Physics Beyond the Standard Model

Theoretical reasons for BSM:
- SM does not exist without cutoff (triviality)
- Higgs-doublet = only simplest extension
- Gauge hierarchy problem
- Gauge unification, charge quantization
- Strong CP problem
- Unification with gravity
- Why: 3 generations, which representations
- Many parameters (9+? masses, 4+? mixings)

Experimental BSM facts:
- Electro weak scale \(<<\) Planck scale
- Gauge couplings almost unify
- Neutrinos have masses & large mixings
- Baryon asymmetry of the Universe
- Dark Matter, Dark Energy, few \(> 2\sigma\) hints?

\(\Rightarrow\) BSM from a neutrino perspective

M. Lindner
Recontres de Blois, June 2011
New Physics: Neutrino Mass Terms

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

New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

6x6 block mass matrix
block diagonalization
$M_R$ heavy $\Rightarrow$ 3 light $\nu$’s

**NEW ingredients, 9 parameters $\Rightarrow$ SM+**
2) Maybe 3+N right handed neutrino fields

⇒ (6+N) x (6+N) mass matrix
⇒ how many of the 6+N eigenvalues are light (also for N=0)

3) new: scalar triplets \((3_L)\)
or fermionic \(1_L\) ro \(3_L\)

⇒ left-handed Majorana mass term:

\[ M_{LL} \]

4) Both \(\nu_R\) and new singlets / triplets:

⇒ see-saw type II, III

\[ m_\nu = M_L - m_D M_R^{-1} m_D^T \]
5) Higher dimensional operators: $d=5$, …

\[ \mathcal{L}_{\text{mass}} = \kappa \cdot \bar{\nu}_L^C \nu_L \Phi^T \Phi \]

$\Rightarrow M_L \bar{L} L^c$

6) Radiative neutrino mass generation

7-N) SUSY, extra dimensions, …
Other effective Operators Beyond the SM

- effects beyond 3 flavours
- Non Standard Interactions = NSIs - effective 4f operators

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

- integrating out heavy physics (c.f. \( G_F \leftrightarrow M_W \))

\[ |\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2} \]

Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow +Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli+Romanino, Bueno et al., Barranco+Miranda+Rashba, Kopp+ML+Ota, …
Overview of Neutrino Mass Knowledge

- **<2.2 eV**
  - tritium endpoint Mainz & Troitsk
- **<0.2 eV**
  - cosmology
- **<23 eV**
  - SN1987A

- **~ 0.2 eV**
  - KATRIN

- **~ 0.05 eV**
  - different types of masses / different systematics

- **~ 0.3 eV**
  - if neutrino is Majorana

- **ν oscillations were observed**
  - finite mass splittings ➔ finite mass

- **~ degenerate**
  - **hierarchical**

M. Lindner
Recontres de Blois, June 2011
3 Light Neutrinos (...assumed)

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

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

**Questions:**
- Dirac / Majorana
- Mass scale: \( m_1 \)
- Mass ordering: \( \text{sgn}(\Delta m^2_{31}) \)
- How small is \( \theta_{13}, \theta_{23} \) maximal?
- Leptonic CP violation
- 3 flavour unitarity?
- Why 3 generations, why \( d=4, \ldots \)
Suggestive Seesaw Features

QFT: natural value of mass operators $\leftrightarrow$ scale of symmetry

$m_D \sim$ electro-weak scale
$M_R \sim$ L violation scale $\leftrightarrow?$ embedding (GUTs, ...)

See-saw mechanism (type I)

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

Numerical hints:

For $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim$ leptons $\Rightarrow$ $M_R \sim 10^{11} - 10^{16}$GeV

$\nu$’s are Majorana particles, $m_\nu$ probes $\sim$ GUT scale physics!

$\Rightarrow$ smallness of $m_\nu$ $\leftrightarrow$ high scale of $L$, symmetries of $m_D, M_R$
2nd Look Questions

Quarks & charged leptons ➔ hierarchical masses ➔ neutrinos?

Quarks and charged leptons:

\[ m_D \sim H^n ; \ n = 0,1,2 \Rightarrow H \geq 20...200 \]

Neutrinos:

\[ m_\nu \sim H^n \Rightarrow H \leq \sim 10 \]

See-saw:

\[ m_\nu = -m_D^T \ M_R^{-1} \ m_D \]

H \sim 10 \ 20 \ ? \ 20

» less hierarchy in \( m_D \) or corr. hierarchy in \( M_R \)? ➔ theoretically not connected!

» other version of see-saw? ➔ type II, III, …?

» Dirac masses?

