Experimental Evidence for Neutrino Mass

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“Standard Model” Neutrino Physics

1914 Electron Spectrum in $\beta$ decay is continuous
1930 Pauli postulates that a new particle is emitted
1933 Fermi names the new particle neutrino and introduces four-fermion interaction
1956 Reines and Cowan discover the neutrino
1962 At least two neutrinos: $\nu_e \neq \nu_\mu$
1989 Measurement of Z width at CERN $\rightarrow N_\nu = 3$
2002 tau neutrino discovered.

Neutrino Astrophysics

1938 Bethe & Critchfield $p + p \rightarrow ^2H + e^+ + \nu_e$
1946 Pontecorvo, 1949 Alvarez propose neutrino detection through $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$
1960’s Ray Davis builds chlorine detector
John Bahcall, generates SSM & solar n flux predictions

“…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars…”
First Indication of ‘Non-Standard’ Neutrinos

Solar Neutrino Flux Measurements

4p + 2e → 4He + 2νₑ + 26.7 MeV (pp chain)

1960’s

- Ray Davis’ Chlorine detector
- First Solar Model calculations

For 30 years

CC and ES measurements of solar νₑ

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Detection Reaction</th>
<th>Ratio Exp/BP2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine (127 t)</td>
<td>1970-1995</td>
<td>$^{37}$Cl + νₑ → $^{37}$Ar + e⁻</td>
<td>0.34 ± 0.03</td>
</tr>
<tr>
<td>Kamiokande (680t)</td>
<td>1986-1995</td>
<td>νₓ + e⁻ → νₓ + e⁻</td>
<td>0.54 ± 0.08</td>
</tr>
<tr>
<td>SAGE (23 t)</td>
<td>1990-1995</td>
<td>$^{71}$Ga + νₑ → $^{71}$Ge + e⁻</td>
<td>0.55 ± 0.05</td>
</tr>
<tr>
<td>Gallex + GNO (12 t)</td>
<td>1991-1995</td>
<td>$^{71}$Ga + νₑ → $^{71}$Ge + e⁻</td>
<td>0.57 ± 0.05</td>
</tr>
<tr>
<td>SuperK (22kt)</td>
<td>1996-1998</td>
<td>νₓ + e⁻ → νₓ + e⁻</td>
<td>0.451 ± 0.017 -0.015</td>
</tr>
</tbody>
</table>

(CC) $^{37}$Cl + νₑ → $^{37}$Ar + e⁻
(ES) $^{71}$Ga + νₑ → $^{71}$Ge + e⁻

→ Data are incompatible with solar models: Solar Neutrino Problem
Neutrino Oscillation

Neutrino States

Mass States
First
Second

$\nu_1$
$\nu_2$

Weak States
First
Second

$\nu_e$
$\nu_\mu$

Time Evolution

$P_{i\rightarrow i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$

Oscillation as an indication of massive neutrinos
Experimental Studies

Natural Sources

The Sun
- $^{37}$Cl
- GALLEX
- SAGE

Atmospheric Neutrinos
- IMB
- Soudan
- MACRO

Accelerators
- K2K
- Opera
- Chorus (LSND)

Nuclear Reactors
- Bugey
- Goesgen
- ILL
- Chooz
- Palo Verde
- KamLAND

Man-Made Sources

Man-Made Sources

- Kamiokande
- SuperKamiokande
- SNO

- Cosmic-ray shower
- Atmospheric neutrino source
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- $\pi^- \rightarrow \nu_e + \bar{\nu}_e + \bar{\nu}_\mu$
- $\pi^- \rightarrow \nu_e + \bar{\nu}_e + \nu_\mu$

- Primary neutrino source $p + p \rightarrow D + \nu_e + \bar{\nu}_e$
- $\sim 10^8$ kilometers

Solar core

Earth

Underground $\nu_e$ detector
Atmospheric Neutrino Studies

$E_\nu \sim 0.5 - 5 \text{ GeV}$
$L_{\text{down}} \sim 10 - 100 \text{ km}$
$L_{\text{up}} \sim 10,000 \text{ km}$
Super-Kamiokande

Atmospheric Neutrino Studies

Detect neutrinos through charged-current interaction in detector
Super-Kamiokande

Atmospheric Neutrino Studies

Deficit of upward-going $\nu_\mu$

Zenith angle dist. of Atmospheric $\nu$ flux

$\nu_\mu \rightarrow \nu_\tau$ 2-flavor osc.

