Neutrinos: Status and Perspectives

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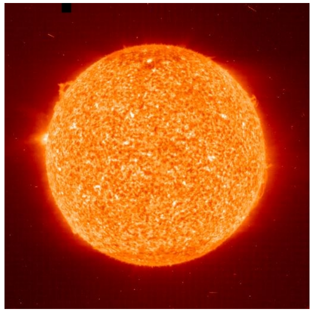
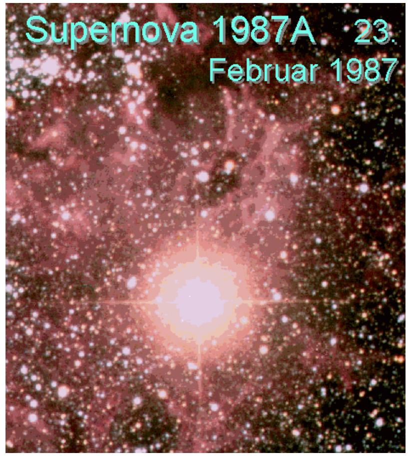
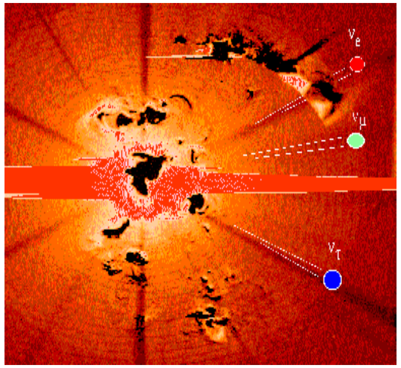
New Physics & Neutrino Sources



← **Sun**

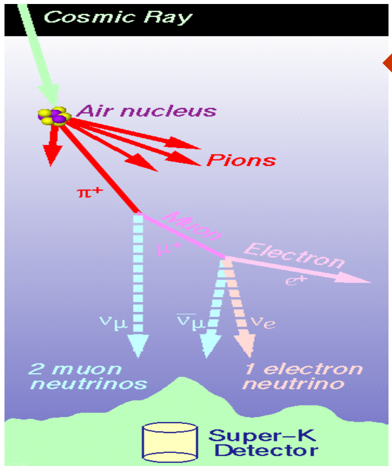
Astronomy: →
Supernovae
GRBs
UHE ν's





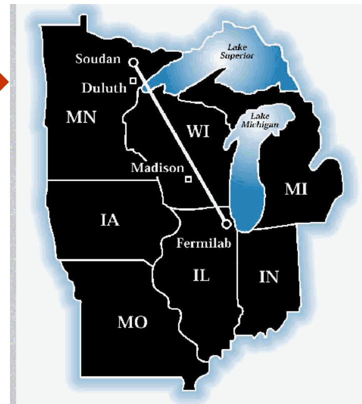
← **Cosmology**

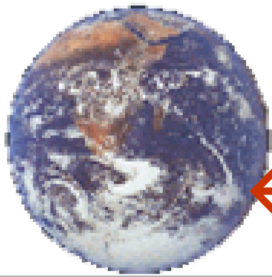
Reactors →



← **Atmosphere**

Accelerators →

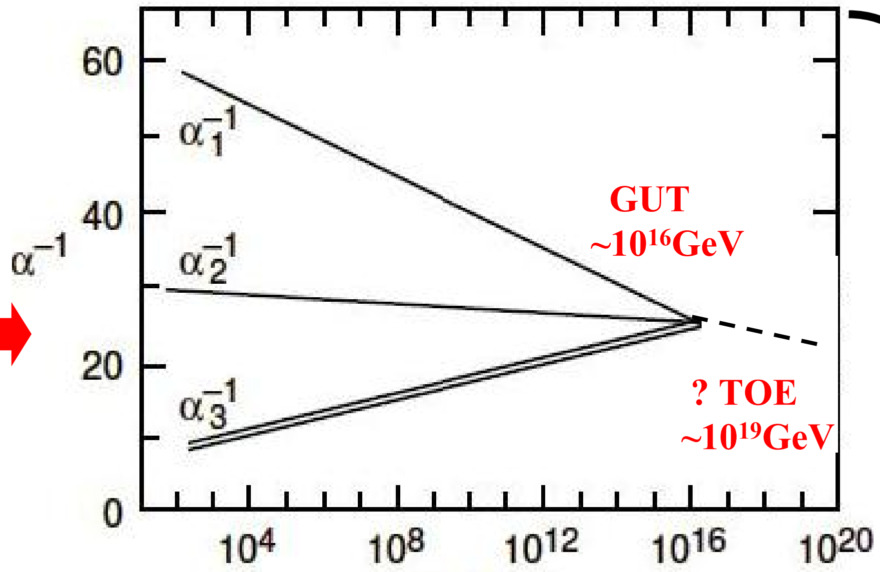




← **Earth**

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

Extending the Standard Model

➔ success of renormalizable gauge field theories in d=4

QED	➔ QCD	➔ SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$

➔ symmetry, renormalizability, no anomalies

➔ particle content (symmtery representations):

gauge sector – fixed by gauge group
scalar sector – must break EW symmetry, $SB \sim 2_L$
fermions – anomaly free combinations

➔ different levels of SM extension…

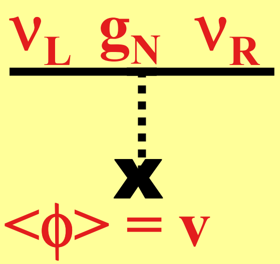
- add further representations
- extend the gauge symmetry
- add supersymmetry
- extend/modify basic concepts: quantum fields and/or space-time

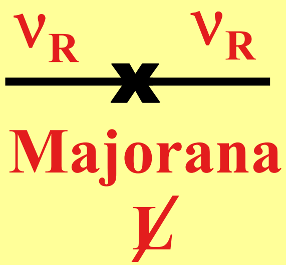
Adding Neutrino Mass Terms

1) Postulate right handed neutrino fields ➔ SM+

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2

not part of SM !
makes table more symmetric
3 right handed neutrinos?
NEW: ➔ 9 parameters
➔ explicit fermion mass term
➔ L number violation





➔

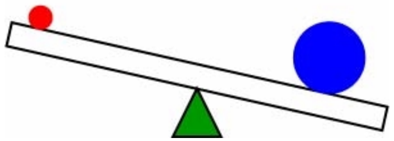
$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^{\mathbf{c}} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^{\mathbf{c}} \\ \nu_R \end{pmatrix}$$

Natural value of mass operators: scale of symmetry

$m_D \sim$ electro-weak scale

$M_R \sim$ L violation scale ←→ embedding into GUTs

See-saw mechanism (type I)



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

$m_h = M_R$

Suggestive hints:

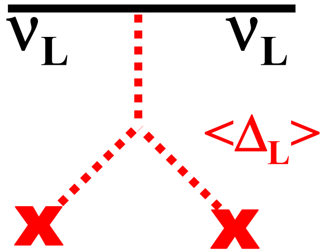
For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons → $M_R \sim 10^{11}$ - 10^{16}GeV

→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

Other Neutrino Mass Operators

2) new Higgs triplets Δ_L:

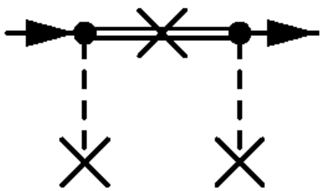


➔left-handed Majorana mass term: **➔ $M_L \overline{L} L^c$**

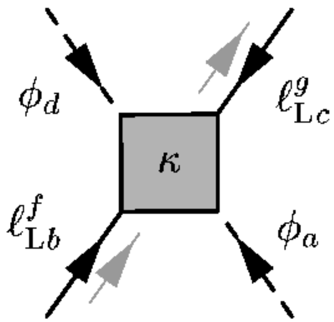
3) Both ν_R and new Higgs triplets Δ_L:

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

4) Higher dimensional operators: d=5, …



$\Rightarrow$



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

➔ $M_L \overline{L} L^c$

Other effective Operators Beyond the SM

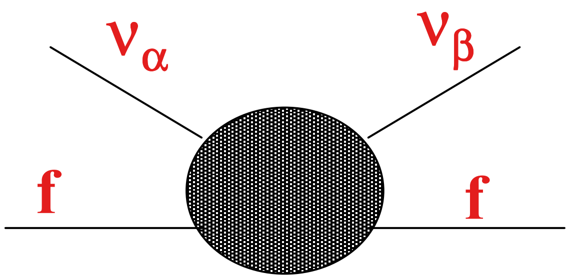
➔ effects beyond 3 flavours

➔ 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)

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



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, …

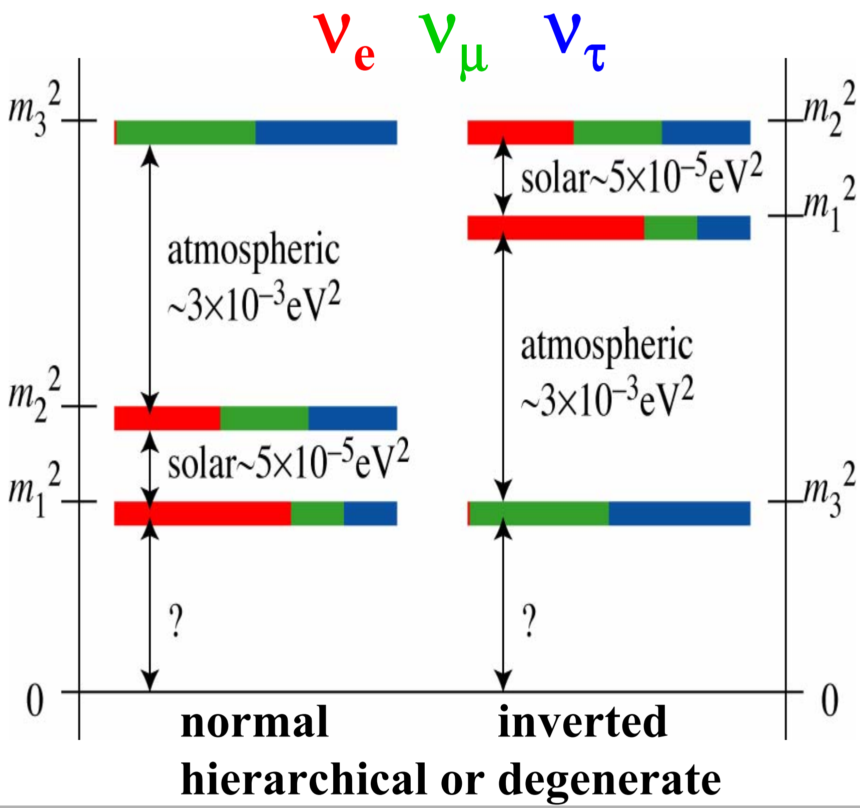
Parameters for 3 Light Neutrinos

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**
- **cosmology**
- **lepton number violation**
  ⇔ ν-less double β-decay
- **oscillations**

