Neutrino mixing and mass
Part 2: mass

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Neutrino mass

Upper bound from direct measurements

Lower bound from oscillation experiments
Neutrino mass

Cosmology
\[ \Sigma = \sum_i m_i \]

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

$\beta$-decay kinematics
\[ m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \]
Questions for today

- How to measure the neutrino mass from cosmology?
- ...and from $0\nu\beta\beta$?
- ...and directly?
- What can we learn if we measure nothing?
Neutrino mass

**Cosmology**

$$\Sigma = \sum_i m_i$$

**Neutrinoless $\beta\beta$ decay**

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**$\beta$-decay kinematics**

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Neutrinos in the universe

• Freeze-out of $\nu$'s 1 s after big bang
• Neutrinos are the most abundant matter particle in the universe
• Today 300 neutrinos per cubic centimeter from the Big Bang
• Even if light they can impact the structure formation
Neutrinos as cosmic architects

Baryons, cold dark matter
Neutrinos as cosmic architects

\[ \Sigma m_\nu = 6.9 \text{ eV} \]

\[ \Sigma m_\nu = 0 \text{ eV} \]

\[ Z = 0.00 \]
Cosmological probes

**Cosmic microwave background**
- CMB temperature anisotropy
- CMB polarization
- CMB lensing

**Galaxy surveys**
- 3-d galaxy distribution
- Weak lensing at different redshift
- Lyman-α forest
Missions

**Cosmic microwave background**
- Planck satellite
- Simons Observatory (1808.07445)
- CMB-S4 (1610.02743)
- LiteBIRD (1801.06987)

**Galaxy surveys**
- Dark Energy Spectroscopic Instrument (DESI)
  - EUCLID (1110.3193)
  - LSST (Vera Rubin Obs.) (0912.0201)
  - WFIRST (now: NGRST) (1208.4012)
Where do we stand?

- Observable: sum of neutrino mass eigenstates: 
  \[ m_\Sigma = \sum_i m_i \]

![Diagram showing the hierarchy and degenerate regimes for neutrino mass eigenstates.](image)
Where do we stand?

Current best limits:
Planck 2018: arXiv:1807.06209v1

- $\sum m_\nu < 540\text{ meV (TT + lowE)}$
- $\sum m_\nu < 260\text{ meV (TTTEEE + lowE)}$
- $\sum m_\nu < 240\text{ meV (TTTEEE + lowE + lensing)}$
- $\sum m_\nu < 120\text{ meV (TTTEEE + lowE + lensing + BAO)}$
Where do we go?

Current best limits:
Planck 2018: arXiv:1807.06209v1
- $\sum m_\nu < 120 - 540$ meV

Future missions:
- $\sigma(\sum m_\nu) \sim 50$ meV (CMB)
- $\sigma(\sum m_\nu) \sim 20$ meV (CMB + BAO)
- $\sigma(\sum m_\nu) \sim 10$ meV (CMB + BAO + LSS)

Careful:
- cosmology sees the amount of hot dark matter
- not a direct neutrino mass measurement
- = model-dependent
Questions for today

How to measure the neutrino mass from cosmology

...and from $0\nu\beta\beta$ ?

...and directly ?

What can we learn if we measure nothing?

- Neutrinos are hot dark matter and wash out small scale structure
- Imprint in CMB and LSS
- Sensitivity at $\sum m_\nu < 0.2$ eV
Neutrino mass

Cosmology

\[ \Sigma = \sum_i m_i \]

Neutrinoless $\beta\beta$ decay

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

$\beta$-decay kinematics

\[ m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \]
The nature of neutrinos

Dirac: „Neutrinos and antineutrinos are different“

Majorana: „Neutrinos are their own antiparticle“
Helicity of Neutrinos

Neutrino
\[ p \rightarrow n + e^+ + \nu_e \]

Anti-Neutrino
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

Neutrinos are left-handed

Antineutrinos are right-handed
Helicity of Neutrinos

Neutrino factory

Anti-Neutrino factory

Majorana: “That’s the only difference”

Dirac: “There is a more fundamental difference between the two”
How can we test who is right?

**Dirac:**
“The neutrino is not identical to the known antineutrino”

**Majorana:**
“The neutrino is identical to the known antineutrino”
How can we test who is right?

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

\[ n + \nu_e \rightarrow p + e^- \]
How can we test who is right?

Dirac: “The reaction is not possible”

Majorana: “This reaction should be possible.”