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0 \times 10^{-3}$ eV$^2$

Null oscillation

Karsten Heeger, LBNL

E$_{\nu} >$ a few GeV

Up/Down Symmetry
KEK to Kamioka (K2K) Experiment

Accelerator-based long baseline neutrino oscillation experiment to test atmospheric oscillations

<table>
<thead>
<tr>
<th>atm</th>
<th>K2K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>$10-10^4$ km</td>
</tr>
<tr>
<td>$E_n$</td>
<td>0.1~100 GeV</td>
</tr>
<tr>
<td>$\Delta m^2$</td>
<td>$10^{-1}\sim10^{-4}$ eV$^2$</td>
</tr>
<tr>
<td>$\nu_e/\nu_\mu$</td>
<td>50%</td>
</tr>
</tbody>
</table>

data from 1999-2001

expected: 80.1 events
observed: 56 events

reconstructed $E_v$

Allowed region

Best fit point $2.8\times10^{-3}$
Super-Kamiokande L/E Analysis

Searching for Direct Evidence of Oscillations

Neutrino oscillation
Neutrino decay
Neutrino decoherence

![Graphs and data from Super-Kamiokande L/E Analysis showing
consistent with standard zenith angle analysis
90% allowed regions]

First dip is observed as expected from neutrino oscillation

Best-fit expectation
$\Delta m^2 = 2.4 \times 10^{-3}, \sin^2 2\theta = 1.00$
$\chi^2_{\text{min}} = 37.8/40$ d.o.f
Atmospheric Neutrino Oscillations

Atmospheric $\nu$ data explained extremely well by oscillations

- primarily $\nu_\mu \rightarrow \nu_\tau$ conversion
- mixing angle $\theta_{23}$ is near maximal
- $\Delta m^2 \sim 2 \times 10^{-3}$ eV$^2$
Elastic Scattering: \( \nu_x + e^- \rightarrow \nu_x + e^- \)

Data/SSM = 0.451 ± 0.005 (stat) + 0.016 - 0.014 (sys.)
Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

Acrylic Vessel, 12 m diameter

1000 Tonnes D$_2$O

Need solar model-independent measurement.

Need experiment that measures $\nu_e$ and $\nu_{\mu,\tau}$ separately.
Neutrino Detection in SNO

Neutrino Interactions on Deuterium and their Flavor Sensitivity

**Charged-Current (CC)**

\[ \nu_e + d \rightarrow e^- + p + p \]

\[ E_{\text{thresh}} = 1.4 \text{ MeV} \]

*Measurement of energy spectrum*

**Neutral-Current (NC)**

\[ \nu_x + d \rightarrow \nu_x + n + p \]

\[ E_{\text{thresh}} = 2.2 \text{ MeV} \]

*Measures total $^8\text{B}$ flux from Sun*

**Elastic Scattering (ES)**

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

*Strong directional sensitivity*
SNO - Enhanced Neutron Detection with NaCl

- Higher capture cross section
- Higher energy release
- Many gammas

\[
n + ^{35}\text{Cl} \rightarrow ^{35}\text{Cl}^* + g
\]

\[
n + ^{36}\text{Cl} \rightarrow ^{36}\text{Cl} + g
\]

\[
\sigma = 0.0005 \text{ b}
\]

\[
\sigma = 44 \text{ b}
\]

\[
^{2}\text{H} + n \rightarrow 8.6 \text{ MeV}
\]

\[
^{3}\text{H} \rightarrow 6.0 \text{ MeV}
\]

\[
^{36}\text{Cl} \rightarrow \text{gamma radiation}
\]
Solar Neutrino Physics with SNO

What can we learn from measuring the NC interaction rate (total active $^8$B solar neutrino flux) at SNO?

