Summary and Perspectives III: Neutrinos and Precision Measurements

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The SM – a Synergy of Concepts

Physics: concepts (variables) $\oplus$ equations / principles
initial conditions $\Rightarrow$ predictions

electrodynamics
relativity
quantum mech.
strong force $\Rightarrow$ QCD
weak decays $\Rightarrow$ Higgs, $\chi$-ral
+ neutrino masses
+ dark matter $\iff$?
+ DE?

territory of speculation:
LR? TC? ...?
SUSY? GUTs? TOE?
extra d.?

d=4 QFTs:

$\begin{align*}
\text{QED} & \Rightarrow \text{QCD} & \Rightarrow \text{SM} \\
\text{U(1)}_{\text{em}} & \Rightarrow \text{SU(3)}_{\text{C}} & \Rightarrow \text{SU(3)}_{\text{C}} \times \text{SU(2)}_{\text{L}} \times \text{U(1)}_{\text{Y}}
\end{align*}$

gravity

weak scale $\lllll$ $M_{\text{planck}}$

Extending the SM? $\Rightarrow$ extra representations? larger gauge group? unification? SUSY?, ???
New Physics: Neutrino Mass Terms

$\text{SM} \sim m_L \phi R = (2,1)$

$\Rightarrow$ new fields $\Rightarrow$ which?

1) **Simplest possibility:** add 3 or N right handed neutrino fields

NEW: mod. global sym., 9 param., multi-scale $\Rightarrow$ SM+ and sea-saw
2) new: scalar triplets (3L)
or fermionic 1L ro 3L

⇒ left-handed Majorana mass term:

3) Both νR + new scalars: ⇒ SS type II, III

mν = M_L - m_D M_R^{-1} m_D^T

4) Higher dimensional operators: d=5

5-N) radiative mass generation, SUSY, GUTs, extra dimensions, ...

⇒ inspiring options, many questions, connections to LFV, LHC, ...
Sterile Neutrinos and QFT

- Many neutrino mass options ↔ we know only a few numbers
- Right-handed ν‘s are simplest possibility ⇒ attractive

QFT: natural value of mass operators ↔ scale of symmetry

$m_D \sim$ electro-weak scale ; $M_R \sim L$ violation (high scale ⇒ $10^{xx}$ GeV)

⇒ See-saw (type I): \[ m_\nu = m_D M_R^{-1} m_D^T \] \[ m_h = M_R \]

The standard expectation:

3 heavy sterile neutrinos

3 light active neutrinos ↔ oscillation data

⇒ reasons for light sterile neutrinos ?!
Conceivable Neutrino Mass Spectra (for $\nu_R$)

$\begin{pmatrix} \nu_L & \nu^c_R \\ \nu_L^c & m_D & M_R \end{pmatrix}$

$M_L$, $m_D$, $M_R$ may have almost any form / values:
- zeros (symmetries)
- $0 +$ tiny corrections
- scales: $M_W$, $M_{GUT}$, ...

$\xrightarrow{\text{diagonalization}}$ 3+N EV

data: 3x3 active almost unitary

$\xrightarrow{\text{small active-sterile mixings}}$

$M_L = 0, m_D = O(\text{GeV}), M_R = \text{high: see-saw}$
$M_R$ singular singular-SS
$M_L = M_R = 0$ Dirac
$M_L = M_R = \epsilon$ pseudo Dirac

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Which Theory are we testing?

a) 3 massive (active) $\nu$’s with unitary $3 \times 3$ mixing matrix
   $\Rightarrow$ corresponds to SM+ with heavy sterile neutrinos
   $\Rightarrow$ also emerges from other mass mechanisms

b) Additionally some light sterile neutrinos
   $\Rightarrow$ e.g. in SM+ with mech. which lowers sterile masses

c) Other accessible LE effects: NSI’s, LFV, mag. moments

$\Rightarrow$ Experiments are analyzed within a certain framework
$\Rightarrow$ usually: hypothesis a) $\Rightarrow$ global fit $\Rightarrow$ parameters
$\Rightarrow$ does not exclude b), c), …

$\Rightarrow$ IMPORTANT: overconstraining
3x3 Neutrino Oscillation Parameters

• Global fits for 3 active neutrinos \( \Rightarrow \) good \( \chi^2 \); more not required; impressive progress over the last \( \sim \)20 years
  \( \Rightarrow \) oscillations established (L/E)
  \( \Rightarrow \) \( \theta_{13} \) is now most precise mixing; CPV becomes real!
  \( \Rightarrow \) DUNE, HyperK, JUNO, RENO-50, ... \( \Rightarrow \) precision \( \nu \) physics!
  \( \Rightarrow \) which precision required to learn? \( \leftrightarrow \) origin of flavour!

