Implications of Future Precision Experiments

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Coming Improvements

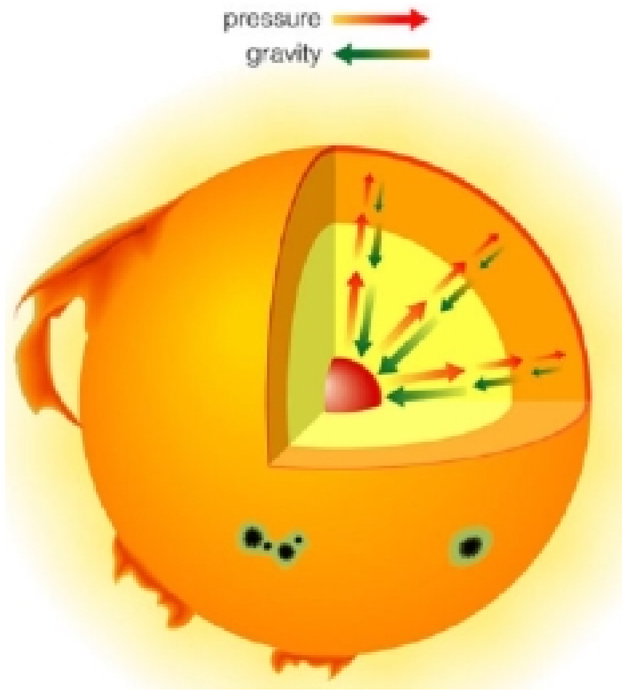
MINOS: improved oscillation parameters
MiniBOONE ←→ LSND
L/E dependence of oscillations
KATRIN
Better $0\nu 2\beta$ limits / signals
…

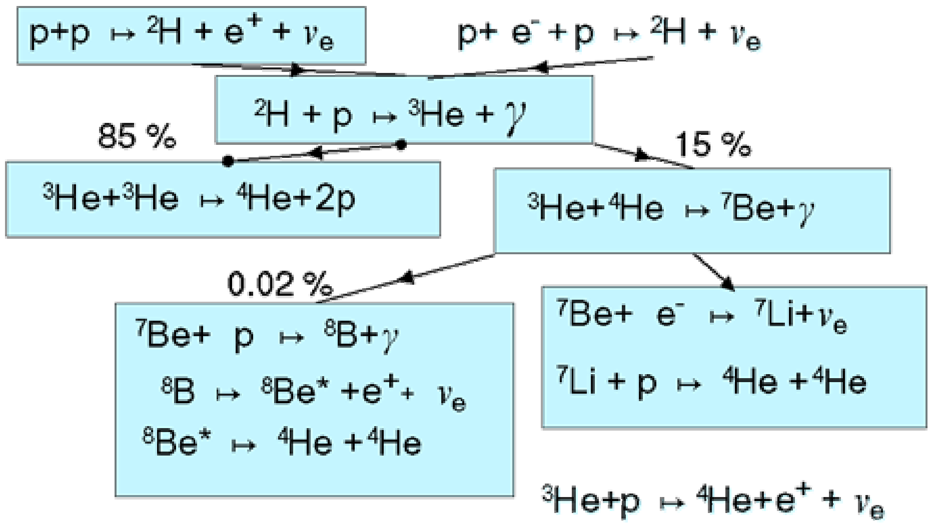
But why do we need precision measurements?

Solar Neutrinos: Learning About the Sun

Observables:

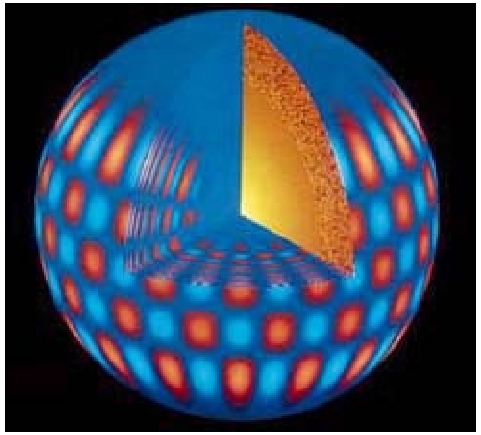
- **optical** (total energy, surface dynamics, sun-spots, historical records, B, ...)
- **neutrinos** (rates, spectrum, ...)



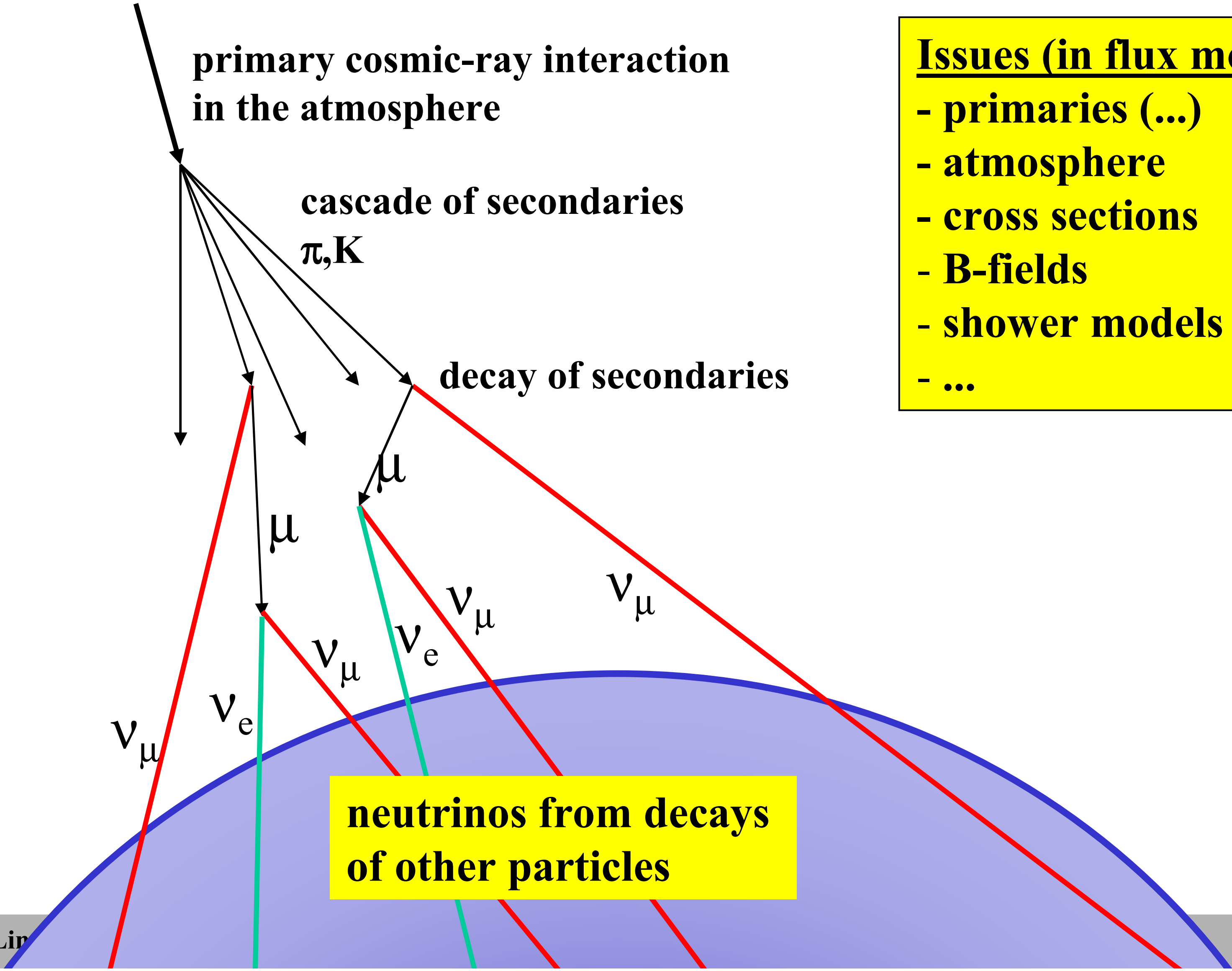


Topics:

- **nuclear cross sections**
- **solar dynamics**
- **helio-seismology**
- **variability**
- **composition**



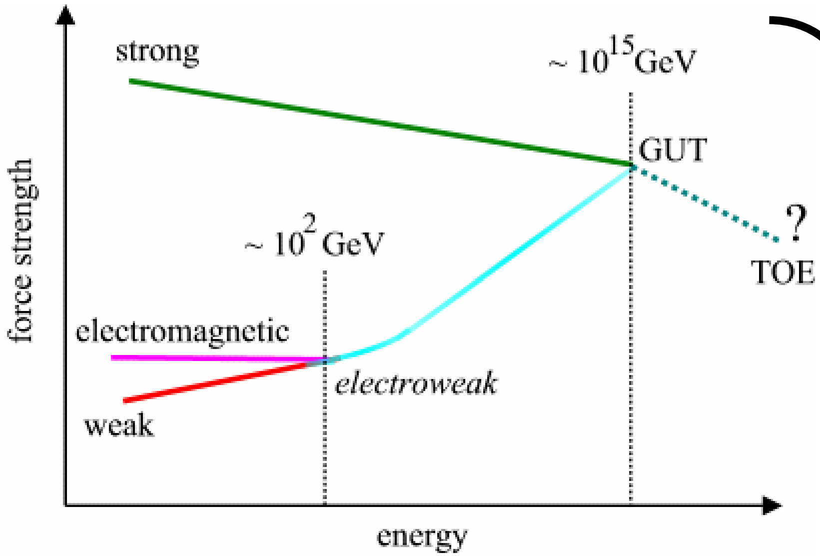
Learning from Atmospheric Neutrinos



Issues (in flux models):
- primaries (...)
- atmosphere
- cross sections
- B-fields
- shower models
- ...

New Physics Beyond the SM

gauge bosons →



Higgs →

gauge hierarchy problem

$\delta m_H^2 \sim \Lambda^2$

quarks leptons →

3 generations, fermion rep.
many parameters (m_i ,mixings)
unification into GUTs

$m_\nu = (m^D)^T M_R^{-1} m_D$

experimental facts:

- Dark Matter
- Dark Energy
- baryon asymetry: $m_\nu > 0$
- neutrino masses & mixings
- ➔ precision

SUSY ~TeV

$\sim\Lambda_{GUT}$ +seesaw

astrophysics & cosmology

Precison with New Neutrino Beams

- **conventional beams, superbeams**

  ➔ **MINOS, CNGS, T2K, NOνA, T2H,…**
- **β-beams**

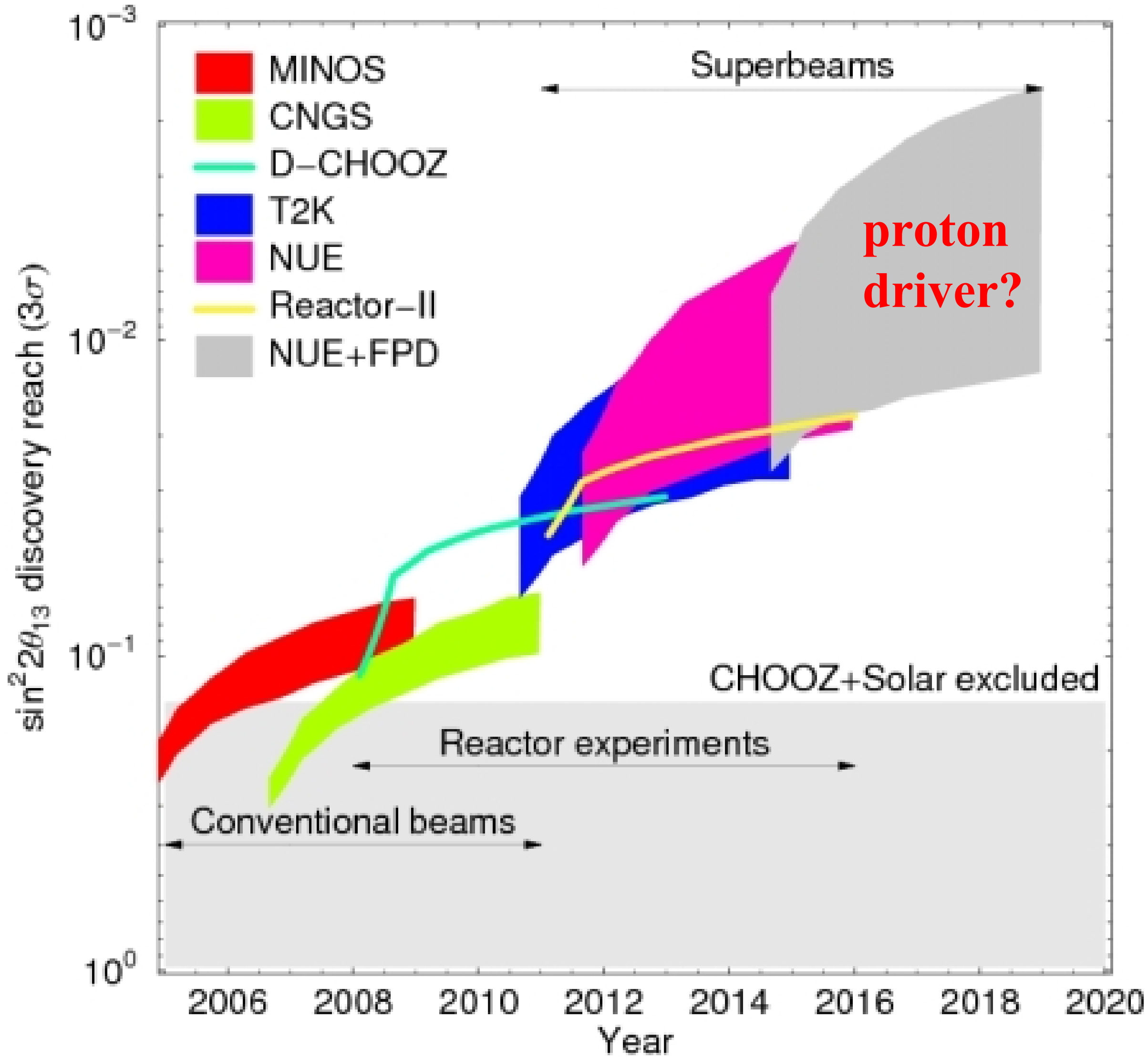
  ➔ **pure ν_e and $\bar{\nu}_e$ beams from radioactive decays; $\gamma \simeq 100$**
- **neutrino factories**

