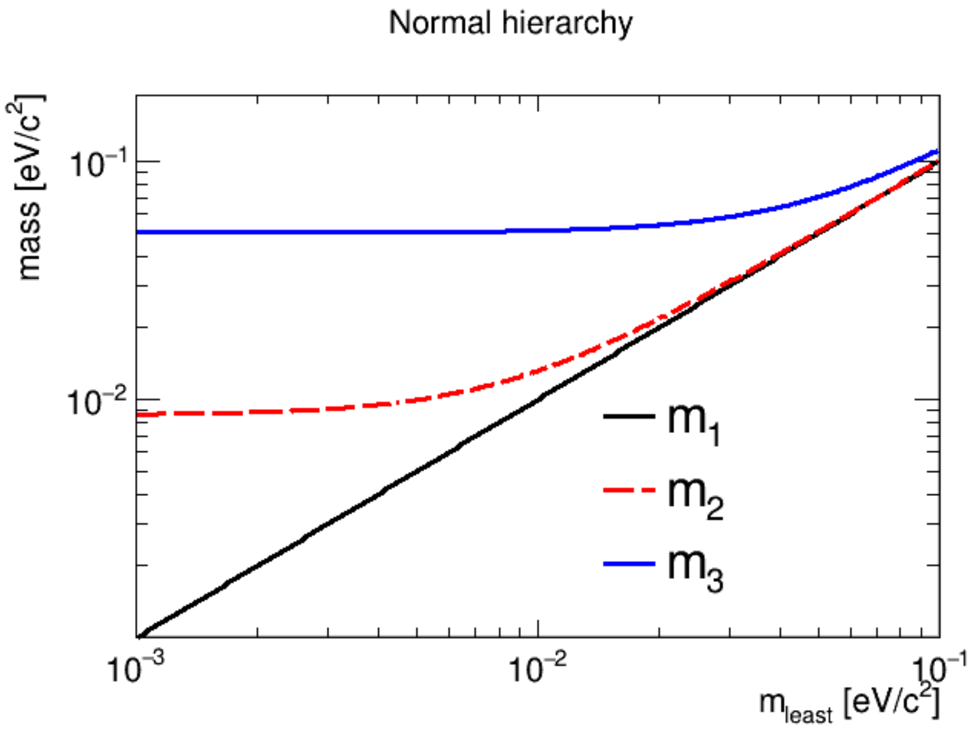
Neutrino Oscillations

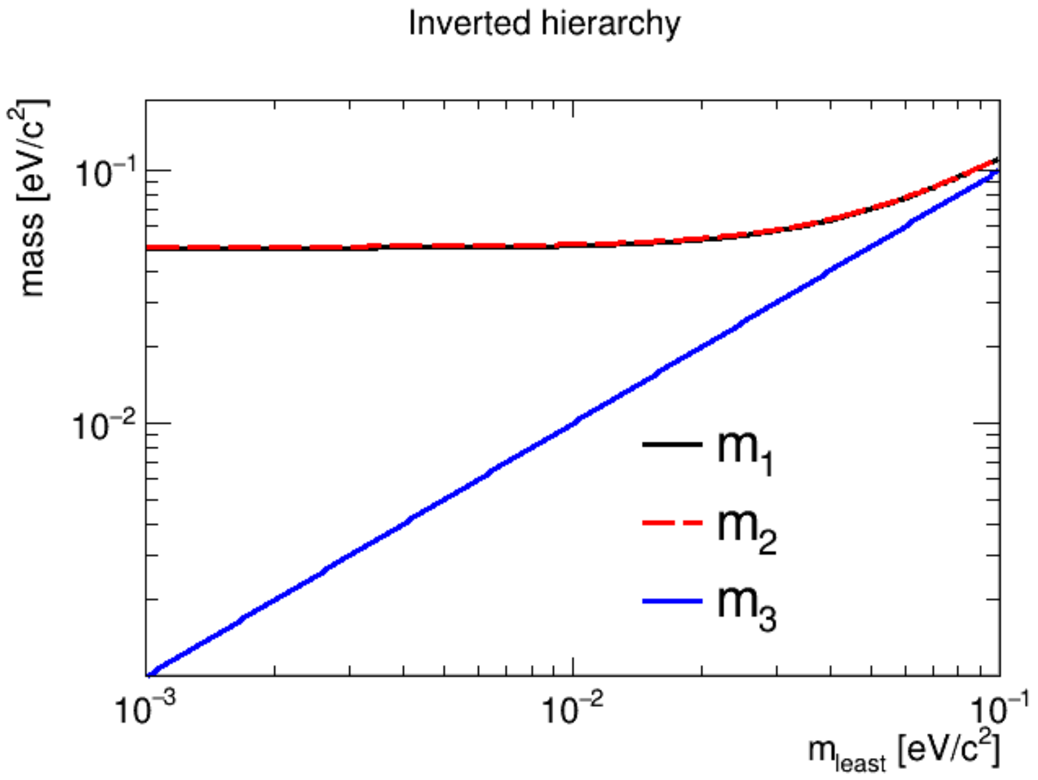
- **Evidence** from atmospheric, solar, reactor and accelerator experiments
- 2015 Nobel Prize in Physics to T. Kajita and A. McDonald
- Tremendous progress in past decade, **precise measurements** of three mixing angles and two Δm^2
- **Ambitious** multi-billion-$ programme over next decades (HyperK, DUNE)
- However, neutrino oscillations only give mass (squared) differences between neutrino mass eigenstates, **no information on absolute neutrino mass**



Constraints from Neutrino Oscillations

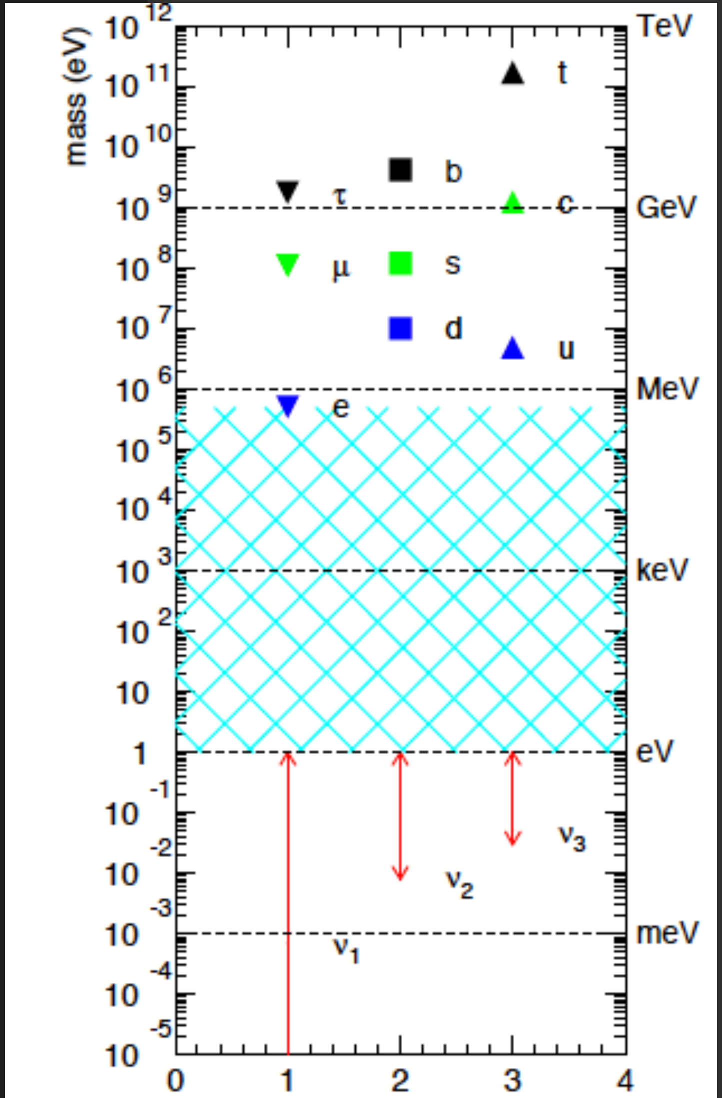






Absolute mass depends on the neutrino mass ordering

Neutrino mass

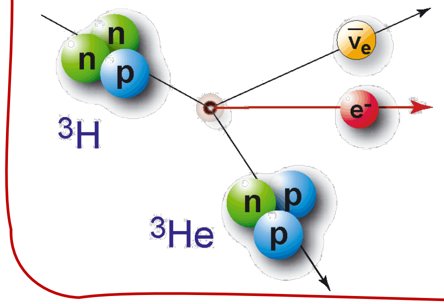


- Only solid particle physics evidence for Physics beyond Standard Model
- Smallness of mass suggests new mass generation mechanism (not “straight” Higgs)
- Connected to new physics
  - Matter-antimatter asymmetry (CP-violation)
  - Lepton Number Violation
  - Sterile-neutrino

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

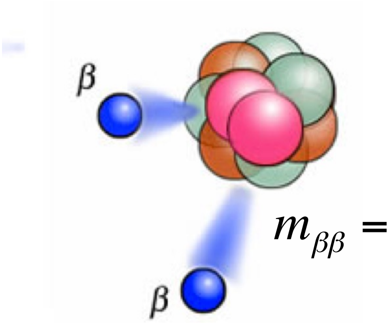
How to access Absolute Neutrino Mass

β-decay



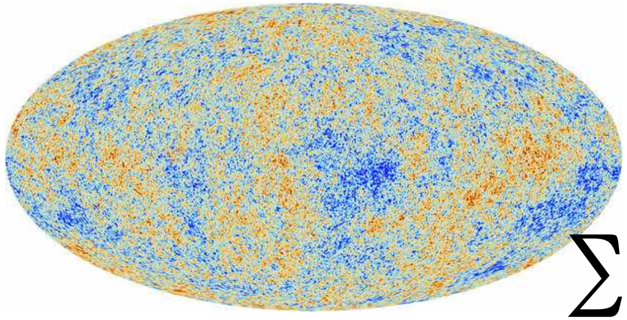
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

