Measuring Neutrino Mass

$m_\nu \ll$ mass of other fermions

$m_\nu$ crucial for understanding masses in general

$\Rightarrow$ we would like to know it
$\Delta m_{23}^2 = 2.4 \cdot 10^{-3} \text{ eV}^2$

$\Delta m_{12}^2 = 8 \cdot 10^{-5} \text{ eV}^2$

we know the sum of the three masses is nonzero

$\Sigma m_i > 67 \text{ meV} / 92 \text{ meV} \ (\text{nh/ih})$

but we do not know the mass scale / the value of the lightest mass
β-endpoint spectroscopy
- influence on decay kinematics

Cosmology
- influence on structure formation

0ν2β – decay
- influence on decay rate

SN time of flight ...
Determination of $m_\nu$ from $\beta$ Decay

$\beta$ decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \nu_e$

$$dN/dE_e = K \cdot F(E,Z+1) \cdot p_e \cdot (E_e + m_e) \cdot (E_0 - E_e) \cdot \sqrt{(E_0 - E_e)^2 - m^2(\nu_e)}$$

phase space: $p_e$, $E_{e,\text{tot}}$, $E_\nu$, $p_\nu$

*modified by electronic final states, recoil corrections, radiative corrections*

Need:
- low endpoint energy
- very high energy resolution
- very high luminosity
- very low background

Tritium $^3\text{H}$, ($^{187}\text{Re}$)

MAC-E-Filter
or bolometer
or new idea
Determination of $m_\nu$ from $\beta$ Decay

**electronic final state excited states** have to be included:
- excitation energy $V_j$
- probability $W_j$

$$dN/dE_e = K F(E,Z+1) p (E_e + m_e)$$

$$\cdot \sum_j W_j (E_0 - E_e - V_j) \sqrt{(E_0 - E_e - V_j)^2 - m^2(\nu_e)}$$

- $V_j$ not seen in MAC-E filter ( + scattering in the source )
- modifies phase space for all types of measurement

$\nu$ mixing:

$$dN/dE_e = K F(E,Z+1) p (E_e + m_e)$$

$$\cdot \sum_j W_j (E_0 - E_e - V_j) \cdot \left( \sum |U_{ei}|^2 \cdot \sqrt{(E_0 - E_e - V_j)^2 - m^2(\nu_i)} \right)$$

$\Rightarrow \beta$ endpoint measures effective $\nu$ mass:

$$m_\beta = \sum |U_{ei}|^2 \cdot m^2(\nu_i)$$
Tritium $\beta$-Spectroscopy with a MAC-E-Filter

- magnetic guiding field
- adiabatic transformation: $\mu = E_\perp / B = \text{const.}$
  $\Rightarrow$ parallel $e^-$ beam
- energy analysis by electrostatic retarding field
  $\Delta E = E \cdot B_{\min} / B_{\max}$
  $= 0.93 \text{ eV (KATRIN)}$
  $\Rightarrow$ sharp integrating transmission function

Magnetic Adiabatic Collimation + Electrostatic Filter
KATRIN - The Karlsruhe Tritium Neutrino Experiment

Tritium source

Transport section

Pre spectrometer

Spectrometer

Detector

\[ \beta \text{ decay} \]

\[ 3\text{H} \rightarrow 3\text{He} + \nu_e + e^- \]

\[ E = 18.6 \text{ keV} \]

\[ 10^{10} \text{ e}^- / \text{s} \]

\[ \Delta E = 0.93 \text{ eV} \]

\[ E > 18.3 \text{ keV} \]

\[ 1 \text{ e}^- / \text{s} \]

\[ \approx 70 \text{ m} \]

Sensitivity on \( m(\nu_e) \):  
\[ 2 \text{ eV/c}^2 \rightarrow 200 \text{ meV/c}^2 \]
long superconducting solenoids
\( \varnothing \ 9 \text{cm}, \text{length: } 10 \text{m}, \ T = 30 \text{ K} \)

Tritium recirculation (and purification)
\( p_{\text{inj}} = 0.003 \ \text{mbar}, \ q_{\text{inj}} = 4.7 \text{Ci/s} \)

allows to measure with near to maximum count rate using
\( \rho d = 5 \cdot 10^{17} / \text{cm}^2 \)
Molecular Windowless Gaseous Tritium Source

KATRIN
the ultimate MAC-E type spectrometer

column density at the limit

more intensive source
⇒ increase source-Ø
⇒ needs larger spectrometer Ø
to keep sensitivity

improve sensitivity ΔE
⇒ even larger spectromter Ø

ΔE/E = B_{min}/B_{max}
spectrometer
transmission function \((E, \theta)\)
- characterized with e-beam
- well understood

so far dominating background:
Rn emanation in getter pumps
- completely removed by cryogenic baffles
contributions with $\delta m_\nu^2 \leq 0.007 \text{ eV}^2$ ($80\text{ meV}$) each:

1. inelastic scatterings of $\beta$’s inside WGTS
   - dedicated e-gun measurements, unfolding of response fct.