  ➔ **clean neutrino beams from decay of stored μ's**

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \;\approx\;& \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm\;& \sin\delta_{CP}\; \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\;& \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\;& \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

➔ **correlations & degeneracies**

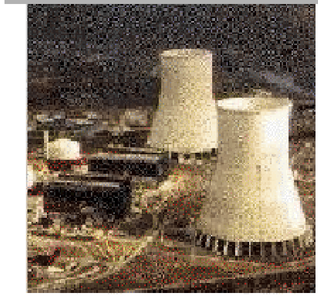
Sensitivity Versus Time



β-beams
neutrino factory

see talk by W.Winter

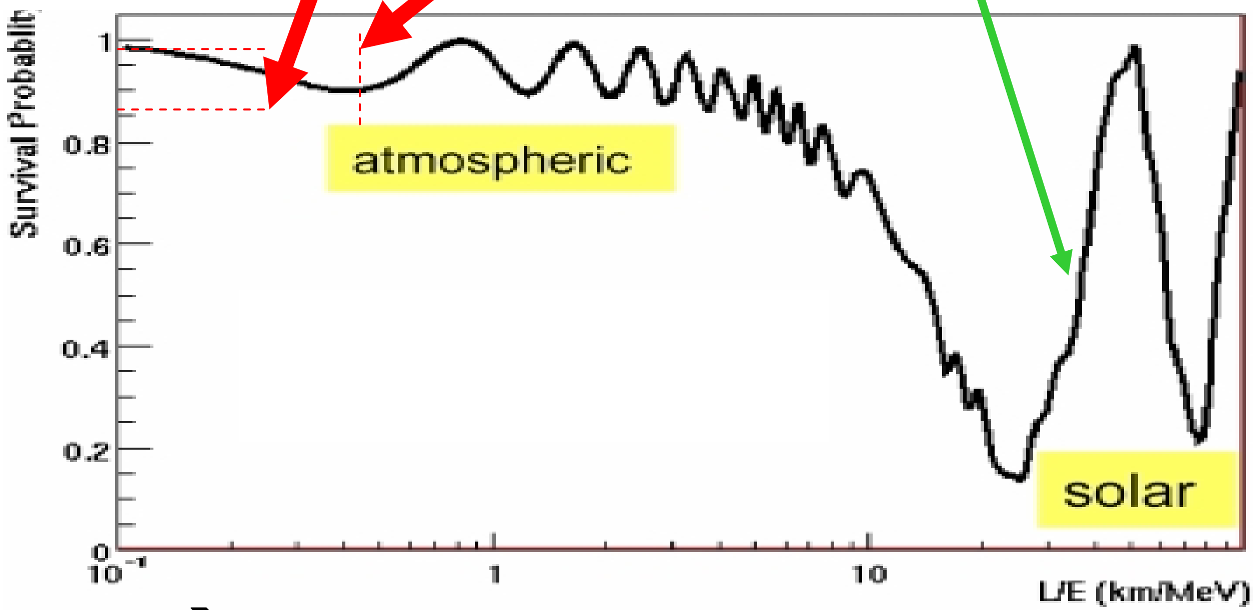
Precision with New Reactor Experiments



$\overline{\nu}_e \Rightarrow$ **near detector** (170m) $\overline{\nu}_e \Rightarrow$ **far detector** (1700m)