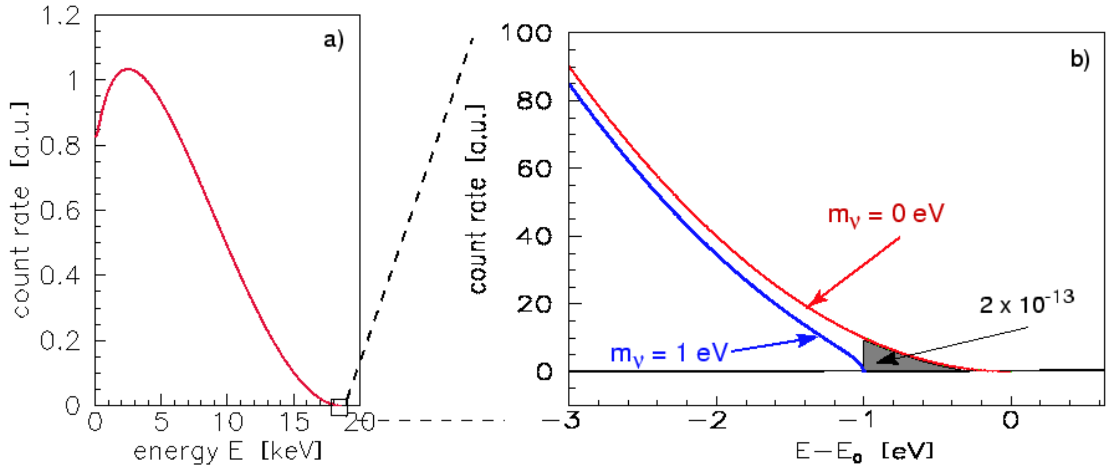
Kinematical Mass Determination

Relativistic kinematics:

$$E^2 = p^2 + m^2; \;\; \sum p_i^\mu = \sum p_f^\mu$$

Endpoint of decays:

Tritium $\rightarrow He^3 + e^- + \overline{\nu}_e$



Bounds:	"Elektron-Neutrino":	$m < 2.2$ eV	(Mainz, Troitsk)
	"Muon-Neutrino":	$m < 170$ keV	
	"Tau-Neutrino":	$m < 15.5$ MeV	

Sensitivity $\Leftrightarrow$ **degenerate ν-spectrum**

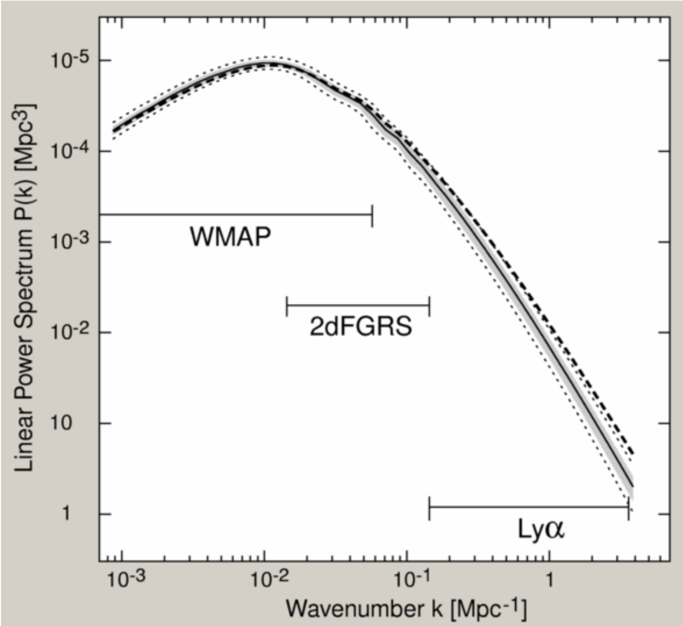
$\Rightarrow$ **Oscillations:** $\Delta m_{ij}^2 \ll m_i^2 \Rightarrow$ $\sum m_i^2 |U_{ei}|^2 < (2.2 \text{ eV})^2$

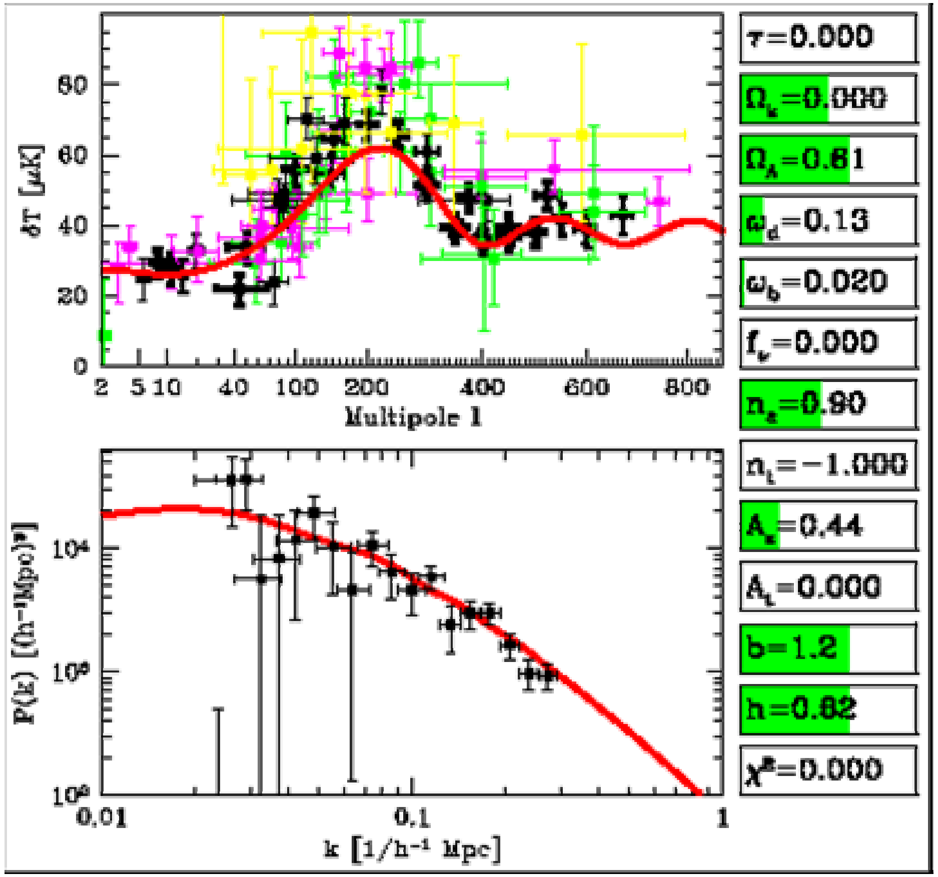
Future: KATRIN → 0.25 eV ↔ **c.f. comological bounds**

Cosmology and Neutrino Mass

- ν's hot dark matter ➔ smears structure @ small scales

Tegmark





- WMAP+2dFGRS + Lyα+...

➔ bound: $\Sigma m_\nu < 0.17 - 1.2$ eV

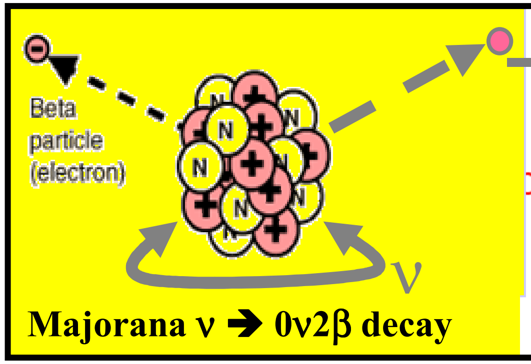
⟷ levels of systematic errors

- 3 degenerate neutrinos, conservative approach

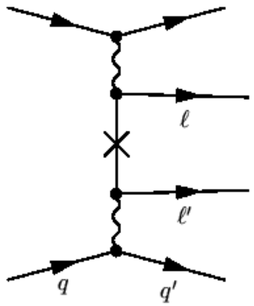
➔ $m_\nu < 0.25$ eV future improvements: ~factor 5-10 ?

