Project Review 2007

Neutrinos and the Flavour Puzzle

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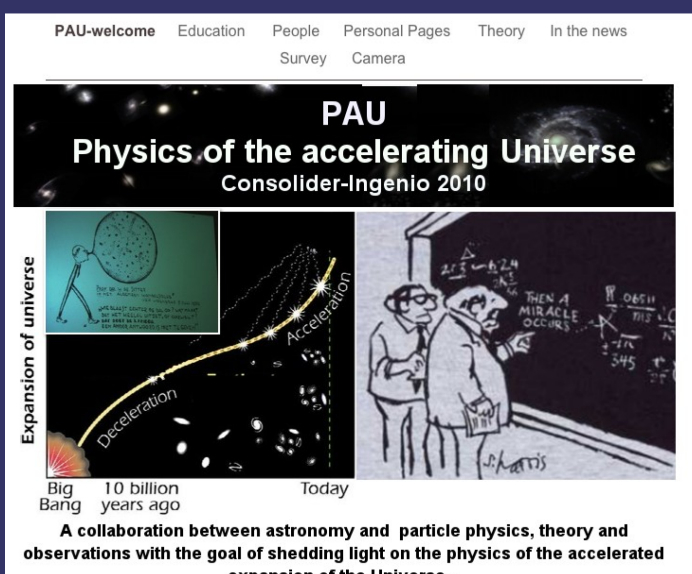
A new group at the MPP ...

- Type: Independent Junior Research Group (SNWG) of the Max-Planck Society
- Research field: Neutrinos and Physics Beyond the Standard Model
- Starting date: September 1st, 2007

- Members:
  - Postdocs:
    - Enrique Fernandez-Martinez
    - Koushik Dutta
  - PhD:
    - Philipp Kostka
    - Martin Spinrath
  - Diploma:
    - Jochen Baumann
  - + myself



International scoping study of a future
Neutrino Factory and super-beam facility
Physics working group

Flavour in the era of the LHC

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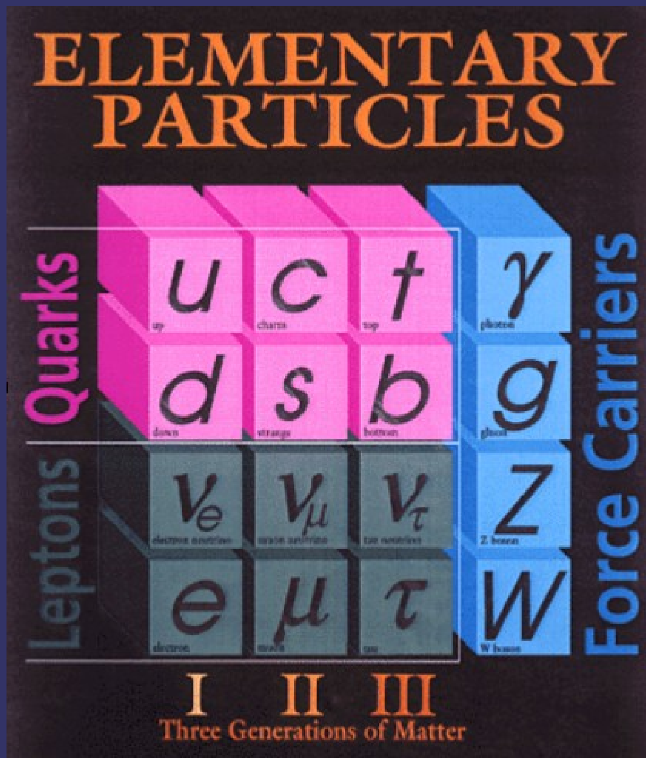
Overview

- Why neutrino masses imply physics 'Beyond the SM'
- Neutrino Physics in context
- Neutrino masses $\leftrightarrow$ flavour puzzle

The Standard Model



- Symmetries of the SM:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{\langle H \rangle = v_{EW}} SU(3)_C \times U(1)_{em}$$

- Masses of particles by the Higgs mechanism
  - Higgs particle(s) not observed so far $\rightarrow$ search @ LHC

- With Symmetries and field content of the SM:
  Neutrinos are massless!

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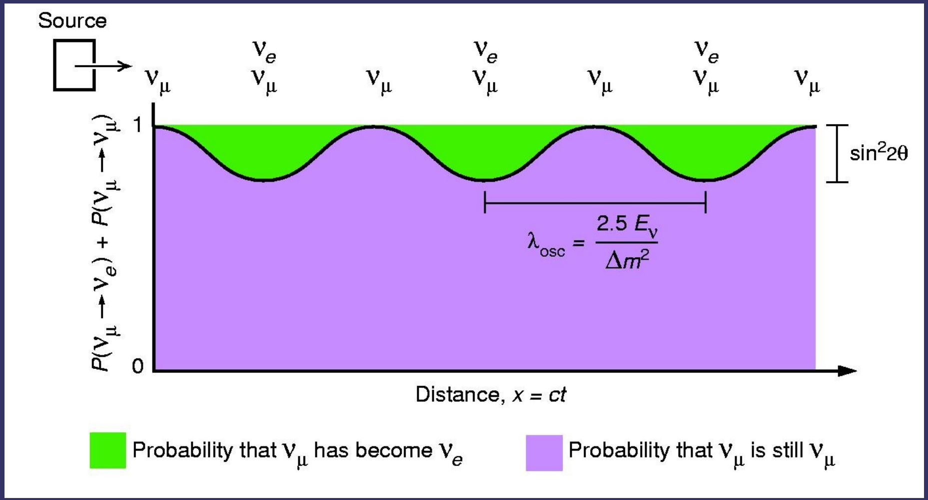
Neutrino oscillations

$$P(\nu_\mu \to \nu_e; L) = \sin^2 2\theta \sin^2 \left[\frac{1.27 \Delta m^2(\mathrm{eV}^2) L(m)}{\mathrm{E\ (MeV)}}\right]$$

Example:
2 families
in vacuum

Pontecorvo ('57)

- Oscillation probability P depends on:
  - L: distance between source and detector
  - E: Energy of neutrinos
  - $\Delta m^2 = m_2^2 - m_1^2$ ('mass squard difference')
  - θ: mixing between flavour and mass eigenstates
- Remarks:
  - 3 families: dependence on CP violating phase δ
  - P modified in matter



