Neutrino Physics: Overview and Directions

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European Neutrino "Town" meeting and ESPP 2019 discussion

CERN, 22-24 October 2018
The SM – a Synergy of Concepts

d=4 QFTs: 

\[
\begin{array}{c}
\text{QED} \ \Rightarrow \ \text{QCD} \quad \Rightarrow \quad \text{SM} \\
\text{U}(1)_{\text{em}} \quad \text{SU}(3)_C \quad \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y
\end{array}
\]

electrodynamics  \quad \text{QED}
relativity

strong force \ \Rightarrow \ \text{QCD}

weak decays + Higgs mech., \(\chi\)-ral
+ neutrino masses
+ dark matter \(\iff\) ?
+ DE ?

AND: gravity

weak scale \(\llll\)

\(M_{\text{Planck}}\)

territory of speculations:
SM \(\Rightarrow\) extra reps? LR?
TC? SUSY? GUTs? TOE?
extra dim.? strings?
Reasons to go Beyond the Standard Model

Theoretical:
! SM does not exist without cutoff (triviality, vacuum stability)
? Gauge hierarchy problem
? Origin of generations / flavour
? Gauge unification, charge quantization
! Strong CP problem
? Unification with gravity
? Global symmetries & GR anomalies

Experimental facts:
? Electro weak scale << Planck scale
? Gauge couplings almost unify
? Flavour: Patterns of masses & mixings
? Dark Energy
! Dark Matter
! Baryon asymmetry of the Universe
! Neutrinos masses & large mixings

➔ how solid are these reasons!?  How does neutrino physics fit in?
**Bottom-up: Minimal Neutrino Masses**

Simplest & suggestive possibility: add 3 right handed singlets ($1_L$)

<table>
<thead>
<tr>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_e$</td>
<td>$e_R^-$</td>
</tr>
<tr>
<td>$v_\mu$</td>
<td>$\mu_R^-$</td>
</tr>
<tr>
<td>$v_\tau$</td>
<td>$\tau_R^-$</td>
</tr>
<tr>
<td>$c_L$</td>
<td>$c_R$</td>
</tr>
<tr>
<td>$s_L$</td>
<td>$s_R$</td>
</tr>
<tr>
<td>$t_L$</td>
<td>$t_R$</td>
</tr>
<tr>
<td>$b_L$</td>
<td>$b_R$</td>
</tr>
</tbody>
</table>

$$\langle \phi \rangle = v$$

**Majorana mass**

$$\nu_R \times \nu_R \rightarrow (\bar{\nu}_L \quad \bar{\nu}_R^c) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

- **Like quarks and charged leptons** → Dirac mass terms (including NMS mixing)
- **9 param. and new ingredients:**
  1) Majorana mass = scales
  2) lepton number violation
- **6x6 block mass matrix**
  block diagonalization
  $M_R$ heavy → 3 light $\nu$’s

**Beyond the SM: SM+ see-saw**

- **L-violation:** A henn & egg problem for embeddings
- **Why N=3 right singlets $\nu_R$?** – other number possible
Other Possibilities

**add scalar triplets** $(3_L)$ **or add fermionic** $(1_L)$ **or** $(3_L)$

- left-handed Majorana mass term: $M_{LLL}^c$

**Both** $\nu_R$ **and new singlets / triplets:**

- see-saw type II, III

$m_\nu = M_L - m_D M_R^{-1} m_D^T$

**Higher dimensional operators:** $d=5$, ...

$\mathcal{L}_{mass} = \kappa \cdot \bar{\nu}_L \nu_L \Phi^T \Phi$

$\Rightarrow M_{LLLL}^c$
Radiative neutrino mass generation

Many more: combine with LR, SUSY, extra d, …

- huge number of possibilities...
  ... but we know only two $\Delta m^2$... (plus mass & unitarity bounds)
- which new scale? high scale (GUT, L-viol.) or low (TeV see-saw)
- neutrino masses can/may solve two of the SM problems:
  - leptogenesis as explanation of BAU
  - keV sterile neutrinos as excellent warm dark matter candidate
- often connections to LFV, LHC, precision observables, DM
3 Light Neutrinos (...assumed)