2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, $T=30\text{K}$ stabilisation,
     e-gun measurements

3. WGTS charging due to remaining ions (MC: < 20mV)
   - monocrystalline rear plate short-cuts potential differences

4. final state distribution
   - reliable quantum chem. Calculations

5. transmission function
   - detailed simulations, angular-selective e-gun measurements

6. HV stability of retarding potential on ~3ppm level required
   - precision HV divider (with PTB), monitor spectrometer beamline
contributions with

1. inelastic scatterings
   - dedicated e-gun measurements

2. fluctuations of WGTS column density
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, e-gun measurements

3. WGTS charging due to remaining ions
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5. transmission function
   - detailed simulations, e-gun measurements

6. HV stability of retarding potential
   - precision HV divider (with PTB)

sensitivity:

\[ m_\nu < 0.2 \text{eV} \]

(90% CL)

discovery potential:

\[ m_\nu = 0.3 \text{eV} \]

(3\sigma)

\[ m_\nu = 0.35 \text{eV} \]

(5\sigma)

start 2016/17

5y data taking
neutrino is most abundant particle (after photon)
as higher $\sum m_\nu$
as higher neutrino contribution
to energy density in the Universe
neutrinos are hot dark matter
$\Rightarrow$ damp structure growth at smaller scales
studying structure at different scales and $z$
is very sensitive to $\sum m_\nu$
CMB, galaxy distribution, Lyman $\alpha$, ...
very sensitive, but model dependent
depending on the data sets included
limits on \( \Sigma m_\nu < 0.17 \ldots 0.72 \) eV

We take the combined constraint further including BAO, JLA, and \( H_0 \) (“ext”) as our best limit
\[
\sum m_\nu < 0.23 \text{ eV} \quad \Omega, h^2 < 0.0025 \quad 95\%, \ Planck \ TT+lowP+lensing+ext. \quad (57)
\]

Planck best limit
\[ \Sigma m_\nu < 0.23 \text{ eV} \]

**EUCLID**: launch 2020
microlensing (galaxy shapes)
as function of redshift \( z \) (spectroscopy)
\( \Rightarrow \) 3D structure of a large part of visible Universe
\( \Rightarrow \) can get as low as \( \Sigma m_\nu < 10 \) meV
\( \Rightarrow \) must see the effect of neutrino-mass

![Graph showing constraints on \( \Sigma m_\nu \) for various data combinations.](image)
β Decay vs Cosmology

Planck result

\[ \sum m_i < 230 \text{ meV} \]

corresponds to β limits of

\[ m_\beta < 60 \text{ meV} \quad \text{NH} \]
\[ m_\beta < 90 \text{ meV} \quad \text{IH} \]

if KATRIN discovers sth, larger than this (sensitivity > 200meV)

\[ \Rightarrow \text{conflict / tension with cosmology} \]
can we get $m_{\text{light}}$?

double beta decay (DBD)

almost no information on $m_{\text{light}}$ (may be $m_{\text{light}} > 0$ )
could tell hierarchy only if

normal hierarchy and effective DBD mass $< 14$ meV
but: errors in matrix elements, we don’t know if $\nu$ is majorana

not really a mass measurement

DBD is about lepton number violation
If we had a ~ (4-5) x better KATRIN (44 meV)

and an improved sensitivity from cosmology

\[ \Sigma m_i < 120 \text{ meV} \]

<table>
<thead>
<tr>
<th>cosmol.</th>
<th>(\beta)-endpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>nothing</td>
<td>nothing</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \text{NH, } m_{\text{light}} < 20 \text{meV} \]
If we had a

\( \sim (4-5) \times \) better KATRIN (44 meV)

and an improved sensitivity from cosmology

\[ \Sigma m_i < 120 \text{ meV} \]

cosmol. | \( \beta \)-endpoint
--- | ---
yes | yes

\[ \Rightarrow \text{hierarchy, if errors small enough (\( \pm 15 \text{ meV} \))} \]
\[ \Rightarrow \text{possibly } m_{\text{light}} > 0 \text{ (relies on cosmology JUNO, ORCA, PINGU can help, NH easier)} \]
If we had a ~ (4-5) x better KATRIN (44 meV)

and an improved sensitivity from cosmology

\[ \sum m_i < 120 \text{ meV} \]

It is worth the effort to look for techniques beyond KATRIN

- together with cosmology can get hierarchy

\( m_{\text{light}} > 0 \) might be possible if large enough
Beyond KATRIN?