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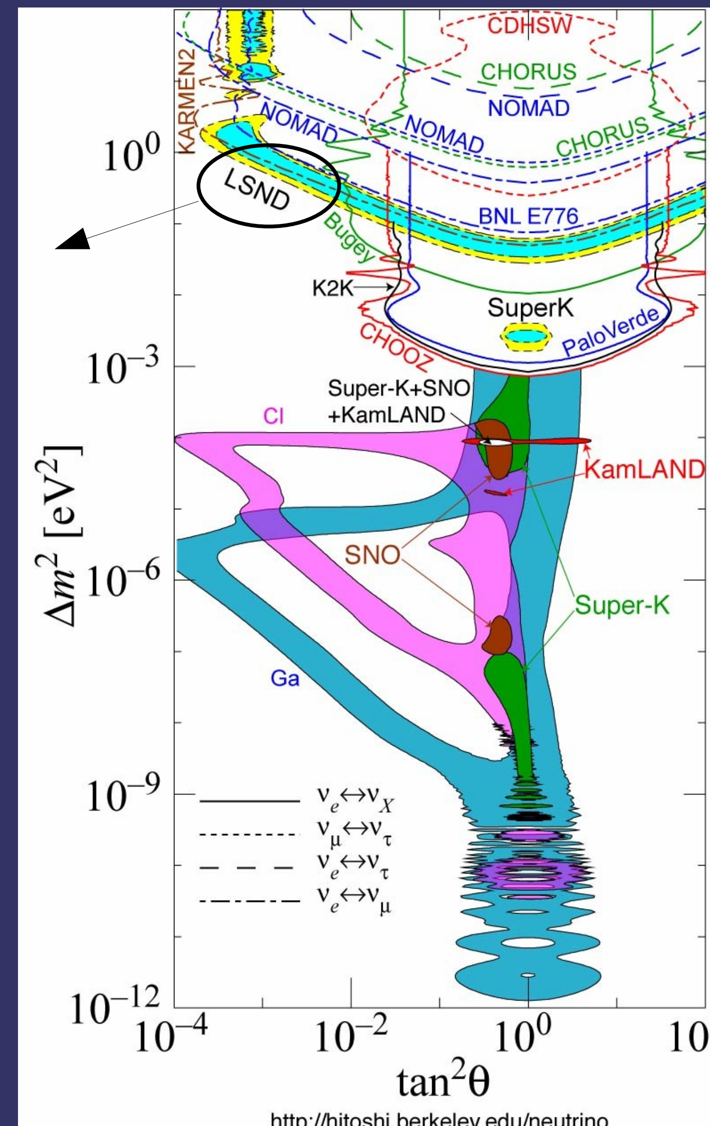
Evidence for neutrino masses

LSND:
if correct, not
from ν-oscillations
(MiniBooNE)



- Strong evidence for neutrino oscillations:
  Neutrinos do have mass
  $\Rightarrow$ The SM has to be extended!

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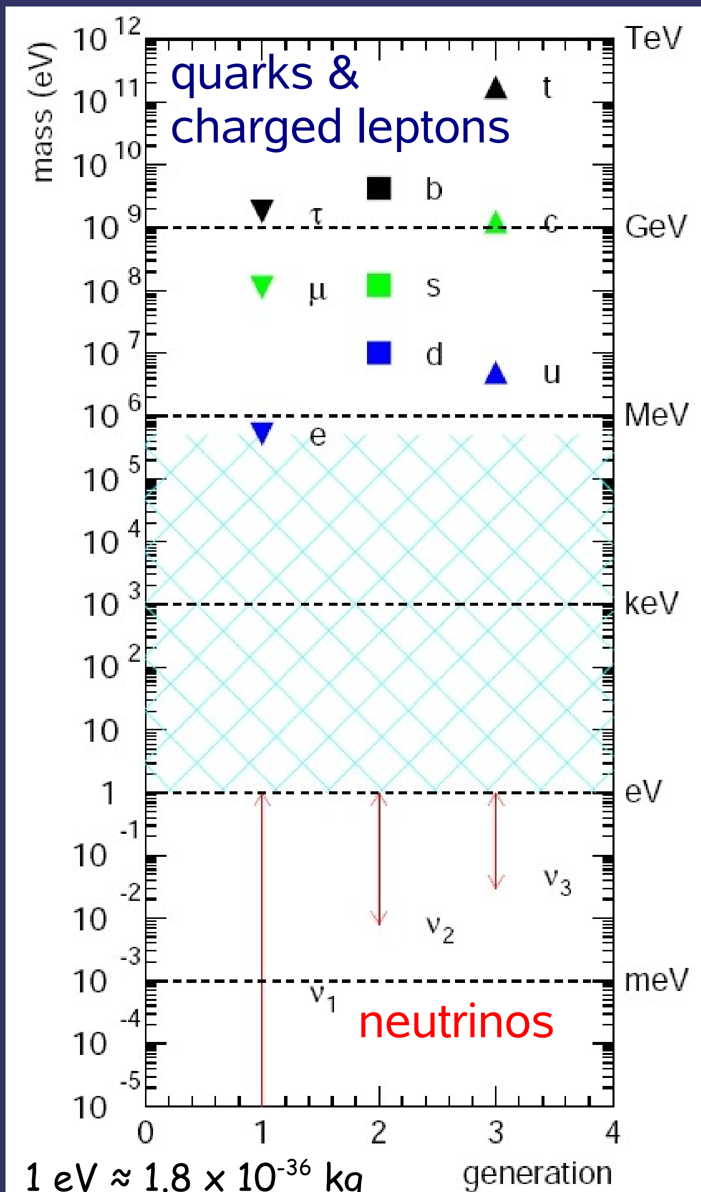
Summary of Results



	Best-fit value	Range	C.L.
θ_{12} [°]	33.2	29.3 – 39.2	99% (3σ)
θ_{23} [°]	45.0	35.7 – 55.6	99% (3σ)
θ_{13} [°]	–	0.0 – 11.5	99% (3σ)
Δm^2_{21} [eV^2]	$7.9 \cdot 10^{-5}$	$7.1 \cdot 10^{-5} - 8.9 \cdot 10^{-5}$	99% (3σ)
$\|\Delta m^2_{31}\|$ [eV^2]	$2.6 \cdot 10^{-3}$	$2.0 \cdot 10^{-3} - 3.2 \cdot 10^{-3}$	99% (3σ)

- Two mixing angles large (θ_{23} close to maximal)
- Constraints from $0\nu\beta\beta$-decay, Tritium β-decay & cosmology: $m_{\nu i}$ below about 0.5 eV
- Open questions: CP violation, mass scale & ordering, θ_{13}, ...

