Neutrinos as Probe of new Physics

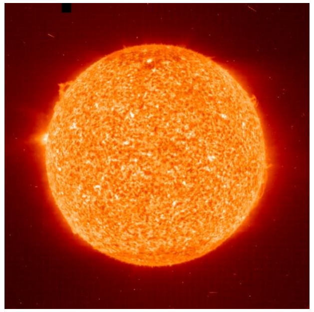
M. Lindner

Max-Planck-Institut
für Kernphysik, Heidelberg

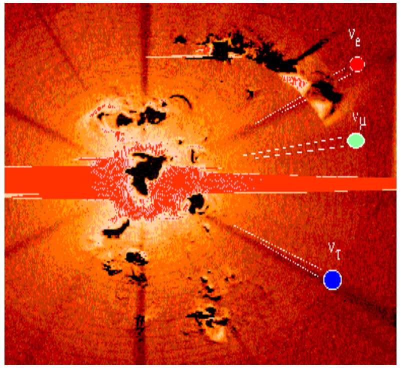
IDS Plenary Meeting

Fermilab, June 9-12, 2008

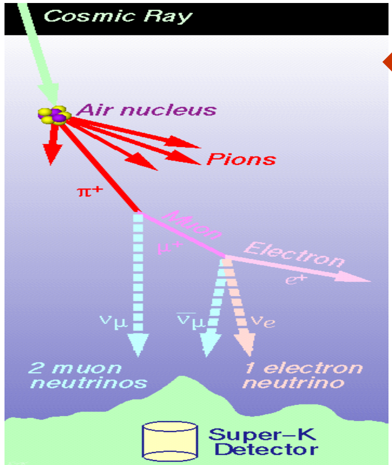
Neutrino Sources



← Sun

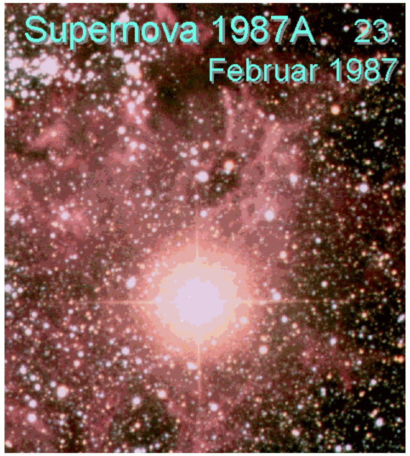


← Cosmology



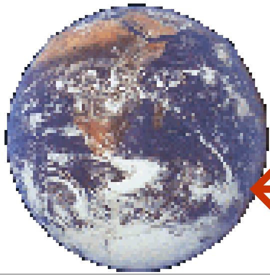
← Atmosphere

Astronomy: →
Supernovae
GRBs
UHE ν's



Reactors →

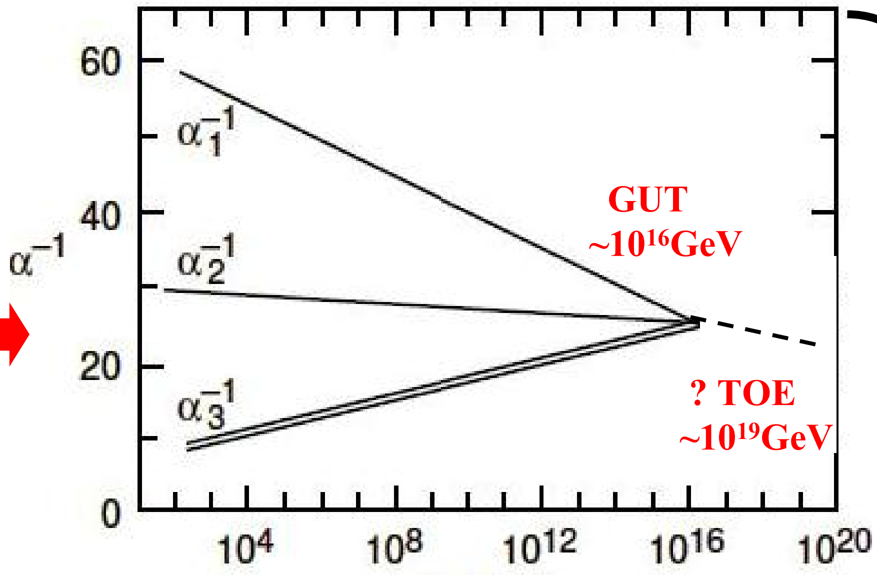
Accelerators →



← Earth

Different Routes Beyond the SM

gauge bosons



experimental facts:

Dark Matter

Dark Energy

neutrino masses & mixings

baryon asymetry ←→ $m_\nu > 0$

➔ indirect tests of VHE physics

Higgs

gauge hierarchy problem:

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

SUSY ~TeV

astrophysics & cosmology

quarks leptons

flavour problem: 3 generations

many parameters (m_i, mixings)

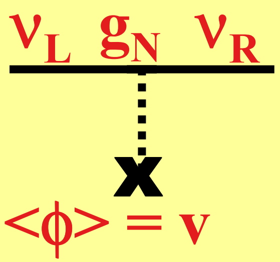
unification into GUTs

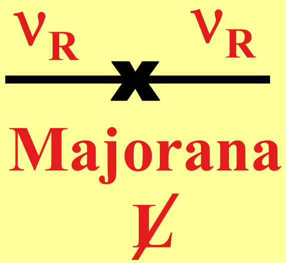
$m_\nu = (m^D)^T M_R^{-1} m_D$

$\sim\Lambda_{GUT}$ +seesaw

Adding Neutrino Mass Terms

1) Simplest possibility: add 3 right handed neutrino fields





➔ $$\left(\bar{\nu}_L \quad \bar{\nu}_R^{\mathbf{c}}\right)\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L^{\mathbf{c}} \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons ➔ Dirac mass terms (including NMS mixing)

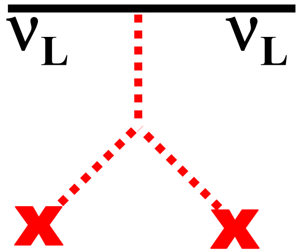
New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

6x6 block mass matrix block diagonalization M_R heavy ➔ 3 light ν's

NEW ingredients, 9 parameters ➔ SM+

Other Neutrino Mass Operators

2) new Higgs triplets Δ_L:

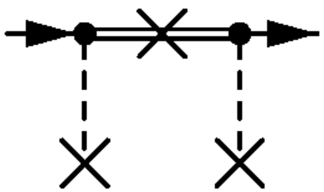


➔ left-handed Majorana mass term: ➔ $M_L \overline{L} L^c$

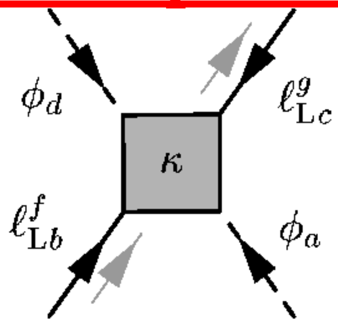
3) Both ν_R and new Higgs triplets Δ_L:

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

4) Higher dimensional operators: d=5, …



$\Rightarrow$



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

➔ $M_L \overline{L} L^c$

5-N) …

Other effective Operators Beyond the SM

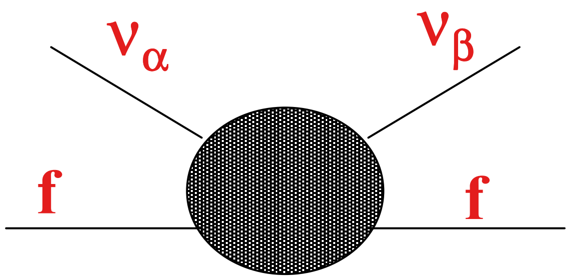
➔ **effects beyond 3 flavours**

➔ **Non Standard Interactions = NSIs ➔ effective 4f opersators**

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

- **integrating out heavy physics (c.f. G_F ⇔ M_W)**

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

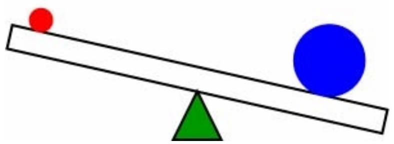


Suggestive See-Saw Features

QFT: natural value of mass operators ⇔ scale of symmetry

$m_D \sim$ electro-weak scale
$M_R \sim$ L violation scale ⇐?⇒ embedding (GUTs, …)

See-saw mechanism (type I)