identical detectors ➔ many errors cancel

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$



E=4MeV ➔ 2km 4km 40km 80km

- ➔ **Double Chooz**
- ➔ **KASKA**
- ➔ **Braidwood**
- ➔ **Angra, …**

no degeneracies
no correlations
no matter effects

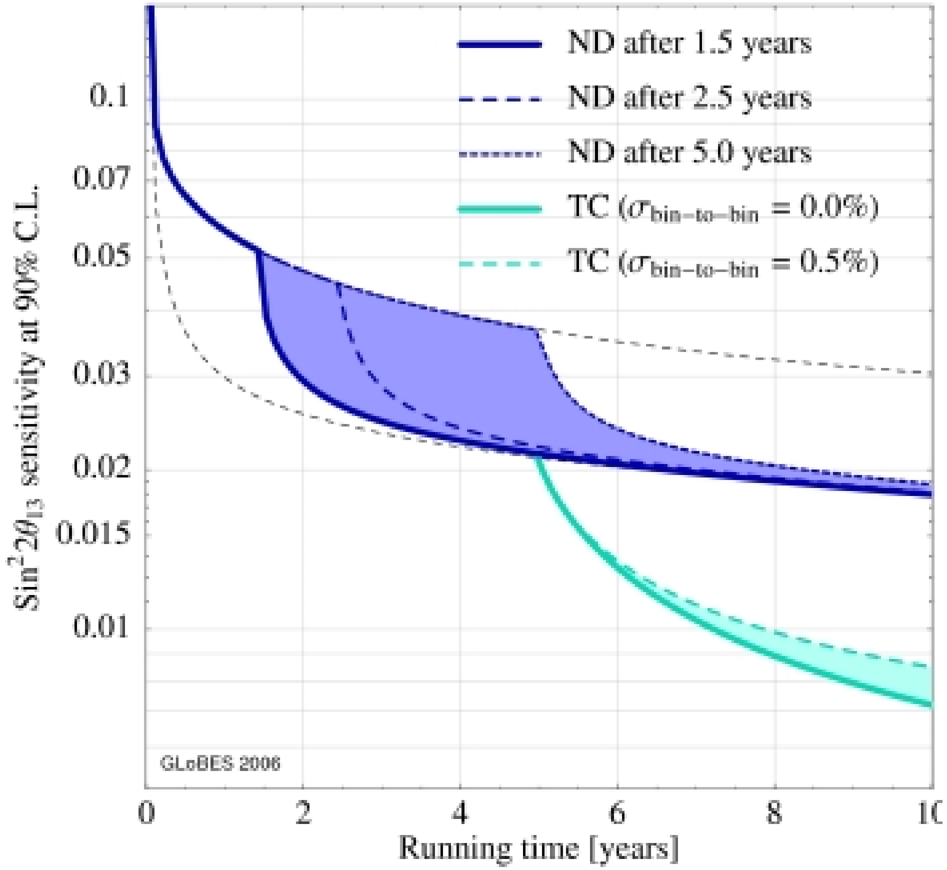
Double Chooz

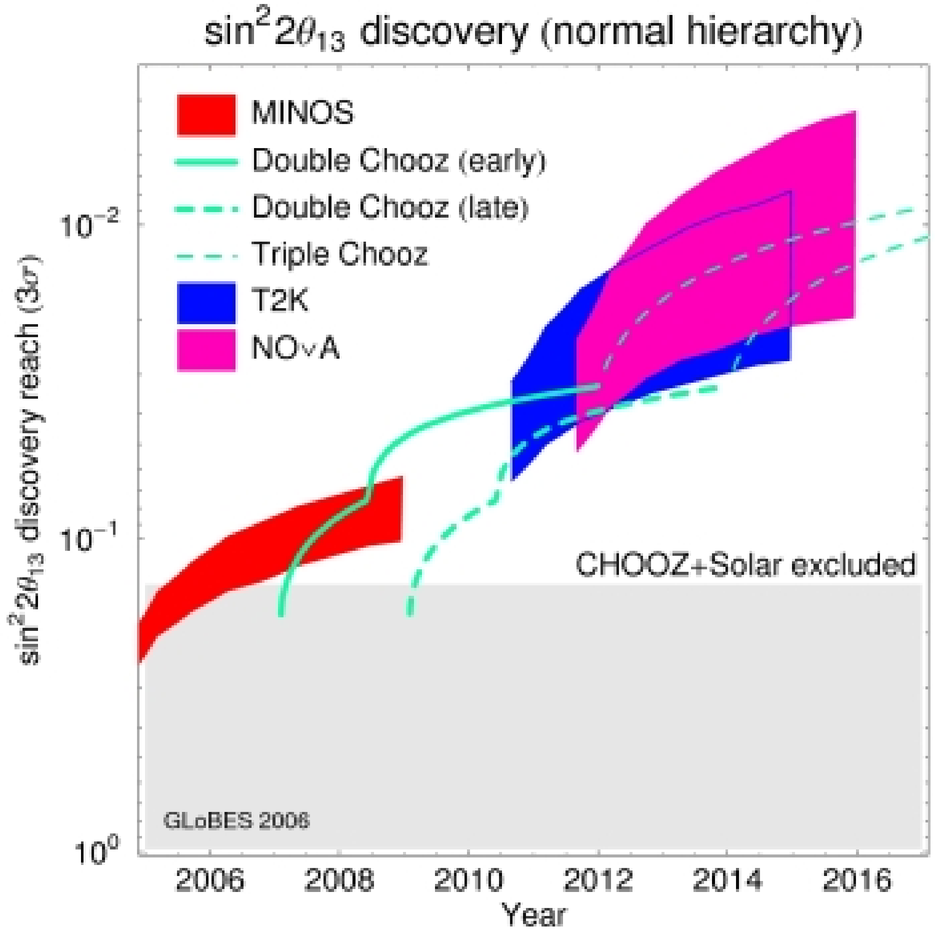
existing far detector hall

… + another
existing big hall!