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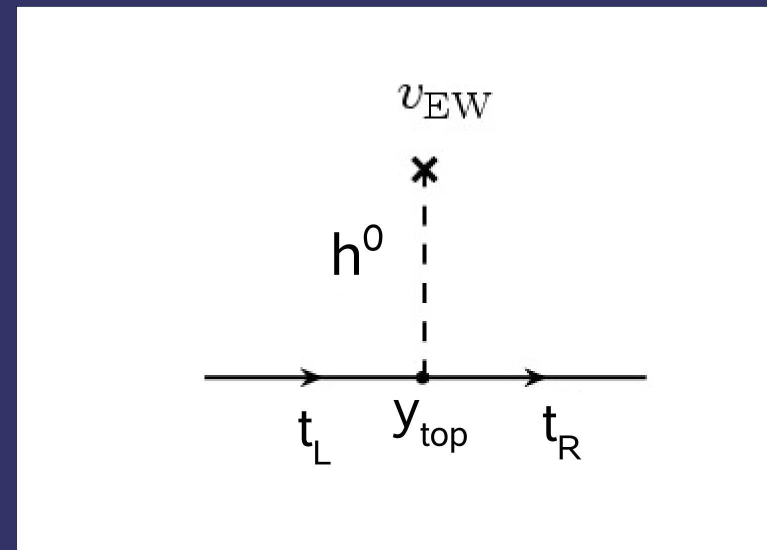
The Higgs Mechanism in diagrams ...



- Famous scientist trying to walk through a room filled with physicists. He feels resistance to movement from interacting with other people = 'acquires mass'

- Particle (e.g. top quark) interacts with the vacuum filled with the Higgs field (strength y_{top}, vacuum expectation value v_{EW})

  $\Rightarrow$ mass $m_{top} = y_{top}\, v_{EW}$

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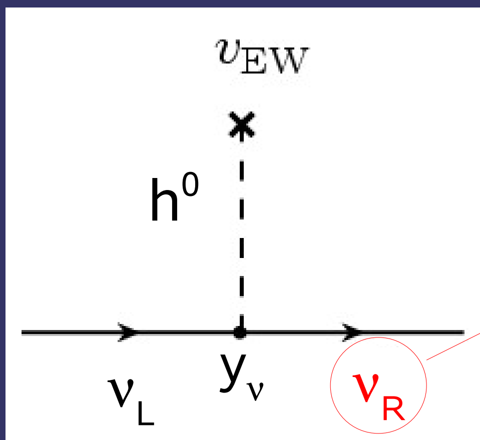
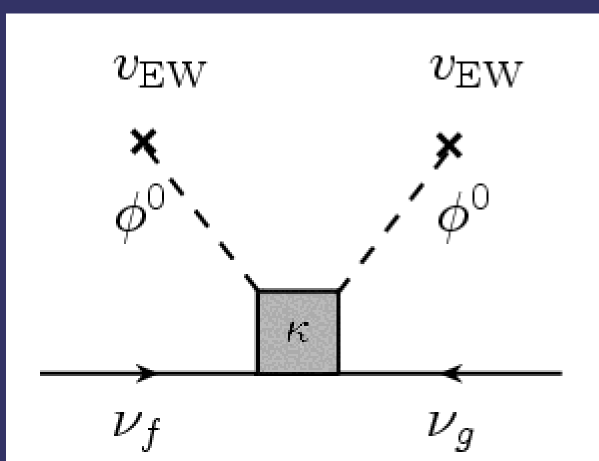
The nature of neutrino masses



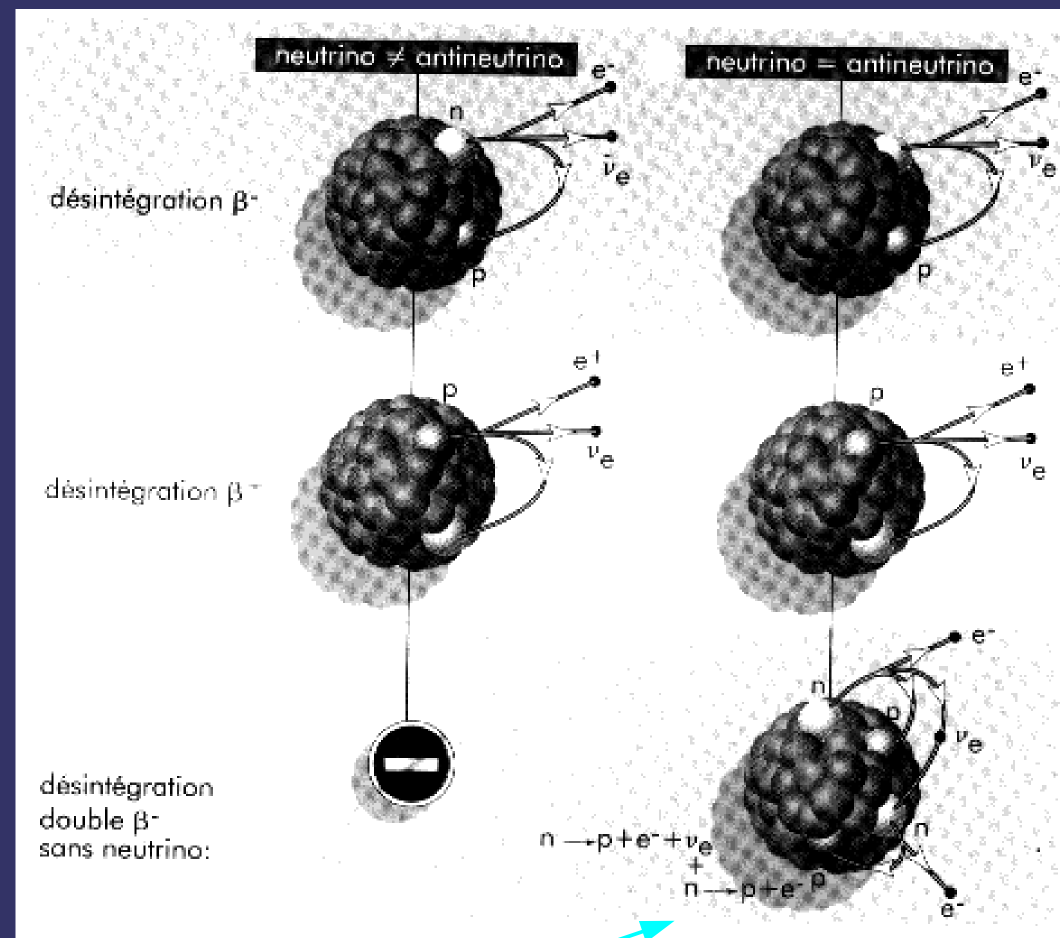
Requires:
- y_ν tiny
- no ν_R mass
- new field