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
Neutrinoless double beta decay: signature

\[ \frac{\text{d}N}{\text{d}E} \propto \frac{E}{Q_{\beta\beta}} \]

\[ \begin{align*}
\text{Energy of the two beta electrons} \\
48\text{Ca}, 76\text{Ge}, 96\text{Zr}, 100\text{Mo}, 110\text{Pd}, 116\text{Cd}, 124\text{Sn}, 130\text{Te}, 136\text{Xe}, 150\text{Nd}
\end{align*} \]
Neutrinoless double beta decay

If $0\nu\beta\beta$ was discovered:
- Proof that Majorana is right
- Discovery of matter-creating process → shed light on matter-anti-matter asymmetry
- Lepton number is violated
- Half life reveals neutrino mass

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q, Z) \cdot |M^{0\nu}|^2 \cdot m_{\beta\beta}^2$$
The Challenge

- What do we need to realize an experiment?

< 1 decay per ton and year
The Challenge

Key requirements:

- Large exposure (tonne-scale)
- Excellent energy resolution (~ 1% @ $Q_{\beta\beta}$)
- Low background (< 1 cts/year/t/ROI)

$< 1$ decay per ton and year
Where do we stand?

- Observable: Coherent sum of neutrino mass eigenstates:

\[ m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{vi} \right| \]
Where do we stand?

- Current limits (GERDA):
  \( T_{1/2} > \mathcal{O}(10^{26} \text{ y}) \) (90% CL)
  \( m_{\beta\beta} < \mathcal{O}(100) \text{ meV} \)

  \( n_1 \sim n_2 \sim n_3 \)

  \( \nu_1 \sim \nu_2 \sim \nu_3 \)

Where do we stand?

- Current limits (GERDA):
  \[ T_{1/2} > \mathcal{O}(10^{26} \text{ y}) \text{ (90\% CL)} \]
  \[ m_{\beta\beta} < \mathcal{O}(100) \text{ meV} \]
  Phys. Rev. Lett. 117 (2016), 082503

- Goal of future experiments:
  Probe inverted mass ordering
Experimental efforts

Scintillation

Phonons

Ionization

Graph: Energy distribution (log scale)
Experimental efforts

Germanium Semiconductors

- Enrichment to 87% in $^{76}$Ge ($Q_{\beta\beta} = 2039$ keV)
- Excellent energy resolution (0.12% FWHM @ $Q_{\beta\beta}$)
- Pulse-shape-discrimination against background
**LEGEND**

- **LEGEND-200**: running with ~100 detectors
- **LEGEND-1000**: 1000 kg of Ge (staged)
- $T_{1/2} (3\sigma \text{ DS}) > 10^{28} \text{ yr, } m_{\beta\beta} < 10 - 17 \text{ meV}$
Questions for today

How to measure the neutrino mass from cosmology

• Neutrinos are hot dark matter and wash out small scale structure
• Imprint in CMB and LSS
• Sensitivity at $\Sigma m_\nu < 0.2 \text{ eV}$

...and from $0\nu\beta\beta$ ?

• Half life of the $0\nu\beta\beta$ decay depends on mass of neutrino
• Signal = peak at $Q_{\beta\beta}$
• Sensitivity at $m_{\beta\beta} < 0.2 \text{ eV}$

...and directly ?

What can we learn if we measure nothing?

• Neutrinos are hot dark matter and wash out small scale structure
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Neutrino mass

Cosmology
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$\beta$-decay kinematics
\[ m_\beta = \sqrt{\sum_i |U_{ei}^2 m_i^2|} \]
Direct neutrino mass measurement

Non-zero neutrino mass distorts the spectrum close to the endpoint

✓ Independent of cosmology
✓ Independent of neutrino nature
Direct neutrino mass measurement

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

• What do we need to realize an experiment?

Only $10^{-13}$ of all decays in last 1 eV
The challenge

- What do we need to realize an experiment?
  - Ultra-strong radioactive source ($10^{11}$ decays/s)
  - Excellent energy resolution (~1 eV, 0.005%)
  - Low background (<100 mcps)

Only $10^{-13}$ of all decays in last 1 eV
Where do we stand?

Observable:

\[ m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2} \]
Where do we stand?

Observable:

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

Current limit

Running experiments

\( m_\beta \) (eV)

\( m_{\text{lightest}} \) (eV)
Where do we stand?

