Neutrino mass, lepton number, and the origin of matter
And why is there **matter** but no **antimatter**?

Sakharov’s criteria:

*Baryon number not conserved…*

*CP violated…*

*Universe not in equilibrium at some point…*
The big questions

1. Major scientific discoveries since 2007
2. Compelling and unique science to be done in the next 5 years
3. Vision for 2020
4. International Context
The big questions

1. Major scientific discoveries since 2007
   - $\theta_{13}$ measured!
   - Higgs found!
   - Borexino, SNO, SK, KamLAND results
   - MiniBooNE results
   - Nuclear theory of DBD
   - EXO and KamLAND results for $^{136}$Xe 2$\nu$$\beta\beta$, 0$\nu$$\beta\beta$
   - Idea to use cyclotron radiation for neutrino mass measurement
Neutrinos oscillate, have mass.
Calibrating the Sun & SNO – MuSun at PSI
The MNSP Mixing Matrix and oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Unitary matrix: 9 parameters not all independent.

3 trig angles enough to describe oscillations.

There are also CP-violating phase(s).

\[\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3\]

\[\lambda = \frac{\hbar}{p} \approx \left( m_j^2 - m_i^2 \right) \frac{L}{2E} \]

Depends on mass-squared differences \( \times \) distance, & the sizes of the \( U_{ei} \)
$\Theta_{13}$ Measured!

Daya Bay

Double Chooz

RENO
Mass and mixing parameters

<table>
<thead>
<tr>
<th>Oscillation</th>
<th>Kinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.54^{+0.21}_{-0.21} \times 10^{-5} \text{ eV}^2$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{32}^2</td>
</tr>
<tr>
<td>$\Sigma m_i$</td>
<td>$&gt; 0.055 \text{ eV (90% CL)}$ &lt; 5.4 eV (95% CL)*</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>$34.1^{+0.9}_{-0.9} \text{ deg}$</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>$39.2^{+1.8}_{-1.8} \text{ deg}$</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>$9.1^{+0.6}_{-0.7} \text{ deg}$</td>
</tr>
<tr>
<td>$\sin^2\theta_{13}$</td>
<td>$0.025^{+0.003}_{-0.003}$</td>
</tr>
</tbody>
</table>

Marginalized 1-D 1-$\sigma$ uncertainties.

Other refs, see Fogli et al. 1205.5254
What do we still want to know?

Are neutrinos their own antiparticles?

Do neutrinos violate CP?

What is the mass?

What is the level ordering (hierarchy)?

And many other things…
Neutrinoless Double Beta Decay

Are neutrinos their own antiparticles?
Is lepton number conserved?

\[
\lambda_{0\nu} \frac{N}{M} = \frac{\ln(2)N_A G_{0\nu}^4 |M_{0\nu}|^2 \langle m_{ee} \rangle^2}{Am_e^2}
\]

\[
\equiv \Gamma_{0\nu} |M_{0\nu}|^2 \langle m_{ee} \rangle^2
\]

\[
\langle m_{ee} \rangle = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta}|
\]

W. Rodejohann, 1206.2560
Neutrinoless Double Beta Decay

1 sigma

W. Rodejohann, 1206.2560
IBM-2 RESULTS (JAN 2012)
LIGHT NEUTRINO EXCHANGE

IBM-2 from J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009) and to be published.
Regions contain calculated matrix elements (SM, QRPA, IBM, GCM) and range of $g_A$ values (free nucleon down to $2\nu\beta\beta$ fits).
### Large-scale experiments