0νββ-decay



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

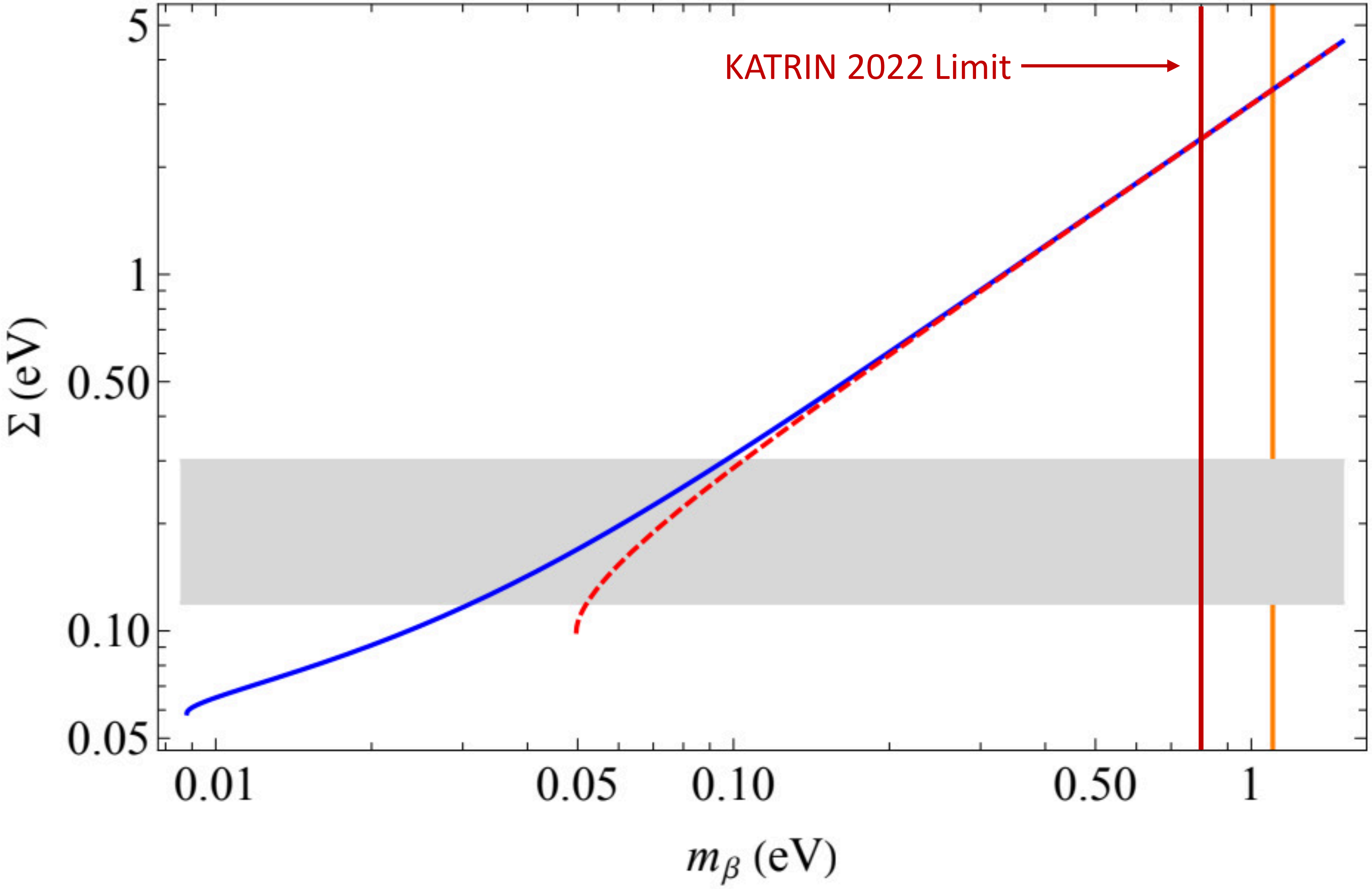
Cosmology

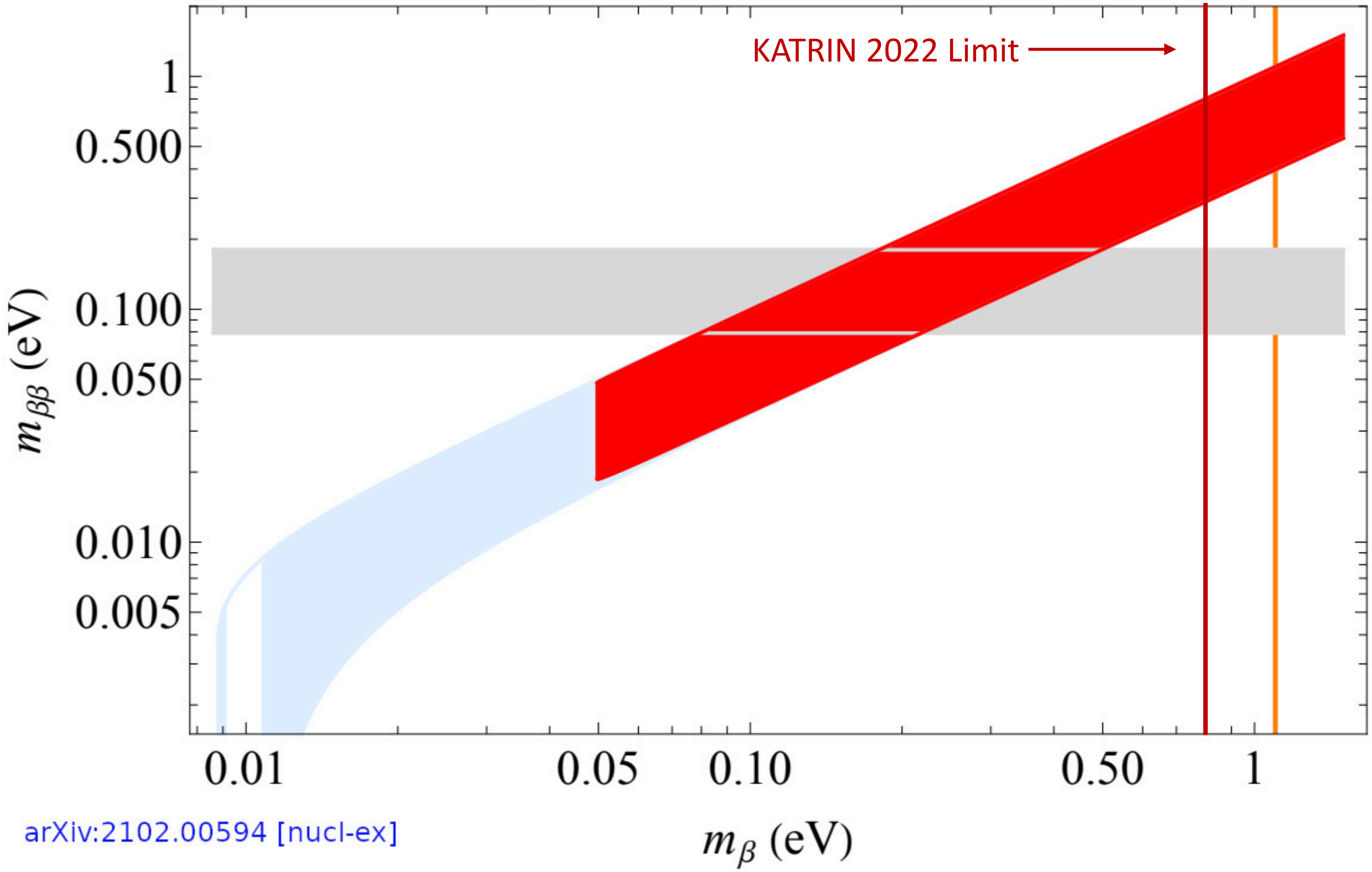


$$\sum_i m_i$$

- Measurement **all three** neutrino mass parameters allows **Majorana CP-violating phases** to be constrained (otherwise inaccessible!) → key for understanding **matter-antimatter asymmetry** of Universe
- Measuring m_β in **β-decay** constrains $m_{\beta\beta}$ (**$0\nu\beta\beta$**) and Σ (**Cosmology**) – next two slides

arXiv:2102.00594 [nucl-ex]

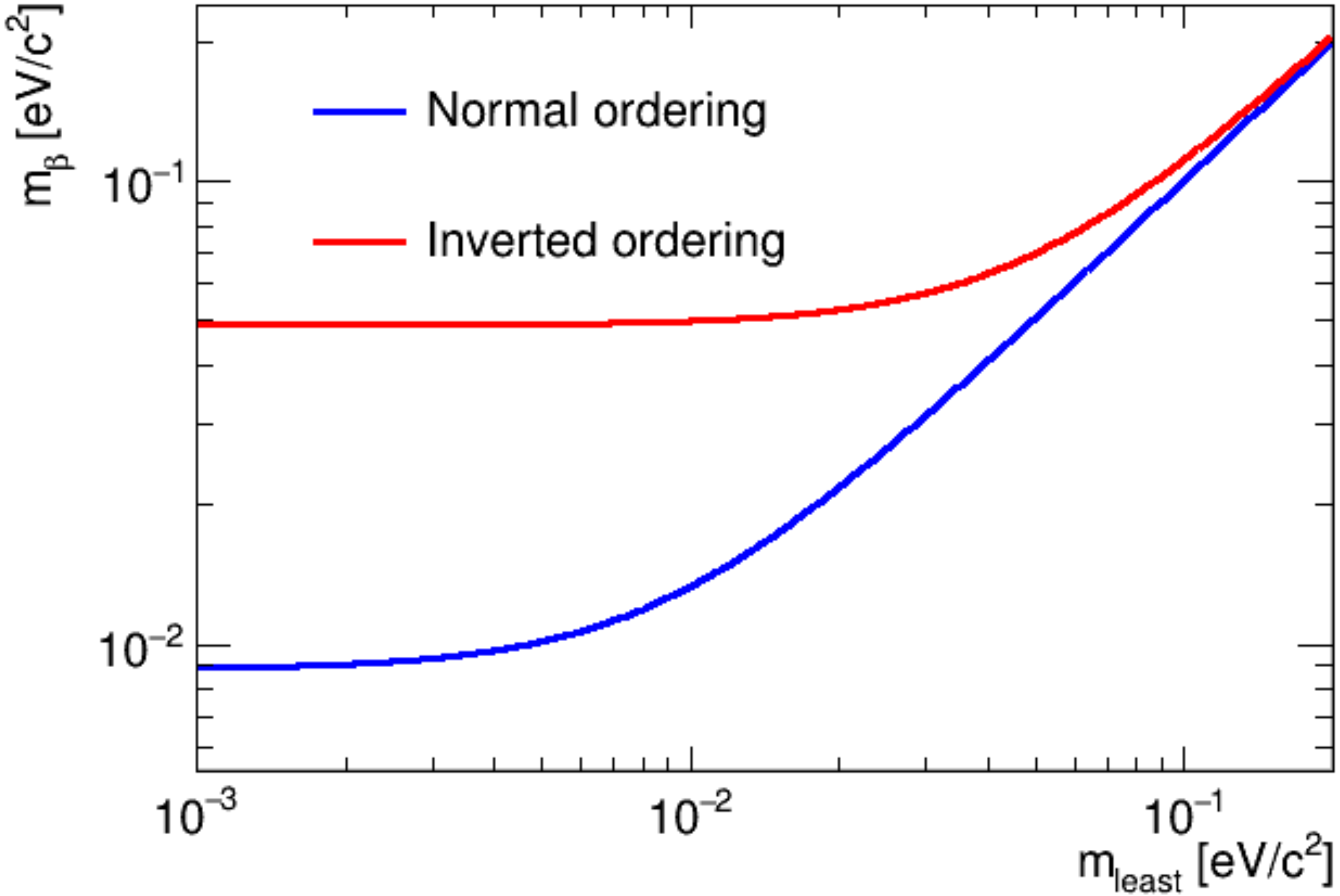




arXiv:2102.00594 [nucl-ex]

To summarise:

- m_β is sensitive to neutrino mass ordering
- Cannot be smaller than 9 meV (worst case scenario)



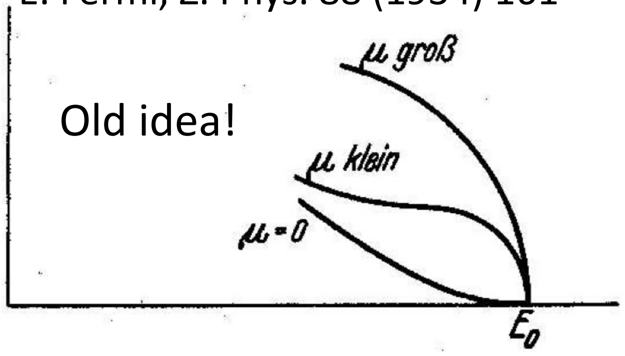
$$m_\beta^2 = m_1^2 + |U_{e2}|^2 \Delta m_{21}^2 + |U_{e3}|^2 \Delta m_{31}^2$$

$\Delta m_{31}^2 > 0$: Normal Ordering

$\Delta m_{31}^2 < 0$: Inverted Ordering

Model Independent Neutrino Mass Measurement

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



Old idea!

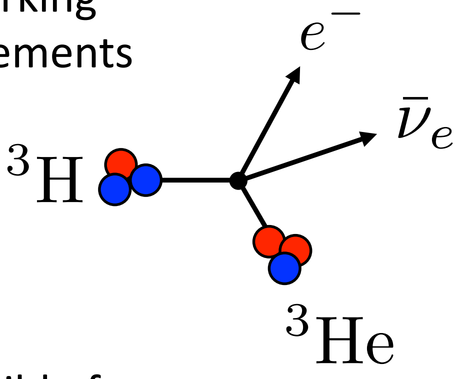
Fig. 1.

Energy conservation is only assumption!

