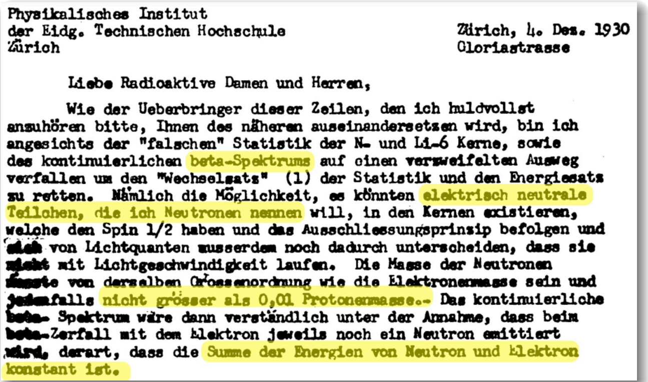
Future Experiments for Neutrinos mass determination

νPhys 2023, London

Wouter Van De Pontseele
Massachusetts Institute of Technology
December 20, 2023
wvdp@mit.edu



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.

- **β-spectrum** seems to **violate energy conservation**.
- Propose a **new particle**: the neutrino
- Must be **neutral** and have a super **tiny mass** ... or no mass at all?

Pauli & Fermi speak at Solvay 1933, and a year later, Fermi writes down a theory about β-decay

- Rejected by Nature
- **Neutrino mass** will affect the shape of the **electron energy spectrum near the endpoint**!
- Independently suggested by Perrin in 1933


TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (¹) di Enrico Fermi

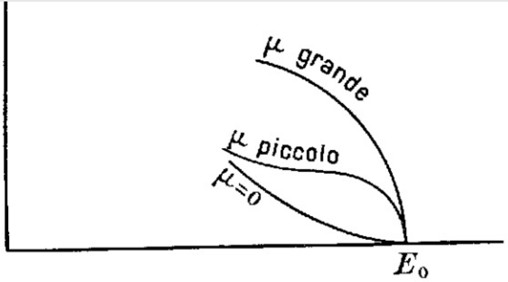


Fig. 1

Pauli & Fermi speak at Solvay 1933, and a year later, Fermi writes down a theory about β-decay

- Rejected by Nature
- **Neutrino mass** will affect the shape of the **electron energy spectrum near the endpoint**!
- Independently suggested by Perrin in 1933

$\Rightarrow$ Does not require detecting neutrinos!


TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (1) di ENRICO FERMI

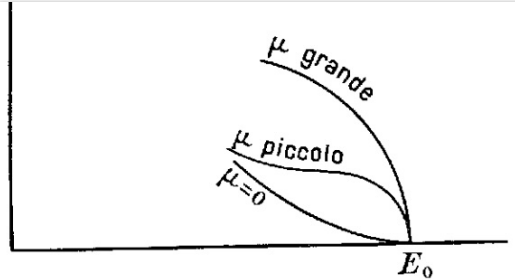
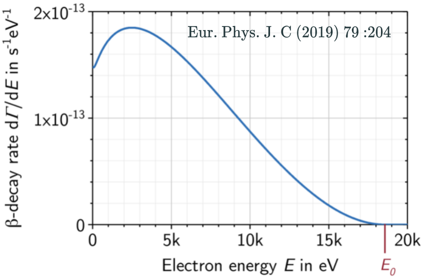


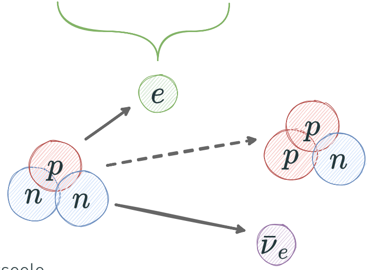
Fig. 1



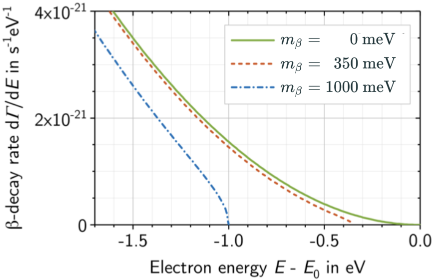
Electron energy distribution from tritium β-decay:

$$\frac{dN}{dE} \sim (E_0 - E)\sqrt{(E_0 - E)^2 - m_\beta^2}$$

$$m_\beta = \sqrt{\sum_{i=1}^{3} \mid U_{ei}^2 \mid m_i^2}$$



zoom in around endpoint E_0



Beta Spectrum of Tritium

S. C. CURRAN, J. ANGUS & A. L. COCKCROFT

Nature **162**, 302–303 (1948)

The β-Spectrum of H³

G. C. HANNA AND B. PONTECORVO

Chalk River Laboratory, National Research Council of Canada, Chalk River, Ontario, Canada

January 28, 1949

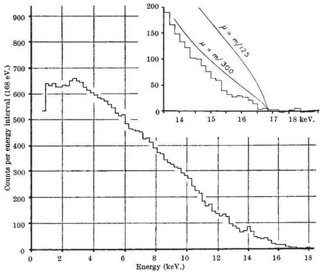
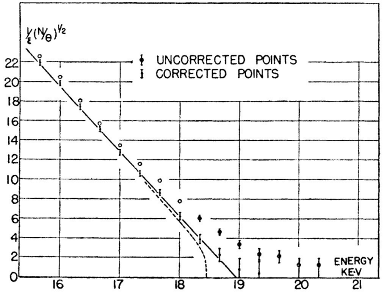
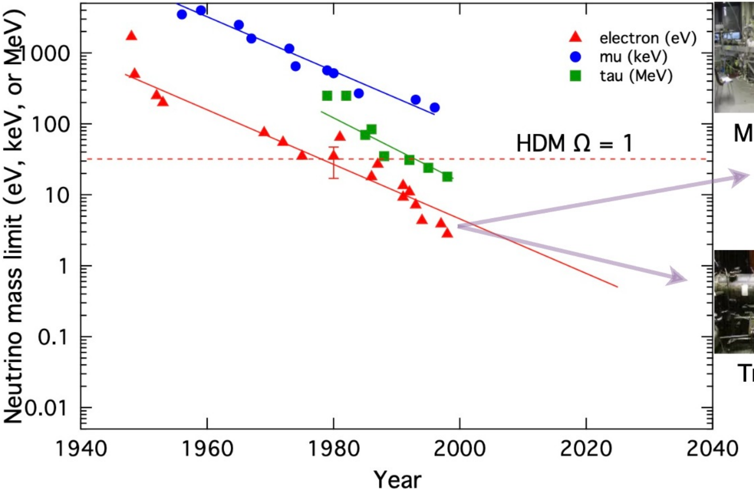


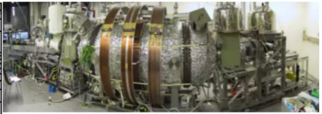
Fig. 2



$m_\beta \lesssim 1700$ eV

$m_\beta \lesssim 500$ eV





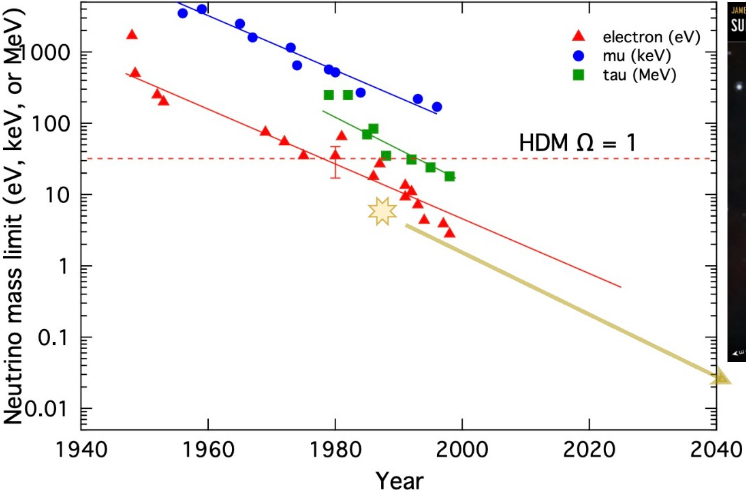
Mainz (2005 final analysis)