➲ Pure Dirac masses



➲ Effective Majorana masses

Dirac Majorana



Neutrinoless double β-decay

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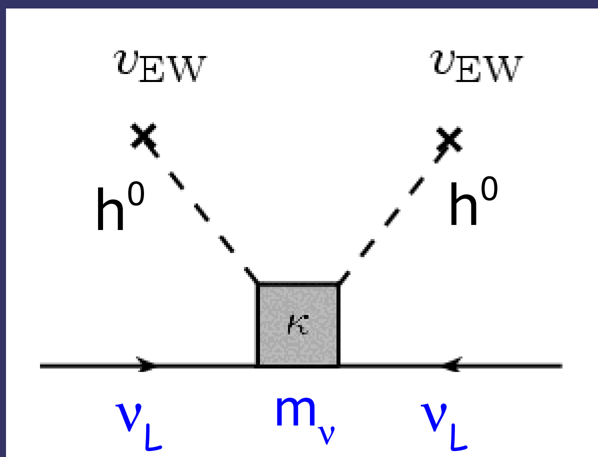
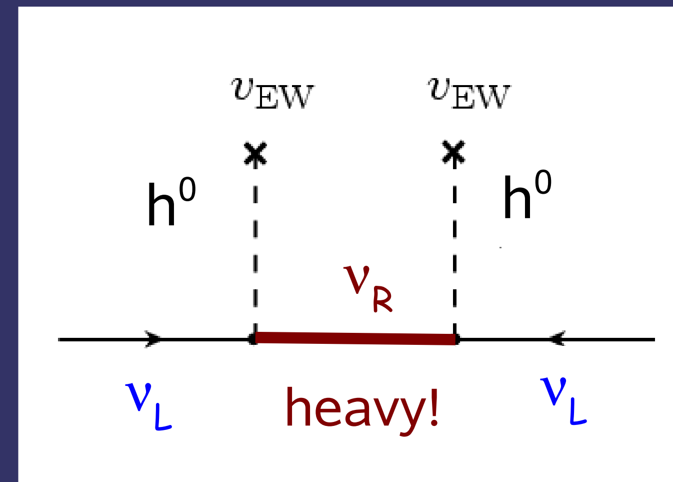
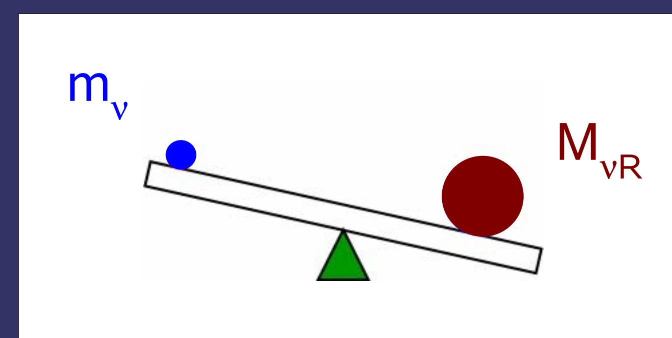
The Seesaw Mechanism (Type I)



$m_\nu \sim v^2_{EW} / M_{\nu R}$



P. Minkowski ('77), ...



- With RH neutrino masses around (somewhat below) the GUT scale, light neutrino masses of the right order are obtained

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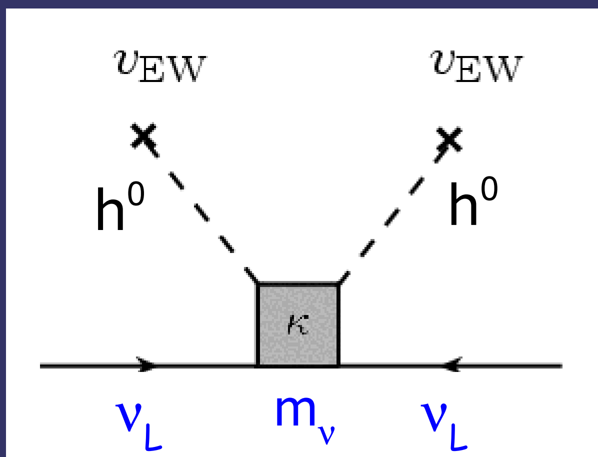
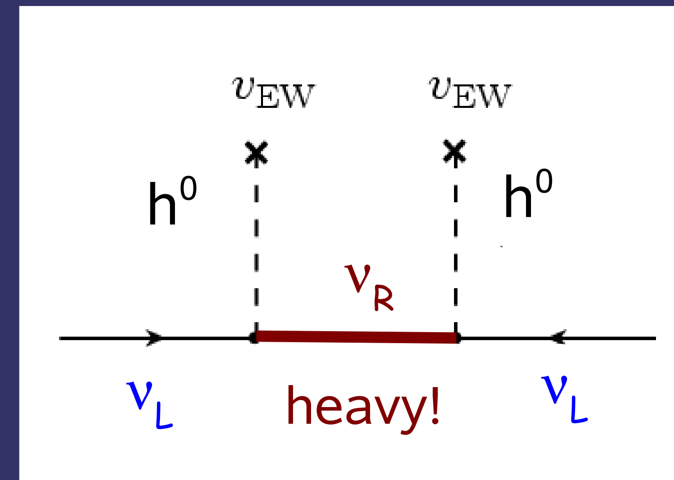
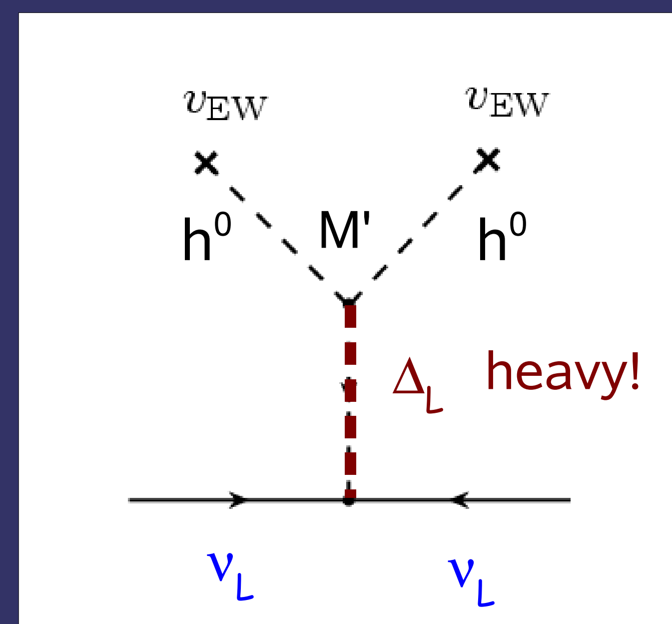
The Type II Seesaw Mechanism