M. Lindner
Recontres de Blois, June 2011
What do we actually measure?
Neutrino-less Double Beta Decay

$2\nu\beta\beta$ decay of $^{76}$Ge observed: 
$\tau = 1.5 \times 10^{21}$ y

Majorana $\nu \rightarrow 0\nu\beta\beta$ decay

**warning:** other lepton number violating processes may exist…

- signal at known Q-value
- $2\nu\beta\beta$ background (resolution)
- nuclear backgrounds
  $\Rightarrow$ use different nuclei
Neutrino Masses from Double $\beta$-Decay

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

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

solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$

atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$  CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

$\Rightarrow$ free parameters: $m_1$, sign$(\Delta m_{31}^2)$, CP-phases $\Phi_2, \Phi_3$
Claim of part of the original Heidelberg-Moscow collaboration ↔ cosmology → 'tension'

**Aims of new experiments:**
- test HM claim
- \((\Delta m_{31}^2)^{1/2} \sim 0.05\text{eV} \pm \text{errors}\)  ➞ reach 0.01eV
- CUORE
- GERDA phases I, II, (III)

**Comments:**
- cosmology: limitation by systematical errors ➞ ~another factor 5?
- \(0\nu\beta\beta\) nuclear matrix elements ~factor 1.3-2 theoretical uncertainty in \(m_{ee}\)
- \(\Delta m^2 > 0\) allows complete cancellation ➞ \(0\nu\beta\beta\) signal not guaranteed, but cancellation appears unlikely
Various possibilities:
- LR symmetry
- SUSY (RPV)
- …

$0\nu\beta\beta$ from Alternative $\Delta L=2$ Operators

Schechter + Valle: Any $\Delta L=2$ violating operator

$0\nu\beta\beta$ signal from *some other* new BSM lepton number violating operator

very promising interplay of neutrino mass determinations, cosmology, LHC, LVF experiments and theory

Schechter + Valle: Any $\Delta L=2$ violating operator

radiative generation of Majorana mass term

Majorana nature of $\nu$'s guaranteed

but how big is the mass?
Direct, TeV scale short range mediation w/o intermediate light $\nu$, e.g.

\[ L^\text{eff}, \Delta L_\phi = 2 \] 

\[ \begin{align*}
\mathcal{L}^\text{eff}_{\lambda_{111} \lambda_{111}'} & = \frac{G_F^2}{2} m_P^{-1} \left[ \bar{e}(1 + \gamma_5) e \right] \\
& \times \left[ (\epsilon_{\bar{g}} + \epsilon_{\bar{\chi}})(J_{PS} J_{PS} - \frac{1}{4} J_T^{\mu \nu} J_T^{\mu \nu}) + (\epsilon_{\chi \bar{g}} + \epsilon_{\chi \bar{\chi}} + \epsilon_{\chi f}) J_{PS} J_{PS} \right]
\end{align*} \]

\[ \epsilon_i \sim \pi \alpha(\text{Strong, EW}) \frac{\lambda_{111}^{22}}{G_F^2} \frac{m_P}{m(\bar{g}, \bar{\chi})} \frac{1}{m_{4}(\bar{g}, \bar{\chi})} \]
\[ \Delta L=2 \text{ Operators and TeV Scale Physics} \]

SUSY: direct test of \( \lambda'_{111} \)

L-R symmetry: heavy N’s

Relative strength of ‘light’ and ‘heavy’ \( 0\nu\beta\beta \) amplitudes:

\[
M_{\text{light}} \sim G_F^2 \frac{m_{\nu}}{\langle \chi^2 \rangle} \\
M_{\text{heavy}} \sim G_F^2 \left( \frac{\lambda}{g_2} \right)^4 \frac{M_N^4}{\Lambda^5}
\]
SV-induced Neutrino Masses

General Lorentz-invariant Lagrangian for $0\nu\beta\beta$ (point operator)

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} (\epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu})$$

$$J = \bar{u} (1 \pm \gamma_5) d, \quad J^{\mu} = \bar{u} \gamma^{\mu} (1 \pm \gamma_5) d \text{ etc.}$$


If other $\Delta L=2$ physics drives $0\nu\beta\beta$ $\Rightarrow$ SV gives $\delta m_\nu = 10^{-24}$ eV

$\Rightarrow$ mass correction too small to explain observed masses and splittings

$\Rightarrow$ explicit neutrino mass operators required

Dirac: $0\nu\beta\beta$ essentially unrelated to neutrino masses $\Leftarrow\Rightarrow$ other BSM

Majorana: dominates over SV contribution

$0\nu\beta\beta$ may be a mixture of Majorana mass and other $\Delta L=2$ physics