Mass & mixing parameters: $m_1$, $\Delta m^2_{21}$, $|\Delta m^2_{31}|$, $\text{sign}(\Delta m^2_{31})$

$$U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}s_{13}e^{-i\delta} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}s_{13}
\end{pmatrix} \text{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

Known:
- two $\Delta m^2$, three mixing angles
- bounds on $m_1$
- weak indications for $\delta_{CP}$ and MH

questions:
- $\rightarrow$ Dirac $\sim$ SM / Majorana $=$ BSM
- mass scale: $m_1$
- mass ordering: $\text{sgn}(\Delta m^2_{31})$
- $\rightarrow$ is $\theta_{23}$ maximal?
- $\rightarrow$ CP violation
The Status of Neutrino Parameters (3f)

See e.g. Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz

<table>
<thead>
<tr>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta \chi^2 = 0.83$)</th>
<th>Any Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.306^{+0.012}_{-0.012}$</td>
<td>$0.306^{+0.012}_{-0.012}$</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.56^{+0.77}_{-0.75}$</td>
<td>$33.56^{+0.77}_{-0.75}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.441^{+0.027}_{-0.021}$</td>
<td>$0.587^{+0.020}_{-0.024}$</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$41.6^{+1.5}_{-1.2}$</td>
<td>$50.0^{+1.1}_{-1.4}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.02166^{+0.00075}_{-0.00075}$</td>
<td>$0.02170^{+0.00076}_{-0.00076}$</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.46^{+0.15}_{-0.15}$</td>
<td>$8.49^{+0.15}_{-0.15}$</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$261^{+51}_{-59}$</td>
<td>$277^{+40}_{-46}$</td>
</tr>
<tr>
<td>$\Delta m_{21}^2/10^{-5}$ eV$^2$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
</tr>
<tr>
<td>$\Delta m_{32}^2/10^{-3}$ eV$^2$</td>
<td>$+2.524^{+0.039}_{-0.040}$</td>
<td>$-2.514^{+0.038}_{-0.041}$</td>
</tr>
</tbody>
</table>

Absolute mass limits from Mainz and Troitsk: $m_1 < 2.2$ eV
Limits from cosmology: 0.15-0.2 eV
KATRIN: started operation $\Rightarrow$ 0.2eV ; Project8, …

Important:
- Active $\nu$ unitarity already tested $> 95\%$
- origin of $\nu$ masses unknown

$\Rightarrow$ Talks by E. Martinez, T. Schwetz, Ch. Weinheimer and others
we have no idea

= too many ideas
we need more data!
Directions in Neutrino Physics

Scenario A) 3 massive ν’s only: determine masses and mixings
- oscillations
- absolute mass ➔ how precise should we be?
- Dirac or Majorana killing models versus deeper insights

Scenario B) more than 3 neutrinos
- sterile neutrinos ➔ any one of them is a major discovery!
- L-violation high risk projects
- NSIs
- large magnetic moments
- magnetic moments, ...

1) precision oscillations: \( \theta_{ij}, \Delta m_{ij}^2, MH, CP, \) over-constraining
2) other: \( m_1, 0\nu\beta\beta, \) sterile searches, NSIs, coherent scattering, ...

3 main physics directions:
- learn about sources
- precise flavour information ➔ origin of masses/flavour?
- lever arm (direct or indirect) to other new physics (e.g. proton decay)
Neutrino Sources and Topics (fixed / man made)

- Sun
- Cosmology
- Atmosphere
- Earth
- Reactors
- Astronomy: Supernovae, SNRs, GRBs, UHE νs
- Accelerators
- β-Sources

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The Value of Precision 3 Flavour ν Physics

• Remember: Many theoretical options ...

• Precise measurements test mass models
e.g. based on flavour symmetries
   ↔ many models... will we learn something generic?