- Total $^8$B $\nu$ flux (NC) *versus* $\nu_e$ flux (CC)
  
  \[
  \frac{[CC]}{[NC]} = \frac{[\nu_e]}{[\nu_e + \nu_\mu + \nu_\tau]} \rightarrow \text{Test of neutrino flavor change}
  \]

- Total flux of solar $^8$B neutrinos
  
  $\rightarrow$ Test of solar models

- Diurnal time dependence
  
  $\rightarrow$ Test of neutrino oscillations

- Distortions of neutrino energy spectrum
  
  $\rightarrow$ Test of neutrino oscillations
SNO Signal Extraction

Data from July 26, 2001 to Oct. 10, 2002

254.2 live days
Blind analysis performed

3055 candidate events:
1339.6 $^{+63.8}_{-61.5}$ CC
1344.2 $^{+69.8}_{-69.0}$ NC
170.3 $^{+23.9}_{-20.1}$ ES
The Solution to the Solar Neutrino Problem: Neutrinos Change Flavor

2/3 of initial solar $\nu_e$ are observed at SNO to be $\nu_{\mu,\tau}$. Results from SNO, 2002.
Flavor Content of $^8$B Solar Neutrino Flux

$^8$B Standard Solar Model (SSM01)\hspace{1cm} 5.05 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$
NC Salt Constrained\hspace{1cm} 4.90 \pm 0.38 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$
NC Salt Unconstrained\hspace{1cm} 5.21 \pm 0.47 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

CC/NC Ratio

0.306 \pm 0.026 (stat) \pm 0.024 (sys)

Standard Solar Model predictions for total $^8$B flux in excellent agreement!
Oscillation Interpretation of Solar Neutrino Data

Energy-dependent effect

Neutrinos interact with matter in Sun and Earth (MSW)

\[
\begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau
\end{pmatrix} = U_{23} \times U_{13} \times \begin{pmatrix}
  \cos \theta_{12} & \sin \theta_{12} & 0 \\
  -\sin \theta_{12} & \cos \theta_{12} & 0 \\
  0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
\end{pmatrix}
\]

hep-ph/0402025
Solar Neutrino Oscillations

Flavor conversion of solar $\nu_e \rightarrow \nu_{\mu,\tau}$

- mixing angle $\theta_{12}$ is large but not maximal, $\Delta m_{12} \sim 7 \times 10^{-5}$ eV$^2$
- matter effects enhance oscillation
- other modes for solar neutrino flavor transformation (sterile, RSFP, CPT ...) can play only a subdominant role.
Neutrino Oscillation Experiments

Reactor and Beamstop Neutrinos
\[ \nu_\mu \Rightarrow \nu_s \Rightarrow \nu_e \]

Atmospheric and Reactor Neutrinos
\[ \nu_\mu \Rightarrow \nu_\tau \]

Solar and Reactor Neutrinos
\[ \nu_e \Rightarrow \nu_{\mu,\tau} \]

Large mixing favored

**LMA solution can be tested with reactor neutrinos**

Status: Summer 2002
Search for Neutrino Oscillations with Reactor Neutrinos

50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

1956 “Detection of Free Antineutrino”, Reines and Cowan
→ Nobel Prize in 1995

No signature of neutrino oscillations until 2002!

Results from solar experiments suggest study of reactor neutrinos with a baseline of ~ 70 km
Reactor Antineutrinos

From Japanese Reactors

Kashiwazaki

Takahama

Ohi

~ 79% of $\nu$ flux from distance 138-214 km.
~ 6 $\overline{\nu}_e$ per fission
~ $2 \times 10^{20} \nu_e/GW_{th}$-sec

Spectrum from Principal Reactor Isotopes

~ 200 MeV per fission

Neutrino Flux at KamLAND

~ 79% of $\nu$ flux from distance 138-214 km.
~ 6.7% from one reactor at 88 km.
KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

Uses reactor neutrinos to study $\bar{\nu}$ oscillation with a baseline of $L \sim 140\text{-}210 \text{ km}$

Coincidence Signal: $\bar{\nu}_e + p \rightarrow e^+ + n$

- **Prompt** $e^+$ annihilation
- **Delayed** $n$ capture, $\sim 190 \mu s$ capture time

KamLAND studies the disappearance of $\bar{\nu}_e$ and measures:
- interaction rate
- energy spectrum
Event Selection

Delayed Energy Window

from $^{12}\text{C}(n,\gamma)$

$t_{\text{cap}} = 188 \pm 23 \text{ msec}$

delayed energy window

Muon veto

2 sec VETO for 6m$\phi$ cylinder
93.6% eff.