see talk by T. Lasserre

Double Chooz and Triple Chooz





<u>$\sin^2 2\theta_{13}$ sensitivity</u>

Chooz limit	< 0.20
Double Chooz	< 0.02
Triple Chooz ?	< 0.008

Huber, Kopp, ML, Rolinec, Winter

Double Chooz and 0ν2β

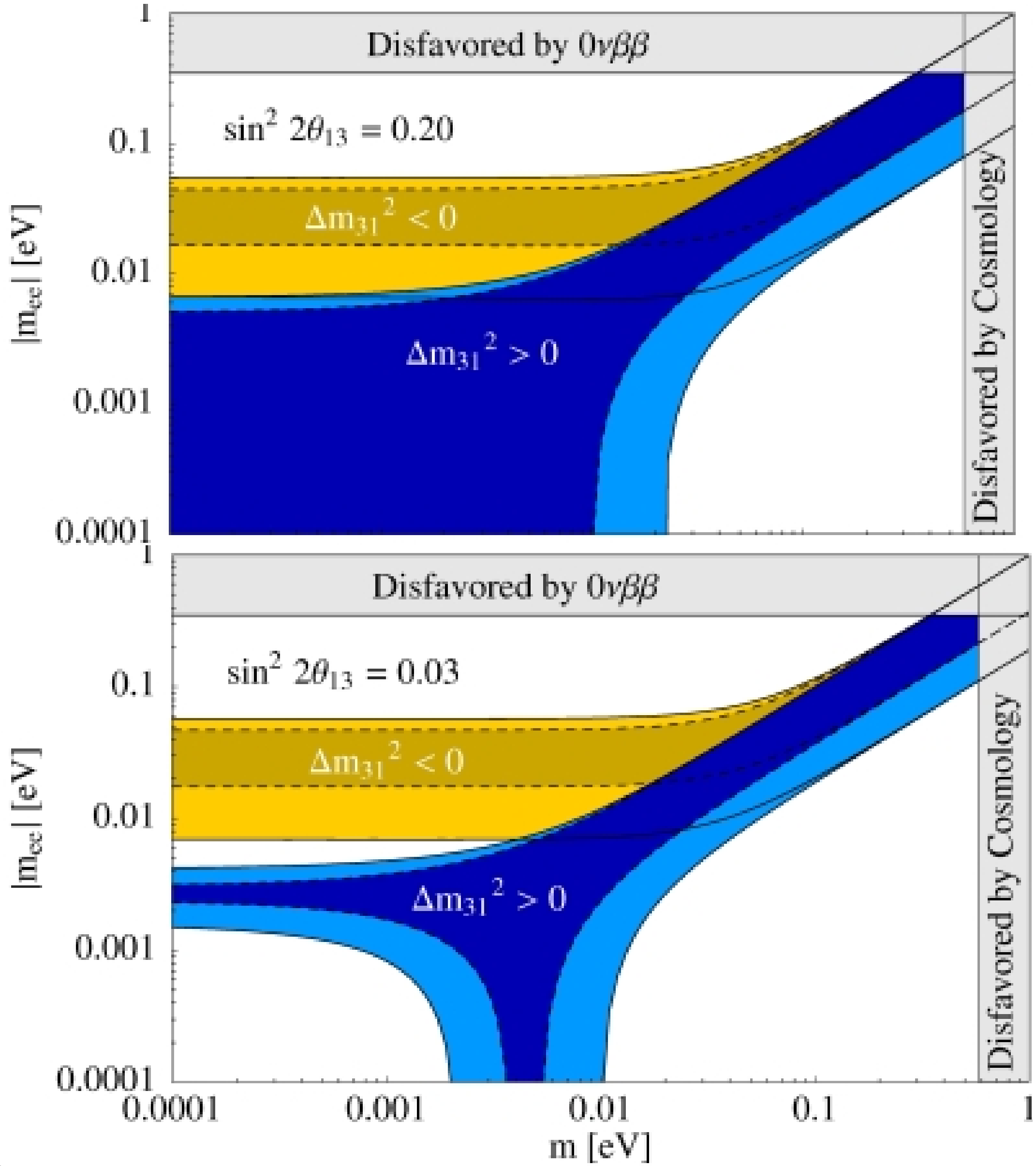
- m_{ee} versus m_1

  for $\sin^2 2\theta_{13} = 0.2$

  for $\sin^2 2\theta_{13} = 0.03$

  ➔ Double Chooz

Bilenky, Pascoli, Petcov
Klapdor, Päs, Smirnov
…
ML,Merle, Rodejohann



precise neutrino parameters

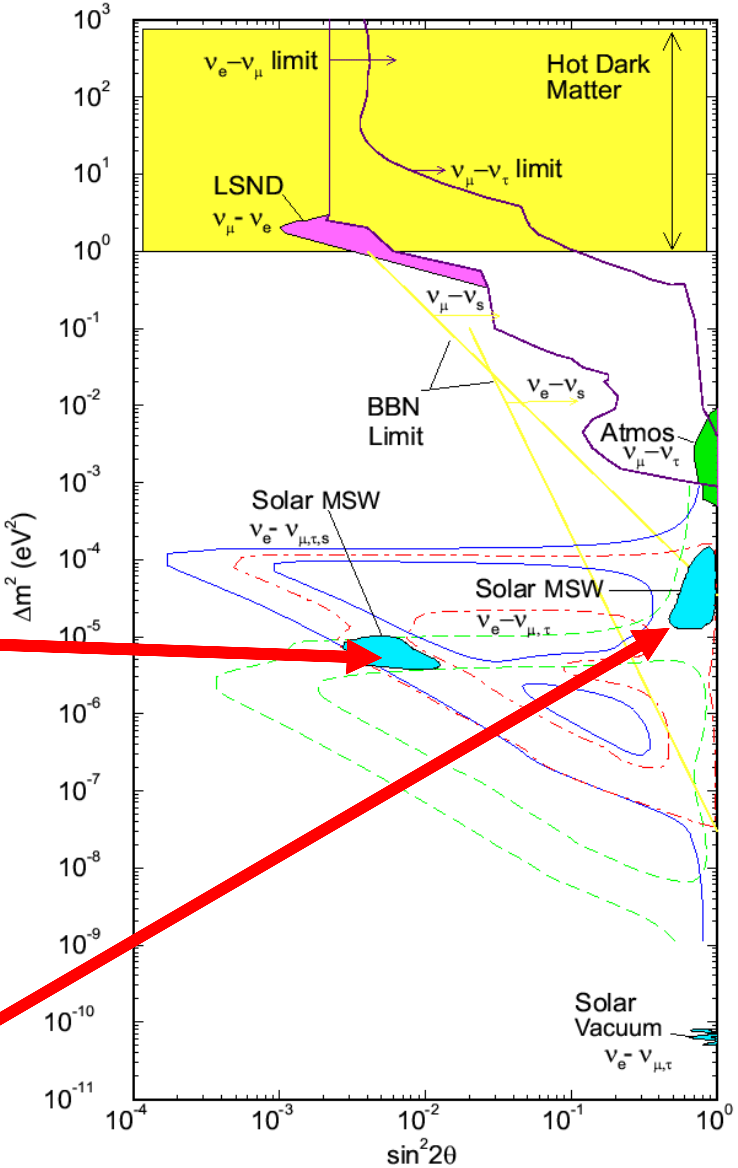
why is this interesting?

- ➔ **unique flavour information**
- ➔ **very precise: no hadronic uncertainties**
- ➔ **different from quarks ⇔ see-saw**
- ➔ **tests models / ideas about flavour**

History: Elimination of SMA

Was favoured by most theorists ⇔ GUTs

preferred by nature



The Value of Precision for θ_{13}

- models for masses & mixings
- input: Known masses & mixings
  ➔ distribution of θ_{13} „predictions“

- θ_{13} often close to experimental bounds
  ➔ motivates new experiments
  ➔ θ_{13} controls 3-flavour effects like leptonic CP-violation

for example: $\sin^2 2\theta_{13} < 0.01$ ➔

physics question: why is θ_{13} so small ?

→ numerical coincidence

→ symmetry

↔ precision!

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
~~*SO(10)*~~		
Goh, Mohapatra, Ng [40]	0.18	0.13
~~*Orbifold SO(10)*~~		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
~~Blazek, Raby, Tobe [43]~~	~~0.05~~	~~0.01~~
Kitano, Mimura [44]	0.22	0.18
~~Albright, Barr [45]~~	~~0.014~~	~~$7.8 \cdot 10^{-4}$~~
~~Maekawa [46]~~	~~0.22~~	~~0.18~~
~~Ross, Velasco-Sevilla [47]~~	~~0.07~~	~~0.02~~
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
~~*SO(10) + texture*~~		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
~~Grimus, Lavoura [52, 53]~~	~~0~~	~~0~~
~~Grimus, Lavoura [52]~~	~~0.3~~	~~0.3~~
~~Babu, Ma, Valle [54]~~	~~0.14~~	~~0.08~~
~~Kuchimanchi, Mohapatra [55]~~	~~0.08 .. 0.4~~	~~0.03 .. 0.5~~
~~Ohlsson, Seidl [56]~~	~~0.07 .. 0.14~~	~~0.02 .. 0.08~~
King, Ross [57]	0.2	0.15
~~*Textures*~~		
~~Honda, Kaneko, Tanimoto [58]~~	~~0.08 .. 0.20~~	~~0.03 .. 0.15~~
Lebed, Martin [59]	0.1	0.04
~~Bando, Kaneko, Obara, Tanimoto [60]~~	~~0.01 .. 0.05~~	~~$4 \cdot 10^{-4}$ .. 0.01~~
Ibarra, Ross [61]	0.2	0.15
3×2 *see-saw*		
~~Appelquist, Piai, Shrock [62, 63]~~	~~0.05~~	~~0.01~~
~~Frampton, Glashow, Yanagida [64]~~	~~0.1~~	~~0.04~~
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
~~*Anarchy*~~		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
~~*Renormalization group enhancement*~~		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Further Implications of Precision

Precision allows to identify / exclude:

- special angles: $\theta_{13}= 0°$, $\theta_{23}= 45°$, ... ⇔ discrete f. symmetries?
- special relations: $\theta_{12}+ \theta_C = 45°$? ⇔ quark-lepton relation?
- quantum corrections ⇔ renormalization group evolution

Provides also measurements or tests of:

- MSW effect (coherent forward scattering and matter profiles)
- cross sections
- 3 neutrino unitarity ⇔ sterile neutrinos with small mixings
- neutrino decay (admixture…)
- decoherence
- NSI
- MVN, ...