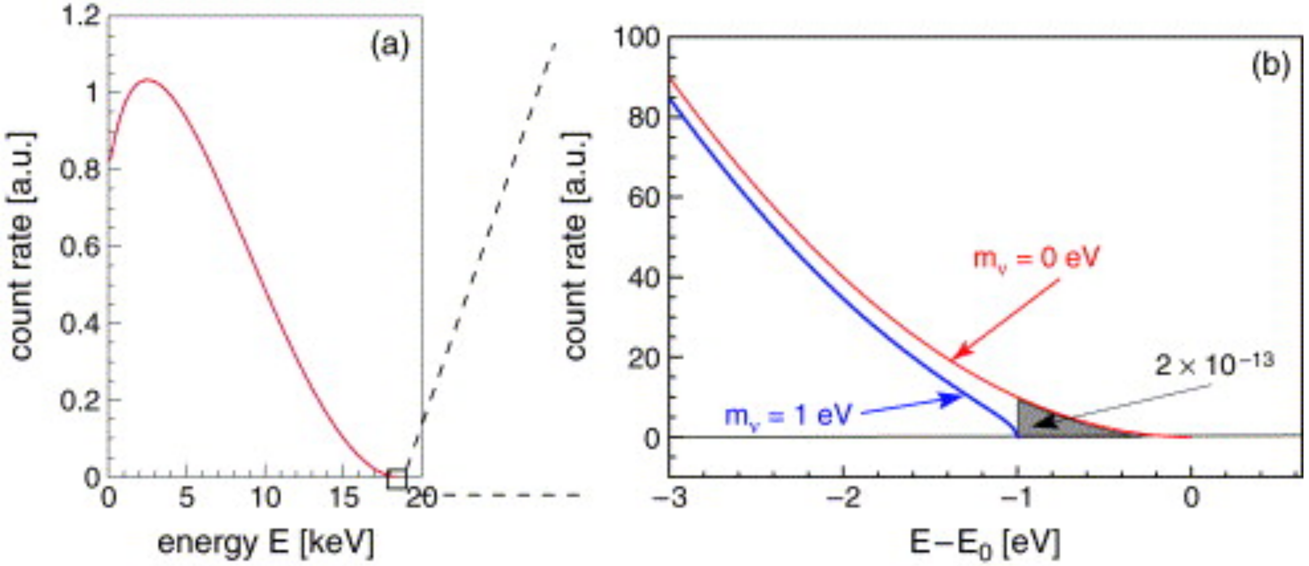
$$\boxed{\frac{d\Gamma_i}{dE} = C\,p(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_\nu^2}\,F(E)\,\theta(E_0-E-m_\nu)}$$

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

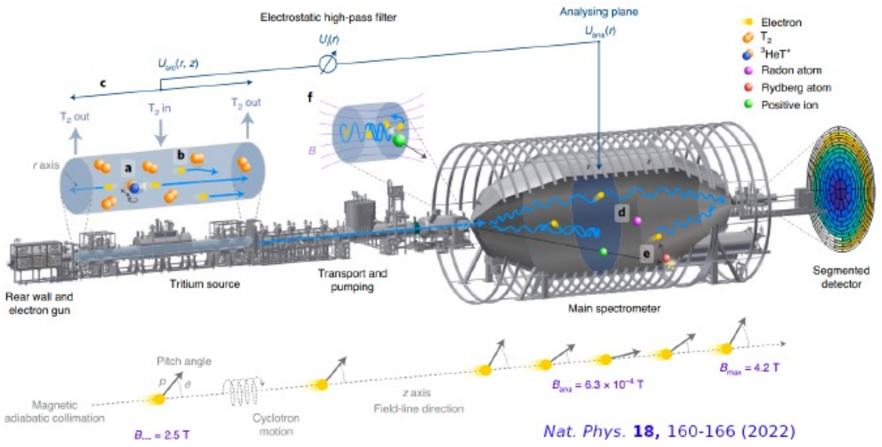
Tritium β-decay is a “working horse” of these measurements



But other isotopes possible for calorimetric measurements

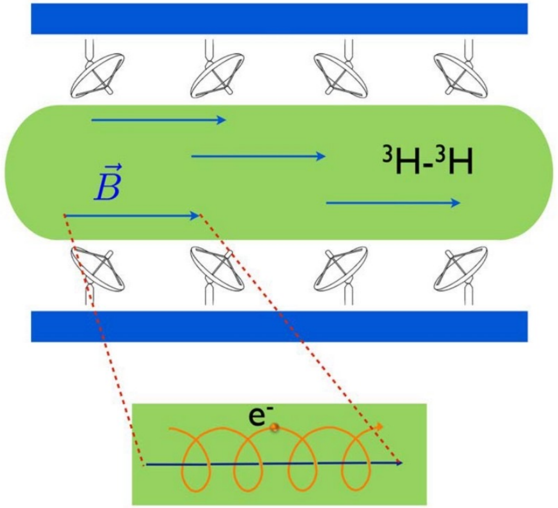


Three methods of m_β measurement

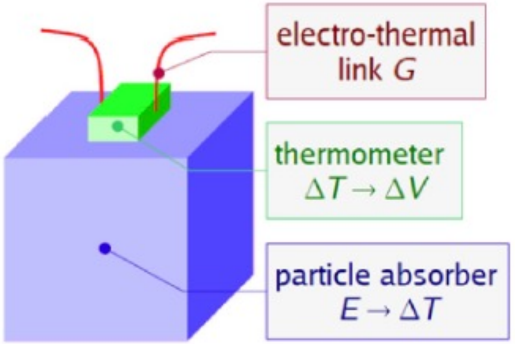


Nat. Phys. **18,** 160-166 (2022)

Electrostatic filter
(retarding potential)



Cyclotron Radiation
Emission Spectroscopy
(CRES)



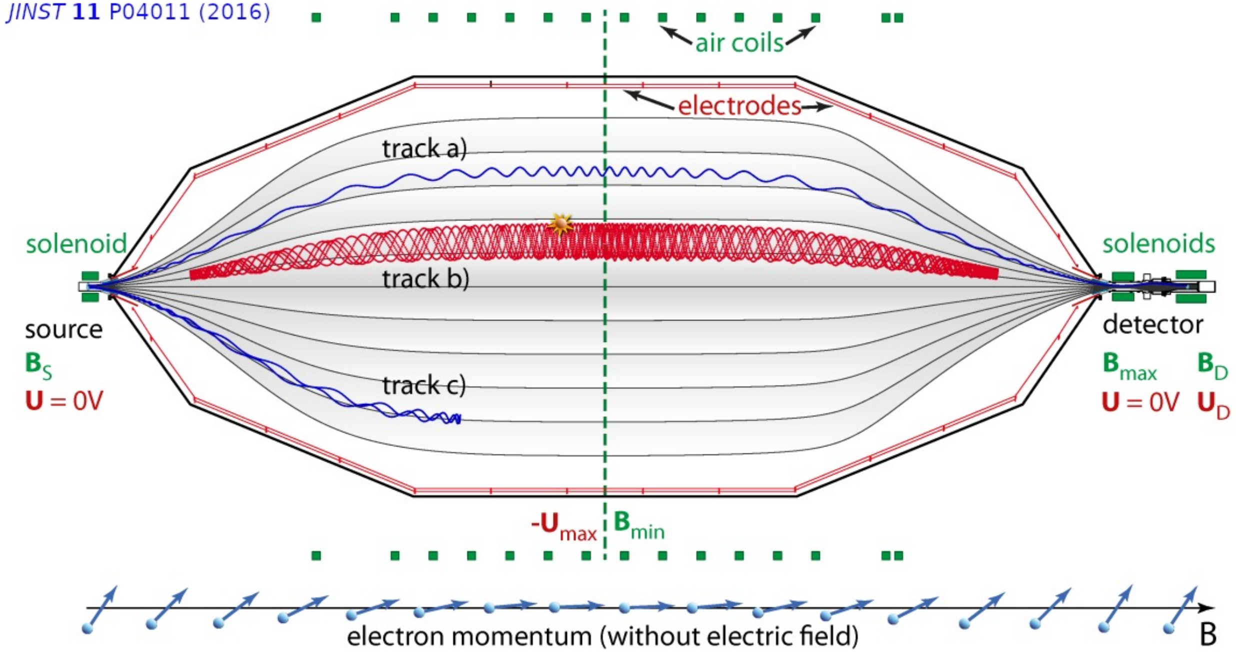
Calorimetry

State-of-the-art: KATRIN Experiment

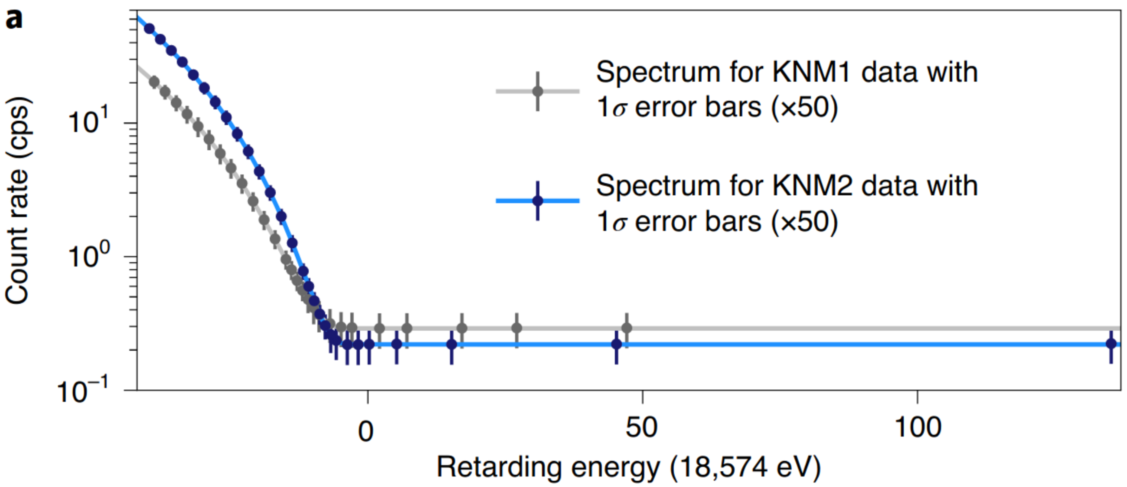
Source activity 10^{11} Bq
T_2 throughput ~ 40 g/day
Operation 24/7, 60 days/run
Necessary inventory >15 g

Magnetic **A**diabatic **C**ollimation + **E**lectrostatic Filter (**MACE**)

JINST **11** P04011 (2016)



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



- Electrons emitted from source in region with high B_s field travel adiabatically along field lines to analysing region with low field B_{min}
- Only electrons with sufficient energy pass the potential barrier at the central plane with retarding potential, re-accelerated and detected

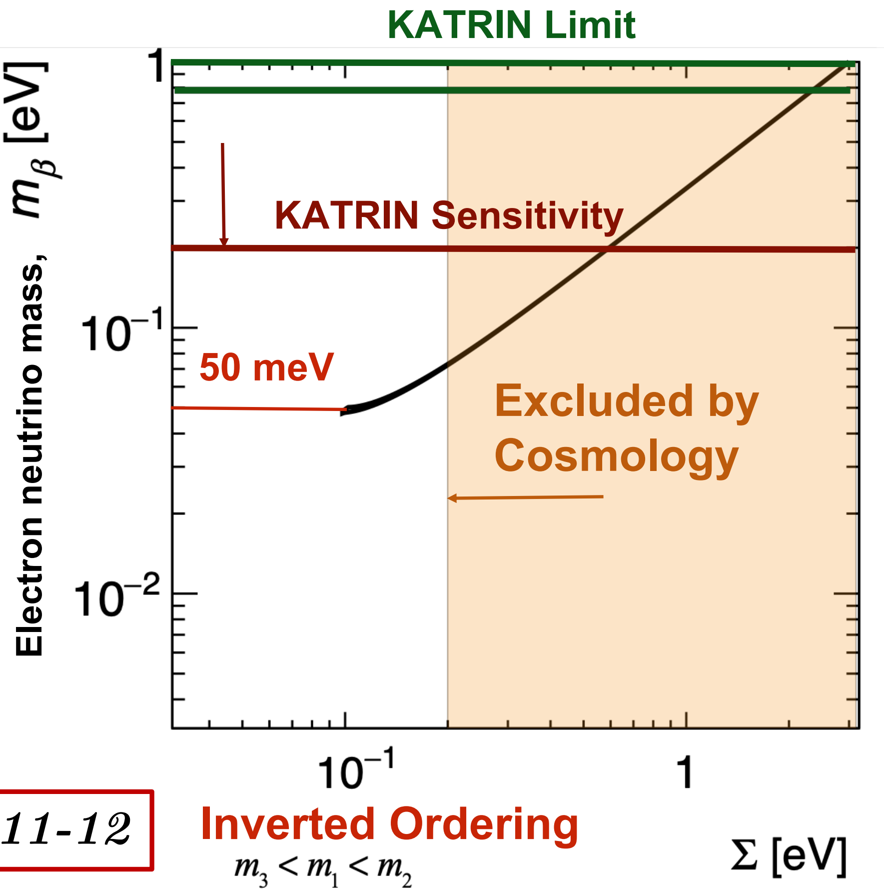
First sub-eV result, $m_\beta < 0.8$ eV c^{-2} at 90%CL !