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

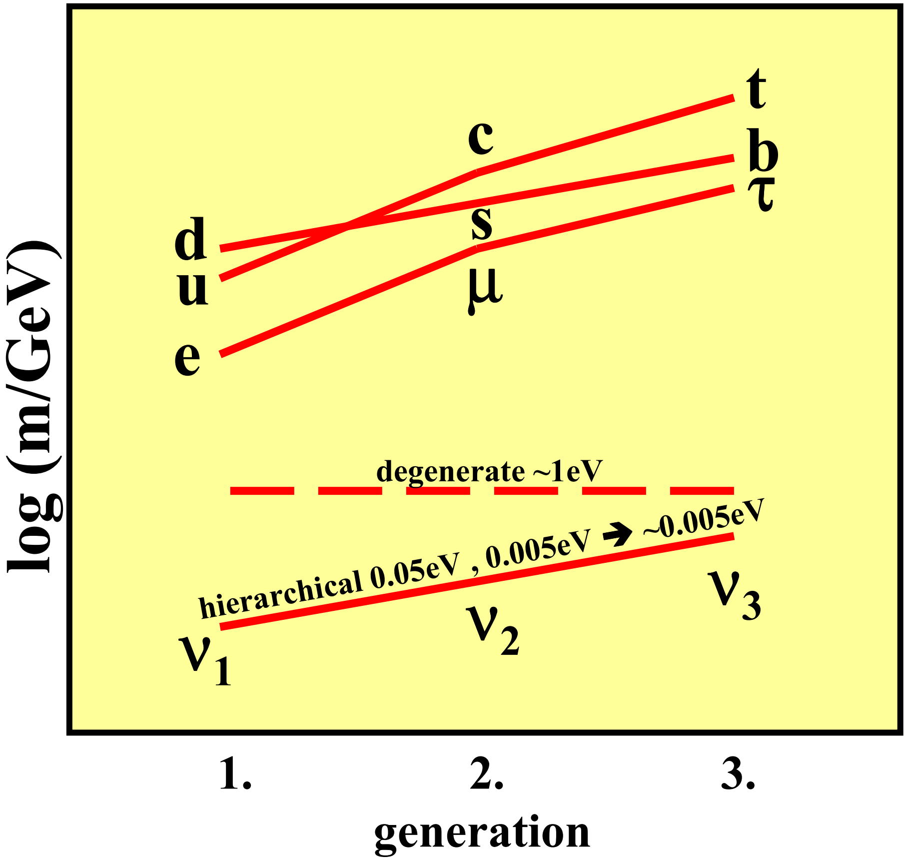
$m_h = M_R$

Numerical hints:

For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons ⇒ $M_R \sim 10^{11} - 10^{16}$GeV
⇒ ν's are Majorana particles , m_ν probes ~ GUT scale physics!
⇒ smallness of m_ν ⇔ high scale of $\not{L}$, 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 ➔ H ≥ 20...200

Neutrinos: $m_\nu \sim H^n$ ➔ H ≤ ~10

See-saw:

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

	m_ν	m_D^T	M_R^{-1}	m_D
H	~10	≥20	?	≥20

- **correlated hierarchy in M_R ? ➔ theoretically connected!**
- **mixing patterns: not generically large, why almost maximal, θ_{13} small?**

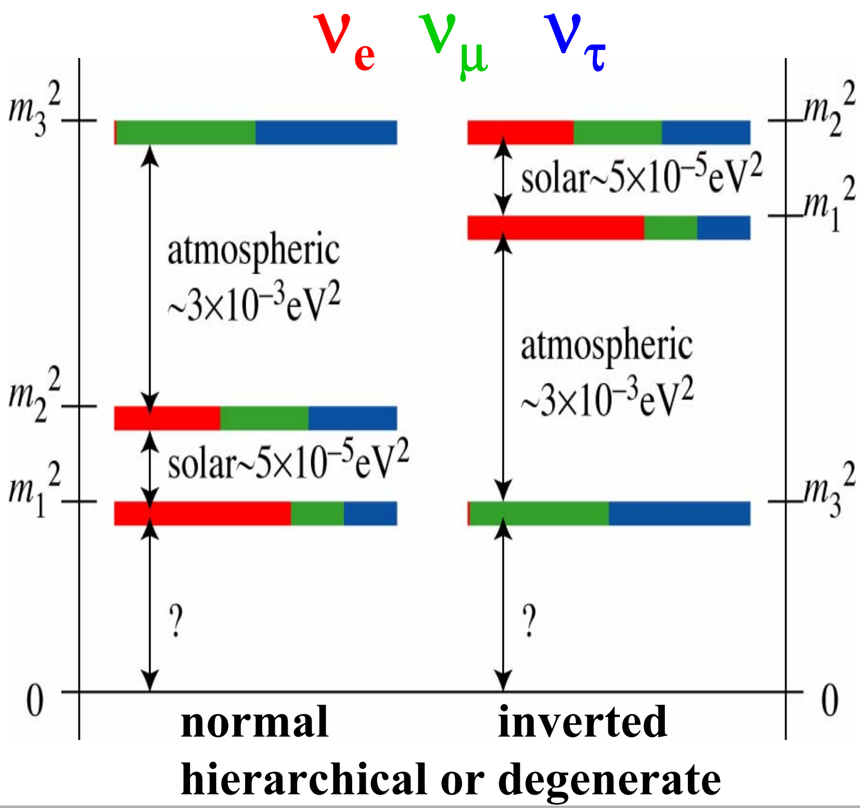
Parameters for 3 Light Neutrinos

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

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

questions:

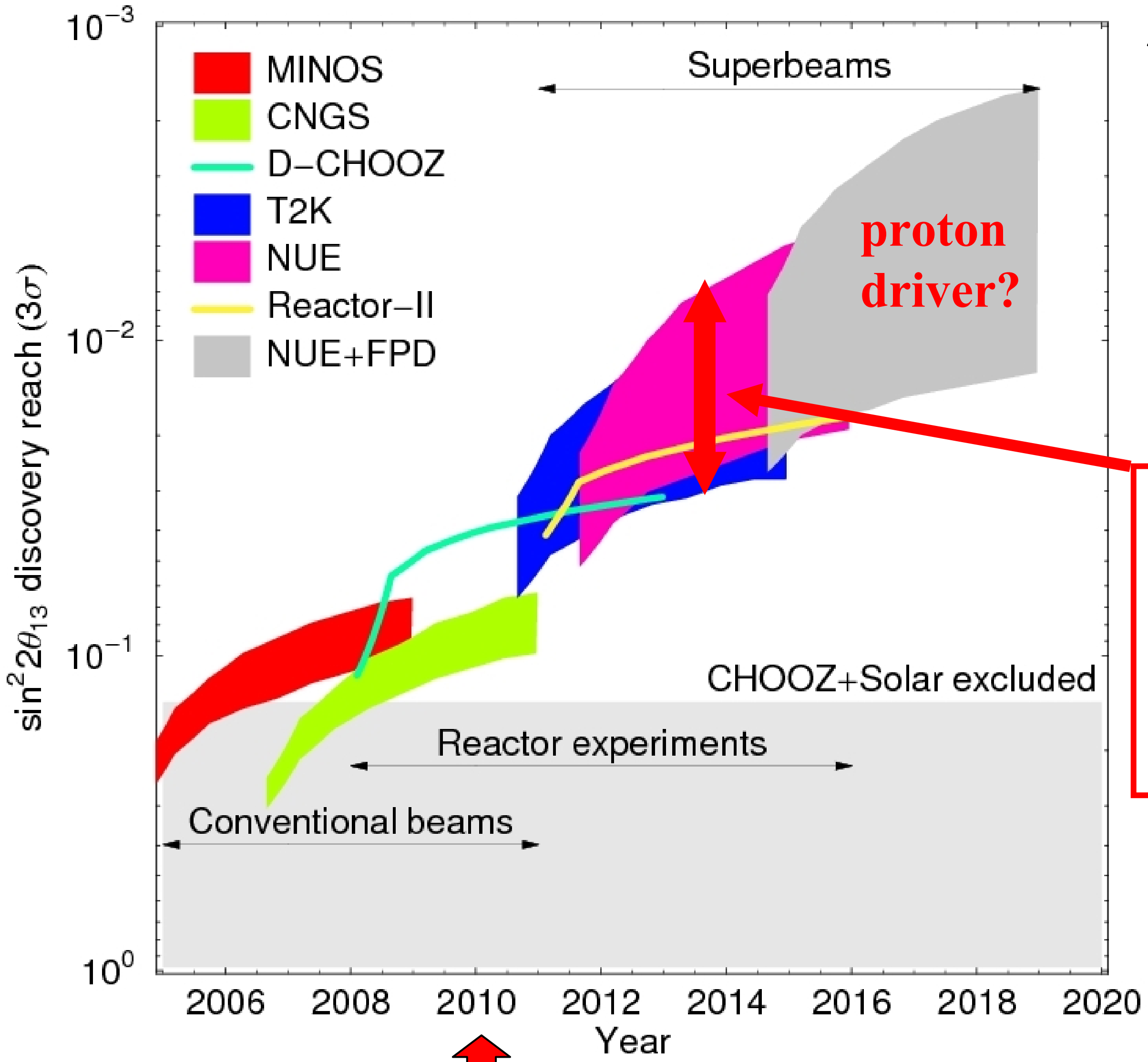
- ➔ Dirac / Majorana
- ➔ mass scale: m_1
- ➔ mass ordering: sgn(Δm^2_{31})
- ➔ how small is θ_{13}, θ_{23} maximal?
- ➔ leptonic CP violation
- ➔ 3 flavour unitarity?
- ➔ why 3 generations, d=4, gauge group, …