• Majorana masses ↔ best explanation of BAU
   ↔ related to heavy Majorana CP phases
   ↔ detection of $\delta_{CP}$ phase makes this more plausible

BUT: Don‘t forget it is only the light Dirac-like phase
   ... and BAU without Majorana (phase transitions, ... , D-leptogenesis)

• Neutrinos are a 0.6% HDM component
   ↔ cosmoological structure formation

• Precision may open the door for more new physics
   ↔ test of 3 flavour unitarity, overconstraining, ...
The Future of three Neutrino Oscillations

Precision oscillation physics now and in the next years

Now: Reactors: Double Chooz, Daya Bay, RENO + Beams: T2K, NOvA

- global fits...: better $\theta_{ij}$ and certain significance for $\delta_{CP}$
- Mass hierarchy: latest NoVA+T2K+cosmology $\Rightarrow >3\sigma$ for normal hierarchy

Future: JUNO, T2HK, DUNE, PINGU, ORCA, …

Precision $\Leftrightarrow$ how much more do we learn about flavour, fermion masses, …?
Depends on obtained precision and values: E.g. $\delta_{CP} = 0^{+1}_{-0.1}\degree$ and consistency

Rodejohann, ML, Xu others…
Beyond three Neutrinos
Sterile Neutrino Hints & Searches

tensions with cosmology…
\[ N_{\text{eff}} = 3.x < \sim 4 \]
BBN…

Nevertheless:
\[ \Rightarrow \text{lab tests important} \]

Also important:
\[ \Rightarrow \text{keV sterile } \nu = \text{WDM..} \]

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<table>
<thead>
<tr>
<th>Project</th>
<th>neutrino</th>
<th>source</th>
<th>( E ) (MeV)</th>
<th>( L ) (m)</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAGE [166]</td>
<td>( \nu_e )</td>
<td>( ^{51}\text{Cr} )</td>
<td>0.75</td>
<td>( \lesssim 1 )</td>
<td>in preparation</td>
</tr>
<tr>
<td>CeSOX [167, 168]</td>
<td>( \bar{\nu}_e )</td>
<td>( ^{144}\text{Ce} )</td>
<td>1.8 – 3</td>
<td>5 – 12</td>
<td>in preparation</td>
</tr>
<tr>
<td>CrSOX [167]</td>
<td>( \nu_e )</td>
<td>( ^{51}\text{Ce} )</td>
<td>0.75</td>
<td>5 – 12</td>
<td>proposal</td>
</tr>
<tr>
<td>Daya Bay [169, 170]</td>
<td>( \bar{\nu}_e )</td>
<td>( ^{144}\text{Ce} )</td>
<td>1.8 – 3</td>
<td>1.5 – 8</td>
<td>proposal</td>
</tr>
<tr>
<td>JUNO [171]</td>
<td>( \nu_e )</td>
<td>( ^{144}\text{Ce} )</td>
<td>1.8 – 3</td>
<td>( \lesssim 32 )</td>
<td>proposal</td>
</tr>
<tr>
<td>LENS [172]</td>
<td>( \nu_e, \bar{\nu}_e )</td>
<td>( ^{51}\text{Cr}, ^{6}\text{He} )</td>
<td>0.75, ( \lesssim 3.5 )</td>
<td>( \lesssim 3 )</td>
<td>abandoned</td>
</tr>
<tr>
<td>CeLAND [173]</td>
<td>( \bar{\nu}_e )</td>
<td>( ^{144}\text{Ce} )</td>
<td>1.8 – 3</td>
<td>( \lesssim 6 )</td>
<td>abandoned</td>
</tr>
<tr>
<td>LENA [174]</td>
<td>( \nu_e )</td>
<td>( ^{51}\text{Cr}, ^{37}\text{Ar} )</td>
<td>0.75, 0.81</td>
<td>( \lesssim 90 )</td>
<td>abandoned</td>
</tr>
</tbody>
</table>