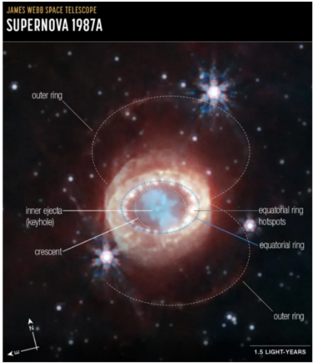
$$m_\beta < 2.3\,\mathrm{eV}$$

Troitsk (2011 re-analysis)

$$m_\beta < 2.05\,\mathrm{eV}$$

adapted from Hamish Robertson

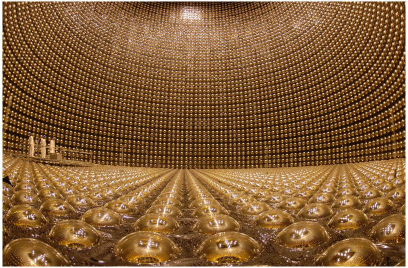


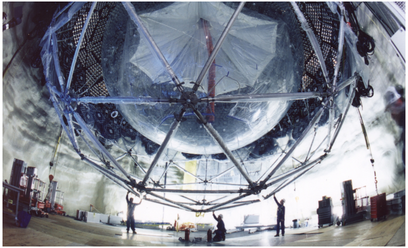


Time of flight: SN1987A

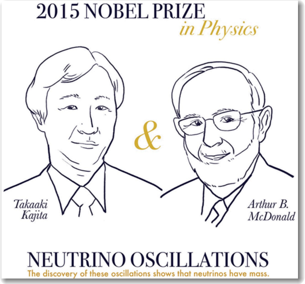
$$m_\beta < 5.7\,\mathrm{eV}$$

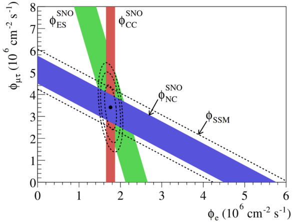
adapted from Hamish Robertson

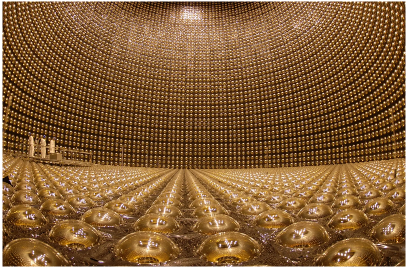


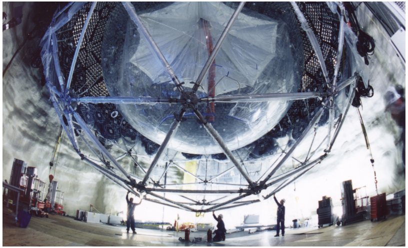


1. Minimal SM prediction $m_\beta = 0$ **must be wrong**
2. We only need to measure m_β **to fix the three mass eigenstates**
3. **Oscillation** measurements **cannot measure the absolute scale**



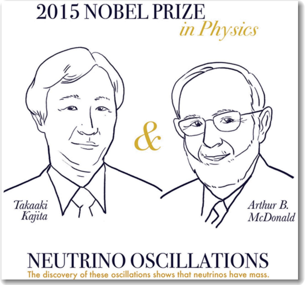


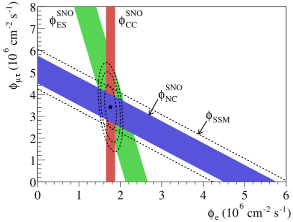




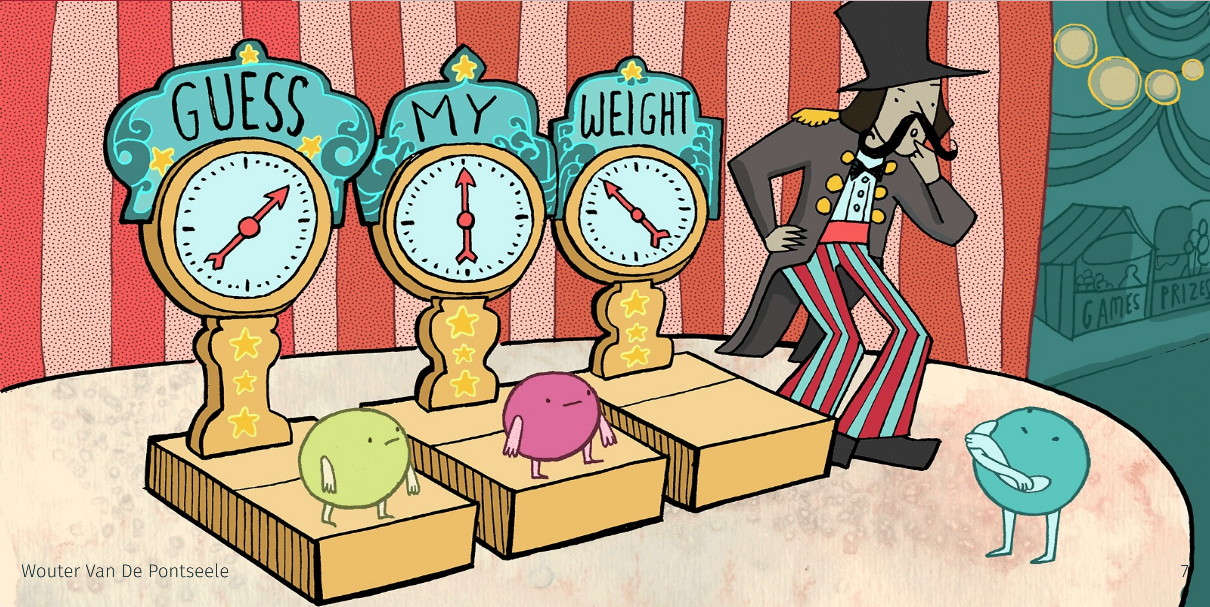
1. Minimal SM prediction $m_\beta = 0$ **must be wrong**
2. We only need to measure m_β **to fix the three mass eigenstates**
3. **Oscillation** measurements **cannot measure the absolute scale**

but set lower limit: $m_\beta \gtrsim 9\,\text{meV}$



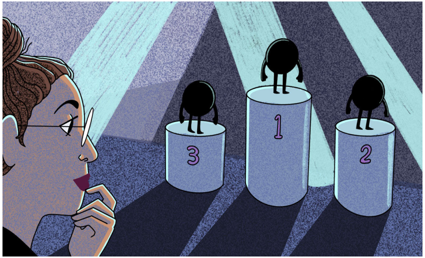


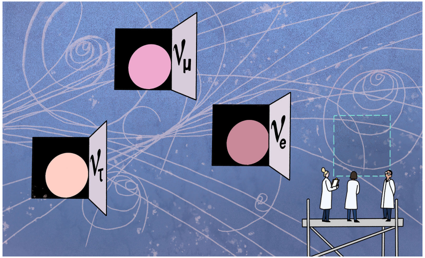
Symmetry Magazine

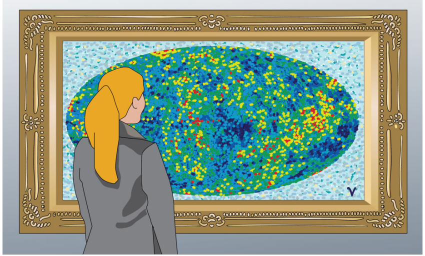


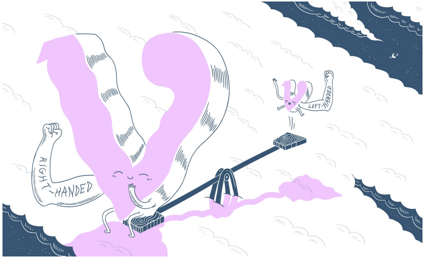
Symmetry Magazine

- Neutrino Mass ordering
- Sensitive to sterile ν's
- Ingredient in cosmological models
- Majorana or Dirac?