2 sec VETO for all volume

Vertex and Time Correlation

$R < 5 \text{ m}$

$0.5 < |\text{d}T| < 660 \mu\text{sec}$

$|\text{d}R| < 1.6 \text{ m}$

$|\text{d}Z| > 1.2 \text{ m}$
First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance

KamLAND provides evidence for neutrino oscillations together with solar experiments.
Is the KamLAND Neutrino Spectrum Distorted?

Search for a Unique Signature of Neutrino Oscillation

2-ν oscillation: best-fit

No oscillation, flux suppression

![Graphs showing data and best oscillation fit consistent at 93% C.L. as determined by Monte Carlo](image_url)

\[ \chi^2 / 8 \text{ d.o.f.} = 0.31 \]

Data and best oscillation fit consistent at 93% C.L.

Data and best oscillation fit consistent at 53% C.L. as determined by Monte Carlo
Oscillation Parameters *Before* and *After* KamLAND

**Before KamLAND**

Before KamLAND, the region favored by solar $\nu$ experiments is shown. The agreement between oscillation parameters for $\bar{\nu}$ and $\nu$ is indicated.

**After KamLAND**

After KamLAND, KamLAND's 95% exclusion by rate and 95% allowed by rate+shape are shown. The agreement between oscillation parameters for $\bar{\nu}$ and $\nu$ is also indicated.
Determination of Oscillation Parameters $\Delta m_{12}^2, \theta_{12}$

**Before SNO-Salt**

**With SNO-Salt**

Assume CPT

$|\Delta m_{\nu}^2 - \Delta m_{\nu}^2| < 1.3 \times 10^{-3}$ eV$^2$ at 90% CL

$\rightarrow$ LMA I only at $> 99\%$ CL

$\rightarrow$ Maximal mixing ruled out (5.4$\sigma$)

Possible Sterile Admixture?

KamLAND + SNO-Salt  $\quad \sin^2 \eta_{\text{sterile}} < 0.09$
Defining $\theta_{12}$ and $\Delta m_{12}^2$ with SNO and KamLAND

Is it all consistent?

Day/Night variation,
Spectrum from MSW Solar
*versus*
Reactor Oscillation …
Evidence for Mixing of Massive Neutrinos

- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that neutrinos oscillate
Cosmological Implications

Experimental Results

Atmospheric neutrinos: \[ \Delta m_{23}^2 \approx 2.0 \times 10^{-3} \text{ eV}^2 \]  
\[ \therefore \text{one neutrino mass} > 0.04 \text{ eV} \]

SNO + KamLAND: \[ \Delta m_{12}^2 \approx 7.3 \times 10^{-5} \text{ eV}^2 \]  
\[ \therefore \text{one neutrino mass} > 0.008 \text{ eV} \]

Limits on “\(\nu_e\) mass” give: \[ m(\nu_{1,2,3}) < 2.2 \text{ eV} \]

Implications

\[ \sum \text{of neutrino masses:} \quad 0.048 < m_1+m_2+m_3 < 6.6 \text{ eV} \]

Laboratory limit on \(n\) fraction of universe closure density: \[ 0.001 < \Omega_\nu < 0.13 \]

Large-scale structure limit: \[ 0.13 < \Omega_\nu < 0.02 \]
Cosmological Information on Neutrino Mass

Neutrinos’ contribution to the Universe’s energy density

\[ \Omega_\nu h^2 = \sum_i m_i / 95.3 \text{ eV} \]

Combining WMAP and large scale structure

\[ \Omega_\nu h^2 < 0.0076 \text{ eV} \quad (95\% \text{ CL}) \]

If \( m_{\nu e} \sim m_{\nu \tau} \) (degenerate neutrino species)

\[ m_\nu < 0.23 \text{ eV} \]

Cosmological neutrino mass limits probe Dirac and Majorana \( \nu \) masses!