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

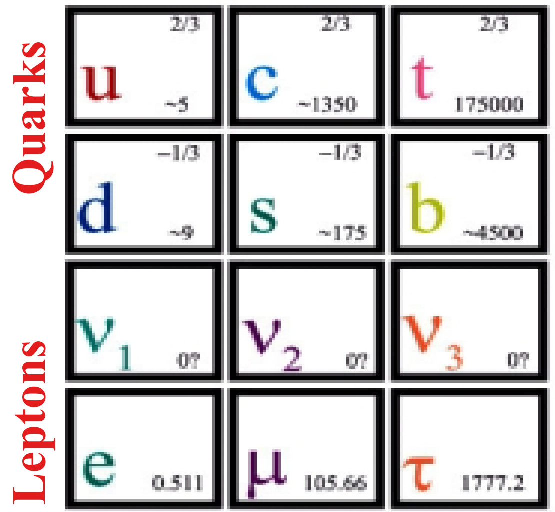
<u>**Requirements:**</u>

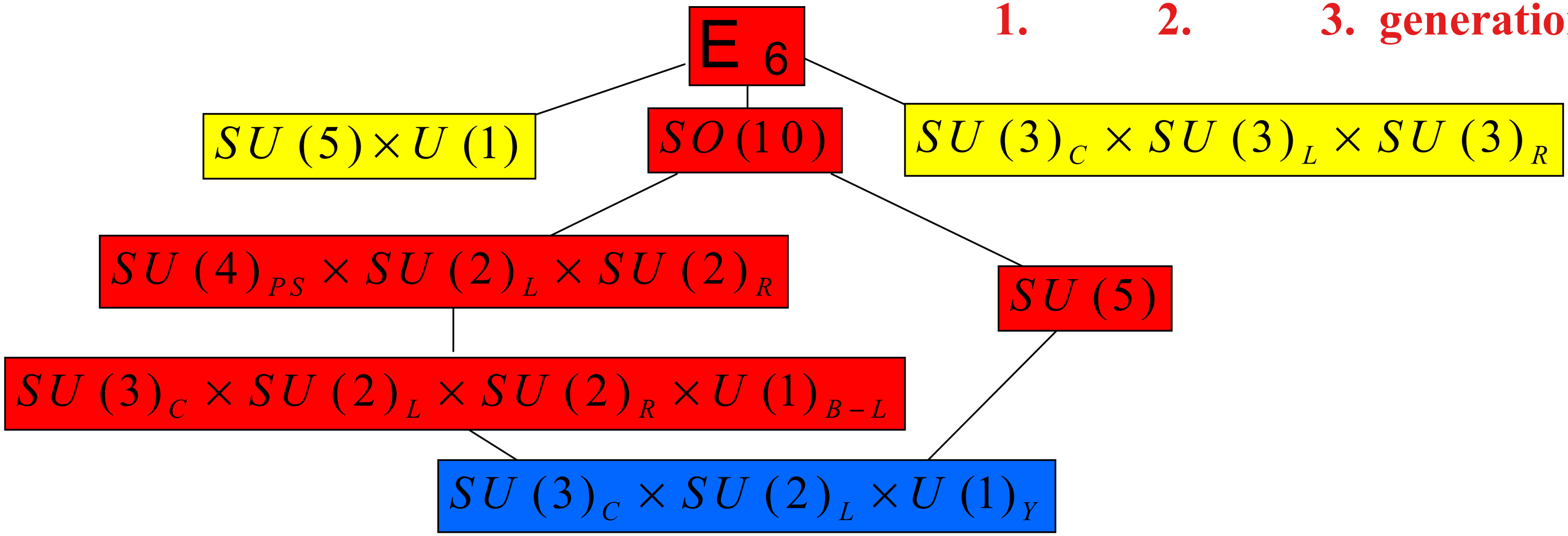
gauge unification

particle multiplets ⇔ ν_R

proton decay

…





GUT Expectations and Requirements

Quarks and leptons sit in the same multiplets

➔ one set of Yukawa coupling for given GUT multiplet

➔ ~ tension: small quark mixings ⇔ large leptonic mixings

➔ this was in fact the reason for the `prediction' of small mixing angles (SMA) – ruled out by data

Mechanisms to post-dict large mixings:

➔ sequential dominance

➔ type II see-saw

➔ Dirac screening

➔ …

Single right-handed Dominance

$$m_D = \begin{pmatrix} . & . & . \\ . & a & b \\ . & c & d \end{pmatrix} \qquad M_R = \begin{pmatrix} . & . & . \\ . & x & 0 \\ . & 0 & y \end{pmatrix}$$

$$\Rightarrow \quad m_\nu = -m_D \cdot M_R^{-1} \cdot m_D^T = \begin{pmatrix} . & . & . \\ . & \frac{a^2}{x} + \frac{b^2}{y} & \frac{ac}{x} + \frac{bd}{y} \\ . & \frac{ac}{x} + \frac{bd}{y} & \frac{c^2}{x} + \frac{d^2}{y} \end{pmatrix}$$

If one right-handed neutrino dominates, e.g. y >> x

- ➔ small sub-determinant ~ $m_2 . m_3$
- ➔ $m_2 << m_3$ i.e. a natural hierrachy
- ➔ tan $\theta_{23} \simeq a/c$ i.e. naturally large mixing

Sequential Dominance

$$m_D = \begin{pmatrix} a & b & c \\ d & e & f \\ g & e & h \end{pmatrix} \qquad M_R = \begin{pmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{pmatrix}$$

$$m_\nu = -m_D \cdot M_R^{-1} \cdot m_D^T = \begin{pmatrix} . & . & . \\ . & . & . \\ . & . & . \end{pmatrix}$$

<u>sequenatial dominance: z >> y >> x</u>

- ➔ **small determinant ~ $m_1 \cdot m_2 \cdot m_3$**
- ➔ **$m_1 << m_2 << m_3$ natural**
- ➔ **naturally large mixings**

King, …

Large Mixings and See-Saw Type II

see-saw type II $m_\nu = M_L - m_D M_R^{-1} m_D^T$

m_D and M_R may posess small mixings and hierarchy

However: M_L can be numerically more important

Example: Break GUT → $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ → M_L from LR

→ large mixings natural for almost degenerate case $m_1 \sim m_2 \sim m_3$

→ type I see-saw would only be a correction

type I – type II interference

→ $M_L \simeq m_D M_R^{-1} m_D^T$

→ many possibilities

Dirac Screening

Question: **Do neutrino masses always depend on the Dirac Yukawa couplings? ➔ no**

ML, Schmidt Smirnov

Assume: ν_L, ν^C_R, S ➔

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu \langle\phi\rangle & 0 \\ Y_\nu^T \langle\phi\rangle & 0 & Y_N^T \langle\sigma\rangle \\ 0 & Y_N \langle\sigma\rangle & M_S \end{pmatrix}$$

➔ double seesaw

$$m_\nu^0 = \left[\frac{\langle\phi\rangle}{\langle\sigma\rangle}\right]^2 Y_\nu \left(Y_N\right)^{-1} M_S \left(Y_N^T\right)^{-1} Y_\nu^T$$

fit fermions into GUT representations
➔ relation between Yukawa couplings, e.g. E6

$$Y_\nu = c \cdot Y_N$$

Consequences of Dirac Screening

➔ complete screening of Dirac structure

$$m_\nu = c^2 \left[\frac{\langle\phi\rangle}{\langle\sigma\rangle}\right]^2 M_S$$

Outcome:

- Neutrino masses can emerge completely from Planck scale physics ←→ generically different from quarks
- Dirac Yukawa structure (small mixings) screened
- Hierarchical neutrino spectrum not required in see-saw
- Quark-lepton complimentarity possible … …with or without degenerate neutrino masses

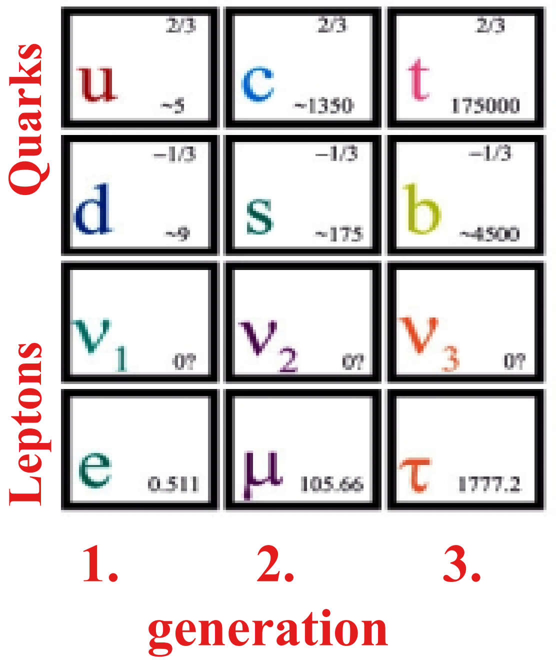
- Double see-saw predics for M_R to be below M_{GUT} first see-saw ➔ $M_R \sim \langle s\rangle/M_S \simeq 10^{-3}\, M_{GUT} \simeq 10^{13}$ GeV