$m^I_\nu \sim v^2_{EW} / M_{\nu R}$



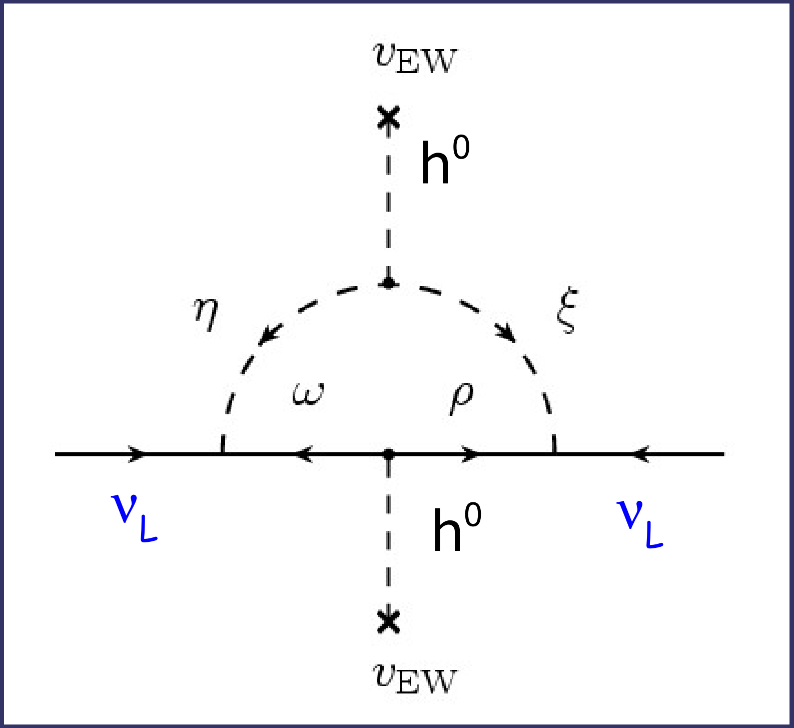
$m^{II}_\nu \sim v^2_{EW} M' / M_\Delta^2$



- Type II Seesaw: Type I + additional contribution from $SU(2)_L$ Higgs triplet:

  $m_\nu = m^I_\nu + m^{II}_\nu$
- Typical in LR-symmetric extensions of the SM

Several alternative mechanisms ...



- For example: Radiative generation of neutrino masses
- Also:
  - Seesaw with fermionic triplets
  - Small Dirac neutrino masses, e.g. from extra dimensions
  - Non-perturbative generation of ν-masses from string theory
  - Low energy seesaw

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Beyond the Standard Model: Evidences and Motivations

- **Neutrino Masses**
  - Clear signal for BSM!
  - Dirac vs. Majorana?
  - Which mechanism?

- **Hierarchy Problem**
  - Proposed solutions: Supersymmetry, Large extra dims, Composite models, Little Higgs ...
  - LHC!

- **Flavour Puzzle**
  - Where does the observed flavour structure come from?

BSM

- **Dark Matter**
  - Candidate from particle physics? LHC!

- **Unification of Forces**

- **Baryon Asymmetry**
  - Why do we exist?

- **Inflation**
  - Candidate for the inflaton field driving inflation?