**Source experiments**

<table>
<thead>
<tr>
<th>Project</th>
<th>( P_{\text{th}} ) (MW)</th>
<th>( M_{\text{target}} ) (tons)</th>
<th>( L ) (m)</th>
<th>Depth (m.w.e.)</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucifer (FRA) [175]</td>
<td>70</td>
<td>0.8</td>
<td>7</td>
<td>13</td>
<td>operating</td>
</tr>
<tr>
<td>Stereo (FRA) [176]</td>
<td>57</td>
<td>1.75</td>
<td>9 – 12</td>
<td>18</td>
<td>running</td>
</tr>
<tr>
<td>DANSS (RUS) [177]</td>
<td>3000</td>
<td>0.9</td>
<td>10 – 12</td>
<td>50</td>
<td>running</td>
</tr>
<tr>
<td>SoLid (BEL) [178]</td>
<td>45 – 80</td>
<td>3</td>
<td>6 – 8</td>
<td>10</td>
<td>running</td>
</tr>
<tr>
<td>PROSPECT (USA) [179]</td>
<td>85</td>
<td>3, 10</td>
<td>7 – 12, 15 – 19</td>
<td>few</td>
<td>in preparation</td>
</tr>
<tr>
<td>NEOS (KOR) [180]</td>
<td>16400</td>
<td>1</td>
<td>25</td>
<td>10 – 23</td>
<td>in preparation</td>
</tr>
<tr>
<td>Neutrino-4 (RUS) [181]</td>
<td>100</td>
<td>1.5</td>
<td>6 – 11</td>
<td>10</td>
<td>proposal</td>
</tr>
<tr>
<td>Poseidon (RUS) [182]</td>
<td>100</td>
<td>3</td>
<td>5 – 8</td>
<td>15</td>
<td>proposal</td>
</tr>
<tr>
<td>Hanaro (KOR) [183]</td>
<td>30</td>
<td>0.5</td>
<td>6</td>
<td>few</td>
<td>proposal</td>
</tr>
<tr>
<td>CARR (CHN) [184]</td>
<td>60</td>
<td>( \sim 1 )</td>
<td>7, 11</td>
<td>few</td>
<td>proposal</td>
</tr>
</tbody>
</table>

**Reactor experiments**

\( \Rightarrow \) searches for eV & keV sterile \( \nu \)'s … \( \Rightarrow \) T. Lasserre, V. Antonelli, A. Boiariskyi

Giunti 1512.04758
Could TeV sterile Neutrinos make Sense?

- Good theoretical reasons for any sterile neutrino mass
- Assume Lagrangian with type I see-saw $\leftrightarrow$ parameter relations
- Global fit to all data: LFV, LHC, EWPO and active neutrinos and consider 3 typical mass spectra

\[
sin^2 \theta_{12} = 0.30 \pm 0.013, \\
sin^2 \theta_{23} = 0.41^{+0.037}_{-0.025}, \\
sin^2 \theta_{13} = 0.023 \pm 0.0023, \\
\delta_{CP} = 300^{+66}_{-138},
\]

<table>
<thead>
<tr>
<th></th>
<th>NH</th>
<th>IH</th>
<th>QD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$ (eV)</td>
<td>$\sim 0$</td>
<td>$4.85 \cdot 10^{-2}$</td>
<td>$\sim 0.1$</td>
</tr>
<tr>
<td>$m_2$ (eV)</td>
<td>$8.660 \cdot 10^{-3}$</td>
<td>$4.93 \cdot 10^{-2}$</td>
<td>$\sim 0.1$</td>
</tr>
<tr>
<td>$m_3$ (eV)</td>
<td>$4.97 \cdot 10^{-2}$</td>
<td>$\sim 0$</td>
<td>$\sim 0.1$</td>
</tr>
</tbody>
</table>

- Deviations from 3f unitarity:
- Quality of fit:

\[
\chi^2_{EWPO} = \sum_i \frac{(O_i - O_{i,\text{SM}})^2}{(\delta O_i)^2 + (\delta O_{i,\text{SM}})^2}
\]

Akhmedov, Kartavtsev, ML, Michaels and J. Smirnov

\[
\epsilon_\alpha \equiv \sum_{i \geq 4} |U_{\alpha i}|^2
\]

\[
\epsilon_e - \epsilon_\mu = 0.0022 \pm 0.0025 \\
\epsilon_\mu - \epsilon_\tau = 0.0017 \pm 0.0038 \\
\epsilon_e - \epsilon_\tau = 0.0039 \pm 0.0040
\]
NH, $\epsilon_e + \epsilon_\mu + \epsilon_\tau$ as a function of the lightest heavy neutrino mass for 4dof

sterile $\nu$’s improve fit for multi-TeV-ish masses
NSI’s $\leftrightarrow$ new physics at high scales
Which are integrated out
$Z'$, new scalars, … $\rightarrow \varepsilon_{ij}$