$f_\nu = \Omega_\nu / \Omega_{matter}$

Neutrino-less Double β-Decay



$\propto$



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

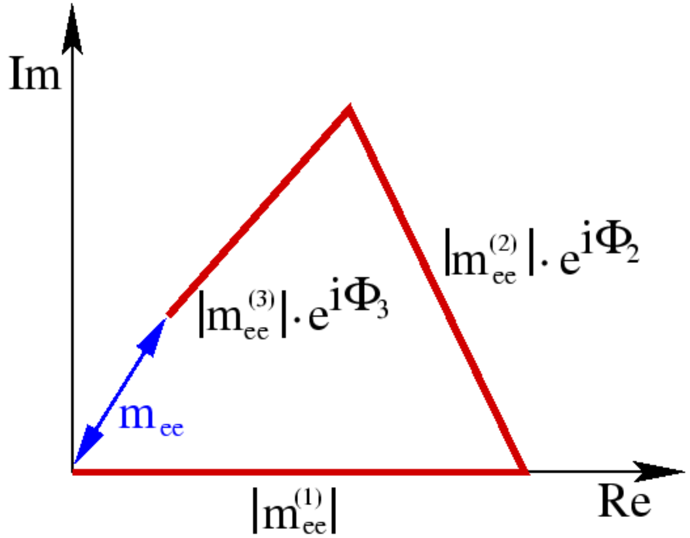
Heidelberg-Moscow experiment

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

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

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

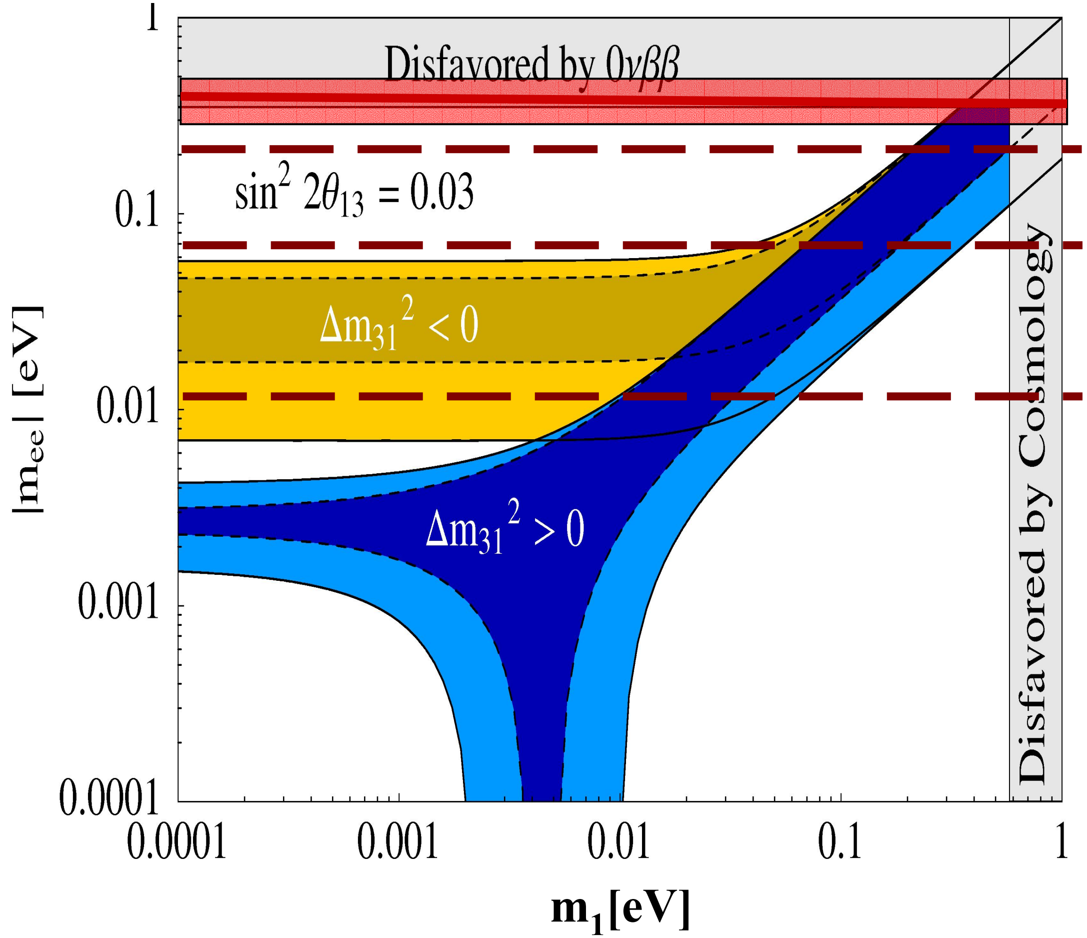
$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



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_{31}^2) , CP-phases Φ_2, Φ_3**

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



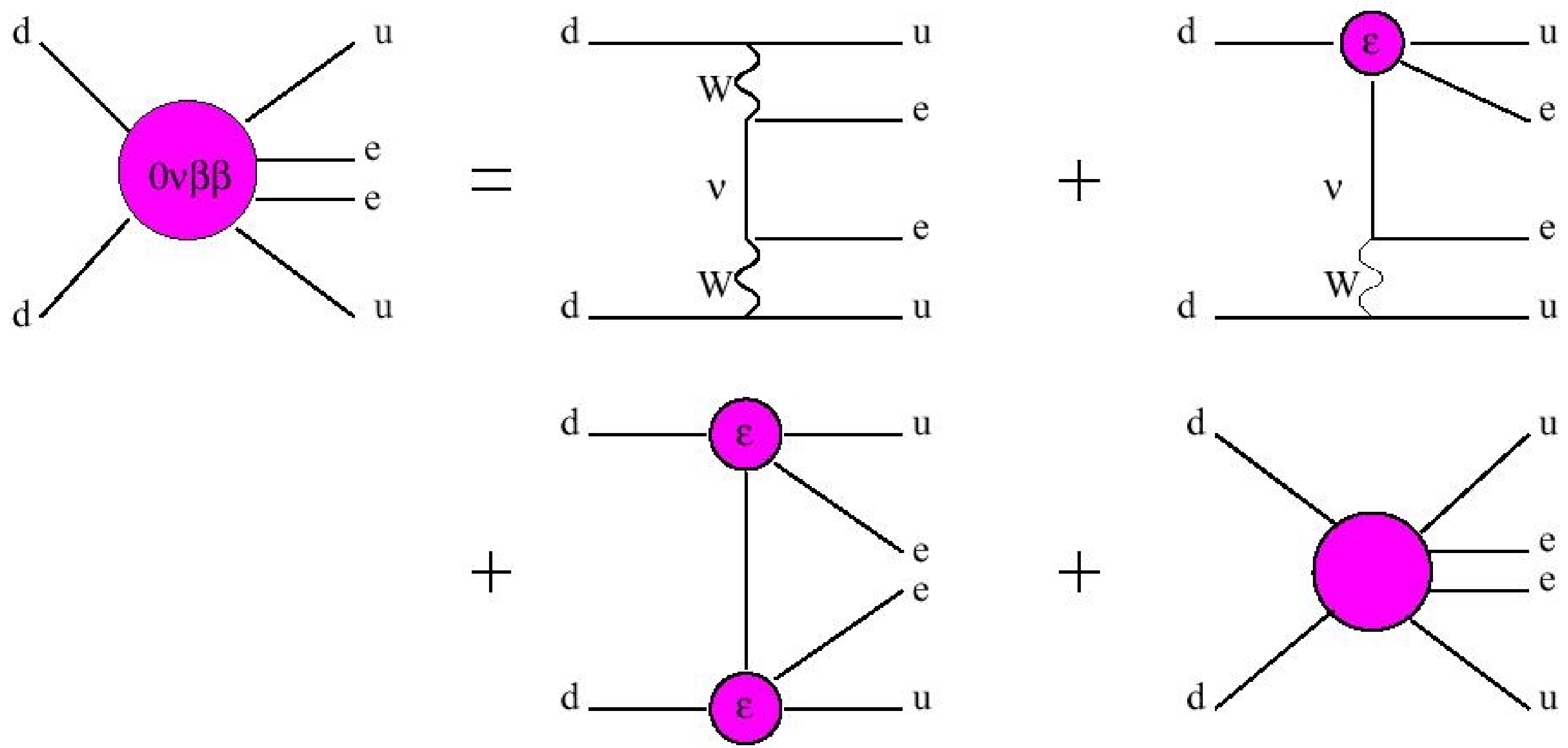
aims of new experiments:

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

Limitations:

- **cosmology: systematical errors ➔ ~factor 10?**
- **errors of 0ν2β nuclear matrix elements! ~factor 2 theoretical uncertainty in m_{ee}**
- **$\Delta m^2 > 0$ allows complete cancellation ➔ 0ν2β signal not guaranteed**
- **0ν2β signal ➔ *some* lepton number violating operator**

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



Schechter+Valle:

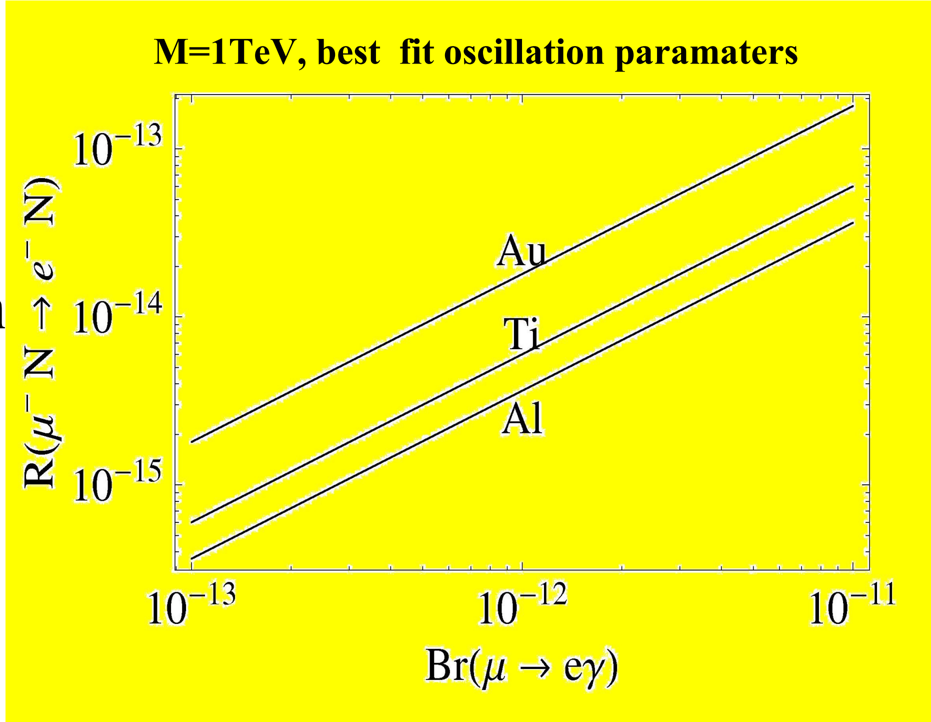
L violating operator ➔ radiative mass generation ➔ Majorana nature of ν‘s

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, …



Deppisch+Kosmas+Valle

➔LFV and leptonic CP violation can even exist for $m_\nu \to 0$

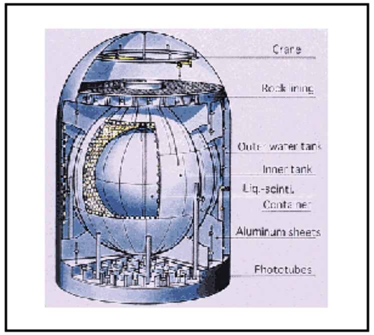
➔ e.g. modifications of correlation between $\mu^- \to e^- \gamma$ decay and nuclear $\mu^- \to e^-$ conversion