- **Dark Energy**

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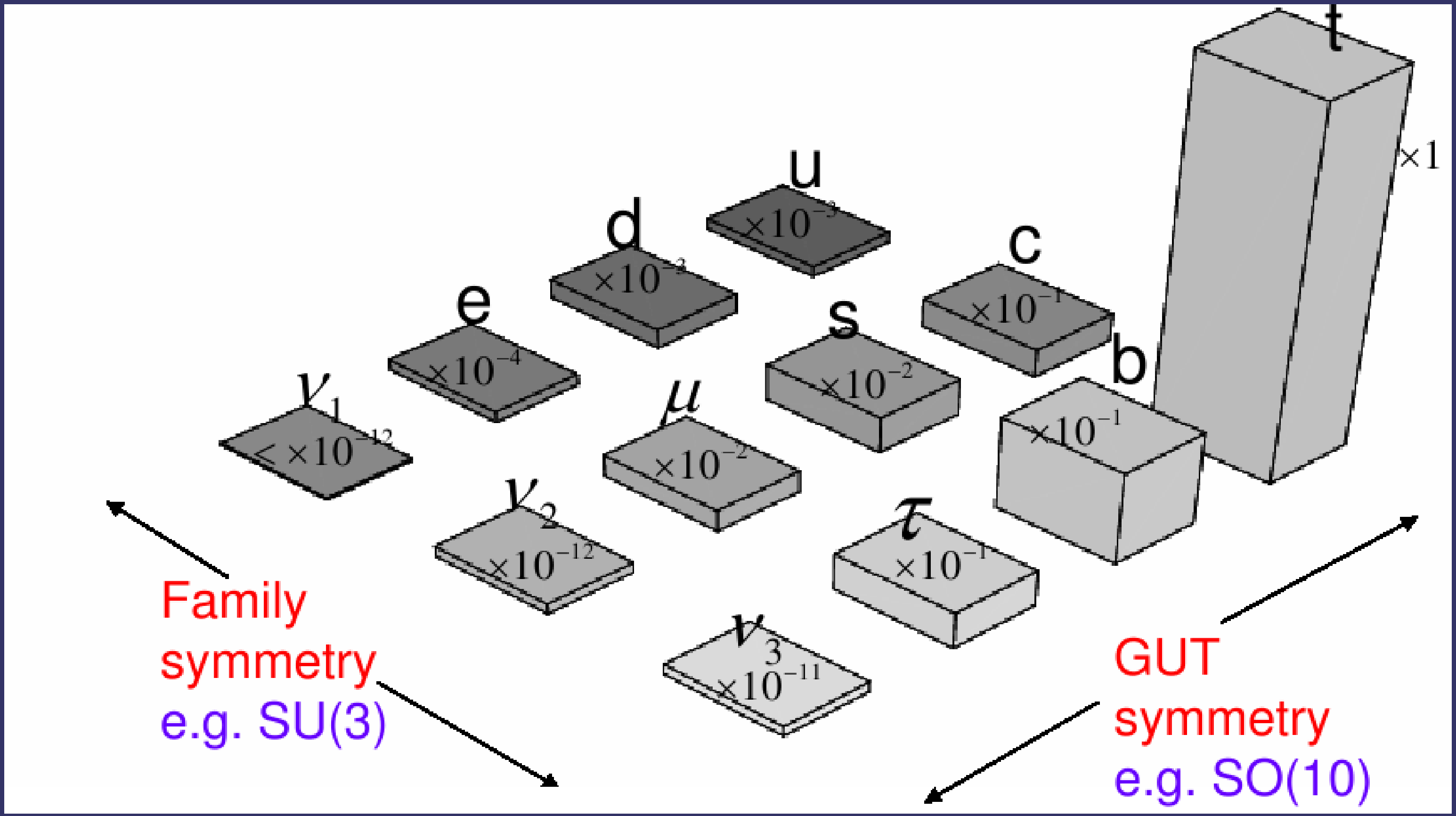
Symmetries: horizontal & vertical ...

- To address the flavour puzzle: Symmetries are powerful tool



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Non-Abelian family symmetries & large neutrino mixing

- Toy model: Seesaw (I / II), SO(3) family symmetry q_L^f, l_L^f in fundamental representation

$$M_{\mathrm{RR}} = \begin{pmatrix} M_{\mathrm{R1}} & 0 & 0 \\ 0 & M_{\mathrm{R2}} & 0 \\ 0 & 0 & M_{\mathrm{R3}} \end{pmatrix}$$

  - <u>Symmetry limit:</u> $Y_{u,d,e,\nu} = 0$, $m^{II}_{LL} = m_0 \, \mathrm{diag}(1,1,1)$, $M_R = \mathrm{diag}(M_A, M_B, M_C)$

$$m^{\mathrm{II}}_{\mathrm{LL}} = m^{\mathrm{II}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  - <u>SO(3) spontaneously broken</u> by $\langle\theta_i\rangle$ (in 3 of SO(3)): $(Y^x)^f_i = \langle\theta_i^f\rangle / \Lambda_x$ (x=u,d,e,ν)

$$Y_\nu = \begin{pmatrix} a_1 \frac{\langle(\theta_1)_1\rangle}{M_{N1}} & a_2 \frac{\langle(\theta_2)_1\rangle}{M_{N2}} & a_3 \frac{\langle(\theta_3)_1\rangle}{M_{N3}} \\ a_1 \frac{\langle(\theta_1)_2\rangle}{M_{N1}} & a_2 \frac{\langle(\theta_2)_2\rangle}{M_{N2}} & a_3 \frac{\langle(\theta_3)_2\rangle}{M_{N3}} \\ a_1 \frac{\langle(\theta_1)_3\rangle}{M_{N1}} & a_2 \frac{\langle(\theta_2)_3\rangle}{M_{N2}} & a_3 \frac{\langle(\theta_3)_3\rangle}{M_{N3}} \end{pmatrix}$$

- In addition: $\langle\theta_i\rangle$ real; each q_{Ri}, l_{Ri} couple only to θ_i

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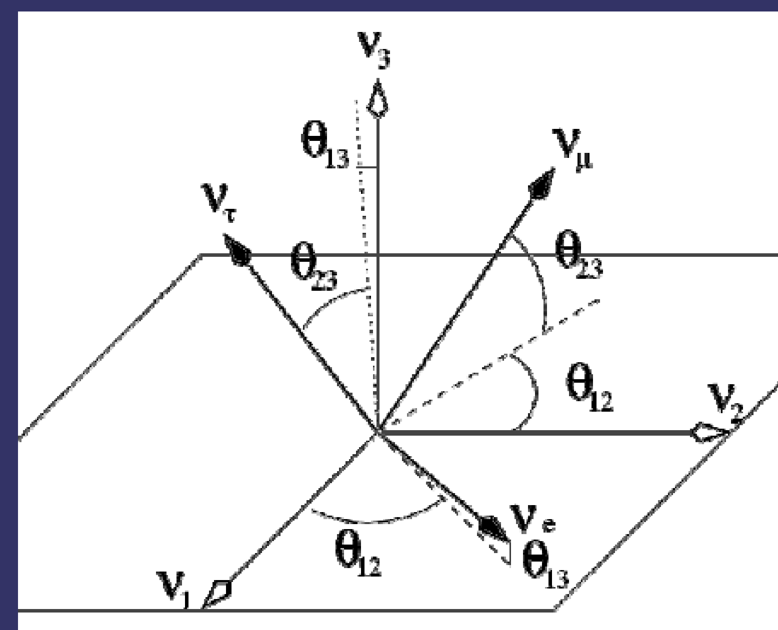
Non-Abelian family symmetries & large neutrino mixing

- Choose SO(3) basis such that:
  $\langle \theta_C \rangle = (0,0,c)$
  $\langle \theta_A \rangle = (0,a_2,a_3)$
  $\langle \theta_B \rangle = (b_1,b_2,b_3)$
  - In this toy model:
    no mixing in quark sector;
    no PMNS mixing from Y_e

$$Y_{u,d,e,\nu} = \begin{pmatrix} * & 0 & 0 \\ * & * & 0 \\ * & * & * \end{pmatrix}$$



- Large neutrino mixing requires (assuming SD):
  - $a_i^2/M_A >> b_i^2/M_B >> c_i^2/M_C$
  - $|a_2| \sim |a_3|$ (large θ_{23})
  - $|b_1| \sim |b_2| \sim |b_3|$ (large θ_{12})
  - <u>small</u> θ_{13} <u>automatic!</u>

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Aside: Killing prejudices ...

