Outlook

- Direct neutrino mass measurement
- Experimental approaches for direct measurements: Spectrometers vs Calorimeters
- The KArlsruhe TRItium Neutrino experiment: KATRIN
- Prospects for Re experiments: MARE
- Conclusion
Direct neutrino mass measurement

neutrino oscillations evidence → $m_\nu \neq 0$
BUT oscillation experiments give only $\Delta m^2$!

direct neutrino mass measurement

Kurie plot near $E_0$

$F_{\Delta E}(0) \approx \left( \frac{\Delta E}{E_0} \right)^3$

$E_0 - m_\nu, E_0$

effect of:
♦ energy resolution
♦ background
♦ Pile up

$K(E_\beta) = (E_0 - E_\beta) \sqrt[4]{1 - \frac{m_\nu^2}{(E_0 - E_\beta)^2}}$

$m_\nu = (\Sigma m_i^2 |U_{ei}|^2)^{1/2}$

2 eV → $^3$H ($E_0 = 18.6$ keV)
& spectrometers
15 eV → $^{187}$Re ($E_0 = 2.47$ keV)
& calorimeters
Different approaches to direct measurement

- **Spectrometers**: source \(\neq\) detector
  - **3H source** → **β counter**
  - **β analyzer**
    - differential or integral spectrometer: βs from the \(^3\text{H}\) spectrum \(\delta E\) are magnetically and/or electrostatically selected and transported to the counter

- **Calorimeters**: source \(\subseteq\) detector
  - **\(^{187}\text{Re source}\)** → **ν_ε**
  - **β calorimeter**
    - ideally measures all the energy \(E\) released in the decay except for the \(ν_ε\) energy
**Calorimeter vs Spectrometer**

**General experimental requirements**

- High statistics at the beta spectrum end-point:
  - low end point energy $E_0$
  - high source activity and high efficiency
- high energy resolution $\Delta E$ (same order of magnitude of $m_\nu$ sensitivity)
- high Signal to Noise ratio
- small systematics effects

**Spectrometer:** $\beta$ source $\neq$ detector

**Advantages:**
- high statistics
- high energy resolution

**Disadvantages:**
- $\times$ systematics due to source effect
- $\times$ systematics due to decay to excited states
- $\times$ background

**Calorimeter:** $\beta$ source $\subseteq$ detector

**Advantages:**
- $\checkmark$ no backscattering
- $\checkmark$ no energy losses in the source
- $\checkmark$ no solid state excitation
- $\checkmark$ no atomic/molecular final state effects

**Disadvantages:**
- $\times$ limited statistics
- $\times$ systematics due to pile-up
- $\times$ background
Precursors of $^{187}\text{Re}$ experiments

**MANU (1999)**
Genova
- 1 crystal of metallic Re: 1.6 mg
- $^{187}\text{Re}$ activity $\approx 1.6$ Hz
- Ge-NTD thermistor
- $\Delta E = 96$ eV FWHM
- 0.5 years live-time
- $m_\nu^2 = -462^{+579}_{-679}$ eV$^2$
- $m_\nu \leq 26$ eV (95 % C.L.)

**MIBETA (2002-2003)**
Milano, Como, Trento
- 10 AgReO$_4$ crystals: 2.71 mg
- $^{187}\text{Re}$ activity = 0.54 Hz/mg
- Si thermistors (ITC-irst)
- $\Delta E = 28.5$ eV FWHM
- 0.6 years live time
- $m_\nu^2 = -112^{+207}_{-90}$ stat$^{+90}_{-90}$ sys eV$^2$
- $m_\nu < 15$ eV (90% CL)

- $6.2 \times 10^6$ $^{187}\text{Re}$ decays above 700 eV
History of tritium Beta decay experiments

ITEP
- $T_2$ in complex molecule
- magn. spectrometer (Tret'yakov)
  - $m_\nu$: 17-40 eV

Los Alamos
- gaseous $T_2$ source
- magn. spectrometer (Tret'yakov)
  - $m_\nu$: < 9.3 eV

Tokio
- $T$ source
- magn. spectrometer (Tret'yakov)
  - $m_\nu$: < 13.1 eV

Livermore
- gaseous $T_2$ source
- magn. spectrometer (Tret'yakov)
  - $m_\nu$: < 7.0 eV

Zürich
- $T_2$ source impl. on carrier
- magn. spectrometer (Tret'yakov)
  - $m_\nu$: < 11.7 eV

Troitsk (1994-today)
- gaseous $T_2$ source
- electrostat. spectrometer
  - $m_\nu$: < 2.5 eV

Mainz (1994-today)
- frozen $T_2$ source
- electrostat. spectrometer
  - $m_\nu$: < 2.3 eV

