• Introduction

• Neutrino mass and cosmology

• Search for neutrinoless double beta decay

• Direct neutrino mass experiments
  - Rhenium $\beta$-decay and MARE
  - The Karlsruhe TRItium Neutrino experiment KATRIN

• Conclusion
Positive results from \( \nu \) oscillation experiments

\( \Rightarrow \) non-trivial \( \nu \)-mixing

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\cdot
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

with:

\[
0.79 < |U_{e1}| < 0.88 \text{ maximal!}
\]
\[
0.47 < |U_{e2}| < 0.61 \text{ large!}
\]
\[
|U_{e3}| < 0.20 \neq 0 ?
\]
\[
7.3 \times 10^{-5} \text{ eV}^2 < \Delta m_{12}^2 < 9.3 \times 10^{-5} \text{ eV}^2
\]
\[
1.6 \times 10^{-3} \text{ eV}^2 < |\Delta m_{23}^2| < 3.6 \times 10^{-3} \text{ eV}^2
\]

\( \Rightarrow \) \( m(\nu_j) \neq 0 \), but unknown!

\[
1.6 \times 10^{-3} \text{ eV}^2 < |\Delta m_{23}^2| < 3.6 \times 10^{-3} \text{ eV}^2
\]

up to now: description by 2-flavour oscillation sufficient
Results of recent oscillation experiments: $\theta_{23}$, $\theta_{12}$, $\Delta m^2_{23}$, $\Delta m^2_{12}$

- **Hierarchical masses**
  - e.g. seesaw mechanism type 1
  - explains smallness of masses, but not large (maximal) mixing

- **Degenerated masses**
  - cosmological relevant
  - e.g. seesaw mechanism type 2

**Need for the absolute $\nu$ mass determination**
1) Cosmology
very sensitive, but model dependent
compares power at different scales
current sensitivity: \( \Sigma m(\nu_i) \approx 0.4 \text{ – } 1 \text{ eV} \)

2) Search for 0νββ
Sensitive to Majorana neutrinos
Evidence for \( m_{ee}(\nu) \approx 0.4 \text{ eV} \) (Klapdor-Kleingrothaus et al.)?

3) Direct neutrino mass determination:
No further assumptions needed. no model dependence
use \( E^2 = p^2 c^2 + m^2 c^4 \Rightarrow m^2(\nu) \) is observable mostly
most sensitive method: endpoint spectrum of β-decay

Introduction
Neutrino mass from cosmology

measurement of CMBR
(Cosmic Microwave Background Radiation)

D.N. Spergel et al., astro-ph/0302209
Neutrino mass from cosmology

measurement of CMBR
(Cosmic Microwave Background Radiation)

measurement of matter density distribution
LSS (Large Scale Structure)
2dF, SDSS, ...

2dF:  M. Colless et al., MNRAS 328 (2001) 1039
Neutrino mass from cosmology

measurement of CMBR
(Cosmic Microwave Background Radiation)

measurement of matter density distribution
LSS (Large Scale Structure)
2dF, SDSS, ...

big bang theory:
neutrino density in universe
\[ n_\nu = 336 / \text{cm}^3 \]
Neutrino mass from cosmology

measurement of CMBR
(Cosmic Microwave Background Radiation)

measurement of matter density distribution
LSS (Large Scale Structure)
2dF, SDSS, ...

big bang theory:
neutrino density in universe
\[ n_\nu = 336 / \text{cm}^3 \]

model development
← National Center for SuperComputer Simulations,
http://cosmicweb.uchicago.edu/sims.html

→ Millenium simulation
http://www.mpa-garching.mpg.de/galform/presse/
Neutrino mass from cosmology

E. Komatsu et al. (WMAP, 5 years, arXiv:0803.0547)
\[ \Sigma m(\nu_i) < 0.67 \text{ eV} \]

CMB, LSS, SN data, always assuming the cosmological concordance model with cosmological constant \( \Lambda = \text{const.} \), no quintessence

GOOBAR, HANNESTAD, MÖRTSELL (astro-ph/0602155)
\[ \Sigma m(\nu_i) < 0.62 \text{ eV} \]