MEG: 10^{-13}

PRISM: 10^{-18}

➔interplay: ν's – LFV - LHC

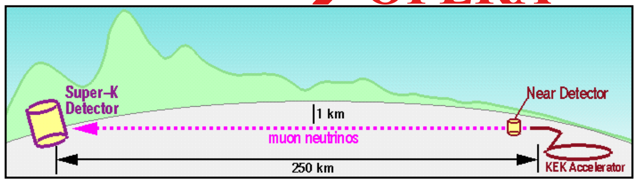
Status of Neutrino Oscillations



Reactors: KAMLAND

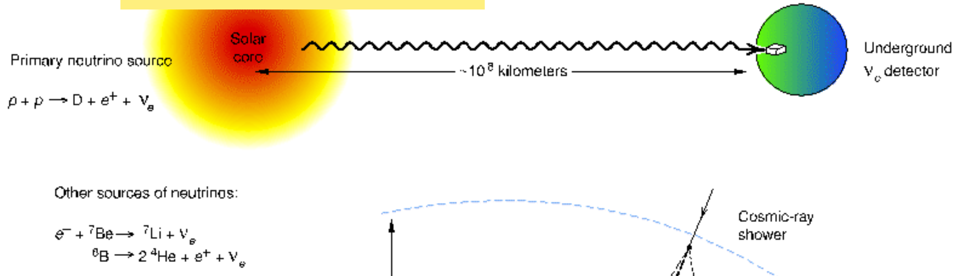
improved result

Beams: K2K ➔MINOS
➔ OPERA

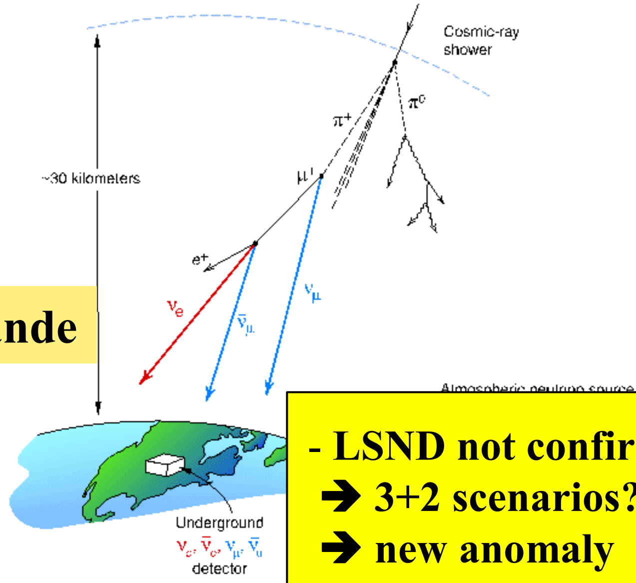


$\Delta m^2_{21} = (7.9 \pm 0.3) * 10^{-5}\ eV^2$
$\tan^2\theta_{12} = 0.39 \pm 0.05$
$\Delta m^2_{31} = (2.4 \pm 0.3) * 10^{-3}\ eV^2$
$\tan^2\theta_{23} = 1.0 \pm 0.3$
$\sin^2 2\theta_{13} < 0.16$ Chooz

solar: GALLEX/GNO ➔ SK, SNO

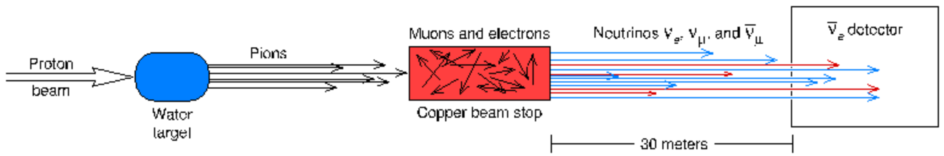


atmospheric: Superkamiokande



- LSND not confirmed !
 ➔ 3+2 scenarios?
 ➔ new anomaly
- upturn at low E ?

LSND? ➔ MiniBooNE



Future Precision Oscillation Physics

Precise measurements ➔ 3f oscillation formulae

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

x Majorana-CP-phases

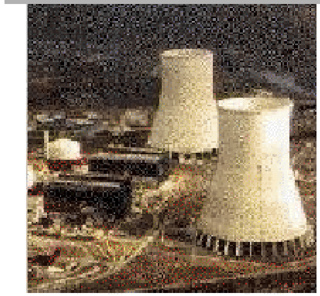
θ_{23} | S_{13} ➔ 3 flavour effects ➔ CP phase δ | θ_{12}

Aims: ➔ **improved precision** of the leading 2x2 oscillations
➔ detection of **generic 3-neutrino effects: θ_{13}, CP violation**

Complication: **Matter effects ➔ effective parameters in matter**
➔ **expansion in small quantities θ_{13} and $a = \Delta m^2_{sol} / \Delta m^2_{atm}$**

Burguet-Castell et al. , Akhmedov et al. …

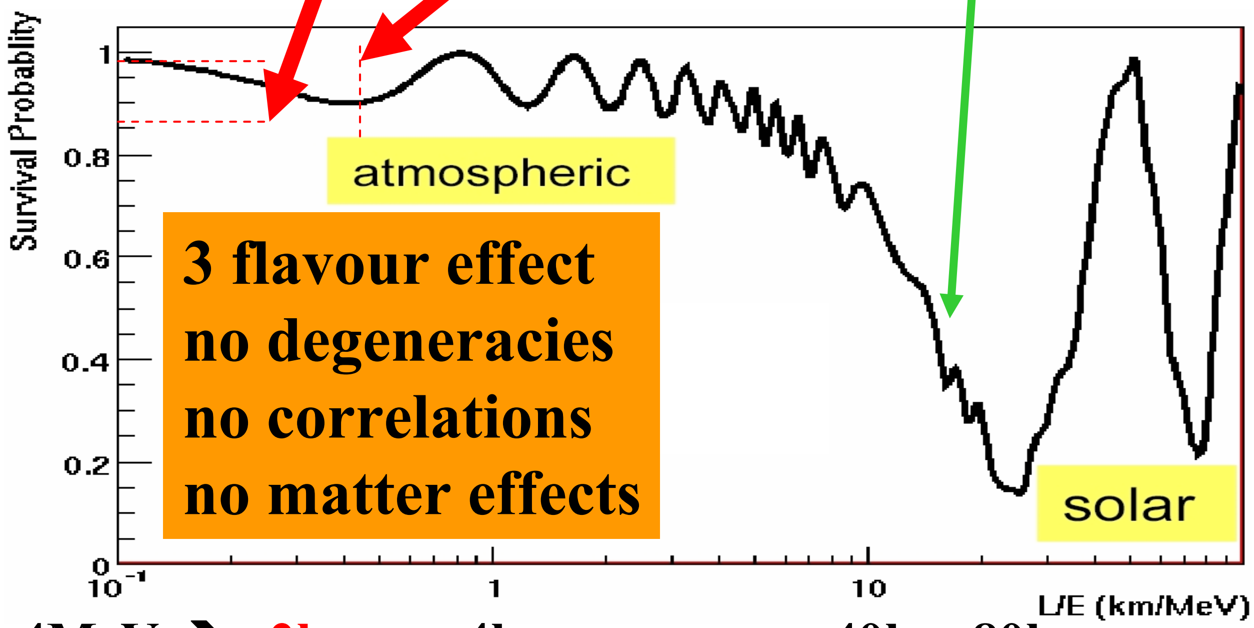
Future Precision with Reactor Experiments



$\overline{\nu}_e \Rightarrow$ **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**
- ➔ **Daya Bay**
- ➔ **Reno**
- ➔ **Angra**