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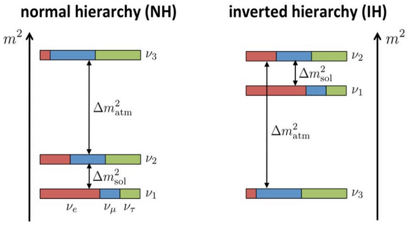
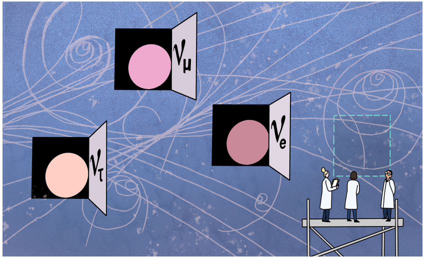
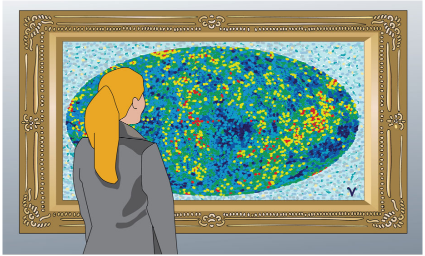
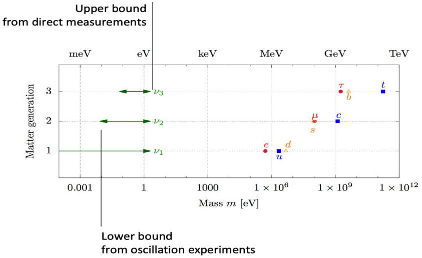








Cosmology

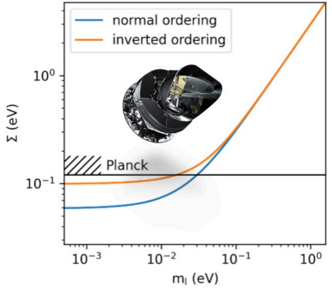
$$\Sigma = \sum_i m_i$$

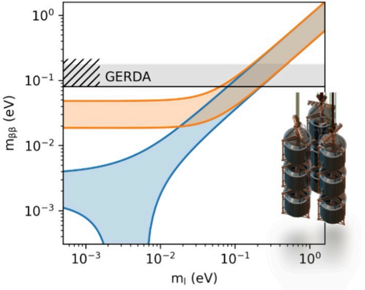
$0\nu\beta\beta$-decay

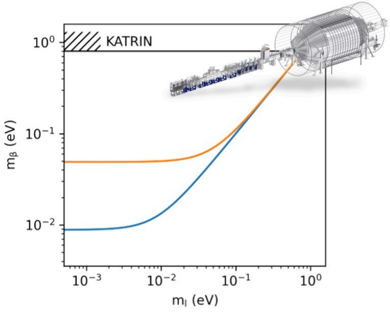
$$m_{\beta\beta} = \sum_i (U_{ei})^2 m_i$$

Kinematics

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







by Susanne Mertens

Cosmology

$$\Sigma = \sum_i m_i$$

- Model dependent

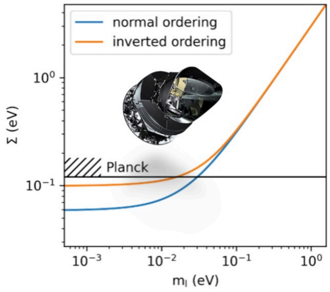
$0\nu\beta\beta$-decay

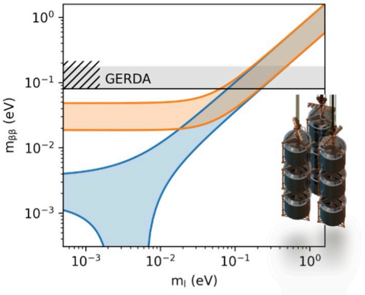
$$m_{\beta\beta} = \sum_i (U_{ei})^2 m_i$$

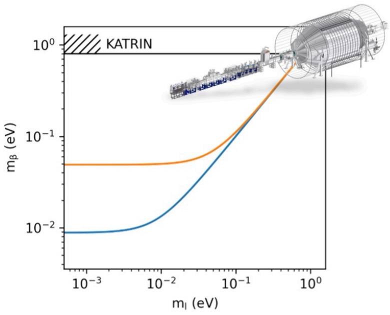
- Only if Majorana

Kinematics

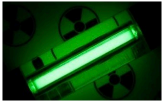
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

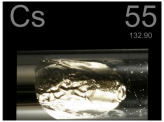






by Susanne Mertens

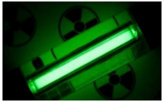


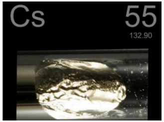


Type	Element	Isotope	Half-life (years)	Mass diff (Q)
β-decay	Tritium	$^3H_2$	12	18 keV
	Indium	^{115}In	4×10^{14}	0.15 keV
	Cesium	^{135}Cs	1×10^6	0.44 keV
	Rhenium	^{187}Re	4×10^{10}	2.5 keV
Electron capture	Holmium	^{163}Ho	4750	2.8 keV

1. **Low Mass difference**: Number of events in last eV goes as $1/Q^3$
2. **Low half-life time**: increases statistics.

Ultra-low Q sources are under study,
Currently Tritium and Holmium are the favorites





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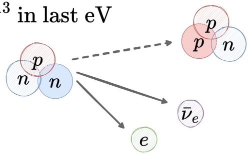
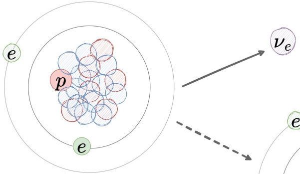
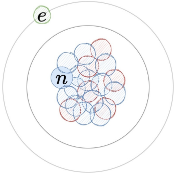
β-decay

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

3×10^{-13} in last eV







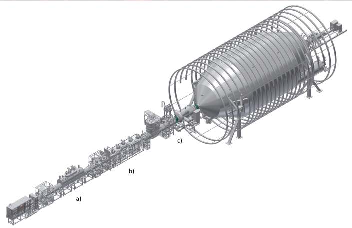
Electron capture

$^{163}\mathrm{Ho} + e^- \rightarrow ^{163}\mathrm{Dy}^* + \nu_e$

$\approx 10^{-12}$ in last eV

What experimental techniques are on the table?

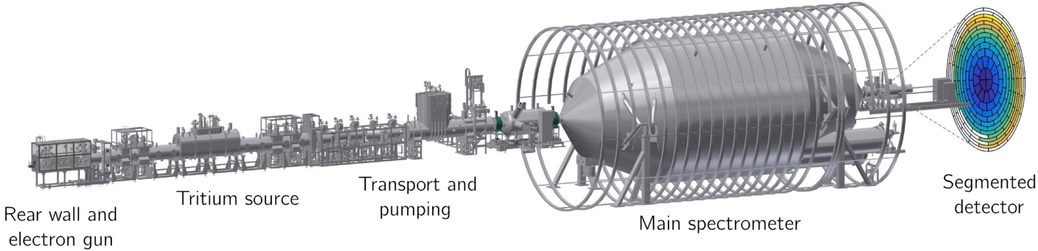
Method	Variable affected by m_ν	Resulting measurements	Isotope
MAC-E filter	**Electron energy**	**Counts above threshold**	**Tritium**
Calorimetry	Deposited energy	Heat/Phonons	Holmium
CRES	Electron energy	Frequency spectrum	Tritium
Levitating particles	Recoil spectrum	Scattered light	TBD



KATRIN
KARLSRUHE TRITIUM NEUTRINO EXPERIMENT

Katrin: Magnetic Adiabatic Collimation combined with an Electrostatic Filter

Adiabatic regime: transverse kinetic energy / $|\vec{B}|$ is constant.



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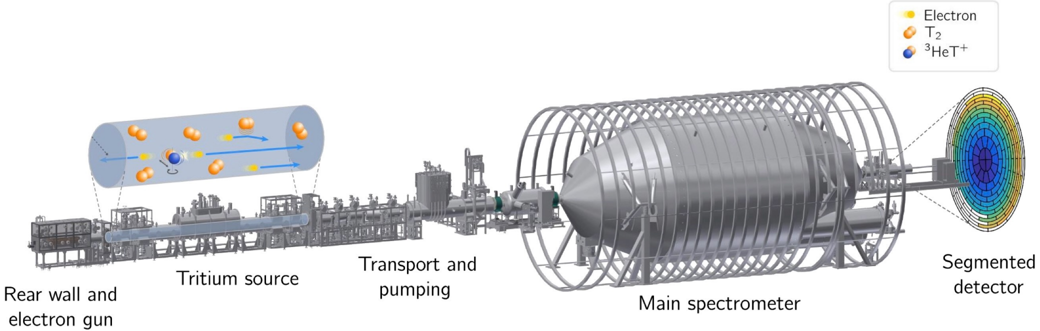