• Good fits do not imply a complete picture
  \( \Rightarrow \) more new physics, but what and where?

• Theoretical robustness of observables:
  1) add small random perturbation to mass matrix
     \( \Rightarrow \) \( \theta_{ij} \) vary moderately, CP phases react a lot
  2) E.g.: Neutrino decay or NSI’s could be a sub-leading effect
     \( \Rightarrow \) small parameter shifts that go initially unnoticed
Example: NSI Interference with Oscillations

the “golden” oscillation channel

NSI contributions to the “golden” channel

note: interference in oscillations $\sim \varepsilon \leftrightarrow$ FCNC effects $\sim \varepsilon^2$
NSI: Offset and Mismatch in $\theta_{13}$

Redundant measurements:
Double Chooz + T2K
*=assumed ‘true’ values of $\theta_{13}$
scatter-plot: $\epsilon$ values random
- below existing bounds
- random phases
NSIs can lead to:
- offset
- mismatch
  ➔ redundancy
  ➔ interesting potential

In general: over-constraining ↔ test of non-minimal scenarios
The absolute Neutrino Mass

- Waiting for KATRIN ➔ data taking to start 2016/2017 ➔ factor 10 improvement to ~ 0.2 eV ➔ and then? PROJECT 8 and other developments…

- Cosmology and the sum of neutrino masses:

\[ \Sigma(m_i) \leq 0.14 \ldots 0.20 \text{ eV} \]

\( m_1^2 \quad m_2^2 \quad m_3^2 \)

- IH seems to become a bit disfavoured by cosmology
- the same (weak) trend seems to appear in global oscillation fits

if real ➔ very important for 0νββ experiments
The Standard Picture of Double Beta 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_{ββ}
- large amount of ^{76}\text{Ge nuclei}
- extreme low backgrounds!

⇒ signal = Majorana mass

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**m_{ee}: The Effective Neutrino Mass**

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

\[ |m_{ee}^{(1)}| = |U_{e1}|^2 m_1 \]
\[ |m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \]
\[ |m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \]

**Comments:**
- cosmology: \( m < 0.2-0.3 \text{ eV} \)
- \( 0\nu\beta\beta \): \( m_{ee} < 0.1-0.3 \text{ eV} \)
- 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

SM

2νββ

BSM

T^{1/2} > O(10^{25}y)

0νββ

0νββ decay

Search unchanged...

2νββ decay

...interpretation changes:

Some ΔL=2 operator
Other Double Beta Decay Processes

**Standard Model:**

\[ \begin{array}{c}
\nu^+ \rightarrow \nu^- + 2e^- + 2\nu \rightarrow 2e^- + 2\nu \beta \beta \\
\end{array} \]

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

\[ \begin{array}{c}
\Rightarrow 2 \text{ electrons} \rightarrow 0\nu \beta \beta \\
\end{array} \]

- Majorana neutrino masses \( \leftrightarrow \) Dirac?
- SM + Higgs triplet
- SUSY
- Important connections to LHC and LFV ...
- Sub eV Majorana mass \( \leftrightarrow \) TeV scale physics

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Interference of $\Delta L=2$ Operators