Four Methods of Mass Determination

- kinematical
- lepton number violation
  ←→ Majorana nature
- astrophysics & cosmology
- oscillations

θ_{13} Sensitivity Versus Time



β-beams
neutrino factory

Range ←→
~ unknown CP phase

combination with reactor
←→ synergies

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
- …

➔ unique & complimentary information

➔ test ideas about the origin of flavour

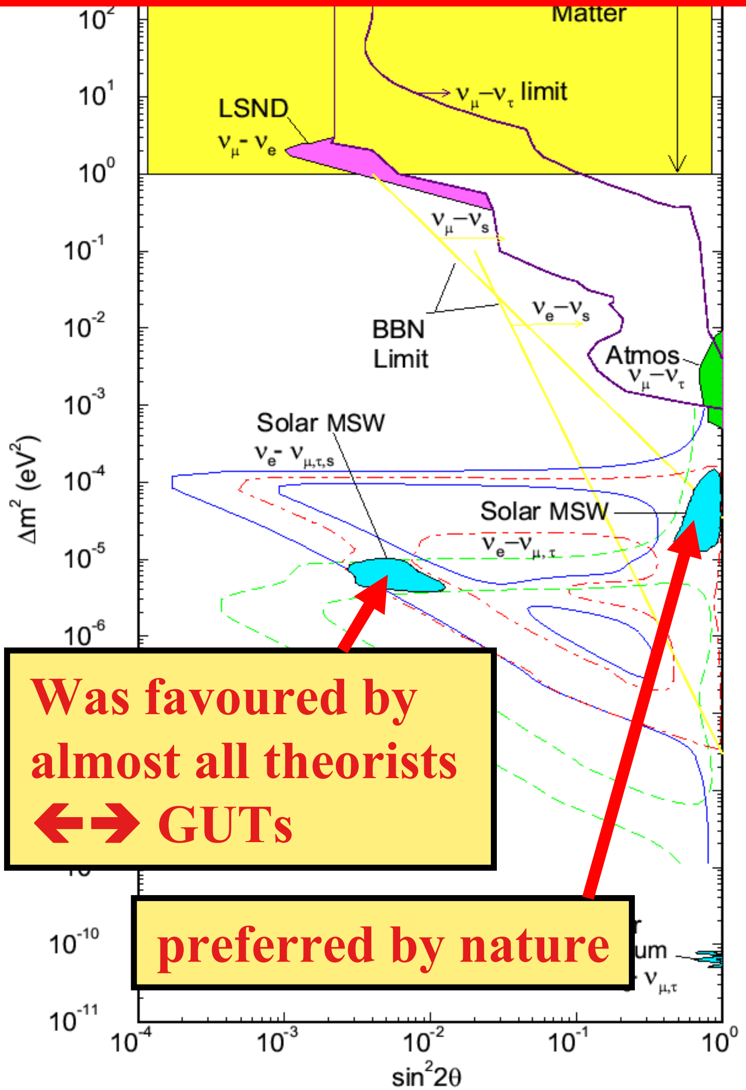
Provides also measurements / tests of:

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

➔ various synergies with LHC and LFV

Learning about Flavour

History: Elimination of SMA



Next: Smallness of θ_{13}, θ_{23} maximal

- models for masses & mixings
- input: known masses & mixings
  - ➔ distribution of θ_{13} predictions
  - ➔ θ_{13} expected close to ex. bound
  - ➔ well motivated experiments

what if θ_{13} is very tiny?
or if θ_{23} is very close to maximal?

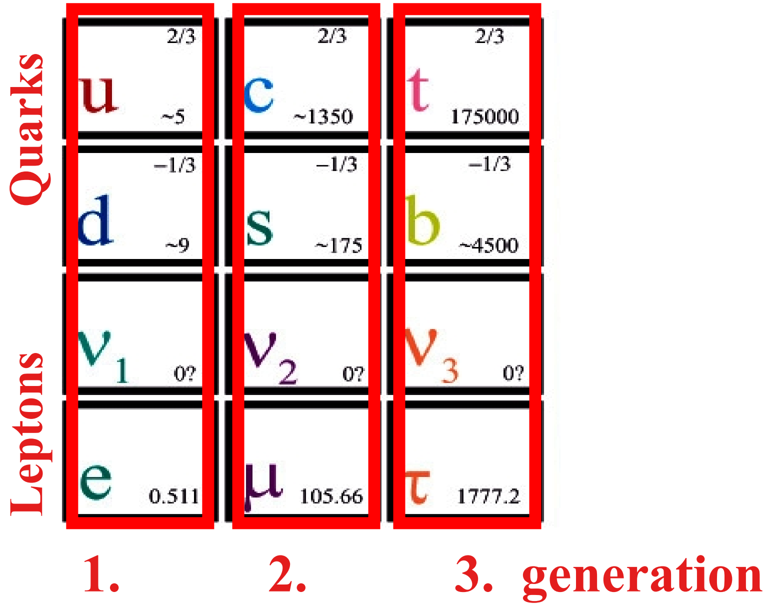
➔ numerical coincidence unlikely
➔ special reasons (symmetry, …)

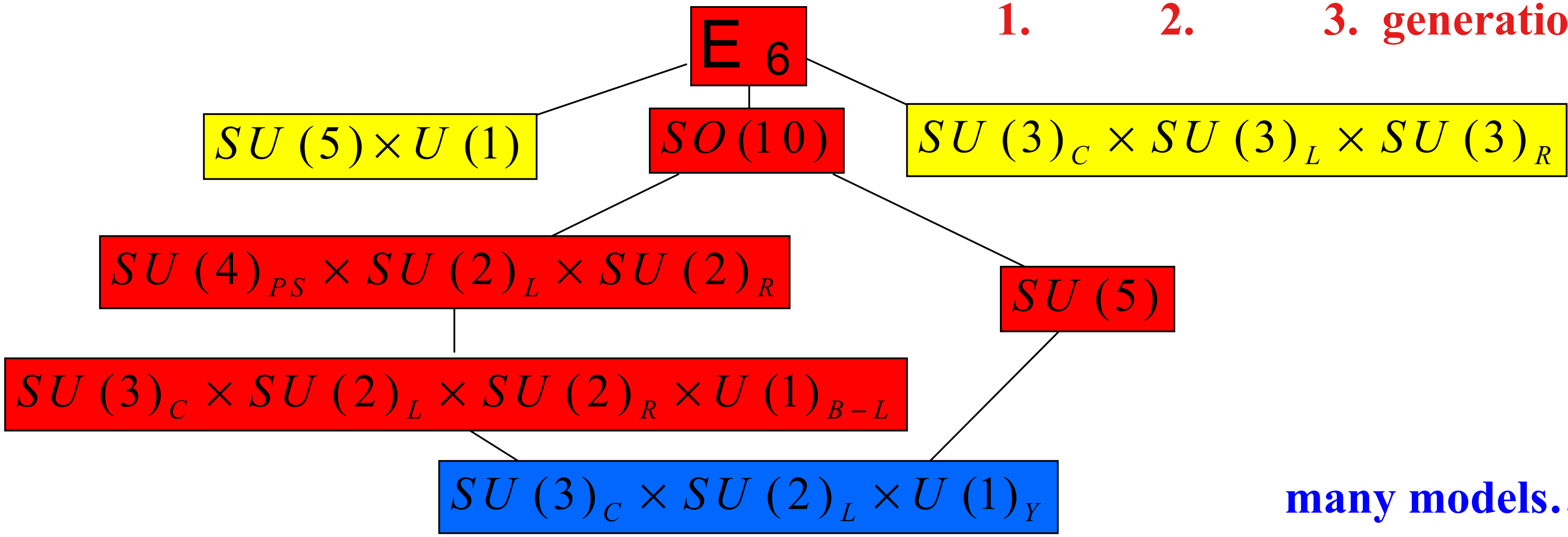
➔ answered by coming precision

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

Requirements:
gauge unification
particle multiplets ⇔ ν_R
proton decay
…





many models…

GUT Expectations and Requirements

Quarks and leptons sit in the same multiplets

➔ one set of Yukawa couplings 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
➔ …