$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2}G_F (\bar{\nu}_{L\beta} \gamma^\rho \nu_{L\alpha})(\bar{f}_L \gamma^\rho f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{ \left[Z(g_V^n + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \sum_{\alpha=\mu, \tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2 \right\}$$

Barranco et al. 2005

$$|\varepsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

$\rightarrow$ Competitive method to test TeV scales
$\varepsilon = 0.01 \leftrightarrow$ TeV scales
NSIs interfere with Oscillations

the “golden” oscillation channel

NSI contributions to the “golden” channel

interference in oscillations $\sim \varepsilon$ ↔ FCNC effects $\sim \varepsilon^2$
Redundant measurements:
Double Chooz + T2K
*=assumed ‘true’ values of $\theta_{13}$

scatter-plot: $\varepsilon$ values random
- below existing bounds
- random phases

NSIs can lead to:
- offset
- mismatch

$\Rightarrow$ redundancy
$\Rightarrow$ interesting potential
The 3ν Picture of 0νββ Decay

2νββ decay seen for diff. isotopes (Kirsten,…)
\[ T^{1/2} = O(10^{18} - 10^{21} \text{ years}) \Rightarrow \text{up to } 10^{11} \otimes T_{\text{Universe}} \]

- observe 2νββ
- look for 0νββ signal at \( Q_{\beta\beta} \)
- large amount of \(^{76}\text{Ge}\) nuclei
- extreme low backgrounds!

\[ T^{1/2} > O(10^{25} \text{y}) \]
The Effective Neutrino Mass

$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$

$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$

$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$

$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$

Comments:
- cosmology: $m < 0.2$-$0.3$ eV
- $0\nu\beta\beta$: $m_{ee} < 0.1$-$0.3$ eV
- NMEs $\Rightarrow$ unavoidable theory errors
- known $\Delta m^2$ from oscillations
  $\Rightarrow$ yellow/blue areas
  $\Rightarrow$ improved sensitivity is very promising!

**Warnings:**
- assumes no *other* $\Delta L=2$ physics
- assumes no sterile neutrinos, ...
More general: L Violating Processes

- **$2\nu\beta\beta$**
  - SM
  - $T^{1/2} > O(10^{25}\text{y})$
  - **$0\nu\beta\beta$**
  - BSM

- **$0\nu\beta\beta$ decay**
- **$2\nu\beta\beta$ decay**

**Search unchanged…**

**…interpretation changes:**

- Some other $\Delta L = 2$ operator

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Other Double Beta Decay Processes

Standard Model:

\[ \text{\(\beta^-\) decay} \quad + \quad \text{\(\beta^-\) decay} \]

\[ 2 \text{ electrons} + 2 \text{ neutrinos} \quad \Rightarrow \quad 2\nu\beta\beta \]

Majorana \(\nu\)-masses or other \(\Delta L=2\) physics:

\[ 2 \text{ electrons} \quad \Rightarrow \quad 0\nu\beta\beta \]

Majorana neutrino masses \(\leftrightarrow\) Dirac? 

SM + Higgs triplet 

SUSY 

important connections to LHC and LFV … 

sub eV Majorana mass \(\leftrightarrow\) TeV scale physics
Majorana or other Physics or Interferences

interferences growing $m_\epsilon$ for fixed $0\nu\beta\beta$

$\rightarrow$ shifts of masses, mixings and CP phases

$\rightarrow$ destroys ability to extract Majorana phases

$\rightarrow$ sensitivity to TeV physics
The Schechter-Valle Theorem induced Mass

- any $\Delta L=2$ operator which leads to $0\nu\beta\beta$ decay induces via loops a Majorana mass
- assume a $0\nu\beta\beta$ signal $\Rightarrow$ how big is the induced mass?