WMAP+SDSS, no Lyman \( \alpha \), but making use of baryon accoustic peaks
free equation of state \( w \) for dark energy
Remark: \( w \) is correlated to \( \Sigma m(\nu_i) \) (arXiv:0709.4152, 0505.551)
\[ \Rightarrow \text{neutrino mass determination can help dark energy (arXiv0710.1952)} \]

Ch. Wetterich et al. (e.g. arXiv:0905.0715): avoids bound on \( \Sigma m(\nu_i) \)
\( \nu \) coupling to cosmon (quintessence model for dark energy)
leads to growing neutrino mass

O.E. Bjaelde et al. (astro-ph/0705.2018): \( \nu \) coupling to scalar field leads to
time-varying neutrino mass and connection to dark energy
Double $\beta$-decay

$\beta-\beta^{-}$

$Z$-1 $Z$ $Z$+1

**normal (2νββ)**

$\nu^{-}$ $\nu$

$n$ $p$ $n$ $p$

$e^{-}$ $\bar{\nu}_{e}$ $e^{-}$ $\bar{\nu}_{e}$

**neutrinoless (0νββ)**

$\nu^{-} = \nu$

$n$ $p$ $n$ $p$

$e^{-}$ $e^{-}$

0νββ requires:
a) $\nu^{-} = \nu$ (Majorana)
b) helicity flip: $m(\nu) \neq 0$

⇒ sensitive to coherent sum:

$$m_{\beta\beta}(\nu) = |\sum |U_{ei}|^2 e^{i\alpha(i)} m(\nu_i)|$$

In contrast to direct mass measurement (single β decay, incoherent sum):

$$m^2(\nu_e) = \sum |U_{ei}|^2 m^2(\nu_i)$$

Signal: line at Q-value

Neutrinoless double $\beta$-decay

Christian Weinheimer

NUFACT09, Fermilab & III, July 2009
Current and future double $\beta$ decay experiments

$m_{ee} \sim (1/enrichment)^{1/2} \cdot (\Delta E \cdot bg/M \cdot t)^{1/4}$

$\Rightarrow$ mass $\rightarrow$ 1t, high enrichment, very low background $bg$

2 ways to measure both $\beta$-electrons:
- semiconductor,
- cryogenic bolometer
- liquid scintillator

running: CUORICINO
setting up: GERDA, CUORE, EXO-200
planned: Majorana, EXO, COBRA, SNO+ ..planned: NEMO-3
running: NEMO-3
setting up: SuperNEMO
planned: MOON

Neutrinoless double $\beta$-decay

Christian Weinheimer  NUFAC09, Fermilab & IIL, July 2009  11
Searching for $0\nu\beta\beta$: NEMO3, CUORICINO

NEMO3: tracking calorimeter
(→ SuperNEMO with enr. $^{82}\text{Se}$)

CUORICINO: Te cryo bolometer
(→ CUORE: 741 kg TeO$_2$)

$^{100}\text{Mo}$: $T^{1/2}_{1/2} (0\nu\beta\beta) > 1.1 \times 10^{24}$ y
$\Rightarrow m_{ee} < (0.45 - 0.93)$ eV

$^{130}\text{Te}$: $T^{1/2}_{1/2} > 3 \cdot 10^{24}$ y
$\Rightarrow m_{ee} < 0.19 - 0.68$ eV

F Mauger, TAUP09

PRC 78 (2008) 35502
Coming soon:
The GERDA experiment

New background reduction methods:
- naked Germanium detectors in noble liquid
- segmented detectors to identify multi-side events
- identify escaping Compton photons by scintillation light in LAr

3 Phases of GERDA
Phase 1: reuse old detectors of Hd-Moscow and IGEX
   start commissioning in 2009
Phase 2: new segmented detectors (40 kg)
Phase 3: (with Majorana) many more detectors (500 kg)

Neutrinoless double $\beta$-decay
Coming soon: EXO 200

EXO200: 200 kg enriched $^{136}\text{Xe}$ at WIPP/New Mexico commissioning will start end of 2009