$\Rightarrow$ mimics higher Majorana neutrino mass
Neutrinos Oscillation Surprises

... many untested assumptions: Majorana, 3 \( \nu \)'s, mass mechanism

\( \Rightarrow \) example: How NSI’s can fool us in precision experiments:

<table>
<thead>
<tr>
<th>Source</th>
<th>Oscillation</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>- neutrino energy ( E )</td>
<td>- oscillation channels</td>
<td>- effective mass, material</td>
</tr>
<tr>
<td>- flux and spectrum</td>
<td>- realistic baselines</td>
<td>- threshold, resolution</td>
</tr>
<tr>
<td>- flavour composition</td>
<td>- MSW matter profile</td>
<td>- particle ID (flavour, charge, event reconstruction, ...)</td>
</tr>
<tr>
<td>- contamination</td>
<td>- degeneracies</td>
<td>- backgrounds</td>
</tr>
<tr>
<td>- symmetric ( \nu/\bar{\nu} ) operation</td>
<td>- correlations</td>
<td>- ( \chi )-sections (at low ( E ))</td>
</tr>
</tbody>
</table>

**precision experiments might see new effects beyond oscillations!**
NSI Operators

• Good reasons for physics beyond the SM+ (with ν’s)
  ➞ expect effects beyond 3 flavours in many models
  ➞ effective 4f interactions

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

• integrating out heavy physics (c.f. \( G_F \leftrightarrow M_W \))

\[ |\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2} \]

Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow+Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli +Romanino, Bueno et al., Kopp+ML+Ota, …
NSIs interfere with Oscillations

the “golden” oscillation channel

NSI contributions to the “golden” channel

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

Redundant measurements:
Double Chooz + T2K
*=assumed ‘true’ values of $\theta_{13}$

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

NSIs can lead to:
- offset
- mismatch

$\Rightarrow$ redundancy
$\Rightarrow$ interesting potential

‘natural magnitude’ …more natural for NuFact

$\Rightarrow$ see talk by S. Pascoli
Evidence(s) for Sterile Neutrinos

LSND - MiniBooNE - MINOS – Gallex - … ➔ evidence for sterile ν’s?
➔ see talk by E. Lisi
➔ New and better data / experiments are needed to clarify the situation
➔ maybe something exciting around the corner?

The standard picture:
3 heavy sterile neutrinos typ. \( \geq 10^{13} \text{ GeV} \)
➔ leptogenesis, role in GUTs, …

3 light active neutrinos
➔ this cold easily be wrong
- more than 3 \( N_R \) states, …
- \( M_R \) may have special eigenvalues, …
➔ light sterile neutrinos ?!
Extra Sterile Neutrinos & CMB

3 active massless neutrinos
+ 
$N_s$ massive neutrinos

3 active massive neutrinos
+ 
$N_s$ massless neutrinos

J. Hamann et al
More Indications for light sterile Neutrinos

Astrophysics:
- Effects of keV-ish sterile neutrinos on pulsar kicks
  Kusenko, Segre, Fuller, Mocioiu, Pascoli
- ...

Cosmology: BBN – ‘feels’ extra light particles:

\[ N_\nu \sim 3.7 \pm 1 \]

Y. Izotov, T. Thuan (2010)
Could Neutrinos be Dark Matter?

• **Active neutrinos = perfect Hot Dark Matter** ➔ ruled out:
  - destroys small scale structures in cosmological evolution
  - required neutrino masses much too small ➔ useful HDM component

• **keV sterile neutrinos: Warm Dark Matter** ➔ works very well:
  ➔ relativistic at decoupling
  ➔ non-relativistic at radiation to matter dominance transition
  • OK for $M_X \sim$ few keV
  • reduced small scale structure ➔ smoother profile, less dwarf satellites
  ➔ scenario where one sterile neutrino is keV-lish, the others heavy

  ➔ right handed neutrinos probably exist
  ➔ only a mechanism to make one state light required
  ➔ observational hints from astronomy
  - hints that a keV sterile particle may exist ➔ right-handed neutrino?
  Biermann, Kusenko & Segre, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …
The νMSM

Asaka, Blanchet, Shaposhnikov, 2005

Particle content:
- Gauge fields of SU(3)_c x SU(2)_W x U(1)_Y: g, W±, Z, g
- Higgs doublet: F=(1,2,1)