Usually

$$\left( T_{1/2}^{0\nu} \right)^{-1} = \left( \frac{|m_{0\nu\beta\beta}|}{m_e} \right)^2 |M^{0\nu}|^2 G^{0\nu}.$$ 

with interferences

$$\left( T_{1/2}^{0\nu} \right)^{-1} = m_{0\nu\beta\beta} M^{0\nu} + \epsilon m_e M^{\epsilon} \left| 2 \frac{G^{\text{int}}}{m_e^2} \right|$$

$$= |(m_{0\nu\beta\beta} + \epsilon m_e M^{\epsilon} (M^{0\nu})^{-1}) M^{0\nu}|^2 \frac{G^{\text{int}}}{m_e^2}$$

$$= |m_{0\nu\beta\beta} |^2 |M^{0\nu}|^2 \frac{G^{\text{int}}}{m_e^2}.$$ 

$G^{\text{int}} = \epsilon m_e M^{\epsilon}$

= overall phase space factor

$\leftrightarrow$ determined by parameters of new physics

$$m_{0\nu\beta\beta} \equiv m_{0\nu\beta\beta} + \epsilon m_e M^{\epsilon} (M^{0\nu})^{-1} \equiv m_{0\nu\beta\beta} + m_e.$$ 

$m_e \sim (\Lambda_{\text{new}})^{-5}$

\[ m_{0\nu\beta\beta} = 1 \text{ eV} \leftrightarrow \Lambda_{\text{new}} \sim \text{TeV} \]
Extreme Cases

$m_{ee}$ from Majorana neutrinos only and no other $\Delta L=2$ physics

$m_\epsilon$ from other $\Delta L=2$ physics with Dirac neutrino masses

and anything in-between
interferences
growing $m_\epsilon$ for fixed $0\nu\beta\beta$
→ shifts of masses, mixings and CP phases
→ destroys ability to extract Majorana phases
→ sensitivity to TeV
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)
Quenching

Half-life: \[ T_{1/2}^{-1} = m_{\beta\beta}^2 G^{0\nu} g_A^4 |M^{0\nu}|^2 \]

Axial-vector coupling \( g_A \):
- Free nucleon: \( g_A \approx 1.27 \)
- Comparison of \( \beta \) and \( 2\nu\beta\beta \) decay with theory: \( g_A \approx 0.6 - 0.8 \)
- Needs further studies
- If applicable to \( 0\nu\beta\beta \)
  \( \Rightarrow \) reduction of sensitivity
  \( \Rightarrow \) big impact on searches
Recent Results on $0\nu\beta\beta$

Recently: New results from

- KamLAND-Zen
- GERDA-II
- Majorana demonstrator

→ slowly getting to IH !?

Plot assumes
- only Majorana mass
- $g_A = 1.27$
  → situation may be worse…

Remember: IH getting less likely from cosmology and global fits ↔ huge experimental effort…
**Biggest vs. smallest Scales: Light sterile ν’s**

**CON: Cosmology / BBN**
- how many light sterile ν’s allowed? (thermalized? LAU? …)
- +/- how many σ’s required? +/- systematics (H ↔ N_{eff})
- pushing it: at most 1,2 steriles …

**PRO: Various hints for sterile neutrinos**
- Reactor anomaly, LSND, MiniBooNE, MINOS, Gallex…
- hints for light sterile ν’s? ➔ not all; one would be enough
- new and better data / experiments are needed

**Sterile neutrinos solve problems:**
- keV sterile ν is an excellent warm dark matter candidate
- avoid small scale crisis of CDM
- leptogenesis as explanation of BAU
- TeV-ish sterile ν’s improve overall EW fits!

**theory:** natural explanation for light sterile ν’s with small mixings
Progress requires new experiments: Reactor $\nu$’s

High Precision Reactor Experiments $\rightarrow \theta_{13}$

- inverse beta decay reaction
- organic liquid scintillator
- loaded with 1 g/L Gd
- measurement of $\theta_{13}$ using $\bar{\nu}_e$ rate and spectral shape

![Double Chooz, Daya Bay, RENO diagrams]
Surprise 1: The Reactor Anomaly

\( \rightarrow \) an extra (sterile) neutrino with a small mixing angle and a mass \( O(eV) \) or heavier would have oscillated @ 10-100m

averaged out: reduction by \( \frac{1}{2} \times \sin^2(\theta_s) \approx 0.06 \)

\( \leftrightarrow \) active \( \nu \)-unitarity tested @ few % \( \rightarrow \) consistent \( \rightarrow \)

\( \rightarrow \) check with a new experiment at shorter baseline
- Event rates = flux * x-section

- x-section is safe
- Uncertainties in ν-flux?!
- More than 800 nuclides from the fission of $^{235}$U
  - And others: $^{238}$U, $^{239}$Pu, $^{241}$Pu, ...
  - Instable fission products → flow equilibrium