R&D: Majorana, SNO++, Cobra
$0\nu\beta\beta$ nuclear matrix elements

short range correlations are important:

experimental tests are important:

F. Simkovic et al., arXiv:0902.0331

Frekers, Schleching 2009
Direct determination of $m(\nu_e)$ from $\beta$ decay

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

$\beta$ electron energy spectrum:

$$\frac{dN}{dE} = K \cdot F(E,Z) \cdot p \cdot E_{\text{tot}} \cdot (E_0 - E_e) \cdot \sum |U_{ei}|^2 \cdot \sqrt{(E_0 - E_e)^2 - m(\nu_i)^2}$$

(modified by electronic final states, recoil corrections, radiative corrections)

E.W. Otten & C. Weinheimer

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

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

$\Rightarrow$ MAC-E-Filter
(or bolometer for $^{187}\text{Re}$)
Comparison of the different approaches to the neutrino mass

Direct kinematic measurement:
\[ m^2(\nu_e) = \sum |U_{ei}|^2 m^2(\nu_i) \]  
(incoherent)

Neutrinoless double $\beta$ decay:
\[ m_{\beta\beta}(\nu) = |\sum U_{ei}|^2 e^{i\alpha(i)} m(\nu_i)| \]  
(coherent)

if no other particle is exchanged (e.g. R-violating SUSY)

problems with uncertainty of nuclear matrix elements

\[ \Rightarrow \text{absolute scale/cosmological relevant neutrino mass in the lab by single } \beta\text{ decay} \]
Cryogenic bolometers with $^{187}$Re MIBETA (Milano/Como)

Parameters

- detectors: 10 (AgReO$_4$)
- rate each: 0.13 1/s
- energy res.: $\Delta E = 28$ eV
- pile-up frac.: $1.7 \times 10^{-4}$

$M_\nu^2 = -141 \pm 211_{\text{stat}} \pm 90_{\text{sys}}$ eV$^2$

$M_\nu < 15.6$ eV (90% c.l.)

(M. Sisti et al., NIMA520 (2004) 125)

MANU (Genova)

- Re metallic crystal (1.5 mg)
- BEFS observed (F.Gatti et al., Nature 397 (1999) 137)
Collaboration: Genova, Goddard Space Flight Center/NASA, Heidelberg, Como, Milano, Trento, U Wisconsin

Idea: 2nd and 3rd generation rhenium β decay experiment

MARE I: 300 detectors (MIBETA: 10)
ΔE = 10 eV (MIBETA: 28 eV)
τ = 10^{-4} s (MIBETA: 10^{-3} s)
with semiconductor sensors (like MIBETA/MANU)

expected sensitivity on m(ν_e): 2-3 eV

Proposal: Microcalorimeter Arrays for a Rhenium Experiment (MARE)
Status of MARE 1 at Milano

- **MARE1 Si-AgReO₄ detectors**
  - Flattened AgReO₄ crystal
  - Silicon spacer
  - Epoxy joints
  - Silicon implanted thermistor
- **MARE1 experimental set-up**
  - Set-up for up to 8 XRS2-2 arrays → 288 detectors
  - Everything ready to deploy 2 arrays → 72 detectors
  - Calibration source pulling string
  - Connection boxes
  - Front-end electronics
  - Mixing Chamber $T \approx 6$ mK
  - Array boards $T \approx 20$ mK
  - Kevlar cross
  - Decoupling jig
  - Polymide based micro-bridges
  - 80 channel JFET box $T \approx 4$ K

- **NASA/GSFC XRS2-2 arrays**
  - 6x6 pixels
  - Flat AgReO₄ single crystals
  - $m \approx 0.5$ mg
  - Detector R&D phase results
  - Best operating $T \approx 90$ mK
  - $\Delta E \approx 30$ eV, $\tau_R \approx 250$ $\mu$s

- **First 11 crystals on one of the two MARE1 arrays**

pictures from A. Nucciotti/Milano

Direct neutrino mass determination

Christian Weinheimer

NUFACT09, Fermilab & IIL, July 2009
Proposal: Microcalorimeter Arrays for a Rhenium Experiment (MARE)