**Mainz & Troitsk have reached their intrinsic limit of sensitivity**
The KArlshure TRItium Neutrino experiment: KATRIN

**Physics Goal:** 1 order of magnitude improvement on $m_\nu$ 
$$2 \text{ eV} \rightarrow 0.2 \text{ eV}$$

**Statistic**
Count rate at the b-endpoint falls off very steeply, small background!

**Improvement of statistics ($\times 10^3$):**
- stronger tritium source and larger spectrometer
- larger measuring period (100 d → 1000 d)

**Systematics**
**Aim:** systematic uncertainties = statistical errors

**Improvement of systematics ($\times 0.1$):**
- improved energy resolution spectrometer with $\Delta E=0.94 \text{ eV}$ (factor 4)
- reduced systematic errors for energy losses in source → windowless gaseous tritium source
**KATRIN**

(Scientific Report FZKA 7090)

- Windowless gaseous molecular tritium source WTGs
- Tritium retention system
- Pre spectrometer
- Main spectrometer
- Detector

![Diagram of KATRIN setup]({static/diagram.png})

- **T$_2$-injection**: 1.8 mbar l/s = $1.7 \times 10^{11}$ Bq/s
- **Differential pumping**
- **Cryogenic pumping**
- **Adiabatic electron guiding** & **T$_2$ flow reduction factor of $10^{14}$**

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- $R > 10^7$
- $\approx 10^{-7}$ mbar l/s
- $< 2.5 \times 10^{-14}$ mbar l/s
KATRIN

- filter out all $\beta$-decay electrons without $m_\nu$ info
- reduction of background from ionising collisions
- large energy resolution
- high luminosity
- ultrahigh vacuum requirements (background)
- simple construction: vacuum vessel at HV + “massless” screening electrode

- Si-Pin diode
- detection of transmitted $\beta$-decay electrons
- low background for endpoint investigation
- high energy resolution
- 148 pixels

detector magnet $B = 3-6 \, T$
**KATRIN sensitivity**

Expectation for 3 full beam years

→ Statistical & Systematic errors contribute equal ($\sigma_{\text{syst}} \sim \sigma_{\text{stat}}$)

**KATRIN discovery potential:**

$m_\nu = 0.35 \text{ eV (3}\sigma)$

$m_\nu = 0.3 \text{ eV (5}\sigma)$

**Sensitivity:**

$m_\nu \leq 0.2 \text{ eV (90% CL)}$

Commissioning of the completed set-up in 2012

2012-2018 regular data taking for 5-6 years (3 full beam year)
**Cryogenic Detectors**

**Detection Principle:**
- $\Delta T = E/C$ where $C$ is the total thermal capacity.
  - low $C$: $C \sim (T/\Theta_D)^3$ in superconductors & dielectric below $T_C$
  - low $T$ (10 ÷ 100 mK)
- ultimate limit to energy resolution:
  - statistical fluctuation of internal energy $\Delta E = (k_B T^2 C)^{1/2}$
- detect all deposited energy, including short-lived excited states (100 $\mu$s)
- achieve very good energy resolution in the keV range
**MARE: Microcalorimeter Array for a Rhenium Experiment**

**Goal**: a sub-eV direct neutrino mass measurement complementary to the KATRIN experiment

**MARE-1**: collection of activities aiming at isotope/technique selection

- \( ^{187}\text{Re} \): high statistics measurement
  - assess systematics
  - test large arrays
  - lower limit to few eV

- \( ^{163}\text{Ho} \): high statistics measurement - R&D for \( ^{163}\text{Ho} \) production
  - measure \( Q_{EC} \)
  - study spectrum shape
  - assess systematics

**Different techniques**:

- TES - Transition Edge Sensor
- MMC - Magnetic MicroCalorimeter
- MKID - Microwave Kinetic Inductance Detector

- multiplexed readout
- large arrays
**MARE 1**

**MARE-1 in Milan**: Milano/Como/IRST/Wisconsin/NASA

- $m_{\nu e} < 2 \text{ eV/c}^2$
- $10^{10}$ events - 300 sensors
- 8 arrays of Si:P thermistors with AgReO$_4$ absorbers
- Energy resolution 25 eV @ 2.6 keV

**The first phase is needed:**
- because it's the only possible one with present technology
- To investigate systematics in thermal calorimeters

**very important to cross-check spectrometer results**
**MARE 1 in Milan**

- **6x6 NASA/GSFC arrays**
  - pixel 300x300x1.5 µm³
  - developed for X-ray spectroscopy with HgTe absorber (ASTRO-E2)

- **flat AgReO₄ single crystal**
  - mass ~ 500mg per pixel ($A_\beta \sim 0.3$ dec/sec)

- **Detector R&D results**
  - best operating $T \approx 85$mK
  - $\Delta E \approx 30$ eV, $\Delta \tau \approx 250$ µs
MARE 1 in Milan: MC sensitivity