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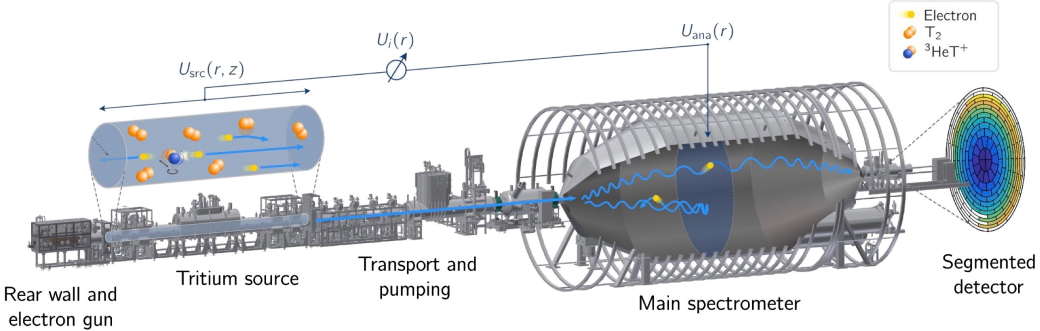
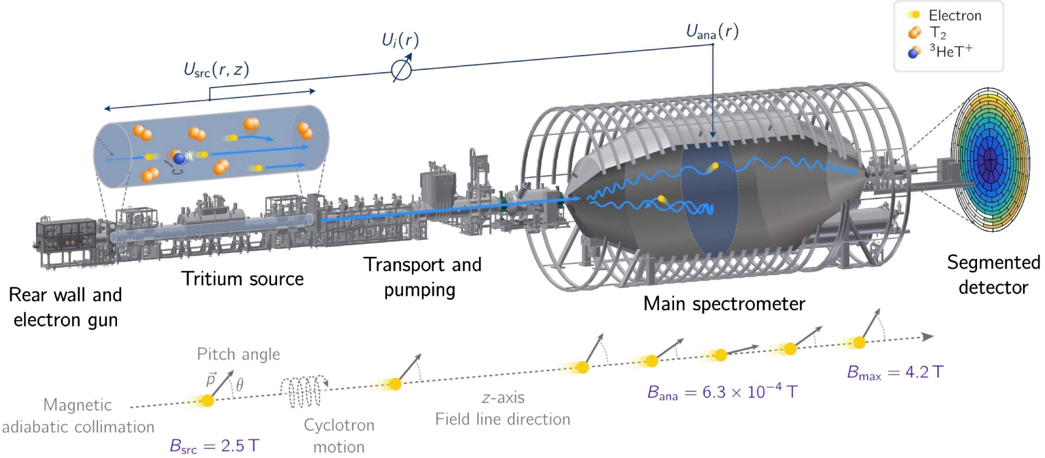


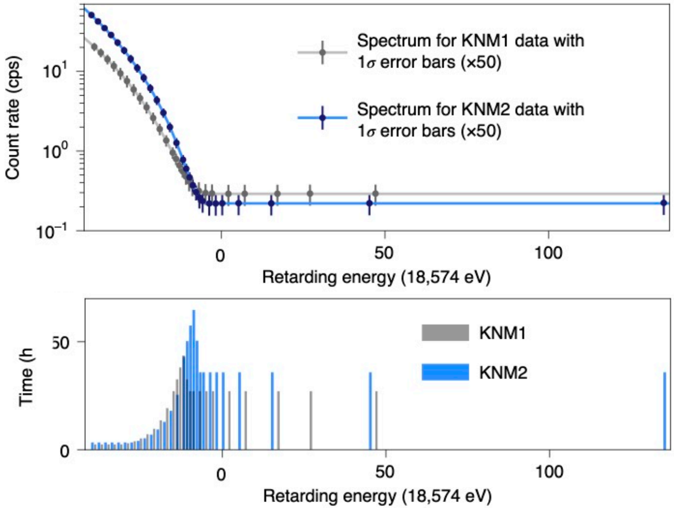
Spectrometer acts as an **integrating high-energy pass filter**

Adiabatic regime: transverse kinetic energy / $|\vec{B}|$ is constant.

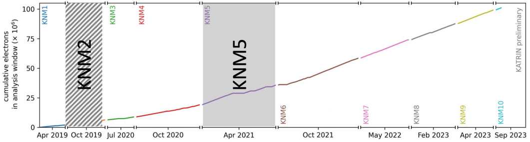


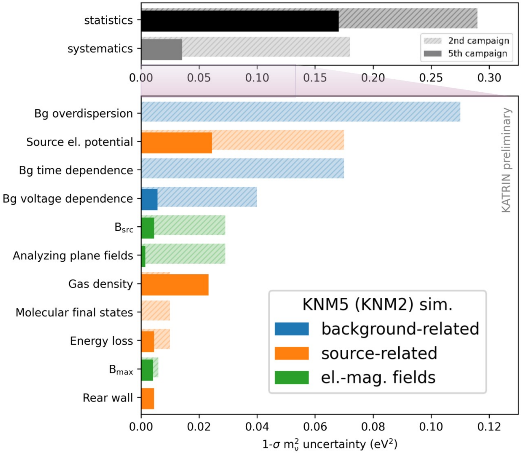
Spectrometer resolution: $\Delta E/E = B_{min}/B_{max}$


GERMANY
400 km
Deggendorf
Karlsruhe
1
2
3
4
5
6
7



- Combination of first two run periods, **less than 100 days of data**.
- Combined result: $m_\beta < 0.8$ **eV** (90% CL)
- KATRIN Collaboration, Nat. Phys. 18, 160–166 (2022)
- Search for relic-ν overabundance, sterile neutrinos and violation of Lorentz invariance



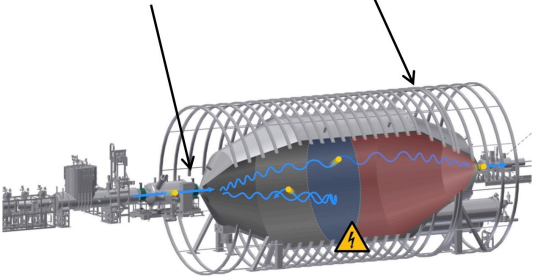


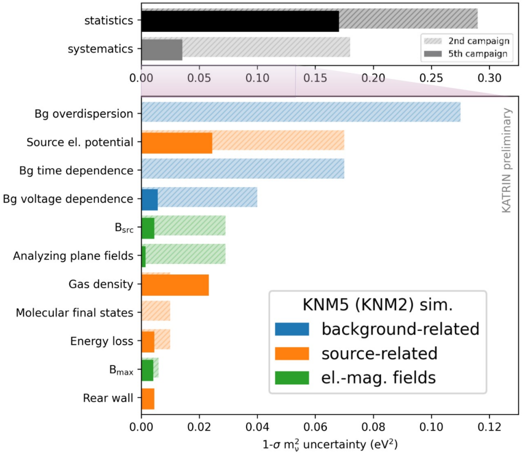
- A lot more data!
- Reduction in systematic uncertainties.

- Reduction in systematic uncertainties.

Shifted analzing plane
Lokhov et al arXiv:2201.11743 (2022)