- Prejudice #1: Quasi-degenerate neutrino spectrum is unnatural
  Wrong! With SO(3) familiy symmetry and type II seesaw, degenerate spectrum of light Majorana neutrino masses in the symmetry limt.

$$m^\nu_{\mathrm{LL}} \approx m^{\mathrm{II}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} (m^{\mathrm{I}}_{\mathrm{LL}})_{11} & (m^{\mathrm{I}}_{\mathrm{LL}})_{12} & (m^{\mathrm{I}}_{\mathrm{LL}})_{13} \\ (m^{\mathrm{I}}_{\mathrm{LL}})_{21} & (m^{\mathrm{I}}_{\mathrm{LL}})_{22} & (m^{\mathrm{I}}_{\mathrm{LL}})_{23} \\ (m^{\mathrm{I}}_{\mathrm{LL}})_{31} & (m^{\mathrm{I}}_{\mathrm{LL}})_{32} & (m^{\mathrm{I}}_{\mathrm{LL}})_{33} \end{pmatrix}$$

S.A., King ('04)

- Prejudice #2: Difficult to obtain large neutrino mixing ...
  Wrong! Within the seesaw mechanism, under generic conditions (sequential RH neutrino dominance *King ('98)*) large neutrino mixing is readily obtained.

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Tri-bimaximal neutrino mixing from non-Abelian family symmetry

- In some classes of models even more specific pat-terns emerges, e.g.:

e.g. King ('05), Ross ('05), ...

$<\theta_C> = c\ (0,0,1)$

$<\theta_A> = a\ (0,-1,1)$

$<\theta_B> = b\ (1,1,1)$

... enforced e.g. by geo-metrical conditions on the SO(3)-breaking vacuum

- In the above example: <u>neutrino mixing predicted tri-bimaximal</u>

Harrison, Perkins, Scott ('02)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{13}^{\nu} = 0°,\ \theta_{12}^{\nu} = 35.3°,\ \theta_{23}^{\nu} = 45°$

- Do we expect to observe this pat-tern directly in experiment?

<u>No! Corrections to it from ...</u>

  - Charged lepton mixing
  - Non-canonical kinetic terms
  - Renormalisation group running

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Including all the corrections ...

- ... there are modifications to all three mixing angles!
- ... however, under quite generic conditions (3rd family wave-function corrections dominate, Cabibbo-like charged lepton mixing corrections) the **corrections are correlated!**
- Result:
  Neutrino mixing sum rule
- ***Stable*** under the above named corrections in LO

$$s = r\cos\delta + \frac{2}{3}a\,.$$

S.A., King, Malinsky ('07)

with:
$\sin\theta_{12} = (1+s)/\sqrt{3}$,
$\sin\theta_{23} = (1+a)/\sqrt{2}$,
$\sin\theta_{13} = r/\sqrt{2}$,
δ: Dirac CP phase

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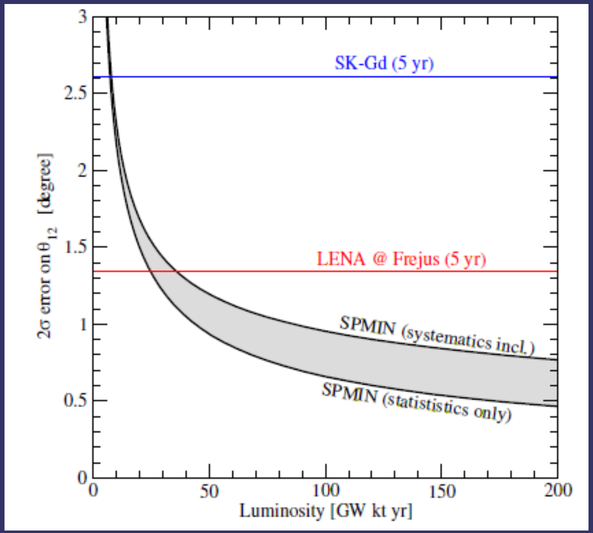
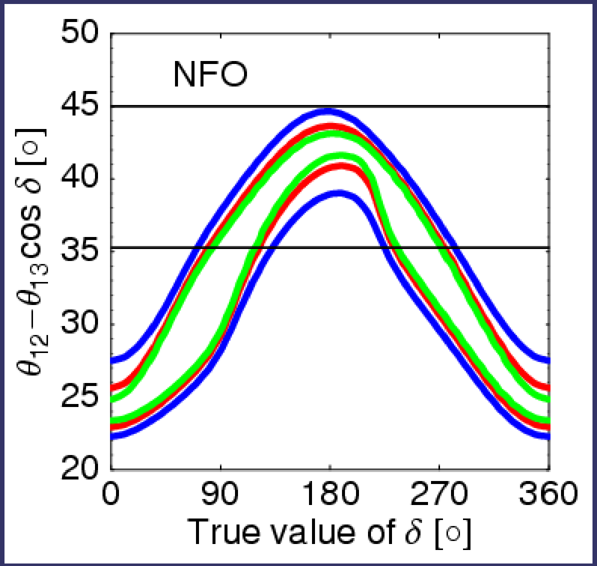
Testing neutrino mixing sum rules

Testing $s = r\cos\delta + \frac{2}{3}a$ requires ...