Flavour Unification

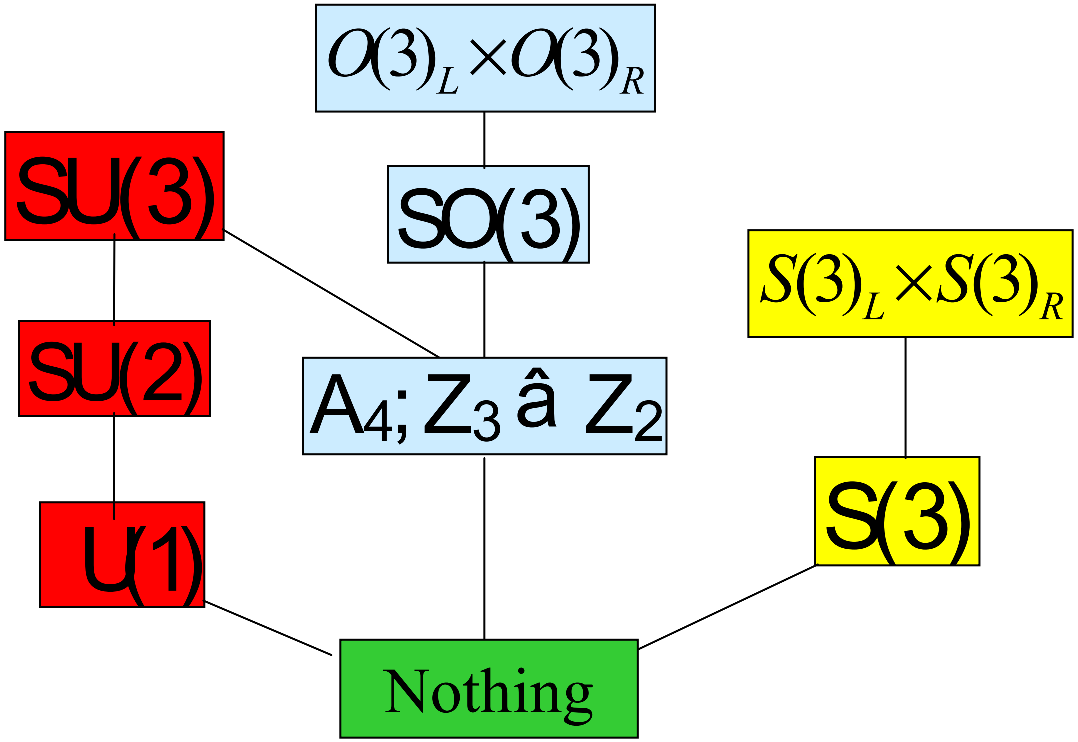
- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

➔ flavour symmetries

➔ not texture zeros



Examples:



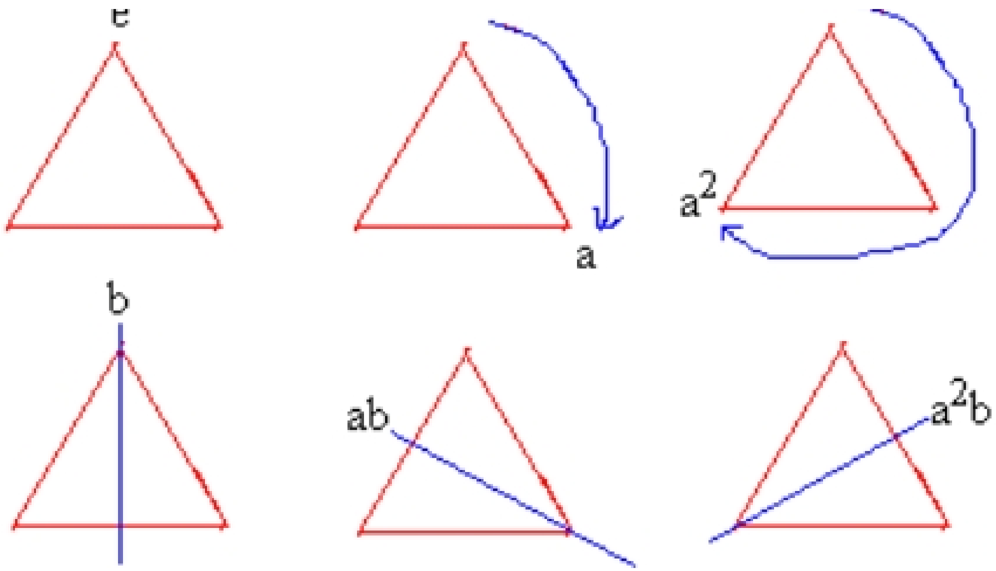
Discrete Flavour Symmetries

Discrete Flavour Symmetries ←→ flavour structure

Example: Dihedral groups D_n

$$< A, B | A^n = 1, B^2 = 1, (AB)^n = 1 >$$

geometric origin of D_3



Specific Example: D_5 Hagedorn, ML, Plentinger

$$< A, B| \, A^n = 1, \, B^2 = 1, \, (AB)^n = 1 > \quad .$$

complex generators

$$2_1: \quad A = \begin{pmatrix} e^{i\frac{2\pi}{5}} & 0 \\ 0 & e^{-i\frac{2\pi}{5}} \end{pmatrix} \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$2_2: \quad A = \begin{pmatrix} e^{i\frac{4\pi}{5}} & 0 \\ 0 & e^{-i\frac{4\pi}{5}} \end{pmatrix} \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

character table

classes	$\mathcal{C}_1$	$\mathcal{C}_2$	$\mathcal{C}_3$	$\mathcal{C}_4$
G	$\mathbb{1}$	B	A	A^2
$h_{\mathcal{C}_i}$	1	5	2	2
$n_{\mathcal{C}_i}$	1	2	5	5
1_1	1	1	1	1
1_2	1	-1	1	1
2_1	2	0	$\frac{1}{2}(-1+\sqrt{5})$	$\frac{1}{2}(-1-\sqrt{5})$
2_2	2	0	$\frac{1}{2}(-1-\sqrt{5})$	$\frac{1}{2}(-1+\sqrt{5})$

Kronecker products

$$\begin{aligned}
1_1 \times 1_1 &= 1_1 \\
1_2 \times 1_1 &= 1_2 \\
2_1 \times 1_1 &= 2_1 \\
2_2 \times 1_1 &= 2_2 \\
1_2 \times 1_2 &= 1_1 \\
2_1 \times 1_2 &= 2_1 \\
2_2 \times 1_2 &= 2_2 \\
2_1 \times 2_1 &= 1_1 + 1_2 + 2_2 \\
2_2 \times 2_1 &= 2_1 + 2_2 \\
2_2 \times 2_2 &= 1_1 + 1_2 + 2_1
\end{aligned}$$