Elimination of penning trap
Eur. Phys. J. C 80: 821, 2020





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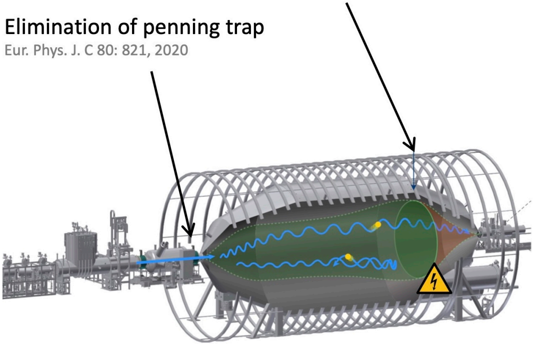
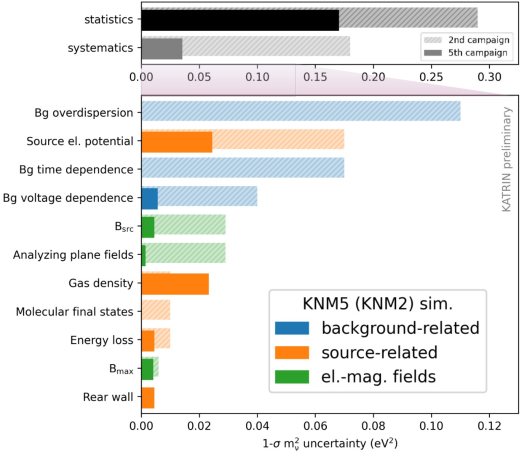
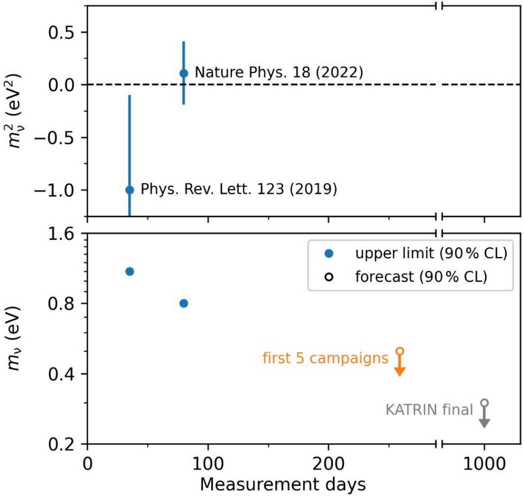
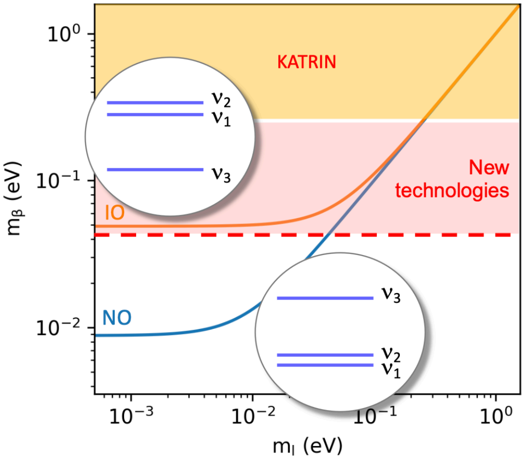






- Finalising analysis of the first five runs
- **Sensitivity**: $m_\beta < 0.5$ eV (90% CL)
- Data taking ongoing till 2025 with **final sensitivity** better than $m_\beta < 0.3$ eV.
- **Next up: Sterile neutrino search** facilitated by silicon-based pixelated e^- detection (TRISTAN).

by Susanne Mertens



- Finalising analysis of the first five runs
- **Sensitivity**: $m_\beta < 0.5$ eV (90% CL)
- Data taking ongoing till 2025 with **final sensitivity** better than $m_\beta < 0.3$ eV.
- **Next up: Sterile neutrino search** facilitated by silicon-based pixelated e^- detection (TRISTAN).

New technologies needed to explore the **inverted mass ordering**!

What experimental techniques are on the table?

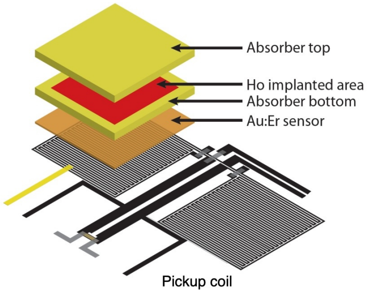
Method	Variable affected by m_ν	Resulting measurements	Isotope
MAC-E filter	Electron energy	Counts above threshold	Tritium
Calorimetry	**Deposited energy**	**Heat/Phonons**	**Holmium**
CRES	Electron energy	Frequency spectrum	Tritium
Levitating particles	Recoil spectrum	Scattered light	TBD

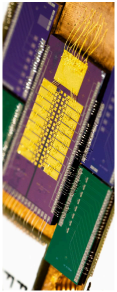
Calorimetric technology

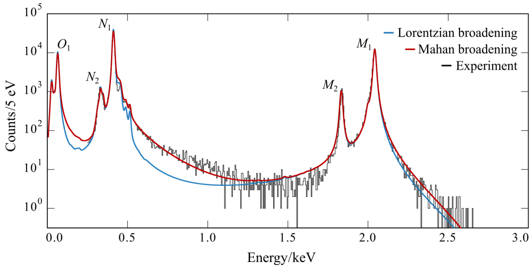
- Magnetic MicroCalorimeter (MMC) Material magnetisation depends on temperature.

Achievements

- Prototype with 4 pixels: $\nu_\beta < 150$ eV.





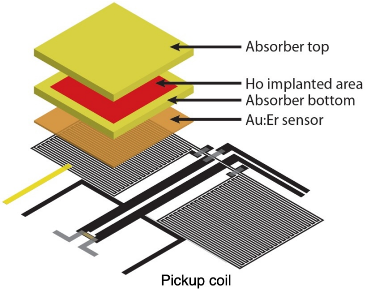


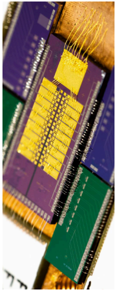
Calorimetric technology

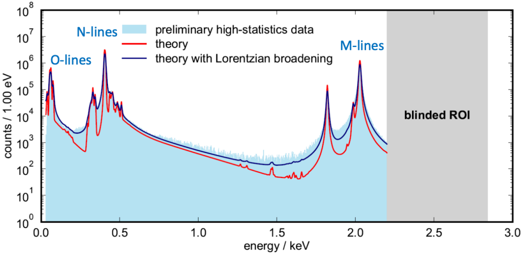
- Magnetic MicroCalorimeter (MMC)
  Material magnetisation depends on temperature.

Achievements

- Prototype with 4 pixels: $\nu_\beta < 150$ eV.
- ECHo-1k: Systematics in progress
  Expected sensitivity: $\nu_\beta < 20$ eV.







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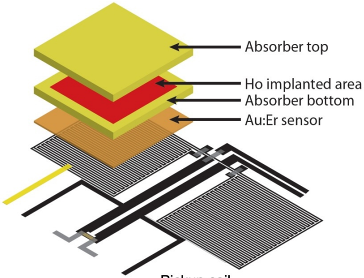
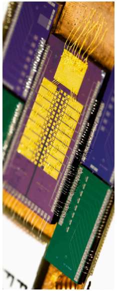
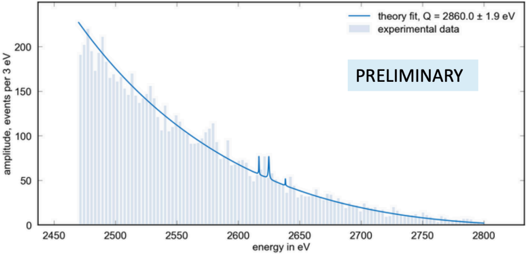






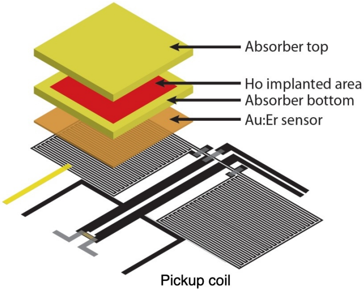
ECHo: Electron Capture ^{163}Holmium experiment

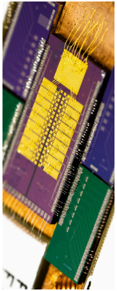
Calorimetric technology

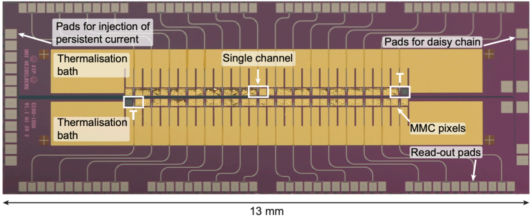
- Magnetic MicroCalorimeter (MMC)
  Material magnetisation depends on temperature.

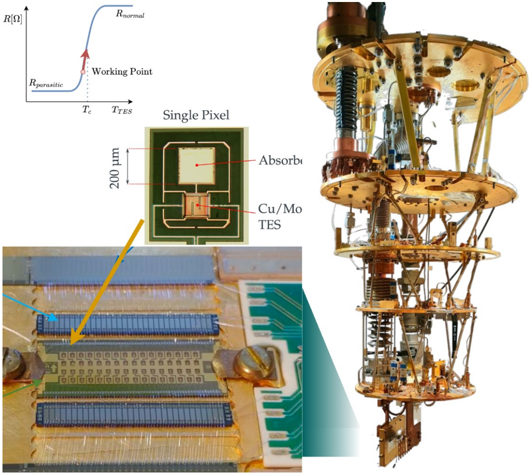
Achievements

- Prototype with 4 pixels: $\nu_\beta < 150$ eV.
- ECHo-1k: Systematics in progress
  Expected sensitivity: $\nu_\beta < 20$ eV.
- ECHo-100k: 1200 multiplexed pixels with $\mathcal{O}$(eV) sensitivity.