Observable:
• \( m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2} \)
Experimental efforts

Electrostatic filter (MAC-E)

Cyclotron Radiation

Phonons
Experimental efforts

- Project-8 (Tritium)
- KATRIN (Tritium)
- Electrostatic filter (MAC-E)
- Ptolemy (Tritium)
- Holmes (Holmium)
- Cyclotron Radiation
- Phonons
- ECHO (Holmium)
Experimental efforts

Electrostatic filter (MAC-E)

KATRIN (Tritium)

Cyclotron Radiation

Phonons
MAC-E-Filter

Tritium source

Spectrometer

Detector

- Retarding energy
- $B_s\ U_s = 0\ kV$
- $B_{\min}\ U_o = -18.6\ keV$
- $B_{\max}$

Count rate [cps]

Retarding energy [eV]
**MAC-E-Filter**

**Isotropic source**

\[ E_{kin} = E_L + E_T \]

**Spectrometer**

- \( B_s = 5T \)
- \( U_s \)
- \( B_{min} = 0.0005T \)
- \( U_0 \)
- \( B_{max} \)

**Detector**

- Large angle acceptance
- eV-scale E-resolution

\[ E_{T,center}^{start} = E_T^{start} \cdot \frac{B_{center, \text{start}}}{B_{start}} \rightarrow E_{T,center, \text{max}} = E \cdot \frac{B_{center, \text{start}}}{B_{start}} \approx 2 \text{ eV} \]
Karlsruhe Tritium Neutrino Experiment
Working Principle
Working Principle

Tritium source
- 100 µg of gaseous $T_2$
- $10^{11} T_2$ decays/s
Working Principle

**Tritium source**
- 100 µg of gaseous T<sub>2</sub>
- 10<sup>11</sup> T<sub>2</sub> decays/s

**Transport section**
- Guidance of electrons
- Removal of tritium
Working Principle

**Tritium source**
- 100 µg of gaseous T\(_2\)
- \(10^{11}\) T\(_2\) decays/s

**Transport section**
- Guidance of electrons
- Removal of tritium

**Spectrometer**
- Electrostatic filter
- MAC-E filter principle

Image and text content include diagrams and illustrations likely related to a tritium source, transport section, and spectrometer, with specifications and functionalities detailed above.
Working Principle

**Tritium source**
- 100 µg of gaseous T<sub>2</sub>
- 10<sup>11</sup> T<sub>2</sub> decays/s

**Transport section**
- Guidance of electrons
- Removal of tritium

**Spectrometer**
- Electrostatic filter
- MAC-E filter principle

**Detector**
- Counts electrons
- Rate vs potential

---

T<sub>2</sub> in

T<sub>2</sub> out

70 m
Working Principle
Latest results

First campaign:
- total statistics: 2 million events
- best fit: \[ m_\nu^2 = (-1.0^{+0.9}_{-1.1}) \text{ eV}^2 \text{(stat. dom.)} \]
- limit: \[ m_\nu < 1.1 \text{ eV (90\% CL)} \]

\[ \text{PRL. 123, 221802 (2019)} \]
\[ \text{Phys. Rev. D 104, 012005 (2021)} \]

Second campaign:
- total statistics: 4 million events
- best fit: \[ m_\nu^2 = (0.26^{+0.34}_{-0.34}) \text{ eV}^2 \text{(stat. dom.)} \]
- limit: \[ m_\nu < 0.9 \text{ eV (90\% CL)} \]

\[ \text{Nat. Phys. 18, 160–166 (2022)} \]

- Combined result: \[ m_\nu < 0.8 \text{ eV (90\% CL)} \]
Latest results

✓ Search for relic big-bang neutrinos

✓ Search for violation of Lorentz invariance
   arxiv:2207.06326 (2022)

✓ Search for light sterile neutrinos
   Phys. Rev. D 105, 072004 (2022)
KATRIN Data Taking Overview

- Commissioning
- Only 0.5% tritium

- 1st $m_\nu$ campaign
  - $m_\nu < 1.1$ eV
  - PRL 123, 221802 (2019)

- 2nd $m_\nu$ campaign
  - $m_\nu < 0.8$ eV
  - Nat. Phys. 18, 160–166 (2022)

+ sterile and relic neutrino searches:
  - PRL 126, 091803 (2021)
  - PRD 105, 072004 (2022)
What’s next?