- Involves poorly known β-emitters

- Especially short lived ↔ high energy
  → BUT: simulations reliable + spectrum!
Reactor Spectrum Predictions

outcome:
- reactor flux anomaly unexplained
- most impressive proof of existence of dark sectors
  \[ P = 4GW_{th} \text{ @15m from core} \Rightarrow 150kW/m^2 \text{ in anti-neutrinos} \]
Surprise 2: A Bump in the Spectrum

Seen by Double Chooz, RENO and Daya Bay →
→ all see unexpected bump in near and far spectrum → $\theta_{13}$ measurement robust

Remember: high energy $\nu$'s ⟷ short lived isotopes …little known

Nuclear theory: theory errors …maybe explainable… better → experimental test
## New Sterile Experiments & Proposals

<table>
<thead>
<tr>
<th>Experiment Type</th>
<th>Appearance / Disappearance</th>
<th>Oscillation Channel</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>Disappearance</td>
<td>(\bar{\nu}_e \to \bar{\nu}_e)</td>
<td>Nucifer, Stéréo, Scram, Neutrino-4, DANSS, Poseidon, MARS, ...</td>
</tr>
<tr>
<td>Radioactive Source</td>
<td>Disappearance</td>
<td>(\bar{\nu}_e \to \bar{\nu}_e) (\nu_e \to \nu_e)</td>
<td>CeLAND, SOX (Cr &amp; Ce), Sage2, SNO+, LENS-s</td>
</tr>
<tr>
<td>Cyclotron</td>
<td>Disappearance</td>
<td>(\bar{\nu}_e \to \bar{\nu}_e)</td>
<td>IsoDAR</td>
</tr>
<tr>
<td>Pion / Kaon Decay-at-Rest</td>
<td>Apparition &amp; Disappearance</td>
<td>(\bar{\nu}_\mu \to \bar{\nu}<em>e) (\nu</em>\mu \to \nu_e)</td>
<td>OscSNS, CLEAR, DAE5ALUS, KDAR</td>
</tr>
<tr>
<td>Pion Decay-in-Flight (Beam)</td>
<td>Appearance &amp; Disappearance</td>
<td>(\bar{\nu}<em>\mu \to \bar{\nu}<em>e) (\nu</em>\mu \to \nu_e) (\nu</em>\mu \to \nu_\mu) (\bar{\nu}_e \to \bar{\nu}_e)</td>
<td>MINOS+, MicroBooNE, LAr1kton+MicroBooNE, Icarus/Nessie@CERN</td>
</tr>
<tr>
<td>Low-E Neutrino Factory</td>
<td>Appearance &amp; Disappearance</td>
<td>(\nu_e \to \nu_\mu) (\bar{\nu}<em>e \to \bar{\nu}</em>\mu) (\bar{\nu}<em>e \to \bar{\nu}</em>\mu) (\nu_\mu \to \nu_\mu) (\bar{\nu}_e \to \bar{\nu}_e)</td>
<td>vSTORM@Fermilab</td>
</tr>
</tbody>
</table>

Potential \(\leftrightarrow\) hints, speed, cost \(\Rightarrow\) test hints as soon and effective as possible
Comparing different Reactor Fuels

⇒ ratio of HEU to LEU spectrum for different hypotheses

Combine STEREO (HEU) and Double Chooz ND (LEU)

2 y runtime

uncertainties: statistical + reference spectra

significance of discrepancy [5, 7] MeV:

- only $^{235}\text{U}$: 4.2 $\sigma$
- no excess in HEU: 5.5 $\sigma$

significance including energy resolution:

- only $^{235}\text{U}$: 3.7 $\sigma$
- no excess in HEU: 4.7 $\sigma$

Buck, Collin, Haser, ML
⇒ can realistically be done
see also Huber
talk by
Seon-Hee Seo

burnup in LEU reactors changes isotope fraction

- effect on spectrum?
- not yet significant

- use HEU+LEU

• what if cosmology ($N_{\text{eff}}$) conflicts with sterile $\nu$’s?
  - check assumptions/errors on both sides
  - or new/extra physics on one side
Neutrinos as Probes into Sources