the source is opaque
⇒ need to increase source Ø
  magnetic flux conservation
  requests larger spectrometer too,
  but a Ø100m spectrometer is not feasible
⇒ make better use of electrons by TOF
  (corresponds to higher statistics)
⇒ use synchrotron radiation from source
  Project 8
start - ideas:
- e⁻ tagger: needs to measure electron without disturbing it => ~ 10meV threshold ??
- use pre-spectrometer as gate

stop:
- time of arrival with present detector $\Delta t = 50$ ns $\rightarrow$ ok

advantage:
- measure many electron energies at one retarding potential
- corresponds to many spectrometer settings at once
- increase of statistics

factor 5 in mass sensitivity under ideal conditions
KATRIN type tritium source in uniform B field

electron radiates coherent cyclotron radiation

\[ \omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \]

antenna array for cyclotron radiation detection

radiation can leave the source and carries the information of the \( \beta \)-electron energy

overcomes size limit to tritium source
Project 8: first single Electron Measurement

D. M. Asner et al., arXiv:1408.5362

observed lines from Kr source

$\Delta E \sim 30\text{eV}$, dominated by inhom. trapping field

$\Rightarrow$ should be much better in large source
Project 8: first single Electron Measurement

proof of principle

needs to be developed into a large scale experiment
Beyond KATRIN?

**the source is opaque**

⇒ need to increase source Ø magnetic flux tube conservation requests larger spectrometer too but a Ø100m spectrometer is not feasible

⇒ make better use of electrons by TOF (corresponds to higher statistics)

⇒ use synchrotron radiation from source Project 8

**resolution with molecular Tritium is limited to** \( \sigma = 0.34 \) eV (\( m_\beta \sim 80 \) meV) by the excitation of vibrational states in the final state

⇒ use atomic Tritium? (Project 8)

⇒ calorimetry: source = detector ECHO, HOLMES, NuMECS
Cryogenic Calorimeters

$$\Delta T = \Delta E / C$$

$$C \sim T^3 \text{ insulator; } \sim T \text{ metall}$$

measures full absorbed energy by temperature rise

**high energy resolution $\Delta E$**

all energy except energy carried away by $\nu$

single final state experiment

$\implies$ no problems with
  - inelastic scattering
  - excited states
  - backscattering …

but still, **phase space might be deformed** by excited states, or multiple de-excitation pathways
Calorimeters: TES, MMC, NTD ...

different types cryogenic calorimeters differ in the way the temperature is measured

TES Superconducting Transition Edge Sensors:

$$\Delta T \Rightarrow \Delta R$$

MMC Magnetic Micro Calorimeters:

$$\Delta T \Rightarrow \Delta M$$

SQUID $$\Rightarrow \Delta U$$

NTD semiconductor termistors:

$$\Delta T \Rightarrow \Delta R \Rightarrow \Delta U$$

no energy filter

$$\Rightarrow$$ has to cope with entire spectrum

$$\Rightarrow$$ as low as possible Q-value (Re, Ho)

$$\Rightarrow$$ pile up problem

$$\Rightarrow$$ needs many detectors

$$\Rightarrow$$ needs fast detectors
MARE Neutrino Mass Project: $^{187}\text{Re}$ β-Decay with Cryogenic Detectors

Q value: 2.465 keV

MARE (Mibeta, Manu)
- Italy, Germany, USA
- Si NTD Thermistors and TES
- 0.5 mg AgReO$_4$ crystals
- $\Delta E \sim 28$eV

- goal $10^4$ - $10^5$ detectors

severe problems

- to build high resolution and fast detectors with Re-absorbers
- very large amount of Re were needed

$\Rightarrow$ stopped
$\Rightarrow$ continue with EC capture in $^{163}\text{Ho}$
$\Rightarrow$ HOLMES, ECHO, NuMECS,

Angelo Nucciotti, Meudon 2011
Neutrino Mass from $^{163}$Ho Electron Capture

Q value: $(2.5-2.8)$ keV

HOLMES – TES sensors
INFN (Milano, Genova, LNGS…), NIST, CIEtech, PSI, ILL …

ECHO – MMC sensors
Germany (Heidelberg, Mainz, Dresden, Tübingen, Frankfurt, Berlin)
France, Slovakia, Russia, India