Collaboration: Genova, Goddard Space Flight Center/NASA, Heidelberg, Como, Milano, Trento, U Wisconsin

Idea: 2\textsuperscript{nd} and 3\textsuperscript{rd} generation rhenium $\beta$ decay experiment

MARE II: 5000 – 50000 detectors (MIBETA: 10)
$\Delta E = 2.5 - 5$ eV (MIBETA: 28 eV)
$\tau = \text{a few } 10^{-6} \text{ s} \quad \text{ (MIBETA: } 10^{-3} \text{ s})$
with superconducting transition edge sensors (TES) or
with metallic magnetic temperature sensors (MMC) or
with multiplexed kinetic inductance detectors (MKID)

expected sensitivity on $m(\nu_e)$: 0.2 eV

very challenging, a lot of R&D necessary
Tritium experiments: source ≠ spectrometer
MAC-E-Filter

- Two supercond. solenoids compose magnetic guiding field
- Adiabatic transformation: \( \mu = E_\perp / B = \text{const.} \)
  \( \Rightarrow \) parallel \( e^- \) beam
- Energy analysis by electrostat. retarding field
  \( \Delta E = E \cdot B_{\text{min}} / B_{\text{max}} \)
  \( = 0.93 \text{ eV (KATRIN)} \)

\( \Rightarrow \) sharp integrating transmission function without tails →

Magnetic Adiabatic Collimation + Electrostatic Filter
After all critical systematics measured by own experiment (inelastic scattering, self-charging, neighbor excitation):

\[ m^2(\nu) = -0.6 \pm 2.2 \pm 2.1 \ \text{eV}^2 \Rightarrow m(\nu) < 2.3 \ \text{eV} \ (95\% \ C.L.) \]


Direct neutrino mass determination
Physics Aim: $m(\nu_e)$ sensitivity of 0.2 eV

- higher energy resolution: $\Delta E \approx 1\text{eV}$ since $E/\Delta E \sim A_{\text{spectrometer}}$
  $\Rightarrow$ larger spectrometer

- relevant region below endpoint becomes smaller even less rate $dN/dt \sim A_{\text{source}} \sim A_{\text{spectrometer}}$
  $\Rightarrow$ larger spectrometer

- small systematics

- much longer measurement time: 100 d $\rightarrow$ 1000 d

The Karlsruhe Tritium Neutrino experiment KATRIN is being set up at the Forschungszentrum Karlsruhe

Direct neutrino mass determination

Christian Weinheimer NUFAC09, Fermilab & ILL, July 2009
Molecular Windowless Gaseous Tritium Source WGTS

**WGTS:**
- Tub in long superconducting solenoids
  - Ø 9 cm, length: 10 m, T = 30 K
- Tritium recirculation (and purification)
  - $p_{inj} = 0.003$ mbar, $q_{inj} = 4.7$ Ci/s
- Allows to measure with near to maximum count rate using $\rho_d = 5 \cdot 10^{17}/\text{cm}^2$
- With small systematics

Check column density by e-gun, $T_2$ purity by laser Raman

Direct neutrino mass determination

Christian Weinheimer
NUFACT09, Fermilab & IIL, July 2009
Conceptional design

2 phase Neon cooling with
operating temperature: 27–28 K

- **spatial** (homogeneity): ± 0.1%
- **time** (stability/hour): ± 0.1%

WGTS has been ordered in Dec. 2004

Kn<<1: Hydrodynamic regime
Kn~1: transitional flow
Kn>>1: Free molecular regime

Direct neutrino mass determination
WGTS under construction

M1,2,3 coil winding finished

vacuum vessels DPS1

Direct neutrino mass determination
Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping with Argon snow at LHe temperatures (successfully tested with the TRAP experiment)

$T_2$-injection 1.8 mbar l/s (STP)

$= 1.7 \times 10^{11}$ Bq/s = 40 g/d

$\Rightarrow$ adiabatic electron guiding & $T_2$ reduction factor of $\sim 10^{14}$