Mass limits comparable to \( 0\nu\beta\beta \) experiments.
Cosmological Density

- Dark Energy: 0.7 ± 0.1
- Matter: 0.3 ± 0.1

Matter Composition

- Cold Dark Matter: 0.35 ± 0.1
- Non-Baryonic Dark Matter
- Baryons: 0.037 ± 0.001
- Dark Baryons
- Stars: ~0.003

Observed Particle Dark Matter

- Neutrinos:
  - Direct neutrino mass measurements + oscillation experiments
  - WMAP
  - < 0.0076
  - > 0.003

Ωνh² Light Neutrino Density from direct neutrino mass measurements + oscillation experiments + WMAP
We have learned …

- $\nu$ transform flavor

- Atmospheric $\nu$ data explained extremely well by oscillations
  - primarily $\nu_\mu \rightarrow \nu_\tau$ conversion
  - mixing angle $\theta_{23}$ is very large, possibly maximal
  - $\Delta m^2 \sim 2 \times 10^{-3} \text{ eV}^2$

- Solar $\nu_e$ change primarily to other active $\nu$’s
  - if oscillations, mixing angle $\theta_{12}$ is large but not maximal and $\Delta m_{12} \sim 7 \times 10^{-5} \text{ eV}^2$ (LMA solution)
  - matter predicted to play a role in transformation
  - other modes for solar neutrino flavor transformation (sterile, RSFP, CPT …) can play only a subdominant role.

“…convincingly show that the flavor transitions of solar neutrinos are affected by Mikheyev-Smirnov-Wolfenstein (MSW) effects”

G.L. Fogli et. al, hep-ph/0309100
Other oscillations?

\[ \nu_\mu \Rightarrow \nu_\tau \]

\[ \nu_\mu \Rightarrow \nu_e \]

\[ \nu_e \Rightarrow \nu_\mu, \nu_\tau \]

Cannot be explained by 3 active neutrinos!

L = 30m
E = ~40 MeV

\[ \Delta m^2 = 0.3 \text{ to } 3 \text{ eV}^2 \]

\[ P_{\text{OSC}} = 0.3 \% \]

Will be checked by MiniBoone at FNAL (2005?)

Karsten Heeger, LBNL
SeeSaw25 - June 10, 2004
**$U_{\text{MNSP}}, \theta_{13}, \text{ and } \mathcal{CP}$**

**$U_{\text{MNSP}}$ Neutrino Mixing Matrix**

$$U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}$$

**Dirac phase**

$$\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{\text{CP}}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{\text{CP}}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}$$

**Majorana phases**

$$\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha/2} & 0 \\
0 & 0 & e^{i\alpha/2 + i\beta}
\end{pmatrix}$$

atmospheric, K2K  reactor and accelerator  SNO, solar SK, KamLAND  $0\nu\beta\beta$

- $\theta_{23} = \sim 45^\circ$
- $\tan^2 \theta_{13} < 0.03$ at 90% CL
- $\theta_{12} \sim 32^\circ$
- $\theta_{13}$ yet to be measured, determines accessibility to CP phase

Ref: Smirnov
Neutrino Masses: What do we know?

Oscillation experiments - indicate \( \nu \) do have mass
- set the relative mass scale,
- set minimum for the absolute scale. \( m_i > \sqrt{\Delta m_{atm}^2} \approx 50 \text{meV} \)

\[ |U_{e3}|^2 \]

\[ m_1^2 \quad m_2^2 \quad m_3^2 \]

atmospheric \(~3 \times 10^{-3} \text{eV}^2\) \(~3 \times 10^{-3} \text{eV}^2\)

\[ \Delta m_\odot^2 \quad \Delta m_{atm}^2 \]

Karsten Heeger, LBNL
SeeSaw25 - June 10, 2004
Constraining the Neutrino Mass

No fundamental reason why neutrinos must be massless.