clean & precise θ_{13} measurments

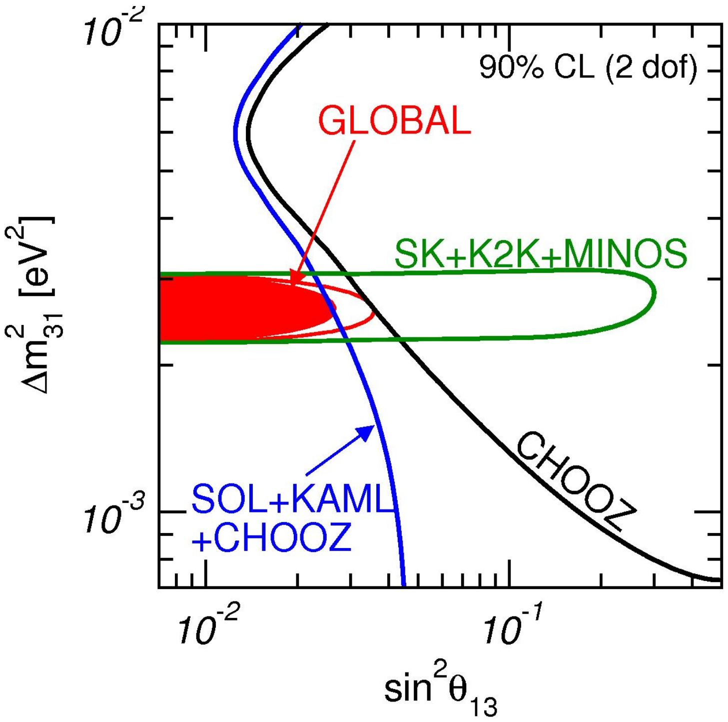
Future Precison with New Neutrino Beams

- **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**

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

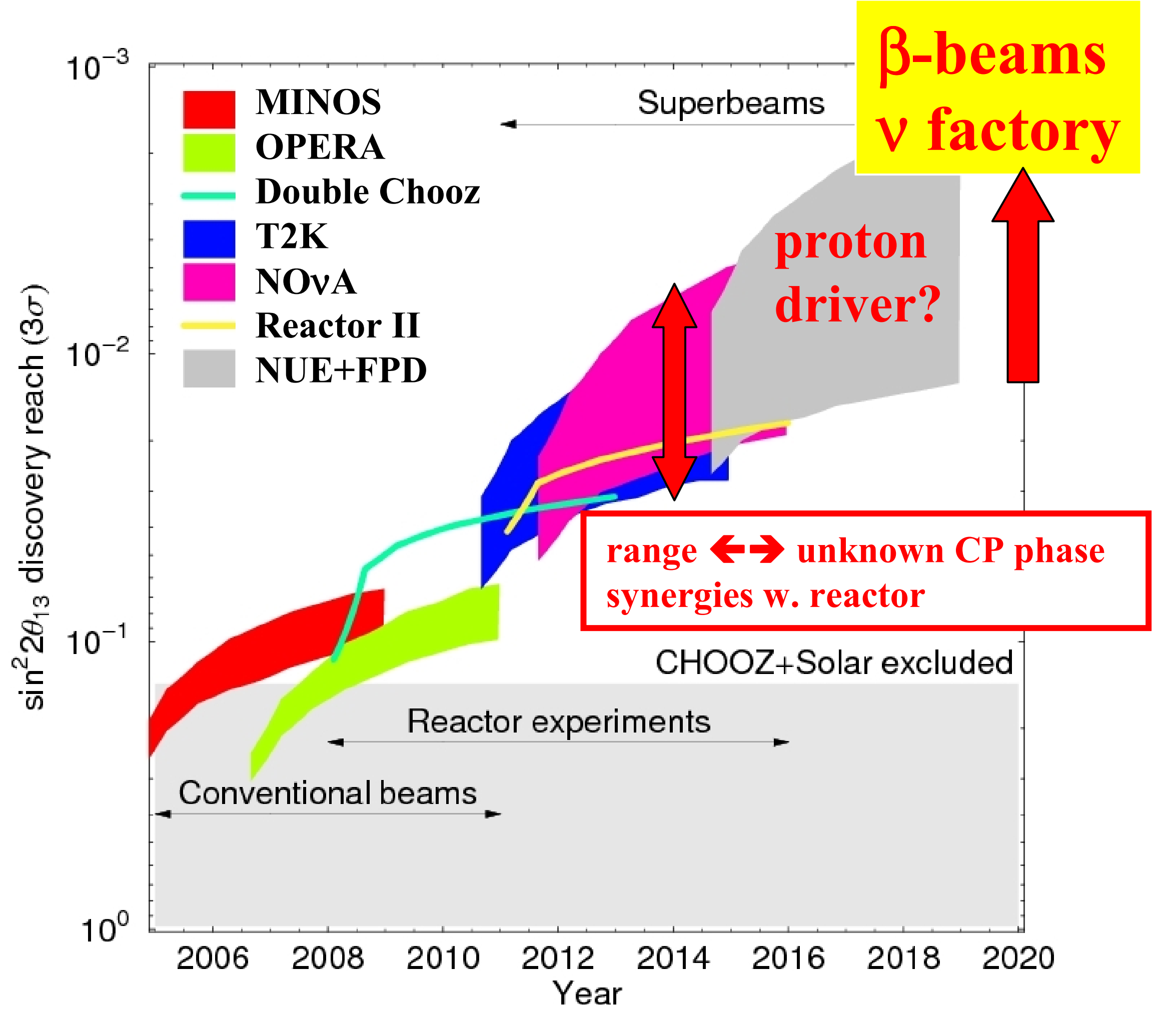
➔ **correlations & degeneracies, matter effects**

θ_{13} – Now and in the Future



Maltoni+Schwetz+Tortola+Valle

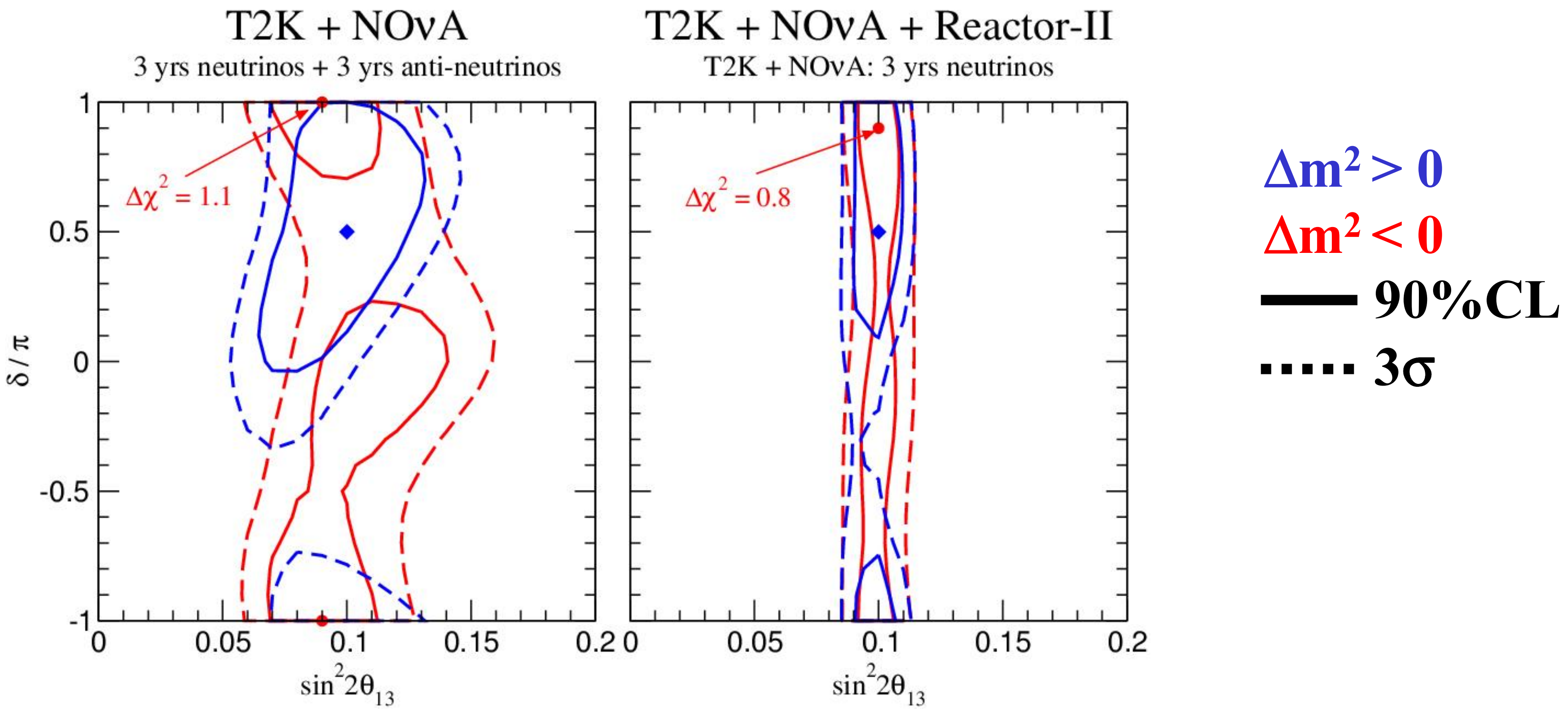
…



Huber, ML, Winter

Leptonic CP-Violation

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



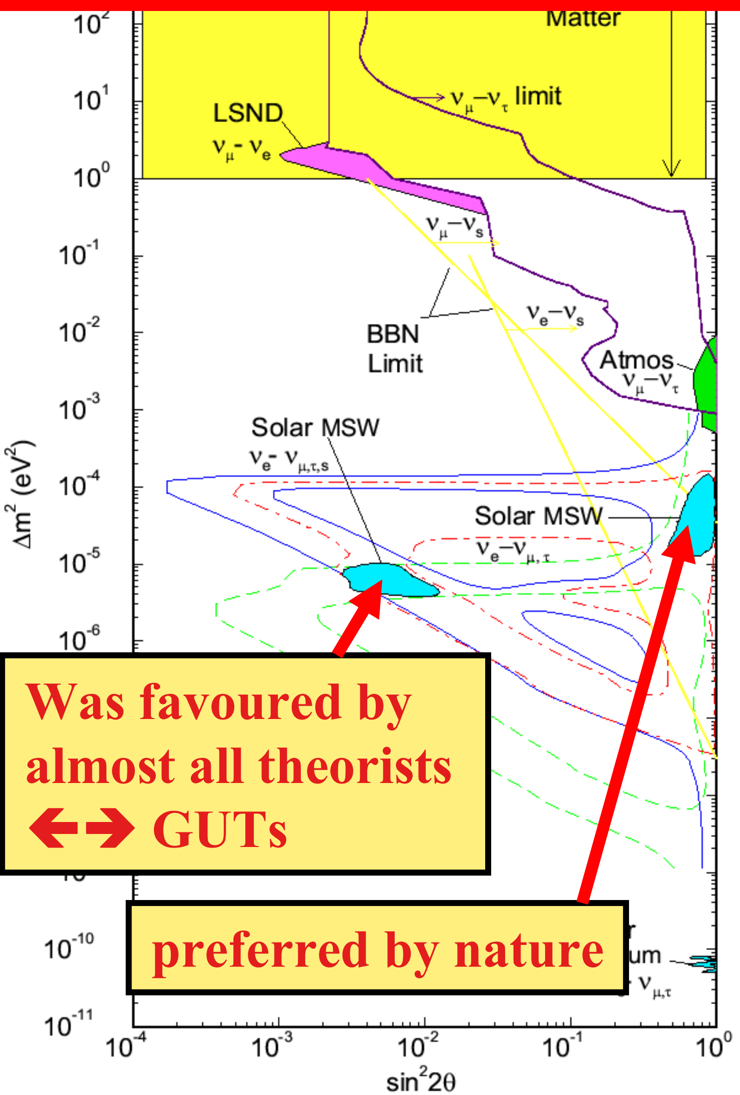
➔ bounds or measurements of leptonic CP-violation

➔ harder for smaller $\sin^2 2\theta_{13}$

➔ β-beams or/and neutrino factory

Learning about Flavour

History: Elimination of SMA



Was favoured by almost all theorists ⇔ GUTs

preferred by nature

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**

Implications of Precision Measurements

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 / 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, ...