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

Ultimate sensitivity 0.2 eV c^{-2}

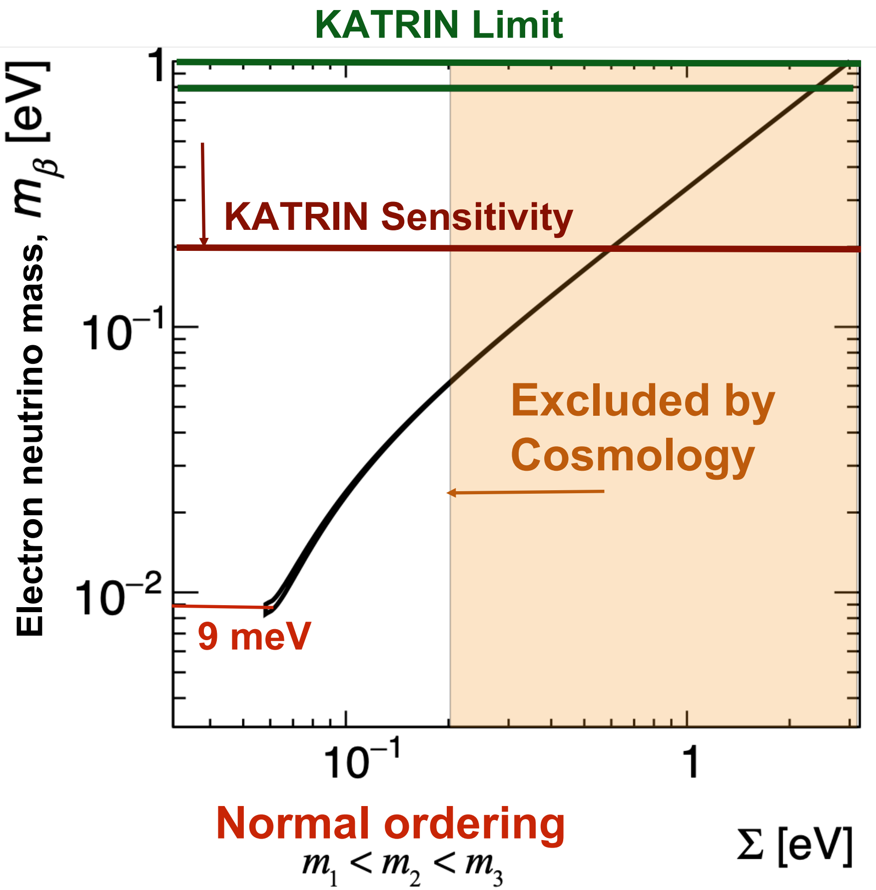
© Forschungszentrum Karlsruhe/KIT Katrin

- Ultimate sensitivity ~ 0.2 eV
- MAC-E cannot be scaled up beyond **KATRIN**



Inverted Ordering
$m_3 < m_1 < m_2$

see also p11-12



Normal ordering
$m_1 < m_2 < m_3$

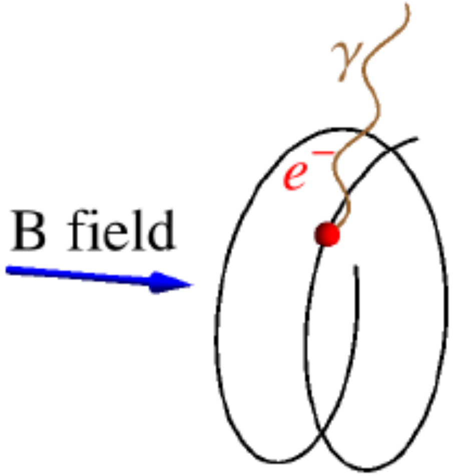
Adapted from M. Agostini et al, Phys. Rev., D96(5):053001, 2017

- 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

How to overcome present technology limitations?

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



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

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

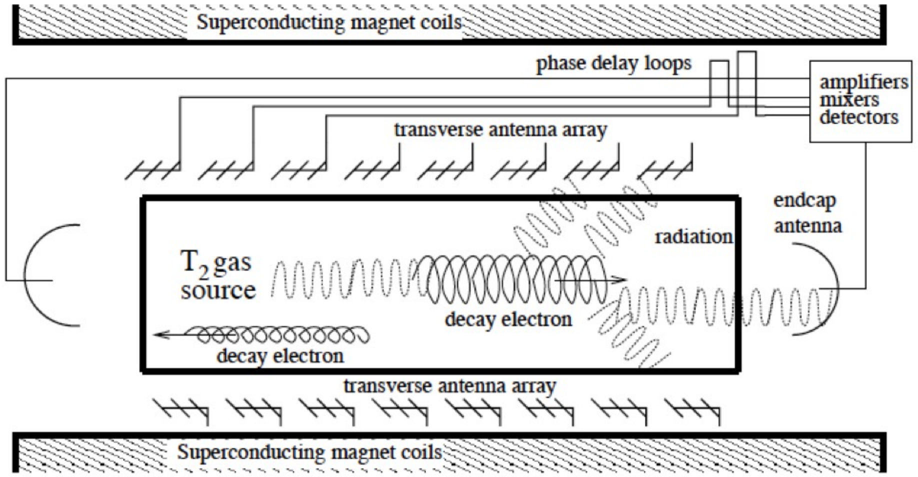
Determine energy of electron emitted in ^{3}H β-decay by measuring the frequency of EM radiation generated due to electron’s cyclotron motion in magnetic field

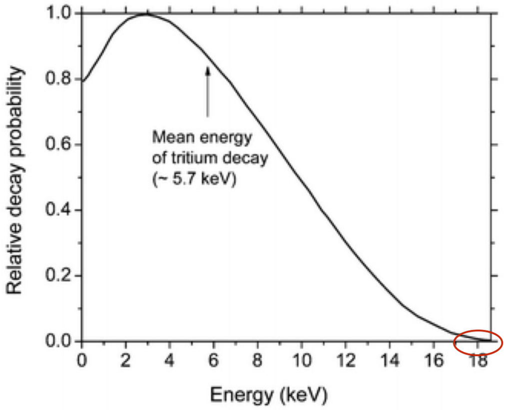
Cyclotron **R**adiation **E**mission **S**pectroscopy (**CRES**)

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

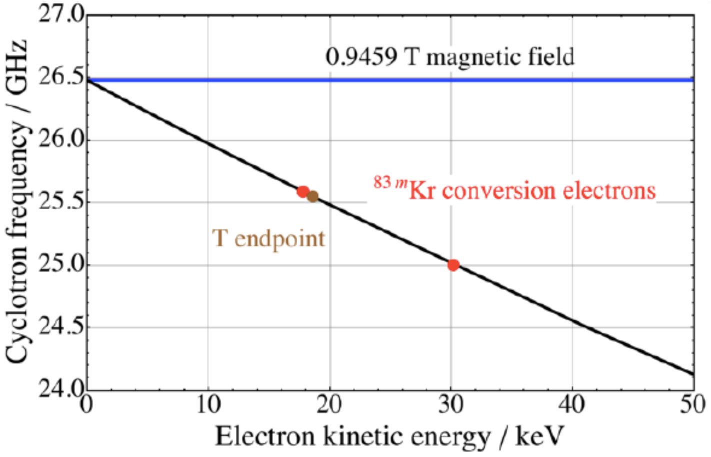
Cyclotron **R**adiation **E**mission **S**pectroscopy (**CRES**) Concept