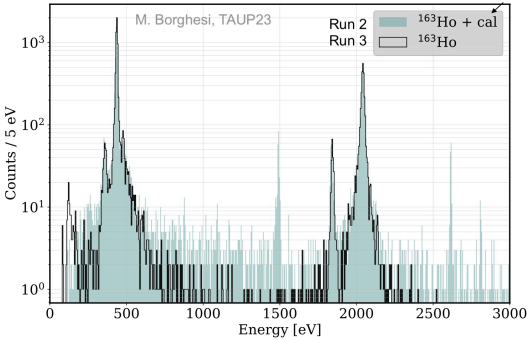




Calorimetric technology

- Transition Edge Sensors (TES)
  Thin film superconductor

First **endpoint measurement in progress**,
Spectrum from 4 pixels with $\Delta E \approx 6\,\text{eV}$:



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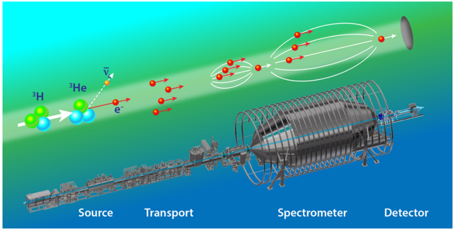
PROJECT 8

QTNM
Quantum Technologies for Neutrino Mass

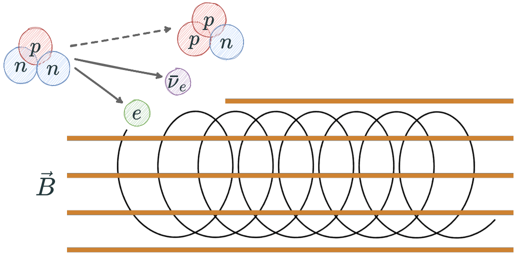
How to **scale down** KATRIN while **increasing** the m_β **sensitivity**?



How to **scale down** KATRIN while **increasing** the m_β **sensitivity**?

1. **Spectroscopic** instead of integral
2. Use a **source inside** the **detector**
   Magnetically trapped atomic tritium.
3. **Frequency detection** of cyclotron radiation emitted by electrons.

Tritium decays inside a **uniform** $\vec{B}$-field.



Electron performs **cyclotron motion** with frequency

$$f(B, E_{kin}) = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

How to **scale down** KATRIN while **increasing** the m_β **sensitivity**?

1. **Spectroscopic** instead of integral
2. Use a **source inside** the **detector**
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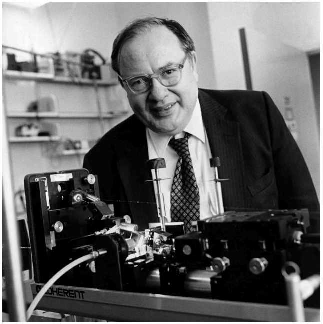
3. **Frequency detection** of cyclotron radiation emitted by electrons.

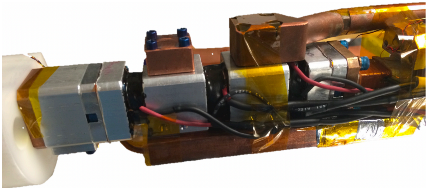
Idea by J. Formaggio and B. Monreal:
Project 8 employs Cyclotron Radiation Emission Spectroscopy (**CRES**)

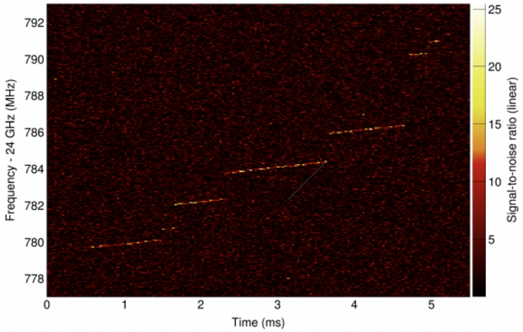


"Never measure anything but frequency"

– Arthur Schawlow, co-inventor of the laser and 1981 Nobel Prize winner

- **Phase I**: First detection of **cyclotron radiation from a single electron**. Gaseous ^{83m}Kr used as a source. Phys. Rev. Lett. 114, 1162501 (2015)





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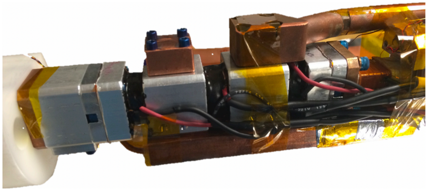

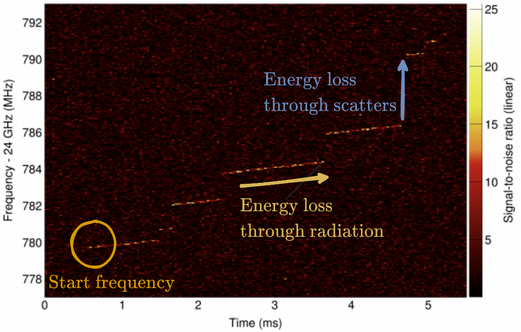

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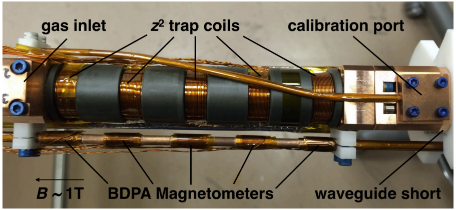

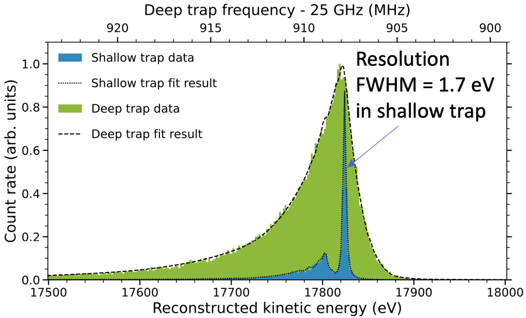

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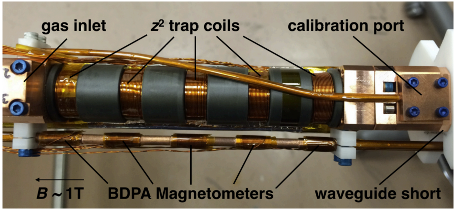
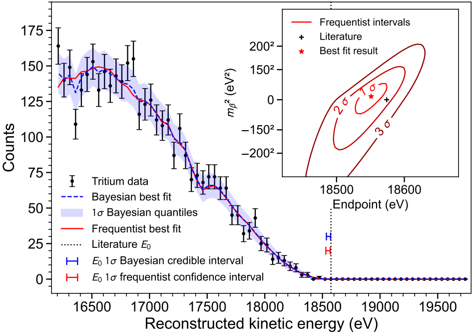
$$m_\beta < 155\,\text{eV}$$



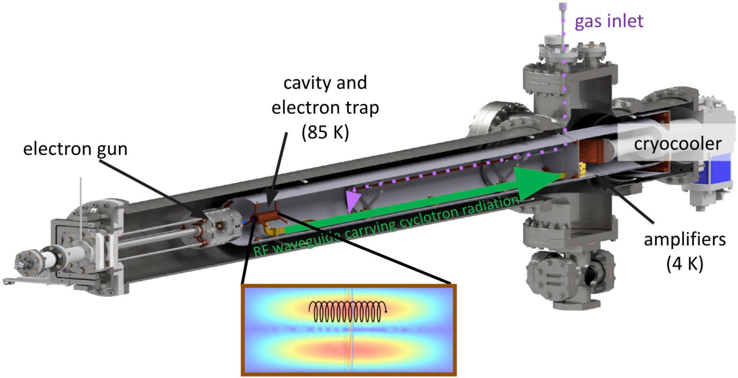


Project 8 Phase II
Spectrometer to scale

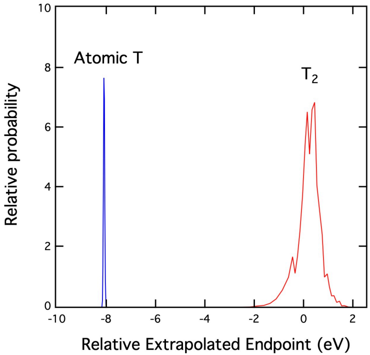
Project 8: What's next?