➔ various synergies with LHC and LFV

Renormalization Group Running

<u>low energies:</u>
- **small masses**
- **large mixings**

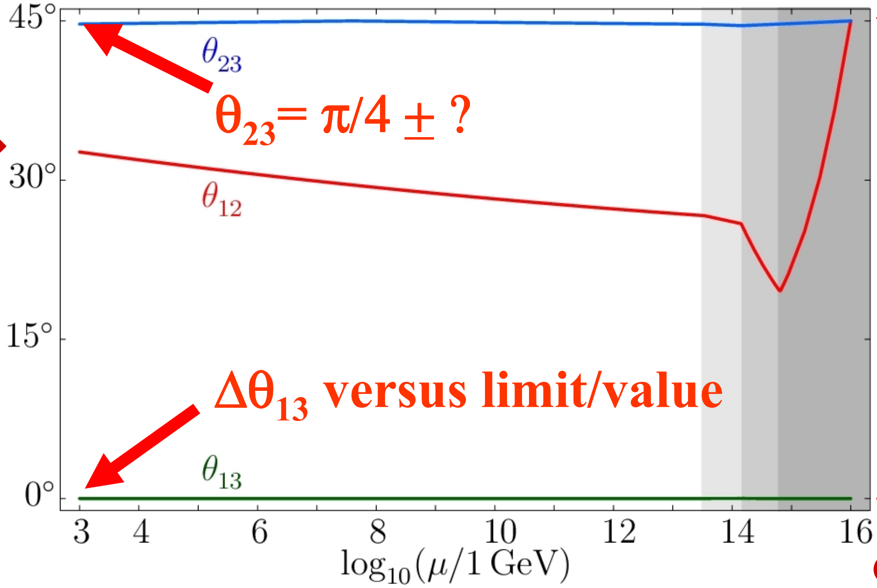
renormalization group running →

<u>high energies:</u>
- **mass models**
- **flavour-symmetries**
- **GUT-models, ...**

atmospheric →

solar →

reactor →



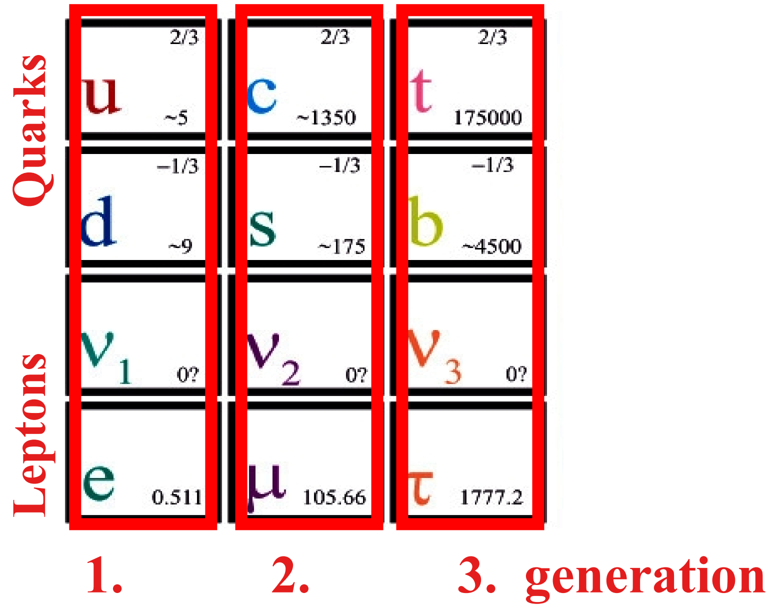
← bi-maximal

← Small or even zero

MSSM example:
Antusch, Kersten, **ML**, Ratz

The larger Picture: GUTs

Gauge unification suggests that some GUT exists



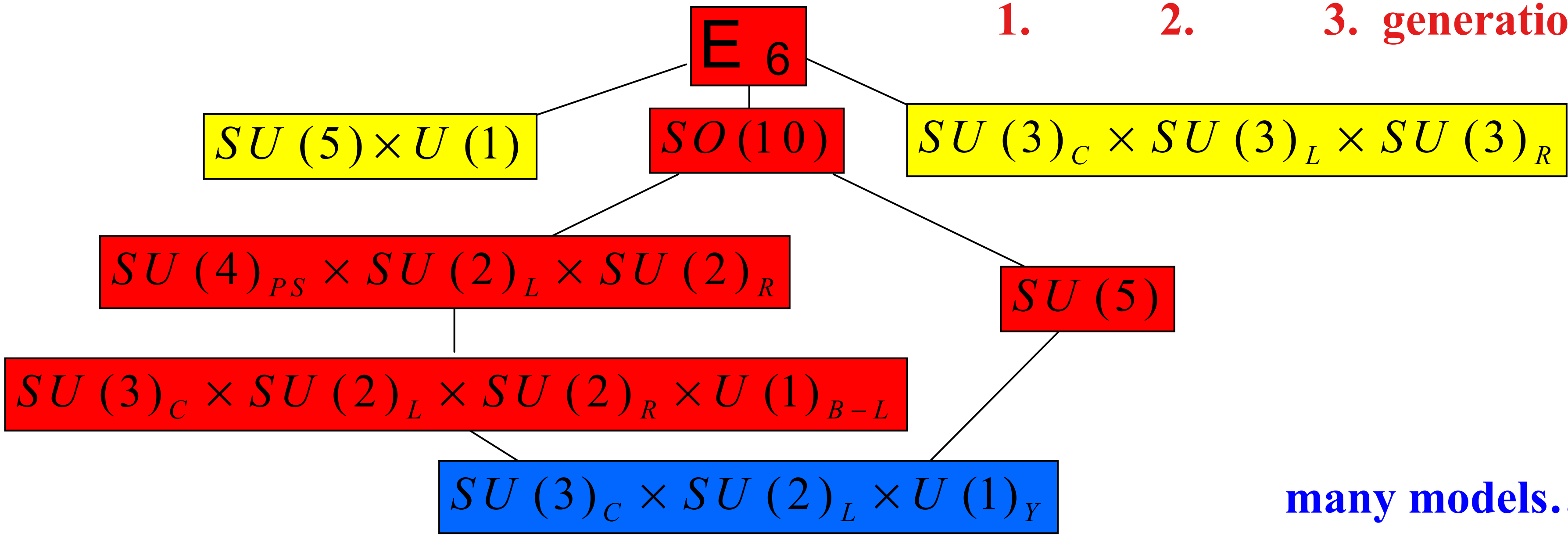
Requirements:

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
- ➔ …

Sequential Dominance

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

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

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

- → small sub-determinant ~ $m_2 . m_3$
- → $m_2 << m_3$ (hierachy) and tan $\theta_{23} \simeq a/c$ (large mixing)

$$M_R = \begin{pmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{pmatrix} \rightarrow$$

x<<y<<z

sequenatial dominance:

$m_1 << m_2 << m_3$ natural

naturally large mixings

S.F. King, ..

Large/Small versus Maximal/Zero Mixings

- **sequential dominance ➔ generically large mixings**

- **experiments will soon tell if**
  - θ_{23} is only large or very close to $\pi/4$
  - θ_{13} is only somewhat small or tiny

➔ distinguish mechanism which
- produce generically large/small mixings
  ➔ e.g. sequential dominance
- produce generically only tiny deviations from $\pi/4$ and 0
  ➔ tiny correction to some limiting case
  e.g. $\theta_{13}=0+\varepsilon$ and $\theta_{23}=\pi/4-\varepsilon$

Large Mixings and See-Saw Type II

see-saw type II:

- rather natural
- interference of two terms

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

m_D and M_R may have 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 → Rodejohann, ML

→ $M_L \simeq m_D M_R^{-1} m_D^T$ → interesting possibilities

→ dominance of one term + perturbation by 2nd term

$U_{e3}=0$; maximal θ_{23} ➔ small perturbation

Leading structure from one type II term➔ perturbation by 2nd

Three simple, stable candidates for $U_{e3}=0$ and maximal θ_{23}

$$(A): \sqrt{\frac{\Delta m_A^2}{4}} \begin{pmatrix} 0 & 0 & 0 \\ \cdot & 1 & -1 \\ \cdot & \cdot & 1 \end{pmatrix} \qquad L_e \quad EV = \sqrt{\Delta m_A^2} \quad NH$$

$$(B): \sqrt{\frac{\Delta m_A^2}{2}} \begin{pmatrix} 0 & 1 & 1 \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{pmatrix} \qquad L_e - L_\mu - L_\tau \quad EV = 0 \quad IH$$

$$(C): m_0 \begin{pmatrix} 1 & 0 & 0 \\ \cdot & 0 & 1 \\ \cdot & \cdot & 0 \end{pmatrix} \qquad L_\mu - L_\tau \quad EV = -m_0 \quad degenerate$$

Perturbation of the Leading Structure

e.g. 'democratic' perturbation:

$$m_\nu^I \simeq v_L \, \epsilon \begin{pmatrix} 1 & 1 & 1 \\ \cdot & 1 & 1 \\ \cdot & \cdot & 1 \end{pmatrix}$$

e.g. as correction to case (A):

➔ **naturally large $\theta_{12} = 1/3$ (tri-bimaximal mixing)**

➔ **finite $\theta_{13} \simeq$** $\sqrt{(\Delta m^2_{sol}/\Delta m^2_{atm})} \simeq 1/30$

➔ **corrections to $\theta_{23}-\pi/4 \simeq$** $\sqrt{(\Delta m^2_{sol}/\Delta m^2_{atm})} \simeq 1/30$

Tri-bimaximal Mixing

- tri-bimaximal mixing works phenomenologically very well
- mass matrix can be written as a sum of three terms

$$m_\nu = \frac{m_1}{6}\begin{pmatrix} 4 & -2 & -2 \\ \cdot & 1 & 1 \\ \cdot & \cdot & 1 \end{pmatrix} + \frac{m_2}{3}\begin{pmatrix} 1 & 1 & 1 \\ \cdot & 1 & 1 \\ \cdot & \cdot & 1 \end{pmatrix} + \frac{m_3}{2}\begin{pmatrix} 0 & 0 & 0 \\ \cdot & 1 & -1 \\ \cdot & \cdot & 1 \end{pmatrix}$$

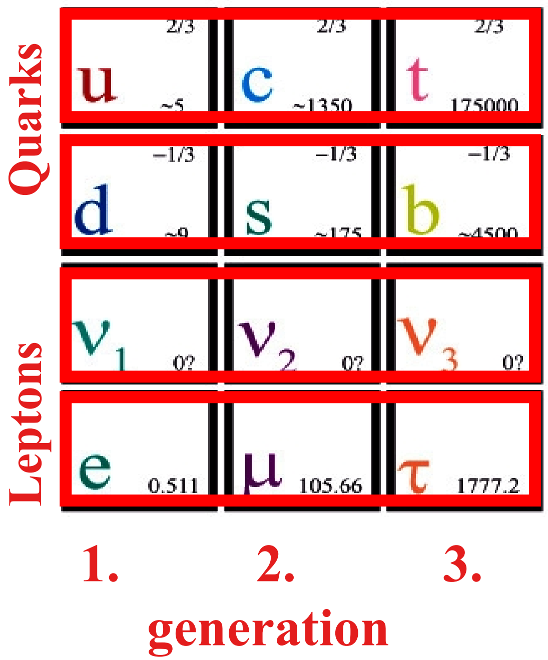
- phenomenologically very sucessful
- tempting to think of it as a consequence of three terms
- type II ⇔ m_2,m_3