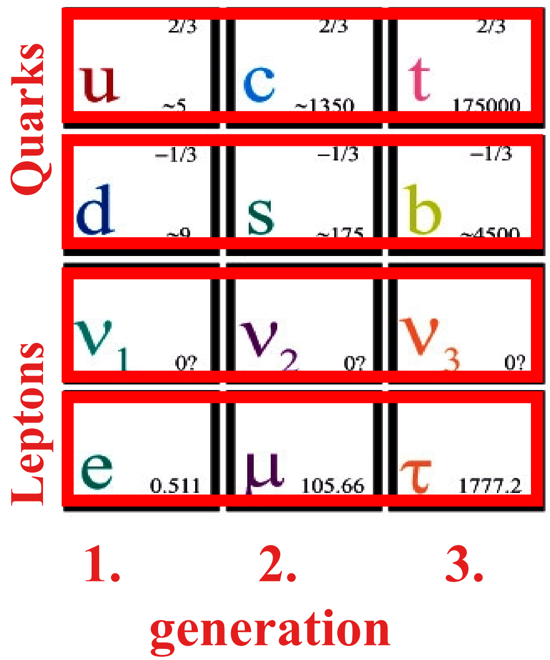
Flavour Unification

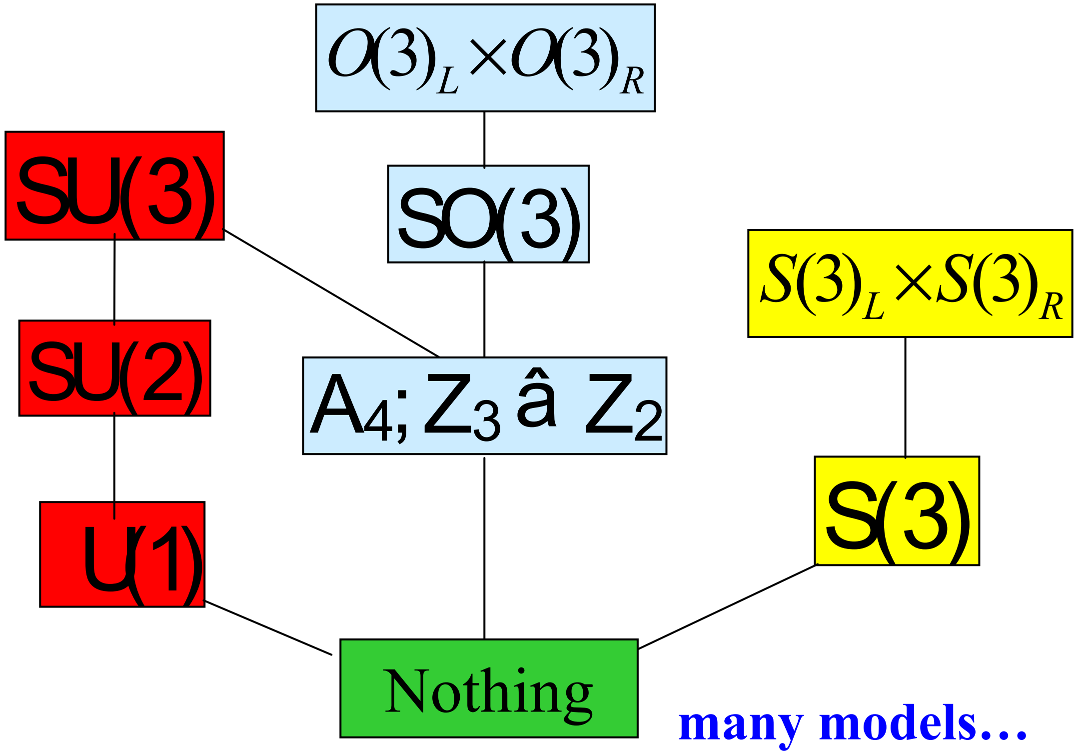
- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

➔ **symmetry** not texture zeros

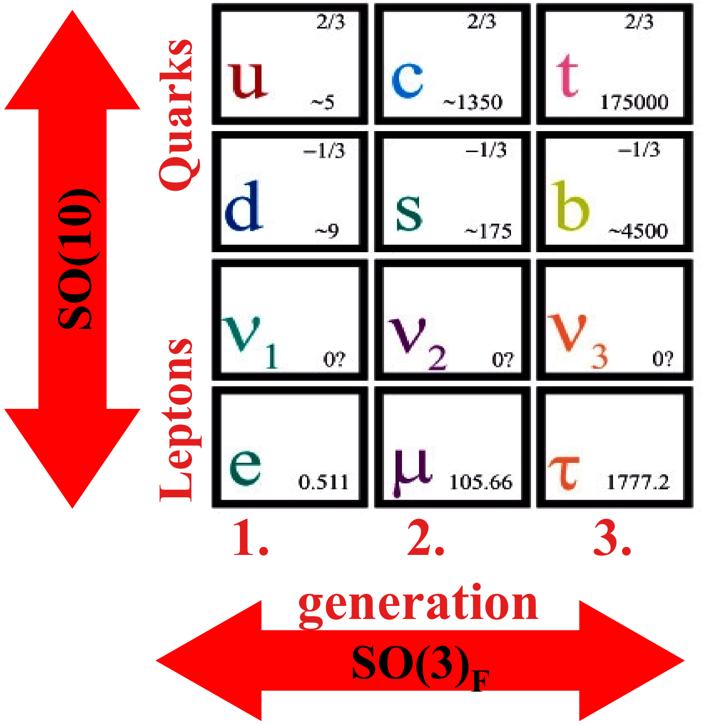
Examples:





many models…

GUT ⊗ Flavour Unification



➔ GUT group ⊗ flavour group

<u>example:</u> SO(10) ⊗ $SU(3)_F$

- SSB of $SU(3)_F$ between Λ_{GUT} and Λ_{Planck}
- all flavour Goldstone Bosons eaten
- discrete sub-groups survive ⇔ SSB
  e.g. Z2, S3, D5, A4
  ➔ structures in flavour space
  ➔ compare with data

GUT ⊗ flavour is rather restricted

⇔ small quark mixings *AND* large leptonic mixings ; quantum numbers

➔ so far only a few viable models
Cai and Yu, Hagedorn, ML and Mohapatra, Chen and Mahantappa, King, Ross