Table 4. Details of the most advanced experiments. Given are life-time sensitivity and the expected limit on \(\langle m_{ee} \rangle\), using the NME compilation from figure 5.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Mass [kg]</th>
<th>Sensitivity (T^{0\nu}_{1/2}) [yrs]</th>
<th>Status</th>
<th>Start of data-taking</th>
<th>Sensitivity (\langle m_{\nu} \rangle) [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>(^{76}\text{Ge})</td>
<td>18</td>
<td>(3 \times 10^{25})</td>
<td>running</td>
<td>(\sim 2011)</td>
<td>0.17-0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>(2 \times 10^{26})</td>
<td>in progress</td>
<td>(\sim 2012)</td>
<td>0.06-0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>(6 \times 10^{27})</td>
<td>R&amp;D</td>
<td>(\sim 2015)</td>
<td>0.012-0.030</td>
</tr>
<tr>
<td>CUORE</td>
<td>(^{130}\text{Te})</td>
<td>200</td>
<td>(6.5 \times 10^{26}\star)</td>
<td>in progress</td>
<td>(\sim 2013)</td>
<td>0.018-0.037</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2.1 \times 10^{26}\star)</td>
<td></td>
<td></td>
<td>0.03-0.066</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>(^{76}\text{Ge})</td>
<td>30-60</td>
<td>((1-2) \times 10^{26})</td>
<td>in progress</td>
<td>(\sim 2013)</td>
<td>0.06-0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>(6 \times 10^{27})</td>
<td>R&amp;D</td>
<td>(\sim 2015)</td>
<td>0.012-0.030</td>
</tr>
<tr>
<td>EXO</td>
<td>(^{136}\text{Xe})</td>
<td>200</td>
<td>(6.4 \times 10^{25})</td>
<td>running</td>
<td>(\sim 2011)</td>
<td>0.073-0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>(8 \times 10^{26})</td>
<td>R&amp;D</td>
<td>(\sim 2015)</td>
<td>0.02-0.05</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>(^{82}\text{Se})</td>
<td>100-200</td>
<td>((1-2) \times 10^{26})</td>
<td>R&amp;D</td>
<td>(\sim 2013-15)</td>
<td>0.04-0.096</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>(^{136}\text{Xe})</td>
<td>400</td>
<td>(4 \times 10^{26})</td>
<td>running</td>
<td>(\sim 2011)</td>
<td>0.03-0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>(10^{27})</td>
<td>R&amp;D</td>
<td>(\sim 2013-15)</td>
<td>0.02-0.046</td>
</tr>
<tr>
<td>SNO+</td>
<td>(^{150}\text{Nd})</td>
<td>56</td>
<td>(4.5 \times 10^{24})</td>
<td>in progress</td>
<td>(\sim 2012)</td>
<td>0.15-0.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>(3 \times 10^{25})</td>
<td>R&amp;D</td>
<td>(\sim 2015)</td>
<td>0.06-0.12</td>
</tr>
</tbody>
</table>

W. Rodejohann, 1206.2560
EXO measures $^{136}$Xe 2νββ, limits 0νββ

\[ T^0_{1/2} \geq 1.6 \times 10^{25} \text{ yr} \]

\[ T^{2\nu}_{1/2} = (2.23 \pm 0.017 \pm 0.22) \times 10^{21} \text{ yr} \]

PRL 109, 032505 (2012)
What is the neutrino mass scale?
Neutrino mass is not a feature of the SM

A signal of unification? See-saw model:

$$m_\nu = \frac{m_D^2}{M}$$
Present LCDM constraints on $S_{m\nu}$:

$\sim 0.6 \text{ eV}$

Planck sensitivity:

1. Planck only $\quad 0.26 \text{ eV}$
2. Planck + SDSS $\quad 0.2 \text{ eV}$
3. CMBR + grav. lensing $\quad 0.15 \text{ eV}$

From Planck “Bluebook”
Present constraints and future sensitivities...

CMB (WMAP7+ACBAR+BICEP+QuaD) + LSS (SDSS-HPS) + HST+SNIa

\[ \sum m_\nu < 0.44 \rightarrow 0.76 \text{ eV (95\% CI)} \]

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y^3W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

\[ \sum m_\nu < 0.38 \rightarrow 0.84 \text{ eV (95\% CI)} \]

Perotto et al. 2006

Planck+Weak lensing (LSST)

\[ \sum m_\nu < 0.074 \rightarrow 0.086 \text{ eV (95\% CI)} \]