4 loops $\Rightarrow \delta m_\nu = 10^{-25}$ eV $\Rightarrow$ very tiny (academic interest)
$\Rightarrow$ cannot explain observed $\nu$ masses and splittings
$\Rightarrow$ explicit Dirac neutrino mass operators required

Extreme possibility:
- $0\nu\beta\beta = L$ violation = other BSM physics
- neutrino masses = Dirac (plus very tiny correction)
# The XENON Dark Matter Program

The XENON program at Gran Sasso, Italy (3600 mwe)

<table>
<thead>
<tr>
<th></th>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T &amp; XENONnT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>2005-2007</td>
<td>2008-2016</td>
<td>2012-2018</td>
</tr>
<tr>
<td><strong>Total mass</strong></td>
<td>25 kg</td>
<td>161 kg</td>
<td>3200 kg</td>
</tr>
<tr>
<td><strong>Drift length</strong></td>
<td>15 cm</td>
<td>30 cm</td>
<td>100 cm</td>
</tr>
<tr>
<td>$\sigma_{SI}$ limit (@50 GeV/c$^2$)</td>
<td>$8.8 \times 10^{-44}$ cm$^2$</td>
<td>$1.1 \times 10^{-45}$ cm$^2$</td>
<td>$1.6 \times 10^{-47}$ cm$^2$ (2018)</td>
</tr>
</tbody>
</table>

**Notes:**
- XENONnT being prepared while XENON1T runs \(\rightarrow\) switching gears.

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Beyond that: DARWIN

- Baseline: 50t LXE
- 40t LXe TPC, aim at 200 t*yr
- TPC dimension 2.6m x 2.6m
- ~1800 * 3” PMTs (or ~1000 4” PMTs)
- Low-background cryostat
- Water Cherenkov shield (~14m diameter)
- Possible location LNGS
- aim at sensitivity of a few $10^{-49}$ cm$^2$, limited by irreducible ν-backgrounds
- R&D and initial design now
- **Timescale: after XENONnT**
- **Cost effective:**
  - use existing Xe gas; buy more & re-sell
  - no enrichment (faster & much cheaper)

JCAP 11, 017 (2016)

www.darwin-observatory.org

DARWIN

27 institutes from EU, US, ...
Pushing the WIMP Sensitivity

![Graph showing the evolution of WIMP sensitivity over time, with key milestones for XENON1T and XENONnT, and a projection for DARWIN.]

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Spin Independent (SI) WIMP Interaction

- tests much of the generic WIMP space
- a declining WIMP case w/o discovery?

→ solar neutrino signal & CNNS with 200 t*yr

JCAP 10, 016 (2015)
Neutrino Physics with DARWIN

- Coherent Neutrino-Nucleus Scattering (CNNS)
  200 t\(^{*}\)yr \(\rightarrow\) ca. 200 (25) events for \(> 3\) (4) keV\(_{\text{NR}}\)

- Low energy solar neutrino signal: pp, \(^{7}\)Be
  \(~1\%\) statistical uncertainty for 100 t\(^{*}\)yr \(\rightarrow\) solar models & \(\nu\) properties

  real-time measurement of the solar neutrino flux:
  \(\rightarrow\) 7.2 events/day from pp
  \(\rightarrow\) 0.9 events/day from \(^{7}\)Be

- Supernova neutrinos:
  \(\rightarrow\) 5\(\sigma\) sensitivity for a 27M\(\odot\) SN progenitor at 10 kpc (\(~700\) events)
  \(\rightarrow\) flavor-insensitive neutrino energy measurement

8.9% natural abundance

$\Rightarrow$ 3.5 t $^{136}$Xe in 40t without enrichment!