➔ rather limited number of possibilities; phenomenological success non-trivial

➔ aim: <u>distinguish models further by future precision</u>

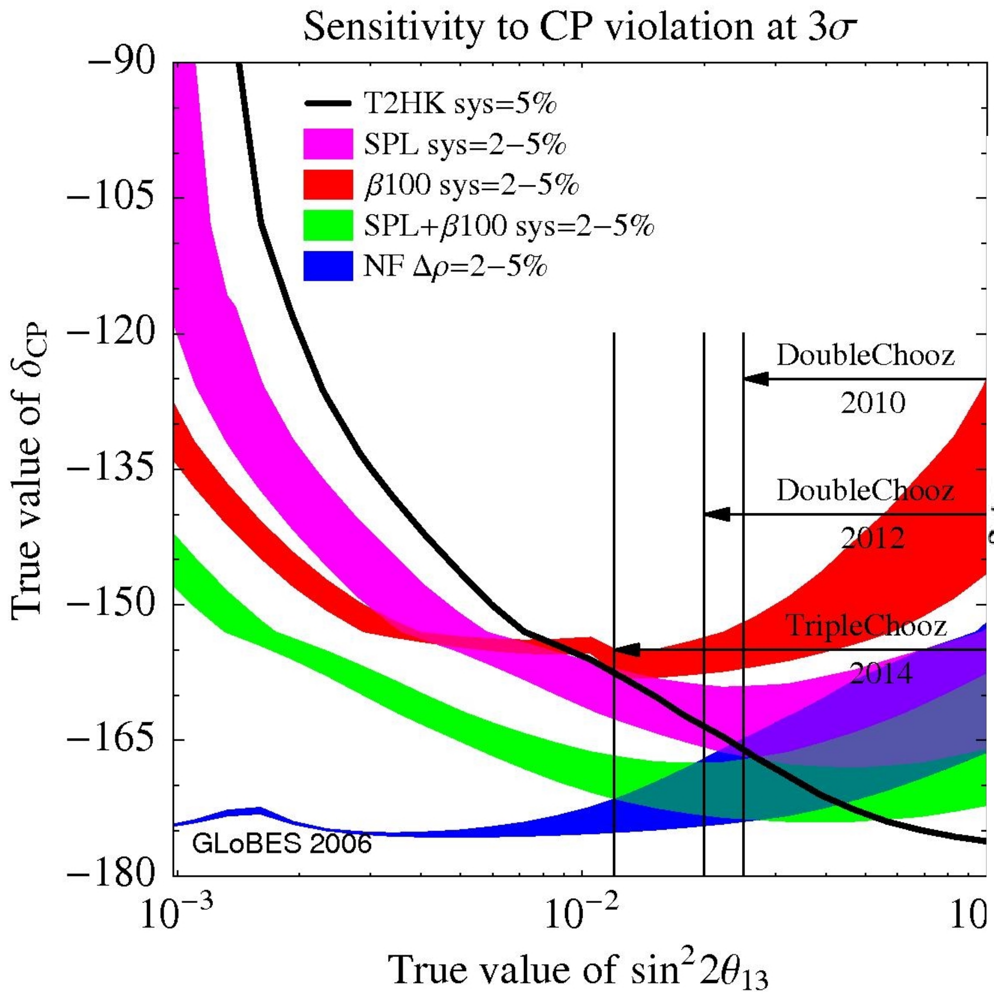
Aims & Questions

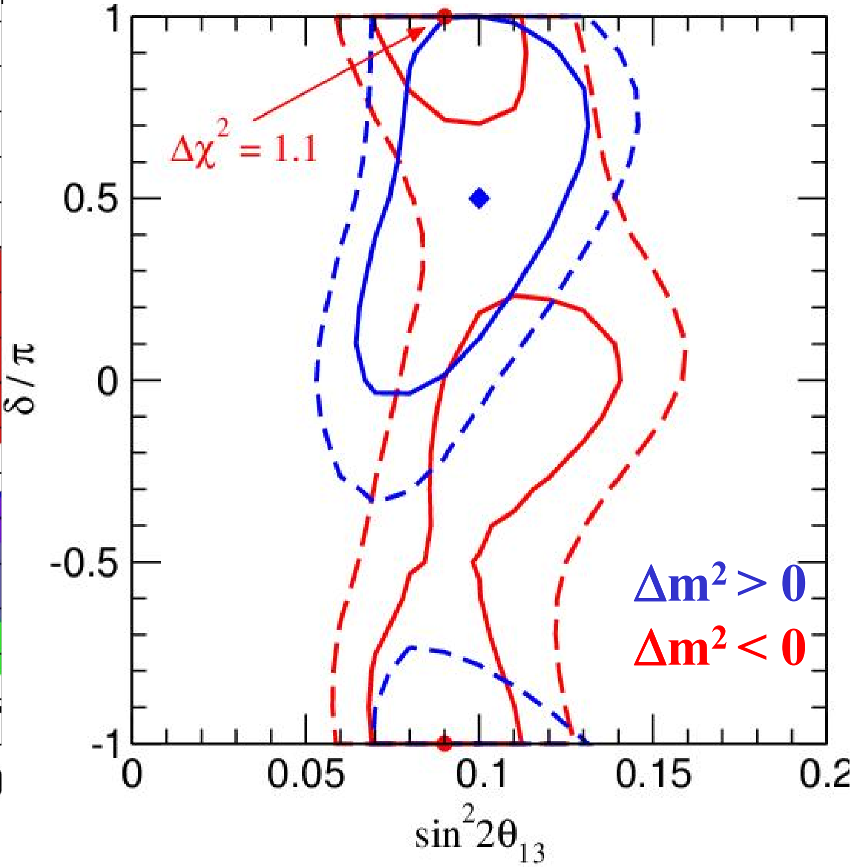
- **Precise angles, phases and masses!**
- **Potential for other physics?**
- **Surprises?**

θ_{13} and Leptonic CP Violation

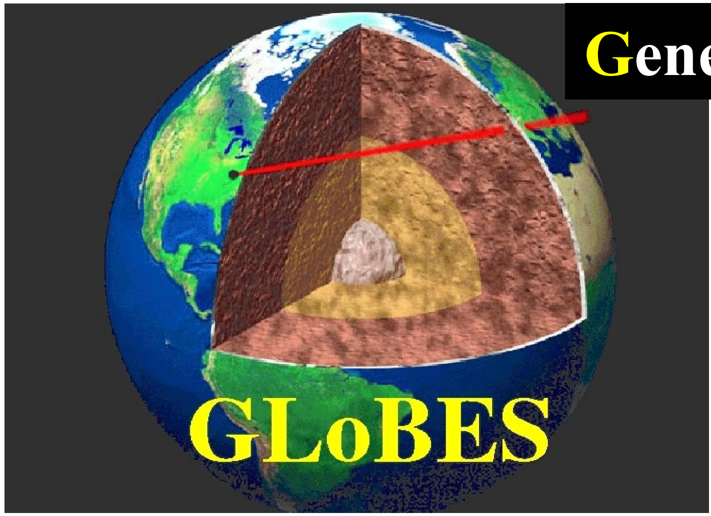
road map for : $\sin^2 2\theta_{13}$
➔ importance of Double Chooz

assume: $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2$ ➔combine:
T2K+NOνA+Reactor





Simulation Tools

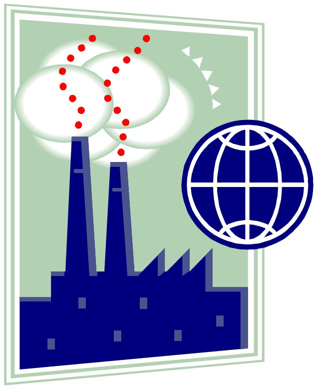


General Long Baseline Experiment Simulator

http://www.mpi-hd.mpg.de/~globes

P. Huber, J. Kopp, ML , W. Winter

very powerful tool



GLoBES & Co

Realistic simulations (event rate based; including realistic experimental aspects):

- ➔ full 3ν oscillation formalism in matter
- ➔ widely used (on-going ISS/IDS study)
- ➔ further improvements
- ➔ test & compare new ideas
- ➔ library of most existing experiments ➔play!
- ➔ identify R&D issues, cost gradients, …

- ➔ extensions beyond 3flavour LBL oscillations
- ➔ include NSIs into simulations

NSIs & Oscillations

Future precision oscillation experiments:

- must include full 3 flavour oscillation probabilities
- matter effects
- define sensitivities on an event rate basis

Source	⊗	Oscillation	⊗	Detector
- neutrino energy E		- oscillation channels		- effective mass, material
- flux and spectrum		- realistic baselines		- threshold, resolution
- flavour composition		- MSW matter profile		- particle ID (flavour, charge, event reconstruction, ...)
- contamination		- degeneracies		- backgrounds
- symmetric $\nu/\overline{\nu}$ operation		- correlations		- x-sections (at low E)

precision experiments migh 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 ⇔ M_W)**

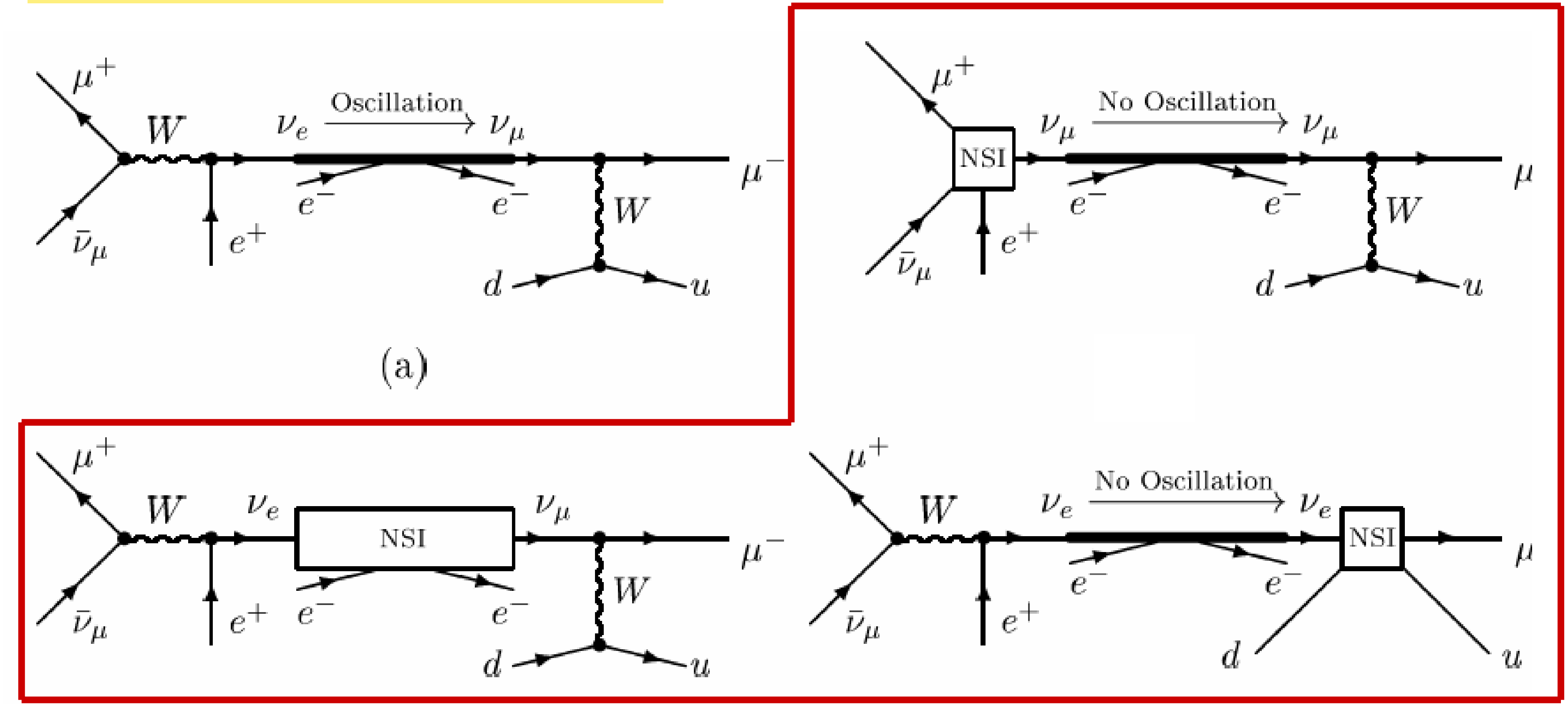
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