Hannestad, Tu & Y^3W 2006

Y.Y.Y. Wong
Neutrino mass from Beta Spectra

With flavor mixing:

\[
\frac{dN}{dT} = \frac{G_F \cos \theta_C}{2\pi^3} |M_{\text{nuc}}|^2 F(Z, T)(T + m)(T^2 + 2mT)^{1/2}(T_0 - T) \sum_i |U_{ei}|^2 [(T_0 - T)^2 - m_i^2]^{1/2}
\]

\[
m_i^2 = \Delta m_{i0}^2 + m_0^2
\]

mixing neutrino masses

from oscillations mass scale
Current status of direct mass measurement

Mainz: solid $T_2$, MAC-E filter

$\mu^{2}(\nu_{e}) = (-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}})$

$m(\nu_{e}) < 2.3 \text{ eV}/c^2$ (95% C.L.)

Troitsk: gaseous $T_2$, MAC-E filter
V. Aseev et al., PRD in press (2011)

$m_{\nu}^{2} = -0.67 \pm 1.89_{\text{stat}} \pm 1.68_{\text{syst}}$

$m_{\nu} < 2.05 \text{ eV}$, 95% C.L.

Together:… $m_{\nu} < 1.8 \text{ eV}$ (95% CL)
KATRIN

At Karlsruhe Institute of Technology
unique facility for closed $T_2$ cycle:
Tritium Laboratory Karlsruhe

5 countries
13 institutions
100 scientists

~ 75 m long with 40 s.c. solenoids
KATRIN’s uncertainty budget

\[ \sigma(m_v^2) \]

\[ 0 \quad 0.01 \text{eV}^2 \]

- Statistical
- Final-state spectrum
- T^- ions in T_2 gas
- Unfolding energy loss
- Column density
- Background slope
- HV variation
- Potential variation in source
- B-field variation in source
- Elastic scattering in T_2 gas

\[ \sigma(m_v^2)_{\text{total}} = 0.025 \text{eV}^2 \]

\[ m_v < 0.2 \text{eV} \text{ (90 \% CL)} \]
Molecular Excitations

Energy loss function

Rovibrational Structure of Ground State

First Electronic Excitation

Saenz et al. PRL 94, 242

quench condensed D₂
Mainz
gaseous T₂, Troitsk

Excitation in \( ^3 \text{HeT}^+ \) (eV)

energy loss \( \varepsilon \) [eV]
Microcalorimeters for $^{187}\text{Re}$ β-decay

MIBETA: Kurie plot of $6.2 \times 10^6 {^{187}}\text{Re}$ β-decay events ($E > 700$ eV)

MANU2 (Genoa)
metallic Rhenium
$m(n) < 26$ eV

MIBETA (Milano)
$\text{AgReO}_4$
m($n$) < 15 eV

MARE (Milano, Como, Genoa, Trento, US, D)
Phase I: $m(n) < 2.5$ eV
hep-ex/0509038

$E_0 = (2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{syst}})$ eV

$m_n^2 = (-112 \pm 207 \pm 90)$ eV$^2$
Electron Capture Holmium Expt (ECHO)

- Using low-temperature Metallic Magnetic Calorimeters to study both $^{187}$Re and $^{163}$Ho.
  - should be able to achieve ultimate resolution $\sim 2$ eV and rise-times of 90 ns

  ![Diagram of absorber and copper/Gold configuration](image)

  - report $Q_{EC} = 2.80 \pm 0.16$ keV
  - shapes of N and M lines not entirely understood
Neutrino Mass Limits from $\beta$ decay

$^{3}\text{H}$

$^{187}\text{Re}$ (Genoa, Milano)

KATRIN

Inv. Hierarchy $<m_e>$

Oscillation lower bound $<m>$

J.F. Wilkerson & HR
If the mass is NOT in the 200-2000 meV window, but <200 meV, how can we measure it? KATRIN may be the largest such experiment possible.

Size of experiment now: Diameter 10 m.