Phase III:

- Resonant cavities



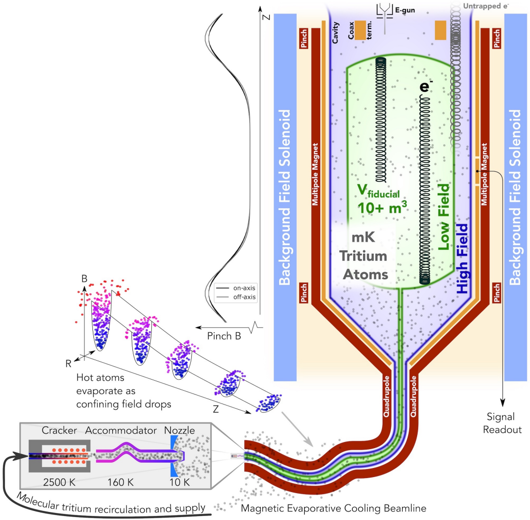
M. Huehn



R. G. H. Robertson

Phase III:

- Resonant cavities
- Atomic tritium as a source



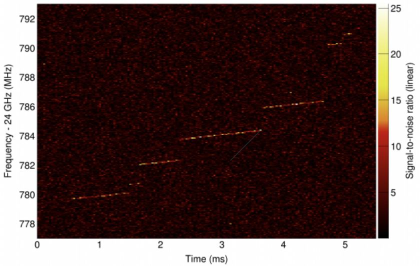
Phase III:

- Resonant cavities
- Atomic tritium as a source
- Scaling to large volumes

Phase IV:

The ultimate neutrino mass experiment probing $m_\beta \approx$ **40 meV**.

- Dropping the magnetic field/frequency to reach $\mathcal{O}(10\ \mathrm{m}^3)$ volume.
- Zeptowatt signals at 325 MHz



Phase III:

- Resonant cavities
- Atomic tritium as a source
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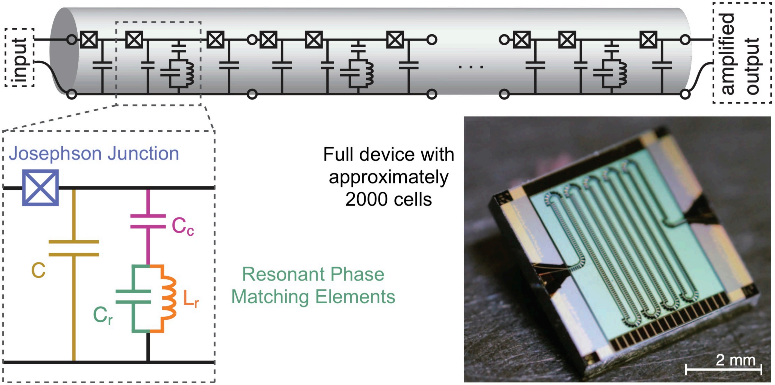
Phase IV:

The ultimate neutrino mass experiment probing $m_\beta \approx$ **40 meV**.

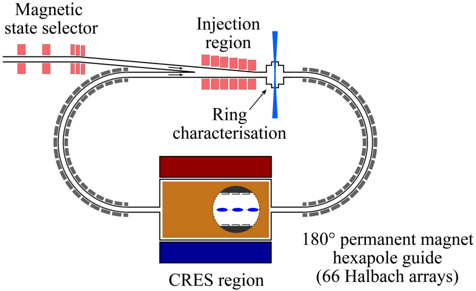
What do we need?

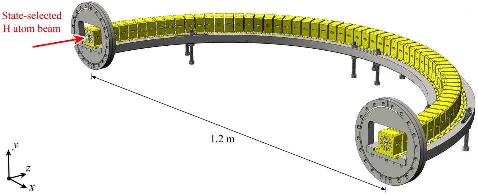
1. A great team!
2. Less noise!



Transmission line-style chain of cells with Josephson Junctions. Bandwidth of $\mathcal{O}$(GHz).

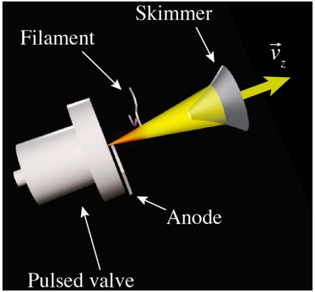
Designed by Kevin O'Brien's group at MIT, fabricated at Lincoln Laboratories.





Storage ring and free space CRES

- Modular with multiple CRES cells
- Antenna array readout



Storage ring and free space CRES

- Modular with multiple CRES cells
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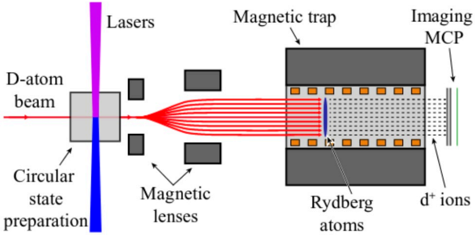
Supersonic beam using DC discharge

- Creates beam with temperature of $\mathcal{O}(10\,\text{mK})$ in the moving frame
- Next steps:
  higher densities and continuous operation



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Rydberg states magnetometry

- Driven transition inside CRES cell.
- $\vec{B}$ sensitivity $<$ µT with $\approx$1 mm resolution.

What experimental techniques are on the table?

Method	Variable affected by m_ν	Resulting measurements	Isotope
MAC-E filter	Electron energy	Counts above threshold	Tritium
Calorimetry	Deposited energy	Heat/Phonons	Holmium
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Searches for Massive Neutrinos with Mechanical Quantum Sensors

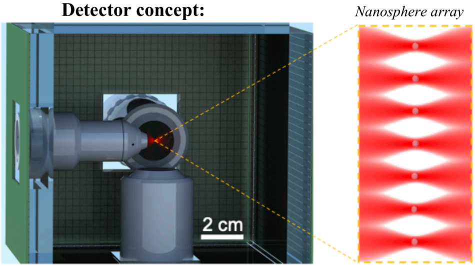
Daniel Carney, Kyle G. Leach, and David C. Moore
PRX Quantum **4**, 010315 – Published 8 February 2023

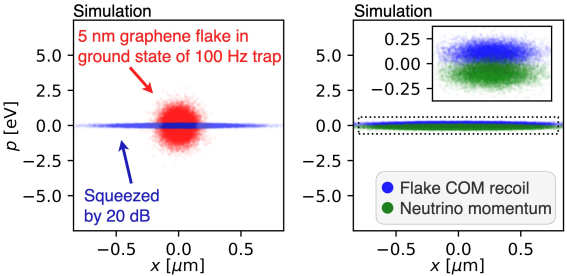
THE BeEST

Particles with diameter $\mathcal{O}(100\,\text{nm})$ to $\mathcal{O}(10\,\mu\text{m})$ can be **optically trapped** in a vacuum.

$\vec{x}, \vec{p}$ measured by back-action of readout laser.

Near-future: dark matter limits, search for millicharged particles & sterile neutrinos.





Squeezing uncertainty into $\vec{x}$ might enable **momentum** detection $\mathcal{O}(100\,\text{meV})$ in the **not-so-near future** from graphene spheres doped with ultra-low Q isotopes.

Conclusions & Outlook

Standing on the shoulders of giants

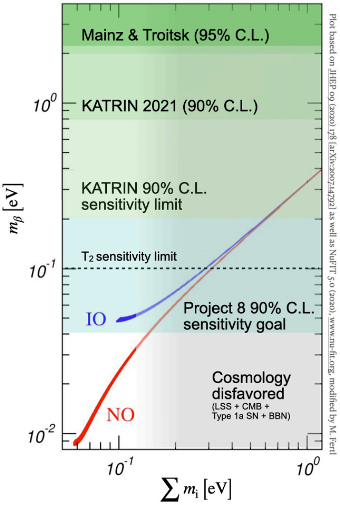
- Neutrino oscillations, theory improvements and collaboration with cosmology & $0\nu\beta\beta$-decay searches.
- **KATRIN**'s tremendous systematic reduction will lead to $\boldsymbol{m_\beta < 0.5\,\mathrm{eV}}$ limits soon.

New kids on the block

- Cyclotron radiation, calorimetric spectrum of electron capture, and atomic tritium are progressing quickly.

...And the challenges ahead

- Plenty of **demonstrator experiments** to look forward to!