Flavour Unification

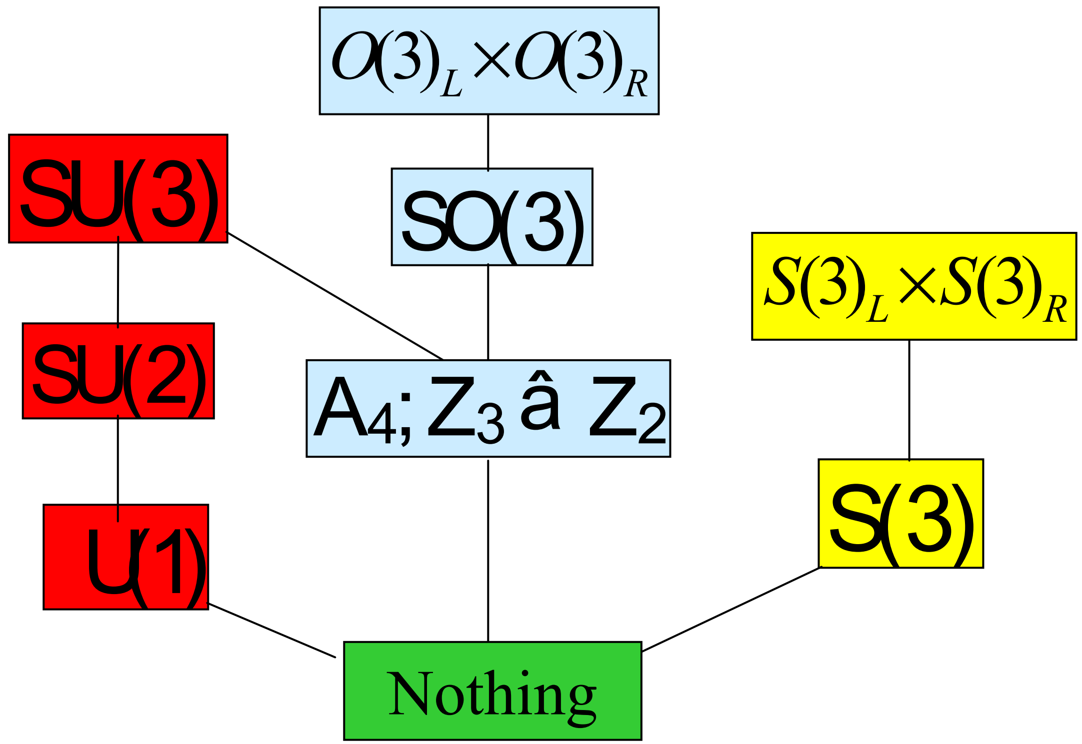
- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

➔ symmetry not texture zeros

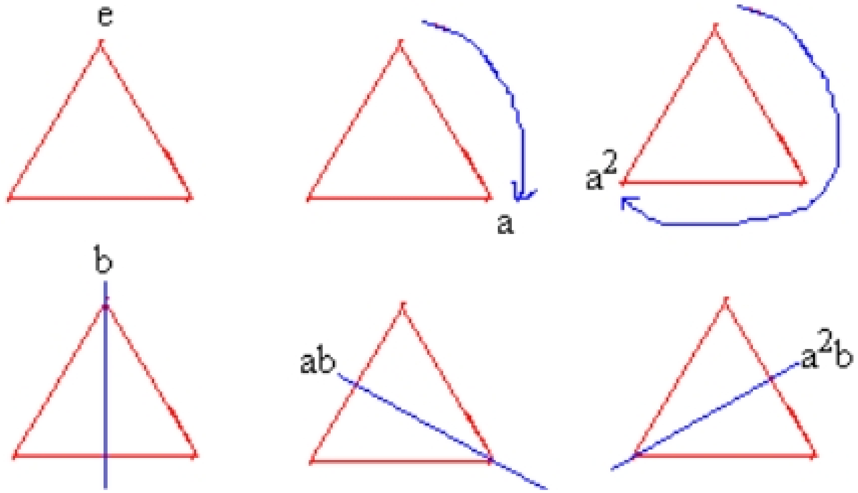


Examples:



Discrete Flavour Symmetries

e.g. dihedral groups D_n



geometric origin of D_3:

phenomenologically promising example: D_5 Hagedorn, ML, Plentinger

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

1) assign fermions to representations $L = \{L_1, L_2, L_3\}$

2) write down any possible mass term using scalars ⇔ singlet under symmetry

D_5 Allowed Mass Terms

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

Majorana mass terms: $$\lambda_{ij} L_i^T \Xi \phi L_j$$

➔**D5 symmetry induced mass matrices:**

Higgses:

$\Phi_1 \sim 1_1$

$\Phi_2 \sim 1_2$

$\Psi_1 \sim 2_1$

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

➔ **check phenomenology** ➔ **OK + "predictions"**

PROBLEM: many sucessful symmetries

List of models with flavor symmetries

(incomplete, by symmetry):

S_3: Pakvasa et al. (1978) Derman (1979), Ma (2000), Kubo et al. (2003), Chen et al. (2004), Grimus et al. (2005), Dermisek et al. (2005), Mohapatra et al. (2006), ...

S4: Pakvasa et al. (1979), Derman et al. (1979), Lee et al. (1994), Mohapatra et al. (2004), Ma (2006), Hagedorn, ML and Mohapatra (2006), Caravaglios et al. (2006), ...

A_4: Wyler (1979), Ma et al. (2001), Babu et al. (2003), Altarelli et al. (2005,2006), He et al. (2006) ...

D_4: Seidl (2003), Grimus et al. (2003,2004), Kobayashi et al. (2005), ...

D_5: Ma (2004), Hagedorn et al. (2006).

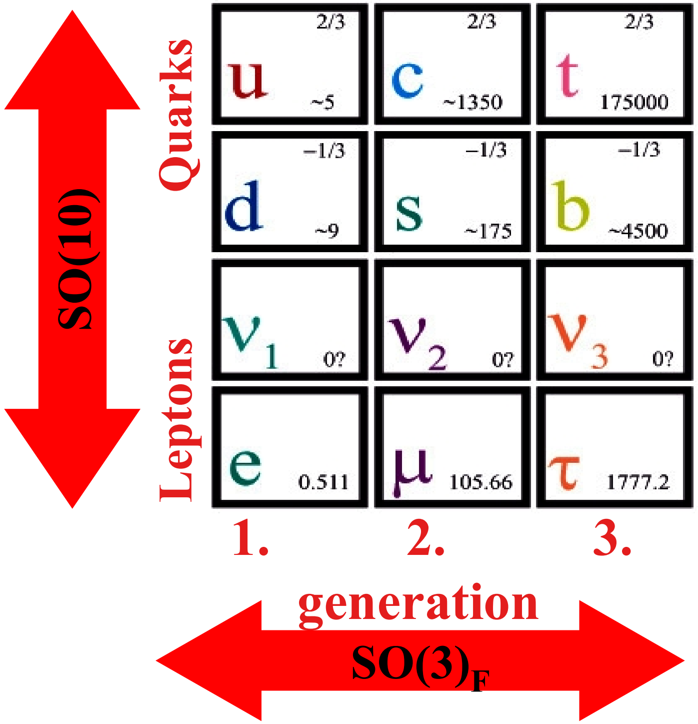
D_n: Chen et al. (2005), Kajiyama et al. (2007), Frampton et al. (1995,1996,2000), Frigerio et al. (2005), Babu et al. (2005), Kubo (2005), ...

T': Frampton et al. (1994,2007), Aranda et al. (1999,2000), Feruglio et al. (2007), Chen and Mahanthappa (2007)

Δ_n: Kaplan et al. (1994), Chou et al. (1997), de Medeiros Varzielas et al. (2005), ...

T_7: Luhn et al.

GUT ⊗ Flavour Unification



➔ GUT group ⊗ flavour group

example: 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: distinguish models further by future precision

NSIs & Neutrino Oscillations

Future precision oscillation experiments:

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

precision experiments migh see new effects beyond oscillations!

➔ modifications of 3f oscillation formulae, different L/E

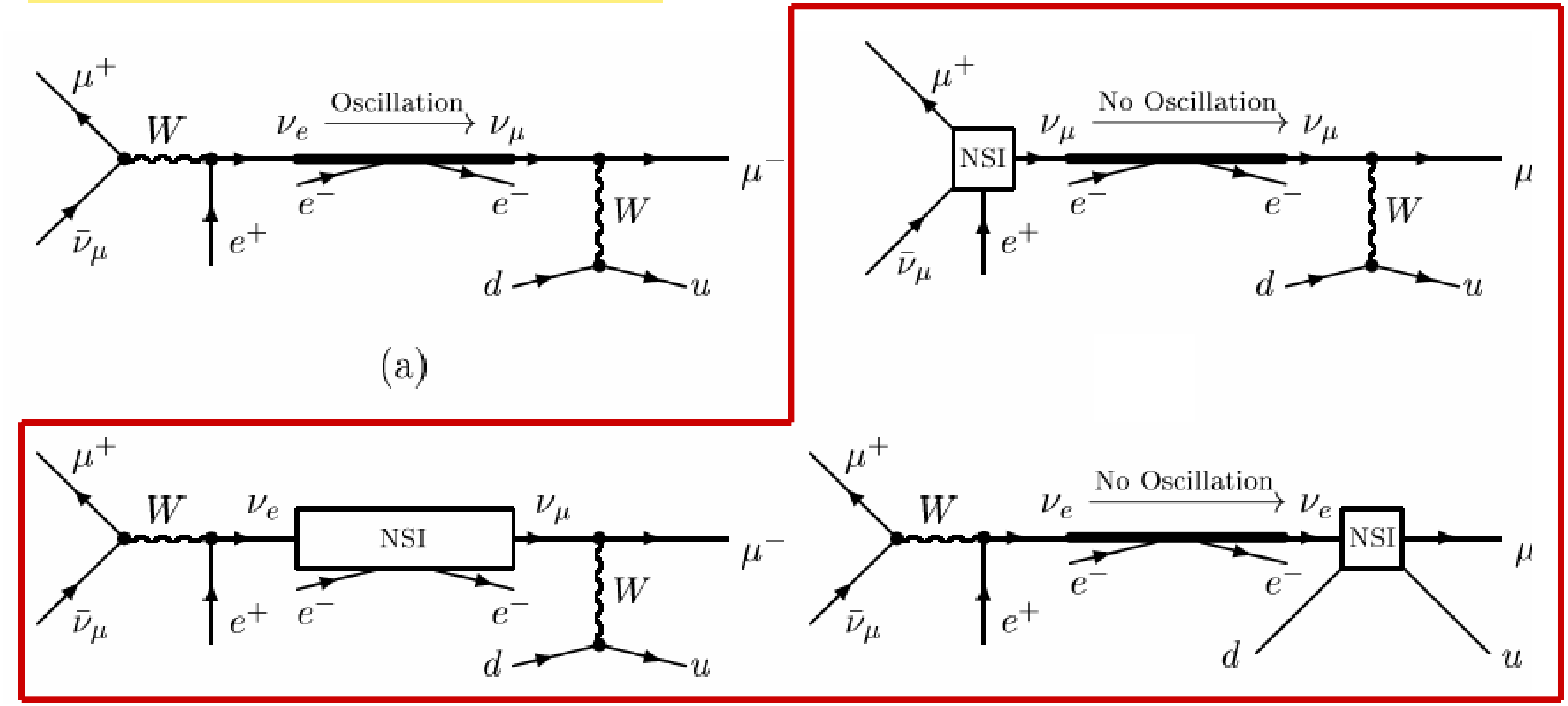
➔ small event rates: offset in oscillation parameters