Detectors
\[ \Delta E_{\text{FWHM}} \sim 15 \text{ eV e } \tau_R \sim 100 \mu \text{s} \]
1 year and 72 channels \( \rightarrow \Sigma(m_\nu) \sim 5 \text{ eV} \)
3 years and 288 channels \( \rightarrow \Sigma(m_\nu) \sim 3 \text{ eV} \)

\[ \Delta E_{\text{FWHM}} \sim 30 \text{ eV e } \tau_R \sim 300 \mu \text{s} \]
1 year and 72 channels \( \rightarrow \Sigma(m_\nu) \sim 6 \text{ eV} \)
3 years and 288 channels \( \rightarrow \Sigma(m_\nu) \sim 3 \text{ eV} \)

- setup designed for 8 arrays
- 288 AgReO\(_4\) crystals
- now starting with 2 arrays (72 ch.)
- gradual deployment

\( \triangleright \) further detector optimization

\[ \Sigma_\nu \text{ at } 90\% \text{ CL versus measurement time } t_M \]

Load
Resistance
50 M\( \Omega \)
detector holder
Pb shield for calibration source
cold pre-amplifier stage
\[ {^{163}\text{Ho}} + e^- \rightarrow {^{163}\text{Dy}^*} + \nu_e \]

- calorimetric measurement of non-radiative Dy atomic de-excitation (mostly non radiative)
- Breit Wigner M,N,O lines have an end-point at the Q-value
  - finite neutrino mass causes a kink at the end point similarly to beta spectrum of \(^{187}\text{Re}\)
- fraction of events at end-point may be as high as for \(^{187}\text{Re}\):
  - depends on \(Q_{EC}\) (2.3\(\pm\)2.8 keV), but \(Q_{EC}\)?
- \(\tau_{1/2} \approx 4570\) y: few active nuclei are needed
  - can be implanted in any suitable absorber
- new NASA/Goddard TES arrays (\(\Delta E = 2\) eV) can be implanted with \(^{163}\text{Ho}\)
- 163 Ho production by neutron irradiation of \(^{162}\text{Er}\) enriched Er
- no high statistics and clean calorimetric measurement so far

MARE 1 activities

- **Isotope physics investigation and systematics assessment**
  - $^{163}$Ho + Si-impl/TES (U Genova - U Milano-Bicocca - U Lisbon/ITN)
  - $\text{AgReO}_4$ + Si-impl (U Milano-Bicocca - U Como - NASA/GSFC - UW Madison)

- **Sensor-Absorber coupling ($^{187}$Re/$^{163}$Ho) and single pixel design**
  - $^{187}$Re + TES (U Genova - U Miami - U Lisbon/ITN)
  - $^{187}$Re + MMC (U Heidelberg)
  - $^{163}$Ho + TES (U Genova)
  - $^{163}$Ho + MMC (U Heidelberg)
  - $^{163}$Ho/$^{187}$Re + MKID (U Milano-Bicocca - JPL/Caltech - U Roma - FBK)

- **Multiplexed sensor read-out**
  - SQUID multiplexing (U Genova - PTB)
  - SQUID microwave multiplexing (U Heidelberg)

- **Software tools**
  - Data Analysis (U Miami)
  - Montecarlo simulations (U Miami - U Milano-Bicocca)
MARE 2 statistical sensitivity: Re & Ho options

- only statistical analysis
- 50000+ detectors gradually deployed
  - arrays distributed in many laboratories around the world
  - about $10^{13} \div 10^{14}$ events after 5 years

### Exposure required for 0.2 eV $m_\nu$ sensitivity

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<thead>
<tr>
<th>$A_p$ [Hz]</th>
<th>$\tau_R$ [us]</th>
<th>$\Delta E$ [eV]</th>
<th>$N_{ev}$ [counts]</th>
<th>exposure [det \times year]</th>
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<td>1.9\times 10^{14}</td>
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<td>10</td>
<td>3.3\times 10^{14}</td>
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- need for new sensor R&D and new read-out techniques

$bkg = 0$

5000 pixels/array
8 arrays
10 years
400 g $^{nat}\text{Re}$

$Q_{EC} = 2200$ eV

$bkg = 0$

5000 pixels/array
3 arrays
1 year
$\sim 2\times 10^{17} \ ^{163}\text{Ho}$ nuclei
**Conclusion**

- Investigation of the kinematics of $\beta$-decay = only model independent measurement of the absolute neutrino mass scale

- **MARE** staged approach based on microcalorimeters -Re $\beta$-decay. The **MARE** project 1st phase is just starting. R&D improvements on the detector technology are crucial for the 2nd phase.

  $^{187}\text{Re calorimetry is complementary to tritium experiments and can give sub-eV sensitivity to } m_\nu.$

- **KATRIN** is the ultimate tritium $\beta$-decay experiment: it will reach a sensitivity of 0.2 eV on $m_\nu$. Expected data taking in 2012.