Next diameter: 300 m!

\[ \sigma(m_\nu) = k \frac{b^{1/6}}{r^{2/3} t^{1/2}}, \]

Rovibrational states of THe\(^+\), HHe\(^+\) molecule
Cyclotron radiation from tritium beta decay

\[ \omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma} \]

\[ \omega_c = 1.758820150(44) \times 10^{11} \text{ rad/s/T} \]

Radiated power \( \sim 1 \text{ fW} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>18.6</td>
<td>keV</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.2627</td>
<td></td>
</tr>
<tr>
<td>( \gamma )</td>
<td>1.0364</td>
<td></td>
</tr>
<tr>
<td>Field</td>
<td>1</td>
<td>T</td>
</tr>
<tr>
<td>( \omega_c )</td>
<td>27.009</td>
<td>GHz</td>
</tr>
</tbody>
</table>
Signal is a rising “chirp” in frequency.
**Major objectives in Neutrino Physics**

**Known Unknowns**
- $\theta_{13}$
- Hierarchy
- Mass
- CP violation
- Majorana or Dirac

**Unknown Unknowns**
- OPERA
- $N_v \sim 4$ from cosmology
- LSND, MiniBooNE
- Reactor anomaly
- Ga source anomaly

*(DOE Nuclear Physics plays a strong role)*
Double Beta Decay: some milestones

CUORE:
- Construction
- “0” Running
- Running

EXO-200:
- Running

KamLAND-Zen
- Running

NeXT:
- Construction
- Running

GERDA:
- “I” Running
- “II” Running

Majorana:
- Construction
- Running

SNO+:
- Construction
- Solar Running
- DBD Running

- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018
Neutrino mass: some milestones

KATRIN:
- Construction
- Running

Project 8:
- Proof concept
- Prototype
- Phase I

Planck:
- Analysis 1
- Analysis 2

2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018
The Neutrino Portfolio in DOE-NP and NSF

Capital Equipment Participation

Solar neutrinos:
  SNO, Borexino, SNO+

Neutrino mass:
  KATRIN, Project 8

Double Beta Decay:
  CUORE, Majorana & COGENT, SNO+, EXO, KamLAND-Zen

Oscillations, UHE neutrinos:
  KamLAND, IceCube, MiniBooNE (from LSND), Daya Bay

Theory:
  Supernova physics, phenomenology, DBD

Facility:
  SURF
Who needs an underground lab?

We do.

The US has been attempting to build a dedicated, deep underground lab since 1975. We did not get that (complicated history), but the science still needs to be done. SURF at Homestake is a new asset for us, a unique home for important parts of that science. It has attracted $70M in private funding, an extraordinary departure for nuclear physics.

Majorana (and LUX) are sited there, and smaller experiments. It’s deeper than most national u/g labs, although probably not deep enough for the tonne-scale DBD expts. It’s still very much a world-class facility, and, at last, we have “a bird in the hand”.

We will use SURF, WIPP, Soudan, Kimballton, SNOLAB, LNGS, Kamioka and we will do the science.

“…it was like stepping from a busy market into the quiet of a cathedral…”

Michael Moe
The big questions

4. International Context
   KamLAND, SK, T2K in Japan
   Daya Bay in China
   SNO+, NeXT ? in Canada
   KATRIN in Germany
   CUORE in Italy
   Majorana/GERDA will join forces for 1-T Ge. Is SURF 4850 deep enough, or will this go to Canada or China?
   EXO-200, MINOS, MiniBooNE in US
   nEXO probably in Canada
   IceCube at the South Pole under US Administration

   The cost and difficulty involved at the neutrino frontier makes international collaboration all but essential. But this should not exclude the possibility of doing some experiments in the US.
2. Compelling and unique science to be done in the next 5 years
   - KATRIN mass measurement
   - 0νββ searches: Ge, Te, Xe, Nd, …
   - SNO+, Borexino: CNO, luminosity constraint tested

3. Vision for 2020 (2030 in neutrino units)
   - Direct mass measurement to +/- 20 meV
   - Neutrinos are Majorana [or Dirac]
   - Hierarchy is Normal [or Inverted]
   - CP violation is found in neutrino sector [or limited]
   - Sterile neutrinos are found [or limited]
   - Solar luminosity ratio (neutrinos/photons) measured to 1%

A very exciting future!