$Q_{\beta\beta} = (2458.7 \pm 0.6)$ keV

Assume:
- 6t fiducial
- energy resolution at $Q_{\beta\beta} \sim 1\%$

Sensitivity @ 95% CL:
- 140 t*yr $\rightarrow T_{1/2} > 8.5 \times 10^{27}$ yr

IMPORTANT: DARWIN might become a powerful, cost effective and time-wise competitive $0\nu\beta\beta$ experiment (no enrichment!)
Z-exchange of a neutrino with nucleus

- nucleus recoils as a whole
- coherent up to $E_\nu \sim 50$ MeV

$$Q_w = N - (1 - 4 \sin^2 \theta_w) Z \sim N$$

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2 \sim N^2$$

$N \sim 40 \Rightarrow N^2 = 1600 \Rightarrow$ detector mass 10t $\Rightarrow$ few kg

Important: Coherence length $\sim 1/E$

- need neutrinos below $O(50)$ MeV for typical nuclei
- low energy $E_\nu$ $\leftrightarrow$ lower cross sections $\leftrightarrow$ maximal flux!
Two Paths

**Low energy $\nu$'s from accelerators:**
- $\pi$-decay-at-rest (DAR) $\nu$ source
- different flavors produced
- relatively high recoil energies
  $\rightarrow$ close to de-coherence
  $\rightarrow$ 1st observation of CE$\nu$NS by COHERENT in 2017

**Reactors:**
- lower $\nu$ energies than accelerators
- lower cross section – higher flux
- different flavor content implications for probes of new physics
  $\rightarrow$ CONUS in 2018
The CONUS Experiment

Brokdorf (Germany) nuclear power plant:

- thermal power $3.9 \text{ GW}_{th}$
- $\nu$ flux: $2.4 \times 10^{13}/\text{cm}^2/\text{s}$; very high duty cycle access during reactor operation

- extreme neutrino flux
  \[ E_\nu \text{ up to } \sim 8 \text{ MeV} \rightarrow \text{fully coherent} \]

- overburden 45 m.w.e
- active shielding (“virtual depth“)
- 4x 1kg ultra low threshold Ge-detectors
- electro-cooling with PTR‘s
- reactor ON/OFF measurements

**NEUTRINO 2018 in June:**

- $2.4\sigma$ after only one month of data taking
- meanwhile 5 months to appear soon
- various plans for next generation experiments
100kg Upscaling: ν Magnetic Moments

Magnetic moment for minimal ν masses are very tiny:

\[ \mu_{kk}^D \simeq 3.2 \times 10^{-19} \left( \frac{m_k}{\text{eV}} \right) \mu_B \]

\[ \mu_{\ell\nu}^M \lesssim 4 \times 10^{-9} \mu_B \left( \frac{M_{\ell\nu}^M}{\text{eV}} \right) \left( \frac{\text{TeV}}{\Lambda} \right)^2 \left| \frac{m_\tau^2}{m_\ell^2 - m_{\ell'}^2} \right| \]

- detectable enhancements via new physics: SUSY, extra dimensions, ...

Best limits so far:

- e-scattering (GEMMA) and astrophysics:

\[ \mu_\nu < 3 \times 10^{-11} \mu_B \]

Scattering on protons coherently enhanced:

- detectable at low E (Vogel & Engel 1989)
- 100kg *5y = 500 kg-year + low threshold
- at least an order of magnitude improvement
100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu

~10 TeV

~TeV
Precise Measurement of $\sin^2\theta_W$ at low E

BSM sensitivity $\leftrightarrow$ precision
$10^{-3} \Rightarrow \Delta\sin^2\theta_W = 0.006$
$10^{-4} \Rightarrow \Delta\sin^2\theta_W = 0.0006$

Other topics:
- Explore coherent scattering $\leftrightarrow$ direct DM experiments
- Sterile neutrino searches (if still alive...)
- Nuclear form factors in neutrino light
- Nuclear safe-guarding
- ...

K. Scholberg
Summary

• Neutrino physics was, is and will remain a hot field

• Many important insights into
  - sources
  - fundamental interactions

• 3 neutrino flavours ➔ precision area
  - reactor neutrinos
  - neutrino beams (NOνA, T2K, T2HK, DUNE, ...)
  ➔ origin of fermion masses? How precise can we get and is that enough?

• More than 3 neutrinos
  - Majorana masses, L-violation, sterile ν‘s, NSIs, large mag. moments,
    direct dark matter searches, proton decay, n-n oscillations, ...
  ➔ any one of them would be a major discovery

• New: Coherent neutrino scattering, a new & fast moving direction

• Road maps: Many paths with unknowns ➔ a good mix of vehicles