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



note: interference in oscillations ~ε ⇔ FCNC effects ~ε²

Physics Potential with NSIs included

Simulations

- full osciallation framework with NSIs included

➔ 4 possibilities for flavour transition:

- Oscillation
- NSI operator at source
- NSI operator at detector
- NSI effects in propagation

} no L/E dependence (NSI operator at source, NSI operator at detector, NSI effects in propagation)

Important: sensitivity limit from few events (small statistics)

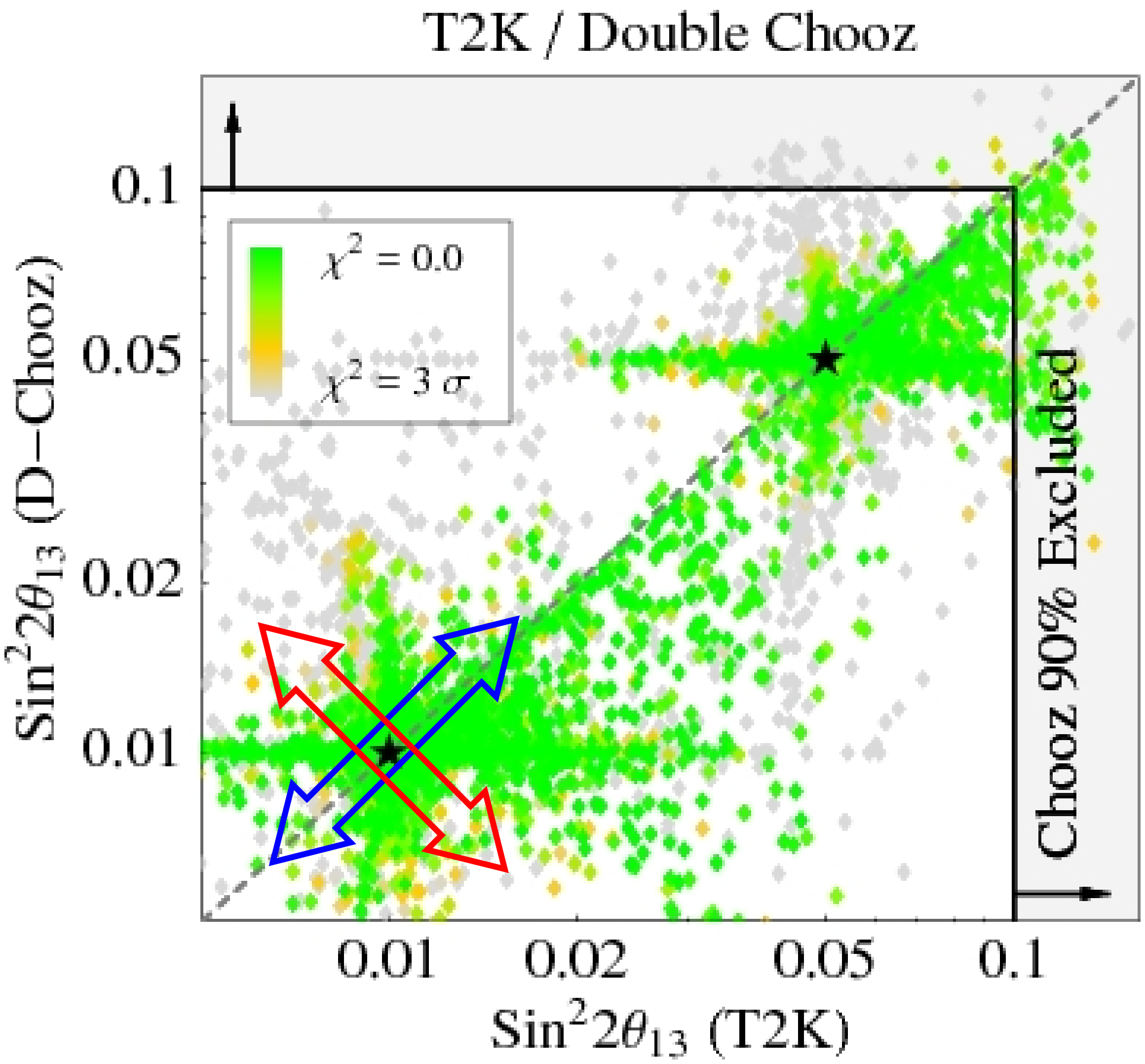
➔ no capability to resolve characteristic L/E dependence of oscillation

➔ potential misinterpretation of NSI flavour transition effects

Potential consequences:

- offsets in parameter determinations
- conflicting data

NSI: Offset and Mismatch in θ_{13}



Redundant measurements:

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

scatter-plot: ε values random

- below existing bounds

- random phases

NSIs can lead to:

- offset

- mismatch

➔ redundancy

➔ interesting potential

Kopp, ML, Ota, Sato

Relevant NSI Operators

$$\mathcal{L}_{\text{NSI}} = \mathcal{L}_{V\pm A} + \mathcal{L}_{S\pm P} + \mathcal{L}_T$$

General Lorentz and flavour structure

$\mathcal{L}_{V\pm A} =$

$$\frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\epsilon}^{s,f,f',V\pm A}_{\alpha\beta} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5) \ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1 \pm \gamma^5) f\right]$$
$$+ \frac{G_F}{\sqrt{2}} \sum_f \tilde{\epsilon}^{m,f,V\pm A}_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5) \nu_\beta\right] \left[\bar{f} \gamma_\rho (1 \pm \gamma^5) f\right] + \text{h.c.}$$

$$\mathcal{L}_{S\pm P} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\epsilon}^{s,f,f',S\pm P}_{\alpha\beta} \left[\bar{\nu}_\beta (1+\gamma^5) \ell_\alpha\right] \left[\bar{f}' (1 \pm \gamma^5) f\right],$$

$$\mathcal{L}_T = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\epsilon}^{s,f,f',T}_{\alpha\beta} \left[\bar{\nu}_\beta \sigma^{\rho\tau} \ell_\alpha\right] \left[\bar{f}' \sigma_{\rho\tau} f\right].$$

Reactor source and detector ($f = u,\ f' = d$)

	Source $\ell_\alpha = e$	Source $\ell_\alpha = \mu$	Source $\ell_\alpha = \tau$	Detector $\ell_\alpha = e$	Detector $\ell_\alpha = \mu$	Detector $\ell_\alpha = \tau$
$V - A$	✓	no μ production	no τ production	✓	no μ production	no τ production
$V + A$	✓	no μ production	no τ production	✓	no μ production	no τ production
$S - P$	strong constraints	no μ production	no τ production	strong constraints	no μ production	no τ production
$S + P$	strong constraints	no μ production	no τ production	strong constraints	no μ production	no τ production
T	strong constraints	no μ production	no τ production	strong constraints	no μ production	no τ production

Superbeam source and detector ($f = u,\ f' = d$)

	Source $\ell_\alpha = e$	Source $\ell_\alpha = \mu$	Source $\ell_\alpha = \tau$	Detector $\ell_\alpha = e$	Detector $\ell_\alpha = \mu$	Detector $\ell_\alpha = \tau$
$V - A$	no e production	✓	no τ production	✓	✓	no τ detection
$V + A$	no e production	✓	no τ production	✓ (mild supp.)	✓ (mild supp.)	no τ detection
$S - P$	no e production	✓	no τ production	strong constraints	chiral supp.	no τ detection
$S + P$	no e production	✓	no τ production	strong constraints	chiral supp.	no τ detection
T	no e production	no P-odd part	no τ production	strong constraints	chiral supp.	no τ detection

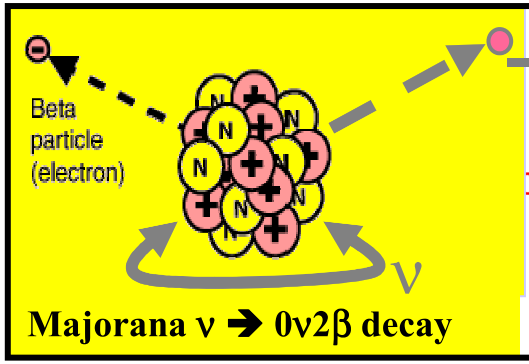
Propagation ($f = e, u, d$)