- Sun
- Cosmology
- Atmosphere
- Earth
- Reactors
- Accerlators
- Supernovae
- GRBs
- UHE $\nu$'s
- Astronomy: Supernovae, GRBs, UHE $\nu$'s, Reactors, Accerlators
Supernova Neutrinos

- Collaps of a typical star $\Rightarrow \sim 10^{57}$ $\nu$'s
- $\sim 99\%$ of the energy in $\nu$'s
- $\nu$'s essential for explosion
- do simulations explode?
  (1d $\Rightarrow$ 2d $\Rightarrow$ 3d $\Rightarrow$ convection...)
2 possibilities:

- Supernova
- neutron star

or

- black hole

Keeps cooling...

abrupt end of $\nu$-emission

- impressive signal of a black hole in neutrino light
- neutrino masses $\leftrightarrow$ edge of $\nu$-signal
Supernovae & Gravitational Waves

additional information about galactic SN

**global fits**: optical + neutrinos + gravitational waves

neutrino properties + SN explosion dynamics

SN1987A: strongest constraints on large extra dimensions

further topics: failed supernovae, hidden SN, ν self-interactions (split, coherence)

Dimmelmeier, Font, Müller
GR Waves: A new Player in ν Physics?

Gravitational waves from merging super massive objects: BH, NS, ...

Characteristic down-spiral:
- increasing frequency
- increasing amplitude
⇒ distance, masses, size, ...

maybe: in some years 100-1000 events...

Some mergers may have jet-like processes
⇒ jets ⇒ occasionally pointing towards us
⇒ GR waves + light + neutrinos
⇒ multi-messenger observations @ Mpc
⇒ enormous lever arm (c, mass dispersion, sources)
Many theories which explain/embed neutrino masses

⇒ more papers than for SUSY (+ discovered)

We know only a few numbers ⇒ many explanations

Inversion: 1) Which observables are most valuable?
               2) How precise do we need to know them

Depends on the theory which you want to test...

Most important: Learn about the origin of flavour
               ⇔ leptons are `clean´

Example: How to explain light sterile neutrinos
               ⇔ generic expectations of QFT
Explaining light sterile Neutrinos

Possible scenario: See-saw + reasons why 1/more sterile $\nu$ is light

$\text{heavy sterile neutrinos typ. } \geq 10^{13} \text{ GeV}$

$\Rightarrow$ extra dimensional physics $\Rightarrow$ ‘split see-saw’
Kusenko, Takahashi, Yanagida,

$\Rightarrow$ flavour symmetries explaining active neutrino masses + charged leptons + quarks
$
\Rightarrow$ consequences for heavy mass matrix
ML, Merle, Niro; Merle, Niro,
Barry, Rodejohann, Zhang

$\Rightarrow$ extended see-saw mechanism
Mohapatra; Smirnov; Zhang

$\Rightarrow$ conformal symmetry $\Rightarrow$ later

one light sterile neutrino $\sim \text{keV} = \text{DM}$

light active neutrinos $< \text{eV}$

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Example: Singular heavy neutrino mass matrix from flavour symmetries:

\[ \Psi \equiv ( (\nu_{eL})^C, (\nu_{\mu L})^C, (\nu_{\tau L})^C, N_{1R}, N_{2R}, N_{3R})^T \]

\[
M_\nu = \begin{pmatrix}
0 & m_{e\mu}^{e\mu} & m_{e\tau}^{e\tau} & m_{e1}^{e1} & 0 & 0 \\
m_{e\mu}^{e\mu} & 0 & 0 & 0 & m_{D}^{\mu2} & m_{D}^{\mu3} \\
m_{e\tau}^{e\tau} & 0 & 0 & 0 & m_{D}^{\tau2} & m_{D}^{\tau3} \\
m_{e1}^{e1} & 0 & 0 & 0 & 0 & 0 \\
m_{D}^{e1} & m_{D}^{\mu2} & m_{D}^{\tau2} & 0 & 0 & 0 \\
m_{D}^{e1} & m_{D}^{\mu3} & m_{D}^{\tau3} & 0 & 0 & 0 \\
\end{pmatrix}
\]

\[ \det(M_{ij}) = 0 \implies M_1 = 0 \]

\[ \implies \text{massless sterile state + soft breaking} \]

\[ \implies \text{naturally light sterile } \nu \]

\[ \implies \text{mechanism possible in many models} \]
Boundary Shifting

Use standard type II see-saw relation for 4x4, 2x4, 4x2 and 2x2 matrices

Use usual see-saw formula for 4x4, 2x4 and 2x2 matrices
Conformal Symmetry & Neutrino Masses