But why are they much lighter than other particles?
Direct Neutrino Mass Searches

Model-Independent Neutrino Masses from $\beta$-decay Kinematics

$$N(E_e) \propto p_e E_e (E_0 - E_e) \sqrt{(E_0 - E_e)^2 - m_\nu^2 c^4}$$

Search for a distortion in the shape of the $\beta$-decay spectrum in the end-point region
Mainz Neutrino Mass Experiment

Current best limit $m_\nu < 2.2$ eV
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The Next Frontier in Neutrino Physics

$\nu$ mode: conventional 2$^{nd}$ order process in nuclear physics

$0\nu$ mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

$\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$

$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \left< m_{\beta\beta} \right>^2$

$G$ are phase space factors

$G_{0n} \sim Q^5$

important physics
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The Next Frontier in Neutrino Physics

2ν mode: conventional 2nd order process in nuclear physics

0ν mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

The only known practical approach to discriminate Majorana vs Dirac $\nu$
Several Proposed $0\nu\beta\beta$ Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (kg)</th>
<th>Type of Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>COBRA</td>
<td>Te-130</td>
<td>10 kg CdTe semiconductors</td>
</tr>
<tr>
<td>DCBA</td>
<td>Nd-150</td>
<td>20 kg Nd layers between tracking chambers</td>
</tr>
<tr>
<td>NEMO</td>
<td>Mo-100, Various</td>
<td>10 kg of $bb$ isotopes (7 kg of Mo)</td>
</tr>
<tr>
<td>CAMEO</td>
<td>Cd-114</td>
<td>1 t CdWO$_4$ crystals</td>
</tr>
<tr>
<td>CANDLES</td>
<td>Ca-48</td>
<td>Several tons CaF$_2$ crystals in liquid scint.</td>
</tr>
<tr>
<td>CUORE</td>
<td>Te-130</td>
<td>750 kg TeO$_2$ bolometers</td>
</tr>
<tr>
<td>EXO</td>
<td>Xe-136</td>
<td>1 ton Xe TPC (gas or liquid)</td>
</tr>
<tr>
<td>GEM</td>
<td>Ge-76</td>
<td>1 ton Ge diodes in liquid nitrogen</td>
</tr>
<tr>
<td>GENIUS</td>
<td>Ge-76</td>
<td>1 ton Ge diodes in liquid nitrogen</td>
</tr>
<tr>
<td>GSO</td>
<td>Gd-160</td>
<td>2 t Gd$_2$SiO$_5$:Ce crystal scint. in liquid scint.</td>
</tr>
<tr>
<td>Majorana</td>
<td>Ge-76</td>
<td>500 kg Ge diodes</td>
</tr>
<tr>
<td>MOON</td>
<td>Mo-100</td>
<td>Mo sheets between plastic scint., or liq. scint.</td>
</tr>
<tr>
<td>Xe</td>
<td>Xe-136</td>
<td>1.56 t of Xe in liq. Scint.</td>
</tr>
<tr>
<td>XMASS</td>
<td>Xe-136</td>
<td>10 t of liquid Xe</td>
</tr>
</tbody>
</table>

The $<m_{\beta\beta}>$ limits depend on background assumptions and matrix elements which vary from proposal to proposal.
A Recent Claim for $0\nu\beta\beta$ in $^{76}\text{Ge}$

5 detectors of overall 10.96 kg enriched to 86-88% in the $\beta\beta$-emitter $^{76}\text{Ge}$

$$T = (0.69 - 4.18) \times 10^{25} \text{ years} \ (3 \sigma)$$

**Majorana $\nu$ Mass**

$$m_\nu = (0.24 - 0.58) \text{ eV} \ (3 \sigma)$$

$$m_\nu \text{ best} = 0.44 \text{ eV}$$

hep-ph/0403018
Massive Neutrinos? Yes! \( \nu \) transform flavor

\[
\begin{align*}
\nu_e &\rightarrow \nu_{\mu,\tau} \\
\nu_\mu &\rightarrow \nu_\tau
\end{align*}
\]

Data explained well by oscillation, other solutions disfavored.

What else?

• What are the absolute masses?
• What is the level ordering of 2,3 (or 1,3)?
• Are \( \nu \)'s Dirac or Majorana particles?
  \[\rightarrow \text{Direct mass measurements and } 0\nu\beta\beta\]

• What are the values of \( \Delta m^2, U_{ij} \)?
  \[\rightarrow \text{Reactor and accelerator experiments}\]
• How many mass states? Are there sterile \( \nu \)?
  \[\rightarrow \text{MiniBoone}\]
A very exciting time for neutrino physics

More to come …