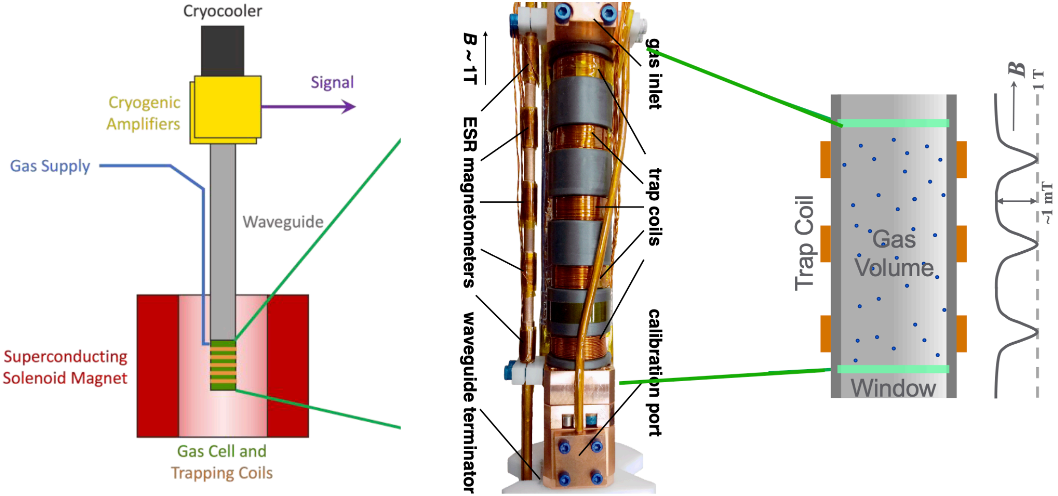


Thank you!

WVDP@MIT.EDU

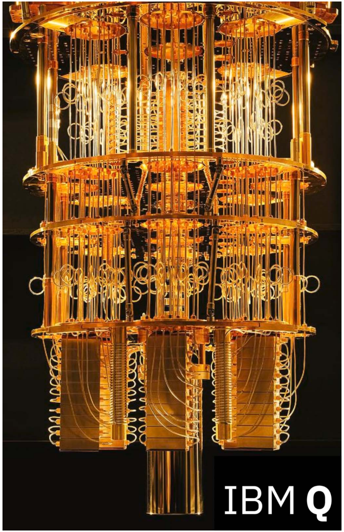
Special thanks to
Project 8, KATRIN, QTNM,
MIT Laboratory for Nuclear Science,
MIT Lincoln Laboratories & MIT.Nano,
J. Formaggio, H. Robertson, S. Mertens, K. Leach

Project 8: Phase II



Driven by Superconducting qubit readout

- **First stage amplifier** limits performance.
- **Bandwidth** enables **multiplexing** qubits.



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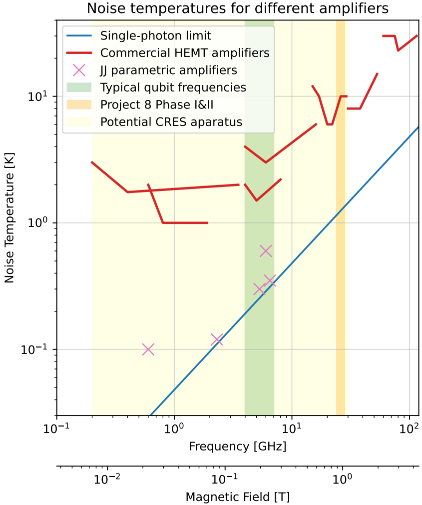
Essential for experiments detecting microwaves

- Lowest noise to detect **CRES signal**.
- Wide frequency range for multiplexing arrays.



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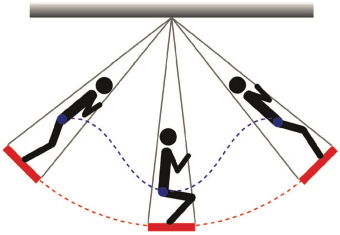
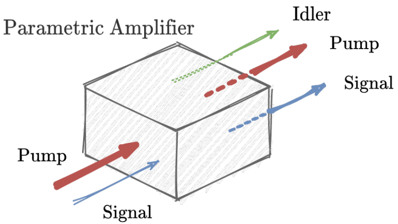
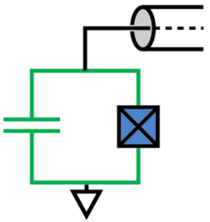
Parametric amplification: $2\omega_p = \omega_s + \omega_i$

- Signal amplification by **exchanging pump power** using the non-linearity of Josephson Junctions.



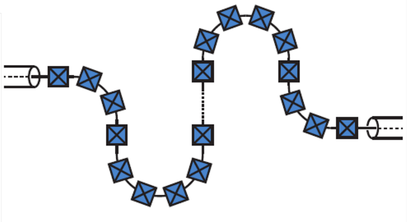


JPA

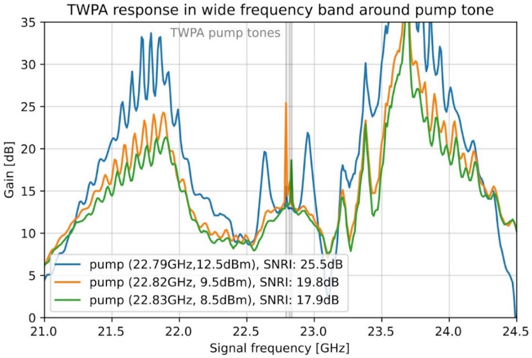


- Few spatial modes – **Cavity** style
- Near **ideal quantum efficiency**
- **Small bandwidth** of $\mathcal{O}(10\,\text{MHz})$.

JTWPA



- **Cell size** $< \lambda$
  $\Rightarrow$ Create nonlinear meta-material.
- Many spatial modes
  $\Rightarrow$ **Transmission line** behaviour.
- Up to $\mathcal{O}(3\,\text{GHz})$ **bandwidth**.



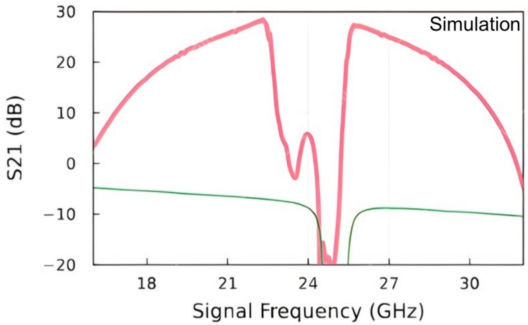
TWPAs fabricated & measured in three frequency bands

Low Frequency	$\mathcal{O}$(0.5 GHz to 1 GHz)
Mid Frequency	$\mathcal{O}$(5 GHz to 9 GHz)
High Frequency	$\mathcal{O}$(17 GHz to 26 GHz)

- At high frequencies, **insertion losses** and package modes matter.
- **Gain ripples** caused by impedance mismatches.
- **Compression power limits** multiplexing applications.

JTWPA improvements on the way

- **Packaging improvements at high frequency:**
  New launch port and connectors.
  Redesigned geometry, **reducing package modes and reflections**.
- **Tri-layer aluminium process**:
  Stable oxides reduce insertion loss.
- **Smoother gain** profile and better **impedance matching** conditions.



Next fabrication round being packaged!

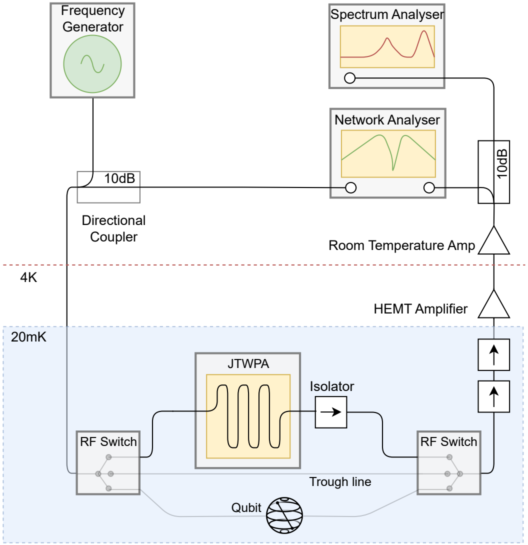
Signal and Noise modelling

- **Axion haloscopes and CRES experiment signals** propagate through and reflect at microwave components.

Signal and Noise power calibration

Relies on a **cryogenic candle**:

- Hot-Cold thermal noise source measurement
- Waveguide coupled Qubit



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Enables photon flux measurement along the transmission line!