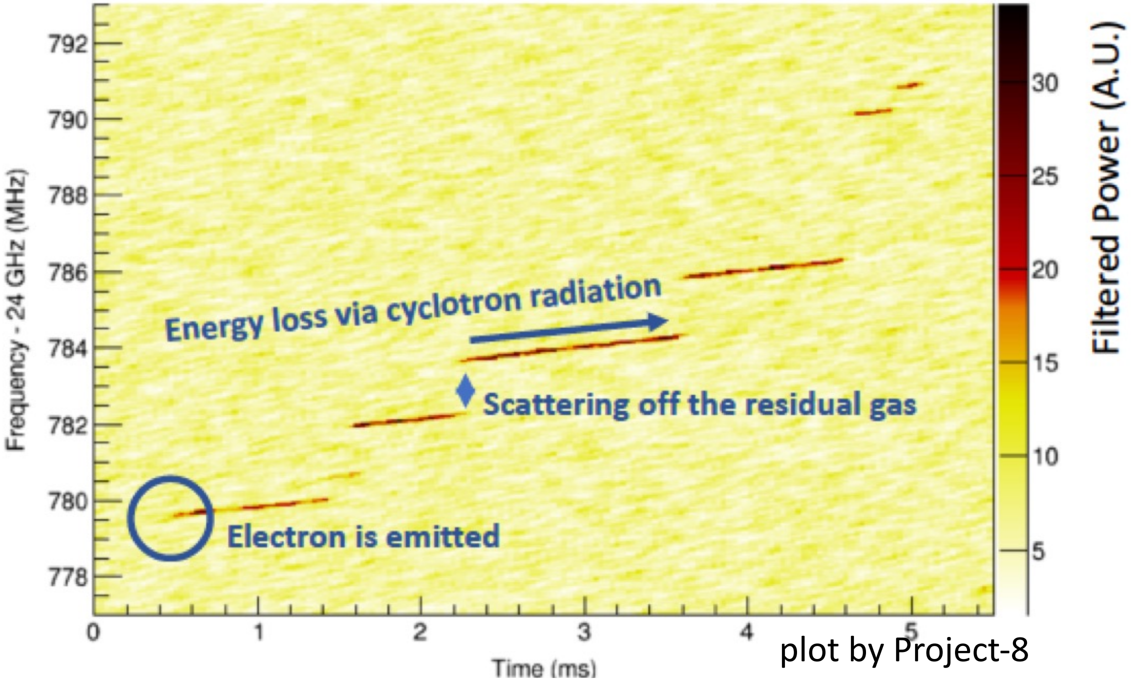


$$^{3}H \rightarrow {}^{3}He + e^{-} + \overline{\nu}_{e}$$

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

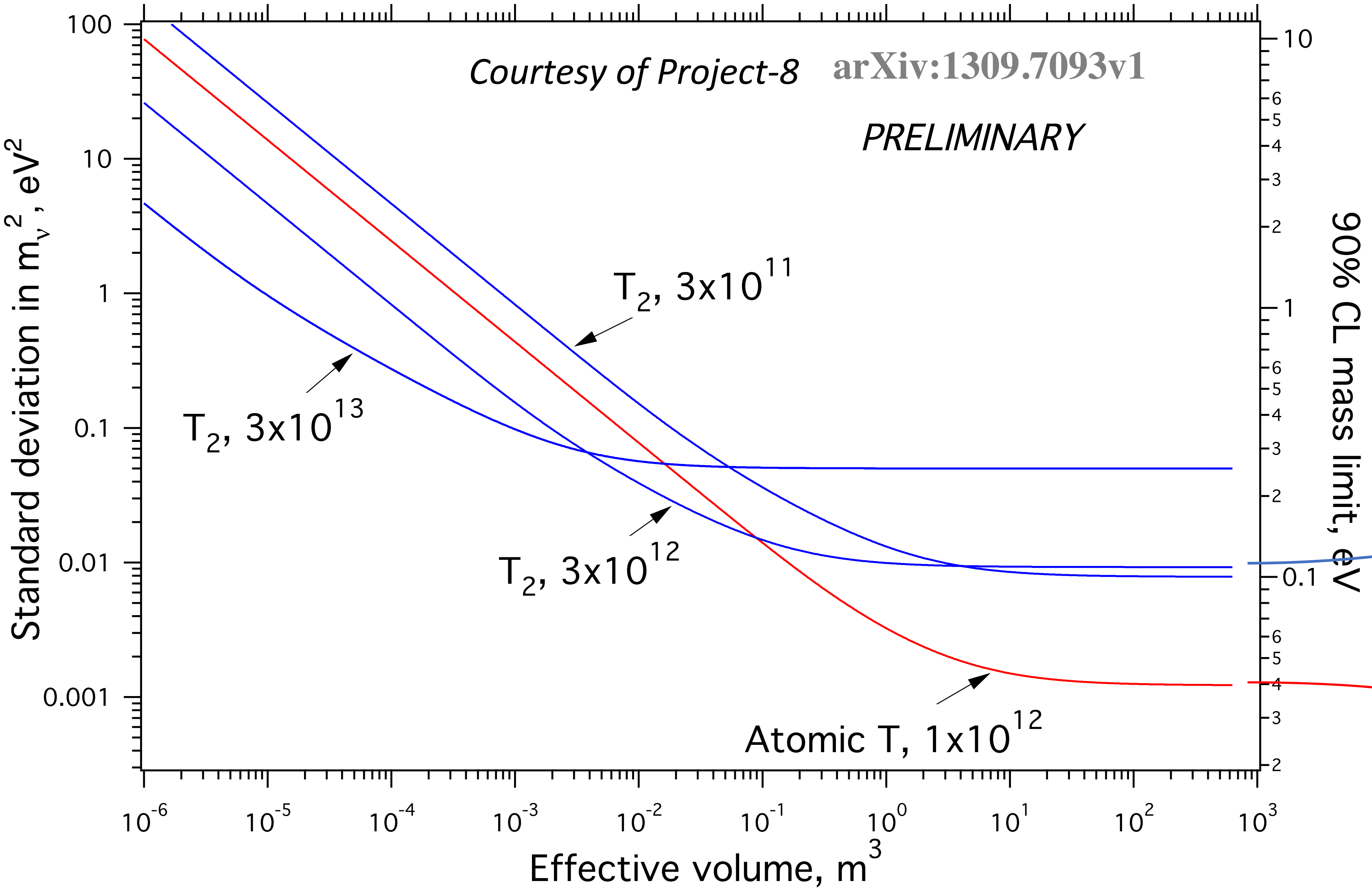


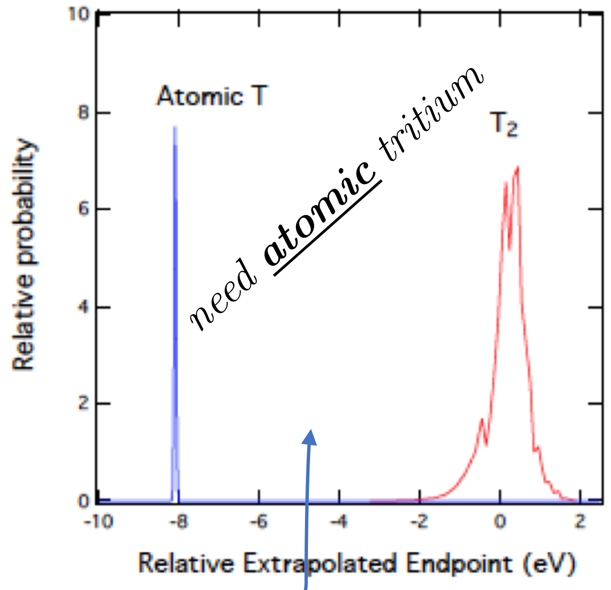
Proof of principle by Project-8 using ^{83m}Kr conversion electrons



plot by Project-8

CRES Sensitivity and Challenges

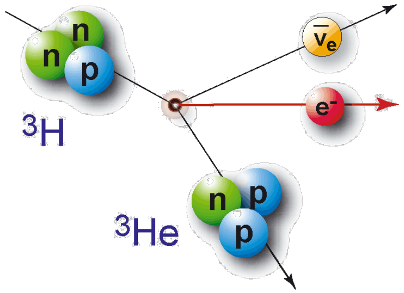




need ***atomic*** tritium

Need ultra-inform B-field ($<$ 0.1ppm)

QTNM



Mission Neutrino mass measurement from ^{3}H β-decay via cyclotron radiation emission spectroscopy using latest advances in **quantum technologies.**

Strategy Phased approach: CRESDA* → CRESDA-Tritium → 100 meV → 50 meV → 10 meV

* **CRES D**emonstrator **A**pparatus

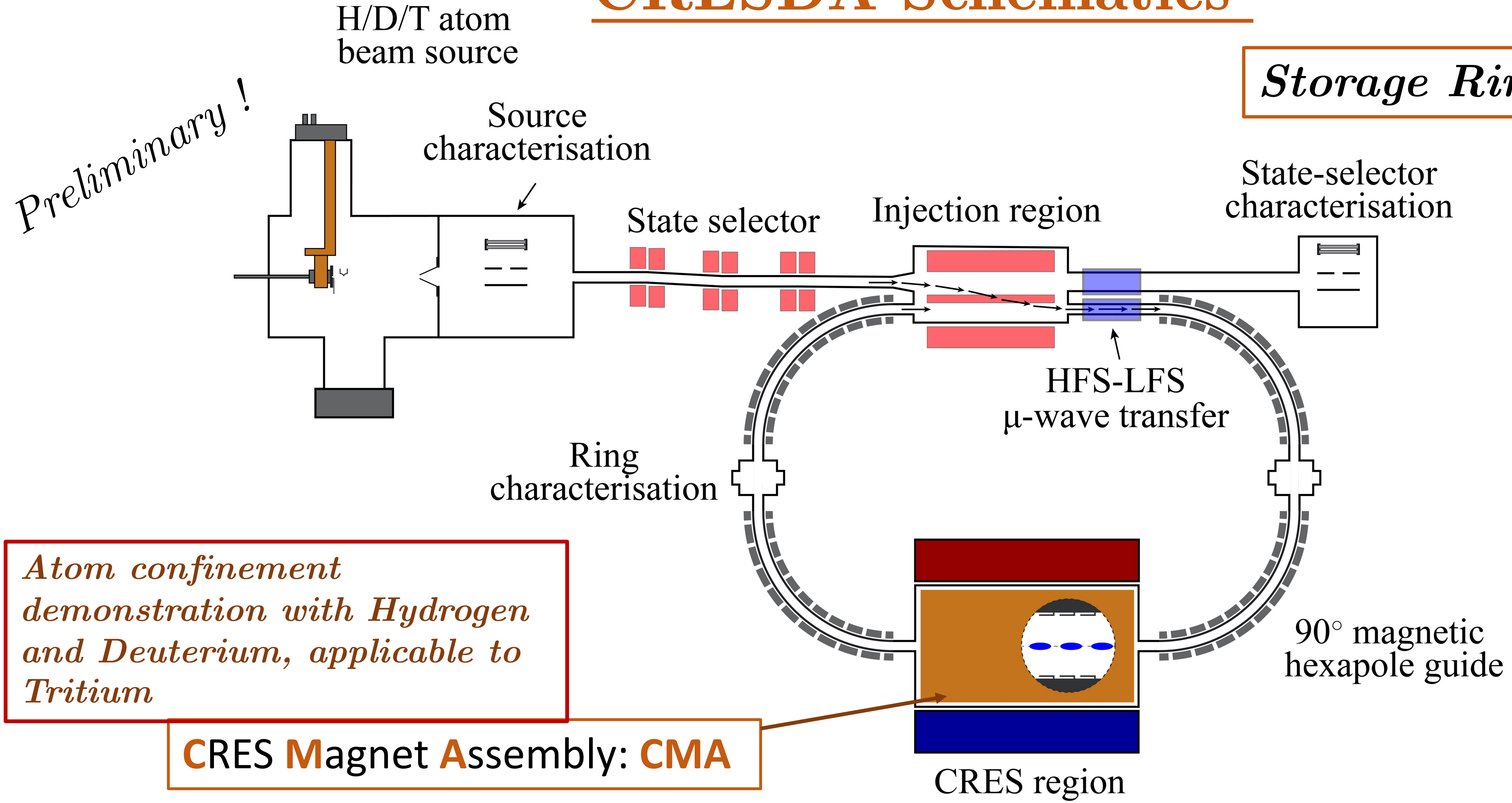
CRESDA Strategic Goals

- Production and confinement of H-atoms, $\geq 10^{12}$ cm^{-3}, scalable to 10^{20} atom × yr exposures
- B-field mapping with $< 1\ \mu$T abs precision and ~1mm spatial resolution
- CRES of O(10keV) electrons scalable to ~m^3 detection volumes with O(10ppm) energy resolution and high detection efficiency

quantum technologies

CRESDA Schematics

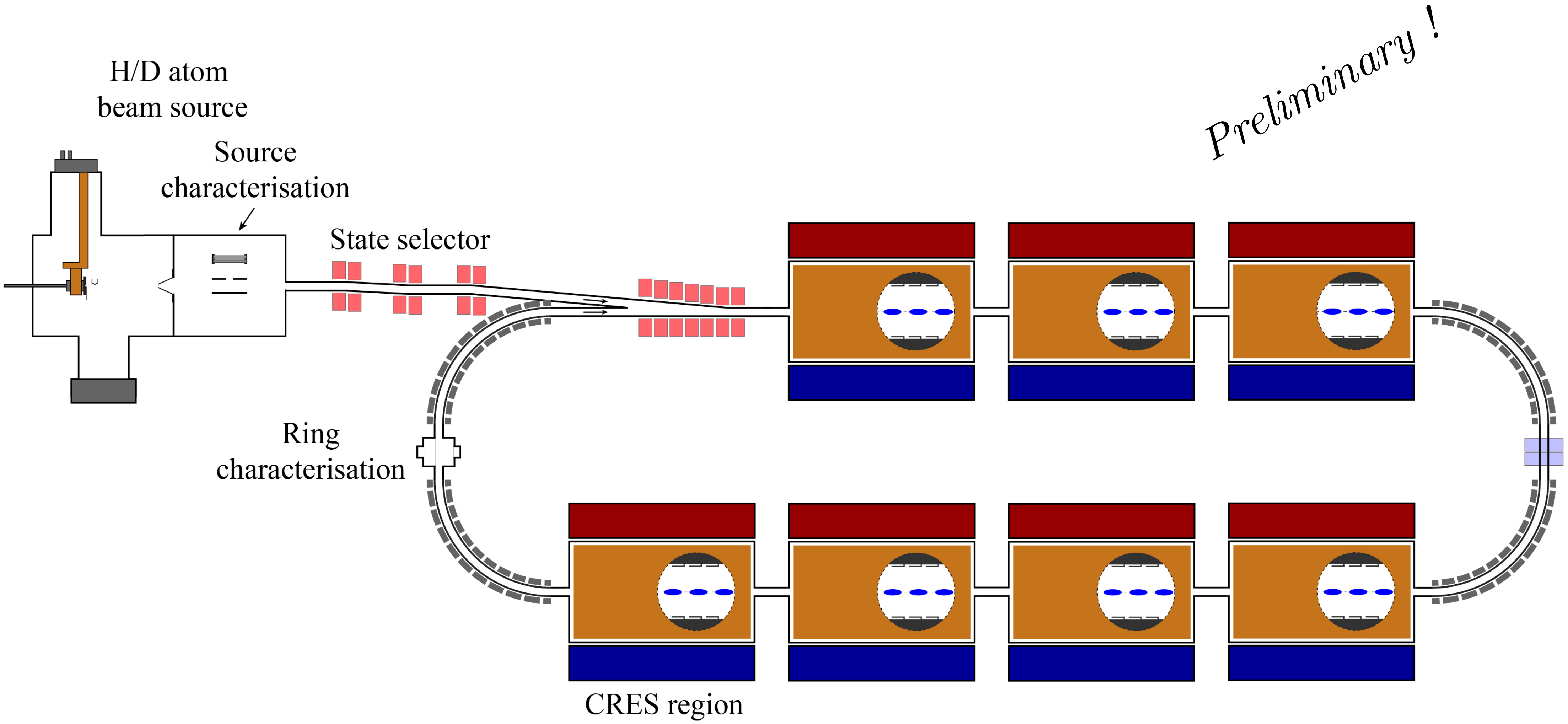
Storage Ring Concept

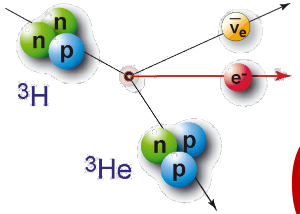


Atom confinement demonstration with Hydrogen and Deuterium, applicable to Tritium