<table>
<thead>
<tr>
<th></th>
<th>SU(3)_c</th>
<th>SU(2)_W</th>
<th>U(1)_Y</th>
<th>U(1)_em</th>
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</thead>
<tbody>
<tr>
<td>(u)</td>
<td>3</td>
<td>2</td>
<td>+1/3</td>
<td>(+2/3)</td>
</tr>
<tr>
<td>(d)</td>
<td>3</td>
<td>1</td>
<td>+4/3</td>
<td>+2/3</td>
</tr>
<tr>
<td>u R</td>
<td>3</td>
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<td>-2/3</td>
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</tr>
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</table>

- lepton sector more symmetric to the quark sector
- Majorana masses for N
- choose for one sterile n ~keV mass \(\Rightarrow\) exceeds lifetime of Universe
Abundance in the νMSM and in Alternatives

• **Virtue and problem of νMSM:**
  - scenario with sterile ν and tiny mixing $\Rightarrow$ never enters thermal equilibrium
  $\Rightarrow$ requires non-thermal production from other particles (avoid over-closure)
  $\Rightarrow$ new physics before the beginning of the thermal evolution sets abundance

• **An alternative scenario:** Bezrukov, Hettmannsperger, ML

  • Three right-handed neutrinos $N_1, N_2, N_3$
  • Dirac and Majorana mass terms
  • N Charged under some (BSM) gauge group $\Rightarrow$ scale $M$
  • Specific LR example: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

  • everything follows nicely from sterile neutrinos
The Scenario

- heavy sterile neutrinos typ. $> 10^{13}$ GeV
- one light sterile neutrino $\sim$ keV = DM
- light active neutrinos $< eV$
Obtaining the right Abundance

Usual thermal case:

$$\frac{135 \xi (3)}{4 \pi^4 g_s}$$

$$\frac{n}{s}$$

HDM:

$$\frac{\Omega}{\Omega_{DM}} \sim \left(\frac{10}{9 * f}\right) \left(\frac{M}{10 \text{eV}}\right)$$

Decoupled relativistic

CDM:

(M>>MeV)

$$\Omega \sim \Omega_{DM}$$

Decoupled nonrelativistic

KeV sterile neutrinos:

$$\frac{135 \xi (3)}{4 \pi^4 g_s}$$

$$\frac{n}{s}$$

MSM

non-thermal production

Here →

Hot thermal relic

'Diluted' relic

Diluted after decoupling (entropy generated by other particle decay)

$$\Omega \sim \Omega_{DM}$$

Never entered thermal equilibrium

M. Lindner

Recontres de Blois, June 2011
Observing keV-ish Neutrino DM

- **LHC**
  - sterile neutrino DM is not observable
  - WIMP-like particles still possible – but not DM

- **direct searches**
  - sterile neutrino DM is not observable

- **astrophysics/cosmology** ➔ at some level: keV X-rays
  ➔ sterile neutrino DM is decaying into active neutrinos
  - decay $N_1 \rightarrow \bar{\nu}\nu\nu$, $N_1 \rightarrow \bar{\nu}\nu\nu$

- not very constraining since
  $\tau >> \tau_{\text{Universe}}$

\[ \tau = 5 \times 10^{23} \sec \left( \frac{M_1}{1\text{keV}} \right)^{-5} \left( \frac{\theta_1^2}{10^{-5}} \right)^{-1} \]
- radiative decays $N_1 \rightarrow \nu \gamma$

- so far: observations limit active-sterile mixing angle

$$\Gamma_{N_1 \rightarrow \nu \gamma} \approx 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1 \text{ keV}}\right)^5 \text{s}^{-1}$$

$$\theta_1^2 \approx 1.8 \times 10^{-5} \left(\frac{1 \text{ keV}}{M_1}\right)^5$$

- mixing tiny, but naturally expected to be tiny: $O$(scale ratio)
Generating keV-ish Sterile Neutrinos

Possible scenario: See-saw + a reason why 1 sterile ν is light

\[ m_\nu \]

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

- extra dimensional physics \( \rightarrow \) ‘split see-saw’
  Kusenko, Takahashi, Yanagida,

- flavour symmetries explaining active neutrino masses + charged leptons + quarks
  \( \rightarrow \) consequences for heavy mass matrix
  \( \rightarrow \) \( L_e - L_\mu - L_\tau \) \( \rightarrow \) flavour problem
  ML, Merle, Niro ; Merle, Niro,
  Barry, Rodejohann, Zhang

one light sterile neutrino \( \sim \) keV = DM

light active neutrinos \( < \) eV
Conclusions

- There are very good reasons to go beyond the SM
- Neutrino masses are still the only solid direct evidence for BSM
- Many non-standard neutrino options & connections exist
  - the three neutrino picture may be incomplete
  - connections to EW-SB, DM, LFV, …

⇒ neutrinos may easily surprise us again!