$\approx 10^{-7}$ mbar l/s

$< 2.5 \times 10^{-14}$ mbar l/s

FT-ICR Penning traps to measure ions from WGTS

Direct neutrino mass determination
Arrival of DPS2-F at FZ Karlsruhe: July 15, 2009

Direct neutrino mass determination

Christian Weinheimer

NUFACT09, Fermilab & IIL, July 2009
Main spectrometer:

- Ø10m, length 24m
  ⇒ large energy resolution: $\Delta E = 0.93$ eV
  ⇒ high luminosity: $L = A_{\text{Seff}} \frac{\Delta \Omega}{4\pi} = A_{\text{analyse}} \frac{\Delta E}{2E} = 20$ cm$^2$

- ultrahigh vacuum requirements (background) $p < 10^{-11}$ mbar (EHV)
- „simple“ construction: vacuum vessel at HV + „massless“ screening electrode

Pre spectrometer

- Transmission of electron with highest energy only
  $(10^{-7}$ part in last 100 eV)
  ⇒ Reduction of scattering probability in main spectrometer
  ⇒ Reduction of background

- only moderate energy resolution required: $\Delta E = 80$ eV
- test of new ideas (EHV, shape of electrodes, avoid and remove of trapped particles, ...)

Direct neutrino mass determination
Electromagnetic design tests at the pre spectrometer

Direct neutrino mass determination

Christian Weinheimer

NUFACT09, Fermilab & IIL, July 2009
Detector Setup

- Si-Pin diode
- Detection of transmitted $\beta$-decay electrons (mHz to kHz)
- **Low background for endpoint investigation**
- High energy resolution $\Delta E < 1$ keV
- 12 rings with 30° segmentation + 4 fold center = **148 pixels**
  - record azimuthal and radial profile of flux tube
  - minimize background
  - investigate systematic effects
  - compensate field inhomogeneity in analyzing plane

(magn. field of 3 - 6 T, active veto shield, post-accel. mode)
Main Spectrometer – Transport to Forschungszentrum Karlsruhe

Leopoldshafen, 25.11.06

Direct neutrino mass determination

Christian Weinheimer
NUFACT09, Fermilab & IIL, July 2009
Direct neutrino mass determination

Christian Weinheimer

NUFACT09, Fermilab & IIL, July 2009

KATRIN’s location at Forschungszentrum Karlsruhe

spectrometer hall
Tritium Laboratory Karlsruhe

support buildings
main spectrometer
Installation of heating/cooling system and first out-baking at 350 °C

After out-baking (with only 6 TMPs):

a) $p = 5 \times 10^{-10} \text{ mbar}$,
   (but pumping speed will still be increased by 2 orders of magnitude by NEGs)

b) out-gasing rate is about KATRIN’s design value of $q<10^{-12} \text{ mbar l/s cm}^2$

Direct neutrino mass determination
Sensitivity requirements

1) Huge statistics: optimized source & large spectrometer

2) Low background: Mainz experiment:
most background from spectrometer
but KATRIN spectrometer is much bigger!
⇒ need something new!

3) Systematic uncertainties:
need to be very small!
Secondaries from wall/electrode by cosmic rays, environmental radioactivity, ...

wire electrode on slightly more negative potential

First realisation:
Mainz III

Mainz V (2004)

New record ! April 04

KATRIN pre spectrometer

Background reduction: shielding by „massless“ wire electrode

Dipl. thesis B. Ostrick (U Mainz, 2002),

Background suppression successfully tested at the Mainz MAC-E filter:

Direct neutrino mass determination
Concept for KATRIN: 690 m² surface: 2-layer wire modules

Two layers:
- to increase background shielding
- to increase electrical shielding
- to allow mechanical precision

Wire electrode system of KATRIN main spectrometer (A=690 m², V=1240 m³):
- 248 modules, 23120 wires, 46240 ceramics

Technical requirements:
- modules have to withstand bake-out at 350°C
- module design needs to be compatible with UHV requirements (10^{-11} mbar)
- exact relative wire position (Δx = 200 μm)
- non-magnetic, non-radioactive, ...
Wire electrode mass production and quality assurance