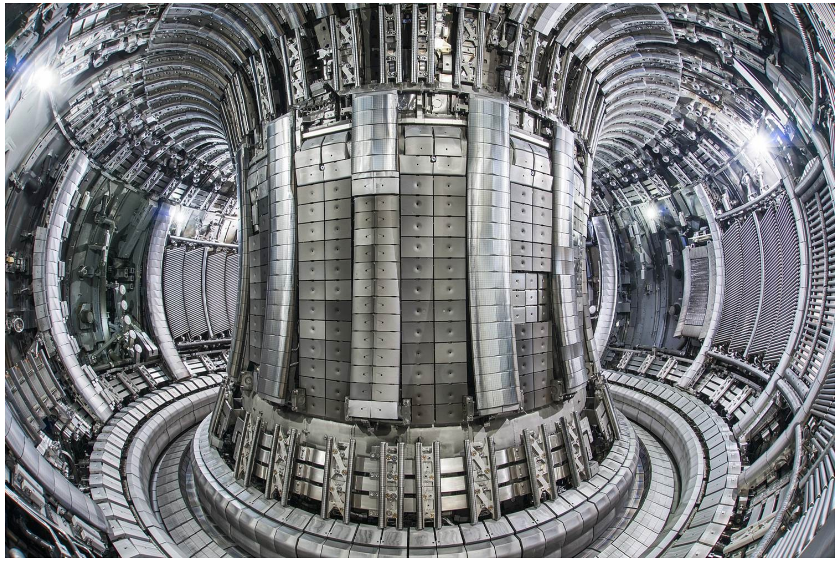
CRES **M**agnet **A**ssembly: **CMA**

Scalability of Storage Ring Concept





QTNM



CCFE

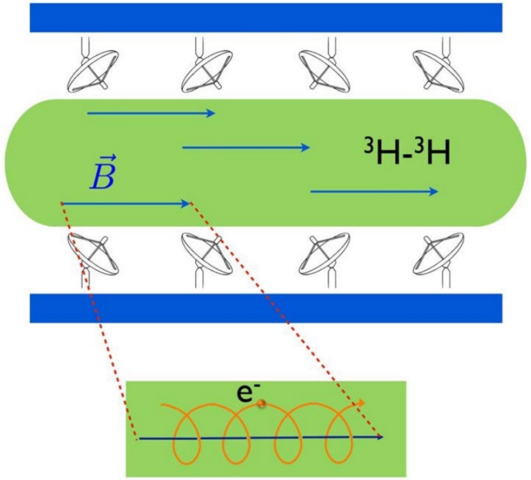
CULHAM CENTRE FOR FUSION ENERGY

Future Outlook

(very tentative)

- Current project: 2021-2024
  - Technology demonstration with Hydrogen and Deuterium, scalable to Tritium (ongoing collaboration with Culham)
- Next step. 2025-2029
  - Moving CRESDA to a Tritium facility (focus on Culham)
  - Tritium phase demonstration
  - O(eV) sensitivity
- ”Ultimate” international project > 2029
  - Consolidate technological breakthroughs (QTNM, Project-8, KATRIN…) to build and operate a detector with a phased sensitivity: 100 meV ⇨ 50 meV ⇨ 10 meV plus sterile neutrino programme

What kind of frequencies are we interested in? How much power can we expect to detect?



Tritium endpoint electron has $E_k \approx 18.6\,\mathrm{keV} = 2.980\,05 \times 10^{-14}\,\mathrm{J}$

Frequency of radiation given by $$f = \frac{1}{2\pi}\frac{e\,B}{m_e + E_k/c^2}$$

If our decay electrons are in a 1 Tesla magnetic field we find:

$$f = \frac{1}{2\pi}\frac{1.602\,18 \times 10^{-19}\,\mathrm{C} \cdot 1\,\mathrm{T}}{9.109\,384 \times 10^{-31}\,\mathrm{kg} + 2.980\,05 \times 10^{-14}\,\mathrm{J}/(2.997\,92 \times 10^{8}\,\mathrm{m/s})^2}$$
$$\approx 27\,\mathrm{GHz}$$

Therefore, we are interested in detecting microwaves with a wavelength of roughly 1 cm

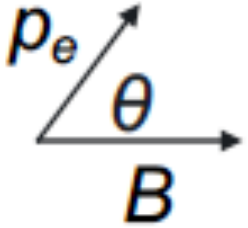
Suitable for detection with either antenna(s), waveguide or resonant cavity

What kind of frequencies are we interested in? How much power can we expect to detect?

Total radiated power given by $P = \frac{2\pi e^2 f_0^2}{3\epsilon_0 c}\frac{\beta^2 \sin^2\theta}{1-\beta^2}$

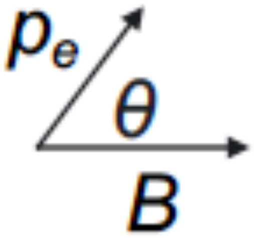
Our endpoint electrons are mildly relativistic $\gamma = 1 + \frac{E_k}{mc^2} = 1.0364 \text{ and } \beta = 0.263$

θ is 'pitch angle' - angle between B field direction and electron momentum

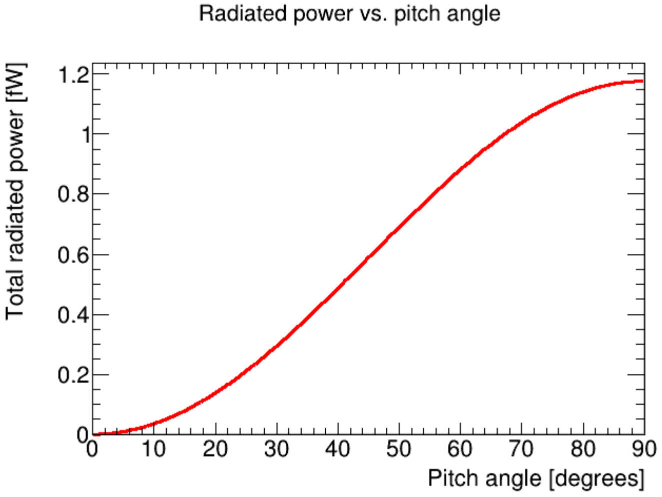


$f_0 = \frac{1}{2\pi}\frac{eB}{m} = 27.9925\,\text{GHz}$ and $P = 1.17\,\text{fW}$ for $B = 1\,\text{T}$ and $\theta = \frac{\pi}{2}$

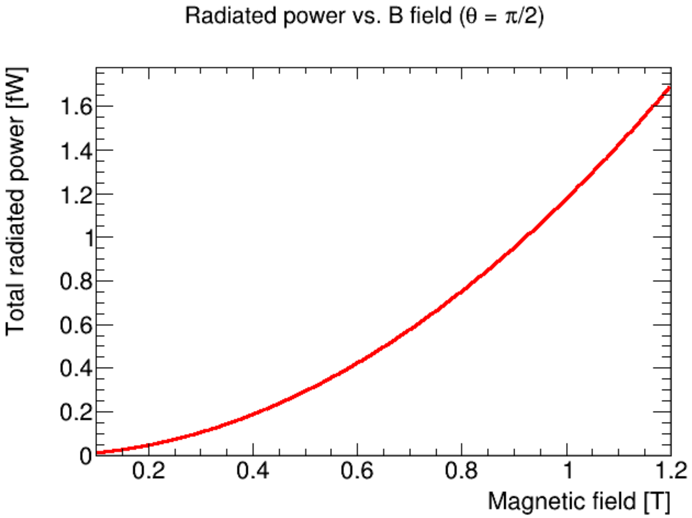
What kind of frequencies are we interested in? How much power can we expect to detect?



$$P = \frac{2\pi e^2 f_0^2}{3\epsilon_0 c} \frac{\beta^2 \sin^2 \theta}{1-\beta^2}$$


Radiated power vs. pitch angle

Those electrons with pitch angles close to 90° are the most detectable

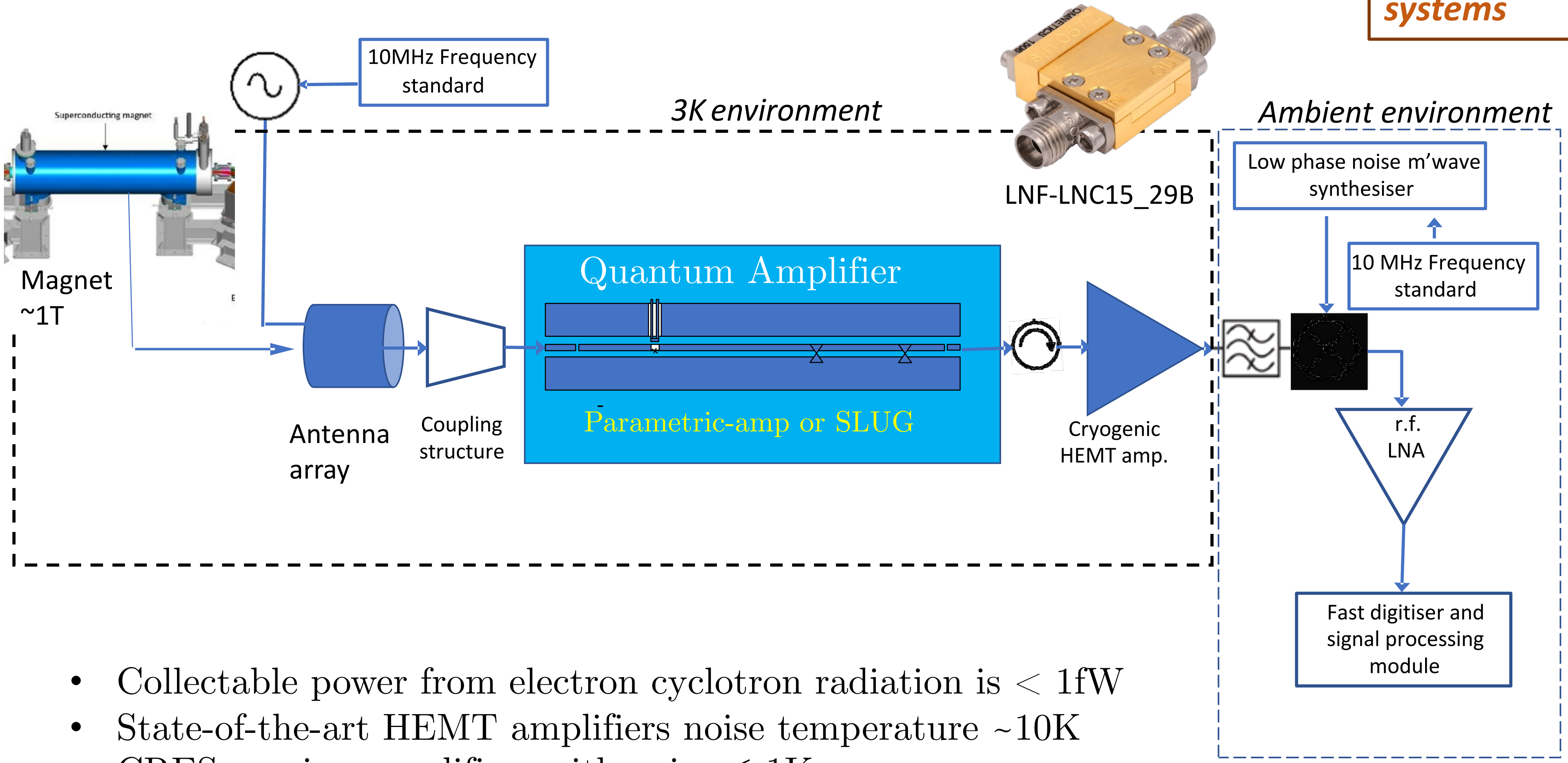

Radiated power vs. B field ($\theta = \pi/2$)

$$P \propto B^2$$

Small radiated power necessitates a strong magnetic field as well as amplifiers with very low noise