NuMECS
USA

\[
\frac{dN}{dE_C} = A \frac{1 - \frac{m_{\nu_e}^2}{(Q_{EC} - E_C)^2}}{(Q_{EC} - E_C)^2} \sum_j \left( \frac{\Gamma_j/2\pi}{(E_C - E_j)^2 + \Gamma_j^2/4} \right) \]

\[
\frac{\Gamma_j/2\pi}{(E_C - E_j)^2 + \Gamma_j^2/4} \sum_j C_j n_j B_j \varphi_j^2(0)
\]
ECHO: $^{163}$Ho EC Spectrum with MMC

high energy resolution

$^{163}$Ho + e$^-$ → $^{163}$Dy* + $\nu_e$ → $^{163}$Dy + $\gamma/e^-$ + $\nu_e$

$\Delta E_{FWHM} = 1.6$ eV @ 6keV

courtesy L. Gastaldo
Technology for large Number of Pixels

\[ \Delta E_{\text{FWHM}} = 3 \text{eV}, \quad f_{\text{pu}} = A \tau_R = 10^{-6} \]

- no filter for events far from endpoint
  \[ \Rightarrow \text{needs large number of counts} \]
  \[ \Rightarrow \text{needs large number of pixels} \]

ECHo-1k

2 x 50 pixel x 10 Bq
4 months \( \rightarrow 10^{10} \) events

ECHo-1M

50 x 2000 pixel x 10 Bq
24 months \( \rightarrow 6 \times 10^{13} \) events

\[ \sim 10^{10} \text{ counts for } m \sim 10 \text{ eV} \]

\[ \sim 10^{13} \text{ counts for } m \sim \text{ sub } 1 \text{ eV} \]

technology to read out such large pixel numbers is available and proven
Technology for large Number of Pixels

no filter for events far from endpoint
⇒ needs large number of counts
⇒ needs large number of pixels

technology is available and proven

frequency multiplexing
⇒ one line, one amplifier for many pixels
Backgrounds

Counts in 10eV below Q-value

- expected signal
  - $m = 0\, \text{eV}$ / $10\, \text{eV}$: 30 / 5
  - pile up: 10

- background
  - $10^{-5}$ cts/ev/d/det: 5

- sum: $45 \pm 10 / 20 \pm 7$

Background level of $10^{-5}$ cts/eV/d/det or better should be possible
Backgrounds: scaling from CRESST

The background level of $10^{-5}$ cts/eV/d/det or better should be possible.
Production of Ho-163 source via n-activation of Er-162-target

chemical purification before and after irradiation

⇒ but still co-production of Ho-166m

⇒ mass separation before implantation into detector pixels

background level of $10^{-5}$ cts/eV/d/det or better should be possible
Pile up: fast Detectors are very important

number of pile up events = number of collected events \* pile up fraction \( f_{pp} \)

\[
f_{pp} = \tau_{\text{rise}} \* A_{\text{det}}
\]

\( \tau_{\text{rise}} \) rise time / time resolution to recognize pile up
\( A_{\text{det}} \) activity in each detector pixel

fraction of pile up events in last eV:

\[ \sim f_{pp} \* 10^{-6} \]

fraction of signal counts in last eV:

\[ \sim \* 10^{-12} \]

maximal tolerable \( f_{pp} \sim 10^{-6} \) \( \Rightarrow \tau_{\text{rise}} < 1 \mu s \); \( A_{\text{det}} \) not larger than 10 Bq

\( \Rightarrow \) needs large number of detector pixels

![Graph showing spectrum for ECHO 1K, 1 year with counts in 10eV below Q-value and expected signal and background values.]

<table>
<thead>
<tr>
<th>counts in 10eV below Q-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected signal m(_v) = 0eV / 10eV</td>
</tr>
<tr>
<td>pile up</td>
</tr>
<tr>
<td>background</td>
</tr>
<tr>
<td>( 10^{-5} ) cts/ev/d/det</td>
</tr>
<tr>
<td>sum</td>
</tr>
</tbody>
</table>
Calorimeters – next Steps

ECHO – 1K / funded
100 detectors / 10Bq better than 10eV within 3 years

deemonstrate scalability
⇒ sub-eV sensitivity

ECHO – 1M
100000 detectors / 10Bq better than 1eV within another 3 years

HOLMES / funded 5y (ERC)
1000 detectors / 300 Bq reach 1 eV sensitivity within 5 years

- scalability
- stability of a large number of pixels
- backgrounds
- pile up
- understanding the spectrum
- can one really get ‘beyond KATRIN’
we know $\sum m_\nu$ is nonzero

KATRIN will measure $m_\beta = \sum |U_{ei}|^2 m^2(\nu_i)$ with 200meV sensitivity

measurements from cosmology tell $\sum m_\nu < 230$ meV .... 700 meV will get even better

we would like to have $m_\beta \sim 45$meV sensitivity or better

=> several techniques: TOF, cyclotron radiation, calorimeters

in ~ 10 years: we will know hierarchy and may be even $m_{\text{light}}$

possible to look for sterile neutrinos