➔ Non Standard Interactions = NSI's

NSIs interfere with Oscillations

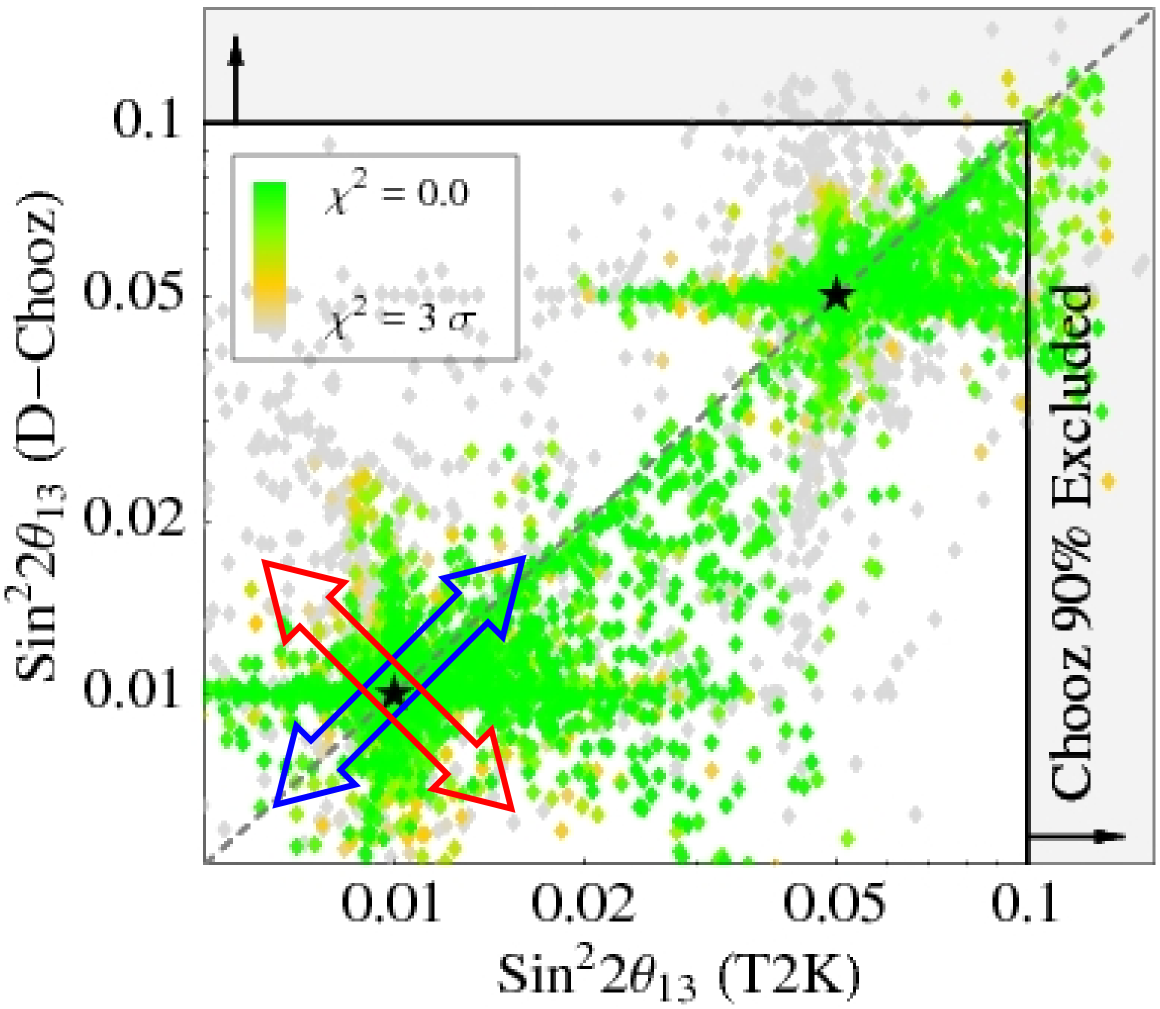
the "golden" oscillation channel

NSI contributions to the "golden" channel



note: interference in oscillations ~ε ⇔ FCNC effects ~ε^2

NSI: Offset and Mismatch in θ_{13}



Kopp, ML, Ota, Sato

redundant measurement of θ_{13}

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

scatter-plot:

- **ε values random**
- **below existing bounds**
- **random phases**

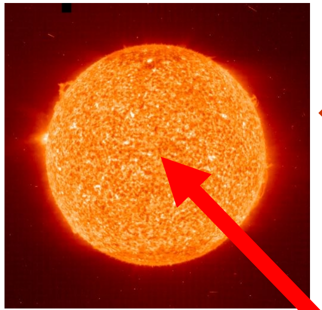
NSIs can lead to:

- **offset**
- **mismatch**

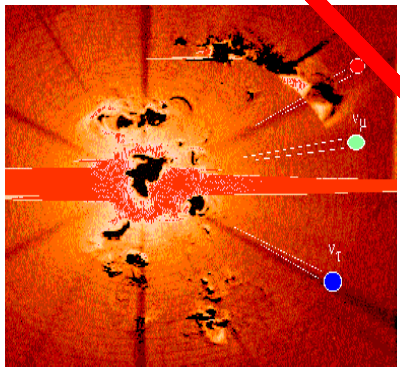
➔ **redundancy**

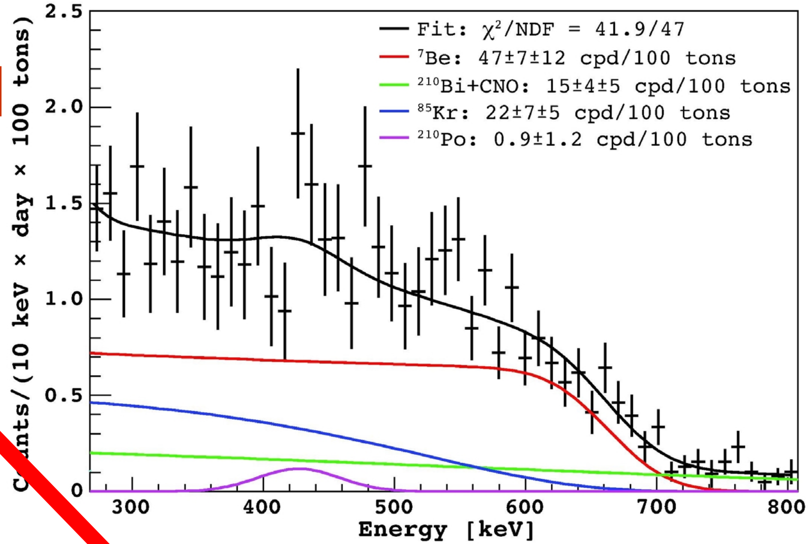
➔ **interesting potential**

New Physics & Neutrino Sources



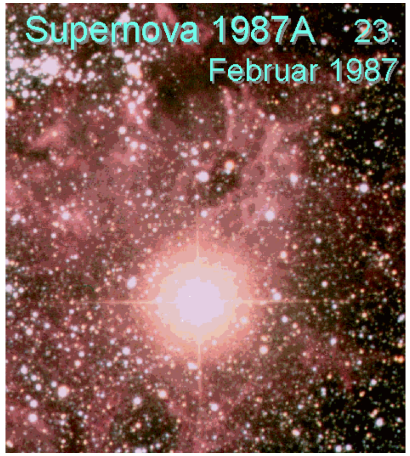
← Su





y: →

ae



rs →

BOREXINO

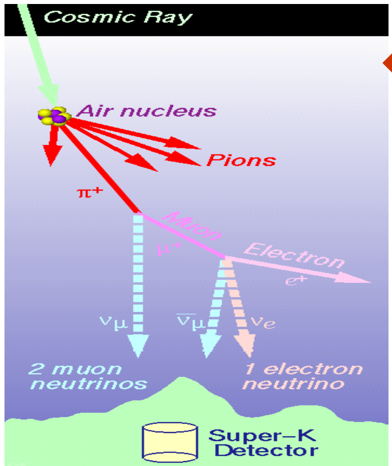
more to come:

More statistics and reduced systematics

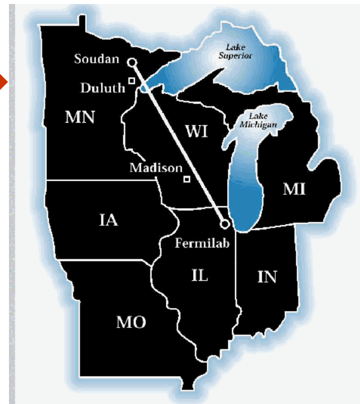
➔ 3.5% seasonal variation…

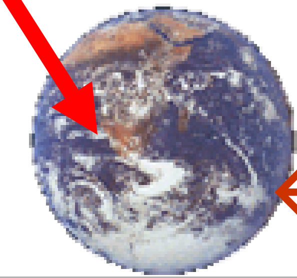
➔ geo-neutrinos, …

← Atmosphere



Accelerators →





← Earth

Conclusions

- **neutrino physics very promising ➔ unique information**

  ➔ sources ➔ important connections to various fields

  ➔ particle physics properties

- **first solid particle physics beyond the standard model**

  - up to 9 more parameters

  - 1st explicit fermion mass terms

  - lepton number violation violation

- **future: precision neutrino physics**

  - very precise measurements

  - NSIs: offsets & mismatch possible ➔ redundancy

  - synergies with LHC and LFV physics

- **interpreting & understanding flavour structures**

  - flavour symmetries - GUTs - SUSY

  - …various fancier ideas

Neutrinos probe new physics in many ways!