Cyclotron Radiation Readout in QTNM

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



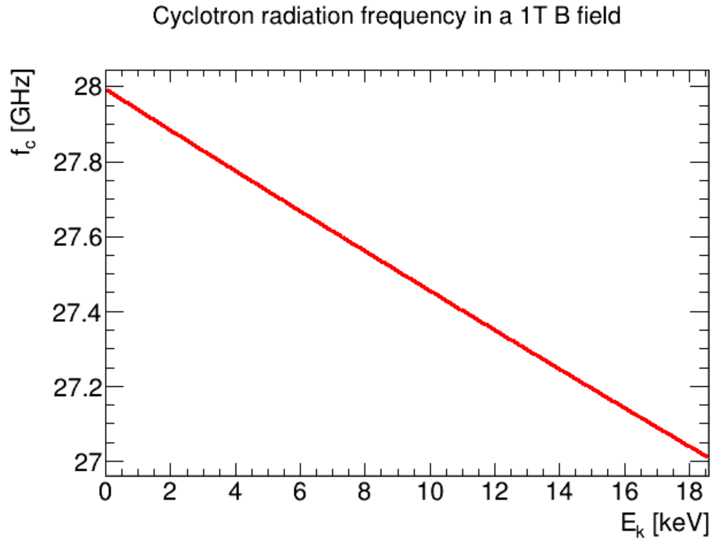
- Collectable power from electron cyclotron radiation is $< 1\text{fW}$
- State-of-the-art HEMT amplifiers noise temperature ~10K
- CRES requires amplifiers with noise $\leq 1\text{K}$

Quantum Amplifiers!

See Lecture on Quantum Electronics Wed at 11:30

What sort of bandwidth are we interested in?

$$f = \frac{1}{2\pi}\frac{eB}{m + E_k/c^2} = \frac{eB}{2\pi}\left(\frac{E}{c^2}\right)^{-1}$$


Cyclotron radiation frequency in a 1T B field

Entire decay spectrum covers a frequency range of about 1 GHz

$$\frac{df}{dE} = -\frac{eBc^2}{2\pi}E^{-2}$$

B = 1 T and kinetic energy = 18.6 keV

Therefore $$\frac{df}{dE} = 3.18 \times 10^{23}\,\mathrm{Hz\,J^{-1}} = 51\,\mathrm{kHz\,eV^{-1}}$$

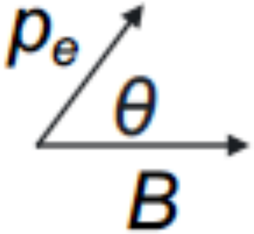
So to measure the last 200 eV of spectrum we require a bandwidth of roughly 10 MHz

Amplifiers and readout chain must be capable of operating over this bandwidth

How long do we need to observe our electrons for?

We have $\frac{df}{dE} = 51\,\mathrm{kHz\,eV^{-1}}$ and require ΔE = 1 eV. Therefore Δf = 51 kHz

$$t_{\mathrm{obs}} \sim \frac{1}{\Delta f} \quad \therefore\ t_{\mathrm{obs}} \geq 20\,\mathrm{\mu s}$$



An endpoint electron with a pitch angle of 89° will travel a distance of

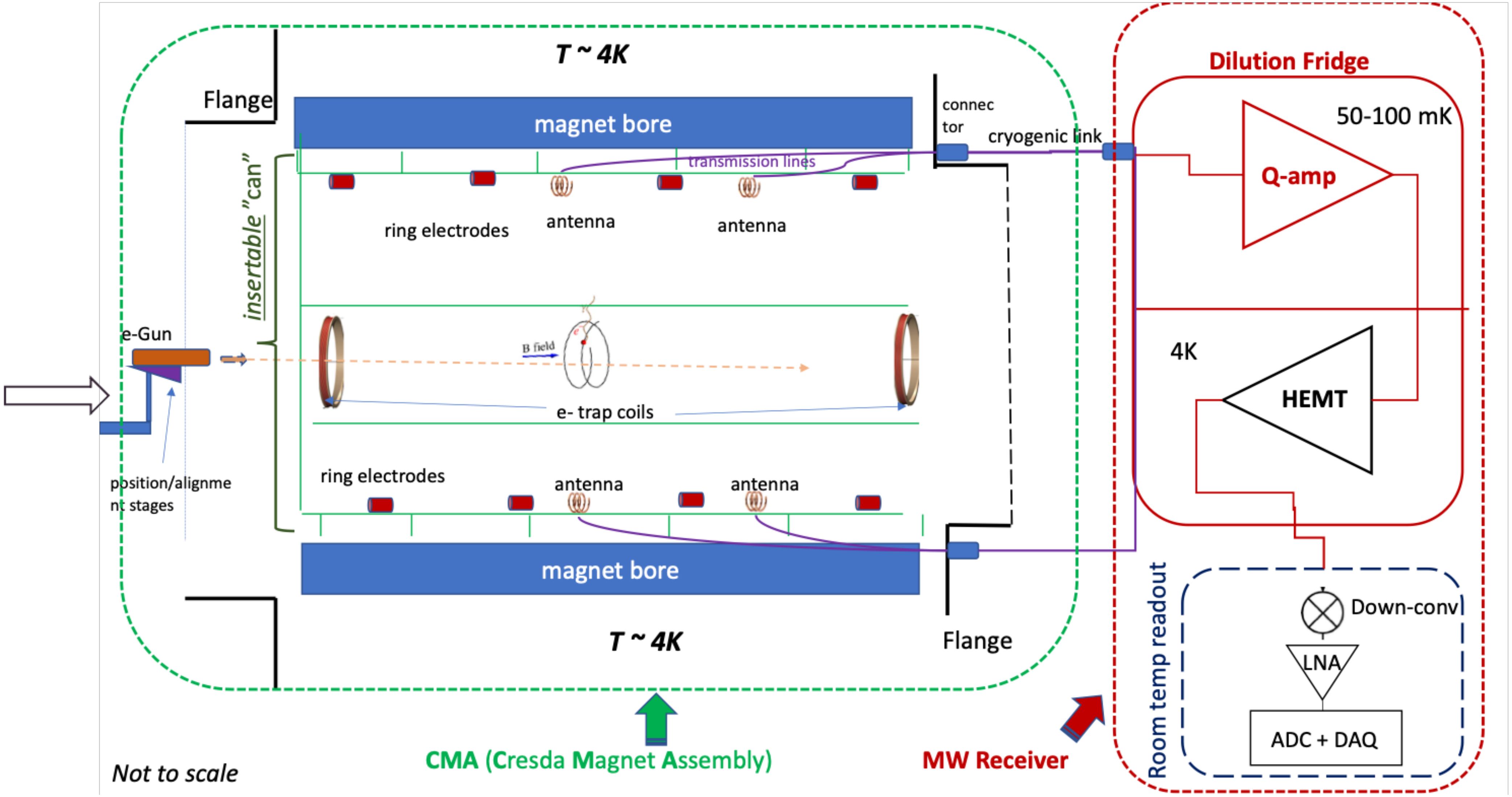
$$v\,t\,\cos\theta = 0.263c \cdot \cos(89^\circ) \cdot 20\,\mathrm{\mu s} = 275\,\mathrm{m}$$

parallel to the magnetic field!

Solution: We need to contain our decay electrons within a 'no-work' trap so they can be observed for the required amount of time

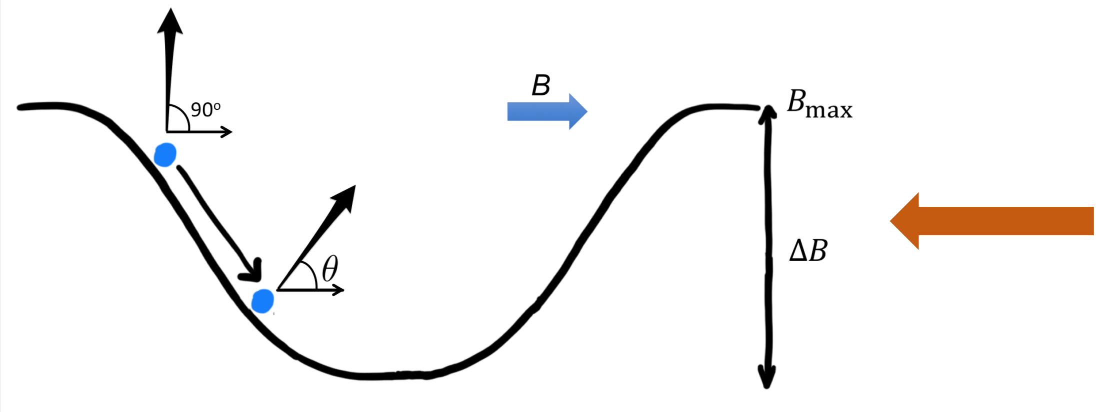
CRES Magnet Assembly: CMA

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



Magnetic trapping of electrons

- Need to trap electrons to achieve required resolution and collect enough power

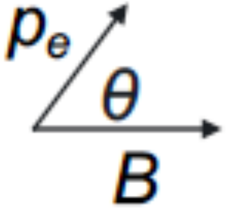


Ashtari Esfahani *et al.*, Phys. Rev. C 99, 055501 (2019)

'No work trap' is magnetic bottle

Local minimum in magnitude of background B field

Only electrons with pitch angles above a certain value are trapped

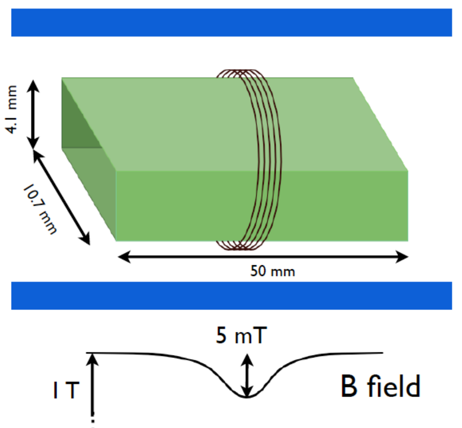


These trapped electrons climb up the magnetic field potential until eventually their pitch angle becomes 90° and they change direction

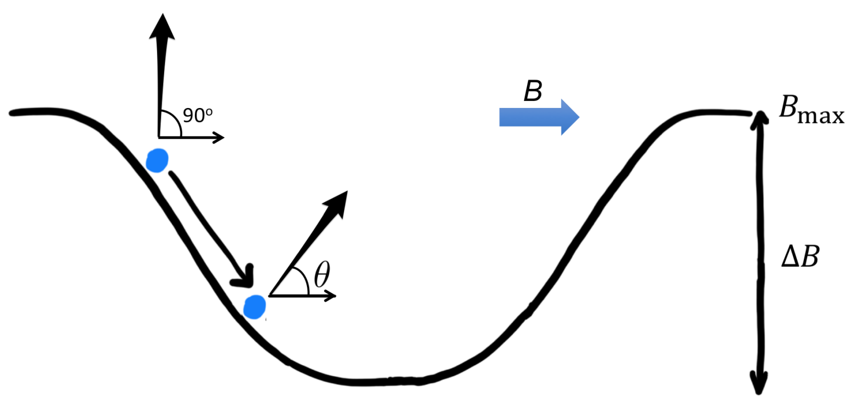
Trapping condition given by:

$$\theta_{\mathrm{bot}} \geq \arcsin\left(\sqrt{1 - \frac{\Delta B}{B_{\mathrm{max}}}}\right)$$