ML, S. Schmidt and J. Smirnov

• No explicit scale ➞ no explicit (Dirac or Majorana) mass term ➞ only Yukawa couplings ⊗ generic scales

• Enlarge the Standard Model field spectrum like in 0706.1829 - R. Foot, A. Kobakhidze, K.L. McDonald, R. Volkas

• Consider direct product groups: SM ⊗ HS

• Two scales: CS breaking scale at $O(\text{TeV})$ + induced EW scale

Important consequence for fermion mass terms:
➤ spectrum of Yukawa couplings ⊗ TeV or EW scale
➤ interesting consequences ↔ Majorana mass terms are no longer expected at the generic L-breaking scale ➞ anywhere

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Examples

\[ \mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle \\ y_D^T \langle H \rangle & y_M \langle \phi \rangle \end{pmatrix} \]

⇒ generically expect a TeV seesaw
BUT: \( y_M \) might be tiny
⇒ wide range of sterile masses ⇒ including pseudo-Dirac case
⇒ suppressed 0\( \nu \beta\beta \)

Yukawa seesaw:
\( \text{SM} + \nu_R + \text{singlet} \)
\[ \langle \phi \rangle \approx \text{TeV} \]
\[ \langle H \rangle \approx 1/4 \text{ TeV} \]

Radiative masses

\[ \mathcal{M} = m_L \quad \text{or} \]
\[ \mathcal{M} = \begin{pmatrix} \mu_1 & y_D \langle H \rangle \\ y_D^T \langle H \rangle & \mu_2 \end{pmatrix} \]

⇒ pseudo-Dirac case

The punch line:
all usual neutrino mass terms can be generated
⇒ suitable scalars
⇒ no explicit masses
all via Yukawa couplings
different numerical expectations
Leptogenesis still works…

...there still exist heavy sterile states with CP phases…

\[ \nu \text{ heavy sterile neutrinos typ. } \geq 10^{13} \text{ GeV} \]

\[ \Rightarrow \text{ Leptogenesis from the decay of the remaining heavy sterile neutrinos works perfectly!} \]

Bezrukov, Kartavtsev, ML

\[ \text{one light sterile neutrino } \sim \text{ keV } = \text{ DM} \]

\[ \text{light active neutrinos } < \text{ eV} \]
• **Very nice talks by R. Bernstein und J. Sato** ~ summary

• $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, ...

• **SM:** $\text{BR}(\mu \rightarrow e\gamma) < 10^{-54}$ → far beyond sensitivities

  ➞ if seen: new physics $\sim \frac{1}{\Lambda^n}$ – otherwise limits...

• Integrating out heavy physics ➞ many models fit?

  ➞ learn from combining $\nu$‘s, magnetic moments, LHC signatures, NSI‘s ... ➞ more selective
Summary

- SM+ works perfectly; (so far) no signs of new physics
- Experimentally guaranteed new physics:
  - Neutrino masses
  - BAU
  - DM ↔ new physics, but might be related to neutrinos
- 3x3 neutrino physics works perfect ➔ precision physics
- 3x3 is most likely not all ➔ major discovery
- Improvements on $0\nu\beta\beta$ and absolute mass
  ➔ IH tension? ➔ seeing $\Delta L=2$ would be a major discovery
- do (light) sterile $\nu$’s exist?
  evidences vs. cosmology ↔ theoretical mechanisms
- Main value: Origin of flavour + more (DM, BAU, BSM, LFV,..)
Detection of the Free Neutrino: a Confirmation

A tentative identification of the free neutrino was made in an experiment present work was done (3). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (4) and incorporated in a quantitative theory of beta decay by Fermi (5).

➔ ν’s were and are still good for surprises!
Thanks!

Van Tran Thanh  P. Q. Hung  Bob Hirosky

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