1. wire layer
Ø = 0.3 mm

2. wire layer
Ø = 0.2 mm

70 mm
25 mm

C-shaped rod
comb

1.80 m

2-dim laser sensor
highres camera

@ Münster University

3-dim coordinate measurement setup in Münster clean-room

Direct neutrino mass determination

Christian Weinheimer

NUFACT09, Fermilab & IIL, July 2009
Electrode module installation at the main spectrometer has started
Systematic uncertainties

A) As smaller $m(\nu)$ as smaller the region of interest below endpoint $E_0$

B) Any unaccounted variance $\sigma^2$ leads to negative shift of $m_\nu^2$: $\Delta m_\nu^2 = -2\sigma^2$

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=30K stabilisation,
     e-gun measurements

3. transmission function
   - spatial resolved e-gun measurements

4. WGTS charging due to remaining ions (MC: $\phi < 20$ mV)
   - inject low energy meV electrons from rear side,
     diagnostic tools available

5. final state distribution
   - reliable quantum chem. calculations

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

a few contributions with $\Delta m_\nu^2 \leq 0.007$ eV$^2$ each
Stability of retarding potential / energy calibration: ppm precision at 18.6 kV

- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined electron line with monitor spectrometer

$\begin{align*}
\text{I}=\frac{1}{2} & \quad 83^m\text{Kr} \\
\text{I}=\frac{5}{2} & \quad 83^m\text{Rb}
\end{align*}$

$\begin{align*}
T_{1/2}=1.83 \text{ h} & \quad \alpha=2011 \\
E=32.1517(5) \text{ keV} & \\
T_{1/2}=15.4 \text{ ns} & \quad \alpha=17 \\
E=9.4 \text{ keV} & 
\end{align*}$

$T_{1/2}=86.2 \text{ d}$

$83^m\text{Kr}$ conversion electron sources:
- condensed $83^m\text{Kr}$: Münster/Mainz
- $83^\text{Rb}/83^m\text{Kr}$: Rez/Mainz/Münster/Karlsruhe
- $83^\text{Rb}$ production: Bonn, Rez

Direct neutrino mass determination
KATRIN´s sensitivity

Example of KATRIN simulation & fit (last 25eV below endpoint, reference):

Expectation for 3 full beam years: \( \sigma_{\text{syst}} \sim \sigma_{\text{stat}} \)

- Sensitivity: \( m < 0.2 \text{eV (90\%CL)} \)
- Discovery potential: \( m_\nu = 0.35 \text{eV (5\sigma)} \)
- \( m_\nu = 0.3 \text{eV (3\sigma)} \)
- Sensitivity: \( m_\nu < 0.2 \text{eV (90\%CL)} \)

Direct neutrino mass determination
KATRIN’s statistical uncertainty

Example of KATRIN simulation & fit (last 25eV below endpoint, reference):

Expectation for 3 full beam years: \( \sigma_{\text{syst}} \sim \sigma_{\text{stat}} \)

\[ m = 0.5 \text{ eV} \]
\[ m = 0.35 \text{ eV} \]
\[ m = 0 \text{ eV} \]

\( \Rightarrow \) KATRIN will improve the sensitivity by 1 order of magnitude

will check the whole cosmological relevant mass range

will detect degenerate neutrinos (if they are degen.)

Direct neutrino mass determination

Christian Weinheimer

NUFACT09, Fermilab & IIL, July 2009
3 complementary probes of the neutrino mass:

- **comosology**: very sensitive, but model-dependent
- **0νββ**: sensitive to Majorana neutrinos
  - Majorana phases and nuclear matrix elements
  - searches for lepton number violation

**direct neutrino mass determination:**
- no other assumptions, kinematics of β-decay at endpoint

**KATRIN: 0.2 eV sensitivity:**
- 2009-11 commissioning of main spectrometer and detector
- 2009-12 commissioning of tritium source and tritium elimination lines
- 2012- regular data taking for 5-6 years (3 full-beam-years)