Clebsch-Gordan Coefficients …

D_5 Allowed Mass Terms

Task: **search for mass terms which are for suitable Higges singlets under D_5**

Notation:
i_{th} generation fermions

$$L = \{L_1, L_2, L_3\}$$

Dirac mass terms:

$$\lambda_{ij} L_i^T (i\sigma_2) \phi L_j^c$$

Majorana mass terms:

$$\lambda_{ij} L_i^T \Xi \phi L_j$$

with

$$\Xi = \begin{pmatrix} \xi^0 & -\frac{\xi^+}{\sqrt{2}} \\ -\frac{\xi^+}{\sqrt{2}} & \xi^{++} \end{pmatrix}$$

Resulting D_5 Symmetry Texture

L	L^C	Mass Matrix
$(1_2, 1_1, 1_1)$	$(2_1, 1_1)$	$\begin{pmatrix} \kappa_1 \psi_2^1 & -\kappa_1 \psi_1^1 & \kappa_4 \phi^2 \\ \kappa_2 \psi_2^1 & \kappa_2 \psi_1^1 & \kappa_5 \phi^1 \\ \kappa_3 \psi_2^1 & \kappa_3 \psi_1^1 & \kappa_6 \phi^1 \end{pmatrix}$

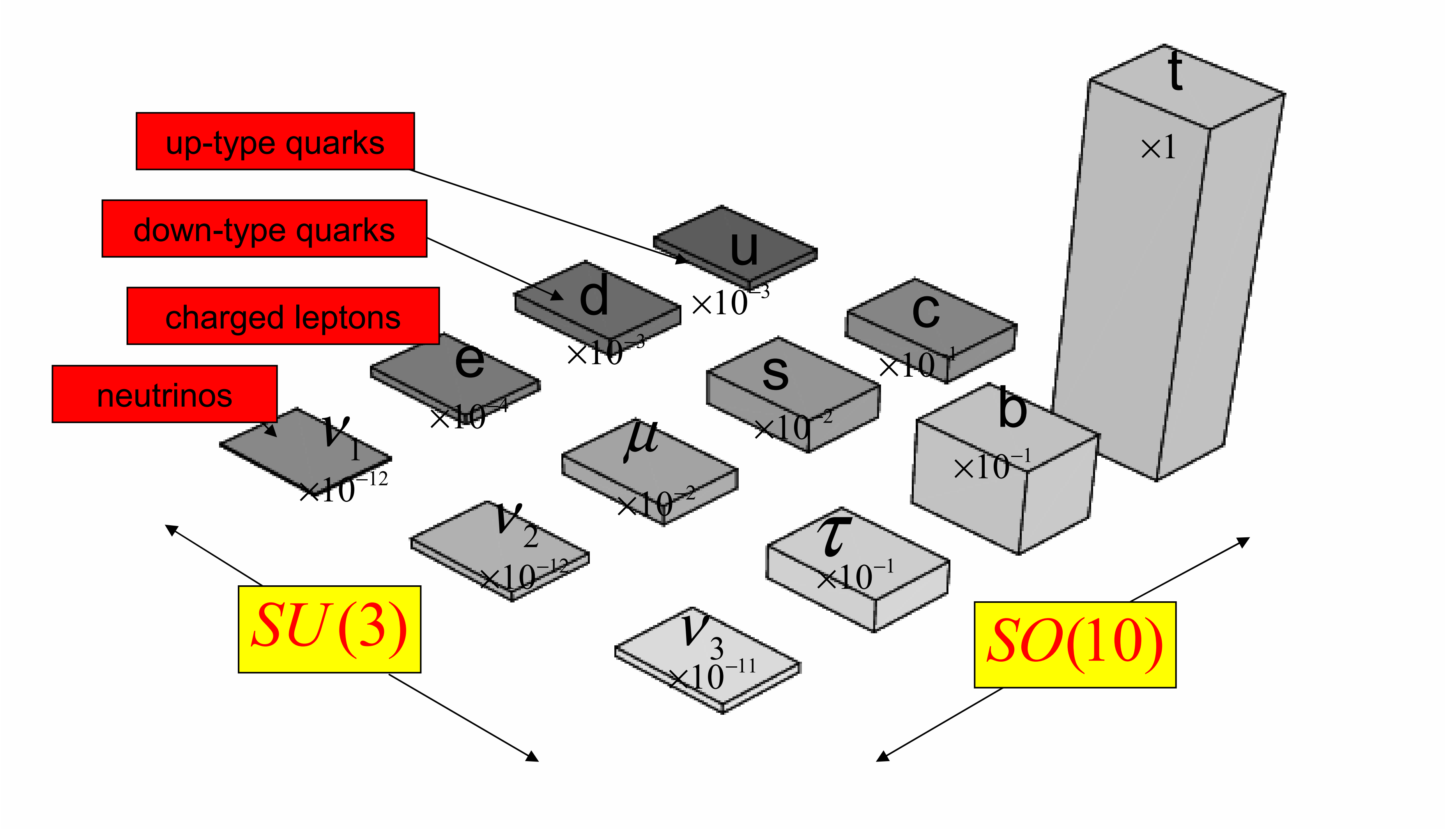
D5 singlet mass terms require the following quantum numbers for the scalars:

$$\begin{aligned} \phi_1 &\sim \mathbf{1}_1 \ , \\ \phi_2 &\sim \mathbf{1}_2 \text{ and} \\ \psi_1 &\sim \mathbf{2}_1 \ . \end{aligned}$$

➔ **Check if phenomenological successful predictions arise**

GUT *and* Flavour Unification

Example: SO(10) x SU(3)



GUT ⊗ Flavour Unification

➔ GUT group ⊗ continuous, gauged flavour group

- for example SO(10) ⊗ $SU(3)_{flavour}$
- Generations are 3_F
- SSB of $SU(3)_{flavour}$ between Λ_{GUT} and Λ_{Planck}

➔ all flavour Goldstone Bosons eaten

➔ discrete (ungauged) sub-group survives ⇔ SSB potential

➔ e.g. Z2, S3, D5, A4, ...

➔ structures in flavour space

GUT $\otimes$ Flavour Challenges

- **GUT $\otimes$ flavour is rather restricted**
  - small quark mixings
  - large leptonic mixings
  - ➔ from unified GUT $\otimes$ flavour representations
  - ➔ strong links between Yukawa couplings
- **Difficulty grows with**
  - size of flavour symmetry
  - size of the GUT group
  - ➔ so far only a few viable models
  - ➔ limited possibilities

➔ Distinguish models by future precision

Conclusion: The Interplay of Topics

SM extensions: SUSY, …
flavour symmetries
unification
fundamental interactions
CPT & Lorentz inv.
extra dimensions
…

leptogenesis
supernovae
BBN
structure formation,
UHE neutrinos
dark matter & energy
...

precision neutrino properties:
masses, mixings, CP-phases, ...

mass spectrum, mixings, CP-phases, lepton flavour violation, 0ν2β–decay, ...

➔ν-parameters extremely valuable

➔ long term: most precise flavour info