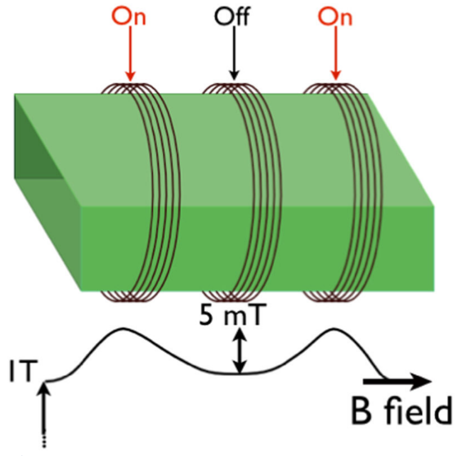
Electron trapping



“Harmonic” Trap

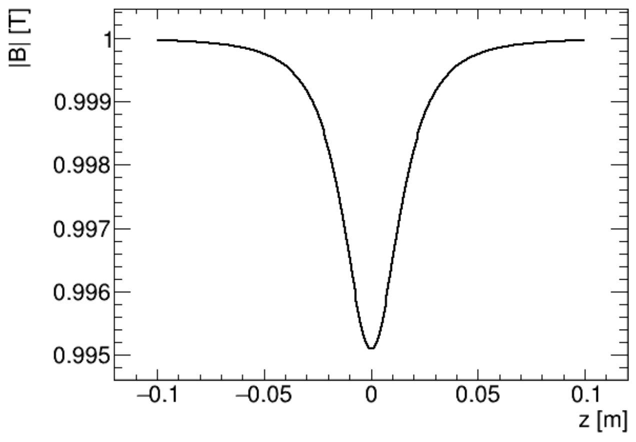


Ashtari Esfahani *et al.*, Phys. Rev. C 99, 055501 (2019)



"Bathtub" Trap

Different field configurations

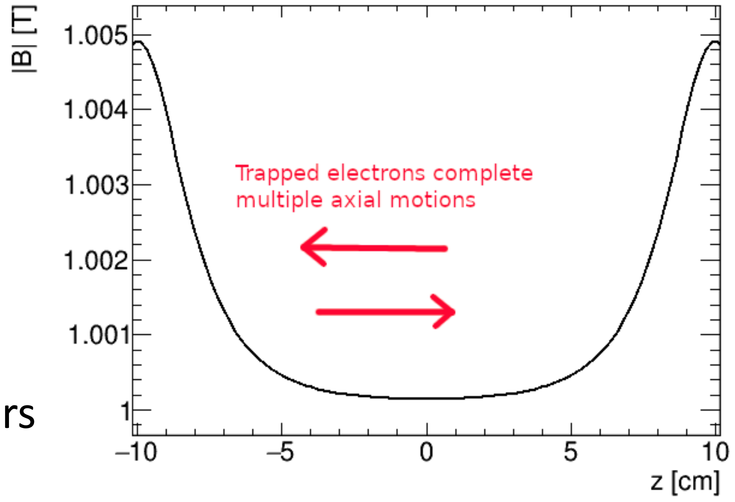


A 5mT trap in a 1T background field gives $\theta_{\text{bot}} \geq 86°$

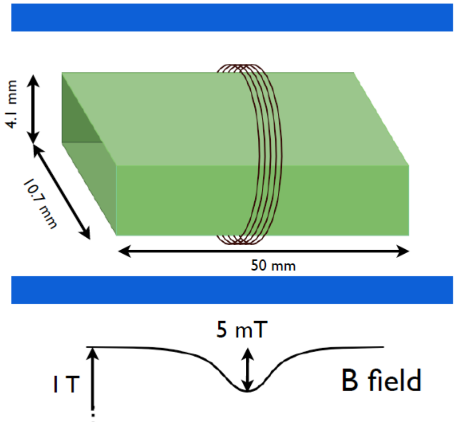
Trapped fraction

$$\eta_{\text{trapped}} = \sin\delta\theta, \quad \delta\theta = \arccos\left(\sqrt{1 - \frac{\Delta B}{B_{\max}}}\right)$$

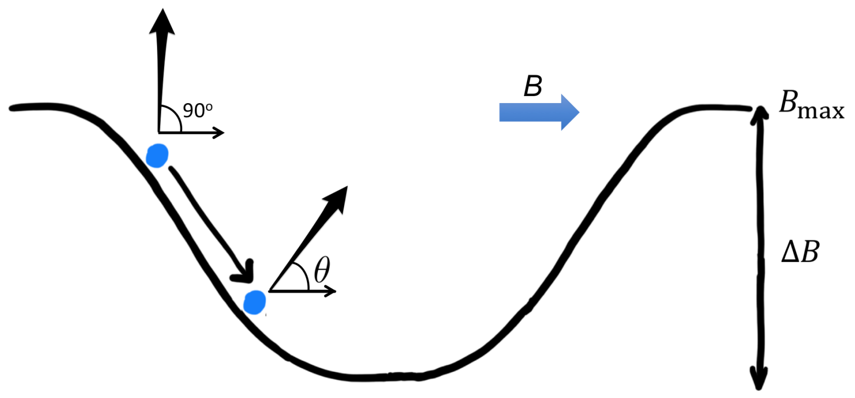
Only 7% of electrons trapped with above parameters



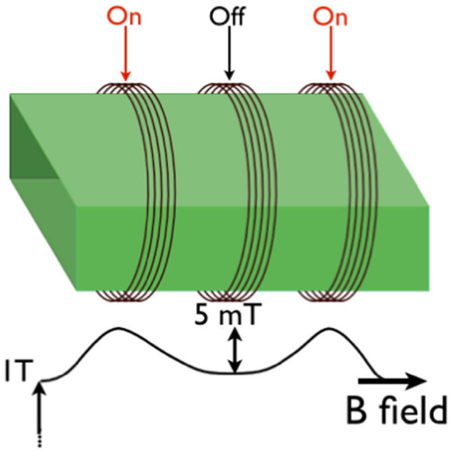
Why not deeper traps?



“Harmonic” Trap



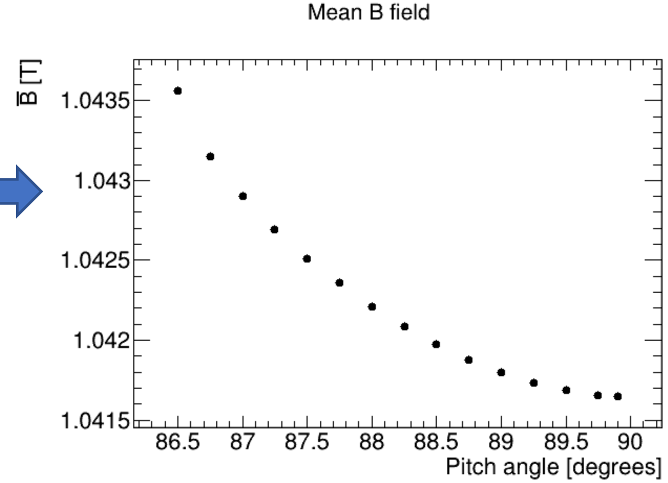
Ashtari Esfahani *et al.*, Phys. Rev. C 99, 055501 (2019)



"Bathtub" Trap

- Trade-off between efficiency and resolution
- Cyclotron frequency depends on average B field experienced by electron
- “Deep” trap – more electrons trapped but poorer frequency(energy) resolution
- “Shallow” trap – better resolution but fewer electrons trapped

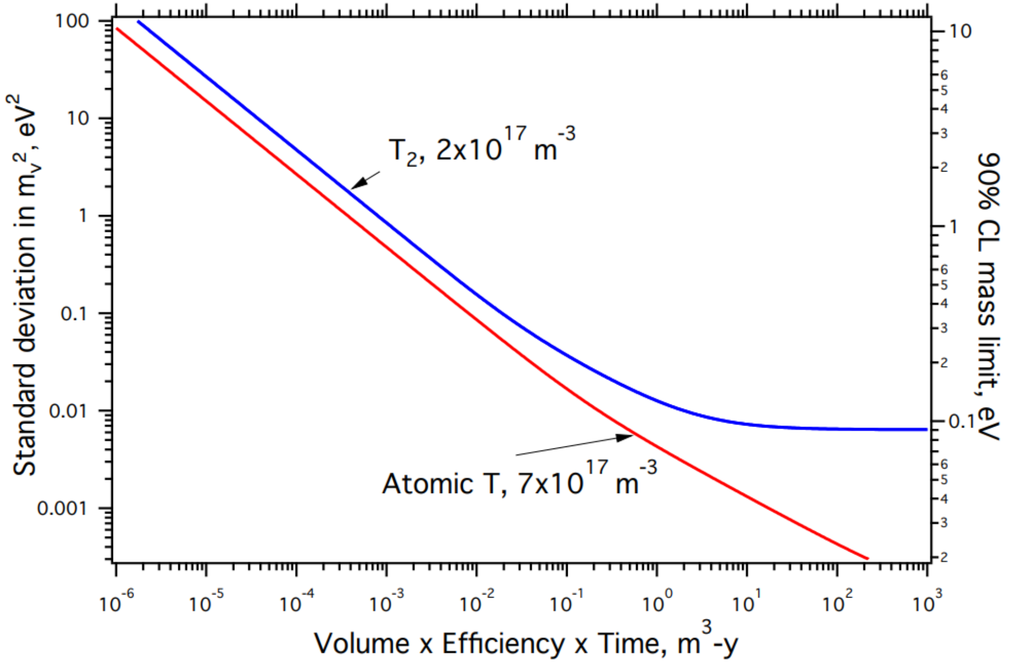
Difference between min. and max. average B field equates to a frequency(energy) difference of 54 MHz(1060 eV)



Crucial that we use signal features to reconstruct electron pitch angle

CRES: targets and challenges

- The 'final' neutrino mass experiment (ensuring a 'guaranteed observation' of neutrino mass) will require:
  - Energy resolution, $\Delta E \sim 0.1$ eV
  - Production of atomic tritium source
  - Trapping and observation of 10^{20} tritium atoms at one time for ~1 year
  - For atomic density of 10^{19} m^{-3}, could be realised with a 3 year run, 75% volume efficiency, 10% pitch angle efficiency and 44 m^3 volume
  - Large volumes with high field uniformity and good acceptance challenging
  - Trap a range of pitch angles *without* degradation of ΔE



- CRESDA provides a pathway towards this final experiment
  - Demonstration of atomic trapping with H/D atoms
  - Detection of CRES signals from electrons around tritium endpoint energy
  - Testing of possible CRES detection options (antennas, waveguides, cavities)
  - Use of quantum-limited electronics to overcome weak signal power
  - High-precision magnetic field mapping

A highly recommended Review from which many plots of this Lecture are taken:

Phys. Rep. 914 1-54 (2021)

Possible Questions for the Tutorial Session (on Overview part)

Q1.1 Why inverted mass ordering is "favourable" for a positive neutrino mass detection? Why m_β *cannot be zero in any scenario if* $m_{1,2,3} \neq 0$*, but* $m_{\beta\beta}$ *can be?*

Q1.2 If Cosmology appears to deliver most sensitive absolute neutrino mass measurement why do we need other methods?

Q1.3 What are pros and cons of the three methods m_β *measurement using* β*-decay?*

Q1.4 Why KATRIN sensitivity is limited to 0.2 eV? What limits the sensitivity of the MAC-E method?

Q1.5 How do we know with "pitch angles" β*-decay electrons are trapped in a magnetic bottle?*

Q1.6 How is the sensitivity of the β*-decay method of measuring the neutrino mass is calculated (back-of-the envelope)?*

Q1.7 How can the B-field homogeneity be controlled/measured at a sub-ppm level?

Q1.8 Is a fully-fledged fusion centre necessary for a neutrino mass experiment?

Are there other options if CCFE not available?