- Commissioning
- Only 0.5% tritium
  - EPJ C 80, 264 (2020)

- 1st $m_\nu$ campaign
  - $m_\nu < 1.1$ eV
  - PRL. 123, 221802 (2019)

- 2nd $m_\nu$ campaign
  - $m_\nu < 0.8$ eV
  - Nat. Phys. 18, 160–166 (2022)

- New result this year

Data taking until 2026
Experimental efforts

- Electrostatic filter (MAC-E)
- Cyclotron Radiation
- Phonons
- Project-8 (Tritium)
Working principle

• **Technology:**
  Cyclotron Radiation Emission Spectroscopy (CRES)

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

• **Advantage**
  • Differential measurement
  • Source = detector

B. Monreal and Joe Formaggio, Phys. Rev D 80:051301
Project 8

• Recent Achievements
  ✓ Proof of concept
  ✓ First tritium spectra measured
    $\Delta E = 2 \text{ eV (FWHM)}, b < 3 \times 10^{-11} \text{ eV}^{-1} \text{ s}^{-1}$
  ✓ First neutrino mass limit: $m_\nu < 185 \text{ eV (90\% CI.)}$

• Next steps / challenges:
  • large-volume traps ($m^3$) (cavity resonator)
  • develop atomic tritium source

• Ultimate goal:
  • 0.04 eV sensitivity (150 meV resolution)
  arXiv:2203.07349 (2022)
Experimental efforts
Working principle

Technology:

- Low-temperature micro-calorimetry
- Holmium enclosed in absorber
- Measure decay energy via temperature rise

Advantage

- Differential measurement
- Source = detector
ECHo

• Achievements
  ✓ first holmium spectra measured
    \( \Delta E = 5 \text{ eV (FWHM)} \), \( b < 1.6 \times 10^{-4} \text{ eV}^{-1} \text{ pixel}^{-1} \text{ day}^{-1} \)
  ✓ first neutrino mass limit: \( m < 150 \text{ eV (95% C.L.)} \)
    
    *EPJ-C 79 1026 (2019)*
  ✓ refined theoretical calculations
    
  ✓ *ECHo-1k completed: \( \sim 60 \text{ Bq (} > 10^8 \text{ events)} \)
    
    *EPJ-C 81, 963 (2021)*

• Next steps/challenges
  • Scaling to higher activity per pixel and more pixels
  • ECHo-100k: \( m < 1.5 \text{ eV} \)

• Ultimate goal:
  • low sub-eV sensitivity
Questions for today

How to measure the neutrino mass from cosmology

- Neutrinos are hot dark matter and wash out small scale structure
- Imprint in CMB and LSS
- Sensitivity at $\sum m_\nu < 0.2$ eV

...and from $0\nu\beta\beta$ ?

- Half life of the $0\nu\beta\beta$ decay depends on mass of neutrino
- Signal = peak at $Q_{\beta\beta}$
- Sensitivity at $m_{\beta\beta} < 0.2$ eV

...and directly ?

- Neutrino mass reduces energy of beta
- Distortion of beta spectrum close to endpoint
- Sensitivity at $m_\beta < 0.8$ eV

What can we learn if we measure nothing?
Complementarity

**Puzzle 1:** If Project-8 would measure a neutrino mass and LEGEND would not observe a signal

Ø Neutrino is a Dirac particle
Ø (Or something is very wrong with our understanding of nuclear physics)

**Puzzle 2:** If LEGEND would see a signal and Project-8 would not measure the neutrino mass...

![Graph showing complementarity between Project-8 and LEGEND experiments](image)
Complementarity

**Puzzle 1:** If Project-8 would measure a neutrino mass, **but** LEGEND would not observe a signal

- Neutrino is a Dirac particle
- (Or something is very wrong with our understanding of nuclear/neutrino physics)

**Puzzle 2:** If LEGEND would see a signal, **but** Project-8 would not measure the neutrino mass...

- different lepton number violating mediator than light Majorana neutrino exchange
Questions for today

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...and directly?

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What can we learn if we measure nothing?