$V - A$	✓
$V + A$	✓

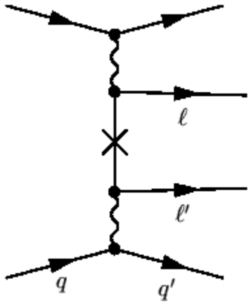
Very important for NF & β-beam

➔ See talks by S.Uchinami , J. Kopp

Neutrino-less Double β-Decay



$\propto$



$\propto |\langle m_{ee} \rangle| \;=\; |\sum m_i U_{ei}^2|$ **$\leq$ 0.35 eV ?**

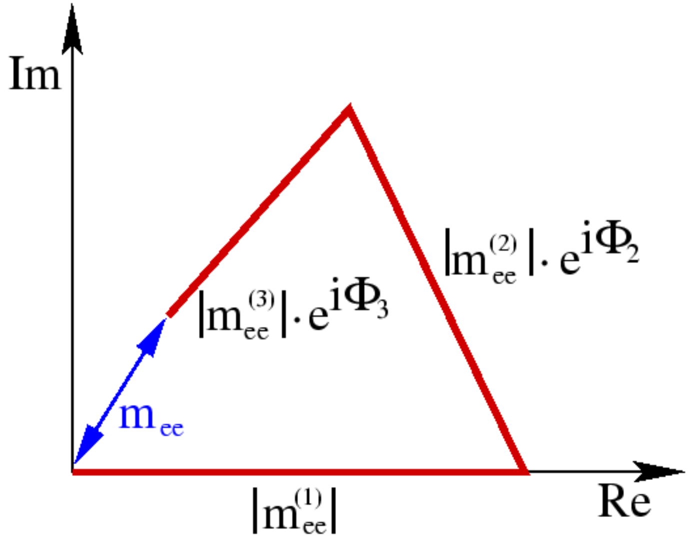
Heidelberg-Moscow experiment

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

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

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

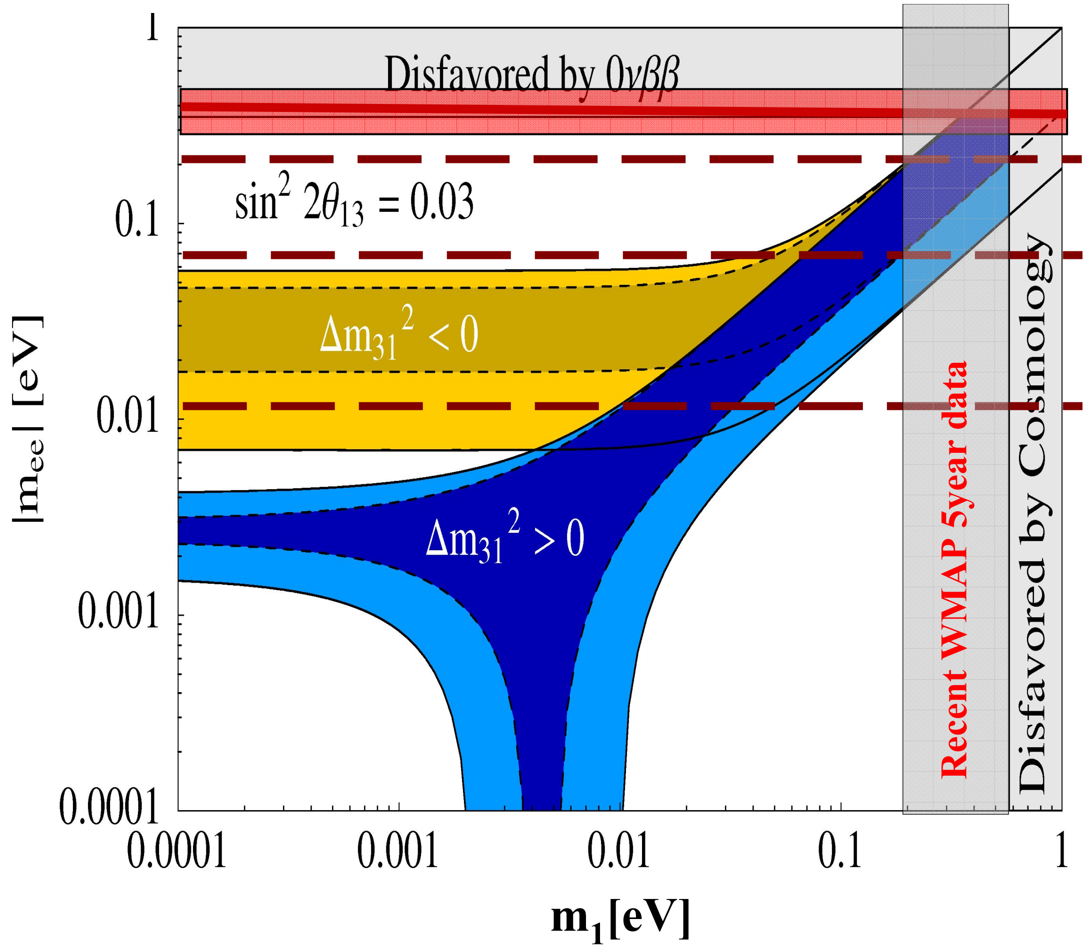
$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

➔ **free parameters: m_1 , sign(Δm^2_{31}) , CP-phases Φ_2, Φ_3**

Claim of part of the original Heidelberg-Moscow experiment ⇔ cosmology ➔ ‚tension‘



aims of new experiments:

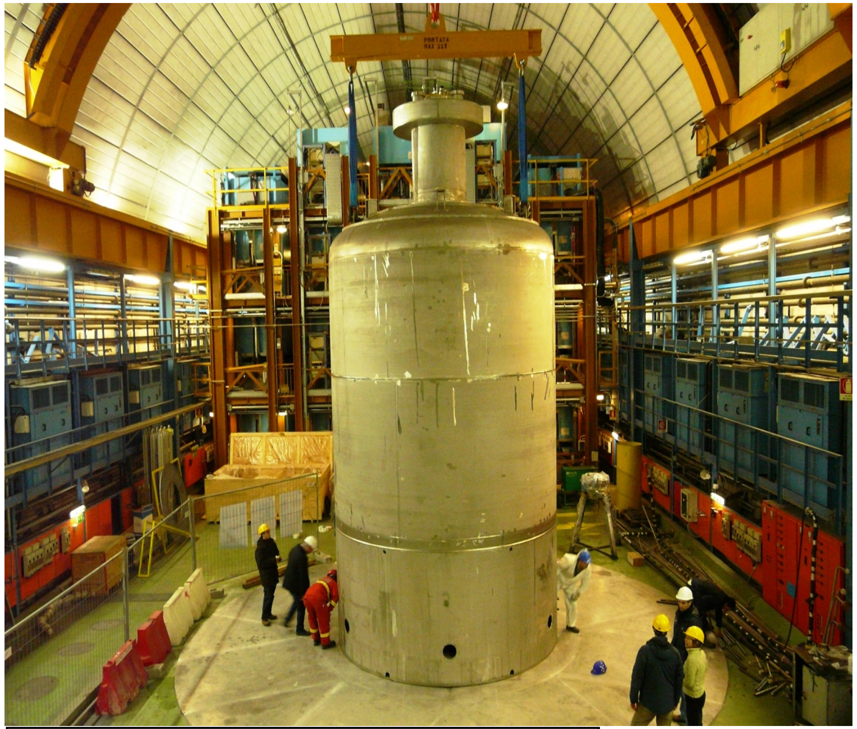
- **test HM claim**
- **$(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV $\pm$ errors**
  - **➔ reach 0.01eV**
  - **➔ CUORE**
  - **➔ GERDA phases I, II, (III)**

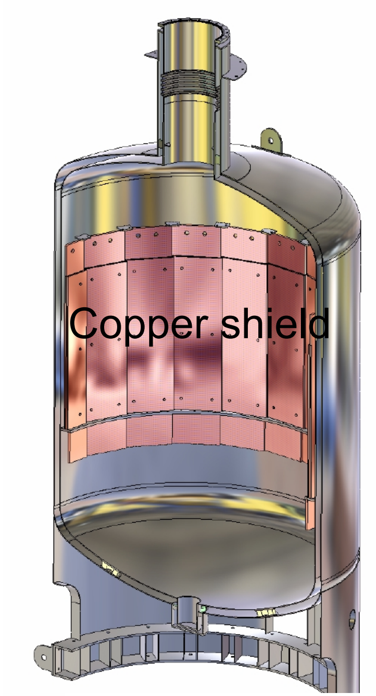
Comments:

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

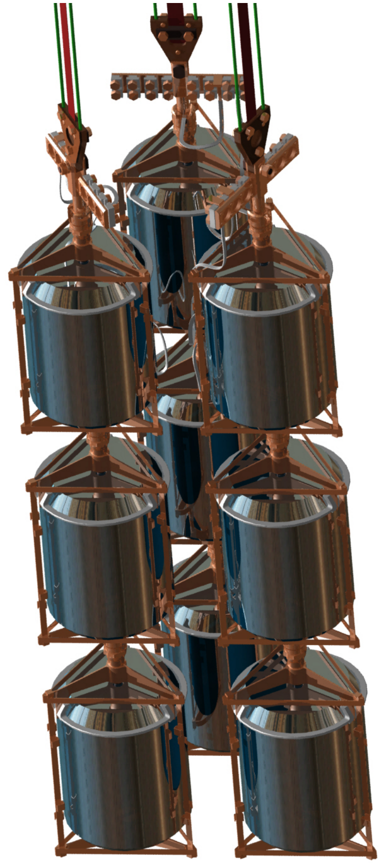
➔ very promising interplay of cosmology, other mass determinations (KATRIN), LHC, LVF experiments and theory

GERDA Construction



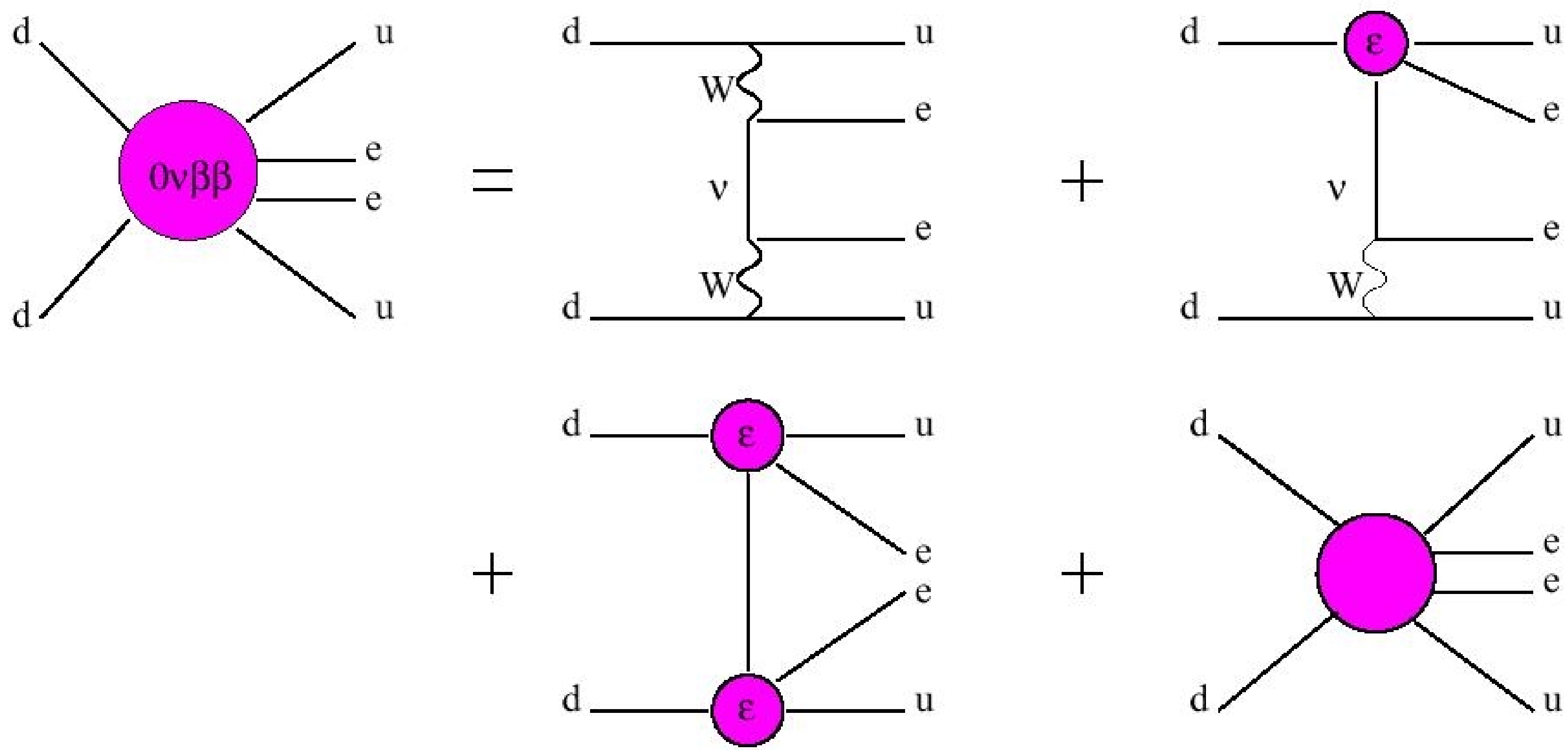


Vacuum-insulated double wall stainless steel cryostat



➔ **data taking 2009**

alternatives: LR, RPV-SUSY, …➔ other $\not{L}$ operators ⟷ NSI's



Schechter+Valle:

L violating operator ➔ radiative mass generation ➔ Majorana nature of ν's

However: This may only be a tiny correction to a much larger Dirac mass term

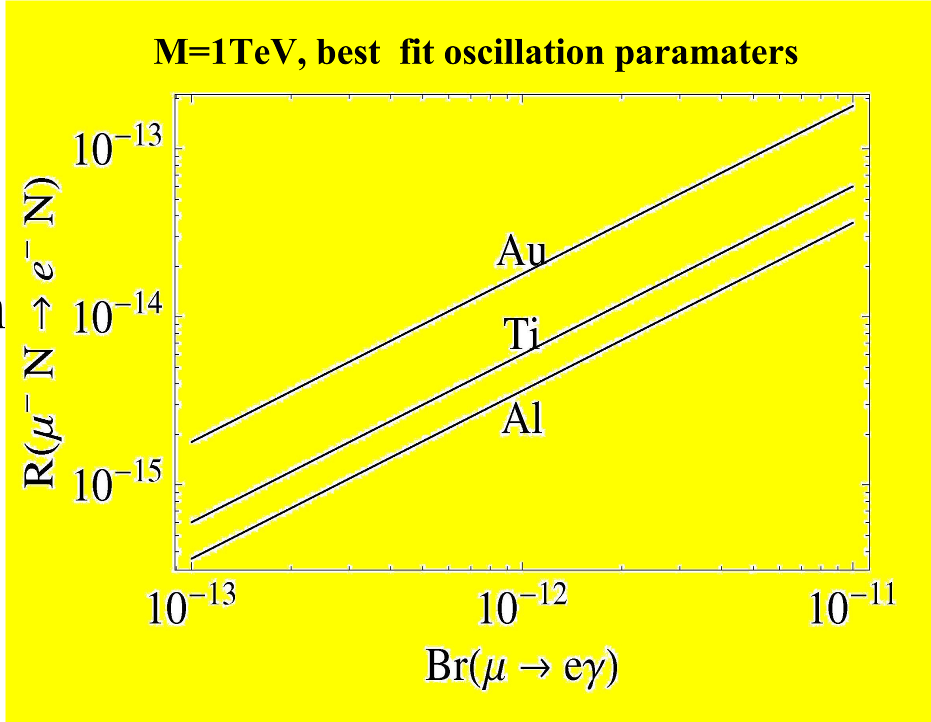
Lepton Flavour Violation

- **Majorana neutrino mass terms**
- **…**
- **R-parity violating supersymmetry**
  Hall+Kosteleck+Rabi, Borzumati+Masiero, Hisano+Tobe, Casas+Ibarra, Antusch+Arganda+Herrero+Teixeira, Joaquim+Rossi, …

➔LFV and leptonic CP violation can even exist for m_ν➔0

➔ e.g. modifications of correlation between μ^- ➔ $e^- \gamma$ decay and nuclear μ^- ➔ e^- conversion
MEG: 10^{-13}
PRISM: 10^{-18}

➔interplay: ν's – LFV – LHC in the coming years



Deppisch+Kosmas+Valle

Conclusions

- **neutrino physics very promising → unique information**
  - insights into various sources
  - unique particle physics properties
- **first solid particle physics beyond the standard model**
  - there are more parameters
  - explicit fermion mass terms
  - L violation
- **future: precision neutrino physics**
  - very precise measurements → potential for surprises!
  - NSIs: offsets and mismatch possible → precise & redundant measurements
  - good potential for synergies with LHC and LFV physics
- **interpreting flavour structures ↔ origin of flavour**
  - flavour symmetries - GUTs - SUSY
  - …many fancier ideas

→ very good motivation for future neutrino beams