... measuring θ_{12} with more precision

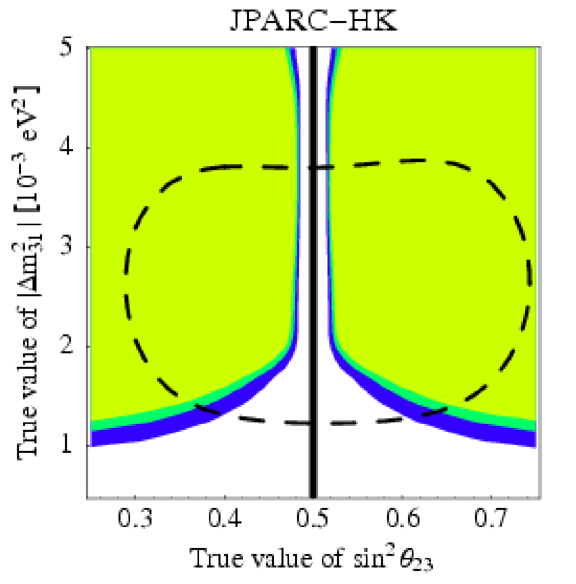


... measuring θ_{13} and δ



S.A., Huber, King, Schwetz ('07)

... measuring deviations of θ_{23} from maximal



S.A., Huber, Kersten, Schwetz, Winter ('04)

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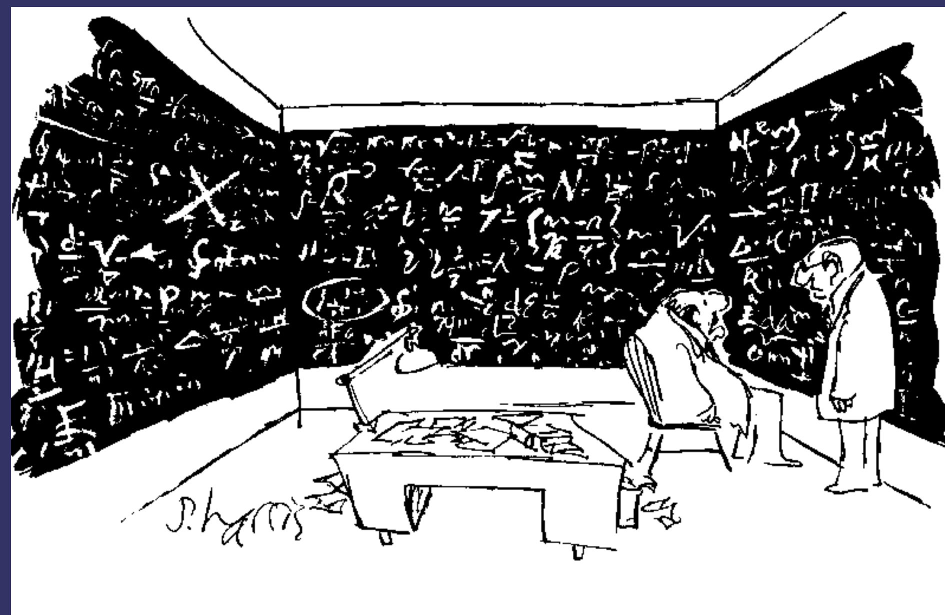
No theory of flavour so far, but ...



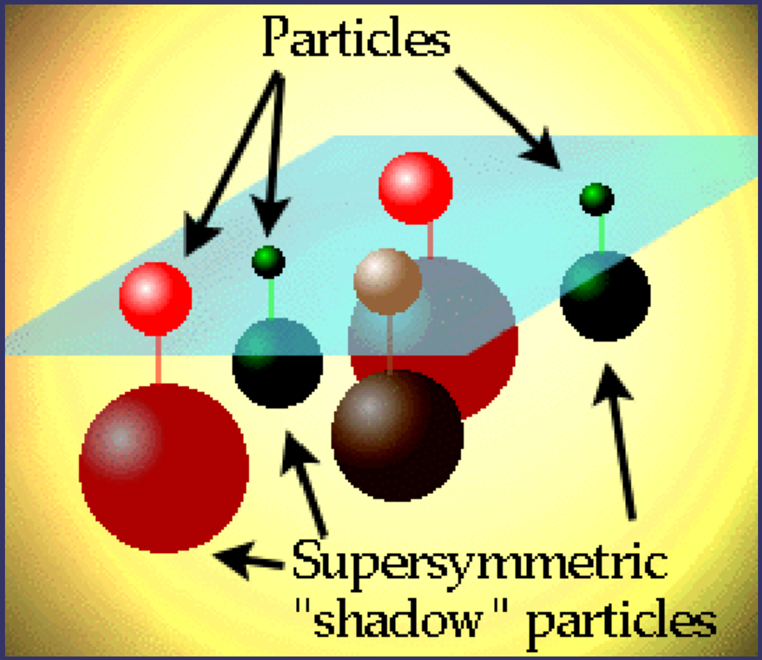
"Whatever happened to *elegant* solutions?"

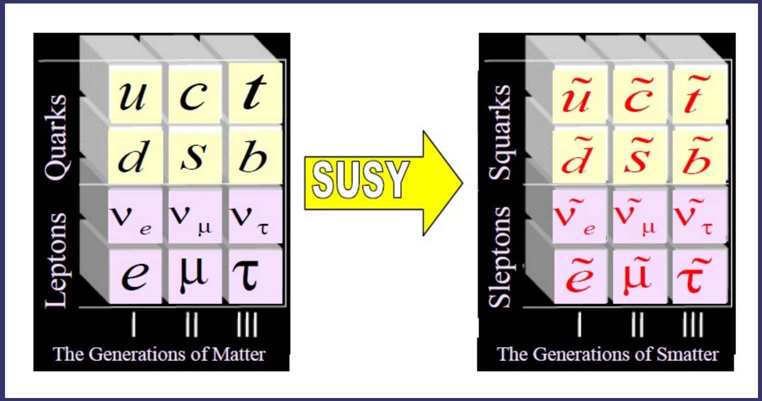
- with future precision neutrino oscillation experiments the neutrino parameters could become the most precise flavour information $\rightarrow$ possible hints towards a theory of flavour ...
- further hints from indirect tests (e.g. LFV in μ and τ decays) & interplay with cosmology (e.g. flavour in leptogenesis)

Outlook

- If low energy supersymmetry discovered @ LHC: flavour puzzle would get 'new dimension'!
  - SUSY flavour problem (general MSSM, large FCNCs)
  - SUSY CP problem (strong constraints on extra SUSY phases)

- Interesting: Non-Abelian family symmetries (e.g. SU(3)) can solve these problems independent of the mechanism of SUSY breaking!
  S.A., Malinsky, King ('07)





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