- Probes measure different combinations of $m_i$
- Observables are complementary
- We need all three of them
Back up
Let's have a closer look

\[ \frac{d\Gamma}{dE} = \sum W_i |\epsilon_i|^2 C \cdot F(E, Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m^2_e} \cdot \sqrt{(E_0 - E)^2 - m_i^2} \]

- Electron energy
- Neutrino energy
- Electron momentum
- Neutrino momentum

The spectrum is a weighted sum of three spectra

- \( m_1 < 0.5 \text{ eV} \)

This is the formula for beta-decay.
Let's have a closer look

\[ \frac{d\Gamma}{dE} = \sum_i |W_{ei}|^2 C \cdot F(E, Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_i^2} \cdot \sqrt{(E_0 - E)^2 - m_i^2} \]

The spectrum is a weighted sum of three spectra

We measure “far away” from the endpoint

\[ \sqrt{1 + x} \approx 1 + \frac{1}{2} x + \cdots \]

\[ \sum_i |W_{ei}|^2 (E_0 - E) \approx \sum_i |W_{ei}|^2 (E_0 - E) \left( 1 - \frac{1}{2} \frac{m_i^2}{(E_0 - E)^2} \right) \]

\[ = (E_0 - E) \left( 1 - \frac{1}{2} \frac{\sum_i |W_{ei}|^2 m_i^2}{(E_0 - E)^2} \right) \]

\[ = \sqrt{(E_0 - E)^2 - \sum_i |W_{ei}|^2 m_i^2} \]

\[ E_0 - E = 5 \text{ eV} \]

\[ m_i < 0.5 \text{ eV} \]
Let's have a closer look

\[ \frac{d\Gamma}{dE} = \sum_i |W_{ei}|^2 C \cdot F(E, Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_i^2} \]

\[ \frac{d\Gamma}{dE} \approx C \cdot F(E, Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - \sum_i |U_{ei}|^2 m_i^2} \]

\[ m_\nu^2 \equiv \sum_i |U_{ei}|^2 m_i^2 \]

incoherent sum of neutrino mass eigenstates
# Helicity vs Chirality

<table>
<thead>
<tr>
<th>Helicity</th>
<th>Chirality</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h = \frac{\mathbf{S} \cdot \mathbf{p}}{</td>
<td>\mathbf{p}</td>
</tr>
<tr>
<td>Weak interaction does not know about helicity</td>
<td>Weak interaction projects out a chiral component of the field</td>
</tr>
<tr>
<td>Helicity of massive particle depends on reference frame</td>
<td>Chirality is frame independent</td>
</tr>
<tr>
<td>Physical particles occur with a definite helicity in nature</td>
<td>Physical particles have no defined chirality</td>
</tr>
</tbody>
</table>
Chirality vs Helicity

QM superposition of helicity eigenstates (composition determined by m/E)

QM superposition of mass eigenstates (composition determined by PMNS matrix)
Helicity vs Chirality

\[ n \rightarrow p + e + \bar{\nu}_e \]
\[ \nu_e + n \rightarrow p + e \]

- Projection on electron neutrino flavor = superposition of mass eigenstate
- The physical neutrino, is the one that propagates through space, it has a definite mass (and no definite flavor)
Helicity vs Chirality

- Projection on right-chiral component of anti neutrino field

\[ n \rightarrow p + e + \bar{\nu}_e \]
\[ \nu_e + n \rightarrow p + e \]

Massless case:

- The physical neutrino appears only with right-handed helicity
Helicity vs Chirality

- Projection on right-chiral component of anti neutrino field

Massive case:
- The physical neutrino appears mostly with right-handed helicity and a bit \( \mathcal{O}(m/E) \) of left-handed helicity

\[ n \rightarrow p + e + \bar{\nu}_e \]
\[ \nu_e + n \rightarrow p + e \]
Helicity vs Chirality

- Projection on right-chiral component of anti neutrino field

Massive case:

- The physical neutrino appears mostly with right-handed helicity and a bit $O(m/E)$ of left-handed helicity
- The vertex will absorb with almost no suppression the left-handed helicity neutrino and a $O(m/E)$ fraction of the right-handed helicity neutrino
- The decay can occur, but is suppressed with $m_\nu$

$n \rightarrow p + e + \bar{\nu}_e$

$\nu_e + n \rightarrow p + e$

LH: will be completely absorbed
RH: A tiny bit $\sim O(m/E)$ will be absorbed
Model dependence

Cosmology

- Beyond $\Lambda$CDM
  - Bounds relaxed up to factor of $\sim 3$

Neutrino physics

- Non-standard p or T distributions
  - Farzan & Hannestad 1510.02201
  - Oldengott et al. 1901.04352
  - Alvey, Escudero, Sabti, Schwetz 2111.14870

- Invisible neutrino decay
  - Escudero, López-Pavón, Rius, Sandner 2007.04994
  - Chacko et al. 1909.05275, 2112.13862

- Time-dependent neutrino mass
  - Dvali & Funcke 1602.03191
  - Lorenz et al. 2102.13618

- Bounds relaxed up to $\sum m_\nu < 3$ eV